Proceedings of the 27th Workshop on General Relativity and Gravitation in Japan

November 27th–December 1st 2017

Higashi Hiroshima Arts & Culture Hall Kurara, Saijo, Higashi-hiroshima, Japan

Volume 1

Workshop Information

Oral Presentations: Day 1, 2

http://www-tap.scphys.kyoto-u.ac.jp/jgrg/index.html

Contents

Preface

The Nobel Prize for Physics 2017 was awarded to the researchers from the Laser Interferometer Gravitational-Wave Observatory (LIGO) Group for their decisive contributions to the LIGO detector and the observation of gravitational waves. In August 2017, the Advanced LIGO detector and Advanced Virgo gravitational-wave detectors first observed a binary neutron star merger event. This merger event was observed not only with the gravitational wave but also electromagnetically at frequencies from radio to gamma rays. These events initiated the breaking dawn of the new era of gravitational wave physics in multi-messenger astronomy. In such a memorable year, we had arranged the 27th Workshop on General Relativity and Gravitation in Japan (JGRG) at Higashi Hiroshima Arts & Culture Hall Kurara in Saijo, Higashi-Hiroshima from November 27 to December 1, hosted by the theoretical astrophysics group of Hiroshima University.

We invited outstanding lecturers, who are very active in the theoretical and observational research fields, such asVladimir Karas (Astronomical Institute, Czech Academy of Sciences), Kenji Toma (Tohoku University, Japan), Diego Blas (CERN TH, Switzerland), Patric Brady (University of Wisconsin-Milwaukee, USA), Takashi Nakamura(Kyoto University, Japan), Koji Kawabata (Hiroshima University, Japan), Nicola Bartolo (Padova University, INFN, Italy), Hideyuki Tagoshi (ICRR, University of Tokyo, Japan), Yasufumi Kojima (Hiroshima University, Japan), Robert R. Caldwell (Dartmouth University, USA), Masaki Shigemori (Queen Mary London, YITP), and Carlos Herdeiro (Aveiro University, Portugal). In addition to the 12 invited speakers, 82 contribution talks were given along with 40 poster presentations. The total number of participants was 184, including 22 participants from 11 overseas countries.

The workshop was supported by MEXT Grant-in-Aid for Scientific Research on Innovative Areas ”Gravitational wave physics and astronomy: Genesis” (PI: Takahiro Tanaka), A02 “New developments of gravity theory research in gravitational wave physics” (PI: Shinji Mukohyama), MEXT Grant-in-Aid for Scientific Research on Innovative Areas ”Cosmic Acceleration” (PI: Hitoshi Murayama), C01 ” Cosmic Acceleration from Ultimate Theory” (PI: Hiroshi Ooguri), a subsidy for the promotion of science by Higashi-hiroshima city, and Hiroshima University under the ”Program for Promoting the Enhancement of Research Universities.” We would like to thank all the participants for their generous assistance during JGRG27.

Kazuhiro Yamamoto
(on behalf of JGRG27 LOC)

Organizing Committee

Scientific Organizing Committee

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Takeshi Chiba (Nihon University),
Tomohiro Harada (Rikkyo),
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Local Organizing Committee (Hiroshima University)

Kazuhiro Yamamoto (Chair),
Yasufumi Kojima,
Nobuhiro Okabe,
Tomohiro Inagaki

Presentation Award

The JGRG presentation award program was established at the occasion of JGRG22 in 2012. This year, we are pleased to announce the following five winners of the Outstanding Presentation Award for their excellent presentations at JGRG27. The winners were selected by the selection committee consisting of the JGRG26 SOC based on ballots of the participants.

Hayato Motohashi (YITP, Kyoto University)
"Healthy degenerate theories with arbitrary higher-order derivatives"(Oral)

Shun Arai (Nagoya University)
"Constraints on Horndeski theory with Gravitational Waves observations"(Oral)

Keisuke Inomata (ICRR, The University of Tokyo)
"O(10)Msolar primordial black holes and string axion dark matter"(Oral)

Emi Masaki (Kobe University)
"Can gravitons be converted into dark photons?"(Oral)

Kota Ogasawara (Rikkyo University)
"Collision of two shells with a high center-of-mass energy in the Banados-Teitelboim-Zanelli spacetime"(Oral)

Eliska Polaskova (Charles University)
"Quasilocal horizons in inhomogenenous cosmological models"(Poster)

Yosuke Misonoh (Waseda University)
"Imitating equation of motion with deep learning"(Poster)

The 27th Workshop on General Relativity and Gravitation in Japan

27(Mon) November - 1(Fri) December 2017

Kurara Hall, Saijo Higashi-hiroshima

TIME	MON		TUE		WED		THU		FRI
9:30 - 9:45	Registration		Patric Brady (Univ. of Wisconsin-Milwaukee)		Nicola Bartolo (Padova Univ., INFN)				Carlos Herdeiro (Aveiro Univ.)
9:45 - 10:00									
10:00 - 10:15							Robert R. Caldwell (Dartmouth Univ.)		
10:15 - 10:30									
10:30 - 10:45	Opening		Short poster talks(2/3)		Short poster talks(3/3)				Coffee break
10:45 - 11:00	Vladimir Karas (Astronomical Institute, Czech Academy of Sciences)		Coffee break		Coffee break				
11:00 - 11:15			Parallel session 2a	Parallel session 2b	Parallel session 4a	Parallel session 4b	Coffee break		session 8a
11:15 - 11:30							Parallel session 6a	Parallel session 6b	
11:30 - 11:45									
11:45 - 12:00	Short poster talks(1/3)								Presentation awards
12:00 - 12:15									Closing
12:15 - 12:30									
12:30 - 14:00	Lunch & poster view		Lunch & poster view		Lunch & poster view		Lunch & poster view		
14:00 - 14:15	Parallel session 1a	Parallel session 1b	Parallel session 3a	Parallel session 3b	Parallel session 5a	Parallel session 5b	Parallel session 7a	Parallel session 7b	
14:15 - 14:30									
14:30 - 14:45									
14:45 - 15:00									
15:00 - 15:15	Coffee break & poster view								
15:15 - 15:30					Coffee break & poster view				
15:30 - 15:45			Coffee break & poster view				Coffee break & poster view		
15:45 - 16:00	Kenji Toma (Tohoku Univ.)								
16:00 - 16:15									
16:15 - 16:30					Hideyuki Tagoshi (ICRR, Univ. of Tokyo)				
16:30 - 16:45			Takashi Nakamura (Kyoto Univ.) Koji Kawabata (Hiroshima Univ., HASC)				Masaki Shigemori (Queen Mary London, YITP)		
16:45 - 17:00	Diego Blas (CERN TH)				Yasufumi Kojima (Hiroshima Univ.)				
17:00 - 17:15									
17:15 - 17:30									
17:30 - 17:45									
17:45 - 18:00					group photo		SOC meeting		
18:00 - 20:00					Banquet				

The 27th Workshop on General Relativity and Gravitation in Japan

27(Mon) November - 1(Fri) December 2017
Kurara Hall, Saijo Higashi-hiroshima

November 27 (MON)

9:30 - **Registration**

10:30 - 10:45 **Opening**

10:45 - 11:45 **(Chair Yasusada Nambu)**
Vladimir Karas (Astronomical Institute, Academy of Sciences, Prague)
Structure of relativistic fluid tori near black holes: effects of self-gravity and electric charge

11:45 - 12:30 **Short poster talks (1/3)**

12:30 - 14:00 **Lunch & poster view (2F room 202-203)**

14:00 - 15:00 **Parallel session 1a & 1b**

Parallel session 1a (Small Hall)
(Chair Hideyuki Tagoshi)

1a1	14:00 - 14:15	**Hajime Sotani (NAOJ)**	**Gravitational waves from protoneutron stars and asteroseismology**
1a2	14:15 - 14:30	**Nami Uchikata (ICRR U. of Tokyo)**	**Black hole ringdown analysis of two-mode signal**
1a3	14:30 - 14:45	**Tak Yamamoto (Kyoto U.)**	**Analysis of ringdown gravitational waveform by neural network**
1a4	14:45 - 15:00	**Remya Nair (Kyoto U.)**	**Synergy between ground and space-based GW interferometers**

Parallel session 1b (3F Salon Hall)
(Chair Ken-ichi Nakao)

1b1	14:00 - 14:15	**Satsuki Matsuno (Osaka City U.)**	**Black holes submmerged in AdS**
1b2	14:15 - 14:30	**Jasel Berra Montiel (Universidad Autonoma de San Luis Potosi)**	**The loop representation of Quantum Gravity as a Deformation Quantization**
1b3	14:30 - 14:45	**Hayato Motohashi (YITP Kyoto U.)**	**Healthy degenerate theories with arbitrary higher-order derivatives**
1b4	14:45 - 15:00	**Aya Iyonaga (Rikkyo U.)**	**Degenerate higher-order multi-scalar-tensor theories**

15:00 - 16:00 **Coffee & poster view (2F room 202 -203)**

(Chair Motoyuki Saijo)
16:00 - 17:00 **Kenji Toma (Tohoku U.)**
Theoretical and Observational Studies on Relativistic Jets Driven by Black Holes
17:00 - 18:00 **Diego T. Blas (CERN TH)**
Testing gravitation with gravitational waves

November 28 (TUE)

(Chair Shinji Tsujikawa)
9:30 - 10:30 **Patric Brady (Univ. of Wisconsin-Milwaukee)**
When neutron stars collide

10:30 - 10:45 **Short poster talks (2/3)**

10:45 - 11:00 **Coffee**

11:00 - 12:30 **Parallel session 2a & 2b**

Parallel session 2a (Small Hall)
(Chair Yasufumi Kojima)

2a1	11:00 - 11:15	**Kei Yamada (Kyoto U.)**	**BH perturbations & gauge dof in the near-horizon limit**

2a2	11:15 - 11:30	Toshiaki Ono (Hirosaki U.)	Gravitomagnetic bending angle of light in stationary axisymmetric spacetimes 1: Formulation
2a3	11:30 - 11:45	Asahi Ishihara (Hirosaki U.)	Gravitomagnetic bending angle of light in stationary axisymmetric spacetimes 2: Application
2a4	11:45 - 12:00	Anton Khirnov (Charles U.)	A new slicing condition for axisymmetric gravitational wave collapse
2a5	12:00 - 12:15	Motoyuki Saijo (Waseda U.)	Dynamics of relativistic r-mode instability in rotating relativistic stars
2a6	12:15 - 12:30	Fabio Novaes (UFRN)	Kerr-de Sitter Quasinormal Modes from Accessory Parameter Expansions
	Parallel session 2b (3F Salon Hall) (Chair Shinji Mukohyama)		
2b1	11:00 - 11:15	Anzhong Wang (Baylor U.)	Pre-inflationary universe in loop quantum cosmology
2b2	11:15 - 11:30	Kazufumi Takahashi (RESCEU U. of Tokyo)	Extended mimetic gravity: Hamiltonian analysis and gradient instabilities
2b3	11:30 - 11:45	Shingo Akama (Rikkyo U.)	The effect of the spatial curvature in the early universe in the Horndeski theory and beyond Horndeski theory
2b4	11:45 - 12:00	Rampei Kimura (Tokyo Institute of Technology)	Are redshift-space distortions actually a probe of growth of structure?
2b5	12:00 - 12:15	Shin'ichi Hirano (Rikkyo U.)	Matter bispectrum in GLPV theory
2b6	12:15 - 12:30	Shun Arai (Nagoya U.)	Constraints on Horndeski theory with Gravitational Waves observations
	12:30 - 14:00	Lunch & poster view	
	14:00 - 15:45	Parallel session 3a & 3b	
	Parallel session 3a (Small Hall) (Chair Hideki Asada)		
3a1	14:00 - 14:15	Tomohiro Harada (Rikkyo U.)	Spins of primordial black holes formed in the matter-dominated era
3a2	14:15 - 14:30	Menglei Zhou (Fudan U.)	Iron Kα line of Kerr black holes with Proca hair
3a3	14:30 - 14:45	Atsushi Nishizawa (Nagoya U.)	Cross-correlating GW and galaxies to identify the host galaxies of binary black holes
3a4	14:45 - 15:00	Tatsuya Narikawa (ICRR U. of Tokyo)	Constraining bimetric gravity by gravitational wave events from compact binary coalescences
3a5	15:00 - 15:15	Naoki Tsukamoto (Huazhong U. of Science and Technology)	A simple strong deflection limit analysis in a general asymptotically flat, static, spherically symmetric spacetime
3a6	15:15 - 15:30	Chulmoon Yoo (Nagoya U.)	PBH abundance from the random Gaussian curvature perturbation and a local density threshold
3a7	15:30 - 15:45	Keisuke Inomata (ICRR U. of Tokyo)	O(10)Msolar primordial black holes and string axion dark matter
	Parallel session 3b (3F Salon Hall) (Chair Hideo Kodama)		
3b1	14:00 - 14:15	Yota Watanabe (Kavli IPMU, YITP)	Stable cosmology in chameleonic bigravity
3b2	14:15 - 14:30	Michele Oliosi (YITP Kyoto U.)	Horndeski extension of the minimal theory of quasidilaton massive gravity
3b3	14:30 - 14:45	Alberto Molgado (Universidadd Autonoma de San Luis Potosi)	MacDowell-Mansouri gravity model from a covariant polysymplectic perspective
3b4	14:45 - 15:00	Mai Yashiki (Yamaguchi U.)	Observational test of the unified model in inflation and dark energy in f(R) gravity
3b5	15:00 - 15:15	Shuntaro Mizuno (YITP Kyoto U.)	Primordial perturbations from hyperinflation
3b6	15:15 - 15:30	Vincenzo Vitagliano (Keio U.)	Covariantly Quantum Field Theory
3b7	15:30 - 15:45	Shintaro Nakamura (Tokyo U. of Science)	Cosmology in beyond-generalized Proca theories
	15:45 - 16:45	Coffee & poster view	
		(Chair Kentaro Takami)	
	16:45 - 17:15	Takashi Nakamura (Kyoto Univ.) New development in astrophysics through multimessenger observations of gravitational waves from 2012 to 2017	
	17:15 - 17:45	Koji Kawabata (Hiroshima Univ., HASC) J-GEM Follow-up Observations for gravitational wave events and GW170817	

November 29 (WED)

(Chair Masaaki Takahashi)
9:30 - 10:30 **Nicola Bartolo (Padova Univ, INFN)**
Inflation: current status and future prospects

10:30 - 10:45 **Short poster talks (3/3)**

10:45 - 11:00 **Coffee**

11:00 - 12:30 **Parallel session 4a & 4b**

Parallel session 4a (Small Hall)

(Chair Takeshi Chiba)

4a1	11:00 - 11:15	Yuki Sakakihara (Osaka City U.)	Dynamics in f(R) gravity with bounded curvature
4a2	11:15 - 11:30	Ryuichi Fujita (YITP Kyoto U.)	Gravitational waves from a particle orbiting a Kerr black hole in Brans-Dicke theory
4a3	11:30 - 11:45	Ippei Obata (Kyoto U.)	Primordial GWs sourced by gauge field
4a4	11:45 - 12:00	Tomohiro Fujita (Kyoto U.)	Statistically Anisotropic Primordial Gravitational Waves from Gauge Field
4a5	12:00 - 12:15	Daiske Yoshida (Kobe U.)	Exploring the string axiverse and parity violation in gravity with gravitational waves
4a6	12:15 - 12:30	Takashi Hiramatsu (Rikkyo U.)	Reconstruction of primordial tensor power spectrum from B-mode observations

Parallel session 4b (3F Salon Hall)

(Chair Hideki Ishihara)

4b1	11:00 - 11:15	Kentaro Tomoda (Kobe U.)	Curvature obstructions to the existence of isometries
4b2	11:15 - 11:30	Masashi Kimura (Instituto Superior Tecnico, U.of Lisbon)	A simple test for stability of black hole by S-deformation
4b3	11:30 - 11:45	Yoshimune Tomikawa (Matsuyama U.)	On uniqueness of static spacetimes with non-trivial conformal scalar field
4b4	11:45 - 12:00	Makoto Nakamura (Yamagata U.)	On the Cauchy problem for semi-linear Klein-Gordon equations in de Sitter spacetime
4b5	12:00 - 12:15	Taishi Ikeda (Nagoya U.)	Dyson bound of energy flux in gravitational collapse
4b6	12:15 - 12:30	Pedro Cunha (Aveiro U. & IST Lisbon)	Light ring stability in ultra-compact objects

12:30 - 14:00 **Lunch & poster view**

14:00 - 15:15 **Parallel session 5a & 5b**

Parallel session 5a (Small Hall)

(Chair Takahiro Tanaka)

5a1	14:00 - 14:15	Ryo Kato (Kobe U.)	Constraint on the axion dark matter using pulsar timing arrays
5a2	14:15 - 14:30	Emi Masaki (Kobe U.)	Can gravitons be converted into dark photons?
5a3	14:30 - 14:45	Arata Aoki (Kobe U.)	Structure formation with fuzzy dark matter
5a4	14:45 - 15:00	Soichiro Morisaki (RESCEU U. Tokyo)	Search for non-minimally coupled scalar field dark matter with gravitational-wave observations
5a5	15:00 15:15	Osamu Seto (Hokkaido U.)	Non-minimally coupled Coleman-Weinberg inflation

Parallel session 5b (3F Salon Hall)

(Chair Tomohiro Harada)

5b1	14:00 - 14:15	Masato Minamitsuji (CENTRA, IST, U. of Lisbon)	Boson stars in a generalized Proca theory
5b2	14:15 - 14:30	Kota Ogasawara (Rikkyo U.)	Collision of two shells with a high center-of-mass energy in the Banados-Teitelboim-Zanelli spacetime
5b3	14:30 - 14:45	Tatsuya Ogawa (Osaka City U.)	Charge screened non-topological solitons
5b4	14:45 - 15:00	Takayuki Ohgami (Yamaguchi U.)	Optical Images of Gravasta Surrounded by dust
5b5	15:00 - 15:15	Tetu Makino (Yamaguchi U.)	Mathematical study of rotating gaseous stars

15:15 - 16:15 **Coffee & poster view**

(Chair Takashi Nakamura)
16:15 - 17:00 **Hideyuki Tagoshi (ICRR Univ. of Tokyo)**
Status and prospect of KAGRA
17:00 - 17:45 **Yasufumi Kojima (Hiroshima Univ.)**
Slow rotation in GR

group photo
18:00 - 20:00 **Banquet (2F Restaurant)**

November 30 (THU)

(Chair Misao Sasaki)
10:00 - 11:00 **Robert R. Caldwell (Dartmouth Univ.)**
A unique and observable prediction in a toy model of axion gauge field inflation

11:00 - 11:15 **Coffee**

11:15 - 12:30 **Parallel session 6a & 6b**

Parallel session 6a (Small Hall)
(Chair Kei-ichi Maeda)

6a1	11:15 - 11:30	Junsei Tokuda (Kyoto U.)	Theoretical consistency of stochastic approach
6a2	11:30 - 11:45	Seiga Sato (Waseda U.)	Hybrid Higgs Inflation
6a3	11:45 - 12:00	Kazuhiro Kogai (Nagoya U.)	Exploring primordial anisotropic non-Gaussianity from galaxy alignment
6a4	12:00 - 12:15	Sakine Nishi (Rikkyo U.)	Anisotropic inflation in Horndeski theory
6a5	12:15 - 12:30	Hiroaki Tahara (RESCEU U. of Tokyo)	Perturbations in the anisotropic attractor with Horndeski theory

Parallel session 6b (3F Salon Hall)
(Chair Akihiro Ishibashi)

6b1	11:15 - 11:30	Naritaka Oshita (RESCEU U. Tokyo)	Probing atoms of spacetime with ringdown gravitational waves from a perturbed black hole
6b2	11:30 - 11:45	Antonino Flachi (Keio U.)	Topological currents and black holes
6b3	11:45 - 12:00	Kunihito Uzawa (Kwansei Gakuin U.	Supersymmetry breaking and singularity in dynamical brane backgrounds
6b4	12:00 - 12:15	Umpei Miyamoto (Akita Prefectural	Nonlinear perturbation of black branes at large D
6b5	12:15 - 12:30	Gon_alo Quinta (Superior Technical Institute, U. of Lisbon)	Vacuum polarization around a charged black hole in 5 dimensions

12:30 - 14:00 **Lunch & poster view**

14:00 - 15:45 **Parallel session 7a & 7b**

Parallel session 7a (Small Hall)
(Chair Jiro Soda)

7a1	14:00 - 14:15	Tomoya Kinugawa (ICRR U. of Tokyo)	Gravitational waves from remnants of first stars
7a2	14:15 - 14:30	Asuka Ito (Kobe U.)	Primordial gravitational waves and early universes
7a3	14:30 - 14:45	Yi-Peng Wu (RESCEU U. of Tokyo)	Inflationary fluctuations with phase transitions
7a4	14:45 - 15:00	Minxi He (RESCEU U. of Tokyo)	Higgs-R^2 Inflation
7a5	15:00 - 15:15	Kiyomi Hasegawa (Hirosaki U.)	A possible solution to the Hubble (non-)constant problem
7a6	15:15 - 15:30	Atsuhisa Ota (Tokyo Institute of Technology)	Spontaneous symmetry breaking in open systems: Toward application to EFT of inflation

Parallel session 7b (3F Salon Hall)
(Chair Tetsuya Shiromizu)

7b1	14:00 - 14:15	Alex Vano-Vinuales (Cardiff U.)	Free hyperboloidal evolution in spherical symmetry
7b2	14:15 - 14:30	Takafumi Kokubu (KEK)	Example of Null junction conditions: Energy emission from a naked singularity
7b3	14:30 - 14:45	Shinpei Kobayashi (Tokyo Gakugei U.)	Fuzzy spacetime in noncommutative gravity
7b4	14:45 - 15:00	Ren Tsuda (Ibaraki U.)	Expanding Polyhedral Universe in Regge Calculus
7b5	15:00 - 15:15	Leon Escobar Diaz (University of Tubingen, Germany)	Asymptotics of solutions of a hyperbolic formulation of the constraint equations
7b6	15:15 - 15:30	Akira Matsumura (Nagoya U.)	Large Scale Quantum Entanglement in de Sitter Spacetime

15:45 - 16:45 **Coffee & poster view**

(Chair Yuko Urakawa)
16:45 - 17:45 **Masaki Shigemori (Queen Mary London, YITP)**
The Black-Hole Microstate Program

December 1 (FRI)

(Chair Tsutomu Kobayashi)
9:30 - 10:30 **Carlos Herdeiro (Aveiro Univ.)**
Kerr black holes with bosonic hair: theory and phenomenology

10:30 - 10:45 **Coffee**

10:45 - 11:45 **Session 8a**

Session 8a (Small Hall)
(Chair Hisaaki Shinkai)

8a1	10:45 - 11:00	Yuko Urakawa (Nagoya U.)	Cosmological imprints of string axions in plateau
8a2	11:00 - 11:15	Hiromi Saida (Daido U.)	Exploring GR effects of super-massive BH at our galactic center
8a3	11:15 - 11:30	Kenji Tomita (YITP Kyoto U.)	Cosmological models with the energy density of random fluctuations and the Hubble-constant problem
8a4	11:30 - 11:45	Marcus Werner (YITP Kyoto U.)	Constructing predictive gravity theories

11:45 - 12:00 **Presentation Awards**
12:00 - **Closing (Kei-ichi Maeda)**

Poster Session

P01	Kiyoshi Shiraishi (Yamaguchi U.)	Large Boson Stars
P02	Tomotaka Suzuki (Hokkaido U.)	Study of the AdS_2 / CFT_1 correspondence with the contribution from the Weyl anomaly
P03	Keitarou Nanri (Yamaguchi U.)	Microlensing effect and shadows of massless braneworld black holes
P04	Keisuke Nakashi (Tokyogakugei U.)	Geodesics and repulsive gravity in BHT massive gravity
P05	Daisuke Nitta (Nagoya U.	Equivalence principle violation after reheating
P06	Takuma Tsukamoto (Nagoya U.)	Sequestering Mechanism in Scalar-Tensor Theory
P07	Shun Yamamoto (Osaka Institute of Technology)	Analysis of ringdown waveform using Auto-Regressive model
P08	Yingli Zhang (Tokyo U. of Science)	Oscillations of Power Spectrum from non-minimal coupling scalar fields of R^2 inflation
P09	Kouji Nakamura (NAOJ)	Double balanced homodyne detection
P10	Yushi Kawamoto (Yamaguchi U.)	f(R) inflation
P11	Masashi Kuniyasu (Yamaguchi U.)	Boson stars in DBI type k-field theories
P12	Suro Kim (Kobe U.)	Toward dissipative and stochastic effects in the EFT of inflation
P13	Tomohiro Nakamura (Nagoya U.)	Chameleon mechanism in inhomogeneous density profile
P14	Teerthal Patel (Nagoya U.)	Magnetogenesis in Axion Monodromy Inflation
P15	Yuya Nakamura (Hirosaki U.)	Weakly self-gravitating objects in Chern-Simons modified gravity
P16	Tsuyoshi Houri (Kyoto U.)	Hidden symmetries of the Jacobi equation
P17	Adrian-Ciprian Sporea (West U. of Timisoara)	Higher dimensional SdS black holes: fermionic Hawking radiation
P18	Kazuho Hiraga (Ibaraki U.)	Inflationary cosmology in M-theory
P19	Eliska Polaskova (Charles U., Prague)	Quasilocal horizons in inhomogenenous cosmological models
P20	Yoshiyuki Morisawa (Osaka City U.)	Cohomogeneity-one-string integrability
P21	Daisuke Yamauchi (Kanagawa U.)	Y-junction intercommutations of current carrying strings
P22	Masataka Tsuchiya (Nagoya U.)	Chaotic Motion of a Cohomogeneity-One String in Extremal Kerr Spacetime
P23	Tomoro Tokusumi (Nagoya U.)	Qubit Model of Hawking Radiation
P24	Kosei Morimoto (Hirosaki U.)	An inhomogeneous cosmology with Lambda where Omega_m and Omega_{Lambda} depend on each observed domain
P25	Hirotaka Yoshino (Osaka City U.)	Axion Bosenova and Gravitational Waves
P26	Yosuke Misonoh (Waseda U.)	Imitating equation of motion with deep learning
P27	Kazushige Ueda (Hiroshima U.)	Entanglement of the Vacuum between Left, Right, Future, and Past
P28	Masaaki Takahashi (Aichi U. of Education)	Jet-Disk structure in a Black hole Magnetosphere
P29	Hiroki Sakamoto (Hiroshima U.)	Attractor behavior of CMB fluctuations in gauged Nambu-Jona-Lasinio inflation

P30	Hisaaki Shinkai (Osaka Institute of Technology)	Event rates of gravitational waves in space-borne detectors based on a hierarchical growth model of SMBHs
P31	Norihiro Tanahashi (Kyushu U.)	Robinson-Trautman solutions with a scalar field
P32	Masashi Yamazaki (Nagoya U.)	Vainshtein mechanism in non-minimal dRGT massive gravity
P33	Shinya Tomizawa (Tokyo U. of Technology)	Asymptotically Flat Rotating Black Lens in Five Dimensions
P34	Toshifumi Noumi (Kobe U.)	Weak Gravity Conjecture and Infrared Consistency
P35	Ryo Saito (Yamaguchi U.)	Effective theories for the partial breaking of the Vainshtein mechanism
P36	Kentaro Takami (Kobe City College of Technology)	Neutron-star Radius from a Population of Binary Neutron Star Mergers
P37	Ulbossyn Ualikhanova (U. of Tartu)	Dynamical systems approach and generic properties of f(T) cosmology
P38	Siyi Zhou	Fluctuations through a Vibrating Bounce
P39	Marcello Rotondo (Nagoya U.)	Interferometry in superspace: decoherence of histories due to gravitational particle creation
P40	Ryotaku Suzuki (Osaka City U.)	Large D Effective Theory of General Relativity

The poster contributors are assigned to one-minute short talk. Only those who will participate from the 2nd or 3rd day are assigned on Tuesday or Wednesday. We expect that almost speakers give one-minute talk on the first day, however, if you cannot, please tell us which day you like to give your talk. Please prepare a (hopefully) 1-page pdf file for your presentation, and send it by e-mail to jgrg27-loc@ml.hiroshima-u.ac.jp, at least 24 hours in advance.

Monday 27th November

Registration 9:30–10:30

Opening 10:30–10:45

Kazuhiro Yamamoto (Hiroshima University)

Invited lecture 10:45–11:45

[Chair: Yasusada Nambu]

Vladimir Karas (Astronomical Institute, Czech Academy of Sciences),

“Structure of relativistic fluid tori near black holes: effects of self-gravity and electric charge“ (50+10)

[JGRG27 (2017) 112701]

Self-gravitating fluid tori with charge

V. Karas[1]

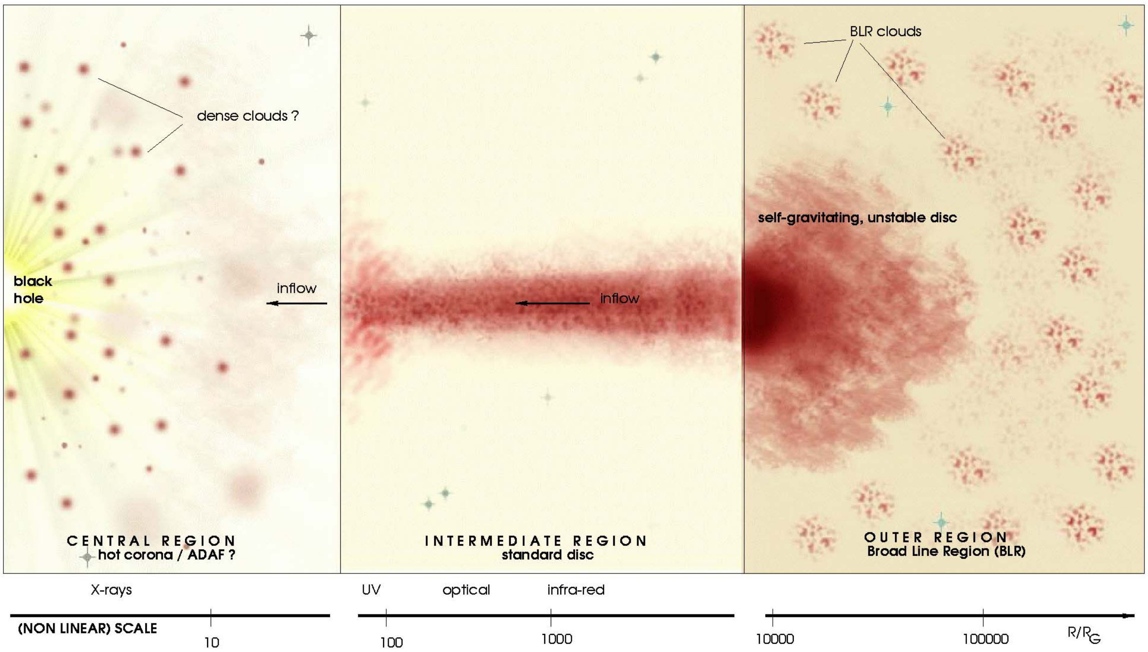
J. Kovář[2], P. Slaný[2], A.Trova[3]

[1]Astronomical Institute, Czech Academy of Sciences, Prague, Czech Republic

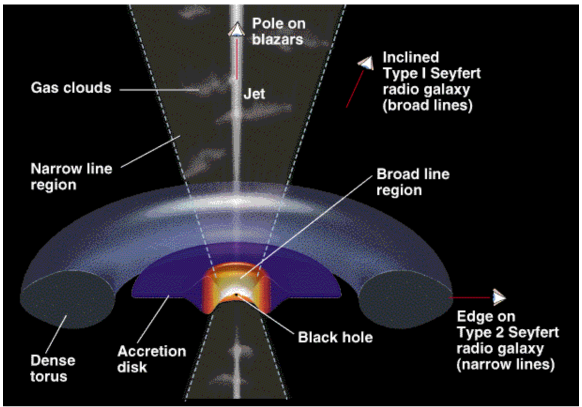
[2]Faculty of Philosophy and Science, Silesian University in Opava, Czech Republic

[3]ZARM – Centre of Applied Space Technology and Microgravity,
University of Bremen, Germany

The 27th Workshop on General Relativity and Gravitation, Saijo, Higashi-Hiroshima
27 Nov–1 Dec 2017



Collin & Hure, A&A (2001)



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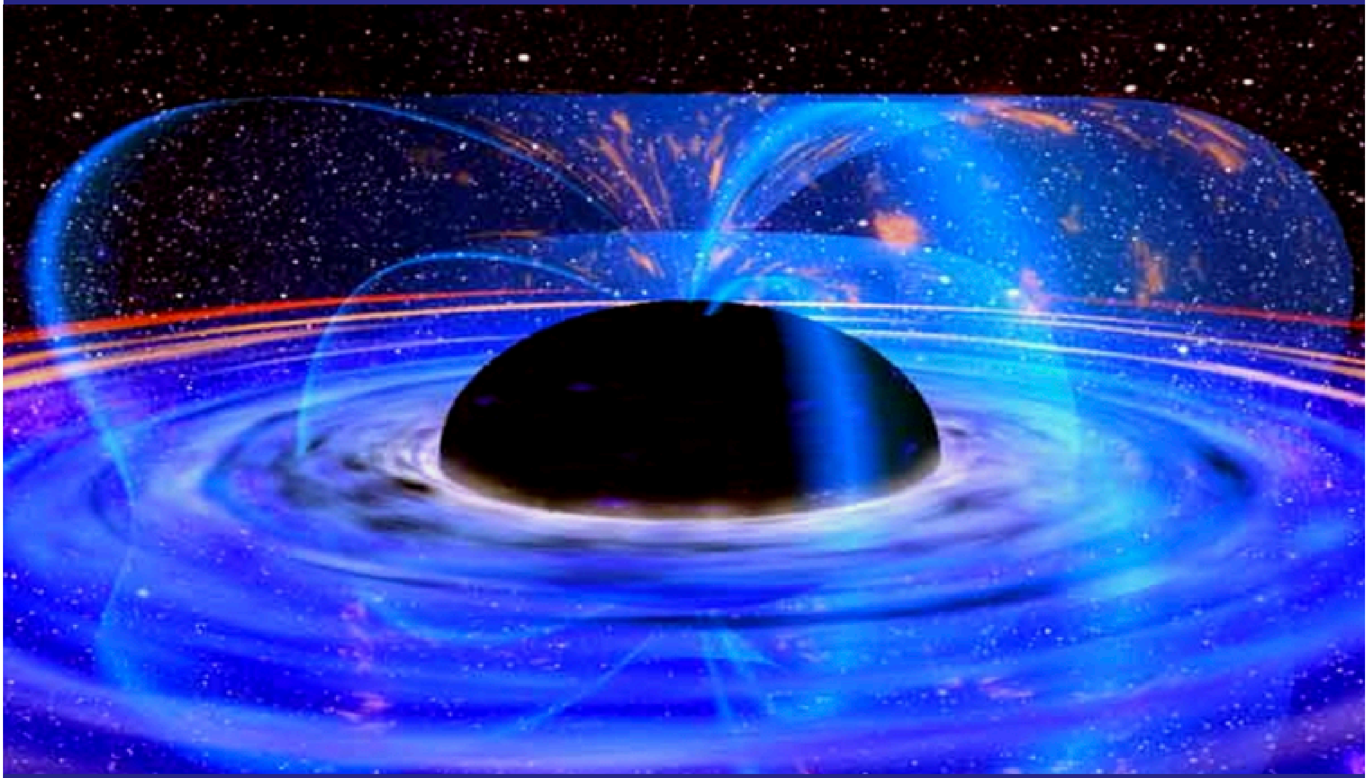
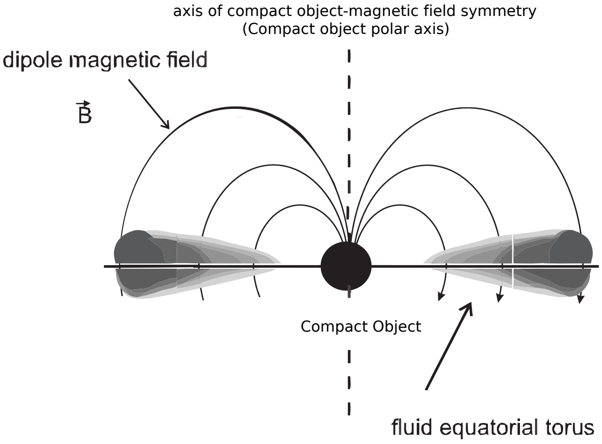
- Nuclei of galaxies: dusty tori and a central SMBH $(M \sim 10^6$–$10^9 M_\odot)$.
- At distance of a few $\times 10^3 R_g$ self-gravity starts operating (Collin & Hure 2001; Karas et al. 2004).



Newtonian vs. GR approach



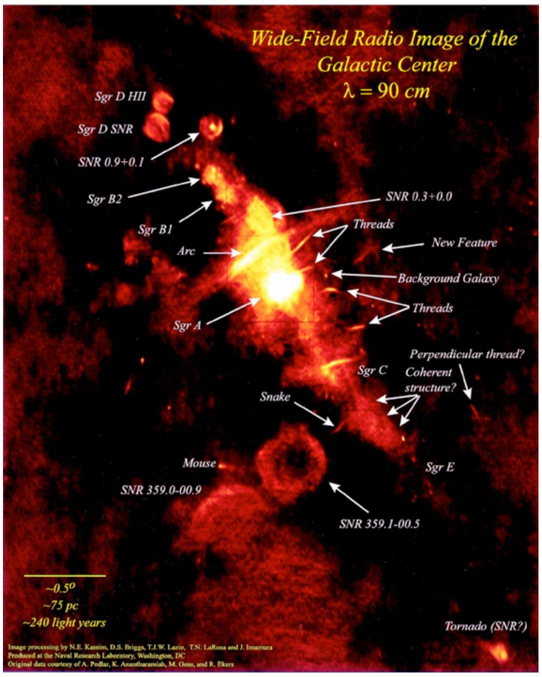
Forces

- Gravity of the central mass
- Internal pressure and electric charge of the fluid
- External magnetic and induced electric field
- Centrifugal force
- Self-gravity of the torus

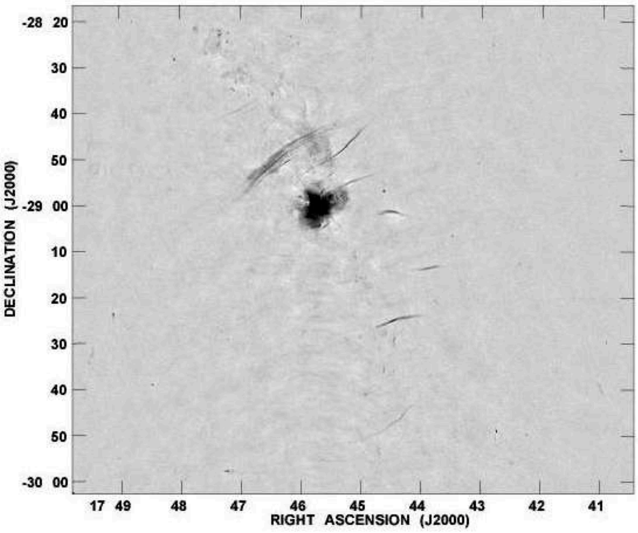
$$\nabla_\beta T^{\alpha\beta}_{\mathrm{mat}} = T^{\alpha\beta}_{\mathrm{ext}} J_\beta \rightarrow dh = dp/(p+\epsilon) \rightarrow \text{fluid surface: } h = 0.$$

Kovář, Kopáček, Karas, & Kojima, CQG (2013)

Filaments as tracers of ordered magnetic fields near SMBH

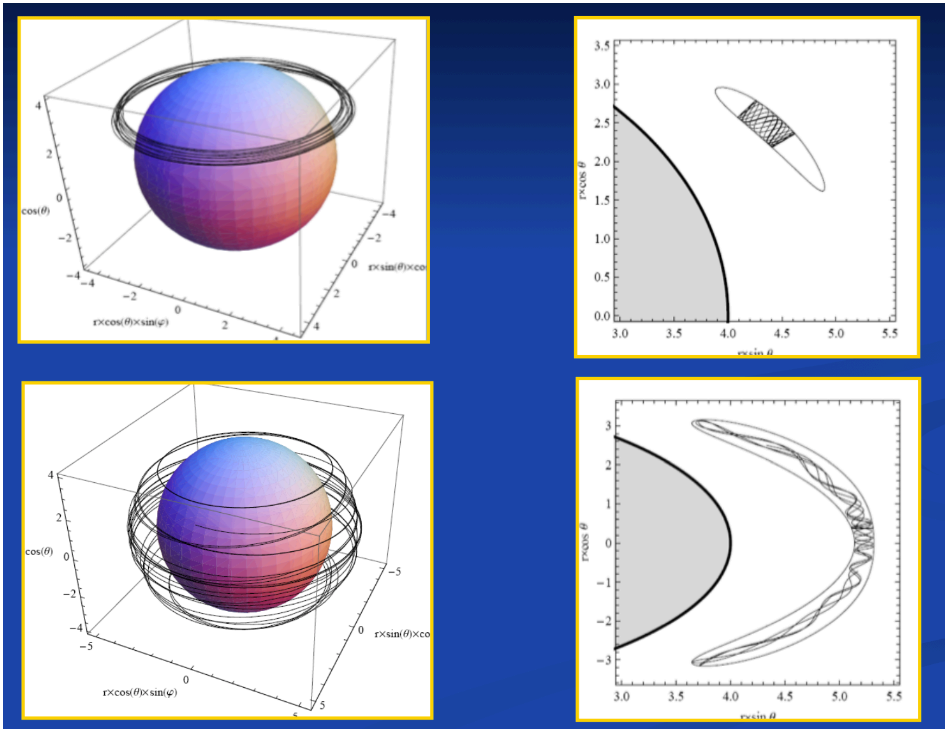


Black hole embedded
in an external magnetic field



LaRosa (2000, 2004)

Electrically charged particles: off-equatorial trajectories

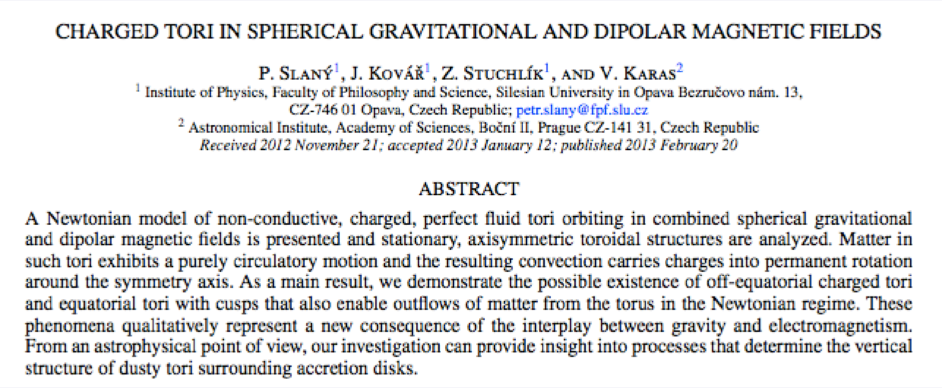


Howard et al. PRL (1999); Kovář et al., CQG (2010)

- Symmetries: (i) axial, (ii) mid-plane, (iii) stationarity.
- Equation of state: incompressible or polytropic fluid
- The integrability condition of the Euler equation → two unknown functions: the orbital velocity $v \equiv v_{\phi}(R, Z)$, and the specific charge profile $q \equiv q(R, Z)$.
- The fluid is embedded in an external magnetic field
- The torus is self-gravitating,

$$\nabla P = -\rho_{\mathrm{m}}\Phi - \rho_{\mathrm{m}}\nabla\Psi - \rho_{\mathrm{m}}\nabla\Psi_{\mathrm{Sg}} - \rho_{\mathrm{m}}\nabla\mathcal{M} \qquad (1)$$

Rotating magnetized torus – with a central body, with charge density of the fluid



CHARGED TORI IN SPHERICAL GRAVITATIONAL AND DIPOLAR MAGNETIC FIELDS

P. Slaný[1], J. Kovář[1], Z. Stuchlík[1], and V. Karas[2]
[1] Institute of Physics, Faculty of Philosophy and Science, Silesian University in Opava Bezručovo nám. 13, CZ-746 01 Opava, Czech Republic; petr.slany@fpf.slu.cz
[2] Astronomical Institute, Academy of Sciences, Boční II, Prague CZ-141 31, Czech Republic

Received 2012 November 21; accepted 2013 January 12; published 2013 February 20

ABSTRACT

A Newtonian model of non-conductive, charged, perfect fluid tori orbiting in combined spherical gravitational and dipolar magnetic fields is presented and stationary, axisymmetric toroidal structures are analyzed. Matter in such tori exhibits a purely circulatory motion and the resulting convection carries charges into permanent rotation around the symmetry axis. As a main result, we demonstrate the possible existence of off-equatorial charged tori and equatorial tori with cusps that also enable outflows of matter from the torus in the Newtonian regime. These phenomena qualitatively represent a new consequence of the interplay between gravity and electromagnetism. From an astrophysical point of view, our investigation can provide insight into processes that determine the vertical structure of dusty tori surrounding accretion disks.

Euler's equation

$$\rho_{\mathrm{m}}(\partial_t v_i + v^j \nabla_j v_i) = -\nabla_i P - \rho_{\mathrm{m}}\nabla_i\Psi + \rho_{\mathrm{e}}(E_i + \epsilon_{ijk}v^j B^k), \qquad (2)$$

Slaný et al (2013)

Euler's equation

$$\nabla P = -\rho_{\mathrm{m}} \nabla \Phi - \rho_{\mathrm{m}} \nabla \Psi - \rho_{\mathrm{m}} \nabla \mathcal{M} \tag{3}$$

Integrability conditions → constraints on the spatial distribution of charge, and the corresponding angular momentum profile

- Orbital velocity: a power law of the radius
- Different distribution of the specific charge density

Equilibrium solution → maxima for the pressure function → angular momentum distribution, strength of the magnetic field.

Equilibrium equation

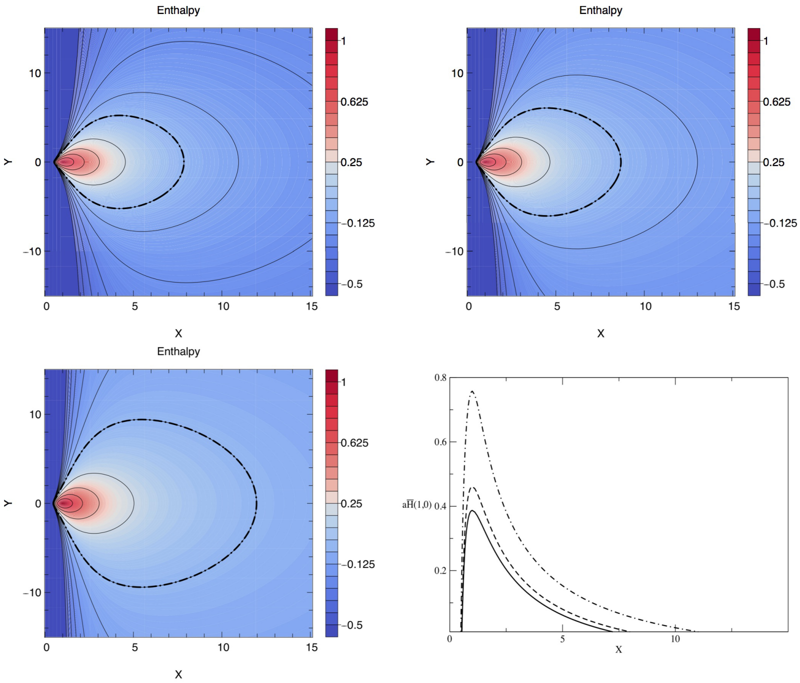
$$aH + d_t \Psi_{\mathrm{Sg}} + \Psi + b\Phi + e\mathcal{M} = \mathrm{const}, \tag{4}$$

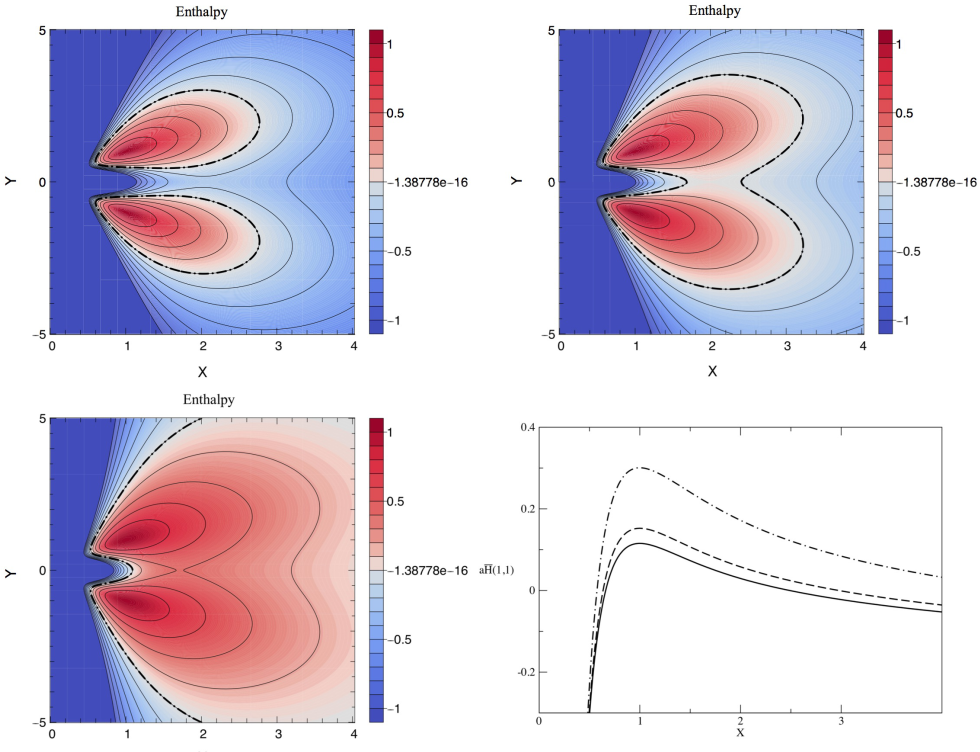
Contraints given by the integrability conditions

Solutions exist if H-function has a maximum → conditions on the magnetic field (value of e) and rotation (value of b). We have to choose a configuration:

- constant angular momentum vs. rigid rotation
- specific charge distribution within the torus
- strength of self-gravity (value of $d_t \equiv m/M$)

Maps of enthalpy → H-function





Strong gravity near a black hole combines with electromagnetic effects due to large-scale magnetic field; acts on electrically charged fluid. The toroidal configuration represents and idealized system that can be explored analytically. Our set-up has allowed us to study the mutual interaction between effects that are expected to occur in astrophysically realistic circumstances.

In active galactic nuclei, accretion of matter from the inner accretion disk leads to intense emission of X-rays. The emerging energetic radiation then irradiates the outer torus, where temperature drops below the critical value for dust sublimation. Dust grains acquire electric charge due to photoelectric effect and the complex plasma environment.

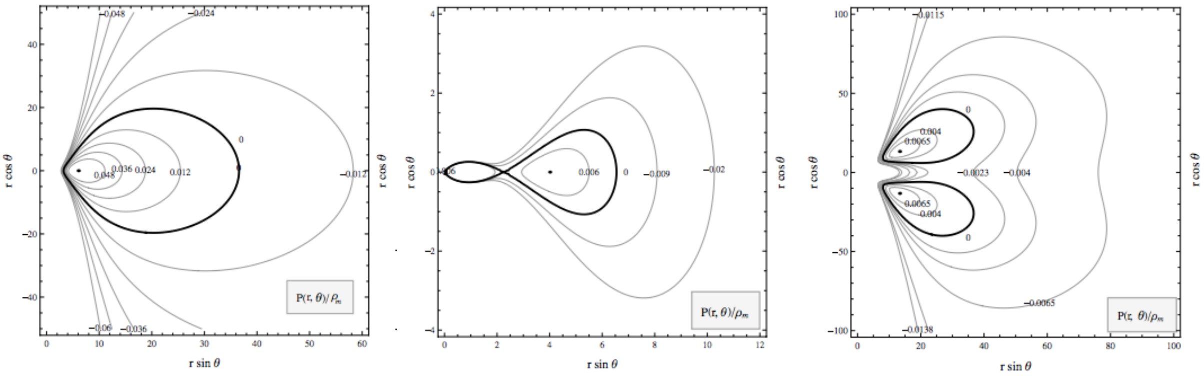
At the same time, the continued accretion events cause the black hole to spin up on a long (cosmological) time-scales. Therefore, the effects of fluid charging and rotation of the central black hole need to be taken into account together. Note that the equilibrium electric charge *on the black hole* itself is likely to converge to an very small value.

- The condition of existence of the tori changes with the strength of self-gravity.
- We find the toroidal configuration, the closed isobars with cusps, and the off-equatorial structures.
- The maximum of pressure rises with self-gravity parameter.
- The closed analytical form provides a way to set constraints on the existence of different configurations.

References: Trova A. et al. (2016), ApJSS, 226, id. 12
Kovář et al. (2016), Phys. Rev D, 93, id. 124055

Thank you!

Discussion



Neukirch A&A (1993); Slaný et al. ApJSS (2016)

Session1a 14:00–15:00 [Chair: Hideyuki Tagoshi]

1a1. Hajime Sotani (NAOJ),

“Gravitational waves from protoneutron stars and asteroseismology“ (10+5)

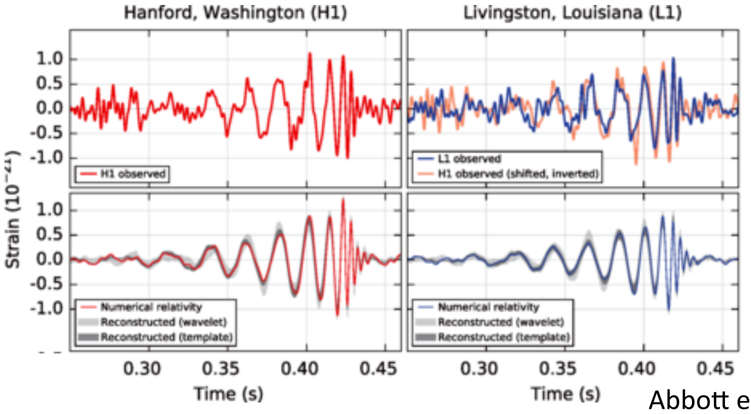
[JGRG27 (2017) 112702]

Gravitational waves from protoneutron stars and asteroseismology

Hajime SOTANI (NAOJ)

Dawn of GW astronomy era

- First detection of GWs from BH-BH merger (GW150914)

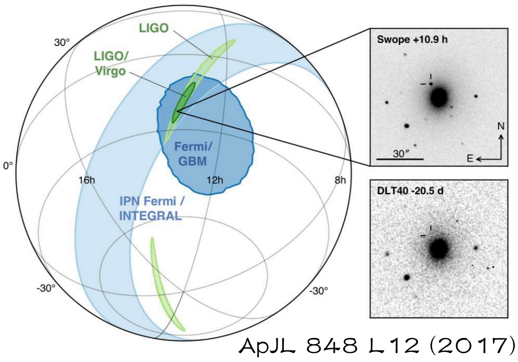


Abbott et al. 16

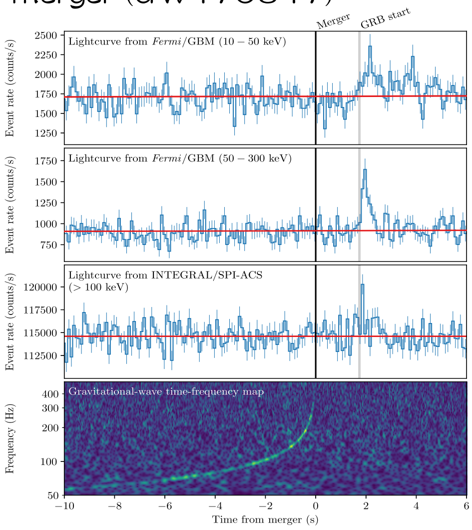
  - $36M_\odot$-$29M_\odot$ binary BH merger (410Mpc)
- GW151226 (Abbott et al. 16) : $14M_\odot$-$7.5M_\odot$ BBH (440Mpc)
- GW170104 (Abbott et al. 17) : $31M_\odot$-$19M_\odot$ BBH (880Mpc)

Dawn of GW astronomy era

- First detection of GWs from NS-NS merger (GW170817)
  - first BNS + EM counter part
  - total mass = 2.74$M_\odot$ (40Mpc)



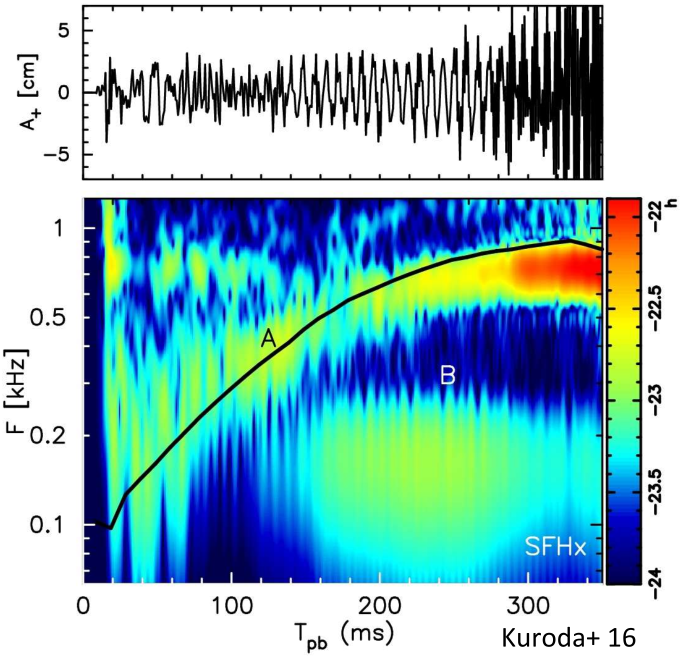
ApJL 848 L12 (2017)



ApJL 848 L13 (2017)

- promising GW sources;
  - BH-BH, BH-NS, and NS-NS mergers
  - supernovae

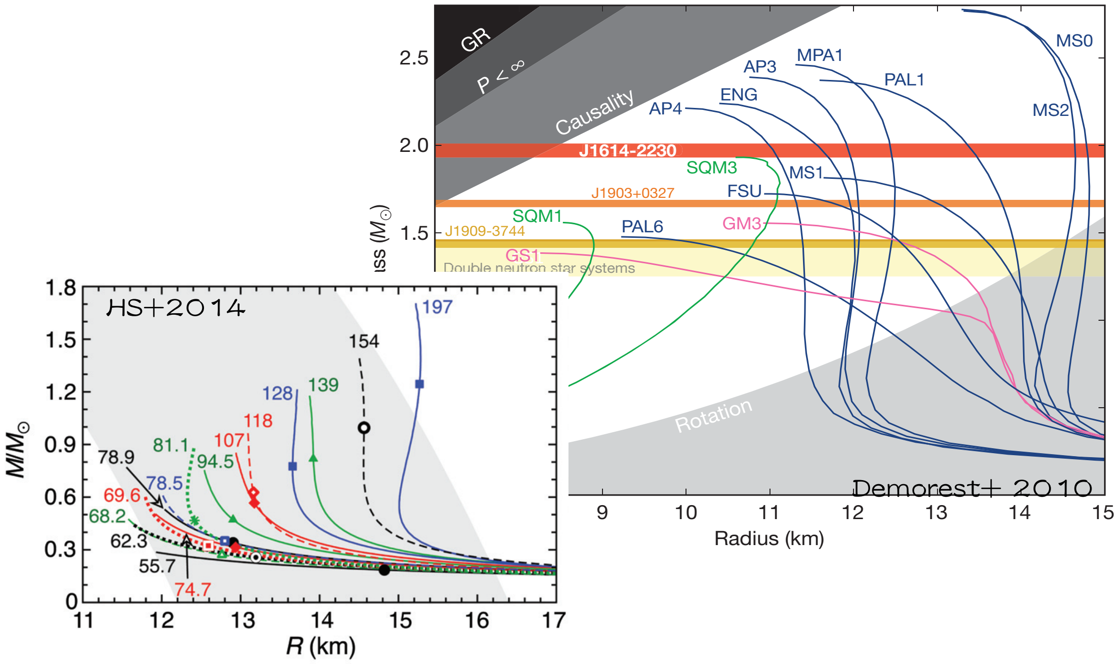
GW from SN?



Kuroda+ 16

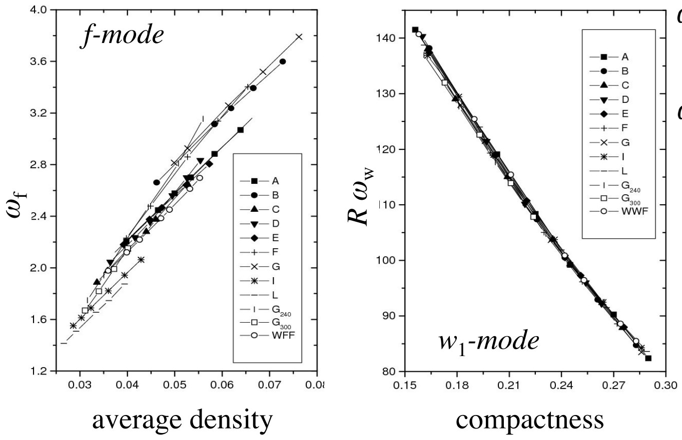
- Numerical simulations tell us the GW spectra.
- difficult
  - to extract physics of PNS and/or SN mechanism
  - to make a long-term numerical calculations
- We adopt the perturbation approach to determine the freq. from PNS.

Cold NS & EOS



Asteroseismology on Cold NSs

- via the observations of GW frequencies, one might be able to see the properties of NSs

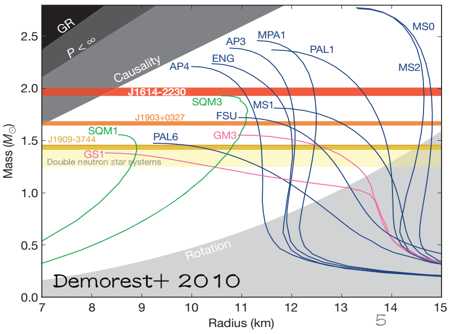


Andersson & Kokkotas (1998)

$$\omega_f \approx 0.78 + 1.64\left[\left(\frac{M}{1.4M_\odot}\right)\left(\frac{10\mathrm{km}}{R}\right)^3\right]^{1/2}$$

$$\omega_w \approx \left(\frac{10\mathrm{km}}{R}\right)\left[20.92 - 9.14\left(\frac{M}{1.4M_\odot}\right)\left(\frac{10\mathrm{km}}{R}\right)\right]$$

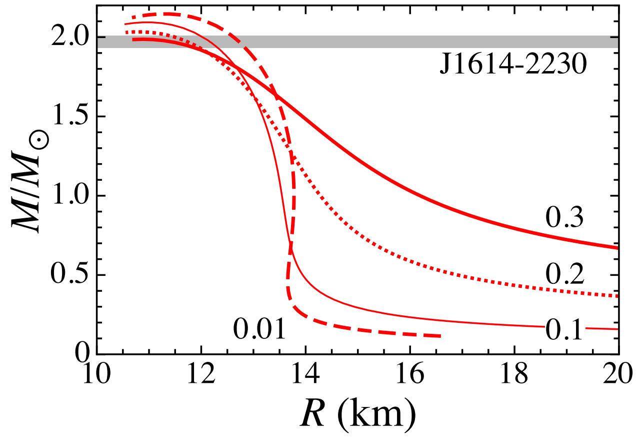
determination of (M, R)



f-mode → M/R^3; w_1-mode → M/R

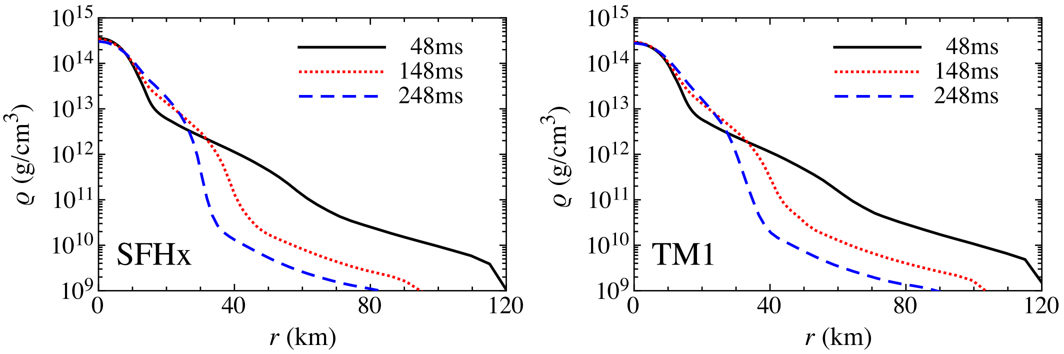
Protoneutron stars (PNSs)

- Unlike cold neutron stars, to construct the PNS models, one has to prepare the profiles of Y_e and s.
  - for example,
    with LS220 and $s = 1.5$ (k_B/baryon), but Y_e =0.01, 0.1, 0.2, and 0.3



PNS models

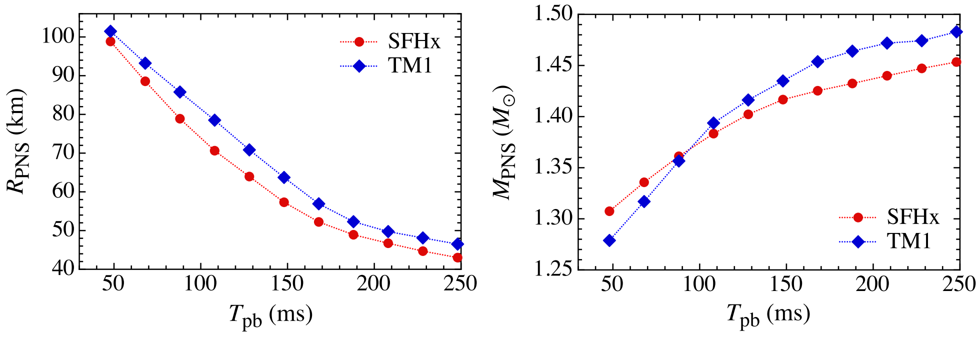
- we adopt the results of 3D-GR simulations of core-collapse supernovae (Kuroda et al. 2016)
  - progenitor mass = $15M_\odot$
  - EOS : SFHx ($2.13M_\odot$) & TM1 ($2.21M_\odot$)



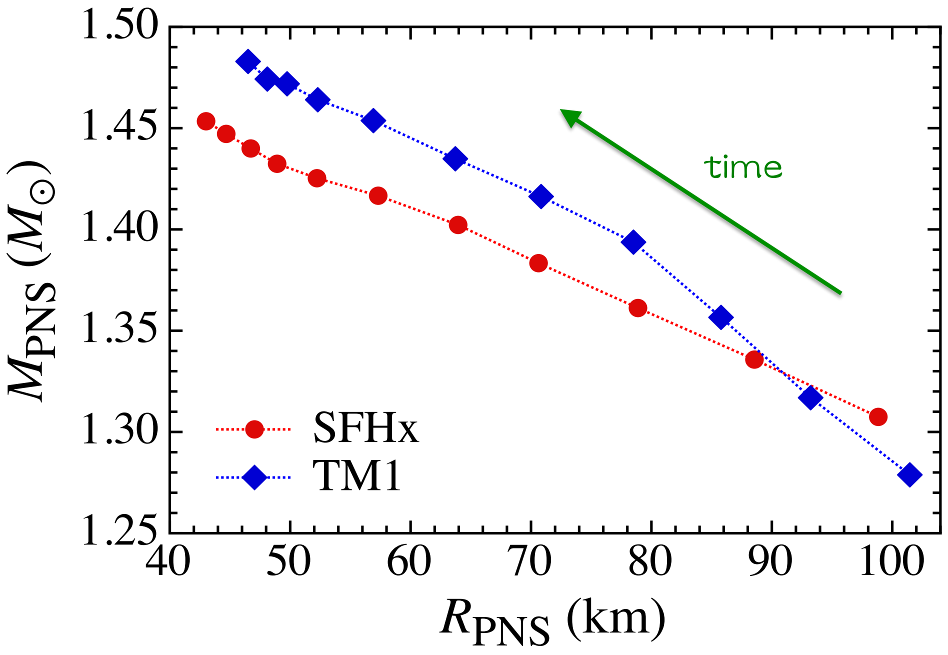
  - R_{PNS} is defined with ρ_s = 10^{10} g/cm^3
  - using the radial profiles as a background PNS model, the eigen-frequencies are determined.

Mass & Radius

- M_{PNS} is increasing by mass accretion
- R_{PNS} is decreasing due to the cooling



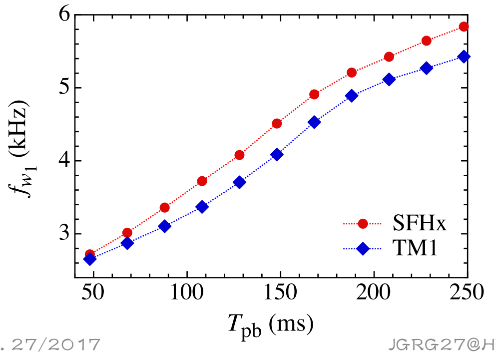
M-R evolution after core-bounce

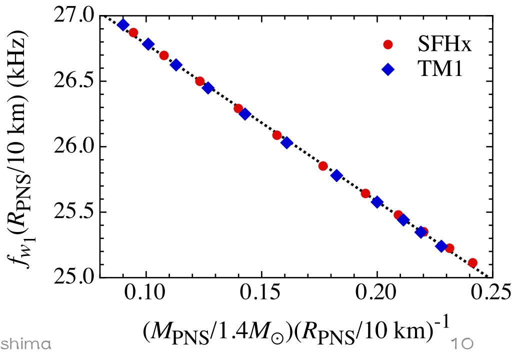


evolution of w_1-modes

- frequencies depend on the EOS.
  - increasing with time
  - can be characterized well by M/R
- as for cold NS, we can get the fitting formula, almost independent from EOS

$$f_{w_1}^{(\mathrm{PNS})}(\mathrm{kHz}) \approx \left[27.99 - 12.02\left(\frac{M_{\mathrm{PNS}}}{1.4\ M_\odot}\right)\left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-1}\right] \times \left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-1}$$





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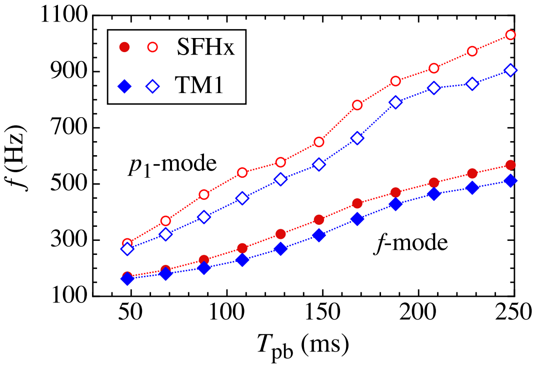
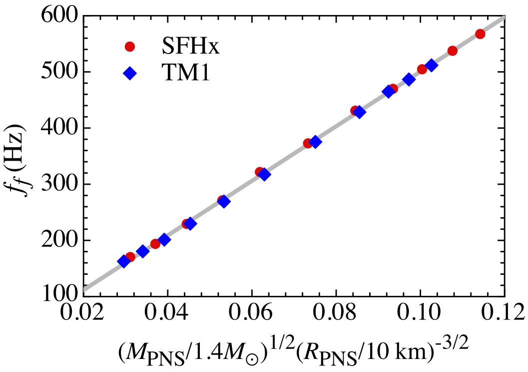
evolution of f-mode

- frequencies can be expressed well by the average density independent of the EOS (and progenitor mass)
- we derive the fitting formula as a function of M/R^3

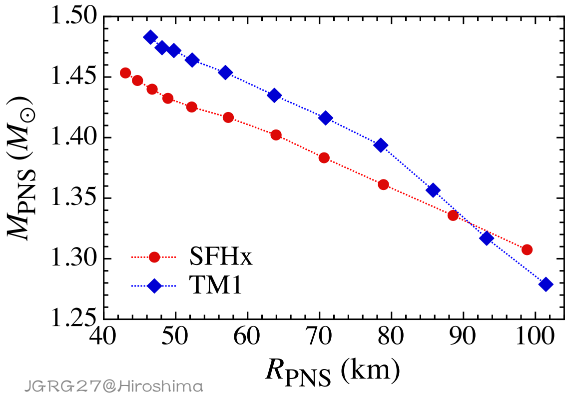
$$f_f^{(\mathrm{PNS})}(\mathrm{Hz}) \approx 14.48 + 4859\left(\frac{M_{\mathrm{PNS}}}{1.4\ M_\odot}\right)^{1/2}\left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-3/2}$$





determination of EOS

- with f- & w_1-modes GW observations, one can get two independent properties at each time after core bounce, which are combination of M_{PNS} & R_{PNS}
- one can determine (M_{PNS}, R_{PNS}) at each time after core bounce
  → determination of the EOS
- unlike cold NS cases, in principle one can determine the EOS even with ONE GW event !



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detectability of w_1-modes

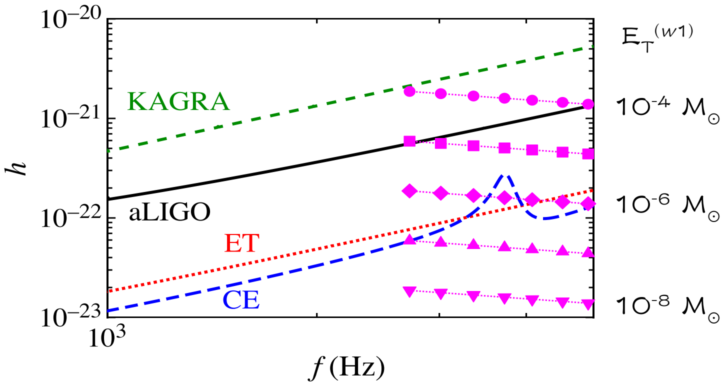
- effective amplitude of w_1-modes

$$h_{\rm eff}^{(w_1)} \sim 7.7\times 10^{-23}\left(\frac{E_{w_1}}{10^{-10}\,M_\odot}\right)^{1/2}\left(\frac{4\,{\rm kHz}}{f_{w_1}}\right)^{1/2}\left(\frac{10\,{\rm kpc}}{D}\right)$$

Andersson & Kokkotas (1996, 1998)

$$\frac{E_{w1}}{E_T^{(w1)}} \approx \frac{\tau_{w1}}{T_{w1}}$$

E_{w1} : energy for each time step
$E_T^{(w1)}$: total radiation energy in w_1-modes



conclusion

- We examine the frequencies of gravitational waves radiating from PNS after bounce.

$$\boxed{f_{w_1}^{(\mathrm{PNS})}(\mathrm{kHz}) \approx \left[27.99 - 12.02\left(\frac{M_{\mathrm{PNS}}}{1.4\ M_\odot}\right)\left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-1}\right] \times \left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-1}}$$

$$\boxed{f_f^{(\mathrm{PNS})}(\mathrm{Hz}) \approx 14.48 + 4859\left(\frac{M_{\mathrm{PNS}}}{1.4\ M_\odot}\right)^{1/2}\left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-3/2}}$$

(M_{PNS}, R_{PNS}) at each time after core bounce

- in principle, even with ONE GW event from supernova, one could determine the EOS for high density region.

1a2. Nami Uchikata (ICRR U. of Tokyo), “Black hole ringdown analysis of two-mode signal” (10+5)

[JGRG27 (2017) 112703]

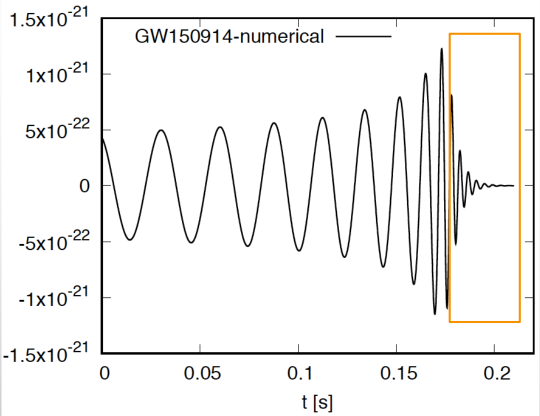
Black hole ringdown analysis of two-mode signal

Nami Uchikata (ICRR, University of Tokyo),

Hideyuki Tagoshi (ICRR, University of Tokyo),
Tatsuya Narikawa (ICRR, University of Tokyo)

Black hole ringdown waveform

- Final part of the gravitational waveform of a binary black hole merger.
- It is dominated by the black hole quasinormal modes.



https://losc.ligo.org/s/events/GW150914/P150914/fig2-unfiltered-waveform-H.txt /

Black hole quasinormal modes (QNM)

- Characteristic oscillations (damping oscillations) of black holes.

(frequency f, quality factor Q)

- Determined by black hole mass M and spin a only.
- Analysis of QNM gives the spin and mass of the final black hole.

$$(f, Q) \rightarrow (a, M)$$

- Based on general relativity, all multipolar modes (l, m) give the same mass and spin. → test of general relativity

Ex) Ideal case.

$$(f_{22}, Q_{22}) \rightarrow (a, M), \quad (f_{33}, Q_{33}) \rightarrow (a, M), \ldots$$

Effect of higher multipolar modes

- Waveform is consisted of several multipolar modes. (Dominant mode $(l, m) = (2,2)$)
- To test general relativity, we have to get the information of each mode.

- How to extract a single mode from several multipolar modes?

Effect of higher multipolar modes

- Berti et al. (2007)

Matched filter the 2 modes damped sinusoidal signals by single mode templates and evaluate the event loss without assuming noise. Signal to noise ratio can be lost by more than 3%.

- Bayesian analysis (test of no hair theorem)

Gossan et al. (2012), Meidam et al. (2014)

Estimate parameters from 2 modes damped sinusoidal signals slightly deviated from general relativity.

Constraints for non GR gravity.

Outline of the analysis

- Use waveforms from the numerical simulation as a signal. We consider a waveform includes two modes.
- Windowed the signal before the merger.
- Analyze the dominant mode by matched filtering.
- Cut off the frequency lower than the estimated dominant mode.
- Analyze the subdominant mode.
- Evaluate the accuracy of parameter estimations.

Matched filtering

- Signal-to-noise ratio

$$\rho \equiv (x, s_t) = 4\,\mathrm{Re}\left(\int_0^\infty \frac{\tilde{x}(f)\tilde{s}_t^*(f)}{S_n(f)} df\right), \qquad x(t) = s(t) + n(t)$$

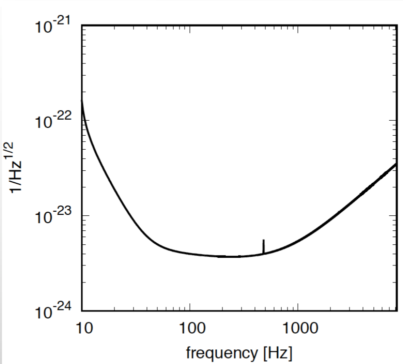
$S_n(f)$: noise power spectrum

(aLIGO zero detuned high power)

$s(t)$: signal (numerical waveform)

$n(t)$: Gaussian noise

$s_t(t)$: template, $(s_t, s_t) \equiv 1$



Signal

- waveform from numerical simulation

(Simulating eXtreme Spacetime) (https://www.black-holes.org)

SXS0293

Initial conditions :mass ratio 3:1, initial spin 0.85

Estimated parameters : ratio of final mass to total mass 0.9362, final spin 0.9124

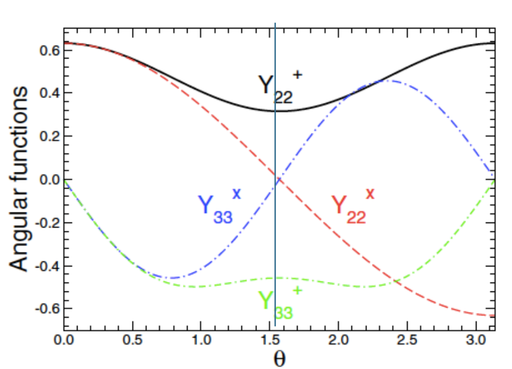
Combine $(l, m) = (2,2)$ and $(3,3)$ modes.

2 mode signal

$$Y^{+}_{lm} \equiv {}_{-2}Y_{lm}(\theta, 0) + (-1)^{l}{}_{-2}Y_{l-m}(\theta, 0),$$
$$Y^{\times}_{lm} \equiv {}_{-2}Y_{lm}(\theta, 0) - (-1)^{l}{}_{-2}Y_{l-m}(\theta, 0).$$

$$\begin{aligned} h(t) = \frac{\overset{\substack{\text{amplitude}\\ \Downarrow}}{\mathcal{A}_{22}}}{r}\Big\{ & e^{-t/\overset{\substack{f/Q\\ \Downarrow}}{\tau_{22}}}[\sin(\overset{\substack{f\\ \Downarrow}}{\omega_r^{22}} t + \overset{\substack{\text{Initial phase}\\ \Downarrow}}{\varphi_{22}} - 2\phi)Y^{+}_{22}\overset{\substack{\text{Antenna pattern}\\ \Downarrow}}{F_{+}} \\ & \cancel{+ \sin(\omega_r^{22} t + \varphi_{22} - 2\phi + \pi/2)Y^{\times}_{22}F_{\times}]} \\ & - \frac{\mathcal{A}_{33}}{\mathcal{A}_{22}} e^{-t/\tau_{33}}[\sin(\omega_r^{33} t + \varphi_{33} - 3\phi)Y^{+}_{33}F_{+} \\ & \cancel{+ \sin(\omega_r^{33} t + \varphi_{33} - 3\phi + \pi/2)Y^{\times}_{33}F_{\times}]\Big\}.} \end{aligned} \quad (2.13)$$

（Berti et al. PRD 76 104044 (2007)）



We assume the inclination angle is 90^{o}, so that the relative amplitude of 33 mode becomes large.

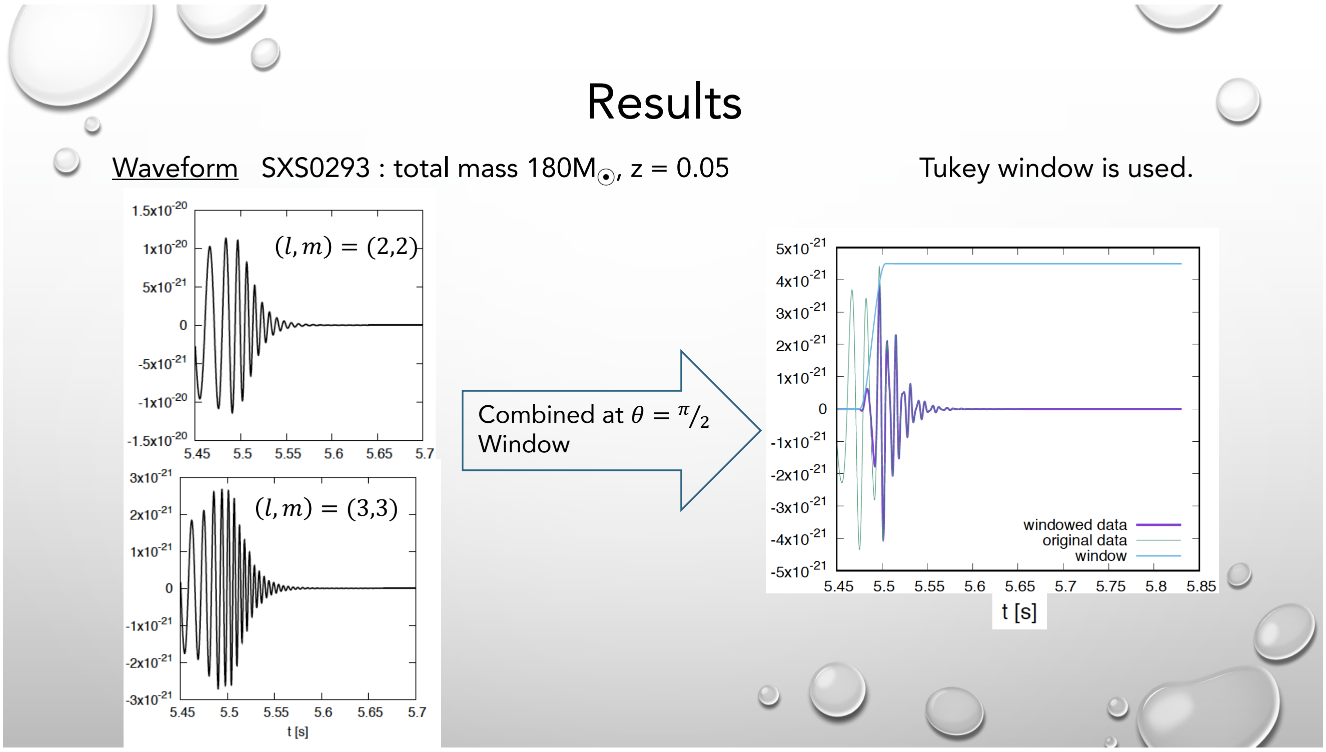
Template

$$s_t(t) = \begin{cases} 0 \quad (t < t_0) \\ \frac{1}{N} e^{-\pi f_t (t-t_0)/Q_t} \cos\{2\pi f_t (t - t_0) - \phi_0\} \quad (t \geq t_0), \end{cases}$$

We change the starting time t_0.

We look for (f_t, Q_t) that gives the maximum SNR for each t_0.

SNR is maximized against the initial phase ϕ_0 (Nakano et al. 2004) for each t_0.

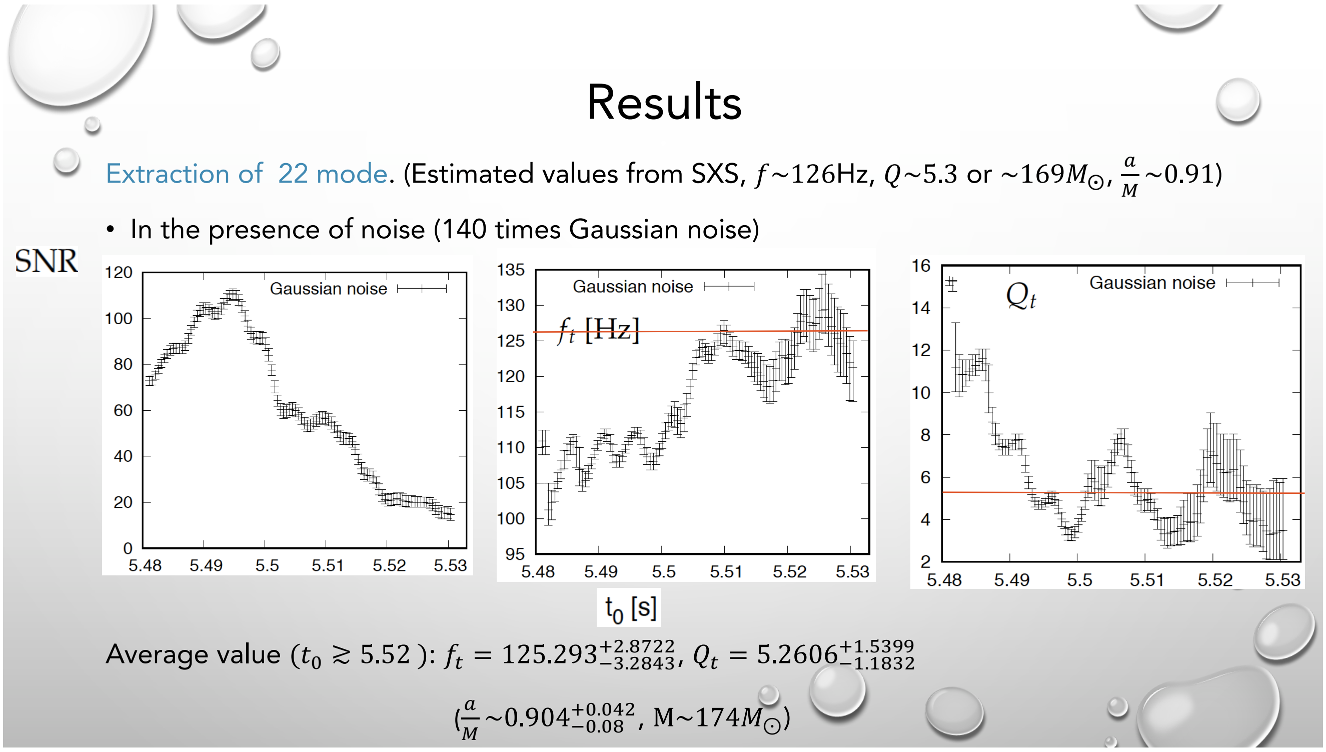


Results

Waveform SXS0293 : total mass 180M$_\odot$, z = 0.05

Tukey window is used.

Combined at $\theta = {}^{\pi}/_{2}$
Window



Results

Extraction of 22 mode. (Estimated values from SXS, $f \sim 126$Hz, $Q \sim 5.3$ or $\sim 169 M_\odot$, $\frac{a}{M} \sim 0.91$)

- In the presence of noise (140 times Gaussian noise)

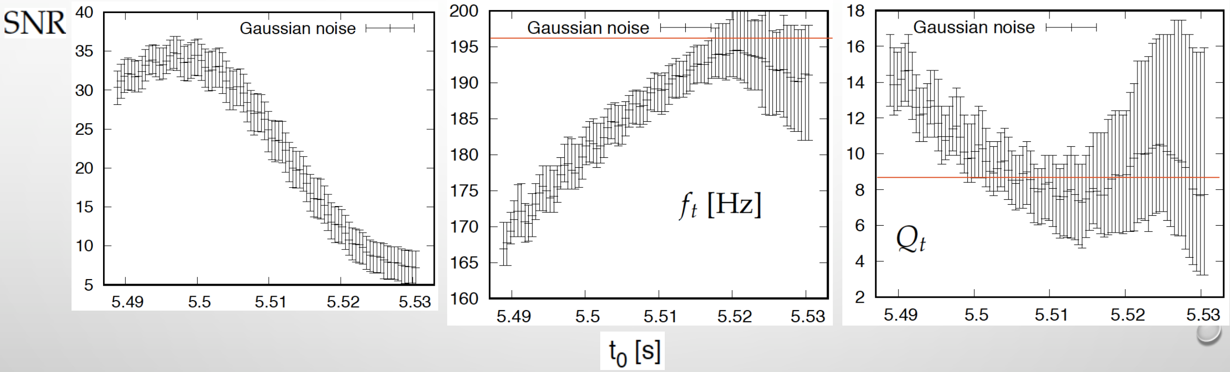
Average value ($t_0 \gtrsim 5.52$): $f_t = 125.293^{+2.8722}_{-3.2843}$, $Q_t = 5.2606^{+1.5399}_{-1.1832}$

($\frac{a}{M} \sim 0.904^{+0.042}_{-0.08}$, M$\sim 174 M_\odot$)

Results

Extraction of 33 mode. Lower cuttoff frequency is 130 Hz.

- In the presence of noise (140 times Gaussian noise) (Estimated f~196Hz, Q~8.5)



Average value ($t_0 \gtrsim 5.52$): $f_t = 191.2225^{+4.8123}_{-5.8573}$, $Q_t = 9.6531^{+5.5373}_{-3.1136}$

$$(\frac{a}{M} \sim 0.936^{+0.041}_{-0.097}, \text{ M} \sim 188 M_{\odot})$$

Summary

- Analyzed a numerical waveform composed of 2 modes by single mode templates under Gaussian noise.
- Though the subdominant mode is less accurate, we can estimate 2 modes separately by matched filtering.
- Application to the constraints for QNM parameters of modified gravity or exotic objects.

1a4. Remya Nair (Kyoto U.),

“Synergy between ground and space-based GW interferometers” (10+5)

[JGRG27 (2017) 112705]

Synergy between ground and space based interferometers

Remya Nair
JSPS Post-Doctoral Fellow
Kyoto University

with Prof. Takahiro Tanaka

JGRG 2017

TAKE HOME

Combining measurements of binary inspiral signals, obtained from ground and space based GW interferometers, gives us better estimates of the source parameters

Why?

Era of GW Astronomy

- 6 inspiral signals detection already
- This includes an EM counterpart event

Success of LISA pathfinder

What we hope to learn from coalescence signals

- Better estimates on binary coalescence parameters

Inspiral - Merger - Ringdown (Uchikata-san, Yamamoto-san)

- Possible evidence for GR corrections

- Formation mechanism

What we did

Studied 30 + 40 Solar mass BH-BH binary to get error estimates on the parameters

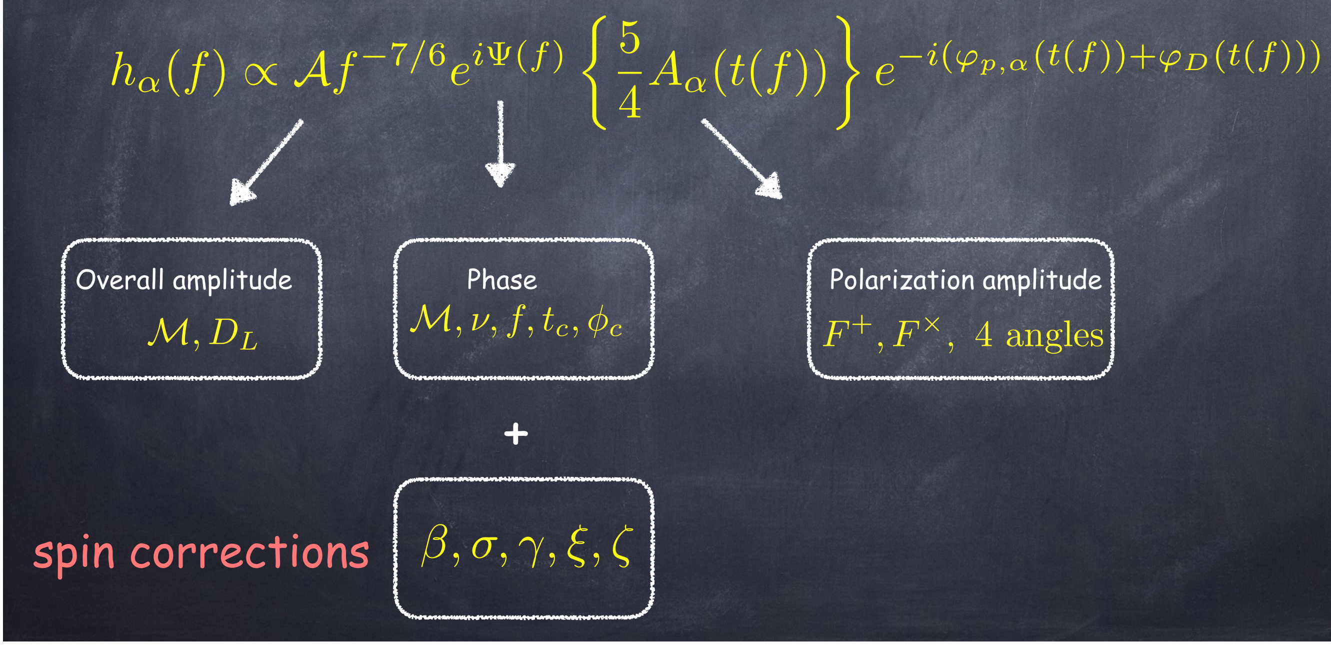
Parameters:

- No spin case: $\mathcal{M}, \nu, t_c, \phi_c + 4 \text{ angles}$
- Spin case (no precession): $\mathcal{M}, \nu, t_c, \phi_c, + \text{spin correction parameters} + 4 \text{ angles}$

How we did it

GW waveform

Restricted post Newtonion (PN)



$$h_\alpha(f) \propto \mathcal{A} f^{-7/6} e^{i\Psi(f)} \left\{ \frac{5}{4} A_\alpha(t(f)) \right\} e^{-i(\varphi_{p,\alpha}(t(f))+\varphi_D(t(f)))}$$

Overall amplitude

$\mathcal{M}, D_L$

Phase

$\mathcal{M}, \nu, f, t_c, \phi_c$

Polarization amplitude

$F^+, F^\times, \text{ 4 angles}$

+

spin corrections $\beta, \sigma, \gamma, \xi, \zeta$

How we did it

Construct the Fisher matrices

The noise weighted inner product for two signals (or a signal and a template waveform)

$$(h_1, h_2) = 2\int_0^\infty \frac{\tilde{h}_1^*(f)\tilde{h}_2(f) + \tilde{h}_2^*(f)\tilde{h}_1(f)}{S_n(f)} df$$

↓

$$P(s|\boldsymbol{\theta}) \propto e^{-(s-h(\boldsymbol{\theta}),s-h(\boldsymbol{\theta}))/2}$$

How we did it

For large SNR parameter estimates follow a Gaussian distribution

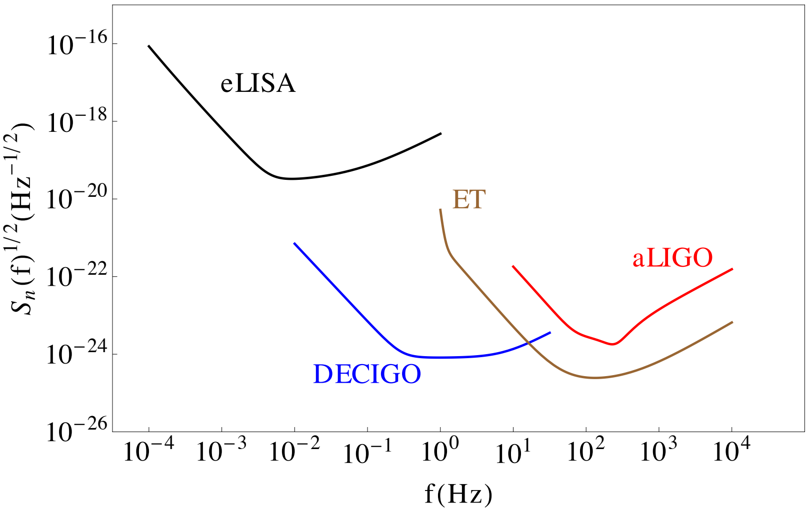
$$P(\Delta\theta^i) \propto e^{-\Gamma_{ij}\Delta\theta^i\Delta\theta^j/2}$$

Fisher Matrix $\Gamma_{ij} \equiv \left(\frac{\partial h}{\partial\theta_i}, \frac{\partial h}{\partial\theta_j}\right)$

Covariance Matrix $C = \Gamma^{-1}$

$\sqrt{\langle(\Delta\theta^i)^2\rangle} = \sqrt{C^{ii}}$ Root mean square error

GW interferometers: Noise curves

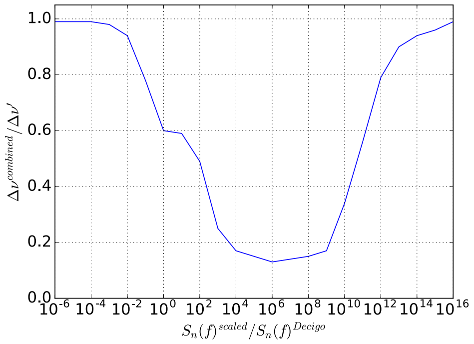


Focus on DECIGO + ET

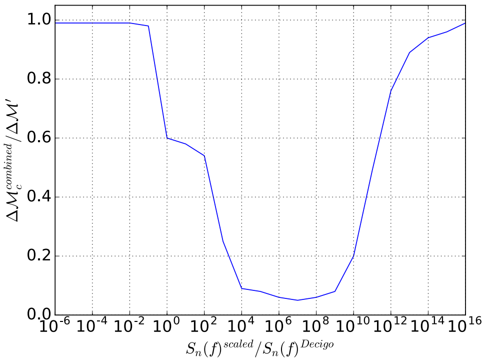
Also consider pre-DECIGO missions $S_n(f)^{\text{scaled}} = \mathcal{K} S_n(f)^{\text{DECIGO}}$

Combined estimates ‘Synergy’ : Non-spinning case

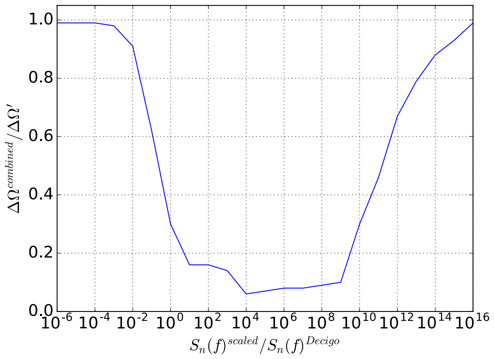
$$S_n(f)^{\text{scaled}} = 10^4 S_n(f)^{\text{DECIGO}}$$



$$\frac{\Delta\nu^S}{\Delta\nu^J} \sim 3$$



$$\frac{\Delta\mathcal{M}^S}{\Delta\mathcal{M}^J} \sim O(10)$$



$$\frac{\Delta\Omega^S}{\Delta\Omega^J} \sim O(10)$$

Spinning case

Five spin corrections

σ → spin-spin correction 2 PN

β → spin-orbit correction 1.5 PN

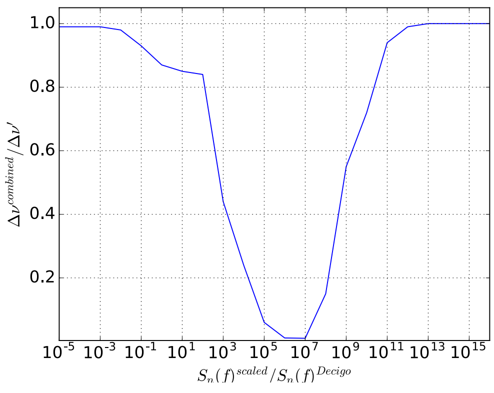
γ → spin-orbit correction 2.5 PN

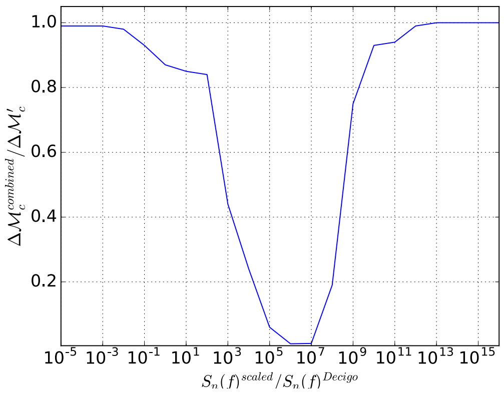
ξ → spin-orbit correction 3 PN

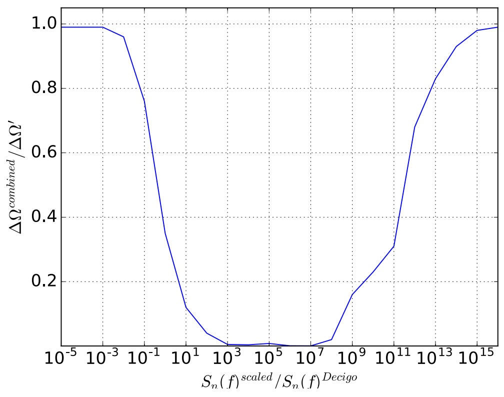
ζ → spin-orbit correction 3.5 PN

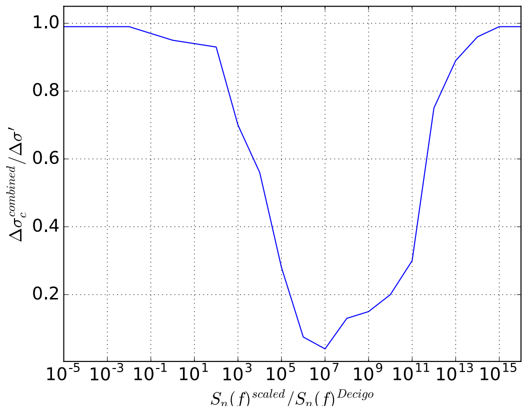
spin-orbit corrections written in terms of two auxiliary parameters — total parameters 11

Combined estimates 'Synergy' : Spinning case







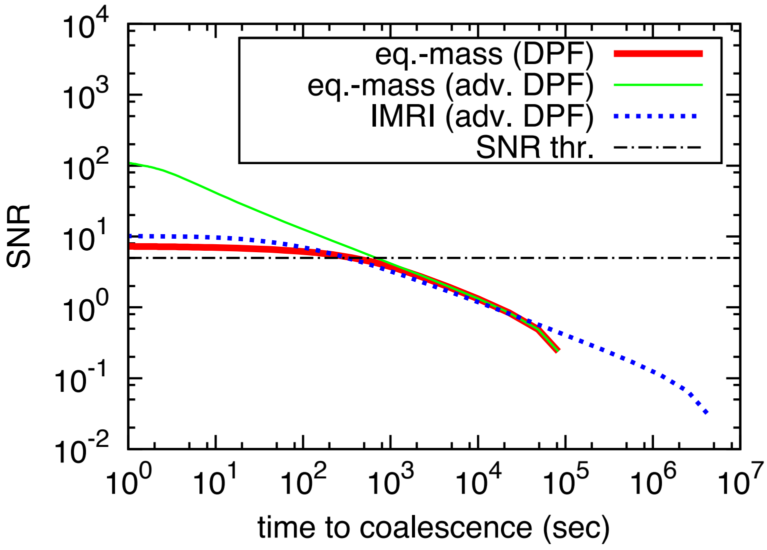


Spinning case: Synergy

$$S_n(f)^{\rm scaled} = 10^4 S_n(f)^{\rm DECIGO}$$

$$\frac{\Delta\theta^S}{\Delta\theta^J} \rightarrow \begin{array}{rr} \mathcal{M} & \sim 4 \\ \nu & \sim 4 \\ \Delta\Omega & \sim O(10^2) \\ \sigma & \sim 2 \\ \beta & \sim 2 \\ \gamma & \sim 2 \\ \xi & \sim 2 \\ \zeta & \sim 2 \end{array}$$

Complementarity between Space and ground based GW detectors



K. Yagi (2011)

Summary

Reported a range of sensitivities for a DECIGO like mission where joint measurements with ET give better error estimates

↓

There is scientific gain in having a space based interferometer observing in the low frequency region, even when we haven’t reached design sensitivity!

Ongoing work   Analyzing precessing systems

Thank you

Supplementary slides

Waveform

$$\mathcal{A} = \frac{1}{\sqrt{30}\pi^{2/3}} \frac{\mathcal{M}^{5/6}}{D_L}$$

$$\begin{aligned}\Psi(f) = 2\pi f t_c - \phi_c + \frac{3}{128}(\pi\mathcal{M}f)^{-5/3}\Bigg\{ & 1 + \left(\frac{3715}{756} + \frac{55}{9}\nu\right)x^{2/3} - 16\pi x \\ & + \left(\frac{15293365}{508032} + \frac{27145}{504}\nu + \frac{3085}{72}\nu^2\right)x^{4/3} + \pi\left(\frac{38645}{756} - \frac{65\nu}{9}\right)\left(1 + \log(6^{3/2}x)\right)x^{5/3} \\ & + \left(\frac{11583231236531}{4694215680} - \frac{640}{3}\pi^2 - \frac{6848}{21}\gamma_E + \left[-\frac{15737765635}{3048192} + \frac{2255}{12}\pi^2\right]\nu + \frac{76055}{1728}\nu^2\right. \\ & \left. - \frac{127825}{1296}\nu^3 - \frac{6848}{63}\log(64x)\right)x^2 + \pi\left(\frac{77096675}{254016} + \frac{378515}{1512}\nu - \frac{74045}{756}\nu^2\right)x^{7/3}\Bigg\}\end{aligned}$$

$$\Delta\Omega \equiv 2\pi|\sin\bar{\theta}_s|\sqrt{\Sigma_{\bar{\theta}_s\bar{\theta}_s}\Sigma_{\bar{\phi}_s\bar{\phi}_s} - \Sigma^2_{\bar{\phi}_s\bar{\theta}_s}}$$

$$\delta\theta_s \sim (\Delta\Omega_s \times (3283/str))^{1/2} \times 60 \text{ arcmin}$$

$$s_1 = \vec{\chi}_s \cdot \hat{\mathrm{L}}_\mathrm{N}$$

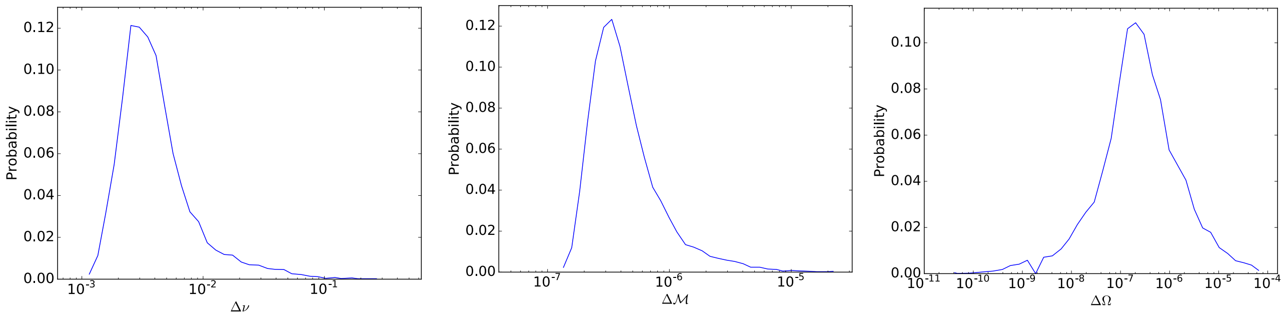
$$s_2 = \vec{\chi}_a \cdot \hat{\mathrm{L}}_\mathrm{N}$$

$$\vec{\chi}_s = \frac{1}{2}(\vec{\chi}_1 + \vec{\chi}_2)$$

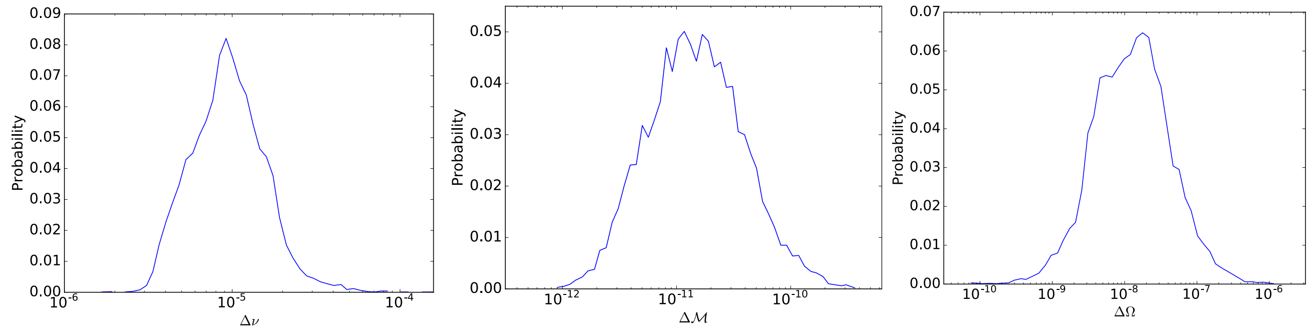
$$\vec{\chi}_a = \frac{1}{2}(\vec{\chi}_1 - \vec{\chi}_2)$$

$$\vec{\chi}_i = \vec{S}_i/m_i^2$$

Error estimates : Non-spinning case



ET



DECIGO

Session1b 14:00–15:00

[Chair: Ken-ichi Nakao]

1b2. Jasel Berra Montiel (Universidad Autonoma de San Luis Potosi),

“The loop representation of Quantum Gravity as a Deformation Quantization” (10+5)

[JGRG27 (2017) 112707]

The loop representation of Quantum Gravity as a Deformation Quantization

Jasel Berra
in collaboration with A. Molgado

Universidad Autónoma de San Luis Potosí (UASLP)

The 27th Workshop on General Relativity and Gravitation in Japan

Saijo, Higashi-Hiroshima

27 November-1 December 2017

Deformation quantization

Definition (Quantization)

Quantization of a classical system $(\mathcal{M}, \{\ ,\ \})$ *is a one to one mapping* $\mathcal{Q}_\hbar : \mathcal{A} \to \mathfrak{A}$ *from the set of classical observables* $C^\infty(\mathcal{M})$, *to the set* $\mathfrak{A}$ *of quantum observables, the set of self adjoint operators on a Hilbert space* $\mathcal{H}$. *The map* $\mathcal{Q}_\hbar$ *satisfies*

$$\lim_{\hbar\to 0} \frac{1}{2} \mathcal{Q}_\hbar^{-1} \left(\mathcal{Q}_\hbar(f_1)\mathcal{Q}_\hbar(f_2) + \mathcal{Q}_\hbar(f_2)\mathcal{Q}_\hbar(f_1) \right) = f_1 f_2$$

$$\lim_{\hbar\to 0} \mathcal{Q}_\hbar^{-1} \left(\{\mathcal{Q}_\hbar(f_1), \mathcal{Q}_\hbar(f_2)\} \right) = \{f_1, f_2\}$$

- There are different structures in quantum mechanics and classical mechanics, so that the correspondence $f \mapsto \mathcal{Q}_\hbar(f)$ is not an isomorphism between Lie algebras.

Groenewold-van Hove theorem

- In general there is no invertible map from classical observables to self adjoint operators in a Hilbert space, such that the Poisson structure is preserved, as Dirac's (functor) heuristics (Groenewold-van Hove theorem).
- A counterexample is given by

$$\{x^3, p^3\} + \frac{1}{12}\{\{p^2, x^3\}, \{x^2, p^3\}\} = 0$$

- It is the Moyal bracket, instead of the Poisson bracket, which maps invertibly to the quantum commutator.
- In the case of the simplest classical system with one degree of freedom, the Heisenberg commutation relations

$$[Q, P] = i\hbar, \;\; [Q, Q] = [P, P] = 0$$

- Then, this implies that $\|Q\|$, $\|P\|$ cannot be both finite.

Weyl map

- In order to solve this difficulty we introduce the unitary operators

$$U(u) = e^{-iuP}, \;\; V(v) = e^{-ivQ}, \;\; U(u)V(v) = e^{i\hbar uv}V(v)U(u)$$

Theorem (Von Neumann)

Every regular, irreducible unitary representation of the Weyl relations is unitarly equivalent to the Schrödinger representation.

- Define a linear map $W : L^1(\mathbb{R}^2) \to \mathcal{L}(\mathcal{H})$, called the Weyl transform, by $\left(S(u, v) = e^{-i\hbar uv/2}U(u)V(v)\right)$

$$W(f) = \frac{1}{2\pi}\int_{\mathbb{R}^2} f(u, v)S(u, v)dudv$$

- The integral is understood in the weak sense, for every $\psi_1, \psi_2 \in \mathcal{H}$

$$\langle W(f)\psi_1, \psi_2\rangle = \frac{1}{2\pi}\int_{\mathbb{R}^2} f(u, v)\,\langle S(u, v)\psi_1, \psi_2\rangle\, dudv$$

Properties of the Weyl transform

For all $f, f_1, f_2 \in L^1(\mathbb{R}^2)$,

1. $W(f)^* = W(f^*)$.
2. $\ker W = 0$.
3. $W(f_1)W(f_2) = W(f_1 \star_\hbar f_2)$, where

$$(f_1 \star_\hbar g_2)(u,v) = \frac{1}{2\pi}\int_{\mathbb{R}^2} e^{\frac{i\hbar}{2}(uv'-u'v)} f_1(u-u', v-v') f_2(u',v') du' dv'.$$

- We have $f_1 \star_\hbar f_2 \in L^1(\mathbb{R}^2)$ and defines a new associative product on $L^1(\mathbb{R}^2)$,

$$f_1 \star_\hbar (f_2 \star_\hbar f_3) = (f_1 \star_\hbar f_2) \star_\hbar f_3$$

- When $\hbar = 0$, the product $\star_\hbar$ becomes the usual convolution product.

Weyl Quantization

- The Weyl transform defines a quantization of classical systems with canonical symplectic form $\omega = dp \wedge dq$

$$\Phi = W \circ \mathcal{F}^{-1} : \mathcal{S}(\mathbb{R}^2) \to \mathcal{L}(\mathcal{H})$$

Theorem

The mapping $\mathcal{S}(\mathbb{R}^2) \ni f \to \Phi(f)$ is a quantization, i.e., it satisfies

$$\lim_{\hbar \to 0} \frac{1}{2}\Phi^{-1}\left(\Phi(f_1)\Phi(f_2) + \Phi(f_2)\Phi(f_1)\right) = f_1 f_2$$

$$\lim_{\hbar \to 0} \Phi^{-1}\left(\{\Phi(f_1), \Phi(f_2)\}\right) = \{f_1, f_2\}$$

- The Weyl quantization defines a bilinear operator

$$f_1 \star_\hbar f_2 = \Phi^{-1}\left(\Phi(f_1)\Phi(f_2)\right) = f_1 \exp\left(\frac{i\hbar}{2}\left(\overleftarrow{\partial}_q \overrightarrow{\partial}_p - \overleftarrow{\partial}_p \overrightarrow{\partial}_q\right)\right) f_2.$$

Polymer representation

- LQG techniques applied to finite dimensional systems.
- Starting with the Hilbert space, $L^2(\mathbb{R}, d\mu_d)$, where the measure is given by (Corichi et al)

$$d\mu_d = \frac{1}{d\sqrt{\pi}} e^{-\frac{q^2}{d^2}} dq.$$

- Let $\phi_\alpha(q) = V(\alpha)\phi_0(q) = e^{-\frac{i}{\hbar}\alpha q} \in L^2(\mathbb{R}, d\mu_d)$, then

$$\lim_{1/d \to 0} \langle \phi_\alpha, \phi_\lambda \rangle_d = \delta_{\alpha\lambda}$$

- In this limit, the operators $V(\alpha)$ become discontinuous (von Neumann uniqueness does not apply here). Then, the position operator is not defined.
- In this limit, the momentum operator $P = -i\hbar\partial_q$ is well defined.

The Weyl transform of the polymer representation

Theorem

The Fourier transform of $\phi(q) \in L^2(\mathbb{R}, d\mu_d)$ is given by

$$\int_{\mathbb{R}} \phi\left(\sqrt{2}q - \frac{i}{\hbar}pd^2\right) d\mu_d$$

Theorem

The Weyl transform in the polymer representation is the linear map

$$W_{poly}(f)\phi(q) = \lim_{1/d \to 0} \frac{1}{2\pi\hbar} \int_{\mathbb{R}^2} f(q - q', v) e^{\frac{-iv}{2\hbar}(q+q')} e^{\frac{1}{2d^2}(q^2 - q'^2)} \phi(q') dq' dv.$$

where the integral is understood in the weak sense, i.e., for all $\phi_1, \phi_2 \in \mathcal{H}_{poly}$

$$\langle W_{poly}(f)\phi_1, \phi_2 \rangle_{poly} = \lim_{1/d \to 0} \langle W_d(f)\phi_1, \phi_2 \rangle_d .$$

The Weyl transform of the polymer representation

- If $f = Id$, the Weyl transform provides the inner product

$$\langle W_{poly}(Id)\phi_\alpha, \phi_\lambda\rangle_{poly} = \lim_{1/d\to 0} \langle W_d(Id)\phi_\alpha, \phi_\lambda\rangle_d = \delta_{\alpha,\lambda}.$$

- Let us analize the position and momentum operator
- $W_{poly}(q)\phi(q)$ is not well defined, then the operator $V(v)$ is not continuous.
- $W_{poly}(p)\phi(q) = -i\hbar\partial_q\phi(q)$, then the operator $U(u)$ is continuous.
- The star product is given by

$$\begin{aligned} & \langle W_{poly}(f_1 \star f_2)\phi_1, \phi_2\rangle_{poly} \\ = \quad & \lim_{1/d\to 0} \frac{1}{2\pi\hbar}\int_{\mathbb{R}^2} (f_1 \star_\hbar f_2)(q-q', v) e^{\frac{-iv}{2\hbar}(q+q')} K(\phi_1(q'))K(\phi_2(q))dqdq'dv \end{aligned}$$

Wigner function of the polymer representation

- The Moyal bracket gives the desire quantum representation of the Poisson bracket

$$\{V(v), p\} = -ivV(v).$$

- The Wigner function in the polymer representation, $f(p,x) = W^{-1}(|\phi\rangle\langle\phi|)$, reads

$$f = \lim_{1/d\to 0} \frac{1}{\sqrt{2\pi\hbar}} \int_{\mathbb{R}} e^{-\frac{i}{\hbar}z(p - i\hbar\frac{q}{d^2})} \phi(q+z/2)\phi^*(q-z/2)\frac{1}{\sqrt{\pi}d} e^{-\frac{(q-z/2)^2}{d^2}} dz$$

- If the system is described in a pure state

$$\int_{\mathbb{R}} f(p,q)dp = \langle\phi(q), \phi(q)\rangle_{poly}$$

$$\int_{\mathbb{R}} f(p,q)dq = |\widetilde{(K\phi)}(p)|^2$$

Free particle

- Taking the $d \to 0$ limit, we obtain (Fewster, Sahlmann)

$$f(\mu, c) = \int \phi^*(c - z/2)e^{-\frac{i}{\hbar}z\mu}\phi(c + z/2)dz,$$

where $\phi(c)$ are the cylindrical functions of $c \in \mathbb{R}_b$, and $\mu \in \hat{\mathbb{R}}_b$.

- The $*$-genvalue equation for the free particle is given by

$$H_{free} \star f = E \star f$$

$$\sin\frac{\mu p}{\hbar}\left[f(q + \frac{\mu}{2}, p) - f(q - \frac{\mu}{2}, p)\right] = 0,$$

$$\left(2 - 2m\frac{\mu^2}{\hbar^2}E\right) f(q, p) = \cos\frac{\mu p}{\hbar}\left[f(q + \frac{\mu}{2}, p) - f(q - \frac{\mu}{2}, p)\right].$$

- The polymer Wigner function is given by

$$f(q, p) = \delta(p - p_E), \quad p_E = \frac{\hbar}{\mu}\arccos\left(1 - \frac{m\mu^2}{\hbar^2}E\right).$$

Uncertainty relation

Lemma

$$\langle g^* \star g\rangle = \int dqdp\,(g^* \star g)f \geq 0$$

- For $a, b, c \in \mathbb{C}$, and $g = a + bq + c\frac{\hbar}{\mu}\sin\frac{\mu p}{\hbar}$, we have

$$\Delta q \Delta p \geq \frac{\hbar}{2}\left(1 + \frac{1}{2}\mu^2\Delta p^2\right) + O(\mu^4)$$

- Generalized uncertainty principle (Hossain, Husain, Seahra).

Perspectives

- Relations of the star product with noncommutativity.
- Examples (Mechanical systems, loop quantum cosmology, inflation, unruh effect . . .).
- Geometric operators, Bekenstein-Hawking entropy.
- Field theory (theories of connections).
- Semiclassical limits.
- "Loop quantum information" (background invariant quantum information), EPR, gravity and quantum entanglement of vacuum.

Thank you for your attention

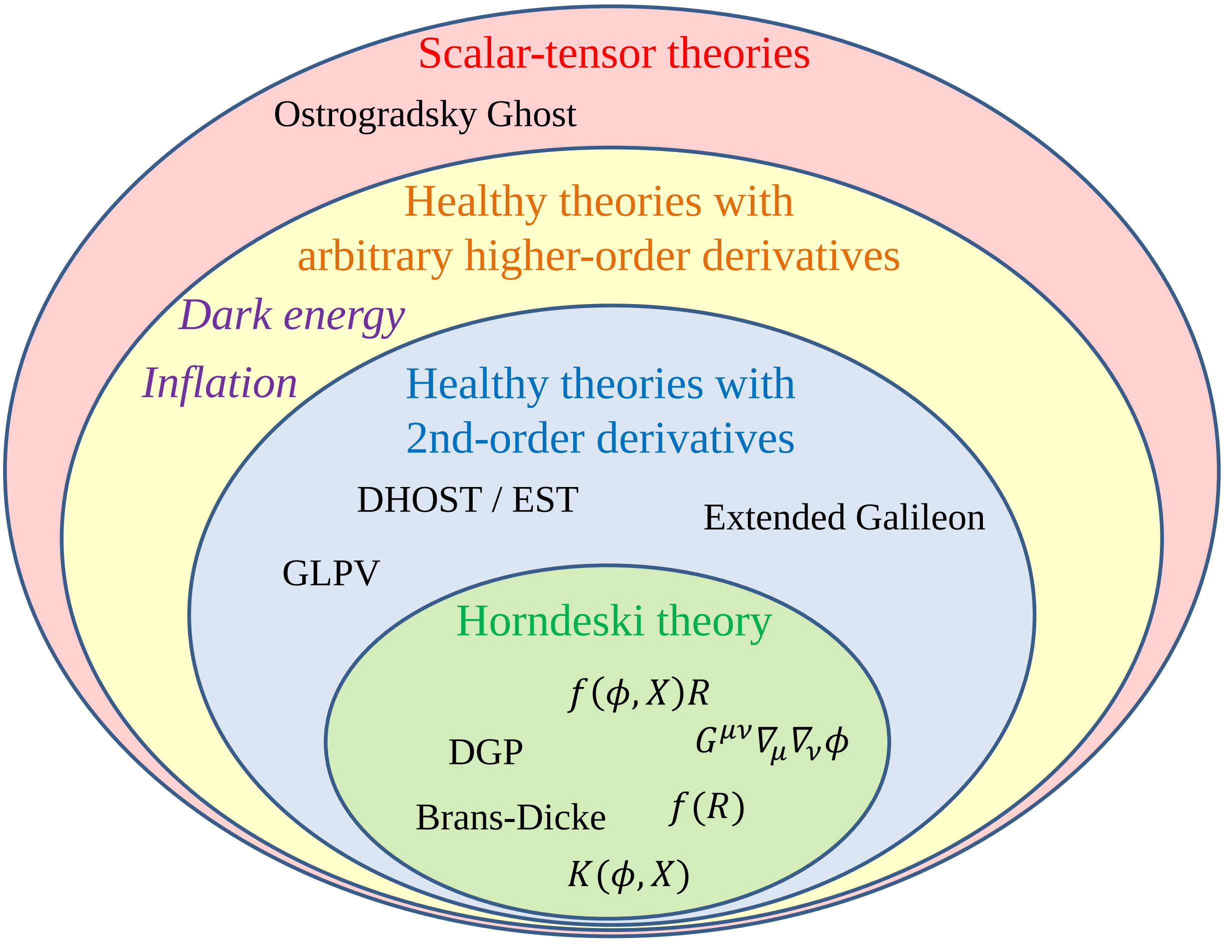
1b3. Hayato Motohashi (YITP Kyoto U.),
“Healthy degenerate theories with arbitrary higher-order derivatives” (10+5)
[JGRG27 (2017) 112708]

Healthy degenerate theories with arbitrary higher-order derivatives

Hayato Motohashi
Center for Gravitational Physics
Yukawa Institute for Theoretical Physics

HM, Suyama, PRD 91 (2015) 8, 085009, [arXiv:1411.3721]
HM, Noui, Suyama, Yamaguchi, Langlois,
JCAP 1607 (2016) 07, 033, [arXiv:1603.09355]
HM, Suyama, Yamaguchi, [arXiv:1711.08125]; in preparation

2017.11.27-12.01 JGRG27, Saijo, Higashi-Hiroshima


Scalar-tensor theories

Ostrogradsky Ghost

Healthy theories with arbitrary higher-order derivatives

Dark energy

Inflation

Healthy theories with 2nd-order derivatives

DHOST / EST

Extended Galileon

GLPV

Horndeski theory

$f(\phi, X)R$

$G^{\mu\nu}\nabla_\mu\nabla_\nu\phi$

DGP

Brans-Dicke

$f(R)$

$K(\phi, X)$

Ostrogradsky theorem for $L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a)$

Woodard, 1506.02210

- $L = L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a)$
- $\phi^a = \phi^a(t)$ and $a = 1, \cdots n$
- $K_{ab} \equiv \frac{\partial^2 L}{\partial \ddot{\phi}^a \partial \ddot{\phi}^b}$ (kinetic matrix)

✓Ostrogradsky theorem

$$\det K \neq 0 \Longrightarrow H \text{ is unbounded}$$

✓Ostrogradsky theorem

$$\det K \neq 0 \Longrightarrow H \text{ is unbounded}$$

- Hamiltonian analysis

$$L_{eq} = L\big(\underset{\ddot{\phi}^n}{\underset{\parallel}{\dot{Q}^a}}, \underset{\dot{\phi}^n}{\underset{\parallel}{Q^a}}, \phi^a\big) + \lambda_a(Q^a - \dot{\phi}^a)$$

$$\overset{\dot{\phi}^a}{\overset{\parallel}{(\boldsymbol{Q}^a, \boldsymbol{\phi}^a, \boldsymbol{\lambda}_a)}}$$

$$\Big\updownarrow$$

$$(\boldsymbol{P}_a, \boldsymbol{\pi}_a, \boldsymbol{\rho}^a)$$

$$K_{ab} \equiv \frac{\partial^2 L}{\partial \ddot{\phi}^a \partial \ddot{\phi}^b}$$

✓Ostrogradsky theorem

$\det K \neq 0 \Longrightarrow H$ is unbounded

- Hamiltonian analysis

$$L_{eq} = L\big(\dot{Q}^a, Q^a, \phi^a\big) + \lambda_a (Q^a - \dot{\phi}^a)$$

$\dot{\phi}^a$
||
$(\boldsymbol{Q^a}, \boldsymbol{\phi^a}, \lambda_a)$
↕
$(\boldsymbol{P_a}, \boldsymbol{\pi_a}, \rho^a)$

Canonical momenta

$$\begin{cases} P_a = \dfrac{\partial L}{\partial \dot{Q}^a} \rightarrow \det\left(\dfrac{\partial P_a}{\partial \dot{Q}^b}\right) \neq 0 \\ \qquad\qquad \Longrightarrow \dot{Q}^a = \dot{Q}^a(P, Q, \phi) \\ \boxed{\begin{array}{l} \pi_a = -\lambda_a \\ \rho^a = 0 \end{array}} \rightarrow \text{Primary constraints (C1)} \end{cases}$$

$$K_{ab} \equiv \frac{\partial^2 L}{\partial \ddot{\phi}^a \partial \ddot{\phi}^b}$$

✓Ostrogradsky theorem

$\det K \neq 0 \Longrightarrow H$ is unbounded

- Hamiltonian analysis

$$L_{eq} = L\big(\dot{Q}^a, Q^a, \phi^a\big) + \lambda_a (Q^a - \dot{\phi}^a)$$

$\dot{\phi}^a$
||
$(\boldsymbol{Q^a}, \boldsymbol{\phi^a}, \lambda_a)$
↕
$(\boldsymbol{P_a}, \boldsymbol{\pi_a}, \rho^a)$

Canonical momenta

$$\begin{cases} P_a = \dfrac{\partial L}{\partial \dot{Q}^a} \rightarrow \det\left(\dfrac{\partial P_a}{\partial \dot{Q}^b}\right) \neq 0 \\ \qquad\qquad \Longrightarrow \dot{Q}^a = \dot{Q}^a(P, Q, \phi) \\ \boxed{\begin{array}{l} \pi_a = -\lambda_a \\ \rho^a = 0 \end{array}} \rightarrow \text{Primary constraints (C1)} \end{cases}$$

$\{\pi_a + \lambda_a, \rho^b\} = \delta_a^b$

$\Longrightarrow$ Second class. No secondary constraints (C2)

$\Longrightarrow n$ healthy + n ghost DOFs

$$K_{ab} \equiv \frac{\partial^2 L}{\partial \ddot{\phi}^a \partial \ddot{\phi}^b}$$

✓Ostrogradsky theorem

$$\det K \neq 0 \Longrightarrow H \text{ is unbounded}$$

- Hamiltonian analysis

$$L_{eq} = L\left(\dot{Q}^a, Q^a, \phi^a\right) + \lambda_a (Q^a - \dot{\phi}^a)$$

$$\begin{array}{c} \dot{\phi}^a \\ \shortparallel \\ (\boldsymbol{Q^a}, \boldsymbol{\phi^a}, \lambda_a) \\ \updownarrow \\ (\boldsymbol{P_a}, \boldsymbol{\pi_a}, \rho^a) \end{array}$$

Canonical momenta

$$\left\{\begin{array}{l} P_a = \dfrac{\partial L}{\partial \dot{Q}^a} \longrightarrow \det\left(\dfrac{\partial P_a}{\partial \dot{Q}^b}\right) \neq 0 \\ \qquad\qquad\qquad \Longrightarrow \dot{Q}^a = \dot{Q}^a(P, Q, \phi) \\ \boxed{\begin{array}{l} \pi_a = -\lambda_a \\ \rho^a = 0 \end{array}} \longrightarrow \text{Primary constraints (C1)} \end{array}\right.$$

Hamiltonian

$$H = H_0(P, Q, \phi) + \pi_a Q^a$$

π_a shows up only linearly. H is unbounded.

$$K_{ab} \equiv \frac{\partial^2 L}{\partial \ddot{\phi}^a \partial \ddot{\phi}^b}$$

✓Ostrogradsky theorem

$$\det K \neq 0 \Longrightarrow H \text{ is unbounded}$$

? No-ghost condition

$$K_{ab} = 0 \overset{?}{\Longrightarrow} H \text{ is bounded}$$

✓Ostrogradsky theorem

$\det K \neq 0 \Longrightarrow H$ is unbounded

$\Updownarrow$

✓$K_{ab} = 0 \Longleftarrow H$ is bounded

↕ Different

? No-ghost condition

$K_{ab} = 0 \overset{?}{\Longrightarrow} H$ is bounded

... though it is a part of no-ghost conditions

“1st degeneracy condition” (DC1)

$L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a)$

HM, Suyama, 1411.3721

$H = H_0 + \pi_a Q^a$

- DC1: $K_{ab} = 0$

$\Longrightarrow$ Additional C1: $\Psi_a \equiv P_a - F_a(Q, \phi) = 0$

✓ Fixed

Still π_a is not fixed.

$$\dot{\phi}^a$$

$$\parallel$$

$$(\boldsymbol{Q}^a, \boldsymbol{\phi}^a, \lambda_a)$$

$$\updownarrow$$

$$(P_a, \boldsymbol{\pi}_a, \rho^a)$$

$L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a)$ HM, Suyama, 1411.3721

$$\dot{\phi}^a$$
$$\parallel$$
$$(\boldsymbol{Q^a}, \boldsymbol{\phi^a}, \lambda_a)$$
$$\updownarrow$$
$$(P_a, \pi_a, \rho^a)$$

$H = H_0 + \pi_a Q^a$

- DC1: $K_{ab} = 0$

$\Longrightarrow$ Additional C1: $\Psi_a \equiv P_a - F_a(Q, \phi) = 0$

✓ Fixed

- DC2: $M_{ab} \equiv \{\Psi_a, \Psi_b\} = 0$

$\Longrightarrow$ C2: $\Upsilon_n \equiv \pi_a - G_a(Q, \phi) = 0$

✓ Fixed

✓ We eliminated all the ghosts. H is bounded.

✓ The most general Lagrangian: $L \sim G(\dot{\phi}^a, \phi^a)$

✓Ostrogradsky theorem

$\det K \neq 0 \Longrightarrow H$ is unbounded

✓No-ghost condition (DC1 & DC2)

$K_{ab} = 0$ & $M_{ab} = 0 \Longrightarrow H$ is bounded

$$K_{ab} \equiv \frac{\partial^2 L}{\partial \ddot{\phi}^a \partial \ddot{\phi}^b}$$

$$M_{ab} \equiv \frac{\partial^2 L}{\partial \ddot{\phi}^a \partial \dot{\phi}^b} - \frac{\partial^2 L}{\partial \ddot{\phi}^b \partial \dot{\phi}^a}$$

✓Ostrogradsky theorem updated

$\det K \neq 0$ or $\det M \neq 0$ $\Longrightarrow$ H is unbounded

✓No-ghost condition (DC1 & DC2)

$K_{ab} = 0$ & $M_{ab} = 0$ $\Longrightarrow$ H is bounded

$$K_{ab} \equiv \frac{\partial^2 L}{\partial \ddot{\phi}^a \partial \ddot{\phi}^b}$$

$$M_{ab} \equiv \frac{\partial^2 L}{\partial \ddot{\phi}^a \partial \dot{\phi}^b} - \frac{\partial^2 L}{\partial \ddot{\phi}^b \partial \dot{\phi}^a}$$

✓Ostrogradsky theorem updated

$\det K \neq 0$ or $\det M \neq 0$ $\Longrightarrow$ H is unbounded

✓No-ghost condition (DC1 & DC2)

$K_{ab} = 0$ & $M_{ab} = 0$ $\Longrightarrow$ H is bounded

Highest

Next-highest

✓ EL eq

$$\cancel{K_{ab}}\ddddot{\phi}^b + (\cancel{\dot{K}_{ab}} + \cancel{M_{ab}})\dddot{\phi}^b = (\text{terms up to } \ddot{\phi}^a)$$

$\Longrightarrow$ 2nd-order system

Arbitrary higher-order derivatives

HM, Suyama, 1411.3721

- $L = L(\phi^{a(d)}, \phi^{a(d-1)}, \dots, \phi^{a})$
- $\phi^{a} = \phi^{a}(t)$ and $a = 1, \cdots n$
- $K_{ab} \equiv \frac{\partial^2 L}{\partial \phi^{a(d)} \partial \phi^{b(d)}}, \; M_{ab} \equiv \frac{\partial^2 L}{\partial \phi^{a(d)} \partial \phi^{b(d-1)}} - \frac{\partial^2 L}{\partial \phi^{b(d)} \partial \phi^{a(d-1)}}$

✓Ostrogradsky theorem updated

$\det K \neq 0$ or $\det M \neq 0$ $\Longrightarrow H$ is unbounded

$K_{ab} = 0$ $\longrightarrow$ ✓ $\cancel{\phi^{a(2d)}}$ from EL eq Highest

$M_{ab} = 0$ $\longrightarrow$ ✓ $\cancel{\phi^{a(2d-1)}}$ from EL eq Next-highest

- Still remain ghosts from lower (> 2) derivatives.

Eliminating Ostrogradsky ghost

✓ $L(\ddot{\phi}, \dot{\phi}, \phi) \Longrightarrow L(\dot{\phi}, \phi)$

✓ $L(\ddot{\phi}^{a}, \dot{\phi}^{a}, \phi^{a}) \Longrightarrow L(\dot{\phi}^{a}, \phi^{a})$

HM, Suyama, 1411.3721

- $L(\phi^{a(d)}, \phi^{a(d-1)}, \dots, \phi^{a})$

Eliminating Ostrogradsky ghost

- ✓ $L(\ddot{\phi},\dot{\phi},\phi) \Longrightarrow L(\dot{\phi},\phi)$
- ✓ $L(\ddot{\phi}^a,\dot{\phi}^a,\phi^a) \Longrightarrow L(\dot{\phi}^a,\phi^a)$ HM, Suyama, 1411.3721
- $L(\phi^{a(d)},\phi^{a(d-1)},\dots,\phi^a)$

HM, Noui, Suyama, Yamaguchi, Langlois, 1603.09355

- $L(\ddot{\phi},\dot{\phi},\phi;\dot{q},q)$
- $L(\ddot{\phi},\dot{\phi},\phi;\dot{q}^i,q^i) \;\sim\; \phi + g_{\mu\nu}$
- $L(\ddot{\phi}^a,\dot{\phi}^a,\phi^a;\dot{q}^i,q^i) \;\sim\; \phi^a + g_{\mu\nu}$

HM, Noui, Suyama, Yamaguchi, Langlois, 1603.09355

$$L(\ddot{\phi}^a,\dot{\phi}^a,\phi^a;\dot{q}^i,q^i)$$

$\dot{\phi}^a$

||

$(\boldsymbol{Q^a},\boldsymbol{\phi^a},\boldsymbol{q^i},\lambda_a)$

↕

$(\boldsymbol{P_a},\boldsymbol{\pi_a},\boldsymbol{p_i},\rho^a)$

- Hamiltonian analysis

$$L_{eq} = L\big(\dot{Q}^a,Q^a,\phi^a;\dot{q}^i,q^i\big) + \lambda_a(Q^a-\dot{\phi}^a)$$

Canonical momenta

$$\begin{cases} P_a = L_{\dot{Q}^a} \\ p_i = L_{\dot{q}^i} \\ \boxed{\begin{array}{l} \pi_a = -\lambda_a \\ \rho^a = 0 \end{array}} \end{cases}$$

→ Primary constraints (C1)

Hamiltonian

$$H = H_0(P,Q,\phi,p,q) + \pi_a Q^a$$

π_a shows up only linearly. H is unbounded.

HM, Noui, Suyama, Yamaguchi, Langlois, 1603.09355

$$L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a; \dot{q}^i, q^i)$$

$$\begin{array}{c}\dot{\phi}^a \\ \parallel \\ (\boldsymbol{Q}^a, \boldsymbol{\phi}^a, \boldsymbol{q}^i, \lambda_a) \\ \updownarrow \\ (P_a, \pi_a, \boldsymbol{p}_i, \rho^a)\end{array}$$

$$H = H_0 + \pi_a Q^a \qquad \boxed{\det L_{\dot{q}^i \dot{q}^j} \neq 0}$$

- DC1: $\boxed{L_{\dot{Q}^a \dot{Q}^b} - L_{\dot{q}^i \dot{Q}^a} L^{-1}_{\dot{q}^i \dot{q}^j} L_{\dot{q}^j \dot{Q}^b} = 0}$

$\Longrightarrow$ Additional C1: $\Psi_a \equiv P_a - F_a(Q, \phi, p, q) = 0$

✓ Fixed

- DC2: $\boxed{M_{ab} \equiv \{\Psi_a, \Psi_b\} = 0}$

$\Longrightarrow$ C2: $\Upsilon_n \equiv \pi_a - G_a(Q, \phi, p, q) = 0$

✓ Fixed

✓ We eliminated all the ghosts. H is bounded.

✓ EL eqs $\Longrightarrow$ 2nd-order system

✓ Applies for a wide class of theories

Applications

✓ Field theory in flat spacetime — Crisostomi, Klein, Roest, 1703.01623

✓ SU(2) — Allys, Peter, Rodriguez, 1609.05870

✓ Boson-Fermion — Kimura, Sakakihara, Yamaguchi, 1704.02717

✓ Scalar-tensor theories

Langlois, Noui, 1510.06930, 1512.06820
Crisostomi, Koyama, Tasinato, 1602.03119
Achour, Langlois, Noui, 1602.08398
Achour, Crisostomi, Koyama, Langlois, Noui, Tasinato, 1608.08135

✓ Vector-tensor theories

Kimura, Naruko, Yoshida, 1608.07066

✓ Tensor theories

Crisostomi, Noui, Charmousis, Langlois, 1710.04531

Eliminating Ostrogradsky ghost

- ✓ $L(\ddot{\phi}, \dot{\phi}, \phi) \Longrightarrow L(\dot{\phi}, \phi)$
- ✓ $L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a) \Longrightarrow L(\dot{\phi}^a, \phi^a)$ HM, Suyama, 1411.3721
- $L(\phi^{a(d)}, \phi^{a(d-1)}, \dots, \phi^a)$

HM, Noui, Suyama, Yamaguchi, Langlois, 1603.09355

- ✓ $L(\ddot{\phi}, \dot{\phi}, \phi; \dot{q}, q)$
- ✓ $L(\ddot{\phi}, \dot{\phi}, \phi; \dot{q}^i, q^i) \sim \phi + g_{\mu\nu}$
- ✓ $L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a; \dot{q}^i, q^i) \sim \phi^a + g_{\mu\nu}$

Eliminating Ostrogradsky ghost

- ✓ $L(\ddot{\phi}, \dot{\phi}, \phi) \Longrightarrow L(\dot{\phi}, \phi)$
- ✓ $L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a) \Longrightarrow L(\dot{\phi}^a, \phi^a)$ HM, Suyama, 1411.3721
- $L(\phi^{a(d)}, \phi^{a(d-1)}, \dots, \phi^a)$

HM, Noui, Suyama, Yamaguchi, Langlois, 1603.09355

- ✓ $L(\ddot{\phi}, \dot{\phi}, \phi; \dot{q}, q)$
- ✓ $L(\ddot{\phi}, \dot{\phi}, \phi; \dot{q}^i, q^i) \sim \phi + g_{\mu\nu}$
- ✓ $L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a; \dot{q}^i, q^i) \sim \phi^a + g_{\mu\nu}$

HM, Suyama, Yamaguchi, 1711.08125; in prep.

- $L(\dddot{\psi}, \ddot{\psi}, \dot{\psi}, \psi; \dot{q}^i, q^i)$
- $L(\dddot{\psi}^n, \ddot{\psi}^n, \dot{\psi}^n, \psi^n; \ddot{\phi}^a, \dot{\phi}^a, \phi^a; \dot{q}^i, q^i)$
- $L(\phi^{i_d(d+1)}, \dots; \phi^{i_{d-1}(d)}, \dots; \dots; \dot{\phi}^{i_0}, \phi^{i_0})$

HM, Suyama, Yamaguchi, 1711.08125

Quadratic model with $\dddot{\psi}^n, \dot{q}^i$

$\det A_{ij} \neq 0$
$\det c_{nm} \neq 0$

$$L = \frac{1}{2} a_{nm} \boxed{\dddot{\psi}^n \dddot{\psi}^m} + \frac{1}{2} b_{nm} \ddot{\psi}^n \ddot{\psi}^m + \frac{1}{2} c_{nm} \dot{\psi}^n \dot{\psi}^m$$
$$+ \frac{1}{2} d_{nm} \psi^n \psi^m + e_{nm} \boxed{\dddot{\psi}^n} \ddot{\psi}^m + f_{nm} \ddot{\psi}^n \dot{\psi}^m$$
$$+ \frac{1}{2} A_{ij} \dot{q}^i \dot{q}^j + \frac{1}{2} B_{ij} q^i q^j + C_{ij} \dot{q}^i q^j + \alpha_{ni} \boxed{\dddot{\psi}^n} \dot{q}^i$$

$\psi^n(t)$
$q^i(t)$

Equivalent form

$$L_{eq} = L(\underset{\dddot{\psi}^n}{\underset{\parallel}{\dot{Q}}}, \underset{\ddot{\psi}^n}{\underset{\parallel}{Q}}, \underset{\dot{\psi}^n}{\underset{\parallel}{R}}, \psi, \dot{q}, q) + \xi_n (\dot{\psi}^n - R^n) + \lambda_n (\dot{R}^n - Q^n)$$

Canonical momenta

$$\begin{cases} P_{Q^n} = a_{nm} \dot{Q}^m + \alpha_{ni} \dot{q}^i + e_{nm} Q^m \\ p_i = \alpha_{ni} \dot{Q}^n + A_{ij} \dot{q}^j + C_{ij} q^j \\ \boxed{\begin{matrix} P_{R^n} = \lambda_n, & \pi_{\psi^n} = \xi_n \\ \rho_{\lambda_n} = 0, & \rho_{\xi_n} = 0 \end{matrix}} \end{cases} \rightarrow$$

Primary constraints (C1)

HM, Suyama, Yamaguchi, 1711.08125

Quadratic model with $\dddot{\psi}^n, \dot{q}^i$

$$\left(\underset{}{\overset{\ddot{\psi}^n}{\overset{\parallel}{\boldsymbol{Q}^n}}}, \overset{\dot{\psi}^n}{\overset{\parallel}{\boldsymbol{R}^n}}, \boldsymbol{\psi}^n, \boldsymbol{q}^i, \lambda_n, \xi_n\right)$$
$$\updownarrow$$
$$\left(P_{Q^n}, P_{R^n}, \pi_{\psi^n}, \boldsymbol{p}_i, \rho_{\lambda_n}, \rho_{\xi_n}\right)$$

$$H = H_0 + P_{R^n} Q^n + \pi_{\psi^n} R^n$$

- DC1: $a_{nm} - \alpha_{ni} A^{ij} \alpha_{jm} = 0$

$\Longrightarrow$ Additional C1: $\Psi_n \equiv P_{Q^n} - \cdots = 0$

✓ Fixed

- DC2: $\{\Psi_n, \Psi_m\} = -2[e_{nm} - \cdots] = 0$

$\Longrightarrow$ C2: $\Upsilon_n \equiv P_{R^n} - \cdots = 0$

✓ Fixed

- DC3: $\{\Upsilon_n, \Psi_m\} = -b_{nm} - \cdots = 0$

$\Longrightarrow$ C3: $\Lambda_n \equiv \pi_{\psi^n} - \cdots = 0$

✓ Fixed

We eliminated all the ghosts? *No!*

HM, Suyama, Yamaguchi, 1711.08125

Quadratic model with $\dddot{\psi}^n, \dot{q}^i$

$$\begin{matrix} \ddot{\psi}^n & \dot{\psi}^n \\ \| & \| \end{matrix}$$

$$(Q^n, \boldsymbol{R^n}, \boldsymbol{\psi^n}, \boldsymbol{q^i}, \lambda_n, \xi_n)$$

$$\updownarrow$$

$$(P_{Q^n}, P_{R^n}, \pi_{\psi^n}, \boldsymbol{p_i}, \rho_{\lambda_n}, \rho_{\xi_n})$$

$$H = H_0 + P_{R^n} Q^n + \pi_{\psi^n} R^n$$

↓ All DCs and Cs

H: linear in Q^n $\Longrightarrow$ *Hidden ghosts appeared*

HM, Suyama, Yamaguchi, 1711.08125

Quadratic model with $\dddot{\psi}^n, \dot{q}^i$

$$\begin{matrix} \ddot{\psi}^n & \dot{\psi}^n \\ \| & \| \end{matrix}$$

$$(Q^n, \boldsymbol{R^n}, \boldsymbol{\psi^n}, \boldsymbol{q^i}, \lambda_n, \xi_n)$$

$$\updownarrow$$

$$(P_{Q^n}, P_{R^n}, \pi_{\psi^n}, \boldsymbol{p_i}, \rho_{\lambda_n}, \rho_{\xi_n})$$

$$H = H_0 + P_{R^n} Q^n + \pi_{\psi^n} R^n$$

↓ All DCs and Cs

H: linear in Q^n $\Longrightarrow$ *Hidden ghosts appeared*

- DC4: $\{\Lambda_n, \Psi_m\} = 2(f_{nm} - \cdots) = 0$

$\Longrightarrow$ C4: $\Omega_n \equiv c_{nm} Q^m - \cdots = 0$

✓ Fixed

- Condition to complete Dirac procedure:

$$\det Z_{nm} \equiv \det\{\Omega_n, \Psi_m\} \neq 0$$

✓ We eliminated all the ghosts. H is bounded.

HM, Suyama, Yamaguchi, 1711.08125

Quadratic model with $\dddot{\psi}^n, \dot{q}^i$

- Dirac matrix

$$D = \begin{array}{c|cccccc}
 & \multicolumn{3}{c}{\overbrace{\hphantom{\Phi_\beta \quad \bar{\Phi}_\beta \quad \Psi_m}}^{\text{C1}}} & \text{C4} & \text{C2} & \text{C3} \\
 & \Phi_\beta & \bar{\Phi}_\beta & \Psi_m & \Omega_m & \Upsilon_m & \Lambda_m \\
\hline
\Phi_\alpha & 0 & -\mathbf{1} & * & * & * & * \\
\bar{\Phi}_\alpha & \mathbf{1} & 0 & 0 & 0 & 0 & 0 \\
\Psi_n & * & 0 & 0 & -Z_{mn} & 0 & 0 \\
\Omega_n & * & 0 & Z_{nm} & * & * & * \\
\Upsilon_n & * & 0 & 0 & * & 0 & Z_{mn} \\
\Lambda_n & * & 0 & 0 & * & -Z_{nm} & *
\end{array}$$

$\det Z_{nm} \neq 0$

$\Longrightarrow \det D \neq 0$; All constraints are second class

$\Longrightarrow$ Healthy $2(N+I)$ DOFs

Eliminating Ostrogradsky ghost

✓ $L(\ddot{\phi}, \dot{\phi}, \phi) \Longrightarrow L(\dot{\phi}, \phi)$

✓ $L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a) \Longrightarrow L(\dot{\phi}^a, \phi^a)$ HM, Suyama, 1411.3721

✓ $L(\phi^{a(d)}, \phi^{a(d-1)}, \dots, \phi^a)$

HM, Noui, Suyama, Yamaguchi, Langlois, 1603.09355

✓ $L(\ddot{\phi}, \dot{\phi}, \phi; \dot{q}, q)$

✓ $L(\ddot{\phi}, \dot{\phi}, \phi; \dot{q}^i, q^i) \sim \phi + g_{\mu\nu}$

✓ $L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a; \dot{q}^i, q^i) \sim \phi^a + g_{\mu\nu}$

HM, Suyama, Yamaguchi, 1711.08125; in prep.

✓ $L(\dddot{\psi}, \ddot{\psi}, \dot{\psi}, \psi; \dot{q}^i, q^i)$

✓ $L(\dddot{\psi}^n, \ddot{\psi}^n, \dot{\psi}^n, \psi^n; \ddot{\phi}^a, \dot{\phi}^a, \phi^a; \dot{q}^i, q^i)$

✓ $L(\phi^{i_d(d+1)}, \dots; \phi^{i_{d-1}(d)}, \dots; \dots; \dot{\phi}^{i_0}, \phi^{i_0})$

Summary

Ostrogradsky ghosts appear as

- $L \ni$ 2nd-order time derivatives $\Longrightarrow H$: linear in P

which can be removed by degeneracy conditions.

The analysis of $L(\ddot{\phi}^a, \dot{\phi}^a, \phi^a; \dot{q}^i, q^i)$ applies for a wide class of model buildings.

We found that for quadratic model with $\dddot{\psi}^n, \dot{q}^i$

- $L \ni$ 3rd-order time derivatives $\Longrightarrow H$: linear in P, Q

We constructed the first ghost-free model with 3rd-order time derivatives in L.

The analyses of general L and field theory are work in progress.

1b4. Aya Iyonaga (Rikkyo U.),

“Degenerate higher-order multi-scalar-tensor theories” (10+5)

[JGRG27 (2017) 112709]

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Degenerate Higher-Order Multi-Scalar-Tensor theories

Aya Iyonaga（Rikkyo Univ.)

collaborator:
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Motivation

<u>Ostrogradsky stable</u> scalar-tensor theories
(EOMs are at most $\ddot{\phi}$) $\nwarrow \phi$ **(single field)**

$$\mathcal{L} = \mathcal{L}(\nabla_\mu \nabla_\nu \phi, \nabla_\mu \phi, \phi; \partial_\rho \partial_\sigma g_{\mu\nu}, \partial_\rho g_{\mu\nu}, g_{\mu\nu})$$

$\longrightarrow$ generally, EOMs are higher derivatives

But some theories' EOMs $\sim \ddot{\phi}$: **degenerate theory**

classify degenerate theories into 2 types:

- "**trivially degenerate**" : EOMs $\sim \nabla\nabla\phi$
  e.g.) Horndeski [Horndeski 1970]
  [Kobayashi, et al. 2011]
- "**nontrivially degenerate**" : EOMs are higher, but at most $\ddot{\phi}$
  e.g.) GLPV [Gleyzes, et al. 2014]
  DHOST [Langlois, Noui 2015]

…we have been talking about single-scalar theories.

Can we construct some degenerate multi-scalar-tensor theories?

Setup

fields' number

$$\mathcal{L} = \mathcal{L}(\underline{\nabla_\mu \nabla_\nu \phi^I}, \nabla_\mu \phi^I, \phi^I; \partial_\rho \partial_\sigma g_{\mu\nu}, \partial_\rho g_{\mu\nu}, g_{\mu\nu}) \quad (I = 1, ..., N)$$

we consider Lagrangians which contain

$\boxed{\nabla\nabla\phi^I}, (\nabla\nabla\phi^I)^2, (\nabla\nabla\phi^I)^3,$ ...

the most general Lagrangian(+ Einstein-Hilbert term) is:

$$\mathcal{L} = \sqrt{-g}\left[\frac{{}^{(4)}R}{2} - \mathcal{A}_{(IJ)K}(\phi^L, X^{MN})\nabla_\mu \phi^I \nabla^\nu \phi^J \nabla_\nu \nabla^\mu \phi^K\right]$$

arbitrary function: $\mathcal{A}_{(IJ)K} = \mathcal{A}_{(JI)K}$

kinetic term: $X^{IJ} := -\frac{1}{2} g^{\mu\nu} \nabla_\mu \phi^I \nabla_\nu \phi^J$

EOMs $\sim \nabla\nabla\nabla\phi^I$

→ **restrict $\mathcal{A}_{(IJ)K}$ and make EOMs degenerate**
(find degeneracy conditions)

after that, we see how these conditions are appeared in the EOMs

Degeneracy conditions

For single-scalar theories: $\det(\text{kinetic matrix}) = 0$

For multi-scalar theories [Crisostomi, et al. 2017]

$$L(\ddot{\phi}^I, \dot{\phi}^I, \phi^I, \dot{q}^\alpha, q^\alpha) = L(\dot{A}^I, A^I, \phi^I, \dot{q}^\alpha, q^\alpha) + \lambda_I(\dot{\phi}^I - A^I)$$

$\dddot{\phi}^I$ can be removed(degenerate) ⟷ $S_{[IJ]} = 0$

where
$$\begin{aligned} S_{[IJ]} :=\ & \partial_i L_{\partial_i A^I \dot{A}^J} + V_I^\alpha \partial_i L_{\partial_i q^\alpha \dot{A}^J} + \partial_i L_{\partial_i A^I \dot{q}^\beta} V_J^\beta + V_I^\alpha \partial_i L_{\partial_i q^\alpha \dot{q}^\beta} V_J^\beta \\ & + \partial_i V_J^\beta \left(L_{\partial_i A^I \dot{q}^\beta} + L_{\dot{A}^I \partial_i \dot{q}^\beta} + 2V_I^\alpha L_{\dot{q}^{(\alpha} \partial_i q^{\beta)}}\right) \\ & + (L_{\dot{A}^I A^J} - L_{A^I \dot{A}^J}) + V_I^\alpha \left(L_{\dot{q}^\alpha A^J} - L_{q^\alpha \dot{A}^J}\right) \\ & + \left(L_{\dot{A}^I q^\beta} - L_{A^I \dot{q}^\beta}\right) V_J^\beta + V_I^\alpha \left(L_{\dot{q}^\alpha q^\beta} - L_{q^\alpha \dot{q}^\beta}\right) V_J^\beta \end{aligned}$$

$$\left(L_{\dot{A}^I \dot{A}^J} := \frac{\partial L}{\partial \dot{A}^I \partial \dot{A}^J}, V_I^\alpha := -L_{\dot{A}_I \dot{q}_\beta} L^{-1}_{\dot{q}_\beta \dot{q}_\alpha}\right)$$

in our case,

$$S_{[IJ]} = 2(\mathcal{A}_{(KJ)I} - \mathcal{A}_{(KI)J})A_*^K + \left(\frac{\partial \mathcal{A}_{(KL)I}}{\partial X^{MJ}} - \frac{\partial \mathcal{A}_{(KL)J}}{\partial X^{MI}}\right) A_*^K A_*^L A_*^M = 0$$

($A_*^I \leftrightarrow \dot{\phi}^I$ is arbitrary)

→ **degeneracy conditions:**

$$\mathcal{A}_{(KJ)I} = \mathcal{A}_{(KI)J}, \quad \frac{\partial \mathcal{A}_{(KL)I}}{\partial X^{MJ}} = \frac{\partial \mathcal{A}_{(KL)J}}{\partial X^{MI}}$$

EOMs

$\frac{\delta\mathcal{L}}{\delta\phi^I}$ contains…

- $\sqrt{-g}\nabla_\sigma\phi^J\left[\underline{\left(2\mathcal{A}_{(IJ)K}-\mathcal{A}_{(JK)I}\right)}\nabla_\mu\nabla^\sigma\nabla^\mu\phi^K-\mathcal{A}_{(JK)I}\nabla^\sigma\nabla_\mu\nabla^\mu\phi^K\right]$

  $\longrightarrow \mathcal{A}_{(JK)I}$ (for $\mathcal{A}_{(IJ)K}=\mathcal{A}_{(JK)I}$)

  $$=\sqrt{-g}\nabla_\sigma\phi^J\mathcal{A}_{(JK)I}\left(\nabla_\mu\nabla^\sigma-\nabla^\sigma\nabla_\mu\right)\nabla^\mu\phi^K$$
  $$=\sqrt{-g}\nabla_\sigma\phi^J\mathcal{A}_{(JK)I}R_\rho{}^\sigma\nabla^\rho\phi^K$$

- $\sqrt{-g}\nabla_\mu\phi^M\nabla_\sigma\phi^N\nabla_\delta\phi^J\underline{\left[\frac{\partial\mathcal{A}_{(MN)I}}{\partial X^{KJ}}\nabla^\sigma\nabla^\delta\nabla^\mu\phi^K-\frac{\partial\mathcal{A}_{(MN)K}}{\partial X^{IJ}}\nabla^\delta\nabla^\sigma\nabla^\mu\phi^K\right]}$

  If $\frac{\partial\mathcal{A}_{(MN)I}}{\partial X^{KJ}}=\frac{\partial\mathcal{A}_{(MN)K}}{\partial X^{IJ}}$ $\searrow$ $\frac{\partial\mathcal{A}_{(MN)I}}{\partial X^{KJ}}R^\mu{}_\rho{}^{\sigma\delta}\nabla^\rho\phi^K$

……

degeneracy conditions ⟶ all $\nabla\nabla\nabla\phi^I$ are removed

(EOMs $\sim\nabla\nabla\phi^I$)

"trivially degenerate"

There are no "nontrivially degenerate" case in linear order of $\nabla\nabla\phi^I$

Quadratic order?

As the next case, we focus on:

$$\mathcal{L}=\mathcal{L}(\underline{\nabla_\mu\nabla_\nu\phi^I},\nabla_\mu\phi^I,\phi^I;\partial_\rho\partial_\sigma g_{\mu\nu},\partial_\rho g_{\mu\nu},g_{\mu\nu})$$

$\llcorner$ $\nabla\nabla\phi^I,\boxed{(\nabla\nabla\phi^I)^2},(\nabla\nabla\phi^I)^3,$ …

$\mathcal{A}_{(IJ)(KL)}=\mathcal{A}_{(KL)(IJ)}$

$\delta^{\mu_1\mu_2\mu_3}_{\nu_1\nu_2\nu_3}=3!\delta^{[\mu_1}_{\nu_1}\delta^{\mu_2}_{\nu_2}\delta^{\mu_3]}_{\nu_3}$

$$\downarrow$$

$$\mathcal{L}=\sqrt{-g}\left[\frac{{}^{(4)}R}{2}+\mathcal{A}_{(IJ)(KL)}(\phi^P,X^{MN})\delta^{\mu_1\mu_2\mu_3}_{\nu_1\nu_2\nu_3}\nabla_{\mu_1}\phi^I\nabla^{\nu_1}\phi^J\nabla_{\mu_2}\nabla^{\nu_2}\phi^K\nabla_{\mu_3}\nabla^{\nu_3}\phi^L\right]$$

ADM form

$$=N\sqrt{\gamma}\left[2\mathcal{C}^{ij}K_{ij}+2\mathcal{F}^{ij}_IV^I_*K_{ij}+\mathcal{K}^{ij,kl}K_{ij}K_{kl}+2\mathcal{C}_IV^I_*-\mathcal{U}\right]$$
$$+\lambda_I(\dot\phi^I-NA^I_*-N^iD_i\phi^I)\qquad A^I_*\sim\dot\phi^I,\,V^I_*\sim\dot A^I_*$$

$$\left(\begin{aligned}\mathcal{K}^{ij,kl}=&\frac{1}{2}(\gamma^{ik}\gamma^{jl}-\gamma^{ij}\gamma^{kl})\\&+\mathcal{A}_{(IJ)(KL)}\left[\left(A^I_mA^m_J-A^I_*A^J_*\right)\left\{A^K_*A^L_*\left(\gamma^{ij}\gamma^{kl}-\gamma^{i(k}\gamma^{l)j}\right)+A^j_KA^{(k}_L\gamma^{l)i}+A^i_KA^{(k}_L\gamma^{l)j}\right\}\right.\\&+\left\{\left(2A^I_*A^{(i}_JA^{j)}_KA^L_*\gamma^{kl}-A^{(i}_IA^{j)}_JA^K_*A^L_*\gamma^{kl}\right)+(ij)\leftrightarrow(kl)\right\}\\&+\frac{1}{2}\left(A^I_*A^J_*A^j_KA^{(l}_L\gamma^{k)i}+(i\leftrightarrow j)\right)+\frac{1}{2}\left(A^K_*A^L_*A^j_IA^{(l}_J\gamma^{k)i}+(i\leftrightarrow j)\right)\\&\left.-\left(A^J_*A^L_*A^j_IA^{(l}_K\gamma^{k)i}+(i\leftrightarrow j)\right)-2A^i_IA^k_JA^j_KA^l_I\right]\end{aligned}\right)$$

degeneracy condition: $S_{[IJ]}\ni\left(\mathcal{K}^{ij,kl}\right)^{-1}$ … difficult to calculate

⟶ **we are now trying another approach**

Quadratic order?

→ cosmological perturbation (work in progress)

in the same way to the quadratic DHOST,

$$\mathcal{L} = \sqrt{-g}\left[f^{(4)}R + C^{\mu\nu\rho\sigma}_{IJ}\nabla_\mu\nabla_\nu\phi^I\nabla_\rho\nabla_\sigma\phi^J\right]$$

where

$$\begin{aligned}C^{\mu\nu\rho\sigma}_{IJ} = {}& \frac{1}{2}\alpha_{1,IJ}\left(g^{\mu\rho}g^{\nu\sigma} + g^{\mu\sigma}g^{\nu\rho}\right) + \alpha_{2,IJ}g^{\mu\nu}g^{\rho\sigma} + \frac{1}{2}\alpha_{3,IJKL}\left(\nabla^\mu\phi^K\nabla^\nu\phi^L g^{\rho\sigma} + \nabla^\rho\phi^K\nabla^\sigma\phi^L g^{\mu\nu}\right)\\ &+ \frac{1}{8}\alpha_{4,IJKL}\left(\nabla^\mu\phi^K\nabla^\rho\phi^L g^{\nu\sigma} + \nabla^\nu\phi^K\nabla^\rho\phi^L g^{\mu\sigma} + \nabla^\mu\phi^K\nabla^\sigma\phi^L g^{\nu\rho} + \nabla^\nu\phi^K\nabla^\sigma\phi^L g^{\mu\rho}\right.\\ &\quad \left.+(K \leftrightarrow L)\right) + \frac{1}{6}\alpha_{5,IJKLMN}\left(\nabla^\mu\phi^K\nabla^\nu\phi^L\nabla^\rho\phi^M\nabla^\sigma\phi^N + \nabla^\mu\phi^K\nabla^\nu\phi^M\nabla^\rho\phi^L\nabla^\sigma\phi^N\right.\\ &\quad +\nabla^\mu\phi^K\nabla^\nu\phi^N\nabla^\rho\phi^M\nabla^\sigma\phi^L + \nabla^\mu\phi^M\nabla^\nu\phi^N\nabla^\rho\phi^K\nabla^\sigma\phi^L + \nabla^\mu\phi^L\nabla^\nu\phi^N\nabla^\rho\phi^K\nabla^\sigma\phi^M\\ &\quad \left.+\nabla^\mu\phi^M\nabla^\nu\phi^L\nabla^\rho\phi^K\nabla^\sigma\phi^N\right)\end{aligned}$$

$$\alpha = \alpha(\phi^I, X^{JK})$$

scalar perturbations

spatially flat gauge: $N = 1 + \delta N,\ N_i = \partial_i\chi,\ \gamma_{ij} = a^2\delta_{ij}$

scalar fields: $\phi^I(t,\boldsymbol{x}) = \bar{\phi}^I(t) + Q^I(t,\boldsymbol{x})$

→ **some restrictions on α-s?**

Summary

Can we construct some degenerate multi-scalar-tensor theories?

$\boxed{(\nabla\nabla\phi^I)^1}$ the most general degenerate Lagrangian is

$$\mathcal{L} = \sqrt{-g}\left[\frac{{}^{(4)}R}{2} - \mathcal{A}_{(IJ)K}(\phi^L, X^{MN})\nabla_\mu\phi^I\nabla^\nu\phi^J\nabla_\nu\nabla^\mu\phi^K\right]$$

with $\mathcal{A}_{(IJ)K} = \mathcal{A}_{(JK)I},\ \dfrac{\partial\mathcal{A}_{(MN)I}}{\partial X^{KJ}} = \dfrac{\partial\mathcal{A}_{(MN)K}}{\partial X^{IJ}}$

(EOMs $\sim \nabla\nabla\phi^I$)

There are no "nontrivially degenerate" case in linear order of $\nabla\nabla\phi^I$

$\boxed{(\nabla\nabla\phi^I)^2}$ difficult to calculate $S_{[IJ]} = 0$

→ cosmological perturbation
(work in progress)

Invited lecture 16:00–18:00

[Chair: Motoyuki Saijo]

Kenji Toma (Tohoku U.),

“Theoretical and Observational Studies on Relativistic Jets Driven by Black Holes“ (50+10)

[JGRG27 (2017) 112710]

Frontier Research Institute for Interdisciplinary Sciences
Tohoku University

Theoretical Astrophysics
Tohoku University

Theoretical and Observational Studies on Relativistic Jets Driven by Black Holes

Kenji TOMA
(Tohoku U, Japan)

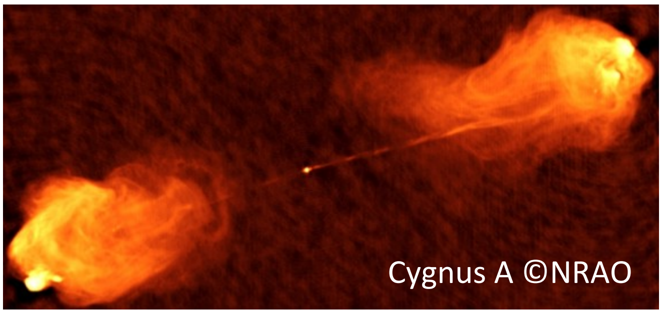
The 27th Workshop on General Relativity and Gravitation in Japan
@ Kurara Hall, Higashi-Hiroshima; Nov 27 − Dec 1, 2017

Outline

1. Introduction on relativistic jets & Blandford-Znajek (BZ) process
2. Essential points of BZ process
3. Observational tests
4. Summary

Relativistic Jets

Active Galactic Nucleus (AGN) jets



$$M_{\rm BH} \sim 10^7 - 10^9 \ M_\odot$$

$$L_j \lesssim L_{\rm Edd} \simeq 10^{46} M_8 \ {\rm ergs}^{-1}$$

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}} = 10 - 100$$

Radio loud AGNs = Elliptical galaxies
Radio quiet AGNs = Spiral galaxies

Gamma-ray bursts (GRBs)

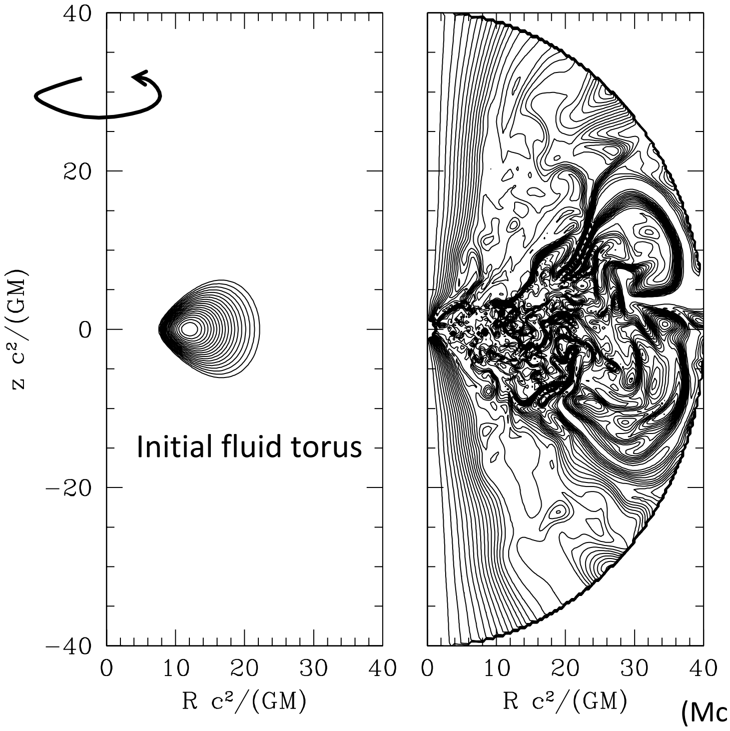
$$M_{\rm BH} \gtrsim 3 \ M_\odot$$

$$L_j \gg L_{\rm Edd}$$

$$\gamma > 100$$

Long GRBs = Peculiar supernovae
Short GRBs = NS-NS or NS-BH mergers (?)

Black Hole – Accretion Flow

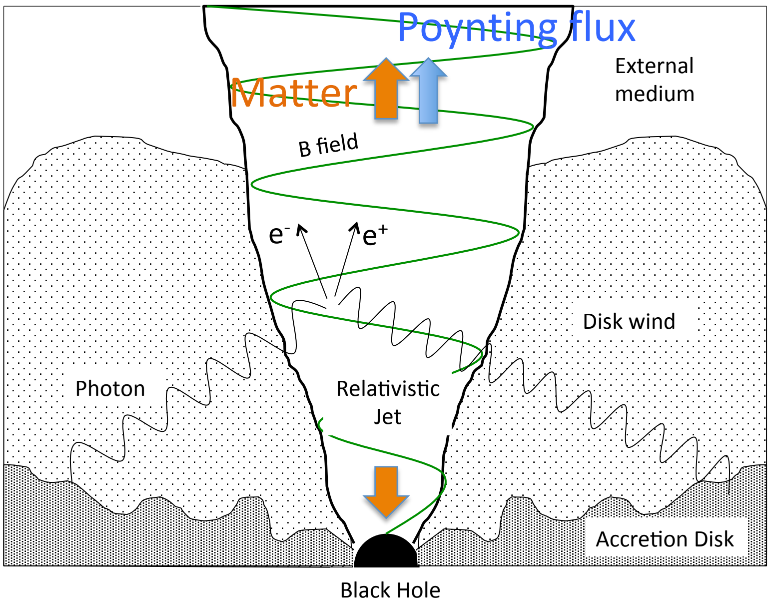


(McKinney & Gammie 2004)

- MHD simulations show that jets can be driven electromagnetically

Jet from black hole

- MHD simulations in fixed Kerr space-time (e.g. Komissarov 01; Koide+ 02; McKinney & Gammie 04; Barkov & Komissarov 08; Tchekhovskoy+ 11)



$$L_j = \gamma \dot{M}_j c^2$$

Electromagnetically-dominated energy flux (jet) in the polar low-density region, which is collimated by the dense disk wind

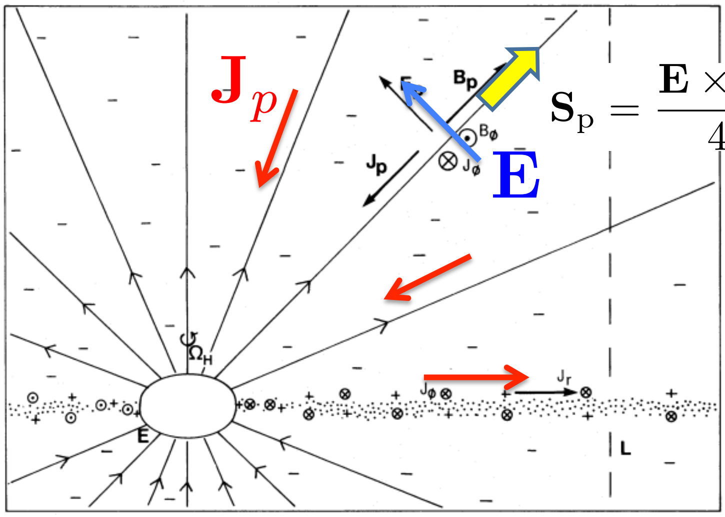
Blandford & Znajek (1977)

- Slowly rotating Kerr BH

$$a = \frac{J}{M r_g c} \ll 1$$

- Steady, axisymmetric
- Split-monopole B field
- Force-free approximation (Electromagnetically dominated)

Flat-space solution $H_\varphi = -2\pi\Omega_{\rm F} B^r \sqrt{\gamma}\sin\theta$



$$\mathbf{S}_{\rm p} = \frac{\mathbf{E}\times\mathbf{H}_\varphi}{4\pi}$$

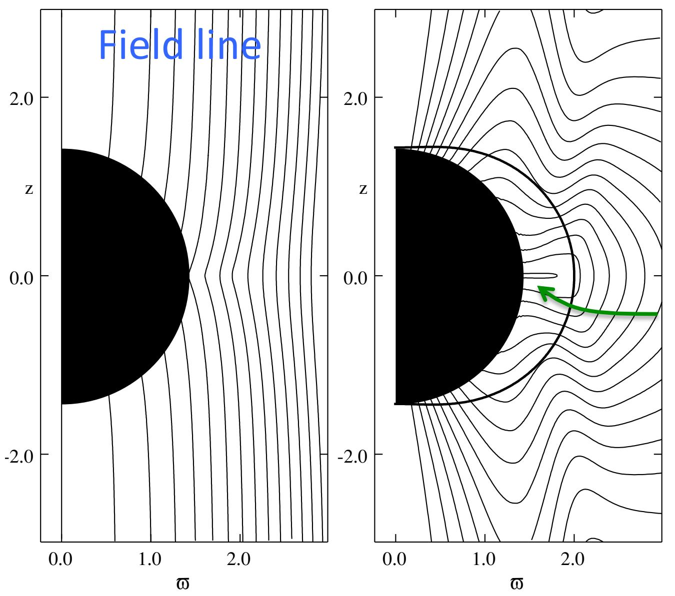
$H_\varphi = 2\pi(\Omega_{\rm F} - \Omega_{\rm H}) B^r \sqrt{\gamma}\sin\theta$ Regularity at horizon

$$\frac{dE}{dt} \sim a^2 B_{\rm H}^2 r_{\rm H}^2$$

This can be enough for observed jets

Issue on BZ process [1]

Resistive force-free simulation (Komissarov 2004)

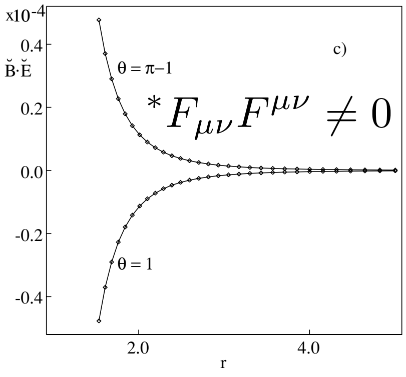


$F_{\mu\nu}F^{\mu\nu}$

Breakdown of force-free/ideal MHD condition

$a = 0.9$

$a = 0.1$



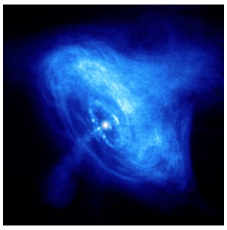
${}^{*}F_{\mu\nu}F^{\mu\nu} \neq 0$

Small deviation from force-free/ideal MHD in monopole solution

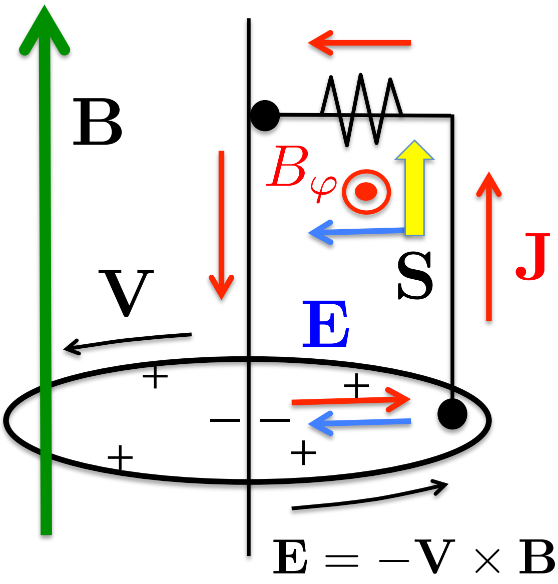
Analytical studies with more general plasma physics may check assumptions of numerical studies

Issue on BZ process [2]

- Membrane paradigm (Thorne et al. 1986)
    - ➢ BZ process = unipolar induction



Crab Nebula in X-rays



$\mathbf{E} = -\mathbf{V} \times \mathbf{B}$

(Faraday 1832; Goldreich & Julian 1969)

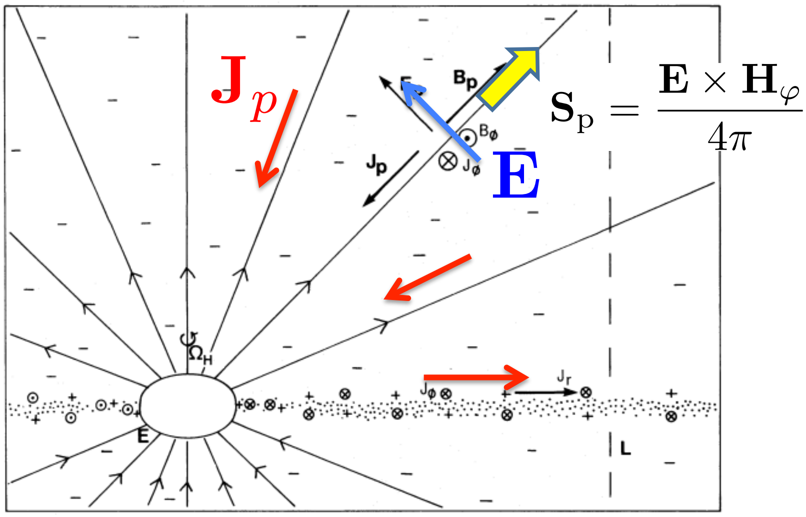
$$\nabla \cdot \mathbf{S} = -\mathbf{E} \cdot \mathbf{J} < 0$$

$$\nabla \cdot \mathbf{S} = 0$$

$$\nabla \cdot \mathbf{S} = -\mathbf{E} \cdot \mathbf{J} > 0$$

But horizon is causally disconnected, and there is no matter-dominant region

Flat-space solution $\boxed{H_\varphi = -2\pi\Omega_{\rm F} B^r \sqrt{\gamma}\sin\theta}$



$$\mathbf{S}_{\rm p} = \frac{\mathbf{E}\times\mathbf{H}_\varphi}{4\pi}$$

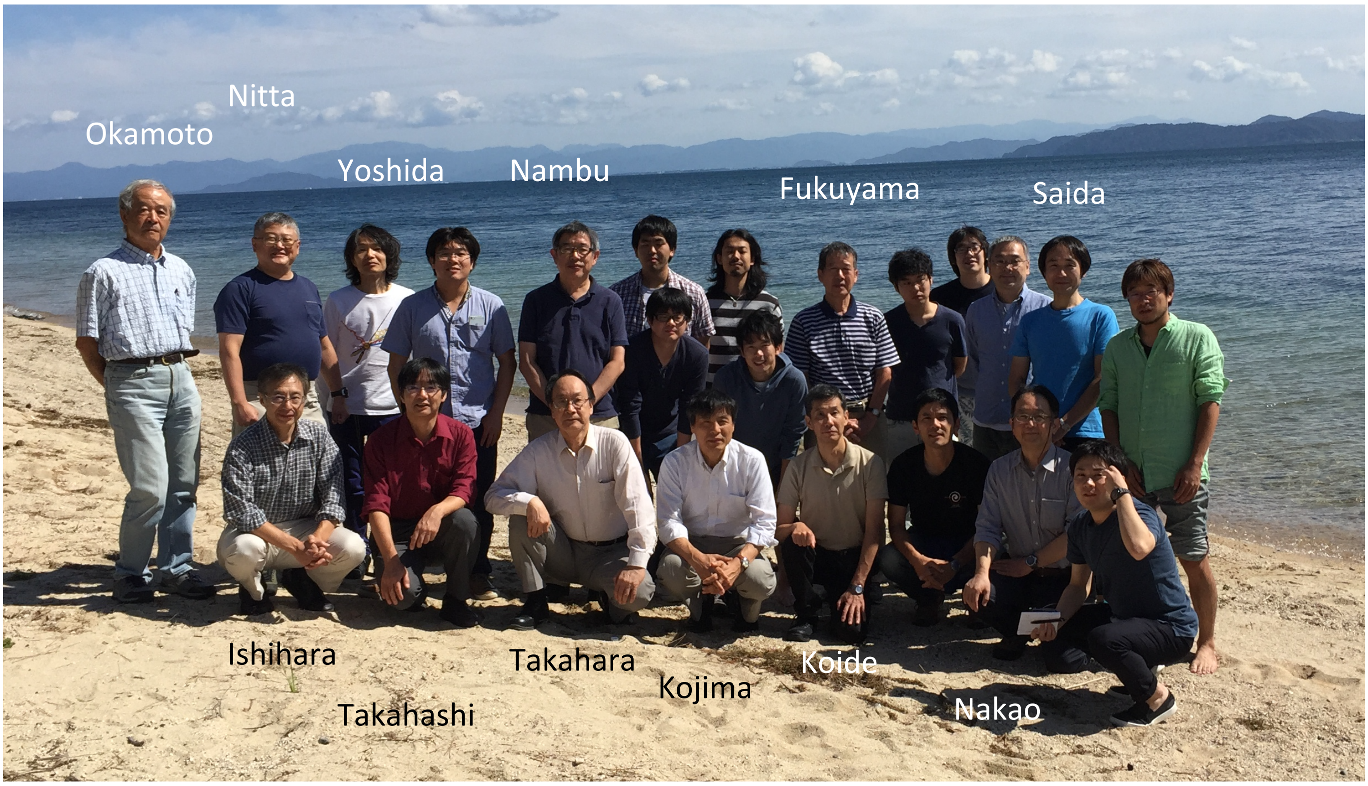
$\boxed{H_\varphi = 2\pi(\Omega_{\rm F} - \Omega_{\rm H}) B^r \sqrt{\gamma}\sin\theta}$ Regularity at horizon

- Force-free or ideal MHD condition is valid?
- How is the electric current driven?
- Is the ergosphere important?
- Negative energy inflow?

(Punsly & Coroniti 89; Takahashi+ 90; Beskin & Kusnetsova 00; Okamoto 06; Komissarov 09; Lasota+ 14; Koide & Baba 14; Kojima 15)

at Workshop『不惑BZ77』, 8/28-30/2017

Consensus achieved



http://www.phyas.aichi-edu.ac.jp/~takahasi/BZ77_WS2017/

Kerr space-time

$$\boxed{ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -\alpha^2 dt^2 + \gamma_{ij}(\beta^i dt + dx^i)(\beta^j dt + dx^j),}$$

Boyer-Lindquist coordinates

$$\alpha = \sqrt{\frac{\varrho^2\Delta}{\Sigma}}, \quad \boxed{\beta^\varphi = -\frac{2ar}{\Sigma}, \quad \equiv -\Omega}$$

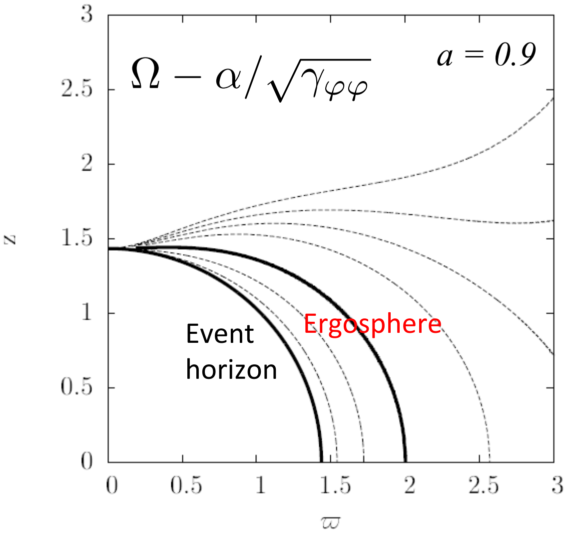
$$\gamma_{\varphi\varphi} = \frac{\Sigma}{\varrho^2}\sin^2\theta, \quad \gamma_{rr} = \frac{\varrho^2}{\Delta}, \quad \gamma_{\theta\theta} = \varrho^2,$$

$$\varrho^2 = r^2 + a^2\cos^2\theta, \quad \Delta = r^2 + a^2 - 2r,$$
$$\Sigma = (r^2 + a^2)^2 - a^2\Delta\sin^2\theta,$$

$$r \to \infty : a \to 1, \Omega \to 0$$

$$r \to r_\mathrm{H} : a \to 0(\Delta \to 0)$$

Coordinate singularity



$$g_{tt} = -\alpha^2 + \gamma_{\varphi\varphi}\Omega^2 > 0$$

Fiducial Observers (FIDOs)

$$\boxed{ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -\alpha^2 dt^2 + \gamma_{ij}(\beta^i dt + dx^i)(\beta^j dt + dx^j),}$$

FIDOs:
Normal to t=const. surface

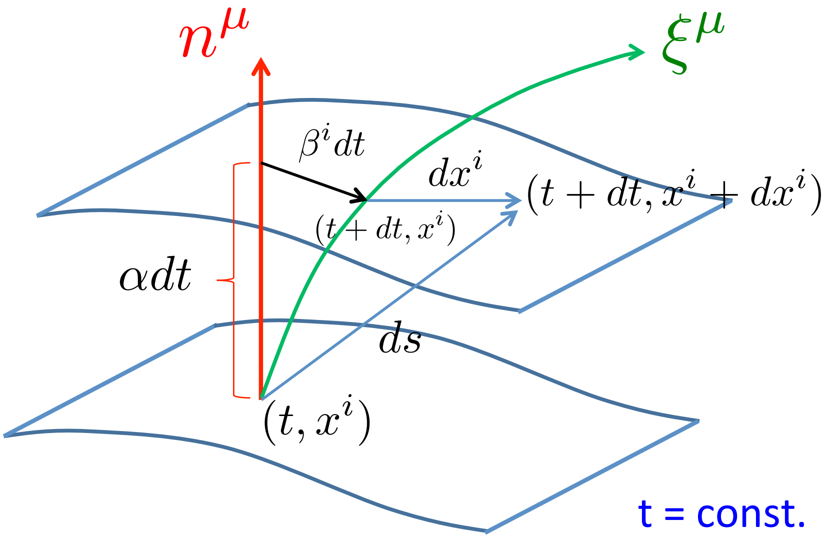
$$n^\mu = \left(\frac{1}{\alpha}, \frac{-\beta^i}{\alpha}\right),$$

$$n_\mu = g_{\mu\nu}n^\nu = (-\alpha, 0, 0, 0).$$

$$n_\mu n^\mu = -1$$

BL FIDOs rotate with $\Omega = -\beta^\phi$ in coordinate basis

Time-like Killing vector:
$dx^i = 0$



3+1 Electrodynamics

$$E^\mu = \gamma^{\mu\nu} F_{\nu\alpha}\xi^\alpha, \quad H^\mu = -\gamma^{\mu\nu *} F_{\nu\alpha}\xi^\alpha$$

Fields in the coordinate basis

$$D^\mu = F^{\mu\nu} n_\nu, \quad B^\mu = -{}^* F^{\mu\nu} n_\nu$$

Fields as measured by FIDOs

$$\nabla \cdot \boldsymbol{B} = 0, \quad \partial_t \boldsymbol{B} + \nabla \times \boldsymbol{E} = 0,$$

$$\nabla \cdot \boldsymbol{D} = 4\pi\rho, \quad -\partial_t \boldsymbol{D} + \nabla \times \boldsymbol{H} = 4\pi \boldsymbol{J},$$

$$\boldsymbol{E} = \alpha \boldsymbol{D} + \boldsymbol{\beta} \times \boldsymbol{B},$$

$$\boldsymbol{H} = \alpha \boldsymbol{B} - \boldsymbol{\beta} \times \boldsymbol{D},$$

Energy equation

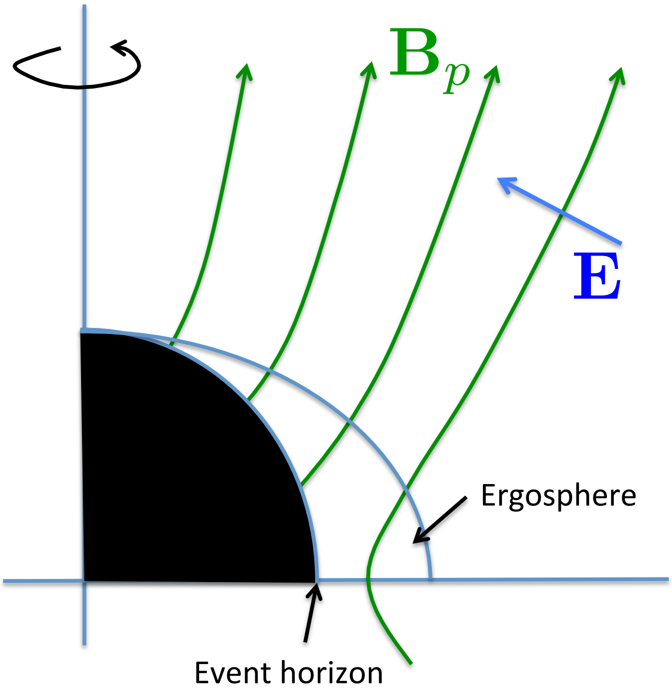
$$\partial_t \underbrace{\left[\frac{1}{8\pi}(\boldsymbol{E}\cdot\boldsymbol{D} + \boldsymbol{B}\cdot\boldsymbol{H})\right]}_{\text{Energy density}} + \nabla \cdot \underbrace{\left(\frac{1}{4\pi}\boldsymbol{E}\times\boldsymbol{H}\right)}_{\text{Poynting flux}} = -\boldsymbol{E}\cdot\boldsymbol{J},$$

$$\frac{D\hat{u}_i}{d\hat{t}} = \frac{q}{m}(\hat{D}_i + \epsilon_{ijk}\hat{v}^j \hat{B}^k)$$

Particle EOM in FIDO's orthonormal basis

(Landau & Lifshitz 1975; Komissarov 2004)

General conditions of magnetosphere



- Kerr spacetime with fixed arbitrary spin a
- Axisymmetric
- Poloidal B field threading the ergosphere (with arbitrary shape)
- Plasma with sufficient number density

$$\mathbf{D} \cdot \mathbf{B} = 0$$

$$(\mathbf{E} \cdot \mathbf{B} = 0)$$

This includes force-free/ideal MHD condition

Steady axisymmetric field

$$\nabla \times \mathbf{E} = 0, \qquad \mathbf{E} \cdot \mathbf{B} = 0$$

⇒

$$\boxed{\mathbf{E} = -\boldsymbol{\omega} \times \mathbf{B}, \quad \boldsymbol{\omega} = \Omega_{\mathrm{F}} \mathbf{m}.}$$

$$\mathbf{m} = \partial_\varphi$$

Angular momentum equation

$$\nabla \cdot \left(\frac{-H_\varphi}{4\pi} \mathbf{B}_{\mathrm{p}} \right) = B^i \partial_i \left(\frac{-H_\varphi}{4\pi} \right) = -(\mathbf{J}_{\mathrm{p}} \times \mathbf{B}_{\mathrm{p}}) \cdot \mathbf{m},$$

Energy equation

$$\nabla \cdot \left(\Omega_{\mathrm{F}} \frac{-H_\varphi}{4\pi} \mathbf{B}_{\mathrm{p}} \right) = B^i \partial_i \left(\Omega_{\mathrm{F}} \frac{-H_\varphi}{4\pi} \right) = -\mathbf{E} \cdot \mathbf{J}_{\mathrm{p}},$$

Poynting flux

Origin of electric potential

$$\boxed{\boldsymbol{E} = \alpha \boldsymbol{D} + \boldsymbol{\beta} \times \boldsymbol{B},}$$

If $E=0$, $H_\phi=\alpha B_\phi=0$ (No ang. mom. or Poynting flux) along a field line,

$$\mathbf{D} = -\frac{1}{\alpha} \beta \times \mathbf{B}_p \quad ⇒ \quad D^2 > B^2 \text{ for } \alpha^2 < \beta^2$$

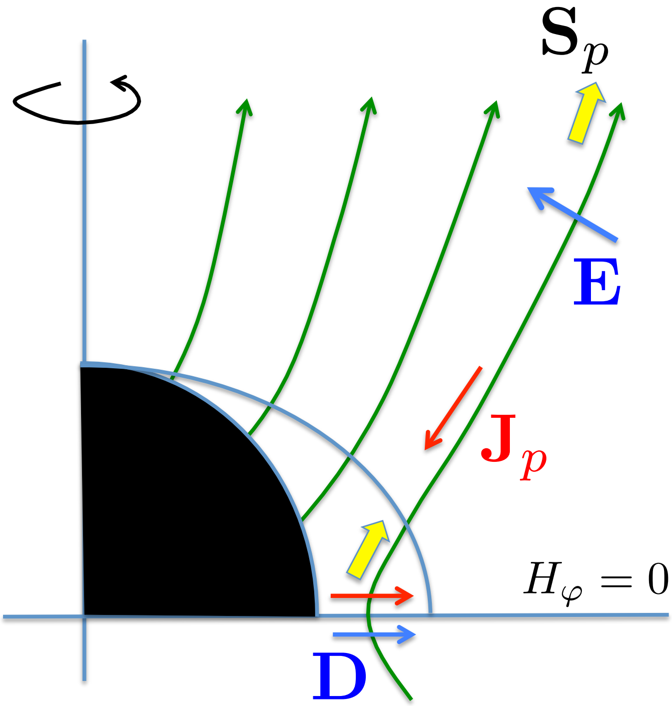
(in the ergosphere)

Then the force-free is violated, and the strong D field drives J_p across B_p ($H_\phi \neq 0$), weakening D ($E \neq 0$).

The origin of the electric potential is ascribed to the ergosphere.

(KT & Takahara 2014; see also Komissarov 2004; 2009)

Steady state for field lines threading equatorial plane



- From the symmetry

$$H_\varphi = 0$$

- $D^2 > B^2$ is possible
- This moves particles across field lines

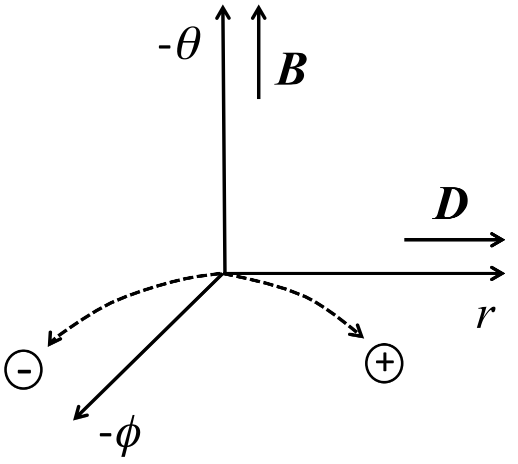
$$\nabla \cdot \mathbf{L}_p = -(\mathbf{J}_p \times \mathbf{B}_p) \cdot \mathbf{m}$$

$$\nabla \cdot \mathbf{S}_p = -\mathbf{E} \cdot \mathbf{J}_p$$

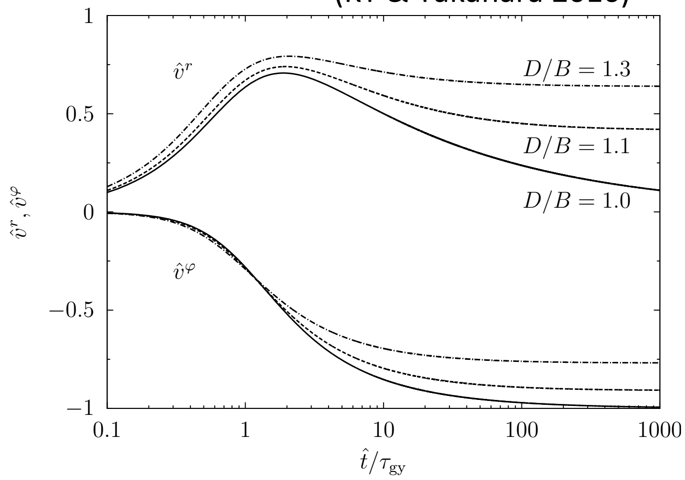
Similar to unipolar induction

(KT & Takahara 2014)

Particles near equatorial plane



(KT & Takahara 2016)



$$\boxed{\hat{v}^\varphi \approx -1}$$

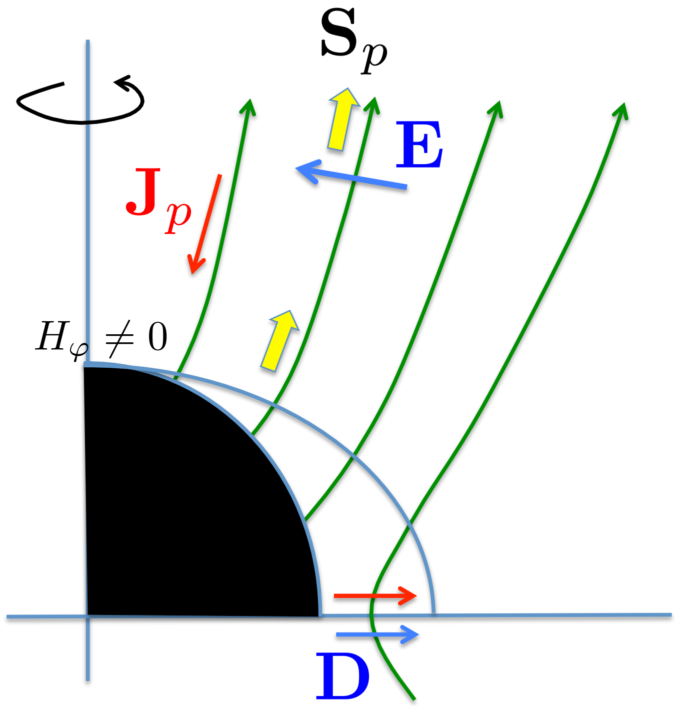
$$\begin{aligned} l_{\rm p} &= u_\mu \chi^\mu = \gamma_{\varphi\varphi}(v^\varphi - \Omega)u^t \\ &= \sqrt{\gamma_{\varphi\varphi}}\hat{v}^\varphi \hat{u}^t, \end{aligned}$$

$$\begin{aligned} e_{\rm p} &= -u_\mu \xi^\mu = [\alpha^2 + \gamma_{\varphi\varphi}\Omega(v^\varphi - \Omega)]u^t \\ &= (\alpha + \sqrt{\gamma_{\varphi\varphi}}\Omega\hat{v}^\varphi)\hat{u}^t, \end{aligned}$$

➡ $l_{\rm p} < 0, \quad e_{\rm p} < 0$

Similar to mechanical Penrose process

Steady state for field lines threading event horizon



- From the regularity at horizon

$$H_\varphi \neq 0, \quad D^2 < B^2$$

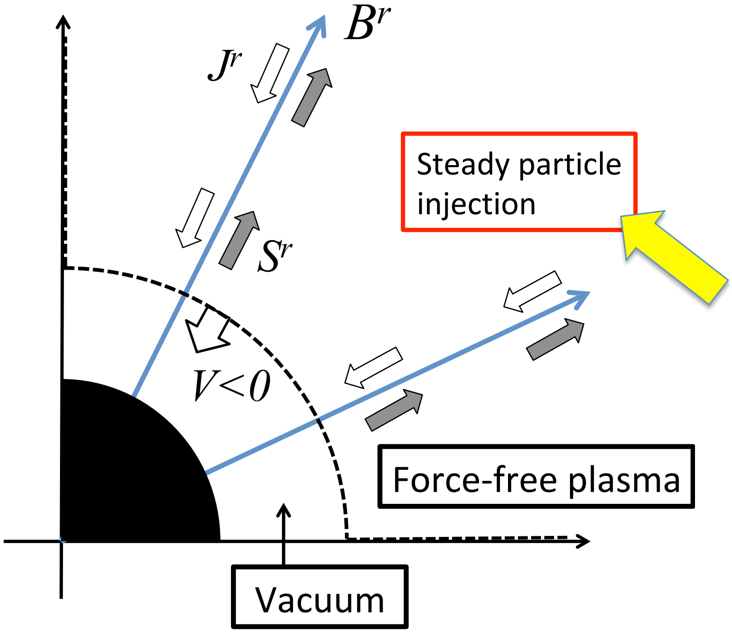
- No current crossing
- Force-free or ideal MHD condition can be valid

(KT & Takahara 16)

- Solutions (Ω_F & H_ϕ) are determined by inner & outer light surfaces; Event horizon is not important

(Takahashi+90; Beskin & Kusnetsova 00; Contpoulos+13; Kinoshita & Igata 17)

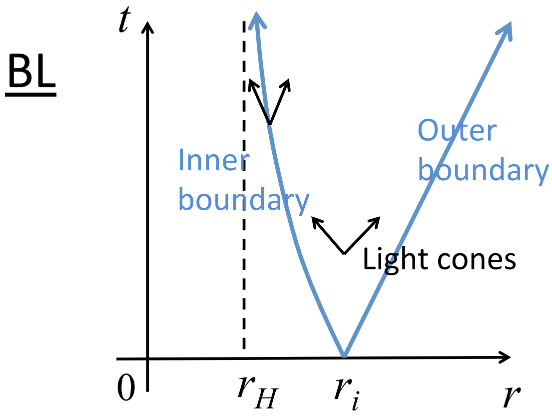
Time dependent state (vacuum → ff plasma)



Steady particle injection

Force-free plasma

Vacuum



$$-\frac{1}{\sqrt{\gamma}}\partial_r H_\varphi = \partial_t D^\theta + 4\pi J^\theta$$

$$\nabla \cdot \mathbf{S}_p = -\partial_t e - \mathbf{E} \cdot \mathbf{J}_p$$

Electromagnetic source works in time dependent state, but does not in steady state

(KT & Takahara 16)

Junction condition at inner boundary (BL coordinates)

$$-\partial_t D^r + \frac{1}{\sqrt{\gamma}}\partial_\theta H_\varphi = 4\pi J^r, \quad \Rightarrow \quad \eta^r = \left.\frac{-D^r_{\rm vac}}{4\pi}\right|_{R=0} V,$$

$$-\partial_t D^\theta - \frac{1}{\sqrt{\gamma}}\partial_r H_\varphi = 4\pi J^\theta, \quad \Rightarrow \quad V = \frac{1}{\sqrt{\gamma}} \left.\frac{H^{\rm ff}_\varphi + 4\pi\sqrt{\gamma}\eta^\theta}{D^\theta_{\rm ff} - D^\theta_{\rm vac}}\right|_{R=0}.$$

$$\partial_t B^\varphi + \frac{1}{\sqrt{\gamma}}(\partial_r E_\theta - \partial_\theta E_r) = 0, \quad \Rightarrow \quad V = \frac{1}{\sqrt{\gamma}} \left.\frac{E^{\rm ff}_\theta - E^{\rm vac}_\theta}{B^\varphi_{\rm ff}}\right|_{R=0},$$

$$\Downarrow$$

$$\boxed{ds^2 = -\alpha^2 dt^2 + \gamma_{rr} dr^2}$$

If $\eta^\theta = 0$, it would be null

$$V = \frac{\pm\alpha}{\sqrt{\gamma_{rr}}}\sqrt{1 + \frac{4\pi\sqrt{\gamma}\eta^\theta}{H^{\rm ff}_\varphi}}. \quad \Rightarrow \quad \eta^\theta > 0,$$

Current crosses field lines !

Same conclusion in KS coordinates

Negative energy inflow?

Conserved energy flux (in force-free approximation)

$$S^r = -\alpha T^r_0 = -\alpha T^r_\mu \xi^\mu_{(t)} = (\mathbf{E} \times \mathbf{H}_\varphi)^r$$
$$= \varepsilon V^r \ (\varepsilon < 0)?$$

$$(\mathbf{E} \times \mathbf{H}_\varphi)^r = \alpha^2 (\mathbf{D} \times \mathbf{B})^r + \Omega(-H_\varphi)\mathbf{B}^r$$

Poynting flux measured by FIDOs (inward near horizon)

Torque due to outward angular momentum flux

$$dM = \frac{\kappa}{8\pi} dA + \Omega_{\rm H} dJ$$

(McDonald & Thorne 84; Okamoto 06)

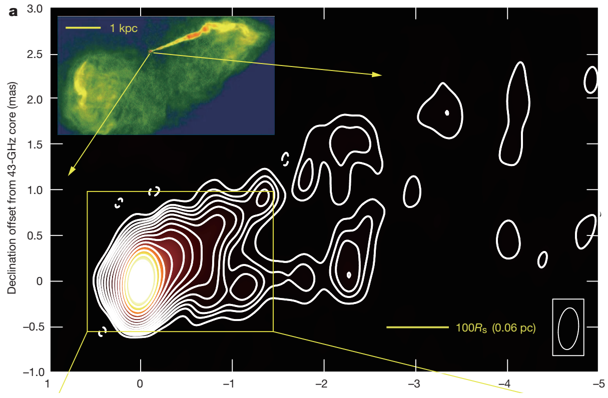
Short summary

- Force-free or ideal MHD condition is valid?
  - Can be valid for field lines threading horizon
  - They can break for very low density case

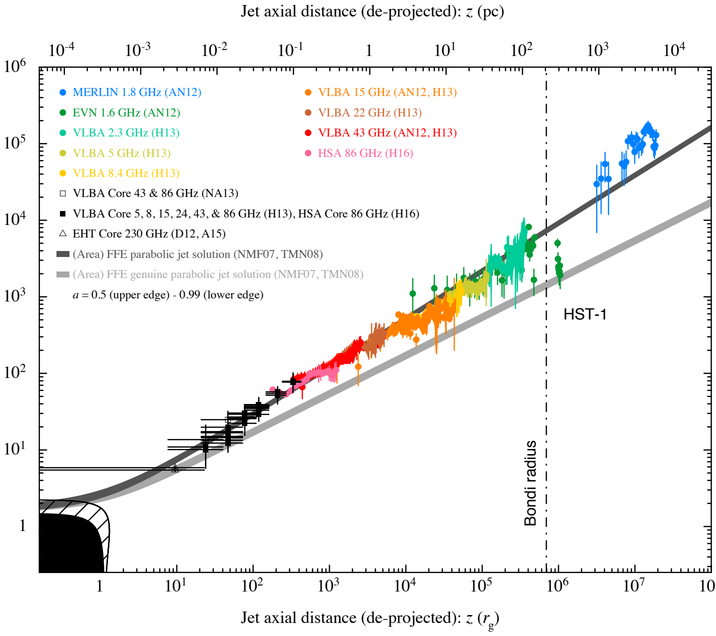
(cf. two-fluid analysis in Kojima 2017)

- How is the electric current driven?
  - Current can be regulated at time-dependent state
- Is the ergosphere important?
  - Origin of electric potential
  - Steady solutions not determined by horizon
- Negative energy inflow?
  - Essential is the outward angular momentum flux

Era of observational tests

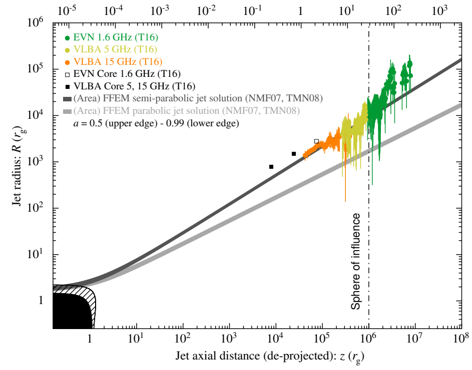


(Hada et al. 2011)



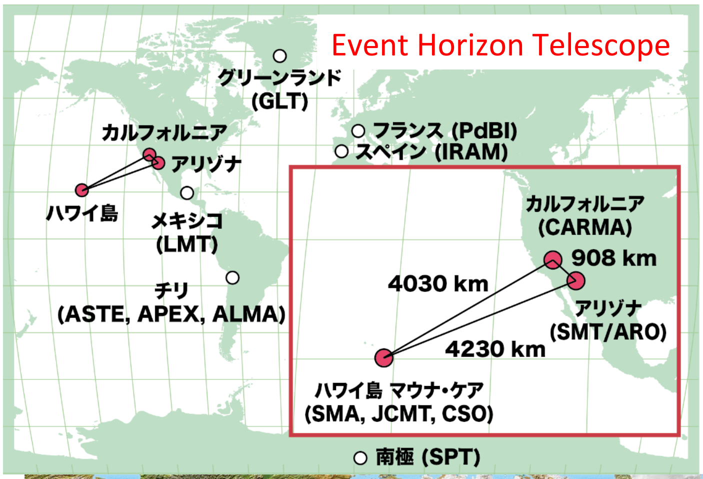
(M. Nakamura, Asada, Hada et al. in prep.)

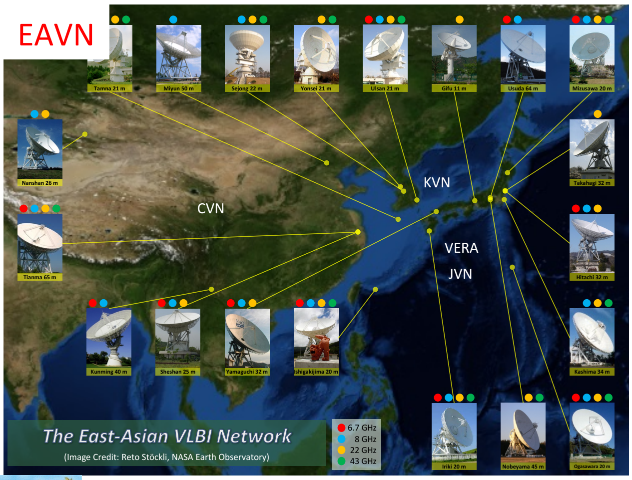
NGC6251

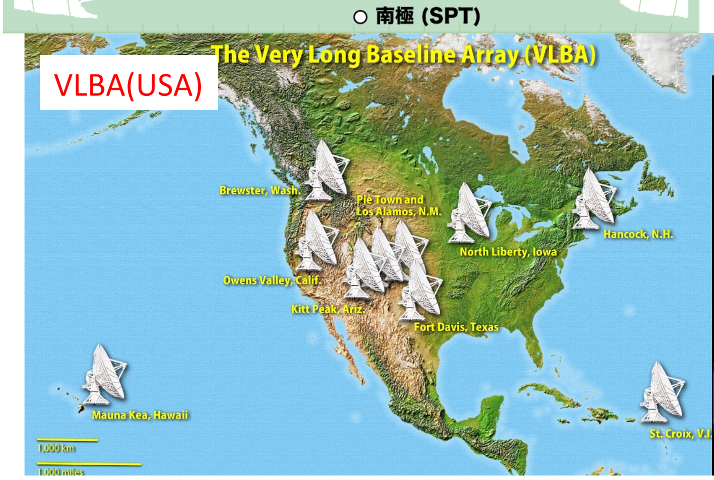


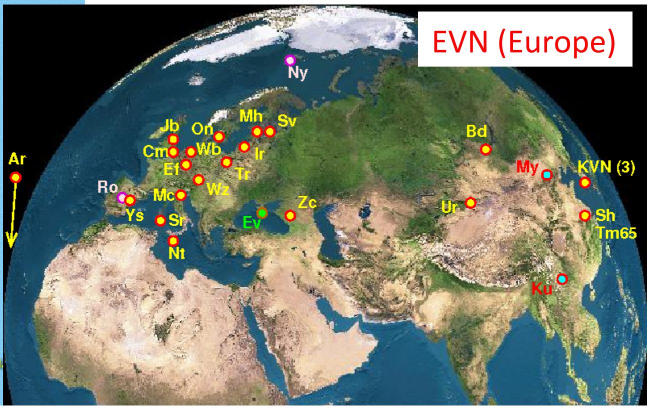
- M87: second largest BH size in the sky
- Strong B field (Kino et al. 2015)
- *Jet from BH?*

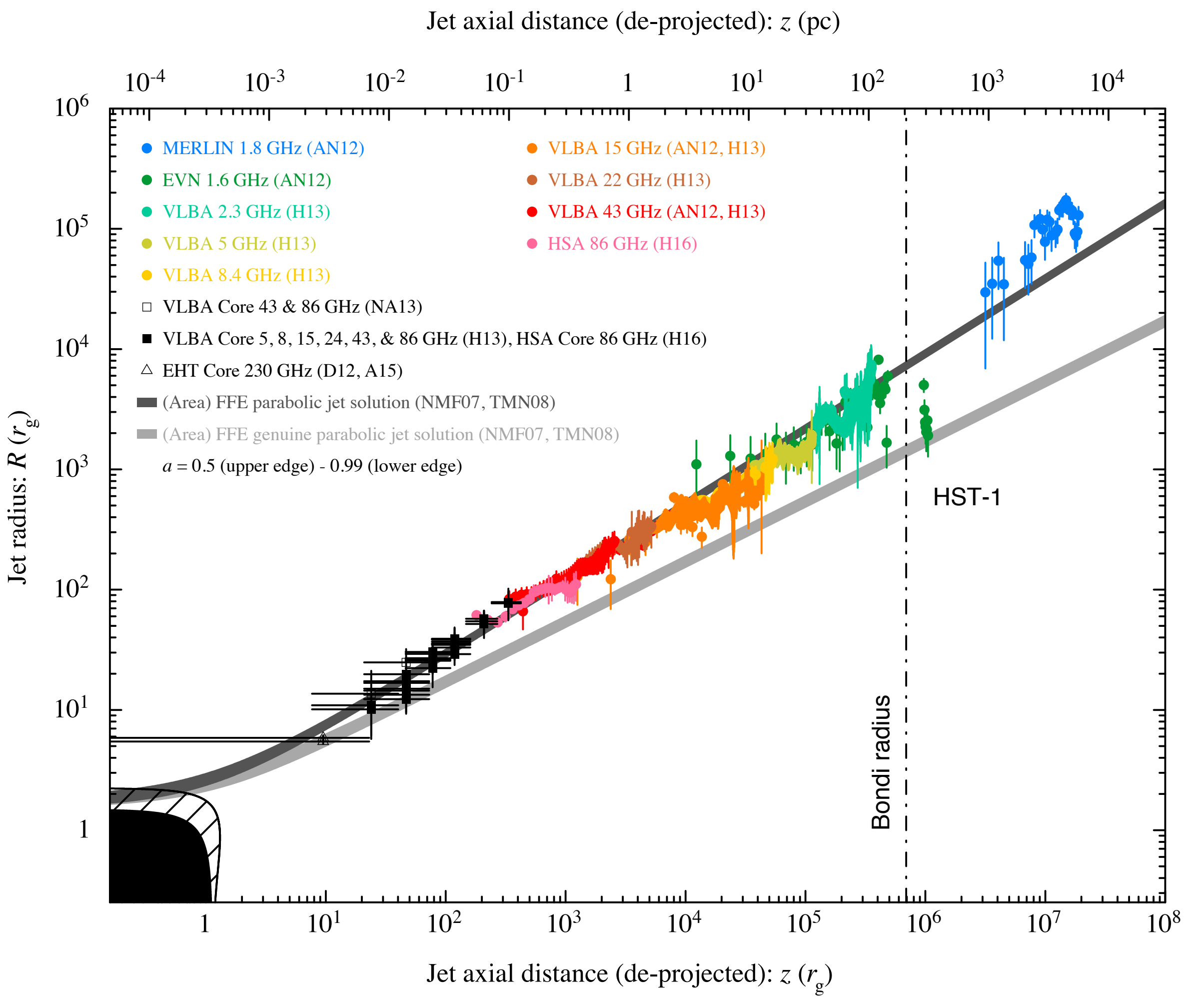
Very Long Baseline Interferometer (VLBI)





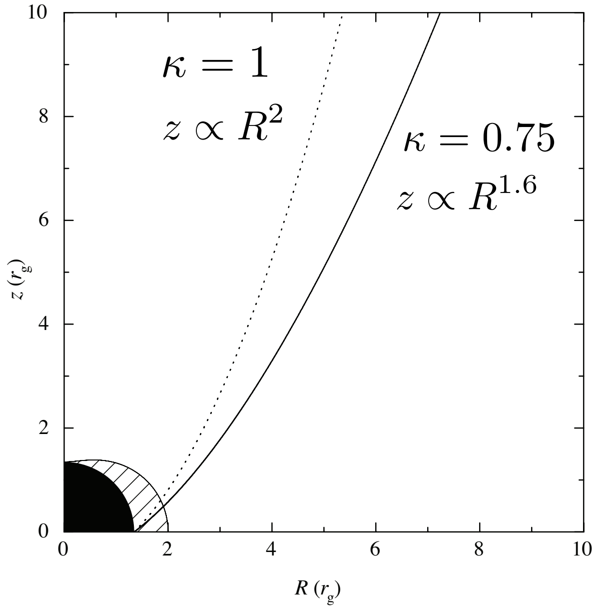




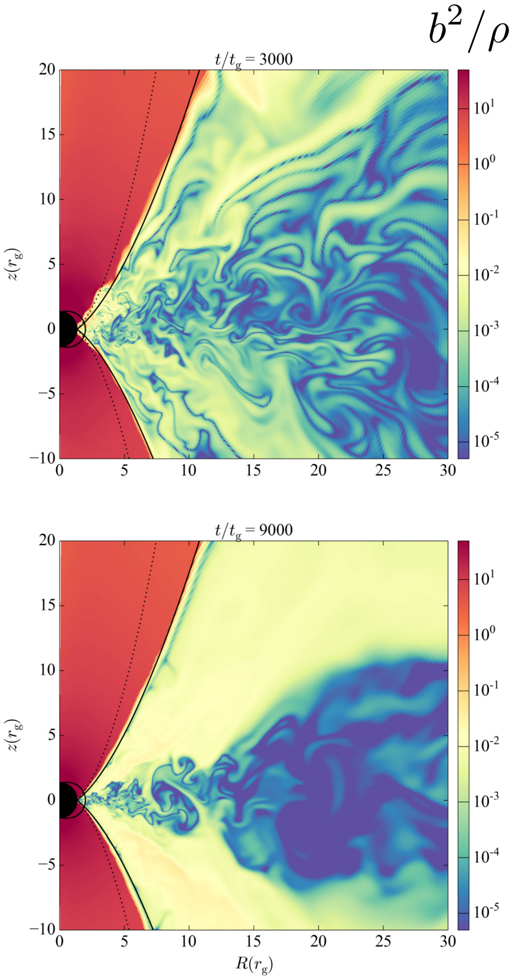


Comparison to force-free & MHD solutions

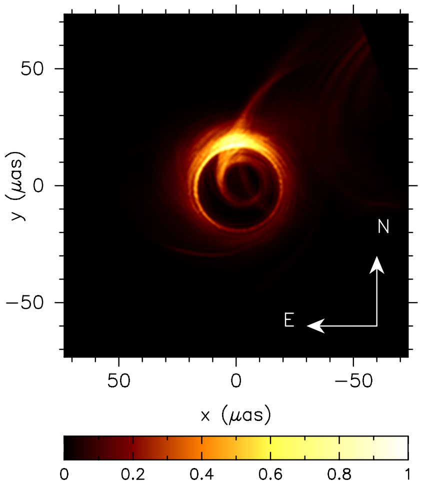
$$\Psi(r,\theta) = \left(\frac{r}{r_{\mathrm{H}}}\right)^{\kappa} (1 - \cos\theta),$$



(M. Nakamura, Asada, Hada et al. in prep.; Narayan+07; McKinney & Gammie 04)

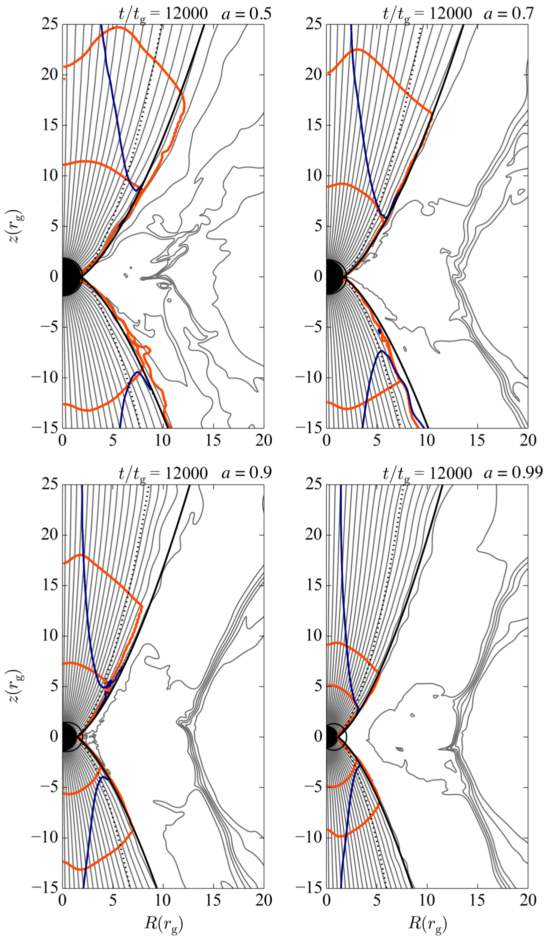


What can be seen with Event Horizon Telescope?



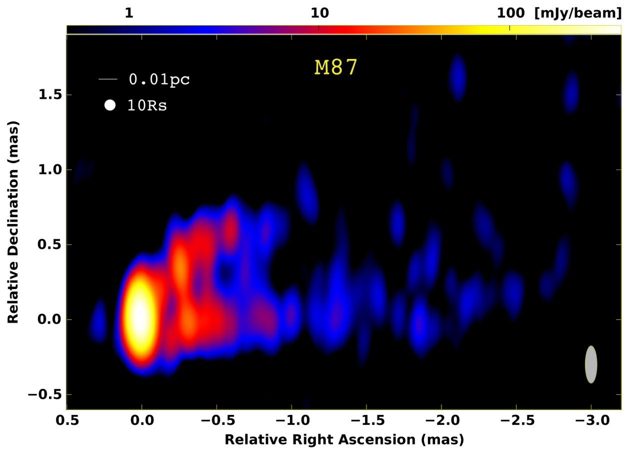
- Approaching counter-jet emission
- Constraint on spin parameter
- But non-thermal electron distribution is quite uncertain

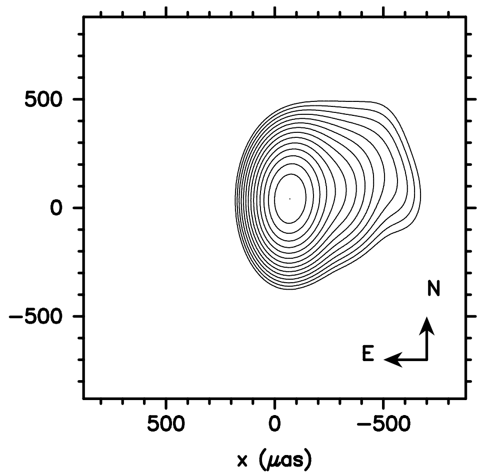
(Moscibrodzka+16)



(M. Nakamura, Asada, Hada et al. in prep.)

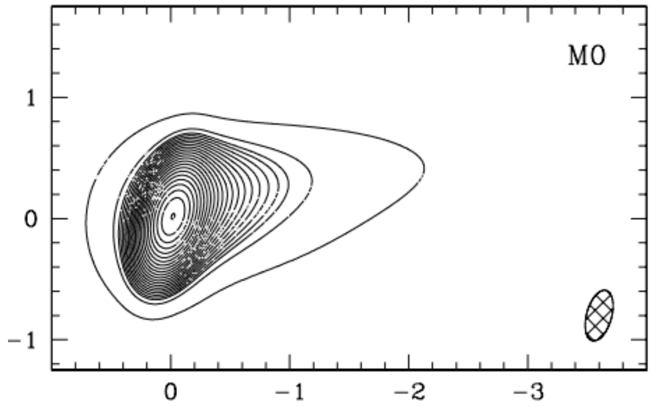
Edge-brightening image of M87





3D GR MHD simulation & radiative transfer

(Moscibrodzka+16)



Steady axisymmetric force-free model

(Broderick & Loeb 09)

Steady axisymmetric force-free model

Kazuya Takahashi

Magnetic flux function (approx.)

$$\Psi = Ar^{\nu}(1 \mp \cos\theta)$$

EM fields：

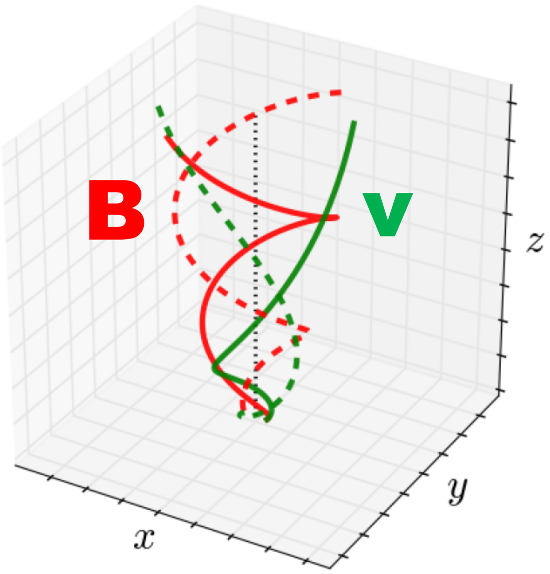
$$\mathbf{B}_p = \frac{1}{R}\nabla\Psi \times \hat{\phi}, \ \ B_\phi = \mp\frac{2\Psi\Omega}{Rc}$$

$$\mathbf{E} = -\frac{1}{c}\Omega\nabla\Psi = -\frac{R\Omega}{c}\hat{\phi} \times \mathbf{B}$$

Particle velocity fields：

$$\mathbf{v} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}c,$$

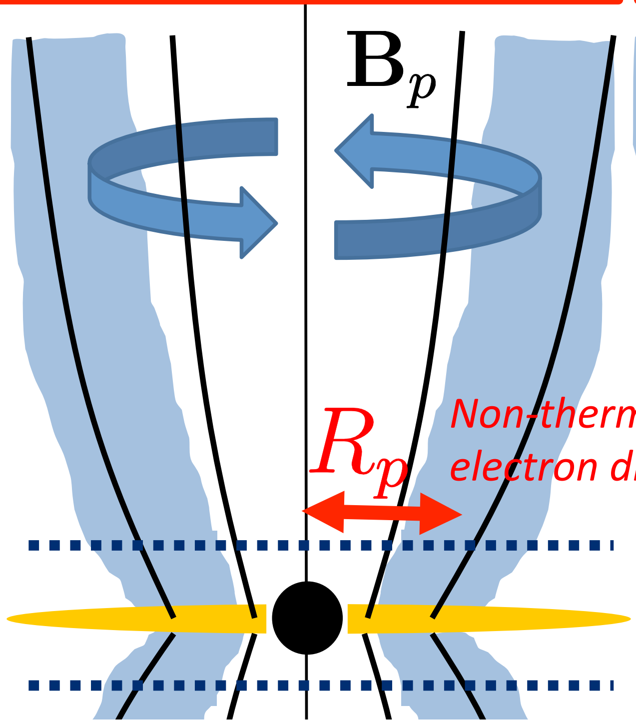
(Takahashi, KT, Kino, Nakamura & Hada in prep.)



Paraboloidal jet with helical fields

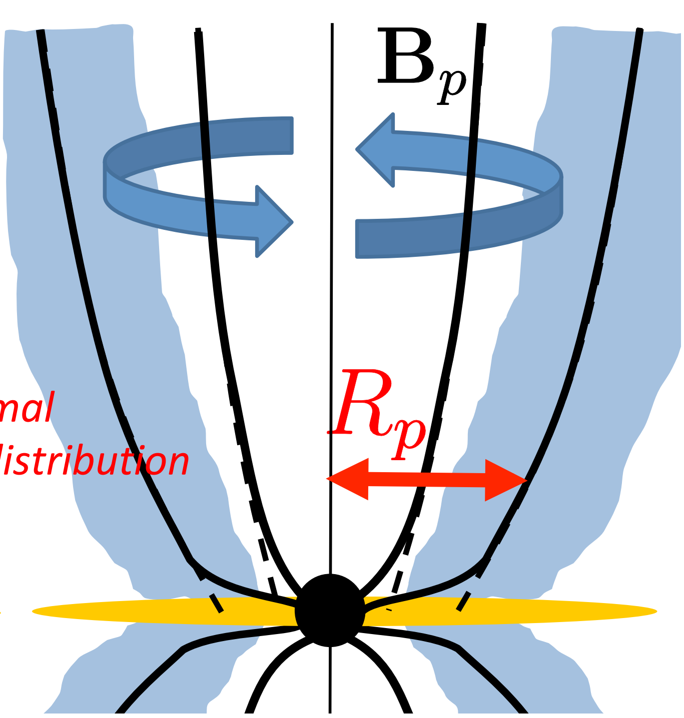
BP type: B fields threading disk

$$\Omega = \Omega_{\rm Kep} = \sqrt{\frac{GM}{R^3}}$$

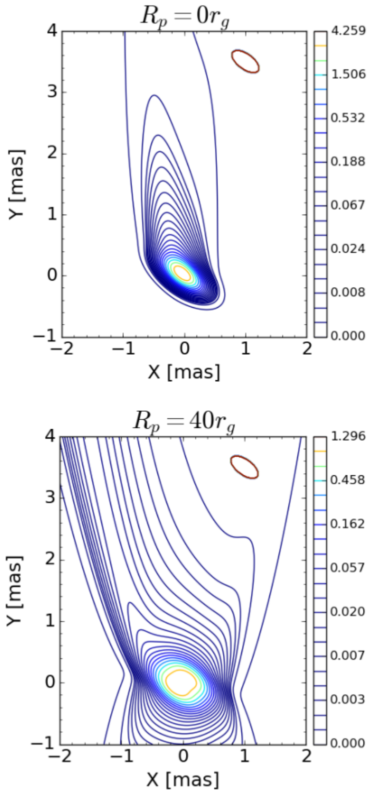


BZ type: B fields threading BH

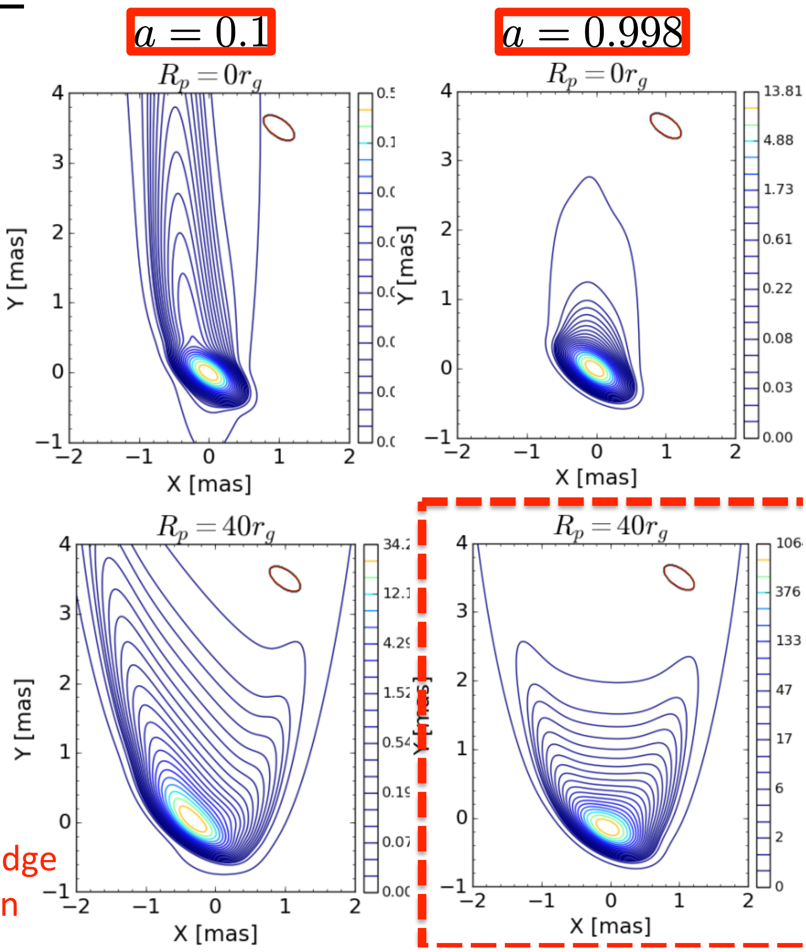
$$\Omega = \frac{1}{2}\Omega_{\rm BH} = {\rm const.}$$



BP type: B fields threading disk



BZ type: B fields threading BH



- Non-thermal electrons around edge
- Symmetric images need high spin

Summary

- MHD simulations show jets are electromagnetically driven by rotating BHs (via Blandford-Znajek process)
- BZ process is ascribed to the ergosphere
- VLBI observations have been much improved
  - Jet from BH? -> Existence of ergosphere
  - Constraint on spin parameter
  - Edge-brightening structure

Diego T. Blas (CERN TH),
“Testing gravitation with gravitational waves“
(50+10)
[JGRG27 (2017) 112711]

CERN

Diego Blas

Testing gravity with gravitational waves

w/ Cornish, Nardini, Barausse, Yagi, Yunes

Gravitation in 2017

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Massless, spin-2, 4D,
unitary, Lorentz Invariant

standard model fields

PDG
particle data group

beautiful and well tested, but can not accommodate

- quantum gravity
- dark matter
- dark energy
- strong CP and hierarchy problem, m_ν

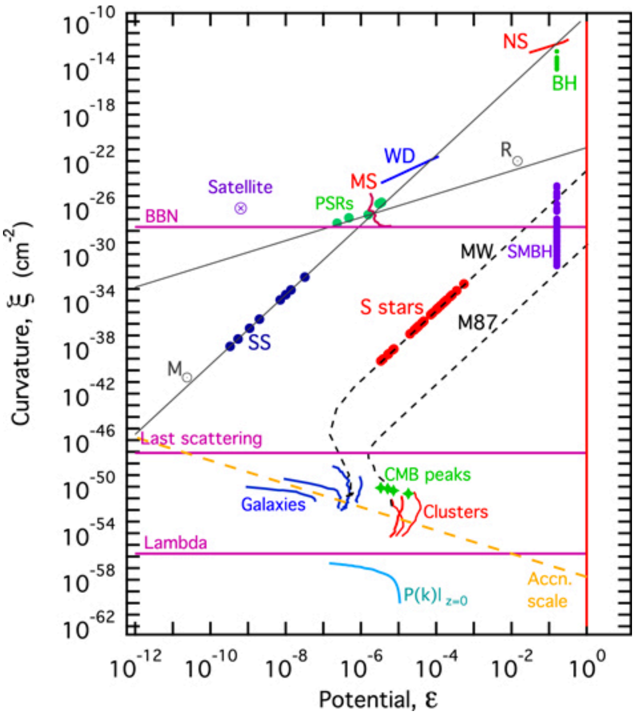
…and there are phenomena that may still hide surprises

- strong gravity, propagating gravity,

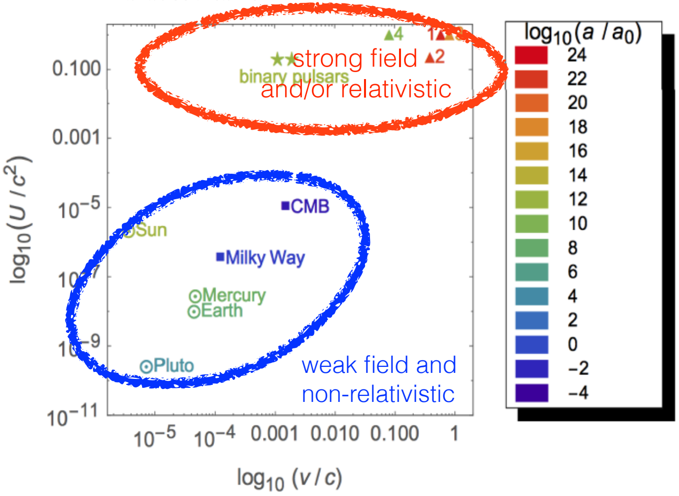
…

Tests of gravity

Baker et al '14



Barausse talks 17



1=BH-BH systems with aLIGO/aVirgo/KAGRA

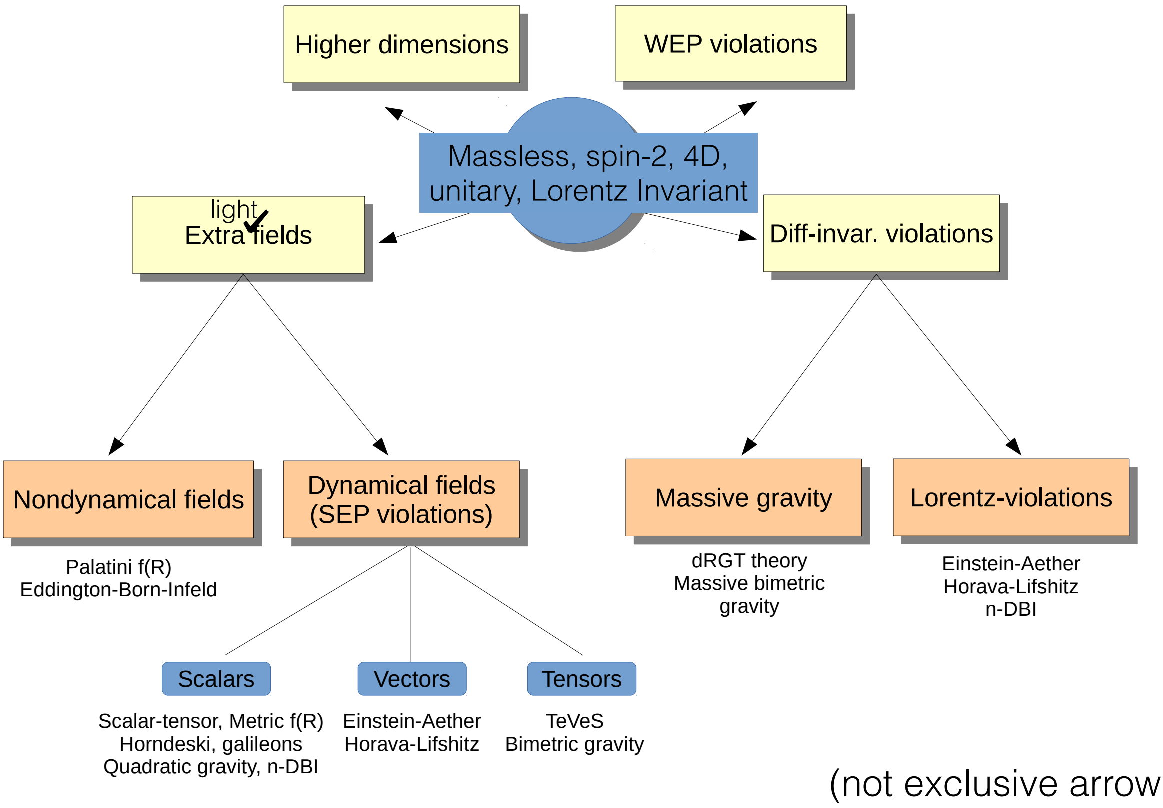
2=NS-NS systems with aLIGO/aVirgo/KAGRA,

3=BH-BH with eLISA,

4=BH- BH with PTAs

Beyond GR roadmaps

Berti et al 15



Higher dimensions

WEP violations

Massless, spin-2, 4D, unitary, Lorentz Invariant

light ✓ Extra fields

Diff-invar. violations

Nondynamical fields

Palatini f(R)
Eddington-Born-Infeld

Dynamical fields (SEP violations)

Massive gravity

dRGT theory
Massive bimetric gravity

Lorentz-violations

Einstein-Aether
Horava-Lifshitz
n-DBI

Scalars

Scalar-tensor, Metric f(R)
Horndeski, galileons
Quadratic gravity, n-DBI

Vectors

Einstein-Aether
Horava-Lifshitz

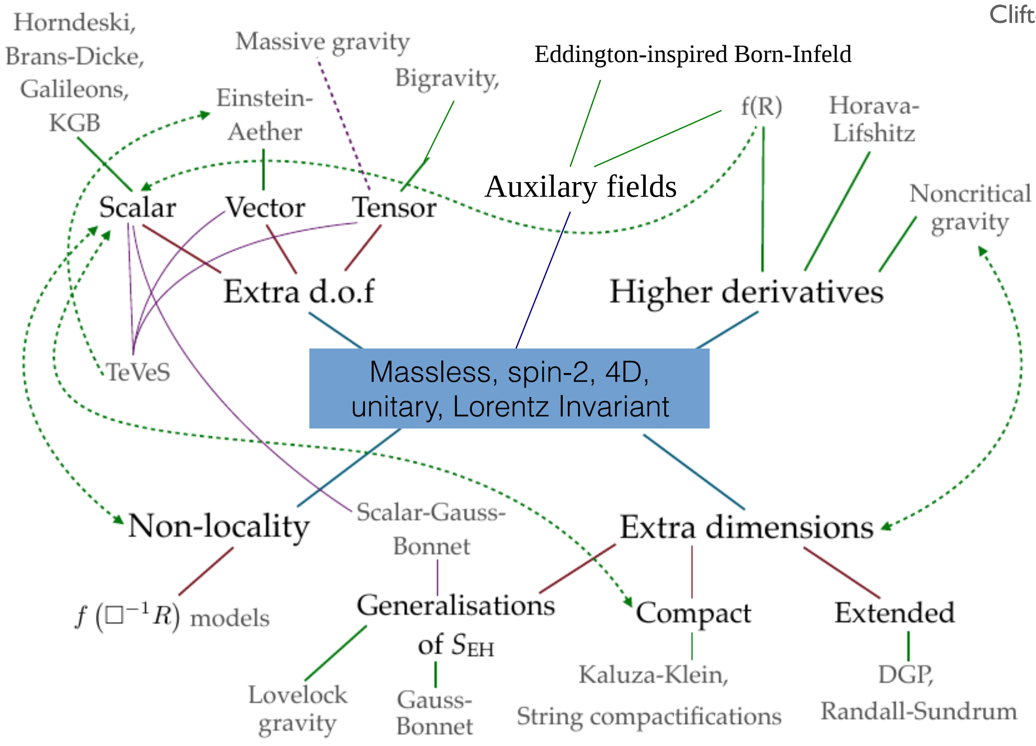
Tensors

TeVeS
Bimetric gravity

(not exclusive arrows)

Beyond GR roadmaps

Clifton et al 11



Horndeski, Brans-Dicke, Galileons, KGB

Massive gravity

Einstein-Aether

Bigravity,

Eddington-inspired Born-Infeld

f(R)

Horava-Lifshitz

Noncritical gravity

Scalar

Vector

Tensor

Auxilary fields

Extra d.o.f

Higher derivatives

TeVeS

Massless, spin-2, 4D, unitary, Lorentz Invariant

Non-locality

Scalar-Gauss-Bonnet

Extra dimensions

$f\left(\Box^{-1}R\right)$ models

Generalisations of $S_{\rm EH}$

Compact

Extended

Lovelock gravity

Gauss-Bonnet

Kaluza-Klein, String compactifications

DGP, Randall-Sundrum

see also Yagi, Yunes Pretorius 16
Yunes Siemens 13
Gair et al 12

Theoretical input

- Keep unitarity, stability of Minkowski and falsiability/predictivity (!)
- learning something fundamental about gravity/Nature
  e.g. *the symmetries of the Lagrangian, # of dimensions…*
- Improve the short distance properties of GR (QG, BH)
- Connection to dark energy/dark matter
- Connection to BSM, e.g. *strong CP problem or other axions,..*
- Interesting (testable) phenomenology

some (biased) examples:

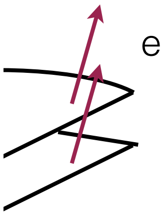
Horava 09	Wilczek, 78	
Horava gravity:	*Ultra-light scalars:*	*CS Gravity*
abandoning Lorentz Invariance may provide UV complete gravity	can fix the sCP may be ubiquotous in strings	…

Building new theories

gravity and X sector

$$\mathcal{L}(g_{\mu\nu}, X)$$

new light degrees of freedom or
rigid strucutures



e.g. a preferred frame (~~LI~~)

dynamical: $u^\mu, \quad u_\mu u^\mu = 1$

rigid: $\bar{u}^\mu = \delta^\mu_0$

strong equivalence principle
generically violated

matter sector

$$\mathcal{L}(SM, g_{\mu\nu}, X)$$

weak-equivalence principle
implies

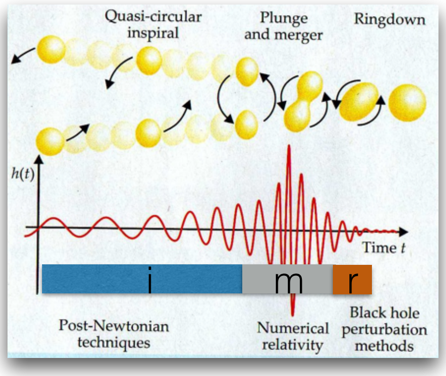
$$\mathcal{L}(SM, X g_{\mu\nu})$$

(at least locally)

(model independent parametrizations are also useful)

Different tests

emission

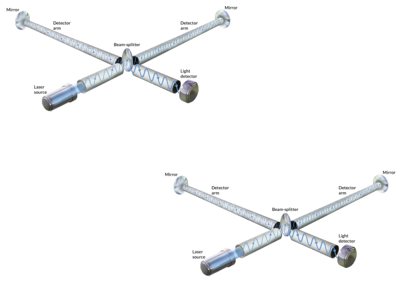


PN orbits
modified quadrupolar
dipolar radiation
scalar hair
no-hair Kerr/I-L-Q
ECOs

propagation

mass of GWs
speed of GWs
polarizations (w/PTAs)
Shapiro delay

detection



speed of GWs
polarizations

SEP violation at emission

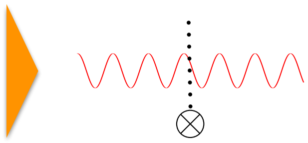
In strongly gravitating bodies, gravitational binding energy gives large contribution to total mass, but *binding energy coupled to extra fields*!

e.g. Einstein-aether theory

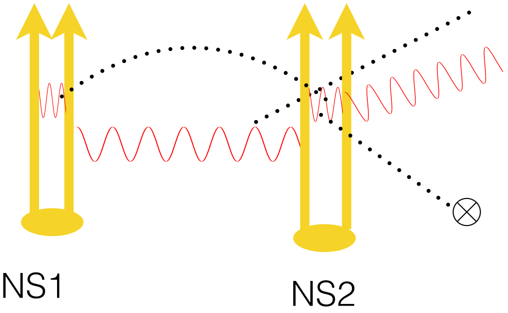
$$\mathcal{L} = M_P^2 R + c_1 (\nabla^\mu u_\nu)^2 + \ldots + \lambda (u^\mu u_\mu - 1)$$

$$\partial^2 uuhh$$

$$\bar{u}^\mu = \delta^\mu_0$$



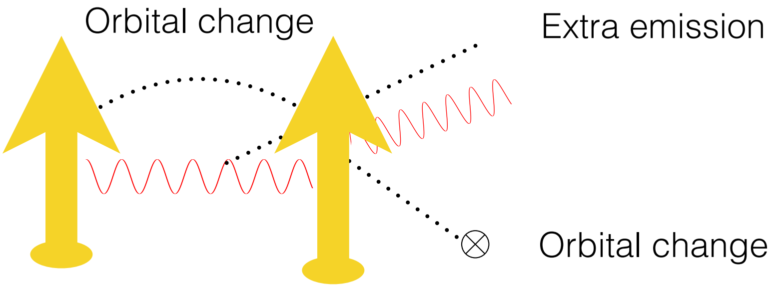
gravitons feel an extra field!
(~~SEP~~)



SEP violation at emission

In strongly gravitating bodies, gravitational binding energy gives large contribution to total mass, but binding energy depends on extra fields!

treated from ‘far away’ two ‘charged point particles! (even if $\mathcal{L}_m(\psi_m, g_{\mu\nu})$)



$$S_m^{eff} = \sum_n \int \mathrm{d}s \, m_n (u^\mu V_\mu)$$

$$V_n^\mu \nabla_\mu (m_n V^\nu) \sim \mathcal{O}(s_n)$$

$$s_n \equiv \frac{\partial \log m_n}{\partial (u^\mu V_\mu)} \sim f(G m_n / R)$$

No longer geodesic motion!

SEP violation at emission

No longer geodesic motion!

$$P^i = \sum m_n v_n^i$$ no longer conserved!
(there is momentum exchanged with u^μ)

$$h \sim \frac{G}{c^3}\frac{P}{r}$$ dipolar radition ~ $s_1 - s_2$

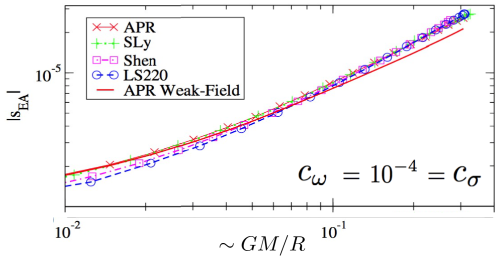
$$\dot{E}_b = -\mathcal{L}_{GW} - \mathcal{L}_{dip}$$

$$\mathcal{L}_{GW} \sim \left(\frac{v}{c}\right)^{10} \qquad \mathcal{L}_{dip} \sim \left(\frac{v}{c}\right)^{8}$$

dipolar radiation forces to inspiral faster and GWs to chirp faster

SEP violation at emission

sensitivities are hard to compute (simulation of NS)



Yagi, DB, Barausse and Yunes 14

they may also be (non-perturbatively) enhanced: scalarization

Damour, Esposito-Farese 95

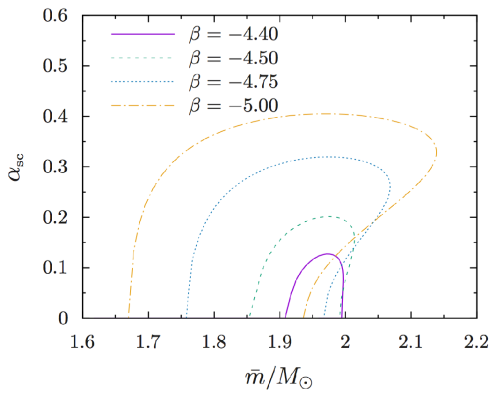
$$S = \int d^4x \frac{\sqrt{-g}}{2\kappa}\left[R - 2\partial_\mu\varphi\partial^\mu\varphi\right] + S_m\left(\psi_m, A^2(\varphi)g_{\mu\nu}\right)$$

$$\alpha = \partial \ln A/\partial\varphi \qquad \beta = \partial\alpha/\partial\varphi$$

$$\Box\varphi \sim \alpha R + \beta\varphi R$$

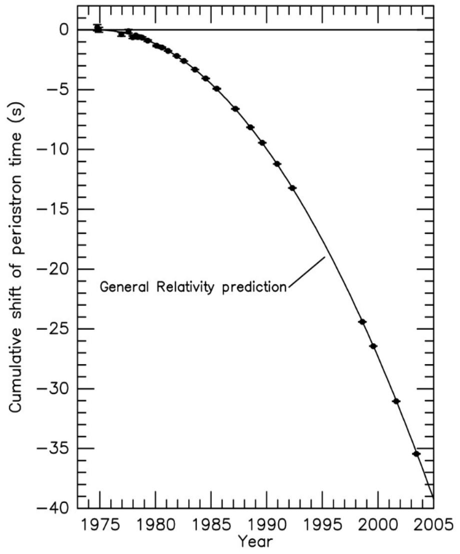
Solar System constrain

$$\alpha_0^{SS} < 10^{-3}$$



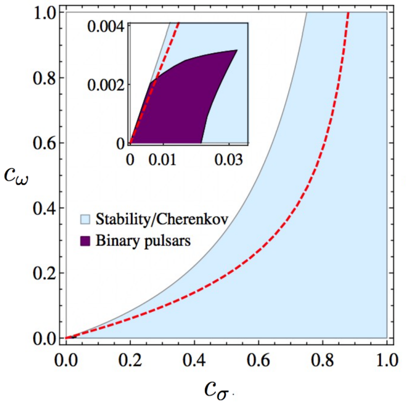
From binary pulsars

Hulse-Taylor



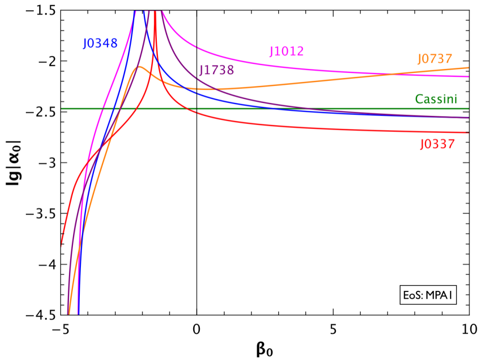
for Einstein-aether

Yagi, DB, Barausse and Yunes 14



for BD theories

N.Wex talk 17



BH binaries

No scalarization and sensitivities harder to compute (+ no hair)

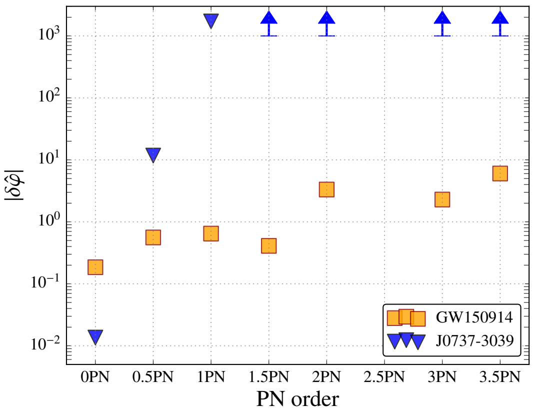
One can always test the PN physics from the waveforms

PN in corrections

$$h(t) = A(t)\cos(\Phi(t))$$

$$\Phi(t) = v(t)^{-5}\sum_{n=0}^{7}(\phi_n + \phi_n^l \log(v(t)))\overset{\downarrow}{v^n}(t) + \delta\hat{\varphi}_n$$

Abbott et al 16



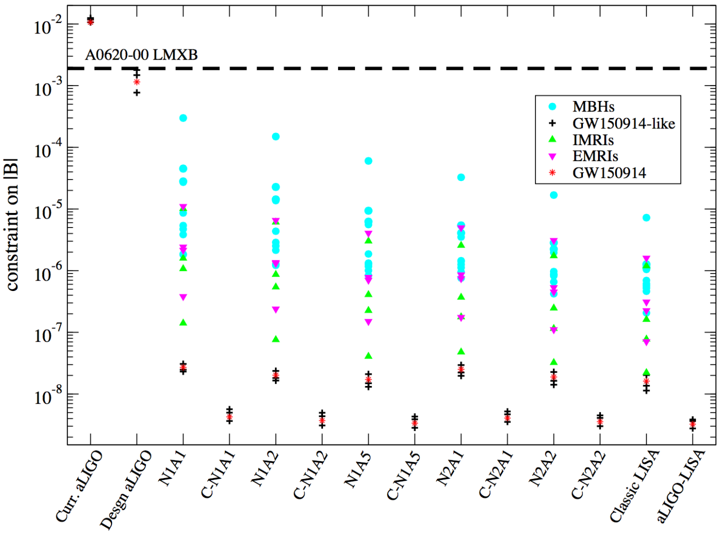
PN is also constraint in SS

Prospects Dipolar emission

$$\dot{E}_{GW} = \dot{E}_{GR}\left[1 + B\left(\frac{v}{c}\right)^{-2}\right]$$

$$B \sim (s_1 - s_2)^2 \lesssim 10^{-9}$$ (from pulsars)

Barausse, Yunes, Chamberlain 16

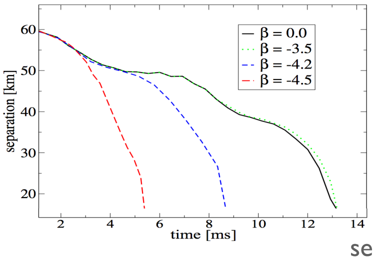


also Croon et al 17, Hooke, Huang17

Merger and ringdown

Merger requires NR: hard to explore
still, some results are known
e.g. earlier plunge of some scalar tensor theories

Barausse, et al 14

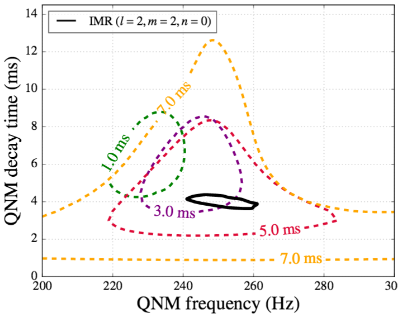


see also Okounkova et al 17, Cayuso et al 17

Ringdown allows to test the NSs properties (ILQ) and BHs no-hair!

Berti, Cardoso, Starinets 09

Abbott et al 16



$$\omega_{lm} = \omega_{lm}^{GR}(M, J)(1 + \delta\omega_{lm})$$

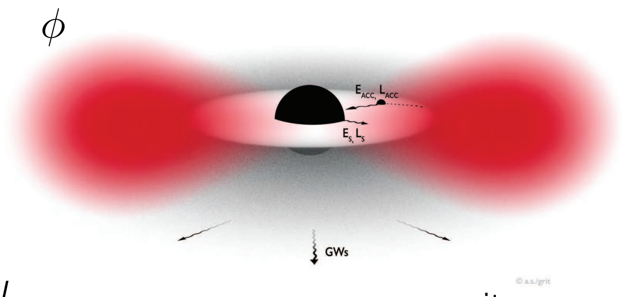
not there yet! (more SNR needed)

Berti, et al 16

Light scalar fields

light fields are ubiquitous in BSM (moduli, dilatons, QCD axion)

Isolated spinning BH + light massive fields ($m_\phi^{-1} \sim r_S$)
are unstable under superradiance



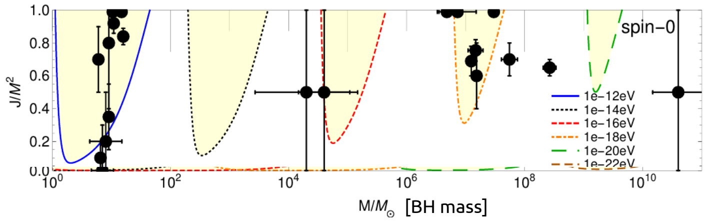
Brito, Cardoso, Pani 16

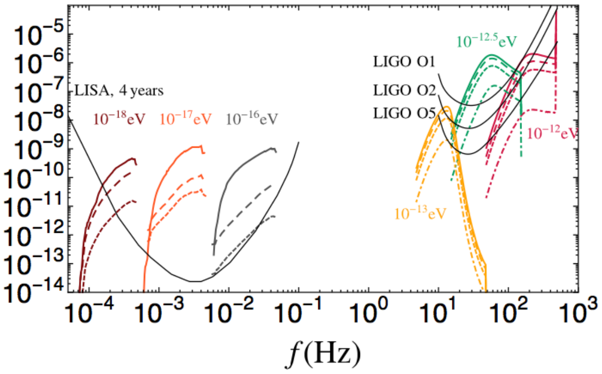
carries away J

emits monochromatic GWs

Brito et al 17

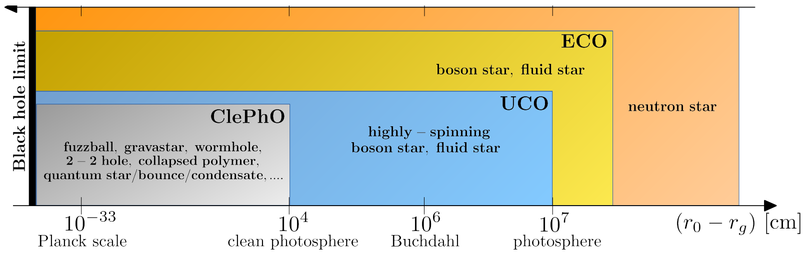
Arvanitaki et al 10





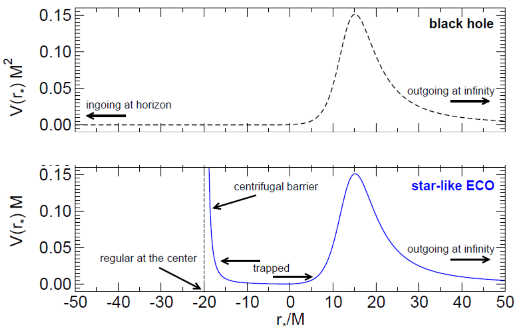
Do we observe BHs?

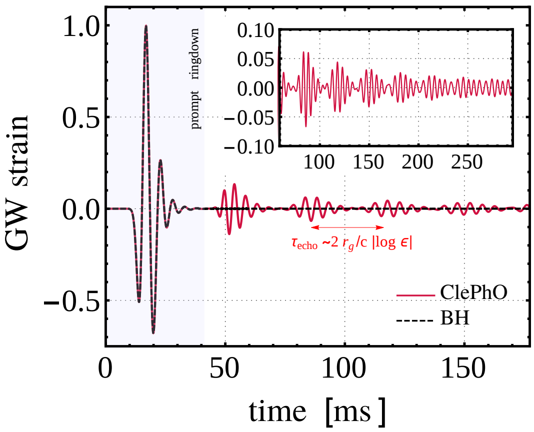
what if we are observing objects more compact than NSs but not BHs?



Cardoso, Pani 17

echoes of the signal





Abedi, Dykaar, Afshordi 16 (3 σ claim!)

Effects in propagation

* up to Shapiro

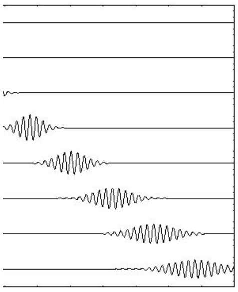
Once the GW is emitted it propagates freely*

$$\omega^2 = m^2 + c_{GW}^2 k^2 + \sum_n \frac{\alpha_n}{\Lambda^{2n}} k^{2n}$$

massive gravity could help in DE

higher order corrections (e.g. QG)

theories with anisotropic stress (e.g. a four-vector)



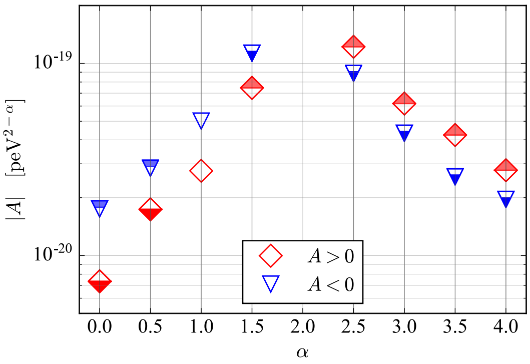
dispersive contributions: no need of counterpart

$$\omega^2 = m^2 + c_{GW}^2 k^2 + \sum_n A_n k^{2n}$$

$$m \leq 7.7 \times 10^{-23}\,\mathrm{eV}$$

(does this totally rule out m? see Bellazzini et al 17)

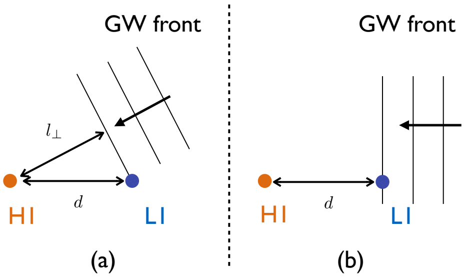
LVC 17



Effects in propagation

non-dispersive contribution
before GW170817...

Cornish, DB, Nardini 17



$$c_{gw} \leq d/\Delta t$$

$$c \leq c_{gw} \leq 1.42c$$

no gravitational Cerenkov

after GW170817: light and GWs from 40 Mpc!

LVC 17

$$-3 \times 10^{-15} c \leq c_{gw} - c \leq 7 \times 10^{-16} c$$

suddenly some gravitational parameters constrained at unprecedented level

(recall PPN 10^{-7})

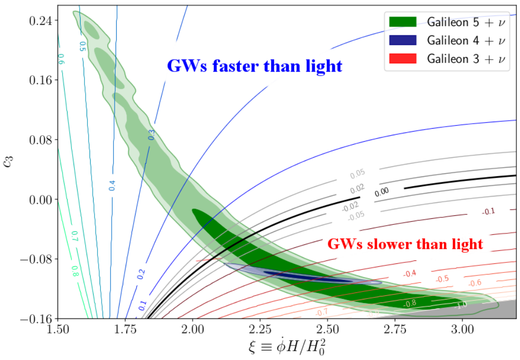
(also Shapiro)

Consequence for modified gravity

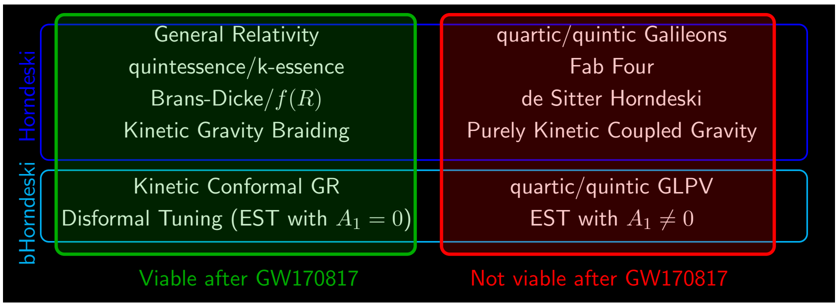
Ezequiaga, Zumalacarregui 17

alternatives to cosmological constant are possible in generalized scalar-tensor theories (Horndeski)

cosmological tests without Λ



homeopathic Horndeski…

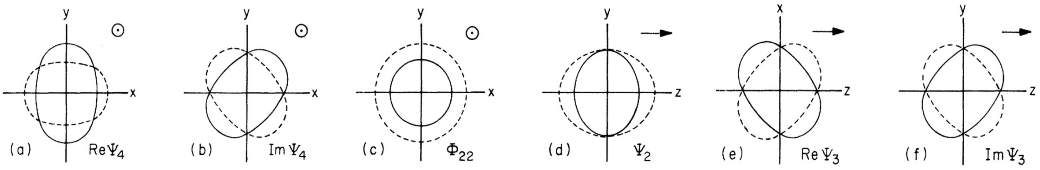


	Viable after GW170817	Not viable after GW170817
Horndeski	General Relativity quintessence/k-essence Brans-Dicke/$f(R)$ Kinetic Gravity Braiding	quartic/quintic Galileons Fab Four de Sitter Horndeski Purely Kinetic Coupled Gravity
bHorndeski	Kinetic Conformal GR Disformal Tuning (EST with $A_1 = 0$)	quartic/quintic GLPV EST with $A_1 \neq 0$

Finally, polarizations

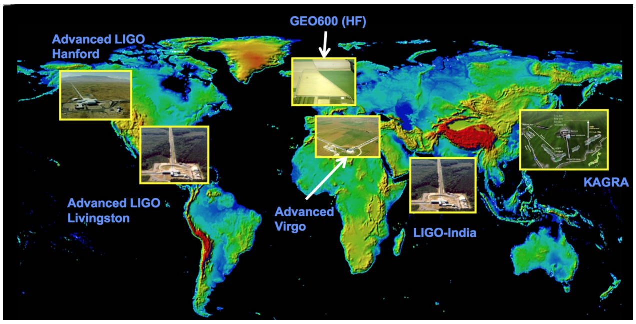
we already saw that extra light d.o.f.s affect the emission

the space metric allows 6-polarizations (2 in GR)



$\Psi_2(u)$ $(s=0)$, $\Phi_{22}(u)$ $(s=0)$ $\Psi_3(u)$ $(s=\pm 1)$, $\Psi_4(u)$ $(s=\pm 2)$

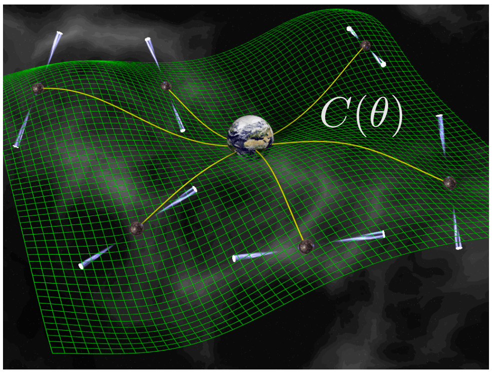
a network of detectors can detect them

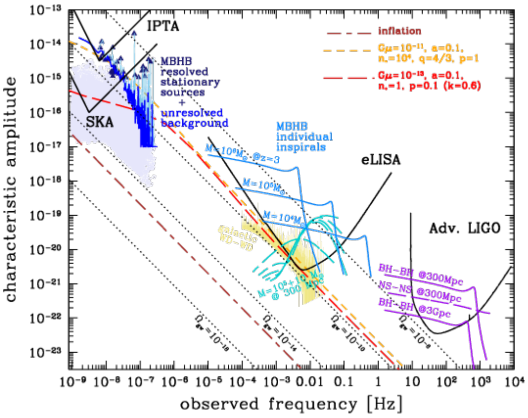


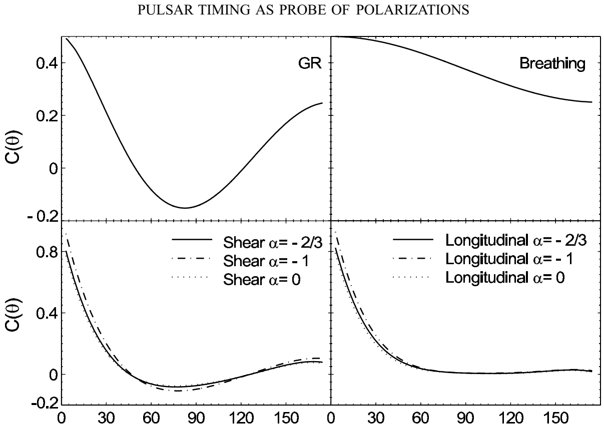
GW170814: LIGO/VIRGO: evidence of spin-2 vs spin-0 or spin-1 only

PTAs and polarizations

Jansen et al (SKA) 15

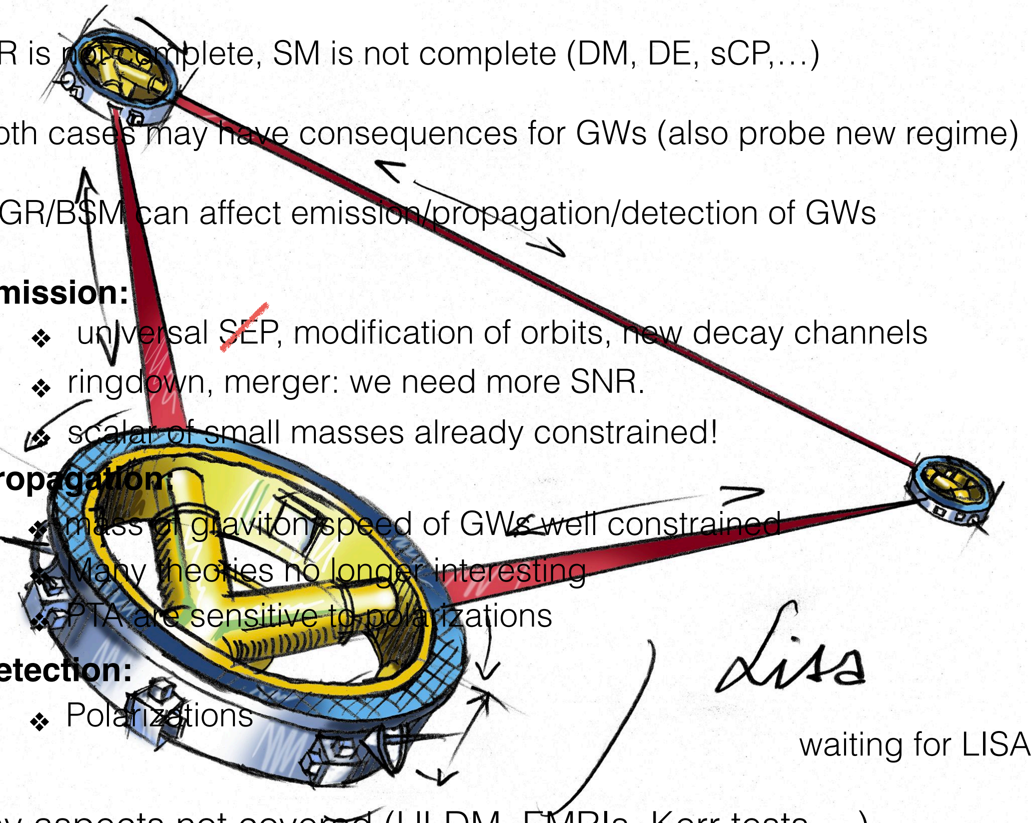






Lee, Jenet & Price (2008)

Conclusions



- GR is not complete, SM is not complete (DM, DE, sCP,…)
- Both cases may have consequences for GWs (also probe new regime)
- MGR/BSM can affect emission/propagation/detection of GWs
- **Emission:**
  - universal ~~S~~EP, modification of orbits, new decay channels
  - ringdown, merger: we need more SNR.
  - scalar of small masses already constrained!
- **Propagation:**
  - mass of graviton/speed of GWs well constrained
  - Many theories no longer interesting
  - PTA are sensitive to polarizations
- **Detection:**
  - Polarizations

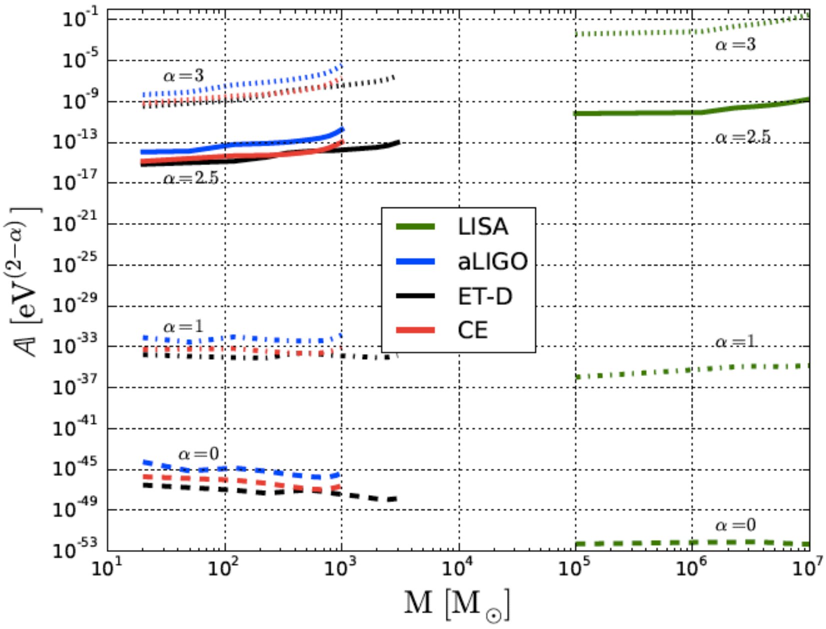
waiting for LISA…

many aspects not covered (ULDM, EMRIs, Kerr tests,…)

big jay mcneely

Prospects on propagation

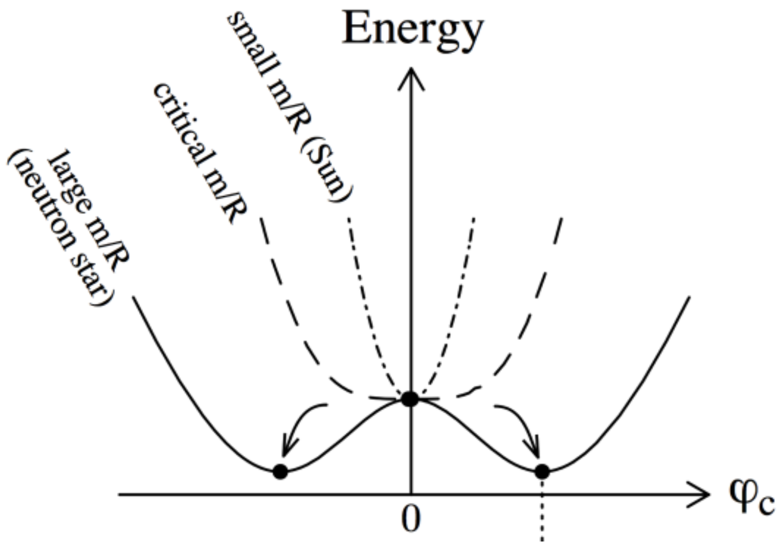
Samajdar, Arun 17



Scalarization

scalar field develops instability inside dense media

Esposito-Farese 04



Tuesday 28th

Invited lecture 9:30–10:30

[Chair: Shinji Tsujikawa)]

Patric Brady (Univ. of Wisconsin-Milwaukee),
“When neutron stars collide“ (50+10)
[JGRG27 (2017) 112801]

Session2a 11:00–12:30

[Chair: Yasufumi Kojima]

2a4. Anton Khirnov (Charles U.),

“A new slicing condition for axisymmetric gravitational wave collapse” (10+5)

[JGRG27 (2017) 112805]

A new slicing condition for axisymmetric gravitational wave collapse

Anton Khirnov Tomáš Ledvinka

Institute of Theoretical Physics, Charles University in Prague

JGRG27

Critical collapse in general relativity

- critical behaviour discovered by Choptuik in 1993 for scalar field in spherical symmetry
- analogous results by Abrahams and Evans in 1993 for gravitational waves in axial symmetry (“Teukolsky waves”)
- several attempts to find critical behaviour for “Brill waves”, so far no reproducible success

Evolution method

- 3+1 splitting à la ADM — spacetime foliated by a sequence of spacelike surfaces labelled by the time parameter t
- evolved variables — spatial 3-metric γ_{ij} and extrinsic curvature K_{ij}
- Einstein equations split into a set of evolution equations and a set of constraints
- solve the constraints to construct initial data
- evolve $\left\{\gamma_{ij}, K_{ij}\right\}$ forward in time using the evolution equations (free evolution)
- coordinate choice — determined by the lapse α and shift β^i

---

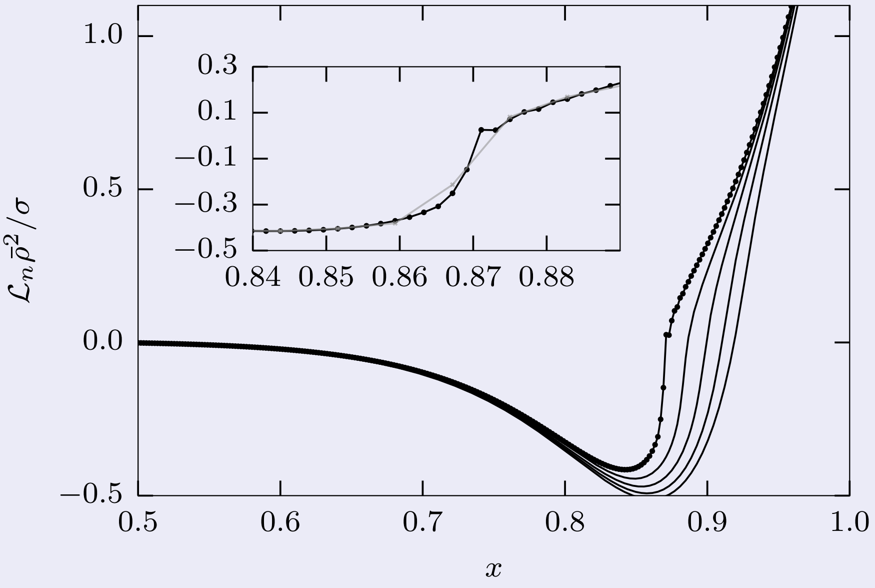
Initial data

- Brill waves — a family of axially symmetric vacuum initial data at the moment of time symmetry
- parametrized by an “amplitude parameter” A
- $A = 0$ is flat space
- $|A| \rightarrow A_{\text{big}}$ is a black hole
- critical point — smallest value of A when a black hole is formed, for our initial data $A^* \approx 4.69$

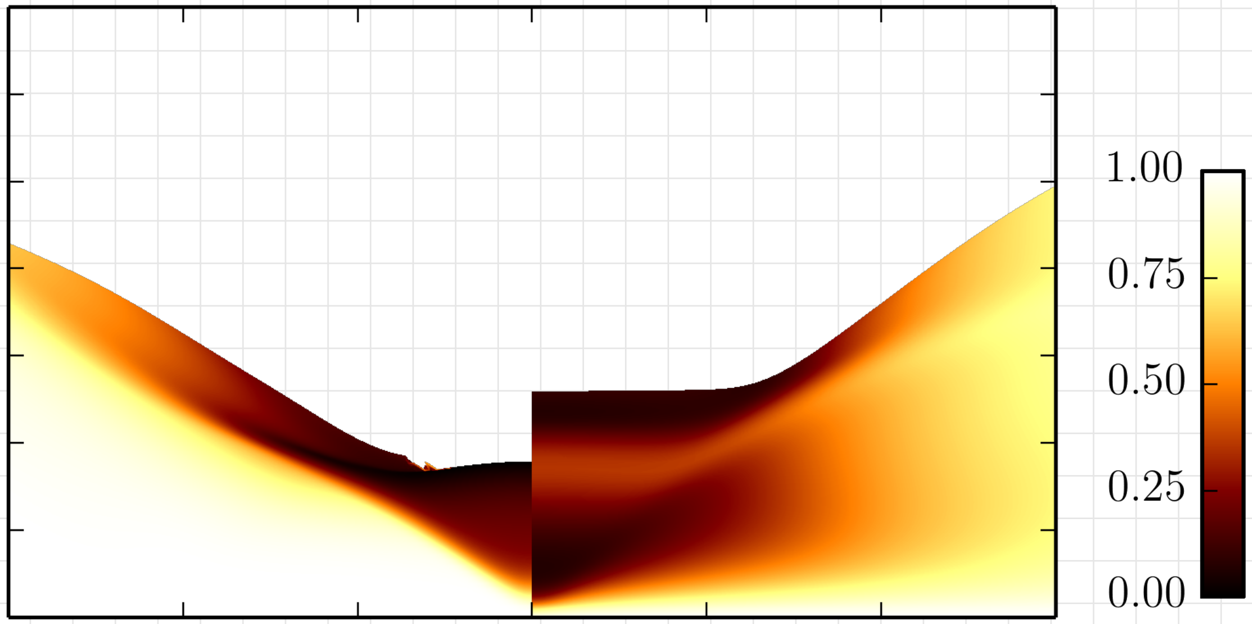
Coordinate choice

- time coordinate encoded in the lapse $\alpha(t, x^i)$
- spatial coordinates determined by the shift vector $\beta^i(t, x^j)$
- $\left\{\alpha, \beta^i\right\}$ freely specifiable functions
- typically chosen dynamically as solutions to hyperbolic or elliptic equations
- common slicings
  - maximal: $K^i_i \equiv K = 0 \Rightarrow D^2\alpha - K_{ij}K^{ij}\alpha = 0$
  - 1+log: $\dot{\alpha} = -2\alpha K$

1+log slicing for near-critical ($A = 5$) Brill waves



1+log slicing vs maximal slicing for $A = 5$



Quasi-maximal slicing I

- 1+log slicing is simple and fast, but breaks down
- maximal slicing is well-behaved, but slow and hard to implement
- try to combine them to get the best of both world
- extract just the “core / lowest-order” information from maximal slicing and plug it into 1+log

Quasi-maximal slicing II

- take the time derivative of the maximal slicing condition

$$0 = \left(\partial_t - \mathscr{L}_\beta\right) \left[D^2\alpha - K_{ij}K^{ij}\alpha\right]$$

- define a new function $W = (\partial_t - \mathscr{L}_\beta)\alpha$
- get an elliptic equation for W

$$\begin{aligned} D^2 W - K_{ij}K^{ij} W = &- 2\alpha K^{ij} D_i D_j \alpha + \gamma^{ij} \left(\partial_t \Gamma^k_{ij}\right) \partial_k \alpha \\ &- \left(\gamma^{ij} D_i D_j \beta^k\right) D_k \alpha - \beta^j R^i_j D_i \alpha \\ &+ \alpha \left(2K^{\cdot}_{ij} K^{ij} + 4\alpha K^i_j K^k_i K^j_k\right) \end{aligned}$$

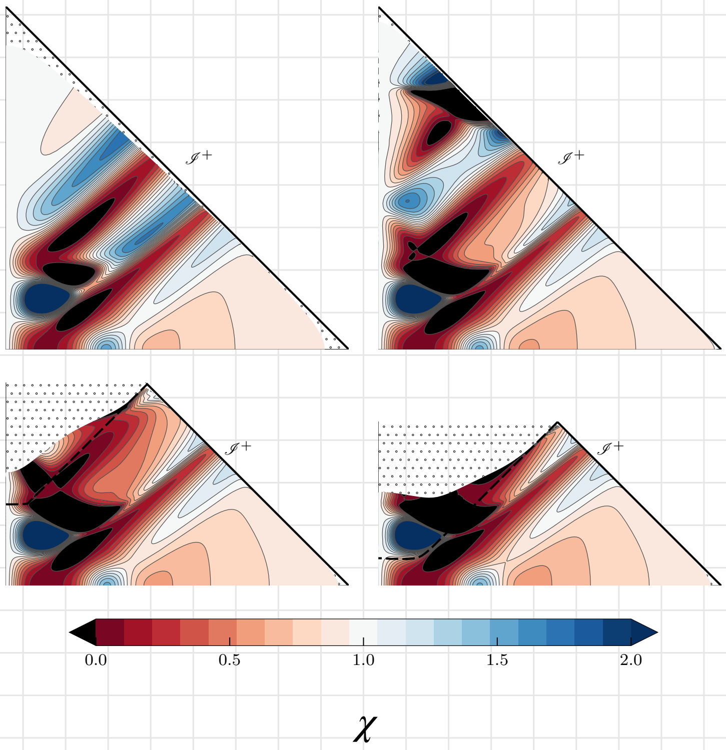
- compute a low-order solution for W and add it as an extra term in 1+log slicing

$$(\partial_t - \mathscr{L}_\beta)\alpha = -2\alpha K + W$$

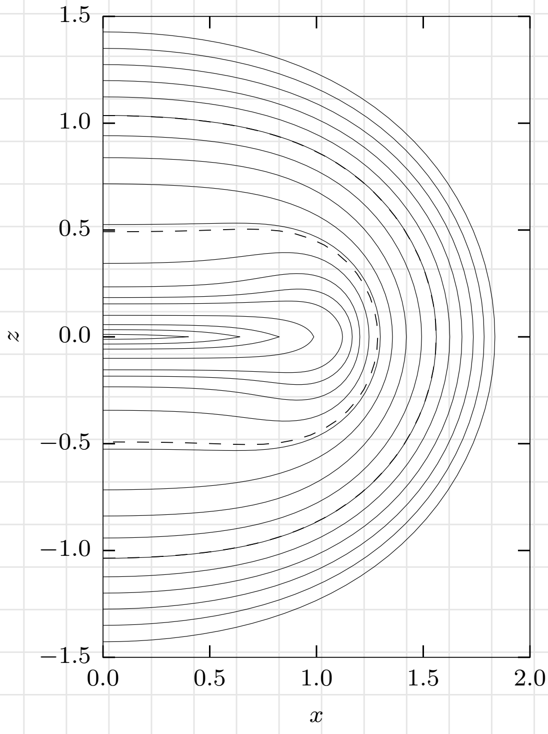
Invariants

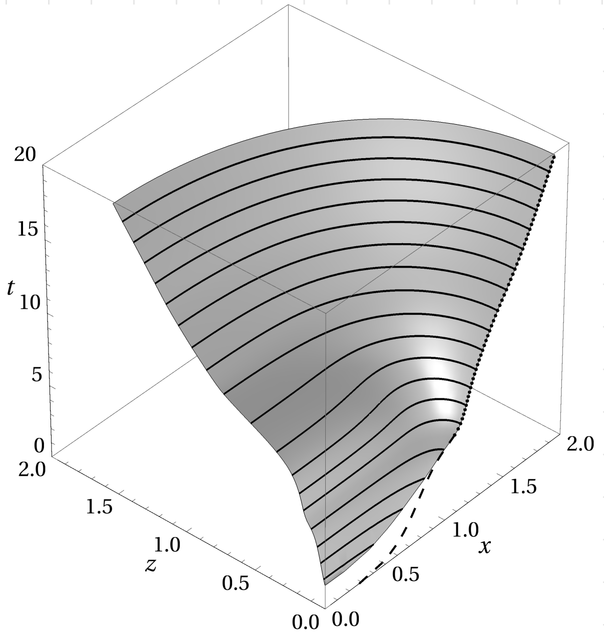
- Kretschmann scalar $\mathscr{K} = R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta}$
- axial symmetry — angular Killing vector η^μ
- circumferential radius $\bar{\rho}^2 = \eta_\mu\eta^\mu$
- $4\bar{\rho}'^2 = \left|\nabla\rho^2\right|^2$
- dimensionless quantity $\chi = \frac{\bar{\rho}'^2}{\bar{\rho}^2}$
- for Schwarzschild $\chi = 1 - \frac{2M}{R}\sin^2\theta$

Conformal diagrams for $A = \{4, 4.65, 4.8, 5\}$



Event horizon evolution for $A = 5$





Summary

- 1+log slicing is pathological for near-critical Brill waves
- we have extended it by adding a source function derived from the maximal slicing
- this “quasi-maximal” slicing allows us to get closer to the critical point
- for supercritical initial data we are able to follow the collapse as an apparent horizon forms and the geometry settles down to a Schwarzschild black hole
- we discover non-regular shape of the event horizon for weakly supercritical data

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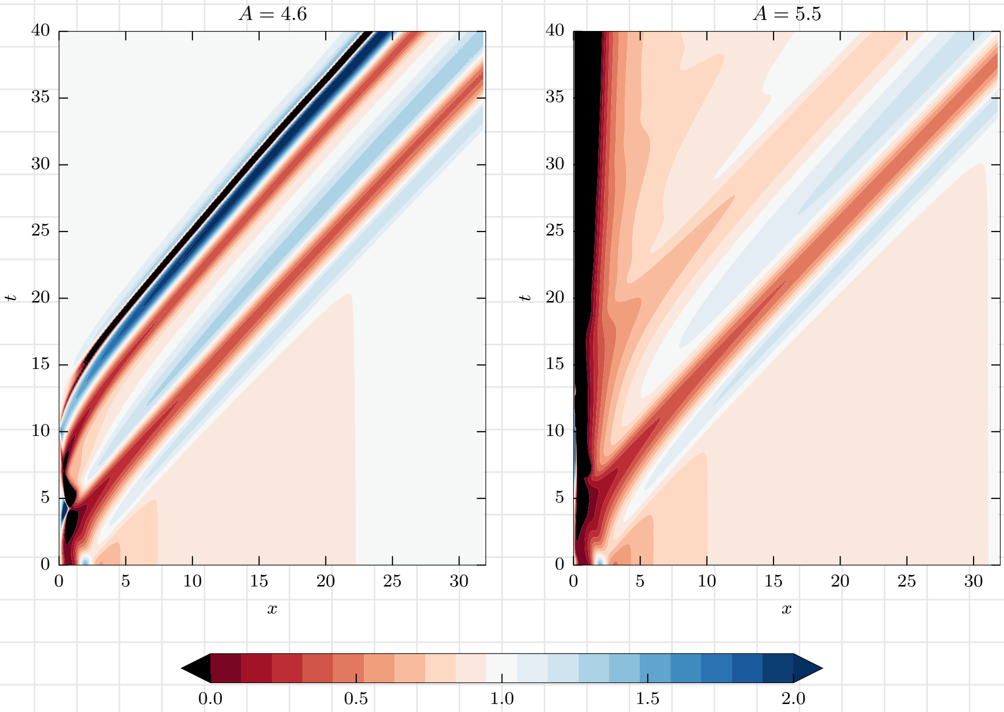
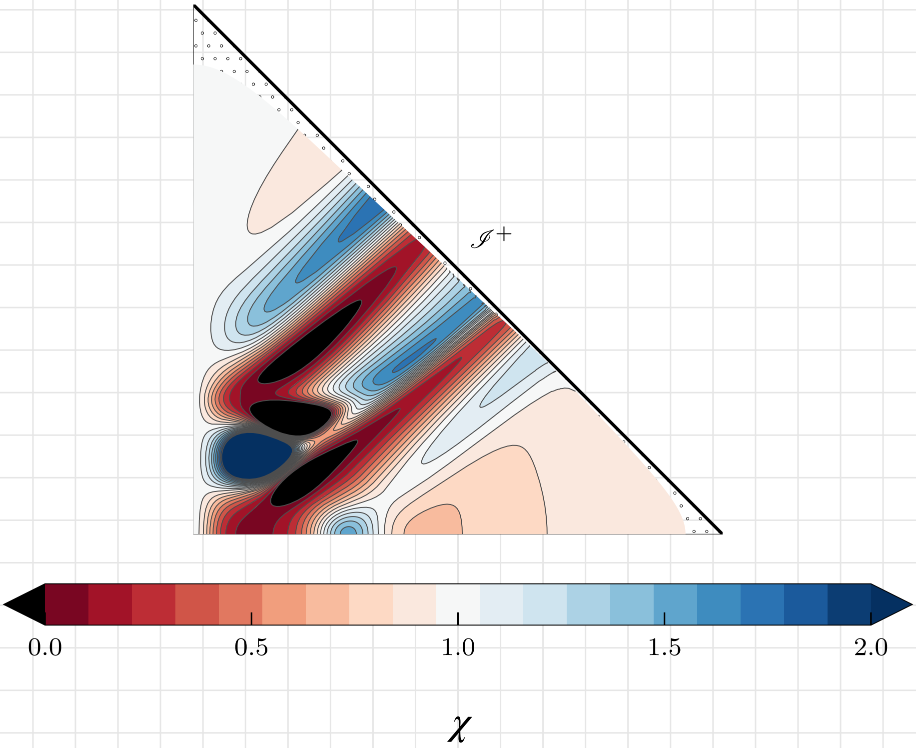
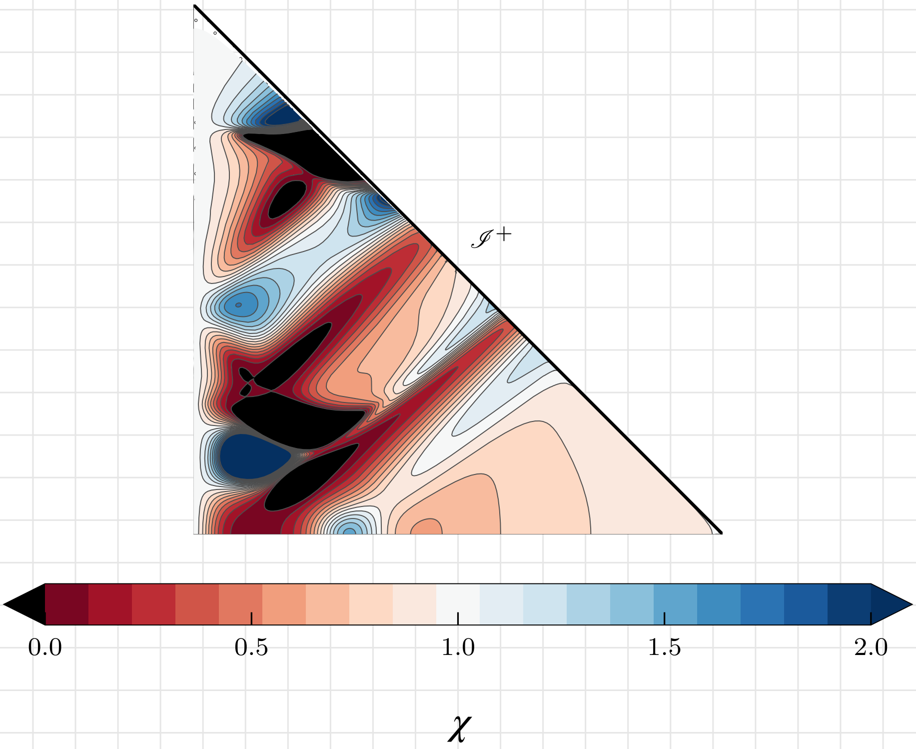
Evolution of χ for $A = 4.6$ and $A = 5.5$



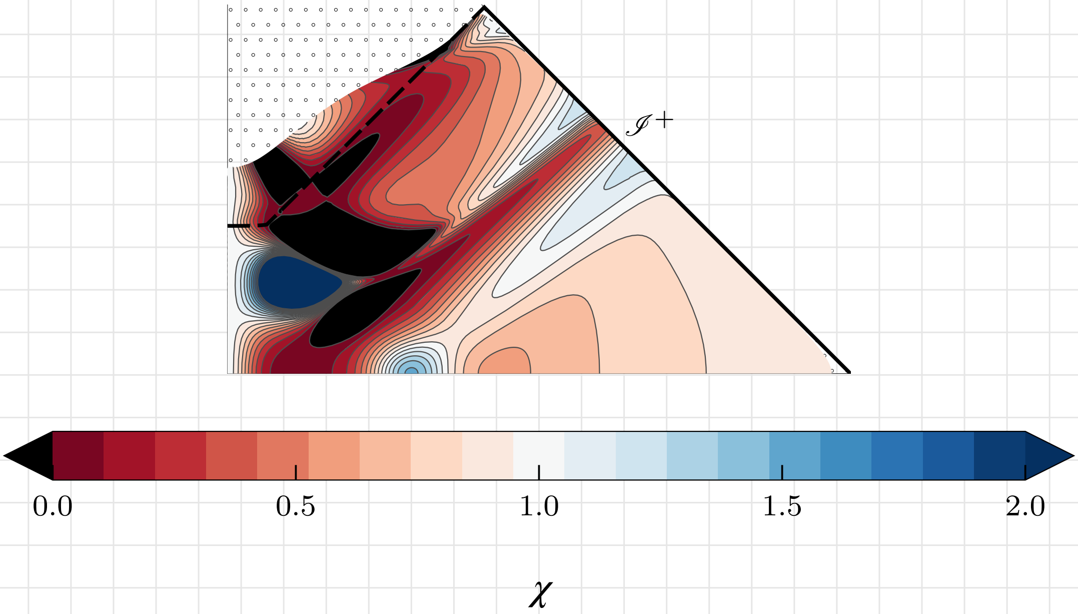
Conformal diagram for $A = 4$



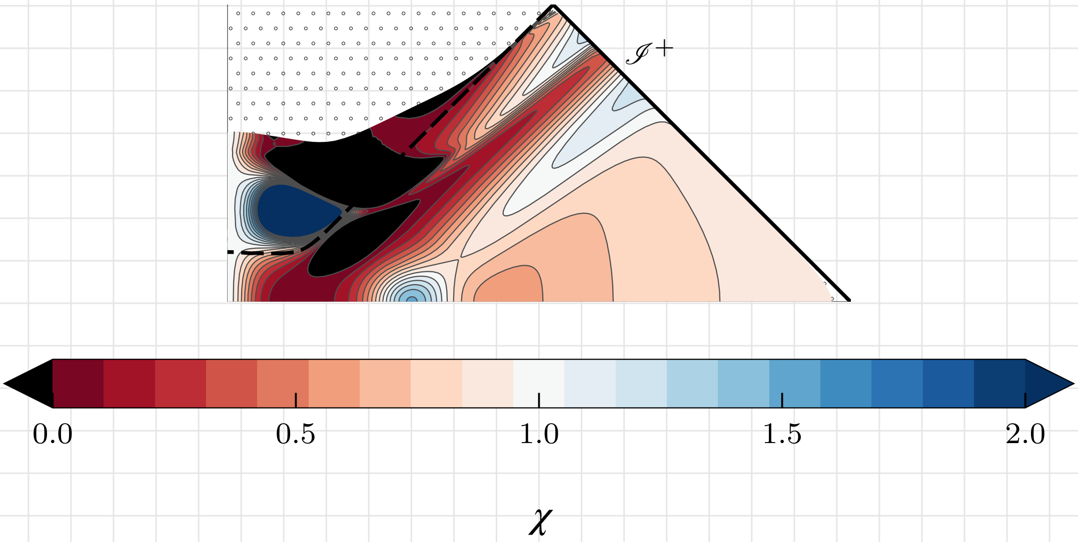
Conformal diagram for $A = 4.65$



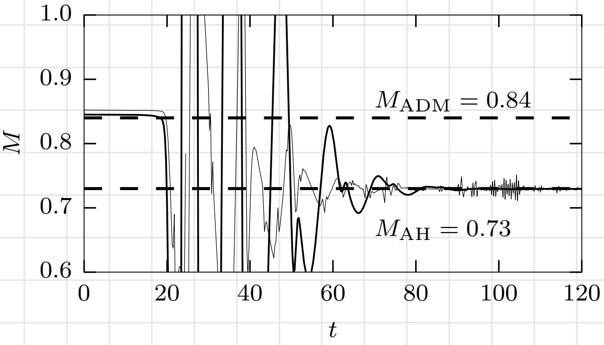
Conformal diagram for $A = 4.8$

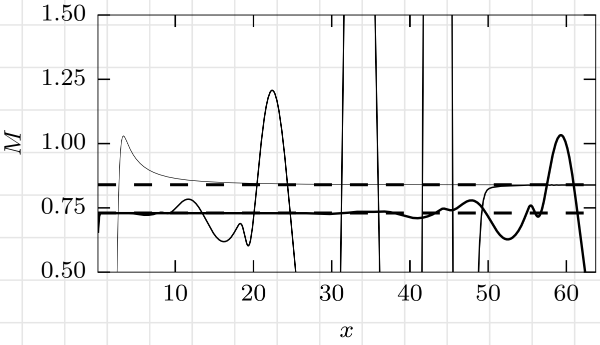


Conformal diagram for $A = 5$



Mass estimates for $A = 5.5$





2a5. Motoyuki Saijo (Waseda U.),

“Dynamics of relativistic r-mode instability in rotating relativistic stars” (10+5)

[JGRG27 (2017) 112806]

Dynamics of relativistic r-mode instability in rotating relativistic stars

Motoyuki Saijo (Waseda U.)

CONTENTS

1. Introduction

Gravitational wave driven (CFS) instability

Eigenmode

(Chandrasekhar 70, Friedman & Schutz 78)

Master equation in nonaxisymmetric perturbation

$$A_i^j \partial_t^2 \xi^i + B_i^j \partial_t \xi^i + C_i^j \xi^i = S^j$$

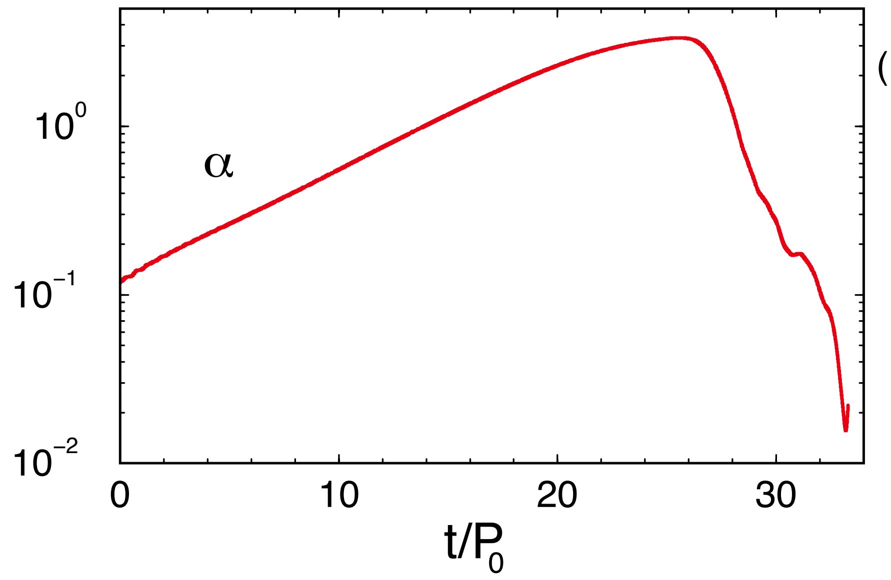
- f-mode(fundermental mode：corresponds to stellar radius)
- p-mode(pressure mode：pressure gradient as restoring force)

Unstablise when the background is almost Keplarian

- g-mode(gravity mode：buoyancy)
- r-mode(rosby mode：Coriolis force)

Unstablise even in small rotation in inviscid fluid

Dynamics of r-mode instability in Newtonian gravity



(Lindblom et al. 00)

- Saturation amplitude of o(1)
- Imposing large amplitude of radiation reaction potential in the system to control secular timescale with dynamics

---

Relativistic gravitation

- Neutron stars contain large compactness (M/R~0.15: relativistic star)
- Newtonian picture may change in relativistic case (e.g. perturbative approach requires both parities) (Lockitch et al. 00)
- No dynamical approach for this instability has been studied in relativistic gravitation (c.f. mass multipole radiation reaction in binary neutron star merger)

Separate two different timescales

- Separate relativistic hydrodynamics (dynamical timescale) and gravitational radiation (secular timescale) to control two timescales
- Control amplification factor in gravitational radiation

Purpose

- Formulate relativistic hydrodynamics with gravitational radiation reaction force
- Reproduce characteristic frequency and growth rate of relativistic r-mode instability through dynamics
- Explore dynamical picture of relativistic r-mode instability

---

2. Relativistic hydrodynamics with radiation reaction force

Radiation reaction force in post-Newtonian gravity

mass quadrupole term

mass-current quadrupole term

(Blanchet 97)

$$\alpha = 1 + \frac{1}{c^2}\phi + \frac{1}{c^4}{}_4\alpha + \frac{1}{c^6}{}_6\alpha + \frac{1}{c^7}{}_7\alpha + \frac{1}{c^8}{}_8\alpha + \frac{1}{c^9}{}_9\alpha + (o^{-10})$$

$$\beta^i \equiv \frac{1}{c^3}{}_3\beta^i + \frac{1}{c^5}{}_4\beta^i + \frac{1}{c^6}{}_6\beta^i + \frac{1}{c^7}{}_7\beta^i + \frac{1}{c^8}{}_8\beta^i + (o^{-9})$$

mass-octupole term

$$\gamma_{ij} = \delta_{ij}\left(1 - \frac{2}{c^2}\phi\right) + \frac{1}{c^4}{}_4h_{ij} + \frac{1}{c^5}{}_5h_{ij} + \frac{1}{c^6}{}_6h_{ij} + \frac{1}{c^7}{}_7h_{ij} + (o^{-8})$$

Only consider muss-current multipole term (3.5pN) to focus on r-mode instability

$${}_9\alpha = 0 \quad {}_8\beta^i = \frac{16}{45}\epsilon_{ijk}x_j x_l S^{(5)}_{kl} \quad {}_7h_{ij} = 0$$

$$S_{ij} = \int d^3x \ \epsilon_{kl(i}x_{j)}x_k \rho v_l$$

Extension to conformally flat gravitation

Conformally flat spacetime ➡ Extension from pN gravity

$$ds^2 = (-\alpha^2 + \beta_k\beta^k)dt^2 + 2\beta_k dx^k dt + \psi^4\delta_{ij}dx^i dx^j$$

α : lapse β^k : shift ψ : conformal factor

Schematic picture

$$\alpha = \boxed{1 + \frac{1}{c^2}\phi} + \frac{1}{c^4}{}_4\alpha + \frac{1}{c^6}{}_6\alpha + \frac{1}{c^7}{}_7\alpha + \frac{1}{c^8}{}_8\alpha + \frac{1}{c^9}{}_9\alpha + (o^{-10})$$

$$\beta^i \equiv \boxed{\frac{1}{c^3}{}_3\beta^i} + \frac{1}{c^5}{}_4\beta^i + \frac{1}{c^6}{}_6\beta^i + \frac{1}{c^7}{}_7\beta^i + \frac{1}{c^8}{}_8\beta^i + (o^{-9})$$

$$\gamma_{ij} = \boxed{\delta_{ij}\left(1 - \frac{2}{c^2}\phi\right)} + \frac{1}{c^4}{}_4h_{ij} + \frac{1}{c^5}{}_5h_{ij} + \frac{1}{c^6}{}_6h_{ij} + \frac{1}{c^7}{}_7h_{ij} + (o^{-8})$$

Replace them by conformally flat gravitataion

Basic equations for relativistic hydrodynamics with radiation reaction force

Continuity equation

$$\frac{\partial\rho_*}{\partial t} + \frac{\partial}{\partial x^j}(\rho_* v^j) = 0$$

Relativistic Euler's equation

3-velocity $v^i = \dfrac{\tilde{u}_i}{\psi^4\tilde{u}^t} - \beta^i$

$$\frac{\partial}{\partial t}(\rho_*\tilde{u}_i) + \frac{\partial}{\partial x^j}(\rho_*\tilde{u}_i v^j + \alpha\psi^6 p\delta^j_i)$$
$$= p\frac{\partial}{\partial x^i}(\alpha\psi^6) - \rho_*\alpha\tilde{u}^t\frac{\partial\alpha}{\partial x^i} + \rho_*\tilde{u}_j\frac{\partial\beta^j}{\partial x^i} + \frac{2\rho_*\tilde{u}_k\tilde{u}_k}{\psi^5\tilde{u}^t}\frac{\partial\psi}{\partial x^i}$$

Modifying shift is sufficient for introducing gravitational radiation reaction force in relativistic hydrodynamics!

Energy equation

$$\frac{\partial}{\partial t}(\rho_* hw - p\psi^6) + \frac{\partial}{\partial x^j}(\rho_* hwv^j + p\psi^6\beta^j)$$
$$= \alpha\psi^6 pK + \frac{\rho_*}{\tilde{u}^t}\tilde{u}_i\tilde{u}_j K^{ij} - \rho_*\tilde{u}_i\gamma^{ij}\frac{\partial\alpha}{\partial x^j}$$

$$\beta^j = \beta^j_{\rm CF} + {}_8\beta^j$$

Some approximations for numerics

Amplification factor

$$ {}_8\beta^i = \frac{16}{45}\epsilon\epsilon_{ijk}x_i x_l S^{(5)}_{jl} $$

Mass-current multipole moment

$$ S_{ij} = \int d^3x \epsilon_{kl(i}x_{j)}x_k \rho_* \tilde{u}_l $$

Vector spherical harmonics expansion

- Adjust timescales
- Eliminate time derivative as possible
- Coincide in Newtonian limit

Characteristic frequency

$$ \omega_{\rm chr} = -\frac{1}{|J_{22}|}\left|\frac{dJ_{22}}{dt}\right| $$

Time derivative

$$ S^{(n)}_{ij} = (i\omega_{\rm chr})^n S^{(0)}_{ij} $$

e.g. $S^{(5)}_{ij} = \omega^4_{\rm chr} S^{(1)}_{ij}$ $S^{(6)}_{ij} = -\omega^6_{\rm chr} S^{(0)}_{ij}$

$S_{ij}^{(1)}$ is computed from the relativistic Euler's equation (excluding radiation reaction term)

---

3. Newtonian r-mode instability

Initial condition

Constructing rotating equilibrium stars

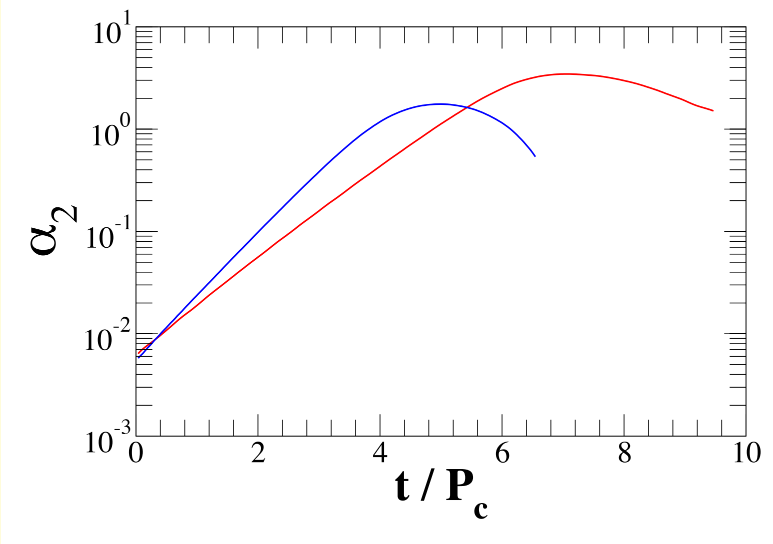
	r_p/r_e	T/W
slow	0.97	0.008
rapid	0.55	0.103

- Uniformly rotating neutron star (n=1, polytropic EOS)

Perturb velocity in the r-mode eigenfunction

$$ \delta v^i = \alpha \Omega R \left(\frac{r}{R}\right)^l Y^{(B)}_{ll} $$

Diagnostics



Kokkotas & Schwenzer 16

According to perturbation theory, 1/3 of the rotational energy loss due to r-mode is pumped into the mode

Lindblom et al. 02

1. r-mode grows exponentially
➡ 2. breaking waves develop strong shocks
3. energy conversion from kinetic to thermal

---

3. Relativistic r-mode instability

Initial condition

Constructing rotating equilibrium stars

- Uniformly rapidly rotating neutron star (n=1, polytropic EOS)

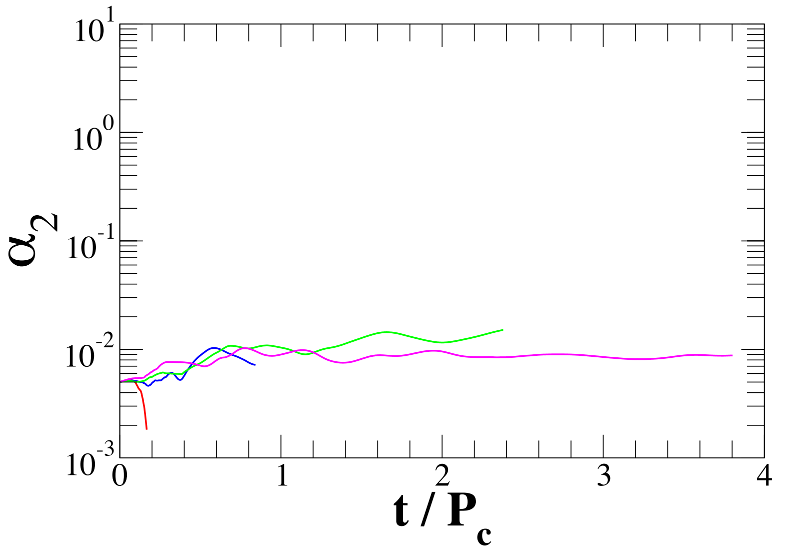
	r_p/r_e	M/R	T/W
I	0.55	0.106	0.099
II	0.55	0.066	0.100
III	0.55	0.016	0.102
IV	0.55	0.002	0.103

Perturb 3-velocity in the r-mode eigenfunction

$$\delta u_i = \gamma_{ij} u^t \alpha \Omega R \left(\frac{r}{R}\right)^l Y_{ll}^{(B)}$$

Successfully reproduced characteristic frequency and growth rate of the instability

Diagnostics



Kokkotas & Schwenzer 16

According to perturbation theory, about 1/3 of the rotational energy loss due to r-mode is pumped into the mode

➡ In contrast to the Newtonian case, r-mode seems to saturate in the early stage and remain its amplitude

Discussion

Comparison between mass quadrupole, mass octupole, and mass-current quadrupole moments on gravitational waves

$$\left(\frac{dE_{\rm mode}}{dt}\right)_{J_{22}} = -\frac{128\pi}{225}\omega^6|J_{22}|^2$$

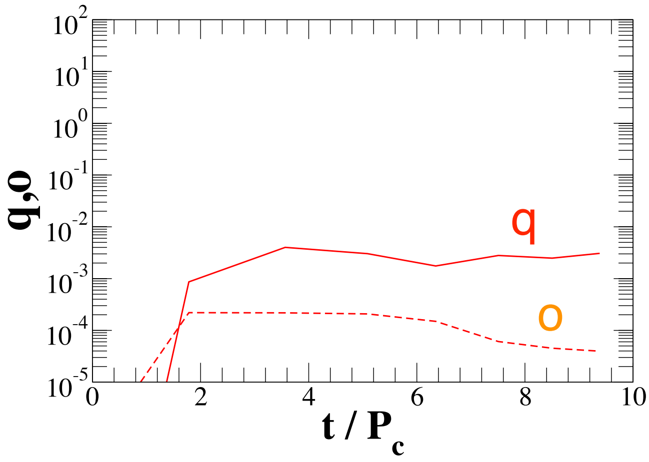
$$\left(\frac{dE_{\rm mode}}{dt}\right)_{Q_{22}} = -\frac{8\pi}{75}\omega^6|Q_{22}|^2$$

$$\left(\frac{dE_{\rm mode}}{dt}\right)_{Q_{32}} = -\frac{8\pi}{6615}\omega^8|Q_{32}|^2$$

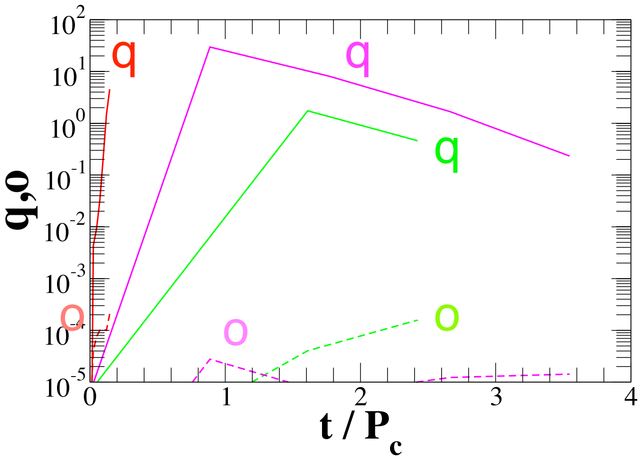
➡ $q = \frac{5}{16}\frac{|Q_{22}|^2}{|J_{22}|^2} \ll 1 \qquad o = \frac{5\omega^2}{2352}\frac{|Q_{32}|^2}{|J_{22}|^2} \ll 1$

should hold to assume radiation reaction force composed of only mass-current quadrupole moment

Newtonian Case



Relativistic case



Satisfies the condition throughout the evolution

Breaks the condition around the saturation

➡ Parity interaction may take place

- Different saturation mechanism in relativistic gravitation
- May require mass quadrupole radiation reaction force

---

4. Summary and Issues

We study relativistic r-mode instability by means of 3D relativistic hydrodynamics with radiation reaction force composed of mass-current quadrupole moment

- We have succeeded in formulating relativistic hydrodynamics with mass-current radiation reaction force
- Successfully recover characteristic frequency and growth rate of relativistic r-mode instability in relativistic hydrodynamics
- Saturation of relativistic r-mode instability may have a different mechanism. Requires at least radiation reaction force of mass quadrupole and mass-current quadrupole moment for full understanding

2a6. Fabio Novaes (UFRN),

“Kerr-de Sitter Quasinormal Modes from Accessory Parameter Expansions” (10+5)

JGRG27 (2017) 112807]

Kerr-de Sitter Quasinormal Modes from Accessory Parameter Expansions

Fábio Novaes

International Institute of Physics
Federal University of Rio Grande do Norte
Natal, Brazil

November 28, 2017

Linear Perturbation of Gravitational Systems

- Linear perturbation of equations of motion

$$S = \frac{1}{16\pi G}\int_M d^D x\sqrt{-g}\,(R - 2\Lambda), \quad g_{ab} = g_{ab}^{BG} + h_{ab}$$

- $D = 4$ Petrov Type D solutions:
  Teukolsky master equations for spin $s = 0, \frac{1}{2}, 1, \frac{3}{2}, 2$
- The master equations are separable for Λ-vacuum Type D solutions
- For higher-dimensions and spherical topology, separable for Kerr-NUT-(A)dS black holes (Frolov and Kubzniak '07)

Kerr-de Sitter Black Hole

$$ds^2 = -\frac{\Delta_r(r)}{r^2+p^2}(dt + p^2 d\varphi)^2 + \frac{\Delta_p(p)}{r^2+p^2}(dt - r^2 d\varphi)^2$$
$$+ \frac{r^2+p^2}{\Delta_r(r)}dr^2 + \frac{r^2+p^2}{\Delta_p(p)}dp^2$$

$$\Delta_p(p) = -\frac{\Lambda}{3}p^4 - \left(1 - \frac{\Lambda a^2}{3}\right)p^2 + a^2, \quad p = a\cos\theta$$

$$\Delta_r(r) = -\frac{\Lambda}{3}r^4 + \left(1 - \frac{\Lambda a^2}{3}\right)r^2 - 2Mr + a^2$$

Horizons: $(r_C, r_+, r_-, -r_- - r_+ - r_C)$

Scalar Field Perturbation

- Conformally coupled massless scalar field $\phi(x)$

$$(\nabla^2 + \tfrac{1}{6}R)\phi(x) = 0, \quad \nabla^2\phi \equiv \frac{1}{\sqrt{-g}}\partial_a(\sqrt{-g}g^{ab}\partial_b\phi)$$

- Separable solutions: $\phi(t,r,\theta,\varphi) = e^{-i\omega t}e^{im\varphi}S_{\omega\ell m}(\theta)R_{\omega\ell m}(r)$
- Radial and Angular equations

$$\partial_r(\Delta_r(r)\partial_r R_{\omega\ell m}) - V_r(r)R_{\omega\ell m} = 0$$
$$\partial_\theta(\Delta_\theta(\theta)\partial_\theta S_{\omega\ell m}) - V_\theta(\theta)S_{\omega\ell m} = 0$$

- Angular eigenvalues from angular equation

Heun Equation in the Conformally Coupled Case

- Perturbation equations reduce to Heun equations

$$y'' + \left(\frac{1-2\theta_0}{z} + \frac{1-2\theta_1}{z-1} + \frac{1-2\theta_x}{z-x} \right) y' + \\ + \left(\frac{1+\theta_\infty}{z(z-1)} - \frac{x(x-1)K_x}{z(z-1)(z-x)} \right) y = 0$$

- Monodromy and Accessory parameter for Kerr-dS

$$\theta_k = \pm \frac{i}{2\pi} \left(\frac{\omega - \Omega_k m}{T_k} \right), \qquad k = 0, 1, x, \infty,$$

$$K_x = \frac{\theta_0 + \theta_x}{2x} + \frac{\theta_1 + \theta_x}{2(x-1)} + \frac{1}{z_\infty - x} \left[1 + \frac{\tilde{\lambda}_{\ell m} L^2}{(r_C - r_+)(r_+ - r_-)} \right]$$

Scattering Amplitudes and Connection Matrix

- Local Frobenius solutions: $y_i^{\pm}(z) \sim (z - z_i)^{\pm\theta_i}(1 + \mathcal{O}(z - z_i))$
- Path-multiplicative solutions: $y_{\sigma_{ij}}^{\pm} \sim z^{\frac{1}{2} \pm \sigma_{ij}} \sum_{n \in \mathbb{Z}} c_n z^n$
- Ingoing and Outgoing solutions:

$$y_0^+ = \frac{1}{\mathcal{T}} y_x^+ + \frac{\mathcal{R}}{\mathcal{T}} y_x^- \ , \qquad |\mathcal{R}|^2 + |\mathcal{T}|^2 = 1$$

- Transmission amplitude in terms of monodromies

$$|\mathcal{T}|^2 = \frac{\sin 2\pi\theta_0 \sin 2\pi\theta_x}{\cos 2\pi(\theta_0 - \theta_x) + \cos 2\pi\sigma_{0x}}$$

(Castro *et al* 1304.3781, Carneiro da Cunha and FN 1404.5188)

Quasinormal Modes of Rotating Nariai Limit

- Quasinormal mode = Pole of Transmission Amplitude

$$\sigma_{0x} = \theta_0 - \theta_x + N + \tfrac{1}{2}, \quad N \in \mathbb{Z}$$

- Rotating Nariai limit $r_C \approx r_+$ (small x) and $\omega = m\Omega_H + \beta\bar{\omega}x$

$$\frac{2\bar{\omega}^{(\pm)}_{N\ell m}}{\eta} = -i\left(N + \frac{1}{2}\right) - mk \pm \sqrt{\bar{\lambda}_{\ell m} + m^2k^2 - \frac{1}{4}}$$

  with $\bar{\lambda}_{\ell m}$ being the normalized angular eigenvalue and $\eta = (r_C - r_+)/r_C$ the extremality parameter (Anninos and Anous '10)

$$k = \frac{2ar_C^2}{\beta(r_C^2 + a^2)}, \quad \beta = \frac{r_C(r_C - r_-)(3r_C + r_-)}{(L^2 + a^2)(r_C^2 + a^2)}$$

Isomonodromic System and Apparent Singularity

- *Deformed* Heun equation with one apparent singularity (Jimbo, Miwa and Ueno '81)

$$\partial_z^2 y + \left(\frac{1-2\theta_0}{z} + \frac{1-2\theta_1}{z-1} + \frac{1-2\theta_t}{z-t} - \frac{1}{z-\lambda}\right)\partial_z y$$
$$+ \left(\frac{\kappa}{z(z-1)} - \frac{t(t-1)K}{z(z-1)(z-t)} + \frac{\lambda(\lambda-1)\mu}{z(z-1)(z-\lambda)}\right) y = 0$$

- $z = \lambda$ is an apparent singularity if

$$K(\lambda, \mu, t; \{\theta_k\}) = \frac{1}{t(t-1)}[\lambda(\lambda-1)(\lambda-t)\mu^2 - \{2\theta_0(\lambda-1)(\lambda-t)$$
$$+ 2\theta_1\lambda(\lambda-t) + (2\theta_t - 1)\lambda(\lambda-1)\}\mu + \kappa(\lambda-t)]$$

Isomonodromic System and Painlevé VI

- Hamiltonian System

$$\frac{d\lambda}{dt} = \frac{\partial K}{\partial \mu}, \quad \frac{d\mu}{dt} = -\frac{\partial K}{\partial \lambda}$$

  generates isomonodromic flow $(\lambda(t), \mu(t))$
- Second-order equation for $\lambda(t)$ = Painlevé VI (PVI)
- Set the initial conditions

$$\lambda(x) = x, \qquad \theta_t = \theta_x - \tfrac{1}{2},$$
$$\mu(x) = -\frac{K_x}{2\theta_t}, \qquad \vartheta_\infty = \theta_\infty + \tfrac{1}{2},$$

  to recover Heun equation (Carneiro da Cunha and FN '14)

Painlevé VI τ-function via AGT Correspondence

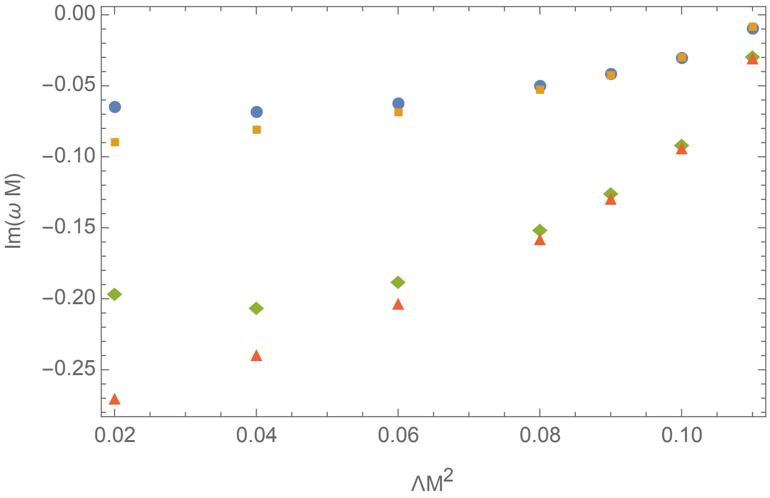
Painlevé VI τ-function expansion (Gamayun, Iorgov and Lisovyi '12)

$$\tau_{\mathrm{VI}}(t) =$$
$$\sum_{n\in\mathbb{Z}} \mathcal{C}_{\mathrm{VI}}\left(\theta_0, \theta_t, \theta_1, \theta_\infty, \sigma + n\right) s_{\mathrm{VI}}^n \, t^{(\sigma+n)^2-\theta_0^2-\theta_t^2} \mathcal{B}_{\mathrm{VI}}\left(\theta_0, \theta_t, \theta_1, \theta_\infty, \sigma + n; t\right)$$

The initial conditions become

$$K_x = \frac{d}{dt}\log[t^{-2\theta_0\theta_t}(1-t)^{-2\theta_1\theta_t}\tau(t;\theta_0,\theta_1,\theta_t,\vartheta_\infty,\sigma,s)]\Big|_{t=x},$$
$$x = \lambda(x)$$

- We obtain an expansion of QNMs around the Nariai limit (order x^5) (Casals, Lencsés and FN, to appear)



Conclusions

- Isomonodromic τ-function determines the accessory parameter of Heun equation
- Allows to calculate black hole quasinormal modes as an expansion around extremality
- Spin 2 quasinormal modes and flat space limit with Painlevé V
- Higher-dimensions can be tackled using generalization of τ-function

Conclusions

- Isomonodromic τ-function determines the accessory parameter of Heun equation
- Allows to calculate black hole quasinormal modes as an expansion around extremality
- Spin 2 quasinormal modes and flat space limit with Painlevé V
- Higher-dimensions can be tackled using generalization of τ-function

Thank you!

Session2b 11:00–12:30

[Chair: Shinji Mukohyama]

2b1. Anzhong Wang (Baylor U.),

“Pre-inflationary universe in loop quantum cosmology” (10+5)

[JGRG27 (2017) 112808]

Universal features of pre-inflationary universe in loop quantum cosmology

Anzhong Wang

Institute for Advanced Physics and Mathematics
Zhejiang University of Technology
&
Physics Department, Baylor University

arXiv:1710.09845; 1705.07544; 1607.06329

In collaboration with G. Cleaver, K. Kirsten, M. Shahalam, M. Sharma, Q. Sheng, Q. Wu and T. Zhu

The 27th Workshop on General Relativity and Gravitation
in Japan - JGRG27, Hiroshima, Japan
November 27 - December 1, 2017

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1. A Brief Introduction to LQC

- Loop quantum gravity (LQG):
  A background independent, nonperturbative quantization of GR by using the Ashtekar variables [1].
- Loop quantum cosmology (LQC):
  Symmetry reduced quantization of cosmology by mimicking the constructions used in LQG [2].
- LQC has not yet been rigorously derived from LQG, but an attempt to use LQG-like methods in cosmology.

---

[1] C. Rovelli and F. Vidotto, Covariant Loop Quantum Gravity: An Elementary Introduction to Quantum Gravity and Spinfoam Theory (Cambridge Monographs on Mathematical Physics, Cambridge, 2015).

[2] M. Bojowald, Rep. Prog. Phys. 78 (2015) 023901;
I. Agullo and P. Singh, arXiv:1612.01236.

1. A Brief Introduction to LQC

- One can naturally define self-adjoint operators representing geometric observables. In particular, there is a smallest nonzero eigenvalue Δ of the area operator, which represents the fundamental area gap and sets an energy scale,

$$\rho_B \equiv \frac{18\pi}{\Delta^3} m_{pl}^4, \ \left(\Delta = 4\sqrt{3}\pi\gamma\right),$$

γ: Barbero-Immirzi parameter.

- Using black hole thermodynamics, one finds $\gamma \simeq 0.2375$ [3], for which we obtain

$$\rho_B \simeq 0.41\rho_{pl}.$$

---

[3] K. A. Meissner, CQG21 (2004) 5245.

---

1. A Brief Introduction to LQC (Cont.)

- In GR, the Friedmann equation

$$H^2 = \frac{8\pi G}{3}\rho$$

always leads to a singularity [4].

- In LQC, the matter density is bounded above [5]

$$\rho \leq \rho_B$$

- In every physical state Ψ_o, the expectation value of ρ achieves a maximum value $\rho_{max} \lesssim \rho_B$.

---

[4] A. Borde and A. Vilenkin, PRL72 (1994) 3305; A. Borde, A. H. Guth, and A. Vilenkin, PRL90 (2003) 151301.

[5] A. Ashtekar, T. Pawlowski and P. Singh, PRL96 (2006) 141301.

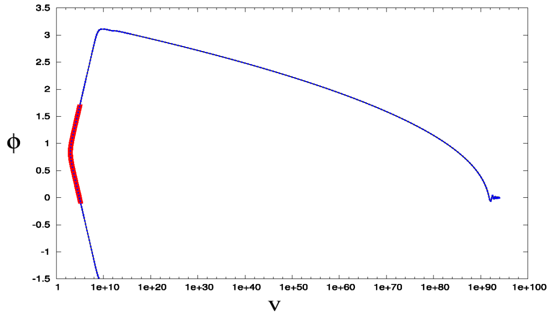
1. A Brief Introduction to LQC (Cont.)

- States Ψ_o are sharply peaked on trajectories for $\rho_{\max} \simeq \rho_B$, and the effective Friedmann and Klein-Gordon equations are modified to,

$$H^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_B}\right), \tag{1}$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0. \tag{2}$$

— A quantum bounce naturally happens at $\rho \simeq \rho_B$.



[$V \propto a^3$. Ashtekar & Barrau, CQG32 (2015) 234001]

1. A Brief Introduction to LQC (Cont.)

- It was found that: the probability for the desired — i.e. in agreement with CMB measurements — slow roll inflation not to occur in an LQC solution is less than about one part in a million [6],

$$\lesssim 1.2 \times 10^{-6}$$

— Slow-roll inflation is an attractor in LQC!

---

[6] P. Singh, K. Vandersloot and G. V. Vereshchagin, PRD74 (2006) 043510;
X. Zhang and Y. Ling, JCAP08 (2007) 012;
A. Ashtekar A and D. Sloan, GRG43 (2011) 3619;
A. Corichi and A. Karami PRD83 (2011) 104006;
L. Linsefors and A. Barrau, PRD87 (2013) 123509;
L. Chen and J.-Y. Zhu, PRD92 (2015) 084063.

1. A Brief Introduction to LQC (Cont.)

- By now, a large number of cosmological models have been studied in detail in LQC [7], including
  - $f(R)$ universe
  - the closed FLRW model
  - FLRW models with Λ with any sings
  - the Bianchi models
  - the Gowdy model, which incorporates the simplest types of inhomogeneities in full GR
- In ALL cases, the singularity is resolved!

---

[7] A. Ashtekar and P. Singh, CQG 28 (2011) 213001; I. Agullo and A. Corichi, arXiv:1302.3833.

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2. Background Evolution

- In the framework of LQC, the background evolution can be divided into two classes:
  - Initially the evolution is dominated by the kinetic energy of the inflaton:

$$\frac{1}{2}\dot{\phi}^2(t_B) > V(\phi(t_B))$$

  - Initially it is dominated by the potential energy:

$$\frac{1}{2}\dot{\phi}^2(t_B) < V(\phi(t_B))$$

- However, a potential dominated bounce is either not able to produce the desired slow-roll inflation or leads to a large amount of e-folds of expansion [8].

---

[8] A. Ashtekar and A. Barrau, CQG32 (2015) 234001

---

2. Background Evolution (Cont.)

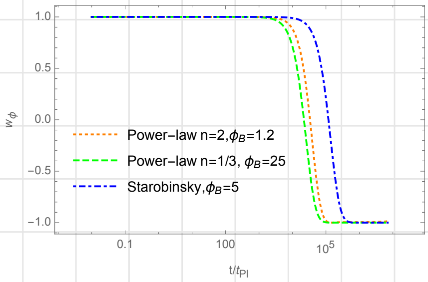
- In the kinetic-energy-initailly dominated case, the evolution of the background can be generically divided into three different phases [9]:

(a) Bouncing, (b) transition, (c) slow-roll inflation

$$w(\phi) \equiv \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)} = \begin{cases} +1, & \text{bouncing} \\ - < w(\phi) < +1, & \text{transition} \\ -1, & \text{slow-roll inflation} \end{cases}$$

- The transition phase is short, during which the kinetic energy decreases dramatically:

$$\dot{\phi}^2/2 \simeq \rho_B \rightarrow 10^{-12}\rho_B \leq V(\phi)$$



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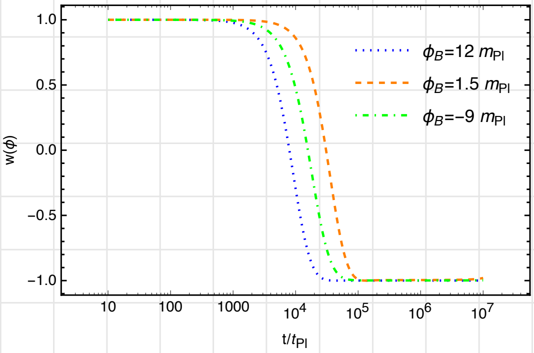
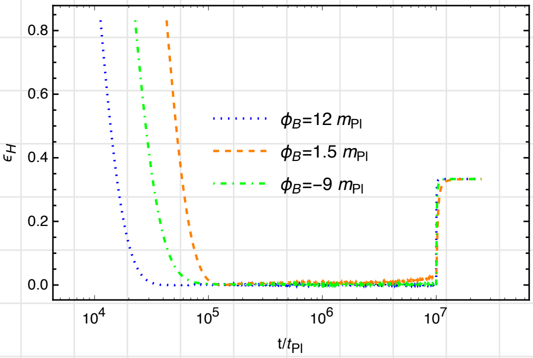
[9] Zhu, AW, Cleaver, Kirsten, Sheng, PLB773 (2017) 196; PRD96 (2017) 083520; Shahalam, Sharma, Wu, AW, arXiv:1710.09845.

2. Background Evolution (Cont.)

The three-phase division is universal:

- Quadratic Potential $V(\phi) = \lambda_0 \phi^2$:





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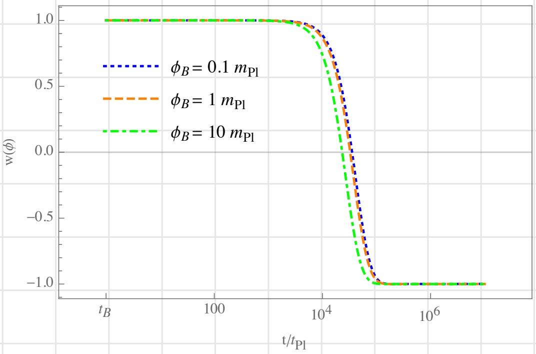
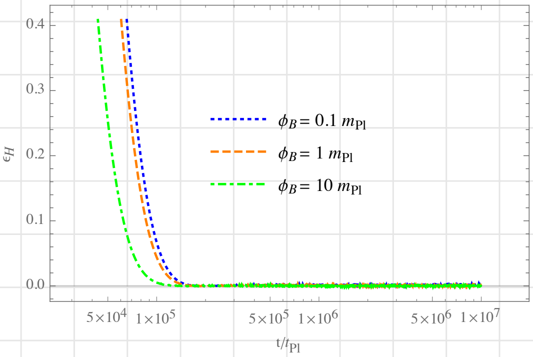
2. Background Evolution (Cont.)

- Power-law Potential $V(\phi) = \lambda_0 \phi^{1/2}$:

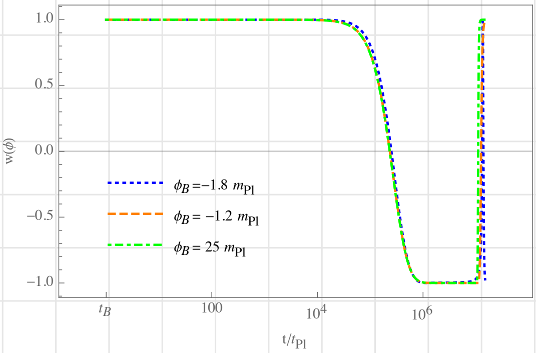


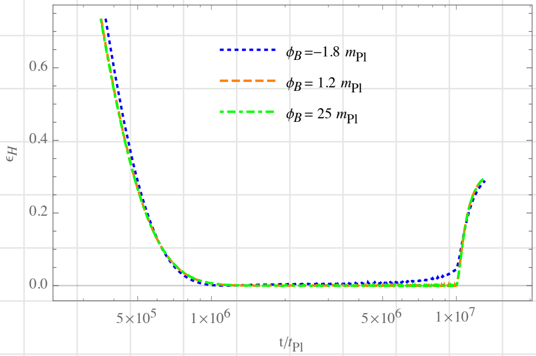


2. Background Evolution (Cont.)

- Starobinsky Potential

$$V(\phi) = \frac{3}{32\pi} M^2 m_{Pl}^2 \times \left(1 - e^{-\sqrt{\frac{16\pi}{3}}\frac{\phi}{m_{Pl}}}\right)^2$$





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2. Background Evolution (Cont.)

- During the bouncing phase, the evolution of $a(t)$ is independent of :

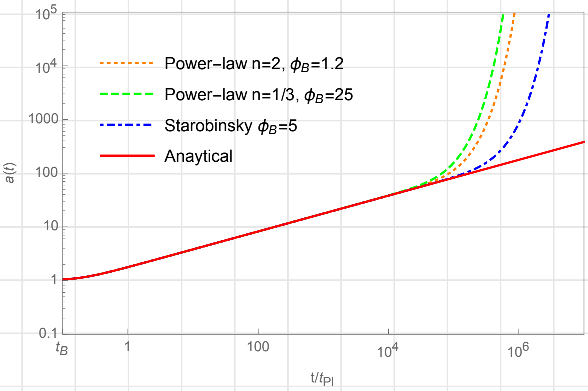
(a) the initial conditions $(\phi_B, \dot{\phi}_B)$

(b) the inflationary potentials

(c) given analytically by

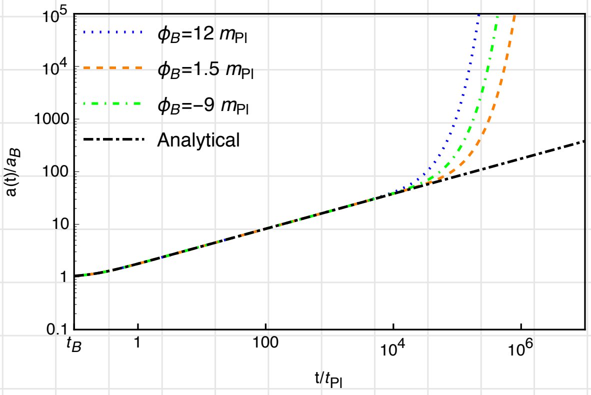
$$a(t) = a_B\left(1 + \gamma_B \frac{t^2}{t_{Pl}^2}\right)^{1/6}, (1) \qquad (3)$$

$\gamma_B \equiv 24\pi\rho_B/m_{Pl}^4$: a dimensionless constant.

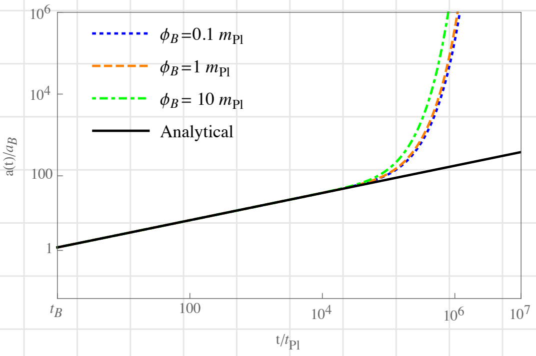


2. Background Evolution (Cont.)

- Evolution of $a(t)$ for different potentials:



$(V = V_0\phi^2)$



$(V = V_0\phi^{1/2})$

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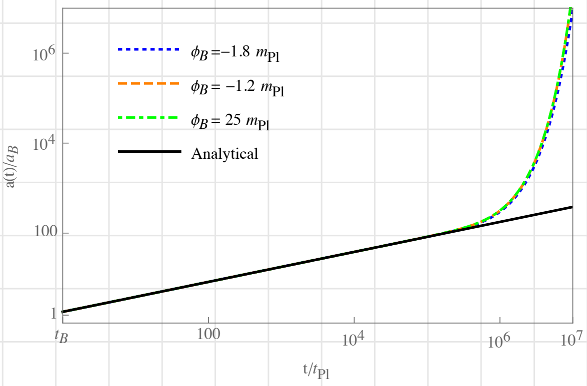
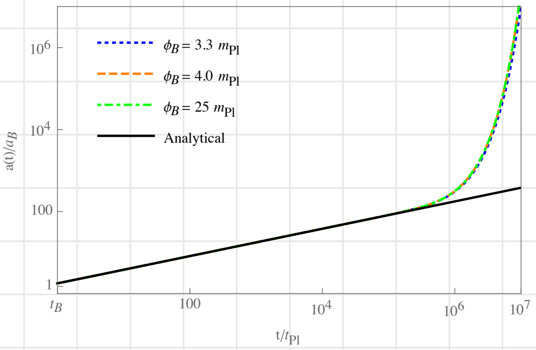
2. Background Evolution (Cont.)

- Evolution of $a(t)$ for the Starobinsky Potential:



$(\dot{\phi}_B > 0)$



$(\dot{\phi}_B < 0)$

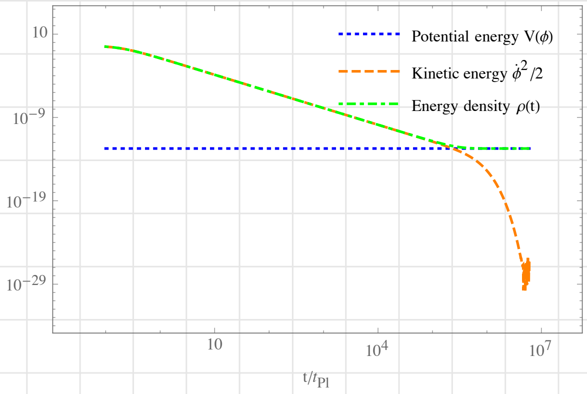
2. Background Evolution (Cont.)

- The main reason is that

$$\frac{1}{2}\dot{\phi}_B^2 \gg V(\phi_B) \quad \Rightarrow \quad \frac{1}{2}\dot{\phi}^2 \gg V(\phi),$$

holds in the whole bouncing phase, once it holds at the bounce $t = t_B$.

- Notice the vertical scales.



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2. Background Evolution (Cont.)

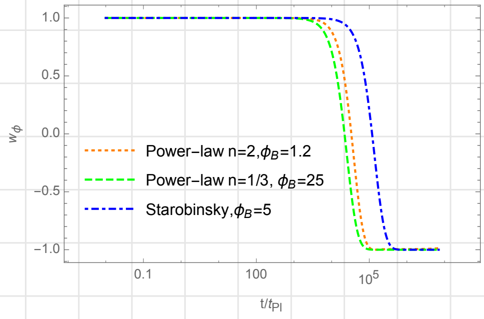
- The evolution during the transition phase is given by,

$$\phi(t) = \phi_c + t_c\dot{\phi}_c \ln\frac{t}{t_c}, \qquad a(t) = a_c\left(1 + t_cH_c \ln\frac{t}{t_c}\right), \tag{4}$$

H_c, a_c, ϕ_c: integration constants

- During the slow-roll inflation, we have

$$a(t) = a_i e^{H_{\text{inf.}}t}, \qquad \phi \simeq \phi_0 \tag{5}$$



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3. Universality of Perturbations

- The scalar and tensor perturbations are given by [10],

$$\mu_k'' + \left(k^2 - \frac{a''}{a} + U(\eta) \right) \mu_k = 0 \qquad (6)$$

where

$$U(\eta) = \begin{cases} a^2 \left(\mathfrak{f}^2 V(\phi) + 2\mathfrak{f} V_{,\phi}(\phi) + V_{,\phi\phi}(\phi) \right), & \text{scalar} \\ 0, & \text{tensor} \end{cases}$$

$$\mathfrak{f} \equiv \sqrt{24\pi G}\dot{\phi}/\sqrt{\rho}.$$

- Both of the scalar and tensor perturbations are universal and independent of the slow-roll inflationary models during the bouncing phase

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[10] A. Ashtekar and A. Barrau, CQG32 (2015) 234001

3. Universality of Perturbations (Cont.)

- This is because the potential $U(\eta)$ is very small in comparing with a''/a, so we have

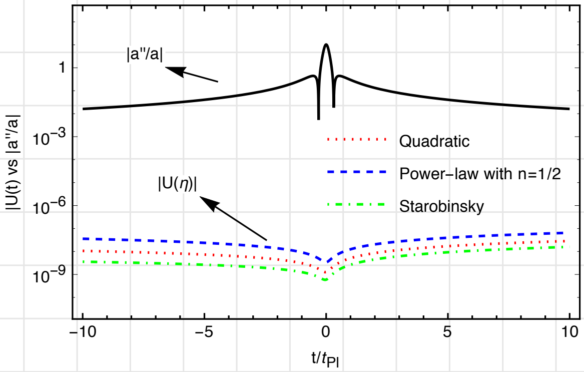
$$\Omega_k^2 = k^2 - \frac{a''}{a} + U(\eta) \simeq k^2 - \frac{a''}{a}$$

during the whole bouncing phase.

- Since $a(t)$ is universal during this phase, clearly the mode functions $\mu_k^{(s,t)}$,

$$\mu_k^{(s,t)''} + \Omega_k^2 \mu_k^{(s,t)} = 0$$

are also universal.



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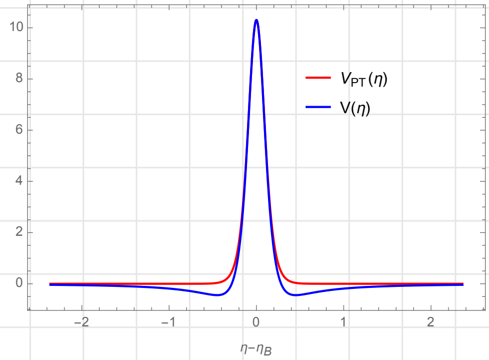
3. Universality of Perturbations (Cont.)

- More interestingly, the term a''/a can be replaced by a Pöschl-Teller (PT) potential,

$$V_{PT}(\eta) = \frac{\mathcal{V}_0}{\cosh^2 \alpha(\eta - \eta_B)}, \quad \mathcal{V}_0 = k_B^2 = \frac{\alpha^2}{6},$$

$$V(\eta) \equiv \frac{a''}{a}$$



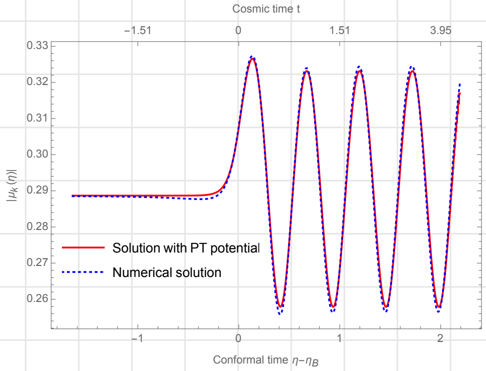
3. Universality of Perturbations (Cont.)

- Then, the mode function has the analytical solution,

$$\begin{aligned}\mu_k^{(\mathrm{PT})}(\eta) \quad &= \quad a_k x^{ik/(2\alpha)}(1-x)^{-ik/(2\alpha)} \\ & \quad \times\, {}_2F_1(a_1-a_3+1, a_2-a_3+1, 2-a_3, x) \\ & \quad + b_k[x(1-x)]^{-ik/(2\alpha)}\; {}_2F_1(a_1, a_2, a_3, x).\end{aligned}$$

a_k, b_k: integration constants, to be determined by initial conditions. ${}_2F_1(a, b, c, x)$: the hypergeometric function

$$\begin{aligned} a_1 &\equiv \frac{1}{2}\left(1+\frac{1}{\sqrt{3}}\right)-\frac{ik}{\sqrt{6}\,k_B}, \\ a_2 &\equiv \frac{1}{2}\left(1-\frac{1}{\sqrt{3}}\right)-\frac{ik}{\sqrt{6}\,k_B}, \\ a_3 &\equiv 1-\frac{ik}{\sqrt{6}\,k_B}.\end{aligned}$$



3. Universality of Perturbations (Cont.)

- In the transition phase, the mode functions are given by,

$$\mu_k(\eta)=\frac{1}{\sqrt{2k}}\left(\tilde{\alpha}_k e^{-ik\eta}+\tilde{\beta}_k e^{ik\eta}\right)$$

$\tilde{\alpha}_k, \tilde{\beta}_k$: integration constants

- In the slow-roll inflation phase, the mode functions are given by the standard forms,

$$\mu_k^{(s,t)}(\eta)\simeq\frac{\sqrt{-\pi\eta}}{2}\left[\alpha_k H^{(1)}_{\nu_{s,t}}(-k\eta)+\beta_k H^{(2)}_{\nu_{s,t}}(-k\eta)\right],$$

α_k, β_k: integration constants.

3. Universality of Perturbations (Cont.)

- Matching them together, we find that the Bogoliubov coefficients, $\alpha_k, \ \beta_k$, are given by

$$\frac{\alpha_k}{\sqrt{2k}} = \left[a_k \frac{\Gamma(2-a_3)\Gamma(a_1+a_2-a_3)}{\Gamma(a_1-a_3+1)\Gamma(a_2-a_3+1)} + b_k \frac{\Gamma(a_3)\Gamma(a_1+a_2-a_3)}{\Gamma(a_1)\Gamma(a_2)}\right] e^{ik\eta_B},$$

$$\frac{\beta_k}{\sqrt{2k}} = \left[a_k \frac{\Gamma(2-a_3)\Gamma(a_3-a_1-a_2)}{\Gamma(1-a_1)\Gamma(1-a_2)} + b_k \frac{\Gamma(a_3)\Gamma(a_3-a_1-a_2)}{\Gamma(a_3-a_1)\Gamma(a_3-a_2)}\right] e^{-ik\eta_B}.$$

- Since $a_i = a_i(k/k_B)$, so $\alpha_k, \ \beta_k$ are in general scale-dependent.

---

3. Universality of Perturbations (Cont.)

- In general $|\beta_k|^2 \neq 0$, so particles are *generically* created at the onset of inflation.
- In GR, we normally impose the BD vacuum at the onset of the inflation,

$$\alpha_k^{GR} = 1, \quad \beta_k^{GR} = 0$$

3. Universality of Perturbations (Cont.)

- Then, the scalar and tensor power spectra are given by,

$$\mathcal{P}_{\mathcal{R}}(k) = |\alpha_k + \beta_k|^2 \mathcal{P}_{\mathcal{R}}^{\text{GR}}(k),$$
$$\mathcal{P}_h(k) = |\alpha_k + \beta_k|^2\, \mathcal{P}_h^{\text{GR}}(k),$$

with

$$\mathcal{P}_{\mathcal{R}}^{\text{GR}}(k) \equiv \frac{k^2}{4\pi^3}\left(\frac{H}{a\dot{\phi}}\right)^2 \Gamma^2(\nu_s)\left(\frac{-k\eta}{2}\right)^{1-2\nu_s},$$
$$\mathcal{P}_h^{\text{GR}}(k) \equiv \frac{k^2}{\pi^3 M_{\text{Pl}}^2}\frac{1}{a^2}\Gamma^2(\nu_t)\left(\frac{-k\eta}{2}\right)^{1-2\nu_t}$$

3. Universality of Perturbations (Cont.)

- Note that, as mentioned above, α_k, β_k are usually k-dependent, so the quantities $\mathcal{P}_{\mathcal{R}}(k)$ and $\mathcal{P}_h(k)$ now also become k-dependent.
- This provides an excellent opportunity to test LQC.
- Clearly, such dependence cannot be strong. Otherwise, it will not be consistent with current observations, which show that the power spectra are almost scale-invariant [11].
- To fix (α_k, β_k) or (a_k, b_k), one needs to impose the initial conditions.

---

[11] P. Collaboration et al., Planck 2015. XX. Constraints on inflation, arXiv:1502.02114.

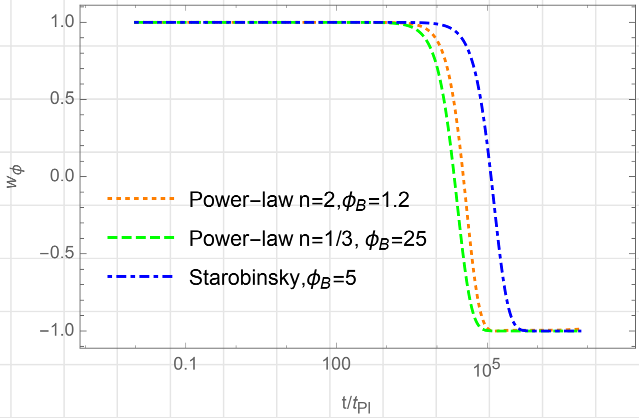
Table of Contents

4. Conclusions

- We study pre-inflationary dynamics in the framework of LQC, and for initially kinetic energy dominated models we find:

  - The evolution of the universe is always divided into three different phases:

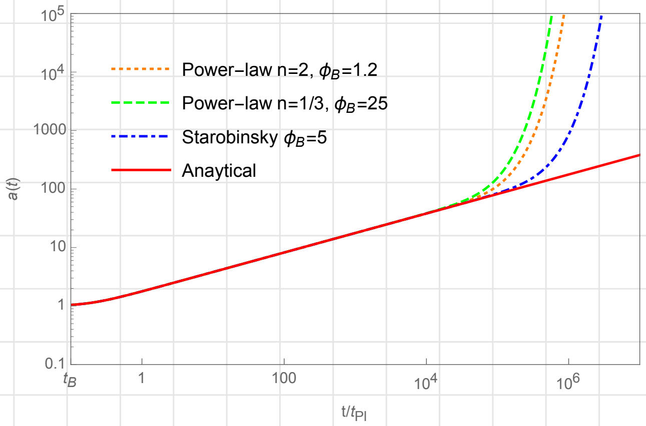
    (1) Bouncing (2) transition (3) slow-roll inflation



4. Conclusions (Cont.)

- The evolution of the expansion factor is universal during the bouncing phase:

$$a(t) = a_B \left(1 + \gamma_B \frac{t^2}{t_{Pl}^2}\right)^{1/6}, \qquad (7)$$



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4. Conclusions (Cont.)

- During the pre-inflationary phase, the evolutions of the scalar and tensor perturbations are all universal and independent of the slow-roll inflationary models.
- In this phase the potentials of the scalar and tensor perturbations can be well approximated by an effective PT potential, for which analytic solutions of the mode functions are known.

- The Bogoliubov coefficients at the onset of the slow-roll inflation are generically non-zero,

$$\beta_k \neq 0,$$

in contrast to GR where the initial conditions are normally taken as the BD vacuum,

$$\beta_k^{GR} = 0.$$

Thank You!

2b2. Kazufumi Takahashi (RESCEU U. of Tokyo),

“Extended mimetic gravity: Hamiltonian analysis and gradient instabilities” (10+5)

[JGRG27 (2017) 112809]

Extended mimetic gravity: Hamiltonian analysis and gradient instabilities

Kazufumi Takahashi (JSPS fellow)
RESCEU, The University of Tokyo

Based on

- **KT**, H. Motohashi, T. Suyama, and T. Kobayashi
  Phys. Rev. D **95**, 084053 (2017), “General invertible transformation and physical degrees of freedom”
- **KT** and T. Kobayashi
  JCAP **1711**, 038 (2017), “Extended mimetic gravity: Hamiltonian analysis and gradient instabilities”

➢ Degenerate scalar-tensor theories

- Scalar-tensor theories (inflation, late-time acceleration, …)
  - Higher derivatives ⋯ Ostrogradsky ghost

    “Any nondegenerate higher derivative theory contains extra ghost-like DOFs”

    e.g. $\det\left(\frac{\partial^2 L}{\partial\ddot{q}^i\partial\ddot{q}^j}\right) \neq 0$ for $L(q^i, \dot{q}^i, \ddot{q}^i)$ ➡ Need degeneracy!

- Degenerate scalar-tensor theories w/ 3 DOFs
  - Horndeski/generalized Galileons
  - GLPV theories
  - quadratic/cubic DHOST theories [*known broadest class*]

Degenerate Higher-Order Scalar-Tensor

➡ Specify all the degenerate theories up to cubic order in $\nabla_\mu\nabla_\nu\phi$

constructed from ϕ and ϕ_μ

$F_0 + F_1\Box\phi$ could further be included

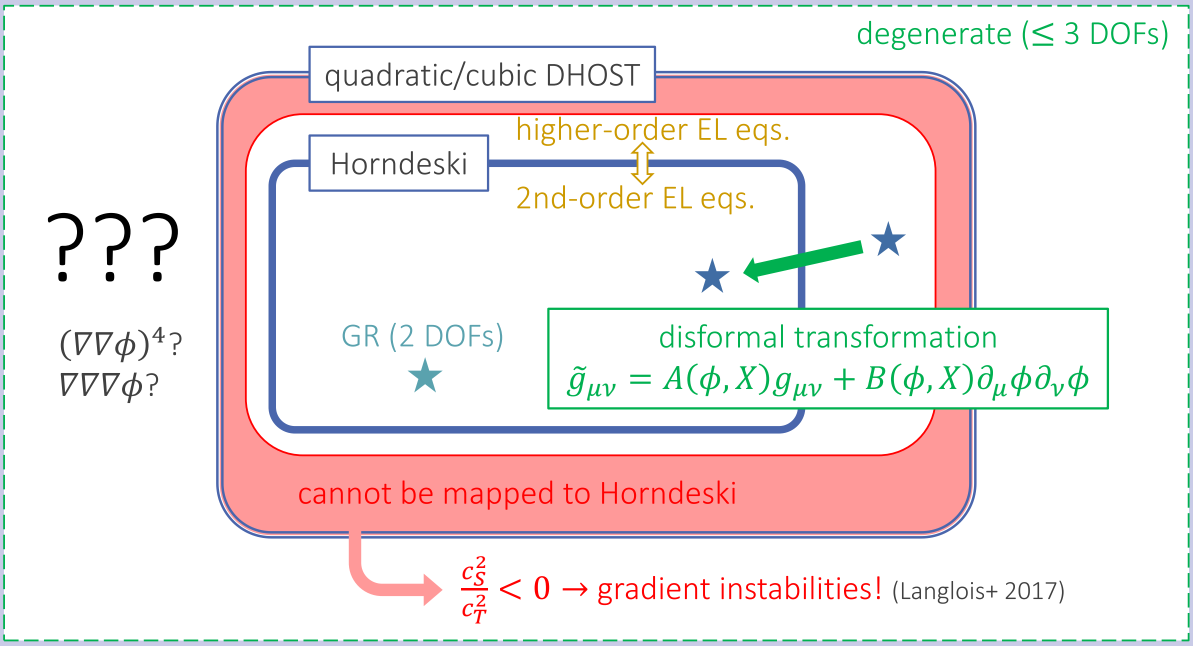
$$S_{\mathrm{q/c}} = \int d^4x\sqrt{-g}\,[\underbrace{f_2\mathcal{R} + a^{\mu\nu\lambda\sigma}\phi_{\mu\nu}\phi_{\lambda\sigma}}_{\text{quadratic}} + \underbrace{f_3\mathcal{G}^{\mu\nu}\phi_{\mu\nu} + b^{\mu\nu\lambda\sigma\alpha\beta}\phi_{\mu\nu}\phi_{\lambda\sigma}\phi_{\alpha\beta}}_{\text{cubic}}]$$

Chosen so that the Lagrangian is degenerate

$\mathcal{R}$: 4D Ricci scalar
$\mathcal{G}_{\mu\nu}$: 4D Einstein tensor
$X \equiv g^{\mu\nu}\phi_\mu\phi_\nu$

➢ Problem in the known theories

nondegenerate (Ostrogradsky ghost)



degenerate ($\lesssim$ 3 DOFs)

???

$(\nabla\nabla\phi)^4$?

$\nabla\nabla\nabla\phi$?

quadratic/cubic DHOST

Horndeski

higher-order EL eqs.

⇕

2nd-order EL eqs.

GR (2 DOFs)

disformal transformation

$\tilde{g}_{\mu\nu} = A(\phi, X) g_{\mu\nu} + B(\phi, X) \partial_\mu \phi \partial_\nu \phi$

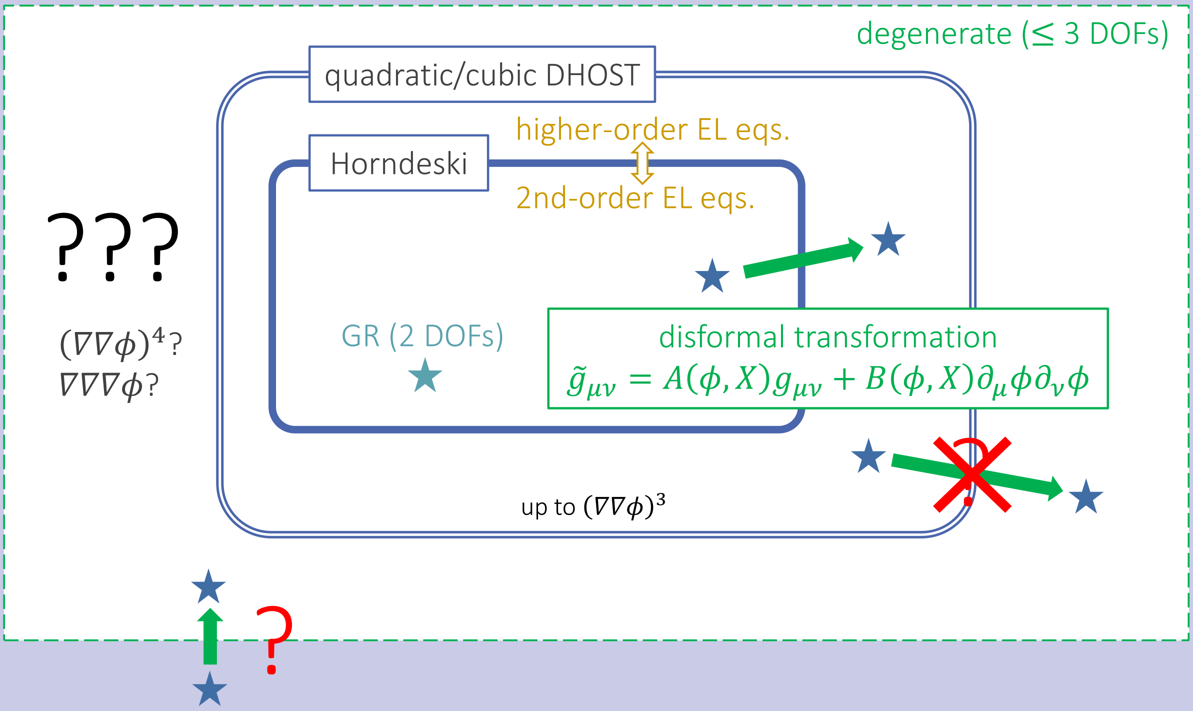
cannot be mapped to Horndeski

$\frac{c_S^2}{c_T^2} < 0 \rightarrow$ gradient instabilities! (Langlois+ 2017)

(except for those w/ nondynamical tensor modes)

➢ Possible extension

nondegenerate (Ostrogradsky ghost)



degenerate ($\lesssim$ 3 DOFs)

???

$(\nabla\nabla\phi)^4$?

$\nabla\nabla\nabla\phi$?

quadratic/cubic DHOST

Horndeski

higher-order EL eqs.

⇕

2nd-order EL eqs.

GR (2 DOFs)

disformal transformation

$\tilde{g}_{\mu\nu} = A(\phi, X) g_{\mu\nu} + B(\phi, X) \partial_\mu \phi \partial_\nu \phi$

up to $(\nabla\nabla\phi)^3$

➢ Way out

- How can we go outside the quadratic/cubic DHOST class?

  ➡ Let's start from nondegenerate theories!

invertible: $\tilde{g}_{\mu\nu} \leftrightarrow g_{\mu\nu}$ one-to-one

- If the transformation is invertible, the resultant theory is also nondegenerate

  (∵ DOFs are invariant under invertible trnsf.) KT, Motohashi, Suyama, Kobayashi, 2017

  ➡ Let's consider noninvertible transformations!

- Noninvertible conformal transformation

$$\tilde{g}_{\mu\nu} = -X g_{\mu\nu}$$

$X \equiv g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$

$X \to \Omega^{-2}X$ under $g_{\mu\nu} \to \Omega^2 g_{\mu\nu}$

$\Rightarrow$ $\tilde{g}_{\mu\nu}$: invariant

- Mimetic gravity

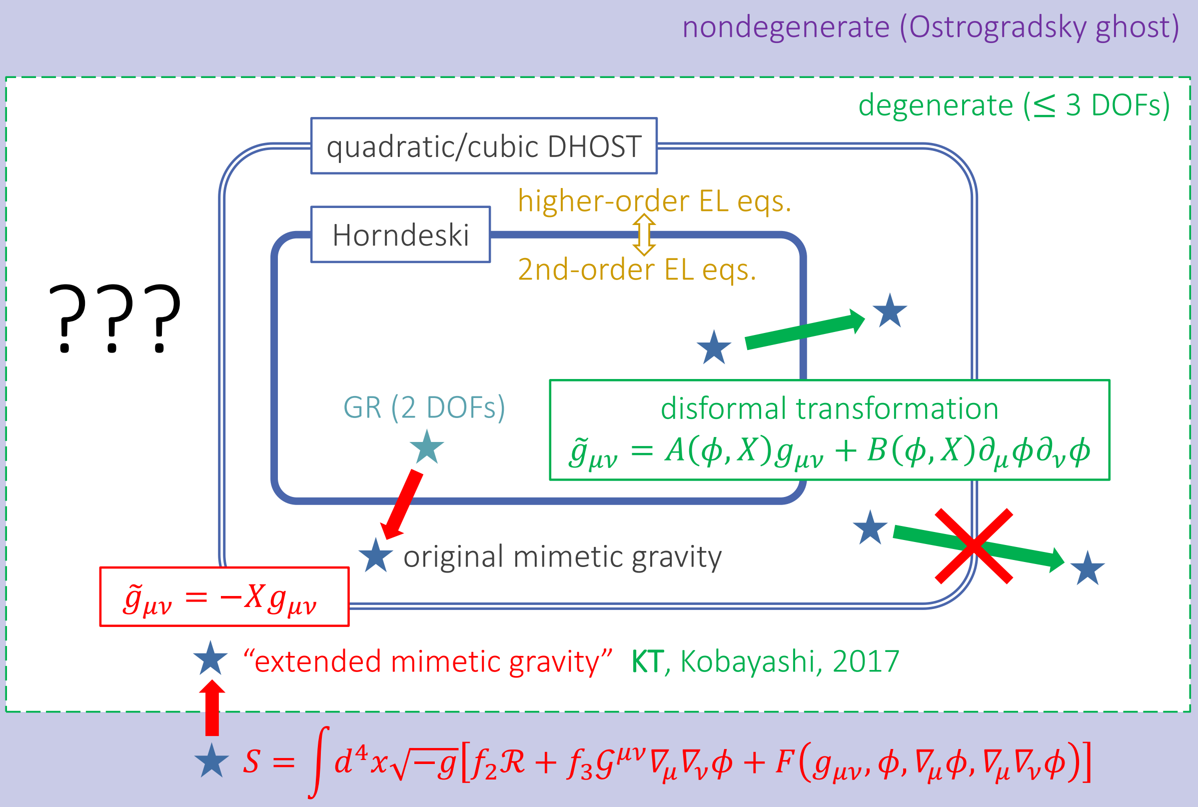
$$\tilde{S}[\tilde{g}_{\mu\nu}, \phi] \longrightarrow S[g_{\mu\nu}, \phi]$$

"seed" ST theory "mimetic theory" conformal sym.

- mimetic = "Copying the behaviour or appearance of sb/sth else"

  Mimetic gravity can mimic dark matter (Chamseddine, Mukhanov, 2013)

➢ Mimetic theories



$$S = \int d^4x\sqrt{-g}\left[f_2\mathcal{R} + f_3 G^{\mu\nu}\nabla_\mu\nabla_\nu\phi + F\left(g_{\mu\nu}, \phi, \nabla_\mu\phi, \nabla_\mu\nabla_\nu\phi\right)\right]$$

Seed theory

- Start from a “seed” action

$$S_{\text{seed}}[g_{\mu\nu},\phi] = \int d^4x\sqrt{-g}\left[f_2(\phi,X)\mathcal{R} + f_3(\phi,X)\mathcal{G}^{\mu\nu}\nabla_\mu\nabla_\nu\phi + F\left(g_{\mu\nu},\phi,\nabla_\mu\phi,\nabla_\mu\nabla_\nu\phi\right)\right]$$

arbitrary functions

- Known healthy theories amount to specific f_2, f_3, F:
  - Horndeski: $\forall f_2, f_3$ functions of (ϕ, X)

$$F = -2f_{2X}\left[(\Box\phi)^2 - \left(\nabla_\mu\nabla_\nu\phi\right)^2\right] + \frac{1}{3}f_{3X}\left[(\Box\phi)^3 - 3\Box\phi\left(\nabla_\mu\nabla_\nu\phi\right)^2 + 2\left(\nabla_\mu\nabla_\nu\phi\right)^3\right]$$

However, for generic choices of f_2, f_3, and F, the theory has 4 DOFs.

- Hamiltonian analysis → 1+3 decomposition
  - First write the seed action in the ADM language and then move to the mimetic theory

---

1+3 decomposition

- ADM variables

$$ds^2 = -N^2dt^2 + \gamma_{ij}\left(dx^i + N^i dt\right)\left(dx^j + N^j dt\right)$$

- For ϕ, we define

canonical variable $\quad A_* \equiv n^\mu\nabla_\mu\phi = \dfrac{\dot{\phi} - N^i D_i\phi}{N}$

velocity of A_* $\quad V_* \equiv n^\mu n^\nu\nabla_\mu\nabla_\nu\phi = \dfrac{\dot{A}_* - D^k\phi D_k N - N^k D_k A_*}{N}$

$n_\mu \equiv -N\delta_\mu^0$
$h_{\mu\nu} \equiv g_{\mu\nu} + n_\mu n_\nu$
$K_{ij} \equiv \dfrac{1}{2N}\left(\dot{\gamma}_{ij} - 2D_{(i}N_{j)}\right)$
D_i: 3D covariant derivative

Derivatives of ϕ are decomposed as

$$\begin{cases} \nabla_\mu\phi = h_\mu^i D_i\phi - n_\mu A_* \\ \nabla_\mu\nabla_\nu\phi = h_{(\mu}^i h_{\nu)}^j\left(D_iD_j\phi - A_*K_{ij}\right) - 2h_{(\mu}^i n_{\nu)}\left(D_iA_* - K_{ij}D^j\phi\right) + n_\mu n_\nu V_* \end{cases}$$

→ $F\left(g_{\mu\nu},\phi,\nabla_\mu\phi,\nabla_\mu\nabla_\nu\phi\right)$ contains $\gamma_{ij}, \phi, A_*, K_{ij}, V_*$, and D_i

1+3 decomposition (cont'd)

- Terms with the curvature tensors:

$$\int d^4x\sqrt{-g}\left[f_2\mathcal{R}+f_3\mathcal{G}^{\mu\nu}\nabla_\mu\nabla_\nu\phi\right]$$

$$=\int dtd^3xN\sqrt{\gamma}\Big\{f_2\left(R+K_{ij}^2-K^2\right)-2Kf_{2\perp}-2D_iD^if_2-\frac{1}{2}\left(R-K_{ij}^2+K^2\right)A_*f_{3\perp}$$

$$-\left[R_{ij}-\frac{1}{2}\left(R+K_{kl}^2-K^2\right)\gamma_{ij}\right]D^i\phi D^jf_3+D_iD_j\left(D^i\phi D^jf_3\right)-D_iD^i\left(D_j\phi D^jf_3\right)$$

$$+\left(K\gamma^{ij}-K^{ij}\right)\left(2K_i^kD_k\phi D_jf_3+f_{3\perp}D_iD_j\phi+A_*D_iD_jf_3\right)+\Lambda\left(NA_*+N^iD_i\phi-\dot{\phi}\right)\Big\}$$

with

$$f_\perp\equiv n^\mu\nabla_\mu f=f_\phi A_*-2f_X\left(K_{ij}D^i\phi D^j\phi+A_*V_*-D^i\phi D_iA_*\right)$$

- Combined with the term $F\left(g_{\mu\nu},\phi,\nabla_\mu\phi,\nabla_\mu\nabla_\nu\phi\right)$, we obtain

$$S_{\mathrm{seed}}[g_{\mu\nu},\phi]=\int dtd^3x\left[N\sqrt{\gamma}L_0\left(\gamma_{ij},R_{ij},\phi,A_*;K_{ij},V_*;D_i\right)+\Lambda\left(NA_*+N^iD_i\phi-\dot{\phi}\right)\right]$$

Fixes $A_*\sim\dot{\phi}$

➡ Perform $g_{\mu\nu}\to\tilde{g}_{\mu\nu}=-Xg_{\mu\nu}$

$\dot{\gamma}_{ij}$ $\dot{A}_*$

velocities

$K_{ij}\sim\dot{\gamma}_{ij}$, $V_*\sim\dot{A}_*$

Extended mimetic gravity

- Under $\tilde{g}_{\mu\nu}=-Xg_{\mu\nu}$,

$$\tilde{N}=\sqrt{-X}N,\qquad\tilde{N}^i=N^i,\qquad\tilde{\gamma}_{ij}=-X\gamma_{ij},\qquad\tilde{A}_*=\frac{1}{\sqrt{-X}}A_*,$$

$$\tilde{R}_{ij}=R_{ij}+\frac{3}{4X^2}D_iXD_jX-\frac{1}{2X}D_iD_jX+\gamma_{ij}\left(\frac{1}{4X^2}D_kXD^kX-\frac{1}{2X}D_kD^kX\right),$$

while the velocities are transformed as

$$\tilde{K}_{ij}=\sqrt{-X}\left[\left(\delta_i^k\delta_j^l-\frac{D^k\phi D^l\phi}{X}\gamma_{ij}\right)V_{kl}+\frac{D^k\phi D_kA_*}{X}\gamma_{ij}\right],$$

$$\tilde{V}_*=-\frac{1}{X^2}D^i\phi D^j\phi\left(A_*V_{ij}-D_iD_j\phi\right),$$

Only in the combination of

$$V_{ij}\equiv K_{ij}+\frac{V_*}{A_*}\gamma_{ij}$$

$K_{ij}\sim\dot{\gamma}_{ij}$

$V_*\sim\ddot{\phi}\ (\sim\dot{A}_*)$

conformal sym.

"extended mimetic gravity"

➡ $S_{\mathrm{mim}}[g_{\mu\nu},\phi]=\int dtd^3x\left[N\sqrt{\gamma}L_{\mathrm{M}}\left(\gamma_{ij},R_{ij},\phi,A_*;V_{ij};D_i\right)+\Lambda\left(NA_*+N^iD_i\phi-\dot{\phi}\right)\right]$

$A_*\sim\dot{\phi}$

- Degenerate kinetic matrix → additional primary constraint
- The additional constraint should be of first class

Hamiltonian analysis

$$S[g_{\mu\nu},\phi]=\int dt d^3x\left[N\sqrt{\gamma}L_{\rm M}(\gamma_{ij},R_{ij},\phi,A_*;B_{ij};D_i)+\Lambda(NA_*+N^iD_i\phi-\dot{\phi})+N\lambda^{ij}(B_{ij}-V_{ij})\right]$$

auxiliary field

$B_{ij}=V_{ij}$

- Canonical variables ⋯ 50-dim. phase space

$$\begin{pmatrix} N & N^i & \gamma_{ij} & \phi & A_* & B_{ij} & \Lambda & \lambda^{ij} \\ \pi_N & \pi_i & \pi^{ij} & p_\phi & p_* & p^{ij} & P & P_{ij} \end{pmatrix}$$

- Primary constraints

$$\pi_N\approx 0,\qquad \pi_i\approx 0,\qquad p^{ij}\approx 0,\qquad P\approx 0,\qquad P_{ij}\approx 0$$

$$\bar{\pi}^{ij}\equiv\pi^{ij}+\frac{1}{2}\lambda^{ij}\approx 0,\qquad \bar{p}_\phi\equiv p_\phi+\Lambda\approx 0$$

and

$$\mathcal{C}\equiv A_*p_*-2\gamma_{ij}\pi^{ij}\approx 0$$

generates conformal transformation of A_*,γ_{ij}

$$V_{ij}=\frac{1}{2N}\left(\dot{\gamma}_{ij}+2\frac{\dot{A}_*}{A_*}\gamma_{ij}\right)+\cdots$$

- Redefine $\mathcal{C}$ for a technical reason:

$$\bar{\mathcal{C}}\equiv\mathcal{C}+2\lambda^{ij}P_{ij}$$

Hamiltonian analysis (cont'd)

- Total Hamiltonian

Primary constraints

$$H_T=\int d^3x\left(N\mathcal{H}+N^i\mathcal{H}_i+\mu_N\pi_N+\mu^i\pi_i+\mu_{ij}\bar{\pi}^{ij}+u_\phi\bar{p}_\phi+u_*\bar{\mathcal{C}}+u_{ij}p^{ij}+UP+U^{ij}P_{ij}\right)$$

with

$$\mathcal{H}\equiv-\sqrt{\gamma}L_{\rm M}(\gamma_{ij},R_{ij},\phi,A_*;B_{ij};D_i)+2\pi^{ij}B_{ij}+p_\phi A_*-\sqrt{\gamma}D_i\left(\frac{p_*}{\sqrt{\gamma}}D^i\phi\right)$$

$$\mathcal{H}_i\equiv-2\sqrt{\gamma}D^j\left(\frac{\pi_{ij}}{\sqrt{\gamma}}\right)+p_\phi D_i\phi+p_*D_iA_*+p^{jk}D_iB_{jk}-2\sqrt{\gamma}D_j\left(\frac{p^{jk}}{\sqrt{\gamma}}B_{ik}\right)$$

generate spatial diffeo. of $\gamma_{ij},\phi,A_*,B_{ij}$

- Secondary constraints

$$\dot{\pi}_N\approx 0\quad\rightarrow\quad\mathcal{H}\approx 0$$

$$\dot{\pi}_i\approx 0\quad\rightarrow\quad\mathcal{H}_i\approx 0$$

$$\dot{p}^{ij}\approx 0\quad\rightarrow\quad\varphi^{ij}\equiv\sqrt{\gamma}\frac{\partial L_{\rm M}}{\partial B_{ij}}-2\pi^{ij}\approx 0$$

- No tertiary constraint if $\det\left(\frac{\partial^2L_{\rm M}}{\partial B_{ij}\partial B_{kl}}\right)\neq 0$

DOF counting

- First-class constraints ⋯ 9 in total

$$\underbrace{\pi_N, \qquad \pi_i,}_{\text{4D diffeo.}} \qquad \underbrace{\mathcal{H}, \qquad \mathcal{H}_i,}_{\text{EM conservation}} \qquad \underset{\text{conformal}}{\bar{\mathcal{C}}} \longleftarrow$$

peculiar to mimetic gravity!

- Second-class constraints ⋯ 26 in total

$$\bar{\pi}^{ij}, \qquad \bar{p}_\phi, \qquad p^{ij}, \qquad P, \qquad P_{ij}, \qquad \varphi^{ij}$$

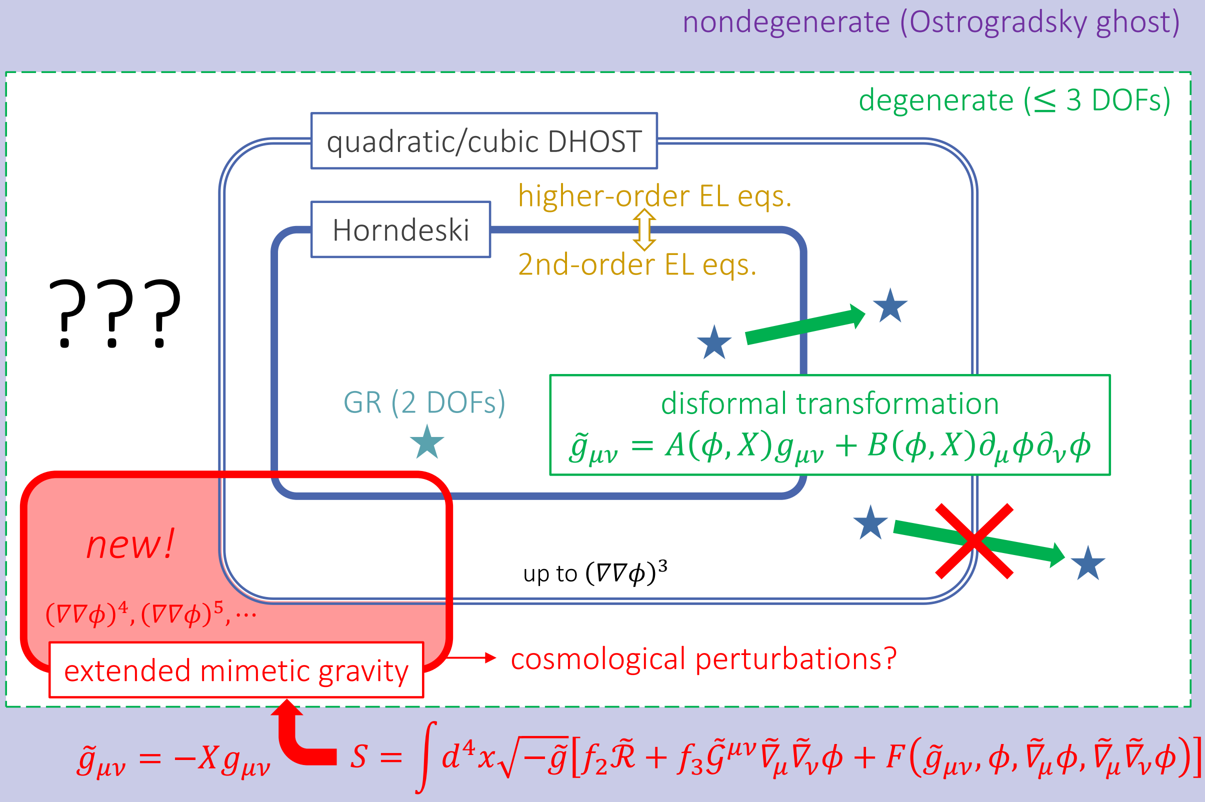
- The number of physical DOFs

$$\frac{1}{2}\big(\underset{\substack{\uparrow \\ \text{phase-space dim.}}}{50} - \underset{\substack{\uparrow \\ \text{\# of first-class}}}{9} \times 2 - \underset{\substack{\uparrow \\ \text{\# of second-class}}}{26}\big) = 3$$

No extra DOF!

- If there are tertiary constraints, the number of DOFs can become even smaller.

Relation to the known classes



nondegenerate (Ostrogradsky ghost)

degenerate (≤ 3 DOFs)

quadratic/cubic DHOST

higher-order EL eqs.

⇕

2nd-order EL eqs.

Horndeski

???

GR (2 DOFs)

disformal transformation

$\tilde{g}_{\mu\nu} = A(\phi, X) g_{\mu\nu} + B(\phi, X) \partial_\mu \phi \partial_\nu \phi$

new!

$(\nabla\nabla\phi)^4, (\nabla\nabla\phi)^5, \cdots$

up to $(\nabla\nabla\phi)^3$

extended mimetic gravity → cosmological perturbations?

$$\tilde{g}_{\mu\nu} = -X g_{\mu\nu} \qquad S = \int d^4x \sqrt{-\tilde{g}} \big[f_2 \tilde{\mathcal{R}} + f_3 \tilde{\mathcal{G}}^{\mu\nu} \tilde{\nabla}_\mu \tilde{\nabla}_\nu \phi + F\big(\tilde{g}_{\mu\nu}, \phi, \tilde{\nabla}_\mu \phi, \tilde{\nabla}_\mu \tilde{\nabla}_\nu \phi\big) \big]$$

➢ Cosmological perturbations

- Gauge fixing: $\phi = t$ and $X = -1$ $(\to N = 1)$

$$S_{\text{mim}} = \int dtd^3x\sqrt{\gamma}\left[\left(f_2 - \frac{1}{2}\dot{f}_3\right)R + \mathcal{F}(t, K, \mathcal{K}_2, \mathcal{K}_3, \cdots, \mathcal{K}_\ell)\right],$$

$$\mathcal{K}_1 \equiv K$$

$$\mathcal{K}_n \equiv K^{i_1}_{i_2}K^{i_2}_{i_3}\cdots K^{i_n}_{i_1}$$

- Metric ansatz (flat FLRW background + perturbations)

$$N = 1, \qquad N_i = \partial_i\chi, \qquad \gamma_{ij} = a^2(t)e^{2\zeta}\left(\delta_{ij} + h_{ij} + \frac{1}{2}h_{ik}h_{kj}\right)$$

scalar pert. TT tensor pert.

- Tensor quadratic action

$$S_{\text{T}}^{(2)} = \int dtd^3x\frac{a^3}{4}\left[\mathcal{B}\dot{h}_{ij}^2 - \mathcal{E}\frac{(\partial_k h_{ij})^2}{a^2}\right]$$

Scalar quadratic action

$$S_{\text{S}}^{(2)} = 2\int dtd^3xa^3\left[\frac{3\mathcal{A} + 2\mathcal{B}}{\mathcal{A} + 2\mathcal{B}}\mathcal{B}\dot{\zeta}^2 + \mathcal{E}\frac{(\partial_k\zeta)^2}{a^2}\right]$$

➡ gradient instabilities!

Here,

$$\mathcal{A} \equiv \sum_{m=1}^{\ell}\sum_{n=1}^{\ell} mnH^{m+n-2}\mathcal{F}_{mn}, \qquad \mathcal{B} \equiv \sum_{n=2}^{\ell}\frac{n(n-1)}{2}H^{n-2}\mathcal{F}_n, \qquad \mathcal{E} \equiv f_2 - \frac{1}{2}\dot{f}_3$$

$$\mathcal{F}_{mn} \equiv \frac{\partial^2\mathcal{F}}{\partial\mathcal{K}_m\partial\mathcal{K}_n} \qquad \mathcal{F}_n \equiv \frac{\partial\mathcal{F}}{\partial\mathcal{K}_n}$$

➢ Conclusions

- How can we go beyond quadratic/cubic DHOST theories via disformal transformation?

➡ Consider noninvertible transformation of nondegenerate theories!

(∵ Invertible transformations cannot change the DOFs) KT, Motohashi, Suyama, Kobayashi, 2017

- "Extended mimetic gravity" KT, Kobayashi, 2017

Perform $\tilde{g}_{\mu\nu} = -Xg_{\mu\nu}$ on theories with 4 DOFs:

$$\tilde{S}_{\text{seed}}[\tilde{g}_{\mu\nu}, \phi] = \int d^4x\sqrt{-\tilde{g}}\left[f_2\tilde{\mathcal{R}} + f_3\tilde{G}^{\mu\nu}\tilde{\nabla}_\mu\tilde{\nabla}_\nu\phi + F\left(\tilde{g}_{\mu\nu}, \phi, \tilde{\nabla}_\mu\phi, \tilde{\nabla}_\mu\tilde{\nabla}_\nu\phi\right)\right]$$

functions of $(\phi, \tilde{X})$ $\qquad \tilde{X} \equiv \tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$

➡ The resultant theory $S[g_{\mu\nu}, \phi]$ has only 3 DOFs due to conformal sym.

- Cosmological perturbations suffer from gradient instabilities

- Similar extension? Phenomenology?

2b4. Rampei Kimura (Tokyo Institute of Technology),

“Are redshift-space distortions actually a probe of growth of structure?” (10+5)

[JGRG27 (2017) 112811]

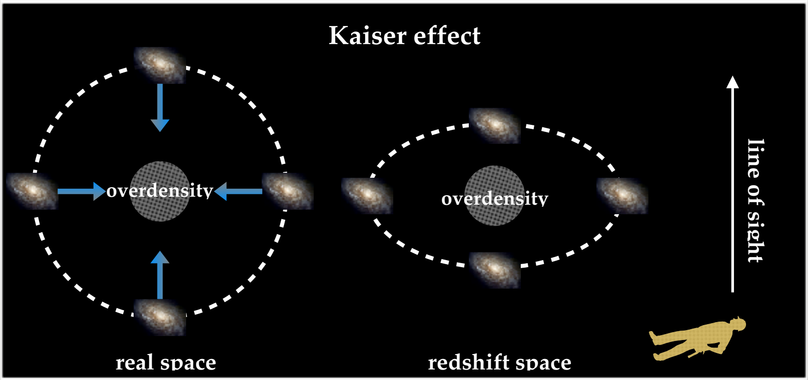
ARE REDSHIFT-SPACE DISTORTIONS ACTUALLY A PROBE OF GROWTH OF STRUCTURE

RAMPEI KIMURA
TOKYO INSTITUTE OF TECHNOLOGY

JGRG27 AT HIROSHIMA 11/28/2017

BASED ON ARXIV : 1709.09371
COLLABORATORS : TERUAKI SUYAMA, MASAHIDE YAMAGUCHI,
DAISUKE YAMAUCHI, SHUICHIRO YOKOYAMA

STANDARD COSMOLOGY I



Mapping to redshift space

galaxy density contrast in real space

galaxy density contrast in redshift space → $\delta_{g,s} = \delta_g - \frac{1}{aH}\nabla_z v_{g,z}$ ← line of sight component of galaxy peculiar velocity

Galaxy vs. matter distribution

$\delta_g = b_g \delta_m$ (linear bias)

$v_g = v_m$

STANDARD COSMOLOGY II

- Newtonian gauge $\mathrm{d}s^2 = -[1+2\Phi(t,\boldsymbol{x})]\mathrm{d}t^2 + a^2(t)[1-2\Psi(t,\boldsymbol{x})]\mathrm{d}\boldsymbol{x}^2$
- Basic equations (sub-horizon approximation)

$$\frac{k^2}{a^2}\Psi = \frac{k^2}{a^2}\Phi = -4\pi G\rho_{\mathrm{m}}\delta_{\mathrm{m}}$$

(Poisson equation)

$$\boxed{\dot{\delta}_{\mathrm{m}} + \frac{k^2}{a^2}v_{\mathrm{m}} = 0} \qquad \dot{v}_{\mathrm{m}} - \Phi = 0$$

(**continuity** & Euler equation)

$$\boxed{\ddot{\delta}_{\mathrm{m}} + 2H\dot{\delta}_{\mathrm{m}} - 4\pi G\rho_{\mathrm{m}}\delta_{\mathrm{m}} = 0}$$

(**Evolution of δ_{m}**)

- Growth factor D_{m} $\quad \delta_{\mathrm{m}}(t,\mathbf{k}) = D_{\mathrm{m}}(t)\,\delta_0(\mathbf{k})$ $\quad \delta_0$: Initial density contrast
- Linear growth rate f_{m} $\quad f_{\mathrm{m}}(t) \equiv \frac{\mathrm{d}\ln D_{\mathrm{m}}}{\mathrm{d}\ln a}$

$$\boxed{v_{\mathrm{m}} = -\frac{a^2H}{k^2}f_{\mathrm{m}}\delta_{\mathrm{m}}}$$

STANDARD COSMOLOGY III

Kaiser formula

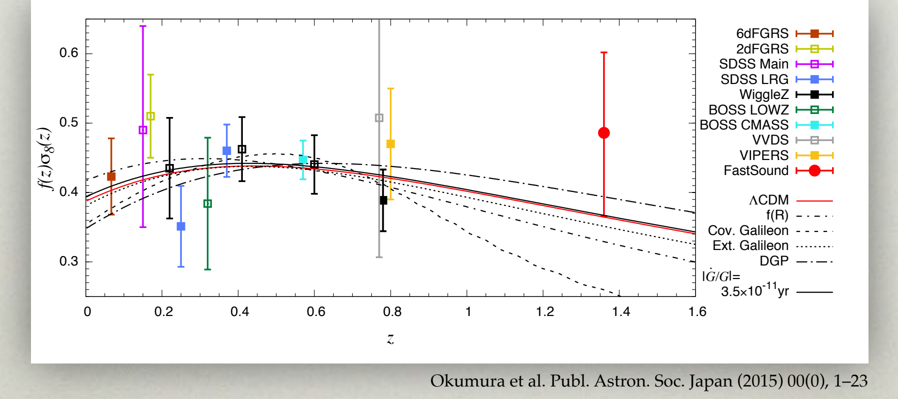
the cosine of the angle between the line of sight & Fourier momentum

$$P_{\mathrm{g},s}(\mathbf{k};t) = b_{\mathrm{g}}^2\left(1+\beta(t)\,\mu^2\right)^2 P_{\mathrm{m}}(k;t)$$

$$\boxed{\beta \equiv \frac{f_{\mathrm{m}}}{b_{\mathrm{g}}}}$$

Power spectrum in redshift space

matter power spectrum



Okumura et al. Publ. Astron. Soc. Japan (2015) 00(0), 1–23

Growth rate can directly measured by RSD

(bias can be fixed by cross-correlation of LSS & weak lensing)

NON-MINIMALLY COUPLED DM

- **GR** + **scalar field** (Dark energy) $S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{Pl}}^2}{2}R[g] + \mathcal{L}_\phi[g,\phi]\right] + S_{\mathrm{b}} + S_{\mathrm{c}}$
- Matter = (standard) **baryon** + **non-minimally coupled cold dark matter**

$$S_{\mathrm{b}} = \int \mathrm{d}^4x\sqrt{-g}\mathcal{L}_{\mathrm{b}}[g_{\mu\nu},\psi_{\mathrm{b}}]$$

$$S_{\mathrm{c}} = \int \mathrm{d}^4x\sqrt{-\bar{g}}\mathcal{L}_{\mathrm{c}}[\bar{g}_{\mu\nu},\psi_{\mathrm{c}}]$$

$$\bar{g}_{\mu\nu} = A(\phi,X)g_{\mu\nu} + B(\phi,X)\partial_\mu\phi\partial_\nu\phi$$

(**conformal** & **disformal** coupling)

Baryon : **sensitive** to solar-system experiments → **minimal** coupling
CDM : **insensitive** to solar system experiments → **non-minimal** coupling

- Energy-momentum conservation

$$\nabla^\mu T_{\mu\nu}^{(\mathrm{b})} = 0 \qquad \boxed{\nabla^\mu\left(T_{\mu\nu}^{(c)} + T_{\mu\nu}^{(\phi)}\right) = 0}$$

Energy transfer between dark energy and CDM

BASIC EQUATIONS

- Basic equations

EM tensor for the total matter
$T_{\mu\nu}^{(\mathrm{m})} := T_{\mu\nu}^{(\mathrm{b})} + T_{\mu\nu}^{(\mathrm{c})}$

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{1}{M_{\mathrm{Pl}}^2}\left(T_{\mu\nu}^{(\mathrm{m})} + T_{\mu\nu}^{(\phi)}\right)$$ (Einstein equation)

$$\nabla^\mu T_{\mu\nu}^{(\mathrm{b})} = 0$$ (Conservation equation for baryon)

$$\nabla^\mu T_{\mu\nu}^{(\mathrm{c})} = -Q\,\partial_\nu\phi$$ (Conservation equation for DM & DE)

$$\Box\phi - V_\phi = Q$$ (scalar field equation)

- Q roughly represents **the magnitude of the coupling between DM & DE**

$$Q \equiv -\frac{1}{\sqrt{-g}}\frac{\delta(\sqrt{-\bar{g}}\mathcal{L}_{\mathrm{c}})}{\delta\phi} = \nabla_\mu W^\mu - Z$$

$$Z = \frac{1}{2A}\left[\left\{A_\phi + \frac{A_X X(A_\phi - 2B_\phi X)}{A - A_X X + 2B_X X^2}\right\}T_{(\mathrm{c})} + \left\{B_\phi + \frac{B_X X(A_\phi - 2B_\phi X)}{A - A_X X + 2B_X X^2}\right\}T_{(\mathrm{c})}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right]$$

$$W^\mu = \frac{1}{2A}\left[2B\,T_{(\mathrm{c})}^{\mu\nu}\partial_\nu\phi - \frac{A - 2BX}{A - A_X X + 2B_X X^2} \times \left(A_X T_{(\mathrm{c})} + B_X T_{(\mathrm{c})}^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi\right)\partial^\mu\phi\right],$$

MODIFIED KAISER FORMULA

(sub-horizon + quasi-static approximation)

- Einstein equations and baryon's equations are the same
- Continuity & Euler equations for CDM are modified !!

$$\dot{\delta}_{\rm c} + \frac{k^2}{a^2} v_{\rm c} = R_0 \left(\dot{\delta}_{\rm c} - \frac{Q_0}{\dot{\phi}} \delta_{\rm c} \right)$$

$v_{\rm c}$ depends on time-derivative of density contrast and **density contrast**

$$\dot{v}_c - \Phi = \Gamma_1 \, v_c + \Gamma_2 \, \dot{\delta}_c + \Gamma_3 \, \delta_c$$

R_0, Q_0, Γ_i : depends on DM-DE coupling parameters

- Evolution of density contrast of CDM

$$\ddot{\delta}_{\rm c} + 2 H_{\rm eff} \, \dot{\delta}_{\rm c} - 4\pi G_{\rm eff} \, \rho_{\rm m} \delta_{\rm m} = 0$$

Growth rate also deviates from the standard cosmology

- Total matter = baryon + CDM $\left(T^{(\rm m)}_{\mu\nu} := T^{(\rm b)}_{\mu\nu} + T^{(\rm c)}_{\mu\nu} \right)$

$$\delta_{\rm m} = \omega_{\rm c} \delta_{\rm c} + \omega_{\rm b} \delta_{\rm b} \qquad v_{\rm m} = \omega_{\rm c} v_{\rm c} + \omega_{\rm b} v_{\rm b} \qquad \omega_{\rm I} = \rho_{\rm I} / \rho_{\rm m}$$

- Velocity of the total matter is modified due to modification of CDM equation

$$v_{\rm m}(t, \mathbf{k}) = -\frac{a^2 H}{k^2} f_{\rm m}^{\rm eff}(t) \delta_{\rm m}(t, \mathbf{k})$$

$$f_{\rm m}^{\rm eff} = f_{\rm m} + \Delta f_{\rm m}$$

Actual linear growth rate

DM-DE coupling effect

$$f_{\rm m}(t) \equiv \frac{{\rm d} \ln D_{\rm m}}{{\rm d} \ln a}$$

$$\Delta f_{\rm m} = -\omega_{\rm c} \frac{D_{\rm c}}{D_{\rm m}} \frac{\Upsilon_2}{1 - \Upsilon_1} \left(f_{\rm c} - \frac{Q_0}{H \dot{\phi}} \right) - \omega_{\rm b} \frac{Q_0 \dot{\phi}}{H \rho_{\rm m}} \frac{D_{\rm c} - D_{\rm b}}{D_{\rm m}}$$

Modified Kaiser formula

$$P_{{\rm g},s}(\mathbf{k}; t) = b_{\rm g}^2 \left(1 + \beta_{\rm eff}(t) \, \mu^2 \right)^2 P_{\rm m}(k; t) \qquad \beta_{\rm eff} \equiv \frac{f_{\rm m}^{\rm eff}}{b_{\rm g}}$$

Modified Kaiser formula

$$P_{g,s}(\mathbf{k};t) = b_g^2 \left(1 + \beta_{\rm eff}(t)\, \mu^2\right)^2 P_m(k;t)$$

$$f_m^{\rm eff} = f_m + \Delta f_m \qquad \beta_{\rm eff} \equiv \frac{f_m^{\rm eff}}{b_g}$$

Minimally coupled CDM (standard scenario)

$$D_m = D_c = D_b$$
$$f_m^{\rm eff} = f_m$$

→ **Kaiser formula**

Non-minimally coupled CDM

- RSD measures **the effective growth rate** $f_m^{\rm eff}$
- Measured $f_m^{\rm eff}$ is not **the actual growth rate** f_m and it contains information of **DM-DE coupling**
- **Single-redshift RSD observations** can not determine the actual growth rate and DM-DE coupling
- **Multiple-redshift RSD observations** can separate the actual growth rate and DM-DE coupling

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SUMMARY

Growth rate obtained from RSD

= actual growth rate + **DM-DE coupling effect**

- DM-DE interaction **modifies continuity and Euler equations** in a cosmological setup.
- Even in DM-DE **direct coupling** (not though conformal or disformal metric) we reach the same conclusion
- **Multiple-redshift RSD measurements** provide us information of both **the actual growth rate** and **DM-DE coupling**

MODIFICATION OF GRAVITY

- Gravitational equations are modified as

$$\frac{k^2}{a^2}\Psi = -4\pi G \rho_{\rm m}\delta_{\rm m} + \text{▨} \qquad\qquad \Psi - \Phi = \text{▨}$$

extra contribution due to modification of gravity **anisotropic stress**

- Continuity and Euler equations remain the same

$$\boxed{\dot{\delta}_{\rm m} + \frac{k^2}{a^2}v_{\rm m} = 0} \qquad \dot{v}_{\rm m} - \Phi = 0$$

- Evolution of matter density contrast follows

$$\boxed{\ddot{\delta}_{\rm m} + 2H\dot{\delta}_{\rm m} - 4\pi G_{\rm eff}\rho_{\rm m}\delta_{\rm m} = 0}$$

The growth rate is different from the standard cosmology,
but the growth rate can directly obtained by RSDs

(because Kaiser formula remain the same)

2b6. Shun Arai (Nagoya U.),

“Constraints on Horndeski theory with Gravitational Waves observations” (10+5)

[JGRG27 (2017) 112813]

JGRG27 @ Saijo, Hiroshima
12:15 - 12:30, 28th. Nov, 2017

presentation No.
2b6

Constraints on Horndeski theory with Gravitational Waves observations

Shun Arai (Cosmology group in Nagoya University)

SA and Atsushi Nishizawa. arXiv:1711.03776

Outline in this talk

- Gravitational Waves (GW) observations for testing gravity : cosmological effects on GW during propagation
- Model classification of Horndeski theory in a numerical way; set-up and its procedure
- Constraints on Horndeski theory from GW170817&GRB170817A
- Summary

Modification of GW propagation

I. D. Saltas et. al PRL 2014
A.Nishizawa arXiv:1710.04825

$$h''_{ij} + (2+\nu)\mathcal{H}h'_{ij} + ({c_T}^2k^2 + a^2\mu^2)h_{ij} = a^2\Gamma\gamma_{ij}$$

ν	time variation of the effective Planck mass	time dependent gravitational coupling
c_T	propagation speed of GW	Lorentz symmetry/Equivalence principle
μ	graviton mass	massive gravity (Shinji-Mukohyama's talk)
Γ	additional sources of GW	Non-minimal coupling with other fields

---

Solution of modified GW propagation at cosmological scale

A.Nishizawa arXiv:1710.04825

Source-less system $\longrightarrow$ $\Gamma = 0$

solutions that alters in cosmological time scale:

$$h = \mathcal{C}_{\mathrm{MG}} h_{\mathrm{GR}} \quad \mathcal{C}_{\mathrm{MG}} \equiv e^{-\mathcal{D}} e^{-ik\Delta T}$$

amplitude $$\mathcal{D} \equiv \frac{1}{2}\int^{\tau} d\tau' \nu\mathcal{H}$$ luminosity distance

phase $$\Delta T \equiv \int^{\tau} d\tau' \left\{ (1-c_T) - \frac{a^2\mu^2}{2k^2} \right\}$$ arrival time difference

e.g. GW associating with
EM wave emission

τ : conformal time

Horndeski theory

G. Horndeski, 1974
T. Kobayashi, M. Yamaguchi, and J. Yokoyama 2011

$$S_{\mathrm{Horn}} = \int d^4x\sqrt{-g}\sum_{i=2}^{5}\mathcal{L}_i$$

$$\mathcal{L}_2 = G_2(\phi, X),$$
$$\mathcal{L}_3 = -G_3(\phi,\, X)\Box\phi\,,$$
$$\mathcal{L}_4 = G_4(\phi,\, X)R + G_{4X}(\phi,\, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]\,,$$
$$\mathcal{L}_5 = G_5(\phi,\, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi,\, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$

$$X \equiv -\phi^{;\mu}\phi_{;\mu}/2$$

- The most generic theory containing only up to 2nd order spacetime derivatives.
- Phenomenologically it can explains cosmic accelerating expansion.

α-parameterization

E.Bellini and I.Sawicky JCAP 2014
D.Langlois et. al. 2017

$$S^{(2)} = \int dtd^3xa^3\frac{M^2}{2}\Big[\delta K_{ij}\delta K^{ij} - \delta K^2 + (1+\alpha_T)\left(R\frac{\delta\sqrt{h}}{a^3} + \delta_2 R\right) + \alpha_K H^2\delta N^2 + 4\alpha_B H\delta K\delta N + (1+\alpha_{\cancel{H}})R\delta N\Big]\,,$$

R :3d Ricci scalar

N.B. Taking the unitary gauge

α_M	$\alpha_M \equiv \frac{1}{HM^2}\frac{dM^2}{dt}$
α_K	Kinetic term of a scalar
α_B	“Braiding” between scalar and tensor
α_T	phase velocity of tensor

ν & c_T in Horndeski theory

E.Bellini & I.Sawicky JCAP 2014

$$M_*^2(t) \equiv 2(G_4 - 2XG_{4X} + XG_{5\phi} - \dot{\phi} H X G_{5X})$$

$$dt = a d\tau$$
$$\dot{A} \equiv \frac{dA}{dt}$$
$$H = \mathcal{H}/a$$

$$\nu \equiv \frac{d\ln M_*^2}{d\ln a} = \alpha_M(t)$$

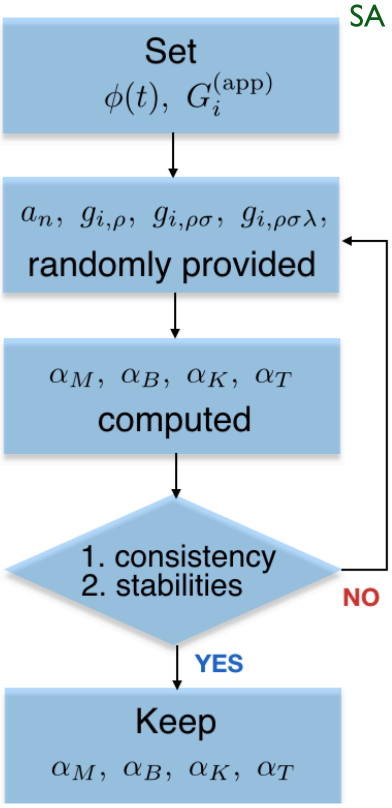
$$c_T{}^2 - 1 \equiv \alpha_T(t) = \frac{2X}{M_*^2}\left(2G_{4X} - 2G_{5\phi} - (\ddot{\phi} - \dot{\phi} H)G_{5X}\right)$$

- GW properties are only involved with G_4 and G_5
- Degeneracies of these parameters should be considered
- Searching the whole parameter space independent with specific models

➡ Numerical simulation

Procedure of the model classification

SA and A.Nishizawa. arXiv:1711.03776



Set
$\phi(t),\ G_i^{(\mathrm{app})}$

$a_n,\ g_{i,\rho},\ g_{i,\rho\sigma},\ g_{i,\rho\sigma\lambda},$
randomly provided

$\alpha_M,\ \alpha_B,\ \alpha_K,\ \alpha_T$
computed

1. consistency
2. stabilities

NO

YES

Keep
$\alpha_M,\ \alpha_B,\ \alpha_K,\ \alpha_T$

Numerical parameterization

SA and A.Nishizawa. arXiv:1711.03776

- time-dependence of $\phi(t)$ at low redshifts

$$\phi(t) = \sqrt{M_{\rm pl} H_0} \left\{ a_0 + a_1 H_0 t_{LB} + \frac{a_2}{2} (H_0 t_{LB})^2 \right\}$$

$$a_0 \equiv 0$$

$$t_{LB} \equiv \int_0^z \frac{dz'}{H_{\Lambda{\rm CDM}}(z') \cdot (1+z')}$$

$$H_{\Lambda{\rm CDM}}(z) = H_0 \left\{ \Omega_{m0}(1+z)^3 + 1 - \Omega_{m0} \right\}^{1/2}$$

Planck 2015 best-fit : $H_0 = 67.8 \ {\rm km \cdot s^{-1} Mpc^{-1}}$ $\Omega_{m0} = 0.3080$

P.Ade. Planck2015

- approximation of the Horndeski G functions

$$G_i^{(\rm app)} \supset \phi, X, \phi X, \phi^2, X^2 (i = 2, 3, 4, 5)$$

$$g_{i\rho}, g_{i\rho\sigma} (\rho, \sigma = \phi \text{ or X})$$

- Jordan-frame with minimally-coupled dust

Criteria for model classification

SA and A.Nishizawa. arXiv:1711.03776

1. Consistency

$$|1 - H/H_{\Lambda CDM}| < \Delta H_{\rm obs}/H_{\rm obs}$$

$$\frac{\Delta H_{\rm obs}}{H_{\rm obs}} \equiv 20\%$$

N.B. Currently without any experimental prior (e.g. Planck 2015) but still reasonable

c.f. Simon et al. (2005) Moresco et al. (2012) Zhang et al. (2012)

2. Stability

Avoiding ghost and gradient instabilities. i.e. $Q_\sigma > 0, c_\sigma^2 > 0$

for a quadratic action as

$$S^{(2)} = \int dt d^3x \sum_{\sigma = \rm scalar, tensor} \left\{ Q_\sigma \dot{\sigma}^2 - c_\sigma^2 (\partial \sigma)^2 \right\}$$

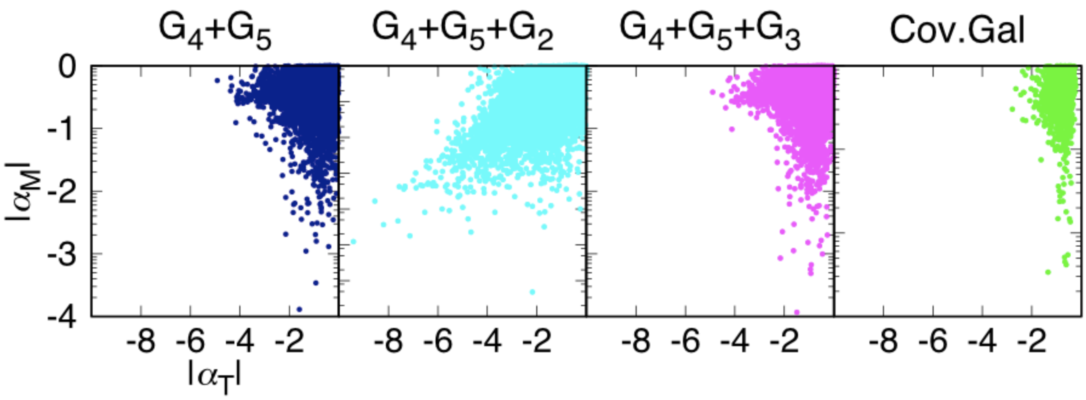
Simulation size : 1,000,000 distanctive models are provided

Model classification of Horndeski theory in a numerical way; simulation set-up and its procedure

Model classification

SA and A.Nishizawa. arXiv:1711.03776

Subclass of Horndeski theory	Parameters of $G_i^{(\mathrm{app})}$	Models
(I) G_4+G_5	$G_2, G_3=0$	self acceleration
(II) $G_4+G_5+G_2$	$g_2, g_{2X}, g_{2\phi\phi}\neq 0$	quintessence/nonlinear kinetic theory $f(R)$ thories
(III) $G_4+G_5+G_3$	$G_3\neq 0$	cubic galileons
(IV) Cov.Gal	$g_{2X}, g_{3X}, g_{4XX}, g_{5XX}\neq 0$	covariant Galileons



Larger α_M and α_T are favored L.Lombriser and A.Taylor JCAP 03 031 2016

Constraints on Horndeski theory from GW170817&GRB170817A

Observables in GW propagation at low redshifts

SA and A.Nishizawa. arXiv:1711.03776

$$\mathcal{D}\equiv\frac{1}{2}\int^{\tau}d\tau'\nu\mathcal{H}\qquad \Delta T\equiv\int^{\tau}d\tau'\underbrace{(1-c_T)}_{\delta_g}$$

$$\nu\simeq\nu_0-\nu_1 H_0 t_{LB}\qquad \delta_g\simeq\delta_{g0}-\delta_{g1}H_0 t_{LB}$$

$$\nu_0=\alpha_{M,0}\quad \nu_1=\frac{\dot{\alpha}_{M,0}}{H_0}\quad \delta_{g0}=-\frac{\alpha_{T,0}}{2}\quad \delta_{g1}=-\frac{\dot{\alpha}_{T,0}}{2H_0}$$

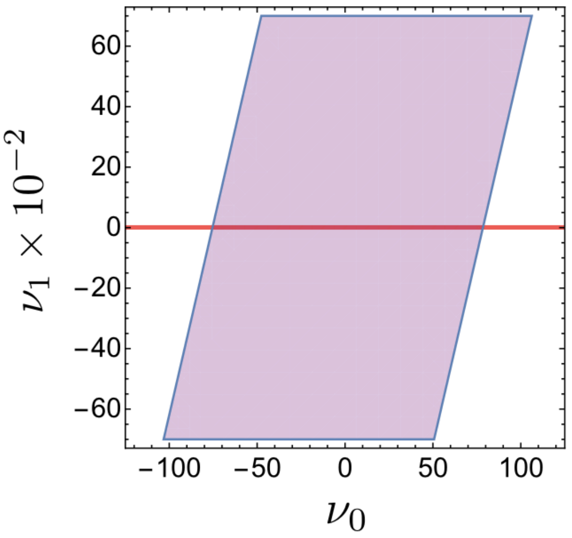
$$\mathcal{D}\simeq\frac{1}{2}\left\{\nu_0\ln(1+z)-\frac{\nu_1}{2}(H_0 t_{LB})^2\right\}$$

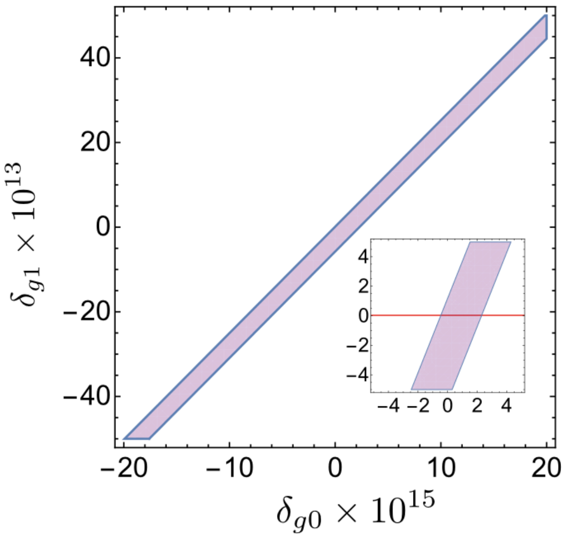
$$\Delta T\simeq\frac{1}{H_0}\left\{\delta_{g0}H_0 t_{LB}-\frac{\delta_{g1}}{2}(H_0 t_{LB})^2\right\}$$

Constraints on Horndeski theory from GW170817&GRB170817A

Observational bounds from GW170817&GRB170817A

SA and A.Nishizawa. arXiv:1711.03776





$-75.3 \leq \nu_0 \leq 78.4$ $\qquad$ $-4.7 \times 10^{-16} \leq \delta_{g0} \leq 2.2 \times 10^{-15}$

- Application for another GW detection is easy on these panel

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Summary

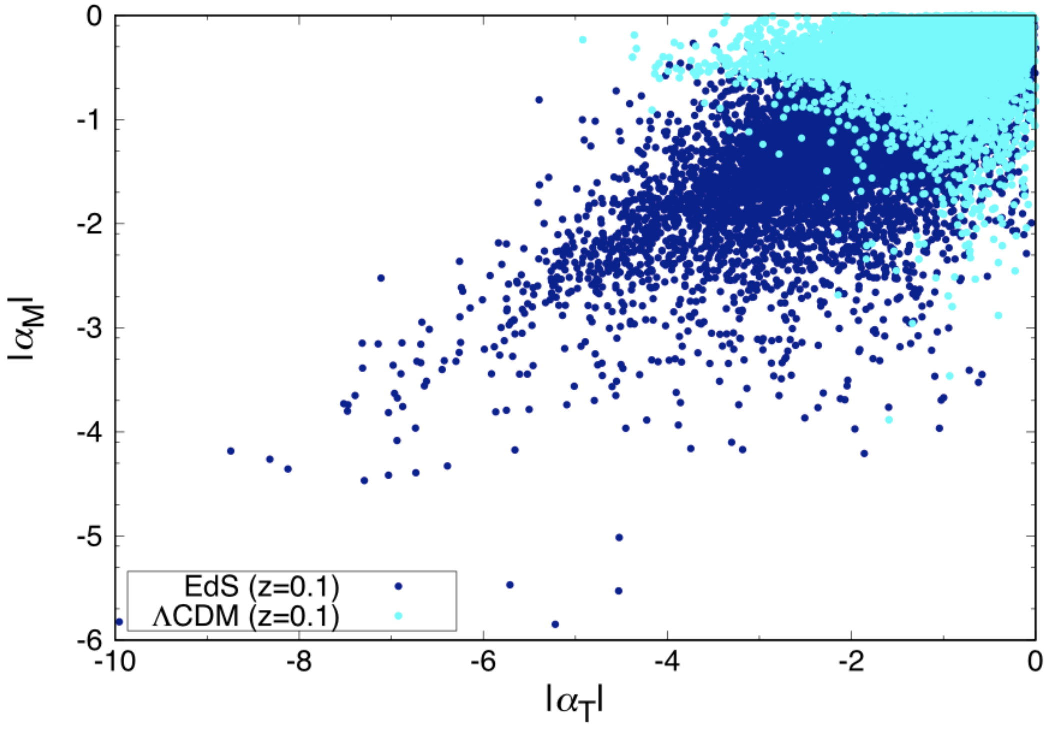
Summary of my talk

- We can test gravity with GW propagation since waveform of a GW is significantly deviate from that of GR at cosmological scale.
- We initiated a concrete study how α-parameters correlate each other in a model-independent point of view ; Monte Carlo simulation.
  c.f. E. Linder JCAP 1605 053 2016
- Applying our method for model classification in the Horndeski theory, we obtain the distributions of the models in α_T-α_M plane.
- Considering the current observation of GW170817 and GRB170817A, the models with G4 and G5 functions hardly account for cosmic accelerating universe and GW observation at the same time. c.f. J.M.Ezquiaga and M.Zumalacarregui 2017
- Multiple GW observations are necessary to make the current constraints much stronger enough to verify GR at cosmological scale.

Back Up

Different expansion histories

SA and A.Nishizawa. arXiv:1711.03776



Observational constraints on cosmic expansion histories

O.Farooq et al. Astrophys. J. 835 (2017)

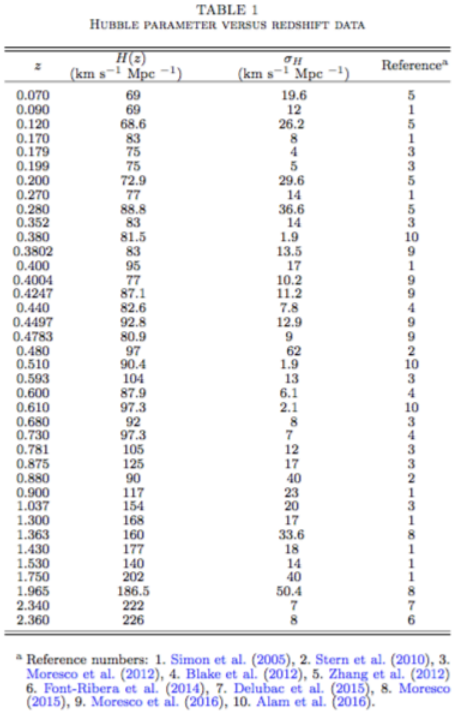
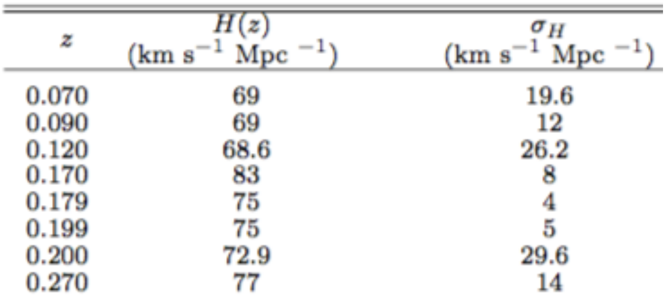


TABLE 1
HUBBLE PARAMETER VERSUS REDSHIFT DATA

z	$H(z)$ (km s^{-1} Mpc $^{-1}$)	σ_H (km s^{-1} Mpc $^{-1}$)	Reference[a]
0.070	69	19.6	5
0.090	69	12	1
0.120	68.6	26.2	5
0.170	83	8	1
0.179	75	4	3
0.199	75	5	3
0.200	72.9	29.6	5
0.270	77	14	1
0.280	88.8	36.6	5
0.352	83	14	3
0.380	81.5	1.9	10
0.3802	83	13.5	9
0.400	95	17	1
0.4004	77	10.2	9
0.4247	87.1	11.2	9
0.440	82.6	7.8	4
0.4497	92.8	12.9	9
0.4783	80.9	9	9
0.480	97	62	2
0.510	90.4	1.9	10
0.593	104	13	3
0.600	87.9	6.1	4
0.610	97.3	2.1	10
0.680	92	8	3
0.730	97.3	7	4
0.781	105	12	3
0.875	125	17	3
0.880	90	40	2
0.900	117	23	1
1.037	154	20	3
1.300	168	17	1
1.363	160	33.6	8
1.430	177	18	1
1.530	140	14	1
1.750	202	40	1
1.965	186.5	50.4	8
2.340	222	7	7
2.360	226	8	6

[a] Reference numbers: 1. Simon et al. (2005), 2. Stern et al. (2010), 3. Moresco et al. (2012), 4. Blake et al. (2012), 5. Zhang et al. (2012) 6. Font-Ribera et al. (2014), 7. Delubac et al. (2015), 8. Moresco (2015), 9. Moresco et al. (2016), 10. Alam et al. (2016).



z	$H(z)$ (km s^{-1} Mpc $^{-1}$)	σ_H (km s^{-1} Mpc $^{-1}$)
0.070	69	19.6
0.090	69	12
0.120	68.6	26.2
0.170	83	8
0.179	75	4
0.199	75	5
0.200	72.9	29.6
0.270	77	14

Simon et al. (2005)
Moresco et al. (2012)
Zhang et al. (2012)

$$\frac{\Delta H_{\rm obs}}{H_{\rm obs}} \simeq 17\%$$

$$@z \sim 0.1$$

GW observations : current situations

- Observables : amplitude/phase
  - standard siren D. E.Holz and S.A.Hughes, PRL 2005
  - arrival time difference C.Will Living Rev. 2006
- Event rate of GW O(100 - 1000) yr^{-1}
  possibly reaching to 1000 yr^{-1} with HLVK network

  HLVK : Hanford/Livingston/VIRGO/KAGRA
- Direct measurement of gravity sector

GW is a powerful way to explore MG

Self Acceleration

$$S_{\rm Horn} = \int d^4x\sqrt{-g}\,\underbrace{\frac{M_*^2(t)c_T^2(t)}{2}}_{\Omega(t)}R + \ldots$$

$$\nu \equiv \frac{1}{M_*^2 H}\frac{dM_*^2}{dt}$$

in the language of the EFT

G.Gubitosi et al. 2013 J.Gleyzes et al. 2013

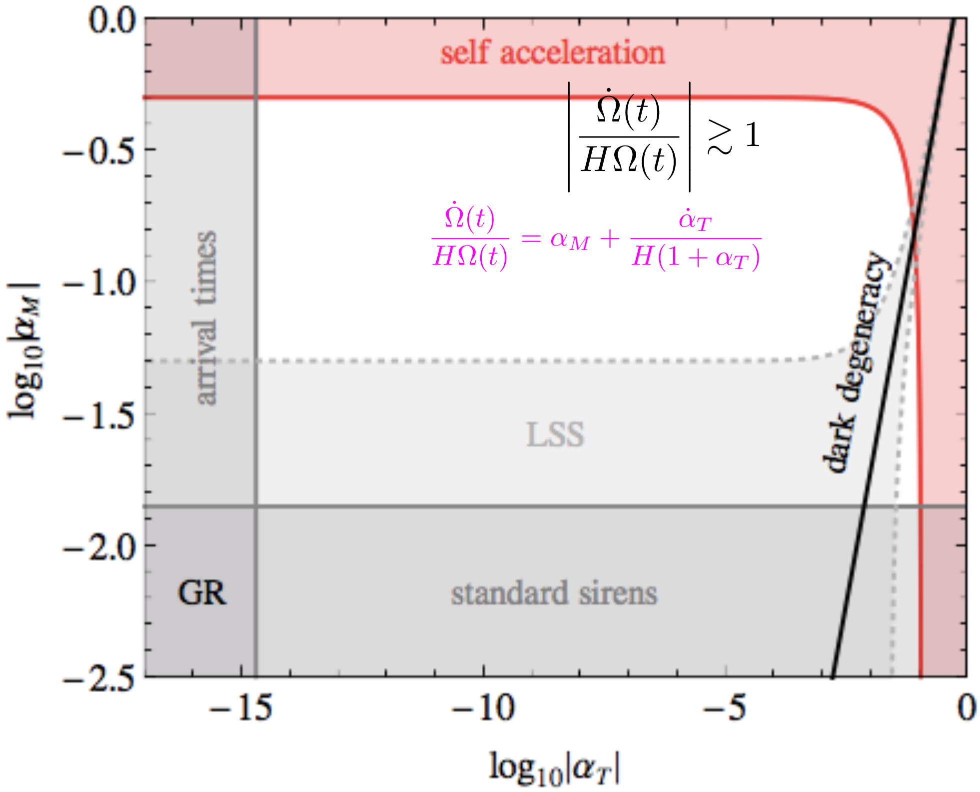
N.B 1.We here use the notation as same as EFT of DE.

N.B 2.This way of acceleration is ONLY seen in the Jordan frame.

$$\left|\frac{\dot{\Omega}(t)}{H\Omega(t)}\right| \gtrsim 1$$

L.Lombriser & A.Taylor JCAP 2016

L.Lombriser and A.Taylor JCAP 03 031 2016



Session3a 14:00–15:45

[Chair: Hideki Asada]

3a1. Tomohiro Harada (Rikkyo U.),

“Spins of primordial black holes formed in the matter-dominated era” (10+5)

[JGRG27 (2017) 112814]

Spins of primordial black holes formed in the matter-dominated era

Tomohiro Harada (Rikkyo U)

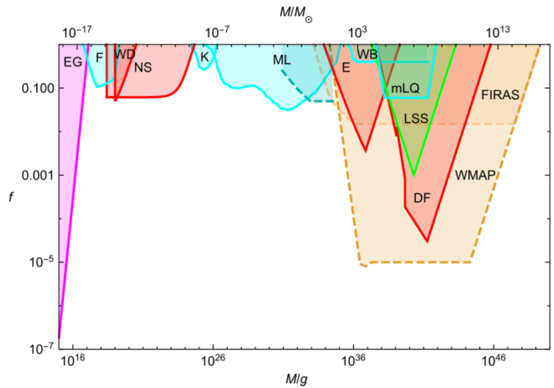
28/11/2017, JGRG27 @ Higashihiroshima

This talk is based on

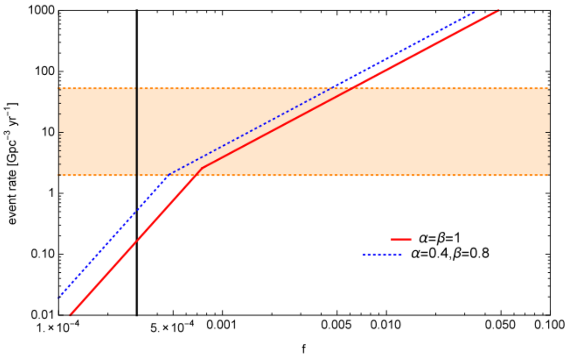
- Harada, Yoo (Nagoya U), Kohri (KEK), Nakao (OCU) & Jhingan (YGU), 1609.01588
- Harada, Yoo, Kohri, & Nakao, 1707.03595

Primordial black hole (PBH)

- PBH = Black hole formed in the early Universe
  - Probe into the early Universe, high-energy physics, and quantum gravity through Hawking radiation, dark matter, and gravitational waves (Carr et al. (2010), Carr et al. (2016))
  - LIGO BBH events may be sourced by PBHs. (Sasaki et al. (2016), Bird et al. (2016), Clesse & Garcia-Bellido (2017))
  - The observation of spins of BHs attracts great attention. (Abbott et al. (2017), Pani & Loeb (2013), McClintock (2011))



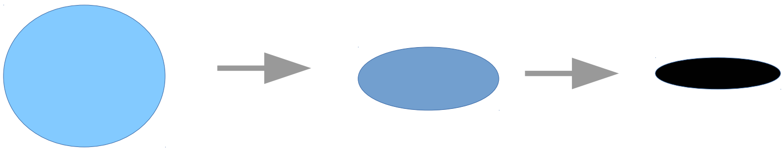
(a) Carr et al. (2016)



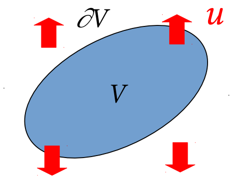
(b) Sasaki et al. (2016)

PBH formation in the matter-dominated (MD) era

- Pioneered by Khlopov & Polnarev (1980). Recently motivated by early MD phase scenarios such as inflaton oscillations, phase transitions, and superheavy metastable particles.
- If pressure is negligible, nonspherical effects play crucial roles.
  - The triaxial collapse of dust leads to a “pancake” singularity. (Lin, Mestel & Shu 1965, Zeldovich 1969)



  - The effect of angular momentum may halt gravitational collapse or spin the formed PBHs.



  - We here rely on the Newtonian approximation to deal with nonspherical dynamics analytically.

Zeldovich approximation

- Zeldovich approximation (ZA) (1969)
  Extrapolate the Lagrangian perturbation theory in the linear order in Newtonian gravity to the nonlinear regime.

$$r_i = a(t)q_i + b(t)p_i(q_j),$$

where $b(t) \propto a^2(t)$ denotes a linear growing mode.

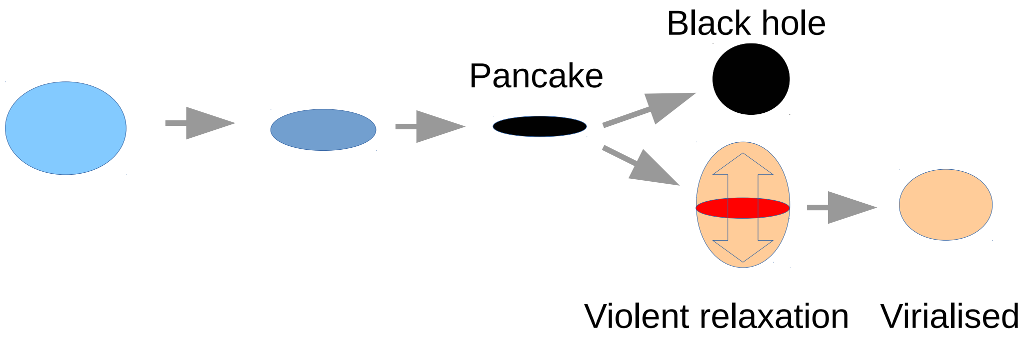
- We can take the coordinates in which

$$\frac{\partial p_i}{\partial q_j} = \mathrm{diag}(-\alpha, -\beta, -\gamma),$$

where we can assume $\infty > \alpha \geq \beta \geq \gamma > -\infty$.

- We assume that α, β and γ are constant over the smoothing scale.
- We normalise b so that $(b/a)(t_i) = 1$ at horizon entry $t = t_i$.

Application of the hoop conjecture to the pancake collapse



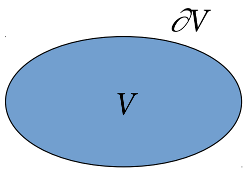
- Hoop conjecture (Thorne 1972): The collapse results in a BH if and only if $C \lesssim 4\pi GM/c^2$, where C is the circumference of the pancake singularity.
- Then, we obtain a BH criterion:

$$h(\alpha,\beta,\gamma) := \frac{C}{4\pi Gm/c^2} = \frac{2}{\pi}\frac{\alpha-\gamma}{\alpha^2}E\left(\sqrt{1-\left(\frac{\alpha-\beta}{\alpha-\gamma}\right)^2}\right) \lesssim 1,$$

  where $E(e)$ is the complete elliptic integral of the second kind.
- If $h \gtrsim 1$? : It does not immediately collapse to a BH.

Spin angular momentum within the region to collapse

- Region V: to collapse in the future



- Angular momentum within V with respect to the COM in the Eulerian coordinates

$$\mathbf{L} = \rho_0 a^4\left(\int_V \mathbf{x}\times\mathbf{u}d^3\mathbf{x} + \int_V \mathbf{x}\delta\times\mathbf{u}d^3\mathbf{x} - \frac{1}{V}\int_V \mathbf{x}\delta d^3\mathbf{x}\times\int_V \mathbf{u}d^3\mathbf{x}\right),$$

  where $\mathbf{x} := \mathbf{r}/a$, $\mathbf{u} := aD\mathbf{x}/Dt$, $\delta := (\rho-\rho_0)/\rho_0$, and $\psi := \Psi - \Psi_0$.
- Linearly growing mode of perturbation

$$\delta_1 = \sum_{\mathbf{k}}\hat{\delta}_{1,\mathbf{k}}(t)e^{i\mathbf{k}\cdot\mathbf{x}},\ \psi_1 = \sum_{\mathbf{k}}\hat{\psi}_{1,\mathbf{k}}(t)e^{i\mathbf{k}\cdot\mathbf{x}},\ \mathbf{u}_1 = \sum_{\mathbf{k}}\hat{\mathbf{u}}_{1,\mathbf{k}}(t)e^{i\mathbf{k}\cdot\mathbf{x}},$$

where

$$\hat{\delta}_{1,\mathbf{k}} = A_{\mathbf{k}}t^{2/3},\ \hat{\psi}_{1,\mathbf{k}} = -\frac{2}{3}\frac{a_0^2}{k^2}A_{\mathbf{k}},\ \hat{\mathbf{u}}_{1,\mathbf{k}} = ia_0\frac{\mathbf{k}}{k^2}\frac{2}{3}A_{\mathbf{k}}t^{1/3}.$$

1st-order effect

$$\mathbf{L} = \rho_0 a^4 \left(\int_V \mathbf{x} \times \mathbf{u} d^3\mathbf{x} + \int_V \mathbf{x}\delta \times \mathbf{u} d^3\mathbf{x} - \frac{1}{V}\int_V \mathbf{x}\delta d^3\mathbf{x} \times \int_V \mathbf{u} d^3\mathbf{x} \right)$$

- If ∂V is not a sphere, the 1st term contribution grows as $\propto a \cdot \mathbf{u} \propto t$.
- If we assume V is a triaxial ellipsoid with axes (A_1, A_2, A_3), we find

$$\langle \mathbf{L}_{(1)}^2 \rangle^{1/2} \simeq \frac{2}{5\sqrt{15}} q \frac{MR^2}{t} \langle \delta^2 \rangle^{1/2},$$

where $r_0 := (A_1 A_2 A_3)^{1/3}$, $R := a(t) r_0$ and $q := \sqrt{\frac{Q_{ij}Q_{ij}}{3\left(\frac{1}{5}Mr_0^2\right)^2}}$ is a nondimensional reduced quadrupole moment of V. (Cf. Catelan & Theuns 1996)

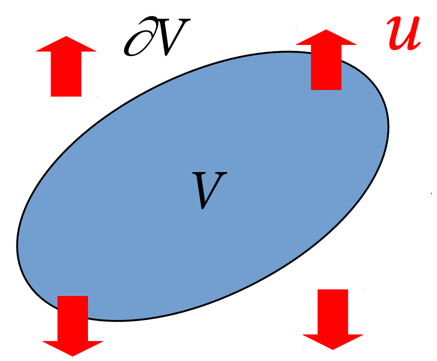


Figure: The 1st-order effect can grow if ∂V is not a sphere.

2nd-order effect

$$\mathbf{L} = \rho_0 a^4 \left(\int_V \mathbf{x} \times \mathbf{u} d^3\mathbf{x} + \int_V \mathbf{x}\delta \times \mathbf{u} d^3\mathbf{x} - \frac{1}{V}\int_V \mathbf{x}\delta d^3\mathbf{x} \times \int_V \mathbf{u} d^3\mathbf{x} \right)$$

- Even if ∂V is a sphere, the remaining contribution grows as 1st order × 1st order $\propto a \cdot \delta \cdot \mathbf{u} \propto t^{5/3}$.

$$\langle \mathbf{L}_{(2)}^2 \rangle^{1/2} = \frac{2}{15} \mathcal{I} \frac{MR^2}{t} \langle \delta^2 \rangle,$$

where δ hereafter is the density perturbation averaged over V. $R := a(t) r_0$. We assume $\mathcal{I} = O(1)$. (Cf. Peebles 1969)

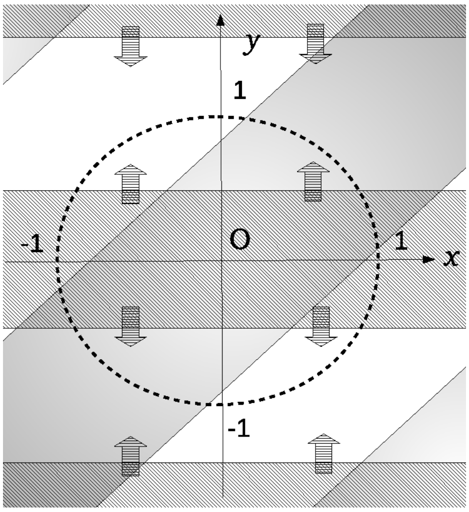


Figure: The 2nd-order effect can grow due to the mode coupling.

The application of the Kerr bound to the PBH formation

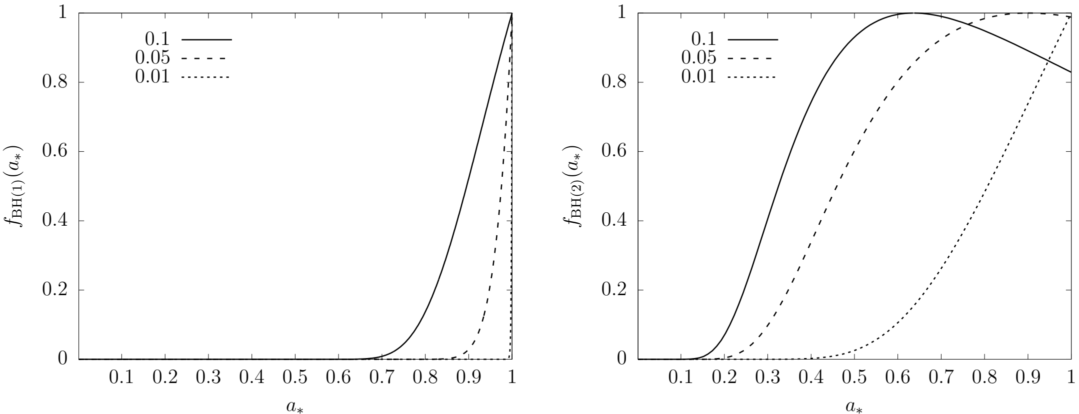
- Time evolution of V and angular momentum
  - Horizon entry ($t = t_H$): $ar_0 = cH^{-1}$, $\delta_H := \delta(t_H)$, $\sigma_H := \langle \delta_H^2 \rangle^{1/2}$
  - Maximum expansion ($t = t_m$): $\delta(t_m) = 1$, typically $t_m = t_H \sigma_H^{-3/2}$
  - $a_* := L/(GM^2/c)$ at $t = t_m$

$$\langle a_{*(1)}^2 \rangle^{1/2} = \frac{2}{5}\sqrt{\frac{3}{5}} q \sigma_H^{-1/2}, \langle a_{*(2)}^2 \rangle^{1/2} = \frac{2}{5}\mathcal{I}\sigma_H^{-1/2}, a_* \simeq \max\left(\langle a_{*(1)}^2 \rangle, \langle a_{*(2)}^2 \rangle\right)$$

  - For $t > t_m$, the evolution of V decouples from the cosmological expansion and hence a_* is kept almost constant.
- Consequences
  - Supercritical angular momentum: typically $\langle a_*^2 \rangle^{1/2} \gtrsim 1$ if $\sigma_H \lesssim 0.1$
  - Most of the PBHs have $a_* \simeq 1$. This contrasts with small spins ($a_* \lesssim 0.4$) of PBHs formed in the RD era. (Chiba & Yokoyama (2017))
  - Suppression: The Kerr bound implies that a_* is typically too large for direct collapse to a BH.

Spin distribution

- Spin distribution of PBHs formed in the MD era



(a) 1st-order effect (b) 2nd-order effect

Figure: The distribution function normalised by the peak value. We assume a Gaussian distribution for the density perturbation. Each curve is labelled with the value of σ_H.

- The region with smaller δ_H has larger a_*. This implies that there appears a threshold δ_{th} below which the angular momentum halts the collapse to a black hole due to the Kerr bound.

Numerical calculation of PBH production rate

- Triple integral for β_0 ($\theta(x)$ is a step function.)

$$\beta_0 \simeq \int_0^\infty d\alpha \int_{-\infty}^{\alpha} d\beta \int_{-\infty}^{\beta} d\gamma \theta[\delta_H(\alpha,\beta,\gamma) - \delta_{\rm th}]\theta[1 - h(\alpha,\beta,\gamma)] w(\alpha,\beta,\gamma),$$

where we use $w(\alpha,\beta,\gamma)$ given by Doroshkevich (1970).

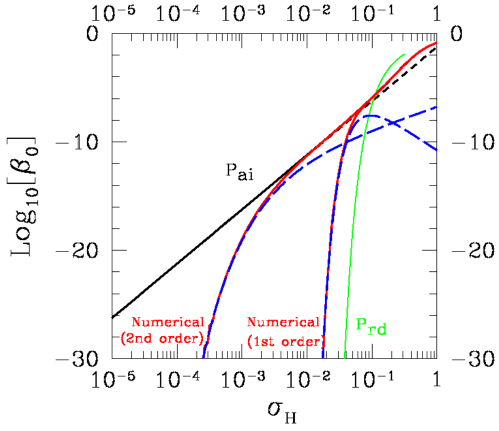


Figure: The red lines are due to both angular momentum and anisotropy. The 1st-order effect depends on q. The black solid line is solely due to anisotropy.

- We have also derived semianalytic formulae for β_0.

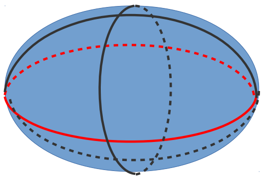
Summary

- PBHs may form in the RD era as well as in the (early) MD era by primordial cosmological fluctuations.
- In the MD era, the effect of anisotropy gives $\beta_0 \simeq 0.05556\sigma_H^5$, while the effect of angular momentum gives further suppression for the smaller values of σ_H.
- PBHs formed in the MD era mostly have large spins ($a_* \simeq 1$) in contrast to the small spins ($a_* \lesssim 0.4$) of PBHs formed in the RD era.

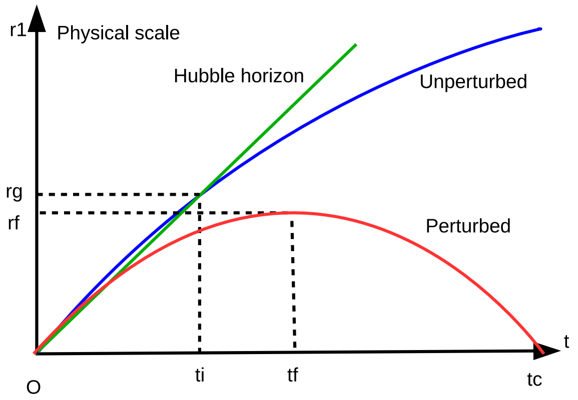
Anisotropic collapse in the ZA

- The triaxial ellipsoid of a Lagrangian ball (assumption)

$$\begin{cases} r_1 = (a - \alpha b)q \\ r_2 = (a - \beta b)q \\ r_3 = (a - \gamma b)q \end{cases}$$



- Evolution of the collapsing region:
  - Horizon entry ($t = t_i$): $a(t_i)q = cH^{-1}(t_i) = r_g := 2Gm/c^2$.
  - Maximum expansion ($t = t_f$): $\dot{r}_1(t_f) = 0$ giving $r_f := r_1(t_f) = r_g/(4\alpha)$.
  - Pancake singularity ($t = t_c$): $r_1(t_c) = 0$ giving $a(t_c)q = 4r_f = r_g/\alpha$.



Application of the Kerr bound to the rotating collapse

- Technical assumption

$$|\mathbf{L}_{(1)}| \simeq \frac{2}{5\sqrt{15}} q \frac{MR^2}{t}\delta, \quad |\mathbf{L}_{(2)}| \simeq \frac{2}{15}\mathcal{I}\frac{MR^2}{t}\langle\delta^2\rangle^{1/2}\delta.$$

- The above assumption implies

$$a_{*(1)} = \frac{2}{5}\sqrt{\frac{3}{5}} q \delta_H^{-1/2}, \quad a_{*(2)} = \frac{2}{5}\mathcal{I}\sigma_H\delta_H^{-3/2}, \quad a_* = \max(a_{*(1)}, a_{*(2)}).$$

- The Kerr bound $a_* \le 1$ gives a threshold $\delta_{\rm th}$ for δ_H, where

$$\delta_{\rm th} = \max(\delta_{\rm th(1)}, \delta_{\rm th(2)}), \quad \delta_{\rm th(1)} := \frac{3\cdot 2^2}{5^3}q^2, \quad \delta_{\rm th(2)} := \left(\frac{2}{5}\mathcal{I}\sigma_H\right)^{2/3}.$$

Discussion of PBH production

- Semianalytic estimate (black dashed line and blue dashed line)

$$\beta_0 \simeq \begin{cases} 2\times 10^{-6} f_q(q_c)\mathcal{I}^6\sigma_H^2 \exp\left[-0.15\frac{\mathcal{I}^{4/3}}{\sigma_H^{2/3}}\right] & \text{(2nd-order effect)} \\ 3\times 10^{-14}\frac{q^{18}}{\sigma_H^4}\exp\left[-0.0046\frac{q^4}{\sigma_H^2}\right] & \text{(1st-order effect)} \\ 0.05556\sigma_H^5 & \text{(anisotropic effect)} \end{cases},$$

  where $f_q(q_c)$: the ratio of regions with $q < q_c = O(\sigma_H^{1/3})$.
- σ_H in terms of P_ζ:

$$\sigma_H^2 \simeq \left(\frac{2}{5}\right)^2 P_\zeta(k_{BH}).$$

3a2. Menglei Zhou (Fudan U.),

“Iron K line of Kerr black holes with Proca hair” (10+5)

[JGRG27 (2017) 112815]

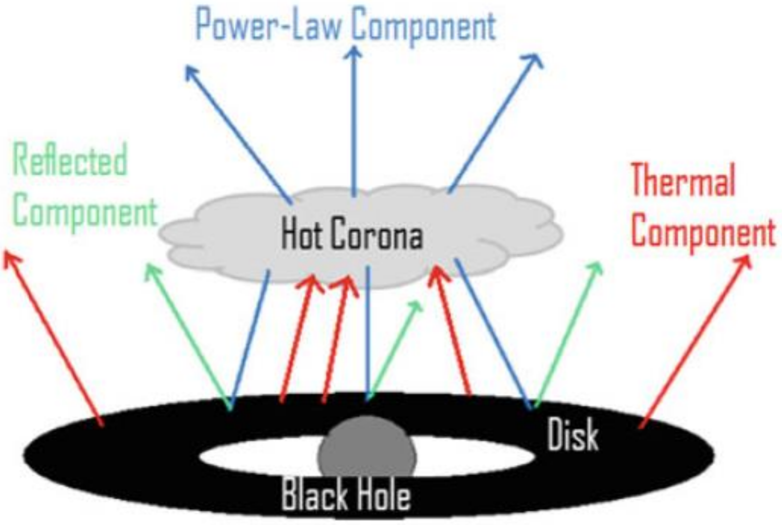
Iron Kα line of Kerr BHs with Proca hair

Presented by: Menglei Zhou
Co-workers: C. Bambi, C. Herdeiro & E. Radu

Fudan University
Shanghai, China

0.1. A brief introduction of **Iron Line Method**

★



0.2. A brief introduction of **Iron Line Method**

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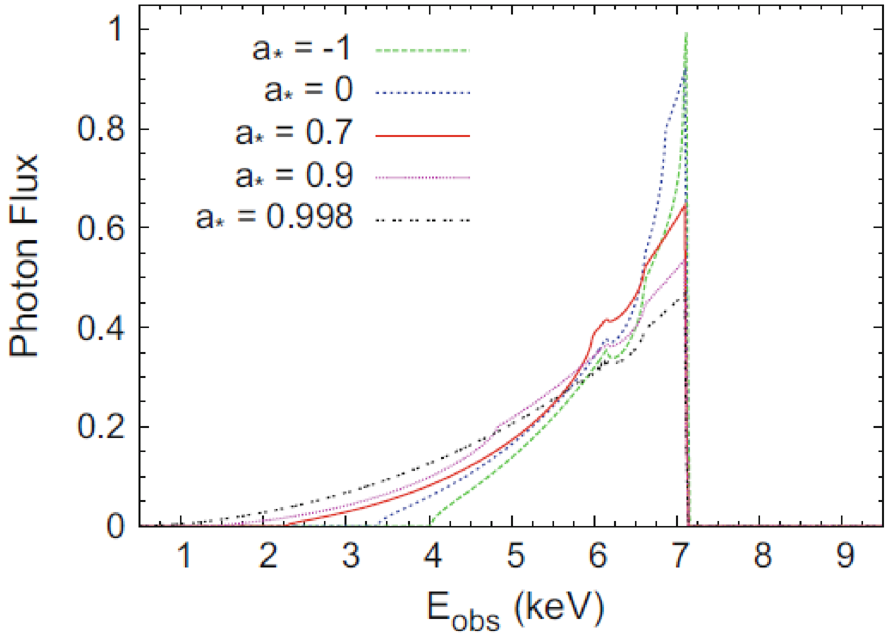


Outline

- Brief Introduction of Kerr BHs with Proca hair (KBHsPH)
- The computation of X-ray reflection spectrum
- Simulations with XIS/Suzaku and LAD/eXTP
- Conclusions

1. Introduction of Kerr BHs with Proca hair

- Kerr solution is a vacuum solution.

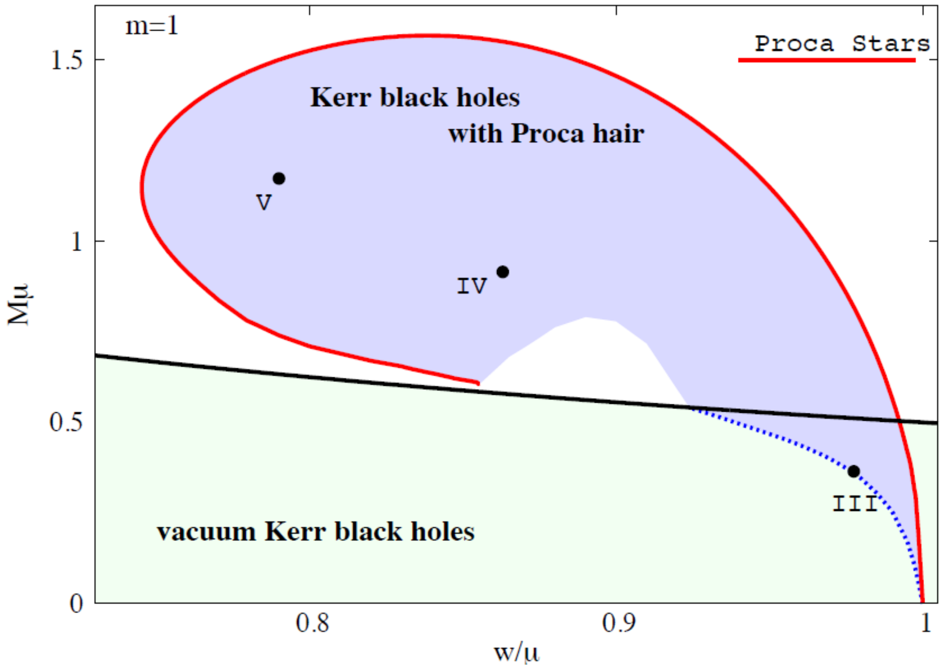
- We want a solution in the presence of matter.

- KBHsPH have a matter field synchronously rotating,

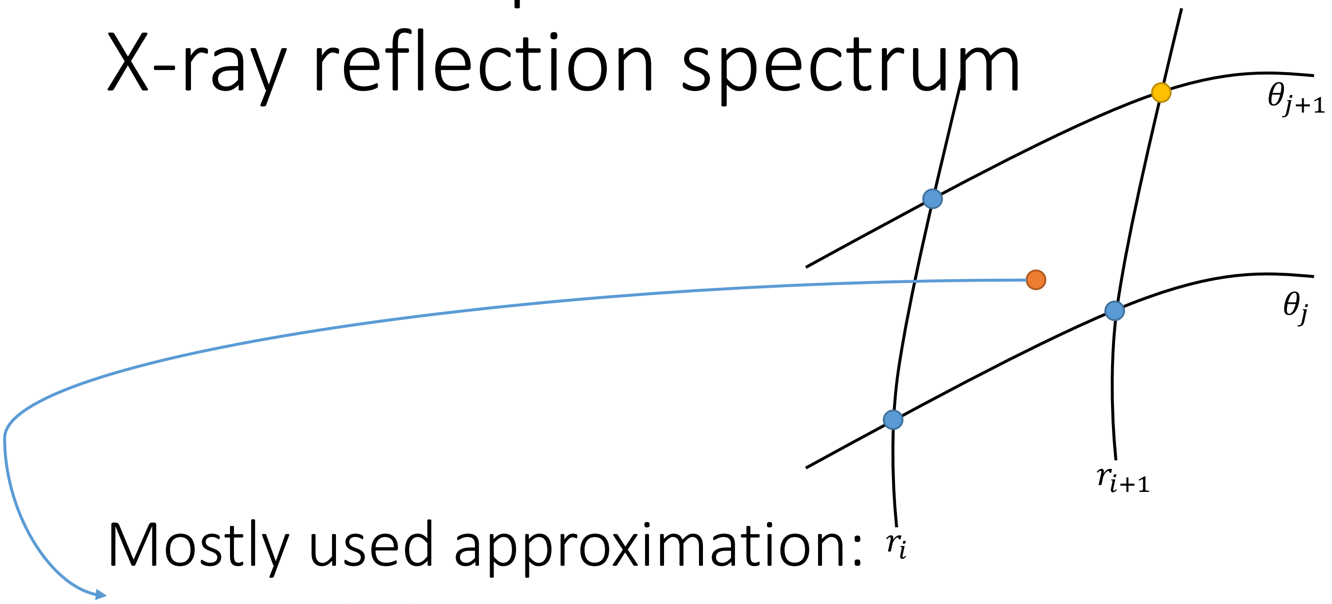
matching the angular velocity of the horizon. These series of solution will not violate the **energy condition** and provide us the stationary BHs' description.

---

1. Introduction of Kerr BHs with Proca hair



2. The computation of X-ray reflection spectrum

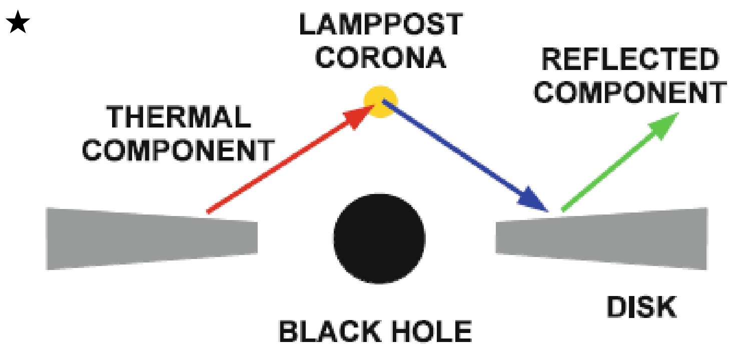


Mostly used approximation:

$$g_{\mu\nu}(r,\theta) \approx g_{\mu\nu}(r_i,\theta_j) +$$

$$\frac{g_{\mu\nu}(r_{i+1},\theta_j) - g_{\mu\nu}(r_i,\theta_j)}{r_{i+1} - r_i}(r - r_i) + \frac{g_{\mu\nu}(r_i,\theta_{j+1}) - g_{\mu\nu}(r_i,\theta_j)}{\theta_{j+1} - \theta_j}(\theta - \theta_j)$$

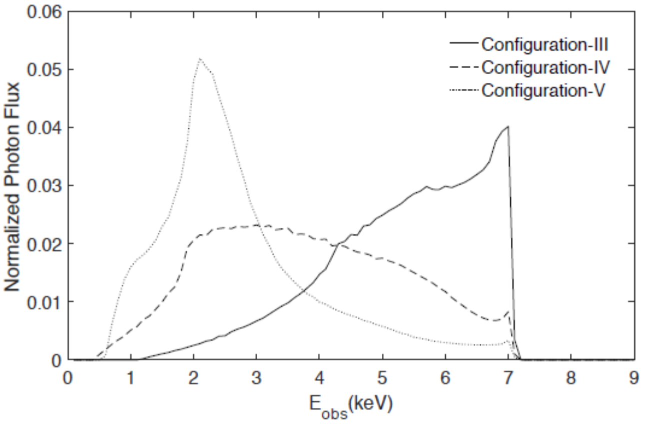
2.1. Intensity Profiles



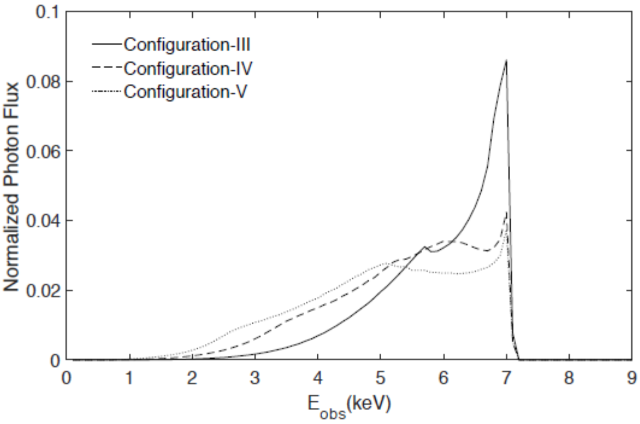
$$I \propto {}^{h}/_{(r^2 + h^2)^{3/2}}$$

$$I \propto {}^{1}/_{r^3}$$

2.2. Iron Line Profiles of KBHsPH



$$I \propto {}^{1}/_{r^3}$$



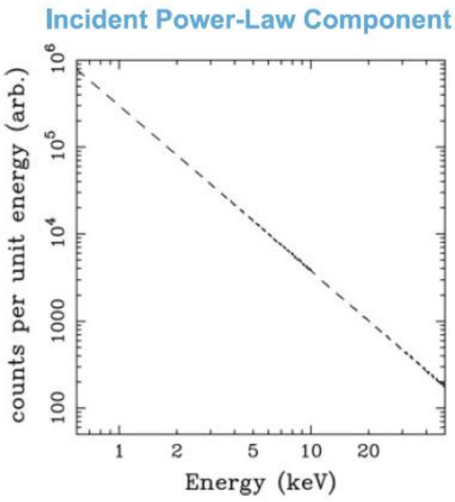
$$I \propto {}^{h}/_{(r^2+h^2)^{3/2}}$$

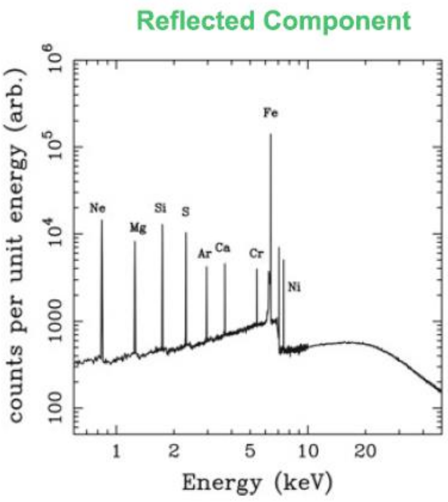
With $h = 2$

3. Simulation

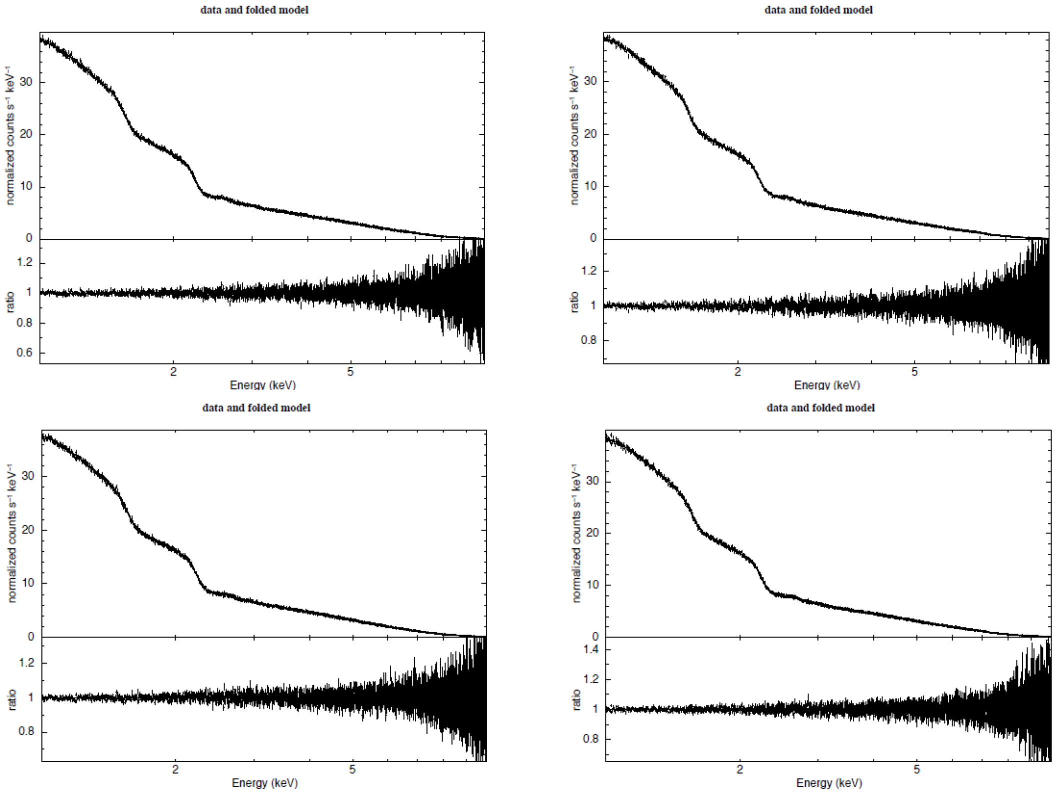
- Data: powerlaw + iron line
- Model: powerlaw + RELLINE

★

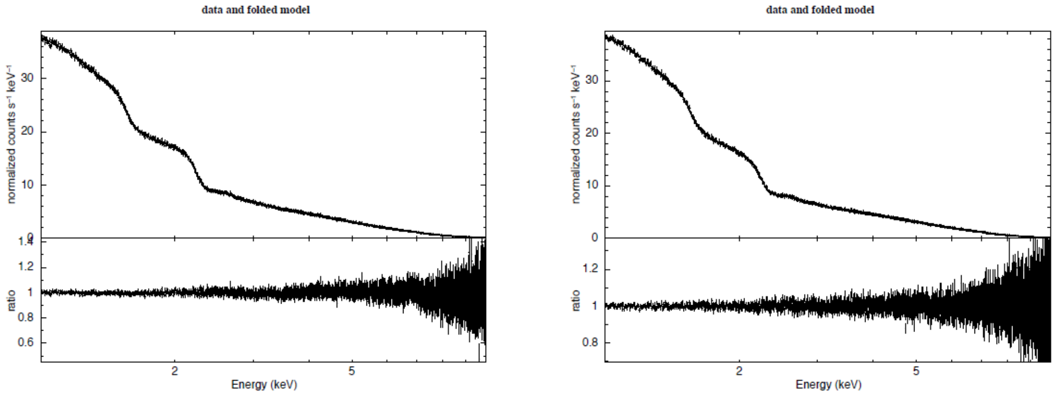

Incident Power-Law Component


Reflected Component

3.1. Simulations with XIS/Suzaku

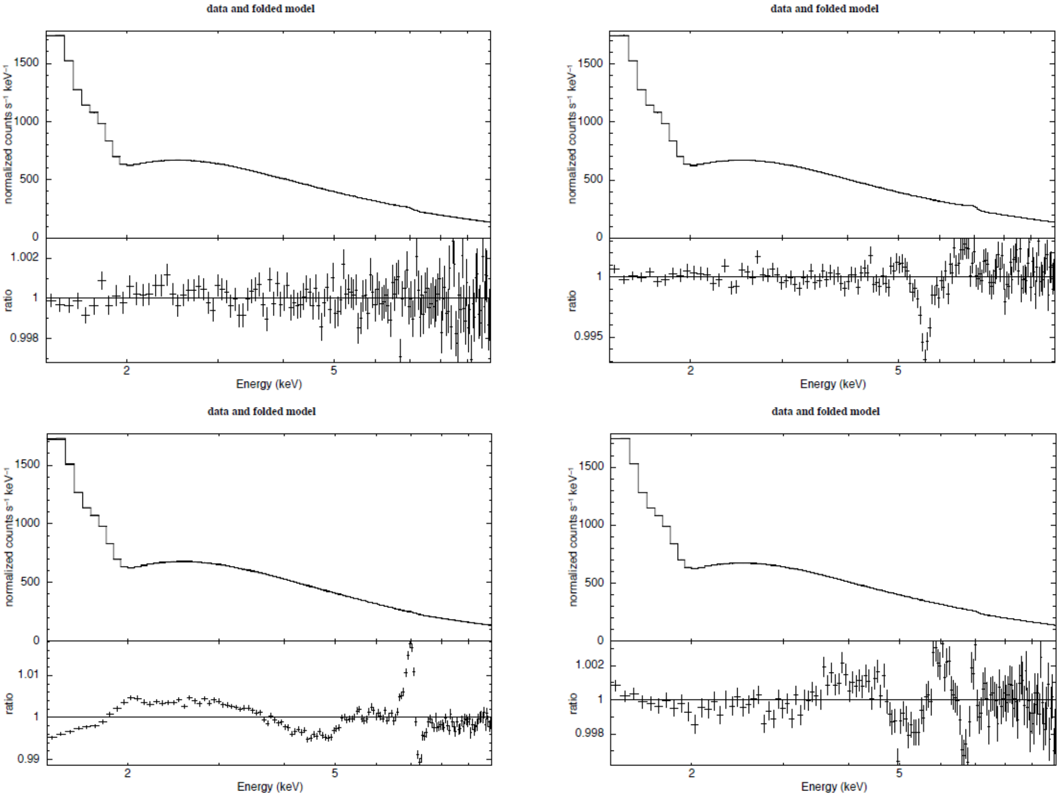


3.1. Simulations with XIS/Suzaku

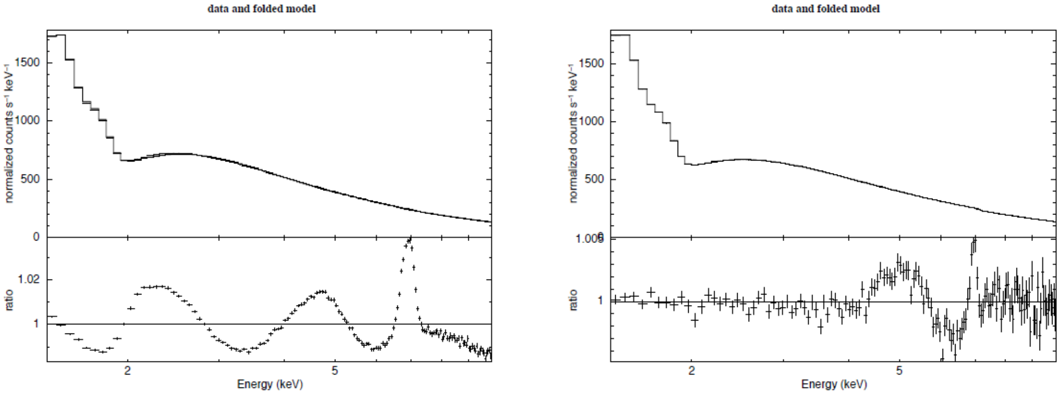


Configuration	Profile	$\chi^2_{\rm min,red}$	a_*	i	q_1	q_2	$r_{\rm br}$	$r_{\rm out}$
III	PL	1.06	0.91(1)	45(1)	7(1)	2.4(4)	4.3(5)	156(66)
IV	PL	1.04	> 0.99	57(2)	8.4(4)	–	–	–
V	PL	1.09	0.974(2)	21(1)	9.6(2)	–	–	–
III	LP	1.04	0.96(15)	45.5(5)	2.1	–	–	–
IV	LP	0.98	0.96(1)	46.7(8)	3.7(1)	–	–	–
V	LP	1.04	> 0.99	46(1)	3.7(3)	–	–	–

3.2. Simulations with LAD/eXTP



3.2. Simulations with LAD/eXTP



Configuration	Profile	$\chi^2_{\mathrm{min,red}}$	a_*	i	q_1	q_2	r_{br}	r_{out}
III	PL	1.15	0.931(2)	44.83(6)	3.98(9)	3.28(5)	4.2(3)	104(23)
IV	PL	31	> 0.99	59.1(3)	7.82(6)	4	–	3.24(7)
V	PL	257	> 0.99	31.5(2)	10	3.98(3)	3.02(2)	20.7(6)
III	LP	3.43	0.923(4)	45.39(4)	10	2.12(2)	2.7(1)	58.4(9)
IV	LP	3.01	0.895(2)	45.59(9)	3.78(2)	3.7(4)	–	–
V	LP	4.02	0.989(4)	45.67(8)	8	3.67(3)	–	27(4)

4. Conclusions

- We presented the iron Kα line profiles for the configurations of III, IV ,V of KBHsPH;

- We **cannot** distinguish KBHsPH from Kerr BHs by current X-ray mission (XIS/Suzaku);

- Future X-ray mission (LAD/eXTP) can detect the presence of Proca hair.

References:

- About iron line method (★):

C. Bambi, *Black Holes: A Laboratory for Testing Strong Gravity*, DOI 10.1007/978-981-10-4524-0_4

- About KBHsPH:

C. Herdeiro, E. Radu and H. Runarsson, Class. Quant. Grav. 33, no. 15, 154001 (2016) [arXiv:1603.02687 [gr-qc]].

- About X-Ray Missions:

http://heasarc.gsfc.nasa.gov/docs/suzaku/

http://www.isdc.unige.ch/extp/

- About model RELLINE:

http://www.sternwarte.uni-erlangen.de/~dauser/research/relxill/

Thanks!

3a3. Atsushi Nishizawa (Nagoya U.),

“Cross-correlating GW and galaxies to identify the host galaxies of binary black holes” (10+5)

[JGRG27 (2017) 112816]

Cross-correlating GW and galaxies to identify the host galaxies of binary black holes

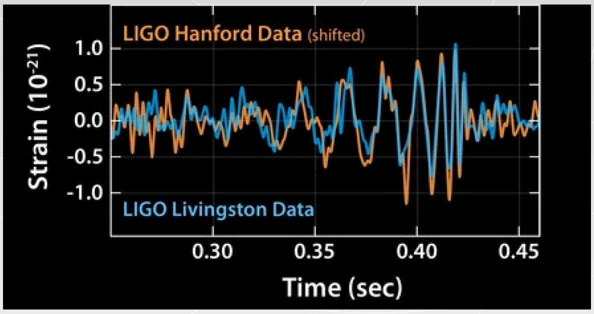
Atsushi Nishizawa (KMI, Nagoya U)

with Atsushi J. Nishizawa (IAR, Nagoya U)
Sachiko Kuroyanagi (IAR, Nagoya U)

Nov. 27 - Dec.1, 2017, 27th JGRG
@ Kurara Hall, Saijo, Higashi-Hiroshima

Gravitational Waves

- GWs from 5 BBH and 1 BNS have been detected.



LIGO Scientific Collaboration 2016 – 2017

- BBH merger rate (from the first three events)

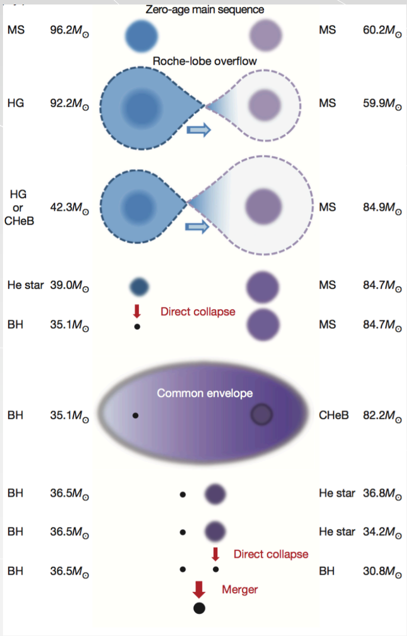
$$12 - 213\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

- aLIGO & aVIRGO are expected to detect more events

$$\sim 100 - 1000\ \mathrm{yr}^{-1} \quad \text{out to } z \sim 1$$

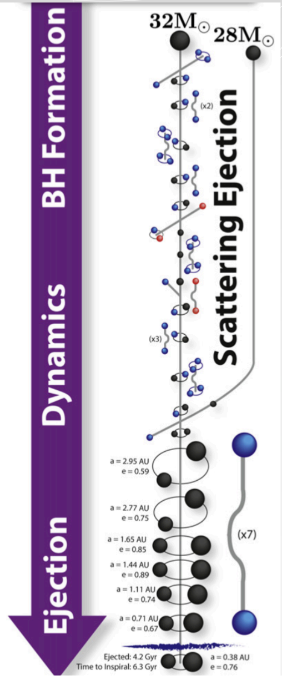
Astrophysical origin of BBH

- isolated field binaries
  (pop II, pop III, homogeneous chemical evolution etc.)



Belczynski et al. 2016

- dense stellar cluster
  (globular cluster, galactic nuclei etc.)



Rodriguez et al. 2016

Discriminating the formation channels

- distance (redshift) distribution of BBH
  shape of distribution, maximum redshift
  Nakamura et al. 2016
- binary parameter distribution
  mass, spin, orbital eccentricity
  Chatterjee et al. 2016; Rodriguez et al. 2016; Breivik et al. 2016, AN et al. 2016
- BBH location and its galaxy association
  clustering properties of BBH & galaxies
  Namikawa, AN, Taruya, 2016a, 2016b; Raccanelli et al. 2016

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- BBH location and its galaxy association

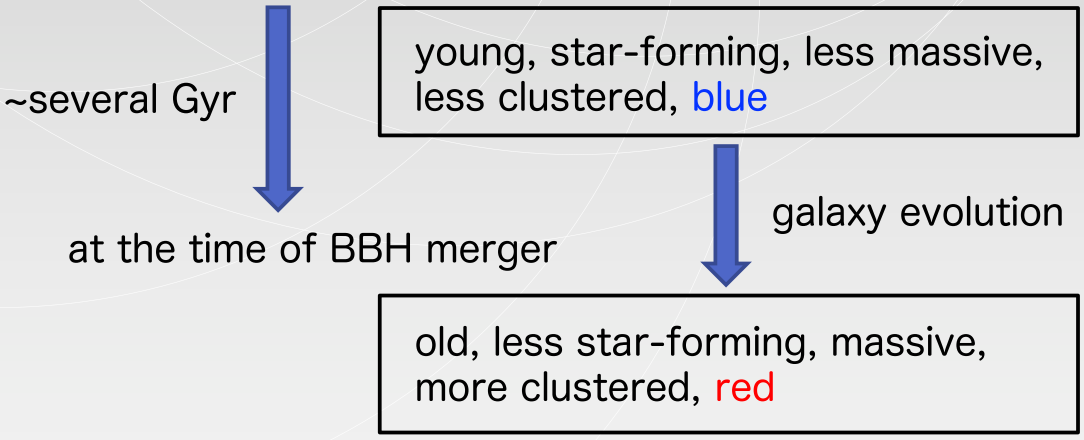
  clustering properties of BBH & galaxies

  Namikawa, AN, Taruya, 2016a, 2016b; Raccanelli et al. 2016

  galaxy properties (color, SFR, age, morphology, etc.)

Naive expectation

the case of isolated field binaries



at the time of BBH formation

~several Gyr

at the time of BBH merger

young, star-forming, less massive, less clustered, blue

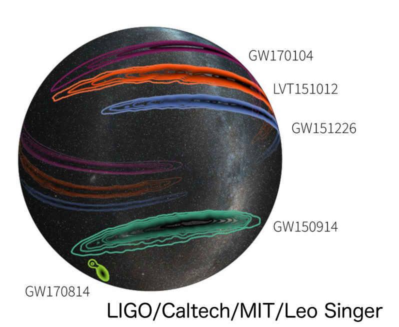
galaxy evolution

old, less star-forming, massive, more clustered, red

GW sources seem to be associated with red galaxies.

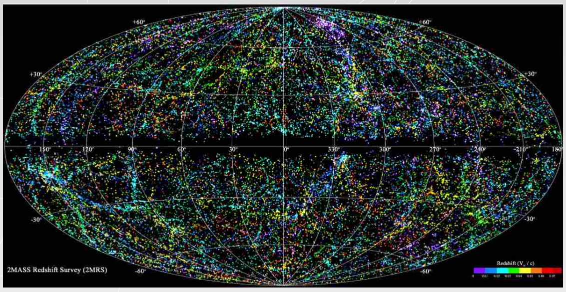
cross-correlating sky maps

No need to identify an electromagnetic counterpart for each BBH



LIGO/Caltech/MIT/Leo Singer

X



GW events

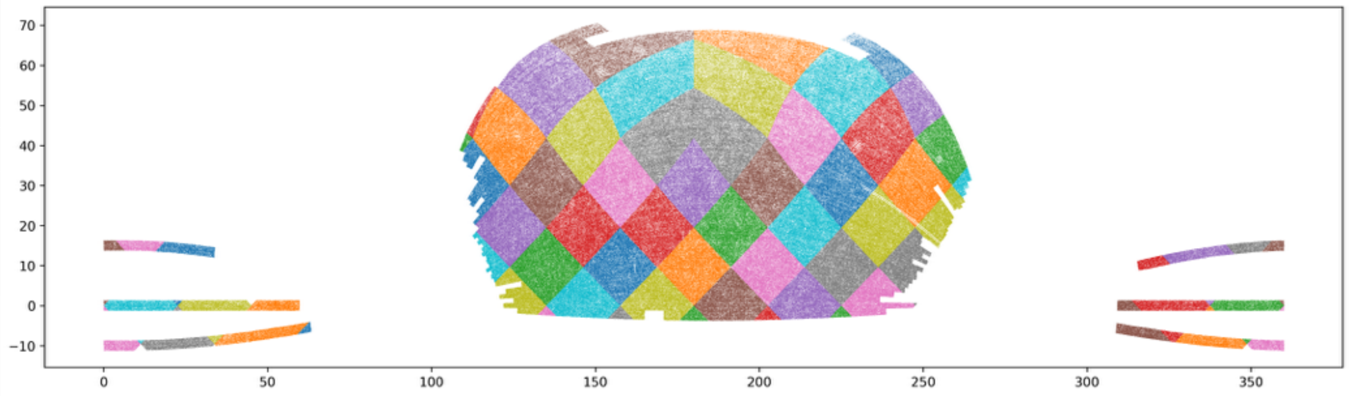
galaxy survey
(2MASS redshift survey)

- How strongly are GW events correlated with galaxies?
- What properties of galaxies are associated with BBH?

---

galaxy catalog

SDSS DR7 photo-z sample



- Each galaxy is classified based on the best-fit SED into subgroups of galaxy colors (red/blue).
- They are classified further by other galaxy properties such as star formation rate, AGN activity, etc.

GW source mock catalog

- Salpiter-type mass function ($\propto m^{-2.35}$) with
  $5\,M_\odot < m_1, m_2 < 100\,M_\odot$ and $M < 100\,M_\odot$
- constant merger rate
- sky position: associated with a real galaxy, weighted by its luminosity in red or blue
- orbital inclination: uniformly random
- phenomenological IMR GW waveform [Khan et al. 2016]
- detector network: aLIGOx2 + aVIRGO
- ~15000 nonspinning binaries with S/N > 8 out to z=0.3 for each galaxy population (red/blue/random)
- Observational errors (distance, angular resolution, etc.) are estimated with a Fisher information matrix

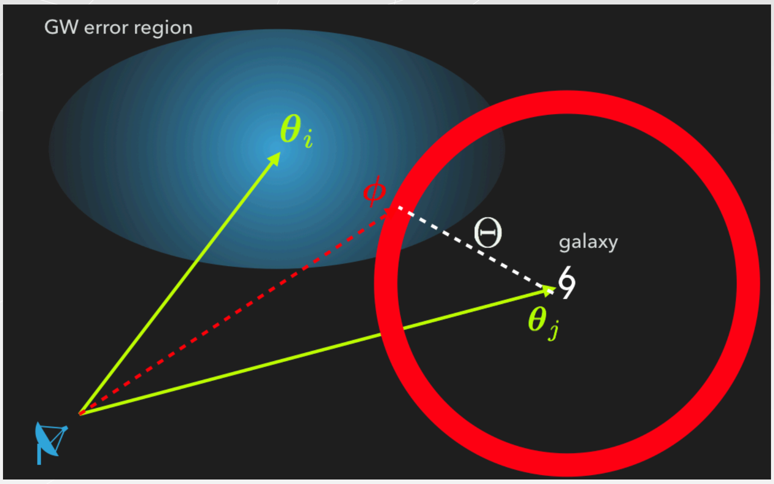
angular cross-correlation

$$w^{\rm cross}(\Theta) = \langle \delta_{\rm GW}(\theta_0)\delta_{\rm gal}(\theta_0+\Theta)\rangle$$

$$\propto \sum_j \int_{|\phi-\theta_j|=\Theta} \underbrace{\sum_i \exp\left[-\frac{1}{2}(\phi-\theta_i){\rm Cov}_i^{-1}(\phi-\theta_i)\right]}_{\text{GW source density field}} d^2\phi$$

summed over all galaxies

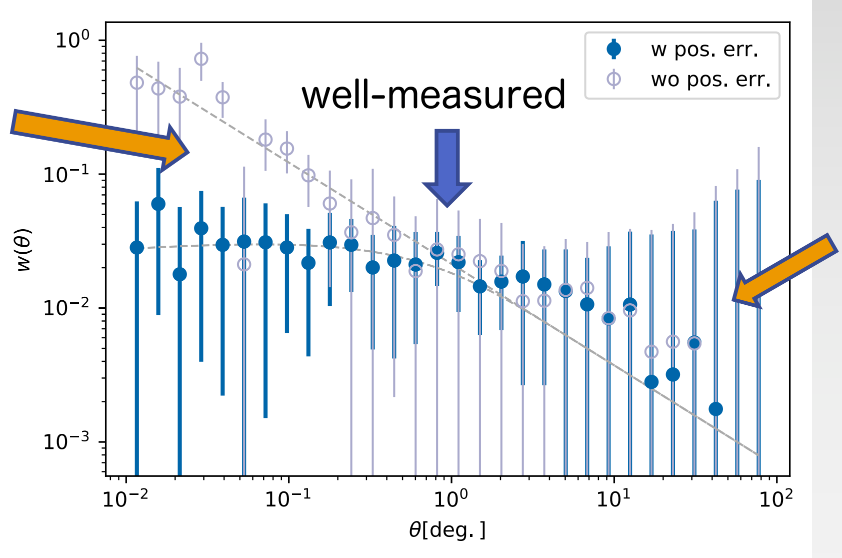
assumption:
GW error region has 3 σ Gaussian profile.



effects of errors on the correlation function

Assume that GW sources are associated with red galaxies.
Use 1000 GW sources observed by 3 GW detectors.

suppressed by positional error of GW



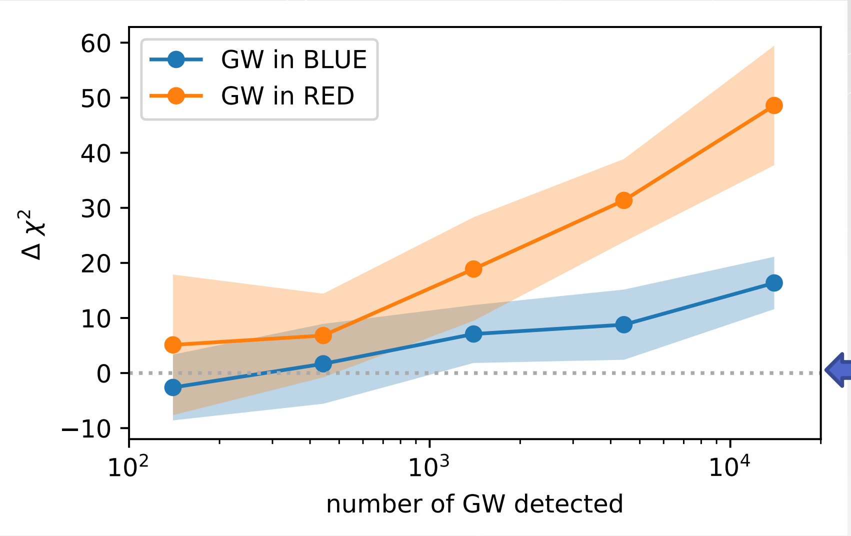
sample variance limited

small scale ⟷ large scale

Number of GW events to distinguish galaxy colors

significance of detecting the clustering

$$\chi^2_{\rm null} = \sum_i \left(\frac{w(\theta_i) - 0}{\sigma_i}\right)^2$$



To reject the null hypothesis of the clustering, we need

a few 100 sources for red galaxies

1000 sources for blue galaxies

no clustering of GW

Summary

- GWs from BBHs have been detected and are expected much more in the future observation.
- However, the origin of BBH is not yet understood well.
- By cross-correlating BBH and galaxies, we can obtain info about how strongly BBH trace the matter distribution.
- Given BBHs are associated with some particular types of galaxies, GWs and galaxies may be correlated differently.
- With GW mock data and SDSS galaxy catalog, we estimated that red/blue galaxy associations can be detected with a few 100/1000 BBHs.

3a4. Tatsuya Narikawa (ICRR U. of Tokyo), “Constraining bimetric gravity by gravitational wave events from compact binary coalescences” (10+5)

[JGRG27 (2017) 112817]

Constraining bimetric gravity by GW events from CBCs

Tatsuya Narikawa

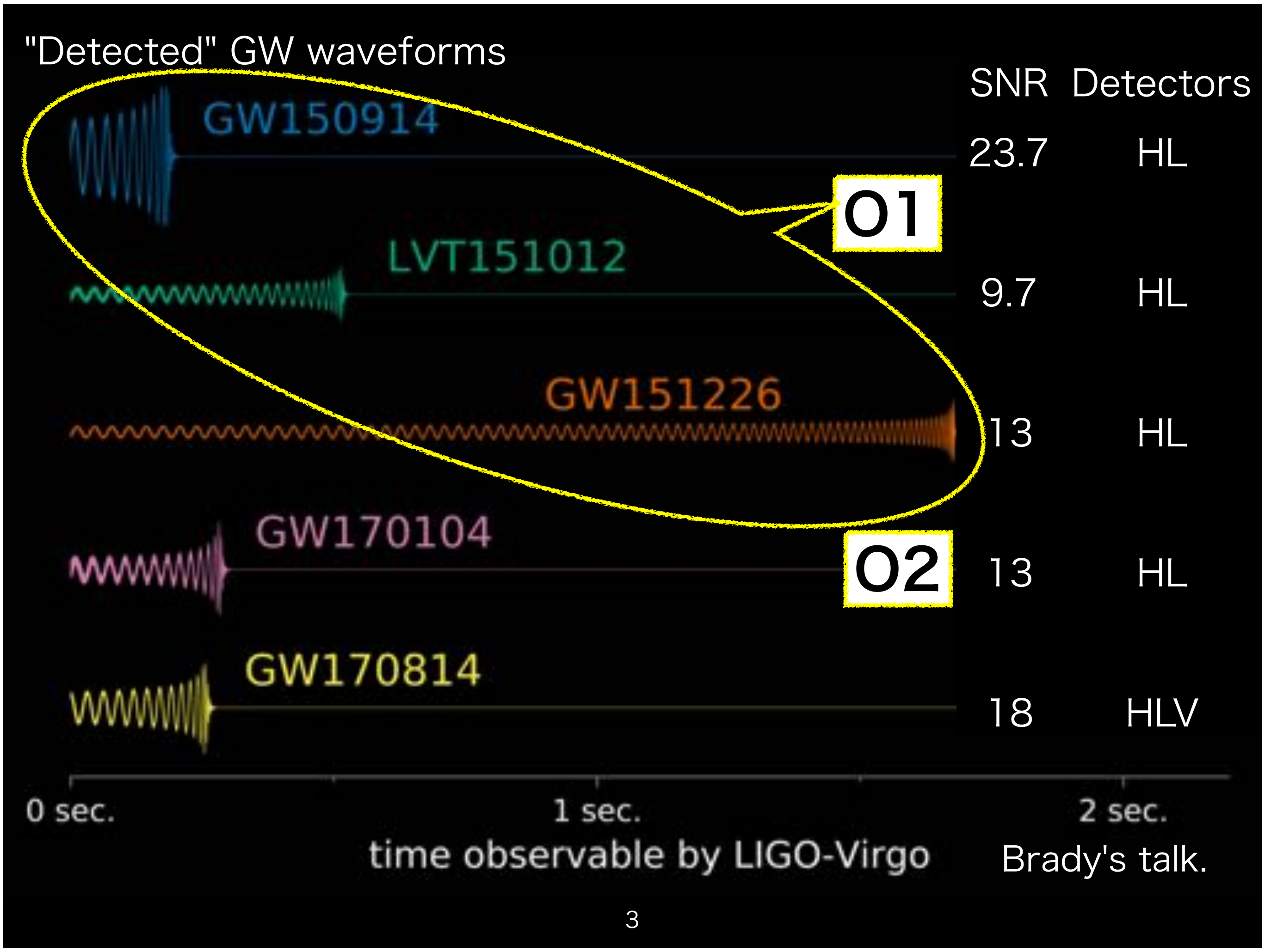
I graduated
from
Hiroshima U.

H. Tagoshi, T. Tanaka, T. Nakamura,
J. Veitch, W. Del Pozzo, A. Vecchio

3a4 JGRG27@Hiroshima, 2017/11/27-12/1

Abstract

- GW events have put a constraint on the deviation from GR.
- Recently, the cosmological viable models of bimetric gravity as an alternative to dark energy, motivated by discovery of the cosmic acceleration, have been proposed.
- In bimetric gravity, two kinds of graviton can oscillate like neutrino oscillations during propagation of gravitational waves. <-- called "graviton oscillations"
- It is difficult to cover graviton oscillations by simple parameterization, such as parameterized post Einsteinian (ppE) or gIMR frameworks.
- We constrain the bimetric gravity by GW events.

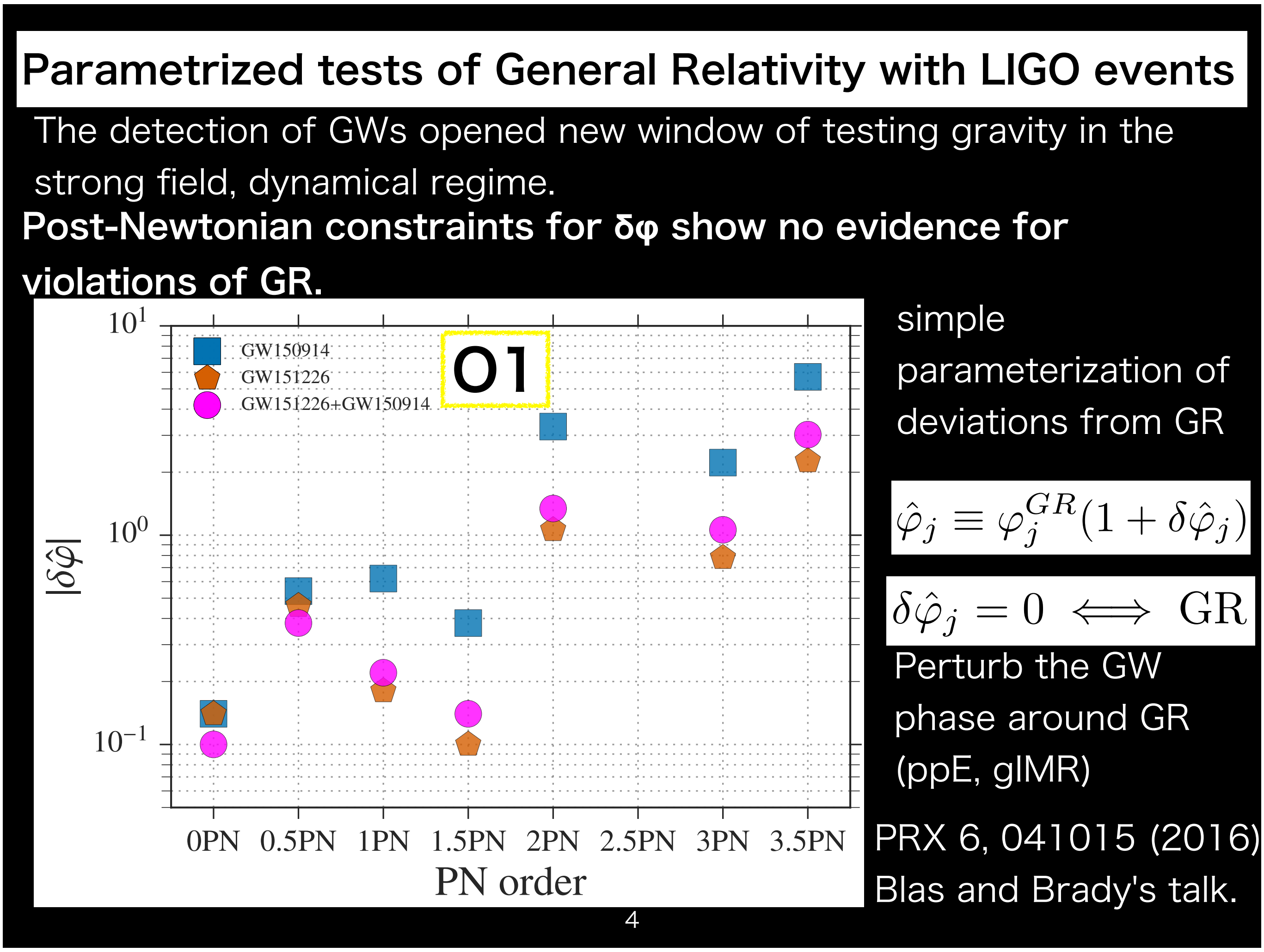


"Detected" GW waveforms

	SNR	Detectors
GW150914	23.7	HL
LVT151012	9.7	HL
GW151226	13	HL
GW170104	13	HL
GW170814	18	HLV

time observable by LIGO-Virgo

Brady's talk.



Parametrized tests of General Relativity with LIGO events

The detection of GWs opened new window of testing gravity in the strong field, dynamical regime.

Post-Newtonian constraints for δφ show no evidence for violations of GR.

simple parameterization of deviations from GR

$$\hat{\varphi}_j \equiv \varphi_j^{GR}(1+\delta\hat{\varphi}_j)$$

$$\delta\hat{\varphi}_j = 0 \iff \text{GR}$$

Perturb the GW phase around GR (ppE, gIMR)

PRX 6, 041015 (2016)
Blas and Brady's talk.

Gravitational wave waveform in bimetric gravity

GR

Bimetric modulation

$$h(f)=\mathcal{A}(f)e^{i\Phi(f)}\left[B_1e^{i\delta\Phi_1(f)}+B_2e^{i\delta\Phi_2(f)}\right]$$

$h_{\rm GR}$

e.g., effective precession
(IMRPhenomPv2)

$\delta h_{\rm Bimetric}$

Summation of two modes
describes graviton oscillations

It is difficult to cover graviton oscillations' waveform by simple parameterization, such as ppE or gIMR.

De Felice, Nakamura, Tanaka (DFNT), PTEP 2014.
TN et al., PRD 91, 062007 (2015).

Key features & parameters of graviton oscillations

$$h(f)=\mathcal{A}(f)e^{i\Phi(f)}\left[B_1e^{i\delta\Phi_1(f)}+B_2e^{i\delta\Phi_2(f)}\right]$$

Key features

Phase corrections: $\delta\Phi_i(f;\mu,\kappa\xi_c^2,D_{\rm L})$

$$\delta\Phi_{1,2}=-\frac{\mu D_L\sqrt{\tilde{c}-1}}{2\sqrt{2x}}\left(1+x\mp\sqrt{1+x^2+2x\frac{1-\kappa\xi_c^2}{1+\kappa\xi_c^2}}\right)$$

Amplitude corrections: $B_i(f;\theta_g(\mu,\kappa\xi_c^2),\rho_{\rm gal})$

Degrees of mixing

$$B_1=\cos\theta_g(\cos\theta_g+\sqrt{\kappa}\xi_c\sin\theta_g)$$
$$B_2=\sin\theta_g(\sin\theta_g-\sqrt{\kappa}\xi_c\cos\theta_g)$$

Key parameters

- effective graviton mass: μ
- modification to gravitational constants: $\kappa\xi_c^2$

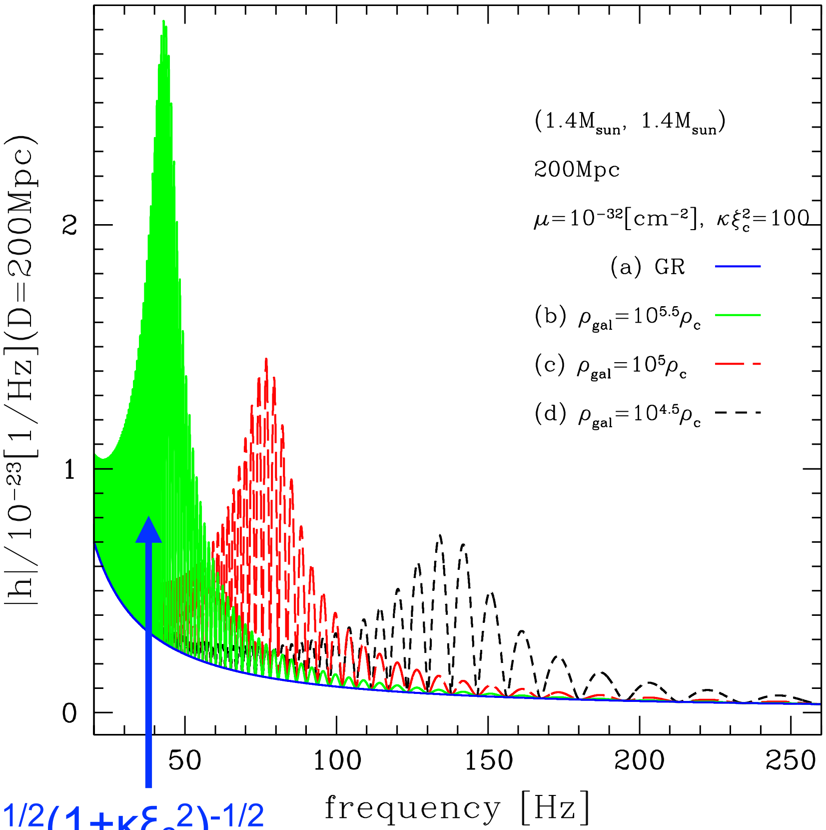
Bimetric gravity's GW waveforms

Key features

- Phase corrections
- Amplitude corrections

Key parameters

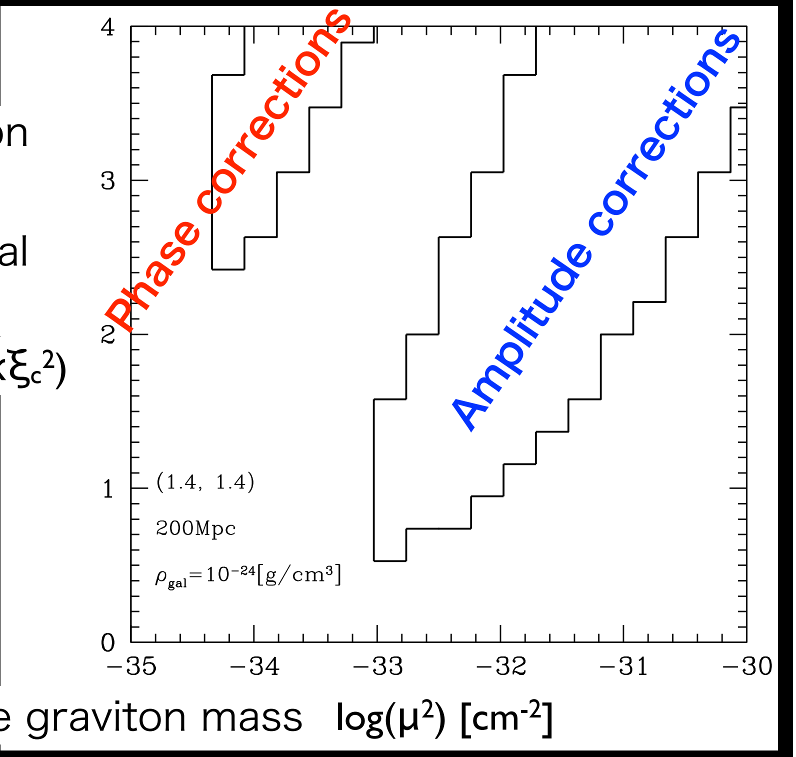
- effective graviton mass: μ
- modification to gravitational constants: $\kappa\xi_c^2$



$f_{peak} \propto \mu^2 \rho_{gal}^{-1/2}(1+\kappa\xi_c^2)^{-1/2}$

Prediction: detectability of graviton oscillations

We have predicted ``Advanced GW interferometer can detect graviton oscillations by using CBC observations." before detections by LIGO-VIRGO.



modification to gravitational constant $\log(\kappa\xi_c^2)$

effective graviton mass $\log(\mu^2)$ [cm^{-2}]

TN et al., PRD 91, 062007 (2015).

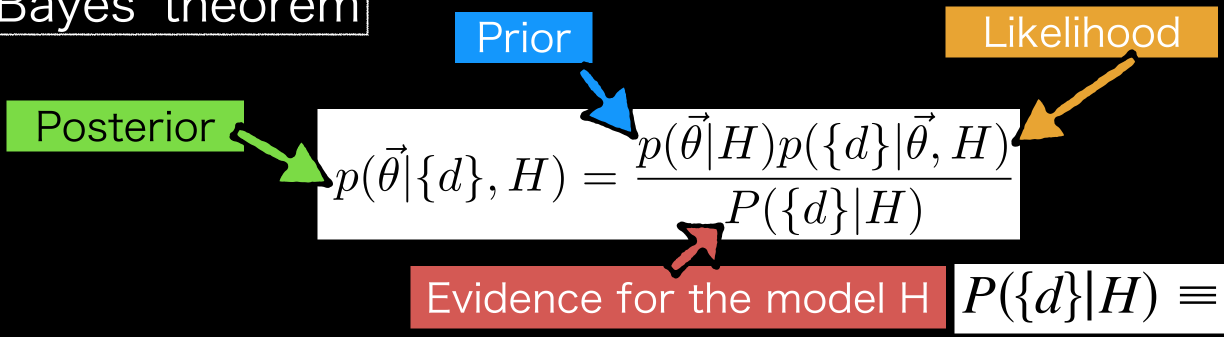
Bayesian parameter estimation of GWs

Why Bayesian statistics and stochastic sampling

- A lot of parameters
- Parameter estimation (PE)
- Model selection

$$L(d|\vec{\theta}) \propto \exp\left(-2\int_0^\infty \frac{|\tilde{d}(f) - h(\vec{\theta}, f)|^2}{S_n(f)} \mathrm{d}f\right)$$

Bayes' theorem



Prior

Likelihood

Posterior

$$p(\vec{\theta}|\{d\}, H) = \frac{p(\vec{\theta}|H)p(\{d\}|\vec{\theta}, H)}{P(\{d\}|H)}$$

Evidence for the model H $P(\{d\}|H) \equiv Z_H$

H: hypothesis (signal embedded in data), {d}: data set, θ: parameters

We calculate posterior and evidence with Markov chain Monte Carlo method, Nested sampling, or MultiNest/BAMBI (LSC Algorithm Library (LAL), LALInference)

Bayesian model selection

Which model better describes the data?

The Bayes factor can be used for model selection.

$$B_{\mathrm{MG,GR}} = \frac{Z_{\mathrm{MG}}}{Z_{\mathrm{GR}}}$$

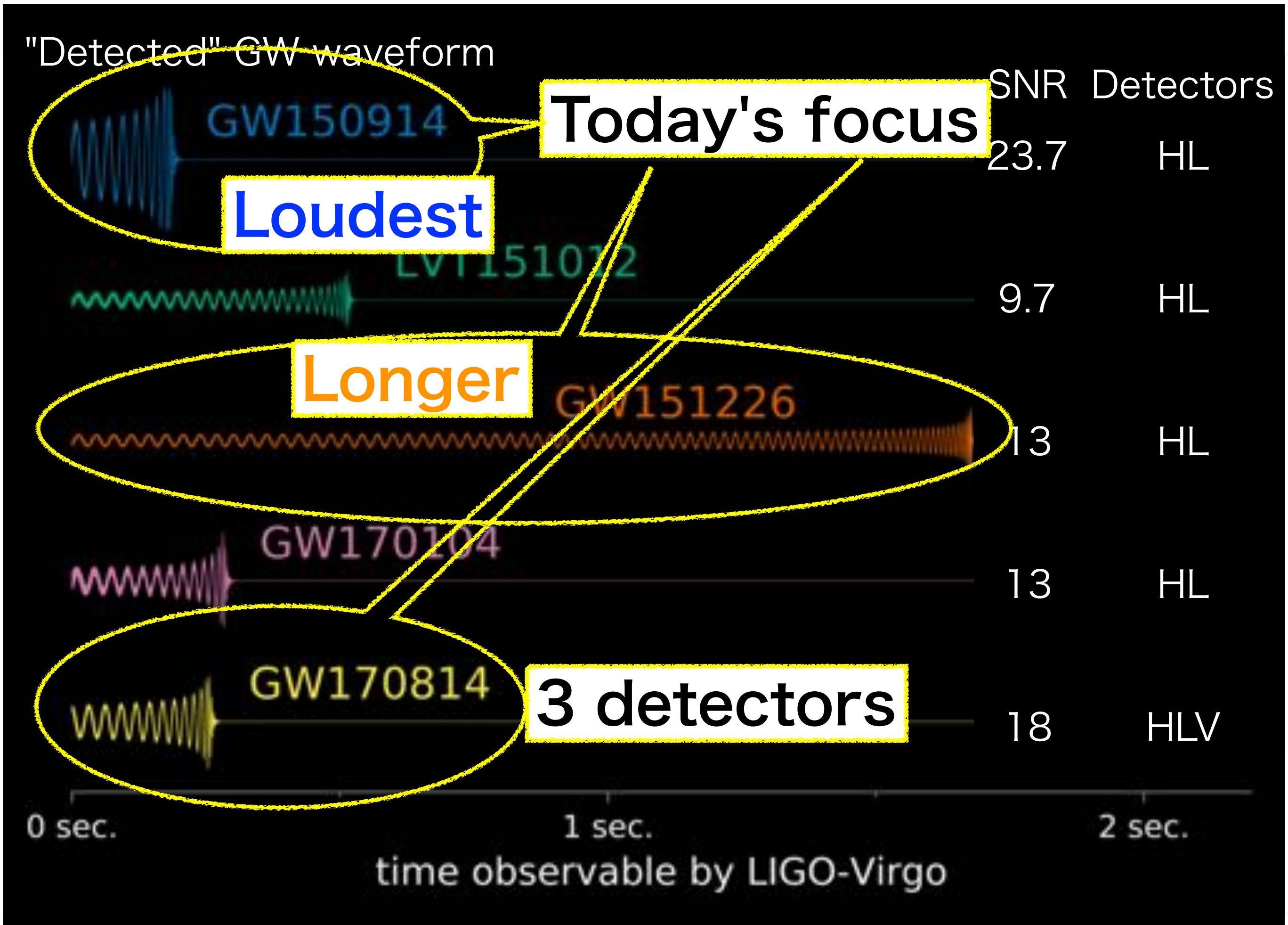
The Bayes factor is the ratio of evidences of hypotheses.

A larger Bayes factor indicates a stronger preference for the model. Or a smaller BF indicates a stronger disfavor for model.

“confidence” levels of B_{XY}

$2\log B_{XY}$	Evidence for model X
<0	Negative (supports model Y)
0 to 2	Not worth more than a bare mention
2 to 5	Positive
5 to 10	Strong
>10	Very Strong

}interest



Today's focus

Loudest

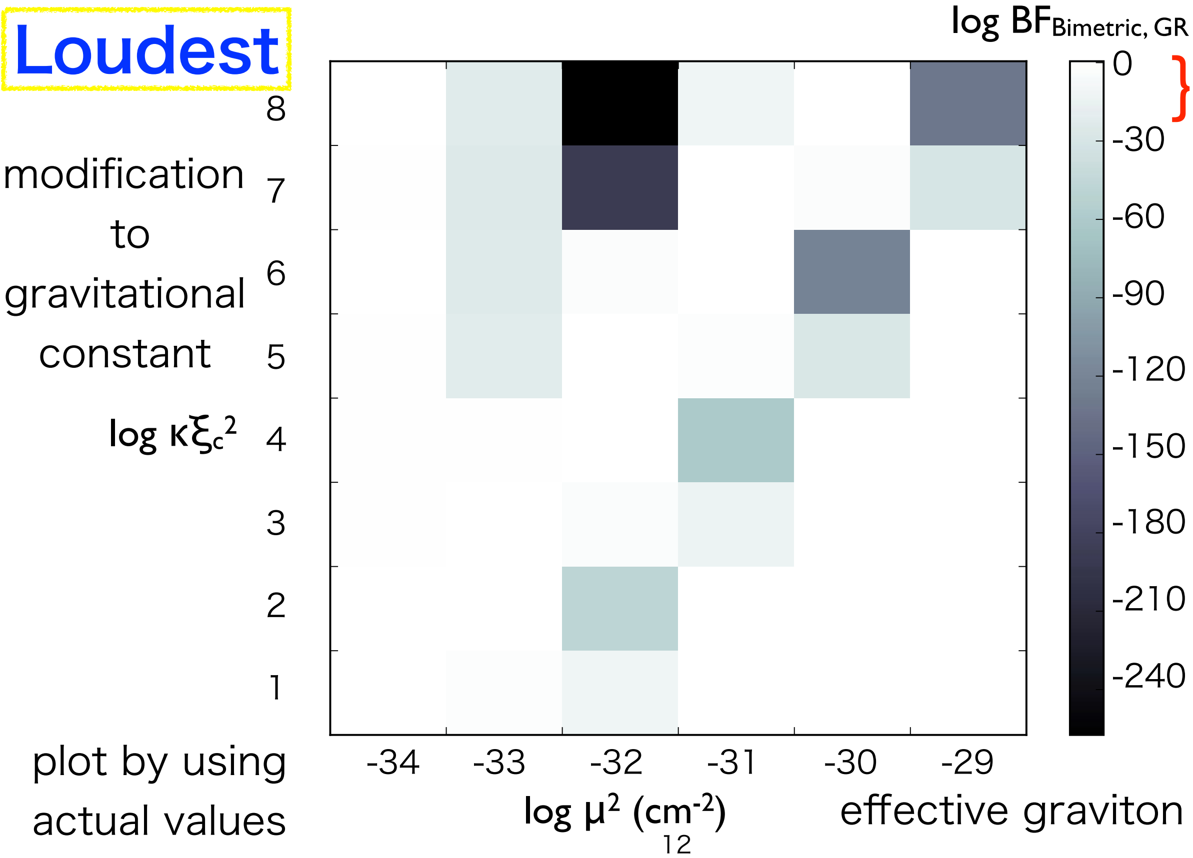
Longer

3 detectors

Constraints on Bimetric gravity

log Bayes-factor between Bimetric gravity and GR for GW150914

Loudest



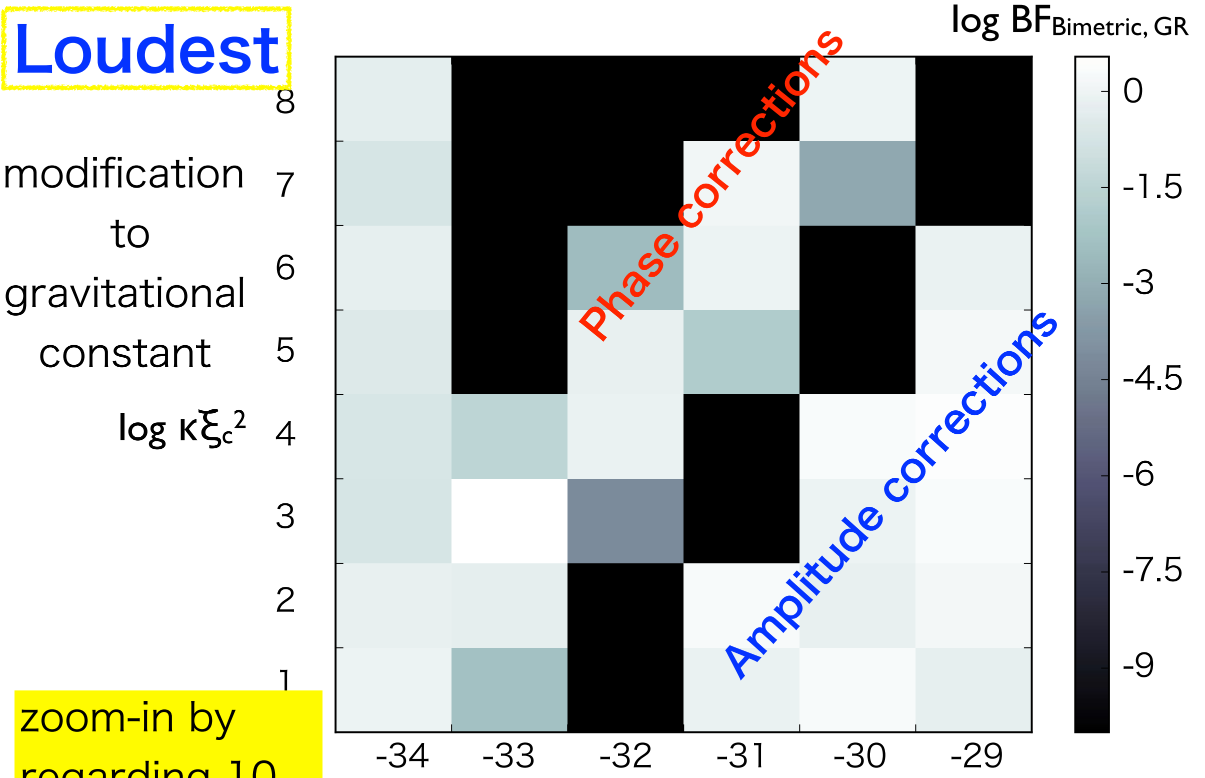
} interest

plot by using actual values

➢ GW150914 prefers GR to the bimetric gravity whole parameter region.

lo

Loudest

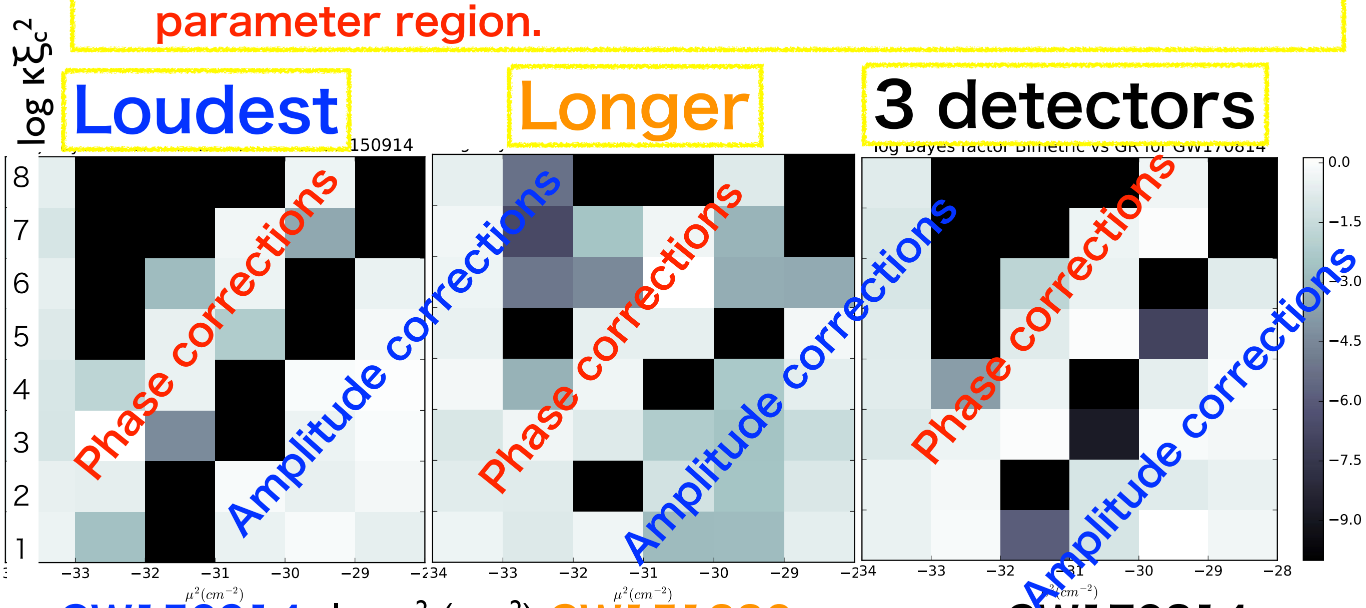


zoom-in by regarding 10 or more as 10.

log μ^2 (cm^{-2}) effective graviton mass

➢ 3 GW events prefer GR to the bimetric gravity whole parameter region.

Loudest **Longer** **3 detectors**



GW150914 log μ^2 (cm^{-2}) **GW151226** **GW170814**

zoom-in by regarding 10 or more as 10.

Stronger constraints on amplitude corrections as louder.

Stronger constraints on phase corrections as longer duration signals with higher SNR.

Summary and Conclusion

- GW events have put a constraint on the deviation from GR.
- It is difficult to cover graviton oscillations by simple parameterizations, such as ppE or gIMR frameworks.
- We have predicted ``Advanced GW interferometer can detect graviton oscillations by using CBC observations." before detections by LIGO-VIRGO in 2015.

- We constrained the bimetric gravity by GW events.
- 3 GW events prefer GR to the bimetric gravity whole parameter region.
- Future loud GW events must be completely ruled out the graviton oscillations. ==> feedback to cosmology

3a5. Naoki Tsukamoto (Huazhong U. of Science and Technology),

“A simple strong deflection limit analysis in a general asymptotically flat, static, spherically symmetric spacetime” (10+5)

[JGRG27 (2017) 112818]

A simple strong deflection limit analysis in a general asymptotically flat, static, spherically symmetric spacetime

Naoki Tsukamoto
Huazhong University of Science and Technology

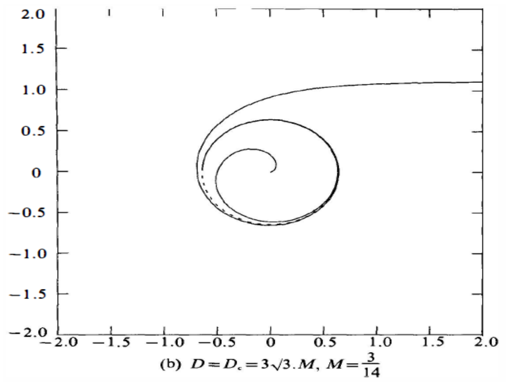
27th November - 1st December 2017, JGRG27 @ Saijyo,
Higashi-hiroshima

N. T., Phys. Rev. D **95**, 064035 (2017).
N. T. and Yungui Gong, Phys. Rev. D **95**, 064034 (2017).

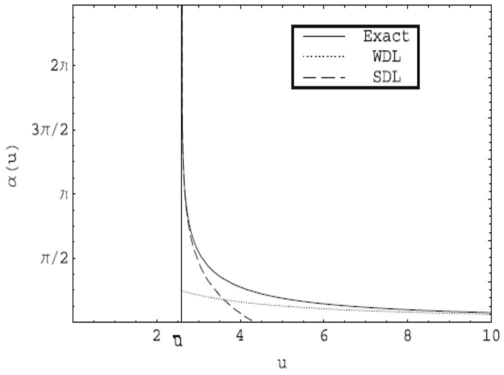
Photon sphere.

Circular orbit of a light called *photon sphere* in a Schwarzschild spacetime was pointed out by Hilbert in 1917.

Strong deflection limit (SDL) is a limit that a light passes infinity near the photons sphere.



Chandrasekhar 1983

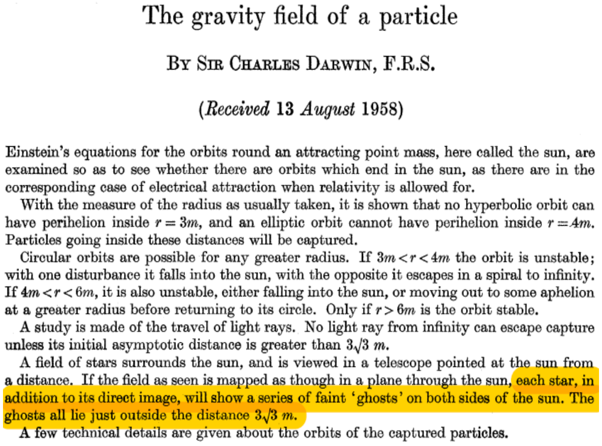


Bozza 2010

Deflection angle α of a light with a impact parameter b is given by

$$\alpha(b) = -\log\left(\frac{b}{b_c} - 1\right) + \log[216(7-4\sqrt{3})] - \pi + O((b-b_c)\log(b-b_c)).$$

Deflection angle in SDL was obtained by Charles G. Darwin.



The gravity field of a particle

By Sir Charles Darwin, F.R.S.

(*Received* 13 *August* 1958)

Einstein's equations for the orbits round an attracting point mass, here called the sun, are examined so as to see whether there are orbits which end in the sun, as there are in the corresponding case of electrical attraction when relativity is allowed for.

With the measure of the radius as usually taken, it is shown that no hyperbolic orbit can have perihelion inside $r = 3m$, and an elliptic orbit cannot have perihelion inside $r = 4m$. Particles going inside these distances will be captured.

Circular orbits are possible for any greater radius. If $3m < r < 4m$ the orbit is unstable; with one disturbance it falls into the sun, with the opposite it escapes in a spiral to infinity. If $4m < r < 6m$, it is also unstable, either falling into the sun, or moving out to some aphelion at a greater radius before returning to its circle. Only if $r > 6m$ is the orbit stable.

A study is made of the travel of light rays. No light ray from infinity can escape capture unless its initial asymptotic distance is greater than $3\sqrt{3}\ m$.

A field of stars surrounds the sun, and is viewed in a telescope pointed at the sun from a distance. If the field as seen is mapped as though in a plane through the sun, each star, in addition to its direct image, will show a series of faint 'ghosts' on both sides of the sun. The ghosts all lie just outside the distance $3\sqrt{3}\ m$.

A few technical details are given about the orbits of the captured particles.

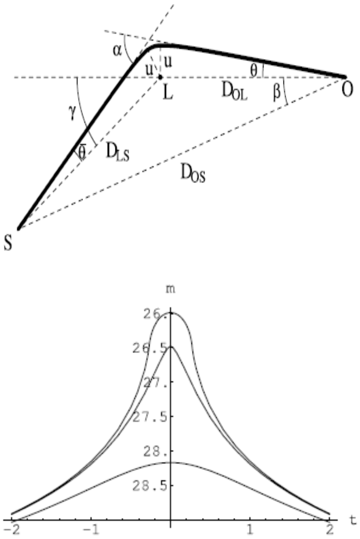
He was a grandson of C. R. Darwin.

Proc.R.Soc.,A249,180 (1959) was submitted when he was 70.

Images near a photon sphere were also considered by Hagihara (1931), Luminet (1979), Ohanian (1987), Nemiroff (1993), Frittelli (2000), Virbhadra and Ellis (2000), Bozza *et al.* (2001), Bozza (2002), Eiroa *et al.* (2002), Bozza and Mancini (2004),,,,,.

Gravitational Lensing by a photon sphere.

1. Obtain a deflection angle α in SDL
$$\alpha(b) = -\bar{a}\log\left(\frac{b}{b_c} - 1\right) + \bar{b} + O(b - b_c).$$
2. Insert α into a lens equation
$$\gamma = \alpha(b) - \theta - \bar{\theta}.$$
3. Obtain the solutions as
$$\theta = \frac{b}{D_{OL}}\left(1 + \exp\frac{\bar{b} - \gamma}{\bar{a}}\right).$$
4. Get the separations and magnifications of images.



Bozza and Mancini (2004)

Deflection angle in SDL. Bozza (2002)

$$ds^2 = -A(r)dt^2 + B(r)dr^2 + C(r)d\Omega^2.$$

$$\alpha(r_0) = I(r_0) - \pi, \quad r_0 \text{ is the closest distance.}$$

$$I(r_0) \equiv 2\int_{r_0}^{\infty} \sqrt{\frac{B}{\left(\frac{A_0 C}{A C_0} - 1\right) C}} dr = I_D(r_0) + I_R(r_0),$$

$$I_D(r_0) \equiv 2\int_0^1 \frac{1}{\sqrt{\beta_0 z + \kappa_0 z^2}} dz = \frac{4}{\sqrt{\kappa_0}} \log\left(\frac{\sqrt{\kappa_0} + \sqrt{\beta_0 + \kappa_0}}{\sqrt{\beta_0}}\right).$$

$$z \equiv \frac{A(r) - A_0}{1 - A_0}, \qquad \beta_0 \equiv \frac{1 - A_0}{C_0 A'_0}(C'_0 A_0 - C_0 A'_0),$$

$$\kappa_0 \equiv \frac{(1 - A_0)^2}{2C_0^2 A_0'^3}\left[2C_0 C'_0 A_0'^2 + (C_0 C''_0 - 2C_0'^2) A_0 A'_0 - C_0 C'_0 A_0 A''{}_0\right],$$

where $\beta_0 \to 0$ in SDL and X_0 denotes $X(r_0)$.
If we can integrate I_R, we get α in SDL analytically.

Motivation of modification of SDL analysis

1. Bozza's method has been applied for dozens spacetimes. **However, $\bar{b}$ can be obtained analytically only in the Schwarzschild spacetime**.

   $$\alpha(b) = -\bar{a} \log\left(\frac{b}{b_c} - 1\right) + \bar{b} + O((b - b_c)\log(b - b_c)).$$

   $\bar{a} = 1$, $\bar{b} = \log[216(7 - 4\sqrt{3})] - \pi$. Darwin (1959), Bozza (2002)
   $-5\sqrt{3}/162(b - b_c)\log(b - b_c)$. Iyer and Petters (2007).
2. The order of the error term $O(b - b_c)$ contradicts with Iyer and Petters' result in the Schwarzschild spacetime.
3. Bozza's formalism does not work in ultrastatic spacetimes with a time translational Killing vector which has a constant norm such as an Ellis wormhole spacetime.

The variable z makes integral I_R difficult.

- Bozza defined z as

$$\begin{aligned} z &\equiv \frac{A(r)-A_0}{1-A_0} \\ &= 1-\frac{r_0}{r} \text{ for the Schwarzschild spacetime} \\ &= 1-\frac{r_0^2(2Mr-Q^2)}{r^2(2Mr_0-Q^2)} \text{ for the Reissner} - \text{Nordström spacetime} \\ &= \text{indeterminated for the Ellis wormhole spacetime.} \end{aligned}$$

- $ds^2 = -dt + dr^2 + (r^2 + a^2)d\Omega^2$ for the Ellis spacetime.

- **If z is defined as $z \equiv 1 - r_0/r$, we can calculate I_R, $\bar{a}$, and $\bar{b}$ analogically in the three cases.**

Deflection angle in the strong deflection limit $b \to b_c$ or r_0(closest distance) $\to r_m$(radius of the photon sphere)

$$ds^2 = -A(r)dt^2 + B(r)dr^2 + C(r)d\Omega^2,$$

$$\alpha(b) = -\bar{a}\log\left(\frac{b}{b_c}-1\right) + \bar{b} + O((b-b_c)\log(b-b_c))$$

$$\bar{a} = \sqrt{\frac{2B_mA_m}{C_m''A_m - C_mA_m''}}$$

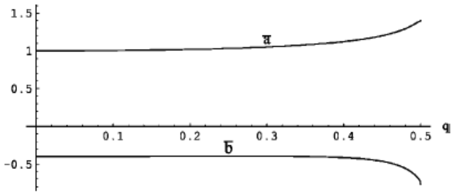
$$\bar{b} = \bar{a}\log\left[r_m^2\left(\frac{C_m''}{C_m} - \frac{A_m''}{A_m}\right)\right] + I_R(r_m) - \pi,$$

I obtained $\bar{a}$ and $\bar{b}$ of RN BH.

Comparing our result with Bozza (2002).

$$\bar{a} = \frac{r_m}{\sqrt{3Mr_m - 4Q^2}}, \qquad r_m = \frac{3M + \sqrt{9M^2 - 8Q^2}}{2}.$$

$$\bar{b} = 2\bar{a}\log\frac{2^{\frac{3}{2}}(3Mr_m - 4Q^2)^{\frac{3}{2}}\left(2\sqrt{Mr_m - Q^2} - \sqrt{3Mr_m - 4Q^2}\right)}{Mr_m(Mr_m - Q^2)} - \pi,$$



Bozza (2002). $q \equiv Q/(2M)$

Q/M	0	0.2	0.4	0.6	0.8
$\bar{b}$	-0.4002	-0.39935	-0.3972	-0.3965	-0.4136
$\bar{b}_{Bozza}$	-0.4002	-0.3993	-0.3972	-0.3965	-0.4136

Comparing our result with Eiroa et al. (2002)

Eiroa *et al.* numerically obtained the deflection angle in SDL $r_0 \to r_m$.

$$\lim_{r_0 \to r_m}\left(\alpha + \mathcal{F}\log\left[\frac{\mathcal{G}(r_0 - r_m)}{2M}\right] + \pi\right) = 0.$$

Q/M	0	0.1	0.25	0.5	0.75	1
$\mathcal{F}$	2.00000	2.00224	2.01444	2.06586	2.19737	2.82843
$\mathcal{F}_{Eiroa}$	2.00000	2.00224	2.01444	2.06586	2.19737	2.82843
$\mathcal{G}$	0.207336	0.207977	0.211467	0.225996	0.262083	0.426777
$\mathcal{G}_{Eiroa}$	0.207338	0.207979	0.21147	0.225997	0.262085	0.426782

We analytically derive $\mathcal{F}$ and $\mathcal{G}$ as

$$\mathcal{F} \equiv 2\bar{a}$$

$$\mathcal{G} \equiv \frac{M}{\bar{a}}\sqrt{\frac{2}{Mr_m - Q^2}}\exp\left(-\frac{\bar{b} + \pi}{2\bar{a}}\right).$$

We have confirmed our results.

Ellis wormhole (often called the Morris-Thorne wormhole).

$$ds^2 = -dt^2 + dr^2 + [(r-p)^2 + a^2]d\Omega^2.$$

- We cannot define the variable z suggested in Bozza (2002) as $z_{Bozza} \equiv (g_{tt}(r) - g_{tt}(r_0))/(1 - g_{tt}(r_0))$.
- The same problem occurs any ultrastatic spacetime.
- We can calculate deflection angle in SDL directly

$$\begin{aligned} \alpha &= 2K\left(\frac{a}{b}\right) - \pi, \\ &= -\log\left(\frac{b}{b_c} - 1\right) + 3\log 2 - \pi + O((b-b_c)\log(b-b_c)). \quad (1) \end{aligned}$$

where $K(k)$ is the complete elliptic integral of the first kind.

- By using $z \equiv 1 - r_0/r$, we obtain the same α as Eq. (1).

Conclusion

- Observables of gravitational lensing reflected by a photon sphere is characterizes by $\bar{a}$ and $\bar{b}$ in SDL.
- We have investigated a simpler SDL calculation than Bozza (2002) and obtained $\bar{a}$ and $\bar{b}$ analytically in some spacetimes.
- It can be apply ultrastatic spacetime like an Ellis wormhole spacetime.
- Our analytical result confirms a numerical method in Eiroa *et al.* (2002).
- The choice of the variable z is as important as the choice of the coordinates.
- **If you choose a proper variable z by yourself for a given spacetime, you may obtain $\bar{a}$ and $\bar{b}$ analytically.**

3a6. Chulmoon Yoo (Nagoya U.),

“PBH abundance from the random Gaussian curvature perturbation and a local density threshold” (10+5)

[JGRG27 (2017) 112819]

PBH abundance from the random Gaussian curvature perturbation and a local density threshold

Yoo, Chulmoon（Nagoya U.）

with Tomohiro Harada
Jaume Garriga
Kazunori Kohri

Primordial BHs

◎Remnant of primordial non-linear inhomogeneity

◎Trace the inhomogeneity in the early universe

◎May provide a fraction of dark matter and BH binaries

◎Several aspects

- -Inflationary models which provide a large number of PBHs
- -Threshold of PBH formation
- -Observational constraints on PBH abundance
- -Spin distribution of PBHs

Estimation of Abundance

◎Simplest conventional estimation

- Assumption 1:threshold is given by the amplitude of ζ
- Assumption 2:Gaussian distribution of ζ at each peak of ζ
- Production probability β_0

$$\beta_0 = 2\left(2\pi\sigma^2\right)^{1/2}\int_{|\zeta_{\rm th}|}^{\infty}\exp\left[-\frac{\zeta^2}{2\sigma^2}\right]d|\zeta| = {\rm erfc}\left(\frac{|\zeta_{\rm th}|}{\sqrt{2}\sigma}\right)$$

◎Questions

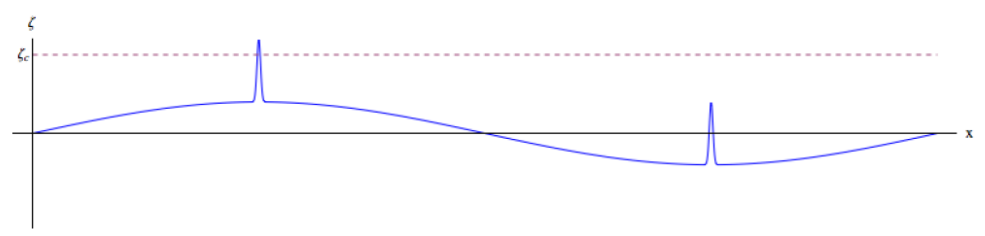
- Is giving the threshold by ζ appropriate?
- Is Gaussian distribution of ζ at each peak of ζ valid?

Threshold of Formation

◎Density perturbation δ VS Curvature perturbation ζ

◎Statistics of ζ is often well known

◎Ambiguity from super-horizon modes[Young et. al.(2014)]



⇒over estimate by many orders of magnitude

◎Threshold for δ seems better

Newtonian Analogy

◎$\zeta \sim \phi$:Newton potential, $\delta \sim \rho$: density

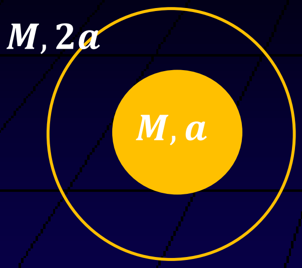
◎Case 1: homogeneous sphere with radius a, mass M

$\phi(r) = -\frac{GM}{r}$ for $r \geq a$

$\phi(r) = -\frac{3GM}{2a} + \frac{GM}{2a^3}r^2$ for $r < a$

$\Rightarrow \phi(0) = -\frac{3GM}{2a}$

◎Case 2: sphere + shell with radius $2a$, mass m



$\phi(r) = -\frac{2GM}{r}$ for $r \geq 2a$

$\phi(r) = -\frac{2GM}{a} + \frac{GM}{2a^3}r^2$ for $r < a$

$\Rightarrow \phi(0) = -\frac{2GM}{a}$

different

◎The potential($\phi \sim \zeta$) depends on environments

δ_{th} and Statistics of ζ

◎Threshold should be set by δ

◎Statistical properties are well known for ζ

◎What we have to do

- Statistics of ζ ⇒ probability of δ ⇒ PBH formation prob.
- w/ long-wavelength approx. and w/ linear approx. as a first step

◎Relation between ζ and δ w/ long-wavelength approx.

$$\delta = -\frac{4(1+w)}{3w+5}\frac{1}{a^2H^2}\, e^{5/2\zeta}\Delta e^{-\zeta/2}$$

comoving slicing, $p = w\rho$

Relation at an Extremum

◎Spatial metric

$$dl^2 = a^2 e^{-2\zeta}\tilde{\gamma}_{ij} dx^i dx^j$$

◎Taylor expansion of ζ

$$\zeta = \zeta_0 + \zeta_1^i x_i + \frac{1}{2}\zeta_2^{ij} x_i x_j + O(x^3)$$

◎Density perturbation at an extremum($\zeta_1^i = 0$)

$$\delta_{\rm ext} = \frac{2(1+w)}{3w+5}\frac{1}{a^2H^2}\, e^{2\zeta_0}\zeta_2 \quad \text{where } \zeta_2 = \zeta_2^{11} + \zeta_2^{22} + \zeta_2^{33}$$

◎Linear relation

$$\delta_{\rm ext} \simeq \frac{2(1+w)}{3w+5}\frac{1}{a^2H^2}\, \zeta_2$$

Horizon Entry

◎Scale of the perturbation:$1/k_*$

$$k_*^2 := -\zeta_2/\zeta_0 \qquad \zeta = \zeta_0 + \zeta_1^i x_i + \frac{1}{2}\zeta_2^{ij} x_i x_j + O(x^3)$$

- **cf. single Fourier mode** $\zeta_0 cos(k_* x) \simeq \zeta_0 - \frac{1}{2}k_*^2 x^2$
- **cf. Gaussian** $\zeta_0 \exp(-\frac{1}{2}k_*^2 x^2) \simeq \zeta_0 - \frac{1}{2}k_*^2 x^2$

◎Horizon entry condition

$k_* = qaH$ **with** $q = O(1)$**: uncertainty of horizon entry**

◎Density perturbation at horizon entry

$$\delta_{\rm ext} = \frac{2(1+w)}{3w+5}\frac{1}{a^2H^2}\, \zeta_2 \Rightarrow \quad \delta_{\rm H} = \frac{2(1+w)}{3w+5}\frac{\mu}{q} \quad \text{with} \quad \mu := -\zeta_0$$

◎Condition for PBH formation: $\delta_{\rm H} < \delta_{\rm th} \Rightarrow \mu_{\rm th} \coloneqq \frac{3{\rm w}+5}{2(1+{\rm w})} q\delta_{\rm th}$

Gaussian Dist. of ζ

[Bardeen et. al.(1986)]

◎Probability distribution of linear combinations of $\zeta(x^i)$

$$\mathcal{P}(V_I)\mathrm{d}^nV = (2\pi)^{-n/2}|\mathrm{det}\mathcal{M}|^{-1/2}\mathrm{exp}\left[-\frac{1}{2}V_I\left(\mathcal{M}^{-1}\right)^{IJ}V_J\right]\mathrm{d}^nV$$

correlation matrix: $\mathcal{M}_{IJ} = \int \frac{d\vec{k}}{(2\pi)^3}\frac{d\vec{k}'}{(2\pi)^3} < \tilde{V}_I\left(\vec{k}\right)\tilde{V}_J\left(\vec{k}'\right) >$

$$\tilde{V}_I\left(\vec{k}\right) = \int d^3x V_I(\vec{x})e^{i\vec{k}\vec{x}}$$

◎Non-zero correlations in pairs of ζ_0**,** ζ_1^i**,** ζ_2^{ij}

$$\sigma_0^2 := \int \frac{dk}{k}P(k) =< \zeta_0\zeta_0 >$$

$$\sigma_1^2 := \int \frac{dk}{k}k^2P(k) = -3 < \zeta_0\zeta_2^{ii} > = 3 < \zeta_1^i\zeta_1^i >$$

$\sigma_2^2 := \int \frac{dk}{k}k^4P(k) = 5 < \zeta_2^{ii}\zeta_2^{ii} > = 15 < \zeta_2^{ii}\zeta_2^{jj} >$ **with** $i \neq j$

Variable Transformations

$$\mathcal{P}(V_I)\mathrm{d}^nV = (2\pi)^{-n/2}|\mathrm{det}\mathcal{M}|^{-1/2}\mathrm{exp}\left[-\frac{1}{2}V_I\left(\mathcal{M}^{-1}\right)^{IJ}V_J\right]\mathrm{d}^nV$$

◎All 10 variables:$V_I = (\zeta_0, \zeta_1^1, \zeta_1^2, \zeta_1^3, \zeta_2^{11}, \zeta_2^{22}, \zeta_2^{33}, \zeta_2^{12}, \zeta_2^{23}, \zeta_2^{31})$

◎Changing variables and integrating w.r.t. some of them
⇒7variables

◎Imposing the horizon entry condition
⇒conditional pdf for 6 variables

$$\mathcal{P}\left(\vec{\xi}, \vec{\eta}\right)\mathrm{d}\vec{\xi}\mathrm{d}\vec{\eta} = \frac{5^{5/2}3^{7/2}}{2(2\pi)^2}|\xi_1|\xi_2(\xi_2^2 - \xi_3^2)$$
$$\mathrm{exp}\left[-\frac{1}{2}(\xi_1^2 + 15\xi_2^2 + 5\xi_3^2 + 3|\vec{\eta}|^2)\right]\mathrm{d}\vec{\xi}\mathrm{d}\vec{\eta}$$

◎Note: $\eta_i \sim \zeta_1$**(1st derivative),** $\xi_i \sim \zeta_2$**(2nd derivative)**

Peak Number Density

[Bardeen et. al.(1986)]

◎Number density distribution of extrema in $(\vec{x},\vec{\xi})$

$n_{\rm ext}\left(\vec{x},\vec{\xi}\right)\Delta\vec{\rm x}\Delta\vec{\xi}$:=**number of extrema in** $\Delta\vec{\rm x}\Delta\vec{\xi}$

$$\Rightarrow n_{\rm ext}\left(\vec{x},\vec{\xi}\right)d\vec{x}d\vec{\xi}=\sum_p\delta(\vec{x}-\vec{x}_p)\delta\left(\vec{\xi}-\vec{\xi}_p\right)d\vec{x}d\vec{\xi}$$

where $\vec{x}_p$: extremum position

$\vec{\xi}_p$:the value of ξ at the extremum

◎Extremum $\zeta^i_1=0\Rightarrow\eta_i=0\Rightarrow\delta(\vec{x}-\vec{x}_p)=\sigma_1^{-3}|\lambda_1\lambda_2\lambda_3|\delta(\vec{\eta})$

with $\lambda_1\lambda_2\lambda_3=\frac{1}{27}\left((\xi_1+\xi_3)^2-9\xi_2^2\right)(\xi_1-2\xi_3)\sigma_2^3$

cf. $\mathcal{P}(\xi_1,\xi_2,\xi_3,\eta_1,\eta_2,\eta_3)d\vec{\xi}d\vec{\eta}$

◎Averaged peak number density $n_{\rm pk}(\vec{\xi})$

$$n_{\rm pk}\left(\vec{\xi}\right)d\vec{\xi}:=<n_{\rm ext}\Theta(\lambda_3)>d\vec{\xi}$$

$$=\sigma_1^{-3}\left[\int d\vec{\xi}_pd\vec{\eta}\left(\mathcal{P}\left(\vec{\eta},\vec{\xi}_p\right)|\lambda_1\lambda_2\lambda_3|\delta(\vec{\eta})\delta\left(\vec{\xi}-\vec{\xi}_p\right)\Theta(\lambda_3)\right)\right]{\rm d}\vec{\xi}$$

PBH Number Density

◎Peak number density(3 variables)

$$n_{\rm pk}\left(\vec{\xi}\right)d\vec{\xi}:=<n_{ext}\Theta(\lambda_3)>d\vec{\xi}$$

$$=\sigma_1^{-3}\left[\int d\vec{\xi}_pd\vec{\eta}\left(\mathcal{P}\left(\vec{\eta},\vec{\xi}_p\right)|\lambda_1\lambda_2\lambda_3|\delta(\vec{\eta})\delta\left(\vec{\xi}-\vec{\xi}_p\right)\Theta(\lambda_3)\right)\right]{\rm d}\vec{\xi}$$

$$=\frac{5^{5/2}3^{1/2}}{2(2\pi)^2}\left(\frac{\sigma_2}{\sigma_1}\right)^3|\xi_1|\xi_2(\xi_2^2-\xi_3^2)[(\xi_1+\xi_3)^2-9\xi_2^2](\xi_1-2\xi_3)$$

$$\exp\left[-\frac{1}{2}(\xi_1^2+15\xi_2^2+5\xi_3^2)\right]\Theta(\xi_1-3\xi_2+\xi_3)d\vec{\xi}$$

◎PBH number density

$$\mathcal{N}_{\rm BH}=\int n_{\rm pk}\left(\vec{\xi}\right)\Theta(\xi_1-\kappa\mu_{\rm th})d\vec{\xi}$$

$$=\frac{3^{3/2}}{2(2\pi)^{3/2}}\left(\frac{\sigma_2}{\sigma_1}\right)^3\int_{\kappa\mu_{th}}^{\infty}f(u)u\exp\left[-\frac{1}{2}u^2\right]{\rm d}u$$

$$f(u)=\frac{1}{2}u(u^2-3)\left[{\rm erf}\left(\frac{1}{2}\sqrt{\frac{5}{2}}u\right)+{\rm erf}\left(\sqrt{\frac{5}{2}}u\right)\right]+\sqrt{\frac{2}{5\pi}}[\left(\frac{8}{5}+\frac{31}{4}u^2\right)\exp\left(-\frac{5}{8}u^2\right)+\left(-\frac{8}{5}+\frac{1}{2}u^2\right)\exp\left(-\frac{5}{2}u^2\right)]$$

PBH Fraction

◎**PBH number density**

$$\mathcal{N}_{\mathrm{BH}} = \frac{3^{3/2}}{2(2\pi)^{3/2}}\left(\frac{\sigma_2}{\sigma_1}\right)^3 \int_{\kappa\mu_{th}}^{\infty} f(u)u\exp\left[-\frac{1}{2}u^2\right]\mathrm{d}u$$

$$\simeq \frac{3^{3/2}}{2(2\pi)^{3/2}}\left(\frac{\sigma_2}{\sigma_1}\right)^3 \kappa^3\mu_{\mathrm{th}}^3 exp\left(-\frac{1}{2}\kappa^2\mu_{\mathrm{th}}^2\right)$$ **for large** $\kappa = k_*^2/\sigma_2$

◎**PBH fraction**

$$\beta_0 = \frac{\mathcal{N}_{\mathrm{BH}}M_{\mathrm{BH}}}{\rho a^3} = \mathcal{N}_{\mathrm{BH}}\frac{4}{3}\pi\alpha(aH)^{-3}$$

with $\alpha = \mathcal{O}(1)$**:uncertainty of** M_{BH}

Moments

◎**Flat spectrum**

$$P(k) = \sigma^2 = \mathrm{const.}$$

◎**Window functions**

$P(k) \to P(k)\left(W(k/k_*)\right)^2$ **with** $W_{CO}(kR) = \Theta(1 - \mathrm{kR})$

$W_G(kR) = \exp\left(-\frac{1}{2}k^2R^2\right)$

◎**Moments**

$$\sigma_1^2 = \int_0^{\infty}\mathrm{d}kk\left(W(kR)\right)^2\sigma^2 = \frac{\sigma^2}{2R^2}$$

$$\sigma_2^2 = \int_0^{\infty}\mathrm{d}kk^3\left(W(kR)\right)^2\sigma^2 = \frac{\sigma^2}{\varepsilon^2R^4}$$

◎$R = 1/k_*$

$\varepsilon = 2$ **for the simple cut-off**

$\varepsilon = \sqrt{2}$ **for the Gaussian**

PBH Fraction

◎**PBH fraction**

$$\beta_0 = \frac{2\sqrt{6}}{\sqrt{2\pi}}\alpha q^3 \varepsilon^{-3} \int_{\kappa\mu_{\rm th}}^{\infty} f(u) u \exp\left(-\frac{1}{2}u\right) du$$

$$\simeq \frac{2\sqrt{6}}{\sqrt{2\pi}}\alpha q^6 \left(\frac{\tilde{\mu}_{\rm th}}{\sigma}\right)^3 \exp\left(-\frac{1}{2\sigma^2}\varepsilon^2 q^2 \tilde{\mu}_{\rm th}^2\right)$$

where $\mu_{\rm th} = q\tilde{\mu}_{\rm th} = q\frac{3w+5}{2(1+w)}\delta_{\rm th}$

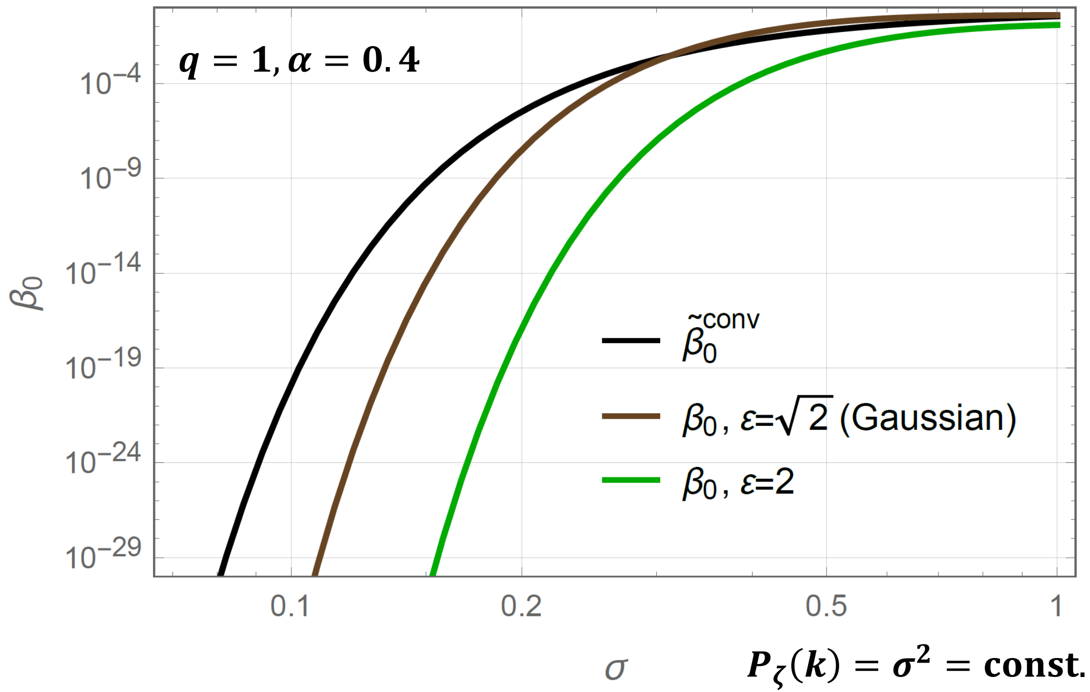
$$\kappa = \frac{k_*^2}{\sigma_2} = \varepsilon/\sigma$$

◎**Threshold value**[Harada et.al.(2013)]

$\delta_{\rm th} = \frac{3(1+w)}{5+3w}\sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right) = 0.4135$ **for** $w = 1/3$

$\Rightarrow \tilde{\mu}_{\rm th} = 0.9305$

Result



$P_\zeta(k) = \sigma^2 = \text{const.}$

smaller than the conventional one small σ

Discussion

◎Caveat: linear approximation cannot be justified

◎Ambiguity-1: Horizon entry(q)

◎Ambiguity-2: Window function(ε)

$$\beta_0 \sim \exp\left(-\frac{1}{2\sigma^2}\varepsilon^2 q^2 \tilde{\mu}_{\rm th}^2\right)$$

◎Possible(?) extension: Non-Gaussian

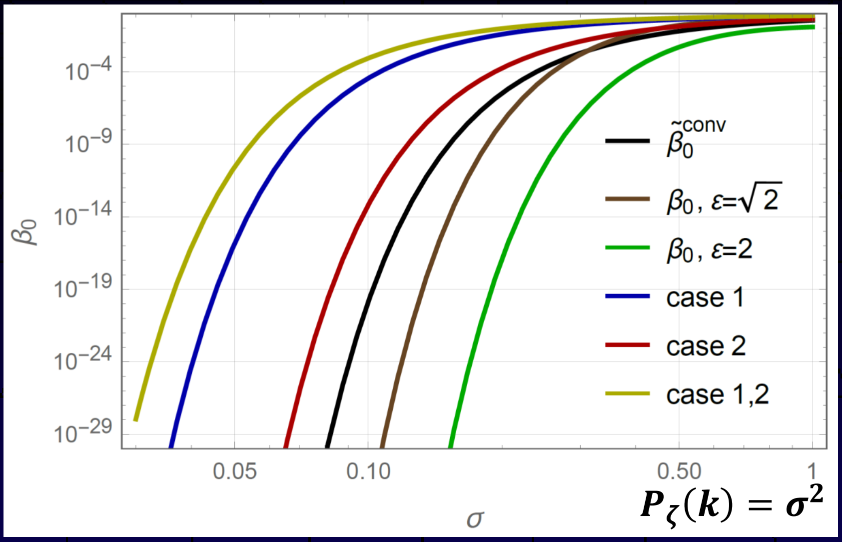
Significance of the Factor

◎How one may get an “optimistically” large abundance

$q = 1, \alpha = 0.4$

◎Optimistic order of estimate 1:$\sigma_\delta \sim \sigma = \sqrt{P(\zeta)} \Rightarrow \mu_{\rm th} = \delta_{\rm th}$

◎Optimistic order of estimate 2:$\delta_{\rm th} = 1/3$



Discussion

◎Caveat: linear approximation cannot be justified

◎Ambiguity-1: Horizon entry(q)

◎Ambiguity-2: Window function(ε)

$$\beta_0 \simeq \frac{2\sqrt{6}}{\sqrt{2\pi}}\alpha q^6 \left(\frac{\tilde{\mu}_{\rm th}}{\sigma}\right)^3 \exp\left(-\frac{1}{2\sigma^2}\varepsilon^2 q^2 \tilde{\mu}_{\rm th}^2\right)$$

◎Possible(?) extension: Non-Gaussian

Thank you
for your attention!

3a7. Keisuke Inomata (ICRR U. of Tokyo), “O(10)Msolar primordial black holes and string axion dark matter” (10+5)

[JGRG27 (2017) 112820]

O(10) solar mass PBHs and string axion DM

Institute for Cosmic Ray Research (ICRR),
University of Tokyo

Keisuke Inomata

Collaborated with
M.Kawasaki, K.Mukaida, Y.Tada, T.T.Yanagida

arXiv: 1709.07865

JGRG27 2017/11/28

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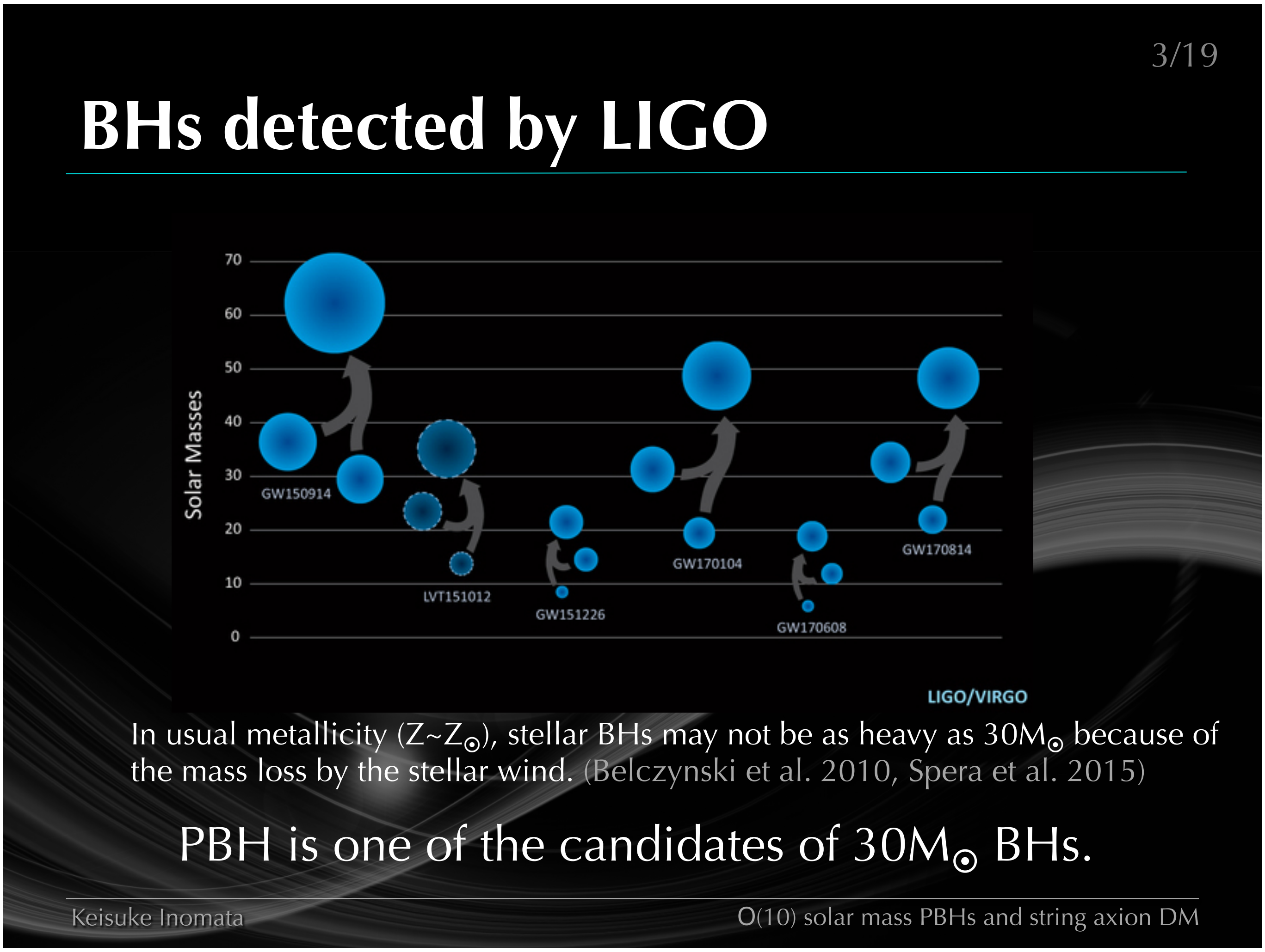
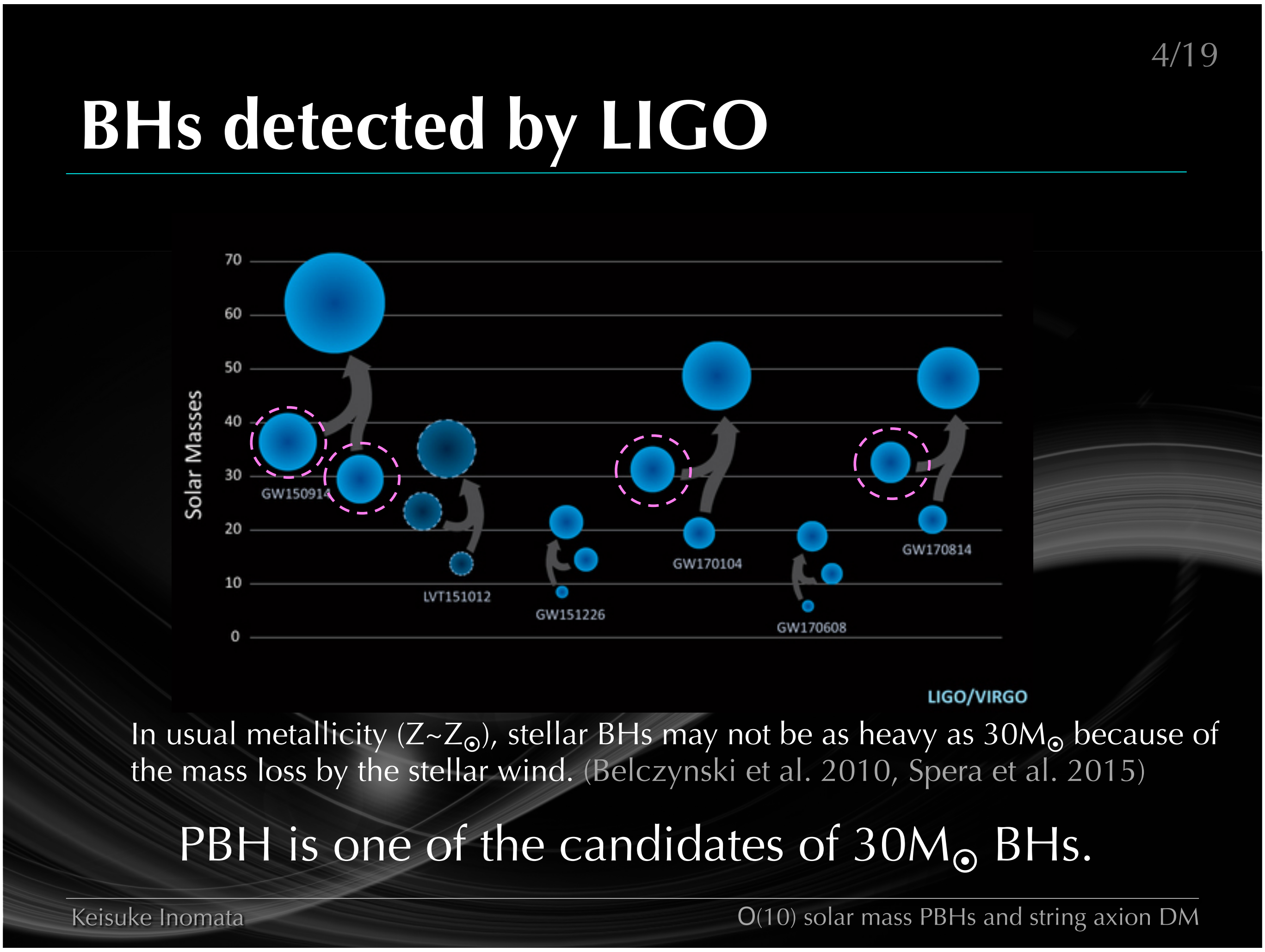


BHs detected by LIGO

In usual metallicity ($Z\sim Z_\odot$), stellar BHs may not be as heavy as $30M_\odot$ because of the mass loss by the stellar wind. (Belczynski et al. 2010, Spera et al. 2015)

PBH is one of the candidates of $30M_\odot$ BHs.



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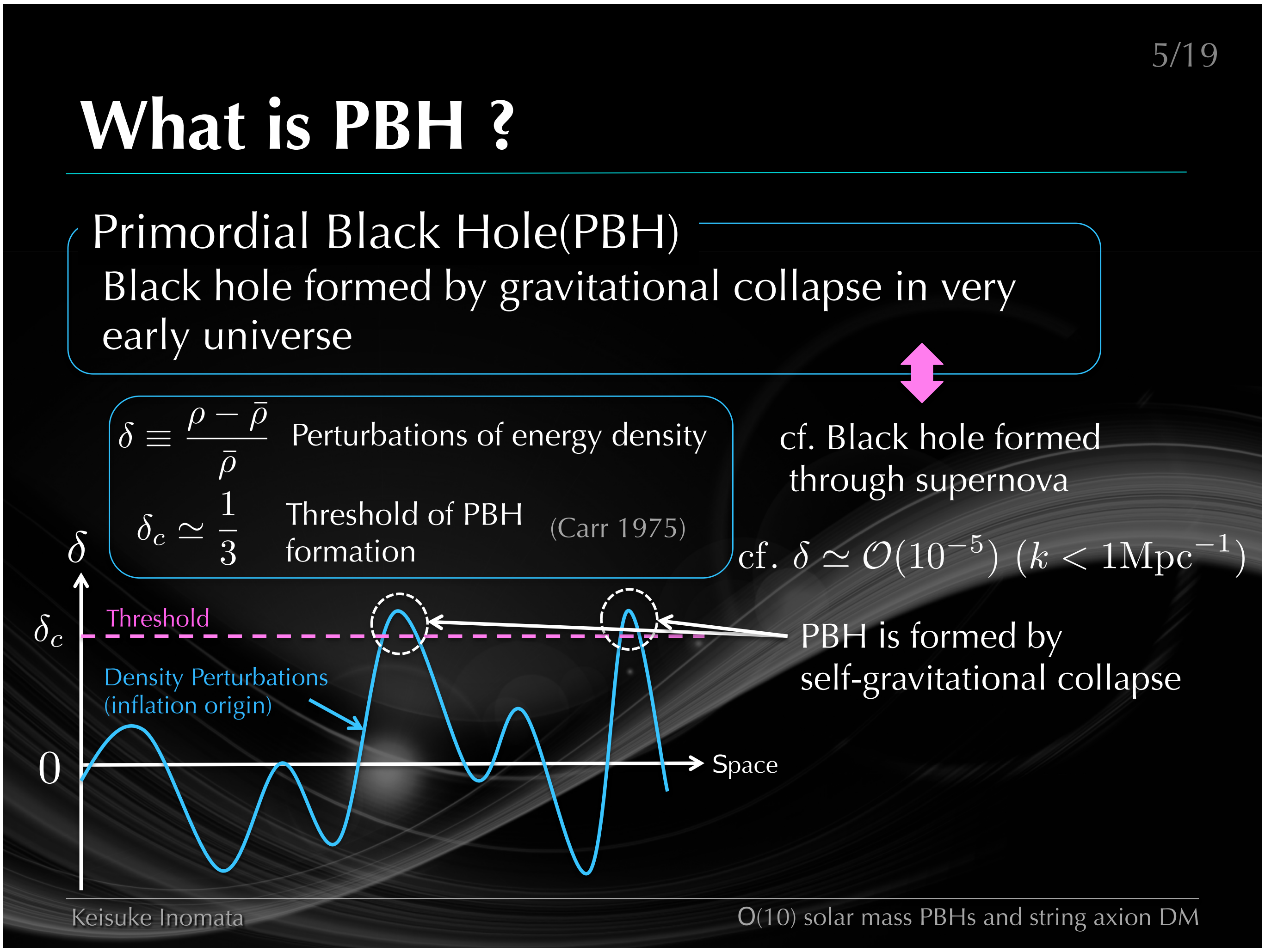


What is PBH ?

Primordial Black Hole(PBH)
Black hole formed by gravitational collapse in very early universe

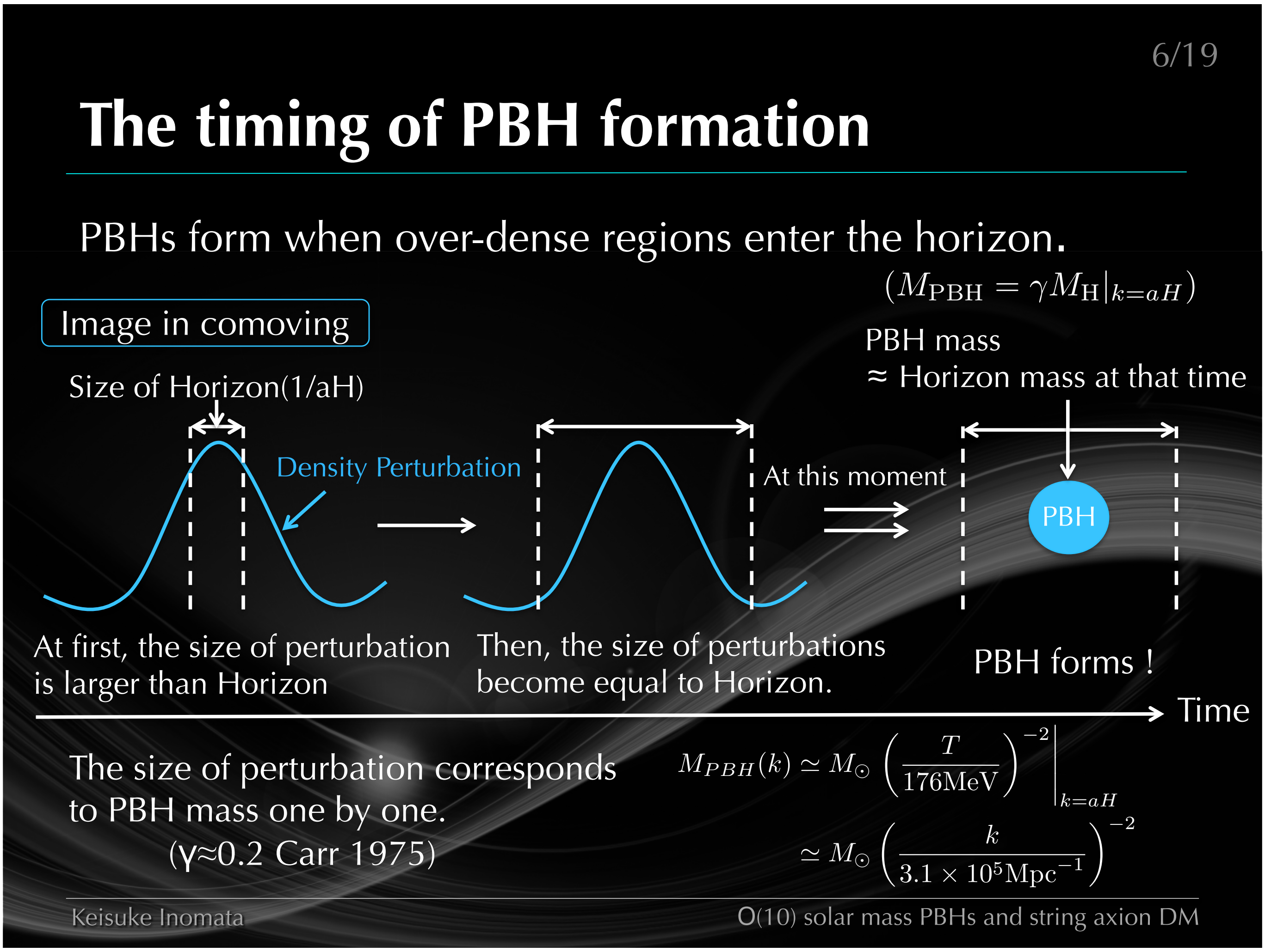
cf. Black hole formed through supernova

$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}$ Perturbations of energy density

$\delta_c \simeq \frac{1}{3}$ Threshold of PBH formation (Carr 1975)

cf. $\delta \simeq \mathcal{O}(10^{-5})$ $(k < 1\mathrm{Mpc}^{-1})$

PBH is formed by self-gravitational collapse



The timing of PBH formation

PBHs form when over-dense regions enter the horizon.

$(M_{\mathrm{PBH}} = \gamma M_{\mathrm{H}}|_{k=aH})$

PBH mass
≈ Horizon mass at that time

Image in comoving

At first, the size of perturbation is larger than Horizon

Then, the size of perturbations become equal to Horizon.

PBH forms !

The size of perturbation corresponds to PBH mass one by one.
(γ≈0.2 Carr 1975)

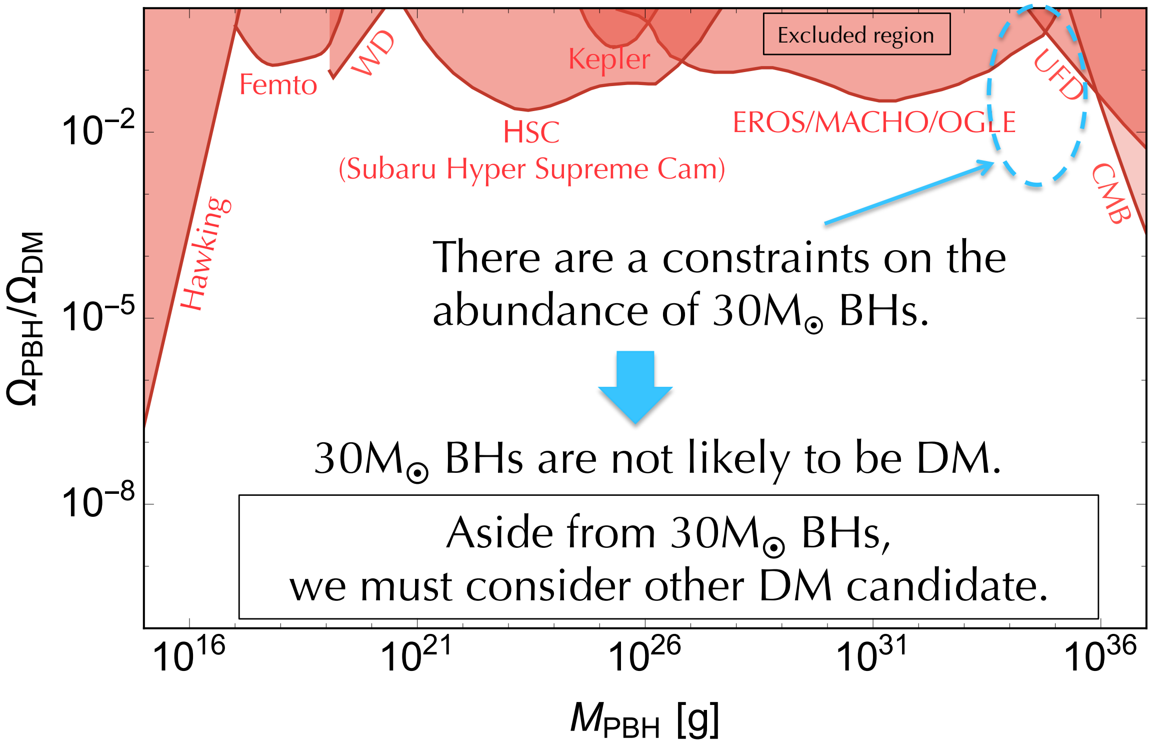
$$M_{PBH}(k) \simeq M_\odot \left(\frac{T}{176\mathrm{MeV}}\right)^{-2}\Bigg|_{k=aH}$$

$$\simeq M_\odot \left(\frac{k}{3.1\times 10^5\mathrm{Mpc}^{-1}}\right)^{-2}$$

Contents

- PBHs for LIGO events
- DM candidates in the presence of PBHs
- O(10) solar mass PBHs and string axion DM
- Summary

Can 30 Solar mass BHs be DM ?



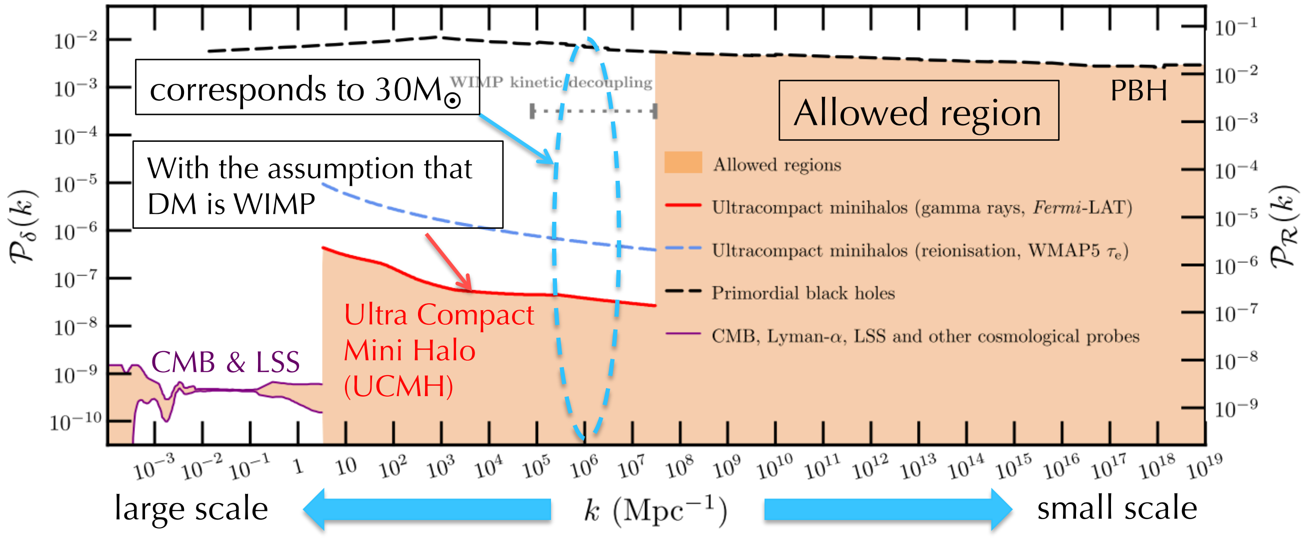
There are a constraints on the abundance of $30M_{\odot}$ BHs.

$30M_{\odot}$ BHs are not likely to be DM.

Aside from $30M_{\odot}$ BHs,
we must consider other DM candidate.

Is WIMP DM ?

Bringmann, Scott, Akrami, Phys.Rev. D85 (2012) 125027



If DM is WIMP, the perturbations corresponding to $30M_\odot$ PBHs are severely constrained by UCMH. → NO $30M_\odot$ PBHs

---

$30M_\odot$ PBHs and DM

What DM is consistent with $30M_\odot$ PBHs?

- $30M_\odot$ PBHs ✖
- WIMP ✖
- $10^{-13}M_\odot$ PBHs ○ (Inomata et al. arXiv:1711.06129)
- axion ○ (What this talk is about)
- …

In the following,
we show the concrete inflation model in which $30M_\odot$ PBHs and axion DM can coexist.

Contents

- PBHs for LIGO events
- DM candidates in the presence of PBHs
- O(10) solar mass PBHs and string axion DM
- Summary

String axion

In general, axion can solve the strong CP problem and explain DM by its coherent behavior.

However

$U(1)_{PQ}$ symmetry can be explicitly broken by the Planck suppressed operators aside from QCD anomaly.

We need to control Planck-scale physics.

(Barr and Seckel 1992, Kamionkowski and March-Russell 1992, Holman et al. 1992)

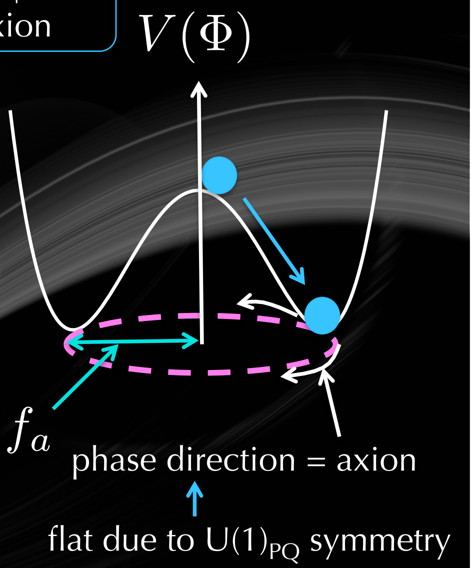
In string theory, after string compactification, axions with f_a~$O(10^{16}GeV)$ appear.

(Conlon 2006, Svrcek and Witten 2006, Choi and Jeong 2006)

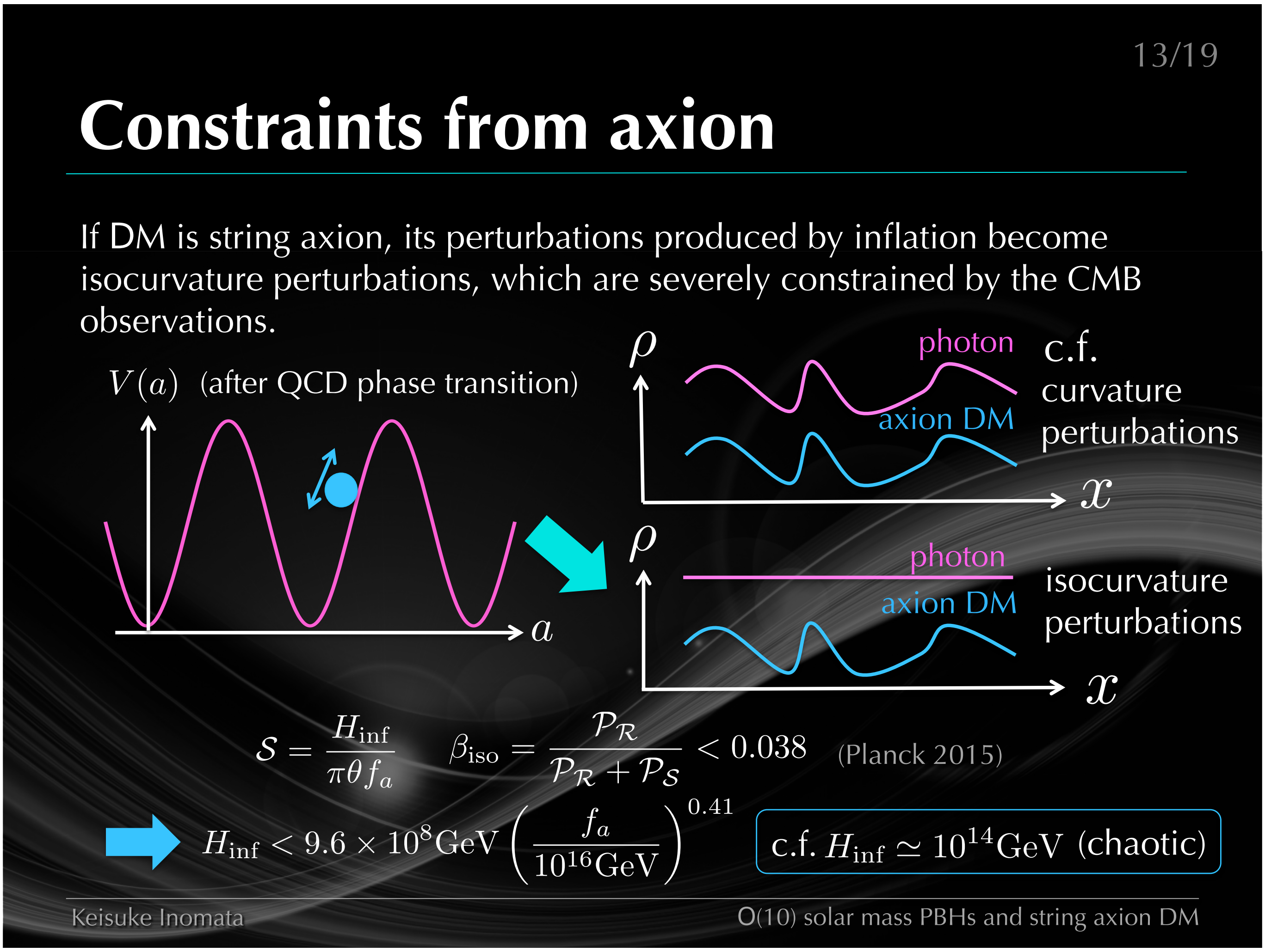
String axion may provide the platform to discuss the quality of $U(1)_{PQ}$ symmetry in the low energy theory. (Choi et al. 2011, Honecker et al. 2014)

$\Phi = |\Phi| e^{ia/f_a}$

a : axion



Constraints from axion



If DM is string axion, its perturbations produced by inflation become isocurvature perturbations, which are severely constrained by the CMB observations.

c.f. curvature perturbations

isocurvature perturbations

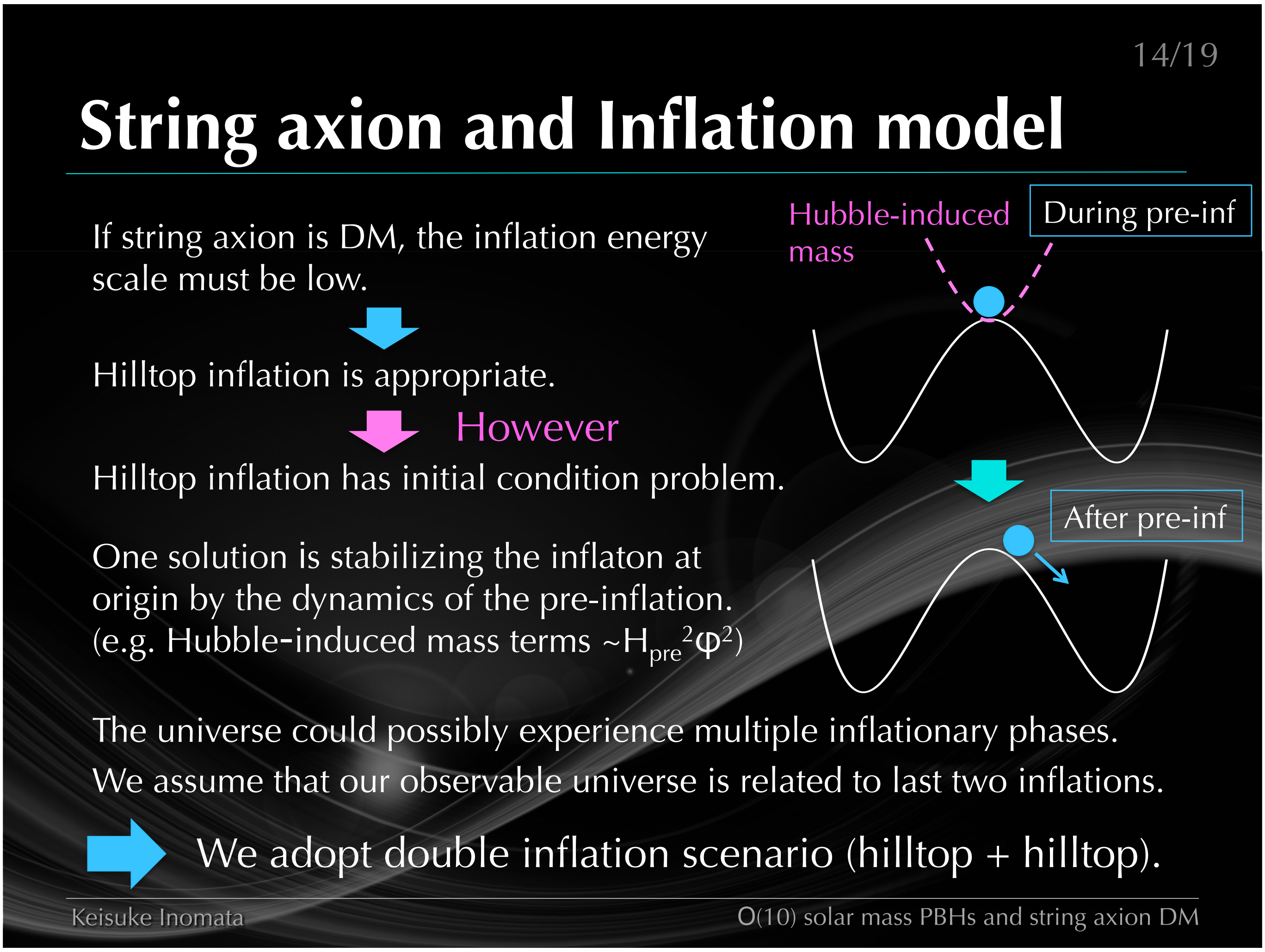
$$\mathcal{S} = \frac{H_{\rm inf}}{\pi\theta f_a} \qquad \beta_{\rm iso} = \frac{\mathcal{P}_\mathcal{R}}{\mathcal{P}_\mathcal{R}+\mathcal{P}_\mathcal{S}} < 0.038$$

(Planck 2015)

➡ $H_{\rm inf} < 9.6\times 10^{8}{\rm GeV}\left(\frac{f_a}{10^{16}{\rm GeV}}\right)^{0.41}$

c.f. $H_{\rm inf} \simeq 10^{14}{\rm GeV}$ (chaotic)

String axion and Inflation model



If string axion is DM, the inflation energy scale must be low.

↓

Hilltop inflation is appropriate.

↓ However

Hilltop inflation has initial condition problem.

One solution is stabilizing the inflaton at origin by the dynamics of the pre-inflation.
(e.g. Hubble-induced mass terms ~$H_{\rm pre}^2\varphi^2$)

The universe could possibly experience multiple inflationary phases.
We assume that our observable universe is related to last two inflations.

➡ We adopt double inflation scenario (hilltop + hilltop).

Double Inflation Model (Kawasaki et al 1998)

Inflaton: χ, ϕ $(M_{\rm Pl} = 1)$

Lagrangian:

$$\mathcal{L} = -\frac{1}{2}(1 - \frac{c_{\rm kin}}{2M_{\rm Pl}^2}\phi^2)\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\chi, \phi)$$

Potential:

$$V(\chi, \phi) = V_{\rm hill,1}(\chi) + V_{\rm hill,2}(\phi) + V_{\rm stb}(\chi, \phi)$$

$\varphi_1 = \chi, \varphi_2 = \phi$

$$V_{{\rm hill},i}(\varphi_i) = v_i^4\left(-\frac{\varphi_i}{\varphi_{l,i}} - \frac{\varphi_i^2}{\varphi_{q,i}^2} + \left(1 - \frac{\varphi_i^3}{\varphi_{{\rm min},i}^3}\right)^2\right)$$

$$V_{\rm stb}(\chi, \phi) = \underline{c_{\rm pot}\frac{V_{\rm new,1}(\chi)}{2}\phi^2}$$

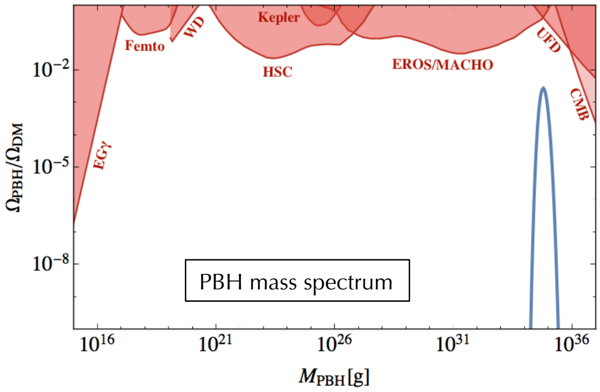
This term stabilizes ϕ at origin during first new inflation

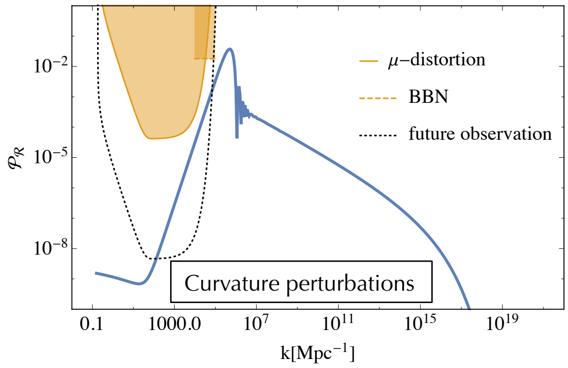
First hilltop inflation → Second hilltop inflation → produce PBHs

χ large scale perturbations

ϕ small scale perturbations

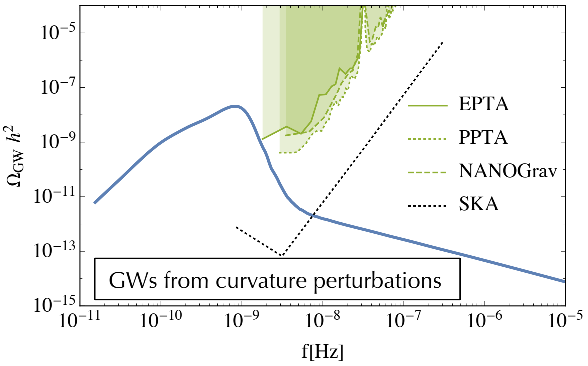
The results for appropriate parameters



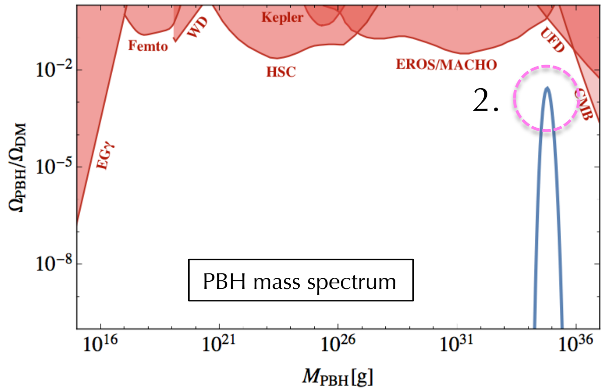


We have checked that the spectrums

1. avoid the isocurvature constraints ($H_{\rm inf}$=10^9GeV)
2. predict the sizable amount of PBHs ($\Omega_{\rm PBH}/\Omega_{\rm DM}$=O($10^{-3}$) (Sasaki et al. 2016))
3. avoid the constraints from mu-distortion and pulsar timing array (PTA)
4. be consistent with CMB observation on large scale (A_s,n_s,r)



The results for appropriate parameters



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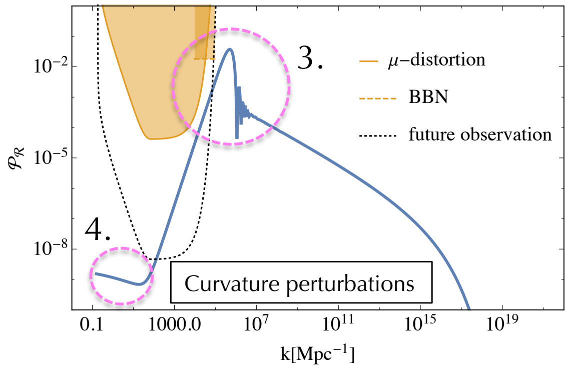

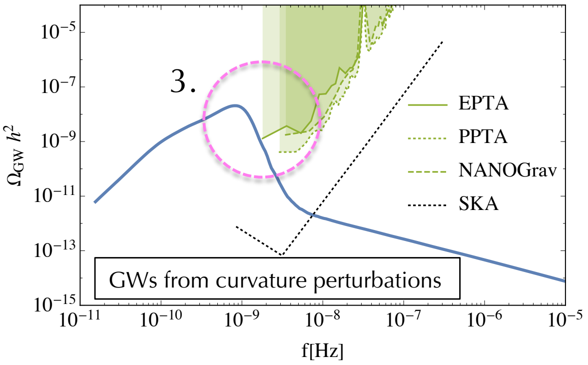

Contents

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Summary

What we did

We have discussed DM in the presence of O(10)$M_\odot$ PBHs.
In particular, we have focused on string axion DM.

Conclusion

In the double inflation model, O(10)$M_\odot$ PBHs and string axion DM can coexist.
We have also checked that the result is consistent with observational constraints, which come from CMB anisotropy, mu-distortion and pulsar timing array.

Session3b 14:00–15:45

[Chair: Hideo Kodama]

3b1. Yota Watanabe (Kavli IPMU, YITP),
“Stable cosmology in chameleonic bigravity” (10+5)
[JGRG27 (2017) 112821]

Stable cosmology in chameleonic bigravity

Yota Watanabe (Kavli IPMU, YITP)

JGRG27, Hiroshima, 28 Nov 2017

Based on 1711.04655
with A. DeFelice,
S. Mukohyama,
M. Oliosi

Contents

1. Bigravity
2. Chameleon extension
3. Stability conditions
4. Numerical realization

Introduction: GW era has come!

- Direct detection of Gravitational Wave (GW) : New test of gravitational theories
  - in the strong-field regime
  - propagated on cosmological scale

- Important to study theoretical consistency of a model which predicts different phenomena from GR

- A theory of massive spin-2 field is interesting
  - Theory construction is nontrivial
  - Different GW waveform could be detected

Fierz, Pauli (1939)
van Dam, Veltman (1970), Zakharov (1970)
Vainshtein (1972), Boulware, Deser (1972)
de Rham, Gabadadze, Tolley (2010)

Bigravity

Hassan, Rosen 1109.3515

Ghost-free theory of massive spin-2 field with FLRW sol.

$$S[g_{\mu\nu}, f_{\mu\nu}] = S_{\mathrm{EH},g} + S_{\mathrm{EH},f} + S_{\mathrm{int}} + S_{\mathrm{mat}}$$

$$S_{\mathrm{EH},g} = \frac{M_g^2}{2}\int d^4x\sqrt{-g}R[g]$$

$$S_{\mathrm{EH},f} = \frac{\kappa M_g^2}{2}\int d^4x\sqrt{-f}R[f]$$

$$S_{\mathrm{int}} = M_g^2 m^2 \int d^4x\sqrt{-g}\Sigma_{i=0}^{4}\beta_i U_i$$

β_i: constant

$$U_0 = 1, \qquad U_1 = T_1, \qquad U_2 = \frac{1}{2}(T_1^2 - T_2),$$

$$U_3 = \frac{1}{6}(T_1^3 - 3T_1^2 + 2T_3),$$

$$U_4 = \frac{1}{24}(T_1^4 - 6T_1^2T_2 + 3T_2^2 + 8T_1T_3 - 6T_4),$$

$$T_n = \mathrm{Tr}[s^n], \qquad s = \sqrt{g^{-1}f}$$

○ One massless tensor, one massive tensor
→ “graviton oscillation” analogous to ν oscillation

DeFelice, Nakamura, Tanaka 1304.3920
Narikawa, Ueno, Tagoshi, Tanaka, Kanda, Nakamura 1412.8074

○ Cosmological constant is included in S_{int}

Chameleon bigravity

DeFelice, Mukohyama, Uzan 1702.04490

➢ Original bigravity is valid

1) for (Energy scale) $\lesssim \left(M_g m^2\right)^{1/3}$

: m must be large, but then phenomena are almost the same as GR, not interesting

2) for $H^2 \lesssim m_{\mathrm{Tensor}}^2$: cannot be applied to early universe

3) with fine-tuning to pass solar-system tests (Vainshtein screening) keeping m small

DeFelice, Nakamura, Tanaka 1304.3920

➢ Chameleon extension

i) Introduce scalar ϕ

ii) $\beta_i \to \beta_i(\phi)$

iii) Couple matter to $\tilde{g}_{\mu\nu} = A^2(\phi)g_{\mu\nu}$

Khoury, Weltman 0309300, 0309411

→ Potential minimum of ϕ depends on matter density ρ

↓

$$\boxed{m_{\mathrm{Tensor}}^2(\beta_i) \propto \rho}$$

Outline of our work

- Stability condition of chameleon bigravity was studied only around de Sitter DeFelice, Mukohyama, Uzan 1702.04490

- Our work: DeFelice, Mukohyama, Oliosi, YW 1711.04655
  - derive stability conditions
    1) of rad/ mat era under homogeneous perturbations
    2) of inhomogeneous perturbations around FLRW
  - 3) numerical realization of stable cosmology
    (not compared with obs. data)

(1/3) Stability of rad/mat era

- Rad/mat era must last long enough.
  Scaling solution of each era
  : every term in background EoM has the same time dependence for $a(t) \sim t^{2/n}$

$$n = \begin{cases} 4 \text{ (rad)} \\ 3 \text{ (mat)} \end{cases}$$

$$\begin{cases} \ln h = \ln h_0 - \frac{n}{2} N_e + \epsilon\, h^{(1)} \\ \varphi = \frac{n}{\lambda} N_e (1 + \epsilon\, \varphi^{(1)}) \\ \xi = \bar{\xi}(1 + \epsilon\, \xi^{(1)}) \\ c = c^{(0)}(1 + \epsilon\, c^{(1)}) \end{cases}$$

$\mathcal{O}(\epsilon)$: perturbations

$$ds_g^2 = -dt^2 + a^2 d\boldsymbol{x}^2$$

$$ds_f^2 = \xi^2(-c^2 dt^2 + a^2 d\boldsymbol{x}^2)$$

$h = H/m,$ $\varphi = \phi/M_g,$

$N_e = \ln a,$ $' = d/dN_e$

$\bar{\xi}, c^{(0)}$: constants

EoM

$$\begin{cases} \varphi^{(1)\prime\prime} + \left(1 + \frac{2}{N_e}\right) \varphi^{(1)\prime} + \mathcal{A}_r \varphi^{(1)} = 0 \text{ (rad)} \\ \varphi^{(1)\prime\prime} + \left(\frac{3}{2} + \frac{2}{N_e}\right) \varphi^{(1)\prime} + \mathcal{A}_m \varphi^{(1)} = 0 \text{ (mat)} \end{cases}$$

Stability conditions

$$\boxed{\mathcal{A}_r > 0, \mathcal{A}_m > 0}$$

(2/3) Stability of inhomo. pert.

- Flat FLRW + inhomogeneous perturbation

$$ds_g^2 = -\mathcal{N}^2 dt^2 + \gamma_{ij}(\mathcal{N}^i dt + dx^i)(\mathcal{N}^j dt + dx^j) \qquad \mathcal{N} = N(1+\Phi)$$

$$ds_f^2 = -\tilde{\mathcal{N}}^2 dt^2 + \tilde{\gamma}_{ij}(\tilde{\mathcal{N}}^i dt + dx^i)(\tilde{\mathcal{N}}^j dt + dx^j) \qquad \tilde{\mathcal{N}} = N\xi c\left(1+\tilde{\Phi}\right)$$

$$\phi = \bar{\phi} + \delta\phi \qquad \psi_{\mathrm{rad/mat\cdot}} = \bar{\psi}_{\mathrm{rad/mat}} + \delta\psi_{\mathrm{rad/mat}} \qquad \gamma_{ij} = a^2\delta_{ij} + \delta\gamma_{ij}$$

$$\tilde{\gamma}_{ij} = \xi^2 a^2 \delta_{ij} + \delta\tilde{\gamma}_{ij}$$

- Tensor sector

$\delta\gamma_{ij} = h_{ij}$, $\delta\tilde{\gamma}_{ij} = \tilde{h}_{ij}$: Transverse traceless

$$\mathcal{L}_T^{(2)} = \frac{M_g^2 N a^3}{8}\left[\frac{\dot{h}^{ij}\dot{h}_{ij}}{N^2} - \frac{k^2}{a^2}h^{ij}h_{ij} + \frac{\kappa\xi^2}{c}\left(\frac{\dot{\tilde{h}}^{ij}\dot{\tilde{h}}_{ij}}{N^2} - c^2\frac{k^2}{a^2}\tilde{h}^{ij}\tilde{h}_{ij}\right) - m^2\Gamma\left(h-\tilde{h}\right)^{ij}\left(h-\tilde{h}\right)_{ij}\right]$$

$$\Gamma = -[\beta_1\xi + (1+c)\beta_2\xi^2 + c\beta_3\xi^3]$$

No-ghost condition for $\tilde{h}_{ij}$ → $\boxed{c > 0}$

$$m_T^2 = \frac{c+\kappa\xi^2}{\kappa\xi^2} m^2\Gamma$$

(2/3) Stability of inhomo. pert.

- Vector sector

$$\mathcal{N}^i = B^i, \qquad \delta\gamma_{ij} = \frac{1}{2}(\partial_i E_j + \partial_j E_i),$$

$$\tilde{\mathcal{N}}^i = \tilde{B}^i, \qquad \delta\tilde{\gamma}_{ij} = \frac{1}{2}(\partial_i \tilde{E}_j + \partial_j \tilde{E}_i),$$

: Transverse modes

Integrate out non-dynamical modes $B_i, \tilde{B}_i$

$$\mathcal{L}_V^{(2)} = \frac{M_g^2 N a^3}{8} \mathrm{A}\left[\frac{\dot{\mathcal{E}}^i\dot{\mathcal{E}}_i}{N^2} - \left(c_V^2\frac{k^2}{a^2} + m_V^2\right)\mathcal{E}^i\mathcal{E}_i\right] \qquad \mathcal{E}_i = E_i - \tilde{E}_i$$

$$m_V^2 = m_T^2$$

$$\mathrm{A} = \frac{m^2\kappa\xi^2 J k^2}{(c+1)\kappa\xi k^2/a^2 + 2m^2(c+\kappa\xi^2)J} \qquad c_V^2 = \frac{(c+1)\Gamma}{2\xi J}$$

$$J = -[\beta_1 + 2\beta_2\xi + \beta_3\xi^2]$$

No-ghost condition → $\boxed{J > 0}$

No-gradient-instability condition→ $\boxed{\Gamma > 0}$

(2/3) Stability of inhomo. pert.

➢Scalar sector

$$\Phi, \qquad \mathcal{N}^i = \partial^i B, \qquad \delta\gamma_{ij} = 2\Psi\delta_{ij} + \left(\partial_i\partial_j - \tfrac{\Delta}{3}\delta_{ij}\right)E,$$

$$\tilde{\Phi}, \qquad \tilde{\mathcal{N}}^i = \partial^i \tilde{B}, \qquad \delta\tilde{\gamma}_{ij} = 2\tilde{\Psi}\delta_{ij} + \left(\partial_i\partial_j - \tfrac{\Delta}{3}\delta_{ij}\right)\tilde{E},$$

Integrate out non-dynamical modes $\Phi, \tilde{\Phi}, B, \tilde{B}, \tilde{\Psi}$
Gauge $\Psi = E = 0$

$$\mathcal{L}_S^{(2)} = \frac{Na^3}{2}\left[\frac{\dot{\mathcal{Y}}^T}{N}\mathcal{K}\frac{\dot{\mathcal{Y}}}{N} + \frac{\dot{\mathcal{Y}}^T}{N}\mathcal{F}\mathcal{Y} - \mathcal{Y}^T\mathcal{F}\frac{\dot{\mathcal{Y}}}{N} - \mathcal{Y}^T\mathcal{M}\mathcal{Y}\right], \qquad \mathcal{Y} = (\tilde{E}\ \delta\phi\ \psi_{\rm rad}\ \psi_{\rm mat})^T$$

- ○ No-ghost condition: Eigenvalues of $\mathcal{K}$ >0 in high k limit
  → Null-Energy Condition for fluids & one nontrivial condition
- ○ No-grad-instability condition:

$$\det\left[c_s^2\frac{k^2}{a^2}\mathcal{K} + \mathcal{M}\right]_{\text{high } k} = 0 \quad \Rightarrow \quad \boxed{c_s^2 > 0}$$

(3/3) Numerical realization

➢Simple couplings

$$\beta_i(\phi) = -c_i e^{-\lambda\varphi}, \quad A(\phi) = e^{\beta\varphi} \qquad c_i, \lambda, \beta\text{: constants}$$

Approximate scaling solution for mat. dom.→ $\beta \approx 0$

➢Example parameters (The other parameters are determined by EoM)

$$c_{\rm ini} = 1.01, \quad c_V^2 = 1, \quad c_1c_3 - c_2^2 = 1, \quad c_1 + 2c_2 + c_3 = 1,$$

$$\Omega_{\Lambda,\rm ini} = 10^{-30}, \quad \Omega_{\rm m,ini} = 10^{-5}, \quad \Omega_{\varphi\rm kin,ini} = \frac{3}{200}, \quad \Omega_{\rm GravPot,ini} = \frac{1}{200},$$

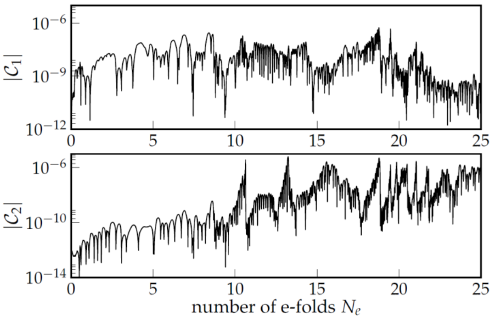
$$\beta = 10^{-2}, \qquad \lambda = 40/3,$$

➢Constraints $\mathcal{C}_1, \mathcal{C}_2$

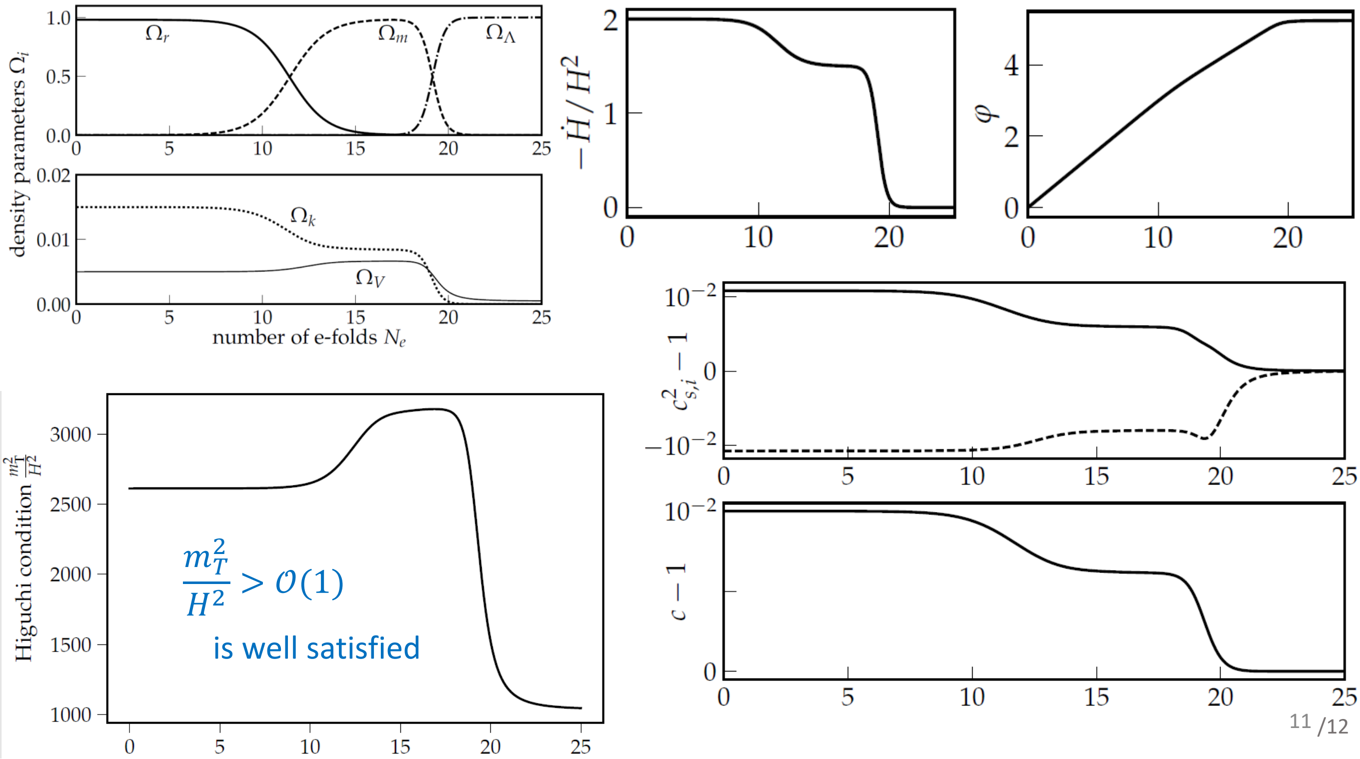
$$\mathcal{C}_1 = \frac{1 - \Sigma_i\Omega_i}{1 + \Sigma_i|\Omega_i|}$$

:Normalized Friedmann eq for $g_{\mu\nu}$

Similarly define $\mathcal{C}_2$ for $f_{\mu\nu}$



(3/3) Numerical realization



$$\frac{m_T^2}{H^2} > \mathcal{O}(1)$$

is well satisfied

Summary

- Bigravity: nontrivial theory of a massive spin-2 field
  But not valid at early universe/solar system
  keeping mass small w/o fine-tuning
- Chameleon bigravity: introduce ϕ,
  its potential minimum depends on environment
  → Graviton mass depends on environment
- Derived stability conditions
  1) of rad/mat era under homogeneous perturbation
  2) of inhomogeneous perturbation around FLRW
- Numerically realize stable cosmology

3b2. Michele Oliosi (YITP Kyoto U.),

“Horndeski extension of the minimal theory of quasidilaton massive gravity” (10+5)

[JGRG27 (2017) 112822]

Minimal theory of quasidilaton massive gravity

JGRG 27, 17.11.28
M. Oliosi (YITP)

Based on

Minimal theory of quasidilaton massive gravity

arXiv 1701.01581

Horndeski extension of the minimal theory of quasidilaton massive gravity

arXiv 1709.03108

Minimal quasidilaton

- A theory of massive gravity + scalar field
- Free of Boulware-Deser ghost
- Breaks Lorentz invariance (LI) to propagate 2 tensor and 1 scalar modes, instead of 6 d.o.f.
- Has the quasidilatation global symmetry
- Modifies gravity at cosmological scales

Construction

i. Start from dRGT massive gravity

ii. Break LI and add the quasidilaton.

iii. Switch to Hamiltonian and analyse "*à la Dirac*"

iv. Add constraints so that the final number of degrees of freedom is 3 "*à la MTMG*".

v. This defines the minimal theory.

dRGT theory (arXiv:1011.1232)

de Rham,
Gabadadze,
Tolley

Contract the physical metric with a new **fiducial metric** $f_{\mu\nu}$

$$\bar{\mathcal{K}}^{\mu}{}_{\rho}\bar{\mathcal{K}}^{\rho}{}_{\nu} = f^{\mu\rho}g_{\rho\nu}\,, \qquad \bar{\mathcal{K}}^{\mu}{}_{\rho}\bar{\mathfrak{K}}^{\rho}{}_{\nu} = \delta^{\mu}_{\nu}$$

Thanks to the special form of the potential, **no Boulware-Deser ghost**.

Propagates 5 d.o.f.

LI breaking form

With ADM decomposition $f_{\mu\nu} \to M,\, M_i,\, \tilde{\gamma}_{ij}$

$g_{\mu\nu} \to N,\, N_i,\, \gamma_{ij}$

$$\mathcal{L}_m = \frac{M_{\rm P}^2}{2}\sum_{i=0}^{4}\mathcal{L}_i$$

$$\mathcal{L}_0 = -m^2 c_0\sqrt{\tilde{\gamma}}\,M\,,$$

$$\mathcal{L}_1 = -m^2 c_1\sqrt{\tilde{\gamma}}\,(N + Me^{\alpha\sigma/M_{\rm P}}\mathcal{K})\,,$$

$$\mathcal{L}_2 = -m^2 c_2\sqrt{\tilde{\gamma}}\left[N\mathcal{K} + \frac{1}{2}Me^{\alpha\sigma/M_{\rm P}}(\mathcal{K}^2 - \mathcal{K}^i{}_j\mathcal{K}^j{}_i)\right],$$

$$\mathcal{L}_3 = -m^2 c_3\sqrt{\gamma}\,(N\,\mathfrak{K} + Me^{\alpha\sigma/M_{\rm P}})\,,$$

$$\mathcal{L}_4 = -m^2 c_4\sqrt{\gamma}N\,.$$

…as in MTMG (De Felice & Mukohyama, arXiv 1506.01594)

Quasidilaton (arXiv 1206.4253)

The Stückelberg fields ϕ^a can be introduced to recover covariance

$$f_{\mu\nu} = \eta_{ab}\partial_\mu\phi^a\partial_\nu\phi^b$$

The Stückelberg sector is shift- and SO(3) symmetric.

Add an **additional global symmetry** in the action. It acts on the Stückelberg fields as

$$\sigma \to \sigma + \sigma_0\,, \quad \phi^i \to \phi^i e^{-\sigma_0/M_{\rm P}}\,, \quad \phi^0 \to \phi^0 e^{-(1+\alpha)\sigma_0/M_{\rm P}}$$

quasidilaton scalar!

LI breaking

Precursor action

Defining a precursor action is the first step in constructing the minimal theory.

$$\boxed{\mathcal{L}_{\rm pre} = \mathcal{L}_{\text{E-H}} + \mathcal{L}_m + \mathcal{L}_\sigma}$$

$$\mathcal{L}_{\text{E-H}} = \frac{M_{\rm P}^2}{2}\sqrt{-g}R[g]$$

$$\mathcal{L}_\sigma = \sqrt{-g}\left[F(X,S) + \chi\,(X - \mathfrak{X}) + \theta S + g^{\mu\nu}\partial_\mu\theta\partial_\nu\sigma\right]$$

We can include a cubic Horndeski structure !

$$\mathcal{L}_m = \frac{M_{\rm P}^2}{2}\sum_{i=0}^{4}\mathcal{L}_i\,,$$

$$\mathcal{L}_0 = -m^2c_0e^{(4+\alpha)\sigma/M_{\rm P}}\,\sqrt{\tilde{\gamma}}\,M\,,$$

$$\mathcal{L}_1 = -m^2c_1e^{3\sigma/M_{\rm P}}\,\sqrt{\tilde{\gamma}}\,(N + Me^{\alpha\sigma/M_{\rm P}}\mathcal{K})\,,$$

$$\mathcal{L}_2 = -m^2c_2e^{2\sigma/M_{\rm P}}\,\sqrt{\tilde{\gamma}}\left[N\mathcal{K} + \frac{1}{2}Me^{\alpha\sigma/M_{\rm P}}(\mathcal{K}^2 - \mathcal{K}^i{}_j\mathcal{K}^j{}_i)\right]\,,$$

$$\mathcal{L}_3 = -m^2c_3e^{\sigma/M_{\rm P}}\sqrt{\gamma}\,(N\,\mathfrak{K} + Me^{\alpha\sigma/M_{\rm P}})\,,$$

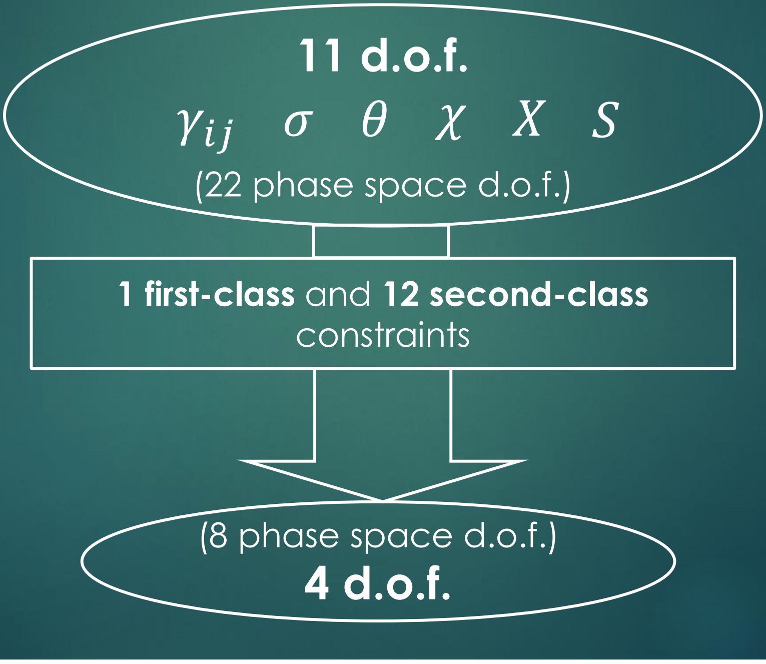
$$\mathcal{L}_4 = -m^2c_4\sqrt{\gamma}N$$

$$F(X,S) = P(X) - G(X)S$$

$$\mathfrak{X} = -\frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma$$

Degrees of freedom in the precursor theory

$$\bar{H}^{(T)}_{\rm pre} = \int d^3x \Big[-N\tilde{\mathcal{R}}_0 - N^i\tilde{\mathcal{R}}_i + \frac{M_{\rm P}^2}{2} m^2 M \mathcal{H}_1 + \xi_X P_X + \xi_\chi P_\chi + \xi_S P_S + \sqrt{\gamma}\left(\lambda_X S_X + \lambda_\chi S_\chi + \lambda_S S_S + \lambda_T \tilde{T}\right) + \lambda^\tau \tilde{\mathcal{C}}_\tau \Big]$$



11 d.o.f.

$\gamma_{ij} \quad \sigma \quad \theta \quad \chi \quad X \quad S$

(22 phase space d.o.f.)

1 first-class and **12 second-class** constraints

(8 phase space d.o.f.)

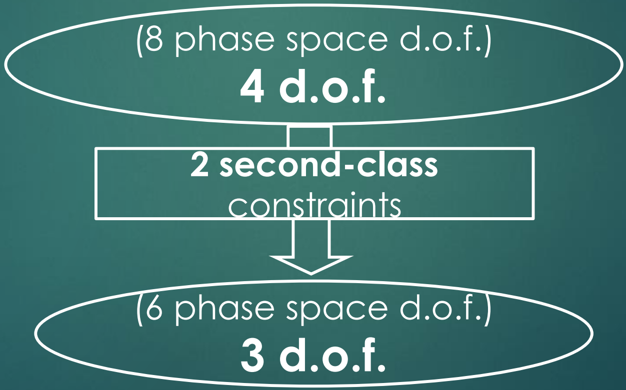
4 d.o.f.

Minimal theory: new constraints

We replace **2 precursor constraints** by **4 new constraints**

$$\tilde{\mathcal{C}}_\tau\,, \qquad \tau \in \{1, 2\}$$

$$\{\tilde{\mathcal{R}}^{\rm GR}_i, H_1\} \approx \frac{M_{\rm P}^2}{2}\mathcal{C}_i\,, \quad \{\tilde{\mathcal{R}}^{\rm GR}_0, H_1\} \approx \frac{M_{\rm P}^2}{2}\mathcal{C}_0$$



(8 phase space d.o.f.)

4 d.o.f.

2 second-class constraints

(6 phase space d.o.f.)

3 d.o.f.

[In practice, 2 tensor modes and the quasidilaton σ]

Minimal theory, action

$$
\begin{aligned}
\mathcal{L} =& N\sqrt{\gamma}\left\{\frac{M_{\rm P}^2}{2}\left[{}^{(3)}R+K_{ij}K^{ij}-K^2\right]+P+G_{,X}g^{\mu\nu}\partial_\mu X\,\partial_\nu\sigma\right\} \\
&+\lambda_\chi N\sqrt{\gamma}\left[\frac{\lambda_T}{N}\left(\partial_\perp\sigma+\frac{\lambda_T}{N}\right)-\frac{\lambda_T^2}{2N^2}-\frac{1}{2}\left(2X+g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma\right)\right] \\
&+\sqrt{\gamma}\,G_{,X}\,\lambda_T^{;i}\sigma_{;i}\left(\partial_\perp\sigma+\frac{\lambda_T}{N}\right)-\frac{m^2M_{\rm P}^2}{2}\left[\mathcal{H}_1+N\mathcal{H}_0+\frac{\partial\mathcal{H}_1}{\partial\sigma}\,\sigma_{;i}\lambda^i+\frac{1}{2}\sqrt{\gamma}\,\Theta^{jk}\gamma_{ki}\lambda^i{}_{;j}\right] \\
&+\frac{m^4M_{\rm P}^2\lambda^2\sqrt{\gamma}}{64N}\left(2\Theta_{ij}\Theta^{ij}-\Theta^2\right)-\frac{m^2M_{\rm P}^2\lambda}{4}\left[2\left(\partial_\perp\sigma+\frac{\lambda_T}{N}\right)\frac{\partial\mathcal{H}_1}{\partial\sigma}+\sqrt{\gamma}K_{ij}\Theta^{ij}\right] \\
&-\frac{\lambda\lambda_T m^2}{4N}\sqrt{\gamma}\,G_{,X}\left(X\,\Theta+\Theta^{ij}\sigma_{;i}\sigma_{;j}\right)+\lambda_T\sqrt{\gamma}\,\{G_{,X}(K_{ij}\sigma^{;i}\sigma^{;j}-K\sigma_{;i}\sigma^{;i}-2X\,K) \\
&+\left(\partial_\perp\sigma+\frac{\lambda_T}{N}\right)\left(G_{,XX}X^{;i}\sigma_{;i}+2G_{,X}\sigma^{;i}{}_{;i}-P_{,X}\right)-G_{,X}\partial_\perp X \\
&-\frac{1}{M_{\rm P}^2}\frac{\lambda_T}{N}\,X\,G_{,X}^2(2\sigma_{;i}\sigma^{;i}+3X)\Big\}
\end{aligned}
$$

There are still some Lagrange multipliers λ, λ_T

Luckily there is a unique mini-superspace solution: $\lambda = \lambda_T = 0$

Mini-superspace solutions

de Sitter attractor

The equation from λ is rewritten in a nice form.

$$\frac{d}{dt}\left[a^{4+\alpha}\mathcal{X}^{1+\alpha}\,J(\mathcal{X})\right]=0 \qquad \mathcal{X}\equiv\frac{e^{\sigma/M_{\rm P}}}{a}$$

$$J\equiv c_0\mathcal{X}^3+3c_1\mathcal{X}^2+3c_2\mathcal{X}+c_3$$

where a is the scale factor. This implies that there exists a de Sitter attractor where either

$\mathcal{X}$ is constant ($\alpha = -4$) or $J(\mathcal{X}) = 0$ ($\alpha \neq -4$).

Stability of de Sitter

Study the quadratic action for linear perturbations, and obtain the no-ghost conditions.

It is nice and stable ! ☺

Gravitational modes in the minimal quasidilaton

$m_g \lesssim 1.2 \times 10^{-22}\, eV\,, \quad |1 - c_g/c| \lesssim 10^{-15}$

GW 150914
GW170817/GRB170817A

The minimal theory of quasidilaton massive gravity successfully passes the tests of both GW and multimessenger detections.

- The sound speed of the tensor modes in the subhorizon limit **coincides with the speed of light**.
- Small graviton **mass of order** $H_0 \sim 10^{-33}\ eV$.

Why the minimal quasidilaton?

Advantages of the minimal quasidilaton

I. From the point of view of **quasidilaton theories**, there is a **smaller number of degrees of freedom**, and thus is more tractable.
II. In contrast to **the MTMG**, the minimal quasidilaton theory allows to use a **Minkowski fiducial metric**

Disadvantages of the minimal quasidilaton

I. More parameters than dRGT or even MTMG, not to be said than the simple **cosmological constant.**
II. LI violation
III. No solution of the “old cosmological constant problem” (no degravitation).

Future prospects

Cosmology with matter and general FLRW.

Small scale behaviour. Vainshtein screening?

Minimal… other theories

Technical naturalness

…keep in touch! ☺

Thank you for your attention !

all rights to 東広島市

3b3. Alberto Molgado (Universidadd Autonoma de San Luis Potosi),

“MacDowell-Mansouri gravity model from a covariant polysymplectic perspective” (10+5)

[JGRG27 (2017) 112823]

MacDowell-Mansouri gravity model from a covariant polysymplectic perspective

Alberto Molgado
(in collaboration with J. Berra-Montiel)

UASLP
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de San Luis Potosí
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JGRG27
Saijo, Higashi-Hiroshima
27 November–1 December, 2017

Motivation

Our main goal is to study Field theories from the multisymplectic perspective at both, classical and quantum levels!

In particular, we want to test the polysymplectic formalism for the MacDowell-Mansouri gravity model

It is relevant to notice the way in which this formalism confronts the symmetry breaking

(Based in J. Berra-Montiel, AM and D. Serrano-Blanco, CQG **34** (2017) 235002, `arXiv:1703.09755 [gr-qc]`)

Consider a field theory given by[1]

$$\delta \int L(y^a, \partial_i y^a, x^i)\widetilde{vol} = 0\,,$$

- $\{y^a\}, 1 \leq a \leq m :=$ Field variables
- $\{x^i\}, 1 \leq i \leq n :=$ Spacetime variables
- $\widetilde{vol} := dx^i \wedge ... \wedge dx^n :=$ Volume form on the spacetime manifold.

$$\partial_i \left(\frac{\partial L}{\partial \partial_i y^a} \right) - \left(\frac{\partial L}{\partial y^a} \right) = 0$$

---

[1] $\det(g) = 1$

De Donder-Weyl Theory

Introduce a new set of variables:

$$p^i_a := \frac{\partial L}{\partial(\partial_i y^a)} \qquad \text{Polymomenta}$$

and

$$H_{DW}(y^a, p^i_a, x^i) := p^i_a \partial_i y^a - L$$

which are defined in a completely space-time symmetric manner.

- H_{DW} is the De Donder-Weyl Hamiltonian
- Canonical form of field equations within the DW theory:

$$\partial_i p^i_a = -\frac{\partial H}{\partial y^a}\,, \quad \partial_i y^a = \frac{\partial H}{\partial p^i_a}$$

De Donder-Weyl Theory

- Extended polymomentum phase space (1st order jet bundle):
  Finite dimensional analogue of phase space

$$z^M := (y^a, p^j_b, x^i), \quad 1 \leq M \leq m + mn + n$$

- Poincaré-Cartan form

$$\Theta_{DW} = p^i_a \wedge dy^a \wedge \partial_i \lrcorner \widetilde{vol} - H_{DW} \widetilde{vol}$$

- Canonical $(n+1)$-form (obtained by taking the exterior differential of Θ_{DW}) is

$$\Omega_{DW} = dp^i_a \wedge dy^a \wedge \partial_i \lrcorner \widetilde{vol} - dH_{DW} \wedge \widetilde{vol}$$

Graded Poisson bracket

- A generalized Lie derivative of any form Φ with respect to the vertical multivector field $\overset{p}{X}$ of degree p is given by

$$\mathcal{L}_{\overset{p}{X}} \Phi := \overset{p}{X} \lrcorner\, d^V \Phi - (-1)^p d^V (\overset{p}{X} \lrcorner\, \Phi)$$

- Given the polysymplectic $(n+1)$-form Ω, we define the set of locally Hamiltonian multivector fields $\overset{p}{X}$, $1 \leq p \leq n$, which satisfy the condition

$$\mathcal{L}_{\overset{p}{X}} \Omega = 0$$

Graded Poisson bracket

- The polysymplectic form Ω_{DW} associates horizontal p-forms $\overset{p}{F}$ with $(n-p)$-multivectors $\overset{n-p}{X}$, by the relation:

$$\overset{n-p}{X} \lrcorner \Omega_{DW} = d^V \overset{p}{F}$$

- Then we may induce a Gerstenhaber bracket of horizontal forms representing the dynamical variables

$$\{\![\overset{p}{F}_1, \overset{q}{F}_2]\!\} \quad := \quad (-1)^{n-p} \overset{n-p}{X}_1 \lrcorner \overset{n-q}{X}_2 \lrcorner \Omega_{DW}$$

- This bracket results a Poisson bracket

- The Poisson-Gerstenhaber bracket of a p-form with a q-form results a form of degree $(p+q-n+1)$
- Thus, the subspace of $(n-1)$-forms constitutes a Lie subalgebra in the Gerstenhaber algebra of Hamiltonian (vertical)-forms.
- Canonical brackets are taken as ($\omega_\mu := \partial_\mu \lrcorner \widetilde{vol}$)

$$\{\![p_a^\mu \omega_\mu, y^b \omega_\nu]\!\} = \delta_a^b \omega_\nu$$

- In particular, $(n-1)$-forms may be associated to the notion of observables (Zapata, Forger)
- By integrating $(n-1)$-forms over $(n-1)$-hypesurfaces we may obtain a relation of the Poisson-Gerstenhaber bracket with Peierls bracket

$$\{\![\overset{n-1}{F}_1, \overset{n-1}{F}_2]\!\} \mapsto \{f_1(x), f_2(x')\} = G(x,x')$$

- One may try to quantize this bracket under Schwinger quantization scheme

---

Yang-Mills theory

(Further details in J. Berra-Montiel, E. Del Río and AM, IJMPA **32** 2017 1750101, `arXiv:1702.03076v2 [hep-th]`)

$$L_{\mathrm{YM}} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a$$

- The components of the field strength $F^a_{\mu\nu}$ are

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a_{bc} A^b_\mu A^c_\nu$$

  - A^a_μ stands for the gauge field
  - g is the coupling constant
  - f_{abc} are the structure constants associated to the gauge symmetry

YM theory

- Polymomenta

$$\pi_a^{\mu\nu} = \frac{\partial L_{\mathrm{YM}}}{\partial(\partial_\mu A_\nu^a)} = -F_a^{\mu\nu}$$

- De Donder-Weyl Hamiltonian

$$\begin{aligned} H_{\mathrm{DW}}^{\mathrm{YM}}(A,\pi,x) &= \pi_a^{[\mu\nu]}\partial_{[\mu}A_{\nu]}^a - L_{\mathrm{YM}} \\ &= -\frac{1}{4}\pi_{[\mu\nu]}^a\pi_a^{[\mu\nu]} - \frac{g}{2}f_a{}^{bc}A_b^\mu A_c^\nu\pi_{[\mu\nu]}^a \end{aligned}$$

- Canonical pair of $(n-1)$ forms

$$\begin{aligned} A_a^{\mu\nu} &:= A_a^\mu\omega^\nu\,, \\ \pi_a^\mu &:= \pi_a^{\mu\nu}\omega_\nu \end{aligned}$$

YM theory

- De Donder-Weyl equations

$$\begin{aligned} d^V A_a^{\mu\nu} &= -\,\{\![\,\widetilde{H}_{\mathrm{DW}}^{\mathrm{YM}}, A_a^{\mu\nu}\,]\!\} \\ &= -\frac{1}{2}\pi_a^{[\mu\nu]} - \frac{g}{2}f_a{}^{bc}A_b^\mu A_c^\nu + \lambda_a^{\mu\nu}\,, \\ d^V\pi_a^\mu &= -\,\{\![\,\widetilde{H}_{\mathrm{DW}}^{\mathrm{YM}}, \pi_a^\mu\,]\!\} \\ &= gf_a{}^{bc}\pi_b^{[\mu\nu]}A_{c\nu} \end{aligned}$$

These equations contain all the information of the model

- Lagrangian field equation

$$D_\nu F^{\mu\nu} = 0$$

- Gauge content of the theory

MM gravity

(Further details in J. Berra-Montiel, AM and D. Serrano-Blanco, CQG **34** (2017) 235002, `arXiv:1703.09755 [gr-qc]`)

- Yang-Mills-type gauge theory with gauge group $\mathrm{SO}(4,1)$.
- The relevance of the MM model relies in the fact that after the symmetry breaking

$$\mathrm{SO}(4,1) \to \mathrm{SO}(3,1)$$

the action describing the gauge theory turns out to be classically equivalent to the standard Palatini action of General Relativity.

MM gravity

- The equivalence is made possible by the fact that the internal Lie algebra admits the orthogonal splitting

$$\mathfrak{so}(4,1) \simeq \mathfrak{so}(3,1) \oplus \mathbb{R}^{3,1}$$

- This decomposition splits the gauge field A into an $\mathrm{SO}(3,1)$-connection ω and a *coframe field* e, such that

$$A = \begin{pmatrix} \omega & \frac{1}{l}e \\ -\frac{1}{l}e & 0 \end{pmatrix} ,$$

where l is a constant chosen with units of length

MM gravity

- The associated gauge curvature

$$R = \mathrm{d}_A A := \mathrm{d}A + A \wedge A$$

also splits into an $\mathfrak{so}(3,1)$-valued 2-form

$$F = \mathrm{d}_\omega \omega - \frac{1}{l^2} e \wedge e$$

and the $\mathbb{R}^{3,1}$-valued 2-form

$$\mathrm{d}_\omega e$$

such that

$$R = \begin{pmatrix} F & \mathrm{d}_\omega e \\ -\mathrm{d}_\omega e & 0 \end{pmatrix}$$

MM gravity

- The general MacDowell-Mansouri action with local gauge group $\mathrm{SO}(4,1)$ reads

$$\mathcal{S}[A] = \int_{\mathcal{C}} \mathrm{tr}\,(R \wedge \star R)$$

- The MacDowell-Mansouri model of gravity is obtained by considering the projection of the curvature R into the subalgebra $\mathfrak{so}(3,1)$, resulting in the action

$$\mathcal{S}_{\mathrm{MM}}[\omega, e] = \int_{\mathcal{C}} \mathrm{tr}\,(F \wedge \star F)$$

- By taking the projection of R, we have broken the $\mathrm{SO}(4,1)$ symmetry down to $\mathrm{SO}(3,1)$.

MM gravity

- De Donder-Weyl equations reduce to the Lagrangian field equations
$$\mathrm{d}_A R = 0$$
- Considering the decomposition of the $SO(4,1)$ symmetry (without breaking it) we find the field equations
$$\begin{aligned} \mathrm{d}_\omega F^{ab} &= \frac{1}{l^2} e^a \wedge (\mathrm{d}_\omega e)^b \,, \\ \mathrm{d}_\omega (\mathrm{d}_\omega e)^a &= -e^b \wedge F^a{}_b \end{aligned}$$
- The $\mathrm{SO}(4,1)$-symmetry breaking in this formalism is achieved by requiring that $p_a^{\mu\nu} = 0$, thus
$$\begin{aligned} \mathrm{d}_\omega F^{ab} &= 0 \,, \\ e^b \wedge F^a{}_b &= 0 \end{aligned}$$

MM gravity

- At the Lagrangian level the variational process does not commute with the symmetry breaking $\mathrm{SO}(4,1) \to \mathrm{SO}(3,1)$, resulting in two inequivalent sets of field equations
- Within the polysymplectic approach we noticed that the symmetry breaking process leaves invariant the emerging De Donder-Weyl equations that follow from the Poisson-Gerstenhaber bracket
- The symmetry breaking at the polysymplectic level includes variations with respect to all the polymomenta, and these polymomenta precisely include spacetime derivatives of the fields in each of the sectors in which the gauge algebra $\mathfrak{so}(4,1)$ is decomposed

Work in progress

- Higher order systems
- Momentum maps
- Canonical transformations
- Quantum aspects (deformation? Schwinger?)
- Application of the formalism to physical models

Thank you!

3b4. Mai Yashiki (Yamaguchi U.),

"Observational test of the unified model in inflation and dark energy in f(R) gravity" (10+5)

[JGRG27 (2017) 112824]

Cosmological evolution of the unified model in inflation and dark energy in $f(R)$ gravity

Mai Yashiki, Nobuyuki Sakai
Yamaguchi Univ.

The 27th workshop on JGRG @ Higashi-hiroshima, 2017. 11. 28

Purpose

Unified model in inflation and dark energy :

$$\boldsymbol{f(R) = R + \alpha R^n - \beta R^{2-n}}$$

Artimowski & Lalak (2014)

⇒ ・They used the BICEP2 data (not be reliable)

・They did not check the existence of radiation-dominated era and matter-dominated era

<u>This work</u>

Reevaluate the condition for n by using Planck data

Check the cosmological evolution in this model

・Whether radiation-dominated era & matter-dominated era exist

Outline

- Introduction: the model we use
- The condition for inflation
- Can $f(R)$ model exist each dominated era?
- Cosmological evolution
- Conclusion & Future work

Intro: the model we use

- $f(R)$ gravity : $S = \frac{1}{2}\int d^4x\sqrt{-g}f(R)$ ($f(R)$= non-linear function of R)
- Starobinsky model: $f(R) = R + \alpha R^2$ $(\alpha > 0)$

Starobinsky (1980), Tomita & Nariai (1971)

⇩

$\boxed{f(R) = R + \alpha R^n - \beta R^{2-n}}$ model $(1 < n \leq 2, \alpha \gg 1, 0 < \beta \ll 1, \alpha\beta \ll 1)$

Artimowski & Lalak (2014)

The second term (αR^n) → inflation

The third term (βR^{2-n}) → the late-time acceleration

The condition for inflation

- Friedmann eq. : $3FH^2 = \frac{FR-f}{2} - 3H\dot{F}$, where $F \equiv \frac{df(R)}{dR}$

- During inflation, R is sufficiently large

$$\boxed{f(R) = R + \alpha R^n} \quad (\alpha R^n \gg \beta R^{2-n} \text{ for } n > 1\,)$$

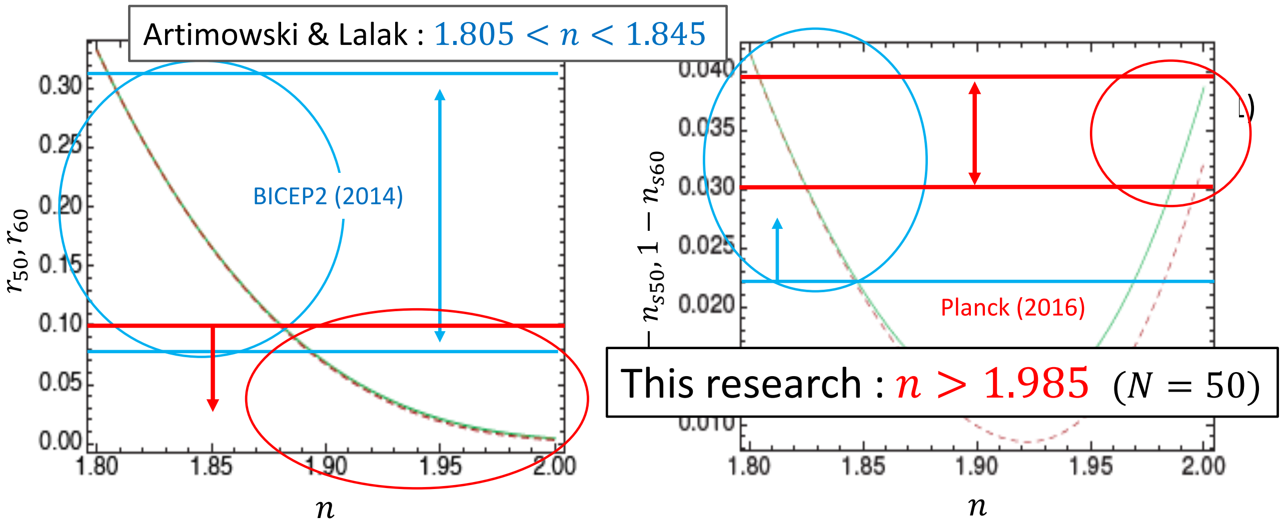
- From $F \sim \alpha n R^{n-1}$ and Friedmann eq.,

  the slow-roll parameter : $\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{2-n}{(n-1)(2n-1)}$

  The condition $\epsilon < 1 \quad \Rightarrow \quad n > \frac{1}{2}\left(1+\sqrt{3}\right)$

The condition for inflation

- The tensor-to-scalar ratio r and the spectral index n_s are



Artimowski & Lalak : $1.805 < n < 1.845$

BICEP2 (2014)

Planck (2016)

This research : $n > 1.985 \quad (N = 50)$

Fig.1 : r and n_s for each n in $f(R) = R + \alpha R^n$ model (Artymowski & Lalak (2014))

MY, Phys. Rev. D **96**, 103518 (2017)

Does each dominated era exist?

- The effective equation of state

$$w_{\rm eff} \equiv -1 - \frac{2\dot{H}}{3H^2}$$

radiation-dominated era: $w_{\rm eff} = \frac{1}{3}$

matter-dominated era: $w_{\rm eff} = 0$

the late-time acceleration: $w_{\rm eff} \sim -1$

- The viability conditions were derived by Amendola et al. (2007)

↳ whether each dominated era exists or not

$\Rightarrow$ All eras exist in this model under the condition for n

$(n > 1.985)$

Cosmological evolution

- Check the evolutions of $\Omega_{\rm m,rad,DE}$ and $w_{\rm eff}$

- Friedmann eq. : $3FH^2 = -3H\dot{F} + \frac{1}{2}(FR - f) + \kappa^2(\rho_m + \rho_{rad})$

$$\Leftrightarrow \qquad 1 = \underbrace{-\frac{\dot{F}}{HF}}_{x_1} \underbrace{-\frac{f}{6FH^2}}_{x_2} + \underbrace{\frac{R}{6H^2}}_{x_3} + \underbrace{\frac{\kappa^2\rho_{rad}}{3FH^2}}_{x_4} + \frac{\kappa^2\rho_m}{3FH^2}$$

- $\Omega_{\rm m} = 1 - x_1 - x_2 - x_3 - x_4$, $\Omega_{\rm DE} = x_1 + x_2 + x_3$, $\Omega_{\rm rad} = x_4$
- $w_{\rm eff} = -\frac{1}{3}(2x_3 - 1)$

Cosmological evolution

- Evolution of Equation:

$$\frac{dx_1}{dN} = -1 + x_1^2 - x_1 x_3 - 3x_2 - x_3 + x_4$$

$$\frac{dx_2}{dN} = \frac{x_1 x_3}{m} - x_2(2x_3 - 4 - x_1)$$

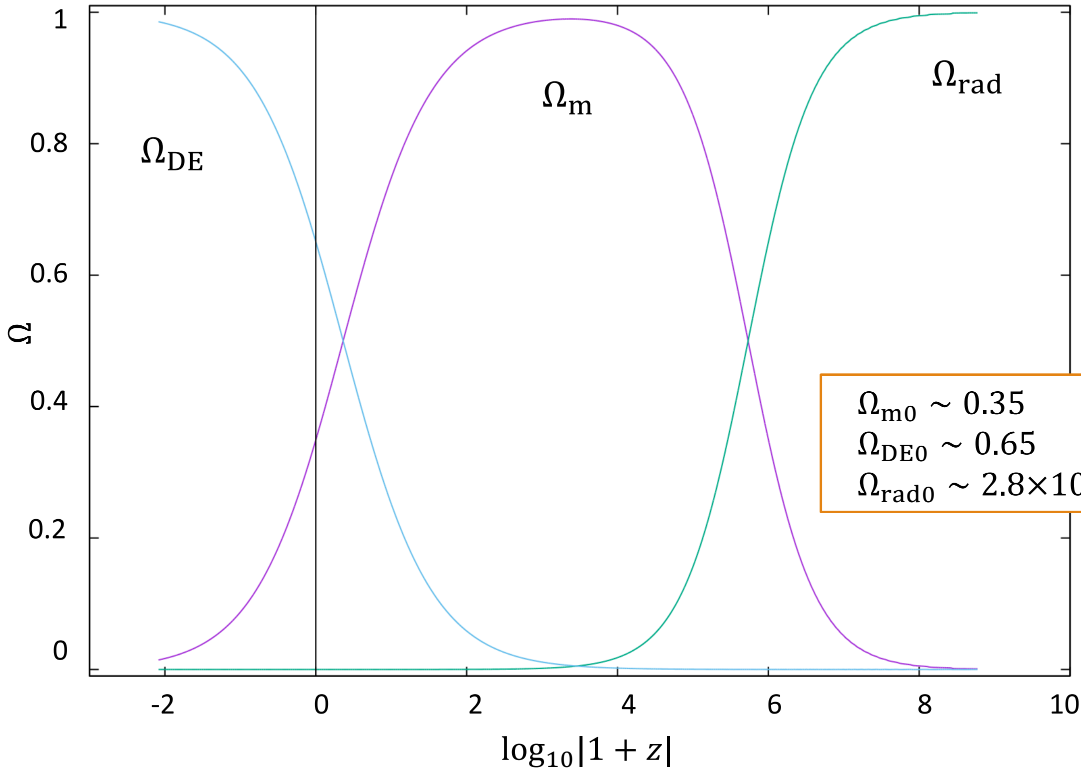
$$\frac{dx_3}{dN} = -\frac{x_1 x_3}{m} - 2x_3(x_3 - 2)$$

$$\frac{dx_4}{dN} = -2x_3 x_4 + x_1 x_4 \qquad \text{, where } N = \ln a$$

$$m \equiv \frac{RF_R}{F}, F_R \equiv \frac{dF}{dR}$$

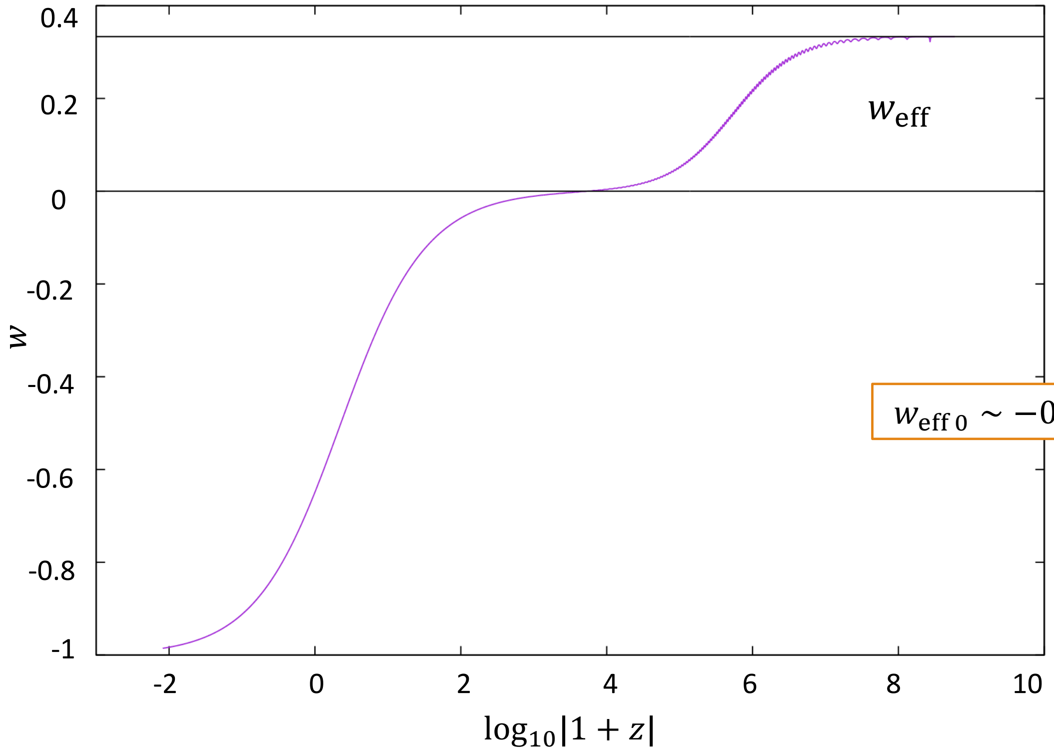
- Use 4th order Runge-Kutta method

The density parameters



$\Omega_{\mathrm{m0}} \sim 0.35$
$\Omega_{\mathrm{DE0}} \sim 0.65$ @ $z = 0$
$\Omega_{\mathrm{rad0}} \sim 2.8\times10^{-6}$

The effective equation of state



$w_{\mathrm{eff}\,0} \sim -0.65 \quad @\, z = 0$

Conclusion & Future work

In $f(R) = R + \alpha R^n - \beta R^{2-n}$ (Artimowski & Lalak) model,

- We get the lower limit of n $n > 1.985$ by using Planck data
- We show the existence of each dominated era
- This model can reproduce the standard cosmological evolution

Future work

- Analyze this result more detailed
  - Dependence of the initial conditions in this model
  - Compare with the observational data …

3b5. Shuntaro Mizuno (YITP Kyoto U.),
"Primordial perturbations from hyperinflation"
(10+5)

[JGRG27 (2017) 112825]

JGRG27 @ Hiroshima

2017/11/27 - 2017/12/1

Primordial perturbations from hyperinflation

Shuntaro Mizuno (YITP, Kyoto)

with Shinji Mukohyama (YITP, Kyoto)

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

arXiv: 1707.05125 [hep-th]

(Physical Review D 96, 103533)

Inflation

- Phenomenological success
  - Solving problems of big-bang cosmology

    (Flatness problem, Horizon problem, Unwanted relics,…)
  - Providing origin of the structures in the Universe

    almost scale invariant, adiabatic and Gaussian perturbations

    supported by current observations (CMB, LSS)
- Theoretical challenge

  Still nontrivial to embed the single-field slow-roll inflation into more fundamental theory (Review, Baumann & McAllister, `14)
  - Difficult to obtain a flat potential
  - Scalar fields are ubiquitous in fundamental theories

Multi-field inflation with a non-trivial field-space

- Formulation to analyze perturbations

  Sasaki & Stewart, `96, Gong & Tanaka, `11, Elliston et al, `12

- Examples (without significant effect on perturbation)

  - Inflation with large extra-dimension Kaloper et al, `00
  - Alpha-attractor scenario Kallosh, Linde, Roest, `13

- Examples (with significant effect on perturbation)

  - Geometrical destabilization Renaux-Petel & Turzynski, `15
  - Hyperinflation Brown, arXiv:1705.03023 [hep-th]

Model

Brown `17

- Action

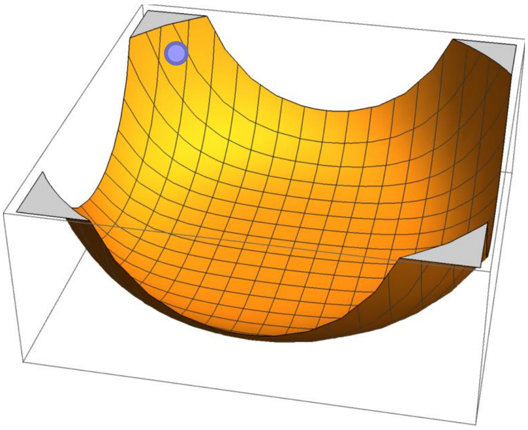
hyperbolic

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}\underline{G_{IJ}}\nabla_\mu\varphi^I\nabla^\mu\varphi^J - \underline{V(\phi)}\right]$$

$\varphi^I = (\phi, \chi)$ ϕ : radial direction χ : angular direction

$$G_{\phi\phi} = 1\,, G_{\chi\chi} = L^2\sinh^2\frac{\phi}{L} \simeq \frac{L^2}{4}e^{2\frac{\phi}{L}} \quad (\text{for} \quad \phi \gg L \quad)$$

- Potential



cf. ``spinflation”

Easson et al, `07

$$\Rightarrow \quad \dot{\chi} = Aa^{-3}e^{-2\frac{\phi}{L}}$$

A : integration constant

Background dynamics of scalar-fields

- Basic equations

$$\left[\begin{array}{l} H^2=\frac{1}{3M_{\rm Pl}^2}\left(\cancel{\frac{1}{2}\dot\phi^2}+\cancel{\frac{1}{2}\frac{L^2}{4}e^{2\frac{\phi}{L}}\dot\chi^2}+V(\phi)\right) \\ \cancel{\ddot\phi}+3H\dot\phi-\frac{L}{4}e^{2\frac{\phi}{L}}\dot\chi^2+V_{,\phi}=0 \end{array}\right.$$

with $\dot\chi=Aa^{-3}e^{-2\frac{\phi}{L}}$

/ for ``slow-roll”

- Inflationary attractors

standard inflation	hyperinflation
$\dot\phi=-\frac{V_{,\phi}}{3H}$	$\dot\phi=-3LH$
$\dot\chi=0$	$\frac{L}{2}e^{\frac{\phi}{L}}\dot\chi=hLH$

with $\boxed{h\equiv\sqrt{\frac{V_{,\phi}}{LH^2}-9}}$

parametrizing angular velocity

$(V_{,\phi}<9LH^2)$ $\quad\frac{V_{,\phi}}{V}=\frac{3L}{M_{\rm Pl}^2}\quad$ $(V_{,\phi}>9LH^2)$

Power-law hyperinflation

SM, Mukohyama `17

- Potential

$$V(\phi)=V_0\exp\left[\lambda\frac{\phi}{M_{\rm Pl}}\right],\ \lambda>0 \quad\Rightarrow\quad h=\sqrt{3\lambda\frac{M_{\rm Pl}}{L}-9}\quad \text{(constant)}$$

(often appears in higher-dimensional theory)

- Slow-roll parameter

$$\epsilon\equiv-\frac{\dot H}{H^2}=\frac{1}{2}\left(\frac{L}{M_{\rm Pl}}\right)^2(9+h^2)=\frac{3}{2}\lambda\frac{L}{M_{\rm Pl}}=\frac{3L}{2}\left(\frac{V_{,\phi}}{V}\right)$$

- Condition for hyperinflaion

$$\epsilon>\frac{9L^2}{2M_{\rm Pl}^2}\quad\Rightarrow\quad M_{\rm Pl}\gg L$$ is required for inflation

Under this condition, inflation from steeper potentials than usual!!

cf. $0<\lambda<\sqrt{2}$ for standard power-law inflation

Lucchin & Matarrese, `85, Kitada & Maeda, `93

Basic equations for linear perturbations

Brown `17

- Perturbation (spatially-flat gauge, $h_{ij} = a(t)^2 \delta_{ij}$)

$$\phi = \bar{\phi} + \delta\phi \,, \quad \chi = \bar{\chi} + \delta\chi \,,$$

- Canonical variables

$$u_\phi \equiv a\delta\phi \,, \quad u_\chi \equiv a\sqrt{G_{\chi\chi}}\delta\chi \,, \quad \text{with} \quad G_{\chi\chi} = \frac{L^2}{4} e^{2\frac{\phi}{L}}$$

- Equations of motion (conformal time $\tau \simeq -\dfrac{1}{aH}$)

$$u_\phi'' + \frac{2h}{\underline{\tau}} u_\chi' - \frac{4h}{\tau^2} u_\chi - \frac{2(\underline{h^2}+1)}{\tau^2} u_\phi + k^2 u_\phi = 0$$

$$u_\chi'' - \frac{2h}{\underline{\tau}} u_\phi' - \frac{2}{\tau^2} u_\chi - \frac{2h}{\underline{\tau^2}} u_\phi + k^2 u_\chi = 0$$

Coupling depending on h $\quad h = \sqrt{\dfrac{V_{,\phi}}{LH^2} - 9}$

Behavior of perturbations in asymptotic regions

- Asymptotic solutions on subhorizon scales $(|k\tau| \gg 1)$

$$u_\chi = C_1 e^{ik\tau + ih\log|k\tau|} + C_2 e^{ik\tau - ih\log|k\tau|} + C_3 e^{-ik\tau + ih\log|k\tau|} + C_4 e^{-ik\tau - ih\log|k\tau|} \,,$$

$$u_\phi = iC_1 e^{ik\tau + ih\log|k\tau|} - iC_2 e^{ik\tau - ih\log|k\tau|} + iC_3 e^{-ik\tau + ih\log|k\tau|} - iC_4 e^{-ik\tau - ih\log|k\tau|}$$

Bunch-Davies vacuum ➡ $C_1 = C_2 = 0 \,, \quad C_3 = C_4 = \dfrac{1}{\sqrt{2k}}$

- Asymptotic solutions on superhorizon scales $(|k\tau| \ll 1)$

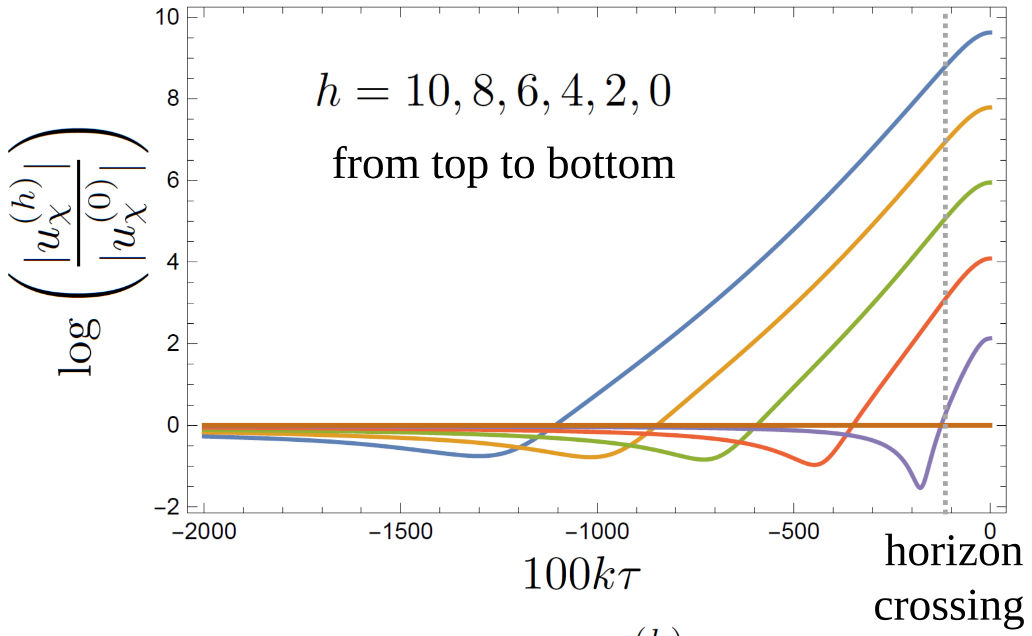
$$u_\chi = \frac{c_1}{(-\tau)} + c_2(-\tau)^2 + c_3(-\tau)^{\frac{1}{2}+\frac{1}{2}\sqrt{9-8h^2}} + c_4(-\tau)^{\frac{1}{2}-\frac{1}{2}\sqrt{9-8h^2}} \,,$$

$$u_\phi = -\frac{3}{h}\frac{c_1}{(-\tau)} + \frac{\sqrt{9-8h^2}-3}{4h} c_3(-\tau)^{\frac{1}{2}+\frac{1}{2}\sqrt{9-8h^2}} - \frac{\sqrt{9-8h^2}+3}{4h} c_4(-\tau)^{\frac{1}{2}-\frac{1}{2}\sqrt{9-8h^2}}$$

(Adiabatic mode, constant shift in χ , two heavy modes)

For the concrete value of c_1 , we need numerical calculations !!

Time evolution of (amplitude of) perturbations



Instability starts at

$k = h|\tau|$

⇒

$$\frac{|u_\chi^{(h)}|}{|u_\chi^{(0)}|} \sim e^{p+qh}$$

at late-time

with $p = 0.395\,, \quad q = 0.924$

Curvature perturbation

SM, Mukohyama `17

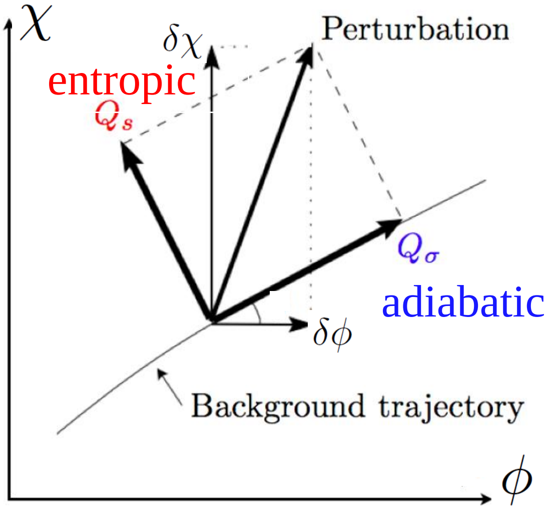
- Curvature perturbation

$$h_{ij} = a^2(1-2\psi)\delta_{ij}\,, \quad T^0{}_i = \partial_i q$$

$$\dot\sigma \equiv \sqrt{\dot\phi^2 + G_{\chi\chi}\dot\chi^2}$$

⇒ $$\mathcal{R} \equiv \psi - \frac{H}{\rho+p}\delta q = \frac{H}{\dot\sigma}Q_\sigma = \frac{H}{\dot\phi}\delta\phi$$

- Super-Hubble evolution of $\mathcal{R}$ in multi-field inflation



Gordon, Wands, Bassett, Maartens `01

$$\dot{\mathcal{R}} \simeq -2\frac{H}{\dot\sigma^2}V_{,s}\boxed{Q_s} = 0$$

For hyperinflation

$$u_\phi = -\frac{3}{h}u_\chi$$

Observational constraints

- Power spectrum

Exponential enhancemet in h !!

$$\mathcal{P}_{\mathcal{R}} = \frac{H^2}{\dot{\phi}^2}\mathcal{P}_{\delta_\phi} = \frac{1}{(2\pi)^2}\frac{1}{2M_{\rm Pl}^2}\frac{H^2}{\epsilon}\boxed{\frac{h^2+9}{h^2}e^{2p+2qh}}$$

with $p = 0.395\,,\quad q = 0.924$

- Spectrum index

$$n_s - 1 \equiv \frac{d\ln\mathcal{P}_{\mathcal{R}}}{d\ln k} \simeq -2\epsilon + (qh-1)\eta \qquad \eta \equiv \frac{\dot{\epsilon}}{H\epsilon}$$

cf. Planck constraint $n_s = 0.9655 \pm 0.0062$ (68% C. L.)

⇨ Deviation from exponential potential is severely constrained !!

- Tensor-to-scalar ratio

$$r \equiv \frac{\mathscr{P}_T}{\mathscr{P}_{\mathscr{R}}} = 16\varepsilon\frac{h^2}{h^2+9}e^{-2p-2qh}$$

⇨ GW detection will reject hyperinflation with large h !!

Summary

- We have confirmed and extended the analysis of hyperinflation

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(\nabla_\mu\phi)^2 - \frac{1}{2}L^2\sinh^2\frac{\phi}{L}(\nabla_\mu\chi)^2 - V(\phi)\right]$$

Brown, 1705.03023

- We have quantified the deviation from de Sitter spacetime

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{3L}{2}\left(\frac{V_{,\phi}}{V}\right)\,, \qquad \eta \equiv \frac{\dot{\epsilon}}{H\epsilon} \simeq 3L\left(\frac{V_{,\phi}}{V} - \frac{V_{,\phi\phi}}{V_{,\phi}}\right)$$

Inflation from potentials steeper than usual for $M_{\rm Pl} \gg L$!!

- We have calculated the power spectrum of $\mathscr{R}$

$$\mathcal{R} = \frac{H}{\dot{\phi}}\delta\phi\,, \quad \mathcal{P}_{\mathcal{R}} = \frac{1}{(2\pi)^2}\frac{1}{2M_{\rm Pl}^2}\frac{H^2}{\epsilon}\frac{h^2+9}{h^2}e^{2p+2qh}\,,$$

$p = 0.395\,,\quad q = 0.924$

$n_s - 1 \simeq -2\epsilon + (qh-1)\eta$

Potentials deviating from exponential are strongly constrained !!

Thank you very much !!

3b6. Vincenzo Vitagliano (Keio U.), “Covariantly Quantum Field Theory” (10+5) [JGRG27 (2017) 112826]

Covariantly Quantum Field Theory

– the case of Galileons –

Vincenzo Vitagliano
Keio University

based on
Saltas & VV PRD17
Saltas & VV JCAP17

A gauge independent effective action

Two main problems in the quantization of gauge theories:
gauge vs gauge condition invariance

Modification of the background field method to ensure at start gauge independence: Vilkovisky-DeWitt effective action

...VDW at work...

Some recent examples:
Quantum corrections to scalar and vector fields, [DJToms (2008, 2010)]
Higgs inflation [P Burda, R Gregory, I Moss (2015)]

Galileon thories in a nutshell

4d Mink [Nicolis et al (2009)] $\Longrightarrow$ 5 galilean-invariant Lagrangians

$$\mathcal{L}_{\rm Galileon} \sim c_1\phi + c_2 X + c_3 X \cdot B + c_4 X \cdot [B^2 - (\partial_\mu\partial_\nu\phi)^2] + \\ + c_5 X \cdot [B^3 - 3B \cdot (\partial_\mu\partial_\nu\phi)^2 + 2(\partial_\mu\partial_\nu\phi)^3]$$

$X \equiv \text{Kin term}$, and $B \equiv \Box\phi$

- invariance under Galilean transformations $\phi(x) \to \phi(x) + b_\mu x^\mu + c$
- 2nd order field EOM
- Screening mechanism

Curved spacetime [Deffayet et al (2009)] $\Rightarrow$ Extra-couplings for 2nd order
Acceleration after radiation and matter domination.[De Felice & Tsujikawa (2010)]

Understanding the quantum corrections

(Non-) Renormalisation theorems
[de Rham (2014), de Rham & Ribeiro (2014), Goon et al (2016)]

Quantum corrections including graviton loops?
[Saltas and VV PRD2017, JCAP2017]

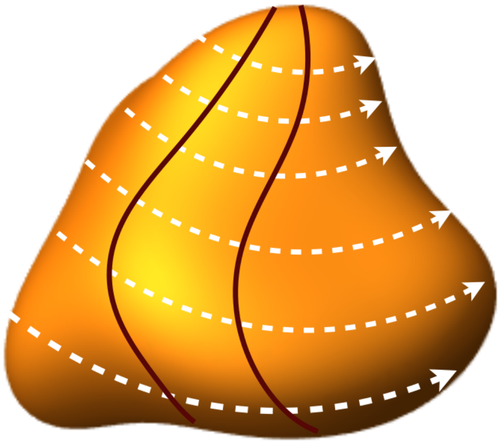
Our choice: the Cubic Galileon theory

$$S_{\rm Cubic} = \int d^4x\sqrt{g}\left[-\frac{2}{\kappa^2}R + X\left(1 + \frac{B}{M^3}\right) + \frac{4\Lambda}{\kappa^2}\right]$$

Geometrical considerations Parker and Toms (2009)

Action $S[\Phi^i = \{g_{\mu\nu}, \phi\}]$ with local symmetries

$$S[\Phi^i] = S[\Phi^i_\epsilon], \qquad \delta\Phi^i \equiv \Phi^i_\epsilon - \Phi^i = K^i_\alpha[\Phi^j]\delta\epsilon^\alpha$$



Field space metric

Define a metric in the field space $ds^2 = \mathfrak{g}_{ij} d\Phi^i d\Phi^j$, then

$$\mathcal{S} \text{ gauge-invariant} \Longrightarrow \mathfrak{g}_{ij,k}K^k_\alpha + 2K^k_{\alpha,(i}\mathfrak{g}_{j)k} = 0$$

Two further ingredients: ultralocal+diagonal [DeWitt (1987)]

$$\mathfrak{g}_{g_{\mu\nu}(x) g_{\rho\sigma}(x')} = \frac{1}{\kappa^2}\sqrt{g(x)}\cdot\left(g^{\mu(\rho}g^{\sigma)\nu} + \frac{c}{2}g^{\mu\nu}g^{\rho\sigma}\right)\delta(x,x')$$

$$\mathfrak{g}_{\phi(x)\phi(x')} = \sqrt{g(x)}\delta(x,x')$$

Is the choice really unique? [Fradkin and Tseytlin (1984), Odintsov (1991)]

The Gospel according to De Witt...

Covariant Vilkovisky-De Witt effective action [Vilko (1984); DeWitt (1987)]

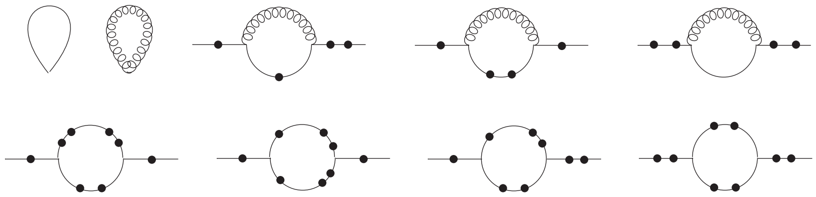
$$\Gamma = -\ln \int [d\eta] \cdot \mathrm{Exp}\Big[-\tfrac{1}{2} \lim_{\alpha \to 0} \eta^i \eta^j (\nabla_i \nabla_j S + \underbrace{\tfrac{1}{2\alpha} K_i^{\beta} K_{j\beta}}_{\text{gauge-fixing}}) \Big]$$

$$G_{\alpha\beta\gamma\delta}(p) = \frac{\delta_{\alpha\gamma}\delta_{\beta\delta} + \delta_{\alpha\delta}\delta_{\beta\gamma} - \frac{2}{n-2}\delta_{\alpha\beta}\delta_{\gamma\delta}}{2(p^2 - 2\lambda)} + \\ + (\alpha - 1)\frac{\delta_{\alpha\gamma}p_\beta p_\delta + \delta_{\alpha\delta}p_\beta p_\gamma + p_\alpha p_\gamma \delta_{\beta\delta} + p_\alpha p_\delta \delta_{\beta\gamma}}{2(p^2 - 2\lambda)(p^2 - 2\alpha\kappa^2\lambda)}$$

$$G(p) = \frac{1}{p^2 + m_\Lambda^2}$$

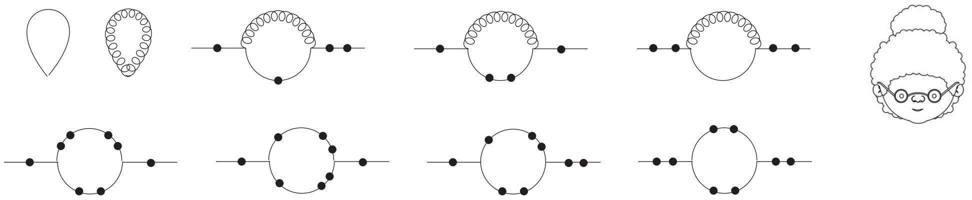
with $\lambda \equiv \Lambda + \gamma\Lambda \left(\frac{n-4}{4-2n}\right)$ and $m_\Lambda^2 = \gamma \cdot \frac{n\Lambda}{2-n}$

1–loop effective action



$$\Gamma^{1\text{–loop}} \overset{\alpha\to 0}{=} a_L \cdot \int d^4x \Big\{ -\frac{1}{16M^6}\phi\Box^{(4)}\phi + \frac{5m_\Lambda^2}{8M^6}\phi\Box^{(3)}\phi + \\ + \phi\Box^{(2)}\phi \left[\frac{\kappa^2}{4} \cdot \left(\alpha\kappa^2\gamma + \frac{3\gamma^2}{4} - \frac{3\gamma}{2} - \frac{\alpha\kappa^2\gamma^2}{4} - \omega - \frac{\gamma\omega}{2} \right) - \frac{15m_\Lambda^4}{8M^6} \right] + \\ + \partial_\mu\phi\partial^\mu\phi \cdot \frac{\kappa^2}{2} \cdot \left[\frac{\gamma m_\Lambda^2}{8} - \lambda\omega^2 - \omega m_\Lambda^2 + 2\alpha\kappa^2\lambda\omega + \frac{\alpha\kappa^2 m_\Lambda^2}{2} - \alpha^2\kappa^4\lambda \right] \Big\}$$

1–loop effective action



$$\Gamma^{\text{1–loop}} \overset{\alpha\to 0}{=} a_L \cdot \int d^4x \Bigg\{ -\frac{1}{16M^6}\phi\Box^{(4)}\phi + \frac{5m_\Lambda^2}{8M^6}\phi\Box^{(3)}\phi + \\ + \phi\Box^{(2)}\phi\left[\frac{\kappa^2}{4}\cdot\left(\alpha\kappa^2\gamma + \frac{3\gamma^2}{4} - \frac{3\gamma}{2} - \frac{\alpha\kappa^2\gamma^2}{4} - \omega - \frac{\gamma\omega}{2}\right) - \frac{15m_\Lambda^4}{8M^6}\right] + \\ + \partial_\mu\phi\partial^\mu\phi\cdot\frac{\kappa^2}{2}\cdot\left[\frac{\gamma m_\Lambda^2}{8} - \lambda\omega^2 - \omega m_\Lambda^2 + 2\alpha\kappa^2\lambda\omega + \frac{\alpha\kappa^2 m_\Lambda^2}{2} - \alpha^2\kappa^4\lambda\right]\Bigg\}$$

What to pack and bring home

The Vilkovisky-DeWitt method ensures background- and gauge- independence and unveils potentially hidden quantum corrections

Galileon case: new interactions at 1-loop

Extra purely quantum-gravitational contributions

The new operators correspond to higher-derivative interactions for the Galileon

$$\sim \frac{\Lambda}{M^6}\phi\Box^{(3)}\phi, \quad \sim -\frac{\Lambda^2}{M^6}\phi\Box^{(2)}\phi$$

.

Example: gen coord transf. $x^\mu \to \tilde{x}^\mu = x^\mu + \delta\epsilon^\mu(x)$

$$\begin{aligned}\delta g^{\rm coor}_{\mu\nu}(x) &= \int d^n x' K^{g_{\mu\nu}(x)}{}_\lambda(x,x')\delta\epsilon^\lambda(x') \\ \delta\phi^{\rm coor}(x) &= \int d^n x' K^{\phi(x)}{}_\lambda(x,x')\delta\epsilon^\lambda(x')\end{aligned}$$

symmetry generators

$$\begin{aligned}K^{g_{\mu\nu}(x)}{}_\lambda(x,x') &= -g_{\mu\nu,\lambda}(x)\delta(x,x') - 2g_{\lambda(\nu}(x)\partial_{\mu)}\delta(x,x') \\ K^{\phi(x)}{}_\lambda(x,x') &= -\partial_\lambda\phi(x)\delta(x,x')\end{aligned}$$

Field displacements

$$\delta\Phi^i = \delta_{||}\Phi^i + \delta_{\perp}\Phi^i = K^i_{\alpha} d\epsilon^{\alpha} + \delta_{\perp}\Phi^i$$

A gauge-fixing condition, $\chi^{\alpha}[\Phi^i] = 0$, introduces in the fields space a gauge surface $\mathcal{S}$ and a set of gauge orbits parametrised by $\{\chi[\Phi]^A, \xi[\Phi]^A\}$

Background field expansion $\Phi^i = \bar{\Phi}^i + \eta^i$

$$g_{\mu\nu}(x) = \bar{g}_{\mu\nu} + \kappa h_{\mu\nu}, \;\; \phi(x) = \bar{\phi} + \psi$$

Pick up a gauge: e.g. Landau-DeWitt (aka background-field)

$$\chi^{\alpha} = K^{\alpha}_i[\bar{\phi}]\eta^i = 0$$

$$\nabla_i\nabla_j S = \partial_i\partial_j S - \gamma\Gamma^k_{ij}\partial_k S$$

(e.g. $\Gamma^{\phi(x)}_{\phi(x')g_{\mu\nu}(x'')} = \frac{1}{4}g^{\mu\nu}(x)\delta(x,x')\delta(x'',x')$)

$$\Gamma \simeq -\ln\int[d\eta]e^{-S_0}\left(1-\delta S+\tfrac{1}{2}\delta S^2\right) \simeq \langle S_2(x,x)\rangle - \frac{1}{2}\langle S_1(x)S_1(y)\rangle$$

Invited lecture 16:45–17:45

[Chair: Kentaro Takami]

Takashi Nakamura (Kyoto Univ.),

“ New development in astrophysics through multimessenger observations of gravitational waves from 2012 to 2017” (25+5)

[JGRG27 (2017) 122828]

Second application　(first one was rejected because KAGRA was included)

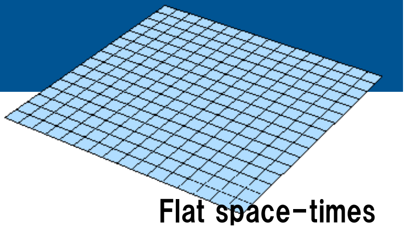
New Development in Astrophysics through multi messenger observation of gravitational waves

2012.5.16 at Ministry of Education

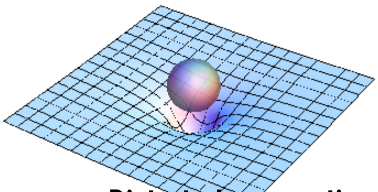
Principal Investigator
Dept. Physics Kyoto University
Takashi Nakamura

JGRG has been partly supported by this innovative area etc

What is gravitational wave？



Flat space-times



Distorted space-times

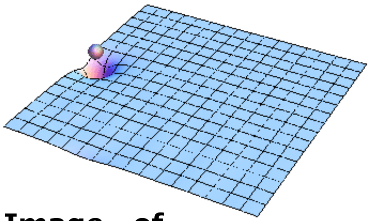


Image　of gravitational wave

- According to general relativity the matter distorts the space-time around it
- If the matter is accelerated, distortion of the space-time propagates with the light velocity as wave.
- This is gravitational wave

It has not been detected directory！！

Why？　Gravity is the weakest force (two protons gravity/electric force=10^{-36})

⇒both generation and detection are difficult。

However　Gravitational wave will be directly detected around 2016 almost definitely

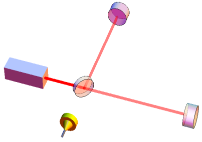
Why definite？ Answer①:Big interferometers are constructed and developed

LIGO: Hanford, WA （米国）

LIGO: Livingston, LA （米国）

LIGO-G030031-00-M

Laser interferometer



VIRGO (仏伊)

GEO(英独)

Why definite？ Answer②:number of events can be predicted

Around 2016 10 times increase of the sensitivity is expected！

1. **Number of events increases in proportion to the third power of sensitivity**

sensitivity∝ detectable distance
number of event ∝ detectable volume ∝distance^3 ∝ sensitivity^3

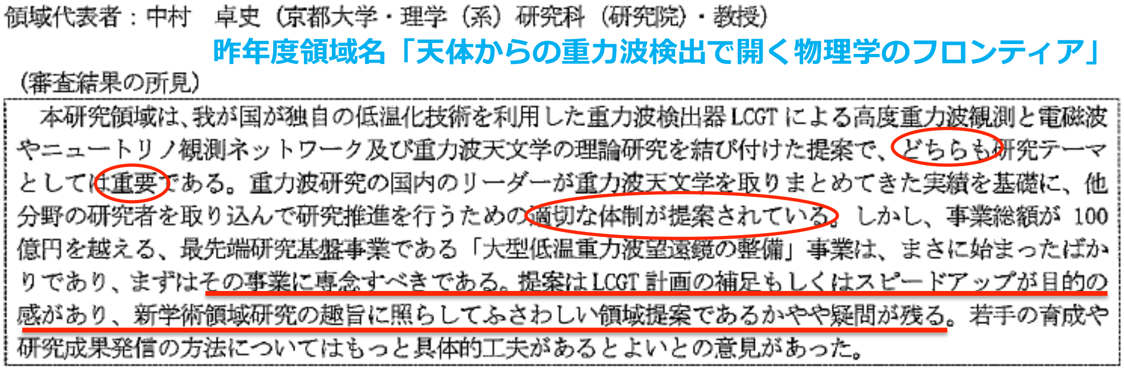
2. **Characteristic of gravitational wave**

Gravitational interaction is the weakest so that gravitational wave passes through any matter and reach long way.

weak point changes best point

Event number ∝ distance^3

10 time increase of sensitivity yields 1000 times number of events！



領域代表者：中村　卓史（京都大学・理学（系）研究科（研究院）・教授）

昨年度領域名「天体からの重力波検出で開く物理学のフロンティア」

（審査結果の所見）

本研究領域は、我が国が独自の低温化技術を利用した重力波検出器 LCGT による高度重力波観測と電磁波やニュートリノ観測ネットワーク及び重力波天文学の理論研究を結び付けた提案で、どちらも研究テーマとしては重要である。重力波研究の国内のリーダーが重力波天文学を取りまとめてきた実績を基礎に、他分野の研究者を取り込んで研究推進を行うための適切な体制が提案されている。しかし、事業総額が 100 億円を越える、最先端研究基盤事業である「大型低温重力波望遠鏡の整備」事業は、まさに始まったばかりであり、まずはその事業に専念すべきである。提案は LCGT 計画の補足もしくはスピードアップが目的の感があり、新学術領域研究の趣旨に照らしてふさわしい領域提案であるかやや疑問が残る。若手の育成や研究成果発信の方法についてはもっと具体的工夫があるとよいとの意見があった。

昨年度	**今年度**　領域名「重力波天体の多様な観測による宇宙物理学の新展開」
重力波検出の基礎実験に関する計画研究2つ	**廃止（KAGRA（旧称LCGT）に移行）**
電磁波・ν対応事象の計画研究1つ	**①ガンマ線・X線、②光・赤外線・電波 ③ニュートリノ観測の計画研究3つに強化**
理論の計画研究1つ 重力波イベント速報の計画研究1つ	**継続**

①重力波天体の電磁波・ニュートリノ対応事象の研究のみに絞った提案

②KAGRA計画とは独立で重力波の実験は含まずに他分野の研究者と理論・データ解析の研究者のみからなる研究提案

Purpose and necessity of this innovative area

2016 will be the start year of detections of gravitational wave

However only from gravitational waves the location can be restricted only about 20 degree square error region
（inside this error region、about 10^5 stars and 10^3 galaxies exist）

Using other methods、we need to identify which star or galaxy is the source of gravitational wave

strong gravity⇒large acceleration⇒high density⇒high temperature⇒neutrino・EM will be emitted

purpose of this area is detection of EM・ν → direction & distance to the sources

KAGRA・LIGO・Virgo → Information of central region of GW sources

Both activity are needed to confirm general relativity in the strong field region and to develop fundamental physics

Both activity are needed to open a new window in astronomy

This area and KAGRA are complementary → budget and organization are independent from KAGRA

重力波源
A. 合体波形
B. バースト波
C. 連続波
D. 背景重力波
E.未知の波源

中性子星連星合体

超新星爆発

X線、γ線、可視光、赤外線、電波、ニュートリノ...

多様な手段で観測

計画研究A01
A01
大立体角の連続モニター
MAXI

計画研究A02
光・赤外広視野望遠鏡　電波観測
A02

計画研究A03
A03　ニュートリノ検出

連携した観測の構築
重力波事象の理解

計画研究A04
A04
重力波のデータ解析

重力波観測

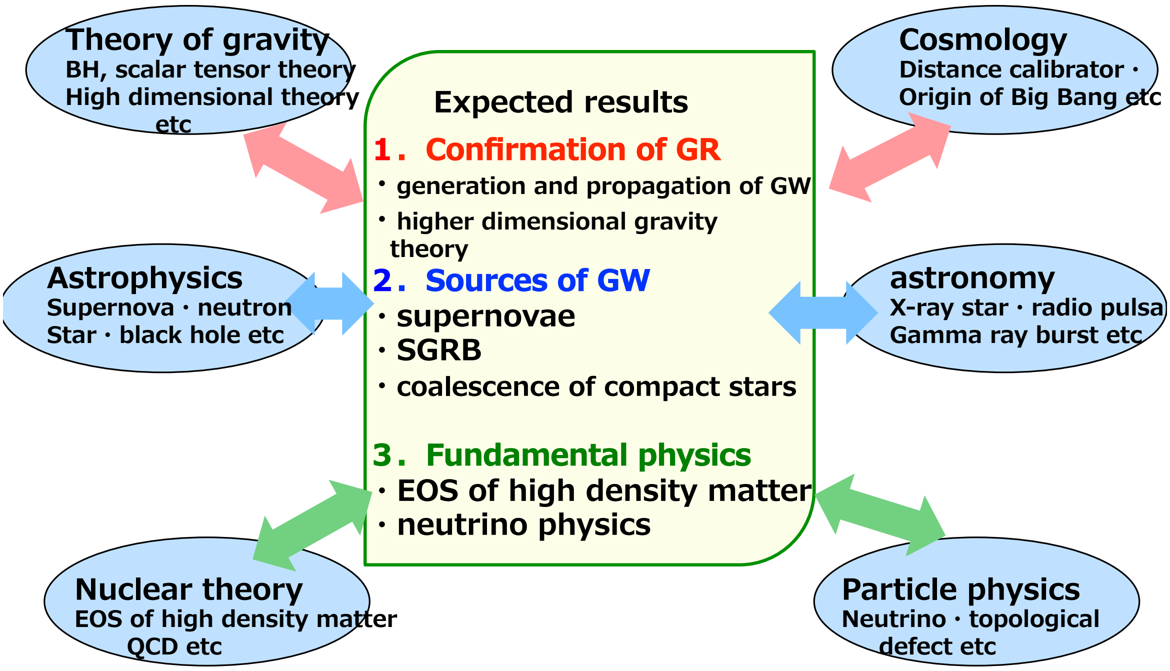
計画研究A05
A05
理論

KAGRA

海外の重力波検出器
aLIGO, aVirgo

各種天体観測
観測衛星
地上の光赤外望遠鏡

Expected results and expansion of this region to other fields



Expected results

1． Confirmation of GR
- ・generation and propagation of GW
- ・higher dimensional gravity theory

2． Sources of GW
- ・supernovae
- ・SGRB
- ・coalescence of compact stars

3． Fundamental physics
- ・EOS of high density matter
- ・neutrino physics

Theory of gravity
BH, scalar tensor theory
High dimensional theory etc

Cosmology
Distance calibrator・Origin of Big Bang etc

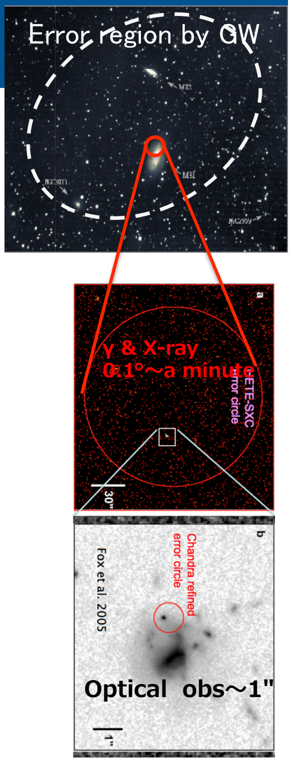
Astrophysics
Supernova・neutron Star・black hole etc

astronomy
X-ray star・radio pulsa
Gamma ray burst etc

Nuclear theory
EOS of high density matter
QCD etc

Particle physics
Neutrino・topological defect etc

Example 1
①How our project treats coalescence of binary neutron stars



Step 1 A04 allerts the position of GW with several degree.

Step 2 A01 observes GW position with 0.1° accuracy by X-ray

Step 3 A02 perform optical observation to determine the position with arc sec accuracy

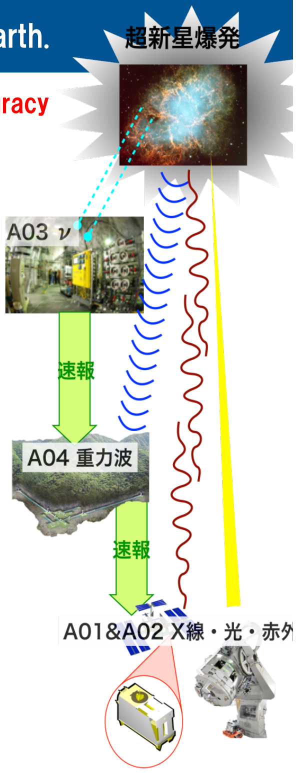
A03 will check ν emission

Step 4 A02 identify host galaxy to determine the distance and compare that from GW If two are the same GR is OK. If not, biggest discovery.

Step 5 A01 and A02 with radio obs. check property of GRB.

Step 6 All group including theory group A05 check if the prediction by Einstein 100 years ago is correct or not ?

Example 2
②When supernova occurs three thousand light year from the earth.



Step 1 From detected ν A03 allert position with several degree accuracy

Step 2 A04 check if GW is emitted

yes ⇒ SN was non spherical explosion

no ⇒ counter example against standard theory

Step 3 A01&A02 perform X-ray and optical observations

Check property of Super Nova

Step 4 A03&A04 Analysis of correlation of ν and GW

Step 5 All group including theory group A05

Check how all the atom in earth and mankind formed

Schedule of each group and correlation

	2012	2013	2014	2015	2016	2017
A01 重力波天体からのX線･γ線放射の探索	WF-MAXI: 試作品開発 MAXI、すざく、Swift等の衛星を用いて、GRB、中性子連星、ブラックホールの研究		WF-MAXI: 搭載品開発 観測装置･ソフトウエア、観測計画に反映		重力波観測フォローアップ	
A02 天体重力波の光学赤外線対応現象の探索	岡山赤外カメラ自動観測化 木曽シュミット望遠鏡整備	GRBフォローアップシステムの整備、京大面分光装置開発	中国に広視野望遠鏡、 木曽シュミット6度カメラインストール	重力波観測フォローアップの試験観測	重力波観測フォローアップ開始	
A03 超新星爆発によるニュートリノ信号と重力波信号の相関の研究	200t R&D データ収集系アップグレード、超新星ニュートリノ検出器の計画	検出器更正 長期観測への準備	他の観測との正確な時刻同期	観測 遠い超新星についてもより良い感度をもつためのオンライン計算の継続的な改良		
A04 多様な観測に連携する重力波探索データ解析の研究	探索解析システムの開発 GRID環境の構築		本機導入 解析ソフトウエア実装	観測データ転送、 重力波探索	パイプライン解析の調整、 速報システム整備	
A05 重力波天体の多様な観測に向けた理論的研究	幅広い理論研究の連携の強化。最適な同時観測、データ解析の体制の改善に向けた理論的知見の発展と整理。重力波波形予測の整備。		重力波観測とその他のプローブによる同時観測に向けた更なる理論的研究の推進。幅広い理論研究の連携の強化。			
KAGRA計画	建設			常温観測 iKAGRA	低温化へ bKAGRA	
海外の重力波検出実験 advanced LIGO advanced Virgo	インストール		装置調整		観測開始	

What each group recommends:

1．This area use GW、ν、gamma ray、X ray、optical・infra red、radio. Full Multi Messenger Astrophysics by a single group

2．A01　world wide activity on research of GRBs

3．A02　world wide Japanese telescopes

4．A03　the first neutrino detectors in the world using Gd to identify anti-neutrino in the detection of supernova nutrino

5．A04　data analysis power fromTAMA300 over 10 years.

6．A05　Various world wide results on post-newtonian GW form, numerical relativity, supernova and so on.

How to bring up students and outreach general people in Japan

Gravitational wave is the field in science with big development in this century so that it is the very important field

① We will bring up necessary young students
- Take place the seminars for wide field young students
- Hire active young researchers

② How to teach scientific results to general people in Japan
- Home Page
- Write articles in general scientific magazines
- Public lectures to high school and university students as well as citizens.
- Consider the possibility that citizens join to data analysis.

Conclusion

New window by gravitational wave will be opened in 2016

Simultaneous observations by gamma, X ray, optical・infrared, radio and neutrino are indispensable

Construct the follow-up system using full power of Japan as soon as possible.
We will answer to questions like
Prediction by Einstein 100y ago is correct or not?
How the atom like gold and platinum was formed？ etc

We promote development of cosmology, particle physics, nuclear physics and so on.

Open the new window to the universe !!
See the new world of science!!

Results after five years

New Development in Astrophysics through multi messenger observation of gravitational waves

2017.9.8 at Ministry of Education

Principal Investigator
Dept. Physics Kyoto University
Takashi Nakamura

Organization of this innovative area

Principal Investigator
Takashi Nakamura（Kyoto Univ.) Total budget 1.24x10^7yen~11M$

Strategic research

- A01「Search for X & gamma ray from GW sources」

PI : Nobuyuki Kawai（Tokyo Inst. Tech.）

- A02「Search for optical & infrared radiation from GW sources」

PI : Michitoshi Yoshida（Hiroshima Univ.）

- A03「Research of correlation of GW and neutrino signal from SN」

PI : Mark Vagins（Tokyo Univ. IPMU）

- A04「Data analysis of GW signal related to various observations 」

PI : Nobuyuki Kanda（Osaka City Unv.）

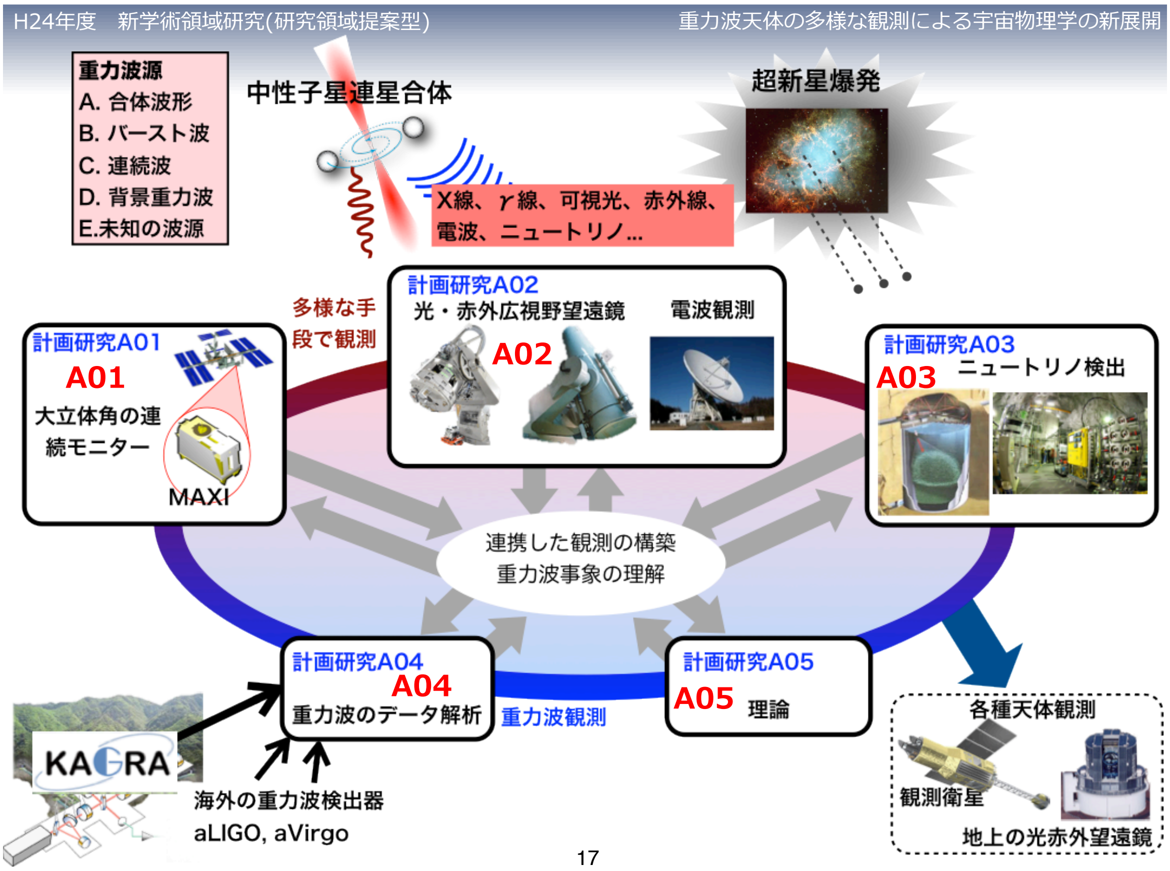
- A05「Theoretical research for various observations of GW sources」

PI : Takahiro Tanaka（Kyoto Univ）

Headquarter

- X00「New development in Astrophysics through multi messenger observation of gravitational waves」

PI : Takashi Nakamura（Kyoto-Univ.）



重力波源
A. 合体波形
B. バースト波
C. 連続波
D. 背景重力波
E.未知の波源

中性子星連星合体

X線、γ線、可視光、赤外線、
電波、ニュートリノ…

超新星爆発

多様な手
段で観測

計画研究A02
A02
光・赤外広視野望遠鏡
電波観測

計画研究A01
A01
大立体角の連
続モニター
MAXI

計画研究A03
A03
ニュートリノ検出

連携した観測の構築
重力波事象の理解

計画研究A04
A04
重力波のデータ解析

重力波観測

計画研究A05
A05
理論

KAGRA

海外の重力波検出器
aLIGO, aVirgo

各種天体観測
観測衛星
地上の光赤外望遠鏡

Operating status of GW detectors

1) aLIGO
O1 (Observing run 1)　2015/9-2016/1

- Sensitivity : ~1/3 of the final one
- Results : two Binary BH events
- A01 and A02 performed follow-up observation based on MOU

2) aLIGO& aVirgo
O2　2016/12-2017/8

- Sensitivity : ~1/6-1/2 of the final one
- Results : 2017.1.4 30―20Msun BBH. There is announce of detections without details. A01 and A02 performed follow-up observations based on MOU up to 2017.8.25
- Rumors suggest the big discovery

3) KAGRA performed room temperature observations from 2016.3 to 2016.4

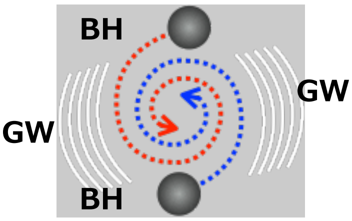
- A04 succeeded to transfer the data and performed the data analysis

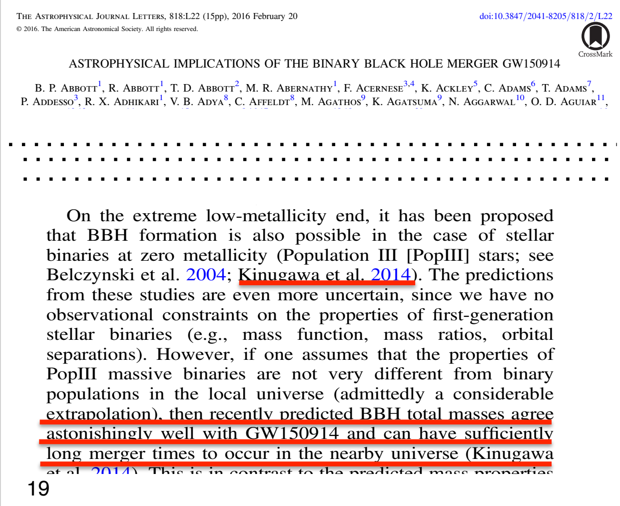
We predicted the first directly observed GW event GW150914 in 2014

30-30 solar mass binary BH from the first stars in the universe

- PI and Kinugawa + 3 graduate students predicted in 2014
- In the summary of GWPAW2015 held June 2015, "30Msun BBH will be detected in September!!! "
- In the LIGO paper, "30Msun BBH predicted by Kinugawa et al. (2014) astonishingly agree with GW150914 "

Ap.J.Letters, 818:L22(2016)




THE ASTROPHYSICAL JOURNAL LETTERS, 818:L22 (15pp), 2016 February 20 doi:10.3847/2041-8205/818/2/L22

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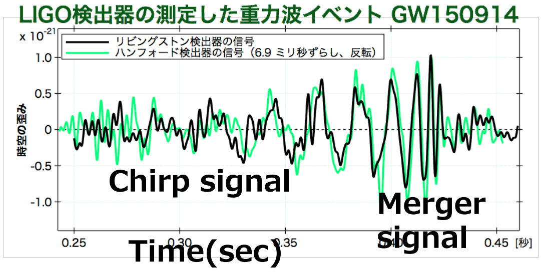
ASTROPHYSICAL IMPLICATIONS OF THE BINARY BLACK HOLE MERGER GW150914

B. P. ABBOTT[1], R. ABBOTT[1], T. D. ABBOTT[2], M. R. ABERNATHY[1], F. ACERNESE[3,4], K. ACKLEY[5], C. ADAMS[6], T. ADAMS[7], P. ADDESSO[3], R. X. ADHIKARI[1], V. B. ADYA[8], C. AFFELDT[8], M. AGATHOS[9], K. AGATSUMA[9], N. AGGARWAL[10], O. D. AGUIAR[11],

……

On the extreme low-metallicity end, it has been proposed that BBH formation is also possible in the case of stellar binaries at zero metallicity (Population III [PopIII] stars; see Belczynski et al. 2004; Kinugawa et al. 2014). The predictions from these studies are even more uncertain, since we have no observational constraints on the properties of first-generation stellar binaries (e.g., mass function, mass ratios, orbital separations). However, if one assumes that the properties of PopIII massive binaries are not very different from binary populations in the local universe (admittedly a considerable extrapolation), then recently predicted BBH total masses agree astonishingly well with GW150914 and can have sufficiently long merger times to occur in the nearby universe (Kinugawa et al. 2014). This is in contrast to the predicted mass properties

LIGO検出器の測定した重力波イベント GW150914



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30 + 30 solar mass BHs

Interesting target for three reasons:

Inspiral and ringdown phases have roughly equal SNRs, so provides good test of GR

First star in the universe

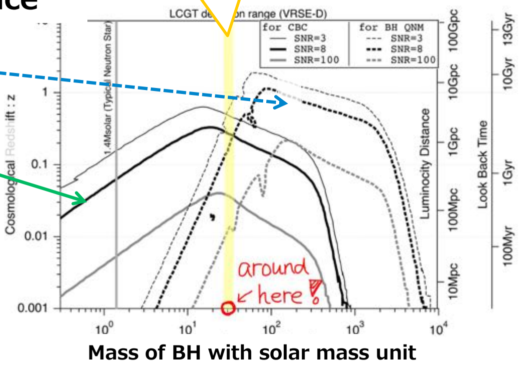
If population III stars (formed at redshifts 5-10) exist, these might be a substantial fraction.

Perhaps we will detect several of them in the first aLIGO data run O1, this September!

Detectable distance

30+30 solar mass is best to detect both chirp and ring down GW

Nakano Talk



This is one of the slides in the summary talk by Bruce Allen at GWPAW2015 held 20th June 2015

質問事項２

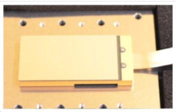
2015年6月に30太陽質量のブラックホール連星の合体の可能性がA05により指摘された。これを受けて、A01-A04において重力波発見に先立った新たな研究を模索する動きはあったのか説明していただきたい。

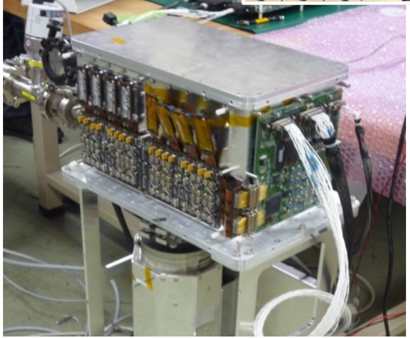
回答

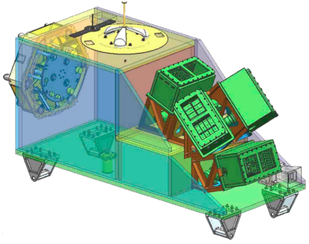
1）GW150914のような30-30太陽質量のブラックホール連星合体では、合体前、合体中、合体後の３つの重力波の解析が重要であるが、合体後の減衰振動は重力が最も強いところでの性質の情報を持って来るので、アインシュタイン理論の正否を決定すると期待されていた。A04では減衰振動の解析法の検討を始めて、Hilbert-Huang変換を用いて、合体中と合体後の区別をする方法を提案した。その結果、aLIGOの解析より精度の良い結果を出せるようになった。しかし、アインシュタイン理論の正否を結論づけるのにはGW150914より、もっとSNの大きいイベントが必要であることがわかった。

2）電磁波とニュートリノ放出はブラックホール合体では期待薄であるが、自然は人類を超越している可能性もあるので、A01,A02, A03では、GW150914等の４つの連星ブラックホール合体の追観測を実施した。A05は合体後に星間物質がブラックホールに落下して太陽光度の1000万倍くらいの電磁波が出る可能性も指摘していたが、これは追観測の士気を上げた。

A01　Search for X & gamma ray from GW sources







Target 1 : Design & trial manufacture of WF-MAXI

- Soft X-ray Large solid angle Camera (SLC)

development of CCD and estimate of ability → done

development of camera and circuit for signal → Thermal design for ISS and rapid read out are done

- Hard X-ray Monitor(HXM)

detector(GAGG scinti+APD)
Data analysis using ASIC
→ Done with two revisions

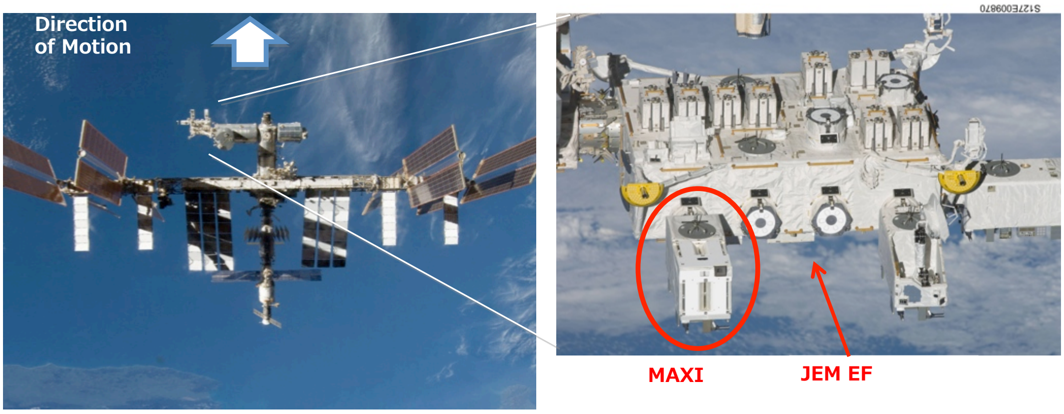
- Apply to small scale mission of ISAS(Japanese counter part of NASA)

2014: 4SLC+HXM (cost~40M$)
Not adopted. ISAS comment was
"The probability of detecting GW is not high. Estimate of cost performance is needed"
→This is completely wrong.

2015: 1SLC (~10M$)

Not adopted（ISAS）
because「ASTROSAT（launched 2015 ）can do the observations by WF-MAXI

MAXI and WF-MAXI

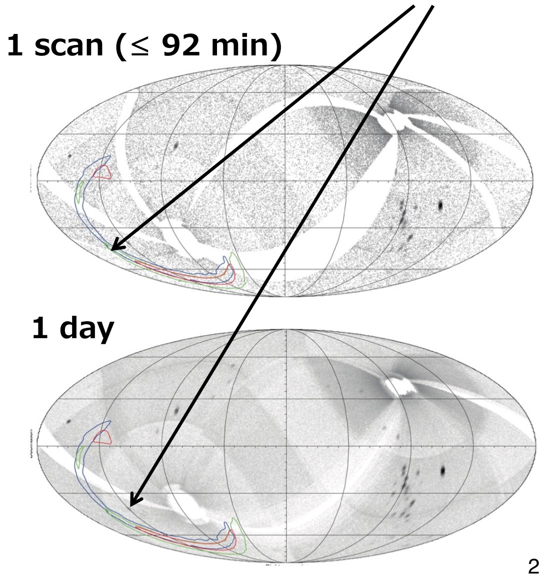


WF(Wide Field)-MAXI covers 20% of sky in X-ray band while MAXI does 1%.

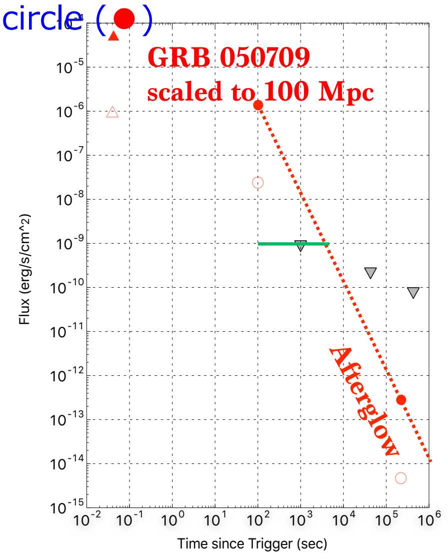
A01　Search for X & gamma ray from GW sources

Obs. of GW150914 by MAXI

- Sky map after 92min and 1 day and the direction to GW by a LIGO



- Upper limit by MAXI(▼) & Expected sGRB X-ray intensity in aLIGO error circle (●)



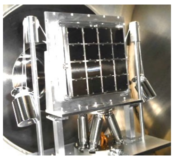
質問事項 1

X 線・ガンマ線での広視野モニター観測の将来計画は結局どのように見直すことにしたのか。また、X線観測装置の今後をどのように考えているのか、将来像を説明いただきたい。

- ISAS「小規模計画」での実現は困難

（質問事項3への回答を参照）

- 方針：国内外の他ミッションへの協力を通じて実現
  - “**HiZ-GUNDAM**”（日本：GRB・GW対応天体追跡観測）
    JAXA小型衛星に再応募予定 (目標: 2018採択、2022〜打上)
    X線広視野モニター（本領域公募研究で開発）を搭載
  - “**Einstein Probe**”（中国：軟X線広視野モニター衛星）
    2022打上を目指して概念設計・試作実施中
    本研究メンバーに検出器開発協力要請
  - 他の提案にも参加
    - **“THESEUS” ESA 中型衛星提案(2016)に参加、本年末に採否決定**
    - **“eXTP” 中国-欧州ミッション、X線広視野モニターチームに参加**



Einstein Probe 試作品

質問事項 3

WF-MAXI に関して、プロトモデルの開発などをしたものの、採択には至らなかったことは残念である。その後、規模を縮小しての提案になっているが、現状での見通しはどうか説明いただきたい。

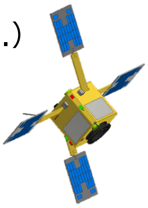
- 計画研究予算による実施目標は達成

搭載装置の開発・試作・評価を実施
ミッションの予備設計実施・ISAS公募にISS搭載を2回提案

- 今後のISAS「小規模計画」への応募は断念

ー公募予算規模の縮小（総額数十億円以下➔総額2億円未満）

- **2015年提案（当初の1/4 縮小~10億円）でも実現不可能**
- **一方、競合ミッションの進行、新技術の出現**
  - (Lobster Eye光学系、CMOS撮像素子、超小型衛星バス、...)



- 対応1：他ミッションへの協力 (→質問事項1)
- 対応2：超小型衛星による科学目標の実現

“**Hibari**” 50 kg級超小型衛星による紫外線突発天体探索
2016衛星設計コンテスト大賞・2017より基盤A+若手Aで開発

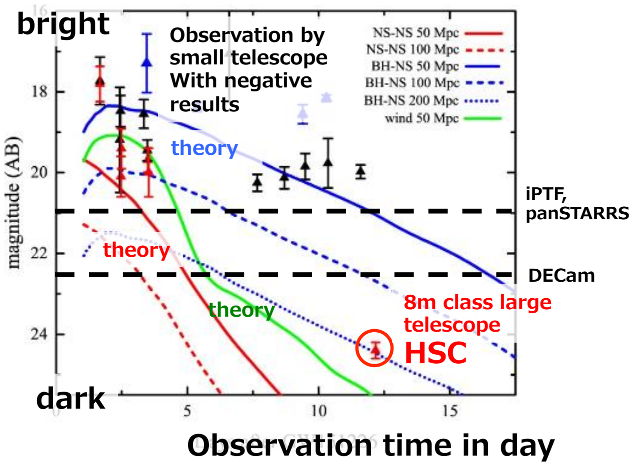
A02　Search for optical & infrared radiation from GW sources

Construction of J-GEM and folow-up obserbation

- J-GEM(Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up)

- GW151226

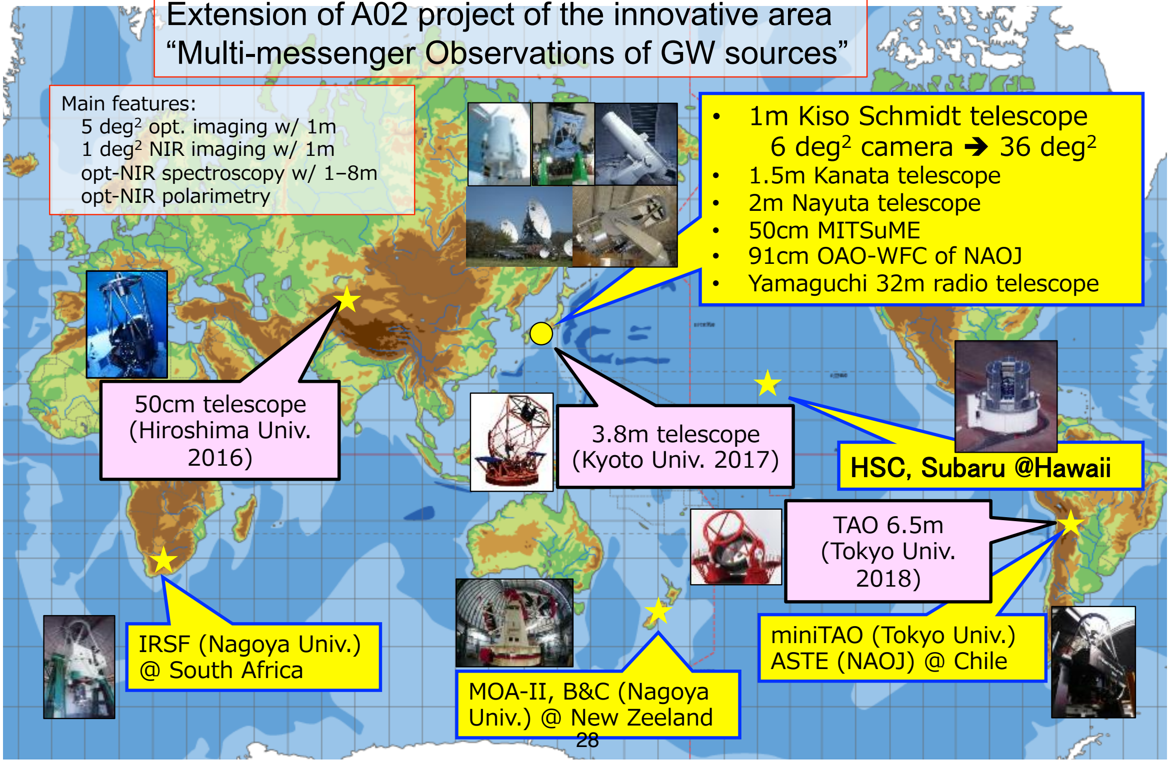
Subau-HSC performed
The deepest observation
➔ 60～100degree²
and proved ability of detection of possible darkest signals in the world



J-GEM's observation of GW151226
Subaru HSC performed the deepest follow-up observation。

J-GEM (Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up)

Extension of A02 project of the innovative area
“Multi-messenger Observations of GW sources”



Main features:
- 5 deg² opt. imaging w/ 1m
- 1 deg² NIR imaging w/ 1m
- opt-NIR spectroscopy w/ 1–8m
- opt-NIR polarimetry

- 1m Kiso Schmidt telescope
  6 deg² camera ➔ 36 deg²
- 1.5m Kanata telescope
- 2m Nayuta telescope
- 50cm MITSuME
- 91cm OAO-WFC of NAOJ
- Yamaguchi 32m radio telescope

50cm telescope
(Hiroshima Univ.
2016)

3.8m telescope
(Kyoto Univ. 2017)

HSC, Subaru @Hawaii

TAO 6.5m
(Tokyo Univ.
2018)

IRSF (Nagoya Univ.)
@ South Africa

MOA-II, B&C (Nagoya
Univ.) @ New Zeeland

miniTAO (Tokyo Univ.)
ASTE (NAOJ) @ Chile

質問事項 4

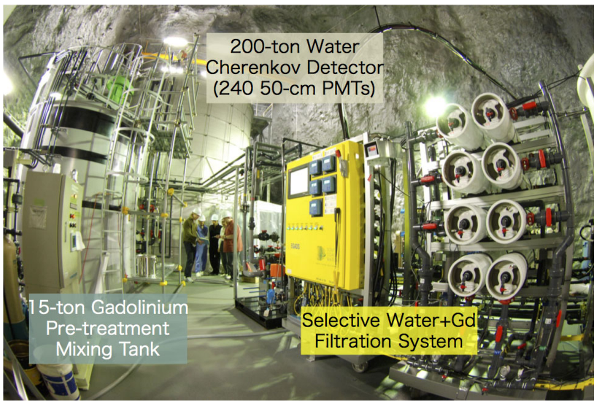
チベットに仮設置した望遠鏡の本格設置は、政治的要因で遅れているようだが、現在も入境許可が 出ていない状況の中、今後の見通しについて説明いただきたい。また、開発したハードウェアーによる これまでの成果について説明していただきたい。

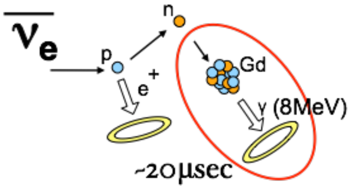
中国チベット・50㎝望遠鏡の状況と今後

- 現在（2017/8）の状況
  - ・2016年9月9日にチベット現地に望遠鏡・観測装置一式を中国所有ドームの中に仮設置し、試験観測を実施した。
  - ・試験観測の結果、望遠鏡＋観測装置の光学性能が設計通りであることを確認した。また、チベットサイトのシーイングが1秒角を切っていることを確認、大気透過率と合わせて、50㎝望遠鏡の限界等級が日本国内の1m望遠鏡に相当することが分かった。科学観測はまだ行っていない。
  - ・2016年10月以降、ドーム設置と望遠鏡の本格設置・定常運用開始を目指してチベット入境を試みているが、当局の許可が得られていない。
- 今後の見通しと方策
  - ・2017年9月後半～10月にチベット入境が許可される見通し ➔ 約3週間の滞在でドーム・望遠鏡設置を行う。
  - ・中国・紫金山天文台から博士留学生が広島大学に来ており、研究の一部として本50㎝望遠鏡に関する開発も行っている。今後も日本人のチベット入境が困難なことが予想されるが、本留学生（紫金山天文台職員）が帰国後に望遠鏡調整・運用の中心となってプロジェクトを継続していくことを計画している。新しい新学術（田中代表）での活躍を期待できる。

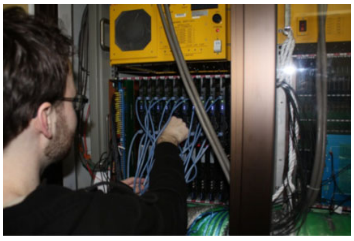
A03: Research of correlation of GW and neutrino signal from SN

200t water cherenkov detector near Super Kamiokande under 1000m





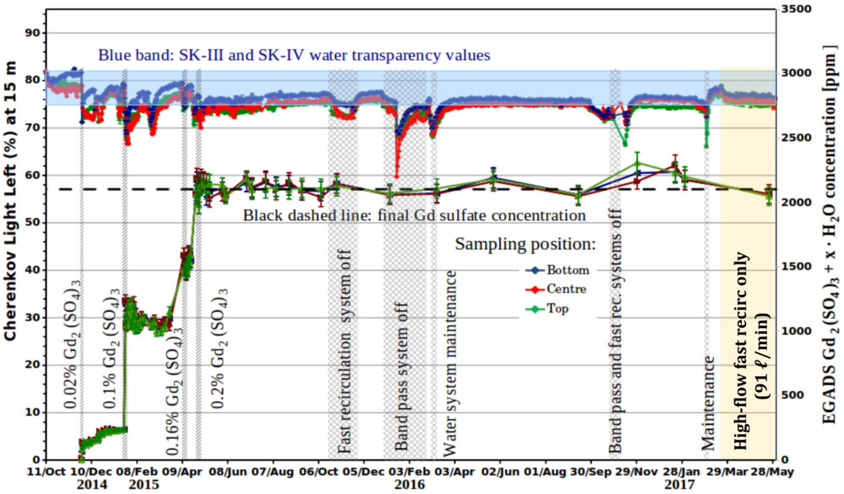
- **Possible to identify anti-neutrino from neutrino**
- **Possible to detect arrival direction**
- **8000 events from SN of Betelegeuse due to increase by new circuit**



Performed continuous observation for two years !

Super-Kamiokande decided introduction of Gd　!

check　transparency of water using of EGAD



- **Similar to pure water transparency**
- **From this success Super-K team decided to add Gd**
- **Neutrino from far SN can be detected in future**

A04 Data analysis of GW signal related to various observations

Success of real time transfer of GW data of KAGRA to Osaka city univ.

- KAGRA at Kamoka mine → Cluster computers at Osaka city univ

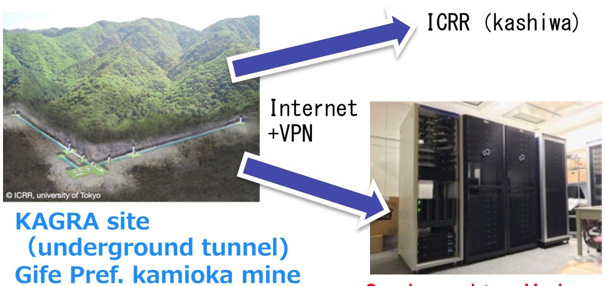
  Average delay time was 3 second !!

  We ourselves made software of data transfer

  Safe operation more than one and half year

  VPN(Virtual Private Network) is safely operated

Mile stone for low delay time data transfer was achieved !



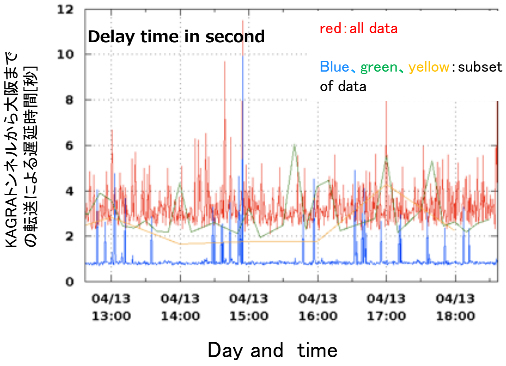
ICRR（kashiwa）

Internet
+VPN

KAGRA site
（underground tunnel)
Gife Pref. kamioka mine

Osaka city Univ.

Data transfer time KAGRA→Osaka

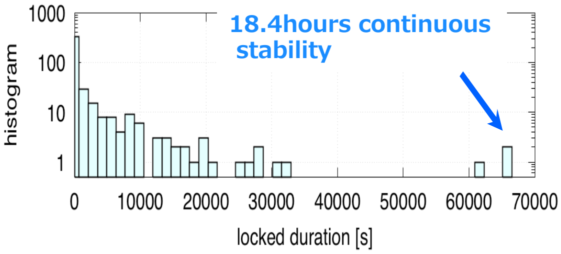


A04 data analysis of GW signal related to various observations

Analysis of real data was done

Data analysis of test operation of KAGRA data in 2016 was performed

- Search for compact binary merger
- Burst wave from supernova
- Continuous wave from pulsar
- Analysis of noise from KAGRA



Histogram of lock time of operation of KAGRA 2016 April

Analysis of GW150914

- Use open data of aLIGO

Construction of data analysis group in Japan including young researcher was done by PI of A05 and team members.

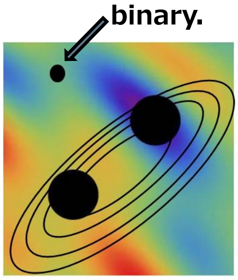
A05 Theoretical research for various observations of GW sources

Density perturbation in the early universe can make 30 solar mass binary BH at its high amplitude region. This can be the origin of dark matter.

- Primordial black hole scenario for the gravitational wave event GW150914 (M. Sasaki, T. Suyama, T. Tanaka, S. Yokoyama)
- Phys. Rev. Lett. Editors' Suggestion

Third body's tidal force can make binary.

- Based on the natural scenario of primordial BH formation, we computed the formation rate of 30 solar mass binary and found that it is compatible with that of GW150914 as well as observation of the deviation of CMB.



The nearer two BHs make binary by the third body and merges at the age of Universe

Various activity and Development of young researchers

We developed many young researchers

1. We use English in every meetings and symposium. We made special sessions for young researchers at the symposium
2. 22 young researchers got research posts. Others got another post doctoral jobs and are continuing the research.
3. We host 13 international conference in Japan and 3 in the abroad.
   Many graduate students and posdocs made oral and poster presentations in English.
4. The total number of refereed papers is 472.
5. 16 awards and 3 promotion to professor or associated professor.

GWPAW(Gravitational Wave Physics and Astrophysics workshop) 2015, in Osaka

---

Outreach, magazines, newspapers and TV

The first direct detection of GW.

- LIGO’s press conference 2016 Feb. 11
  Answer to questions from Reporters of news papers and TV.
- Many Public lectures.
- Many Public writings


重力波の初観測に成功したという発表の映像を見ながら説明する大阪市立大学大学院理学研究科の田越秀行准教授（中央）。右は神田展行教授＝大阪市住吉区で２０１６年２月１２日午前０時５２分、三浦博之撮影

Mainichi news paper web site Explain LIGO’s press release by member of A04

Public lectures for high school students and citizens

- Public lectures for 100 anniversary of general theory of relativity were held at 15 places in Japan with 2500 participants
- Free electric book for high school students at HP of this innovative area

Written by Nakamura(PI) “The last one second” (75pages)

2868 down loads (at 2017/9/4)

Poster of Public lectures 100 anniversary of general theory of relativity

Conclusion

A01

- Brought one year advance of X-ray follow-up of GW events detected by aLIGO using MAXI and CALET for three years expecting fine results in O2.
- For WF-MAXI which covers 20% of the sky, we succeeded in preliminary design and construction of the apparatus.

A02

- Brought one year advance of optical・infrared follow-up observation of GW events detected by aLIGO for three years. Organized J-GEM (Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up) which has high evaluation in the world.
- In aLIGO O2, A02 might have big results.

A03

- Operated 200t water Cerenkov detector which can distinguish anti-neutrino first in the world for two and half years,
- From this good result, SK decided to include Gd next year

A04

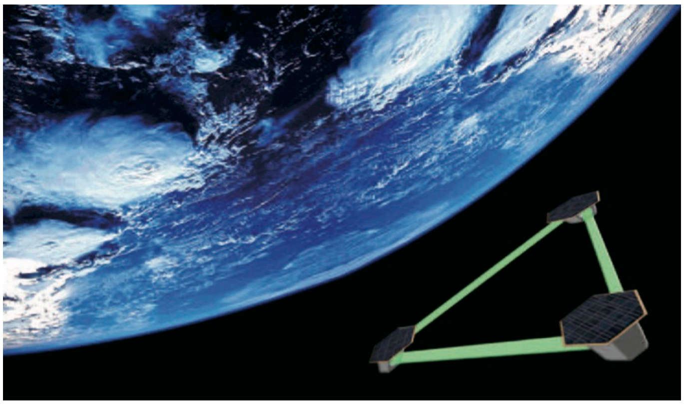
- Succeeded in fast and stable transfer of GW data from KAGRA and analysis of the data. A02 is now ready for operation of KAGRA detector.
- Found new data analysis methods using open data of aLIGO.

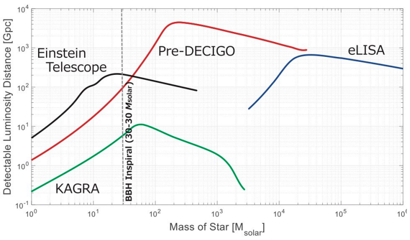
A05

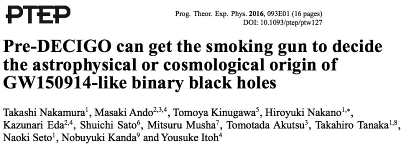
- Predicted 30Msun BH binary from the first star in the universe which is detected by aLIGO.
- Also predicted 30Msun BH binary from the density perturbation in the early universe.
- To identify which is the case, it is needed to construct 0.1Hz band cosmic detector called DECIGO.

This innovative area performed many themes appropriate at the time of the first direct detection of the gravitational wave. These results are fine for the development of new world of gravitational wave and related physics and astronomy.

B-DECIGO(DECi hertz laser Interferometer Gravitational wave Observatory)





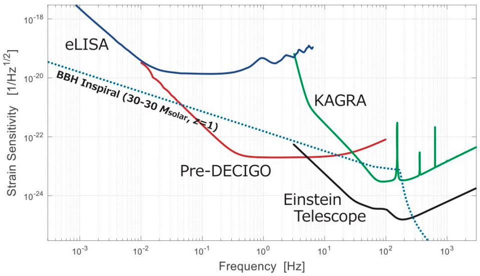


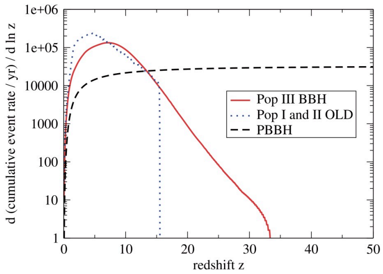
PTEP

Prog. Theor. Exp. Phys. **2016**, 093E01 (16 pages)
DOI: 10.1093/ptep/ptw127

Pre-DECIGO can get the smoking gun to decide the astrophysical or cosmological origin of GW150914-like binary black holes

Takashi Nakamura[1], Masaki Ando[2,3,4], Tomoya Kinugawa[5], Hiroyuki Nakano[1,*], Kazunari Eda[2,4], Shuichi Sato[6], Mitsuru Musha[7], Tomotada Akutsu[3], Takahiro Tanaka[1,8], Naoki Seto[1], Nobuyuki Kanda[9] and Yousuke Itoh[4]





Announce of GW170817/SGRB170817A was Oct.16th

Therefore we could not argue this important event at the final hearing although follow-up observations by A01 and A02 had been done.

Next speaker Kawabata will talk on the activity by J-GEM and MAXI in details.

Moreover A05 wrote papers on GW170817 such as

1)Ioka, K. Nakamura,T. Can an Off-axis Gamma-Ray Burst Jet in GW170817 Explain All the Electromagnetic Counterparts? arXiv:1710.05905

2)Kisaka, S., Ioka, K.,Kashiyama, K., Nakamura,T. Scattered Short Gamma-Ray Bursts as Electromagnetic Counterparts to Gravitational Waves and Implications of GW170817 arXiv:1711.00243

3) Yamazaki, R. Ioka, K. Nakamura, T. Prompt emission from the counter jet of a short gamma-ray burst

arXiv:17011.06856

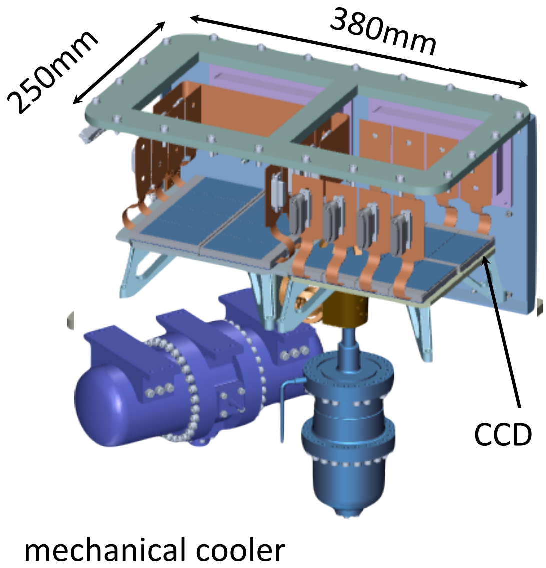
4)Shibata, M., Fujibayashi, S., Hotokezaka, K., Kiuchi, K., Kyutoku, K., Sekiguchi, Y., Tanaka, M.,

GW170817: Modeling based on numerical relativity and its implications arXiv:1710.07579

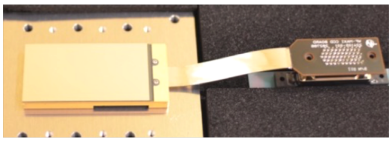
補足資料

A01　重力波天体からのX線・γ線放射の探索

SLC (軟Ｘ線大立体角カメラ)



- 質量 ~25kg (w/o compressor)
- 試作品を科研費で開発、カメラ＋冷凍機試作試験中
- 符合化マスク: 位置決定性能シミュレーション、パターン試作
- CCDピクセルとマスクの平行確保
- 熱設計 (24C°流体による冷却ー冷凍機ーCCD –100 C (TBD))
    - 冷凍機を使わない放射冷却も検討
- 専用CCD (ASTRO-H SXI技術継承)



A01　重力波天体からのX線・γ線放射の探索

目標2: 重力波対応天体の観測

- MAXI - LIGO/VirgoチームとMOU締結

GW150914, GW151226 重力波源誤差領域全域の追跡観測をＸ線領域で唯一実施、上限値測定

- **将来の中性子星合体重力波に対しての価値を実証**
- **予想よりも早く実現**
- **LIGO-O2 (2016/11〜2017/8)に年度繰越で参加**

- MAXIによる重力波関連天体の観測

GRB および 短時間Ｘ線トランジェントの観測

新ブラックホールの発見

ほぼ1年に一個の割合で発見
銀河系のブラックホールの数の推定へ

Ｘ線連星のアウトバースト、状態遷移の観測

中性子星やブラックホールへの降着過程の解明
中性子星の回転の変化→質量と半径への制限
ブラックホールの質量推定

A02　天体重力波の光学赤外線対応現象の探索

設定目的の達成度

- 光学赤外線追跡観測ネットワークの構築

4つの装置開発の**達成度：80%**

木曽超広視野カメラTomoe　80%
岡山広視野赤外線カメラ　OAO-WFC　90%
京大3.8m用面分光システム　100%
中国50㎝望遠鏡　70%

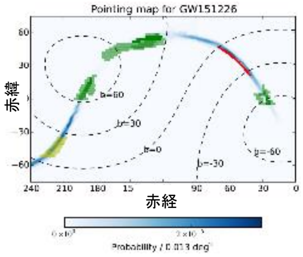
Tomoeプロトタイプ

- 望遠鏡ネットワークを用いた重力波源の追跡観測

  LIGO/Virgo国際共同研究の電磁波フォローアップコンソーシアムに参加➔J-GEM立ち上げ（15機関・10望遠鏡が参加）

  J-GEMによりLIGOが検出した重力波源の追跡観測に成功➔当初計画以上の成果　**達成度：100%以上**

GW150914　24平方度サーベイ＋銀河観測
GW151226　1000平方度サーベイ＋銀河観測
🡐すばる望遠鏡HSCにより世界一の深さ
（24等級）で追跡観測に成功



J-GEMのサーベイ領域
緑:木曽、赤:すばるHSC、黄:MOA

青はLIGOの重力波観測で推定する到来方向。
青の濃いところほど可能性が大きい。

A02　天体重力波の光学赤外線対応現象の探索

主な研究成果

- LIGOによる重力波源の追跡観測

GW150914：人類初の重力波直接検出

Abbott, et al. ApJL, 826, L13 (2016); Abbot, et al. 2016, ApJS, 225, 8 (2016); Morokuma, et al. PASJ, 68, 9 (2016)

GW151226：二番目の重力波検出

Yoshida, et al. PASJ, 69, 9 (2017); Utsumi, et al. PASJ submitted (2017)

- 重力波源追跡のための観測装置開発

  超広視野カメラTomoeのプロトタイプ完成・試験観測成功（2015）
  広視野赤外カメラOAO-WFC完成・定常運用開始（2015）
  面分光システム完成・定常運用開始（2015）
  中国50㎝望遠鏡完成・チベット設置（2016）

- 重力波源の光学対応天体に関連する理論的・観測的研究

  中性子星合体による電磁波放射の理論的研究（Tanaka, et al. 2014他）
  極超新星と超新星のミッシングリンク天体の発見（Takaki et al. 2013）
  超チャンドラセカール質量のIa型超新星発見（Yamanaka, et al. 2016）

A02　天体重力波の光学赤外線対応現象の探索

中国チベット・50㎝望遠鏡の状況と今後

- 現在（2017/8）の状況
  - ・2016年9月9日にチベット現地に望遠鏡・観測装置一式を中国所有ドームの中に仮設置し、試験観測を実施した。
  - ・試験観測の結果、望遠鏡＋観測装置の光学性能が設計通りであることを確認した。また、チベットサイトのシーイングが1秒角を切っていることを確認、大気透過率と合わせて、50㎝望遠鏡の限界等級が日本国内の1m望遠鏡に相当することが分かった。科学観測はまだ行っていない。
  - ・2016年10月以降、ドーム設置と望遠鏡の本格設置・定常運用開始を目指してチベット入境を試みているが、当局の許可が得られていない。
- 今後の見通しと方策
  - ・2017年9月後半～10月にチベット入境が許可される見通し　➔　約3週間の滞在でドーム・望遠鏡設置を行う。
  - ・中国・紫金山天文台から博士留学生が広島大学に来ており、研究の一部として本50㎝望遠鏡に関する開発も行っている。今後も日本人のチベット入境が困難なことが予想されるが、本留学生（紫金山天文台職員）が帰国後に望遠鏡調整・運用の中心となってプロジェクトを継続していくことを計画している。

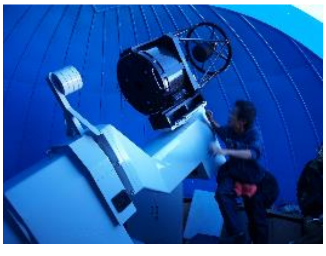
A02　天体重力波の光学赤外線対応現象の探索

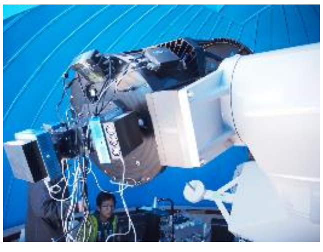
- 50㎝望遠鏡のチベット・阿里サイトへ設置 (2016/9)

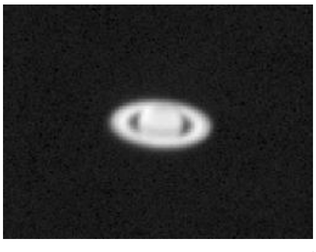

チベット・阿里サイト


望遠鏡を仮設置したドーム


望遠鏡設置の様子

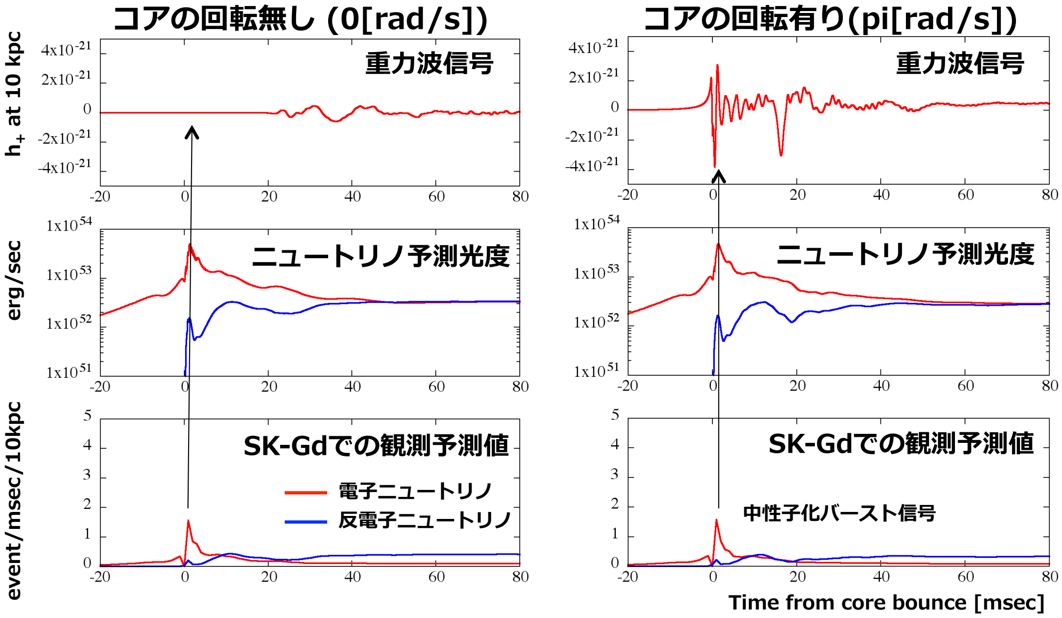

設置された望遠鏡


試験観測の様子


試験観測で得られた土星の紫外線画像

計画研究　A03)
超新星爆発における重力波信号とニュートリノ信号の相関

ApJ 811, 86 (2015)



ニュートリノ信号と重力波信号からコアの回転の有無がわかる

GW150914とGW151226におけるSKでのニュートリノ探索

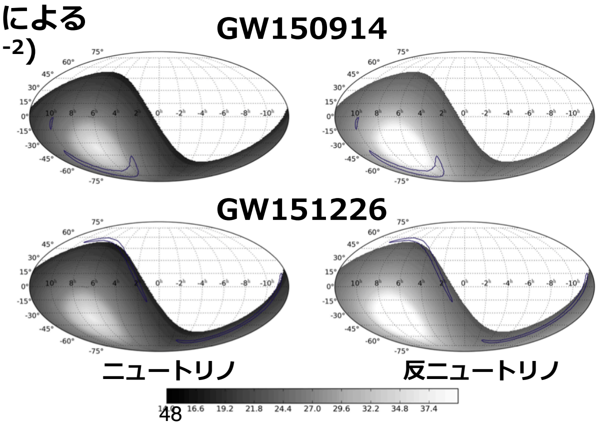
ApJL 830, L11(6pp) (2016)

信号はなかった

最も探索感度の高い上向きミュー事象により見積もった
ニュートリノ放出エネルギー上限値

- GW150914 < (1-6) x 10^{55} erg
- GW151226 < (2-7) x 10^{55} erg

フルエンスの到来方向による
90%C.L.上限値（cm^{-2}）



計画研究A04
多様な観測に連携する重力波観測データ解析の研究

データ保管・解析用クラスターシステム

計画研究の進行と重力波観測実験の状況に沿って順次増強した。

- 760コアのCPU
- 総計304TBのデータ容量

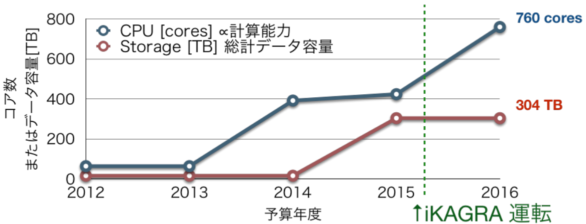
日本の重力波データ解析を支える重要な計算機資源として活躍


大阪市大に設置した低遅延のイベント探索用Linuxクラスタ計算機

解析ソフトウエアライブラリ ”KAGALI” の開発

- KAGRA Algorithmic Library

独自の解析手法の開発に連動して必要。
ブラックボックスのない、完全に理解できる環境を開発。
若手を含む多人数の解析環境の提供としても役立っている。



計画研究A04
多様な観測に連携する重力波観測データ解析の研究

- KAGRA解析スクール

大学生、大学院生を対象に５回開催。
A04メンバーが中心に講師や演習を担当。
総括班からも補助。
受講した学部生の中から、重力波分野へ進学者がいる。

計画研究A04
多様な観測に連携する重力波観測データ解析の研究

新しい解析手法の開発
- ヒルベルト-ファン変換(Hilbert-Huang Transform, HHT)
- 非調和解析(Non-Harmonic Analysis, NHA)

時間ー周波数空間での新しい解析手法の応用

画像解析（医療（がん診断）や工業製品検査など）でも用いられている新しい手法

HHT解析では、初観測イベントGW150914波形について、独自の手法で波形後半のブラックホール準固有振動のパラメーター（質量、スピン）を求めた。

- 非ガウス雑音モデルの新しい数学的取り扱い
- 実データ分布を用いて非ガウス統計的評価
- 非線形相関解析

米国LIGO実験のオープンデータを有効活用

重力波のサイエンス
- 世界初観測の重力波イベントに新しい解析手法を適用した（下図HHT,NHA）
- 連星合体波形を用いた一般相対論を超えた重力理論の検証
- ブラックホール準固有振動解析の研究
- 大質量ブラックホール連星の起源を明らかにするための解析の研究(A05と共同)
- 超新星爆発の解明のための解析の研究(A03,A05と共同)

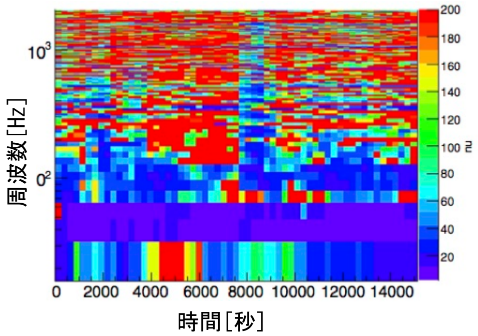
計画研究A04
多様な観測に連携する重力波観測データ解析の研究

- 統計数理学のデータ解析への応用

非線形相関や非ガウス雑音の分析、定量化に応用。

重要雑音の非ガウス性や非線形相関は、重力波のデータ解析では常に問題だが、定量的な扱いや適切なモデル化が簡単ではない。

統計数理学の協力を得て、新手法の導入やモデル評価に成功



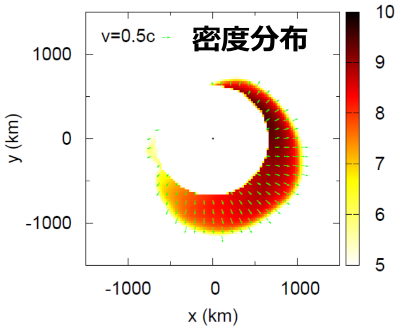
左図：LIGOの公開観測データに非ガウス雑音モデルを適用して定量評価。経時変化を周波数ごとに調べ、色でガウス性を示している。青いところはガウス性が悪い。

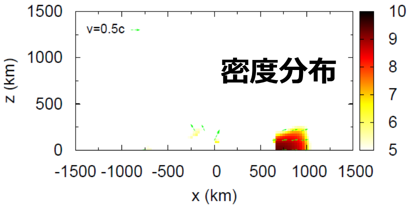
この図は、Physics Review D誌の掲載論文のなかで優れて印象的な図を紹介する「Kaleidoscope(万華鏡)」という項目に選ばれた。

計画研究A05 重力波天体の多様な観測に向けた理論的研究

ブラックホールー中性子星合体からの質量放出は非等方的になることを示した。一方、連星中性子星の合体では、等方的で相対論的な質量放出を伴うことを示した。

- Anisotropic mass ejection from black hole-neutron star binaries: Diversity of electromagnetic counterparts
  K. Kyutoku, K. Ioka, M. Shibata
  Phys. Rev. D88 (2013) 041503
- X-ray-powered macronovae
  S. Kisaka, K Ioka, E. Nakar
- **非等方的な質量放出は観測者の角度による放射の多様性を生むことを示した。**
- **相対論的な質量放出が星間物質を掃く時にできる衝撃波からの放射を電波からX線にわたって求めた。**





計画研究A05 重力波天体の多様な観測に向けた理論的研究

様々な重力波源の探査と重力波波形の解明（担当：中村）：

- 初代星起源の30太陽質量BH連星の存在を予言し、GW150914の起源を論じたLIGO論文において、非常によく観測を説明すると述べられている。
- BH合体からの準固有振動から、BH時空のホライズン近くを明らかにできることをGW150914以前に指摘した。
- 将来の宇宙重力波アンテナB-DECIGOにより、イベントの赤方偏移分布がもとまり、ブラックホール連星の起源を明白にできることを明らかにした。
- 既存の観測と無矛盾でGW150914を説明する原始BHシナリオを示した。
- ショートガンマ線バーストの観測からSGRBの10%がNS-BHならKAGRA等の重力波検出器で年間70イベント程度観測される事を示した。

超新星爆発の物理（担当：山田）：

- ニュートリノ輸送を記述するボルツマン方程式を近似なしに解き、爆発する軸対称モデルを発表した。
- 核密度以下で統計平衡状態にある多核子が扱える現実的な状態方程式を独自に構築し、電子捕獲率のより正確な計算を可能にした。
- ニュートリノ輸送を近似的に扱い３次元計算をおこない、高速自転するコアを持つ超新星爆発からの重力波の円偏向観測からコアの回転の証拠が得られることを明らかにした。

計画研究A05 重力波天体の多様な観測に向けた理論的研究

電磁波等との同時観測から得られる物理 (担当：井岡)：

- BH・中性子星合体からの質量放出は非等方的になるのに対し、連星中性子星の合体では、等方的で相対論的な質量放出をともなうことを示した。
- ガンマ線バーストのジェットが周囲の物質を突き抜けて、ジェットが周囲の物質によって絞られる可能性があることを初めて指摘した。
- 放出物質の中心天体へのフォールバックにより、ジェットが長期間持続可能であることを示した。
- 暗いガンマ線バーストが、高エネルギーニュートリノ源になる可能性を指摘した。

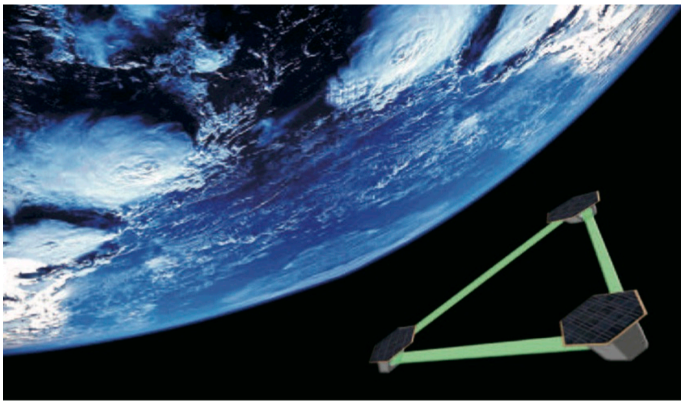
新しい重力波観測・データ解析法の提案（担当：瀬戸）：

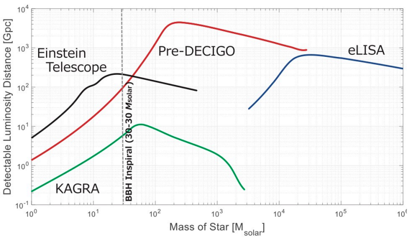
- 楕円軌道コンパクト連星について、古在機構による進化過程を直接３体計算で調べ、標準的な軌道平均法の問題点を明らかにした。その結果、地上干渉計の重力波観測における残留離心率が大きくなる可能性を指摘した。
- 電磁波対応天体探査に、楕円連星の重力波解析を行う利点を指摘した。

宇宙論・修正重力理論の観点からの重力波研究（担当：田中）：

- 高階微分が存在する重力理論におけるコンパクト連星からの重力波波形の進化を明らかにし、理論に制限がつけられることを示した。
- 既存の観測と無矛盾な双重力理論で、重力波振動が起こることを発見し、観測可能なパラメータ領域の存在を明らかにした。

Pre-DECIGO(DECi hertz laser Interferometer Gravitational wave Observatory)



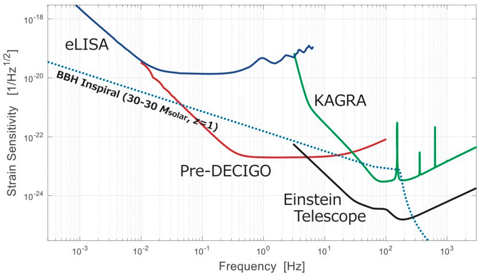


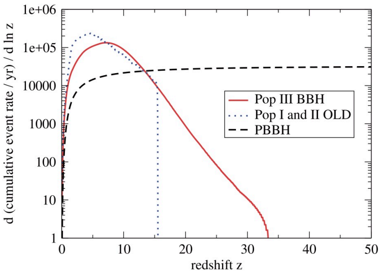
PTEP

Prog. Theor. Exp. Phys. **2016**, 093E01 (16 pages)
DOI: 10.1093/ptep/ptw127

Pre-DECIGO can get the smoking gun to decide the astrophysical or cosmological origin of GW150914-like binary black holes

Takashi Nakamura[1], Masaki Ando[2,3,4], Tomoya Kinugawa[5], Hiroyuki Nakano[1,*], Kazunari Eda[2,4], Shuichi Sato[6], Mitsuru Musha[7], Tomotada Akutsu[3], Takahiro Tanaka[1,8], Naoki Seto[1], Nobuyuki Kanda[9] and Yousuke Itoh[4]



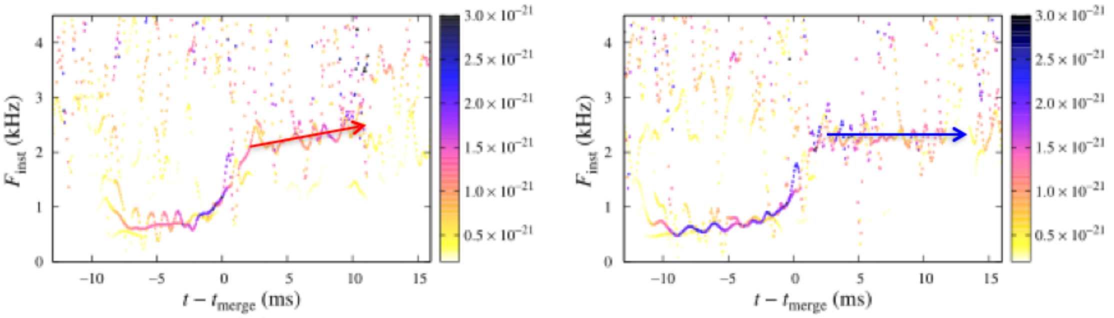


融合研究論文

情報学と物理学

- ヒルベルト-ファン変換(Hilbert-Huang Transform, HHT)
- 非調和解析(Non-Harmonic Analysis, NHA)

情報分野で提案された新しい解析技術を重力波に応用。これらの手法は医療（撮像データからのガンの発見など）や工業製品検査などでも使われている。



Hyperon EOS (H135)　　Standard nuclear matter (Shen EOS (S15))

Phys. Rev. D93, 123010 (2016). HHTによる、数値相対論重力波波形の比較解析。中性子星の状態方程式の違いが、HHT解析によって重力波波形に見て取れる。

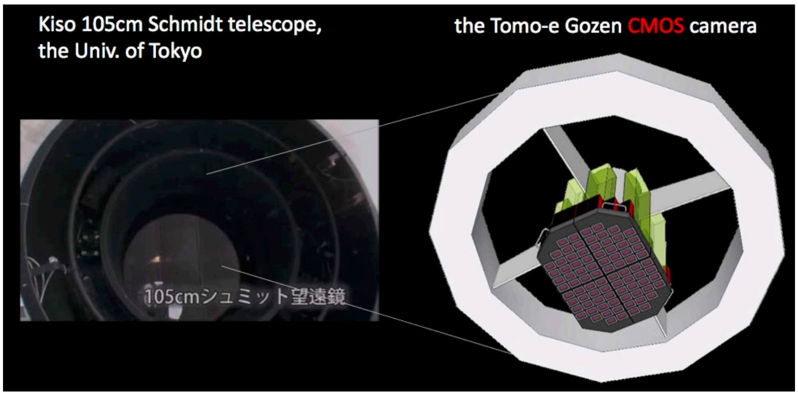
融合研究論文

天文学と精密光学

- 木曽超広視野高速カメラTomo-e Gozen の開発

大面積・高性能のCMOS撮像素子（キヤノン）＋シュミット望遠鏡

広視野かつ高速読出の可能な天体探索を可能に



CMOS： 各画素ごとに読み出し回路を備えたイメージング検出器。読み出し時に電荷転送を伴うCCDに比べて迅速な信号読み出しが可能。CMOSは消費電力の少ない論理回路を実現できる。

CMOSの使用により
- 1秒以下の読み出しが可能となり短時間の変動現象を終えるようになった。
- CMOSは常温で作動 → 大規模な冷却装置が不要。安価・軽量かつ巨大なカメラを製作できるようになった。

Koji Kawabata (Hiroshima Univ., HASC),
“J-GEM Follow-up Observations for gravitational wave events and GW170817” (25+5)
[JGRG27 (2017) 112829]

27th JGRG in Hiroshima (2017)

J-GEM Follow-up Observations for gravitational wave events and GW170817

Koji S. Kawabata (Hiroshima Univ.)
on behalf of J-GEM team

J-GEM

Japanese collaboration of Gravitational wave Electro-Magnetic follow-up observations

Founded for KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas, 2012-2016,
"New development in astrophysics through multimessenger observations of gravitational wave sources" (PI: T. Nakamura@Kyoto Univ.)

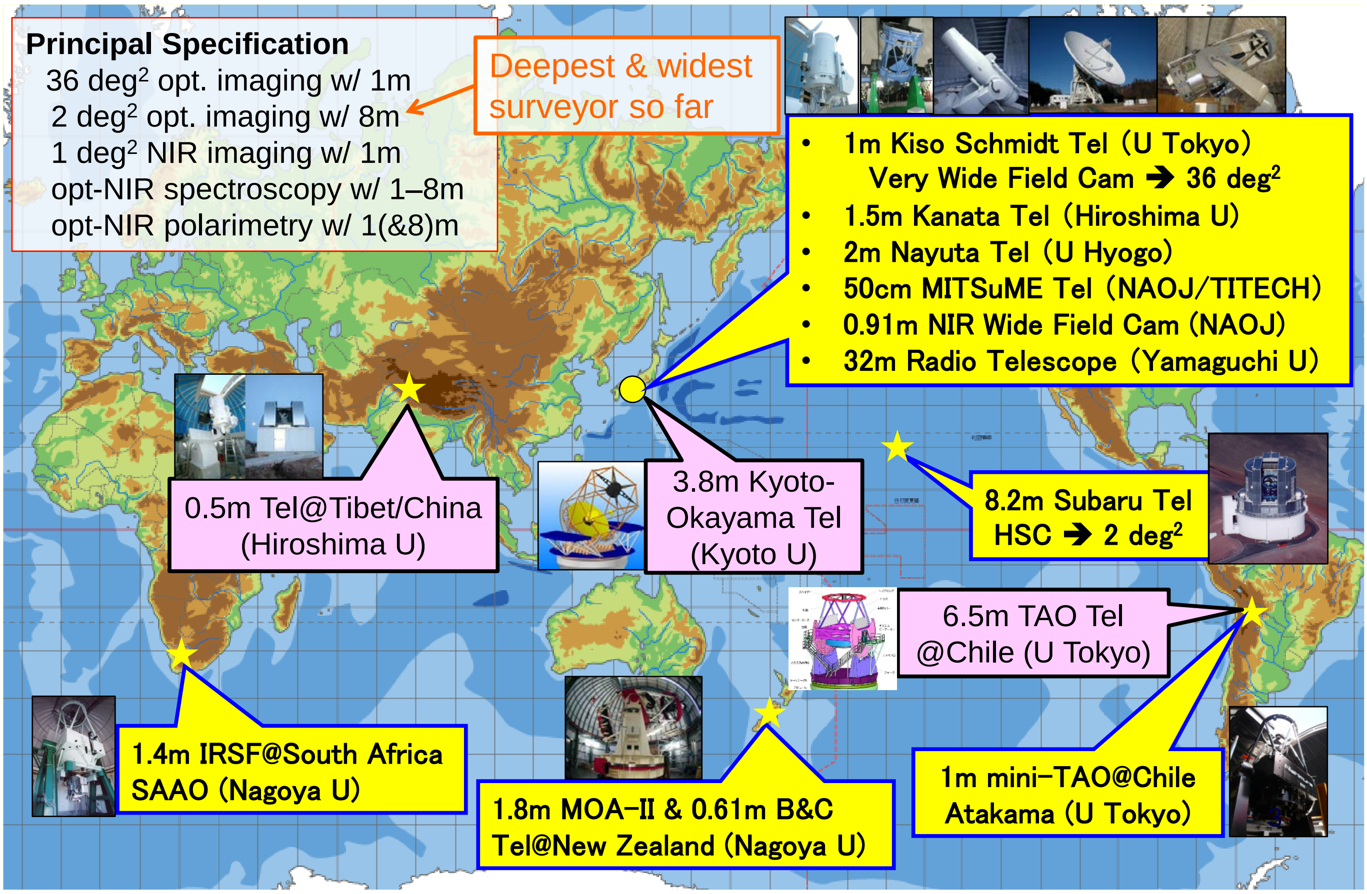
A02 "Searching for Optical and Infrared Counterpart Source of Astronomical Gravitational Wave" (PI: M. Yoshida@Hiroshima Univ. → 2017.4 Subaru, NAOJ)

Members

Hiroshima Univ: K. S. Kawabata, M. Uemura, H. Nagashima
Stanford Univ: Y. Utsumi (2017.11 HU → SU)
NAOJ: M. Yoshida (2017.4 HU → NAOJ) M. Tanaka, K. Yanagisawa, D. Kuroda, H. nagai, W. Aoki
Univ of Tokyo: K. Motohara, T. Morokuma, M. Doi, S. Sako, R. Ohsawa, M. Yamaguchi, N. Yasuda, T. Shigeyama, H. Tagoshi
TITECH: N. Kawai, Y. Saito, Y. Yatsu, R. Itoh, K. Murata
Nagoya Univ: F. Abe, Y. Tamura, H. Kaneda, (the late) Y. Asakura
Kyoto Univ: K. Ohta, K. Matsubayashi, T. Nakamura, T. Tanaka, N. Seto, K. Ioka
Konan Univ: N. Tominaga
Kagoshima Univ: T. Nagayama
Toho Univ: Y. Sekiguchi
Osaka City Univ: N. Kanda
University of Hyogo: Y. Itoh, T. Saito, B. Stefan, S. Ho
Yamaguchi Univ: K. Fujisawa

Group of specialists on opt/NIR observations and transient objects (theoretically & observationally) , cooperated with a few GW people.

Observing Facility in J-GEM



Principal Specification
36 deg^2 opt. imaging w/ 1m
2 deg^2 opt. imaging w/ 8m
1 deg^2 NIR imaging w/ 1m
opt-NIR spectroscopy w/ 1–8m
opt-NIR polarimetry w/ 1(&8)m

Deepest & widest surveyor so far

- 1m Kiso Schmidt Tel（U Tokyo）
  Very Wide Field Cam ➔ 36 deg^2
- 1.5m Kanata Tel（Hiroshima U）
- 2m Nayuta Tel（U Hyogo）
- 50cm MITSuME Tel（NAOJ/TITECH）
- 0.91m NIR Wide Field Cam (NAOJ)
- 32m Radio Telescope（Yamaguchi U）

0.5m Tel@Tibet/China (Hiroshima U)

3.8m Kyoto-Okayama Tel (Kyoto U)

8.2m Subaru Tel
HSC ➔ 2 deg^2

6.5m TAO Tel @Chile (U Tokyo)

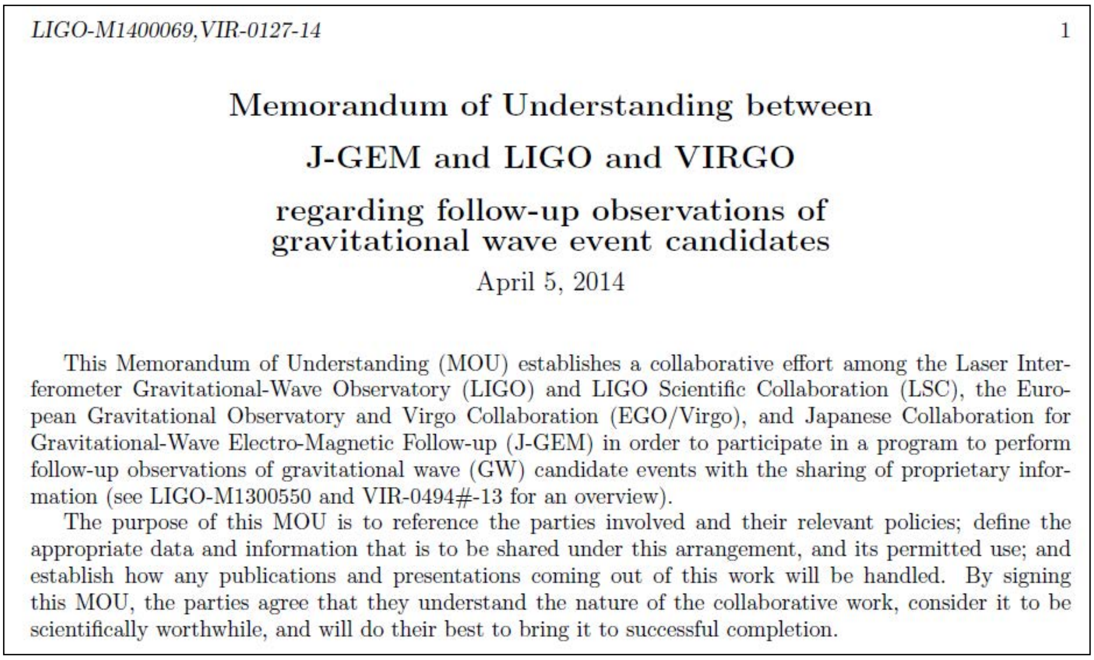
1.4m IRSF@South Africa SAAO（Nagoya U）

1.8m MOA–II & 0.61m B&C Tel@New Zealand（Nagoya U）

1m mini–TAO@Chile Atakama（U Tokyo）

Hiroshima U / Tibet 0.5m Telescope @ 5100m a.s.l. construction was completed on 2017 Oct 6 !

Start of J-GEM Activity: MoU with LIGO/VIRGO



LIGO-M1400069,VIR-0127-14 1

Memorandum of Understanding between
J-GEM and LIGO and VIRGO

regarding follow-up observations of gravitational wave event candidates

April 5, 2014

This Memorandum of Understanding (MOU) establishes a collaborative effort among the Laser Interferometer Gravitational-Wave Observatory (LIGO) and LIGO Scientific Collaboration (LSC), the European Gravitational Observatory and Virgo Collaboration (EGO/Virgo), and Japanese Collaboration for Gravitational-Wave Electro-Magnetic Follow-up (J-GEM) in order to participate in a program to perform follow-up observations of gravitational wave (GW) candidate events with the sharing of proprietary information (see LIGO-M1300550 and VIR-0494#-13 for an overview).

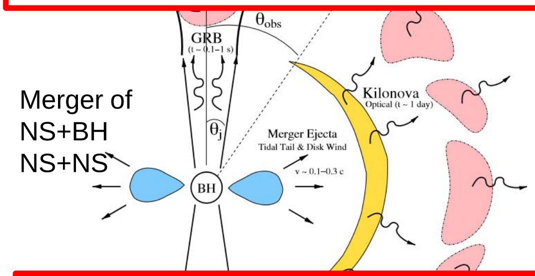
The purpose of this MOU is to reference the parties involved and their relevant policies; define the appropriate data and information that is to be shared under this arrangement, and its permitted use; and establish how any publications and presentations coming out of this work will be handled. By signing this MOU, the parties agree that they understand the nature of the collaborative work, consider it to be scientifically worthwhile, and will do their best to bring it to successful completion.

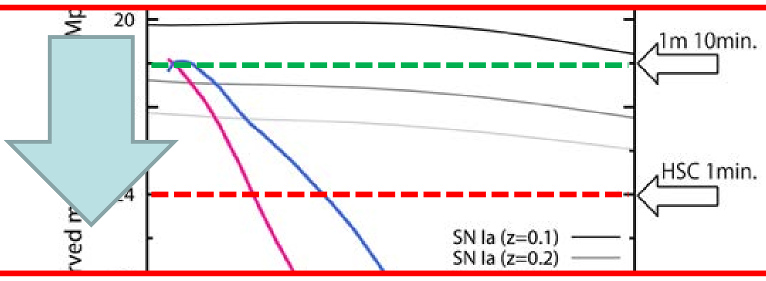
Sharing proprietary GW information under the MoU.

>70 teams have signed an MoU with LIGO/VIRGO.

Kilonova/Macronova model and obs. strategy

If NS-NS or BH-NS merger occurs at 100Mpc, 1m-class telescope can detect within 1-2 days and 8m Subaru/HSC can follow through ~10 days with only 1min exposure.





Immediate galaxy-targeted obs. with 1m-class tel. & blank survey with wide-field cameras of Subaru/HSC and Kiso WFC (or Tomo-e Gozen)

（Only Subaru/HSC can perform blank survey with 8-10m tel's.）

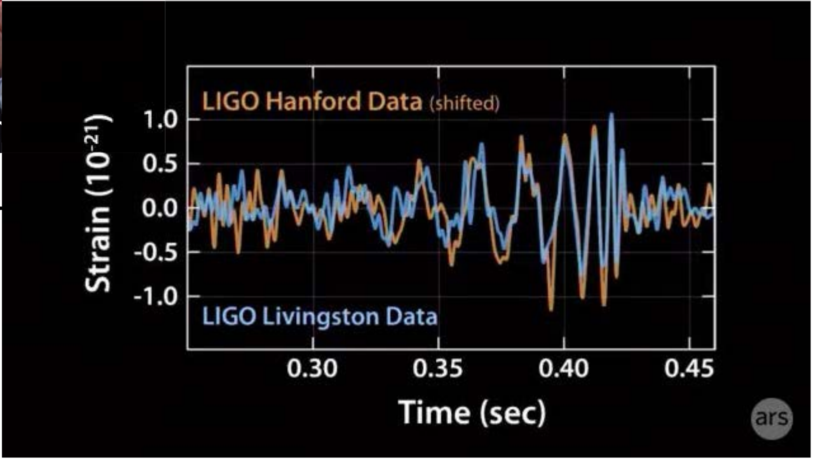
O1 observing run:

2015 Sep 12 (18) – 2016 Jan 12

GW150914: The First detected GW event

David Reitze@LIGO/Caltech

Public on 2016 Feb 11

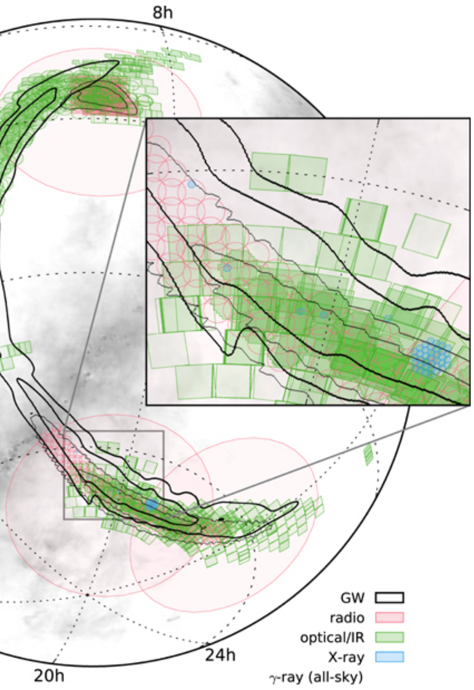


S/N=24

GW150914: The First detected GW event

>25 teams performed follow-up observations. But, no possible candidate was found.

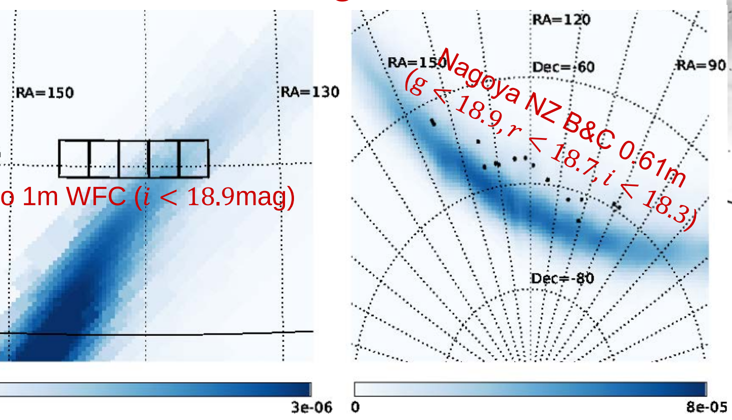
(e.g., Abbott+ 2016)



Abbott+ 2016

J-GEM Observed regions (Morokuma+ 2016)

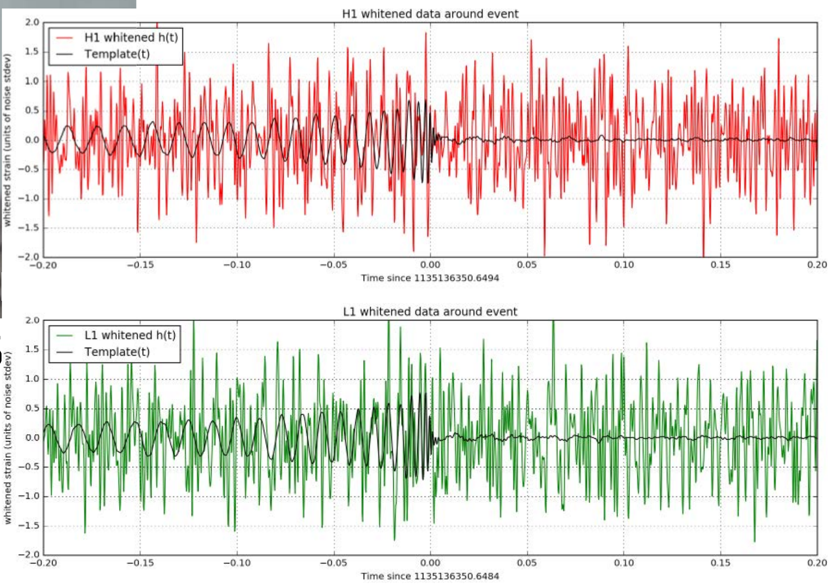
Morokuma



GW151226: Second GW event

David Reitze@LIGO/Caltec

Public on 2016 Jun 15

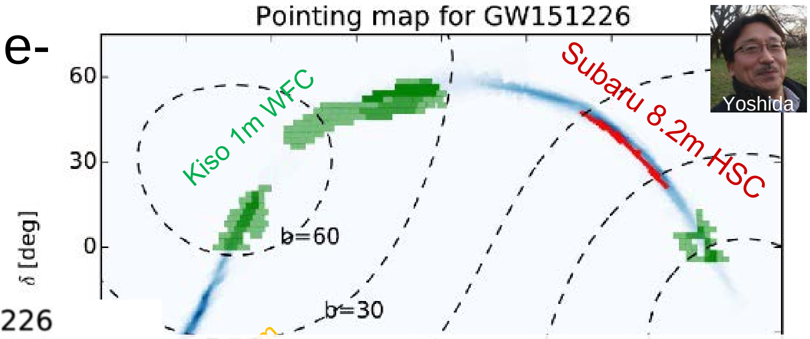


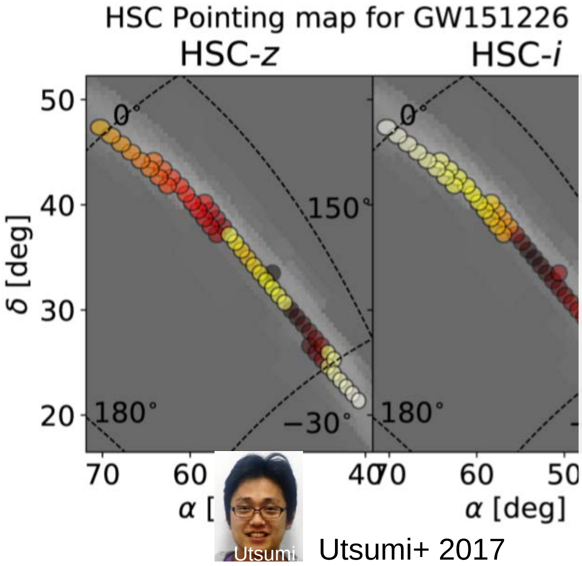
S/N=13

GW151226: Second GW event

J-GEM performed wide-field survey (including Subaru/HSC) and galaxy-targeted obs.

Yoshida+ 2017

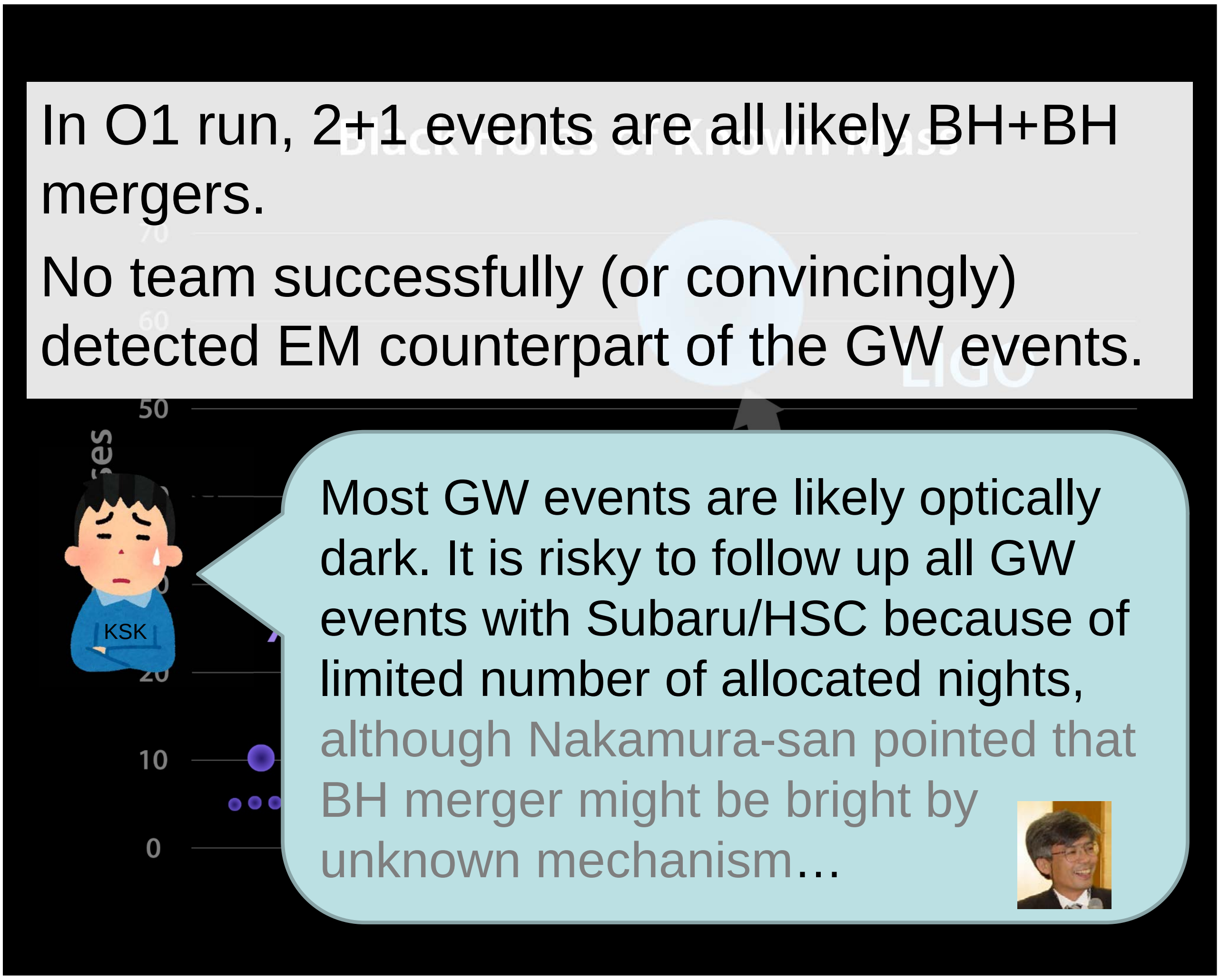




Utsumi+ 2017

HSC covered 63.5deg^2 (7% localization probability) at three epochs (+12, +18, +42 days), and no kilo-nova like candidate brighter than $i \sim 23$ (5σ) was found among detected 1744 variable objects.

(Utsumi+ 2017; Yoshida+ 2017)



In O1 run, 2+1 events are all likely BH+BH mergers.

No team successfully (or convincingly) detected EM counterpart of the GW events.

Most GW events are likely optically dark. It is risky to follow up all GW events with Subaru/HSC because of limited number of allocated nights, although Nakamura-san pointed that BH merger might be bright by unknown mechanism…

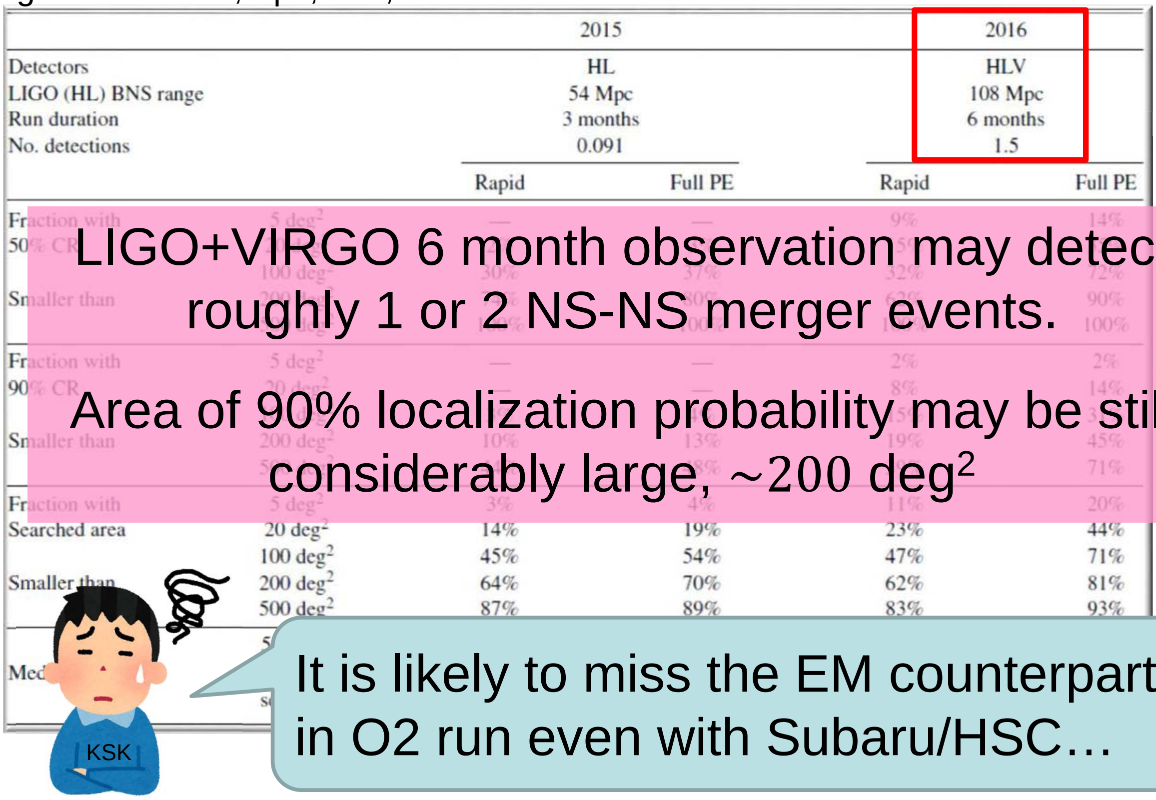
O2 observing run:
2016 Nov 30 – 2017 Aug 25

Updates:

- *New parameters "ProbHasNs" and "ProbHasRemnant" are filled out in CBC GW detection Alerts, ensuring electromagnetically bright (or not).*
- *Probability sky map becomes 3D (including distance) in CBC alerts.*
- *After 2017 August 1 VIRGO GW detector joins.*

Prediction of detection rate of binary neutron star merger event in realistic cases

Singer et al. 2014, ApJ, 795, 105

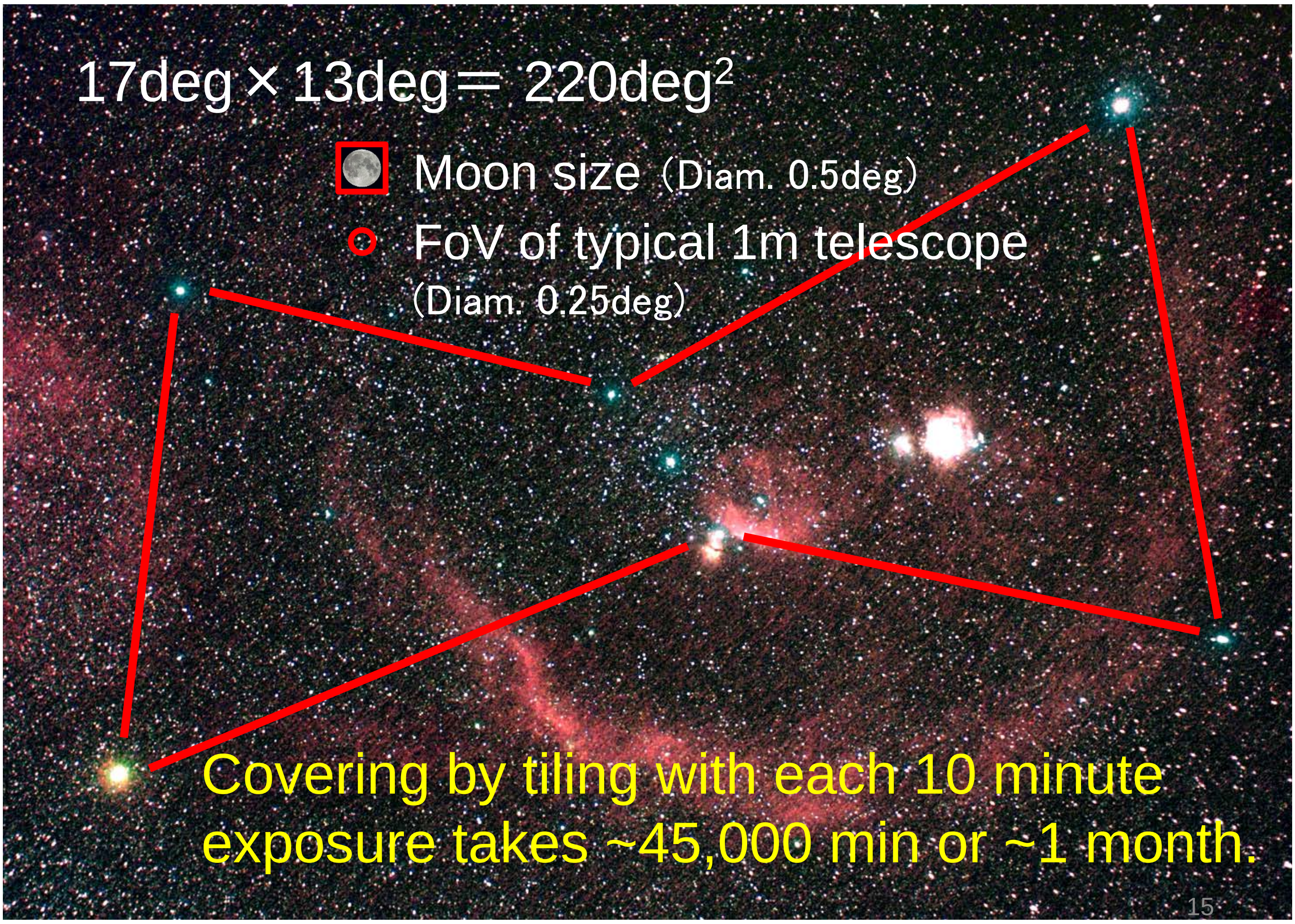


		2015		2016	
Detectors		HL		HLV	
LIGO (HL) BNS range		54 Mpc		108 Mpc	
Run duration		3 months		6 months	
No. detections		0.091		1.5	
		Rapid	Full PE	Rapid	Full PE
Fraction with 50% CR	$5\ \mathrm{deg}^2$	—	—	9%	14%
	$20\ \mathrm{deg}^2$	[illegible]	[illegible]	[illegible]	[illegible]
	$100\ \mathrm{deg}^2$	30%	37%	32%	72%
Smaller than	$200\ \mathrm{deg}^2$	[illegible]	80%	62%	90%
	$500\ \mathrm{deg}^2$	[illegible]	100%	[illegible]	100%
Fraction with 90% CR	$5\ \mathrm{deg}^2$	—	—	2%	2%
	$20\ \mathrm{deg}^2$	—	—	8%	14%
	$100\ \mathrm{deg}^2$	[illegible]	[illegible]	[illegible]	[illegible]
Smaller than	$200\ \mathrm{deg}^2$	10%	13%	19%	45%
	$500\ \mathrm{deg}^2$	[illegible]	[illegible]	[illegible]	71%
Fraction with	$5\ \mathrm{deg}^2$	3%	4%	11%	20%
Searched area	$20\ \mathrm{deg}^2$	14%	19%	23%	44%
	$100\ \mathrm{deg}^2$	45%	54%	47%	71%
Smaller than	$200\ \mathrm{deg}^2$	64%	70%	62%	81%
	$500\ \mathrm{deg}^2$	87%	89%	83%	93%

LIGO+VIRGO 6 month observation may detect roughly 1 or 2 NS-NS merger events.

Area of 90% localization probability may be still considerably large, ~200 deg^2

It is likely to miss the EM counterpart in O2 run even with Subaru/HSC…



$17\text{deg} \times 13\text{deg} = 220\text{deg}^2$

Moon size（Diam. 0.5deg）

FoV of typical 1m telescope
（Diam. 0.25deg）

Covering by tiling with each 10 minute exposure takes ~45,000 min or ~1 month.

List of J-GEM follow-up observations

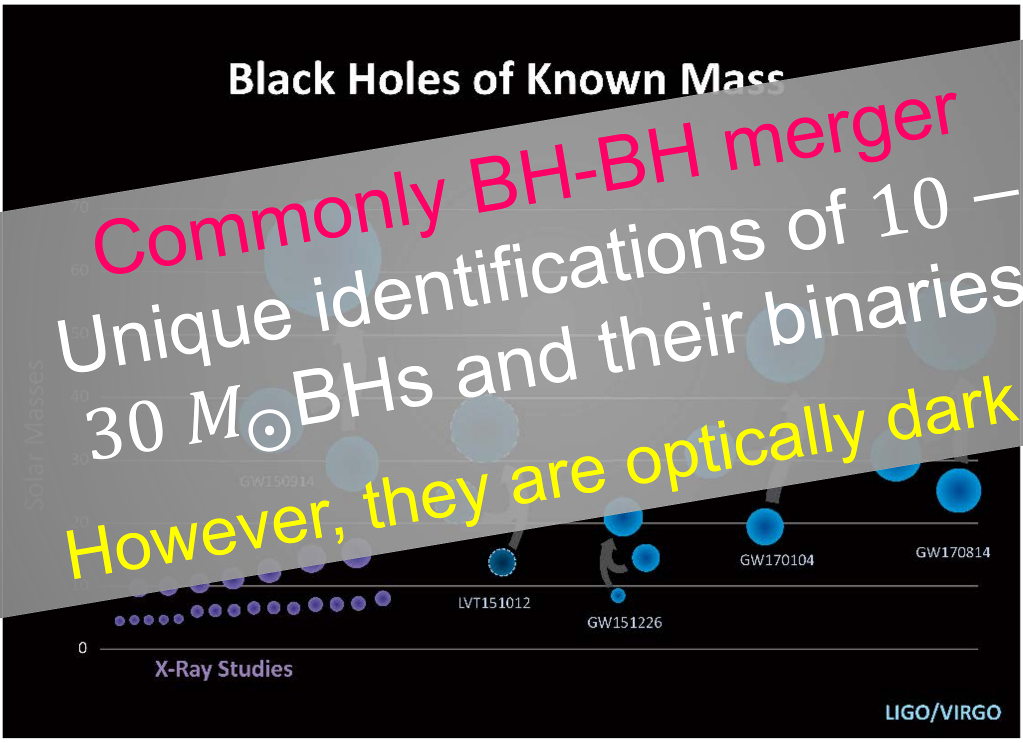
1．GW150914　No counterpart identified (Morokun😊016)

2．GW151226　Subar/HSC was input for the firs😐 time, but no counterpart identified. (Yoshida+17; Utsumi+17)

3．GW170104　ProbHasNs=0% and 😓 ProbHasRemnant=0%. → No counterpart.

4．GW170814　Again, ProbHasNs=0% and ProbHasRemnant=0%, although the localization 😵 probability is considerably narrowed because of joining with VIRGO. → No counterpart.

Masses of compact binaries detected by GW events so far



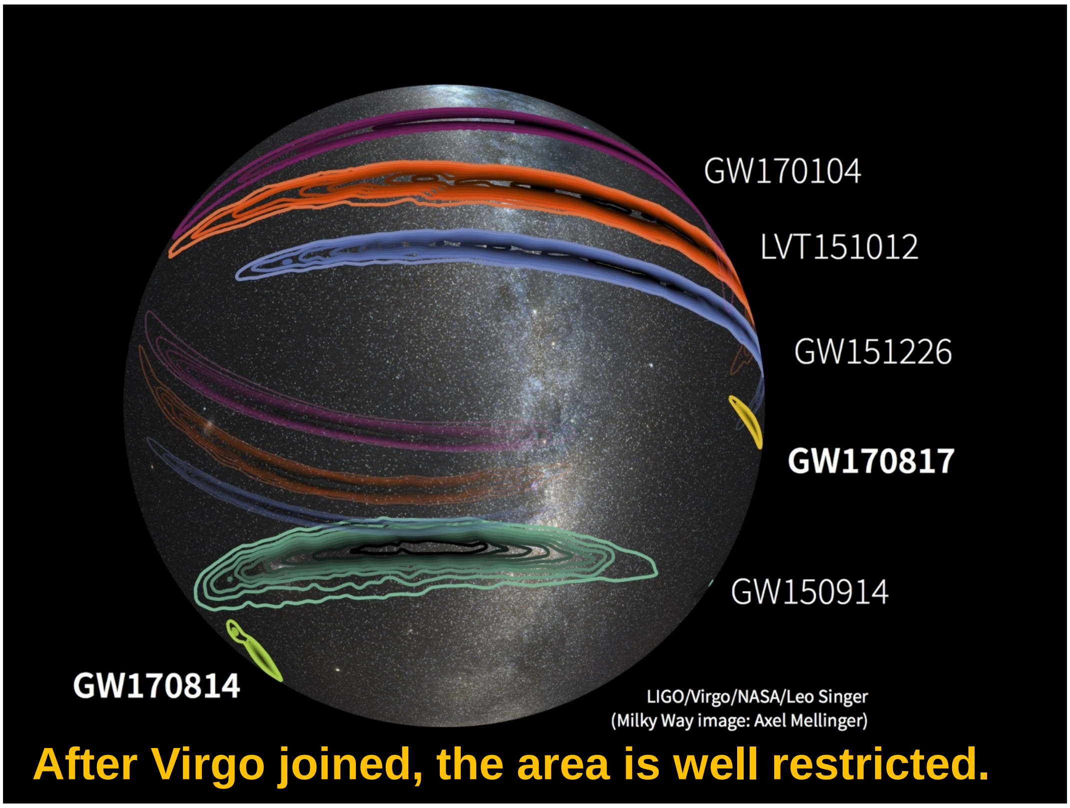
Commonly BH-BH merger

Unique identifications of 10 – 30 $M_\odot$ BHs and their binaries

However, they are optically dark…

LIGO/Caltech/Sonoma State (Aurore Simonnet)

Localization probability map



LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

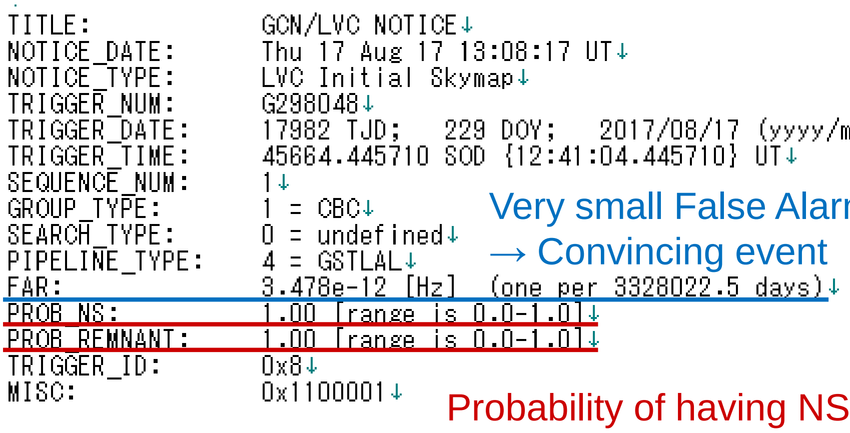
After Virgo joined, the area is well restricted.

J-GEM on 2017 Aug 17

- We were performing optical/NIR follow-up observations of GW170814 event with Subaru/HSC, Kiso WFC, Akeno 0.5m, etc.
- I (probably) had little or no hope to detect the counterpart for GW170814, but just expecting to anchor a more reliable upper-limit because of larger coverage of localization probability area.
- I began to think that no more GW event would appear in O2 run finishing on Aug 25.

KSK

Alert of GW170817 !!



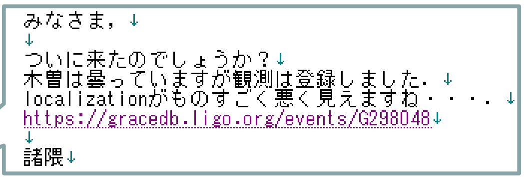
```
TITLE:             GCN/LVC NOTICE↓
NOTICE_DATE:       Thu 17 Aug 17 13:08:17 UT↓
NOTICE_TYPE:       LVC Initial Skymap↓
TRIGGER_NUM:       G298048↓
TRIGGER_DATE:      17982 TJD;   229 DOY;   2017/08/17 (yyyy/mm/dd)
TRIGGER_TIME:      45664.445710 SOD {12:41:04.445710} UT↓
SEQUENCE_NUM:      1↓
GROUP_TYPE:        1 = CBC↓
SEARCH_TYPE:       0 = undefined↓
PIPELINE_TYPE:     4 = GSTLAL↓
FAR:               3.478e-12 [Hz]  (one per 3328022.5 days)↓
PROB_NS:           1.00 [range is 0.0-1.0]↓
PROB_REMNANT:      1.00 [range is 0.0-1.0]↓
TRIGGER_ID:        0x8↓
MISC:              0x1100001↓
```

Very small False Alarm Rate
→ Convincing event

Probability of having NS --- 100%!
Probability of ejecta/remnant 100%!
Very close to us（~40Mpc）!

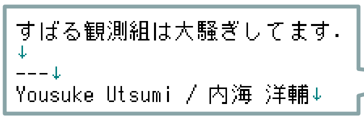
Immediately stimulated observing J-GEM members…

22:33 JST = 13:33 UT



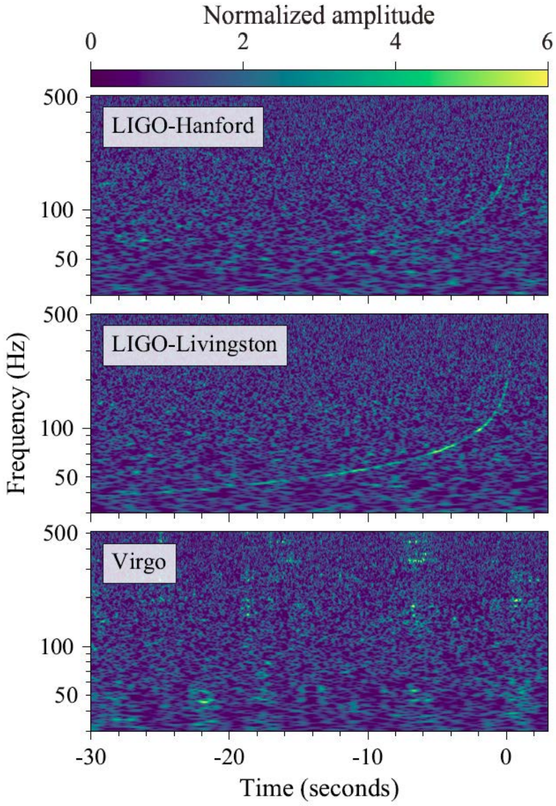
```
みなさま，↓
↓
ついに来たのでしょうか？↓
木曽は曇っていますが観測は登録しました．↓
localizationがものすごく悪く見えますね・・・．↓
https://gracedb.ligo.org/events/G298048↓
↓
諸隈↓
```

22:33 JST = 13:33 UT



```
すばる観測組は大騒ぎしてます．
↓
---↓
Yousuke Utsumi / 内海 洋輔↓
```

GW170817: Slow rising `chirp’ frequency



Taking ~2 order longer time than GW150914

→

$M_{chirp} \sim 1.2 M_{\odot}$

NS+NS merger!

© LIGO-Virgo Consortium

EM obs. of GW170817

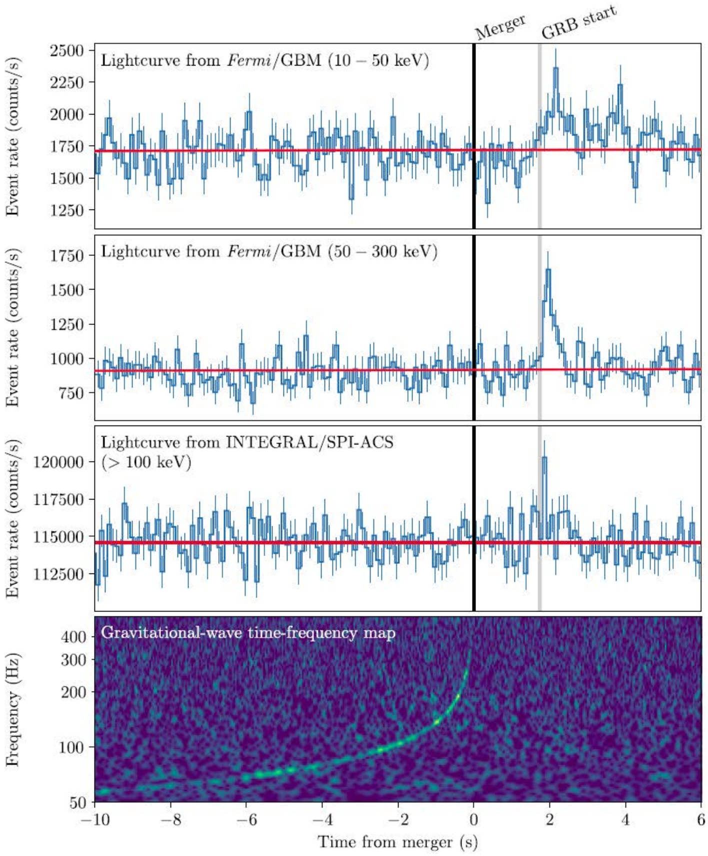
8/17 12:41:04 GW detected

8/17 12:41:06 Fermi GBM detected gamma-ray

0.5days SWOPE tel. (Chile) optically identified the candidate counterpart.（Coulter+ GCN 21529）

Unfortunately, the position is in southern hemisphere and close to the sun, and it was hard to be observed in northern hemisphere.

0.7days Subaru 8.2m/HSC optical obs. began
1.2days Nagoya U/SAAO IRSF 1.4m NIR obs. began
1.8days Nagoya U/NZ MOA 1.8m/B&C 0.61m obs.
(2.9days Hiroshima U/Kanata 1.5m NIR obs.)
14.3days Suraru/MOIRCS NIR obs. began
…soon became too close to the sun and obs. finished.



Fermi/GBM
(10-50 keV)

Fermi/GBM
(50-300 keV)

INTEGRAL
(>100 keV)

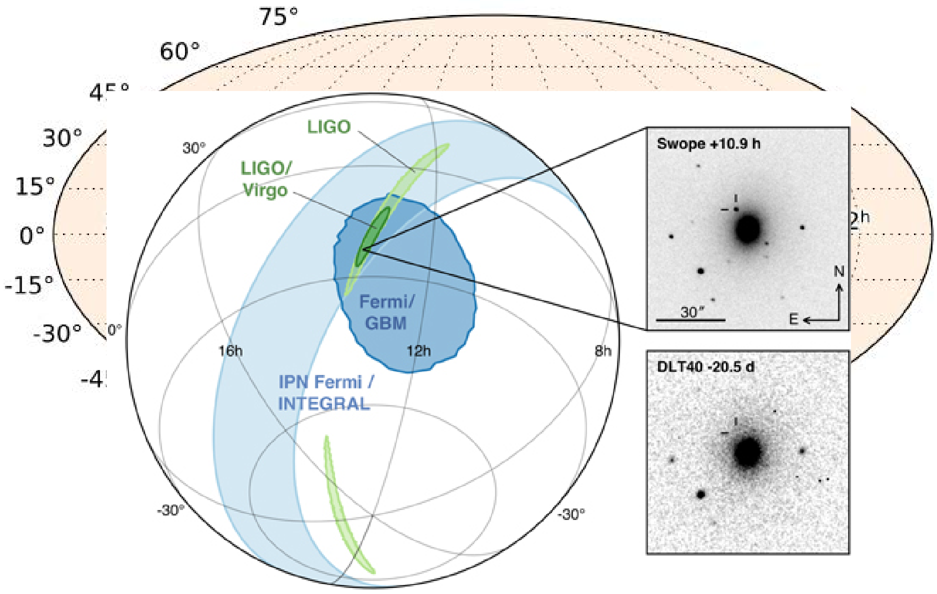
GW Frequency

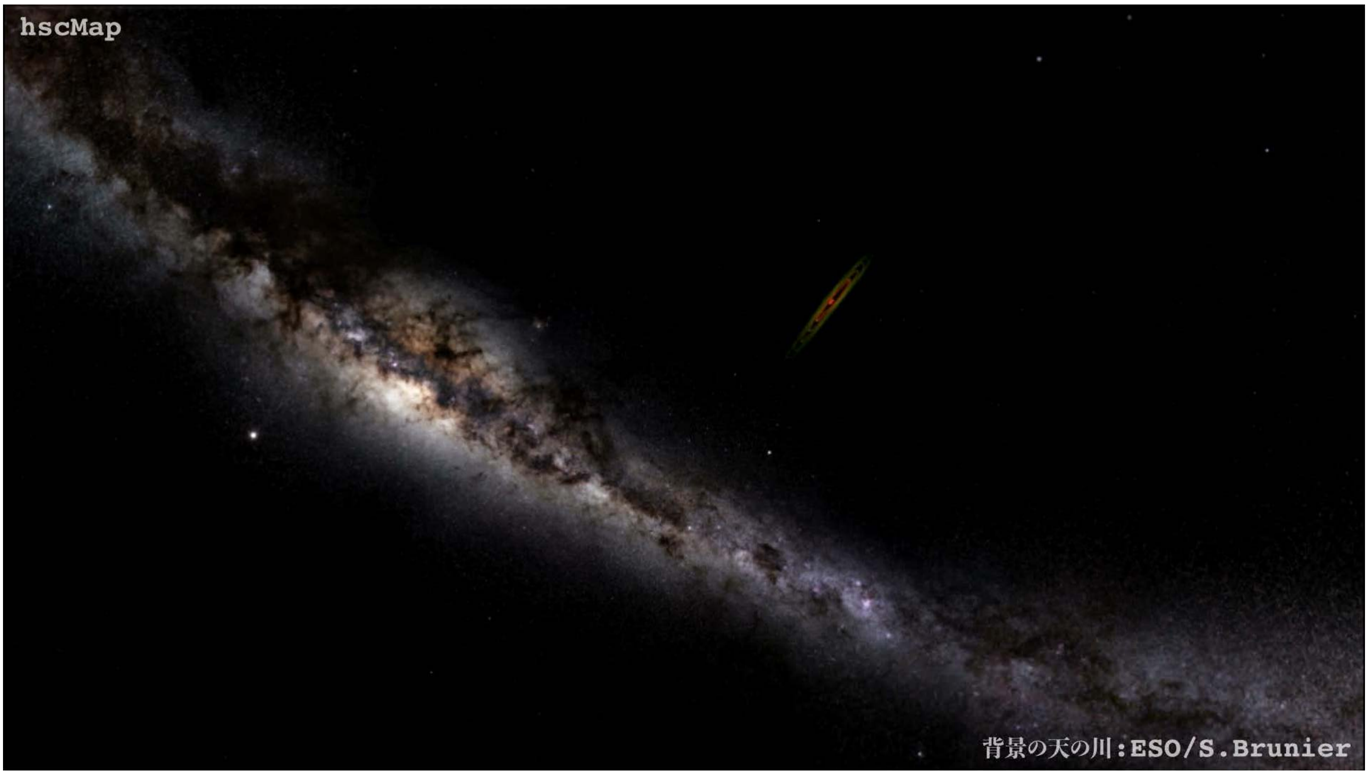
Time from merger (sec)

Abbott et al. (2017)

2D localization probability map

2017-08-17 17:21 (UT) H+L+V

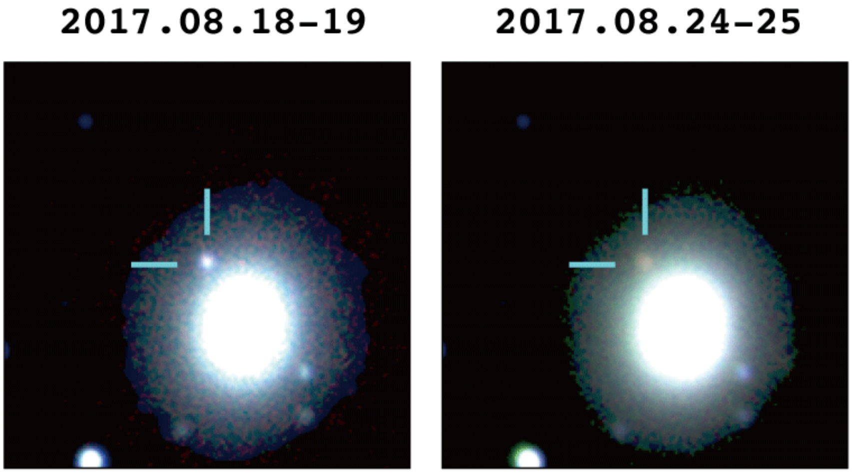




小池（国立天文台）ほか

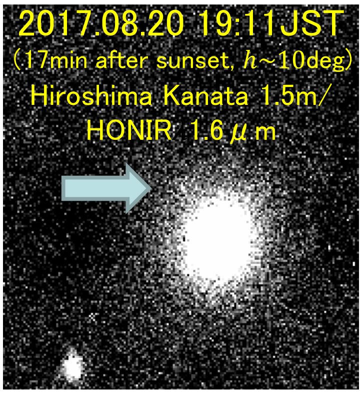
J-GEM obs. of the counterpart: SSS17a

Decayed and reddened quickly



Subaru HSC λ0.9μm、IRSF1.2μm, 2.2μm composite color image

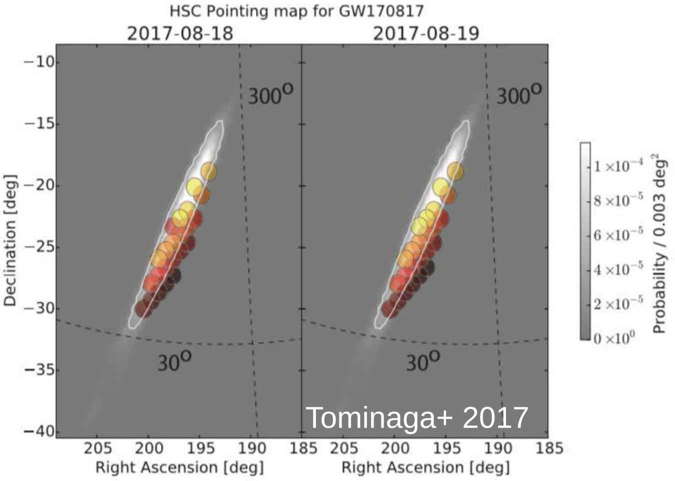
Utsumi et al. 2017;
Tanaka et al. 2017;
Tominaga et al. 2017;



Nakaoka et al. 2017;
Utsumi et al. 2017

Severe to photometry from Japan

Other candidate exist?



Tominaga+ 2017;

- Subaru 8.2m/HSC: 24 arcdeg^2 (covering 67% credible region) for $z \leq 20.6$mag, and detected 60 extragalactic variables. →All (except for SSS17a) are excluded by distance, luminosity, color and their variations

Soares-Santos+ 2017

- DECam (4m in Chile): 70 arcdeg^2 (covering 93%) survey for $z \leq 21.3$mag (1500 variables) gives similar result.

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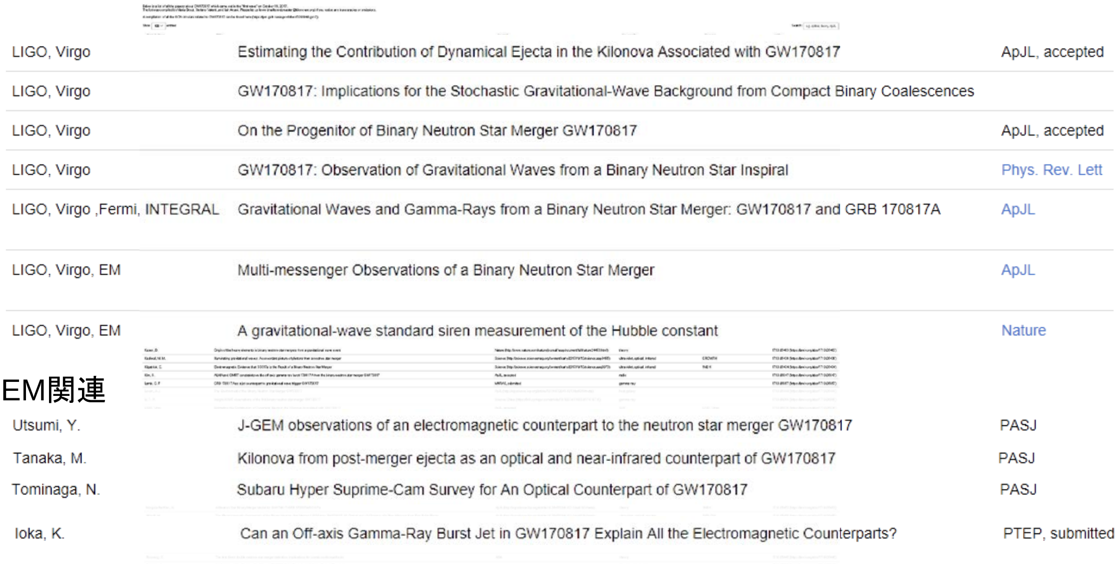
84 papers appeared just after the embargo (Oct 16)



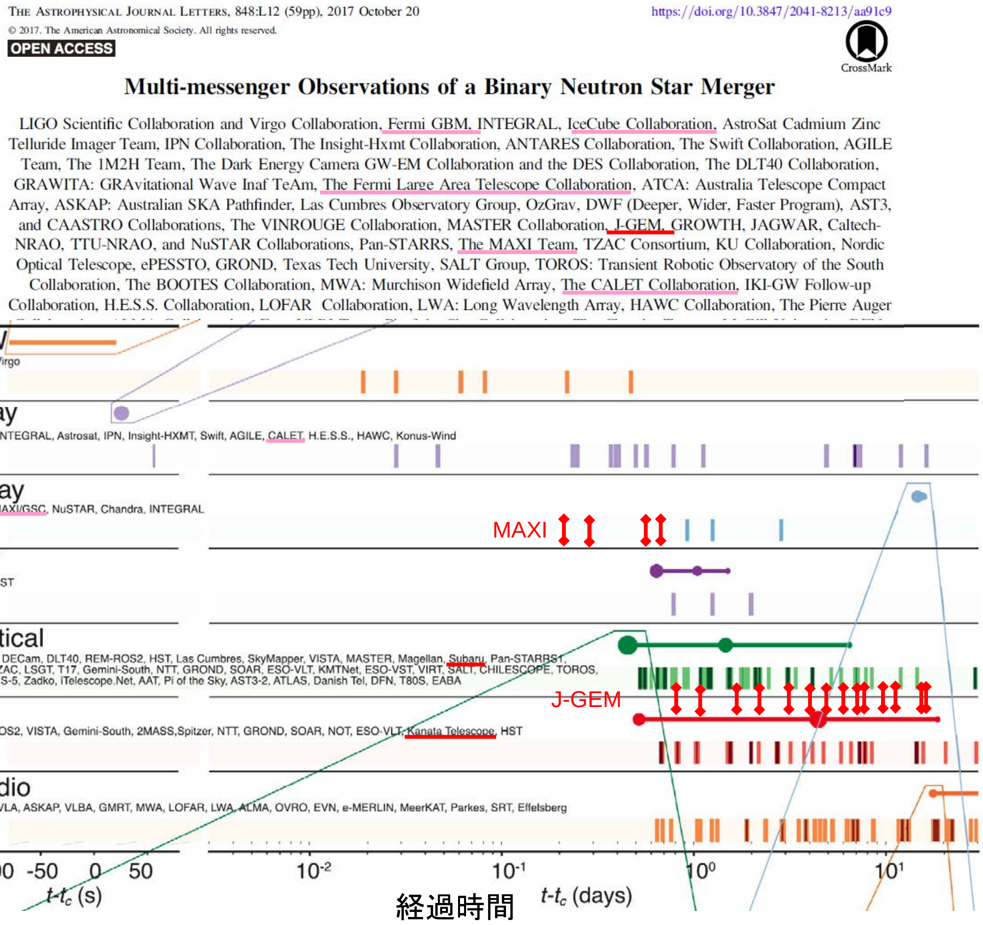
LIGO, Virgo	Estimating the Contribution of Dynamical Ejecta in the Kilonova Associated with GW170817	ApJL, accepted
LIGO, Virgo	GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Coalescences	
LIGO, Virgo	On the Progenitor of Binary Neutron Star Merger GW170817	ApJL, accepted
LIGO, Virgo	GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral	Phys. Rev. Lett
LIGO, Virgo ,Fermi, INTEGRAL	Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A	ApJL
LIGO, Virgo, EM	Multi-messenger Observations of a Binary Neutron Star Merger	ApJL
LIGO, Virgo, EM	A gravitational-wave standard siren measurement of the Hubble constant	Nature

J-GEM関連

Utsumi, Y.	J-GEM observations of an electromagnetic counterpart to the neutron star merger GW170817	PASJ
Tanaka, M.	Kilonova from post-merger ejecta as an optical and near-infrared counterpart of GW170817	PASJ
Tominaga, N.	Subaru Hyper Suprime-Cam Survey for An Optical Counterpart of GW170817	PASJ
Ioka, K.	Can an Off-axis Gamma-Ray Burst Jet in GW170817 Explain All the Electromagnetic Counterparts?	PTEP, submitted

Maria Drout, Stefano Valenti, and Iair Arcavi
(https://lco.global/~iarcavi/kilonovae.html)

追跡観測のとりまとめ論文

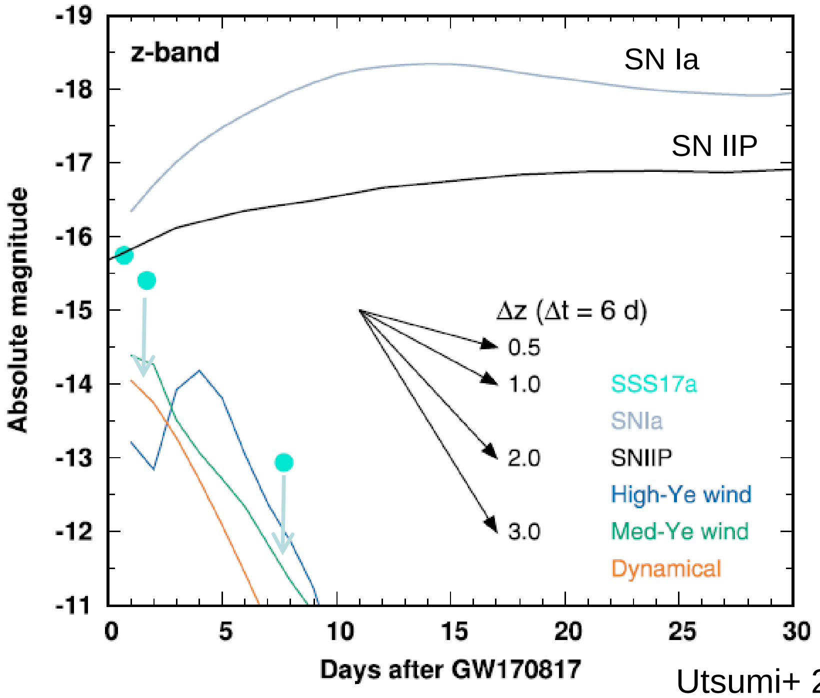


The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger

Photometry of *z*’-band（λ 0.9μm）（●）

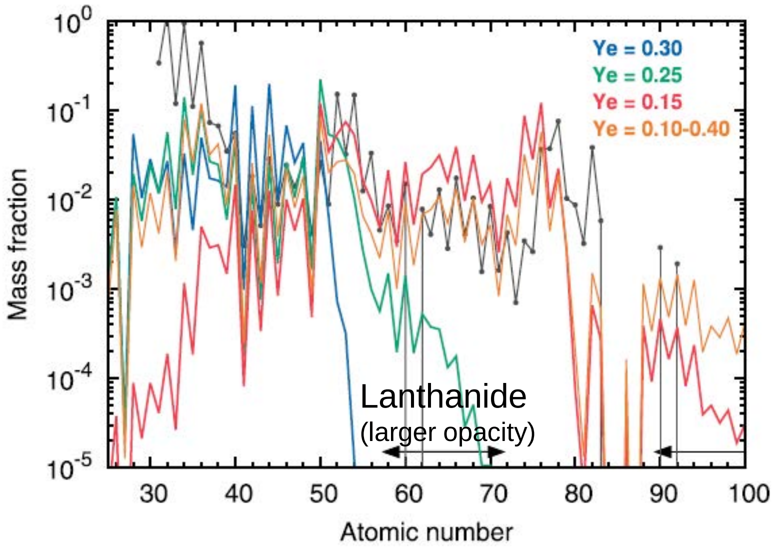


Kilonova model ($0.01M_\odot$ ejecta) well explains the decay rate, but ~1mag fainter.

Utsumi+ 2017

Probing the properties of ejecta..

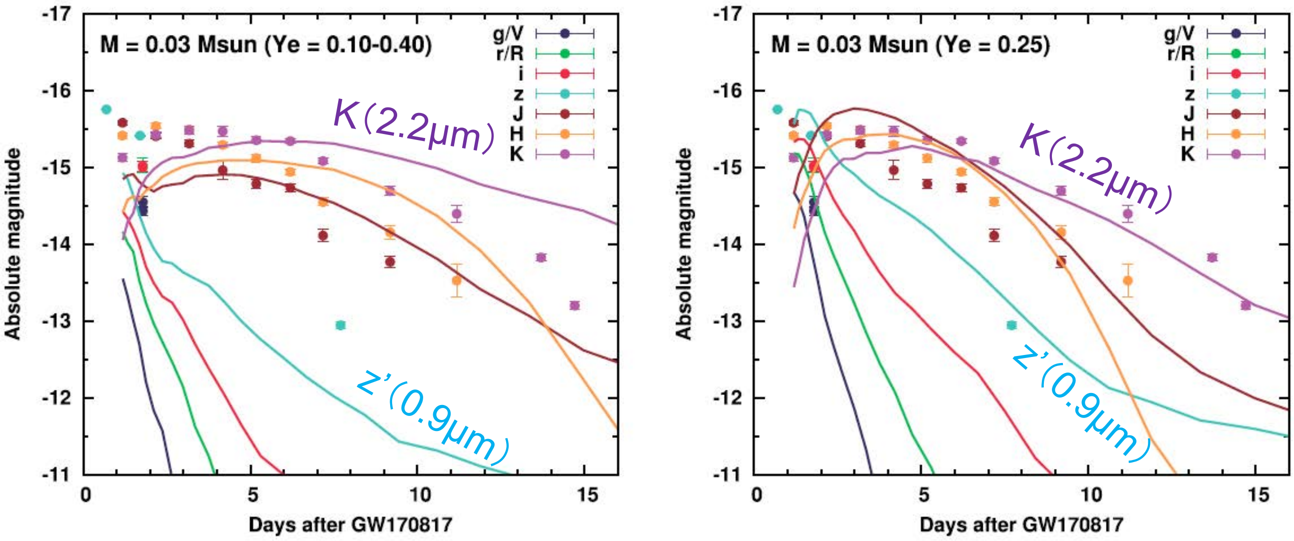
Electron fraction Ye (number of proton per nucleon) and product in *r*-process



Tanaka et al. 2017; Wanajo et al. 2014

Comp. w/ kilonova model: Opt/NIR LCs

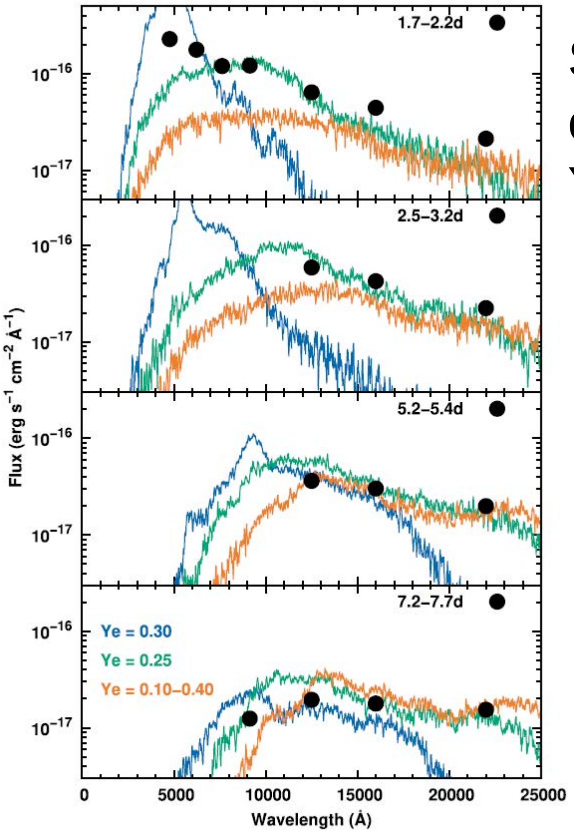
Tanaka et al. 2017



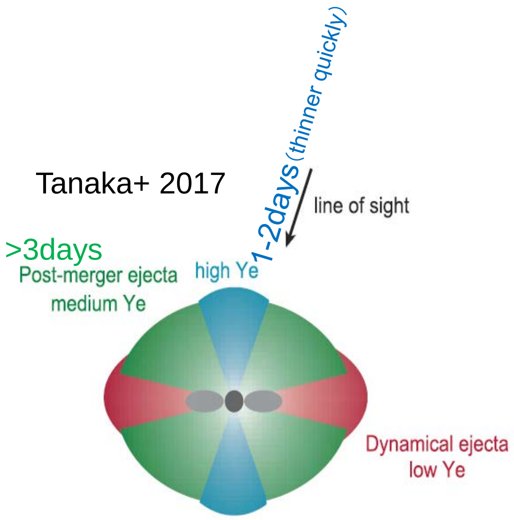
Medium electron fraction (Ye=0.25) model well reproduces LCs after 3 days, requiring somewhat larger ejecta (~0.03$M_\odot$)

Comp. w/ kilonova model: Opt/NIR SED

Tanaka et al. 2017



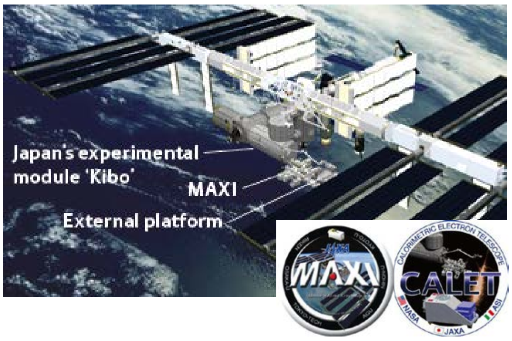
SED after 3 days is also consistent with medium Ye=0.25 model



MAXI/GSC and CALET obs.

(Sugita+ 2017)

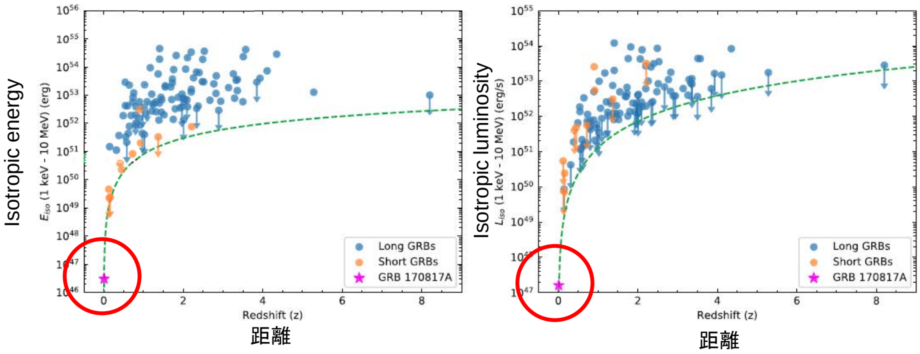
- At the LIGO detection, the high-volt. Of MAXI/GSC was off, unfortunately.
- At ~170 sec, it turned on, but, again unfortunately, the Fermi/GBM localization was near the pole of ISS orbital rotation and MAXI/GSC could not point the field.
- MAXI/GSC (2-10 keV) finally gives upper-limits of $< 1.65 \times 10^{45}, < 1.47 \times 10^{46}, 8.0 \times 10^{44}$ and 5.4×10^{44} erg/s at 0.19, 0.26, 0.50 and 0.57 days, respectively.



(Nakahira+ 2017)

- At the LIGO detection, CALET GBM was operated, but no on-board trigger occurred.
- CGBM/SGM (40keV-28MeV) was 71 deg off-axis from SSS17A and covered 99% GW localization probability in its FoV and gives 7σ upper-limit of 5.5×10^{-7}erg/cm^2/sec (10-1000 keV, 1sec exp.), being consistent with the peak flux observed by Fermi/GBM.

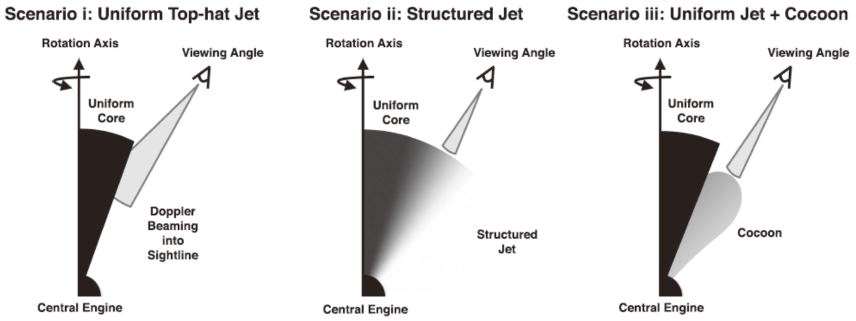
On the prompt short GRB



Abbott+ 2017

Much fainter than other GRBs intrinsically

→ Viewed from inclined direction from rotation/jet axis?



Abbott+ 2017

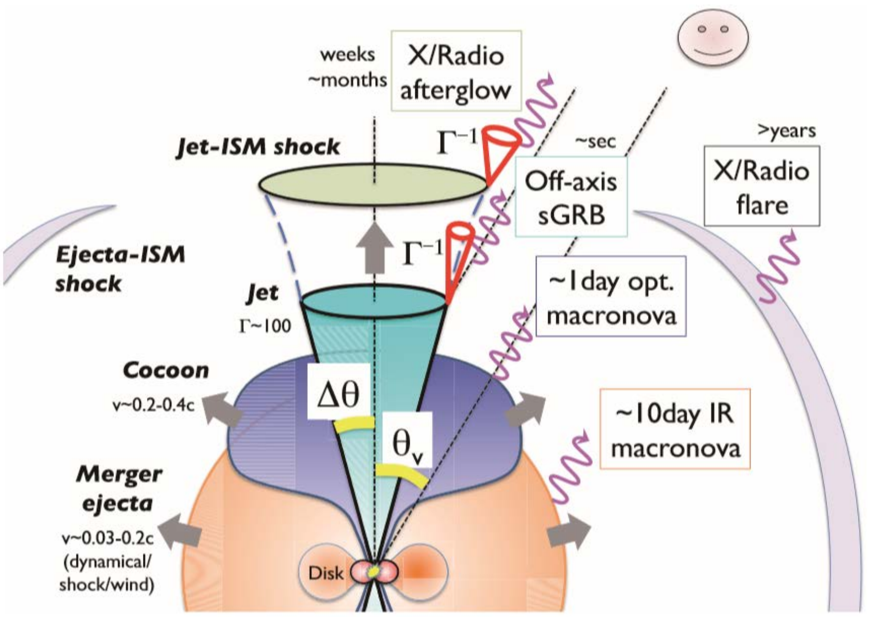
Faint sGRB and following EW emissions can be explained by a model of

E_{iso}~$10^{51} - 10^{52}$erg

Jet opening angle ~20°

Viewing angle ~30°

(Ioka & Nakamura 2017)



Summary

- Japanese GW EM counterpart observation team, J-GEM, gave contributions to optical/NIR follow-up observations of past GW events, even for GW170817 which appeared at the location where the ground-based telescopes in main-land of Japan could not see in the night sky.
- Collaboration with other teams in Japan (X-ray, gamma-ray, neutrino, etc.; theoretical groups) seems effectively working under the KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas, 2012-2016 (PI: Nakamura) and 2017-2021 (PI: Tanaka).