Proceedings of
the 25th Workshop on General Relativity and Gravitation in Japan

7—11 December 2015

Yukawa Institute for Theoretical Physics, Kyoto University
Kyoto, Japan

Volume 1

Workshop Information
Oral Presentations: First Day

Contents

Preface

Year 2015 was the centenary from the proposal of general relativity. So far, not only its theoretical beauty but also various verification experiments and observations give general relativity a firm position as the theory describing the gravity at low energies. Modern cosmology and high-energy astrophysics have been developed based on general relativity. Although the history of general relativity and gravity is long, recent development of research is still showing new expanding directions. On one hand, untrapped with the prejudice that physically meaningful target of research is limited to the one about four-dimensional spacetime, the scope of research has been widely opened to higher-dimensional spacetime. On the other hand, as a result of rapid development computer and computational techniques, it has also become possible to study the evolution of less symmetric dynamical spacetime.

In order to celebrate the milestone of JGRG25 as well as 100 years of general relativity, we had arranged the 25th workshop on general relativity and gravitation (JGRG) at the Yukawa institute, which is one of the most influential centers of research on general relativity in Japan. We had invited outstanding lecturers who can give a scope of the long history of research on general relativity, such as Abhay Ashtekar (Penn State U), Robert M. Wald (Chicago U), Richard Schoen (Stanford U), Mordehai Milgrom (Weizmann Institute of Science), Takashi Nakamura (Kyoto University), Hideo Kodama (KEK). In addition to the lectures by such domestic and foreign prominent researchers, lively discussions following the invited lectures by younger researchers have been made. Besides the 12 invited lectures, there were 86 contribution talks and 33 poster presentations. The total number of participants was 198, which exceeded the number recorded by the past JGRG workshops. We had parallel sessions using Maskawa hall to respond to a large number requests of oral presentations that greatly exceeded our original expectation.

The workshop was supported by Grant-in-Aid for Scientific Research on Innovative Areas No. 24103006 "Theoretical study for astrophysics through multimessenger observations of gravitational wave sources" and No. 15H05888 "Multifaceted Study of the Physics of the Inflationary Universe".

We would like to thank all the participants for their kindly help of JGRG25.

Takahiro Tanaka
(on behalf of the JGRG25 LOC)

Organizing Committee

Scientific Organizing Committee

Hideki Asada (Hirosaki)
Takeshi Chiba (Nihon)
Tomohiro Harada (Rikkyo)
Kunihito Ioka (KEK)
Akihiro Ishibashi (Kinki)
Hideki Ishihara (Osaka City)
Masahiro Kawasaki (ICRR, Tokyo)
Hideo Kodama (KEK)
Yasufumi Kojima (Hiroshima)
Kei-ichi Maeda (Waseda)
Shinji Mukohyama (YITP, Kyoto)
Takashi Nakamura (Kyoto)
Ken-ichi Nakao (Osaka City)
Yasusada Nambu (Nagoya)
Ken-ichi Oohara (Niigata)
Misao Sasaki (YITP, Kyoto)
Masaru Shibata (YITP, Kyoto)
Tetsuya Shiromizu (Nagoya)
Jiro Soda (Kobe)
Naoshi Sugiyama (Nagoya)
Takahiro Tanaka (Kyoto)
Masahide Yamaguchi (Titech)
Jun'ichi Yokoyama (RESCEU, Tokyo)

Local Organizing Committee (Kyoto University)

Takahiro Tanaka (Chair)
Naoki Seto
Hiroyuki Nakano
Hiroyuki Kitamoto
Kei Yamada
Tomoya Kinugawa

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 six winners of the Outstanding Presentation Award for their excellent presentations at JGRG25. The winners were selected by the selection committee consisting of the JGRG25 SOC based on ballots of the participants.

Keiju Murata (Keio University)
“Turbulent strings in AdS/CFT”

Xian Gao (TiTech)
“Disformal transformation and cosmological perturbations of spatially covariant theories of gravity”

Naritaka Oshita (RESCEU, The University of Tokyo)
“Black holes as seeds of baby univers”

Katsuki Aoki (Waseda University)
“Relativistic stars in the bigravity theory”

Shinichi Hirano (Rikkyo University)
“Large scale suppression with ultra slow-roll inflation scenario”

Mao Iwasa (Kyoto University)
“Orbital evolution of stars around shrinking massive black hole binaries”

Oral Presentations: First Day

Monday 7 December

9:30 Reception desk opens

10:30 Opening address
[*]

Plenary Session 1 [Chair: Misao Sasaki]

10:45 Abhay Ashtekar (Penn State U.) [Invited]
"Gravitational waves from isolated systems: The phantom menace of a positive Λ"
[JGRG25(2015)I01]

11:45 Short poster talks (1/3)

12:30-14:00 Lunch & poster view

Parallel Session 1a [Chair: Naoki Seto]

14:00 Yoshio Kamiya (ICEPP)
"Experimental Constraints on Fifth Force Candidates in Nanometer Range"
[JGRG25(2015)1a1]

14:15 Tatsuya Narikawa (Osaka City U.)
"Model-independently testing gravitational theory with gravitational-wave observations"
[JGRG25(2015)1a2]

14:30 Naoki Tsukamoto (Rikkyo U.)
"Microlens of light rays near photon sphere"
[JGRG25(2015)1a3]

14:45 Kazunari Eda (RESCEU)
"All-sky coherent search for continuous gravitational waves in 6-7 Hz band with a torsion-bar antenna"
[JGRG25(2015)1a4]

15:00 Sousuke Noda (Nagoya U.)
"Wave Optics in the Kerr spacetime and the black hole shadow"
[JGRG25(2015)1a5]

15:15 Kazuki Sakai (Nagaoka U. of Tech.)
"Amplitude-based approach to the detection of gravitational-wave bursts with the

Hilbert- Huang Transform"
[JGRG25(2015)1a6]

Parallel Session 1b [Chair: Chulmoon Yoo]

14:00 Alexander Vikman (FZU, ASCR, & YITP)
"Mimetic Dark Matter"
[JGRG25(2015)1b1]

14:15 Masashi Kimura (DAMTP)
"On massive scalar field in AdS$_2$"
[JGRG25(2015)1b2]

14:30 Cristian Martinez (CECs)
"Mass of asymptotically anti-de Sitter hairy spacetimes"
[JGRG25(2015)1b3]

14:45 Yosuke Misonoh (Waseda U.)
"Black holes and Thunderbolt Singularities with Lifshitz Scaling terms"
[JGRG25(2015)1b4]

15:00 Shoichiro Miyashita (Waseda U.)
"Monopole black holes in asymptotically AdS spacetime"
[JGRG25(2015)1b5]

15:15 Keiju Murata (Keio U.)
"Turbulent strings in AdS/CFT"
[JGRG25(2015)1b6]

15:30-16:30 Coffee break & poster view

Plenary Session 2 [Chair: Hideo Kodama]

16:30 Sean Hartnoll (Stanford U.)
"Disordered Horizons"
[JGRG25(2015)I02]

17:15 Masaomi Tanaka (NAOJ)
"Electromagnetic Emission from Compact Binary Mergers"
[JGRG25(2015)I03]

“Gravitational waves from isolated systems: The phantom menace of a positive Λ”

by Abhay Ashtekar (invited)

[JGRG25(2015)I01]

Gravitational waves from isolated systems: The phantom menace of a positive Λ

Abhay Ashtekar
Institute for Gravitation and the Cosmos, Penn State

Summary of work with Béatrice Bonga and Aruna Kesavan in the weak field approximation (CQG+, CQG 32, 025004 (2015); PRD 92, 044011 (2015); PRD 10432 (2015)) (ABK), and, outline the proposal for gravitational radiation theory full GR AA (in preparation).

We profited a great deal from correspondence and discussions with:
Bicak, Blanchet, Chrusciel, Costa, Garriga, Goldberg, Lehner, Poisson, & Saulson.

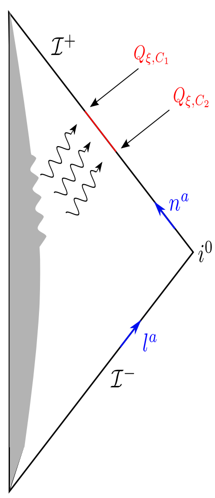
JGRG 25, Kyoto 7-11 December, 2015

Isolated Systems and Gravitational Waves

• Confusion regarding the reality of gravitational waves in full GR (Einstein: 1916-18 vs 1936; the Levi-Civita c-metric)

• The Bondi, Penrose et al framework (1960s-1980s): Notion of null infinity $\mathcal{I}$. Topology $\mathbb{S}^2 \times \mathbb{R}$. Because $\mathcal{I}$ is null, it is ruled by its null normals. This structure reduces the asymptotic symmetry group from Diff($\mathcal{I}$) to the Bondi-Metzner-Sachs Group $\mathcal{B} = \mathcal{S} \rtimes \mathcal{L}$.

• $\mathcal{B}$ admits a unique 4-d normal subgroup $\mathcal{T}$ of translations. Used critically in the definition of energy-momentum.



• Gravitational radiation: Curvature of the intrinsic connection D on $\mathcal{I}$ defines the Bondi News tensor N_{ab}. No incoming radiation: $N_{ab} = 0$ on $\mathcal{I}^-$. The BMS group naturally reduces to the Poincaré on $\mathcal{I}^-$.

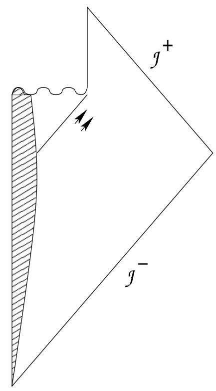
• Bondi 4-momentum and fluxes: Balance laws

$$Q_\xi[C_2] - Q_\xi[C_1] = \int_{\Delta\mathcal{I}^+} \xi |N_{ab}|^2 \, \mathrm{d}^3\mathcal{I}^+$$

Flux is manifestly positive (Bondi: "Gravitational waves are real; you can boil water with them."). Positive energy theorem for $Q_\xi[C]$ (Horowitz & Perry; Schoen & Yau).

The menace of a positive Λ

• None of the rich structure, just discussed, exists if there is $\Lambda > 0$. We do not have even the basic notions: Bondi news to characterize gravitational radiation; non-trivial balance laws; positive Bondi energy and positive energy-flux; 'no incoming radiation condition' on $\mathcal{I}^-$. Don't know what gravitational waves mean in full, non-linear GR if $\Lambda > 0$, however tiny! (Some of the Difficulties have been pointed out by Penrose, Bičák, Krtouš, Podolský, ... over the years.)



• We do not have a canonical positive and negative frequency decomposition that is needed in the construction of asymptotic Hilbert spaces.

Organization of the talk

1. Asymptotically de Sitter space-times: Unforeseen Difficulties.
2. Linear Theory: Novel features.
3. Generalization of the Bondi-Penrose framework: Proposal
4. Summary and Outlook.

1. $\Lambda > 0$: Unforeseen Difficulties

Gravitational radiation introduces qualitative differences

• Recall first the notion of Asymptotic flatness. A Physical space-time $(\tilde{M}, \tilde{g}_{ab})$ is said to be asymptotically Minkowski if $\tilde{g}_{ab}$ approaches a Minkowski metric as $1/r$ as we recede from sources in null directions. In Bondi coordinates:

$$\mathrm{d\tilde{s}^2 \to -du^2 - 2dudr + r^2\,(d\theta^2 + \sin^2\theta\, d\varphi^2)}$$

• Presence of gravitational waves adds an unforeseen twist: there is no longer a canonical Minkowski metric that $\tilde{g}_{ab}$ approaches! The possible Minkowski metrics differ by angle dependent translations (i.e. BMS supertranslations). The asymptotic symmetric group is not the Poincaré Group $\mathcal{P} = \mathcal{T} \rtimes \mathcal{L}$ but the BMS group $\mathcal{B} = \mathcal{S} \rtimes \mathcal{L}$. The BMS group $\mathcal{B}$ reduces to $\mathcal{P}$ if there is no radiation, i.e. for the class of space-times with $N_{ab} = 0$.

• It is not even larger, i.e., Diff($\mathcal{I}^+$), because there is extra structure: $\mathbb{S}^2 \times \mathbb{R}$ topology and, more importantly, the ruling of $\mathcal{I}^+$ by its null normal.

The first key difficulty in a nutshell

• One would like to say that a Physical space-time $(\tilde{M},\, \tilde{g}_{ab})$ is asymptotically de Sitter if $\tilde{g}_{ab}$ approaches a de Sitter metric as $1/r$ as we recede from sources in null directions. This condition is indeed satisfied by stationary space-times such as Kerr-de Sitter. Then the asymptotic symmetry group is just the de Sitter group $\mathcal{D}$. Allows us to define de Sitter momenta (mass, angular momentum, ...).

• But in presence of gravitational waves, there is an entirely new twist: Now $\tilde{g}_{ab}$ deviates from de Sitter metric (in a controlled fashion) even to leading order! For example, in the axi-symmetric case, an appropriate generalization of the Bondi ansatz gives, to leading order, (He, Cao)

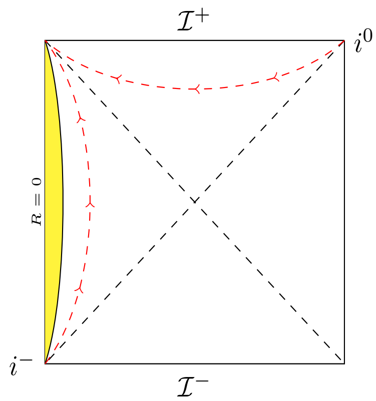
$$\mathrm{ds}^2 \to -(1-(\Lambda/3)\mathrm{r}^2)\mathrm{du}^2 - 2\mathrm{dudr} + \mathrm{r}^2\,(\mathrm{e}^{2\Lambda\mathrm{f}}\,\mathrm{d}\theta^2 + \mathrm{e}^{-2\Lambda\mathrm{f}}\,\sin^2\theta\,\mathrm{d}\varphi^2)$$

where $f = f(u,\theta)$. The de sitter metric results at infinity only if $f = 0$. But in that case, there is no radiation radiation (ABK).

• In presence of gravitational waves, then, the asymptotic symmetry group is not the de Sitter group $\mathcal{D}$ but Diff($\mathcal{I}^+$) (Strominger et al, ABK). No semi-direct product structure; No notion of 'de Sitter momentum or angular momentum.'

More precisely ...

• A physical space time $(\tilde{M},\, \tilde{g}_{ab})$ is said to be asymptotically de Sitter if it admits a conformal completion $(M,\, g_{ab})$, where $M = \tilde{M} \cup \mathcal{I}$ is a manifold with boundary $\mathcal{I}$ and $g_{ab} = \Omega^2 \tilde{g}_{ab}$ s.t.
(i) At the boundary $\mathcal{I}$, we have $\Omega = 0$ and $\nabla_a \Omega \neq 0$;
(ii) $\tilde{g}_{ab}$ satisfies Einstein's equations $\tilde{G}_{ab} + \Lambda \tilde{g}_{ab} = 8\pi G_{\mathrm{N}} \tilde{T}_{ab}$, with $\tilde{T}_{ab}$ falling off appropriately; and,
(iii) $\mathcal{I}$ is topologically $\mathbb{S}^3$ (minus punctures, e.g. $\mathbb{S}^2 \times \mathbb{R}$) and complete in an appropriate sense.



• Field equations now imply that $\mathcal{I}$ is space-like so its normal is no longer tangential to it. Hence now $\mathcal{I}$ does not have an extra structure like a preferred ruling. Asymptotic symmetry group is just Diff($\mathcal{I}$)! Not clear how to define energy, momentum, or angular momentum at $\mathcal{I}$.

Strengthening the boundary conditions removes gravitational waves!

• Can we strengthen the boundary conditions to reduce Diff($\mathcal{I}$) to a manageable size? A natural strategy, commonly used in the literature is to demand that the intrinsic metric on $\mathcal{I}$ be conformally flat. Natural because the intrinsic geometry of $\mathcal{I}$ is then the same as in de Sitter space.

• Not only is the group reduced but it is reduced precisely to the de Sitter group! One can define Bondi-like charges $Q_\xi[C] = \oint_C E_{ab}\xi^a \mathrm{dS}^\mathrm{b}$. Yield expected answers in Kerr-de Sitter.

• However, the condition is too strong (Friedrich)! Explicitly, conformal flatness of intrinsic geometry $\Leftrightarrow$ $B_{ab} = 0$ at $\mathcal{I}$ (ABK). Since $\mathcal{I}$ is space-like, half the solutions simply thrown out. Physical restriction: In cosmological perturbations, for example, it removes by hand the 'growing mode', leaving behind only the 'decaying mode'! Furthermore, all de Sitter fluxes associated with these remaining solutions vanish identically! In the full theory, $Q_\xi[C]$ are well-defined but absolutely conserved! No flux of de Sitter energy, momentum or angular momentum!

• Contrast with the AdS case: Since $\mathcal{I}$ is time-like there, an additional 'reflective' boundary condition is needed to make the evolution well-defined. So absolute conservation of $Q_\xi[C]$ is physically reasonable e.g. in the AdS/CFT analysis.

2. Linear fields on de Sitter

• We have a quandary in full non-linear GR. Practical Strategy: Bypass it by going to the weak field limit; analyze key issues; and return to the full theory using guidance from the linear analysis. There are surprises already in the linear theory!

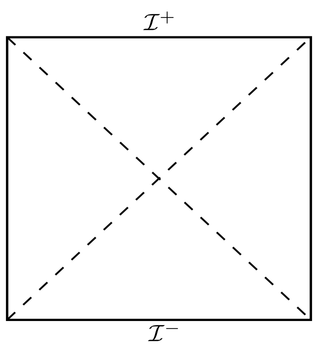
• The background de Sitter space-time provides isometries. Straightforward to define the corresponding de Sitter momenta for test fields, say, Maxwell: $F_\xi = \int_\Sigma \tilde{T}_{ab}\, \xi^a \mathrm{dS}^\mathrm{b}$; can take limit $\Sigma \to \mathcal{I}^+$. But for gravitational waves, we do not have a stress-energy tensor. Can use symplectic methods instead.

• Covariant phase space Γ_{cov} consists of space of regular solutions to Maxwell's equations and is equipped with a symplectic structure:

$$\omega(A, A') = \int_\Sigma (A_a F'^{ab} - A'_a F^{ab})\, \mathrm{dS_b};$$

which is conserved and gauge invariant.

• Infinitesimal transformation $A_a \to A_a + \epsilon \mathcal{L}_\xi A_a$ preserves ω and the Hamiltonian $\mathbf{H}_\xi := \frac{1}{2}\omega(\mathcal{L}_\xi A, A)$ exactly equals F_ξ!



• These Hamiltonian methods can be applied to the linearized (and indeed, full) GR, bypassing the need of a stress-energy tensor.

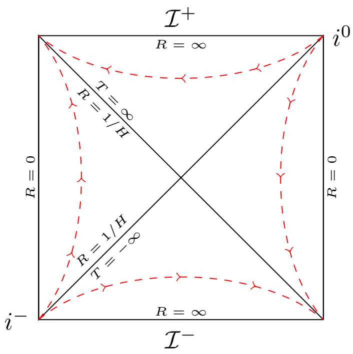
de Sitter momentum fluxes

- To compute energy, momentum and angular momentum carried by gravitational waves, start with the covariant phase space $\Gamma_{\rm cov}$ of linearized solutions (on a Poincaré patch –with an eye to the quadrupole formula). Then,

$$\omega(h,h') = \frac{1}{H\kappa}\int_\Sigma h_{ab}E'^{ab} - h'_{ab}E^{ab})\mathrm{dV}, \quad \text{where } H=\sqrt{\Lambda/3}.$$

- We can calculate Hamiltonians $\mathbf{H}_\xi = \frac{1}{2}\omega(\mathcal{L}_\xi h, h)$ correspond to any de Sitter symmetry ξ^a. A de Sitter 'time translation' T^a yields de sitter 'energy': $\mathbf{H}_T = \frac{1}{2H\kappa}\int_{\mathcal{I}^+} E^{ab}\,(\mathcal{L}_T h_{ab} - 2H\,h_{ab})\,\mathrm{dV}$

  - Note that gravitational waves can carry arbitrarily large negative de Sitter energy, no matter how tiny Λ is. The limit $\Lambda \to 0$ is subtle but well-defined and we recover the standard positive definite answer in Minkowski space-time. Thus, the lower bound of energy carried by gravitational waves has an infinite discontinuity! Same holds for electromagnetic waves in de Sitter.



- Note also that if B_{ab} vanishes on $\mathcal{I}^+$, so does h_{ab}. Hence these gravitational waves in de Sitter carry no energy (or momentum and angular momentum).

The Quadrupole formula

- During 1916-18, Einstein used the first post-Minkowskian, first PN approximation, to obtain the celebrated quadrupole formula:

$$\dot{E} = \frac{G}{8\pi}\int_{\mathcal{I}^+} (\dddot{Q}_{ab}\dddot{Q}^{ab}_{\rm TT})_{\rm Ret}\ \ d\mathcal{I}^+$$

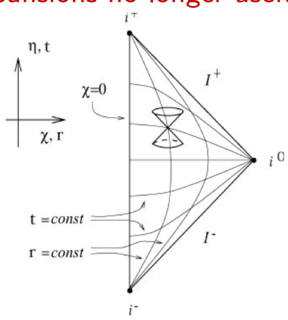
The problem of extending it to the $\Lambda > 0$ case has been open for almost a century because a host of unforeseen difficulties arise no matter how tiny Λ is!

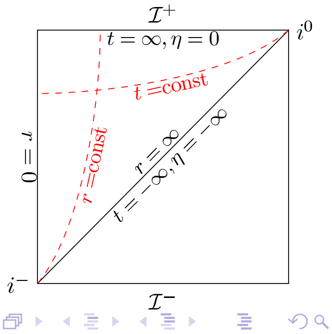
(i) Gravitational waves can carry arbitrarily large negative energy. Potential for instability! Physical quantities can be discontinuous in the $\Lambda \to 0$ limit.

(ii) For $\Lambda = 0$ one considers energy fluxes across time-like cylinders r=const approaching $\mathcal{I}^+$, and makes a heavy use of the $1/r$-expansions. But in de Sitter space-time, these cylinders approach a past cosmological horizon (across which there is no energy-flux for retarded solutions) rather than $\mathcal{I}^+$. The familiar $1/r$-expansions no longer useful!

(iii) A tail term in the retarded solution already in the first post-de Sitter order. At $\mathcal{I}^+$, as significant as the sharp term.

(iv) wave-lengths increase as the wave propagates, making the geometrical optics approximation invalid near $\mathcal{I}^+$.





Generalization to include $\Lambda > 0$

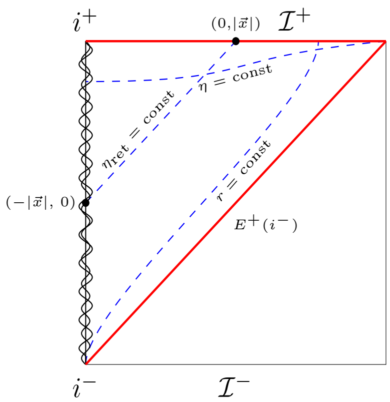
- Find retarded solution in the first post de Sitter, first PN approximation and then energy flux using Hamiltonian methods. The final expression has the form:

$$\dot{E}_T = \frac{G}{8\pi} \int_{\mathcal{I}^+} (\mathcal{R}_{ab}\, \mathcal{R}^{ab}_{\mathrm{TT}})\, \mathrm{d}\mathcal{I}^+ \quad \text{where,}$$

$$\mathcal{R}_{ab} = \big[\dddot{Q}^{(\rho)}_{ab} + 3H\ddot{Q}^{(\rho)}_{ab} + 2H^2\dot{Q}^{(\rho)}_{ab} + H\ddot{Q}^{(p)}_{ab} + 3H^2\dot{Q}^{(p)}_{ab} + 2H^3 Q^{(p)}_{ab}\big]_{\mathrm{Ret}}$$

- We know from the Raychaudhuri equation in cosmology that pressure contributes to gravitational attraction. We now learn that it also sources gravitational radiation! Lower derivative terms also for the standard (density) quadrupole.

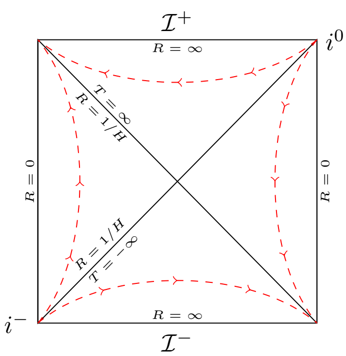
- One can show that the energy radiated is positive definite: Although a neighborhood of $\mathcal{I}^+$ does admit gravitational waves with negative energy of arbitrarily large magnitude, they cannot be produced by a time changing quadrupole!



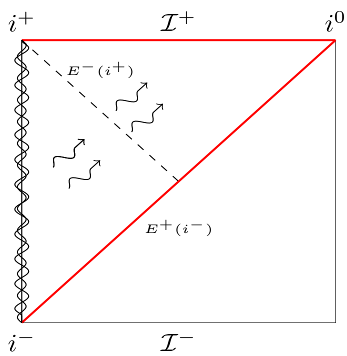
- If $\mathcal{L}_T T_{ab} = 0$, then $\mathcal{R}_{ab} = 0$.

Also, in the limit $\Lambda \to 0$ we recover the Einstein formula. Furthermore, there is full control to systematically calculate the corrections due to non-zero Λ.

Why did the $\Lambda > 0$ menace turn out to be phantom?



(i) Positivity of energy: energy reaching $\mathcal{I}^+$ can be negative only because T^a is past-directed along a portion of the cosmological horizon $E^+(i^-)$. But retarded solutions have no flux across $E^+(i^-)$. So the energy-flux through $\mathcal{I}^+$ is positive!



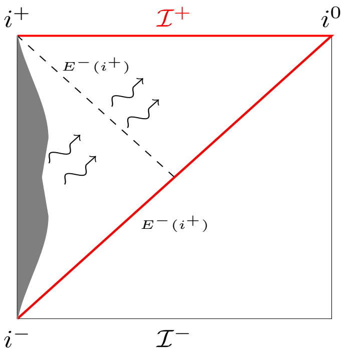
(ii) The $1/r$ expansion is indeed not useful. But one can replace it with a new late time expansion near $\mathcal{I}^+$.

(iii) The retarded solution has a non-trivial tail term. But what matters for energy loss are time derivatives and their propagation is sharp. But the tail term in the solution essential to make the flux well-defined.

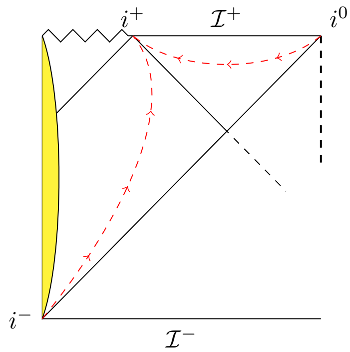
(iv) Since time derivatives $\dddot{\mathcal{R}}_{ab}$ in the in the energy loss formula is evaluated at the retarded time instant, what enters is the wave length at the source, not in the asymptotic region.

3. Full non-linear GR: Proposal

• As in the development of the $\Lambda = 0$ theory, let us use insights from the linear theory to develop the $\Lambda > 0$ analog of the Bondi-Penrose framework.



• Isolated Systems that remain spatially bounded define points $i^\pm$ on $\mathcal{I}^\pm$. System and radiation it emits is visible only to the future of the cosmological horizon $E^+(i^-)$. So we focus only on this region.

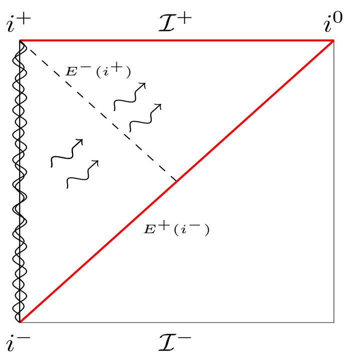


• In the quadrupole formula, the 'no incoming radiation condition' imposed across $E^+(i^-)$. Plays a key role in assuring positivity of energy flux at $\mathcal{I}^+$. So we ask that $H^- := E^+(i^-)$ be a weakly isolated horozn: Topology $\mathbb{S}^2 \times \mathbb{R}$; non-expanding null surface whose null normal ℓ^a is a symmetry of the intrinsic metric and the 'extrinsic curvature' of H^-. (AA, Beetle, Lewandoswki,...). H^- replaces $\mathcal{I}^-$ of Asymptotically Minkowski space-times.

Symmetries and Bondi-type Charges

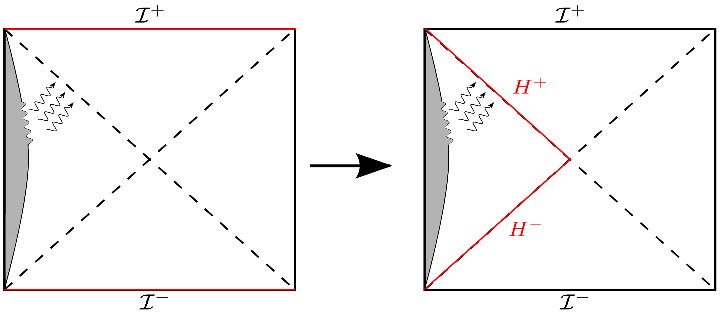
• General Paradigm is realized in Kerr-deSitter, Vaidya, and numerical simulations of collapse and BH collisions (Shibata, Shapiro and Sperhake groups).

• If H^- is axi-symmetric, it carries a 7-dimensional symmetry group. Can define energy, momentum and angular momentum using the electric part of the Weyl tensor, E^{ab}, on H^-. Absolutely conserved as expected and standard answers in Kerr-de Sitter. Thus good control on the past boundary that replaces $\mathcal{I}^-$.



• Two strategies for analyzing radiation at future infinity are being pursued. In the first, One works with $\mathcal{I}^+$ without imposing the condition $B_{ab} = 0$ at $\mathcal{I}^+$. So the intrinsic +,+,+ metric q_{ab} at $\mathcal{I}^+$ is not conformally flat. The idea is to extract a fiducial equivalence class of conformally flat metric $\{\mathring{q}_{ab}\}$ 'that would result if the radiation were to be switched off' and the de Sitter group it selects. Only partial results so far.

A Second Strategy: 'Local' $\mathcal{I}^+$



• Local $\mathcal{I}^+$: Restricting to the 'local universe' of 5 GPc size around us. Idea: Use the past cosmological horizon $H^+ := E^-(i^+)$ in place of $\mathcal{I}^+$. Note the resemblance to the conformal diagram of Asymptotically Minkowski space-times! $H^\pm$: local $\mathcal{I}^\pm$.

• Using the structure at the bifurcate horizon, one can drag the Weakly isolated horizon structure from H^- to H^+. The symmetries of this fiducial WIH enable one to define Bondi-like charges and fluxes across H^+. For example, Bondi-type energy

$$Q_T[C] = \frac{1}{\kappa} \oint_C r \big[\mathrm{Re}(\Psi_2 + \bar\sigma_{(\ell)}\sigma_{(\mathrm{n})}) + \theta_{(\mathrm{n})} \left(\tfrac{1}{\mathrm{r}} - \tfrac{1}{2}\theta_\ell\right)\big] \mathrm{d}^2\mathrm{V}$$
$$= \frac{r}{2G}\left[1 - H^2 r^2 + 2\dot r\right] \quad \text{related to the area of } C! \text{ (as expected of horizons).}$$
$$\to \frac{1}{\kappa} \oint_C r \big[\mathrm{Re}(\Psi_2 + \bar\sigma_{(\ell)}\sigma_{(\mathrm{n})})\big]\, \mathrm{d}^2\mathrm{V} \quad \text{in the } \Lambda \to 0 \text{ limit.}$$

• $Q_T[C]$ would be positive if $r < 1/H$ the cosmological radius.

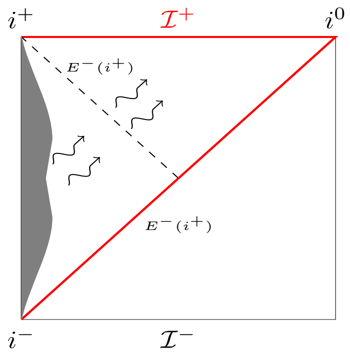
4. Summary and Outlook

• Primary motivation: conceptual. Some 100 Years have passed since Einstein's discovery quadrupole formula and some 50 years since the Bondi-Penrose framework. For 15 years, we have known that the accelerated expansion of the universe is best explained by a positive Λ. Now, numerical relativists, observers and experimentalists have taken us to the dawn of the new era of gravitational wave science. So it is high time that we have a firm theoretical framework describing gravitational waves in GR with $\Lambda > 0$. (Recall the confusion about reality of gravitational waves during the first 50 years of GR!)

• The issue of this extension has been open so long because inclusion of Λ, however small, introduces novel conceptual issues both in full theory and in the linear approximation. These arise because the asymptotic space-time structure changes non-trivially: $\mathcal{I}^+$ is space-like rather than null. Hence problems persist if Λ were to be replaced by some other form of 'dark energy' so long as the accelerated expansion continues to the future.

• Stability of $\mathcal{I}^+$ for $\Lambda > 0$ was established in a pioneering work by Friedrich in 1991. But the problem of extracting physical information has been open: Bondi news; energy, momentum and angular momentum 2-sphere integrals; expressions of fluxes of these quantities; relation between the radiated power to properties of sources in the weak field, slow motion limit, ... Even a tiny Λ casts a long shadow!

• These issues have now been resolved in the weak field limit: Post de Sitter, first post-Newtonian approximation. A priori it is not obvious that tiny Λ can only make negligible corrections because the limit is discontinuous in important ways: $\mathcal{I}^+$ changes its character. But detailed analysis provides systematic ways of calculating the 'error' terms and shows why and how the concerns can be by-passed. For full, non-linear GR, well-developed strategies but further work is needed.



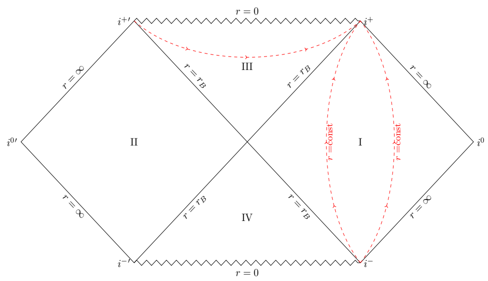
• Open issues: Examples:

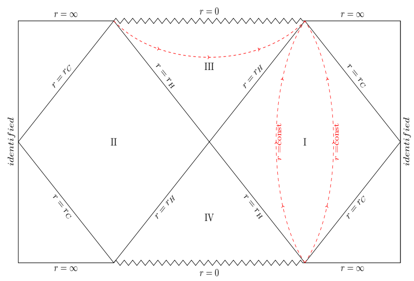
(i) Is the analog of Bondi-energy 2-sphere integral positive if the matter satisfies energy conditions and H^- is a weakly isolated horizon? Recall the importance of the positive energy theorem in geometric analysis.

(ii) Is the radiated flux positive (since there is no energy flux across H^-) as in the new quadrupole formula? If not, there would be gravitational instabilities.

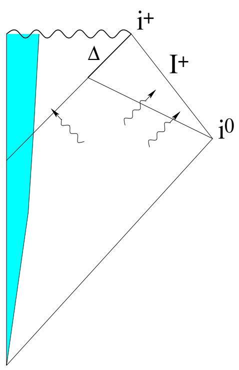
Comment: Definitions of de Sitter momenta of Abbott & Deser; Kelley & Marolf; Chruściel, Jezierski & Kijowski; ... refer to i^o. Positive energy theorems of Kastor & Traschen; Luo, Xie and Zhang also refer to i^o and, furthermore, a conformal Killing field in de Sitter, which is not an asymptotic symmetry. Szabodas & Tod: Positive charge but interpretation unclear.

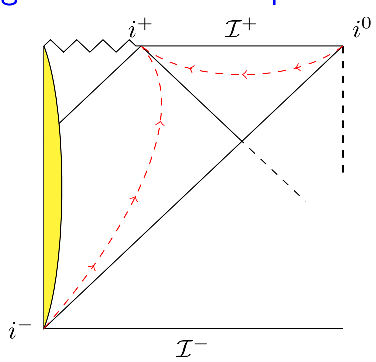
Gravitational Collapse & BH evaporation





$\Lambda = 0$ versus $\Lambda > 0$ gravitational Collapse





Conceptual problems in specifying asymptotic Hilbert spaces for the Hawking radiation resolved in the new scenario: incoming states can be specified on H^- and outgoing on H^+ , even allowing for back-reaction due to outgoing radiation.

“Experimental Constraints on Fifth Force Candidates in Nanometer Range”

by Yoshio Kamiya

[JGRG25(2015)1a1]

Experimental Constraints on Fifth Force Candidates in the Nanometer Range

Y. Kamiya, Y. Sasayama, S. Komamiya, and G. N. Kim
The Univ. of Tokyo / Kyngpook Nat. Univ.

supported by JSPS KAKENHI Grant No. 25870160

“Gravity-like”

Experimental Constraints on Fifth Force Candidates in the Nanometer Range

Y. Kamiya, Y. Sasayama, S. Komamiya, and G. N. Kim
The Univ. of Tokyo / Kyngpook Nat. Univ.

supported by JSPS KAKENHI Grant No. 25870160

New Interactions (5th forces)

Start with this Lagrangian for scalar field

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \xi M^4(\frac{\phi}{M})^{-n} - \Sigma_i \frac{\eta_i}{M_{Pl}}\rho_i\phi$$

- $m_\phi^2 = -\mu^2$, $n = -4$, $\xi = \lambda/4!$, $\eta_i/M_{Pl} = 1/v$

==> Higgs

- $\xi = 0$, $\eta_i = \eta$ (universal)

The equation of motion simply become the Klein-Gordon equation, and the new interaction is described by the Yukawa-type scattering potential for massive mediator.

Yukawa-type Scattering Potential

use more friendly notation of the strength of the Yukawa interaction

$$\Sigma_i \frac{\eta}{M_{Pl}}\rho_i = gm\delta(x)$$

where *m* is a fermion mass and *g* is a proportional constant,
then, scattering potential between two objects is obtained as

coupling charges

mass

$$V_\phi(r) = -\frac{1}{4\pi}g^2 m_1 m_2 \frac{e^{-m_\phi r}}{r}$$

coupling strength

The coupling charge of this new interaction is mass.
The new interaction appears as a source which violates the Newtonian, inverse square law of the universal gravity.

→ called "gravity-like" forces

Testing Gravity ~ 10^12 m

Verified by analyzing planetary and lunar movements

(exception) Pioneer Anomaly

The Pioneer 10/11 spacecrafts were observed to be pulled by the Sun a little bit stronger than the expectation on trajectories out of the Solar System. (1980)

It is now “tentatively" solved by taking into account an anisotropic thermal radiation precisely.

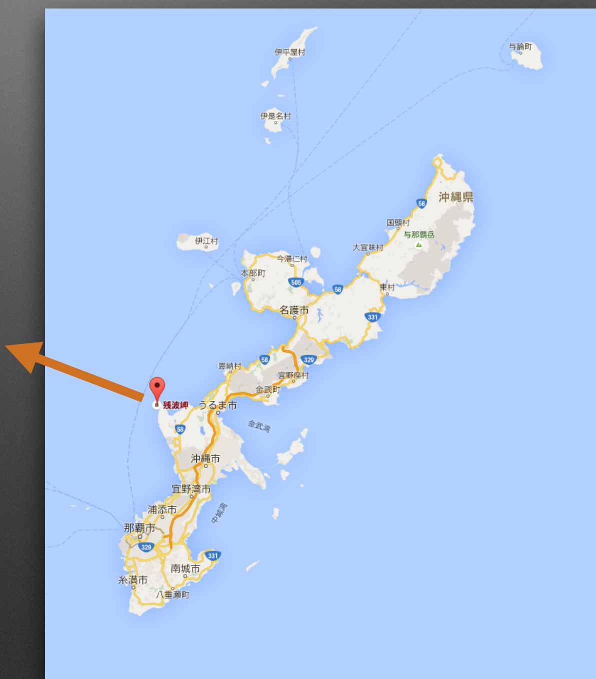
--- PRL108, 241101(2012)

3/15

Testing Gravity ~ 10^1 m

verified in the field of Geophysics

Daiki Goto / Zanpa cape



4/15

Testing Gravity < 1 m

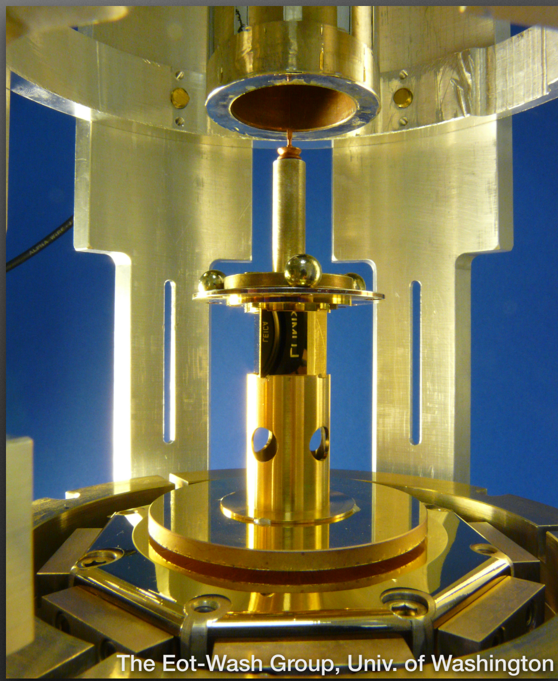
No significant deviation from the Newtonian Gravity has been observed in the interaction range down to 100 microns.

Many Gravity tests in the shorter range have been conducted in several institute energetically.

Yukawa-type scattering potential

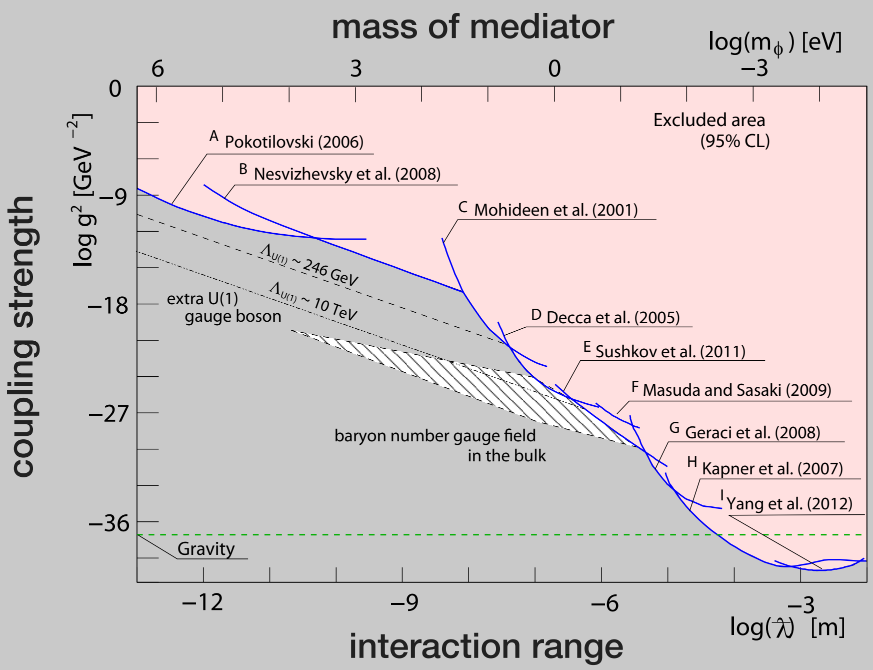
$$V_\phi(r) = -\frac{1}{4\pi}\underbrace{g^2}_{\text{coupling strength}}\overbrace{m_1 m_2}^{\text{coupling charges}}\frac{e^{-\overbrace{m_\phi}^{\text{mass}} r}}{r}$$

parameter space: (g^2, m_ϕ) or $(g^2, \lambda\!\!\!^- = 1/m_\phi)$

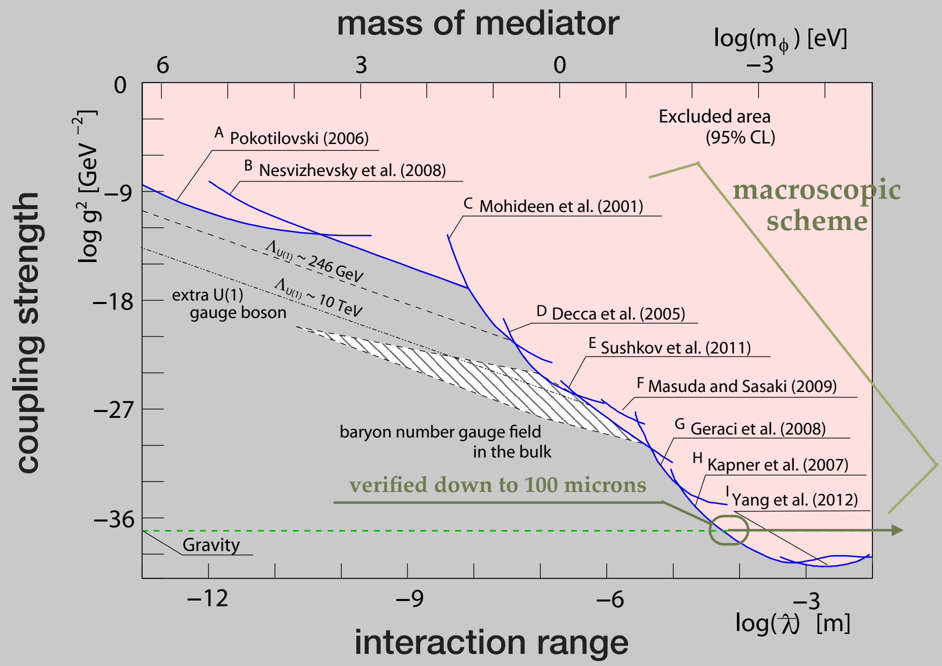


http://www.npl.washington.edu/eotwash/sr

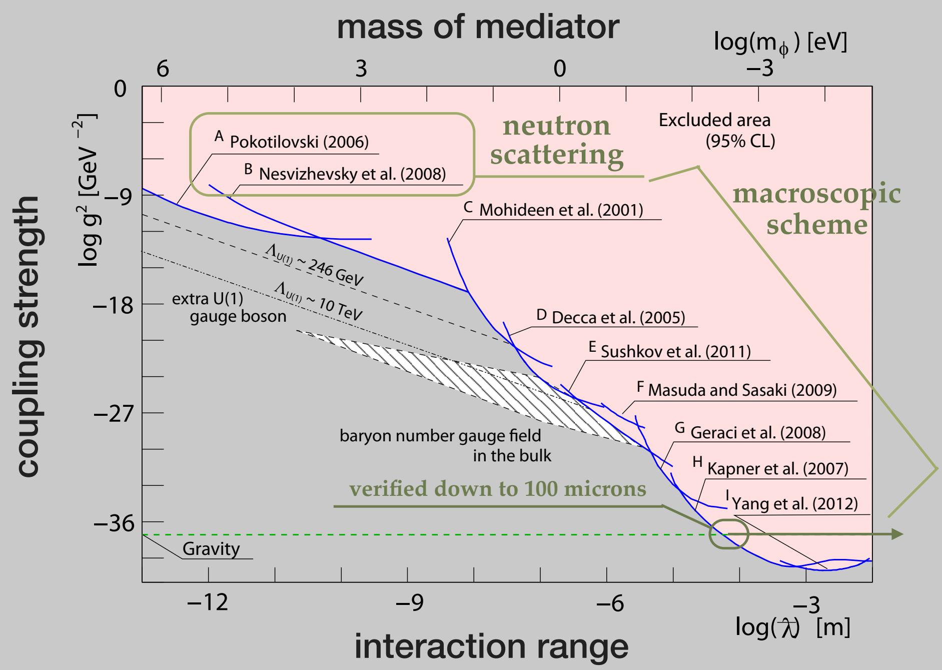
Experimental Constraints on the Yukawa-type Parametrization



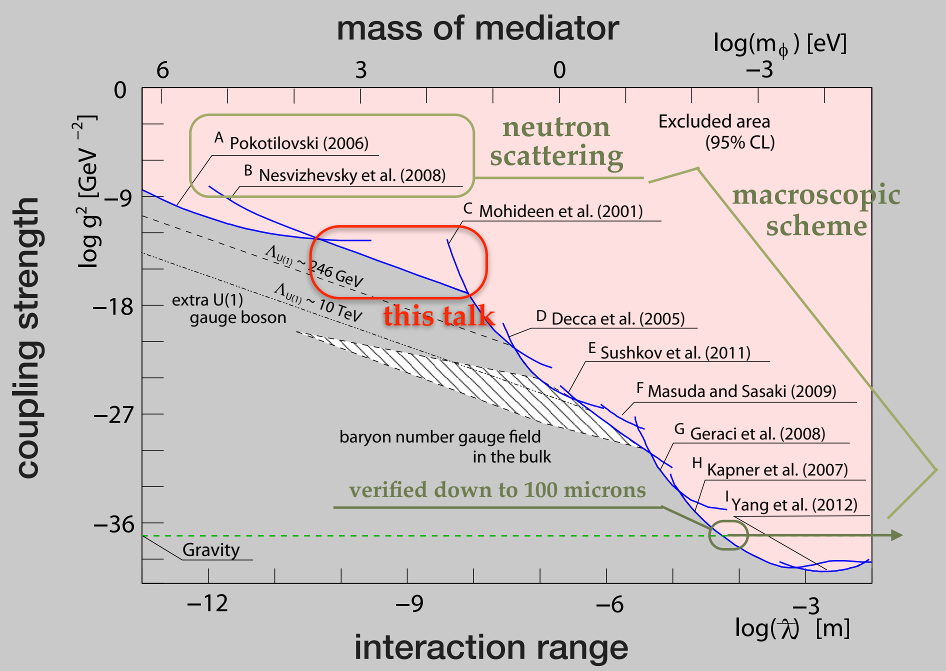
Experimental Constraints on the Yukawa-type Parametrization



Experimental Constraints on the Yukawa-type Parametrization



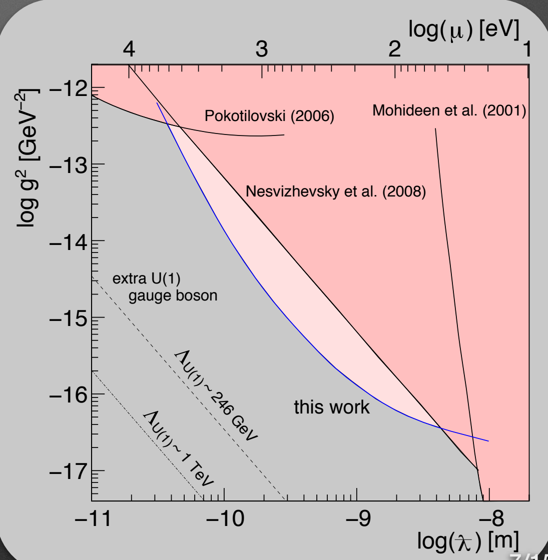
Experimental Constraints on the Yukawa-type Parametrization



New Force Search using Neutron Scattering

1) measure the angular distribution of 5 A neutrons scattering off atomic xenon gas

2) evaluate deviations from the expectations from know interactions to set limits on additional, unknown interactions



New Force Search using Neutron Scattering

1) measure the angular distribution of 5 A neutrons scattering off atomic xenon gas

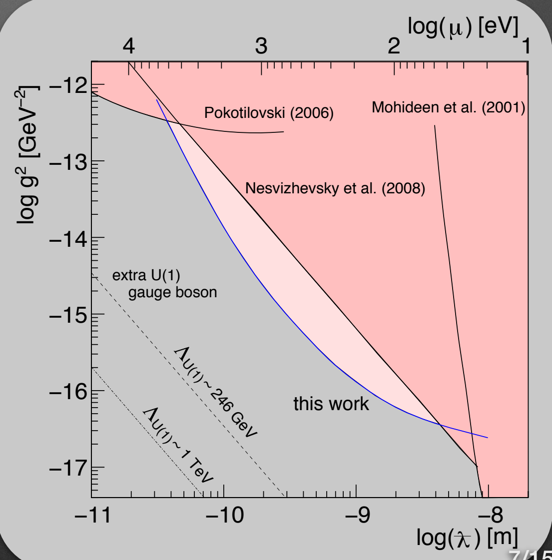
2) evaluate deviations from the expectations from know interactions to set limits on additional, unknown interactions

This experiment have started from 2013 with financial support of KAKENHI No. 25870160

We have finally succeeded to improve previous constraints for gravity-like forces in the 4 to 0.04 nm range by a factor of up to 10.

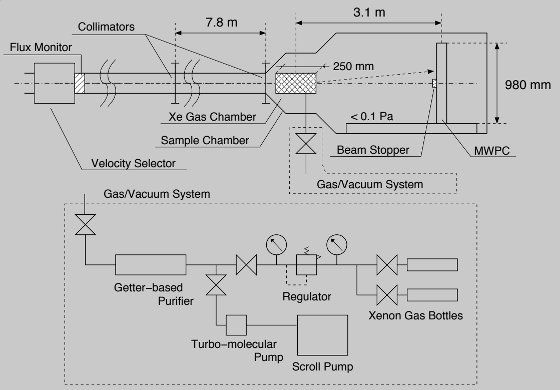
— Phys. Rev. Lett. 114, 161101 (2015)

This talk is mostly about this paper.

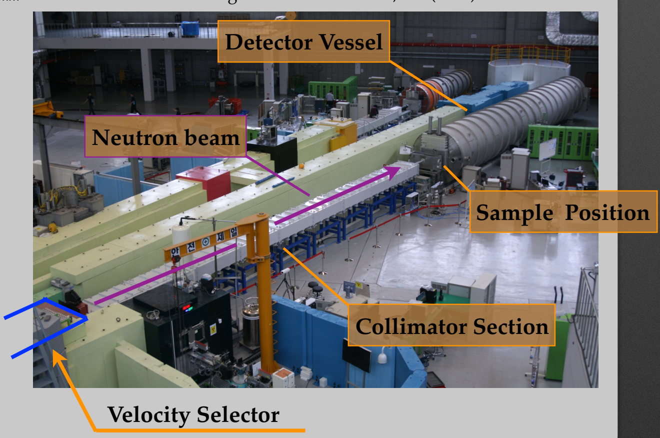


Experimental Site

40 m small angle neutron scattering beam line at HANARO research reactor



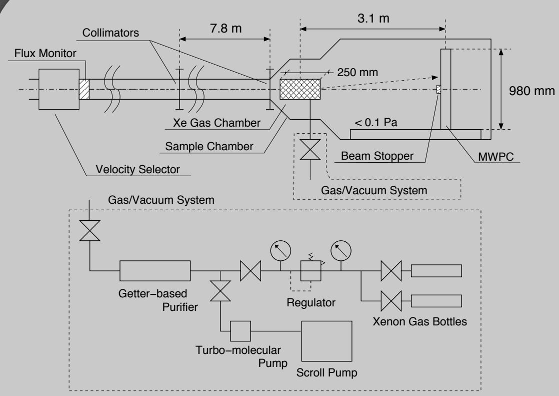
figs. from Young-Soo Han et.al, The 11th Japan-Korea Meeting on Neutron Science, I01 (2011)

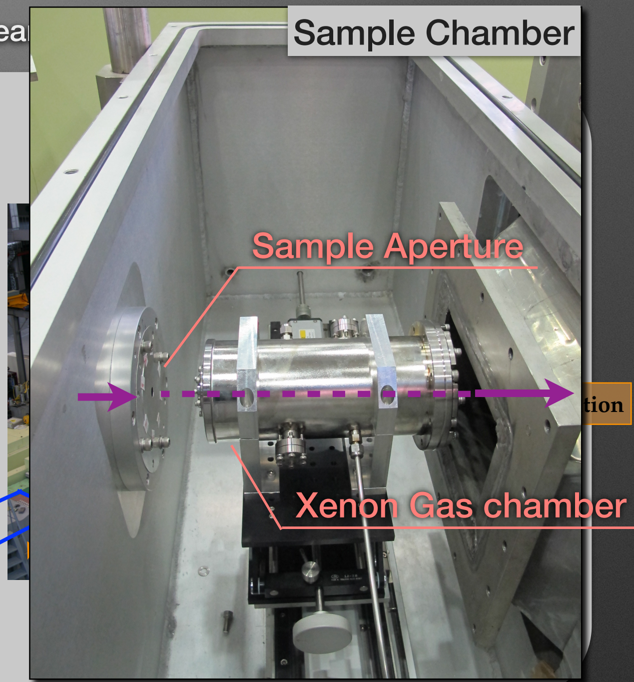


- Wavelength: 5 Å
- Beam size: 22 ϕ
- Divergence: ~ 3 mrad
- Intensity: ~ 1.4 x 10^5 neutrons/sec

Experimental Site

40 m small angle neutron scattering bea





- Wavelength: 5 Å
- Beam size: 22 ϕ
- Divergence: ~ 3 mrad
- Intensity: ~ 1.4 x 10^5 neutrons/sec

Scattering Length

Scattering Length is divided into
coherent/incoherent/Schwinger scatt. Length

$$b(\boldsymbol{q}) = b_c(\boldsymbol{q}) + \frac{1}{\sqrt{I(I+1)}}\,\boldsymbol{\sigma}\cdot\boldsymbol{b_i}(\boldsymbol{q})\cdot\boldsymbol{I} + ib_s(\boldsymbol{q})\,\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}$$

+ coherent scattering length

$$b_c(\boldsymbol{q}) = \underbrace{(b_{Nc} + b_p)}_{\sim 5\ \text{fm}} - \underbrace{(b_F + b_I)}_{\sim -1\times10^{-1}\ \text{fm}} Z[1 - f(\boldsymbol{q})]$$

+ incoherent scattering length

$$\boldsymbol{b}_i(\boldsymbol{q}) = \underbrace{b_{Ni}}_{\sim 0\ \text{fm}}\boldsymbol{1} - \sqrt{I(I+1)}\,g\underbrace{b_F}_{\sim -1\times10^{-3}\ \text{fm}}(\boldsymbol{1} - \hat{\boldsymbol{q}}\hat{\boldsymbol{q}})$$

+ Schwinger scattering length

$$b_s = \underbrace{b_F}_{\sim -1\times10^{-1}\ \text{fm}} Z[1 - f(\boldsymbol{q})]\cot\theta$$

$\sigma/2$: neutron spin
I : Nucleus spin
$\hat{n}$: unit vector ⊥ scattering plane

atomic form factor:

$$f(q) = [1 + 3(\frac{q}{q_0})^2]^{-0.5}$$

$q_0 \sim 7$ A^{-1}

b_{Nc}: coherent nuclear scatt. length
b_p: polarization scatt. length
b_F: Foldy scatt. length
b_I: intrinsic n-e scatt. length
b_{Ni}: incoherent nuclear scatt. length
g: magnetic dipole moment ~ 0.9

Scattering Length

Scattering Length is divided into
coherent/incoherent/Schwinger scatt. Length

$$b(\boldsymbol{q}) = b_c(\boldsymbol{q}) + \frac{1}{\sqrt{I(I+1)}} \boldsymbol{\sigma} \cdot \boldsymbol{b_i}(\boldsymbol{q}) \cdot \boldsymbol{I} + i b_s(\boldsymbol{q})\, \boldsymbol{\sigma} \cdot \hat{\boldsymbol{n}}$$

+ coherent scattering length

$$b_c(\boldsymbol{q}) = \underbrace{(b_{Nc} + b_p)}_{\sim 5\ \text{fm}} - \underbrace{(b_F + b_I)}_{\sim -1\text{x}10^{-1}\ \text{fm}} Z[1 - f(\boldsymbol{q})]$$

$\sigma/2$: neutron spin
I : Nucleus spin
$\hat{n}$: unit vector ⊥ scattering plane

atomic form factor:

$$f(q) = [1 + 3(\frac{q}{q_0})^2]^{-0.5}$$

$q_0 \sim 7$ A^{-1}

b_{Nc}: coherent nuclear scatt. length
b_p: polarization scatt. length
b_F: Foldy scatt. length
b_I: intrinsic n-e scatt. length
b_{Ni}: incoherent nuclear scatt. length
g: magnetic dipole moment ~ 0.9

Scattering Length

Scattering Length is divided into
coherent/incoherent/Schwinger scatt. Length

$$b(\boldsymbol{q}) = b_c(\boldsymbol{q}) + \frac{1}{\sqrt{I(I+1)}} \boldsymbol{\sigma} \cdot \boldsymbol{b_i}(\boldsymbol{q}) \cdot \boldsymbol{I} + i b_s(\boldsymbol{q})\, \boldsymbol{\sigma} \cdot \hat{\boldsymbol{n}}$$

+ coherent scattering length

$$b_c(\boldsymbol{q}) = \underbrace{(b_{Nc} + b_p)}_{\sim 5\ \text{fm}} - \underbrace{(b_F + b_I)}_{\sim -1\text{x}10^{-1}\ \text{fm}} Z[1 - f(\boldsymbol{q})]$$

$$= (b_{Nc} + b_p)\ \{1 + \chi[1 - f(\boldsymbol{q})]\} \qquad \chi \equiv -\frac{b_F + b_I}{b_{Nc} + b_p} Z \sim 3\text{x}10^{-2}$$

Scattering Length

Scattering Length is divided into
coherent/incoherent/Schwinger scatt. Length

$$b(\boldsymbol{q}) = b_c(\boldsymbol{q}) + \frac{1}{\sqrt{I(I+1)}}\,\boldsymbol{\sigma}\cdot\boldsymbol{b_i}(\boldsymbol{q})\cdot\boldsymbol{I} + i b_s(\boldsymbol{q})\,\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}$$

+ coherent scattering length

$$b_c(\boldsymbol{q}) = \underbrace{(b_{Nc}+b_p)}_{\sim 5\text{ fm}} - \underbrace{(b_F+b_I)}_{\sim -1\text{x}10^{-1}\text{ fm}} Z[1-f(\boldsymbol{q})]$$

$$= (b_{Nc}+b_p)\ \{1+\chi[1-f(\boldsymbol{q})]\} \qquad \chi \equiv -\frac{b_F+b_I}{b_{Nc}+b_p}Z \sim 3\text{x}10^{-2}$$

+ coherent scattering length with the new forces

$$b_c(\boldsymbol{q}) = (b_{Nc}+b_p)\ \{1+\chi[1-f(\boldsymbol{q})] + \chi_y[(\frac{q}{\mu})^2+1]^{-1}\}$$

via the Born approximation

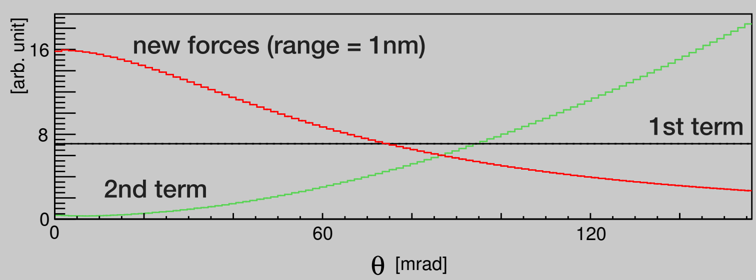
$$\chi_y \equiv \frac{m_n}{2\pi}g^2 m_1 m_2 \frac{1}{(b_{Nc}+b_p)m_\phi^2}$$

Differential Cross Section

$$\frac{d\sigma}{d\Omega} \simeq (b_{Nc}+b_p)^2\ (1+2\chi[1-f(\boldsymbol{q})]+2\chi_y[(\frac{q}{\mu})^2+1]^{-1})$$

Expected angular scattering distribution to be measured was derived from this differential cross section convoluted with the finite beam size, the length of the scattering chamber, and the thermal motion of the xenon gas.

Calculated Distributions



distributions are clearly distinguished each other

fitting using the shape is effective

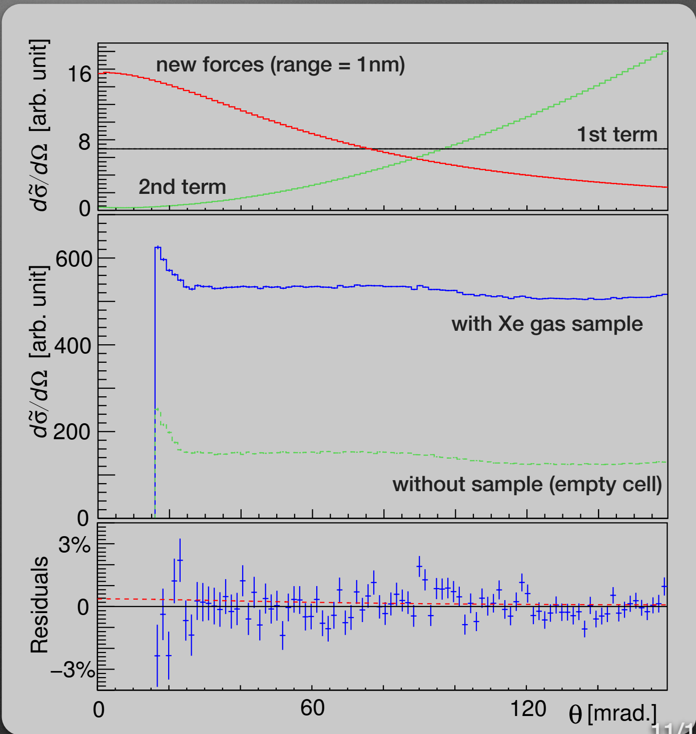
Measured Distribution

Top figure is the same one previous slide and they are the reference distributions to evaluate the measurement.

Center figure is measured scattering distributions w/ Xe gas sample and w/o sample

By subtracted the empty cell data and by fitted with the references, residual distribution from the known interactions is obtained.

No additional non-Newtonian forces are observed within this sensitivity.



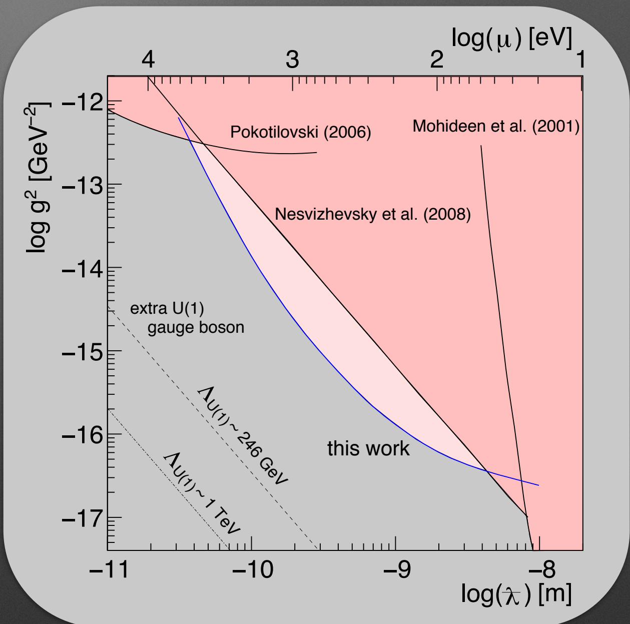
New Constraints

Limits of g^2 at 95% C.L. are evaluated using the Feldman Cousins approach.

We have succeeded to improve previous constraints for gravity-like forces in the 4 to 0.04 nm range by a factor of up to 10.

(Discussions)

- to longer range?
  — possible with neutron lenses
  21pDF-10 Sasayama (JPS2015 spring)
- for other type of new forces?
  — now investigating



Y. Kamiya, K. Itagaki, M. Tani, G. N. Kim, and S. Komamiya, Phys. Rev. Lett. 144, 161101 (2015)

New Interactions (5th forces)

Start with this Lagrangian for scalar field

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \xi M^4(\frac{\phi}{M})^{-n} - \Sigma_i \frac{\eta_i}{M_{Pl}}\rho_i\phi$$

- $m_\phi^2 = -\mu^2$, $n = -4$, $\xi = \lambda/4!$, $\eta_i/M_{Pl} = 1/v$

==> Higgs

- $\xi = 0$, $\eta_i = \eta$ (universal)

The equation of motion simply become the Klein-Gordon equation, and the new interaction is described by the Yukawa-type scattering potential for massive mediator.

Chameleon Fields

Start with this Lagrangian for scalar field

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \xi M^4(\frac{\phi}{M})^{-n} - \Sigma_i \frac{\eta_i}{M_{Pl}}\rho_i\phi$$

- $m_\phi^2 = 0$ $\eta_i = \eta$ (universal) —> Nonlinearity will be of particular note

vev: $\phi_{vac} = M(\frac{\eta\rho}{n\xi M_{Pl}M^3})^{-\frac{1}{n+1}}$

depends on fermion surround

mass: $m_{vac} = \sqrt{n(n+1)\xi M}|\frac{M}{\phi_{vac}}|^{\frac{n}{2}+1}$

Chameleon Fields

(example) $n = -4$, $\xi \sim 1$, $\eta \sim 1$

In the Universe

$\rho = 10^{-24}$ g/cm^3 $\quad 1/m_{vac} \sim 100$ km

Too short to see the effect by cosmological observations

In usual material

$\rho = 1$ g/cm^3 $\quad 1/m_{vac} \sim 0.1$ mm

Interaction charge can not be accumulated (Thin-shell Effect)

$\longrightarrow$ Chameleon is still alive somewhere
Experiments at shorter ranges are effective

The Chameleon partially contribute to solve
the cosmological constant problem!

Summary

- Searches for new gravity-like short-range forces have been performed at many institutes.
- We improved previous constraints for the Yukawa-type gravity-like fifth forces in the 4 to 0.04 nm range by a factor of up to 10.
  Y. Kamiya, K. Itagaki, M. Tani, G. N. Kim, and S. Komamiya, Phys. Rev. Lett. 144, 161101 (2015)
- There are plenty parameter space remaining for new exciting physics such as the Chameleon field.
- The research field is still active and exciting.
- Please join this experimentally reachable field to your field and please make any predictions beyond the standard model.

Thank you for your attention.

“We plan to continue our work until defeated by systematic errors.”
— William M. Snow (Indiana Univ.)

“Model-independently testing gravitational theory with gravitational-wave observations”

by Tatsuya Narikawa

[JGRG25(2015)1a2]

1a2

Model-independently testing gravitational theory with gravitational-wave observations

Tatsuya Narikawa

Osaka City U.

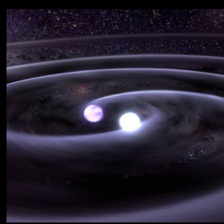
JGRG25, Parallel Session 1a@YITP, Panasonic Hall

14:15-14:30, 2015/12/7

1

Gravitational waves will be detected within a few years.

Advanced GW detectors, aLIGO, aVirgo, and bKAGRA will open a new window for GW astrophysics.



One of topics:
Testing GR in the dynamical strong-field regime.

Our recent work on **"Gravity-by-GW Test".**

[Narikawa, & Tagoshi, in prep.]

We demonstrate that Advanced GW detectors have potential for new bounds on deviations from GR.

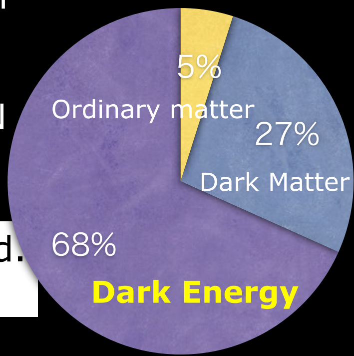
2

Why considering Alternative Theories of Gravity?

- GR passes all tests with flying colors so far.

But, is GR the correct theory of gravity in the entire regime?

- Problems for GR → Motivations for modified gravity theories
  - Black Hole singularity ← Unphysical!
  - Unification with other forces or Quantization of gravity
  - Alternative to Dark Energy and/or Dark Matter
  - Useful to contrast their predictions with GR
    → evaluate the correctness of GR, e.g., ppN

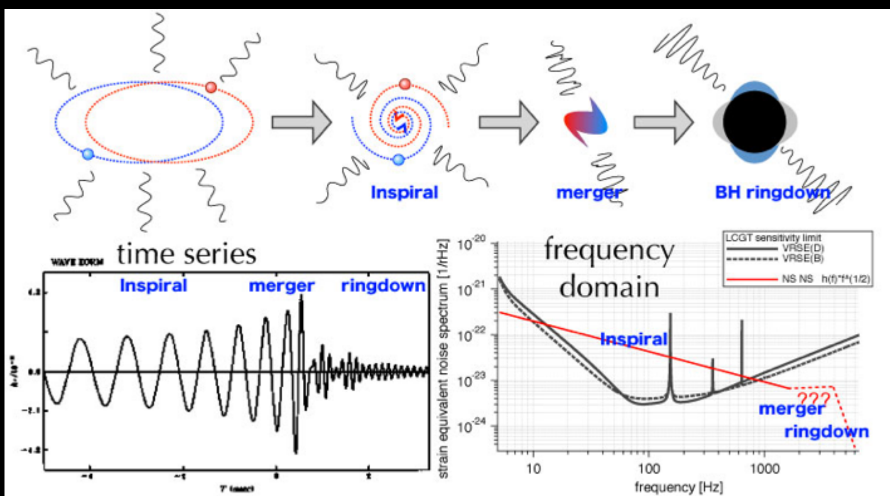


The Universe is undergoing an accelerated period.
Unknown components dominate.
We do not understand much of the Universe.

Cosmic Pie Chart
[Planck, 2014]

3

CBC The most promising source for advanced detectors.



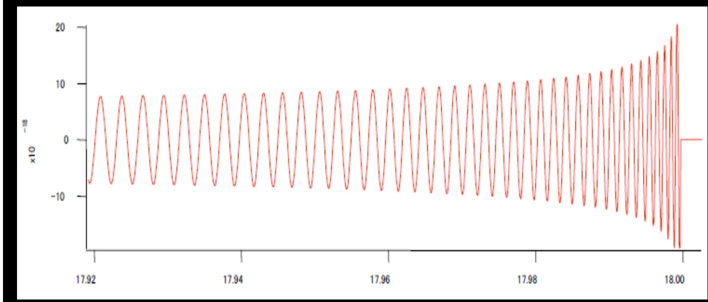
Expected GW detection rate for neutron star binary:

$$\mathcal{R}_{\rm det} = 8^{+10}_{-5}\ {\rm yr}^{-1}$$ in advanced detectors.

[Kim, Perera, & McLaughlin, MNRAS 2013 [arXiv:1308.4676]]

4

Restricted Inspiral Waveform



In GR,

Solving the energy balance law

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

Waveform

$$\tilde{h}_{\mathrm{GR}}(f) = A_{\mathrm{GR}} e^{i\Psi_{\mathrm{GR}}(f)}$$

Amplitude

$$A_{\mathrm{GR}} = \mathcal{A}\frac{\mathcal{M}^{5/6}}{D_{\mathrm{L}}} u^{-7/2}$$

Phase

$$\Psi_{\mathrm{GR}} = 2\pi f t_c - \Phi_c + \sum_{k=0}^{7}\left[\psi_k + \psi_k^{\log}\log(u)\right] u^{k-5},$$

where the inspiral reduced frequency $u=(\pi\mathcal{M}f)^{1/3}$

and the chirp mass $\mathcal{M} := (m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$

- -Point particles: clean system
- -Well-known analytic waveform (the small number of parameters)
- -Extracting Binary parameters: {Mc, η, D_L, t_c, Φ_c, sky location}
- -Testing GR and extended models of gravity

5

Parametrized post-Einsteinian Framework

[Yunes & Pretorius, PRD 2009]

$$\tilde{h} = \tilde{h}_{\mathrm{GR}}\left[1 + \alpha u^a\right]\exp[i\beta u^b]$$

A generic parametrization which characterizes the departures from GR through free parameters (a,α,b,β).

The ppE framework reproduces most the models

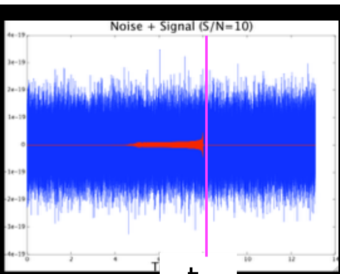
Modified Gravity Zoo

Theory	α_{ppE}	a_{ppE}	β_{ppE}	b_{ppE}
Jordan–Fierz–Brans–Dicke	$-\frac{5}{96}\frac{S^2}{\omega_{\mathrm{BD}}}\eta^{2/5}$	-2	$-\frac{5}{3584}\frac{S^2}{\omega_{\mathrm{BD}}}\eta^{2/5}$	-7
Dissipative Einstein-Dilaton-Gauss–Bonnet Gravity	0	·	$-\frac{5}{7168}\zeta_3\eta^{-18/5}\delta_m^2$	-7
Massive Graviton	0	·	$-\frac{\pi^2 D\mathcal{M}_c}{\lambda_g^2(1+z)}$	-3
Lorentz Violation	0	·	$-\frac{\pi^{2-\gamma_{\mathrm{LV}}}}{(1-\gamma_{\mathrm{LV}})}\frac{D_{\gamma_{\mathrm{LV}}}}{\lambda_{\mathrm{LV}}^{2-\gamma_{\mathrm{LV}}}}\frac{\mathcal{M}_c^{1-\gamma_{\mathrm{LV}}}}{(1+z)^{1-\gamma_{\mathrm{LV}}}}$	$-3\gamma_{\mathrm{LV}}-3$
$G(t)$ Theory	$-\frac{5}{512}\dot{G}\mathcal{M}_c$	-8	$-\frac{25}{65536}\dot{G}_c\mathcal{M}_c$	-13
Extra Dimensions	·	·	$-\frac{75}{2554344}\frac{dM}{dt}\eta^{-4}(3-26\eta+24\eta^2)$	-13
Non-Dynamical Chern–Simons	α_{PV}	3	β_{PV}	6

and may also cover unknown models.

Matched filtering - A pattern matching technique

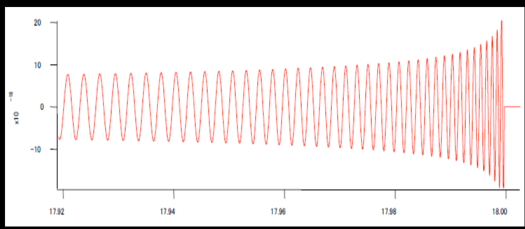
d



data: s=n+h_{true}

$\otimes$ t_c coalescence time

h

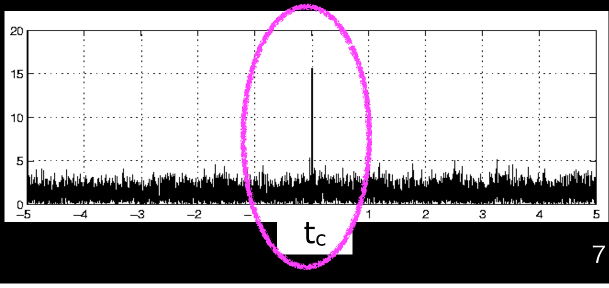


time[sec]

template: h

Sn(f): One-sided power spectrum density of noise

ρ



t_c

$$\rho = (s, \hat{h}) = 2\int_{-\infty}^{\infty} df \frac{\tilde{s}(f)\hat{h}^*(f)}{S_n(f)}$$

If h∝d, ρ becomes maximum.

Bayesian model selection

Which model better describes the data?

the odds ratio for MG over GR

$$\mathcal{O} \equiv \frac{P(\mathrm{MG}|s)}{P(\mathrm{GR}|s)} = \frac{P(\mathrm{MG})}{P(\mathrm{GR})}\frac{P(s|\mathrm{MG})}{P(s|\mathrm{GR})}$$

Analytical approximation of BF

[Cornish et al. PRD 2011]

$$\mathcal{O} \propto e^{\mathrm{SNR}^2(1-\mathrm{FF})}$$

Assumptions: large SNR, FF~1,...

Fitting Factor

$$\mathrm{SNR} = |h| = \sqrt{(h|h)} \qquad \mathrm{FF}(\theta_{\mathrm{MG}}) = \max_{\theta_{\mathrm{GR}}} \frac{(h_{\mathrm{GR}}(\theta_{\mathrm{GR}})|h_{\mathrm{MG}}(\theta_{\mathrm{MG}}))}{|h_{\mathrm{GR}}(\theta_{\mathrm{GR}})||h_{\mathrm{MG}}(\theta_{\mathrm{MG}})|}$$

1-FF characterizes the strength of MG corrections.

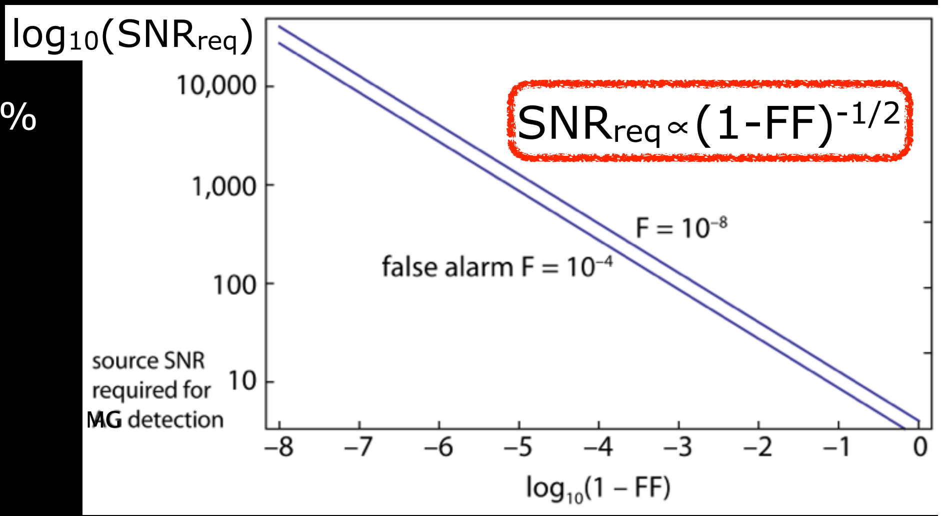
A analytic Bayesian decision scheme [Vallisneri, PRD 2012]

using the odds ratio as a detection statistic,
with approximation for odds ratio $O \propto \exp[SNR^2(1-FF)]$,
setting O_{thr} by requiring a given FAP:

$O_{MG,GR} > O_{thr}$ for a FAP → MG detection!

Efficiency E=50%
FAP $F=10^{-4}$

FF	SNR_{req}
0.9	8.699
0.95	12.3
0.99	27.5

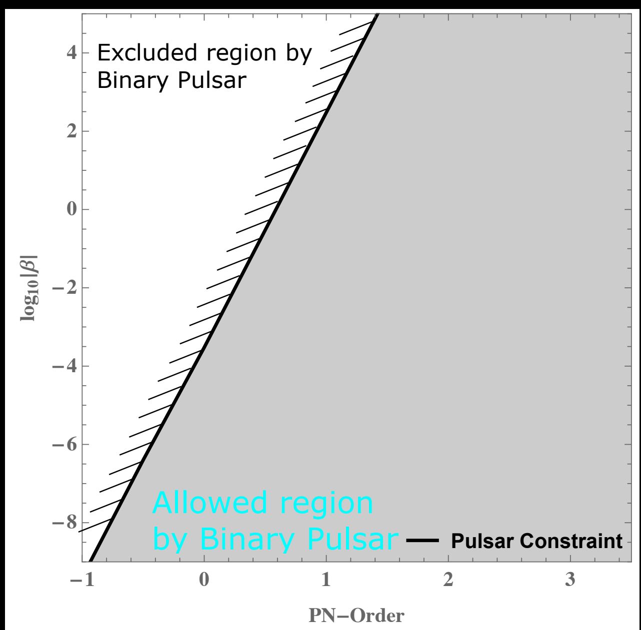


SNRreq : the value of the signal SNR required to detect a given deviation from GR waveform.

B. Phase corrections

$$\tilde{h} = \tilde{h}_{GR} \exp[i\beta u^b]$$

For BNS (1.4, 1.4)



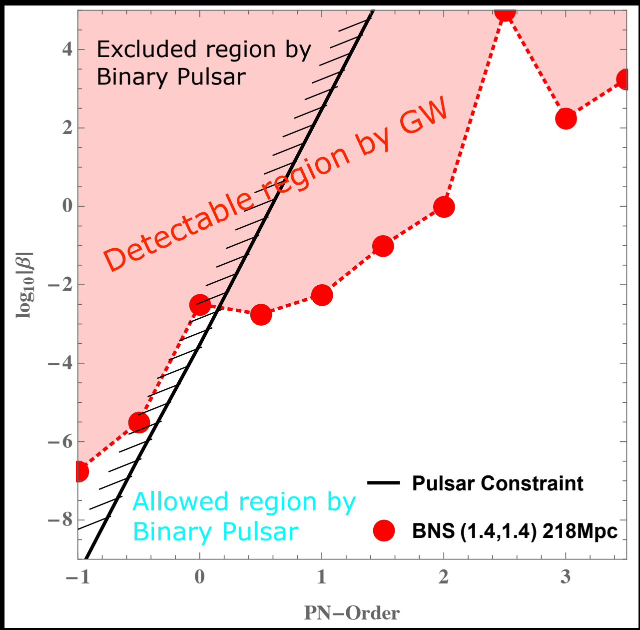
Bounds from binary pulsar observations for PSR J0737-3039.

B. Phase corrections

Detectable Region (SNR>SNR$_{req}$)

$$\tilde{h} = \tilde{h}_{\rm GR} \exp[i\beta u^b]$$

For BNS (1.4, 1.4)



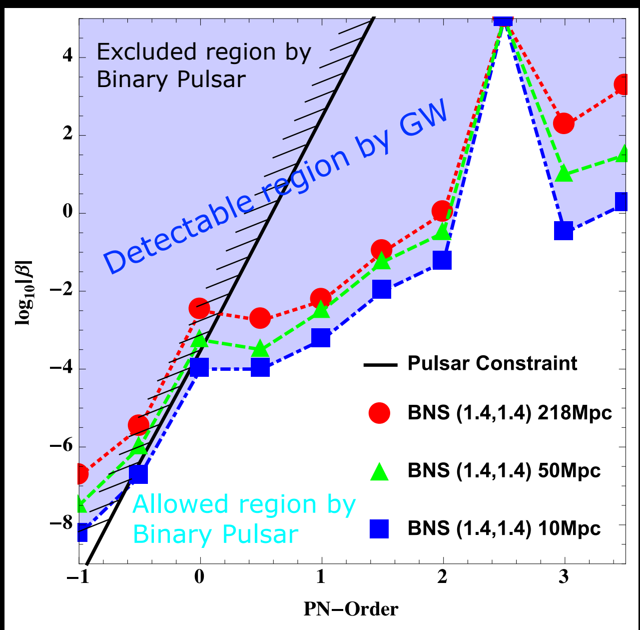
Even if a detection threshold event will be detected, GW constraints can be stronger than those of binary pulsar constraints at high-PN order.

B. Phase corrections

Detectable Region (SNR>SNR$_{req}$)

$$\tilde{h} = \tilde{h}_{\rm GR} \exp[i\beta u^b]$$

For BNS (1.4, 1.4)



Even if a detection threshold event will be detected, GW constraints can be stronger than those of binary pulsar constraints at high-PN order.

The results demonstrate that Advanced GW detectors have potential for new bound on phase-deviations from GR.

Summary

Model-independently testing gravitational theory with GW observations

Strategy

[Narikawa, & Tagoshi, in prep.]

Parametrized post-Einsteinian Framework
Approximate Bayesian analysis
Detectable regions of ppE corrections to GR

We demonstrate that Advanced GW detectors have potential for new bounds on deviations from GR.

Our results provide prior information for modified-gravity search.

Thank you for your attention.

“Microlens of light rays near photon sphere”

by Naoki Tsukamoto

[JGRG25(2015)1a3]

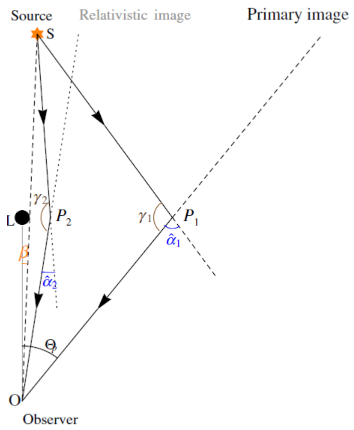
Microlens of light rays near photon sphere.

Naoki Tsukamoto
Rikkyo University
($\rightarrow$ Huazhong University of Science and Technology in China)

N. Tsukamoto and T. Harada, arXiv:160x.xxxxx

December 7th 2015, JGRG25 @ Yukawa Institute for Theoretical Physics, Kyoto University

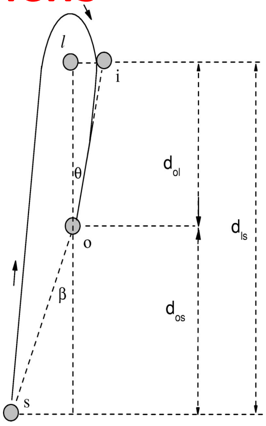
Relativistic images near Photon sphere.



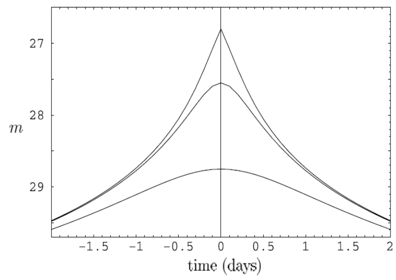
Virbhadra 2009

- If a lens is a black hole, infinite number of images appear near photon sphere at $r = 3r_g/2$.
- Since these relativistic images are always dimmer than primary images, we can ignore its effects on microlenses.

Retrolens



Eiroa and Torres 2004.

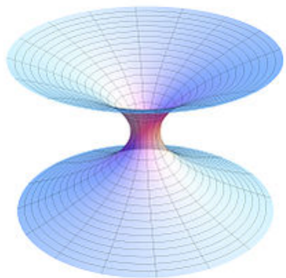


Holz and Wheeler 2002.
The lens is BH with $10M_{sun}$ at 0.02pc and the source is the Sun.

- Retrolensed image is brighter by 30 times than relativistic images.
- **Retrolensed image and primary image appear at different direction.**
- Retrolensed image is sensitive to the photon spehre.

Microlens of light rays which pass a wormhole throat.

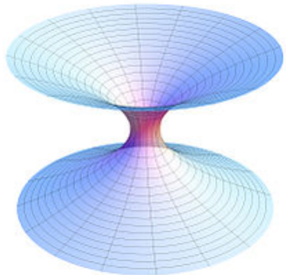
- Images near photon sphere are dominant.



Morris-Thorne Wormhole Morris and Thorne (1988).

- A static and spherically symmetric WH.
- Two infinities are linked by a throat (two-dimensional spheres with minimal area on a space-like hypersurface).
- If we assume general relativity without Λ, exotic matters ($w \equiv p/\rho_e < -1$) are needed to support the throat because of the violation of the null energy condition ($T_{\mu\nu}k^\mu k^\nu \geq 0$).

  (p: pressure, ρ_e: energy density, k^μ:null vector.)
- Here, we will concentrate on methods to find wormholes with gravitational lenses.



Ellis wormhole Ellis 1973 and Bronikov 1973.

- The earliest and simplest example of Morris-Thorne class.

By solving the Einstein equations and the wave equation with respect to a phantom scalar field $\chi(r)$

$$R_{\mu\nu} - \frac{1}{2}R^\lambda{}_\lambda g_{\mu\nu} = -2\left(\chi(r)_{;\mu}\chi(r)_{;\nu} - \frac{1}{2}\chi(r)^{;\lambda}\chi(r)_{;\lambda}g_{\mu\nu}\right), \quad \chi(r)^{;\mu}{}_{;\mu} = 0$$

with the boundary condition $\lim_{r\to\infty}\chi(r) = 0$, we obtain a static and spherical wormhole solution as

$$\begin{aligned} ds^2 &= \frac{r^2+a^2-m^2}{\left|r^2+a^2-m^2\right|}\left\{-e^{-\frac{2m\chi(r)}{a}}dt^2 + e^{\frac{2m\chi(r)}{a}}\left[dr^2 + \left(r^2+a^2-m^2\right)d\Omega^2\right]\right\}, \\ \chi(r) &= \frac{a}{\sqrt{a^2-m^2}}\left[\frac{\pi}{2} - \arctan\frac{r}{\sqrt{a^2-m^2}}\right]. \end{aligned}$$

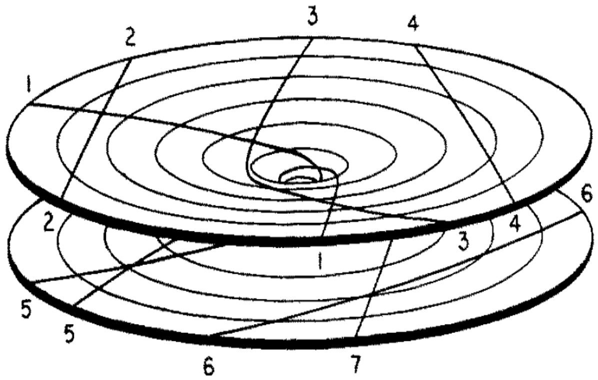
- As $r \to \infty$, it is asymptotic to Schwarzschild spacetime with the mass m.
  Its gravitational lens effects under the weak-field approximation are same as Schwarzschild lens.
- As $r \to -\infty$,

$$ds^2 = -\left(1 + \frac{2me^{\frac{m\pi}{a}}}{r}\right) d\left(e^{-\frac{m\pi}{a}} t\right)^2 + \frac{dr^2}{1 + \frac{2me^{\frac{m\pi}{a}}}{r}} + r^2 \left(d\theta^2 + \sin^2\theta d\phi^2\right).$$

  It is asymptotic to Schwarzschild spacetime with a negative mass $-me^{\frac{m\pi}{a}}$. **This is an example of so-called natural wormhole.**
- For $m = 0$, it becomes the **so-called Ellis wormhole**.

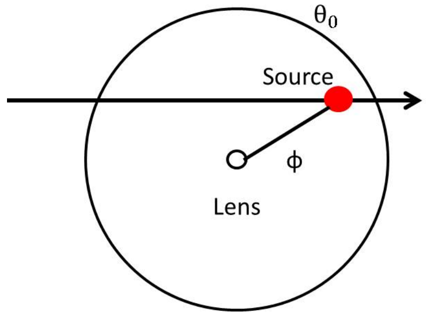
$$ds^2 = -dt^2 + dr^2 + (r^2 + a^2)(d\theta^2 + \sin^2\theta d\phi^2),$$

Large impact parameter case. Ellis 1973



- Usual lens configuration.

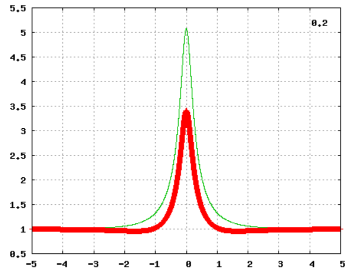
Microlens with large impact parameter. Abe, 2010.

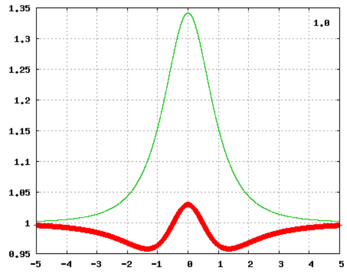


- A source go across near a lens object on the lens plane.
- Ellis WH: characteristic de-magnification.
- We cannot say the difference between positive Mass worm-holes and usual massive objects.

Green :Mass lens

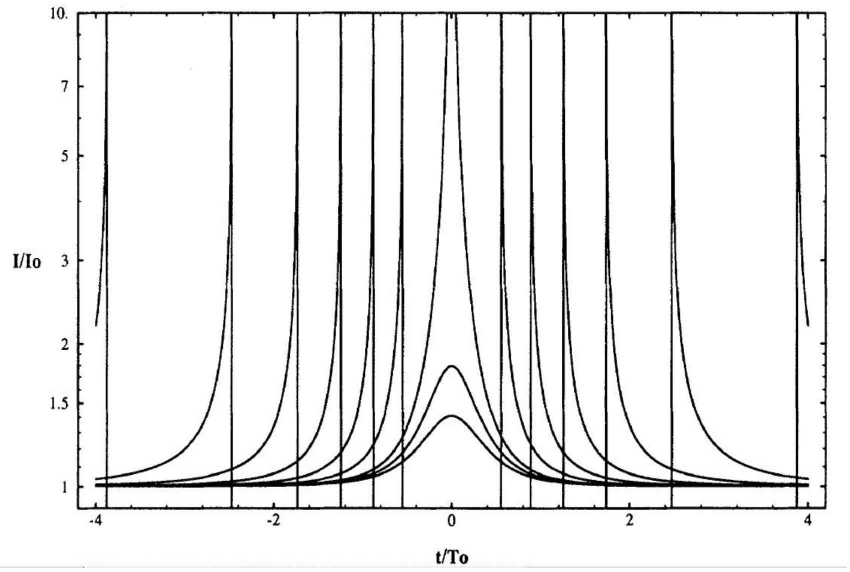
Red :Ellis WH





9

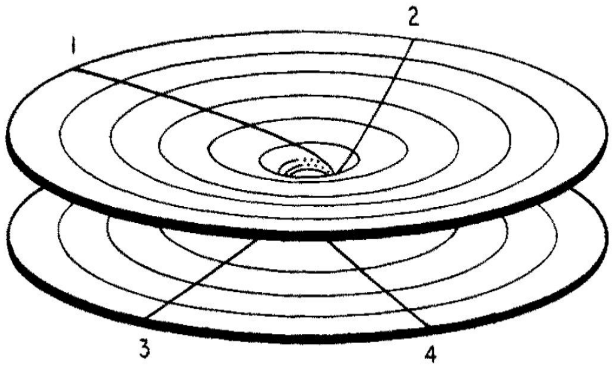
Microlens of natural wormhole. Cramer et al. (1995)



Two peaks can appear.

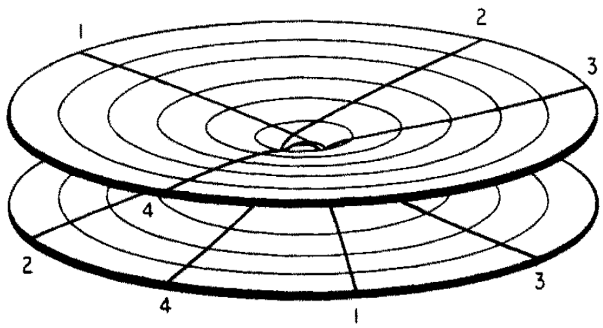
10

Critical impact parameter case. Ellis 1973



- The photon sphere exists at the throat.

Small impact parameter case. Ellis 1973

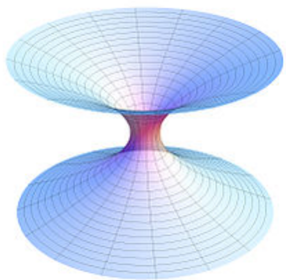


- **We want to give a method to find positive mass wormholes!**
- Photon sphere, non-existance of horizon, geodesically complete,
- We will investigate this case.

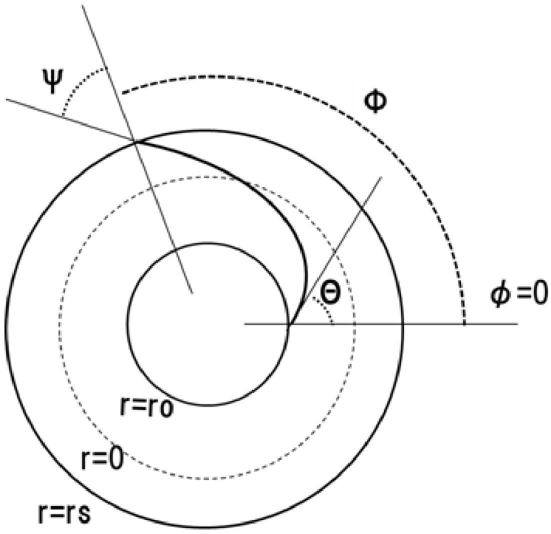
Microlens of light rays passing through a wormhole throat.

Tsukamoto and Harada 2016.

- To distinguish the wormhole with a positive mass from other massive objects, we investigate the microlensing by the light rays coming from the another flat region through the wormhole throat by using the exact lens equation (See Perlick 2004).
- For simplicity, we concentrate on the so-called Ellis wormhole.
- Our method would be applied for passable wormholes with positive masses easily.



The configuration of the gravitational lens.



- Θ is the image angle on the observer's sky.
- For $\phi \sim \pi$, two images near photon sphere are dominant.

The difference of magnitude

$$\Delta m = m - m_0 = 2.5 \log_{10}\left(D_{lum}^2\right)$$

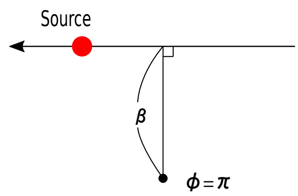
where m_0 is the magnitude of the primary image at $\Theta = 0$.
D_{lum} is the luminosity distance:

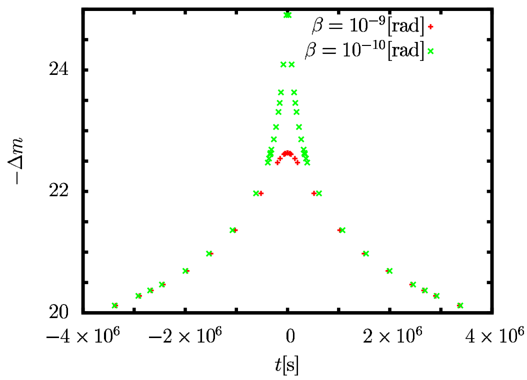
$$D_{lum}^2 = \left| \int_{r_O}^{r_S} \frac{\sqrt{r_S^2 + a^2\cos^2\Theta - r_O^2\sin^2\Theta}\sqrt{r_O^2+a^2}\sqrt{r^2+a^2}\cos^2\Theta dr}{\left(\sqrt{r^2+a^2\cos^2\Theta - r_S^2\sin^2\Theta}\right)^3} \right.$$
$$\left. \times \frac{\sqrt{r_S^2+a^2}}{\sin\Theta} \sin\left(\int_{r_O}^{r_S} \frac{\sqrt{r_O^2+a^2}\sin\Theta dr}{\sqrt{r^2+a^2}\sqrt{r^2+a^2\cos^2\Theta - r_O^2\sin^2\Theta}}\right) \right|$$

- We will assume $a = 10^{-2}$ pc and $r_S = -r_O = 10$ kpc.

Light curves

- We assume the source velocity $\hat{v} = 3 \times 10^{-15}$ rad/s near $\phi = \pi$ on the source plain.
- β: The closest separation between the source and $\phi = \pi$.





Summary.

- We have investigated the microlensing of the light rays which have passed Ellis wormhole throat.
- The closest distance β between the source and $\phi = \pi$ decides the maximum of apparent brightness of the light curve.
- We would distinguish the light curves from the usual light curves of mass lenses.
- Our method would be applied for passable wormholes with positive masses easily.

Thank you.

“All-sky coherent search for continuous gravitational waves in 6-7 Hz band with a torsion-bar antenna”

by Kazunari Eda

[JGRG25(2015)1a4]

All-sky coherent search for continuous gravitational waves in 6-7 Hz band with a torsion-bar antenna

- Phys.Rev. D90 (2014) 6, 064039
- arXiv:1511.08354

Kazunari Eda

University of Tokyo, RESCEU

(RESearch Center for the Early Universe)

Collaborators:
A.Shoda, Y.Kuwahara, Y.Itoh & M.Ando

2015/12/07
JGRG25 @ Kyoto

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Motivation

- Previous works — Phys.Rev.D90,6,064039 KE, A.Shoda, Y.Itoh, and M.Ando (2014), A.Shoda (2015)
  - ✓ We proposed a new antenna configuration for a torsion bar antenna (TOBA) last year.
  - ✓ Correspondingly, we have upgraded the TOBA.
  - ✓ We operated the upgraded TOBA for about 24-hours last year.
  - ✓ The sensitivity reached 10^{-10} $\mathrm{Hz}^{-1/2}$ at around 1 Hz.

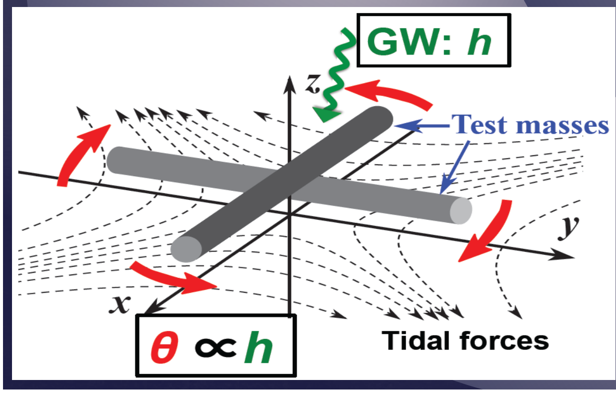
arXiv:1511.08354
KE, A.Shoda, Y.Kuwahara, Y.Itoh, and M.Ando (2015)

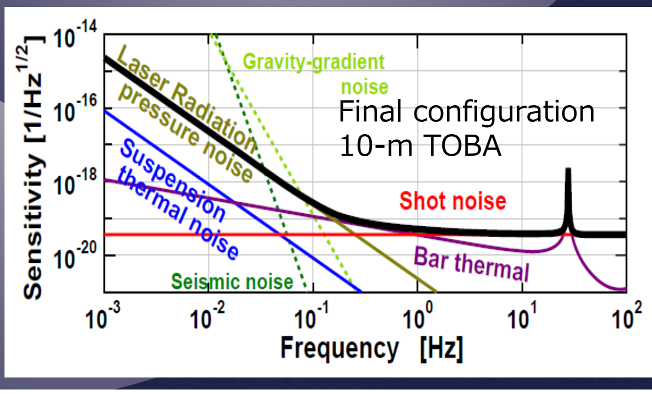
- We search for continuous GW from a rapidly rotating neutron star in low-frequency regime using the upgraded TOBA.
- All-sky search for continuous GWs below 10 Hz have yet to be investigated so far.
- We put constraints on the GW amplitude.

What is TOBA ?

- TOrsion-bar Antenna (TOBA) (Ando et al. PRL 105, 161101 (2010))
  - ✓ Low-frequency GW antenna which measures rotations of bars
  - ✓ formed by two bar-shaped orthogonal test masses
  - ✓ sensitive to low-frequency GWs (f=0.1-1 Hz) even on the ground thanks to its resonant frequency f_{res} < 1mHz.

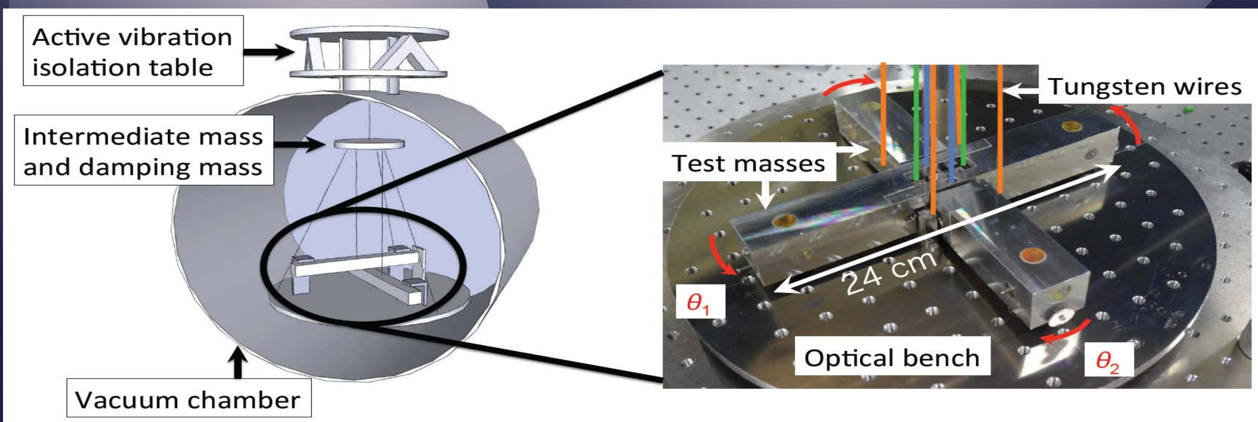
Main Targets ⇨
- Compact binary coalescence
- Stochastic GW background





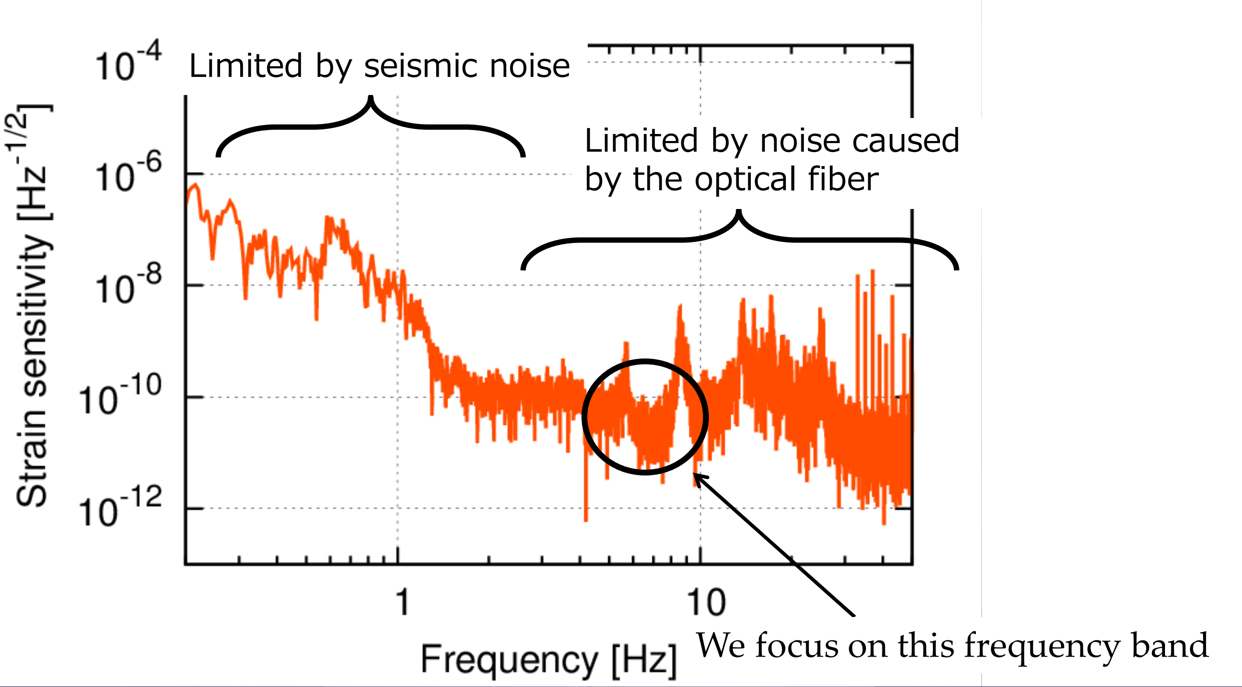
Design overview

- Phase-I TOBA Ph.D. thesis, K.Ishidoshiro (2010)
  - ✓ Single bar suspended by magnetic force with a superconductor.
  - ✓ Its sensitivity is limited by the magnetic noise below 0.2 Hz.
- Phase-II TOBA Ph.D. thesis, A.Shoda (2015)
  - ✓ Two 24-cm bars suspended by tungsten wires
  - ✓ Common mode noise rejection via a null stream
  - ✓ Hexapod-type active vibration isolation system



Measured strain sensitivity

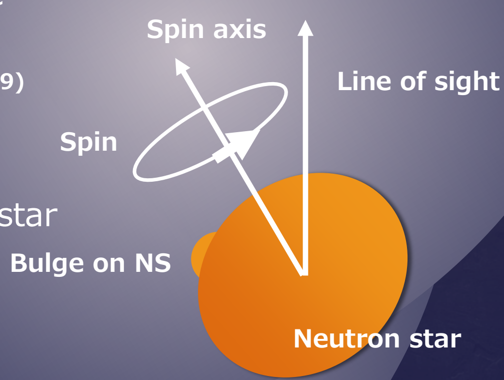
- Sensitivity curve of the Phase-II TOBA



Continuous GWs

- Continuous GW from a rapidly rotating neutron star (NS)
  - ✓ NS's non-axisymmetry ε ➡ GWs
  - ✓ GW frequency = 2×spin frequency → nearly constant
  - ✓ GW duration time >> Observation time
- Ellipticity ε
  - ✓ NS's non-axisymmetry
  - ✓ Maximum possible value $\varepsilon \sim 4\text{x}10^{-6}$
  - ✓ 1-cm-high bulge on the 10-km-radius star
- Typical amplitude

Horowitz & Kadau (2009)



$$h_0 = \frac{4\pi^2 G}{c^4 r}\varepsilon I f_0^2$$

$$= \underbrace{1.0 \times 10^{-29}}_{\text{GW amplitude}} \underbrace{\left(\frac{\varepsilon}{10^{-6}}\right)}_{\text{NS's deformation}} \underbrace{\left(\frac{I}{10^{38}\ \mathrm{kgm}^2}\right)}_{\text{NS's moment of inertia}} \underbrace{\left(\frac{0.1\ \mathrm{kpc}}{r}\right)}_{\text{Distance to the NS}} \underbrace{\left(\frac{f_0}{1\ \mathrm{Hz}}\right)^2}_{\text{GW frequency}}$$

Search method: *F*-statistic

- *F*-statistic — Jaranowski, Krolak, and Schutz (1998)
  - ✓ The method of maximum likelihood ratio
  - ✓ Indicator to see whether the GW signal is present or not
  - ✓ $2F > 2F_{\mathrm{thr}}$ ➡ GW detection

$$\ln \Lambda(\boldsymbol{s};\boldsymbol{h}) = \ln \frac{P(\boldsymbol{s}|\boldsymbol{h})}{P(\boldsymbol{s}|\boldsymbol{h}=\boldsymbol{0})} = (\boldsymbol{s}|\boldsymbol{h}) - \frac{1}{2}(\boldsymbol{h}|\boldsymbol{h})$$

$$2\mathcal{F} \equiv \max_{h_0,\phi_0,\iota,\psi}\left[2\ln\Lambda(\boldsymbol{s};\lambda)\right]$$

$$\mathrm{E}[2\mathcal{F}] = 4 + (\mathrm{S/N})^2$$

s : Output
h : GW signal
(· | ·) : Inner product

- Threshold of *F*-statistic
  - ✓ S/N=8 ➡ $2F_{\mathrm{thr}}$=68.
  - ✓ $2F < 2F_{th}$ ➡ Upper limits on GW amplitudes

Flow chart of our search pipeline

- LAL (LSC Algorithm Library)
  - ✓ Useful tool for GW data analysis
  - ✓ Developed by LIGO
  - ✓ Written in C language
    - MakeSFTs.c
    - ComputeFstatistic_v2.c
    - ComputeFstatMCUpperLimit.c
    - ……

Input *h*(*t*) data
↓
Make 9000-sec SFTs (Short Fourier Transform)
↓
Compute *F*-statistic
→ $2F > 2F_{\mathrm{thr}}$
- No → Set an upper limit on h_0
- Yes → List of candidates

Computations were mainly conducted on the ORION computer cluster of the Osaka City University.

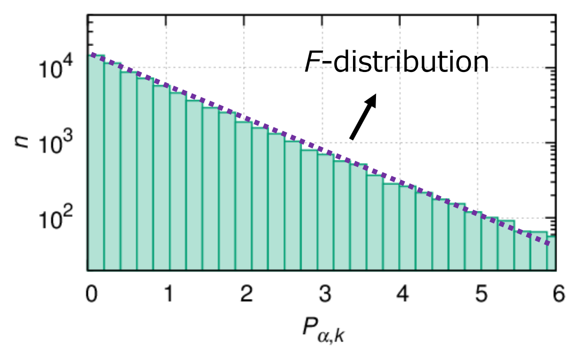
Data analysis 1

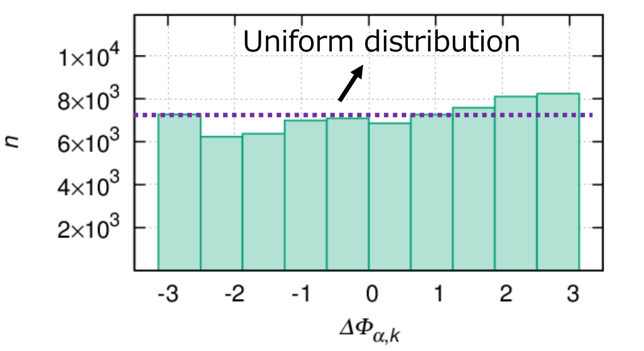
arXiv:1511.08354
KE, A.Shoda, Y.Kuwahara, Y.Itoh, M.Ando (2015)

- Preparation for data analysis
  - ✓ Convert time-series data into GWF (GW frame) format for LAL
  - ✓ Make 9,000-sec SFTs from the 22.5-hour TOBA data (***S***hort ***F***ourier ***T***ransform)
- Statistical properties
  - ✓ Statistical properties of our data in 6-7Hz band of interest
  - ✓ We evaluate the Gaussianity and the stationarity of the noise.

(a) Gaussianity check
Histogram of an averaged power in a single frequency bin

(b) Stationarity check
Histogram of a difference between the adjacent phases



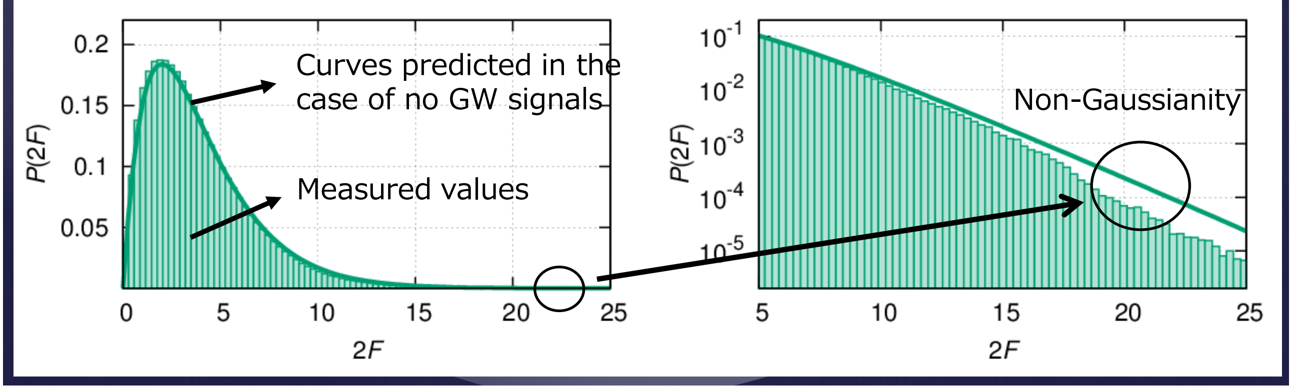


Data analysis 2

arXiv:1511.08354
KE, A.Shoda, Y.Kuwahara, Y.Itoh, M.Ando (2015)

- Computation of *F*-statistic
  - ✓ Employing ComputeFstatistic_v2.c in the LAL code
  - ✓ *F*-statistic for all-sky regions in 6.10-6.11 Hz band
- Results
  - ✓ No GW signals ➡ PDF for *F*-stat. obeys χ^2-distribtuion with 4 dof.
  - ✓ Our data is filled with almost Gaussian noise.
  - ✓ For large *F*-stat, small non-Gaussianity appear.

Probability distribution function for *F*-statistic over 0.01 Hz band

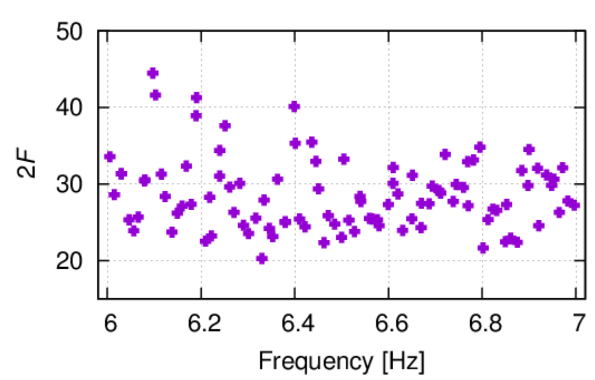


Data analysis 3

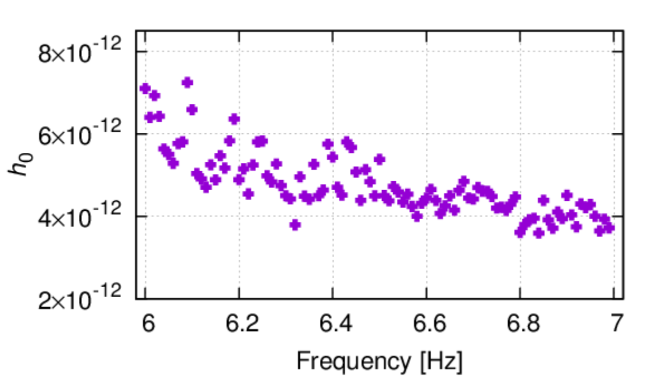
arXiv:1511.08354
KE, A.Shoda, Y.Kuwahara, Y.Itoh, M.Ando (2015)

- Upper limits on GW amplitudes
  - ✓ 1Hz band is divided in to 0.01Hz sub-band.
  - ✓ We evaluate the loudest values of F-stat in each sub-band.
- Results
  - ✓ The threshold $2F_{\mathrm{thr}}$ is set to be 68 corresponding to S/N=8.
  - ✓ The measured values of F-stat in each sub-band are below F_{thr} .
  - ✓ The most strict UL in this band with 95% confidence level is 3.6x10^{-12} at 6.84Hz.

Loudest values of F-statistic



Upper limits on h_0



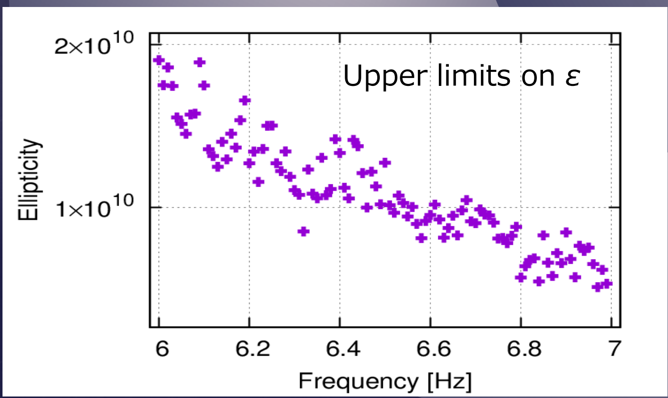
Discussion

arXiv:1511.08354
KE, A.Shoda, Y.Kuwahara, Y.Itoh, M.Ando (2015)

- Expected upper limits on GW amplitudes
  - ✓ From JKS98 paper, expected upper limits are 4.0x10^{-12}.
  - ✓ Our upper limits are typically h_0~5 x 10^{-12}.

$$\langle h_0^{\mathrm{UL}} \rangle_{\psi,\iota,\phi_0} = 11.4\sqrt{\frac{S_n(f_0)}{T_{\mathrm{obs}}}}$$

- Upper limits on ellipticity ε
  - ✓ The ULs on h_0 can be interpreted in terms of ULs on the ellipticity.
  - ✓ Maximum possible value ε ~ 10^{-6} (Horowitz&Kadau (2009))
  - ✓ Our ULs on ε are far from an interesting parameter region.



$$h_0 = \frac{4\pi^2 G}{c^4 r}\varepsilon I f_0^2$$

- ✓ Distance : r = 0.1 kpc
- ✓ Moment of Inertia : I = 10^{38} kgm^2
- ✓ Gravitational constant : G
- ✓ Speed of light : c
- ✓ GW frequency : f_0

Summary

- The Phase-II TOBA was constructed.
- We operated the Phase-II TOBA in the end of last year.
- The sensitivity reached 10^{-10} $Hz^{-1/2}$ at around 1 Hz.

⇩

- Using the data from the upgraded TOBA, We searched for continuous GWs in 6-7 Hz for all-sky regions which had yet to be searched so far.
- No significant GW signals are found in this frequency band.
- The most strict upper limit on h_0 with 95% confidence level is 3.6×10^{-12} at 6.84 Hz.

Thank you !!

“Wave Optics in the Kerr spacetime and the black hole shadow”

by Sousuke Noda

[JGRG25(2015)1a5]

名古屋大学

Wave Optics in the Kerr spacetime and the black hole shadow

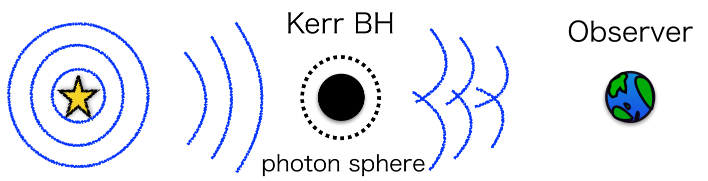
Sousuke Noda (Nagoya Univ.)

Collaborator
Yasusada Nambu (Nagoya Univ.)

7/12/2015 JGRG25 @ YITP

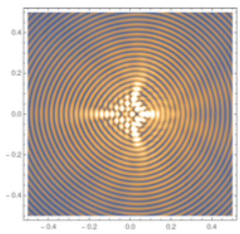
In this presentation…

① Wave scattering by a Kerr black hole



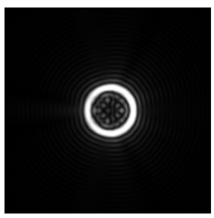
② Image construction from the scattered wave

Interference pattern



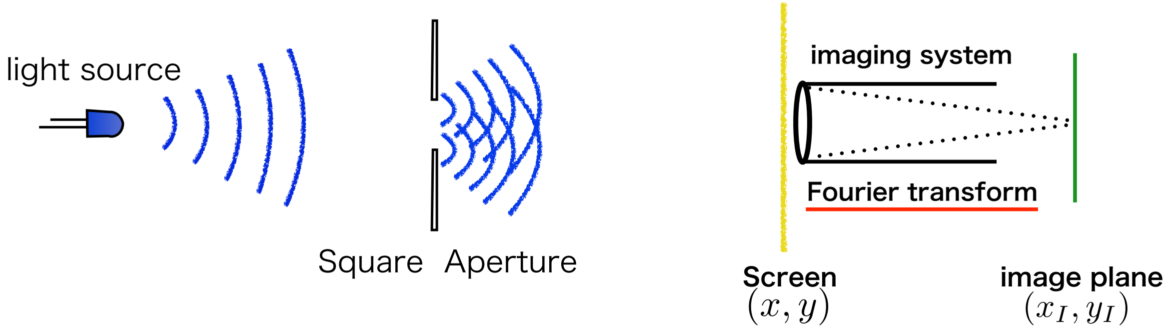
caustics

Wave optical image

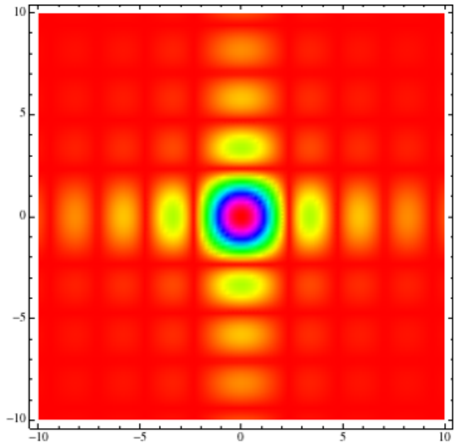


Black hole shadow

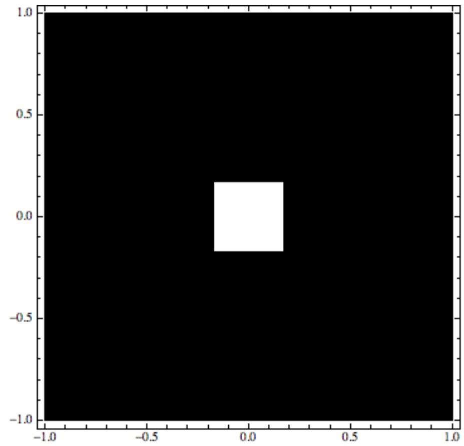
Image construction in wave optics



Interference pattern

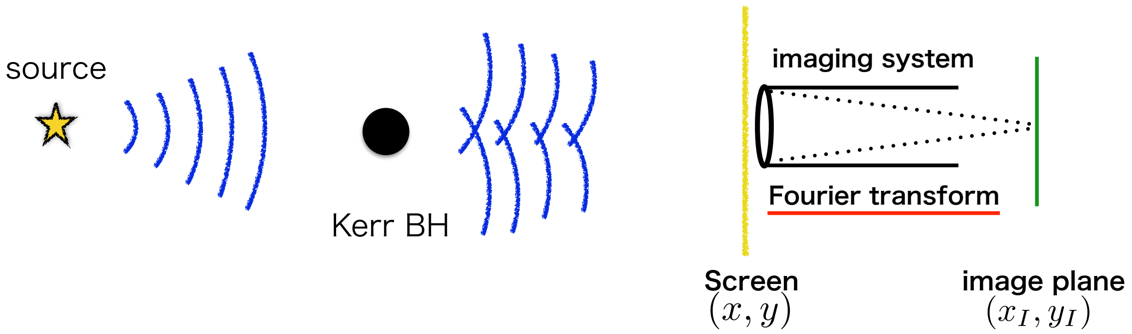


Image

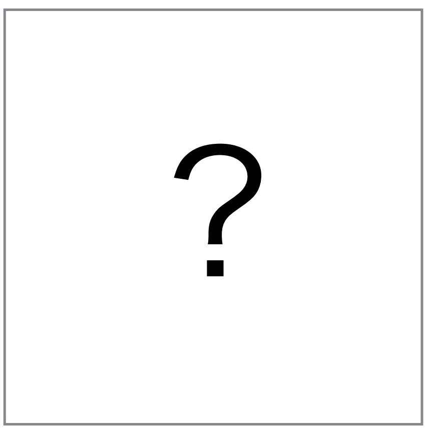


3

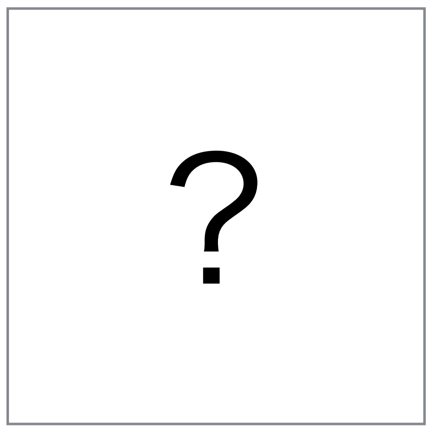
Image construction in wave optics



Interference pattern

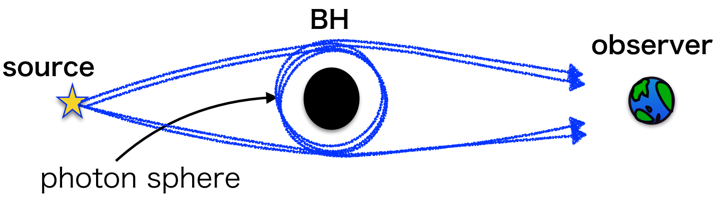


Image

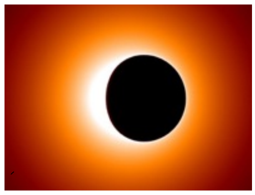


Why Wave Optics ??

- Geometrical Optics



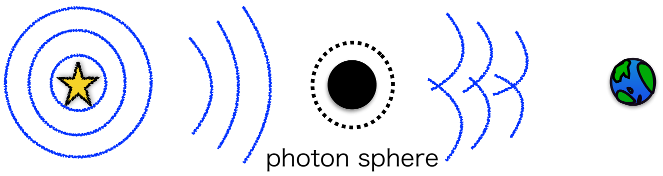
BH Shadow



M. Moscibrodzka & H. Falcke, Radboud-Universität Nimwegen

photon sphere ⇔ rim of shadow

- Wave Optics



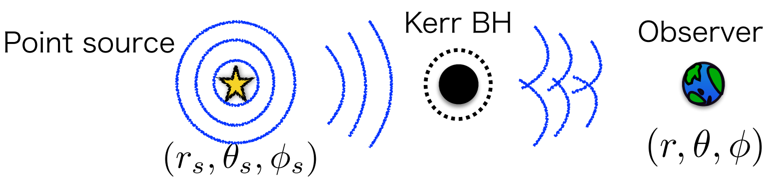
Wave Optical BH Shadow

photon sphere ~ Quasi Normal Modes

Wave optical effects

e.g.) Diffraction
Beat between modes etc.

Set up



(r_s, θ_s, ϕ_s) (r, θ, ϕ)

- Kerr metric ・・・ Boyer Lindquist coordinates $\frac{a}{M} = 0 \sim 1$
- Source ・・・ monochromatic, scalar wave

short wavelength $\omega M \gg 1$

Klein Gordon eq.

$$\Box\Phi = S \qquad \Phi \sim e^{-i\omega t} \;(\text{stationary}), \quad S \sim \delta^{(3)}(\vec{x} - \vec{x}_s)$$

- Helmholtz eq.

$$\nabla^2 \underbrace{G(\vec{x}, \vec{x}_s)}_{\text{Green function}} = -\delta^{(3)}(\vec{x} - \vec{x}_s)$$

partial wave expansion

$$G(x, x_s) = \sum_l \sum_m \frac{\tilde{G}_{lm}(r, r_s)}{\sqrt{r^2 + a^2}\sqrt{r_s^2 + a^2}} \underbrace{S_{lm}(\theta) S^*_{lm}(\theta_s)}_{\text{spheroidal harmonics}} e^{im(\phi - \phi_s)}$$

The radial part short wavelength case $\omega M \gg 1$

○ The radial part

$$\tilde{G}_{lm} = -\frac{u_{in}(r_s)u_{up}(r)}{w(u_{in}, u_{up})} \qquad w(u_{in}, u_{up}) \text{ : Wronskian}$$

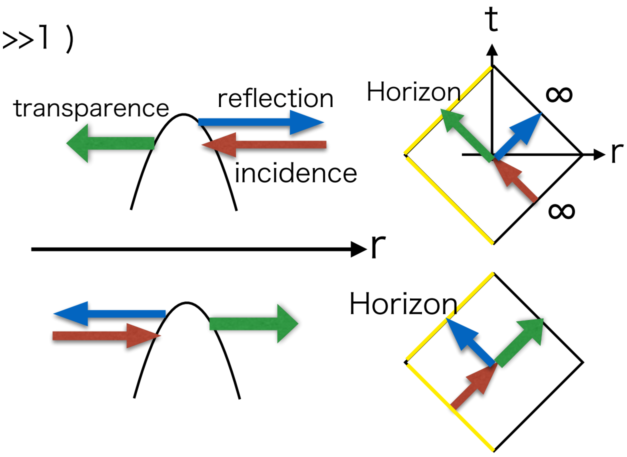
○ The radial equation (homogeneous)

$$\frac{d^2u(r_*)}{dr_*^2} + Qu(r_*) = 0 \qquad Q = \frac{[\omega(r^2+a^2) - ma]^2 - \Delta(A_{lm} + a^2\omega^2 - 2am\omega)}{(r^2+a^2)^2}$$

○ Independent linear **WKB** solutions (r >>1)

$$u_{in} \sim \sin\left(\omega r_* - \frac{\pi l}{2} + \delta_{lm} + \frac{A_{lm} + a^2\omega^2}{2\omega r}\right)$$

$$u_{up} = \exp\left(i\left\{\omega r_* - \frac{\pi l}{2} + \delta_{lm} + \frac{A_{lm} + a^2\omega^2}{2\omega r}\right\}\right)$$



Green function

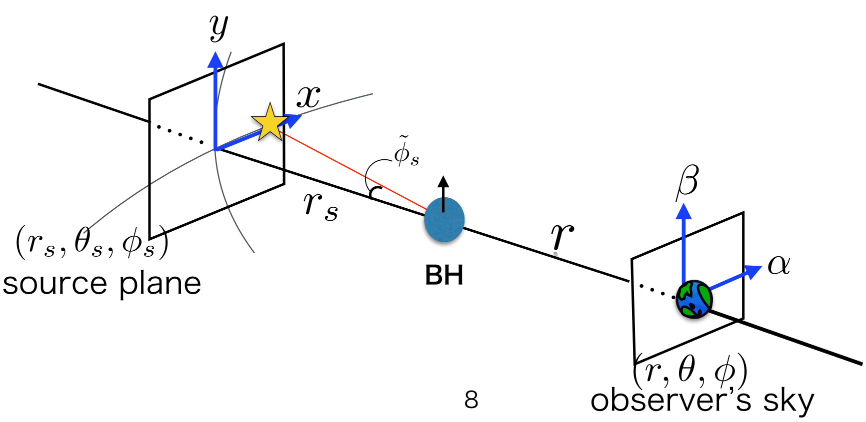
partial wave expansion

$$G(x, x_s) = \sum_l \sum_m \frac{\tilde{G}_{lm}(r, r_s)}{\sqrt{r^2+a^2}\sqrt{r_s^2+a^2}} S_{lm}(\theta) S^*_{lm}(\theta_s) e^{im(\phi-\phi_s)}$$

radial part

$$\tilde{G}_{lm} = -\frac{u_{in}(r_s)u_{up}(r)}{w(u_{in}, u_{up})}$$

$$\boxed{G(x, x_s) = \frac{e^{i\omega(r^* + r_s^*)}}{2i\omega r r_s} \sum_{l=0}^{\infty} \sum_{m=-l}^{l} e^{i\frac{A_{lm}+a^2\omega^2}{2\omega}\left(\frac{1}{r}+\frac{1}{r_s}\right)} e^{i2\delta_{lm}} S_{lm}(\theta) S_{lm}(\theta_s) e^{im(\phi+\tilde{\phi}_s)}}$$



Decomposition of the Green function

$$G(x,x_s) = \frac{e^{i\omega(r^*+r_s^*)}}{2i\omega r r_s}\sum_{l=0}^{\infty}\sum_{m=-l}^{l} e^{i\frac{A_{lm}+a^2\omega^2}{2\omega}\left(\frac{1}{r}+\frac{1}{r_s}\right)} e^{i2\delta_{lm}} S_{lm}(\theta)S_{lm}(\theta_s)e^{im(\phi+\tilde{\phi}_s)}$$

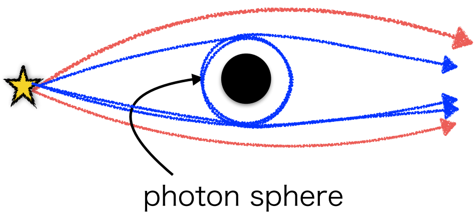
Poisson's formula

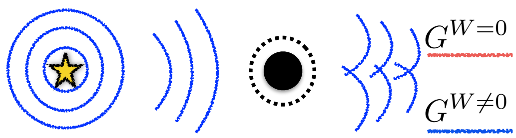
$$\sum_{l=0}^{\infty} \rightarrow \sum_{W=-\infty}^{\infty}\int_C dL\, e^{i2\pi W(L-1/2)} \qquad L = l+1/2$$

W : integer

$$= \underline{G^{W=0}} + \underline{G^{W\neq 0}}$$

Direct part Winding part





Decomposition of the Green function

$$G(x,x_s) = \frac{e^{i\omega(r^*+r_s^*)}}{2i\omega r r_s}\sum_{l=0}^{\infty}\sum_{m=-l}^{l} e^{i\frac{A_{lm}+a^2\omega^2}{2\omega}\left(\frac{1}{r}+\frac{1}{r_s}\right)} e^{i2\delta_{lm}} S_{lm}(\theta)S_{lm}(\theta_s)e^{im(\phi+\tilde{\phi}_s)}$$

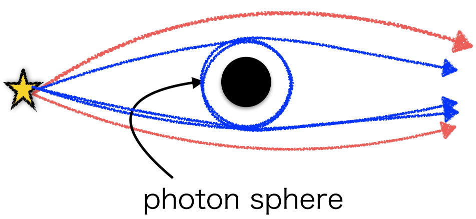
Poisson's formula

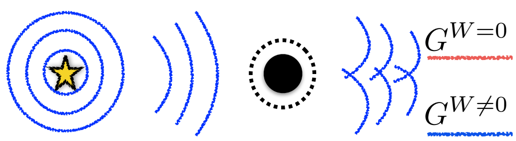
$$\sum_{l=0}^{\infty} \rightarrow \sum_{W=-\infty}^{\infty}\int_C dL\, e^{i2\pi W(L-1/2)} \qquad L = l+1/2$$

W : integer

$$= \underline{G^{W=0}} + \underline{G^{W\neq 0}}$$

Direct part Winding part





Sum in the Green function & QNMs

○ Winding part

$$G^{W\neq 0} = \frac{e^{i\omega(r^*+r_s^*)}}{2i\omega r r_s}\sum_{W=1}^{\infty}\int_C dL \sum_{m=-l}^{l} e^{2\pi W(L-1/2)} e^{i\frac{A_{lm}+a^2\omega^2}{2\omega}\left(\frac{1}{r}+\frac{1}{r_s}\right)} \underbrace{e^{2i\delta_{lm}}}_{\text{S matrix}} S_{lm}(\theta)S_{lm}(\theta_s)e^{im(\phi+\tilde{\phi}_s)}$$

○ Poles of the S matrix

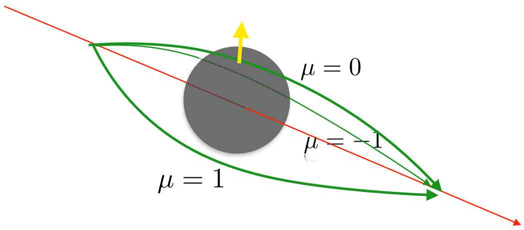
$$S^{(l,m)} = e^{2i\delta_{lm}} = -(-)^l \frac{e^{i\pi\nu}}{\sqrt{2\pi}}\left(\nu+\frac{1}{2}\right)^{\nu+1/2} e^{-(\nu+1/2)}\Gamma(\underbrace{-\nu}_{=n})$$

Quasi Normal Modes

$$\boxed{\nu = n \quad n=(0,1,\cdots)}$$

○ Sum over m

$$\sum_{m=-l}^{l} \to \int_{-1}^{1} d\mu\ L \qquad \boxed{\mu = \frac{m}{L}}$$



Short wave length

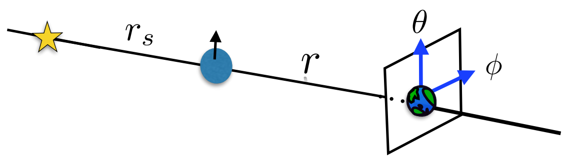
impact parameter $b \sim \frac{l}{\omega}$ $\gg$ wave length $\lambda \sim \frac{1}{\omega}$ → $L \gg 1$

$\mu = 1$: prograde

$\mu = 0$: polar

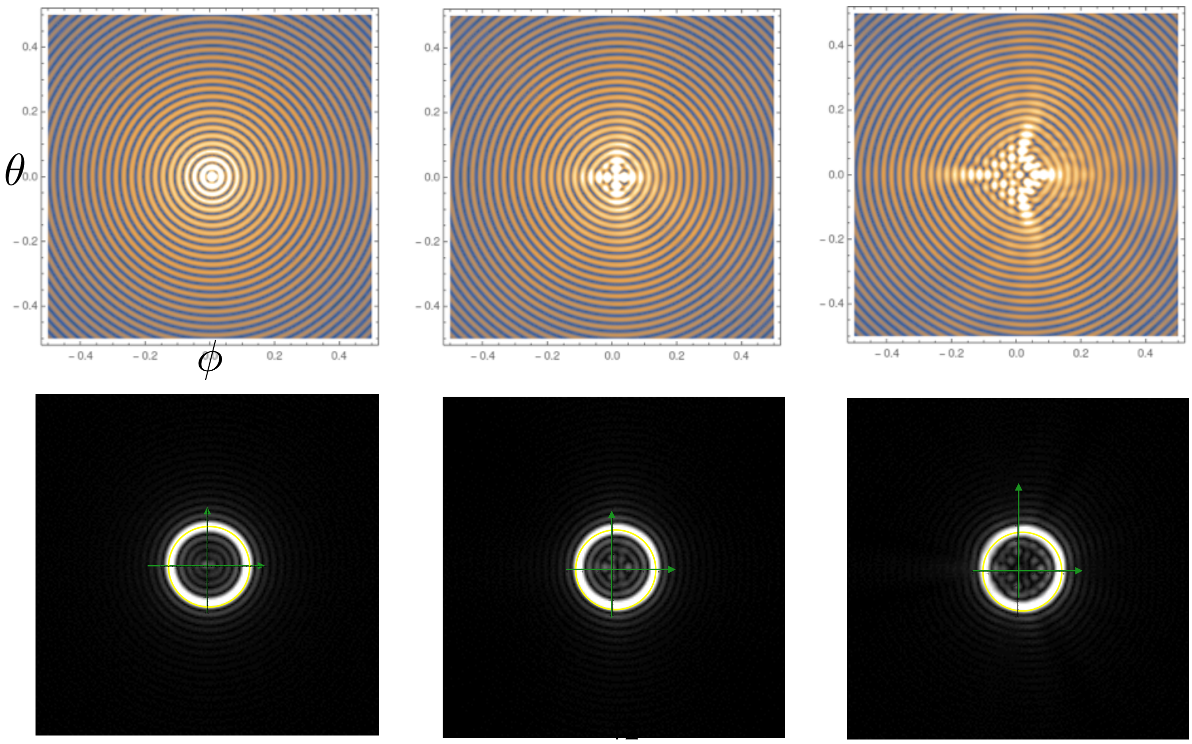
$\mu = -1$: retrograde

Interference patterns & images

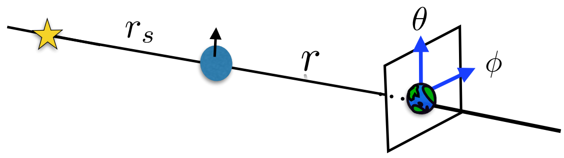


$M\omega = 25$

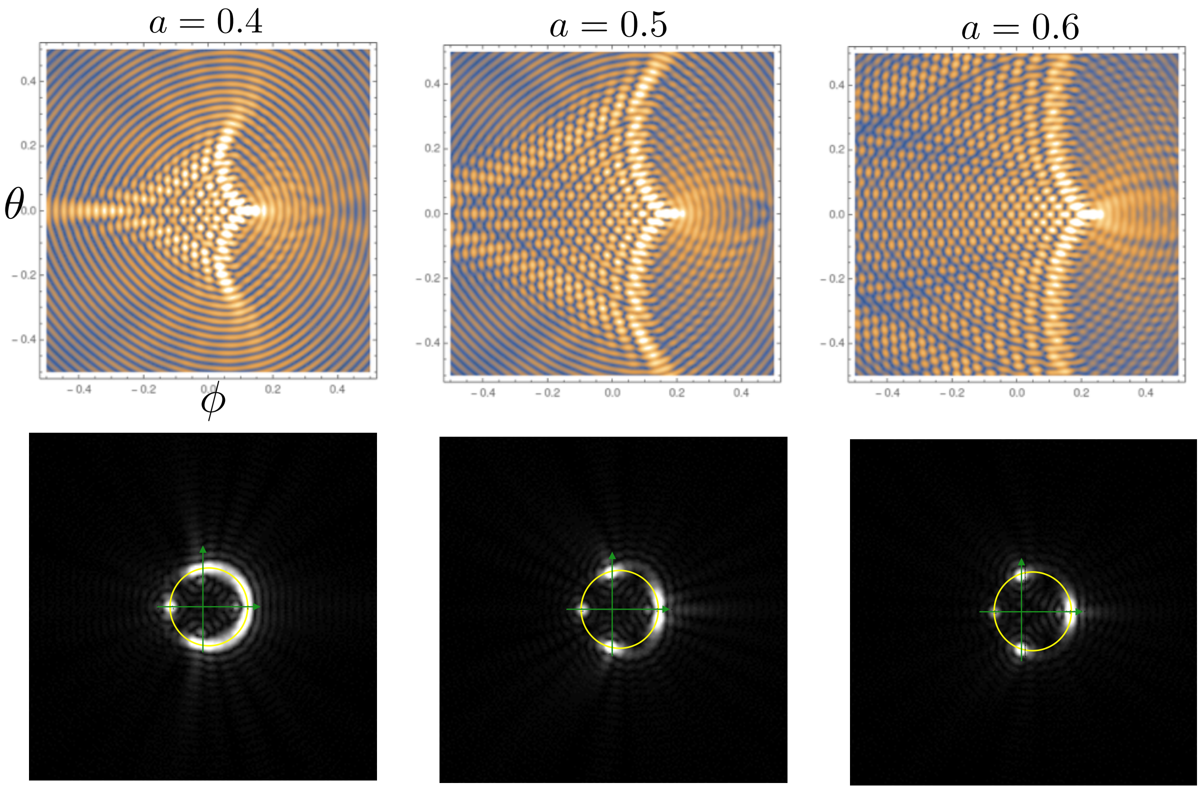
$a = 0.1$ $a = 0.2$ $a = 0.3$



Interference patterns & images



$M\omega = 25$



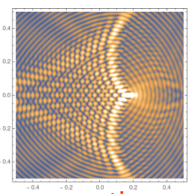
Summary & Future work

○ Green function

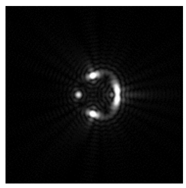
$$G(x, x_s) = \frac{e^{i\omega(r^* + r_s^*)}}{2i\omega r r_s} \sum_{l=0}^{\infty} \sum_{m=-l}^{l} e^{i\frac{A_{lm}+a^2\omega^2}{2\omega}\left(\frac{1}{r}+\frac{1}{r_s}\right)} e^{i2\delta_{lm}} S_{lm}(\theta) S_{lm}(\theta_s) e^{im(\phi+\tilde{\phi}_s)} \to G^{W=0} + G^{W\neq 0}$$

Direct part & Winding part

○ Interference & Image



caustics



wave optical BH shadow

Future work

1. Direct part (W=0) → · Image double ring? double cross?
   · Beat between direct part & winding part

2. Super radiance → We can see it in power spectrum? $\omega < m\Omega_H$
   angular velocity of horizon

3. Polarization → electrowave gravitational wave

4. Mimic BH → It may be possible to distinguish the mimic BH from BHs

“Amplitude-based approach to the detection of gravitational-wave bursts with the Hilbert- Huang Transform”

by Kazuki Sakai

[JGRG25(2015)1a6]

1

JGRG25 1a6 @Kyoto Univ. 7th Dec. 2015

Amplitude-based approach to the detection of gravitational-wave bursts with the Hilbert-Huang Transform

Kazuki Sakai, Ken-ichi Oohara[A], Masato Kaneyama[B], Satoshi Ueki, Yukitsugu Sasaki and Hirotaka Takahashi

e-mail : k_sakai@stn.nagaokaut.ac.jp

Nagaoka University of Technology, Japan,
[A]Niigata Univ., [B]Osaka City Univ.

2

Outline

Background

- Gravitational-Wave detectors will be ready soon
- Difficulty of the detection of grabitational-wave bursts

Method

- Hilbert-Huang Transform : new approach for time-frequency analysis
- Our proposing detection method

Simulation & Results

- Evaluation with simulated aLIGO noise and simulated waveform of gravitational-wave bursts from SNe

3

Background

Advanced ground-based laser interferometer detectors for GWs are about to be operated now.

Their main targets are GWs from compact binary coalescences, whose waveforms are predictable in Post-Newtonian approximation

GWs from SNe are thought as detectable by these detectors, but their waveforms cannot be predicted in detail.

Detection method without waveform information is needed

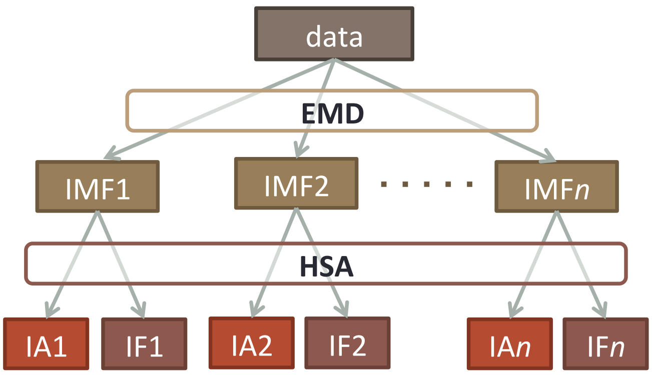
4

Method 1 : Hilbert-Huang Transform

To examine observed data, Time-Freq analysis is useful.

Hilbert-Huang Transform (HHT) is a new approach of T-F analysis for non-linear and non-stationary data[Huang et.al. 1998].
A characteristic feature of it is *a posteriori* defining basis.

To validate a possibility of a new approach with this new technique



Essence of IMF

- |#(extrema) - #(zero cross)| ≦ 1
- local mean is zero

➢ **These make hilbert transform well-behaved.**

EMD	Empirical Mode Decomposition
IMF	Intrinsic Mode Function
HSA	Hilbert Spectral Analysis
IA	Instantaneous Amplitude
IF	Instantaneous Frequency

5

Method 2 : Our Proposing Method

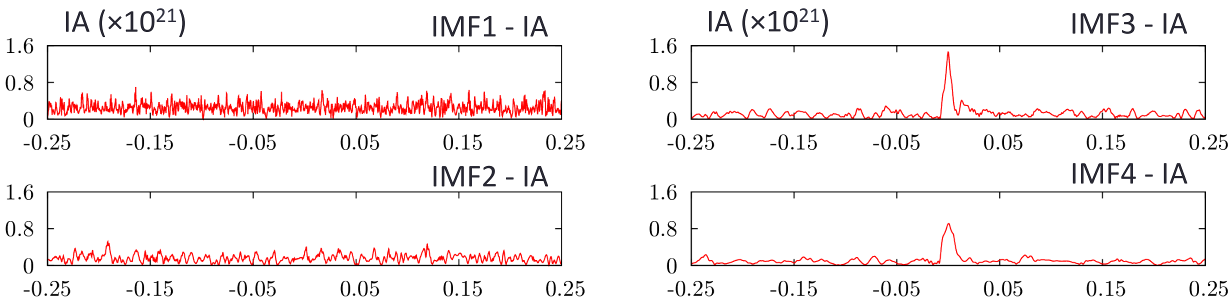
By means of EMD;

- Noise will be dispersed to **all** IMFs with equal amplitudes
- Burst signals is expected to be decomposed to **specific** IMFs

If signal exists, significantly high IA exist in specific IMFs

Policy of the method:

1. If average IA in a region doesn't exceed noise level, signal doesn't exist.
2. If the average IA exceed pre-determined threshold, signal exists.



6

Method 2 : Our Proposing Method

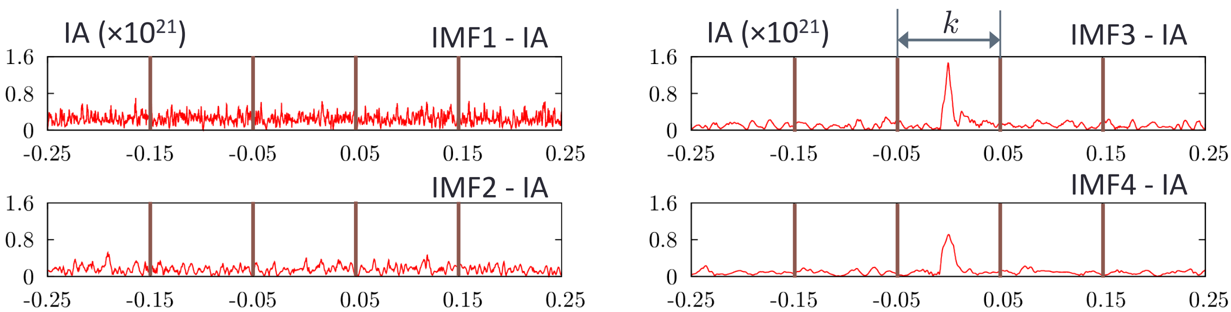
By means of EMD;

- Noise will be dispersed to **all** IMFs with equal amplitudes
- Burst signals is expected to be decomposed to **specific** IMFs

If signal exists, significantly high IA exist in specific IMFs

Policy of the method:

1. If average IA in a region doesn't exceed noise level, signal doesn't exist.
2. If the average IA exceed pre-determined threshold, signal exists.



Method 2 : Our Proposing Method

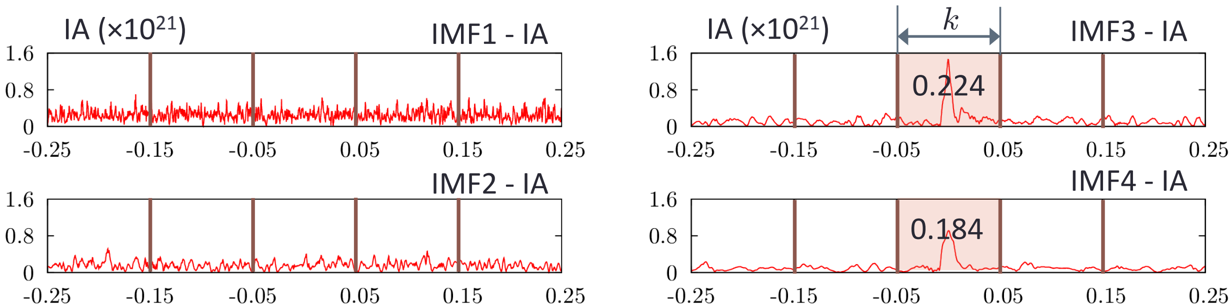
By means of EMD;

- Noise will be dispersed to **all** IMFs with equal amplitudes
- Burst signals is expected to be decomposed to **specific** IMFs

If signal exists, significantly high IA exist in specific IMFs

Policy of the method:

1. If average IA in a region doesn't exceed noise level, signal doesn't exist.
2. If the average IA exceed pre-determined threshold, signal exists.

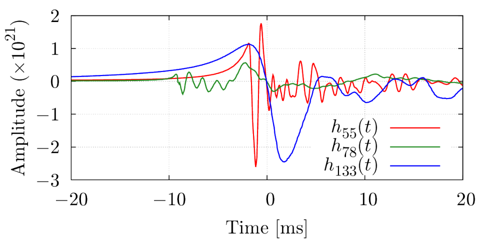


Evaluation 1 : Simulation setup

SIGNAL : Simulated waveforms of GW from SNe[Dimmelmeier 2008]

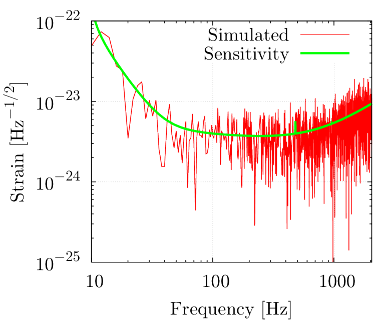
<u>Assume</u>

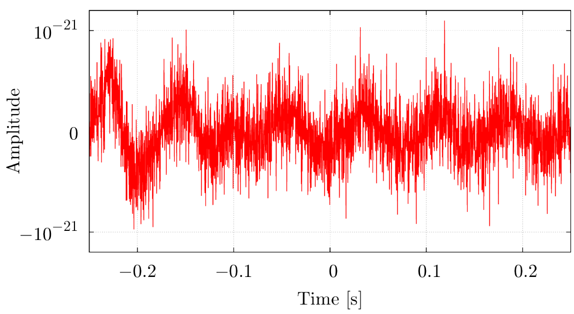
- GWs enter from optimal direction
- SNe occur in our galaxy
  (at most 30kpc apart)



We assigned numbers to 136 waveforms in alphabetical order

NOISE : 1000 colored Gaussian noises based on aLIGO sensitivity

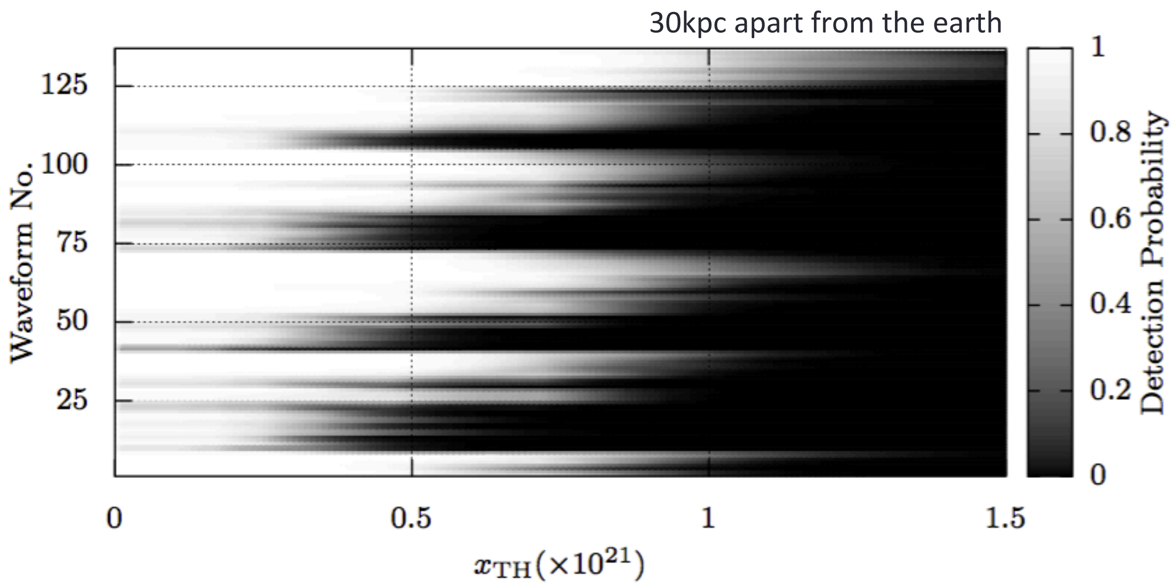




Evaluation 2 : Detection Probabilities

Variations in DP for each waveform with threshold value

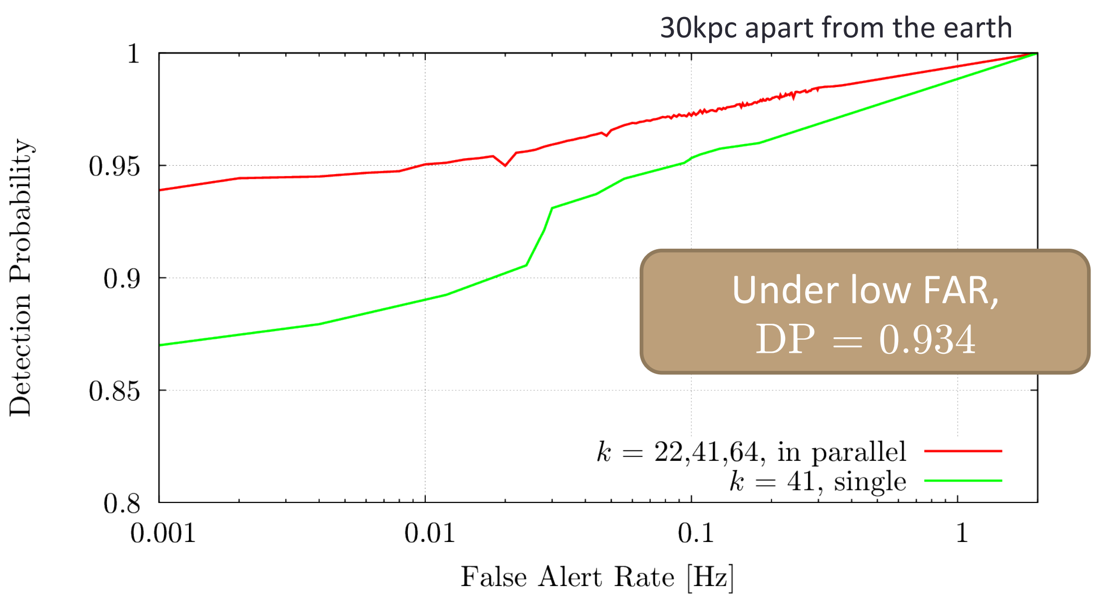
In case of window width $k = 41$ samples (optimal value)



Evaluation 3 : ROC Curve

ROC (Receiver Operating Characteristic) Curve

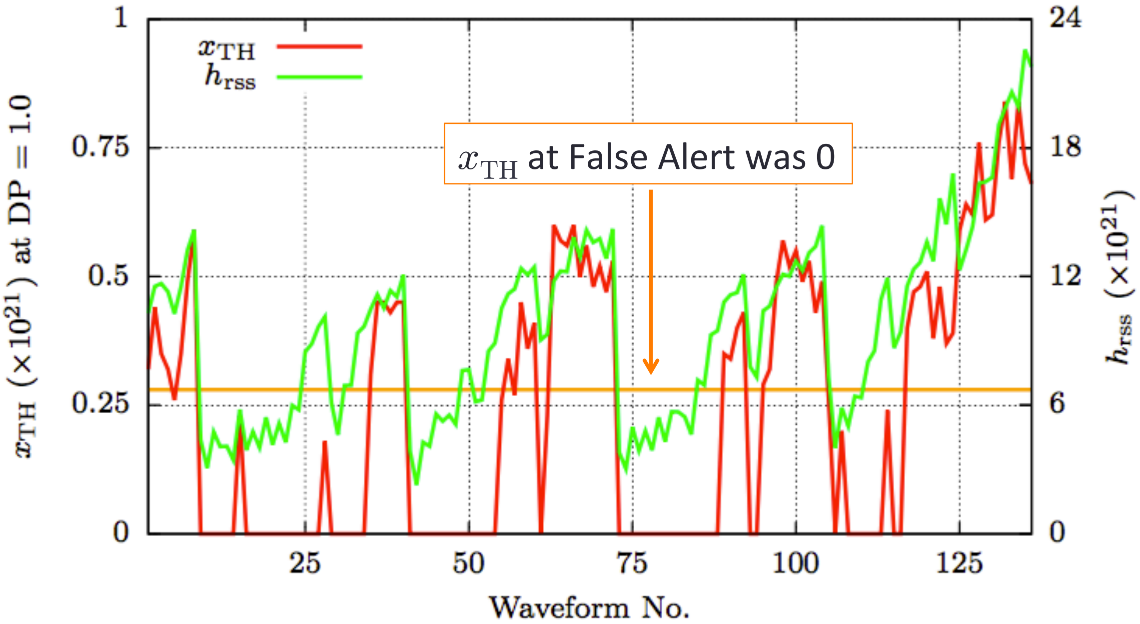
- parallel : Analyze the same data with different configs.



Discussion : Contributions to the trend

x_{TH} at DP = 1.0 and h_{rss} of each waveform

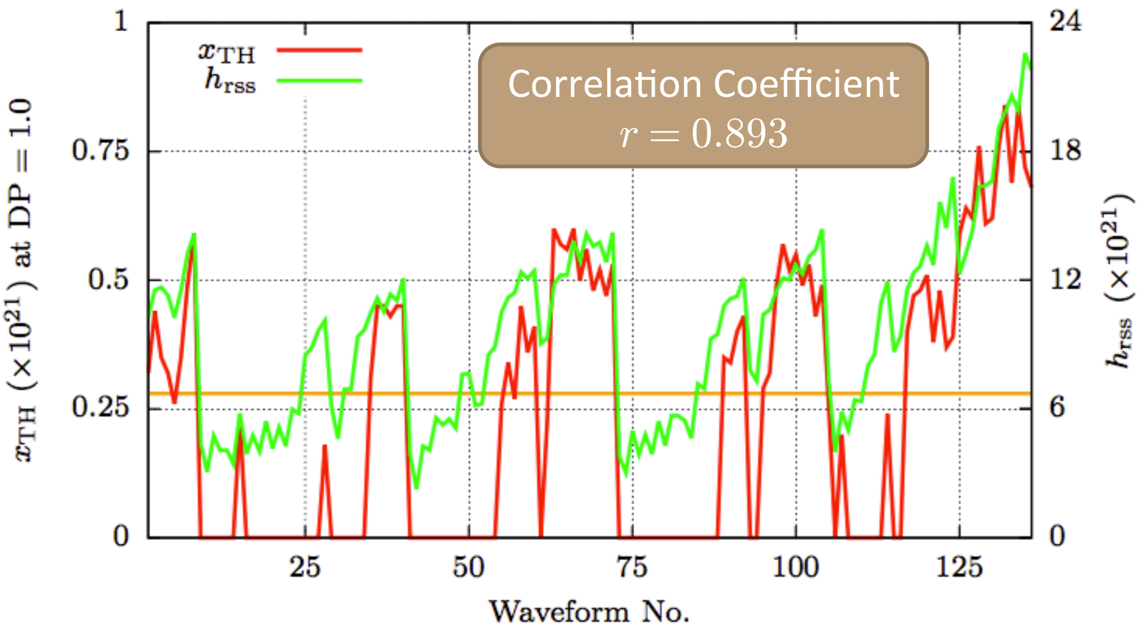
$$h_{\mathrm{rss}} = \sqrt{\int \mathrm{d}t\, |h(t)|^2}$$



Discussion : Contributions to the trend

x_{TH} at DP = 1.0 and h_{rss} of each waveform

$$h_{\mathrm{rss}} = \sqrt{\int \mathrm{d}t\, |h(t)|^2}$$



Discussion : Contributions to the trend

Focus waveforms which could have DP = 1.0 with FA = 0

Table: Parameters in waveform simulation of those

$M_{\text{prog}} = \{11.2, 15.0, 20.0, 40.0\}$, $A = \{50.0, 1.0, 0.5\}$

core-model	M_{prog} $[M_\odot]$	A $[10^8$ cm$]$	min $\Omega_{\text{c,i}}$ [rad/s]	EoS
e15	15.0	–	4.18	LS/Shen
e20	20.0	–	11.01	LS
e20†	20.0	–	3.13	Shen
S11A3	11.2	0.5	10.65	LS/Shen
S15A2	15.0	1.0	7.60	LS
S15A2†	15.0	1.0	4.56	Shen
S15A3	15.0	0.5	5.95	LS/Shen
S20A2	20.0	1.0	6.45	LS/Shen
S20A3	20.0	0.5	5.95	LS/Shen
S40A2	40.0	1.0	3.40	LS/Shen
S40A3	40.0	0.5	4.21	LS/Shen

† The detection probability in LS EoS with the same parameters is 0.999.

Waveforms whose $A = 50.0$ (almost uniform) is not contained.

Differential rotation is more important parameter than mass

Conclusion

Present Works

- To detect GW Bursts with the detectors, a method which does not require the information of waveform is needed.
- We have constructed an amplitude-based method with the Hilbert-Huang Transform, new approach for Time-Freq analysis.
- In our simulation, Detect Probability = 0.934 with False Alert = 0.
- From investigation of waveform dependency, we know that differential rotation is important rather than other parameters.

Future Works

- Further Evaluation by using real observed data form detectors.
- Considering more efficient feature value (eg. using IF)

"Mimetic Dark Matter"

by Alexander Vikman

[JGRG25(2015)1b1]

JGRG25
The 25th Workshop on General Relativity and Gravitation in Japan
7 (Mon) - 11 (Fri) December 2015
Yukawa Institute for Theoretical Physics, Kyoto University

Mimetic Dark Matter

Alexander Vikman

Institute of Physics of the Czech Academy of Sciences
Fyzikální ústav Akademie věd ČR, v. v. i.
YITP Yukawa Institute for Theoretical Physics

07.12.15

This talk is mostly based on

- arXiv: **1403.3961,** JCAP 1406 (2014) 017
  A. H. Chamseddine and V. Mukhanov, A. Vikman
- arXiv: **1412.7136,** JCAP 1506 (2015) 06, 028
  L. Mirzagholi, A. Vikman
- arXiv: **1003.5751,** JCAP 1005 (2010) 012
  I. Sawicki, E. Lim, A. Vikman

Mimetic Matter

Chamseddine, Mukhanov (2013)

- One can *encode* the conformal part of the *physical* metric in a scalar field:

$$g_{\mu\nu} = \tilde{g}_{\mu\nu}\left(\tilde{g}^{\alpha\beta}\,\partial_\alpha\phi\,\partial_\beta\phi\right)$$

physical metric of free fall *auxiliary metric, dynamical variable*

$$S\left[\tilde{g}_{\mu\nu},\phi,\Phi_m\right] = \int \mathrm{d}^4x\left[\sqrt{-g}\left(-\frac{1}{2}R(g) + \underbrace{\mathcal{L}(g,\Phi_m)}_{\text{“matter”}}\right)\right]_{g_{\mu\nu}=g_{\mu\nu}(\tilde{g},\phi)}$$

Mimetic Matter

Chamseddine, Mukhanov (2013)

- $$g_{\mu\nu} = \tilde{g}_{\mu\nu}\left(\tilde{g}^{\alpha\beta}\,\partial_\alpha\phi\,\partial_\beta\phi\right)$$

physical metric of free fall *auxiliary metric, dynamical variable*

- The theory becomes invariant with respect to Weyl transformations:

$$\tilde{g}_{\mu\nu} \to \Omega^2(x)\,\tilde{g}_{\mu\nu}$$

- The scalar field obeys the relativistic Hamilton-Jacobi equation:

$$g^{\mu\nu}\,\partial_\mu\phi\,\partial_\nu\phi = 1$$

$$g^{\mu\nu} = \tilde{g}^{\mu\nu}\left(\tilde{g}^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi\right)^{-1}$$

the Hamilton-Jacobi equation

$$g^{\mu\nu}\,\partial_\mu\phi\,\partial_\nu\phi = 1$$

corresponding four-velocity

$$u_\mu = \partial_\mu\phi$$

is geodesic

$$a_\mu = u^\lambda \nabla_\lambda u_\mu = \nabla^\lambda \phi \left(\nabla_\lambda \nabla_\mu \phi\right) = \frac{1}{2}\partial_\mu \left(\partial\phi\right)^2 = 0$$

Modification of the Einstein equation

$$\frac{\delta S}{\delta \tilde{g}^{\mu\nu}} \Rightarrow G_{\mu\nu}\left(g\right) - T_{\mu\nu}\left(g\right) - \left(G\left(g\right) - T\left(g\right)\right)\partial_\mu\phi\partial_\nu\phi = 0$$

Einstein equations with dust or DM

$$G_{\mu\nu} = T_{\mu\nu} + \rho u_\mu u_\nu$$

$$\rho = G - T$$

Mimetic Dark Matter

Chamseddine, Mukhanov; Golovnev; Barvinsky (2013)
Lim, Sawicki, Vikman; (2010)

- use Weyl-invariance and fix $g_{\mu\nu} = \tilde{g}_{\mu\nu}$
- constraint via Lagrange multiplier $\rho\left((\partial\phi)^2 - 1\right)$

$$S[g,\phi,\rho,\mathrm{SM}] = \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{2}R + \frac{1}{2}\rho\left((\partial\phi)^2 - 1\right) + \mathscr{L}_{\mathrm{SM}}\right)$$

$$T_{\mu\nu} = \rho\, u_\mu u_\nu$$

Dark Matter

Lagrange multiplier is the energy density

$$u_\mu = \partial_\mu\phi$$

- dust / DM via Lagrange multiplier

$$\rho\left((\partial\phi)^2 - 1\right)$$

- Cosmological Constant / DE via Lagrange multiplier

$$\Lambda\left(\nabla_\mu V^\mu - 1\right)$$

M. Henneaux and C. Teitelboim (1989)

$$S\left[\tilde{g}_{\mu\nu},\phi,\Phi_m\right]=\int \mathrm{d}^4x\left[\sqrt{-g}\left(-\frac{1}{2}R\left(g\right)+\mathscr{L}\left(g,\Phi_m\right)\right)\right]_{g_{\mu\nu}=g_{\mu\nu}\left(\tilde{g},\phi\right)}$$

with $g_{\mu\nu}\left(\tilde{g},\phi\right)=\tilde{g}_{\mu\nu}\,\tilde{g}^{\alpha\beta}\,\partial_\alpha\phi\,\partial_\beta\phi$

is *not* in the Horndeski (1974) construction of the most general scalar-tensor theory with *second order* equations of motion

But it is still a system with one degree of freedom + standard two polarizations for the graviton!

Disformal Transformation

Nathalie Deruelle and Josephine Rua (2014), Domènech et al. (2015)

One obtains the same dynamics (***the same Einstein equations***), if instead of varying the Einstein-Hilbert action with respect to the metric $g_{\mu\nu}$

one plugs in a *disformal transformation* (Bekenstein 1993)

$$g_{\mu\nu}=F\left(\Psi,w\right)\ell_{\mu\nu}+H\left(\Psi,w\right)\partial_\mu\Psi\partial_\nu\Psi$$

with $w=\ell^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi$ and $w^2F\frac{\partial}{\partial w}\left(H+\frac{F}{w}\right)\neq 0$

and varies with respect to $\ell_{\mu\nu},\ \Psi$

Mimetic gravity is an exception! And it does provide new dynamics!

Mimicking any cosmological evolution

Chamseddine, Mukhanov, Vikman (2013)
Lim, Sawicki, Vikman; (2010)

- Just add a potential $V(\phi)$!

$$T_{\mu\nu} = \rho\, u_\mu u_\nu + g_{\mu\nu} V$$

- $g^{\mu\nu}\,\partial_\mu\phi\,\partial_\nu\phi = 1$ → Convenient to take ϕ as time

- potential provides time-dependent pressure

Enough freedom to obtain any cosmological evolution!

Perturbations I

Chamseddine, Mukhanov, Vikman (2013)
Lim, Sawicki, Vikman; (2010)

Even with potential, the energy
still moves along the timelike geodesics

$$c_{\mathrm{S}} = 0$$

Newtonian potential:

$$\Phi = C_1(\mathbf{x})\left(1 - \frac{H}{a}\int a dt\right) + \frac{H}{a} C_2(\mathbf{x})$$

*Here on **all scales** but in the usual cosmology it is an approximation for **superhorizon** scales*

Next term in the gradient expansion

Chamseddine, Mukhanov, Vikman (2013)

$$\gamma\left(\Box\phi\right)^2$$

the unique quadratic term with higher derivatives

There are ***no new degrees of freedom***, because higher time derivatives can be eliminated by differentiating the Hamilton-Jacobi equation.

$\nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi$ is not that useful:

$$\int \mathrm{d}^4x\,\sqrt{-g}\;\phi_{;\mu;\nu}\phi^{;\mu;\nu} = \int \mathrm{d}^4x\,\sqrt{-g}\left(\left(\Box\phi\right)^2 - R^{\mu\nu}\phi_{;\mu}\phi_{;\nu}\right)$$

expansion $\theta = \Box\phi = \nabla_\mu u^\mu$

CHARGE CONSERVATION

no potential ➔ $\phi \to \phi + c$ symmetry

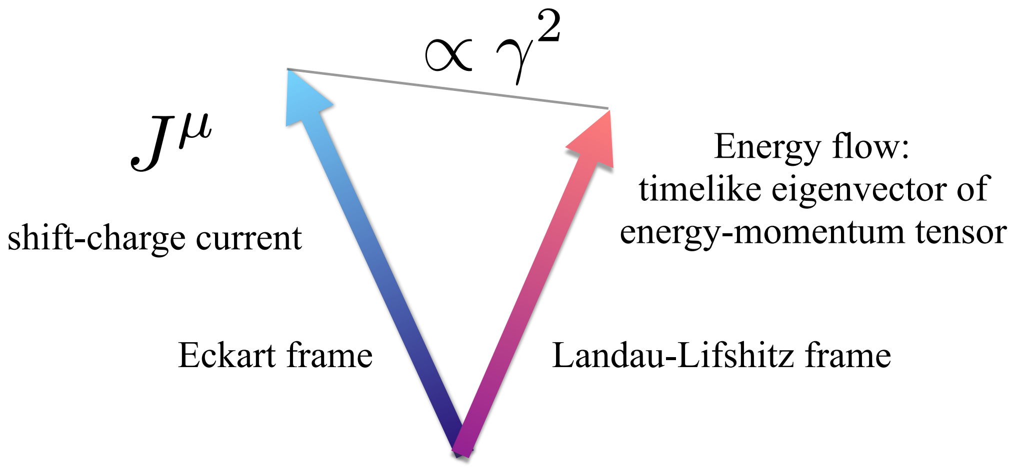
$$\nabla_\mu J^\mu = 0$$

Noether current:

charge density

$$n \propto a^{-3}$$

Imperfection



Imperfection in the Noether current

$$J_\mu = \rho u_\mu - \gamma \theta_{,\mu}$$

expansion $\quad \theta = \Box \phi = \nabla_\mu u^\mu$

Imperfect Dark Matter

Mirzagholi, Vikman (2014)

(no potential)

$$T_{\mu\nu} = \varepsilon u_\mu u_\nu - p \perp_{\mu\nu} + q_\mu u_\nu + q_\nu u_\mu$$

$$\perp_{\mu\nu} = g_{\mu\nu} - u_\mu u_\nu$$

energy flow $\quad q_\mu = -\gamma \perp_\mu^\lambda \nabla_\lambda \theta$

expansion $\quad \theta = \nabla_\mu u^\mu$

energy density $\quad \varepsilon = \rho - \gamma \left(\dot{\theta} - \frac{1}{2}\theta^2 \right)$

pressure $\quad p = -\gamma \left(\dot{\theta} + \frac{1}{2}\theta^2 \right)$

$$\dot{\theta} = u^\mu \nabla_\mu \theta$$

Vorticity for a **single dof** DM!

in the frame moving with the charges (Eckart frame)

$$V^\mu = \frac{J^\mu}{\sqrt{J^\alpha J_\alpha}} \qquad \theta = \Box\phi = \nabla_\mu u^\mu$$

Vorticity vector:

$$\Omega^\mu(V) = \frac{1}{2}\varepsilon^{\alpha\beta\gamma\mu} V_\gamma V_{\beta;\alpha} \simeq \frac{\gamma}{2\rho^2}\varepsilon^{\alpha\beta\gamma\mu}\rho_{,\alpha}\,\theta_{,\beta}\,\phi_{,\gamma}$$

the circulation is conserved up to $\mathcal{O}\left(\gamma^2\right)$

Perturbations II

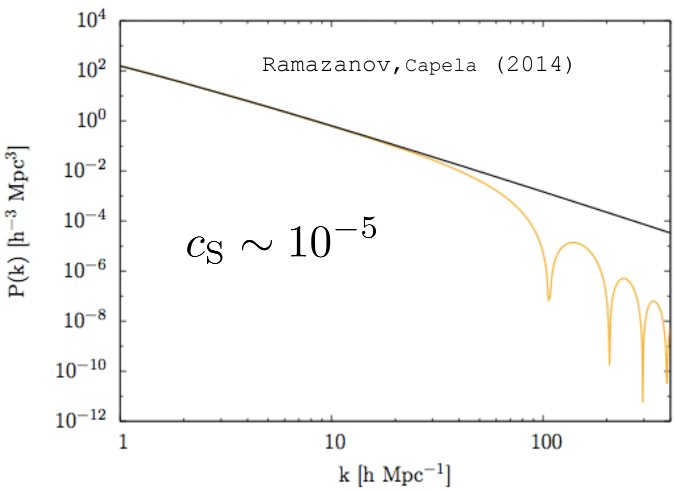
$$\delta\ddot{\phi} + H\delta\dot{\phi} - \frac{c_s^2}{a^2}\Delta\delta\phi + \dot{H}\,\delta\phi = 0$$

with the sound speed

$$c_s^2 = \frac{\gamma}{2-3\gamma}$$

Newtonian potential:

$$\Phi = \delta\dot{\phi}$$



Background cosmology

$$\varepsilon = \frac{2}{2-3\gamma}n + 3c_S^2\,\rho_{\text{ext}} \qquad p = 3c_S^2 P_{\text{ext}}$$

DM

$$n \propto a^{-3}$$

$$G_{\text{eff}} = G_N\left(1 + 3c_S^2\right)$$

δG_N bounds are mild: $3\left(c_S^2|_{\text{matter}} - c_S^2|_{\text{radiation}}\right) \lesssim 0.066 \pm 0.039$

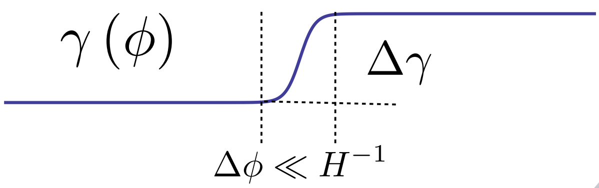
Narimani, Scott, Afshordi (2014)

mimetic construction *and* inflation

$$n \propto a^{-3}$$

shift-symmetry breaking is needed for *mimetic* DM!

Generating shift-charge (DM) during radiation domination époque



$$\nabla_\mu J^\mu = \frac{1}{2}\gamma'\left(\phi\right)\theta^2$$

$$\theta = 3H$$

$$n\left(t_{\rm cr}\right) \propto a^{-3}\int dt'\, a^3\dot{\gamma}H^2 \simeq \rho_{\rm rad}\left(t_{\rm cr}\right)\Delta\gamma$$

at DM / radiation equality $\rho_{\rm DM}\left(z_{\rm eq}\right) = \rho_{\rm rad}\left(z_{\rm eq}\right)$

$$\Delta\gamma \simeq \left(\frac{a_{\rm cr}}{a_{\rm eq}}\right) \simeq \frac{z_{\rm eq}}{z_{\rm cr}} \leq \gamma \leq 10^{-10} \quad \Rightarrow \quad T_{\rm cr} \simeq \frac{T_{\rm eq}}{\Delta\gamma} \gtrsim 10\,\mathrm{GeV}$$

Conclusions

- New large class of Weyl-invariant scalar-tensor theories
- Unification of Dark Matter with Dark Energy in one degree of freedom.
- Imperfect Dark Matter, with a small sound speed and vorticity. Only one free parameter for the late Universe.
- New class of inflationary models with suppressed gravity waves and low non-Gaussianity.

Thanks a lot for attention!

“On massive scalar field in AdS$_2$”

by Masashi Kimura

[JGRG25(2015)1b2]

On massive scalar field in AdS2

Masashi Kimura
(DAMTP, University of Cambridge)
w/ T.Houri (Kobe Univ.) in preparation

7th December 2015

Introduction

Supersymmetric BH : extremal horizon

Near horizon behavior of test fields
～ massive scalars on AdS2

e.g.) massless KG eq on 4Dim
extremal RN BH

$$(\Box_{AdS_2} - m^2)\Phi = 0 \qquad m^2 = \ell(\ell+1)$$

Introduction

Aretakis showed the "instability" of scalar field on 4Dim extremal RN BH

It is useful to use the Aretakis const.

$$\partial_r^{k+1}\Phi|_{\mathcal{H}} = \mathrm{const.}$$

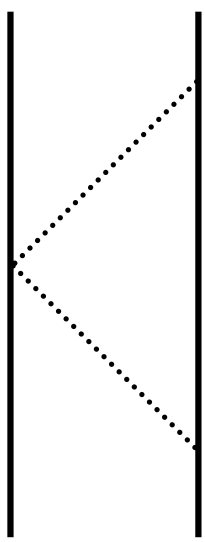
if $m^2 = k(k+1)$ $(k = 0, 1, 2, 3\cdots)$

We would like to study massive KG eq with $m^2 = k(k+1)$ on AdS2

Aretakis constant in AdS2

$$ds^2 = -r^2 du^2 + 2dudr$$

$$(\Box - m^2)\Phi = 0 \qquad m^2 = k(k+1)$$



$$\underline{\left[\frac{\partial}{\partial u} + r^2\frac{\partial}{\partial r}\right]}\left[r^{2(k+1)}\partial_r^{k+1}\phi\right] = 0$$

out going null vector

$$r^{2(k+1)}\partial_r^{k+1}\phi = f(u + 2/r) \ (= f(v))$$

Massless case

$$ds^2 = -r^2 du^2 + 2dudr$$
$$= -\frac{4}{(u-v)^2} dudv \qquad (v := u + 2/r)$$

$$\Box\Phi = 0 \quad \Longrightarrow \quad \Phi = f(v) + g(u)$$

$$\partial_v \Phi = \frac{df(v)}{dv}$$

This is the Aretakis constant in the massless case

We may have similar understanding for general $m^2 = k(k+1)$

5/11

Massive case

$$\left[\frac{\partial}{\partial u} + r^2 \frac{\partial}{\partial r}\right] \left[r^{2(k+1)} \partial_r^{k+1} \phi\right] = 0$$

$$\hat{D}_v := (u-v)^2 \partial_v$$

$$\Longrightarrow \quad \frac{\partial}{\partial u}\left[\frac{1}{(u-v)^{2(k+1)}} \hat{D}_v^{k+1} \Phi\right] = 0$$

$$\frac{1}{(u-v)^{2(k+1)}} \hat{D}_v^{k+1} \Phi = f(v)$$

$$\hat{D}_u := (u-v)^2 \partial_u \qquad \frac{\partial}{\partial v}\left[\frac{1}{(u-v)^{2(k+1)}} \hat{D}_u^{k+1} \Phi\right] = 0$$

$$\frac{1}{(u-v)^{2(k+1)}} \hat{D}_u^{k+1} \Phi = g(u)$$

6/11

Massive case

$$\frac{1}{(u-v)^{2(k+1)}}(\hat{D}_v^{k+1}+\hat{D}_u^{k+1})\Phi = f(v)+g(u)$$

$$\mathcal{L}^{(k+1)} := \frac{1}{(u-v)^{2(k+1)}}(\hat{D}_v^{k+1}+\hat{D}_u^{k+1})$$

$$\tilde{\Phi} := \mathcal{L}^{(k+1)}\Phi$$

$$\Box\tilde{\Phi} = 0$$

(Inversely, we can find Φ from $\tilde{\Phi}$)

$m^2 = k(k+1)$ massive scalars can be mapped into massless scalars

7/11

Aretakis constant in AdS2

$(\Box - m^2)\Phi = 0$ with $m^2 = k(k+1)$

$$\Longrightarrow \quad \Box\tilde{\Phi} = 0 \qquad (\tilde{\Phi} := \mathcal{L}^{(k+1)}\Phi)$$

$$\tilde{\Phi} = f(v)+g(u)$$

$$\partial_v\tilde{\Phi} = \frac{df(v)}{dv}$$:const.

on v = const. null surface

8/11

Commutator

$$[\Box_{AdS_2}, \mathcal{L}^{(k+1)}] = -k(k+1)\mathcal{L}^{(k+1)} + \hat{F}^{(k+1)}(\Box_{AdS_2} - k(k+1))$$

$\mathcal{L}^{(k+1)}$ maps $m^2 = k(k+1)$ massive scalars into massless scalars

Summary and Discussions

- Massive KG eq with $m^2 = k(k+1)$ can be mapped into massless KG eq by acting (k+1)-th order differential operator
- The Aretakis constant on AdS2 can be understood as a result of this hidden conformal symmetry.
- We need to discuss black hole case without taking a near horizon geometry limit

Ongoing work

- We can also define the operators which define maps from massless scalar to massive scalar with $m^2 = k(k+1)$

- Recently, we found more fundamental operators, mass shift operator, which is related to conformal symmetry and BF bound

- We can also generalize to the Einstein spaces /spacetimes in arbitrary dims

11/11

Thank you

“Mass of asymptotically anti-de Sitter hairy spacetimes”

by Cristian Martinez

[JGRG25(2015)1b3]

Mass of asymptotically anti-de Sitter hairy spacetimes

Cristián Martínez

Centro de Estudios Científicos (CECs)
Valdivia – Chile
martinez@cecs.cl

JGRG25

Dec 7, 2015

In collaboration with

- Andrés Anabalón
  Universidad Adolfo Ibáñez, Viña del Mar, Chile
- Dumitru Astefanesei
  Pontificia Universidad Católica de Valparaíso, Chile
- arXiv:1407.3296. PRD 91, 041501(R) (2015).

Outline

Let us consider $\mathcal{L}_{\text{Hilbert}} = \frac{R}{2\kappa}$, with $\kappa = 8\pi G$

$$ds^2{}_{r\to\infty} \sim -\overbrace{\left(1 - \frac{\mu}{r}\right)}^{\text{lapse function}} dt^2 + \left(\delta_{ij} + \mu\frac{x_i x_j}{r^3}\right) dx^i dx^j$$

Mass:

$$M = \frac{4\pi}{\kappa}\mu$$

- In the standard asymptotic expansion of four dimensional static asymptotically flat spacetimes, *the coefficient of the first subleading term of the lapse function* can be identified with the *mass* of the spacetime.

Outline

- Main result. Using the Hamiltonian formalism we show that, in asymptotically locally anti-de Sitter spacetimes (ALAdS) endowed with a scalar field, the mass can read off in the same way only when the *boundary conditions are compatible with the asymptotic realization of the anti-de Sitter symmetry*.

Lapse function for an ALAdS

$$-g_{tt} = \frac{r^2}{l^2} + k - \frac{\mu}{r} + O(r^{-2})$$

where $2k$ is the scalar curvature of the "angular section" with volume $V(\Sigma)$, then

$$M = \frac{V(\Sigma)}{\kappa}\mu$$

only if the boundary condition on the scalar field preserves the AdS symmetry.

How it works?

- Since the mass is determined only by the spatial metric and the scalar field, the above effect appears by considering not only the constraints, but also the *dynamic field equations*, which relate the spatial metric with the lapse function.

- Proper boundary conditions on the scalar field.

- This result implies that prescriptions for computing the mass of a hairy spacetime —based on g_{tt}— are not suitable when the *scalar field breaks the asymptotic anti-de Sitter invariance*.

Plan of the talk

- Part 1: Introduction
  - Brief review of the scalar fields in asymptotically AdS spacetime.
  - Hamiltonian formalism for computing the mass: Regge-Teitelboim method
- Part 2: Explicit example in 4D for $m^2 = -2l^{-2}$
  - Inclusion of the dynamic field equations. Mass *on-shell*.
  - Analysis on the boundary conditions and their effect on the mass and asymptotic symmetry.

Brief review of the scalar fields in asymptotically AdS spacetime

Preliminaries: Action and field equations

- A real scalar field minimally coupled to D-dimensional Einstein gravity with $\Lambda = -(D-1)(D-2)l^{-2}/2$ and a self-interaction potential $U(\phi)$

$$I[g_{\mu\nu}, \phi] = \int d^Dx\sqrt{-g}\left(\frac{R-2\Lambda}{2\kappa} - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - U(\phi)\right),$$

  where κ is the gravitational constant.
- Field equations:

$$E_{\mu\nu} \equiv G_{\mu\nu}+\Lambda g_{\mu\nu}-\kappa\left[\partial_\mu\phi\partial_\nu\phi - \left(\frac{1}{2}\partial^\beta\phi\partial_\beta\phi + U(\phi)\right)g_{\mu\nu}\right] = 0,$$

  and

$$\Box\phi - \frac{dU(\phi)}{d\phi} = 0.$$

Fixed AdS background and a massive scalar field

Let us consider a scalar field of mass m, i. e. $U(\phi) = \frac{1}{2}m^2\phi^2$ coupled to an AdS background

$$ds^2 = -\left(1+\frac{r^2}{l^2}\right)dt^2 + \left(1+\frac{r^2}{l^2}\right)^{-1}dr^2 + r^2 d\Omega^2_{D-2},$$

From the Klein-Gordon equation we obtain the asymptotic form of ϕ

$$\phi \sim \frac{a}{r^{\Delta_-}} + \frac{b}{r^{\Delta_+}}$$

where

$$\Delta_\pm = \frac{D-1}{2}\left(1 \pm \sqrt{1+\frac{4l^2m^2}{(D-1)^2}}\right)$$

are the roots of $\Delta(D-1-\Delta) + m^2l^2 = 0$.

- Both branches are physically acceptable [Ishibashi, Wald, 2004] if

$$m_*^2 \leq m^2 < m_*^2 + \frac{1}{l^2}$$

where $m_*^2 = -\frac{(D-1)^2}{4l^2}$ (BF mass)

- $$\frac{D-1}{2} \geq \Delta_- > \frac{D-3}{2} \qquad \frac{D-1}{2} \leq \Delta_+ < \frac{D+1}{2}$$

Switching on nonlinear interactions and backreaction

Now, consider the following expansion for the self-interaction potential around $\phi = 0$

$$U(\phi) = \frac{1}{2}m^2\phi^2 + C_3\phi^3 + C_4\phi^4 + C_5\phi^5 + O(\phi^6)\ .$$

For the static, spherically symmetric case, the asymptotic behavior of the scalar field and the deviation from AdS metric $h_{\mu\nu} \equiv g_{\mu\nu} - g_{\mu\nu}^{\text{AdS}}$ are [Henneaux, CM, Troncoso, Zanelli, 2007]

$$\phi = ar^{-\Delta_-} + \underbrace{\beta_1 a^2 r^{-2\Delta_-} + \beta_2 a^3 r^{-3\Delta_-} + \beta_3 a^4 r^{-4\Delta_-}}_{\text{nonlinear terms in a}} + br^{-\Delta_+} + \cdots$$

and

$$h_{rr} = r^{-2}(\overbrace{\alpha_1 a^2 r^{-2\Delta_-} + \cdots + \alpha_4 a^5 r^{-5\Delta_-}}^{\text{nonlinear terms in a}}) + \frac{f_{rr}}{r^5} + \cdots$$

$$h_{tt} = \frac{f_{tt}}{r} + \cdots$$

where the final dots $(\cdots)$ indicate subleading terms that do not contribute to the mass.

Logarithmic branches

- In general, for any dimension, logarithmic branches are present when $\frac{\Delta_+}{\Delta_-} = n$ is a positive integer. In this case the scalar field acquires a logarithmic branch of the form

$$\phi = ar^{-\Delta_-} + \cdots + h\, a^n r^{-\Delta_+} \log(r) + br^{-\Delta_+} + \cdots ,$$

where h is a fixed constant for each case.
The critical values of the spacetime dimensions and mass for which this phenomenon occurs are [Henneaux, CM, Troncoso, Zanelli, 2007]
  - $D \geq 4$, $m^2 = m_*^2$, $n = 1$,
  - $D = 4, 5, 6$, $m^2 = m_*^2 + \frac{(D-1)^2}{36 l^2}$, $(n = 2)$,
  - $D = 4$, $m^2 = m_*^2 + \frac{9}{16\, l^2}$, $(n = 3)$,
  - $D = 4$, $m^2 = m_*^2 + \frac{81}{100 l^2}$, $(n = 4)$.

Hamiltonian formalism for computing the mass.

- The canonical generator of an asymptotic symmetry defined by the vector $\xi = (\xi^\perp, \xi^i)$ is a linear combination of the constraints $\mathcal{H}_\perp, \mathcal{H}_i$ plus a surface term $Q[\xi]$

$$H[\xi] = \int d^{D-1}x \left(\xi^\perp \mathcal{H}_\perp + \xi^i \mathcal{H}_i \right) + Q[\xi].$$

- The surface term $Q[\xi]$ is chosen so that the generator has well-defined functional derivatives [Regge, Teitelboim,1974].

- $\delta Q[\xi] = \delta Q_G(\xi) + \delta Q_\phi(\xi)$, where

$$\delta Q_G(\xi) = \frac{1}{2\kappa}\int d^{D-2}S_l G^{ijkl}(\xi^\perp \delta g_{ij;k} - \xi^\perp_{,k}\delta g_{ij}) + \int d^{D-2}S_l(2\xi_k\delta\pi^{kl} + (2\xi^k\pi^{jl} - \xi^l\pi^{jk})\delta g_{jk}),$$

$$\delta Q_\phi(\xi) = -\int d^{D-2}S_l(\xi^\perp g^{1/2} g^{lj}\partial_j\phi\delta\phi + \xi^l\pi_\phi\delta\phi),$$

- g_{ij} denotes the components of the $(D-1)$-spatial metric, π^{ij} are their conjugate momenta, and π_ϕ is the momentum associated to ϕ. We have also defined $G^{ijkl} \equiv \frac{1}{2}g^{1/2}(g^{ik}g^{jl} + g^{il}g^{jk} - 2g^{ij}g^{kl})$.
- In the static case all the momenta vanish, and there is a symmetry generated by the vector ∂_t.
- The mass M is the conserved charge associated with this symmetry.

Mass

- Therefore,

$$\delta M = \delta Q(\partial_t) = \delta Q_G(\partial_t) + \delta Q_\phi(\partial_t).$$

- The variation of the mass δM requires asymptotic boundary conditions to be integrated.
- As is expected from physical grounds, the mass is well defined after imposing suitable boundary conditions.

$m^2 = -2l^{-2}$ in $4D$

- This value of the scalar field mass is relevant for gauged supergravities in four dimensions. Also, there exist analytic hairy black hole solutions [CM R. Troncoso and J. Zanelli, 2004, A. Aceña, A. Anabalón, D. Astefanesei and R. Mann,2014, A. Anabalón and D. Astefanesei, 2014].
- In absence of a cubic term in the self-interaction potential, the fall-off of the scalar field is
$$\phi = \frac{a}{r} + \frac{b}{r^2} + O(r^{-3}),$$
- For static metrics that match (locally) AdS at infinity, the relevant fall-off is
$$\begin{aligned} -g_{tt} &= \frac{r^2}{l^2} + k - \frac{\mu}{r} + O(r^{-2}), \\ g_{mn} &= r^2 h_{mn}, \\ g_{rr} &= \frac{l^2}{r^2} + \frac{Al^4}{r^4} + \frac{l^5 B}{r^5} + O(r^{-6}), \end{aligned}$$
- $h_{mn}(x^m)$ is the two-dimensional metric associated to the 'angular section' Σ_k (volume $V(\Sigma)$, curvature $2k$).

We obtain the gravitational contribution

$$\delta M_G = \frac{V(\Sigma)}{\kappa}[r\delta A + l\delta B + O(1/r)],$$

and scalar contribution

$$\delta M_\phi = \frac{V(\Sigma)}{l^2}[ra\delta a + a\delta b + 2b\delta a + O(1/r)].$$

$$\delta M = \frac{V(\Sigma)}{\kappa l^2}[r(l^2\delta A + \kappa a\delta a) + l^3\delta B + \kappa(a\delta b + 2b\delta a) + O(1/r)]$$

The above expression for δM is meaningful only in the case of vanishing constraints. For the asymptotic conditions considered here, $H_\perp = 0$ implies

$$\frac{k+A}{\kappa} + \frac{a^2}{2l^2} = 0.$$

In this way, the divergent piece is removed and the asymptotic variation of the mass takes a finite value

$$\delta M = \frac{V(\Sigma)}{\kappa l^2}[l^3\delta B + \kappa(a\delta b + 2b\delta a)].$$

To integrate the variations we need to impose boundary conditions on the scalar field. If we define $b = dW(a)/da$, the mass of the spacetime is given by [1]

$$M = V(\Sigma)\left[\frac{lB}{\kappa} + \frac{1}{l^2}\left(a\frac{dW(a)}{da} + W(a)\right)\right].$$

- At this point, it is important to emphasize that the coefficient of the first subleading term, μ, in the expansion of g_{tt} does not appear explicitly in the expression of the mass.
- In fact, in static spacetimes g_{tt} is the lapse function which is not a canonical variable and consequently, does not appear either in the constraints or in the surface terms. However, as we will see shortly, once we use the dynamic equations of motion the situation will change.

[1] [see also T. Hertog, G. Horowitz, 2005]

Inclusion of the dynamic field equations. Mass *on-shell*

Now, for a given solution with the required asymptotics, we have additional information since not only the constraints are satisfied, but also the equations of motion. The $E_t^t - E_r^r$ combination of the Einstein-scalar field equations, which is not a constraint, is independent of the scalar field potential and yields

$$E_t^t - E_r^r = \frac{2A + 2k + \kappa a^2 l^{-2}}{r^2} + \frac{-3\mu + 3Bl + 4\kappa abl^{-2}}{r^3} + O(r^{-4}) = 0.$$

The first term gives the same relation as the constraint $H_\perp = 0$, but the second one provides a relation containing μ and the parameters of the asymptotic expansions of g_{rr} and the scalar field

$$Bl = \mu - \frac{4}{3}\kappa abl^{-2}.$$

$$M = V(\Sigma)\left[\frac{\mu}{\kappa} + \frac{1}{l^2}\left(W(a) - \frac{1}{3}a\frac{dW(a)}{da}\right)\right].$$

Analysis on the boundary conditions and their effect on the mass and asymptotic symmetry

$$M = V(\Sigma)\left[\frac{\mu}{\kappa} + \frac{1}{l^2}\left(W(a) - \frac{1}{3}a\frac{dW(a)}{da}\right)\right].$$

Therefore, there are only three situations when the mass reduces to $M = \mu V(\Sigma)\kappa^{-1}$:

- $a = 0$: this is the usual Dirichlet boundary condition and ensures asymptotic AdS invariance;
- $b = 0$: this is the Neumann boundary condition and also ensures asymptotic AdS invariance;
- $b = Ca^2$: this boundary condition corresponds to multi-trace deformations in the dual field theory [Witten, 2001] and is also compatible with the asymptotic AdS symmetry [Amsel, Marolf, 2006],[Henneaux, CM, Troncoso, Zanelli, 2007].

Logarithmic branches

We are interested in a scalar field with the conformal mass $m^2 = -2l^{-2}$. To obtain the logarithmic branch, a cubic term in the asymptotic expansion of the scalar field potential is necessary [Henneaux, CM, Troncoso, Zanelli, 2007]

$$V(\phi) = -\frac{3}{\kappa l^2} - \frac{\phi^2}{l^2} + \lambda\phi^3 + O(\phi^4)$$

so that the fall-off of the scalar field to be considered is

$$\phi(r) = \frac{a}{r} + \frac{b}{r^2} - 3a^2\lambda l^2\frac{\ln(r)}{r^2} + O(r^{-3}),$$

and the one for g_{rr} is

$$g_{rr} = \frac{l^2}{r^2} + \frac{l^4 A}{r^4} + \frac{l^5 B}{r^5} + \frac{l^5 C\ln r}{r^5} + O\left[\frac{\ln(r)^2}{r^6}\right]$$

The Hamiltonian constraint $H_\perp = 0$ implies

$$A = -\frac{a^2\kappa}{2l^2} - k \qquad \text{and} \qquad C = 4\kappa\lambda l^4 a^3$$

Now, we have

$$\delta M_G = \left[\frac{\delta A}{\kappa} r + \frac{l\delta C}{\kappa} \ln r + \frac{l\delta B}{\kappa}\right] V(\Sigma)$$

and

$$\delta M_\phi = \left[\frac{a\delta a}{l^2} r - 12\lambda a^2 \delta a \ln r + \frac{a\delta b + 2b\delta a + 3a^2 l^2 \lambda \delta a}{l^2}\right] V(\Sigma)$$

Both contributions contain linear and logarithmic divergences, which are cancelled out by virtue of Hamiltonian constraint. Thus, we obtain a finite expression for the variation of the mass,

$$\delta M = \left[\frac{l\delta B}{\kappa} + \frac{a\delta b + 2b\delta a + 3a^2 l^2 \lambda \delta a}{l^2}\right] V(\Sigma)$$

Again, we need a boundary condition, a functional relation between a and b, in order to integrate δM. We consider the general relation $b = \frac{dW}{da}$, so that the Hamiltonian mass is given by

$$M = \left[\frac{lB}{\kappa} + \frac{1}{l^2}\left(a\frac{dW}{da} + W + a^3 l^2 \lambda\right)\right] V(\Sigma)$$

B can be related with μ by using the $E_t^t - E_r^r$ combination

$$B = \frac{\mu}{l} - \frac{2a\kappa\left(a^2\lambda l^2 + 2b\right)}{3l^3}$$

Thus, the mass can be written as

$$M = \left[\frac{\mu}{\kappa} + \frac{1}{l^2}\left(W - \frac{1}{3}a\frac{dW}{da} + \frac{1}{3}a^3 l^2 \lambda\right)\right] V(\Sigma)$$

Therefore, the expression $M = \mu\sigma_k\kappa^{-1}$ is obtained only for $a = 0$, or $b = 0$, or

$$W(a) = a^3\left[C_0 + l^2\lambda \ln a\right]$$

which correspond to AdS invariant boundary conditions [Henneaux, CM, Troncoso, Zanelli, 2007].

“Black holes and Thunderbolt Singularities with Lifshitz Scaling terms”

by Yosuke Misonoh

[JGRG25(2015)1b4]

Black holes and Thunderbolt Singularities with Lifshitz Scaling terms

Yosuke Misonoh (Waseda Univ.)
collaborate with Kei-ichi Maeda (Waseda Univ.)

based on YM and K.Maeda, Phys. Rev. D92, 084049(2015) [arXiv:1509.01378[gr-qc]]

Introduction

- Horava-Lifshitz gravity :
  (power-counting) renormalizable, Lorentz violating gravity

- LV leads unusual dispersion relation :

$$\omega^2 = ak^2 + bk^{2n} \longrightarrow c_{\mathrm{UV}} \sim k^{n-1} \to \infty \text{ for } n > 1$$

It becomes instantaneous in UV limit

Question : Can we construct BH without Lorentz invariance?
Instantaneous mode c=∞ should be taken into account.

What we done

theory : classical Horava-Lifshitz (HL) gravity (LV theory, with UV correction)

ansatz : static, spherically symmetric and asymptotically flat spacetime

solutions : BH and a kind of singularity "thunderbolt"
(Hawking and Stewart, 1992)

Previous works : theory

- "Einstein-aether" (IR limit of HL gravity)

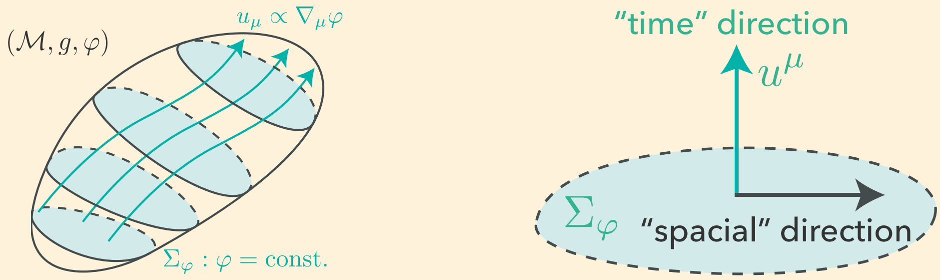
The action : effective theory of Lorentz violating gravity

gravitational dynamical fields : $g_{\mu\nu}$, aether u^μ (timelike, fixed-norm, twistless)

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\,[R - c_{13}(\nabla_\alpha u_\beta)(\nabla^\beta u^\alpha) - c_2(\nabla_\alpha u^\alpha)^2 + c_{14}u^\alpha u^\beta(\nabla_\alpha u_\gamma)(\nabla_\beta u^\gamma)]$$

$u^\mu := \nabla^\mu\varphi/\sqrt{-(\nabla_\alpha\varphi)(\nabla^\alpha\varphi)}$: aether, φ : khronon

- spacetime : preferred foliation via khronon φ



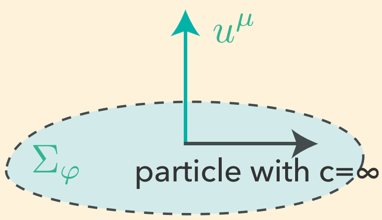
Lorentz violation : breaking rotational symmetry in spacetime

Previous works : universal horizon

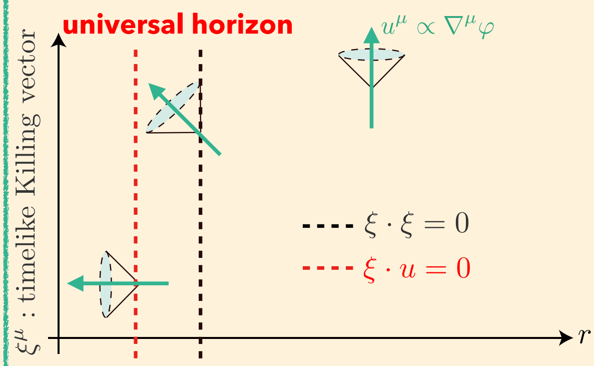
- Universal horizon : static limit for instantaneous particle with c=∞.

Local structure

Light cone angle $\begin{cases} = 90^\circ & \text{(null)} \\ > 90^\circ & \text{(superluminal)} \\ = 180^\circ & \text{(instantaneous)} \end{cases}$



global structure



any particle cannot escape from UH even if c=∞

Lorentz violating BH ⇔ solution with universal horizon

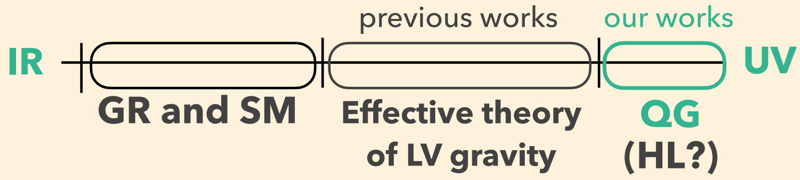
- Static and spherical symmetric BH with universal horizon.

(Barausse et al. 2011; Blas and Sibiryakov 2011; Berglund et al. 2012)

our motivation

motivation

Einstein-aether is a effective theory of LV gravity.



if it were exist HL gravity in UV, can we find BH?

HL gravity : "Einstein-aether" + up to sixth "spacial" derivatives

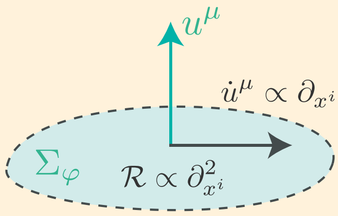
power-counting renormalizability of gravity

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}(\mathcal{L}_{\rm IR} + \mathcal{L}_{\rm UV})$$

$$\mathcal{L}_{\rm IR} := R - c_{13}(\nabla_\alpha u_\beta)(\nabla^\beta u^\alpha) - c_2(\nabla\cdot u)^2 + c_{14}(\dot{u}^\alpha \dot{u}_\alpha)$$

$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm UV}[\mathcal{R}_{\mu\nu}, \dot{u}^\mu]$ (# of possible terms is over 30)

where, $\mathcal{R}_{\mu\nu}[g,u]$ is a 3-Ricci tensor and $\dot{u}^\mu := u^\alpha\nabla_\alpha u^\mu$.



$\mathcal{L}_{\rm UV}$ is regarded as renormalization counter-term

our model

Theory motivated by HL : "Einstein-aether" + $\underbrace{\text{fourth "spacial" derivatives}}_{\text{UV correction}}$

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}(\mathcal{L}_{\rm IR} + \mathcal{L}_{\rm UV})$$

$$\mathcal{L}_{\rm IR} := R - c_{13}(\nabla_\alpha u_\beta)(\nabla^\beta u^\alpha) - c_2(\nabla\cdot u)^2 + c_{14}(\dot{u}^\alpha \dot{u}_\alpha)$$

$$\boxed{\mathcal{L}_{\rm UV} := -m_{\rm pl}^{-2}\left[\beta_1(\dot{u}_\alpha\dot{u}^\alpha)^2 + \beta_2\mathcal{R}^2\right]}$$

- Reason why we choose above $\mathcal{L}_{\rm UV}$
  - (1) For simplicity
  - (2) Modified dispersion relation of gravity

$\mathcal{R}^2$ term effect

$$\omega_{\rm G}^2 = \frac{1}{1-c_{13}}k^2 \qquad \omega_{\rm S}^2 = \frac{(c_{13}+c_2)(2-c_{14})}{c_{14}(1-c_{13})(2+c_{13}+3c_2)}k^2 + \boxed{\frac{8(c_{13}+c_2)\beta_2}{2+c_{13}+3c_2}\left(\frac{k^2}{m_{\rm pl}}\right)^2}$$

scalar graviton becomes instantaneous if $\mathcal{R}^2$ term joins

method

Numerical solutions in static and spherically symmetric spacetime with asymptotic flatness

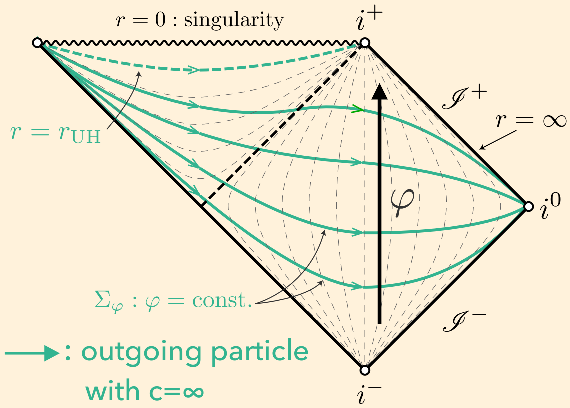
ansatz : $ds^2 = -T(r)dv^2 + 2B(r)dvdr + r^2d\Omega^2\,,\ u^\mu = (a(r), b(r), 0, 0)$

New solution : BH with UV correction

Black hole solution with regular universal horizon

Properties

- BH with universal horizon can be found when $\mathcal{L}_{\rm UV}$ includes $(\dot{u}^\alpha \dot{u}_\alpha)^2$ without $\mathcal{R}^2$. In this case dispersion relation of gravity is not modified.
- solution is dependent on two parameters : M (mass), α (aether distribution)
- If we choose large α, aether field around horizon is collapsed, which generates physical singularity.

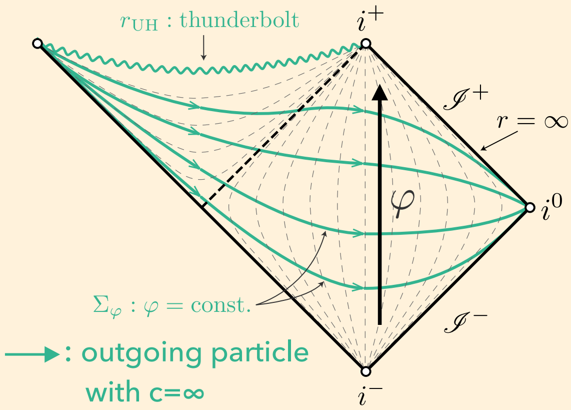


New solution : “Thunderbolt singularity”

Solution with singular universal horizon

Properties

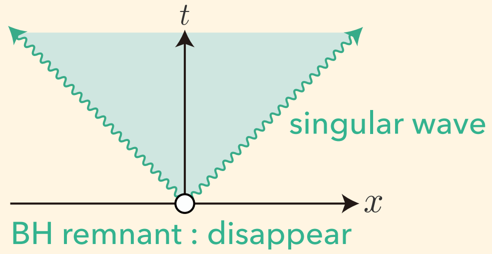
- This kind of solution can be found when $\mathcal{R}^2$ term is joined in $\mathcal{L}_{\rm UV}$, which modify the dispersion relation of scalar graviton.
- Universal horizon always turns to be physical singularity. Thus it is not BH.
- This singularity has similar properties to thunderbolt singularity.

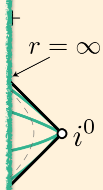


New solution : "Thunderbolt singularity"

What is Thunderbolt singularity?

- One of the final state of BH evaporation in 2 dim. quantum gravity.
  (Hawking and Stewart,1992; Ishibashi and Hosoya,2002)





- At the end, singularity spreads across spacelike or null surface.
- "*It hit you and wipes you out*", as it were, hitting with a thunderbolt.

Reconsider our solution

- If UV correction becomes dominant, universal horizon turns to be singular.
- the BH singularity may be captured on the universal horizon.
- Modification in gravitational dispersion relation may leads this singularity.

conclusion

results

- Black hole solution can be constructed including only $(\dot{u}^\alpha \dot{u}_\alpha)^2$ term as UV correction motivated by Horava-Lifshitz gravity.
- However, $\mathcal{R}^2$ correction term leads singular universal horizon, which means **BH cannot exist if such a correction term is present**.
- The solution with singular universal horizon has similar property to thunderbolt as a final state of BH evaporation in 2 dim. quantum gravity.
- Horava-Lifshitz gravity may reproduce the property of quantum black holes.

future works

- There are about 30 possible terms left in $\mathcal{L}_{\rm UV}$.
- Although our thunderbolt solution does not violate Cosmic Censorship at background level, it is unclear that it is also preserved even if perturbation is considered.

“Monopole black holes in asymptotically AdS spacetime”

by Shoichiro Miyashita

[JGRG25(2015)1b5]

Monopole black holes in asymptotically AdS spacetime

Waseda U.
Shoichiro Miyashita
Kei-ichi Maeda

Introduction

Black hole uniqueness

"M,Q,J specify the BH solution uniquely"

in Einstein-Maxwell system, correct

in Einstein-Yang-Mills system incorrect [Bizon(1992)]

⇒ Kerr-Newmann + non trivial (Non-abelian BH)

Extention to asymptotically AdS

	colored BH[Bizon(1992)] ⇒	**AdS colored BH**[Winstanley, (1999)]
Stability	**unstable**	**stable**
Charge	**M**	**M,Q**

Introduction

Monopole BH : magnetically charged non-abelian BH

in SO(3)EYMH system [Lee et, al 1992]
[Breitenlohner et. al 1992]
[Ortiz 1992]

It exhibits various phase transitions

in asymptotically flat spacetime. [Tachizawa et al. 1995]

In this work,

we extend it to asymptotically AdS spacetime

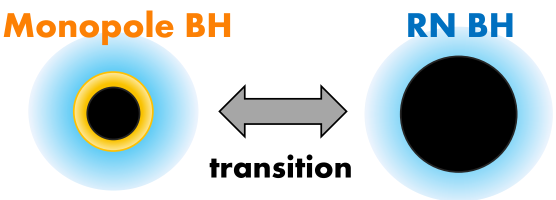
★ **BH uniqueness ?**

★ **effect of negative Λ ?**

★ **phase transition ?** (★ **Holography ?**)

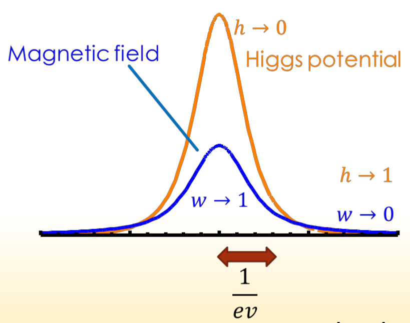
Monopole BH

Monopole BH : "Black Holes in Magnetic Monopole"
[Lee, Nair and Weinberg 1992]



t' Hooft Polyakov monopole

- **finite size** $\sim \frac{1}{ev}$
- **inside** $\rightarrow$ **non-abelian**
- **outside** $\rightarrow$ **U(1)**



Phase transition

- **monopole BH $\Leftrightarrow$ RN BH**
- **monopole BH $\Rightarrow$ extreme RN BH**

AdS monopole BH: setup

★action

$$S=\int d^4x\sqrt{-g}\,[\mathcal{L}_G+\mathcal{L}_{YM}+\mathcal{L}_H];$$

$$\mathcal{L}_G\equiv\frac{1}{16\pi G}(R-2\Lambda)$$

$$\mathcal{L}_{YM}\equiv-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$$

$$\mathcal{L}_H\equiv-\frac{1}{2}D_\mu\Phi^aD^\mu\Phi^a-\frac{\lambda}{4}(\Phi^a\Phi^a-v^2)^2$$

$$D_\mu\Phi^a=\partial_\mu\Phi^a-e\epsilon^{abc}A^b_\mu\Phi^c$$

★ansatz

metric

$$ds^2=-\mu(r)e^{-2\delta(r)}dt^2+\mu(r)^{-1}dr^2+r^2d\Omega^2$$

$$\mu(r)=1-\frac{2Gm(r)}{r}-\frac{\Lambda}{3}r^2$$

matter fields (Hedgehog)

$$\Phi^a=v\hat{r}^ah(r)$$

$$A^a_i=w^c_i\epsilon^{abc}\hat{r}^b\frac{1-w(r)}{er}$$

$$A^a_t=0$$

e:coupling of Yang-Mills v:VEV of Higgs

λ:coupling of Higgs

AdS monopole BH: equation

Basic equations

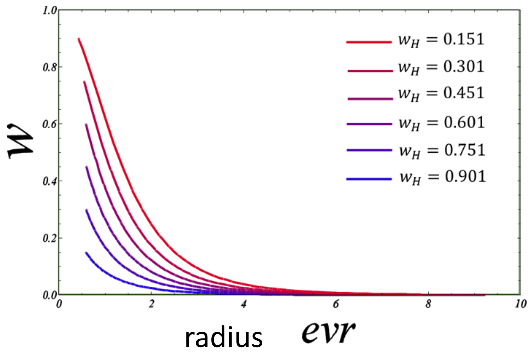
$$m'=4\pi\left[\mu\left(\frac{1}{e^2}(w')^2+\frac{r^2}{2}v^2(h')^2\right)+\frac{(w^2-1)^2}{2e^2r^2}+v^2w^2h^2\right]+\pi\lambda v^4r^2(h^2-1)^2$$

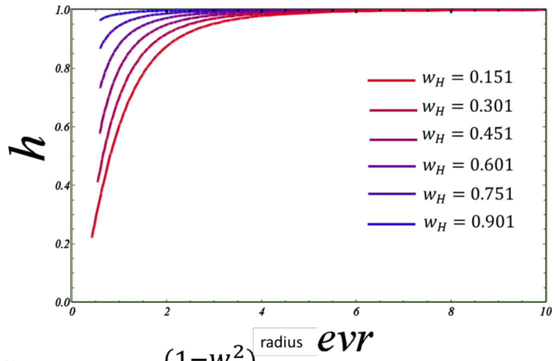
$$\delta'=-8\pi r\left[\frac{1}{e^2r^2}(w')^2+\frac{1}{2}v^2(h')^2\right]$$

$$w''=\frac{1}{r^2\mu}[w(w^2-1+e^2v^2r^2h^2)-\left(2m-\frac{2}{3}\Lambda r^3\right)w'+8\pi v^2rw'\left\{\frac{(w^2-1)^2}{2e^2v^2r^2}+w^2h^2+\lambda\frac{v^2r^2(h^2-1)^2}{4}\right\}]$$

$$h''=-2\frac{1}{r}h'+\frac{1}{r^2\mu}[2hw^2+\lambda v^2r^2h(h^2-1)-\left(2m-\frac{2}{3}\Lambda r^3\right)h'+8\pi v^2rh'\left\{\frac{(w^2-1)^2}{2e^2v^2r^2}+w^2h^2+\lambda\frac{v^2r^2(h^2-1)^2}{4}\right\}]$$

AdS monopole BH: solutions



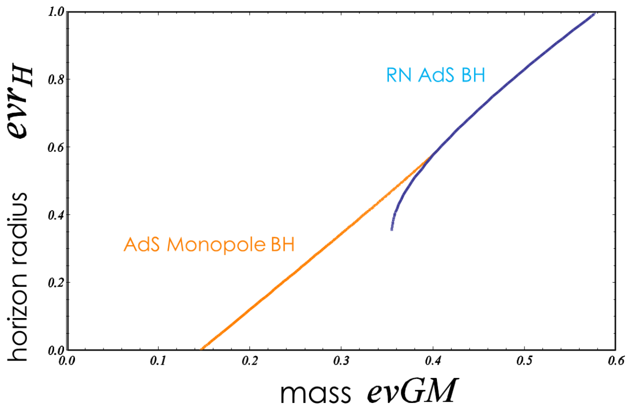


Magnetic field $B \propto \frac{(1-w^2)}{r^2}$

Higgs potential $V_H \propto (h^2-1)^2$

$(\frac{\lambda}{e^2} = 0.1, \sqrt{G}v = 0.1, \frac{\Lambda}{(ev)^2} = -0.1)$

BH uniqueness



$(\frac{\lambda}{e^2} = 0.1, \sqrt{G}v = 0.1, \frac{\Lambda}{(ev)^2} = -0.1)$

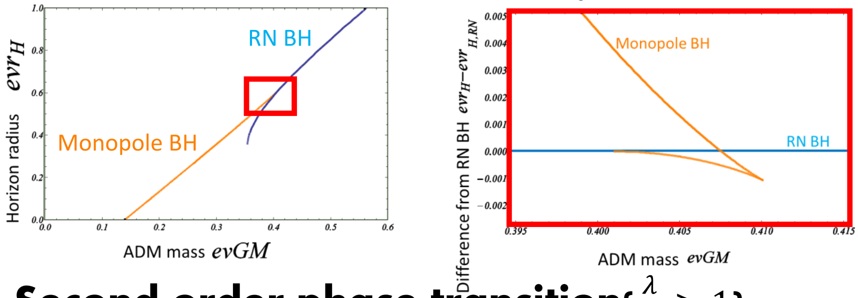
Not able to specify solution uniquely with M (and Q)

Uniqueness breaks down even in AdS case

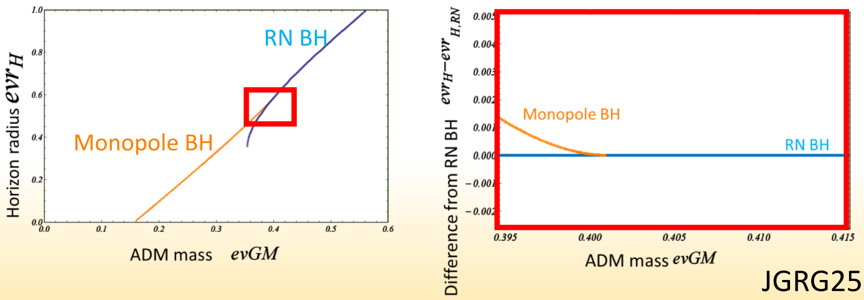
BH thermodynamics: flat case (review)

[Tachizawa, Torii and Maeda 1995]

First order phase transition($\frac{\lambda}{e^2} \lesssim 1$)



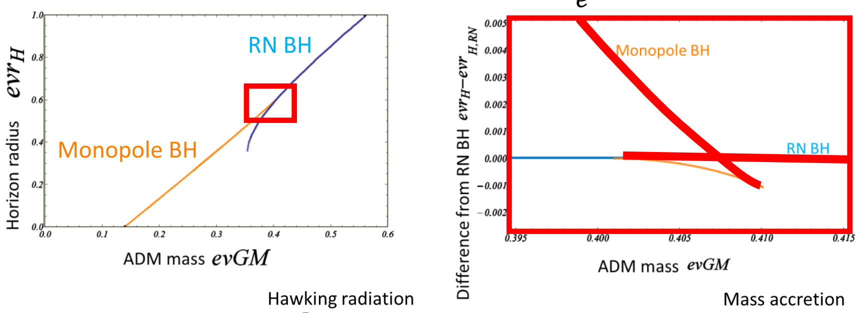
Second order phase transition($\frac{\lambda}{e^2} > 1$)



BH thermodynamics: flat case (review)

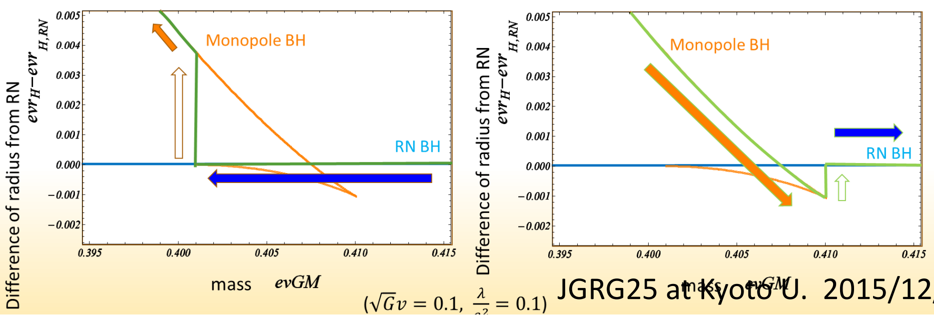
[Tachizawa, Torii and Maeda 1995]

First order phase transition($\frac{\lambda}{e^2} \lesssim 1$)



Hawking radiation
⇒ 「RN BH→Monopole BH」 1st ordered

Mass accretion
⇒ 「Monopole BH→RN BH」 1st ordered

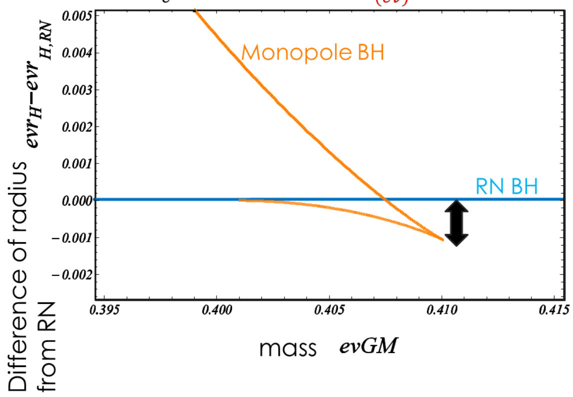


$(\sqrt{G}v = 0.1,\ \frac{\lambda}{e^2} = 0.1)$

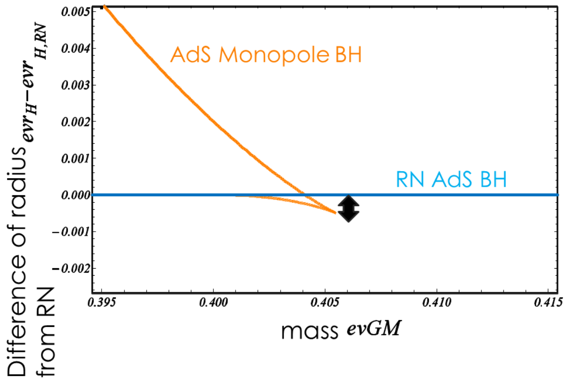
BH thermodynamics: AdS case

The cusp structure gets smaller in AdS

$(\frac{\lambda}{e^2} = 0.1, \sqrt{G}v = 0.1, \frac{\Lambda}{(ev)^2} = 0)$



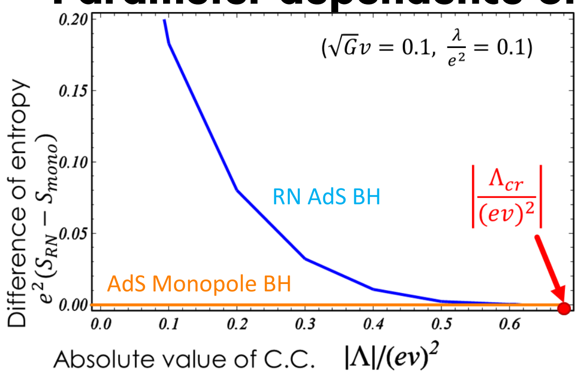
$(\frac{\lambda}{e^2} = 0.1, \sqrt{G}v = 0.1, \frac{\Lambda}{(ev)^2} = -0.1)$



Let's see the $|\Lambda|$ dependence of the entropy discontinuity

BH thermodynamics: AdS case

Parameter dependence of cusp structure



There exist critical value

$$\frac{\Lambda_{cr}}{(ev)^2}\left(\sqrt{G}v, \frac{\lambda}{e^2}\right)$$

where 1st $\Rightarrow$ 2nd ordered

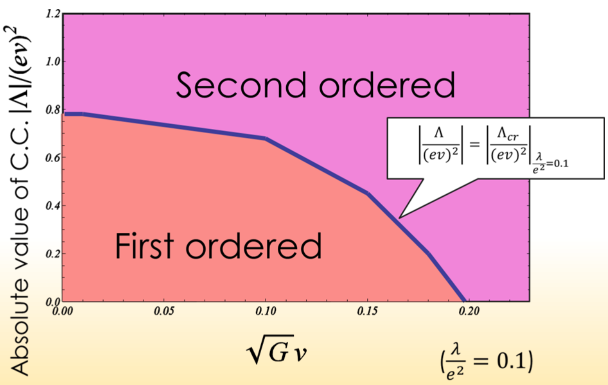
The condition for 1st ordered

- **in asymptotically flat**

$$\frac{\lambda}{e^2} \lesssim 1$$

- **in asymptotically AdS**

$$\frac{|\Lambda|}{(ev)^2} \leqq |\tilde{\Lambda}_{cr}(\tilde{v}, \tilde{\lambda})| \lesssim O(1)$$



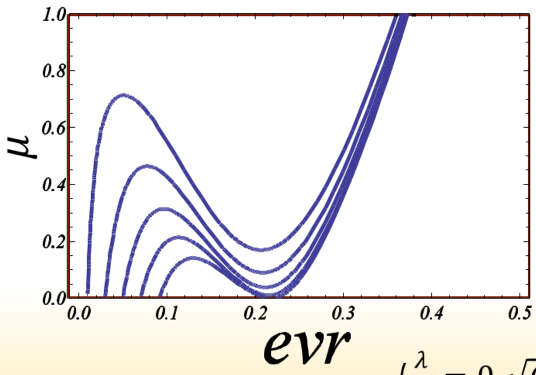
Other type of 1st order phase transition

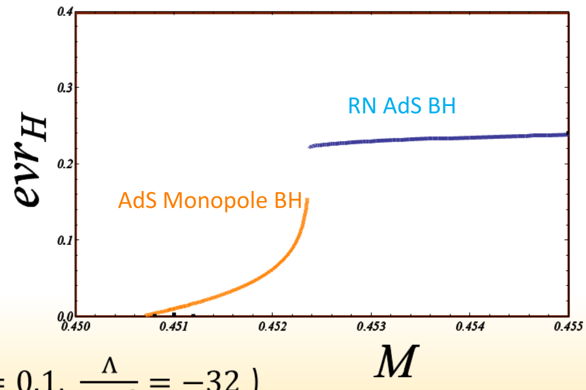
$$\mu(r) = 1 - \frac{2Gm(r)}{r} - \frac{\Lambda}{3}r^2$$

When $|\Lambda|$ is small enough, phase transition is first ordered, and when not, phase transition is second ordered.

However, when $|\Lambda|$ is sufficiently large,

"AdS monopole BH $\Rightarrow$ extreme RN AdS BH" occurs.

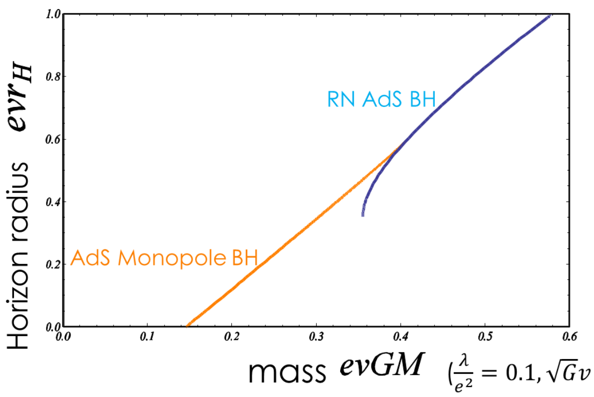




$(\frac{\lambda}{e^2} = 0, \sqrt{G}v = 0.1, \frac{\Lambda}{(ev)^2} = -32)$

Stability of AdS monopole BH

"entropical stability"～"solution's stability"



$(\frac{\lambda}{e^2} = 0.1, \sqrt{G}v = 0.1, \frac{\Lambda}{(ev)^2} = -0.1)$

AdS monopole BH is entropically stable.

$\Rightarrow$ AdS monopole BH solution may be stable...

Summary

★ We show the AdS monopole BH solution numerically.

★ As in asymptotically flat case,
BH uniqueness is violated some parameter region.

★ The second or first order phase transition occurs.
The type of transition depends on Λ

★ From entropy consideration,
AdS monopole BH solution <u>may</u> be stable.

☆Hawking-Page phase transition

“Turbulent strings in AdS/CFT”

by Keiju Murata

[JGRG25(2015)1b6]

Turbulent strings in AdS/CFT

Keio University
Keiju Murata
With T. Ishii

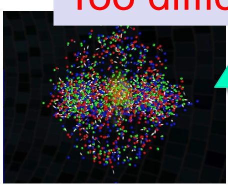
"Turbulent strings in AdS/CFT", arXiv:1504.02190 [hep-th]

Non-equilibrium process in AdS/CFT

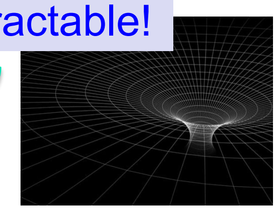
Quantum field theories ⟷ AdS/CFT ⟷ Gravity theories

Non-equilibrium process

Too difficult…



Tractable!



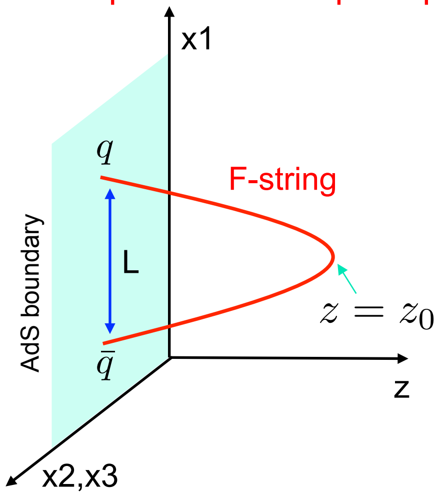
In this talk,

non-equilibrium process in $q\bar{q}$ pair in N=4 SYM

Dynamics of quark-antiquark pair in AdS/CFT

quark and antiquark pair = fundamental string in AdS

Maldacena,98
Rey&Yee,98



$$ds^2 = \frac{1}{z^2}[-dt^2 + dz^2 + d\vec{x}^2]$$

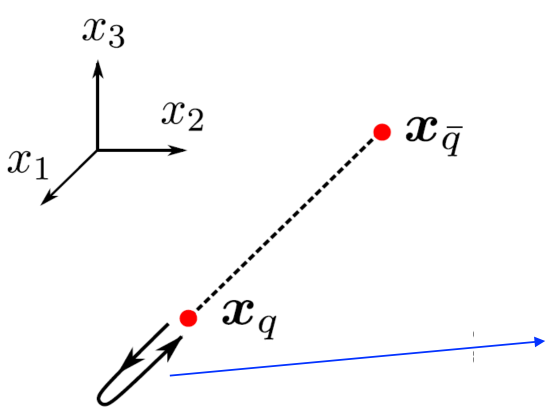
We give a perturbation on the string and study its non-linear dynamics numerically.

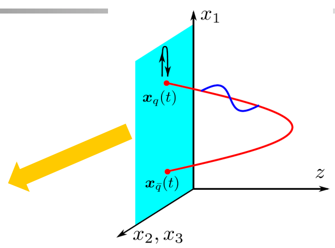
$$S = -\int d^2\sigma\sqrt{-h}$$

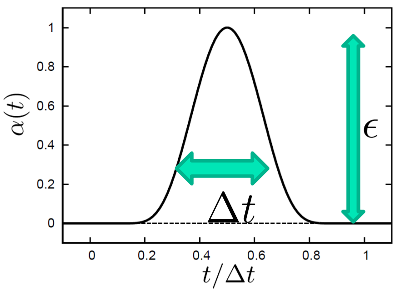
Non-equilibrium physics of q-$\bar{q}$ pair.

Longitudinal "quench" of quark position

3d space in the boundary





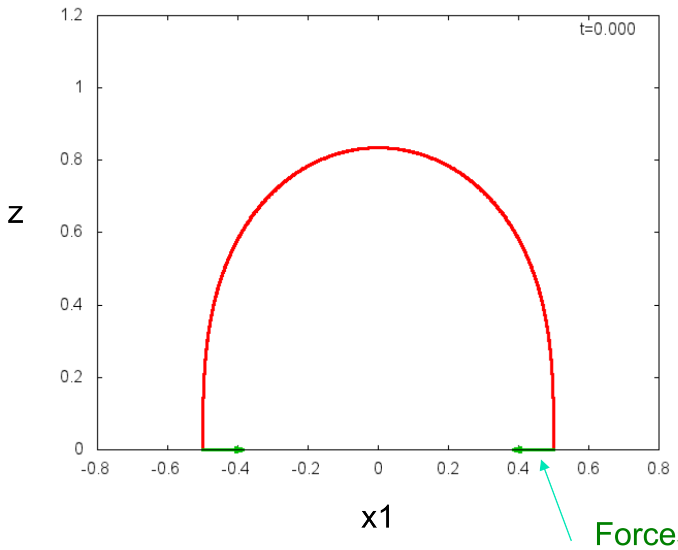


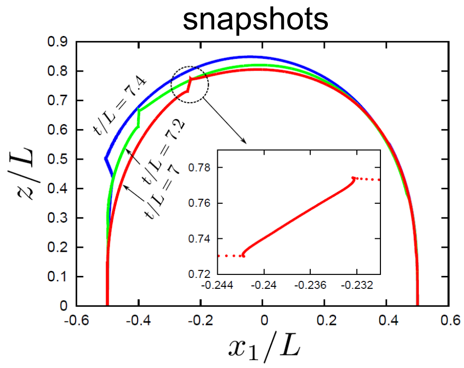
The string motion along (x2, x3)-directions is not induced by this quench.

The string is restricted in (2+1)-dimensions. (t,z,x1)

Numerical solution for longitudinal quench

$\epsilon = 0.03, \Delta t = 2L$





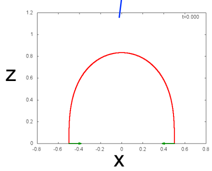
Cusp formation.

Forces acting on quarks = $\dfrac{\delta S[x_q, x_{\bar{q}}]}{\delta x_q}$

String turbulence

We decompose the non-linear solution into normal modes in the linear theory.

$$Z(t,x) = \sum_n c_n(t) e_n(x)$$



Eigen function in linear theory

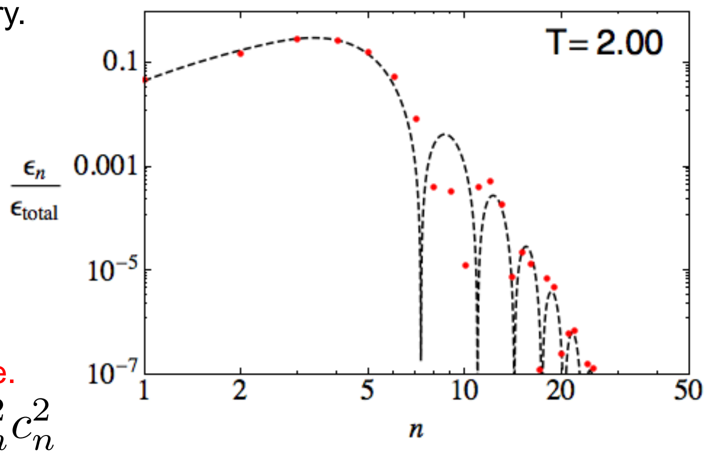
Energy contribution from the n-th mode.

$$\varepsilon_n = \dot{c}_n^2 + \omega_n^2 c_n^2$$

Energy flow from large to small scales.

The spectrum obeys power law.

$\epsilon = 0.01, \Delta t = 2L$

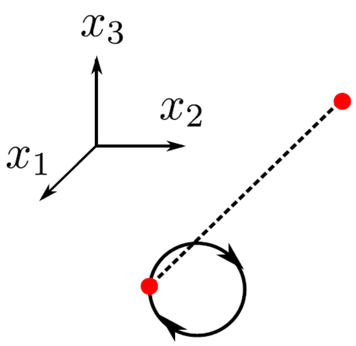


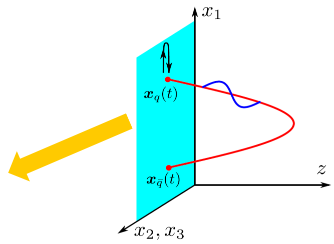
Weak turbulence.

Bizon&Rostworowski, 11

Transverse circular quench

3d space in the boundary



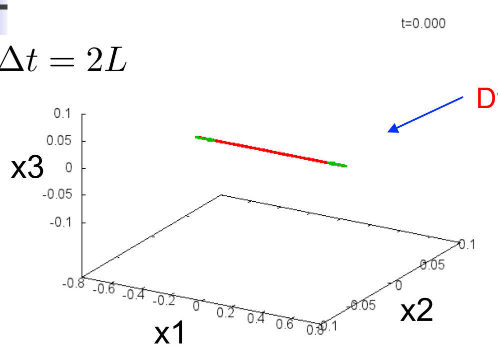


The string motion is in (4+1)-dimensions.

(t, z, x1, x2, x3)

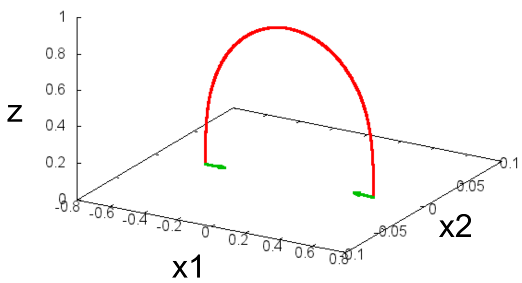
Numerical solution for transverse circular quench

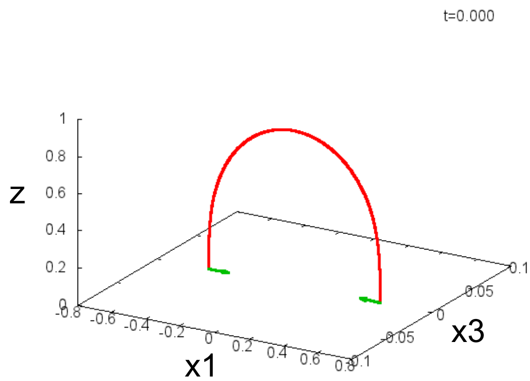
$\epsilon = 0.02, \Delta t = 2L$



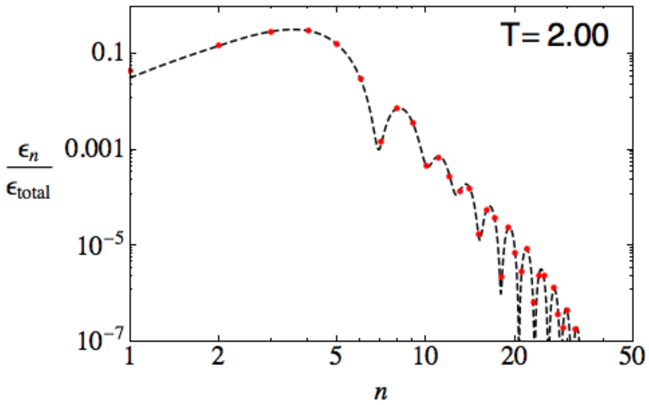
Dynamics of the “flux tube” in N=4 SYM.

We did not find any cusp formations.





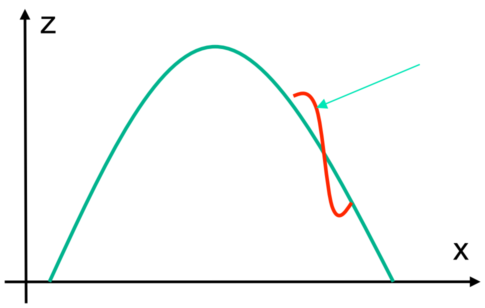
Direct and inverse energy cascade



Although we did not find cusp formations, we found the weak turbulence.

We also found inverse energy cascade after the direct one.

Field theory interpretation of the string turbulence



n-th nomal mode

⇕

n-th excited state of a fluxtube in the boundary theory.

excited state

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle + c_2|2\rangle + \cdots$$

The weight of the highly excited state increases as a function of time.

⇨ The quark-antiquark pair tends to be observed as a heavy state.

Summary and future work

We studied non-linear dynamics of the string in AdS5.

- cusp formations for (2+1)- or (3+1)-dimensional case
- energy flow from large to small scales = weak turbulence

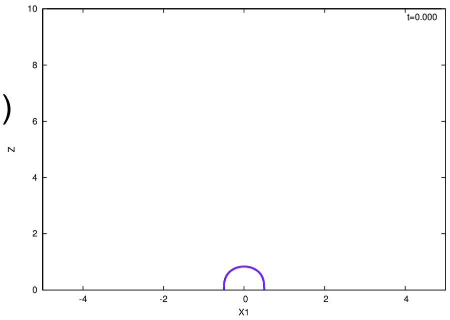
The quark-antiquark pair tends to be observed as a heavy state.

Future works

Strong quench $\epsilon \sim 1$. (in this work, $\epsilon \sim 0.01$)

Finite temperature.

Confined geometry.
(AdS soliton or Witten geometry).



“Disordered Horizons”

by Sean Hartnoll (invited)

[JGRG25(2015)I02]

Disordered Horizons

Sean Hartnoll (Stanford)

JGRG25 — YITP, 2015

Based on: 1402.0872 with J. Santos,
1504.03324 with D. Ramirez and J. Santos,
1508.04435 with D. Ramirez and J. Santos.

Motivation: disordered QFTs

- I will mainly talk about some new types of black holes in Anti-de Sitter spacetime.
- I would like to convince you these black holes have interesting properties that we have not fully understood.
- Before, I will give a brief dual field theory motivation.
- The motivation has to do with the description of disordered fixed points, which are an important but also difficult topic in condensed matter physics.

Motivation: disordered QFTs

- Let us first remember a basic fact from QFT.
- A perturbation of a scale-invariant theory by an operator

$$\mathcal{L} \to \mathcal{L} + h\,\mathcal{O}(x)$$

  is relevant or irrelevant, depending on the dimension $\Delta_{\mathcal{O}}$. Relevant if the dimension is < d (spacetime dimension).
- Relevant operators have strong effects on low energies and long wavelengths. For example, they can cause confinement or superconductivity.

Motivation: disordered QFTs

- Via the AdS/CFT correspondence, this QFT perturbation can be mapped into a gravitational problem.
- The operator $\mathcal{O}$ corresponds to a scalar field ϕ in AdS.
- The scaling dimension determines the mass

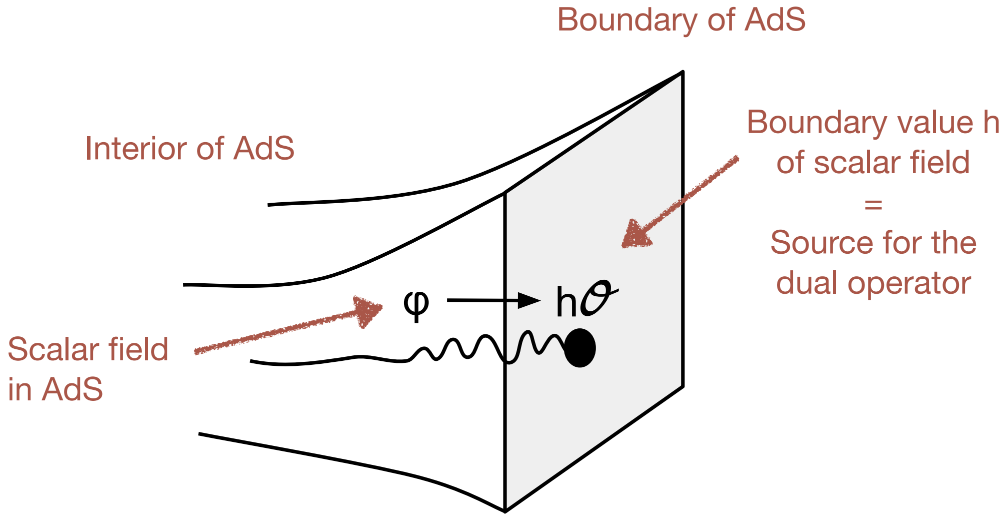
$$L_{\text{AdS}}^2 m_\phi^2 = \Delta_{\mathcal{O}}(\Delta_{\mathcal{O}} - d)$$

- Near the AdS boundary (r → 0), the scalar behaves as

$$\phi(x,r) = \phi^{(0)}(x)\, r^{d-\Delta_{\mathcal{O}}} + \cdots$$

- The effect of the boundary value $\phi^{(0)}(x)$ grows towards the interior (r → ∞) precisely if the operator is relevant.

Motivation: disordered QFTs



Motivation: disordered QFTs

- Spatially homogeneous couplings:
  Option 1. Geometry ends (gap).
  Option 2. Geometry flows to a new AdS (IR fixed point).

- In condensed matter it is often important to consider the effect of quenched disordered couplings:

$$\mathcal{L} \to \mathcal{L} + V(x)\mathcal{O}(x,t)$$

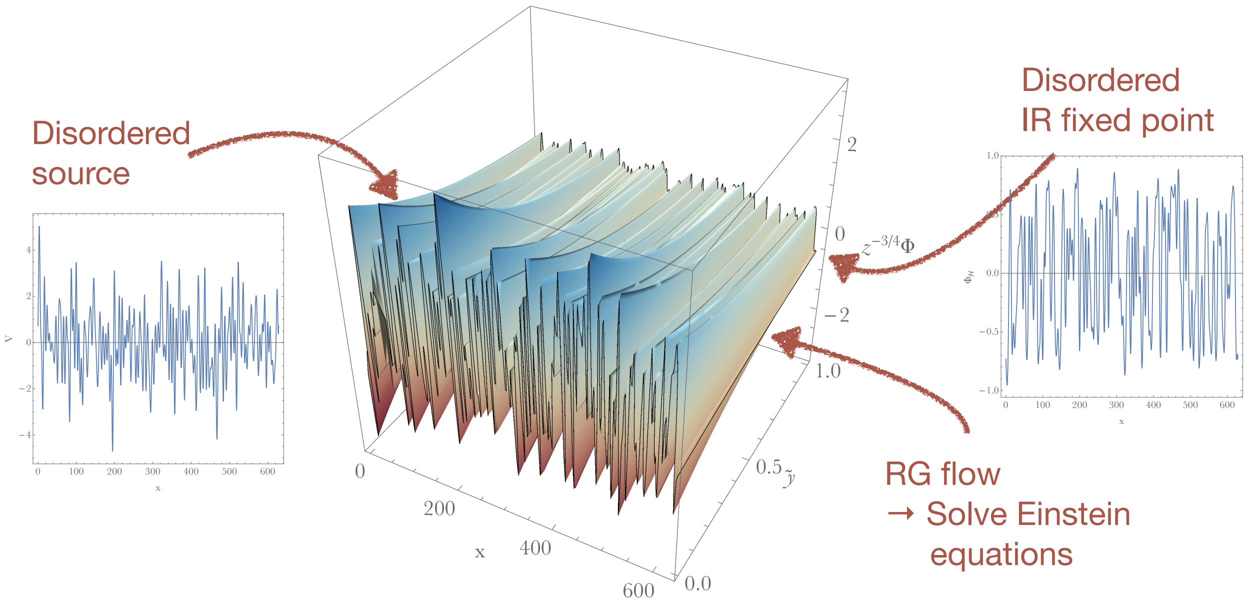
- Here V(x) is drawn from some random distribution (let's say, Gaussian + short range, for simplicity).

- The Harris criterion says this coupling is relevant if:

$$\Delta < \frac{d+1}{2}$$

Motivation: disordered QFTs

- This talk will be about the search for disordered fixed points in AdS. We will find spacetimes that look like:



Motivation: disordered QFTs

- In homogeneous cases, fixed points in the interior of the spacetime (at zero temperature), are characterized by an emergent scaling invariance of an extremal ‘horizon’:

$$ds^2 \sim -\frac{dt^2}{r^2} + \frac{dr^2}{r^2} + \frac{d\vec{x}^2}{r^{2/z}} \qquad \text{as } r \to \infty$$

- z=1: Poincare AdS horizon
  z=∞: extremal Reissner-Nordstrom horizon
  1<z<∞: Lifshitz ‘horizon’

- What does a disordered fixed point look like?

Disordered spacetimes

- We will be finding solutions to the following theory:

$$S = \int d^{d+1}x\sqrt{-g}\left(R + \frac{d(d-1)}{L^2} - 2\left(\nabla\Phi\right)^2 - 2\alpha\Phi^2\right)$$

- It is a theorem that Gaussian disorder can be modeled with a sum over cosines with random phases:

Short distance cutoff

$$V(x) = \overline{V}\sum_{n=1}^{N-1} 2\sqrt{\Delta k}\cos\left(n\Delta k\, x + \gamma_n\right)$$

Disorder strength

Long distance cutoff

$$\Delta k = \frac{k_{\mathrm{UV}}}{N}$$

Random phase, uniformly drawn from [0,2π]

Disordered spacetimes: zero T [Hartnoll-Santos '14]

- Perturbative analytical and numerical study of 1+1 and 2+1 boundary dimensions.

- Constructed the solutions then looked at the metric averaged over boundary space dimensions. I.e. take

$$ds^2 = \frac{L^2}{r^2}\left(-A(x,r)dt^2 + dr^2 + B(x,r)dx^2\right)\,, \qquad \Phi = \phi(x,r)$$

and then

$$A(r) = \langle A(x,r)\rangle_{\mathrm{disorder}}\,, \quad \text{etc.}$$

- Perturbatively we write: $A(x,r) = 1 + \overline{V}^2 A_{(2)}(x,r) + \cdots\,, \quad \text{etc.}$

Disordered spacetimes: zero T

- Start with the case of marginal disorder.
- Perturbation theory shows a log divergence:

[First found by Adams and Yaida]

$$A_{(2)}(r) \sim \# \log(r) + \cdots \qquad \text{as } r \to \infty$$

- Naively, suggests a resummation to get:

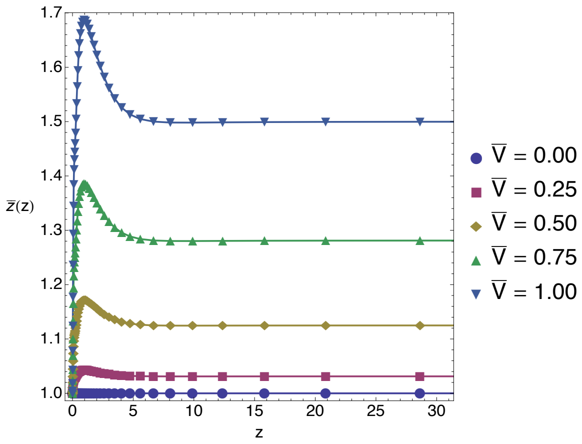
$$A(r) \sim r^{\overline{V}^2 \#} \equiv r^{2(1-z)} \qquad \text{as } r \to \infty$$

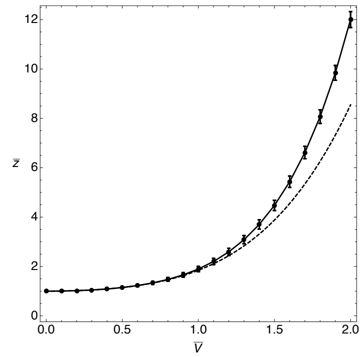
- Perturbatively we found (in 1+1 boundary)

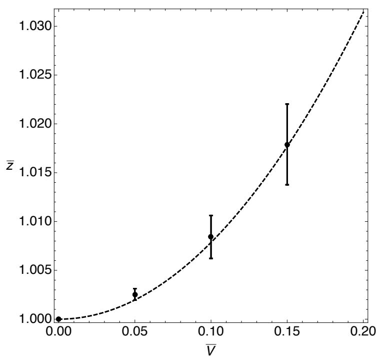
$$z = 1 + \frac{1}{2}\overline{V}^2 + \frac{\log 2}{2}\overline{V}^4 + \cdots$$

Disordered spacetimes: zero T

- Numerical confirmation:





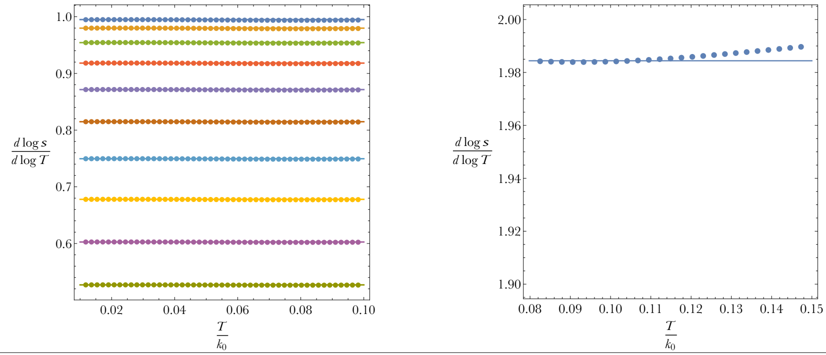


Disordered spacetimes: finite T [Hartnoll-Ramirez-Santos '15a]

- Wanted: a more physical observable that shows scaling.
- The entropy is an integral over the horizon and therefore self-averaged. Expect, as T → 0:

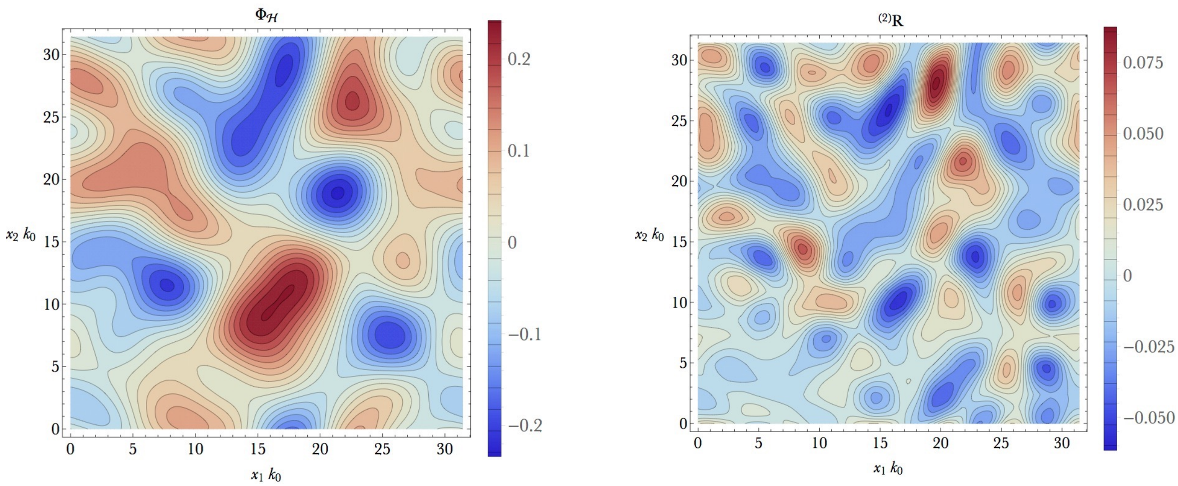
$$s \sim T^{(d-1)/z}$$

- In perturbation theory, same z appears. Numerically:



Disordered spacetimes: finite T

- The horizon:

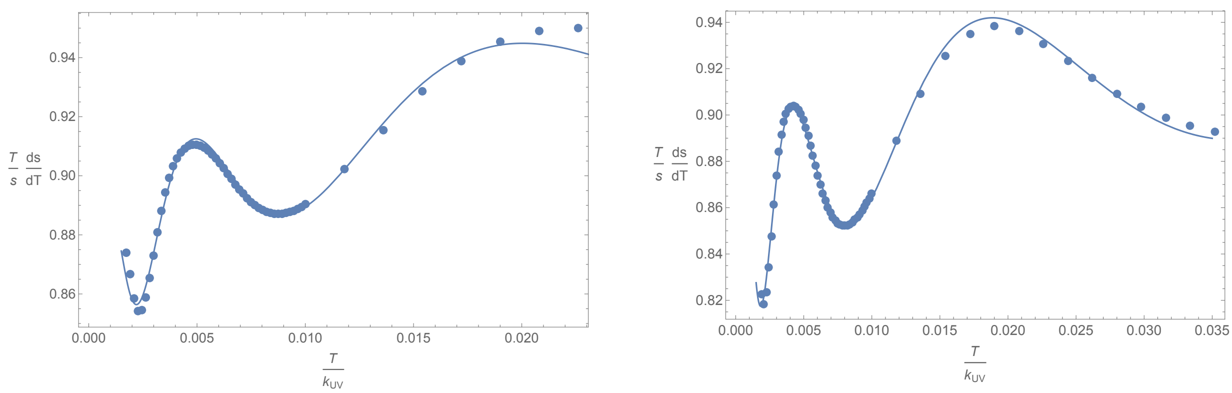


- It is important to take the IR cutoff on the disorder to be at an energy scale below the horizon temperature.

Relevant disorder [Hartnoll-Ramirez-Santos '15b]

- So far: evidence that marginal disorder leads to an emergent disordered fixed point characterized by $z > 1$.
- Geometrized by a highly inhomogeneous 'disordered horizon' for which averaged quantities show scaling.
- Would like to understand the horizon more intrinsically.
- Now consider relevant disorder. The disorder grows with a power of r away from the boundary. Perturbation theory not useful (no plausible resummation). Do numerics for 1+1 boundary with a particular choice of mass.

Relevant disorder



- Oscillations at low temperatures! Fits to:

$$\frac{T}{s}\frac{ds}{dT} = T^{\gamma}\left(b_0 + b_1 \sin\left[\delta \log \frac{T_0}{T}\right]\right)$$

- Characteristic of discrete scale invariance. Corresponds to complex scaling exponent: $T^{\gamma+i\delta}$. Find $\delta \approx 4.5$ in both cases.

Relevant disorder

- Discrete scale invariance is often associated with instabilities (e.g. field below BF bound in AdS). Related to fact that CFT operators have real scaling exponents.
- Disordered fixed points are not CFTs. Perturbative computations in condensed matter also found discrete scale invariance at disordered fixed points. It was believed to be an artifact of certain approximations in those computations. Our results suggest it is real.
- Again, would like to understand these solutions better.

Thermal conductivity [Hartnoll-Ramirez-Santos '15b]

- Finally, there is another very natural observable to obtain. The thermal conductivity of the dual field theory:

$$\vec{Q} = -\kappa \nabla T$$

- In the spacetime, it is the rate at which the horizon absorbs certain gravitational radiation. It is given by

$$\kappa = \frac{\pi^2 T^2}{2 G_N} \left[\frac{1}{L_x} \int dx \frac{\left(\partial_x \Phi(r_+, x)\right)^2}{L \sqrt{g_{xx}(r_+, x)}} \right]^{-1}$$

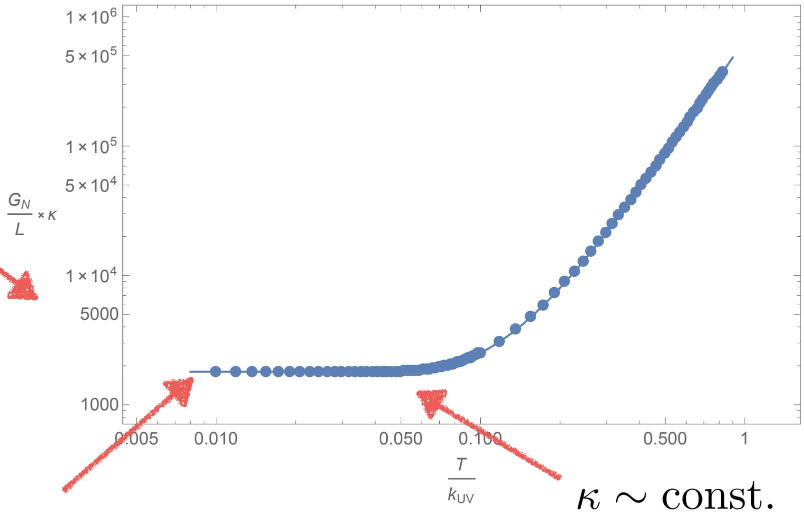
[cf. Donos-Gauntlett]

- Nice quantity because it is infinite if the horizon is homogeneous (because momentum does not relax). Direct probe of disorder.

Thermal conductivity

- Weak disorder, marginal case V = 0.01.

$$\kappa \sim \frac{1}{\overline{V}^2}$$



$$\kappa \sim \text{const.} \quad \text{as} \quad T \to 0$$

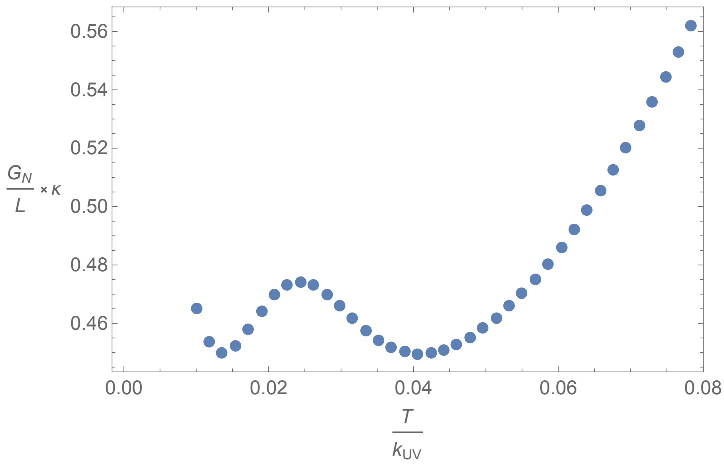
Analytic perturbative
result using 'memory matrix'

$$\Gamma = \frac{h^2}{sT} \lim_{\omega \to 0} \int \frac{d^d k}{(2\pi)^d} \frac{k^2}{d} \frac{\operatorname{Im} G^R_{\mathcal{O}\mathcal{O}}(\omega, k)}{\omega} .$$

[SAH-Herzog '08]

Thermal conductivity

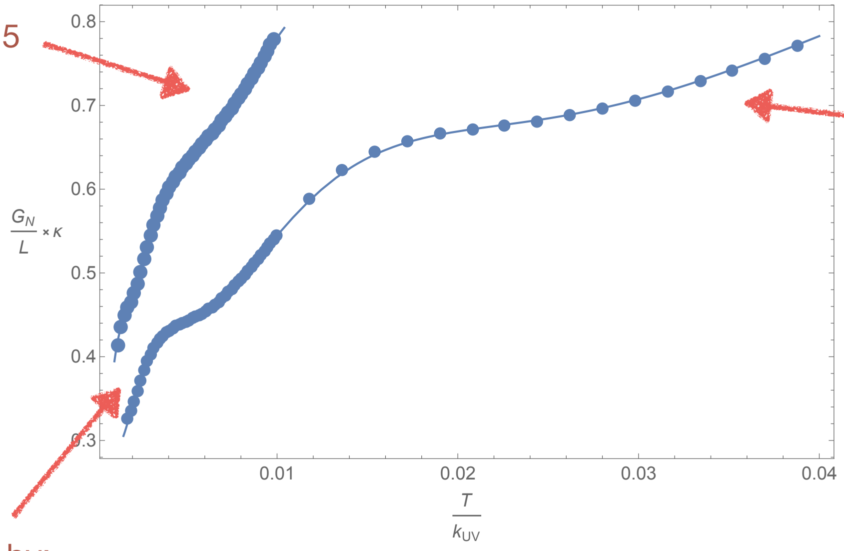
- Stronger disorder, marginal case. V = 1.



- See oscillations on top of constant behavior. Evidence for discrete scale invariance in the marginal case too!

Thermal conductivity

- Relevant disorder.



Both well fit by:

$$\kappa \approx T^{0.3} \sin\left(4.5 \log \frac{T_0}{T}\right)$$

Discrete scale invariance!
→ Complex scaling exponent

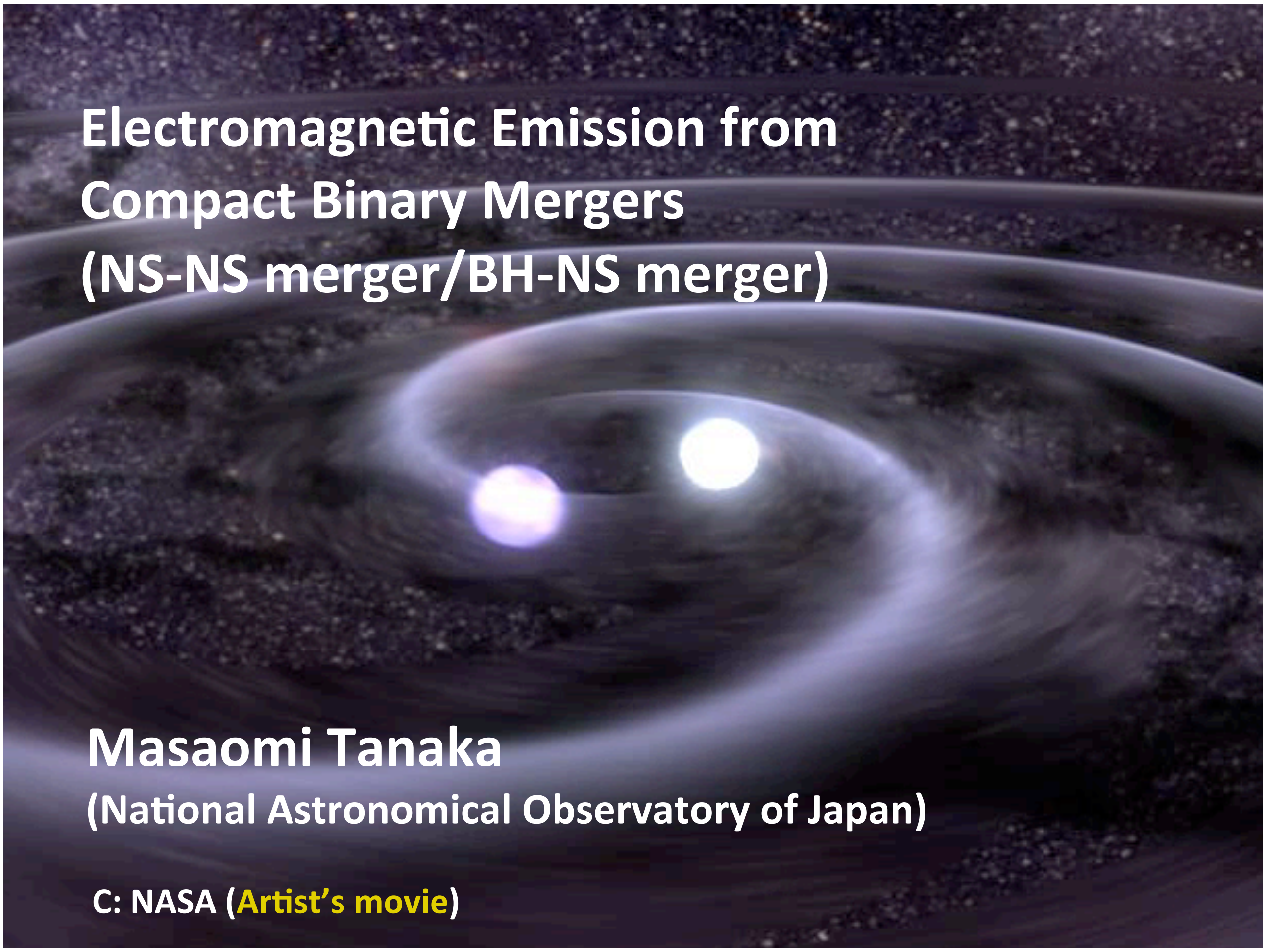
Summary

- AdS spacetime with a disordered source on the boundary leads to new classes of horizons.
- These horizons are inhomogeneous. Want to understand them. Looked at three observables:
  (i) Disorder-averaged metric.
  (ii) Entropy as a function of temperature.
  (iii) Thermal conductivity as a function of temperature.
- All show evidence for an emergent scaling.
- Needed: better analytical techniques to get a handle on the near horizon geometry of these solutions.

“Electromagnetic Emission from Compact Binary Mergers”

by Masaomi Tanaka (invited)

[JGRG25(2015)I03]



Electromagnetic Emission from Compact Binary Mergers

- Why electromagnetic emission?
- Radioactively powered emission
- Prospects for observations

New astronomy with gravitational wave (GW)

Neutron star (NS) merger within ~200 Mpc
=> ~30 (0.3-300) events/ 1 yr

LIGO O1 started on Sep 18, 15:00 UT (24:00 JST)

Friday September 18, 2015 quietly marked the start of the first observing run (O1) of LIGO's advanced detectors, heralding a new, more sensitive than ever search for gravitational waves. (Photo: K. Burtnyk)

The Newest Search for Gravitational Waves has Begun

News Release • September 18, 2015

On, Friday, September 18th 2015, the first official 'observing run' (O1) of LIGO's advanced detectors in Hanford WA and Livingston LA quietly began when the clock struck 8 a.m. Pacific time. While this date marks the official start of data collection, both interferometers have been operating in engineering mode collecting data for some weeks already as technicians, scientists, and engineers worked to refine the instrument to prepare it for official data-collection duties. What *IS* different about today is the scope of the search for gravitational waves. Today, the broader astronomical community has been added to the team. From now on, LIGO will be able to notify any number of 75 astronomical observatories around the world who have agreed to, at a moment's notice, point their telescopes to the sky in search of light signals corresponding to possible gravitational wave detections.

For some, the start of O1 is just another day at the office. Nevertheless, it is still a day to celebrate as it comes after a grueling over 5-year complete redesign and rebuild of the interferometers at both Hanford and Livingston, work performed by hundreds of skilled staff and engineers at the two observatory sites, at Caltech, and at MIT. LIGO staff are excited about this new phase in LIGO's mission.

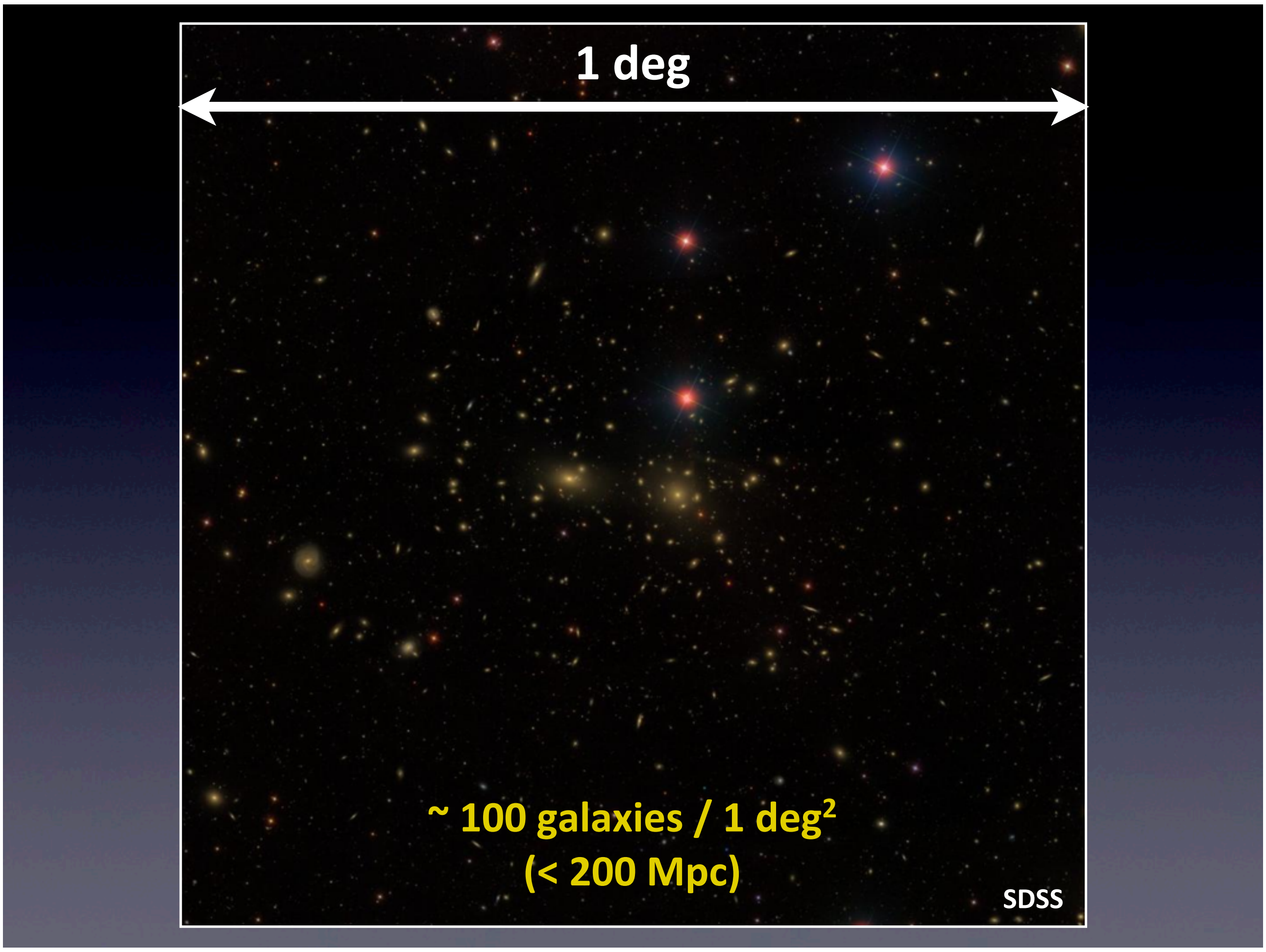
"It is incredibly exciting — and satisfying — to see the planning, designing, building, testing, installing, and commissioning of Advanced LIGO come together so successfully. Kudos to the whole team!", said Dr. David Shoemaker, Director of the MIT LIGO Laboratory.

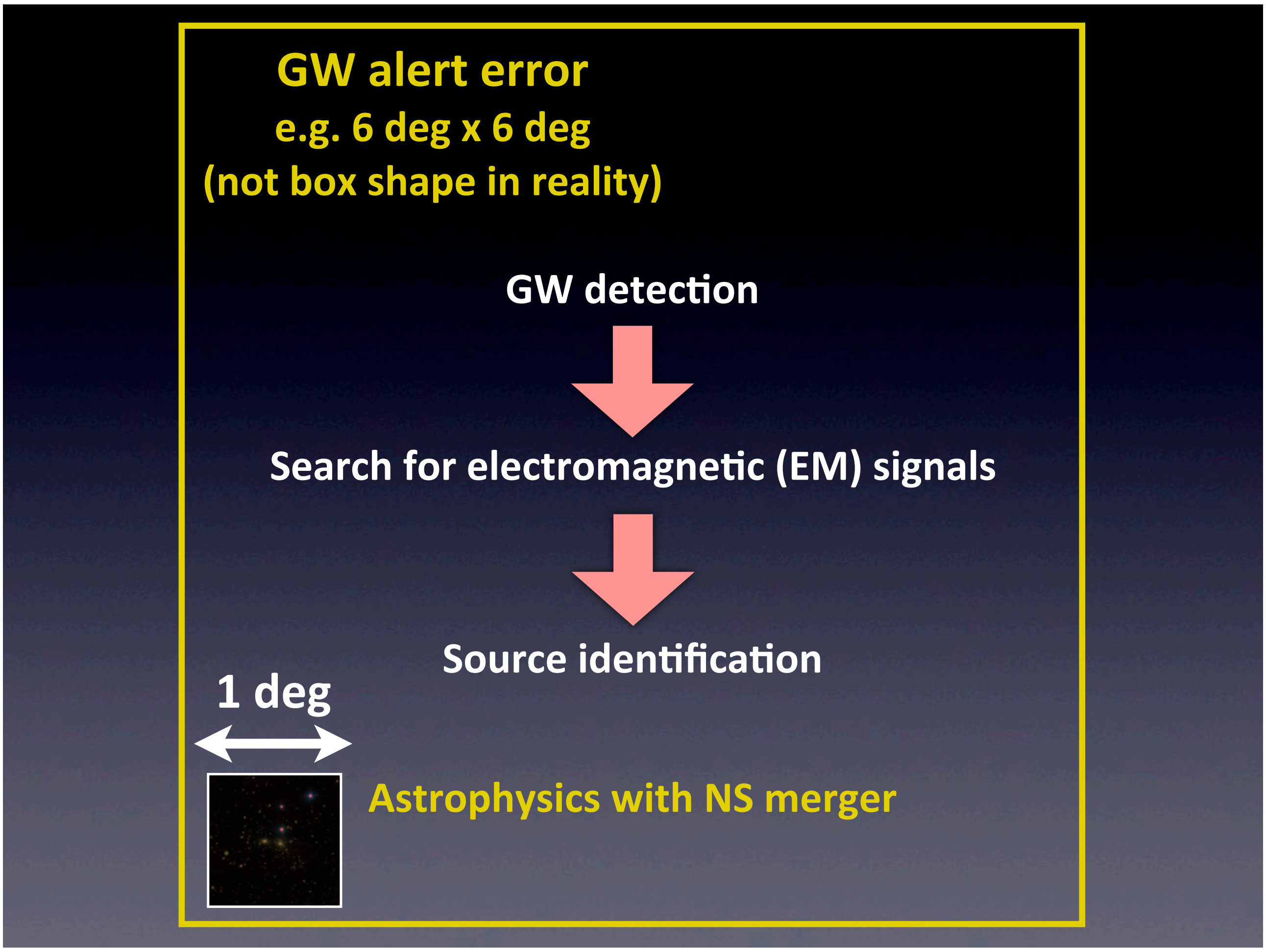
https://ligo.caltech.edu/news/ligo20150918

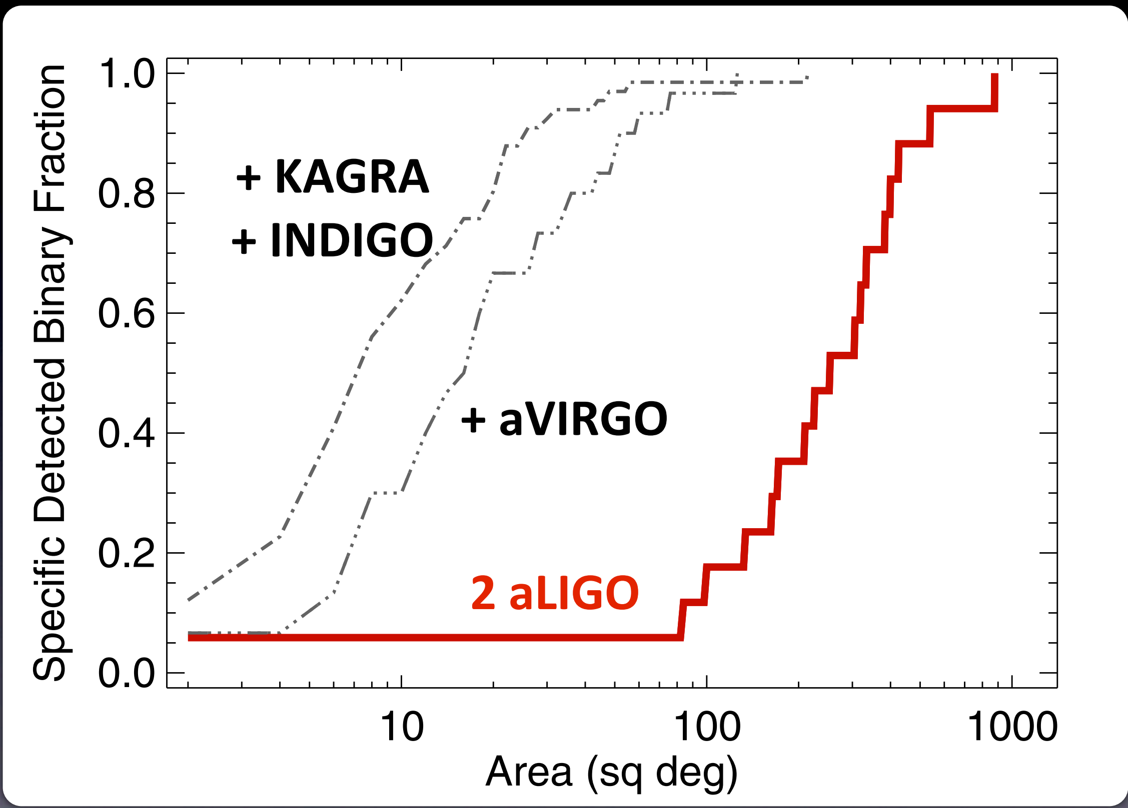
d ~ 80 Mpc

Expected event rate ~ 0.1 events / 3 months (0.01-1)

Electromagnetic follow-up campaigns also started


1 deg
~ 100 galaxies / 1 deg^2
(< 200 Mpc)
SDSS

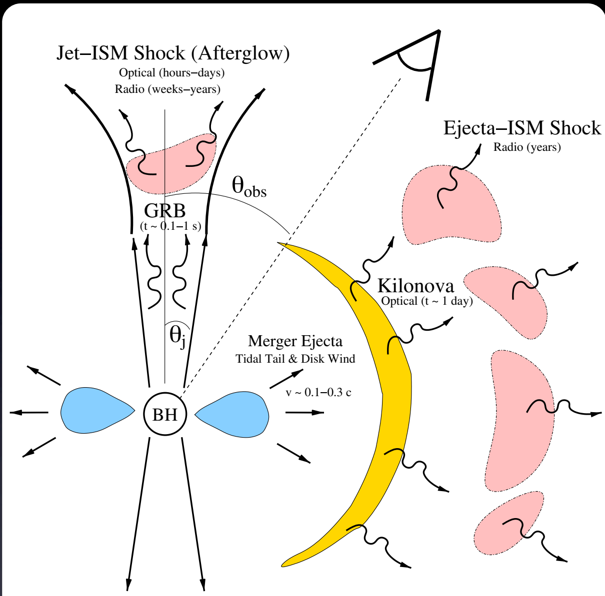

GW alert error
e.g. 6 deg x 6 deg
(not box shape in reality)
GW detection
Search for electromagnetic (EM) signals
Source identification
1 deg
Astrophysics with NS merger



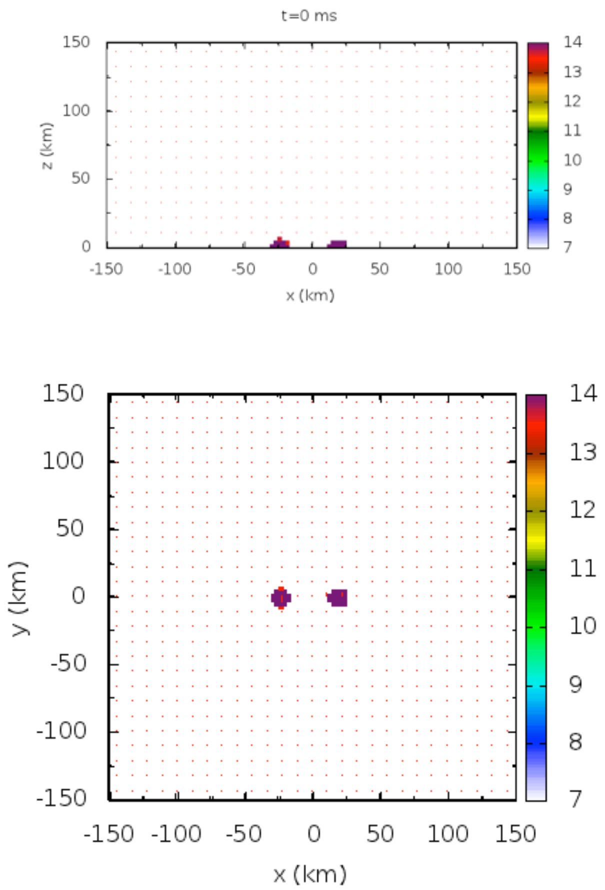
Kasliwal & Nissanke 2014

EM signature from NS merger

- On-axis short GRB
  - strongly beamed ✗
- Off-axis radio afterglow
  - isotropic ✓
  - long delay (~> 1 yr) ✗
- Soft X-ray signal
  - isotropic (probably)
  - short delay (< min) ✓
- Radioactive emission "kilonova" or "macronova"
  - isotropic ✓
  - short delay (~ days) ✓



Metzger & Berger 2012, ApJ 746, 48



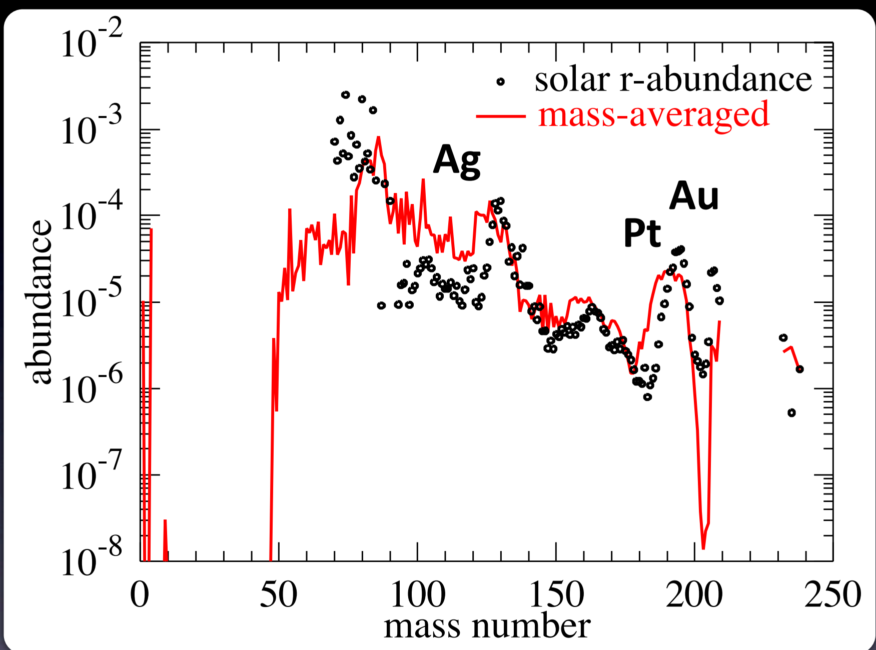
Mass ejection in NS mergers (numerical relativity)

$M \sim 10^{-3} - 10^{-2}$ Msun
$v \sim 0.1 - 0.2$ c

Hotokezaka+13, PRD, 87, 4001
Rosswog+13, MNRAS, 430, 2580

Talks by Kiuchi-san, Kyutoku-san, & Kawaguchi-san

r-process nucleosynthesis



Wanajo et al. 2014, ApJ, 789, L39

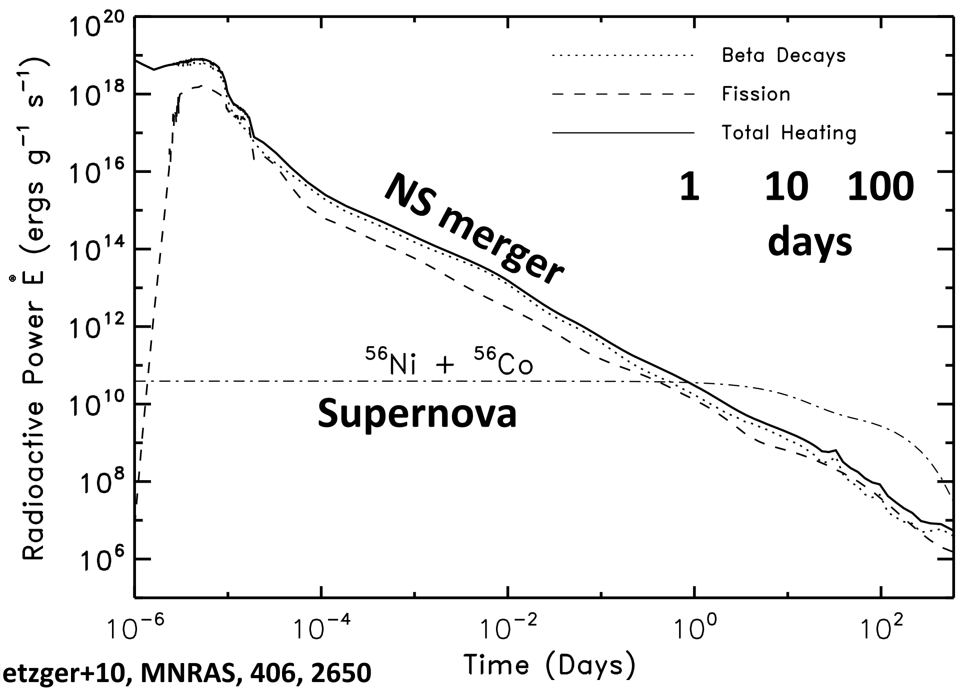
NS merger can be the origin of r-process elements
- Rate ~ 10^{-4} events/yr/Galaxy (<= GW)
- Mej ~ 10^{-2} Msun/event (<= Opt/IR)

<=> Supernova

Electromagnetic Emission from Compact Binary Mergers

- Why electromagnetic emission?
- Radioactively powered emission
- Prospects for observations

r-process nucleosynthesis => EM signal

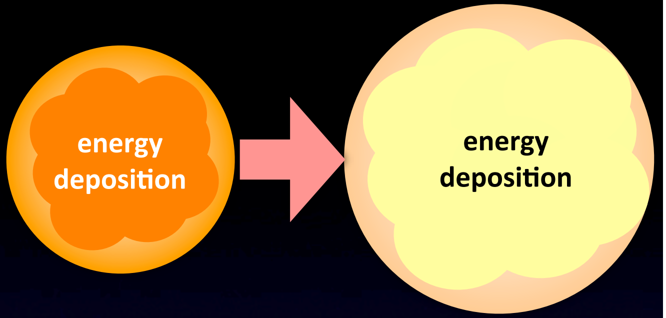


Metzger+10, MNRAS, 406, 2650

Thick against gamma-rays => optical emission

"kilonova/macronova"

Li & Paczynski 98, ApJ, 507, L59
Kulkarni 05, arXiv:0510256
Metzger+10, MNRAS, 406, 2650



Timescale

$$t_p \sim \underline{1\ \mathrm{day}}^{\,\mathbf{10}} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{0.1\ \mathrm{cm^2\ g^{-1}}}\right)^{1/2}$$

Luminosity

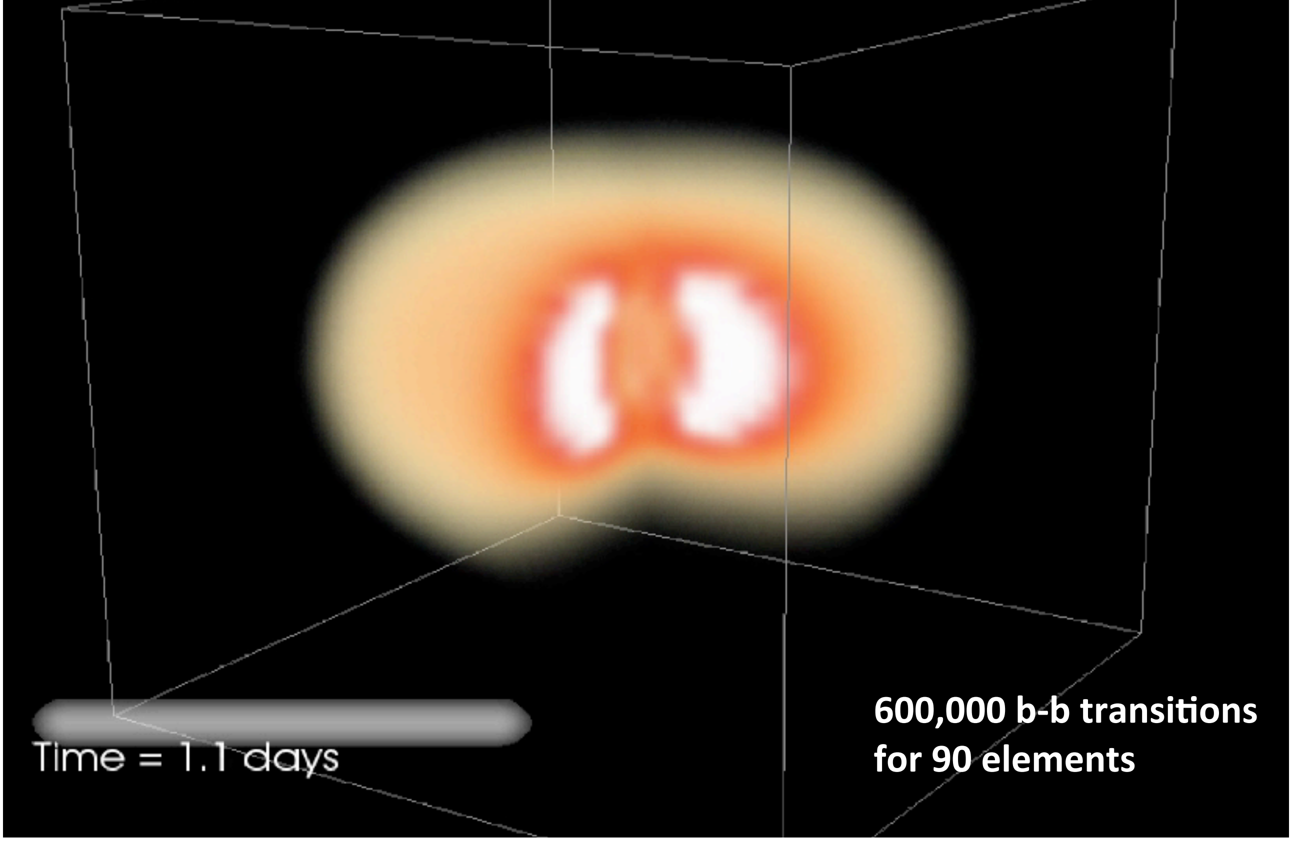
$$L \sim \underline{10^{42}\ \mathrm{erg\ s^{-1}}}^{\,\mathbf{10^{41}}} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \boxed{\left(\frac{\kappa}{0.1\ \mathrm{cm^2\ g^{-1}}}\right)^{-1/2}}$$

Opacity of r-process elements
κ ~ 10 cm^2 g^{-1}
- Kasen+13, ApJ, 774, 25 (for Nd)
- MT & Hotokezaka 13, ApJ, 775, 113
  (for mixture of r-process elements)

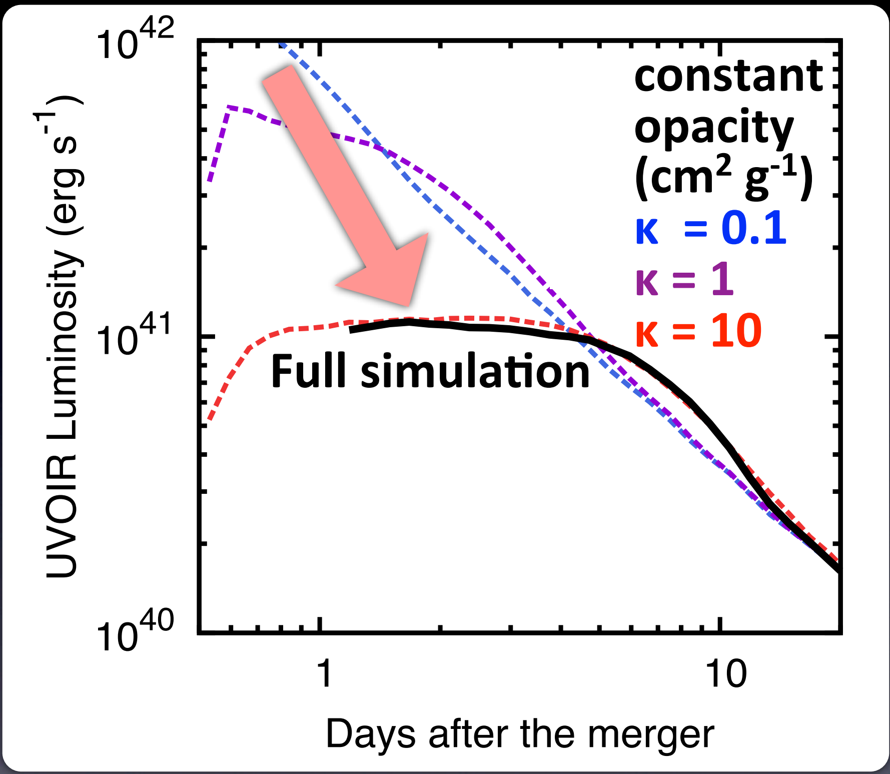
Opacity of Fe

3D radiative transfer simulations for NS merger

MT & Hotokezaka 2013, ApJ. 775, 113

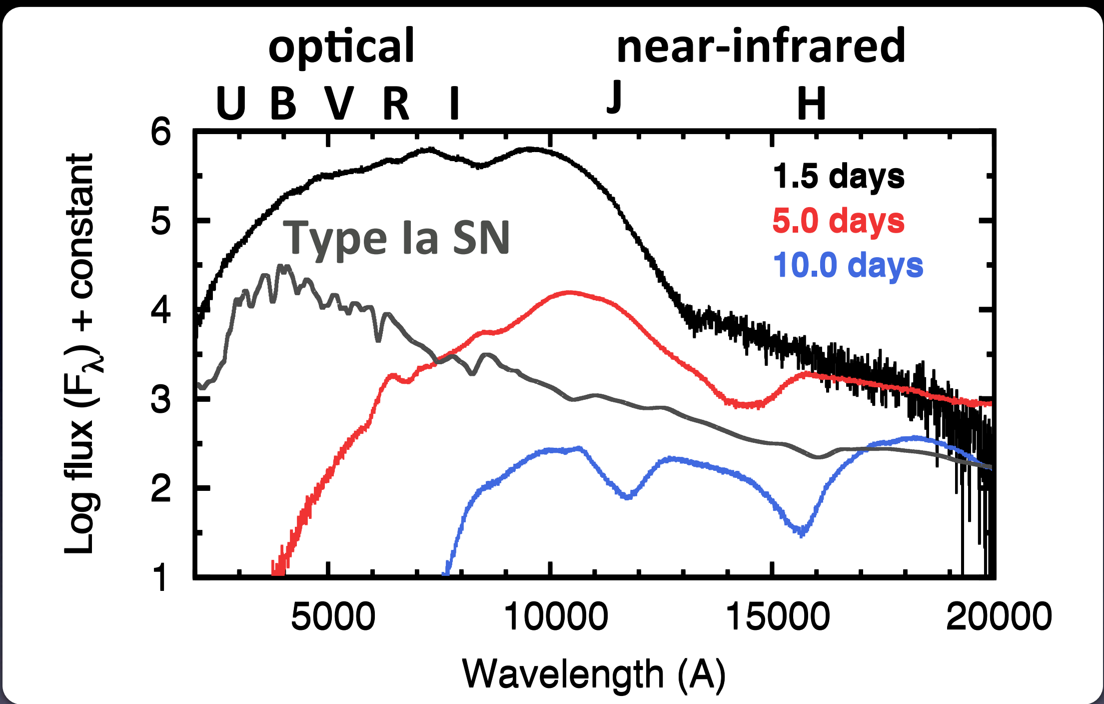


600,000 b-b transitions
for 90 elements



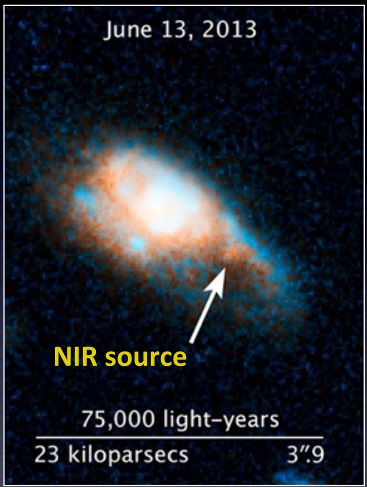
Fainter by a factor of 10!

(see also Kasen+13, ApJ, 774, 25, Barnes & Kasen 13, ApJ, 775, 18)

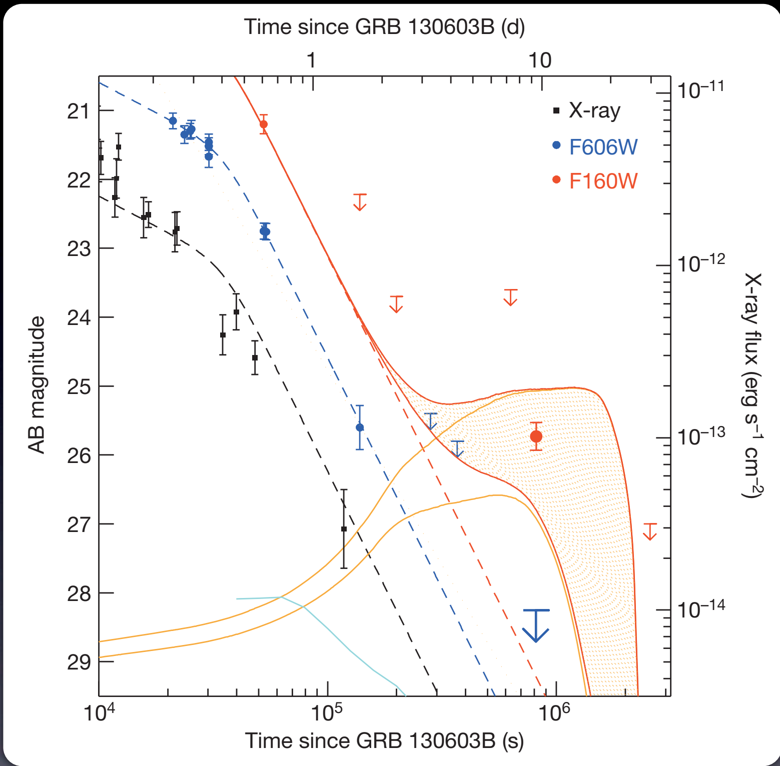


- Red spectrum (peak at near-infrared)
- Extremely broad-line (feature-less) spectra

GRB 130603B
(short GRB <= NS merger)

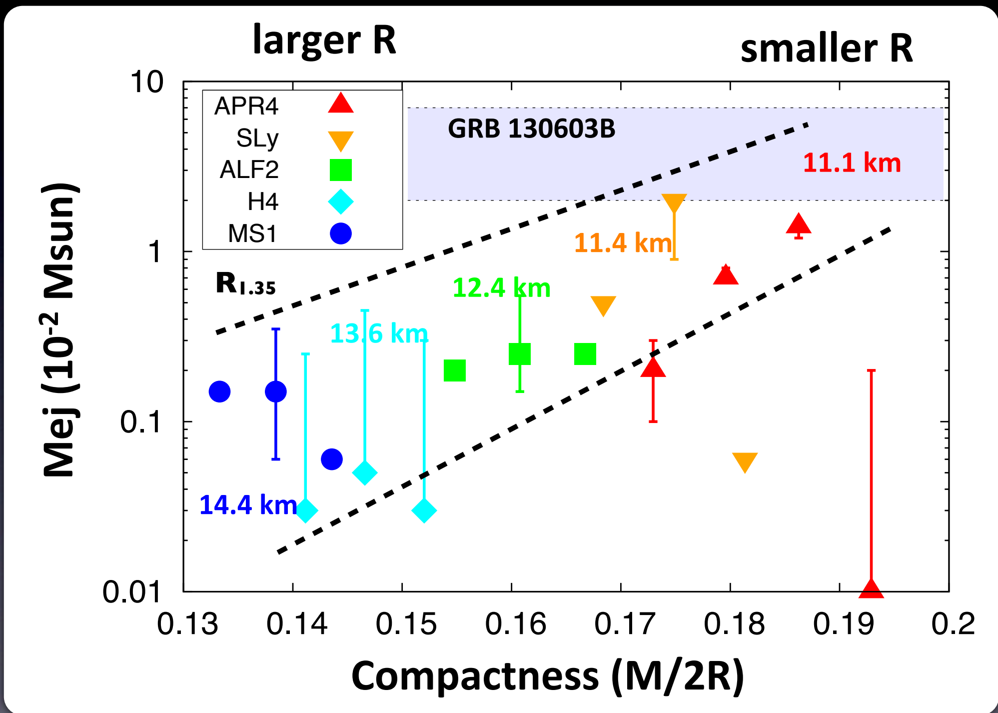


Tanvir+2013, Nature, 500, 547
Berger+2013, ApJ, 774, L23



Consistent with expectation (faint and red)
==> ejection of ~0.02 Msun

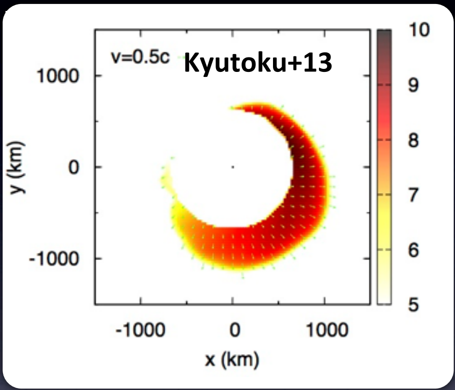
Observations <=> NS radius
(NS merger: smaller R => more mass ejection)

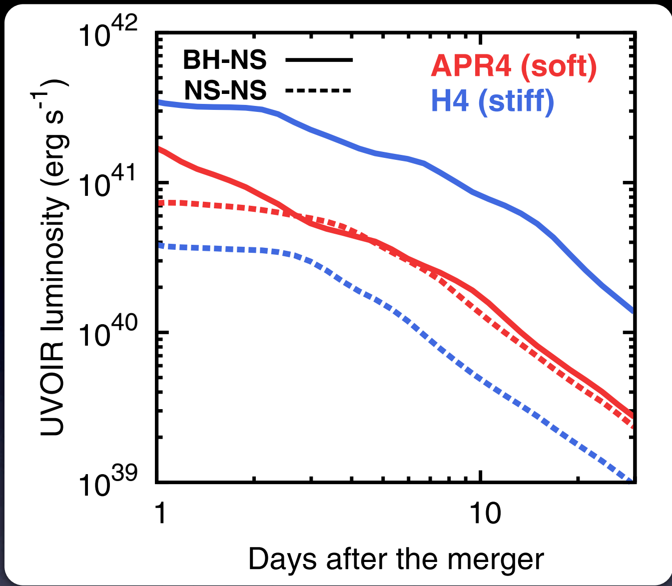


Hotokezaka, Kyutoku, MT, Kiuchi, Sekiguchi, Shibata, Wanajo 2013, ApJ, 778, L16

BH-NS Mergers

N(<800 Mpc)
~ 10 (0.2-300) / yr





Mej ~< 10^{-1} Msun

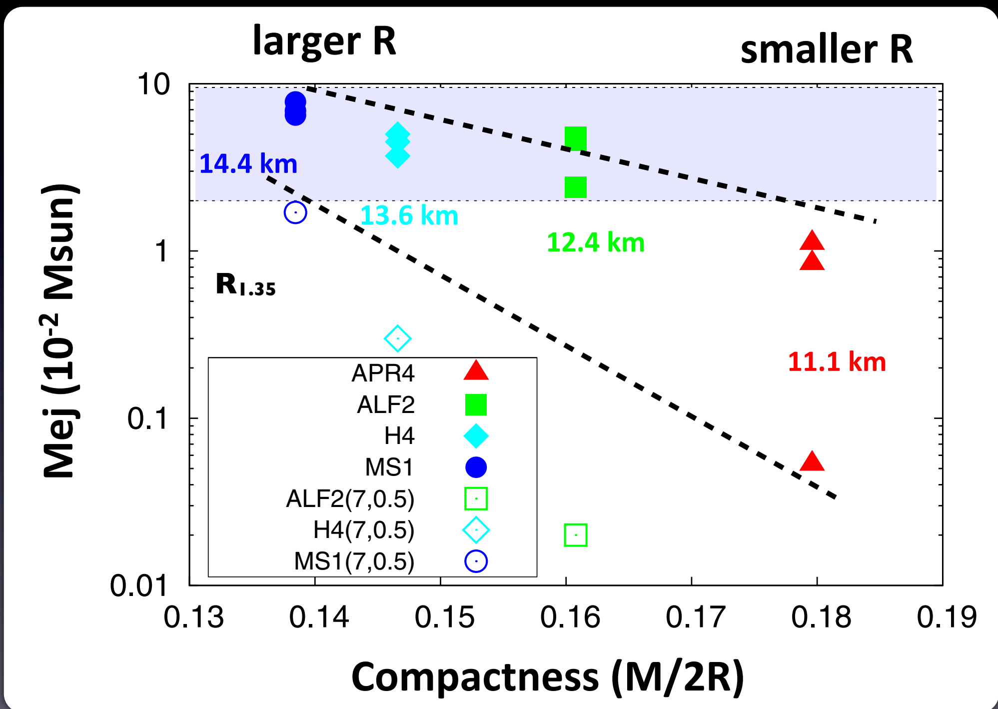
Can be brighter than NS merger (but depends on spin, inclination, and mass ratio)

MT, Hotokezaka, Kyutoku, Wanajo, Kiuchi, Sekiguchi, Shibata 2014, ApJ, 780, 31

see talks by Kiuchi-san, Kyutoku-san, and Kawaguchi-san

Observations <=> NS radius

(BH-NS merger: larger R => more mass ejection)

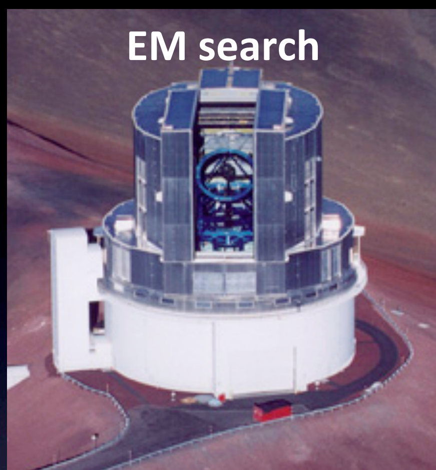


Hotokezaka, Kyutoku, MT, Kiuchi, Sekiguchi, Shibata, Wanajo 2013, ApJ, 778, L16

Electromagnetic Emission from Compact Binary Mergers

- Why electromagnetic emission?
- Radioactively powered emission
- Prospects for observations

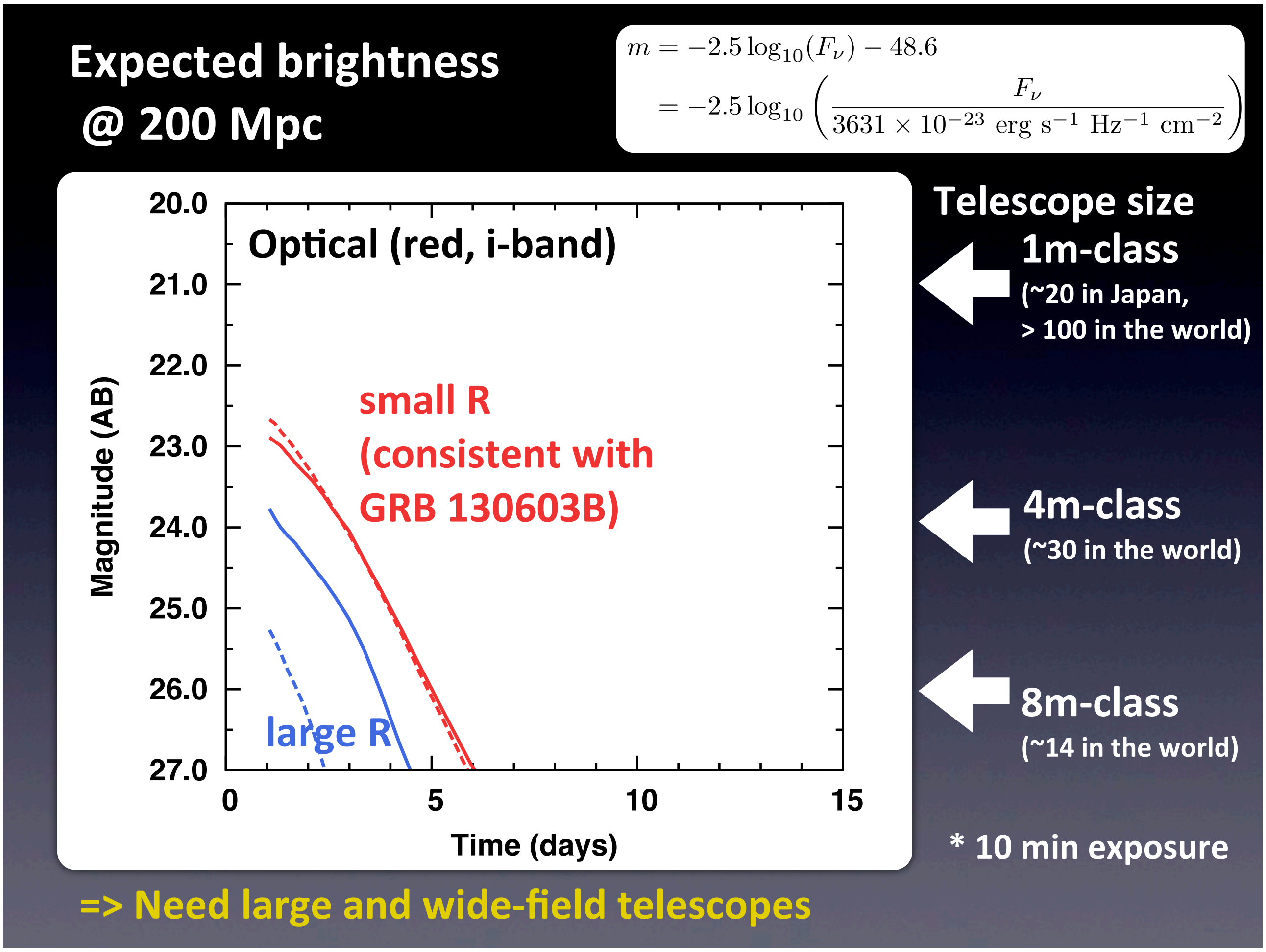
trigger

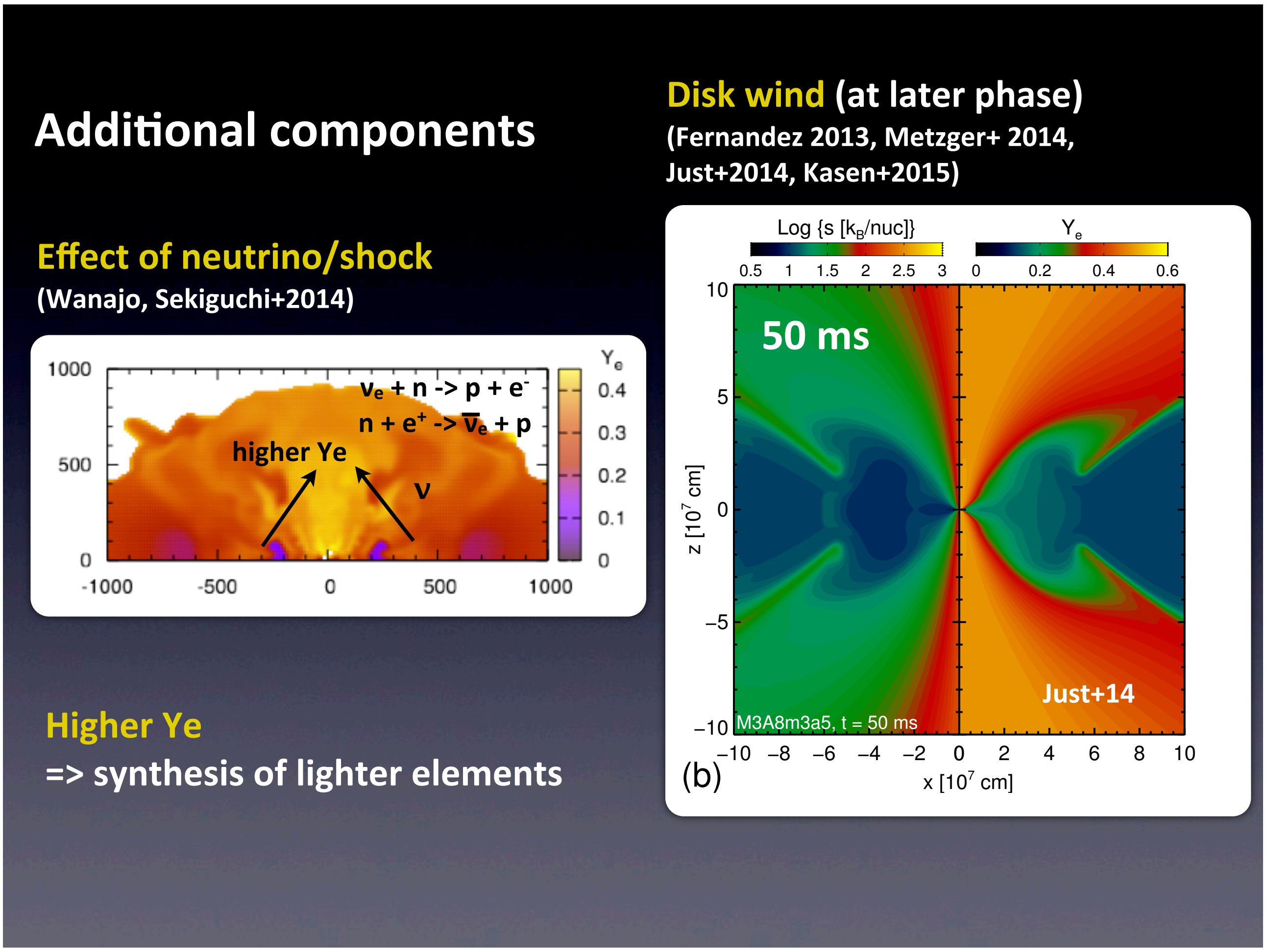


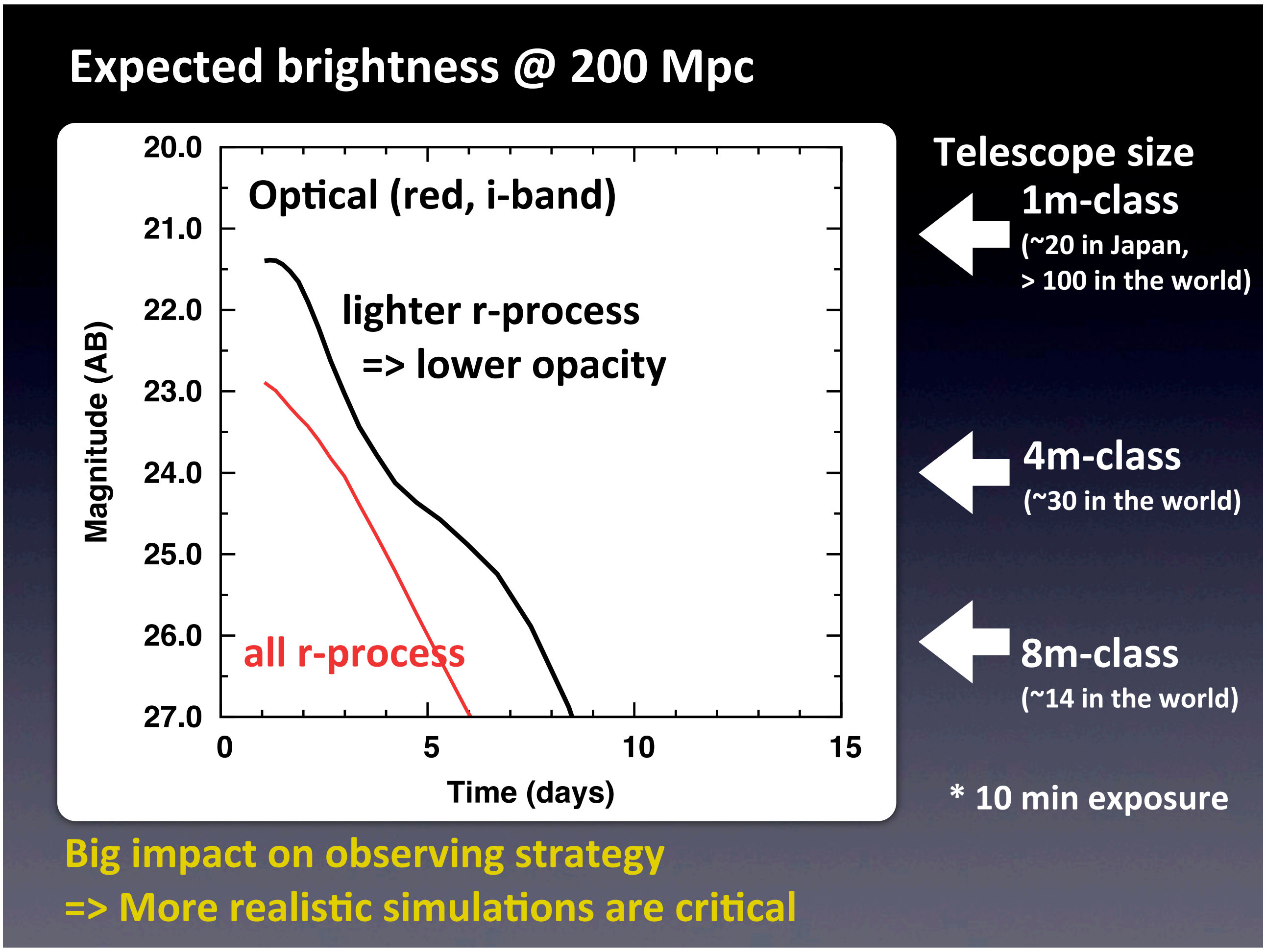
- NS-NS or BH-NS
  (chirp/reduced masses)
- Event rates

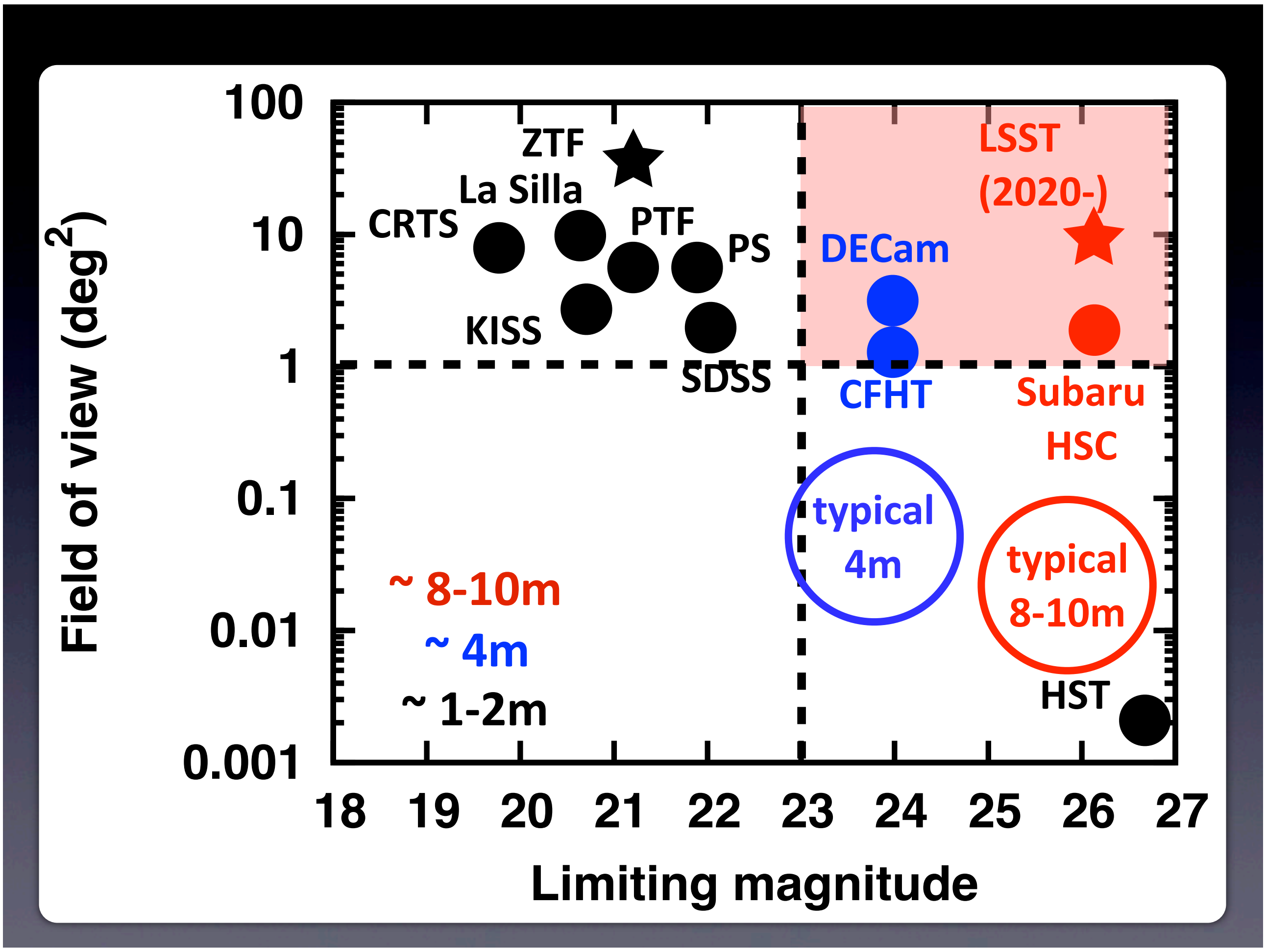
- Mass of ejecta
- NS radius
  (w/ help of
  numerical relativity)

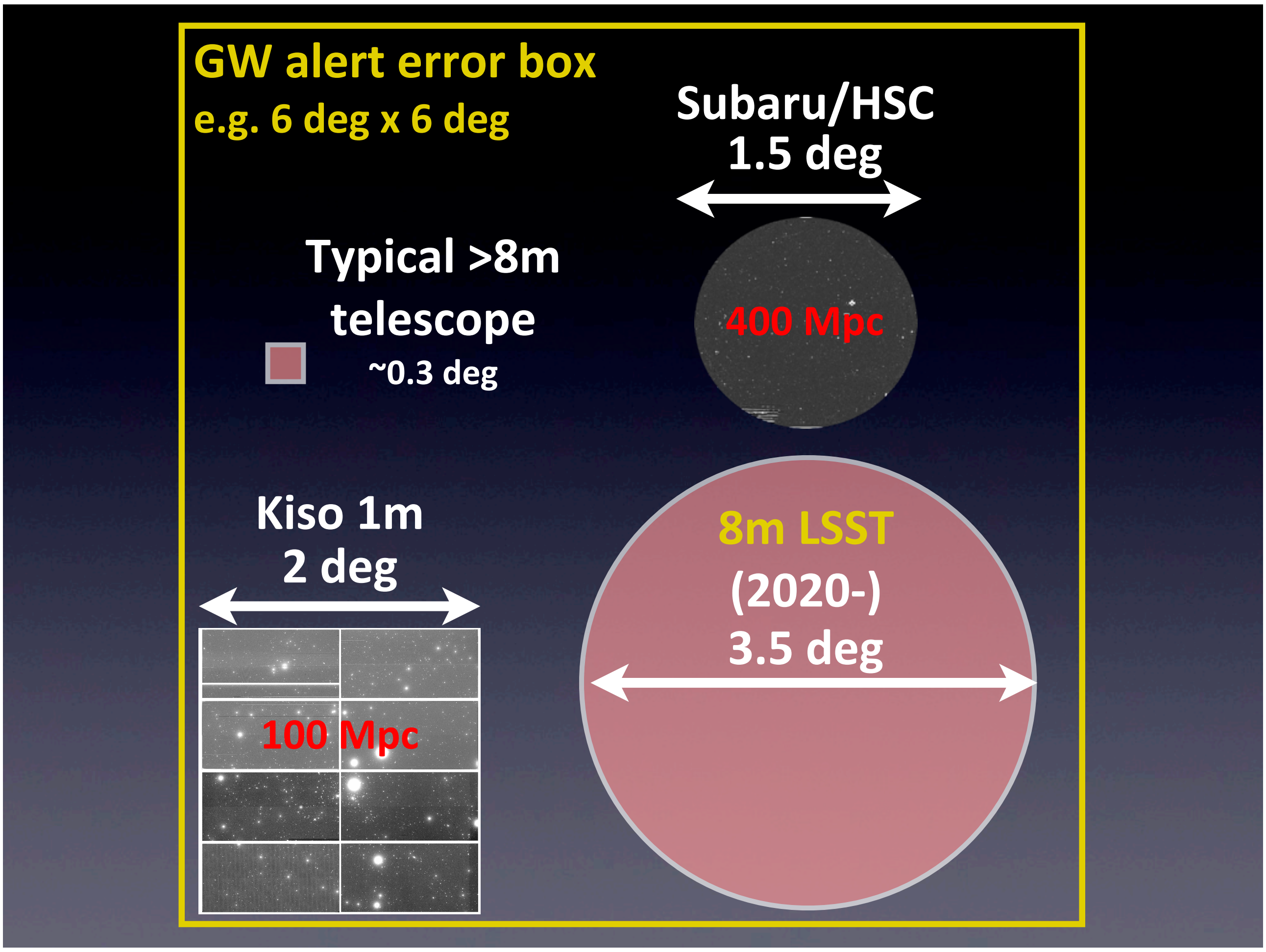
Origin of r-process elements
High-density EOS

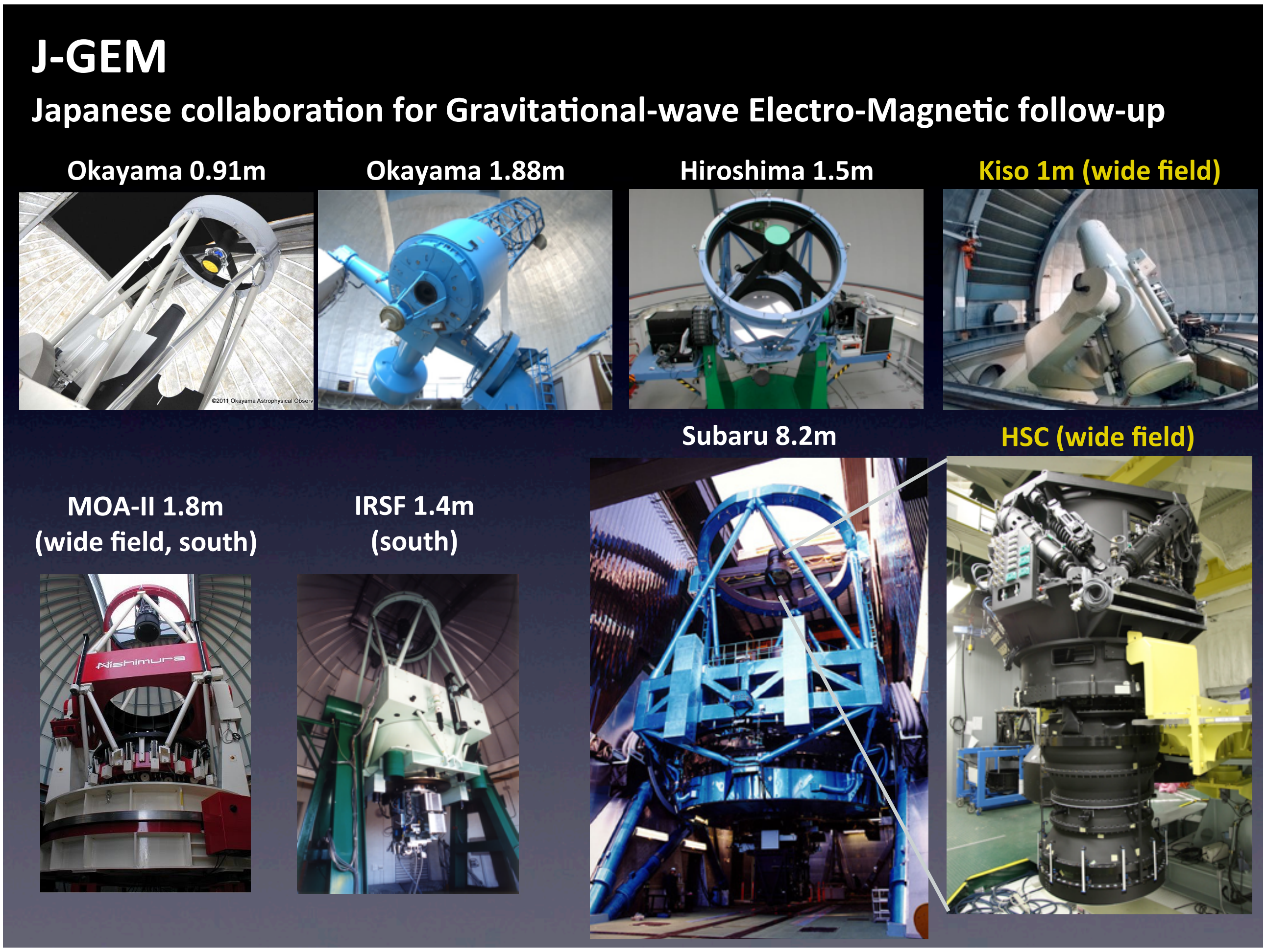

Expected brightness
@ 200 Mpc
$m = -2.5\log_{10}(F_\nu) - 48.6$
$= -2.5\log_{10}\left(\frac{F_\nu}{3631 \times 10^{-23}\ \mathrm{erg\ s^{-1}\ Hz^{-1}\ cm^{-2}}}\right)$
Optical (red, i-band)
small R
(consistent with
GRB 130603B)
large R
Magnitude (AB)
20.0
21.0
22.0
23.0
24.0
25.0
26.0
27.0
0
5
10
15
Time (days)
Telescope size
1m-class
(~20 in Japan,
> 100 in the world)
4m-class
(~30 in the world)
8m-class
(~14 in the world)
* 10 min exposure
=> Need large and wide-field telescopes

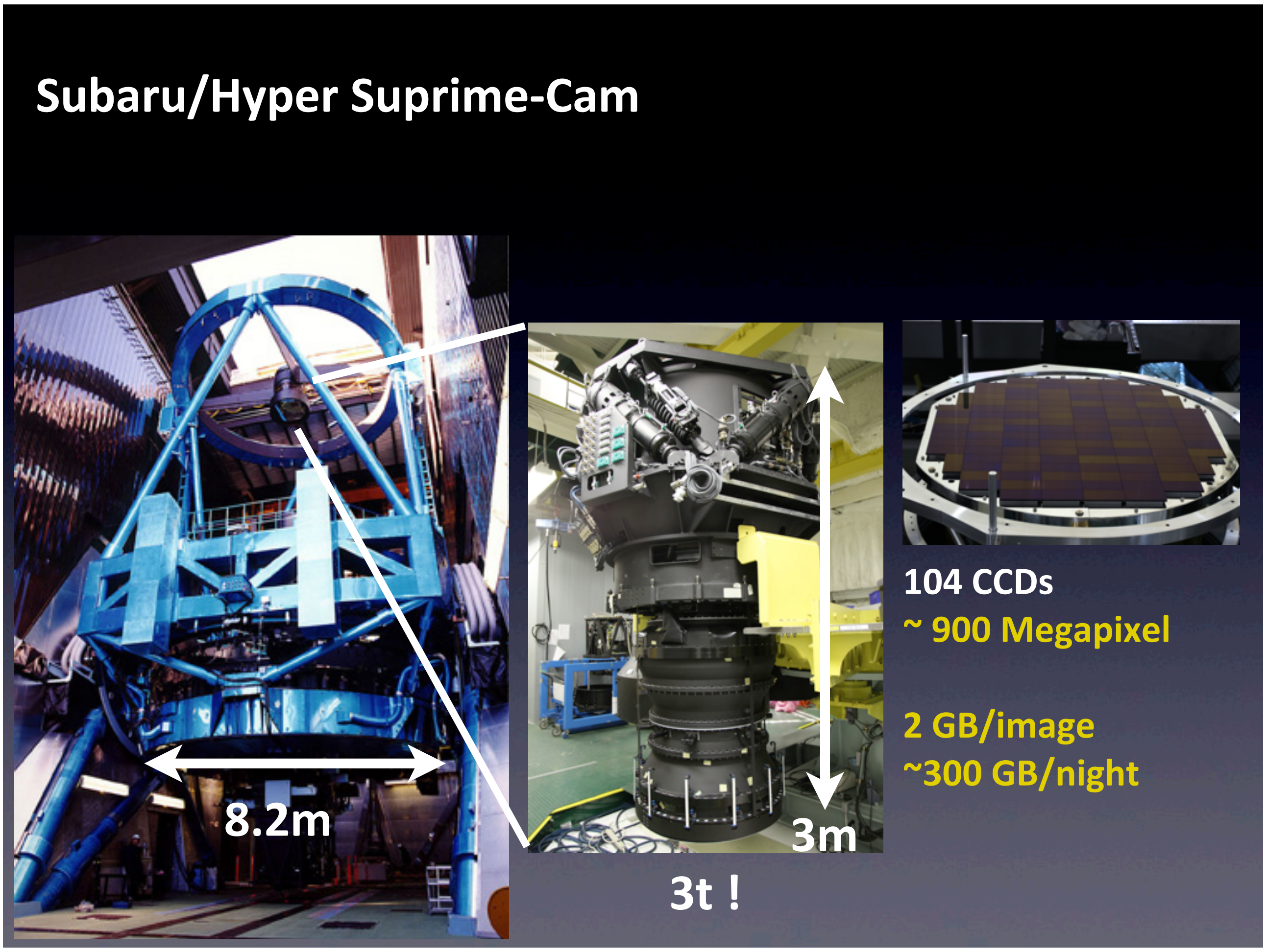

Additional components
Effect of neutrino/shock
(Wanajo, Sekiguchi+2014)
$\nu_e + n \rightarrow p + e^-$
$n + e^+ \rightarrow \bar{\nu}_e + p$
higher Ye
ν
Y_e
1000
500
0
-1000
-500
0
500
1000
0.4
0.3
0.2
0.1
0
Higher Ye
=> synthesis of lighter elements
Disk wind (at later phase)
(Fernandez 2013, Metzger+ 2014,
Just+2014, Kasen+2015)
Log {s [k_B/nuc]}
Y_e
0.5 1 1.5 2 2.5 3
0 0.2 0.4 0.6
50 ms
M3A8m3a5, t = 50 ms
Just+14
z [10^7 cm]
x [10^7 cm]
10
5
0
−5
−10
−10 −8 −6 −4 −2 0 2 4 6 8 10
(b)

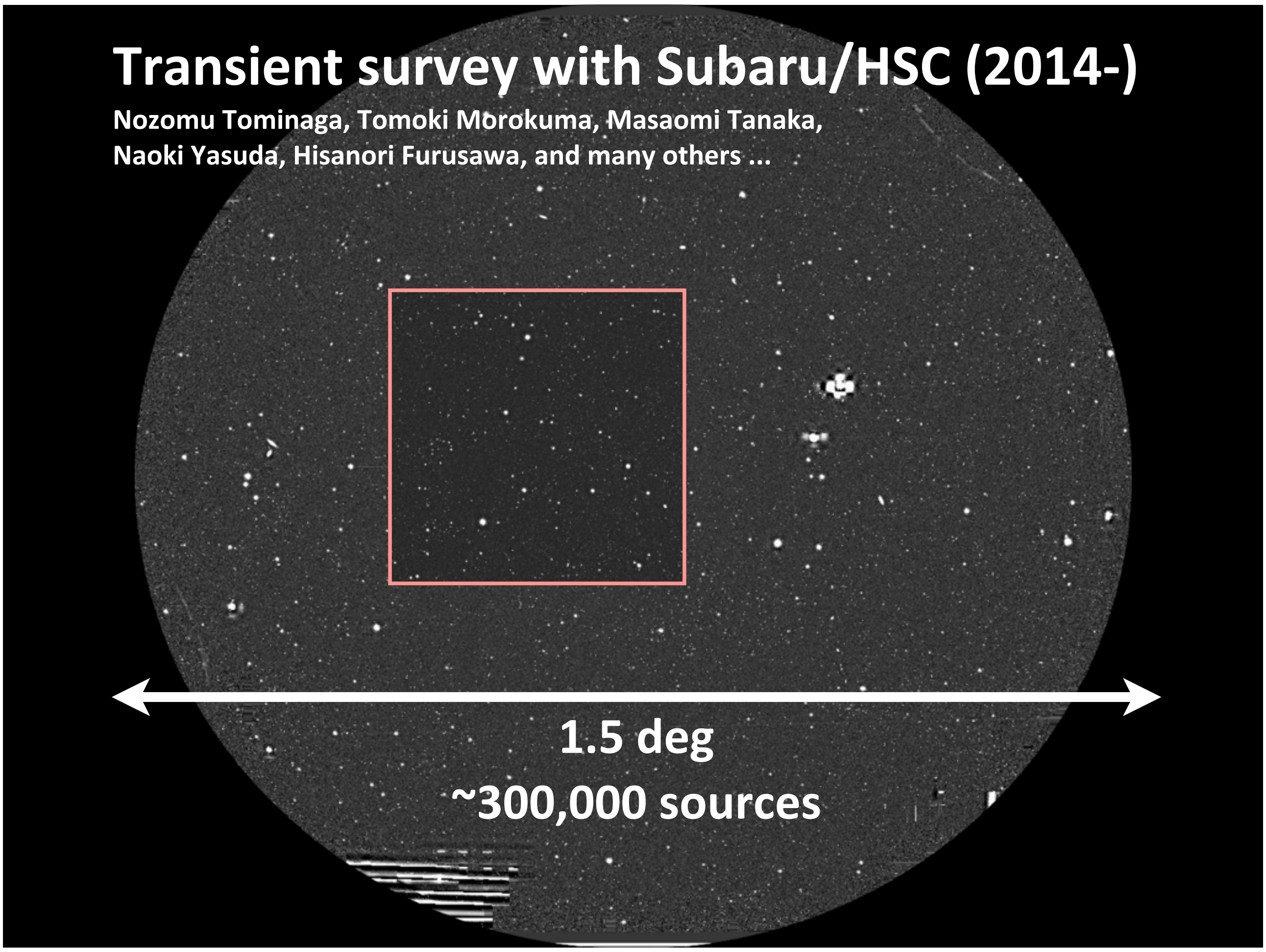

Expected brightness @ 200 Mpc
Optical (red, i-band)
lighter r-process
=> lower opacity
all r-process
Magnitude (AB)
20.0
21.0
22.0
23.0
24.0
25.0
26.0
27.0
0
5
10
15
Time (days)
Telescope size
1m-class
(~20 in Japan,
> 100 in the world)
4m-class
(~30 in the world)
8m-class
(~14 in the world)
* 10 min exposure
Big impact on observing strategy
=> More realistic simulations are critical


Field of view (deg²)
100
10
1
0.1
0.01
0.001
ZTF
La Silla
CRTS
PTF
PS
KISS
SDSS
LSST
(2020-)
DECam
CFHT
Subaru
HSC
typical
4m
typical
8-10m
HST
~ 8-10m
~ 4m
~ 1-2m
18
19
20
21
22
23
24
25
26
27
Limiting magnitude


GW alert error box
e.g. 6 deg x 6 deg
Subaru/HSC
1.5 deg
400 Mpc
Typical >8m
telescope
~0.3 deg
Kiso 1m
2 deg
100 Mpc
8m LSST
(2020-)
3.5 deg


J-GEM
Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up
Okayama 0.91m
Okayama 1.88m
Hiroshima 1.5m
Kiso 1m (wide field)
Subaru 8.2m
HSC (wide field)
MOA-II 1.8m
(wide field, south)
IRSF 1.4m
(south)


Subaru/Hyper Suprime-Cam
8.2m
3m
3t !
104 CCDs
~ 900 Megapixel
2 GB/image
~300 GB/night


Transient survey with Subaru/HSC (2014-)
Nozomu Tominaga, Tomoki Morokuma, Masaomi Tanaka,
Naoki Yasuda, Hisanori Furusawa, and many others ...
1.5 deg
~300,000 sources

Realtime transient selection

2014 Jul

The Astronomer's Telegram

First supernova candidates discovered with Subaru/Hyper Suprime-Cam

ATel #6291; *Nozomu Tominaga (Konan U./Kavli IPMU, U. Tokyo), Tomoki Morokuma (U. Tokyo), Masaomi Tanaka (NAOJ), Naoki Yasuda (Kavli IPMU, U. Tokyo), Hisanori Furusawa (NAOJ), Jian Jiang (U. Tokyo), Satoshi Miyazaki (NAOJ), Takashi J. Moriya (U. Bonn), Junichi Noumaru (NAOJ), Kiaina Schubert (NAOJ), and Tadafumi Takata (NAOJ)*
on 4 Jul 2014; 15:51 UT

Candidate selection in ~10 hr after the observation

2014 Nov

Supernova candidates discovered with Subaru/Hyper Suprime-Cam

ATel #6763; *Nozomu Tominaga (Konan U./Kavli IPMU, U. Tokyo), Tomoki Morokuma (U. Tokyo), Masaomi Tanaka (NAOJ), Naoki Yasuda (Kavli IPMU, U. Tokyo), Hisanori Furusawa (NAOJ), Jian Jiang (U. Tokyo), Nobuhiro Okabe (Kavli IPMU, U. Tokyo), Toshifumi Futamase (Tohoku Univ.), Satoshi Miyazaki (NAOJ), Takashi J. Moriya (AIfA, U. Bonn), Junichi Noumaru (NAOJ), Kiaina Schubert (NAOJ), and Tadafumi Takata (NAOJ)*
on 27 Nov 2014; 18:03 UT

~1 hr after the observation

Issues for GW follow-up
- Wider field (~10 deg^2 ==> ~100 deg^2)
- Fields without pre-images

=> Need bigger surveys

Summary

- Why EM emission from NS merger?
  - Crucial for identification of GW sources
  - LIGO O1 started in 2015 Sep
- Radioactively-powered emission
  - r-process nucleosynthesis
  - Fainter and redder than expected, but detectable
  - GRB 130603B => possible constraints on EOS (NS radius)
  - More realistic simulations are critical (wind components, BH-NS mergers, and ...)
- Prospects for observations
  - J-GEM: Japanese EM follow-up network
  - Subaru/HSC is important (transient search started)