THE 13TH RESCEU INTERNATIONAL SYMPOSIUM

JGRG31

October 24 - 28, 2022

The 31st Workshop on General Relativity and Gravitation
Koshiba Hall, The University of Tokyo
(Online-hybrid style)

Volume I: Invited Talks

Scientific Organizing Committee

Hideki Asada (Hirosaki U.)
Tomohiro Harada (Rikkyo U.)
Kenta Hotokezaka (RESCEU)
Kunihito Ioka (YITP)
Akihiro Ishibashi (Kindai U.)
Yosuke Ito (Osaka Metropolitan U.)
Keisuke Izumi (Nagoya U.)
Kohei Kamada (RESCEU)
Sugumi Kanno (Kyusyu U.)
Tsutomu Kobayashi (Rikkyo U.)
Koutarou Kyutoku (Kyoto U.)
Kei-ichi Maeda (Waseda U.)
Hayato Motohashi (Kogakuin U.)
Shinji Mukohyama (YITP)
Keiju Murata (Nihon U.)
Atsushi Nishizawa (RESCEU)
Toshifumi Noumi (Kobe U.)
Ryo Saito (Yamaguchi U.)
Teruaki Suyama (Tokyo Institude of Technology)
Takahiro Tanaka (Kyoto U.)
Shinji Tsujikawa (Waseda U.)
Masahide Yamaguchi (Tokyo Institude of Technology)
Kazuhiro Yamamoto (Kyusyu U.)
Ryo Yamazaki (Aoyama Gakuin U.)
Jun'ichi Yokoyama (RESCEU)
Shuichiro Yokoyama (Nagoya U.)
Chul-Moon Yoo (Nagoya U.)
Hirotaka Yoshino (Osaka Metropolitan U.)

Local Organizing Committee (RESCEU, The University of Tokyo)

Kenta Hotokezaka (chiar),
Kohei Kamada,
Atsushi Nishizawa,
Toshikazu Shigeyama,
Jun'ichi Yokoyama

Sponsors

- MEXT Grant-in-Aid for Scientific Research on Innovative Areas "重力波創世記 (Gravitational wave physics and astronomy: Genesis 17H06357)" (PI: Takahiro Tanaka) 総括班-A02 "重力波物理学・天文学における重力理論研究の新展開 (New developments of gravity theory research in gravitational wave physics 17H06359)" (PI: Shinji Mukohyama)

- Research Center for the Early Universe (RESCEU), School of Science, The University of Tokyo

The Presentation Award

Oral presentations

“Masaya Amo (YITP, Kyoto U.)
Generalization of the photon sphere referring to null infinity”

Kohei Fujikura (Kobe U.)
“Microlensing constraints on axion stars including finite lens and source size effects”

Paul Martens (YITP, Kyoto U.)
“Stability of the Fundamental Quasinormal Mode in Time-Domain Observations”

Morifumi Mizuno (Tokyo Institute of Technology)
“Weak lensing of gravitational waves in wave optics: Beyond Born approximation”

MIchiru Niibo (Ochanomizu U.)
“Neutrino lines from MeV dark matter annihilation and decay in JUNO”

Poster presentations

Jin Saito (Rikkyo U.)
“Black hole perturbations in modified gravity with two tensorial degrees of freedom”

Participant list

ID	Family name	Given name	Middle name	Affiliation	On-site
1	Abe	Yayoi		Waseda University	No
2	Amo	Masaya		Yukawa Institute for Theoretical Physics, Kyoto University	Yes
3	Anegawa	Takanori		Osaka Univ. Particle Physics Theory Group	No
4	Aoki	Katsuki		YITP, Kyoto University	Yes
5	Aoki	Sinya		Yukawa Institute for Theoretical Physics, Kyoto University	Yes
6	Aoyama	Takuma		Yamaguchi university	No
7	Arai	Shun		Kobayashi Maskawa Institute, Nagoya University	No
8	Arakida	Hideyoshi		Nihon Univ.	No
9	Asada	Hideki		Hirosaki University	No
10	Asami	Hiroki		Nagoya University	Yes
11	Bahamonde	Sebastian		Tokyo Institute of Technology	Yes
12	Baiotti	Luca		Osaka University	No
13	Bamba	Kazuharu		Fukushima University	Yes
14	Bernardo	Reginald Christian		Institute of Physics, Academia Sinica	No
15	Bhattacharya	Krishnakanta		Indian Association for the Cultivation of Science	No
16	Cannon	Kipp		The University of Tokyo	Yes
17	Cao	Mengdi		Beijing Normal University	No
18	Chen	Che-Yu		Institute of Physics, Academia Sinica	No
19	Chiang	Hsu-Wen		LeCosPA	No
20	Chiba	Takeshi		Nihon University	Yes
21	Cui	Yongxiang		Central China Normal University	No
22	De Felice	Antonio		YITP, Kyoto University	No
23	Di Filippo	Francesco		yitp	No
24	Diedrichs	Robin Fynn		Goethe University Frankfurt	No
25	Dimastrogiovanni	Ema		University of Groningen	No
26	Dong	Yu-Qi		Lanzhou University	No
27	Faraji	Shokoufe		ZARM Germany	No
28	Frost	Torben	Christian	ZARM, University of Bremen	No
29	Fujikura	Kohei		Kobe University	Yes
30	Fujisawa	Kotaro		University of Tokyo	No
31	Fujita	Tomohiro		Waseda University	Yes
32	Furugori	Hideo		Nagoya University	Yes
33	Garg	Suyog		ICRR, UTokyo	No
34	Giorgetti Landim	Ricardo Cesar		Technical University of Munich	Yes
35	Gondolo	Paolo		University of Utah, Tokyo Institute of Technology, Kavli IPMU	Yes
36	Gorji	Mohammad Ali		Yukawa Institute, Kyoto University	No
37	Hamana	Takashi		NAOJ	No
38	Harada	Tomohiro		Rikkyo University	Yes
39	Harada	Reiko		RESCEU, The University of Tokyo	No
40	Hashimoto	Yuki		Faculty of Symbiotic Systems Sci. Fukushima Univ.	Yes
41	Hayashi	Eiji		Riron-kon	No
42	He	Minxi		KEK	Yes
43	Higashino	Yurika		Waseda Univ.	No
44	Himemoto	Yoshiaki		Nihon university	No
45	Hioki	Kenta		Sumitomo Mitsui Banking Corporation	No
46	Hiramatsu	Takashi		Rikkyo University	No
47	Hirano	Shin'ichi		Tokyo Institute of Technology	No
48	Hirano	Koichi		Tsuru University	No
49	Hiranuma	Yuta		Niigata University	No
50	Homma	Kensuke		Hiroshima University	No
51	Hong	Muzi		UTokyo	No
52	Hoshino	Hidetomo		Waseda University	No
53	Hotokezaka	Kenta		University of Tokyo	Yes
54	Hu	Kun		Central China Normal University	No
55	Ichiki	Kiyotomo		Nagoya University	No
56	Ichinose	Shoichi		Shizuoka University	No
57	Ide	Daichi		Tokyo Institute of Technology	No
58	Igata	Takahisa		Gakushuin University	No
59	Iguchi	Hideo		Nihon University	No
60	Iizuka	Hayami		Rikkyo university	Yes
61	Ikeda	Tact		Rikkyo Univ.	No
62	Inoue	Masato		Tokyo Institute of Technology	No
63	Inui	Ryoto		Nagoya University	No
64	Ishibashi	Akihiro		Kindai University	No
65	Ishihara	Hideki		Osaka Metropolitan University	No
66	Ito	Asuka		QUP,KEK	No
67	Itoh	Yousuke		Osaka Metropolitan University	Yes
68	Izumi	Keisuke		Nagoya U., KMI & Dept. of Math.	Yes
69	Jeong	Hyun		The University of Tokyo, Graduate School of Science	Yes
70	Jiao	Jiageng		AMSS,CAS	No

71	Kakizaki	Mitsuru		University of Toyama	No
72	Kaku	Youka		Nagoya university	Yes
73	Kamada	Kohei		RESCEU, U-Tokyo	Yes
74	Kamata	Masaru		National Institute of Technology, Kisarazu College	No
75	Kaminaga	Yasuhito		National Institute of Technology, Gunma College	No
76	Kamiya	Yoshio		The University of Tokyo	No
77	Kan	Nahomi		National Institute of Technology, Gifu College	No
78	Kanai	Takamasa		Nagoya university	No
79	Kanamori	Shotaro		Depertment of physics ,The University of Tokyo	No
80	Kanda	Nobuyuki		Osaka Metropolitan University	No
81	Kanno	Sugumi		Kyushu University	No
82	Karmakar	Purnendu		RESCEU, University of Tokyo	No
83	Kasai	Kentaro		University of Tokyo	No
84	Katagiri	Takuya		Tohoku University	No
85	Katayama	Tomoki		SOKENDAI	No
86	Kato	Akira		Master's student	No
87	Kato	Takashi		ICRR, U.Tokyo	No
88	Katsumata	Akihito		Rikkyo University	Yes
89	Katsuragawa	Taishi		Central China Normal University	No
90	Kawaguchi	Ryodai		Waseda University	No
91	Kimura	Masashi		Daiichi Institute of Technology	No
92	Kimura	Rampei		WIAS	No
93	Kinoshita	Shunichiro		Nihon University / Chuo University	No
94	Kitaku	Ryo		Nagoya-u	No
95	Kitami	Yuuki		Fuculty of Symbiotic Systems Sci. Fukushima Univ.	No
96	Kobayashi	Tsutomu		Rikkyo University	Yes
97	Kobayashi	Hajime		YITP, Kyoto University	No
98	Kodama	Tatsuki		Saga university	Yes
99	Koga	Yasutaka		Nagoya University	No
100	Kohri	Kazunori		KEK	No
101	Koike	Tatsuhiko		Keio University	No
102	Komatsubara	Ryosuke		The University of Tokyo	Yes
103	Kondo	Kei-Ichi		Chiba University	No
104	Konno	Kohkichi		National Institute of Technology, Tomakomai College	No
105	Konno	Shigeru		Tokai univ.	No
106	Kozaki	Hiroshi		National Institute of Technology, Ishikawa College	No
107	Kristiano	Jason		RESCEU, The University of Tokyo	Yes
108	Kubo	Ryosuke		Hirosaki university	No
109	Kubota	Kei-ichiro		YITP, Kyoto University	No
110	Kudo	Ryuya		Hirosaki University	No
111	Kumar	Sravan	K	Tokyo Institute of Technology	Yes
112	Kume	Jun'ya		RESCEU, University of Tokyo	Yes
113	Kuroda	Hitomi		Ochanomizu University	Yes
114	Kuwahara	Soichiro		U of Tokyo, RESCEU	No
115	Kyutoku	Koutarou		Kyoto University	No
116	Lee	Kangjae		Nagoya University	Yes
117	Lehner	Luis		Perimeter Institute	No
118	Lei	Fu		graduate school of mathematics, Nagoya university	No
119	Levi Said	Jackson		University of Malta	No
120	Li	Siyao		Tokyo Institute of Technology	Yes
121	Li	Zhixiang		ucas	No
122	Maeda	Hideki		Hokkai-Gakuen University	No
123	Maeda	Kei-ichi		Waseda University	No
124	Manita	Yusuke		Kyoto University	No
125	Mann	Robert	Bruce	University of Waterloo	No
126	Martens	Paul	J. L.	YITP, Kyoto University	Yes
127	Matsui	Hiroki		YITP, Kyoto University	No
128	Matsui	Yuma		Nagoya University	No
129	Matsumoto	Shuichi		University of the Ryukyus	No
130	Matsumura	Akira		Kyushu University	No
131	Matsuno	Ken		Osaka Metropolitan University	No
132	Miao	Haixing		Tsinghua University	No
133	Michinobu	Yuri		Yukawa institute for theoretical physics	No
134	Michishita	Yoji		Kagoshima university	No
135	Miki	Daisuke		Kyushu University	Yes
136	Mikura	Yusuke		Nagoya University	No
137	Minato	Keita		Kyoto university	No
138	Mishima	Takashi		Nihon University	Yes
139	Miyamoto	Umpei		Akita Prefectural University	No
140	Miyashita	Yuichi		Tokyo Institute of Technology	Yes
141	Miyashita	Shoichiro		Waseda University	No

142	Miyauchi	You		Keio university	No
143	Miyauchi	Yu		Kyoto university	No
144	Miyoki	Shinji		ICRR, The University of Tokyo	Yes
145	Mizuguchi	Yurino		Nagoya University	No
146	Mizui	Kotaro		Waseda University	No
147	Mizuno	Morifumi		Tokyo Institute of Technology	Yes
148	Mizuno	Shuntaro		National Institute of Technology, Hachinohe College	No
149	Morikawa	Masahiro		Ochanomizu Univ.	No
150	Morisawa	Yoshiyuki		OCAMI, Osaka Metropolitan University	No
151	Morita	Masaaki		no affiliation	No
152	Motohashi	Hayato		Kogakuin University	Yes
153	Mukohyama	Shinji		YITP, Kyoto U	Yes
154	Murai	Kai		University of Tokyo	No
155	Murakoshi	Yuta		Faculty of Symbiotic Systems Sci. Fukushima Univ.	No
156	Muraoka	Yoshiki		Kanazawa University	No
157	Murata	Tomoaki		Rikkyo University	Yes
158	Murata	Keiju		Nihon University	Yes
159	Nagao	Keiichi		Ibaraki University, Niels Bohr Institute	No
160	Nagasawa	Michiyasu		Kanagawa University	No
161	Nakagawa	Shota		Tohoku University	No
162	Nakamura	Kouji		NAOJ, Gravitational-Wave Science Project	Yes
163	Nakamura	Yuya		Hirosaki University	No
164	Nakano	Takaomi		Nagoya university	No
165	Nakao	Ken-ichi		Osaka Metropolitan University	No
166	Nakarachinda	Ratchaphat		Naresuan University, Phitsanulok, Thailand	Yes
167	Nakasawa	Noriaki		Nagoya univ.	No
168	Nakashi	Keisuke		Kochi KOSEN	Yes
169	Nakato	Ann		Kobe University	Yes
170	Namba	Ryo		RIKEN iTHEMS	No
171	Nanda	Amlan		Graduate School of Science	No
172	Naokawa	Fumihiro		The University of Tokyo	Yes
173	Narikawa	Tatsuya		ICRR, The University of Tokyo	No
174	Narita	Makoto		National Instituteu of Technology, Okinawa College	No
175	NARUKO	Atsushi		Center for Gravitational Physics and Quantum Information, Yukaw	No
176	Niibo	Michiru		Ochanomizu university	Yes
177	Nishizawa	Atsushi		RESCEU, The University of Tokyo	Yes
178	Nomura	Kimihiro		Kobe University	Yes
179	Noui	Karim		IJCLab, Paris Saclay University	No
180	Noumi	Toshifumi		Kobe University	No
181	Nozawa	Masato		Osaka Institute of Technology	No
182	Numajiri	Kota		Nagoya University	No
183	Obata	Ippei		Max-Planck-Institute for Astrophysics	No
184	Ogasawara	Kota		Kyoto University	Yes
185	Ogawa	Naoki		YITP	No
186	Ogawa	Tatsuya		Osaka Metropolitan University	No
187	Ohta	Nobuyoshi		National Central University	No
188	Okabayashi	Kazumasa		Yukawa Institute of Theoretical Physics	No
189	Okamatsu	Fumiya		saga university	No
190	Okawa	Hirotada		Waseda Institute for Advanced Study	No
191	Okumura	Teppei		Academia Sinica Institute of Astronomy and Astrophysics	No
192	Omiya	Hidetoshi		Kyoto U	Yes
193	Oohara	Ken-ichi		The Open University of Japan	No
194	Oshita	Naritaka		RIKEN, iTHEMS	Yes
195	Pani	Paolo		Sapienza U. of Rome	No
196	Panpanich	Sirachak		Waseda University	Yes
197	Pi	Shi		Institute of Theoretical Physics, Chinese Academy of Sciences	Yes
198	Porter	Edward	K.	APC, Observatoire de Paris	No
199	Rahman	Mostafizur		Indian Institute of Technology, Gandhinagar	Yes
200	Sago	Norichika		Kyoto University/Osaka Metropolitan U.	No
201	Saida	Hiromi		Daido University	No
202	Saito	Daiki		Nagoya University	Yes
203	Saito	Jin		Rikkyo University	Yes
204	Saito	Ryo		Yamaguchi University	Yes
205	Sakai	Nobuyuki		Yamaguchi University	Yes
206	Sakellariadou	Mairi		King's College London	Yes
207	Sano	Fumiya		Tokyo Institute of Technology	No
208	Sasaki	Tatsuya		Hirosaki University	No
209	Sasaki	Misao		Kavli IPMU, University of Tokyo	No
210	Sasaoka	Seiya		Tokyo Institute of Technology	No
211	Sato	Ki-ichiro		Tokyo University of Science	No
212	Sato	Katsuhiko		Research Center For Science Systems,JSPS	No

213	Satoh	Kei		Waseda University	No
214	Sawada	Takahiro		NITEP, Osaka Metropolitan University	No
215	Sekiguchi	Yuichiro		Toho University	No
216	Sendouda	Yuuiti		Hirosaki University	No
217	Senovilla	Jose	M M	University of the Basque Country (Spain) / YITP (Japan)	Yes
218	Seto	Naoki		kyoto university	Yes
219	Seto	Osamu		Hokkaido University	No
220	Shibahara	Kensuke		Hirosaki University	No
221	Shigeyama	Toshikazu		University of Tokyo	Yes
222	Shinkai	Hisaaki		Osaka Institute of Technology	No
223	Shinohara	Ryota		Waseda University	No
224	Shinohara	Takumi		Saga University	No
225	Shiraishi	Kiyoshi		Yamaguchi University	No
226	Shiromizu	Tetsuya		Nagoya University	Yes
227	Soligon	Diego		Nagoya University	Yes
228	Somiya	Kentaro		Tokyo Institute of Technology	No
229	Sugiyama	Yuki		Kyushu University	Yes
230	Suyama	Teruaki		Tokyo Institute of Technology	No
231	Suzuki	Ryotaku		Toyota Technological Institute	Yes
232	Suzuki	Toya		SOKENDAI, KEK	No
233	Tachinami	Tomoya		Hirosaki University	No
234	Tada	Yuichiro		Nagoya University	Yes
235	Tahara	Hiroaki		Rikkyo University	Yes
236	Taira	Keisuke		Faculty of Symbiotic Systems Sci. Fukushima Univ.	No
237	Takadera	Toshiki		Rikkyo University	No
238	Takahashi	Kazufumi		YITP, Kyoto University	Yes
239	Takahashi	Takuya		Kyoto University	Yes
240	Takahashi	Tomo		Saga University	Yes
241	Takahashi	Mikiya		University of Tsukuba	No
242	Takahashi	Kaisei		Hirosaki University	No
243	Takahashi	Rohta		NIT, Tomakomai College	No
244	Takami	Kentaro		Kobe City College of Technology	No
245	Takamori	Yohsuke		National Institute of Technology, Wakayama College	No
246	Takatani	Kyouhei		Osaka Metropolitan University	No
247	Takeda	Hiroki		Kyoto University	No
248	Takeda	Mei		Osaka City University	No
249	Takizawa	Keita		Hirosaki University	No
250	Tanahashi	Norihiro		Chuo University	Yes
251	Tanaka	Takahiro		Kyoto University	Yes
252	Tanaka	Junya		The University of Tokyo	No
253	Tanida	Koki		Nagoya University	No
254	Taniguchi	Masahiko		Hiroshima University	Yes
255	Taniguchi	Keisuke		University of the Ryukyus	No
256	Tatekawa	Takayuki		National Institute of Technology, Kochi college	No
257	Toda	Yo		Hokkaido University	Yes
258	Tokeshi	Koki		RESCEU, the University of Tokyo	No
259	Tomikawa	Keitaro		Rikkyo University	No
260	Tomikawa	Yoshimune		Tokyo Denki University	No
261	Tomita	Kota		Osaka Metropolitan University	No
262	Tomizawa	Shinya		Toyota Technological Institute	No
263	Tomonari	Kyosuke	Suguro	Tokyo Institute of Technology	No
264	Tonooka	Sae		Faculty of Symbiotic Systems Sci. Fukushima Univ.	No
265	Trova	Audrey		ZARM	No
266	Tsuda	Ren		Chuo University	No
267	Tsujikawa	Shinji		Waseda University	No
268	Tsuyuki	Takanao		Kogakuin	No
269	Uchida	Fumio		RESCEU, U. Tokyo	Yes
270	Uchikata	Nami		ICRR, Univ. of Tokyo	No
271	Uchiyama	Takashi		ICRR, UT	No
272	Ueda	Kazushige		Kyushu University	Yes
273	Uehara	Koichiro		Nagoya university	No
274	Uemichi	Keiya		Nagoya University	No
275	Umakoshi	Ryusei		Yamaguchi University	No
276	Urakawa	Yuko		KEK	Yes
277	Uryu	Koji		University of the Ryukyus	No
278	Uzawa	Kunihito		Kwansei Gakuin University	Yes
279	Valbusa Dall'Armi	Lorenzo		Università degli Studi di Padova	Yes
280	van Putten	Maurice	HPM	Sejong University	No
281	Wall	Aron	C.	U. of Cambridge	No
282	Wang	Shao-Jiang		Institute of Theoretical Physics, Chinese Academy of Sciences	No
283	Wang	Ziwei		Kobe University	No

284	Wang	He		ICTP-AP	No
285	Washimi	Tatsuki		NAOJ	No
286	Watabiki	Yoshiyuki		Tokyo Institute of Technology	Yes
287	Watanabe	Yuki		NIT, Gunma College	Yes
288	Watarai	Daiki		RESCEU, the University of Tokyo	No
289	Wei	Zixia		YITP, Kyoto University	No
290	Wu	Zhen-Yuan		Yamaguchi University	Yes
291	Yamada	Masaki		Tohoku University	No
292	Yamaguchi	Masahide		Tokyo Institute of Technology	Yes
293	Yamahira	Kakeru		Hirosaki University	No
294	Yamamoto	Takahiro	S	Nagoya University	No
295	Yamamoto	Naoki		Keio University	No
296	Yamamoto	Kazuhiro		Kyushu University	No
297	Yamauchi	Kohei		Hirosaki University	No
298	Yamauchi	Daisuke		Kanagawa University	No
299	Yashiki	Mai		Yamaguchi University	No
300	Yingcharoenrat	Vicharit		Kavli IPMU, University of Tokyo	No
301	Yoda	Takuya		Kyoto University	No
302	Yokoyama	Jun'ichi		RESCEU	Yes
303	Yokoyama	Shuichiro		KMI, Nagoya University	Yes
304	Yokozawa	Takaaki		ICRR, University of Tokyo	No
305	Yoneda	Gen		Waseda University	No
306	Yoo	Chulmoon		Nagoya University	Yes
307	Yoshida	Daisuke		Nagoya University	Yes
308	Yoshida	Shijun		Tohoku University	No
309	Yoshino	Hirotaka		Osaka Metropolitan University	Yes
310	Yoshioka	Naoki		Hiroshima University	No
311	Zhang	Ying-li		Tongji University	No
312	Zhang	Jiale		Ochanomizu University	No
313	Zhou	Siyi		Kobe University	No

Program

JGRG31 Program

This program is based on Japanese standard time (JST) = GMT+9.

	24 (Mon)	25 (Tue)	26 (Wed)	27 (Thu)	28 (Fri)
9:00		Short talks (9:00–10:45)	Invited talk: Luis Lehner Short talks (9:45–10:30)	Invited talk: Mairi Sakellariadou Short talks (9:45–10:45)	Short talks (9:00–10:45)
10:00	Opening remarks Invited talk: Takahiro Sawada		Short talks (10:50–11:05)		
11:00	Short talks (11:10–12:25)	Short talks (11:05–12:35)	Poster flash talks (11:35–12:35)	Short talks (11:05–12:35)	Short talks (11:05–12:05)
12:00					Award & Closing
13:00	Short talks (13:40–15:25)	Short talks (13:40–14:55)	Poster presentations (13:40–15:10)	Short talks (13:40–15:25)	
14:00					
15:00	Short talks (15:45–17:15)	Short talks (15:15–16:45)	Short talks (15:25–16:40)	Short talks (15:45–17:00)	
16:00					
17:00	Invited talk: Karim Noui	Invited talk: Haixing Miao Invited talk: Paolo Pani	Invited talk: Emanuela Dimastrogiovanni Invited talk: Edward Porter	Invited talk: Robert Mann Invited talk: Aron Wall	
18:00				SOC meeting	

Asterisk (*) is fixed to candidates for the award (non-tenure).
[o] is fixed to online speakers.

Oct 24th (Mon)

Morning session 1 (Chair: Kenta Hotokezaka)		
10:00 – 10:10		Yasushi Suto (Director of RESCEU, U. of Tokyo)
		Opening remarks
10:10 – 10:55	I01[o]	Takahiro Sawada (Osaka Metropolitan U.)
		KAGRA: Status and Prospects

Morning session 2 (Chair: Atsushi Nishizawa)		
11:10 – 11:25	C01	Shi Pi (Institute of Theoretical Physics, Chinese Academy of Sciences)
		Starobinsky's linear potential model revisited
11:25 – 11:40	C02*	Hiroaki Tahara (Rikkyo U.)
		Distance dependence of auto-pulsar correlations in pulsar timing arrays
11:40 – 11:55	C03*[o]	Takahiro Yamamoto (Nagoya U.)
		Deep learning for intermittent gravitational wave signals
11:55 – 12:10	C04*[o]	Reginald Christian Bernardo (Institute of Physics, Academia Sinica)
		Stochastic gravitational wave background phenomenology beyond Einstein
12:10 12:25	C05[o]	Masaki Yamada (Tohoku U.)
		Cosmic strings and gravitational waves from pure Yang-Mills theory

Afternoon session 1 (Chair: Chul-Moon Yoo)		
13:40 – 13:55	C06*	Minxi He (KEK)
		Temperature Profile around a Primordial Black Hole
13:55 – 14:10	C07*	Yo Toda (Hokkaido U.)
		Varying electron mass solution to the Hubble tension and Big Bang Nucleosynthesis
14:10 – 14:25	C08*	Daiki Saito (Nagoya U.)
		Spins of primordial black holes with soft EoS parameter
14:25 – 14:40	C09[o]	Ying-li Zhang (Tongji U.)
		From the merger rate of Primordial Black Hole Binaries to the Power Spectrum of primordial curvature perturbation
14:40 – 14:55	C10*[o]	Koichiro Uehara (Nagoya U.)
		Numerical simulation of type II primordial black hole formation
14:55 – 15:10	C11*[o]	Yasutaka Koga (Nagoya U.)
		Effective inspiral spin distribution of primordial black hole binaries
15:10 – 15:25	C12*[o]	Kentaro Kasai (U. of Tokyo)
		Primordial black holes from Affleck-Dine mechanism

Afternoon session 2 (Chair: Tsutomu Kobayashi)		
15:45 – 16:00	C13*	Kazufumi Takahashi (YITP, Kyoto U.)
		Generalized disformal Horndeski theories: cosmological perturbations and consistent matter coupling
16:00 – 16:15	C14*	Tomohiro Fujita (Waseda U.)
		UV divergence in DHOST and its renormalization by EFT of LSS
16:15 – 16:30	C15*[o]	Kota Numajiri (Nagoya U.)
		Revisiting TOV Problems in F(R) Gravity
16:30 – 16:45	C16*[o]	Yu-Qi Dong (Lanzhou U.)
		Polarizations of gravitational waves in Palatini-Horndeski theory
16:45 – 17:00	C17*[o]	Shin'ichi Hirano (Tokyo Institute of Technology)
		Scalar Gauss-Bonnet and dynamical Chern-Simons black holes in EFT extension of GR
17:00 – 17:15	C18*[o]	Yusuke Manita (Kyoto U.)
		Spin-2 dark matter from Bianchi type-I Universe in ghost-free bigravity

Afternoon session 3 (Chair: Shinji Mukohyama)		
17:30 – 18:15	I02[o]	Karim Noui (IJCLab, Paris Saclay University)
		TBA

Oct 25th (Tue)

Morning session 1 (Chair: Shuichiro Yokoyama)

9:00 – 9:15	C19*	Yuichiro Tada (Nagoya U.)
		Hybrid metric-Palatini Higgs inflation
9:15 – 9:30	C20*	Ann Nakato (Kobe U.)
		Anisotropic warm inflation
9:30 – 9:45	C21*	Tomoaki Murata (Rikkyo U.)
		SU(N)-natural inflation in axisymmetric background
9:45 – 10:00	C22*	Jason Kristiano (RESCEU, U. of Tokyo)
		One-loop perturbativity bound in single-field inflation
10:00 – 10:15	C23*	Tatsuki Kodama (Saga U.)
		Multi-field inflation with non-minimal coupling in the metric/Palatini formalism
10:15 – 10:30	C24*[o]	Ippei Obata (Kavli IPMU)
		Inflation with two-form field: the production of primordial black holes and gravitational waves
10:30 – 10:45	C25[o]	Ryo Namba (RIKEN, iTHEMS)
		Resummed formulation of particle production as gravitational wave source

Morning session 2 (Chair: Teruaki Suyama)

11:05 – 11:20	C26*	Ricardo Cesar Giorgetti Landim (Technical U. of Munich)
		New constraints on (holographic) interacting dark energy
11:20 – 11:35	C27*	Michiru Niibo (Ochanomizu U.)
		Neutrino lines from MeV dark matter annihilation and decay in JUNO
11:35 – 11:50	C28*[o]	Siyi Zhou (Kobe U.)
		Superheavy Dark Matter Production from Symmetry Restoration First-Order Phase Transition During Inflation
11:50 – 12:05	C29*[o]	Ren Tsuda (Chuo U.)
		A Proposal for Simple Model of Acoustic Black Hole
12:05 – 12:20	C30*	Daisuke Miki (Kyushu U.)
		Generating quantum entanglement between macroscopic objects with continuous measurement and feedback control
12:20 – 12:35	C31*	Youka Kaku (Nagoya U.)
		Quantum gravity witness of harmonics oscillator system using Leggett-Garg inequality

Afternoon session 1 (Chair: Hayato Motohashi)

13:40 – 13:55	C32*	Hidetoshi Omiya (Kyoto U.)
		Gravitational waves from the self-interacting axion cloud
13:55 – 14:10	C33*	Takuya Takahashi (Kyoto U.)
		Can we detect the signature of axion clouds in extreme mass ratio inspirals?
14:10 – 14:25	C34*	Kimihiro Nomura (Kobe U.)
		Axion emission from photon spheres of black holes due to photon-axion conversion
14:25 – 14:40	C35*	Kohei Fujikura (Kobe U.)
		Microlensing constraints on axion stars including finite lens and source size effects
14:40 – 14:55	C36*	Siyao Li (Tokyo Institute of Technology)
		Interaction between cosmic strings with point sources approximation

Afternoon session 2 (Chair: Naoki Seto)

15:15 – 15:30	C37	Hayato Motohashi (Kogakuin U.)
		Quasinormal modes of Schwarzschild black holes on the real axis
15:30 – 15:45	C38*	Paul Martens (YITP, Kyoto U.)
		Stability of the Fundamental Quasinormal Mode in Time-Domain Observations
15:45 – 16:00	C39*[o]	Norichika Sago (Kobe U. / Osaka Metropolitan U.)
		Observation of quasi-normal mode overtones in ringdown gravitational waves
16:00 – 16:15	C40*[o]	Nami Uchikata (ICRR, U. of Tokyo)
		Searching for gravitational wave echo signals from binary black hole mergers
16:15 – 16:30	C41*[o]	Tatsuya Narikawa (ICRR, U. of Tokyo)
		Follow-up analyses of the binary-neutron-star signals GW170817 and GW190425 by using post-Newtonian waveform models
16:30 – 16:45	C42*[o]	Ryoto Inui (Nagoya U.)
		Induced stochastic gravitational waves associated with primordial black holes as dark matter in the exponential-tailed case

Afternoon session 3 (Chair: Hirotaka Yoshino)

17:00 – 17:45	I03[o]	Haixing Miao (Tsinghua U.)
		Probing the nature of gravity via quantum correlation of light
17:45 – 18:30	I04[o]	Paolo Pani (Sapienza U. of Rome)
		Exotic compact objects: what we have learned so far

Oct 26th (Wed)

Morning session 1 (Chair: Takahiro Tanaka)		
9:00 – 9:45	I05[o]	Luis Lehner (Perimeter Institute)
		Gravitational waves, contrasting the 'standards' (BHs/NSs in GR) with 'beyond standard' scenarios (ECOs and/or extensions to GR)
9:45 – 10:00	C43*	Naritaka Oshita (RIKEN, iTHEMS)
		Thermal ringdown and the excitation of Kerr overtones
10:00 – 10:15	C44*	Kazushige Ueda (Kyushu U.)
		Conversion of squeezed gravitons into photons during inflation
10:15 – 10:30	C45*	Yuki Sugiyama (Kyushu U.)
		Consistency between causality and complementarity guaranteed by Robertson inequality in quantum field theory
Morning session 2 (Chair: Kohei Kamada)		
10:50 – 11:05	C46	Yoshiyuki Watabiki (Tokyo Institute of Technology)
		Accelerating Expansion of the Universe by Porcupinefish-like spacetime
11:05 – 11:20	C47*	Yuki Hashimoto (Fukushima U.)
		Non-singular bouncing universe under the null energy condition
11:20 – 11:35	C48*[o]	Hiroki Matsui (YITP, Kyoto U.)
		DeWitt boundary condition is consistent in Hořava-Lifshitz quantum gravity
11:35 – 12:35		Poster flash talks
Afternoon session 1 (Chair: Kohei Kamada)		
13:40 – 15:10		Poster presentations
Afternoon session 2 (Chair: Ryo Saito)		
15:25 – 15:40	C49*	Fumio Uchida (RESCEU, U. Tokyo)
		The magneto-hydrodynamic evolution of the cosmological magnetic fields
15:40 – 15:55	C50*	Sravan Kumar (Tokyo Institute of Technology)
		Hemispherical asymmetry of primordial power spectra
15:55 – 16:10	C51*	Morifumi Mizuno (Tokyo Institute of Technology)
		Weak lensing of gravitational waves in wave optics: Beyond Born approximation
16:10 – 16:25	C52*	Fumihiro Naokawa (RESCEU, U. Tokyo)
		Gravitationally Lensed Cosmic Birefringence
16:25 – 16:40	C53*[o]	Shao-Jiang Wang (Institute of Theoretical Physics, Chinese Academy of Sciences)
		Hubble tension and local environment of SNe Ia host galaxies
Afternoon session 3 (Chair: Jun'ichi Yokoyama)		
17:00 – 17:45	I06[o]	Emanuela Dimastrogiovanni (U. of Groningen)
		Testing the early universe with small-scale anisotropies
17:45 – 18:30	I07[o]	Edward Porter (APC, Observatoire de Paris)
		The status of Einstein Telescope

Oct 27th (Thu)

Morning session 1 (Chair: Masahide Yamaguchi)

9:00 – 9:45	I08	Mairi Sakellariadou (King's College London)
		Hunting for the gravitational-wave background: Detection methods and implications for astrophysics, high energy physics, and the early Universe
9:45 – 10:00	C54*	Lorenzo Valbusa Dall'Armi (Università degli Studi di Padova)
		Cosmology with cross-correlation of Gravitational Waves
10:00 – 10:15	C55*	Zhen-Yuan Wu (Yamaguchi U.)
		Angular correlations of the inflationary stochastic gravitational-wave background
10:15 – 10:30	C56*	Jun'ya Kume (RESCEU, U. Tokyo)
		Multi-messenger constraints on the Abelian-Higgs cosmic string model
10:30 – 10:45	C57*	Mostafizur Rahman (Indian Institute of Technology, Gandhinagar)
		Prospects for determining the nature of the secondaries of extreme mass-ratio inspirals using the spin-induced quadrupole deformation

Morning session 2 (Chair: Shinji Tsujikawa)

11:05 – 11:20	C58	Keisuke Nakashi (Kochi KOSEN)
		Time evolution and quasinormal modes of odd parity perturbations of stealth black holes in DHOST theory
11:20 – 11:35	C59*	Katsuki Aoki (YITP, Kyoto U.)
		Effective field theory of vector-tensor theories
11:35 – 11:50	C60*	Yuichi Miyashita (Tokyo Institute of Technology)
		Gravitational field of scalar lumps in higher-derivative gravity
11:50 – 12:05	C61*	Sebastian Bahamonde (Tokyo Institute of Technology)
		New black hole solutions with a dynamical traceless nonmetricity tensor in Metric-Affine Gravity
12:05 – 12:20	C62*[o]	Tact Ikeda (Rikkyo U.)
		Vector-tensor theories in the metric-affine formalism
12:20 – 12:35	C63*[o]	Hsu-Wen Chiang (LeCosPA)
		Long-lived quasinormal modes of a black hole with matter inflow

Afternoon session 1 (Chair: Tomohiro Harada)

13:40 – 13:55	C64*	Kota Ogasawara (Kyoto U.)
		Photon escape probability and near-horizon extremal Kerr geometry
13:55 – 14:10	C65*	Diego Soligon (Nagoya U.)
		Maximum size of black holes in the accelerating universe
14:10 – 14:25	C66*	Ryotaku Suzuki (Toyota Technological Institute)
		Rotating black holes at large D in Einstein-Gauss-Bonnet theory
14:25 – 14:40	C67*[o]	Che-Yu Chen (Institute of Physics, Academia Sinica)
		Geometric-optics correspondence of deformed black holes
14:40 – 14:55	C68*[o]	Takuya Katagiri (Tohoku University)
		Vanishing Love of Black Holes in General Relativity: From Spacetime Conformal Symmetry in a Two-dimensional Reduced Geometry
14:55 – 15:10	C69*[o]	Audrey Trova (ZARM, U. of Bremen)
		Quasi-periodic oscillations of a particle in the background of a deformed compact object
15:10 – 15:25	C70*[o]	Shokoufe Faraji (ZARM, U. of Bremen)
		Magnetized tori configurations and epicyclic oscillations near an accelerated black hole

Afternoon session 2 (Chair: Keisuke Izumi)

15:45 – 16:00	C71	Keiju Murata (Nihon U.)
		Creating stars orbiting in AdS
16:00 – 16:15	C72*	Kunihito Uzawa (Kwansei Gakuin U.)
		De-singularizing the extremal GMGHS black hole via higher derivatives corrections
16:15 – 16:30	C73*	Ratchaphat Nakarachinda (Naresuan U.)
		Holographic dark energy from the anti-de Sitter black hole
16:30 – 16:45	C74*	Norihiro Tanahashi (Chuo U.)
		Brane Dynamics of Holographic BCFTs
16:45 – 17:00	C75*[o]	Naoki Ogawa (YITP, Kyoto U.)
		Wedge Holography in Flat Space and Celestial Holography

Afternoon session 3 (Chair: Akihiro Ishibashi [o])

17:15 – 18:00	I09[o]	Robert Mann (U. of Waterloo)
		Signatures of Quantum Superpositions of Black Holes
18:00 – 18:45	I10[o]	Aron Wall (U. of Cambridge)
		Cauchy slice holography

19:00 – 19:30		SOC meeting

Oct 28th (Fri)

Morning session 1 (Chair: Keiju Murata)

9:00 – 9:15	C76*[o]	Torben Frost (ZARM, U. of Bremen)
		Gravitational Lensing in the NUT Metric
9:15 – 9:30	C77*[o]	Ryuya Kudo (Hirosaki U.)
		Photon cylinder in a static cylindrically symmetric spacetime
9:30 – 9:45	C78*	Masaya Amo (YITP, Kyoto U.)
		Generalization of the photon sphere referring to null infinity
9:45 – 10:00	C79*	Kangjae Lee (Nagoya U.)
		Four types of attractive gravity probe surfaces
10:00 – 10:15	C80*[o]	Keita Takizawa (Hirosaki U.)
		Gravitational lens on the optical constant-curvature background
10:15 – 10:30	C81*[o]	Kun Hu (Central China Normal U.)
		ADM formulation and Hamiltonian analysis of f(Q) gravity
10:30 – 10:45	C82*[o]	Kyosuke Tomonari (Tokyo Institute of Technology)
		On boundary conditions for constraint systems

Morning session 2 (Chair: Yousuke Itoh)

11:05 – 11:20	C83	Sinya Aoki (YITP, Kyoto U.)
		Colliding gravitational waves and singularities
11:20 – 11:35	C84	Tomohiro Harada (Rikkyo U.)
		Periapsis shift of a quasi-circular orbit in a general, static and spherically symmetric spacetime
11:35 – 11:50	C85	Jose Senovilla (U. of the Basque Country / YITP, Kyoto U.)
		Ultra-massive spacetimes
11:50 – 12:05	C86	Paolo Gondolo (U. of Utah, Tokyo Institute of Technology, Kavli IPMU)
		Surface stress tensor and junction conditions on a rotating null horizon
12:05 – 12:25		Kenta Hotokezaka
		Award
12:25 – 12:35		Jun'ichi Yokoyama
		Closing

Posters

P01*	Kouji Nakamura (NAOJ)
	Gauge-invariant perturbation theory on the Schwarzschild background spacetime including l=0.1 modes --- Realization of exact solutions ---
P02	Keisuke Izumi (Nagoya U., KMI & Dept. of Math.)
	Generalization of Riemannian Penrose inequality in weak gravity region
P03*	Hiroki Asami (Nagoya U.)
	The Einstein-Vlasov system with a R×SU(2)×U(1) symmetry
P04	Yuki Watanabe (NIT, Gunma College)
	Gravitational Wave from Axion-SU(2) Gauge Fields in Kinetically Driven Inflation
P05	Takashi Mishima (Nihon U.)
	Mode conversion phenomena of the Einstein-Maxwell system in the cylindrically symmetric spacetime by full nonlinearity
P06	Chulmoon Yoo (Nagoya U.)
	Threshold of Primordial Black Hole Formation against Velocity Dispersion in Matter-Dominated Era
P07*	Hideo Furugori (Nagoya U.)
	Soft Graviton Theory and Infrared Triangle
P08	Kazuharu Bamba (Fukushima U.)
	Generation of helical magnetic fields and baryogenesis from the coupling of electromagnetic fields with a higher curvature term in inflationary cosmology
P09*	Masahiko Taniguchi (Hiroshima U.)
	Cartan F(R) gravity and Inflaition
P10*	Jin Saito (Rikkyo U.)
	Black hole perturbations in modified gravity with two tensorial degrees of freedom
P11	CANCELED
P12[o]	Hideki Asada (Hirosaki U.)
	Time-domain reconstruction of pulsar GW polarizations
P13[o]	Takayuki Tatekawa (NIT, Kochi college)
	High-Precision Simulations for Collisional Self-Gravitating Systems Incorporating Relativistic Effects
P14*[o]	Ken Matsuno (Osaka Metropolitan U.)
	Hawking radiation of scalar particles from four-dimensional Einstein-Gauss-Bonnet black holes based on a generalized uncertainty principle
P15*[o]	Keisuke Taira (Fukushima U.)
	Cosmological evolution of gravitational leptogenesis with right-handed neutrinos
P16*[o]	Yuta Murakoshi (Fukushima U.)
	Spectrum of gravitational waves due to the axion-gravity Chern-Simons coupling
P17*[o]	Kotaro Fujisawa (U. of Tokyo)
	General relativistic rotating stars with arbitrary differential rotation
P18[o]	Hideki Maeda (Hokkai-Gakuen U.)
	Criteria for energy conditions
P19[o]	Taishi Katsuragawa (Central China Normal U.)
	Hunting dark energy with pressure-dependent photon-photon scattering
P20[o]	Umpei Miyamoto (Akita Prefectural U.)
	Determining parameters of a black-hole accretion-disk system by observing the shadow
P21[o]	Kensuke Homma (Hiroshima U.)
	Perspectives of a stimulated GHz-photon collider for probing gravitationally weak coupling scalar fields
P22[o]	Yoshio Kamiya (U. of Tokyo)
	Testing the equivalence principle using a gravitationally bound quantum system: with a short report of technological developments
P23*[o]	Ryo Kitaku (Nagoya U.)
	Turbulence of Nambu-Goto string on AdS spacetime :Non linear perturbation analysis and Numerical simulation
P24*[o]	Kei-ichiro Kubota (YITP, Kyoto U.)
	Propagation of scalar and tensor gravitational waves in Horndeski theory

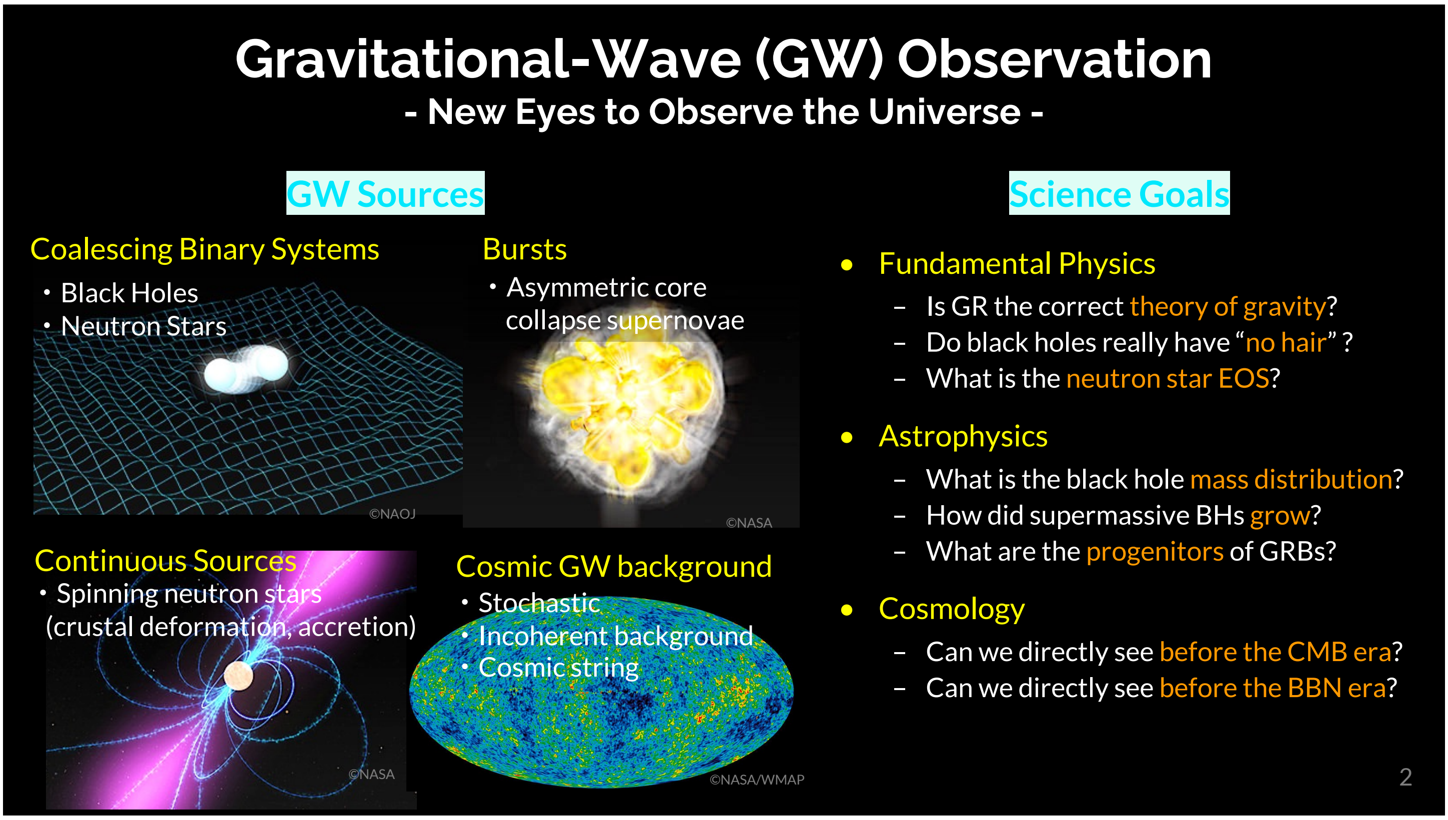
Invited talks

I01

JGRG31, October 24th, 2022

KAGRA: Status and Prospects

Takahiro Sawada (NITEP, Osaka Metropolitan University)
on behalf of the KAGRA collaboration



Gravitational-Wave (GW) Observation

- New Eyes to Observe the Universe -

GW Sources

Coalescing Binary Systems
- Black Holes
- Neutron Stars

©NAOJ

Bursts
- Asymmetric core collapse supernovae

©NASA

Continuous Sources
- Spinning neutron stars (crustal deformation, accretion)

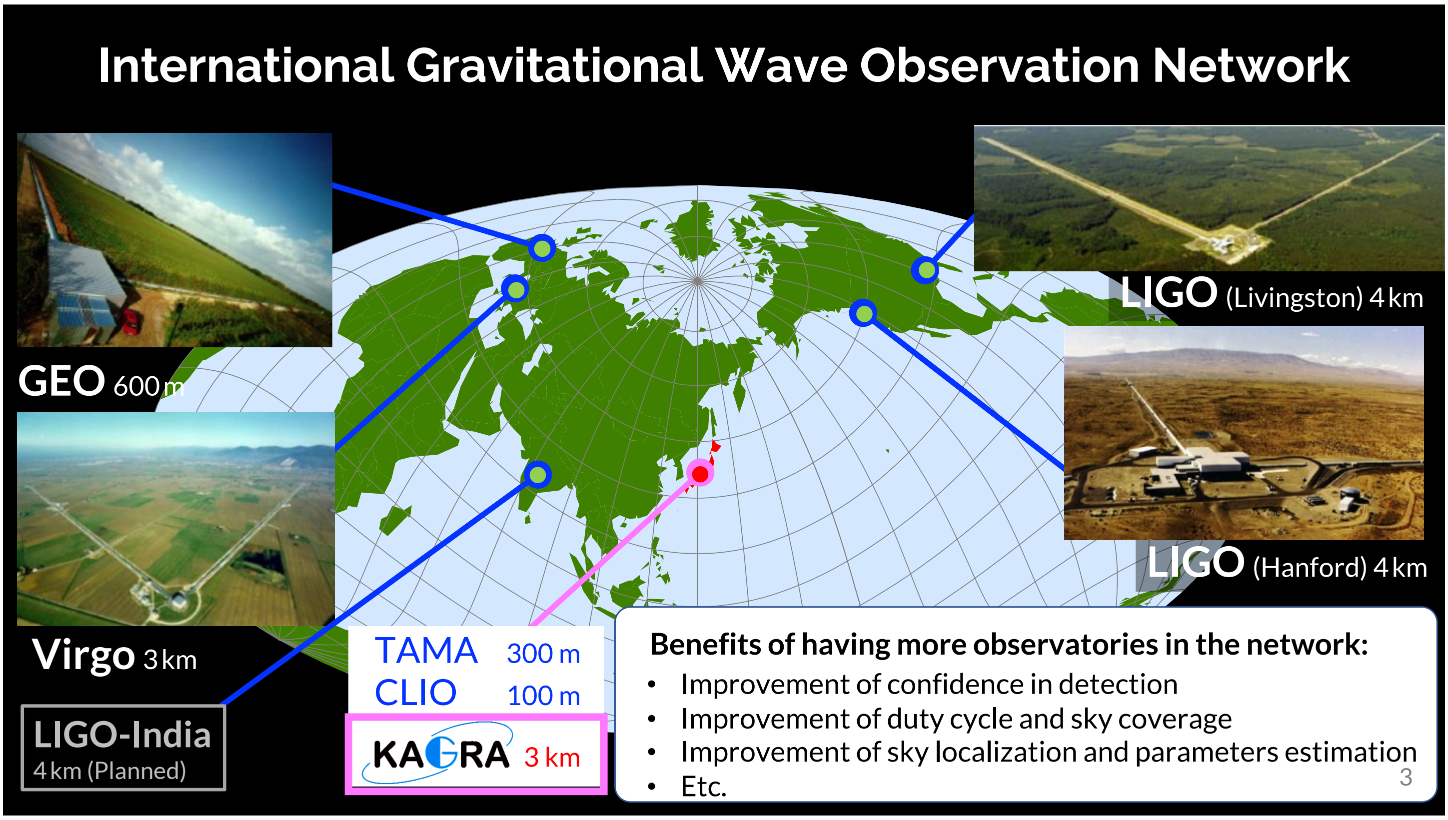
©NASA

Cosmic GW background
- Stochastic
- Incoherent background
- Cosmic string

©NASA/WMAP

Science Goals

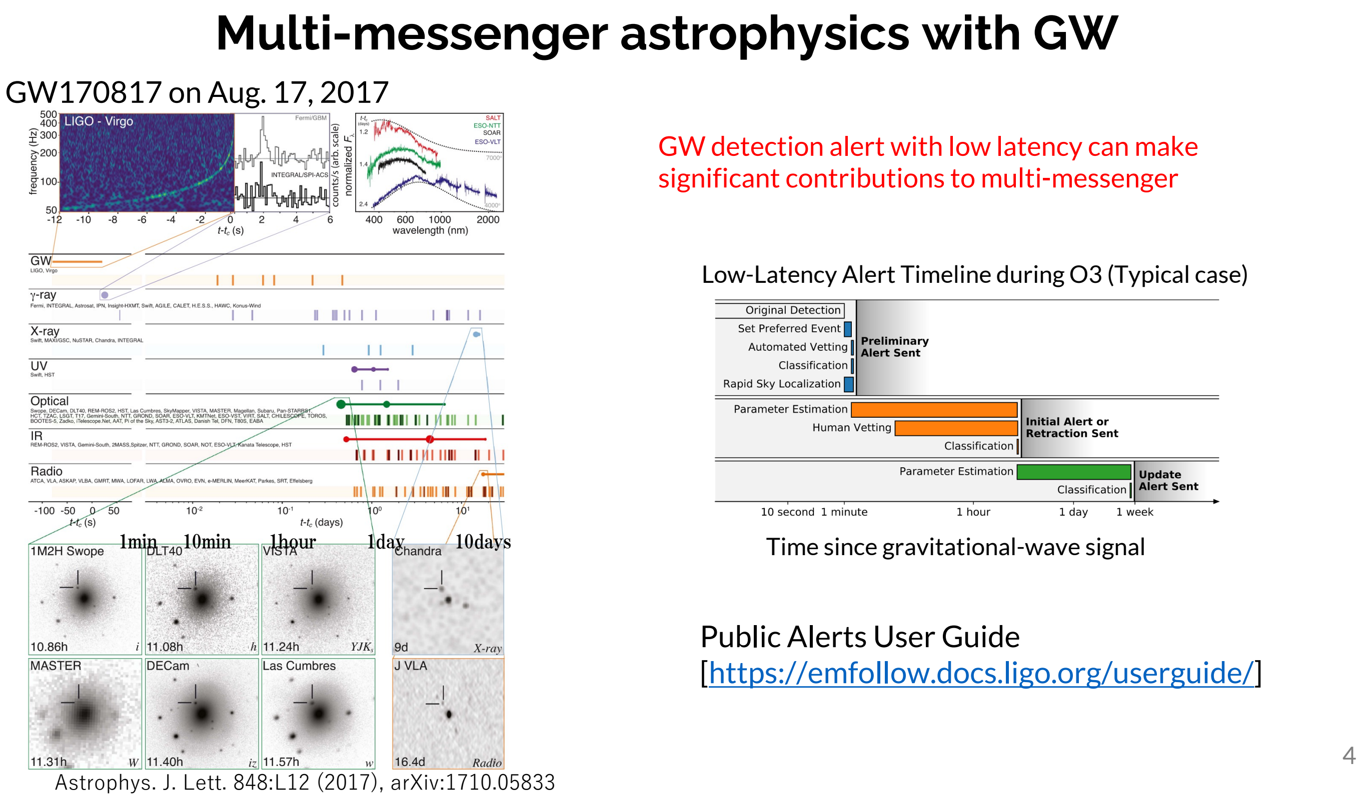
- Fundamental Physics
  - Is GR the correct theory of gravity?
  - Do black holes really have “no hair” ?
  - What is the neutron star EOS?
- Astrophysics
  - What is the black hole mass distribution?
  - How did supermassive BHs grow?
  - What are the progenitors of GRBs?
- Cosmology
  - Can we directly see before the CMB era?
  - Can we directly see before the BBN era?



International Gravitational Wave Observation Network

Benefits of having more observatories in the network:

- Improvement of confidence in detection
- Improvement of duty cycle and sky coverage
- Improvement of sky localization and parameters estimation
- Etc.



Multi-messenger astrophysics with GW

GW170817 on Aug. 17, 2017

Astrophys. J. Lett. 848:L12 (2017), arXiv:1710.05833

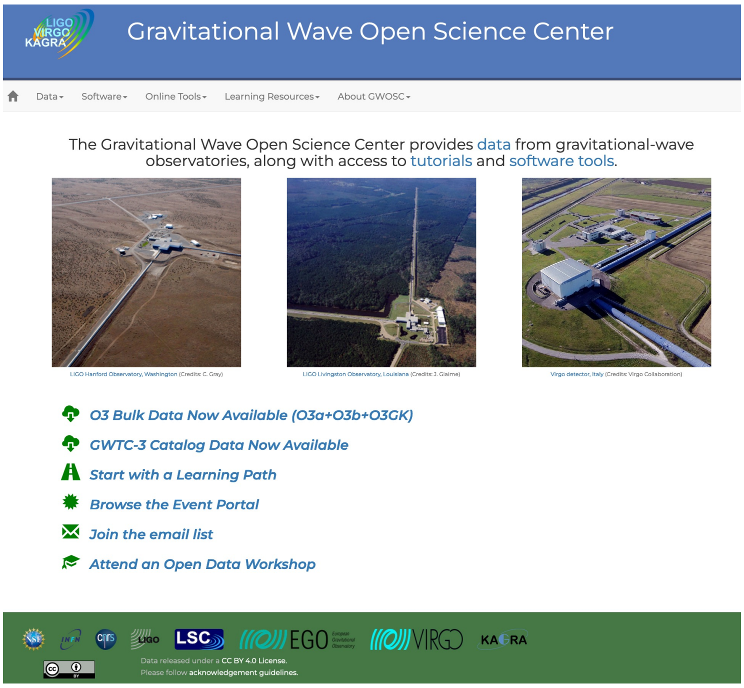
GW detection alert with low latency can make significant contributions to multi-messenger

Low-Latency Alert Timeline during O3 (Typical case)

Time since gravitational-wave signal

Public Alerts User Guide
[https://emfollow.docs.ligo.org/userguide/]

Public access to GW data products



Gravitational Wave Open Science Center

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

LIGO Hanford Observatory, Washington (Credits: C. Gray)

LIGO Livingston Observatory, Louisiana (Credits: J. Giaime)

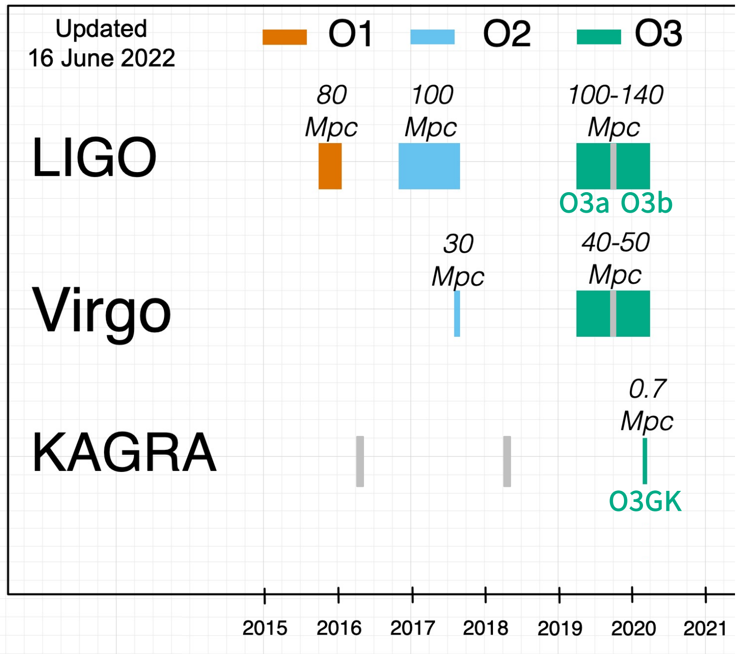
Virgo detector, Italy (Credits: Virgo Collaboration)

- O3 Bulk Data Now Available (O3a+O3b+O3GK)
- GWTC-3 Catalog Data Now Available
- Start with a Learning Path
- Browse the Event Portal
- Join the email list
- Attend an Open Data Workshop

Data released under a CC BY 4.0 License.
Please follow acknowledgement guidelines.

- LIGO-Virgo-KAGRA (LVK) provides the public access to GW data products, tutorials, and software tools through Gravitational Wave Open Science Center (GWOSC).
  https://www.gw-openscience.org
- Data from O1 to O3 and some earlier data are now available.
- KAGRA also publishes the data from O3GK.

Observing runs conducted so far



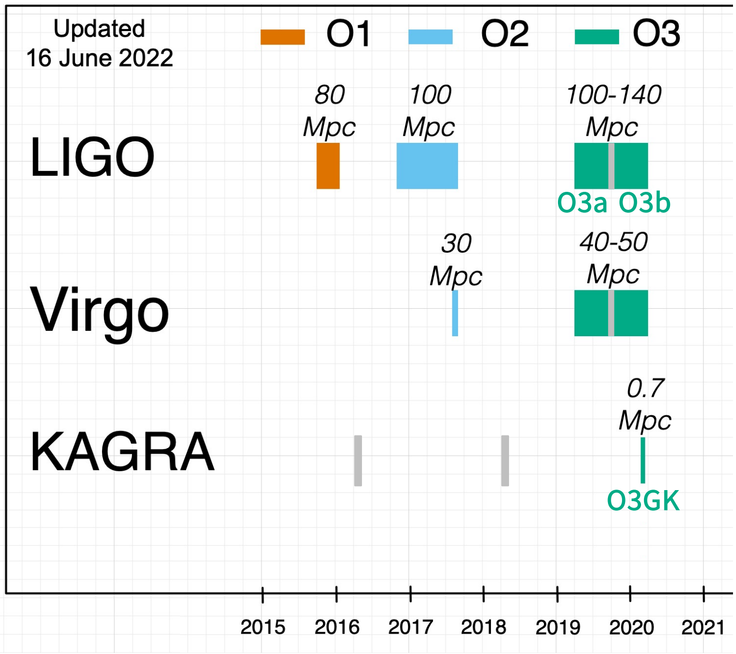
1st Observing Run (O1)
2015. 9 - 2016. 1

- LIGO only
- **GW150914**: First direct detection of GWs – binary black hole merger (BH-BH)

2nd Observing Run (O2)
2016. 11 - 2017. 8

- First LIGO only, Virgo from August 1st onwards
- **GW170814**: First triple-detector GW detection
- **GW170817**: First binary neutron star merger detection (NS-NS)
- Birth of multi-messenger astronomy with GW

Observing runs conducted so far



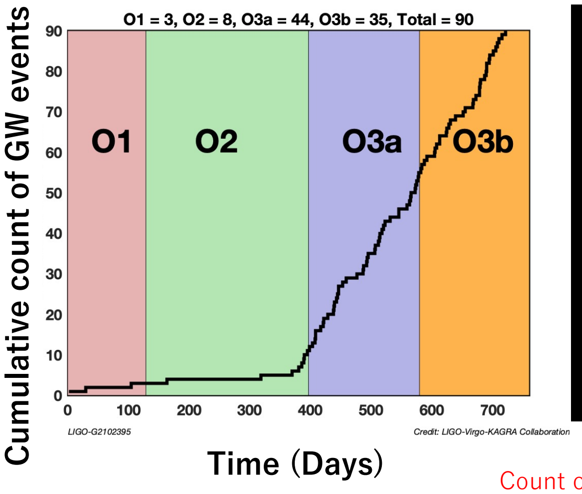
3rd Observing Run (O3)

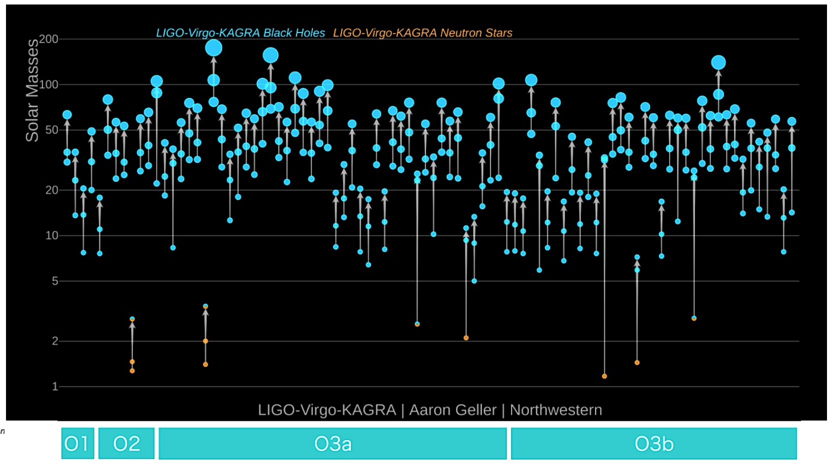
- **2019. 4 - 2020. 3 (O3a, O3b)**
  - LIGO+Virgo
  - Initially planned to complete at the end of April 2020,

    but due to a COVID-19 disaster, it ended in March 2020.
- **2020. 4 (O3GK)**
  - GEO+KAGRA

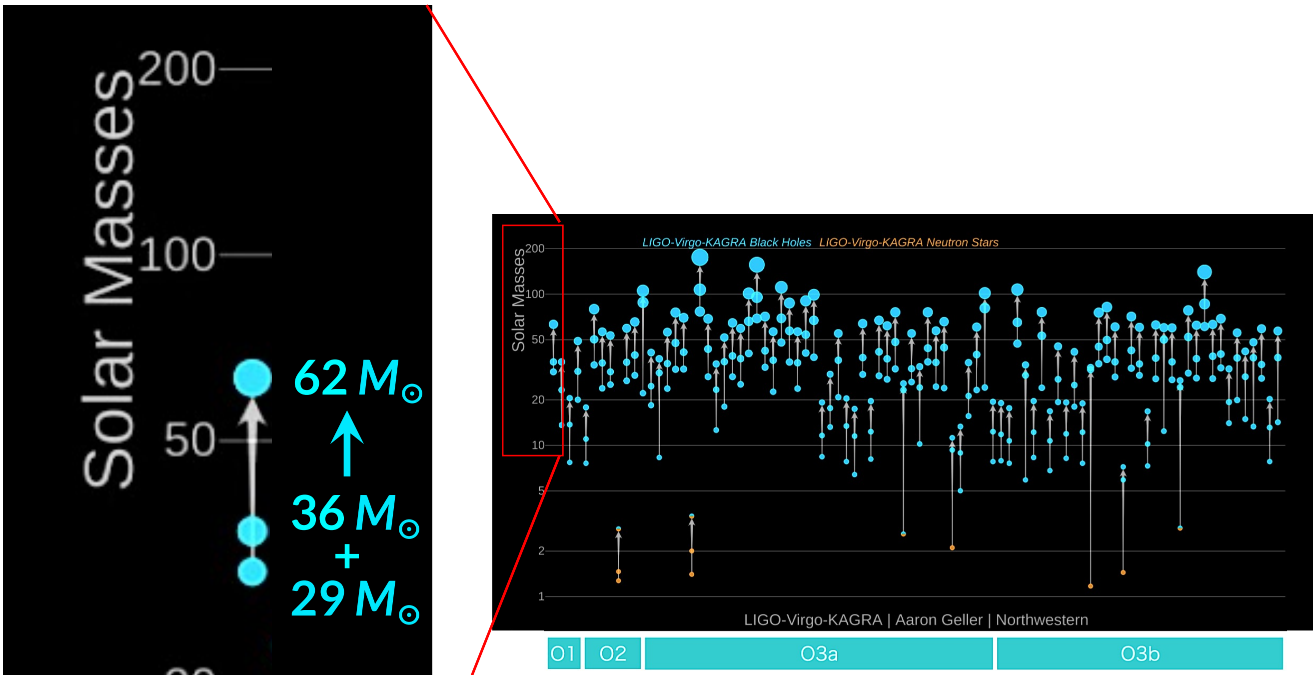
LIGO and Virgo have found a total of 90 convinced events* so far, since the first discovery of GW in 2015

* Candidate GW sources with probability of astrophysical origin greater than 50%.



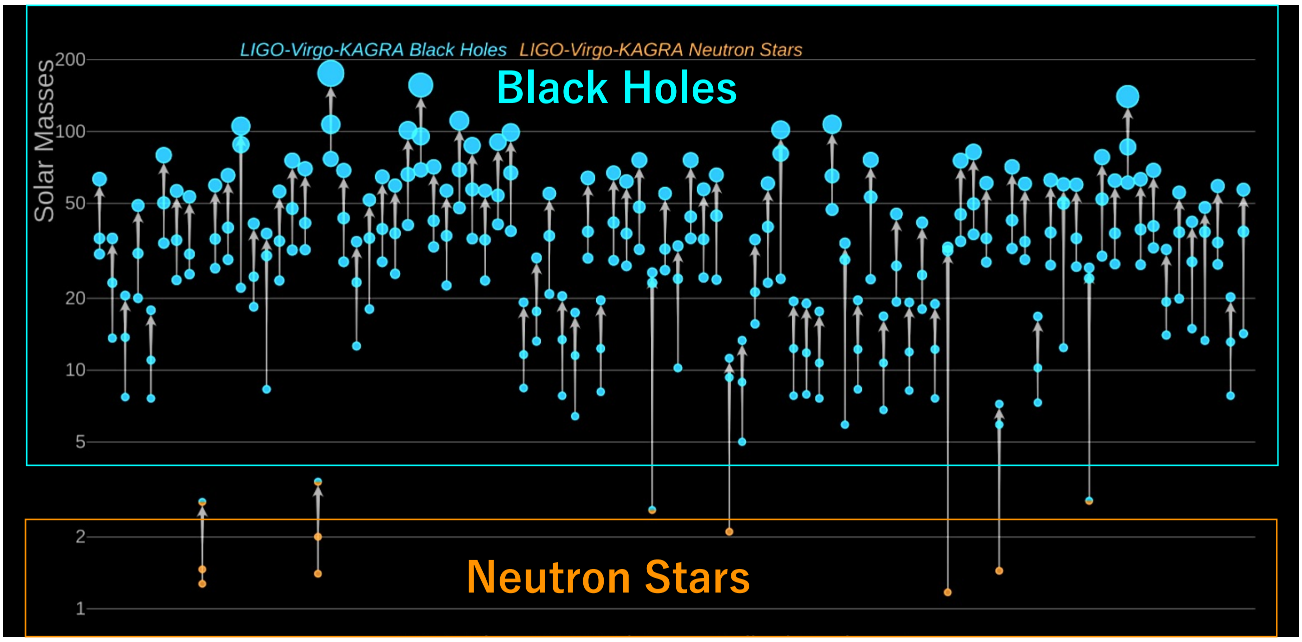


	O1	O2	O3a	O3b
Count of GW events	3	8	44	35



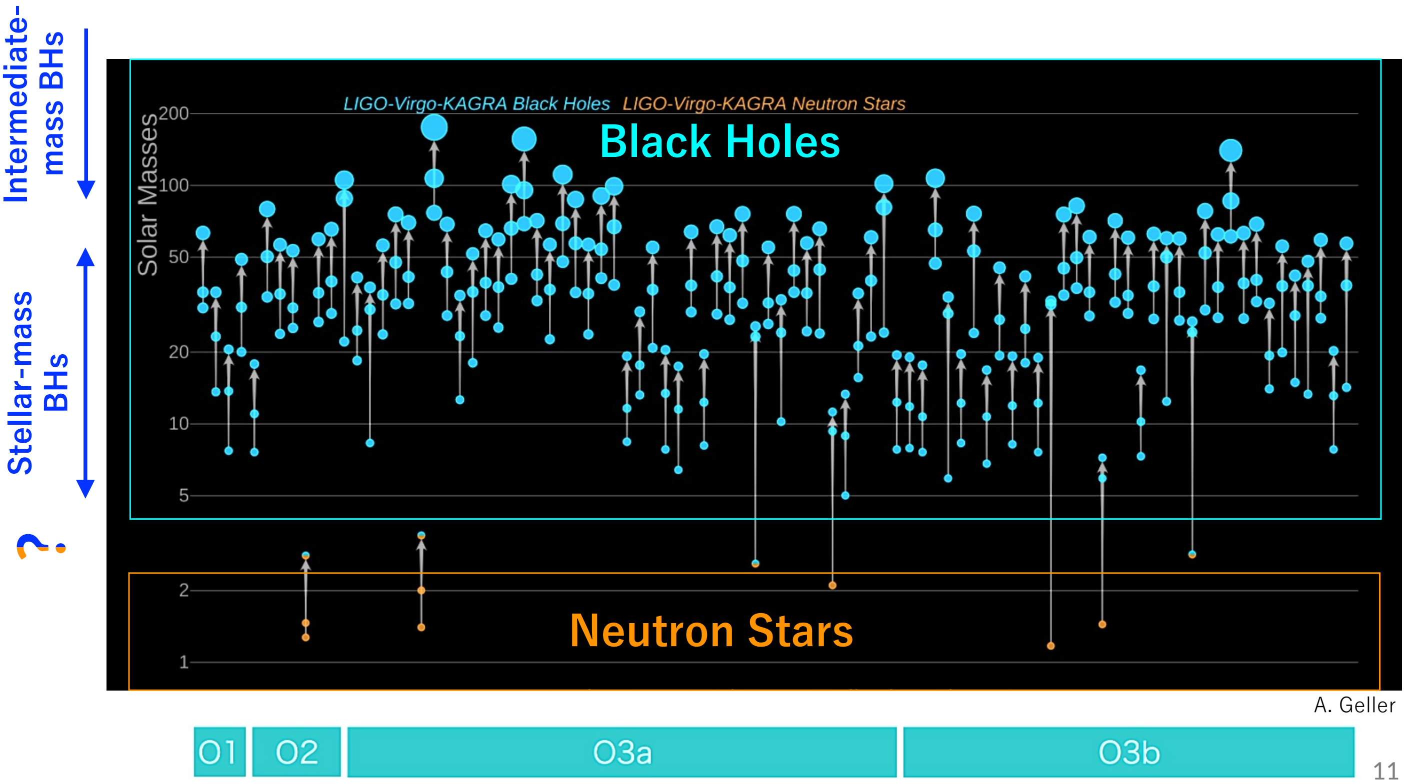
	O1	O2	O3a	O3b
ount of W events	3	8	44	35

* Candidate GW sources with probability of astrophysical origin greater than 50%.



A. Geller

O1	O2	O3a	O3b

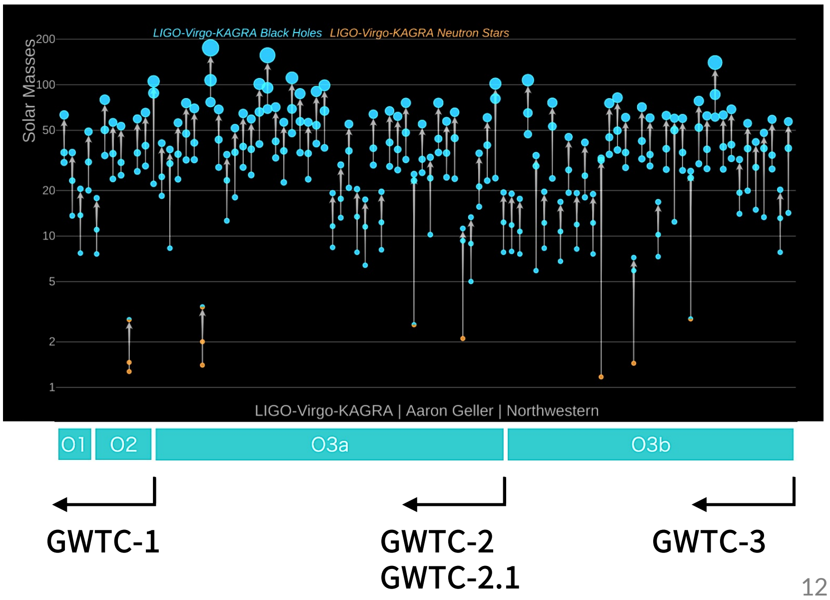


A. Geller

Gravitational-Wave Transient Catalogs (GWTCs)

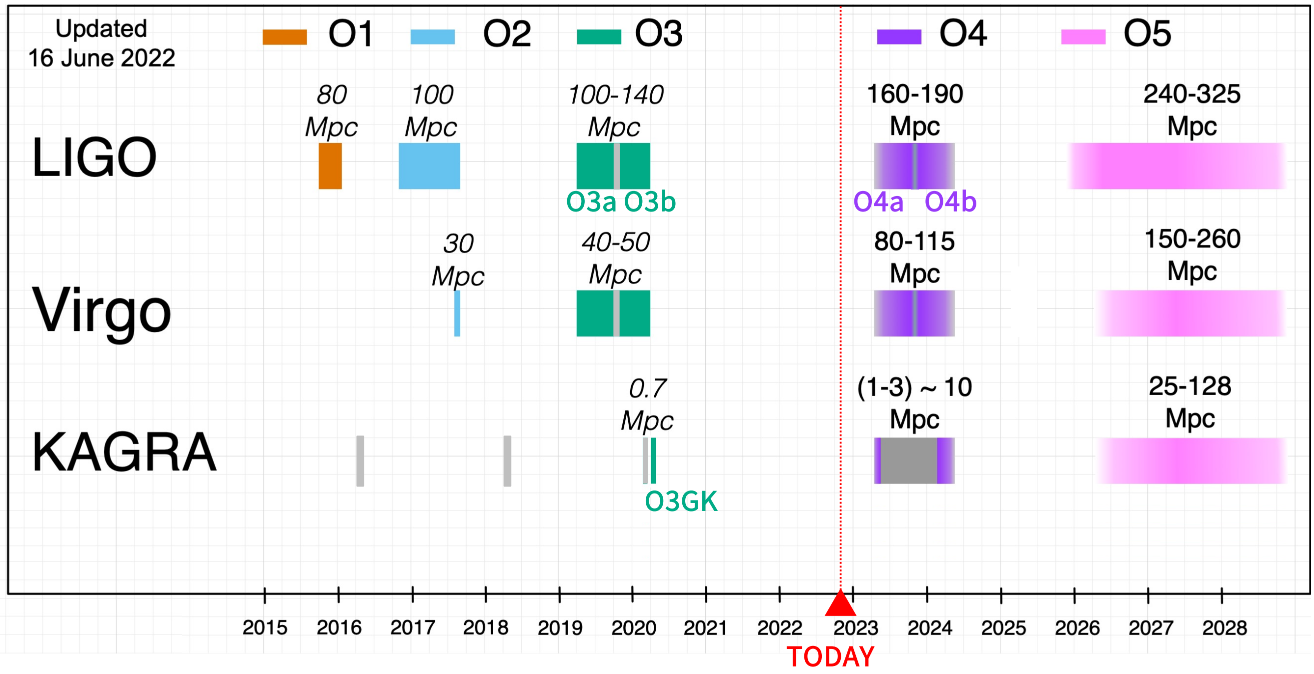
GWTCs cover the convinced GW events during the observing runs

- **GWTC-1**
  Phys. Rev. X 9, 031040 (2019), arXiv:1811.12907
- **GWTC-2**
  Phys. Rev. X 11, 021053 (2021), arXiv:2010.14527
- **GWTC-2.1**
  "Deep Extended" catalog
  arXiv:2108.01045
- **GWTC-3**
  arXiv:2111.03606



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

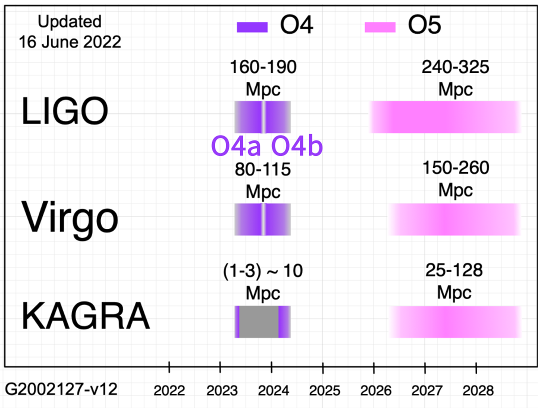
Observing Run Plans



Observing Run Plans (Future)

O4

- Scheduled to start in March 2023.
- 1 year observation with 1 month mid-run commissioning break.
- GW alerts may be released during engineering running that precedes O4.



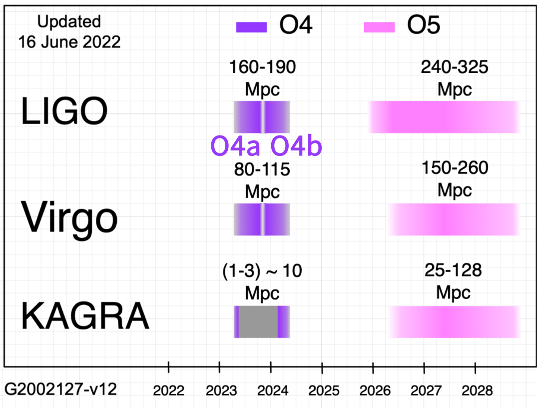
KAGRA@O4

- **O4a** (1-3 Mpc)
    - Join O4a from the beginning with LIGO and Virgo
    - Approx. 1 month of observation.
- **mid-break**
    - In the middle of O4a, step away for commissioning to improve the sensitivity toward O4b.
- **O4b** (3-10 Mpc)
    - In the middle of O4b, return to observing with a greater sensitivity.
    - Approx. 3 months (or longer) of observation in the latter half of O4b.

Observing Run Plans (Future)

Beyond O4

- O5 schedule is still tentative.
- We anticipate the need in O5 for one or more commissioning breaks of a few month duration each.
- Post-O5 plans are being developed; observations will continue.



Next update: November 15, 2022

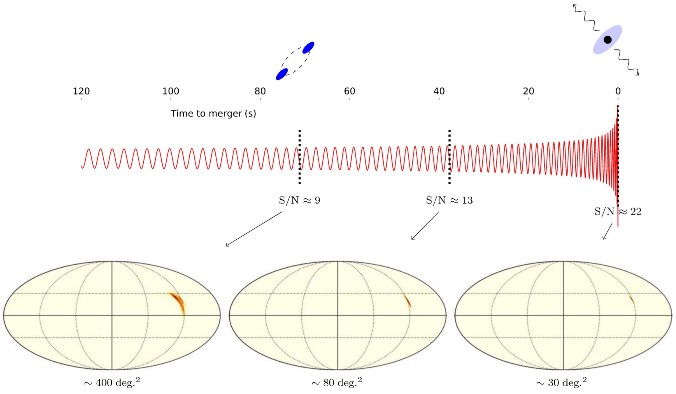
- LVK will continue to review and update observing run plans periodically.

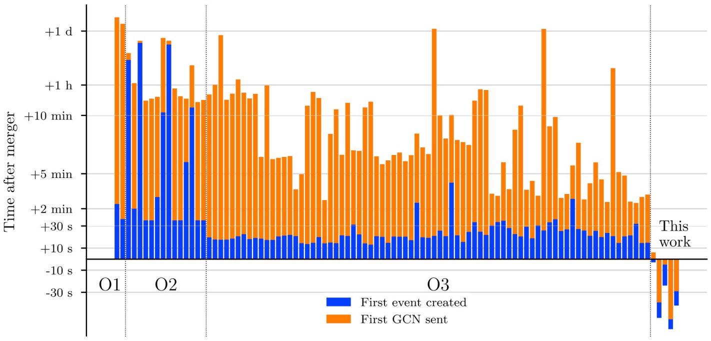
https://observing.docs.ligo.org/plan/

Early Warning Alert (Negative Latency Alert) at O4

Public Alert User Guide:
[https://emfollow.docs.ligo.org/userguide/early_warning.html]

Astrophys. J. Lett. 910:L21 (2021), arxiv:2102.04555



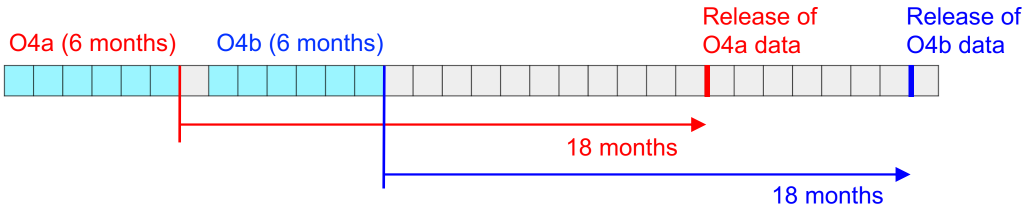


End-to-end latencies across public alerts in the first three observing runs and the mock data challenge for EW.

And many other updates for O4 alert.
See the announcements at OpenLVKEM town hall telecon for details.

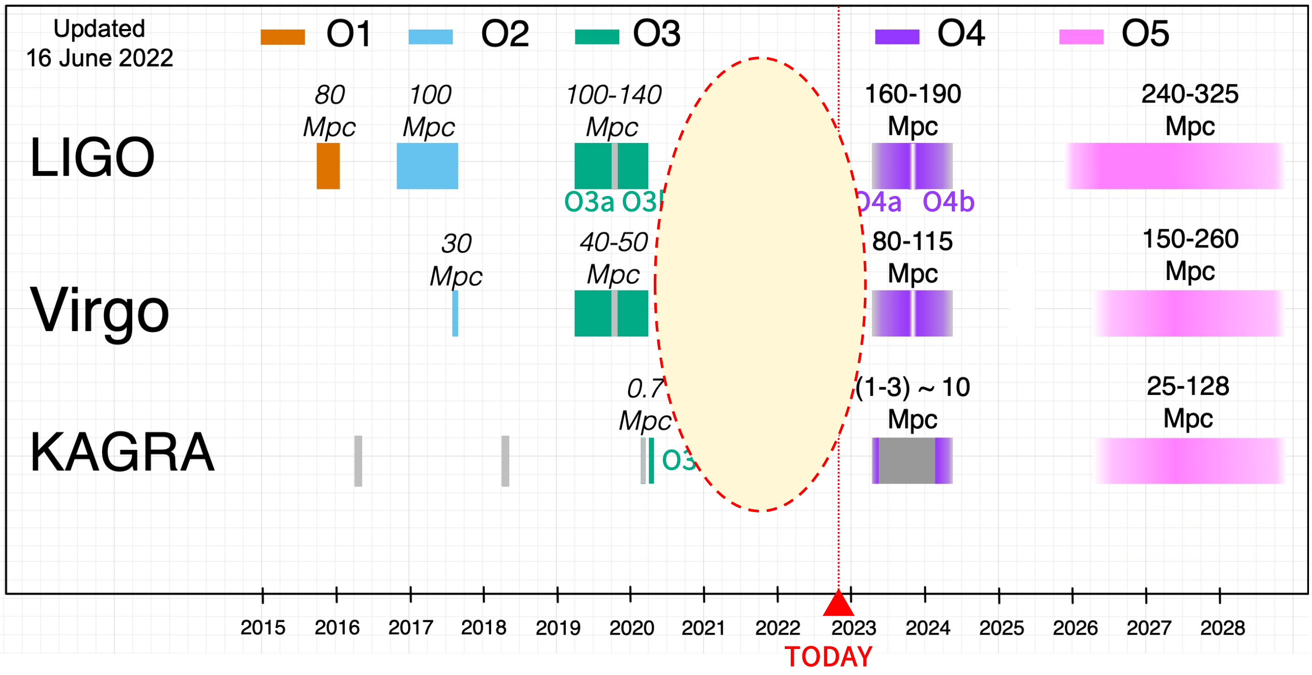
O4 Data Release Plan

The calibrated strain data and data quality flags will be released 18 months after each 6-month long observation period.



- **O4a:** Mar. 2023 - Sep. 2023 → **Data Release: Mar. 2025**
- **O4b:** Oct. 2023 - Apr. 2024 → **Data Release: Oct. 2025**

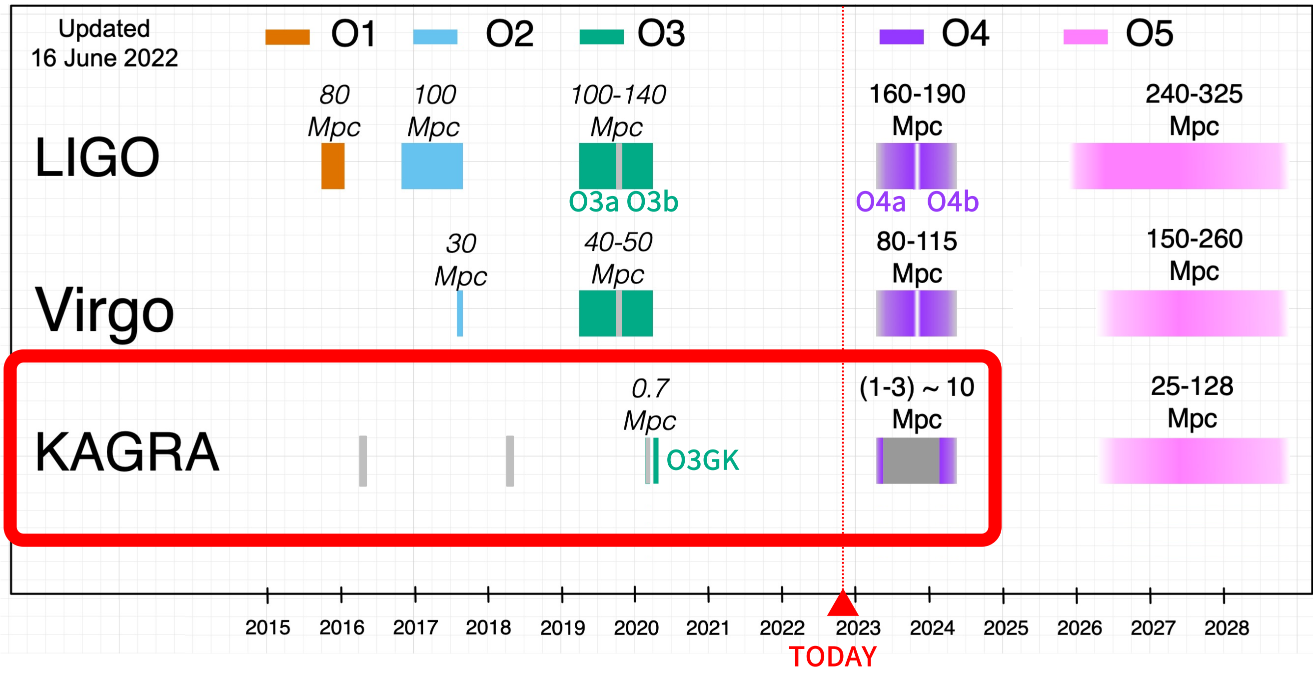
Observing Run Plans

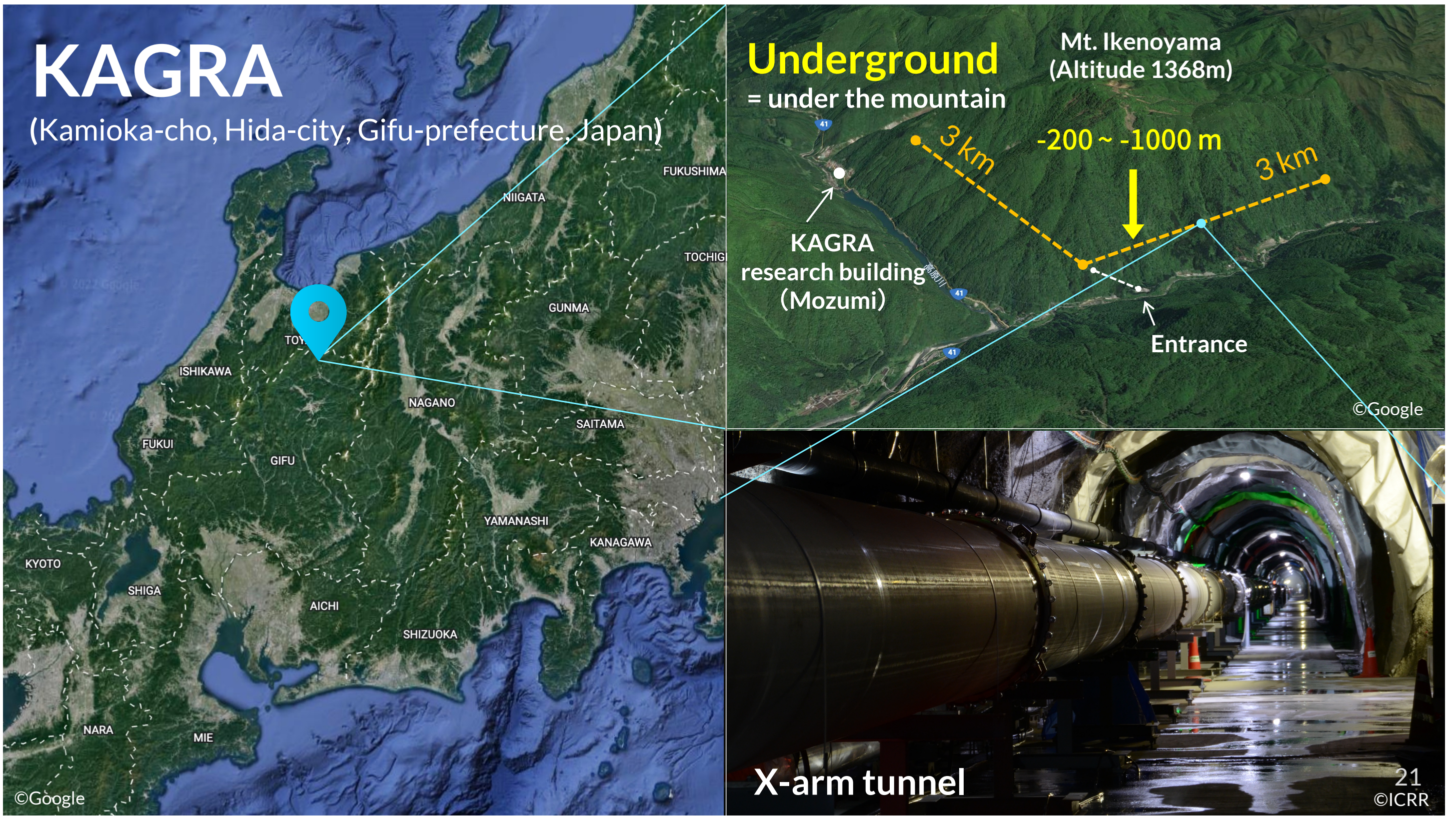


Status of Detectors’ upgrade

- Scientists, Engineers, Technicians, and Students at LIGO, Virgo, and KAGRA working to:
    - Finalize the installation of upgrades.
    - Commission the detectors to reach the expected sensitivities with operational stability.
- Some technical uncertainties still remain, which may impact our schedule. (Potential risks)
- **Explanatory Materials**
    - LVK webinar held on 28 April 2022:
      Recorded Video: https://www.youtube.com/watch?v=Ut7Ef5AiA_M
      Slides: https://dcc.ligo.org/LIGO-G2200736/public
    - OpenLVKEM town hall telecon:
      Web Home: https://wiki.gw-astronomy.org/OpenLVEM

Observing Run Plans (Past and Future)





KAGRA

(Kamioka-cho, Hida-city, Gifu-prefecture, Japan)

Underground

= under the mountain

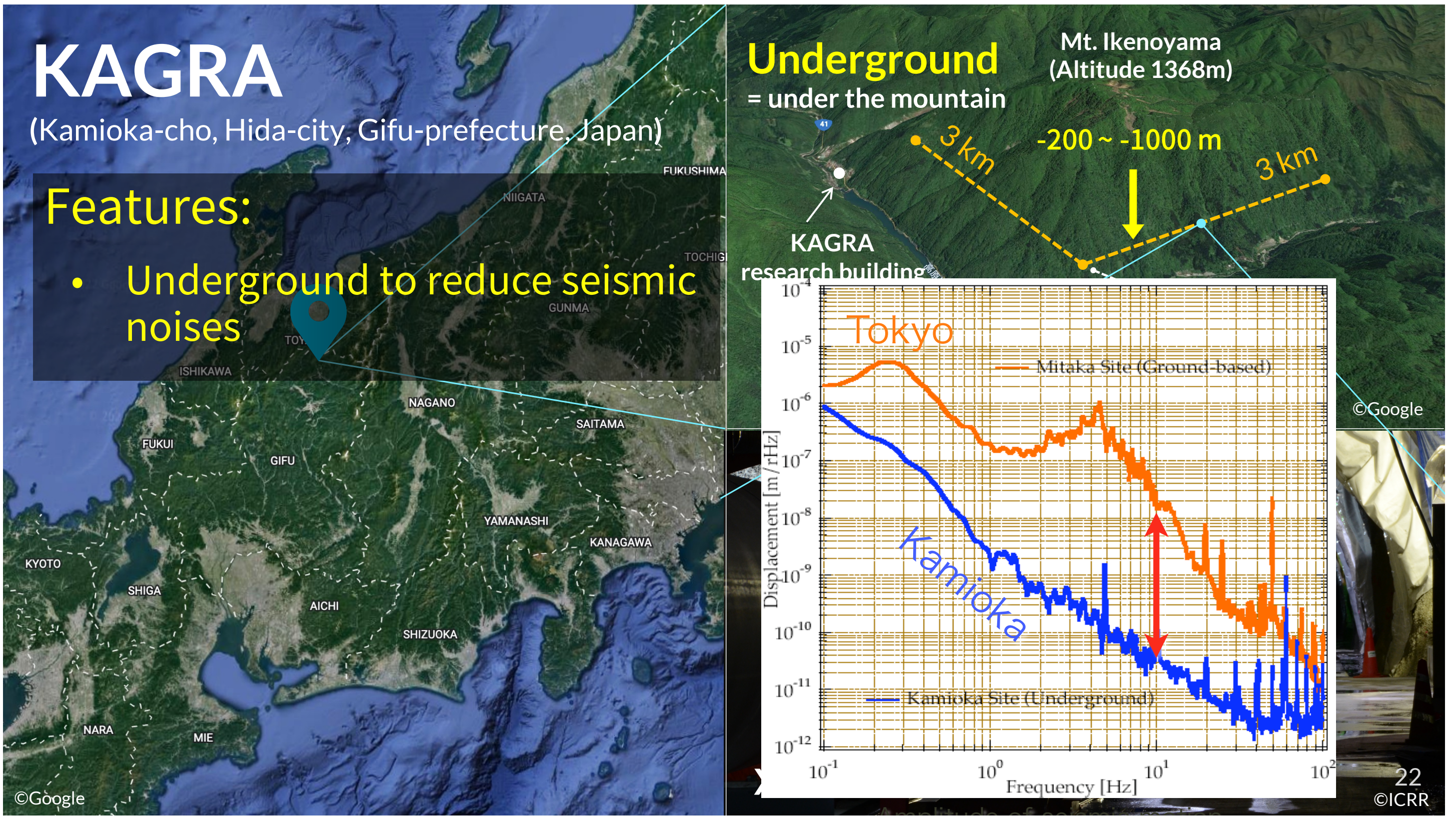
Mt. Ikenoyama
(Altitude 1368m)

-200 ~ -1000 m

©Google

©Google

©ICRR



KAGRA

(Kamioka-cho, Hida-city, Gifu-prefecture, Japan)

Features:

- Underground to reduce seismic noises

Underground

= under the mountain

Mt. Ikenoyama
(Altitude 1368m)

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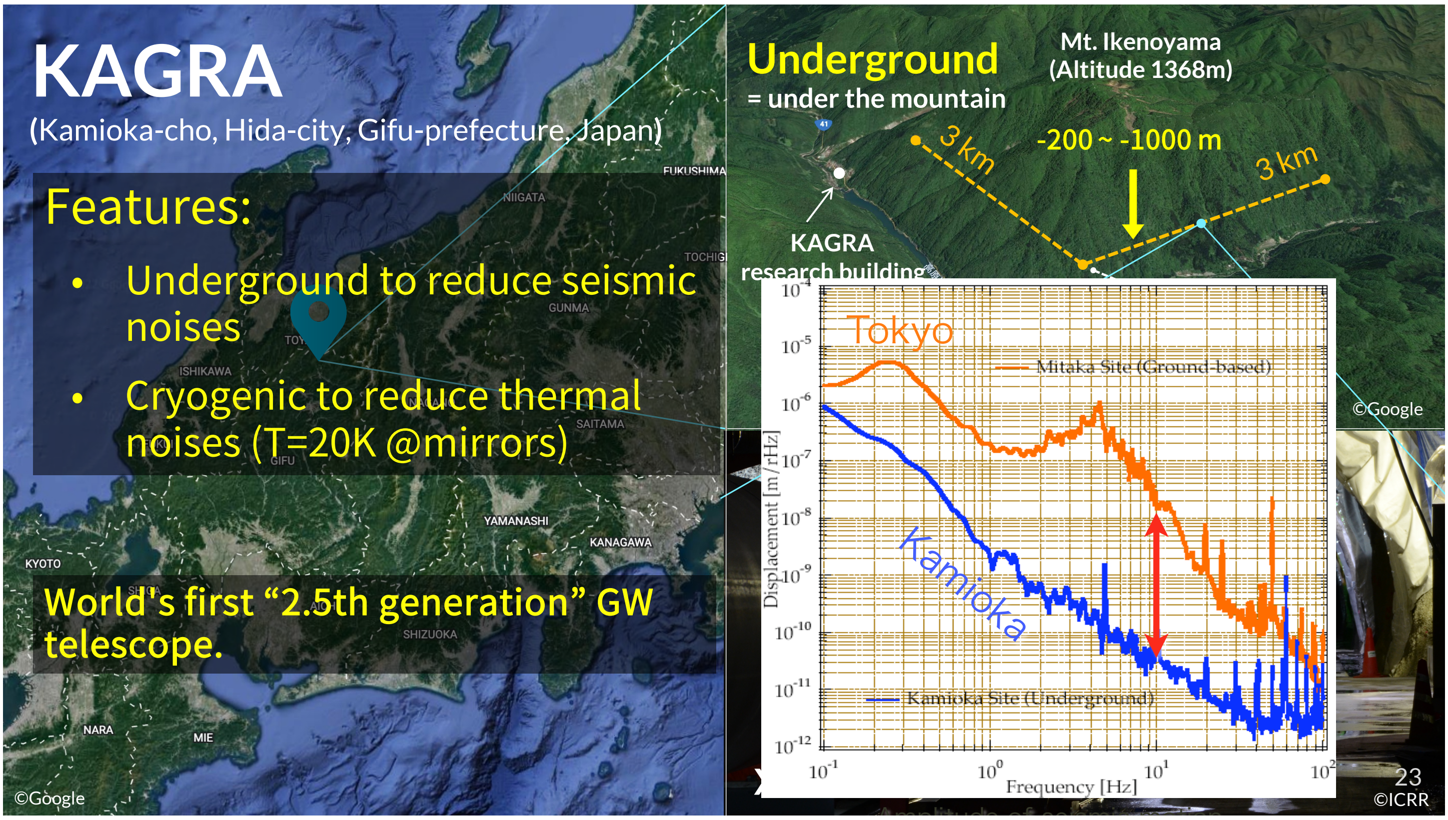


KAGRA

(Kamioka-cho, Hida-city, Gifu-prefecture, Japan)

Features:

- Underground to reduce seismic noises
- Cryogenic to reduce thermal noises (T=20K @mirrors)

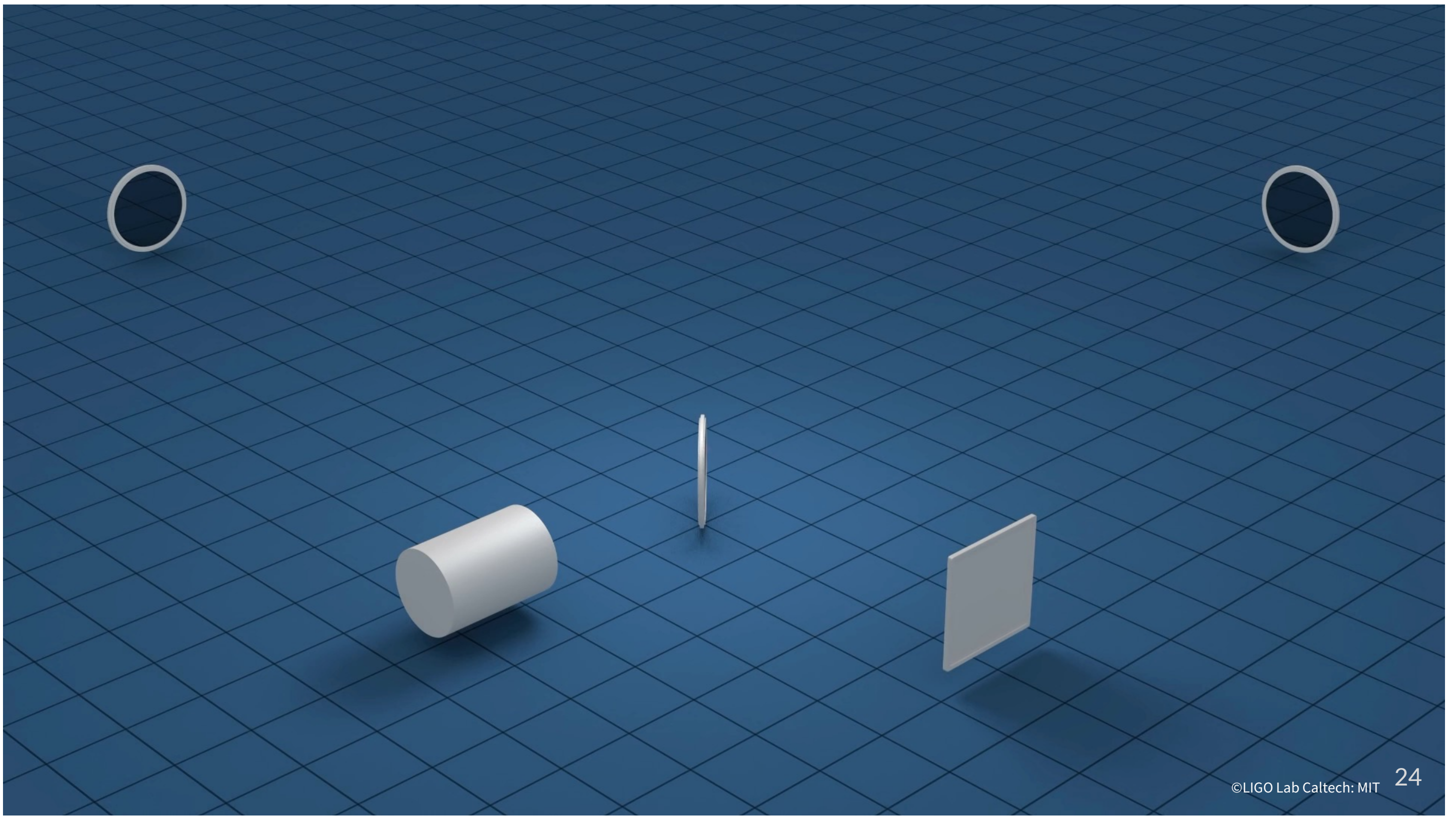
World's first “2.5th generation” GW telescope.

Underground

= under the mountain

Mt. Ikenoyama (Altitude 1368m)

©ICRR

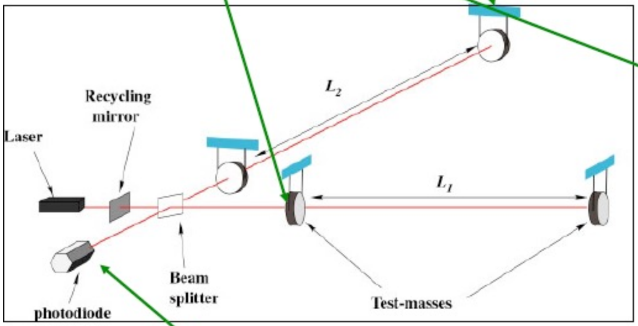


©LIGO Lab Caltech: MIT

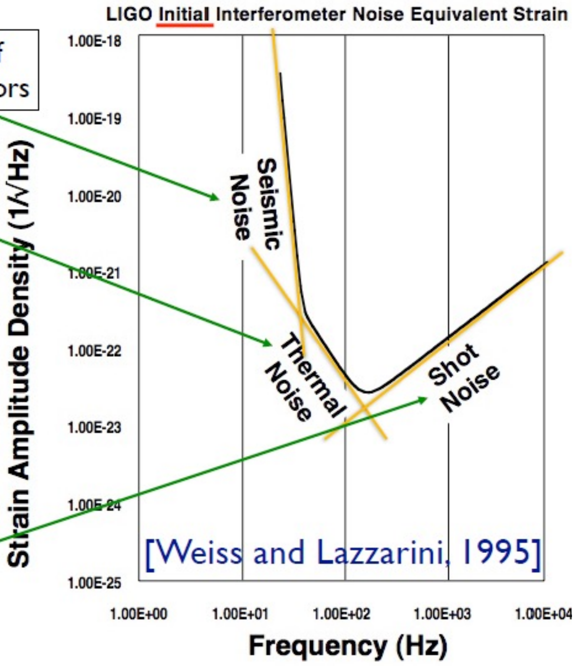
Origin of the noise curve

Thermal motion of molecules shakes mirrors

Seismic motion of ground shakes mirrors

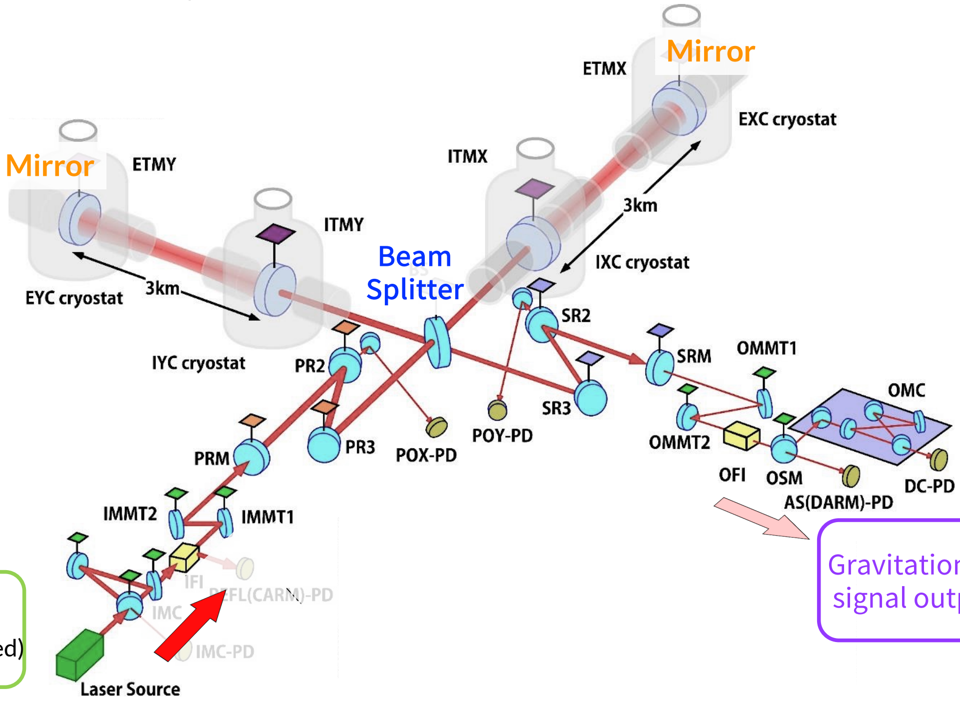


Photons arrive in a statistical pitter patter



J. Smith

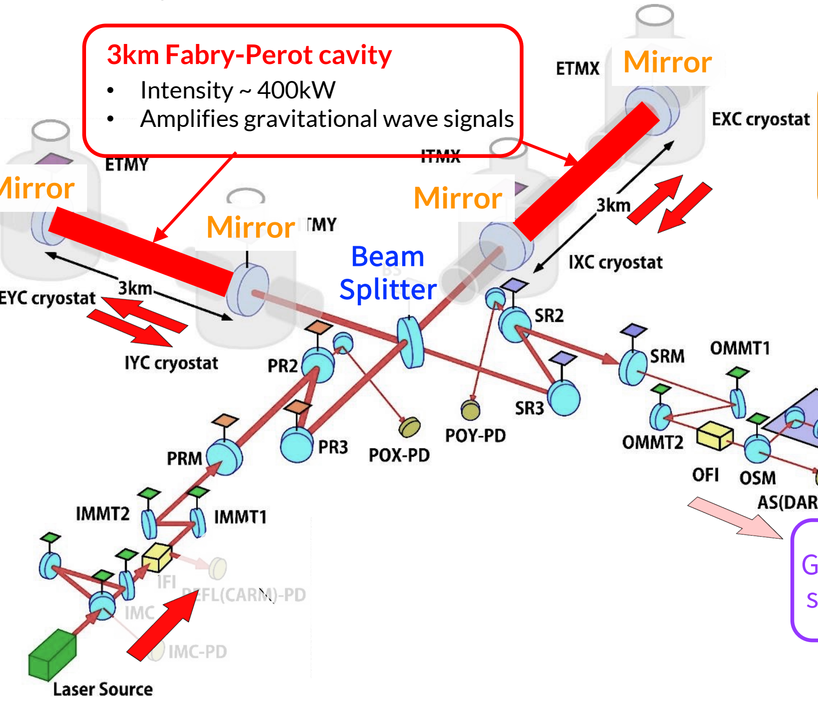
KAGRA system (design configuration)



Laser light source
- 100~180W (Planned)

Gravitational wave signal output port

KAGRA system (design configuration)



3km Fabry-Perot cavity
- Intensity ~ 400kW
- Amplifies gravitational wave signals

Mirror

Mirror

Mirror

Mirror

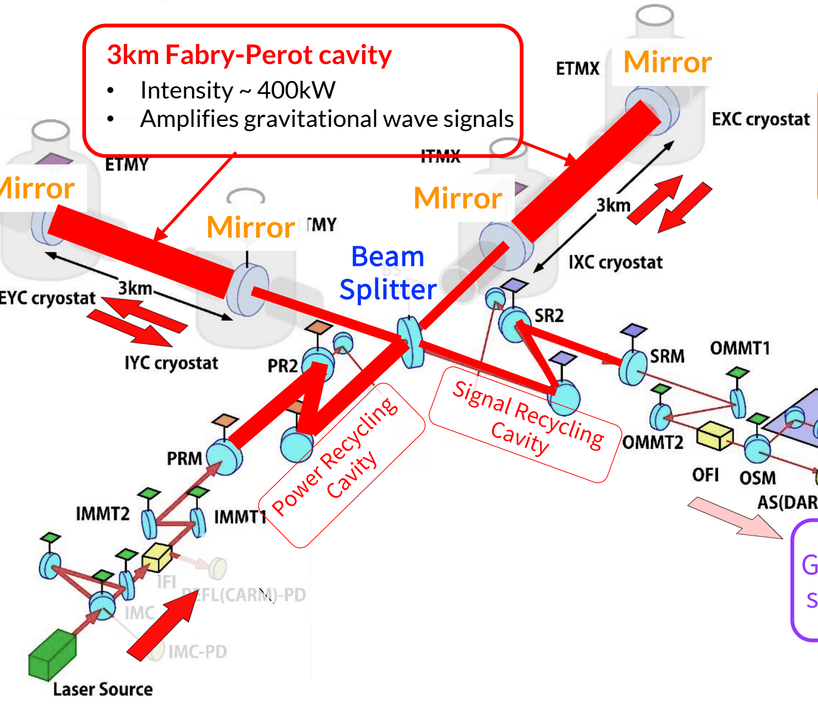
Beam Splitter

4 main mirrors
- Approx. ϕ22cm
- Sapphire

Laser light source
- 100~180W (Planned)

Gravitational wave signal output port

KAGRA system (design configuration)



3km Fabry-Perot cavity
- Intensity ~ 400kW
- Amplifies gravitational wave signals

Mirror

Mirror

Mirror

Mirror

Beam Splitter

Power Recycling Cavity

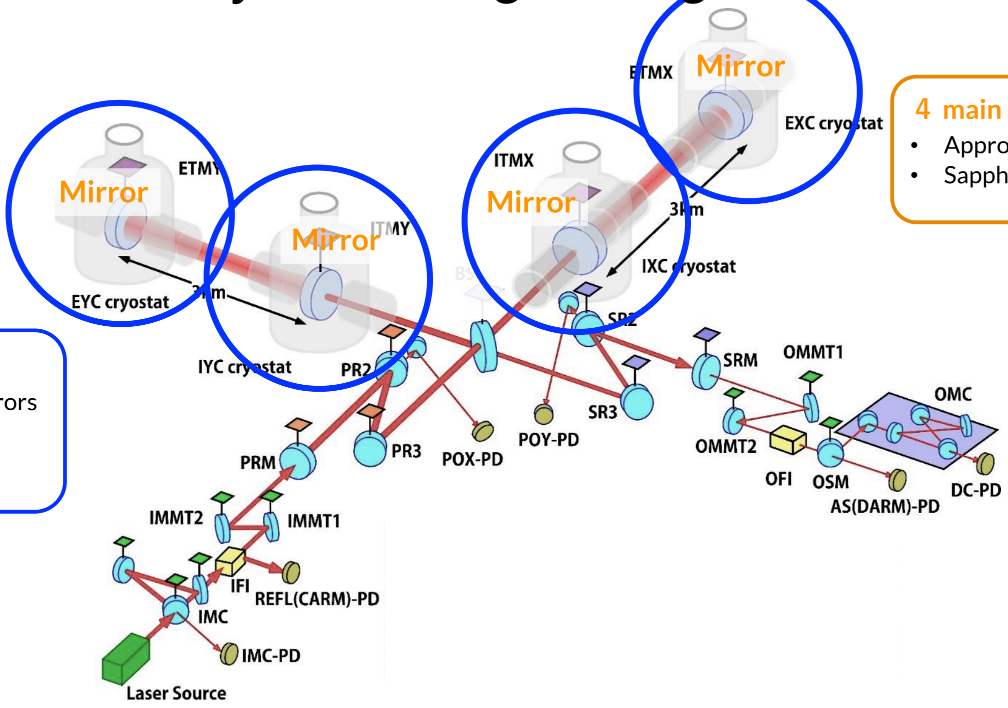
Signal Recycling Cavity

4 main mirrors
- Approx. ϕ22cm
- Sapphire

Laser light source
- 100~180W (Planned)

Gravitational wave signal output port

KAGRA system (design configuration)



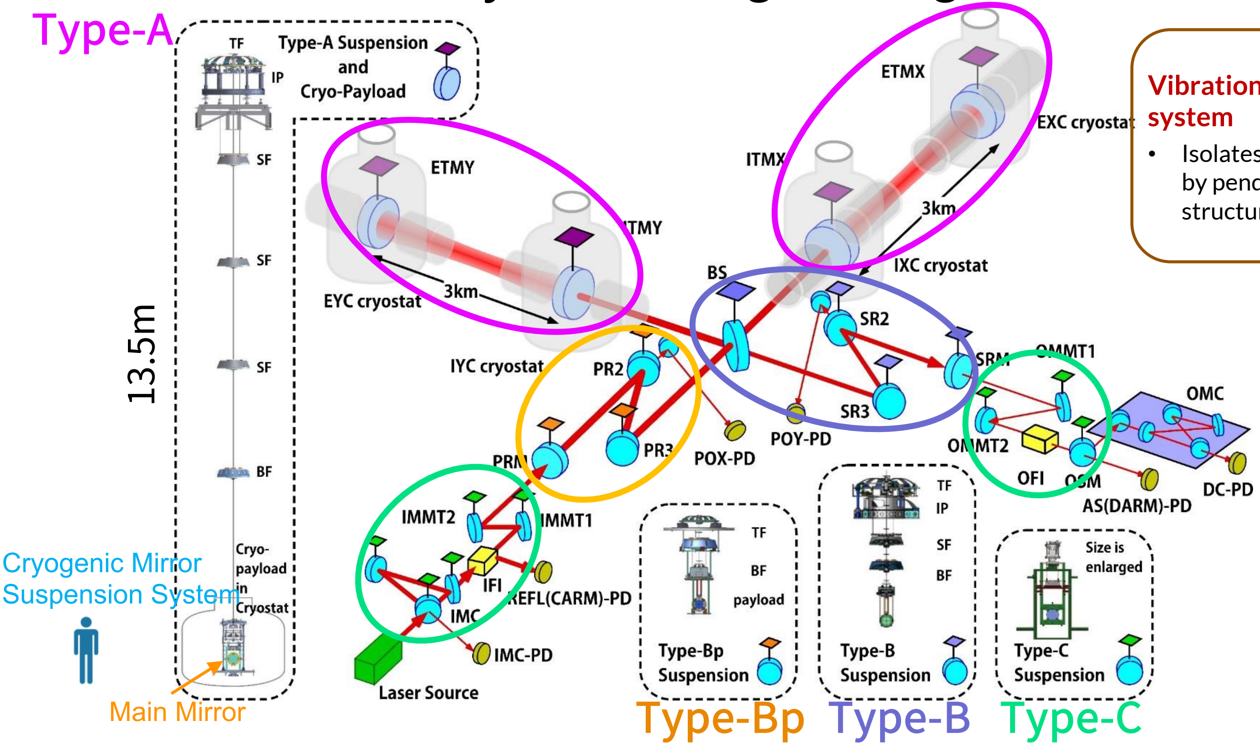
4 main mirrors

- Approx. ϕ22cm
- Sapphire

Cooling system

- Cools 4 main mirrors on both arms
- ~20K

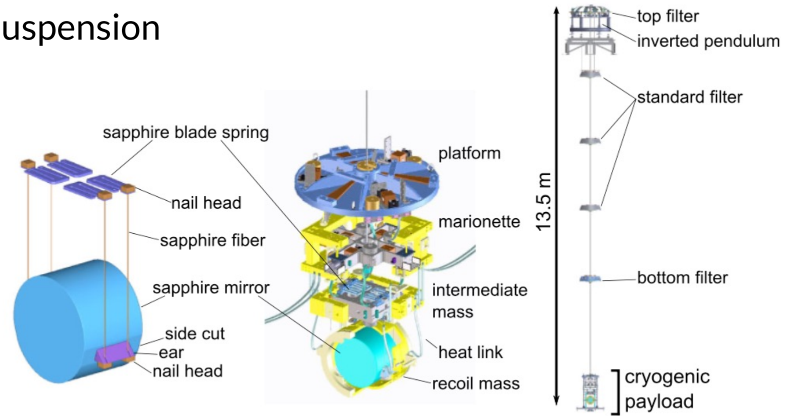
KAGRA system (design configuration)



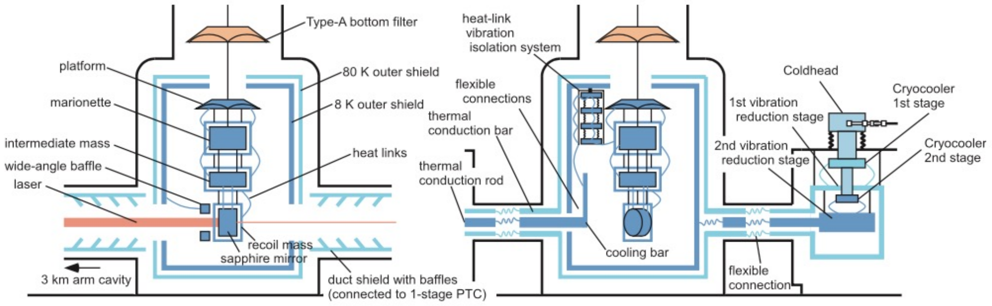
Vibration isolation system

- Isolates the mirrors by pendulum structure.

Type A suspension

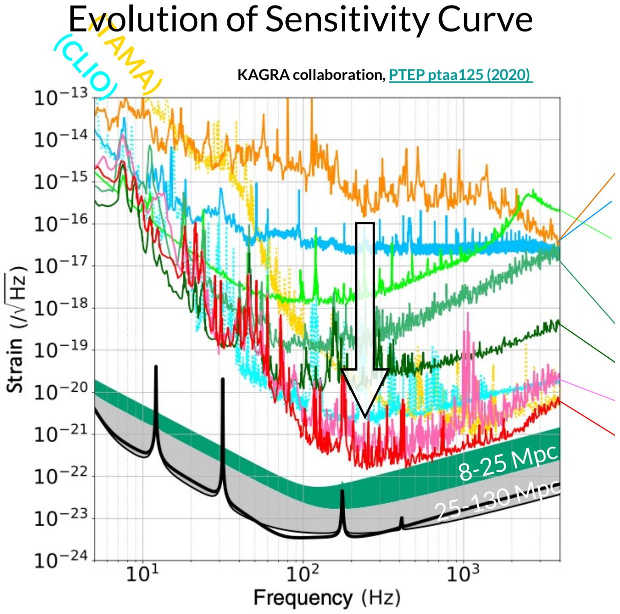


Cooling system



History of KAGRA

Evolution of Sensitivity Curve



KAGRA collaboration, PTEP ptaa125 (2020)

2010 Funded by MEXT Japan
2012 Started Construction
2016 Test Operation @ room temp. (iKAGRA)
2018 Cryogenic Test Operation (bKAGRA)
2019/8 FPMI

2019/10 Joined Research MoA with LIGO-Virgo

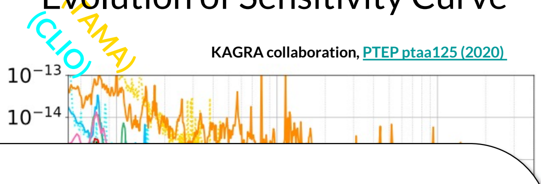
2019/11 FPMI
2019/12 FPMI
2020/2 PRFPMI
2020/3 PRFPMI

2020/3 Joined O3 PRFPMI @ room temp.
2020/4 Observation O3GK

FPMI = Fabry-Perot Michelson Interferometer
PRFPMI = Power Recycling Fabry-Perot Michelson Interferometer

History of KAGRA

Evolution of Sensitivity Curve



KAGRA collaboration, PTEP ptaa125 (2020)

Joint Research MoA with LIGO-VIRGO
Signed on Oct. 4, 2019

2010 Funded by MEXT Japan
2012 Started Construction
2016 Test Operation @ room temp. (iKAGRA)
2018 Cryogenic Test Operation (bKAGRA)
2019/8 FPMI
2019/10 Joined Research MoA with LIGO-Virgo
2019/11 FPMI
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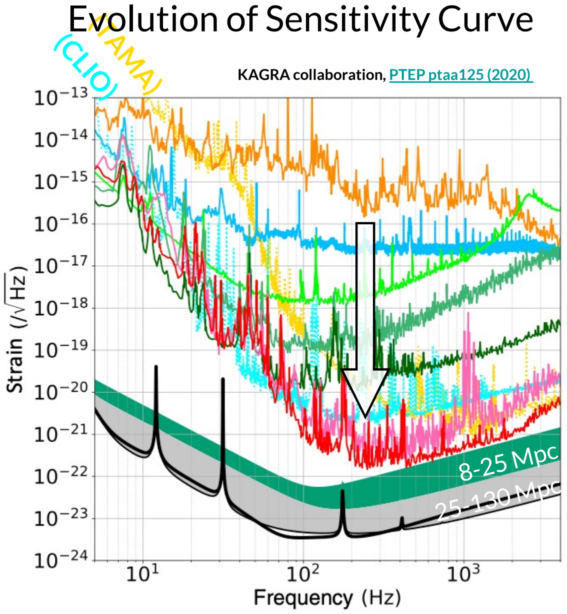
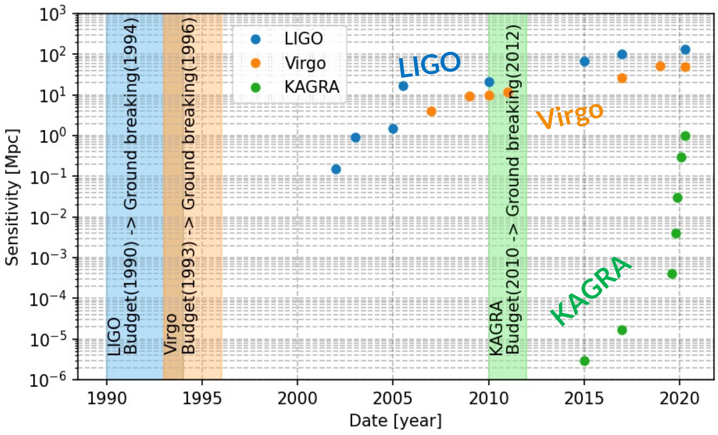
History of KAGRA

Evolution of Sensitivity Curve



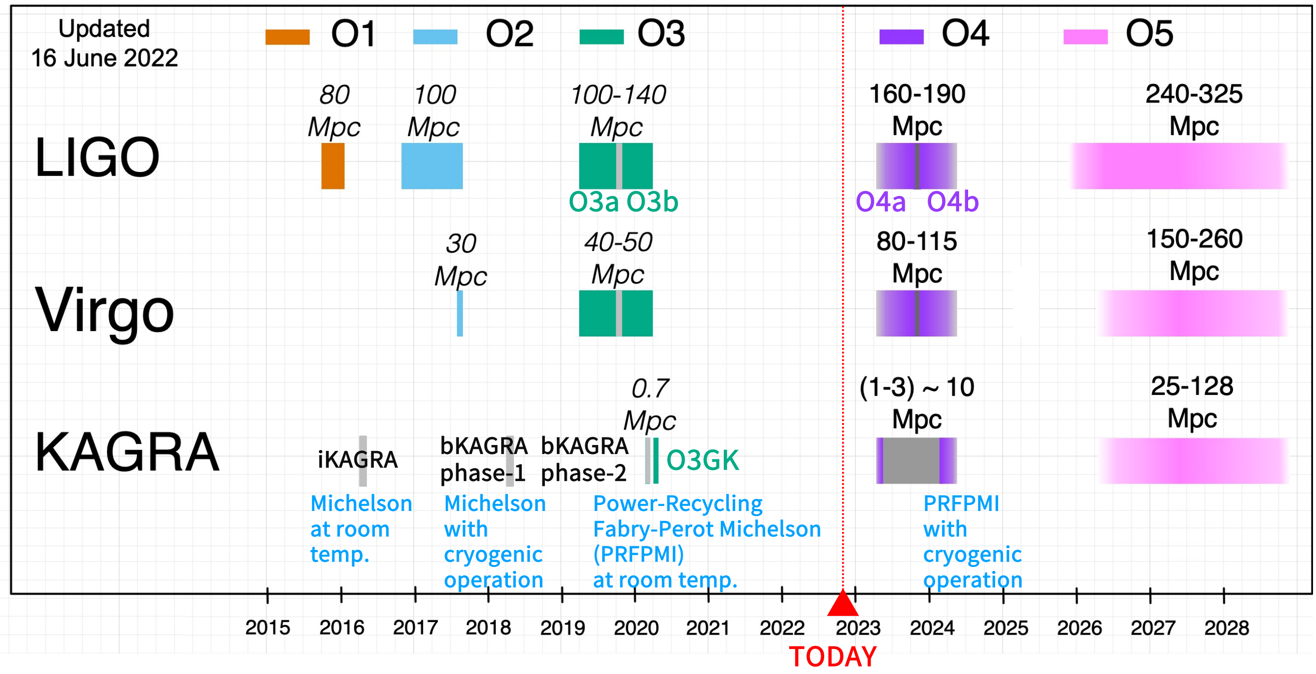
KAGRA collaboration, PTEP ptaa125 (2020)

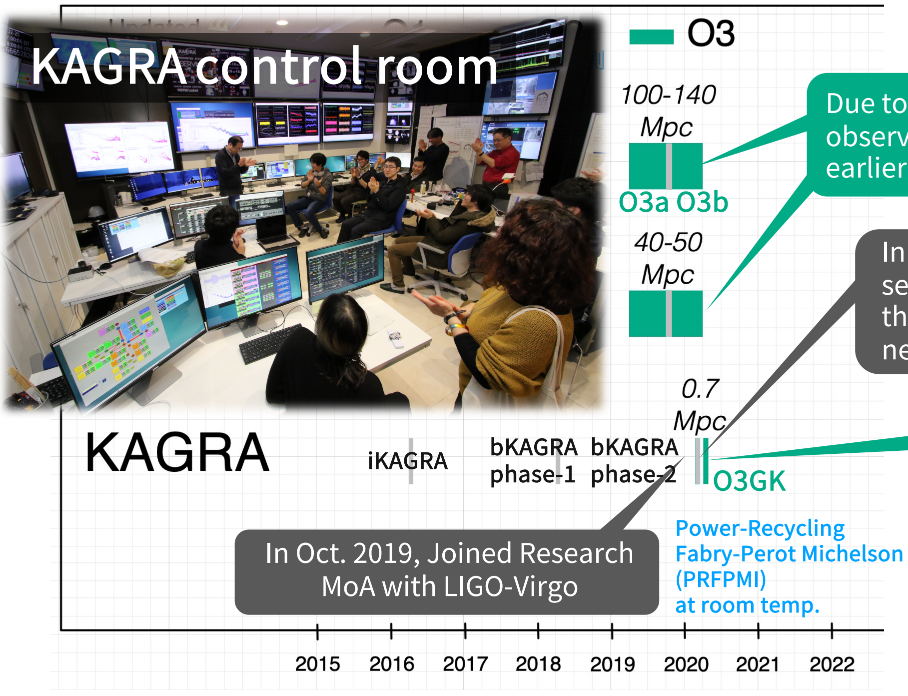
Evolution of the BNS range: distance to which a binary neutron star (BNS) merger is detectable with S/N> 8 [Mpc]



KAGRA started 20 (17) years after LIGO (Virgo). Its sensitivity has been improving very rapidly since the start of its operation.

Observing Run Plans (Past and Future)





Due to COVID-19, LIGO-Virgo ended observations in late March 2020, earlier than originally planned.

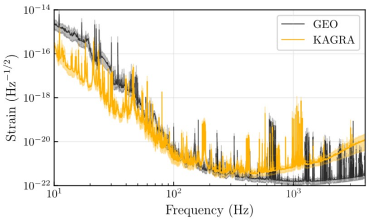
In late March 2020, achieved a sensitivity of over 1 Mpc and joined the international GW observation network.

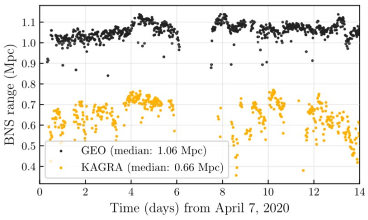
In April 2022, conducted international joint observation "O3GK" with GEO600, for 2 weeks.

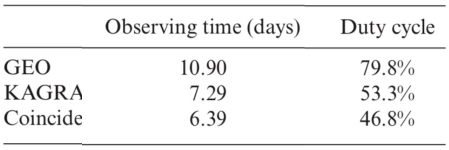
In Oct. 2019, Joined Research MoA with LIGO-Virgo

O3GK; Joint observation by GEO600 and KAGRA during the 3rd observation (O3)

- Observation Period: 2020/4/7 08:00 – 4/21 00:00 (UTC) (2 weeks)
- Observing time: 7.3 days (Duty cycle: 53 %)
- Achieved sensitivity：~0.66 Mpc（Max. ~ 1 Mpc, under test operation)





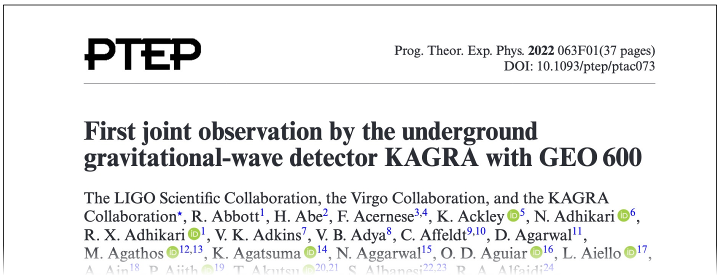


	Observing time (days)	Duty cycle
GEO	10.90	79.8%
KAGRA	7.29	53.3%
Coincide	6.39	46.8%

- KAGRA's first joint observation with another GW detector.
- Achievements of O3GK:
  - First full-scale experience of collaborative analysis and paper writing since KAGRA joined LV (GEO600 is a part of LIGO). KAGRA researchers played a key role.
  - Building pipelines from acquisition to analysis of data from observation networks, incorporating KAGRA Data-Quality.
  - The GW search results are reported in a scientific paper.

The GW search results at O3GK

https://doi.org/10.1093/ptep/ptac073



PTEP

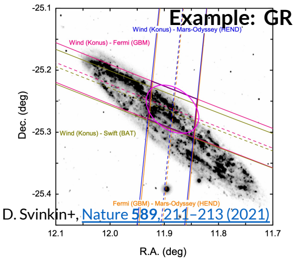
Prog. Theor. Exp. Phys. **2022** 063F01(37 pages)
DOI: 10.1093/ptep/ptac073

First joint observation by the underground gravitational-wave detector KAGRA with GEO 600

The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration*, R. Abbott[1], H. Abe[2], F. Acernese[3,4], K. Ackley[5], N. Adhikari[6], R. X. Adhikari[1], V. K. Adkins[7], V. B. Adya[8], C. Affeldt[9,10], D. Agarwal[11], M. Agathos[12,13], K. Agatsuma[14], N. Aggarwal[15], O. D. Aguiar[16], L. Aiello[17],

- During O3GK, several gamma-ray bursts (GRBs) were observed by astronomers.

Example: GRB200415A@NGC 253



D. Svinkin+, Nature **589**, 211–213 (2021)

©ESO/J. Emerson/VISTA

- LVK collaboration made a series of associated GW searches:
  - all-sky searches for binary neutron star (BNS) coalescences and generic unmodelled bursts,
  - targeted searches for compact binary coalescences (CBCs) and unmodelled bursts associated with the GRBs reported during the run (GRB-targeted searches).
- No GW signals were identified from the resulting data, as expected given the sensitivity of the detectors.
- However, these analyses demonstrate that the analysis efforts are ready to incorporate KAGRA data, which will be increasingly important as KAGRA nears its design sensitivity.

Noise budget at O3GK

PTEP

Prog. Theor. Exp. Phys. **2022** (35 pages)
DOI: 10.1093/ptep/ptac093

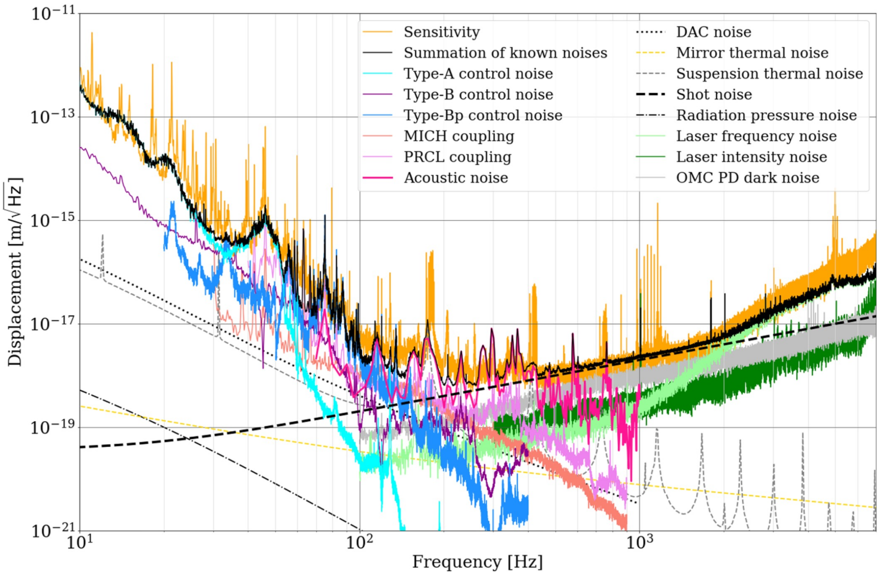
Performance of the KAGRA detector during the first joint observation with GEO 600 (O3GK)

KAGRA Collaboration,

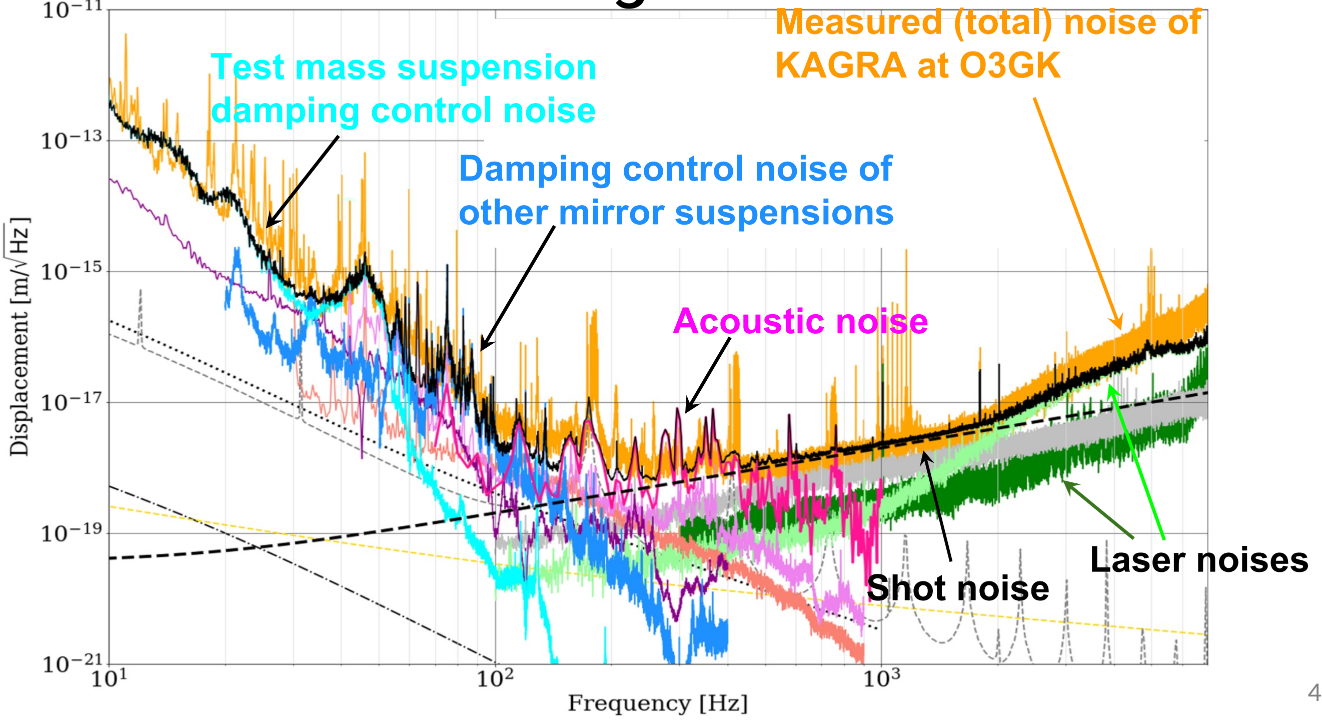
https://doi.org/10.1093/ptep/ptac093

After the O3GK, the noise sources which limited the sensitivity have been properly identified. (Noise Budget)

→ Improve the noises and increase sensitivity by the start of O4.



Noise budget at O3GK



Test mass suspension damping control noise

Measured (total) noise of KAGRA at O3GK

Damping control noise of other mirror suspensions

Acoustic noise

Shot noise

Laser noises

What is becoming apparent from O3GK

What noise sources limited the sensitivity in each frequency range?

Test mass suspension control noises

Coupling from auxiliary degrees of freedom

Acoustic noise

Shot noise

Laser frequency fluctuation

Low frequency ⟷ **High frequency**

Countermeasures toward O4 (work in progress)

- **Improvement of vibration isolation control**
  - Improvement of sensors
  - Installation of additional accelerometers on Top filter
  - Installation of additional sensors on the Platform and Marionette
  - Replacement of the magnets that control the mirrors with more powerful ones
  - Improvement of moving mass
- **Introduction of new angle sensor (Wavefront Sensing) for the interferometer mirrors**

- **Prevention of stray light**
  - Installation of additional baffles
- **Reduction of environmental noise**
  - Installation of additional environmental monitors
  - Conducting noise injection test

- **Introduction of high-power laser**
  - Maximum power: 60 W (120 W in the future)
- **Realization of PRFPMI**

etc.

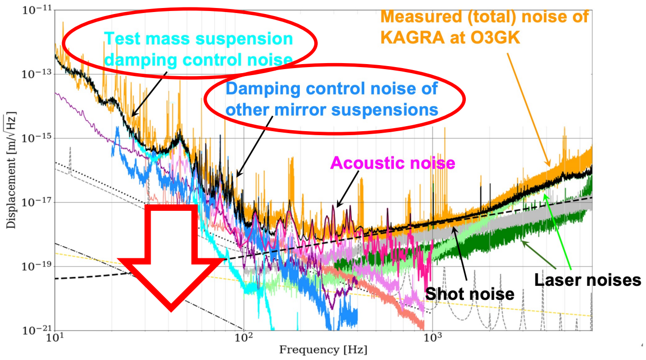
- **Improvement of cooling equipments and procedures**

(Installation of defrosting heaters, Absorbing the frost onto the duct shield during cooling, Start cooling after confirming sufficient vacuum)

etc.

Suspension Upgrades

- Fixed mechanical failures
- Improved various local sensors
  - Accelerometers
  - LVDTs
  - Optical Levers
- Improved actuator balances



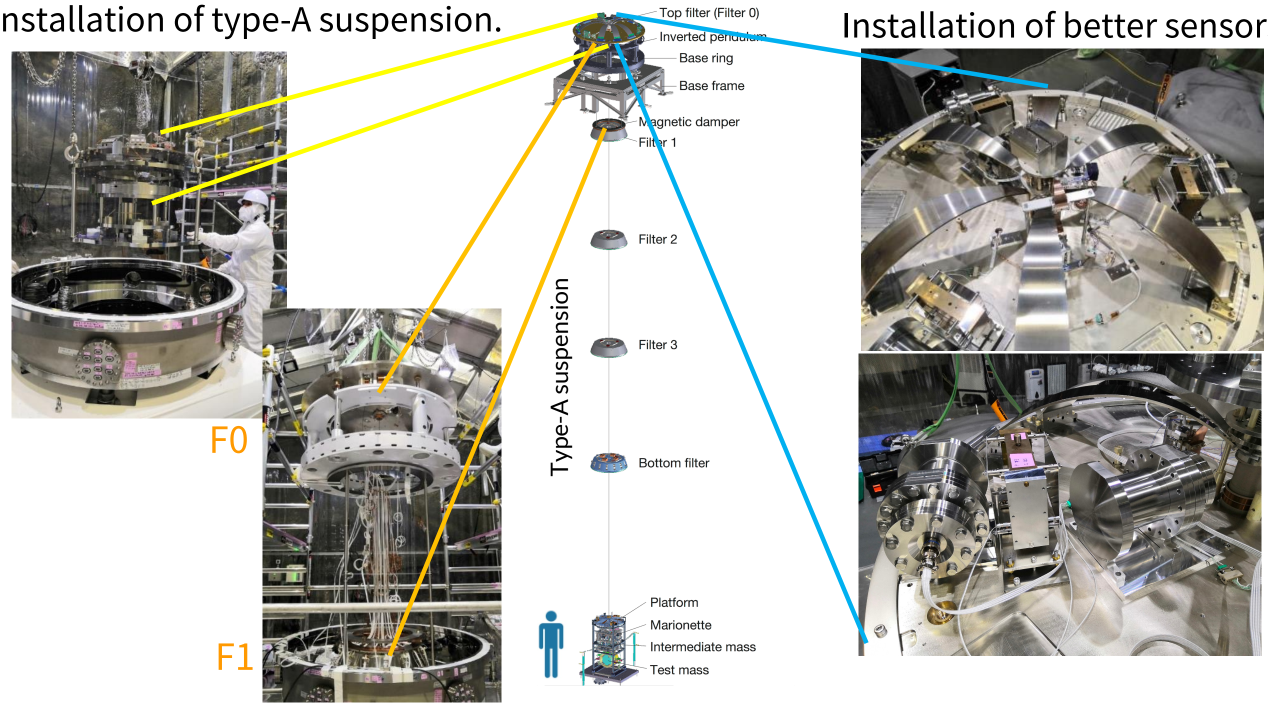
Better optimization of damping control filters

- We know what is limiting the current suspension noise and working on to improve it.

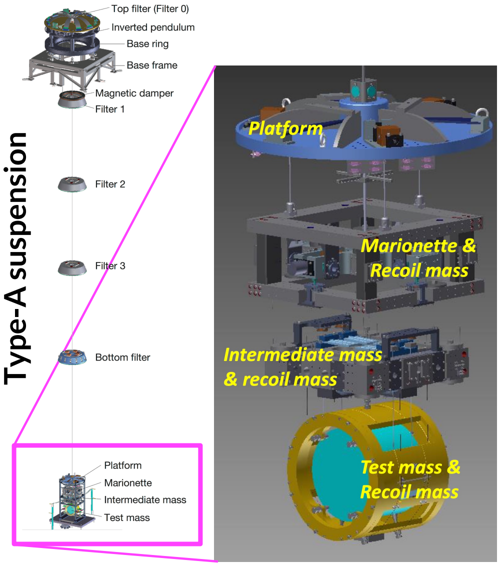
Suspension Upgrades

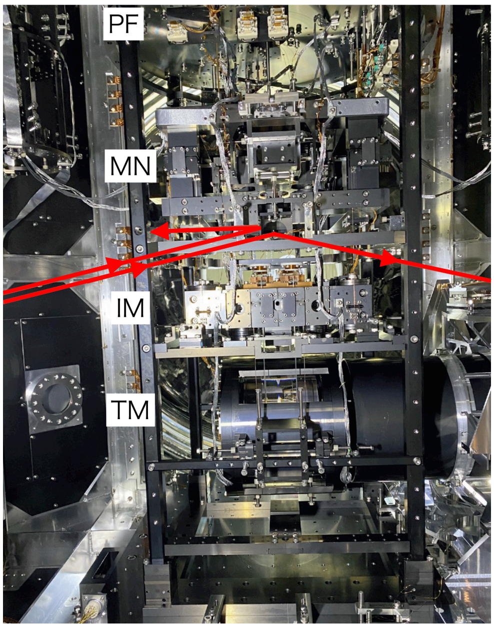
Re-installation of type-A suspension.

Installation of better sensors

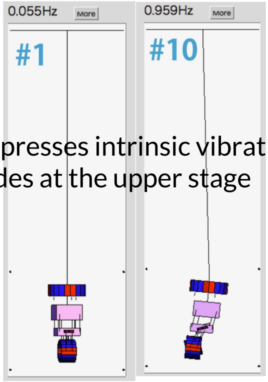


Installation of more and better Optical Levers





- **Platform (PF) stage:**
  3 degree of freedom
  (Pitch/Yaw/Long)
- **Marionette (MN) stage:**
  6 degree of freedom
  (Pitch/Yaw/Long/Roll/Trans/Vert)



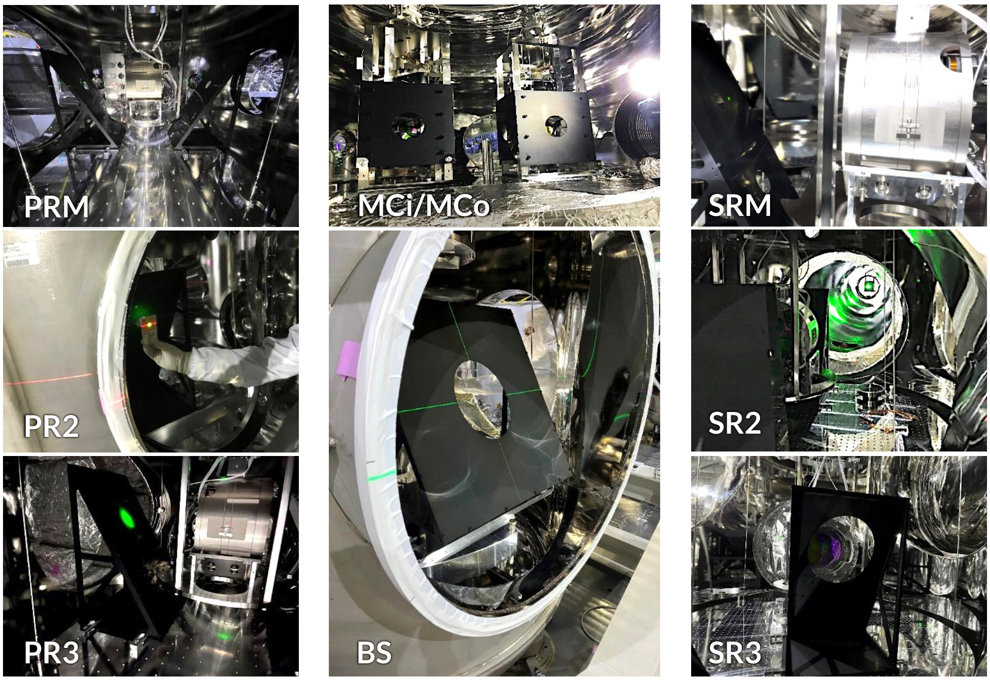
Suppresses intrinsic vibration modes at the upper stage

Y whole chain 0th

L pendulum 1st, common 0th

Installation of additional baffles

→ Reduction of scattered light noise

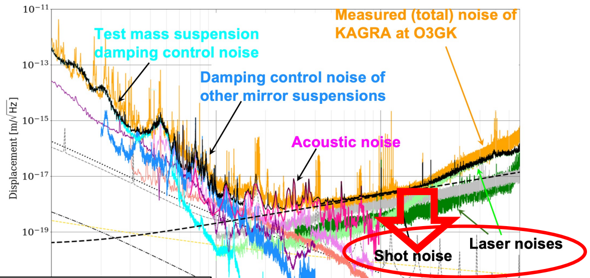


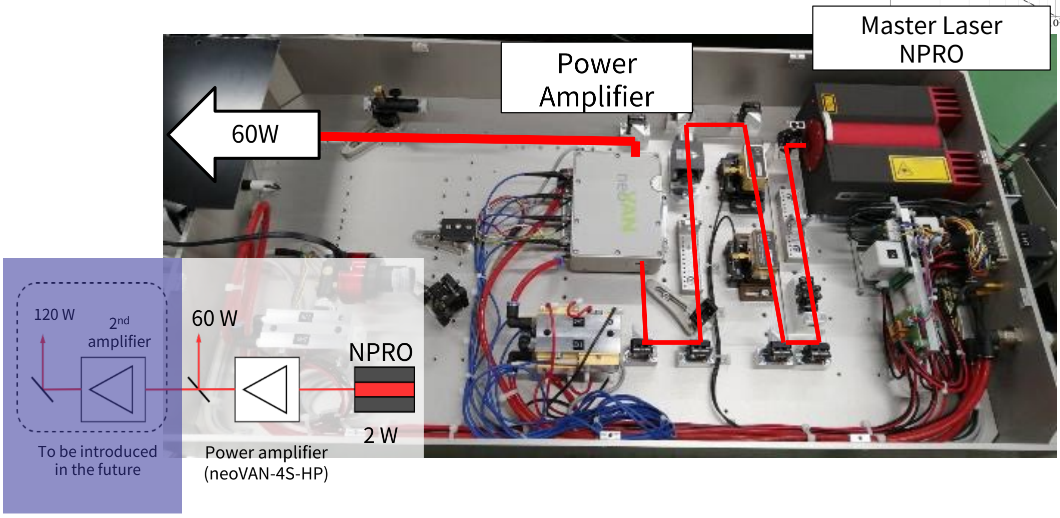
→
- improve sensitivity and operational stability
- reduce non-stationary noise and improve data quality for analysis

---

Introduction of high-power laser

- 40 W → 60 W (120 W in the future)
  - Only 4 W used during O3GK

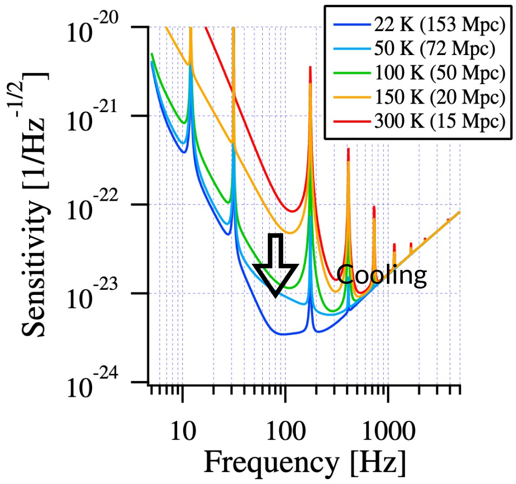




Vacuum & Cryogenic Upgrades

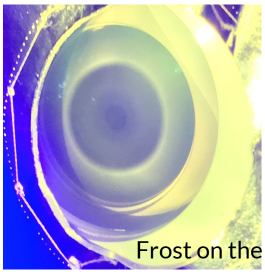
We want to reduce thermal noise by cooling the mirror, but..

KAGRA collaboration, PTEP ptaa125 (2020)



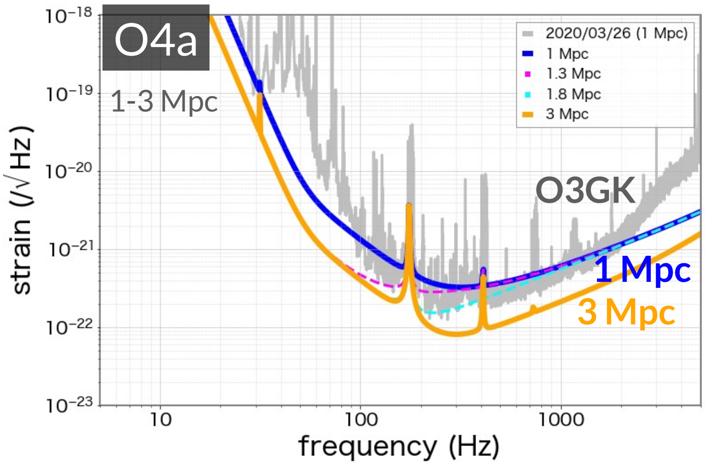
Problems occurred in the preparations for O3

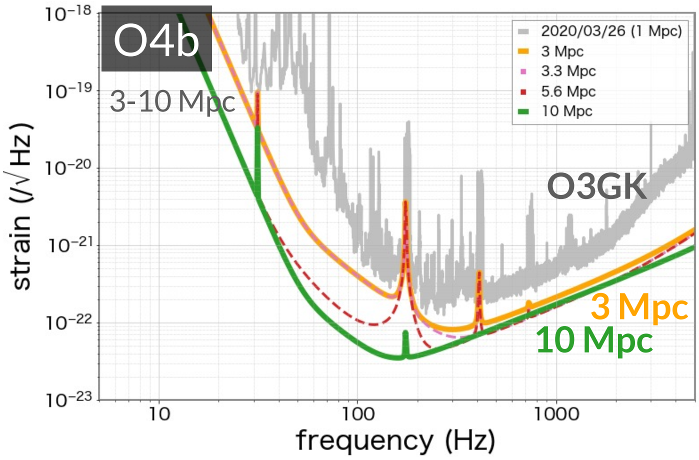

A beam spot blurred by frost on the mirror.


Frost on the view port

- Additional vacuum pumps
  - 12 more ion-pumps
  - 10 more turbo molecular pumps
- Better vacuum
- Avoid molecular adsorption on mirrors during cooling
- Defrosting heaters

Expected improved sensitivities by commissioning towards O4a/b





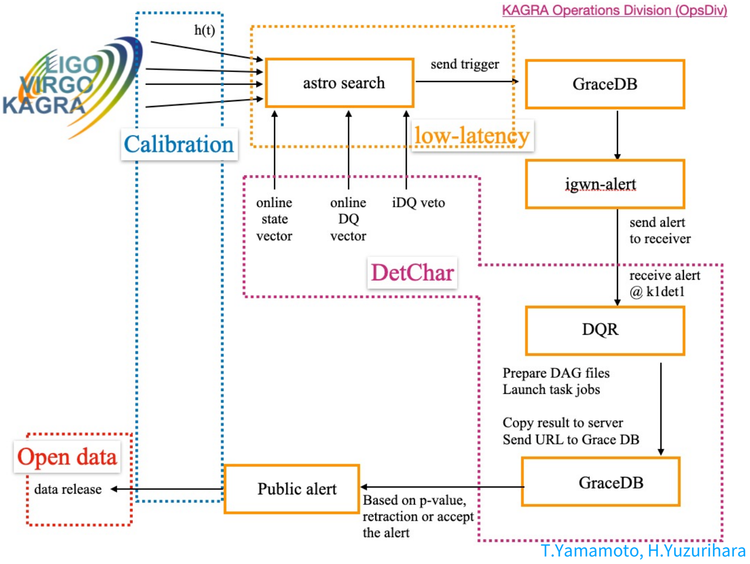
- Reduce noises in low frequency bands by improving the vibration isolation system control.
- Reduce scattered light by installing additional baffles.
- Increase laser power and replace photodetectors.
- Reduce quantum noise by non-reflection of signal-recycling mirror.

- Reduces noise in the low-frequency band.
- Reduces thermal noise by cooling the mirror below 100 K.

One Example for other LVK joint efforts

A framework for practical coordination with LV has been formalized.

- Preparations are underway to share various information in addition to the h(t) and status flags provided in O3.
- Preparations and tests for GW alert in O4 are underway. Discussion on Rapid Response Team has also started.



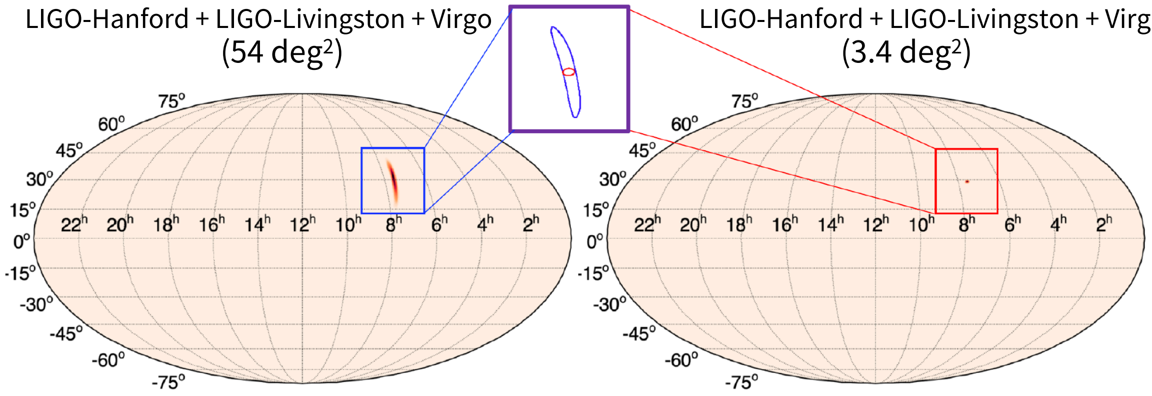
T.Yamamoto, H.Yuzurihara

Flow to accept/retract when the low-latency search pipeline triggers a GW candidate.

Once KAGRA achieves its full sensitivity, it will significantly contribute to sky localization

LIGO-Hanford + LIGO-Livingston + Virgo
(54 deg^2)

LIGO-Hanford + LIGO-Livingston + Virgo + KAGRA
(3.4 deg^2)



In addition,

- Better confidence in detection of signals
- Better duty cycle and sky coverage for searches
- Better resolving degeneracy of polarization, orbital plane inclination angle and distance

Summary

- LIGO - Virgo - KAGRA (LVK) collaboration has been launched.
- O3GK
    - International joint observation O3GK with GEO600 was conducted for two weeks in April 2020.
- Upgrade works for the next observing run O4 are currently in progress.
- Next joint observation O4
    - It is scheduled to start in March 2023.
    - KAGRA will join the observation with the improved sensitivity with LIGO-Virgo for part of the period.
    - We will aim for the first detection of GW from KAGRA data.

⇓

Contributions to multi-messenger astrophysics, astronomy, fundamental physics, etc.

A Study of Black Hole Perturbations in Modified Gravity

Karim Noui

IJCLab, Paris-Saclay - JGRG31, October 2022, 24th

⋆ ⋆ ⋆

ANR StronG

Talk based on articles in collaboration with D. Langlois and H. Roussille

Our works rely on many important contributions by other authors

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Plan of the talk

Purpose of the talk : a short review and new results (as the audience is rather broad)

My apologies to those who know and are working on this topic.

1. Motivations : Era of Gravitational Waves

- Ringdown Phase of Black Hole Binaries : Possibility to see deviations from GR ?

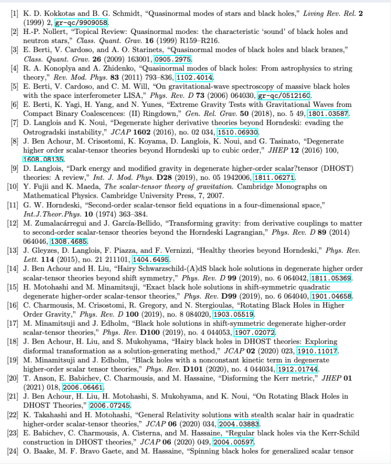
2. Modified Gravity : Scalar-Tensor Theories

- Adding one more scalar degree of freedom in addition to gravitational modes
- Lagrangian and Disformal transformations of the metric

3. Modified Black Holes : a study of their perturbations

- New (non-rotating) Hairy Black Hole solutions
- Axial Perturbations and the effective metric
- Even Perturbations : coupling to the scalar field perturbations (no time !)

Some references in a very active field of research !



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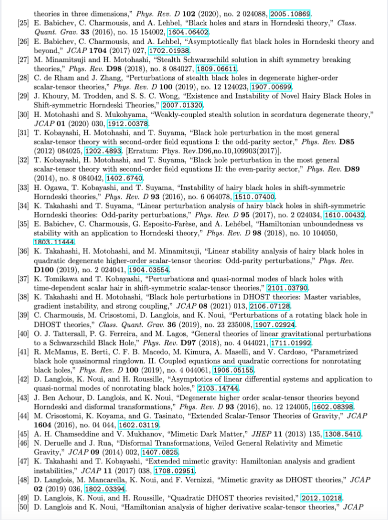

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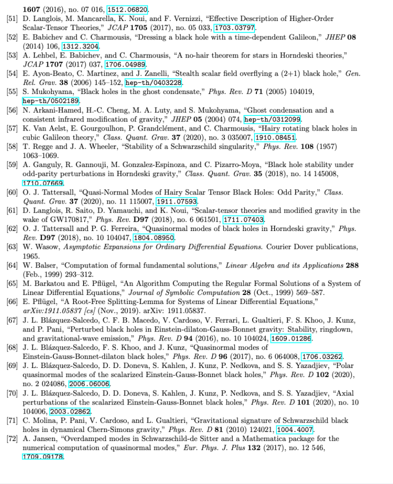

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Many new references almost everyday...

A lot of important contributions from Japanese laboratories

Part on Gravitational Waves

LIGO-Virgo-KAGRA Collaborations

Part on Scalar-Tensor Theories

A. De Felice, Y. Fujii, K. Izumi, T. Kobayashi, K. Maeda, H. Motohashi, S. Mukohyama, M. Sasaki, N. Tanahashi, S. Tsujikawa, T. Suyama, K. Takahashi, M. Yamaguchi, etc.

Part on Black Hole Perturbations

- On solutions : Ben Achour, T. Fujita, T. Kobayashi, M. Minamitsuji, H. Motohashi, S. Mukohyama, K. Numajiri, T. Suyama, K. Takahashi, K. Tomokawa, etc.
- On perturbations : same researchers + S. Hirano, V. Yingcharoenrat, etc.

I apologize for my (probably many) omissions...

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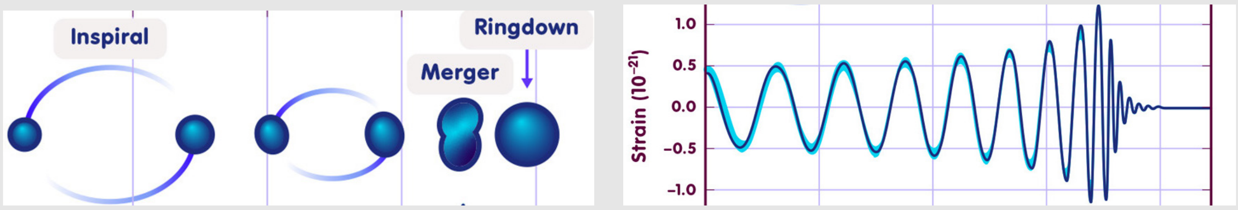
1. Motivations

Ringdown of Black Hole Binaries

The era of Gravitational Wave Astronomy [Illustration from LIGO-Virgo]



The Ringdown phase is the simplest and fully understood in General Relativity

For a Schwarzschild Black Hole, two types of perturbations (axial and polar) described in terms of a function decomposed as follows [Regge-Wheeler, Zerilli],

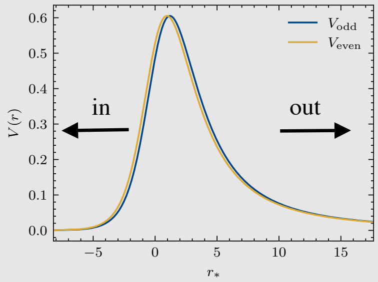
$$\psi(t,r,\theta,\varphi) = \psi(r) Y_{\ell m}(\theta,\varphi) e^{-i\omega t}$$

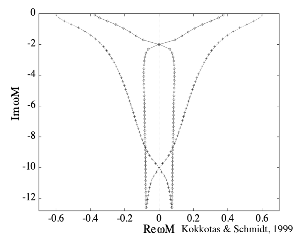
The radial component satisfies a Schrödinger-like equation

$$-\psi'' + V(r)\,\psi = \omega^2\,\psi \quad \Longrightarrow \quad \text{Spectral Problem}$$

Perturbations and Quasi-Normal Modes : a few results

Dynamics of perturbations and Quasi-Normal-Modes





Kokkotas & Schmidt, 1999

- Perturbations are shown to be stable [Vishveshwara ('70) ; Wald ('80)]
- Perturbations can be decomposed into Quasi-Normal Modes [see Nollert ('99) for instance]
- Quasi-Normal Modes are in-going at horizon and out-going at infinity
- Discrete spectrum with a negative imaginary part [see Kokkotas et al ('99) for instance]
- Similar results for a Kerr Black Hole [Teukolsky ('73)]

Ringdown : a window onto Strong Gravity (see Berti et al. [1801.03587])

We want to test General Relativity in the strong gravity regime

⟶ Could we see deviations from General Relativity in the ringdown phase ?

The strategy one follows in general consists in several steps

⟶ Considering Modified Theories of Gravity

⟶ Adapting the methods developed in General Relativity to study perturbations

⟶ Predict and/or Constrain deviations from General Relativity

Problem : Most of the “nice” features of General Relativity are lost !

- Each step is involved
- But, this also makes the study of deviations physically very interesting !

What are the difficulties ?

General Relativity is unique [Lovelock] !

- Modified Gravity is not unique. What type of modifications shall we consider ?
- Many approaches : massive gravity, scalar-tensor theories, EFT of modified gravity...

Black Holes in General Relativity have no hair !

- Black Hole solutions are (in general) hairy and no more unique in modified gravity.
- How to find them ? How to classify them ?

⟶ All this makes the study of the dynamics of perturbations more involved, due to the presence of extra degrees of freedom

⟶ Here we restrict ourselves to **scalar-tensor theories**

2. Scalar-Tensor Theories

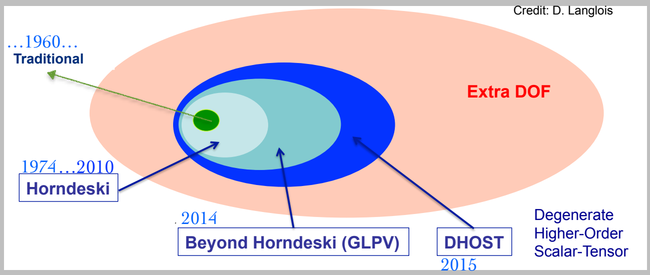
Modified Gravity and scalar-tensor theories

Beyond General Relativity : Relaxing hypothesis of Lovelock Theorem

→ Lovelock : A massless spin 2 field (with Diff-invariance) in 4 dimensions is uniquely described by GR with a cosmological constant

→ Relaxing one hypothesis leads to a huge landscape of modified gravity theories !

Classification of most general scalar-tensor theories : (U-) DHOST theories


Credit: D. Langlois

Action $S[g_{\mu\nu}, \phi]$ involves higher derivatives $\nabla_\mu \nabla_\nu \phi$ but only one scalar dof propaging in addition to the tensor modes.

→ Long history with a renewal of ST theories in '00 due to the problem of dark energy

A few words on Horndeski theories : the cornerstone !

Horndeski theories [rediscovered by Deffayet et al, Kobayashi et al, after Nicolis et al.]

The most general $S[g_{\mu\nu},\phi]$ whose Eq.of Motion are second order

$$L[g_{\mu\nu},\phi] = F(\phi,X)\,R + P(\phi,X) + Q(\phi,X)\Box\phi + 2F_X(\phi_{\mu\nu}\phi^{\mu\nu} - \Box\phi^2) + \cdots$$

With $X = \phi_\mu\phi^\mu$, $\phi_\mu = \nabla_\mu\phi$ and $\phi_{\mu\nu} = \nabla_\mu\nabla_\nu\phi$.

Important Properties of Horndeski theories [see reviews by Kobayashi, Deffayet-Steer or Langlois]

→ EFT for dark energy (motivated by brane cosmology scenarii) where ϕ is dark energy

→ Metric not uniquely defined due to disformal transformations [Bekenstein]

$$g_{\mu\nu} \longrightarrow \tilde{g}_{\mu\nu} \equiv C(\phi,X)g_{\mu\nu} + D(\phi,X)\phi_\mu\phi_\nu\,.$$

→ Possibility of non-minimal couplings to matter : $L_{\rm mat}[\psi] = \tilde{g}^{\mu\nu}\partial_\mu\psi\partial_\nu\psi + \cdots$

From Horndeski to DHOST theories and then U-DHOST theories

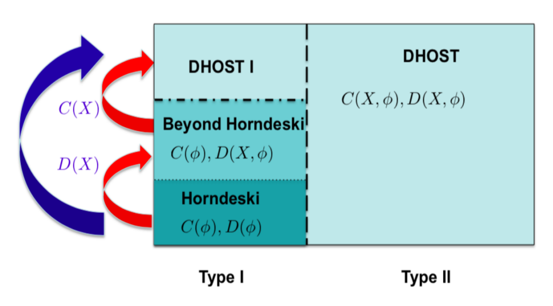
Case of Quadratic DHOST Theories

The DHOST action $S[g_{\mu\nu},\phi]$ whose E.o.M. are not necessarily second order

$$L[g_{\mu\nu},\phi] = F(\phi,X)\,R + P(\phi,X) + Q(\phi,X)\Box\phi + \sum_{i=1}^{5} A_i(\phi,X)L_i$$

$$L_1 = \phi_{\mu\nu}\phi^{\mu\nu}\,,\quad L_2 = \Box\phi^2\,,\quad L_3 = \phi^\mu\phi_{\mu\nu}\phi^\nu\Box\phi\,,\quad L_4 = (\phi^\mu\phi_{\mu\nu})^2\,,\quad L_5 = (\phi^\mu\phi_{\mu\nu}\phi^\nu)^2$$

With degeneracy conditions relating the functions A_i and $F \Longrightarrow$ 2 classes of theories.



Geometric Formulation of quadratic DHOST theories

Type I are physically viable (with no gradient instabilities, nor ghosts)

- Disformally related to Horndeski theories : $S[g_{\mu\nu}, \phi] = S_H[\tilde{g}_{\mu\nu}, \phi]$
- DHOST theories are not equivalent to Horndeski theories in the presence of matter

Geometric Formulation

→ Let Σ_ϕ be the hypersurface of constant ϕ (ϕ plays the role of time when $X < 0$)

→ Then, Type I theories are disformally related to the simple action

$$S[g_{\mu\nu}, \phi] = \frac{M_P^2}{2} \int d^4x \sqrt{-g} \left({}^4R + \lambda(\phi, X)\, {}^3R\right)$$

→ ${}^3R$ is the 3-dimensional Ricci scalar on Σ_ϕ.

---

3. Black Hole Perturbations

DHOST Theories as EFT of Hairy Black Holes

Evading the No-Hair Theorem [Babichev-Charmousis]

New static and spherically symmetric black holes with (for shift-symmetric theories)

$$ds^2 = -A(r)dt^2 + \frac{1}{B(r)}dr^2 + C(r)d\Omega^2 \,, \qquad \phi(t,r) = qt + \psi(r) \,.$$

A few analytic solutions [Mukohyama, Babichev-Charmousis-Lehebel, Lu-Pang]

- Stealth solutions with $A(r) = B(r) = 1 - 2M/r$, $C(r) = r^2$ and $X = \mathrm{cst}$
- BCL solution with $A(r) = B(r) = (1 - r_+/r)(1 + r_-/r)$ and $C(r) = r^2$
- $D \to 4$ Gauss-Bonnet solution with

$$A(r) = B(r) = 1 - \frac{2M(r)}{r} \,, \quad M(r) = \frac{2M}{1 + \sqrt{1 + 8\alpha M/r^3}} \,, \quad C(r) = r^2$$

Dynamics of Linear Perturbations [see list of authors in introduction]

Modified Einstein equations at linear order

$$g_{\mu\nu} = \overline{g}_{\mu\nu} + h_{\mu\nu} \,, \qquad \phi = \overline{\phi} + \delta\phi$$

- Axial perturbations : $\delta\phi = 0$ while $h_{\mu\nu}^{\mathrm{axial}}$ depend on $\chi = \psi(r)e^{-i\omega t}Y_{\ell m}(\theta,\varphi)$

$$-\frac{d^2\psi}{dr^2} + V(r)\psi = \frac{\omega^2}{c(r)^2}\psi$$

- Polar perturbations : $\delta\phi$ and $h_{\mu\nu}^{\mathrm{polar}}$ are coupled with no explicit decoupling

Effective metric of axial perturbations

Dynamics of $h_{\mu\nu}^{\mathrm{axial}}$ about $\overline{g}_{\mu\nu}$ in DHOST are equivalent to those in GR with $\tilde{g}_{\mu\nu}$

$$\tilde{g}^{\mu\nu}\tilde{\nabla}_\mu\tilde{\nabla}_\nu\psi - m_{\mathrm{eff}}^2\psi = 0 \,.$$

On the effective metric of Axial perturbations

Physical interpretation : coupling between the metric and the scalar field

→ (Minimally coupled) photons and Gravitons do not see the same space-time

→ Photons are sensitive to the background metric $\overline{g}_{\mu\nu}$ while gravitons evolve in $\tilde{g}_{\mu\nu}$

→ Consequence of the interactions between gravitons and the scalar field (as if gravitons were evolving in a medium)

Disformal transformations

In quadratic DHOST theories, $\tilde{g}_{\mu\nu}$ is disformally related to $\overline{g}_{\mu\nu}$ by

$$\tilde{g}_{\mu\nu} = \sqrt{F(F - XA_1)} \left(\overline{g}_{\mu\nu} + \frac{A_1}{F - XA_1} \overline{\phi_\mu} \, \overline{\phi_\nu} \right)$$

Where the functions are evaluated on the background solution.

Causal structures of the background and effective metrics

Examples of effective metrics

The effective metric can be very different from the background metric

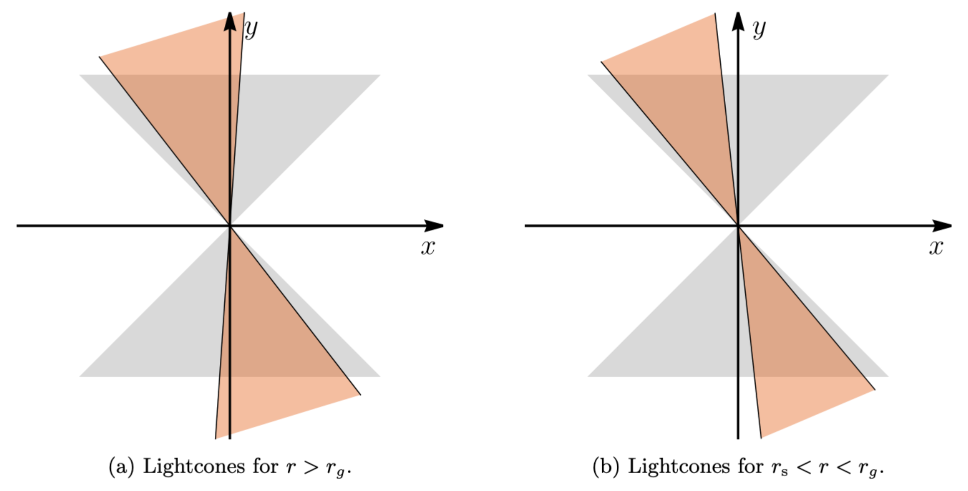
- Stealth solutions : $\tilde{g}_{\mu\nu}$ is still a black hole with a different horizon

$$R_s = 2GM/c_\gamma^2 \,, \quad R_g = 2GM/c_g^2 \,, \qquad c_g < c_\gamma$$

- BCL solution : $\tilde{g}_{\mu\nu}$ is a black hole with the same horizon
- $D \to 4$ Gauss-Bonnet solution : $\tilde{g}_{\mu\nu}$ is a naked singularity

$\Longrightarrow$ Eventual strong physical pathologies and/or instabilities ?

Case of the stealth solution : causal structures are compatible



(a) Lightcones for $r > r_g$. (b) Lightcones for $r_s < r < r_g$.

No instabilities between the two horizons following 1803.11444 [Babichev et al] **confirmed by** [K. Nakashi et al]

On the stability of Axial Perturbations in DHOST Theories [To appear]

The general effective metric takes the generic form

$$d\tilde{s}^2 = -\tilde{A}(r)\,dt_*^2 + \frac{1}{\tilde{B}(r)}dr^2 + \tilde{C}(r)\,d\Omega^2 .$$

Essentially Self-Adjoint Schrödinger operator

The potential associated with Axial perturbations takes the general form

$$V = S^2 - \partial_* S + 2\lambda\frac{\tilde{A}}{\tilde{C}}, \quad S = \frac{1}{2}\frac{\partial_*\tilde{C}}{\tilde{C}}, \quad (\tilde{A}(r)\tilde{B}(r))^{1/2}\frac{\partial r_*}{\partial r} = 1$$

The Schrödinger operator is positive

→ Eliminate the S-part which is a so-called S-deformation

→ $\tilde{A}$ and $\tilde{C}$ are positive if we assume one horizon and no-signature change

$\Longrightarrow$ Axial perturbations are generically stable.

4. Conclusion

Deviations from GR in the Strong Gravity regime : background/perturbations

DHOST Theories as EFT of gravity in the Strong Gravity regime

- Background solutions : Hairy Black Holes or Exotic compact objects
- Axial perturbations : effective metric different from background metric
- Polar perturbations : interactions between the graviton and the scalar
  → not easy to handle and to decouple
  → needs new techniques to study the coupled dynamics : asymptotic analysis

Going further....

▷ Compute Quasi-Normal Modes and Deviations from General Relativity

▷ Constrain theories from the systematic study of pathologies and instabilities

Thank you for your attention

I03

Probing the Nature of Gravity via Quantum Correlation of Light

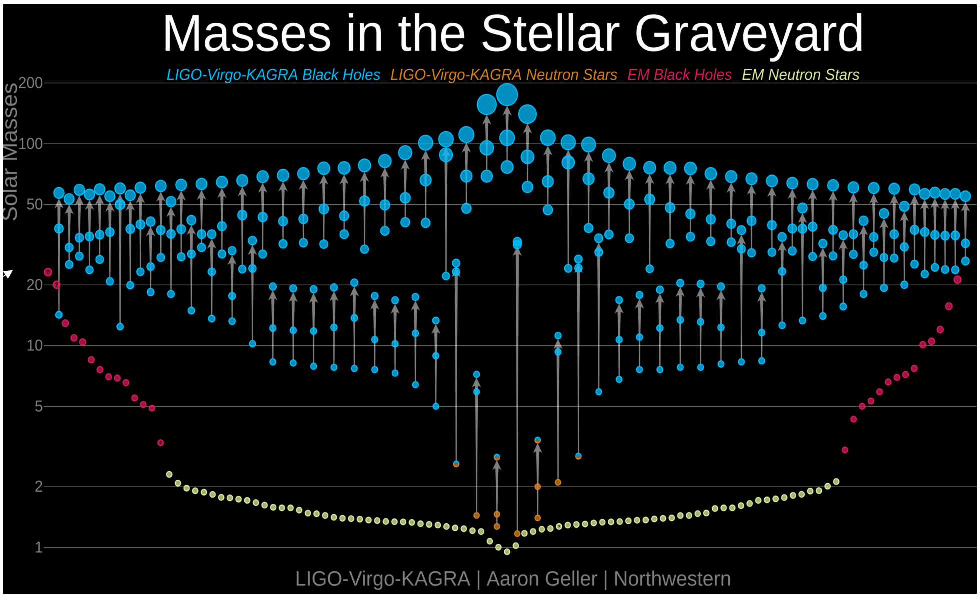
Haixing Miao

In collaboration with
Yanbei Chen, Animesh Datta, Yubao Liu, Yiqiu Ma, Denis Martynov, and Huan Yang

JGRG31

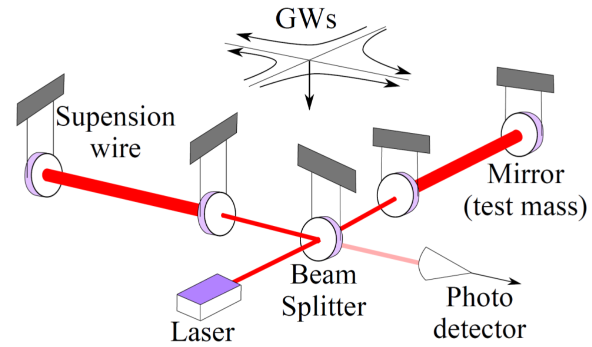
Some backgrounds

Gravitational-wave Discoveries



LIGO-Virgo-KAGRA collaboration, *GWTC-2.1: Deep Extended Catalog of Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run,* arXiv: 2108.01045 (2021).

Why Quantum?



Strain sensitivity of km size detector:

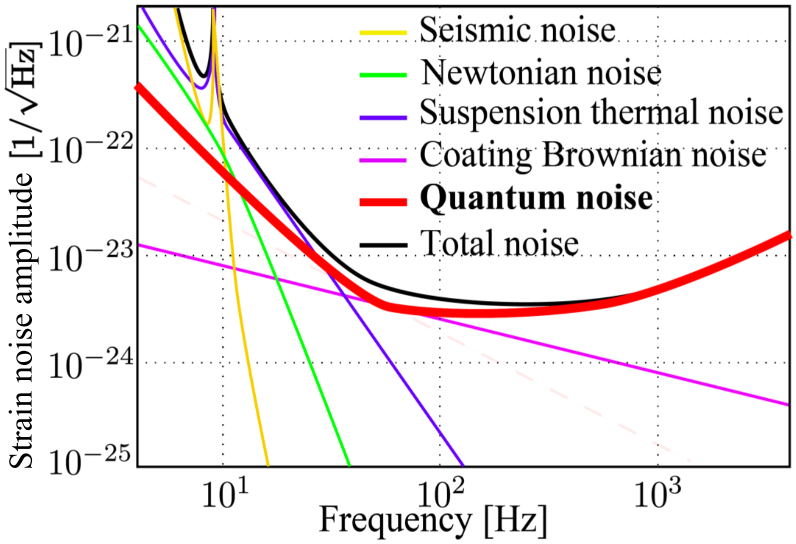
$$h = \frac{\Delta L}{L} \sim 10^{-22} \quad \Rightarrow \quad \Delta L \sim 10^{-19}\mathrm{m}$$

de Broglie wavelength of kg size test mass: $\lambda_\mathrm{d} \sim \sqrt{\hbar/(2\pi\, m\, f)}|_{100\mathrm{Hz}} \sim 10^{-19}\,\mathrm{m}$

Quantum effects are indeed important!

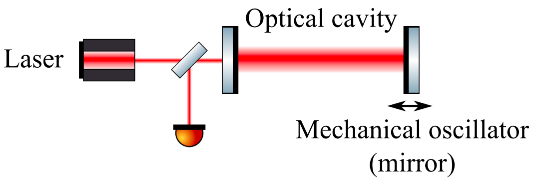
Why Quantum? A Quantitative Measure

Advanced LIGO design sensitivity curve:



LIGO Scientific Collaboration, *Advanced LIGO*, Class. Quantum Grav. **32**, 74001 (2015).

Optomechanics & Macroscopic Quantum Mechanics (MQM)

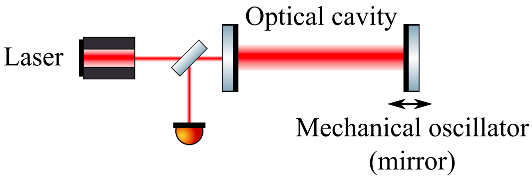


Optomechanics

Mechanics modulates the optical phase;
Radiation pressure affects the mechanics.

Y. Chen, *MQM: theory and experimental concepts of optomechanics,* J. Phys. B: AMO Phys. **46** 104001 (2013).
M. Aspelmeyer *et al.*, *Cavity optomechanics*, Rev. Mod. Phys. **86**, 1391 (2014).

Optomechanics & Macroscopic Quantum Mechanics (MQM)



Optomechanics

Mechanics modulates the optical phase;
Radiation pressure affects the mechanics.

Characteristic parameters:

Optomechanical cooperativity: $\mathcal{C} \propto \frac{P_{\rm cav}\mathcal{F}Q_m}{m}$

Thermal occupation number: $\bar{n}_{\rm th} = \frac{k_B T}{\hbar\omega_m}$

Quantum radiation pressure dominated regime [1-3]:

$$\mathcal{C} \geq \bar{n}_{\rm th}$$

[1] T. Purdy, R. Peterson, and C. Regal, Science **339**, 801 (2013).
[2] C. B. Møller, R. A. Thomas, G. Vasilakis *et al.*, Nature 547, 191 (2017).
[3] M. Rossi, D. Mason, J. Chen, Y. Tsaturyan, and A. Schliesser, Nature 563, 53 (2018).

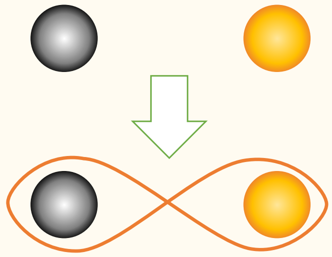
One Motivation of MQM with Optomechanics

To study gravity

Quantum effect of gravity

Single object but in a superposition

Interaction between two objects



Entanglement

One classical gravity model

Classical spacetime

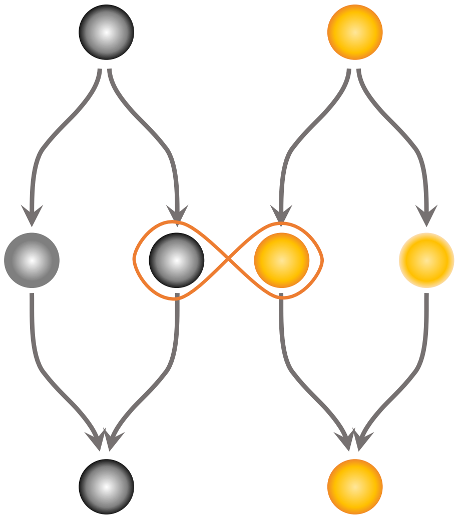
$$\underline{G_{\mu\nu}} = \frac{8\pi G}{c^4}\langle\psi|\underline{\hat{T}_{\mu\nu}}|\psi\rangle$$

Quantum matter

Neither producing superposed spacetime
nor creating bipartite quantum entanglement

C. Møller, Colloques Internationaux CNRS **91**, 1 (1962).
L. Rosenfeld, Nuclear Physics **40**, 353 (1963).

Experimental proposals with matter-wave interferometers



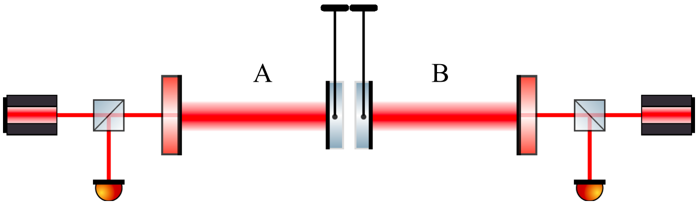
Also see Youka Kaku's talk and study

[1] S. Bose, A. Mazumdar, G. Moley, H. Ulbricht, M. Toros, M. Paternostro, A. Geraci, P. Barker, M. Kim, and G. Milburn, *Spin Entanglement Witness for Quantum Gravity,* Phys. Rev. Lett. **119**, 240401 (2017).

[2] C. Marletto, and V. Vedral, *Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity*, Phys. Rev. Lett. **119**, 240402 (2017).

Our Proposed Scheme

Using two optomechanical devices



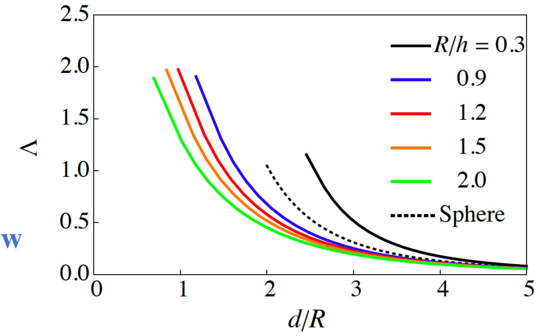
$$\hat{H}_{\rm AB} = \frac{Gm^2}{|d+\hat{x}_A-\hat{x}_B|} \approx \frac{Gm^2}{d} + \hbar\frac{\omega_g^2}{\omega_m}\hat{Q}_A\hat{Q}_B \qquad (\hat{Q}_{A,B}\equiv \hat{x}_{A,B}\sqrt{2m\omega_m/\hbar})$$

Characteristic frequency:

$$\omega_g = \sqrt{\Lambda\, G\, \rho}$$

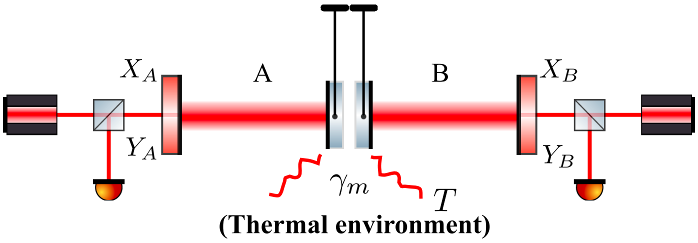
(typically 0.1 mHz)

Gravitational interaction rate is low



Condition for entanglement

Condition for Entanglement



$$\gamma_m = \frac{\omega_m}{Q_m}$$

Consider optical modes near the mechanical frequency ω_m

Covariance Matrix:

$$\begin{array}{c|cc|cc} & X_A & Y_A & X_B & Y_B \\ \hline X_A & \multicolumn{2}{c|}{\multirow{2}{*}{$\mathbf{V}_A$}} & \multicolumn{2}{c}{\multirow{2}{*}{$\mathbf{V}_{AB}$}} \\ Y_A & & & & \\ \hline X_B & \multicolumn{2}{c|}{\multirow{2}{*}{$\mathbf{V}'_{AB}$}} & \multicolumn{2}{c}{\multirow{2}{*}{$\mathbf{V}_B$}} \\ Y_B & & & & \end{array}$$

Condition for Entanglement

Gaussian bipartite entanglement:

Covariance Matrix:

$$\begin{array}{c|cc|cc} & X_A & Y_A & X_B & Y_B \\ \hline X_A & \multicolumn{2}{c|}{\multirow{2}{*}{$\mathbf{V}_A$}} & \multicolumn{2}{c}{\multirow{2}{*}{$\mathbf{V}_{AB}$}} \\ Y_A & & & & \\ \hline X_B & \multicolumn{2}{c|}{\multirow{2}{*}{$\mathbf{V}'_{AB}$}} & \multicolumn{2}{c}{\multirow{2}{*}{$\mathbf{V}_B$}} \\ Y_B & & & & \end{array}$$

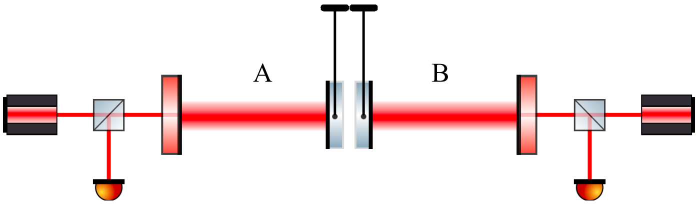
Applying Simon's entanglement criterion [1, 2, 3] leads to

$$\gamma_m k_B T \leq \hbar \omega_g^2$$

Only determined by mechanical property!

[1] R. Simon, Phys. Rev. Lett. **84**, 2726 (2000).
[2] R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, Rev. Mod. Phys. **81**, 865 (2009).
[3] S. Qvarfort, S. Bose, and A. Serafini, arXiv: 1812.09776 (2018).

Condition for Entanglement



$$\gamma_m k_B T \leq \hbar\,\omega_g^2 \qquad (\gamma_m = \omega_m/Q_m\,,\ \omega_g^2 = \Lambda G \rho)$$

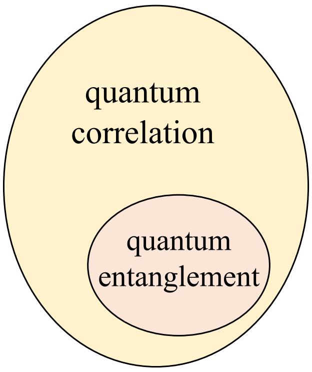
In terms of temperature to quality factor ratio:

$$\frac{T}{Q_m} \leq 1.5 \times 10^{-18}\mathrm{K} \left(\frac{\Lambda}{2.0}\right) \left(\frac{1\,\mathrm{Hz}}{\omega_m/2\pi}\right) \left(\frac{\rho}{19\,\mathrm{g/cm^3}}\right)$$

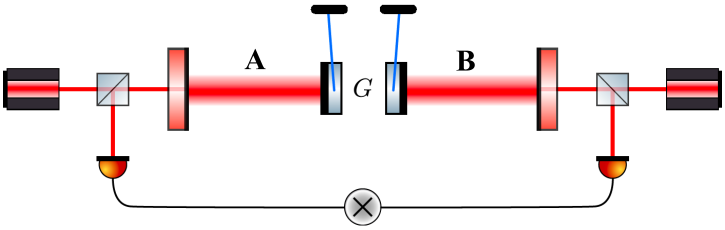
This is beyond the state-of-the-art of optomechanics.

"Less quantum" figures of merit (not quantumless:-)

- ❖ Cross correlation
- ❖ Quantum discord
- ❖ Conditional squeezing



Cross-correlation measurement



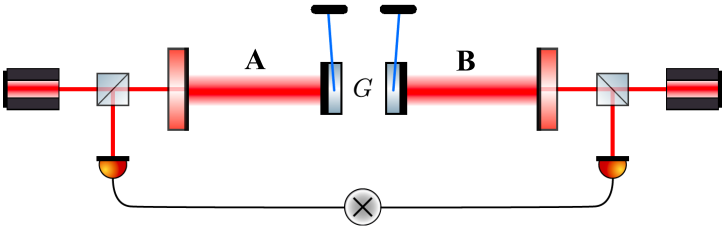
$$\begin{array}{c|cc} & X_A \quad Y_A & X_B \quad Y_B \\ \begin{matrix}X_A\\Y_A\end{matrix} & \mathbf{V}_A & \mathbf{V}_{AB} \\ \begin{matrix}X_B\\Y_B\end{matrix} & \mathbf{V}'_{AB} & \mathbf{V}_B \end{array}$$

$$\mathbf{V}_{AB} = \begin{bmatrix} 0 & \mathcal{G}^* \\ \mathcal{G} & 0 \end{bmatrix}$$

Measure the off-diagonal term in the covariance matrix

$\mathcal{G}$: Amplitude fluctuation of A $\xrightarrow{\text{Quantum radiation pressure}}$ Test mass A $\xrightarrow{\text{Gravitational interaction}}$ Test mass B $\xrightarrow{\text{Phase modulation}}$ Phase fluctuation of B

Cross-correlation measurement



$$\mathbf{V}_{AB} = \begin{bmatrix} 0 & \mathcal{G}^* \\ \mathcal{G} & 0 \end{bmatrix} \qquad |\mathcal{G}| = 2\sqrt{\mathcal{C}_A\mathcal{C}_B}\,Q_m\left(\frac{\omega_g}{\omega_m}\right)^2$$

Optomechanical cooperativity: $\mathcal{C} \propto \dfrac{P_{\mathrm{cav}}\mathcal{F}Q_m}{m}$

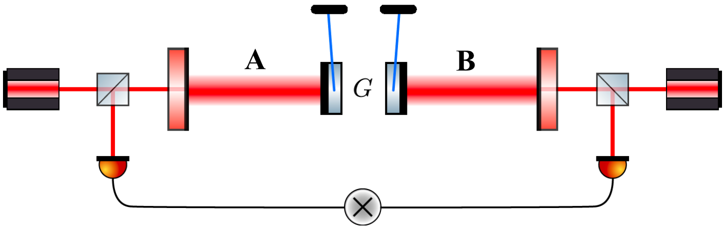
Signal-to-Noise Ratio

$$\mathrm{SNR} \propto \tau_{\mathrm{int}}^{1/2}\left(\frac{\mathcal{C}_A}{\bar{n}_{\mathrm{th}}^{B}}\right)^{1/2}$$

increases as the integration time

$\mathcal{G}$: Amplitude fluctuation of A $\xrightarrow{\text{Quantum radiation pressure}}$ Test mass A $\xrightarrow{\text{Gravitational interaction}}$ Test mass B $\xrightarrow{\text{Phase modulation}}$ Phase fluctuation of B

Cross-correlation measurement



Reaching SNR ~ 1 at room temperature:

$$\tau_{\rm int} \approx 1.0\,{\rm year}\left(\frac{\bar{n}_{\rm th}/\mathcal{C}}{0.4}\right)\left(\frac{\omega_m/2\pi}{1\,{\rm Hz}}\right)^3\left(\frac{10^6}{Q_m}\right)\left(\frac{19\,{\rm g/cm^3}}{\rho}\right)^2$$

$$\frac{\bar{n}_{\rm th}}{\mathcal{C}} \approx 0.4\left(\frac{m}{1\,{\rm g}}\right)\left(\frac{2\,{\rm kW}}{P_{\rm cav}}\right)\left(\frac{6000}{\rm Finesse}\right)\left(\frac{T}{300\,{\rm K}}\right)$$

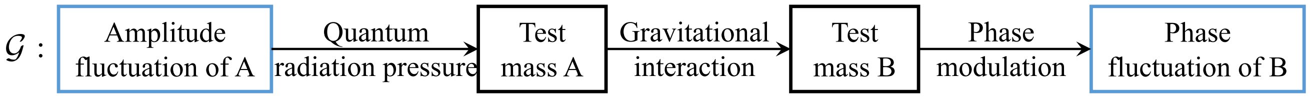
m	$\omega_m/2\pi$	Q_m	$P_{\rm cav}$
1 g	1 Hz	10^6	2 kW
1 mg	10 Hz	10^9	2 W
1 μg	100 Hz	10^{12}	2 mW

One Problem

Cross-correlation affected by the classical amplitude noise

Need a better figure of merit

Quantum discord



$$\begin{array}{cc} & X_A \quad Y_A \quad X_B \quad Y_B \\ \begin{array}{c} X_A \\ Y_A \\ X_B \\ Y_B \end{array} & \left(\begin{array}{cc} \mathbf{V}_A & \mathbf{V}_{AB} \\ \mathbf{V}'_{AB} & \mathbf{V}_B \end{array}\right) \end{array}$$

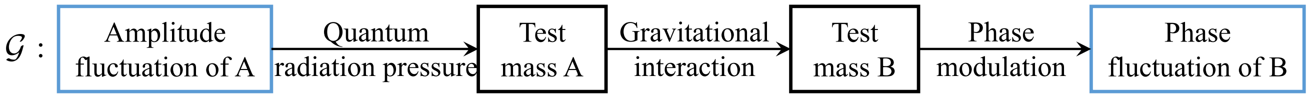
$$\mathbf{V}_{AB} = \begin{bmatrix} 0 & \mathcal{G}^* \\ \mathcal{G} & 0 \end{bmatrix}$$

Quantum discord [1, 2, 3]:

$$\mathcal{D} \equiv \mathcal{S}(\hat{\varrho}_A|\hat{\varrho}_B) - [\mathcal{S}(\hat{\varrho}_{AB}) - \mathcal{S}(\hat{\varrho}_A)] = f(\mathbf{V}_A, \mathbf{V}_B, \mathbf{V}_{AB})$$

[1] H. Ollivier and W. H. Zurek, Phys. Rev. Lett. **88**, 017901 (2001).
[2] G. Adesso and A. Datta, Phys. Rev. Lett. **105**, 030501 (2010).
[3] P. Giorda and M. G. A. Paris, Phys. Rev. Lett. **105**, 020503 (2010).

Quantum discord



$$\begin{array}{cc} & X_A \quad Y_A \quad X_B \quad Y_B \\ \begin{array}{c} X_A \\ Y_A \\ X_B \\ Y_B \end{array} & \left(\begin{array}{cc} \mathbf{V}_A & \mathbf{V}_{AB} \\ \mathbf{V}'_{AB} & \mathbf{V}_B \end{array}\right) \end{array}$$

$$\mathbf{V}_{AB} = \begin{bmatrix} 0 & \mathcal{G}^* \\ \mathcal{G} & 0 \end{bmatrix}$$

Quantum discord $(\bar{n}_{\mathrm{th}}\mathcal{C} \gg 1)$**:**

$$\mathcal{D} \approx \frac{\hbar G \rho}{2\gamma_m k_B T} = 1.0 \times 10^{-9} \left(\frac{1\,\mathrm{Hz}}{\omega_m/2\pi}\right)\left(\frac{Q_m}{10^9}\right)\left(\frac{\rho}{19\,\mathrm{g/cm^3}}\right)\left(\frac{1\,\mathrm{K}}{T}\right)$$

Quantum discord

$$\mathcal{G}:\ \boxed{\text{Amplitude fluctuation of A}} \xrightarrow[\text{radiation pressure}]{\text{Quantum}} \boxed{\text{Test mass A}} \xrightarrow[\text{interaction}]{\text{Gravitational}} \boxed{\text{Test mass B}} \xrightarrow[\text{modulation}]{\text{Phase}} \boxed{\text{Phase fluctuation of B}}$$

$$\begin{array}{c} \\ \begin{matrix} X_A \\ Y_A \\ X_B \\ Y_B \end{matrix} \end{array} \begin{array}{c} \begin{matrix} X_A & Y_A & X_B & Y_B \end{matrix} \\ \left(\begin{array}{cc} \mathbf{V}_A & \mathbf{V}_{AB} \\ \mathbf{V}'_{AB} & \mathbf{V}_B \end{array} \right) \end{array} \qquad \mathbf{V}_{AB} = \begin{bmatrix} 0 & \mathcal{G}^* \\ \mathcal{G} & 0 \end{bmatrix}$$

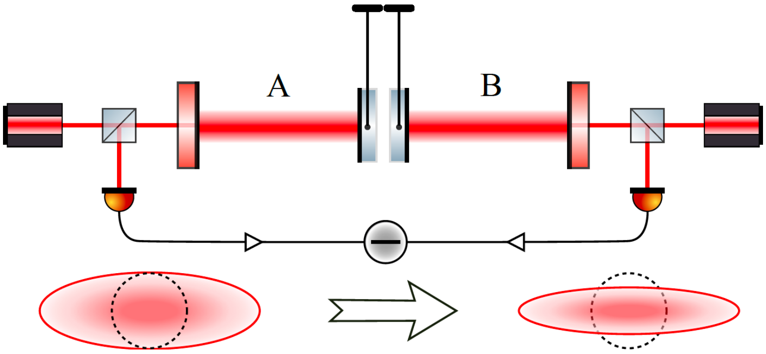
Quantum discord $(\bar{n}_{\rm th}\mathcal{C} \gg 1)$**:**

$$\mathcal{D} \approx \frac{\hbar G \rho}{2\gamma_m k_B T} = 1.0 \times 10^{-9} \left(\frac{1\,\mathrm{Hz}}{\omega_m/2\pi}\right)\left(\frac{Q_m}{10^9}\right)\left(\frac{\rho}{19\,\mathrm{g/cm^3}}\right)\left(\frac{1\,\mathrm{K}}{T}\right)$$

Very sensitive to measurement errors :-(

Need an even better figure of merit

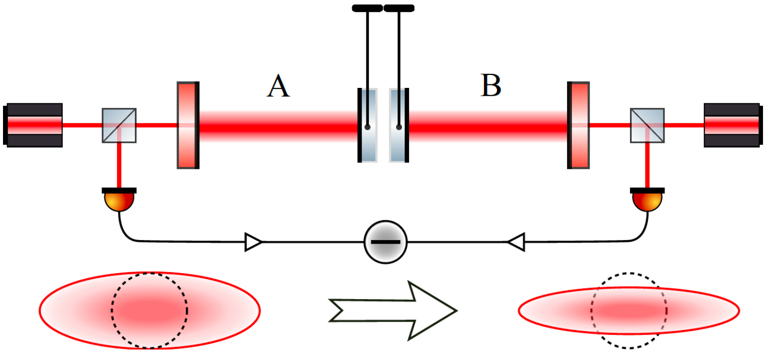
Conditional squeezing



Amplitude fluctuation is at the
vacuum level
(independent of mirror motion)

H. Miao, D. Martynov, H. Yang, and A. Datta, Phys. Rev. A **101**, 063804 (2020).

Conditional squeezing

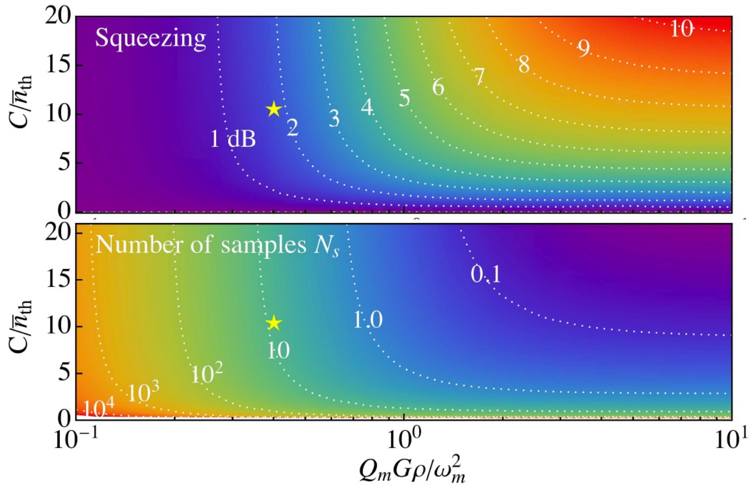


In the quantum-radiation-pressure-limited regime:

$$\mathcal{S} = 10\log_{10}\left[1+\left(\frac{2Q_m G\rho}{\omega_m^2}\right)^2\right] \approx 2\,\mathrm{dB}\left(\frac{0.5\,\mathrm{Hz}}{\omega_m/2\pi}\right)^4\left(\frac{Q_m}{3\times10^6}\right)^2\left(\frac{\rho}{19\,\mathrm{g/cm^3}}\right)^2$$

$$\tau \approx 1\,\mathrm{year}\left(\frac{\omega_m/2\pi}{0.5\,\mathrm{Hz}}\right)^3\left(\frac{3\times10^6}{Q_m}\right)\left(\frac{19\,\mathrm{g/cm^3}}{\rho}\right)^2$$

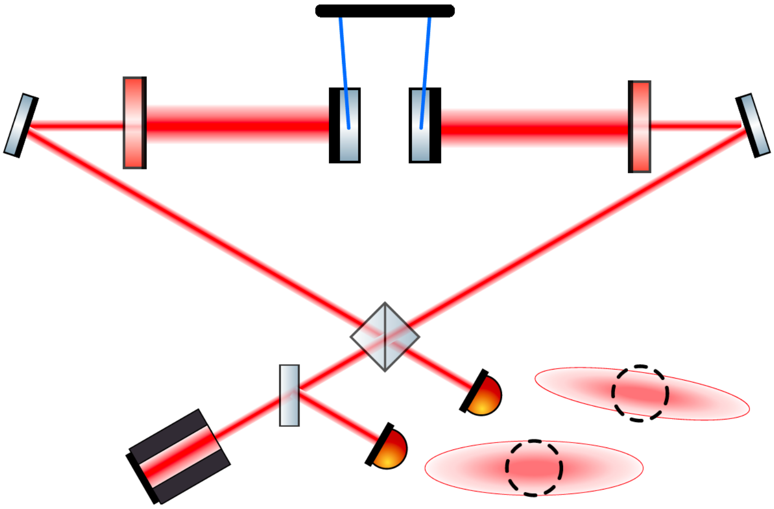
Conditional squeezing



$$\mathcal{S} = 10\log_{10}\left[1+\left(\frac{2Q_mG\rho}{\omega_m^2}\right)^2\right] \approx 2\,\mathrm{dB}\left(\frac{0.5\,\mathrm{Hz}}{\omega_m/2\pi}\right)^4\left(\frac{Q_m}{3\times10^6}\right)^2\left(\frac{\rho}{19\,\mathrm{g/cm^3}}\right)^2$$

$$\tau \approx 1\,\mathrm{year}\left(\frac{\omega_m/2\pi}{0.5\,\mathrm{Hz}}\right)^3\left(\frac{3\times10^6}{Q_m}\right)\left(\frac{19\,\mathrm{g/cm^3}}{\rho}\right)^2$$

"Optical subtraction": ponderomotive squeezing



ponderomotive squeezing for the differential mode (homodyne readout)

A. Datta, and H. Miao, Quantum Science and Technology **6**, 045014 (2021)

Predictions of Some Classical Gravity Models

Semi-classical Gravity:

$$G_{\mu\nu} = \frac{8\pi G}{c^4}\langle\psi|\hat{T}_{\mu\nu}|\psi\rangle \xrightarrow[\text{limit [1]}]{\text{Non-relativistic}} \hat{H}^{\mathrm{SN}}_{\mathrm{AB}} = \hbar\frac{\omega_g^2}{2\omega_m}\left(\langle\hat{Q}_A\rangle\hat{Q}_B + \hat{Q}_A\langle\hat{Q}_B\rangle\right) \longrightarrow$$

Zero Correlation
/Squeezing
(for preselection [2])

Emergent gravity [3, 4, 5]:

$$H_{AB} = TS(\langle\hat{Q}_A\rangle - \langle\hat{Q}_B\rangle) \quad \textbf{or} \quad \hat{H}_{AB} = TS(\hat{Q}_A - \hat{Q}_B) + \delta\hat{H}_{AB}$$

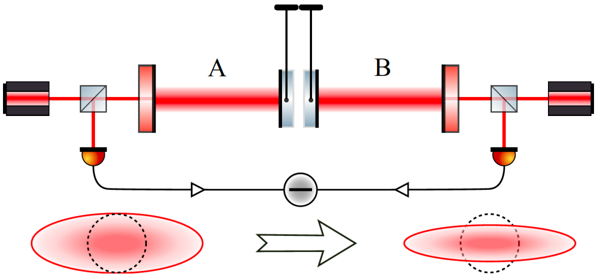
$\downarrow$ **Zero Correlation/squeezing**

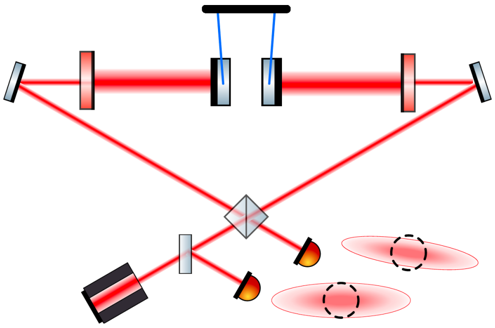
$\downarrow$ **Reduced correlation SNR**

[1] H. Yang, H. Miao, D. Lee, B. Helou, and Y. Chen, Phys. Rev. Lett. **110**, 170401 (2013).
[2] Y. Liu, H. Miao, Y. Chen, and Y. Ma, arXiv: 2207.05966 (2022).
[2] T. Jacobson, Phys. Rev. Lett. 75, 1260 (1995).
[3] E. Verlinde, Journal of High Energy Physics 2011, 29 (2011).
[4] T. Padmanabhan, Modern Physics Letters A 30, 1540007 (2015).

Conclusions

- ❖ Squeezing can be served as an intermediate step towards entanglement.
- ❖ Some classical models of gravity predict testable levels of squeezing.
- ❖ Low-frequency, high-quality factor oscillators are required.
- ❖ More detailed design studies of the experimental schemes are needed.



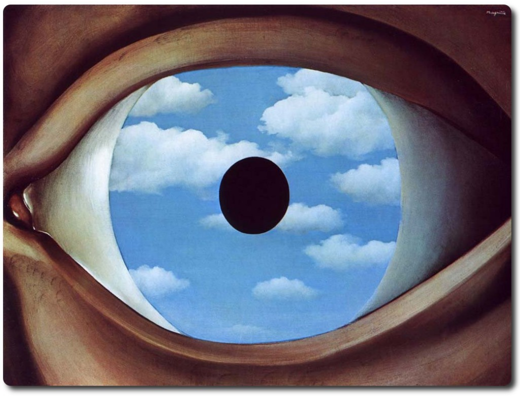


Thank you!

I04

Exotic Compact Objects

What we have learned so far



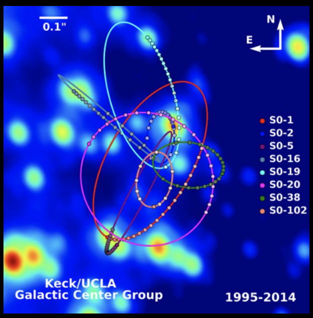
Paolo Pani

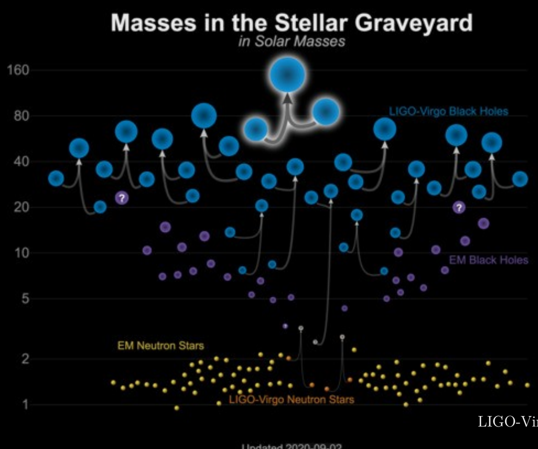
Sapienza University of Rome & INFN Roma1

https://web.uniroma1.it/gmunu

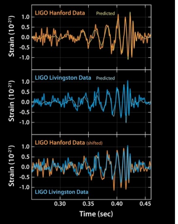
http://www.DarkGRA.org

Black Holes (BHs) are now everywhere!

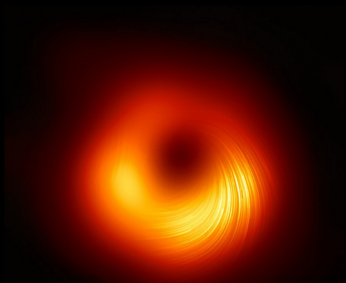




Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



LIGO-Virgo-KAGRA Collaboration



Event Horizon Telescope Collaboration

2017 2020

Why (still) testing the BH picture?

Why?

- **Are there compact objects other than black holes and neutron stars?**
    - LIGO/Virgo mass-gap (GW190814, GW190521) events?
    - Supermassive BH seeds?
    - (Dark) matter compact objects? (e.g. boson/axion stars)

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- **Observational signatures of quantum BHs?** (*if not now, when?*)
    - Information loss, singularities, Cauchy horizons…
    - New physics at the horizon (e.g. firewalls, nonlocality) [Almheri+, Giddings+, 2012-2017]
    - Regular, horizonless compact objects (e.g. fuzzballs) [Lunin+, Mathur+, Bena+, Bianchi+, Giusto+, …]

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Observations of exotic compact objects (ECOs) would imply new physics / new matter

The zoo of ECOs

Solutions to GR with exotic matter sources
(*e.g. anisotropic stars, boson stars, axion stars, gravastars, wormholes*)

Solutions to modified gravity
(*e.g. fuzzballs/microstates, 2-2 holes, superspinars, wormholes*)

- No sharp distinction in some cases
- Modified gravity required for true BH mimickers?
- Some models require modified gravity only in the interior / close to the horizon → assuming GR in the exterior is often a good approx.
- Some models are phenomenological (formation, dynamics, stability?)
- There are also coherent and well-motivated *ab-initio* models

[**Cardoso-Pani, LRR 2019; Carballo-Rubio+ PRD 2018; Maggio+ 2021** for ECO models, constraints, and details]

Quantifying the shades of darkness

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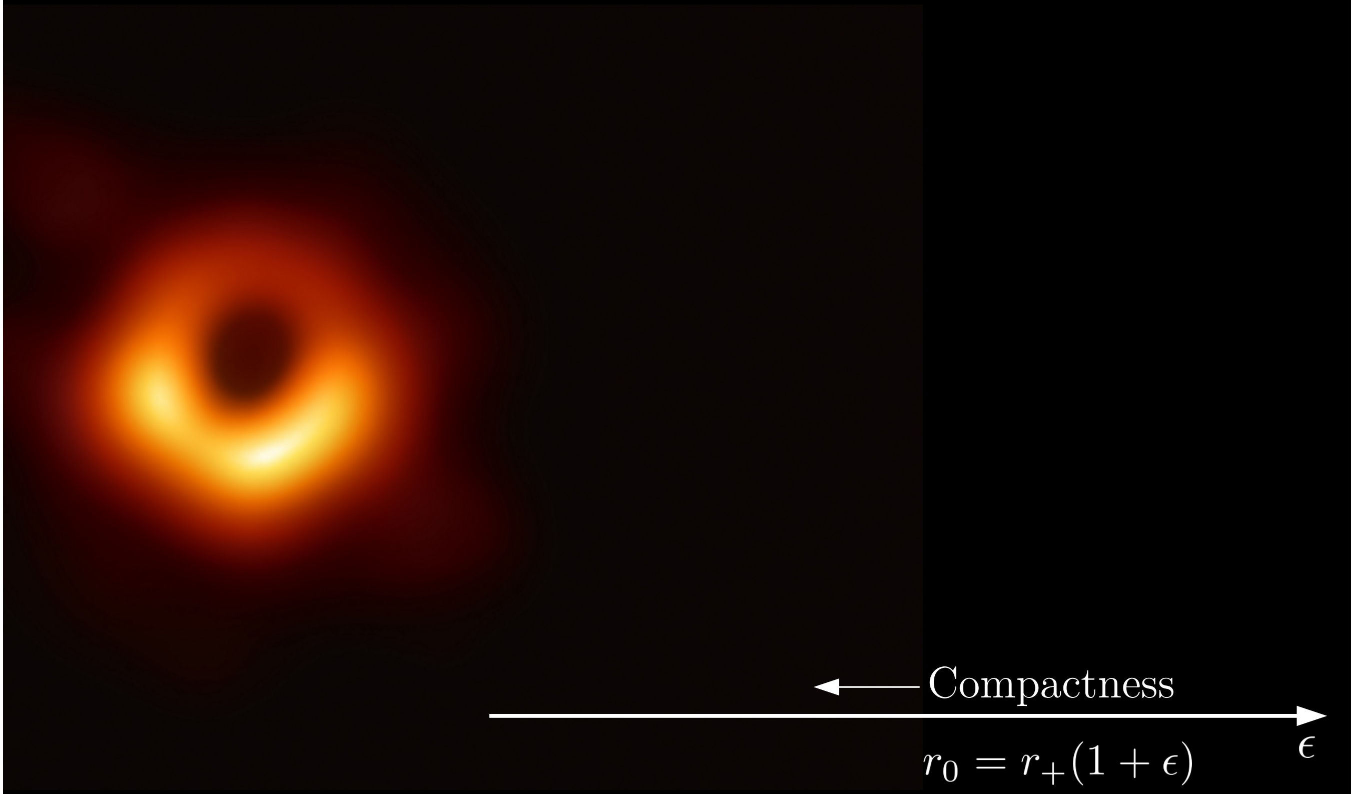

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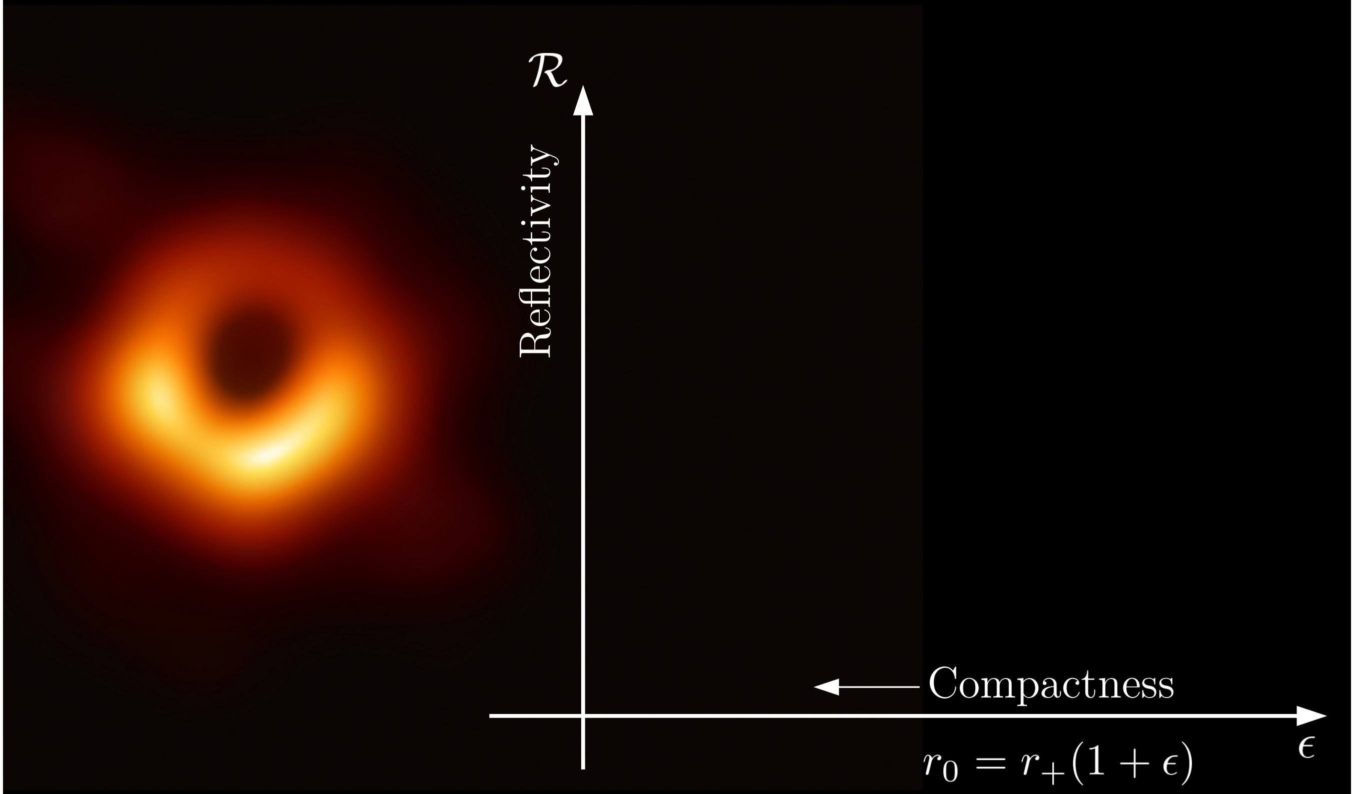

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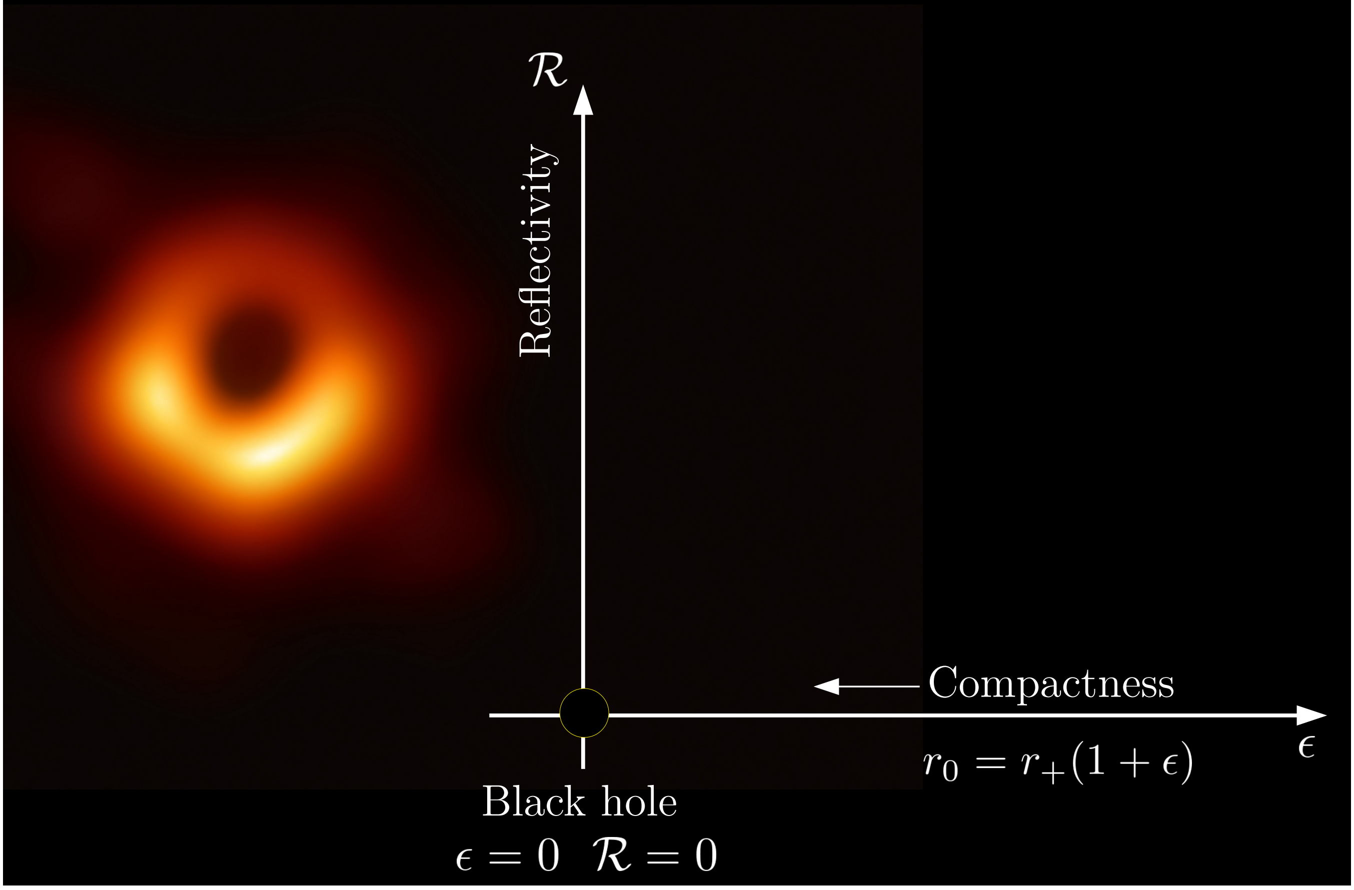


$\mathcal{R}$

Reflectivity

Compactness

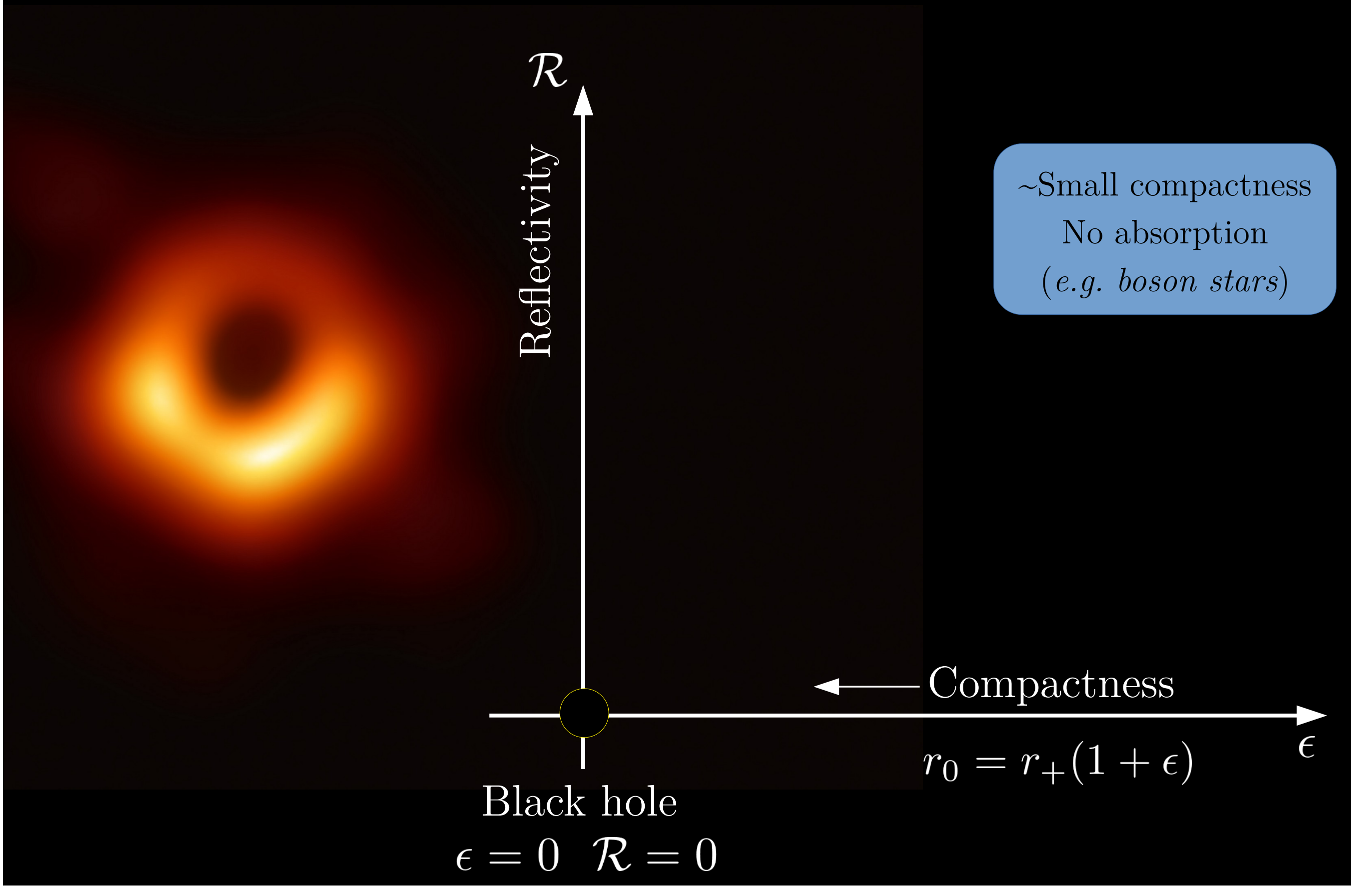
$r_0 = r_+(1+\epsilon)$

ϵ

Black hole

$\epsilon = 0 \quad \mathcal{R} = 0$

Quantifying the shades of darkness



$\mathcal{R}$

Reflectivity

~Small compactness

No absorption

(*e.g. boson stars*)

Compactness

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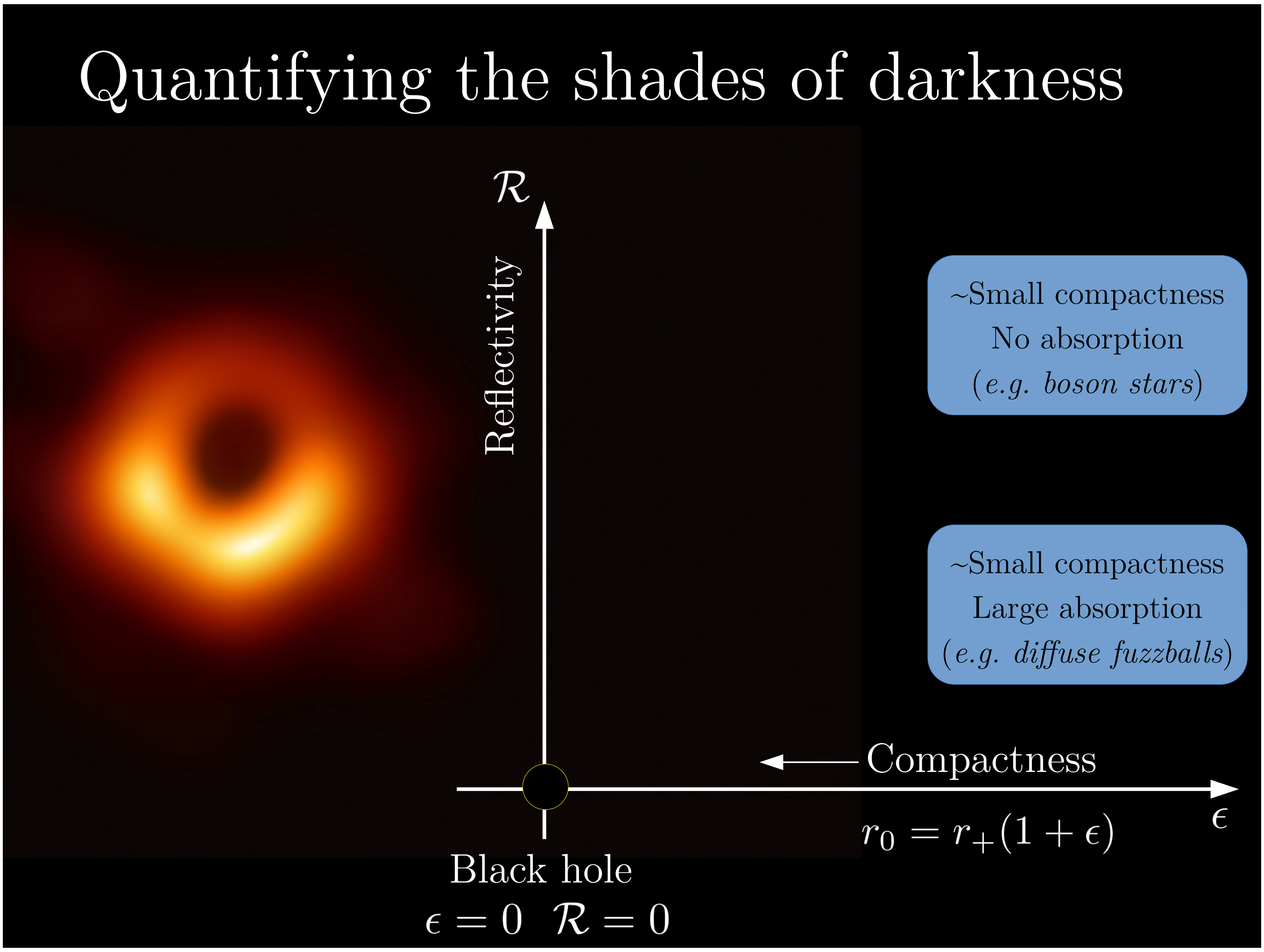


Quantifying the shades of darkness

$\mathcal{R}$

Reflectivity

∼Small compactness
No absorption
(*e.g. boson stars*)

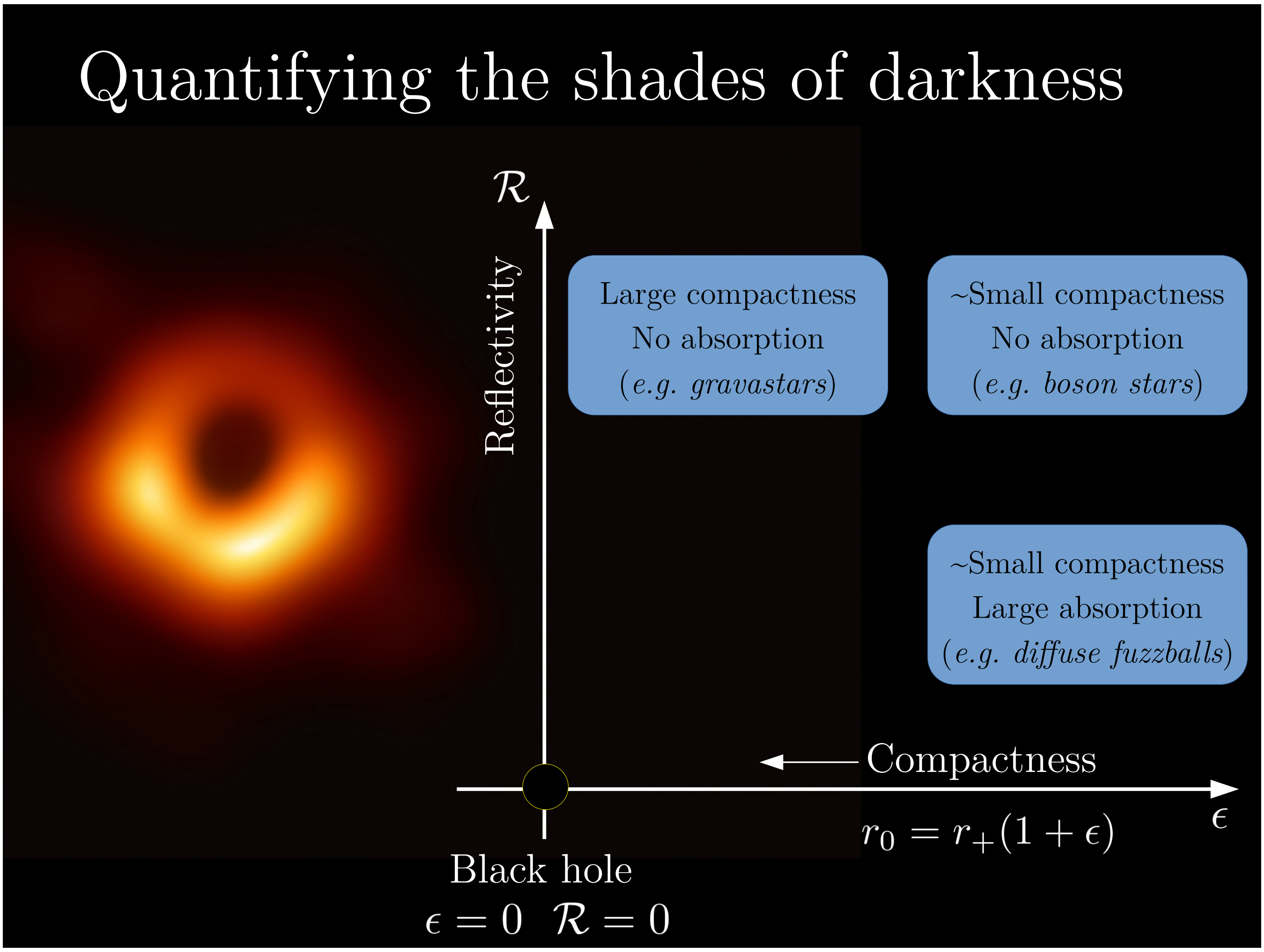
∼Small compactness
Large absorption
(*e.g. diffuse fuzzballs*)

← Compactness

ϵ

$r_0 = r_+(1+\epsilon)$

Black hole
$\epsilon = 0 \quad \mathcal{R} = 0$



Quantifying the shades of darkness

$\mathcal{R}$

Reflectivity

Large compactness
No absorption
(*e.g. gravastars*)

∼Small compactness
No absorption
(*e.g. boson stars*)

∼Small compactness
Large absorption
(*e.g. diffuse fuzzballs*)

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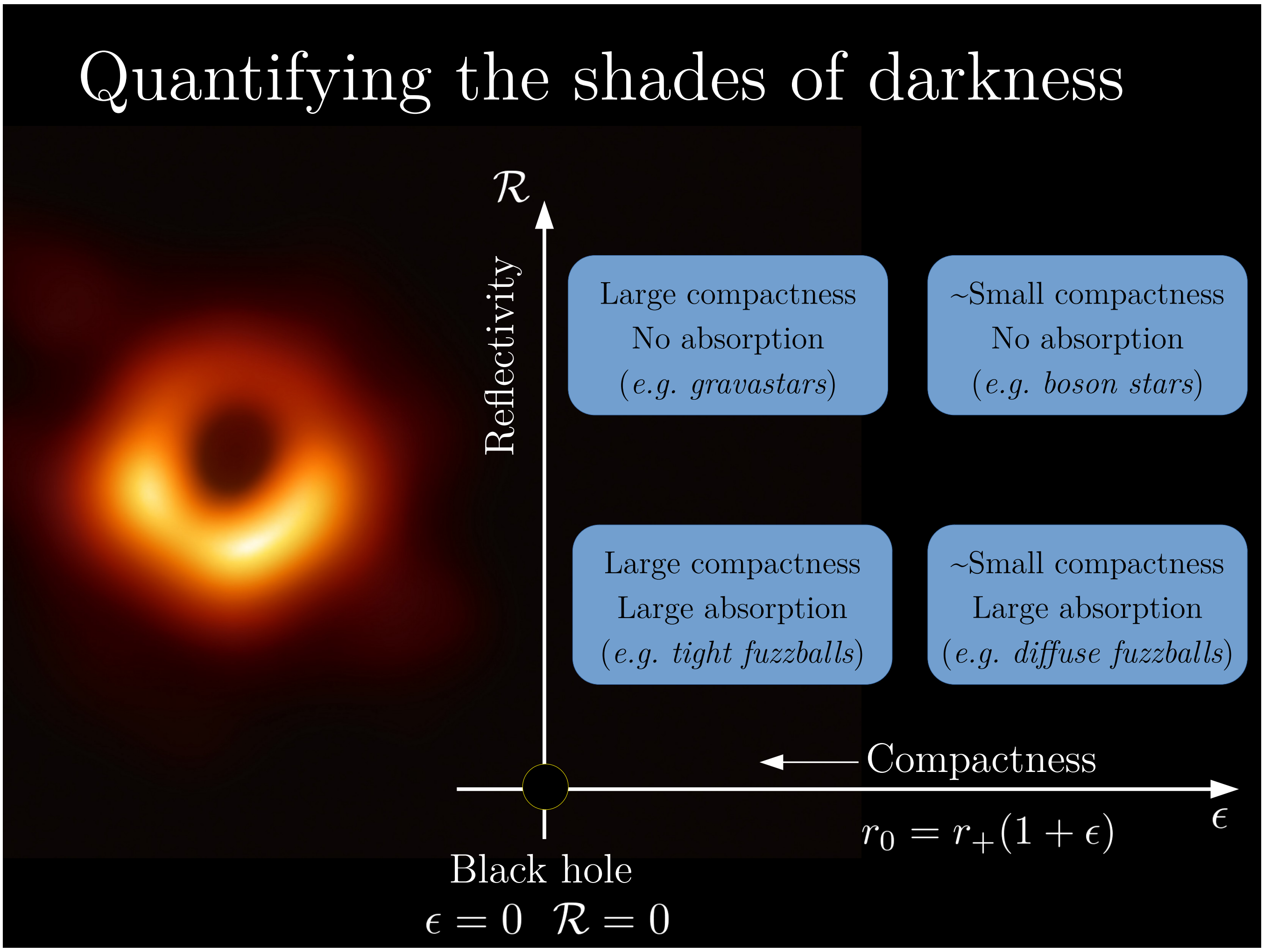

Quantifying the shades of darkness

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Reflectivity

Large compactness
No absorption
(*e.g. gravastars*)

~Small compactness
No absorption
(*e.g. boson stars*)

Large compactness
Large absorption
(*e.g. tight fuzzballs*)

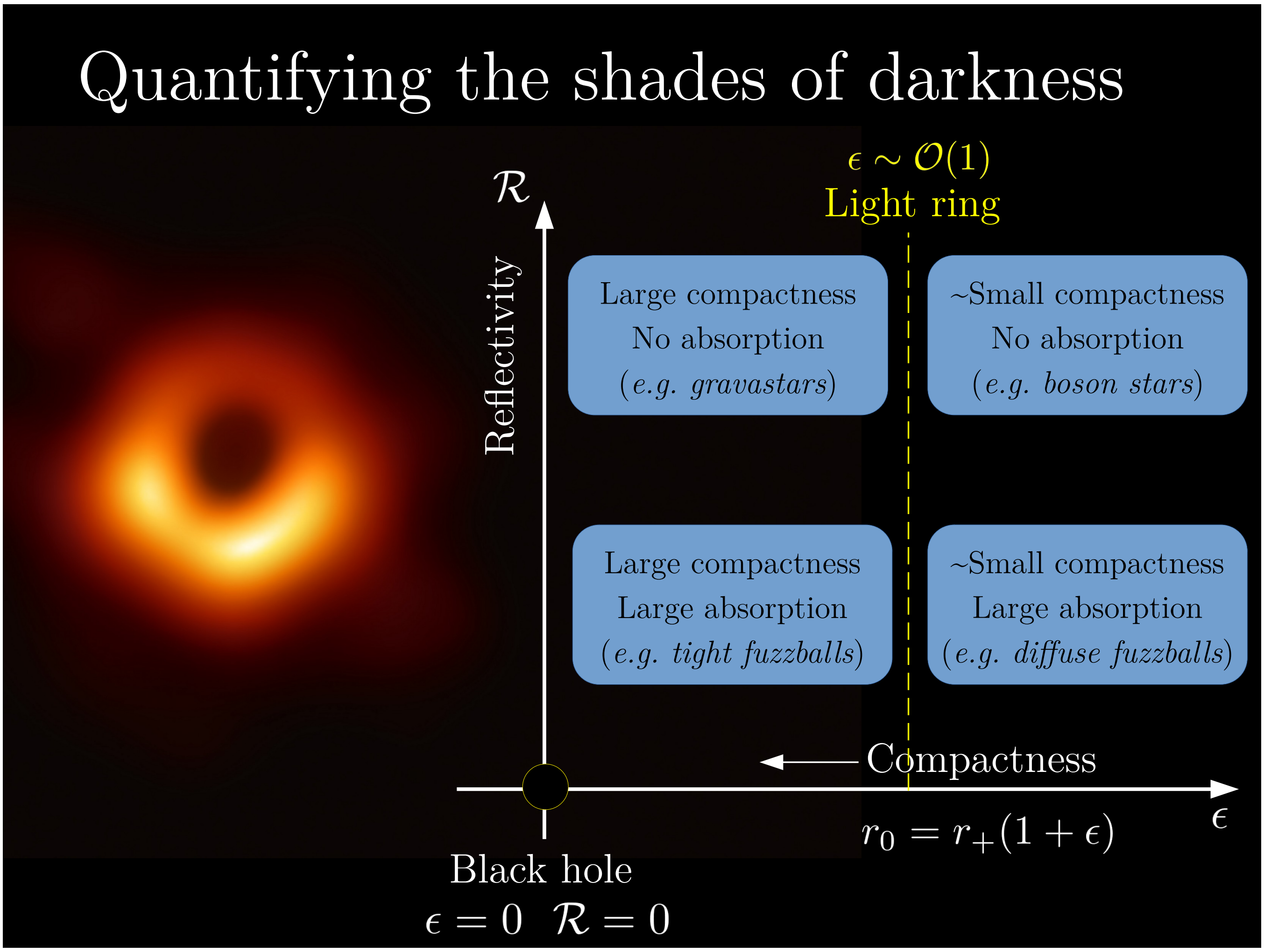
~Small compactness
Large absorption
(*e.g. diffuse fuzzballs*)

← Compactness

$r_0 = r_+(1+\epsilon)$

ϵ

Black hole
$\epsilon = 0 \quad \mathcal{R} = 0$



Quantifying the shades of darkness

$\epsilon \sim \mathcal{O}(1)$
Light ring

$\mathcal{R}$

Reflectivity

Large compactness
No absorption
(*e.g. gravastars*)

~Small compactness
No absorption
(*e.g. boson stars*)

Large compactness
Large absorption
(*e.g. tight fuzzballs*)

~Small compactness
Large absorption
(*e.g. diffuse fuzzballs*)

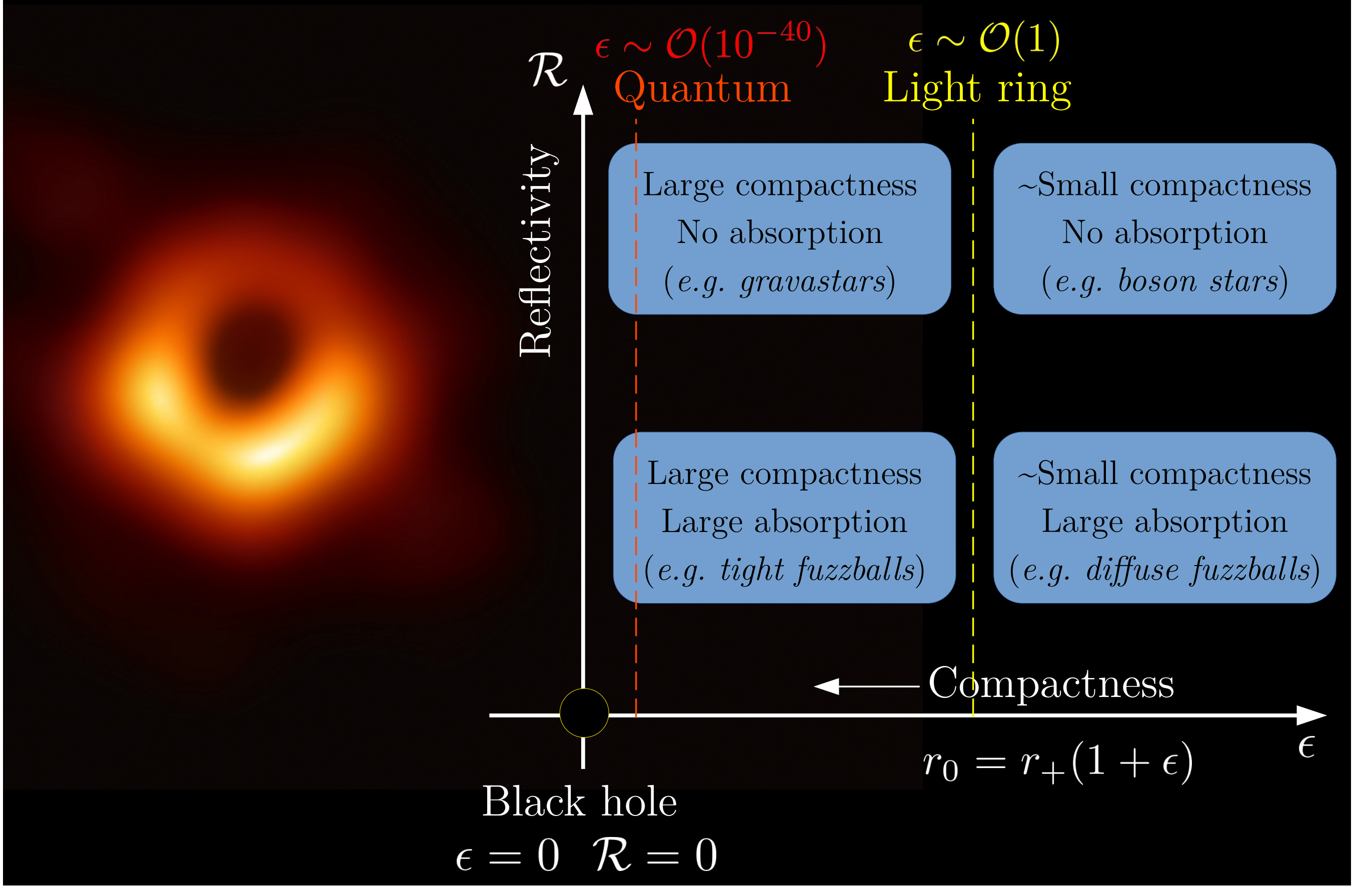
← Compactness

$r_0 = r_+(1+\epsilon)$

ϵ

Black hole
$\epsilon = 0 \quad \mathcal{R} = 0$

Quantifying the shades of darkness



$\mathcal{R}$ Reflectivity

$\epsilon \sim \mathcal{O}(10^{-40})$ Quantum

$\epsilon \sim \mathcal{O}(1)$ Light ring

Large compactness
No absorption
(*e.g. gravastars*)

~Small compactness
No absorption
(*e.g. boson stars*)

Large compactness
Large absorption
(*e.g. tight fuzzballs*)

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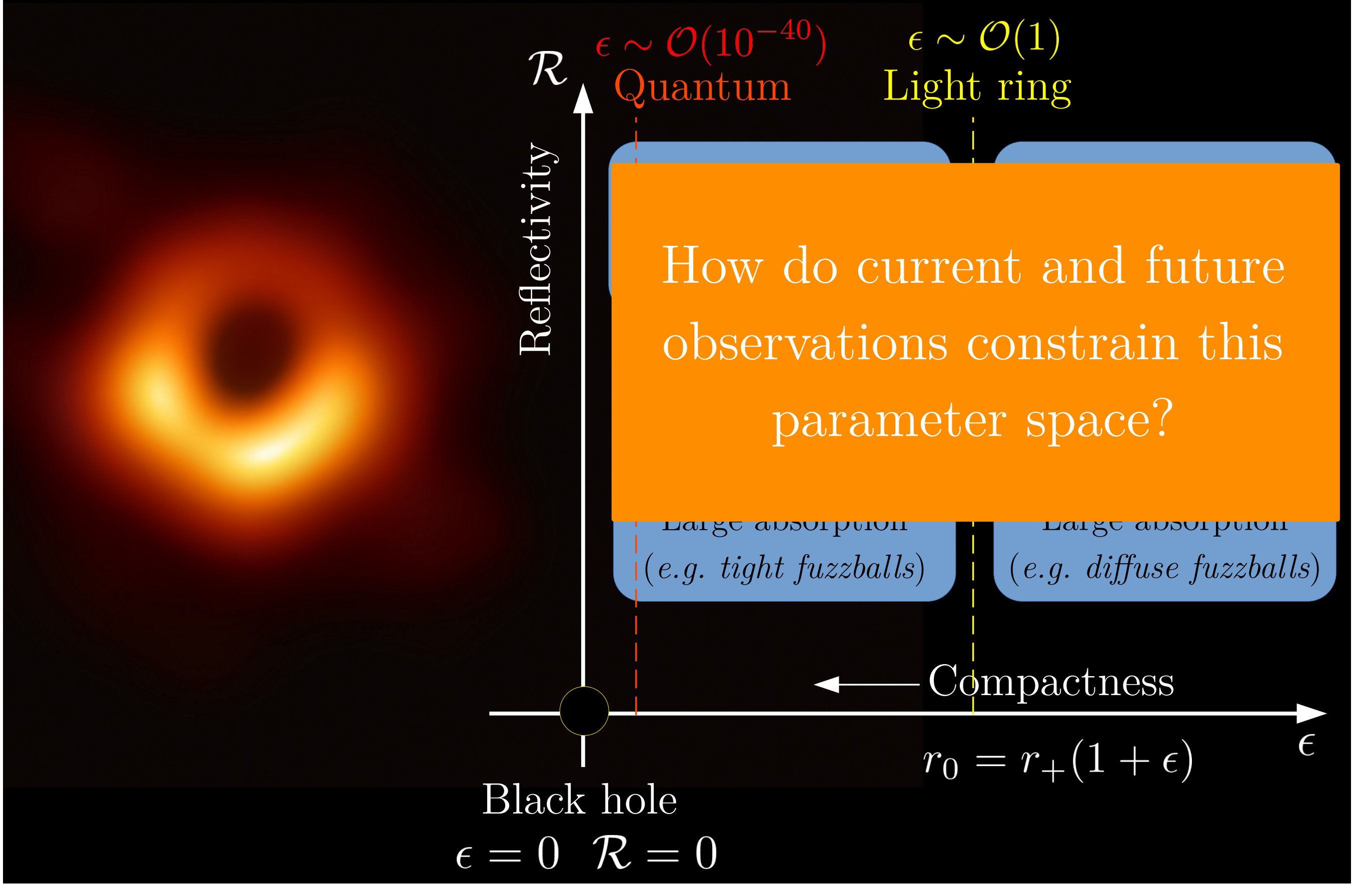
← Compactness

$r_0 = r_+(1+\epsilon)$ ϵ

Black hole
$\epsilon = 0$ $\mathcal{R} = 0$

Quantifying the shades of darkness



$\mathcal{R}$ Reflectivity

$\epsilon \sim \mathcal{O}(10^{-40})$ Quantum

$\epsilon \sim \mathcal{O}(1)$ Light ring

How do current and future observations constrain this parameter space?

(*e.g. tight fuzzballs*)

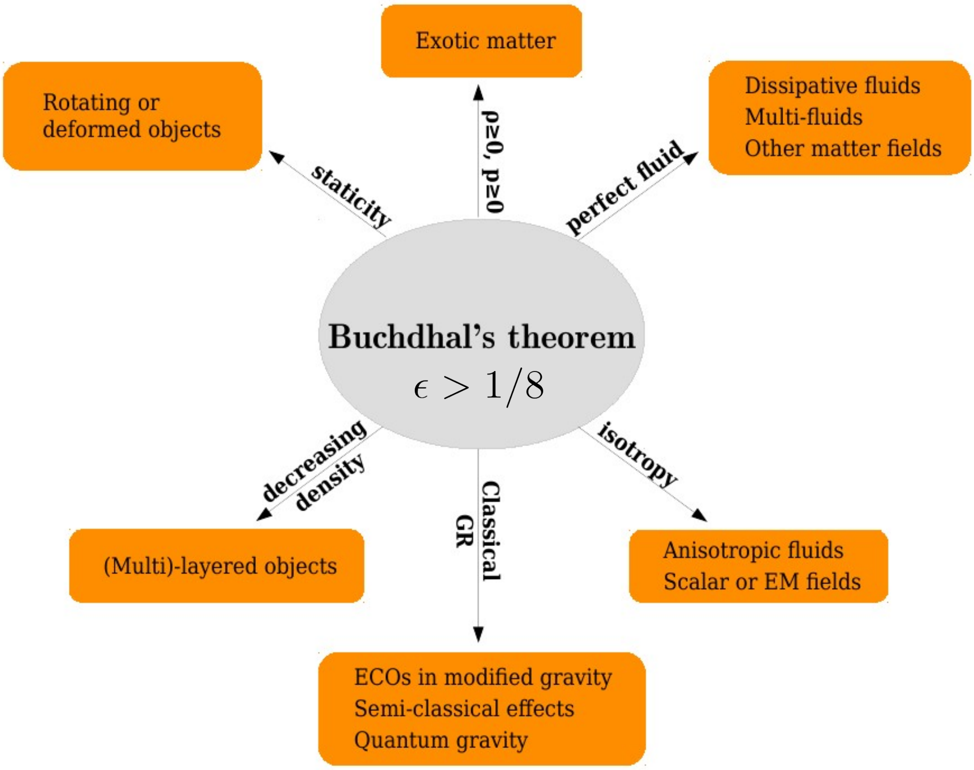
(*e.g. diffuse fuzzballs*)

← Compactness

$r_0 = r_+(1+\epsilon)$ ϵ

Black hole
$\epsilon = 0$ $\mathcal{R} = 0$

A compass to navigate the ECO atlas



Buchdhal's theorem

$\epsilon > 1/8$

Exotic matter

Rotating or deformed objects

Dissipative fluids
Multi-fluids
Other matter fields

(Multi)-layered objects

Anisotropic fluids
Scalar or EM fields

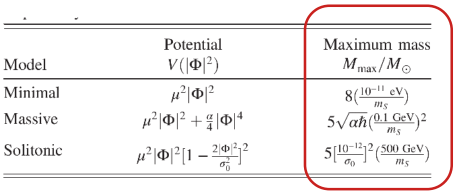
ECOs in modified gravity
Semi-classical effects
Quantum gravity

Evading Buchdhal #1:Boson stars

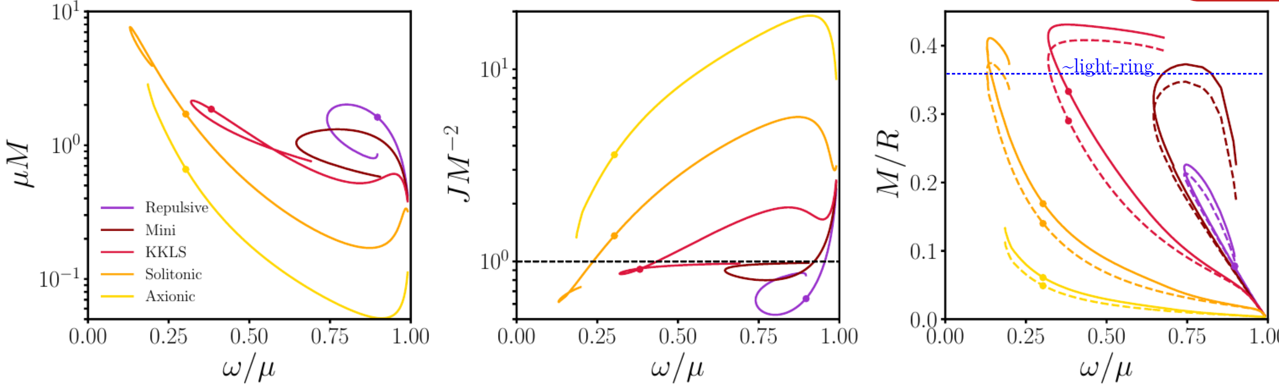
Liebling & Palenzuela Living Rev. Rel. (updated 2022)

$$\mathcal{L} = \frac{R}{16\pi G} - \partial_\mu \phi\, \partial^\mu \phi^\star - \mu^2|\phi|^2 + \lambda|\phi|^4 + \gamma|\phi|^6 + \dots$$

- Well-motivated and consistent: Self-gravitating solutions to GR + (complex) boson
- Max. mass and compactness depend on self-interactions
- Spinning (scalar) boson stars are unstable unless strongly interacting [Sanchis-Gual+ PRL 2019, Siemonsen-East PRD 2021]



Model	Potential $V(\lvert\Phi\rvert^2)$	Maximum mass $M_{\max}/M_\odot$
Minimal	$\mu^2\lvert\Phi\rvert^2$	$8(\frac{10^{-11}\text{ eV}}{m_S})$
Massive	$\mu^2\lvert\Phi\rvert^2 + \frac{\alpha}{4}\lvert\Phi\rvert^4$	$5\sqrt{\alpha\hbar}(\frac{0.1\text{ GeV}}{m_S})^2$
Solitonic	$\mu^2\lvert\Phi\rvert^2[1-\frac{2\lvert\Phi\rvert^2}{\sigma_0^2}]^2$	$5[\frac{10^{-12}}{\sigma_0}]^2(\frac{500\text{ GeV}}{m_S})$



[Siemonsen & East, Phys. Rev. D 103 (2021)]

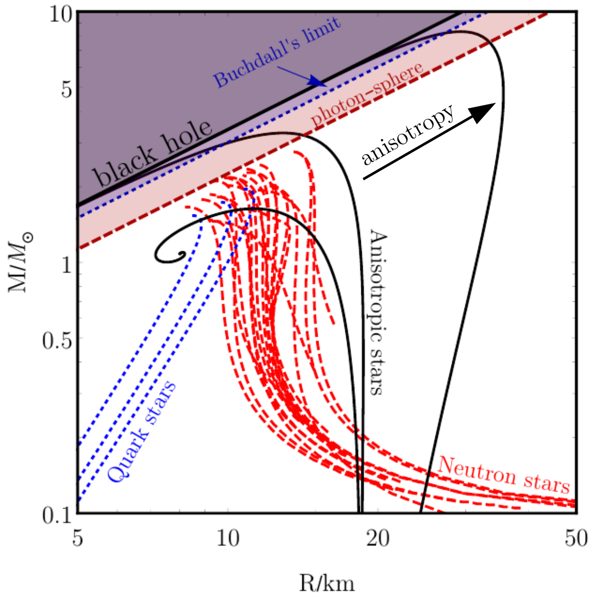
- Strong interactions give rise to multiple stable branches [Guerra, Macedo, PP, JCAP 2019] and pecularriar multipolar structrure [Ryan 1997, Vaglio+, PRD 2022]

Evading Buchdhal #2a: anisotropic stars

Raposo+, Phys. Rev. D 99, 104050 (2019)

$$T_{\mu\nu} = T^{\rm ISO}_{\mu\nu} + \sigma_1 k_\mu k_\nu + \sigma_2 \xi_\mu \xi_\nu + \sigma_3 \eta_\mu \eta_\nu$$

- Covariant framework for anisotropic fluids in GR, ready for 3+1 simulations
- Consistent proxy for ultracompact objects
- Satisfy WEC and SEC; highly-anisotropic configurations violate DEC
- How about causality?



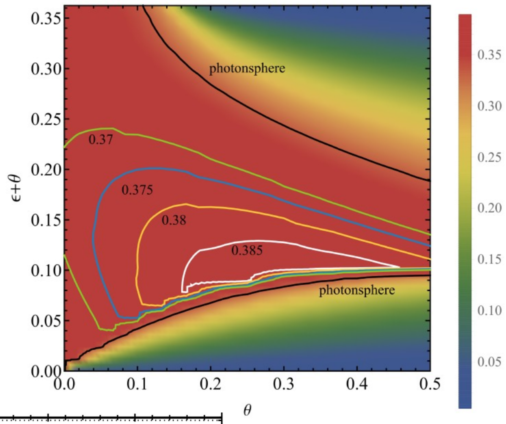
Anisotropies are key to build ultracompact horizonless objects

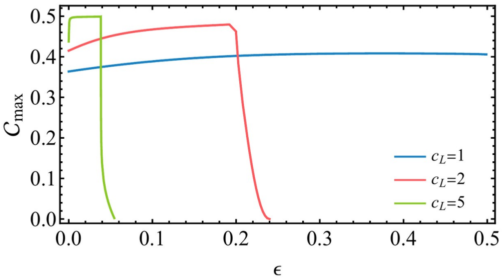
Evading Buchdhal #2b: elastic stars

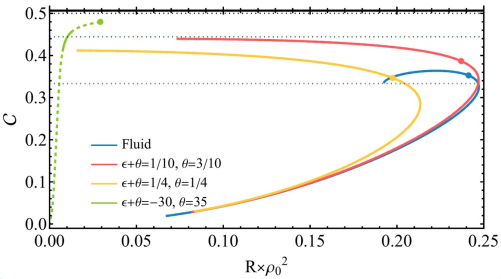
$$\frac{dp_{\rm rad}}{dr} = \frac{2}{r}(p_{\rm tan} - p_{\rm rad}) - (p_{\rm rad} + \rho)\frac{d\alpha}{dr}$$

Alho, Natario, Pani, Raposo,
PRD 106 (2022) 4, L041502;
PRD 105 (2022) 4, 044025

- Anisotropic TOV equations + stored energy function for elastic matter
- Two extra equation-of-state parameters
- Evades Buchdahl but only for superluminality
- Causal limit: $\mathcal{C}_{\rm PA} \lesssim 0.462$
- Stability: $\mathcal{C}_{\rm PAS} \lesssim 0.389$

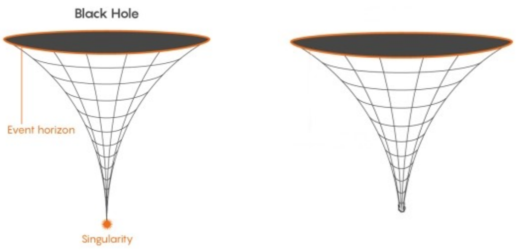


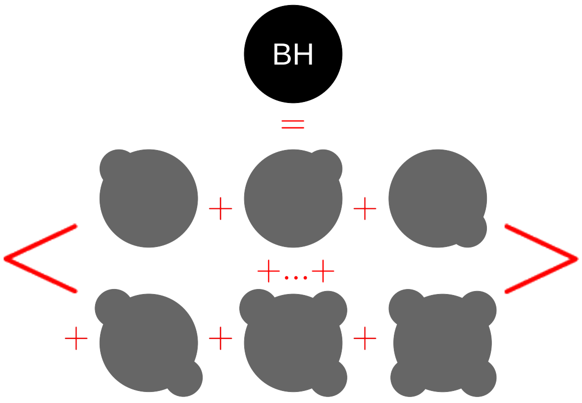




Evading Buchdhal #3: fuzzballs

- Fuzzball paradigm: classical BHs are ensembles of a huge number of regular, horizonless, microstates geometries [Lunin+ 2001, Mathur 2005+, Bena+, Bianchi+, Giusto+, ...]
- BH entropy explained by the number of microstates. BH entropy accounted for in special cases [Strominger 1996, Horowitz 1996, Maldacena 1997]
- (Low-energy truncations of) string theory admits huge families of solutions [Bena+ 2007, 2015-2017]
- Pros: well motivated, <u>mass is free parameter</u>
- Cons: complicated, mostly extremal charged BHs [but see Bah+ 2021-2022 for recent non-SUSY extension]
- Open issues: measurement problem (typical vs atypical states, averaging?), phenomenology [Mayerson 2020]

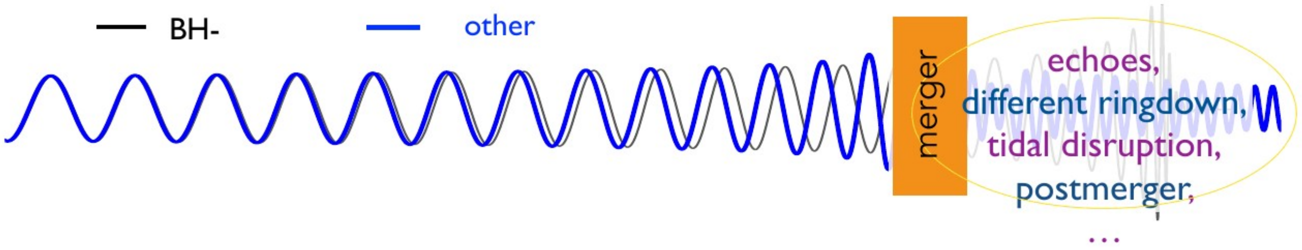




$\sim e^{\frac{M^2}{M_P^2}}$ microstates

GW-based tests of ECOs

Slide concept by T. Hinderer and A. Maselli



echoes, different ringdown, tidal disruption, postmerger, ...

~point masses: same signal for all objects

tidal effects + multipolar structure

absence of horizon **absorption effects**

echoes

Testing the Kerr bound

- GR BHs have dimensionless spin $\chi \equiv \dfrac{J}{M^2} \leq 1$
- ECOs (eg. fuzzballs, boson stars) can evade this bound
  - Microstates of *static* BHs are generically (slowly?) spinning
  - Quantum gravity generically admits “superspinars” [Gimon-Horava PRD 2009]

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- Kerr bound can be tested in a model-independent way:
  1. Point particle PN phase up to 1.5PN depends only on masses & spins
     - but no consistent PN inspiral or IMR waveforms
  2. Measuring secondary spin in an EMRI with LISA? [Piovano+ PLB 2020]
     - but correlated with other parameters! [Piovano+ PRD 2021]
     - can spin precession and generic orbits break degeneracy?

Post-Newtonian inspiral: BH vs ECO

$$\tilde{h}(f) = \mathcal{A}(f) e^{i(\psi_{\rm PP} + \psi_{\rm TH} + \psi_{\rm TD})}$$

$$1\text{PN} = \frac{v^2}{c^2}$$

Blanchet, Living Rev. Relativity 17, 2 (2014)

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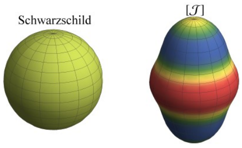
Blanchet, Living Rev. Relativity 17, 2 (2014)

- **2PN:** Point-particle phase depends on **multipole moments** of the bodies
  - Tests of the BH no-hair theorem [Hansen 1974]



$$\underbrace{M_\ell^{\rm Kerr}}_{\text{Mass moments}} + i\underbrace{S_\ell^{\rm Kerr}}_{\text{Spin moments}} = M^{\ell+1}\left(i\chi\right)^\ell$$

Post-Newtonian inspiral: BH vs ECO

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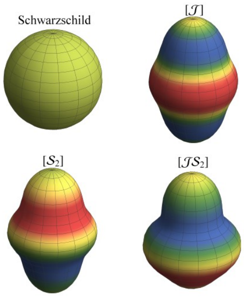


Credits: G. Raposo

$$\underbrace{M_\ell^{\rm Kerr}}_{\text{Mass moments}} + i\underbrace{S_\ell^{\rm Kerr}}_{\text{Spin moments}} = M^{\ell+1}\left(i\chi\right)^\ell$$

  - **ECOs** (axisymmetric case):

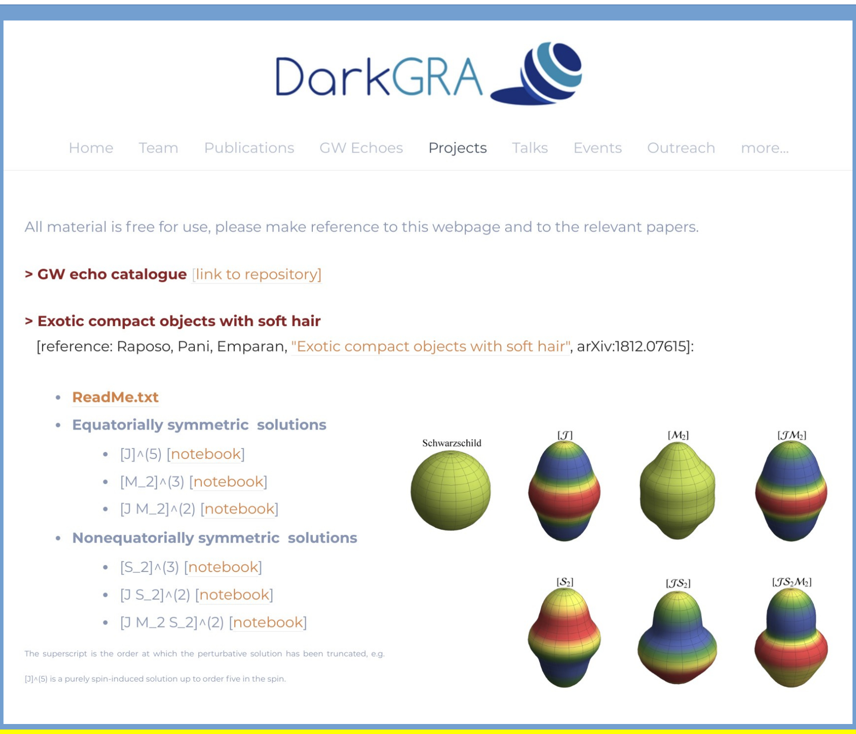
$$M_\ell \quad = \quad M_\ell^{\rm Kerr} + \delta M_\ell \qquad\qquad S_\ell \quad = \quad S_\ell^{\rm Kerr} + \delta S_\ell$$

- 3G/LISA can constrain mass quadrupole (M_2) and spin octupole (S_3) [Krishnendu+ 2018]
- In the BH limit → **“hair conditioner” theorem** [Raposo, PP, Emparan, PRD 2019]

$$\frac{\delta M_\ell}{M^{\ell+1}} \to a_\ell \frac{\chi^\ell}{\log\epsilon} + b_\ell\,\epsilon + \ldots \qquad\qquad \frac{\delta S_\ell}{M^{\ell+1}} \to c_\ell \frac{\chi^\ell}{\log\epsilon} + d_\ell\,\epsilon + \ldots$$

(assumes exterior is ~ GR and curvature near the surface is small)

The multipolar structure of ECOs



All material is free for use, please make reference to this webpage and to the relevant papers.

> GW echo catalogue [link to repository]

> Exotic compact objects with soft hair
[reference: Raposo, Pani, Emparan, "Exotic compact objects with soft hair", arXiv:1812.07615]:

- **ReadMe.txt**
- **Equatorially symmetric solutions**
  - [J]^(5) [notebook]
  - [M_2]^(3) [notebook]
  - [J M_2]^(2) [notebook]
- **Nonequatorially symmetric solutions**
  - [S_2]^(3) [notebook]
  - [J S_2]^(2) [notebook]
  - [J M_2 S_2]^(2) [notebook]

The superscript is the order at which the perturbative solution has been truncated, e.g.

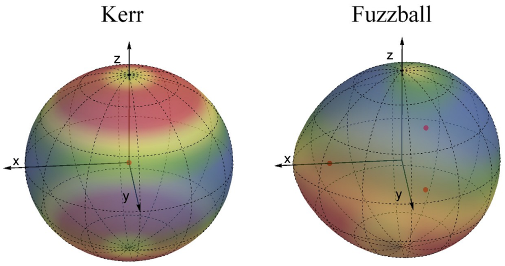
[J]^(5) is a purely spin-induced solution up to order five in the spin.

Credits: G. Raposo

Several families of analytical ECO solutions with soft hair available
@ **www.darkgra.org**

The multipolar structure of fuzzballs

- Stationary ECOs can break: [fuzzballs: Bena+ 2020-2021; Bianchi+ PRL-JHEP 2020; boson stars: Herdeiro+ PLB 2020]
  - equatorial symmetry: e.g. $S_2 \neq 0$, $M_3 \neq 0$
  - axial symmetry: e.g. $M_{20} \neq 0$, $M_{21} \neq 0$, $M_{22} \neq 0$



Credits: G. Raposo

- Fuzzballs (in N=2 supergravity):
  - certain multipole ratios are ~ universal [Bena-Mayerson PRL-JHEP 2020]
  - certain multipole invariants are minimum for BPS BHs [Bianchi+ PRL-JHEP 2020] …

….but not for non-BPS states [Bena+ 2021]

- Lot of progress: current models should be extended beyond Kerr symmetries:
  - Searching for equatorial-symmetry breaking with LISA EMRIs [Fransen-Mayerson PRD 2022]
  - Axial-symmetry breaking introduces precession & phase modulation [Loutrel+ PRD 2022; Loutrel, Pani, Yunes, gr-qc/2210.10571]

Post-Newtonian inspiral: BH vs ECO

$$\tilde{h}(f) = \mathcal{A}(f)e^{i(\psi_{\rm PP}+\psi_{\rm TH}+\psi_{\rm TD})}$$

- **2.5log PN: tidal heating** [Alvi PRD 2001, Poisson, PRD 2009]
  - BHs absorb radiation at horizon
  - Tidal heating is ~ absent for ECOs
  - Small even for 3G for q~1 → IMRIs or LISA [Maselli+, 2018, Hughes PRD 2001, Datta+ PRD 2020]

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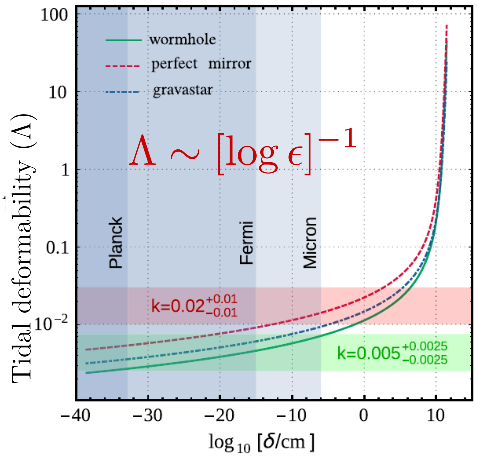


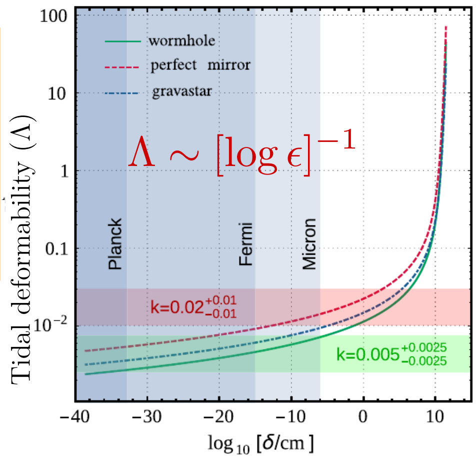
$\Lambda \sim [\log\epsilon]^{-1}$

- **5PN: tidal deformability and Love numbers**
  - Love = 0 for a BH in GR [Damour '86; Binnington-Poisson PRD 2009; Dar
  - Love ≠ 0 for ECOs and BHs in modified gravity [Porto+ Fortsch. Phys. 2016, Cardoso+, PRD 2017]
  - LISA able to distinguish BHs from *any* boson star model [Cardoso+, PRD 2017, Pacilio+ PRD 2021]
  - In several ECO models Love scales logarithmically → strong constraints with LISA
    [Uchikata+ PRD 2016; Maselli+, PRL 2018, CQG 2019; Addazi+ PRL 2019]

Post-Newtonian inspiral: BH vs ECO

$$\tilde{h}(f) = \mathcal{A}(f)e^{i(\psi_{\rm PP}+\enclose{circle}{\psi_{\rm TH}}+\enclose{circle}{\psi_{\rm TD}})}$$

Evidence of Love ≠ 0 in a supermassive object would imply a departure from the standard <u>vacuum GR BH</u> picture



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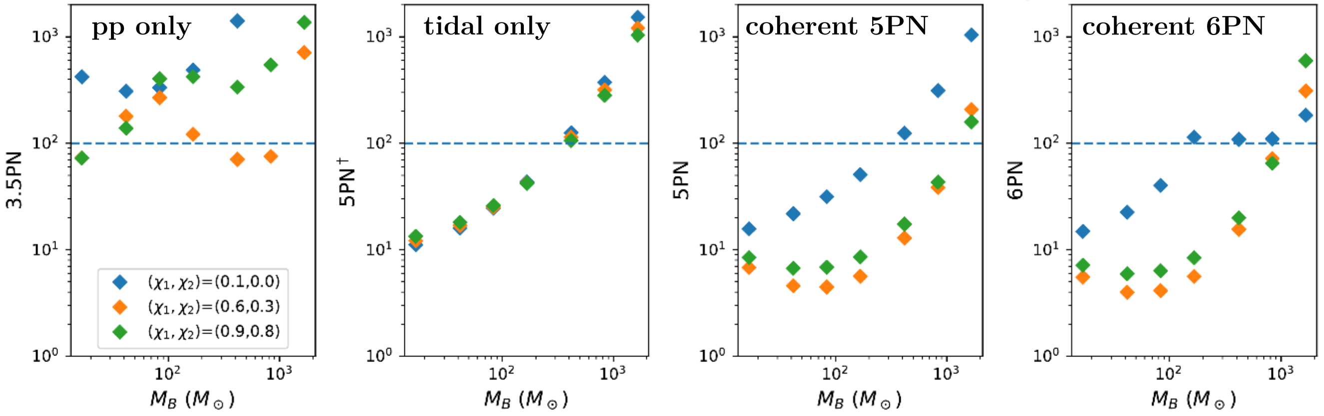
BH vs Boson Stars: coherent model

$$\mathcal{L} = \frac{R}{16\pi G} - \partial_\mu\phi\,\partial^\mu\phi^\star - m^2|\phi|^2 + \lambda|\phi|^4 + \gamma|\phi|^6 + \ldots$$

Coherent inspiral waveform → all deviations from Kerr (multipoles, tidal, etc) <u>depend only on masses & spins and on the theory's coupling constants</u>

- Tidal deformability strongest, but coherent model significantly improves the constraints
- Constraining power of current detectors is marginal: 3G/LISA required to constrain boson-star couplings

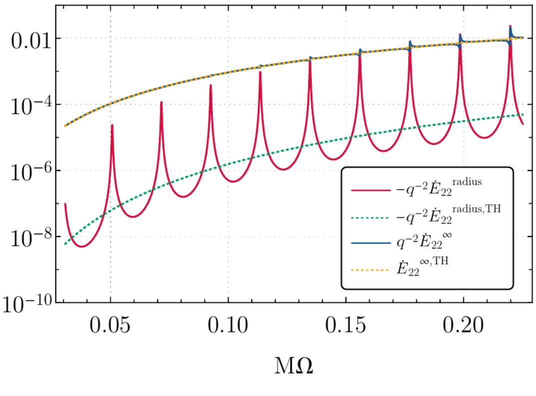
[Pacilio+ PRD 2020, see also Toubiana+ PRD 2021, Sanchis-Gual+, 2208.11717]

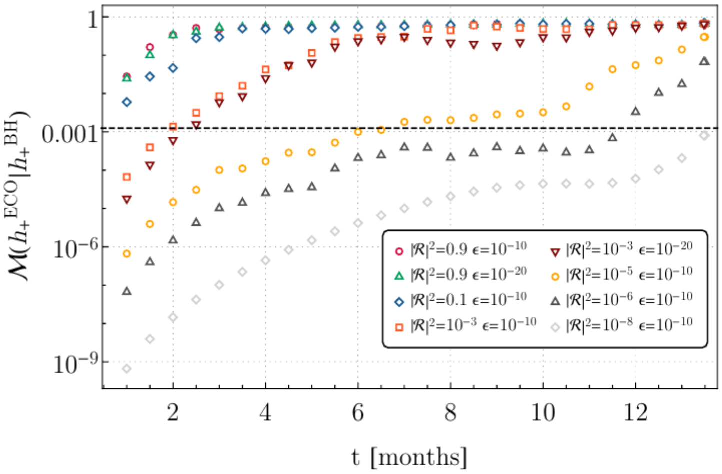


ECO tests with EMRIs/IMRIs

- EMRIs are unique probes of *both* multipolar structure and dynamics
- Non-BH corrections are amplified for small mass-ratio:
  - Spin-induced multipole moments → $\delta\bar{M}_2 \sim 10^{-4}$ [Barack-Cutler, PRD 2007, Babak+ 2017]
  - Equatorial symmetry breaking → $\delta\bar{S}_2 \sim 10^{-2}$ [Fransen-Mayerson PRD 2022]
  - Tidal heating → $|\mathcal{R}|^2 \lesssim 10^{-8}$ [Datta+ PRD 2020, Maggio+ PRD 2021]
  - Tidal Love numbers → $\bar{\Lambda} \sim 10^{-5}$ [Pani-Maselli 2019, Piovano+ 2207.07452]
  - Tests of the Kerr bound (χ<1) could be much simpler and accurate with EMRIs *if one can measure the spin of the secondary* [Piovano+, PRD-PLB 2020, PRD 2021]
- ECO tests with EMRIs/IMRIs → many challenges in modeling, parameter estimation, rates, etc… → careful with simplistic projected bounds!

Testing horizon absence with EMRIs





- ECO QNM excitation in fluxes [Sago-Tanaka PRD 2021, Maggio, van de Meent, Pani; PRD 2021]
- EMRIs can potentially constrain the reflectivity at the level of $|\mathcal{R}|^2 \lesssim 10^{-8}$
- Specific models (e.g. $\mathcal{R}(\omega) = e^{-\frac{|\omega - m\Omega|}{2T_H}}$) can be confirmed/ruled out
- However: careful with time scales and "greenhouse" effect [Cardoso-Duque, PRD 2022]

Ringdown tests

of the nature of compact objects

BH spectroscopy

- Post-merger signal → superposition of quasinormal modes (QNMs)

[e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)]

$$h_+ + ih_\times \sim \sum_{i=(\ell,m,n)} A_i \sin(\omega_i t + \phi_i) e^{-t/\tau_i}$$

- Smoking guns of "new physics":
  - Shift of QNMs (bkg geometry + dynamics + boundary conditions):

$$\omega_{lmn} = \omega_{lmn}^{\rm Kerr}(M,\chi) + \delta\omega_{lmn}(M,\chi,\ell_{\rm new})$$

  - Extra modes (e.g., polarizations, matter modes) → amplitudes?
  - Isospectrality breaking (probably subdominant, resolvable?)

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- **LIGO/Virgo:** some events where the dominant QNM has been measured, hints of secondary modes in GW150914 and GW190521?

- **LISA:** O(1-100) events/yr allowing for BH spectroscopy at 1-10% level for 3+ QNM quantities [Bhagwat+ PRD 2022]

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ω_{lm} ew)

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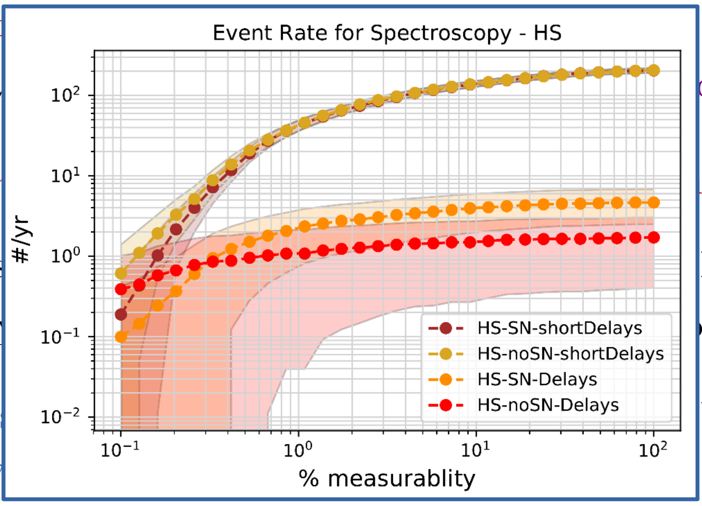

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QNMs: BHs vs Rest of the World

$$\frac{\partial^2\Psi}{\partial t^2} - \frac{\partial^2\Psi}{\partial r_*^2} + V_{slm}(r_*)\Psi = S$$

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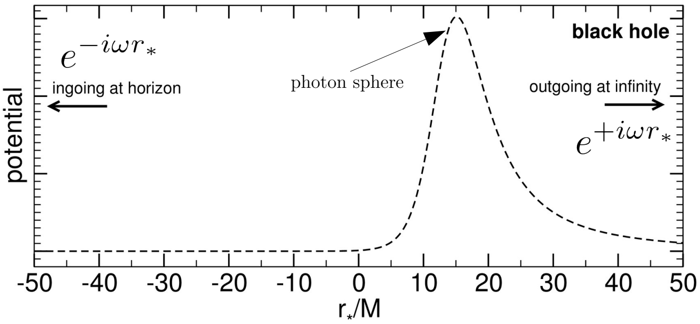

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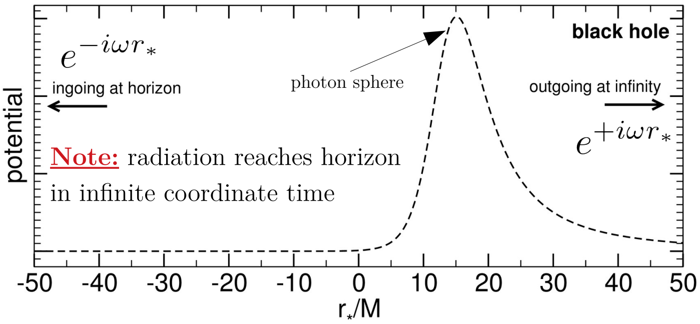

Note: radiation reaches horizon in infinite coordinate time

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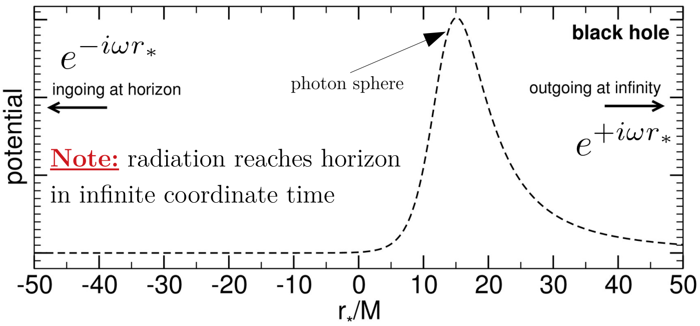

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Only (classical) BHs absorb everything!

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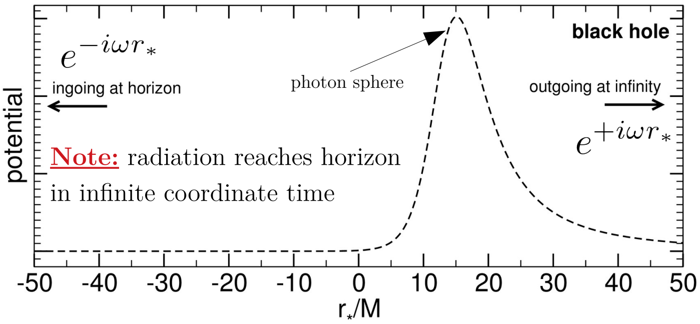

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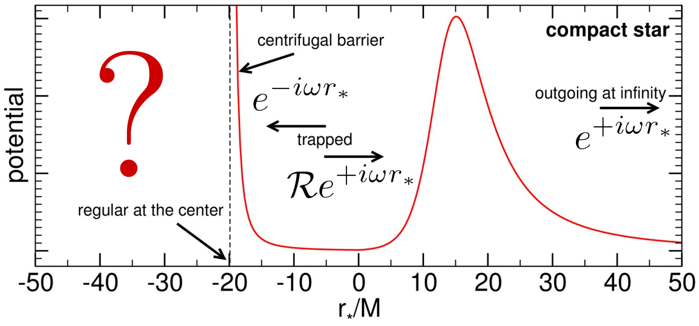
Only (classical) BHs absorb everything!

- Total absorption is the defining property of a BH
- Some reflectivity in any other case
- Reflectivity = weak GW interaction!



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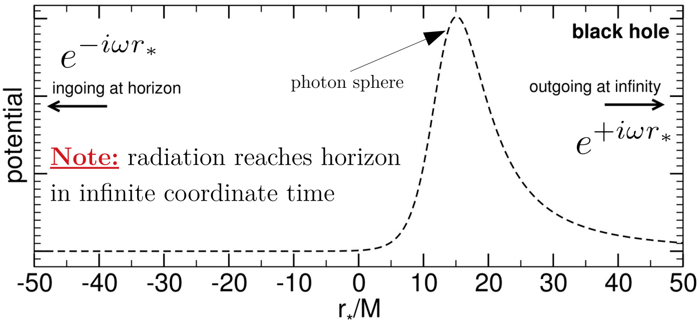

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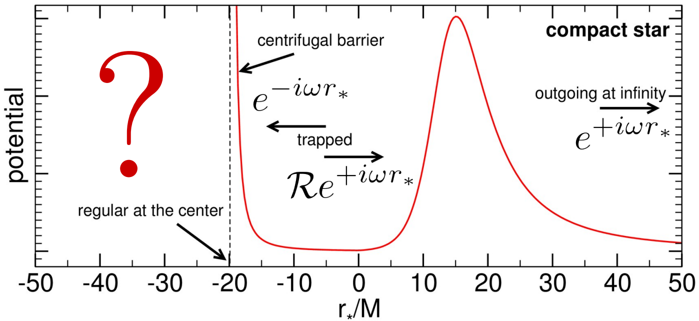
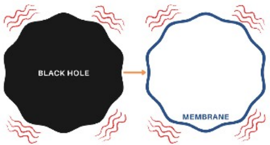


No horizon → different ringdown

QNMs: boundaries & metric

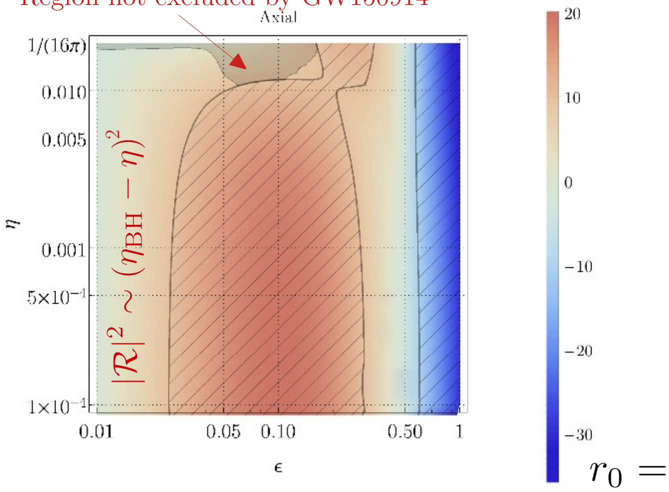
[Oshita+ 2019, Maggio+ PRD 2020]

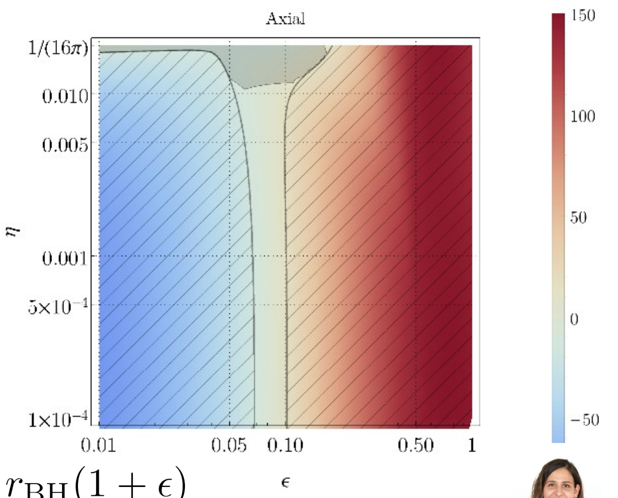
- Neglecting spin and assuming GR in the exterior
- Interior modeled by the *membrane paradigm* [Damour, Thorne, ...]
- Boundary conditions → viscosity of a *fictitious* fluid



$$\eta_{\rm BH}=\frac{1}{16\pi}$$

Region not excluded by GW150914





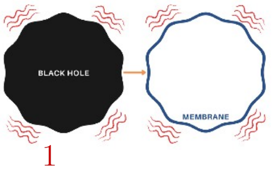
$$r_0=r_{\rm BH}(1+\epsilon)$$

Credits:
Elisa Maggio

- Axial and polar modes are not isospectral but harder to resolve

QNMs: boundaries & metric

[Oshita+ 2019, Maggio+ PRD 2020]



- Neglecting spin and assuming GR in the exterior
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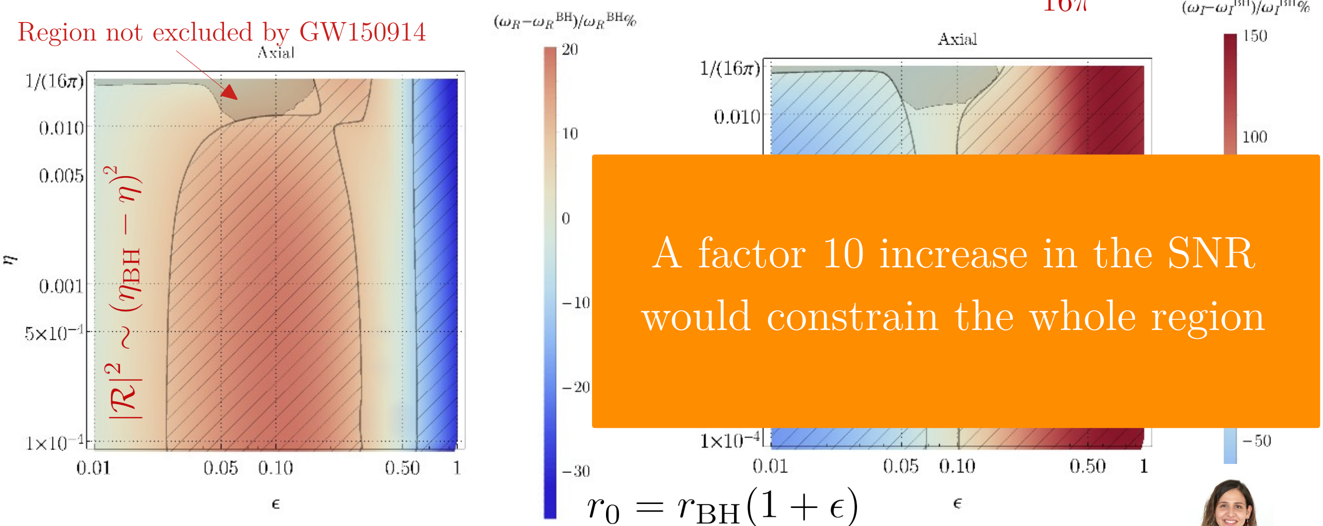
- Boundary conditions → viscosity of a *fictitious* fluid

$$\eta_{\rm BH} = \frac{1}{16\pi}$$

Region not excluded by GW150914



A factor 10 increase in the SNR would constrain the whole region

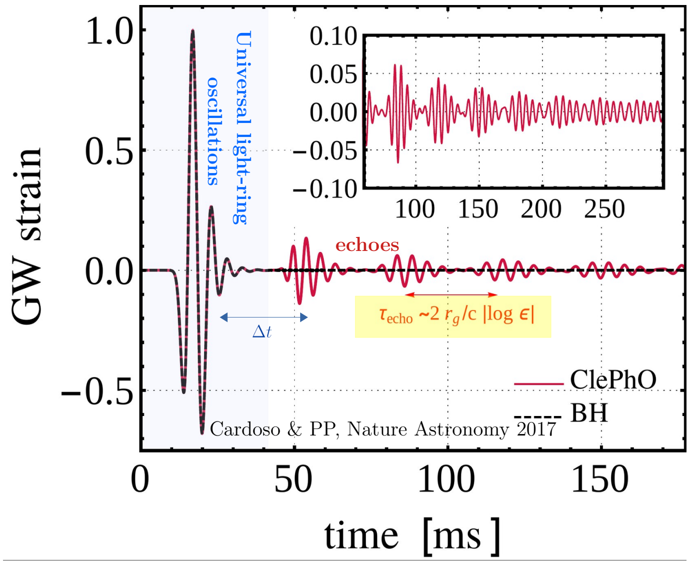
$$r_0 = r_{\rm BH}(1+\epsilon)$$

- Axial and polar modes are not isospectral but harder to resolve

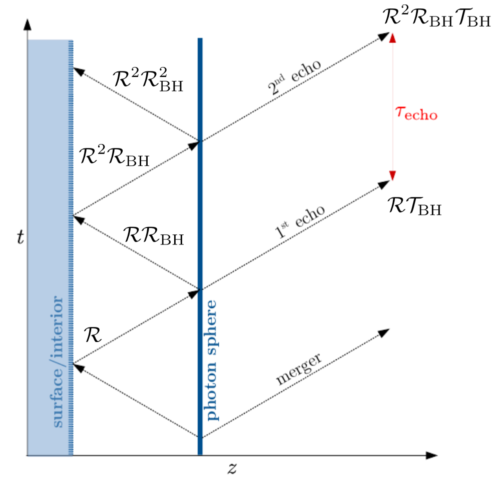
Credits:
Elisa Maggio

GW echoes

- For ultracompact objects ($\epsilon<0.01$) prompt ringdown is identical to BHs but **GW "echoes"** appear at later times [Cardoso+ PRL-PRD 2016...]



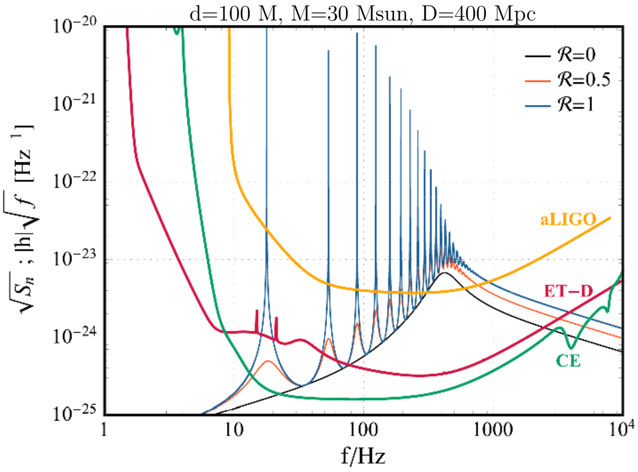
Cardoso & PP, Nature Astronomy 2017

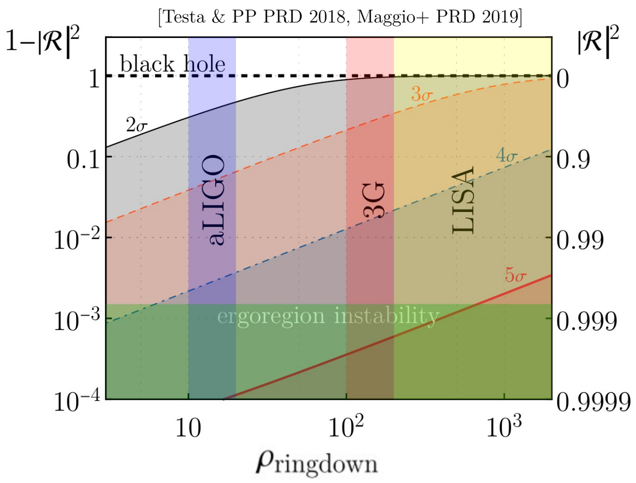


Vilenkin PLB 1978, Mark+ PRD 2017, Abedi+ PRD 2017

- Echo delay time scales logarithmically with compactness
- Claim: echoes require either exotic matter or beyond GR [Alho+ 2022] $\mathcal{C}_{\rm PAS} \lesssim 0.389$

Echo detectability

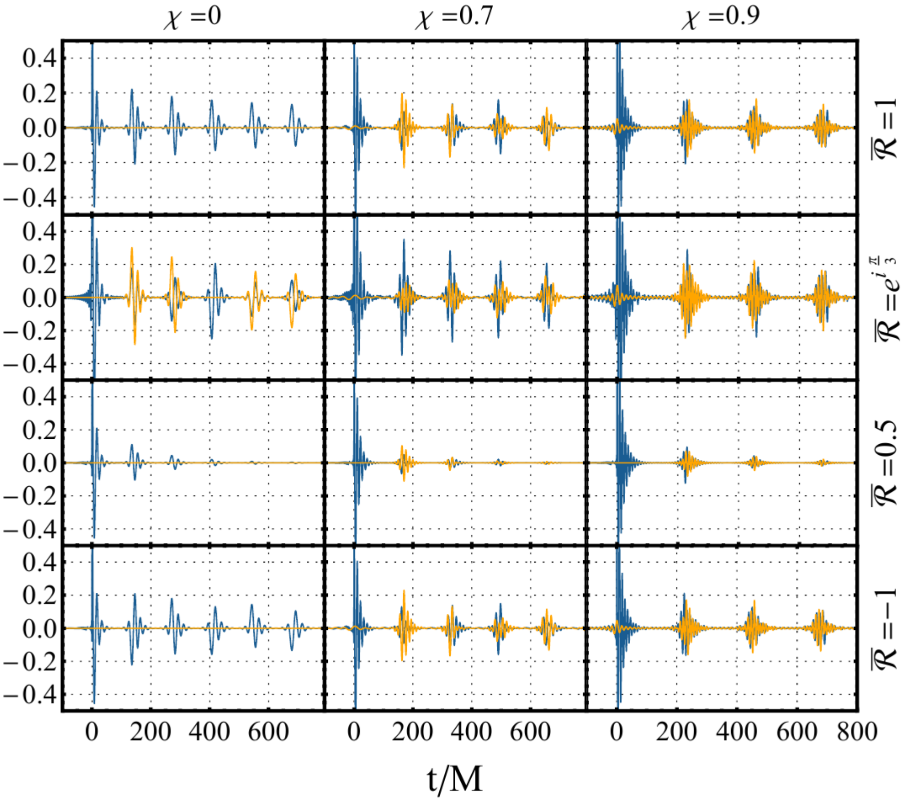




[Testa & PP PRD 2018, Maggio+ PRD 2019]

- Contrasting results with LIGO data [Abedi+, 2017/18, Conklin+ 2018/19, Ashton+ 2017, Westerweck+ 2018] but no statistical evidence in LVKC searches [Uchikata+ 2019, Tsang+ 2019, GWTC-3 2021]
- Recent "measurement" claims in GW190521 [Abedi+ 2022]
- Near-horizon corrections are within reach! Echo search pipelines now routine in LVKC
  - LIGO/Virgo can probe only large reflectivity, much better prospects with 3G/LISA!
- Lot of progress on echo waveform modeling, pipelines, and searches [Abedi+, Universe (2020)]

GW echo slideshow



Coherent, analytical template in the FD:

- complex reflectivity

- mixing of polarizations

- spin-dependent modulation

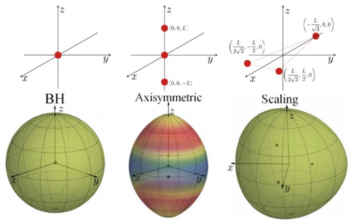
- This complexity absent in current searches

..and still a toy model!

Waveforms, templates, and movies available @ http://www.DarkGRA.org/gw-echo-catalogue.html

BH microstate spectroscopy

Ikeda+, PRD 2021



Bianchi+ 2020

- Background: family of sols to N=2 supergravity [Bena-Warner 2008]
- 3+1 evolution of Klein-Gordon equation on generic microstate
- No spatial isometries in general

4D ansatz:

$$ds^2 = -e^{2U}(dt+\omega)^2 + e^{-2U}\sum_{i=1}^{3} dx_i^2 ,$$

$$e^{-4U} = Z_1 Z_2 Z_3 V - \mu^2 V^2 ,$$

$$*_3 d\omega = \tfrac{1}{2}\left(V dW - W dV + K^I dL_I - L_I dK^I\right)$$

$$Z_I = L_I + \frac{|\epsilon_{IJK}|}{2}\frac{K^J K^K}{V} ,$$

$$\mu = \frac{W}{2} + \frac{L_I K^I}{2V} + |\epsilon_{IJK}|\frac{K^I K^J K^K}{6V^2}$$

N centers:

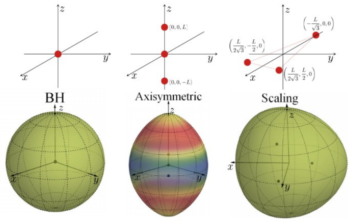
$$V = 1 + \sum_{a=1}^{N}\frac{v_a}{|\vec{x}-\vec{x}_a|} , \qquad L_I = 1 + \sum_{a=1}^{N}\frac{\ell_{I,a}}{|\vec{x}-\vec{x}_a|} ,$$

$$K^I = \sum_{a=1}^{N}\frac{k_a^I}{|\vec{x}-\vec{x}_a|} , \qquad W = \sum_{a=1}^{N}\frac{m_a}{|\vec{x}-\vec{x}_a|} ,$$

- Note: no ergoregion by construction → no ergoregion instability
- Works for any stationary 4D geometry (e.g., also non-SUSY, neutral) [Bah+ 2021-2022]

BH microstate spectroscopy

Ikeda+, PRD 2021



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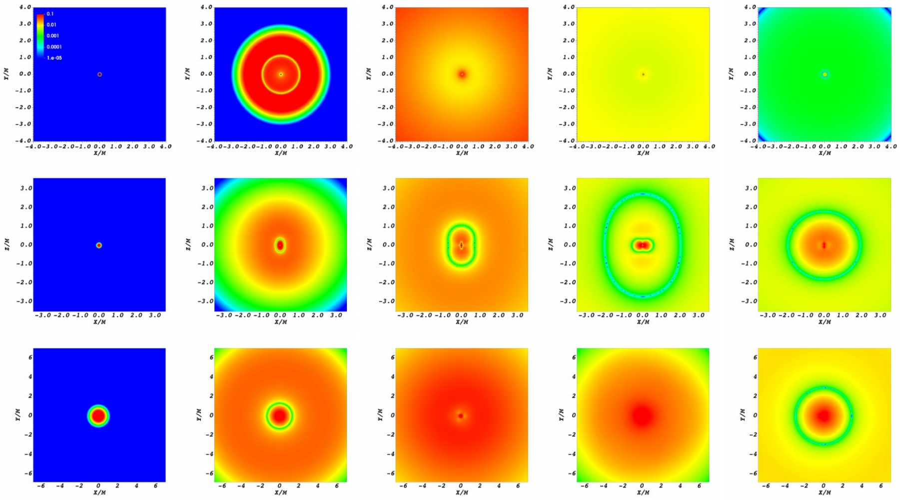
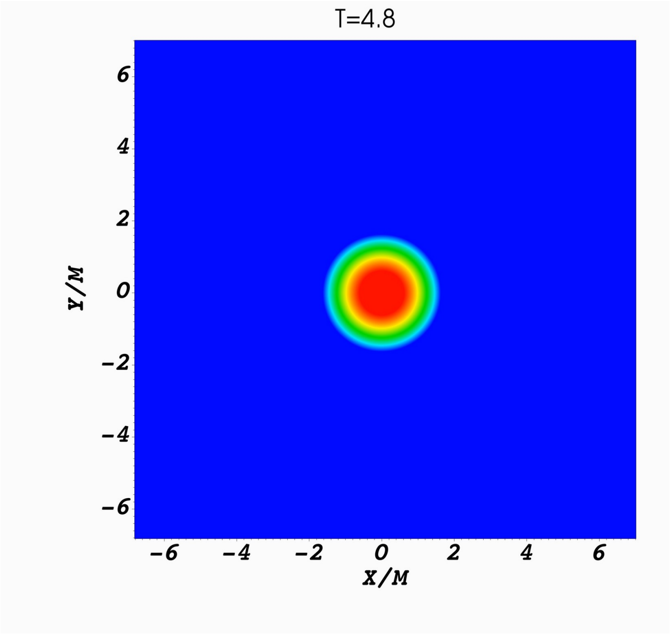


Credits:
Taishi Ikeda

Movies @ https://web.uniroma1.it/gmunu/fuzzballs-multipole-moments-and-ringdown

BH microstate spectroscopy

Ikeda+, PRD 2021



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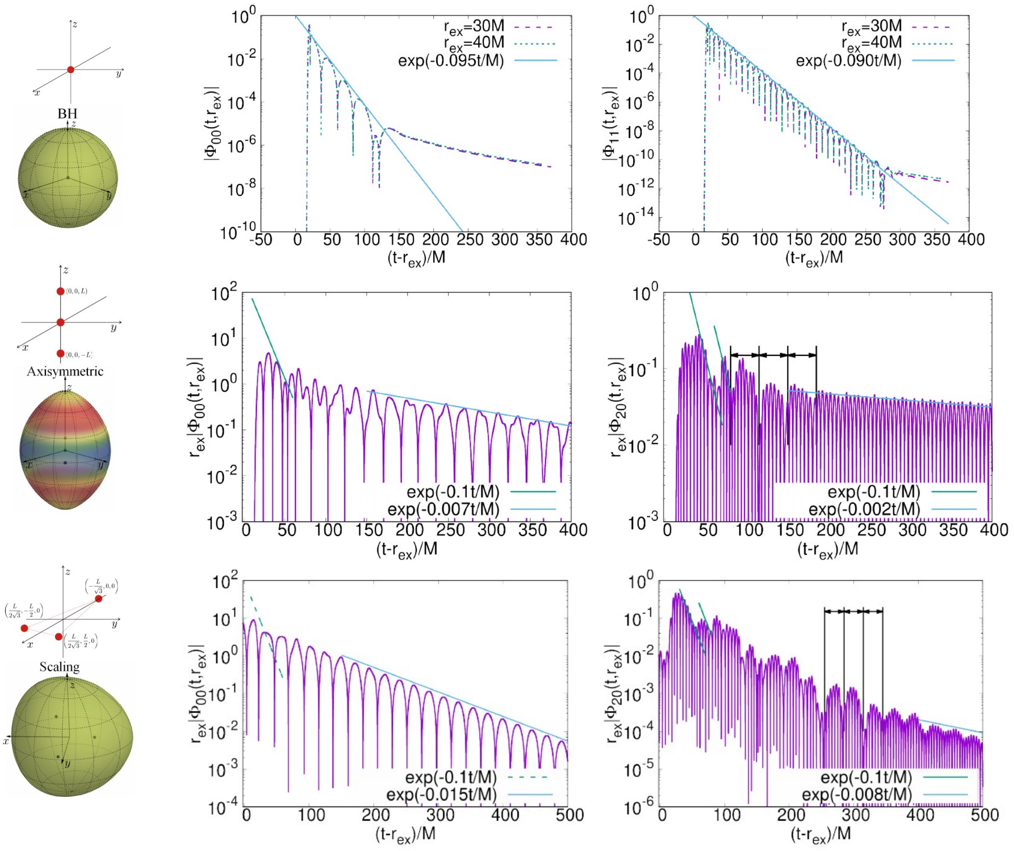
BH microstate spectroscopy

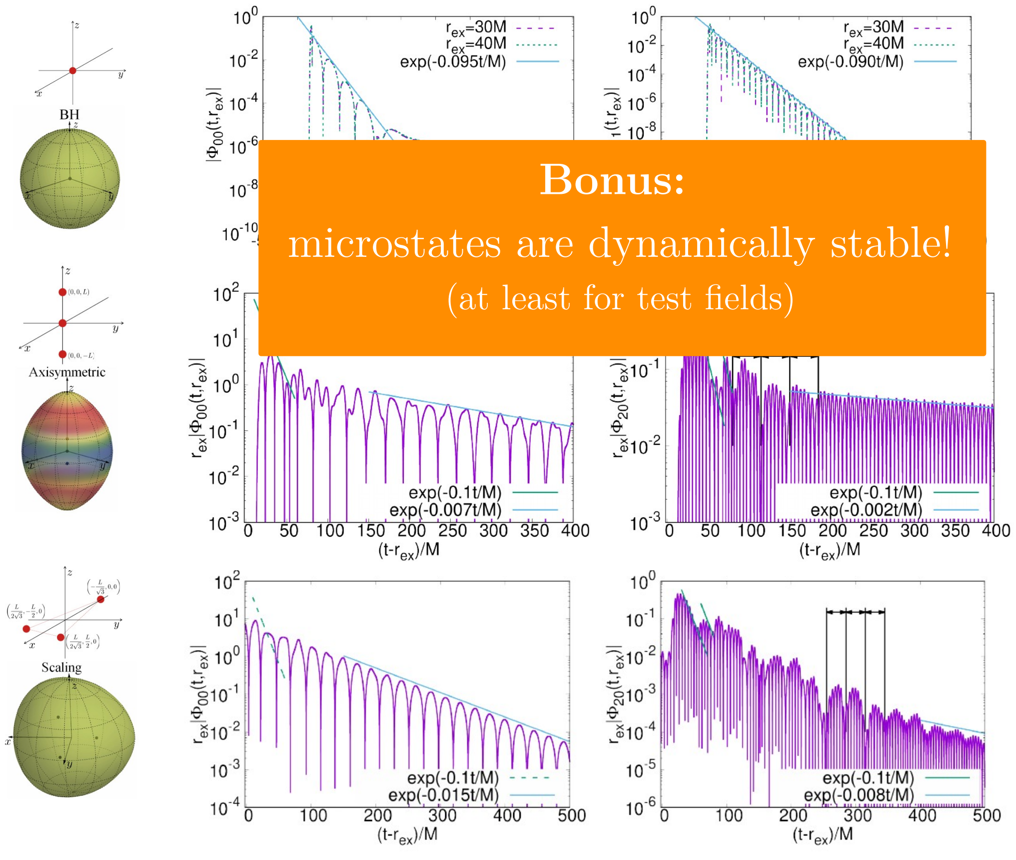
Ikeda+, PRD 2021



Overall structure qualitatively clear but mode mixing complicates the signal

BH microstate spectroscopy

Ikeda+, PRD 2021



Bonus:

microstates are dynamically stable!

(at least for test fields)

Overall structure qualitatively clear but mode mixing complicates the signal

---

Conclusion

- *Living the BH era*: discovery opportunities for new physics!
- Dramatic improvements on ECOs on all fronts in the last few years
- Any signature of beyond-Kerrness would shake physics to its grounds
- Strong evidence for light rings & constraints on the reflectivity from GWs/EM
- Exquisite constraints in the future, esp. with EMRIs
- Horizons are special: portal to observables quantum gravity effects?

If Not Now, When?

Backup slides

“Nothing is More Necessary than the Unnecessary” [cit.]

BONUS SLIDES

What is the fate of Hawking evaporation in gravity theories with higher curvature terms?

Based on
Fabrizio Corelli, Marina De Amicis, Taishi Ikeda, PP
2205.13006; **2205.13007 (PRD in press)**

Quadratic gravity as a test-bed

- UV completion unknown or too involved

  → need a consistent framework to study nonperturbative dynamics

- Einstein-scalar-Gauss-Bonnet (EdGB) gravity:

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left\{\mathcal{R} - (\nabla\phi)^2 + 2F[\phi]\mathcal{G}_{\rm GB}\right\} + S_{\rm matter}$$

$$F[\phi] = \lambda e^{-\gamma\phi} \qquad \mathcal{G}_{\rm GB} = R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd}$$

- Inspired by heterotic and bosonic string theories
- The only quadratic-gravity theory with second-order field equations
- Can be studied beyond the perturbative (EFT) regime

$$\ell \propto \sqrt{\lambda}$$ (not necessarily Planckian)

BHs in EdGB gravity

$$G_{\mu\nu} = 8\pi\mathcal{T}^{\rm eff}_{\mu\nu} \qquad \Box\phi = -F'(\phi)\mathcal{G}_{\rm GB}$$

- Violates BH no-hair theorems → static BHs with (secondary) scalar hair [Kanti+ PRD 1996]
- Phase space depends on the coupling:

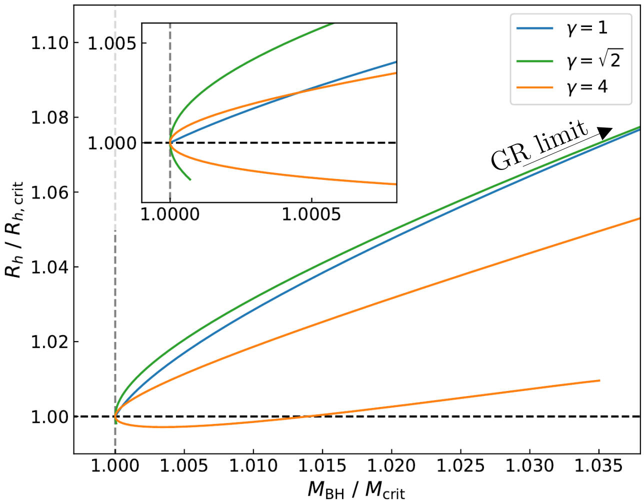
$$F[\phi] = \lambda e^{-\gamma\phi}$$

$\gamma \lesssim 1.3$

→ singular minimum-mass BH

$\gamma \gtrsim 1.3$

→ two branches of solutions
→ minimum mass is regular
→ minimum-radius solution
→ singular sol. at the end of 2nd branch



BHs in EdGB gravity

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- Violates BH no-hair theorems → static BHs with (secondary) scalar hair [Kanti+ PRD 1996]
- Phase space depends on the coupling:

$F[\phi] = \lambda e^{-\gamma\phi}$

$M_{\text{crit}} \propto \sqrt{\lambda}$

$\gamma \lesssim 1.3$

→ singular minimum-mass BH

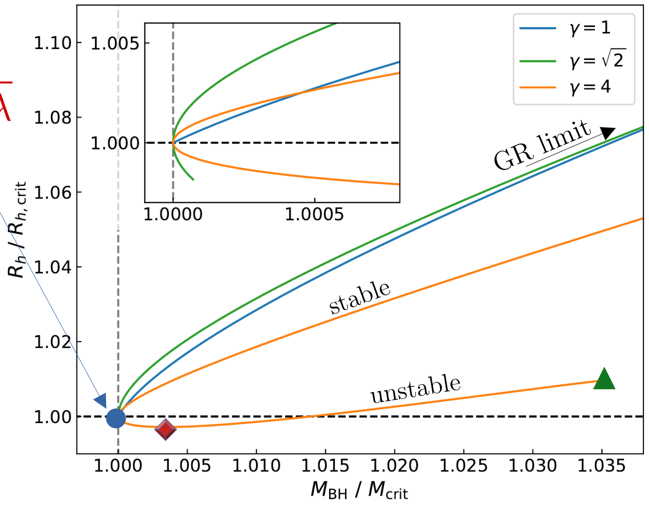
$\gamma \gtrsim 1.3$

→ two branches of solutions

→ <u>minimum mass is regular</u>

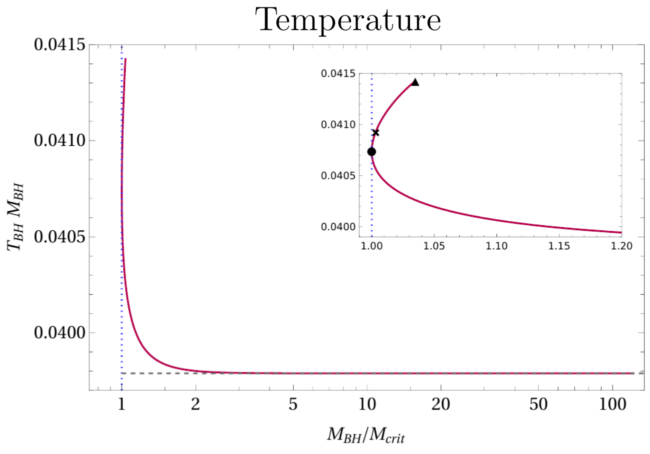
→ minimum-radius solution

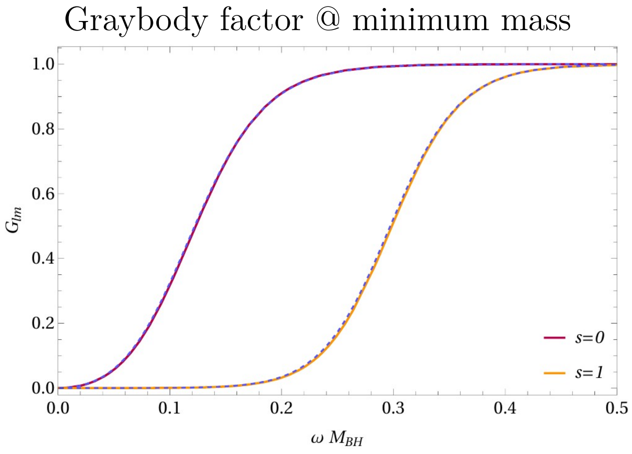
→ singular sol. at the end of 2nd branch



BHs in EdGB gravity

Torii-Maeda PRD 1997; Konoplya+ PRD 2019; M. De Amicis's Msc thesis 2021


Temperature

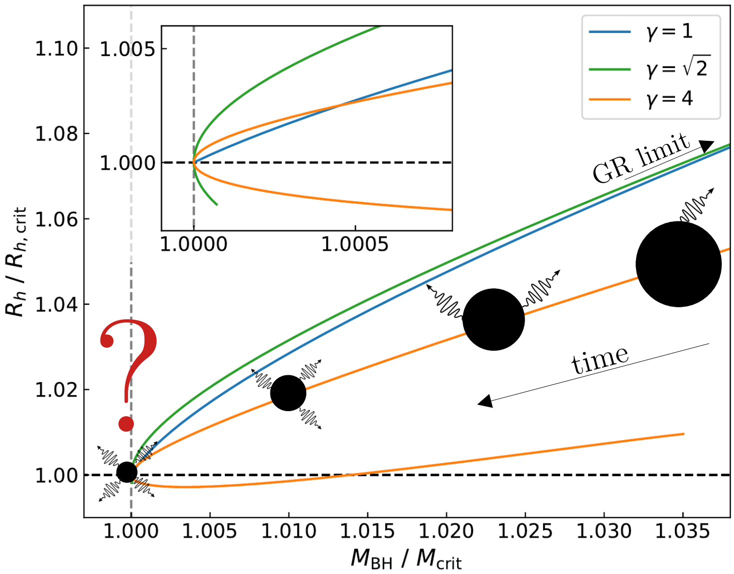

Graybody factor @ minimum mass

- Minimum-mass solution has nonzero temperature and graybody factor

$$\frac{dM_{\text{BH}}}{dt} = -\frac{1}{2\pi}\sum_{l,m}\int d\omega \frac{\omega G_{lm}(\omega)}{e^{\omega/T_H} \pm 1}$$

→ emission ~10% faster than in GR

The Puzzle

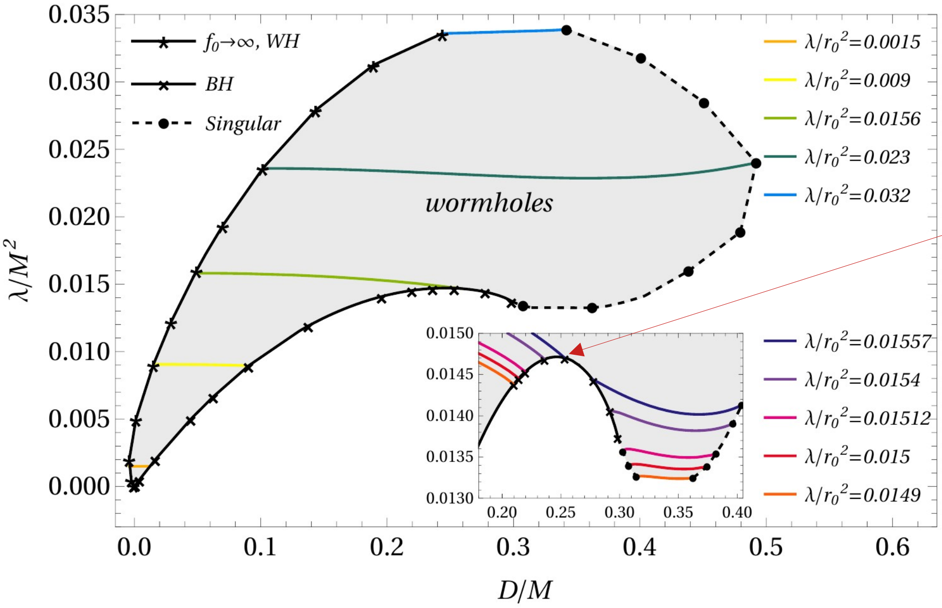


EdGB scale needs not being Planckian →

puzzle should be resolvable without invoking quantum gravity!

Another piece of the puzzle?

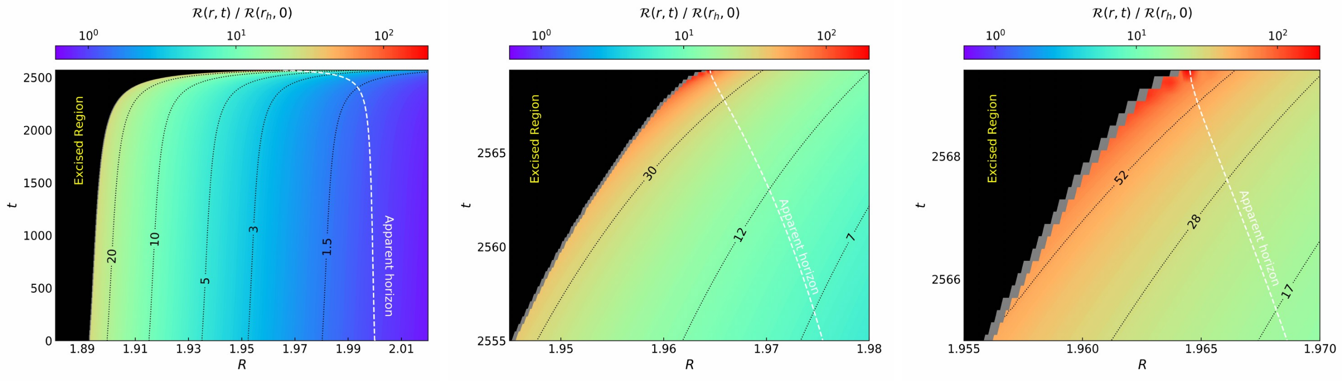
Kanti-Kleihaus-Kunz PRL-PRD 2021
Kleihaus-Kunz-Kanti PLB 2019, PRD 2020; M. De Amicis's Msc thesis 2021



Minimum mass is a *double point*

- BHs: 1-param family
- Wormholes: 2-param family
- Cusps: 1-param family
- Particle-like: 2-param family

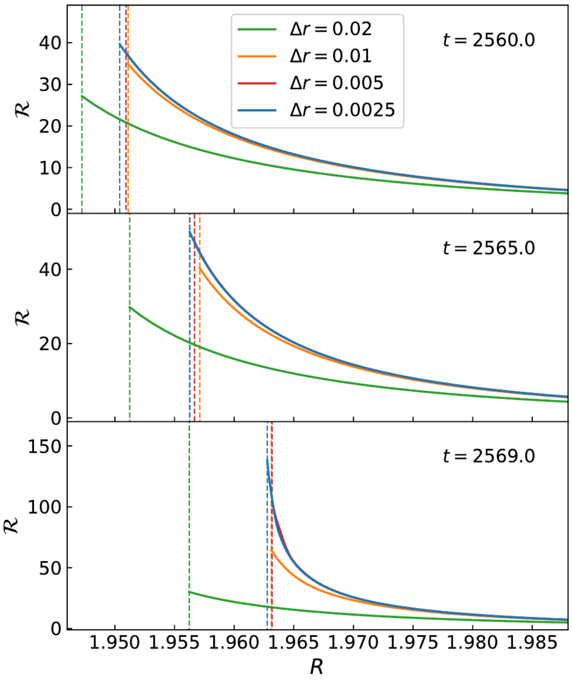
Mass loss past minimum mass

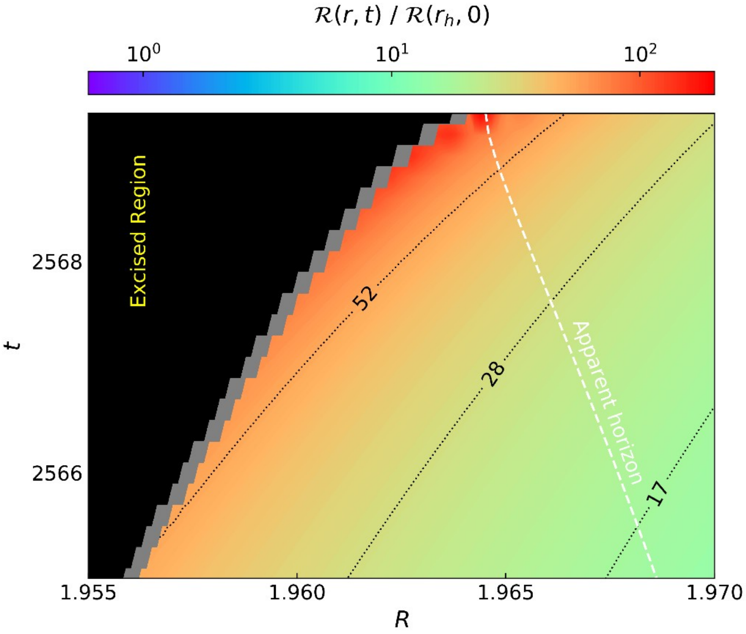


Naked singularity formation?

(or at least naked elliptic region?)

To be or not to be (physics)?

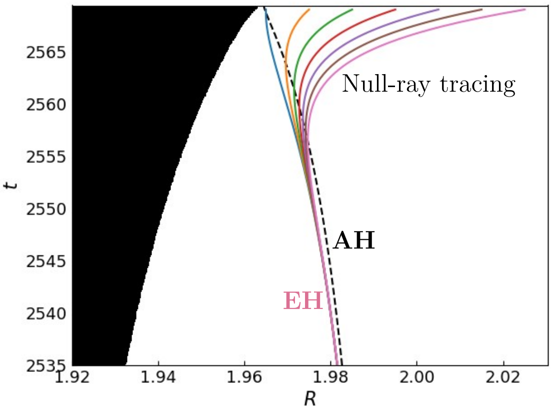




Good convergence up to the very last stages

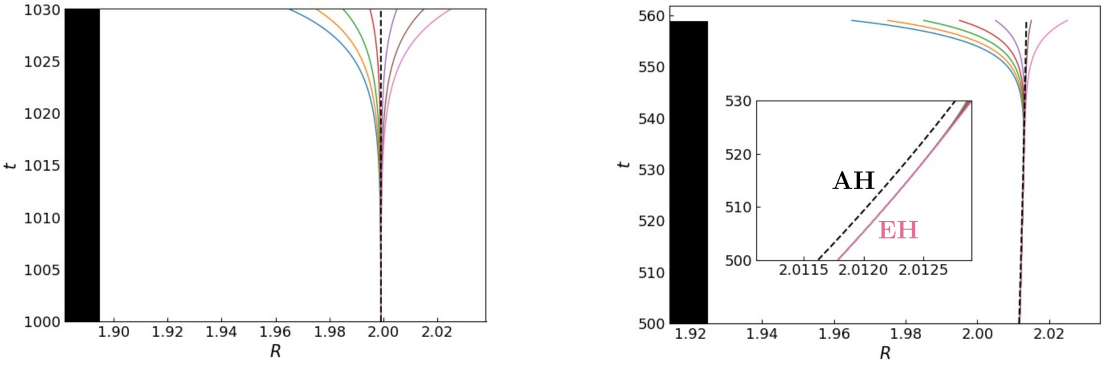
High-curvature region expands tracking the elliptic region

Event vs Apparent horizon



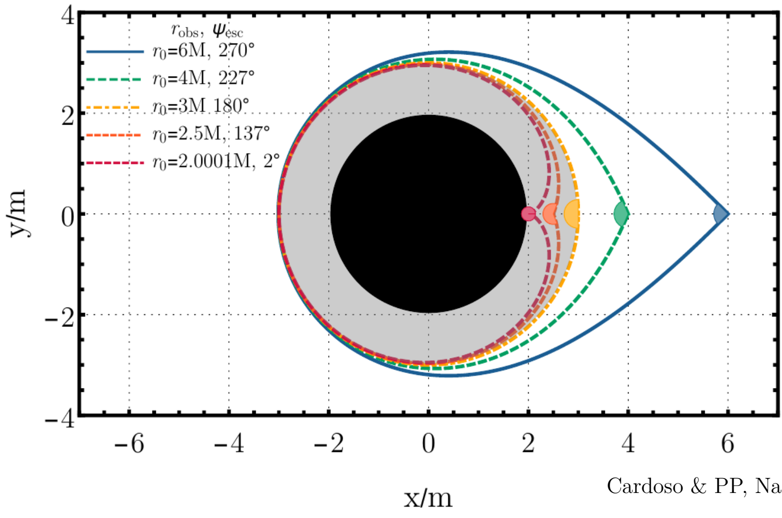
In EdGB the apparent horizon is **not** necessarily inside the event horizon

Also event horizon shrinks in time towards large curvature regions



Imaging the horizon?

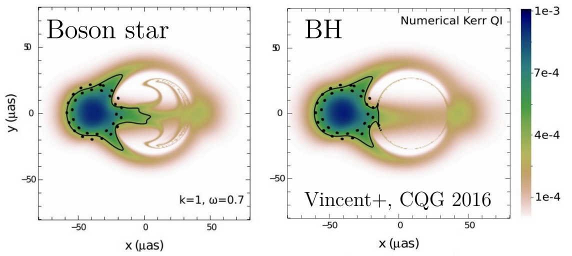
Escape angle ~ O(ε)



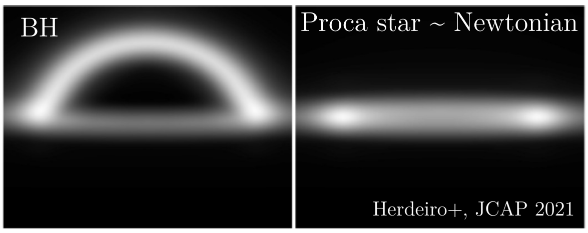
Cardoso & PP, Nature Astronomy (2017)

- EM tests when ε→0 are very challenging [Abramowicz+ (2012)]
- Existence of a light ring is a strong discriminator

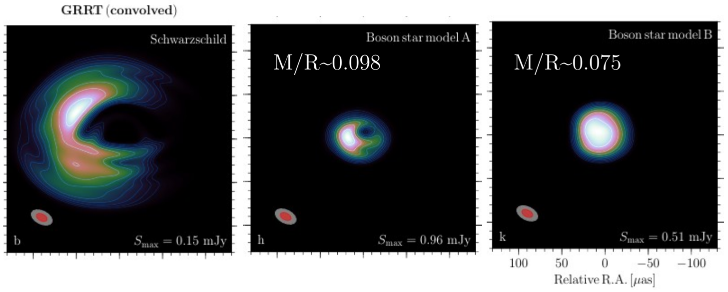
The imitation game



Vincent+, CQG 2016



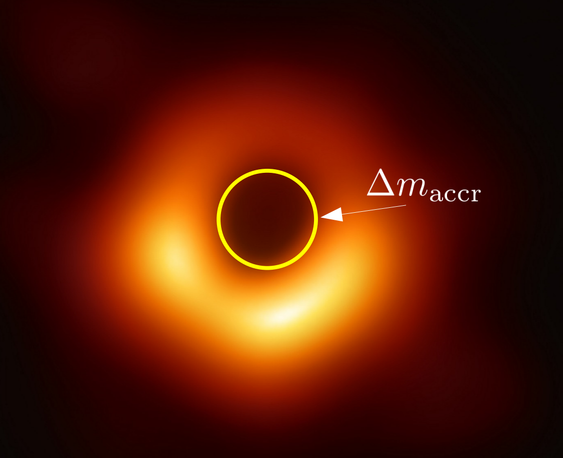
Herdeiro+, JCAP 2021



- Moderately compact ECOs distinguishable, especially if accreting [Olivares+ MNRAS 2020]
- More compact ECOs with light rings harder to distinguish [Cardoso, Duque, Foschi PRD 2021]
- Tests based on shadows can constrain ε~O(1) [EHT 2019, Cardoso-Pani 2019, Volkel+ 2020]
- Degeneracy with spin, distance, accretion model, emissivity?

How about accretion?

$$\frac{\Delta m_{\rm accr}}{M} \sim f_{\rm Edd}\frac{T_{\rm age}}{\tau_{\rm Salpeter}} \approx 3\times 10^{-2}\left(\frac{f_{\rm Edd}}{10^{-4}}\right)$$



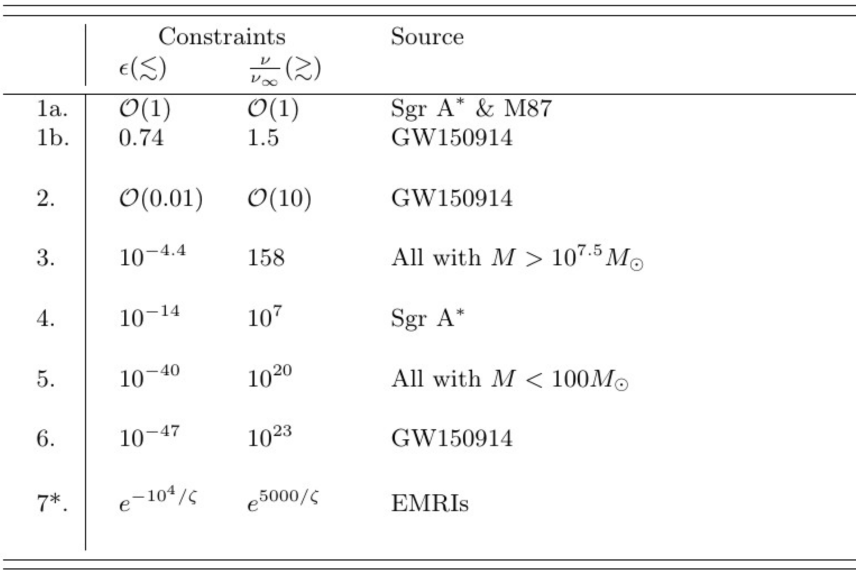
Assuming thermal equilibrium and hard surface yields much tighter constraints
[Broderick-Narayan CQG 2007]

$$\epsilon < 10^{-14}$$

This stringent constraint is evaded if the object has just a tiny absorption
[Carballo-Rubio+, Phys.Rev.D 98 12 124009 (2018)]

Quantifying the “unbearableness”

How well does the BH geometry describe the dark compact objects in our universe?



	Constraints		Source
	$\epsilon(\lesssim)$	$\frac{\nu}{\nu_\infty}(\gtrsim)$	
1a.	$\mathcal{O}(1)$	$\mathcal{O}(1)$	Sgr A* & M87
1b.	0.74	1.5	GW150914
2.	$\mathcal{O}(0.01)$	$\mathcal{O}(10)$	GW150914
3.	$10^{-4.4}$	158	All with $M > 10^{7.5} M_\odot$
4.	10^{-14}	10^7	Sgr A*
5.	10^{-40}	10^{20}	All with $M < 100 M_\odot$
6.	10^{-47}	10^{23}	GW150914
7*.	$e^{-10^4/\zeta}$	$e^{5000/\zeta}$	EMRIs

Cardoso & Pani, Living Rev Relativ (2019) 22:4
for description of the effects, caveats, and references

Searching for the absence

When testing *BHs we don't look for something, but for the* ***absence*** *thereof*

- Surface / internal structure
- Radiation *from* the object
- Hair / multipolar structure
- Tidal Love numbers

BHs are **unique** yet **simple**

- BHs in GR+SM described by 3 params → multiple consistency tests

Need models and framework to go beyond null tests

Extreme compact objects (ECOs)

- Several models/proposals
- Different levels of "robustness"
  - Equilibrium sols?
  - Stability?
  - Formation? Coalescence?
- Phenomenologically:
  - "Good" ECOs
  - "Bad" ECOs

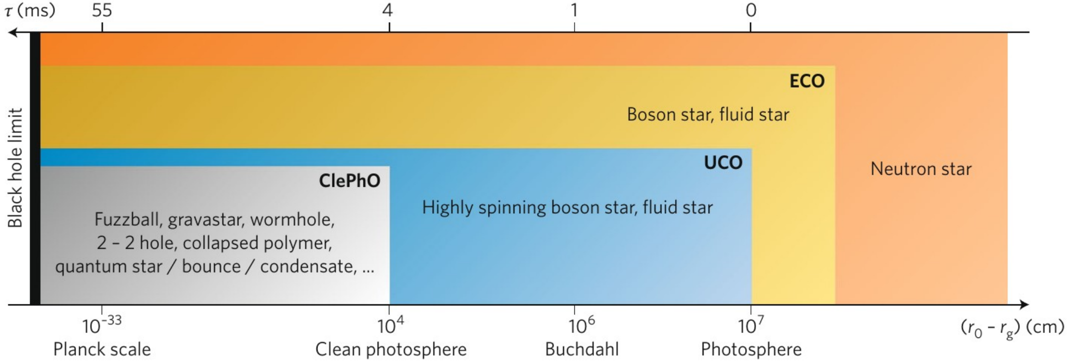
Phenomenology can be investigated even in absence of a first-principle framework

Cardoso & Pani, Living Rev Relativ (2019) 22:4

Model	Formation	Stability	EM signatures	GWs
Fluid stars	✓ [90]	✓ [85, 88, 109–113]	✓	✓ [85, 109, 112, 114]
Anisotropic stars	✗	✓ [115–117]	✓ [118–120]	✓ [115, 119, 120]
Boson stars & oscillatons	✓ [53, 54, 121–123]	✓ [86, 124–128]	✓ [91, 129, 130]	✓ [131–138]
Gravastars	✗	✓ [127, 139]	✓ [140–142]	∼ [112, 113, 135, 136, 138, 142]
AdS bubbles	✗	✓ [149]	∼ [149]	✗
Wormholes	✗	✓ [150–153]	✓ [154–157]	∼ [136, 138, 148]
Fuzzballs	✗	✗ (but see [158–161])	✗	∼ (but see [135, 148, 162]
Superspinars	✗	✓ [163, 164]	✗ (but see [165])	∼ [135, 148]
$2-2$ holes	✗	✗ (but see [166])	✗ (but see [166])	∼ [135, 148]
Collapsed polymers	✗ (but see [167, 168])	✓ [169]	✗ [168]	∼
Quantum bounces / Dark stars	✗ (but see [170, 171])	✗	✗	∼ [172]
Compact quantum objects*	✗ [73, 173, 174]	✗	✗	✓ [38]
Firewalls*	✗	✗	✗	∼ [135, 175]

Quantifying the shade of darkness

Cardoso & Pani, Living Rev Relativ (2019) 22:4



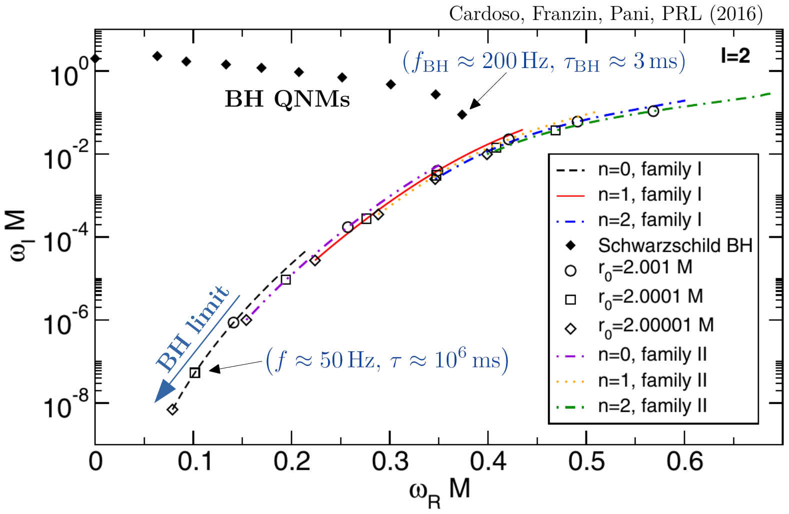
Two classes of ECOs (depending on the "*closeness*" parameter) $r_0 \equiv \frac{2GM}{c^2}(1+\epsilon)$

- "Neutron-star like" (e.g. boson stars) $\rightarrow \epsilon \sim \mathcal{O}(1)$
- "BH like" (e.g. fuzzballs, "quantum BHs") $\rightarrow \epsilon \sim 10^{-39} - 10^{-46}$

Goal: probe smaller and smaller values of ϵ
→ requires combination of targeted and agnostic searches

QNM spectrum of an UCO

Cardoso, Franzin, Pani, PRL (2016)



- Generic feature: low-frequency, long-lived QNMs in the BH limit

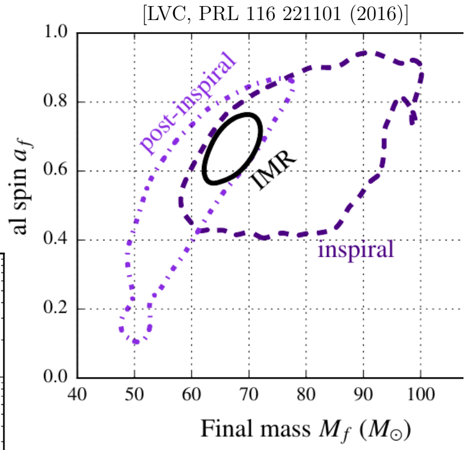
$$f_{\rm QNM} \sim |\log\epsilon|^{-1} \qquad\qquad \tau \sim |\log\epsilon|^{2l+3}$$

- QNM spectrum dramatically different → ringdown?

Ringdown and GW spectroscopy

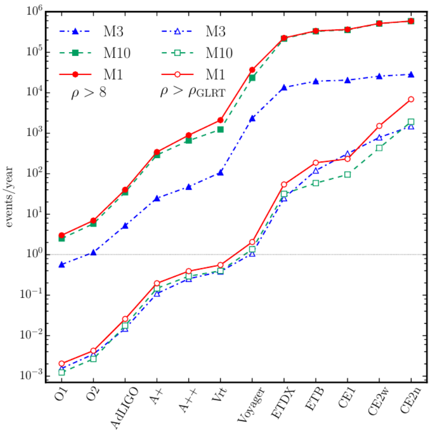
- Current detections consistent with Kerr, but low SNR in the ringdown (~1cycle/damping time)
- Ringdown tests possible with **3G** and **LISA** [Berti+, PRL. 117 101102 (2016)]

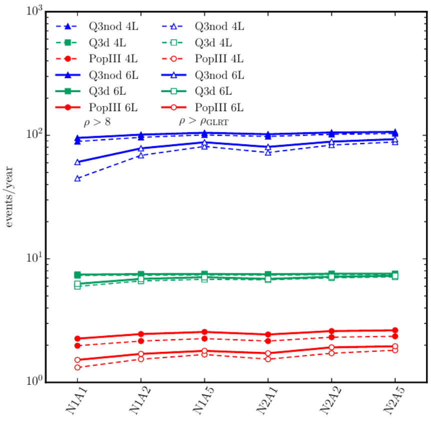
[LVC, PRL 116 221101 (2016)]



$$\mathrm{SNR}_{\rm ringdown} \propto \frac{M_{\rm BH}^{3/2}}{\sqrt{S_h(f)}}$$

Supermassive sources more than compensate
for smaller detector sensitivity

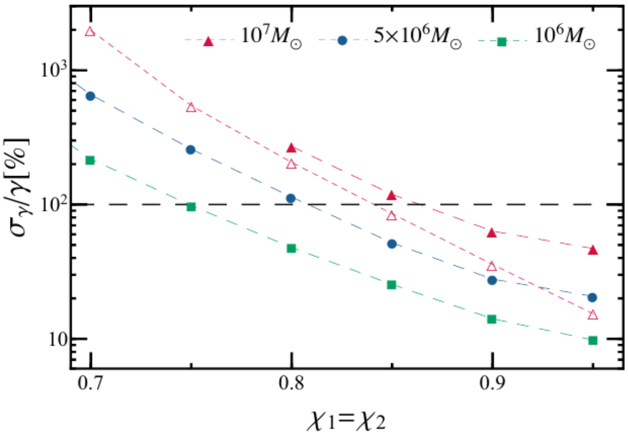




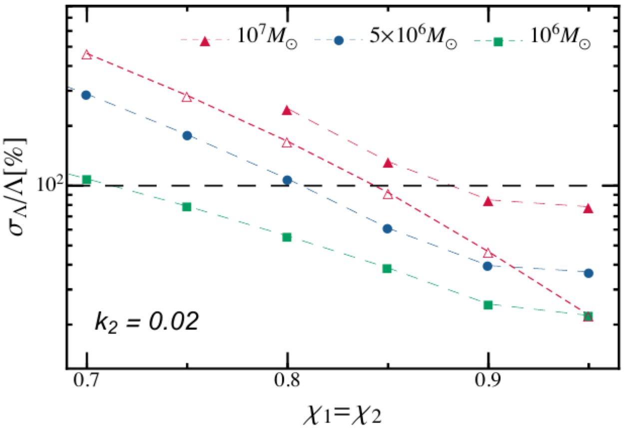
Probing BH quantum structures with LISA

Maselli, PP+; PRL 120 081101 (2018)

Absence of tidal heating



Tidal deformability



- Small corrections → requires spinning supermassive binaries @ 2-20 Gpc
- LISA binaries are golden sources to probe Planckian corrections!
- Tidal terms recently computed to 6.5PN [Abdelsalhin, Gualtieri, PP; 1805.01487]

I05

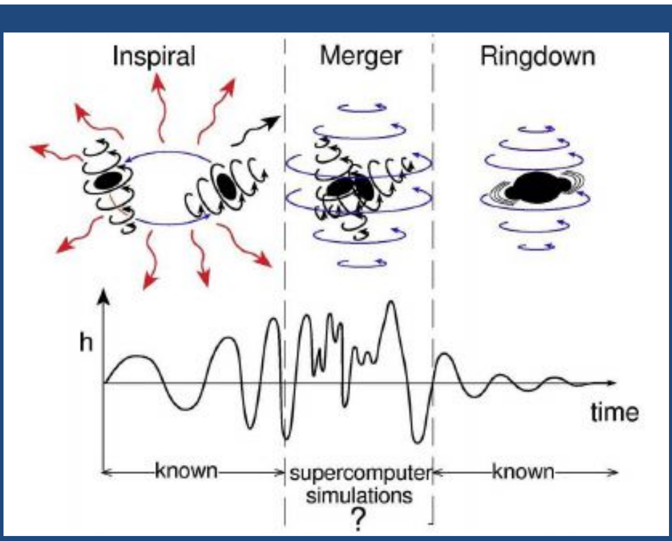
Gravitational waves, contrasting the 'standards' (BHs/NSs in GR) with `beyond standard scenarios (ECOs and/or extensions to GR)

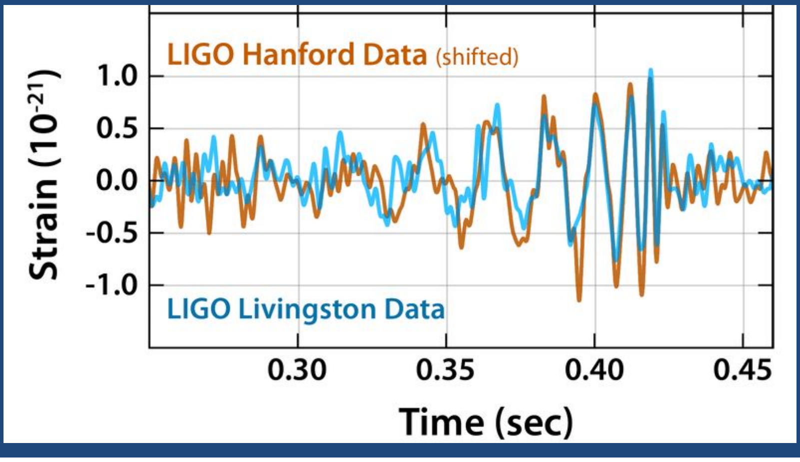
Luis Lehner
Perimeter Institute for Theoretical Physics

Outline

- Motivation
- Dissecting a gravitational wave train
- Beyond ‘phenomenology/wishful models’
  - Beyond BHs/NSs?
  - Beyond GR
- Analysis?

‘Ground rules’





- consistency with what we’ve seen even without modeling
- based on ‘solid/complete’ results
- Mindful of tests that can/will be carried out

Current types of tests

- *Null tests of GR* → consistency with GR vs not Do we know what to expect in GR completely?
- *Parameterized tests of GR* →build deviations in inspiral, merger, RD (pPN,pPE,RD,deformed match). But, stages are not independent
  - Go solely on each stage with smoking guns? (polarizations, dipolar radn, QNMs, echoes). Do we know what to expect?
- *Full waveforms* in specific theories. Can this be done self-consistently?

Current models BBHs

IMR <-> h('PN' + {EOB/PHENOM} + (QN)Ringdown)

- When to match?
  - I-to-M: 'lots of room' for when
  - M-to-R: lots of temptation for 'as early' as possible

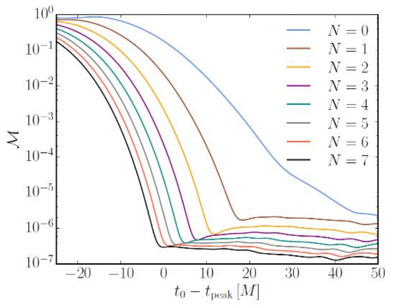
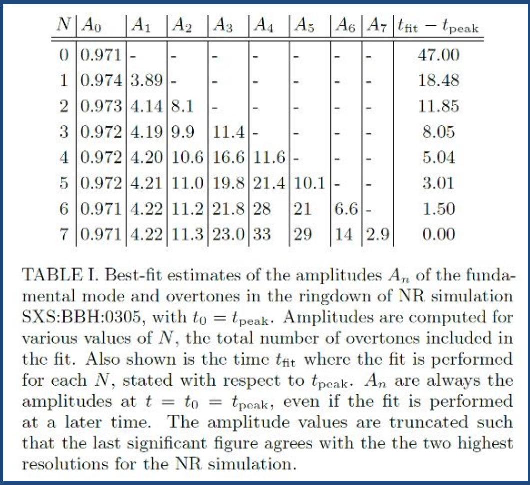


FIG. 1. Mismatches as a function of time for the eight models, each including up to N QNM overtones. The mismatch associated with each model at a given t_0 corresponds to the mismatch computed using Eq. (2), between the model and the NR waveform for $t \geq t_0$, where t_0 specifies the lower limit used in Eq. (3). Each additional overtone decreases the minimum achievable mismatch, with the minimum consistently shifting to earlier times.



N	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	$t_{\rm fit} - t_{\rm peak}$
0	0.971	-	-	-	-	-	-	-	47.00
1	0.974	3.89	-	-	-	-	-	-	18.48
2	0.973	4.14	8.1	-	-	-	-	-	11.85
3	0.972	4.19	9.9	11.4	-	-	-	-	8.05
4	0.972	4.20	10.6	16.6	11.6	-	-	-	5.04
5	0.972	4.21	11.0	19.8	21.4	10.1	-	-	3.01
6	0.971	4.22	11.2	21.8	28	21	6.6	-	1.50
7	0.971	4.22	11.3	23.0	33	29	14	2.9	0.00

TABLE I. Best-fit estimates of the amplitudes A_n of the fundamental mode and overtones in the ringdown of NR simulation SXS:BBH:0305, with $t_0 = t_{\rm peak}$. Amplitudes are computed for various values of N, the total number of overtones included in the fit. Also shown is the time $t_{\rm fit}$ where the fit is performed for each N, stated with respect to $t_{\rm peak}$. A_n are always the amplitudes at $t = t_0 = t_{\rm peak}$, even if the fit is performed at a later time. The amplitude values are truncated such that the last significant figure agrees with the the two highest resolutions for the NR simulation.

From Giesler etal *Phys.Rev.X* 9 (2019) 4, 041060

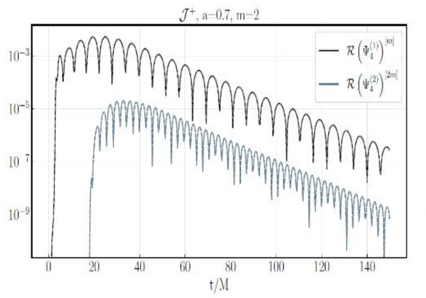
- **2nd order perturbation** for rotating black holes [Loutrel+ PRD'21; Ripley+ PRD'21, Pound '20]

- m=2 ⟶ m={0, 4} modes.

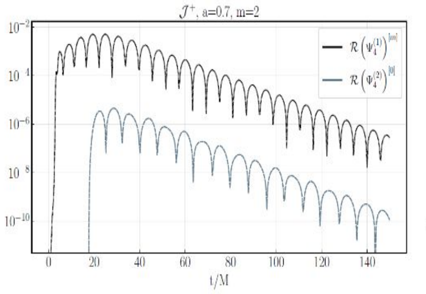
Of ~ 10^{-2} relative strength wrt to main one

- CAV: Stand alone analysis, ambiguity

  wrt to initial conditions
- BUT: basics of mechanism are robust



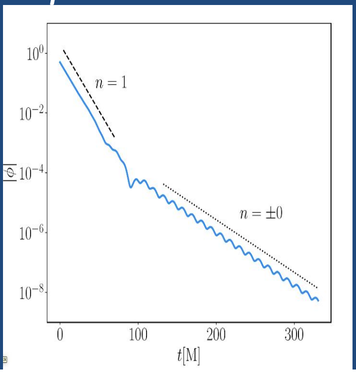
(a) $\mathcal{R}\psi_4^{(1)[2]}$, $\mathcal{R}\psi_4^{(2)[4]}$



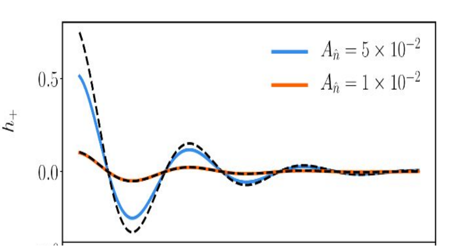
(c) $\mathcal{R}\psi_4^{(1)[2]}$, $\mathcal{R}\psi_4^{(2)[0]}$

‘Background’ impact

- Modes propagate on a changing background as BH accretes, and the time-scale of such change is not adiabatic [Sberna+ PRD 105 ‘22]
- *Secular effect*, mass/angular momentum changes -> a mode will be ‘projected’ onto new ones. ***AIME****: absorption induced mode excitation*



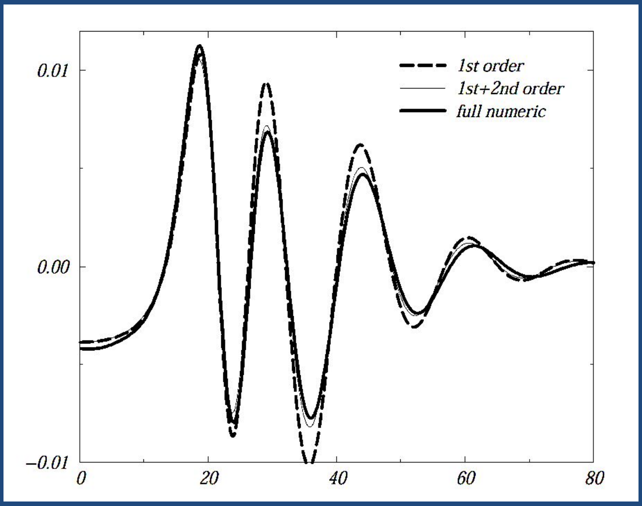
- CAV: sims and thorough comparison for a scalar field in asymptotic AdS spacetimes
- Mode influence assuming no time offset in comparison
- BUT: basic mechanism is clear, and will take place in AF scenarios.



[Sberna,Bosch-Gomez,Green,East,LL]

Warnings:

1. Overfitting/overinterpreting?
2. Subtle differences misinterpreted?

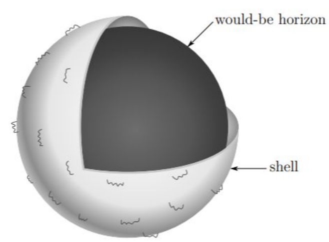


[Nicasio + PRD’99]

And echoes?

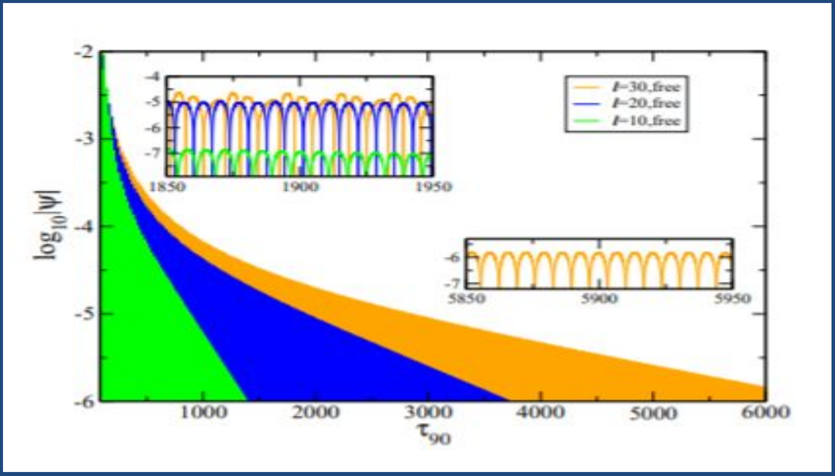
- Existence of ‘surface’ invoked for analysis. Reflection, or partial (total) absorption/re-emission.
  →largely, ‘wishful thinking’ calculations, as (with the exception of NSs/BSs) not sufficiently complete model to ‘ask the complete questions’ [e.g. Pani+]

- AdS black bubbles: spacetime is unstable to decay to an AdS spacetime. Heavily suppressed, but when matters ‘threatens’ to collapse and form a BH such nucleation is entropically enhanced.
- If an AdS bubble forms, matter can turn into *massless* open strings and a *shell* divides the regions
- [Danielsson,Dibitetto,Giri ‘17;
  Danielsson,LL,Pretorius ‘21]



AdS black bubbles

- ‘Echo’ behavior highly dependent on interior structure, ‘re-emission’ gets strongly modified by characteristic modes from the interior solution. Are we looking ‘in the right place’?--> it need not be a ‘copy’ of what went in

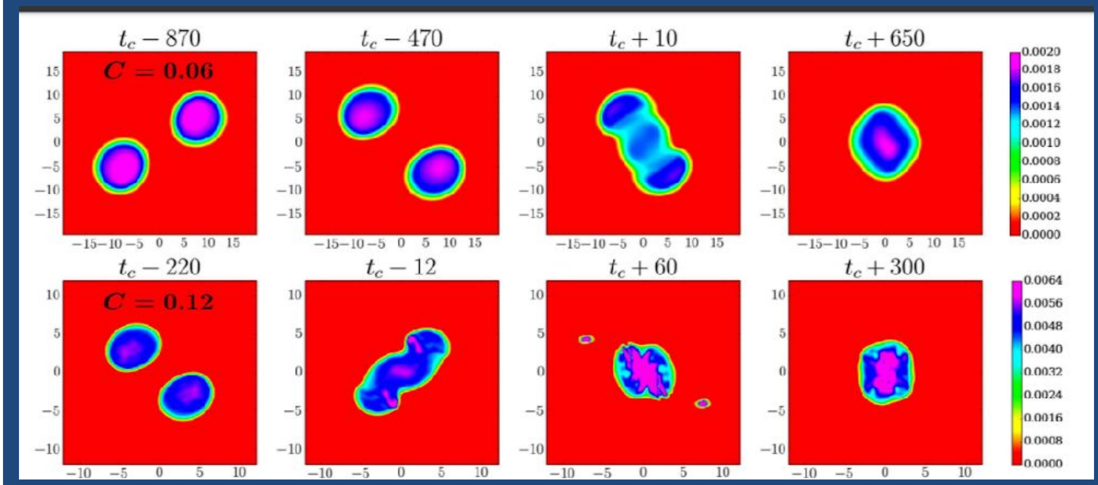


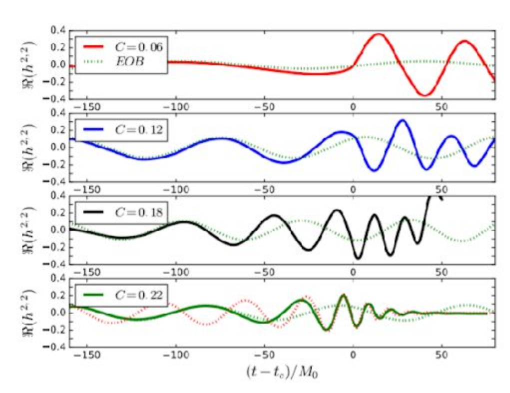
Coupling with scalars/(vectors)

- *Minimally coupled* ⟶ to produce 'ECO' : boson stars (also to describe DM), give hair, further physical effect: 'gravitational cooling'
- *Non-minimally coupled* ⟶ the above + modify gravity: dipole radiation
  - Spontaneous scalarization [D-EF]
  - But also: (i) induced scalarization: scalarized when not possible in isolation
  - (ii) dynamical scalarization: match scalar charge even with a mass ratio

---

Boson stars 'vs' BBHs/BNSs: cooling and solutions



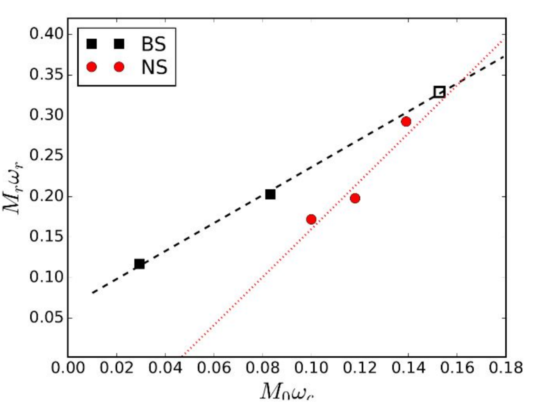


[Palenzuela+ '17]

- Inspiral: ‘similar’ to BBH (BNS) ⟶ tidal effects?
- Post-merger :

  ⟶ if BH, as in GR

  ⟶if a BS, no-angular momentum!

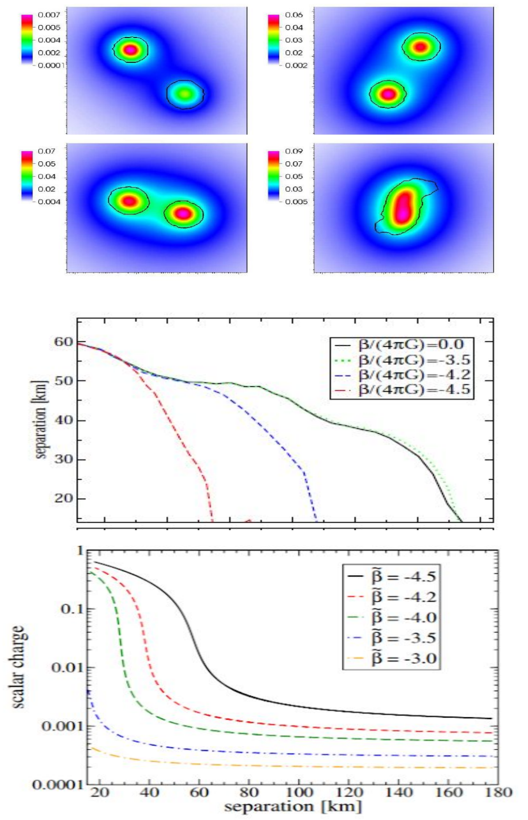


- Except for highly spinning BSs?
  - With suitable non-linear interactions? [East-Siemonsen]
  - multi-field/frequency bss [Sanchis-Gual etal]

Non-minimal coupling: Scalar-tensor gravity

- Induced/dynamical scalarization can endow further structure absent in isolation. And, even ‘take it away’ as merger approaches: ‘GR -> non GR -> GR’ . Thus, a non-monotonic behavior!

[Modeled: Sampson+’14,
Unmodeled: Edelman ‘22…]



Beyond GR? / standard compact objects?

Options?

- *Model Building:* specific theories built from key assumptions of new physics. E.g. Brans-Dicke, Horndenskii, CS, theories

- *Effective Field Theories (EFTs):* no 'new' degrees of freedom (as they are integrated out), and new phenomena arises through short scale interactions organized in higher derivatives

Recall GR is rich!, theorems of stability of Minkowski and singularity hints at a rich phenomenology.

Full IMR?

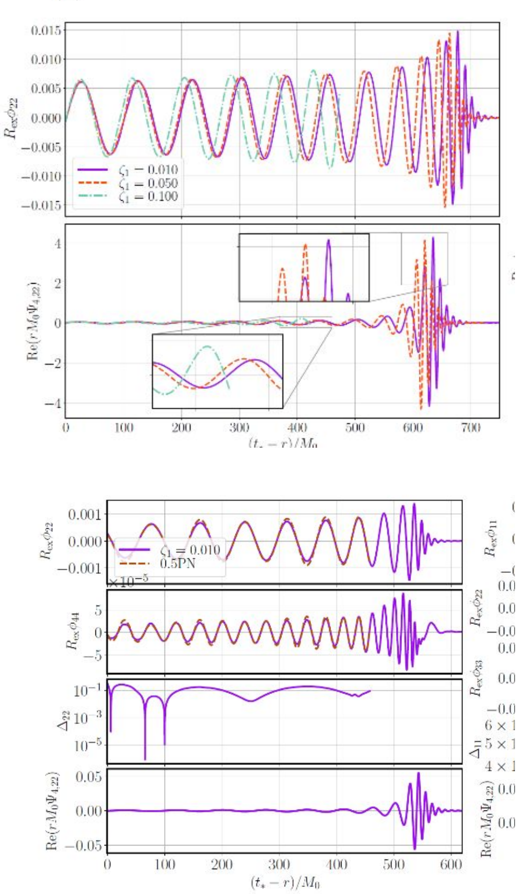
- Many 'interesting' theories: BHs different from those in GR, breaking some symmetries (e.g. Lorentz; parity violations…). Some BHs found, *are such solutions 'physical'? Are the theories viable?*

- 2nd order EOMs + 1 extra d.o.f → Horndenski family. Many can develop mathematical pathologies through evolution!

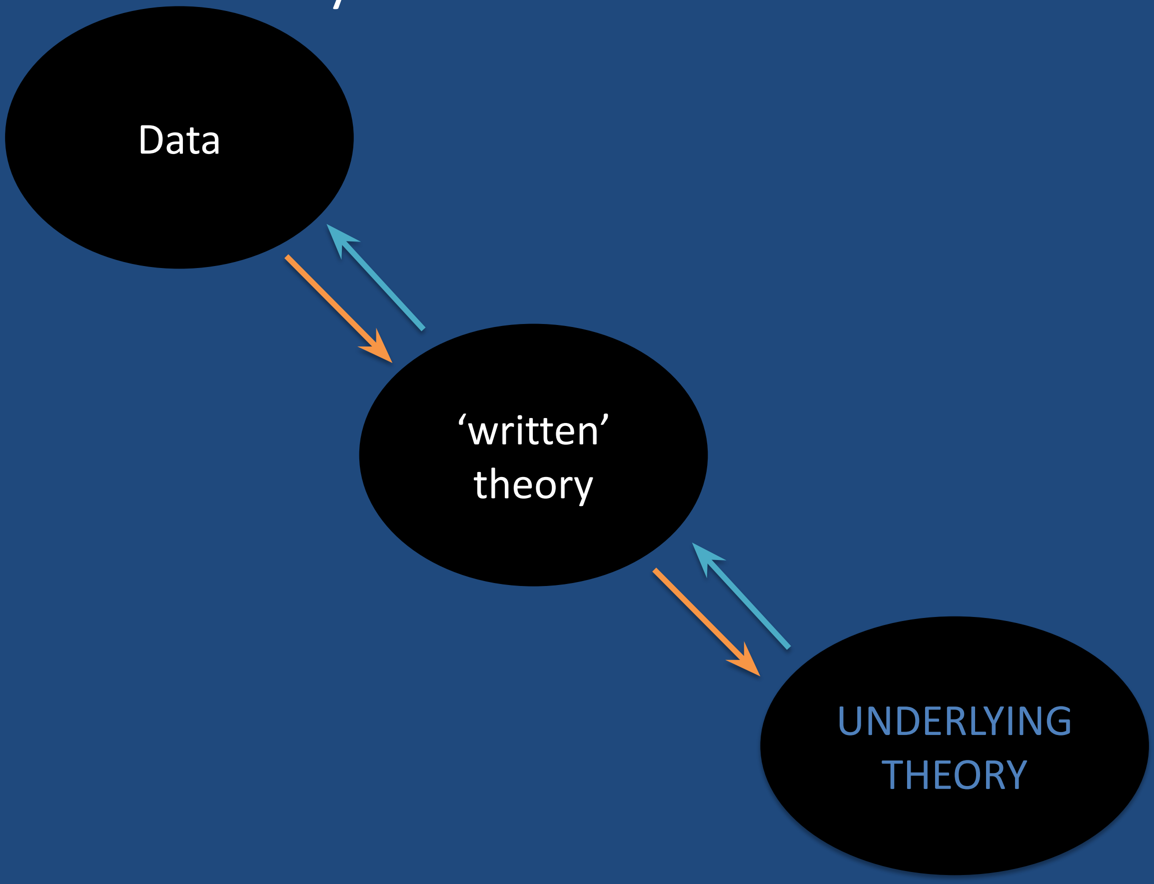
- EFT for gravity → higher derivatives: definite mathematical pathologies

Einstein Scalar Gauss Bonnet

- Full waveforms for sufficiently smooth scalar field profile and low couplings, breaking of hyperbolicity otherwise.
- At least close to merger, PN waveforms [Yagi+'12,Shiralilou+'21] dephase wrt to full solution, amplitude however is better [Corman+ '22,Areste Salo+'22]
- Scalar field enhancement at merger, 'faster' merger



- What one really wants….



Data

'written' theory

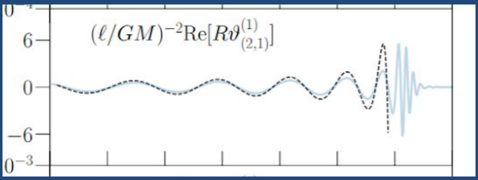
UNDERLYING THEORY

Strategies?

- ‘Iteration/perturbation’

$$B(g^*) = 0 \;\rightarrow B(g) = S(g^*)$$

  - Rinse and repeat: but during what time frame?
  - Perturbative hierarchy [e.g. Okounkova+ ‘17]



  - justified? can one guarantee the fidelity of the solution obtained?

- ‘Modification’

$$B(g) = F \, ; F_t = -\lambda(F - S(g))$$

  - Modify system of equations to ‘fix’ problems [Cayuso+ ‘17]
  - Introduces a new timescale λ, can one guarantee the fidelity of the solution obtained?

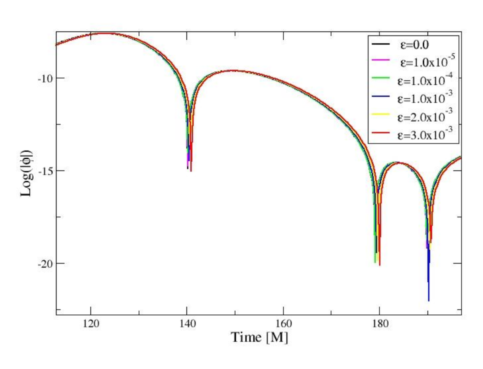
- Application [Cayuso R,LL]

$$S_{\rm eff} = \int d^4x \sqrt{-g}\, 2M_{\rm pl}^2 \left(R - \frac{\mathcal{C}^2}{\Lambda^6} - \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} - \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6} \right)$$

$$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta} R^{\alpha\beta\gamma\delta} \,, \quad \tilde{\mathcal{C}} \equiv R_{\alpha\beta\gamma\delta} \tilde{R}^{\alpha\beta\gamma\delta} \,,$$

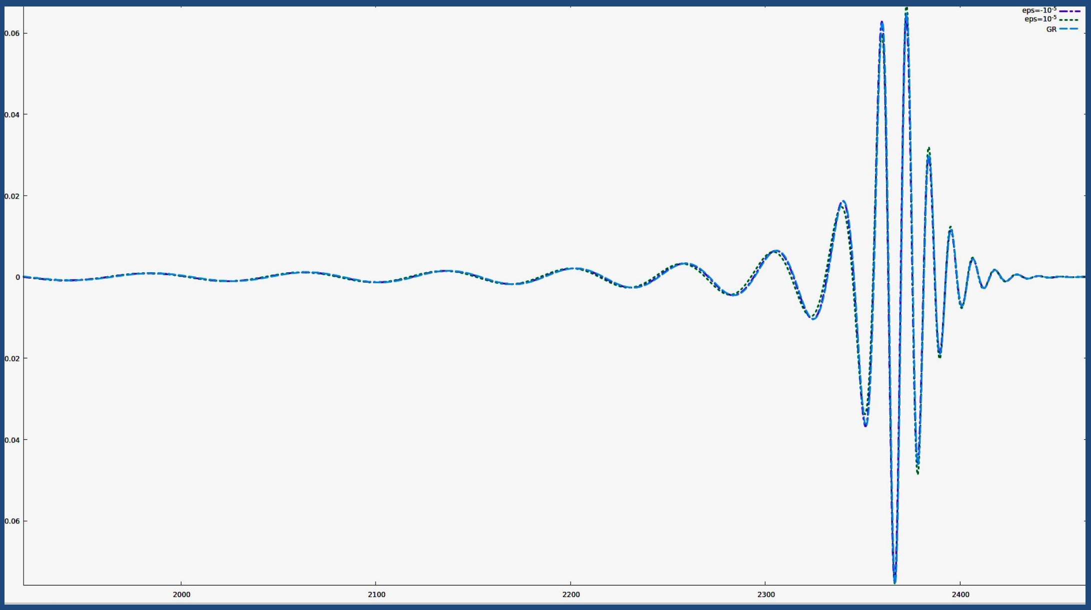
[Endlich,Gorbenko,Huang,Senatore]

EOMS -> G_{ab} [g/L^2] ~ F(g^3/L^8)



$$R_{\mu\nu} = \epsilon\left(4\hat{\mathcal{C}}\, C_\mu{}^{\alpha\beta\gamma}\, C_{\nu\alpha\beta\gamma} - \frac{3}{2}\hat{\mathcal{C}}^2\, g_{\mu\nu} + 8\, C_\mu{}^\alpha{}_\nu{}^\beta\, \nabla_\alpha\nabla_\beta\hat{\mathcal{C}}\right)\,,$$

$$\tau\,\mathcal{L}_n\hat{\mathcal{C}} - \sigma\,\nabla^2\hat{\mathcal{C}} = \mathcal{C} - \hat{\mathcal{C}}\,.$$

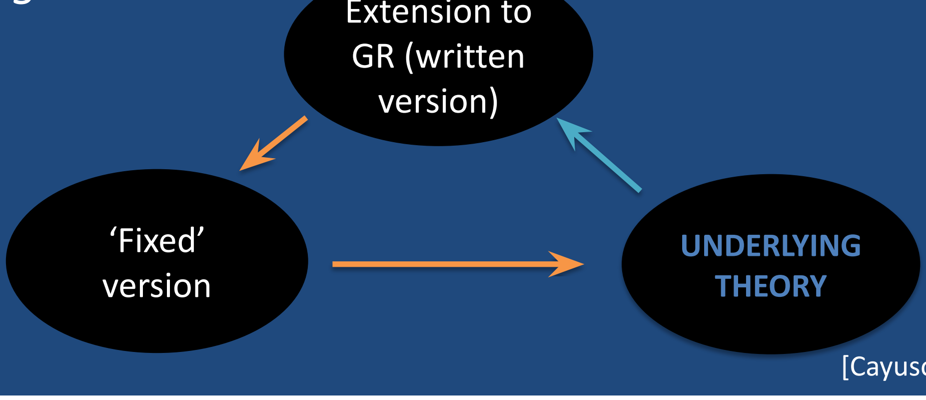


- Inspiral, small tidal effects. Delay/hasten merger depending on sign
- subtle impact on radiation characteristics (IMR)

[Cayuso,Franca,Figueras,LL in prep]

- *Option 1: delicate (& uncertain?). Option 2: fine but can it be justified? One could argue yes in 3+1 dimensions but not above*
  - (drawing from LIGO/VIRGO, fluid-gravity correspondence and specific ‘2nd order’ BH perturbation calculations) all methods are intrinsically relying on this!

There seems to be a way to avoid ‘not going to non-linear-land’ with (many) GR alternatives and face upcoming data


Extension to GR (written version)

‘Fixed’ version

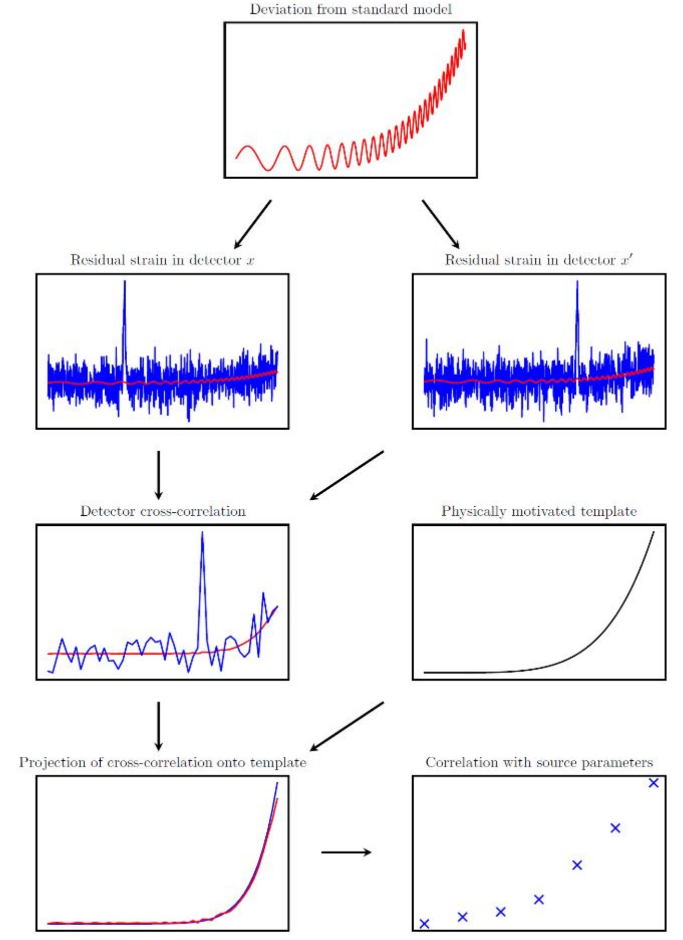
UNDERLYING THEORY

[Cayuso,Ortiz,LL ‘17]

Wrapping up

- Signals in GR, understood ‘reasonably well’ , though still corners under-explored [spins, mass ratio, eccentricity]
- Beyond GR/beyond BHs/NSs progressing, but why “such theory/such ECO”?
- Ultimately, searching for ‘unmodeled’ physics will play a prominent role, what to do?

- ‘agnostic’ analysis of signals/residual (e.g. bayeswave; coherent spline [Edelman+]...),
- cross-correlation of residuals: SCoRe [Dideron,Mukherjee,LL]



Final words

- Beyond ‘standards’ (GR + BH/NS) efforts pointing out possible ‘smoking gun’ features to search for. [e.g. post-merger BS, echoes, tidal effect and EFTs, scalarization and related phenomena,BH solns in other theories…]

- ‘Conservatively’, these are to be taken as motivations to design ‘next-generation’ of analysis strategies. Both in the context of single events, or collectively

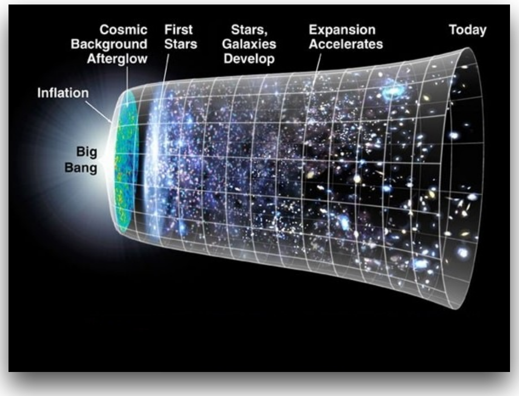
Testing the early universe with small-scale anisotropies

Ema Dimastrogiovanni
The University of Groningen

JGRG31- RESCEU - October 26th 2022

Talk based on papers in collaboration with:

Peter Adshead, Niayesh Afshordi, Matteo Fasiello, Tomohiro Fujita,
Marc Kamionkowski, Eugene Lim, Ameek Malhotra,
Daan Meerburg, Giorgio Orlando, Maresuke Shiraishi,
Gianmassimo Tasinato



Inflation predicts a stochastic gravitational wave background

- How does it look like?
- What info does it provide on inflation?
- How do we characterise it (and distinguish it from other SGWBs)?

— Frequency profile
— Chirality
— Non-Gaussianity
— **Anisotropies**

Stochastic background of gravitational waves

Cosmological sources:

* **Inflation**
* Reheating
* Phase transitions
* Cosmic strings
…

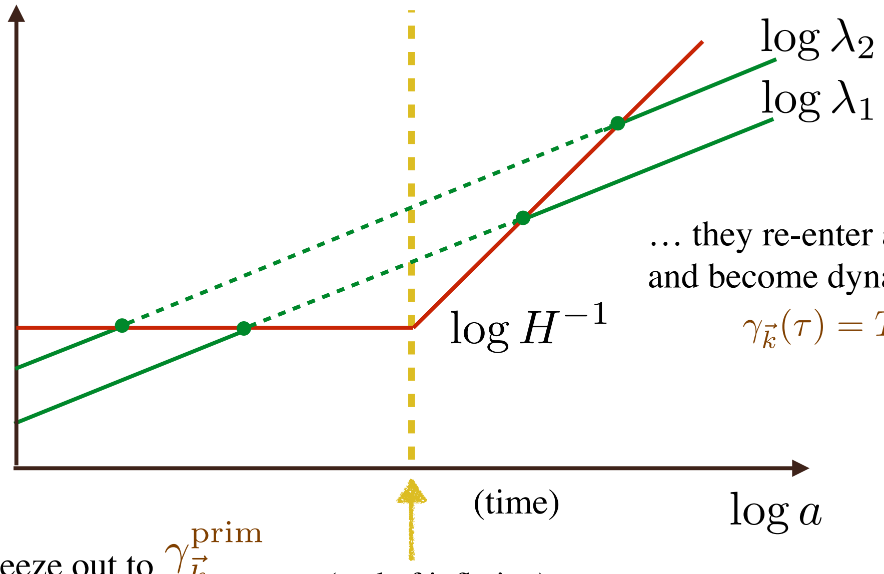
Astrophysical sources:

a stochastic gravitational wave background is expected, due e.g. to the superposition of signals from a large number of astrophysical sources (e.g. mergers of black holes, neutron stars,…)

Scales

wavenumber → e-folding → time of re-entry

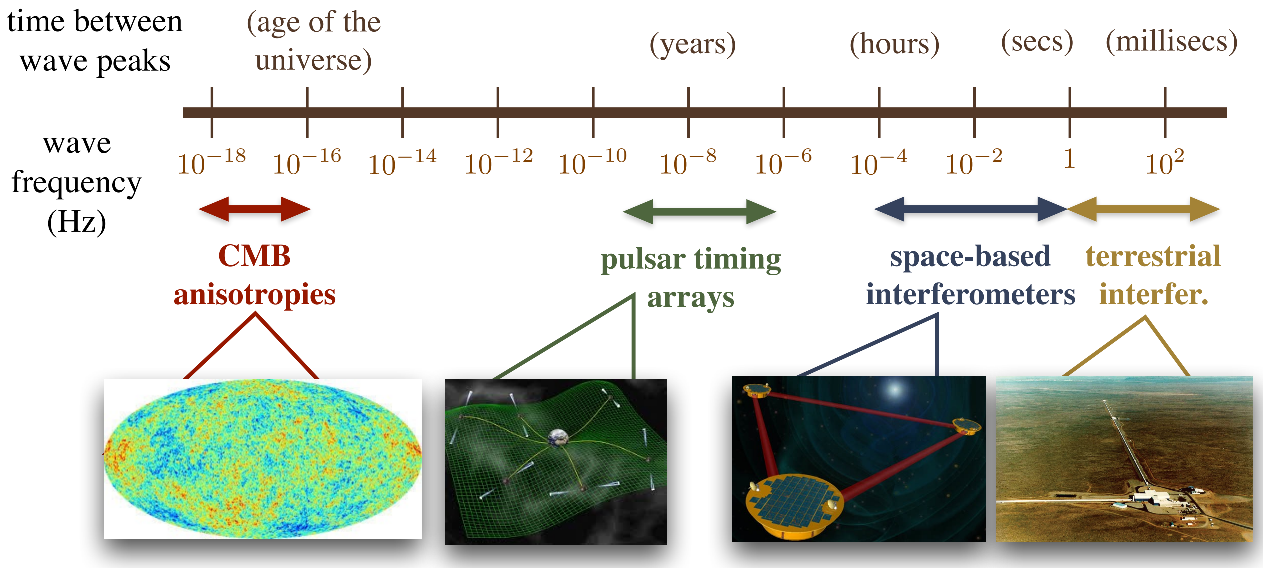
$k \sim f$ N_k



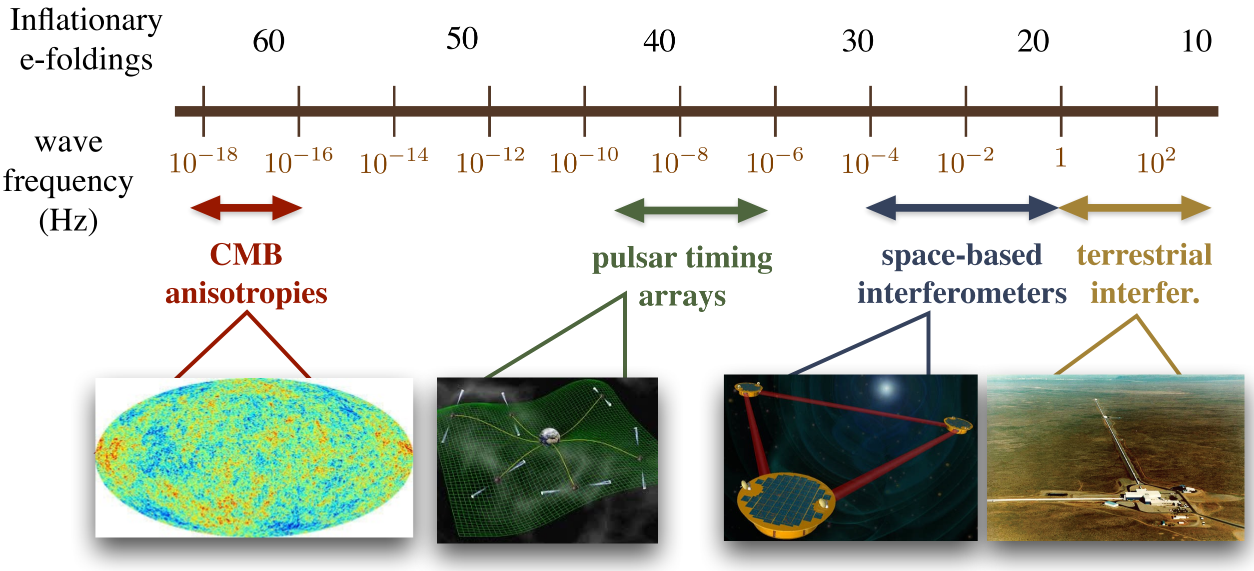
… they re-enter after inflation and become dynamical again $\gamma_{\vec{k}}(\tau) = T(\tau, k)\gamma_{\vec{k}}^{\rm prim}$

Perturbation modes leave horizon during inflation and freeze out to $\gamma_{\vec{k}}^{\rm prim}$

Scales — Experiments



Scales — Experiments



Inflationary e-foldings: 60, 50, 40, 30, 20, 10

wave frequency (Hz): 10^{-18}, 10^{-16}, 10^{-14}, 10^{-12}, 10^{-10}, 10^{-8}, 10^{-6}, 10^{-4}, 10^{-2}, 1, 10^{2}

CMB anisotropies

pulsar timing arrays

space-based interferometers

terrestrial interfer.

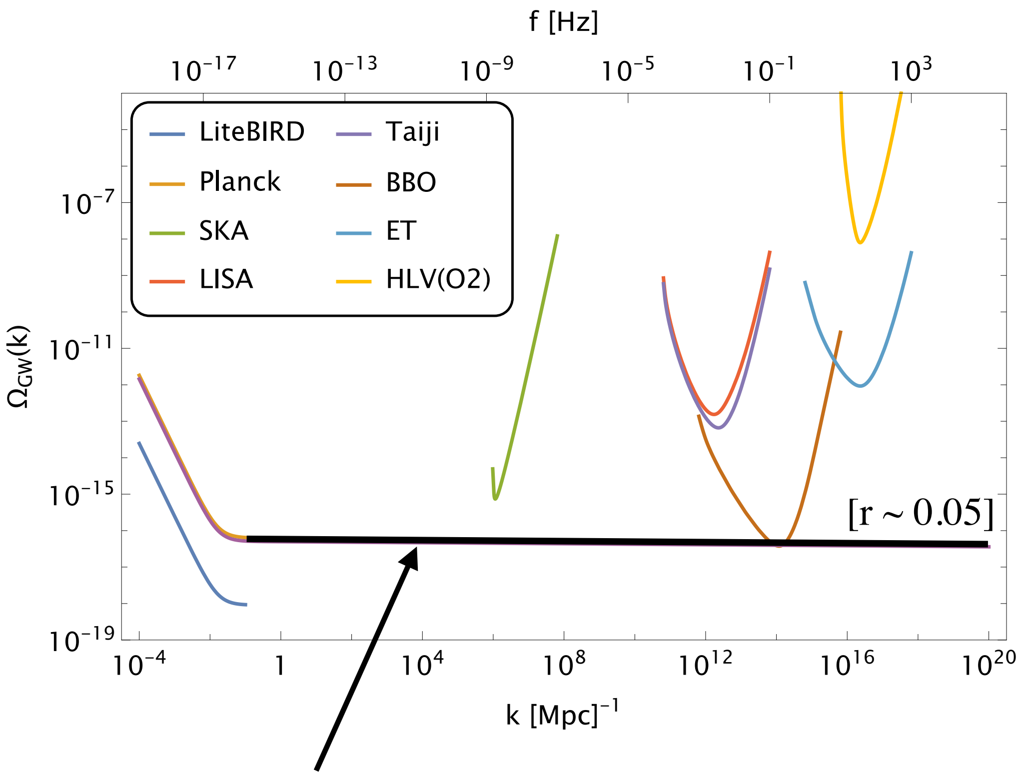
GW can tell us a whole lot about inflation: examples

- GW from the amplification of vacuum fluctuations

$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + k^2\gamma_{ij} = 0$$

Production of gravitons out of the vacuum
in an expanding universe!

Prediction and sensitivity limits



Standard SFSR would go undetected at small scales (**red tilt**)

Inflationary GW from vacuum fluctuations (SFSR)

- **Energy scale** of inflation: $V_{\rm inf}^{1/4} \simeq 10^{16}{\rm GeV}(r/0.01)^{1/4}$

  $H \simeq 2 \times 10^{13}{\rm GeV}(r/0.01)^{1/2}$

- Red **tilt**: $n_T \simeq -2\epsilon = -r/8$

- Non-**chiral**: $P_L = P_R$

- Nearly **Gaussian**: $f_{\rm NL} \ll 1$

GW can tell us a whole lot about inflation:

- GW from the amplification of vacuum fluctuations
- Generation of GW from additional fields during inflation

GW can tell us a whole lot about inflation: examples

- GW from the amplification of vacuum fluctuations
- Generation of GW from additional fields during inflation

$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + k^2\gamma_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

anisotropic stress-energy tensor

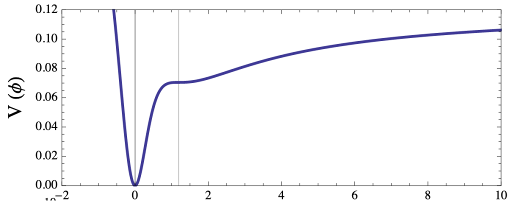
- Axion-gauge field models $\frac{\lambda\chi}{4f}F\tilde{F}$
  [Anber - Sorbo 2009, Cook - Sorbo 2011, Barnaby - Peloso 2011, Adshead - Wyman 2011, Maleknejad - Sheikh-Jabbari, 2011, ED - Fasiello - Tolley 2012, ED - Peloso 2012, Namba - ED - Peloso 2013, Adshead - Martinec -Wyman 2013, ED - Fasiello - Fujita 2016 Agrawal - Fujita - Komatsu 2017, Caldwell - Devulder 2017, Domcke et al. 2018, …]
- GW from extra non-minimally coupled spin-2 field (EFT formulation)
  [Bordin et al, 2018; …]
- Spectator fields with small sound speed
  $$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + k^2\gamma_{ij} = 16\pi G\,\Pi_{ij}^{TT} \propto \partial_i\sigma\partial_j\sigma$$
  [Biagetti, Fasiello, Riotto 2012, Biagetti, ED, Fasiello, Peloso 2014, …]
- . . .

GW can tell us a whole lot about inflation:

- GW from the amplification of vacuum fluctuations
- Generation of GW from additional fields during inflation
- Second order GW from peaks in the scalar power spectrum

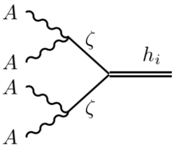
[Ananda et al - 2007, Baumann et al - 2007, …]

- Potentials with inflection points



[Garcia-Bellido, Morales 2017]

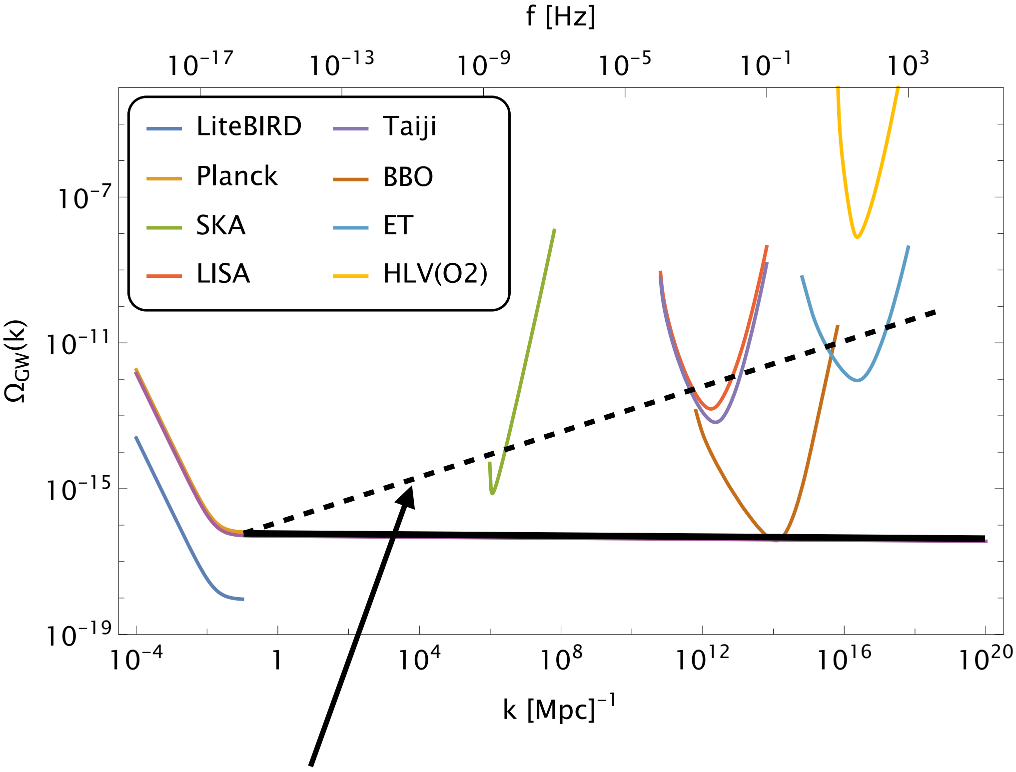
- Inflation with axion and gauge fields



[Garcia-Bellido, Peloso, Unal 2017]

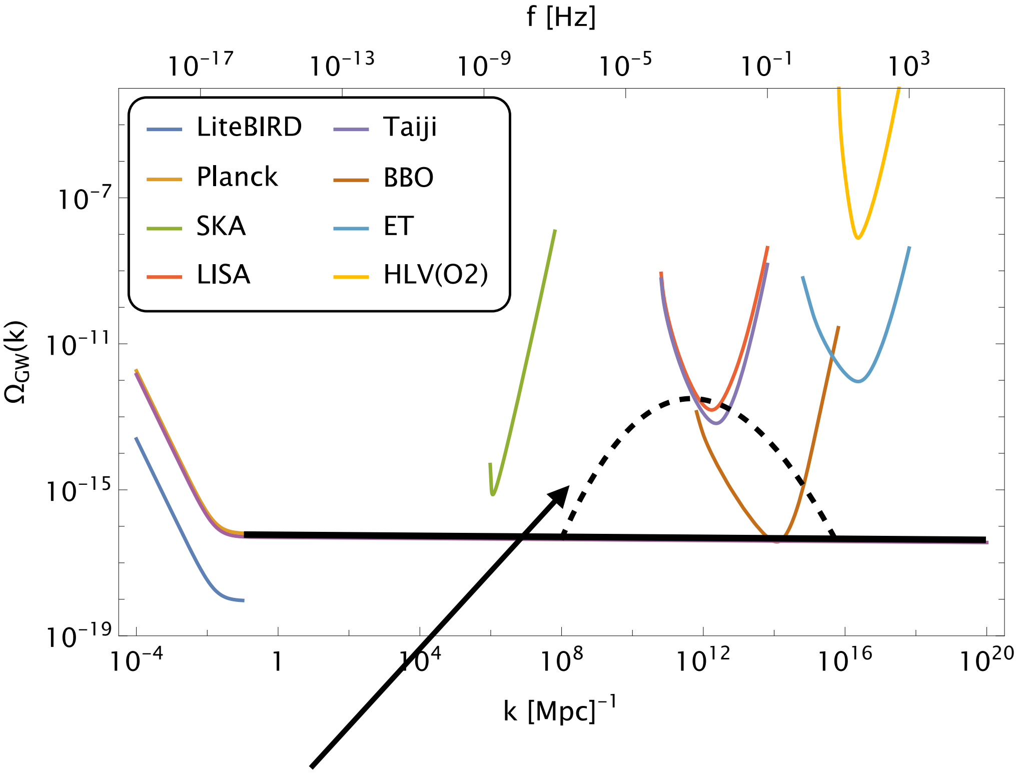
- . . .

Prediction and sensitivity limits



Power spectrum larger at small scales: e.g. **blue tilt**

Prediction and sensitivity limits



Power spectrum larger at small scales: e.g. **bump**

Axion-Gauge fields models: Chern-Simons coupling

$$g(\phi)\ F\ \tilde{F}$$

gauge-field strength and its dual

axion-like field

- naturally light inflaton
- support reheating
- mechanism for baryogenesis
- primordial black holes formation
- **sourced chiral gravitational waves**

[Freese - Frieman - Olinto 1990, Anber - Sorbo 2009, Cook - Sorbo 2011, Barnaby - Peloso 2011, Adshead - Wyman 2011, Maleknejad - Sheikh-Jabbari, 2011, ED - Fasiello - Tolley 2012, ED - Peloso 2012, Namba - ED - Peloso 2013, Adshead - Martinec -Wyman 2013, ED - Fasiello - Fujita 2016, Garcia-Bellido - Peloso - Unal 2016, Agrawal - Fujita - Komatsu 2017, Fujita - Namba - Obata 2018, Domcke - Mukaida 2018, Kaloper-Westphal 2021, Iarygina - Sfakianakis 2021, …]

Axion-Gauge fields models: SU(2)

[Adshead - Wyman 2011]

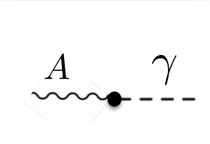
$$\mathcal{L} = \mathcal{L}_{\rm inflaton} - \overbrace{\underbrace{\frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}FF + \frac{\lambda\chi}{4f}F\tilde{F}}_{\mathcal{L}_{\rm spectator}}}$$

$$\mathcal{L}_{\rm inflaton} \downarrow P_{\gamma,\rm vacuum} \qquad \mathcal{L}_{\rm spectator} \rightarrow P_{\gamma,\rm sourced}$$

- Inflaton field dominates energy density of the universe
- Spectator sector contribution to curvature fluctuations negligible

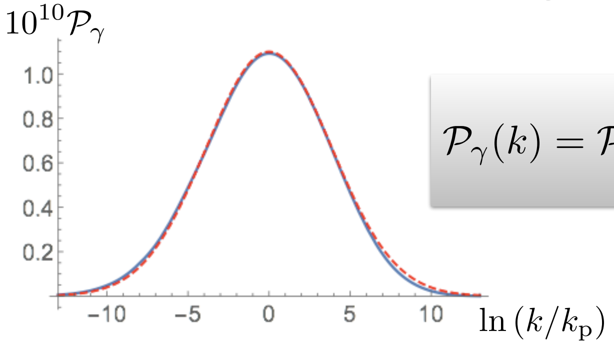
$$\boxed{\begin{aligned} A_0^a &= 0 \\ A_i^a &= aQ\delta_i^a \end{aligned}}$$ slow-roll background attractor solution

$$\boxed{\delta A_i^a = t_{ai} + \ldots}$$ TT-component



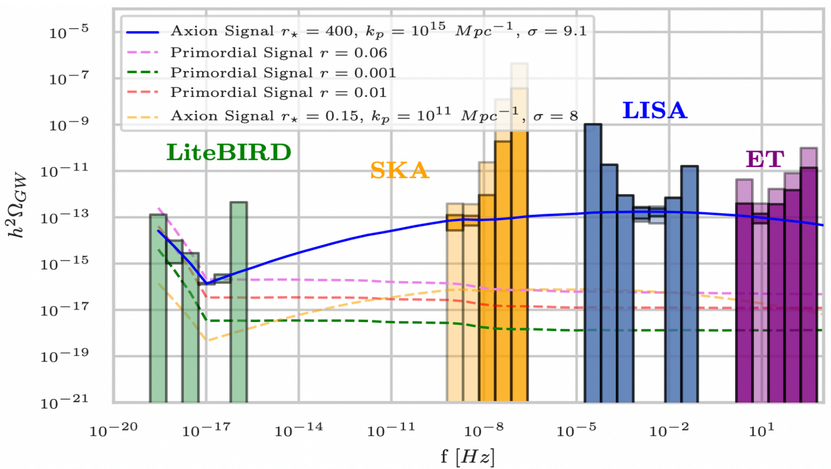
[ED-Fasiello-Fujita 2016]

Axion-Gauge fields models: SU(2)



$$\mathcal{P}_\gamma(k) = \mathcal{P}_{\gamma,\,L}^{(\rm sourced)}(k) = r_*\,\mathcal{P}_\zeta(k)e^{-\frac{1}{2\sigma^2}\ln^2(k/k_{\rm p})}$$

[ED-Fasiello-Fujita, 2016 — Thorne et al, 2017]



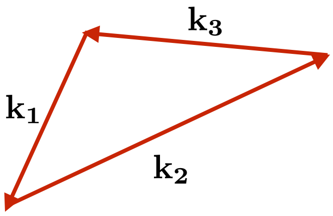
[Campeti et al, 2020]

Inflationary GW from vacuum fluctuations (SFSR)

- **Energy scale** of inflation: $V_{\rm inf}^{1/4} \simeq 10^{16}{\rm GeV}(r/0.01)^{1/4}$
  $H \simeq 2 \times 10^{13}{\rm GeV}(r/0.01)^{1/2}$
- Red **tilt**: $n_T \simeq -2\epsilon = -r/8$
- Non-**chiral**: $P_L = P_R$
- Nearly **Gaussian**: $f_{\rm NL} \ll 1$

Primordial non-Gaussianity and anisotropies in the GW energy density

Non-Gaussianity: beyond the power spectrum

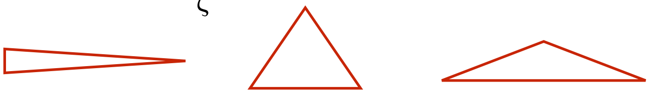


$$\langle \gamma^{\lambda_1}_{\mathbf{k_1}}\gamma^{\lambda_2}_{\mathbf{k_2}}\gamma^{\lambda_3}_{\mathbf{k_3}}\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})B_\gamma^{\lambda_1\lambda_2\lambda_3}(k_1,k_2,k_3)$$

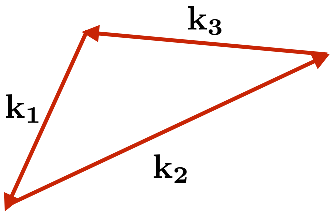
tensor bispectrum

amplitude: $f_{NL} = \dfrac{B}{P_\zeta^2}$

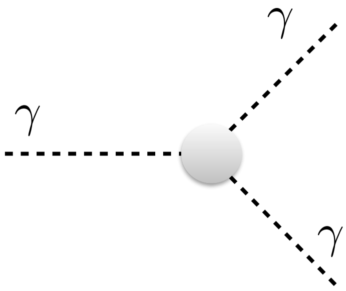
shape:



Tensor non-Gaussianity

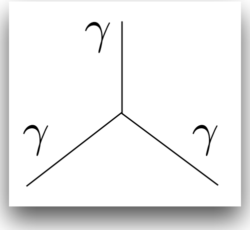


from interactions of the tensors with other fields or from self-interactions



Tensor non-Gaussianity

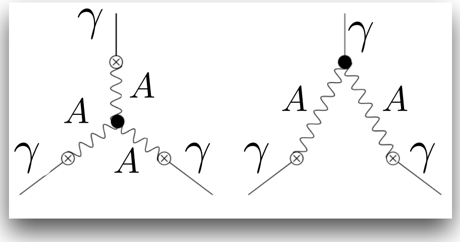
basic single-field inflation



$$f_{NL} = \mathcal{O}(r^2)$$

too small for detection

axion-gauge fields models



$$f_{NL} = r^2 \cdot \frac{25}{\Omega_A} \gtrsim \mathcal{O}(r^2 \cdot 10^6)$$

- detectable by upcoming CMB space missions

[Agrawal - Fujita - Komatsu 2017]

Non-Gaussianity (tensor / mixed): CMB constraints

- We do have constraints from CMB anisotropies and future B mode observations are expected to bring important improvements

Example: LiteBIRD-like experiment could detect an O(1) signal for

$f_{\rm NL}^{tss,{\rm sq}}$ $f_{\rm NL}^{ttt,{\rm sq}}$ $f_{\rm NL}^{ttt,{\rm eq}}$ **[Shiraishi, 2019]**

- The formalism for constraining non-Gaussianity with CMB anisotropies is by now well developed

Non-Gaussianity at interferometers

Shapiro time delay:

$$\gamma'' + 2\mathcal{H}\gamma' - [1 + (12/5)\zeta]\,\gamma_{,kk} = 0$$

GW propagating in FRW background
+ long-wavelength perturbations

$$\gamma_{ij} = A_{ij}\, e^{ik\tau + ik\cdot 2\int^{\tau} d\tau'\,\zeta[\tau',(\tau'-\tau_0)\hat{k}]}$$

GW from different directions
undergo different phase shift
due to intervening structure

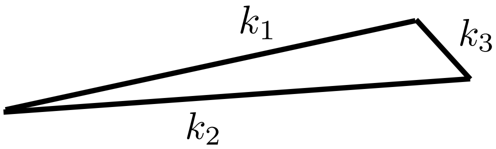
→ decorrelation → cannot measure bispectrum directly with interferometers

[Bartolo, De Luca, Franciolini, Lewis, Peloso, Riotto 2018]

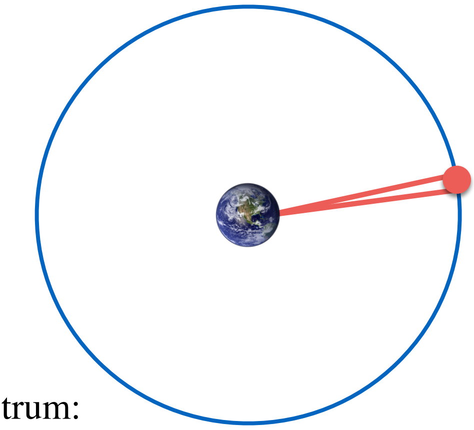
Note: signal measured by an interferometer arises from the superposition of signals from a large number of Hubble patches (CLT)

[Adshead, Lim 2009 — Caprini, Figueroa 2018 — Bartolo, De Luca, Franciolini, Lewis, Peloso, Riotto 2018]

Ultra squeezed non-Gaussianity



Correlation among two short-wavelength modes (e.g. interferometer scale) and 1 very long-wavelength mode: the latter has not undergone propagation!



Signals originate from the same patch!

How do we constrain this ultra-squeezed bispectrum:

Look for anisotropies in the SGWB!

$$\Omega_{\rm GW}(k) = \bar{\Omega}_{\rm GW}(k)\left[1 + \frac{1}{4\pi}\int d^2\hat{n}\,\delta_{\rm GW}(k,\hat{n})\right]$$

[ED, Fasiello, Tasinato, PRL 124(2020)6 061302]

SGWB anisotropies from primordial non-Gaussianity

$$\Omega_{\rm GW}(k) = \bar{\Omega}_{\rm GW}(k)\left[1 + \frac{1}{4\pi}\int d^2\hat{n}\,\delta_{\rm GW}(k,\hat{n})\right]$$

isotropic
component

anisotropic
component

$$\Omega_{\rm GW}(k) \equiv \frac{1}{\rho_{\rm cr}}\frac{d\rho_{\rm GW}}{d\ln k}$$

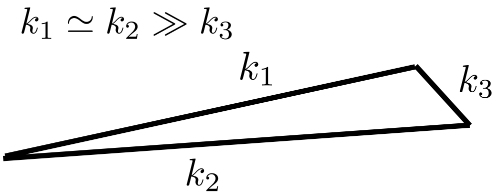
energy density spectrum
for the stochastic GW background

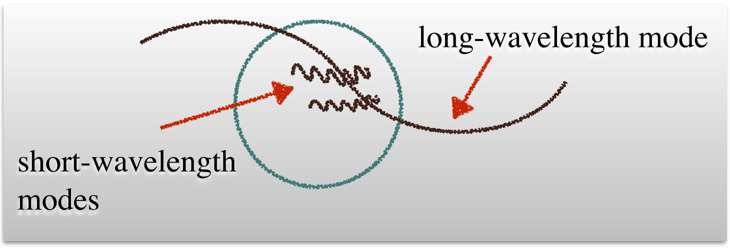
k= comoving wavenumber (proportional to the observed frequency)

$\hat{n}$= direction of incoming graviton

How do SGWB anisotropies relate to non-Gaussianity?

Soft limits and 'fossils'





long wavelength modes introduces a modulation
in the primordial power spectrum of the short wavelength modes

$$B^{F\gamma\gamma} \equiv \langle F_L \gamma_S \gamma_S \rangle' \sim F_L \cdot \langle \gamma_S \gamma_S \rangle'_{F_L}$$

$$\downarrow$$

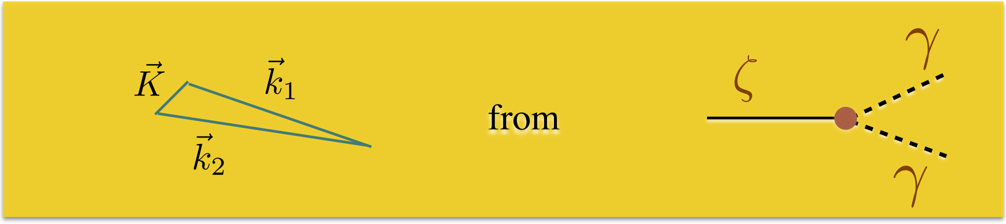
$$\delta\langle \gamma_S \gamma_S \rangle \equiv \langle \gamma_S \gamma_S \rangle_{F_L} \sim \frac{B^{F\gamma\gamma}}{P_F(k_3)} \cdot F_L^* = P_\gamma(k_1) \cdot \overset{f_{\rm NL}^{F\gamma\gamma}}{\boxed{\frac{B^{F\gamma\gamma}}{P_F(k_3) P_\gamma(k_1)}}} \cdot F_L^*$$

$$\downarrow$$

$$\boxed{\langle \gamma_S \gamma_S \rangle'_{\rm total} = P_\gamma(k_1) \left(1 + f_{\rm NL}^{F\gamma\gamma} \cdot F_L^*\right)}$$

[ED, Fasiello, Jeong, Kamionkowski - 2014, ED, Fasiello, Kamionkowski - 2015, …]

Soft limits and fossils



$$\downarrow$$

$$\boxed{\delta_{\rm GW}(k, \hat{n}) = \int \frac{d^3 q}{(2\pi)^3} e^{-id\hat{n}\cdot\mathbf{q}} \zeta(\mathbf{q}) F_{\rm NL}^{\rm stt}(\mathbf{k}, \mathbf{q})}$$

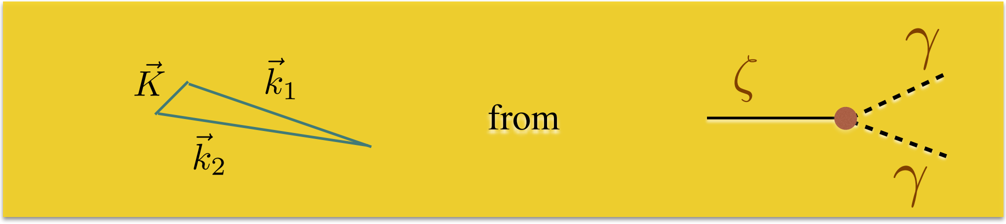
large scale variation large scale variations in the energy density of GW

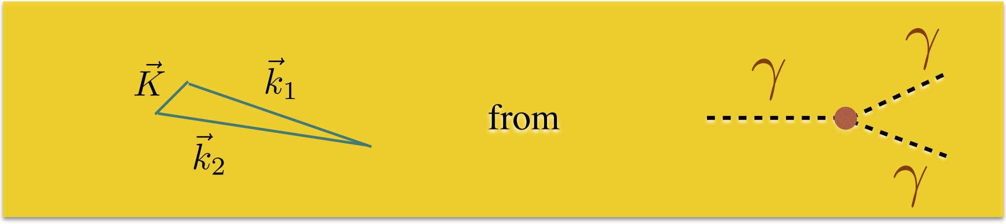
$$\mathbf{d} = -(\eta_0 - \eta_{\rm in})\hat{n}$$

$$\Omega_{\rm GW}(k) = \bar{\Omega}_{\rm GW}(k) \left[1 + \frac{1}{4\pi} \int d^2\hat{n}\, \delta_{\rm GW}(k, \hat{n})\right]$$

[ED, Fasiello, Tasinato, PRL 124(2020)6 061302]

Soft limits and fossils





[ED, Fasiello, Tasinato, PRL 124(2020)6 061302]

for derivation with in-in formalism and applications:
see: **[ED, Fasiello, Pinol, 2022]**

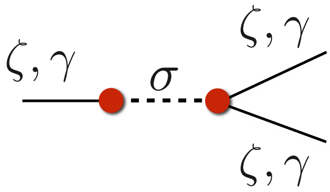
Soft limits in inflation

- ***Extra*** *fields* / superhorizon ***evolution***

  [Chen - Wang 2009, Baumann - Green 2011, Chen et al 2013,
  ED - Fasiello - Kamionkowski 2015, …]

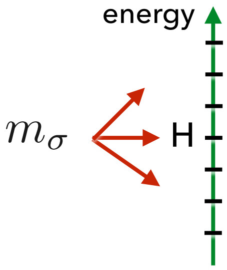
Soft limits in inflation

- ***Extra** fields*



Soft limits reveal (extra) fields mediating inflaton or graviton interactions

squeezed bispectrum delivers
info on mass spectrum!!!



Soft limits in inflation

- ***Extra** fields* / superhorizon ***evolution***

  [Chen - Wang 2009, Baumann - Green 2011, Chen et al 2013, ED - Fasiello - Kamionkowski 2015, …]

- ***Non-Bunch Davies*** initial states

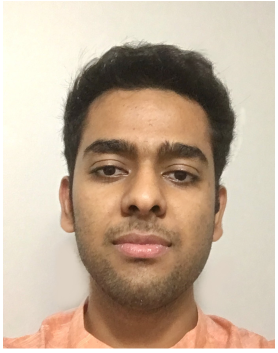
  [Holman - Tolley 2007, Ganc - Komatsu 2012, Brahma - Nelson - Shandera 2013, …]

- ***Broken space diffs***
  (e.g. space-dependent background)

  [Endlich et al. 2013, ED - Fasiello - Jeong - Kamionkowski 2014, Celoria - Comelli - Pilo - Rollo 2021…]

Ideal probe for (extra) fields, pre-inflationary dynamics, (non-standard) symmetry patterns

SGWB anisotropies from primordial non-Gaussianity



- Typical amplitude of these anisotropies:

$$\delta^{\rm tss}_{\rm GW} \sim F^{\rm tss}_{\rm NL}\sqrt{A_{\rm S}}$$

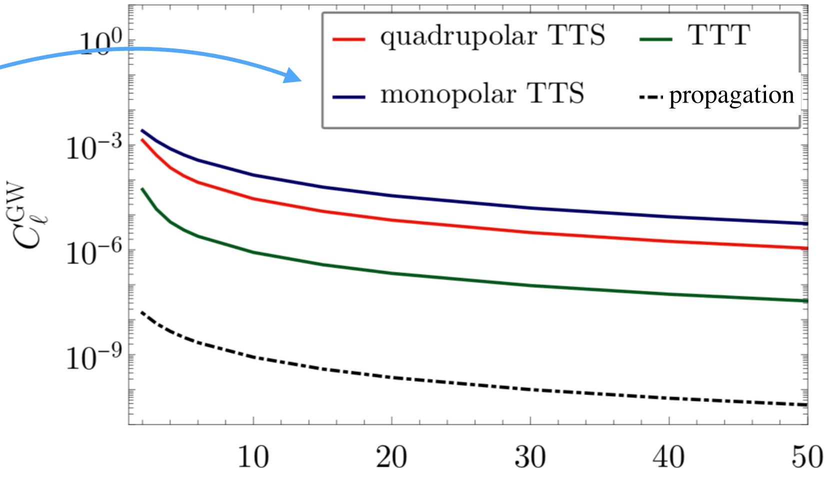
$$\delta^{\rm ttt}_{\rm GW} \sim F^{\rm ttt}_{\rm NL}\sqrt{r\,A_{\rm S}}$$

scalar power spectrum amplitude at CMB scales

tensor-to-scalar ratio

angular dependence of $F_{\rm NL}(\mathbf{k},\mathbf{q})$

(scale-invariant case)

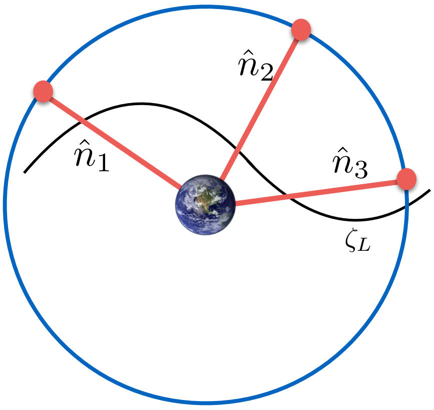


$\langle \delta_{{\rm GW},\ell_1 m_1}\delta_{{\rm GW},\ell_2 m_2}\rangle$

[Malhotra, ED, Fasiello, Shiraishi 2020 - ED, Fasiello, Malhotra, Meerburg, Orlando 2021]

Anisotropies from propagation

GW propagate through the perturbed universe ⟶ subject to Sachs-Wolfe / integrated Sachs-Wolfe …, just like CMB photons



Large-scales: SW dominates

$$\boxed{\frac{\delta f(\hat{n})}{f} = \frac{1}{5}\left[\zeta_{L({\rm today})} - \zeta_L(\hat{n}\cdot\eta_0)\right]}$$

Gravitational redshift/blueshift of gravitons

[Alba - Maldacena, 2015]

$$\zeta_L(\hat{n}_1\cdot\eta_0) \neq \zeta_L(\hat{n}_2\cdot\eta_0)$$

↓

Direction-dependent frequency shift

↓

Anisotropy in the GW energy density $\boxed{\delta_{\rm GW} \sim \left(\frac{\partial \ln\Omega_{\rm GW}}{\partial \ln k}\right)\zeta_{\rm L}}$

↓

$\delta_{\rm GW} \simeq \mathcal{O}(1)\,\zeta_{\rm L} \simeq 10^{-5}$ (for SFSR Inflation)

[See Contaldi, 2017- Bartolo et al 2019 - for full Boltzmann treatment; see also: Pitrou et al, 2020]

Boltzmann treatment for gravitational waves

FRLW in Poisson gauge: $$ds^2 = a^2(\eta)\left[-e^{2\Phi}d\eta^2 + (e^{-2\Psi}\delta_{ij} + \chi_{ij})dx^i dx^j\right]$$

Boltzmann equation for
the distribution function of gravitons
($\delta_{\rm GW} \propto \Gamma$)

$$\Gamma(\eta_0, \vec{x}_0, \hat{n}, q) = \underbrace{\Gamma(\eta_{\rm i}, \vec{x}_i, q)}_{\Gamma_I} + \underbrace{\Phi(\eta_{\rm i}, \vec{x}_i) + \int_{\eta_{\rm i}}^{\eta_0} d\eta(\Phi' + \Psi')}_{\Gamma_S}$$

Initial perturbations
(analogous to CMB
intrinsic fluctuations + …)

From propagation in the
inhomogeneous universe
(SW + ISW)

$$\vec{x}_i = \vec{x}_0 - (\eta_0 - \eta_i)\hat{n}$$

Time and position
of the observer

Time of emission

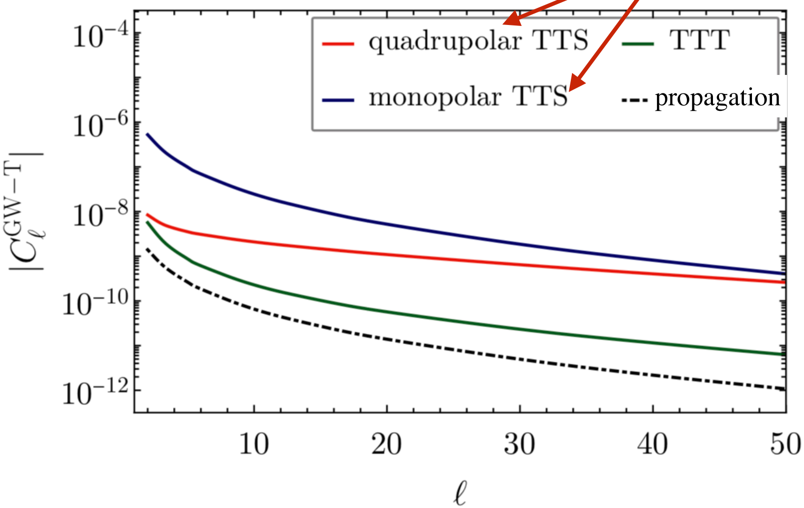
[Bartolo et al 2019]

Cross-correlations of GW and CMB anisotropies

$$\delta_{\rm GW}^{\rm propagation} \sim \zeta_L$$

$$\delta_{\rm GW}^{\rm stt} \sim F_{\rm NL}^{\rm stt} \cdot \zeta_L$$

$$\left.\begin{array}{l} \delta_{\rm GW}^{\rm stt} \sim F_{\rm NL}^{\rm stt} \cdot \zeta_L \\ \dfrac{\Delta T}{T} \sim \zeta_L \end{array}\right\} \; C_\ell^{\rm GW\text{-}T} \sim F_{\rm NL}^{\rm stt} \cdot C_\ell^{TT}$$



Different multipole scaling

$$\propto \frac{1}{\ell^2} \text{ vs. } \frac{1}{\ell^{1/2}}$$

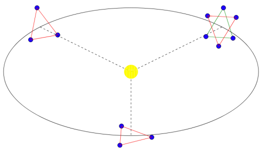
[Adshead, Afshordi, ED, Fasiello, Lim, Tasinato 2020
Malhotra, ED, Fasiello, Shiraishi 2020
ED, Fasiello, Malhotra, Meerburg, Orlando 2021]

Projected constraints on $F_{\rm NL}^{\rm tss}$

$$F_{ij} = \sum_{XY} \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} \frac{\partial C_\ell^X}{\partial \theta_i} \left(\mathcal{C}_\ell^{XY}\right)^{-1} \frac{\partial C_\ell^Y}{\partial \theta_j} \qquad X, Y = \{\text{TT,GW,GW-T}\}$$

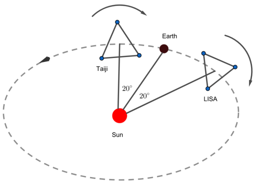
$$\mathscr{C}_\ell = \frac{2}{2\ell+1} \begin{bmatrix} (C_\ell^{\rm TT})^2 & (C_\ell^{\rm GW-T})^2 & C_\ell^{\rm TT} C_\ell^{\rm GW-T} \\ (C_\ell^{\rm GW-T})^2 & (C_\ell^{\rm GW})^2 & C_\ell^{\rm GW} C_\ell^{\rm GW-T} \\ C_\ell^{\rm TT} C_\ell^{\rm GW-T} & C_\ell^{\rm GW} C_\ell^{\rm GW-T} & \frac{1}{2}(C_\ell^{\rm GW-T})^2 + \frac{1}{2} C_\ell^{\rm TT} C_\ell^{\rm GW} \end{bmatrix}$$

- BBO: 4 LISA-like constellations



[Crowder - Cornish, 2005]

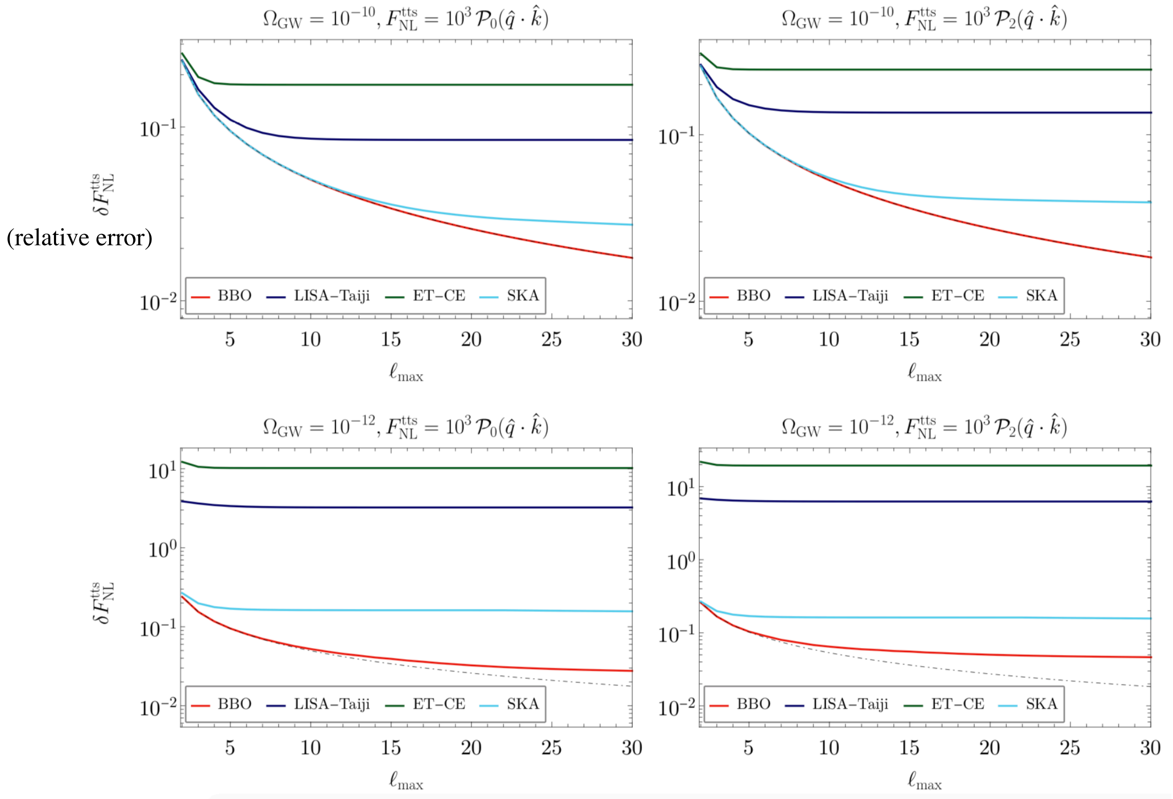
- LISA+Taiji



[Ruan et al, 2020]

- ET + CE
- SKA (assumed 50 identical pulsars)

Forecasts for $F_{\rm NL}^{\rm tss}$



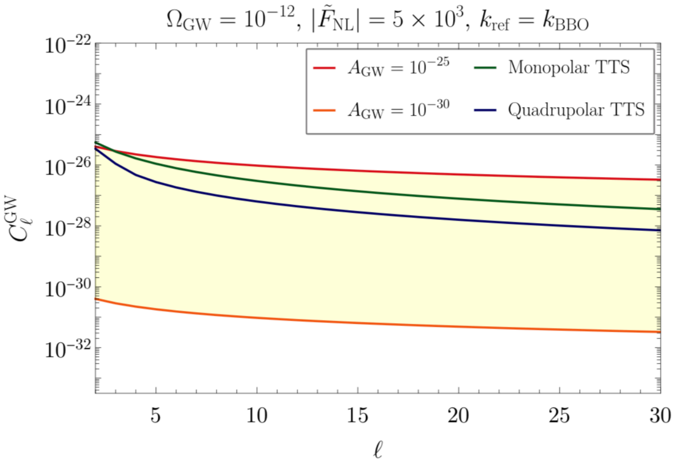
[ED, Fasiello, Malhotra, Meerburg, Orlando 2021]

SGWB anisotropies: astrophysical sources

- SGWB from superposition of signals from black holes, neutron star binaries
- ASGWB also expected to be anisotropic due to the distribution of sources
- Anisotropies in the ASGWB can inform us about many things (e.g. start formation model, mass distribution, etc) **[see e.g. Cusin et al, 2018-19-20]**
- On large scales anisotropies in the ASGWB do not correlate strongly with CMB, (cross-correlations with LSS observables much more effective) **[Ricciardone et al, 2021]**

GW-CMB correlation excellent probe of cosmological SGWB!

Astrophysical foregrounds

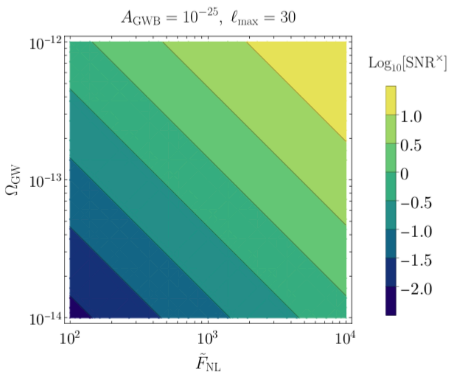


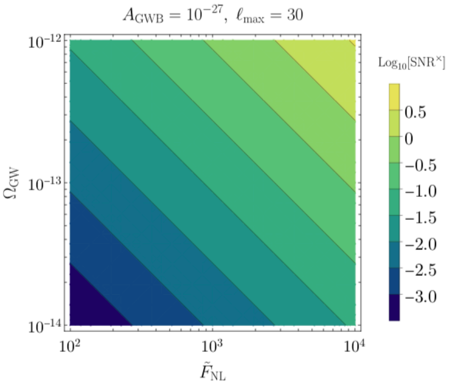
SNR for GW-CMB cross-correlations:

$$\mathrm{SNR}^{\times} = \left[\sum_{\ell_{\rm min}}^{\ell_{\rm max}} (2\ell+1) \frac{\left(\mathrm{C}_\ell^{\rm GW-T,signal}\right)^2}{\left(\mathrm{C}_\ell^{\rm GW-T,total}\right)^2 + \mathrm{C}_\ell^{\rm GW,total}\mathrm{C}_\ell^{\rm TT}}\right]^{1/2}$$

$$C_\ell^{\rm GW-T,signal} = C_\ell^{\rm GW-T,tts}$$
$$C_\ell^{\rm GW-T,total} = C_\ell^{\rm GW-T,signal} + C_\ell^{\rm GW-T,induced}\,,$$
$$C_\ell^{\rm GW,total} = C_\ell^{\rm GW,tts} + C_\ell^{\rm GW,induced} + C_\ell^{\rm GW,astro} + N_\ell^{\rm GW}$$

Monopolar stt bispectrum

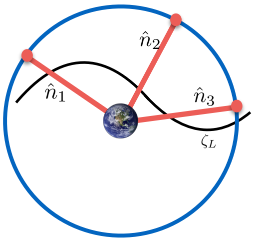




Quadrupolar stt bispectrum

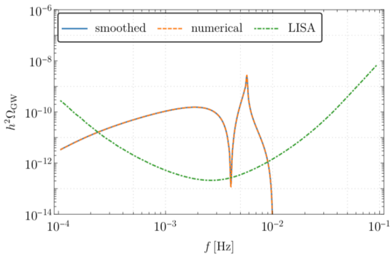
Modeling of astrophysical background using results in [Cusin, Dvorkin, Pitrou, Uzan 2018-2019]

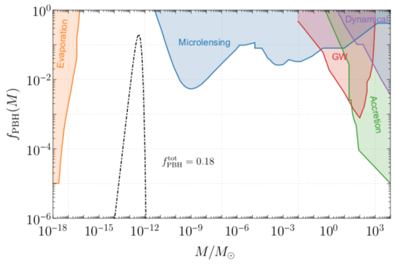
Anisotropies from propagation



Models with sharp peaks in the scalar power spectrum (e.g. PBH production)

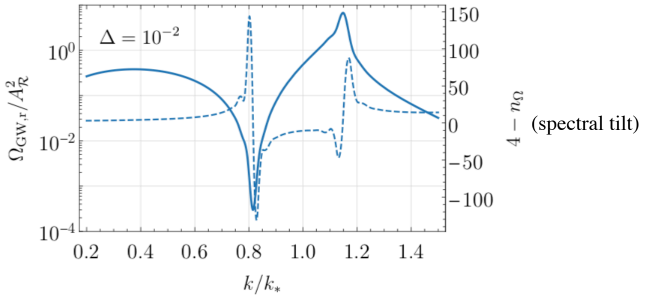
- a large GW background with sharp peaks induced at second order from scalar perturbations



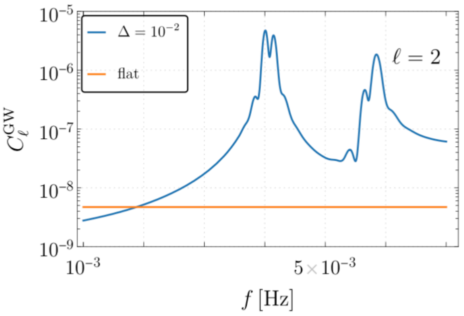


- the anisotropies can be typically enhanced by O(10-100)

$$\delta_{\rm GW} \sim \left(\frac{\partial \ln \Omega_{\rm GW}}{\partial \ln k}\right) \zeta_{\rm L}$$



- the angular power spectrum of the SGWB anisotropies inherits the frequency dependence



[ED, Fasiello, Malhotra, Tasinato 2022]

Primordial gravitational waves

- Different production mechanisms during inflation lead to a variety of signals

- We can characterise the various GW sources from inflation using:
  - spectral shape
  - chirality
  - non-Gaussianity
  - SGWB anisotropies

- Powerful observables with the potential to disentangle inflationary GW from those generated in the post-inflationary universe

Hunting for the gravitational-wave background: Detection methods and implications for astrophysics, high energy physics, and the early Universe

Mairi Sakellariadou

THE 13TH RESCEU INTERNATIONAL SYMPOSIUM

JGRG31

October 24 (Mon) - 28 (Fri), 2022

The 31st Workshop on General Relativity and Gravitation in Japan

Koshiba Hall, The University of Tokyo, Tokyo (Hybrid style)

Outline

- Introduction: GW signals, GWB
- Detection methods
- GWB from compact binary coalescences: info about astrophysics
- SGWB from cosmic strings, first order phase transitions: info about beyond standard model
- GWB from pop III stars, parity violation: info about early universe
- Anisotropies in the GWB: info about large-scale structure
- Conclusions and Remarks

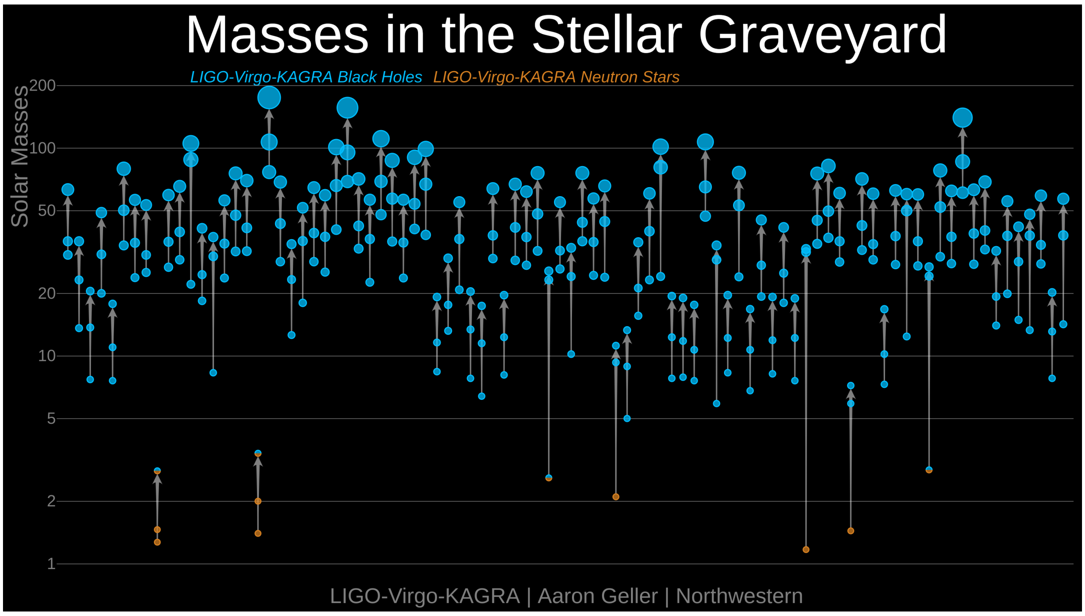
Masses of LVK Collaboration compact binaries

O1, O2: 11 events

O3a: + 44 events

O3b: +35 events

O1+O2+O3: 90 events



Taxonomy of GW signal morphologies

Does the signal only appear in the detector for a relatively short time, or it is 'always on'?

Transient

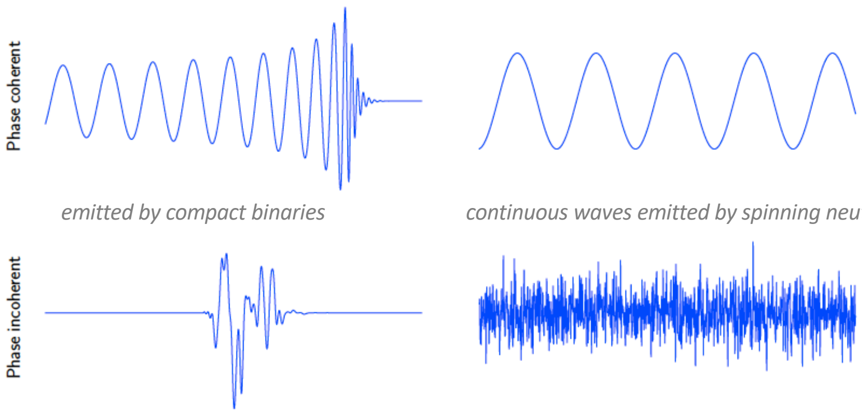
Persistent

Are we able to deterministically model the phase of the signal, or does our lack of knowledge about the source force us to treat the phases as random?

Phase coherent

Phase incoherent

Taxonomy of GW signal morphologies



Transient

Persistent

Phase coherent

emitted by compact binaries

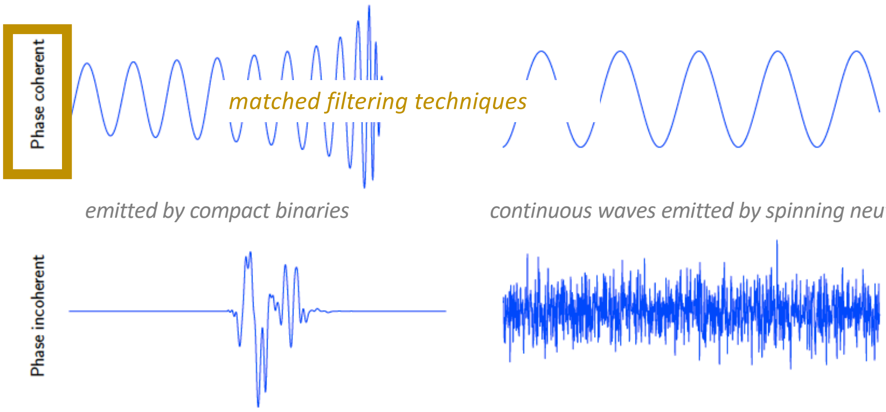
continuous waves emitted by spinning neutron stars

Phase incoherent

bursts emitted by core-collapse supernova

stochastic GW background

Taxonomy of GW signal morphologies



Transient

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Phase coherent

matched filtering techniques

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continuous waves emitted by spinning neutron stars

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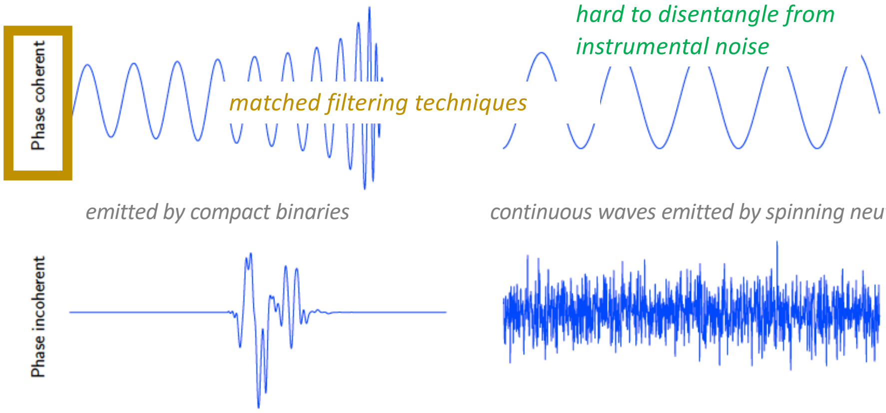
Taxonomy of GW signal morphologies

Transient

Persistent

hard to disentangle from instrumental noise



matched filtering techniques

emitted by compact binaries

continuous waves emitted by spinning neutron stars

bursts emitted by core-collapse supernova

stochastic GW background

Taxonomy of GW signal morphologies

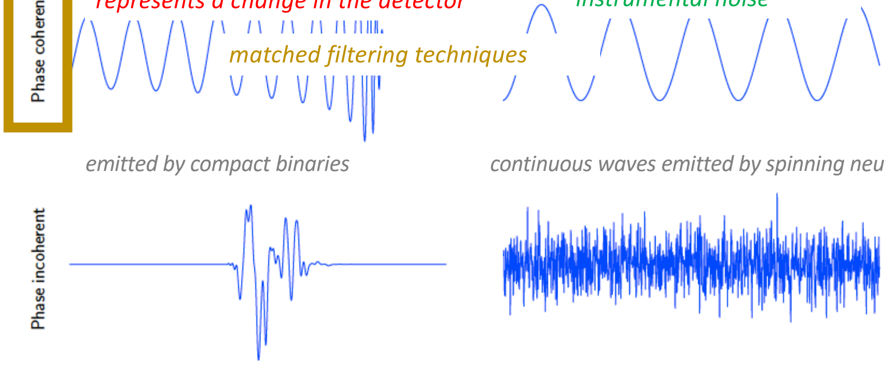
Transient

easier to search for as their arrival represents a change in the detector

Persistent

hard to disentangle from instrumental noise

LVK Collaboration, arXiv: 1811.12907
arXiv:2010.14527
arXiv:2108.01045



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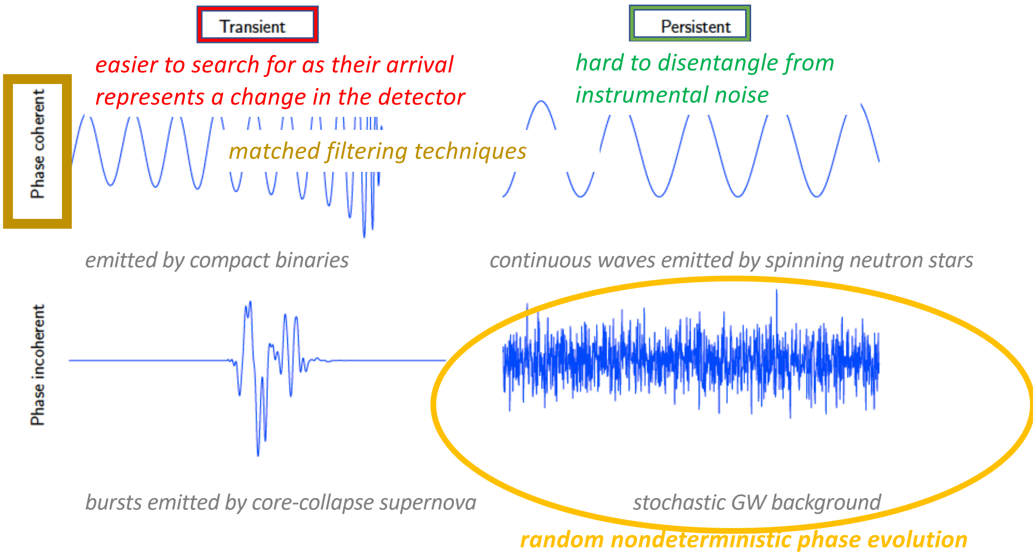

easier to search for as their arrival represents a change in the detector

hard to disentangle from instrumental noise

matched filtering techniques

emitted by compact binaries

continuous waves emitted by spinning neutron stars

bursts emitted by core-collapse supernova

stochastic GW background

random nondeterministic phase evolution from a large number of distant sources

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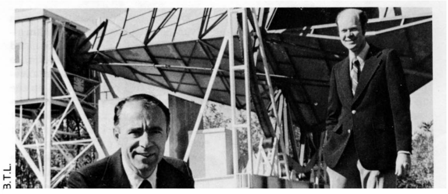
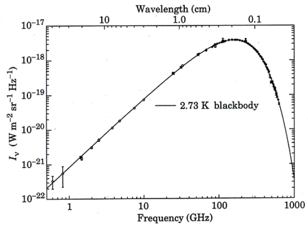
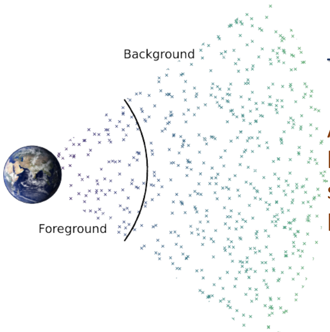
Gravitational-Wave Background (GWB)





Penzias and Wilson (1965) discovered that the Universe is permeated by the CMB electromagnetic radiation



Credit: Alex Jenkins

The Universe is permeated by a stochastic GWB generated in the early Universe

A **background of GWs** can also emerge from the incoherent superposition of a large number of astrophysical sources, too weak to be detected separately, and such that the number of sources that contribute to each frequency bin is much larger than one

$$\boxed{\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\frac{\mathrm{d}\rho_{\rm GW}}{\mathrm{d}f}}$$

$$\rho_{\rm GW} \sim \dot{h}^2$$

Gravitational-Wave Background (GWB)

Metric perturbations affect the phase of GWs as they propagate through inhomogeneous Universe

→ Stochastic GWB (cosmological origin) **looses any phase coherence** present at emission or horizon entry

GWB generated by overlapping signals from many individual (astrophysical) sources below confusion limit of detector : **no phase-coherence**

For a standard cosmological model, complete loss of coherence above frequencies $f \sim 10^{-12}\ \mathrm{Hz}$

Margalit, Contaldi, Pieroni, (2004)

$$\tilde{h}(f) = \mathcal{A}\exp(i\phi) \xrightarrow{\textit{phase random}} \langle \tilde{h}(f) \rangle = 0 \xrightarrow[\textit{amplitude useful}]{\textit{no phase info}} \Omega_{\mathrm{GW}} \sim \langle \tilde{h}\tilde{h}^\star \rangle = \mathcal{A}^2$$

Gravitational-Wave Background (GWB)

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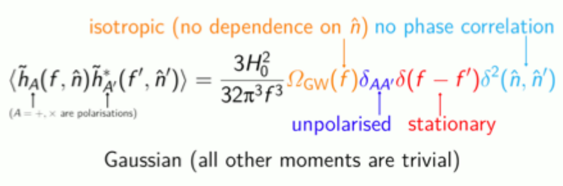
Standard assumptions:



$$\langle \underset{\uparrow}{\tilde{h}_A}(f,\hat{n})\underset{\uparrow}{\tilde{h}^*_{A'}}(f',\hat{n}')\rangle = \frac{3H_0^2}{32\pi^3 f^3}\,\Omega_{GW}(\overset{\substack{\text{isotropic (no dependence on }\hat{n})\\ \downarrow}}{f})\,\underset{\substack{\uparrow\\ \text{unpolarised}}}{\delta_{AA'}}\,\delta(f\underset{\substack{\uparrow\\ \text{stationary}}}{-}f')\,\overset{\substack{\text{no phase correlation}\\ \downarrow}}{\delta^2(\hat{n},\hat{n}')}$$

(A = +, × are polarisations)

Gaussian (all other moments are trivial)

How de we detect a GWB ?

A detection of the GWB from unresolved compact binary coalescences could be made by Advanced LIGO and Advanced Virgo at their design sensitivities

It would appear as noise in a single GW detector

$$\tilde{s}_i(f) = \tilde{h}_i(f) + \tilde{n}_i(f)$$

But *noise* *>>* *strain*

To detect a GWB take the correlation between two detector outputs:

$$\boxed{\begin{aligned}\langle \tilde{s}_i^*(f)\tilde{s}_j(f')\rangle = \langle \tilde{h}_i^*(f)\tilde{h}_j(f')\rangle + \langle \tilde{h}_i^*(f)\tilde{n}_j(f')\rangle \\ + \langle \tilde{n}_i^*(f)\tilde{h}_j(f')\rangle + \langle \tilde{n}_i^*(f)\tilde{n}_j(f')\rangle\end{aligned}}$$

SNR grows (slowly) over time:

$$\boxed{\langle s_1 s_2\rangle \sim \mathrm{Var}[s_1 s_2] \sim T_{\mathrm{obs}} \Rightarrow \mathrm{SNR} = \frac{\langle s_1 s_2\rangle}{\sqrt{\mathrm{Var}[s_1 s_2]}} \sim \sqrt{T_{\mathrm{obs}}}}$$

How de we detect a GWB ?

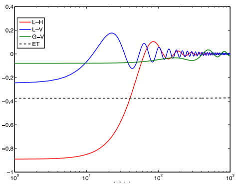
Assuming the GWB to be isotropic, Gaussian, stationary and unpolarised:

$$\begin{aligned}\langle \tilde{s}_i^*(f)\tilde{s}_j(f')\rangle = \langle \tilde{h}_i^*(f)\tilde{h}_j(f')\rangle + \langle \tilde{h}_i^*(f)\tilde{n}_j(f')\rangle \\ + \langle \tilde{n}_i^*(f)\tilde{h}_j(f')\rangle + \langle \tilde{n}_i^*(f)\tilde{n}_j(f')\rangle\end{aligned}$$

$$\boxed{\hat{C}_{ij}(f;t) = \frac{2}{T}\frac{\mathrm{Re}[\tilde{s}_i^*(f;t)\tilde{s}_j(f;t)]}{\Gamma_{ij}(f)S_0(f)}}$$

$$\boxed{S_0(f) = 3H_0^2/(10\pi^2 f^3)}$$

$\Gamma_{ij}(f)$



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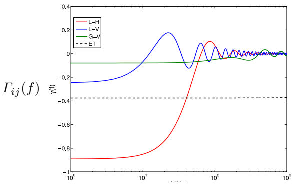

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$$\langle \tilde{h}_i^*(f)\tilde{h}_j(f')\rangle = \frac{1}{2}\delta_T(f-f')\Gamma_{ij}(f)S_{\mathrm{gw}}(f)$$

Single power spectral density (PSD)

$$S_{\mathrm{gw}}(f) = \frac{3H_0^2}{10\pi^2}\frac{\Omega_{\mathrm{gw}}(f)}{f^3}$$

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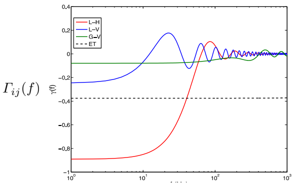

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$$\langle \hat{C}_{ij}(f;t)\rangle = \Omega_{\mathrm{gw}}(f) + 2\,\mathrm{Re}\left[\frac{\langle \tilde{n}_i^*(f;t)\tilde{n}_j(f;t)\rangle}{T\Gamma_{ij}(f)S_0(f)}\right]$$

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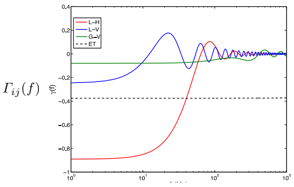

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In the absence of correlated noise: $\langle \tilde{n}_i^*(f)\tilde{n}_j(f)\rangle = 0,$

$\Longrightarrow$ $\langle \hat{C}_{ij}(f)\rangle$ is an estimator for $\Omega_{\rm gw}(f)$

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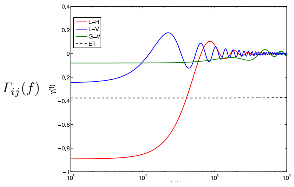

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what if:

$$\boxed{\langle \tilde{n}_i^*(f)\tilde{n}_j(f)\rangle \neq 0}$$

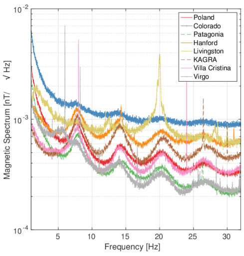
In the absence of correlated noise: $\langle \tilde{n}_i^*(f)\tilde{n}_j(f)\rangle = 0,$

$\Longrightarrow$ $\langle \hat{C}_{ij}(f)\rangle$ is an estimator for $\Omega_{\rm gw}(f)$

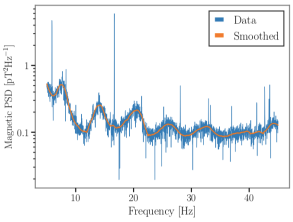
How are we sure that there is a real GWB detection?

Schumann Resonances

- Resonances in the global electromagnetic field of Earth
- **Correlated** magnetic noise contamination



Median power spectral density of magnetometers. [1802.00885]



Power spectral density of magnetometer data near aVIRGO, showing 5 harmonics of Schumann resonances

$$\langle \hat{C}_{ij}(f) \rangle = \Omega_{\rm gw}(f) + \Omega_{{\rm M},ij}(f),$$

magnetic contribution

Joint magnetic +GWB fit : a novel approach:

- *Model background from the local magnetic field*
- *Model its coupling to the strain channel of the detectors via transfer function*
- *Obtain the magnetic contribution*

Meyers, Martinovic, Christensen, Sakellariadou, PRD102 (2020) 10, 102005

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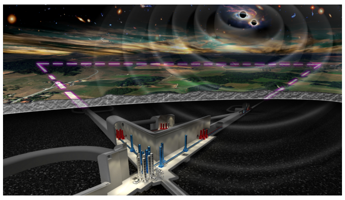
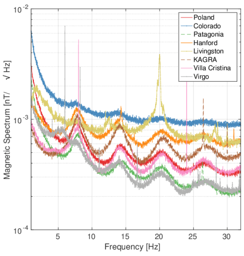


Underground 3g detector
10km length arms, f~(1-100) Hz
- new quantum technologies to reduce fluctuations of light
- new measures to reduce environmental perturbations



For GWB searches below ~30 Hz it will be necessary for the Einstein Telescope magnetic isolation coupling to be 2-4 orders of magnitude better than that measured in current aLIGO/aVirgo detectors

Janssens, Martinovic, Christensen, Meyers, Sakellariadou, PRD104 (2021) 10, 48550

Median power spectral density of magnetometers. [1802.00885]

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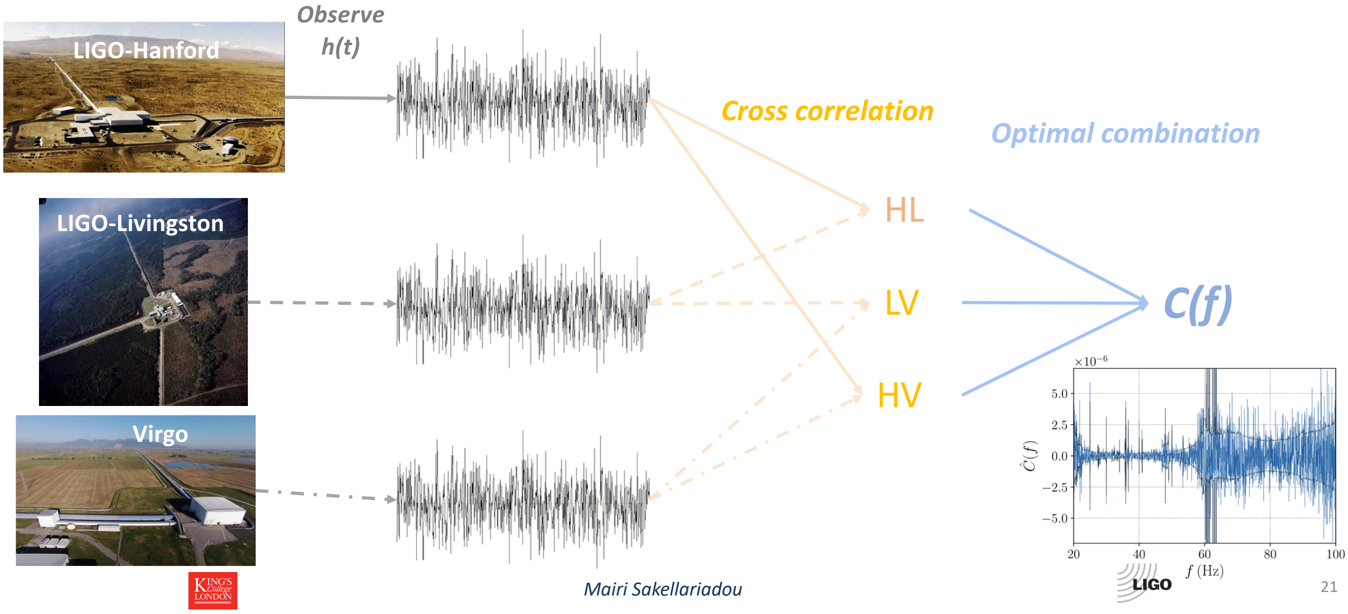
Meyers, Martinovic, Christensen, Sakellariadou, PRD102 (2020) 10, 102005

Using the detector network



Observe h(t)

LIGO-Hanford

LIGO-Livingston

Virgo

Cross correlation

HL

LV

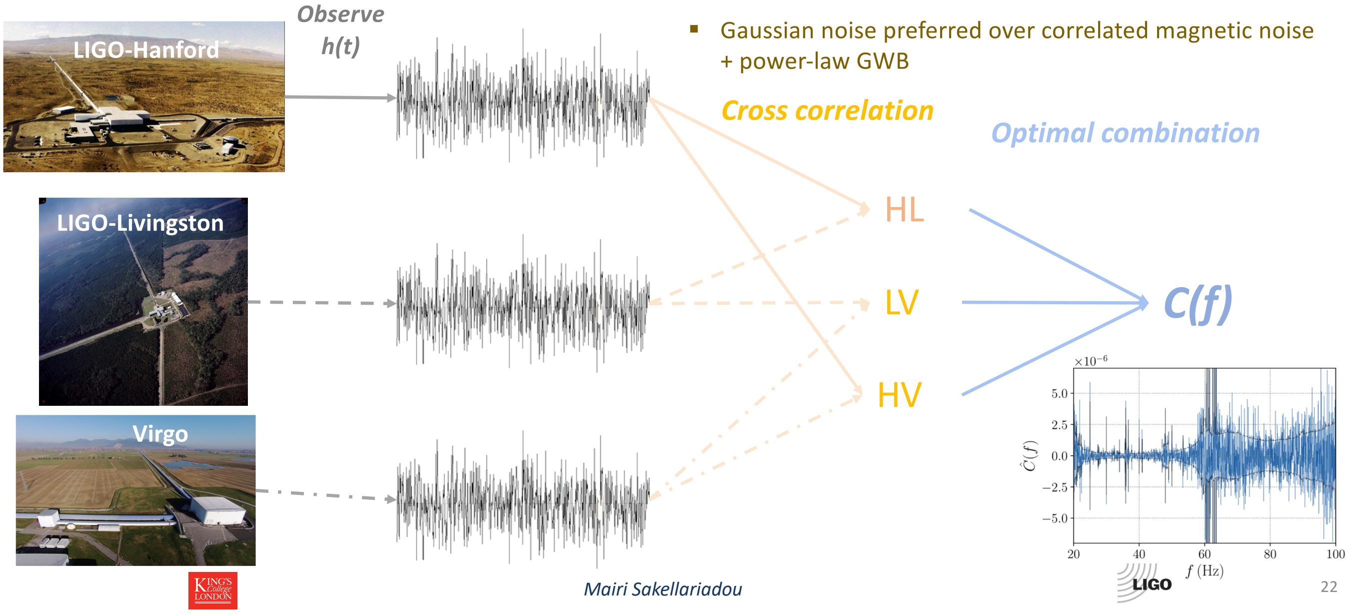
HV

Optimal combination

C(f)

Using the detector network

- Gaussian noise preferred over correlated magnetic noise
- Gaussian noise preferred over correlated magnetic noise + power-law GWB



Observe h(t)

LIGO-Hanford

LIGO-Livingston

Virgo

Cross correlation

HL

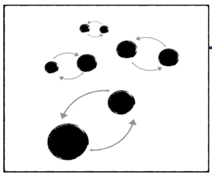
LV

HV

Optimal combination

C(f)

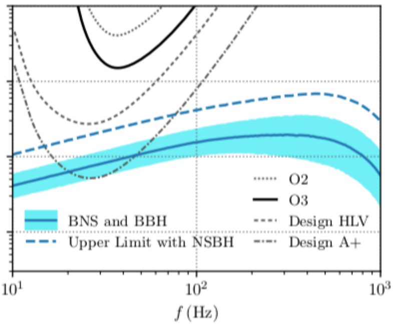
GWB from compact binary coalescence (CBC)



$$\Omega_{\rm GW}(f) = \Omega_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{\alpha}$$

$\alpha=2/3$

$$\frac{dE_{\rm GW}}{df} = \frac{(G\pi)^{2/3}}{3}\,\frac{m_1 m_2}{(m_1+m_2)^{1/3}}\,f^{-1/3}$$



$$\Omega_{\rm GW} \ll \Omega_{\rm CMB} \approx 10^{-5}$$

So, detection is indeed hard!

$$\boxed{\Omega_{\rm GW}(f) \leq 3.4\times 10^{-9} \quad \text{at } 25\ \text{Hz}}$$

LVK Collaboration, PRD 104 (2021), 2, 022004

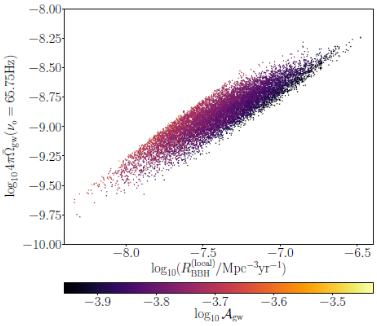
GWB from CBC: info about Compact Binaries

$$\boxed{\Omega_{\rm GW}(f,\theta) = \frac{f}{\rho_{\rm c} H_0}\int_0^{z_{\rm max}} {\rm d}z\,\frac{R_{\rm m}(z;\theta)\frac{{\rm d}E_{\rm GW}(f_{\rm s};\theta)}{{\rm d}f_{\rm s}}}{(1+z)E(\Omega_{\rm M},\Omega_\Lambda,z)}}$$

$$E(\Omega_{\rm M},\Omega_\Lambda,z) = \sqrt{\Omega_{\rm M}(1+z)^3+\Omega_\Lambda}$$

$$f_{\rm s} = (1+z)f$$

Most important quantities describing each BBH are the **masses** and **spins** of each component BH



Truncated power-law BH mass distribution

$m_{\rm min} = 5M_\odot$ *total* $M_{\rm max} = 200M_\odot$

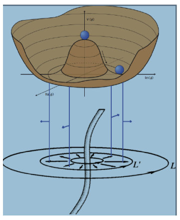
Beta distribution for the BH spins

The **total energy density varies over nearly two orders of magnitude**

→ **a new probe of population of compact objects**

Jenkins, O'Shaughnessy, Sakellariadou, Wysocki, PRL 122, 111101 (2019)

SGWB from cosmic strings: info beyond Standard Model



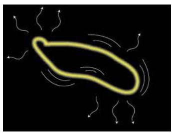
1dim topological defects formed in the early universe as a result of a PT followed by SSB, characterised by a vacuum manifold with non-contractible closed curves

$G \to \cdots \to G_{\rm SM}$ $\pi_1(\mathcal{M}) \neq 0$

Kibble (1976)

Generically formed in the context of GUTs

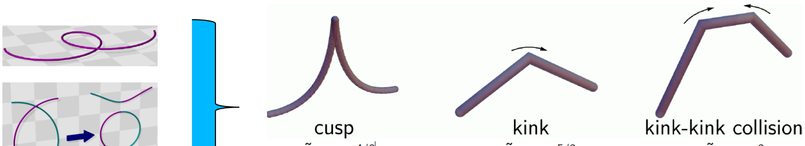
Jeannerot, Rocher, Sakellariadou, PRD68 (2003) 103514



CS loops (length ℓ) oscillate periodically ($T = \ell/2$) in time emitting GWs (fundamental frequency $\omega = 4\pi/\ell$)

$$\tau \sim \frac{\ell}{G\mu}$$

$$G\mu \sim T_{\rm SSB}^2$$



cusp
$\tilde{h} \sim f^{-4/3}$
beamed

kink
$\tilde{h} \sim f^{-5/3}$
beamed

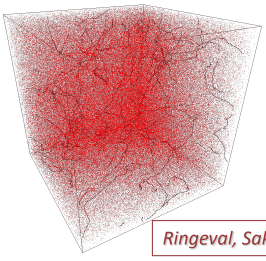
kink-kink collision
$\tilde{h} \sim f^{-2}$
isotropic

Oscillating loops of cosmic strings generate a SGWB that is strongly non-Gaussian, and includes occasional sharp bursts due to cusps and kinks

---

SGWB from cosmic strings: info beyond Standard Model

$$\bar{\Omega}_{\rm gw} = \frac{2(G\mu)^2}{3\pi^2 H_0^2 \nu_{\rm o}}\int_0^{t_*}\frac{{\rm d}t}{t^4}a^5\int_0^{\gamma_*}\frac{{\rm d}\gamma}{\gamma}\bar{\mathcal{F}}\Theta\left(\gamma-\frac{2a}{\nu_{\rm o}t}\right)\left[N_{\rm k}^2+4AN_{\rm k}\left(\frac{\nu_{\rm o}\gamma t}{a}\right)^{1/3}+A^2N_{\rm c}\left(\frac{\nu_{\rm o}\gamma t}{a}\right)^{2/3}\right]$$

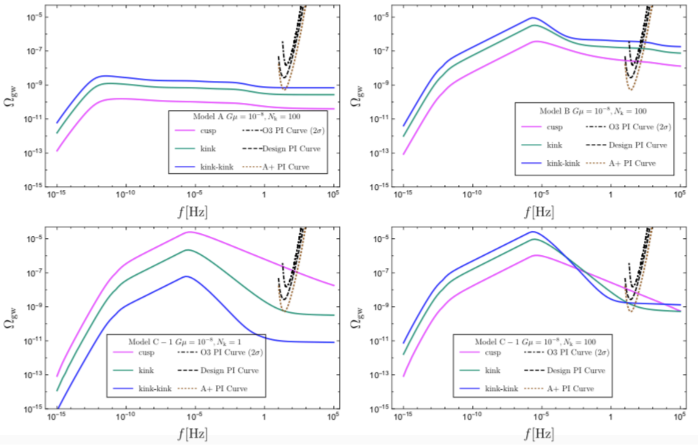


Ringeval, Sakellariadou, Bouchet (2007)

$$G\mu = \frac{\text{mass}}{\text{length}} \sim \left(\frac{\text{new physics scale}}{\text{Planck scale}}\right)^2 \ll 1$$

$$G\mu \sim T_{\rm SSB}^2$$

Model A: Blanco-Pillado, Olum, Shlaer (2014)
Model B: Lorenz, Ringeval, Sakellariadou (2010)
Model C: Auclair, Ringeval, Sakellariadou, Steer (2019)



LVK Collaboration, PRL 126 (2021) 24, 241102

SGWB from cosmic strings: info Beyond the Standard Model

Excluded regions:

Model A: $G\mu \gtrsim (9.6 \times 10^{-9} - 10^{-6})$

strongest limit from PTA $G\mu \gtrsim 10^{-10}$

Model B: $G\mu \gtrsim (4.0 - 6.3) \times 10^{-15}$
strongest limit from LVK stochastic

Model C1: $G\mu \gtrsim (2.1 - 4.5) \times 10^{-15}$
strongest limit from LVK stochastic

Model C2: $G\mu \gtrsim (4.2 - 7.0) \times 10^{-15}$
strongest limit from LVK stochastic

Energy scale $\approx \sqrt{\frac{G\mu}{10^{-10}}} 10^{14} \mathrm{GeV}$

Energy scale	Width	Linear density
GUT : 10^{16} GeV	2×10^{-32} m	$G\mu \approx 10^{-6}$
3×10^{10} GeV	5×10^{-27} m	$G\mu \approx 10^{-17}$
10^{8} GeV	2×10^{-24} m	$G\mu \approx 10^{-22}$
EW : 100 GeV	2×10^{-18} m	$G\mu \approx 10^{-34}$

Model A: Blanco-Pillado, Olum, Shlaer (2014)
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LVK Collaboration, PRL 126 (2021) 24, 241102

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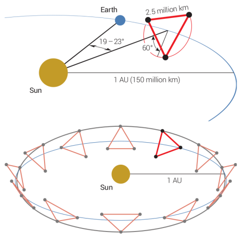


$[10^{-5}, 1]$ Hz,

LISA will be able to probe cosmic strings with tensions $G\mu \gtrsim \mathcal{O}(10^{-17})$

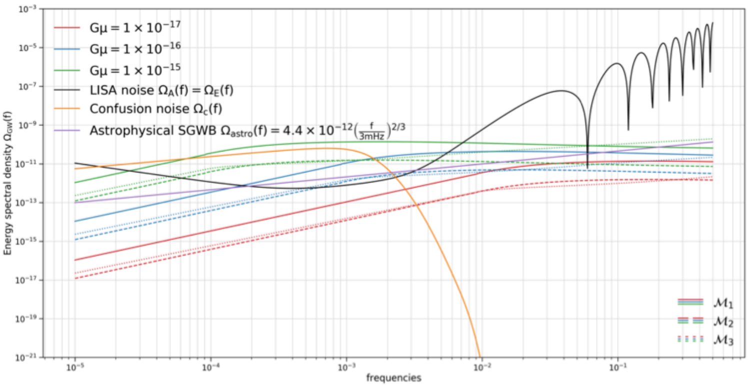
Auclair et al (Sakellariadou), JCAP (2020)

But …

- instrumental noise

- **astrophysical background from CBCs**
- **Galactic foreground from WD binaries**

A CS tension in the $G\mu \approx 10^{-16}$ to $G\mu \approx 10^{-15}$ range or bigger could be measured by LISA, with the galactic foreground affecting this limit more than the astrophysical background

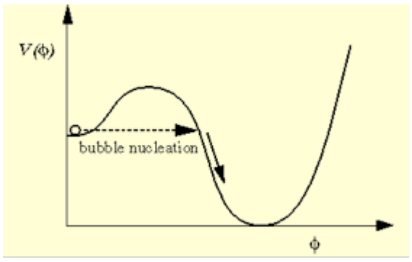


Boileau, Jenkins, Sakellariadou, Meyer, Christensen, PRD 105 (2022) 2, 023510

SGWB from first order phase transition(FOPT): info Beyond the Standard Model

The universe might have undergone a series of phase transitions

In the case of a FOPT, once the temperature drops below a critical value, the Universe transitions from a meta-stable phase to a stable one, through a sequence of **bubble nucleation**, **growth**, and **merger**



FOPT: the matter fields get trapped in a "false vacuum" state from which they can only escape by nucleating bubbles of the new phase, i.e the "true vacuum" state

Many compelling extensions of the Standard Model predict strong FOPTs (e.g., GUTs, SUSY, extra dimensions, composite Higgs models, models with extended Higgs sector)

The nature of cosmological PTs depends strongly on the particle physics model at high energy scales

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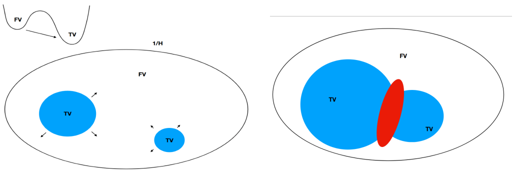
SGWB from first order phase transition(FOPT): info Beyond the Standard Model

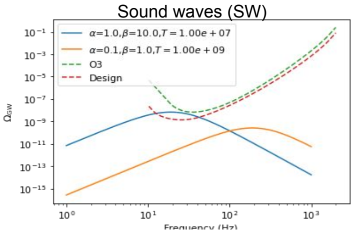


Sources of GWs:
- **Sound waves** (coupling between scalar field and thermal bath)
- **Bubble collisions**
- Magnetohydrodynamic turbulence

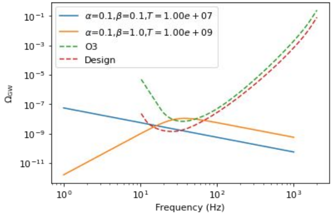
SGWB: broken power law with peak frequency mainly determined by temperature of FOPT

If $T_{\rm pt} \sim (10^7 - 10^9)\ {\rm GeV}$ (not accessible by LHC) : **SGWB is within aLIGO/aVIRGO**

Sound waves (SW)



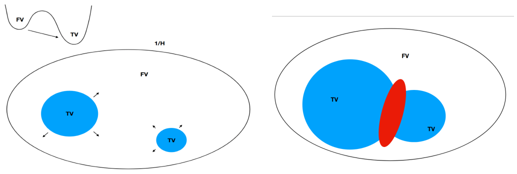
Bubble collisions (BC)



α : strength of FOPT

β : inverse duration of FOPT

SGWB from first order phase transition(FOPT): info Beyond the Standard Model



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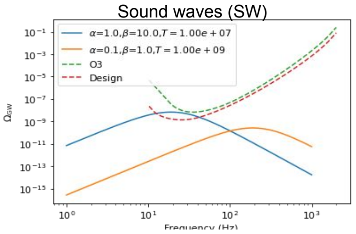
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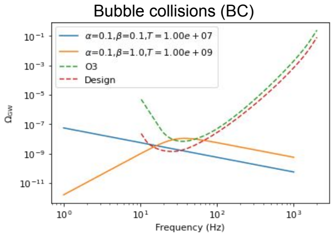
Bubble collisions (BC)

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β : inverse duration of FOPT

O1+O2+O3:

$$\Omega_{\rm CBC} < 6.1 \times 10^{-9}$$
$$\Omega_{\rm BPL} < 4.4 \times 10^{-9}$$

Romero, Martinovic, Callister, Guo, Martinez, Sakellariadou, Yang, Zhao, PRL 126 (2021) 15, 151301

SGWB from second order scalar perturbations: information about early universe

- PBH formation through large curvature perturbations during inflation

⟹ **Strong SGWB generated at 2nd order in perturbation theory from scalar perturbations**

O1+O2+O3: upper limits on the amplitude of power spectrum and
on the fraction of the DM in terms of ultralight PBHs

For LIGO/Virgo sensitivity: $M_{\rm PBH} \lesssim 10^{16}\,{\rm g}.$

Romero-Rodriguez, Martinez, Pujolas, Sakellariadou, Vaskonen, PRL 128 (2022) 5, 051301

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Integrated power of peak

position of peak

$$\mathcal{P}_\zeta(k) = \frac{A}{\sqrt{2\pi}\Delta}\exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$

log-normal shape for the peak in curvature power spectrum

width of peak

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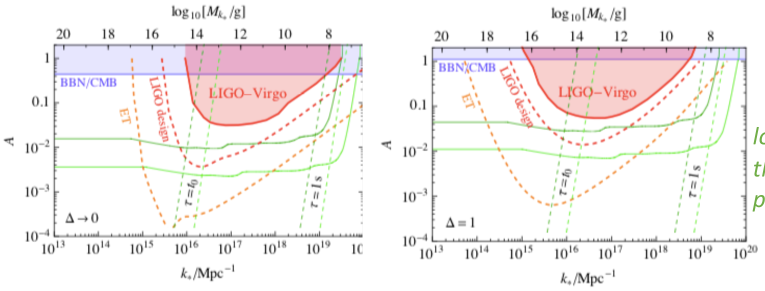

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No evidence for such a SGWB
95% CL upper limits on integrated power of the curvature power spectrum peak down to 0.02 at $10^{17}\,{\rm Mpc}^{-1}$

Romero-Rodriguez, Martinez, Pujolas, Sakellariadou, Vaskonen, PRL 128 (2022) 5, 051301

Gravitational parity violation: info about the early universe

Observed matter-antimatter asymmetry in the radiation era requires sources of parity violation (Sakharov criteria, 1967)

- Early universe mechanisms can create parity violation → production of asymmetric amounts of right- and left-handed circularly polarised isotropic GWs
- Astrophysical GWB sources are unlikely to have circular polarisation

↓

- Detection of parity violation can allow cosmologically sourced GWs to be distinguished from the astrophysically sourced component of the GWB
- Analysis of polarised GWB can place constraints on parity violating theories

- *Chern-Simons gravitational term* *Yagi, Yang (2018)*
- *Axion inflation* *Crowder, Namba, Mandic, Mukoyama, Peloso (2013)*
- *Turbulence in the primordial plasma: FOPT (EW or QCD) or primordial magnetic fields coupled to cosmological plasma* *Martinovic, Badger, Sakellariadou, Mandic , PRD 2021*

Gravitational parity violation: info about the early universe

$$\boxed{\begin{pmatrix}\langle h_R(f,\hat{\Omega})h_R^*(f',\hat{\Omega}')\rangle\\ \langle h_L(f,\hat{\Omega})h_L^*(f',\hat{\Omega}')\rangle\end{pmatrix} = \frac{\delta(f-f')\delta^2(\hat{\Omega}-\hat{\Omega}')}{4\pi}\begin{pmatrix}I(f,\hat{\Omega})+V(f,\hat{\Omega})\\ I(f,\hat{\Omega})-V(f,\hat{\Omega})\end{pmatrix}}$$

For V=0: the correlator of unpolarised SGWB

Cross-correlator estimator

$$\boxed{\langle\hat{C}_{d_1d_2}\rangle = \frac{3H_0^2T}{10\pi^2}\int_0^\infty df\,\frac{\Omega'_{\rm GW}(f)\gamma_I^{d_1d_2}(f)\tilde{Q}(f)}{f^3}}$$

$$\boxed{\Omega'_{\rm GW} = \Omega_{\rm GW}\left[1+\Pi(f)\frac{\gamma_V^{d_1d_2}(f)}{\gamma_I^{d_1d_2}(f)}\right]}$$

Polarisation degree

$$\Pi(f) = V(f)/I(f)$$

-1 : fully L polarisation
1 : fully R polarisation
0 : unpolarised isotropic SGWB

Gravitational parity violation: info about the early universe

Parameter estimation and fit GW models to data

We search for parity violation in O3 data with a uniform power in Π in [-1,1]

We find no evidence for PV. We place an upper limit on the amplitude, $\Omega_{\rm GW}^{95\%}(25\,{\rm Hz}) = 7.0 \times 10^{-9}$, and cannot estimate α and Π.

$$\Omega_{\rm gw}(f) = \Omega_\alpha \left(\frac{f}{f_{\rm ref}}\right)^\alpha$$

Model-dependent search: **helical turbulence in the early universe as source of PV**

Brandenburg, Kahniashvili, et al (2020)

We model the turbulence GW remnant as a broken power law

In this case the polarisation degree is frequency-dependent $\Pi(f)=f^\beta$

$$\Omega_{\rm GW} = \begin{cases} \Omega_{\rm peak}(f/f_{\rm peak}) & \text{for } f \leq f_{\rm peak}, \\ \Omega_{\rm peak}(f/f_{\rm peak})^{-8/3} & \text{for } f > f_{\rm peak}. \end{cases}$$

There is a β-dependent threshold GW amplitude above which we recover Π(f)

There are two relevant SGWB upper limits:

- One that confirms presence of polarised GW signal
- A larger one that estimates the degree of polarisation with confidence

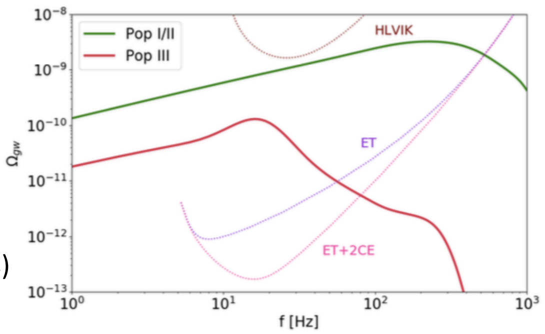
⇒ Even if we detect a turbulence signal, we may **not** be able to deduce its polarisation

Martinovic, Badger, Sakellariadou, Mandic, PRD 104 (2021) 8, L081101

Footprints of pop III stars in the GWB: info about the early universe

Pop III stars could have led to formation of supermassive BHs and help understanding the early epochs of the Universe such as reionisation and galaxy evolution

Pop III stars are thought to have formed at high redshifts and as such have low metallicity compared to the more recently formed, pop I/II stars



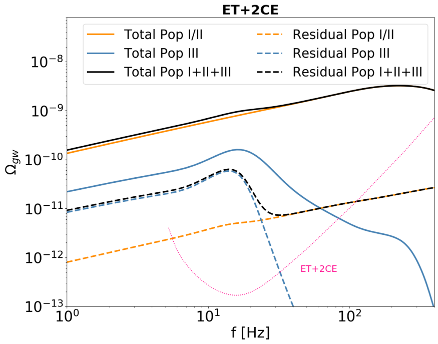
2G detector networks: pop III is practically invisible and its contribution to the global SNR is negligible

To uncover pop III stars, we need to look at residual backgrounds (subtract individually detected merger events)

Martinovic, Perigois, Regimbau, Sakellariadou, 2109.09779, ApJ (2022)

Footprints of pop III stars in the GWB

3G detectors may reveal a pop III background



ET + 2CE: uncover pop III after subtraction of individually resolved merger events

- Subtraction methods are less efficient to detect the high-z and low-f pop III CBCs
- Being more difficult to resolve, binaries from pop III persist, resulting in a large contribution to the residual CBC background (dominant for f below ~ 20 Hz)

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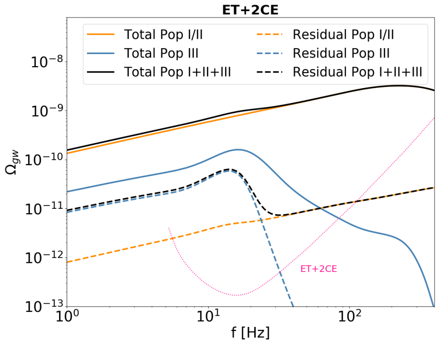

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These *further away stars will lead to more redshifted frequencies and therefore be detected in their merger and ringdown phases*

$$\Omega_{\rm GW}(f) = \Omega_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{\alpha}$$

The power law estimate is different from the characteristic 2/3 for the inspiral phase: broken power-law

Detection of pop III GWB and estimation of peak frequency could reveal important information, such as the average redshifted total mass

Martinovic, Perigois, Regimbau, Sakellariadou, 2109.09779, ApJ (2022)

Search for non-GR polarisations: information about theories of gravity

Alternative theories of gravity: scalar (S), vector (V), tensor (T) polarisations

$$\boxed{\Omega_{\rm SVT-PL}(f) = \sum_{\rm p} \beta^{(\rm p)}_{IJ}(f)\,\Omega^{(\rm p)}_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{\alpha_{\rm p}}} \quad {\rm p} = \{{\rm T},{\rm V},{\rm S}\};$$

$$\beta^{(\rm p)}_{IJ}(f) = \gamma^{(\rm p)}_{IJ}(f)/\gamma_{IJ}(f)$$

Current generation (number, orientation) of detectors cannot determine polarisation of transient GW signals

Bayesian method to detect and characterise the polarisation of the SGWB

Callister, et al (Sakellariadou), PRX 7 (2017) 041058

There is no evidence of non-GR polarisations
The non-detection of scalar and vector polarised GW is consistent with predictions of GR

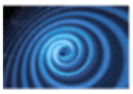
LVK Collaboration, PRD 104 (2021), 2, 022004

Can we distinguish between astrophysical vs cosmological sources?

GW models:

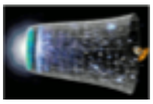
- CBC background

$$\Omega_{\rm CBC}(f) = \Omega_{2/3}\left(\frac{f}{25\,{\rm Hz}}\right)^{2/3}$$



- CS background (flat)

$$\Omega_{\rm CS}(f) = {\rm const.}$$



- PT background (smooth broken power law (BPL))

$$\Omega_{\rm BPL} = \Omega_*\left(\frac{f}{f_*}\right)^{\alpha_1}\left[1+\left(\frac{f}{f_*}\right)^{\Delta}\right]^{(\alpha_2-\alpha_1)/\Delta}$$

we fix. $\alpha_1 = 3, \alpha_2 = -4, \Delta = 2$ to approximate sound waves contribution

Martinovic, Meyers, Sakellariadou, Christensen, PRD 103 (2021) 4, 043023

Can we distinguish between astrophysical vs cosmological sources?

log-likelihood for a single detector pair

$$\log p(\hat{C}_{ij}(f)|\boldsymbol{\theta}_{\rm GW}) = -\frac{1}{2}\sum_f \frac{\left[\hat{C}_{ij}(f) - \Omega_{\rm GW}(f,\boldsymbol{\theta}_{\rm GW})\right]^2}{\sigma_{ij}^2(f)} \quad -\frac{1}{2}\sum_f \log\left[2\pi\sigma_{ij}^2(f)\right]$$

CBC Power Law: $\boldsymbol{\theta} = (\Omega_{2/3})$,
CBC + CS: $\boldsymbol{\theta} = (\Omega_{2/3}, \Omega_{\rm CS})$.
CBC + BPL: $\boldsymbol{\theta} = (\Omega_{2/3}, \Omega_*, f_*)$.

Model selection   To compare two models we use Bayes factors

Detector networks

- Hanford, Livinston, Virgo, O4 sensitivity, 1 year of run time
- Cosmic Explorers (CE) at Hanford and Livingston locations, Einstein Telescope (ET) at Virgo, 1 year of run time

- Current GW detectors are unable to separate astrophysical from cosmological sources
- Future GW detectors (CE, ET) can dig out cosmological signals, provided one can **subtract the *loud* astrophysical foreground**

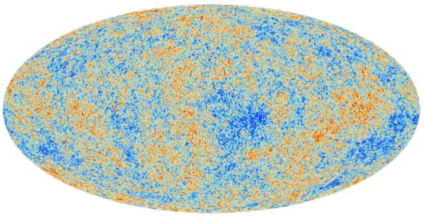
Martinovic, Meyers, Sakellariadou, Christensen, PRD 103 (2021) 4, 043023

BBH will not limit observation of primordial backgrounds, but BNS population will limit sensitivity of 3G detectors to about $\Omega_{\rm GW} \sim 10^{-11}$ at 10 Hz

Sachdev, Regimbau, Sathyaprakash (2020)

Anisotropies in the GW Background: info about large-scale-structure

To a first approximation, the SGWB is assumed to be isotropic (analogous to the CMB)



The afterglow radiation left over from the Hot Big Bang

- its temperature is extremely uniform all over the sky
- **tiny temperature fluctuations** (one part 100,000)

$$C_\ell = \int \mathrm{d}^2\hat{\boldsymbol{n}} P_\ell(\cos\theta)\,\langle \delta T_\gamma \delta T_\gamma \rangle_\theta$$

LSS

SGWB

$$C_\ell = \int \mathrm{d}^2\hat{\boldsymbol{n}} P_\ell(\cos\theta)\,\langle \delta\Omega_{\rm GW} \delta\Omega_{\rm GW} \rangle_\theta$$

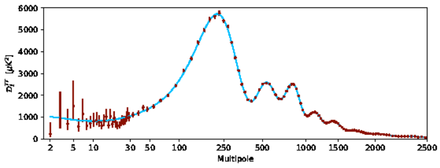


Image credit: Planck collaboration

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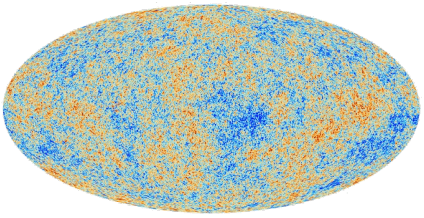

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$$\langle \tilde{h}_A(f,\hat{n})\tilde{h}^*_{A'}(f',\hat{n}')\rangle = \frac{3H_0^2}{8\pi^2 f^3}\overset{\substack{\text{now a function on the sky}\\ \downarrow}}{\Omega_{\mathrm{GW}}(f,\hat{n})}\delta_{AA'}\delta(f-f')\underset{\text{still no phase correlation}}{\delta^2(\hat{n},\hat{n}')}$$

LSS

SGWB

$$C_\ell = \int \mathrm{d}^2\hat{\boldsymbol{n}} P_\ell(\cos\theta)\,\langle \delta\Omega_{\mathrm{GW}}\delta\Omega_{\mathrm{GW}}\rangle_\theta$$

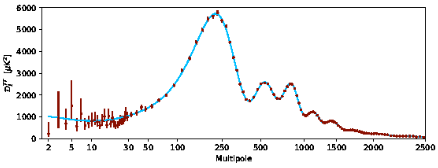

Image credit: Planck collaboration

Anisotropies in the GW Background: info about large-scale-structure

Gravitational wave sources with an anisotropic spatial distribution lead to a GWB characterised by preferred directions, and hence anisotropies

Assuming an unpolarised, Gaussian and stationary GWB, the quadratic expectation value of GW strain distribution across different sky directions and frequencies:

$$\langle h^*_A(f,\Theta)\,h_{A'}(f',\Theta')\rangle = \frac{1}{4}\mathcal{P}(f,\Theta)\,\delta_{AA'}\,\delta(f-f')\,\delta(\Theta,\Theta')$$

GW strain power:

$$\mathcal{P}(f,\Theta) = H(f)\,\mathcal{P}(\Theta),$$

$$H(f) = \left(\frac{f}{f_{\mathrm{ref}}}\right)^{\alpha-3}$$

spectral shape

angular distribution of GW power

Cross-correlation spectra from two detectors I, J, in terms of a set of basis functions, labeled by μ, on the 2-sphere:

$$\langle C_{IJ}(t;f)\rangle = H(f)\,\gamma_\mu\,\mathcal{P}_\mu$$

For the SHD, we use the spherical harmonic basis:

$$\mu \rightarrow \ell m$$

For the BBR and NBR analyses we use the pixel basis:

$$\mu \rightarrow \Theta.$$

LVC PRD 104 (2021), 2, 022005

Anisotropies in the GW Background: info about large-scale-structure

Anisotropy due to source density contrast $\delta_n \equiv \frac{n-\bar{n}}{\bar{n}}$

Intensity of GWB: $\Omega_{\rm gw}(f_0, \hat{e}_0) \equiv \bar{\Omega}_{\rm gw}(1+\delta_{\rm gw})$

$\theta_{\rm o} \equiv \cos^{-1}(\hat{e}_{\rm o} \cdot \hat{e}'_{\rm o})$

2PCF : $C_{\rm gw}(\theta_0, f_0) \equiv \langle \delta^{(\rm s)}_{\rm gw}(f_0, \hat{e}_0) \delta^{(\rm s)}_{\rm gw}(f_0, \hat{e}'_0) \rangle$

$$C_{\rm gw}(\theta, f_0) = \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} C_\ell(f_0) P_\ell(\cos\theta_0)$$

Jenkins, Sakellariadou, PRD 98, 063509 (2018)

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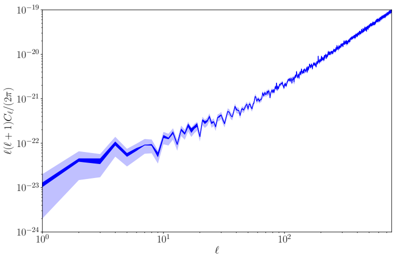
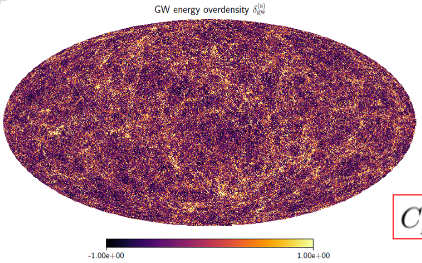
Jenkins, Sakellariadou, PRD 98, 063509 (2018)

Get galaxies from the Millenium catalogue –> compute merger rate for each galaxy –> superimpose to get a GWB map





Angular resolution: 13.7 arcminutes -
--- 7.3 galaxies per pixel

$C_\ell^{1/2} \sim 10^{-12}\,{\rm sr}^{-1}$ for $1 \leq \ell \leq 4$

Jenkins, Regimbau, Sakellariadou, Slezak, PRD 98, 063501 (2018)

Anisotropies in the GW Background: info about large-scale-structure

Anisotropy due to source density contrast $\delta_n \equiv \frac{n-\bar{n}}{\bar{n}}$

To consider propagation effects, see:
Bertacca, Sakellariadou, et al , PRD 101 (2020) 10, 103513
Bellomo, Sakellariadou, et al, JCAP 06 (2022) 06, 030

Intensity of GWB: $\Omega_{\rm gw}(f_0, \hat{e}_0) \equiv \bar{\Omega}_{\rm gw}(1+\delta_{\rm gw})$

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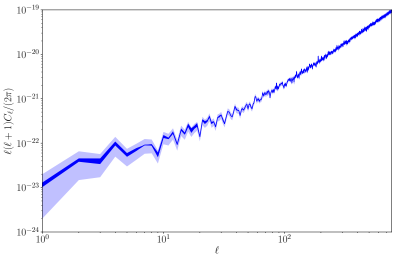

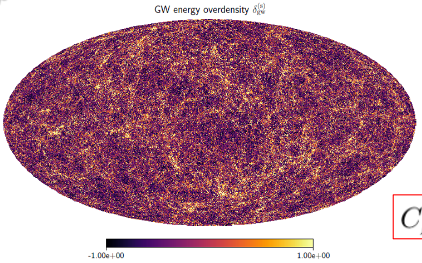

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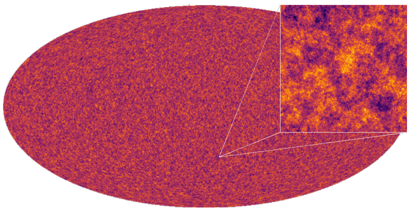
Jenkins, Sakellariadou, PRD 98, 063509 (2018)

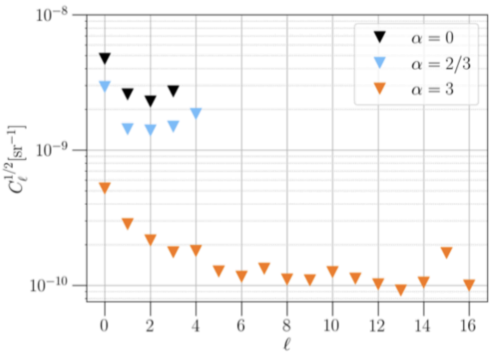
Anisotropies largely independent of the cosmic string loop distribution model



$C_1^{1/2} \lesssim 10^{-12}\mathrm{sr}^{-1}$

Jenkins, Sakellariadou, PRD 98, 063509 (2018)

Anisotropies in the GW Background: info about large-scale-structure



95% upper limits on C_ℓ for different α using combined O1+O2+O3 data

Diffraction-limited angular resolution Θ on the sky:

$$\theta = \frac{c}{2Df} \qquad \ell_{\max} = \frac{\pi}{\theta}$$

distance between detectors

most sensitive frequency

$\alpha = 2/3,$ $C_\ell^{1/2} < 1.9 \times 10^{-9}\,\mathrm{sr}^{-1},$

$\alpha = 0$ $C_1^{1/2} < 2.6 \times 10^{-9}\,\mathrm{sr}^{-1}$

LVC PRD 104 (2021), 2, 022005

Conclusions

A detection of the GWB from unresolved compact binary coalescences is expected to be made by Advanced LIGO and Advanced Virgo at their design sensitivities

- **Detecting a GWB in the presence of correlated magnetic noise**
- **Simultaneous estimation of astrophysical and cosmological GW backgrounds with terrestrial interferometers**
- **GWB will give information about astrophysical models (compact binaries), beyond the standard model particle physics (cosmic strings, phase transitions), large-scale-structure, early universe cosmology (inflation, parity violation), gravity theories**
- **Isotropic and directional searches are an ongoing effort of the LIGO/Virgo/KAGRA Collaboration**

Remarks

The implications of gravitational-wave detections can hardly be overestimated. For instance:

- Tests of General Relativity and extended gravity theories

  LVC PRD 103 (2021) 12, 122002

  Belgacem, Sakellariadou, et al JCAP 07 (2019) 024

  Baker, Sakellariadou, et al, arXiv:2203.00566

- Tests of Quantum Gravity proposals

  Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, JCAp 10 (2019) 012 ; PLB 798 (2019) 135000

- Info about nature of dark matter and constraints (axions, PBH, etc)

  LVC PRD 103 (2021) 12, 122002

  LVC PRD 105 (2022) 12, 102001

  Zhang, Lyu, Huang, Johnson, Sagunski, Sakellariadou, Yang, PRL 127 (2021) 16, 161101

- Info about cosmology (cosmic expansion history)

  LVC, arXiv:2111.03604

- Info about astrophysics (neutron star radii and equation of state, black hole masses and spins)

  LVC, PRL 121 (2018) 161101

  Biscoveanu, et al, arXiv:2204.01578

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  LVC, PRL 121 (2018) 161101

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どうもありがとうございます

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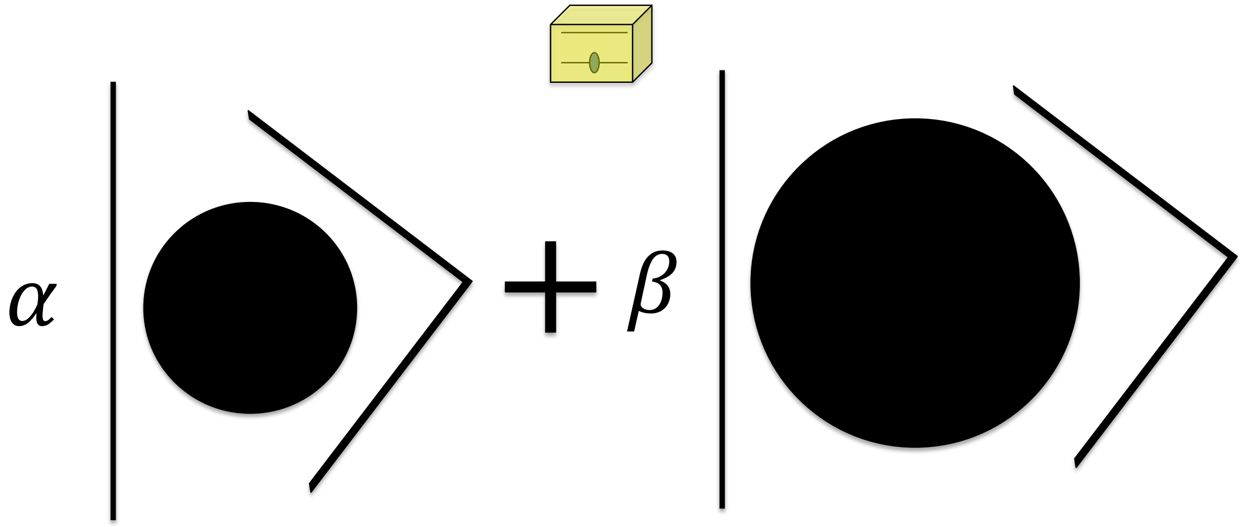
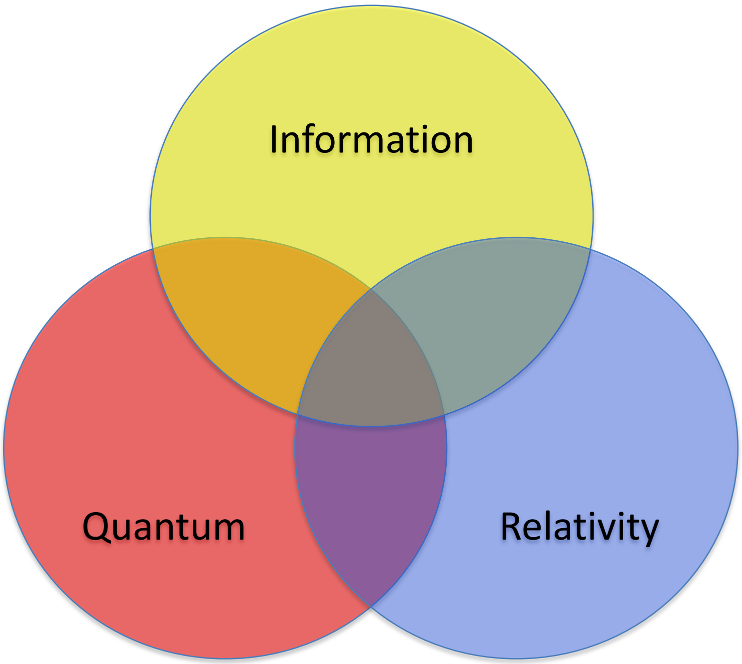
Signatures of Quantum Superpositions of Black Holes



Robert B. Mann
J. Foo C. Arabaci M. Zych

Physical Review Letters (to appear) 2111.13315

Relativistic Quantum Information



Information

Quantum

Relativity

Some Big Picture Questions

- What is the relationship between Information and Spacetime?
- How do relativistic effects influence quantum information tasks?
  - And how can we exploit this?
- What can we learn about spacetime through studying quantum information?

Probing Quantum Fields in Curved Spacetime(s)

- QFT in curved spacetime treats both quantum matter fields and gravitation as having equal physical significance
- Provides clues as to what can be expected from a `true’ quantum gravity theory
- Many issues
  - Causal structure
  - Black hole entropy
  - Cosmic evolution
  - Vacuum entanglement
  - Black Hole Superposition

The Quantum Vacuum

- Empty space isn't empty!
  - It is filled with fields (electric, magnetic, scalar,…)
- These fields are like a set of coupled springs, one at every point

- Vacuum (ground) state is a global field state
  - springs vibrate with zero-point energy
  - entanglement between local modes
  - Bell-like inequality can be violated by local fluctuations
- And we can extract the entanglement!

Summers/Werner
PL A110 (1985) 5;
J. Math Phys 28 (1987) 2440

Reznik
Fnd Phys 33
(2003) 167

Valentini PLA153(1991) 321

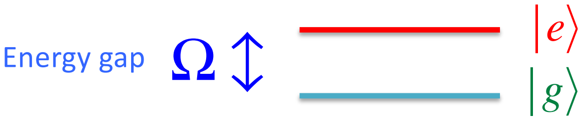
Salton/RBM/Menicucci NJP17 (2015) 035001

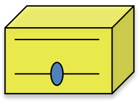
Quantum Detectors

- Model systems that couple to quantum fields
- Operational approach to probing quantum fields
- Example: Atoms – respond to EM field (photons!)
  - Absorb a photon → electron jumps up a level
  - Emit a photon → electron drops down a level
- Simplest atom? A qubit!

Unruh de Witt (UdW) detector (qubit)

B. deWitt in *General Relativity: An Einstein Centenary Survey* (CUP 1980)





UdW detector
→ like a quantum dot

$P \longrightarrow$ Probability that the detector gets excited

Quantum Detectors

S-Y Lin, B.L.Hu PRD73 (2006) 124018
PRD76 (2007) 064008

$$S_I = \lambda_0 \int d\tau \int d^4x Q(\tau)\Phi(x)\delta^4\left(x^\mu - z^\mu(\tau)\right)$$

Vacuum

$$S = \frac{m_0}{2}\underbrace{\int d\tau\left[\left(\partial_\tau Q\right)^2 - \Omega_0^2 Q^2\right]}_{\text{detector}} - \underbrace{\int d^4x\sqrt{-g}\,\frac{1}{2}\left(\nabla\Phi(x)\right)^2}_{\text{field}} + S_I$$

interaction

Cavity

$$\hat{H} = \overbrace{\Omega_d \hat{a}_d^\dagger \hat{a}_d}^{\text{detector}} + \frac{dt}{d\tau}\sum_n \overbrace{\omega_n \hat{a}_n^\dagger \hat{a}_n}^{\text{field}} + \overset{\text{interaction}}{H_I}$$

$$H_I = \lambda(\tau)(\hat{a}_d e^{-i\Omega\tau} + \hat{a}_d^\dagger e^{i\Omega\tau})\sum_n \left(\hat{a}_n u_n[x(\tau),t(\tau)] + \hat{a}_n^\dagger u_n^*[x(\tau),t(\tau)]\right)$$

Provide an operational means of probing the quantum character of spacetime

E.G. Brown, E. Martin-Martinez, N. Menicucci, RBM PRD87 (2013) 084062
D. Bruschi, A. Lee, I Fuentes J. Phys A46 (2013) 165303

2-Detector Formalism

$$S = -\int d^4x\sqrt{-g}\left[R + \frac{1}{2}\partial_\mu\Phi(x)\partial^\mu\Phi(x) - \xi R\Phi^2(x)\right]$$

$$+\int d\tau\left\{\frac{m_0}{2}\left[\left(\partial_\tau Q\right)^2 - \Omega_0^2 Q^2\right] + \sum_D \lambda_D \int d^4x Q_D(\tau)\Phi(x)\delta^4\left(x^\mu - z_D^\mu(\tau)\right)\right\}$$

$$U = \mathcal{T}e^{-i\int dt\left[\sum_D \frac{d\tau_D}{dt} H_{ID}(\tau_D)\right]}$$

$$H_{ID}(\tau) = \chi_D(\tau)\left[e^{i\Omega_D\tau}\sigma_D^+ + e^{-i\Omega_D\tau}\sigma_D^-\right]\Phi[z_D(\tau)]$$

switcher

monopole operator

$$\chi_D = \exp\left(-\frac{(\tau - \tau_D)^2}{2\sigma_D^2}\right)$$

$$\sigma_D^+ \coloneqq |1_D\rangle\langle 0_D| = |e_D\rangle\langle g_D|$$

$$\sigma_D^+ \coloneqq |0_D\rangle\langle 1_D| = |g_D\rangle\langle e_D|$$

$$\rho_{ij} \coloneqq \mathrm{Tr}_\Phi(U|\Psi\rangle_i\langle\Psi|_i U^\dagger) = \begin{pmatrix} 1 - P_A - P_B & 0 & 0 & X \\ 0 & P_B & C & 0 \\ 0 & C^* & P_A & 0 \\ X^* & 0 & 0 & 0 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\rho = \begin{pmatrix} 1-P_A-P_B & 0 & 0 & X \\ 0 & P_B & C & 0 \\ 0 & C^* & P_A & 0 \\ X^* & 0 & 0 & 0 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$W(x,x') := \langle 0|\phi(x)\phi(x')|0\rangle$$

$$\tau_D = \gamma_D t$$

$$P_D = \lambda^2 \int_{-\infty}^{\infty} d\tau_D \int_{-\infty}^{\infty} d\tau_{D'}\, \chi_D(\tau_D)\chi_{D'}(\tau_{D'}) e^{-i\Omega_D(\tau_D-\tau_{D'})} W\left(x_D(\tau_D), x_D(\tau_{D'})\right) \quad D = A, B$$

Local excitations

$$C = \lambda^2 \int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} dt' \frac{d\tau_A}{dt}\frac{d\tau_B}{dt'} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_A\tau_A-\Omega_B\tau_B)} W\left(x_A(t), x_B(t')\right)$$

Local correlations

$$X = -\lambda^2 \int_{-\infty}^{\infty} dt \int_{-\infty}^{t} dt' [\frac{d\tau_A}{dt'}\frac{d\tau_B}{dt} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_B\tau_B+\Omega_A\tau_A)} W\left(x_A(t'), x_B(t)\right)$$
$$+ \frac{d\tau_A}{dt}\frac{d\tau_B}{dt'} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_A\tau_A+\Omega_B\tau_B)} W\left(x_B(t'), x_A(t)\right)]$$

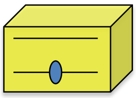
Non-Local correlations

Entanglement measure:

Concurrence

$$\mathcal{C} = 2\mathcal{N} = \max\{0, |X| - \sqrt{P_A P_B}\} + \mathcal{O}(\lambda^4)$$

Accelerating Detectors Get Hot!



$$\xrightarrow{a}$$

$$P \rightarrow \text{ thermal} \quad T = \frac{a}{2\pi}\left(\frac{\hbar}{k_B c}\right)$$

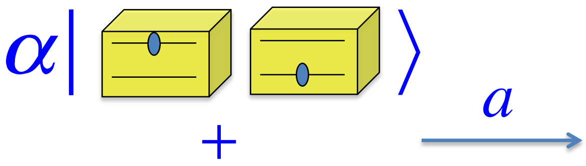
S.A. Fulling PRD7 (1973) 2850 P.C.W. Davies J Phys A8 (1975) 609 W. G. Unruh PRD14 (1976) 3251

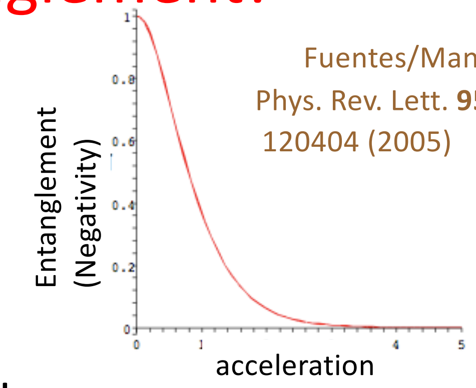
- A single detector, accelerating uniformly forever, will respond as though it is in a heat bath
- Idealized conditions can be relaxed
  - Finite time acceleration
  - Motion within cavities
  - Non-uniform motion
- A cold vacuum to one observer is a hot vacuum to another
- Effect is robust

Can even turn this into a heat engine!

Arias/ Oliveira/ Sarandy JHEP **18** (2018) 168
F. Gray/RBM JHEP **11** (2018) 174

Entangled Accelerating Detectors → Degraded Entanglement!



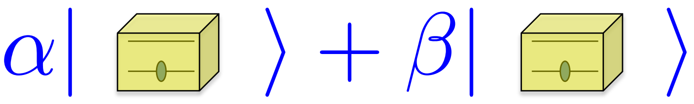


Fuentes/Mann
Phys. Rev. Lett. **95**
120404 (2005)

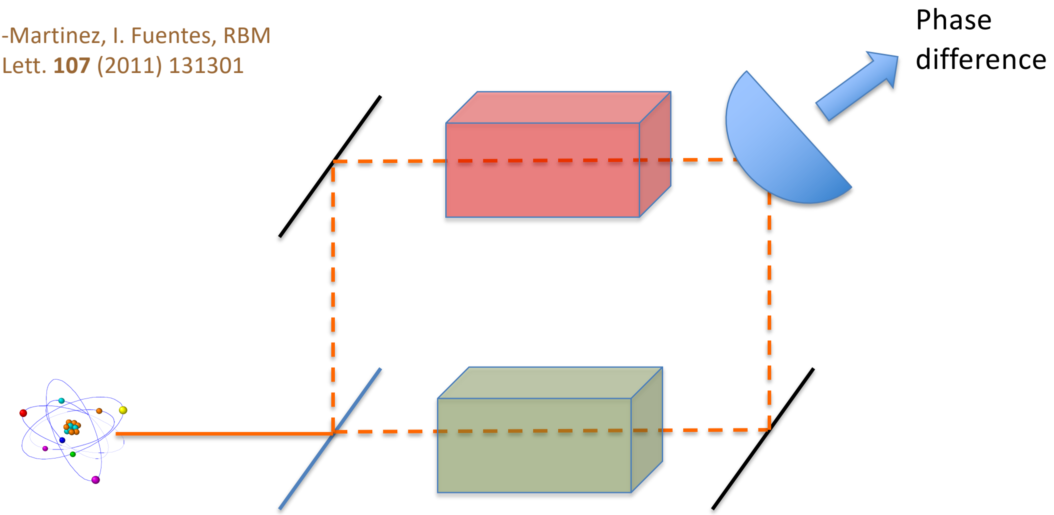
Alsing/Fuentes/RBM/Tessier
Phys. Rev. A**74**
032326 (2006)

- 2 maximally entangled detectors lose entanglement if one of them accelerates!
- More acceleration → less entanglement!
- But gravity and acceleration are locally the same!
- → Gravity (curved spacetime) should affect quantum entanglement!

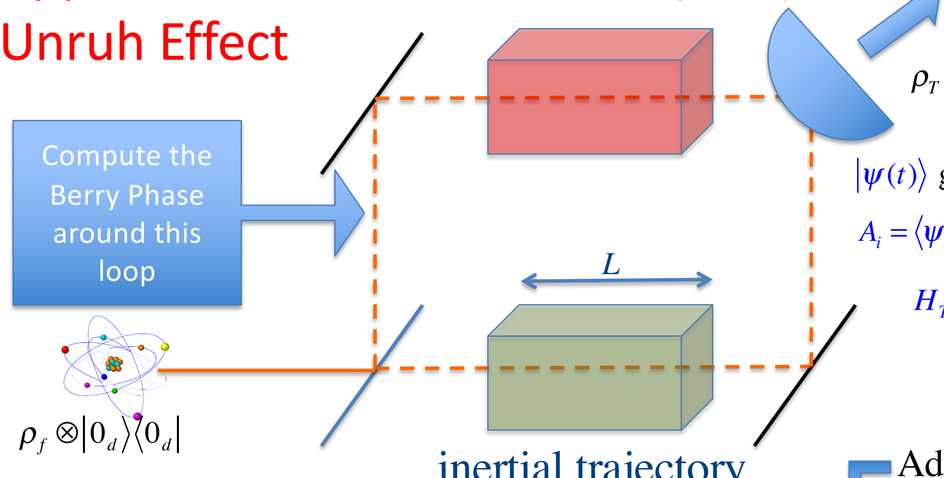
Detectors in Superposition



E. Martin-Martinez, I. Fuentes, RBM
Phys.Rev.Lett. **107** (2011) 131301



Application: Unruh Effect



accelerated trajectory

Compute the Berry Phase around this loop

L

$\rho_f \otimes |0_d\rangle\langle 0_d|$

inertial trajectory

Phase difference

$$\rho_T = U_R^\dagger\left(\rho_f \otimes |0_d\rangle\langle 0_d|\right)U_R$$

$|\psi(t)\rangle$ gains phase $i\gamma = \oint_R \vec{A}\cdot \mathrm{d}\vec{\mathrm{R}}$

$$A_i = \langle\psi(t)|\partial_{R_i}|\psi(t)\rangle$$

$$H_T = \Omega_a a^\dagger a + \Omega_b b^\dagger b + \lambda(b+b^\dagger)[a^\dagger e^{i(kx-\Omega_a t)} + a e^{-i(kx-\Omega_a t)}]$$

Adiabatic for small λ

For either cavity $|0_f 0_d\rangle \to \sum_{n,m} \langle n_f m_d|U|00\rangle U^\dagger |n_f m_d\rangle \simeq U^\dagger|0_f 0_d\rangle + \mathcal{O}(\lambda^2)$

Berry Phase

$$\frac{\gamma_I}{2\pi} = \frac{\omega_a \sin^2 v \sinh[2(C-v)] + \omega_b \sinh(2v)\sinh^2(C-v)}{\omega_a \sinh[2(C-v)] + \omega_b \sinh(2v)}$$

$2C = \ln\left(\omega_a / \omega_b\right)$

inertial trajectory

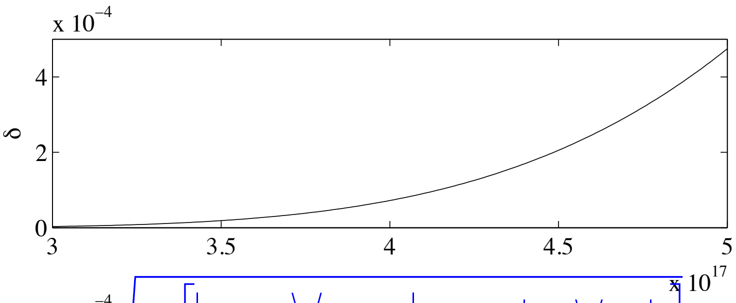
$$\gamma_a = \gamma_I - \mathrm{Arg}\left(\cosh^2 q - e^{2\pi i G}\sinh^2 q\right)$$

accelerated trajectory

$$q = \arctan\left(e^{-\pi\Omega_a c/a}\right) \quad G = \frac{\omega_b \sinh(2v)\cosh[2(C-v)]}{\omega_a \sinh[2(C-v)] + \omega_b \sinh(2v)}$$

E. Martin-Martinez, I. Fuentes, RBM
Phys.Rev.Lett. **107** (2011) 131301

$$\delta = \gamma_a - \gamma_I$$



$\Omega_a \simeq 2.0\mathrm{GHz}$
$\Omega_b \simeq 2.0\mathrm{GHz}$
$\lambda \simeq 34\mathrm{Hz}$

- Visibility $V = \sqrt{\mathrm{Tr}\left[|0_f 0_d\rangle\langle 0_f 0_d|(\rho_f \otimes |0_d\rangle\langle 0_d|)\right]} = \cosh^{-1} q \simeq 1$ due to low accelerations
- Maximal phase difference $\delta = \pi \Rightarrow a \approx 4.5\cdot 10^{17}\,\mathrm{m/s^2}$ $\Rightarrow$ 30,000 cycles $\Rightarrow$ 95 μs
- For $a \approx 10^{17}\,\mathrm{m/s^2}$ relativistic speeds ($\approx 0.15c$) reached in times $t \approx \Omega_a^{-1}$
- Current metrology permits $\Delta\phi \approx 10^{-8}$ sensitivity in phase difference

Dragan/Martin-Martinez,/Fuentes/RBM,
N J Phys **15** 053036 (2013)

Quantum Controlled Detectors

Foo/Onoe/Zych
PRD **102** (2020) 085013
Foo/Onoe/RBM/Zych
PRR **3** (2021) 043056

Recall: Single Detector

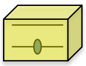
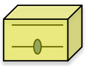
$$H_{ID}(\tau) = \chi_D(\tau)\left[e^{i\Omega_D\tau}\sigma_D^+ + e^{-i\Omega_D\tau}\sigma_D^-\right]\Phi[z_D(\tau)]$$

$$W(x,x') := \langle 0|\phi(x)\phi(x')|0\rangle$$

$$P_D = \lambda^2 \int_{-\infty}^{\infty} d\tau_D \int_{-\infty}^{\infty} d\tau_{D'}\, \chi_D(\tau_D)\chi_{D'}(\tau_{D'}) e^{-i\Omega_D(\tau_D-\tau_{D'})} W\big(x_D(\tau_D), x_D(\tau_{D'})\big) \qquad D = A,B$$

$$\tau_D = \gamma_D t$$

Superposed Detector → use Quantum Control

$\alpha|$  $\rangle + \beta|$  $\rangle$

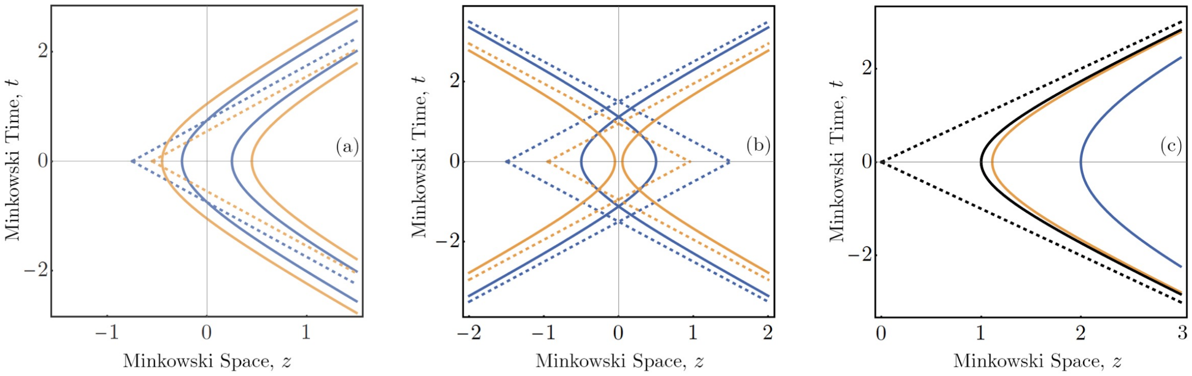
$$\hat{H}_I(\tau) = \lambda\left[e^{i\Omega\tau}\sigma^+ + e^{-i\Omega\tau}\sigma^-\right]\sum_{i=1}^{N}\chi_i(\tau)\Phi(\mathsf{z}_i(\tau)) \otimes |c_i\rangle\langle c_i|$$

Measure in control state $|c\rangle = \frac{1}{\sqrt{N}}\sum_{i=1}^{N}|c_i\rangle$

$$P_D = \frac{\lambda^2}{N^2}\sum_{i,j=1}^{N}\int_{-\infty}^{\infty} d\tau' \chi_i(\tau') e^{-i\Omega\tau'} \int_{-\infty}^{\infty} d\tau'' \overline{\chi_j}(\tau'') e^{-i\Omega\tau''} \mathcal{W}_+^{ji}(\tau',\tau'')$$

Superposed trajectories exhibit interference

$$P_D = \frac{\lambda^2}{N^2}\sum_{i,j=1}^{N}\int_{-\infty}^{\infty} d\tau' \chi_i(\tau') e^{-i\Omega\tau'} \int_{-\infty}^{\infty} d\tau'' \overline{\chi_j}(\tau'') e^{-i\Omega\tau''} \mathcal{W}_+^{ji}(\tau',\tau'')$$



Superposed
Parallel Accelerations

Superposed
Anti-parallel Accelerations

Superposed
Accelerations of
Different Magnitude

$$T_U \neq \frac{a}{2\pi}$$

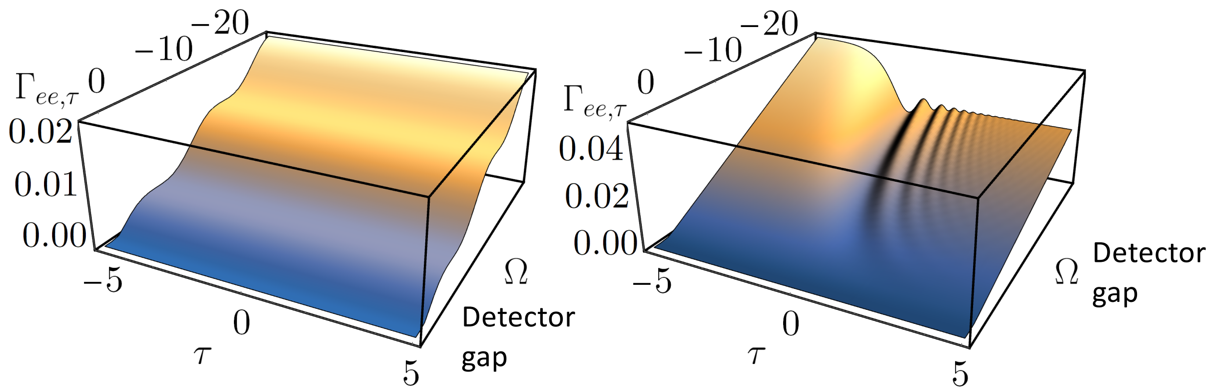
Superposed Detectors with same uniform acceleration do NOT have a thermal response!

A Superposed Detector gains information about the field!

$$\Gamma \propto \sum_{i,j=1}^{N} \int_{-\infty}^{\tau} d\tau' \chi_j(\tau') e^{-i\Omega\tau'} \int_{-\infty}^{\tau} d\tau'' \overline{\chi}_i(\tau'') e^{-i\Omega\tau''} \mathcal{W}_{+}^{ji}(\tau', \tau'')$$

Response Rate: Thermal Bath

Response Rate: de Sitter



Gibbons/Hawking
PRD (1979)

- Superposed detector separated by a distance *L*
- Single detector cannot distinguish between a thermal bath and conformal vacuum of expanding universe at same temperature
- Superposed detector CAN distinguish these two settings

Schroedinger's Cat in de Sitter Space

Superpositions of stationary detector trajectories in a single spacetime

⟷

A single detector in a superpositions of diffeomorphic spacetimes

$$|\Psi\rangle_{\text{iFD}} = \frac{1}{\sqrt{2}}\left(|\xi\rangle + |\xi + \mathcal{L}\rangle\right)|g\rangle|0_{\text{dS}}\rangle$$

$$= \frac{1}{\sqrt{2}}\underbrace{\left(\mathbb{I} + \hat{\mathcal{T}}(\mathcal{L})\right)|\xi\rangle|g\rangle}_{\text{Detector in superposed trajectory}}|0_{\text{dS}}\rangle$$

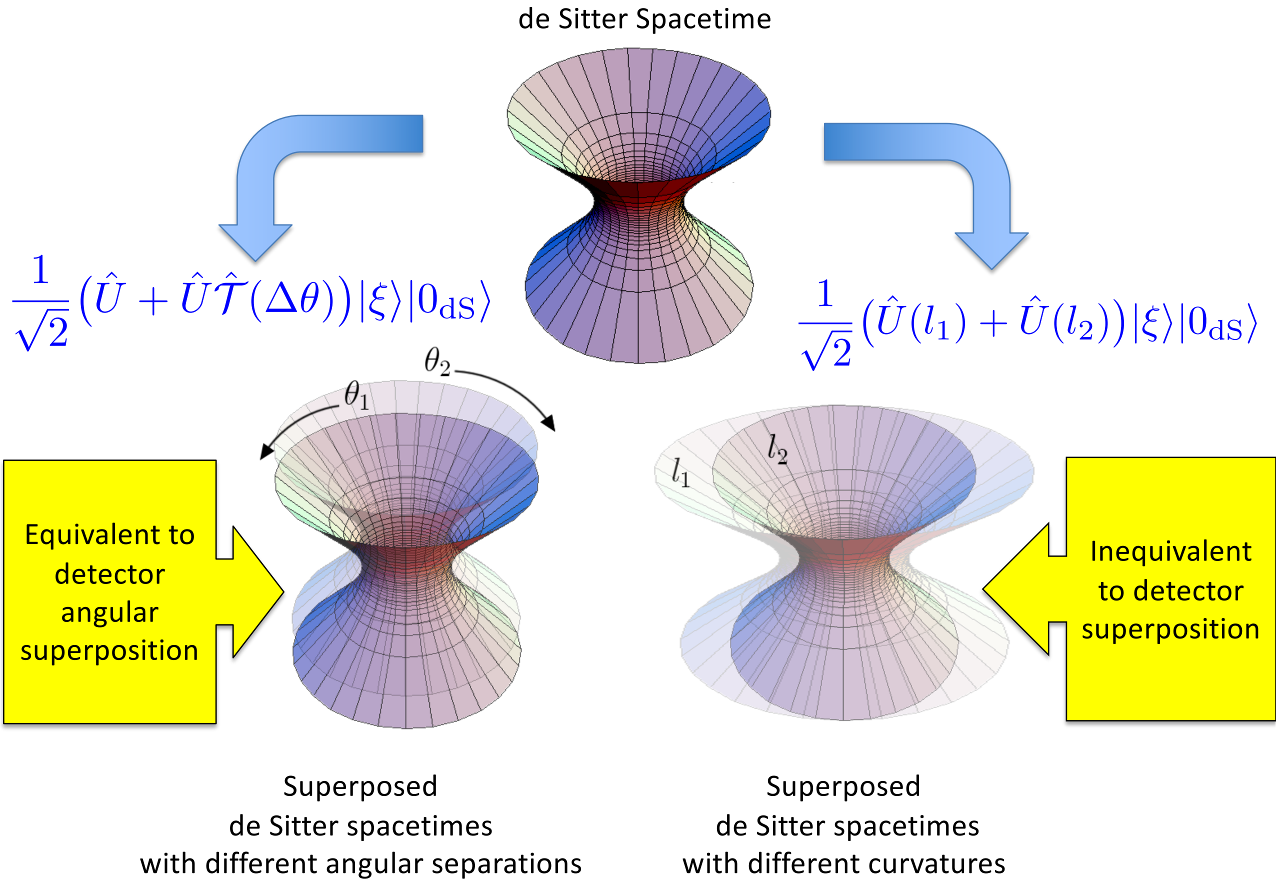
Time evolution

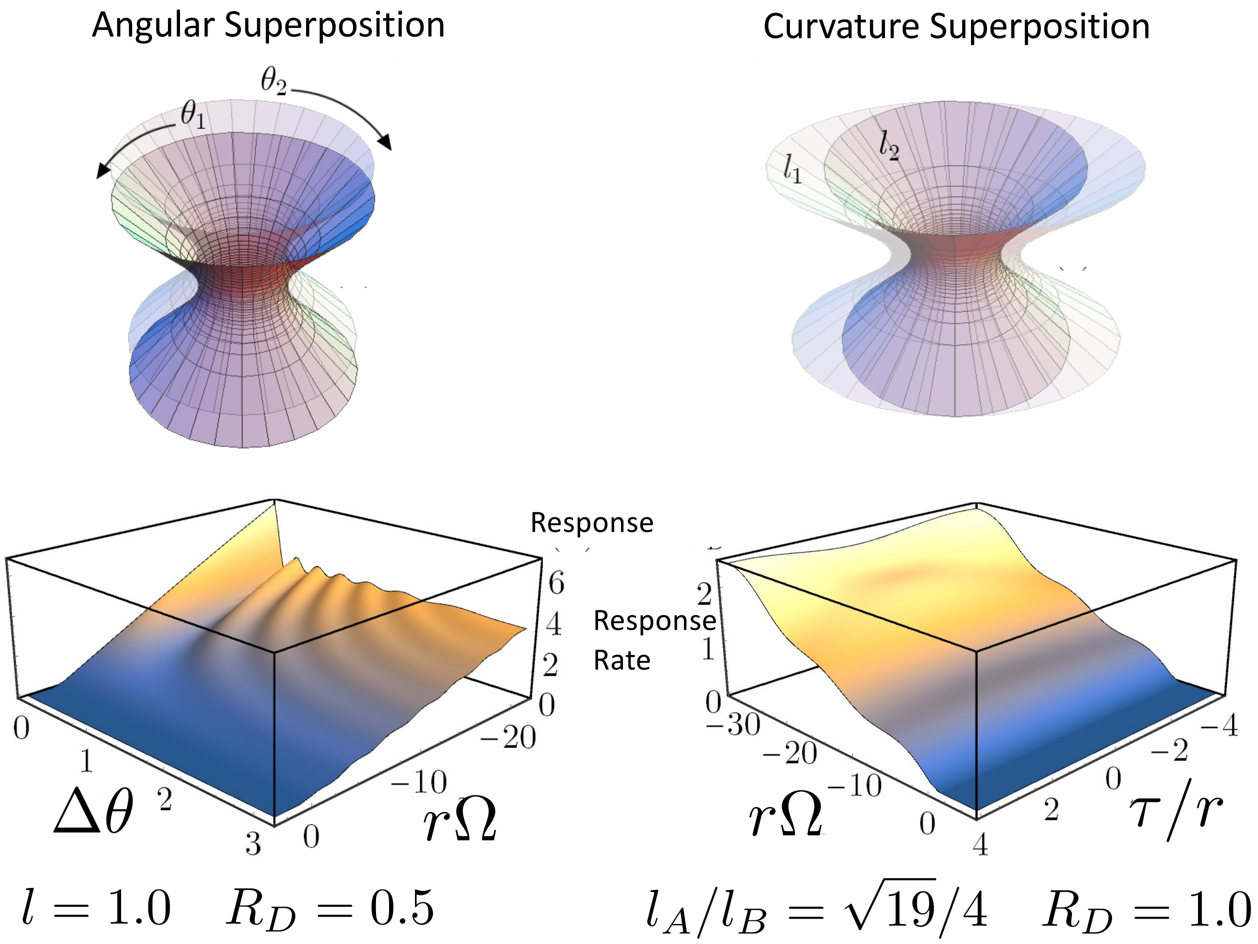
$$\hat{U}|\Psi\rangle_{\text{iFD}} = \frac{1}{\sqrt{2}}\left(\hat{U} + \hat{U}\hat{\mathcal{T}}(\mathcal{L})\right)|\xi\rangle|0_{\text{dS}}\rangle|g\rangle$$

$$|\Psi\rangle_{FD} = \frac{1}{2}\underbrace{\left(\hat{U}(\xi) + \hat{U}(\xi + \mathcal{L})\right)|0_{\text{dS}}\rangle}_{\text{superposed spacetime/field}}|g\rangle$$

Measure in control basis

Foo/RBM/Zych
CQG **38** (2021)
115010


de Sitter Spacetime
$\frac{1}{\sqrt{2}}(\hat{U}+\hat{U}\hat{\mathcal{T}}(\Delta\theta))|\xi\rangle|0_{\rm dS}\rangle$
$\frac{1}{\sqrt{2}}(\hat{U}(l_1)+\hat{U}(l_2))|\xi\rangle|0_{\rm dS}\rangle$
θ_2
θ_1
l_2
l_1
Equivalent to detector angular superposition
Inequivalent to detector superposition
Superposed de Sitter spacetimes with different angular separations
Superposed de Sitter spacetimes with different curvatures


Angular Superposition
Curvature Superposition
θ_2
θ_1
l_2
l_1
Response
6
4
2
0
0
1
2
3
$\Delta\theta$
0
-10
-20
$r\Omega$
Response Rate
2
1
0
-30
-20
-10
0
$r\Omega$
4
2
0
-2
-4
τ/r
$l=1.0 \quad R_D=0.5$
$l_A/l_B=\sqrt{19}/4 \quad R_D=1.0$

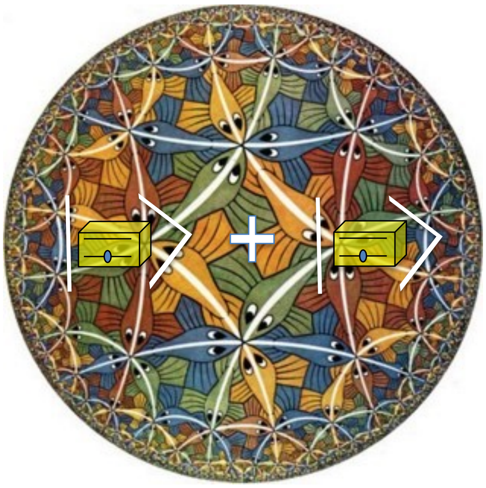
Black Hole Superposition

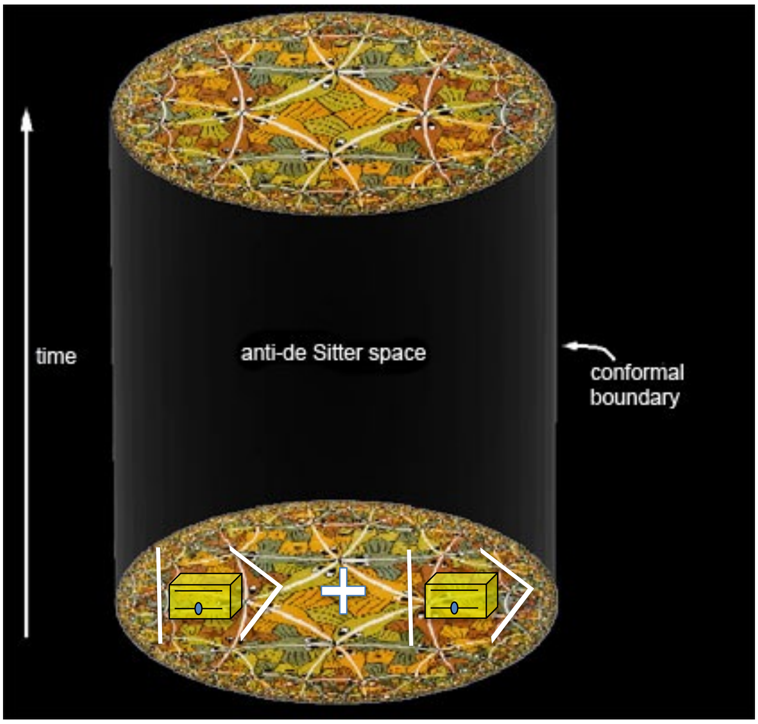
- Still lack a quantum theory of gravity
- General Expectation: Spacetime superposition
- Specifically: black hole superposition
  - Complicated in general: curvature not constant
  - Wightman functions are mode superpositions
- Test lab: BTZ black hole
  - Constant curvature black hole
  - Superpose using methods from de Sitter space

Two (superposed) Detectors in Anti de Sitter Space

2+1: Henderson/Hennigar/Smith/Zhang/RBM JHEP **05** (2019) 178

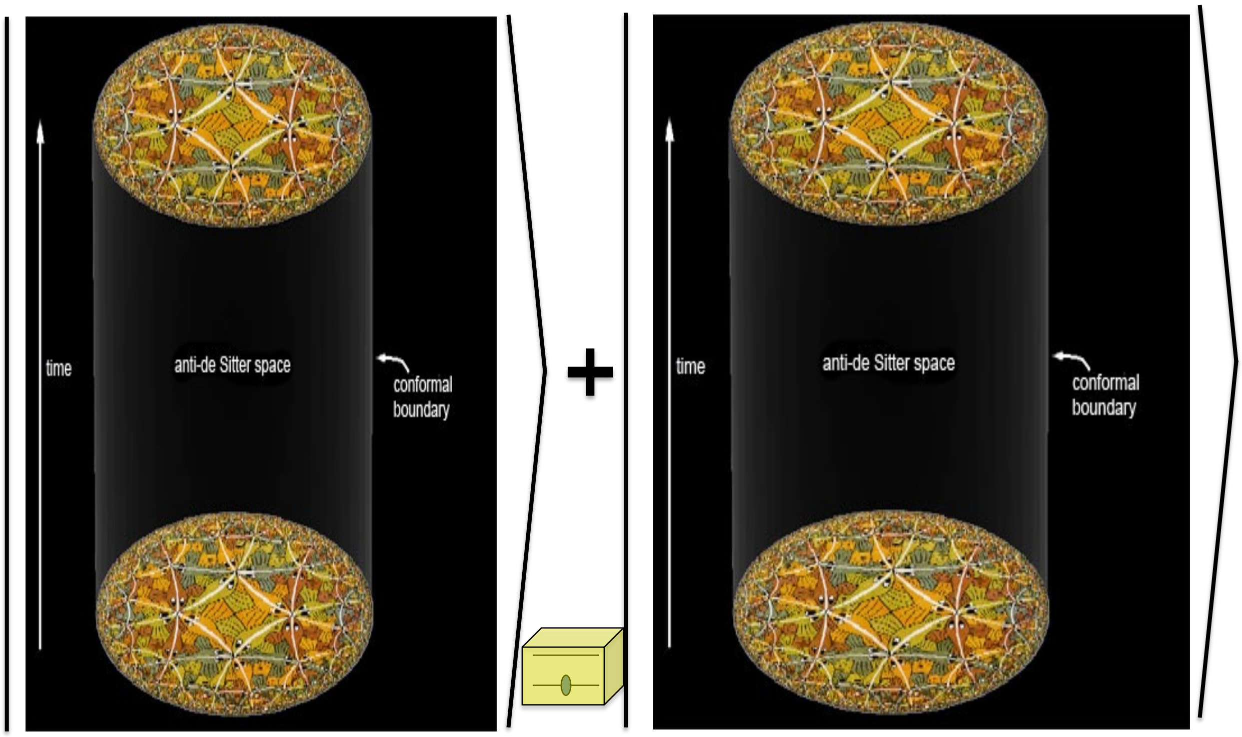
3+1: Ng/Martin-Martinez/RBM PRD98 (2018) 125005





Detector in Superposed Anti de Sitter Space

Arabaci/Foo/RBM/Zych PRL (2022)



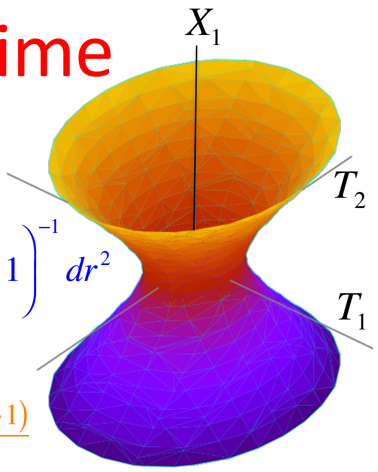
Anti de Sitter Spacetime

$$\sum_{J=1}^{D-1} X_J^2 - T_1^2 - T_2^2 = -\ell^2$$

$$ds^2 = -dT_1^2 - dT_2^2 + \sum_{J=1}^{D-1} dX_J^2$$

Hyperboloid in flat spacetime

$$ds^2 = -\left(\frac{r^2}{\ell^2}+1\right)dt^2 + \left(\frac{r^2}{\ell^2}+1\right)^{-1} dr^2 + r^2 d\Omega_{D-2}^2$$



$$\Lambda = -\frac{(D-2)(D-1)}{2\ell^2}$$

Conformal scalar coupling

$$W_{AdS}^{(\zeta)}(x,x') = \frac{1}{4\pi\ell\sqrt{2}}\left(\frac{1}{\sqrt{\sigma_\epsilon(x,x')}} - \frac{\zeta}{\sqrt{\sigma_\epsilon(x,x')+2}}\right)$$

2+1

Geodesic length

$\zeta = 1$ (Dirichlet)
$\zeta = 0$ (Transparent)
$\zeta = -1$ (Neumann)

$$W_{AdS}^{(\zeta=1)}(x,x') = \sum_{\omega=0}^{\infty}\sum_{lm}\frac{1}{2\omega}e^{-i\omega(t-t')}\varphi_{\omega lm}(x)\bar{\varphi}_{\omega lm}(x')$$

3+1

Sum over modes

$$\Phi_{\omega lm}(t,x) = \frac{1}{\sqrt{2\omega}}e^{-i\omega t}\varphi_{\omega lm}(x)$$

The BTZ Black Hole

$$ds^2 = -dT_1^2 - dT_2^2 + dX_1^2 + dX_2^2$$

covering space metric

$$-l^2 = -T_1^2 - T_2^2 + X_1^2 + X_2^2$$

hyperbolic constraint surface

$$T_1 = l\sqrt{\frac{r^2}{l^2}}\cosh\phi \qquad X_1 = l\sqrt{\frac{r^2}{l^2}}\sinh\phi$$

$$T_2 = l\sqrt{\frac{r^2}{l^2}-1}\sinh\frac{t}{l} \qquad X_2 = l\sqrt{\frac{r^2}{l^2}-1}\cosh\frac{t}{l}$$

$$ds^2 = -\left(\frac{r^2}{l^2}-1\right)dt^2 + \left(\frac{r^2}{l^2}-1\right)dr^2 + r^2 d\phi^2 \begin{cases} \phi \quad \text{unidentified} \Rightarrow & \text{AdS Rindler space} \\ \phi \to \phi + 2\pi\sqrt{M} \Rightarrow & \text{BTZ black hole} \end{cases}$$

$$r = \tilde{r}/\sqrt{M} \quad t = \tilde{t}\sqrt{M} \quad \phi = \tilde{\phi}\sqrt{M}$$

$$ds^2 = -\left(\frac{\tilde{r}^2}{l^2}-M\right)d\tilde{t}^2 + \left(\frac{\tilde{r}^2}{l^2}-M\right)^{-1}d\tilde{r}^2 + \tilde{r}^2 d\tilde{\phi}^2$$

$$\tilde{\phi} \to \tilde{\phi} + 2\pi$$

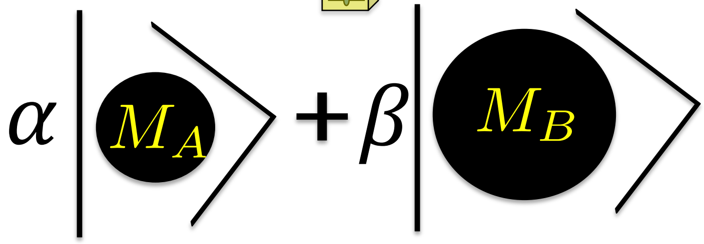
BTZ
black hole

The Superposed BTZ Black Hole

Arabaci/Foo/RBM/Zych
PRL (to appear)

$$ds^2 = -\left(\frac{r^2}{l^2}-1\right)dt^2 + \left(\frac{r^2}{l^2}-1\right)dr^2 + r^2 d\phi^2 \quad \Gamma : \phi \to \phi + 2\pi\sqrt{M}$$

Superpose the identifications:



$$\Gamma_A : \phi \to \phi + 2\pi\sqrt{M_A} \qquad \Gamma_B : \phi \to \phi + 2\pi\sqrt{M_B}$$

AdS Wightman fn

$$W^{(\zeta)}_{AdS}(x,x') = \frac{1}{4\pi\ell\sqrt{2}}\left(\frac{1}{\sqrt{\sigma_\epsilon(x,x')}} - \frac{\zeta}{\sqrt{\sigma_\epsilon(x,x')+2}}\right)$$

untwisted

$$\eta = \pm 1$$

twisted

⇨ $$W_{\mathrm{BTZ}}(\mathsf{x},\mathsf{x}') = \frac{1}{\sum_k \eta^{2k}}\sum_n\sum_m \eta^n\eta^m W_{\mathrm{AdS}}(\Gamma^n\mathsf{x},\Gamma^m\mathsf{x}')$$

BTZ Wightman fn

⇨ $$W^{(AB)}_{\mathrm{BTZ}}(\mathsf{x},\mathsf{x}') = \frac{1}{\sum_k \eta^{2k}}\sum_{n,m} \eta^n\eta^m W_{\mathrm{AdS}}(\Gamma^n_A\mathsf{x},\Gamma^m_B\mathsf{x}')$$

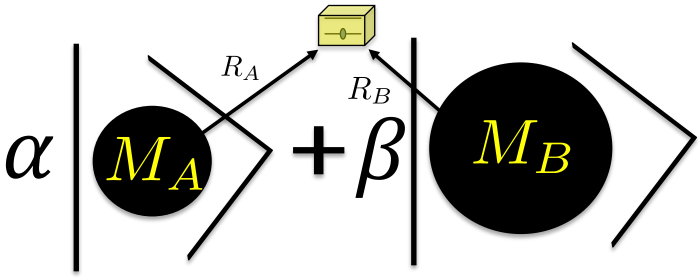
Superposed
BTZ Wightman fn

$$W^{(AB)}_{\mathrm{BTZ}}(\mathsf{x},\mathsf{x}') = \frac{1}{\sum_k \eta^{2k}} \sum_{n,m} \eta^n \eta^m W_{\mathrm{AdS}}(\Gamma^n_A \mathsf{x}, \Gamma^m_B \mathsf{x}')$$

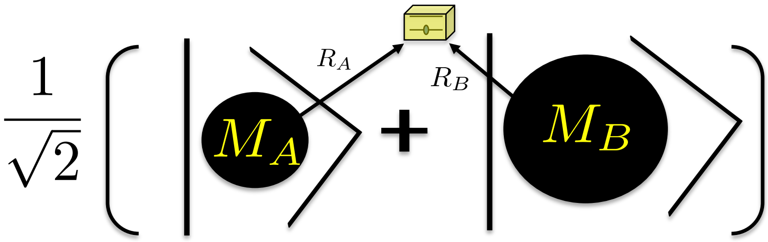
$$W^{(\zeta)}_{AdS}(x,x') = \frac{1}{4\pi\ell\sqrt{2}}\left(\frac{1}{\sqrt{\sigma_\epsilon(x,x')}} - \frac{\zeta}{\sqrt{\sigma_\epsilon(x,x')+2}}\right)$$

$\zeta = 1$ (Dirichlet)
$\zeta = 0$ (Transparent)
$\zeta = -1$ (Neumann)

$$\sigma(\Gamma^n_A \mathsf{x}, \Gamma^m_B \mathsf{x}') = \sqrt{\frac{R_A^2}{l^2}}\sqrt{\frac{R_B^2}{l^2}} \cosh\left[2\pi(m\sqrt{M_A} - n\sqrt{M_B})\right] - 1$$
$$- \sqrt{\frac{R_A^2}{l^2} - 1}\sqrt{\frac{R_B^2}{l^2} - 1} \cosh\left(\frac{t-t'}{l}\right)$$



Dynamical Evolution



$$|\psi(t_i)\rangle = \frac{1}{\sqrt{2}}(|M_A\rangle + |M_B\rangle)|0\rangle|g\rangle \Rightarrow |\psi(t_f)\rangle = e^{-iH_{0,s}t_f}\hat{U}e^{iH_{0,s}t_i}|\psi(t_i)\rangle$$

Condition on $|\pm\rangle = (|M_A\rangle \pm |M_B\rangle)/\sqrt{2}$ and trace out the field

$$\mathrm{Tr}_\phi\left[\langle\pm|\psi(t_f)\rangle\langle\psi(t_f)|\pm\rangle\right] = \frac{|g\rangle\langle g|}{2}P_G^{(\pm)} + \lambda^2\frac{|e\rangle\langle e|}{2}P_E^{(\pm)}$$

$$= \frac{|g\rangle\langle g|}{2}\Big(1 \pm \cos(\Delta E \Delta t)\Big)\left[1 - \frac{\lambda^2}{2}\int_{-t_f}^{t_f} d\tau \int_{-t_f}^{t_f} d\tau' \eta(\tau)\eta(\tau')e^{-i\Omega(\tau-\tau')}\Big(W(x_A,x_A') + W(x_B,x_B')\Big)\right]$$

$$+\frac{\lambda^2|e\rangle\langle e|}{4}\int_{-t_f}^{t_f} d\tau \int_{-t_f}^{t_f} d\tau' \eta(\tau)\eta(\tau')e^{-i\Omega(\tau-\tau')}\Big(W(x_A,x_A') + W(x_B,x_B') \pm 2\cos(\Delta E\Delta t)W(x_A,x_B')\Big)$$

Reduced Density Matrix of the Detector

$$P_G^{(\pm)} = \frac{1}{2}\Big(1 \pm \cos(\Delta E \Delta t)\Big)\Big[1 - \frac{\lambda^2}{2}\Big(P_A + P_B\Big)\Big]$$

$$P_E^{(\pm)} = \frac{\lambda^2}{4}\Big(P_A + P_B \pm 2\cos(\Delta E \Delta t) L_{AB}\Big)$$

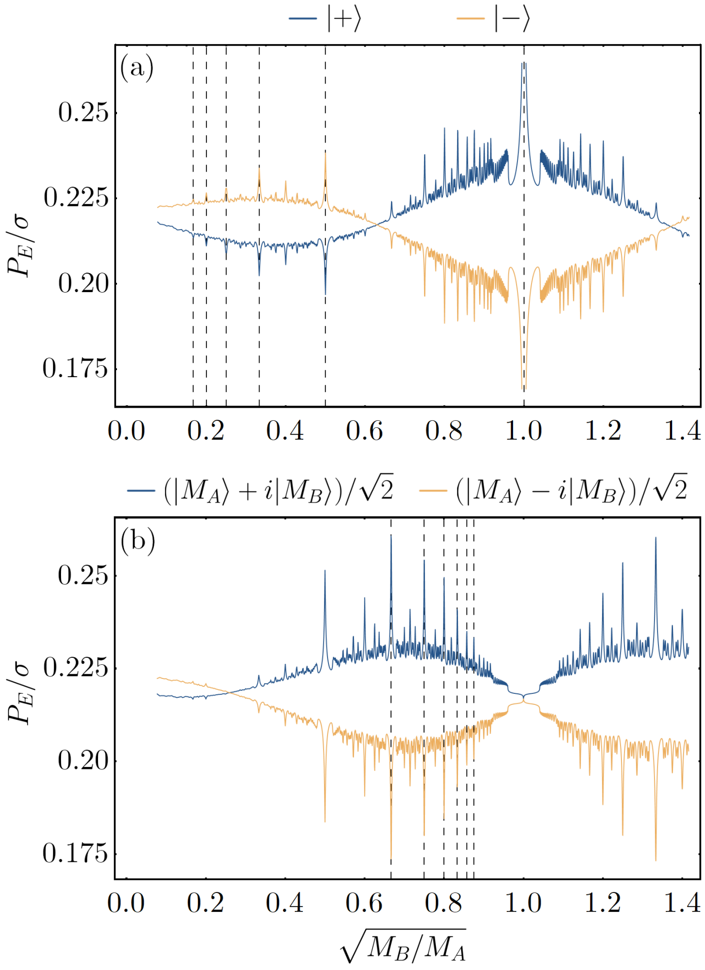
Probabilities oscillate in time
due to different energies (masses)

$$\frac{P_D}{\sigma} = \frac{\sqrt{\pi} H_0(0)}{8} - \frac{i}{8\sqrt{\pi}} \mathrm{PV} \int_{-t_f/2l}^{t_f/2l} \frac{dz\, X_0(2lz) H_0(2lz)}{\sinh(z)} + \frac{1}{4\sqrt{2\pi} \sum_n \eta^{2n}} \sum_{n \neq m} \mathrm{Re} \int_0^{t_f/l} \frac{dz\, X_0(lz) H_0(lz)}{\sqrt{\beta_{nm} - \cosh(z)}}$$

$$\beta_{nm} = \frac{1}{\gamma_D^2}\left[\frac{R_D^2 \cosh(2\pi(n-m)\sqrt{M_D})}{M_D l^2} - 1\right]$$

$$\alpha_{nm} = \frac{1}{\gamma_A \gamma_B}\left[\frac{R_D^2 \cosh(2\pi(m\sqrt{M_A} - n\sqrt{M_B}))}{\sqrt{M_A M_B} l^2} - 1\right]$$

$$\frac{L_{AB}}{\sigma} = \frac{Y_0}{\sum_n \eta^{2n}} \sum_{n,m} \mathrm{Re} \int_0^{t_f/l} \frac{dz\, Z_0(lz) Q_0(lz)}{\sqrt{\alpha_{nm} - \cosh(z)}}.$$



Arabaci/Foo/RBM/Zych
PRL (to appear)

Dashed lines:
$\sqrt{M_B/M_A} = (n-1)/n$
where $n = \{3, \ldots 8\}$

Resonant peaks at integer values of (mass ratios)$^{1/2}$!

Consistent with Bekenstein's black hole mass quantization conjecture

Superposed Metric?

Classically:

$$g_{\mu\nu}(x) = -\lim_{x\to x'} \frac{\partial}{\partial x^\mu} \frac{\partial}{\partial x'^\nu} \sigma(\mathsf{x}, \mathsf{x}')$$

Knowledge of Synge geodesic distance
→ metric

Quantum Mechanically:

$$g_{\mu\nu} = -\frac{1}{2}\left(\frac{\Gamma(d/2-1)}{(4\pi^{d/2})}\right)^{\frac{2}{d-2}} \lim_{x\to x'} \frac{\partial}{\partial x^\mu} \frac{\partial}{\partial x'^\nu} W(\mathsf{x}, \mathsf{x}')^{\frac{2}{d-2}}$$

Saravani/Aslanbeigi/Kempf
PRD 93 (2016) 045026
Kempf
Front Phys **9** (2021) 247

Superposed Black Hole Metric?

$$g_{\mu\nu} = \Lambda(d) \lim_{x\to x'} \frac{\partial}{\partial x^\mu} \frac{\partial}{\partial x'^\nu} \sum_{D,D'} f_D f^\star_{D'} W(x_D, x'_{D'})^{\frac{2}{d-2}}$$

Summary

- Construction of superposed spacetimes
  - – curvature-superposed de Sitter
  - – mass-superposed black hole
  - – Operational description via Wightman function
  - – Generalizable to other spacetimes

Arabaci/Foo/RBM/Zych
2208.12083

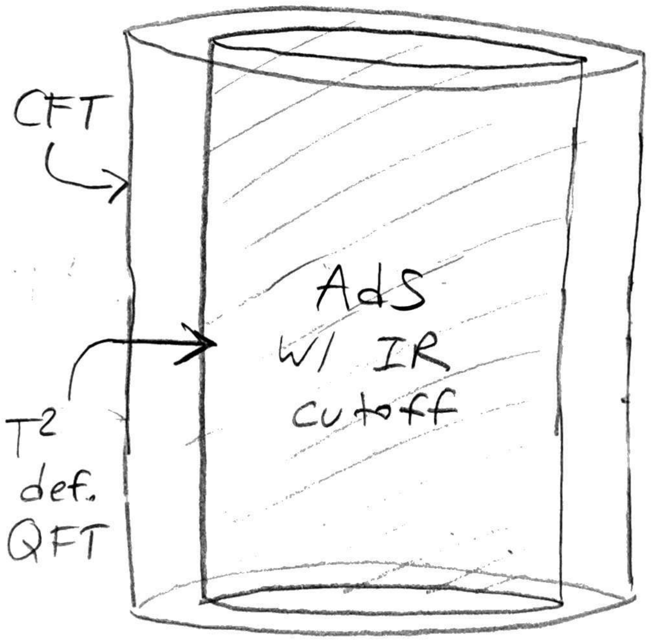
- Detector response
  - – Peaks at rational values of (mass-ratio)$^{1/2}$
  - – Consistent with Bekenstein' Conjecture
- Provides a pathway for understanding effects of quantum gravitational phenomena even without a quantum theory of gravity!

HOLOGRAPHIC CAUCHY SLICES

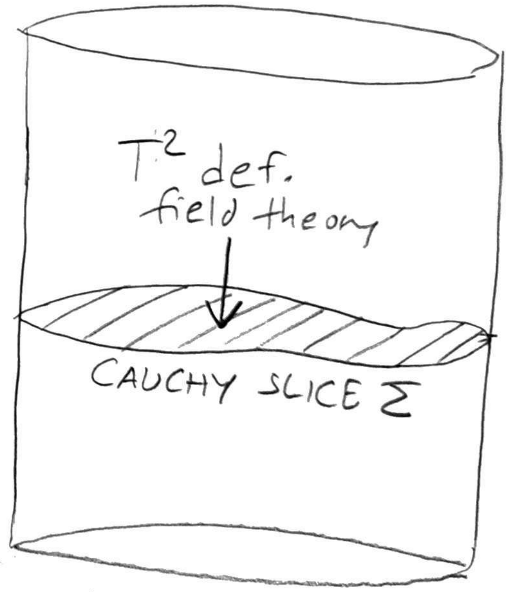
arxiv:2204.00591

In the usual AdS/CFT duality, the dual CFT lives at spatial ∞. Recently, there's been lots of interest in a "$T\bar{T}$" (or "T^2" in $d>2$) irrelevant deformation [will write later!] which is dual to a bulk w/ Dirichlet b.c.

usually implemented as finite radial cutoff:



but we* wish to have emergent time instead



(more like tensor network models)

It turns out you can do this with the same irrelevant deform. (but in a different regime).

* we = me + my 2 senior PhD students: Gonçalo Araujo-Regado & Rifath Khan

We want a field theory whose partition fn is also a Wheeler-DeWitt QG state:

$$Z[\underbrace{g, \phi \ldots}_{\substack{\text{fixed QFT background} \\ \text{Sources in } d \text{ (Euclidean)} \\ \text{Spacetime dimensions}}}] = \Psi_{WDW}[\underbrace{g, \phi \ldots}_{\substack{\text{dynamical spatial} \\ \text{Config variables} \\ \text{(evolves in } d+1 \text{ spacetime)}}}]$$

$$\underset{\substack{\uparrow \\ \text{stress-tensor}}}{-\frac{\sqrt{g}}{2} T^{ab}} = \frac{\delta}{\delta g_{ab}} = \underset{\substack{\uparrow \\ \text{ADM momentum}}}{i \Pi^{ab}}$$

(Similar for $\frac{\delta}{\delta \phi}$)

DUAL NOTIONS OF CONJUGATE VARIABLE

(source, operators) ⟷ (position, momentum)

THERMO / QFT MECHANICS

T_{ab} is imaginary ?!?

Yes, this is because the T^2 field thy exhibits $\boxed{\text{SPONTANEOUS CPT BREAKING}}$

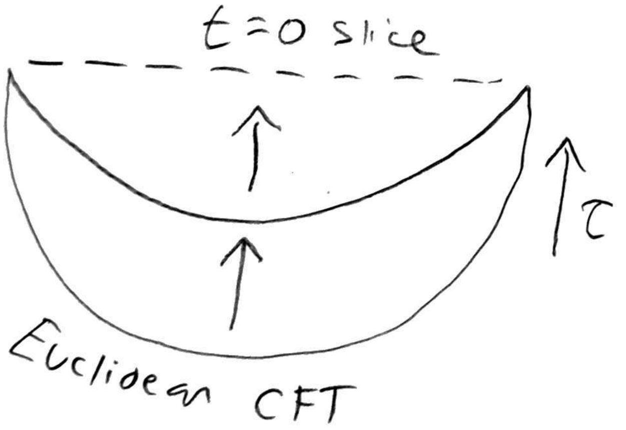
Doesn't contradict CPT Theorem since it also isn't unitary! (Lorentzian WDW states are not reflection positive)

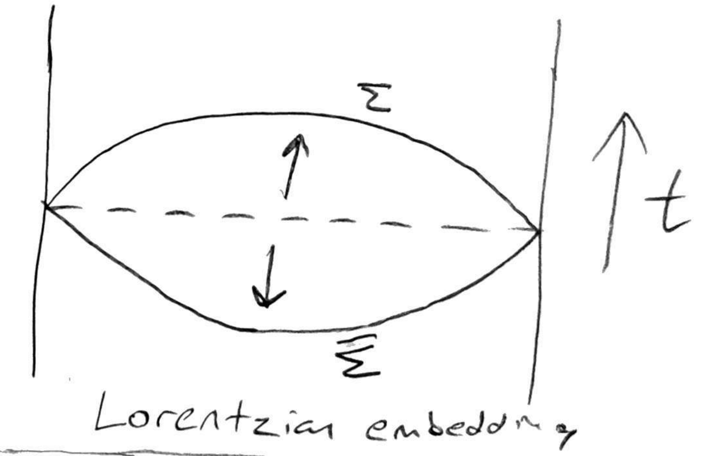
We start with a Euclidean holographic CFT defined on metric g_{ab}. We also need to pick a conformal frame since we're about to turn on an irrelevant T^2 coupling μ^*.

(*Here, we take μ to be constant. There is an alternative picture where we let μ be spatially dependent, but everything that can be done that way, can also be done by varying g_{ab}.)

cf. Caputa-Kruthoff-Parrikar '20

If g_{ab} is a uniform hyperbolic geometry, then as we increase μ, the boundary moves to the $t=0$ slice.



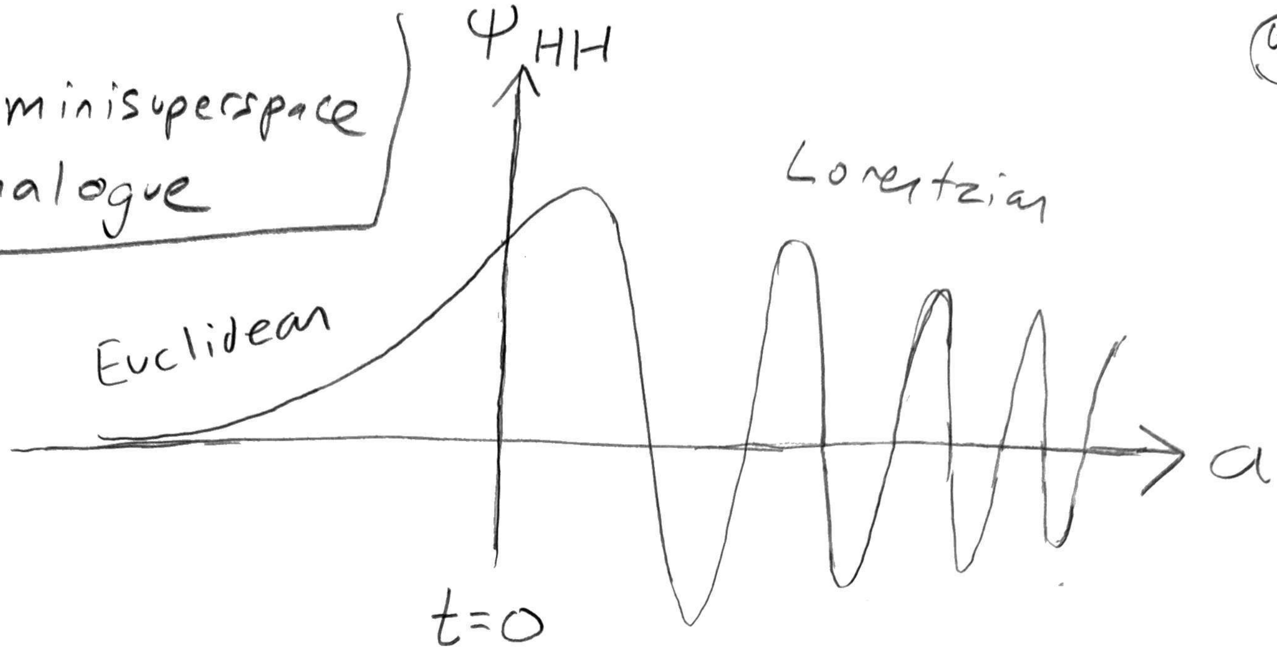


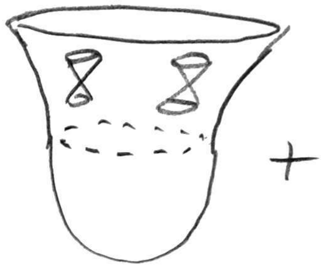
Past some critical value μ_0, the slice Σ moves to Lorentzian AdS. This breaks T (since $\bar{\Sigma}$ is equally good) without touching P or C. Hence, CPT broken!

Controlled by $\mathcal{H}$ constraint: $\Pi^2 \sim -(R-2\Lambda)$

so Π becomes real for slices with $R < 2\Lambda$

dS minisuperspace analogue





+ T reverse

$a < R_{AdS}$

$\Psi_{HH} > 0$

$a = R_{AdS}$

$a > R_{AdS}$

Ψ_{HH} mixed sign
(non reflection pos.)

at critical radius,
WKB approx breaks down
[see Witten 2018, "A Note on Boundary Conditions in Euclidean Gravity"]
but $\Psi_{HH}(a)$ OK

The Deformation:

Inspired by Hartman-Kruthoff-Shagholin-Tajdini '18

$$\mathcal{H}(x) \xleftrightarrow[\text{[up to } D^a \text{ terms]}]{\text{commutes past}} \Pi(x) \ \left[\begin{smallmatrix}\text{modulo}\\ \text{anomaly}\end{smallmatrix}\right]$$

$$\boxed{Z^{(\mu)}[g,\phi] = e^{CT}\left(P\exp\int_{\epsilon}^{\mu}\frac{d\lambda}{\lambda}O(\lambda)\right)Z^{(\epsilon)}_{CFT}[g,\phi]}$$

T^2 coupling

counterterms

deformation operator

UV regulator to deal w/ log divergences associated w/ CFT anomalies

Here $O(\lambda)$ takes the form of a local integral

$$O(\lambda) = \int d^dx\, X^{(\lambda)}(x),$$

where $X^{(\lambda)} = \sum_p \lambda^p X_{(p)}$ is arranged so λ is the <u>only</u> dimensiontful parameter in the flow (algebra vastly simpler!)

E.g. for $D = 3+1$ GR, CT is of form $\int (a+bR)\sqrt{g}\,d^dx$

and:

$$\begin{aligned} X^{(\lambda)} &= -\frac{\lambda}{3\alpha}\frac{1}{\sqrt{g}}\left(:\Pi_{ab}\Pi^{ab} - \tfrac{1}{2}\Pi^2:\right) \\ &\quad + i\frac{2}{3}\lambda^{2/3}\left(G_{ab}\Pi^{ab} - \tfrac{1}{2}G\Pi\right) \\ &\quad + \frac{\alpha}{3}\lambda^{1/3}\sqrt{g}\left(G_{ab}G^{ab} - \tfrac{1}{2}G^2\right) \end{aligned} \quad \Bigg| \quad \alpha = \frac{L^{d-1}_{AdS}}{16\pi G_N}$$

See our paper for proposed definition of $: \ :$ to make this work at the quantum level (pert. in $1/N$)

More generally...

We start with an arbitrary Hamiltonian constraint obeying the standard ADM closure cond:

$$[H(x), H(y)] = i\left(D^a(x)\,\partial_a^{(x)} - D^a(y)\,\partial_a^{(y)}\right)\delta(x-y)$$

where D^a = momentum constraint $\nabla_b \Pi^{ab} + \ldots = 0$

($D^a Z = 0$ automatic for any covariant Z)

without this, deformation fails to close & theory becomes nonlocal!

ELIMINATE RELEVANT TERMS:

We conjugate $\mathcal{H}$ by counterterms

$$\tilde{\mathcal{H}} = e^{-CT}\mathcal{H}e^{CT}$$

to remove any part that looks like a relevant operator (in CFT language).

MATCH MARGINAL TERMS:

We require as an anomaly matching condition that the marginal part of $\tilde{\mathcal{H}}$ satisfy

$$-i\mu^{1/d}\tilde{\mathcal{H}}^{(\mu)}_{\text{marginal}}(x) = \underset{\substack{\uparrow \\ \text{Weyl generator} \\ 2\Pi - \Delta_\phi \phi \Pi_\phi}}{\mathcal{W}(x)} - i\underset{\substack{\uparrow \\ \text{CFT} \\ \text{anomaly}}}{A(x)}$$

This includes:

e.g. c, a matching

$\Delta(\Delta - d) = m^2$ constraints

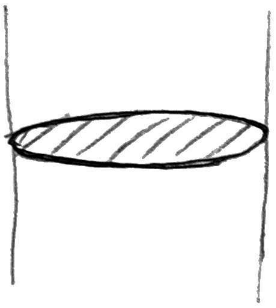
Then: $-i\,dX^{(\lambda)} = i\mu^{1/d}\tilde{\mathcal{H}}^{(\lambda)} + \mathcal{W}$

Geometrodynamics Dictionary

If you know the T^2 partition fn, you get explicit AdS/CFT maps!

bulk → bdy map

an open partition fn naturally defines a state on its boundary $\partial\Sigma$

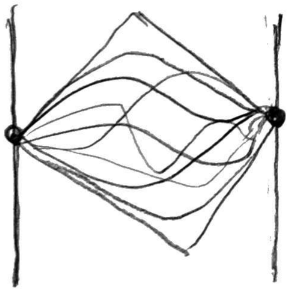


$$\Psi_{CFT}[\{\chi\}] = Z[\overbrace{g,\phi\ldots}^{\text{you pick this}}\{\chi\}]$$

Some complete basis for CFT data on $\partial\Sigma$

bdy → bulk map

Sum over χ to get WDW state w/ amplitudes for all possible "times" in WDW patch.



$$\Psi_{WDW}[g,\phi] = \int d\{\chi\}\, Z[g,\phi,\{\chi\}]\,\underbrace{\psi_{CFT}[\{\chi\}]}_{\text{you pick this}}$$

obeys constraints

bulk → bulk map

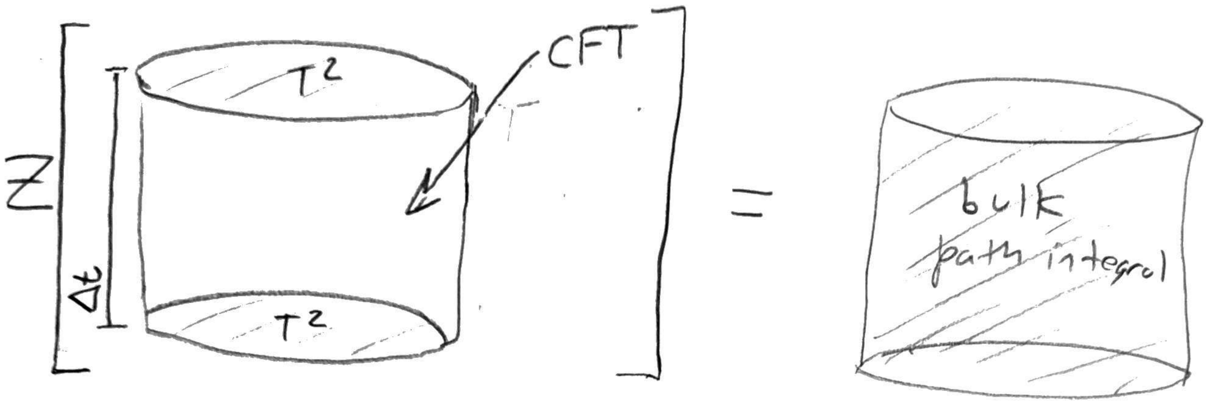
The above maps are NOT inverses! Rather, we hypothesize that (in suitably semiclassical contexts) their composition is the <u>bulk gravitational path integral</u> which defines the dynamical bulk Hilbert Space:

$$\langle g_2\phi_2|g_1\phi_1\rangle = \sum_{M}\int_{g_1}^{g_2}\frac{Dg\,D\phi}{Diff(M)}\,e^{\pm i I_{grav}[g,\phi]}$$

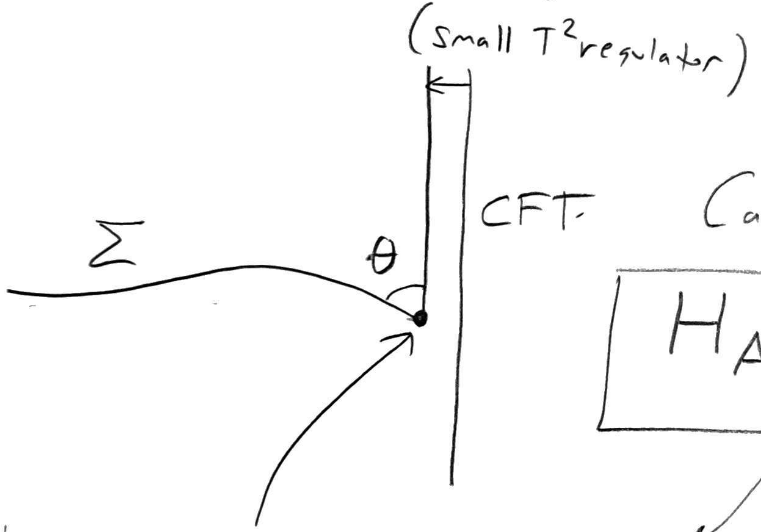
where we integrate over all bulk interiors g,ϕ w/ <u>both</u> signs of lapse.

* and a suitable choice of contour TBD!

Can also evolve for finite Δt on bdy



$\Rightarrow$ time evolution agrees on both sides.



Can also show (at least @ $N = \infty$)

$$\boxed{H_{ADM} = H_{CFT}}$$

requires nontrivial junction conditions when T^2 theory bends @ sharp angle.

(distributional constraints, equiv. to rotation of $K_{ij}^{(a)}$ by θ)

In a forthcoming paper, I will use these same J.C. to show that the microcanonical entropy of T^2 satisfies:

$S = A/4$ for marginally trapped* surfaces

$> A/4$ for trapped (due to Im E eigenstates)

$< A/4$ for untrapped

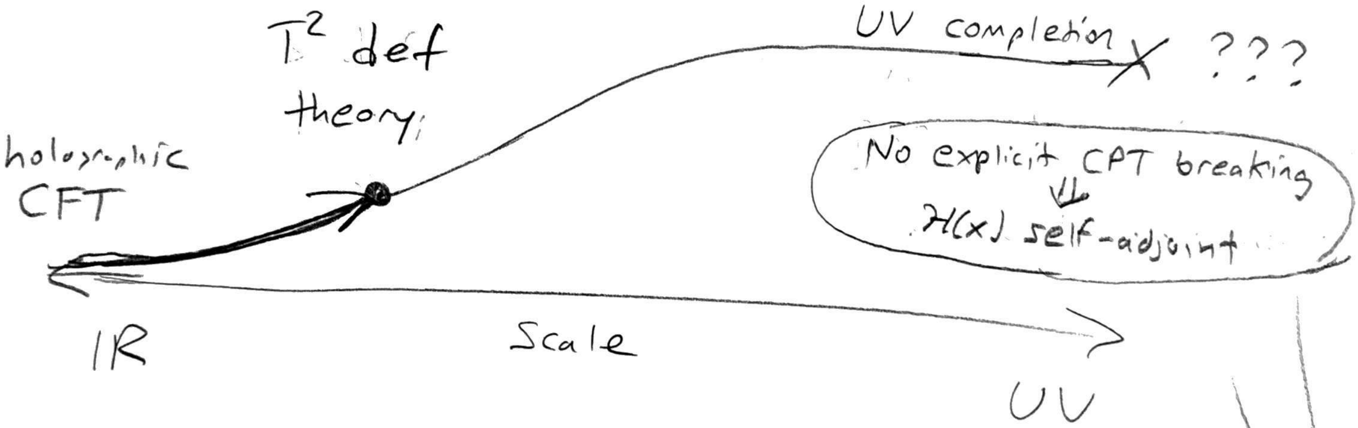
* Some terms & Conditions apply, e.g. inner horizons have $S = A/4$ of outer H.

UV completion?

T^2 is exactly soluable:

- when $d=2$ (for pure GR, flat cylinders)
- at $N=\infty$, prob. in $1/N$ expansion

Away from these cases, not clear it is fully defined, for the usual reason (irrelevant coupling).



If a UV completion were found,

$\Longrightarrow$ nonperturbative bulk QG definition!


a.k.a. The Holy Grail

Plausibly easier than traditional QG:

1) theory is defined on fixed background g_{ab}
2) easier to UV regulate Euclidean theories
3) we already sacrificed unitarity.....

Obviously, need some principle to ensure bulk observers see prob $\gtrsim 0$.
Related to BH info paradox questions?