Modified theories of gravity and exotic compact objects: An overview

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Future of Gravitational Wave Astronomy 2025, ICTS Bangalore
October 27 2025

Subrahmanyan Chandrasekhar:

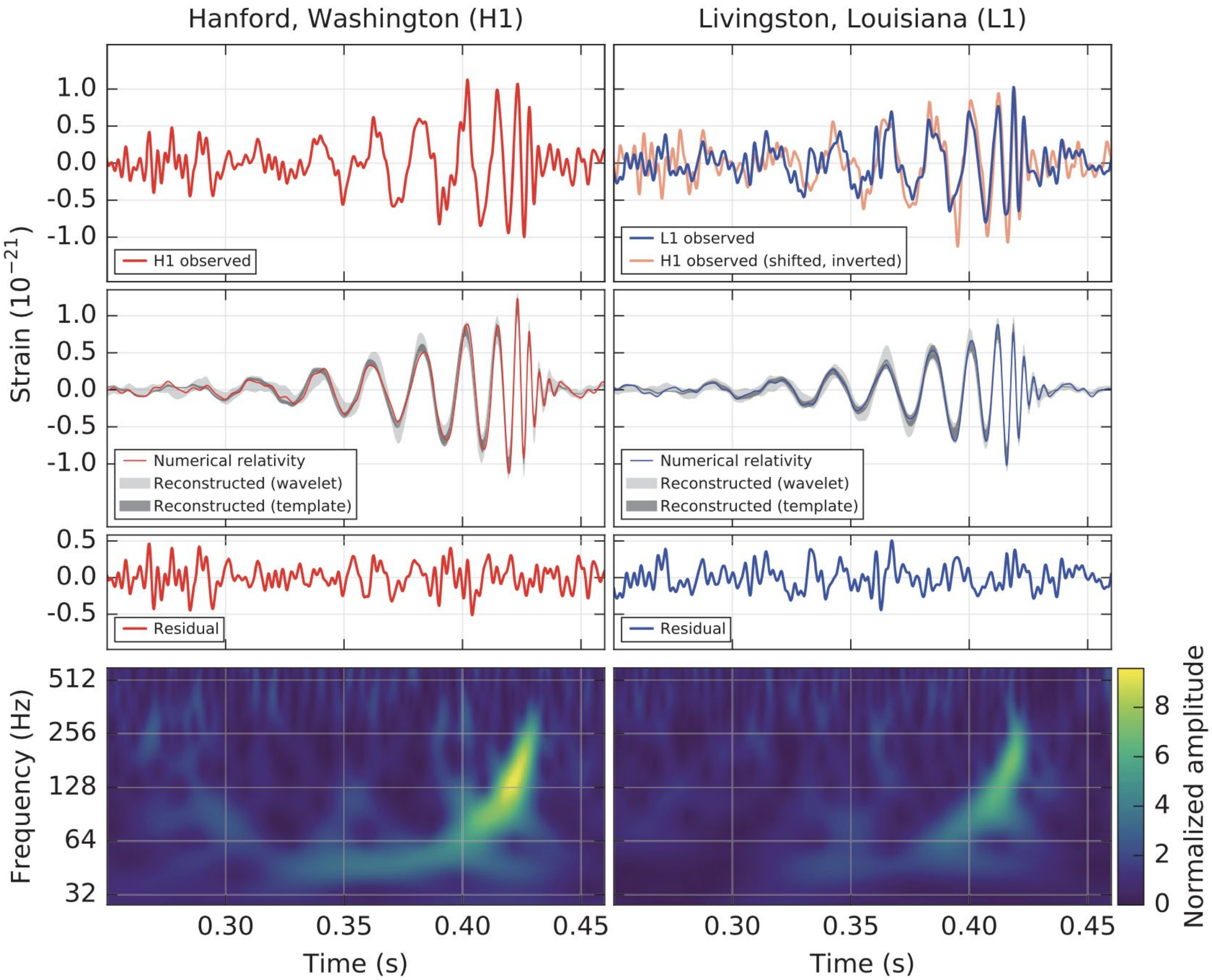
"Why do you bother testing general relativity?
We know that the theory is right."

Anonymous:

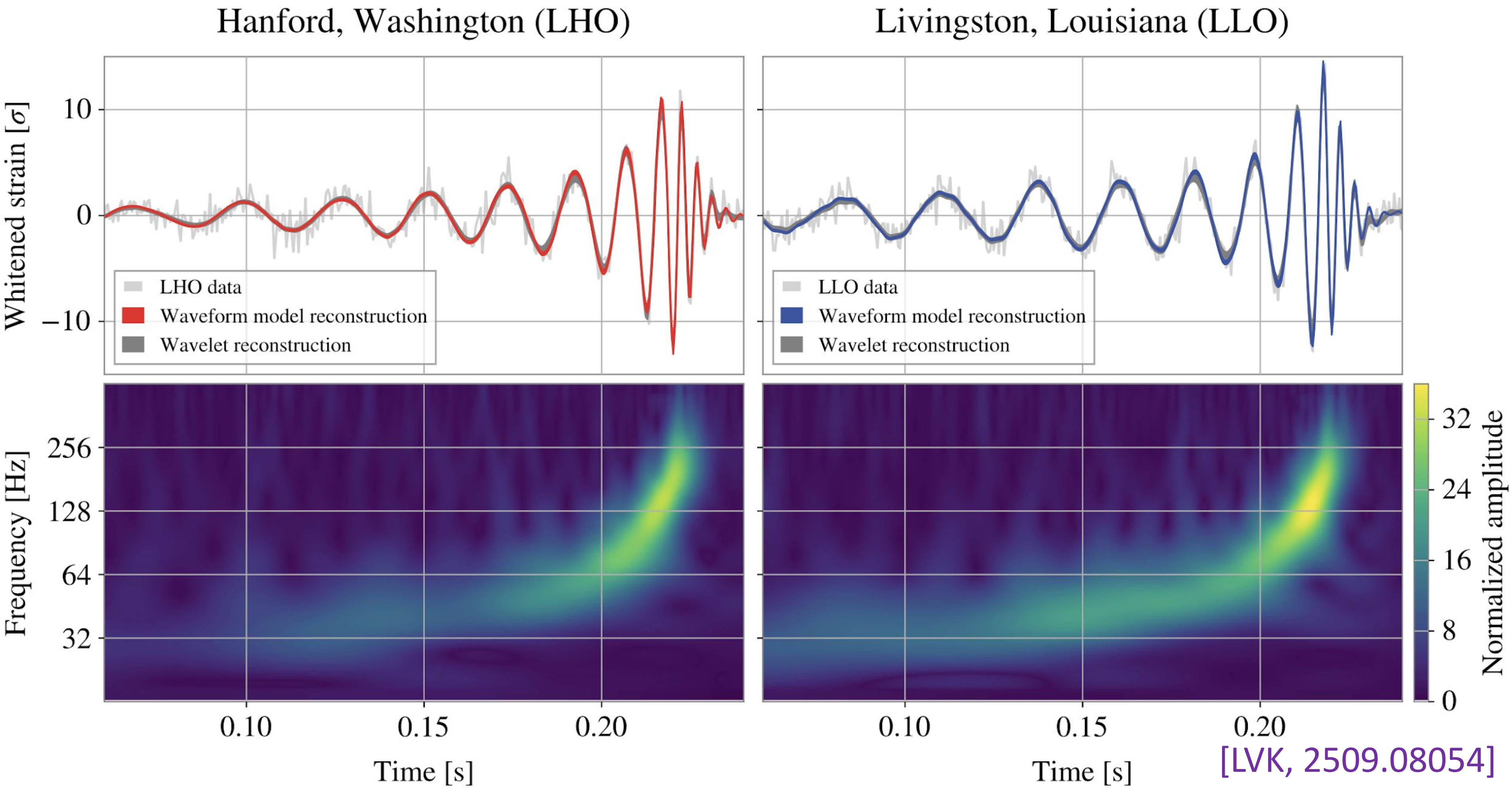
"…but Einstein said he had palpitations when he found out that the theory was in agreement with experiment."

Subrahmanyan Chandrasekhar:

"That's because Einstein did not understand his theory very well."


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
8
6
4
2
0

GW250114: Testing Hawking’s Area Law and the Kerr Nature of Black Holes



[LVK, 2509.08054]

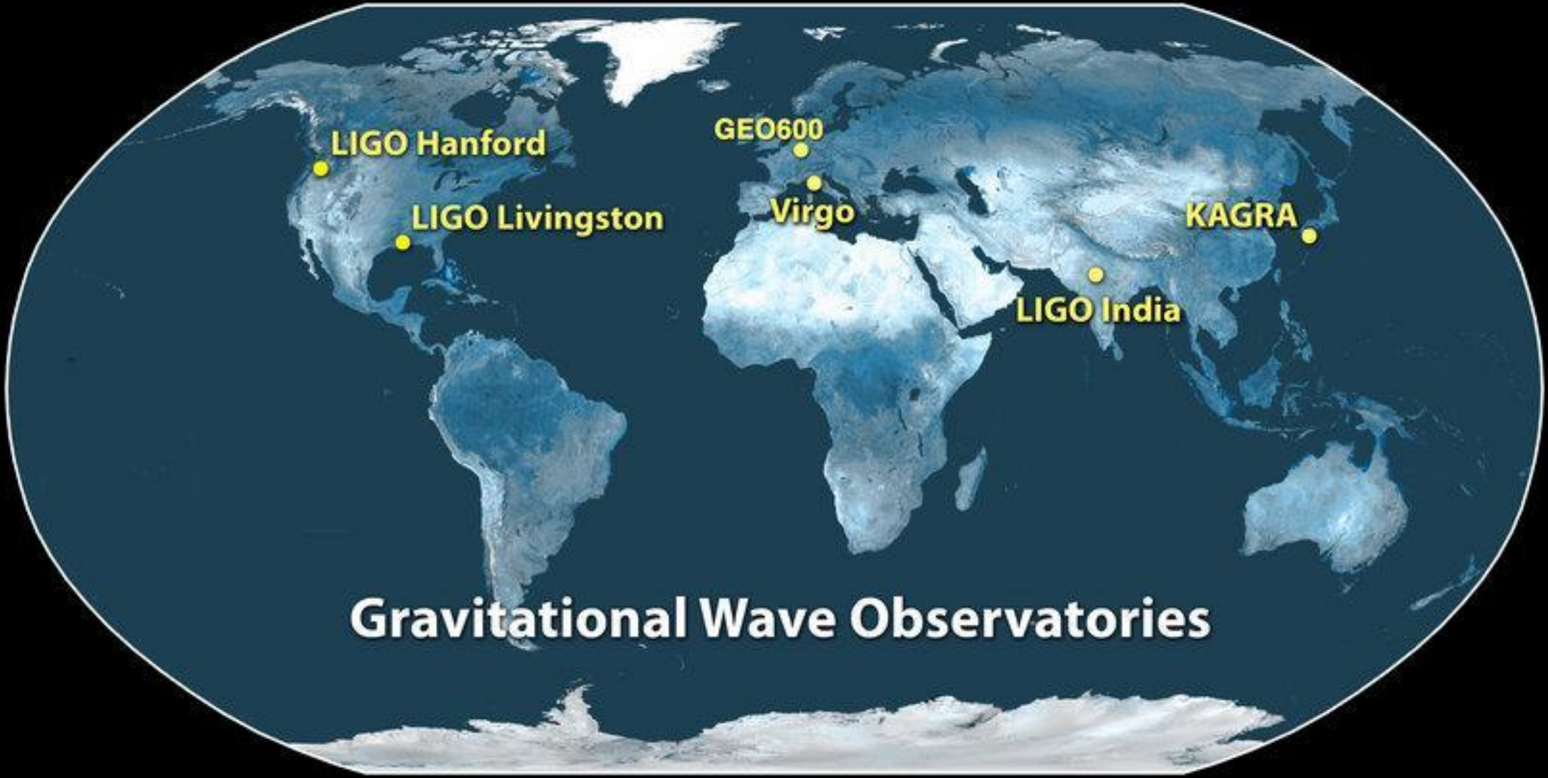
LIGO tests of GR (GWTC-3)

TABLE I. Summary of methods and results. This table summarizes the names of the tests performed, the corresponding sections, the parameters involved in the test, and the improvement with regard to our previous analysis. The analyses performed are: RT = residuals test; IMR = inspiral–merger–ringdown consistency test; PAR = parametrized tests of GW generation; SIM = spin-induced moments; MDR = modified GW dispersion relation; POL = polarization content; RD = ringdown; ECH = echoes searches. The last column provides the *approximate* improvement in the bounds over the previous analyses reported in [11]. This is defined as $X_{\mathrm{GWTC-2}}/X_{\mathrm{GWTC-3}}$, where X denotes the width of the 90% credible interval for the parameters for each test, using the combined results on all events considered. For the MDR test, some of the bounds have worsened in comparison to GWTC-2. See the corresponding section for details. Note that the high improvement factor for pSEOB is due to the larger number of events from GWTC-2 analysed here compared to [11].

Test	Section	Quantity	Parameter	Improvement w.r.t. GWTC-2
RT	IV A	p-value	p-value	Not applicable
IMR	IV B	Fractional deviation in remnant mass and spin	$\left\{\frac{\Delta M_{\mathrm{f}}}{\bar{M}_{\mathrm{f}}}, \frac{\Delta \chi_{\mathrm{f}}}{\bar{\chi}_{\mathrm{f}}}\right\}$	1.1–1.8
PAR	V A	PN deformation parameter	$\delta\hat{\phi}_k$	1.2–3.1
SIM	V B	Deformation in spin-induced multipole parameter	$\delta\kappa_s$	1.1–1.2
MDR	VI	Magnitude of dispersion	$\lvert A_\alpha \rvert$	0.8–2.1
POL	VII	Bayes Factors between different polarization hypotheses	$\log_{10}\mathcal{B}^{\mathrm{X}}_{\mathrm{T}}$	New Test
RD	VIII A 1	Fractional deviations in frequency (pyRing)	$\delta\hat{f}_{221}$	1.1
	VIII A 2	Fractional deviations in frequency and damping time (pSEOB)	$\{\delta\hat{\tau}_{220}, \delta\hat{f}_{220}\}$	1.7–5.5
ECH	VIII B	Signal-to-noise Bayes Factor	$\log_{10}\mathcal{B}_{\mathrm{S/N}}$	New Test

[LVK GWTC-3, 2112.06861]

Present and future detectors

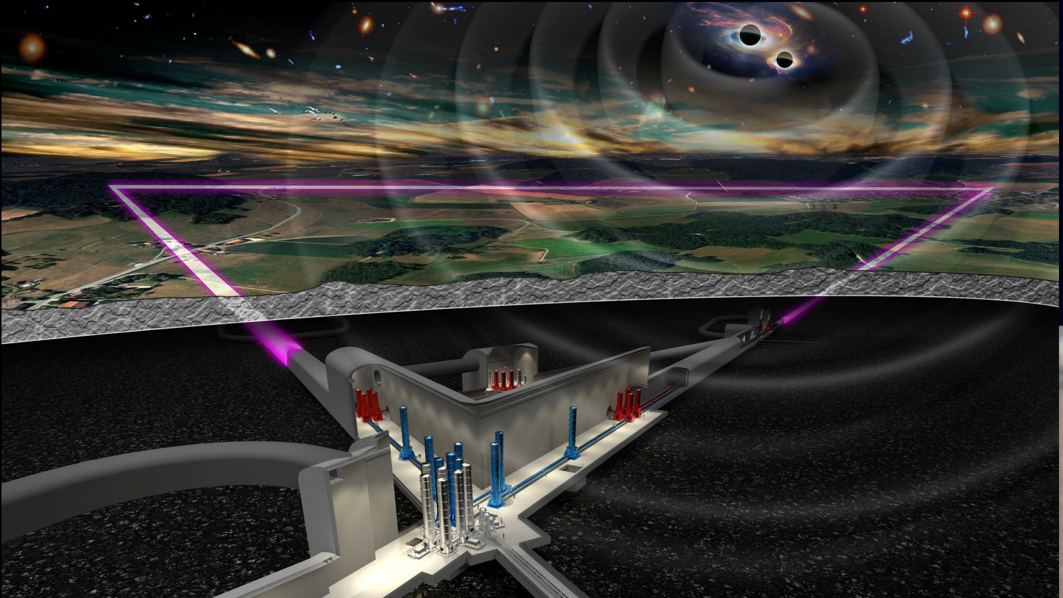


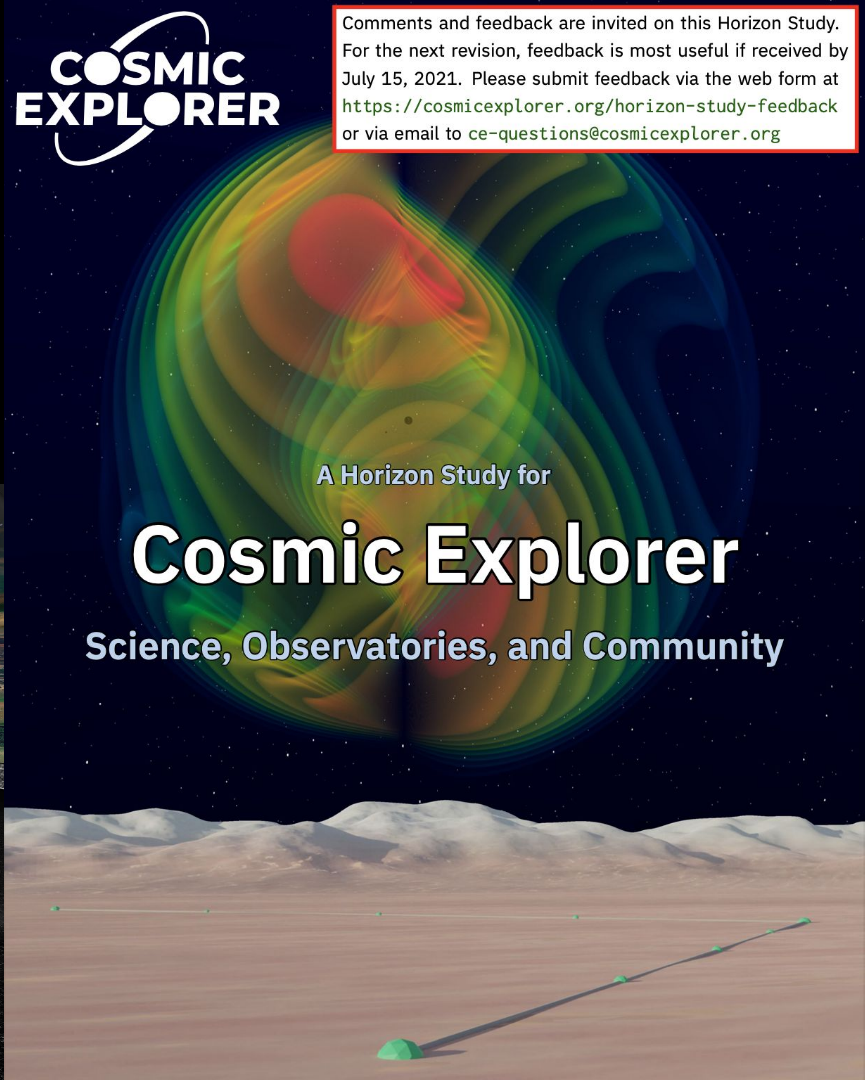
Also "current generation": PTAs, A+, A#

Next generation (XG)

Einstein Telescope 2021 ESFRI, site(s)?
Cosmic Explorer Horizon Study, MPSAC

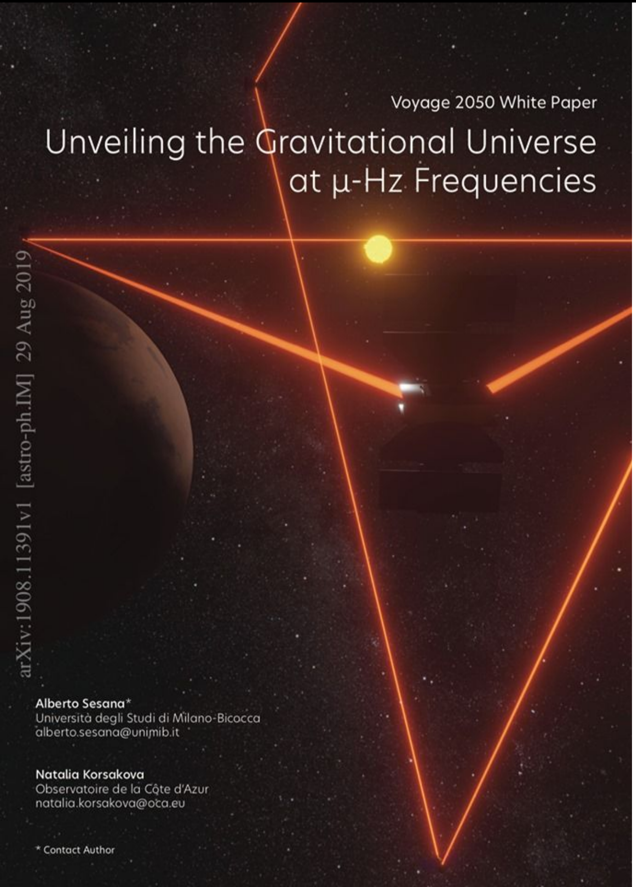
Moon? (LGWA, LILA, LSGA…)
Atom interferometry, NEMO, MHz





Space: LISA, TianQin, Taiji, and far future detectors beyond LISA

Lower frequencies? Better sensitivity? Decihertz?



arXiv:1908.11390v1 [astro-ph.HE] 29 Aug 2019

A Voyage 2050 Science White Paper Submission

Probing the Nature of Black Holes: Deep in the mHz Gravitational-Wave Sky

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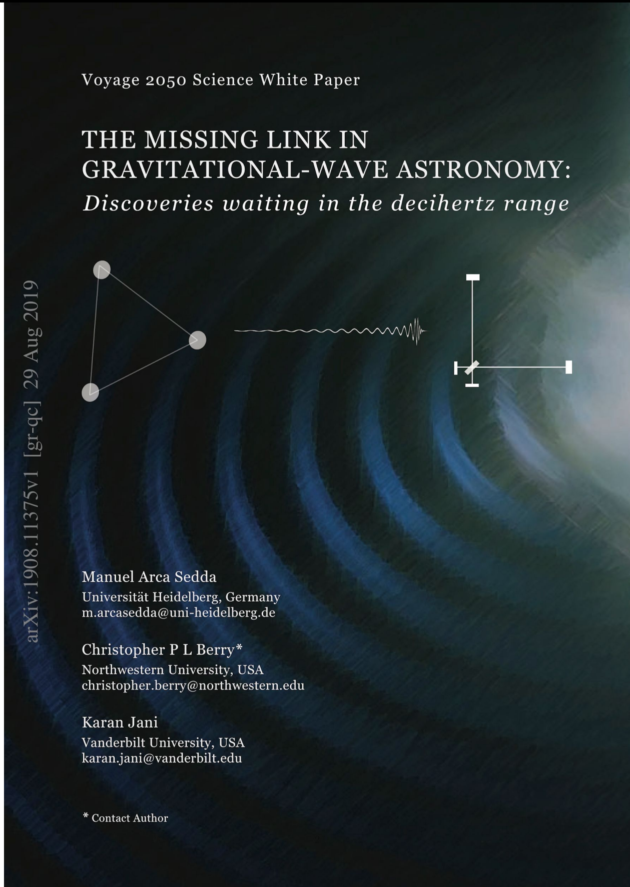
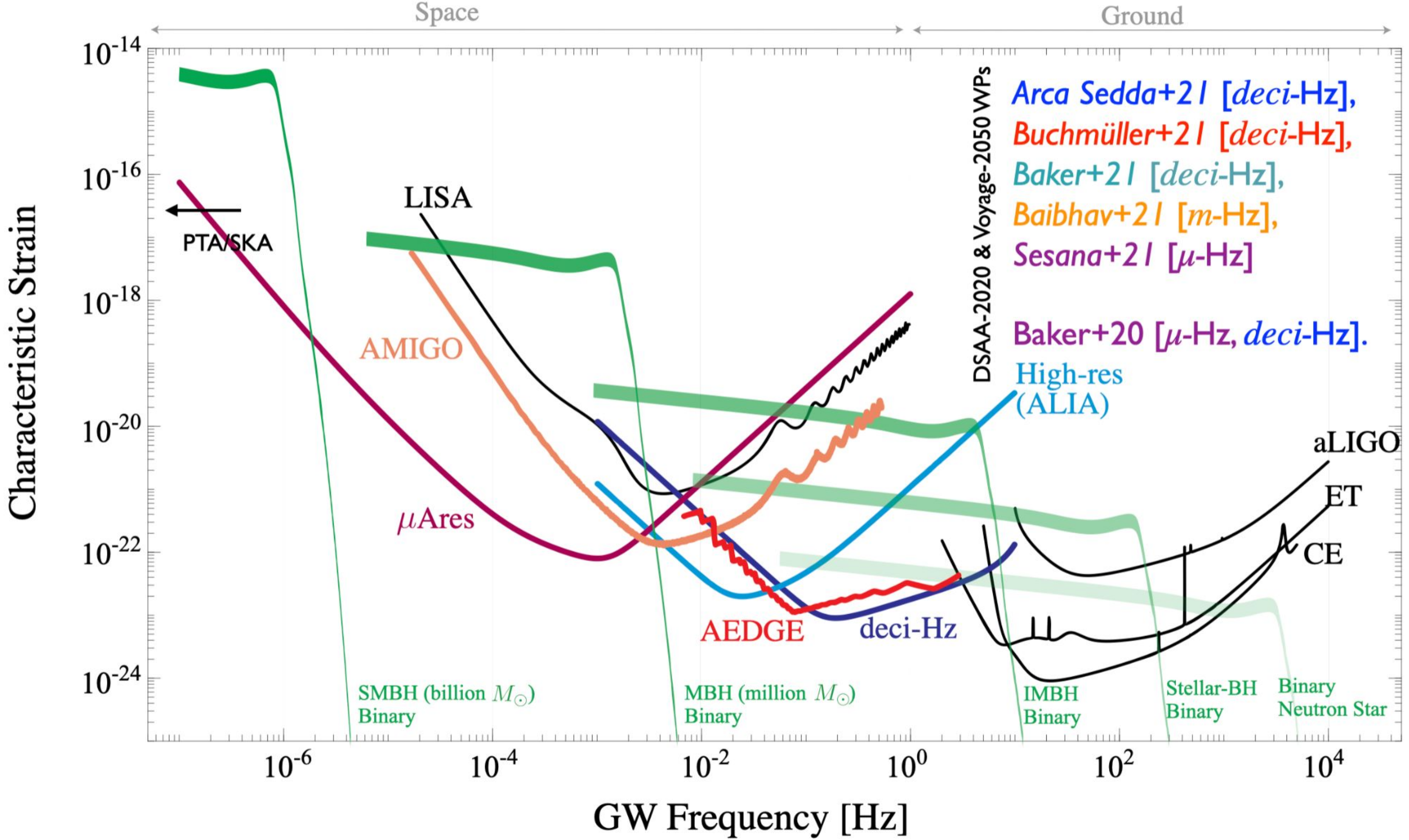
Abstract: Black holes are unique among astrophysical sources: they are the simplest macroscopic objects in the Universe, and they are extraordinary in terms of their ability to convert energy into electromagnetic and gravitational radiation. Our capacity to probe their nature is limited by the sensitivity of our detectors. The LIGO/Virgo interferometers are the gravitational-wave equivalent of Galileo's telescope. The first few detections represent the beginning of a long journey of exploration. At the current pace of technological progress, it is reasonable to expect that the gravitational-wave detectors available in the 2035-2050s will be formidable tools to explore these fascinating objects in the cosmos, and space-based detectors with peak sensitivities in the mHz band represent one class of such tools. These detectors have a staggering discovery potential, and they will address fundamental open questions in physics and astronomy. Are astrophysical black holes adequately described by general relativity? Do we have empirical evidence for event horizons? Can black holes provide a glimpse into quantum gravity, or reveal a classical breakdown of Einstein's gravity? How and when did black holes form, and how do they grow? Are there new long-range interactions or fields in our universe, potentially related to dark matter and dark energy or a more fundamental description of gravitation? Precision tests of black hole spacetimes with mHz-band gravitational-wave detectors will probe general relativity and fundamental physics in previously inaccessible regimes, and allow us to address some of these fundamental issues in our current understanding of nature.

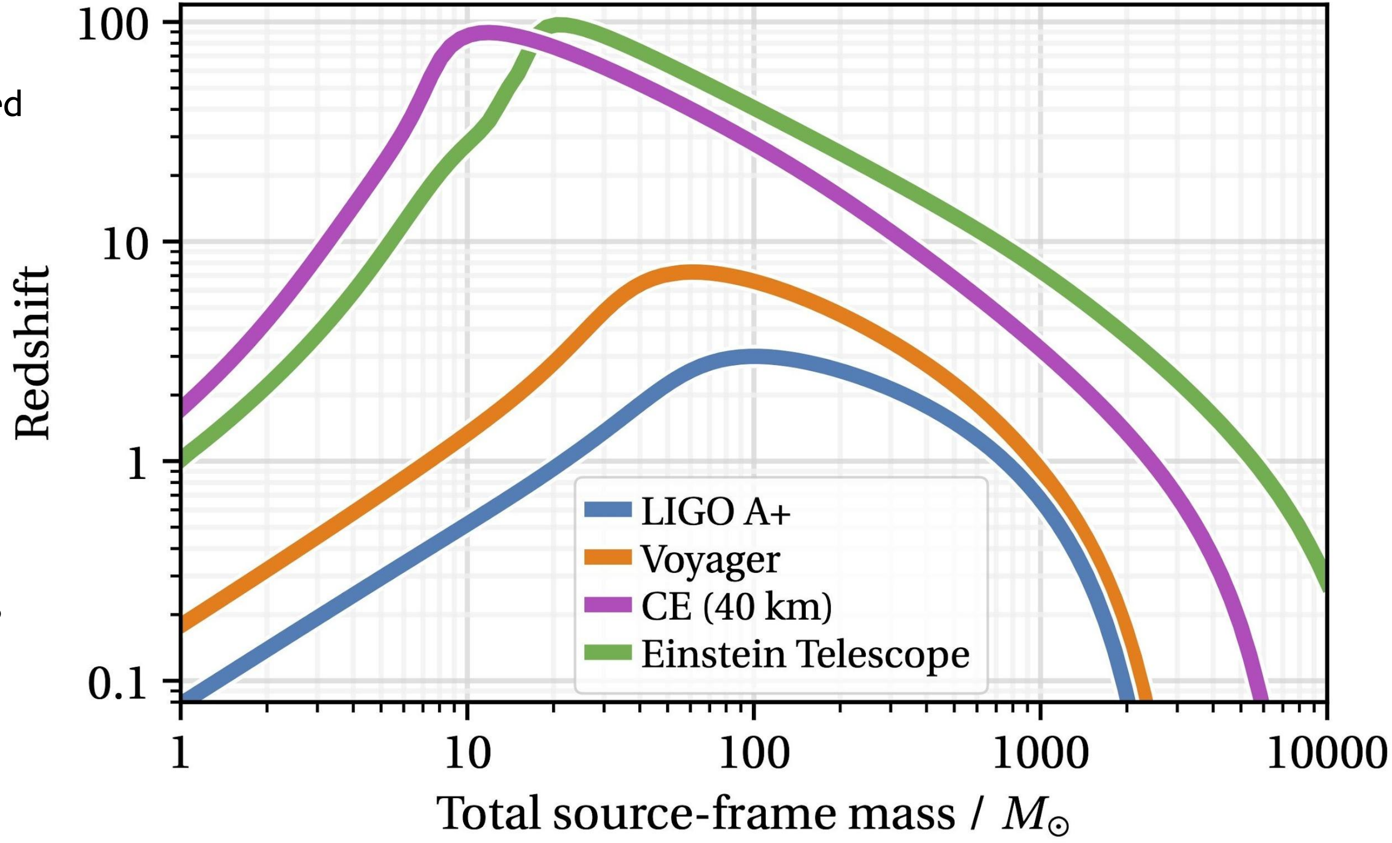




Space
Ground
Characteristic Strain
GW Frequency [Hz]
PTA/SKA
LISA
AMIGO
μAres
AEDGE
deci-Hz
High-res (ALIA)
aLIGO
ET
CE
DSAA-2020 & Voyage-2050 WPs
Arca Sedda+21 [deci-Hz],
Buchmüller+21 [deci-Hz],
Baker+21 [deci-Hz],
Baibhav+21 [m-Hz],
Sesana+21 [μ-Hz]
Baker+20 [μ-Hz, deci-Hz].
SMBH (billion $M_\odot$) Binary
MBH (million $M_\odot$) Binary
IMBH Binary
Stellar-BH Binary
Binary Neutron Star

From 2G to XG: opportunities and challenges

- Factor of 10 in sensitivity and lower frequency bound
- ET: triangle, or two L-shaped
- CE: CE40 and CE20
- Hundreds of signals every day!
- Hundreds of BNSs/ thousands of BBHs every year with SNR>100
- **Opportunities:**
  New synergies, null stream?
  New algorithms (MDCs)
- **Challenges:**
  Long waveforms
  Overlapping signals
  Waveform systematics
  Strong foreground



[Credits: Sathya]

Opportunities and challenges (for a theorist)

Opportunities	Challenges
Single events exotic events, neutron star EOS, spin dynamics, MMA	Waveform systematics Physics modeling (gravity, EM emission) Fast PE
Populations Astrophysical formation channels	Parametrized models or population synthesis? Too many parameters? Inference?
High-redshift GW universe Population III, IMBHs, PBHs…	Can we measure z and binary properties? How many XG detectors are needed?
SGWBs (astrophysical or cosmological)	Subtraction problem (Cutler-Harms, masking, Bayesian…)
Tests of general relativity (inspiral: ppE, black hole spectroscopy)	**This talk!** How much better can we do? Do we care?

Albert Michelson (1894 dedication of Ryerson Physical Laboratory, Chicago)

While it is never safe to affirm that the future of Physical Science has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice. It is here that the science of measurement shows its importance — where quantitative work is more to be desired than qualitative work.
An eminent physicist [Lord Kelvin?] remarked that the future truths of physical science are to be looked for in the sixth place of decimals.

…as quoted also in Weinberg, "Dreams of a final theory"

Modifications of GR, no-hair theorems, and EFTs

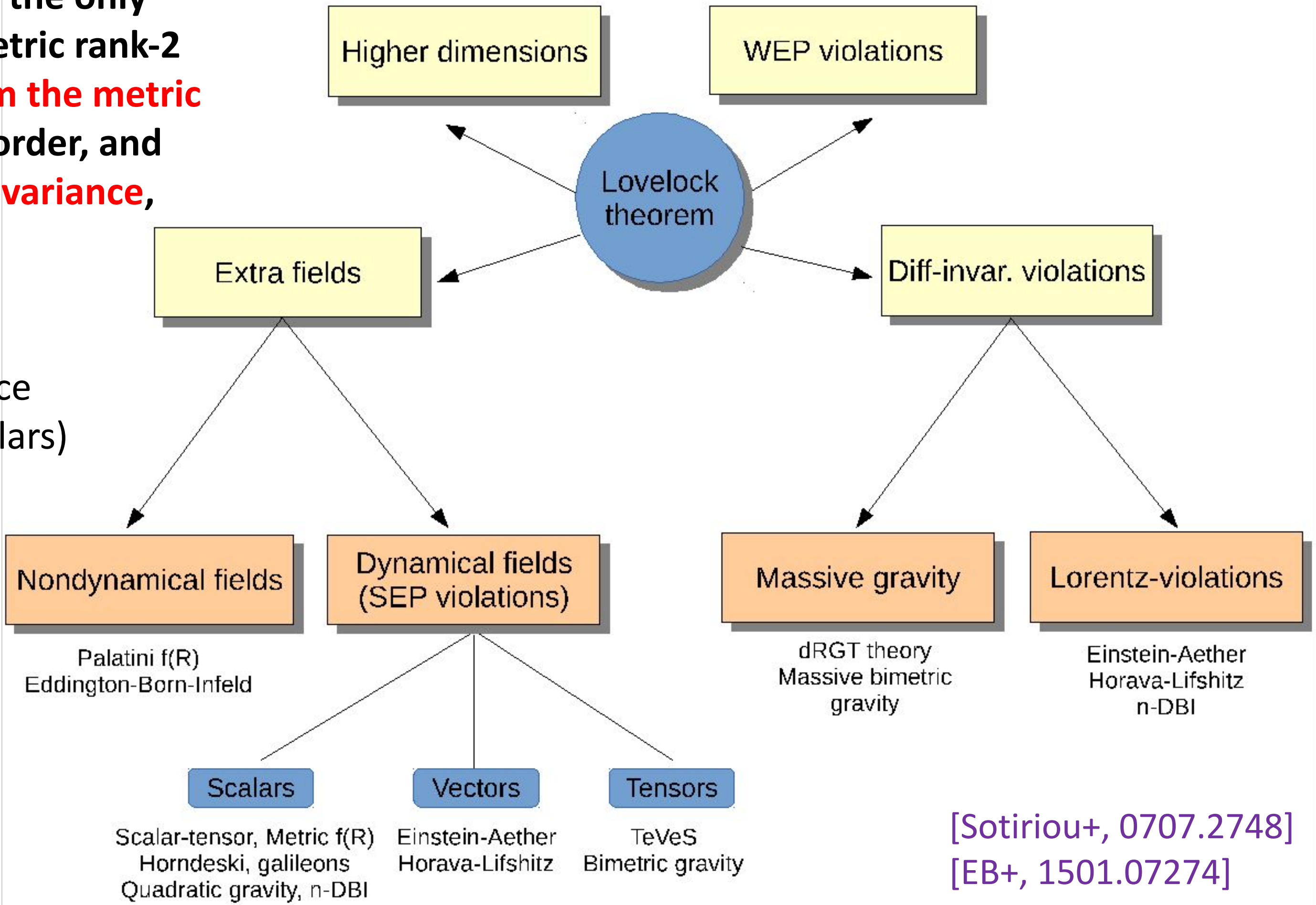
A guiding principle to modified GR: Lovelock's theorem

In four spacetime dimensions the only divergence-free (WEP) symmetric rank-2 tensor constructed solely from the metric and its derivatives up to 2nd order, and preserving diffeomorphism invariance, is the Einstein tensor plus Λ.

Generic modifications introduce additional fields (simplest: scalars)

Minimal requirements:

- Action principle
- Well-posed
- Testable predictions
- Black holes, neutron stars
- Cosmologically viable



[Sotiriou+, 0707.2748]
[EB+, 1501.07274]

(Often) black holes are the same as in GR! No-hair theorems in scalar-tensor theories

$$S = \frac{1}{16\pi}\int \sqrt{-g}d^4x\left[\phi R - \frac{\omega(\phi)}{\phi}g^{\mu\nu}\phi_{,\mu}\phi_{,\nu} + M(\phi)\right] + \int \mathcal{L}_{\rm M}(g^{\mu\nu},\Psi)d^4x$$

Orbital period derivative: $\frac{\dot{P}}{P} = -\frac{\mu m}{r^3}\kappa_D(s_1 - s_2)^2 - \frac{8}{5}\frac{\mu m^2}{r^4}\kappa_1$

$$\kappa_D = 2\mathcal{G}\xi\left(\frac{\omega^2 - m_s^2}{\omega^2}\right)^{\frac{3}{2}}\Theta(\omega - m_s)$$

$$\kappa_1 = \mathcal{G}^2\left[12 - 6\xi + \xi\Gamma^2\left(\frac{4\omega^2 - m_s^2}{4\omega^2}\right)^{\frac{5}{2}}\Theta(2\omega - m_s)\right]$$

$$\xi = \frac{1}{2 + \omega_{\rm BD}}$$

$$G = 1 - \xi(s_1 + s_2 - 2s_1 s_2)$$

$$\Gamma = 1 - 2\frac{s_1 m_2 + m_1 s_2}{m}$$

For black hole binaries, $s_1 = s_2 = \frac{1}{2}$ and dipole vanishes identically

Quadrupole: $\Gamma = 0$

Result extended to higher PN orders; it is exact in the large mass ratio limit
[Will & Zaglauer 1989; Alsing+, 1112.4903; Mirshekari & Will, 1301.4680; Yunes+, 1112.3351; Bernard 1802.10201, 1812.04169, 1906.10735]

Ways around: matter (but EOS degeneracy), cosmological BCs (but small corrections), or **curvature itself sourcing the scalar field: dCS, EsGB** [Yagi+ 1510.02152]

Systematically exploring *small* corrections: the effective field theory (EFT) viewpoint

Expand all operators in the action in terms of some length scale
(must be macroscopic to be relevant for GW tests).
Theories: sum over curvature invariants with scalar-dependent coefficients

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{|g|}\left[R + \sum_{n=2}^{\infty} \ell^{2n-2}\mathcal{L}_{(n)}\right]$$

and more specifically, at order ℓ^4

EsGB dCS (dilaton+axion)

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{|g|}\Big\{R + \alpha_1\phi_1\ell^2 R_{\rm GB} + \alpha_2(\phi_2\cos\theta_m + \phi_1\sin\theta_m)\ell^2 R_{\mu\nu\rho\sigma}\tilde{R}^{\mu\nu\rho\sigma}$$
$$+\lambda_{\rm ev}\ell^4 R_{\mu\nu}^{\rho\sigma}R_{\rho\sigma}^{\delta\gamma}R_{\delta\gamma}^{\mu\nu} + \lambda_{\rm odd}\ell^4 R_{\mu\nu}^{\rho\sigma}R_{\rho\sigma}^{\delta\gamma}\tilde{R}_{\delta\gamma}^{\mu\nu} - \frac{1}{2}(\partial\phi_1)^2 - \frac{1}{2}(\partial\phi_2)^2\Big\}$$

Einsteinian cubic gravity (+parity-breaking) - causality constraints [Camanho+ 1407.5597]
Next order, no new DOFs [Endlich-Gorbenko-Huang-Senatore, 1704.01590]

$$S_{(4)} = \frac{\ell^6}{16\pi G}\int d^4x\sqrt{|g|}\left\{\epsilon_1\mathcal{C}^2 + \epsilon_2\tilde{\mathcal{C}}^2 + \epsilon_3\mathcal{C}\tilde{\mathcal{C}}\right\}$$

$$\mathcal{C} = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}, \quad \tilde{\mathcal{C}} = R_{\mu\nu\rho\sigma}\tilde{R}^{\mu\nu\rho\sigma}$$

[Cano-Ruipérez, 1901.01315; Cano-Fransen-Hertog, 2005.03671. See also work by Hui, Penco…]

Einstein-scalar-Gauss-Bonnet gravity: a loophole in no-hair theorems

Horndeski Lagrangian: most general scalar-tensor theory with second-order EOMs

$$S = \sum_{i=2}^{5} \int d^4x \sqrt{-g}\mathcal{L}_i$$

$$G_i = G_i(\phi, X) \qquad \phi_{\mu\nu}^2 \equiv \phi_{\mu\nu}\phi^{\mu\nu}$$

$$X = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi \qquad \phi_{\mu\nu}^3 \equiv \phi_{\mu\nu}\phi^{\nu\alpha}\phi_\alpha^\mu$$

$$\begin{aligned}
\mathcal{L}_2 &= G_2 \\
\mathcal{L}_3 &= -G_3\Box\phi \\
\mathcal{L}_4 &= G_4R + G_{4X}\left[(\Box\phi)^2 - \phi_{\mu\nu}^2\right] \\
\mathcal{L}_5 &= G_5G_{\mu\nu}\phi^{\mu\nu} - \tfrac{1}{6}G_{5X}\left[(\Box\phi)^3 + 2\phi_{\mu\nu}^3 - 3\phi_{\mu\nu}^2\Box\phi\right]
\end{aligned}$$

Set:

$$\begin{aligned}
G_2 &= X + 8f^{(4)}X^2(3 - \ln X) \\
G_3 &= 4f^{(3)}X(7 - 3\ln X) \\
G_4 &= \tfrac{1}{2} + 4f^{(2)}X(2 - \ln X) \\
G_5 &= -4f^{(1)}\ln X
\end{aligned}$$

$$S = \int d^4x \sqrt{-g}\left(\frac{1}{2}R + X + f(\phi)\mathcal{G}\right)$$

$$\mathcal{G} \equiv R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2$$

Shift symmetry: invariance under $\phi \to \phi + c$, i.e. $G_i = G_i(X)$

EsGB is **a special case of Horndeski *and* of quadratic gravity**

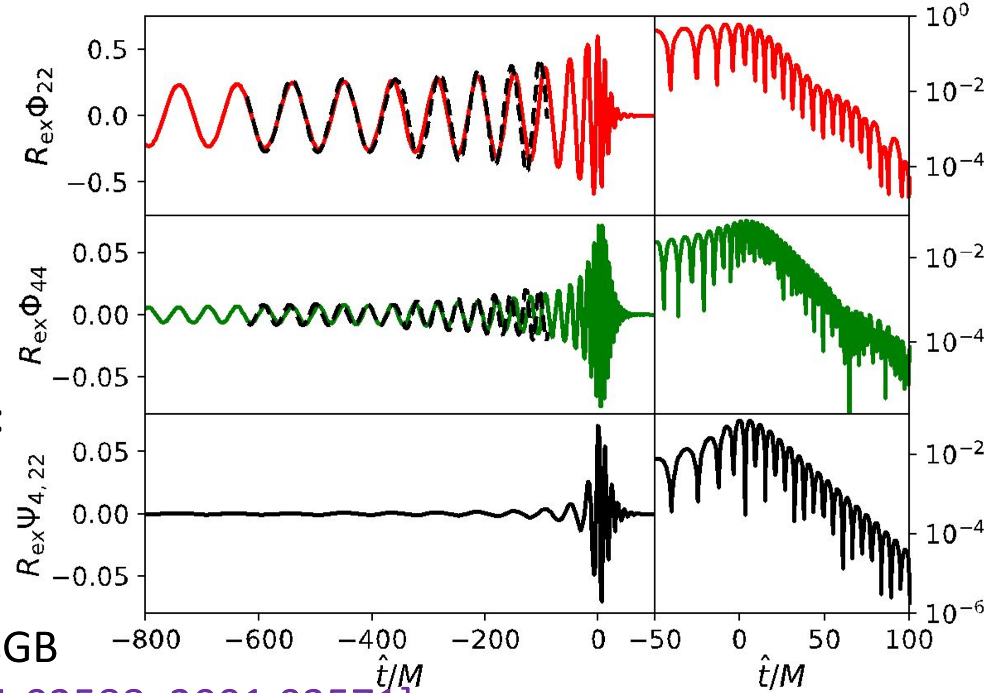
[Kobayashi+, 1105.5723; Sotiriou+Zhou, 1312.3622; Maselli+, 1508.03044]

Binaries in Einstein-scalar-Gauss-Bonnet: analytical and numerical work

- Post-Newtonian calculations in the weak coupling limit:
  [Yagi+, 1110.5990]
  Higher-order in coupling, generic EsGB:
  [Julié+, 1909.05258]

- Dynamical scalarization:
  [Khalil+, 1906.08161]

- Numerical simulations (weak coupling limit):
  Scalar waveforms
  Scalar-led QNMs + gravitational-led QNMs
  [Witek+, 1810.05177]
  Related work in dynamical Chern-Simons+EsGB
  [Okounkova+ 1705.07924, 1906.08789, 1911.02588, 2001.03571]



- Full merger simulations
  [East-Ripley 2105.08571; Corman+ 2210.09235, 2405.15581; Doneva, Aresté Saló+…]

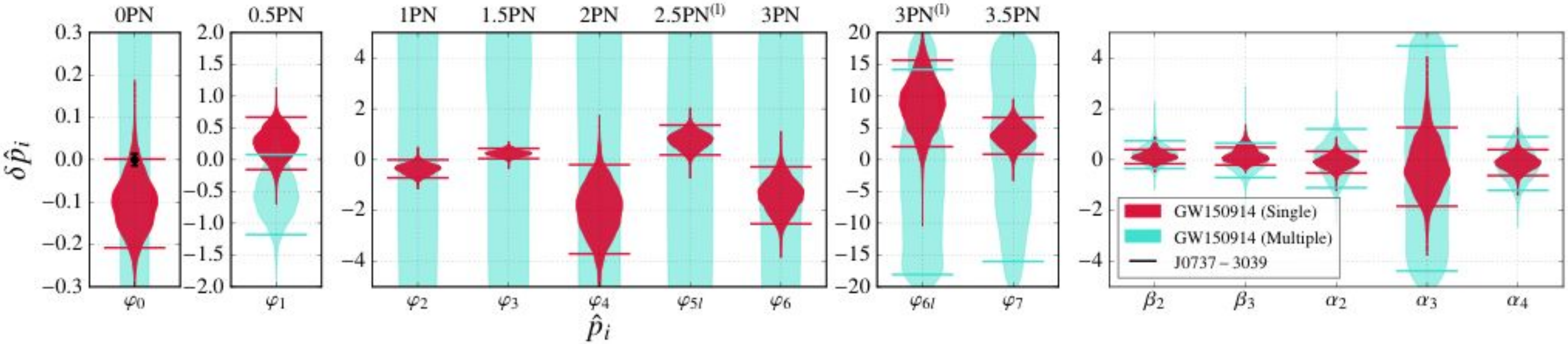
Specific Theories Summary

- EsGB: subclass of Horndeski theory that evades no-hair theorems
- Scalarized solution exist, are radially stable (as long as backreaction is included), can differ sensibly from GR
- Stable, nonspinning scalarized solutions are well motivated in EFT
- Scalarized solution become close to GR for spins of interest to LIGO remnant - more interesting phenomenology for spin-induced scalarization
- BHBs produce dipolar radiation [Yagi+ 1510.02152; Julié+, 1909.05258]
- Binaries have been simulated in the weak-coupling limit [Witek+ 1810.05177]
- Full mergers simulated, but open issues with well posedness in the strong-coupling limit [Papallo-Reall, Ripley-Pretorius, Bernard+, Julié+EB…]

Deviations from GR in the inspiral?

Inspiral tests of GR: the parametrized post-Einsteinian / FTI formalism

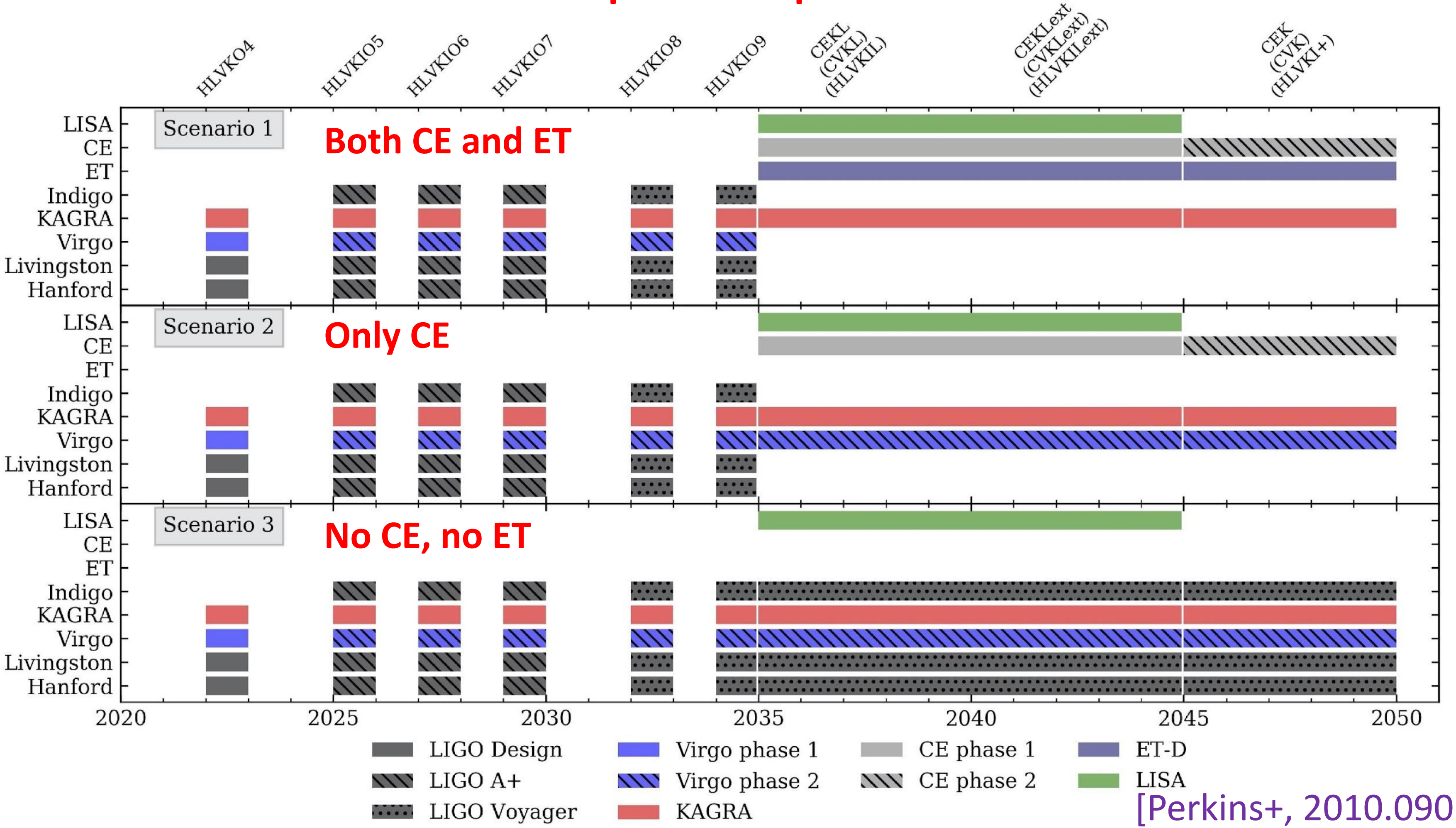
$$\tilde{h}(f) = \tilde{A}_{\rm GR}(f)\left[1+\alpha_{\rm ppE}\, v(f)^a\right] e^{i\Psi_{\rm GR}(f)+i\beta_{\rm ppE}\, v(f)^b}$$



How much better can we do with XG detectors?

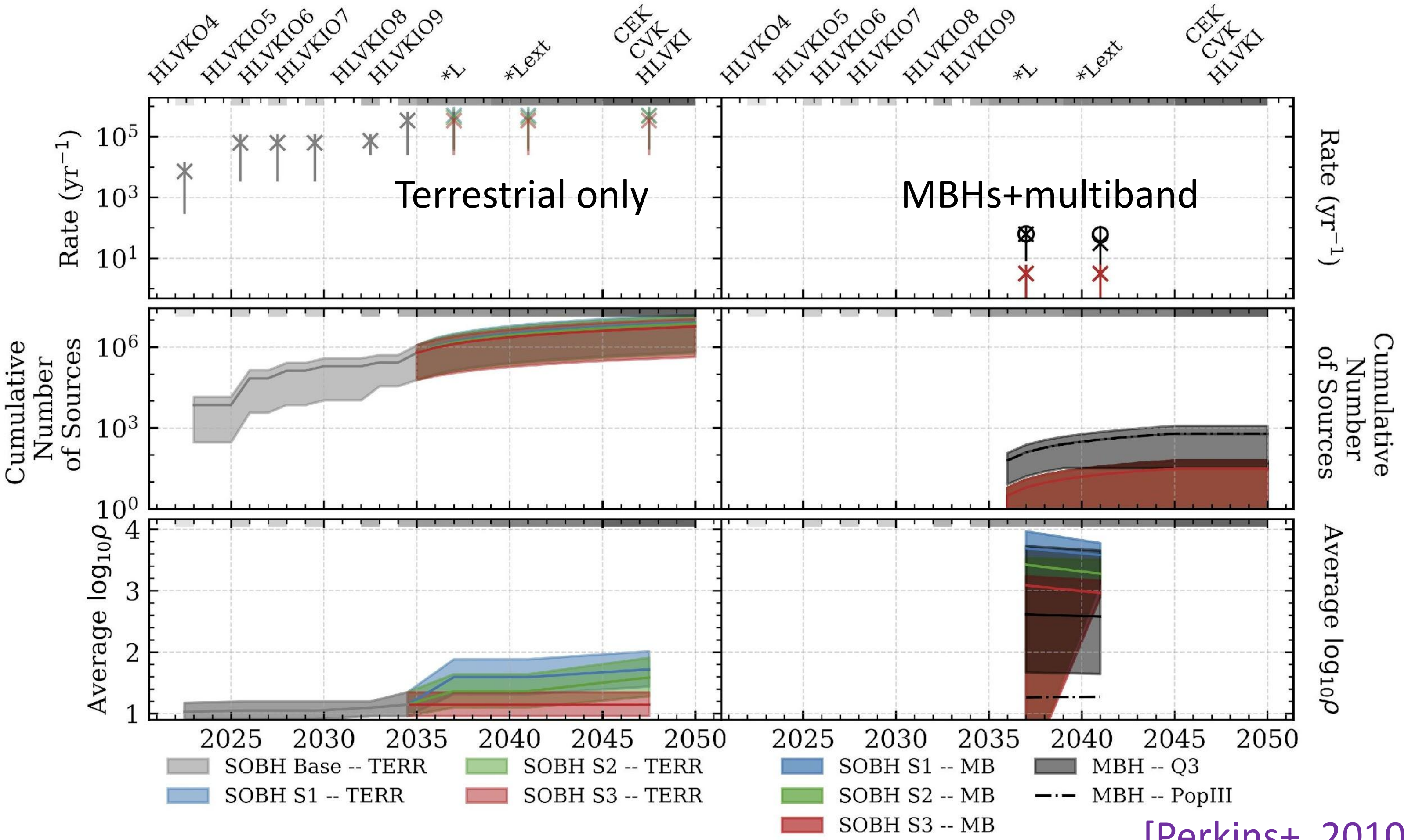
[LVK, 1602.03841 + 2112.06861; Yunes-Pretorius+, 0909.3328; Perkins-Yunes-EB, 2010.09010; Mehta+ 2203.13937]

How will the bounds improve? Depends on detector timeline



[Perkins+, 2010.09010]

How will the bounds improve? Depends on number of sources and SNR



[Perkins+, 2010.09010]

What sources/detectors are best?
Depends…

$$\tilde{h}\left(\vec{\lambda}_{\mathrm{PhenomPv2}}, \beta\right) = \tilde{h}_{\mathrm{GR}} e^{i\beta(\mathcal{M}\pi f)^{b/3}}$$

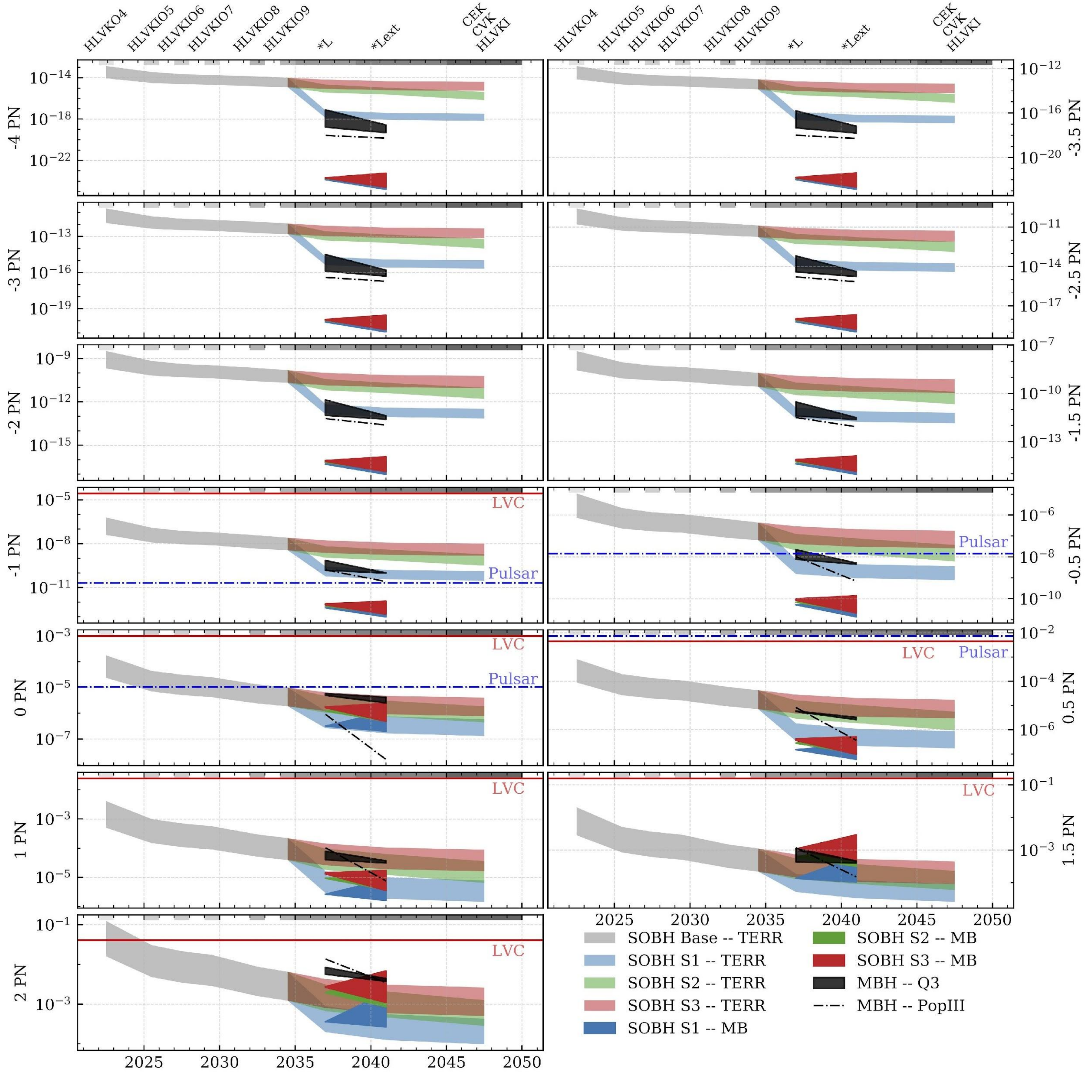
A term $(\pi\mathcal{M}f)^{b/3}$ in the phasing is of $(b+5)/2$ PN order

Multiband (MB) sources best at negative PN orders

MBH better than SOBH at negative PN orders

Terrestrial slightly better than LISA MBHs at positive PN orders

Terrestrial improvements matter most at negative PN orders



Mapping to specific theories. Big caveat: no systematics!

Table 2 Mapping of ppE parameters to those in each theory for a black hole binary

Theory	$\beta_{\rm ppE}$	b
Scalar–tensor [36, 179, 180]	$-\frac{5}{1792}\dot{\phi}^2\eta^{2/5}\left(m_1 s_1^{\rm ST} - m_2 s_2^{\rm ST}\right)^2$	-7
EdGB, D^{2}GB [23]	$-\frac{5}{7168}\zeta_{\rm GB}\frac{\left(m_1^2 s_2^{\rm GB} - m_2^2 s_1^{\rm GB}\right)^2}{m^4\eta^{18/5}}$	-7
dCS [181]	$\frac{1549225}{11812864}\frac{\zeta_{\rm CS}}{\eta^{14/5}}\left[\left(1-\frac{231808}{61969}\eta\right)\chi_s^2 + \left(1-\frac{16068}{61969}\eta\right)\chi_a^2 - 2\delta_m\chi_s\chi_a\right]$	-1
EA [182]	$-\frac{3}{128}\left[\left(1-\frac{c_{14}}{2}\right)\left(\frac{1}{w_2^{\rm \not{E}}} + \frac{2c_{14}c_+^2}{(c_+ + c_- - c_- c_+)^2 w_1^{\rm \not{E}}} + \frac{3c_{14}}{2w_0^{\rm \not{E}}(2-c_{14})}\right) - 1\right]$	-5
Khronometric [182]	$-\frac{3}{128}\left[(1-\beta_{\rm KG})\left(\frac{1}{w_2^{\rm KG}}\ \frac{3\beta_{\rm KG}}{2w_0^{\rm KG}(1-\beta_{\rm KG})}\right) - 1\right]$	-5
Extra dimension [183]	$\frac{25}{851968}\left(\frac{dm}{dt}\right)\frac{3-26\eta+34\eta^2}{\eta^{2/5}(1-2\eta)}$	-13
Varying G [151]	$-\frac{25}{65536}\dot{G}\mathcal{M}$	-13
Mod. disp. rel. [184]	$\frac{\pi^{2-\alpha_{\rm MDR}}}{(1-\alpha_{\rm MDR})}\frac{D_{\alpha_{\rm MDR}}}{\lambda_{\mathbb{A}}^{2-\alpha_{\rm MDR}}}\frac{\mathcal{M}^{1-\alpha_{\rm MDR}}}{(1+z)^{1-\alpha_{\rm MDR}}}$	$3(\alpha_{\rm MDR}-1)$

Missing GR physics (precession, higher modes) affect ppE bounds already at current sensitivity. Systematics will dominate for XG detectors, even more so for LISA!

[Chandramouli+, 2410.06254]

A cautionary tale: good events can easily kill theories! Not only GW170817…

Tests of General Relativity with GW230529: a neutron star merging with a lower mass-gap compact object

Elise M. Sänger,[1,*] Soumen Roy,[2,3,†] Michalis Agathos,[4,5] Ofek Birnholtz,[6] Alessandra Buonanno,[1,7] Tim Dietrich,[8,1] Maria Haney,[2] Félix-Louis Julié,[1] Geraint Pratten,[9] Jan Steinhoff,[1] Chris Van Den Broeck,[2,3] Sylvia Biscoveanu,[10] Prasanta Char,[11] Anna Heffernan,[12] Prathamesh Joshi,[13] Atul Kedia,[14] R. M. S. Schofield,[15] M. Trevor,[7] and Michael Zevin[16]

On 29 May 2023, the LIGO Livingston observatory detected the gravitational-wave signal GW230529_181500 from the merger of a neutron star with a lower mass-gap compact object. Its long inspiral signal provides a unique opportunity to test General Relativity (GR) in a parameter space previously unexplored by strong-field tests. In this work, we performed parameterized inspiral tests of GR with GW230529_181500. Specifically, we search for deviations in the frequency-domain GW phase by allowing for agnostic corrections to the post-Newtonian coefficients. We performed tests with the Flexible Theory Independent (FTI) and Test Infrastructure for General Relativity (TIGER) frameworks using several quasi-circular waveform models that capture different physical effects (higher modes, spins, tides). We find that the signal is consistent with GR for all deviation parameters. Assuming the primary object is a black hole, we obtain particularly tight constraints on the dipole radiation at −1PN order of $|\delta\hat{\varphi}_{-2}| \lesssim 8 \times 10^{-5}$, which is a factor $\sim$ 17 times more stringent than previous bounds from the neutron star–black hole merger GW200115_042309, as well as on the 0.5PN and 1PN deviation parameters. We discuss some challenges that arise when analyzing this signal, namely biases due to correlations with tidal effects and the degeneracy between the 0PN deviation parameter and the chirp mass. To illustrate the importance of GW230529_181500 for tests of GR, we mapped the agnostic −1PN results to a class of Einstein-scalar-Gauss-Bonnet (ESGB) theories of gravity. We also conducted an analysis probing the specific phase deviation expected in ESGB theory and obtain an upper bound on the Gauss-Bonnet coupling of $\ell_{GB} \lesssim 0.51\ M_\odot$ ($\sqrt{\alpha_{GB}} \lesssim 0.28$ km), which is better than any previously reported constraint.

[Sänger+, 2406.03568]

Deviations from GR in the ringdown?

Black hole spectroscopy: from theory to experiment

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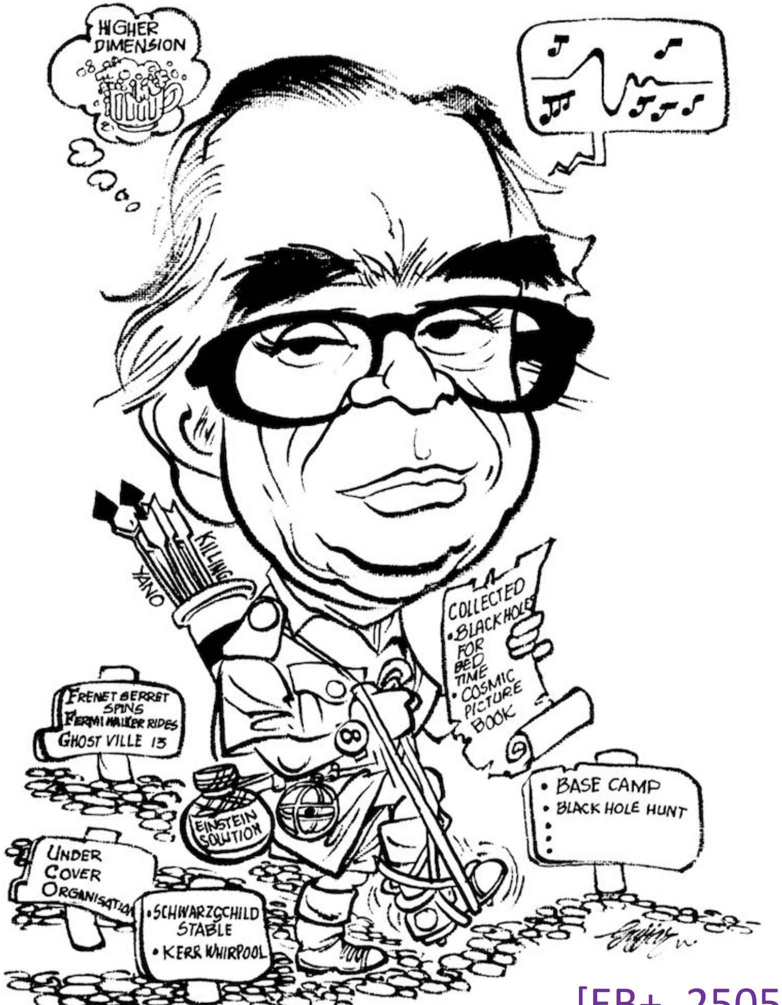
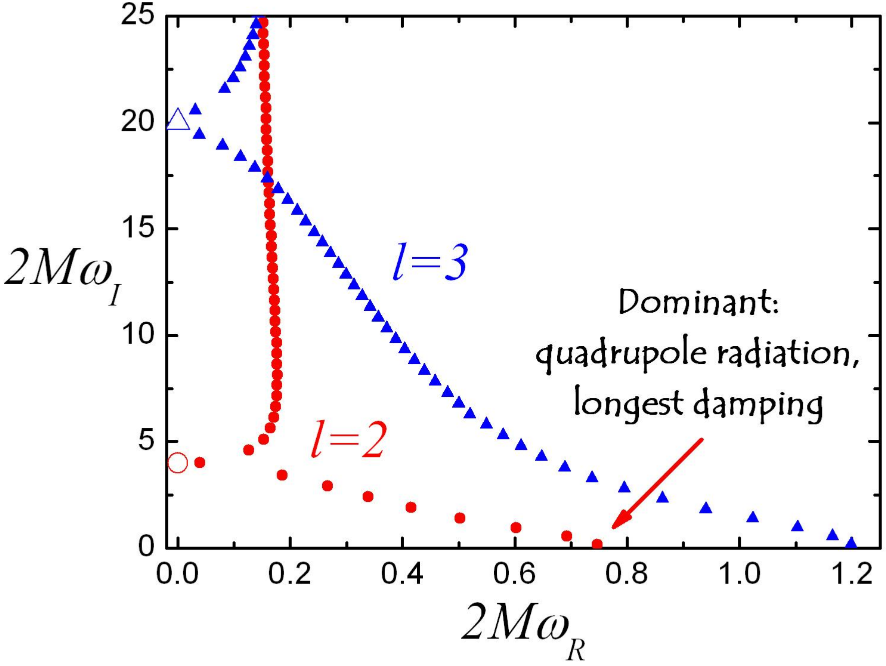
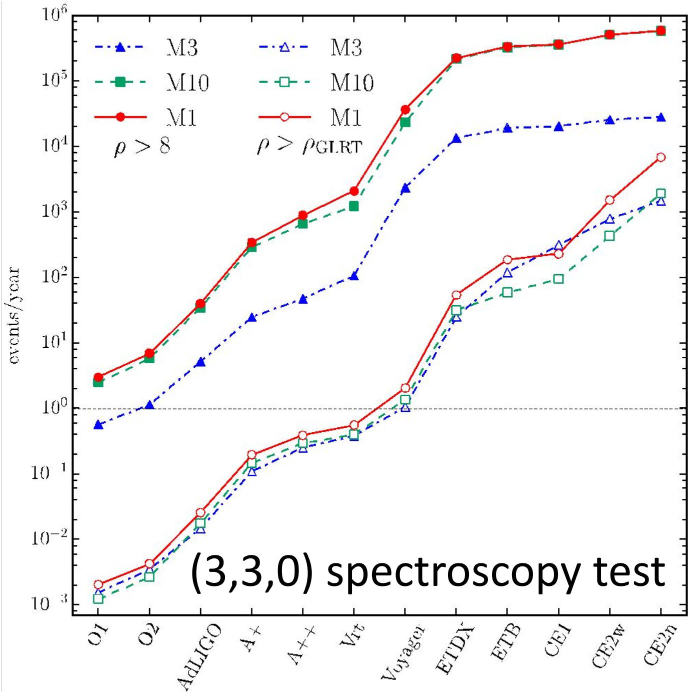
Abstract. The "ringdown" radiation emitted by oscillating black holes has great scientific potential. By carefully predicting the frequencies and amplitudes of black hole quasinormal modes and comparing them with gravitational-wave data from compact binary mergers we can advance our understanding of the two-body problem in general relativity, verify the predictions of the theory in the regime of strong and dynamical gravitational fields, and search for physics beyond the Standard Model or new gravitational degrees of freedom. We summarize the state of the art in our understanding of black hole quasinormal modes in general relativity and modified gravity, their excitation, and the modeling of ringdown waveforms. We also review the status of LIGO-Virgo-KAGRA ringdown observations, data analysis techniques, and the bright prospects of the field in the era of LISA and next-generation ground-based gravitational-wave detectors.



[EB+, 2505.23895]

Black hole spectroscopy: are we there yet?





- **One mode** fixes mass and spin – and the whole spectrum!
- **N modes:** N tests of GR dynamics…**if** they can be measured. Overtones or higher multipoles?
- Conventional wisdom: need large SNR, Voyager-class detectors (pessimistic assumptions) [EB+, gr-qc/0512160; gr-qc/0707.1202; 1605.09286; Chirenti-Ota, 2108.01774…]

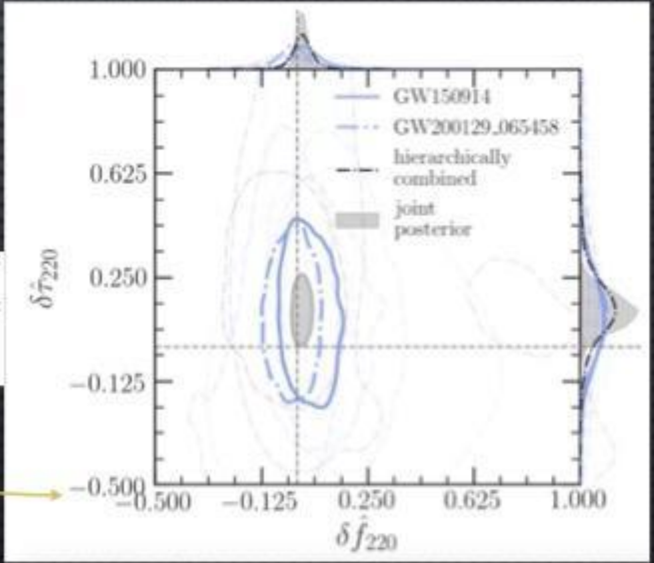
  …**or do we not?** [Isi+, Capano+, Cotesta+ and last week's workshop]

[Bhagwat, *Ringdown Inside & Out*]

SUMMARY

- VERY PROMISING AND STRINGENT NULL TESTS – GOLDENTEVENTS WITH SNR ~300 FOR 3G DETECTORS, ~1000 FOR LISA
- AN INVITATION TO BRING IN AMPLITUDE AND PHASE INTO OUR BATTERY OF CONSISTENCY TESTS
- BREAKING PARAMETER DEGENERACIES WITH RINGDOWN
- POPULATION BASES TESTS!

ET (+1CE)	$N_{det}(SNR \geq 12)$	$N_{det}(SNR \geq 50)$	$N_{det}(SNR \geq 100)$	max(SNR)
Δ-10 km	17268	188	18	298
Δ-15 km	23634	311	29	350



Tests of General Relativity with GWTC-3
~10 events!

Rotating BH QNMs in modified gravity: the EFT viewpoint

QNM calculations:
Significant progress in the past few years

Theories: sum over curvature invariants with scalar-dependent coefficients

$$S=\frac{1}{16\pi G}\int d^4x\sqrt{|g|}\left[R+\sum_{n=2}^{\infty}\ell^{2n-2}\mathcal{L}_{(n)}\right]$$ and more specifically, at order ℓ^4

EsGB dCS (dilaton+axion)

$$S=\frac{1}{16\pi G}\int d^4x\sqrt{|g|}\Big\{R+\alpha_1\phi_1\ell^2R_{\rm GB}+\alpha_2(\phi_2\cos\theta_m+\phi_1\sin\theta_m)\ell^2R_{\mu\nu\rho\sigma}\tilde{R}^{\mu\nu\rho\sigma}$$
$$+\lambda_{\rm ev}\ell^4R_{\mu\nu}^{\rho\sigma}R_{\rho\sigma}^{\delta\gamma}R_{\delta\gamma}^{\mu\nu}+\lambda_{\rm odd}\ell^4R_{\mu\nu}^{\rho\sigma}R_{\rho\sigma}^{\delta\gamma}\tilde{R}_{\delta\gamma}^{\mu\nu}-\frac{1}{2}(\partial\phi_1)^2-\frac{1}{2}(\partial\phi_2)^2\Big\}$$

Einsteinian cubic gravity (+parity-breaking) - causality constraints [Camanho+ 1407.5597]
Next order, no new DOFs [Endlich-Gorbenko-Huang-Senatore, 1704.01590]

$$S_{(4)}=\frac{\ell^6}{16\pi G}\int d^4x\sqrt{|g|}\left\{\epsilon_1\mathcal{C}^2+\epsilon_2\tilde{\mathcal{C}}^2+\epsilon_3\mathcal{C}\tilde{\mathcal{C}}\right\}\qquad \mathcal{C}=R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma},\quad \tilde{\mathcal{C}}=R_{\mu\nu\rho\sigma}\tilde{R}^{\mu\nu\rho\sigma}$$

[Cano, *Ringdown Inside & Out*]

Great progress in calculations of rotating BH QNMs in modified gravity

Teukolsky equation separability is special: Petrov Type D, hidden symmetries (Killing tensor)
Beyond GR: no analytical background, no Petrov Type D, non-separability, higher-order EOMs

Metric perturbations

Slowly rotating BHs in specific theories (EdGB/EsGB, dCS), not restricted to small coupling
[Molina+ (dCS), Blazquez-Salcedo+ (EdGB/EsGB), Pierini-Gualtieri (EsGB)…]

Generalized Teukolsky equations

Linear shift in QNM frequencies can be computed (Leaver, eigenvalue perturbation techniques)
Algorithm to compute small-coupling corrections to the frequencies, up to order 18 in rotation
[Li-Wagle-Chen-Yunes, Hussain-Zimmerman, Cano-Fransen-Hertog-Maenaut, Cano+]

Spectral methods

Arbitrary coupling, in principle (but not in practice) arbitrary rotation
[Chung-Wagle-Yunes, Blazquez-Salcedo-Scen Koo-Kleihaus-Kunz]

[Cano, *Ringdown Inside & Out*]

Outlook and challenges

Methods: pros and cons

Method	Rotation	Analytical	Finite coupling
Metric perturbations	slow	✓	✓
Generalized Teukolsky	high	✓	✗
Spectral methods	high	✗	✓

QNM spectrum of each theory: state of the art

Theory	Max. rotation	Harmonics (l, m)	Overtones n
EFT of GR	0.7-0.95	$l = 2, 3, 4, -l \leq m \leq l$	2
sGB	0.6-0.85	(2,2), (2,1), (3,3), (3,2)	0
dCS	0.2	$l = 2, 3, 4, -l \leq m \leq l$	0

[Cano, *Ringdown Inside & Out*]

Parametrized ringdown (in the ppE spirit) for small coupling

Modifications to the gravity sector and/or beyond Standard Model physics: expect

- small modifications to the functional form of the potentials – parametrize
- coupling between the wave equations

$$V = V_\pm + \delta V_\pm \qquad \delta V_\pm = \frac{1}{r_H^2}\sum_{j=0}^{\infty} \alpha_j^\pm \left(\frac{r_H}{r}\right)^j \qquad \omega_{\rm QNM}^\pm = \omega_0^\pm + \sum_{j=0}^{\infty} \alpha_j^\pm e_j^\pm$$

$$V = V_s + \delta V_s \qquad \delta V_s = \frac{1}{r_H^2}\sum_{j=0}^{\infty} \beta_j^s \left(\frac{r_H}{r}\right)^j \qquad \omega_{\rm QNM}^s = \omega_0^s + \sum_{j=0}^{\infty} \beta_j^s d_j^s$$

Maximum of $f(r)\alpha_j^\pm \left(\frac{r_H}{r}\right)^j$ is $\alpha_j^\pm \frac{(1+1/j)^{-j}}{j+1}$, so corrections are small if:

$$(\alpha_j^\pm, \beta_j^s) \ll (1+1/j)^j (j+1)$$

Can map to specific theories like ppE, now extended to rotating black holes

[Cardoso+, 1901.01265; McManus+, 1906.05155; Kimura+; Cano+ 2407.15947, 2409.04517]

Parametrized spectroscopy (ParSpec): how many observations do we need?

Use a small-spin expansion and add parametric deviations to frequency and damping time
Assume you detect **N** sources, and **q** QNM frequencies for each source

$J = 1, 2, \dots, q$ modes/source

Order in the spin expansion: need at least 4 or 5 in GR

$$\omega_i^{(J)} = \frac{1}{M_i} \sum_{n=0}^{D} \chi_i^n w_J^{(n)} \left(1 + \gamma_i \delta w_J^{(n)}\right)$$

$i = 1, \dots, N$ sources

$$\tau_i^{(J)} = M_i \sum_{n=0}^{D} \chi_i^n t_J^{(n)} \left(1 + \gamma_i \delta t_J^{(n)}\right)$$

Expansion coefficients in GR

Small, universal non-GR corrections

How many parameters?
If $\gamma_i = \alpha$ for all sources ,
reabsorb $\gamma_i \delta w^{(n)} \to \delta w^{(n)}$

$\mathcal{P} = 2(D+1)q \longrightarrow D = 4$

- $q = 1$, $\ell = m = 2$ $\longrightarrow$ $\mathcal{P} = 10$
- $q = 2$, $\ell = m = 2$, $\ell = m = 3$ $\longrightarrow$ $\mathcal{P} = 20$

How many observables? $\mathcal{O} = 2N \times q$

Need only $N \geq D + 1$

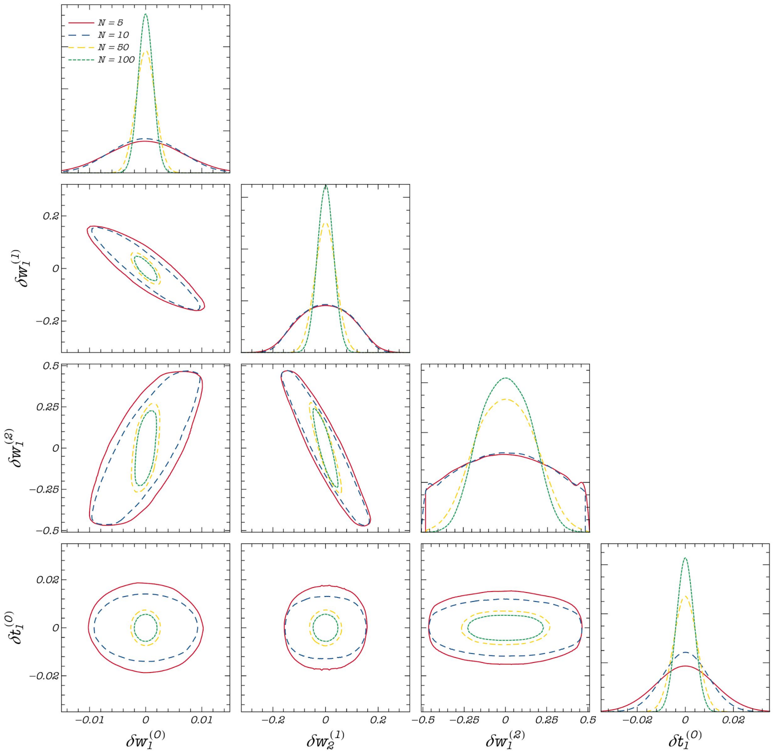
[Maselli+, 1910.12893]

Parametrized spectroscopy (ParSpec): a proof of principle

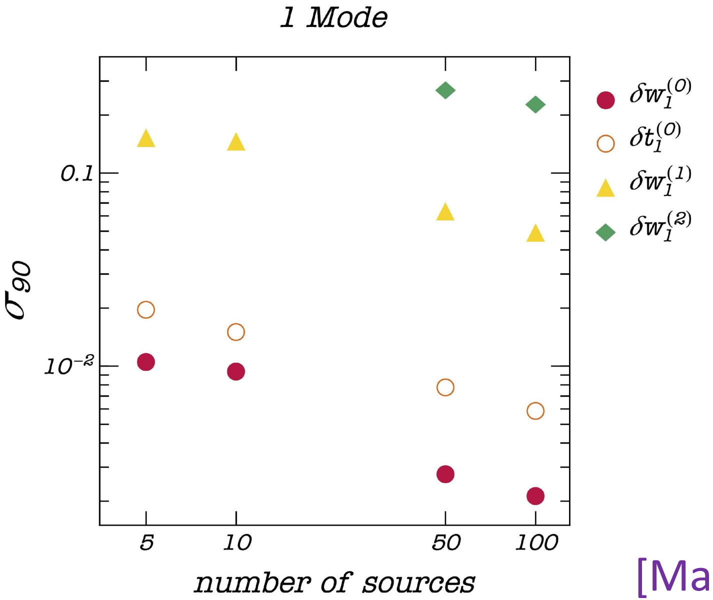
Complication: the coupling is often dimensionful $\gamma_i = \frac{\alpha}{(M_i^{\mathrm{s}})^p} = \frac{\alpha(1+z_i)^p}{M_i^p}$

Use Bayesian inference (MCMC), $p=0,\ q=1$(one mode), simple source distributions

Einstein Telescope: constrain first three frequency coeffs and only the first damping coeffs



Width at 90% confidence gets better as we get more observations:



[Maselli+, 1910.12893]

arXiv > gr-qc > arXiv:2411.17893

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General Relativity and Quantum Cosmology

[Submitted on 26 Nov 2024]

Ringdown Analysis of Rotating Black Holes in Effective Field Theory Extensions of General Relativity

Simon Maenaut, Gregorio Carullo, Pablo A. Cano, Anna Liu, Vitor Cardoso, Thomas Hertog, Tjonnie G. F. Li

Quasinormal modes of rapidly rotating black holes were recently computed in a generic effective-field-theory extension of general relativity with higher-derivative corrections. We exploit this breakthrough to perform the most complete search for signatures of new physics in black hole spectra to date. We construct a template that describes the post-merger gravitational-wave emission in comparable-mass binary black hole mergers at current detector sensitivity, notably including isospectrality breaking. The analysis of all events with detectable quasinormal-driven ringdown signatures yields no evidence of higher-derivative corrections in the spectra, and we set an upper bound $\ell \lesssim 35$ km on the length scale of new physics. Looking ahead, our scheme enables new studies on the capabilities of future detectors to robustly search for signatures of new gravitational physics.

Comments: 9 pages, 6 figures
Subjects: **General Relativity and Quantum Cosmology (gr-qc)**
Report number: LIGO-P2400551
Cite as: arXiv:2411.17893 **[gr-qc]**
(or arXiv:2411.17893v1 **[gr-qc]** for this version)
https://doi.org/10.48550/arXiv.2411.17893

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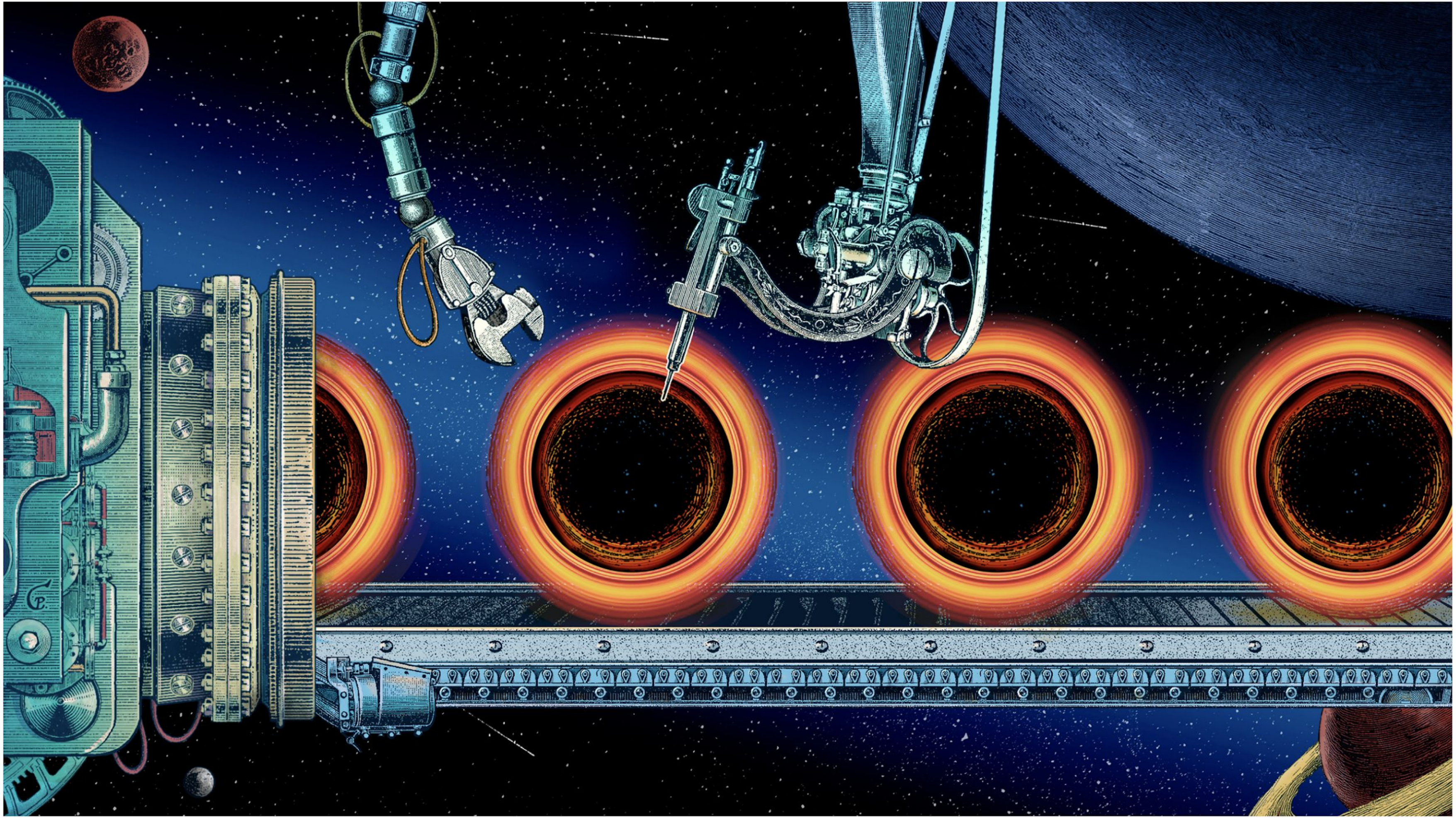
GRAVITY

Astrophysicists Find No 'Hair' on Black Holes

6 |

According to Einstein's theory of gravity, black holes have only a small handful of distinguishing characteristics. Quantum theory implies they may have more. Now an experimental search finds that any of this extra 'hair' has to be pretty short.



Do black holes have a cookie-cutter form, or subtle distinctions that reveal each one's unique history and makeup?

Celsius Pictor for *Quanta Magazine*

Parametrized spectroscopy (ParSpec): full population study for ET/CE

Construct astrophysical populations based on LVK observations, different assumptions on spins

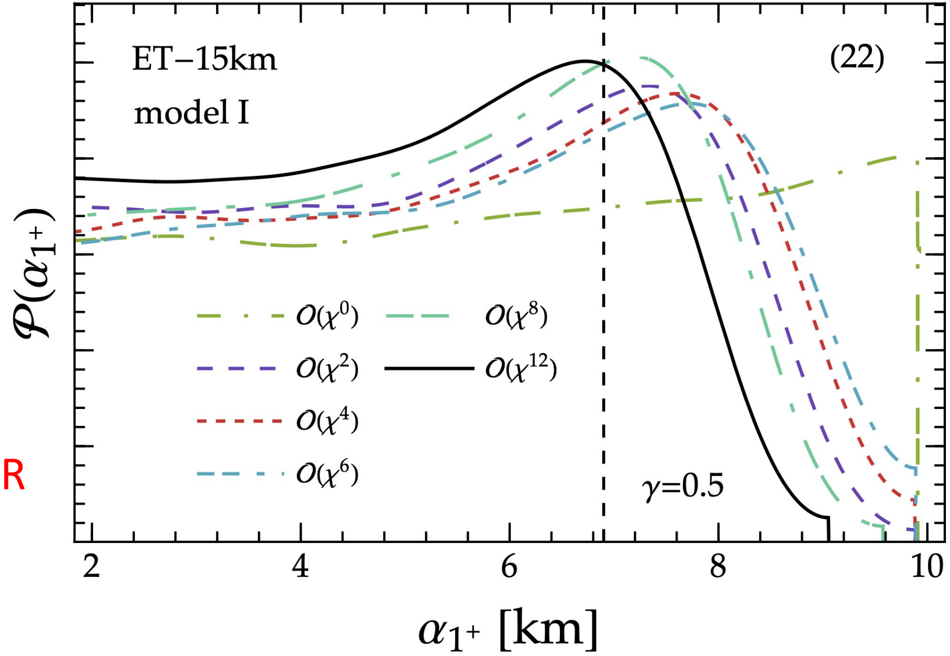
Theory-agnostic tests (with/without knowledge of mass and spin)
Theory-specific bounds for EsGB, dCS, various classes of EFTs

Convergence of EsGB and dCS bounds
limited by low order of the spin expansion
(but this can be improved with recent results)

EFT posteriors converge with spin
(peak tends to injected value)

Bad news: bounds generally compatible with GR
Why?

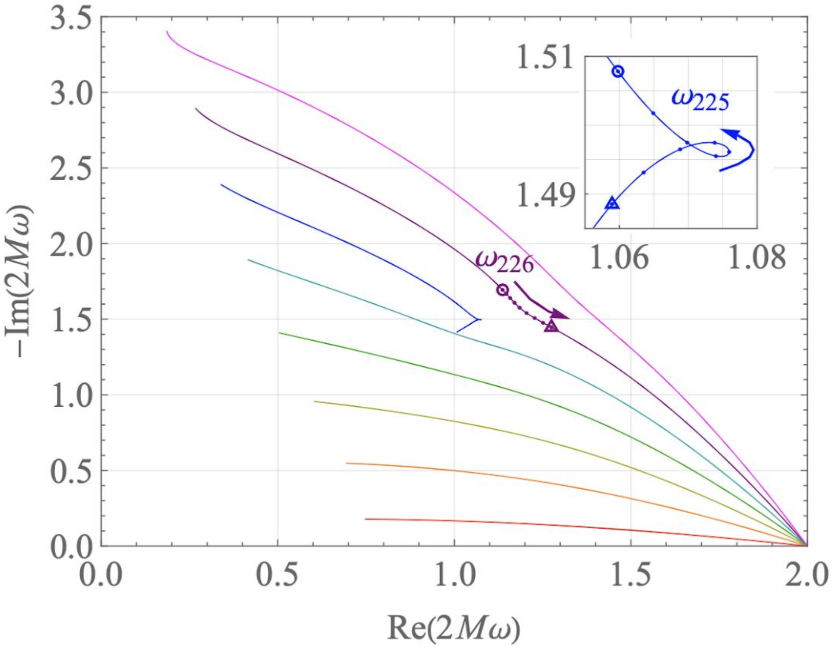
low-mass binaries have low SNR
high mass binaries have small curvature corrections

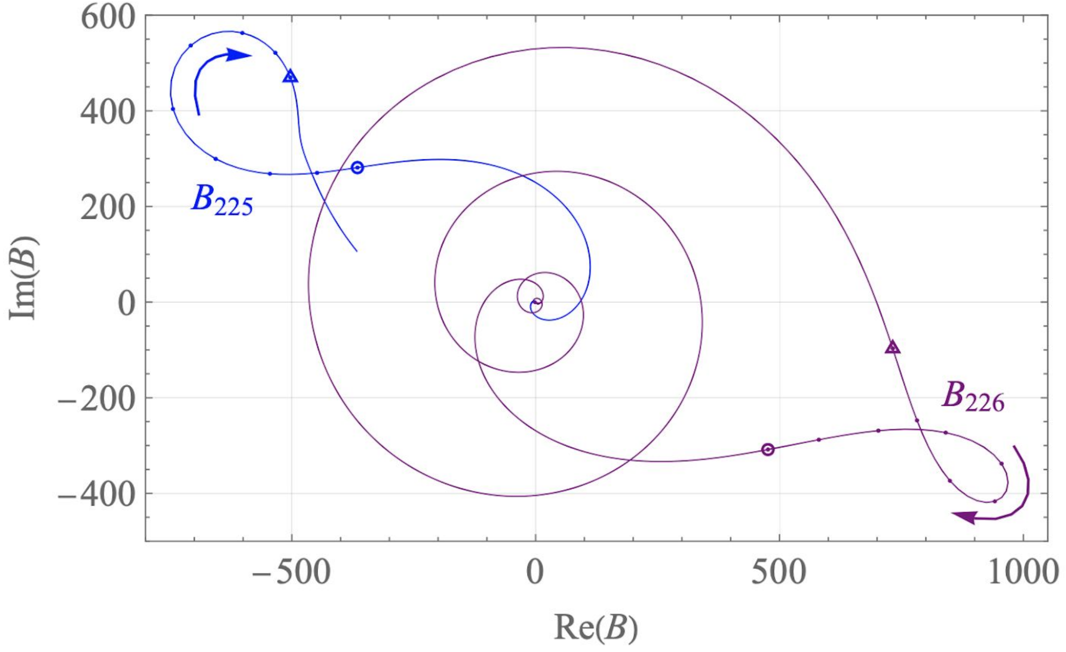


[Maselli+, 2311.14803]

Avoided crossings and resonant excitation

Avoided crossings correspond to a resonant growth of the
excitation factors and excitation coefficients (roughly, the QNM amplitudes)





Is this observationally interesting, e.g. under matter perturbations/modified gravity?
Example: resonance between gravitational-, EM- and axion-led modes in Einstein-Maxwell-axion

[Motohashi, 2407.15191; Lo+, 2504.00084; Takahashi-Motohashi-Takahashi, 2505.03883]


WITH GREAT SNR
COMES GREAT
RESPONSIBILITY.
SPIDERMAN

Beware! False general relativity violations already in binary pulsar

Tests of general relativity in the nonlinear regime: a parametrized plunge-merger-ringdown gravitational waveform model

Elisa Maggio,[1] Hector O. Silva,[1] Alessandra Buonanno,[1,2] and Abhirup Ghosh[1]

[1] *Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany*
[2] *Department of Physics, University of Maryland, College Park, Maryland 20742, USA*

(Dated: August 3, 2023)

The plunge-merger stage of the binary-black-hole coalescence, when the bodies' velocities reach a large fraction of the speed of light and the gravitational-wave luminosity peaks, provides a unique opportunity to probe gravity in the dynamical and nonlinear regime. How much do the predictions of general relativity differ from the ones in other theories of gravity for this stage of the binary evolution? To address this question, we develop a parametrized waveform model, within the effective-one-body formalism, that allows for deviations from general relativity in the plunge-merger-ringdown stage. As first step, we focus on nonprecessing-spin, quasicircular black hole binaries. In comparison to previous works, for each gravitational wave mode, our model can modify, with respect to general-relativistic predictions, the instant at which the amplitude peaks, the instantaneous frequency at this time instant, and the value of the peak amplitude. We use this waveform model to explore several questions considering both synthetic-data injections and two gravitational wave signals. In particular, we find that deviations from the peak gravitational wave amplitude and instantaneous frequency can be constrained to about 20% with GW150914. Alarmingly, we find that GW200129_065458 shows a strong violation of general relativity. We interpret this result as a false violation, either due to waveform systematics (mismodeling of spin precession) or due to data-quality issues depending on one's interpretation of this event. This illustrates the use of parametrized waveform models as tools to investigate systematic errors in plain general relativity. The results with GW200129_065458 also vividly demonstrate the importance of waveform systematics and of glitch mitigation procedures when interpreting tests of general relativity with current gravitational wave observations.

[Maggio+, 2212.09655]

Possible causes of false general relativity violations

Data in Tension with GR

Due to Noise Artifacts?

- Non-Stationarity
- Non-Gaussianity, Glitches
- Overlapping Signals
- Data Gaps, Detector Calibration

Caused by Waveform Systematics?

- Missing Physics
  - Eccentricity
  - Tides, Viscosity
  - Kicks
  - Ringdown Modes
- Inaccurate Modelling

Due to Astrophysical Causes?

- Gravitational Lensing
- Environments
- Mistaken Source Class
- Astrophysical Population

[Gupta+, 2405.02197]

SHARE

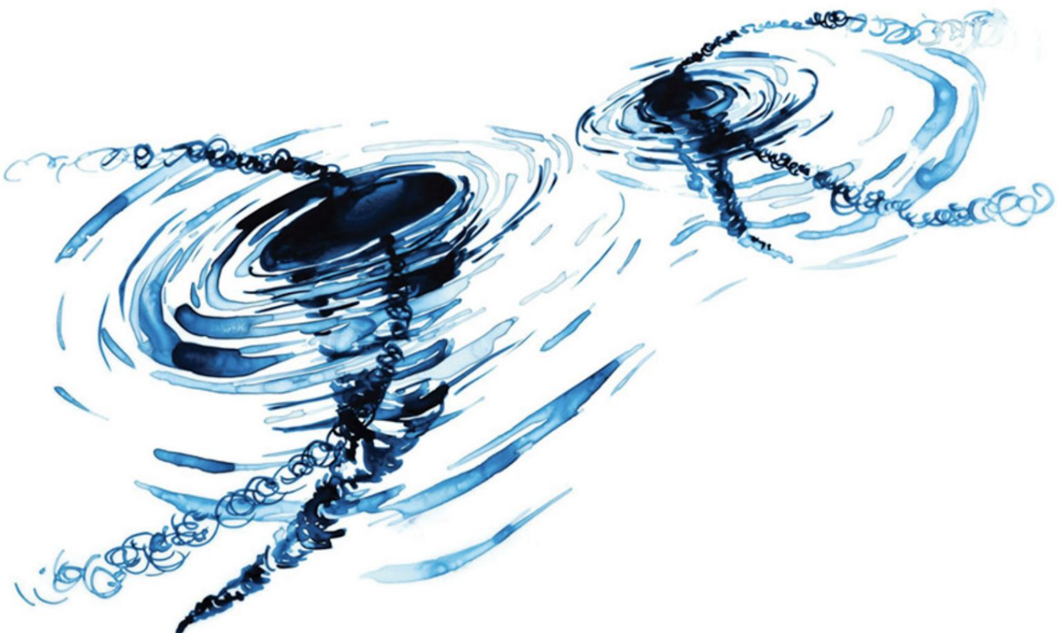
How black hole spectroscopy can put general relativity to the test FREE

10 April 2025

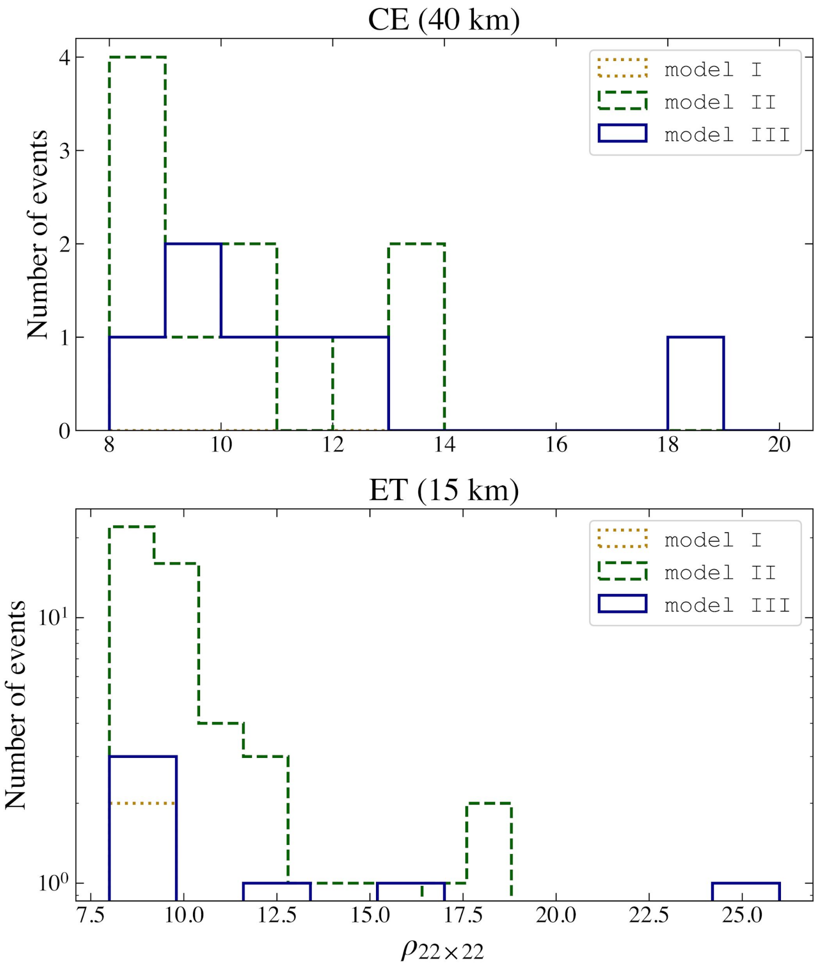
Einstein's theory makes specific predictions about the nonlinear spacetime oscillations that propagate from merging black holes. Next-generation gravitational-wave detectors should enable researchers to evaluate those predictions.

Emanuele Berti, Mark Ho-Yeuk Cheung, and Sophia Yi

DOI: https://doi.org/10.1063/pt.fvtp.lpxx

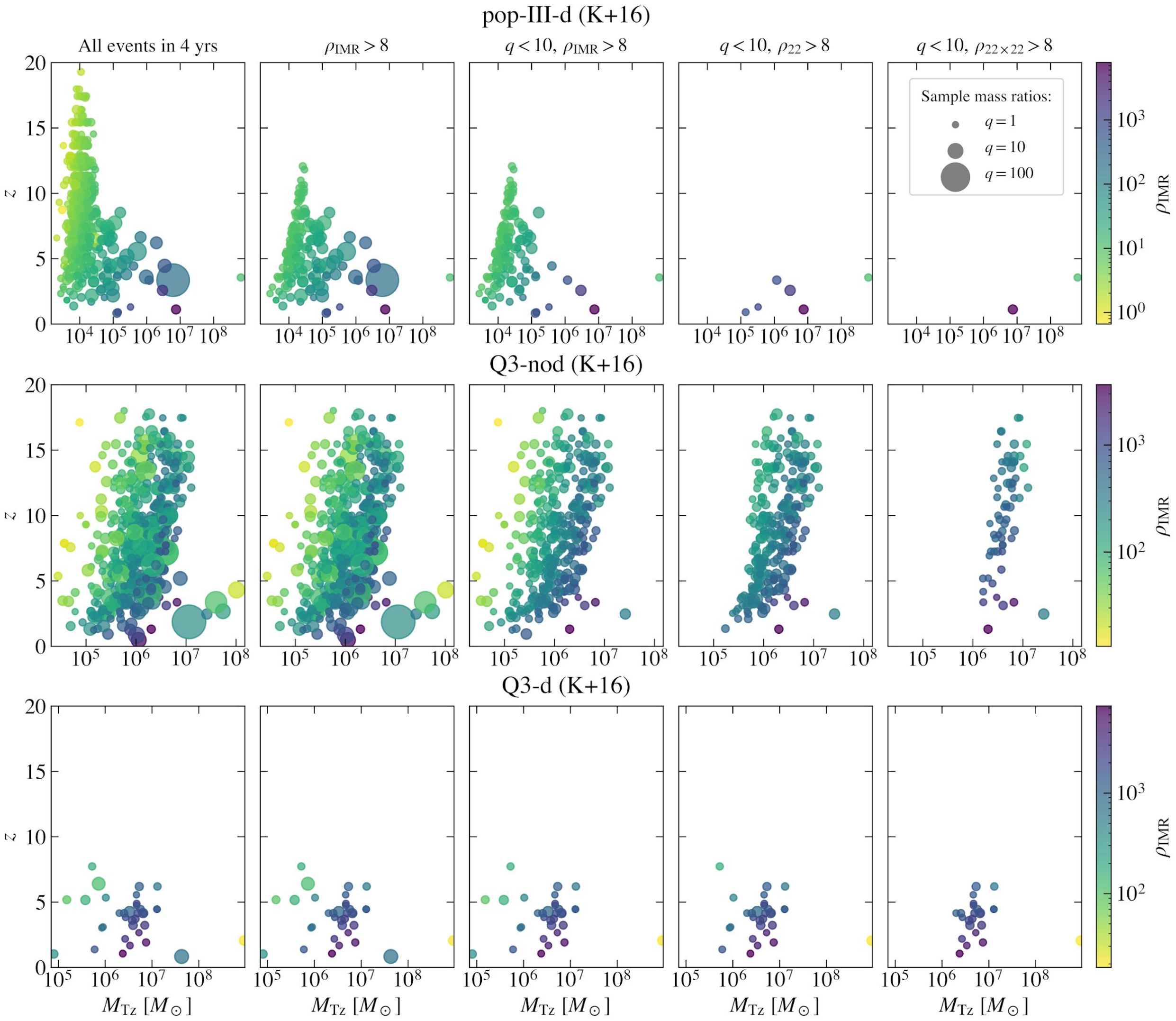


XG ground-based detectors, quadratic $(220)^2$ mode in the (44) multipole



[Yi+, 2403.09767]

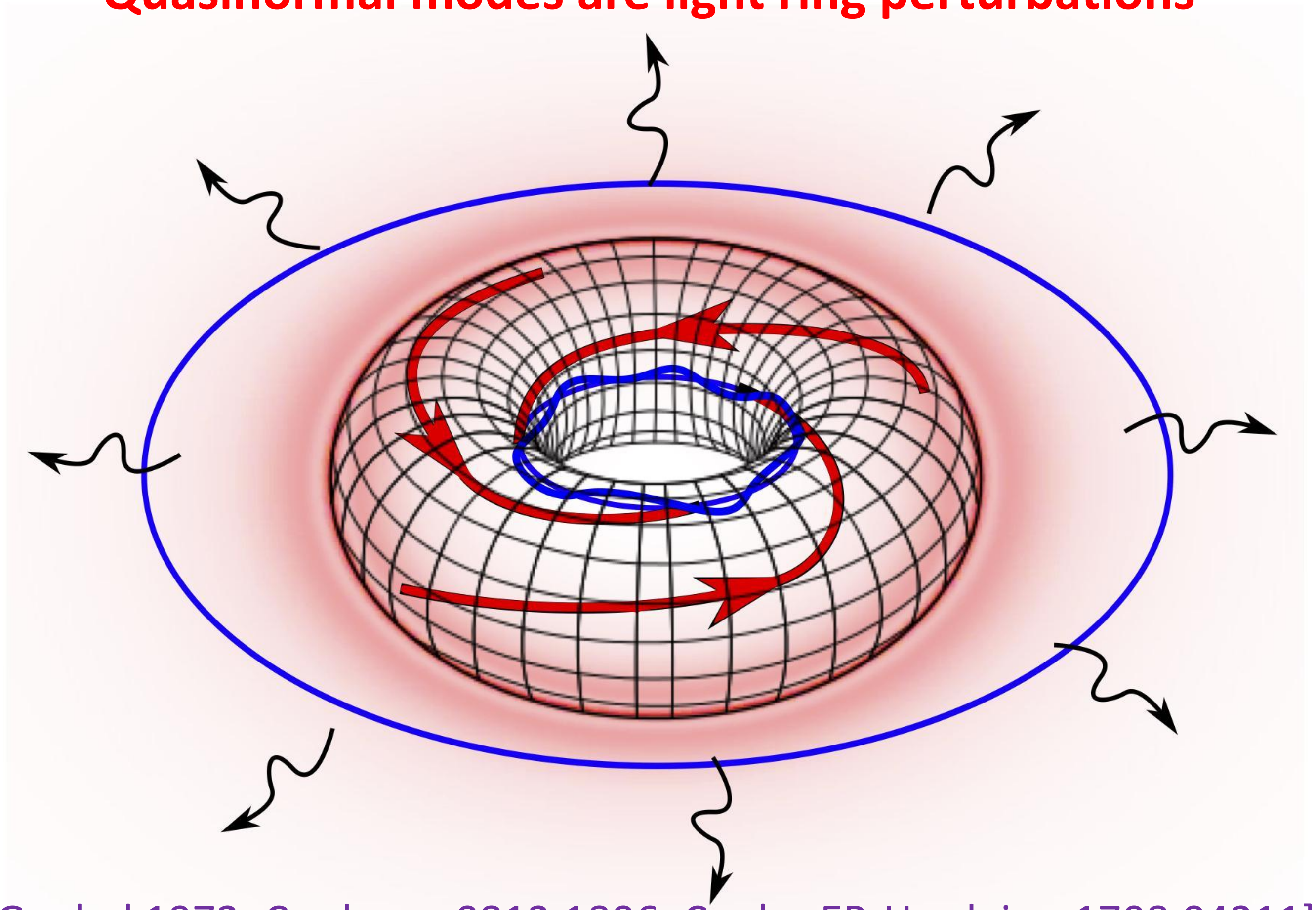
LISA: much better prospects!



[Yi+, 2403.09767]

Exotic compact objects

EHT and spectroscopic tests are related!
Quasinormal modes are light ring perturbations



[Goebel 1972; Cardoso+ 0812.1806; Cunha-EB-Herdeiro, 1708.04211]

Nonlinear (Keir) instabilities?

arXiv > gr-qc > arXiv:2207.13713

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General Relativity and Quantum Cosmology

[Submitted on 27 Jul 2022 (v1), last revised 9 Feb 2023 (this version, v2)]

Exotic Compact Objects and the Fate of the Light-Ring Instability

Pedro V. P. Cunha, Carlos Herdeiro, Eugen Radu, Nicolas Sanchis-Gual

Ultracompact objects with light-rings (LRs) but without an event horizon could mimic black holes (BHs) in their strong gravity phenomenology. But are such objects dynamically viable? Stationary and axisymmetric ultracompact objects that can form from smooth, quasi-Minkowski initial data must have at least one stable LR, which has been argued to trigger a spacetime instability; but its development and fate have been unknown. Using fully non-linear numerical evolutions of ultracompact bosonic stars free of any other known instabilities and introducing a novel adiabatic effective potential technique, we confirm the LRs triggered instability, identifying two possible fates: migration to non-ultracompact configurations or collapse to BHs. In concrete examples we show that typical migration/collapse time scales are not larger than $\sim 10^3$ light-crossing times, unless the stable LR potential well is very shallow. Our results show that the LR instability is effective in destroying horizonless ultracompact objects that could be plausible BH imitators.

Comments: 5 pages + Appendices; Videos can be found in this URL this http URL v2. Title changed per request of journal. Published in Physical Review Letters as Editor's Suggestion and Featured in Physics

arXiv > gr-qc > arXiv:2508.11527

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General Relativity and Quantum Cosmology

[Submitted on 15 Aug 2025]

Assessing the stability of ultracompact spinning boson stars with nonlinear evolutions

Tamara Evstafyeva, Nils Siemonsen, William E. East

We reinvestigate the stability properties of ultracompact spinning boson stars with a stable light ring using fully nonlinear 3+1 and 2+1 numerical relativity simulations and two different formulations of the Einstein equations. We find no evidence of an instability on timescales of $t\mu \sim 10^4$ (in units of the scalar mass), when allowing the star to be perturbed either solely by discretization error or by imposing various types of perturbations to our initial data. We find that the initially imposed perturbations exhibit slow decay, even for magnitudes just below the order where immediate collapse is induced.

[Keir, 1404.7036; Cunha+, 2207.13713; Evstafyeva+, 2508.11527]

Take-home messages

- Focused on tests of general relativity for LVK, Einstein Telescope, Cosmic Explorer, LISA

- Science case much broader: nuclear EOS, MMA, populations, high-z universe, SGWBs…
- Moon detectors, NEMO, Mhz, μHz detectors would probe different sources/physics

- Beyond-GR bounds from the inspiral:

- Several orders of magnitude depending on source class/detector combinations
- "Future truths of physical science are to be looked for in the sixth place of decimals"
- Must control systematics in GR+other sources of GR violations. We are not even close.

- Merger/ringdown spectroscopy:

- Ringdown bounds on theories with mass-dependent scales severely limited by SNR/curvature interplay for ground-based detectors; LISA will only do worse
- Key tests of nonlinearities in GR: quadratic QNMs, amplitude/phase tests, memory…
- Complementarity with ngEHT, BHEX: imaging & ringdown probe same physics (light ring)

- Exotic compact objects

- Nonlinear instabilities?
- Formation mechanism for boson stars/gravastars? Topological stars?