WG3: Fundamental problems in high energy and gravitational physics

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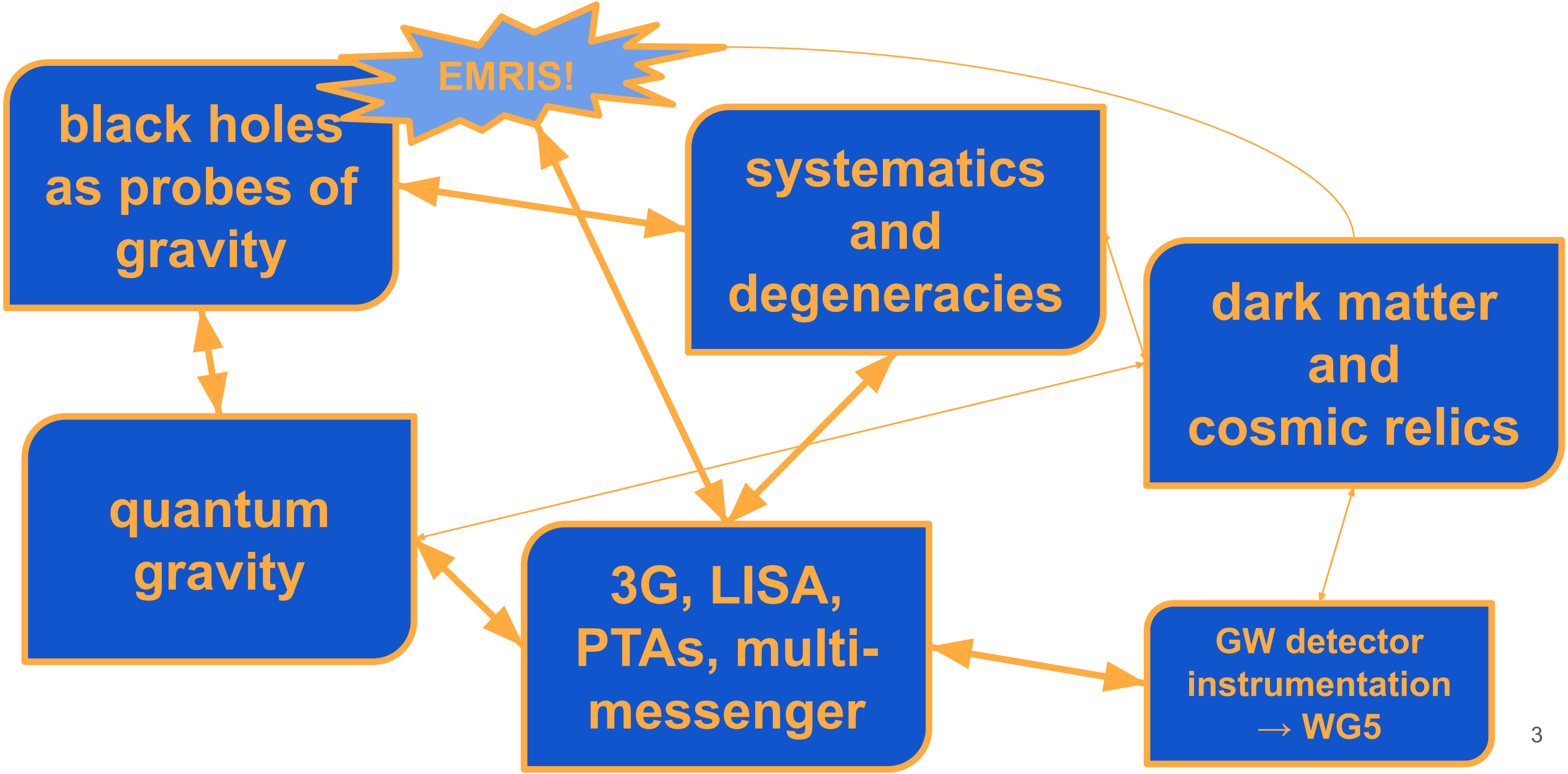
Bottom-Up Cross-Cutting Workshop
“JENAS Initiative Gravitational Wave Probes of Fundamental Physics”
(Rome, 13/02/2024)
https://agenda.infn.it/event/37487

DCC: LIGO-G2400285

scope: WG3 vs the world?

- title of the overall initiative and “workshop:
  “Gravitational Wave ***Probes of Fundamental Physics***”
- WG3: “***Fundamental problems*** in high energy and gravitational physics”
- Obviously this does not mean that any of the problems discussed in the other 4 WGs are any less “fundamental”! :-)
- We’ll treat this a bit as the “misc” section of the workshop.
- But mainly guided by the 29 WG3 submissions in "key questions" spreadsheet
  → let’s try to get these sorted a bit…

“key questions” from the JENAS initiative spreadsheet



EMRIS!

black holes as probes of gravity

systematics and degeneracies

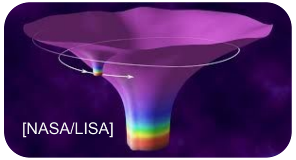
dark matter and cosmic relics

quantum gravity

3G, LISA, PTAs, multi-messenger

GW detector instrumentation → WG5

“key questions”: BHs as probes of gravity


[NASA/LISA]

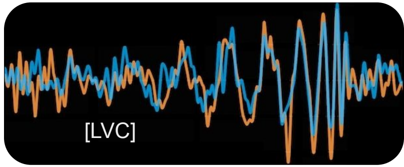

[SXS]

- Tests of BH thermodynamics by GW-BBH observations
- What is the event horizon of a black hole like and how to probe it with gravitational waves?
- Scattering amplitudes and GWs: up to where?
- How does the quantum nature of black holes impact gravitational wave observations?
- Black hole gravitational wave echos
- Are all black holes the same?
- EMRIs as probes of fundamental physics
- Can we model EMRIs to high accuracy in alternative theories of gravity
- Nonlinearities in the black hole ringdown: can we leverage methods from particle physics?
- Numerical relativity beyond GR - how far can we go?
- Waveform generation in modified gravity and efficient confrontation against GW data

→ focus slides by Elisa

EMRIS are popular!

“key questions”: systematics and degeneracies

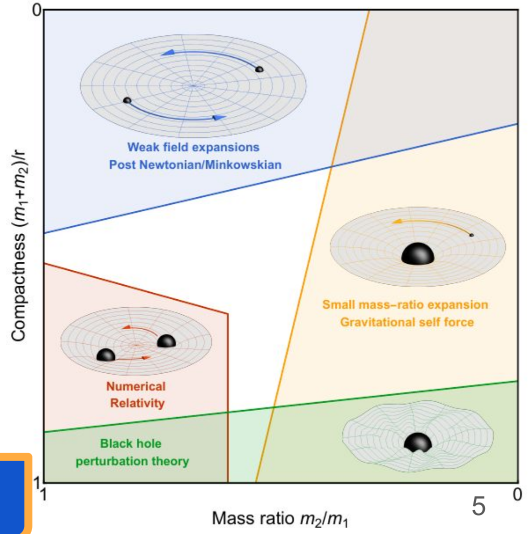


- Can we tell deviations from GR from matter/waveform systematics?
- Tests of gravity vs modelling systematics
- Interplay between Hierarchical Tests of Gravity and Population Inference
- Importance of environmental effects to estimate cosmological parameters and to investigate the nature of dark matter

comments DK:

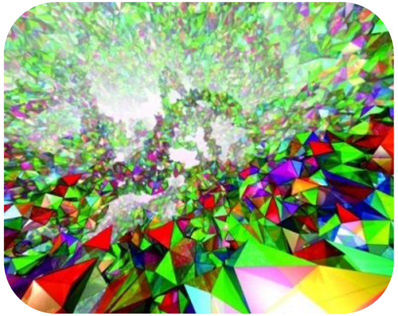
- most tests rely on matched filtering against waveform models (IMRPhenom/SEOBNR/NRSur)
- any other “out of manifold” effect of a given waveform model (HoMs/precession/eccentricity/beyond-GR/lensing/environments/…) can kill your search for a particular one
- extends to “hyper” analyses:
  population inference, cosmology, stacked searches
- running theme in ongoing LVK work, historically a bit overlooked, but now all sorts of combinations are being actively investigated
- set to be even more important in 3G+LISA

+ slides by Elisa



[2311.01300]

“key questions”: quantum gravity



[T.Thiemann / Milde Marketing]

- What is the fundamental nature of gravity?
- GWs probes of quantum gravity
- Imprints of Quantum nature of space time in GW
- Probing the quantum/fine structure of spacetime using gravitational waves
- Can gravitational wave detectors probe the fluctuating nature of the quantum gravity vacuum?
- Quantizing General Relativity and its GW-Signatures

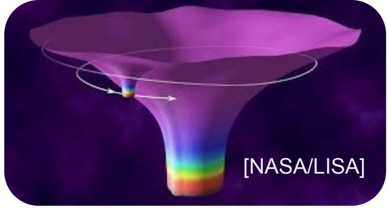
comments DK:

- main avenue 1: modifications to BBH waveforms – see the previous 2 items
- main avenue 2: early universe physics – relics and stochastic backgrounds
- of course this involves the biggest unknowns of theoretical physics
- actual observable signatures often unclear – we need both bright ideas and critical, statistically conservative thinking about the methods

+ slides by Elisa

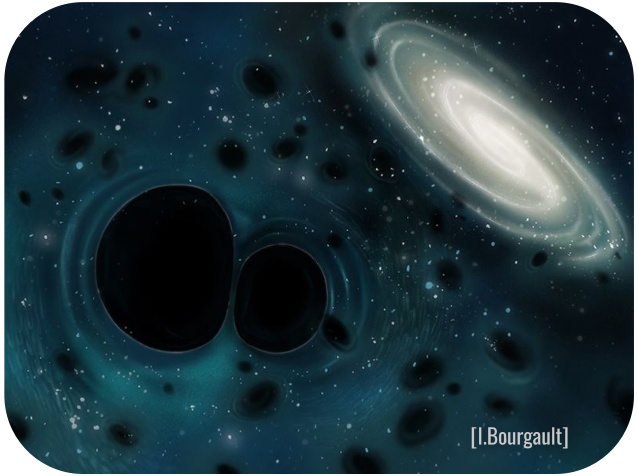
→ also N. Afshordi talk

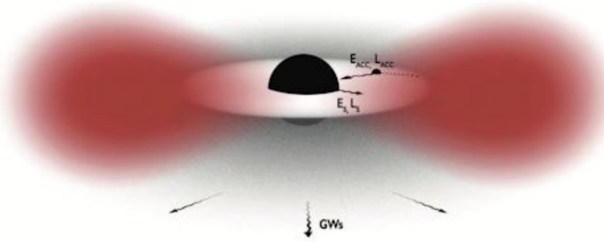
“key questions”: dark matter & cosmic relics


[NASA/LISA]

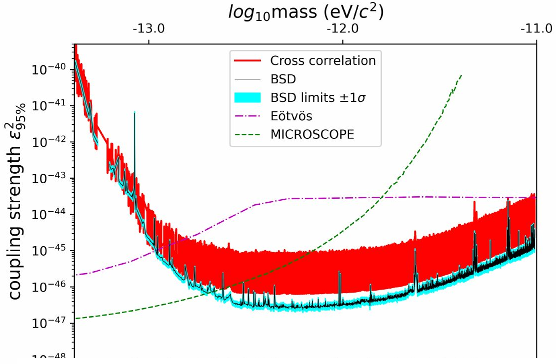
- Dark Matter Fundamental Nature
- Can we identify the nature of dark matter from its environmental effect on EMRIs?
  [← those again! everyone loves EMRIs 💞]
- What is the best way to discover PBH, via SSM or IMBH GW detection?

→ a few more slides soon


[I.Bourgault]



[Brito, Cardoso & Pani]

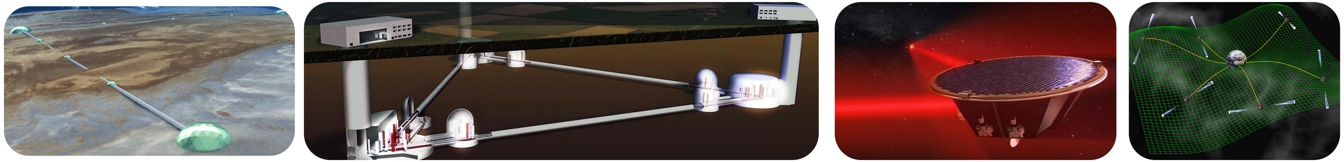


[LVK PRD105,063030, updated in erratum dcc.ligo.org/P2300439/public]

“key questions”: 3G, LISA, PTAs, multi-messenger

- Status of the PTA data and their interpretation
- What can we learn about fundamental physics by detecting or constraining any stochastic GW background from the early universe?
- What else do we want to search for that LISA or 3G enables but that will not already be ruled out by the late 2030s?
- Multi-messenger observation of primordial magnetic fields

→ also WG2&4

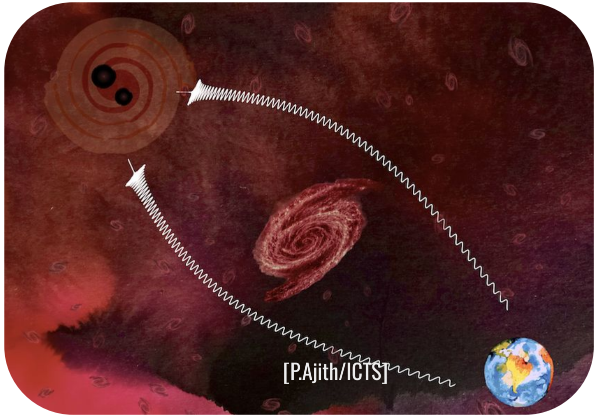


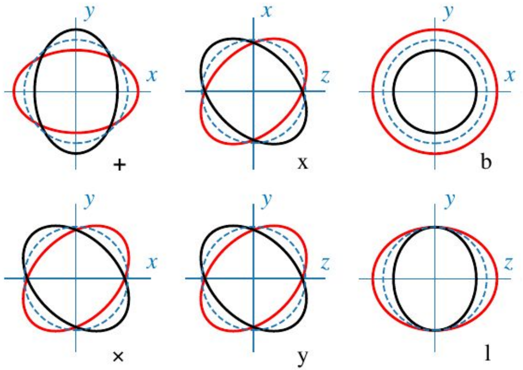
comments DK:

- multi-messenger is not just BNSs
- GWs beyond CBCs: persistent sources, stochastic backgrounds, cosmic relics
- of course, could have pasted here again everything about our friends the EMRIs
- multi-wavelength future of GW observations: PTAs + LISA&friends + 3G on the ground

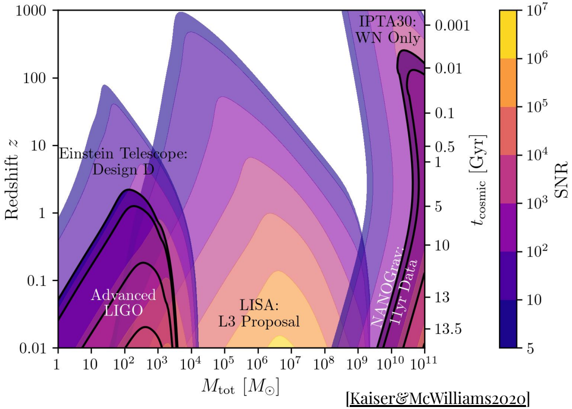
DK’s pet topic I: fundamental physics with lensed GWs

- putting together 2 of the most famous predictions of GR
- first searches: Hannuksela ApJ874:L2 (2019), LVC ApJ923:14 (2021), LVK arXiv:2304.08393
- expected event rate going up with GW detector redshift reach
- probing fundamental physics via the lensing imprints on GW signals:
  - speed of GWs (in multi-messenger case)
  - beyond-GR polarizations, birefringence, …
    (but: beware degeneracies!)
  - tool for cosmography
- probes of fundamental physics via finding exotic lenses: IMBHs? MACHOs?


[P.Ajith/ICTS]

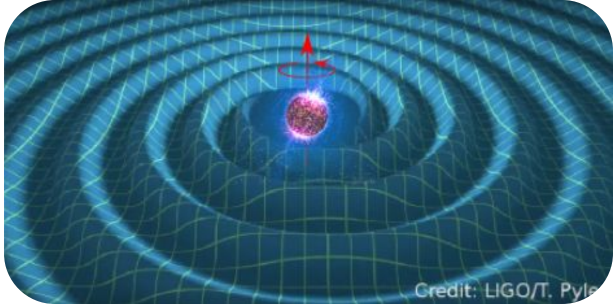


[Goyal+2021]

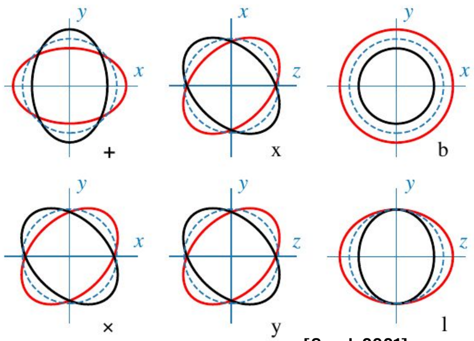


[Kaiser&McWilliams2020]

DK’s pet topic II: fundamental physics with Continuous GWs (CWs/CGWs)


Credit: LIGO/T. Pyl

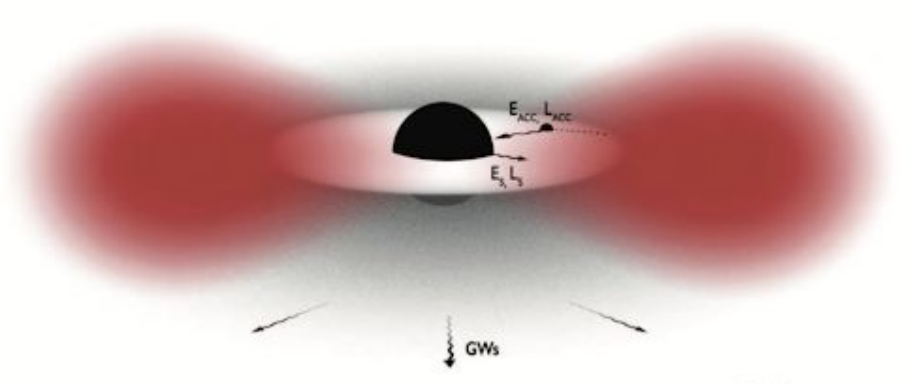
- neutron stars – “low” temperature, extreme density
  nuclear physics laboratories → extensively covered yesterday
- when we finally detect CWs from a deformed spinning NS:
  a *persistent* source, we can keep observing it and build up signal-to-noise
- likely to be multimessenger sources: either GW co-detection of a known pulsar (more sensitive search due to small trials factor), or a GW blind detection enabling deep EM follow-up
- beyond nuclear physics: long observing times enable detailed polarization tests of beyond-GR theories
- beyond neutron stars: dark matter,
  early-inspiral binaries
  (especially: PBHs for LVK, WD-WD for LISA!)



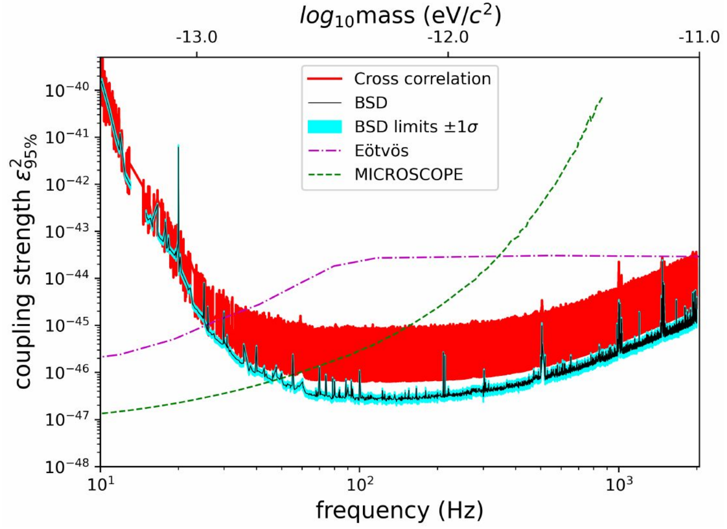
[Goyal+2021]

dark matter: direct & indirect detection

- dedicated CW-like searches → see R. Brito, C. Palomba talks



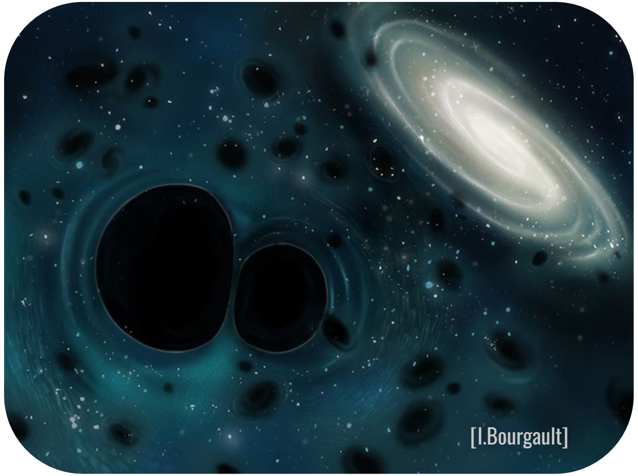
[Brito, Cardoso & Pani]



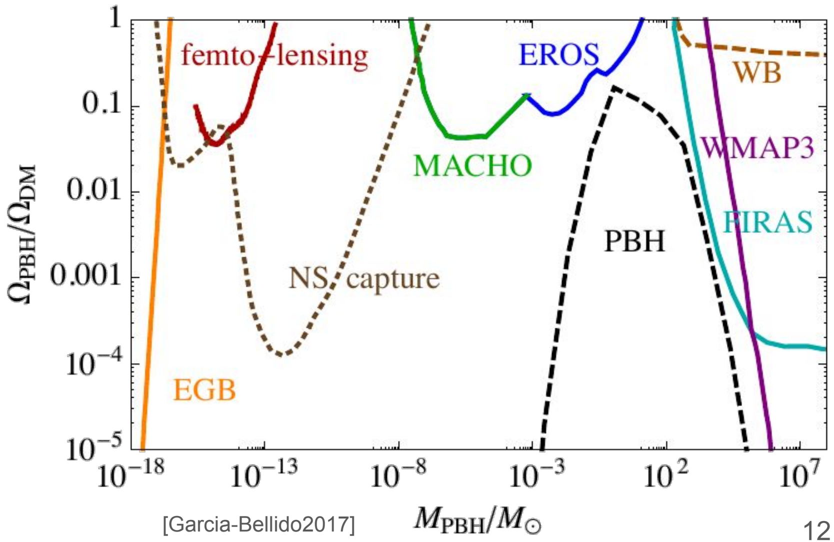
[LVK PRD105,063030, updated in erratum dcc.ligo.org/P2300439/public]

- effects on binary inspirals → e.g. K. Clough, P. Cole talks
- lensing signatures

the early Universe: PBH relics



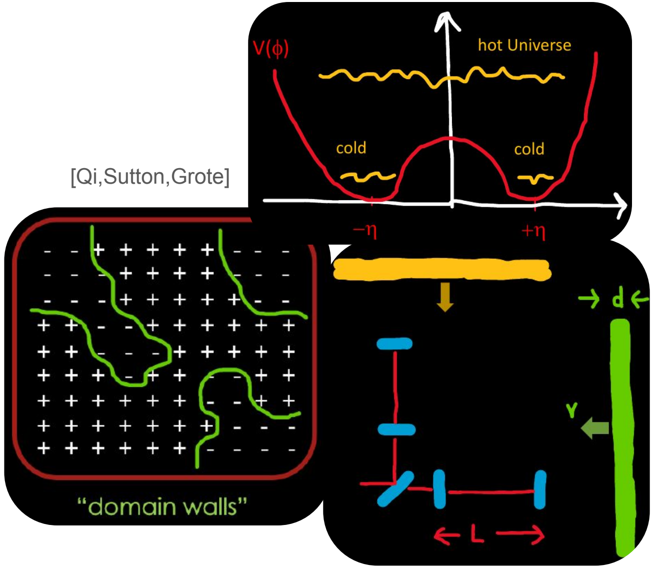
- depending on formation channel, **primordial black holes** can cover a huge range of masses and number densities
- sensitive probe of early-Universe physics
- GW signatures:
  - features in BBH mass, redshift, spin distributions inconsistent with stellar origins
  - early inspiral phase for sub-solar-mass range: CBC-like or, even lower, CW-like
  - GW lensing
  - stochastic background from unresolved inspirals



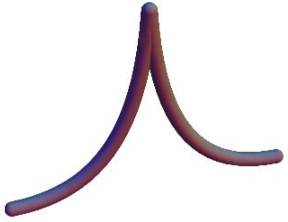
[Garcia-Bellido2017]

the early Universe: cosmic strings, domain walls and other relics

- frozen-in “defects”
- burst-like signatures
  - string intersections or kink collisions
  - a domain wall passing Earth
- stochastic backgrounds from strings

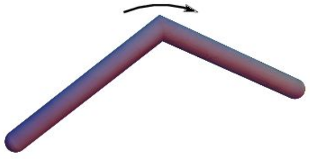


[Qi,Sutton,Grote]

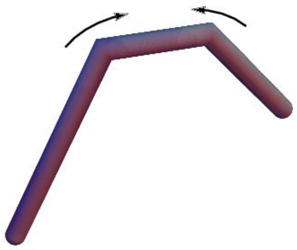


Cusp

[Long, Hyde and Vachaspati]

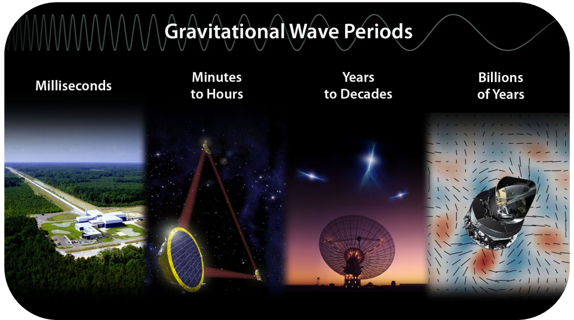


Kink



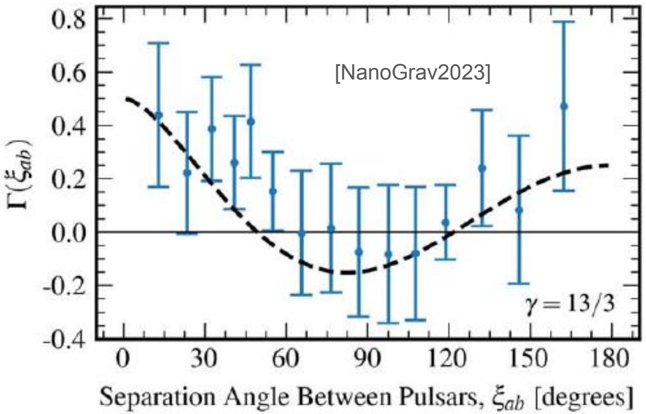
Kink–Kink Collision

what about other wavelengths…? →

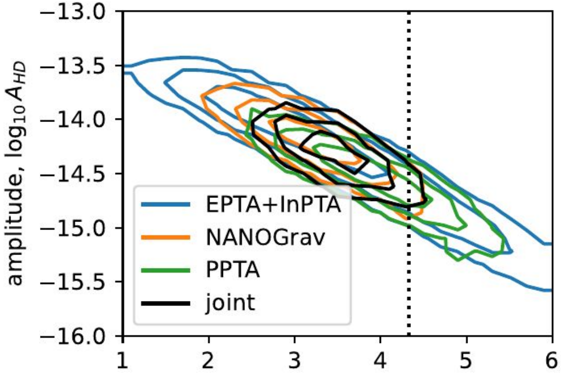


the early Universe: stochastic GW backgrounds

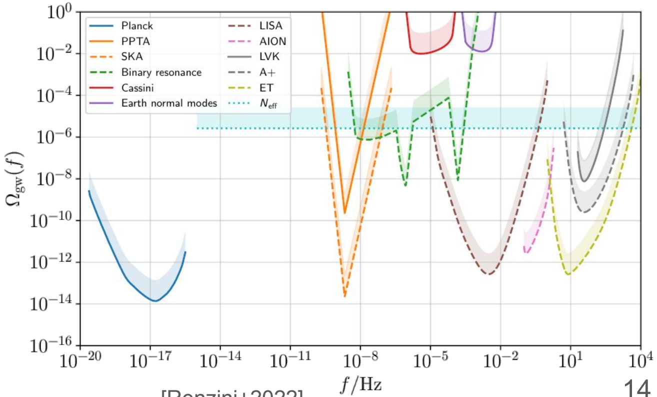
- in all detector bands: astrophysical vs cosmological backgrounds
- PTAs have likely detected something… most people think unresolved SMBHBs… but cosmological alternatives proliferate on the arXiv.
- More data needed for 5σ and for a robust spectral index measurement that informs LVK/3G/LISA detection prospects.
- How to break the “whatever is detected, people will manage to explain it with their favourite pet theory” degeneracy?



[NanoGrav2023]



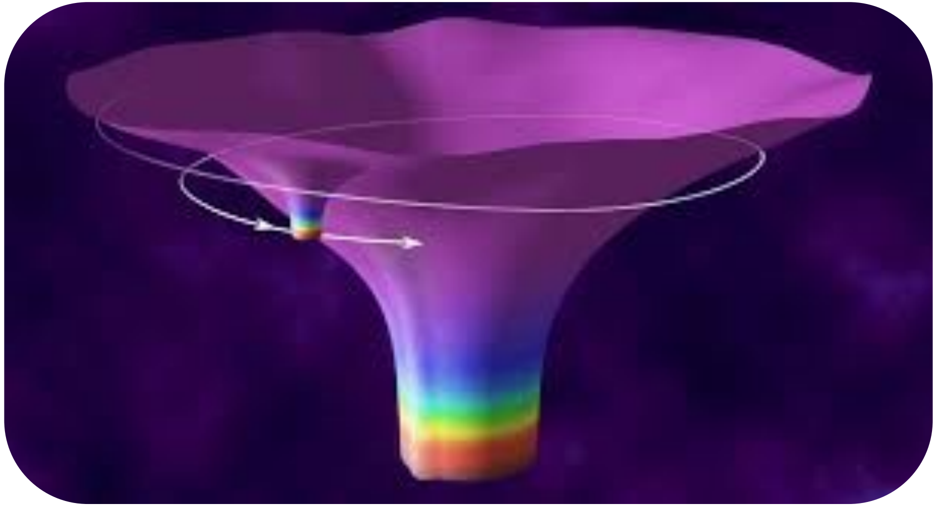
[IPTA2023] spectral index, γ_{HD}



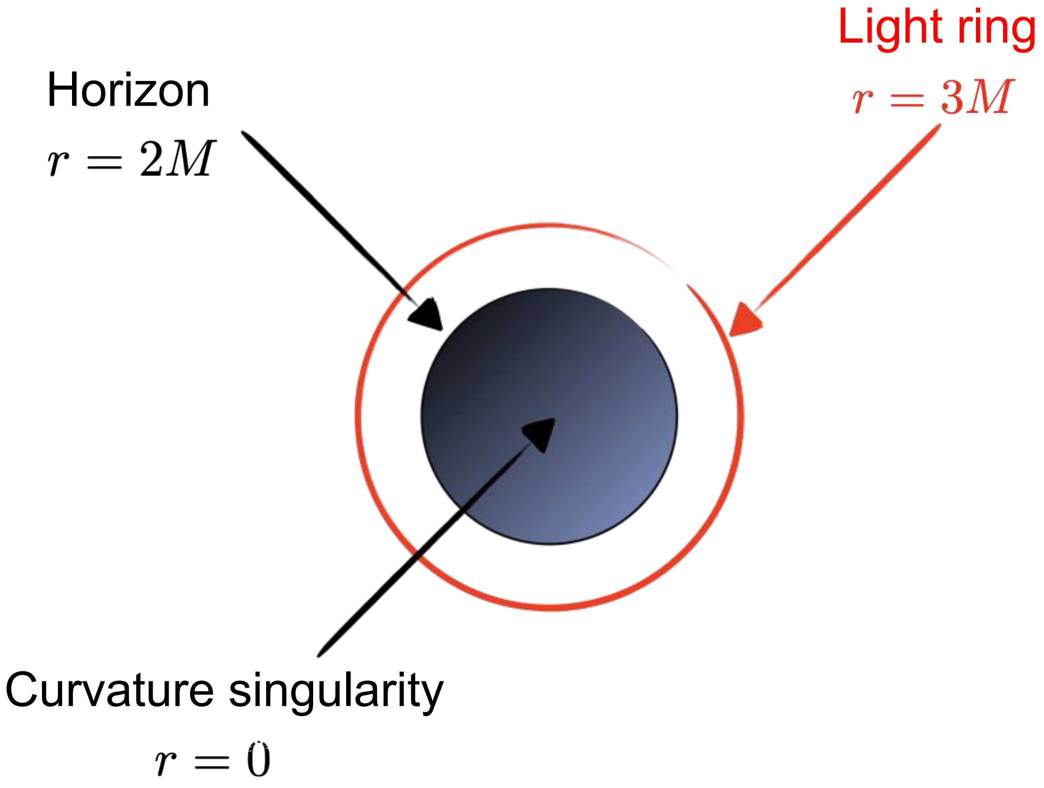
[Renzini+2022]

back to:

black holes as probes of gravity



Probing the horizon of black holes



Light ring

$r = 3M$

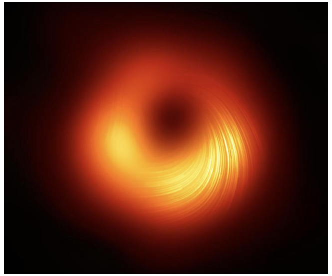
Horizon

$r = 2M$

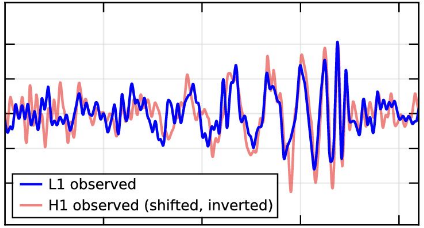
Curvature singularity

$r = 0$

Current electromagnetic and gravitational observations have probed the black hole spacetime close to the light ring.



EHT, ApJL **910**, L12 (2021)



Abbott+, PRL **116**, 061102 (2016)

Horizonless compact objects

New physics can prevent the formation of the horizon:

- in quantum-gravity extensions of general relativity
  e.g., fuzzballs, gravastars, quantum BHs

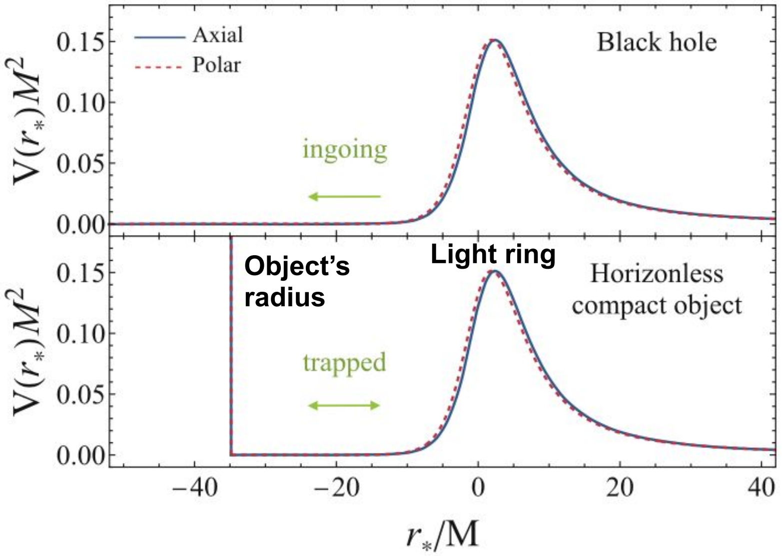
  Mathur, Fortsch. Phys. **53**, 793-827 (2005); Mazur+, PNAS **101**, 9545-9550 (2004); Oshita+, JCAP **04** (2020) 016

- in general relativity with dark matter or exotic fields
  e.g., boson stars, wormholes

  Liebling+, LRR **20**, 5 (2017); Brito+, Phys. Lett. B **752** (2016) 291-295 ; Morris+, Am. J. Phys. **56**, 395-412 (1988)

The ringdown

The ringdown is dominated by the **quasi-normal modes** (QNMs) of the remnant, which describe the response of a compact object to a perturbation.



EM, Pani, Raposo, Handbook for GW Astronomy, Springer (2021)

$$\frac{d^2\psi(r)}{dr_*^2} + \left[\omega^2 - V(r)\right]\psi(r) = 0$$

Regge, Wheeler, Phys.Rev. **108** (1957) 1063-1069
Zerilli, PRL **24** (1970) 737-738

No horizon ⟶ Different QNMs

Fundamental quasi-normal mode

Schwarzschild black hole: $M\omega = 0.37 - i0.089$

Perfectly reflecting object with radius at microscopical distance from the horizon:

$$M\omega = \begin{cases} 0.07 - i2\times 10^{-9} & \text{axial} \\ 0.04 - i3\times 10^{-11} & \text{polar} \end{cases}$$

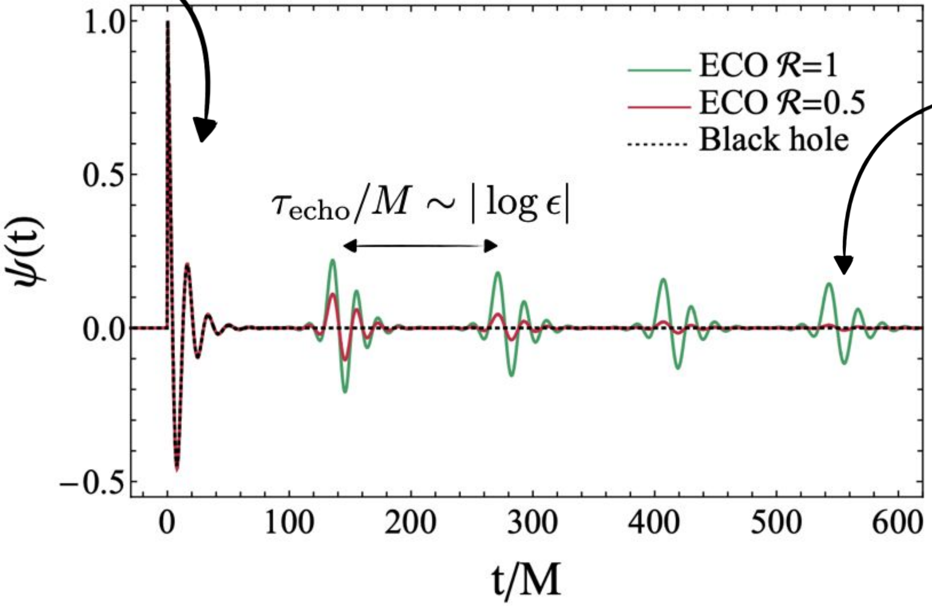
Horizonless compact objects have low-frequency and long-lived QNMs.

Cardoso+, PRL **116**, 171101 (2016); EM, Cardoso, Dolan, Pani, PRD **99**, 064007 (2019)

Postmerger signal

Same black-hole ringdown

due to the excitation of the light ring



Gravitational-wave echoes

due to trapped modes

Cardoso+, PRL **116**, 171101 (2016); EM, Testa, Bhagwat, Pani, PRD **100**, 064056 (2019)

Searches for gravitational-wave echoes

- A tentative evidence for echoes in the GW data has been reported

  Abedi+, PRD **96**, 082004 (2017); Conklin+, PRD **98**, 044021 (2018)

- Independent searches argued that the statistical significance for echoes is consistent with noise

  Westerweck+, PRD **97**, 124037 (2018); Nielsen+, PRD **99**, 104012 (2019); Uchikata+, PRD **100**, 062006 (2019); Lo+, PRD **99**, 084052 (2019); Tsang+, PRD **101**, 064012 (2020)

- No evidence for echoes by the LIGO/Virgo/KAGRA collaboration

  Abbott+, PRD **103**, 122002 (2021); Abbott+, arXiv: 2112.06861 (2021)

- Einstein Telescope will constrain the reflectivity of compact objects at percent level for a GW150914-like remnant. Branchesi+, EM, Pacilio, Pani, JCAP **07** (2023) 068

Signatures of horizonless objects in the inspiral

- **Tidal heating**: energy absorption by the black-hole horizon is modified as

$$\dot{E}_{\rm ECO} = \left(1 - |\mathcal{R}|^2\right) \dot{E}_{\rm H}$$

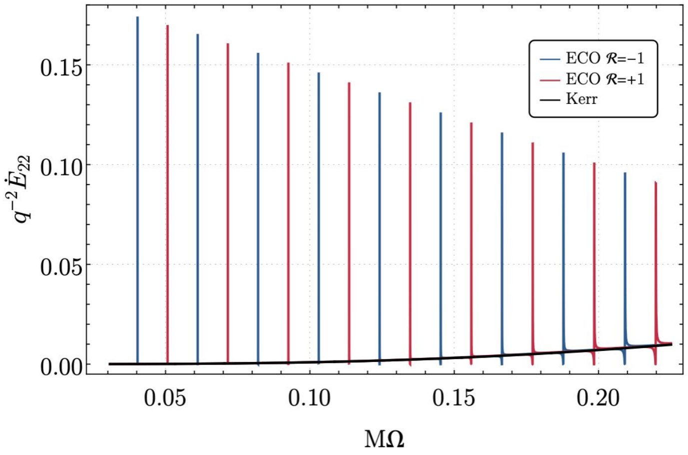
Datta+, PRD **101**, 044004 (2020)

- **Tidal deformability:** Horizonless objects have nonzero tidal Love numbers.

Cardoso+, PRD **95**, 084014 (2017); Chakraborty+, arXiv:2310.06023 (2023); Piovano+, PRD **107**, 024021 (2023)

- **Resonances** are excited when the orbital frequency matches the quasi-normal modes of the central horizonless object.

Cardoso+, PRD **100**, 084046 (2019); EM+, PRD **104**, 104026 (2021)

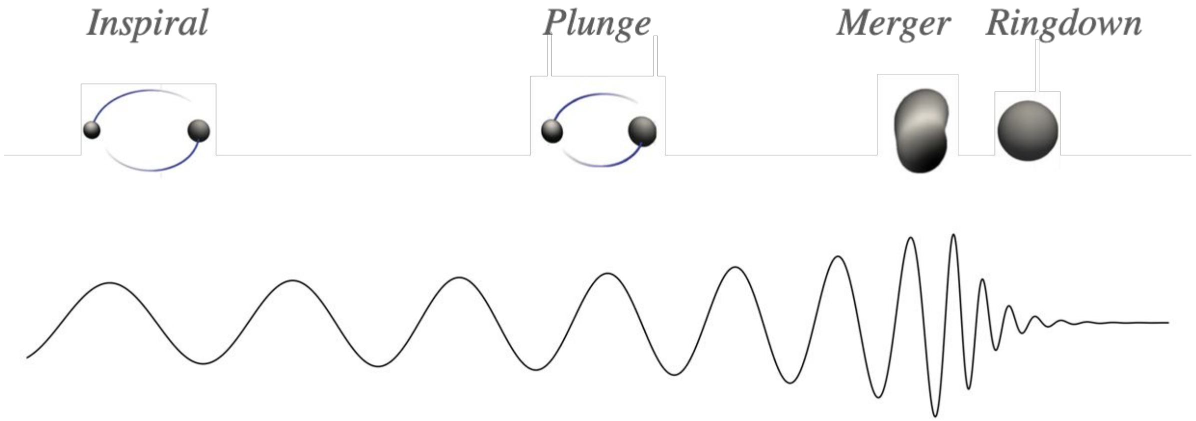


Parametrised tests of general relativity

Parametrised tests of GR introduce fractional deviations to the GR parameters as

$$\theta_{\rm GR} \rightarrow \theta_{\rm GR}(1+\delta\theta)$$

to constrain the degree to which the data agree with GR.

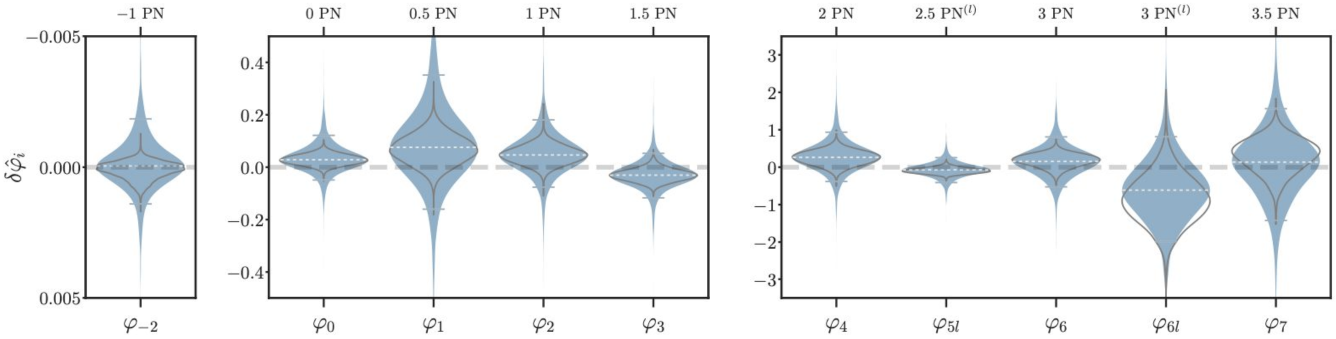


Abbott+, PRD **100**, 104036 (2019); Abbott+, PRD **103**, 122002 (2021); Abbott+, arXiv: 2112.06861 (2021)

Parametrised tests of general relativity

- Constraints on post-Newtonian coefficients

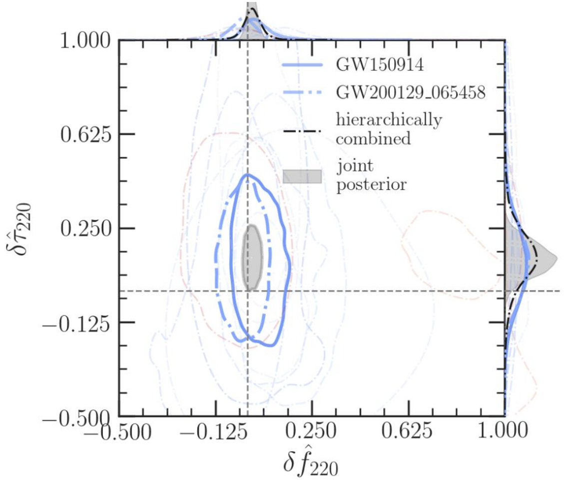
Abbott+, arXiv:2112.06861 (2021); Mehta+, PRD **107**, 044020 (2023); Li+, PRD **85**, 082003 (2012); Agathos+, PRD **89**, 082001 (2014)



- Constraints the fundamental quasi-normal mode in the ringdown

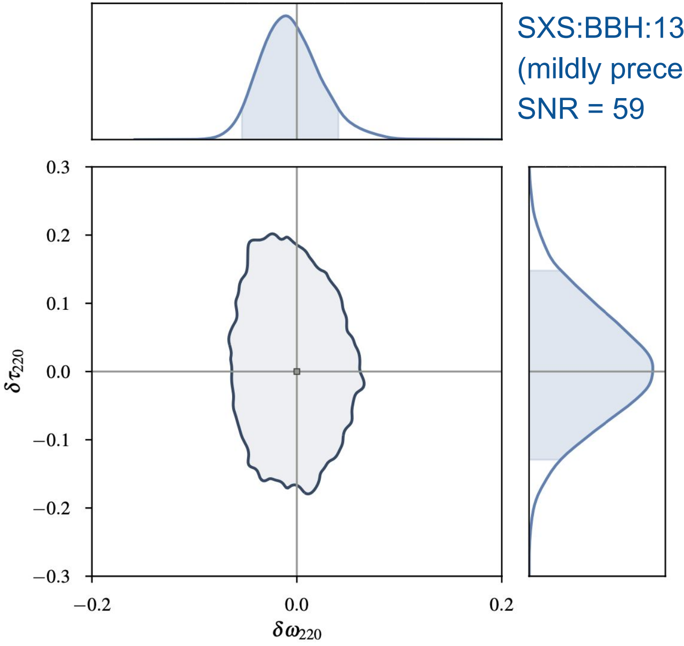
Abbott+, arXiv:2112.06861 (2021); Brito+, PRD **98**, 084038 (2018); Ghosh+, PRD **103**, 124041 (2021); Carullo+, PRD **99**, 123029 (2019); Isi+, arXiv:2107.05609

- Can be mapped in modified theories of gravity or models of horizonless objects



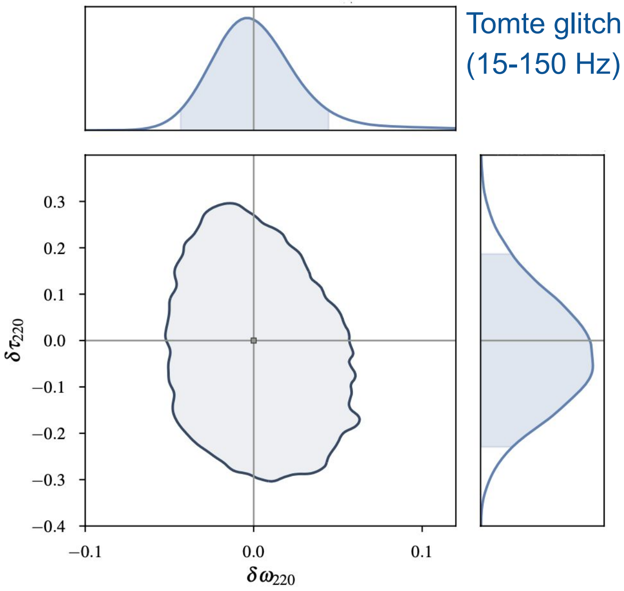
Biases in tests of general relativity

Waveform systematics and data-quality issues could lead to false violations of GR.



SXS:BBH:1386
(mildly precessing)
SNR = 59

Spin-precession



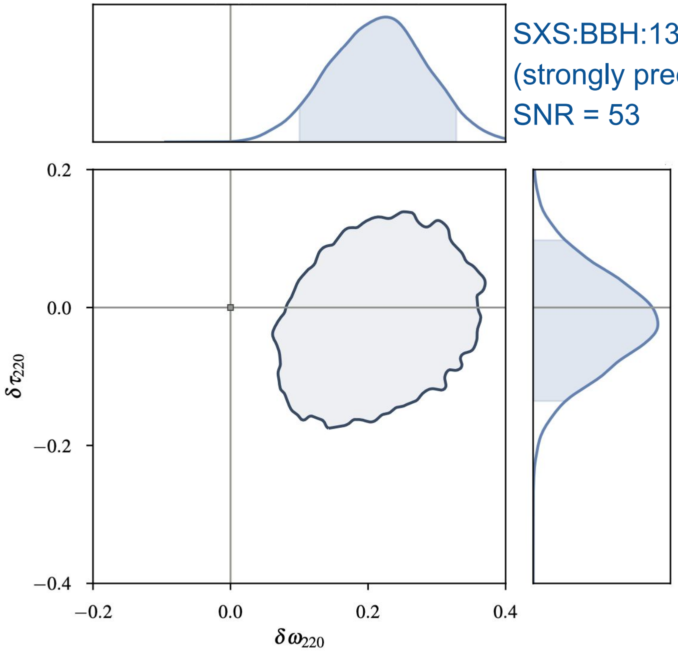
Tomte glitch
(15-150 Hz)

GW150914-like signal + glitch

LVK Testing General Relativity group, in preparation

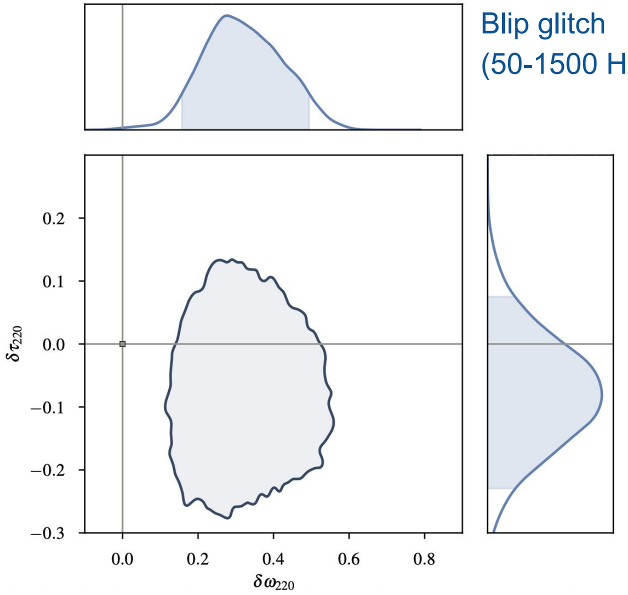
Biases in tests of general relativity

Waveform systematics and data-quality issues could lead to false violations of GR.



SXS:BBH:1397
(strongly precessing)
SNR = 53

Spin-precession



Blip glitch
(50-1500 Hz)

GW150914-like signal + glitch

LVK Testing General Relativity group, in preparation

Open questions

- How to tell a deviation of GR from waveform systematics, noise and environmental effects?
- Numerical relativity beyond GR: how far can we go?
- What can we learn about the remnant from a non-observation of echoes?
- Are simulations of the formation of horizonless compact objects available?
- How to extract fundamental physics from CW observations?
- How will GW detectors compete with other DM detection efforts?
- How to extract detailed information from SGWBs and control model degeneracy?
- What other remnants from the early Universe can we find at very low (or maybe very high!) frequencies?

WG3: today (Tuesday)

Overview by Conveneers	*David Keitel et al.*	*Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome*	16:30 - 17:00
The ringdown of spinning horizonless compact objects	*Elisa Maggio*	*Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome*	17:00 - 17:25
Black holes as point particles: from amplitudes to self-force	*Riccardo Gonzo*	*Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome*	17:25 - 17:50
Rotating metrics from scattering amplitudes in arbitrary dimensions	*Claudio Gambino*	*Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome*	17:50 - 18:15
Quantum Gravity Effects on Dark Matter and Gravitational Waves	*Rishav Roshan*	*Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome*	18:15 - 18:40

WG3: Thursday

Dynamical friction on compact binary systems *Vincent Desjacques*

Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome 14:30 - 14:55

Podium 2: Report from Conveners of WG3 and WG4 (P2) *Carlo Tasillo, Elisa Maggio, Simone Mastrogiovanni*

Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome 14:55 - 16:25

Acknowledgments

D. Keitel is supported by the Spanish Ministerio de Ciencia, Innovación y Universidades (ref. BEAGAL 18/00148) and cofinanced by the Universitat de les Illes Balears, and would like to acknowledge additional support by the Spanish Agencia Estatal de Investigación grants CNS2022-135440, PID2022-138626NB-I00, PID2019-106416GB-I00, RED2022-134204-E, RED2022-134411-T, funded by MCIN/AEI/10.13039/501100011033; the MCIN with funding from the European Union NextGenerationEU/PRTR (PRTR-C17.I1); Comunitat Autonòma de les Illes Balears through the Direcció General de Recerca, Innovació I Transformació Digital with funds from the Tourist Stay Tax Law (PDR2020/11 - ITS2017-006), the Conselleria d'Economia, Hisenda i Innovació grant numbers SINCO2022/18146 and SINCO2022/6719, co-financed by the European Union and FEDER Operational Program 2021-2027 of the Balearic Islands; and the "ERDF A way of making Europe".

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DIRECCIÓ GENERAL RECERCA, INNOVACIÓ I TRANSFORMACIÓ DIGITAL

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Impost de Turisme Sostenible

UIB Universitat de les Illes Balears

IAC3 Institute of Applied Computing & Community Code.

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Financiado por la Unión Europea
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Plan de Recuperación, Transformación y Resiliencia

E. Maggio acknowledges funding from the Deutsche Forschungsgemeinschaft (DFG) - project number: 386119226.

Backup slides

Injection studies

- **SXS:BBH:1386** - strongly precessing

$$M = 60\ M_{\odot}, q = 1.35$$

$$\chi_{\text{eff}} = -0.02, \chi_p = 0.80 \text{ at an } m = 2 \text{ frequency of } 9.6 \text{ Hz}$$

- **SXS:BBH:1397** - mildly precessing

$$M = 60\ M_{\odot}, q = 1.56$$

$$\chi_{\text{eff}} = -0.06, \chi_p = 0.28 \text{ at an } m = 2 \text{ frequency of } 8.6 \text{ Hz}$$

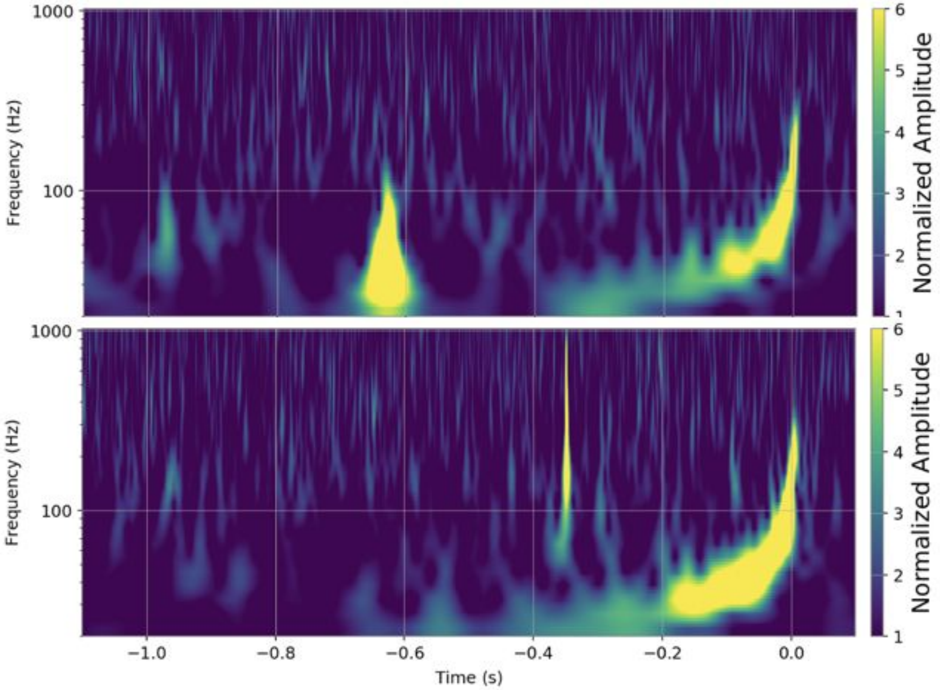
The injections are analyzed with the predicted power spectral density for O4 and the detector network of LIGO Hanford, Livingston and Virgo.

LVK Testing General Relativity group, in preparation

Injection studies

- **Tomte glitch**
  mid duration (0.1-1.0 s)
  low-mid frequency band (50-150 Hz)

- **Blip glitch**
  short duration (<0.1 s)
  mid-high frequency band (>150 Hz)



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