Asymmetric Binaries meet Fundamental Astro-Physics

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Testing the horizon of black holes with gravitational waves

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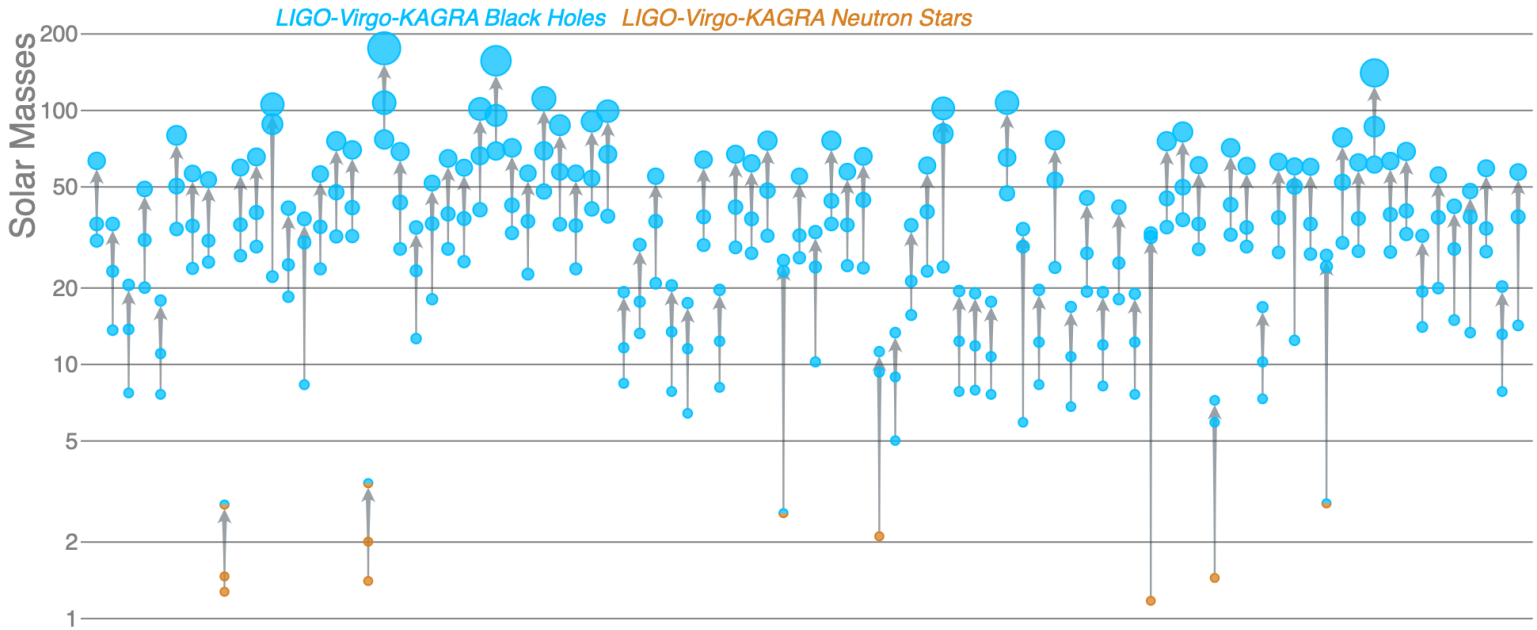
Gravitational-wave detections

The interferometers LIGO and Virgo have detected 90 gravitational-wave events from the coalescence of compact binaries.

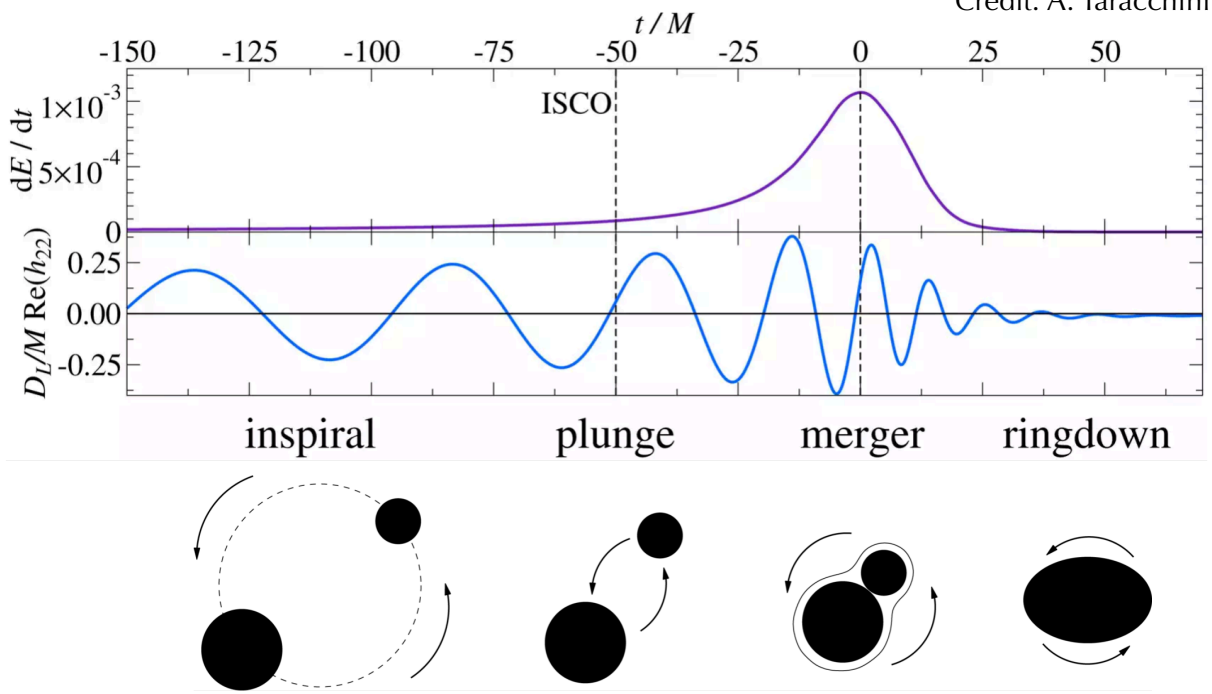


Abbott+, PRX **9**, 031040 (2019); Abbott+, PRX **11**, 021053 (2021); Abbott+, arXiv:2111.03606 (2021)

The O4 observing run has started in May 2023 and will last 20 months. 39 candidate events have been detected. https://gracedb.ligo.org

The stages of compact binary coalescences

Credit: A. Taracchini



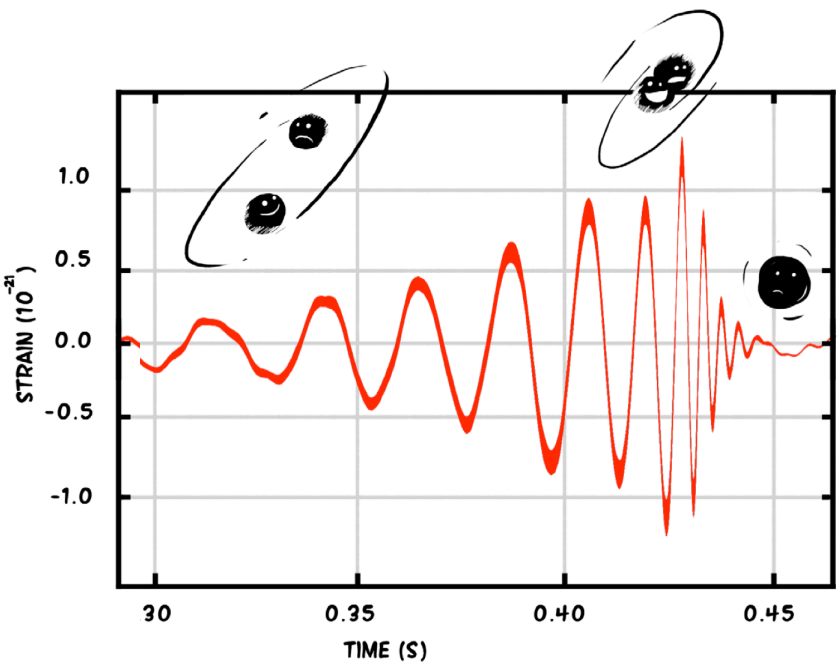
Parametrized tests of general relativity (GR) introduce deviations from the GR waveform to constrain the degree to which the data agree with GR.

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

The ringdown stage

The ringdown stage is dominated by the characteristic oscillation frequencies of the remnant, the so-called **quasi-normal modes**:

$$\omega_{\ell mn} = \omega_{R,\ell mn} + i\omega_{I,\ell mn}$$



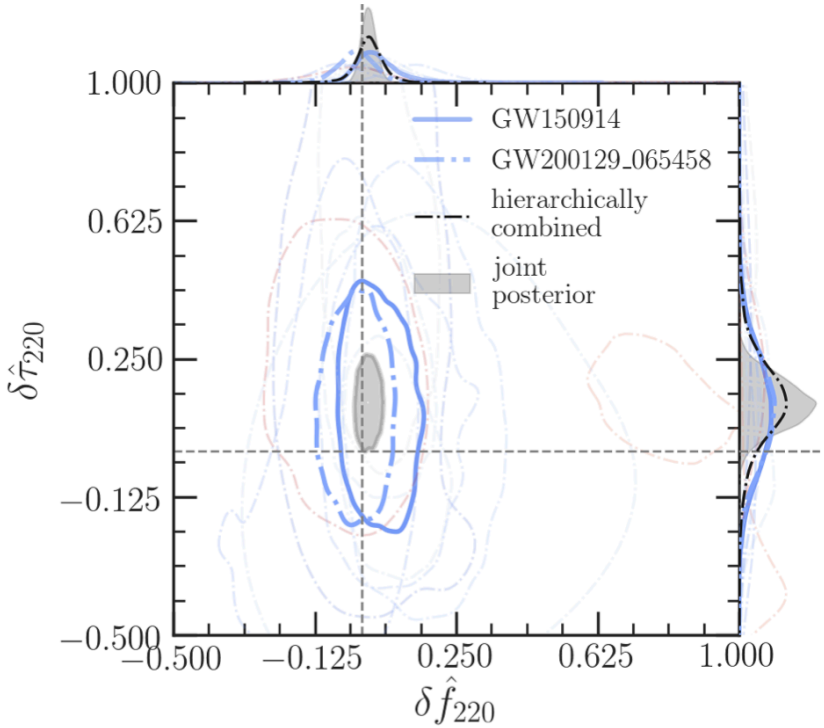
The ringdown is modeled as a sum of exponentially damped sinusoids:

$$f_{\ell mn} = \frac{\omega_{R,\ell mn}}{2\pi}$$

$$\tau_{\ell mn} = -\frac{1}{\omega_{I,\ell mn}}$$

Ringdown tests

The least-damped dominant quasi-normal mode has been observed in the ringdown of $\mathcal{O}(10)$ gravitational-wave events.



Abbott+, arXiv: 2112.06861 (2021)

The ringdown observations are compatible with **Kerr black hole remnants** with:

$$\delta f_{220} = 0.02^{+0.07}_{-0.07}$$

$$\delta \tau_{220} = 0.13^{+0.21}_{-0.22}$$

Tests of the black hole paradigm

Kerr black holes are determined uniquely by 2 parameters:

- mass
- angular momentum

Carter, PRL **26**, 331 (1971); Robinson, PRL **34**, 905 (1975)

A test of the no-hair theorem requires the identification of **at least two quasi-normal modes** in the ringdown.

The detection of modes other than the fundamental one is challenging. (overtones, higher modes and nonlinearities)

Isi+, PRL **123** (2019) 11, 111102; Bhagwat+, PRD **101** (2020) 4, 044033; Cotesta+, PRL **129** (2022) 11, 111102; Capano+, arXiv: 2209.00640 (2022); Baibhav+, arXiv: 2302.03050 (2022); Nee+, arXiv: 2302.06634 (2022)

Horizonless compact objects

New physics can prevent the formation of the horizon:

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

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

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

Liebling+, LRR **20**, 5 (2017); Morris+, Am. J. Phys. **56**, 395-412 (1988)

Horizonless compact objects can mimic black holes and quantify the existence of horizons.

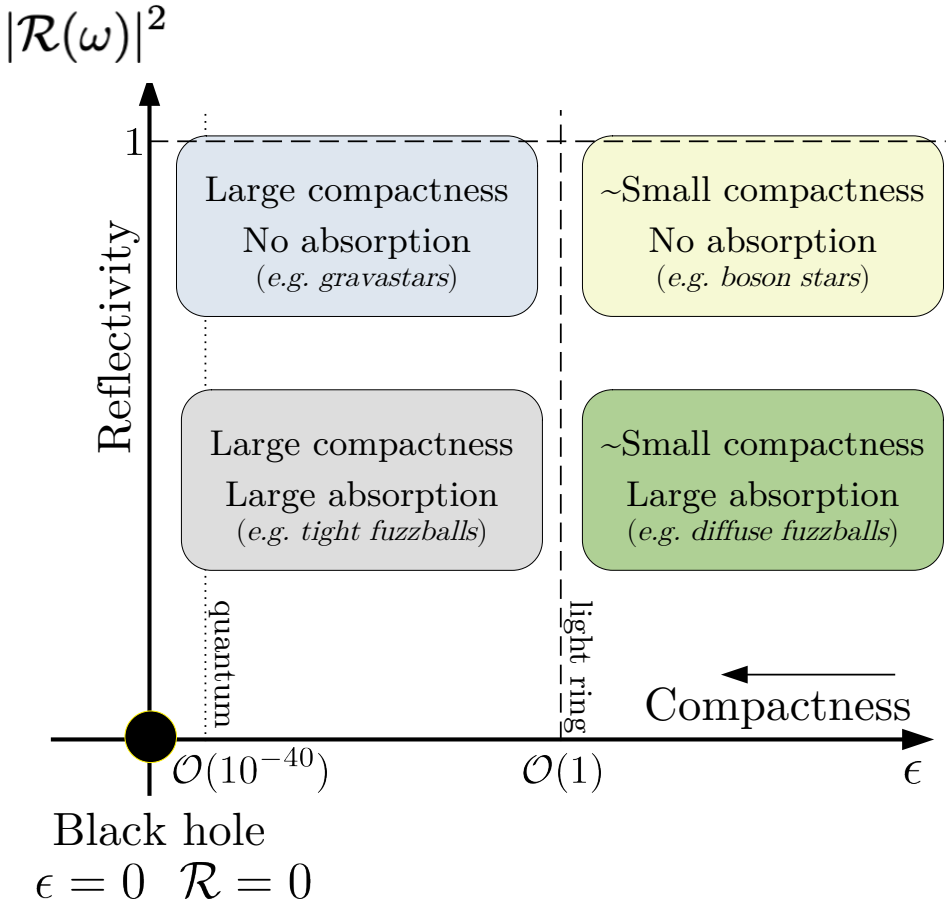
Giudice+, JCAP **10** (2010) 001; Cardoso+, LRR **22**:4 (2019); EM+, Handbook for GW Astronomy, Springer (2021)

A parametrized classification

We analyze a generic model that deviates from a black hole for its:

- **Compactness**
  since the radius of the object is at $r_0 = r_+(1+\epsilon)$

- **Reflectivity**
  that differs from the totally absorbing black hole case



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

Questions

- What are the signatures of horizonless compact objects in the ringdown?
- What are the current limitations in ringdown tests of general relativity?
- How current pipelines respond to possible deviations from general relativity?

Ringdown of horizonless compact objects

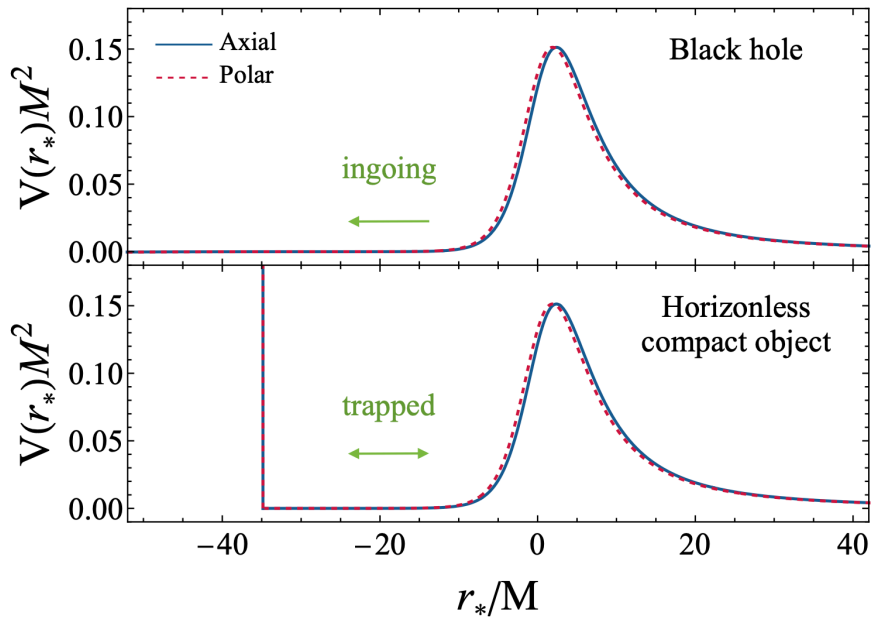
The ringdown

We analyze a horizonless compact object described by the Schwarzschild metric and perturbed by a gravitational perturbation:

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

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

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

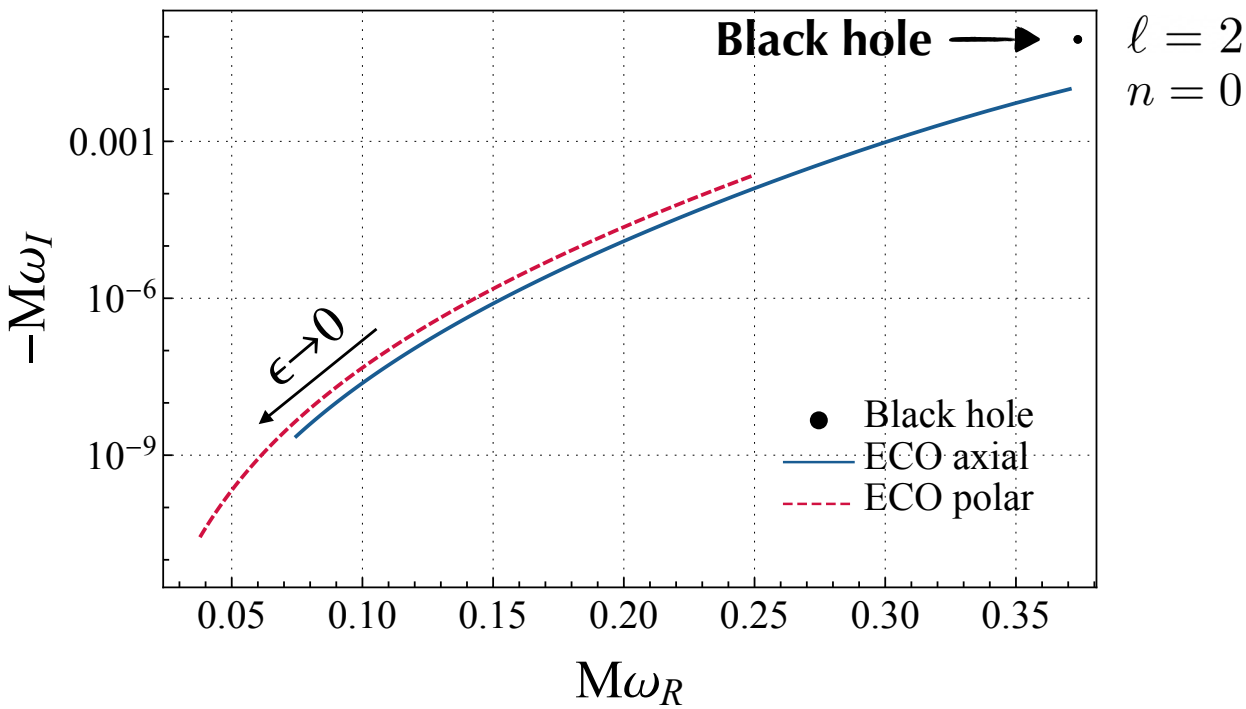


+ 2 boundary conditions:

- At infinity: outgoing waves
- At r_0: ultracompact object ($\epsilon \ll 1$), $\psi(r_0) \sim e^{-i\omega r_*} + \mathcal{R}(\omega)e^{i\omega r_*}$

Quasi-normal mode spectrum

Ultracompact object ($\epsilon \ll 1$) with a perfectly reflecting surface:



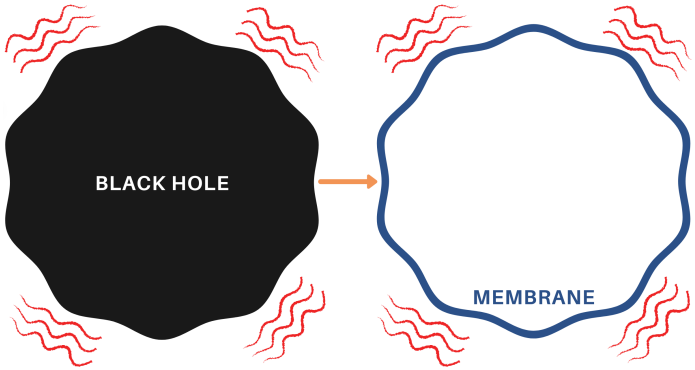
- Axial and polar modes are not isospectral.
- For $\epsilon \to 0$, the quasi-normal modes are low-frequencies and long-lived.

Cardoso+, PRL **116**, 171101 (2016); EM+, Handbook for GW Astronomy (2021)

Membrane paradigm

We derive the boundary condition that describes **horizonless compact objects with any compactness** and a Schwarzschild exterior.

EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

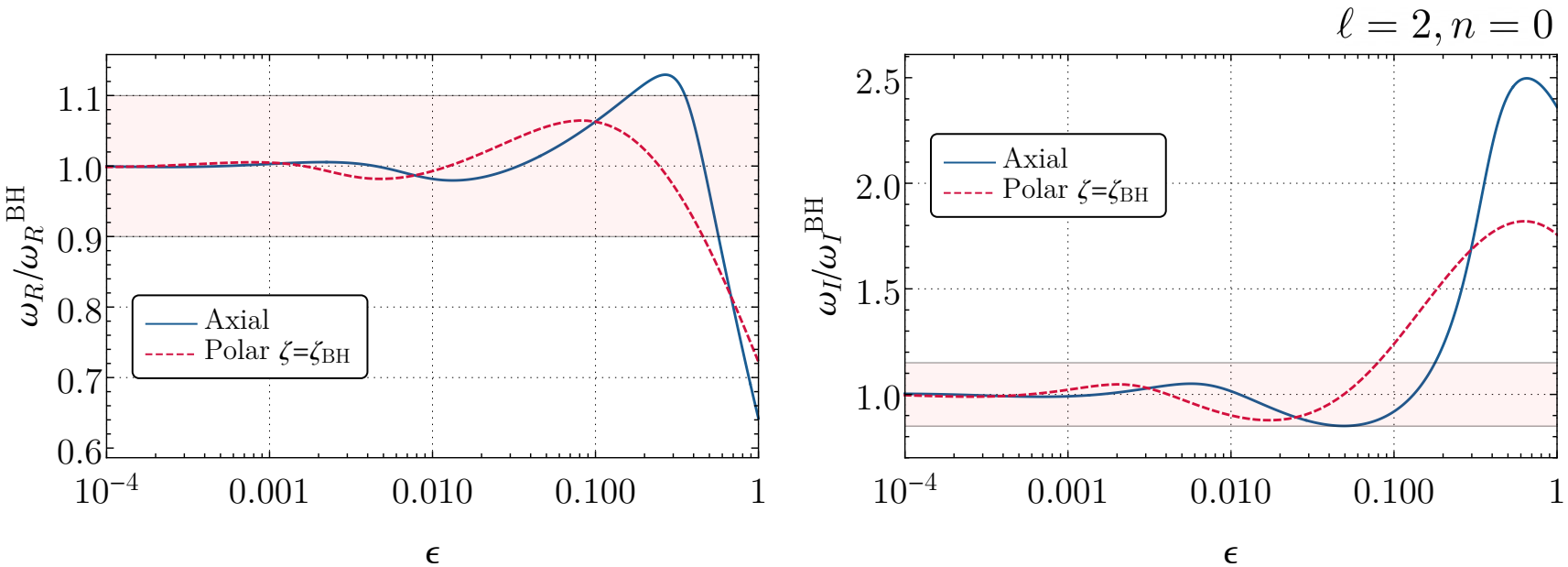


Damour, PRD **18**, 10 (1978); Price, Thorne, PRD **33**, 4 (1986)

A static observer can replace the interior of a black hole by a fictitious membrane located at the horizon, which is a **viscous fluid** with shear viscosity η and bulk viscosity ζ.

Spectrum of compact objects

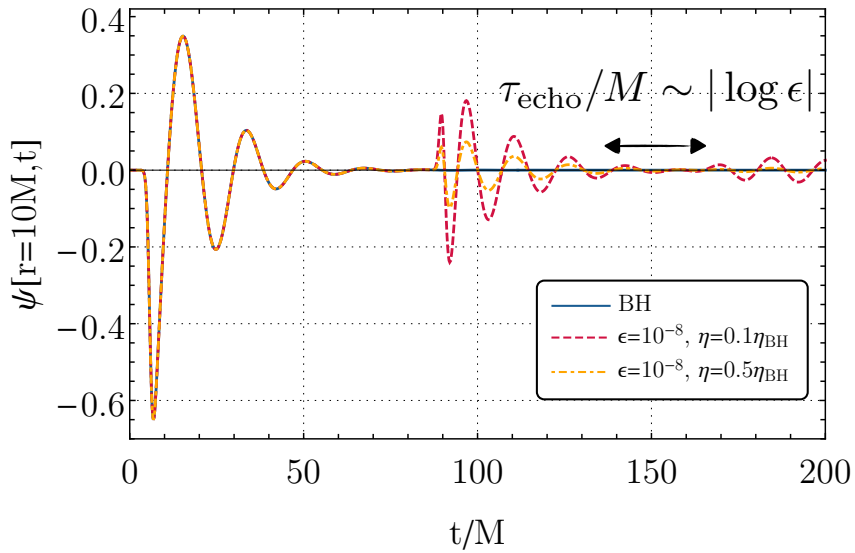
Totally absorbing compact object with $\epsilon \gtrsim 0.01$:



EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

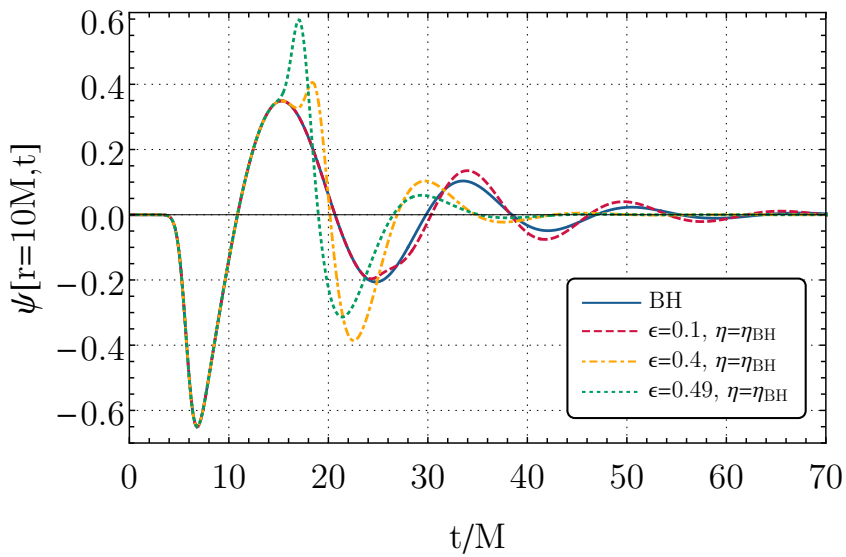
Horizonless compact objects with $\epsilon \lesssim 0.1$ are compatible with the measurement accuracy of the fundamental quasi-normal mode in GW150914.

Ringdown of horizonless objects



Ultracompact objects ($\epsilon \ll 1$):

- Same prompt ringdown due to the excitation of the light ring
- Echoes due to trapped modes



Compact objects ($\epsilon \gtrsim 0.01$):

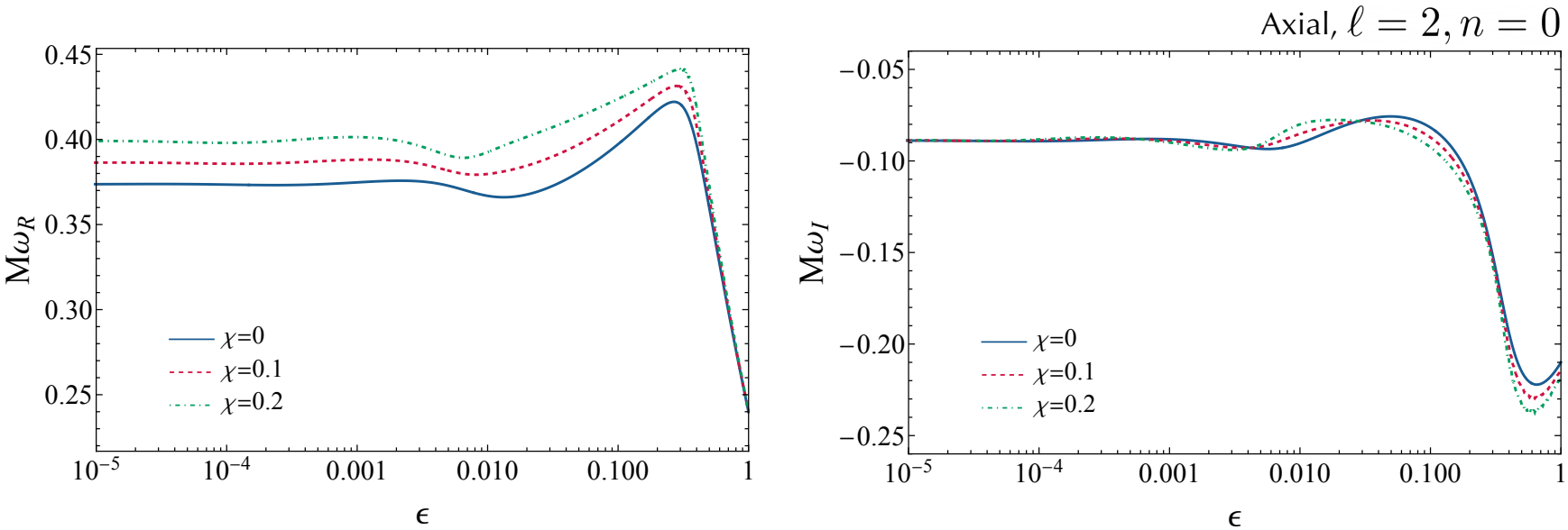
- Modified prompt ringdown
- No echoes

EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

Spinning horizonless compact objects

We generalize the membrane paradigm to spinning horizonless compact objects described by the **Kerr metric to linear order in spin**.

M.V.S. Saketh, EM, in preparation (2023)



The extension to higher values of the spin would allow to constrain the properties of the remnants of GW events.

Parametrized tests of general relativity in the ringdown stage

Parametrized ringdown model

The pSEOBNR analysis introduces fractional deviations to the frequency and the decay time of the fundamental quasi-normal modes:

Ghosh+, PRD **103**, 124041 (2021); Brito+, PRD **98**, 084038 (2018)

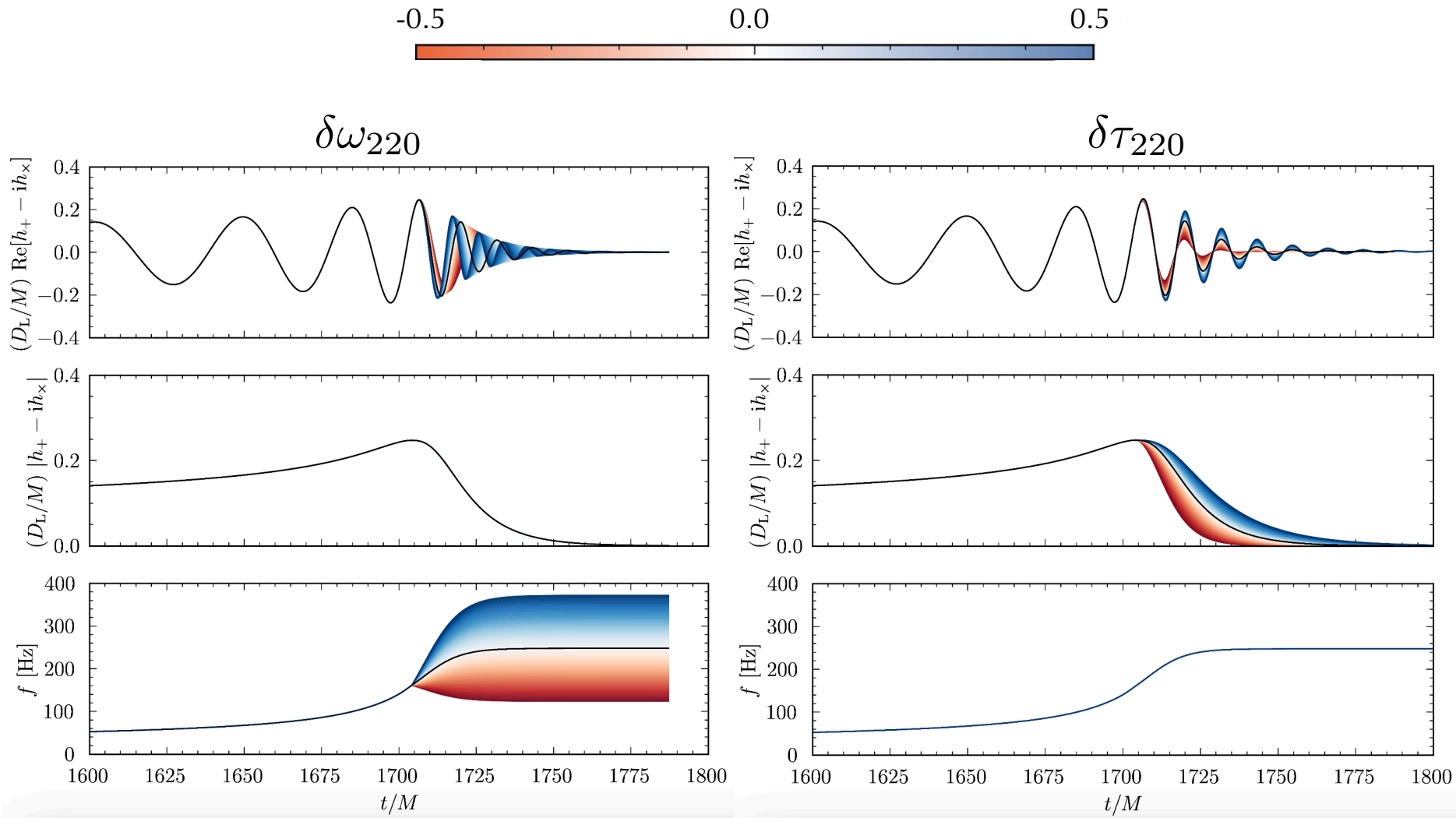
$$\omega_{\ell m 0} = \omega^{\rm GR}_{\ell m 0}(1 + \delta\omega_{\ell m 0})$$

$$\tau_{\ell m 0} = \tau^{\rm GR}_{\ell m 0}(1 + \delta\tau_{\ell m 0})$$

where $(\ell, |m|) = (2,2), (2,1), (3,3), (4,4), (5,5)$. Current analyses focus on deviations to the fundamental quasi-normal mode, i.e., $(\delta\omega_{220}, \delta\tau_{220})$.

The GR values are predicted from estimates of the mass and spin of the remnant and fits with numerical relativity (NR).

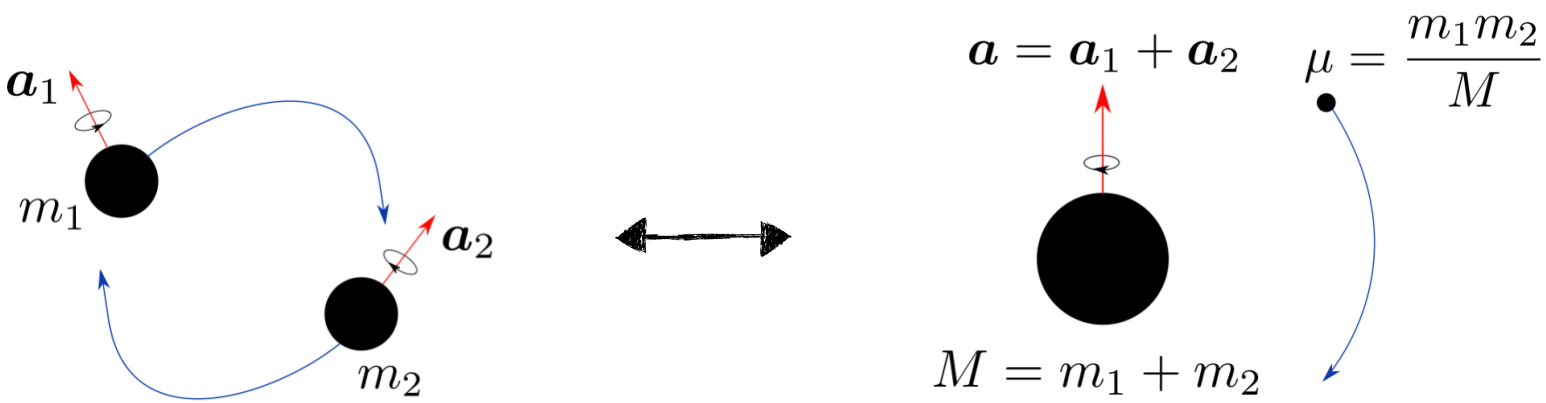
Parametrized ringdown model



Credit: H. O. Silva

Waveform model in general relativity

The baseline model is the waveform constructed in the effective-one-body formalism and calibrated to NR for quasicircular and spin-aligned binaries:



Credit: M. Khalil

$$h_{\ell m}(t) = h_{\ell m}^{\mathrm{insp-plunge}} \theta(t_{\mathrm{match}}^{\ell m} - t) + h_{\ell m}^{\mathrm{merger-RD}} \theta(t - t_{\mathrm{match}}^{\ell m})$$

Buonanno, Damour, PRD **59**, 084006 (1999); Buonanno, Damour, PRD 62 (2000), 064015; Bohé+, PRD **95**, 044028 (2017); Cotesta+, PRD **98**, 084028 (2018); Nagar, Rettegno, PRD 99 (2019) no.2, 021501; Mihaylov+, PRD **104**, 124087 (2021).

Mock Data Challenge

We inject mock data signals with any physics that is not included in the recovered waveform model, namely:

- Spin precession
- Kerr-Newman remnant
- Glitches

We test whether waveform systematics and data-quality issues would lead to false violations of general relativity.

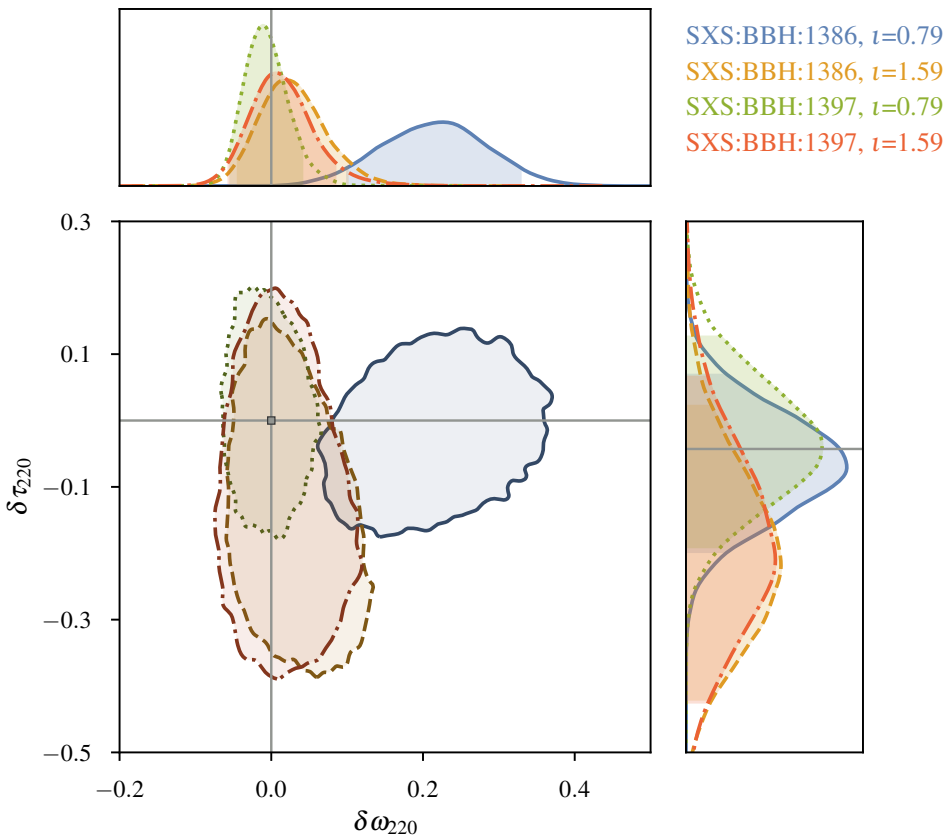
The injections are analyzed using the O4 power spectral density for the detector network of LIGO Hanford, Livingston and Virgo.

LVK TGR group, in preparation

Spin-precessing injections

We inject spin-precessing signals from NR with inclinations $\iota = 0.79, 1.59$:

- SXS:BBH:1386 - strongly precessing case $(\mathrm{SNR} = 59, 33)$
- SXS:BBH:1386 - less strongly precessing case $(\mathrm{SNR} = 53, 34)$

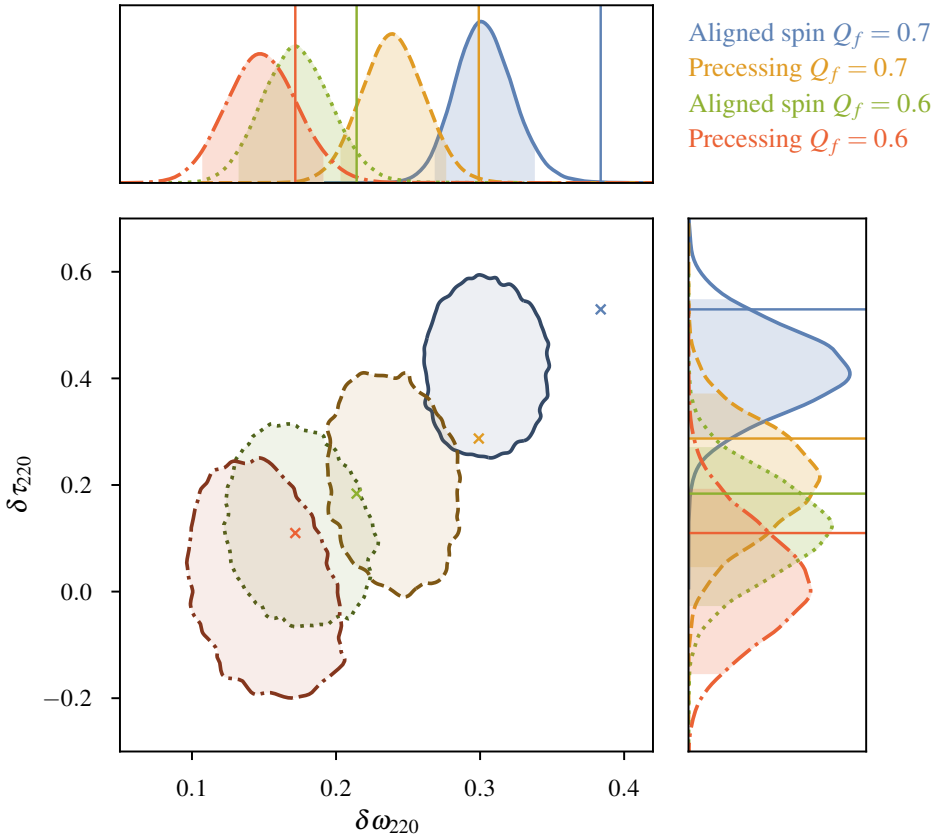


The ringdown is consistent with GR, except for the **strongly precessing and large SNR case** where a false violation of GR appears.

Kerr-Newman remnant

We inject a signal where the QNM spectrum for the $(2,2,0), (2,2,1), (3,3,0)$ modes is modified to that of a Kerr-Newman BH with charges $Q_f = 0.7, 0.6$.

Dias+, PRD **105**, 084044 (2022); Carullo+, PRD **105**, 062009 (2022); Johnson-McDaniel+, PRD **105**, 044020 (2022)



The analysis recovers the GR deviations in the aligned-spin and spin-precessing cases.

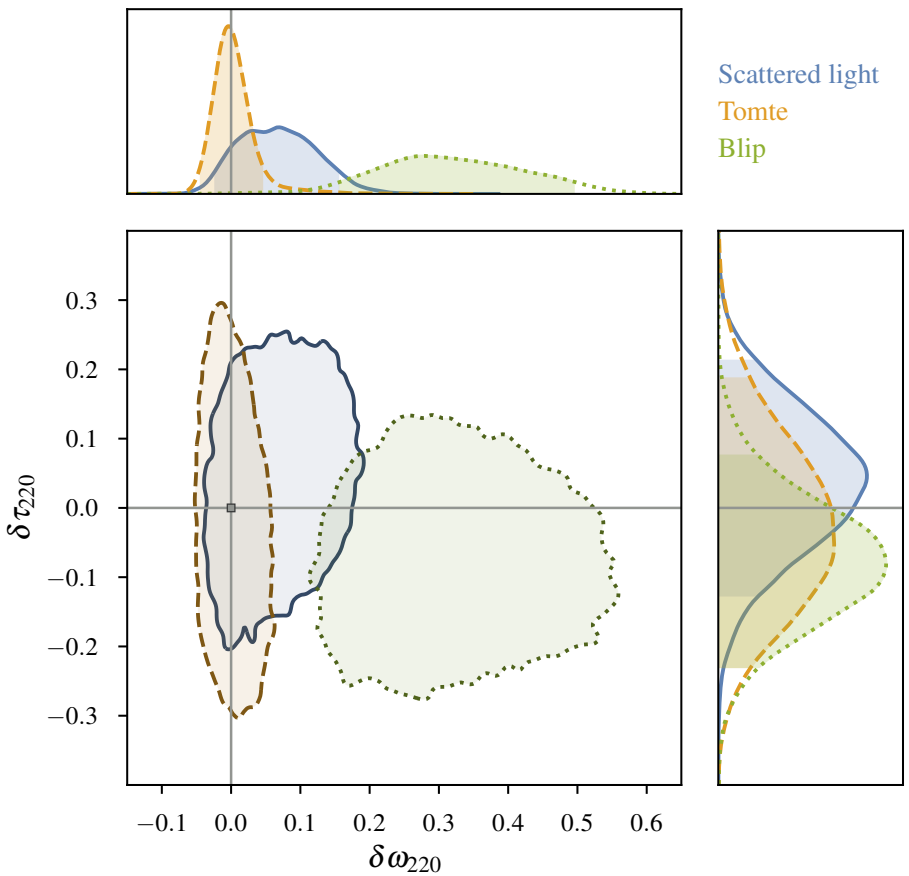
However, the injected values with $Q_f = 0.7$ are outside the 90% posterior distributions on the deviation parameters.

Glitches

We inject a glitch in the inspiral stage of a GW150914-like event, namely:

Kwok+, PRD **105**, 024066 (2022)

- **Scattered light**
  long duration $(> 1.0\ \mathrm{s})$
  low frequency band $(< 50\ \mathrm{Hz})$
- **Tomte**
  mid duration $(0.1 - 1.0\ \mathrm{s})$
  low-mid frequency band $(50 - 150\ \mathrm{Hz})$
- **Blip**
  short duration $(< 0.1\ \mathrm{s})$
  mid-high frequency band $(> 150\ \mathrm{Hz})$



Conclusions and future prospects

- We can look for new physics at the horizon scale with gravitational waves.
- Horizonless compact objects are not excluded by current observations.
- Tests of general relativity could lead to false violations of general relativity due to waveform systematics and glitches.
- Perform accurate studies of the biases that affect tests of general relativity.
- Develop a framework to translate parametrized constraints on general relativity to horizonless compact objects.