JENAS Initiative: Gravitational Wave Probes of Fundamental Physics

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The ringdown of spinning horizonless compact objects

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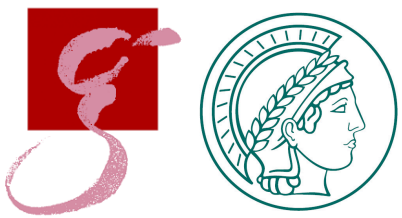


The ringdown stage

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

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

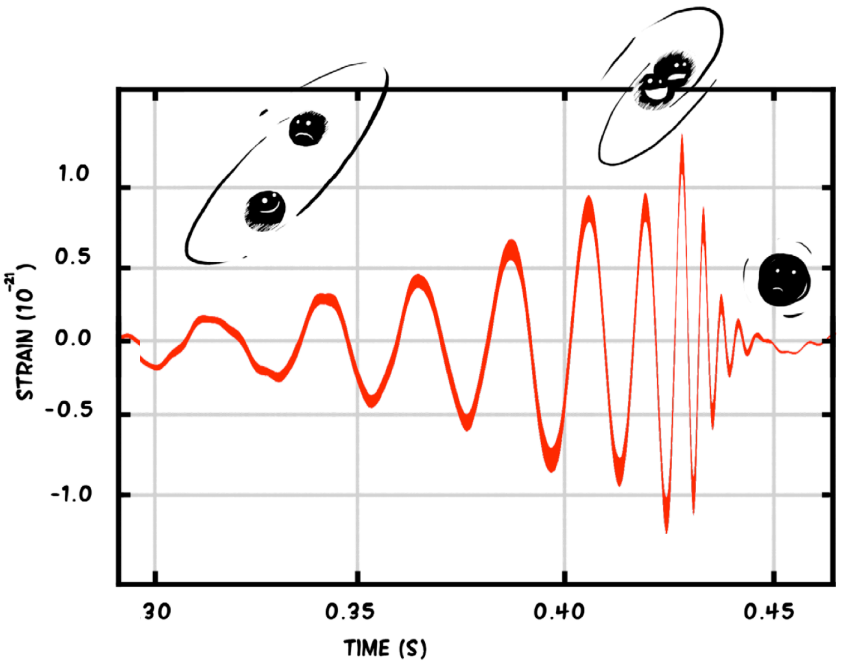


Illustration for GW150914 by Nutsinee Kijbunchoo
https://www.ligo.org/magazine/LIGO-magazine-issue-8.pdf

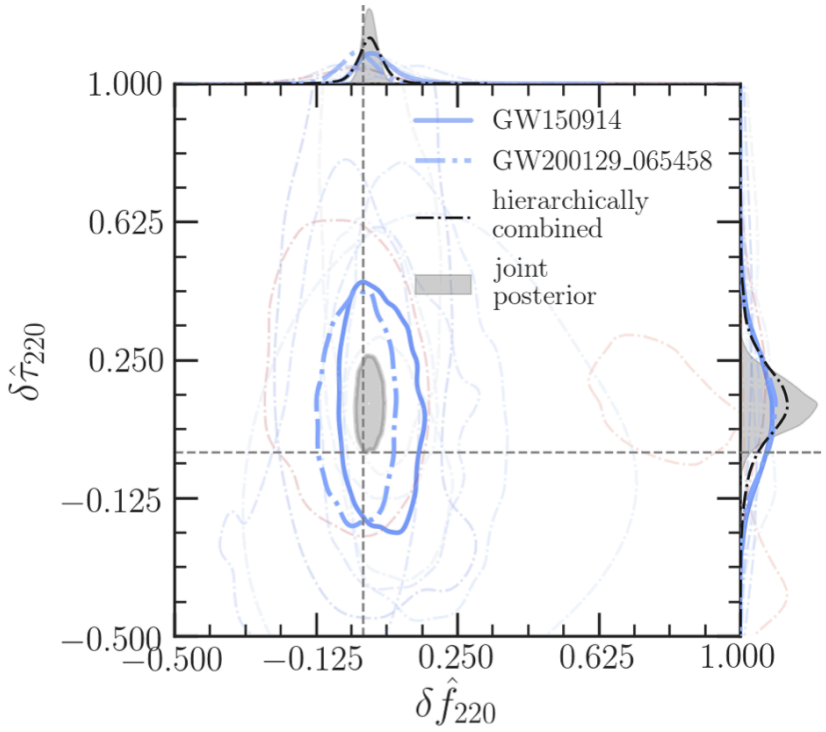
The ringdown is modeled as a sum of exponentially damped sinusoids:

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

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

Ringdown tests

The fundamental quasi-normal mode ($\ell = m = 2, n = 0$) 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:

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

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

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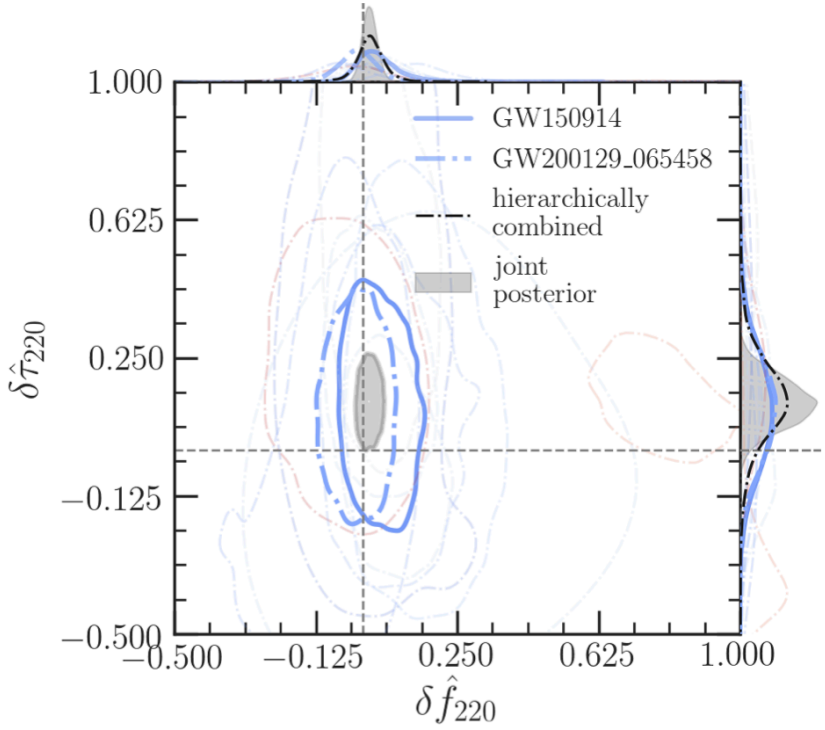

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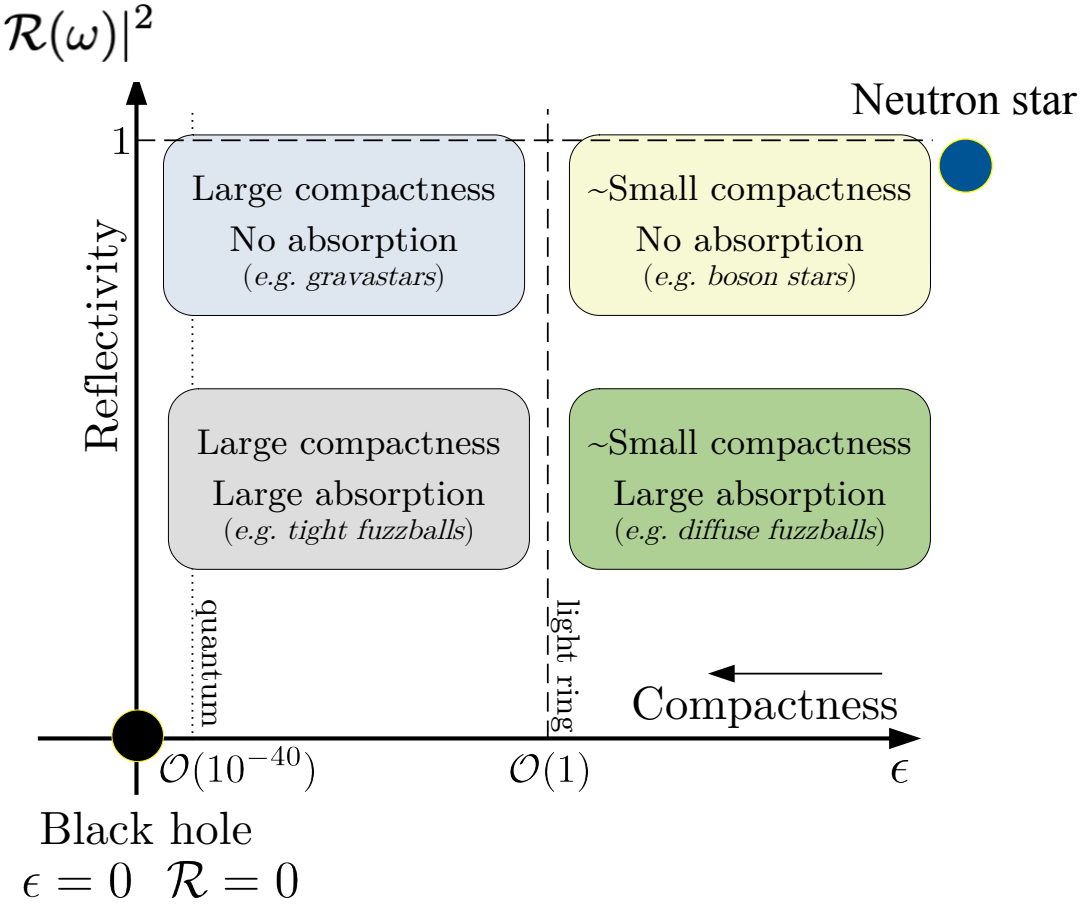
Can current observations be mapped into constraints on the remnant?

Horizonless compact objects

We analyse 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)

The ringdown

The radial component of the gravitational perturbation is governed by a Schrödinger-like equation Regge, Wheeler, Phys.Rev. **108** (1957) 1063-1069; Zerilli, PRL **24** (1970) 737-738

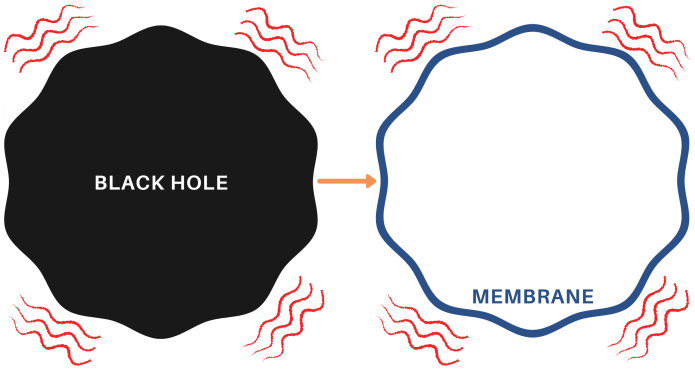
$$\frac{d^2\psi(r)}{dr_*^2} + \left[\omega^2 - V(r)\right]\psi(r) = 0$$

+ 2 boundary conditions to derive the QNMs:

- At infinity: outgoing waves
- At r_0: impose a boundary condition that describes a generic horizonless compact object

Membrane paradigm

A static observer can replace the interior of a perturbed BH by a perturbed **fictitious** membrane located at the horizon. Damour, PRD **18**, 10 (1978); Price+, PRD **33**, 4 (1986)



The Israel junction conditions $[[K_{ab} - Kh_{ab}]] = -8\pi T_{ab}$ impose that the membrane is a **viscous fluid** with shear viscosity η and bulk viscosity ζ.

→ We generalized the membrane paradigm to horizonless compact objects with a Schwarzschild exterior. EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

Boundary condition for compact objects

The gravitational perturbation is governed by

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

Regge, Wheeler, PR **108**, 4 (1957); Zerilli, PRL **24**, 13 (1970)

+ 2 boundary conditions:

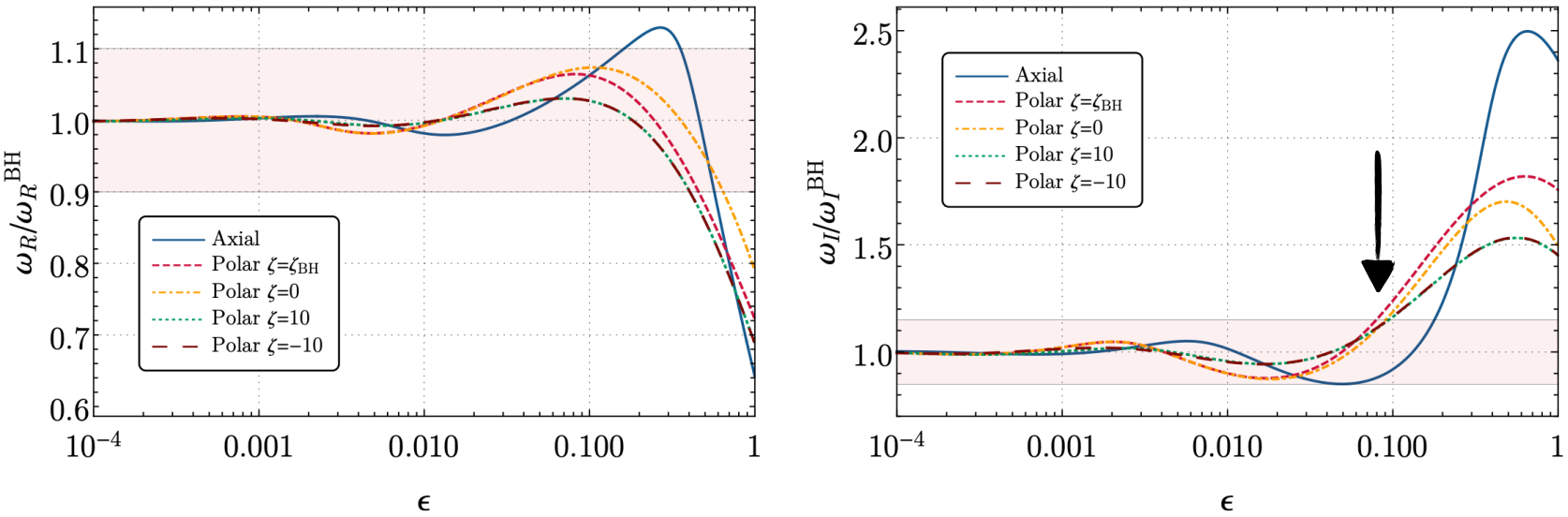
- At infinity: outgoing waves
- At r_0: $\dfrac{\psi'(r_0)}{\psi(r_0)} = \begin{cases} -\dfrac{i\omega}{16\pi\eta} - \dfrac{r_0^2 V(r_0)}{2\,(r_0 - 3M)} & \text{Axial} \\ -16\pi i\eta\omega + G(r_0, \omega, \eta, \zeta) & \text{Polar} \end{cases}$

The **BH limit** is recovered for $\epsilon = 0$ and $\eta = 1/(16\pi)$. Price, Thorne, PRD **33**, 4 (1986)

Quasi-normal mode spectrum

Totally absorbing object with small compactness:

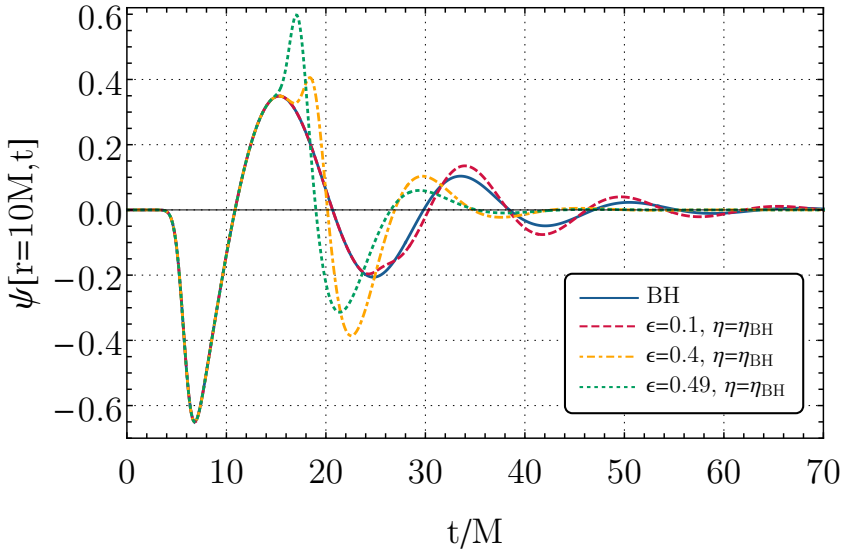
$\ell = 2, n = 0$



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

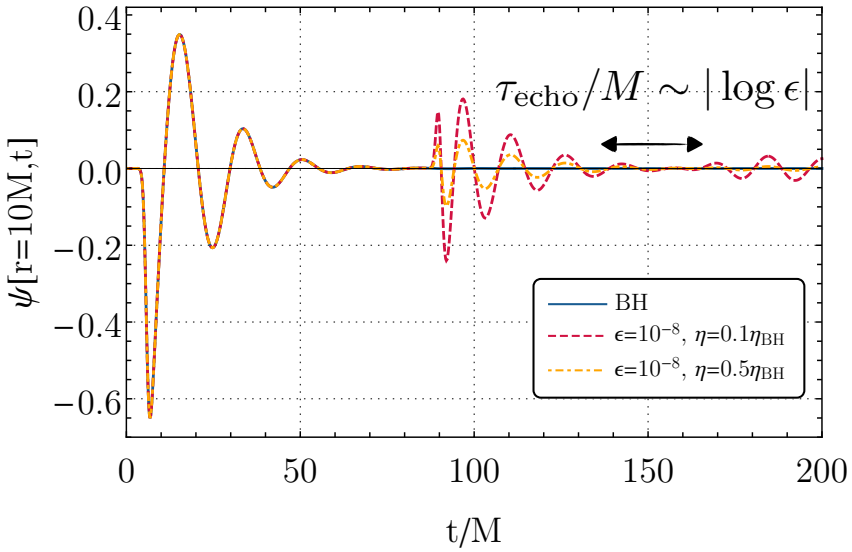
Horizonless compact objects with $\epsilon \lesssim 0.1$ are compatible with the measurement accuracy of the fundamental QNM of GW150914.

Ringdown of horizonless objects



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

- Modified prompt ringdown
- No echoes



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

- Same prompt ringdown
- Echoes

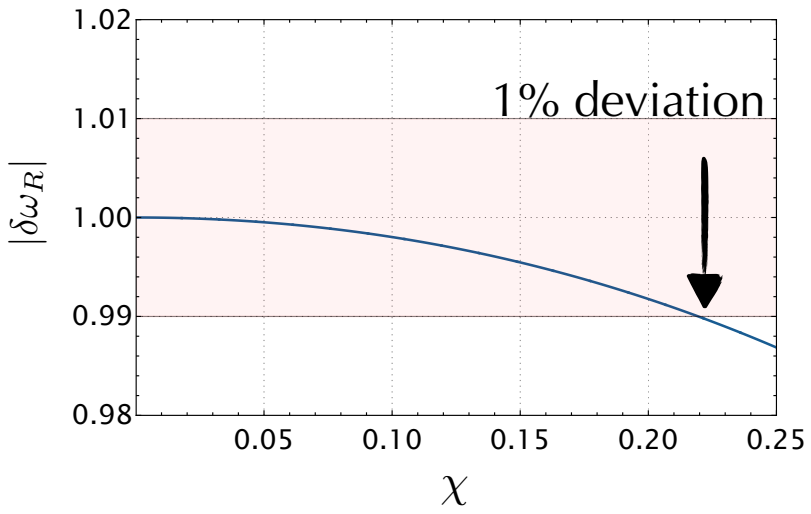
EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

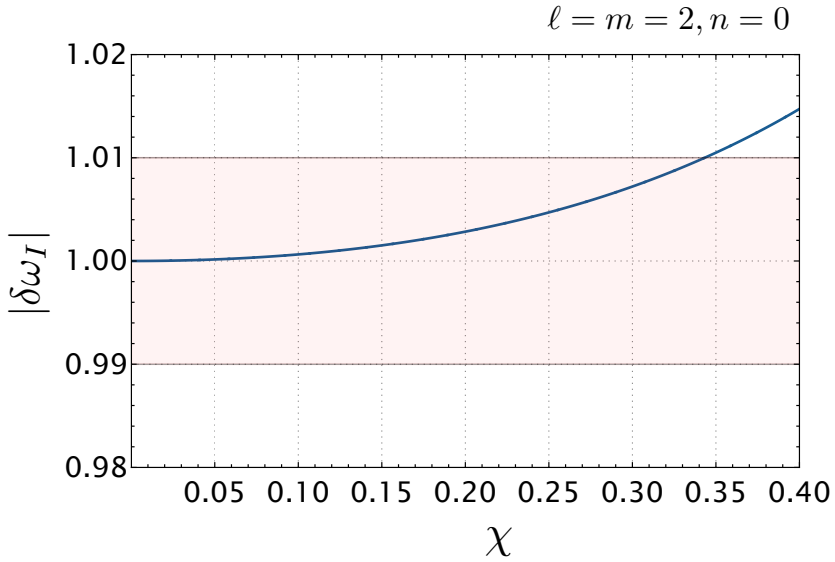
Spinning horizonless compact objects

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)

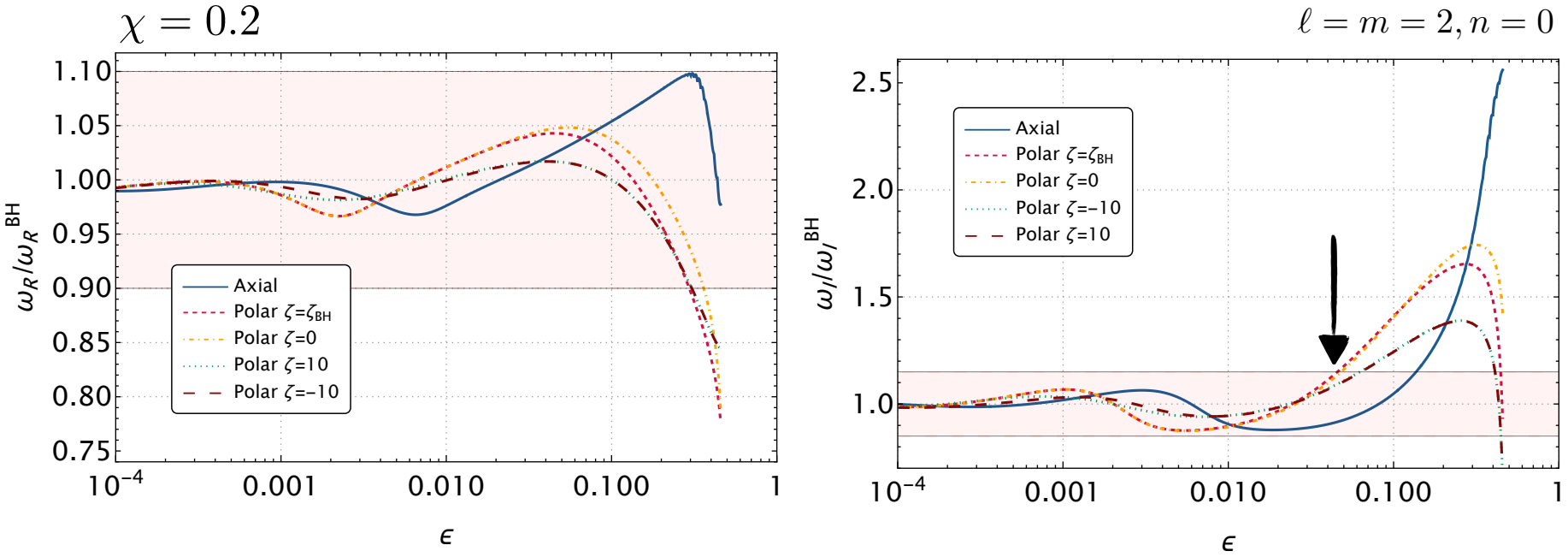
From a comparison with the BH case, this description is valid until the maximum value of the spin $\chi = 0.2$.





Quasi-normal mode spectrum

The spin makes the constraints on the compactness of objects more stringent.



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

Horizonless compact objects with $\epsilon \lesssim 0.04$ are compatible with the measurement accuracy of the fundamental QNM of GW150914.

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.
- Need to include spin effects in the ringdown of horizonless compact objects and in modified theories of gravity.
- Generalise the study of the ringdown to higher orders in the spin.
- Constrain the properties of the remnant with a Bayesian framework.