How does a dark compact object ringdown?

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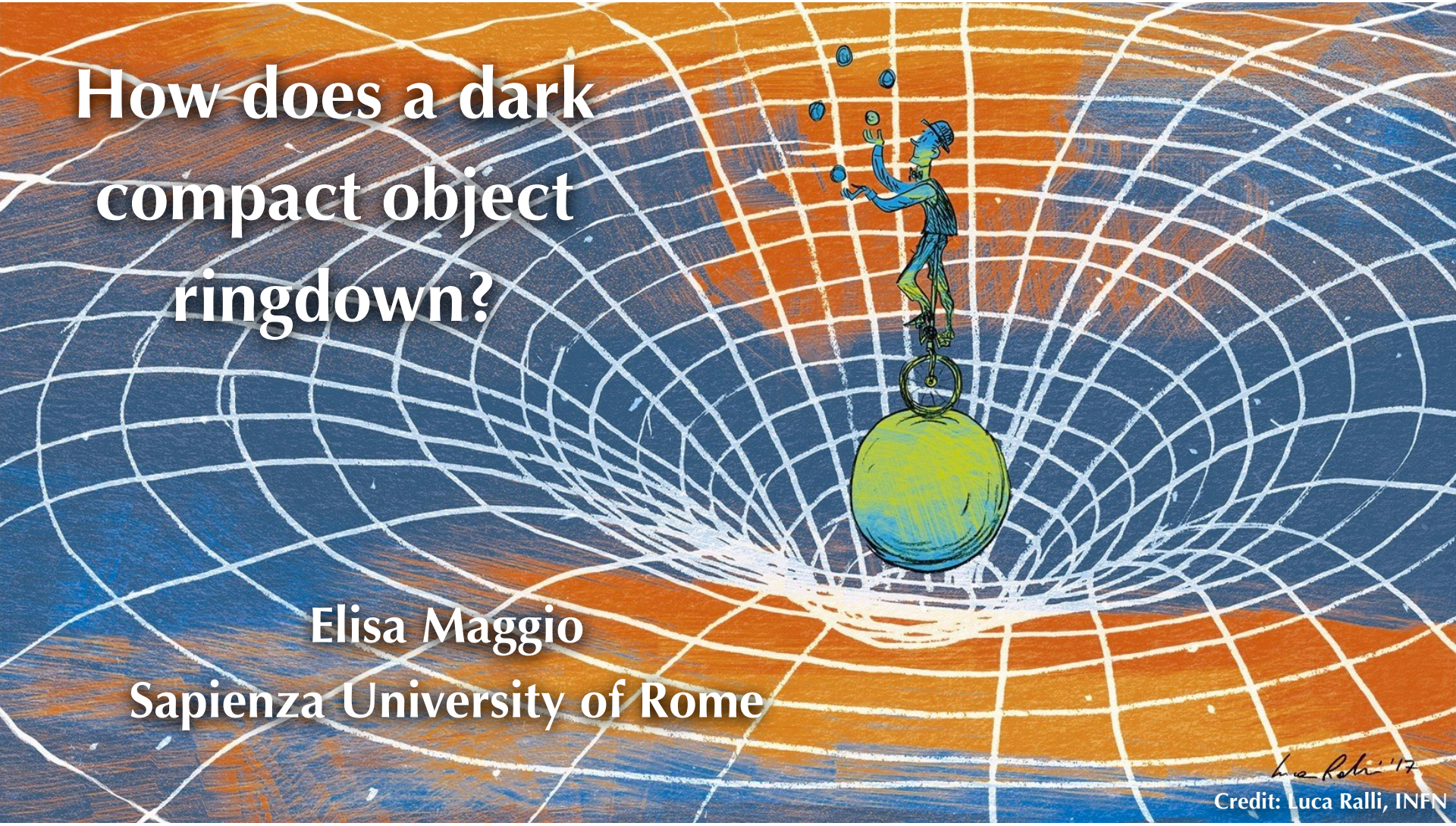

Credit: Luca Ralli, INFN

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DarkGRA

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Outline

- **Testing the nature of astrophysical sources with gravitational waves**

  Ringdown stage

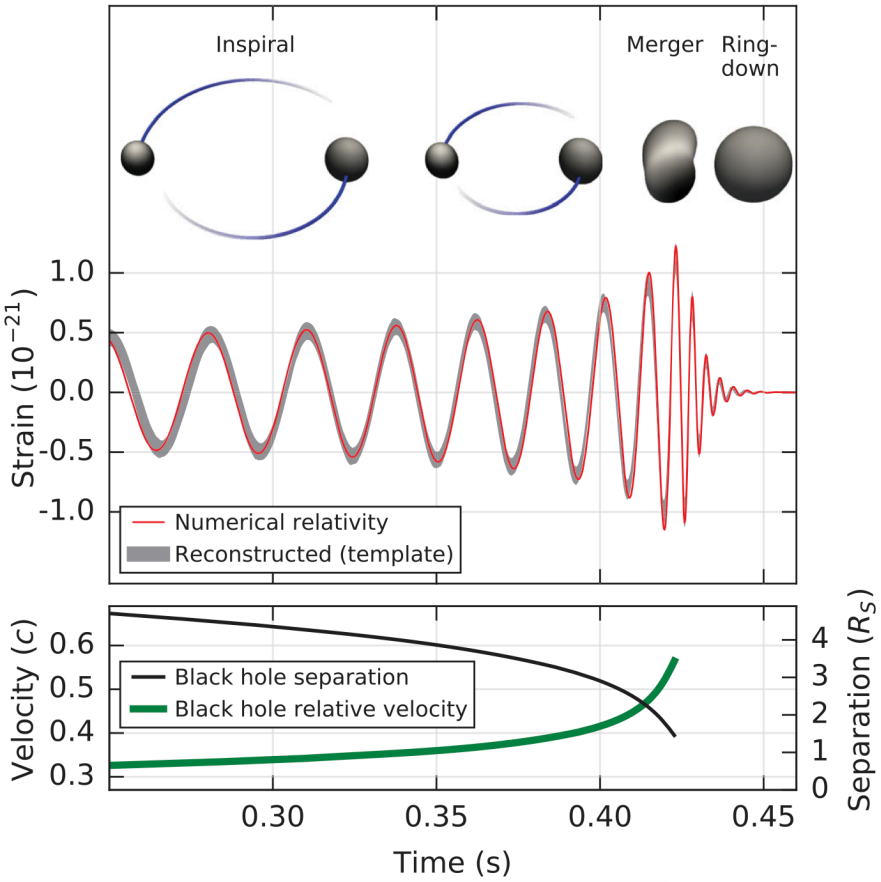
- **Horizonless alternatives to black holes**

  Quasi-normal mode spectrum

  Gravitational-wave echoes

  Detectability

Ringdown signal



LVC, PRL **116** (2016) 061102

The ringdown is dominated by the **quasi-normal modes** of the remnant:

$$\omega = \omega_R + i\omega_I$$

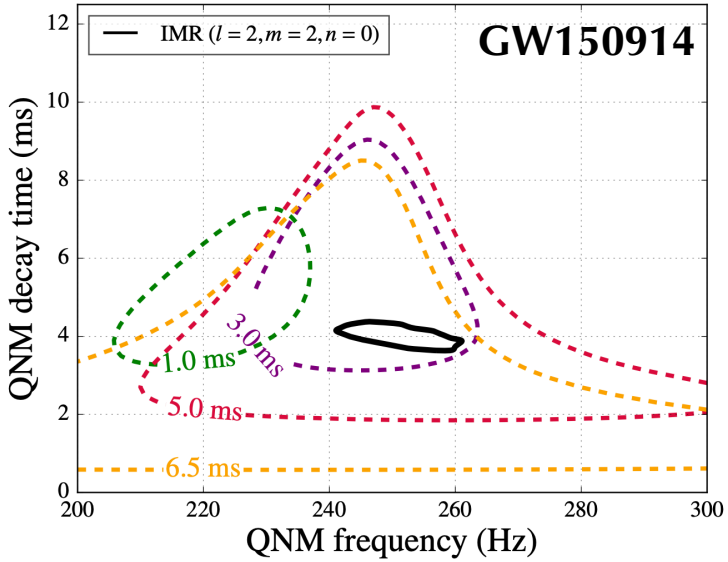
The ringdown is modeled as a sum of exponentially damped sinusoids:

$$f_{\rm GW} = \frac{\omega_R}{2\pi} \qquad \tau_{\rm damp} = -\frac{1}{\omega_I}$$

Ringdown detections

The fundamental quasi-normal mode has been observed in the ringdown of several GW events and is compatible with Kerr BH remnants.

Abbott+, arXiv:2010.14529 (2020)

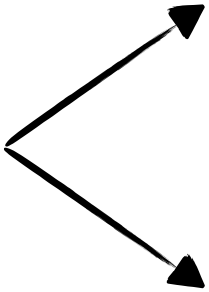


Abbott+, PRL **116**, 221101 (2016)

A **test of the no-hair theorem** requires the identification of at least two quasi-normal mode frequencies in the ringdown. Dreyer+, CQG **21**, 787 (2004)

Alternatives to black holes

There are several models of **horizonless** compact objects which:



are solutions to *modified gravity* and can overcome the paradoxes of black holes

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

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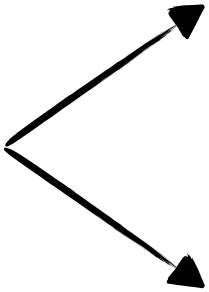

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- can mimic black holes in terms of electromagnetic observations

  Abramowicz+, A&A 396, L31-L34 (2002); EHT, ApJ **875**, L5 (2019)

- are not excluded by current GW observations

  Abbott+, ApJ **896**: L44 (2020); Abbott+, PRL **125**, 101102 (2020); Calderón Bustillo+, arXiv: 2009.05376 (2020)

Dark compact objects

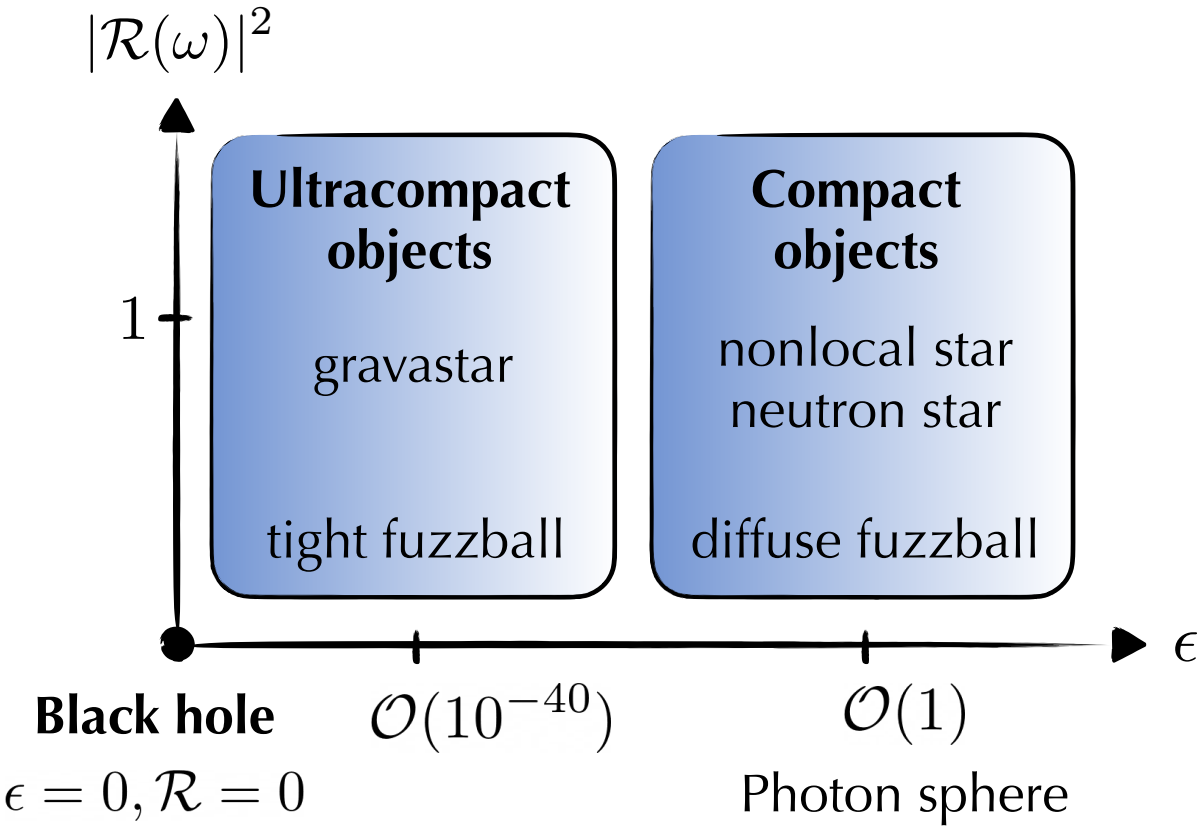
We analyze a generic model which deviates from a black hole for its:

- **Compactness**

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

- **"Darkness"**

  which is related to the reflectivity of the object $\mathcal{R}(\omega)$



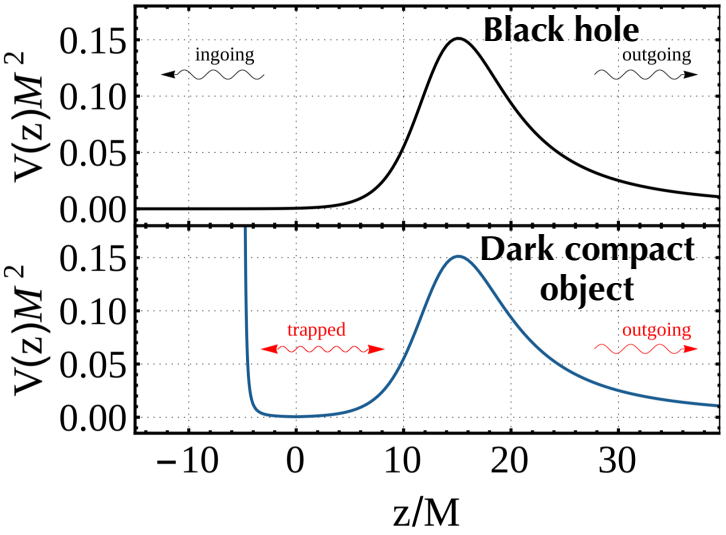
Quasi-normal mode spectrum

We can distinguish dark compact objects from BHs via quasi-normal modes.

We consider a gravitational perturbation:

$$\frac{d^2\psi}{dz^2} + V(z,\omega)\psi = 0$$

Detweiler, Proc. R. Soc. Lond. A **352** (1977)



Cardoso, Pani, LRR **22**:4 (2019)

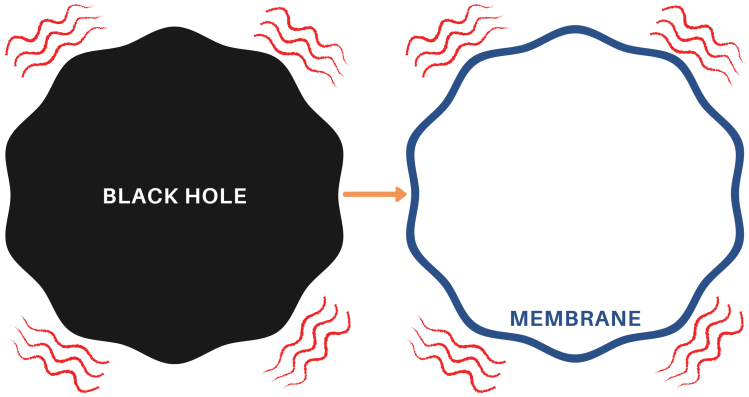
+2 boundary conditions:
Eigenvalue problem for the QNMs

- At infinity: outgoing waves
- At r_0: dark compact object with reflectivity $\mathcal{R}(\omega)$

BH membrane paradigm

A static observer outside the horizon can replace the interior of a perturbed BH by a perturbed **fictitious** membrane located at the horizon.

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

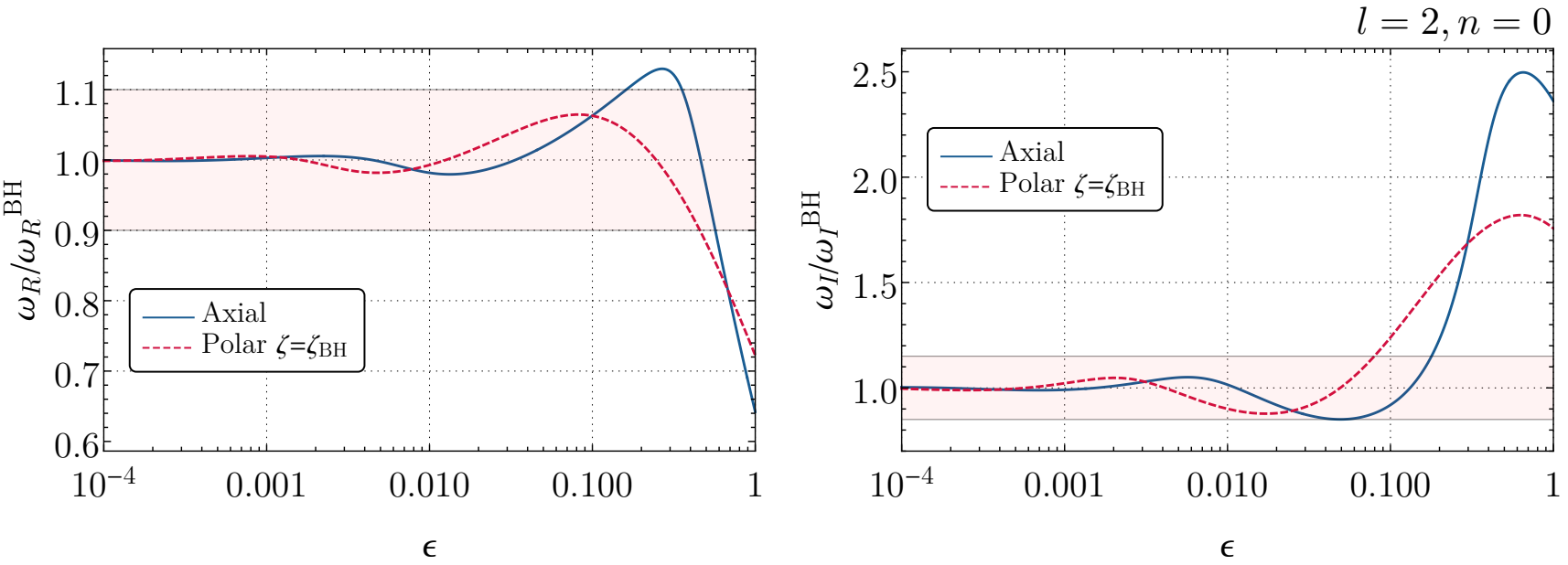


The Israel junction conditions $[[K_{ab} - K h_{ab}]] = -8\pi T_{ab}$ impose that the membrane is a **viscous fluid** with shear viscosity η and bulk viscosity ζ.

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

Quasi-normal modes of dark compact objects

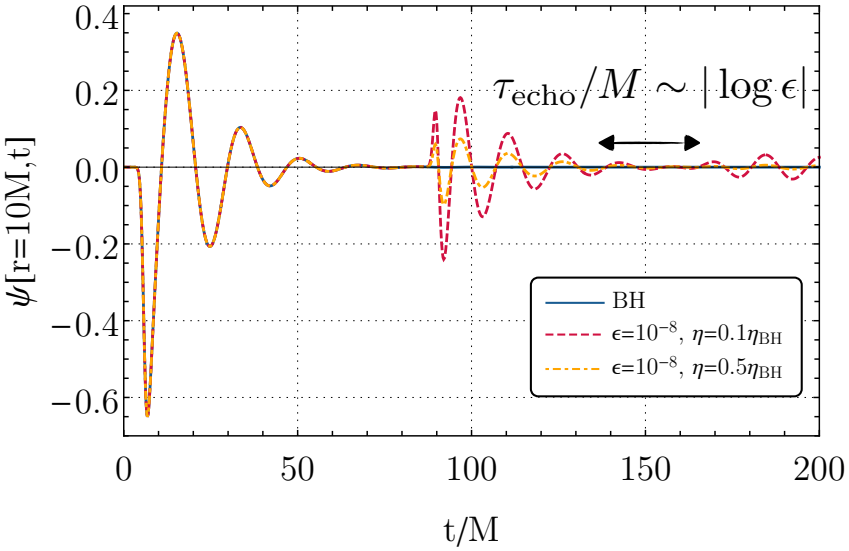
Totally absorbing object $\eta = \eta_{\rm BH}$:

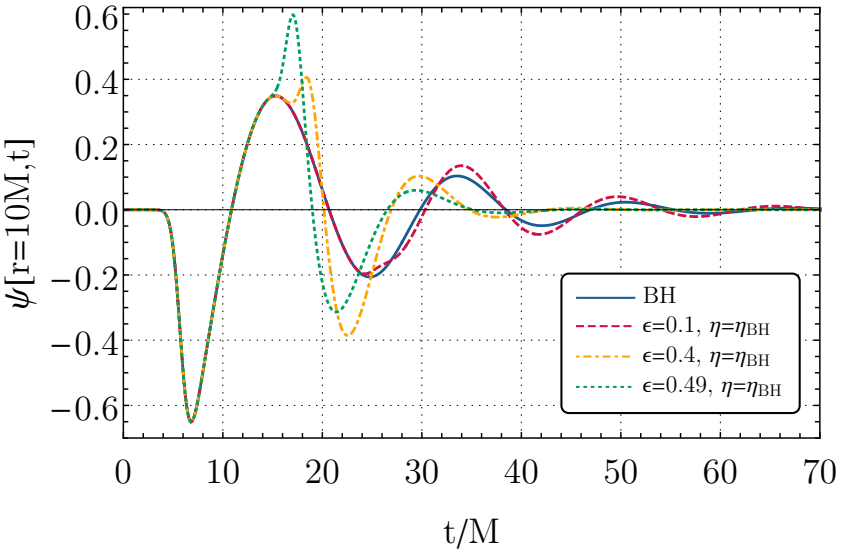


- The **isospectrality** of axial and polar modes in black holes is broken.
- The measurement accuracy of the QNM of GW150914 agrees with a dark compact object with $\epsilon \lesssim 0.1$.

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

Ringdown of dark compact objects





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

- Same prompt ringdown due to excitation of photon sphere
- Echoes due to trapped modes

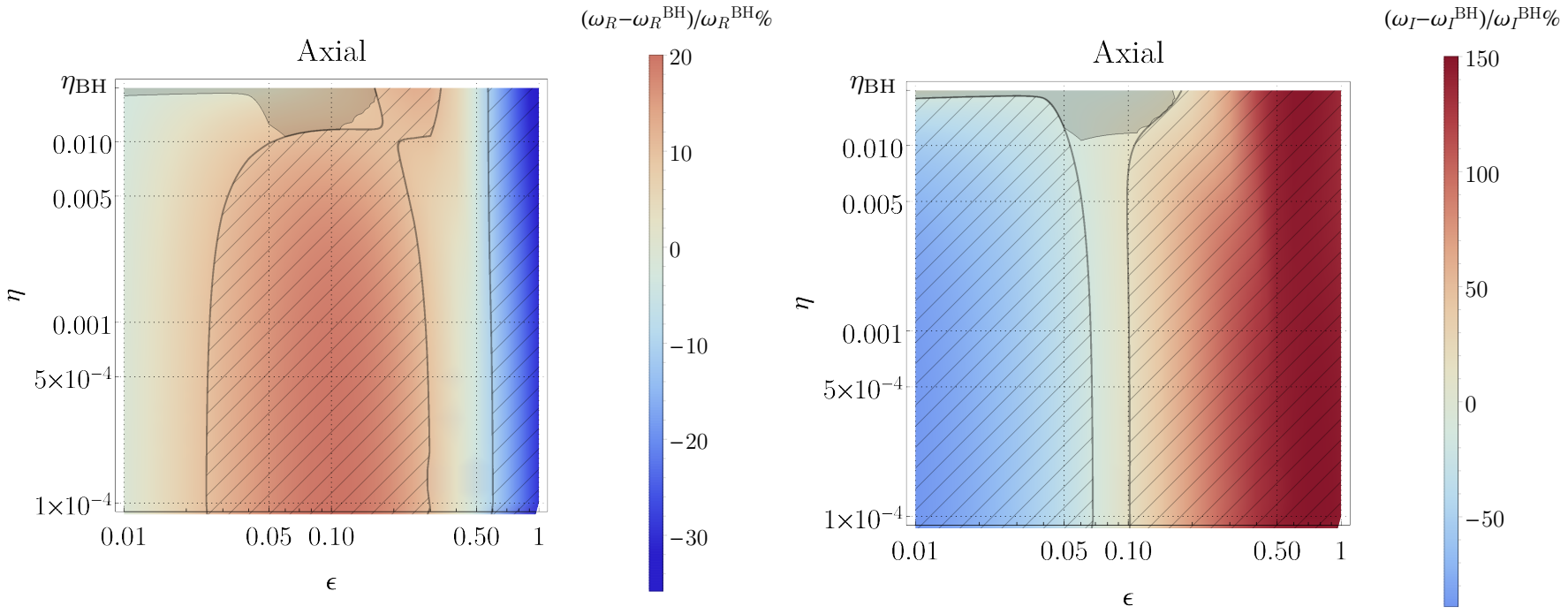
Compact objects ($\epsilon \gtrsim 0.01$):

- Modified prompt ringdown
- No echoes

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

Constraints on the compactness

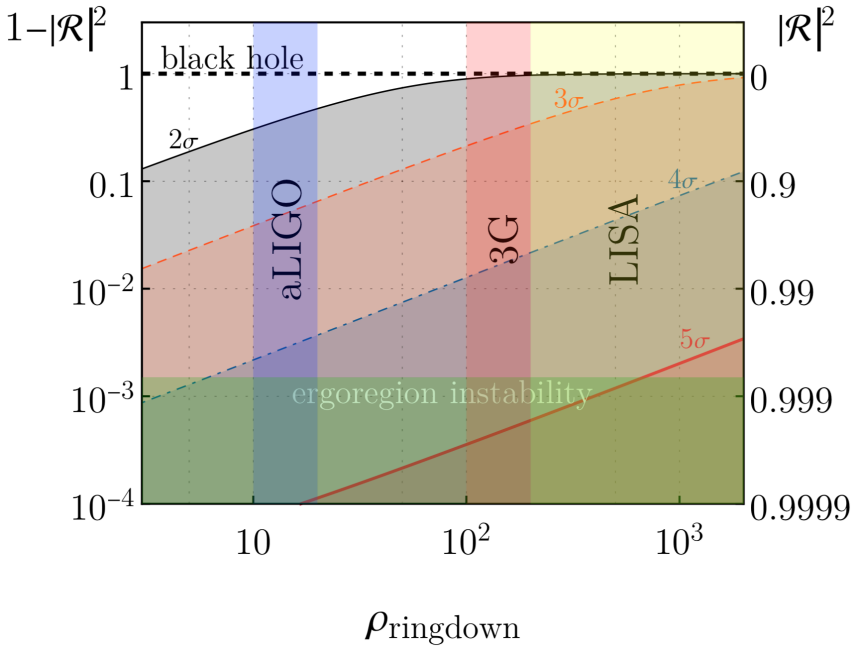
- No evidence for echoes in Ligo/Virgo O3a Abbott+, arXiv:2010.14529 (2020)
- Current measurement accuracies impose that the compactness of the remnant cannot be smaller than 99% that of a black hole.



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

Constraints on the reflectivity

- Perfectly reflecting models are ruled out since the energy emitted in the echoes would be larger than the energy emitted in the ringdown.
- Third-generation detectors will be able to probe values of the **reflectivity close to the BH one**.



EM, Testa, Bhagwat, Pani, PRD **100**, 064056 (2019)

Conclusions and future prospects

- We can infer the nature of compact objects and look for new physics at the horizon scale with **gravitational waves**.

- **Horizonless alternatives to black holes** are not excluded by current GW measurements.

- We derived the **ringdown and the echo signal** for dark compact objects.

- **Third generation detectors** will allow to perform unprecedented tests of the BH paradigm.