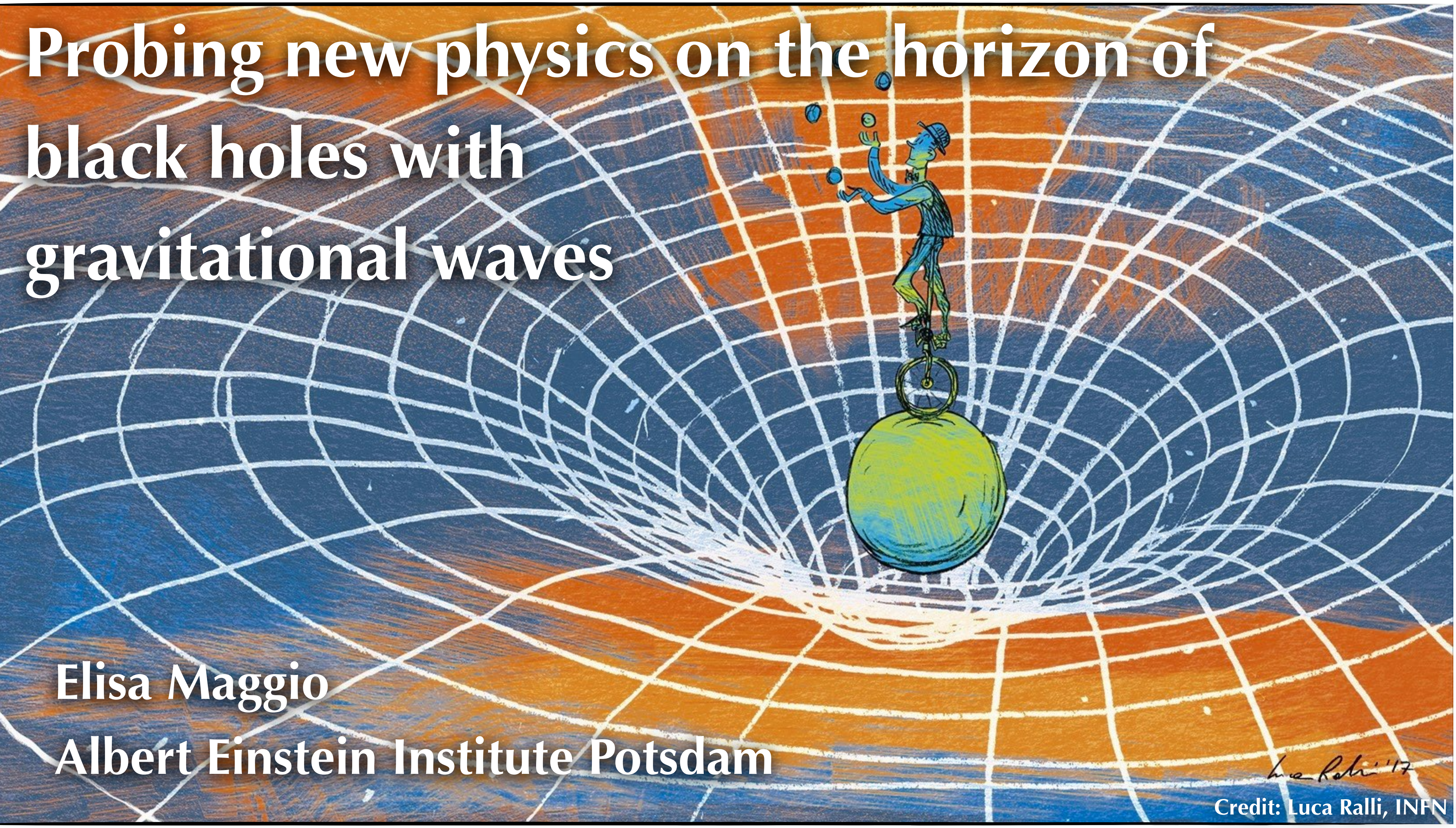
Storming the Gravitational Wave Frontier @KITP

Probing new physics on the horizon of black holes with gravitational waves

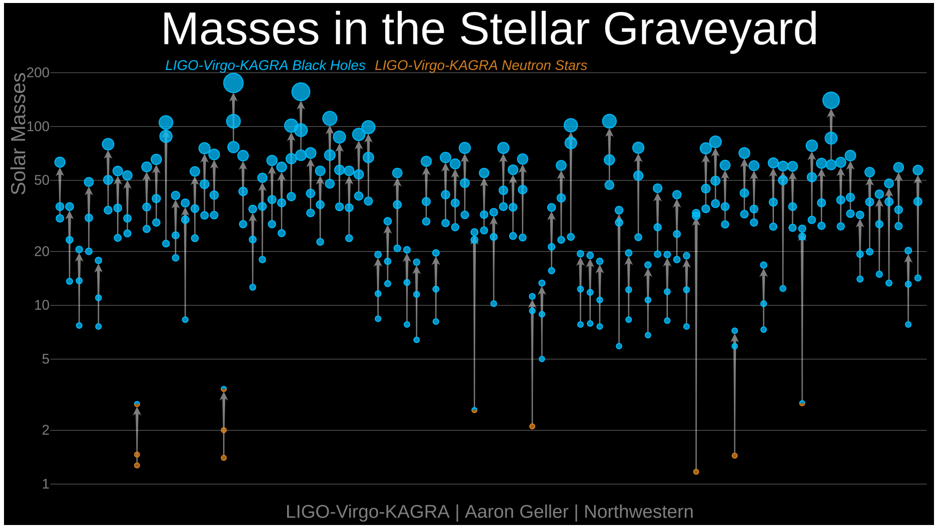
Elisa Maggio
Albert Einstein Institute Potsdam



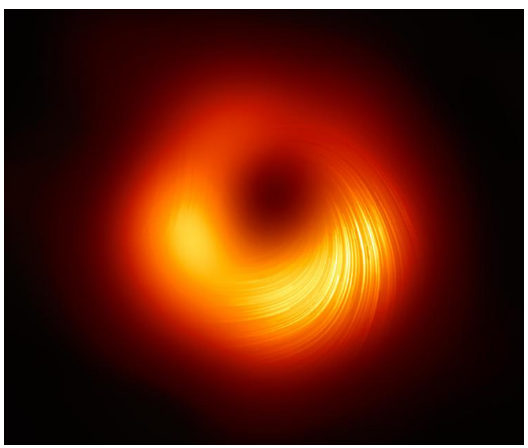
Credit: Luca Ralli, INFN

21/04/2022

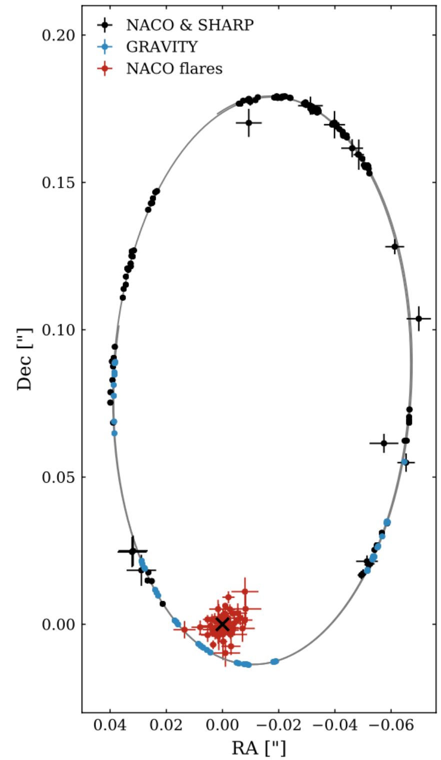
Black hole observations



LVK, arXiv:2111.03606 (2021)

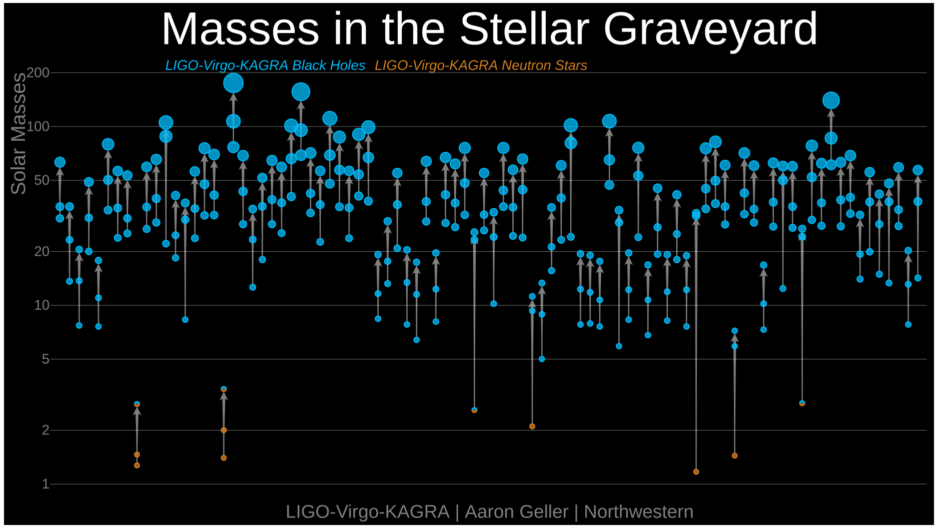


EHT, ApJL **910**, L12 (2021)



GRAVITY, A&A **636**, L5 (2020)

Black hole observations



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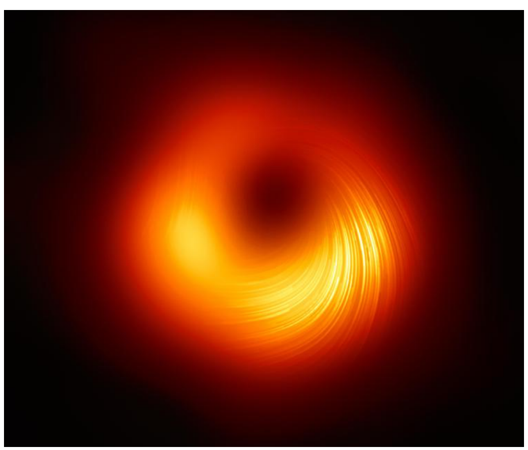
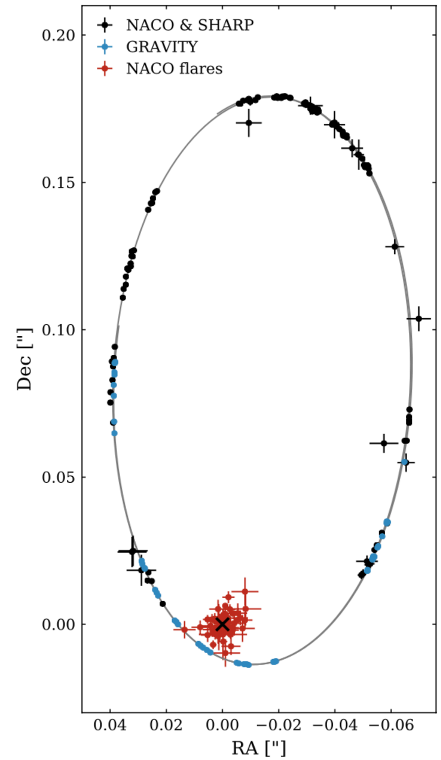


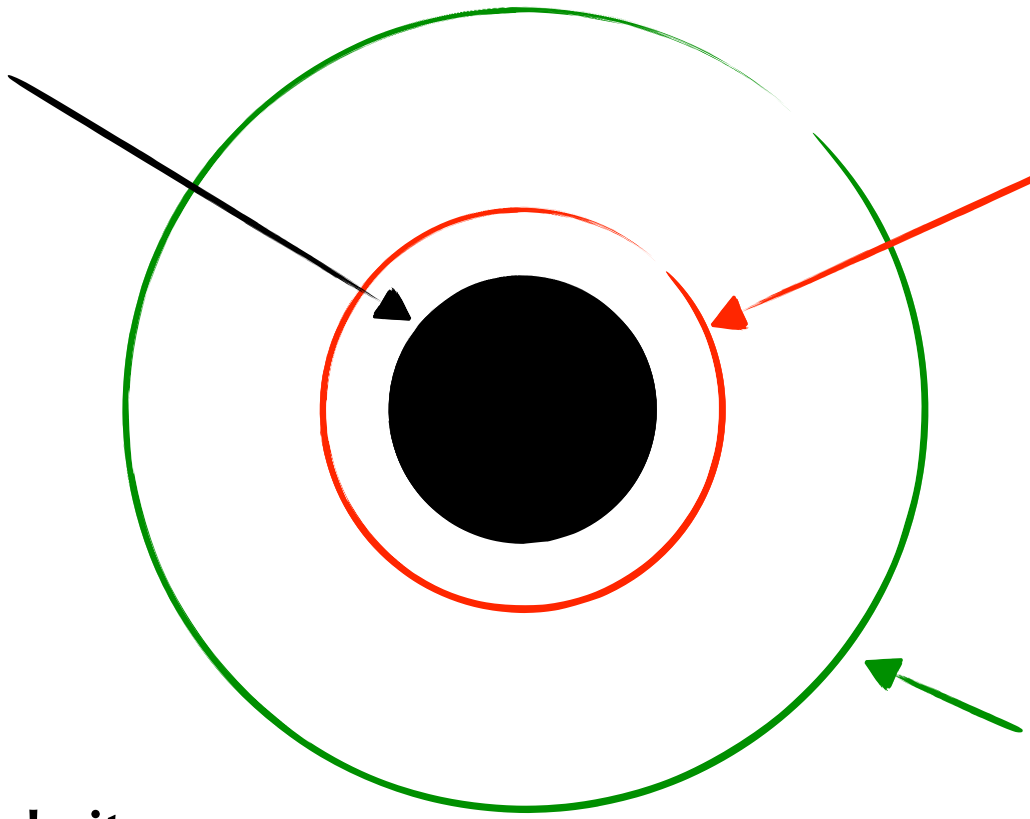
EHT, ApJL **910**, L12 (2021)



GRAVITY, A&A **636**, L5 (2020)

Are we really observing black holes?

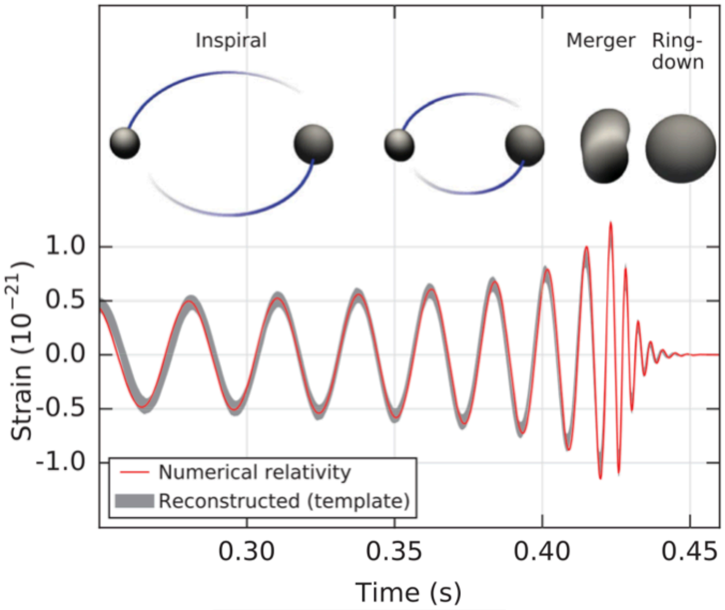
Black holes in general relativity



Ringdown stage

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

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



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

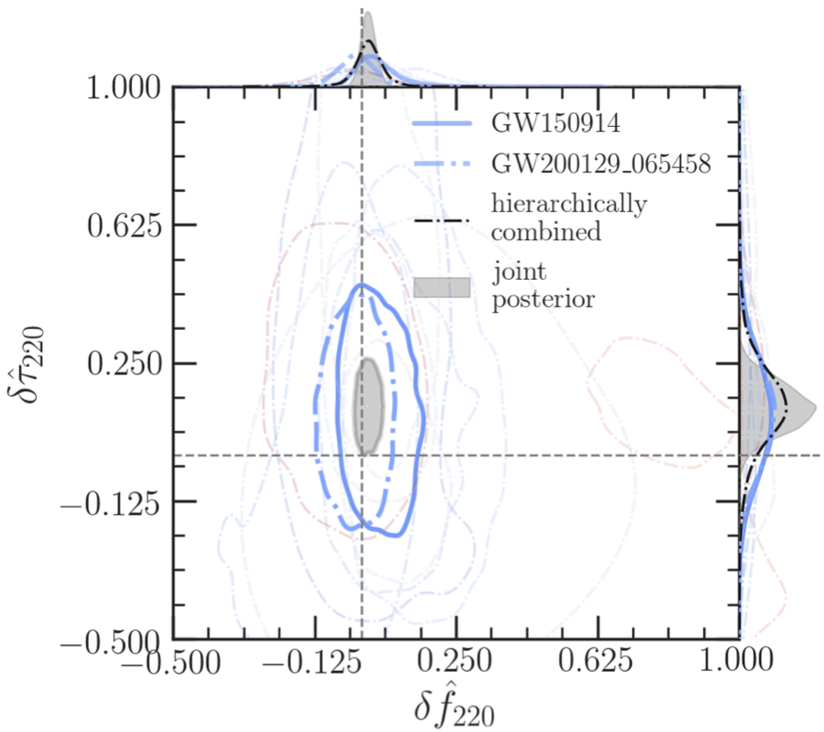
The ringdown is modeled as a sum of exponentially damped sinusoids:

$$f = \omega_R/(2\pi)$$

$$\tau = -1/\omega_I$$

Ringdown tests

The fundamental quasi-normal mode has been observed in the ringdown of several gravitational-wave events.



Abbott+, arXiv: 2112.06861 (2021)

The ringdown detections are compatible with **Kerr black hole remnants** but the characterization of the remnant is still an open problem.

Test of the black hole paradigm

Kerr black holes are uniquely determined by 2 parameters:

- Mass
- Angular momentum

Carter, PRL **26**, 331 (1971)

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

Dreyer+, CQG **21**, 787 (2004); Abbott+, arXiv: 2112.06861 (2021)

Next generation detectors, e.g. the space-based interferometer LISA, will allow to test the black hole paradigm.

Berti+, PRD **73**, 064030 (2006)

Some questions

- Are there horizonless and singularity-free alternatives to black holes?
- What are their signatures in gravitational-wave signals?
- Are their signatures detectable by current and future detectors?

Are there horizonless alternatives to black holes?

Horizonless compact objects

New physics can prevent the formation of the horizon:

in theories of quantum gravity (e.g., gravastars, fuzzballs)

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

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

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

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- Horizonless compact objects can be “black-hole mimickers”

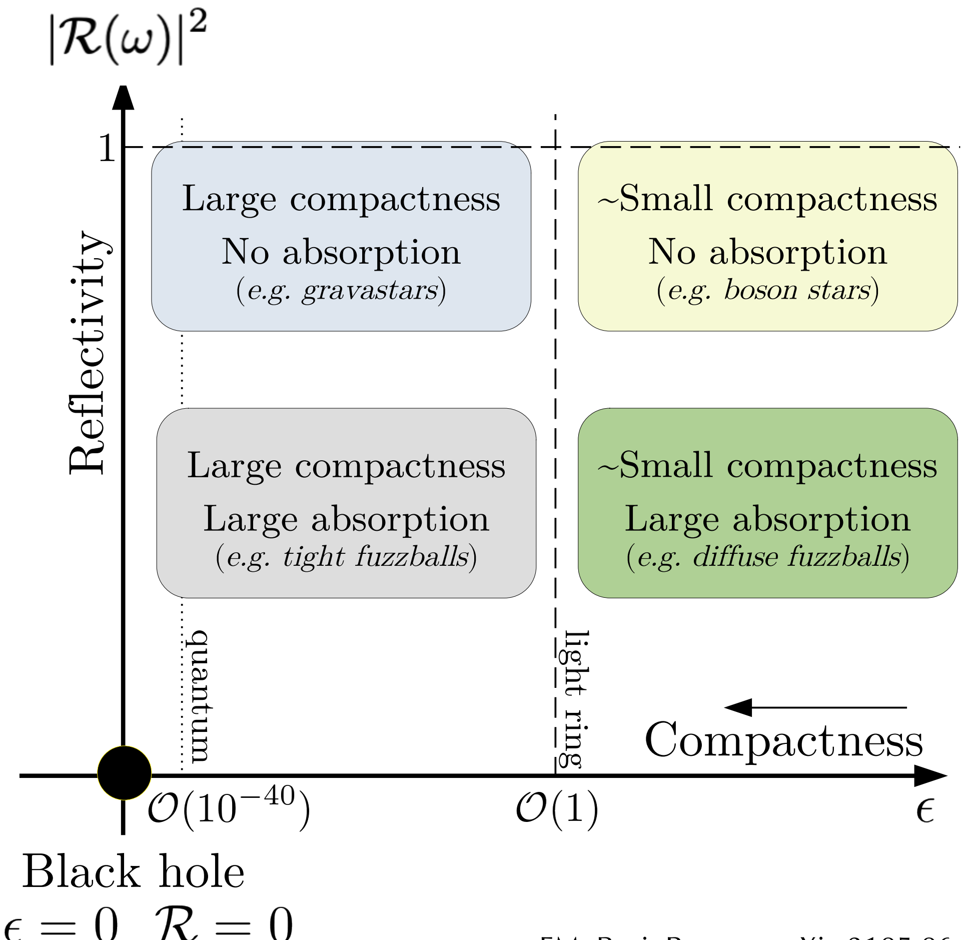
  Cardoso+, LRR **22**:4 (2019); EHT, ApJ **875**, L5 (2019)

- They quantify the existence of horizons

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**
  which differs from the totally absorbing BH case



EM, Pani, Raposo, arXiv:2105.06410 (2021)

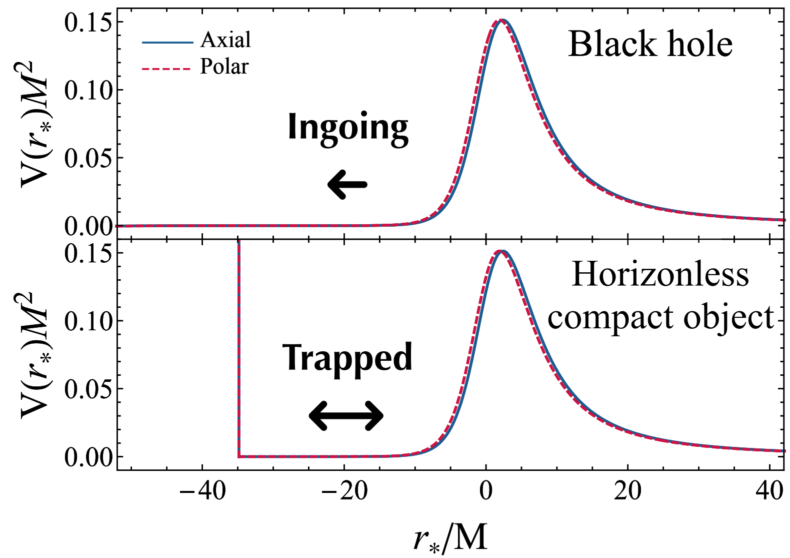
What are the gravitational-wave signatures of horizonless compact objects?

Ringdown

Let us analyze a horizonless compact object which is 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



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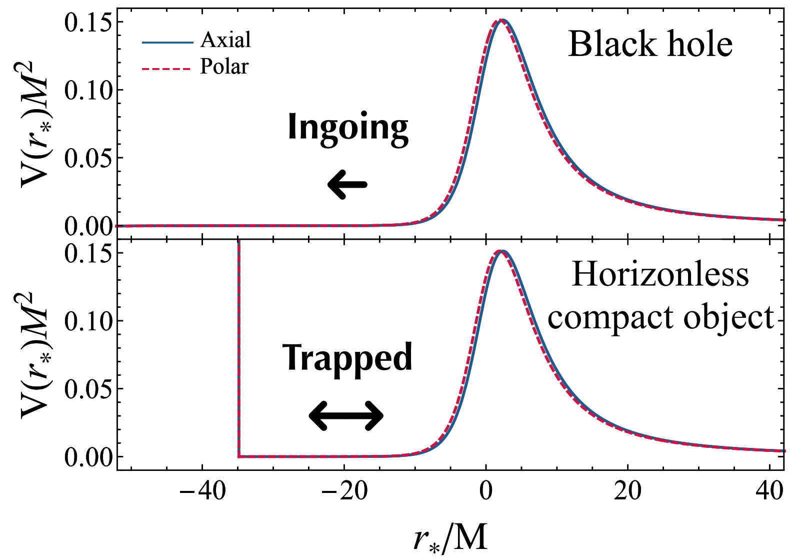


EM, Pani, Raposo, arXiv:2105.06410 (2021)

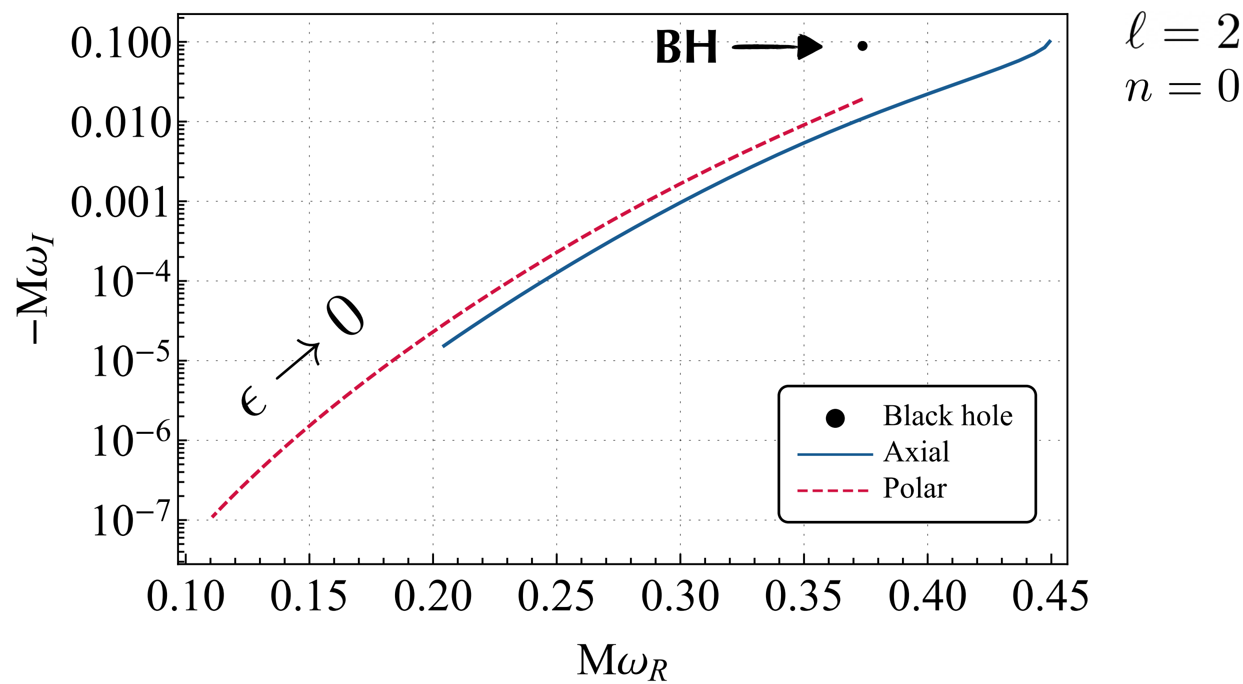
+ 2 boundary conditions:

- At infinity: outgoing waves
- At r_0: **ultracompact object** ($\epsilon \ll 1$)

$$\psi(r_0) \sim C_{\rm in} e^{-ikr_*} + C_{\rm out} e^{ikr_*} \quad \text{where} \quad \mathcal{R}(\omega) = \frac{C_{\rm out}}{C_{\rm in}} e^{2ikr_*^0}$$

Quasi-normal mode spectrum

Ultracompact object with a perfectly reflecting surface:

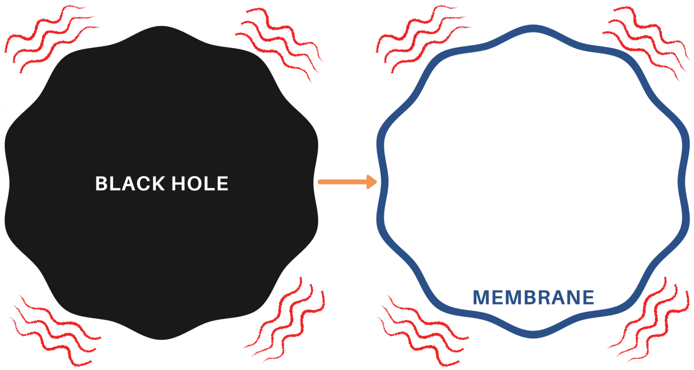


- Axial and polar modes are not isospectral and form a doublet.
- For $\epsilon \to 0$, the quasi-normal modes are low-frequencies and long-lived.

Cardoso+, PRL **116**, 171101 (2016); EM+, arXiv:2105.06410 (2021)

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)

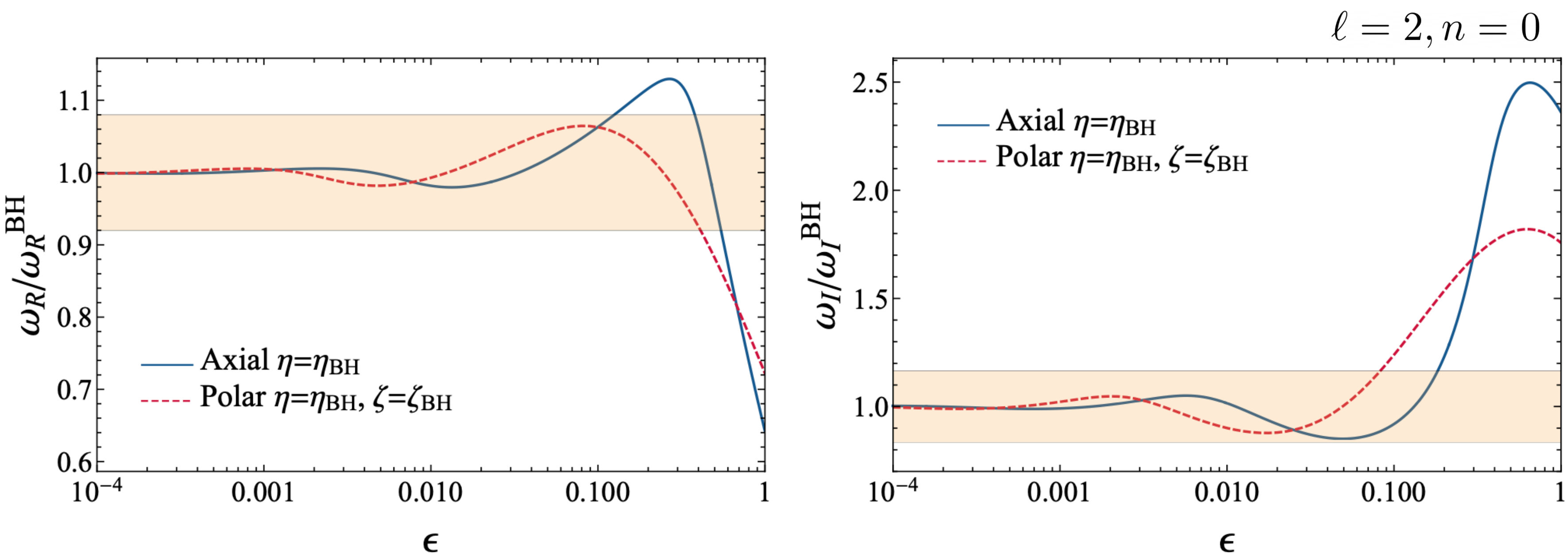


The Israel junction conditions impose that the membrane is a **viscous fluid** with shear viscosity η and bulk viscosity ζ.

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

Quasi-normal mode spectrum

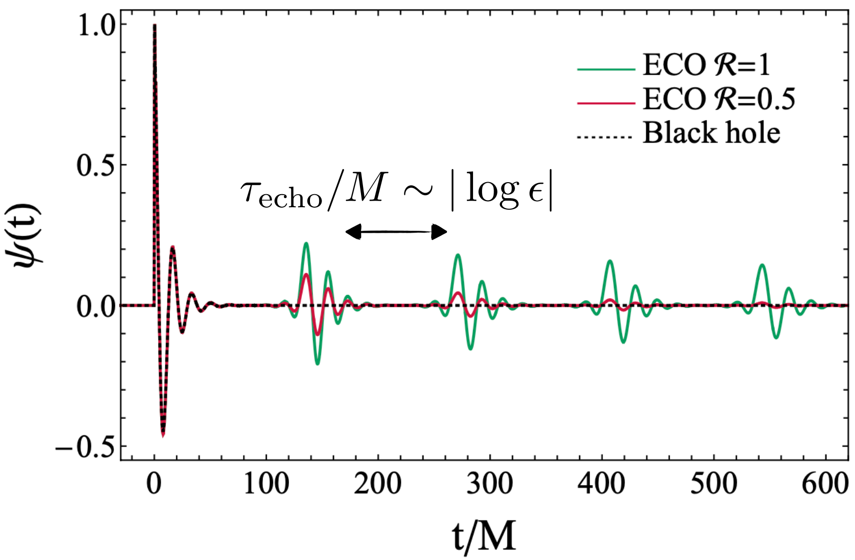
Totally absorbing object with small compactness:



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

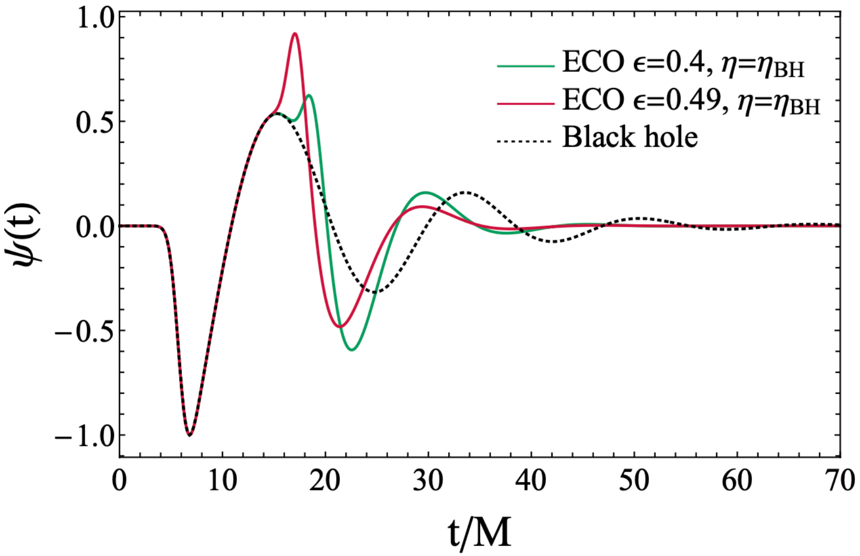
Horizonless compact objects with $\epsilon \lesssim 0.1$ are compatible with the measurement accuracy of the fundamental quasi-normal mode of GW150914.

Ringdown of horizonless objects



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

- Same prompt ringdown
  due to excitation of 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)

Are gravitational waves from horizonless compact objects detectable by current and future detectors?

Detectability of GW echoes

- A tentative evidence for echoes in LIGO/Virgo data has been reported

  Abedi+, PRD **96**, 082004 (2017); Conklin+, PRD **98**, 044021 (2018); Abedi+, JCAP **11**, 010 (2019)

- Independent searches argued that the statistical significance of echoes is low and 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)

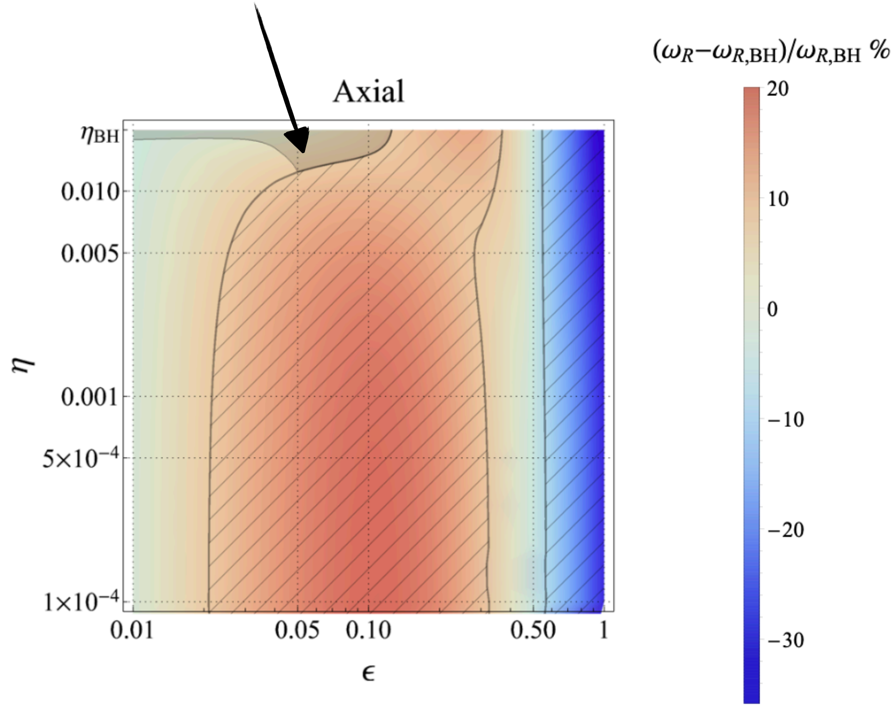
- No evidence for echoes in Ligo/Virgo O3b

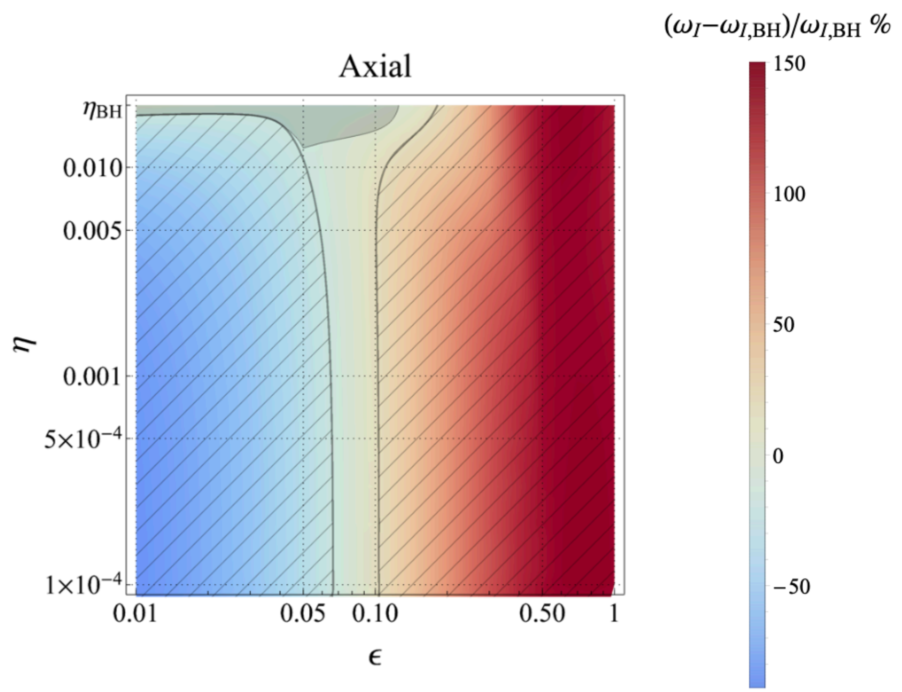
  Abbott+, PRD **103**, 122002 (2021); Abbott+, arXiv: 2112.06861 (2021)

Constraints on the compactness

Current measurement accuracies impose that the compactness of the remnant is larger than 90% the one of a BH.

Region not excluded by GW150914



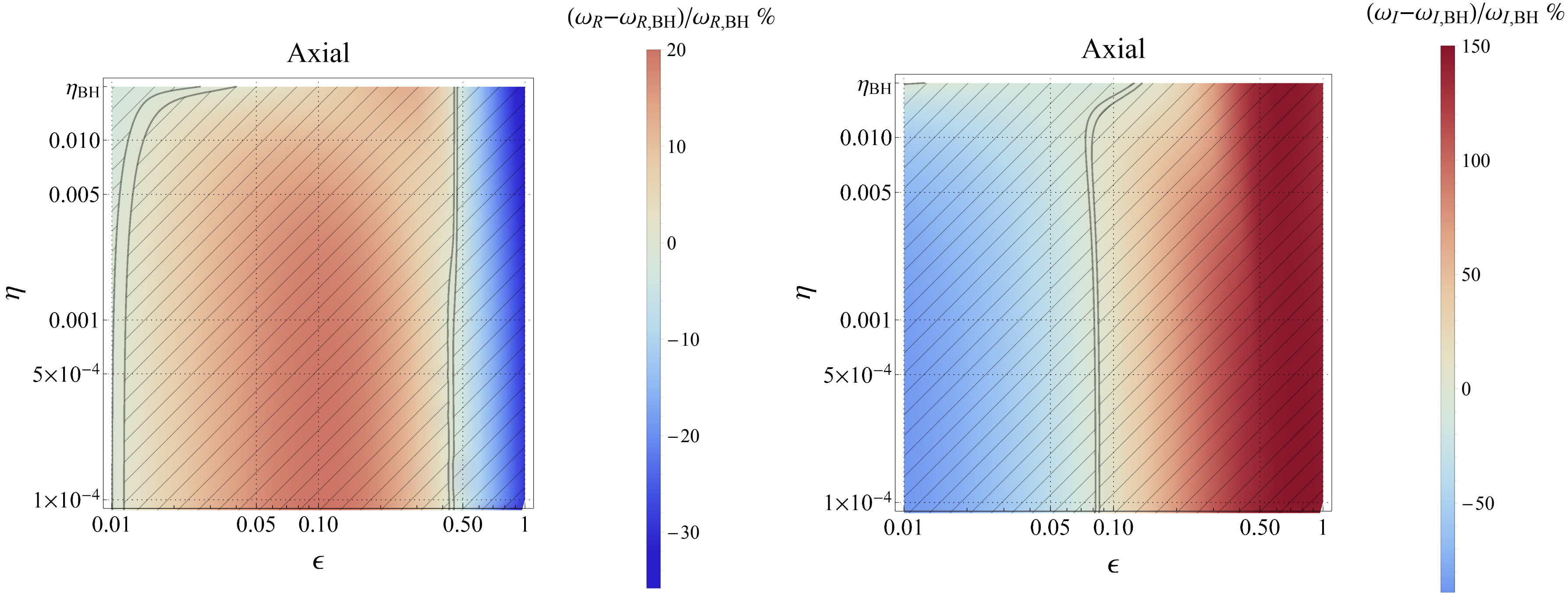


EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

Constraints on the compactness

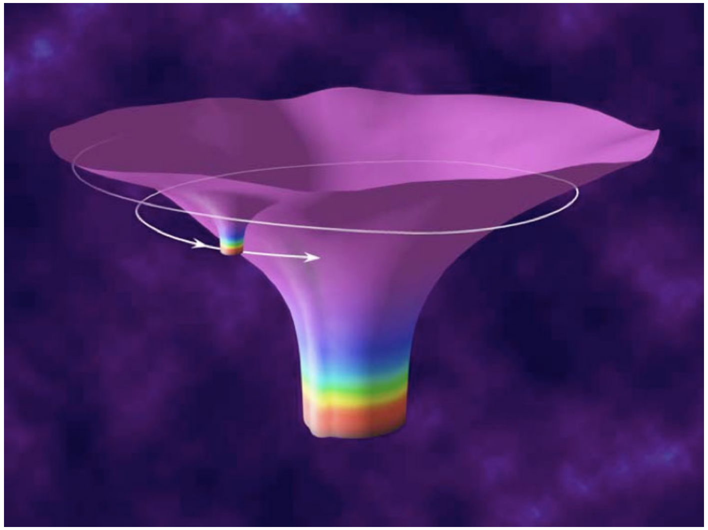
Current measurement accuracies impose that the compactness of the remnant is larger than 90% the one of a BH.

A factor of 10 increase in the SNR would constrain the whole region!



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

Extreme mass-ratio inspirals



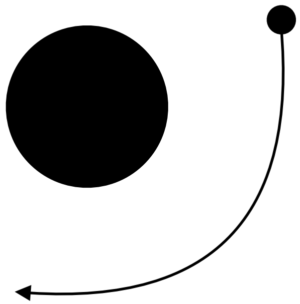
LISA will detect gravitational waves from the inspiral of stellar mass objects around supermassive compact objects at the center of galaxies.

- Any evidence of **reflectivity** would indicate a departure from the classical black hole picture.

- **Low-frequency modes** can be excited when the orbital frequency matches the quasi-normal mode frequencies of the central object.

EM, van de Meent, Pani, PRD **104**, 104026 (2021)

EMRIs around a horizonless object



We analyze a point particle in circular equatorial orbits from $r = 10M$ to $r_{\rm ISCO}$ around a spinning horizonless compact object.

Central horizonless object:

extra outgoing radiation at the radius

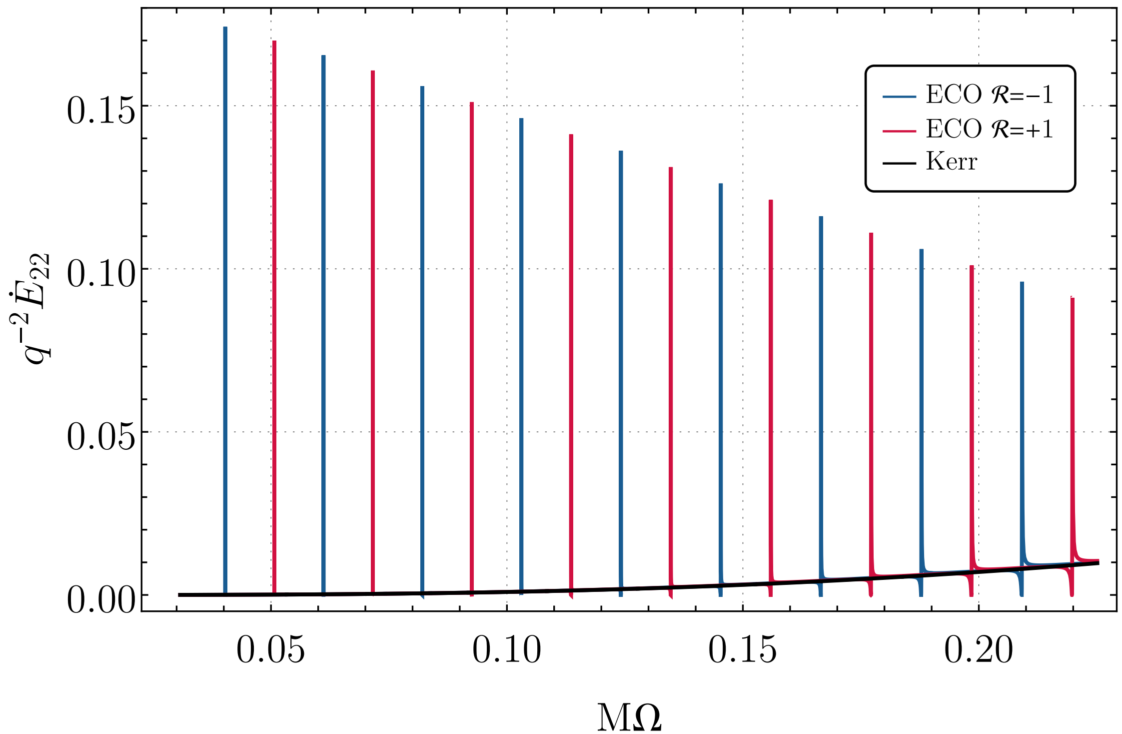
$$R_{\ell m\omega} \sim \begin{cases} Z^{H^+}_{\ell m\omega}\Delta^2 e^{-ikr_*} + Z^{H^-}_{\ell m\omega} e^{ikr_*} & \text{as } r_* \to r_*^0 \\ Z^{\infty}_{\ell m\omega} r^3 e^{i\omega r_*} & \text{as } r_* \to +\infty \end{cases}$$

Total energy flux: $\dot{E}(\Omega) = \dot{E}^{\infty}(\Omega) + \dot{E}^{H^+} - \dot{E}^{H^-}$

EM, van de Meent, Pani, PRD **104**, 104026 (2021)

Energy flux

The flux is resonantly excited when the orbital frequency matches the quasi-normal modes of the central object $\Omega = \omega_R/m$.



$\epsilon = 10^{-10}$

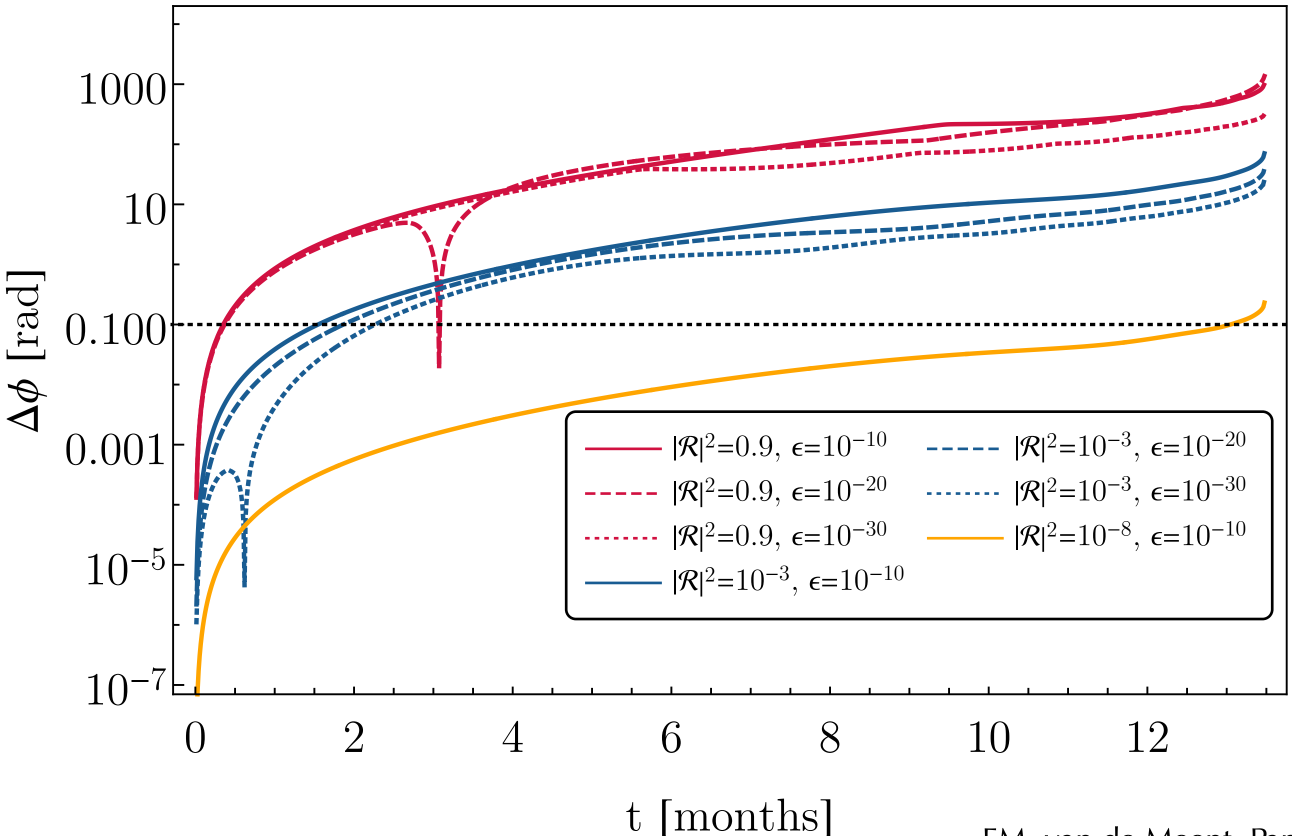
$\chi = 0.9$

EM, van de Meent, Pani, PRD **104**, 104026 (2021)

GW dephasing

The GW dephasing accumulated up to a certain time between the BH and the horizonless case is:

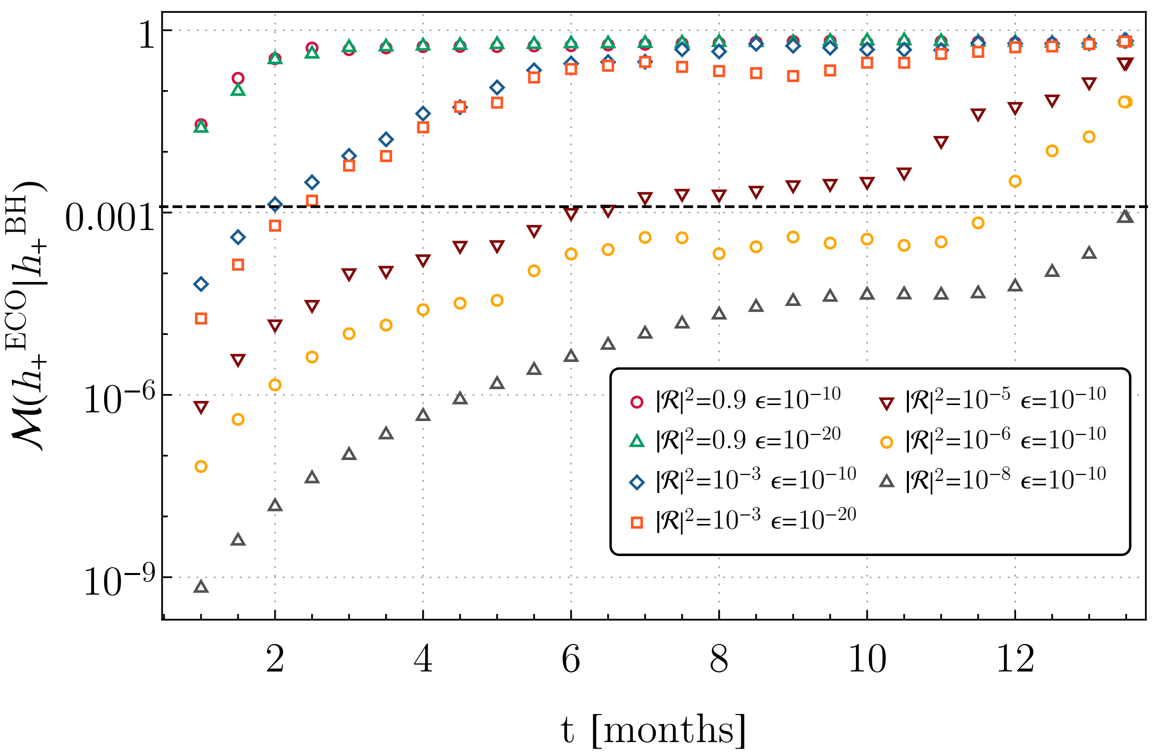
$$\Delta\phi(t) = \phi_{\rm GW}^{\rm BH}(t) - \phi_{\rm GW}^{\rm ECO}(t)$$



EM, van de Meent, Pani, PRD **104**, 104026 (2021)

Waveform mismatch

To assess the measurability of a deviation from a reference signal we compute the **mismatch** which is maximized over an arbitrary time and phase shift.



$\chi = 0.8$

$q = 3 \times 10^{-5}$

LISA is sensitive to a reflectivity of the central object $|\mathcal{R}|^2 = \mathcal{O}(10^{-8})$

EM, van de Meent, Pani, PRD **104**, 104026 (2021)

Conclusions and future prospects

- We can look for new physics at the horizon scale with gravitational waves.
- **Horizonless alternatives to black holes** are not excluded by current GW measurements.
- **Third-generation detectors** will allow us to perform unprecedented tests of the black hole paradigm.
- Development of full **inspiral-merger-ringdown waveforms** for alternative sources and in modified theories of gravity.
- Performance of accurate **statistical analyses** of the detectability of EMRIs with a horizonless source.