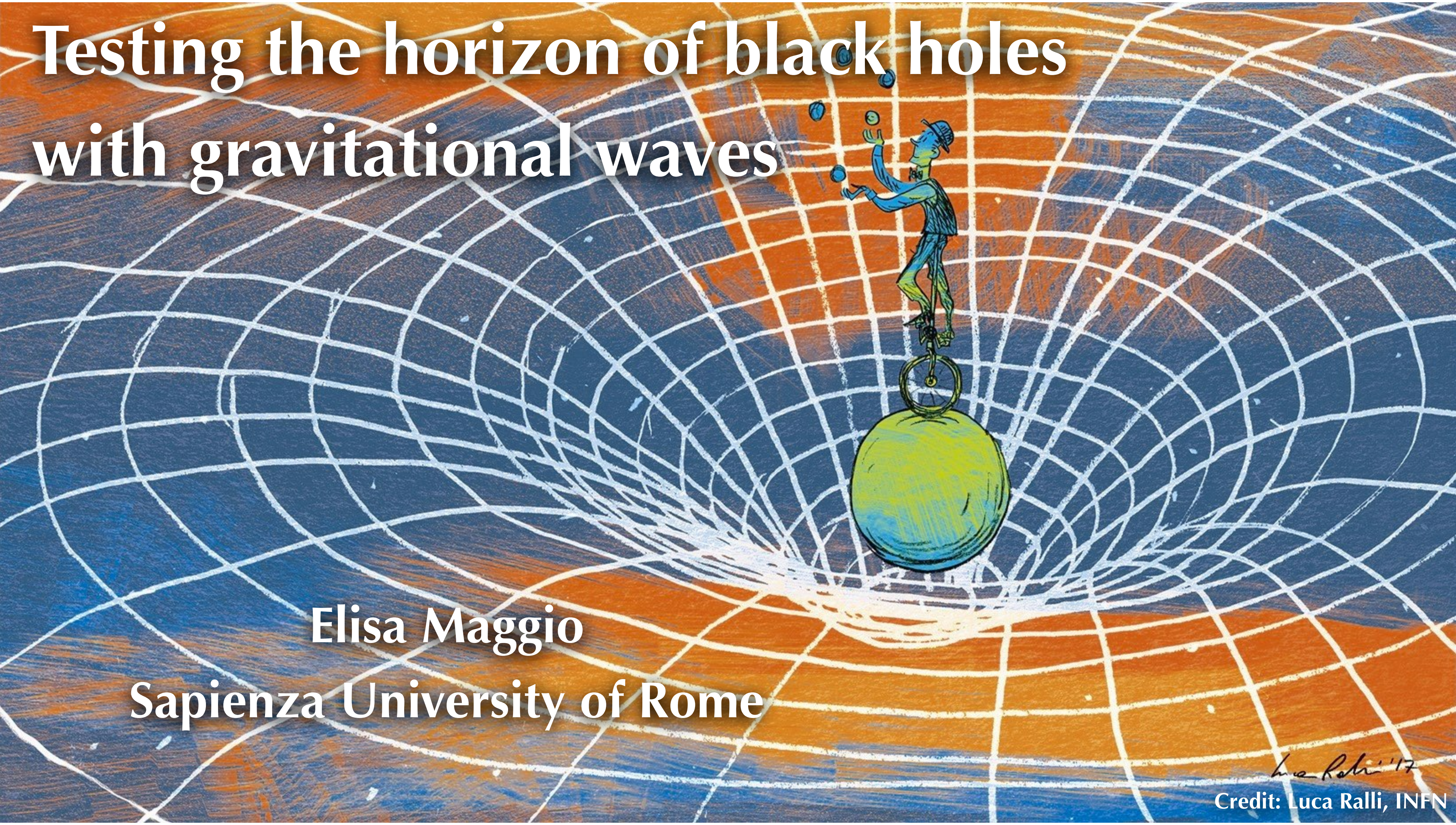
PhD Seminars

Testing the horizon of black holes with gravitational waves



Credit: Luca Ralli, INFN

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INFN Istituto Nazionale di Fisica Nucleare
DarkGRA
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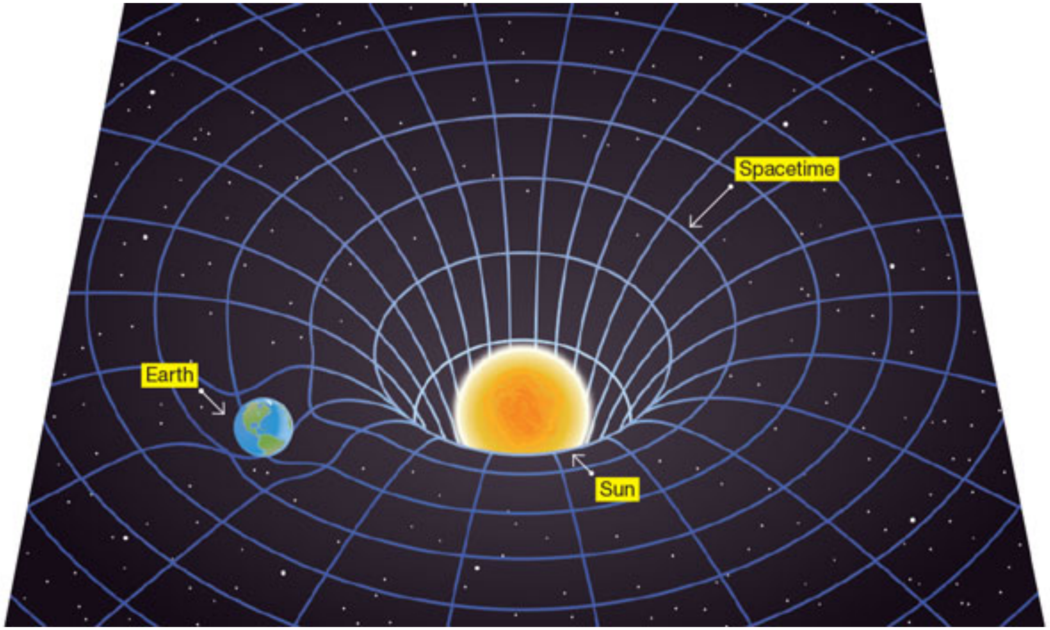
Einstein's spacetime



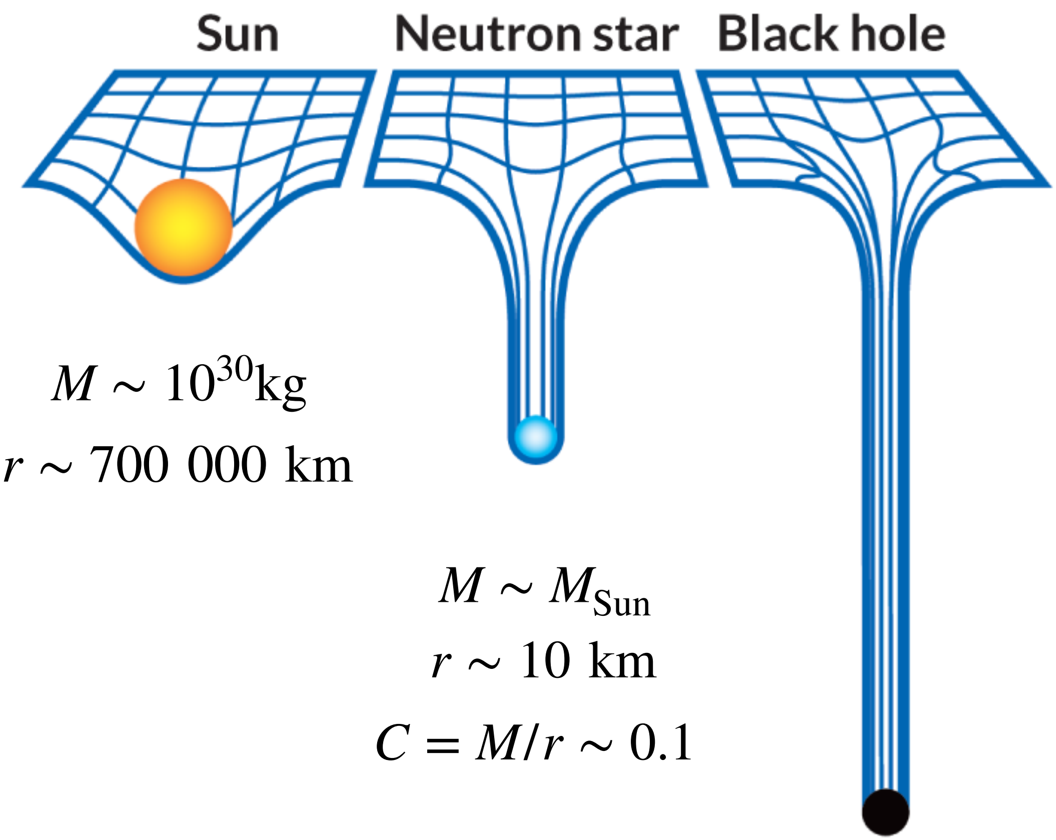
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Curvature tensor **Stress-energy tensor**

$\mu, \nu = 1, \underbrace{2,3,4}$

1 → time; 2,3,4 → space coordinates

Black holes



$M \sim 10^{30}$kg

$r \sim 700\ 000$ km

$M \sim M_{\rm Sun}$

$r \sim 10$ km

$C = M/r \sim 0.1$

$M \sim 10 \div 10^6 M_{\rm Sun}$

$C = 0.5$

- **Stellar black holes** are the endpoint of the evolution of a star.
- **Supermassive black holes** are at the centre of galaxies.

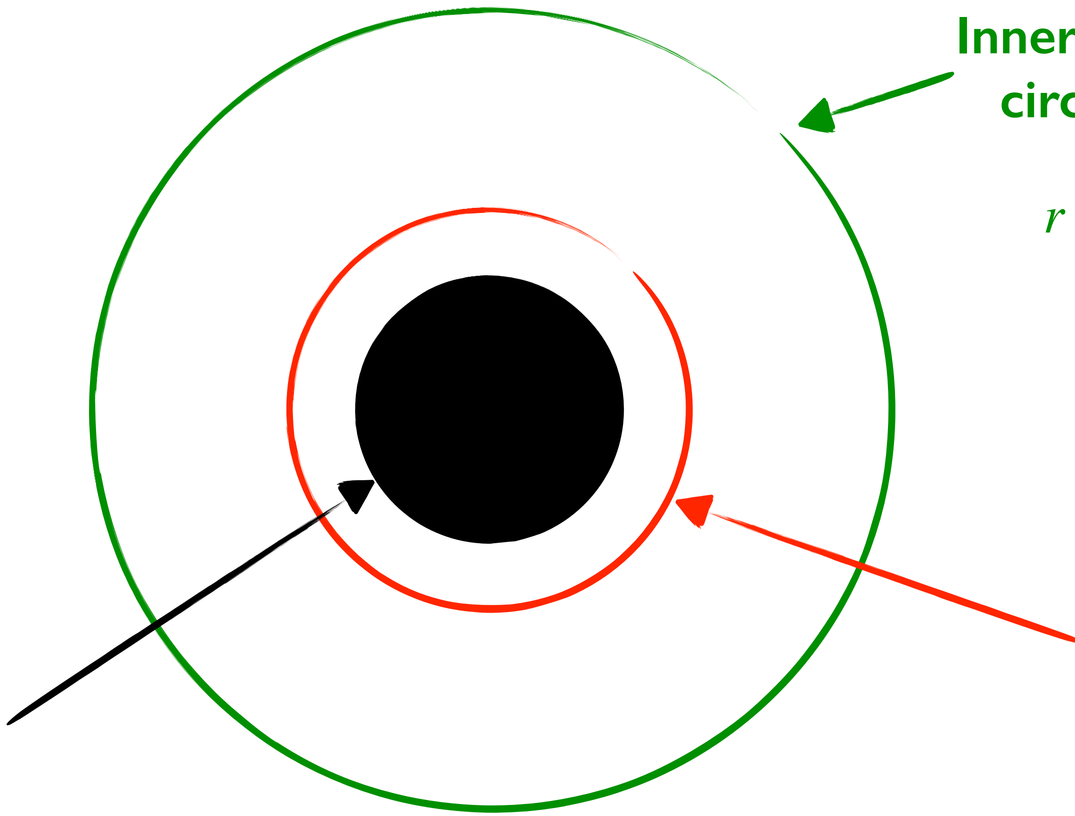
Black holes in General Relativity

Curvature singularity

$$r = 0$$

Innermost stable circular orbit

$$r = \frac{6GM}{c^2}$$



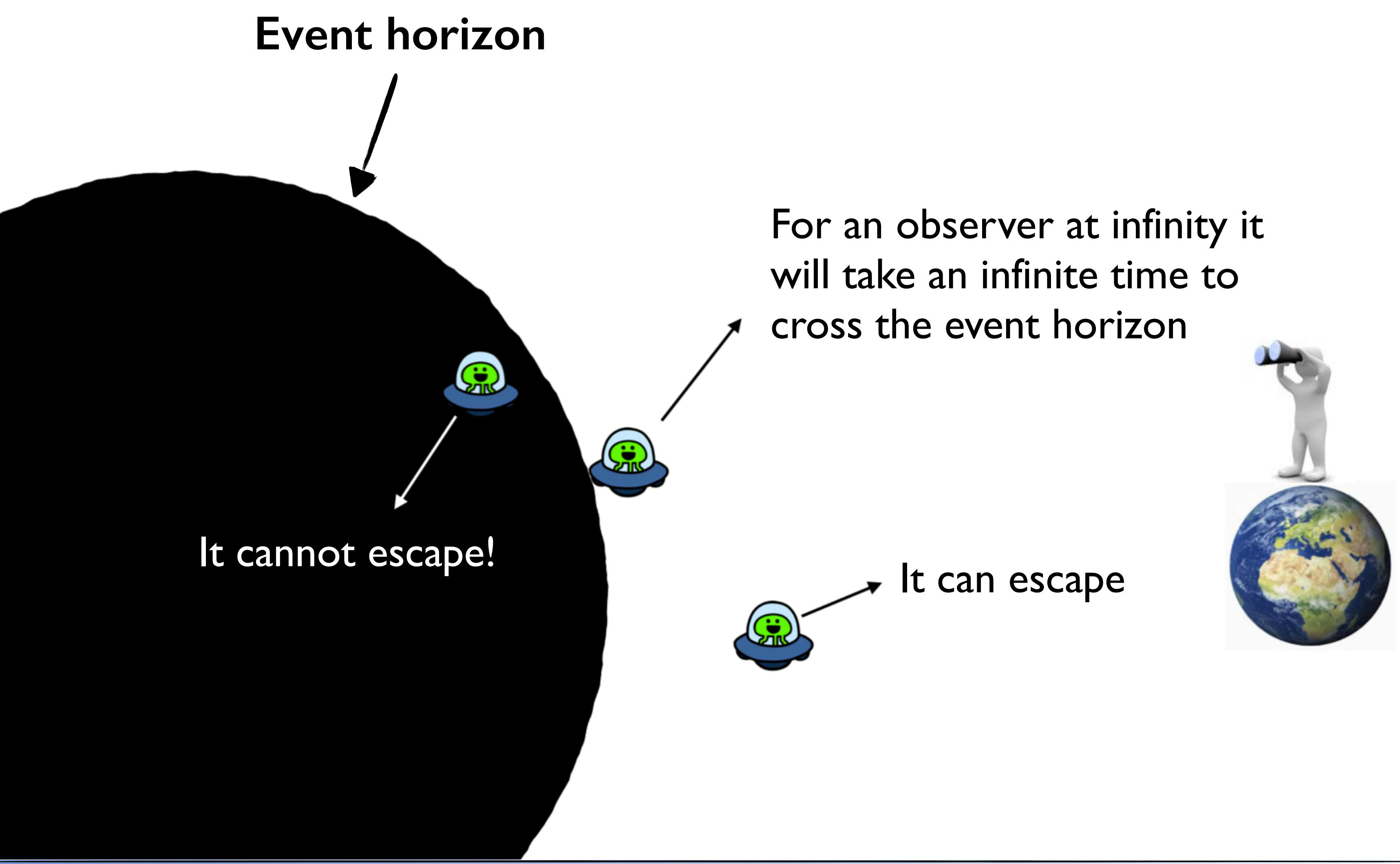
Light ring

$$r = \frac{3GM}{c^2}$$

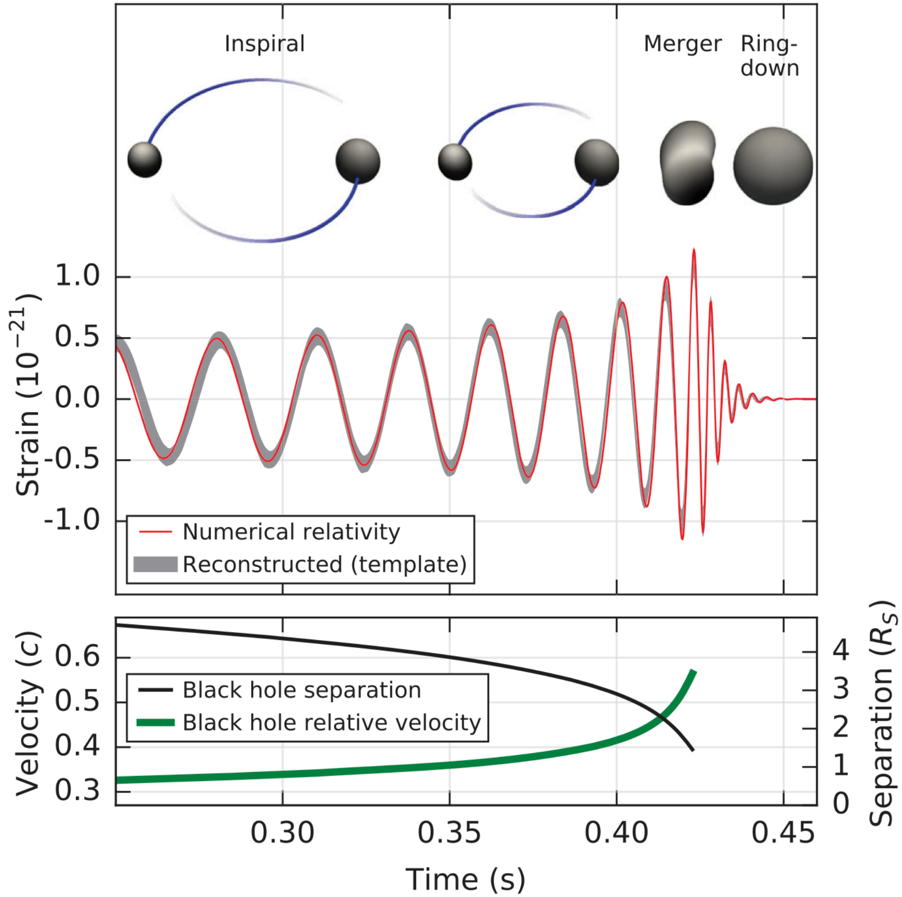
Event horizon

$$r = \frac{2GM}{c^2}$$

Black holes in General Relativity



Compact binary coalescences

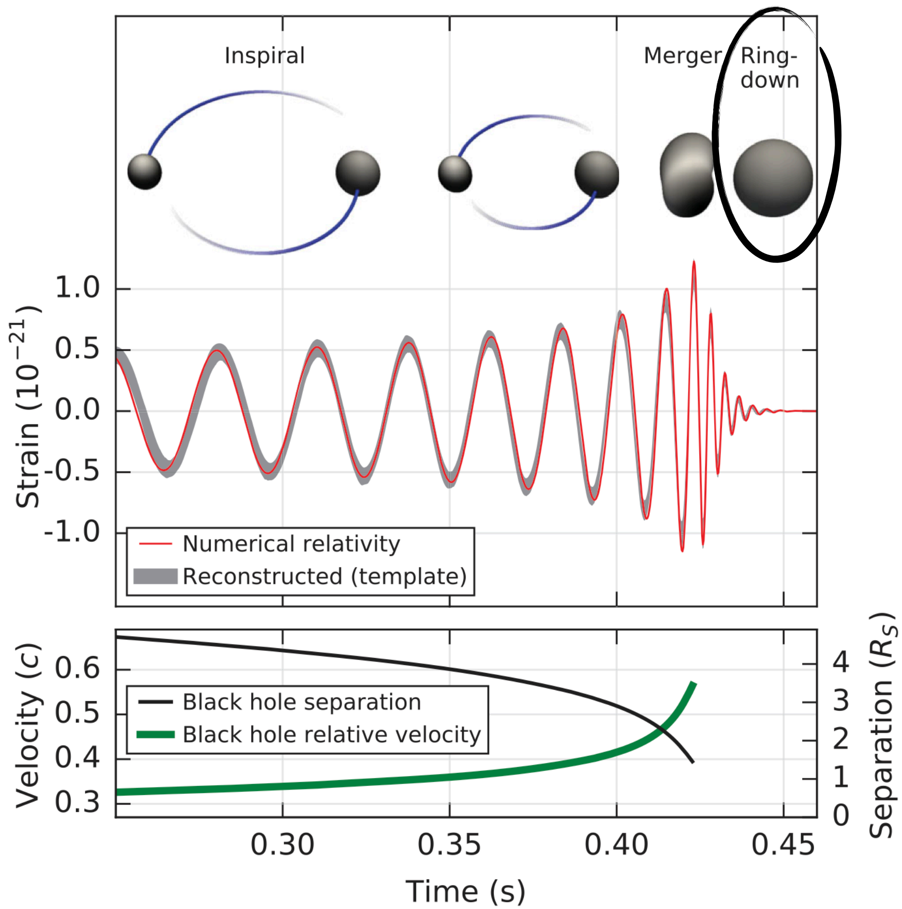


Abbott+, PRL **116**, 061102 (2016)

The signal emitted by the coalescence of compact binaries is characterized by 3 stages:

- Inspiral
- Merger
- Ringdown

Compact binary coalescences



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

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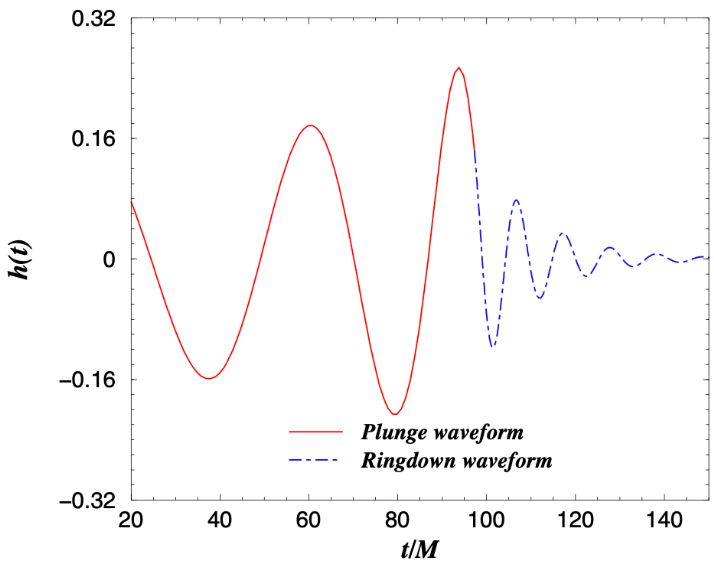
Are we really observing black holes?

Ringdown stage

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

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

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



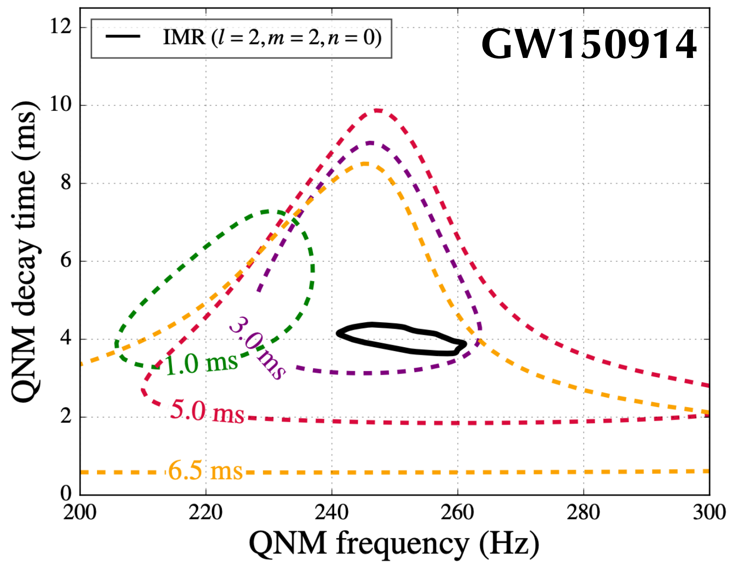
Buonanno, CQG **19**, 1267-1278 (2002)

$$f_{\text{GW|ringdown}} = \frac{\omega_R}{2\pi}$$

$$\tau_{\text{damping}} = -\frac{1}{\omega_I}$$

Ringdown detections

The **fundamental quasi-normal mode** has been observed in several gravitational-wave events and is compatible with black hole remnants.



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

A **test of the black hole paradigm** 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)

- are solutions to general relativity with *dark matter or exotic fields*

  Liebling, Palenzuela, LRR **20**, 5 (2017); Brito+, Phys. Lett. B **752**, 291-295 (2016)

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- are solutions to general relativity with *dark matter or exotic fields*

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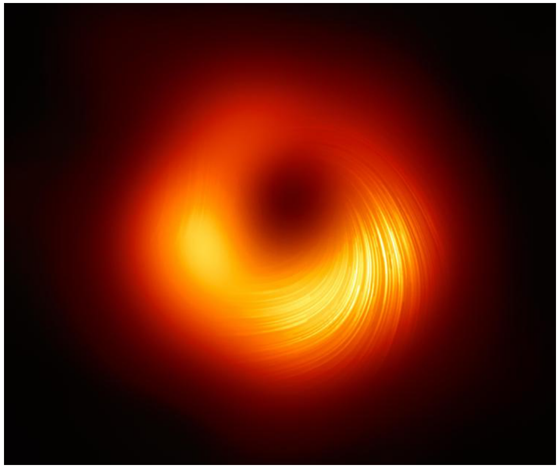
- can mimic black holes in terms of electromagnetic observations

  EHT, ApJ **875**, L5 (2019)

- are not excluded by current gravitational wave observations

  Abbott+, ApJ **896**: L44 (2020); Calderón Bustillo+, PRL **126**, 081101 (2021)



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

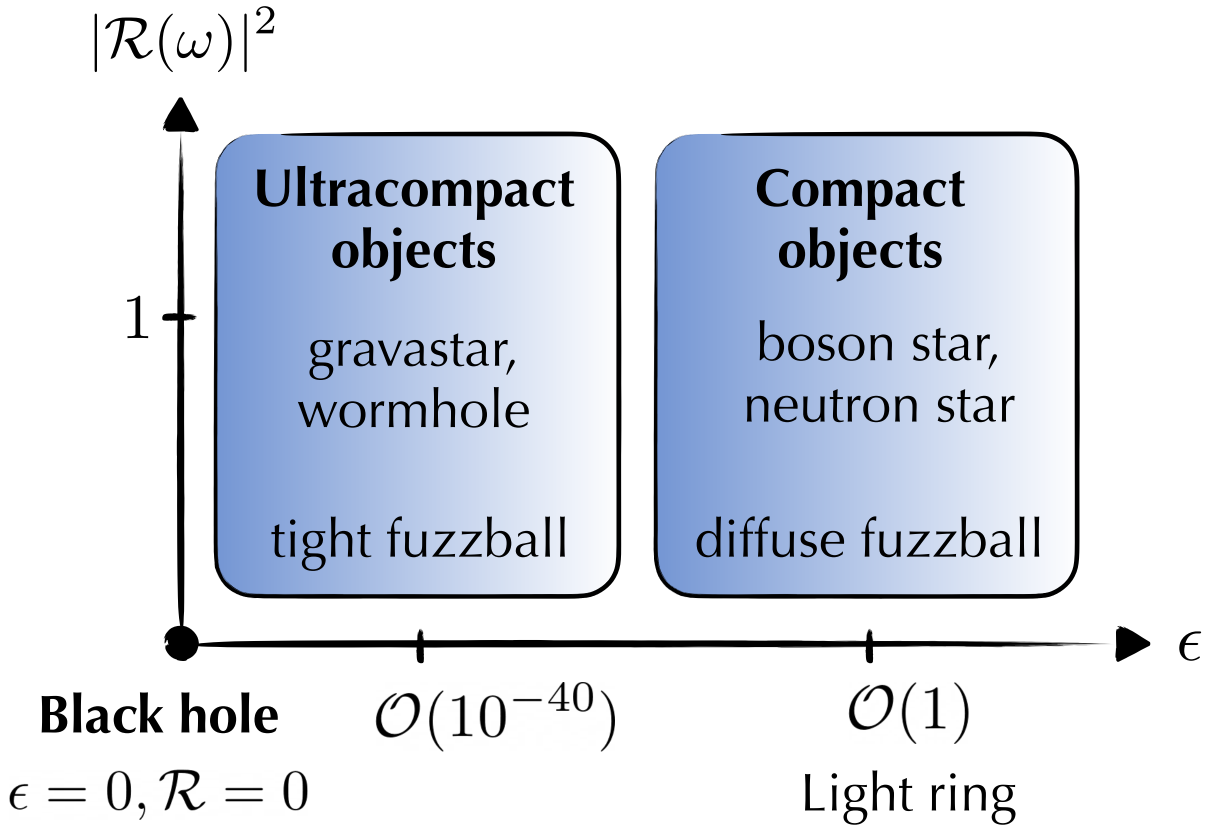
Exotic compact objects

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**



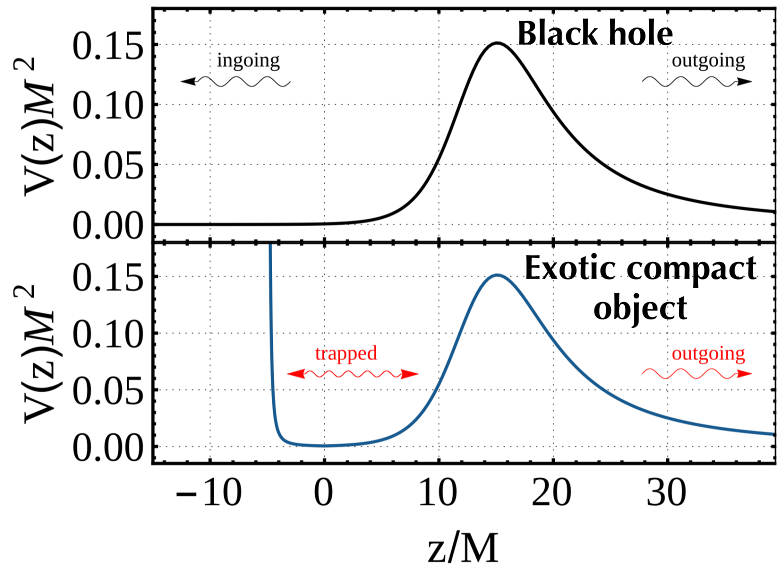
Quasi-normal modes

We can distinguish exotic compact objects from black holes via their quasi-normal mode spectrum.

We consider a gravitational perturbation:

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

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



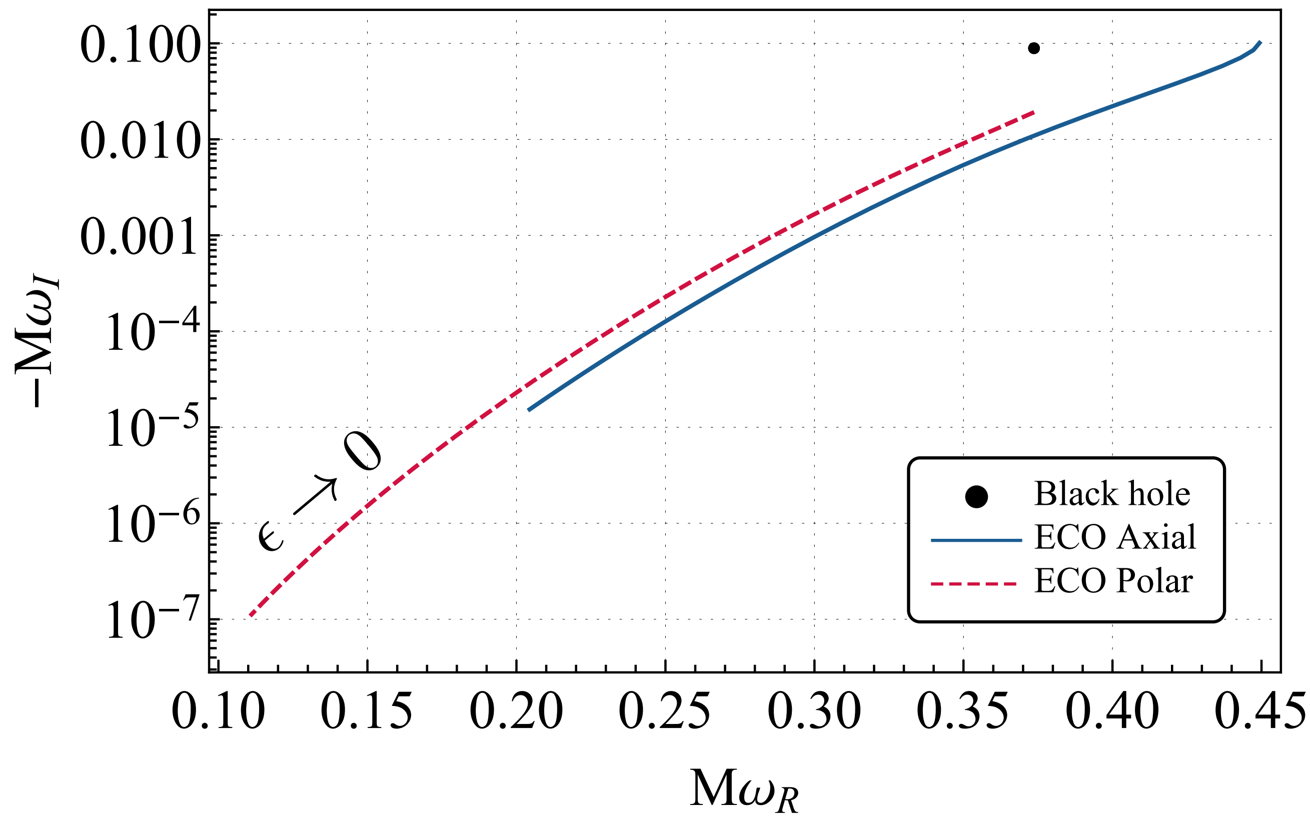
Cardoso, Pani, LRR **22**:4 (2019)

+2 boundary conditions:

Eigenvalue problem for the quasi-normal modes

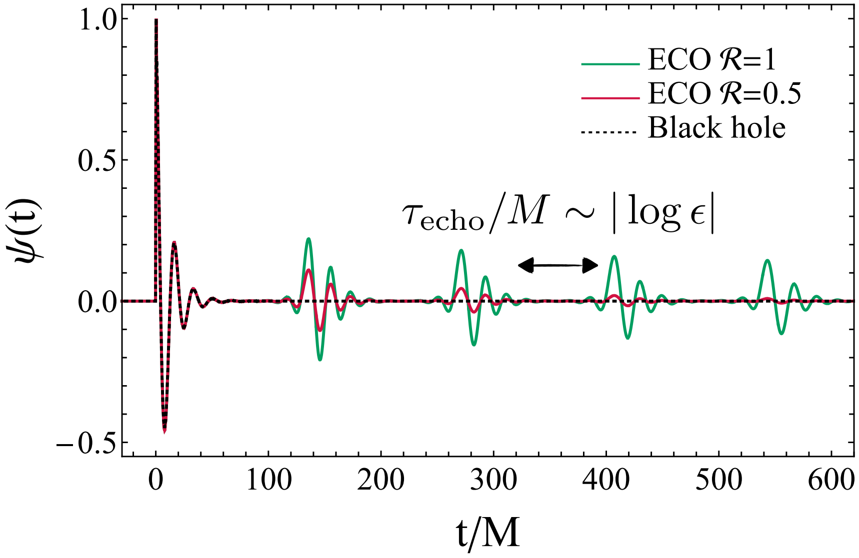
Quasi-normal mode spectrum

For $\epsilon \to 0$, the quasi-normal modes of the compact object deviate from the black hole quasi-normal mode and are **low frequencies**.



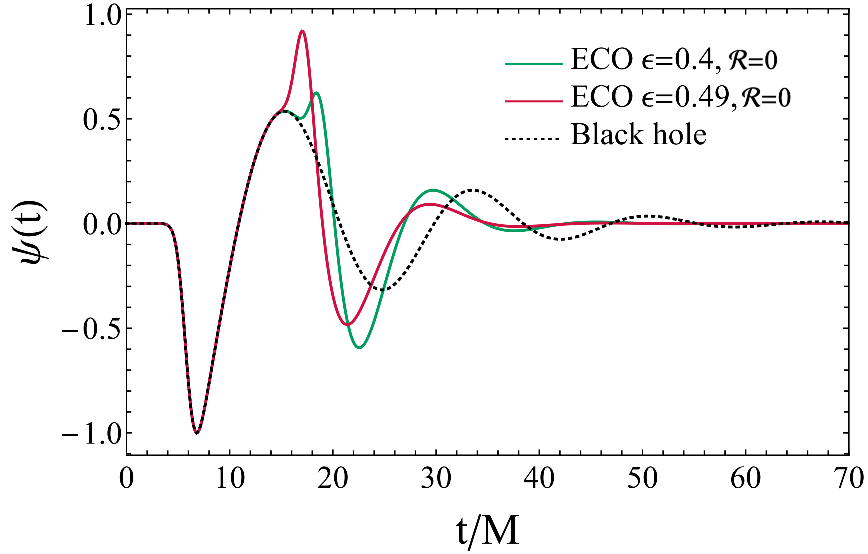
Cardoso, Franzin, Pani, PRL **116**, 171101 (2016); EM, Pani, Ferrari, PRD **96** (2017) 104047; EM, Cardoso, Dolan, Pani, PRD **99** (2019) 064007

Ringdown of exotic compact objects



Ultracompact objects:

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

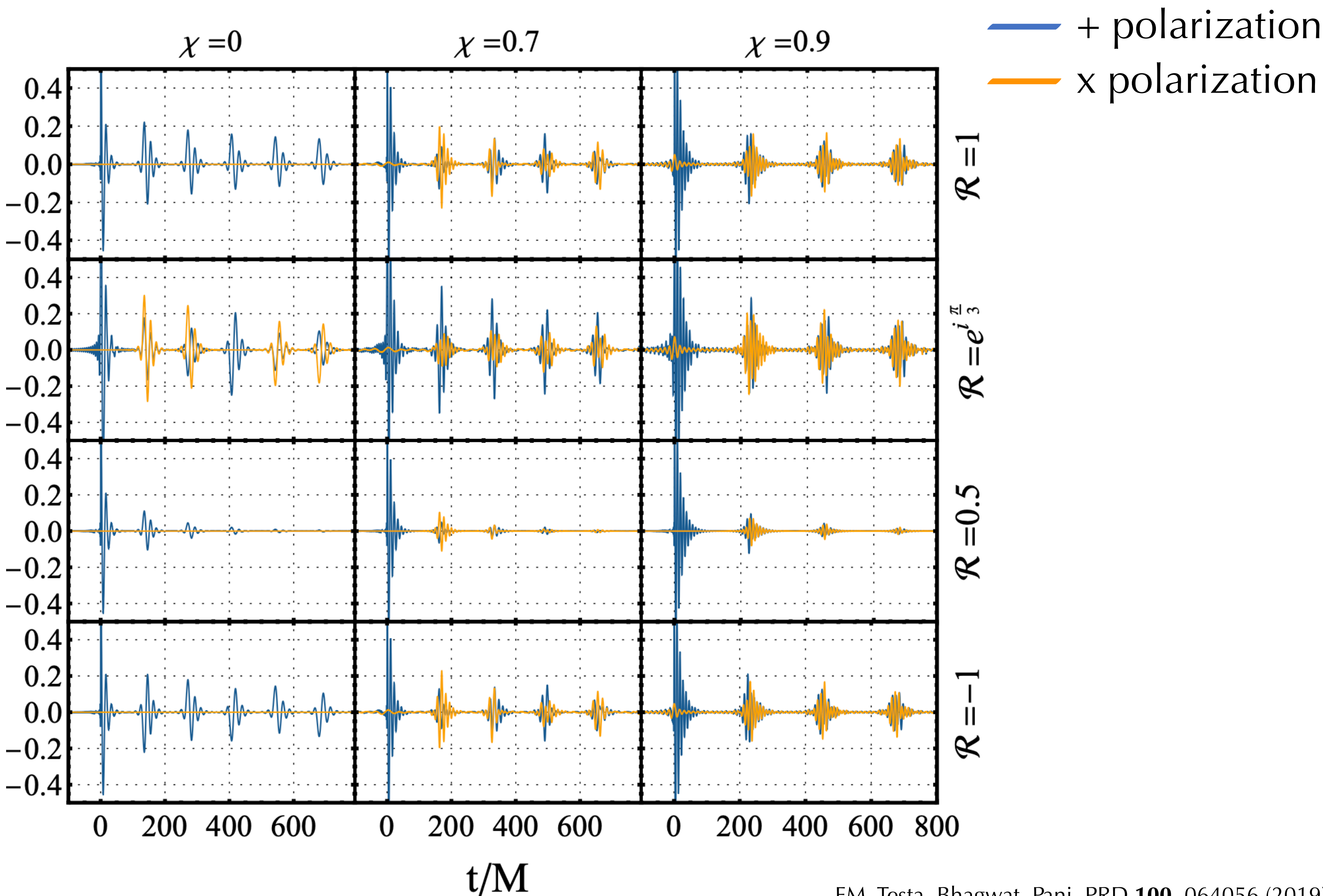


Compact objects:

- Modified prompt ringdown
- No echoes

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

Template for echoes



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

Detectability

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

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

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

  Westerweck+, PRD **97**, 124037 (2018); Tsang+, PRD **101**, 064012 (2020)

- **No evidence for echoes in Ligo/Virgo O3a** Abbott+, arXiv:2010.14529 (2020)

- **Next generation detectors**, i.e., LISA and ET, will allow for unprecedented tests of the black hole paradigm. Berti+, PRD **73** (2006) 064030

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 measurements.
- We derived the **ringdown and the echo signal** for exotic compact objects.
- Simulations of the formation of exotic compact objects need to be developed.
- Analysis of the sources detectable by the next generation detectors is needed.

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Thank you!