GravityShapePisa 2023

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Tests of the nature of black holes with gravitational waves

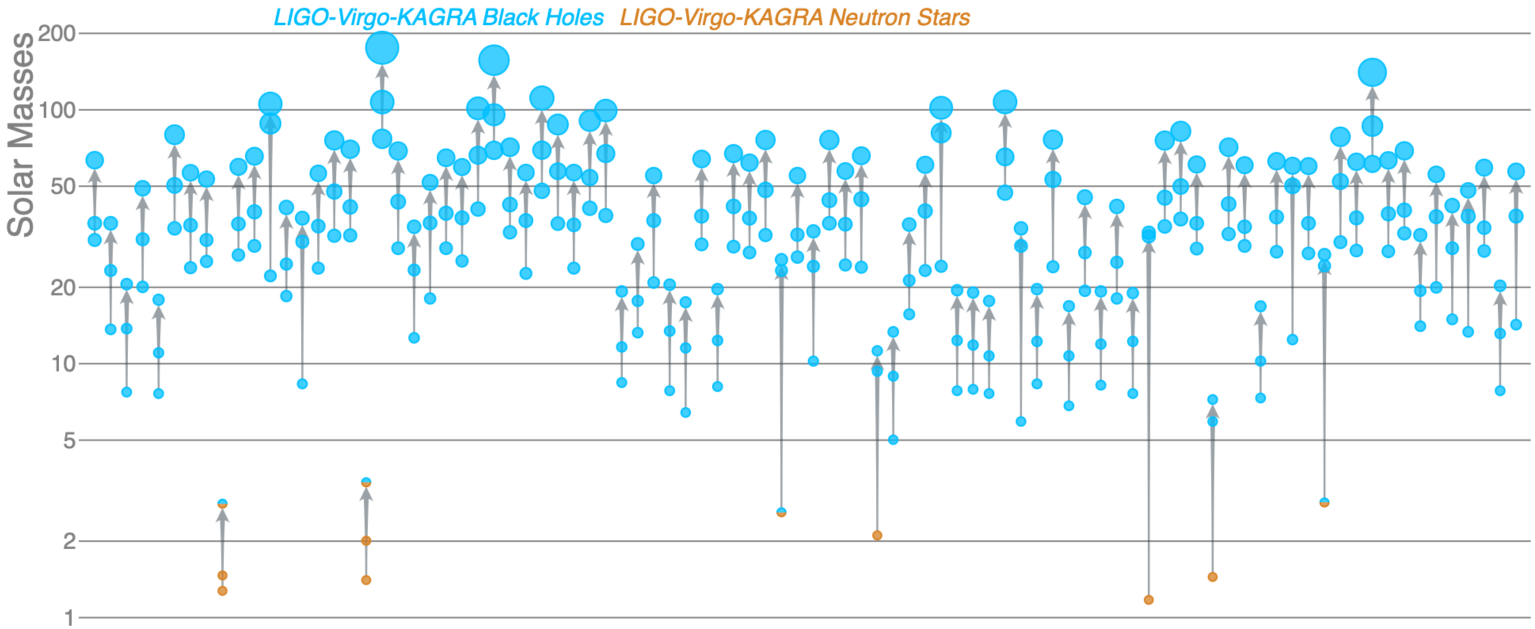
Elisa Maggio

Max Planck Institute for Gravitational Physics,

Albert Einstein Institute, Potsdam

Gravitational-wave detections

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

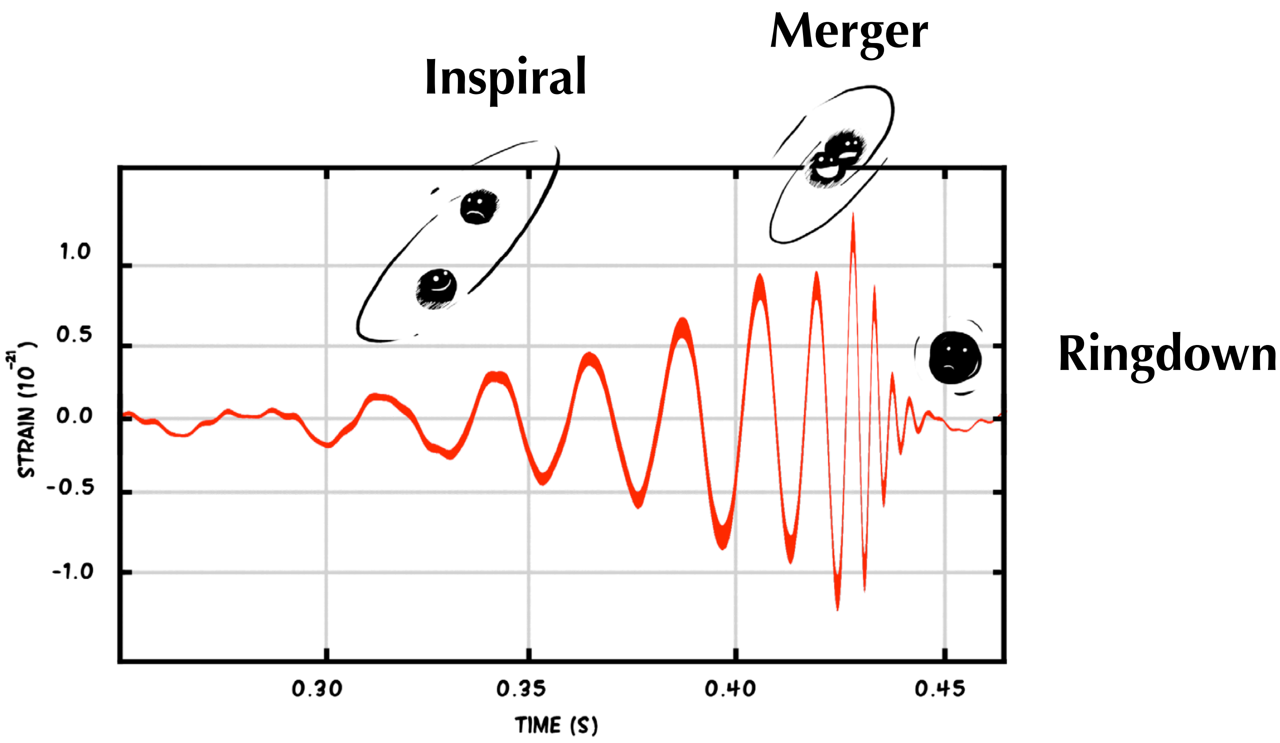


Abbott+, PRX **9**, 031040 (2019); Abbott+, PRX **11**, 021053 (2021); Abbott+, arXiv:2111.03606 (2021)

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

Gravitational waves from binary mergers

The stages of compact binary coalescences are:



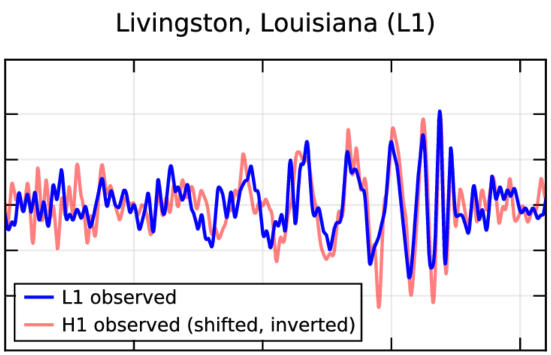
Gravitational waves provide a unique channel for probing general relativity.

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

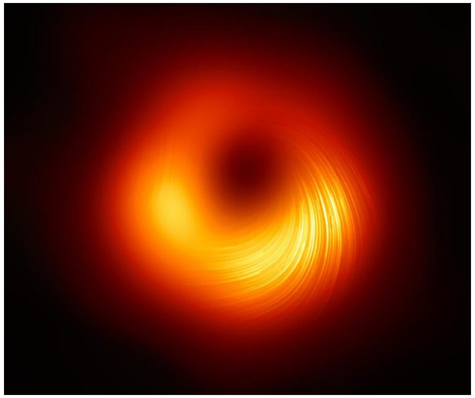
Motivation

Current electromagnetic and gravitational observations are compatible with the **Kerr black holes**. *Why do we need further tests?*

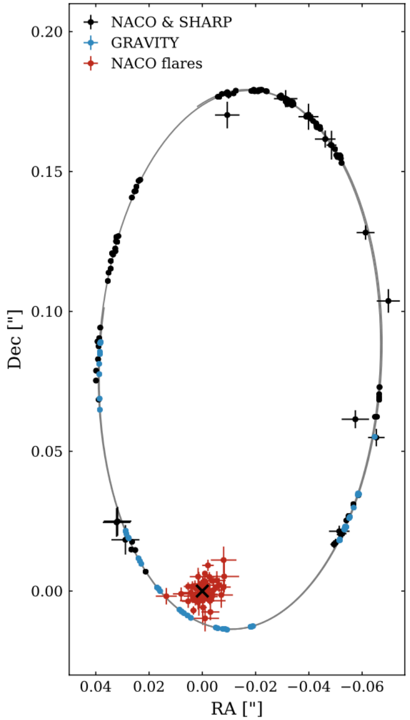
The evidence for black holes is the observation of dark, compact and massive objects.



Abbott+, PRL **116** n.6 (2016) 061102

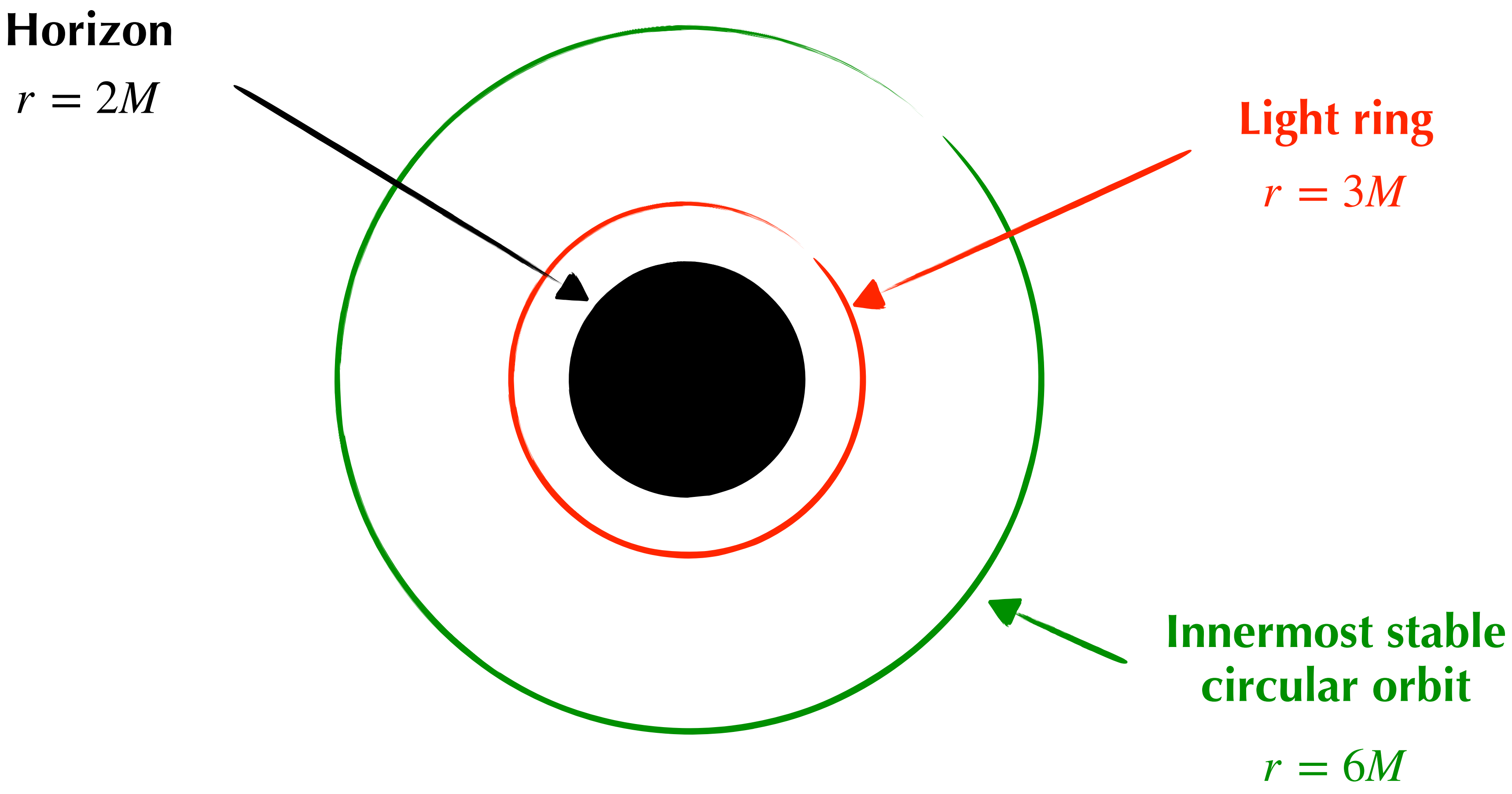


EHT, ApJL **910**, L12 (2021)



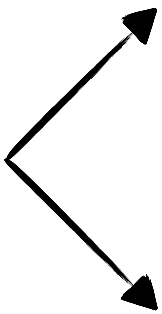
GRAVITY, A&A **636**, L5 (2020)

Black holes in general relativity



Exotic 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)

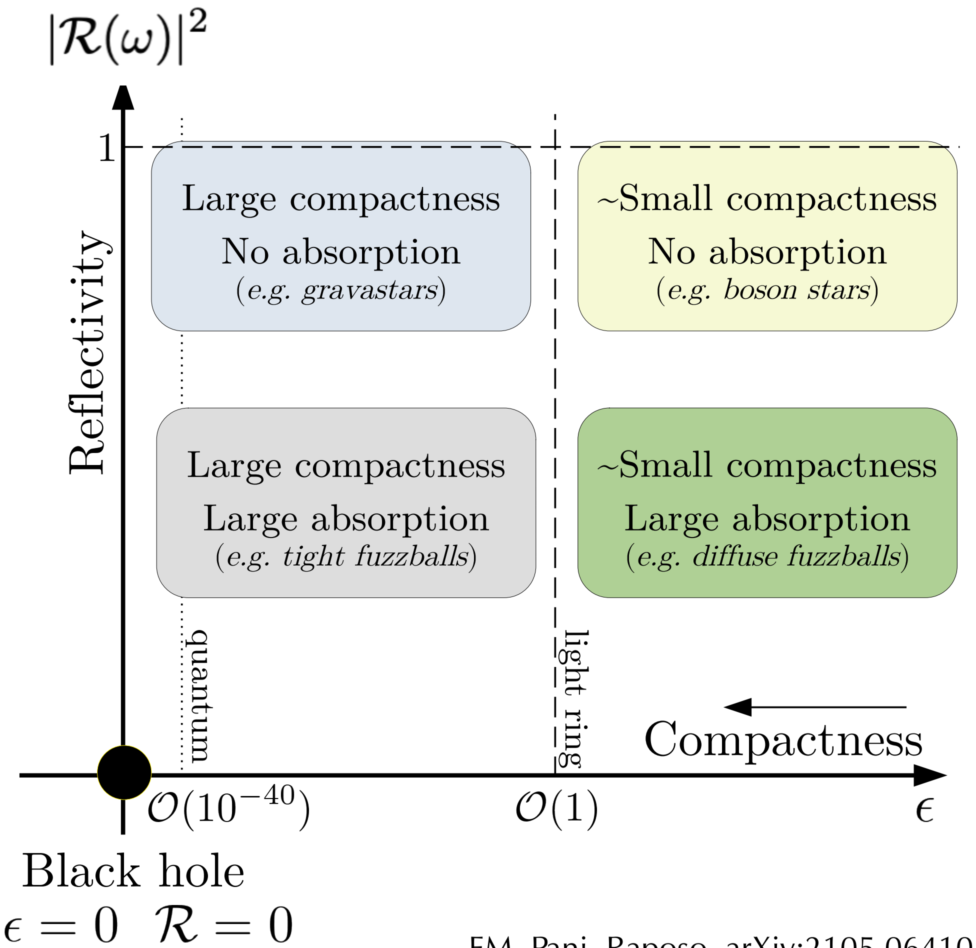
ECOs can mimic black holes and quantify the existence of horizons.

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

A parametrised 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, arXiv:2105.06410 (2021)

Some questions

- What are the signatures of exotic compact objects in the ringdown?

- Are exotic compact objects astrophysically viable?
  [see also Adriano Frattale Mascioli's talk]

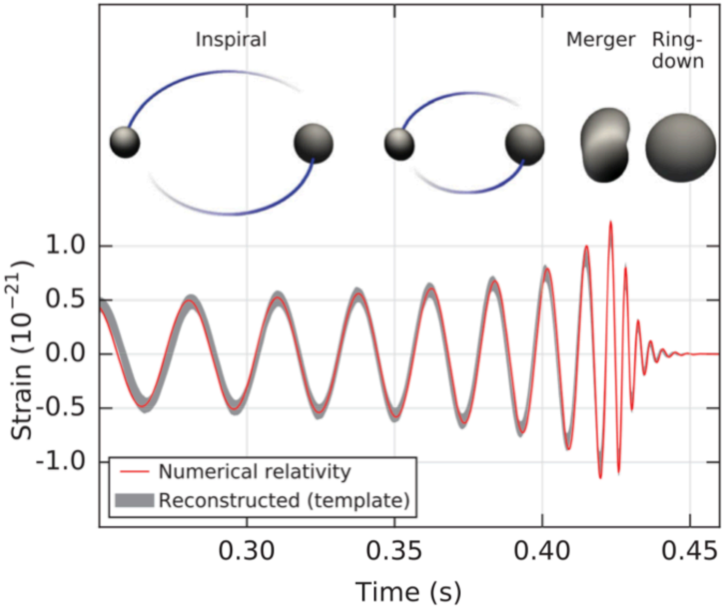
- What are the signatures of exotic compact objects in the inspiral?

Ringdown of exotic compact objects

The ringdown stage

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

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



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

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

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

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

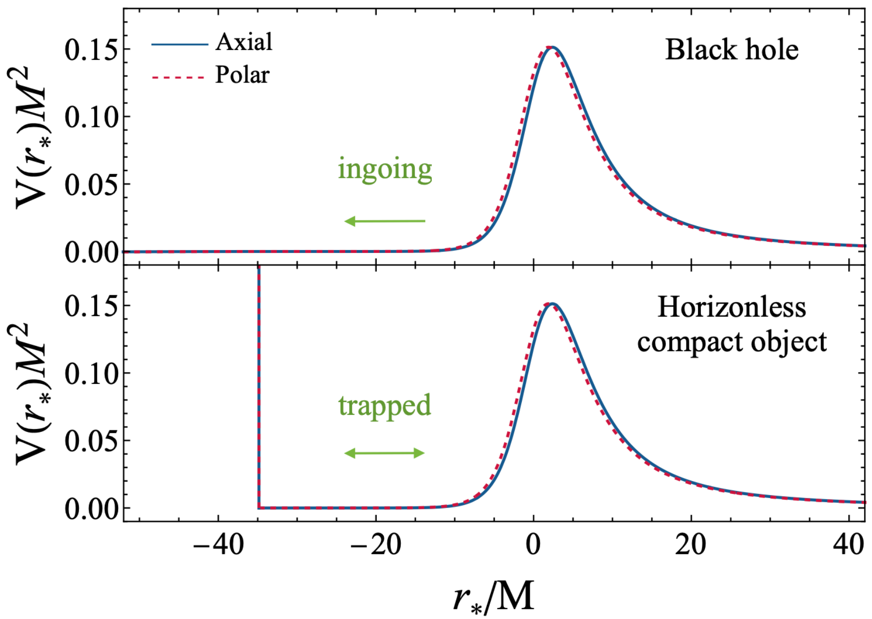
Quasi-normal mode spectrum

We analyse a **static ECO**, which is 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)



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Regge, Wheeler, Phys.Rev. **108** (1957) 1063-1069
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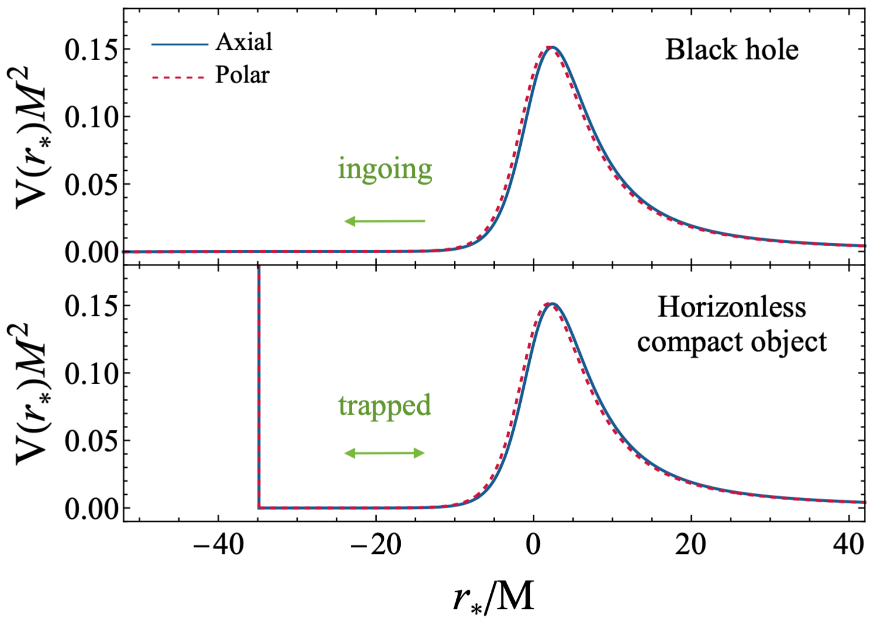
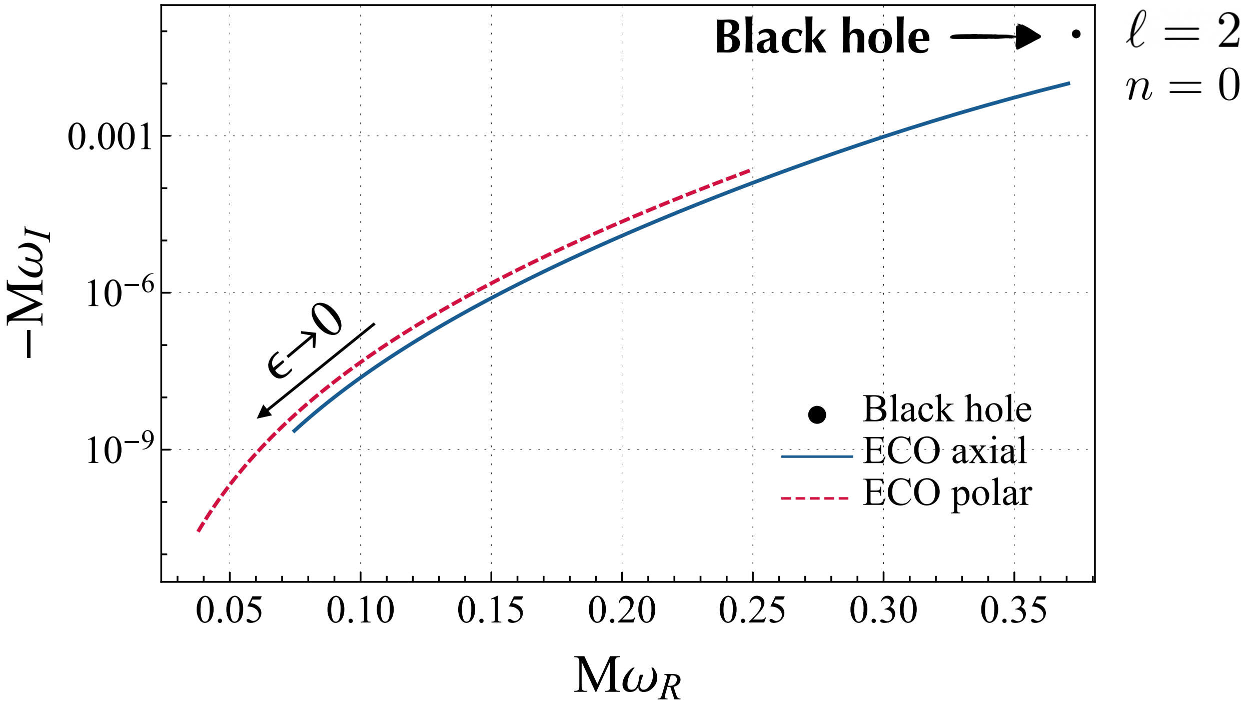


+ 2 boundary conditions:

- At infinity: outgoing waves
- At the ECO radius: $\psi(r_0) \sim e^{-i\omega r_*} + \mathcal{R}(\omega)e^{i\omega r_*}$

Quasi-normal mode spectrum

Static compact object with a perfectly reflecting surface:



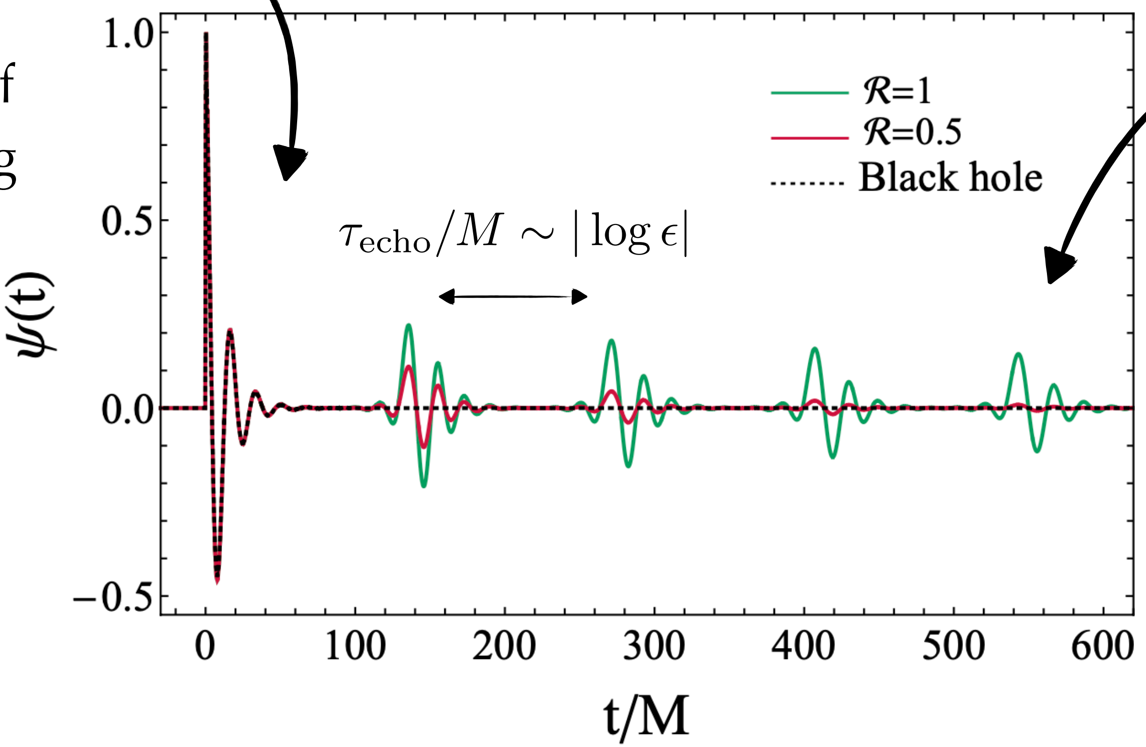
- In ECOs, axial and polar modes are not isospectral.
- For $\epsilon \to 0$, the quasi-normal modes are low-frequencies and long-lived.

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

Ringdown of exotic compact objects

Same prompt ringdown

due to the excitation of the light ring



GW echoes

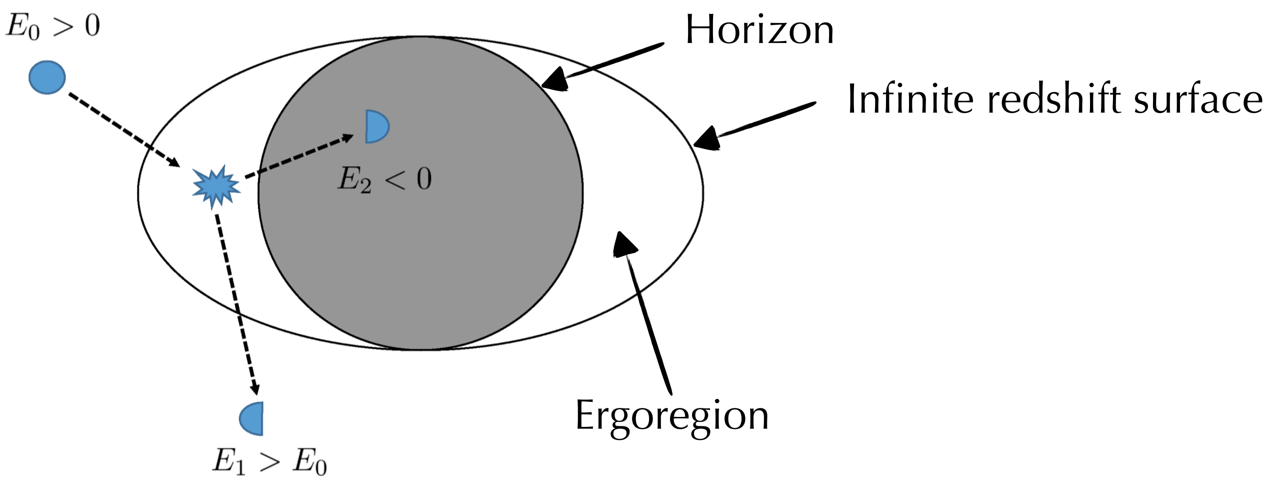
due to trapped modes

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

Astrophysical viability of spinning exotic compact objects

Ergoregion instability

Spinning compact objects with an ergoregion but without a horizon might be unstable due to the ergoregion instability.

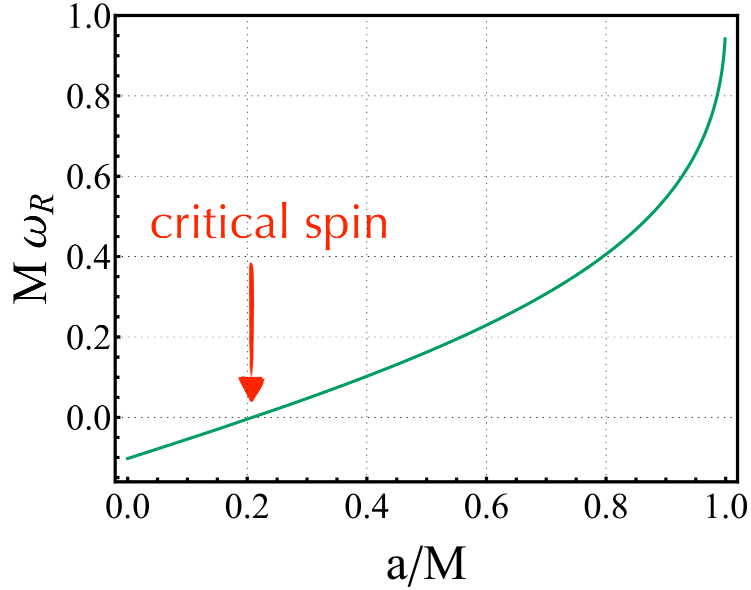


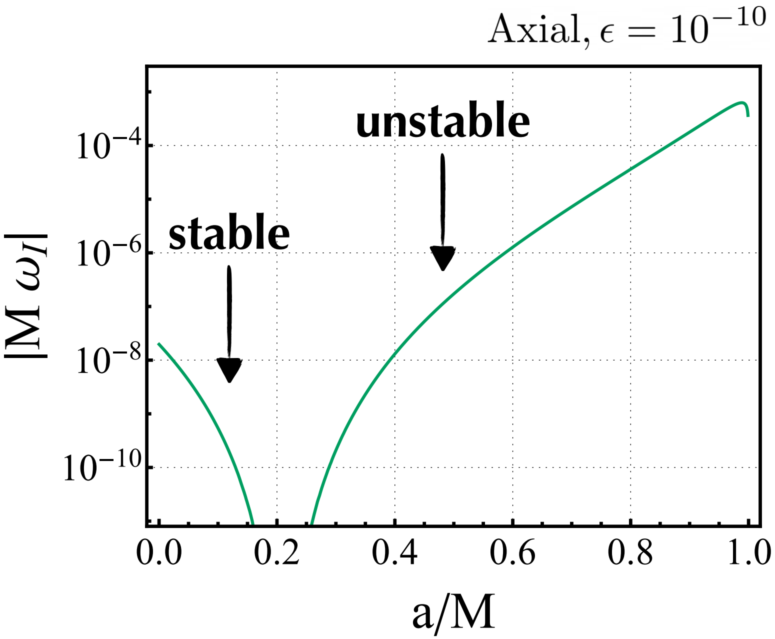
Friedman, Commun. Math. Phys. **63**, 243-255 (1978); Brito+, Lect. Notes Phys. (2020)

If confirmed, the ergoregion instability could provide a strong theoretical argument in favor of the black hole paradigm.

Ergoregion instability

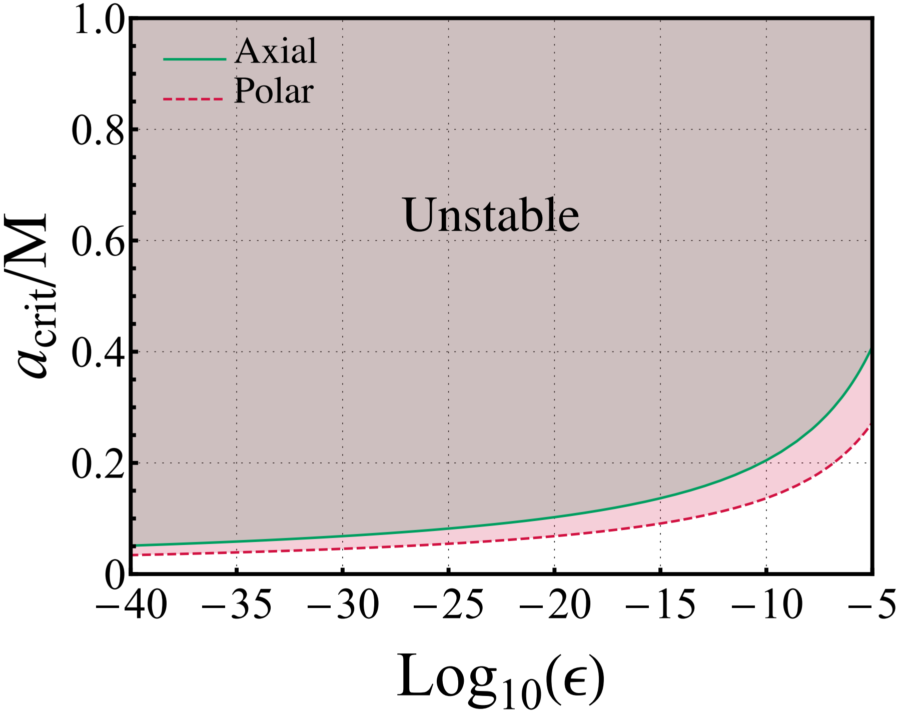
Horizonless compact objects with a **perfectly reflecting surface** are unstable above a critical value of the spin due to the ergoregion instability.





EM, Pani, Ferrari, PRD **96**, 104047 (2017); EM, Cardoso, Dolan, Pani, PRD **99**, 064007 (2019)

Astrophysical impact of the instability



For $\epsilon \to 0$, slowly spinning horizonless compact objects are unstable.

The timescale of instability is short compared to astrophysical timescales:

$$\tau_{\rm instability} \sim 50 \left(\frac{M}{10 M_\odot}\right) \mathrm{s}$$

EM, Cardoso, Dolan, Pani, PRD **99** (2019) 064007

See *Adriano Frattale Mascioli's talk* for searches for ECOs from the spin distribution of compact binary coalescences.

How to quench the ergoregion instability

Partial absorption at the surface makes horizonless compact objects stable.

The minimum absorption rate to quench the instability is the maximum amplification factor of superradiance of black holes.

Spin	**Absorption**
0.7	0.3%
0.9	6%
any	~60%

EM, Cardoso, Dolan, Pani, PRD **99**, 064007 (2019)

Inspiral of exotic compact objects

Inspiral-based tests of ECOs

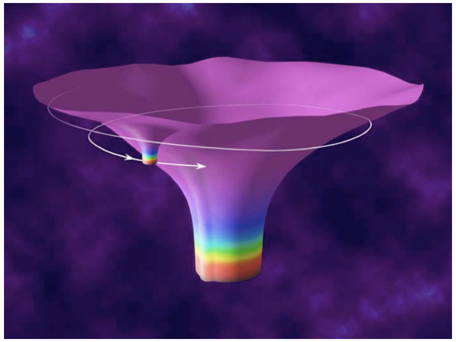
- For black holes, energy absorption by the horizon is responsible for **tidal heating** in a binary.

  For ECOs, the energy flux across the surface depends on the reflectivity of the object: Datta+, PRD **101**, 044004 (2020)

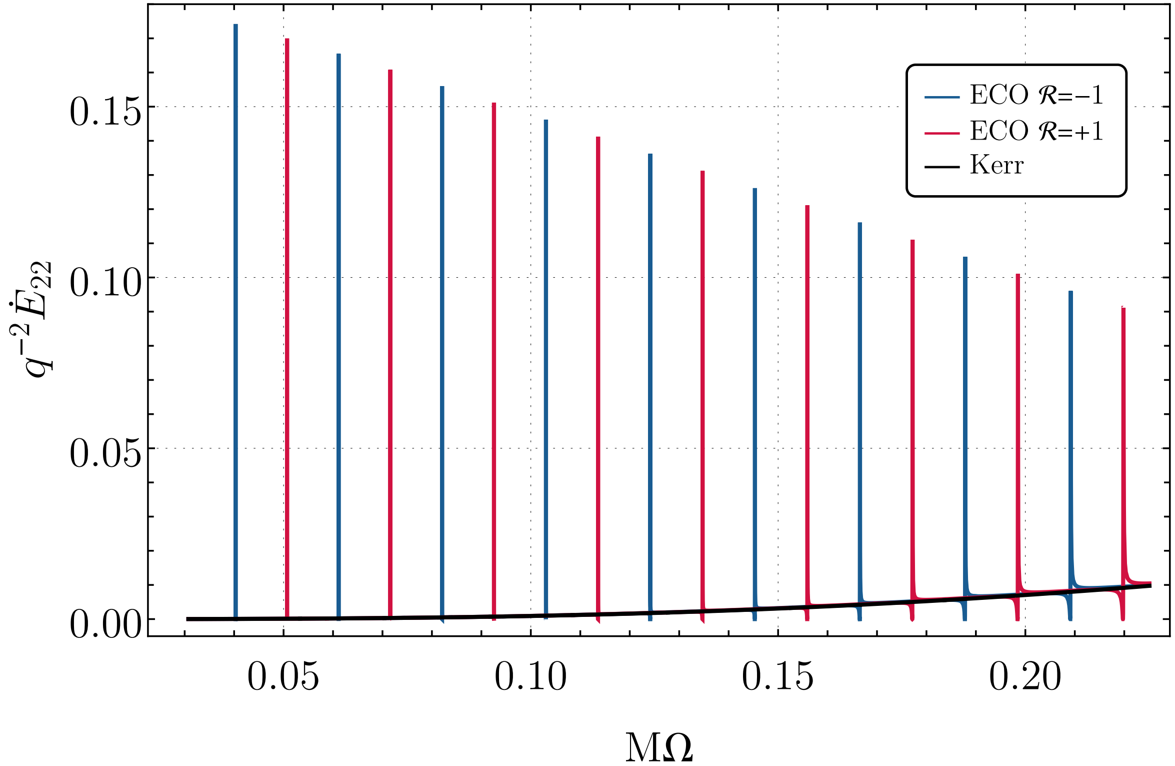
$$\dot{E}_{\mathrm{ECO}} = \left(1 - |\mathcal{R}|^2\right) \dot{E}_H$$

- **Low-frequency resonances** can be excited when the orbital frequency matches the ECO quasi-normal mode frequencies. Cardoso+, PRD **100**, 084046 (2019)

Extreme mass-ratio inspirals



We analyze the inspiral of a stellar-mass object around a supermassive ECO in circular and equatorial orbits.

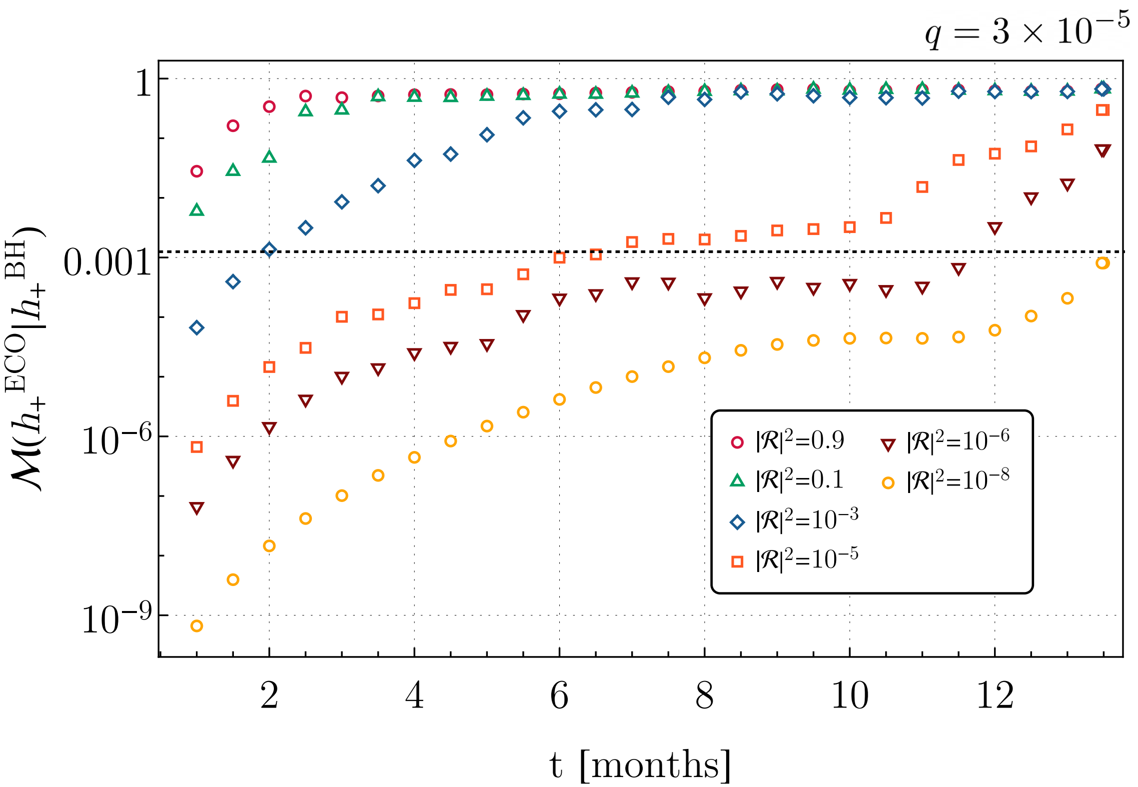


The energy flux is resonantly excited when the orbital frequency matches the quasi-normal modes of the central ECO.

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

Waveform mismatch

We compute the **mismatch** between the waveforms with a central black hole and a horizonless compact object.



Detectability threshold for LISA

In one year of observation, LISA can measure the reflectivity of the central object up to $|\mathcal{R}|^2 = \mathcal{O}(10^{-8})$.

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

Tidal deformability

The gravitational field of an object in a binary acts as a tidal field on its companion, inducing a tidal deformation.

The tidal Love numbers are:

$$k_{\ell m}(\omega) = \frac{1}{2}\mathrm{Re}F_{\ell m}(\omega)$$

where $F_{\ell m}(\omega)$ is the tidal response, which is computed from the Weyl scalar:

$$\Psi_4 \propto \int d\omega \sum_{\ell m} r^{\ell-2}\left[1 + F_{\ell m}(\omega)\left(\frac{r_0}{r}\right)^{2\ell+1}\right] {}_{-2}Y_{\ell m}$$

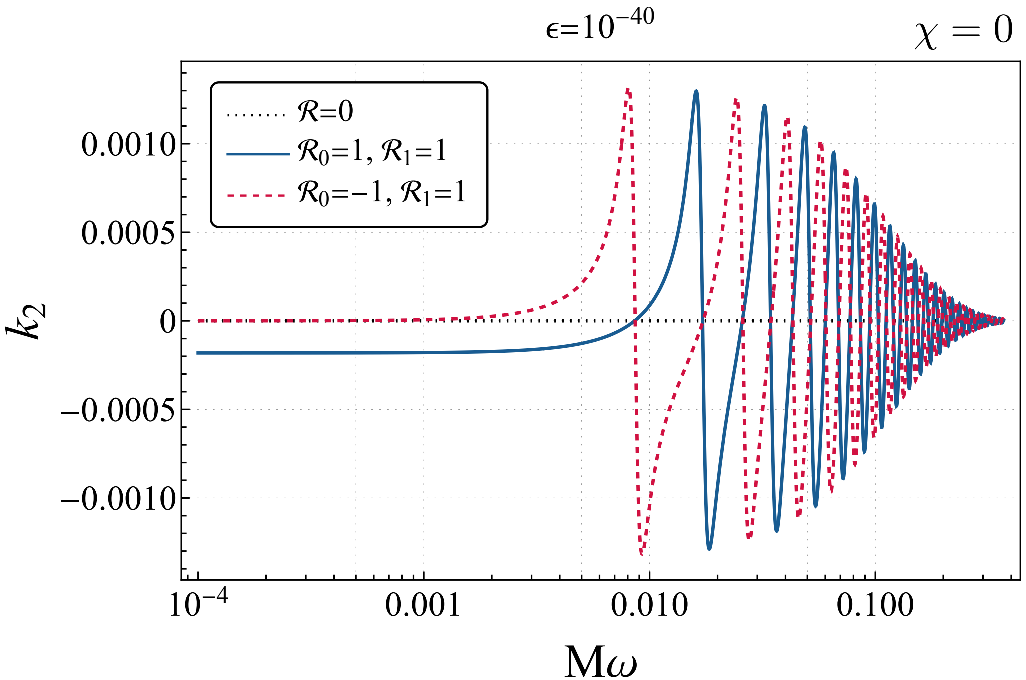
Chia, PRD **104**, 024013 (2021)

Tidal Love numbers

- The tidal Love numbers of black holes are vanishing. Chia, PRD **104**, 024013 (2021)

- Its violation is a smoking gun for deviations from the black-hole paradigm.

Cardoso+, PRD **95**, 084014 (2017); Maselli+, PRL **120**, 081101 (2018)



$$\mathcal{R} = \mathcal{R}_0 + i\omega M \mathcal{R}_1$$

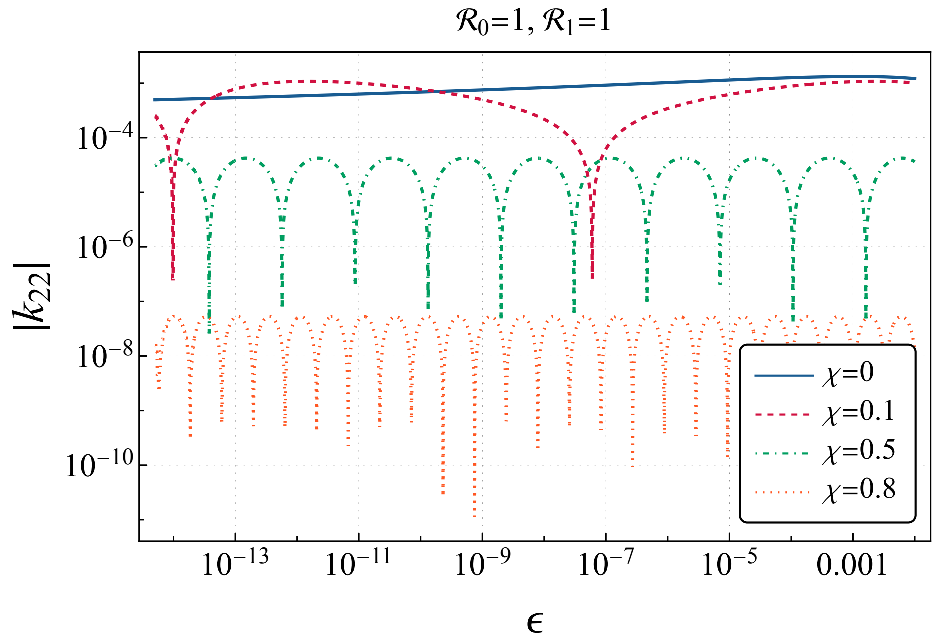
In the zero-frequency limit, the tidal Love number vanish for any reflectivity except for $\mathcal{R}_0 = 1$:

$$k_2 = \frac{1}{60 \log \epsilon}$$

Chakraborty, EM, Silvestrini, Pani, arXiv:2310.06023 (2023)

Tidal Love numbers

For **rotating compact objects**, the tidal Love number decreases when the spin increases or the reflectivity decreases.



Fast-rotating objects are difficult to deform by applying external tidal forces.

Chakraborty, EM, Silvestrini, Pani, arXiv:2310.06023 (2023)

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.
- Develop a framework to translate parametrised constraints on general relativity to horizonless compact objects.
- Performance of accurate statistical analyses for the detectability of horizonless sources by next-generation detectors.