XIII ET Symposium

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Searches for near-horizon structures and echoes

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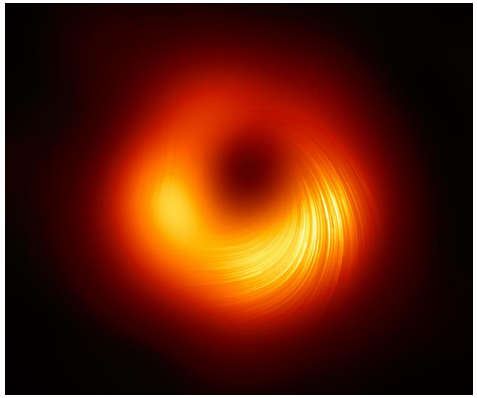
MARIE CURIE ACTIONS

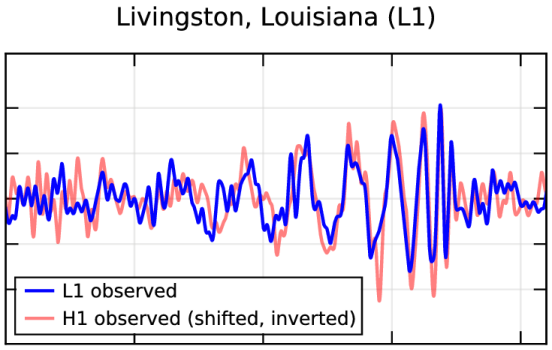
Motivation

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

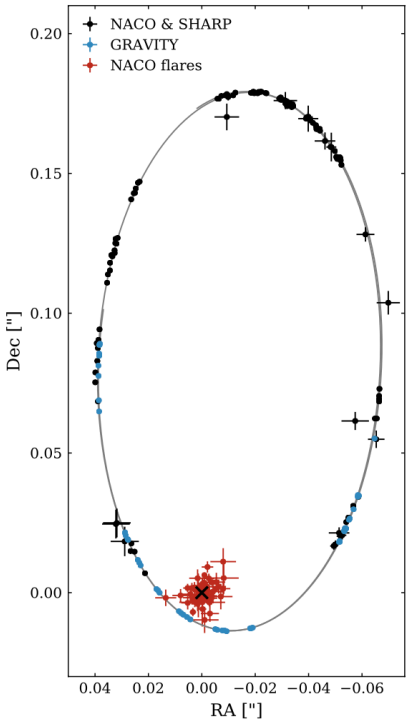
The evidence for black holes is the observation of dark, compact and massive objects.



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



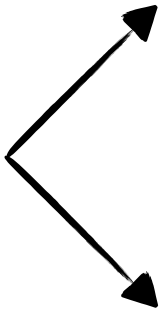
Abbott+, PRL **116** n.6 (2016) 061102



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

Near-horizon structures

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)

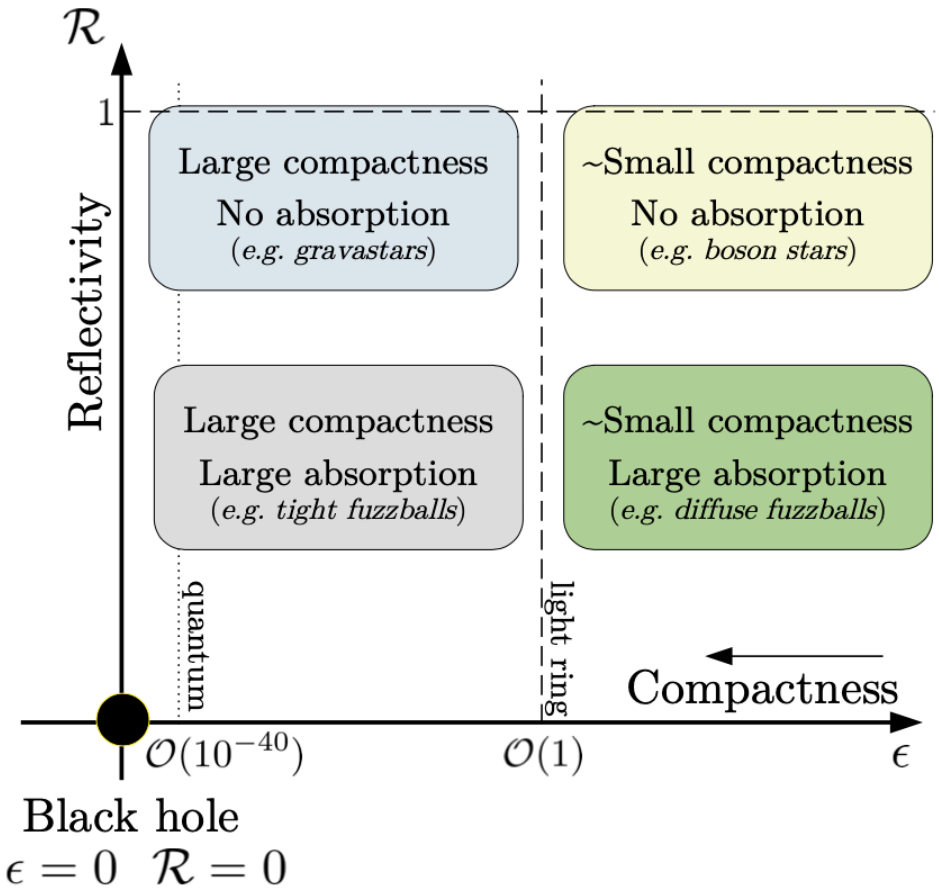
Horizonless compact objects can mimic black holes and quantify the existence of horizons.

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

A 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**
  that differs from the totally absorbing black hole case

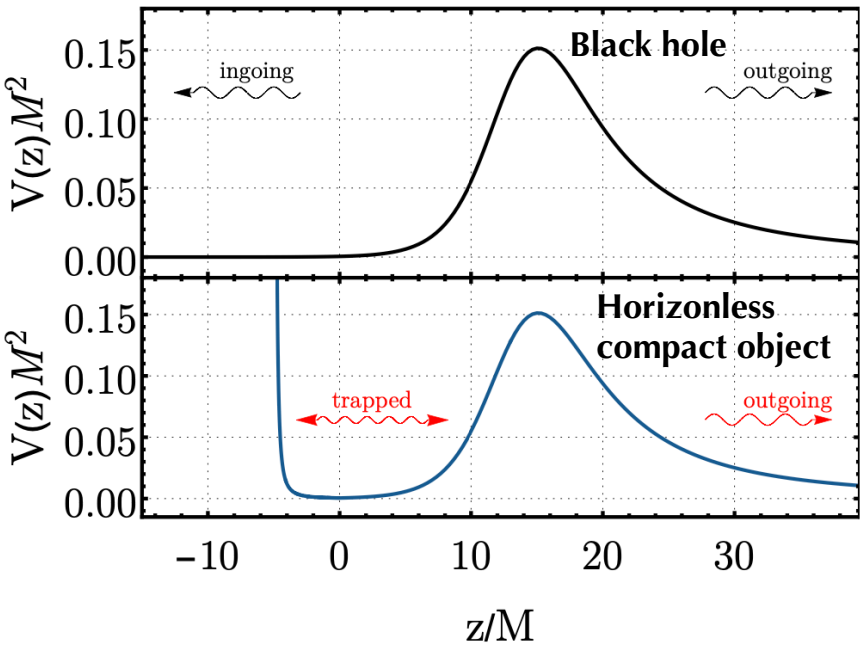


EM, Pani, Raposo, Handbook for GW Astronomy, Springer (2021)

The ringdown

The ringdown stage is dominated by the **quasi-normal modes** of the remnant which describe the response of the compact object to a perturbation.

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



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

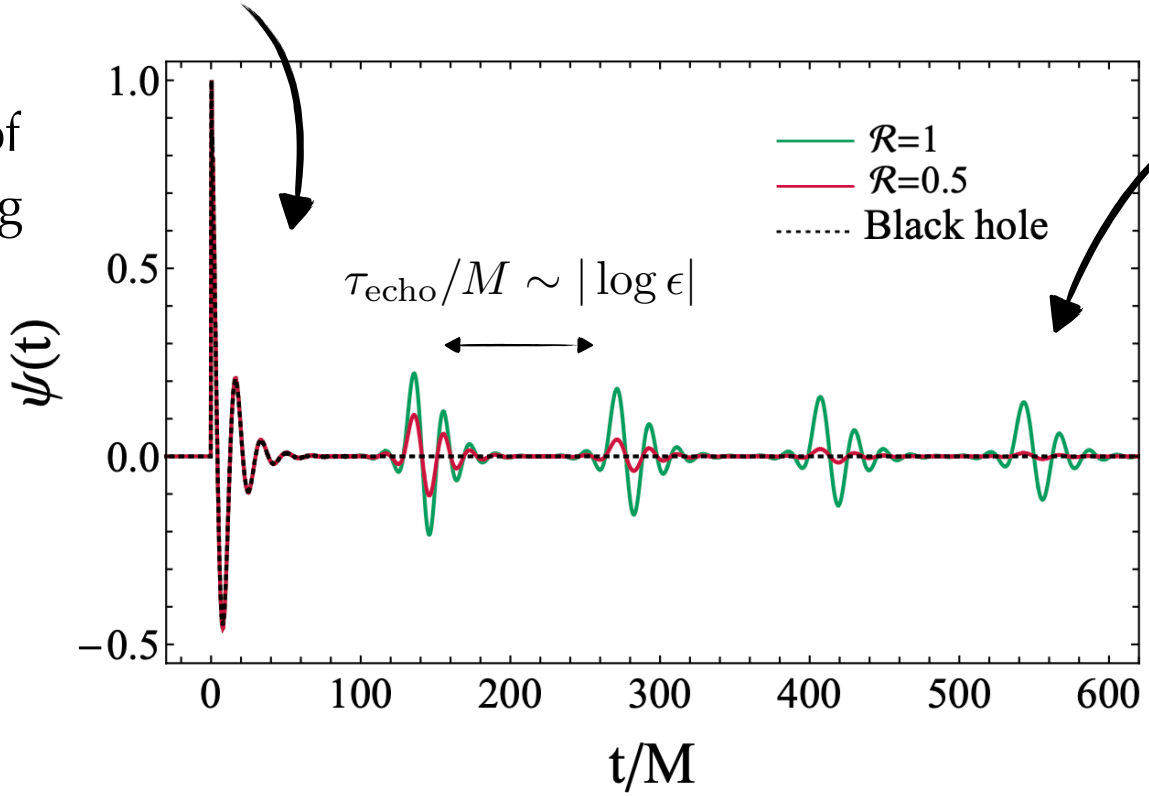
Teukolsky, Press, ApJ **193** (1974) 443-461

No horizon → Trapped modes → Low- frequency quasi-normal modes

Ringdown of horizonless 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)

Searches for GW echoes

- A tentative evidence for echoes in GWTC-1 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 consistent with noise

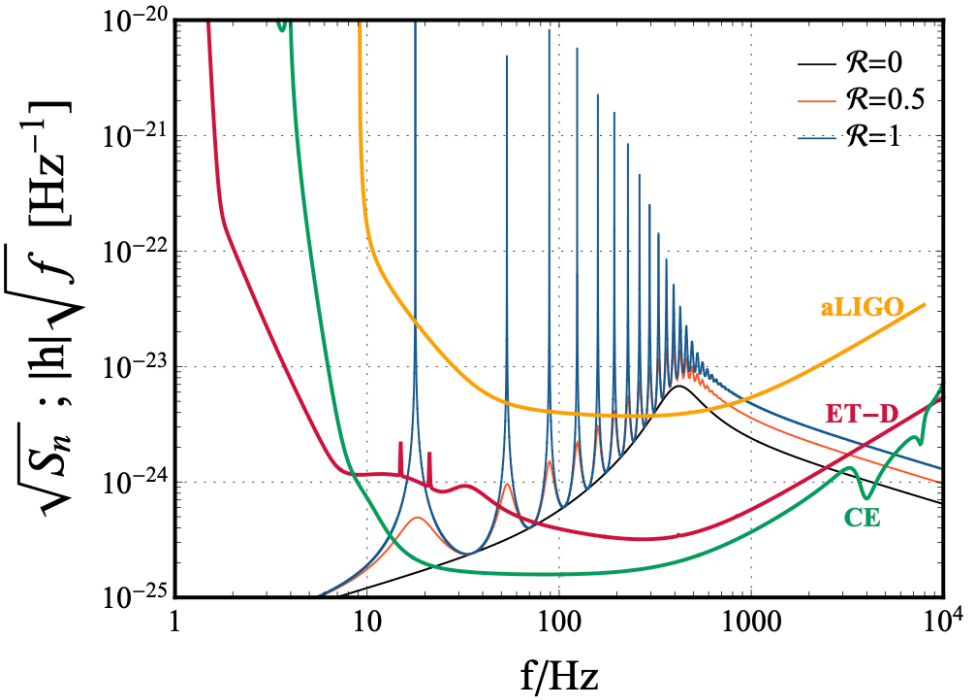
  Westerweck+, PRD **97**, 124037 (2018); Nielsen+, PRD **99**, 104012 (2019); Uchikata+, PRD **100**, 062006 (2019); Lo+, PRD **99**, 084052 (2019); Tsang+, PRD **101**, 064012 (2020)

- No evidence for echoes in GWTC-2 and GWTC-3 data

  Abbott+, PRD **103** (2021) 12, 122002; Abbott+, arXiv:2112.06861 (2021)

Prospects with next-generation detectors

In the frequency domain, **low-frequency resonances** are excited at the quasi-normal modes of the horizonless compact object.



$M = 30 M_\odot$

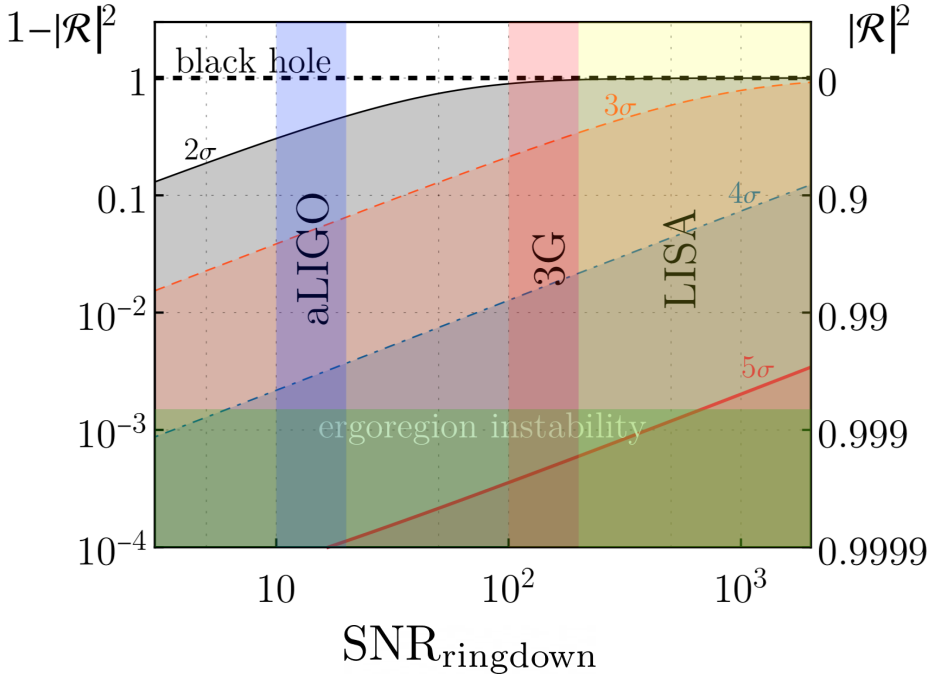
$D = 400$ Mpc

- Models with $\mathcal{R} \approx 1$ can be detected or ruled out by aLIGO/Virgo
- ET/CE can detect models with generic reflectivities

Testa, Pani, PRD **98** (2018) 4, 044018

Prospects with next-generation detectors

With a Fisher analysis we can assess the **detectability of the reflectivity** of compact objects as a function of the signal-to-noise ratio in the ringdown.



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

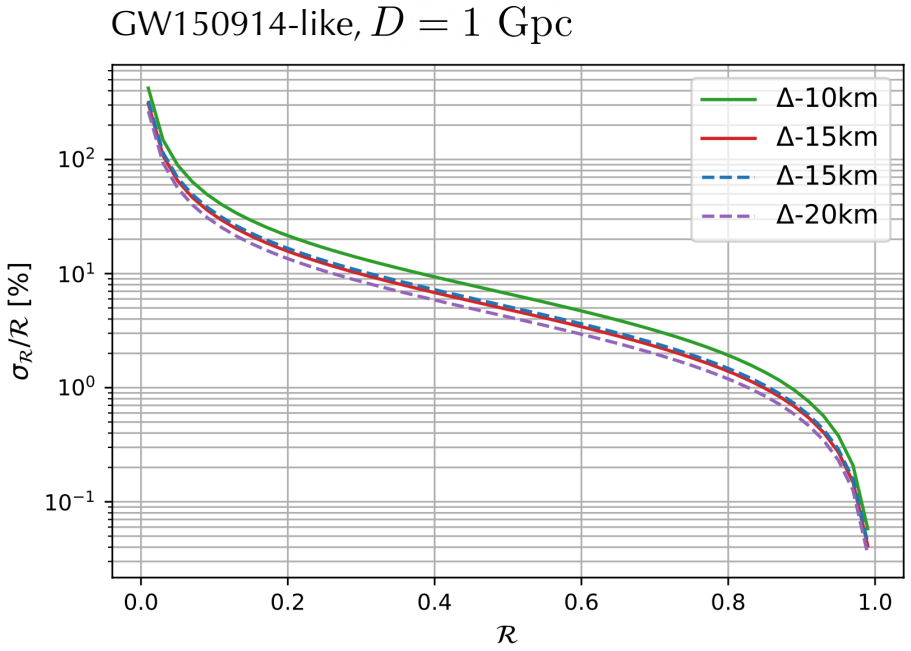
Excluding or detecting echoes for models with $|\mathcal{R}|^2 < 1$ requires:

$$\mathrm{SNR}_{\mathrm{ringdown}} \gtrsim 100$$

which will be achieved by ET/CE.

Science with ET: a comparison of designs

With a Fisher analysis we derived the fractional percentage **errors on the reflectivity of compact objects** for different ET configurations.



	$\sigma_{\mathcal{R}}/\mathcal{R}$ [%]		
	$\mathcal{R} = 0.01$	$\mathcal{R} = 0.5$	$\mathcal{R} = 0.99$
Δ-10 km	422	7	0.06
Δ-15 km	308	5	0.04
2L-15 km	326	5	0.04
2L-20 km	265	4	0.03

The accuracy on the reflectivity is affected by a factor of ~2 between the 10 km and 20 km designs due to the arm length configurations.

Branchesi+, EM, Pacilio, Pani, arXiv:2303.15923 (2023)

Conclusions and future prospects

- Third-generation detectors will allow us to perform unprecedented tests of the black hole paradigm.

- As a future prospect, accurate Bayesian analyses of the detectability of GW echoes need to be performed.

- Open challenges in the modeling:
  - How loud are GW echoes?
  - Which initial conditions describe the ringdown of a horizonless compact object when numerical simulation of inspiral-merger-ringdown waveforms in alternative scenarios are not available/limited?

Micchi+, PRD **103** (2021) 044028; Annulli+, CQG **39** (2022) 105005; Xin+, PRD **104** (2021) 104005; Ma+, PRD **105** (2022) 104007

- Open challenges in the searches:

  Are matched-filtered or unmodelled searches more suitable to search for GW echoes?