Cortona Young

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Gravitational wave signatures of exotic compact objects

Elisa Maggio

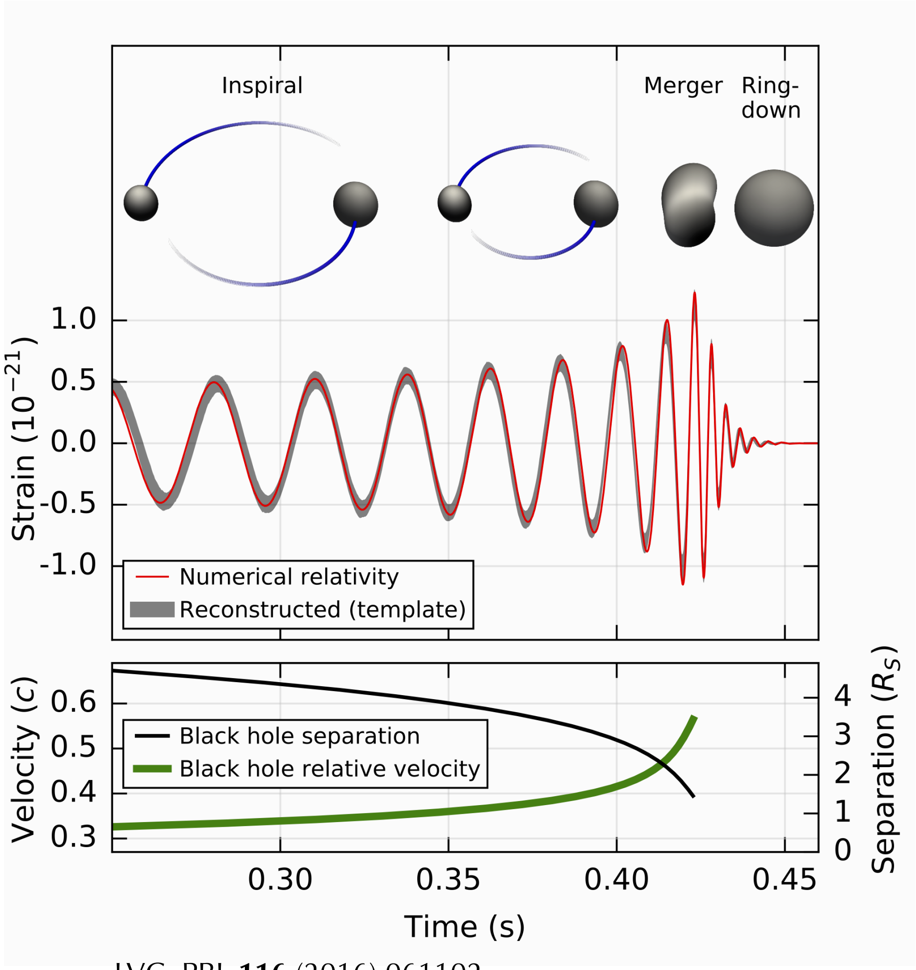
Sapienza University of Rome

Istituto Nazionale di Fisica Nucleare

Outline

- Gravitational waves as probes of strong gravity
- Exotic compact objects
- Ergoregion instability
- Gravitational wave echoes

Compact binary coalescence

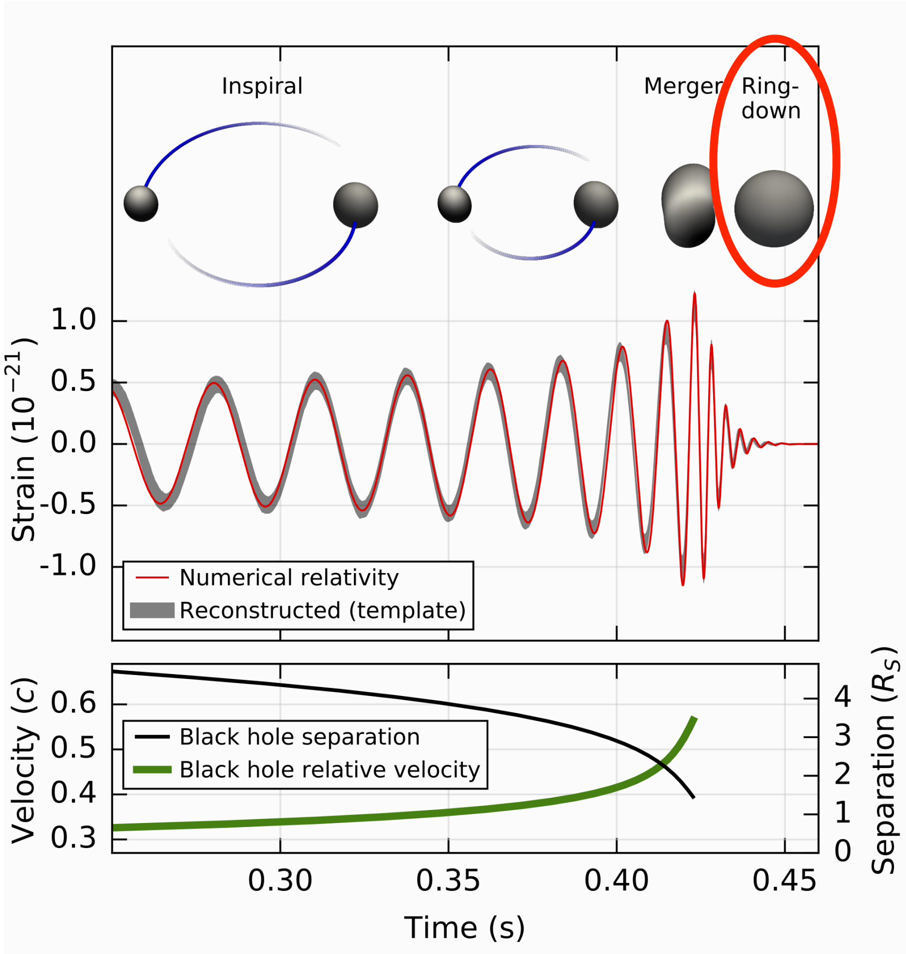


LVC, PRL **116** (2016) 061102

On September 14th 2015 the first gravitational wave from a compact binary merger was detected.

Three stages:

- Inspiral
- Merger
- Ringdown



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

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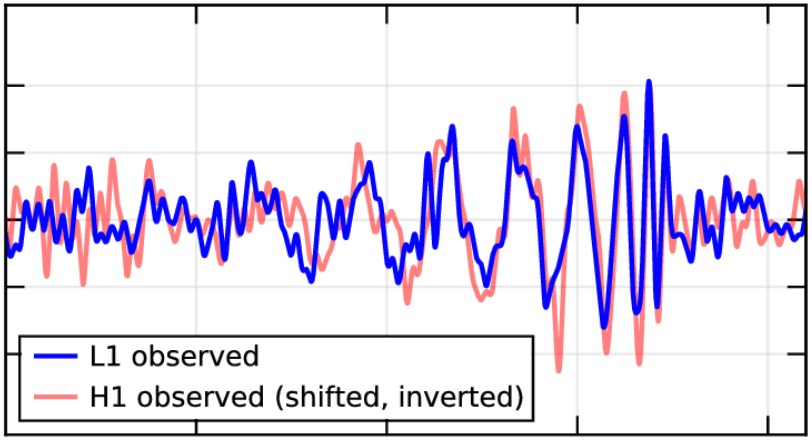
Ringdown stage

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

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

The signal is a sum of exponentially damped sinusoids:

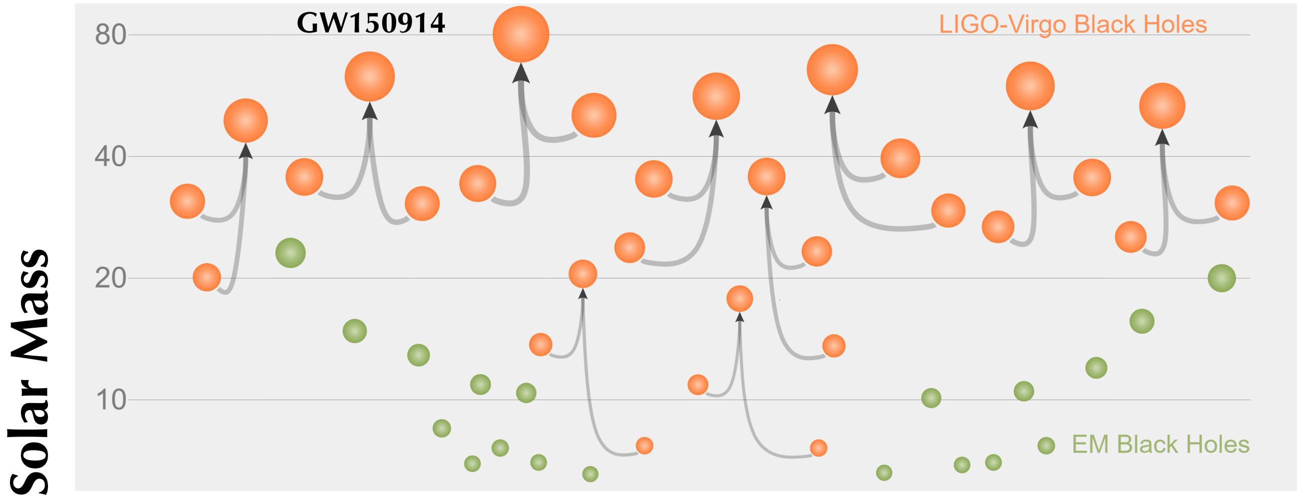


LVC, PRL **116** (2016) 061102

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

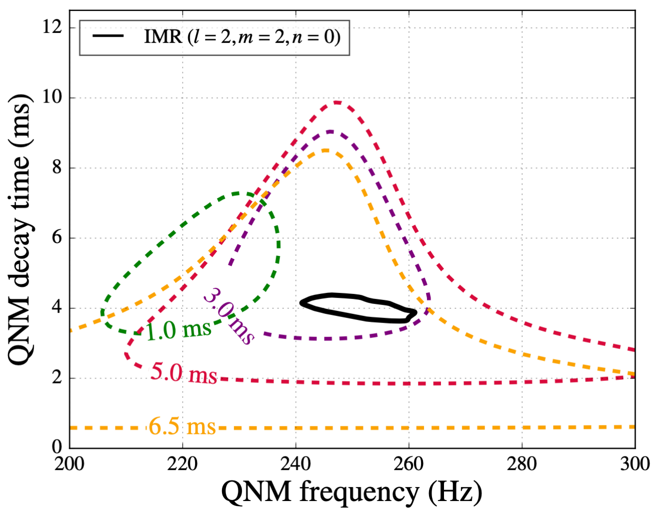
$$\tau_{\text{damp}} = -\frac{1}{\omega_I}$$

Gravitational wave detections



LVC, PRX **9** (2019) 031040

LVC, PRL **116** (2016) 221101



During the 1st and 2nd observing runs, LIGO and Virgo detected **1 quasi-normal mode** compatible with a Kerr black hole:

$$f_{\rm QNM} = 251^{+8}_{-8} \text{ Hz}$$

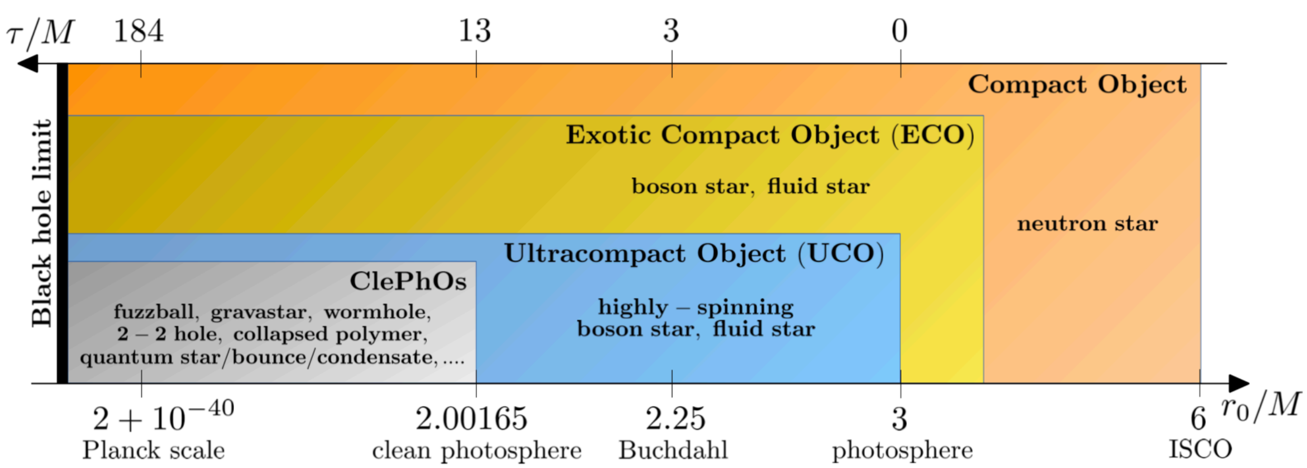
$$\tau_{\rm QNM} = 4.0^{+0.3}_{-0.3} \text{ ms}$$

Exotic compact objects

ECOs are theoretical compact objects **without horizon** which

- can mimic black holes in terms of electromagnetic observations
  Abramowicz+, A&A 396, L31-L34 (2002)

- can overcome paradoxes of BHs Mazur, Mottola, PNAS (2004)
  - thermodynamical instability
  - huge entropy



Cardoso, Pani, Nat. Astron. **1**, 586 (2017)

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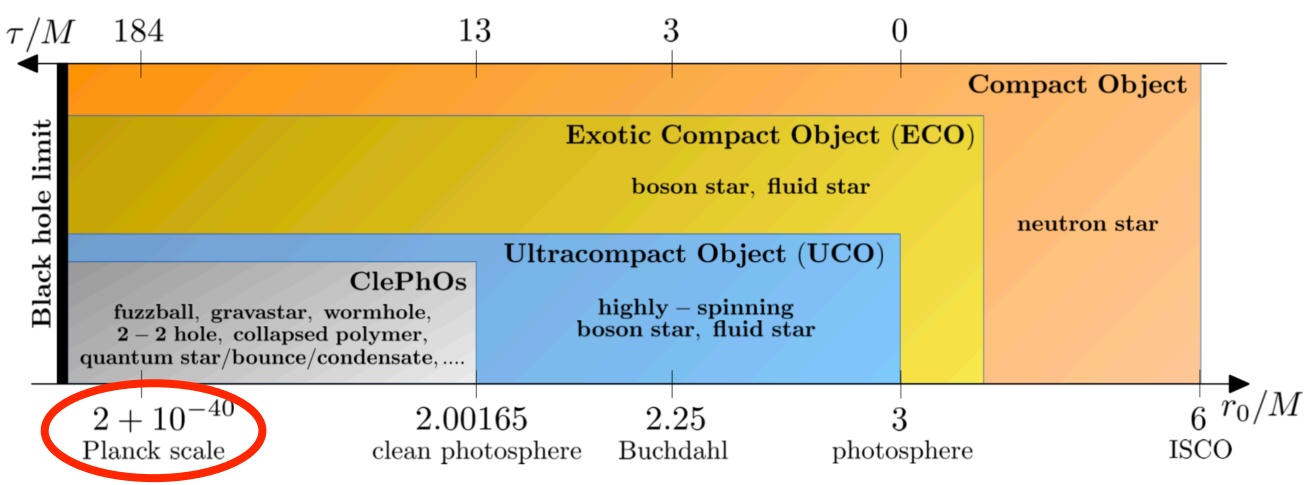


Cardoso, Pani, Nat. Astron. **1**, 586 (2017)

Rotating exotic compact object

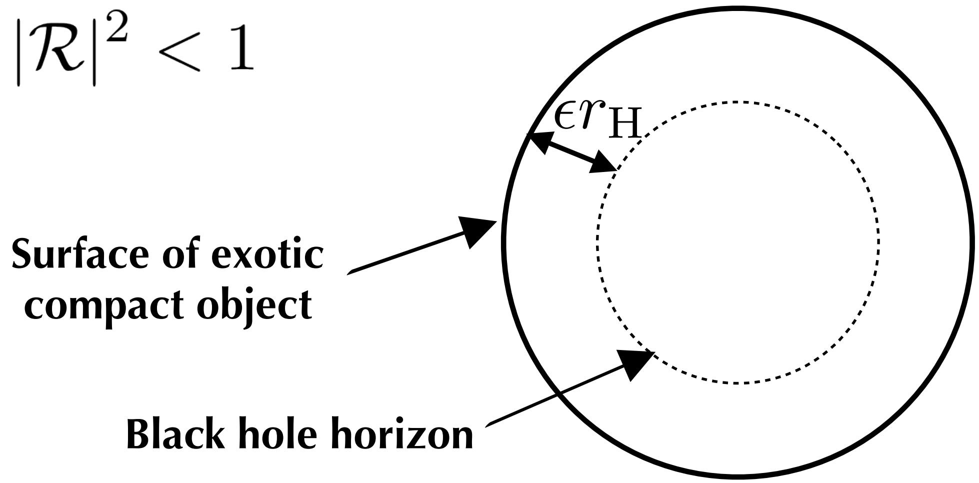
EM, Pani, Ferrari, PRD **96** (2017) 104047

We analyze a compact object described by the Kerr metric with radius

$$r_0 = r_{\rm H}(1+\epsilon), \qquad \epsilon \ll 1$$

whose surface is parametrized by a **complex reflectivity coefficient** $\mathcal{R}$**:**

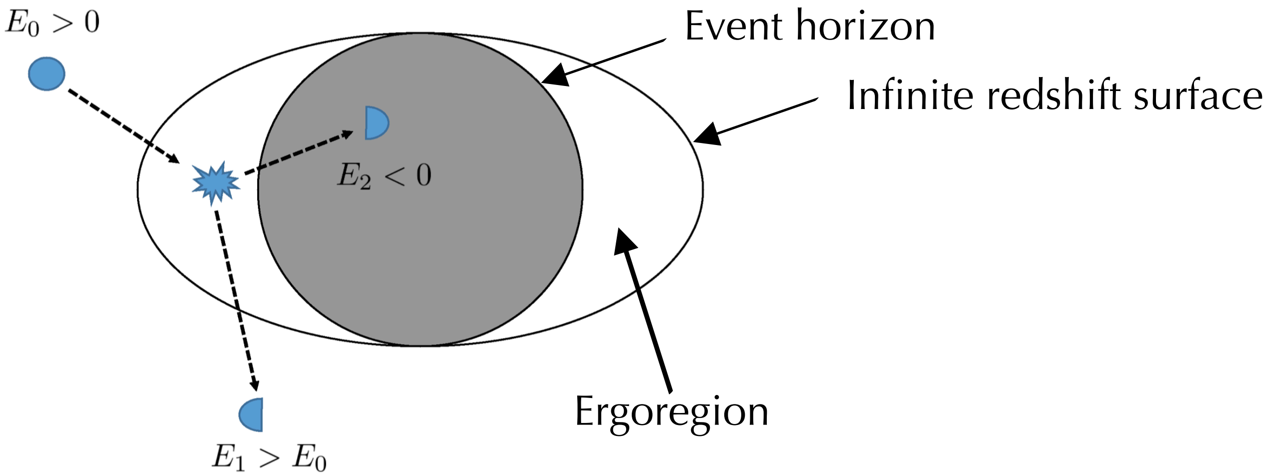
- Perfectly reflecting surface $|\mathcal{R}|^2 = 1$
- Partially absorbing surface $|\mathcal{R}|^2 < 1$



Ergoregion instability

Friedman, Commun. Math. Phys. **63** (1978) 243

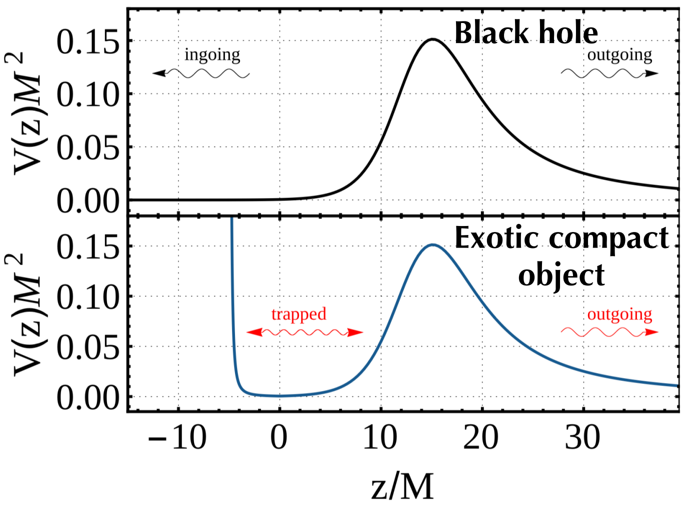
Spinning compact objects with an ergoregion but without an event horizon might be unstable due to the ergoregion instability.



Brito, Cardoso, Pani, Lect. Notes Phys. **906** (2016)
Penrose, Nuovo Cimento.J. **Serie 1** (1969) 252

The only way to prevent the instability is by absorbing negative-energy states through **dissipation mechanisms** at the surface of the object.

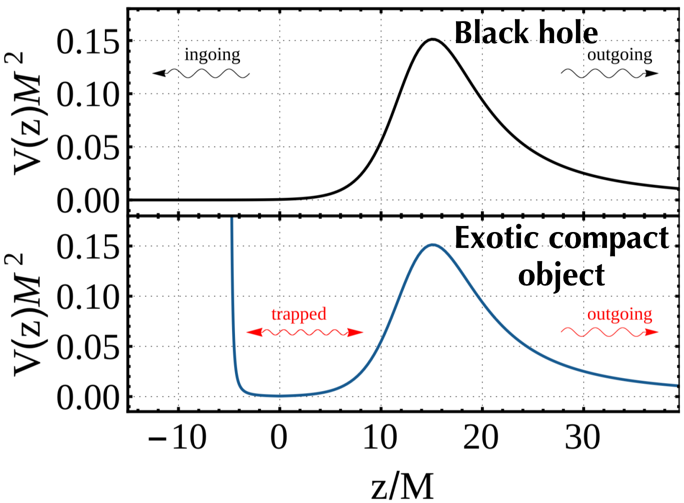
Ringdown of exotic compact objects



The quasi-normal modes are derived by

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

No horizon → Trapped Modes → Different QNMs



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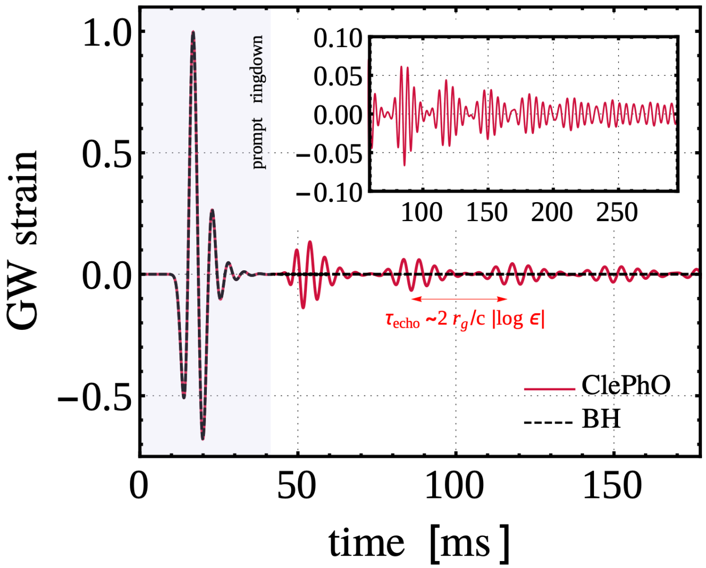
No horizon → Trapped Modes → Different QNMs

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

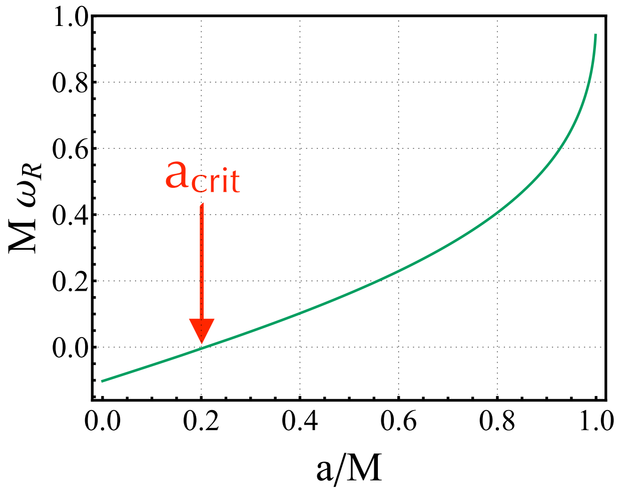
Cardoso, Pani, Nat. Astron. **1**, 586 (2017)

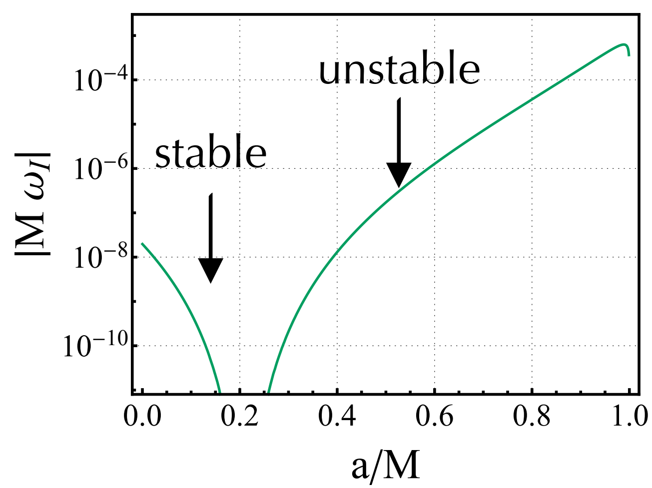


Quasi-normal mode spectrum

EM, Pani, Ferrari, PRD **96** (2017) 104047

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





$|\mathcal{R}|^2 = 1$

$\epsilon = 10^{-10}$

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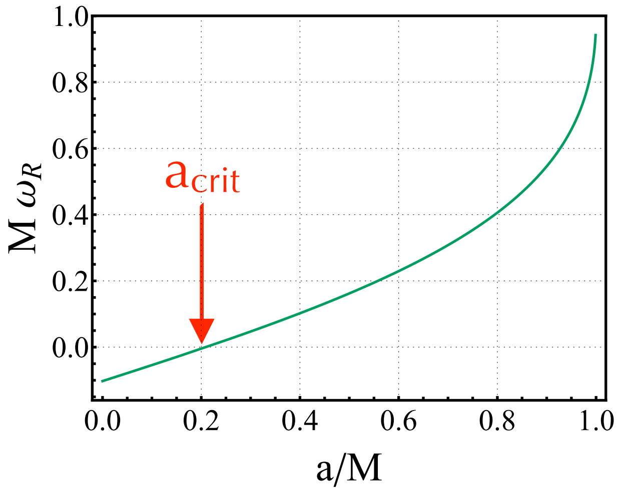

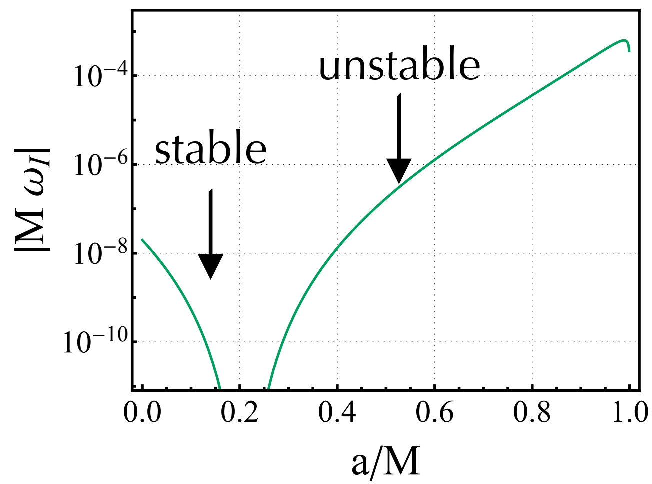

$$|\mathcal{R}|^2 = 1$$
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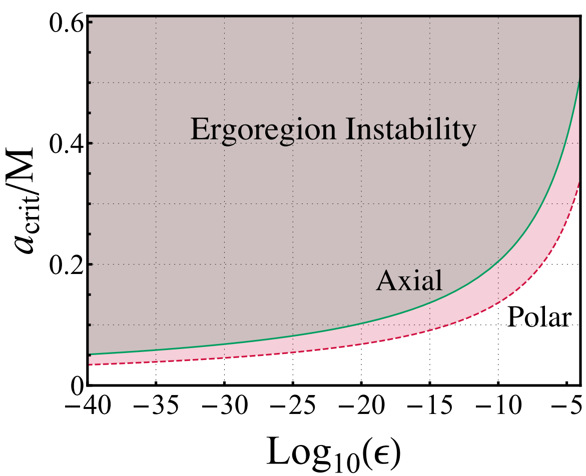


- For $\epsilon \to 0$, slowly spinning ECOs are unstable.
- The timescale of instability is short compared to astrophysical timescales

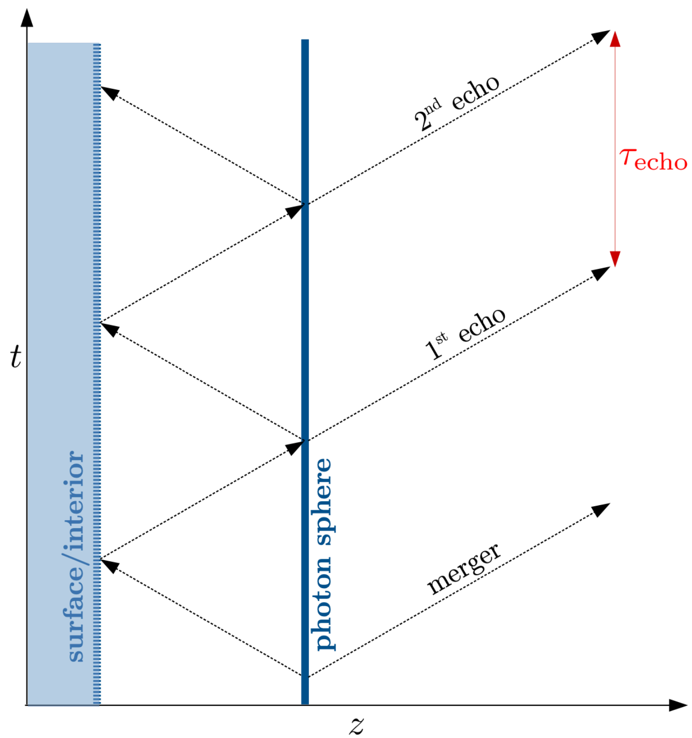
$$\tau_{\rm inst} \sim 50 \left(\frac{M}{10 M_\odot}\right) \mathrm{s}$$

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

How to quench ergoregion instability

Partial absorption at the surface $|\mathcal{R}|^2 < 1$ destroys the instability.

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



Cardoso, Pani, LRR (2019) 22:4
Vilenkin, Phys. Lett. 78B (1978) 301

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

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

Template for echoes

The signal emitted by an ECO at infinity can be written in terms of the signal emitted by a BH: Mark+, PRD **96** (2017) 084002

$$\tilde{Z}^{+}_{\mathrm{ECO}}(\omega) = \tilde{Z}^{+}_{\mathrm{BH}}(\omega) + \mathcal{K}\tilde{Z}^{-}_{\mathrm{BH}}(\omega)$$

$\mathcal{K}$ → Transfer function

Parameters:

- Standard BH ringdown: $M, \chi, A_{+,\times}, \phi_{+,\times}, t_0$
- 2 of the ECO: $\epsilon, \mathcal{R}$

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Transfer function

Analytical template

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

Parameters:

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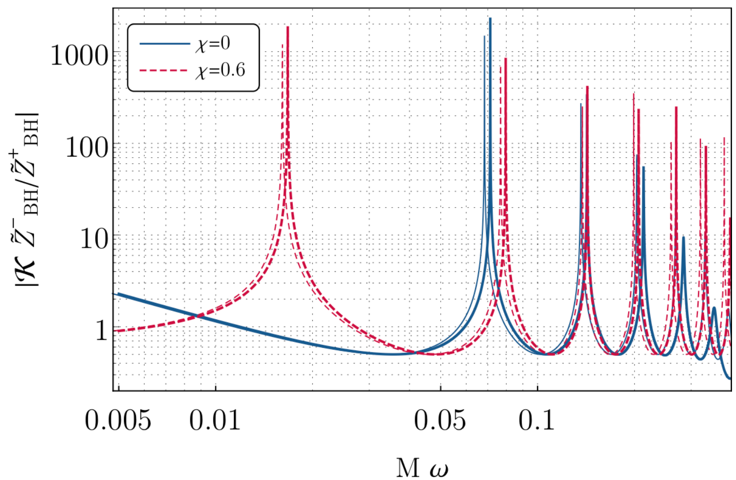
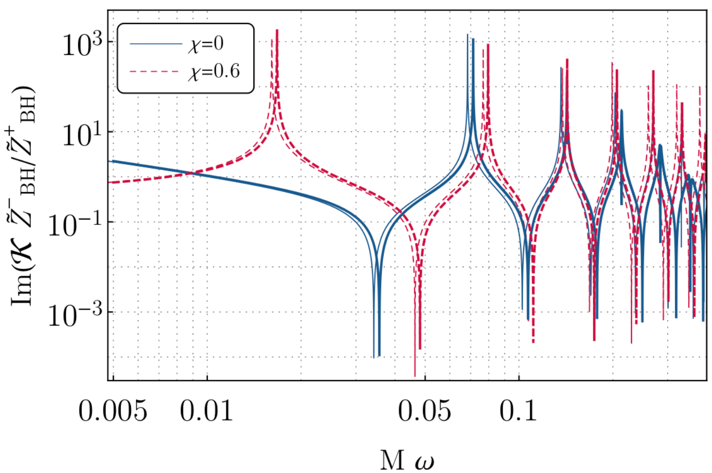
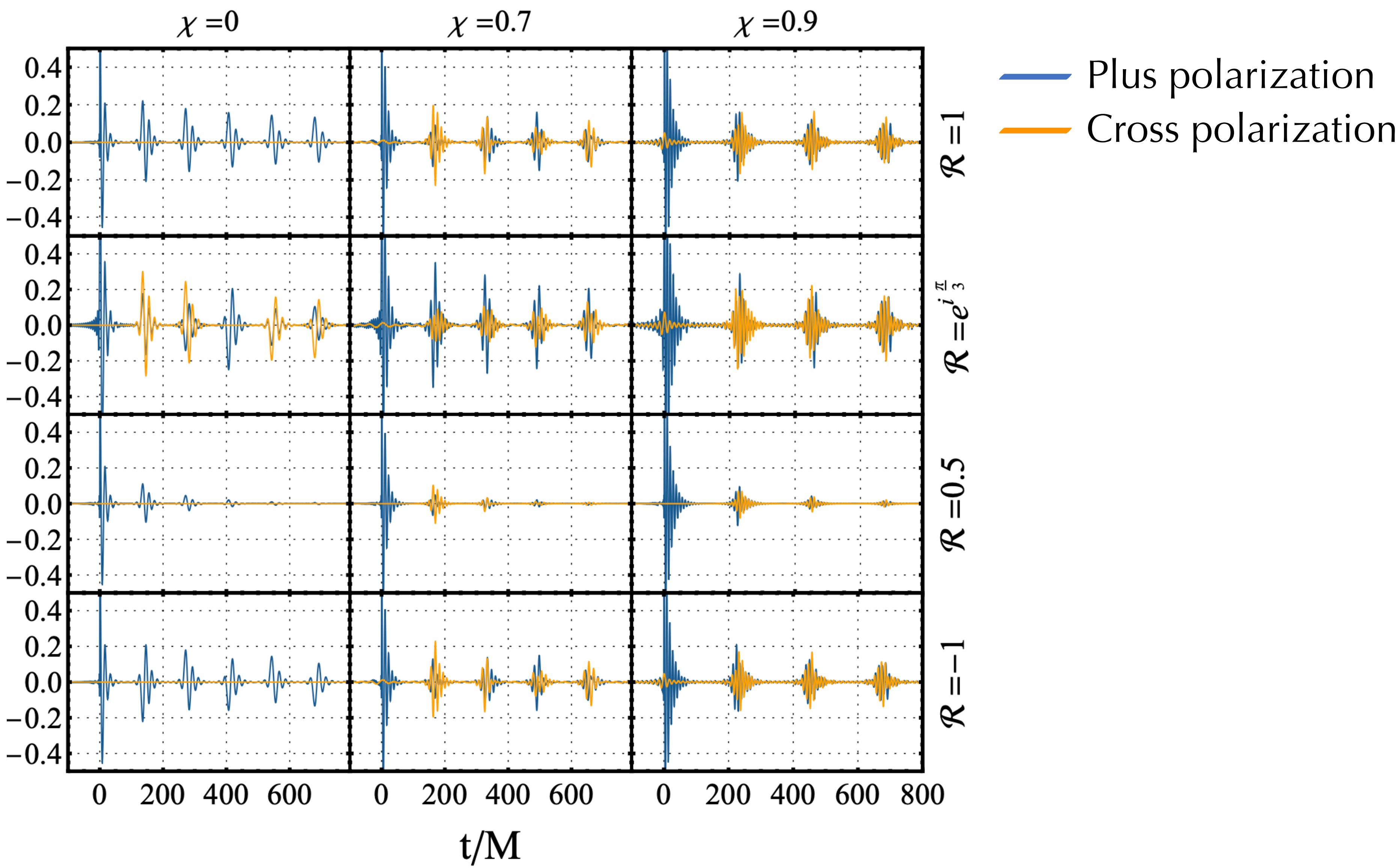




Ringdown+echo waveforms

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



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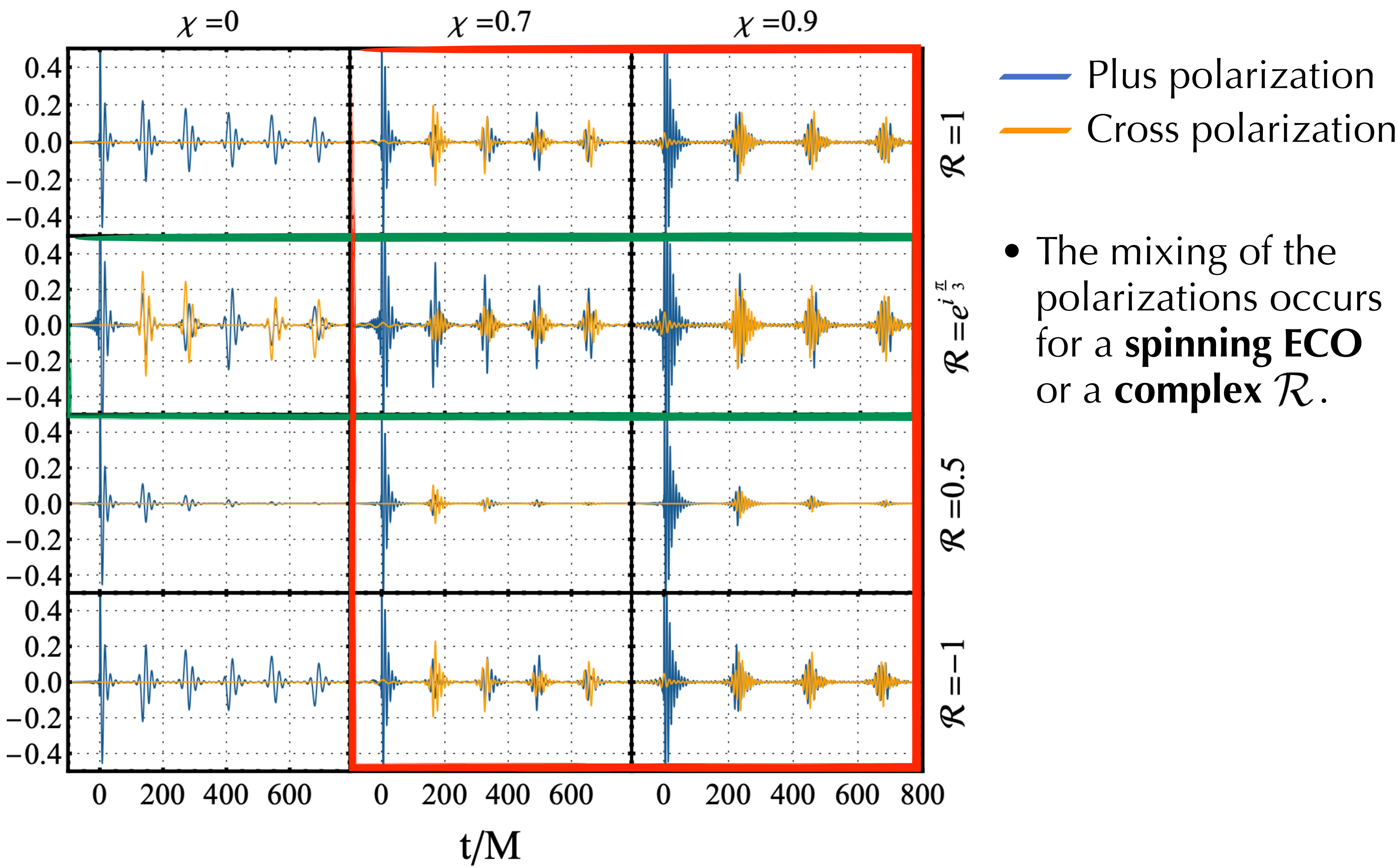
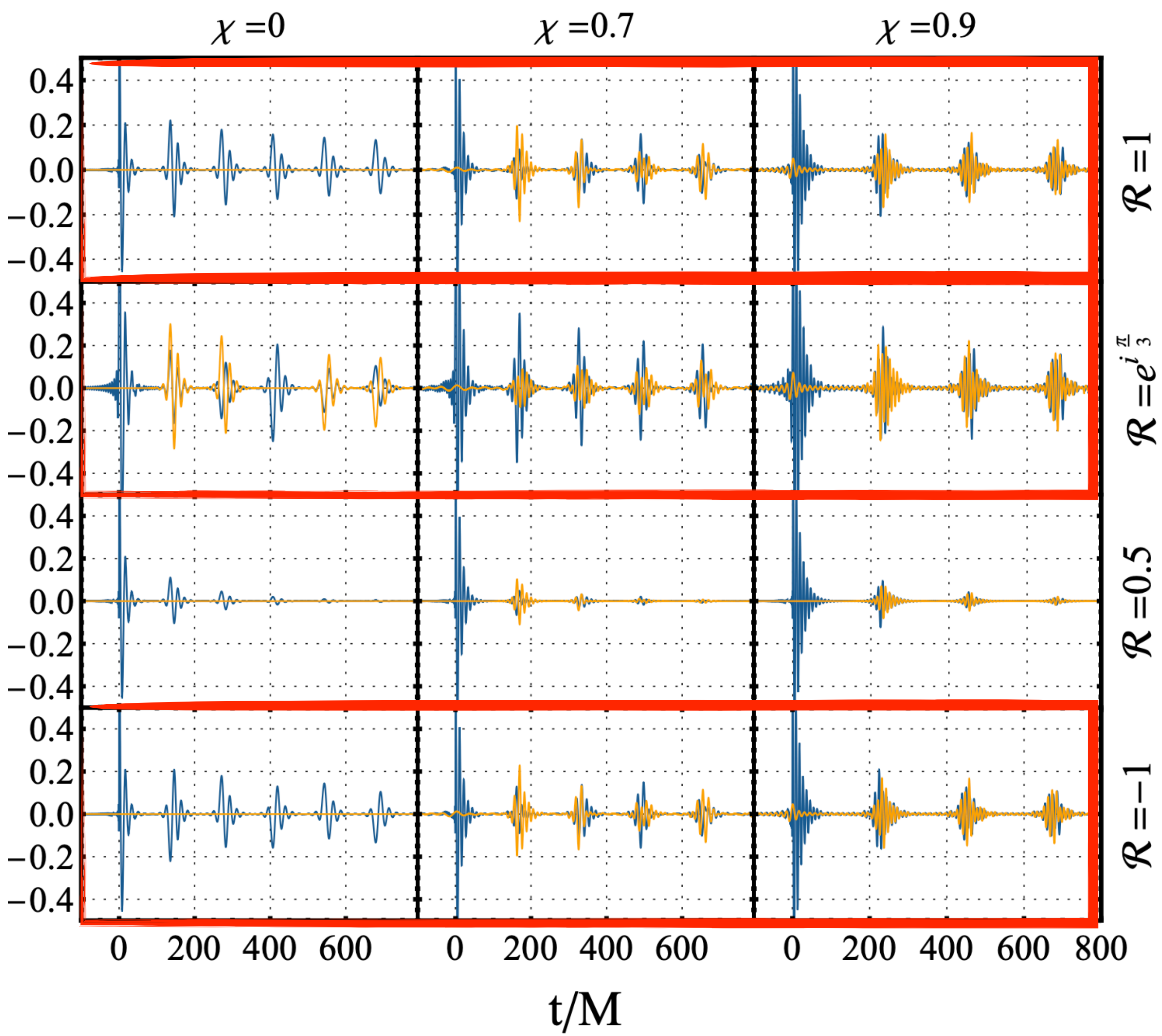
EM, Testa, Bhagwat, Pani, PRD **100** (2019) 064056



- The mixing of the polarizations occurs for a **spinning ECO** or a **complex** $\mathcal{R}$.

Ringdown+echo waveforms

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



- The mixing of the polarizations occurs for a **spinning ECO** or a **complex** $\mathcal{R}$.

- The **phase** in $\mathcal{R}$ modifies the echo pattern.

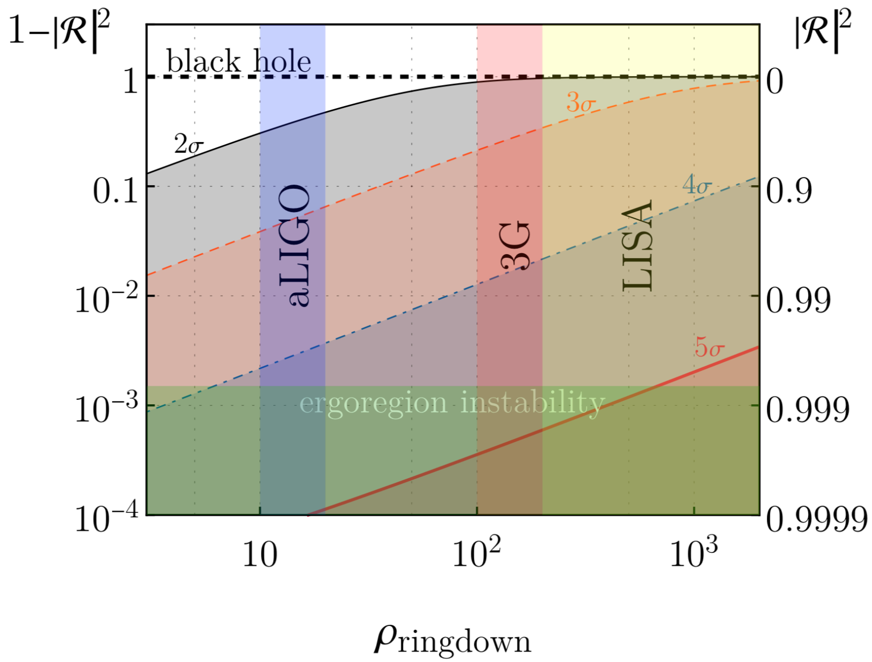
Detection of exotic compact objects?

- Debate on the evidence of echoes in LIGO/Virgo data

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

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

- Third generation and space based detectors will allow us to detect or exclude exotic compact objects with a partially absorbing surface.



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

Conclusions and future prospects

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

- We analyzed the stability of a rotating **exotic compact object**:

  Perfectly reflecting surface ⟶ Ergoregion instability

  Partially absorbing surface ⟶ Stability

- We derived an analytical **gravitational-wave template** for the postmerger ringdown and the echo signal.

- Accurate matched-filter searches for gravitational wave echoes