First EPS Conference on Gravitation

Ergoregion instability of Exotic Compact Objects

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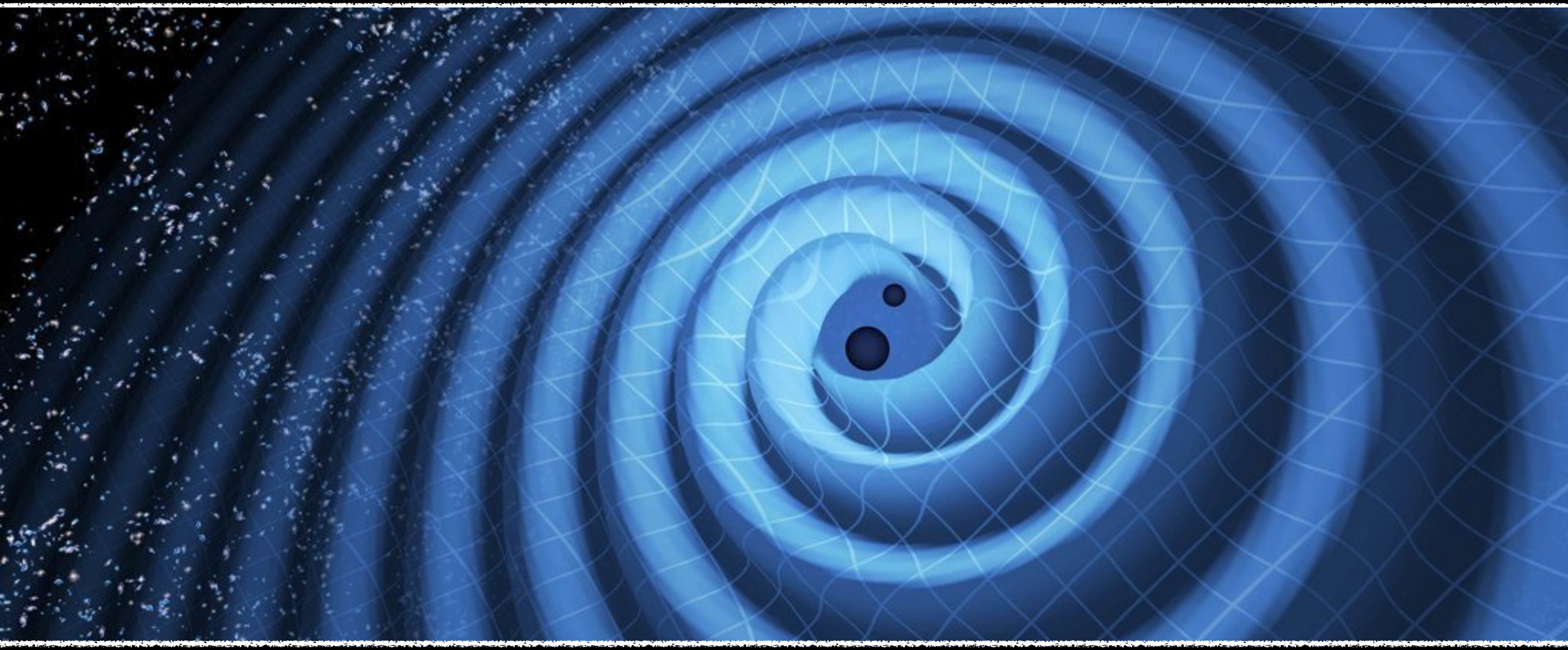
Outline

- Gravitational waves as probes of strong gravity
  - Ringdown stage
- Exotic Compact Objects
  - Kerr-like ECOs
  - Ergoregion instability
- Stability of Kerr-like ECOs
  - Scalar and electromagnetic perturbations
  - Extension to gravitational case
  - How to quench the ergoregion instability

Gravitational waves as probes of strong-gravity

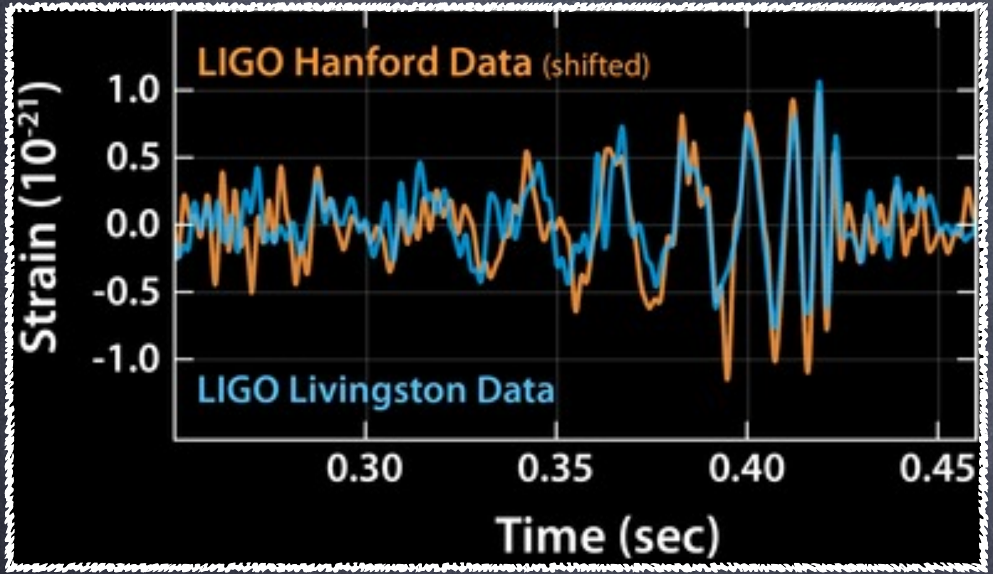


Ringdown stage

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

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

Exponentially damped sinusoid



Virgo, LIGO Scientific, Phys. Rev. Lett. 116, 061102 (2016)

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

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

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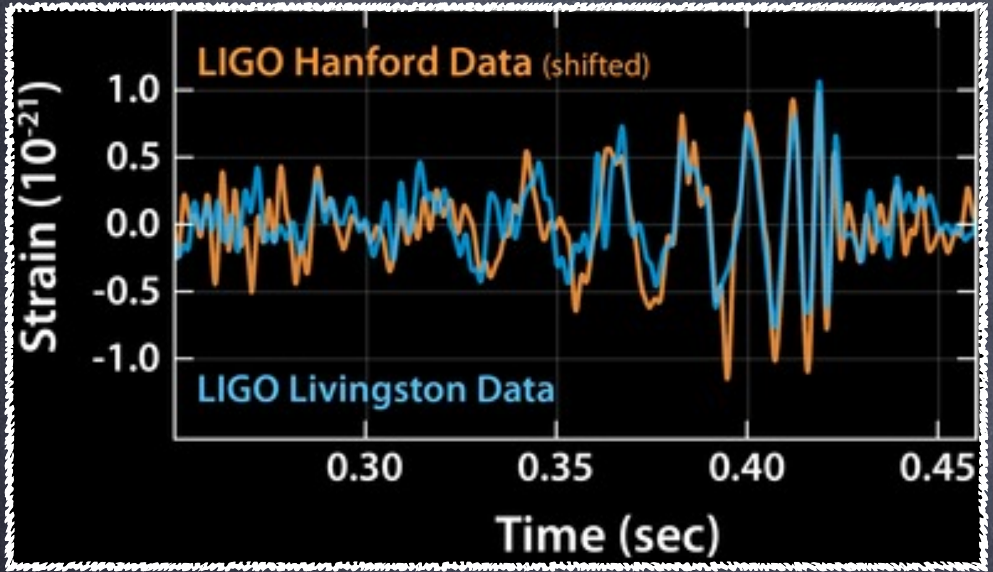


Virgo, LIGO Scientific, Phys. Rev. Lett. 116, 061102 (2016)

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

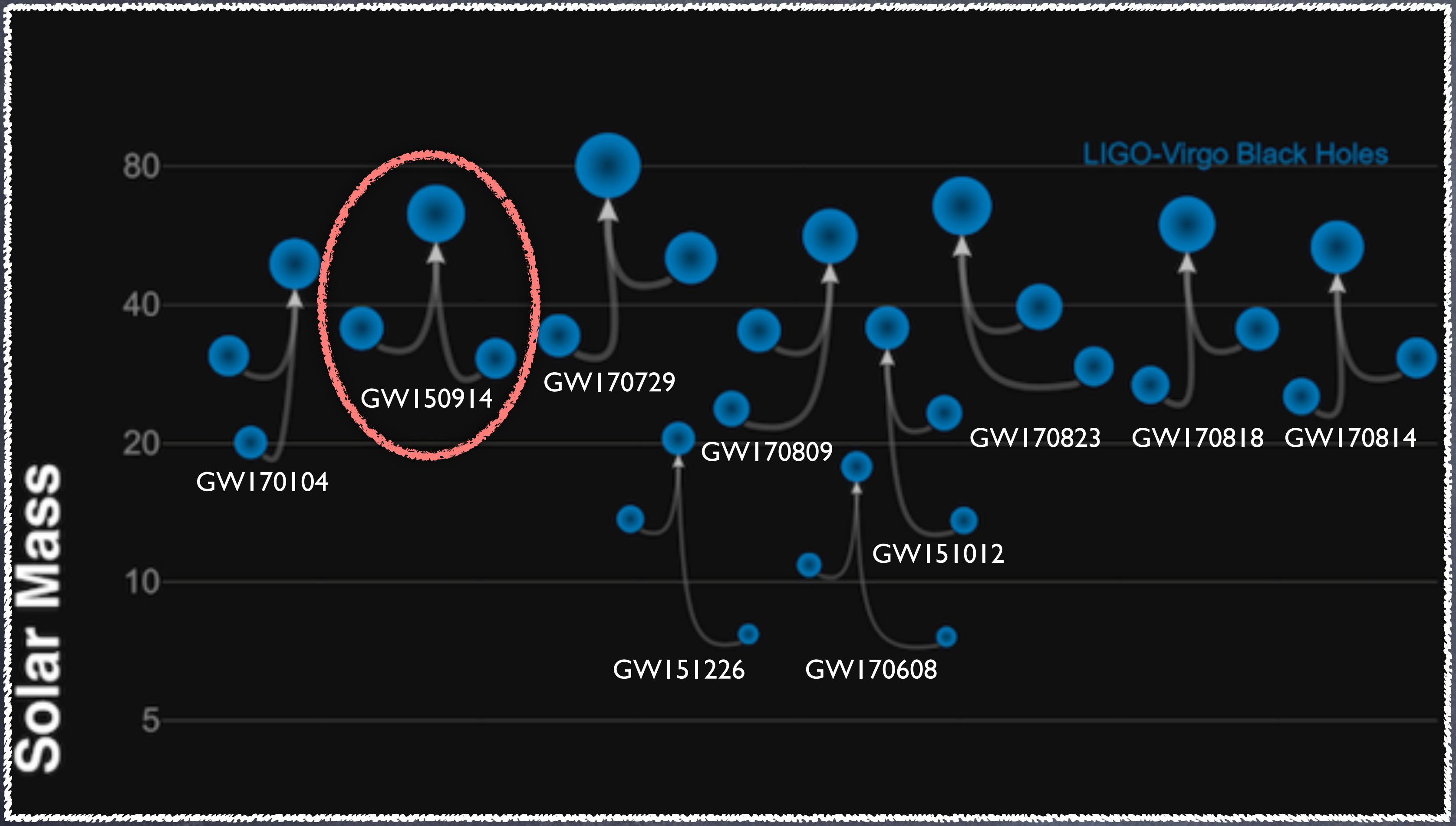
$$\tau_{\mathrm{damp}} = -\frac{1}{\omega_I}$$

$\omega_I < 0$ stable

$\omega_I > 0$ unstable

From the detection of the ringdown we can infer the QNMs of the remnant and understand nature of the latter.

Ringdown detection



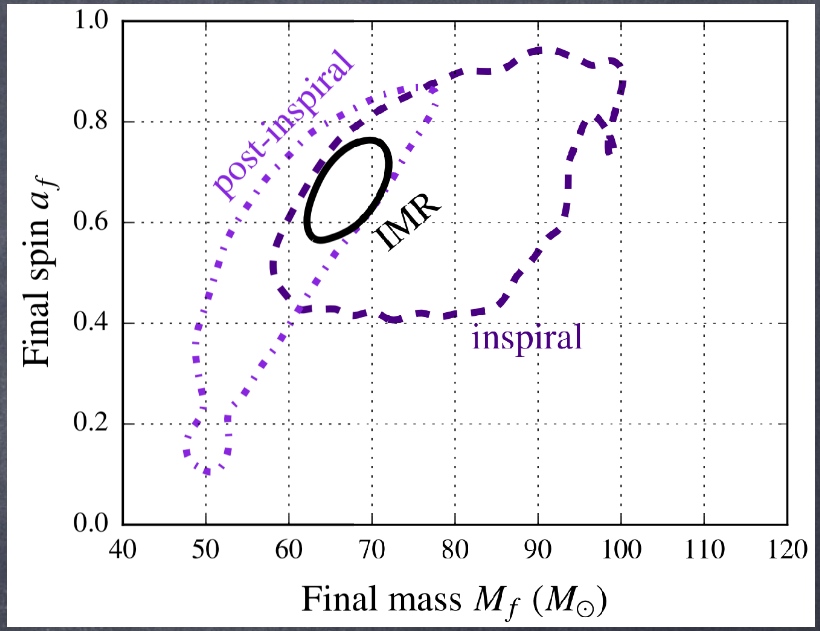
Virgo, LIGO Scientific, arXiv:1811.12907 (2018)

1 QNM observed:

$$f_{\rm GW} \sim 250 \text{ Hz}$$

$$\tau_{\rm damp} \sim 4 \text{ ms}$$

compatibile with a Kerr BH:

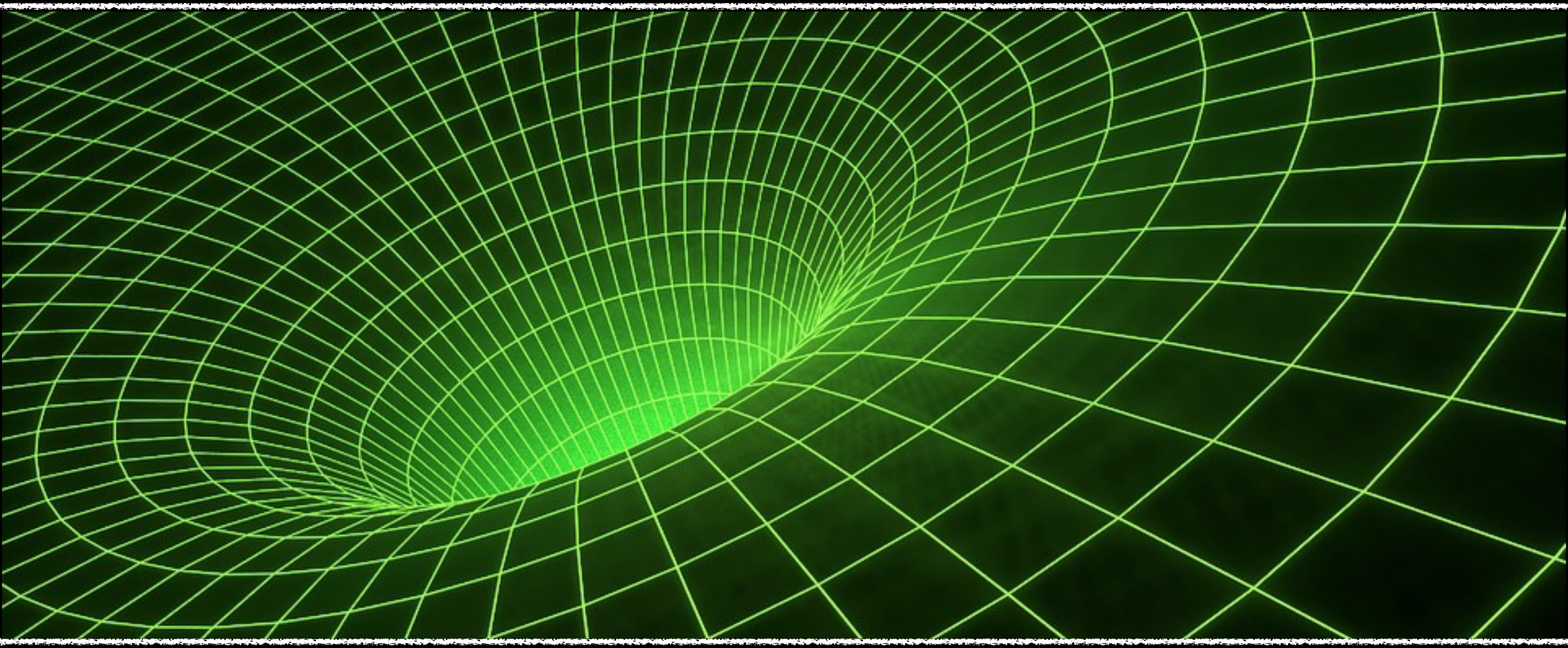


Virgo, LIGO Scientific, Phys. Rev. Lett. 116, 221101 (2016)

However the characterization of the remnant is still an open problem.

A precise modeling of the gravitational waveform in a variety of strong-gravity processes is necessary, including the signal emitted by alternatives to black holes.

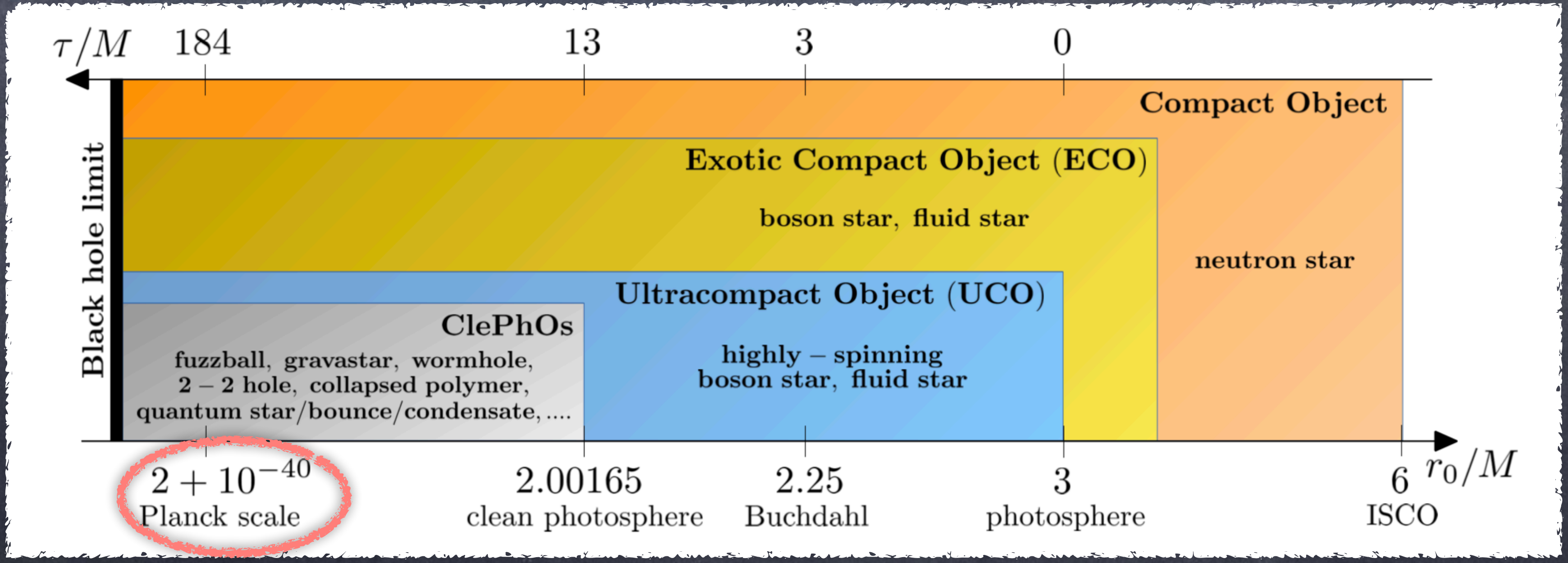
Exotic Compact Objects



Exotic Compact Objects (ECOs)

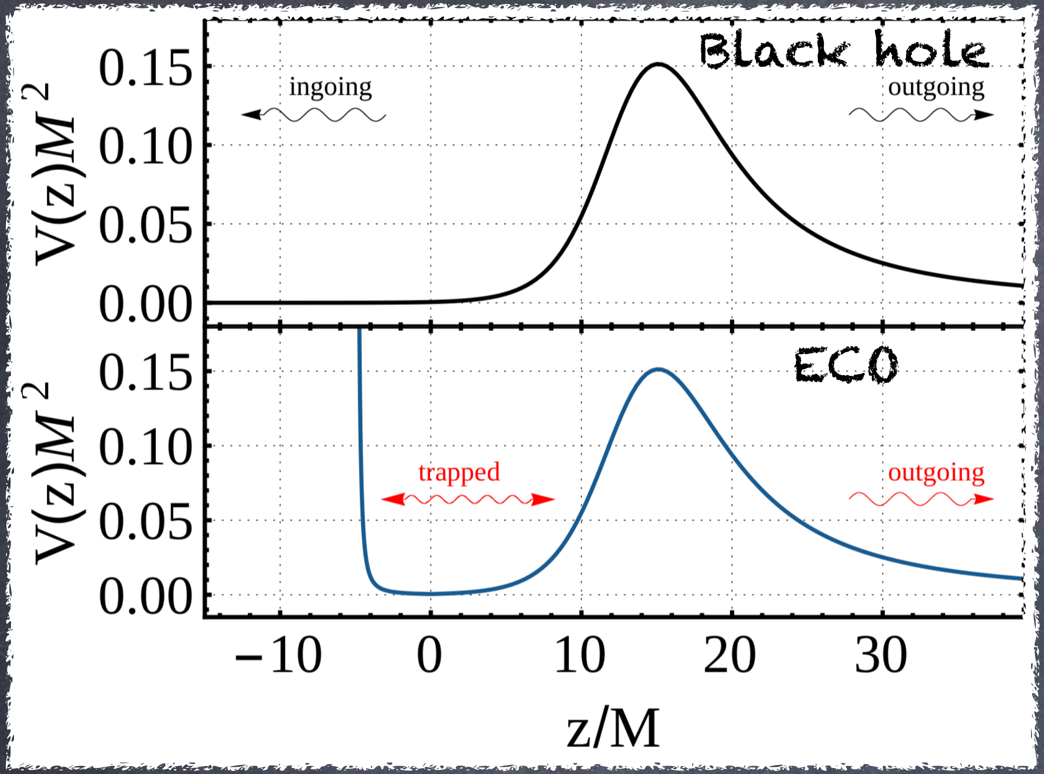
ECOs are theoretical compact objects without horizon which:

- overcome paradoxes of BHs
  - > curvature singularity
  - > thermodynamical instability
  - > huge entropy [Mazur, Mottola, PNAS (2004)]
- are formed in the presence of dark matter fields beyond Standard Model [Liebling, Palenzuela, Liv. Rev. (2012)]
- quantify the existence of horizons



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

ECOs: detectability in ringdown



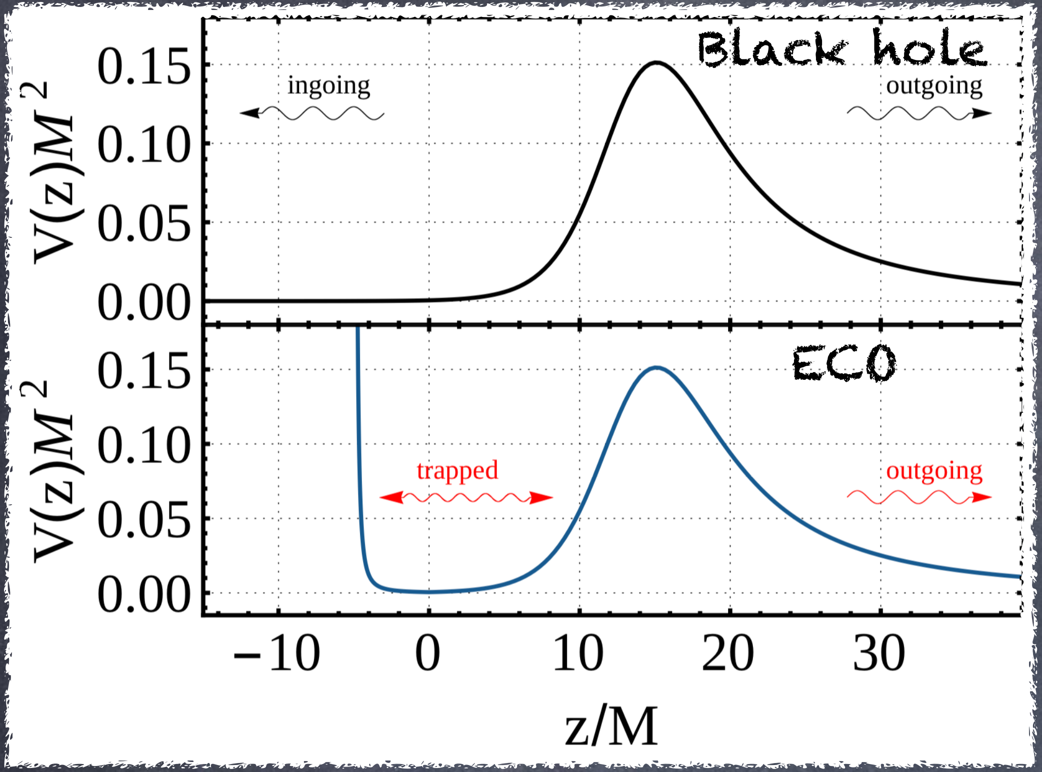
Cardoso, Pani, arXiV:1707.03021 (2017)

We can distinguish black holes from ECOs through QNMs:

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

No horizon → Trapped Modes → Different QNMs

ECOs: detectability in ringdown



Cardoso, Pani, arXiV:1707.03021 (2017)

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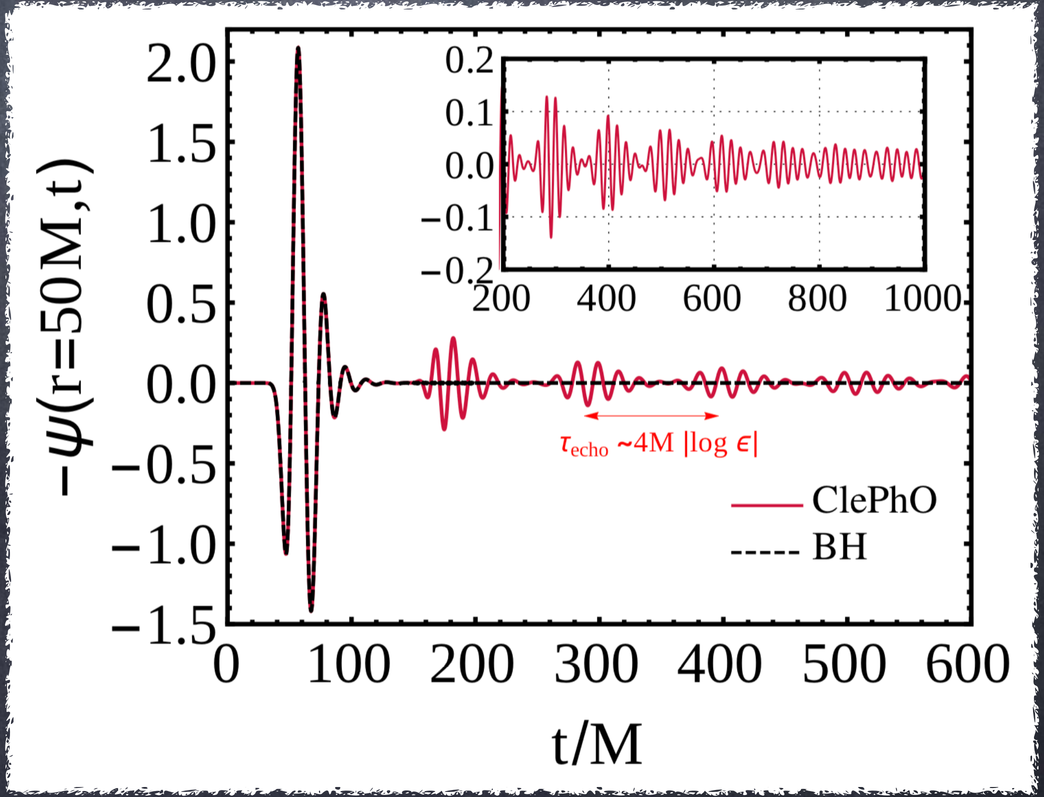
$$\frac{d^2\psi}{dz^2} + V(z)\psi = 0$$

No horizon → Trapped Modes → Different QNMs

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



Cardoso, Pani, arXiV:1707.03021 (2017)

Kerr-like ECOs

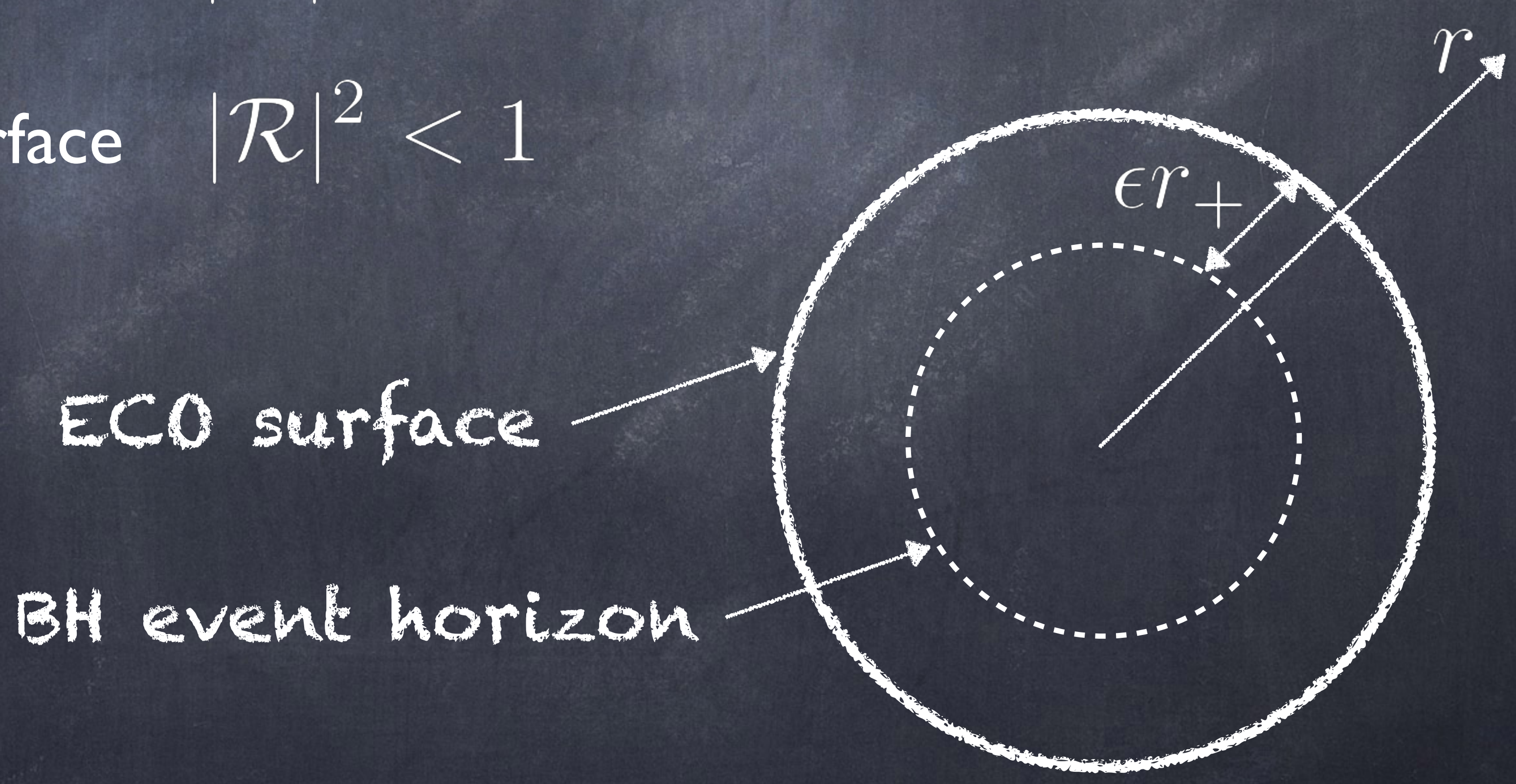
EM, Pani, Ferrari, PRD 96 (2017) 104047

We consider a geometry described by the Kerr metric when $r > r_0$ and

$$r_0 = r_+(1+\epsilon) \qquad \epsilon \ll 1$$

is the location of the surface of the ECO with reflectivity coefficient $\mathcal{R}$:

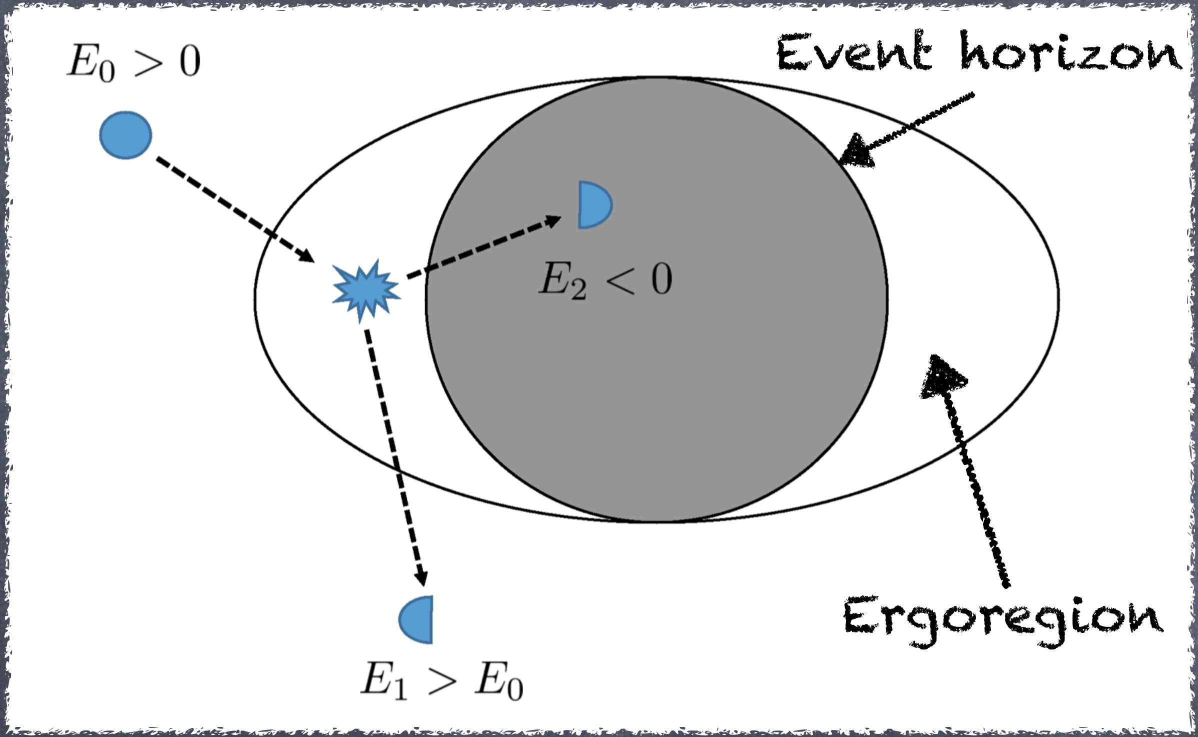
- Perfectly reflecting surface $|\mathcal{R}|^2 = 1$
- Partially absorbing surface $|\mathcal{R}|^2 < 1$



Ergoregion instability

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

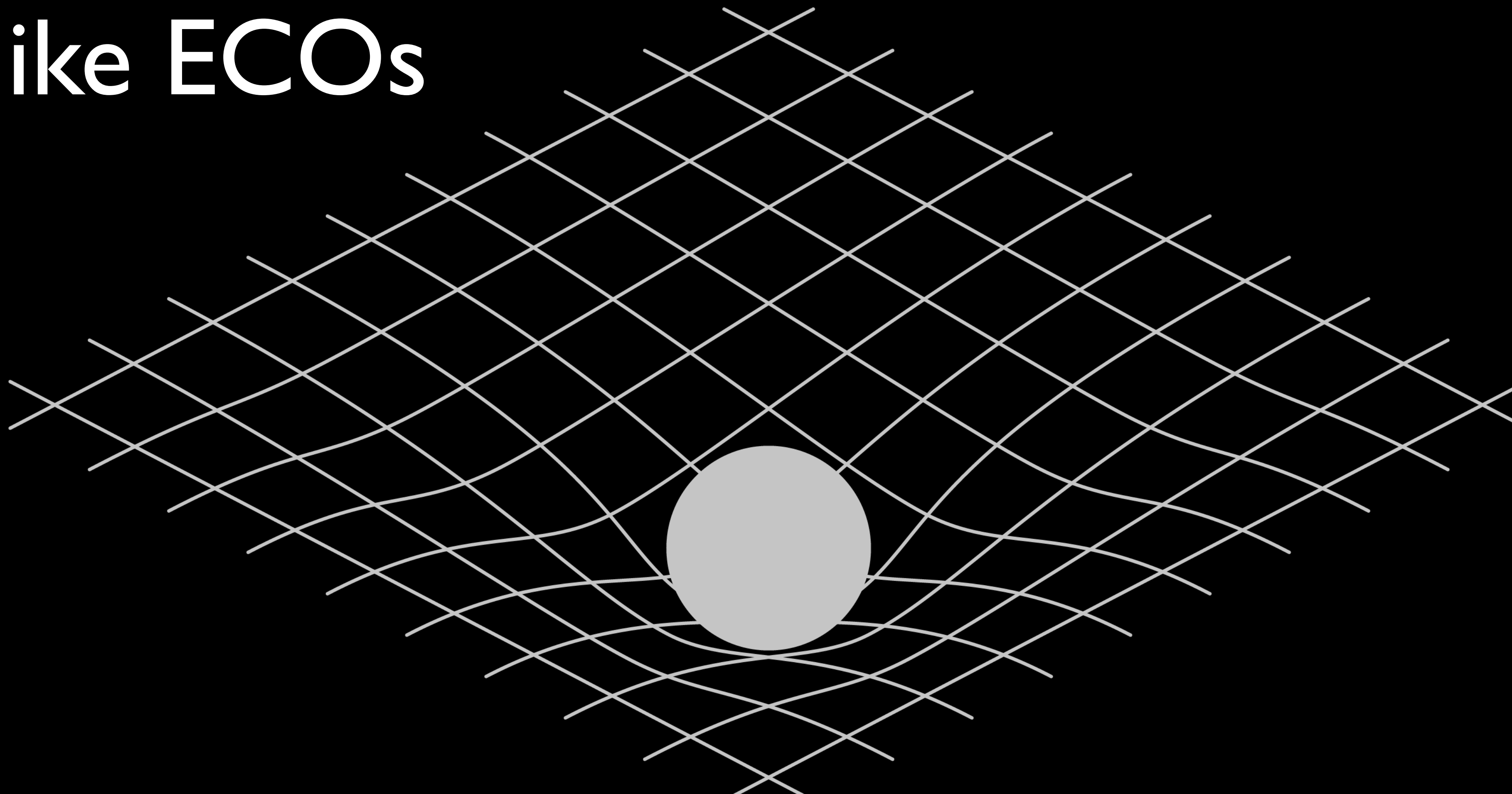
Spinning compact objects with an ergoregion but without an event horizon might turn unstable due to the ergoregion instability.



Brito, Cardoso, Pani, Lect. Notes Phys. 906 (2016)
Penrose, Nuovo Cimento J. Serie1, 252 (1969)

In the absence of dissipation mechanisms, the instability has a crucial impact on the dynamics of the ECO.

Stability of Kerr-like ECOs



QNM spectrum

In order to study the stability of ECOs, we consider a test spin-s perturbation governed by Teukolsky's equations

$$\Delta^{-s}\frac{d}{dr}\left(\Delta^{s+1}\frac{dR_s}{dr}\right)-V_sR_s=0$$

Teukolsky

Teukolsky, Ap.J. 185, 635 (1973)

QNM spectrum

In order to study the stability of ECOs, we consider a test spin-s perturbation governed by Teukolsky's equations

Real potential

$$\Delta^{-s}\frac{d}{dr}\left(\Delta^{s+1}\frac{dR_s}{dr}\right) - V_s R_s = 0 \quad \longrightarrow \quad \frac{d^2 X_s}{dr_*^2} - U_s(r,\omega) X_s = 0$$

Teukolsky

Teukolsky, Ap.J. 185, 635 (1973)

Detweiler

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

+ 2 boundary conditions: eigenvalue problem for the QNM frequencies

- At infinity: outgoing waves
- At r_0: perfectly reflecting surface

Perfectly reflecting surface

- Scalar field (s=0)

Dirichlet	$R_0(r_0) = 0$	inverted phase $(\mathcal{R} = -1)$
Neumann	$\partial_r R_0(r_0) = 0$	in phase $(\mathcal{R} = 1)$

- Electromagnetic field (s=-1)

Perfect conductor: normal $\vec{E}$ and tangential $\vec{B}$ at the surface

$\epsilon \ll 1$ →

Dirichlet axial	$X_{-1}(r_0) = 0$
Neumann polar	$\partial_r X_{-1}(r_0) = 0$

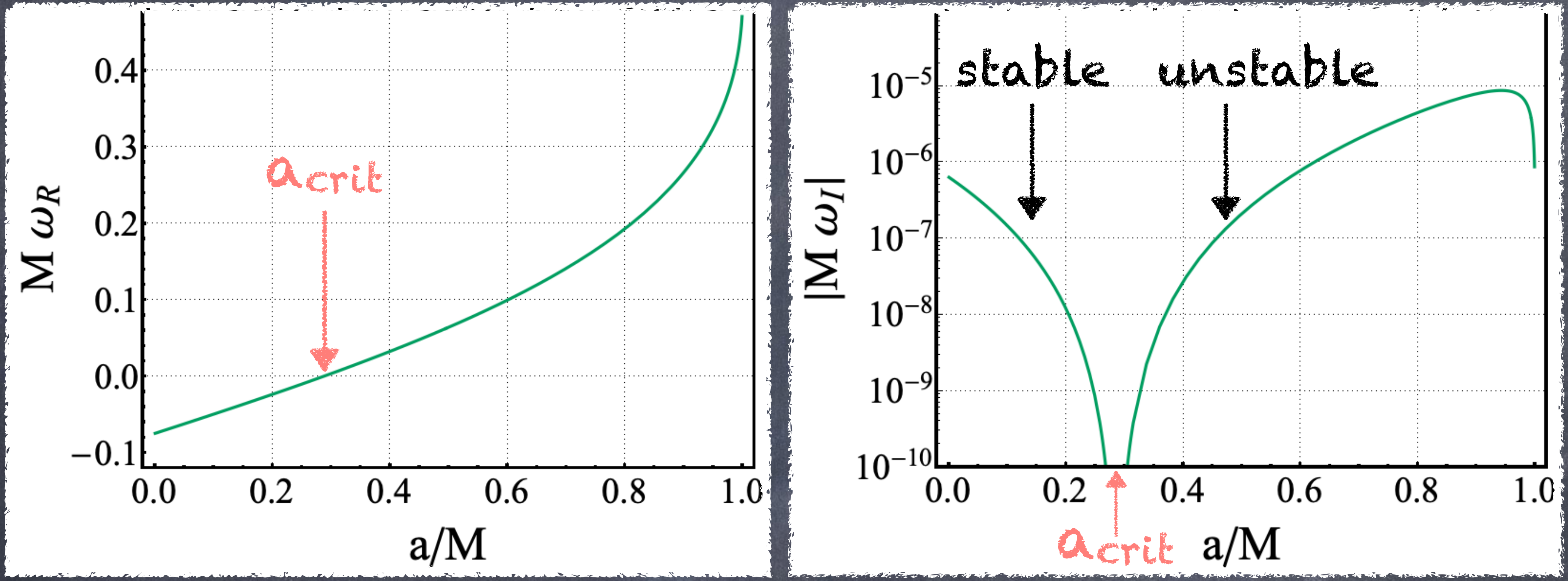
- Gravitational field (s=-2) ?

Ergoregion instability

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

— Scalar Dirichlet

$l = m = 1, \; \epsilon = 10^{-10}$



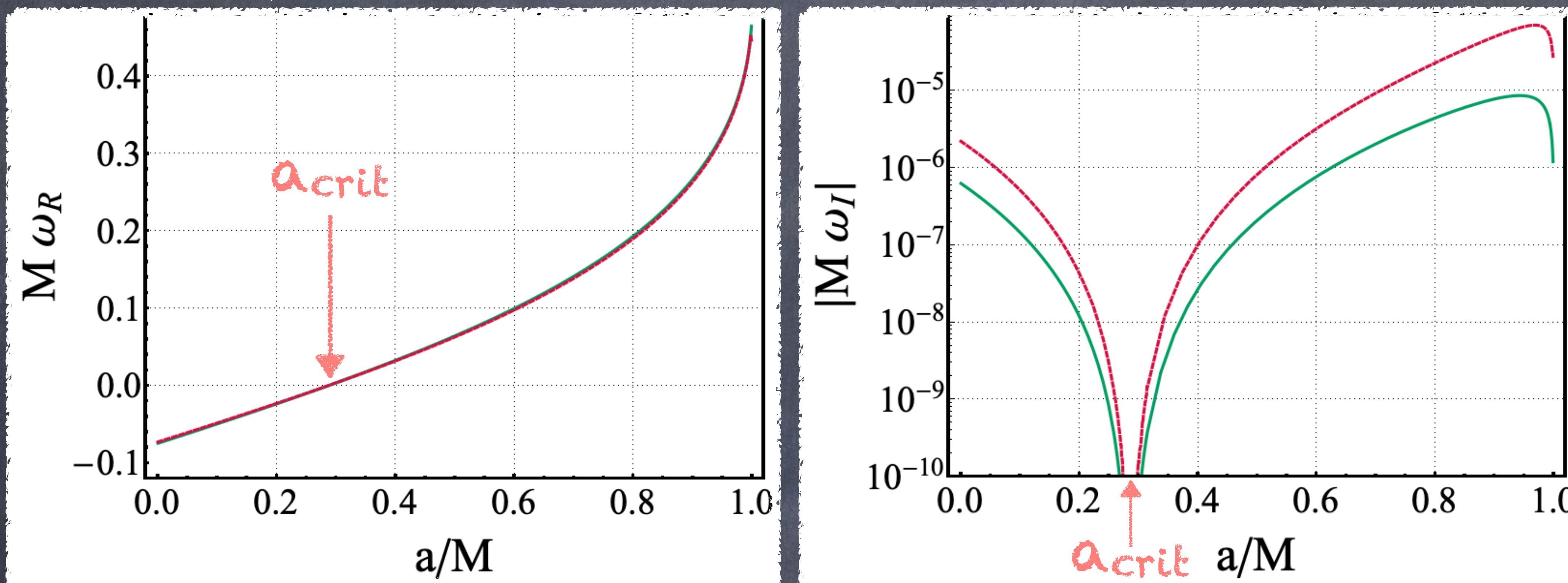
For $a > a_{\rm crit}$ ERGOREGION INSTABILITY

Ergoregion instability

EM, Cardoso, Dolan, Pani, PRD in press (arXiv:1807.08840)

Scalar Dirichlet   Electromagnetic axial

$l = m = 1, \ \epsilon = 10^{-10}$

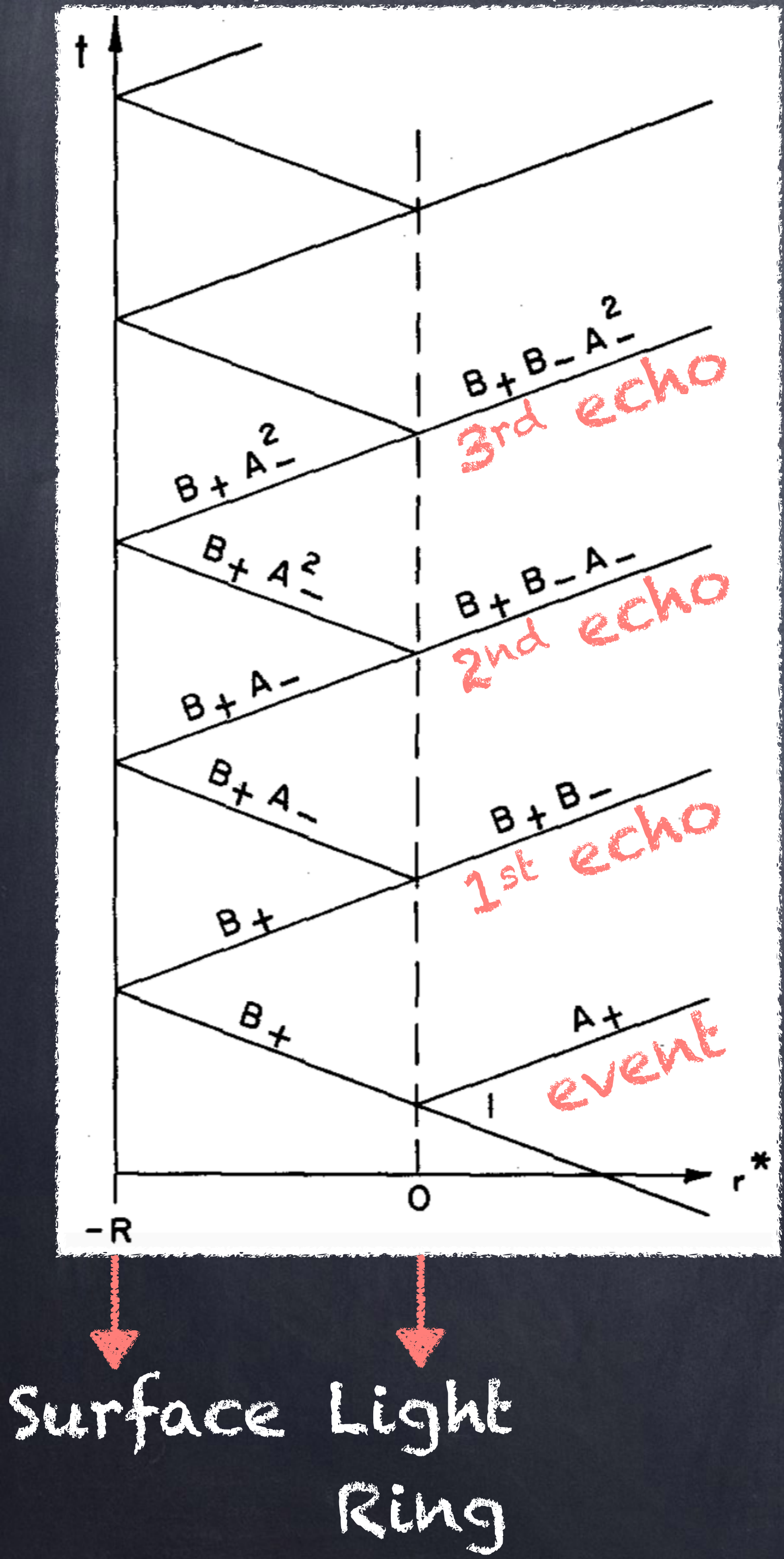


For $a > a_{\rm crit}$ ERGOREGION INSTABILITY

The timescale of instability is shorter for electromagnetic perturbations since $\tau_{\rm inst} := 1/\omega_I$.

"Bounce-and-amplify" argument

Vilenkin, Phys. Lett. 78B, 301 (1978)



The waves are reflected into the cavity and slowly leak out through tunneling in the photon-sphere barrier.

$\omega_R \propto$ Width of cavity
Independent on perturbation

$\omega_I \sim Z\omega_R$

→ Superradiant amplification factor of BHs

Low frequency: $Z \propto \beta_{sl}$

Starobinsky, Churilov, Zh. Eksp. Teor. Fiz. 65, 3 (1973)

Time scale of instability: $\tau_{\rm inst} \propto 1/\beta_{sl}$

Extension to gravitational perturbations

EM, Cardoso, Dolan, Pani, PRD in press (arXiv:1807.08840)

- Boundary condition

We argue that the "bounce-and-amplify" description can be extended to $s = -2$ perturbations:

Dirichlet axial $X_{-2}(r_0) = 0$

Neumann polar $\partial_r X_{-2}(r_0) = 0$

Corrections to Detweiler's formulation

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EM, Cardoso, Dolan, Pani, PRD in press (arXiv:1807.08840)

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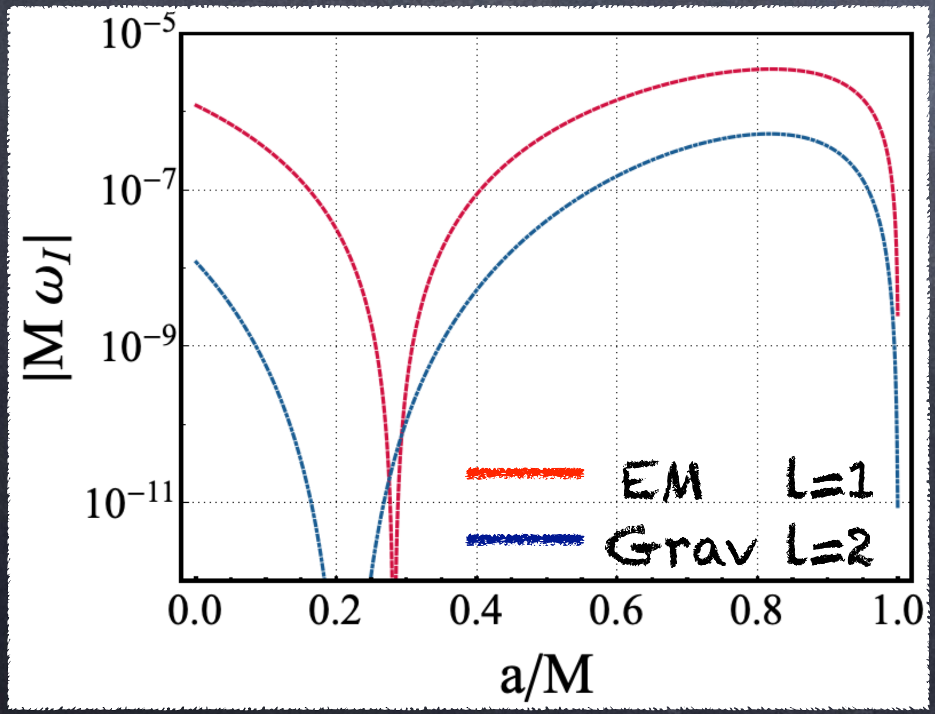
  Dirichlet axial $\quad X_{-2}(r_0) = 0$

  Neumann polar $\quad \partial_r X_{-2}(r_0) = 0$

  Corrections to Detweiler's formulation

- The dominant gravitational instability ($l = 2$) is *weaker* than the dominant electromagnetic instability ($l = 1$).



However, the instability timescale is short compared to astrophysical timescales:

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

Partially absorbing surface

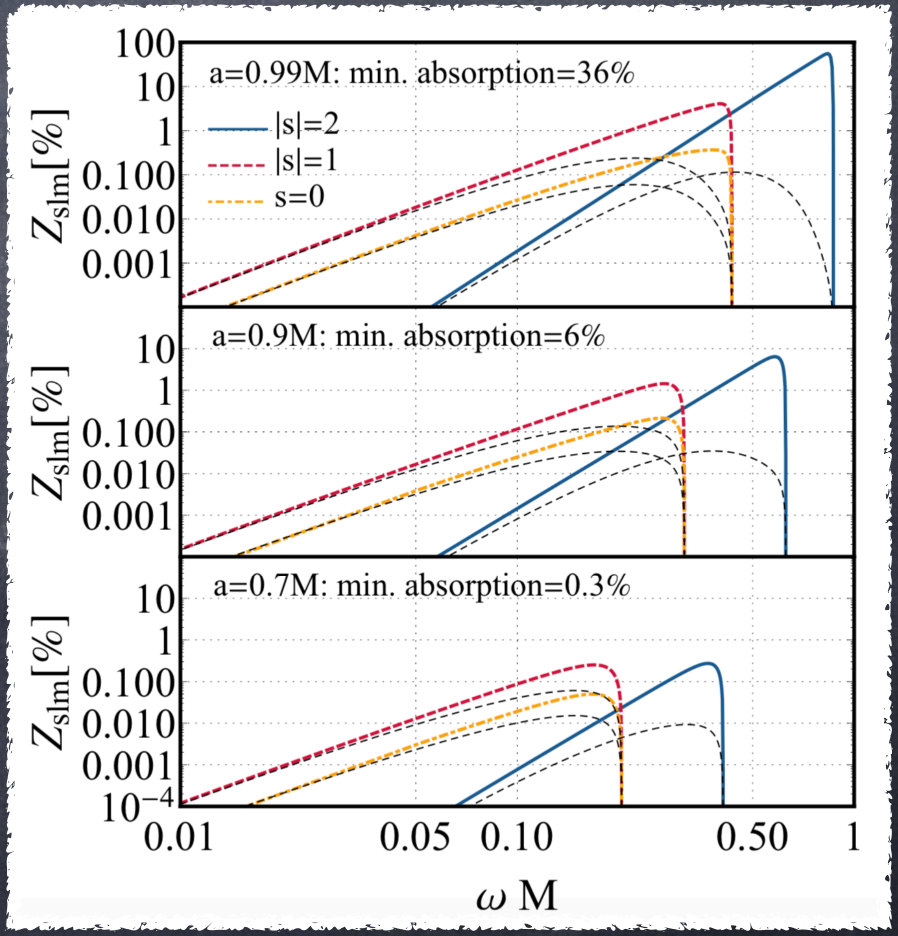
- Partial absorption ($|\mathcal{R}|^2 < 1$) destroys the instability.
- The minimum absorption rate to quench the instability is the maximum amplification factor of superradiance:

$$|\mathcal{R}|^2 > \frac{1}{1+Z_{\rm max}}$$

- In order to have a stable ECO for any perturbation:

Spin	Absorption
0.7	0.3%
0.9	6%
~1	~60%

EM, Cardoso, Dolan, Pani, PRD in press (arXiv:1807.08840)



Conclusion and future perspectives

- In the newly-born era of gravitational waves we can understand the nature of compact objects and look for new physics at the horizon scale.

- We analyzed the stability of Kerr-like ECOs. We showed that for any kind of perturbation

  Perfectly reflecting surface → Ergoregion instability

  Partially absorbing surface → Stable

> Template for echoes from spinning objects [Testa, Pani, Phys. Rev. D98, 044018 (2018)]

> Frequency-dependent absorption [Burgess, Plestid, Rummel, M. J. High Energ. Phys. (2018)]

> Formation of ECOs