Title: Gravitational wave signatures of black hole mimicking objects

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Collection/Series: Strong Gravity

Subject: Strong Gravity

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Abstract:

Gravitational wave observations of strongly gravitating compact objects allow us not only to probe black holes and neutron stars, but also have the potential to uncover new fundamental physics. To distinguish black holes from their mimickers, sufficiently accurate predictions for gravitational wave signatures of these objects are required. Boson stars, a particular representative of the larger class of ultra compact objects, can be used to understand the behavior of these systems and their imprints left on the emitted waveform. I will discuss the inspiral and merger dynamics of binary boson stars, focusing particularly on the ringdown phase, and comment on the appearance of gravitational wave echoes in the post-merger phase of black hole mimickers more broadly.

Strong Gravity Seminar

Gravitational wave signatures of black hole mimickers

Nils Siemonsen
Princeton Gravity Initiative

February 6, 2025

Princeton gravity Initiative

GW190814: Gravitational Waves from the Coalescence of a $23\,M_\odot$ Black Hole with a $2.6\,M_\odot$ Compact Object

LIGO Scientific Collaboration and Virgo Collaboration

(Dated: June 24, 2020)

ABSTRACT

We report the observation of a compact binary coalescence involving a $22.2 - 24.3\,M_\odot$ black hole and a compact object with a mass of $2.50 - 2.67\,M_\odot$ (all measurements quoted at the 90% credible level). The gravitational-wave signal, GW190814, was observed during LIGO's and Virgo's third observing run on August 14, 2019 at 21:10:39 UTC and has a signal-to-noise ratio of 25 in the three-detector network. The source was localized to 18.5 $\deg^2$ at a distance of 241^{+41}_{-45} Mpc; no electromagnetic counterpart has been confirmed to date. The source has the most unequal mass ratio yet measured with gravitational waves, $0.112^{+0.008}_{-0.009}$, and its secondary component is either the lightest black hole or the heaviest neutron star ever discovered in a double compact-object system. The dimensionless spin of the primary black hole is tightly constrained to ≤ 0.07. Tests of general relativity reveal no measurable deviations from the theory, and its prediction of higher-multipole emission is confirmed at high confidence. We estimate a merger rate density of 1–23 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ for the new class of binary coalescence sources that GW190814 represents. Astrophysical models predict that binaries with mass ratios similar to this event can form through several channels, but are unlikely to have formed in globular clusters. However, the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models for the formation and mass distribution of compact-object binaries.

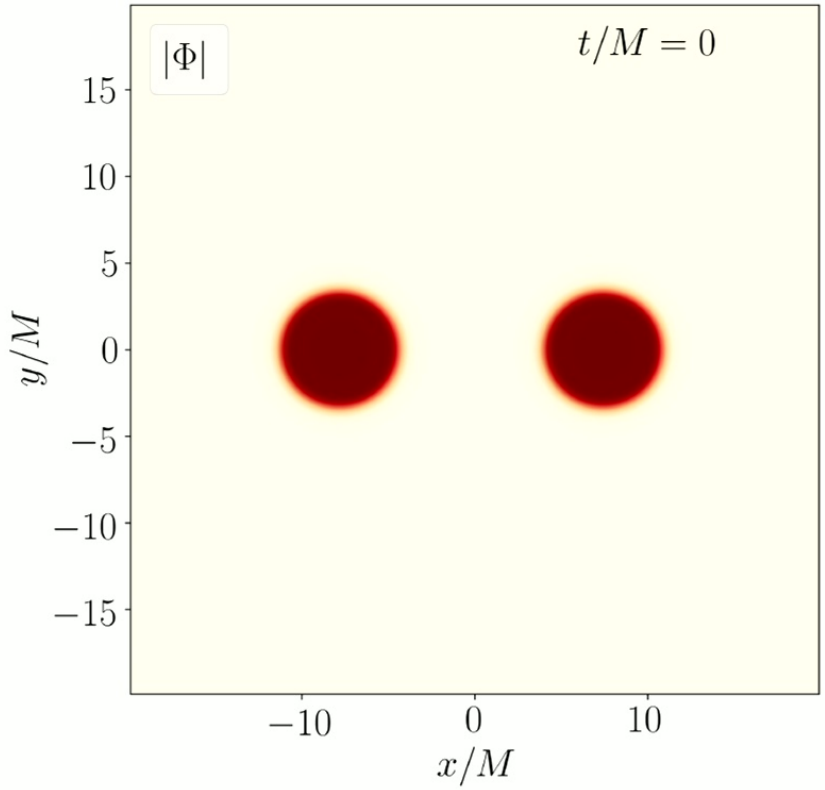
Exotic compact objects

[Cardoso & Pani, 2019]

Model	Formation	Stability	EM signatures	GWs
Fluid stars	✓ [90]	✓ [85, 88, 109–113]	✓	✓ [85, 109, 112, 114]
Anisotropic stars	✗	✓ [115–117]	✓ [118–120]	✓ [115, 119, 120]
Boson stars & oscillatons	✓ [53, 54, 121–123]	✓ [86, 124–128]	✓ [91, 129, 130]	✓ [131–138]
Gravastars	✗	✓ [127, 139]	✓ [140–142]	∼ [112, 113, 135, 136, 138, 142–148]
AdS bubbles	✗	✓ [149]	∼ [149]	✗
Wormholes	✗	✓ [150–153]	✓ [154–157]	∼ [136, 138, 148]
Fuzzballs	✗	✗	✗	

Gravitational waveforms
NS & East (2023)

$$C_{1,2} = 0.13 \quad \chi_{1,2} = 0 \quad q = 1 \quad e \sim 10^{-3}$$



Gravitational waveforms
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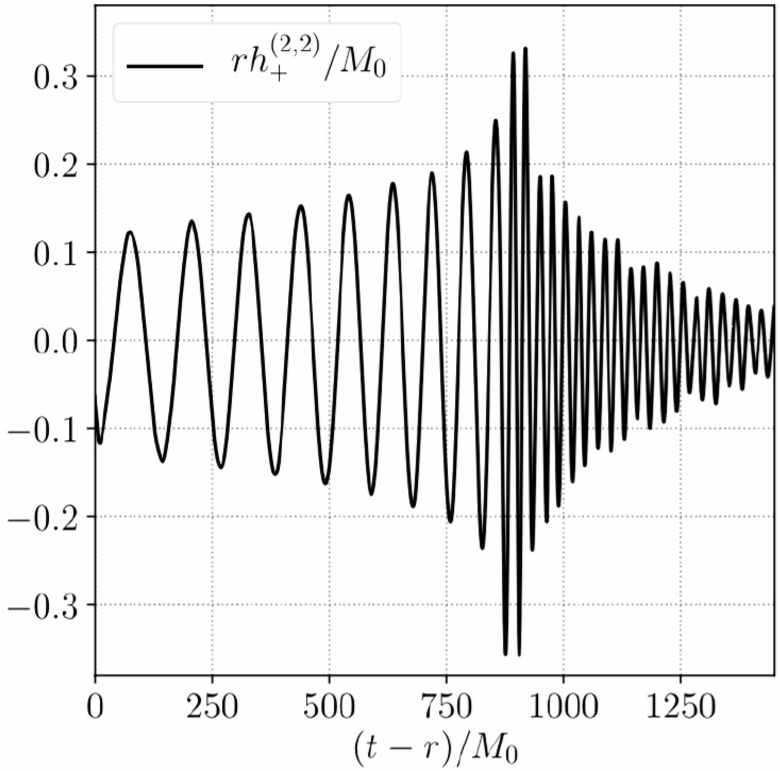
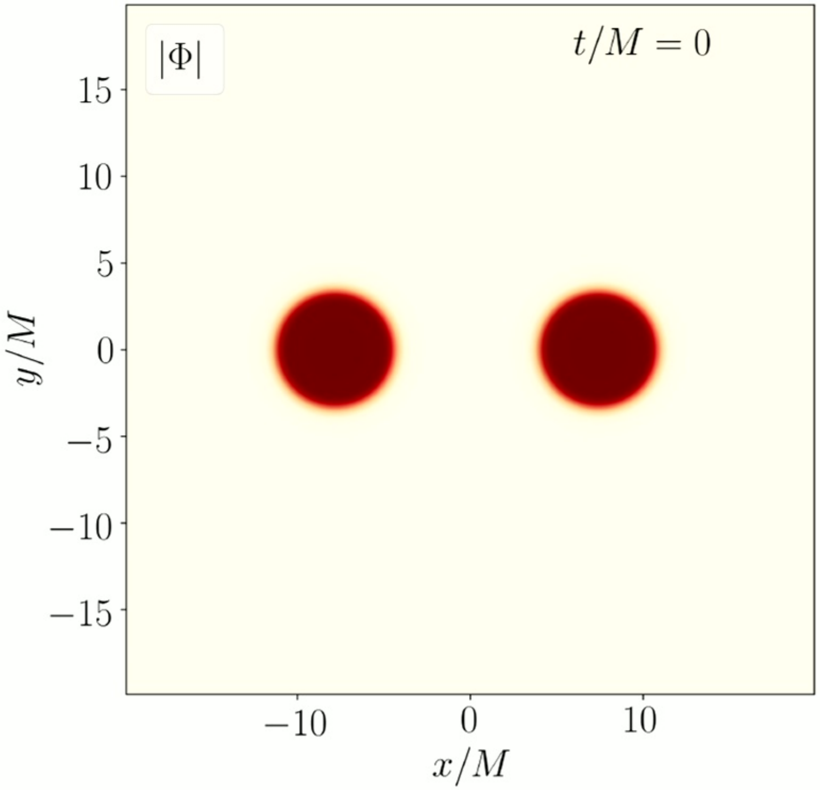


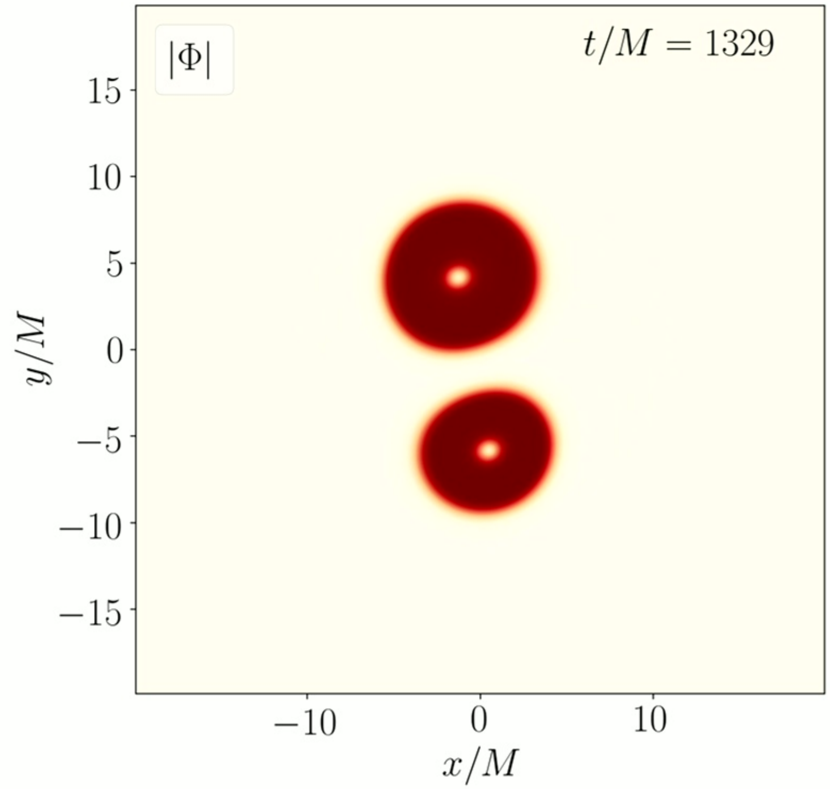


Gravitational waveform

NS & East (2023)

$C_1 = 0.17 \qquad \chi_1 = 1.4 \qquad e \sim 10^{-3}$

$C_2 = 0.14 \qquad \chi_1 = 1.7 \qquad q = 1.43$



Gravitational waveforms
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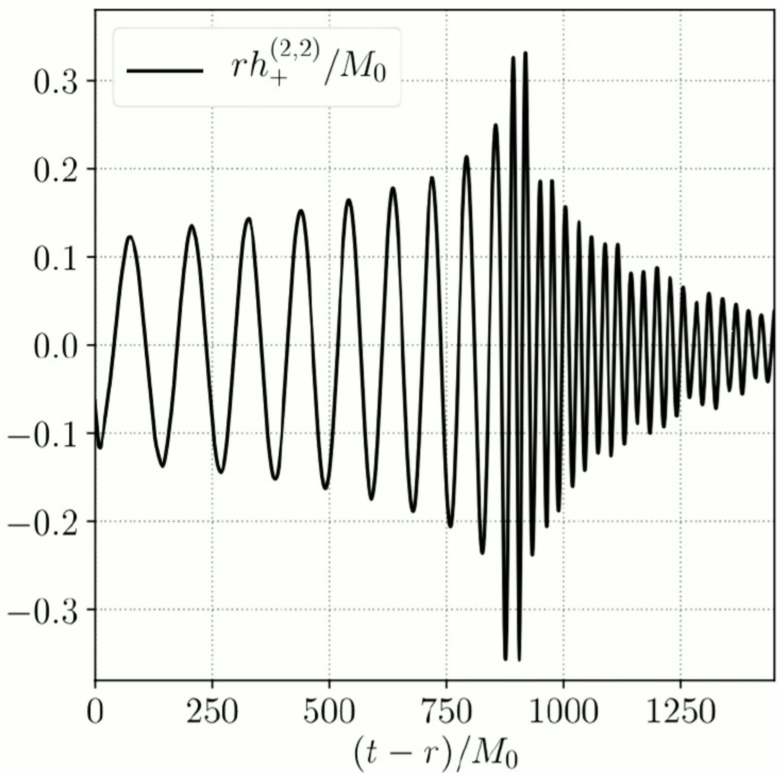
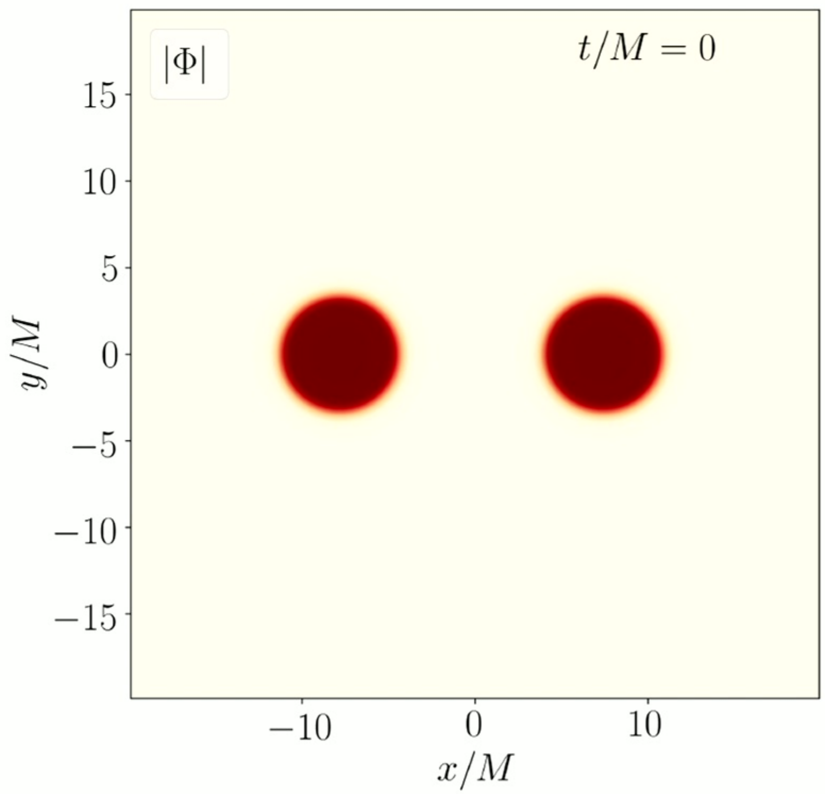
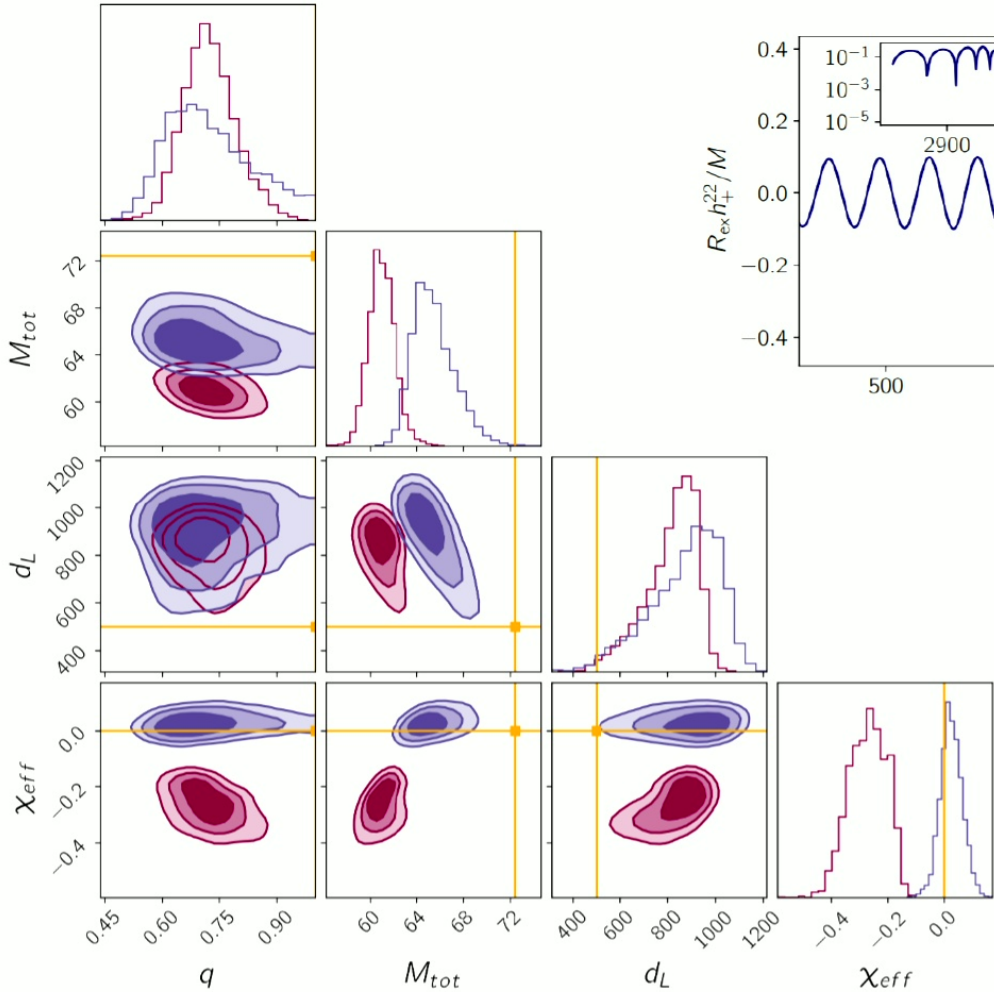
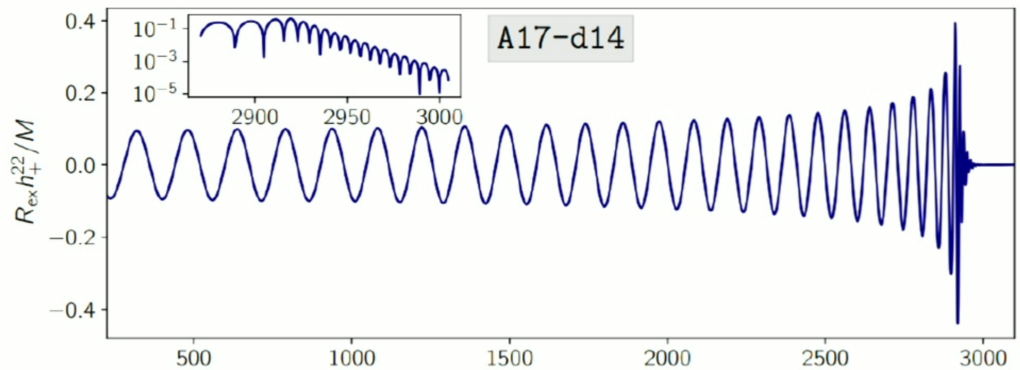




[Evstafyeva et al., 2024]





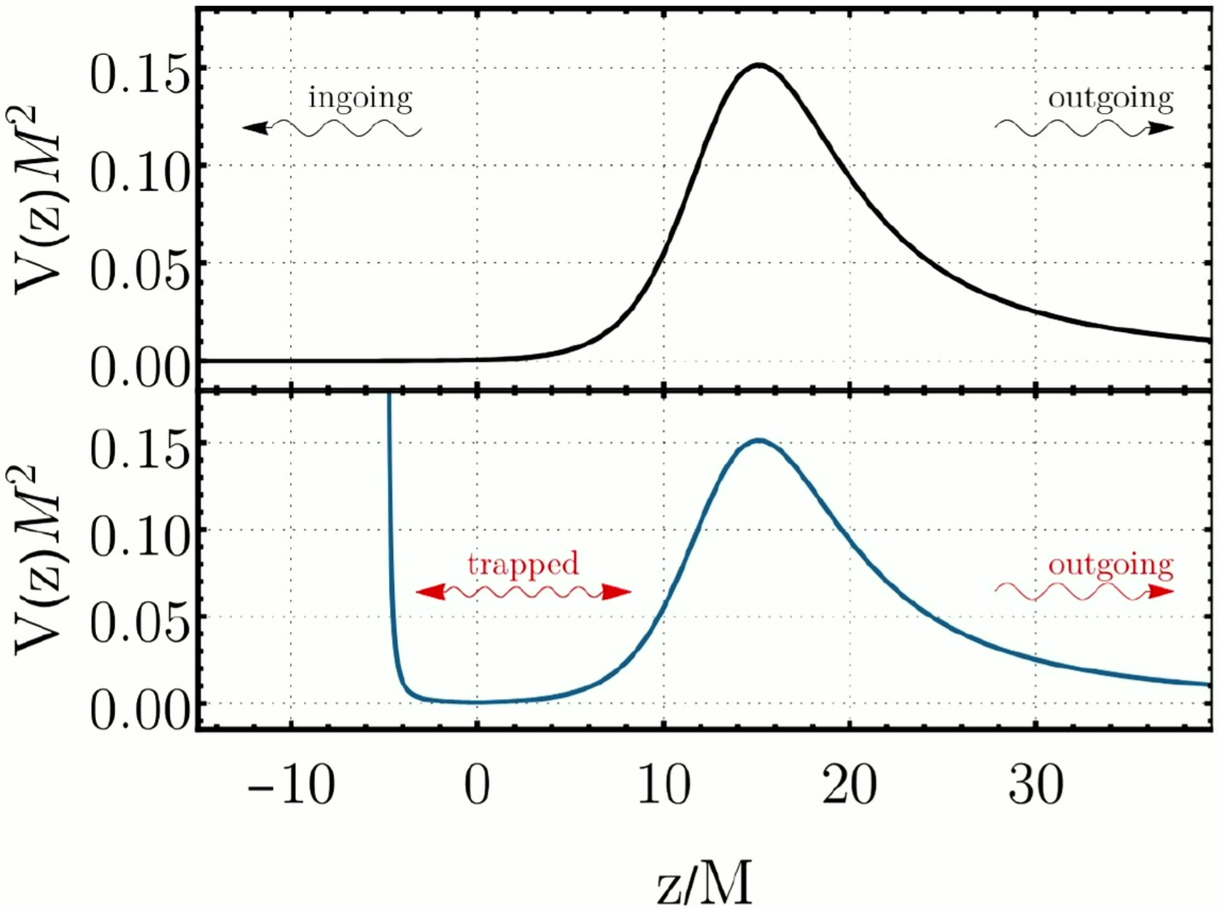
Black hole mimickers

- Classifying objects by their compactness $C = M/R$
  - Newtonian object: $C \ll 0.1$
  - Neutron star: $C \sim 0.1$
  - Black hole: $C = 0.5$
  - Black hole mimicker: $C \lesssim 0.5$

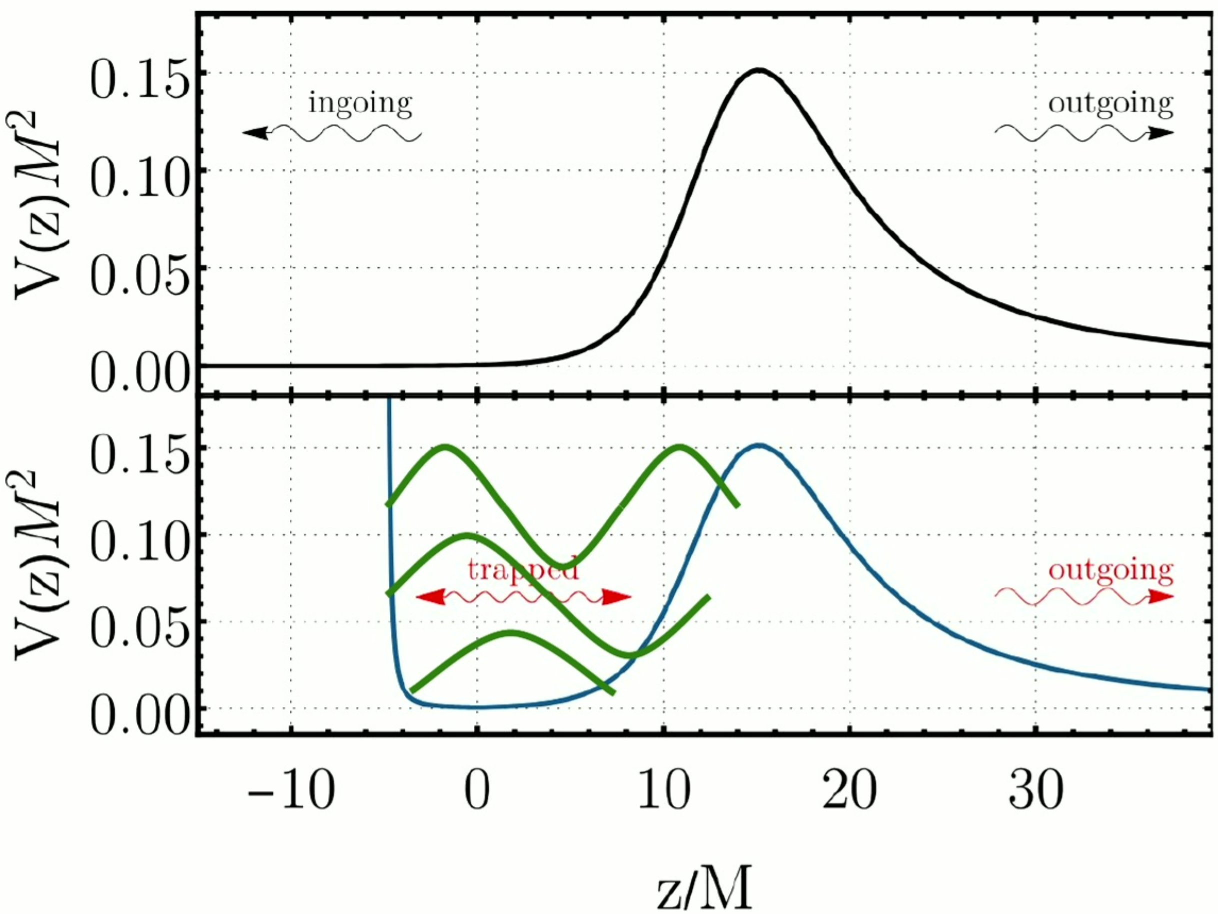
- High-energy physics inspired:
  - AdS black shells [Giri, Danielsson, ...]
  - Fuzzballs [Mazur, Heidemann, ...]
  - Gravastars [Mottola, Mathur, ...]
  - Frozen stars [Brustein, ...]

- Relativistic features: “dark”, no horizons, stable light rings, ergoregions, ...

[Cardoso & Pani, 2019]

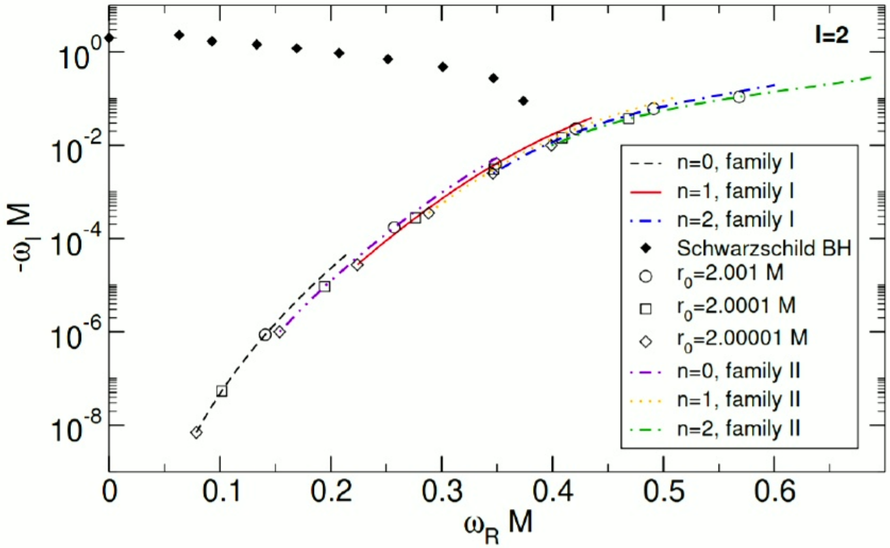


[Cardoso & Pani, 2019]

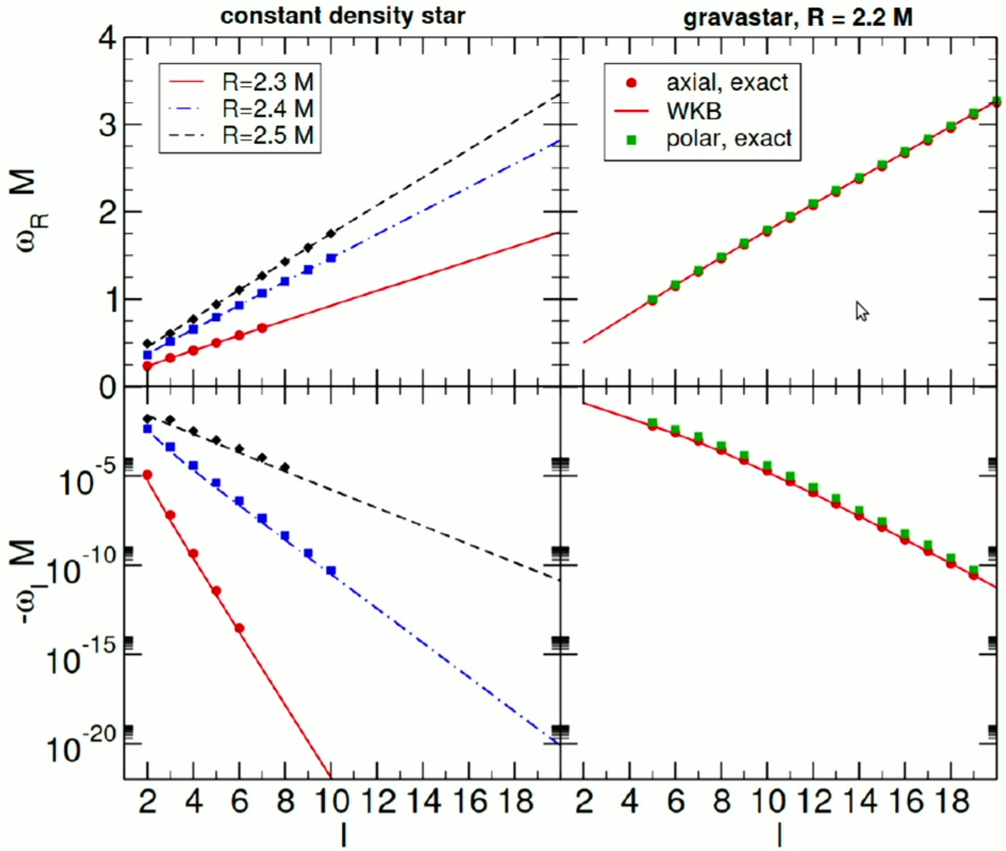


Mimicker QNM spectra

[Cardoso+, 2016]

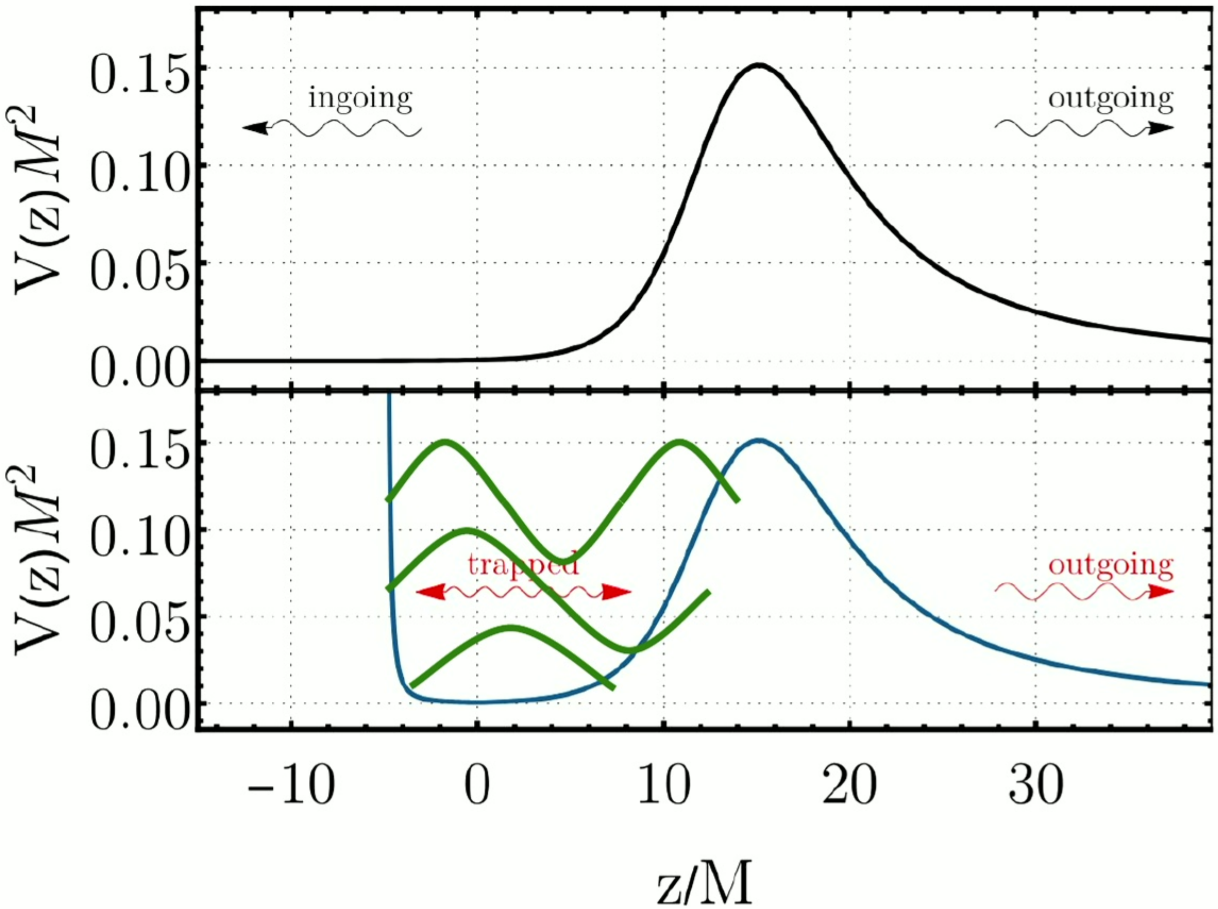


[Cardoso+, 2014]

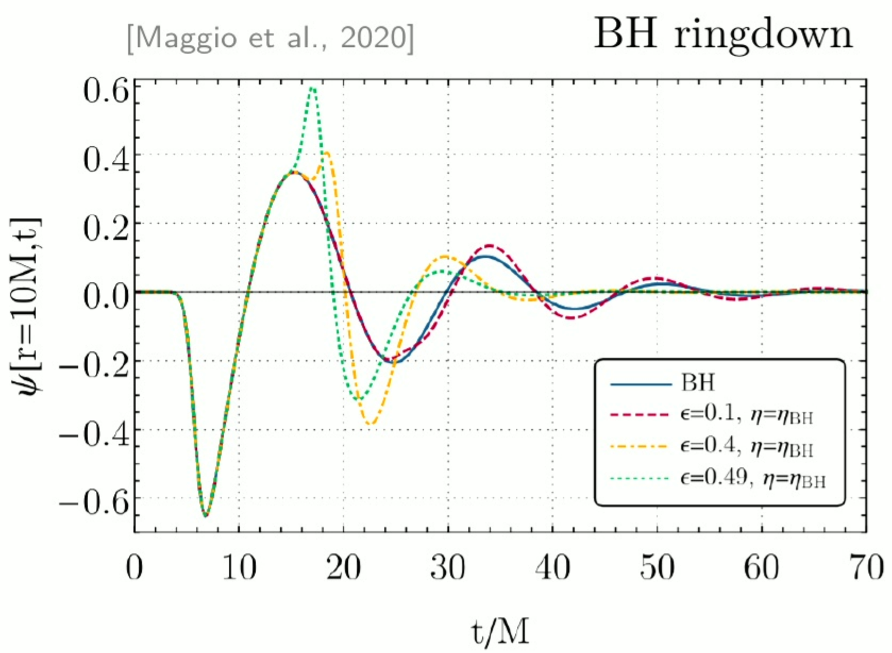


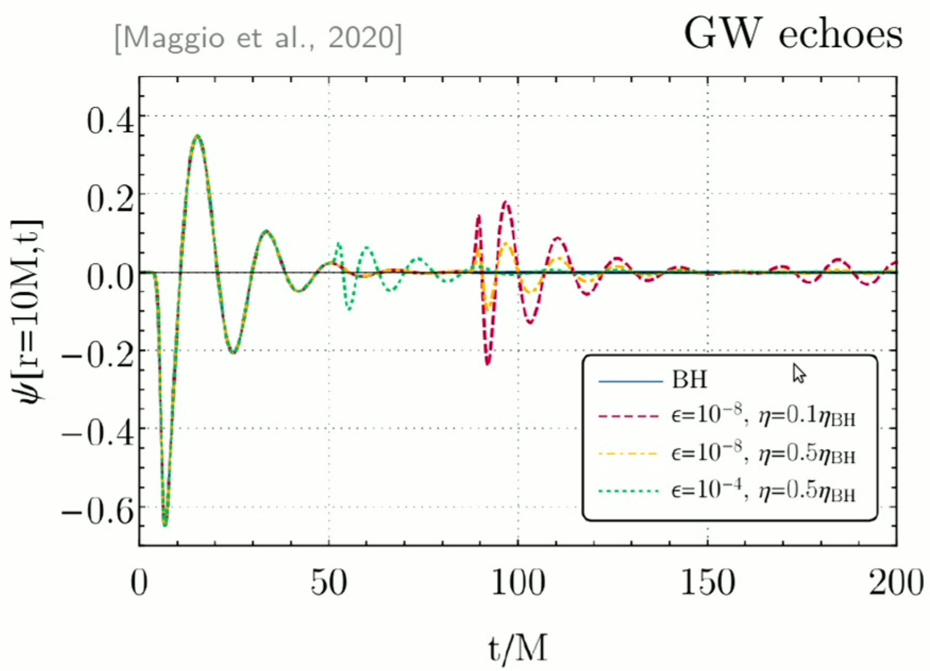
- Black hole modes
- Tower of long-lived modes
- Eikonal limit: $\omega_I \to 0$

[Cardoso & Pani, 2019]



Gravitational wave echoes

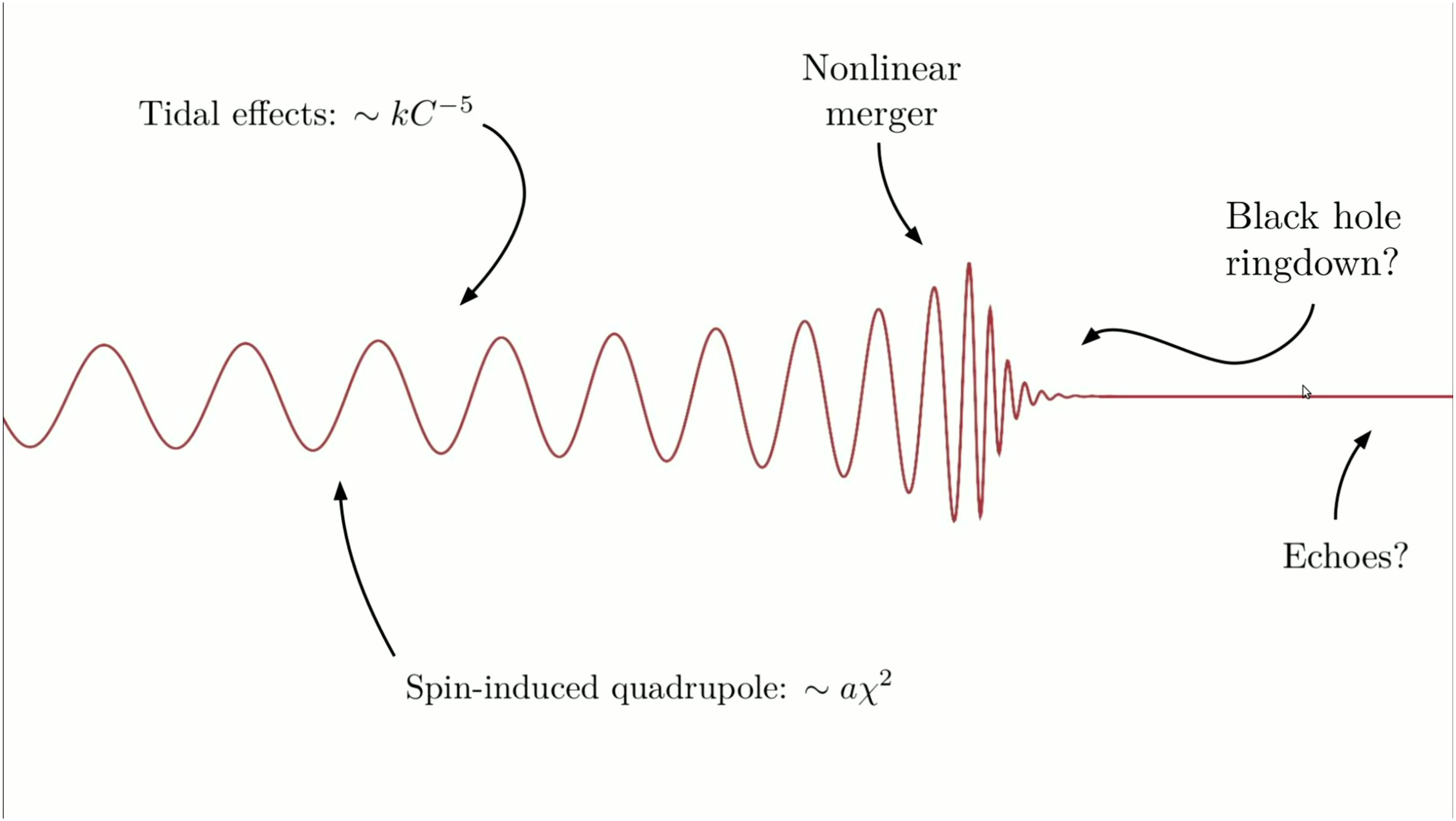




$$R_{\rm obj} = 2M(1+\epsilon)$$

$$\text{BH} : \epsilon = 0$$

$$\text{LR} : \epsilon = 1/2$$



Tidal effects: $\sim kC^{-5}$
Nonlinear merger
Black hole ringdown?
Echoes?
Spin-induced quadrupole: $\sim a\chi^2$

Mimicker ringdown so far

- Point particle falling into Kerr-like mimicker imposing boundary conditions
  Cardoso+ (2016), Mark+ (2017), Maggio+ (2021), Micchi+ (2021), ...
- Test-field scattering waves
  Cardoso+ (2016), Raposo+ (2018), Maggio+ (2020), Ikeda+ (2021), ...
- Mappings using binary black hole waveforms
  Chen+ (2020), Xin+ (2021), Annulli+ (2021), Srivastava+ (2021), ...
- Other approaches
  Danielsson+ (2021), Dailey+ (2023)

$\Rightarrow$ The nonlinear problem is not solved

Missing physics:

i Nonlinear gravitational effects

ii Role of matter sourcing the spacetime

iii Finize size effects of the objects

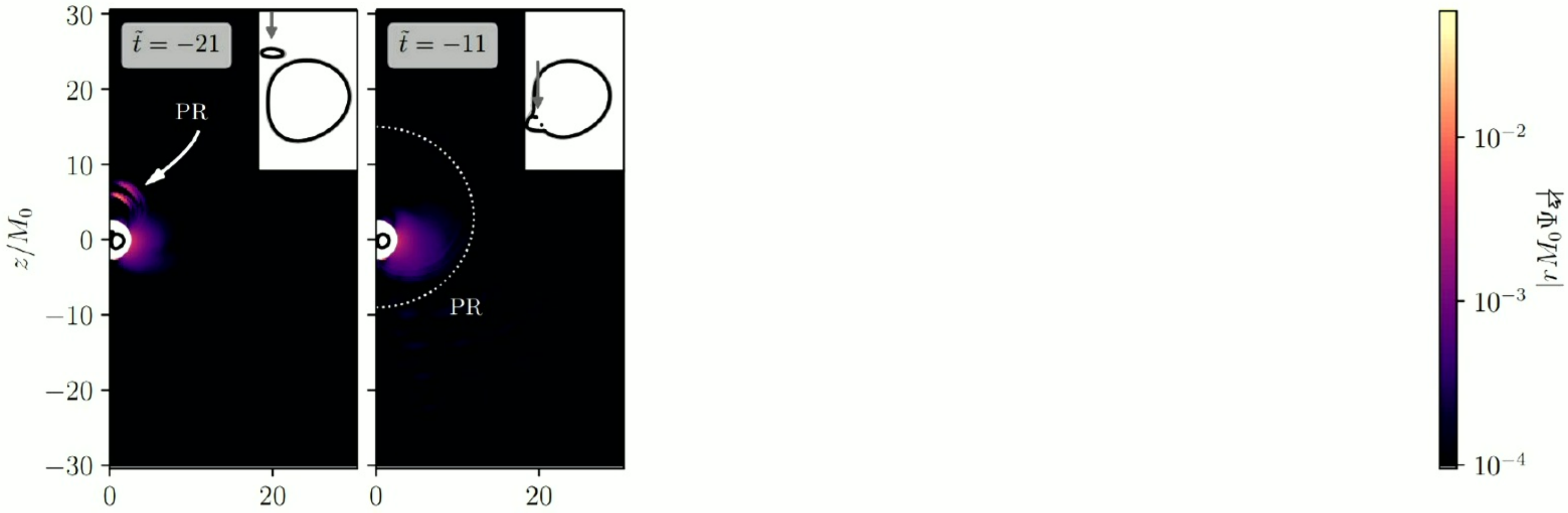
Open questions:

i Is the prompt emission black hole-like?

ii What are the amplitudes of the remnant's quasi-normal modes?

iii How does the remnant's spin impact these conclusions?

Merger dynamics
NS (2024)



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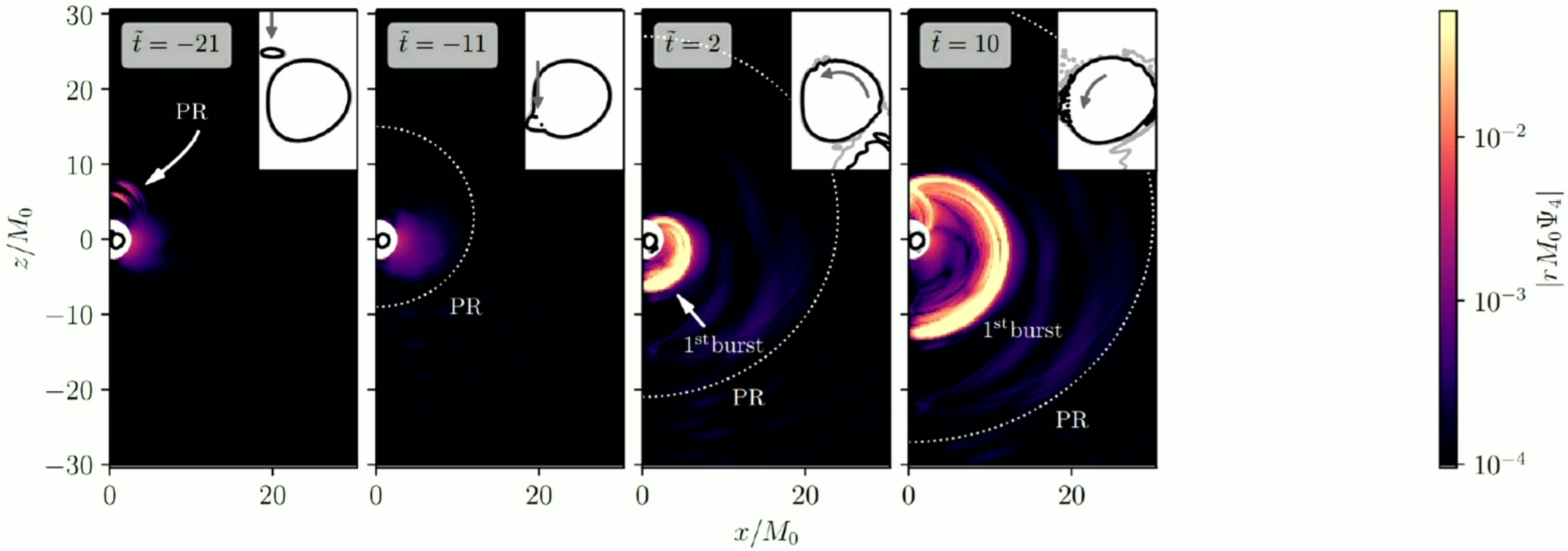
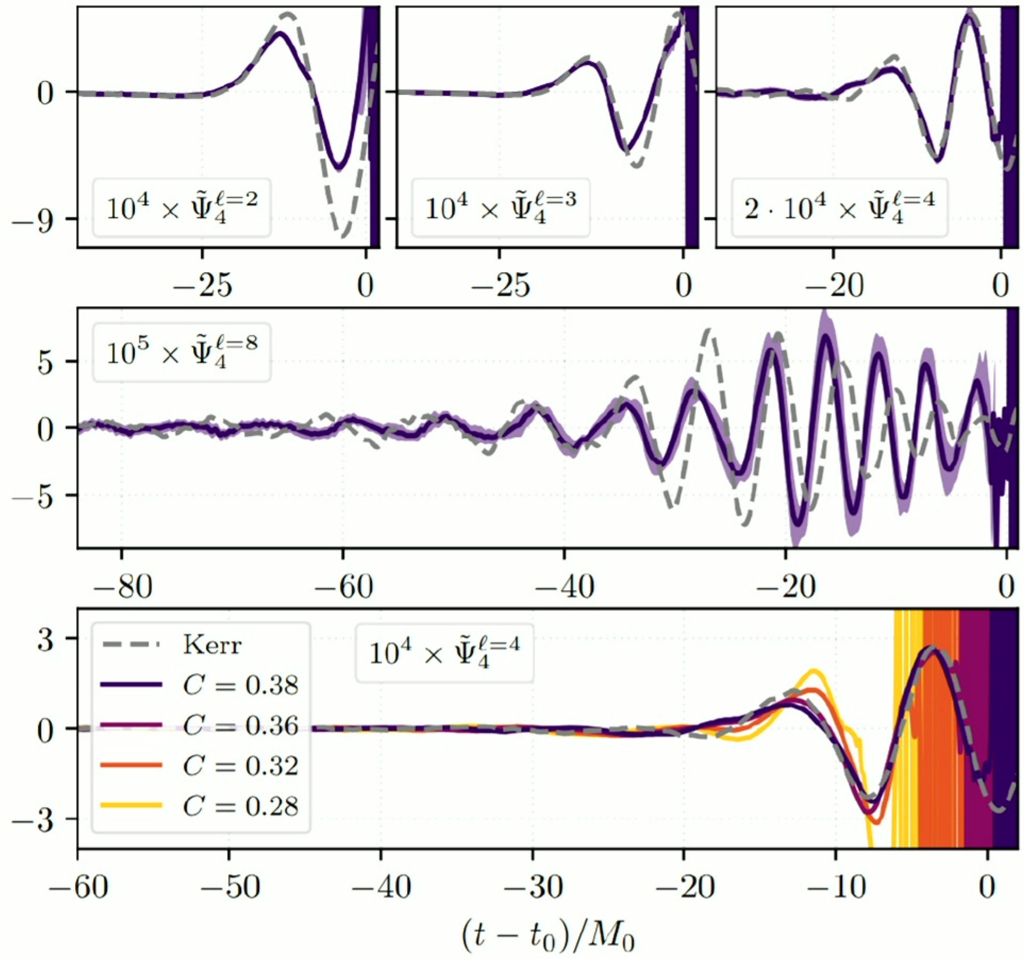
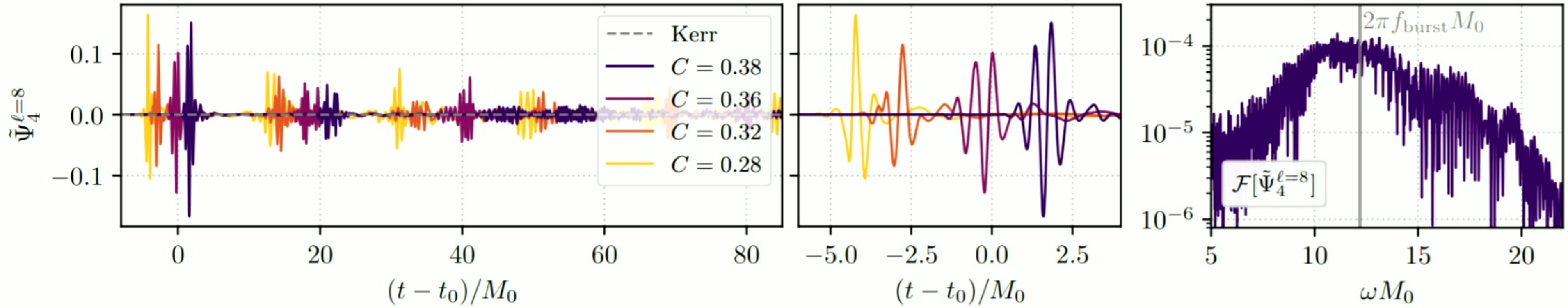


Prompt response
NS (2024)

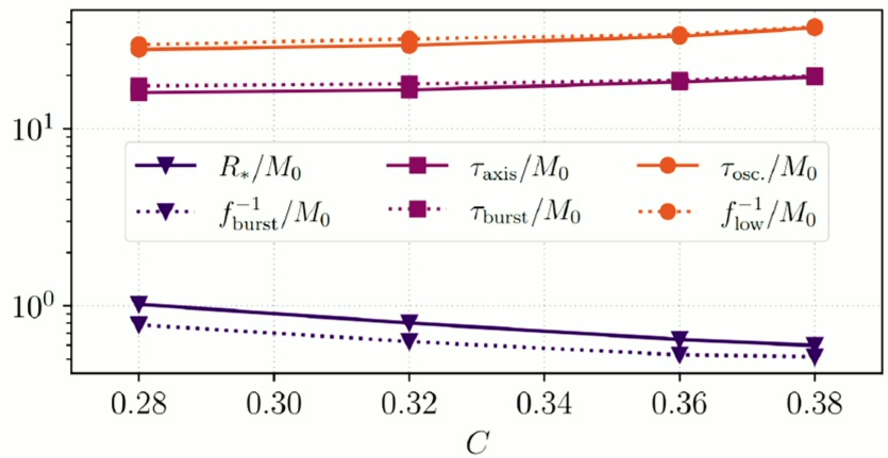


High-frequency component
NS (2024)

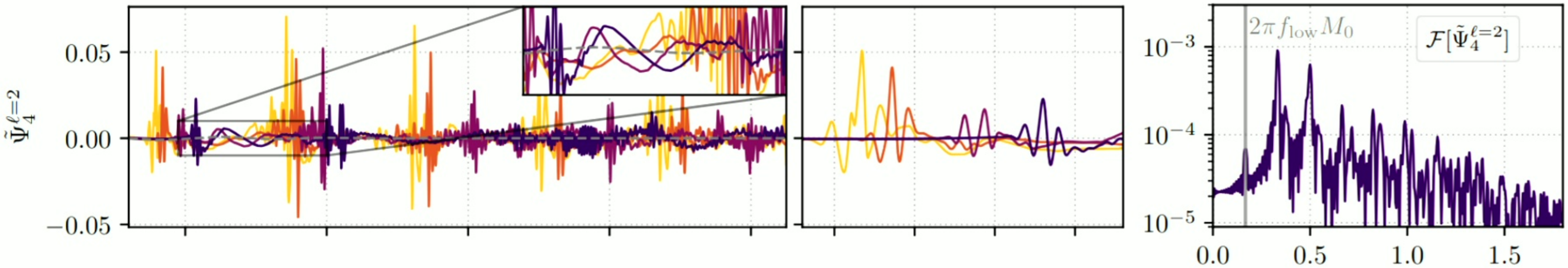


Relevant scales:

- $f_{\rm burst}$: Burst frequency
- $\tau_{\rm burst}$: Burst period
- $\tau_{\rm axis}$: Light crossing time
- R_*: Size of secondary

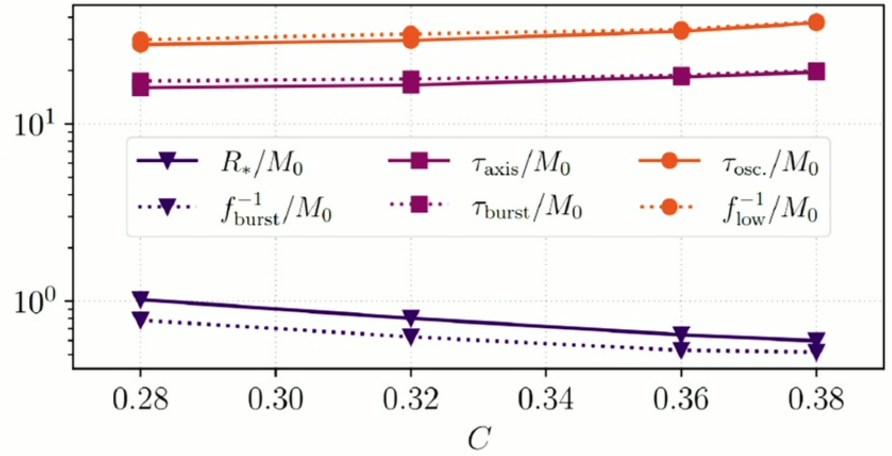


Low-frequency component
NS (2024)



Relevant scales:

- $f_{\rm low}$: Frequency of low-frequency component
- $\tau_{\rm osc.}$: Remnant oscillation period



Comments & Speculations

Comments:

- Burst frequency related to size of secondary
- Large long-lived component
- $h_{\rm burst} \ll h_{\rm long-lived}$

$\Rightarrow$ Waveform not just series of echoes

Speculations:

- For $q \to 1 \;\Rightarrow\; R_*, f_{\rm burst}^{-1} \to M_{\rm remnant}$: Need to model matter
- For $R_* \to M_{\rm remnant}$: Long-lived QNMs excited at large amplitude?

Low-frequency component

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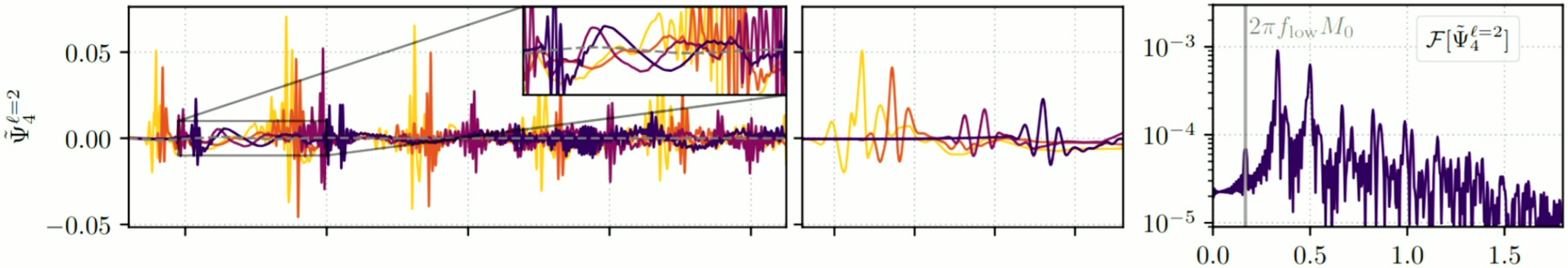

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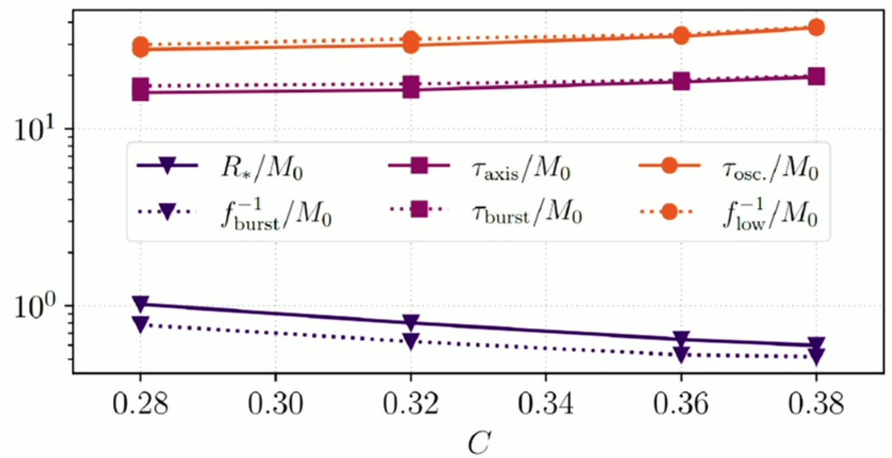

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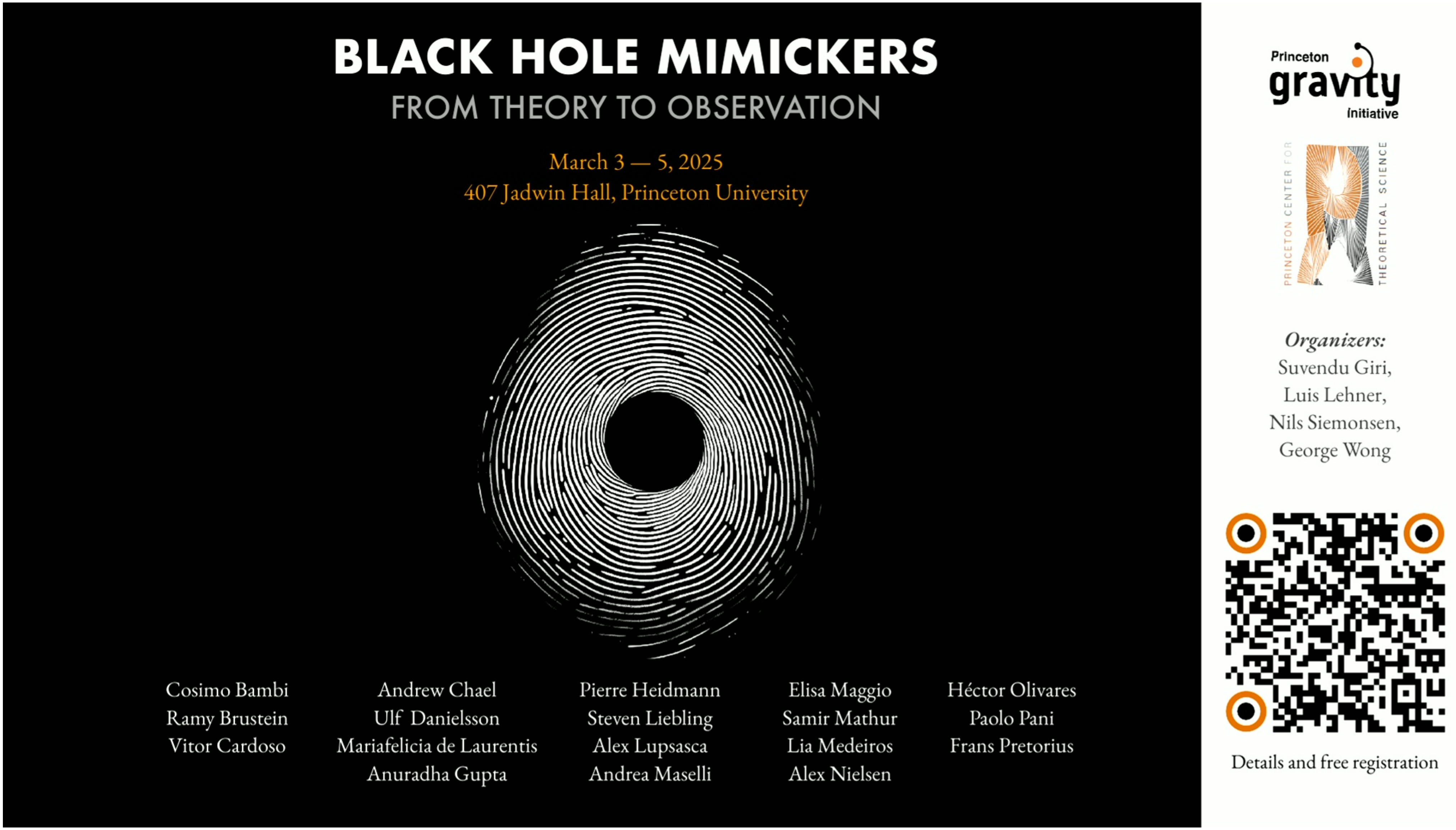
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March 3 — 5, 2025
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