# Hushing black holes: tails in dynamical spacetimes

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# Motivation

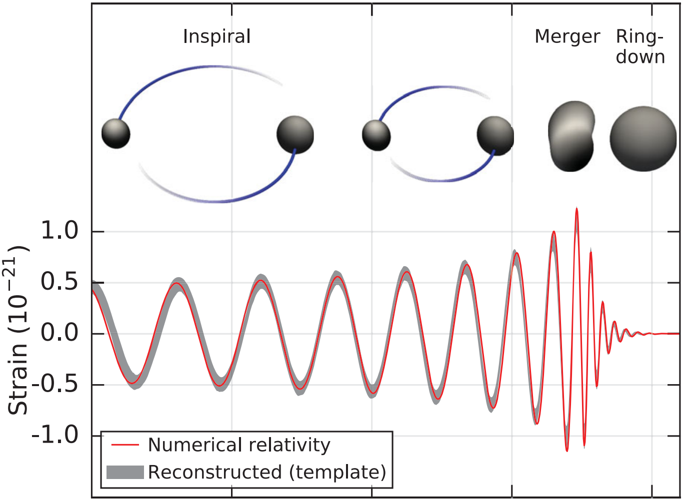



Figure: Inspiral, merger and ringdown phases of coalescence binary black holes (Credit: LIGO and Virgo, 2016)

# Motivation

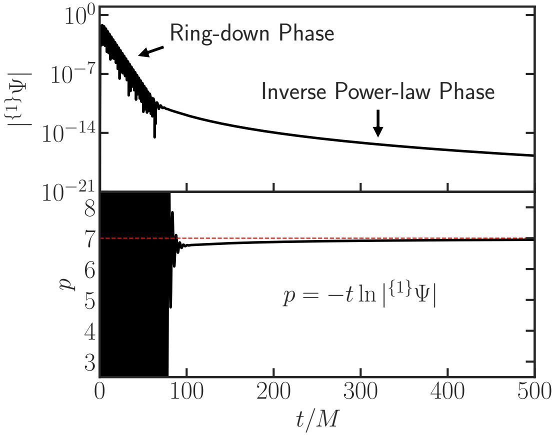



Figure: First order polar gravitational perturbations ($\ell = 2$) on a Schwarzschild background

- Stationary, asymptotically flat black hole solutions belong to the Kerr family
- But, how does one apporach a Kerr black hole, dynamically?
- **Price law**: **Massless field** in **non-spinning BH** background decays at **fixed spatial position**: $|\Psi| \sim t^{-2\ell-3}$

# Eccentric coalescence

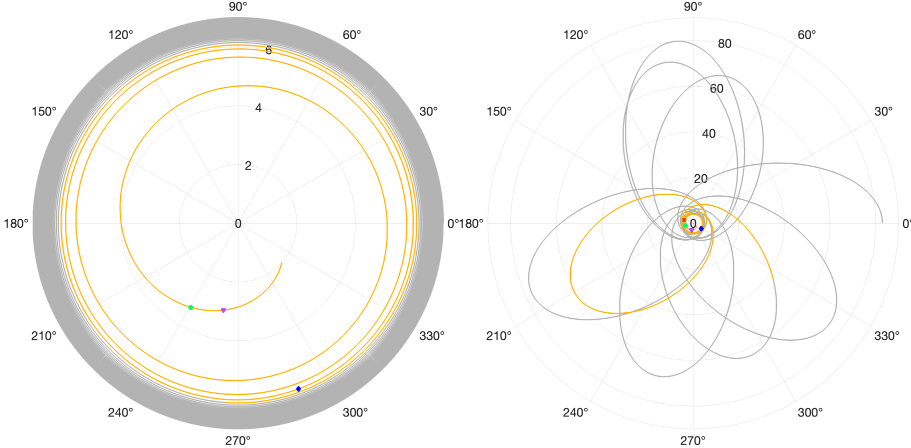



Figure: Effective One Body, Trajectories with initial eccentricity $e_0 = 0$ (quasi-circular) and $e_0 = 0.9$ (Credit: S. Albanesi et al., 2023)

# Eccentric coalescence

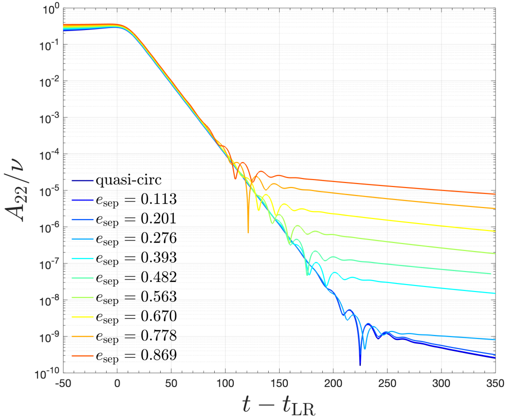
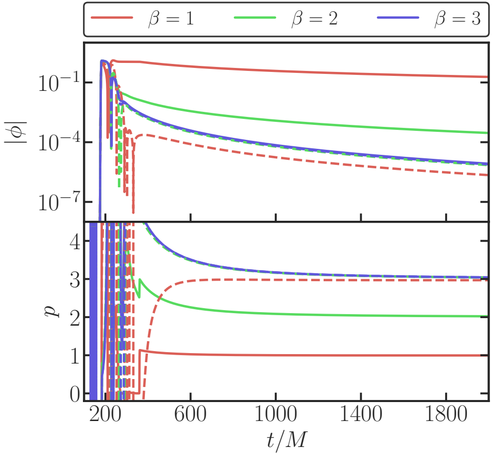



Figure: (Credit: S. Albanesi et al., 2023)

- **Ringdown stage can be much shorter than previously thought**, and very soon dominated by large amplitude transients which **decay slower than Price tails** (Nonlinear: G. Carullo and M. De Amicis, 2023)
- **Linear** but triggered by the motion of sources in the BH vicinity
- **Nonlinear**: (S. Okuzumi et al, 2008)
- Only a transient?




Scalar field, sourced by a **point-like charge** of the form:

$$\nabla^a \nabla_a \Phi = \mathcal{S}\,,$$

$$\mathcal{S} = \sum_{\ell,m} \frac{\delta(x - x_s - vt)}{r^{\beta+1}} Y_{\ell m}$$

$$\frac{\mathrm{d}r}{\mathrm{d}x} = 1 - \frac{2M}{r}$$

Figure: Scattering of a scalar field ($\ell = 0$) in a Schwarzschild background, with $v = \pm 0.5$, $p = -t \log|\phi|$. Solid (dashed) lines denote outward (inward) motion.

# Pointlike object around a BH

$$\nabla^a \nabla_a \Phi = \sum_{\ell,m} \frac{\delta(x - x_s - vt)}{r^{\beta+1}} Y_{\ell m}$$

**$-1 \leq v < 0$**

$$\Phi \sim t^{-3-2\ell}$$

**$0 < v < 1$**

$$\Phi \sim t^{-\beta-\ell}\,, \quad \beta \leq \ell + 2\,,$$
$$\Phi \sim t^{-3-2\ell}\,, \quad \text{otherwise}$$

**$v = 1$**

$$\Phi \sim t^{-\beta-\ell}\,, \quad \text{for} \quad \beta = 0, 1\,,$$
$$\Phi \sim t^{-2-2\ell}\,, \quad \text{for} \quad 2 \leq \beta \leq \ell + 2\,,$$
$$\Phi \sim t^{-3-2\ell}\,, \quad \text{otherwise}\,.$$

# A realistic setup: pointlike mass following a radial geodesic

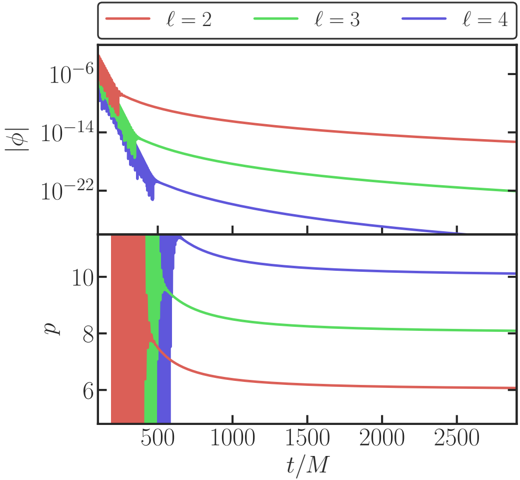



Figure: Tails for massless particle on outgoing radial geodesics on a Schwarzschild background

- **gravitational radiation** from **a pointlike particle** following a **radial geodesic** in a Schwarzschild background, governed by the **Zerilli equation**

$$-\partial_t^2\Psi + \partial_x^2\Psi - V_Z\Psi = \mathcal{S},$$

- **massless particles:** $\mathcal{S} \sim r^{-2}, \beta = 2, \upsilon = 1$

# Second order perturbations

- Perturbative expansion

$$\tilde{g}_{\mu\nu} = g_{\mu\nu} + \sum_{n=1}^{\infty} \frac{\varepsilon^n}{n!} {}^{\{n\}}h_{\mu\nu} \tag{1}$$

- **Polar gravitational perturbations**, governed by the Zerilli equation

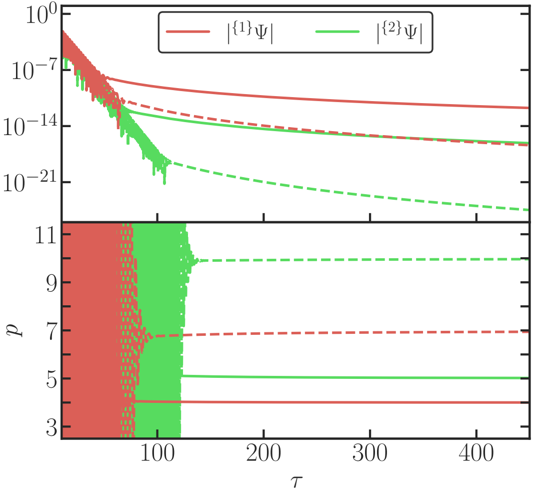
$$-\partial_t^2 {}^{\{1\}}\Psi + \partial_x^2 {}^{\{1\}}\Psi - V_Z {}^{\{1\}}\Psi = 0, \tag{2}$$

$$-\partial_t^2 {}^{\{2\}}\Psi + \partial_x^2 {}^{\{2\}}\Psi - V_Z {}^{\{2\}}\Psi = {}^{\{2\}}\mathcal{S}_\Psi, \tag{3}$$

- 2nd-order source depends on the 1st-order perturbation metric ${}^{\{1\}}h_{\mu\nu}$

$${}^{\{1\}}\Psi \rightarrow {}^{\{1\}}h_{\mu\nu} \rightarrow {}^{\{2\}}\mathcal{S}_\Psi \tag{4}$$

- fall-off of the source term at infinity: ${}^{\{2\}}\mathcal{S}_\Psi \sim r^{-2}$ **($\beta = 2$?)**




- 1st-order ($\ell = m = 2$) (red line) and 2nd-order polar gravitational perturbations ($\ell = m = 4$) (green line) sourced by self-coupling of the former.
- **2nd-order tails can dominate over linear ones at late times** $^{\{2\}}\Psi \sim t^{-2-2\ell}$ **for some selection rules.**
- QNM for 2nd-order
  - QNM with $\ell = 4$
  - two times QNM with $\ell = 2$

# Final Remarks

- Source-driven tails for outwards travelling sources
- The 2nd-order tails can dominate over linear ones with some selection rules

$$(\ell = 2, m = 2) \rightarrow (\ell = 4, m = 4)$$

- The second order perturbations have two family of quasinormal modes
  - linear modes
  - two times the linear modes for self-coupling case
- **Strong Cosmic Censorship Conjecture (SCCC)**
  - **SCCC is violated** if we only consider **(charged scalar field or charged Dirac field) linear perturbations** in **near-extremal RNdS** (Reissner-Nordström-de Sitter) spacetime.
  - Our results suggest that the nonlinear effect might save SCCC.

# About me

- My name is **Zhen Zhong**, a third-year PhD student, under supervision of Prof. Vitor Cardoso, based on University of Lisbon (**expect to graduate in summer of 2025**).
- I have published **14 papers, including 1 PRL, 8 PRDs, 2 JHEPs, and 3 PLBs** (more papers are ongoing or under review). My research mainly focus on **GR and Black Hole Physics**, such as
  - Numerical Relativity
  - Black Hole Shadows
  - Strong Cosmic Censorship
- Technically speaking, I focus on simulating interesting physical phenomena using **state-of-the-art numerical techniques** and **professional programming skills**.
- I'm looking for a postdoc position for 2025

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