Black Hole Ringdown in an Astrophysical Environment

Petr Kotlařík

based on joint work with Che-Yu Chen, arXiv:2307.07360

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Quasinormal modes

ringing a black hole

$\longrightarrow$ field dynamics $\Rightarrow$ the whole system is dissipative

$\longrightarrow$ exponential decay of gravitational waves

$\longrightarrow$ sum of exponentially damped sinusoids $\equiv$ **quasinormal modes**

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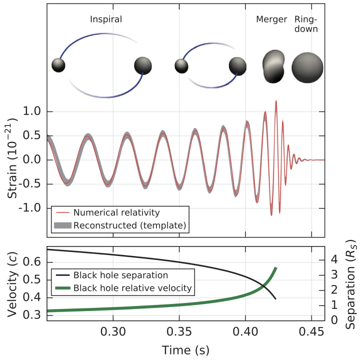

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Black hole spectroscopy is a powerful tool for **testing general relativity** (imprints of new physics?):

- modified theories of gravity
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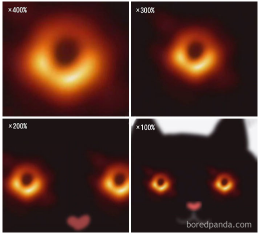

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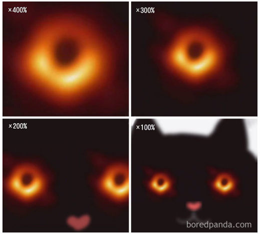

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Ringing astrophysical black holes

Most studies focus on the **static and spherically symmetric case**:a Schwarzschild black hole surrounded by a (dark-)matter halo or dust shells.
(Barausse, Cardoso, and Pani, 2014; Cheung et al., 2022; Cardoso et al., 2022; Konoplya, 2021; Pezzella et al., 2025).

Some open questions:

- Certain **small changes to the system** lead to **instabilities in the QNM spectrum** (Cheung et al., 2022).
- The **fundamental mode** can be extracted from time-domain simulations (Berti et al., 2022), but the role of **overtones** remains uncertain.
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This talk: Accretion disk as a natural astrophysical environment of a black hole

$\longrightarrow$ departing from the spherical symmetry.

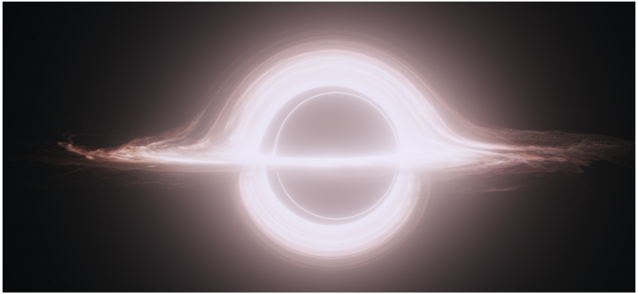

Figure 1: Interstellar black hole (James et al., 2015).

Outline

1. The Schwarzschild + disk model (SBH+disk)
2. QNMs of a scalar field
3. Particular results

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Weyl metric

Gravitational field of **static** and **axially symmetric** vacuum spacetimes is described by

$$ds^2 = -e^{2\nu}\,dt^2 + \rho^2 e^{-2\nu}\,d\phi^2 + e^{2\lambda-2\nu}(d\rho^2 + dz^2)\ , \tag{1}$$

where t, ρ, ϕ, z are the **Weyl** cylindrical **coordinates** and $\nu(\rho, z), \lambda(\rho, z)$.

Vacuum (outside of sources) Einstein equations:

$$\nabla \cdot (\nabla \nu) = 0 \tag{2}$$

$$\lambda_{,\rho} = \rho(\nu_{,\rho}^2 - \nu_{,z}^2) \tag{3}$$

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Multiple sources in GR

Consider **two** distinct **solutions**, described respectively by ν_1, ν_2, and λ_1, λ_2 respectively

Their common gravitational field is given by

$$\nu = \nu_1 + \nu_2 \,, \tag{5}$$

$$\lambda = \lambda_1 + \lambda_2 + \lambda_{int} \,, \tag{6}$$

where λ_{int} satisfies

$$\lambda_{\text{int},\rho} = 2\rho(\nu_{\text{Schw},\rho}\nu_{\text{disk},\rho} - \nu_{\text{Schw},z}\nu_{\text{disk},z}) \,, \tag{7}$$

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SBH+disk model

Schwarzschild black hole in Weyl coordinates

$$\nu_{\mathrm{Schw}} = \frac{1}{2} \ln \left(\frac{R_+ + R_- - 2M}{R_+ + R_- + 2M} \right) , \qquad \lambda_{\mathrm{Schw}} = \frac{1}{2} \ln \left[\frac{(R_+ + R_-)^2 - 4M^2}{4R_+ R_-} \right] , \tag{9}$$

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$$R_\pm = \sqrt{\rho^2 + (|z| \mp M)^2} \, . \tag{10}$$

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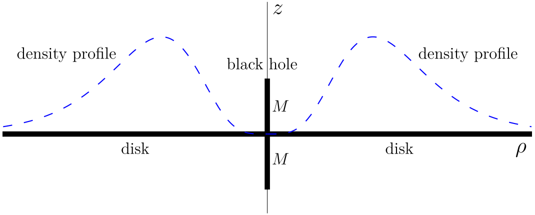

- a **family** of thin disks; potential first considered by (Vogt and Letelier, 2009)
- both metric functions ν, λ found analytically in **closed form** (polynomials and square roots)

$$\text{Newtonian disk density} \propto \frac{\mathcal{M} b^{2m+1} \rho^{2n}}{(\rho^2 + b^2)^{m+n+3/2}}, \quad m, n \in \mathbb{N}_0, \tag{11}$$

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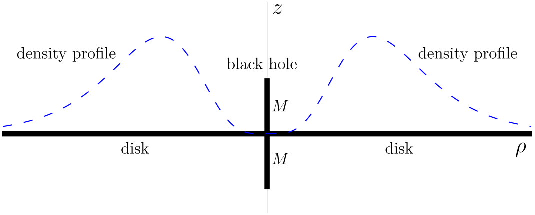

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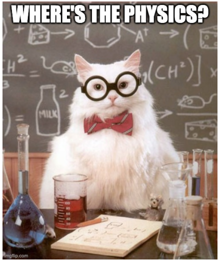
Two simple physical interpretations:

1. ideal fluid with surface density σ and azimuthal pressure P (set of solid hoops)
2. two identical counter-orbiting dust streams with surface densities ($\sigma_+ = \sigma_- \equiv \sigma/2$) following circular geodesics



Both characteristics σ and P are encoded in the jump of the normal derivative of the gravitational potential

$$\sigma + P = \frac{\nu_{,z}(z=0^+)}{2\pi} e^{\nu-\lambda}, \qquad P = \frac{\nu_{,z}(z=0^+)}{2\pi} \rho \nu_{,\rho} e^{\nu-\lambda}.$$

For a wide range of parameters, the disk in SBH+disk model satisfies all energy conditions.

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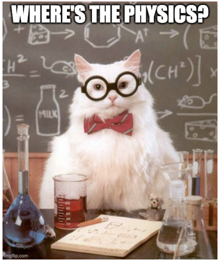

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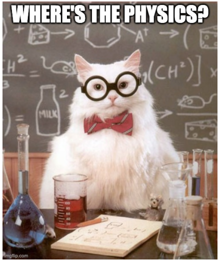

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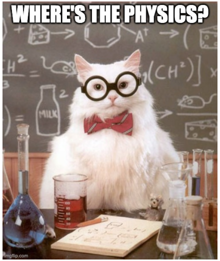

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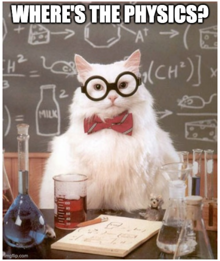

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QNMs of a scalar field

A simpler problem: perturbations of a **massless scalar field**, which are governed by the Klein-Gordon equation

$$\Box\psi = 0\ . \tag{12}$$

The wave equation is separable on the Schwarzschild background in the Schwarzschild coordinates (r,θ): $\rho = \sqrt{r(r-2M)}\sin\theta\,, z = (r-M)\cos\theta\,.$

In particular, the ansatz

$$\psi = \frac{\psi_{\omega\ell m_z}(r)}{r} Y_{\ell m_z}(\theta,\phi) e^{-i\omega t}\,, \tag{13}$$

where $Y_{\ell m_z}$ are the spherical harmonics, leads to the famous Regge–Wheeler-type equation for a scalar field:

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Cano, Fransen, and Hertog (2020): "almost separable" systems, projection method.

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If $\epsilon \equiv \mathcal{M}/M \ll 1$, the wave equation again leads to the Reggee–Wheeler form

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Effective potential

The disk is described by **4 parameters**: 2 positive real $\mathcal{M}$, b, and a pair (m, n).

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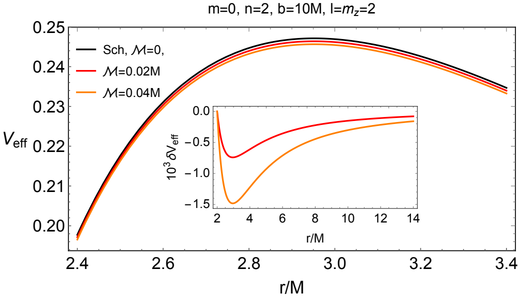
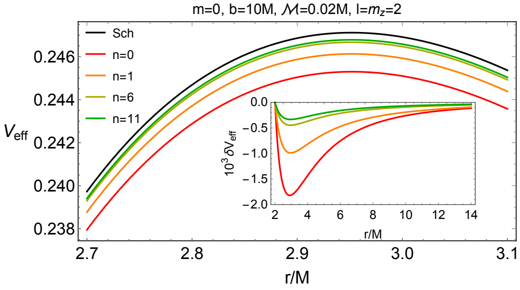
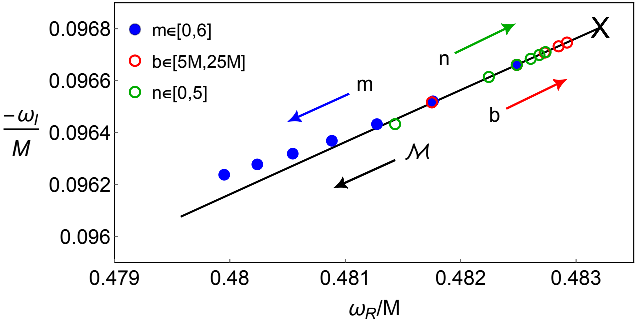




Universal behaviour?

QNM frequencies of the fundamental mode for $\ell = m_z = 2$:



Newtonian disk density

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Remarks:

- BH immersed in spherically symmetric (dark)matter exhibits similar behavior (Cardoso et al., 2022; Konoplya, 2021; Pezzella et al., 2025; Chakraborty, Compère, and Machet, 2025)
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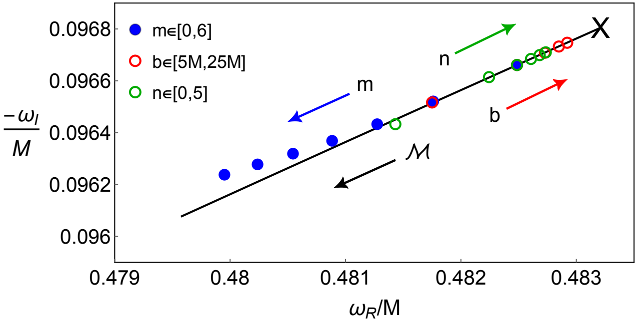

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- Analyze **gravitational QNMs** and address some of the open questions $\longrightarrow$ two types of perturbations involved:
  - deformation of spacetime due to the surrounding matter
  - ringdown gravitational waves
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  - ringdown gravitational waves
- **Systematically compare** with predictions of **alternative theories** of gravity: can the astrophysical environment imitate or obscure potential signatures of modifications to GR?

Brief summary

- QNMs of a scalar field propagating in the SBH+disk background
- disk flattens the effective potential
- QNMs seem to follow a **universal relation**
- can we **disentangle** environmental effects from those induced by alternative theories of gravity?

Thank you for your attention.

Questions?

Brief summary

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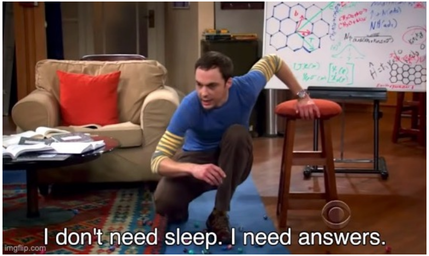
Questions?



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