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Quasi Normal Modes of black holes surrounded by dark matter halos

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Premio Milla Baldo Ceolin
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Milestones

Gravitational wave astronomy as laboratory to test predictions of vacuum GR.

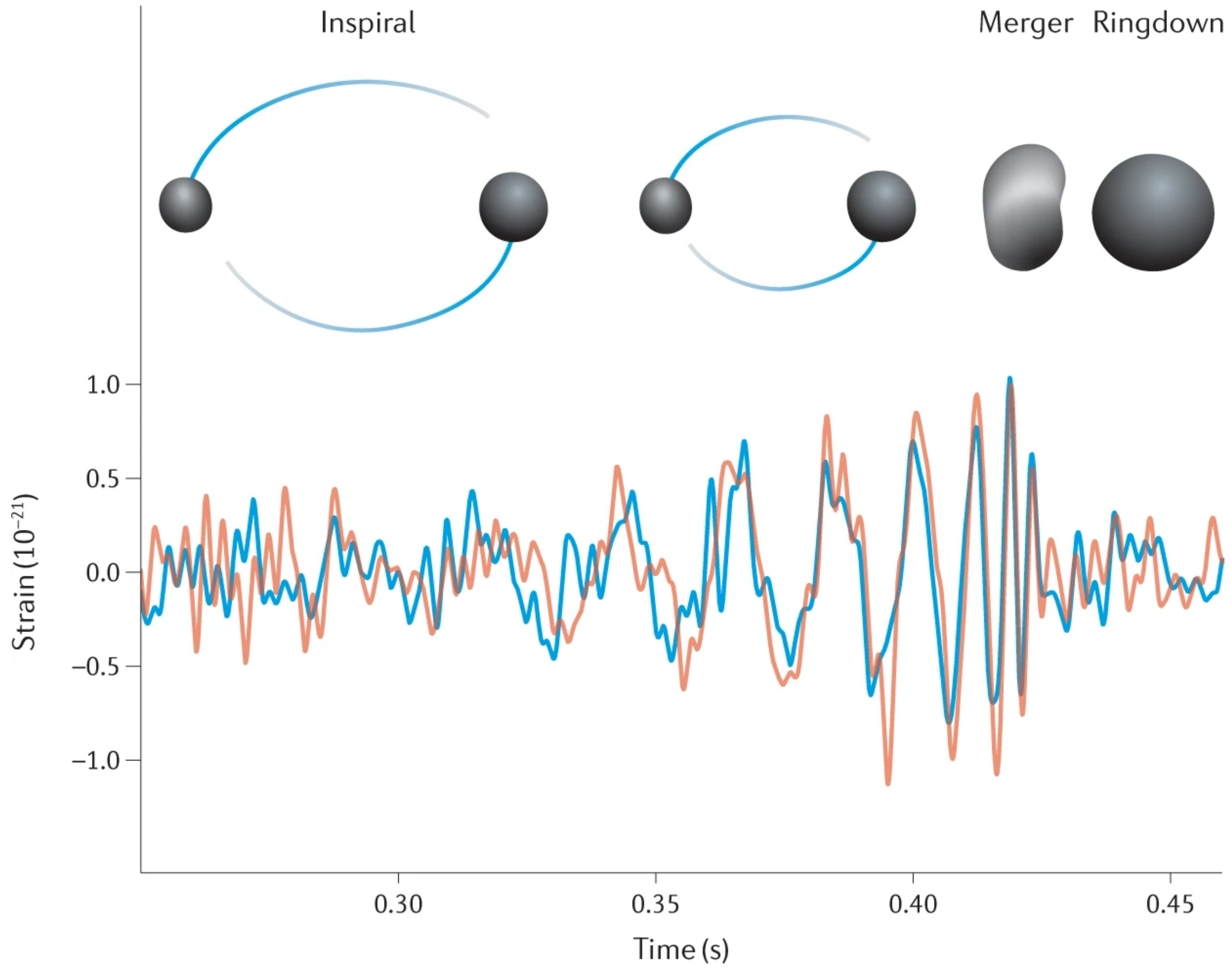
Research topics:

- Test on theories beyond GR
- Study of compact objects
- Study of the environment in which binaries and astrophysical objects evolve

Gravitational waves

Although the concept of gravitational waves was introduced by Einstein in 1916, the debate on their existence was not settled until the 1960s.

For coalescing events, the signal should comprise three pieces: an inspiral waveform, a merger waveform and a ringdown waveform.



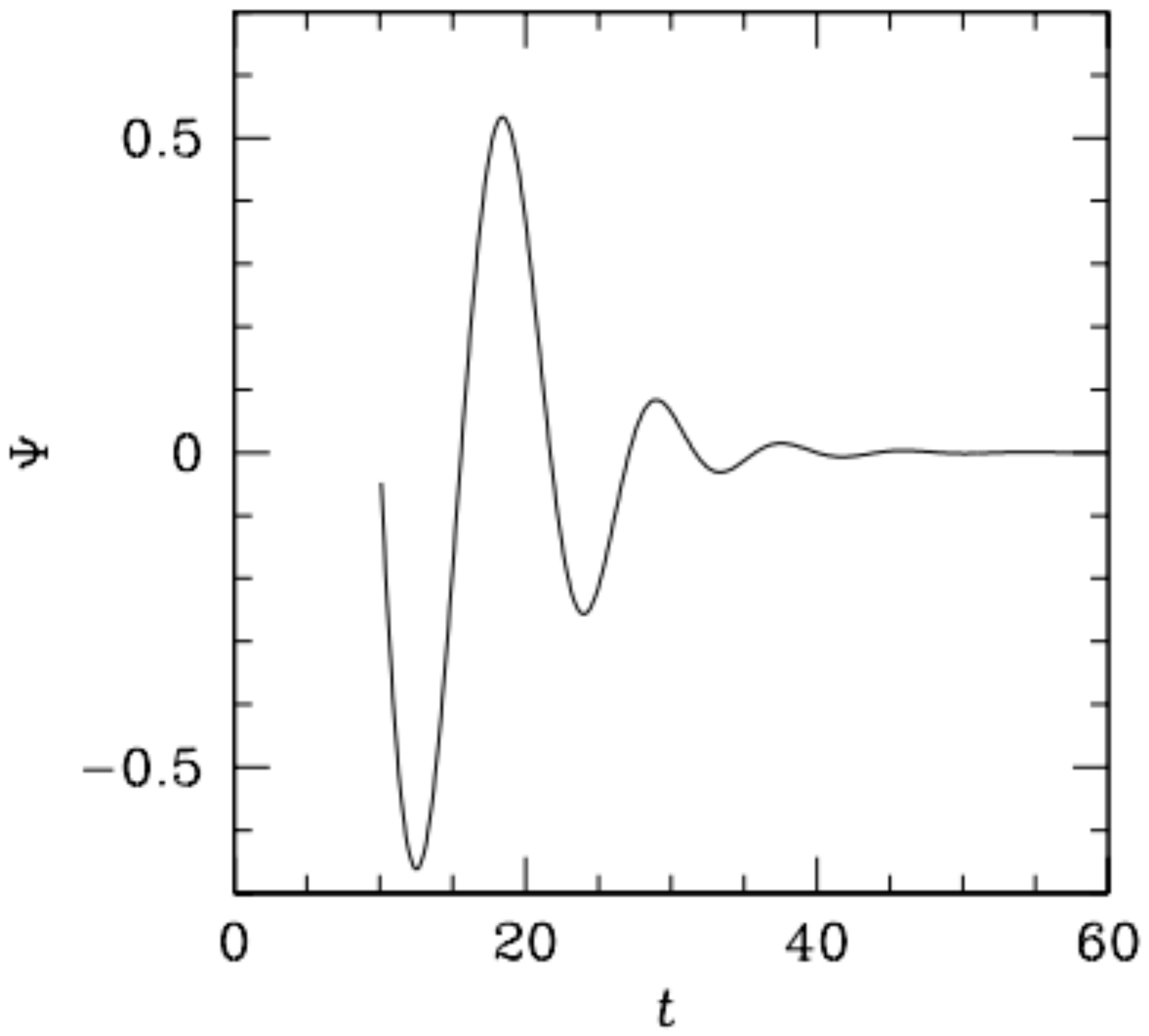
Abbott, B. P. et al, *Phys. Rev. Lett.* **116** (2016).

Ringdown and QNM

The ringdown waveform originates from the distorted final product of the merger.

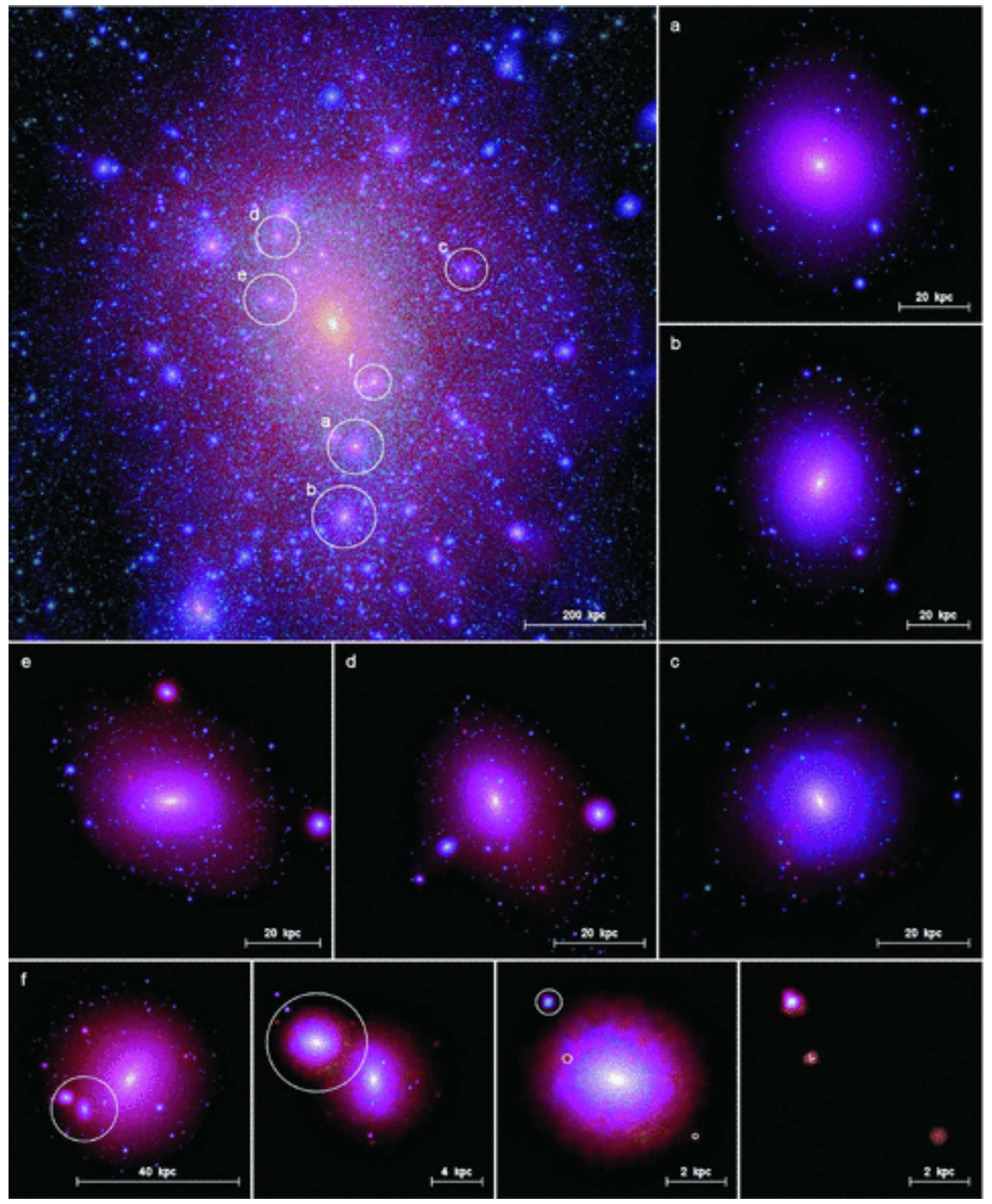
The ringdown can be approximated by a superposition of a complex set of eigenvalues: the quasinormal modes (QNMs).

In vacuum GR, QNMs depend only on the mass and spin of BHs.



V. Cardoso, 2003

Dirty black holes



V. Springel+, 2008

Compact objects evolve embedded in a variety of gas/matter fields, which may leave detectable imprints on GW.

Dark matter may cluster at the center of galaxies and close to BHs, affecting the dynamics of compact binaries and the propagation of gravitational waves.

Some questions

- Can we infer properties on the environment in which binaries evolve?
- Are there systematic effects in waveform modeling due to environmental effects?
- How do different computational methods behave when extending the search for QNMs from vacuum GR to the case of dirty black holes?

The perturbation scheme

The gravitational perturbations of a BH background induced by a massless probe field

Can be decoupled into

$$g_{\mu\nu} = g^0_{\mu\nu} + h_{\mu\nu}$$

$$h_{\mu\nu} = h^{\text{pol}}_{\mu\nu} + h^{\text{ax}}_{\mu\nu}$$

where the polar components share the same parity as the scalar spherical harmonics $(-1)^\ell$ and the axial components the opposite parity $(-1)^{\ell+1}$

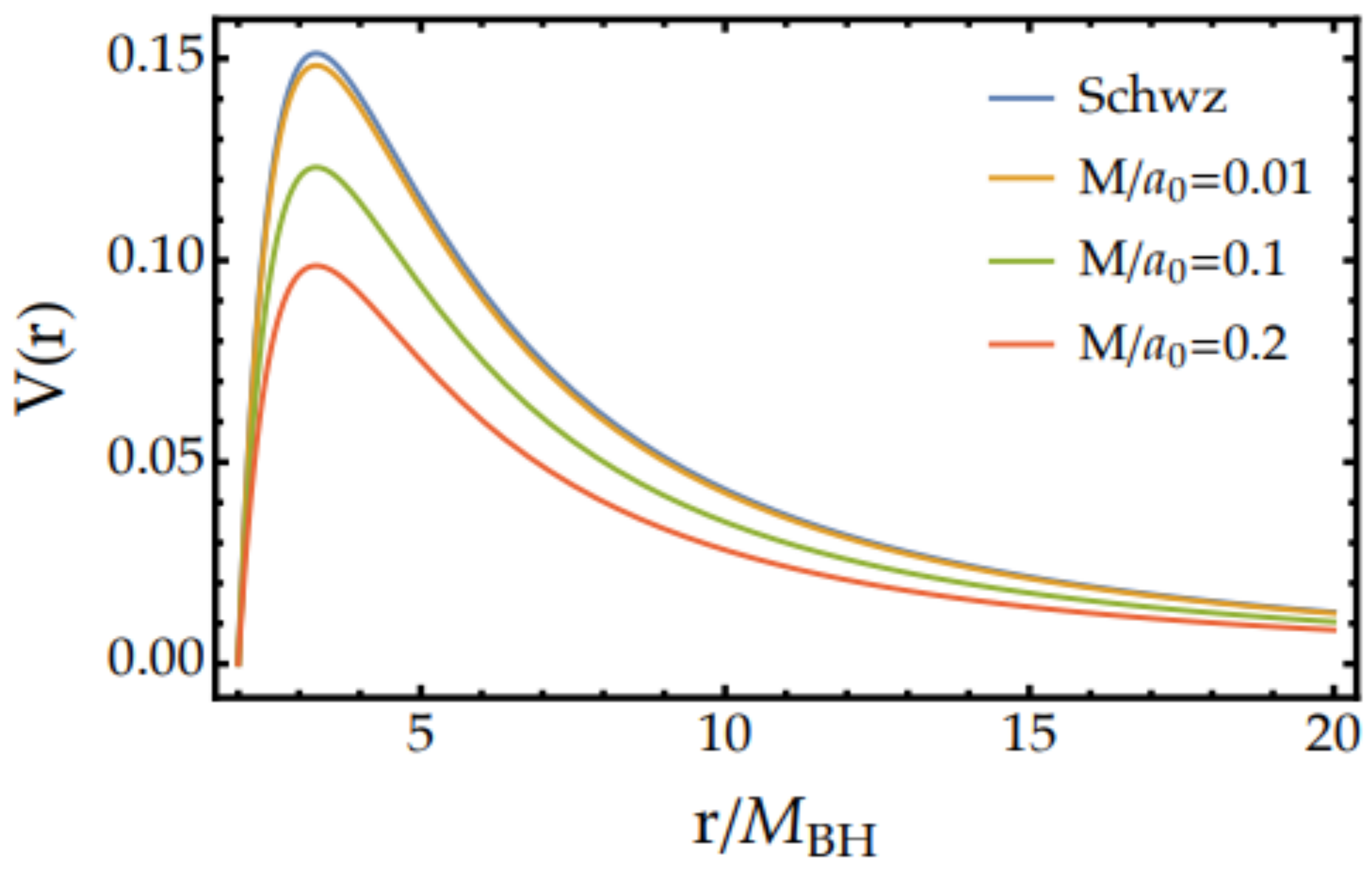
- For a spherically symmetric background the two families decouple.

BH and halo: axial modes

Solving the field equation in Fourier space, the master equation is obtained

Regge-Wheeler equation

$$\frac{d^2\Psi_{\ell m}}{dr_*^2} + \left[\omega^2 - V_\ell\right]\Psi_{\ell m} = 0 \qquad V_\ell = \frac{a(r)}{r^2}\left[\ell\left(\ell+1\right) - \frac{6m(r)}{r} + m'(r)\right]$$



- The halo affects the structure of the potential, as well the boundary conditions of the wave propagation at the horizon and at infinity
- Axial modes do not couple to matter

The background

By using the Einstein cluster prescription, it is possible to find the right background geometry.

A. Einstein, 1939
V.Cardoso +, 2022

- Assume the average stress energy tensor

$$T^{\mu}_{\nu} = \mathrm{diag}\left(-\rho, 0, p_t, p_t\right)$$

- Spherical symmetry

$$\mathrm{d}s^2 = -a(r)\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{1 - \frac{m(r)}{r}} + r^2\mathrm{d}\Omega^2$$

- Hernquist mass profile

$$m(r) = M_{\mathrm{BH}} + \frac{Mr^2}{\left(a_0 + r\right)^2}\left(1 - \frac{2M_{\mathrm{BH}}}{r}\right)^2$$

The background

Solution of the field equation

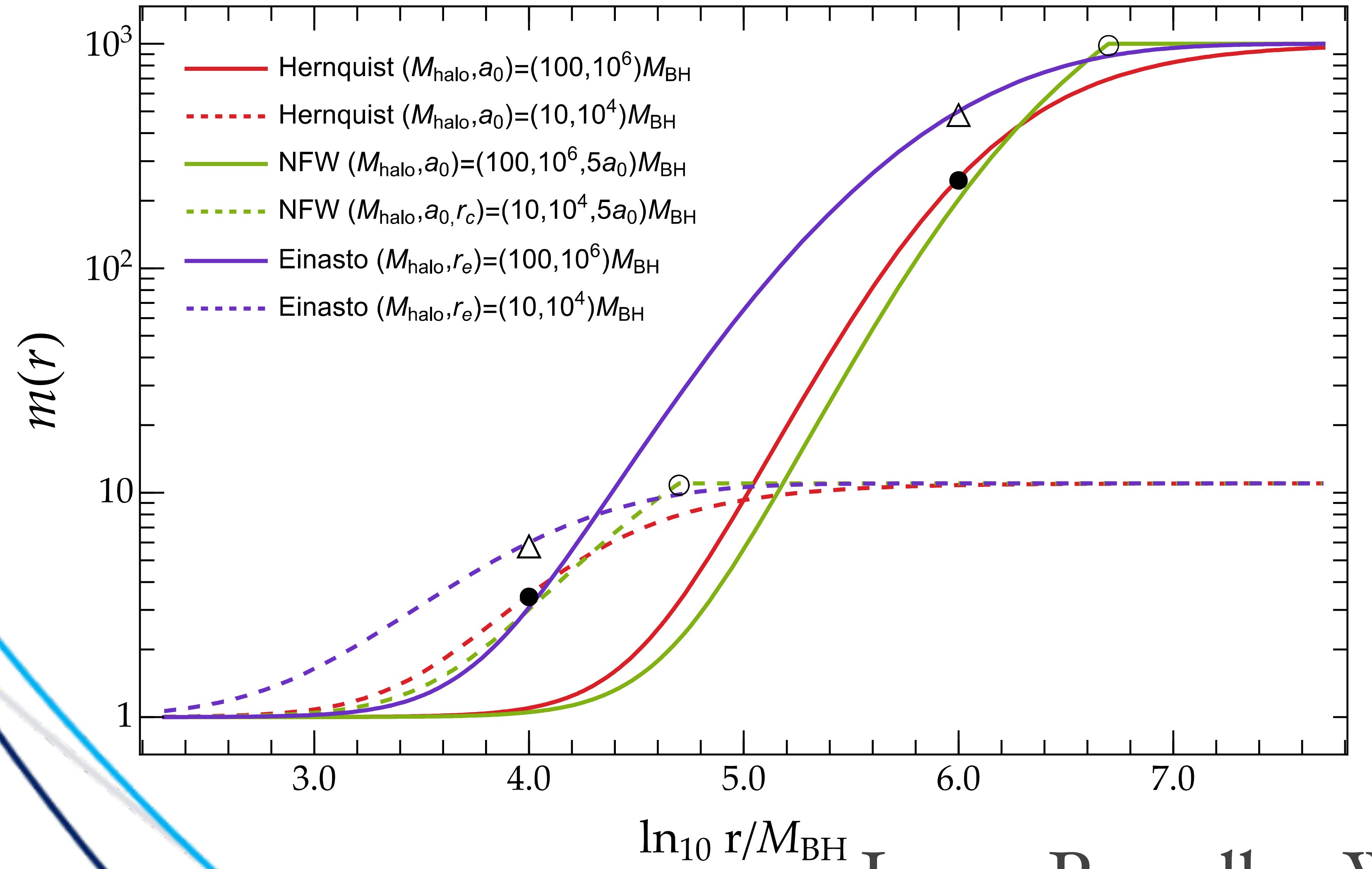
$$\rho(r) = \frac{2M\left(a_0 + 2M_{\rm BH}\right)}{4\pi r \left(a_0 + r\right)^3}\left(1 - \frac{2M_{\rm BH}}{r}\right)$$

$$a(r) = \left(1 - \frac{2M_{\rm BH}}{r}\right) e^{\Upsilon}$$

$$\Upsilon = \sqrt{\frac{M}{\xi}}\left(-\pi + 2\arctan\frac{r + a_0 - M}{\sqrt{M\xi}}\right)$$

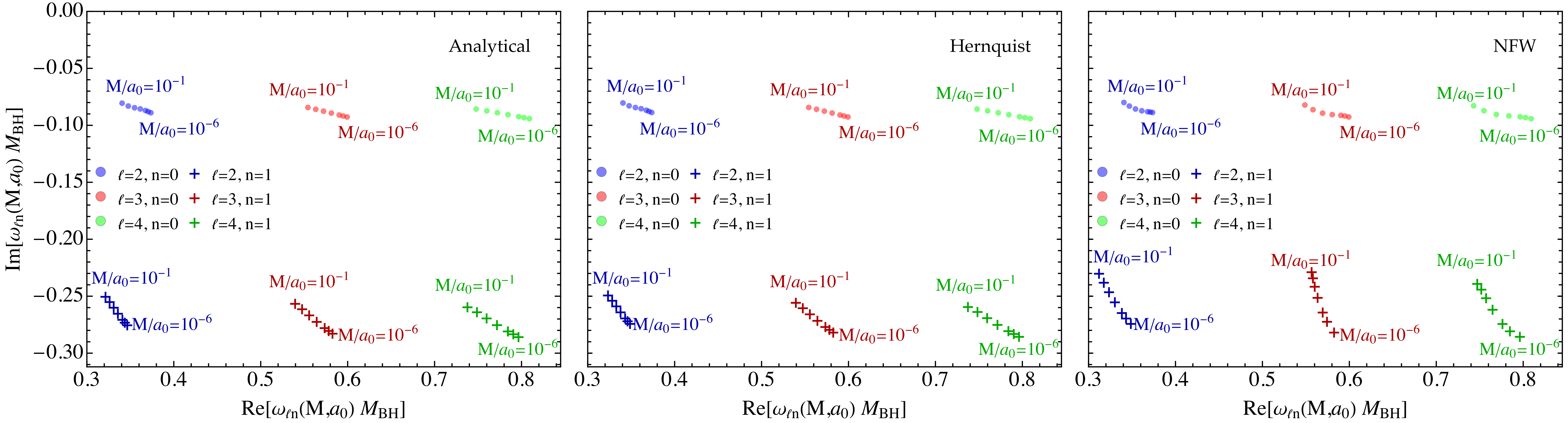
$$\xi = 2a_0 - M + 4M_{\rm BH}$$

$$e^{\Upsilon} \xrightarrow[r \to 2M_{\rm BH}]{} 1 - \frac{2M_{\rm BH}}{r}$$



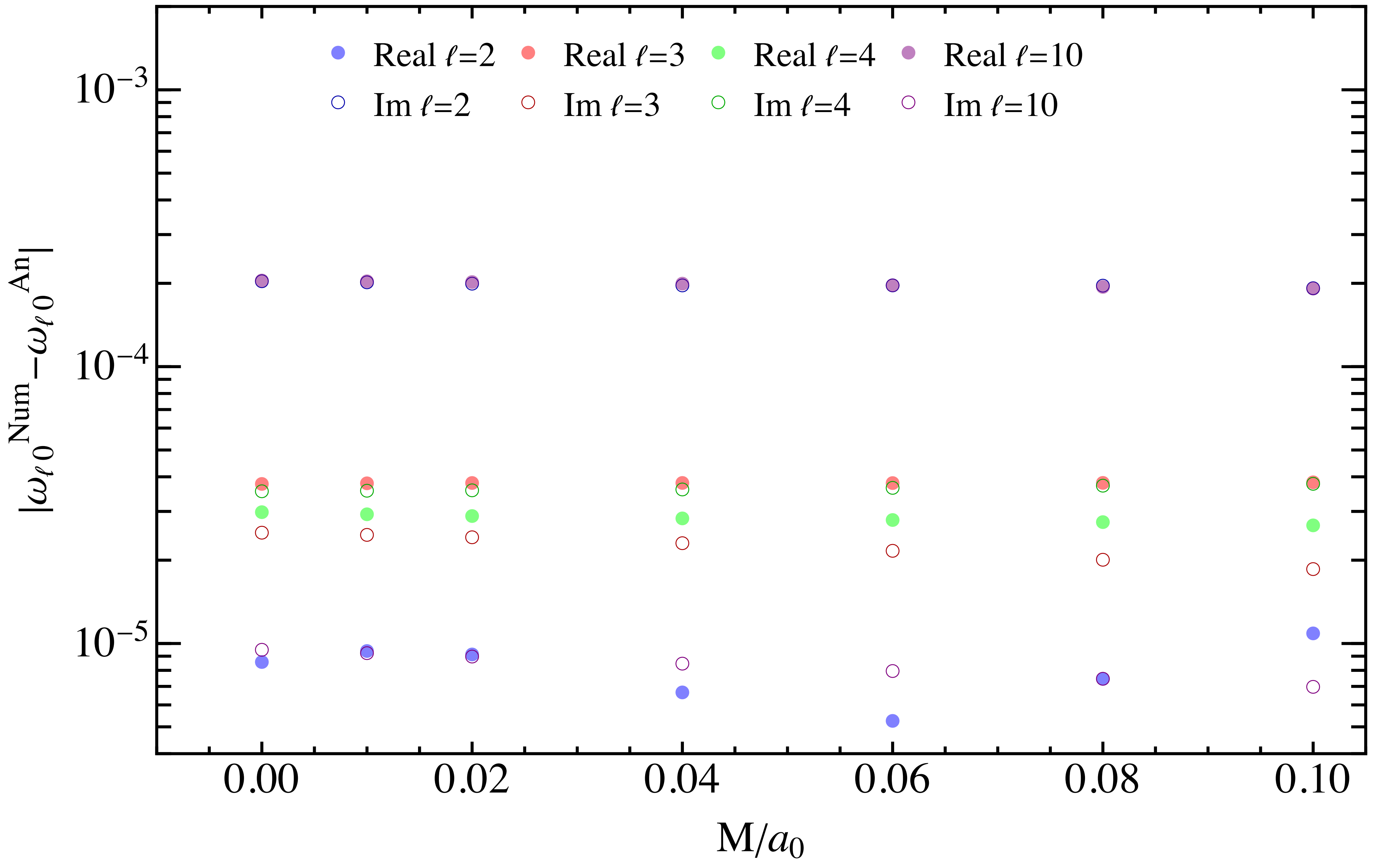
- The solution is asymptotically flat
- The horizon is at $r = 2M_{\rm BH}$
- To mimic galaxy observations, $a_0 \gtrsim 10^4$
- $M_{\rm BH} \ll M \ll a_0$

Numerical configuration



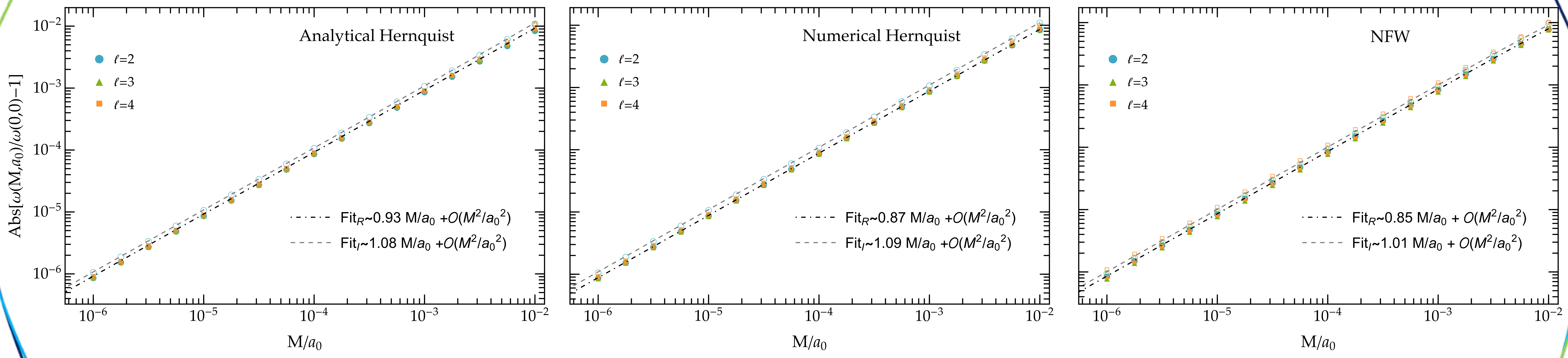
- ☑ Developed a fully numerical approach to treat any dark matter distribution $\rho(r)$
- ☑ This code can be applied to new DM models

Numerical configuration



☑ Good agreement with the QNMs of the analytical case

BHs and halos



- ☑ The leading order changes in the QNMs can always be described in terms of a **gravitational redshift** $\omega\left(M, a_0\right) = \omega_{\rm vac}\left(1 - M/a_0\right)$

Summary

- ☑ First ab initio calculation of QNMs of a BH spacetime in a DM environment
- ☑ First calculation for numerical BH spacetime in a DM environment
- ☑ QNMs appear to be redshifted: the frequencies are rescaled by a factor which depends on the compactness of the halo

Future projects

- Exploring the polar sector
- Detectability of halo parameters
- Ringdown modeling of asymmetric mass ratio mergers

Thank you for your attention!

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