How does a dark compact object ringdown?

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Abstract

According to general relativity, black holes have a horizon that hides a singularity where Einstein's theory breaks down. When formed in a merger, black holes vibrate in a process called "ringdown," which leaves the gravitational-wave footprint of the horizon. Some quantum-gravity models predict the presence of horizonless and singularity-free compact objects with an effective reflectivity. Such dark compact objects can emit a different gravitational-wave ringdown relative to the black hole case. Here, we derive a generic framework to compute the characteristic oscillation frequencies of dark compact objects. We argue that current gravitational-wave observations do not exclude dark compact objects as remnants of compact binary coalescences but impose constraints on their compactness.

Dark compact objects

Dark compact objects (DCOs) are horizonless compact objects that deviate from black holes (BHs) for two parameters [1]:

- The *compactness* since their radius is located at

$$r_0 = r_+(1+\epsilon)\,,$$

where r_+ is the BH horizon. Two categories are: DCOs with small compactness whose radius is comparable with the light ring of BHs, where $\epsilon = \mathcal{O}(0.1-1)$; ultracompact objects with Planckian corrections at the horizon scale, where $\epsilon = \mathcal{O}\left(10^{-40}\right)$.

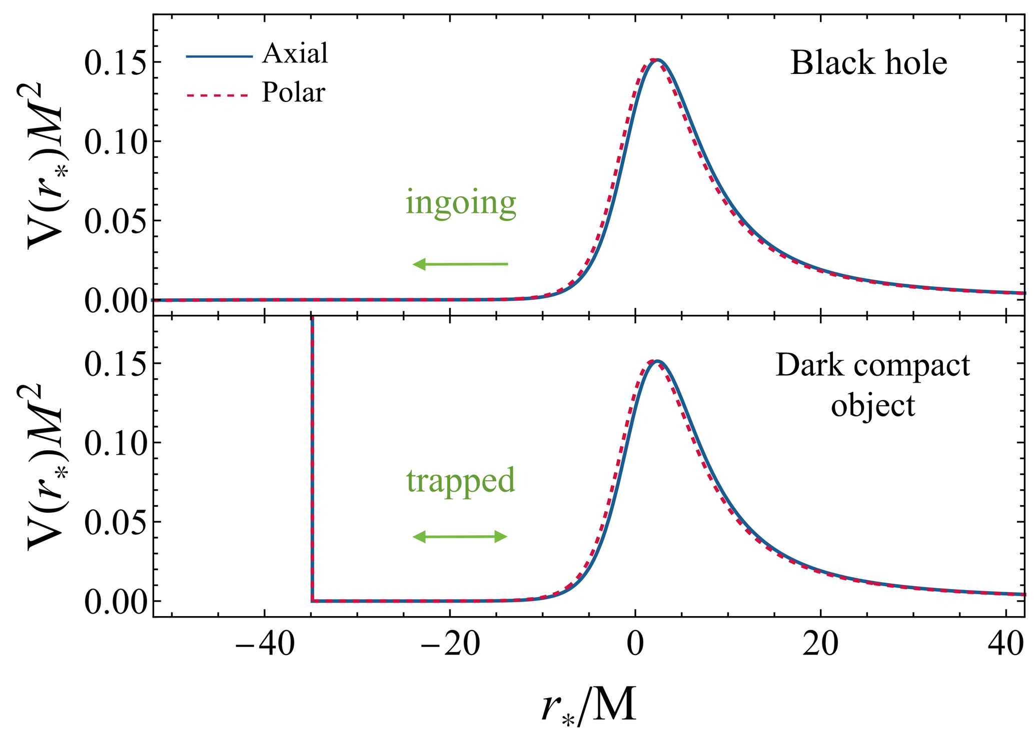
- The *darkness* that is related to the reflectivity at the radius of the object, $\mathcal{R}(\omega)$. The $\mathcal{R}=0$ case describes a totally absorbing object that reduces to the BH case when $\epsilon \to 0$. A perfectly reflecting object has $|\mathcal{R}|^2 = 1$, whereas intermediate values of $\mathcal{R}$ describe partially absorbing objects due to dissipation.

The ringdown

The ringdown is the final stage of a compact binary coalescence when the merger remnant relaxates to an equilibrium solution. This stage is dominated by the characteristic frequencies of the remnant, the so-called *quasi-normal modes* (QNMs), which describe the response of the compact object to perturbations. The radial component of the perturbation is governed by a Schrödinger-like equation:

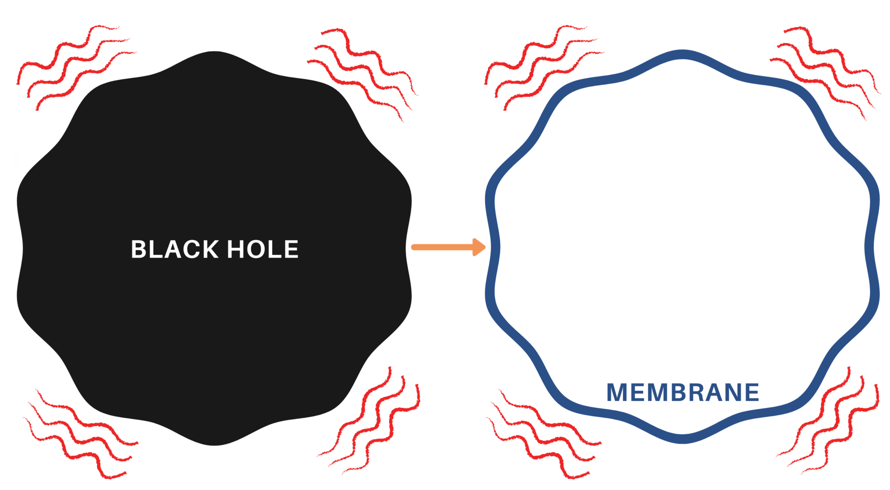
$$\frac{d^2\psi(r)}{dr_*^2} + \left[\omega^2 - V(r_*)\right]\psi(r) = 0\,,$$

where r_* is the tortoise coordinate. The effective potential for BH perturbations allows for purely ingoing waves at the horizon, whereas the effective potential for DCOs supports trapped modes between the radius of the object and the light ring [2].



The membrane paradigm

To derive the QNM spectrum of DCOs, we make use of the membrane paradigm. According to the BH membrane paradigm [3, 4], a static observer can replace the interior of a perturbed BH by a perturbed fictitious membrane located at the horizon. The junction conditions impose that the fictitious membrane is a viscous fluid with shear η and bulk viscosity ζ.

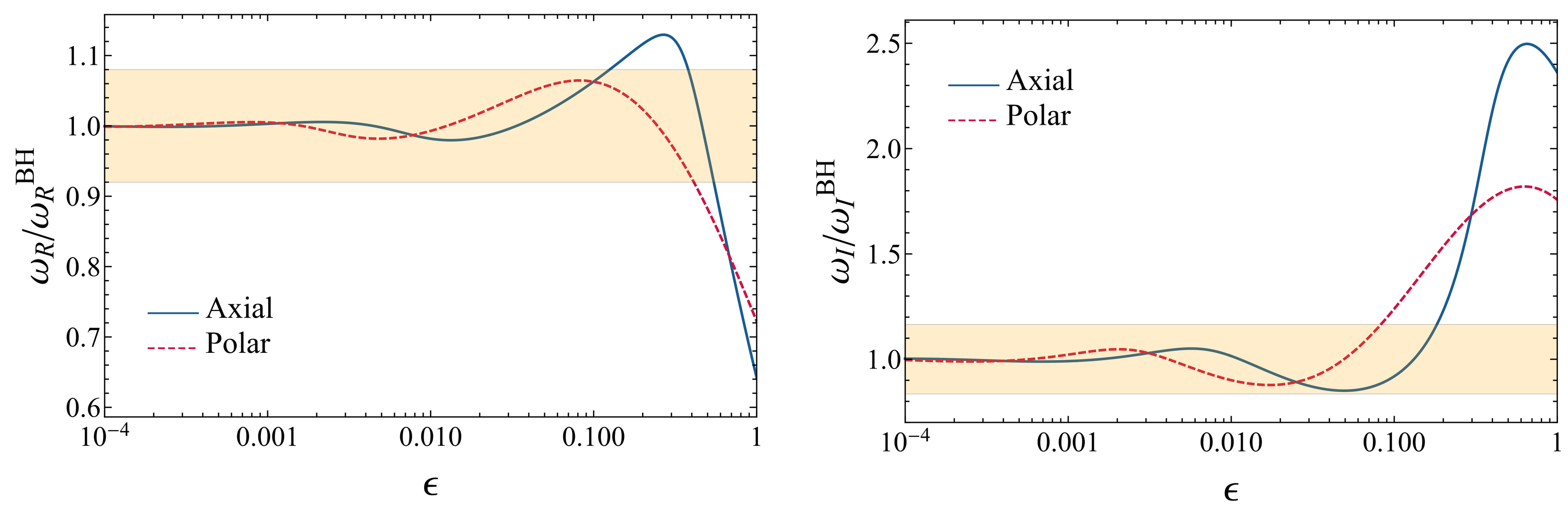


We generalise the BH membrane paradigm to any dark compact object with a Schwarzschild exterior, where no specific model is assumed for the object interior. This allows us to derive the boundary conditions for dark compact obects:

$$\frac{d\psi(r_0)/dr_*}{\psi(r_0)} = \begin{cases} -\frac{i\omega}{16\pi\eta} - \frac{r_0^2 V_{\rm axial}(r_0)}{2(r_0-3M)}\,, & \text{axial}\,,\\ -16\pi i\eta\omega + G(r_0,\omega,\eta,\zeta)\,, & \text{polar}\,. \end{cases}$$

Quasi-normal mode spectrum

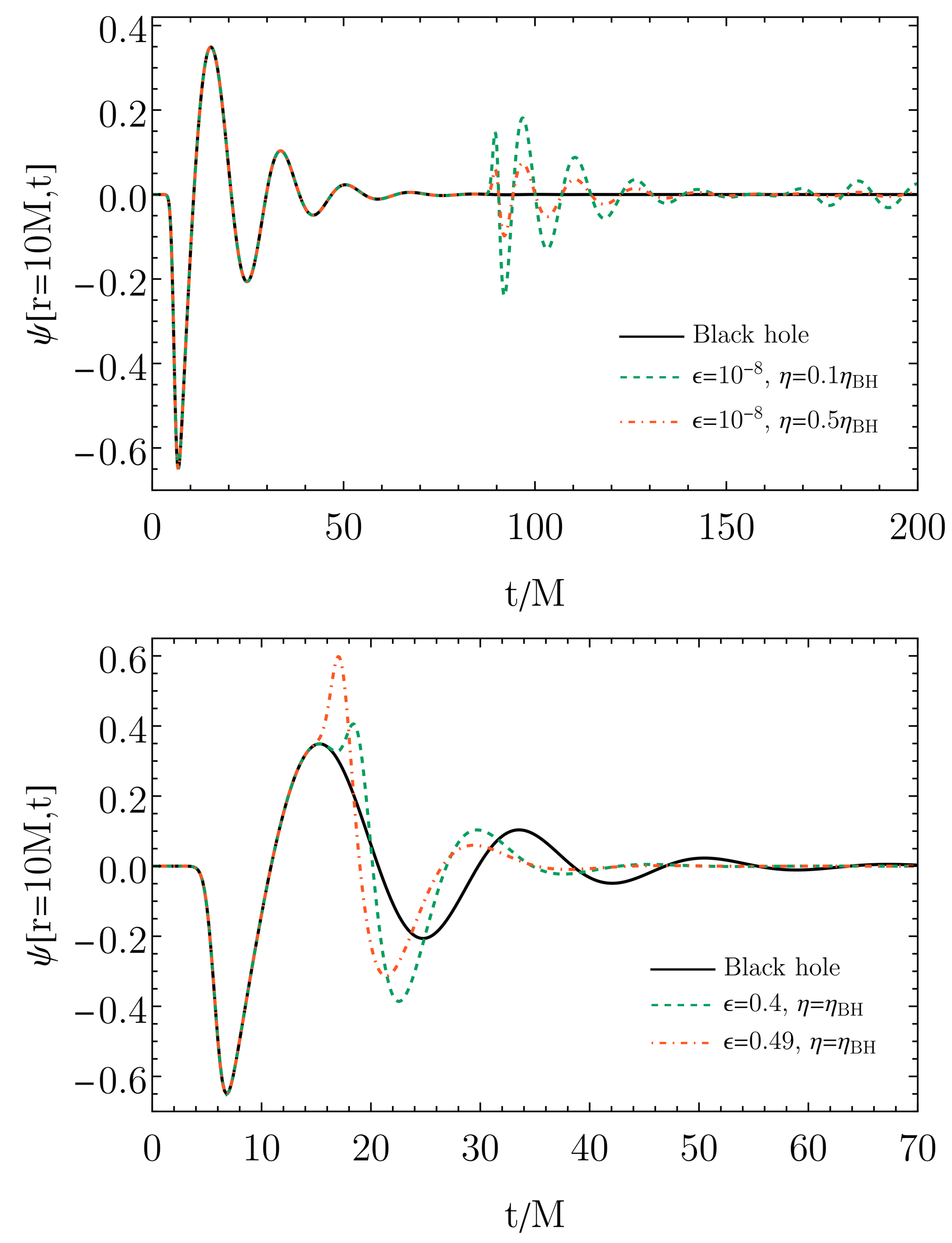
We show the QNM spectrum of a dark compact object with the same reflective properties of a BH as a function of the compactness. The totally absorbing case is obtained for $\eta = \eta_{\rm BH} = 1/(16\pi)$. For $\epsilon \to 0$, the QNM spectrum coincides with the BH one; whereas when the radius of the compact object increases, the QNM spectrum changes.



The highlighted region is the maximum allowed deviation (with 90% credibility) for the fundamental QNM in the event GW150914. The figure shows that dark compact objects with $\epsilon \lesssim 0.1$ would be compatible with current measurement accuracies.

Gravitational waveform

- If the remnant of a compact binary coalescence is an *ultracompact object* with $\epsilon \ll 1$ (top panel), the prompt ringdown is the same as the BH one since it is excited at the light ring. A train of subsequent gravitational-wave echoes appear in the postmerger signal due to trapped modes in the cavity that leak out of the potential barrier. The time delay of the echoes depends on the width of the cavity, whereas the amplitude of the echoes depends on the reflectivity at the radius of the object.
- If the merger remnant is a *compact object* with $\epsilon = \mathcal{O}(0.1, 1)$ (bottom panel), the prompt ringdown is modified due to the interference of the signal from the excitation of the light ring with the first gravitational-wave echo. No subsequent echoes appear since the cavity is small and does not trap the modes efficiently.



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