QUANTUM BLACK HOLE RINGDOWN

RAGTIME 28 CONFERENCE

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Overview

- Bound states with discretised spectrum $M = E_n$
- [Bekenstein+95]: horizon area is quantised in 'tiles' of size $\sim \hbar$

$$\left.\begin{array}{rl} \text{entropy} & S \sim A \sim n\hbar \\ \text{state degeneracy} & g_n = e^{S_n} \end{array}\right\} \quad \frac{M^2}{m_P^2} = \frac{\ln(\alpha)}{4\pi} n \quad \alpha \in \mathbb{N}$$

The qBH is excited by quanta $\delta M \equiv \hbar\varpi$.

Question: how is an arbitrary $m \neq \delta M$ absorbed?

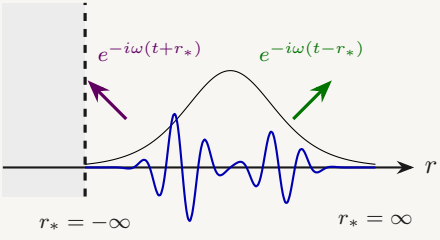
Ringdown

Massless scalar ϕ on Schwarzschild

$$\frac{1}{\sqrt{|g|}}\partial_\mu\left(\sqrt{|g|}g^{\mu\nu}\partial_\nu\phi(r,t)\right)=0$$

where the solutions is:

- ingoing at $r_* \to -\infty$, so that $\phi \sim e^{-i\omega(t+r_*)}$
- outgoing at $r_* \to +\infty$, so that $\phi \sim e^{-i\omega(t-r_*)}$.



Result: spectrum of QNM frequencies $\omega_{QNM} = \omega - i\gamma$

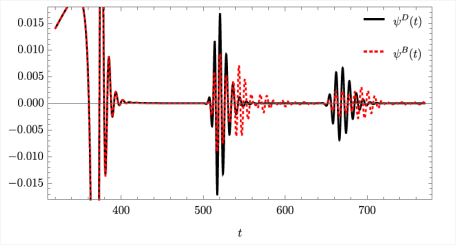
Question revisited: in general, $\varpi \neq \mathrm{Re}(\omega_{QNM})$

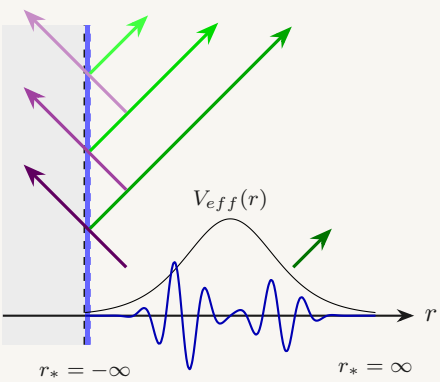
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Horizon reflectivity

Frequency-dependent reflectivity $R_H(\omega)$ at horizon & reflectivity $R(\omega)$ at $r \approx \frac{3}{2} r_S$:

- Simulation studies for modified QNMs [Cardoso+19]
- **Echoes** of the ringdown signal
- What mechanism can generate echoes?

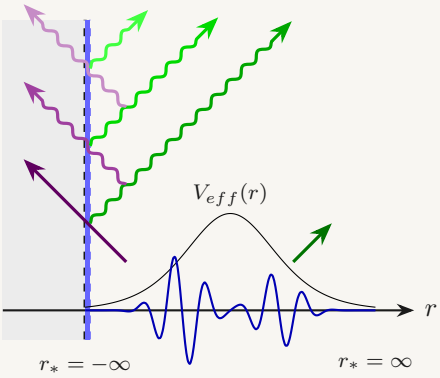




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Dissipation via soft gravitons

- Energy difference $E_{\text{infalling}} - E_{\text{excitation}}$ carried by emitted graviton(s).
- Dissipative gravitons emitted at *every* instance of an infalling particle.
- S-matrix approach to compute probability amplitudes of transitions. [Aoki+25]



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Transition of n levels $\rightarrow \delta M = n\hbar\varpi$

Spacetime metric

Classical solution as expectation value of quantum field $\hat{f}$ [Casadio22]:

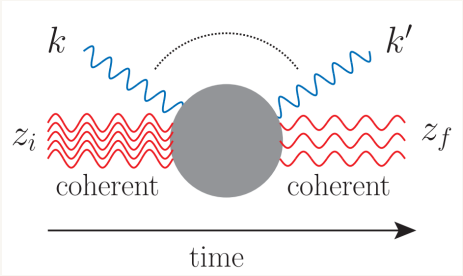
$$ds^2 = -\left\langle \hat{f} \right\rangle dt^2 + \frac{1}{\left\langle \hat{f} \right\rangle} dr^2 + r^2 d\Omega^2$$

qBH state

State of $\hat{f}$ reproducing a BH of mass M:

$$\left| M_{\text{in/out}} \right\rangle = \int \frac{dk\ k^2}{2\pi^2} e^{-\frac{1}{2}|g_{(k)}|^2} e^{g_{(k)} \hat{\alpha}_k^\dagger} |0\rangle$$

$$g_{(k)} = -\frac{4\pi}{\sqrt{2} k^{3/2}} \frac{M_{\text{in/out}}}{m_P} e^{ikt}$$



[Ilderton+18]

Mass quantisation

The state $|M\rangle$ reproduces the BM law?

$$\frac{M^2}{m_P^2} = \frac{1}{4 \int_{k_{IR}}^{k_{UV}} \frac{dk}{k}} \left\langle \hat{N} \right\rangle$$

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Resulting relative probability

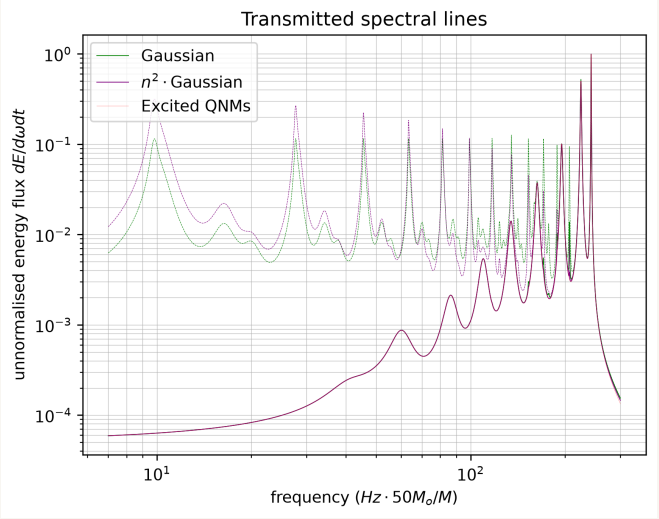
From the amplitude

$$\langle M + n\hbar\varpi, 1_{out}|M, 1_{in}\rangle$$

we compute

$$\mathcal{P}(n) = e^{-\frac{16}{\pi^2}\left(\int_{k_{IR}}^{k_{UV}} \frac{dk}{k}\right)\frac{(n\hbar\varpi)^2}{m_P^2}} \cdot \left|\langle 1_{out}|S_{bkg}|1_{in}\rangle\right|^2$$

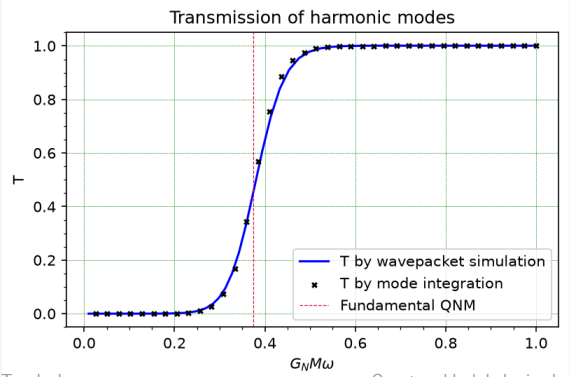
with regularising cutoffs k_{IR}, k_{UV}.
Model: *Gaussian(n)* $\cdot n^2$.

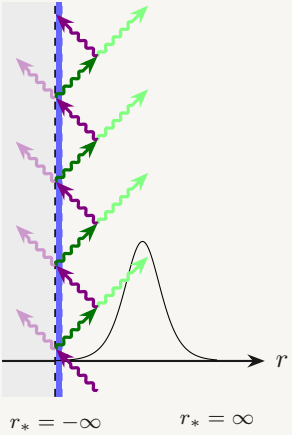


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Spacetime greybody factors

- Computation of $T(\omega)$ for the Zerilli effective potential by evolving wavepackets across the barrier.
- Low-frequency transmission is heavily suppressed.

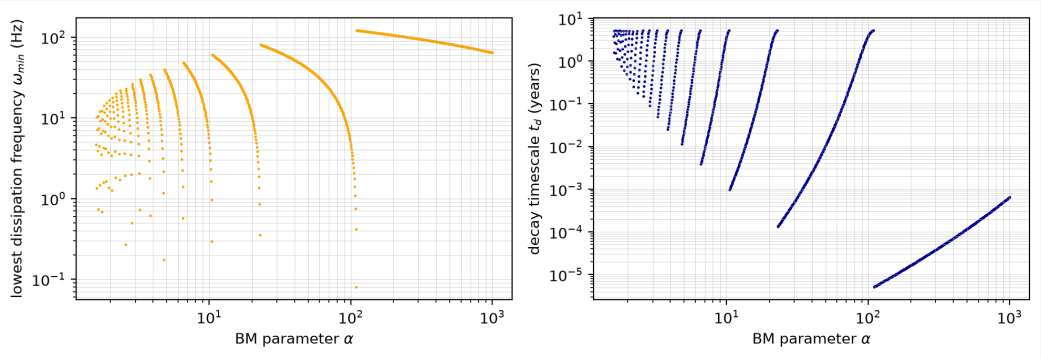




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Decay timescale estimate

- The trapped dissipative energy will be deposited on the lowest emitted ω_{min}.
- For $\alpha = 2$, $M = 50M_\odot$ and $T_{min}(\omega_{min}) \sim 10^{-8}$: Taking $E_j = E_0 e^{-T_{min} j}$ at the j-th trip we find a duration $t_{\text{signal}} \sim 10^8 t_{\text{round trip}} \sim 0.3 yrs$.



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Summarising:

- The qBH can remain a perfect absorber, motivated by familiar quantum systems.
- The energy increments that cannot be absorbed may be radiated via soft gravitons.
- The ringdown spectrum is then enriched by the presence of gravitons with frequencies corresponding to these energy increments as $\omega = \frac{1}{\hbar}\Delta E$.
- Transmission of these frequencies is heavily suppressed, leading to a weak but long flux of the lowermost frequencies.

arXiv:2609.14160

Thank you for your attention.