Black Hole Quasi-Normal Modes in Beyond General Relativity

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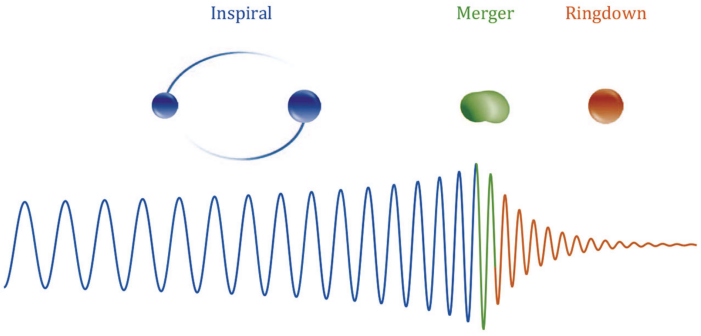
Ringdown and quasi-normal modes (QNMs)

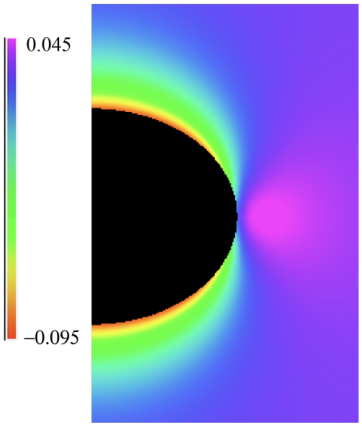
- Black hole (BH) ringdown is governed by quasi-normal modes.
- In GR, the Kerr QNM spectrum depends only on mass M and spin χ.
- Modified gravity can shift the spectrum or introduce additional modes.
- Ringdown spectroscopy therefore provides a probe of strong-field gravity.



Inspiral–merger–ringdown waveform. Figure from Antelis & Moreno (2017).

Einstein–scalar–Gauss–Bonnet gravity (EsGB)

- Scalar field ϕ coupled to curvature through the Gauss–Bonnet invariant $\mathcal{G}$.
- Deviations from GR become strongest near highly curved black holes.
- Black holes develop scalar "hair" and carry scalar charge.
- Perturbative studies predict breaking of isospectrality:
  - Polar (even-) and axial (odd-parity) QNMs acquire different complex frequencies $\omega = \omega_R + i\omega_I$.
- Main goal: can fully nonlinear NR simulations resolve this parity-dependent structure?



Scalar profile for a rapidly rotating BH.
Figure from East & Ripley (2021)

Numerical setup and fitting

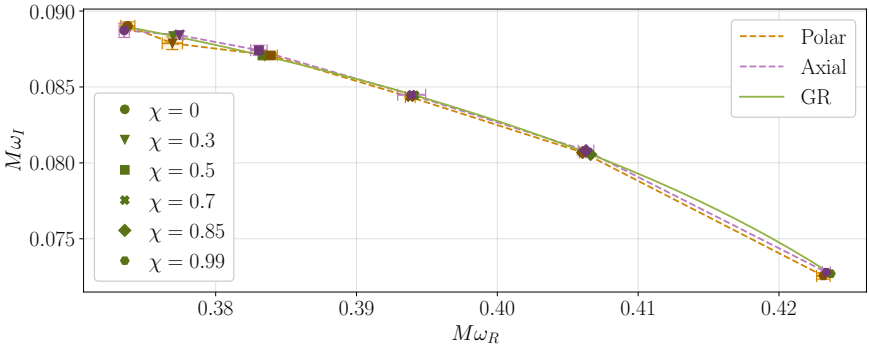
- Evolve isolated black holes perturbed by localized Gaussian pulses.
- Axisymmetric setup:
  - Focus on $(\ell, m) = (2, 0)$ modes rather than $(2, 2)$ modes dominant in binary mergers.
  - Allows substantially higher resolution than full 3D simulations.
- Perturbations excite:
  - Polar (even-parity) sector
  - Axial (odd-parity) sector
  - Or both simultaneously
- Extract $\psi_4 \simeq \ddot{h}_+ - i\ddot{h}_\times$ and fit ringdown using damped exponentials:

$$\psi_4(t) \sim \sum_k A_k e^{i\omega_k t}$$

- Frequency extraction proved highly sensitive to fitting choices and numerical resolution $\rightarrow$ this changed our initial objectives.

GR benchmarking

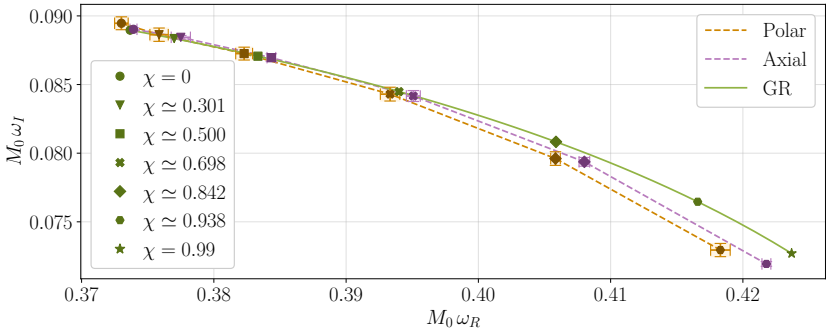
- First validate the pipeline against GR, where the Kerr spectrum is known.
- Polar and axial fits agree with each other and with the Kerr frequencies.
- No artificial parity splitting observed at the production resolution.



Fitted $(2, 0)$ QNM frequencies from GR simulations.

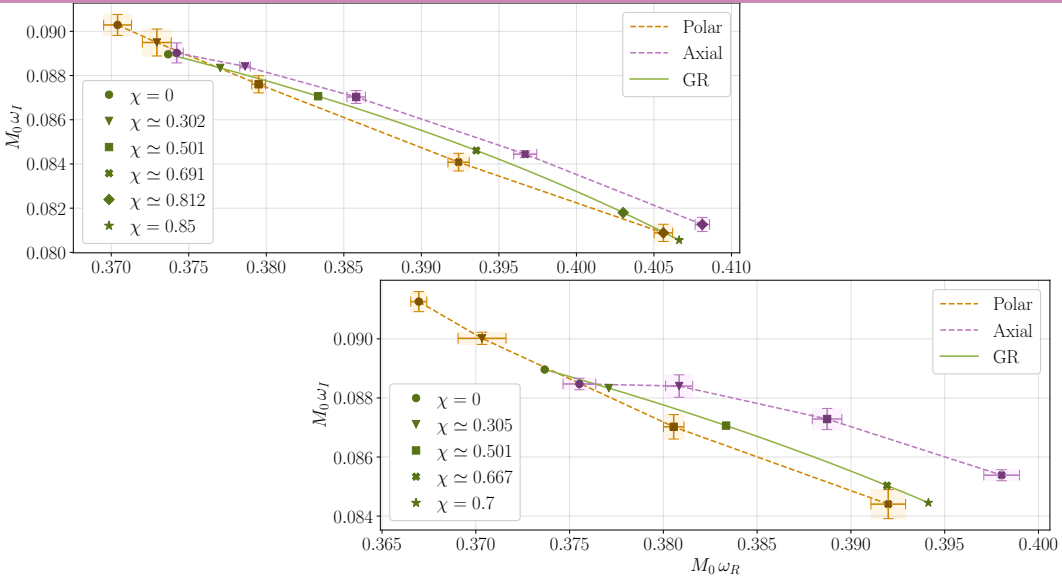
Spin dependence at initial dimensionless coupling $\lambda/M_0^2 = 0.04$

- Small but systematic deviations from Kerr appear already at weak coupling.
- Polar and axial modes separate coherently in the complex-frequency plane.
- Splitting grows with coupling strength and is generally largest for rapid spins.



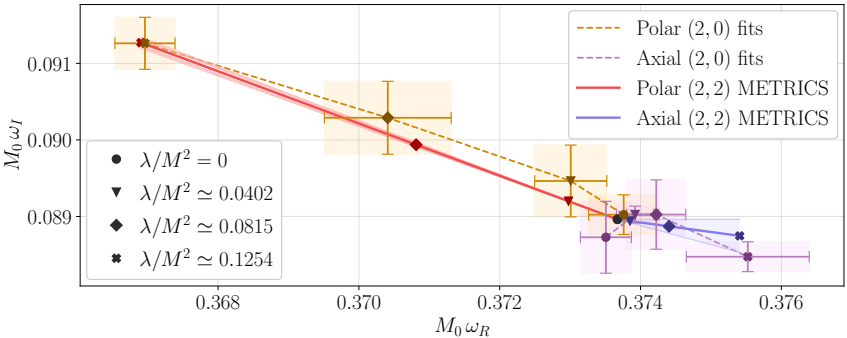
Fitted $(2,0)$ frequencies for $\lambda/M_0^2 = 0.04$.

Spin dependence at $\lambda/M_0^2 = 0.08$ (top) and $\lambda/M_0^2 = 0.12$ (bottom)



Comparison with perturbative predictions

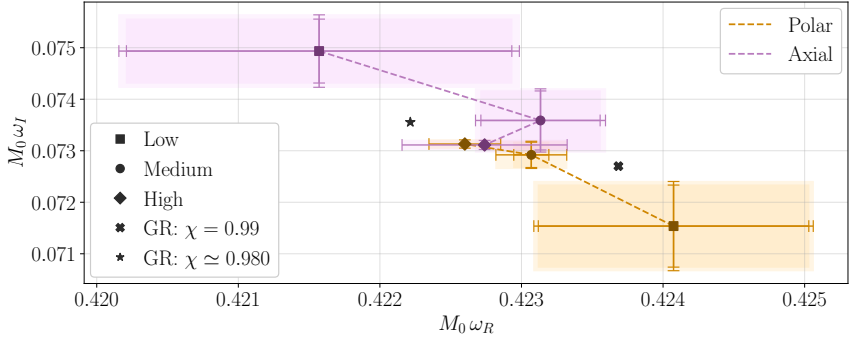
- For non-spinning black holes, QNM frequencies are independent of m.
- Allows direct comparison between our nonlinear $(2,0)$ simulations and perturbative $(2,2)$ calculations by Chung & Yunes (2024).
- Overall agreement is encouraging across the coupling range considered.



Comparison between nonlinear simulations and perturbative METRICS predictions.

Resolution dependence

- Resolution studies turned out to be essential.
- At weak coupling ($\lambda/M_0^2 = 0.02$), some apparent low-resolution splitting disappears under refinement.
- At larger coupling, the splitting persists and becomes increasingly well resolved.
- Accurate frequency extraction is therefore computationally demanding.



Resolution study for a near-extremal spin, weak-coupling configuration $(\chi_0, \lambda/M_0^2) = (0.99, 0.02)$.

Conclusions

- We perform nonlinear NR simulations of perturbed black holes in EsGB gravity.
- We find coherent parity-dependent deviations in the ringdown spectrum.
- The nonlinear results show encouraging agreement with perturbative predictions.
- Reliable frequency extraction requires careful waveform modeling and high numerical resolution.
- Future work should extend these studies to higher resolutions and eventually full 3D binary mergers.

Thank you