Nonlinear effects in the black hole ringdown: absorption-induced mode excitation

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Punchline

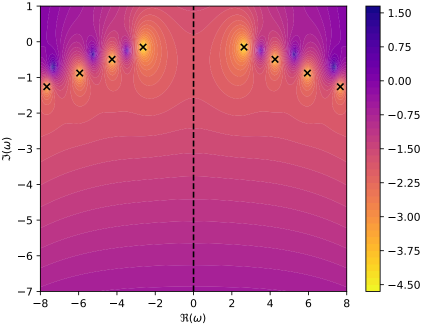
- We find that nonlinear effects have a significant contribution to BBH ringdown

General Motivation for Ringdown Studies

- Astrophysics
  - Spectroscopically characterize the final black hole
  - Test GR in an extremely dynamical scenario
  - Deviations from GR [LVK,ET,CE]
  - Degree of nonlinear mode interaction in astrophysical mergers
- Classical General Relativity
  - Fundamentally a nonlinear theory $\rightarrow$ the ringdown is no exception (mode doubling) [Bantilan+, Ripley+]
  - Consistency with no-hair theorems and final state conjecture [Penrose, Israel, Carter]
- (Holography)

Quasi-Normal Frequencies

- QN Spectrum
  - characterized by $\omega = \omega_{\mathrm{R}} + i\omega_{\mathrm{I}}$
  - ω_{R} are the oscillations
  - ω_{I} decaying timescale of the mode
  - higher overtones (larger n) decay faster



Looking for nonlinearities

Using a 'toy' model

- Can nonlinear effects take place during ringdown?
  - Can a mode present at early times excite additional modes
- Nonlinearities after $t - t_{h_{\text{peak}}} = 0$ might still be important

Our Model

- Fields
  - g_{ab} Metric
  - ϕ Complex scalar
- Lagrangian

$$16 G_{\mathrm{N}} \mathcal{L} = R + \frac{6}{L^2} - |\partial_a \phi|^2$$

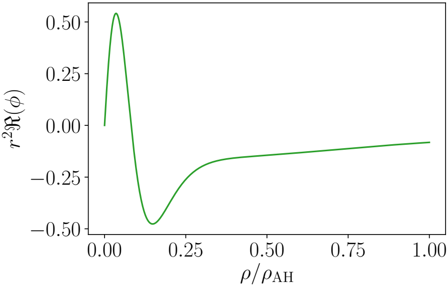
- We set $L = 1$ throughtout

QNM Initial Data

To prepare n^{th} overtone initial data

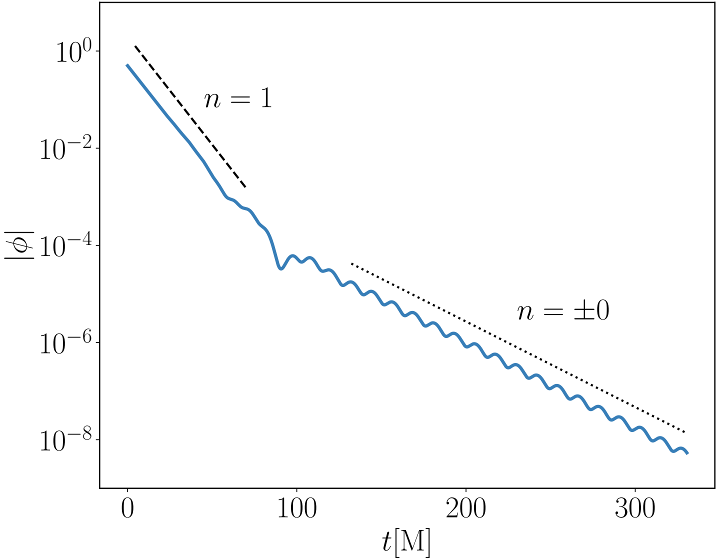
- We obtain target ovetone frequency with Leaver's method
- We solve the radial equation for the radial mode function

  (both are numerical operations)



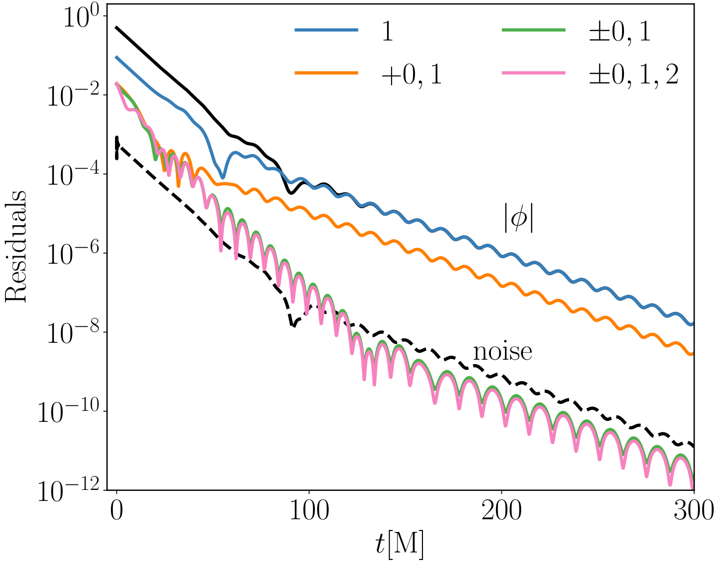
Results

Fully Nonlinear Evolution



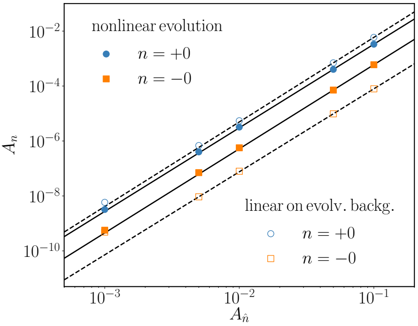
Results

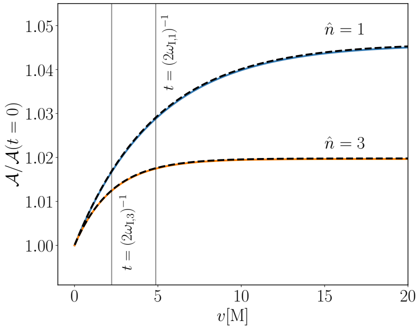
Fit to Nonlinear Evolution



Results

Absorption-Induced Mode Excitation



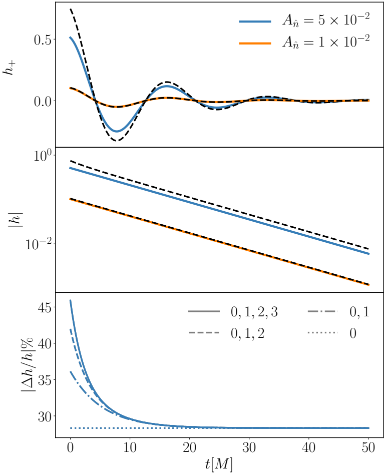


$$A_{n \neq \bar{n}} \sim A_{\bar{n}}^3$$

Towards Astrophysical BH

Schwarzschild-AF

- The perturbing mode is the fundamental mode $n = 0$
- Using amplitudes inferred from a fit to GW150914
- Percent level corrections



Conclusion & Outlook

Summary

- Ringdown is an ideal testbed for GR
  - some time after merger the signal can be described by perturbation theory
- We explored the dynamics of perturbed black holes beyond linear order
- We identify a high order secular effect AIME
  - expect it to be more relevant than mode doubling (for GW)
- Overtones are excited generically and dynamically due to the flux across the horizon