Title: A recipe for echoes from exotic compact objects

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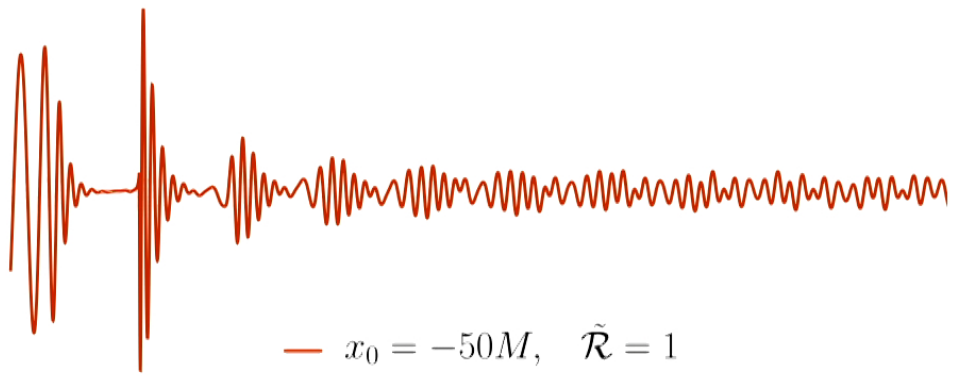
Abstract: Gravitational wave astronomy provides an unprecedented opportunity to test the nature of black holes and search for exotic, compact alternatives. Recent studies have shown that exotic compact objects (ECOs) can ring down in a manner similar to black holes, but can also produce a sequence of distinct pulses resembling the initial ringdown. These â€œechoesâ€• would provide definite evidence for the existence of ECOs. In this work we study the generation of these echoes in a generic, parameterized model for the ECO, using Greenâ€™s functions. We show how to reprocess radiation in the near-horizon region of a Schwarzschild black hole into the radiation from the corresponding source in an ECO spacetime. Our methods allow us to understand the connection between distinct echoes and ringing at the resonant frequencies of the compact object. We find that the quasinormal mode ringing in the black hole spacetime plays a central role in determining the shape of the first few echoes. We use this observation to develop a simple template for echo waveforms. This template performs well over a variety of ECO parameters, and with improvements may prove useful in the analysis of gravitational waves.
Related Arxiv #: https://arxiv.org/abs/1706.06155

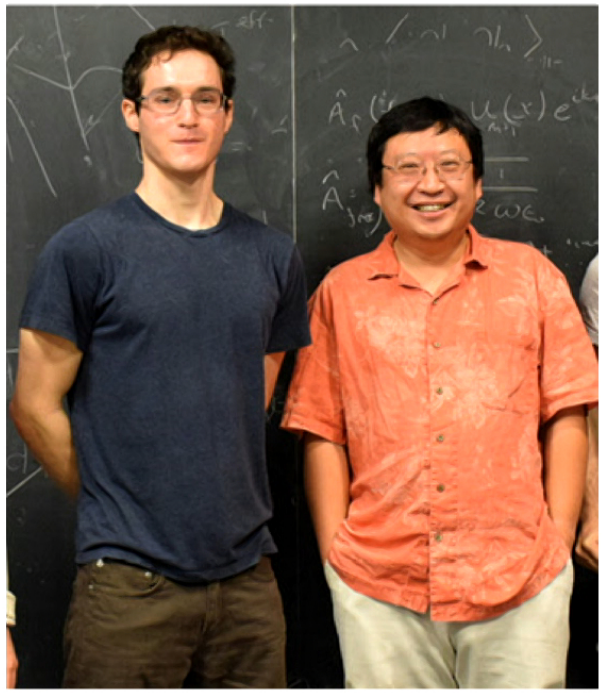
A recipe for echoes from compact objects



Aaron Zimmerman
Zachary Mark, Song Ming Du, Yanbei Chen

Strong gravity seminar
July 20, 2017

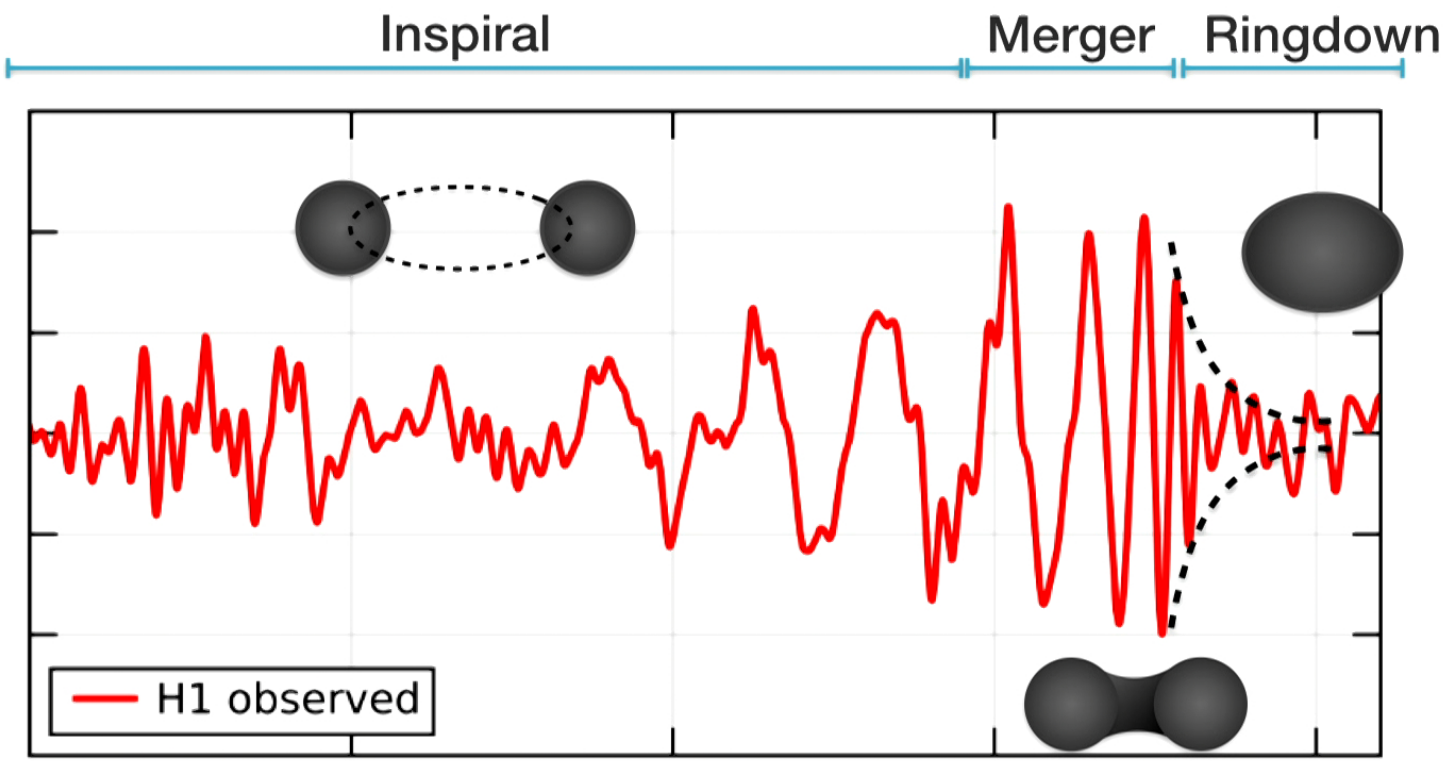
Collaborators



Zachary Mark Yanbei Chen

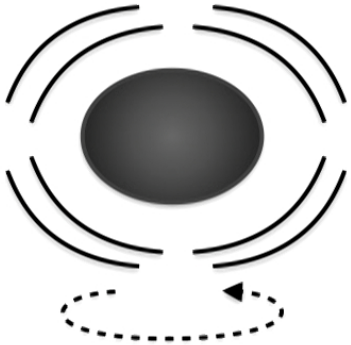
Song Ming Du

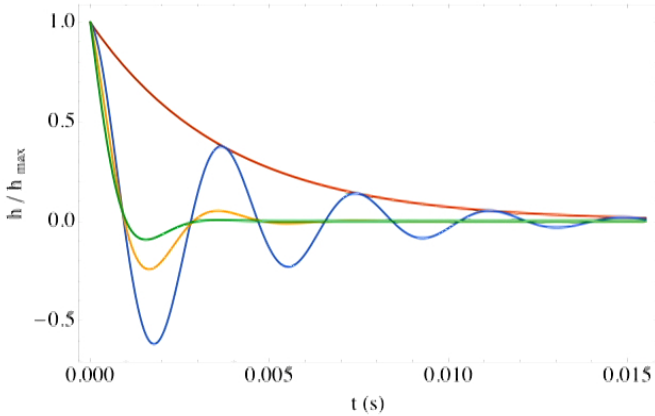
Binary black hole inspiral



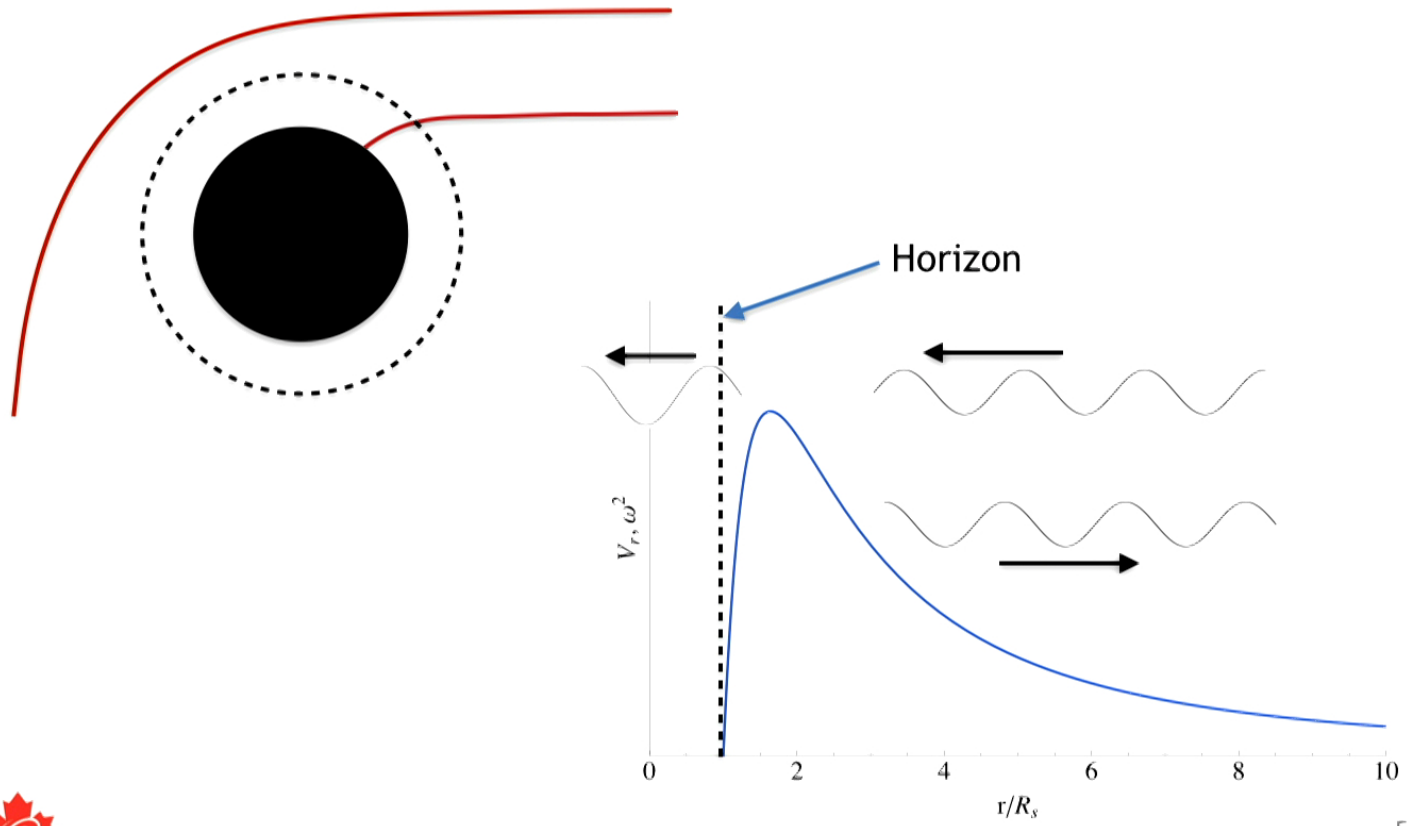
Black hole ringdown

- After merger, the remnant BH is strongly deformed
- View as a perturbation about the final state
- Perts excite resonant modes of the BH
- These decay exponentially in a “ringdown"

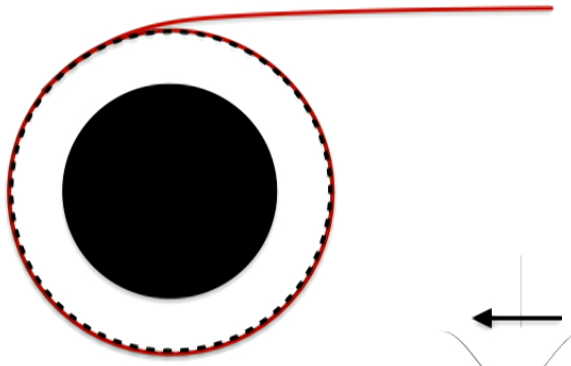


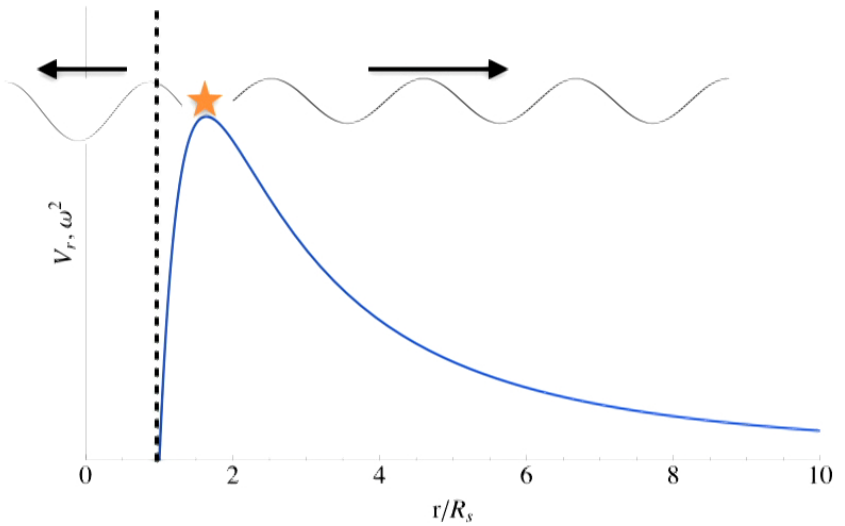


Waves around black holes



Quasinormal modes





Quasinormal modes: the math

- Scalar wave equation: $\Box\Phi = -\rho$
- Separation of variables:

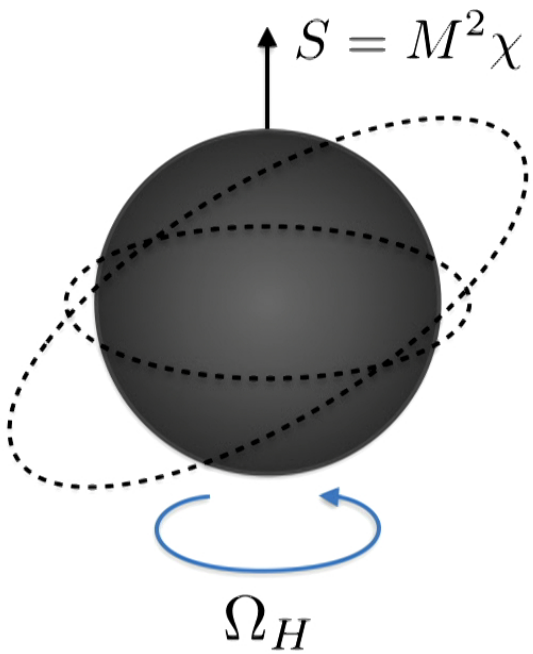
$$\Phi_{lm\omega} \sim \frac{1}{r} e^{-i\omega t} \tilde{\psi}_{lm\omega}(r) Y_{lm}(\theta, \phi)$$

- Radial equation:

$$\frac{d^2\tilde{\psi}}{dx^2} + (\omega^2 - V)\tilde{\psi} = \tilde{S} \qquad \frac{dx}{dr} = \frac{1}{1 - 2M/r}$$

- Only certain freqs work for BCs: ω_{lm}, τ_{lm}
- Story same for GWs ${}_s\psi_{\omega lm} \to h$

Modes of rotating black holes



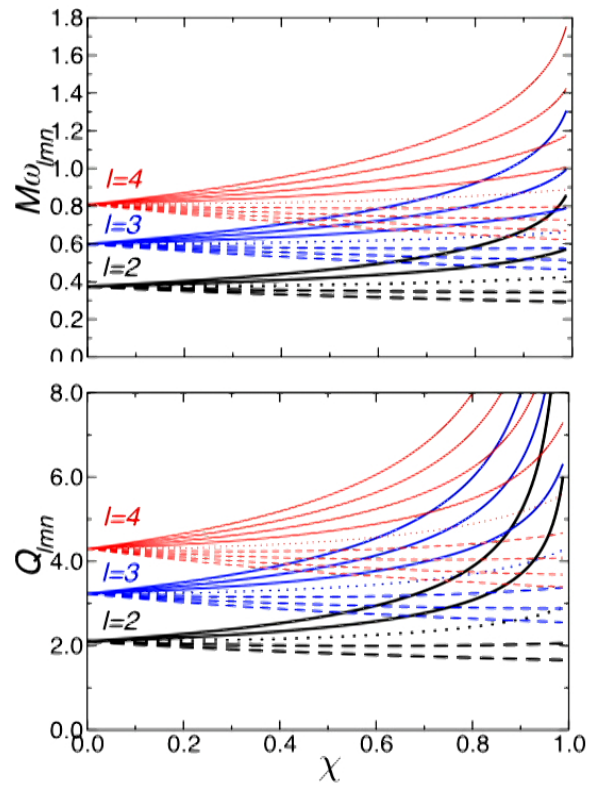
- Orbits of light split according to inclination
- Wave picture: everything holds, but freq and decay split with m
- Math story carries through ${}_s\psi_{\omega lm} \to h$
- Spin increases: freq increases, decay rate decreases

Measuring mass and spin

- Unique and clean measure of mass and spin
- Mass: overall scale

$$\omega \propto 200 \left(\frac{M_\odot}{M}\right) \mathrm{kHz}$$

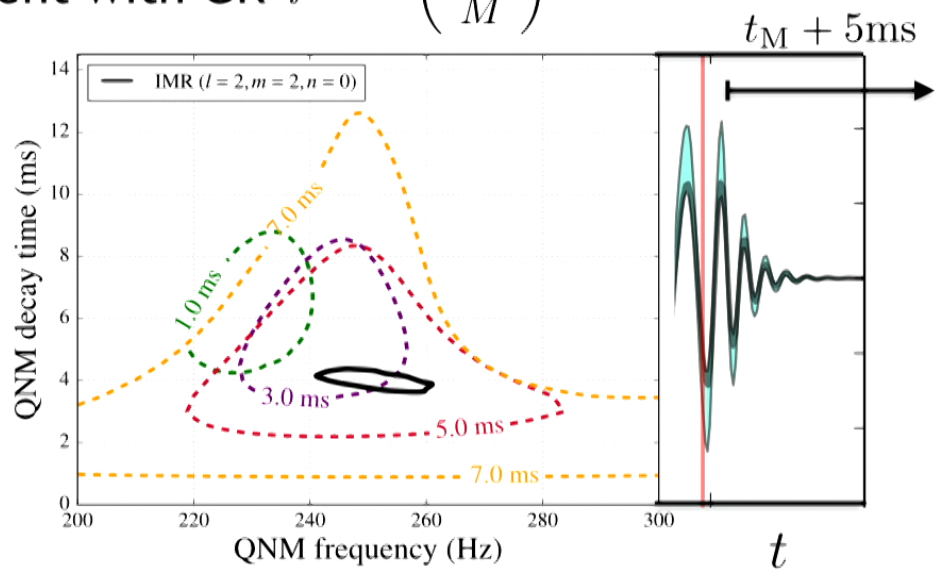
- ω , τ vary with mode and spin
- Low $Q = \omega\tau/2$
- Two modes: test of GR



Berti,Cardoso, Starinets (2009)

The ringdown of GW150914

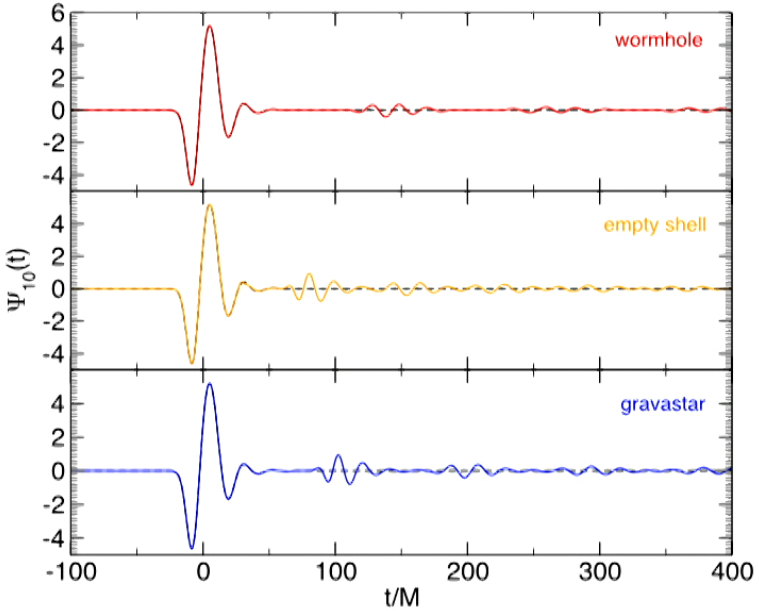
- First detection of a BH ringdown
- Freq and decay of lowest overtone for $\ell = 2,\ m = 2$
- Consistent with GR $f \propto 30 \left(\frac{M_\odot}{M}\right) \mathrm{kHz}$



LVC arXiv:1602.03841

Echoes from compact objects

- Cardoso, Franzin, Pani, arXiv:1602.07309
- Ringdown doesn't guarantee BH
- But these spacetimes produce "echoes"
- Holds across many examples
- Subject is taking off

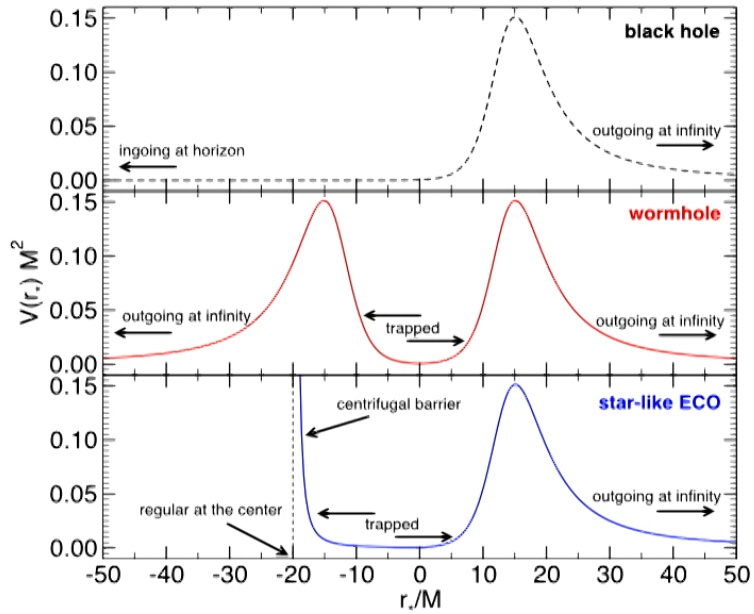


Cardoso et al. 1608.08637

Echoes from compact objects

- When LR present, still get trapping
- Potentially mimics usual QNMs
- But ECOs qualitatively modify potential at origin
- Expect long lived ECO modes

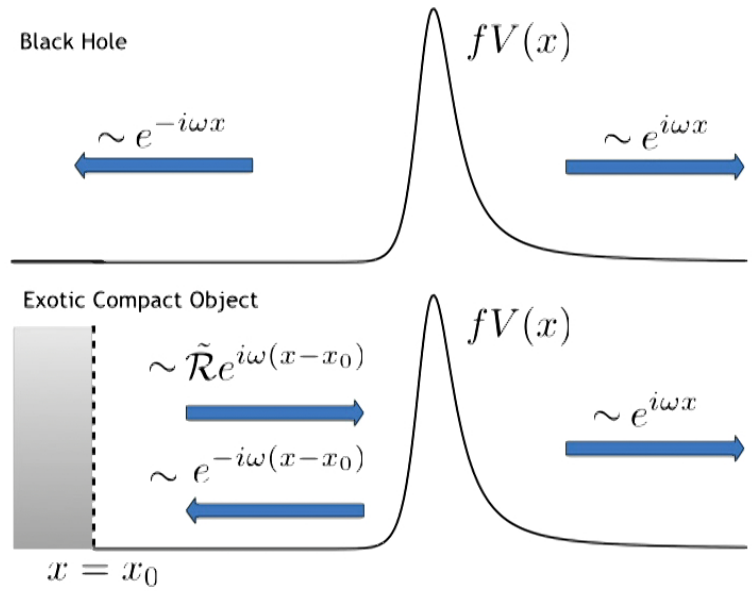
$$\gamma \sim \frac{1}{|\ln(r_0 - 2M)|^p}$$



Cardoso et al. 1608.08637

Parametrized model for very compact objects

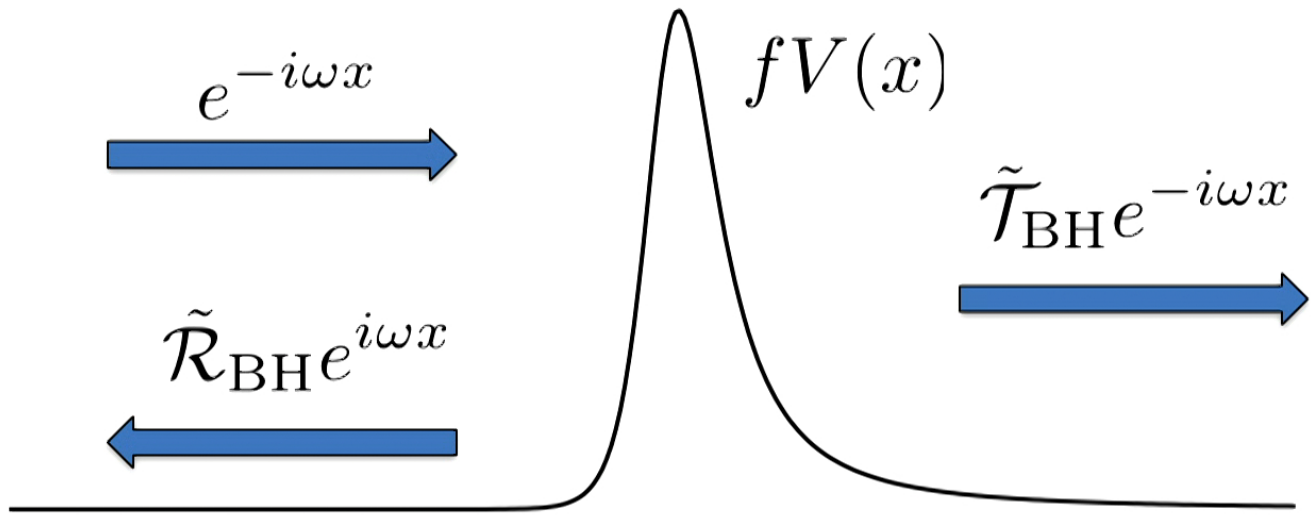
- Focus on scalar field case
- Near the horizon, waves propagate freely
- For very compact objects, BCs require combo of in and out
- Reflectivity and position give model



$$\tilde{\psi} \propto e^{-i\omega(x-x_0)} + \tilde{\mathcal{R}}(\omega) e^{i\omega(x-x_0)}$$

Aside: BH reflection and transmission

- We use a nonstandard convention:

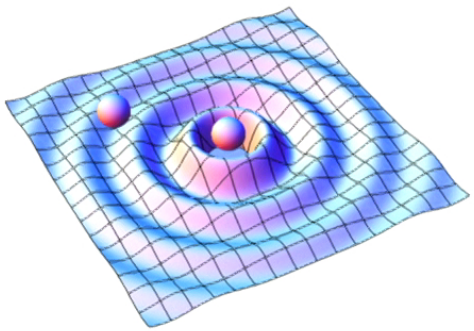


Green's function approach

- Have homogenous slns

$$\tilde{\psi}_{\rm in}(x) \sim e^{-i\omega x} \qquad x \to -\infty$$

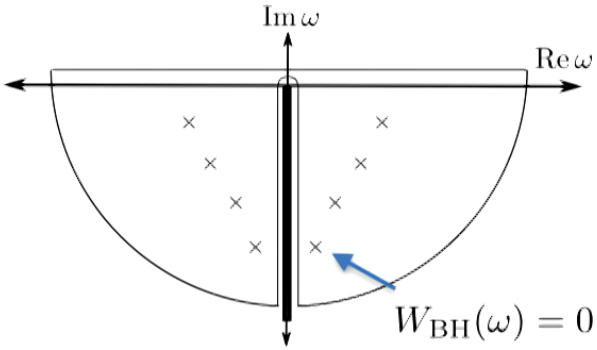
$$\tilde{\psi}_{\rm up}(x) \sim e^{i\omega x} \qquad x \to \infty$$



- Freq domain response

$$\tilde{g}_{\rm BH}(x,x') = \frac{\tilde{\psi}_{\rm up}(x)\tilde{\psi}_{\rm in}(x')}{W_{\rm BH}}$$

$$W_{\rm BH} = \tilde{\psi}_{\rm in}\psi'_{\rm up} - \tilde{\psi}_{\rm up}\psi'_{\rm in}$$



Green's function with reflection

- With reflection GF obeys different BC

$$\tilde{g}_{\rm ref}(x,x') \propto e^{-i\omega(x-x_0)} + \tilde{\mathcal{R}}(\omega)e^{i\omega(x-x_0)}$$

- Build from hom slns to enforce this:

$$\tilde{\psi}_{\rm in} \sim e^{-i\omega x} \qquad \tilde{\psi}_{\rm up} \sim \frac{1}{\tilde{\mathcal{T}}_{\rm BH}}e^{i\omega x} + \frac{\tilde{\mathcal{R}}}{\tilde{\mathcal{T}}_{\rm BH}}e^{-i\omega x}$$

- Some algebra shows that

$$\tilde{g}_{\rm ref}(x,x') = \tilde{g}_{\rm BH}(x,x') + \tilde{\mathcal{K}}\frac{\tilde{\psi}_{\rm up}(x)\tilde{\psi}_{\rm up}(x')}{W_{\rm BH}}$$

$$\tilde{\mathcal{K}} = \frac{\tilde{\mathcal{T}}_{\rm BH}\tilde{\mathcal{R}}e^{-2i\omega x_0}}{1-\tilde{\mathcal{R}}_{\rm BH}\tilde{\mathcal{R}}e^{-2i\omega x_0}}$$

Echoes from GF

- With the GF we can show

$$Z^{\infty} = Z^{\infty}_{\rm BH} + \tilde{\mathcal{K}}\, Z^{\rm H}_{\rm BH}$$

- Transfer function in two ways:

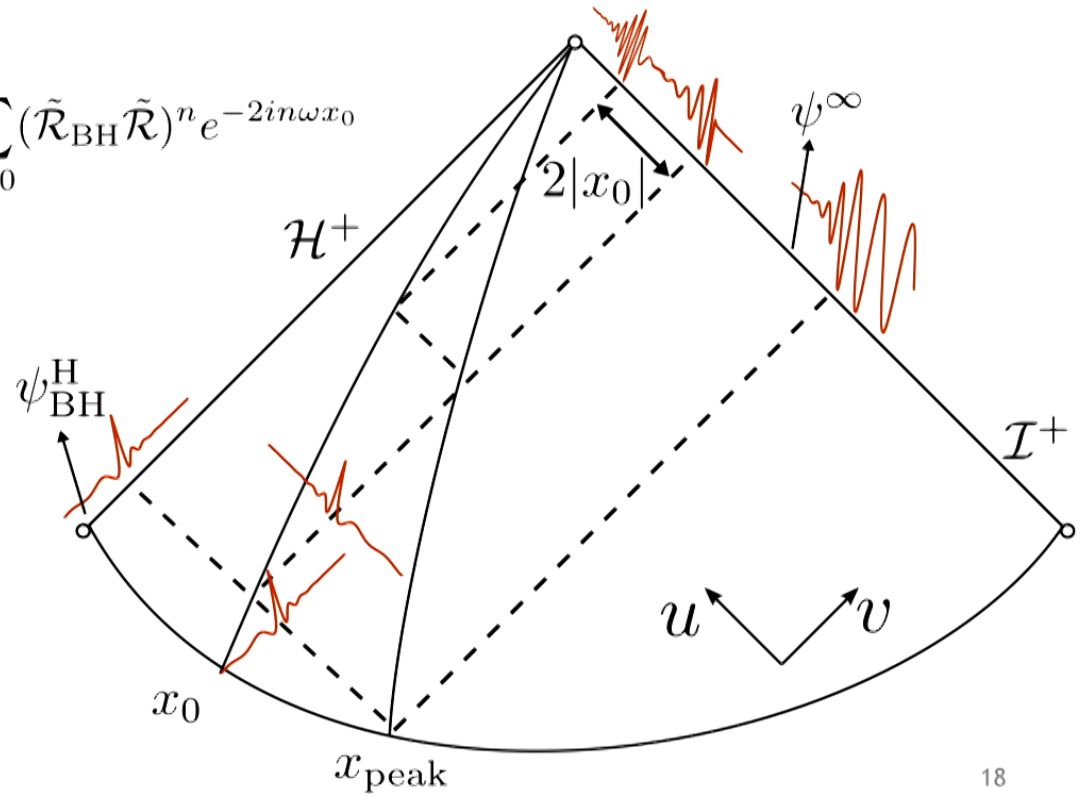
$$\tilde{\mathcal{K}} = \frac{\tilde{\mathcal{T}}_{\rm BH}\tilde{\mathcal{R}}e^{-2i\omega x_0}}{1-\tilde{\mathcal{R}}_{\rm BH}\tilde{\mathcal{R}}e^{-2i\omega x_0}}$$

- Sum of echoes:

$$\tilde{\mathcal{K}} = \tilde{\mathcal{T}}_{\rm BH}\tilde{\mathcal{R}}e^{-2i\omega x_0}\sum_{n=0}^{\infty}(\tilde{\mathcal{R}}_{\rm BH}\tilde{\mathcal{R}})^n e^{-2in\omega x_0}$$

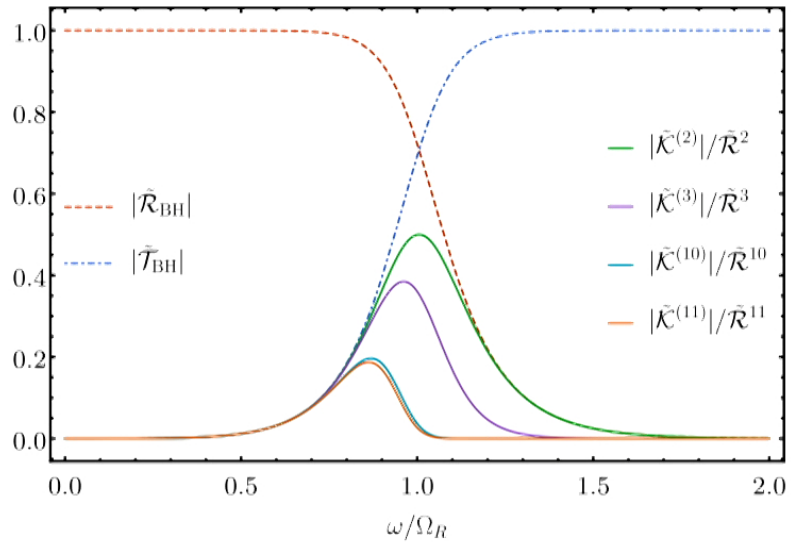
Echoes from a Green's function approach

$$\tilde{\mathcal{K}} = \tilde{\mathcal{T}}_{\rm BH}\tilde{\mathcal{R}}e^{-2i\omega x_0}\sum_{n=0}^{\infty}(\tilde{\mathcal{R}}_{\rm BH}\tilde{\mathcal{R}})^n e^{-2in\omega x_0}$$



Echo transfer function

- Transfer func gives universal properties
- Transmission: high pass filter
- Reflection: low pass filter
- Second echo band passed to near QNM f
- Eventually pieces of sum stop changing much



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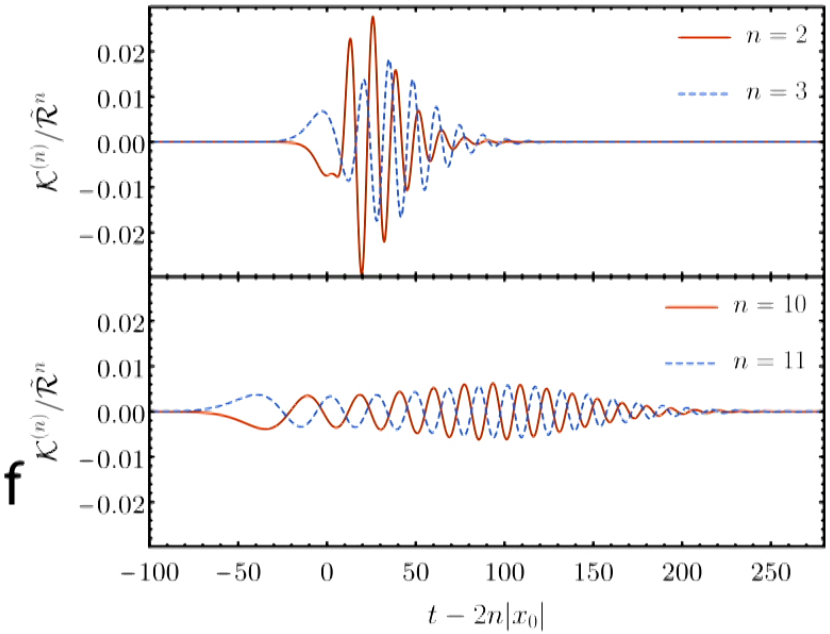

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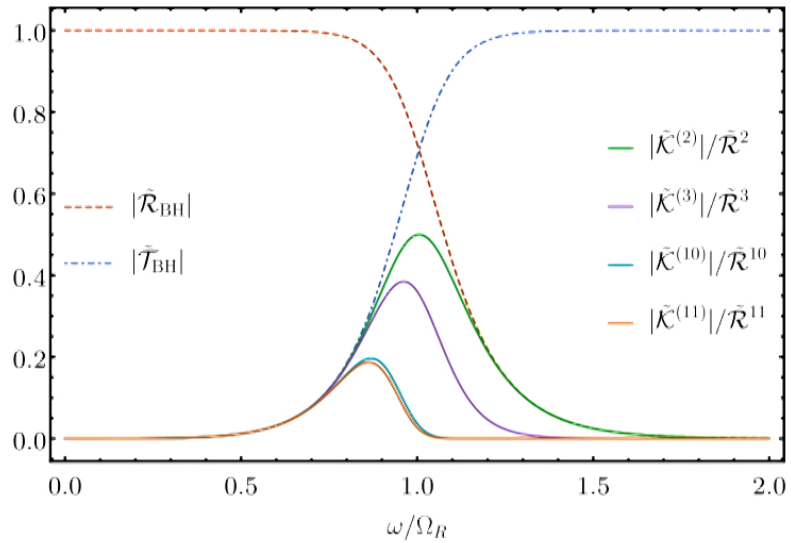
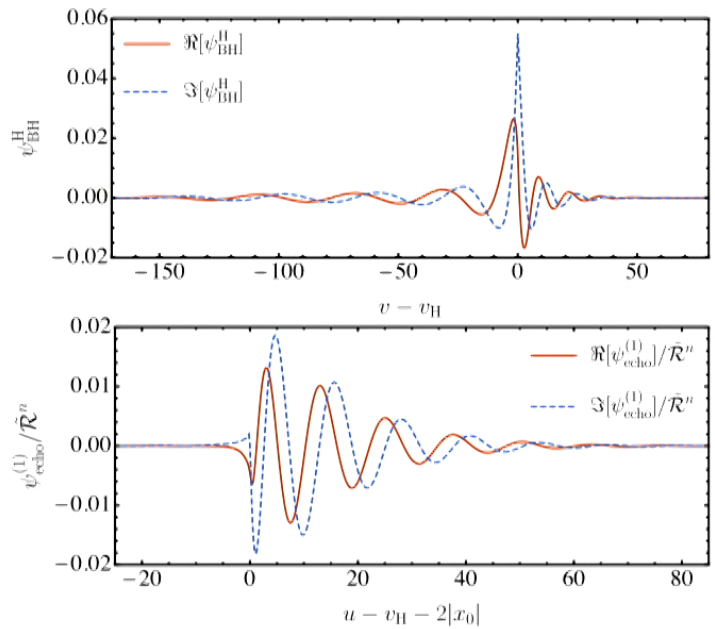


Individual echoes

- Morphology of individual echoes similar to echo transfer functions
- Sum allows for interference

Plunge from ISCO



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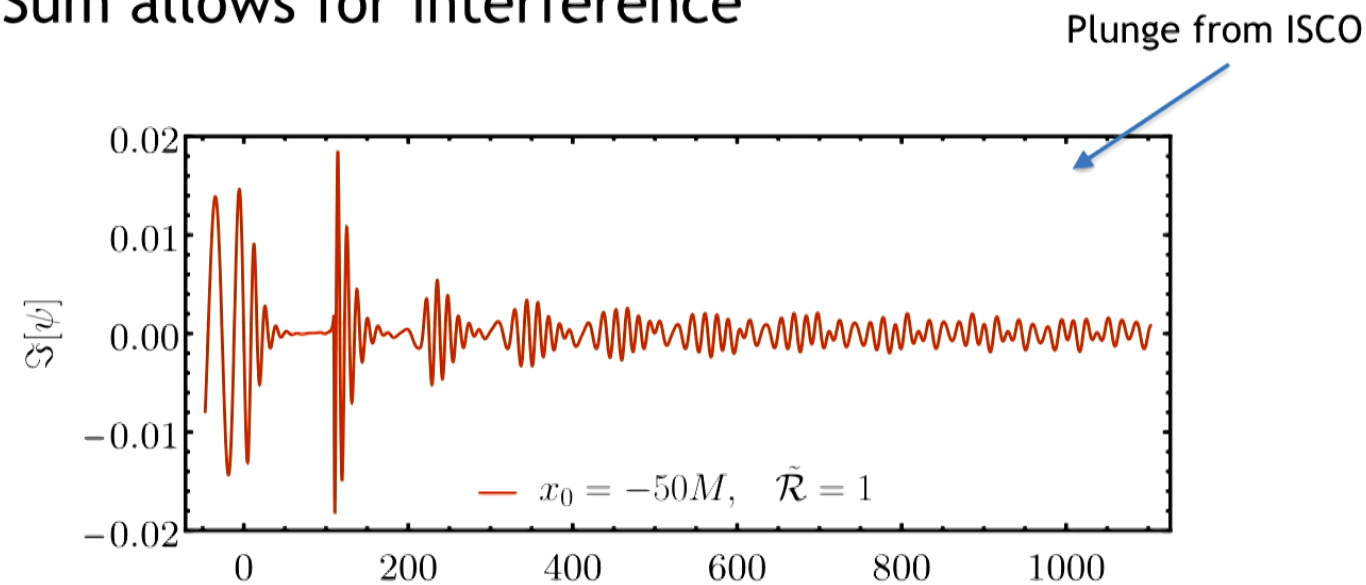
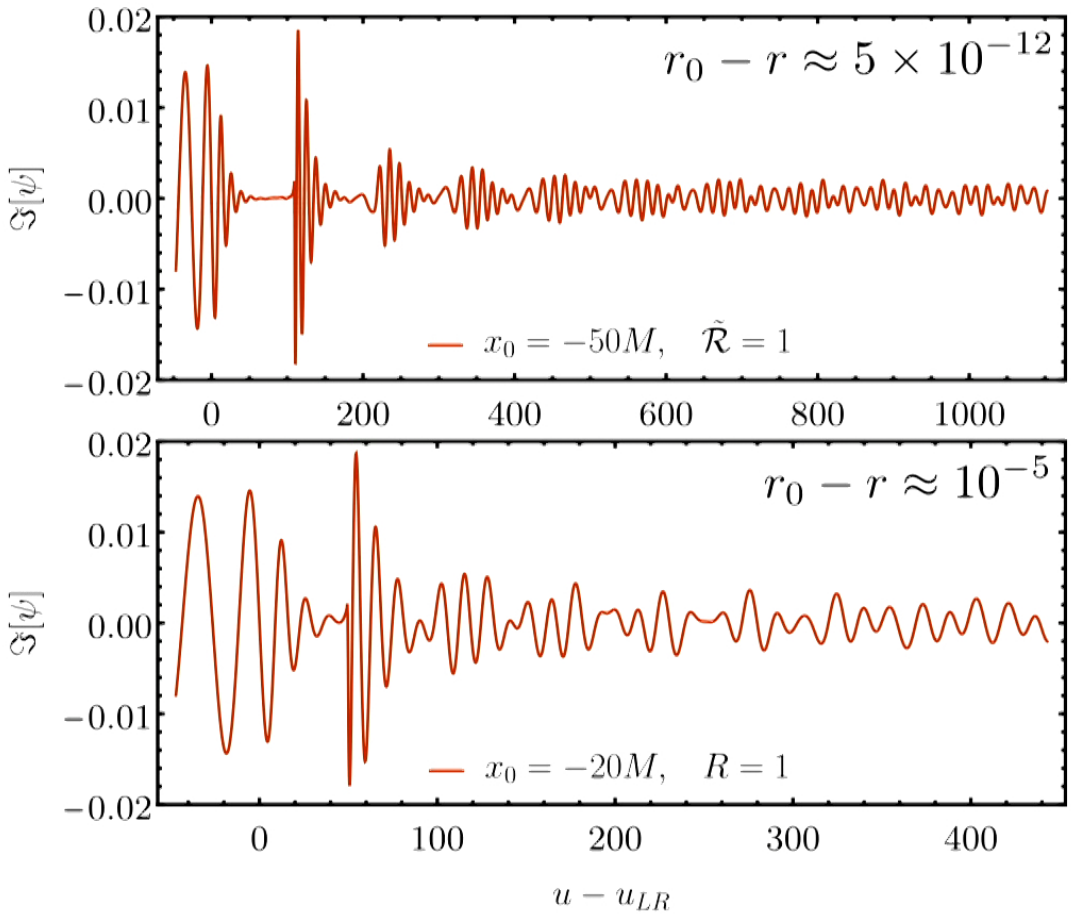
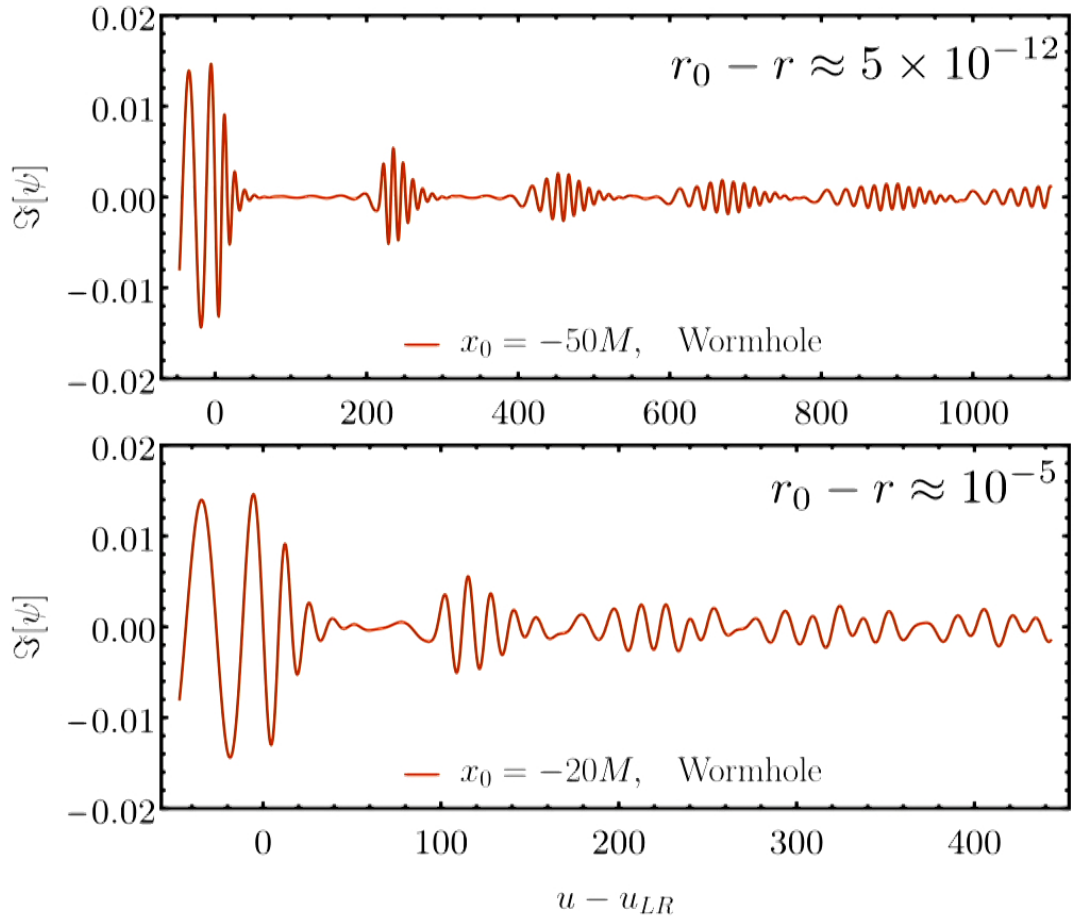


Echo sum: constant R



Echo sum: Wormhole



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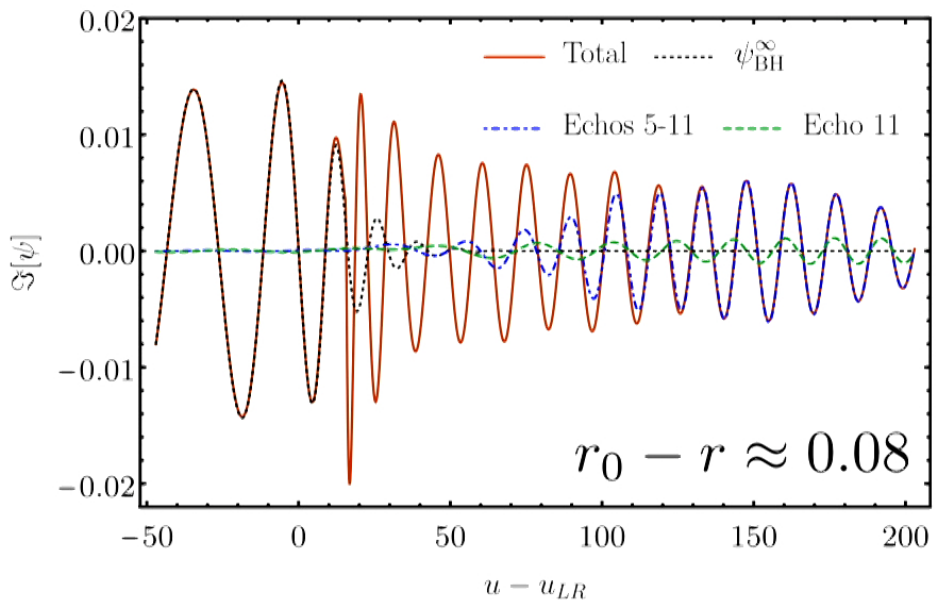
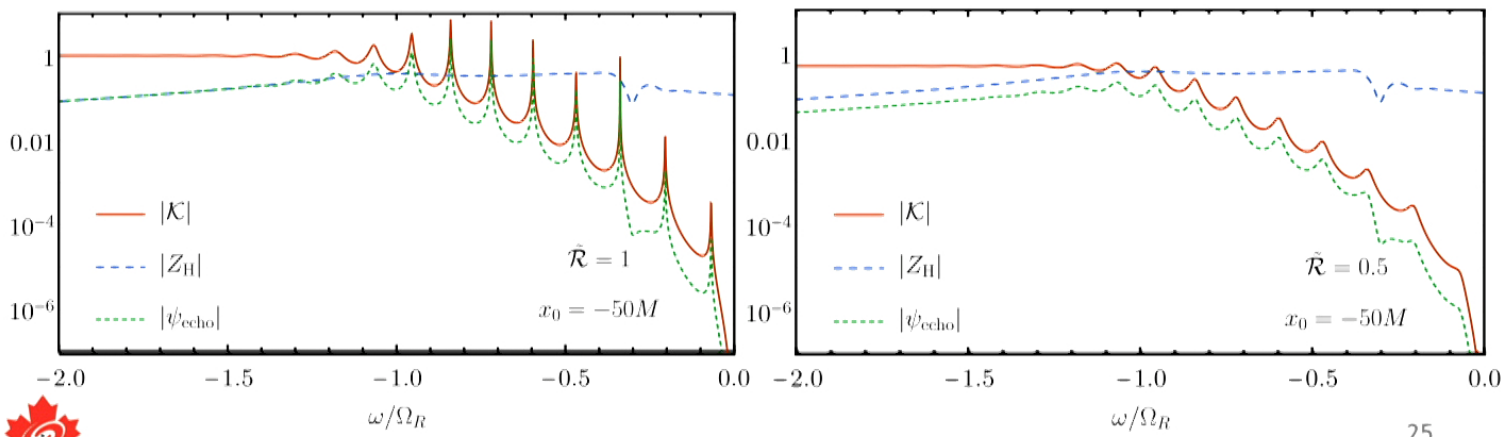
QNMs of ECO?

- Scattering potential indicates we should have slowly decaying QNMs. BH QNMs not poles!
- For bdry farther from horizon, excite ECO mode:



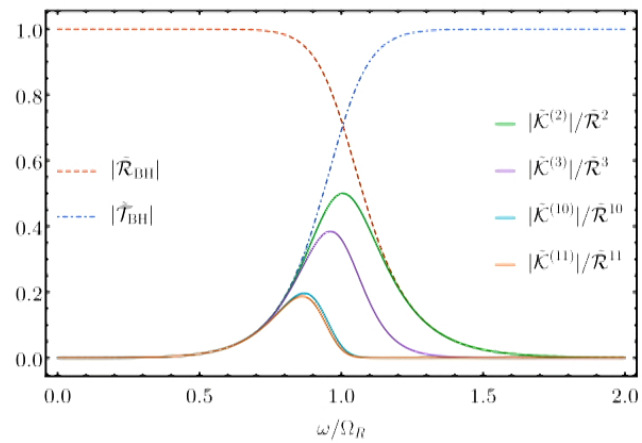
Echoes as ECO modes

- Number of resonances in $\tilde{\mathcal{K}}$ depends on r_0, $\tilde{\mathcal{R}}$
- For large r_0, one mode excited strongly
- For r_0 nearer horizon, many ECO modes excited
- Echoes are superposition of these modes



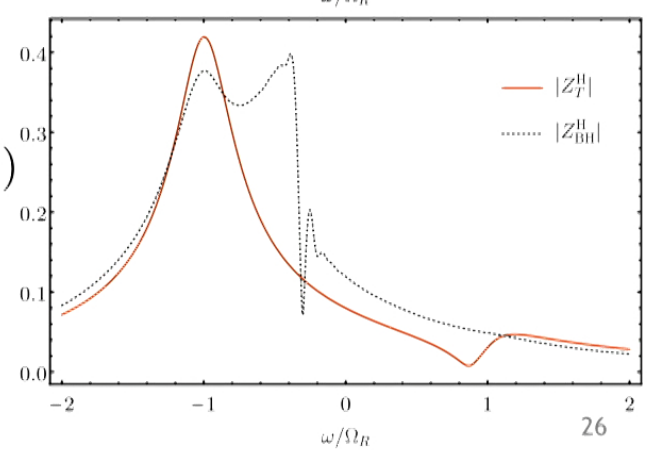
QNM echo template

- Echo transfer funcs act as band pass filter on QNM freq
- Much of the power in psiH is from QNM osc
- Idea: replace source with generic QNM ringing



$$\psi_{\rm QNM} = \Theta(t)(-ie^{-\gamma t})(\alpha_+ e^{-i\Omega t} + \alpha_- e^{i\Omega t})$$

$$\psi_T^{\rm H} = [\psi_{\rm QNM} * \mathcal{N}(t_s, 1/\beta)](t)$$

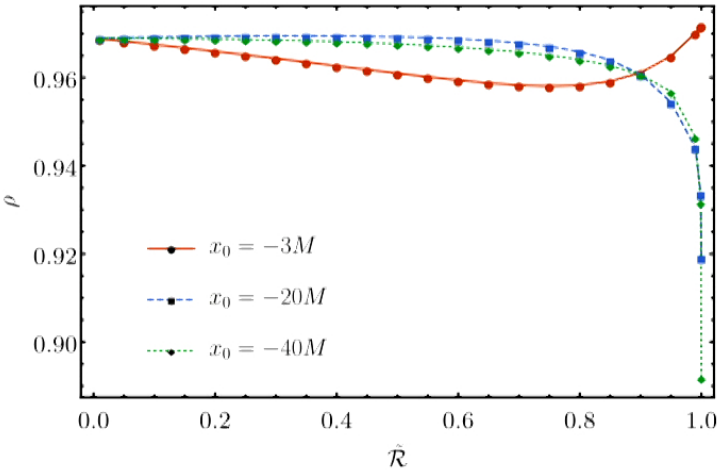


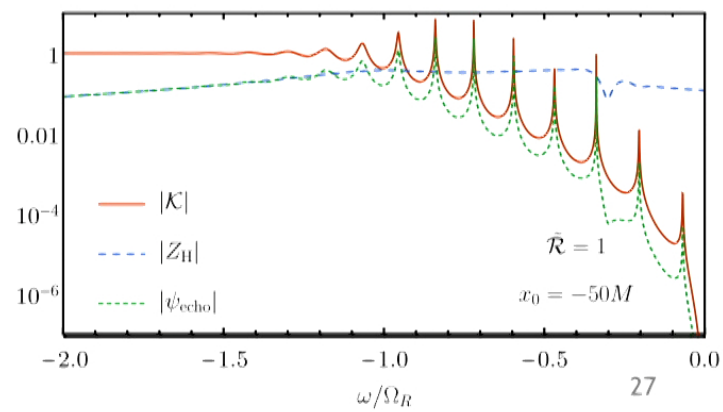
QNM echo template

- Frequency domain:

$$Z_{\mathrm{T}}^{\mathrm{H}} = e^{i\omega t_s} e^{-\omega^2/(2\beta^2)} \left(\frac{\alpha_+}{\omega - \Omega_+} + \frac{\alpha_-}{\omega - \Omega_-} \right)$$

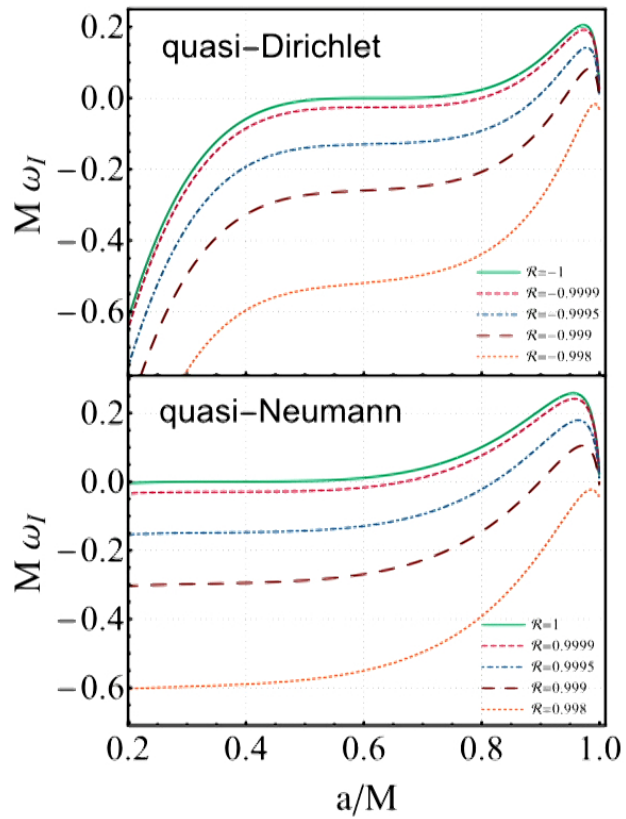
- Maximize overlap by varying template params at fixed $\tilde{\mathcal{R}}$, x_0
- Simple template recovers full waveform well
- Difficulties at large $\tilde{\mathcal{R}}$





What's next: Kerr

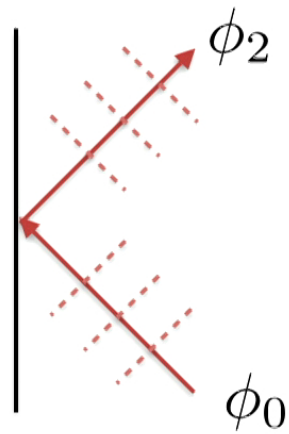
- For scalar fields, extension is straightforward
- New features: superradiant instability of modes
- Spins down hole until instability shuts off
- Easily quenched by some decay of echoes



Maggio et al. 1703.03696

What's next: GWs

- Extension to gravitational perts not trivial (Price & Khanna 1702.04833)
- Need BCs on multiple scalar fields
- Or convert to complicated BCs
- Simplification should be possible

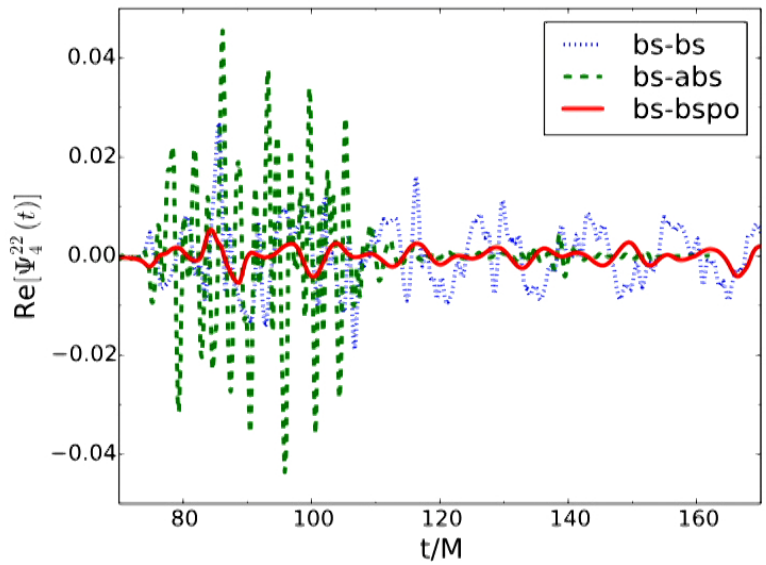


$$E^{\hat{\theta}} = 0$$

$$E^{\hat{\theta}} = \frac{\sqrt{1-2M/r}}{\sqrt{2}}\mathrm{Re}[\phi_0] - \frac{\sqrt{2}}{\sqrt{1-2M/r}}\mathrm{Re}[\phi_2]$$

What's next: beyond test field

- To date: all results for test fields in fixed backgrounds
- Exception: boson star collisions
- Extension to comparable mass mergers?
- Full numerical simulations of ECOs?



Cardoso et al. 1608.08637

Summary and Outlook

- Echoes are the generic result of perts around very compact objects
- Param model reprocesses waves on BH spacetimes into echoes
- Workable template may be simplex
- Still much to do to understand GW echoes