Constructing Echo Waveforms from Spinning Exotic Compact Objects

Shuo Xin, Tongji University

Mentors: Ling Sun, Yanbei Chen, Baoyi Chen, Rico Lo

Overview

Introduction: What and why?

Method: How to construct echoes?

Results

Perspectives

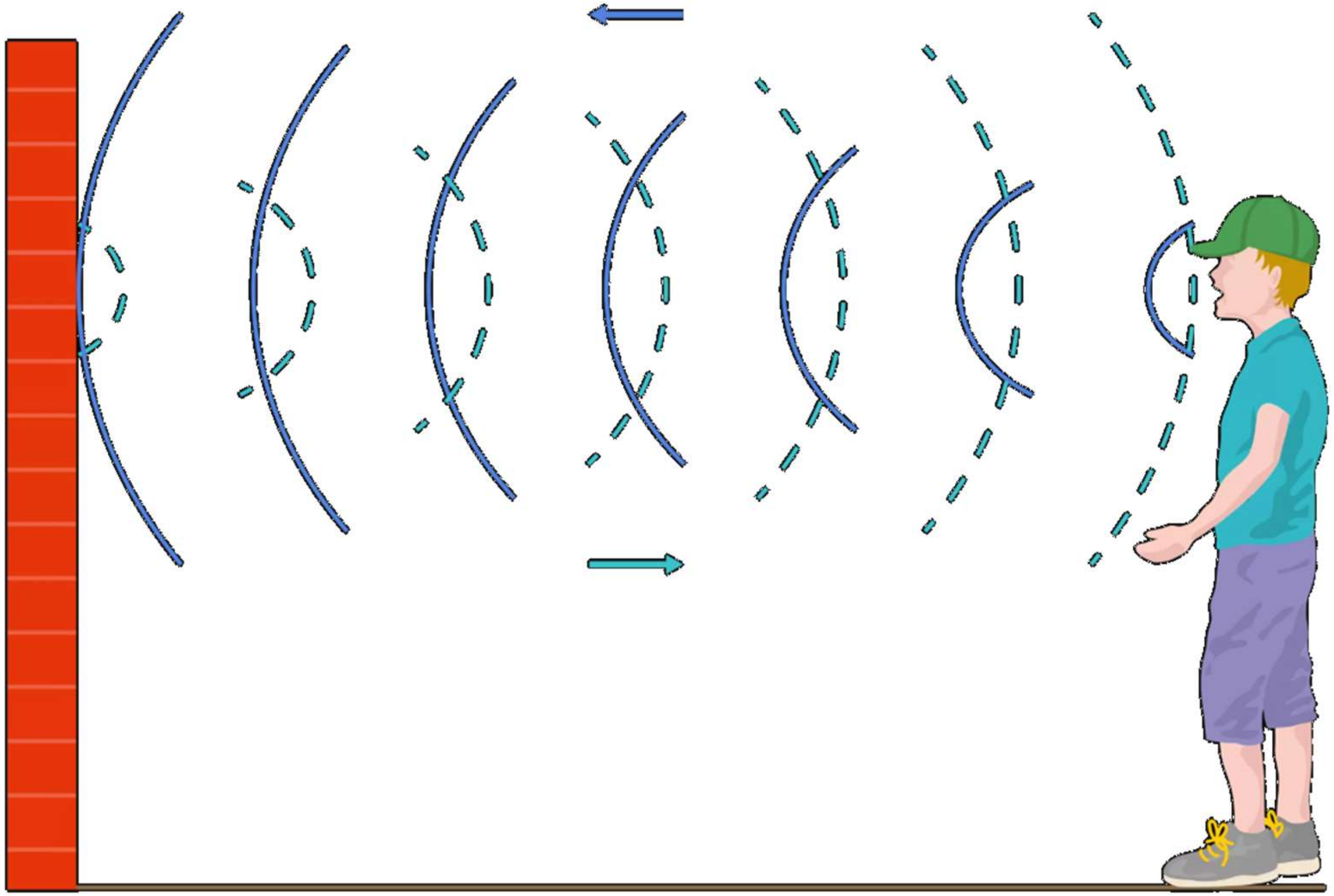
Introduction

What is echo?

Why is it important?

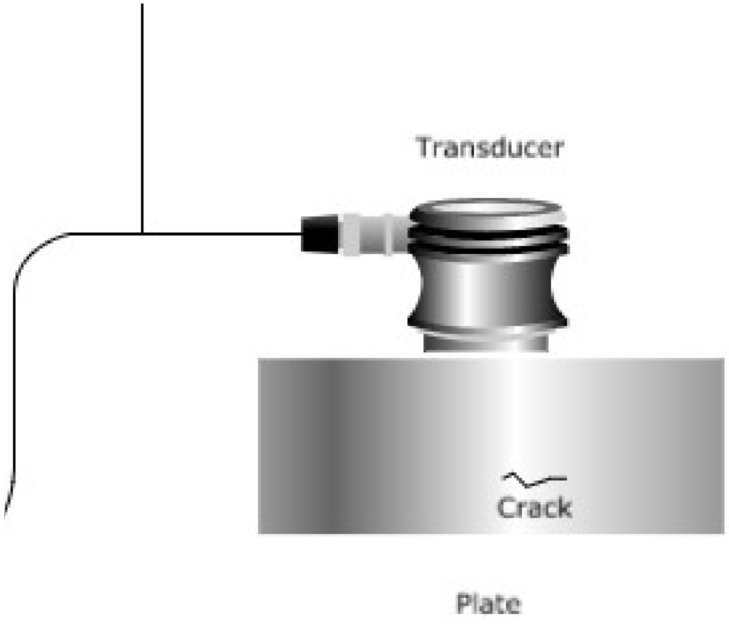
Recent discussions

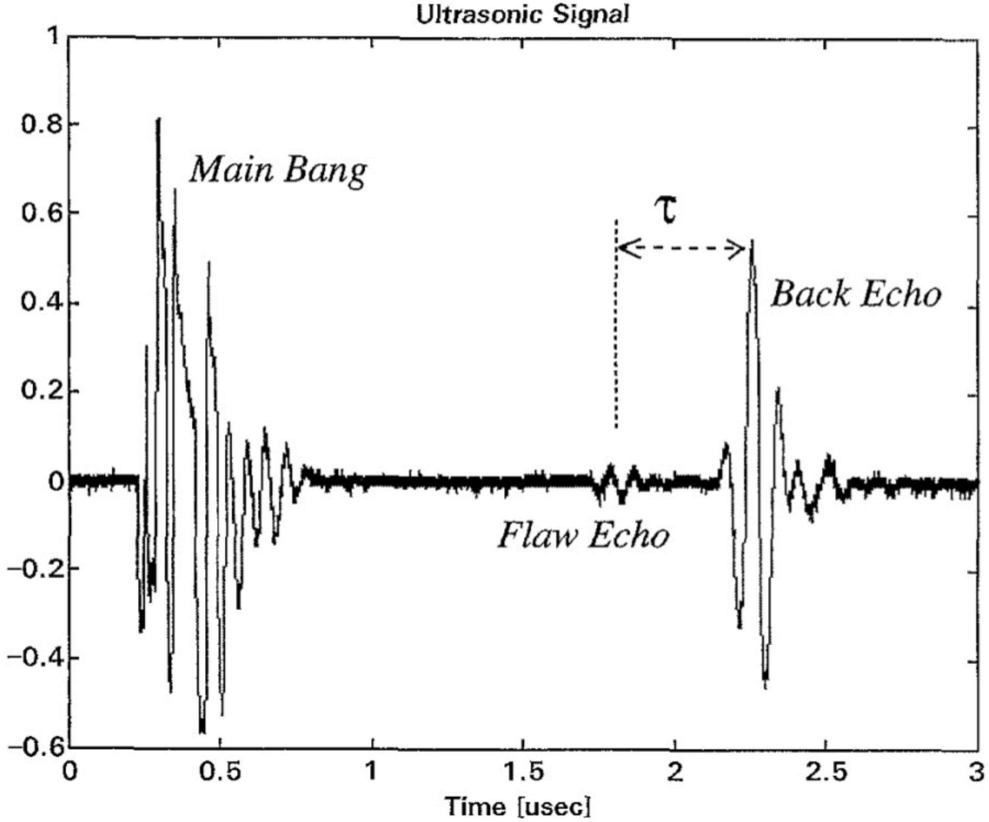
What is echo: familiar echoes



Credit: https://www.dkfindout.com/uk/science/sound/echoes/

Find mechanical crack



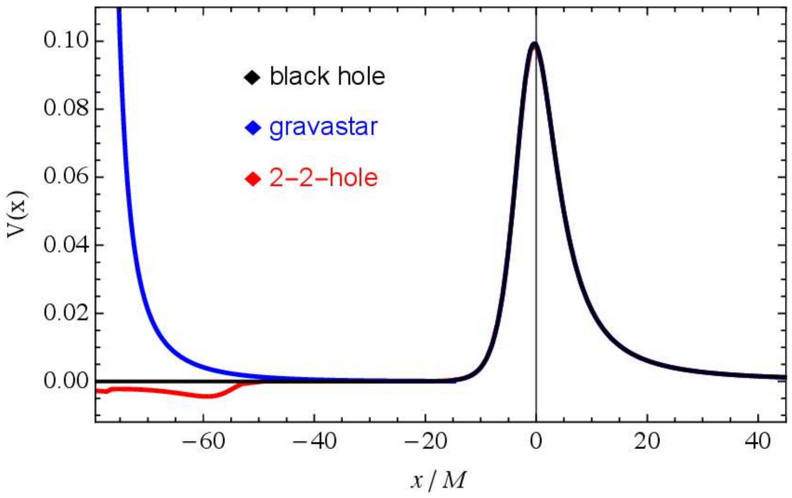


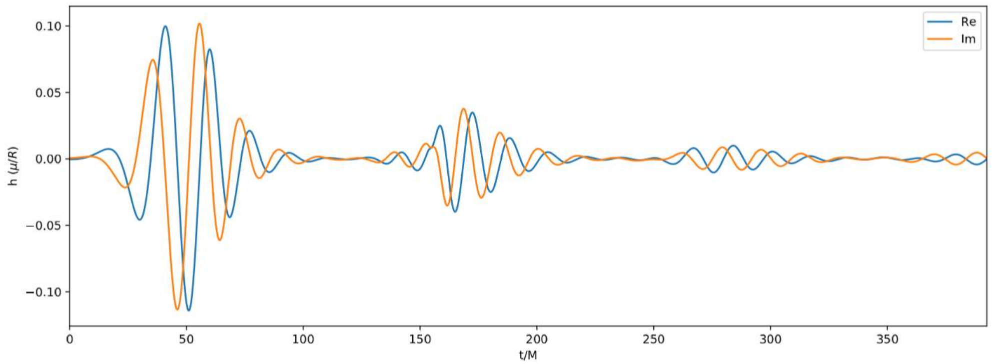
Agostino Abbate et al. IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 44(1):14–26, 1997.

Find crack in compact object?

Horizon ← Crack ↓

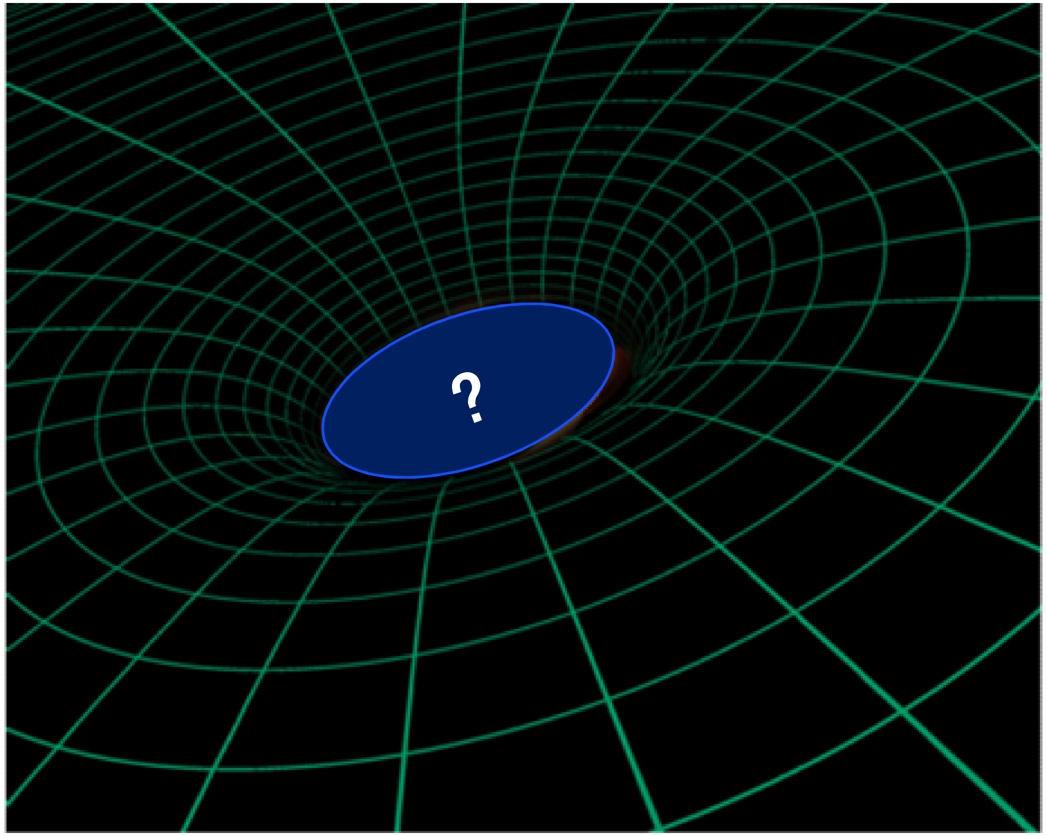
Ringdown Signal





Randy S. Conklin, Bob Holdom, and Jing Ren. Gravitational wave echoes through new windows. Phys. Rev. D, 98:044021, Aug 2018.

Potential hint for exotic physics

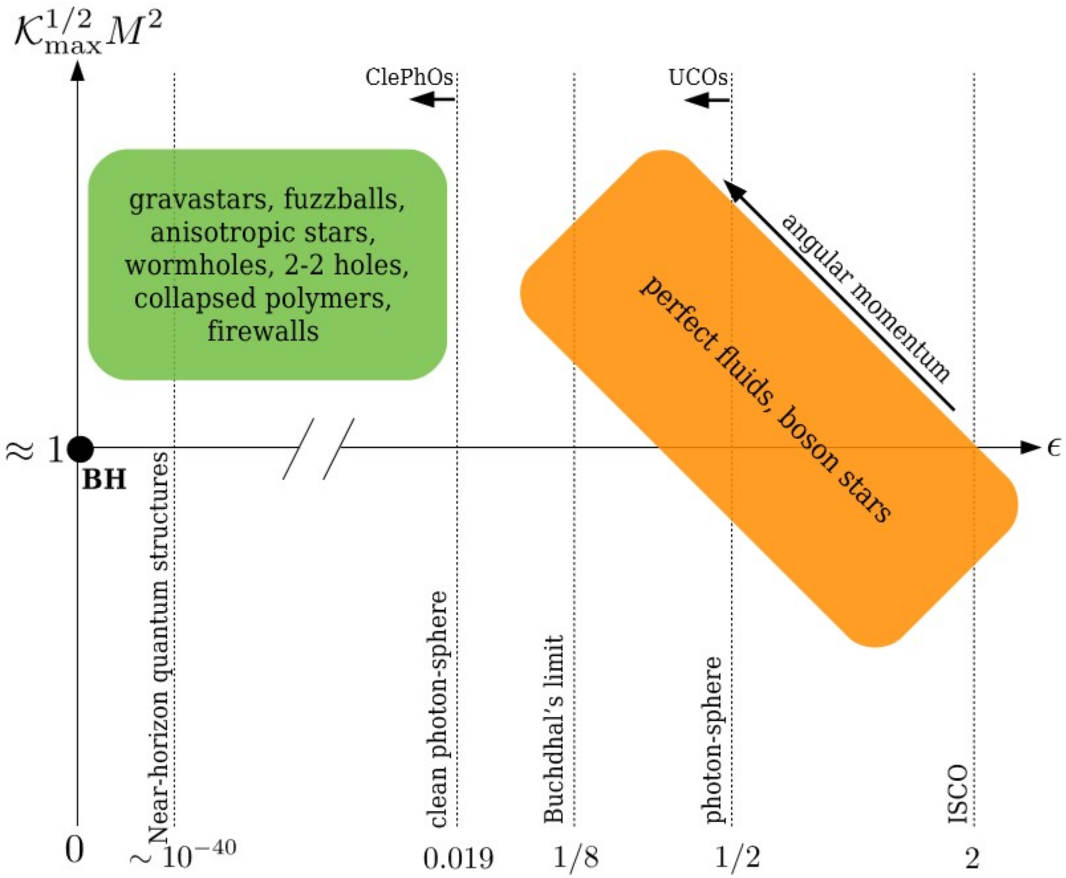


What's hiding near horizon?

Black hole?
Wormhole?
Fuzzball?
…

Echo may tell.

Exotic Compact Objects (ECOs)



Vitor Cardoso, Paolo Pani. Testing the nature of dark compact objects: a status report. arXiv:1904.05363

ϵ: Compactness, defined by

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

r_0: radius of ECO,

r_+: radius of "horizon"

$\mathcal{K}_{max}$: Kretschmann scalar, characterizing maximum curvature in the spacetime

Recent discussions

Data Analysis (no echo is found yet)

Jahed Abedi et al. Phys. Rev. D, 96:082004, Oct 2017.

Andrea Maselli et al. Phys. Rev. D, 96:064045, Sep 2017.

Ka WaTsang et al. Phys. Rev. D, 98:024023, Jul 2018.

R Ka Lok Lo et al. Phys. Rev. D, 99: 084052, April 2019.

And a lot …

Models for echoes from non-spinning ECO

Zachary Mark et al. Phys. Rev. D, 96:084002, Oct 2017.

Song Ming Du et al. Phys. Rev. Lett., 121:051105, Aug 2018.

And a lot …

Models for echoes from spinning ECO

Qingwen Wang et al. Phys. Rev. D, 97:124044, June 2018

Hiroyuki Nakano et al. Prog. Theo. Exp. Phys., 2017(7), 07 2017.

Elisa Maggio et al. ArXiv 1907.03091

Past work for spinning ECO

Qingwen Wang et al. Phys. Rev. D, 97:124044, June 2018

- » Making echoes: ingoing wave packet from infinity

Hiroyuki Nakano et al. Prog. Theo. Exp. Phys., 2017(7), 07 2017.

- » Making echoes: ingoing wave is assumed phenomenologically

$$h(t) \propto \frac{e^{-i\omega_{\mathrm{QNM}}\tilde{t}}}{1 + \exp[-2\beta t|\Im(\omega_{\mathrm{QNM}})|]}$$

Elisa Maggio et al. ArXiv 1907.03091

- » Low frequency expansion

Method

Black Hole (BH) perturbation theory

From BH to ECO

Physical picture

BH perturbation theory

Teukolsky equation *Phys. Rev. Lett. 29: 1114, 1973*:

- Describes evolution of ψ_s ($s = 0,1,2,3,4$), projection of Weyl curvature tensor on Newman-Penrose tetrads

$$\left[\frac{(r^2+a^2)^2}{\Delta} - a^2\sin^2\theta\right]\frac{\partial^2\psi}{\partial t^2} + \frac{4Mar}{\Delta}\frac{\partial^2\psi}{\partial t\,\partial\varphi} + \left[\frac{a^2}{\Delta} - \frac{1}{\sin^2\theta}\right]\frac{\partial^2\psi}{\partial\varphi^2} - \Delta^{-s}\frac{\partial}{\partial r}\left(\Delta^{s+1}\frac{\partial\psi}{\partial r}\right) - \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\psi}{\partial\theta}\right)$$

$$-2s\left[\frac{a(r-M)}{\Delta} + \frac{i\cos\theta}{\sin^2\theta}\right]\frac{\partial\psi}{\partial\varphi} - 2s\left[\frac{M(r^2-a^2)}{\Delta} - r - ia\cos\theta\right]\frac{\partial\psi}{\partial t} + (s^2\cot^2\theta - s)\psi = 4\pi\Sigma T.$$

Boundary condition:

- Only ingoing wave at horizon
- Only outgoing wave at infinity

At infinity, solution is related to gravitational waves by

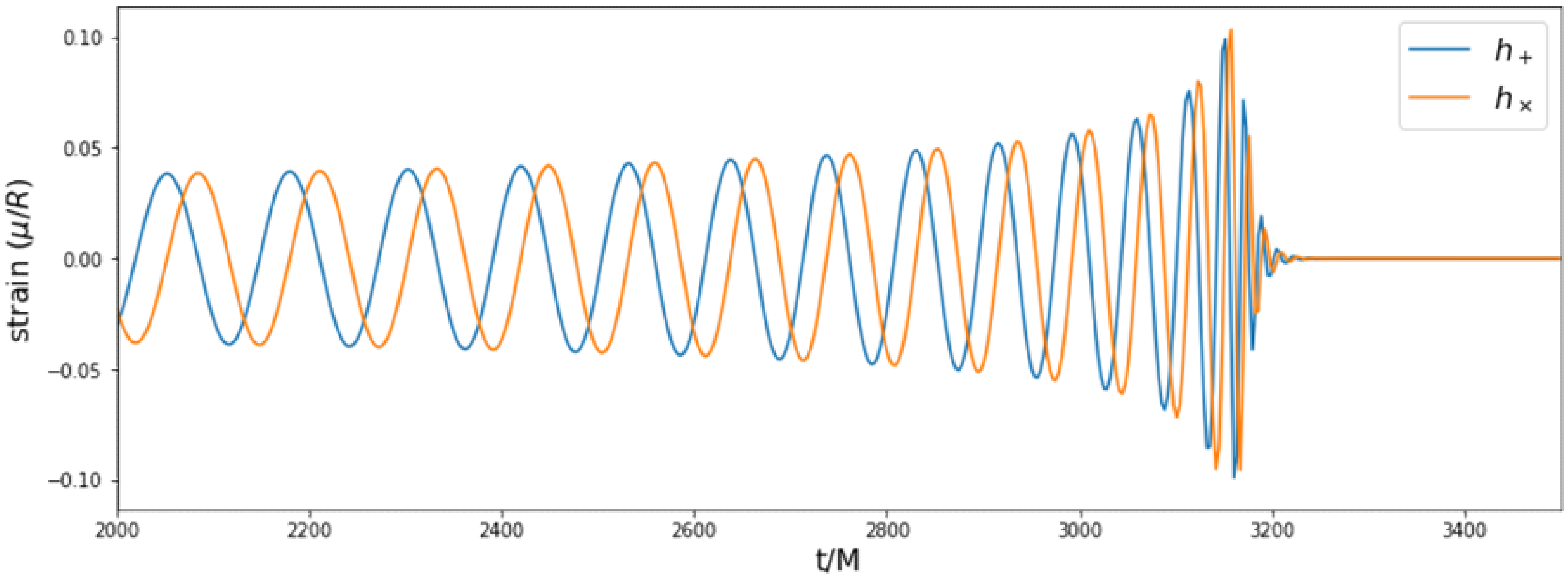
$$\psi_4(r\to\infty) \to \frac{1}{2}(\ddot{h}_+ - i\ddot{h}_\times)$$

A well tested Fortran code is already in hand

Wen-Biao Han and Zhoujian Cao. Constructing effective one-body dynamics with numerical energy flux for intermediate-mass-ratio inspirals. Phys. Rev. D, 84:044014, Aug 2011.

BH perturbation theory

Waveform example based on Post-Newtonian orbit
for 2 BH with total mass M and mass ratio 0.25,
Starting from an equatorial circular orbit with radius 15M



Form F0900043-v2

From BH solution to ECO solution

Regard ECO as a reflecting boundary located at r_0^* with reflectivity $\tilde{R}(\omega)$

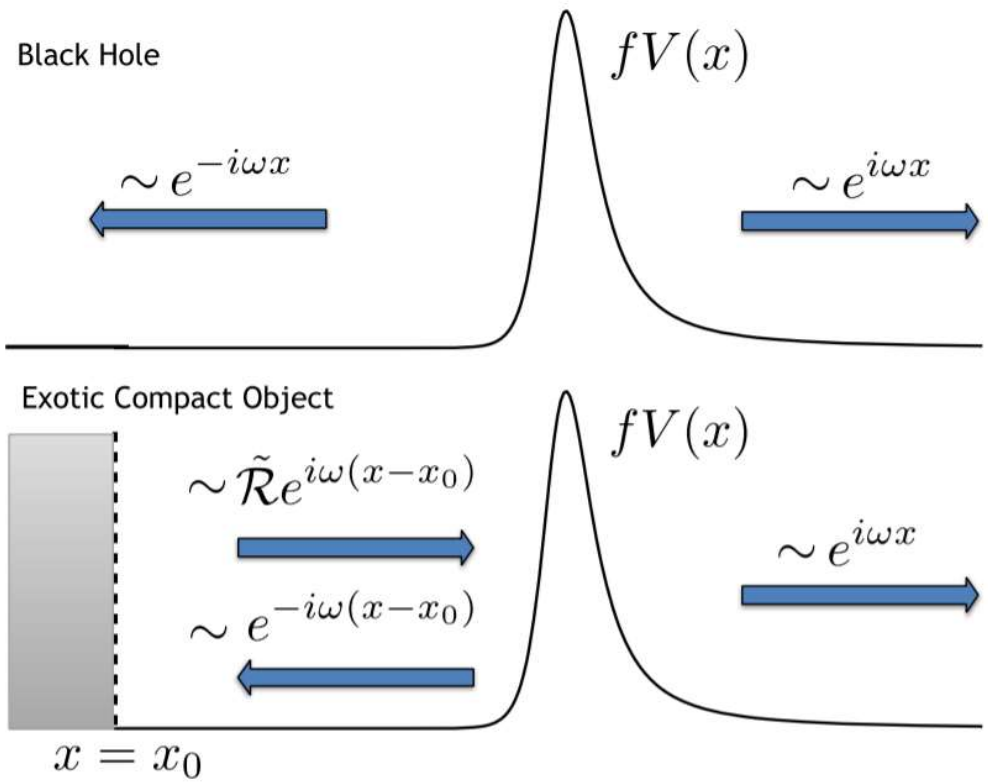
BH boundary condition:

- Only ingoing at horizon
- Only outgoing at infinity

ECO boundary condition:

- Reflecting at r_0^*
- Only outgoing at infinity

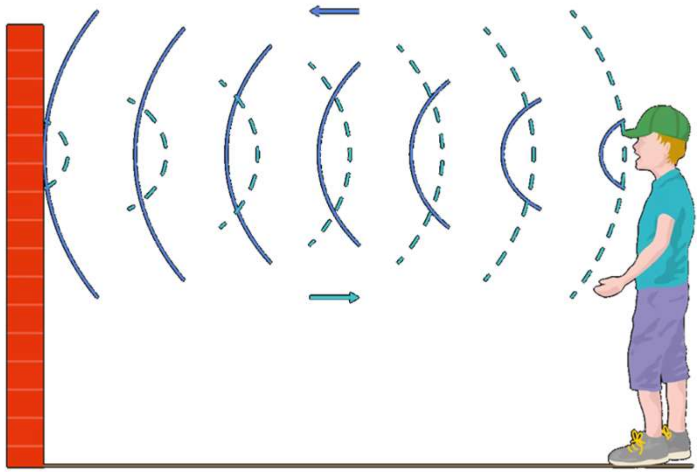
Solution in ECO background can be constructed from solution in BH background



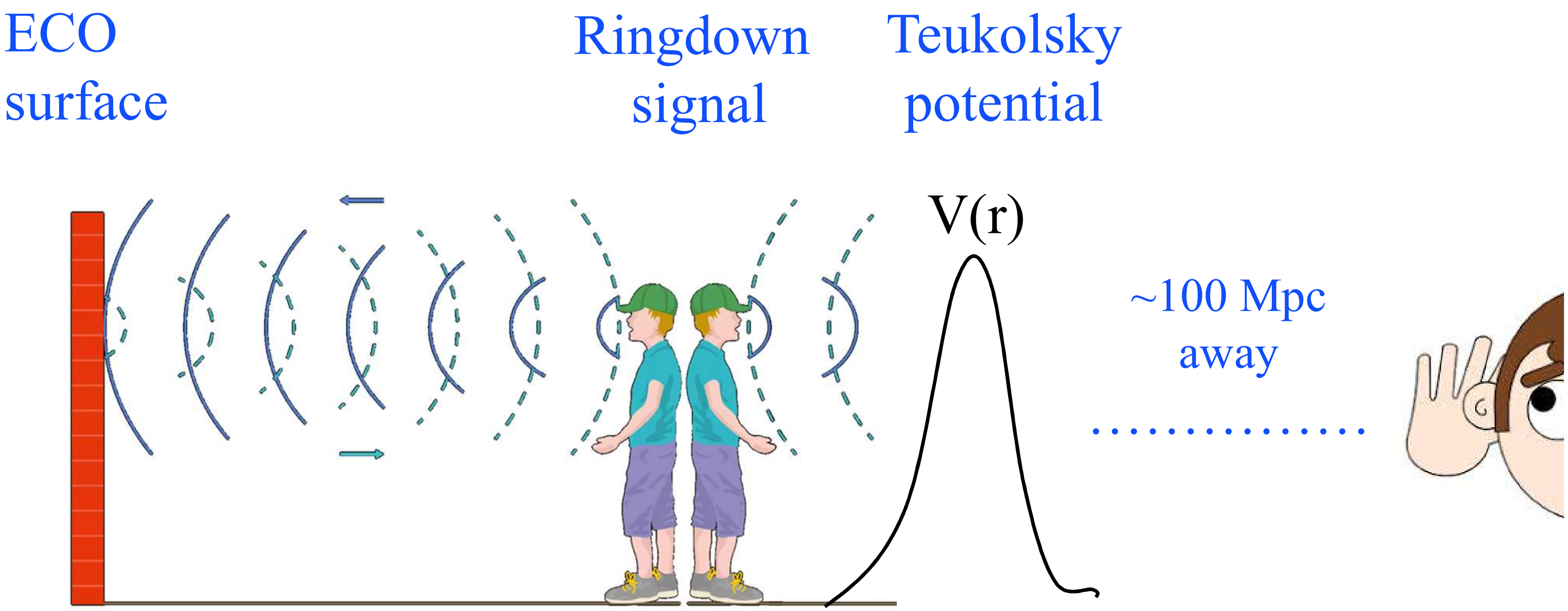
Zachary Mark, Aaron Zimmerman, Song Ming Du, and Yanbei Chen. A recipe for echoes from exotic compact objects. Phys. Rev. D, 96:084002, Oct 2017.

Physical picture

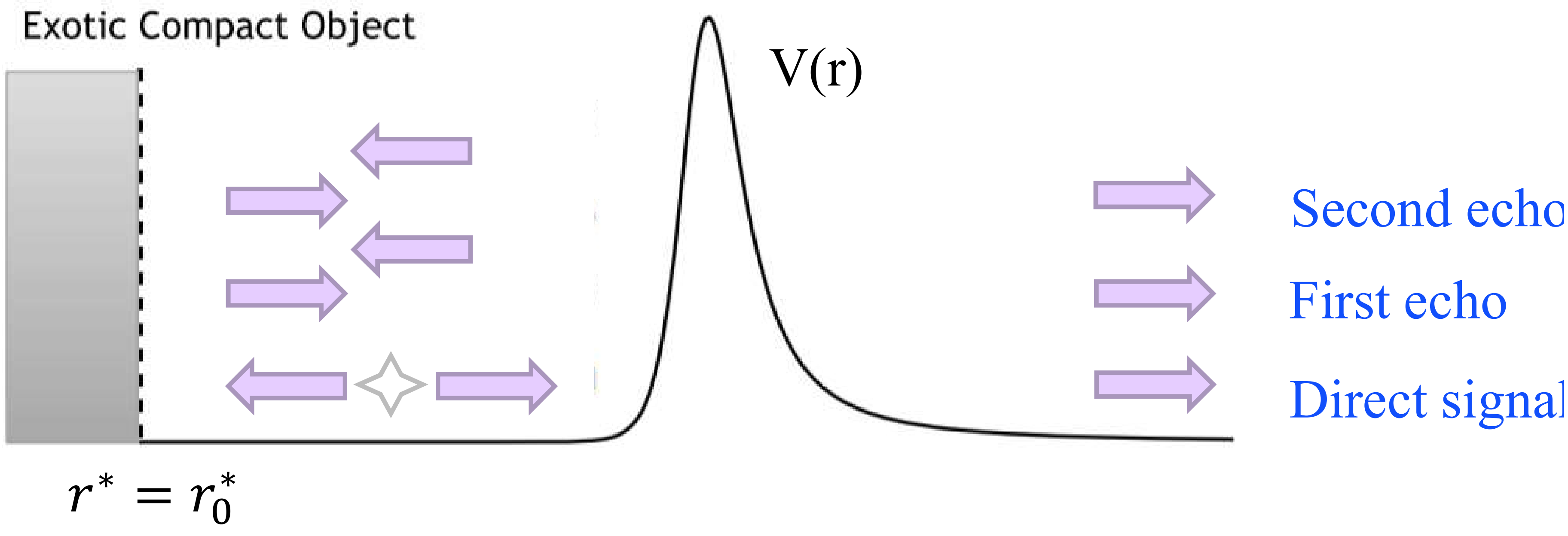
Naïve echo



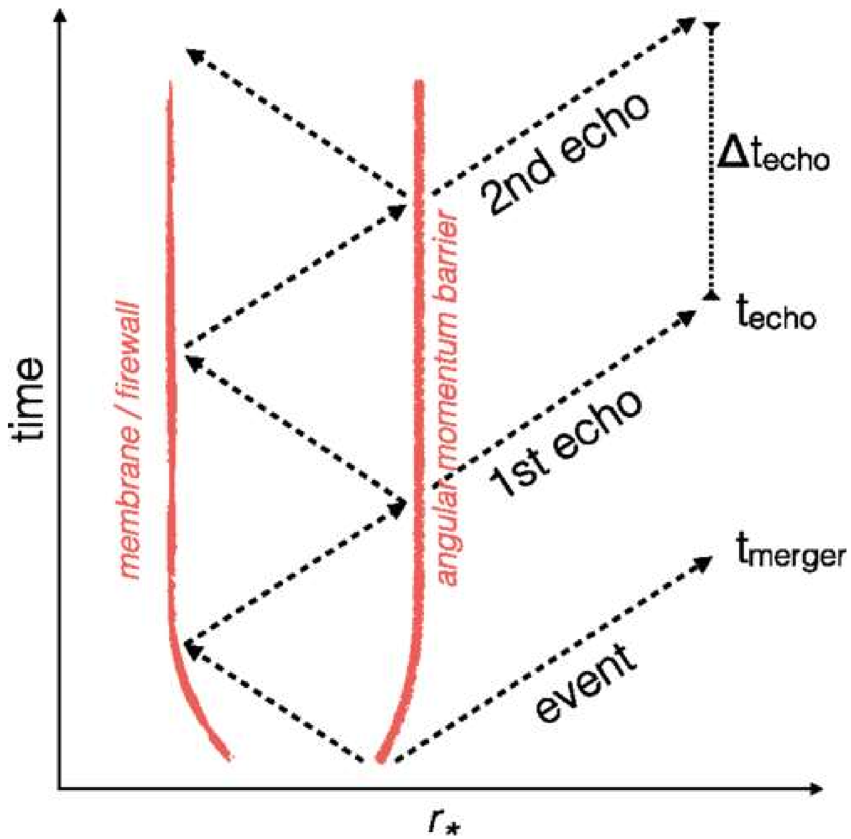
Physical picture



Physical picture



Physical picture



Jahed Abedi et al. Phys. Rev. D, 96:082004, Oct 2017.

Results

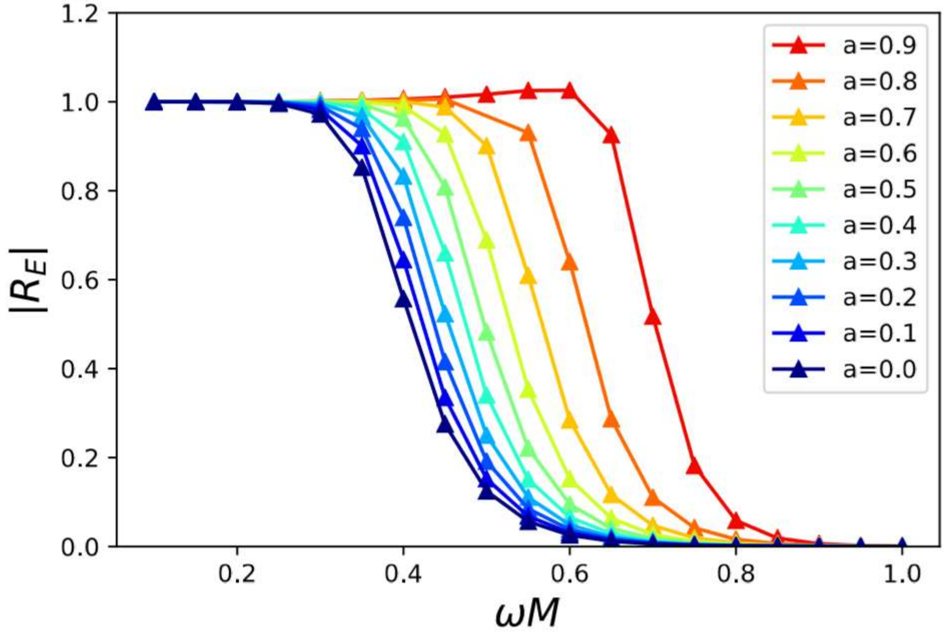
“Superradiance”

Waveform examples

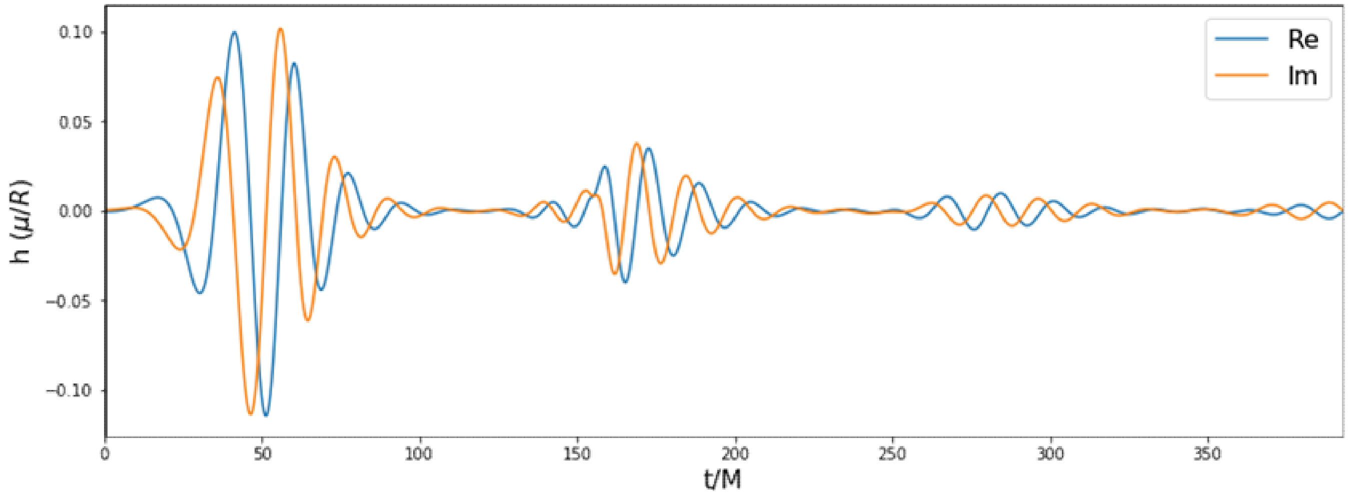
- Plunging particle source
- Phenomenological source

“Superadiance”

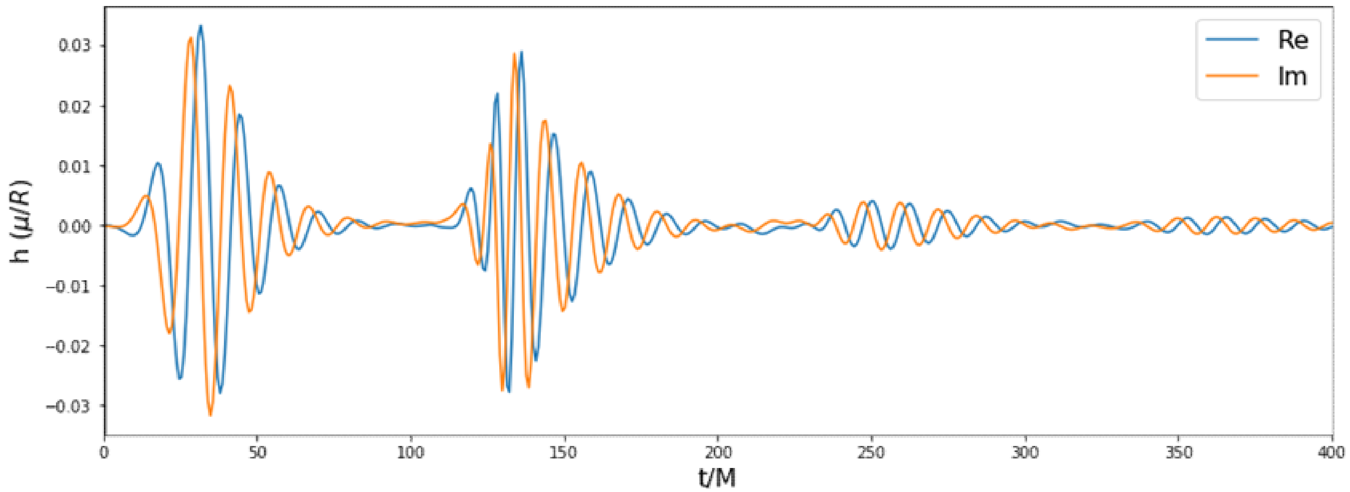
Energy reflectivity may exceed 1 when spin turns on



Waveform examples



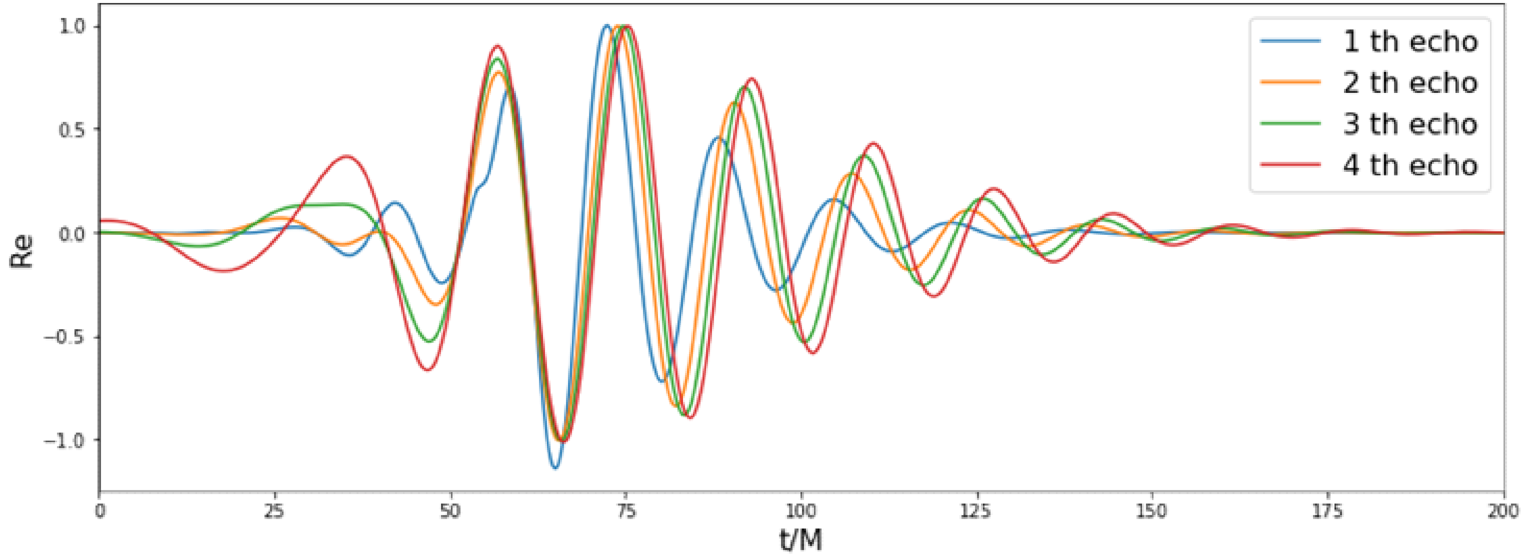
$a/M = 0$



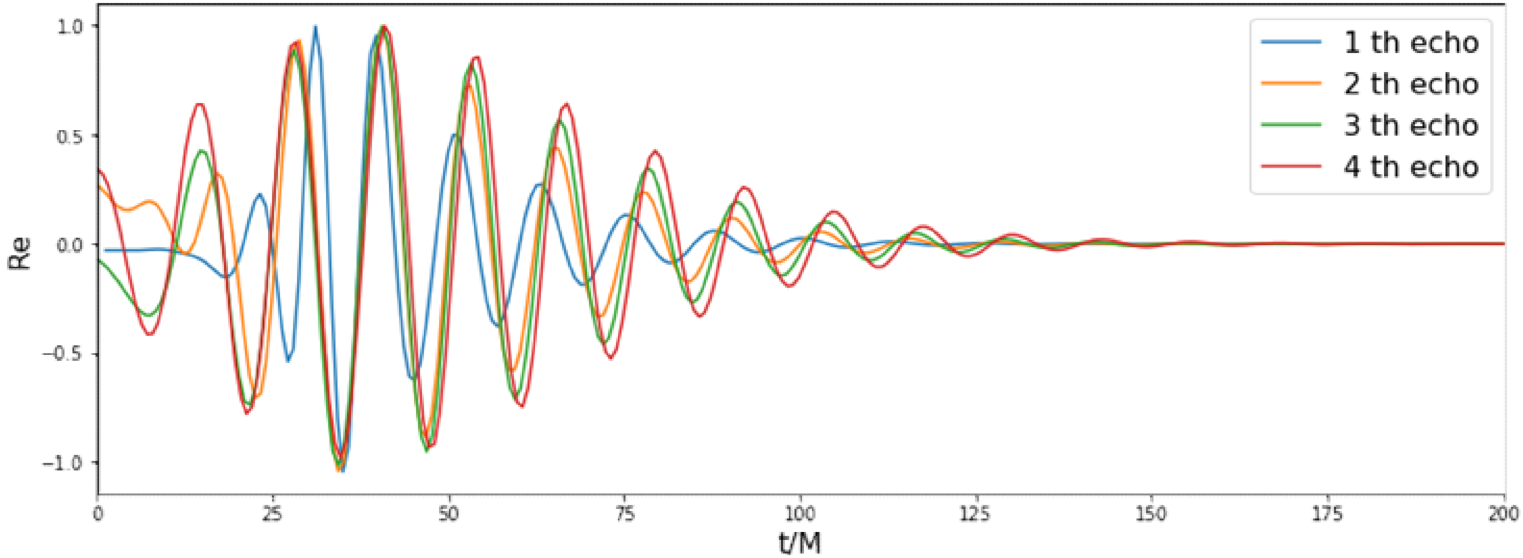
$a/M = 0.6$

Sourced by plunging orbit. Central ECO: $\tilde{R} = 0.5, r_0^* = -50$

Waveform examples



$a/M = 0$



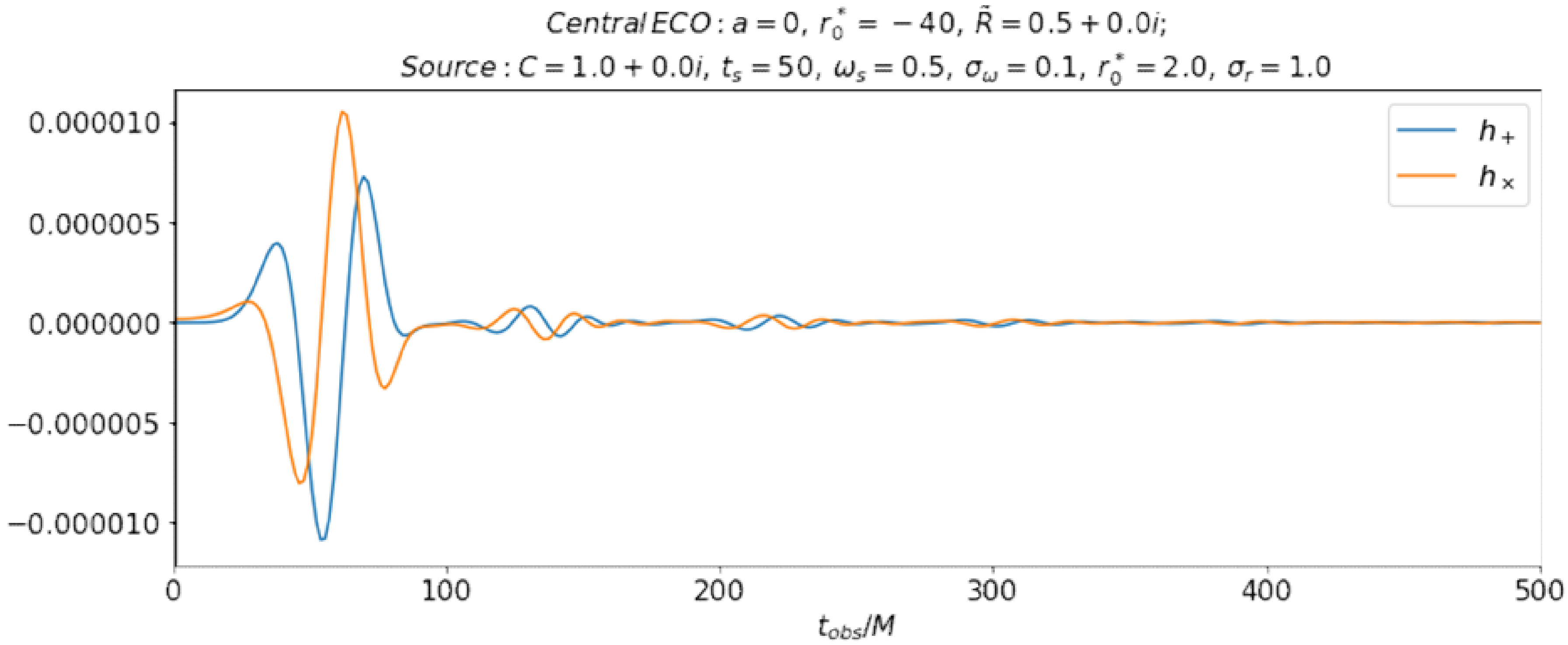
$a/M = 0.6$

Phenomenological source

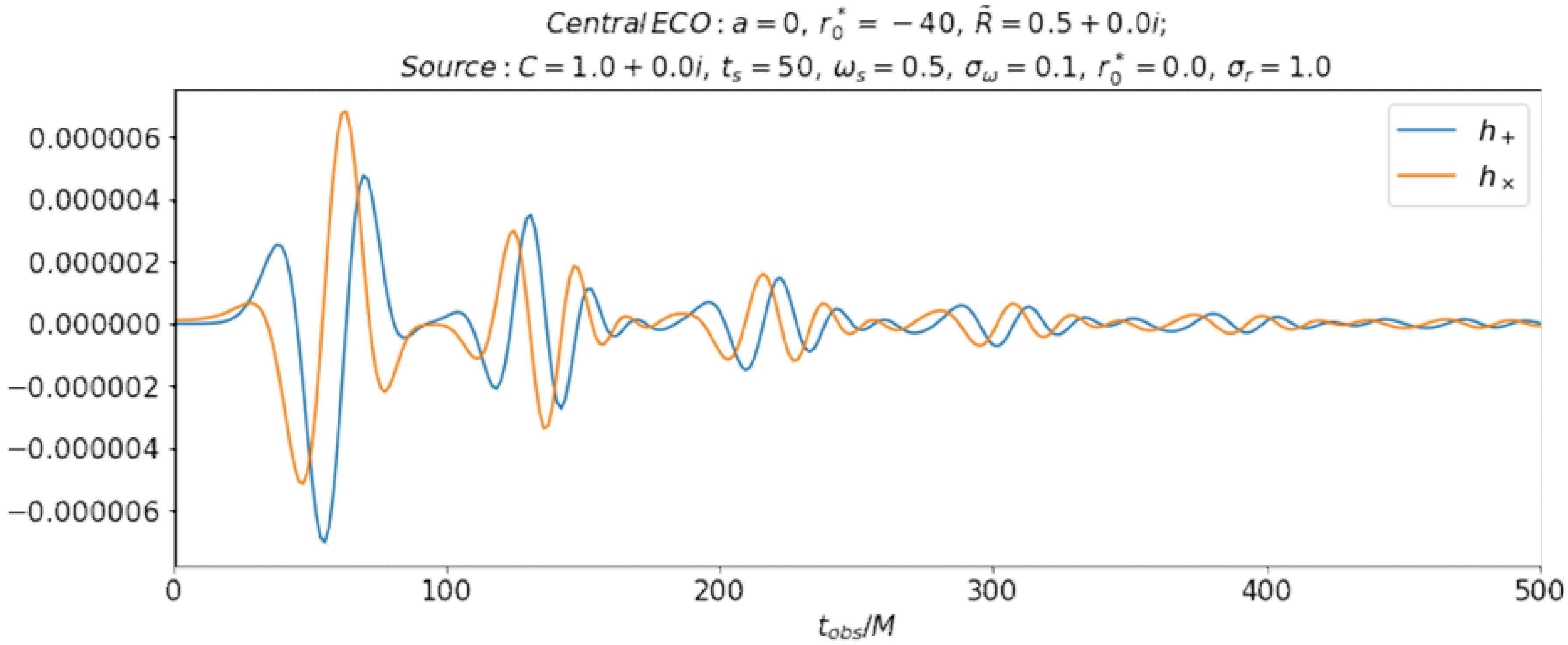
$$\mathscr{T}_{lm\omega}/\Delta^2 = Ce^{i\omega t_s}\exp(-\frac{(\omega-\omega_s)^2}{2\sigma_\omega^2})\exp(-\frac{(r^*-r_s^*)^2}{2\sigma_r^2})$$

C: amplitude
t_s: arrival time
ω_s: primary frequency content of the source
σ_ω: dispersion in frequency
r_s^*: the source is localized near r_s^*
σ_r: dispersion in space

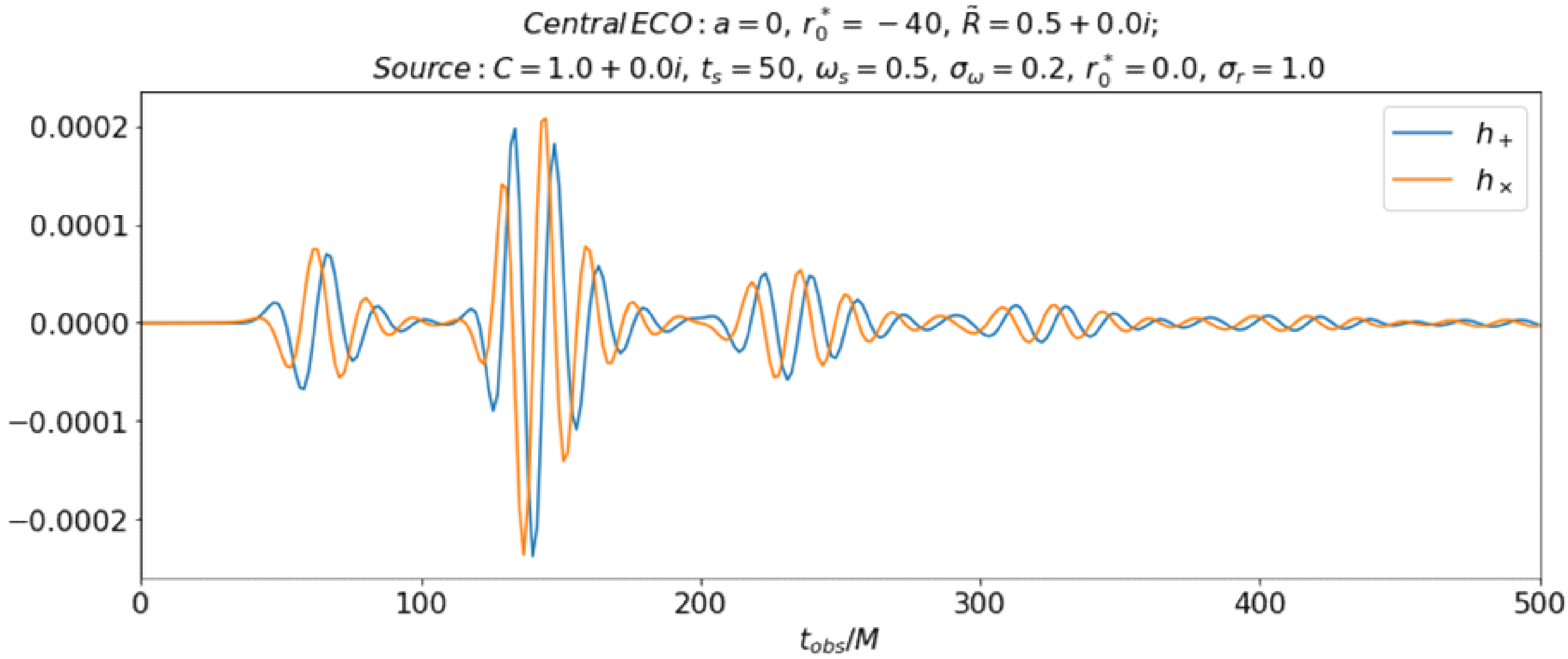
Waveform examples



Waveform examples



Waveform examples



Perspectives

- Improve the formalism
  - The integral in Teukolsky formalism is diverging when source is unbounded
  - Regularization is needed *PhysRevD.55.639*
- Implement the waveform in data analysis

Thanks!