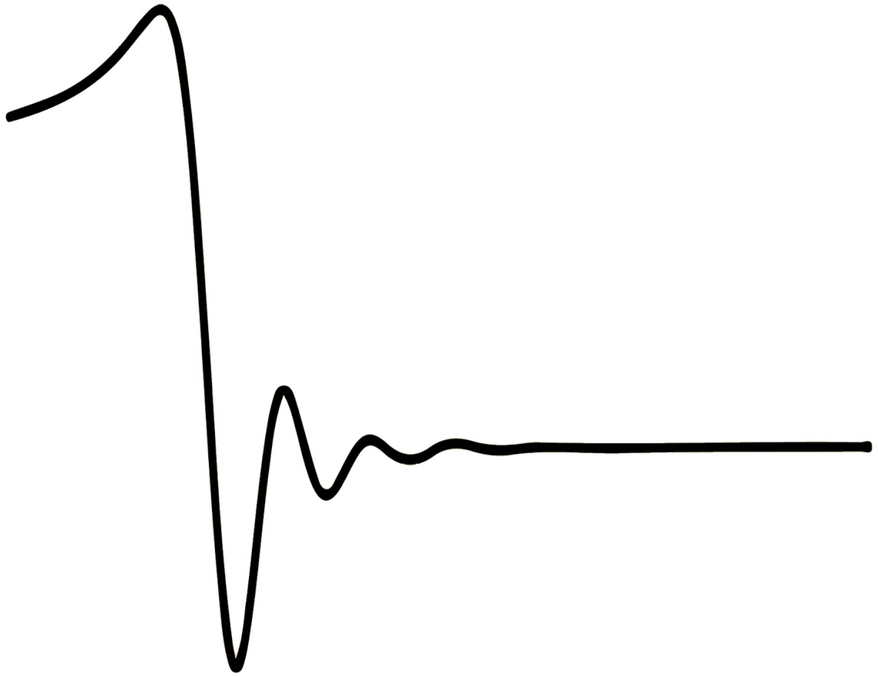
*Exotic **compact** objects and their gravitational-wave signatures*



Andrea Maselli

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V. Cardoso and P. Pani, Nature Astronomy 1: 586 (2017)
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A recipe for echoes from exotic compact objects
Phys. Rev. D 96, 084002 (2017)

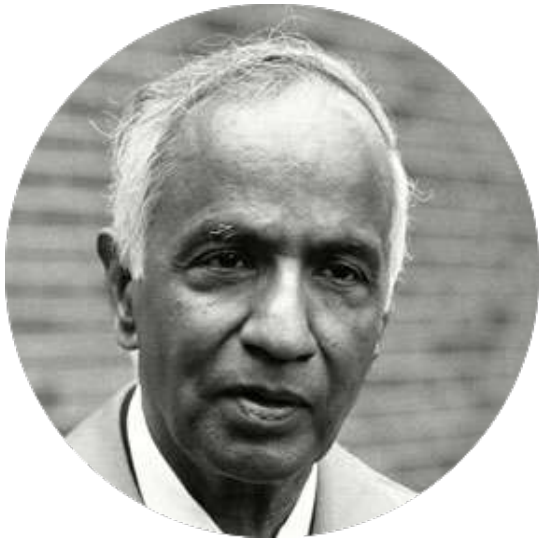
BH sociology

"As you see, the war treated me kindly enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas: …"

Karl Schwarzschild to Albert Einstein
Letter dated 22 December 1915

"In my entire scientific life, extending over forty-five years, the most shattering experience has been the realisation that an exact solution of Einstein's equations of general relativity provides the absolutely exact representation of untold numbers of black holes that populate the universe."

S. Chandrasekhar
The Nora and Edward Ryerson lecture, Chicago April 22 1975



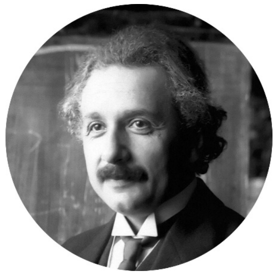
History of (black) holes

1783

Mitchell

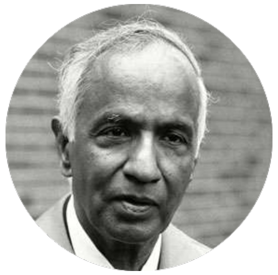
1916

Schwarzschild



Einstein

Eddington



Chandrasekhar

1963

Kerr

Wheeler

Oppenheimer

Penrose

Carter

Hawking

2017

Thorne

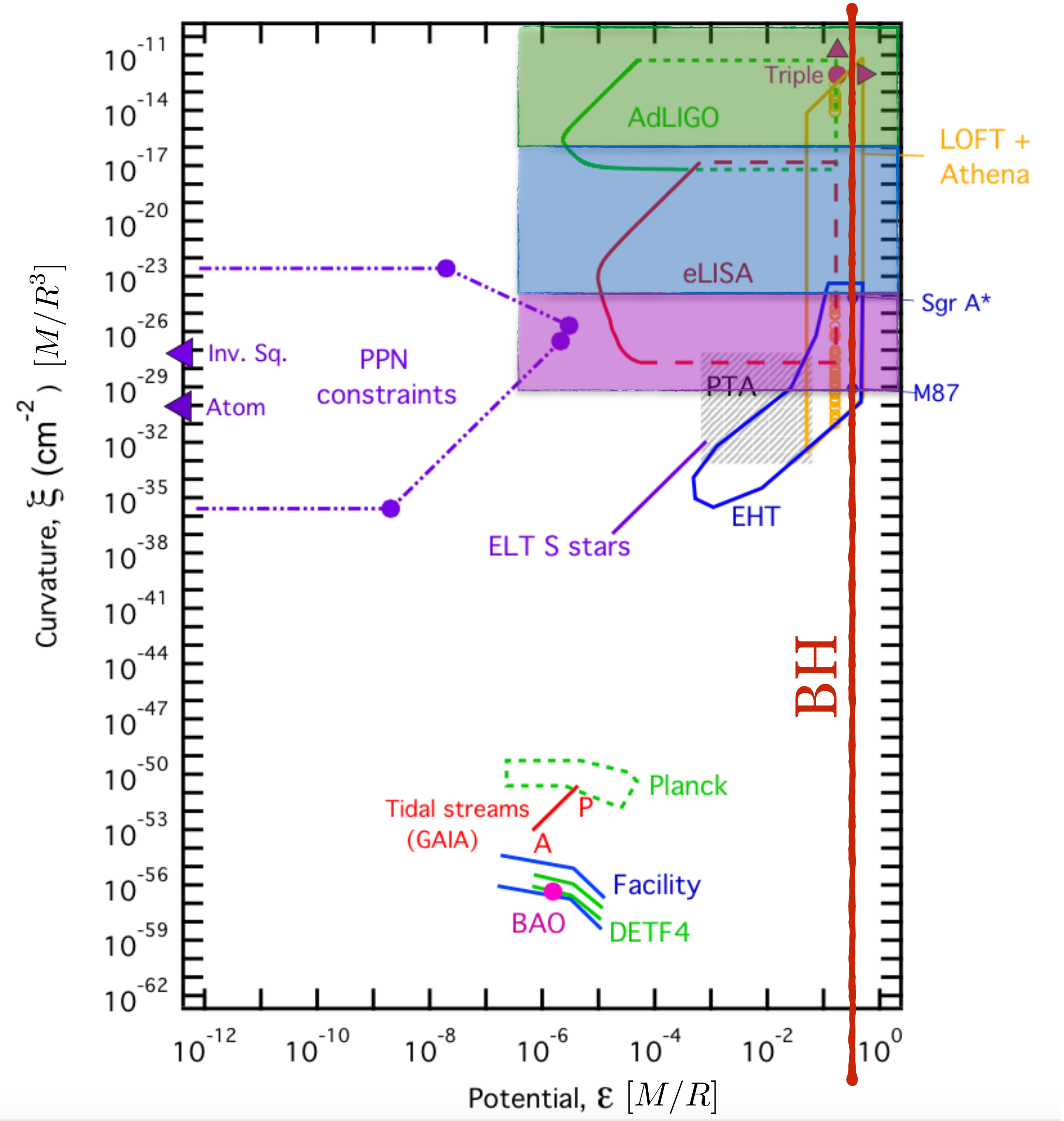
Many more…

BHs vs experiments

stellar

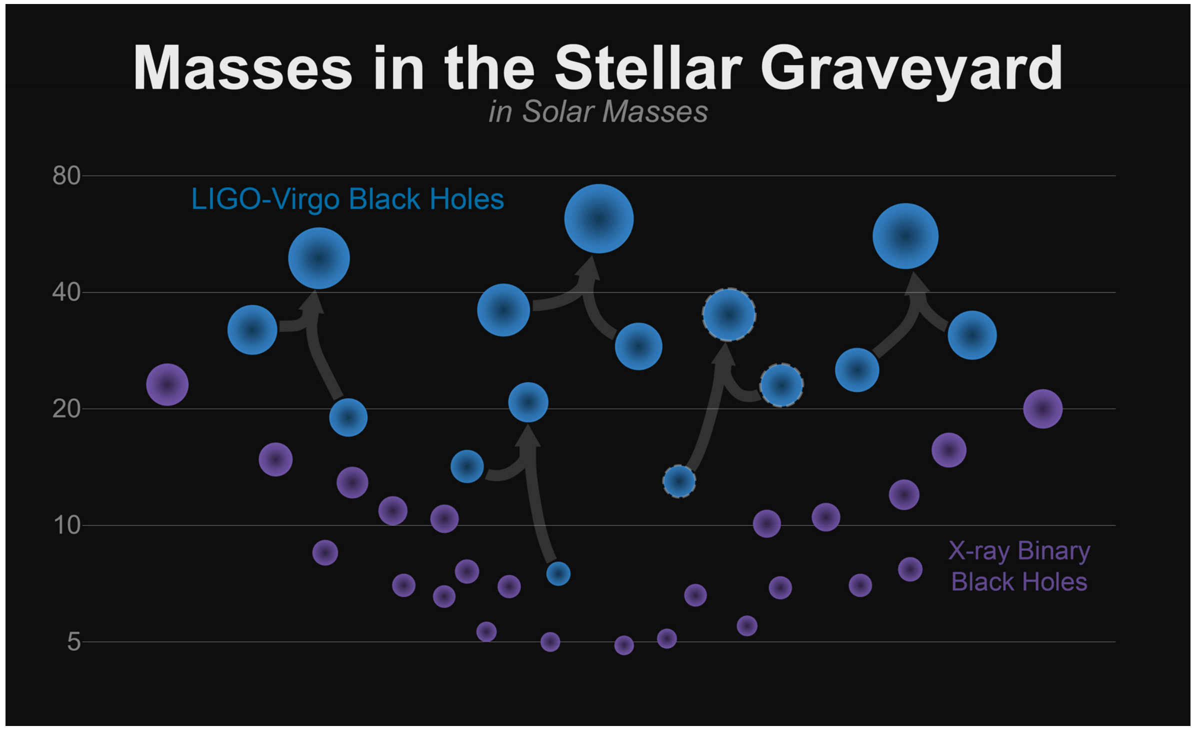
intermediate

supermassive



[Baker et al., ApJ '15]

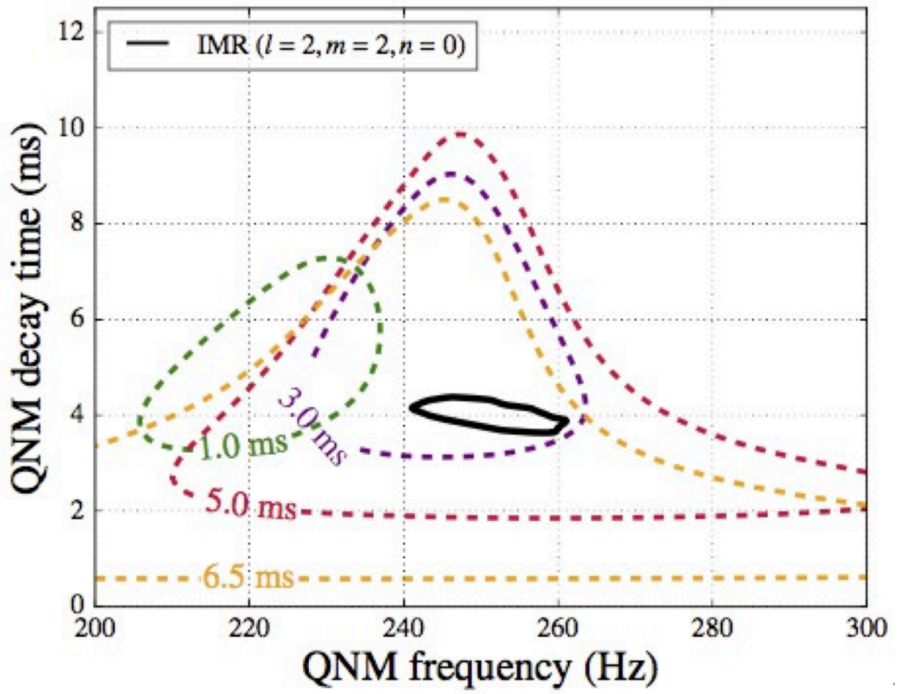
BHs in the sky



✓ Black holes form in nature as binary systems

✓ BBH coalesce within the Hubble time

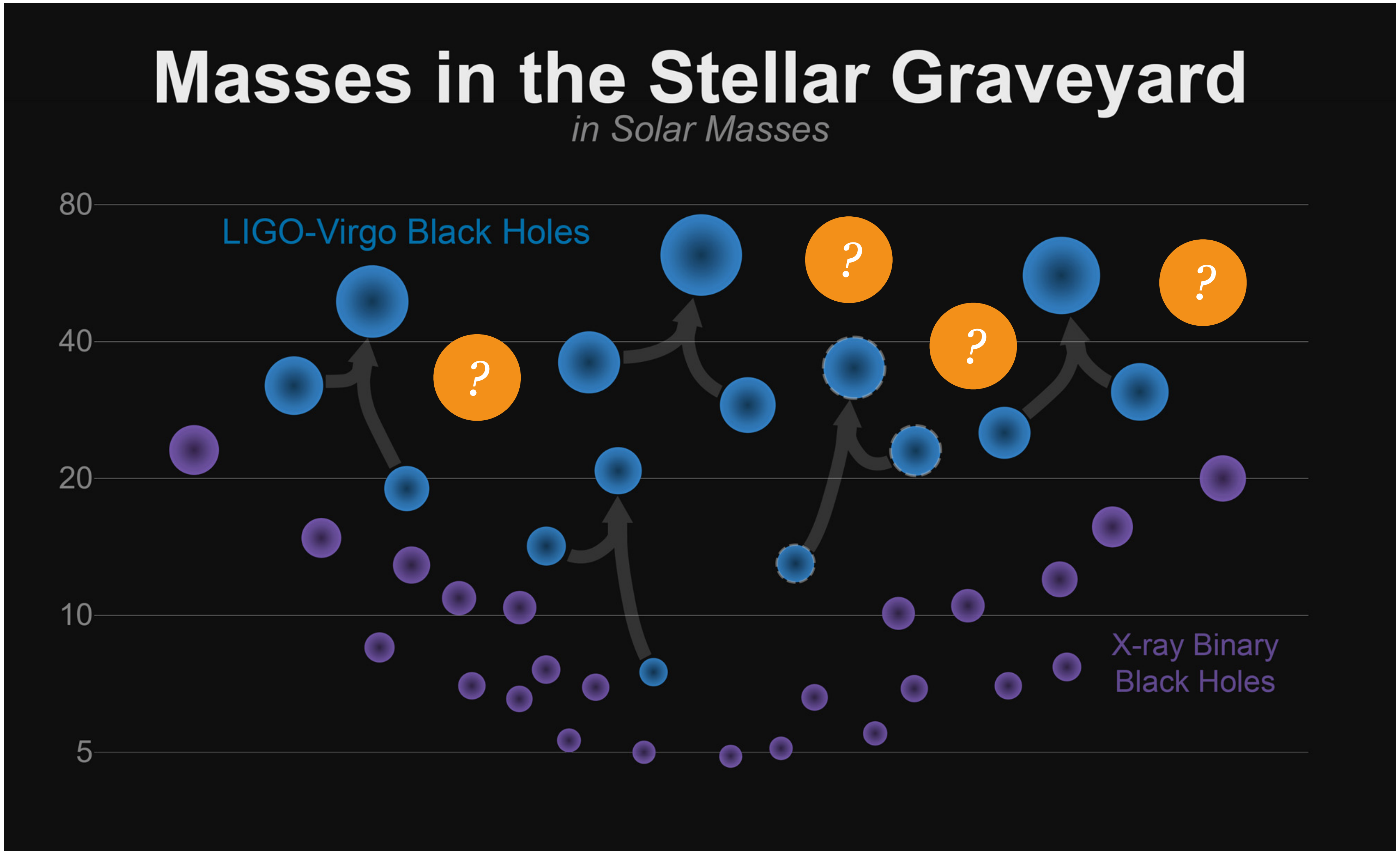
First attempt to detect BH
Quasi-Normal-Modes



[Abbott et al. LVC 2016-2018]

Everything clear ?

Are they alone in the Universe?



Why do we look for alternatives?

- ✓ BH exterior is pathology-free, but interior is not. Singularities and Cauchy horizons, signalling breakdown of predictability
- ✓ Quantum effects are not fully understood, namely information loss, which could lead to new end-states
- ✓ An horizon does exist in any spacetime harbouring a singularity (*cosmic censorship*)
  - ✓ "*Remarkable claims require remarkable evidences*"
- ✓ Observational limits in tests strong field regime around BHs
- ✓ If we don't devise alternative, we don't find them

Everything clear ?

BHs as endpoints of stellar evolution ?

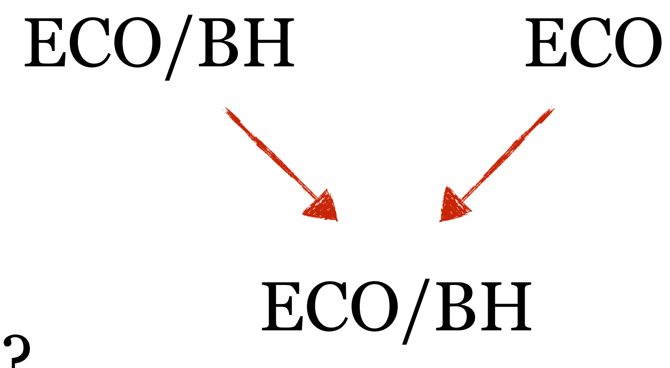
- ✓ Unexpected processes may avoid their formation
- ✓ Other **E**xotic **C**ompact **O**bjects may be the output of stellar collapse, which form without an event horizon
- ✓ Can we distinguish ECOs with no horizon, compact enough to mimic a BH?
- ✓ GWs from coalescing binaries may provide new answers

ECOs: formation and evolution

If they form in Nature

- ✓ Stability requirements

- ✓ Single sources v.s. binary systems
  - ✓ Which are the main evolutionary channels?
  - ✓ Detection rates, masses, distances: which detector?

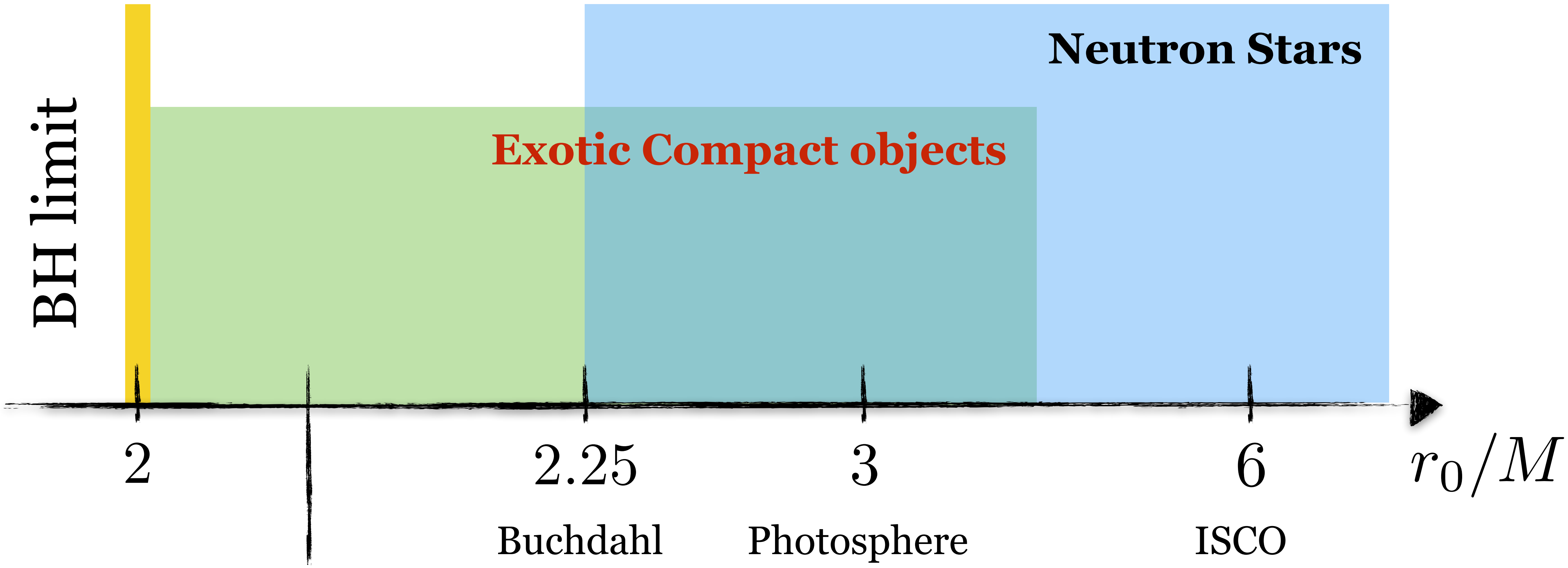


- ✓ Realistic astrophysical environments: accretion disk?
  - ✓ Favour electromagnetic observables

ECOs vs BHs

A first order classification

[Cardoso, Pani, '17]



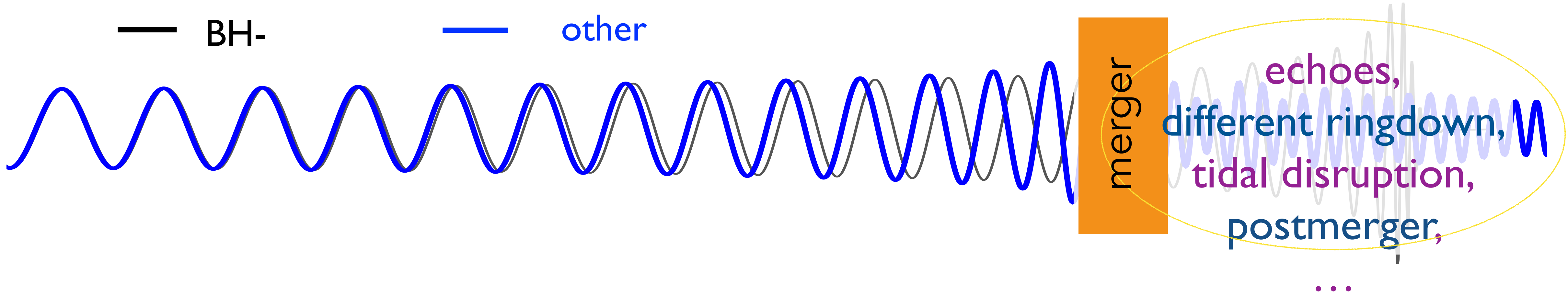
$$R_{\rm ECO} = 2M(1+\epsilon)$$

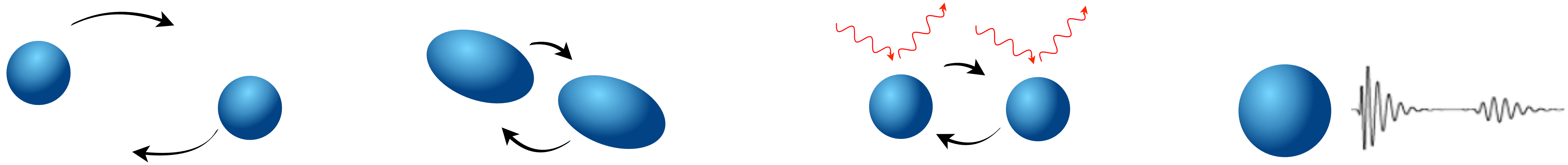
10^{-30}

$$M_{\rm BH}/R_{\rm BH} = 0.5 \qquad \text{v.s.} \qquad M_{\rm ECO}/R_{\rm ECO} = 0.49(99\ldots)$$

ECOs of your heart

Where do we look for?





~point masses:
same signal
for all objects

tidal effects
+
spins
deformations

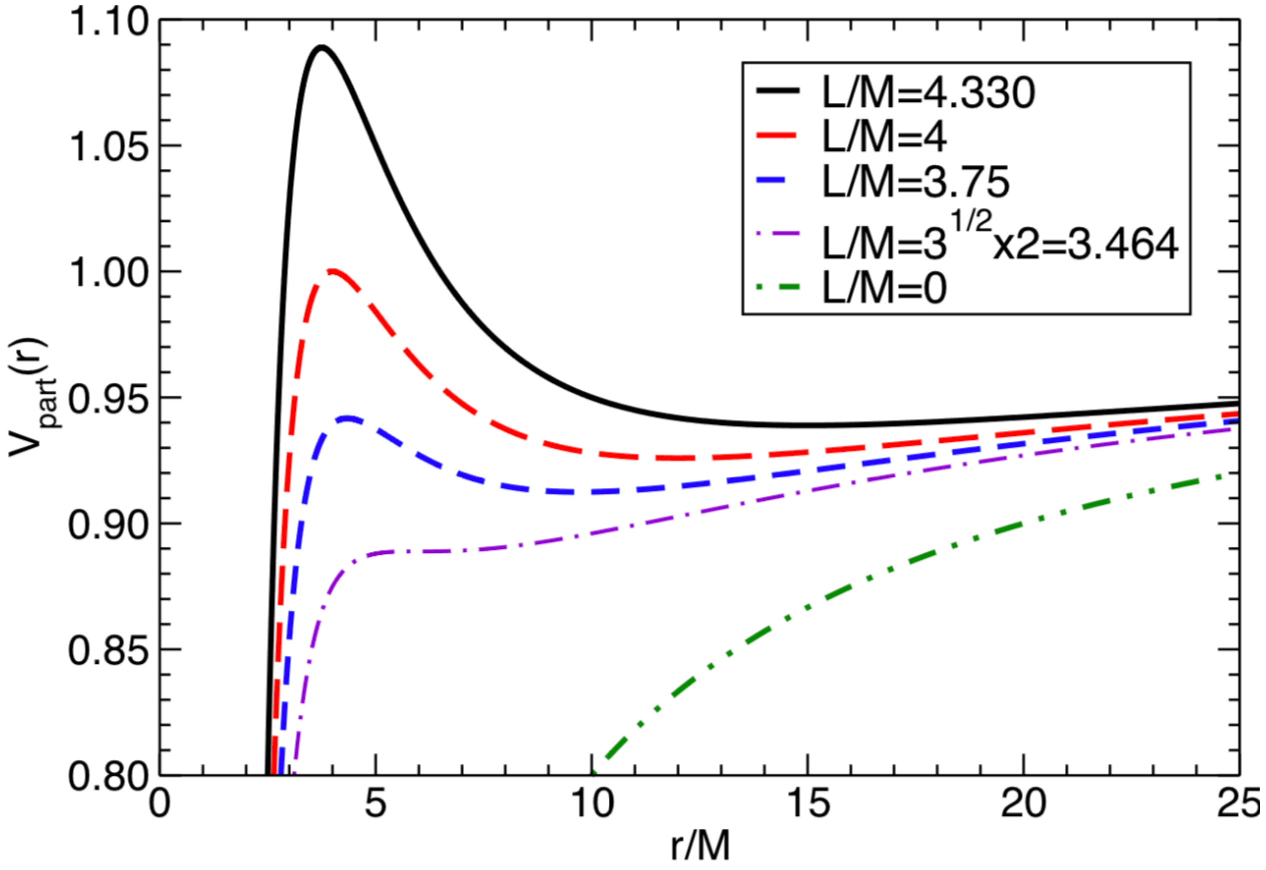
absence of horizon
absorption
effects

modified
QNMs and
echoes

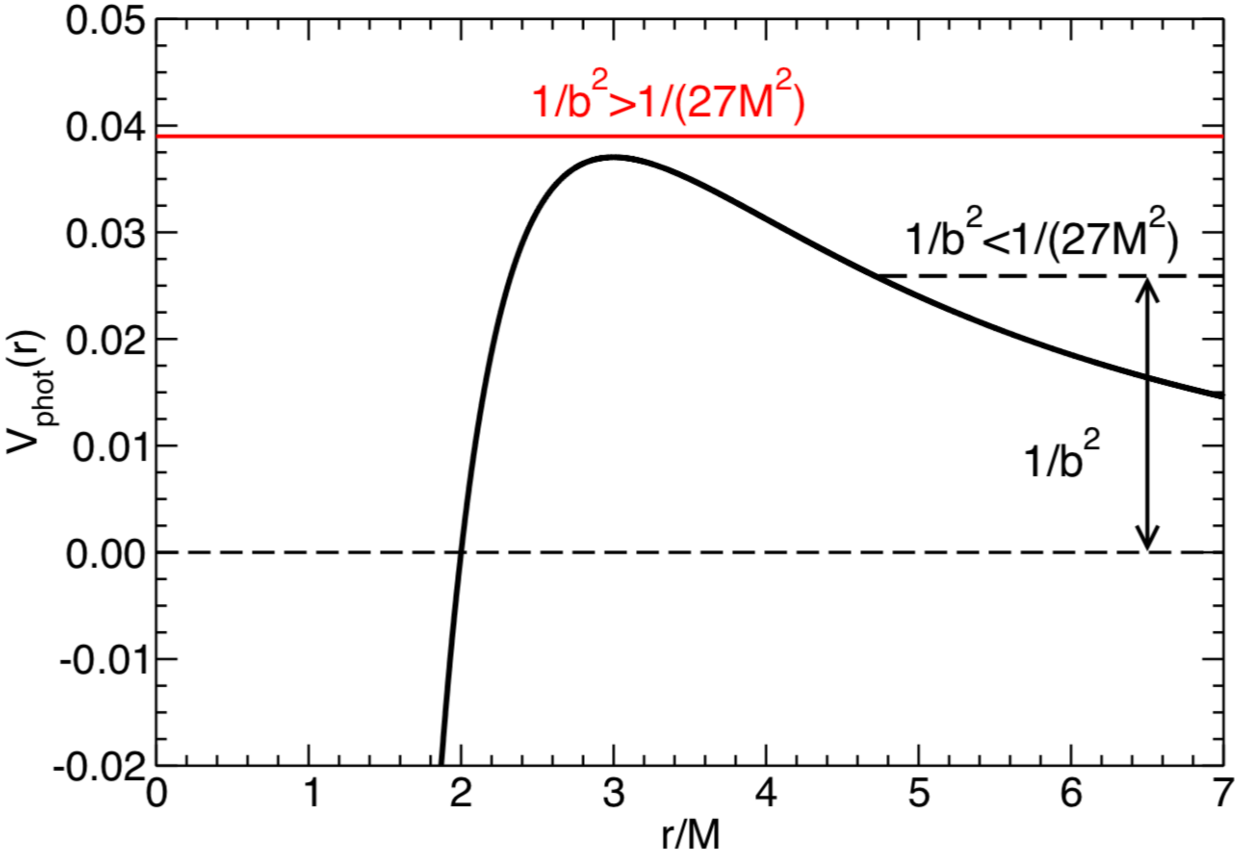
Geodesics of spherically symmetric spacetimes

Effective potentials

massive

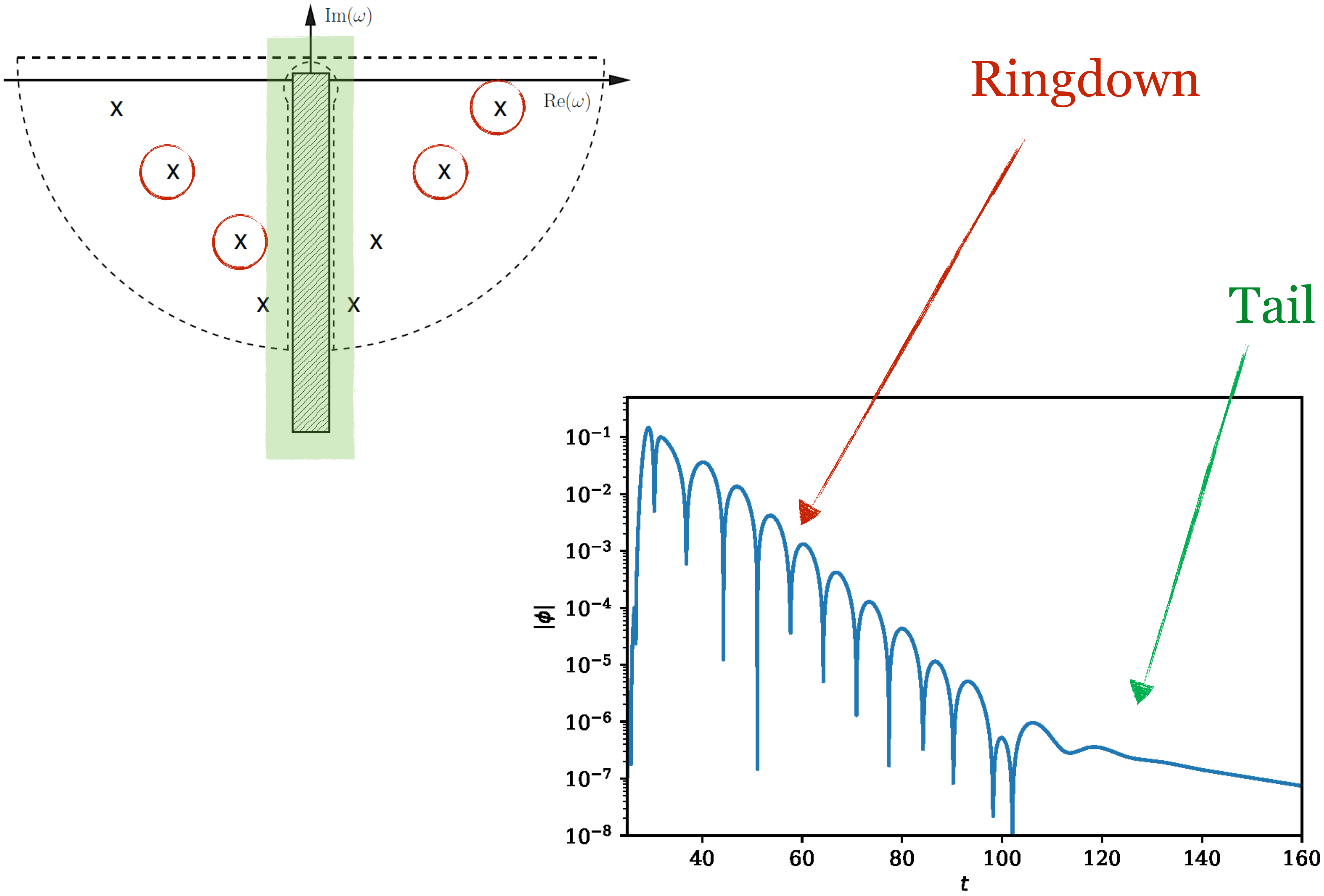


massless

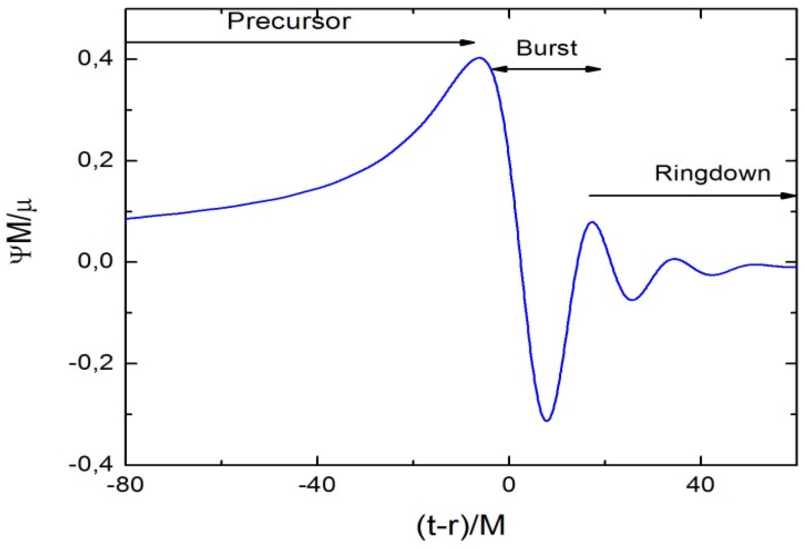


Black Hole Quasi Normal Modes

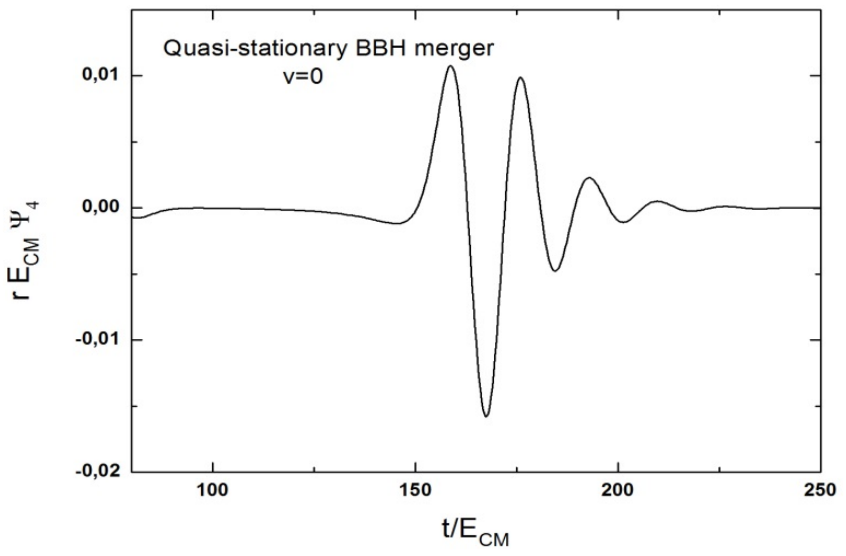
BH - QNMs


Im(ω)
Re(ω)
x
Ringdown
Tail
|ϕ|
10−1
10−2
10−3
10−4
10−5
10−6
10−7
10−8
40
60
80
100
120
140
160
t

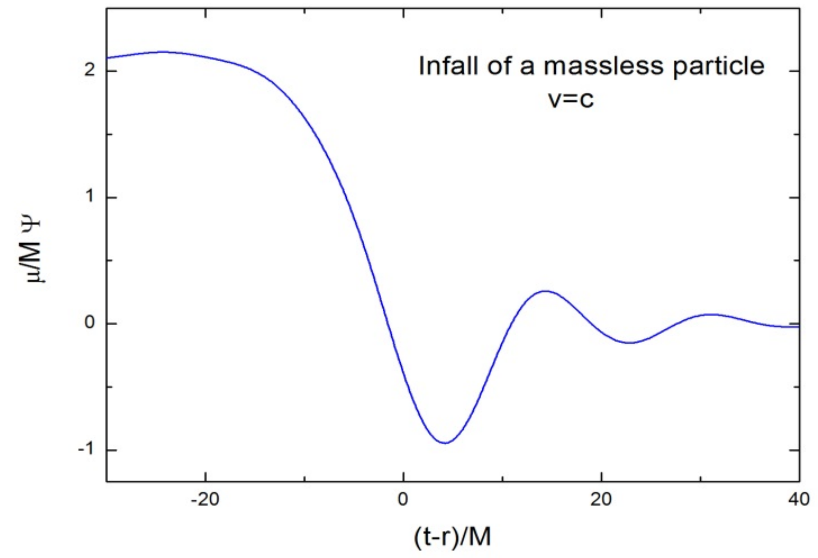
Some examples



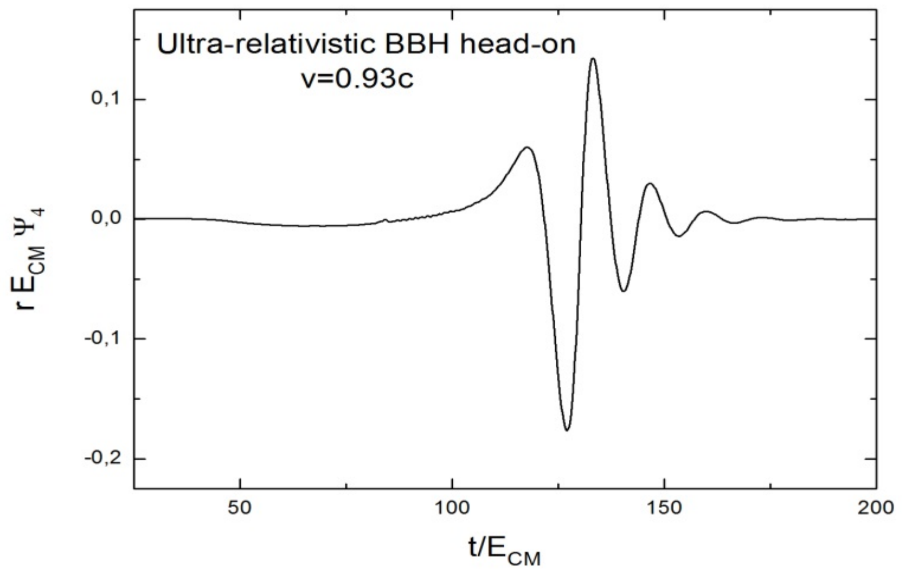
[Davis et al, 1971]



[Anninos et al, 1993]



[Cardoso, Lemos, 2002]



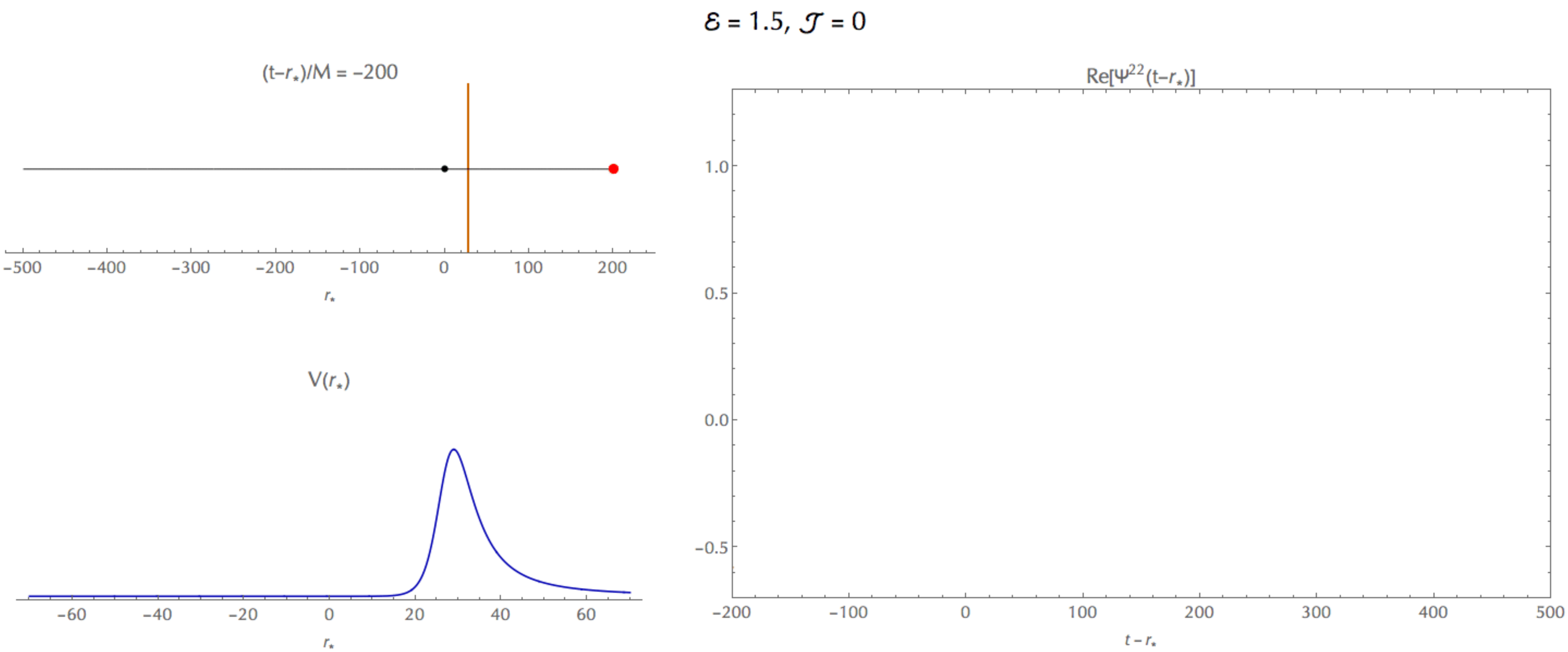
[Sperhake et al, 2008]

$$e^{-0.0898\, t/M_{BH}} \sin\left(0.374\, t/M_{BH}\right)$$

something at the horizon)

Light-ring-connection

Excitation of ringdown happening close to crossing of light ring

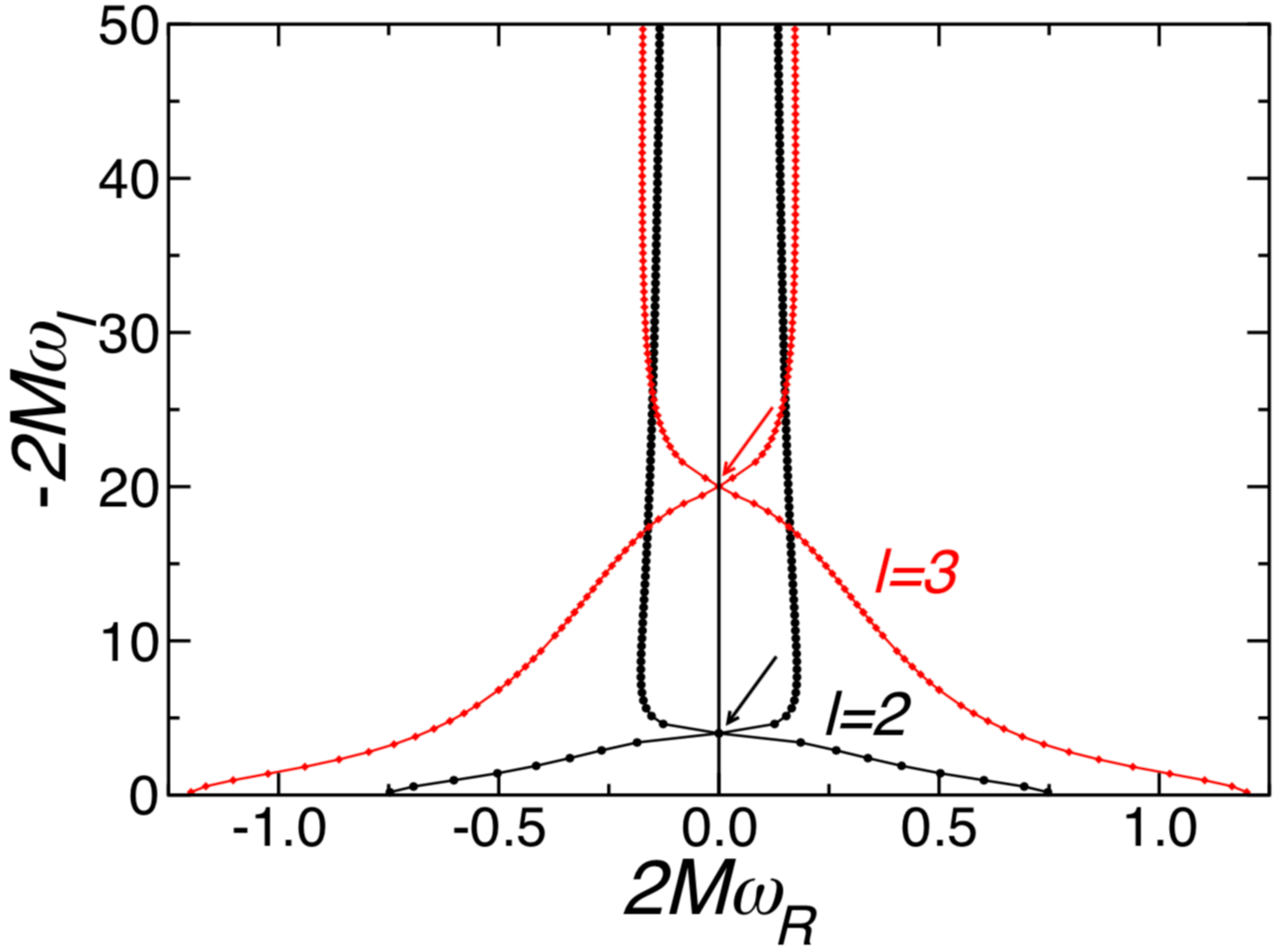


Radiated energy

		Radiated energy	**Numerical Relativity**
Head-on	Point particle	$E_{\rm rad}=0.010\frac{\mu^2}{M}$	$E_{\rm rad}=0.010\frac{\mu^2}{M}$
	Equal mass	$E_{\rm rad}=0.00065M$	$E_{\rm rad}=0.00057M$
Q-Circular	Point particle	$E_{\rm rad}=0.057\mu$	Not done
	Equal mass	$E_{\rm rad}=0.014M$	$E_{\rm rad}=0.048M$

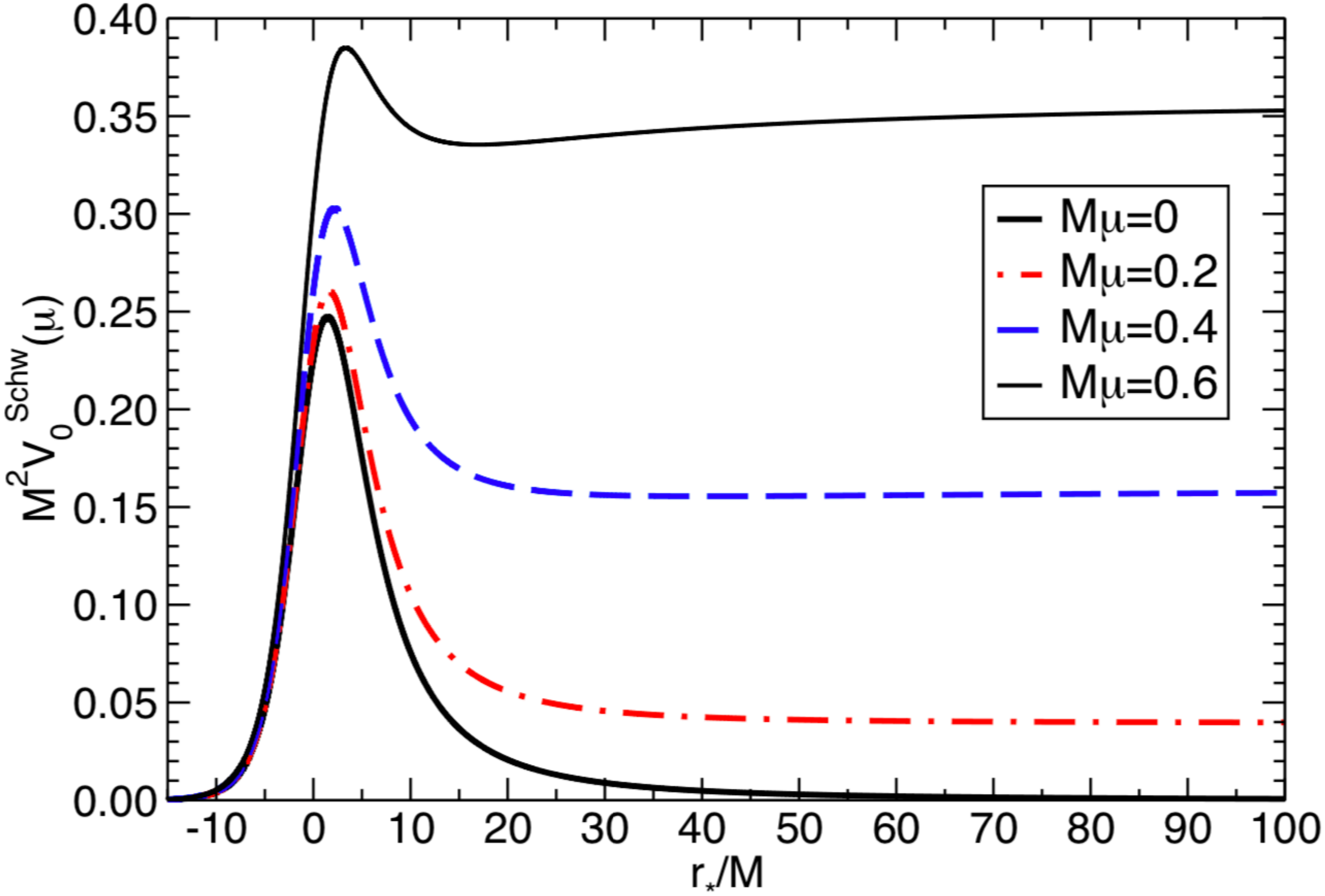
[Berti et al. '07, Sperhake et al. '11, Hemberger et al '13]

Schwarzschild frequencies



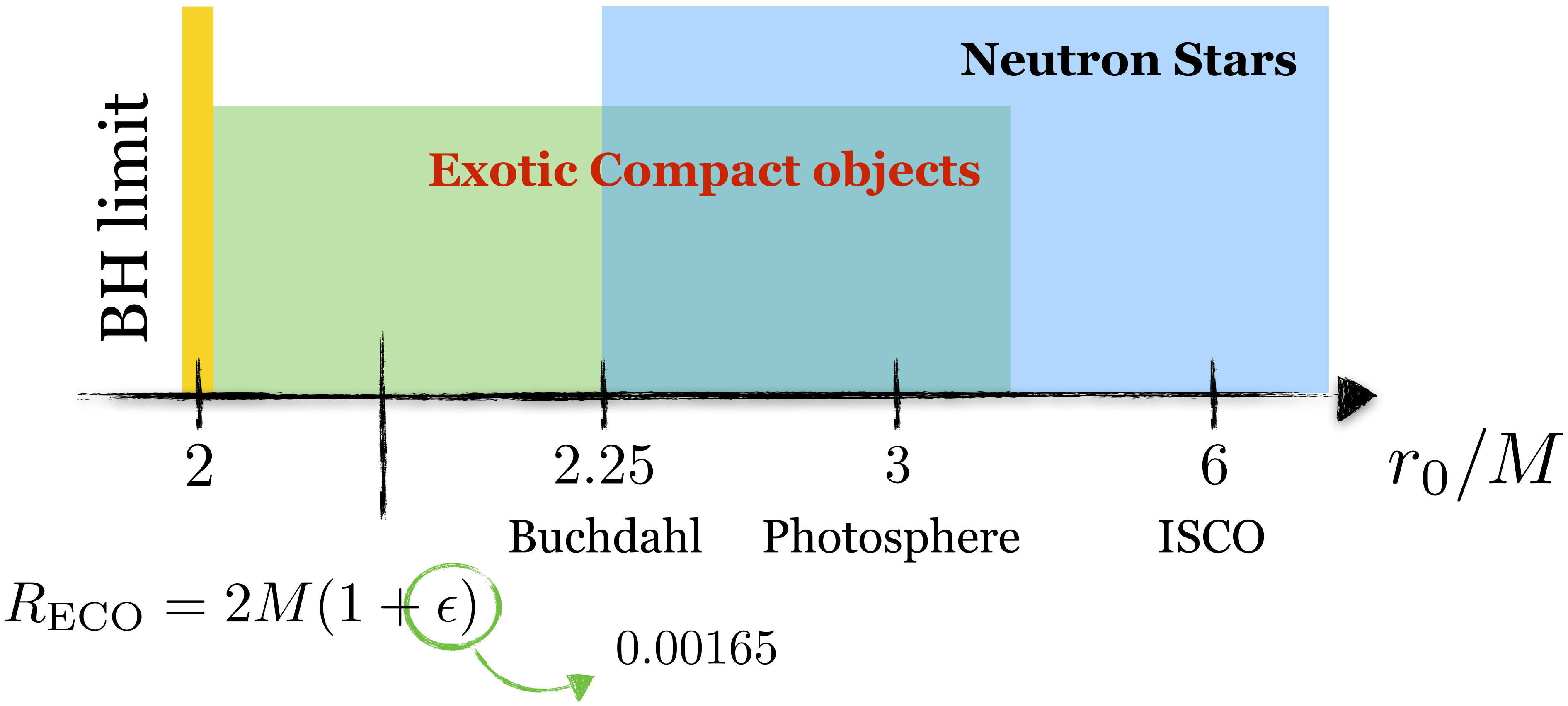
Scalar Waves

Scalar wave - Potential



ECOs
and echoes

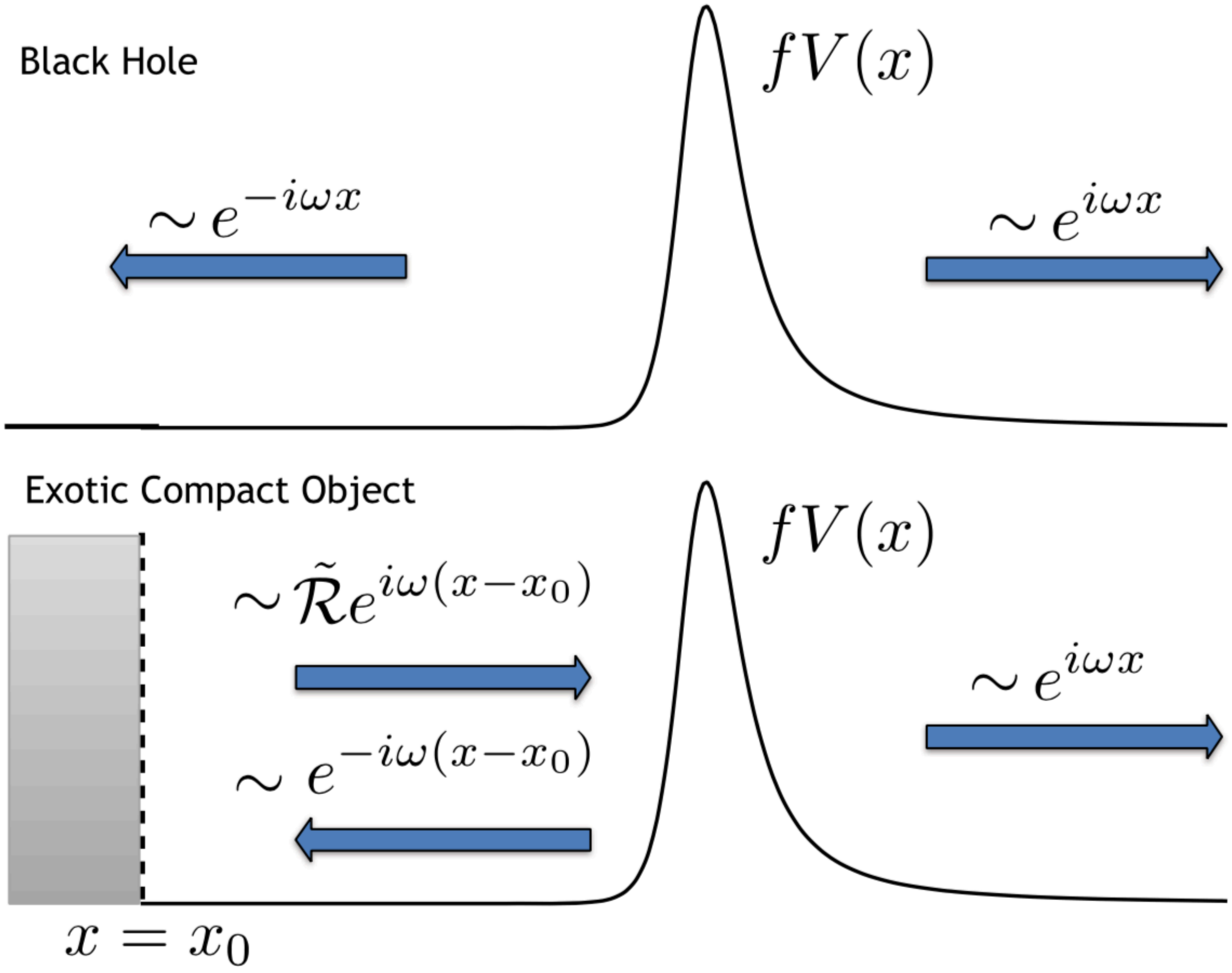
ECO vs BH



✓ QNMs spectrum different from the BH case

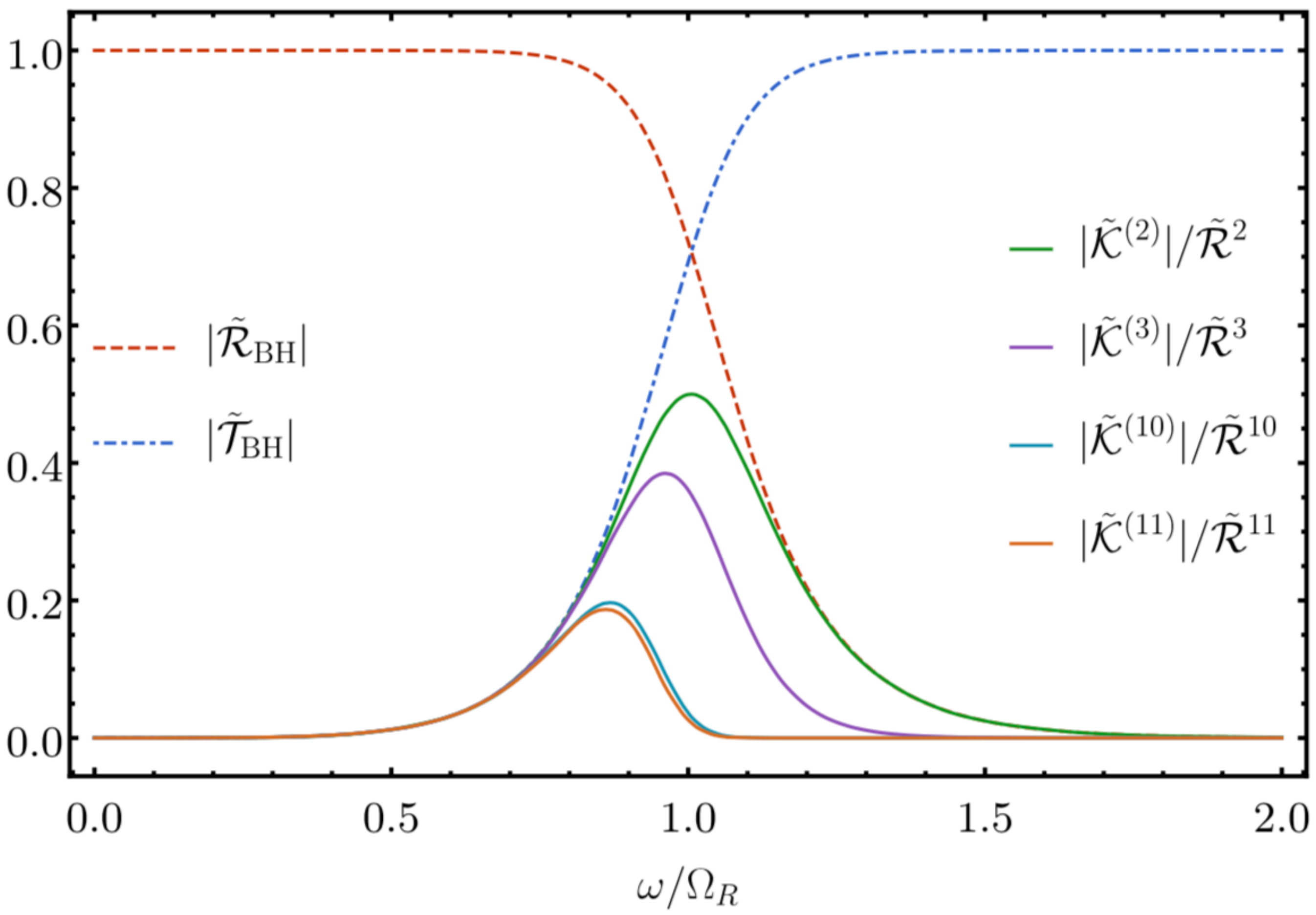
✓ New structure may be visible in the waveform: the **echoes**

ECO: the boundary conditions



[Mark et al., '17]

ECO: Reflection and Transmission



low frequencies

$$(M\omega)^2 \ll V$$

$$|\mathcal{T}_{\rm BH}| \to 0 \qquad |\mathcal{R}_{\rm BH}| \to 1$$

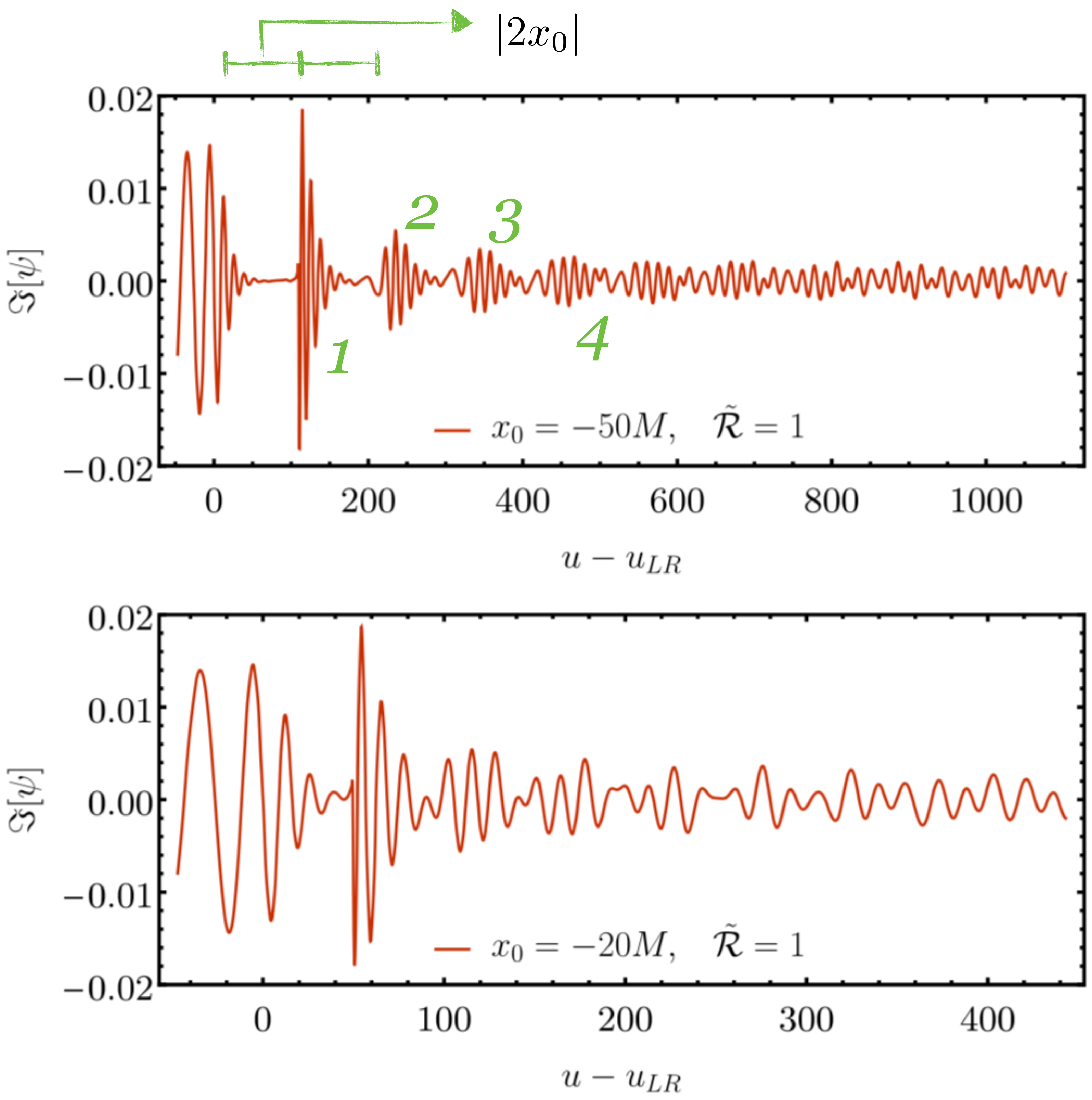
high frequencies

$$(M\omega)^2 \gg V$$

$$|\mathcal{R}_{\rm BH}| \to 0 \qquad |\mathcal{T}_{\rm BH}| \to 1$$

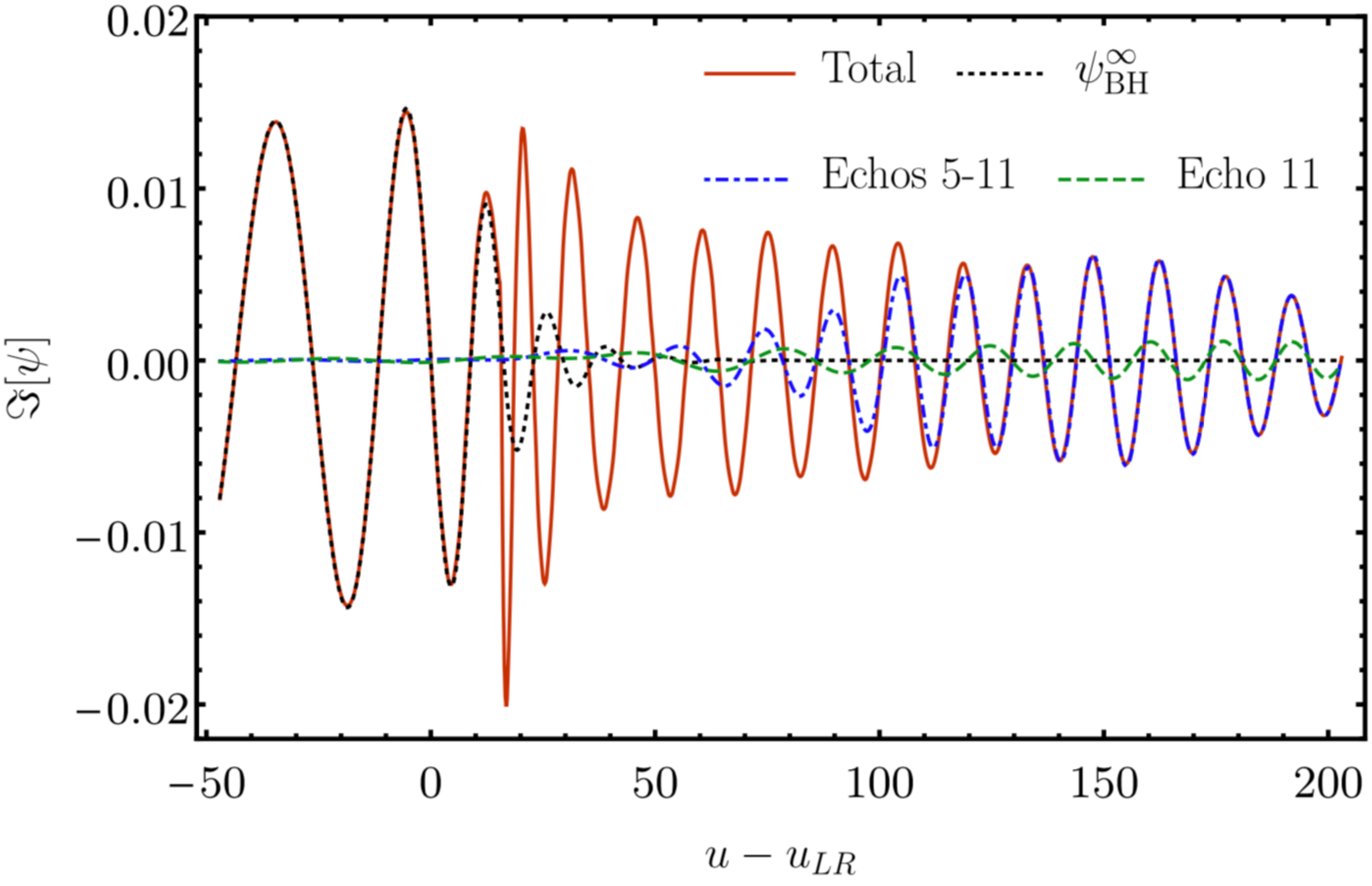
[Mark et al., '17]

Echoes from ECO



[Mark et al., '17]

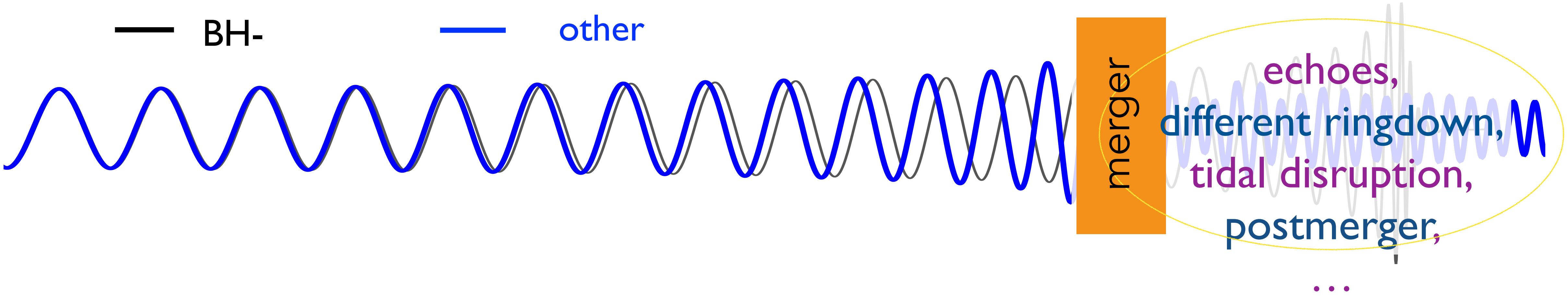
Echoes from ECO

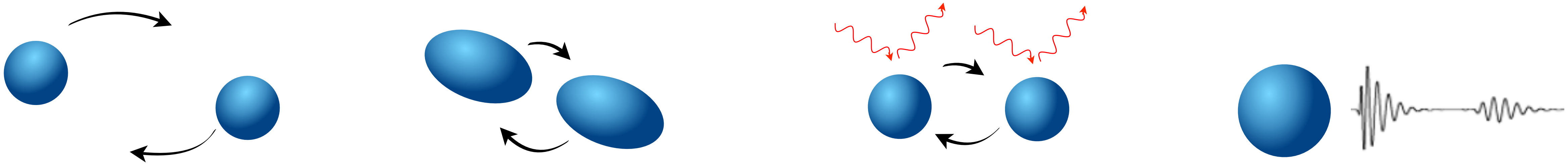


[Mark et al., '17]

ECOs
phenomenology

Where do we look for?





~point masses:
same signal
for all objects

tidal effects
+
spins
deformations

absence of horizon
absorption
effects

modified
QNMs and
echoes

Tidal Love Numbers

Tidal interactions leave the footprint of the ECO's structure within GW signals [learning from NS]

Hinderer, '08; Binnington & Poisson '09
Damour & Nagar '10

✓ Deformation properties encoded within the Love numbers

ECO's quadrupole

$$\mathcal{Q}_{ij} = \frac{2}{3} k_2 R^5 \mathcal{E}_{ij} = \lambda \mathcal{E}_{ij}$$

external tidal field

✓ λ depends on the **internal** composition of the ECO

✓ λ enters within the gravitational waveform

Tidal effects: the recipe

Polar-type perturbation of background metric

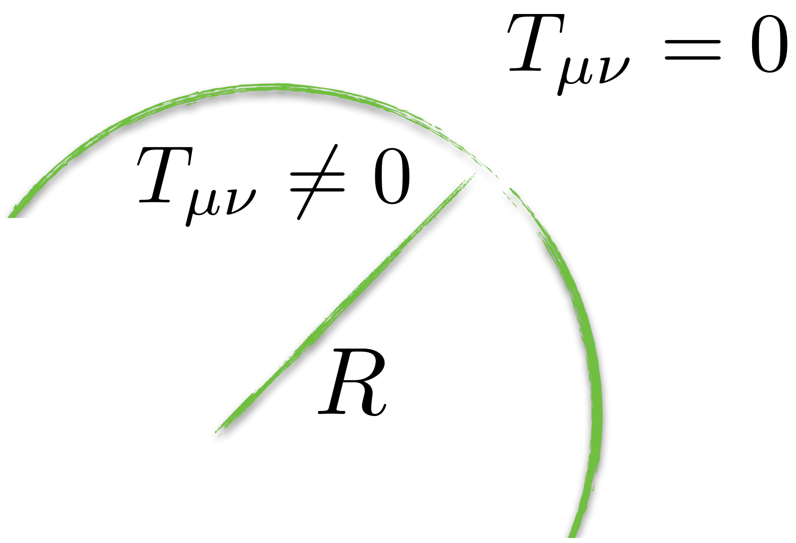
[Regge & Wheeler '57]

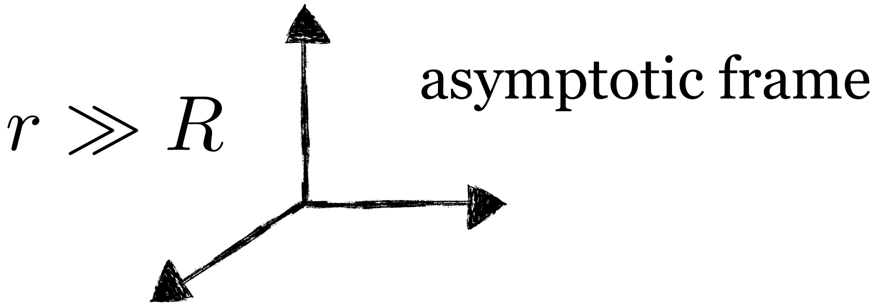
$$g_{\mu\nu} = g_{\mu\nu}^{(0)} + h_{\mu\nu}$$

$$\begin{pmatrix} -e^{\nu(r)} & 0 & 0 & 0 \\ 0 & e^{\lambda(r)} & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2 \sin^2\theta \end{pmatrix} + \begin{pmatrix} -e^{\nu(r)} H_0(r) & 0 & 0 & 0 \\ 0 & e^{\lambda(r)} H_2(r) & 0 & 0 \\ 0 & 0 & r^2 K(r) & 0 \\ 0 & 0 & 0 & r^2 K(r) \sin^2\theta \end{pmatrix} Y_{lm}(\theta, \phi)$$

- ✓ Cook everything within Einstein's equations $G_{\mu\nu} = kT_{\mu\nu}$
- ✓ Solve at linear oder in the perturbations
- ✓ Numerically integrate from center to outside with appropriate boundary conditions

Tidal effects: the recipe





$$g_{tt} = -1 + \frac{2M}{r} + \frac{3Q_{ij}\hat{n}^i\hat{n}^j}{r^3} + \mathcal{O}\left(\frac{1}{r^3}\right)$$
$$-\mathcal{E}_{ij}x^i x^j + \mathcal{O}(r^3)$$

✓ Matching interior & exterior solution

$$\mathcal{Q}_{ij} = \frac{2}{3}k_2 R^5 \mathcal{E}_{ij} = \lambda \mathcal{E}_{ij}$$

✓ Deformation properties encoded within the Love numbers

[Hinderer, '08; Binnington & Poisson '09
Damour & Nagar '10]

Tidal Love Numbers

k_2 (orλ) depends on the compactness $\mathcal{C} = M/R$, only

Neutron stars

$\mathcal{C} \in [0.1 \div 0.2]$

$k_2 \neq 0$

GW170104

constrain the NS
equation of state

Black holes

$\mathcal{C} = 1/2$

$k_2 = 0$

ECOs

$\mathcal{C} < 0.5$ $\quad k_2 \neq 0$

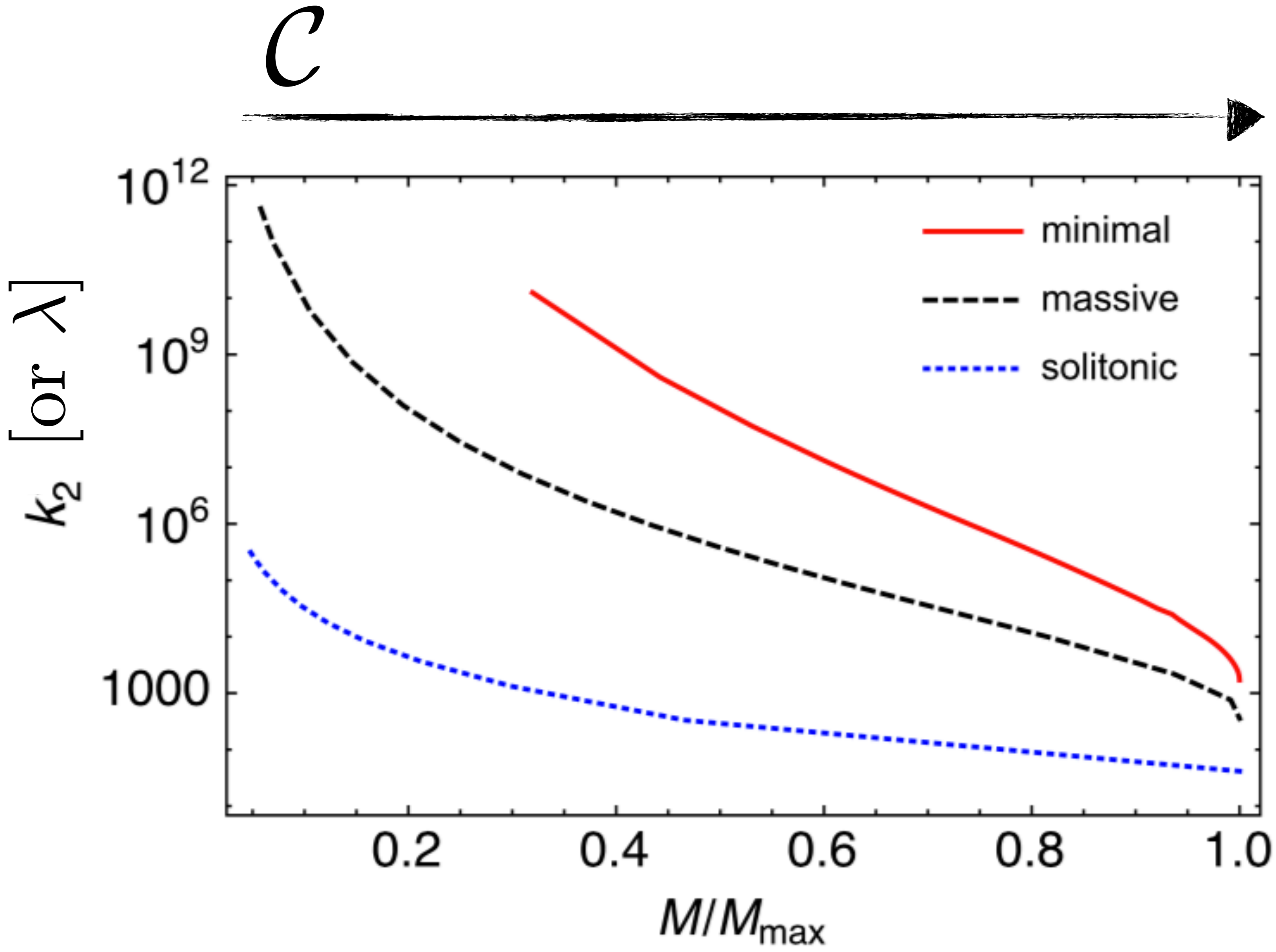
$\mathcal{C} \to 0.5$ $\quad k_2 \to 0$

signature to distinguish
ECO and BH's inspiral

*[Cardoso et al., '17 , Maselli et al., '17
Sennetet al., 17]*

The boson star case

Monotonic function of the compactness $\mathcal{C} = M/R$



- ✓ λ decreases as the compactness grows and goes to zero

[see LIGO 1805.11581 for the NS game]

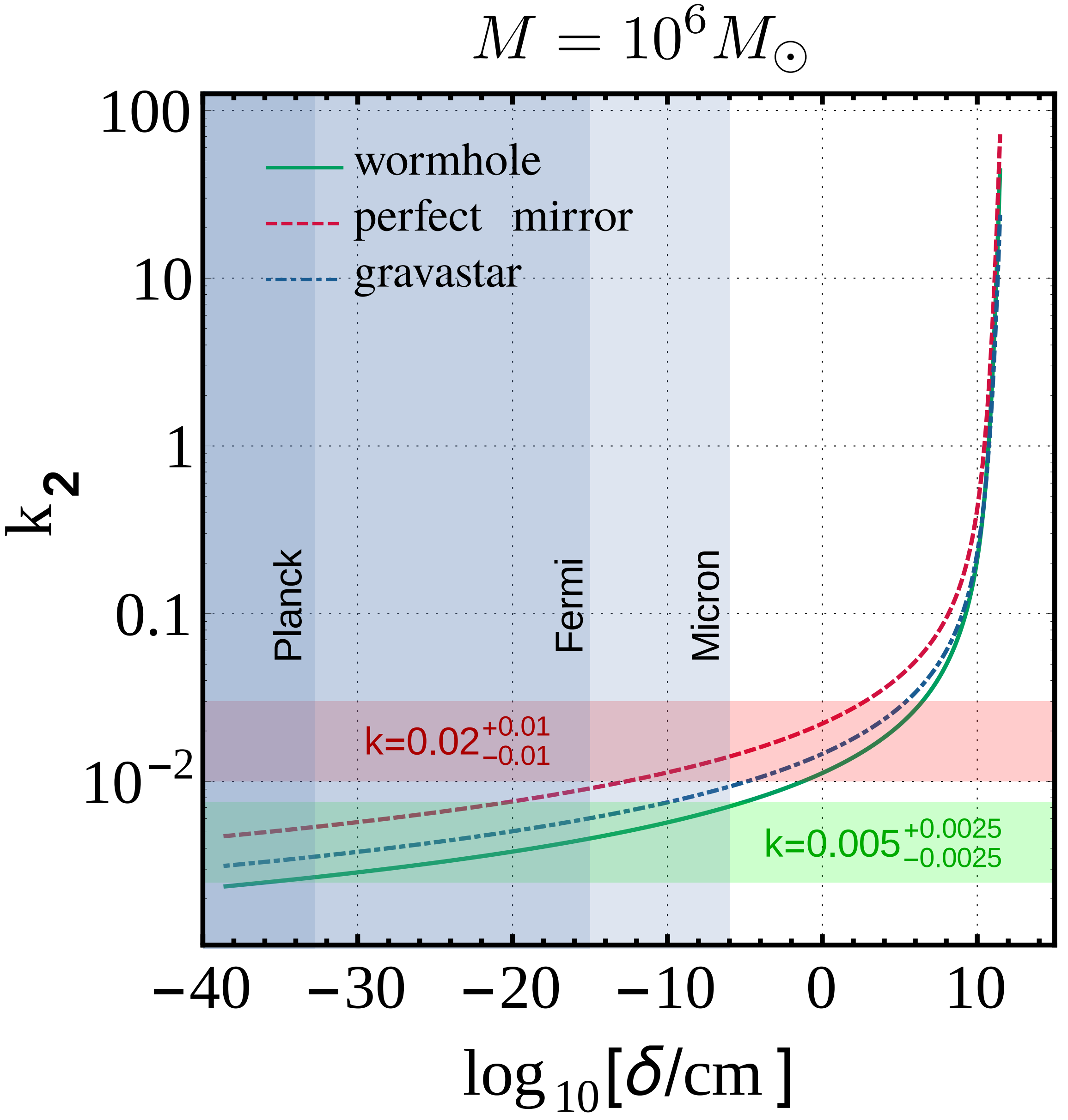
ECO Love numbers

- ✓ $k_2$vanishes logarithmically in the BH limit $k_2 \sim 1/|\log\delta|$
- ✓ k_2 translate in distance ECO surface from its Schwarzschild radius

$$\boxed{\delta \equiv r_0 - 2M \sim 2Me^{-1/k_2}}$$

$$k_2 \simeq 0.005$$

$$\delta \simeq 10^{-33}\text{cm} \sim \ell_P$$



Where do we look in?

Tidal effects add linearly to the GW phase $h(f) = \mathcal{A} e^{i[\psi_{\rm PP}(f) + \psi_{\rm T}(f)]}$

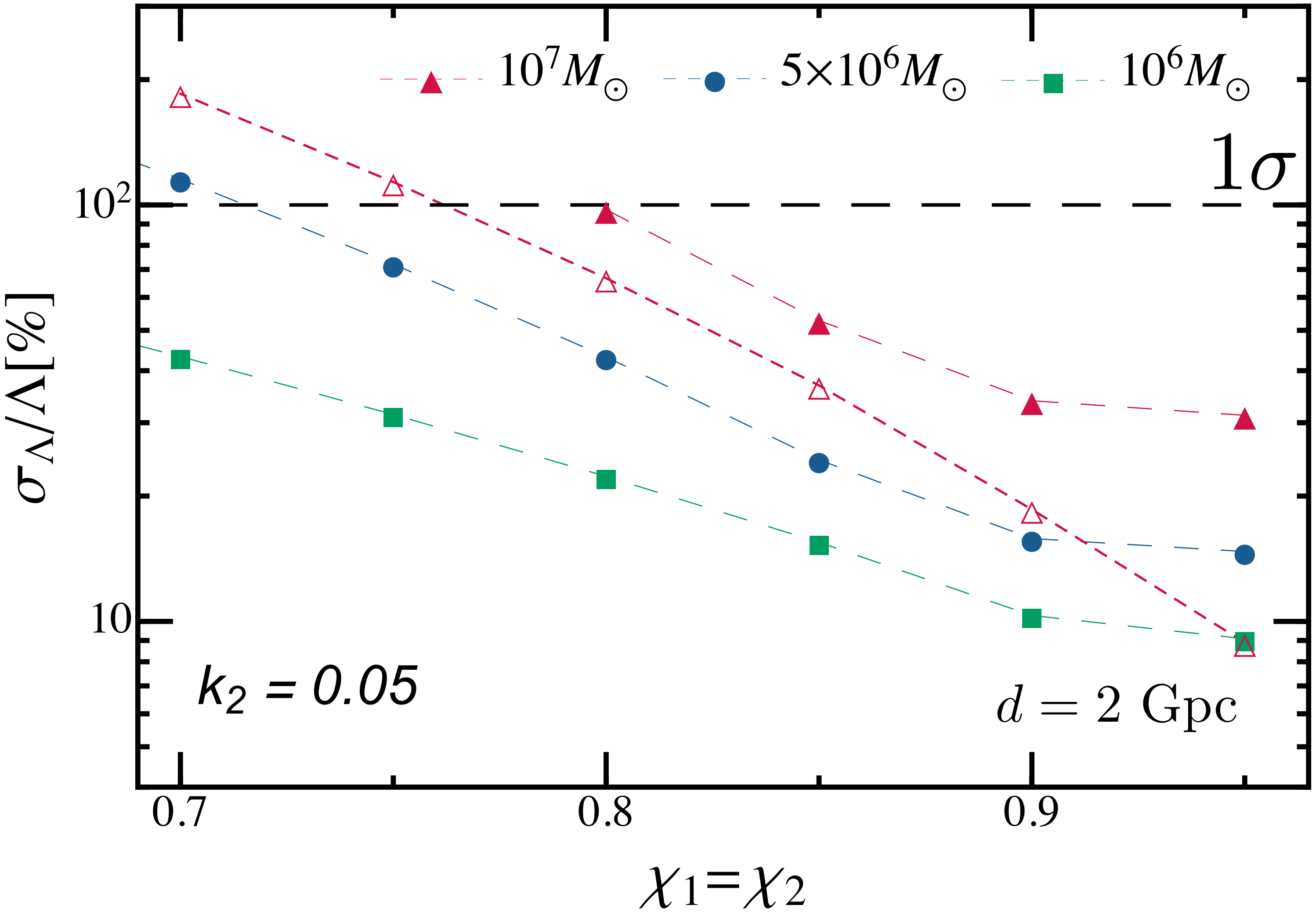
$$\psi_{\rm PP} \propto \left[\underset{\substack{\uparrow \\ \text{Newt}}}{1} - \left(\frac{743}{336} + \frac{11}{4}\nu \right) \underset{\substack{\uparrow \\ \text{1 PN}}}{\frac{(m\pi f)^{2/3}}{c^2}} + \underset{\substack{\uparrow \\ \text{1.5 PN}}}{\frac{\cdots}{c^3}} + \quad \cdots \quad + \frac{\cdots}{c^7} \right]$$

$$\psi_{\rm T} \propto \underbrace{\frac{1}{26} \left[\left(1 + \frac{12 m_2}{m_1} \right) \lambda_1 + \left(1 + 12 \frac{m_1}{m_2} \right) \lambda_2 \right]}_{\Lambda} \frac{(m\pi f)^{10/3}}{c^{10}} + \frac{\cdots}{c^{11}}$$

✓ The *average* tidal deformability enters the signal at the leading order

Detectability with LISA

✓ Spins lead to more than one order of magnitude improvement



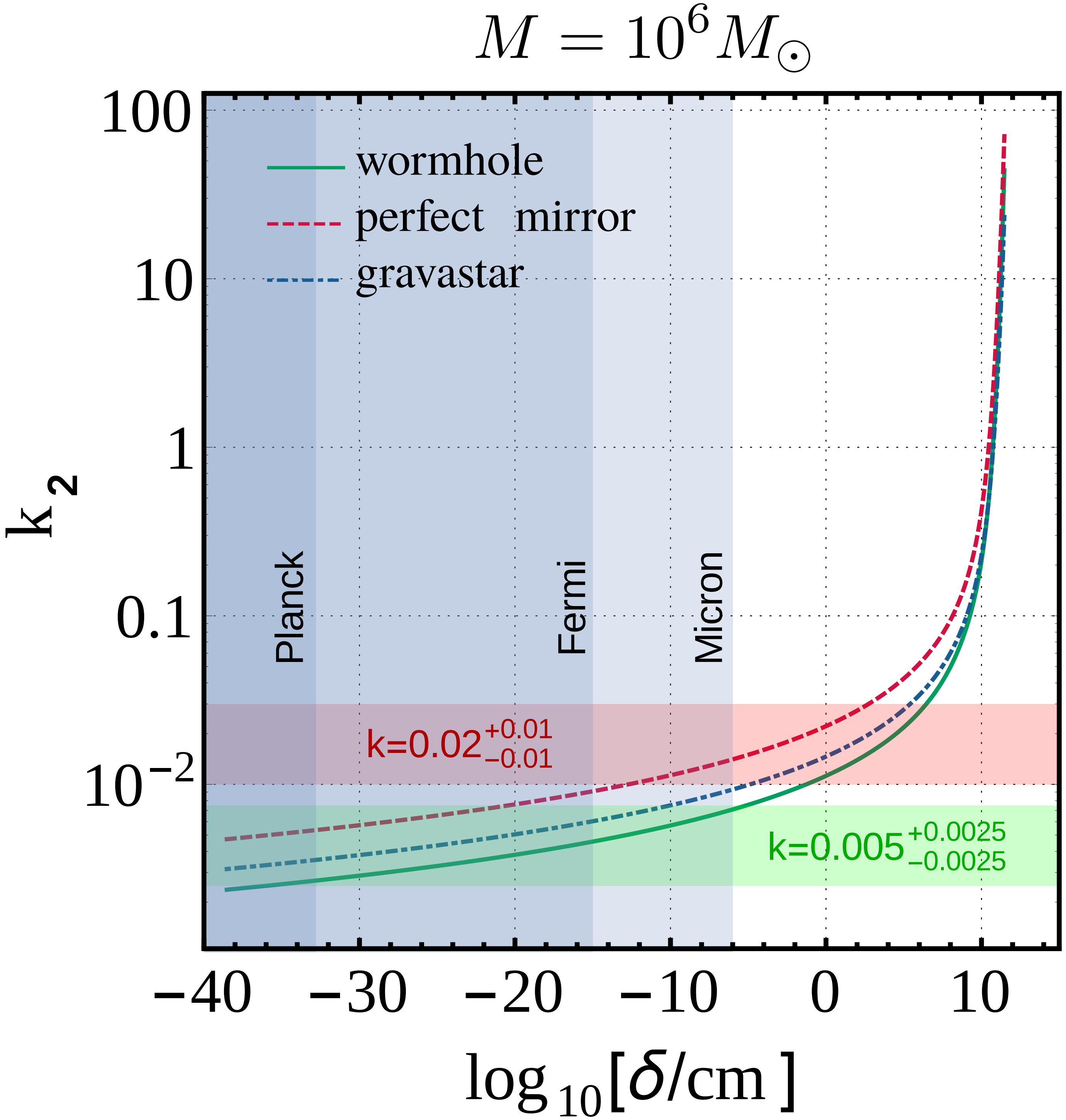
- $\sigma_\Lambda/\Lambda \sim 1/k_2$

$k_2 = 0.005$ @ $d = 2$ Gpc

- $\sigma_\Lambda/\Lambda \sim d$

$k_2 = 0.05$ @ $d = 20$ Gpc

ECO Love numbers

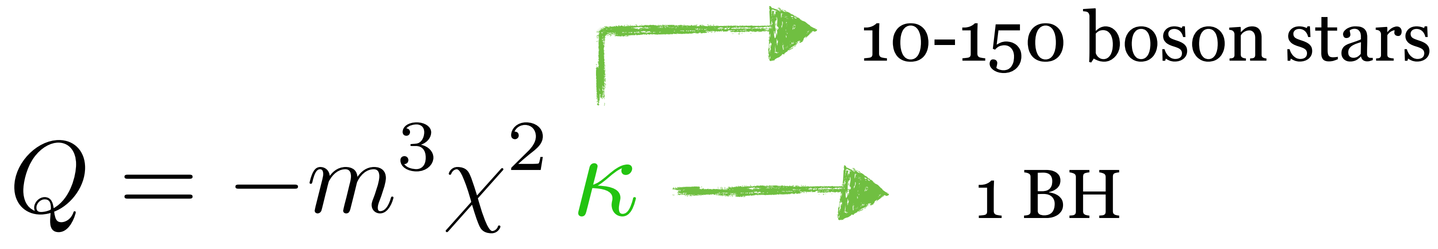


Modified Quadrupole

Test based on the no-hair theorem

[Krishnendu et al., '17]

- ✓ Agnostic deformation of the quadrupole



$$Q = -m^3\chi^2\,\kappa$$

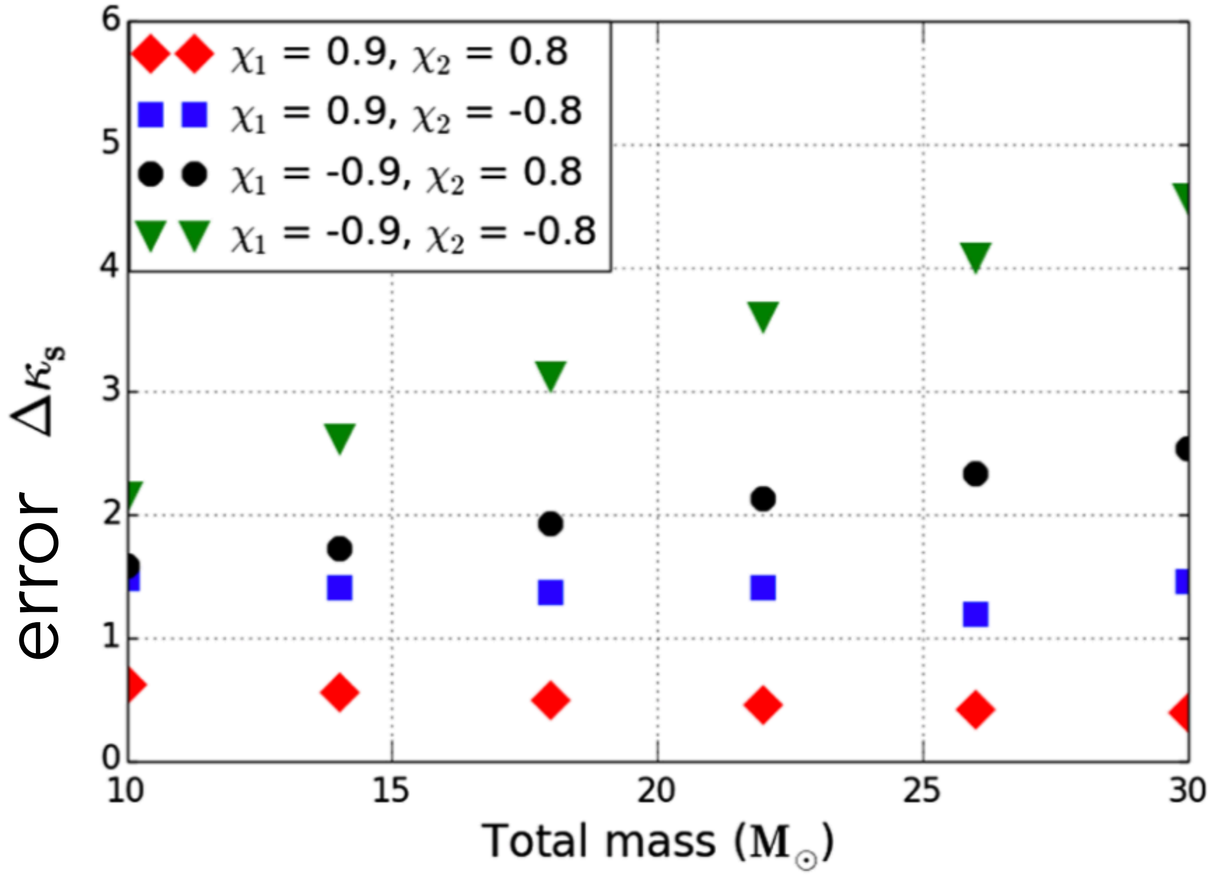
10-150 boson stars

1 BH

- ✓ Q enters the GW signal at 2 PN through

$$\kappa_s = (\kappa_1 + \kappa_2)/2$$

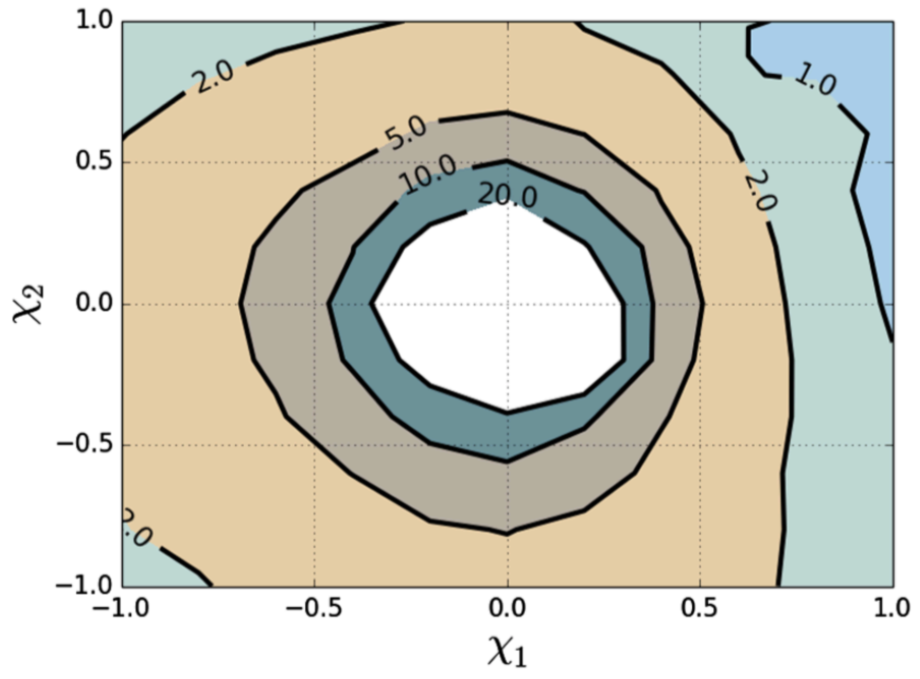
$$\kappa_a = (\kappa_1 - \kappa_2)/2$$



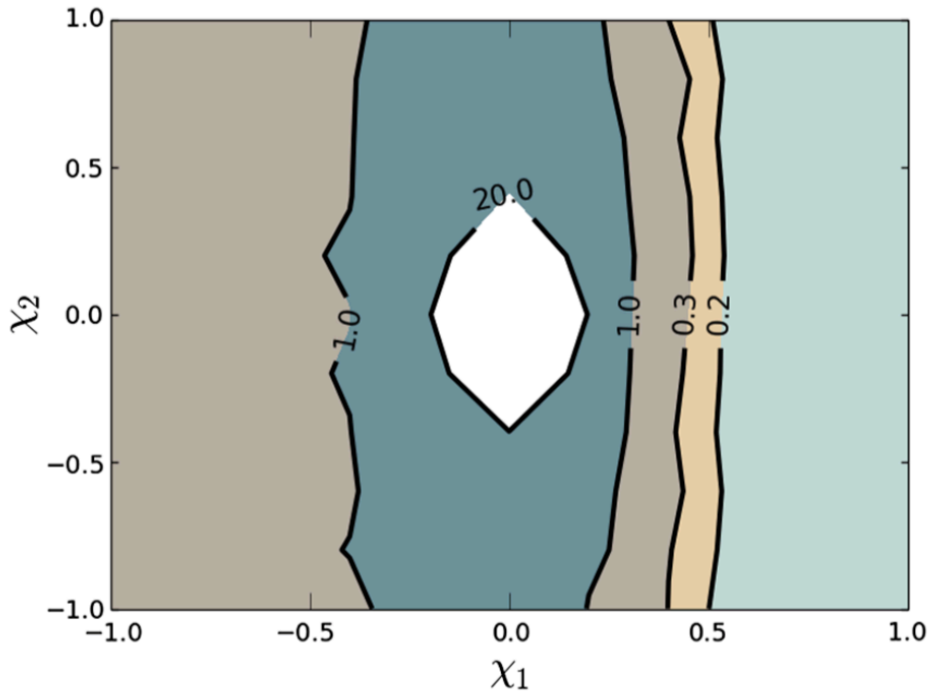
Quadrupole errors

LIGO - SNR = 10

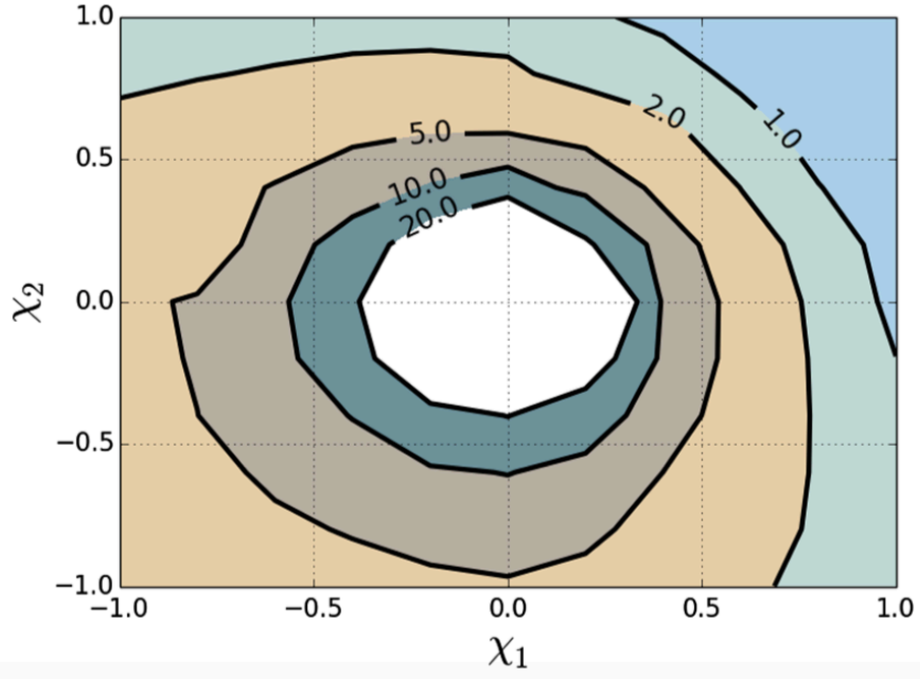
LISA - d = 3Gpc



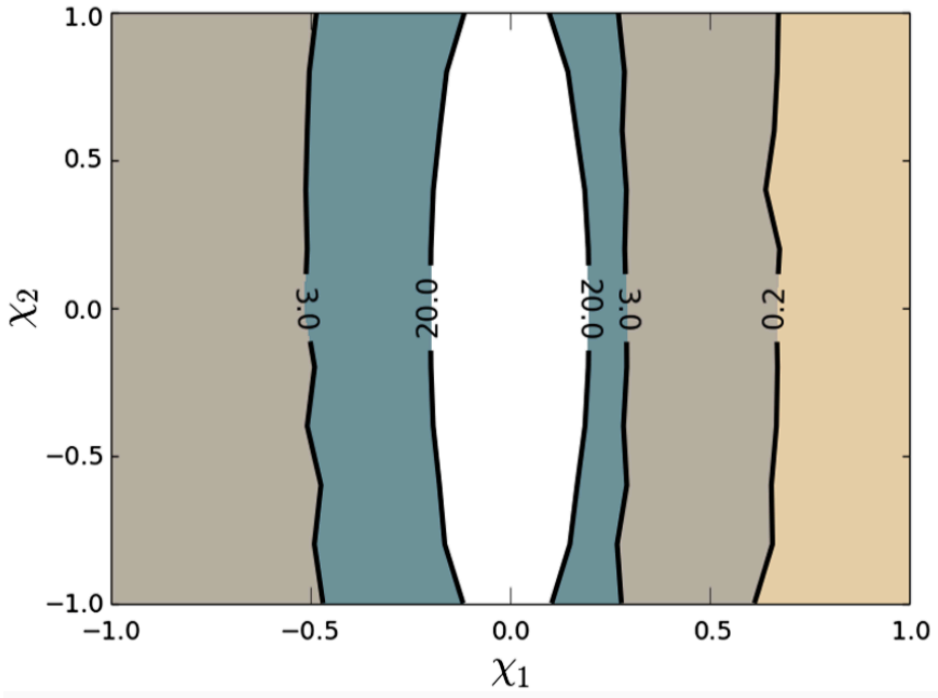
$(5, 4)M_\odot$



$(5 \times 10^6, 10^6)M_\odot$



$(10, 9)M_\odot$



$(10^7, 10^6)M_\odot$

Tidal Heating

BH as classical viscous fluid

- ✓ Small contribution to the orbital evolution given by dissipation of energy and angular momentum at the horizon

$$\psi_{\rm TH}^{\rm BH} = \underset{\text{2.5PN}}{\bigcirc} \qquad G(m_i)\frac{(m\pi f)^{8/3}}{\underset{\text{4PN}}{\boxed{c^8}}}$$

- ✓ For known matter GW absorption is negligible

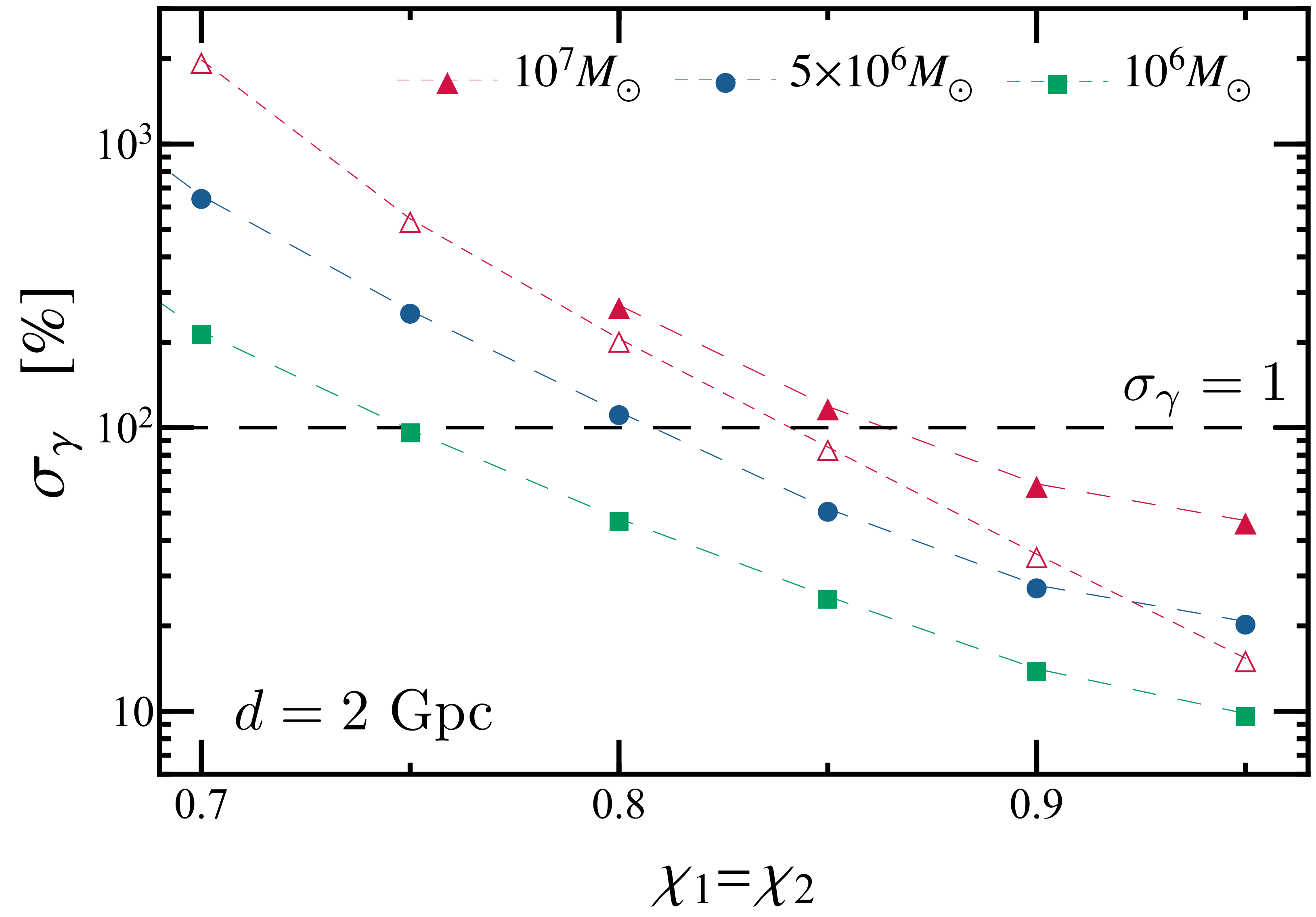
$$h(f) = \mathcal{A}e^{i[\psi_{\rm PP}(f)+\psi_{\rm TH}(f)]}$$

$$\psi_{\rm TH} = \gamma \times \psi_{\rm TH}^{\rm BH}$$

$\gamma = 0$ ⟷ ECO

$\gamma = 1$ ⟷ BH

Detectability: tidal heating



- ✓ Spin enhancement is more dramatic
- ✓ Chances to put interesting constraints up to 20 Gpc