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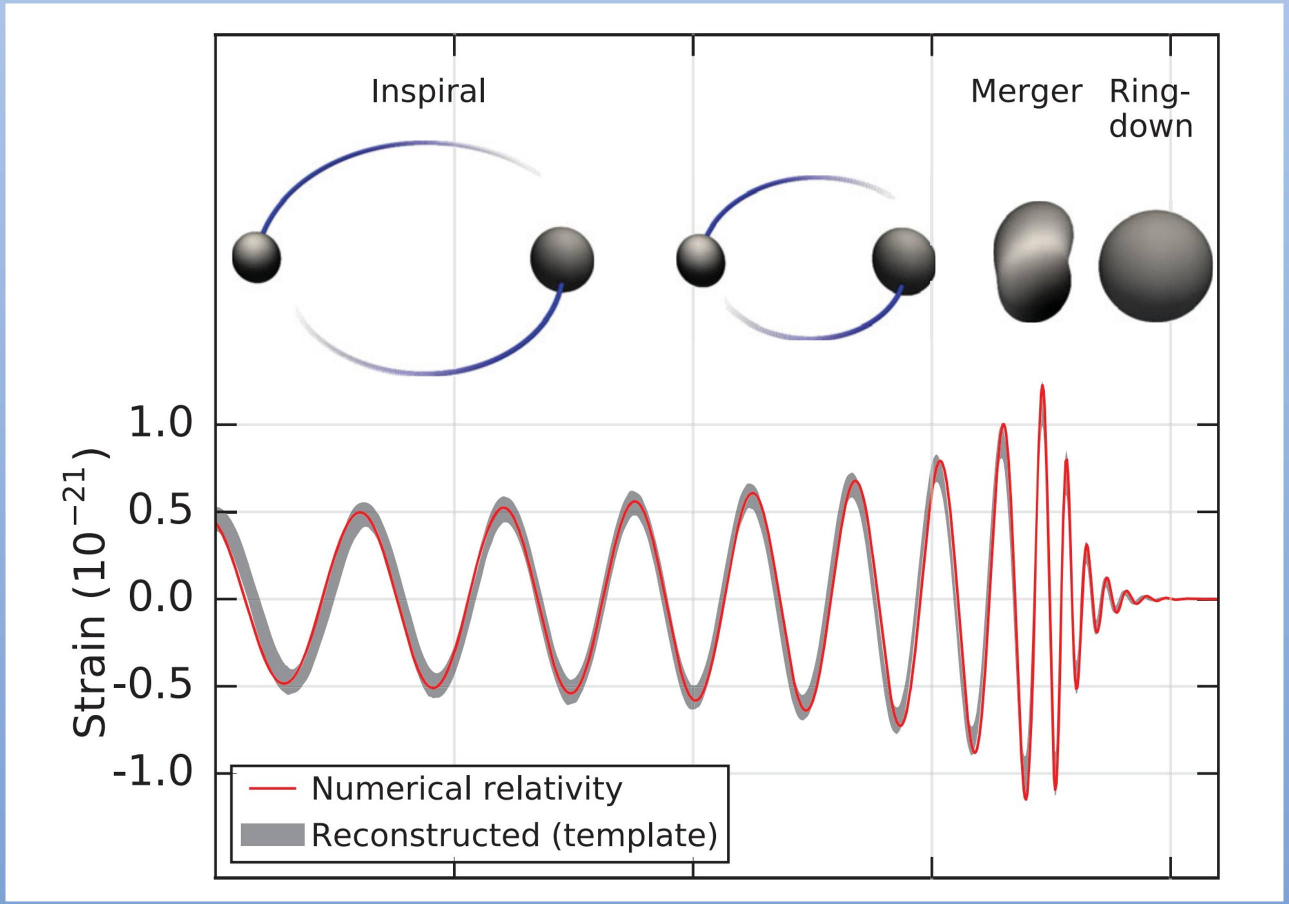
H2020-MSCA-RISE-2015 StronGrHEP-690904

Rencontre du GdR Tests de la Relativité Génerale
February 4th 2020:

Mimicking Black Hole mimickers



Black hole signal
LIGO/VIRGO Collaboration
PRL 2016

Goal:
Construct a waveform for black hole mimickers and assess if ground based detectors could distinguish it from a black hole

Black Hole Mimickers

- Compact Objects similar to black holes from the gravitational point of view:

$$C = \frac{M}{R} \gtrsim 0.1 \qquad C_{BH} \geq \frac{1}{2}$$

- No horizon
- Merger can lead to a BH or object of same nature
- Example: Boson Stars

Boson Stars

- Scalar field solution of Einstein-Klein Gordon equation
- Example: Massive Boson Stars:

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{R}{16\pi} - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} m_\phi^2 |\phi|^2 - \frac{1}{4} \lambda |\phi|^4 \right]$$

Colpi, Shapiro, Wasserman (PRL 1986):

$$M_{max} \simeq \left(\frac{0.10 \text{ GeV}}{m_\phi} \right)^2 \lambda^{1/2} M_\odot$$

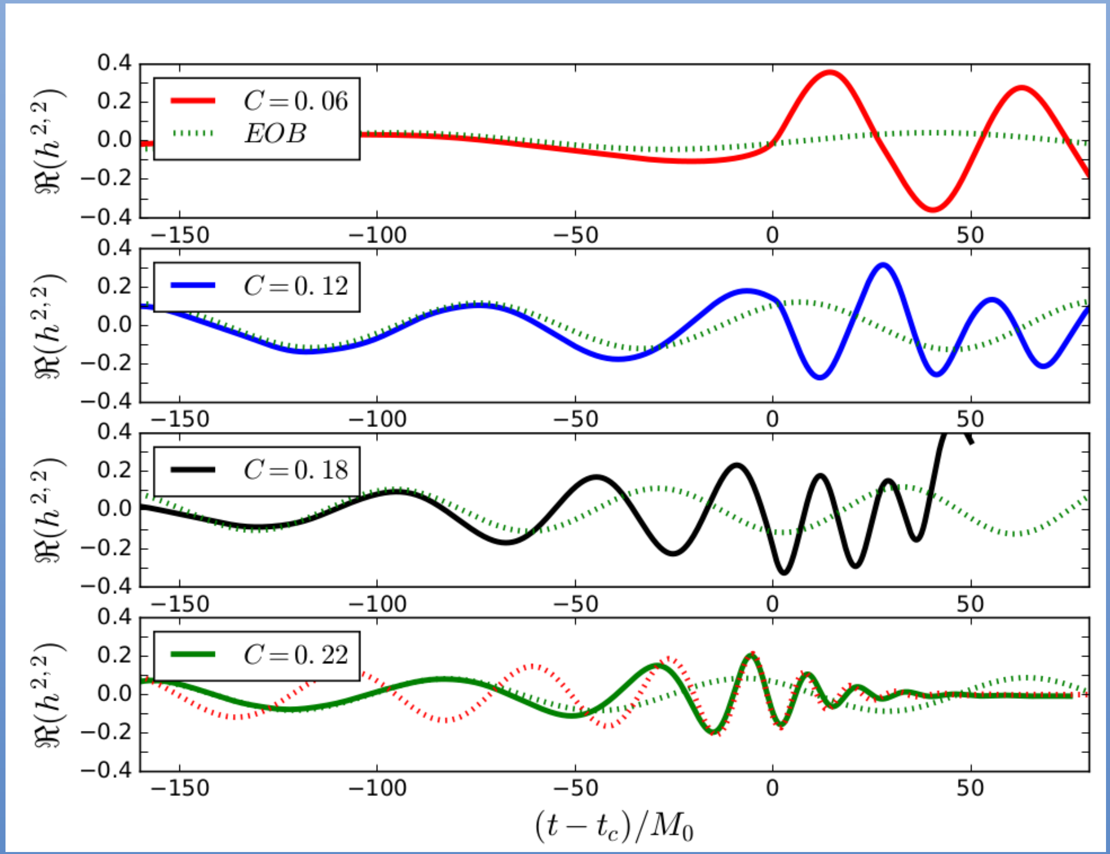
- Self interaction increases mass and compactness

$$C \lesssim 0.3$$

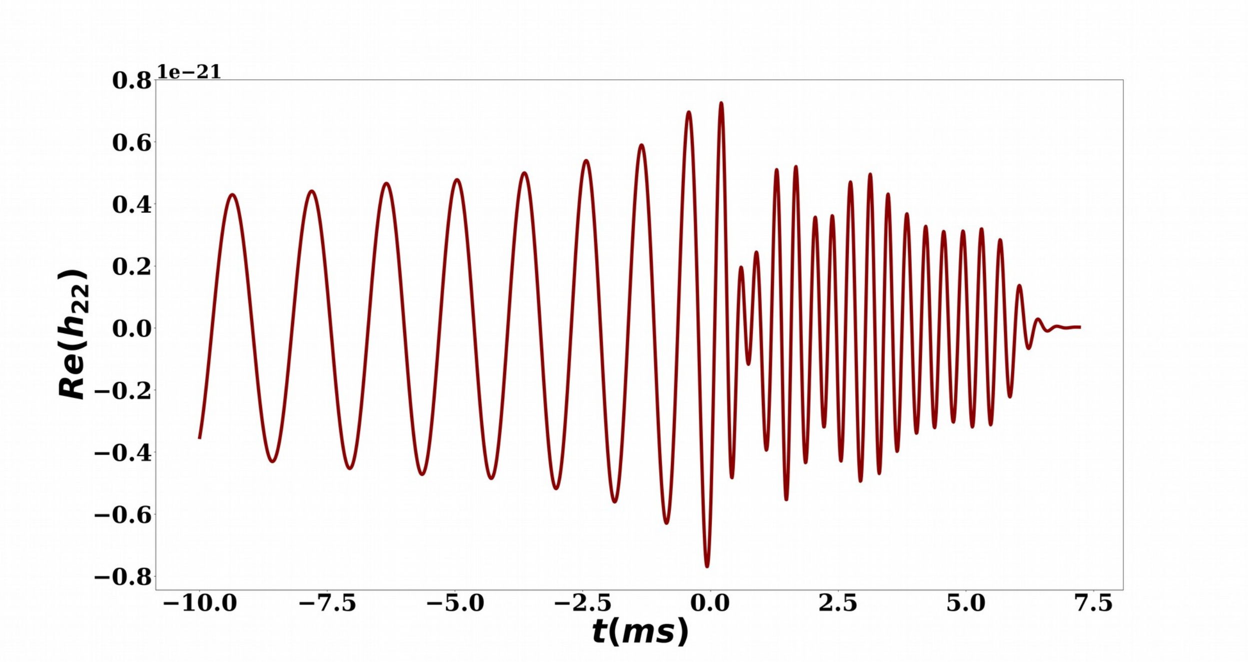
Numerical simulations of Boson Stars

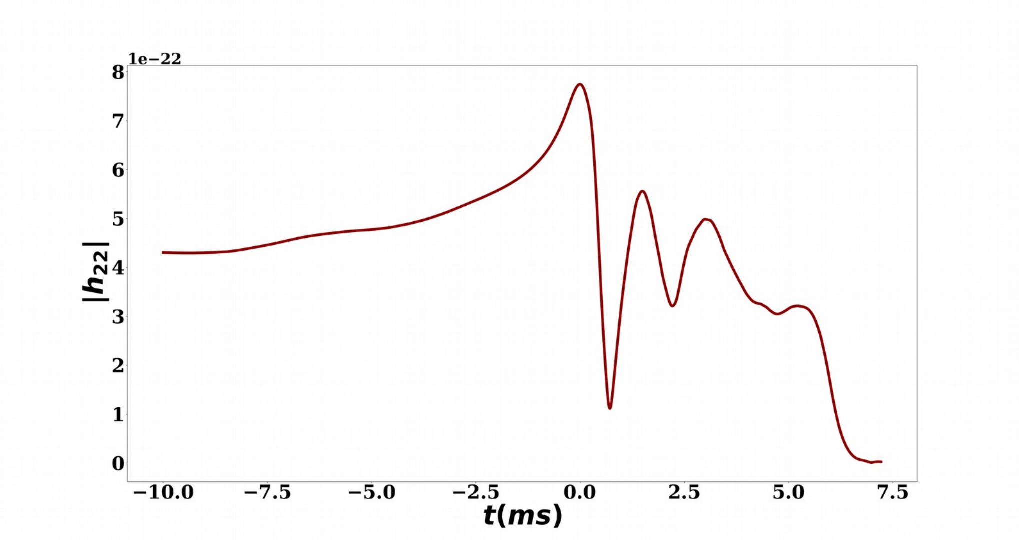
- If formed from collapse or coalescence seemingly do not support rotation (Sanchis-Gual et. al PRL 2019, Bezares et. al Phys. Rev. D 2017, Palenzuela et al. Phys Rev D 2017)
- Radial oscillations at characteristic frequency (Palenzuela et al. Phys Rev D 2017):

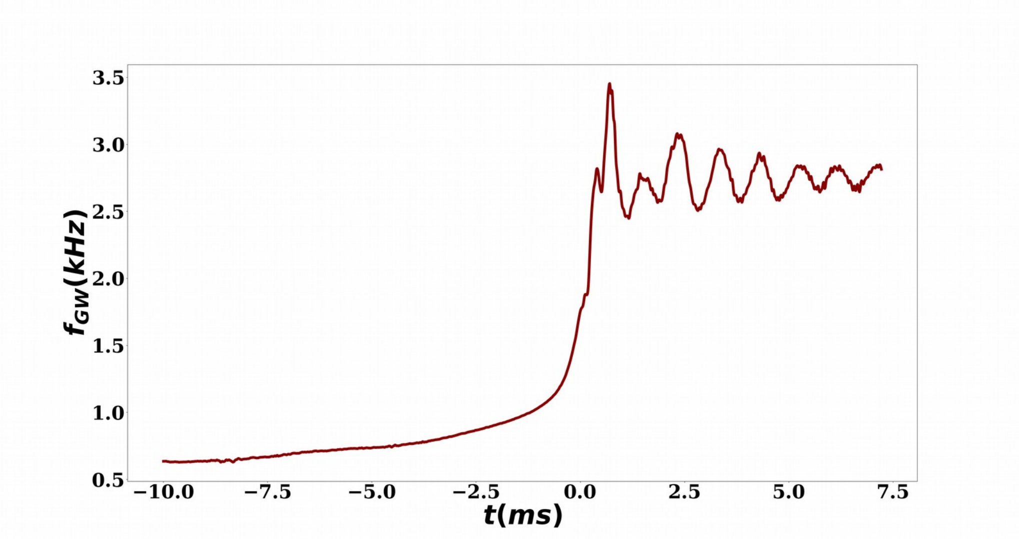
$$M_r \omega_r = -0.064 + 1.72 M_0 \omega_c$$



Post-merger signal of Neutron Star from Numerical Simulations





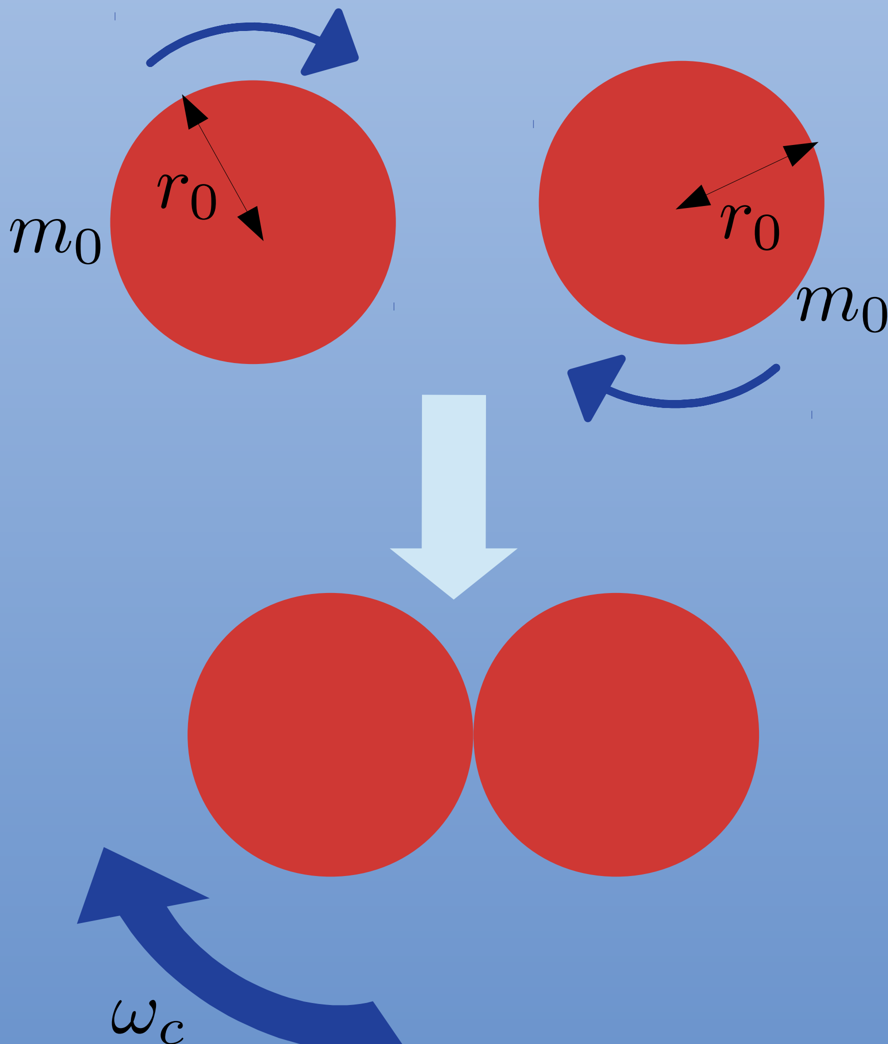


Equation of state: ALF2

$$m_1 = m_2 = 1.35 M_\odot$$

Taken from:
http://www.computational-relativity.org

Toy Model

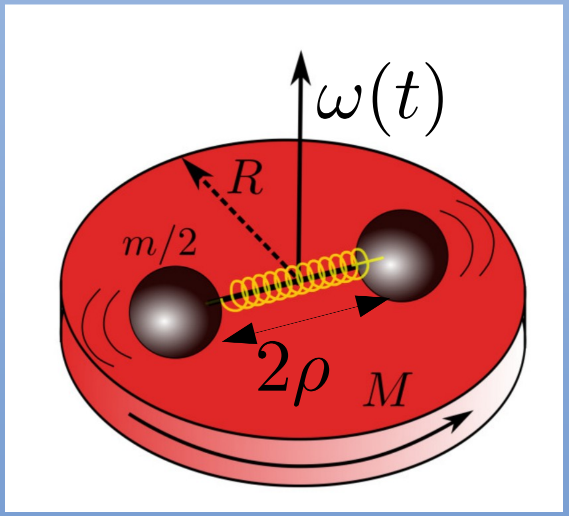


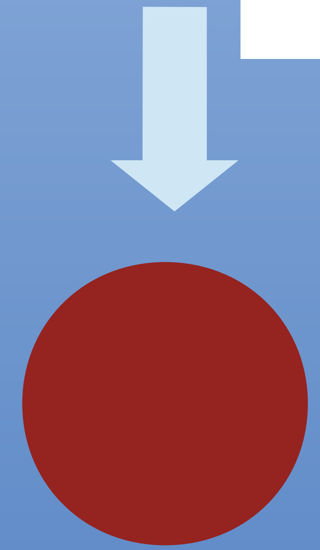
$$C_0 = \frac{m_0}{r_0}$$

$$a_0 = 0$$

$$\Delta t \simeq \frac{1}{2}\frac{2\pi}{\omega_c}$$

Toy Model for the intermediary phase (Takami, Rezzolla, Baiotti Phys. Rev. D 2015)





Settings

- 4 free parameters related to the equation of state of the initial bodies:
  - m ($M = 2m_0 - m$ assuming mass conservation)
  - R
  - Spring constant: k
  - Length at rest: $2\rho_0$

k, ρ_0

Softer → Stiffer

- Initial conditions:

$$\rho(0) = R - r_0 \qquad E(0) = E_c$$

$$\varphi(0) = \varphi_0 \qquad J(0) = \alpha J_c$$

$$\begin{cases} \alpha = 0 : \text{ "Boson Star"} \\ \alpha = 1 : \text{ "Neutron Star"} \end{cases}$$

Evolution of the system

- Effective particle in an effective potential:

$$V_{\text{eff}} = V_{\text{centrifugal}} + V_{\text{gravitational}} + V_{\text{spring}}$$

- Adiabatic evolution over one period:

$$\dot{\rho} = \sqrt{\frac{2}{m}}\sqrt{E - V_{eff}(\rho)}$$

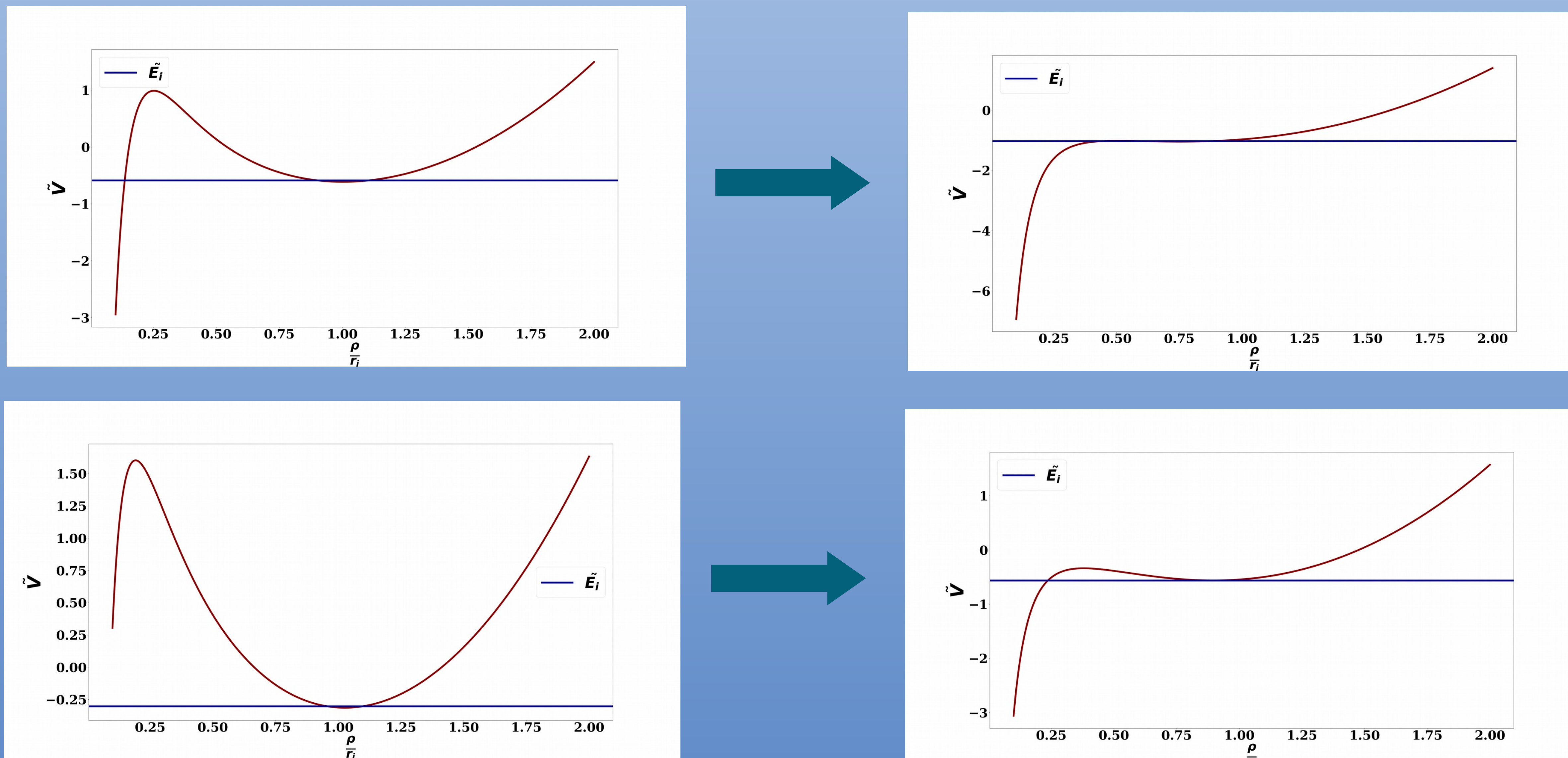
$$\dot{\varphi} = \omega = \frac{J}{I}$$

$$\dot{E} = - < P_{rad} >$$

$$\dot{J} = - < J_{rad} >$$

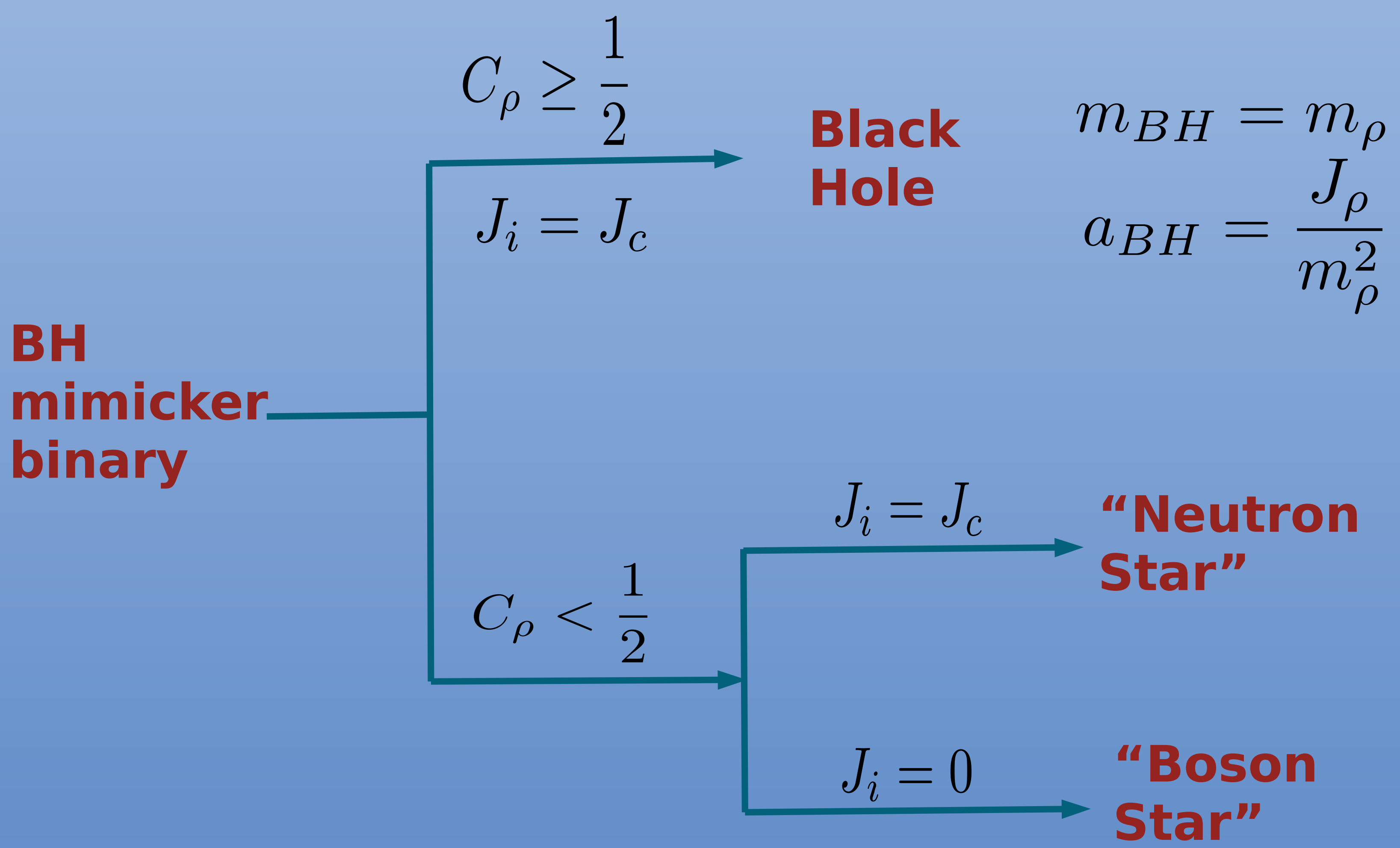
Computed with quadrupole formula assuming non perturbed equations of motion

Evolution of the system

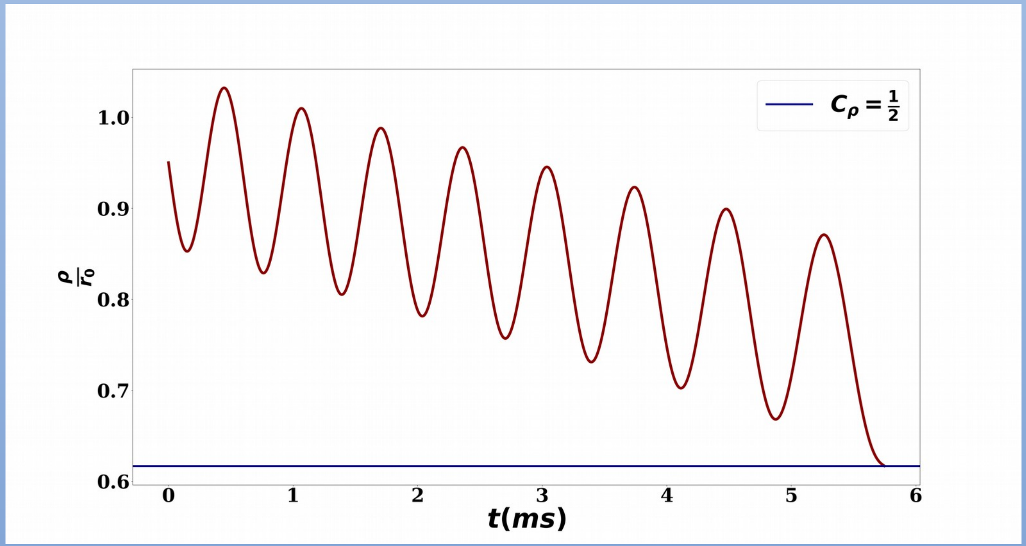


End scenarios:

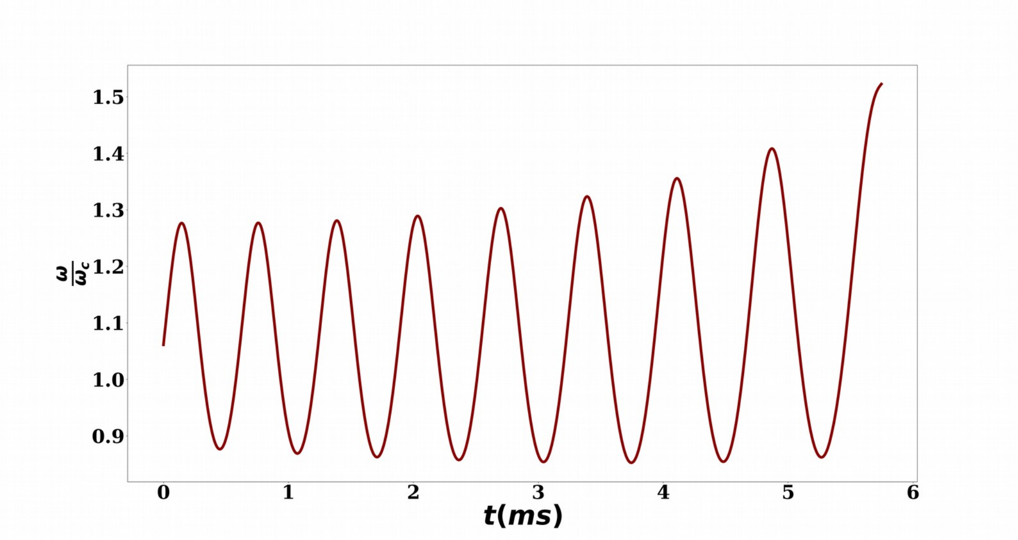
- Compactness: $C_\rho = \frac{m_\rho}{\rho} = \frac{m + M\left(\frac{\rho}{R}\right)^2}{\rho}$

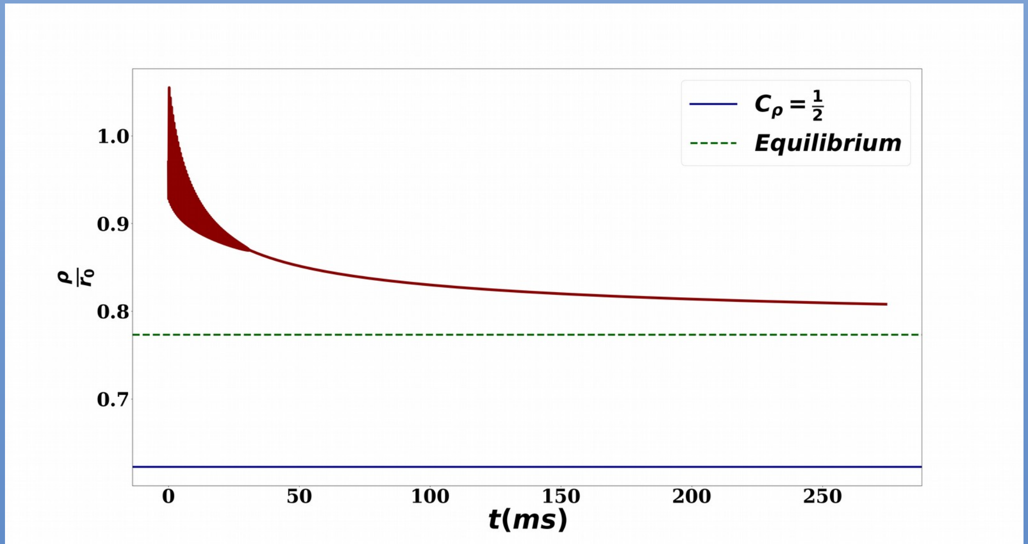


Dynamics

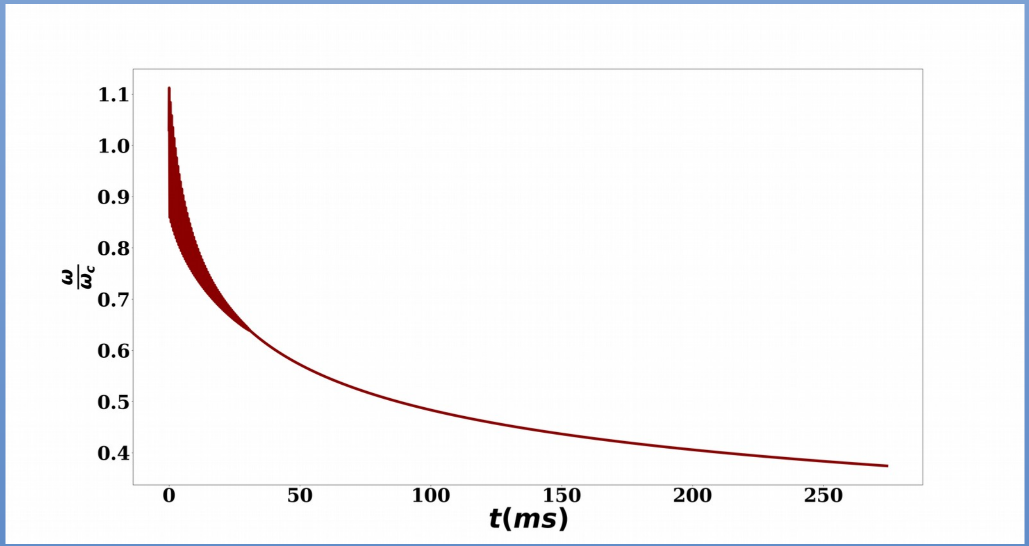


End state:
BH





End state:
“NS”



Full signal

- Inspiral: IMRPhenomD_NRTidal until $f_{GW} = 2f_c$
-
- Toy model computed with quadrupole formula

Full signal

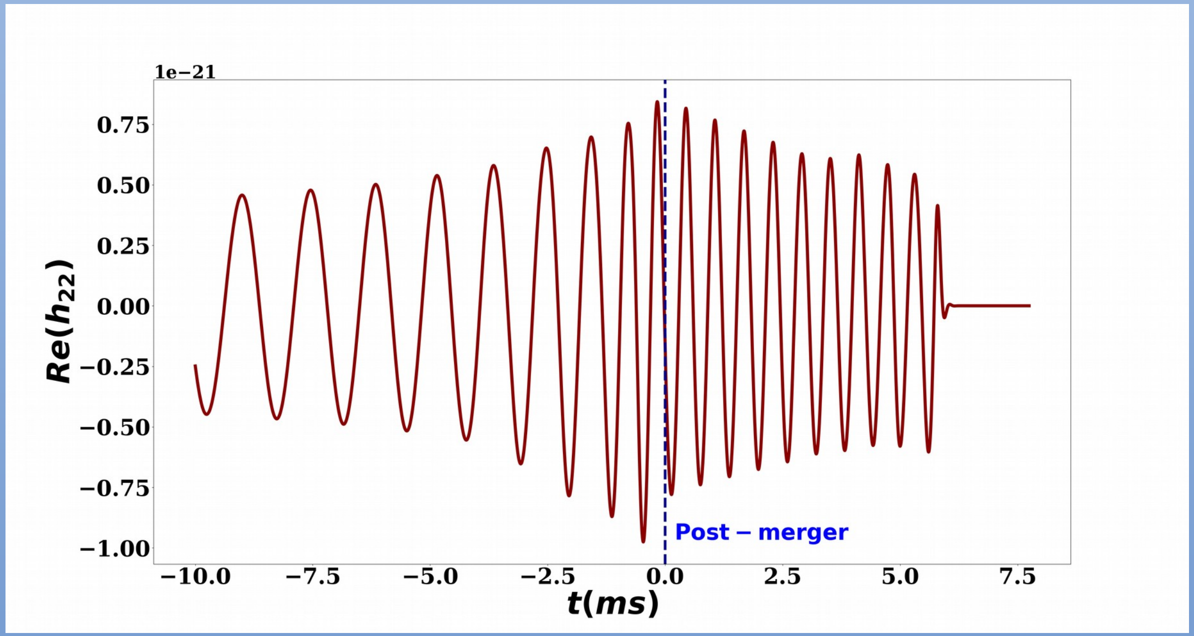
- Inspiral: IMRPhenomD_NRTidal until $f_{GW} = 2f_c$
- Matching in amplitude and phase for $\Delta t = \frac{1}{2}\frac{1}{f_c}$
- Toy model computed with quadrupole formula

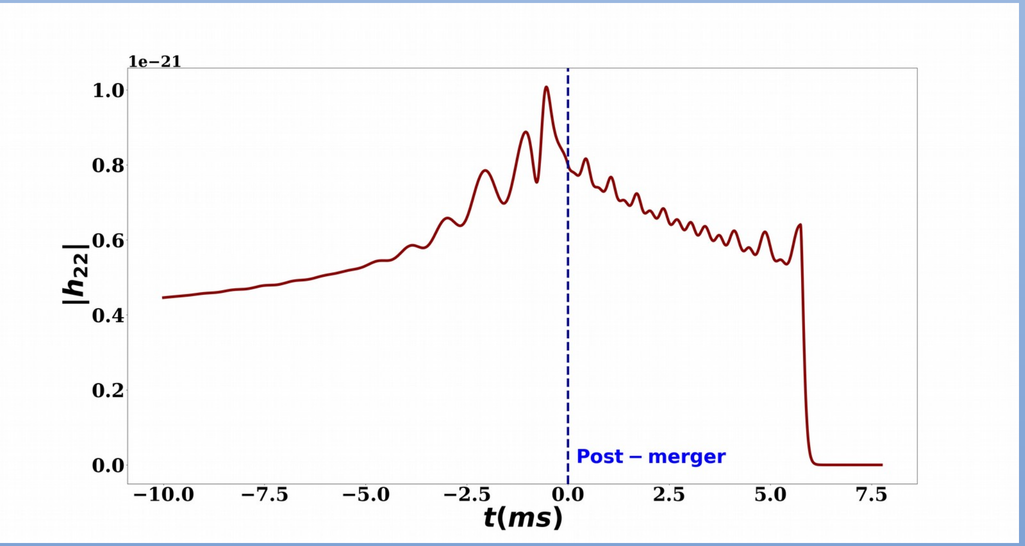
Full signal

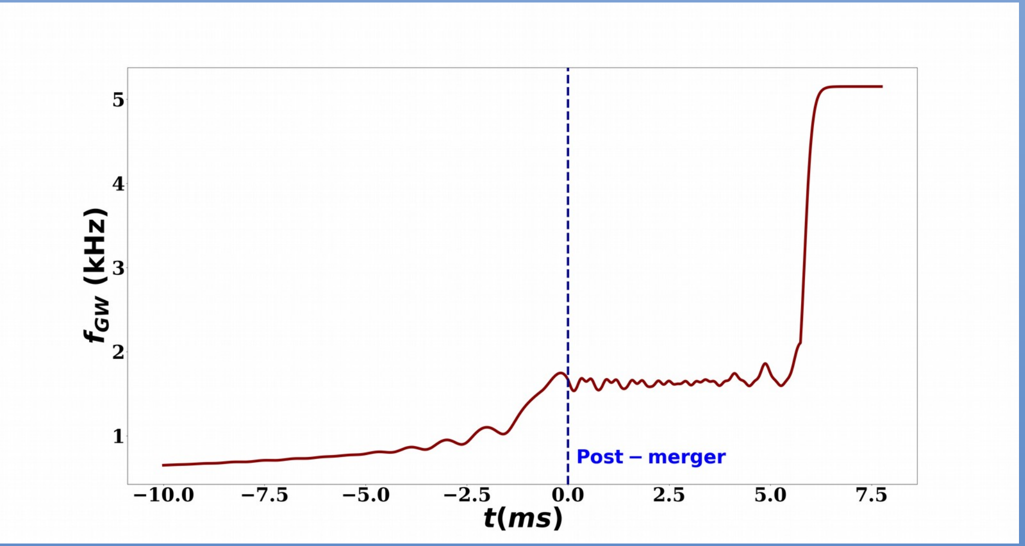
- Inspiral: IMRPhenomD_NRTidal until $f_{GW} = 2f_c$
- Matching in amplitude and phase for $\Delta t = \frac{1}{2}\frac{1}{f_c}$
- Toy model computed with quadrupole formula
- If final state is BH, attach ringdown as

  in Damour and Nagar (Phys. Rev. D 2014) with
  QNMs from Berti et.al (Class.Quant.Grav 2009)
- Flexibility for different end behaviours

Time domain: collapse to a BH





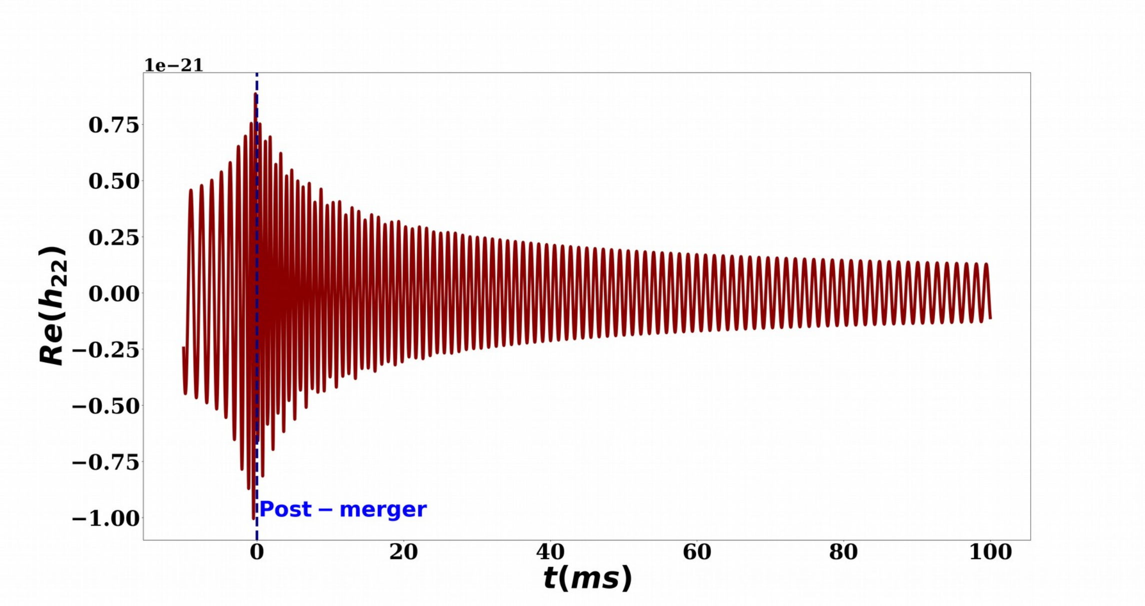


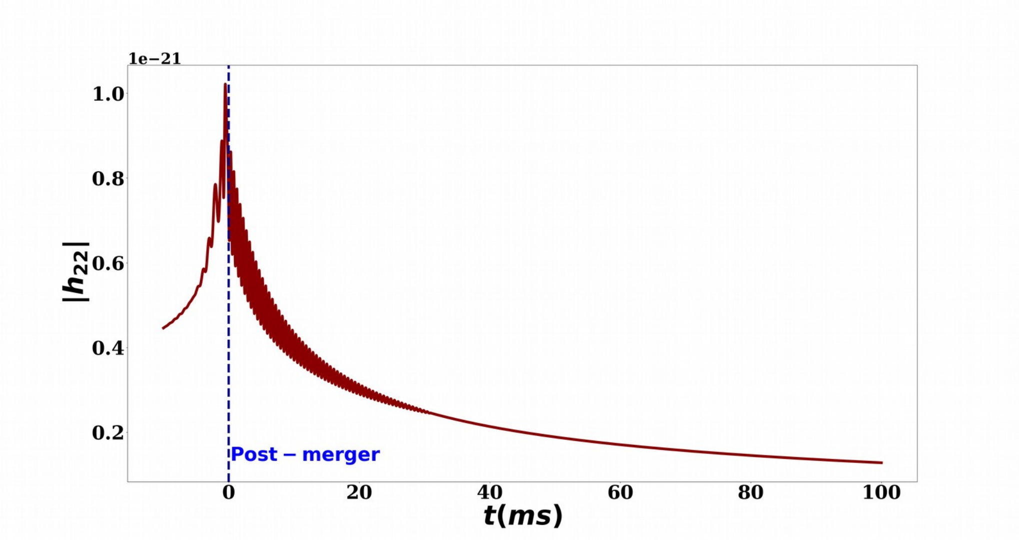
$$m_1 = m_2 = 1.35 M_\odot$$

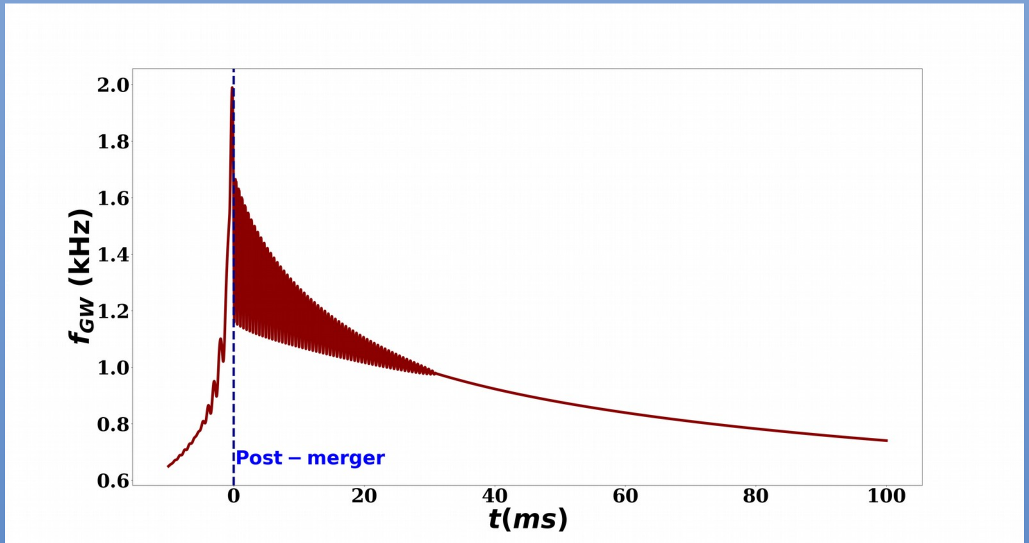
$$C_0 = 0.16$$

$$m_{BH} = 2.60 M_\odot$$
$$a_{BH} = 0.37$$

Time domain: “NS” remnant







$$m_1 = m_2 = 1.35 M_\odot$$

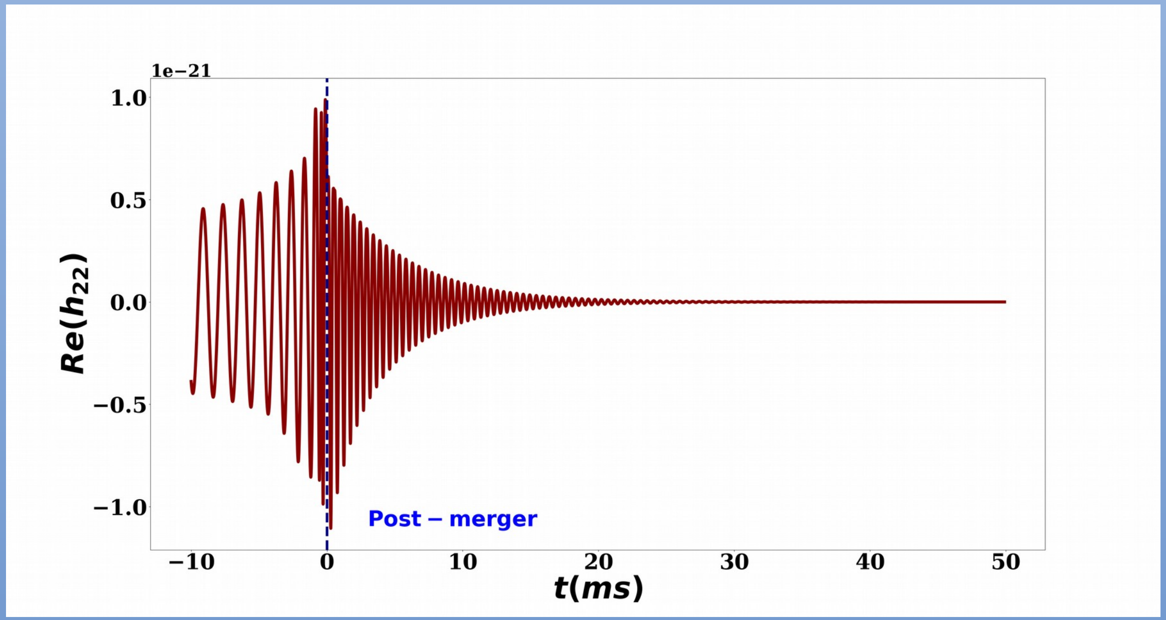
$$C_0 = 0.16$$

$$m_{BH} = 2.60 M_\odot$$

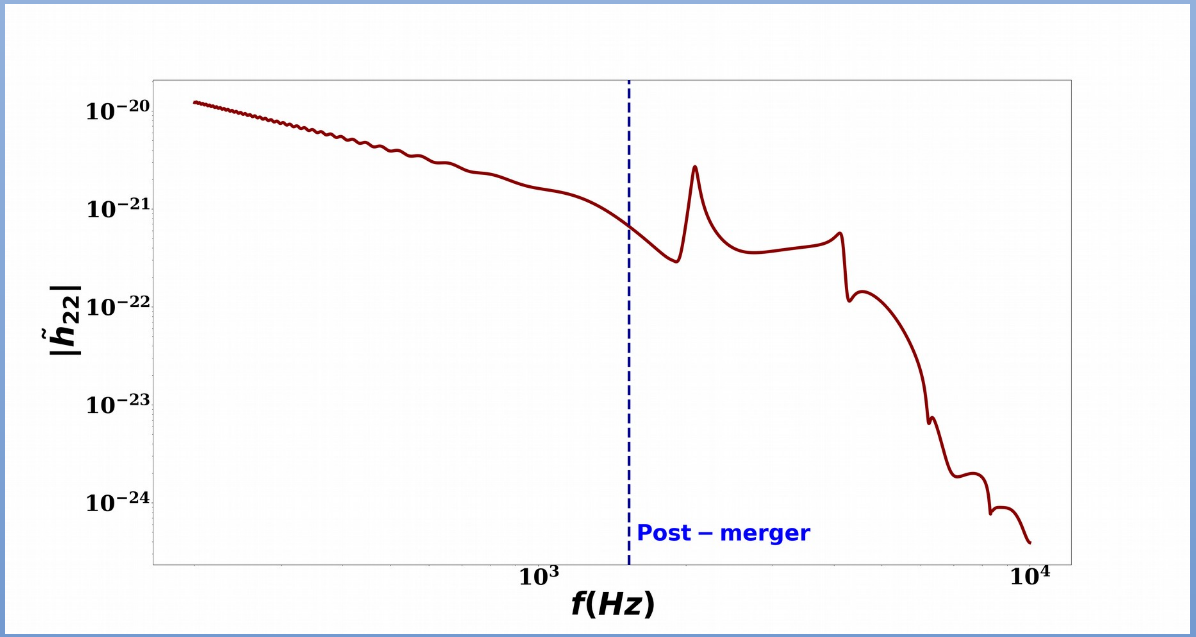
$$a_{BH} = 0.37$$

“BS” remnant

$$m_1 = m_2 = 1.35 M_\odot \qquad C_0 = 0.16$$



Time domain

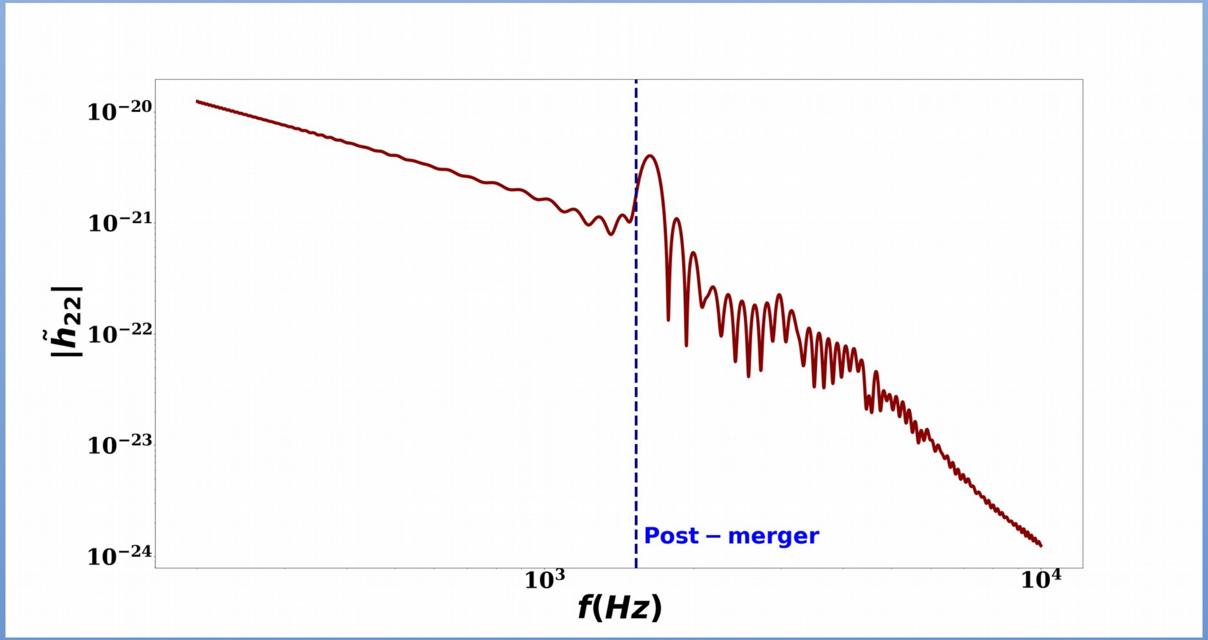


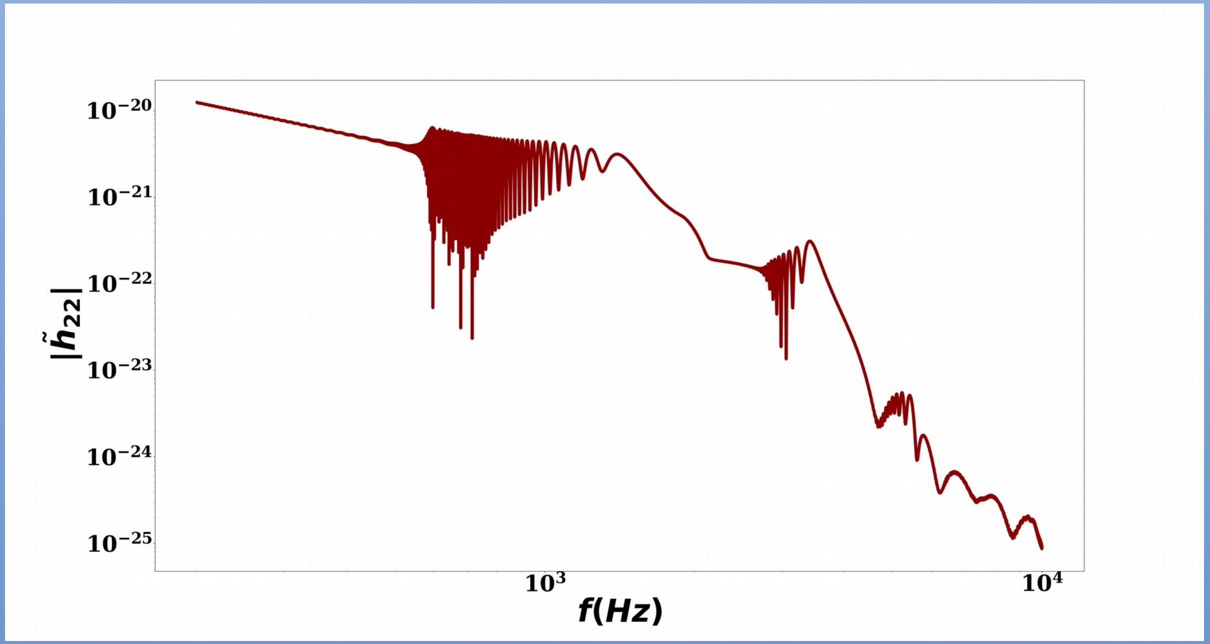
Frequency domain

$$J_i = 0 \qquad \omega_{car} = 2.1 \text{ kHz}$$

Frequency domain

$$m_1 = m_2 = 1.35 M_\odot \quad C_0 = 0.16$$





Collapse to a BH

$$m_{BH} = 2.60 M_\odot$$

$$a_{BH} = 0.37$$

"Neutron Star"

Data analysis

- Inner product: $(d|h) = 4\mathcal{R}\left(\int \frac{\tilde{d}(f)\tilde{h}^*(f)}{S_n(f)}\mathrm{d}f\right)$

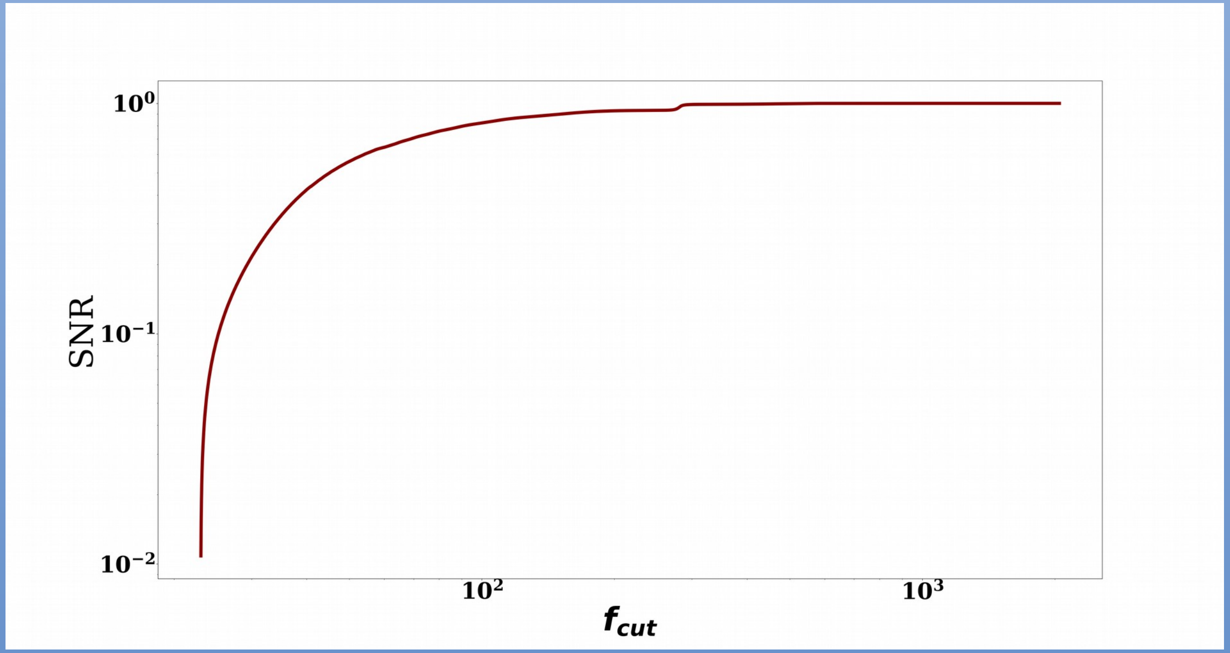
- Signal to Noise Ratio (SNR): $\sqrt{(h|h)}$

- Is the post merger signal detectable?
- Is the signal distinguishable from a GR BH?

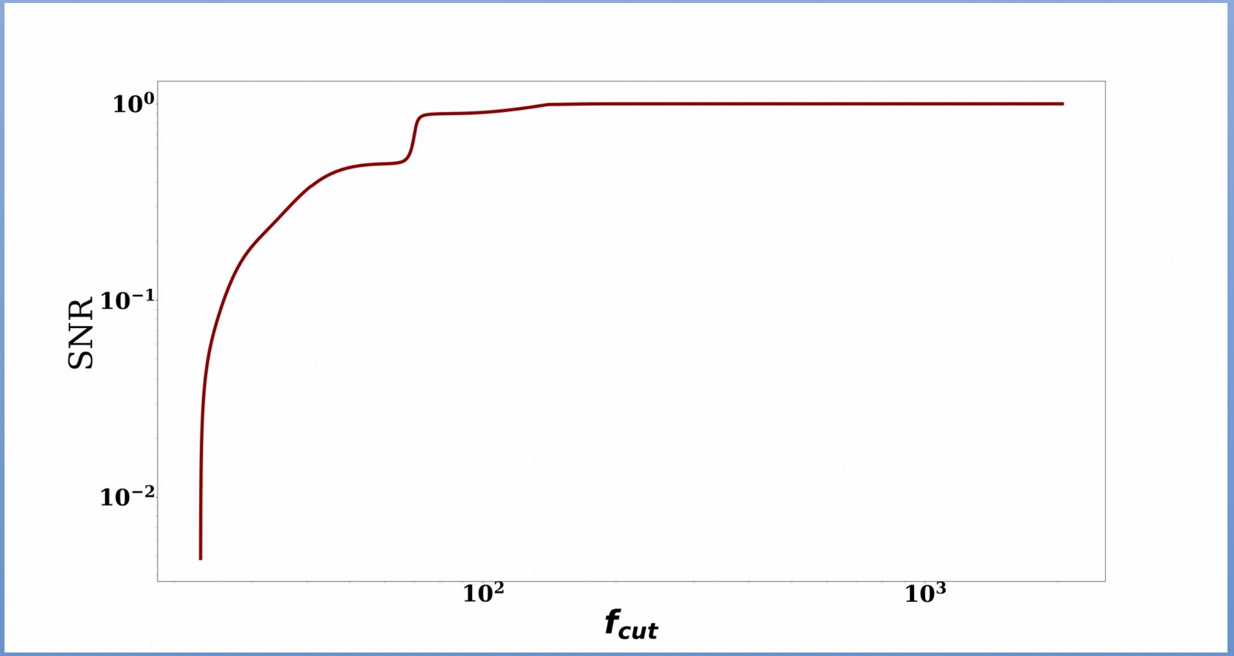
Impact on the SNR

Optimally oriented system:

"Boson Star" in Advanced Ligo:



$$m_{tot} = 20 M_\odot$$
$$SNR_{pm} = 0.37\ SNR_{tot}$$



$$m_{tot} = 80 M_\odot$$
$$SNR_{pm} = 0.84\ SNR_{tot}$$

Detectability

- Threshold: $SNR_{pm} > 8$

	End state		
Distance	Black Hole	"Boson Star"	"Neutron Star"
40 Mpc	$5.8M_\odot$	$7.5M_\odot$	$3.8M_\odot$
400 Mpc	$18M_\odot$	$20.5M_\odot$	$12.5M_\odot$

Minimum total mass for detectability of post-merger signal with **Advanced Ligo**

	End state		
Distance	Black Hole	"Boson Star"	"Neutron Star"
40 Mpc	$2.1M_\odot$	$2M_\odot$	$1.1M_\odot$
400 Mpc	$3.6M_\odot$	$4.2M_\odot$	$2.3M_\odot$

Minimum total mass for detectability of post-merger signal with **Einstein Telescope**

Detectability in O1/O2 events

Event	$\mathcal{M}_c$ ($M_\odot$)	$\mathrm{SNR_{obs}}$	$C = 0.16$		
			BH	BS	NS
GW150914	28.6	24.4	20.1	19.5	21.5
GW150112	15.2	10.0	6.4	5.8	7.9
GW151226	8.9	13.1	5.9	5.0	8.7
GW170104	21.4	13.0	9.8	9.2	11.0
GW170608	7.9	14.9	6.1	5.0	9.4
GW170729	35.4	10.8	9.4	9.1	9.7
GW170809	24.9	12.4	9.8	9.4	10.7
GW170814	24.1	15.9	12.5	12.0	13.7
GW170818	26.5	11.3	9.1	8.8	9.8
GW170823	29.2	11.5	9.5	9.2	10.2

SNR for O1/O2 events if those were some BH mimicker binary assuming equal mass ratio.The SNR have been rescaled so that the total SNR matches the one measured by the detectors.

Distinguishability

- Fitting factor: $FF = max_h \frac{(d|h)}{\sqrt{(d|d)(h|h)}}$ $d:$ BH mimicker signal; $h:$ GR BH template
- $m_1 = m_2 = 15M_\odot$ in Advanced Ligo $SNR_{pm} \simeq SNR_{inspiral}$
- Maximimizing over time phase and intrinsic parameters:

Black Hole	"Boson Star"	"Neutron Star"
$FF = 0.85$	$FF = 0.8$	$FF = 0.63$
$m_1 = 32M_\odot$ $a_1 = 0.08$	$m_1 = 29M_\odot$ $a_1 = -0.17$	$m_1 = 29M_\odot$ $a_1 = -0.13$
$m_2 = 7M_\odot$ $a_2 = 0.18$	$m_2 = 8M_\odot$ $a_2 = 0.36$	$m_2 = 8M_\odot$ $a_2 = 0.10$

Summary:

- Phenomenological model for BH mimickers waveforms
- Main difference is post merger signal
- Could already be seen in current detectors

- **Next steps**:
  - Consider different initial angular momentum:

$$J(0) = \alpha J_c \quad 0 \leq \alpha \leq 1$$

  - More rigorous data analysis
  - Analysis of residuals

Numerical integration

- Define: $\rho = \dfrac{p}{1 + e\cos(\chi)}$ $\quad e = \dfrac{\rho_+ - \rho_-}{\rho_+ + \rho_-}$

$$p = 2\frac{\rho_+\rho_-}{\rho_+ + \rho_-}$$

- $\rho_+,\ \rho_-,\ \rho_3,\ \rho_4,\ \rho_5$ are the roots of $E - V_{\text{eff}} = 0$

- So that: $\dot{\chi} = 2\sqrt{\dfrac{k}{m}}\dfrac{(1 + e\cos(\chi))}{\sqrt{1-e^2}}\sqrt{\dfrac{(\rho-\rho_3)(\rho-\rho_4)(\rho-\rho_5)}{\rho(\frac{MR^2}{2m} + \rho^2)}}$

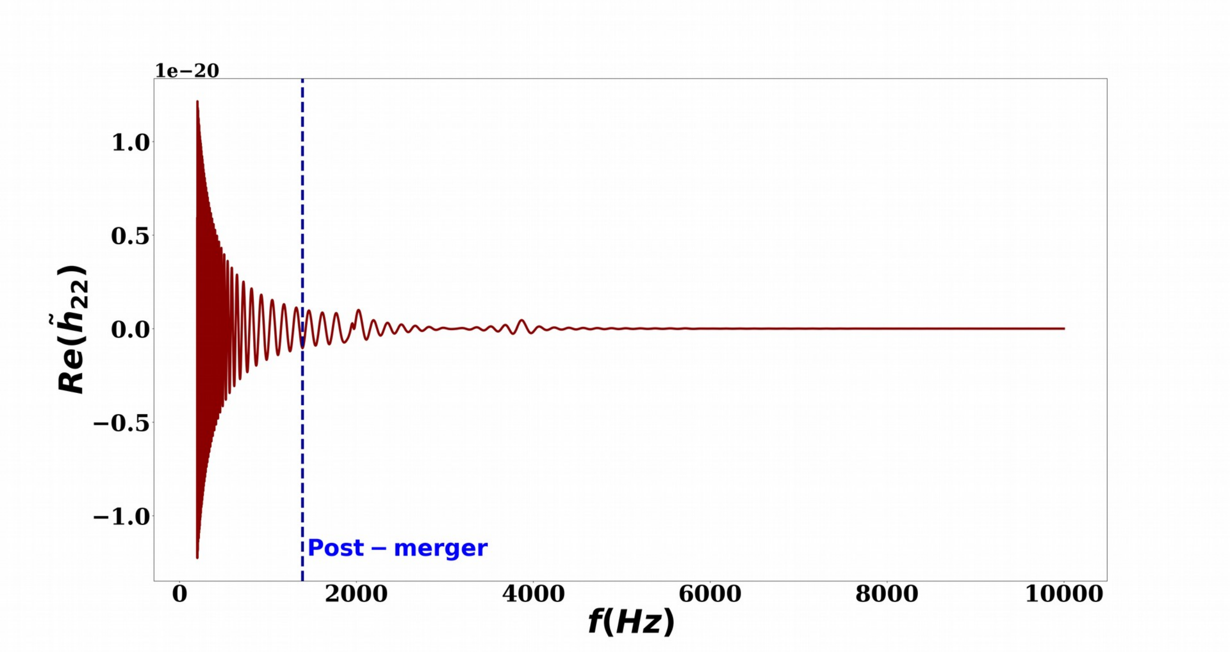
Massive Boson Stars

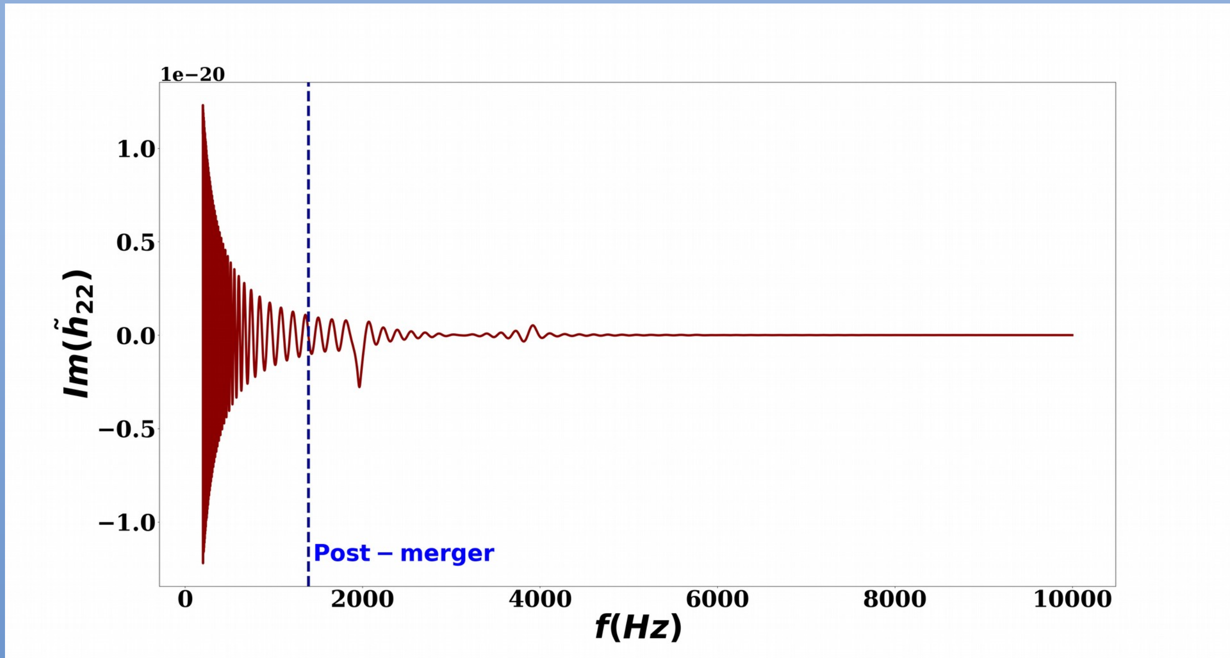
$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi} - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{1}{2}m_\phi^2|\phi|^2 - \frac{1}{4}\lambda|\phi|^4\right]$$

- Colpi, Shapiro, Wasserman (PRL 1986):

$$M_{max} \simeq \left(\frac{0.10\ \mathrm{GeV}}{m_\phi}\right)^2 \lambda^{1/2} M_\odot$$

“Boson Star” waveform (FD)





Black hole waveform (FD)