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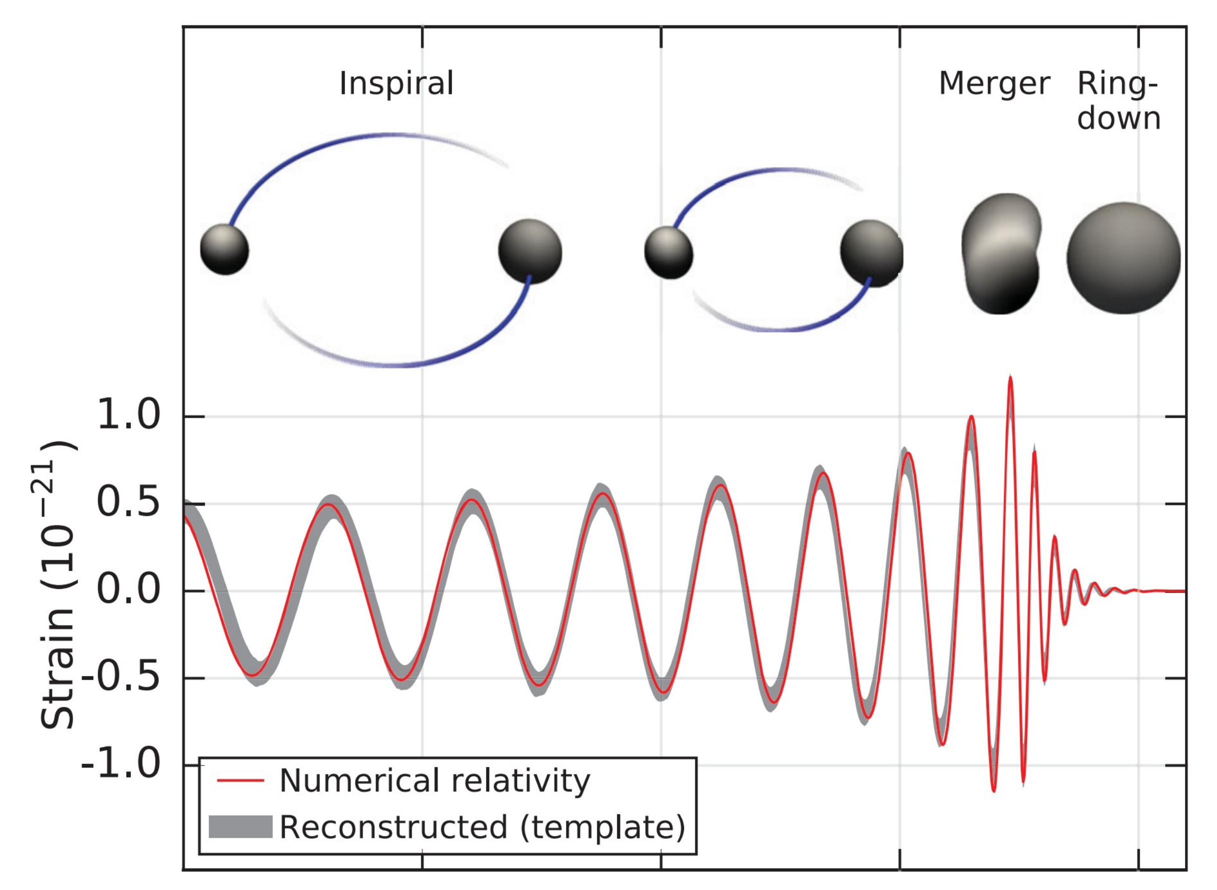
COST General Meeting 2020:

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
- Self interaction increases mass and compactness

$$C \lesssim 0.3$$

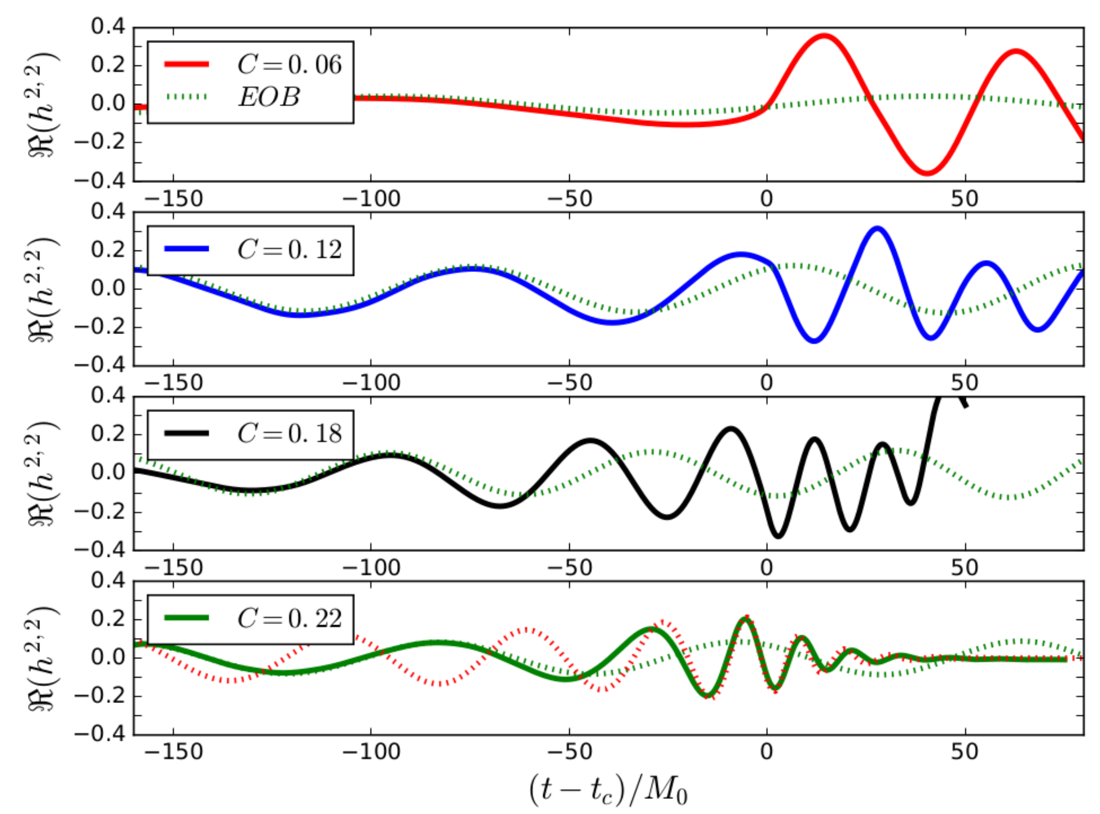
- If formed from collapse or coalescence seemingly do not support rotation

  (Sanchis-Gual et. al PRL 2019, Bezares et. al Phys. Rev. D 2017, Palenzuela et al. Phys Rev D 2017)

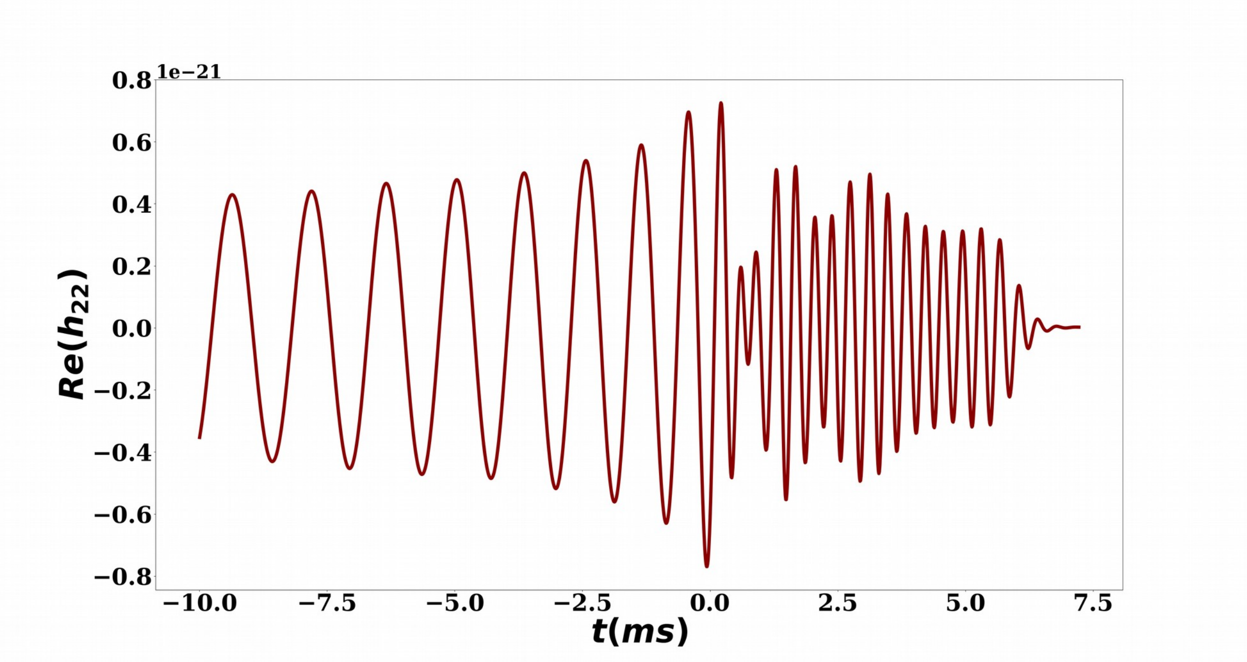
Numerical simulations of Boson Stars

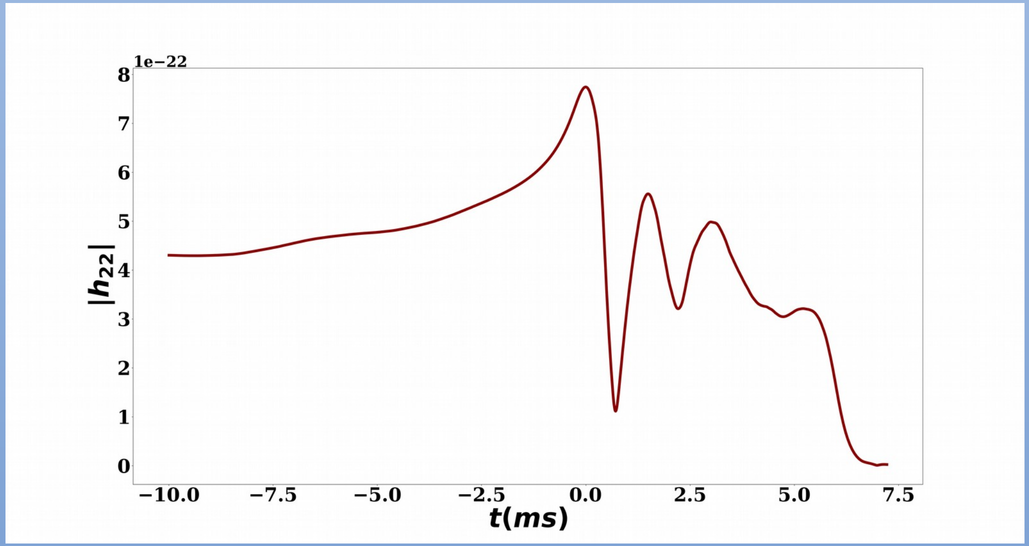
- If compact enough form a BH
- If form a boson star, angular momentum radiated very early
- Radial oscillations at characteristic frequency (Palenzuela et al. Phys Rev D 2017):

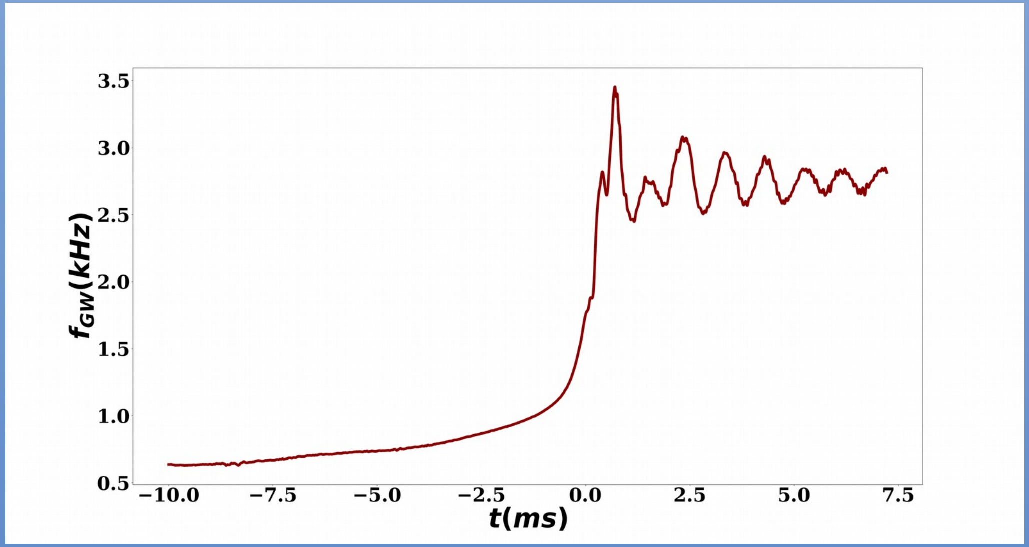
$$M_r\omega_r = -0.064 + 1.72 M_0 \omega_c$$



Post-merger signal of Neutron Star from Numerical Simulations





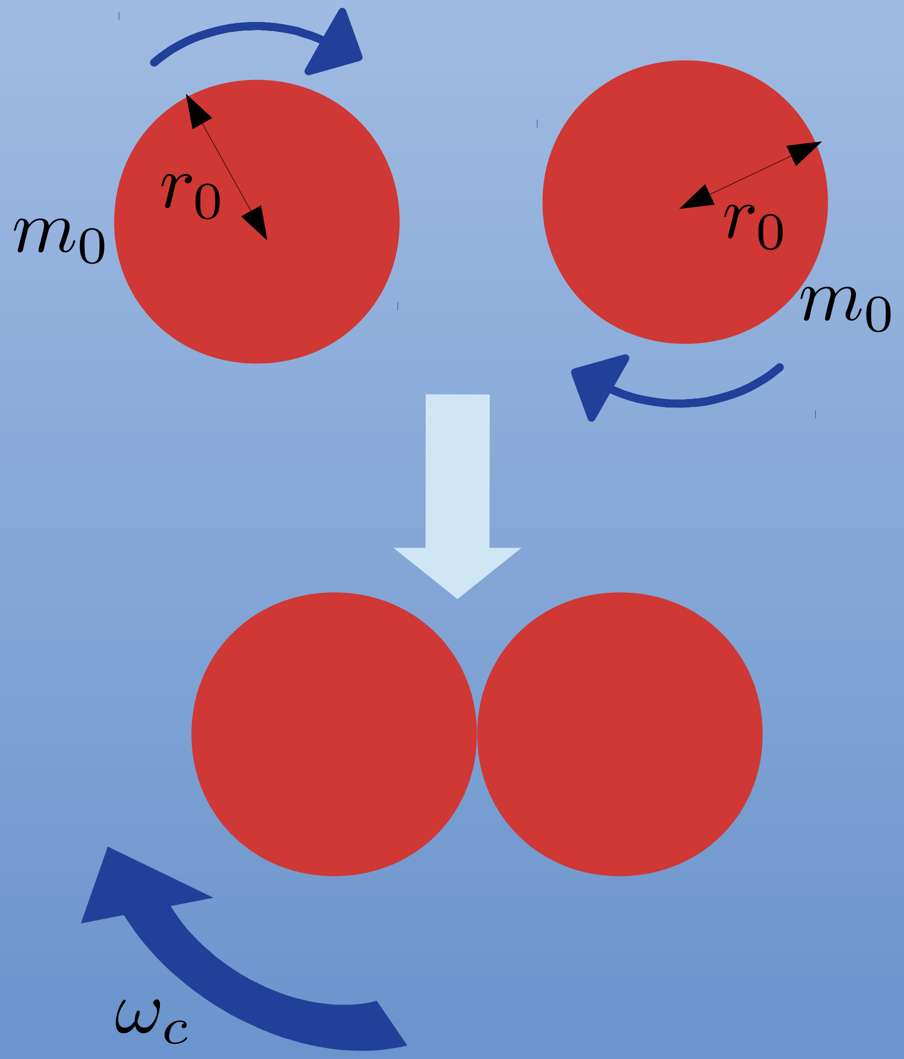


Equation of state: ALF2

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

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

Toy Model

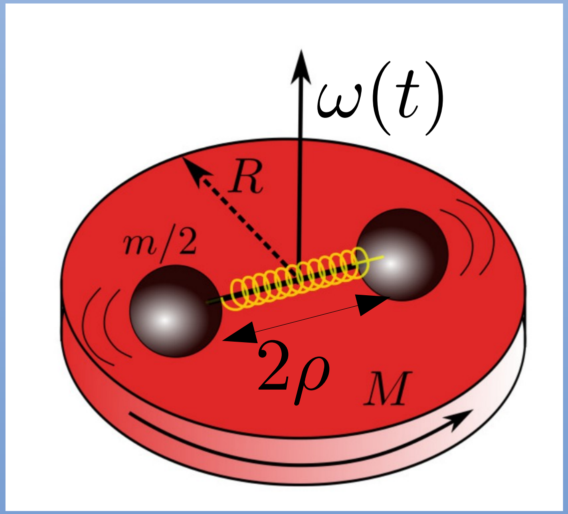


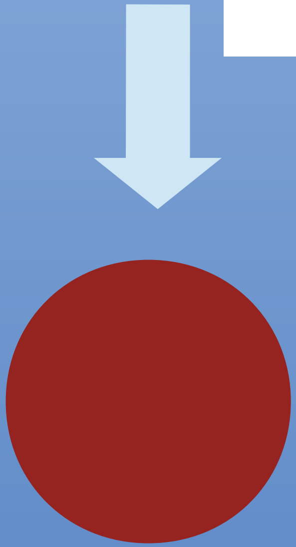
$$C_0 = \frac{m_0}{r_0}$$

$$a_0 = 0$$

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

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: $2\rho_0$

Softer $\xrightarrow{k,\ \rho_0}$ 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:

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

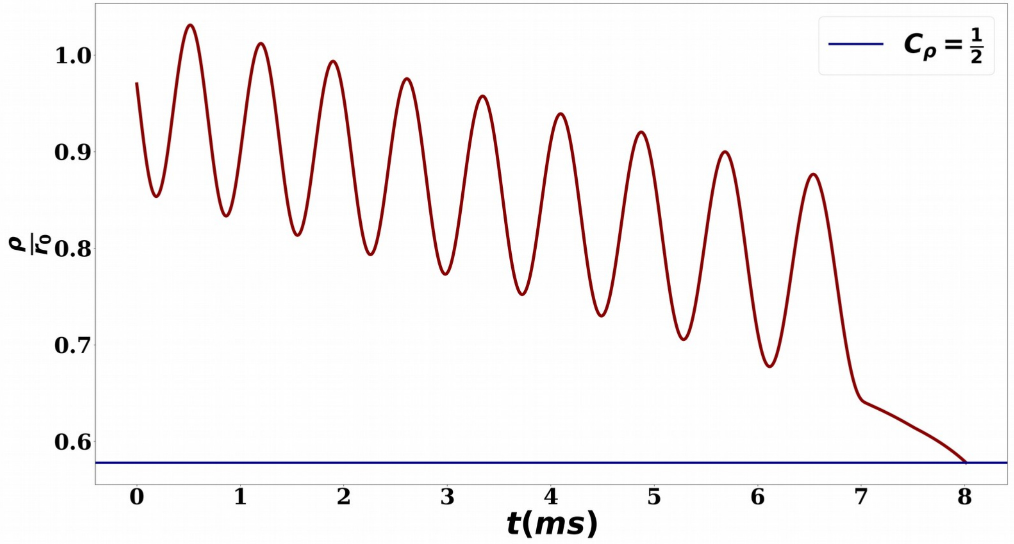
$$\dot{\varphi} = \omega = \frac{J}{I}$$

$$\left.\begin{aligned} \dot{E} &= - < P_{rad} > \\ \dot{J} &= - < J_{rad} > \end{aligned}\right\}$$

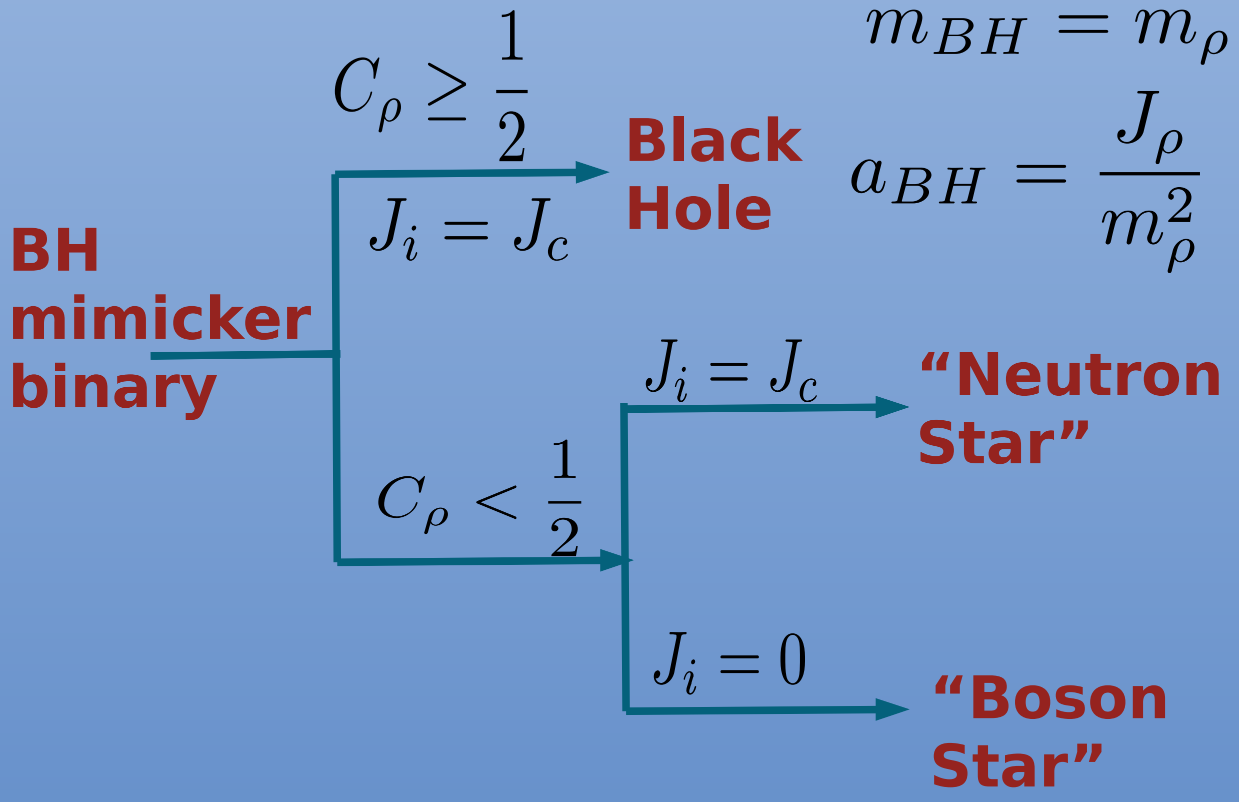
Computed with quadrupole formula assuming non perturbed equations of motion

End scenarios:

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



Evolution of the distance to the center in a case collapsing to a BH



BH mimicker binary

$C_\rho \geq \frac{1}{2}$

$J_i = J_c$

Black Hole

$m_{BH} = m_\rho$

$a_{BH} = \frac{J_\rho}{m_\rho^2}$

$C_\rho < \frac{1}{2}$

$J_i = J_c$

“Neutron Star”

$J_i = 0$

“Boson Star”

Full signal

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

Full signal

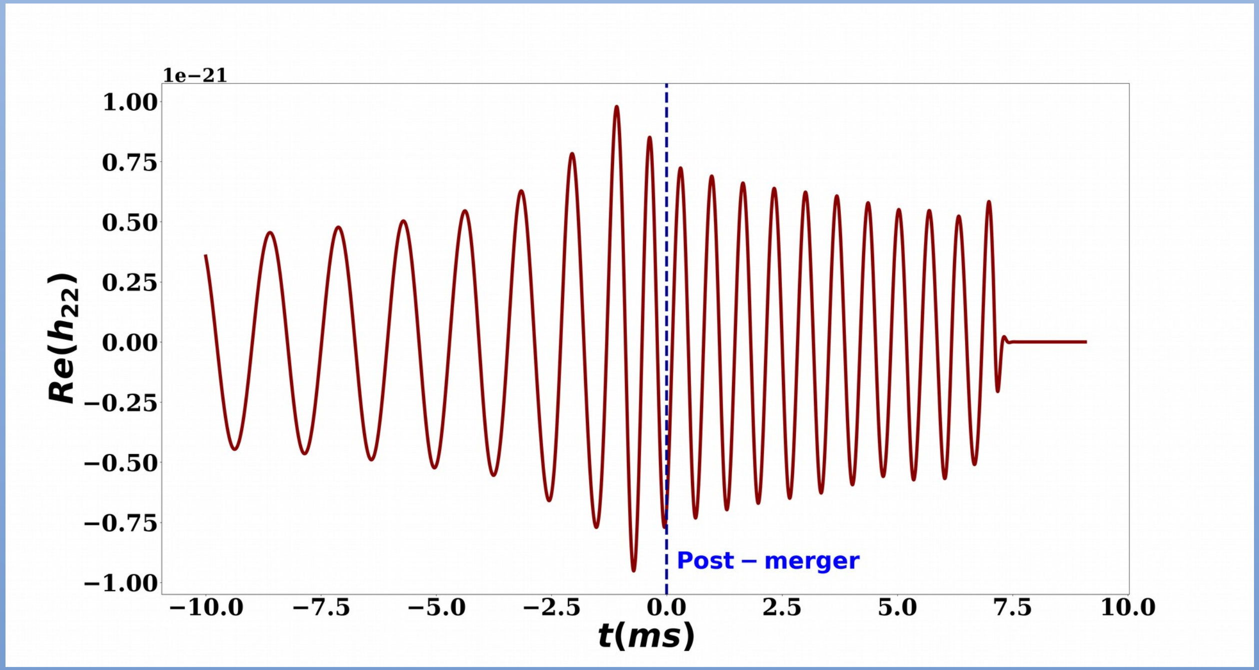
- Inspiral: IMRPhenomD_NRTidal until $f_{GW} = 2f_c$
- Matching in amplitude and phase for $\Delta t = \frac{1}{2}\frac{1}{f_c}$
- Toy model computed with quadrupole formula

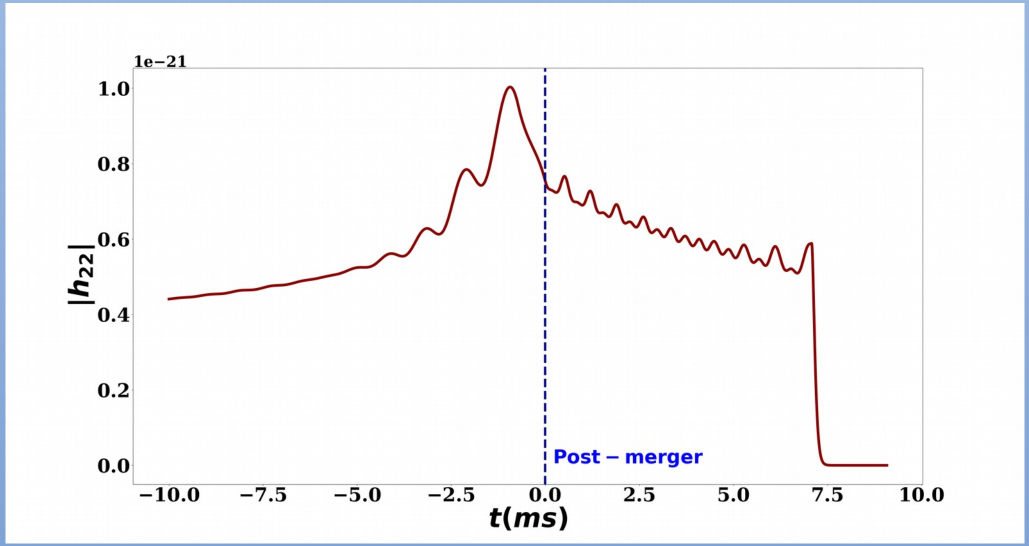
Full signal

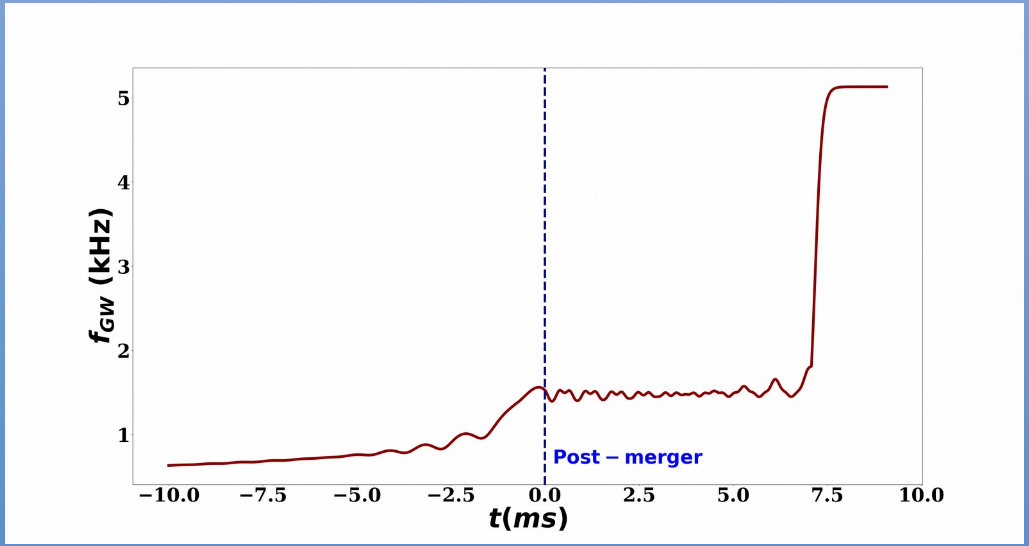
- Inspiral: IMRPhenomD_NRTidal until $f_{GW} = 2 f_c$
- Matching in amplitude and phase for $\Delta t = \frac{1}{2}\frac{1}{f_c}$
- Toy model computed with quadrupole formula
- If final state is BH, attach ringdown as

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

Full signal: collapse to a BH







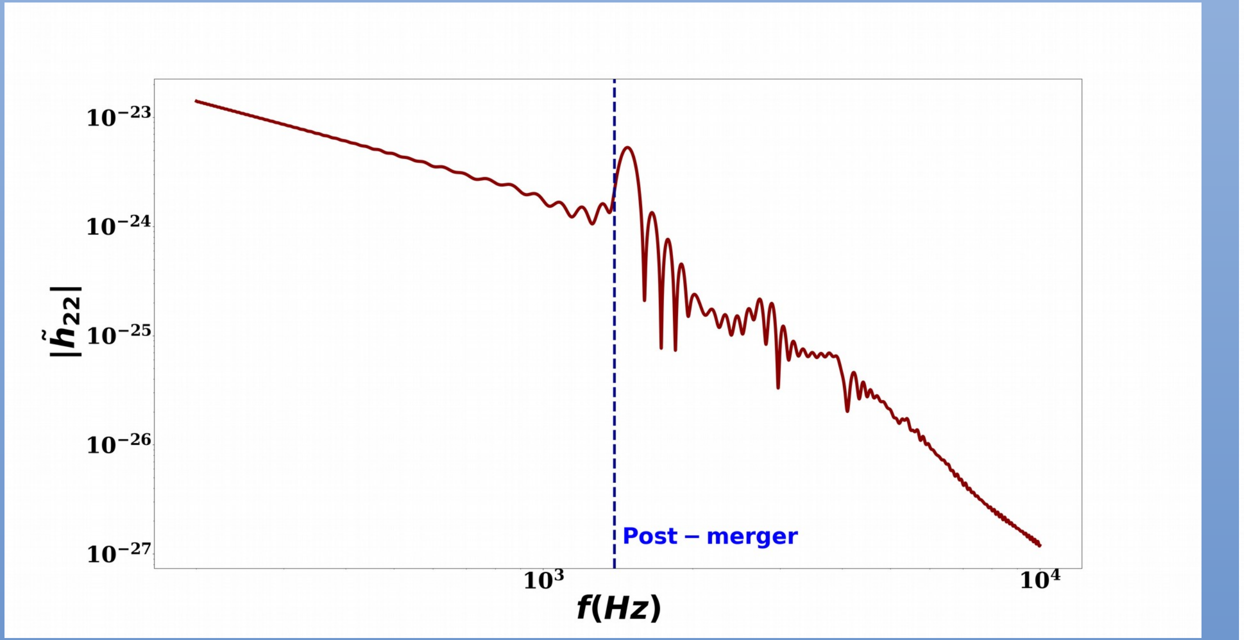
$$m_1 = m_2 = 1.35 M_\odot$$

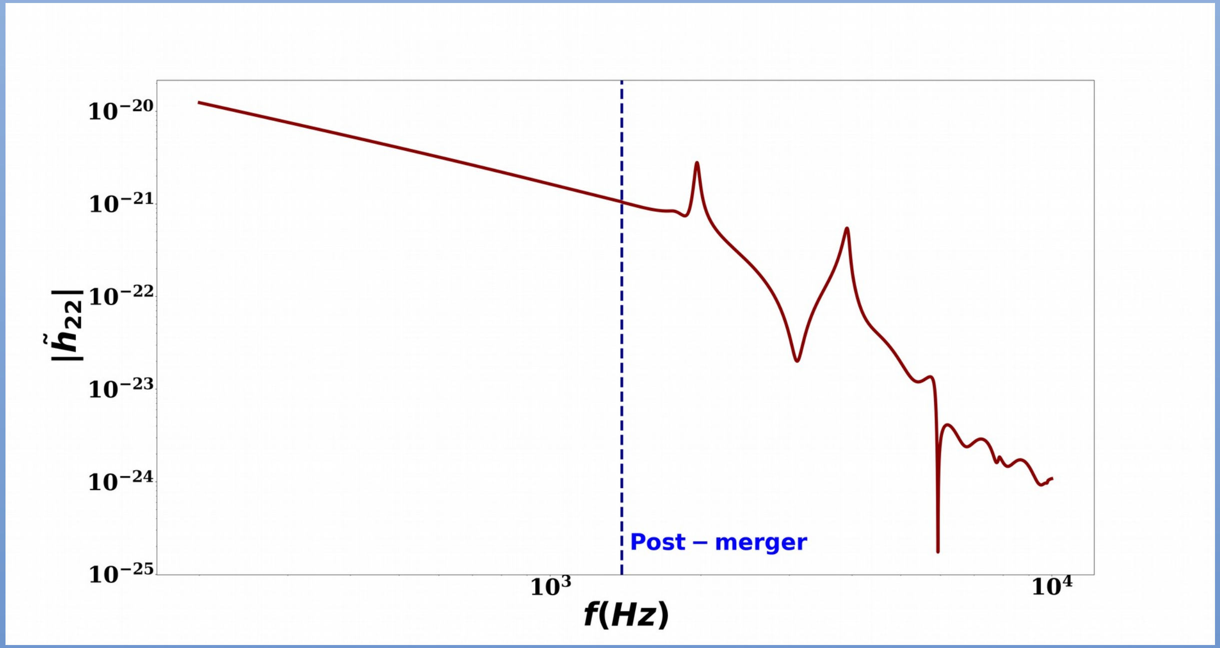
$$C_0 = 0.15$$

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

Frequency domain

$$m_1 = m_2 = 1.35 M_\odot \qquad C_0 = 0.15$$





Collapse to a BH

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

$$a_{BH} = 0.37$$

"Boson Star" $J_i = 0$

$$\omega_{car} = 1.95 \text{ kHz}$$

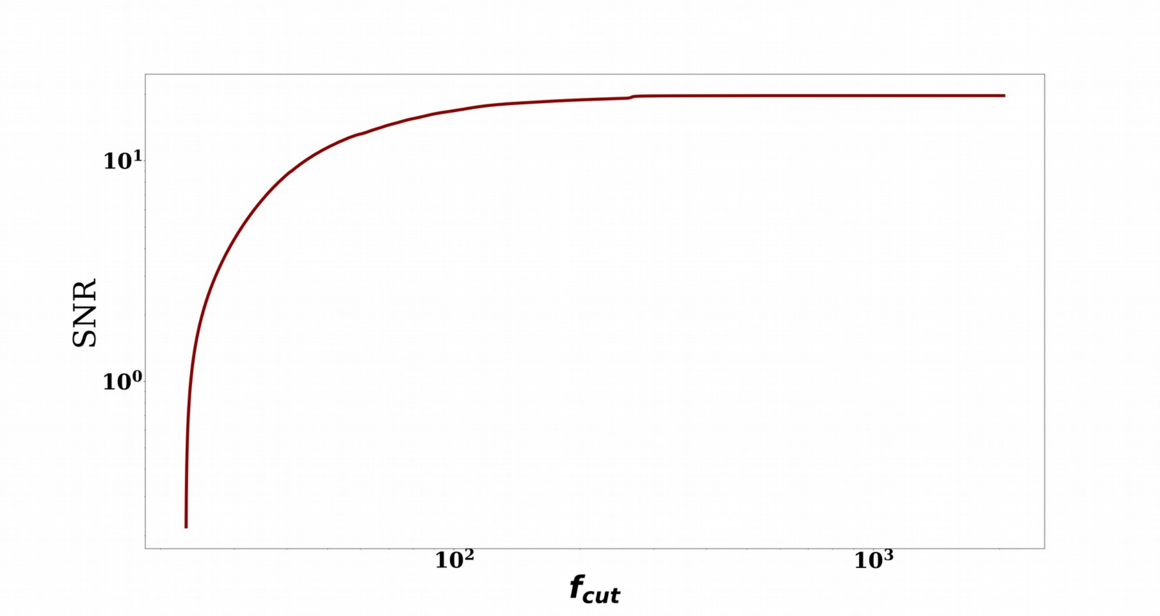
Data analysis

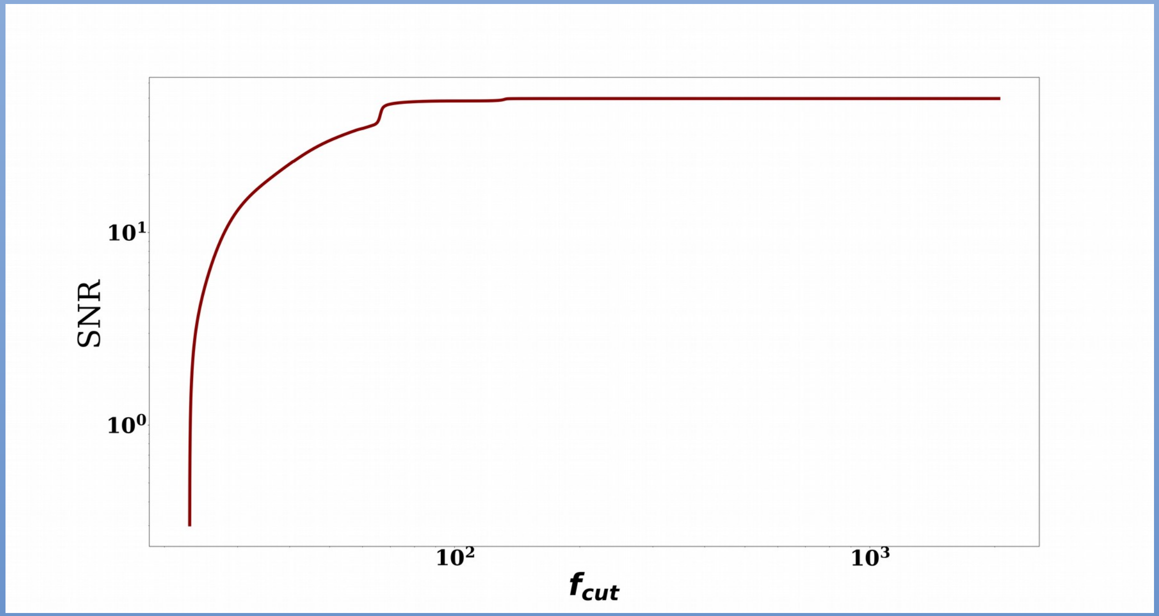
- Inner product: $(d|h) = 4\mathcal{R}\left(\int \frac{\tilde{d}(f)\tilde{h}^*(f)}{S_n(f)}\mathrm{d}f\right)$
- Signal to Noise Ratio (SNR): $\sqrt{(h|h)}$
- Is the post merger signal detectable?
- Is the signal distinguishable from a GR BH?

Impact on the SNR

Optimally oriented system, at 400 Mpc:

“Boson Star” in Advanced Ligo:





$$m_{tot} = 20M_\odot$$

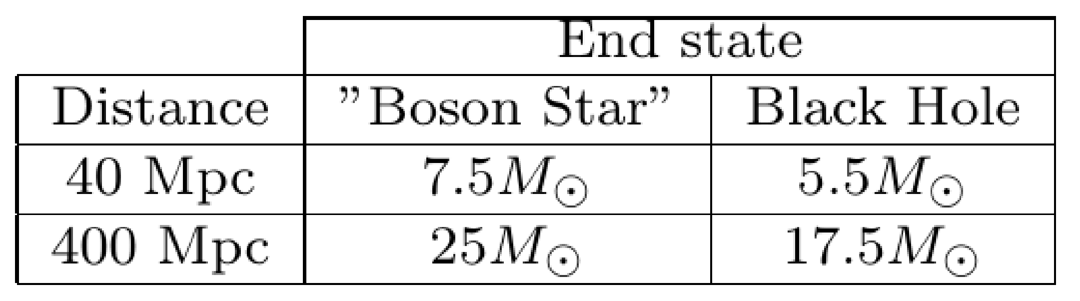
$$SNR_{pm} = 5.6 \qquad SNR_{tot} = 19.7$$

$$m_{tot} = 80M_\odot$$

$$SNR_{pm} = 38.3 \quad SNR_{tot} = 49.6$$

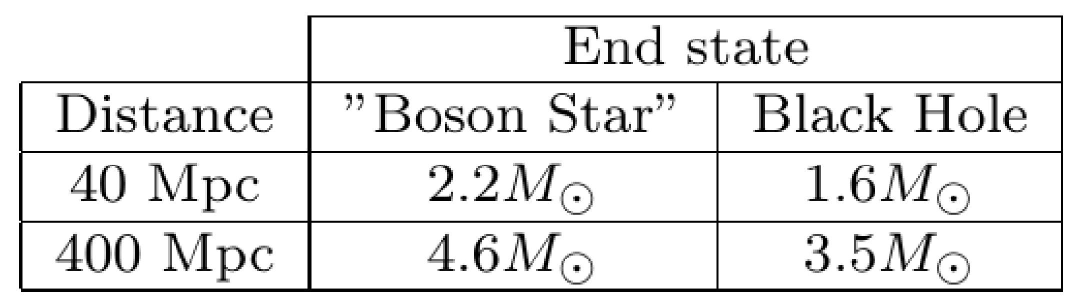
Detectability

- Threshold: $SNR_{pm} > 8$



	End state	
Distance	"Boson Star"	Black Hole
40 Mpc	$7.5 M_\odot$	$5.5 M_\odot$
400 Mpc	$25 M_\odot$	$17.5 M_\odot$

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



	End state	
Distance	"Boson Star"	Black Hole
40 Mpc	$2.2 M_\odot$	$1.6 M_\odot$
400 Mpc	$4.6 M_\odot$	$3.5 M_\odot$

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

Distinguishability

- Fitting factor: $FF = max_h \dfrac{(d|h)}{\sqrt{(d|d)(h|h)}}$ $d:$ 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"

$$FF = 0.84$$

$$m_1 = 29M_\odot \quad a_1 = -0.20$$
$$m_2 = 8M_\odot \quad a_2 = 0.26$$

$$FF = 0.77$$

$$m_1 = 30M_\odot \quad a_1 = -0.15$$
$$m_2 = 8M_\odot \quad a_2 = 0.22$$

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

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):

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

Numerical integration

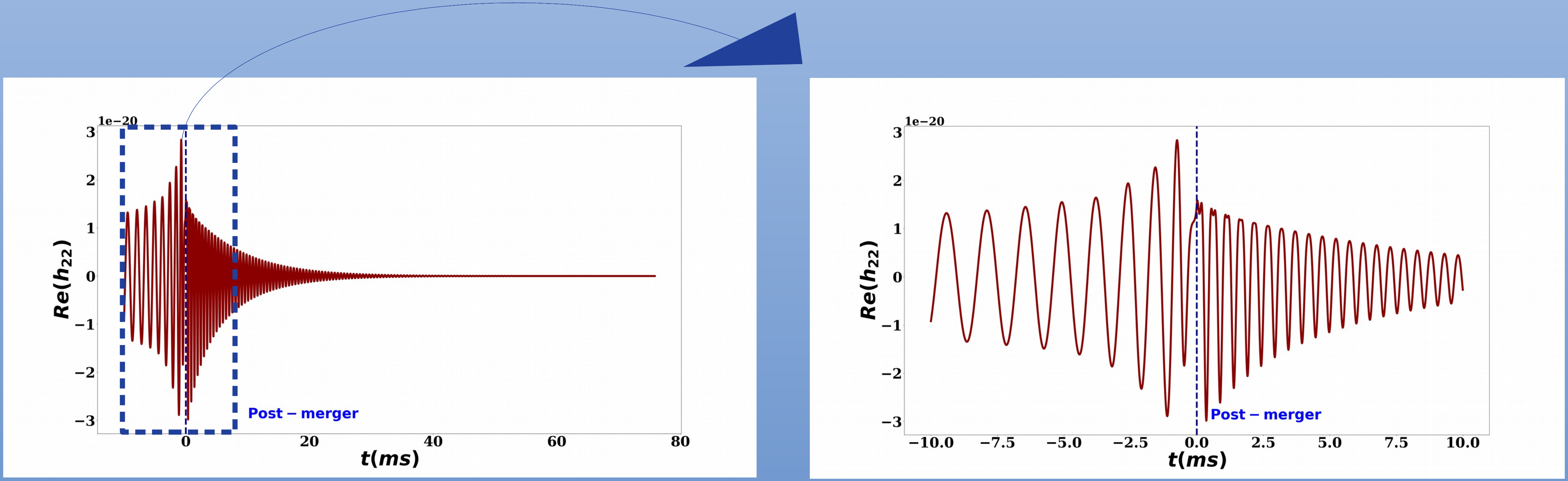
- Define: $\rho = \frac{p}{1 + e\cos(\chi)}$ $\qquad e = \frac{\rho_+ - \rho_-}{\rho_+ + \rho_-}$

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

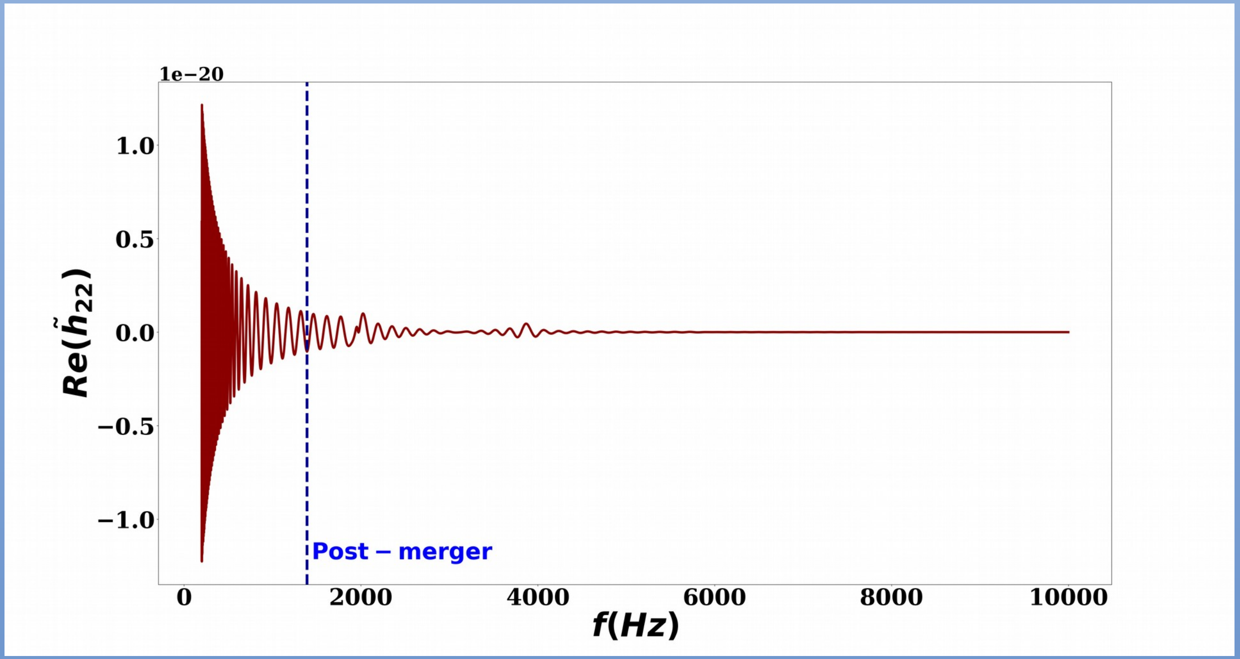
- $\rho_+,\ \rho_-,\ \rho_3,\ \rho_4,\ \rho_5$ are the roots of $E - V_{\text{eff}} = 0$

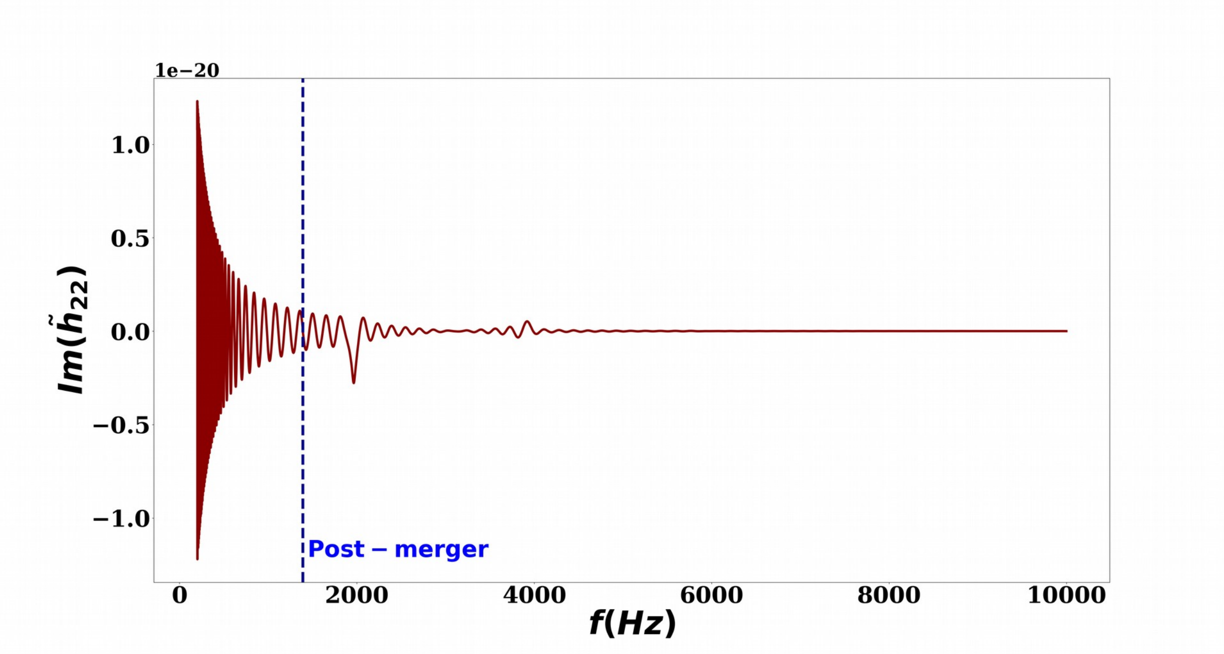
- So that: $\dot{\chi} = 2\sqrt{\frac{k}{m}}\frac{(1 + e\cos(\chi))}{\sqrt{1 - e^2}}\sqrt{\frac{(\rho - \rho_3)(\rho - \rho_4)(\rho - \rho_5)}{\rho(\frac{MR^2}{2m} + \rho^2)}}$

“Boson Star” waveform



“Boson Star” waveform (FD)





Black hole waveform (FD)