A REVIEW ON THE POST-MERGER GRAVITATIONAL WAVES EMITTED IN BINARY NEUTRON STAR MERGERS

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ABSTRACT

Gravitational waves from the inspiral stage of a binary neutron star merger give information about the nature of the initial masses, spins and tidal deformabilities. Similarly, observations of the post-merger stage would give hints on the characteristics and the evolution of the remnant of these coalescences. Since post-merger observations by Earth-based detectors are not available yet, only numerical simulations are used to study this stage. Therefore, we will review the main characteristics of this kind of mergers, as well as the results given by numerical simulations in order to better understand the different outcomes that are produced in these systems and how the final fate is related to the initial components.

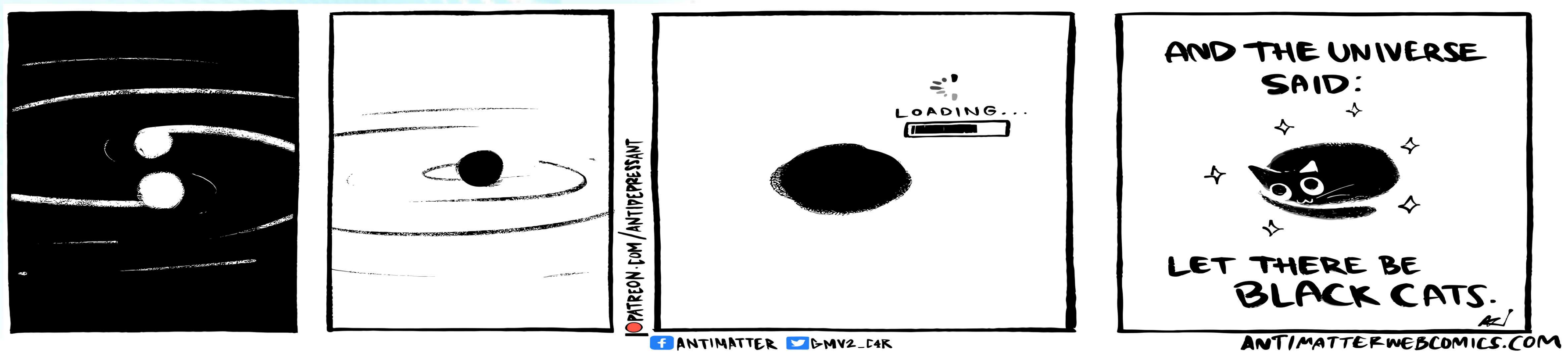
INSPIRAL STAGE

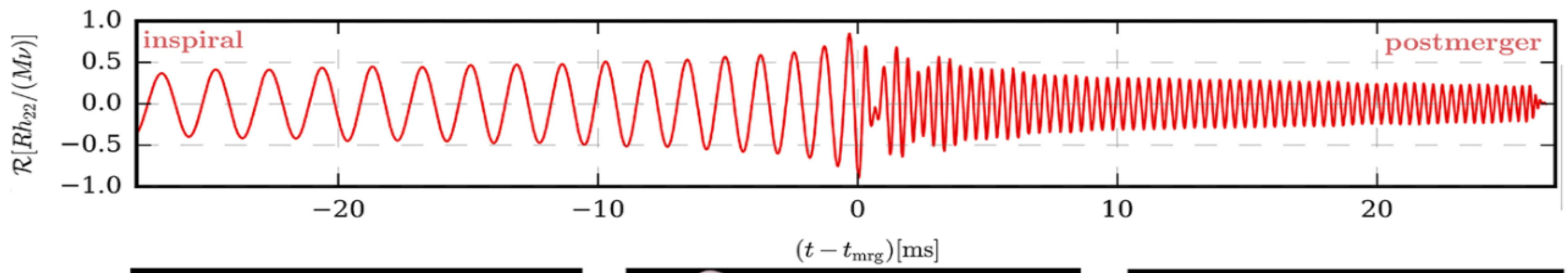
Neutron stars (NSs) are inspiraling around each other generating gravitational radiation with its amplitude and frequency increasing as the stars get closer and closer.

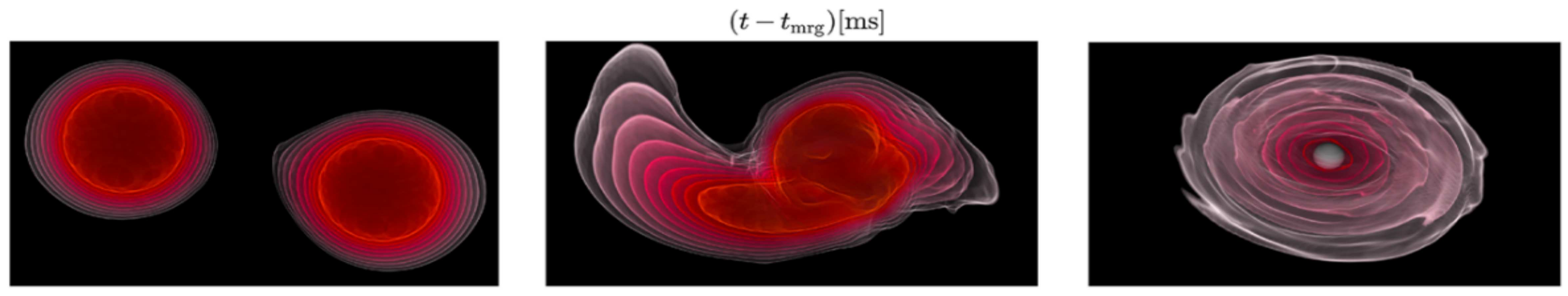
Since NSs are dense-matter compact objects, there are tidal effects due to the gravitational field of one star that deforms the other one, and viceversa. Also, since each star has an intrinsic rotation, there are matter effects that deform the original shape.

The inspiral frequencies are about 1 - 2 kHz, depending on the equation of state (EoS) that describes the state of matter under extreme conditions.

Measuring this stage provides information about each component, such as: mass, spin, tidal deformability, EoS, etc.







Credit: Dietrich et al., 2021

Post-Newtonian Approximations

Numerical Relativity

MERGER STAGE

The neutron stars begin to merge leading to the maximum amplitude for the gravitational wave and achieving frequencies around ~ 2 kHz.

Simulations need to solve full equations of general relativity -> Numerical Relativity is applied.

POST-MERGER STAGE

Once the neutron stars' cores have completely merged, the GW amplitude of the new and more massive object starts to decrease, but the frequency keeps increasing and its value depends on the nature of the formed remnant. Possible outcomes are:

*Black Hole (BH). Promptly formed if $M \gtrsim 3\,M_{Sun}$. Frequencies: ~ 5-7 kHz.

*Hypermassive Neutron Star (HMNS). A differentially rotating neutron star with frequencies around 2-4 kHz and mass $M > M_{max}$ ++.

*Supermassive Neutron Star (SMNS). A rigidly rotating neutron star with frequencies around 2-4 kHz and mass M_{TOV} + < M < M_{max} ++.

*Massive Neutron Star (MNS). More massive than its progenitors with frequencies around 2-4 kHz and mass M < M_{TOV} +.

Parameters

Chirp Mass

$$M_C = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

Tidal Deformability

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4}{M^5}\Lambda_1 + (1 \leftrightarrow 2), \quad \tilde{\Lambda}_i = \frac{2}{3}k_2^i\left(\frac{Gm_i}{r_i c^2}\right)^5$$

Total Mass

$$M = m_1 + m_2$$

Mass Ratio

$$q = \frac{m_1}{m_2}$$

Effective Spin

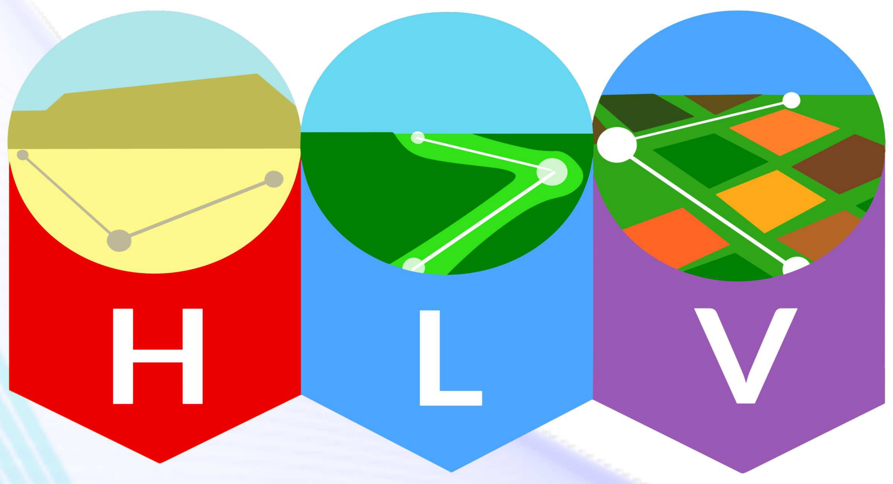
$$\chi_{\rm eff} = \frac{m_1\chi_{1z} + m_2\chi_{2z}}{M}, \quad \chi_i = \frac{c\mathbf{S}_i}{Gm_i^2}$$

Parameters

Numerical simulations show that the most robust parameter for the post-merger (PM) stage is in the frequency-domain. For example: the main peak frequency f_2. This, along with other sub-dominant frequencies describe the rotational state and the EoS of the remnant. Also, quasi-universal relations between inspiral and PM parameters have been proposed giving a hint to explore the nature of the merger product. e. g.

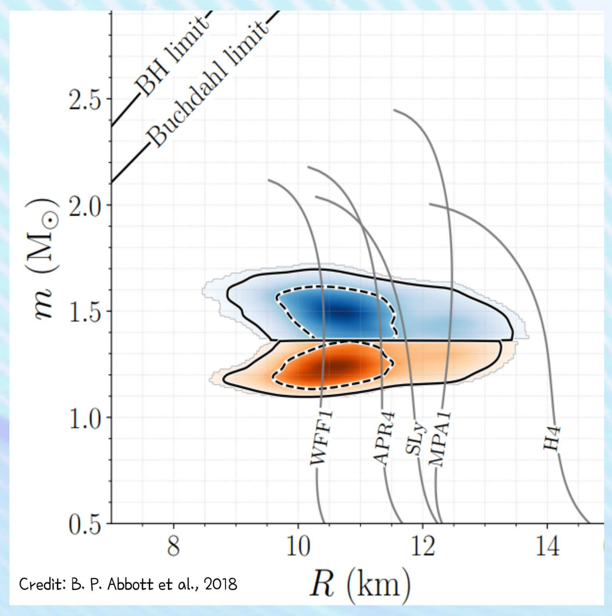
$$f = f(M, \tilde{\Lambda}), \quad Mf_2 = \beta\frac{1+A\zeta}{1+B\zeta}, \quad \zeta = \frac{3}{18}\tilde{\Lambda} - n\frac{M}{M_{\rm TOV}}$$

EARTH-BASED DETECTORS



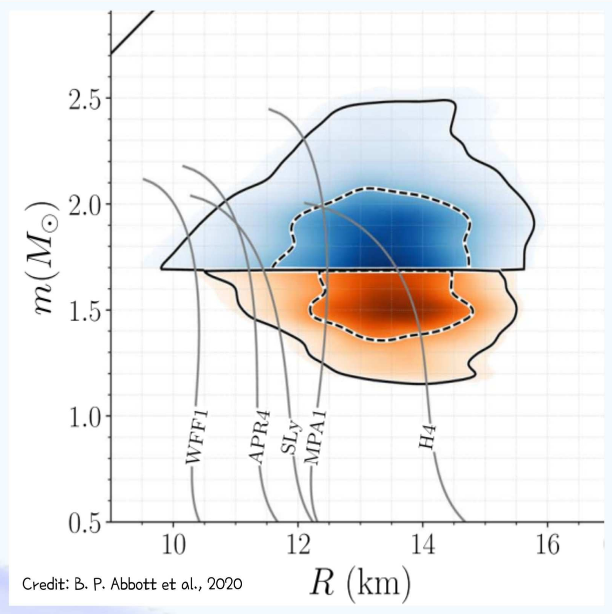
GW170817

Event	GW170817
$M_{\rm chirp}[M_\odot]$	$1.186^{+0.001}_{-0.001}$
q	$(0.73 - 1.00)$; $(0.53 - 1.00)*$
$m_1[M_\odot]$	1.5
$\Delta m_1[M_\odot]$	$(1.36 - 1.60)$; $(1.36 - 1.89)*$
$m_2\ [M_\odot]$	1.3
$\Delta m_2\ [M_\odot]$	$(1.16 - 1.36)$; $(1.00 - 1.36)*$
$M\ [M_\odot]$	$2.73^{+0.04}_{-0.01}$; $2.77^{+0.22}_{-0.05}*$
$\bar{\Lambda}$	300^{+500}_{-190}; $(0 - 630)*$
χ_1	$(0.00 - 0.04)$; $(0.00 - 0.50)*$
χ_2	$(0.00 - 0.04)$; $(0.00 - 0.61)*$
$\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$; $0.02^{+0.08}_{-0.02}*$
R [km]	< 13
EoS	WFF1, APR4, SLy, MPA1



Credit: B. P. Abbott et al., 2018

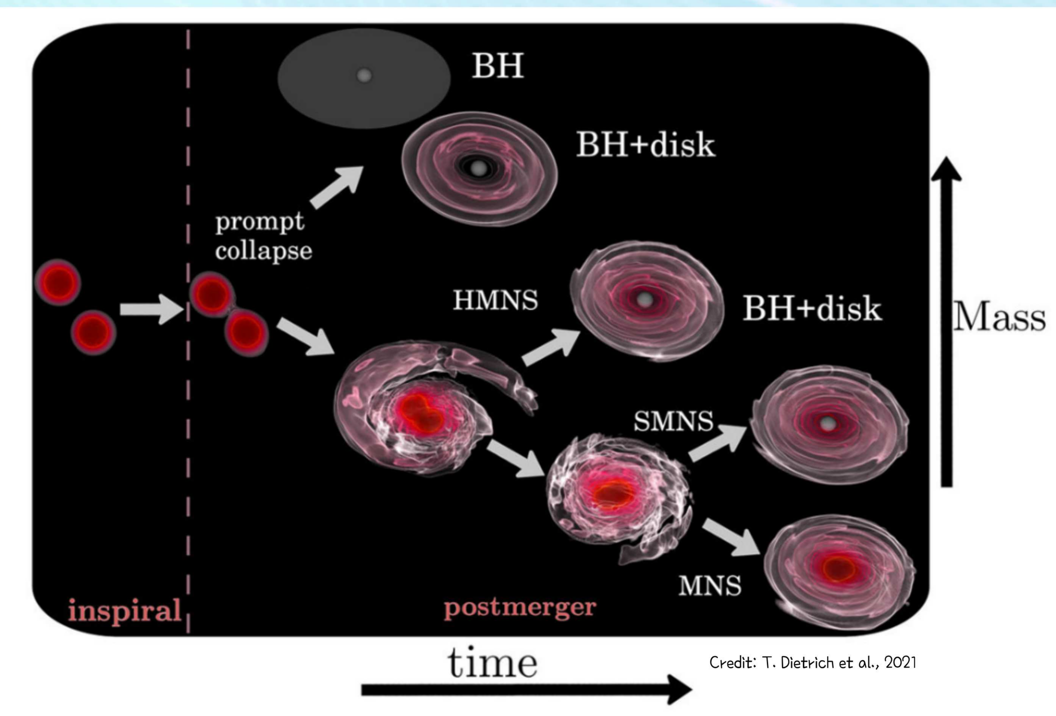
GW190425



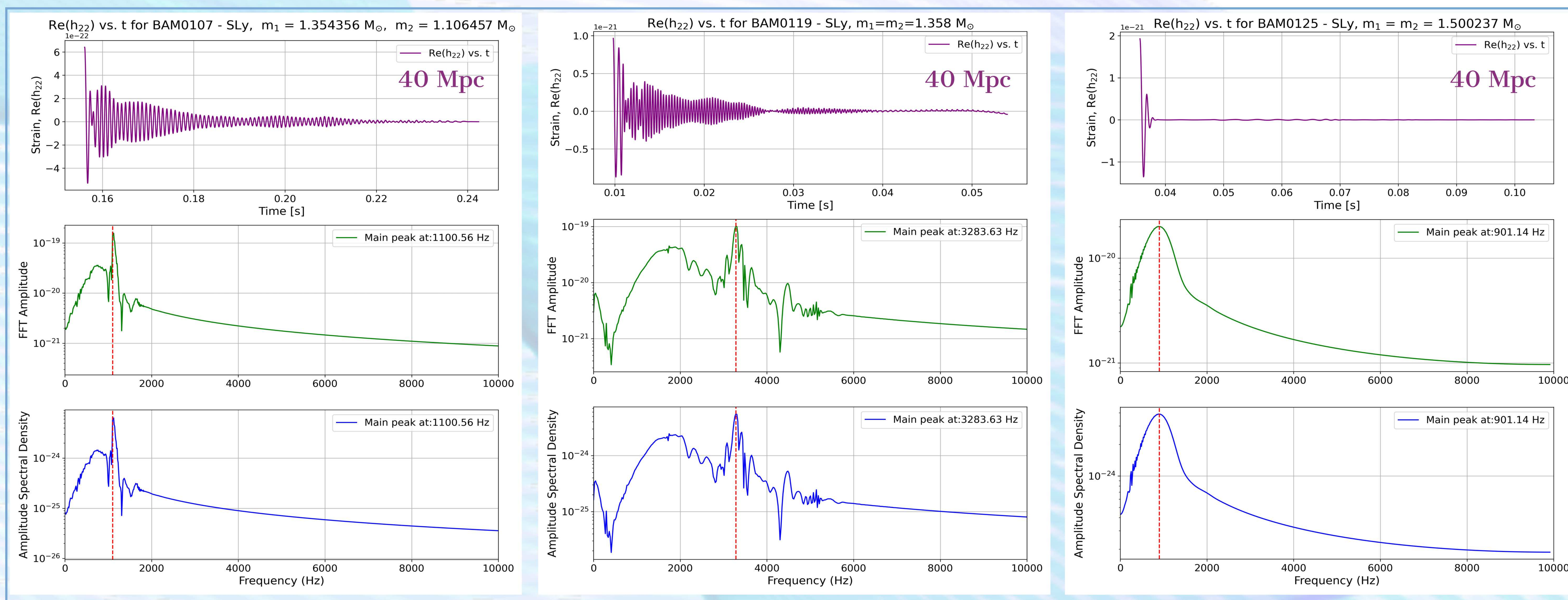
Credit: B. P. Abbott et al., 2020

Event	GW190425
$M_{\rm chirp}[M_\odot]$	$1.44^{+0.02}_{-0.02}$
q	$(0.8 - 1.0)$; $(0.4 - 1.0)*$
$m_1[M_\odot]$	2.0
$\Delta m_1[M_\odot]$	$(1.60 - 1.87)$; $(1.61 - 2.52)*$
$m_2\ [M_\odot]$	1.4
$\Delta m_2\ [M_\odot]$	$(1.46 - 1.69)$; $(1.12 - 1.68)*$
$M\ [M_\odot]$	$3.3^{+0.1}_{-0.1}$; $3.4^{+0.3}_{-0.1}*$
$\bar{\Lambda}$	≤ 600; $\leq 1100*$
χ_1	0.012
χ_2	0.058
$\chi_{\rm eff}$	$0.012^{+0.01}_{-0.01}$; $0.058^{+0.11}_{-0.05}*$
R [km]	< 15
EoS	H4, MPA1, SLy, APR4

WHAT ABOUT THE OUTCOME?



Credit: T. Dietrich et al., 2021



PM time and frequency domains for simulations from CoRe Database. Assumed distance: 40 Mpc. They have the same EoS: SLy

BAM0107: M = 2.46 M_{Sun}, no spin.

BAM0119: M = 2.72 M_{Sun}, non zero spin.

BAM0125: M = 3.00 M_{Sun}, no spin.

++ $M_{max} \lesssim 1.20^{+0.02}_{-0.05}\, M_{TOV}$

+ $2.01^{+0.04}_{-0.04} \lesssim M_{TOV}/M_{Sun} \lesssim 2.16^{+0.17}_{-0.15}$

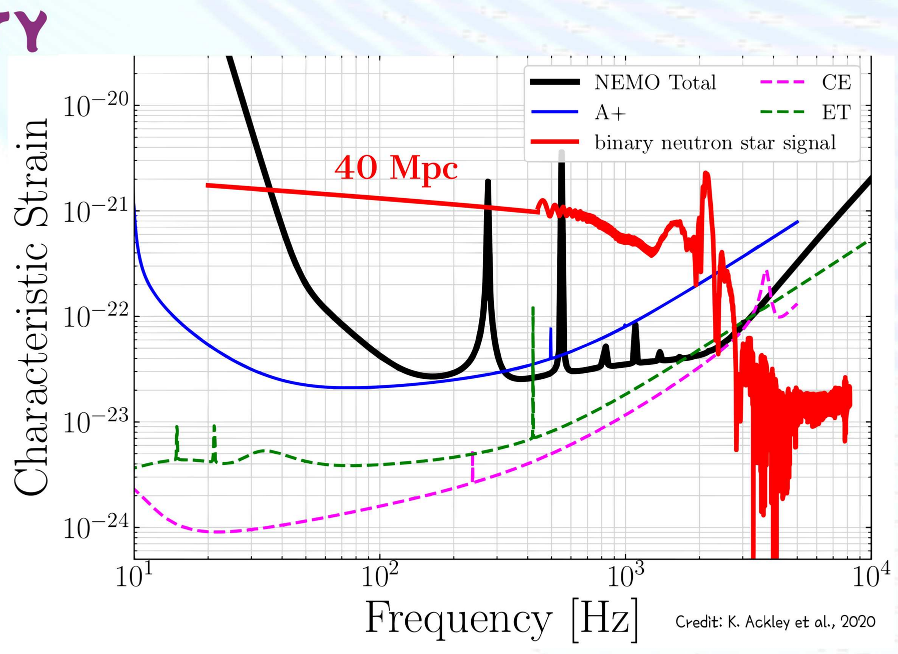
DETECTOR SENSITIVITY

Cosmic Explorer (CE)

Einstein Telescope (ET)

HIGH KBAND DETECTORS

Neutron-star Extreme Matter Observatory (NEMO)



Credit: K. Ackley et al., 2020

TAKE AWAY

*Binary neutron star stages: Inspiral, Merger, Post-Merger.
*Inspiral parameters: masses, spins, tidal deformabilities -> radii & EoS.
frequency band: up to 1 - 2 kHz.
LVKI detector band.
*Post-merger parameters: main frequency and sub-dominant frequencies.
frequency band: 2 - 4 kHz (HMNS, SMNS, MNS).
5 - 7 kHz (BH, BH + disk).
Future detectors: CE, ET, NEMO.
*BNS outcomes: Hypermassive Neutron Star, Supermassive Neutron Star, Massive Neutron Star, Prompt collapse Black Hole.

References