Quasi-universal relations of gravitational wave signal from binary neutron star mergers

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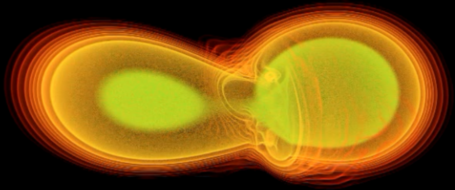

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Motivation:

- easily identifiable frequencies in the GW signal strongly correlate with
  - total mass of the system M_{tot},
  - mass ratio of the components q,
  - EOS-specific quantites, e.g. tidal deformability $\kappa_2^T = \kappa_2^T(\text{EOS})$

Here:

- propose new, accurate universal relations for these frequencies
- investigate the subdominant $m = 1$ mode and its secular growth
- report findings consistent across 3 codes and 3 initial data solvers

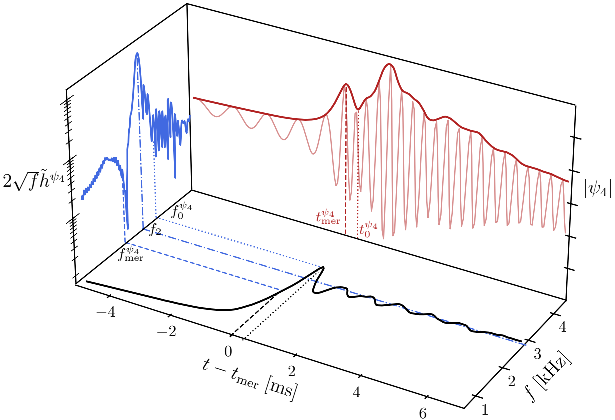
Used data

- waveforms from GU group[1 2], and others[3] (CoRe database)
- in total, ~ 120 simulations in GRHD (no B field, $s_1 = s_2 = 0, e < 0.01$)
- 12 EOS, some including a strong 1-st order PT and deconfined quark phase
- $M_{\rm tot} \in [2.4, 3.33] M_\odot$, $q \in [0.485, 1.0]$, $\kappa_2^T \in [33, 458]$

[1] Tootle et al.; Astrophys.J.Lett. **922** (2021) 1, L19
[2] Tootle et al.; SciPost Phys. **13** (2022) 109
[3] Gonzalez et al.; 2022, Class.Quant.Grav. **40** (2023) 8, 085011

Waveform - amplitude, frequency, spectral density

ELEMENTS



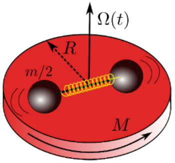


Figure: *

Takami et al.; Phys.Rev.D **91**, 064001 (2015)

Three characteristic frequencies identifiable:

- merger frequency $f_{\rm mer}$
- quenched-quadrupole moment frequency f_0
- long-lived post-merger frequency f_2

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Parametrizing the dependence

Relation between

$$(f_{\text{mer}}, f_0, f_2) \longleftrightarrow (M_{\text{tot}}, q, \kappa_2^T)\ ?$$

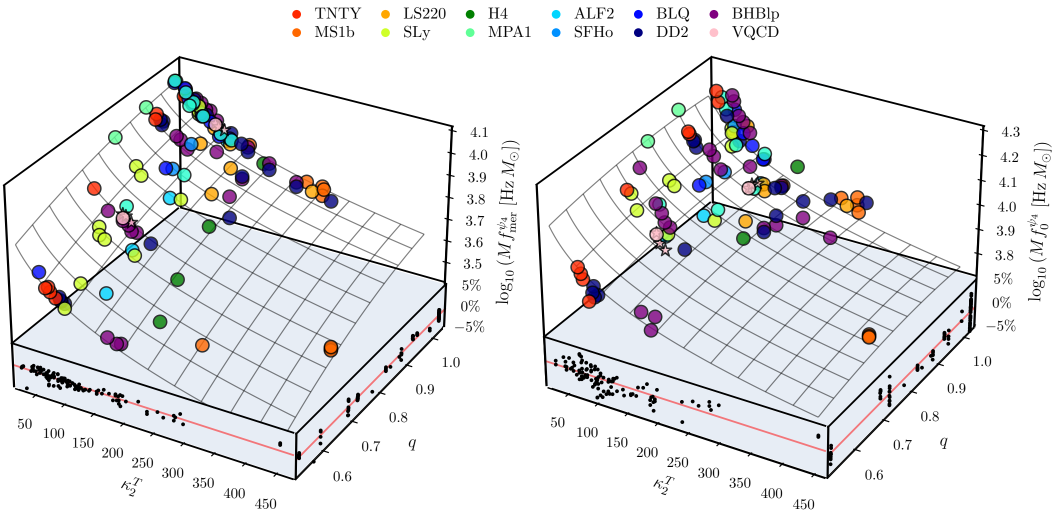
Augment previous Ansatz [4] [5] with mass ratio corrections:

$$\log_{10}\left[\frac{M_{\text{tot}}}{M_\odot}\frac{f}{\text{Hz}}\right] = a_0 + (b_0 + b_1 q + b_2 q^2)(\kappa_2^T)^n$$

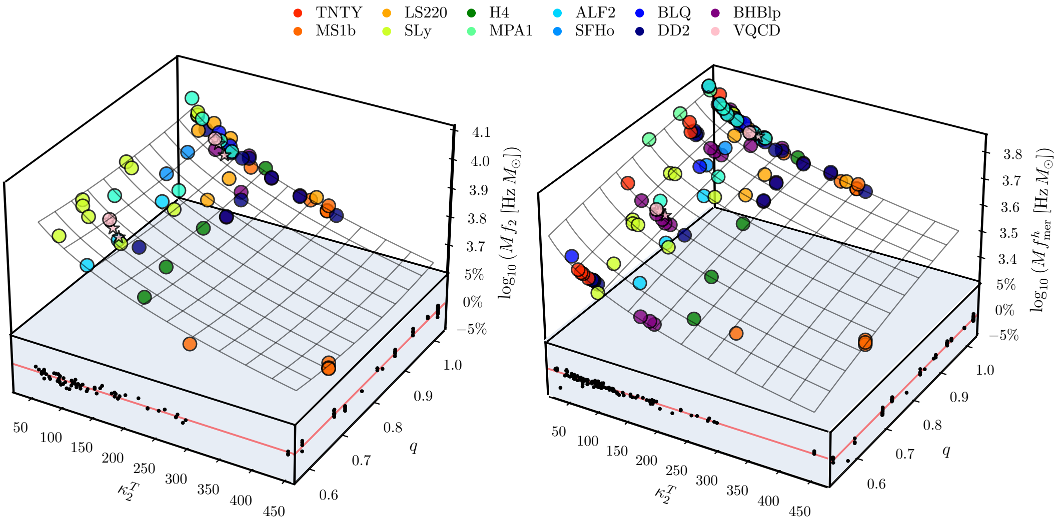
5 parameters a_0, b_0, b_1, b_2, n sufficient, previous Ansatz had 3.

[4] Rezzolla, Takami; Phys.Rev.D **93**, 124051 (2016)
[5] Read et al.; Phys. Rev. D **88**, 044042 (2013)

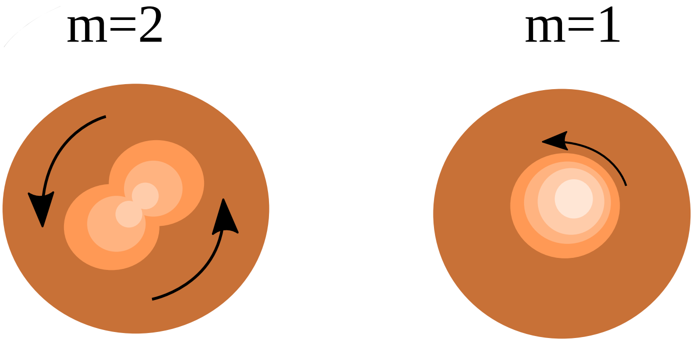
Result of the fits



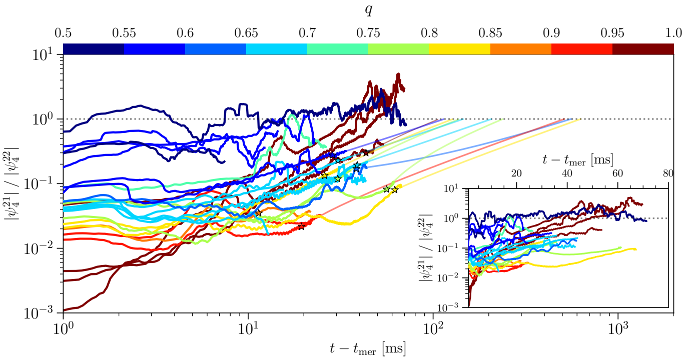
Result of the fits



Modes of radiation



Secular growth of the subdominant mode



- contribution of the $m = 1$ mode to the overall strength of the signal is generic
- initial (~ 10 ms) contribution dependent on mass asymmetry
- secular growth of the $m = 1$ mode, might dominate as early as $\sim 20 - 50$ ms
- dominant $m = 1$ frequency is $\sim \frac{1}{2} f_2$

Potential uses

Accurate universal relations on large datasets can be useful for:

- informing the phase part of the waveform models;
  $(M_{\rm tot}, q, {\rm EOS}) \to ({\rm f_{mer}}, {\rm f_0}, {\rm f_2}) \to {\rm f_{GW}}(t)$
- identifying universality-breaking physics (HQ PT, new DOF, etc.)
- inference of the underlying EOS and/or parameters of binary

Dominance of the subdominant mode long-term:

- potential for detection by present detectors with high SNR or by 3G detectors
- might couple to post-merger differently from $m = 2$ mode (viscosity, phase transitions)

Conclusion

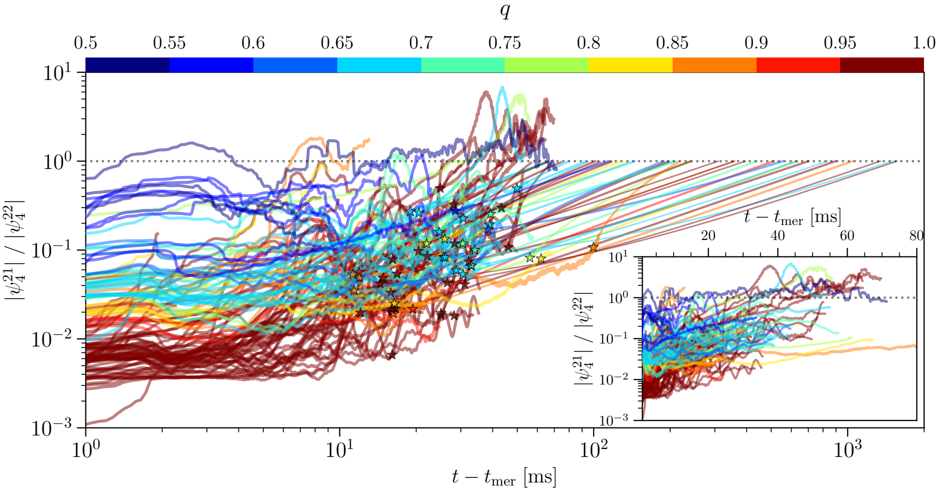
In summary:

- suggest new functional relations for the merger and post-merger frequencies

$$\log_{10}\left[\frac{M_{\text{tot}}}{M_\odot}\frac{f}{\text{Hz}}\right] = a_0 + (b_0 + b_1 q + b_2 q^2)(\kappa_2^T)^n$$

  which use a smaller number of parameters and are more accurate
- identify a new frequency f_0 and explain its origin using a toy model
- confirm the secular growth of the $m = 1$ mode for generic binaries

Secular growth - all datasets



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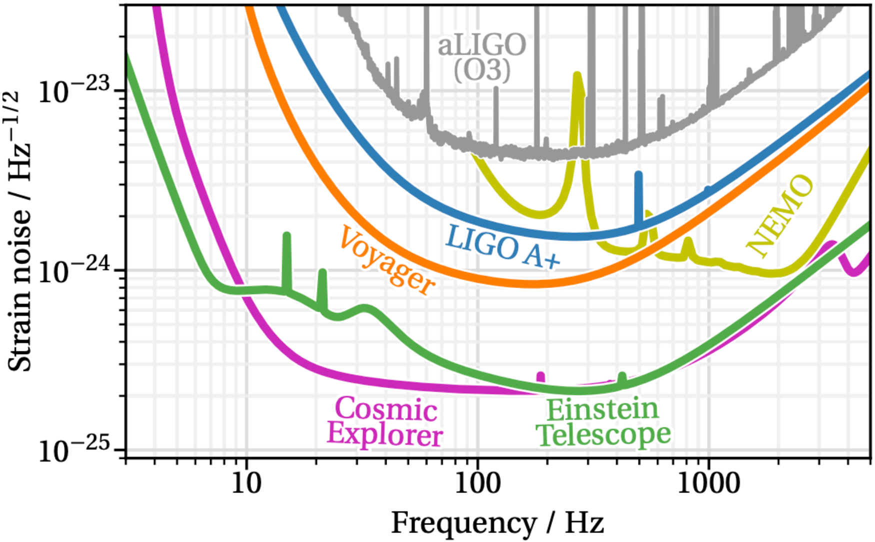
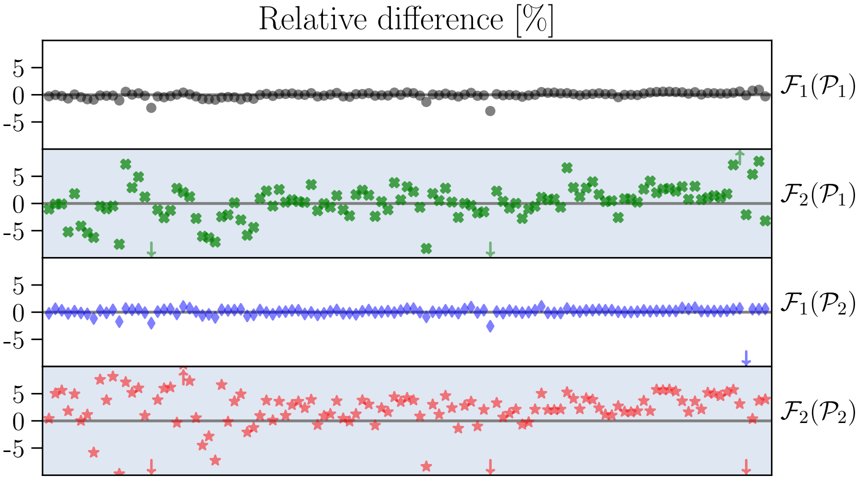
Detector sensitivity



Comparing the fits



Quantifying the equation of state dependence

Tidal forces acting on a companion star impact the GW frequency. To lowest order, this influence is related to:

$$k_2 = \frac{Q_{ij}}{\mathcal{E}_{ij}} \qquad \left(\frac{\text{response}}{\text{tidal field}}\right)$$

We then define $\Lambda = \frac{2}{3}\frac{k_2}{\mathscr{C}^5}$, with $\mathscr{C} = \frac{M_{ADM}}{R}$. Finally, we parametrize the joint interaction with:

$$\kappa_2^T = \frac{M_1 M_2}{M^2}\left[\left(\frac{M_1}{M}\right)^3 \Lambda_1 + \left(\frac{M_2}{M}\right)^3 \Lambda_2\right] = \kappa_2^T(M_{\text{total}}, q, \text{EOS})$$

By invoking *quasi-universality*, we mean that we can construct fits for the frequencies that involve κ_2^T, but that it does not matter which EOS this κ_2^T comes from originally (degeneracy).

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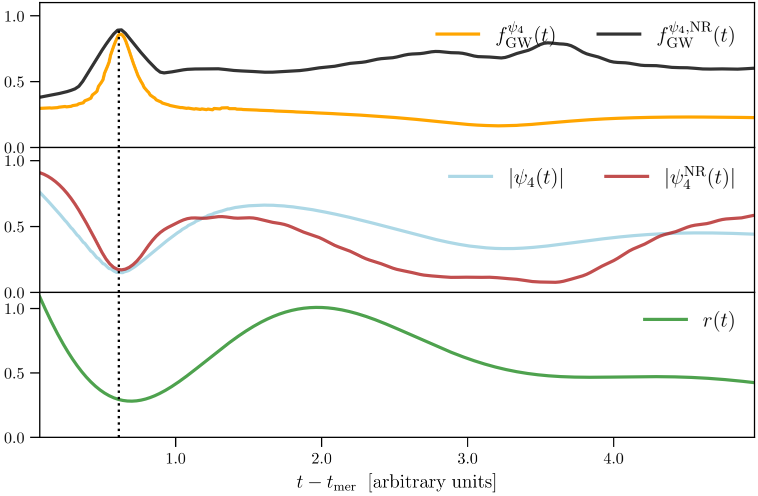
Toy model for the f_0 frequency



- with tuning of the intial paramteres, the f_0 frequency can be mimicked

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Fit parameters

Freq.	a_0	b_0	b_1	b_2	n	$\langle \Delta f/f \rangle$ [%]	$\max(\Delta f/f)$ [%]	χ^2	$\chi^2_{\rm red}$ $\times 10^{-3}$	R^2
$f^{\psi_4}_{\rm mer}$	4.589	−0.581	0.543	−0.236	0.20	0.65	4.52	0.135	1.19	0.934
$f^{h}_{\rm mer}$	4.201	−0.330	0.198	−0.067	0.20	0.32	2.99	0.035	0.30	0.957
$f^{\psi_4}_{\rm mer}$	6.067	−2.142	0.970	−0.410	$0.07^\dagger$	0.59	4.24	0.114	1.00	0.938
$f^{h}_{\rm mer}$	4.457	−0.578	0.262	−0.087	$0.14^\dagger$	0.32	2.94	0.034	0.30	0.957
$f^{\psi_4}_{0}$	6.550	−2.099	0.518	−0.304	$0.06^\dagger$	1.38	4.22	0.477	4.92	0.611
f_2	4.617	−0.170	−0.264	0.160	$0.20^\dagger$	0.45	1.34	0.030	0.48	0.926

Table 1. Best-fit values for the coefficients of the functional form $\mathcal{F}_1$. Also reported are the maximal and average relative difference, as well as the χ^2, $\chi^2_{\rm red}$ and R^2 coefficients of the fit. Indicated with a † are the best-fit values of n when this coefficient is constrained by the fit.