Modeling the postmerger gravitational wave signal and extracting binary properties from future binary neutron star detections

Phys.Rev. D100 (2019) no.4, 044047, arXiv:1907.02424

Ka Wa Tsang
T. Dietrich, C. Van Den Broeck

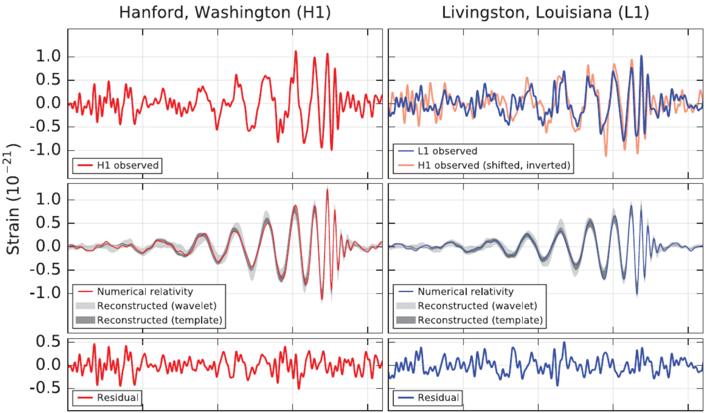
National Institute for Subatomic Physics (Nikhef)

NNV, 2019 Nov 01

Utrecht University

What is postmerger? (BBH)

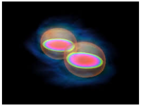
Binary Black Holes (BBH) coalescence:
Inspiral-Merger-Ringdown (IMR), e.g., GW150914

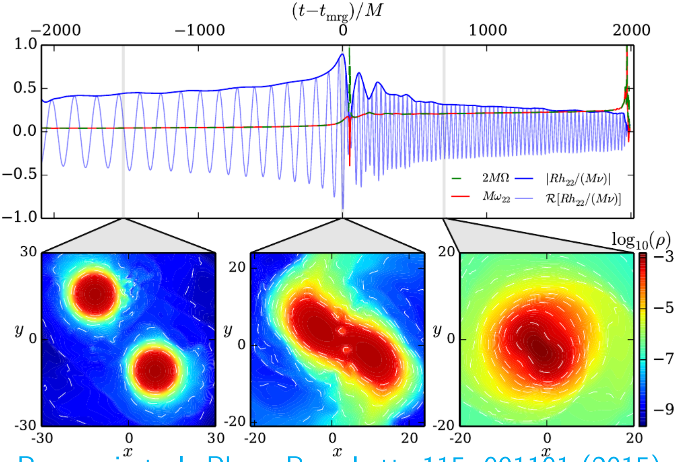


LVC Phys. Rev. Lett. 116, 061102 (2016)

What is postmerger? (BNS)

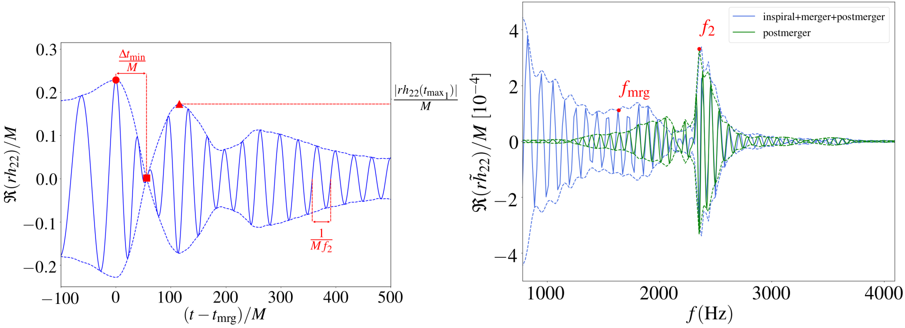
Binary Neutron Stars (BNS) coalescence:
Inspiral-Merger-Postmerger (IMP)





Bernuzzi et al. Phys. Rev. Lett. 115, 091101 (2015)

General morphology



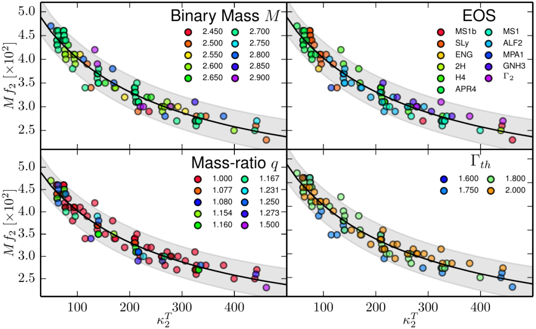
A typical postmerger signal (THC:0021)

- Non-monotonic amplitude and frequency evolution
- After merger, the amplitude decreases showing a clear minimum
- After this minimum, the amplitude grows to reach a maximum
- The postmerger emission becomes steady with a dominant emission frequency f_2

Motivation

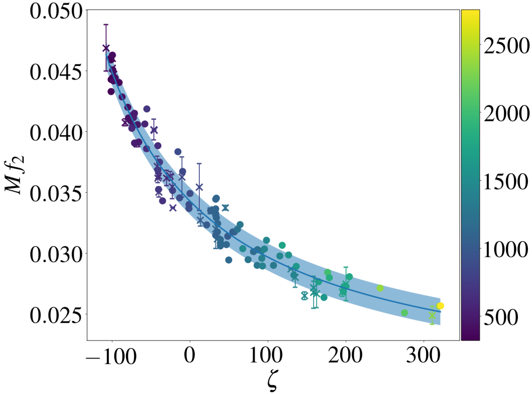
Two ways to extract the equation of state (EOS) information of a neutron star from a GW detection.

1. Inspiral
   - Waveform approximant that include tidal effects (characterized by κ_2^T, $\kappa_{\text{eff}}^T = \frac{3}{16}\tilde{\Lambda}$)
2. Postmerger
   - Measure the dominant emission frequency f_2



Bernuzzi et al. Phys. Rev. Lett. 115, 091101 (2015)

Quasi-universal relations in frequency domain (Mf_2)



$$Mf_2 = \alpha \frac{1 + \beta\zeta}{1 + \gamma\zeta}$$

where $\zeta = \kappa^{\mathrm{T}}_{\mathrm{eff}} + a\frac{M}{M_{\mathrm{TOV}}}$,

$a = -131.7010$,

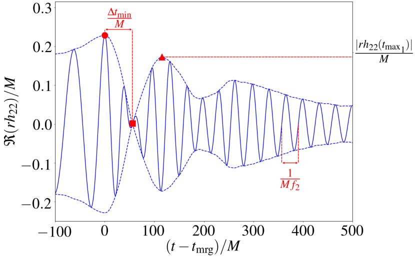
$\alpha = 3.4285 \times 10^{-2}$,

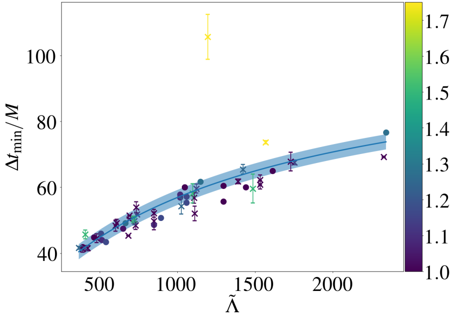
$\beta = 2.0796 \times 10^{-3}$,

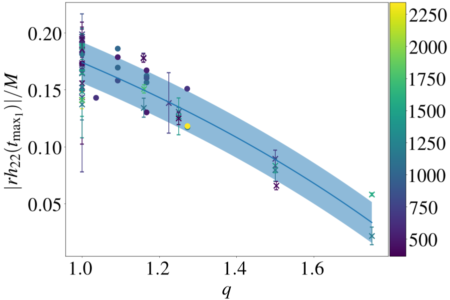
$\gamma = 3.9588 \times 10^{-3}$

- Data points used: 99 $\rightarrow$ 121
- Mf_2 decreases with ζ, colorbar shows the $\tilde{\Lambda}$
- M_{TOV} is the maximum allowed mass of a non-rotating neutron star.
- M/M_{TOV} encodes how close the remnant is to black hole formation
- M/M_{TOV} reduces the root-mean-square error by $\approx$ 28%

Quasi-universal relations in time domain



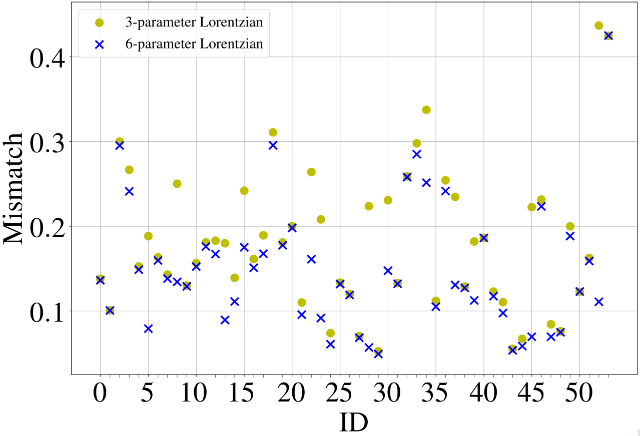




Model functions and f_2 measurement

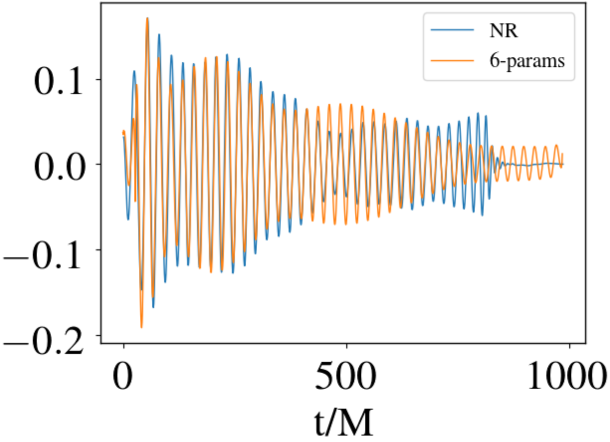
3- (6-) parameter Lorentzian can model the postmerger with an average mismatch of 0.18 (0.15).

$$\tilde{h}_{22}(f) = \frac{c_0 \ c_2}{\sqrt{(f-c_1)^2 + c_2^2}} e^{-i \arctan\left(\frac{f-c_1}{c_2}\right)}; \ \tilde{h}_{22}(f) = \frac{c_0 \ c_2}{\sqrt{(f-c_1)^2 + c_2^2}} e^{-ic_3 \arctan\left(\frac{f-c_5}{c_4}\right)}$$



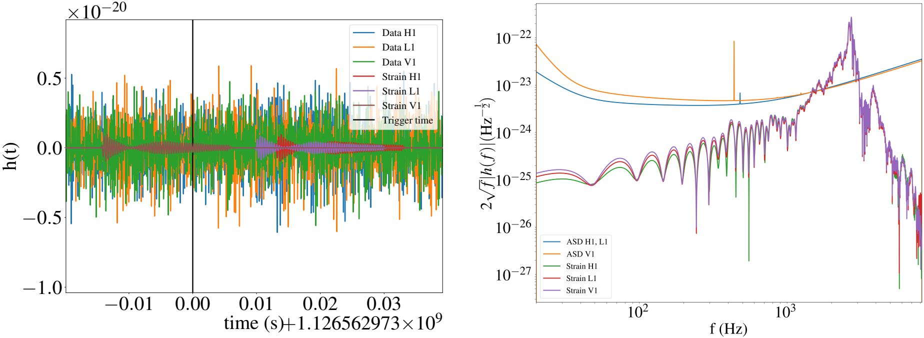
Example: THC:0006

$\kappa_{\rm eff}^{\rm T} = 129.$
Mass ratio $= 1.$
Mismatch $= 0.087$



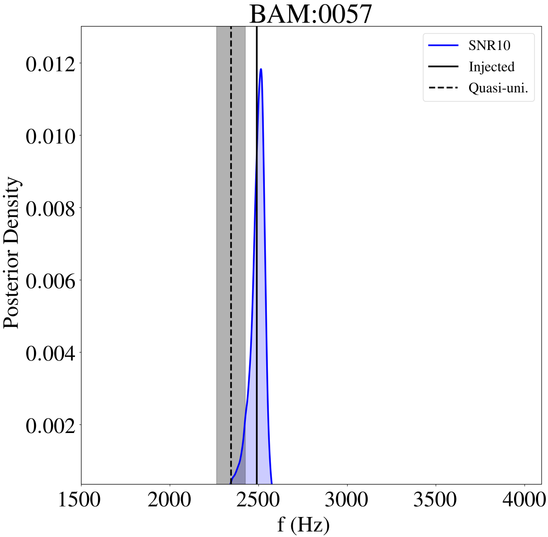
Simulations

Four selected cases are THC:0021, THC:0031, BAM:0048 and BAM:0057. For each numerical waveform, the postmerger is isolated at $t_{\min}$ and then immersed in simulated gaussian noise.

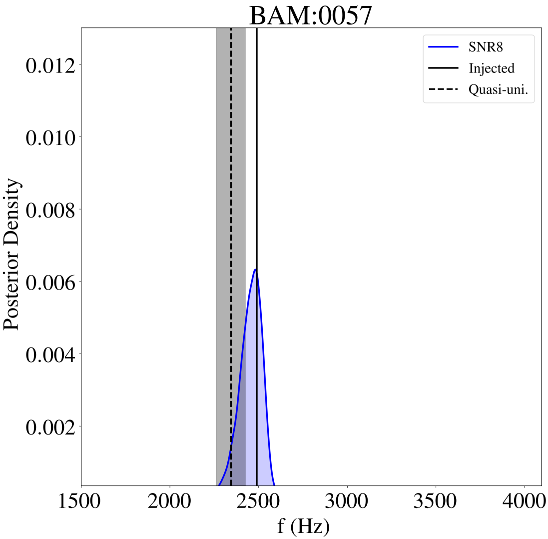


THC:0021 example with Signal-to-Noise Ratio (SNR) 8

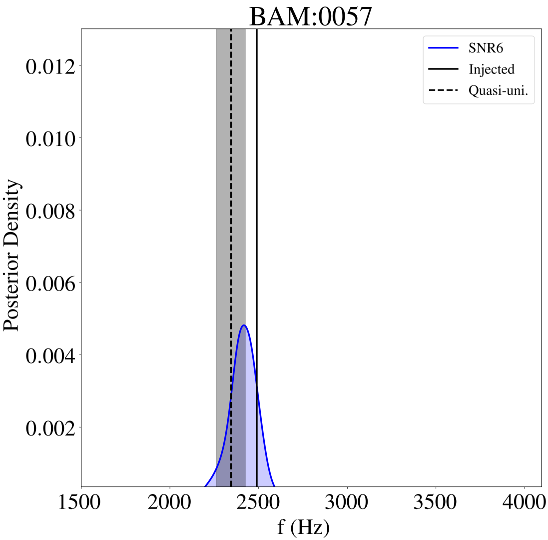
Result: c_1 posterior (BAM:0057 SNR 10)



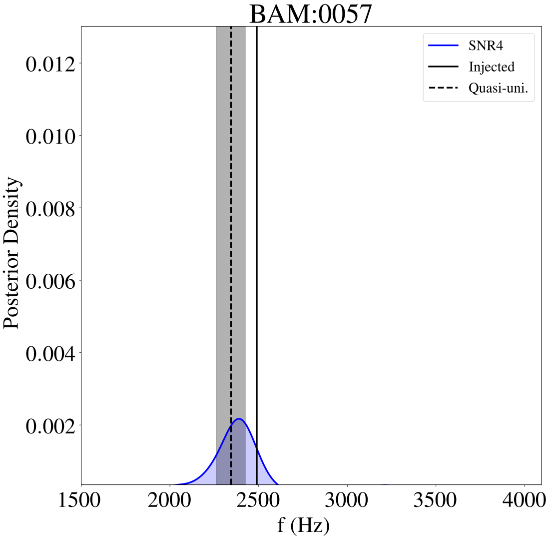
Result: c_1 posterior (BAM:0057 SNR 8)



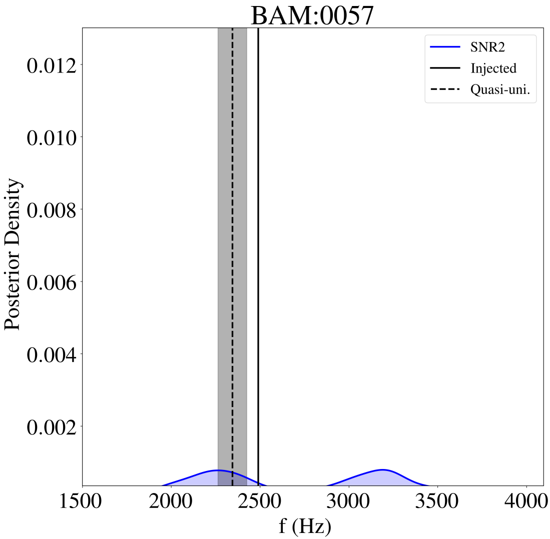
Result: c_1 posterior (BAM:0057 SNR 6)



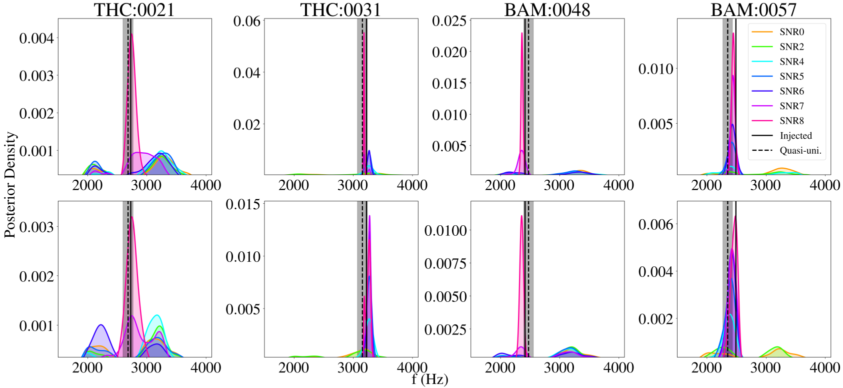
Result: c_1 posterior (BAM:0057 SNR 4)



Result: c_1 posterior (BAM:0057 SNR 2)

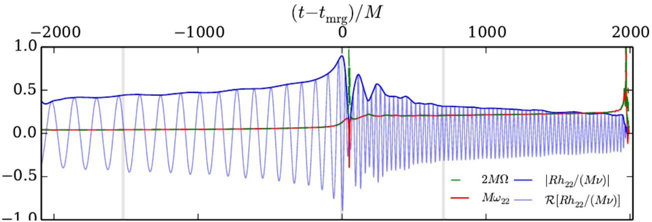


Result: c_1 posterior



- Depending on the exact setting (e.g., the intrinsic source properties, noise realisation, sky location) one can recover the f_2 frequency with an SNR ~ 4 for the best and ~ 8 for the worst considered scenarios
- For GW170817
  - At LIGO and Virgo's design sensitivities, postmerger SNR $\sim$ 2-3
  - With 3rd generation detectors, postmerger SNR $\sim$ 10

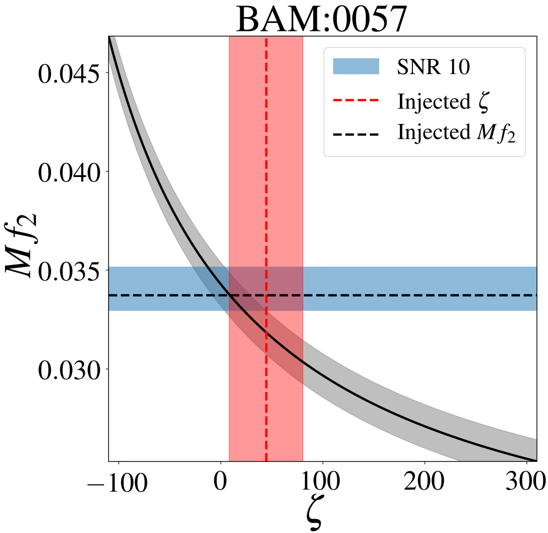
Inspiral, Merger and Postmerger (IMP) Consistency



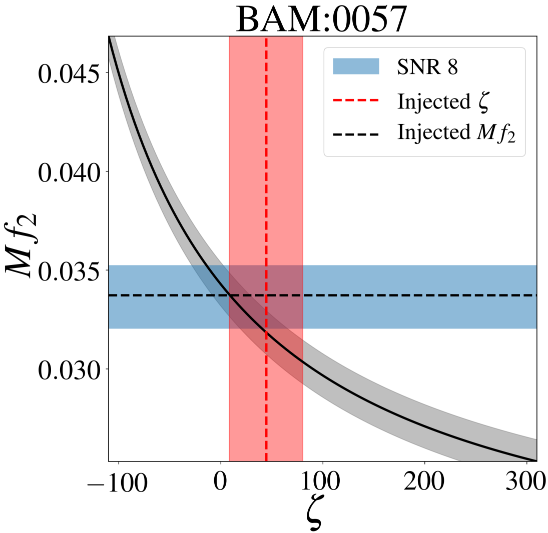
- Inspiral: Measurement of $\tilde{\Lambda}$ and M
- Merger: Relation connecting $\zeta = \kappa^{\rm T}_{\rm eff} + a\frac{M}{M_{\rm TOV}}$ and f_2
- Postmerger: Measurement of f_2 with a model (Lorentzian model)
- Other: Measurement of $M_{\rm TOV}$
  - J0740+6620: $M = 2.17^{+0.11}_{-0.10} M_\odot$
  - GW170817: $M_{\rm TOV} \lesssim$ 2.17-2.35$M_\odot$

Here we assume $\Delta M = \Delta M_{\rm TOV} = \pm 0.04 M_\odot$ and $\Delta\kappa^{\rm T}_{\rm eff} = \pm 30$.

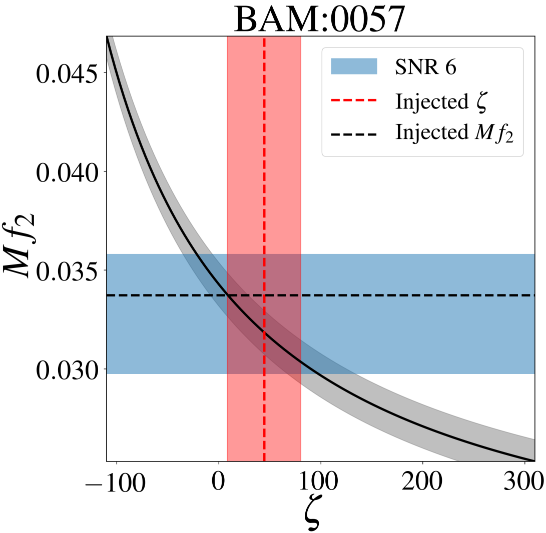
Result: IMP consistency test (BAM:0057 SNR 10)



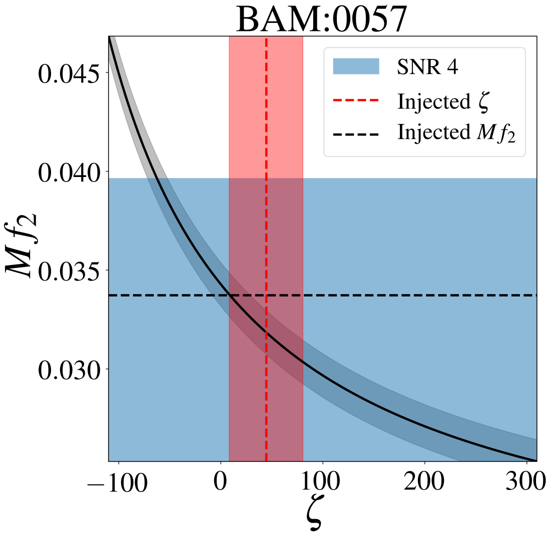
Result: IMP consistency test (BAM:0057 SNR 8)



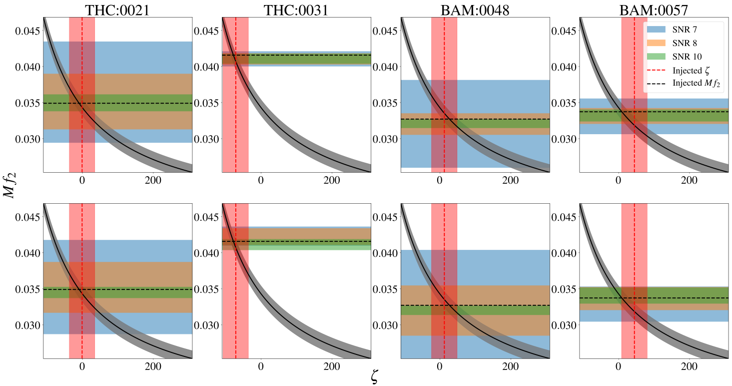
Result: IMP consistency test (BAM:0057 SNR 6)



Result: IMP consistency test (BAM:0057 SNR 4)



Result: IMP consistency test



Inconsistency implies either one of the following assumptions is wrong:

- General Relativity
- Nuclear physics description

Conclusions

1. New quasi-universal relations in both frequency and time domains
2. Modeling of the postmerger
3. Demonstration of constraining EOS with the measurement of f_2 and quasi-universal relation
4. Inspiral, Merger and Postmerger Consistency test