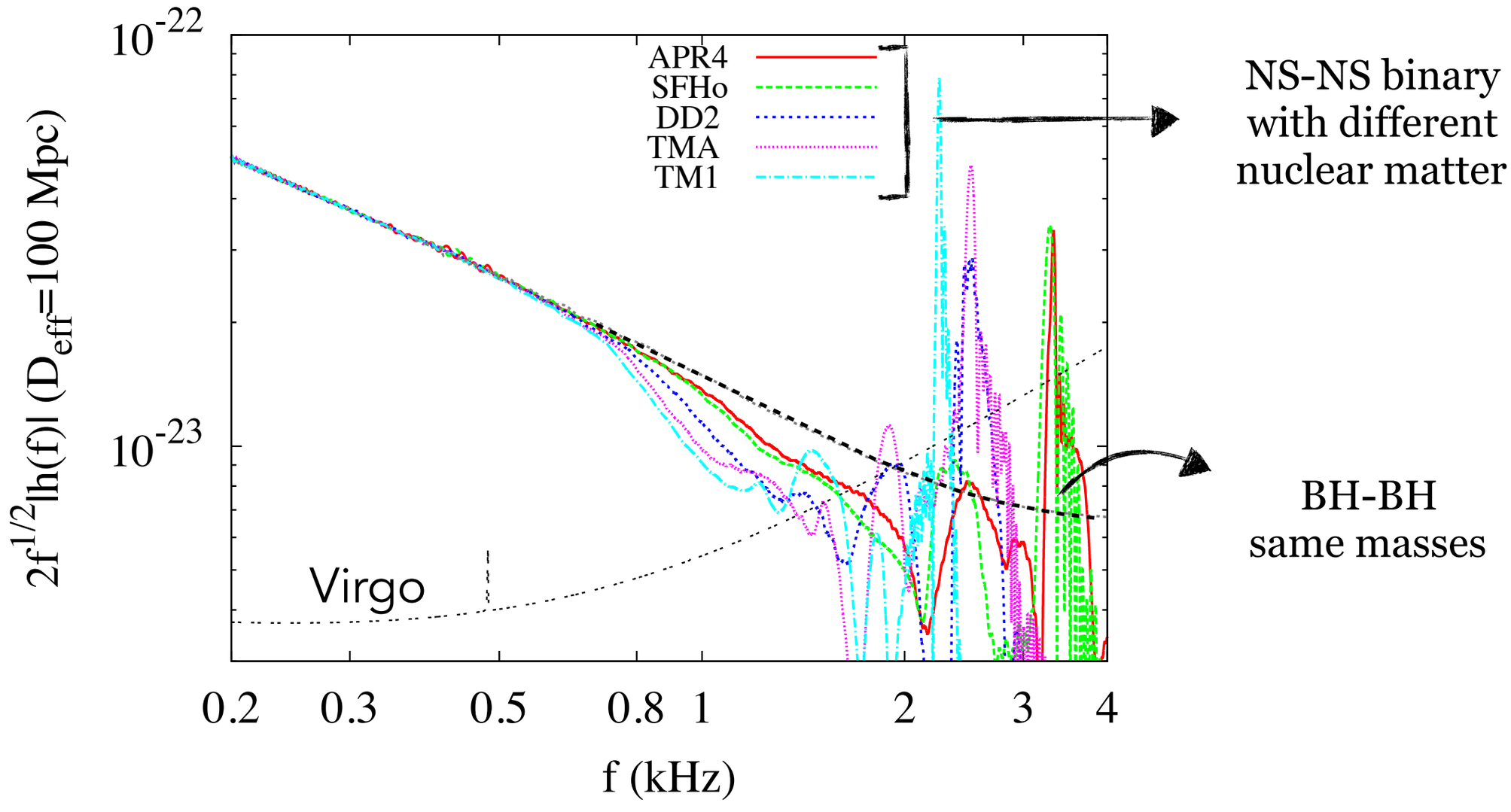
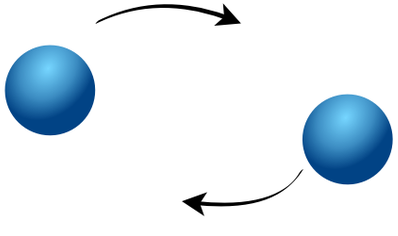
The NS Equation of State: basics

Hotokezaka 2016

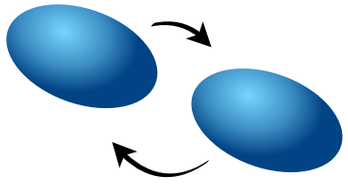


NS-NS binary with different nuclear matter

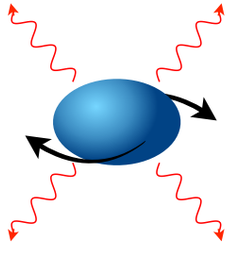
BH-BH same masses



point masses



tidal interactions



merger/post-merger

The NS Equation of State: basics

Tidal effects add linearly to point-particle $\quad h(f) = \mathcal{A} e^{i[\psi_{\rm PP}(f)+\psi_{\rm T}(f)]}$

$$\psi_{\rm PP} \propto \left[1 - \left(\frac{743}{336} + \frac{11}{4}\eta\right)\frac{(m\pi f)^{2/3}}{c^2} + \frac{\dots}{c^3} + \dots + \frac{\dots}{c^7}\right]$$

Newt — 1 PN — 3.5 PN ≀≀

$$\psi_{\rm T} \propto \frac{1}{26}\left[\left(1 + 12\frac{m_2}{m_1}\right)\lambda_1 + \left(1 + 12\frac{m_1}{m_2}\right)\lambda_2\right]\frac{(m\pi f)^{10/3}}{c^{10}} + \frac{\dots}{c^{12}}$$

Λ — $\mathcal{O}(10^4)$ — 5 PN: small term!

average Love

GW modelling

Inspiral phase: the analytic side

- *Effect of electric-**static** tides successfully included within templates [6pN + 6.5pN leading tail contribution]*

  Flanagan, Hinderer 08; Hinderer 08; Damour Nagar 09, Binnington, Poisson 09; Vines, Flanagan, Hinderer 11; Damour, Nagar, Villain 12

- *Improved form fo tidal-EOB*

  Damour, Nagar, Villain 12; Bernuzzi, Nagar et al. 12

- *Spin-tidal coupling [6.5 pN]*

  Abdelsalhin et al. 18; Forteza et al. 18

- *Rotational Love Numbers [6.5 pN]*

  Pani er al. 15; Landry, Poisson 15

- *Magnetic Love numbers [6 pN]*

  Damour, Nagar 09; Binnington Poisson 09; Yagi 17

GW modelling

Inspiral phase: source of systematics

- *higher-order tidal effects?*
- *Lack of complete point-particle knowledge of the waveform up to 5 pN?*

Favata 14; Messina et al. 19

- *Inclusion of spin-tidal Love number?*

Forteza et al. 18

- *Rotational Love numbers? Spin magnitudes for NS?*

GW modelling: new physics

Inspiral phase: extra effects to take into account?

- *may be relevant for signals at high-frequencies*

  - *Dynamical tides, aka non constant Love numbers*

    Maselli et al. 12; Steinhoff, Hinderer et al.16; Schmidt, Hinderer 19

  - *Resonant oscillations, for circular and hyperbolic encounters*

    Ho, Lai 99; Flanagan Racine 07; Tsang 13; Yu, Weinberg 16

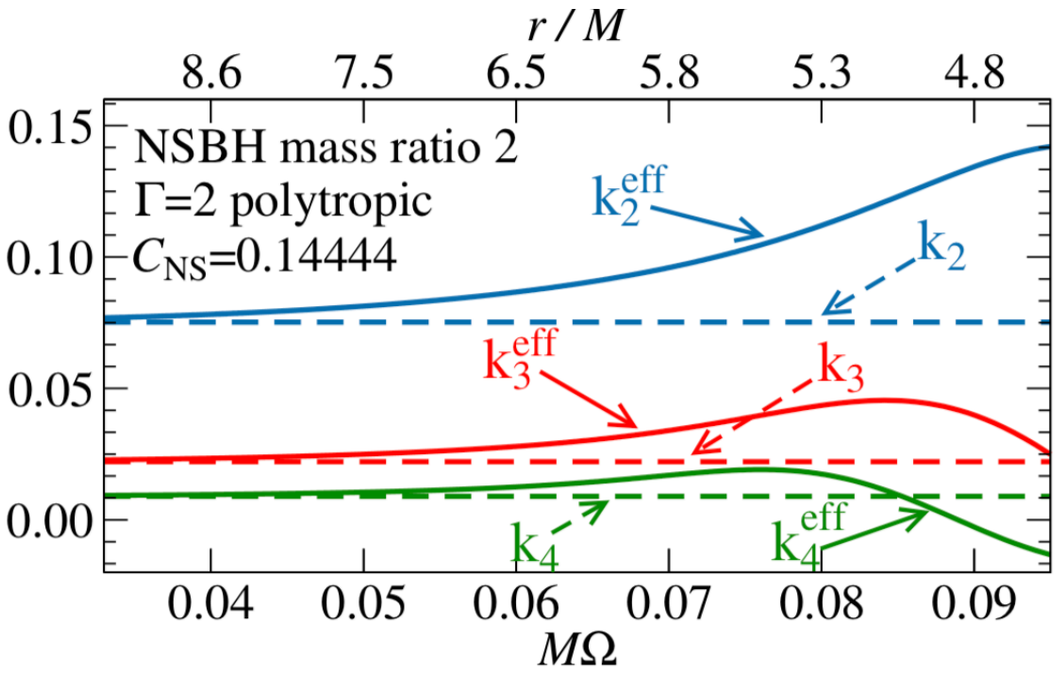
  - *Non-linear couplings of higher modes (pressure, gradient modes)*

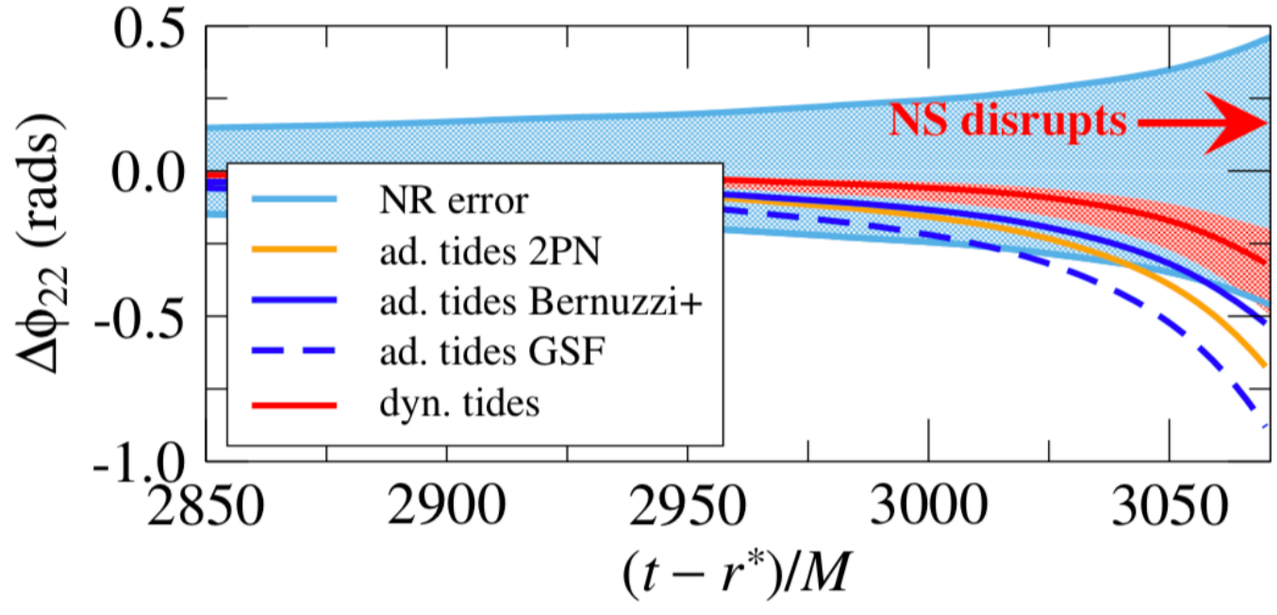
    Weinberg 16; Essick, Vitale, Weinberg 16

GW modelling: new physics

Inspiral phase: dynamical tides

Hinderer et al. 16





Constraints

Inspiral phase: radius constraints

- *LOFT, eXTP, NICER: measurement of* $R_{\rm NS}$ *at the order of ~%*
- *LVC for GW170817 measurement of* $R_{\rm NS}$ *~ 10%*

GW170818 - LVC 18

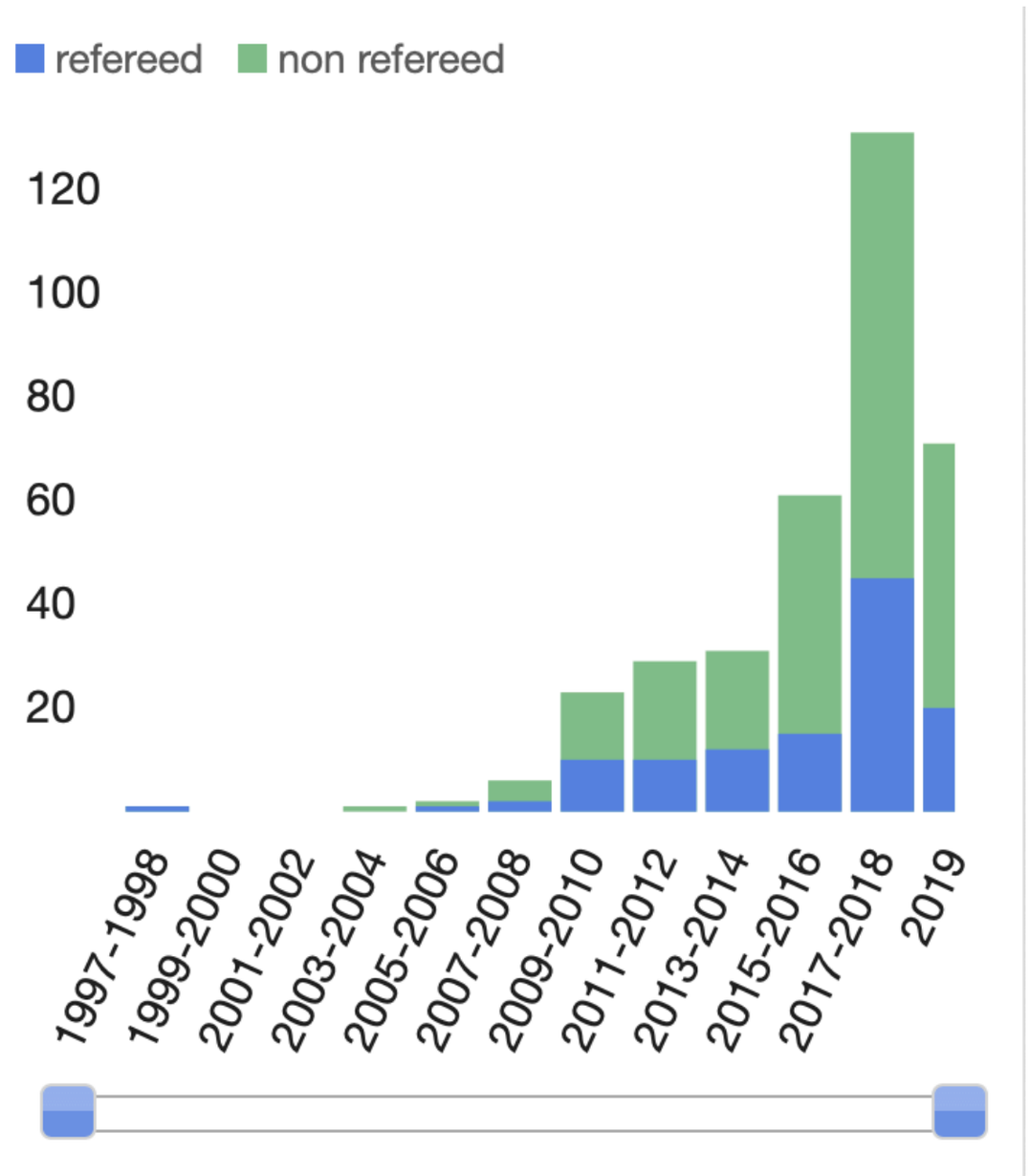
  - *number of events should beat this limit*
  - *3G single observation aim to be comparable and better than future satellites,* $R_{\rm NS}$ *~ 100 meters*

- *multi-messenger pipeline to join GW and EM signals with the stellar EoS as a goal?*

Fasano et al. 19

Multi-messenger

Multi-messenger on the AdS



BNS - Spectroscopy

Post-merger phase:

- *Signals depend noticeably on the NS structure*

Bauswein et al. 19;
Most et al.19

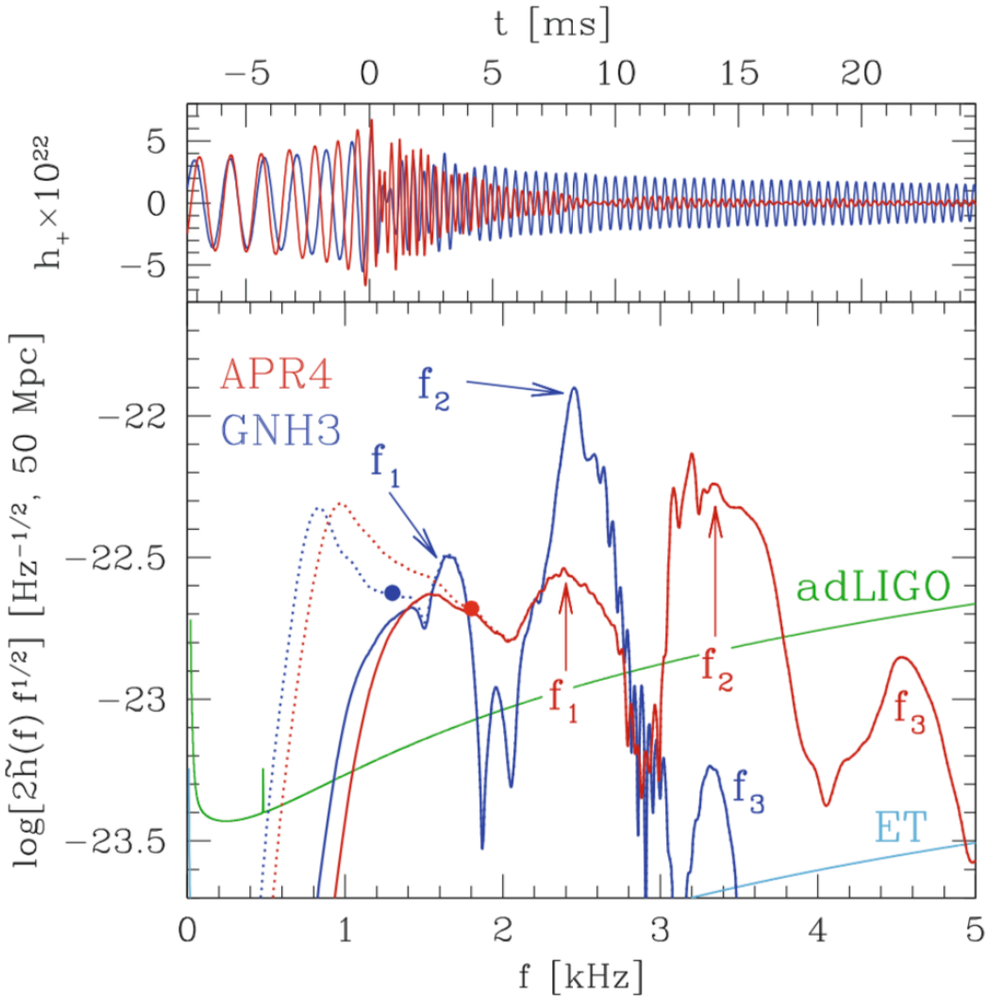
- *Highly-rewarded challenge: possible formation of new-states of matter*

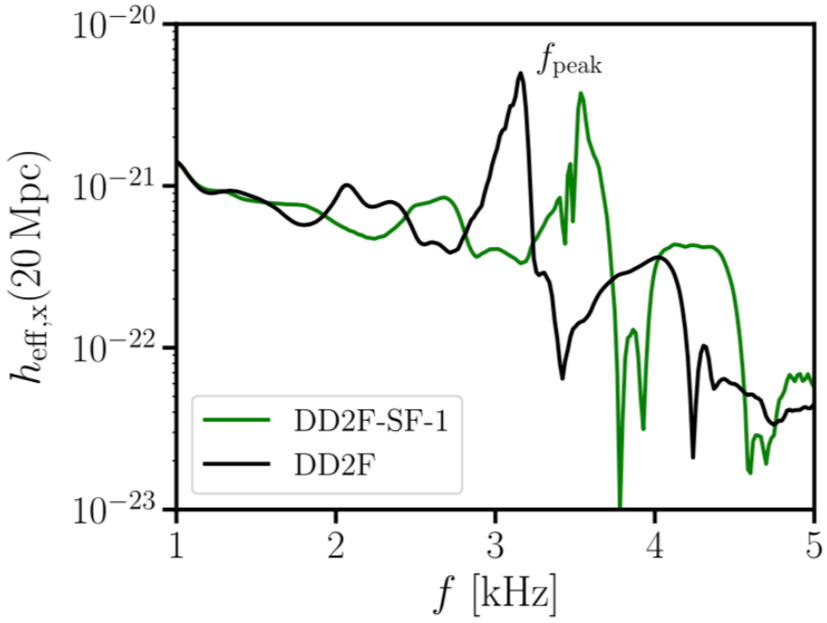
BNS-spectroscopy

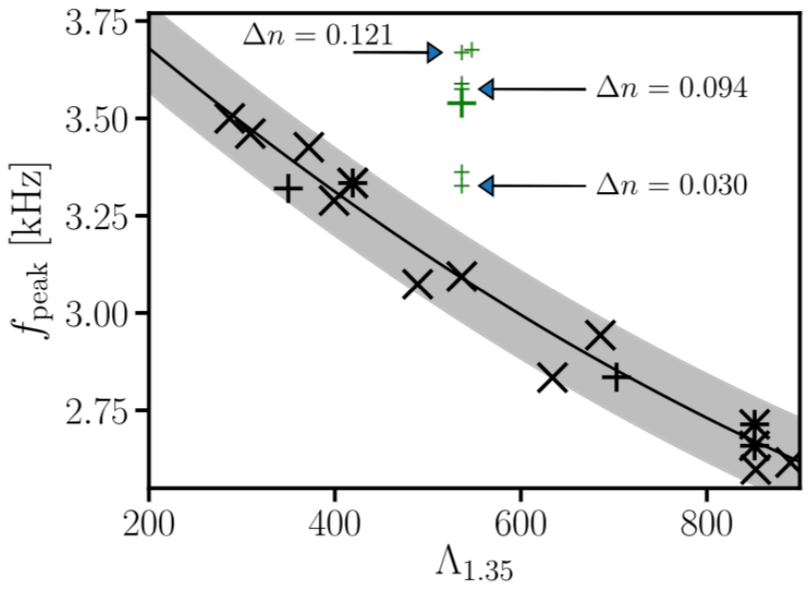
- *high-frequency content: 3G goal*
- *non linear evolution: status of numerical simulations?*
- *full-understanding of physical process?*

BNS - Spectroscopy

Takami et al. 14







Bauswein et al. 19

BNS - Spectroscopy

- *correlation between frequency lines and NS properties?*
  - *phenomenological relations between peaks and radius/ compactness of the **cold** EoS*

    Bauswein, Janka 2012; Stergioulas et al.11; Takami et al. 15

  - *correlation of the frequency peak with the Love number*

    Bernuzzi et al. 15

- *post-merger frequencies evolve in time. How much SNR needed to resolve them?*

ECO Love numbers

Neutron stars

$\mathcal{C} \in [0.1 \div 0.2]$

$k_2 \neq 0$

GW170817

constrain the NS equation of state

Black holes

$\mathcal{C} = 1/2$

$k_2 = 0$

Pani, Gualtieri, Maselli, Ferrari PRD 92 '15

ECOs

$\mathcal{C} < 0.5 \qquad k_2 \neq 0$

$\mathcal{C} \to 0.5 \qquad k_2 \to 0$

signature to distinguish ECO and BH's inspiral

Cardoso, Franzin, Maselli + PRD 95 '17
Maselli + PRL 120 "17
Maselli + grqc: 181103689 '18