Estimating the neutron-star radius and constraining the mass-radius relation with short gamma-ray bursts

Victor Guedes (UVA)

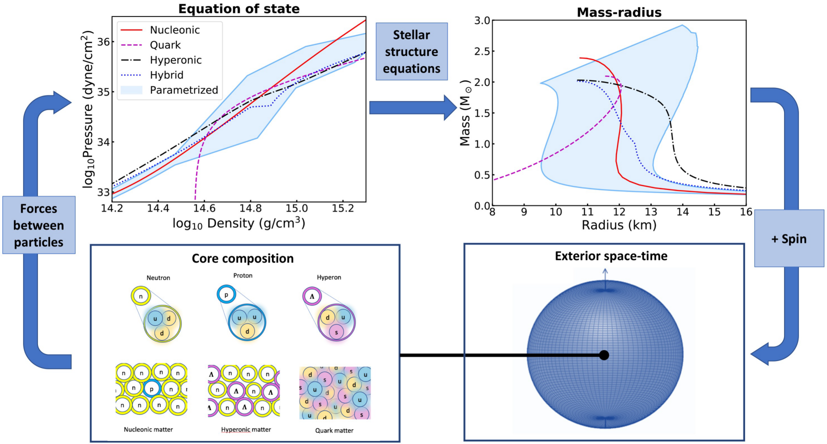
based on arXiv:2408.16534

Collaborators: David Radice (PSU), Cecilia Chirenti (UMD), Kent Yagi (UVA)

EOS Measurements with Next-Generation Gravitational-Wave Detectors
Panel: Protoneutron Stars & Postmerger Remnants

INT, Seattle
Sep 5, 2024

The problem: neutron-star (NS) equation of state (EOS)

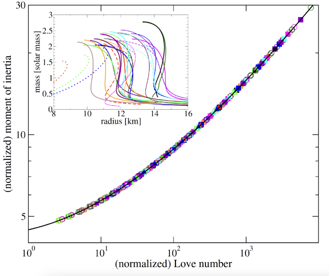


Watts 2019 (arXiv:1904.07012)

A possible solution: (quasi)universal relations

Relations between NS observables that have no (or weak) dependence on the EOS, e.g.:

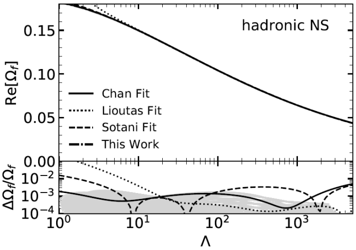
"I-Love" relation



Yagi & Yunes 2013

(arXiv:1303.1528)

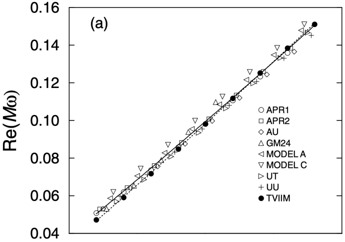
"f-Love" relation*



Zhao & Lattimer 2022

(arXiv:2204.03037)

"f-C" relation



Tsui & Leung 2005

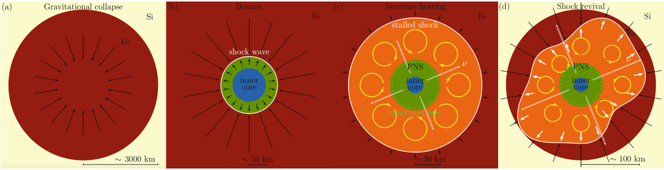
(arXiv:gr-qc/0412024)

and many others...

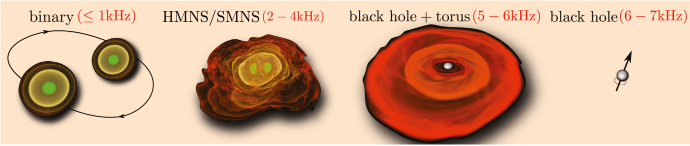
*First proposed in Chan+ 2014 (arXiv:1408.3789), see also Lau+ 2010 (arXiv:0911.0131) for "f-I" relation

However...

Next-generation detectors are expected to probe more realistic scenarios†, e.g.: protoneutron stars (PNSs) and hypermassive neutron stars (HMNSs)



Rezzolla+ 2018 (Springer)

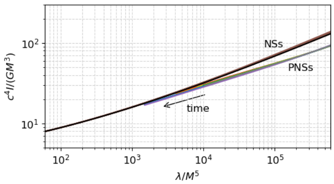


Baiotti & Rezzolla 2017 (arXiv:1607.03540)

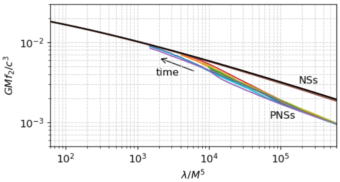
† See, e.g., CE prospects: Evans+ 2021 (arXiv:2109.09882)

How are these relations for PNSs and HMNSs?

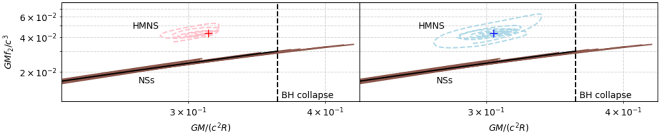
"I-Love" relation for PNSs



"f-Love" relation for PNSs



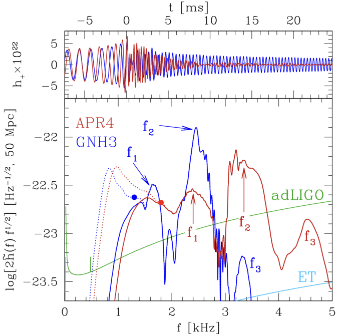
"f-C" relation for HMNSs



Guedes+ 2024 (arXiv:2402.10868)

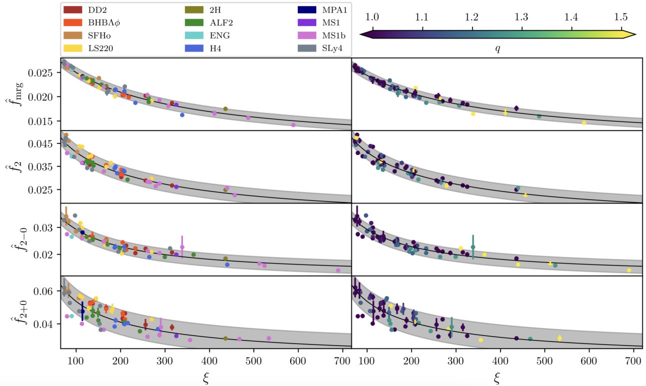
See also Raduta+ 2020 (arXiv:2008.00213), Marques+ 2017 (arXiv:1706.02913), Martinon+ 2014 (arXiv:1406.7661)

Numerical relativity (NR) simulations



Takami+ 2014

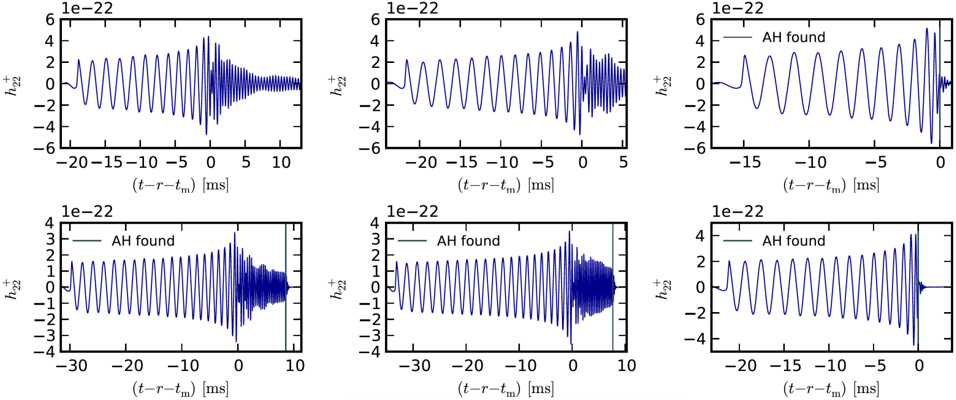
(arXiv:1403.5672)



Breschi+ 2019 (arXiv:1908.11418)[‡]

[‡] ξ is the effective tidal polarizability, which is proportional to the effective tidal deformability $\tilde{\Lambda}$ for symmetric binaries.

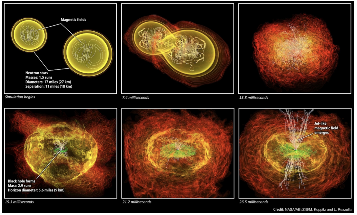
HMNS oscillations



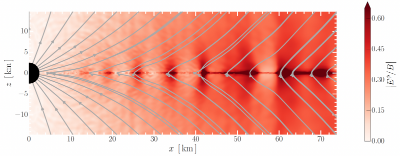
Kastaun & Galeazzi 2015 (arXiv:1411.7975)

Short gamma-ray burst (GRB) oscillations

- Short GRBs can be generated in binary NS mergers, and can be powered by:
  - the accretion disk of the rotating black hole, in case of prompt collapse;
  - the short-living, rapidly-rotating, and strongly-magnetized remnant NS (i.e., the HMNS), and its accretion disk;
- The oscillation spectrum of short GRB could be associated with that of the BH or the HMNS;



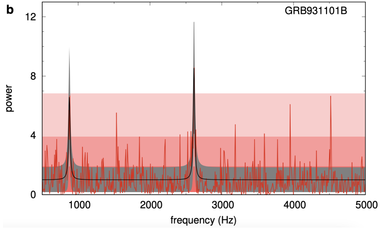
Koppitz and Rezzolla



Most+ 2024 (arXiv:2404.01456)

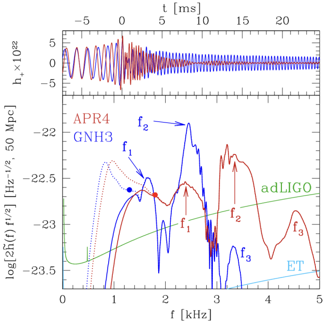
Measurements and interpretation

- High-frequency ($\sim$ kHz) quasiperiodic oscillations (QPOs) were recently found in GRBs 910711 and 931101B;
- Two **measured** frequencies: $\nu_2 \sim 2.6$ kHz and $\nu_0 \sim 1.0$ kHz (detector frame);



Chirenti+ 2023 (arXiv:2408.16534)

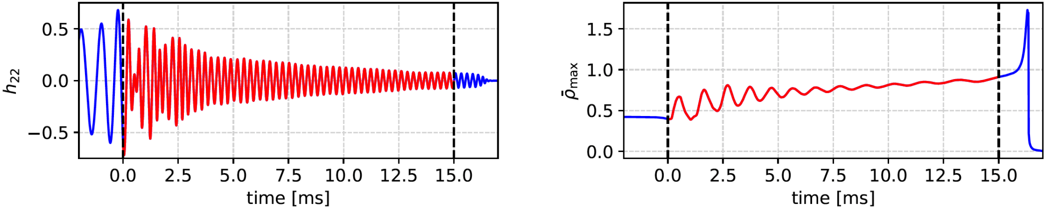
- **Assumption**: ν_2 and ν_0 can be identified with f_2 and f_0 of the HMNS (source frame);
- Note: $f_1 = f_2 - f_0$ and $f_3 = f_2 + f_0$;



Takami+ 2014 (arXiv:1403.5672)

Extracting f_2 and f_0 from NR data

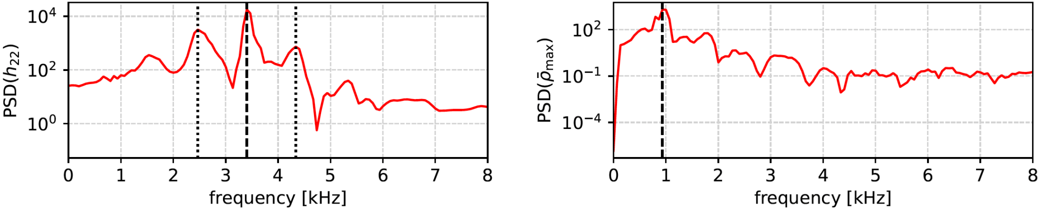
- We use a set of ~ 100 simulations from the CoRe (Computational Relativity) collaboration: Breschi+ 2019 (arXiv:1908.11418);
- This is an example for a $1.35 + 1.35$ binary NS, using the piecewise polytropic fit for the SLy4 EOS;



Guedes+ 2024 (arXiv:2408.16534)

Extracting f_2 and f_0 from NR data

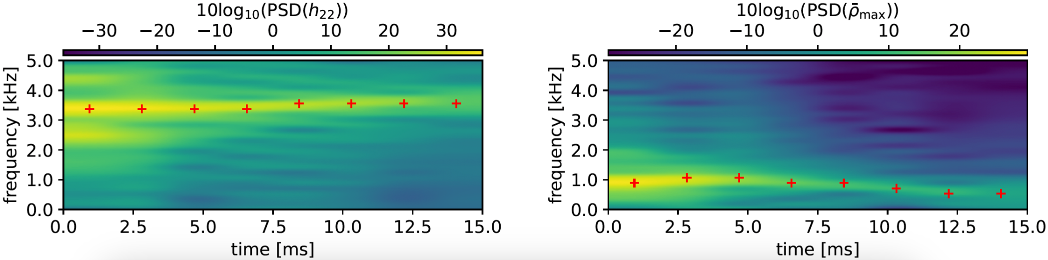
- We can do a Fourier transform of h_{22} ($\ell = m = 2$ mode) and $\bar{\rho}_{\rm max}$ ($\equiv \rho_{\rm max}/\rho_{\rm TOV}$) to obtain f_2 and f_0;
- Note: f_2 and f_0 are comparable with ν_2 and ν_0;



Guedes+ 2024 (arXiv:2408.16534)

Extracting f_2 and f_0 from NR data

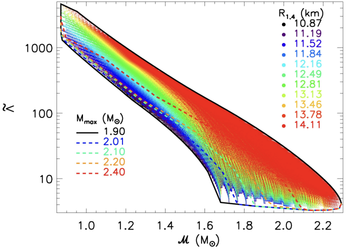
- For information in both time and frequency domains we can look at the spectrograms;
- Note: f_2 and f_0 are approximately constant;



Guedes+ 2024 (arXiv:2408.16534)

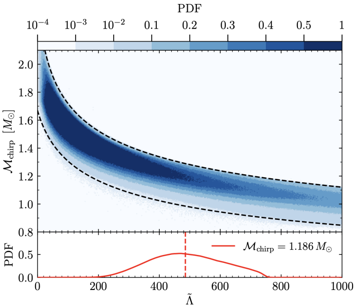
Correlations: $\mathcal{M}$ vs. $\tilde{\Lambda}$

$$\mathcal{M} \equiv \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}, \qquad \tilde{\Lambda} \equiv \frac{16}{13}\left(\frac{(M_1+12M_2)M_1^4\Lambda_1}{(M_1+M_2)^5} + (1\leftrightarrow 2)\right), \quad \text{where} \quad \Lambda_{1,2} = \frac{\lambda_{1,2}}{M_{1,2}^5}$$



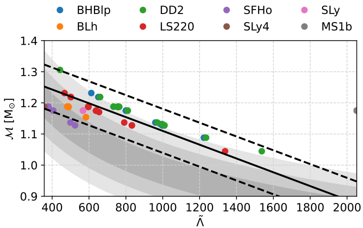
Zhao & Lattimer 2018

(arXiv:1808.02858)



Altiparmak+ 2022

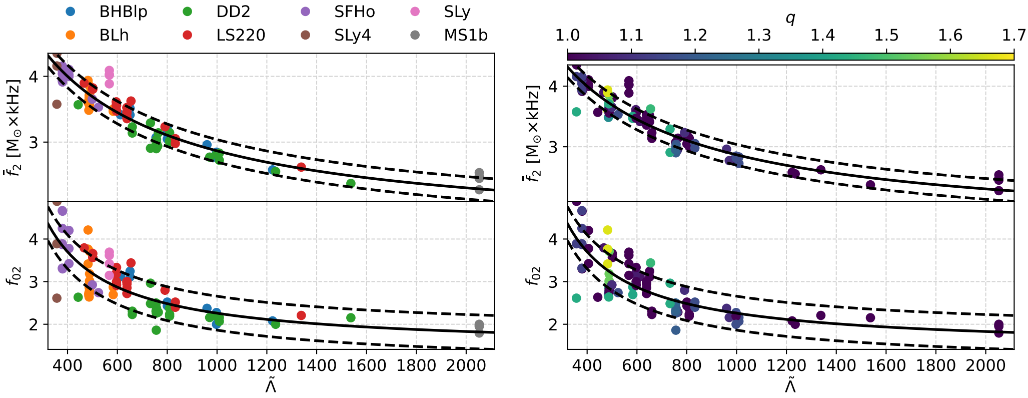
(arXiv:2203.14974)



NR simulations that we consider

in our work (Breschi+ 2019)

Correlations: $f_{02} \equiv f_2/f_0$ vs. $\tilde{\Lambda}$ & $\bar{f}_2 \equiv \mathcal{M} f_2$ vs. $\tilde{\Lambda}$



Guedes+ 2024 (arXiv:2408.16534)

Bayesian inference: prior

We use the relations $\mathcal{M}(\tilde{\Lambda})$, $\bar{f}_2(\tilde{\Lambda})$, and $f_{02}(\tilde{\Lambda})$, and their corresponding $\sigma_{\mathcal{M}}$, $\sigma_{\bar{f}_2}$, and $\sigma_{f_{02}}$, in a Bayesian framework to obtain the joint posterior on the parameters $\tilde{\Lambda}$, $\mathcal{M}$, and z:

$P(\tilde{\Lambda}, \mathcal{M}, z) \propto p(\tilde{\Lambda}, \mathcal{M}, z)\mathcal{L}(\tilde{\Lambda}, \mathcal{M}, z)$, where p is the prior and $\mathcal{L}$ is the likelihood.

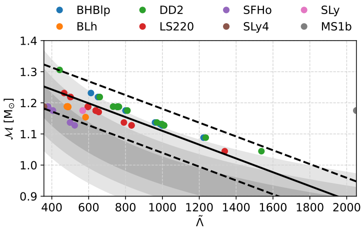
We decompose the prior as:

$$p(\tilde{\Lambda}, \mathcal{M}, z) = p(\tilde{\Lambda})p(\mathcal{M}|\tilde{\Lambda})p(z).$$

where $p(\tilde{\Lambda}) = U(357, 2053)$,

$$p(\mathcal{M}|\tilde{\Lambda}) \propto \exp\left(-\frac{(\mathcal{M} - \mathcal{M}(\tilde{\Lambda}))^2}{2\sigma_{\mathcal{M}}^2}\right),$$

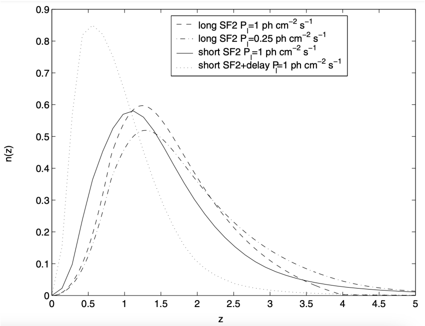
for $\mathcal{M} \in [1.04, 1.31]$ $\mathrm{M}_\odot$,



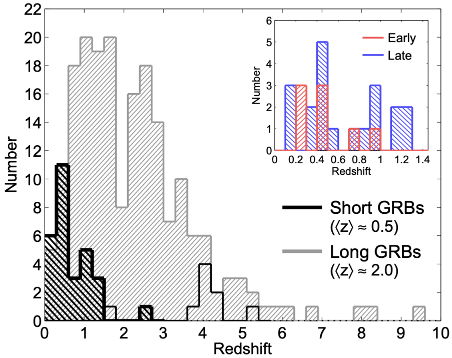
NR simulations that we consider in our work (Breschi+ 2019)

Bayesian inference: prior

and $p(z)$ is the redshift distribution, for $z \in [0, 5]$, for short GRBs inferred from the BATSE data, with a peak in ~ 0.5:



Guetta and Piran 2005 (arXiv:astro-ph/0407429)



Berger 2014 (arXiv:1311.2603)

Bayesian inference: likelihood

We decompose the likelihood as:

$$\mathcal{L}(\tilde{\Lambda}, \mathcal{M}, z) = \mathcal{L}_{\nu_{02}}(\tilde{\Lambda}) \mathcal{L}_{\nu_2}(\tilde{\Lambda}, \mathcal{M}, z),$$

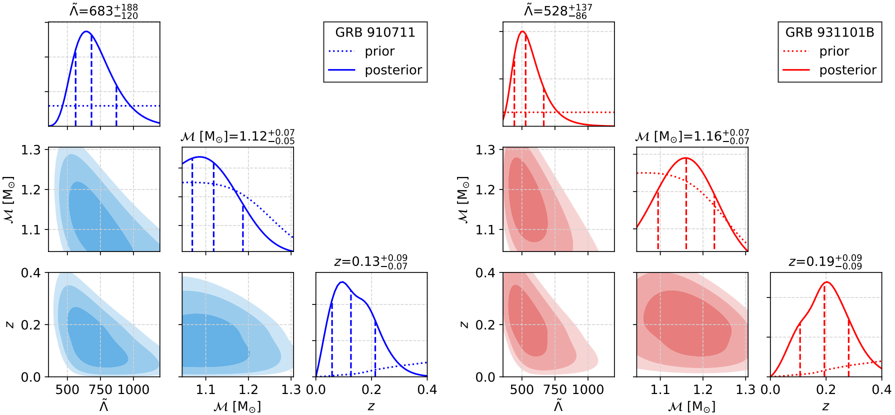
where:

$$\mathcal{L}_{\nu_{02}}(\tilde{\Lambda}) \equiv \mathcal{L}(\nu_{02} | f_{02}(\tilde{\Lambda})) \propto \exp\left(-\frac{(\nu_{02} - f_{02}(\tilde{\Lambda}))^2}{2(\sigma^2_{\nu_{02}} + \sigma^2_{f_{02}})} \right),$$

$$\mathcal{L}_{\nu_2}(\tilde{\Lambda}, \mathcal{M}, z) \equiv \mathcal{L}(\nu_2 | f_2^{\mathrm{obs}}(\tilde{\Lambda}, \mathcal{M}, z)) \propto \exp\left(-\frac{(\nu_2 - f_2^{\mathrm{obs}}(\tilde{\Lambda}, \mathcal{M}, z))^2}{2(\sigma^2_{\nu_2} + \sigma^2_{f_2^{\mathrm{obs}}}(\mathcal{M}, z))} \right),$$

with the definitions $f_2^{\mathrm{obs}}(\tilde{\Lambda}, \mathcal{M}, z) \equiv \bar{f}_2(\tilde{\Lambda}) / \mathcal{M}(1+z)$ and $\sigma_{f_2^{\mathrm{obs}}}(\mathcal{M}, z) \equiv \sigma_{\bar{f}_2} / \mathcal{M}(1+z)$.

Bayesian inference: posterior



Guedes+ 2024 (arXiv:2408.16534)

Inferring f_2 and f_0

We determine the source-frame frequencies $f_\ell = f_\ell^{\rm obs}(1+z)$ ($\ell \in \{0,\, 2\}$);

From the parameter estimation, we have $P(\tilde{\Lambda}, \mathcal{M}, z)$, thus:

$$P(z) = \int P(\tilde{\Lambda}, \mathcal{M}, z)\mathrm{d}\tilde{\Lambda}\mathrm{d}\mathcal{M}.$$

$z = z(f_\ell, f_\ell^{\rm obs})$ and $P(f_\ell^{\rm obs})$ is a normal distribution with mean ν_ℓ and std. dev. σ_{ν_ℓ}, then:

$$P(f_\ell) = \int \frac{1}{\sqrt{2\pi}\sigma_{\nu_\ell}} \exp\left(-\frac{(f_\ell^{\rm obs} - \nu_\ell)^2}{2\sigma_{\nu_\ell}^2}\right) P(z(f_\ell, f_\ell^{\rm obs}))\mathrm{d}f_\ell^{\rm obs}.$$

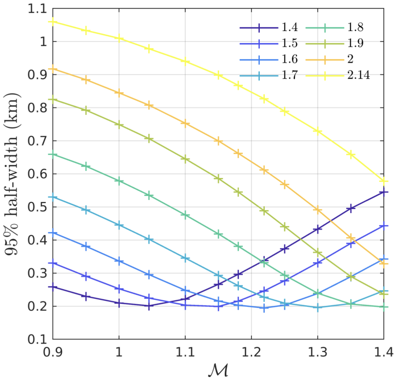
We infer: $f_2 = 2.99^{+0.24}_{-0.21}$ kHz and $f_0 = 1.25^{+0.10}_{-0.09}$ kHz for GRB910711
$f_2 = 3.16^{+0.26}_{-0.24}$ kHz and $f_0 = 1.06^{+0.08}_{-0.08}$ kHz for GRB931101B

Inferring $R_{1.4}$ and $M - R$

We determine the radius R_M of a NS of mass M and constrain the $M - R$ relation using the quasiuniversal relations proposed by Godzieba and Radice 2021:

$$R_M(\tilde{\Lambda}, \mathcal{M}) = \alpha \left(\frac{\mathcal{M}}{1\ \mathrm{M}_\odot}\right) \left(\frac{\tilde{\Lambda}}{800}\right)^{\frac{1}{\beta}},$$

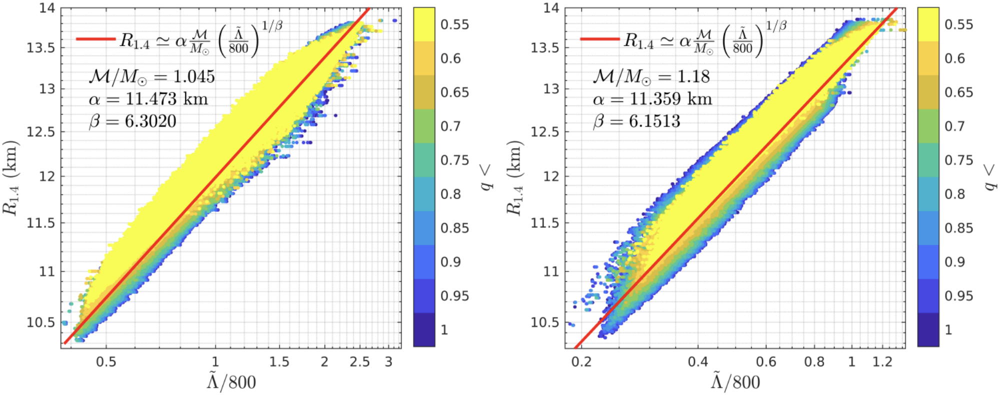
where α and β are functions of $\mathcal{M}$ and M, and $M \in [1.4, 2.14]\ \mathrm{M}_\odot$.



Godzieba and Radice 2021

(arXiv:2109.01159)

Inferring $R_{1.4}$ and $M - R$



Godzieba and Radice 2021 (arXiv:2109.01159)

Inferring $R_{1.4}$ and $M - R$

We obtain the joint posterior for $\tilde{\Lambda}$ and $\mathcal{M}$ by marginalizing $P(\tilde{\Lambda}, \mathcal{M}, z)$ over z:

$$P(\tilde{\Lambda}, \mathcal{M}) = \int P(\tilde{\Lambda}, \mathcal{M}, z)\mathrm{d}z.$$

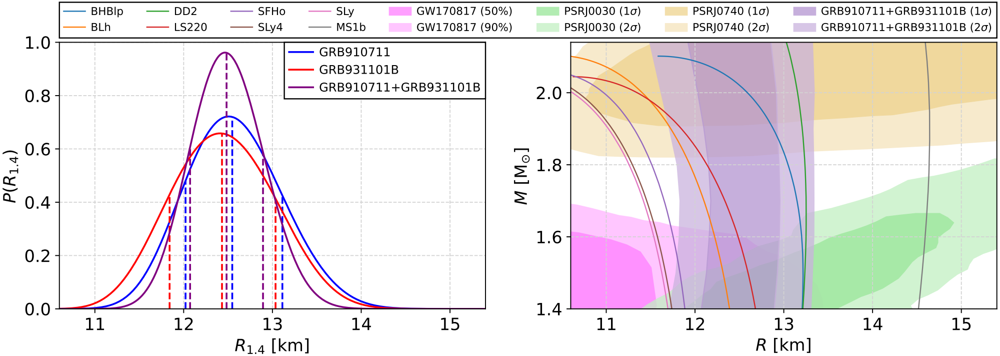
$\tilde{\Lambda} = \tilde{\Lambda}(\mathcal{M}, R_M)$ and we account for the EOS and mass-ratio variation of $R_M(\tilde{\Lambda}, \mathcal{M})$ by assuming that each R_M is the mean of a normal distribution with std. dev. $\sigma_{R_M}(\mathcal{M})$, then:

$$P(R_M) = \iint \frac{1}{\sqrt{2\pi}\sigma_{R_M}(\mathcal{M})} \exp\left(-\frac{(R'_M - R_M)^2}{2\sigma^2_{R_M}(\mathcal{M})}\right) P(\tilde{\Lambda}(\mathcal{M}, R'_M), \mathcal{M})\mathrm{d}R'_M\mathrm{d}\mathcal{M}.$$

We infer: $R_{1.4} = 12.55^{+0.56}_{-0.53}$ km for GRB910711
$R_{1.4} = 12.43^{+0.60}_{-0.59}$ km for GRB931101B
$R_{1.4} = 12.48^{+0.41}_{-0.41}$ km for GRB910711+GRB931101B
(under our assumptions, this is one of the tightest $R_{1.4}$ to date[§])

[§] See also: Dittman+ 2024 (arXiv:2406.14467), Biswas & Rosswog (arXiv:2408.15192)

Inferring $R_{1.4}$ and $M - R$



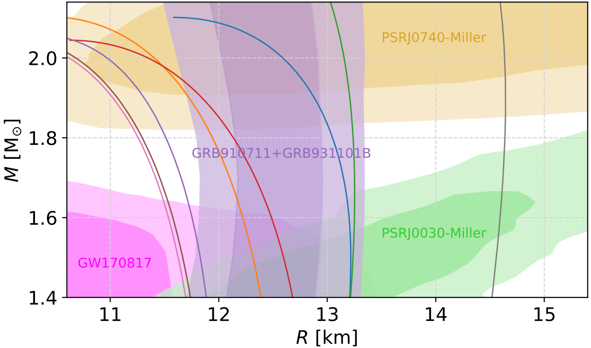
Guedes+ 2024 (arXiv:2408.16534)

Conclusions

- We associate the frequencies of the QPOs in GRBs 910711 and 931101B reported by Chirenti et al. 2023 with BNS postmerger oscillation modes and obtain constraints on z, as well as $\tilde{\Lambda}$ and $\mathcal{M}$ of the BNSs whose mergers were presumably their source;
- The correspondence between frequencies of QPOs in short GRBs and those in the GW spectrum of BNS mergers is not fully certain. Additional modelling and simulations are needed to clarify this scenario[¶];
- Future detections of GWs (in coincidence with GRBs with QPOs) with next-generation ground-based detectors will allow for a direct comparison between the postmerger and QPO frequencies;
- This is a novel way to obtain information about the EOS: with gamma rays.

[¶] See, e.g., Siegel & Ciolfi (arXiv:1508.07911, arXiv:1508.07939), Mösta+ 2020 (arXiv:2003.06043), Most & Quataert 2023 (arXiv:2303.08062), Curtis+ 2024 (arXiv:2305.07738), Most+ 2024 (arXiv:2404.01456)

Take-home thought: ~~GRB~~ GW 910711 & ~~GRB~~ GW 931101B?



Guedes+ 2024 (arXiv:2408.16534)

Thank you!