Neutron star binaries: mergers, matter and modeling

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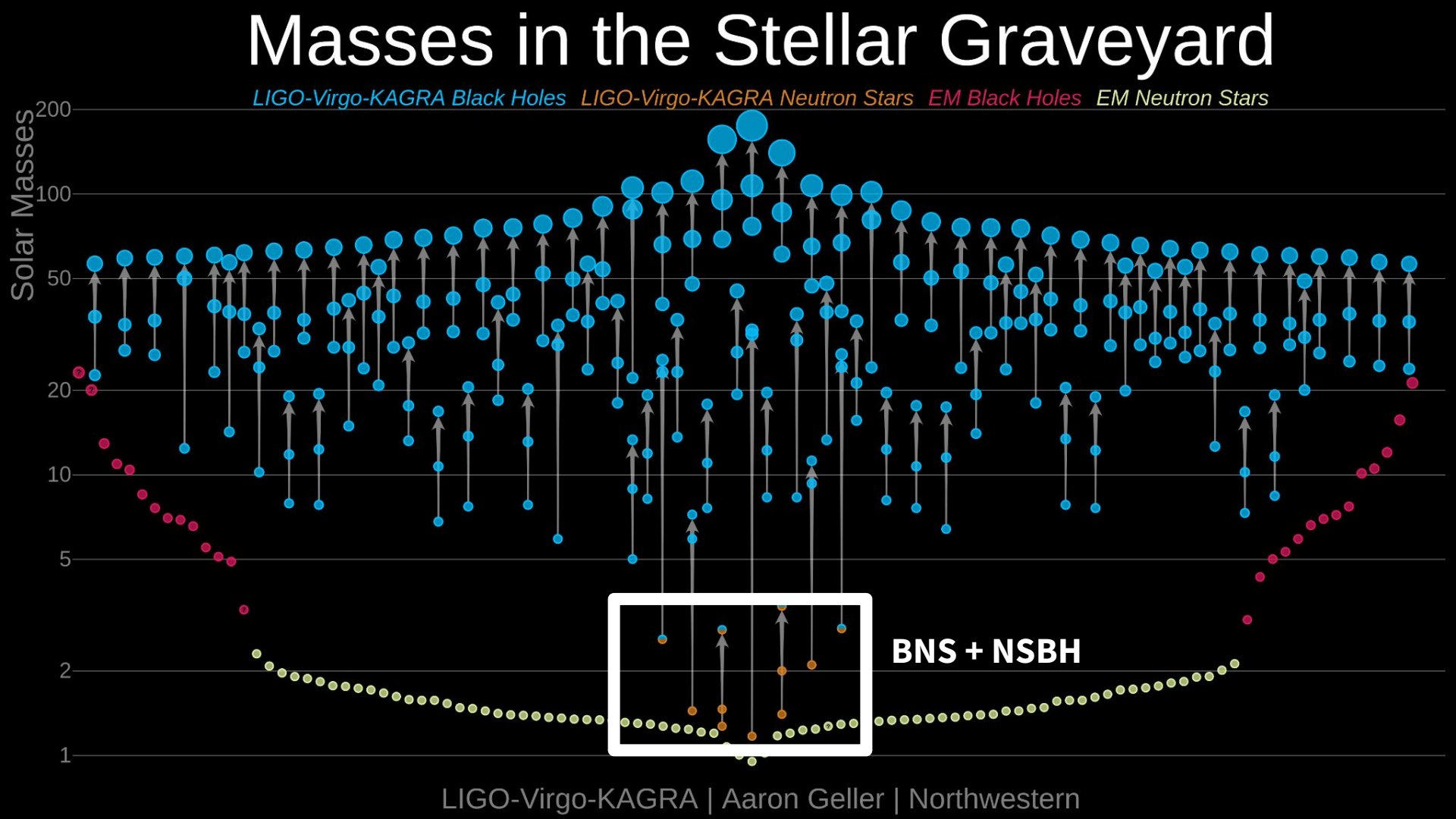
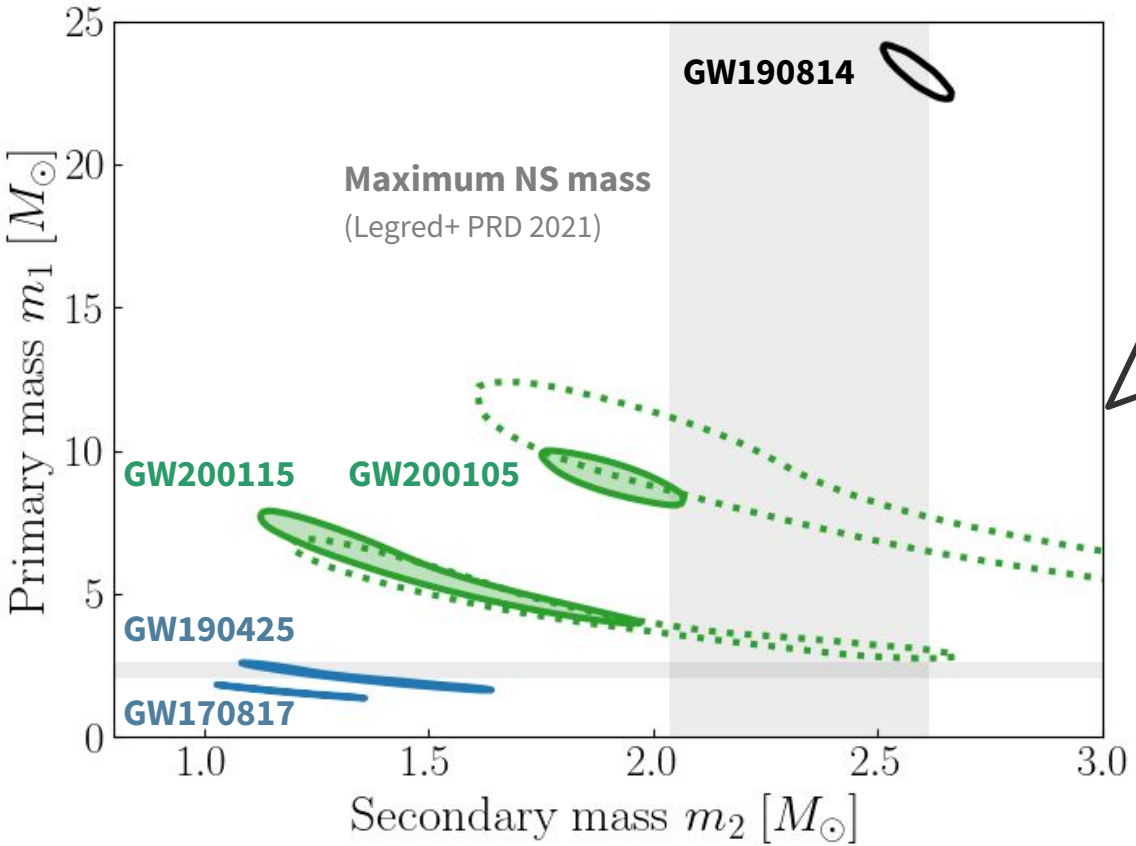
CITA
ICAT

KITP ◆ 19 April 2022

LIGO
VIRGO


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
BNS + NSBH
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Cataloging low-mass compact binary mergers

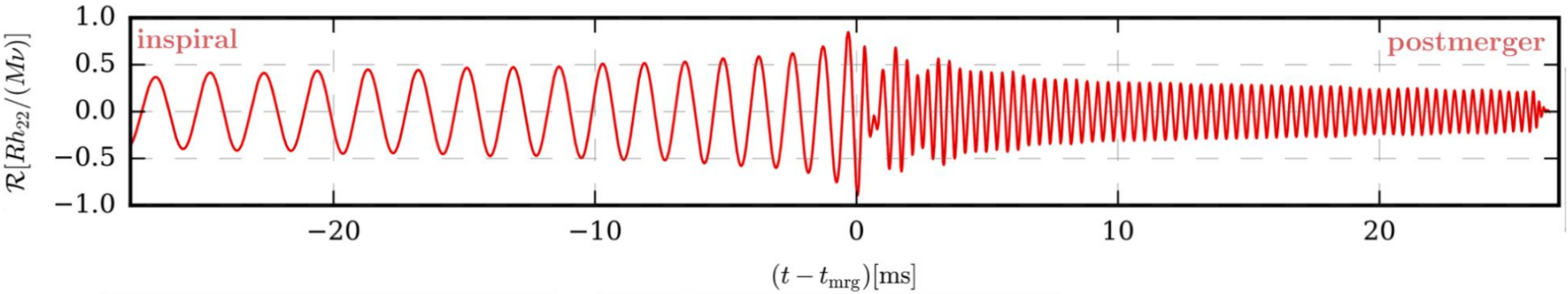


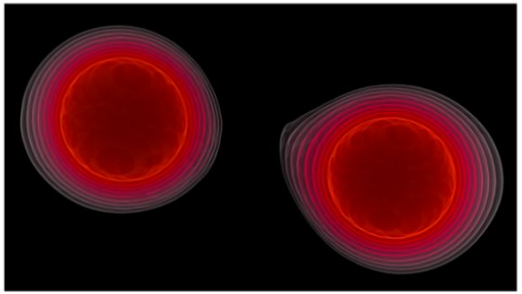
GWTC-3
(LVK arXiv:2111.03606)

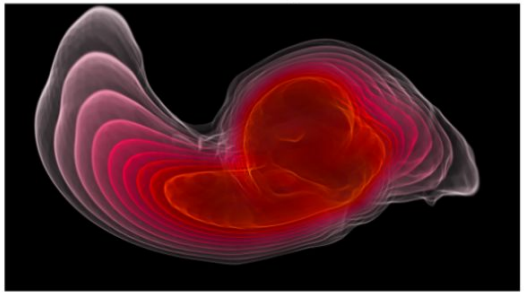
2 BNS
2 NSBH
1 ??BH

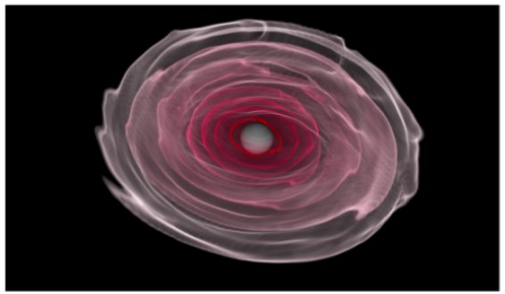
What's so special about neutron star mergers?

Dietrich+ GRG 2020









1. **Matter effects**
2. **Masses**

3. **Electromagnetic counterparts**

4. **Postmerger remnant**

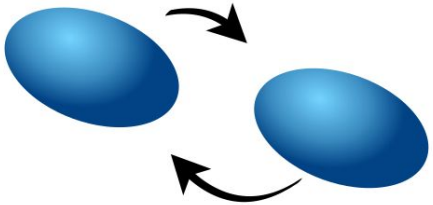
1. Matter effects

GW170817: a sign of the tides

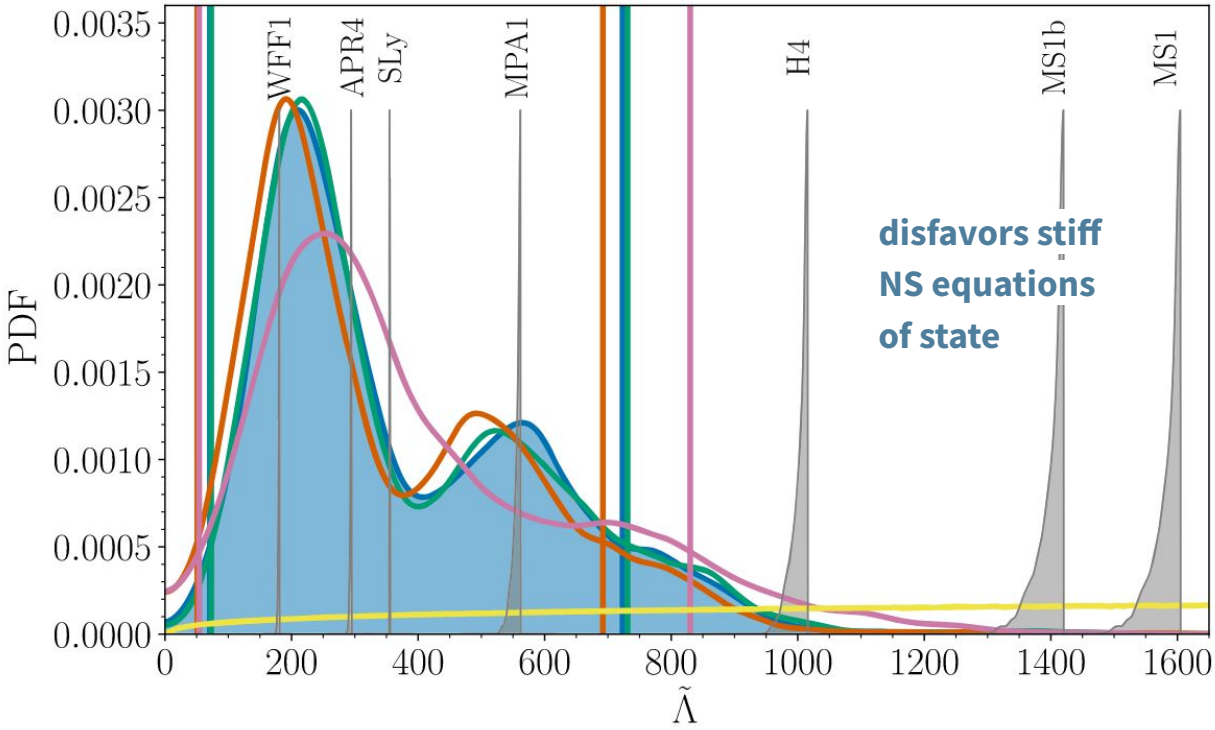
✔ Masses consistent with Galactic DNS

✔ EM counterparts

✔ **First measurement of tidal deformations**



low spin assumption LVK PRX 2019



GW170817: a sign of the tides

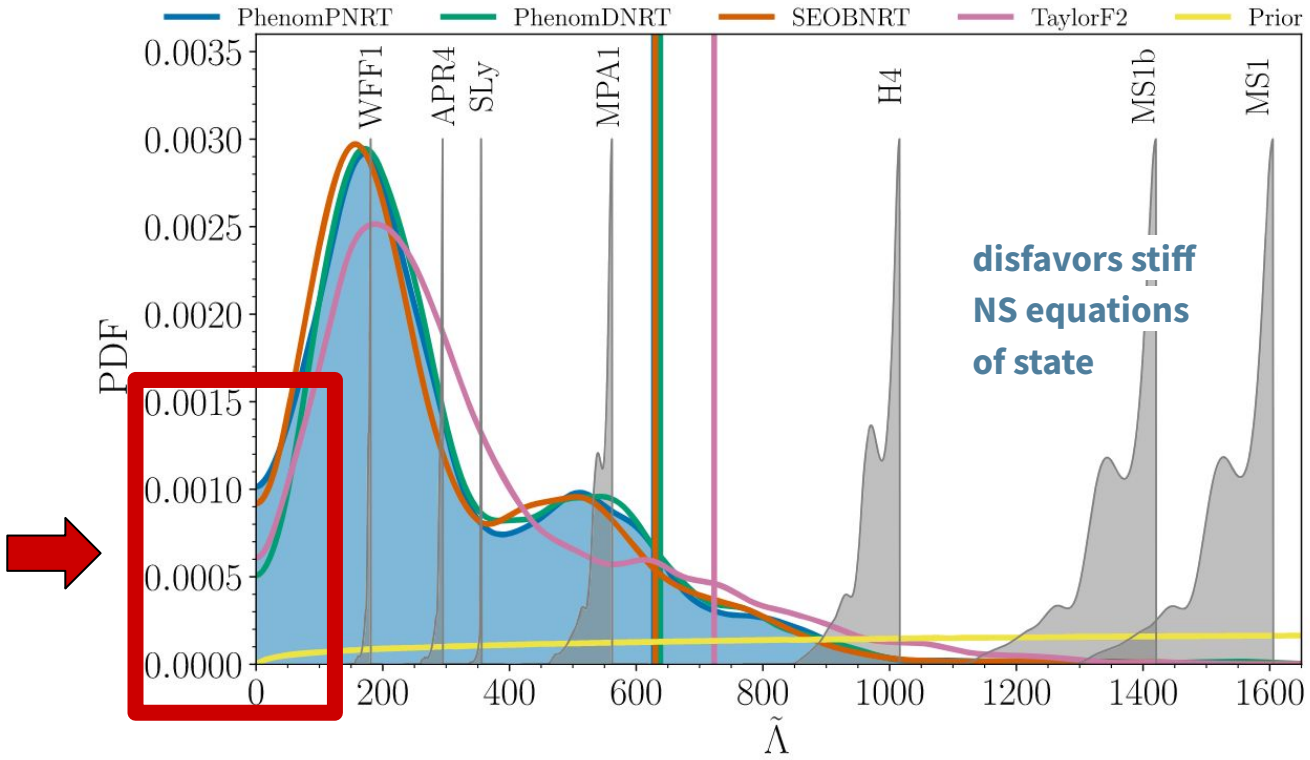
✔ Masses consistent with Galactic DNS

✔ EM counterparts

✔ **First measurement of tidal deformations**

technically can't rule out BBH scenario from GWs alone

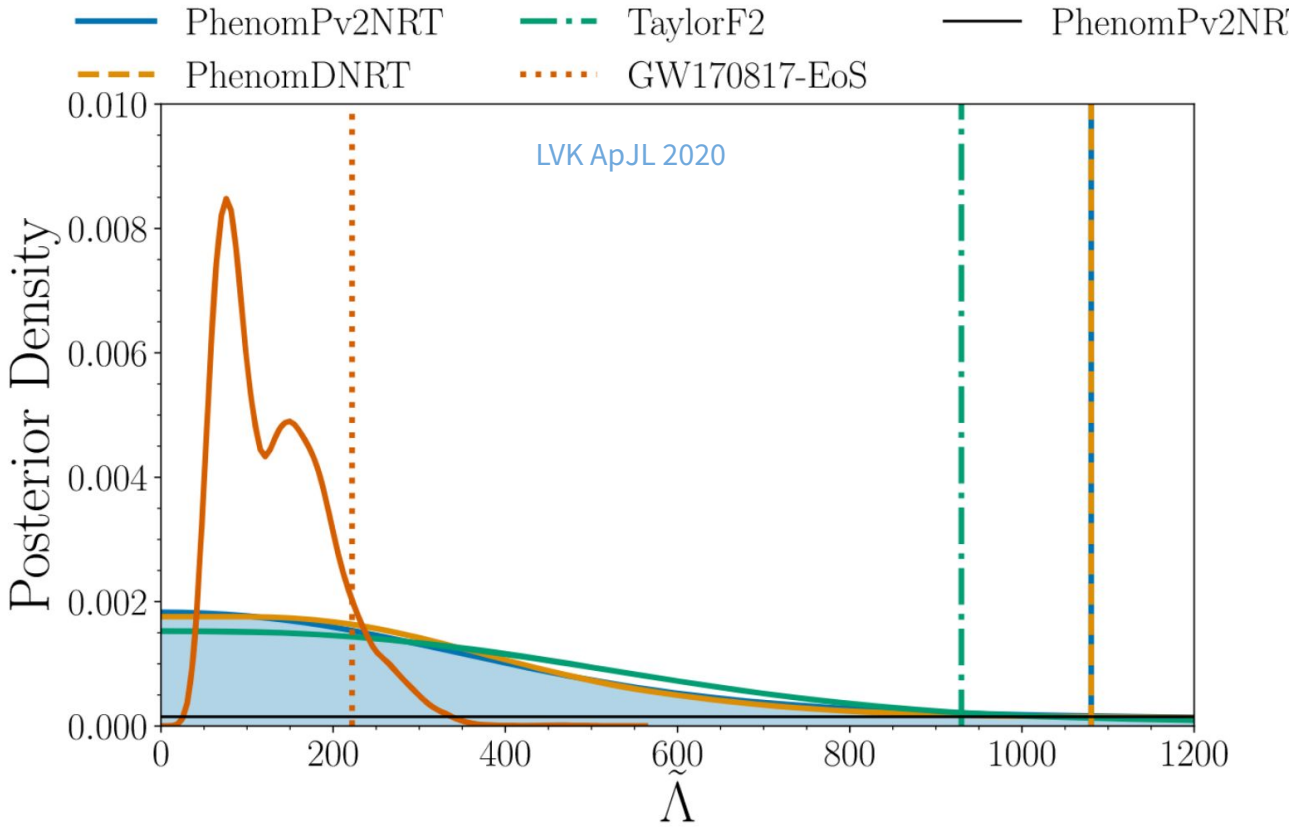
no assumption about spin LVK PRX 2019



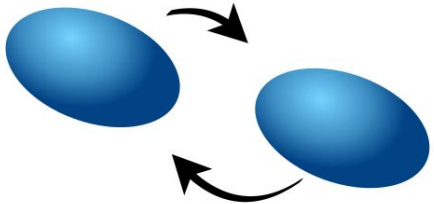
What about GW190425?

✗ No EM counterpart observed

- **Uninformative tidal measurement relative to expected signal**



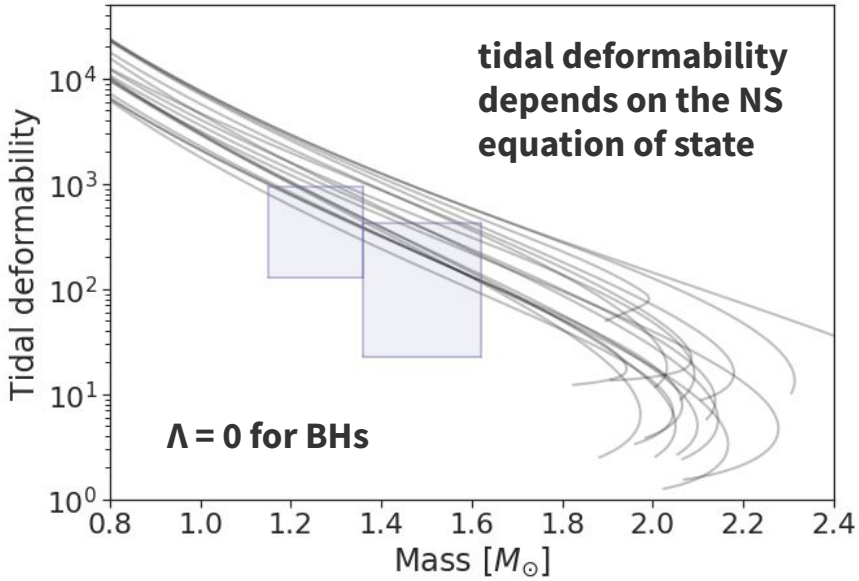
Tidal deformations

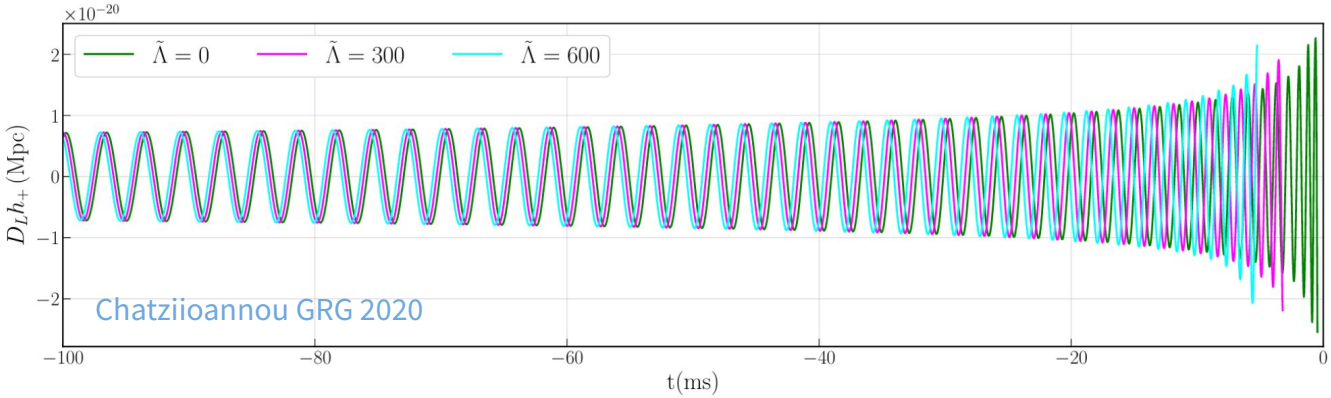


tidal deformability

$$Q_{ij} = - \Lambda\, m^5\, \mathcal{E}_{ij}^{\text{tidal}}$$

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$





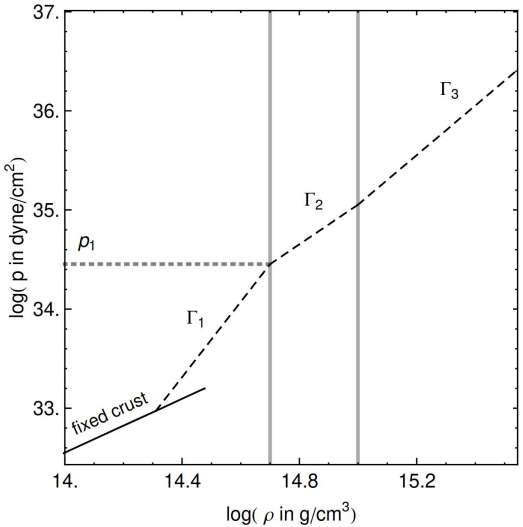
tidal phasing from leading-order quadrupole tides

Modeling the equation of state

Hierarchical Bayesian inference of the EOS

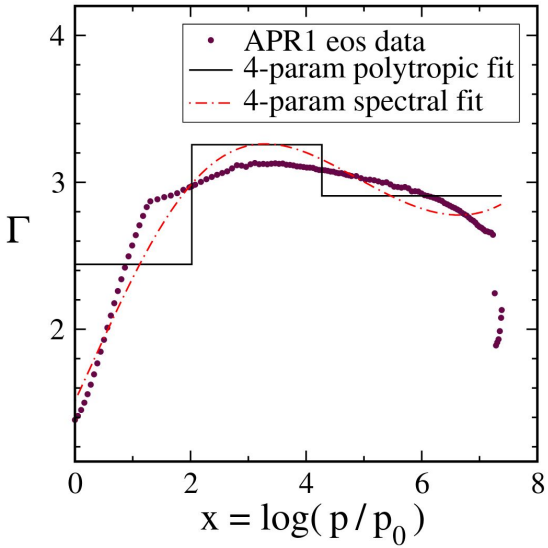
$$P(\Gamma_k|d) \propto P(\Gamma_k) \prod_i \int P(d_i|m^i_{1,2}, \Lambda^i_{1,2}) P(m^i_{1,2}, \Lambda^i_{1,2}|\Gamma_k) dm^i_{1,2} d\Lambda^i_{1,2}$$

eos prior **gw likelihood** **prior on gw params**



piecewise polytrope

Read+ PRD 2008



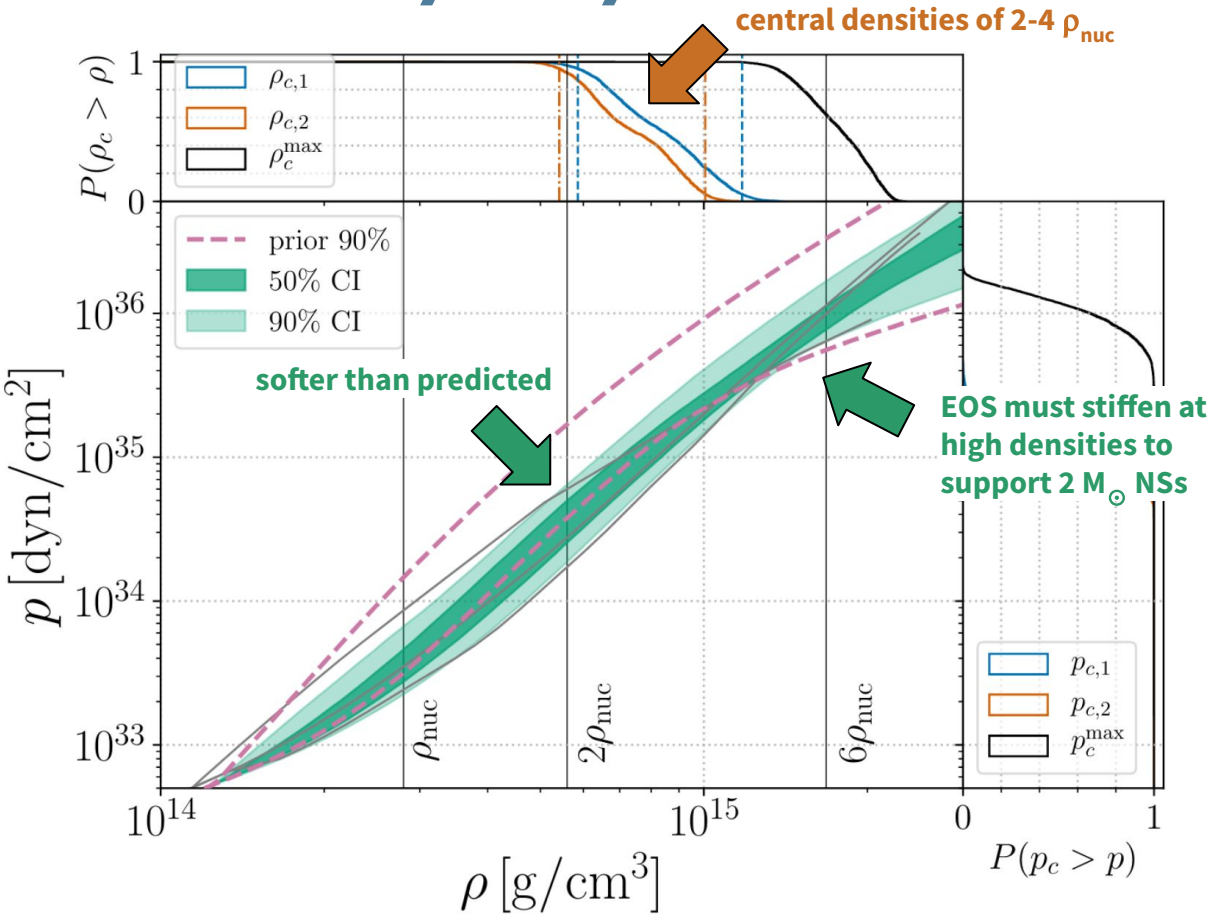
spectral expansion

Lindblom PRD 2010

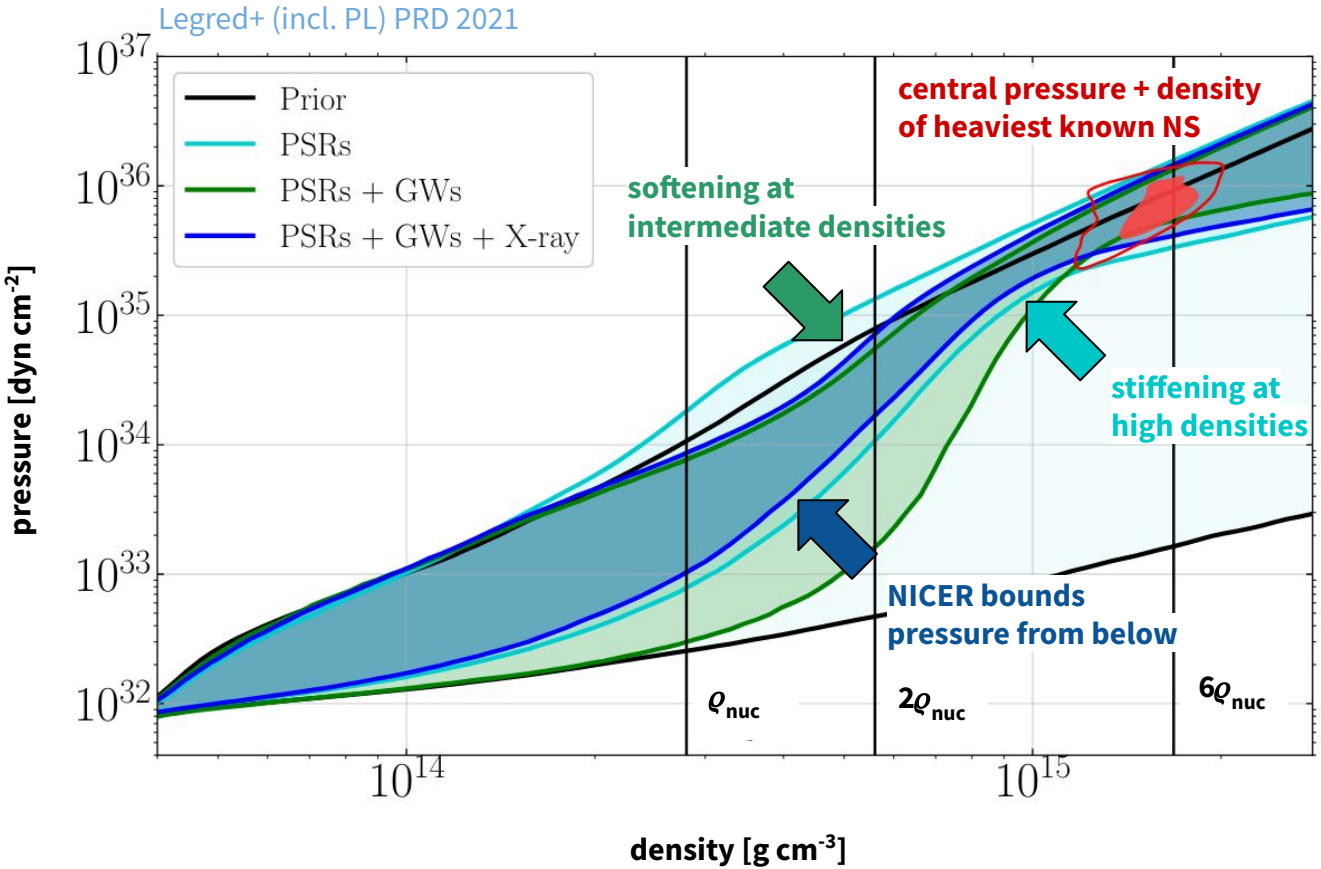
EOS constraints: GW170817

post-GW170817 EOS constraints

LVC (+PL) PRL 2018



Multimessenger EOS constraints

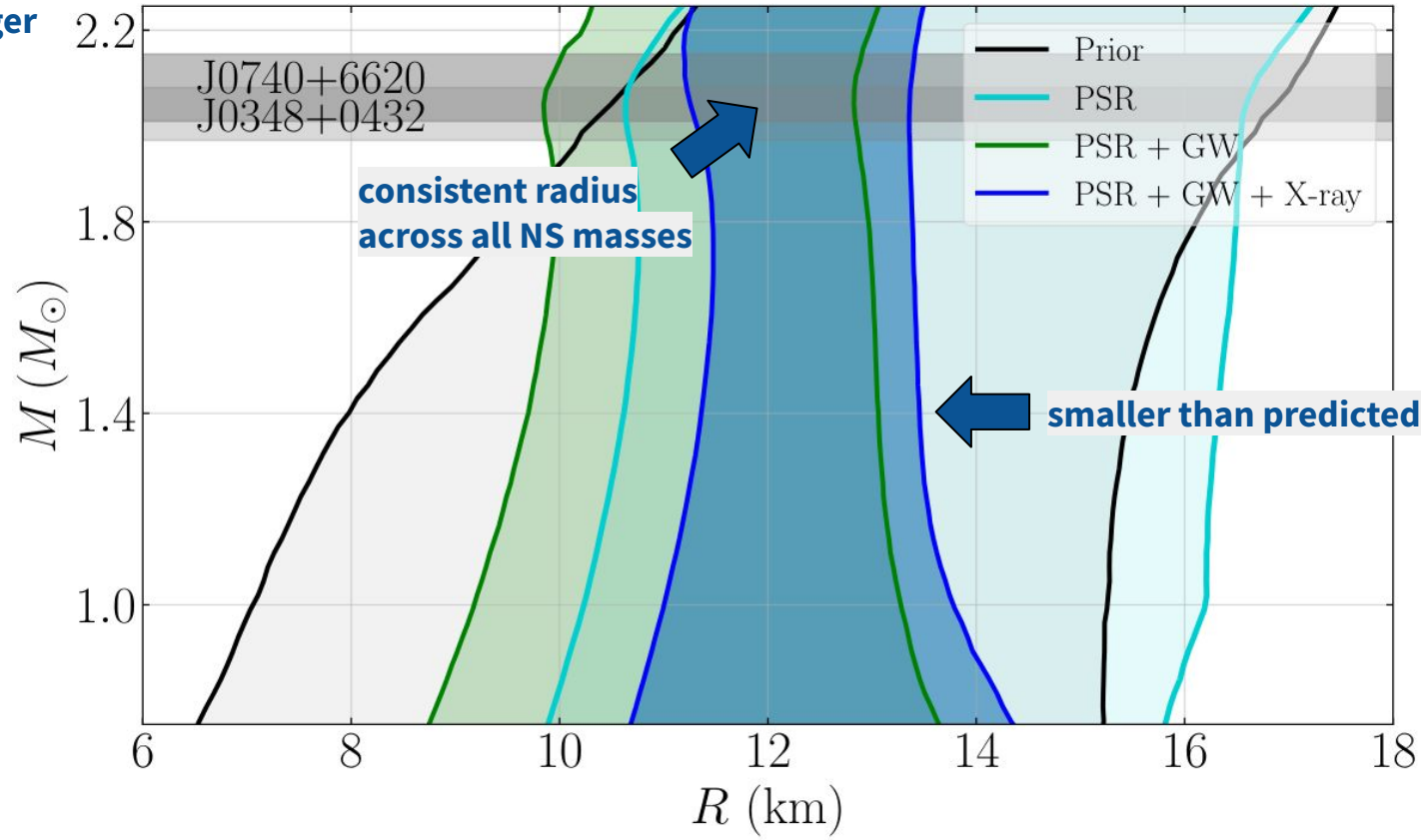


multimessenger EOS constraints

How big are neutron stars?

Legred+ (incl. PL) PRD 2021

multimessenger R constraints



What's the maximum neutron star mass?

Lower bound from...

- Mass of heaviest known pulsar

PSR J0740
m = 2.08 ± 0.07 $M_\odot$
Fonseca+ ApJL 2021

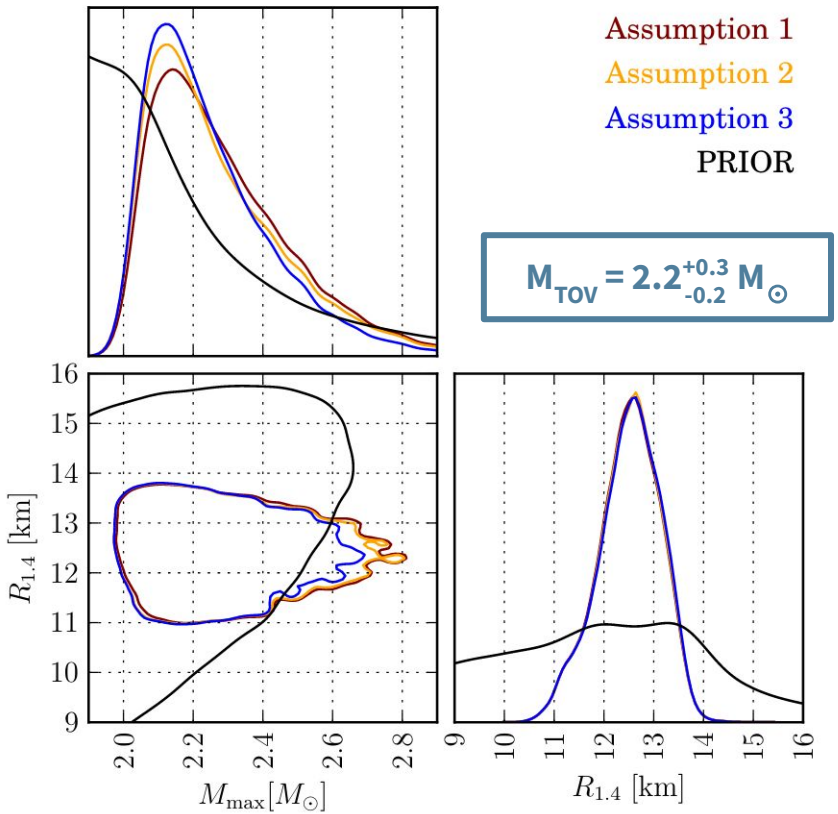
Upper bound from...

- Causality Rhoades+Ruffini PRL 1974
- Collapse of GW170817's 2.7 $M_\odot$ remnant

What about rotation?

- Rapid rotation can stabilize NSs up to ~20% more massive than the TOV mass, M_{TOV} Cook+ ApJ 1994
- Translates GW170817's rotating remnant mass to an upper bound of $M_{TOV} \lesssim 2.3\ M_\odot$ LVC (incl. PL) CQG 2020

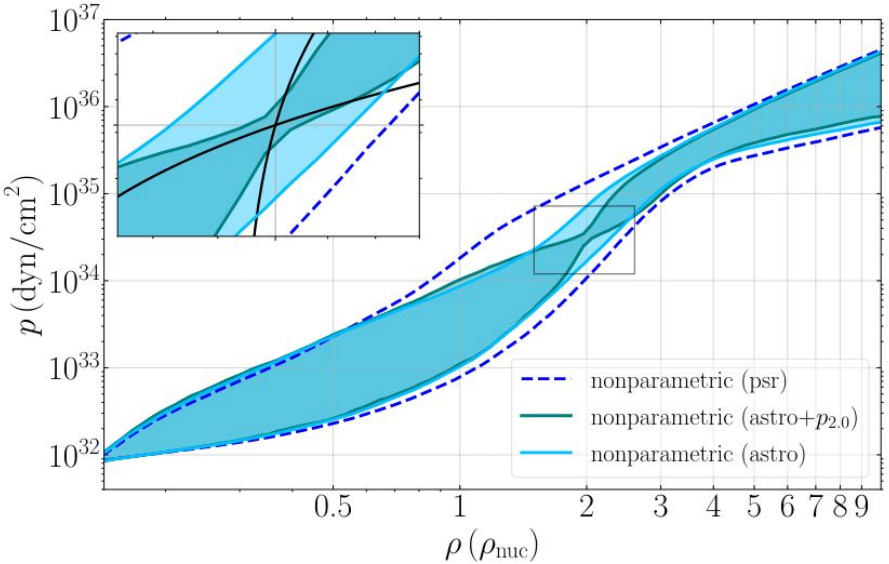
Legred+ (incl. PL) PRD 2021



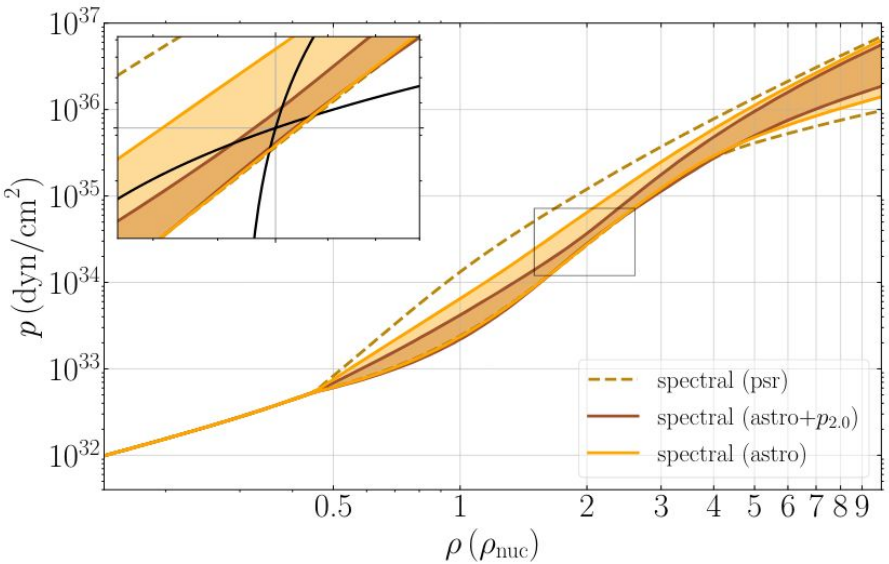
Modeling the equation of state II

Parametric EOS representations can introduce **artificial correlations** between different densities
(Legred+ (incl. PL) PRD 2022)

nonparametric



parametric



Modeling the equation of state II

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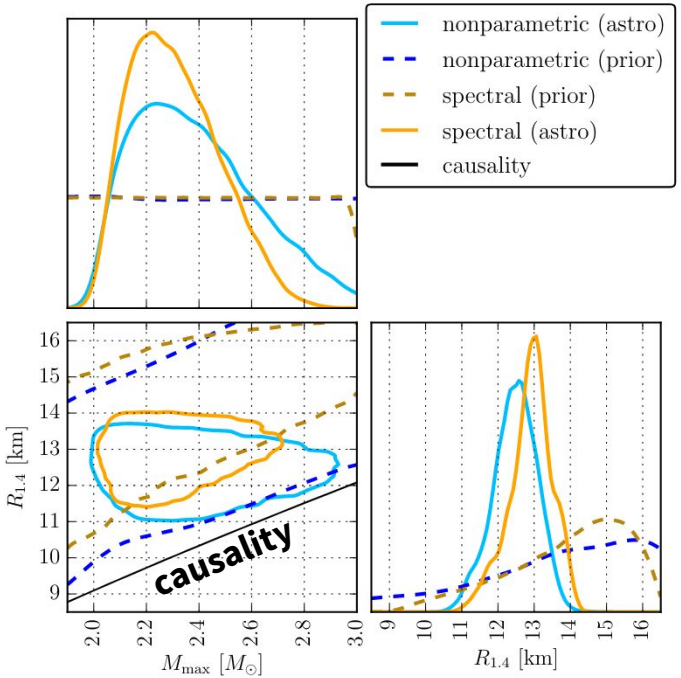
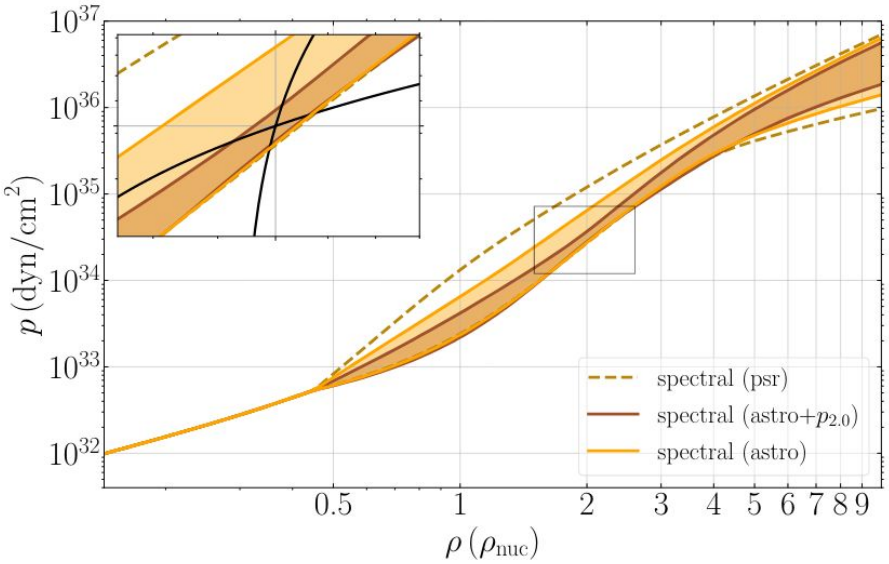


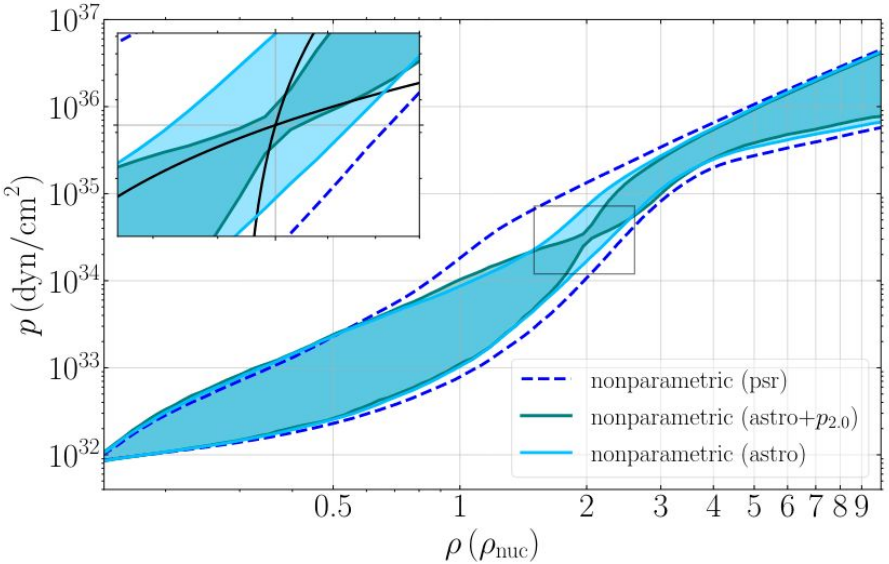
parametric

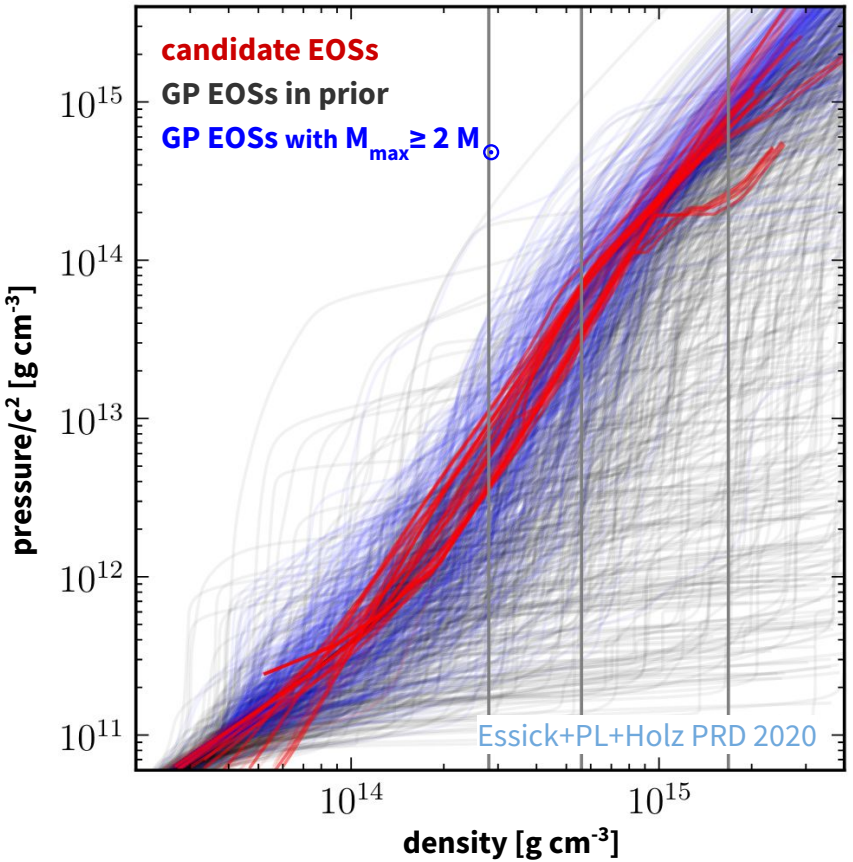


Modeling the equation of state II

Mitigate these **artificial correlations** with EOSs generated by Gaussian process regression
(Landry+Essick PRD 2018)

nonparametric

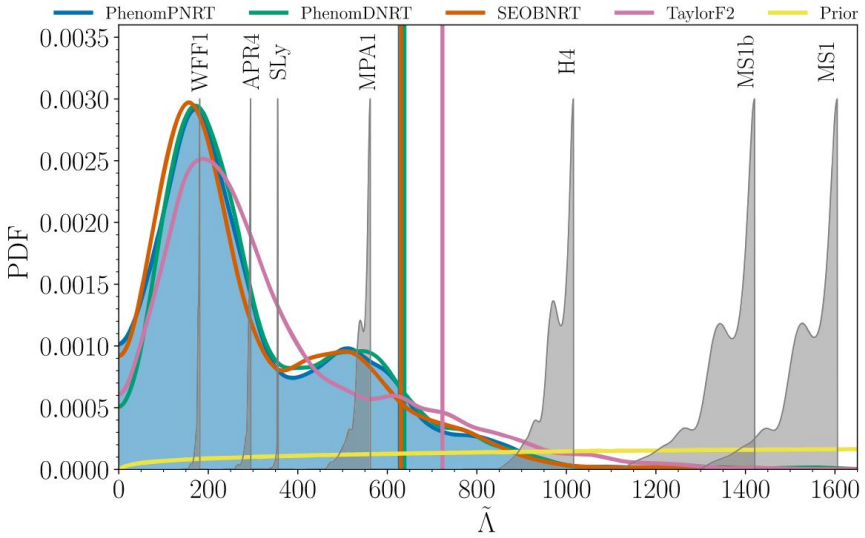




Waveform systematics

TaylorF2 – analytic post-Newtonian model
EOB – semi-analytic effective one-body model
NRT – tidal sector calibrated to numerical relativity
Phenom – PN model calibrated against EOB and NR

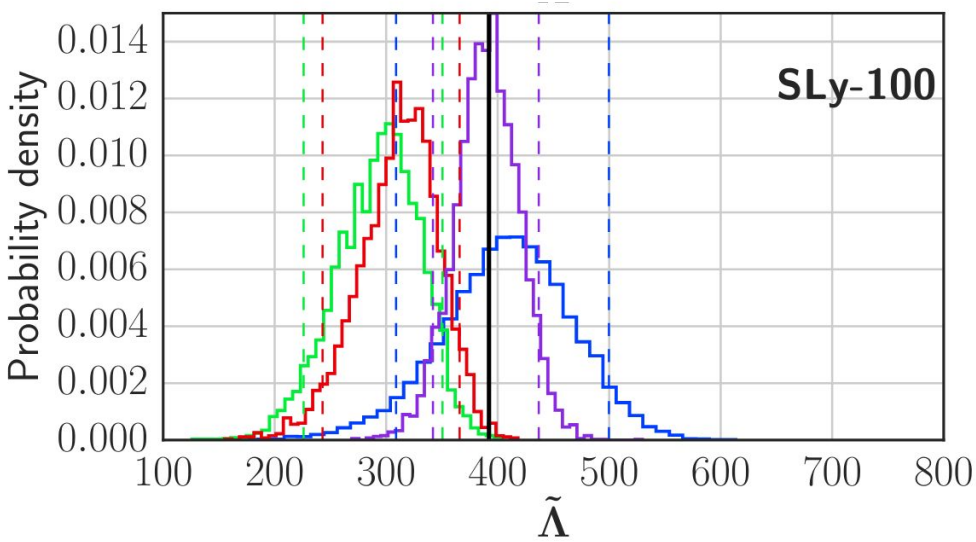
LVK PRX 2019



Systematics under control at SNR 32

Systematics a problem at SNR 100

Dudi+ PRD 2018



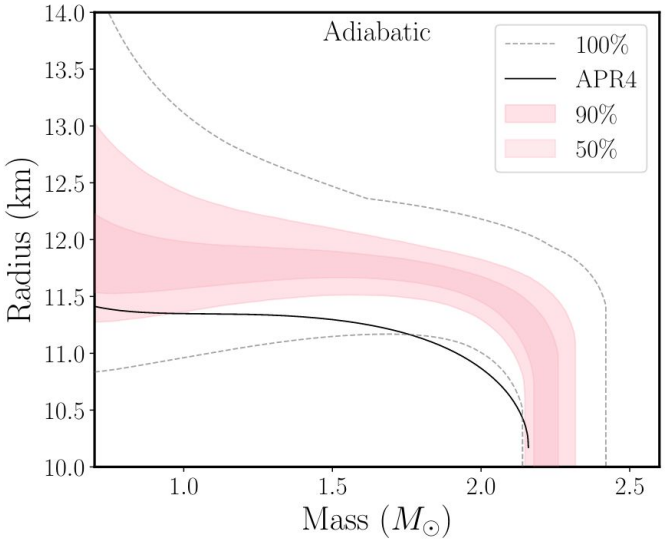
Beyond leading-order tides

Dynamical tides become important when $f_{mode} \sim f_{orb}$

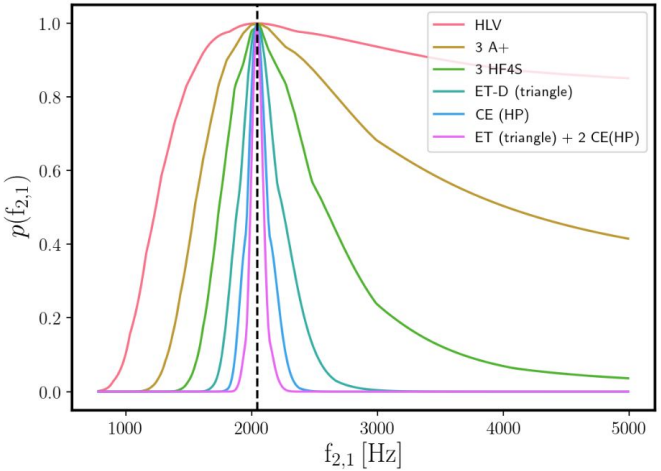
Largest tidal phasing comes from **fundamental mode**

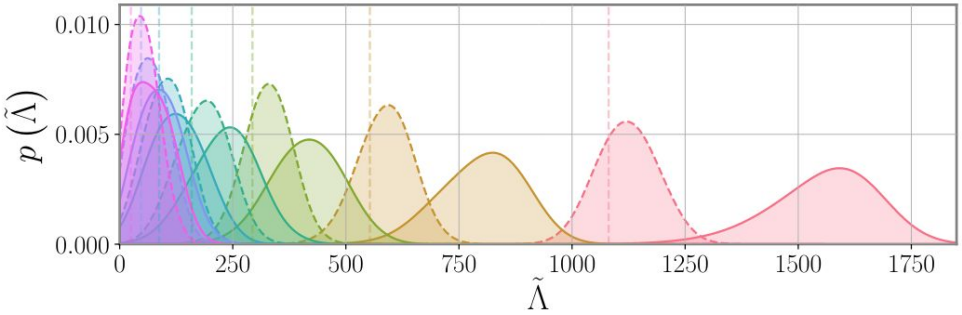
Not yet resolvable, but **biases EOS recovery** if not modeled

Pratten+ arXiv:2109.07566



Pratten+ NatComm 2020

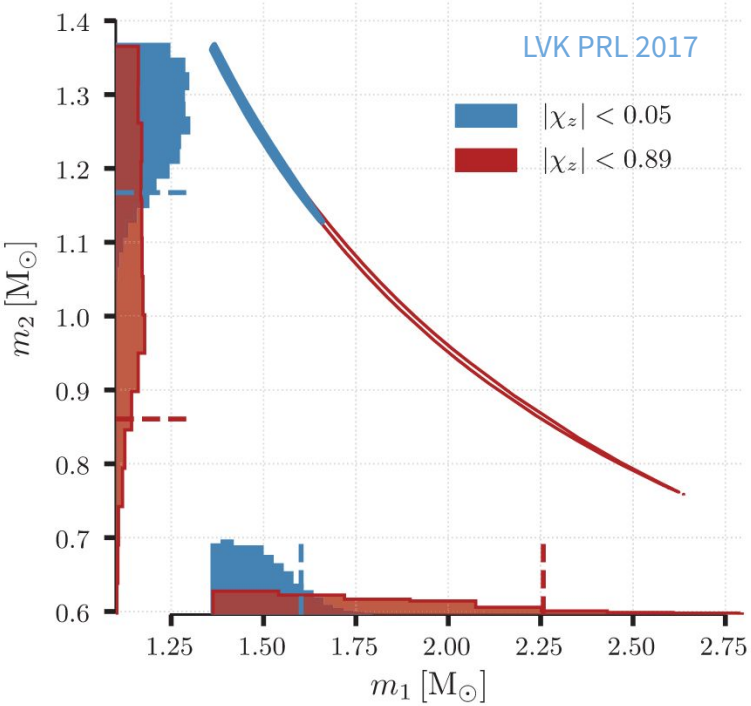


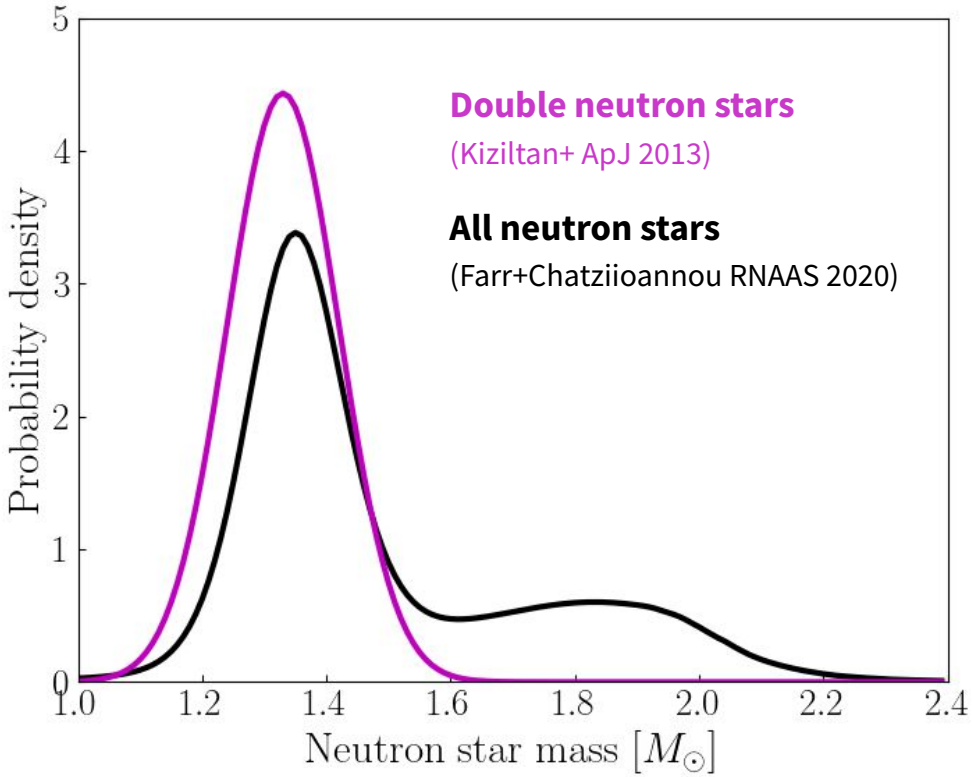


2. Masses

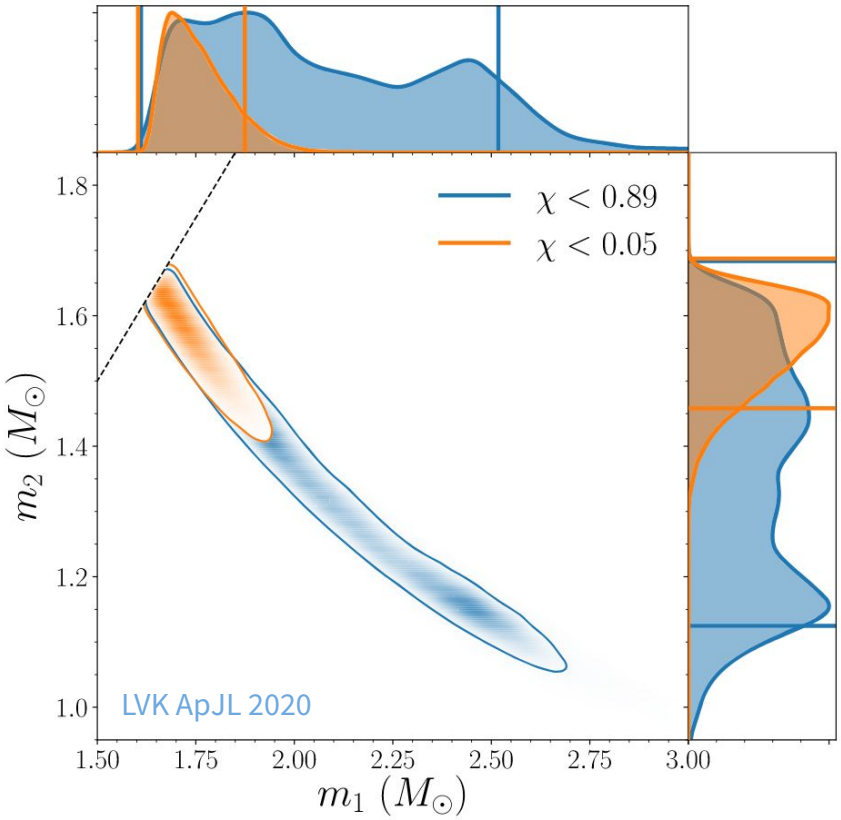
Binary neutron star masses: GW170817

GW170817 is a vanilla BNS

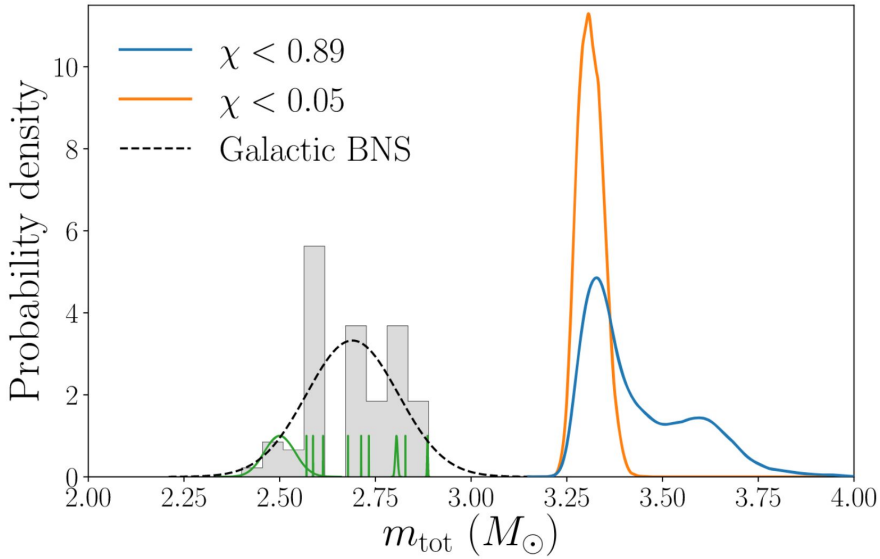




Binary neutron star masses: GW190425

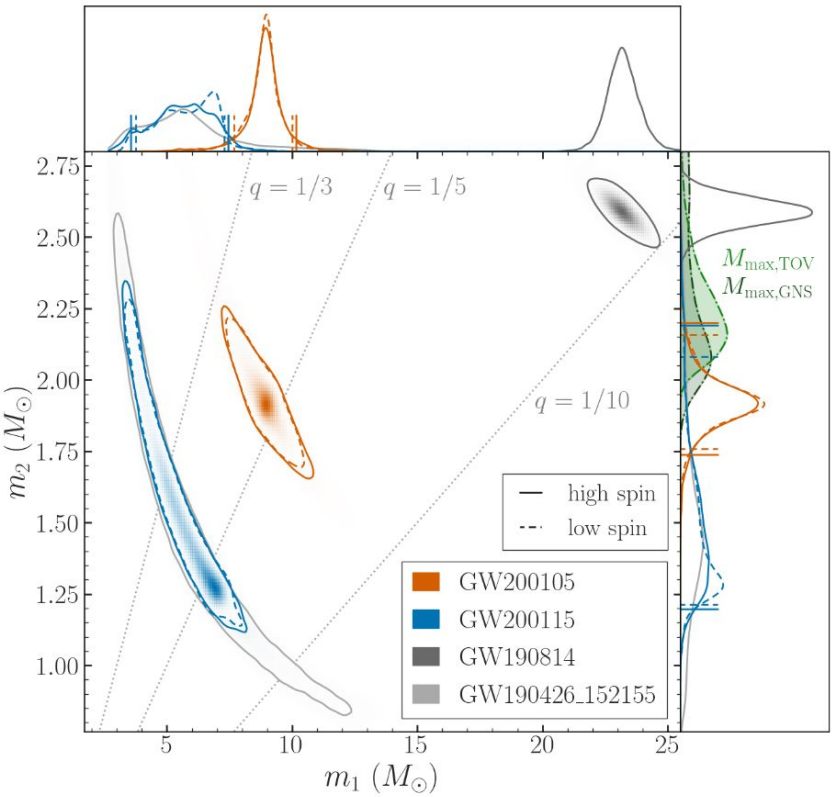


GW190425 is an outlier in total mass



Neutron star-black hole mergers?

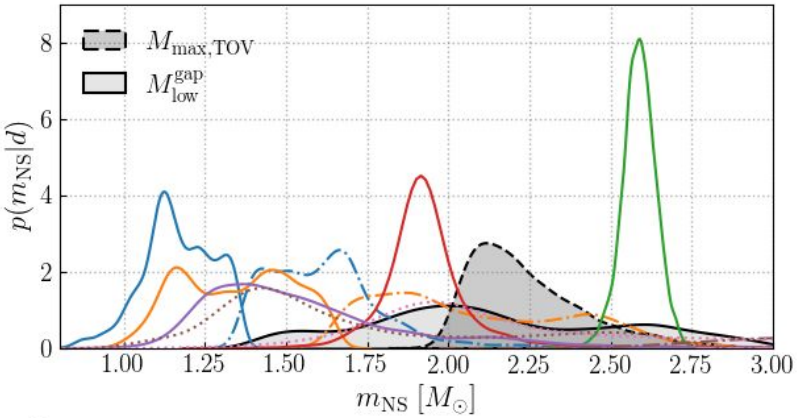
LVK arXiv:2111.03606



No tides or EM counterpart observed for these events

GW200105 and GW200115 secondary masses are both securely below M_{TOV}

LVK arXiv:2111.03634



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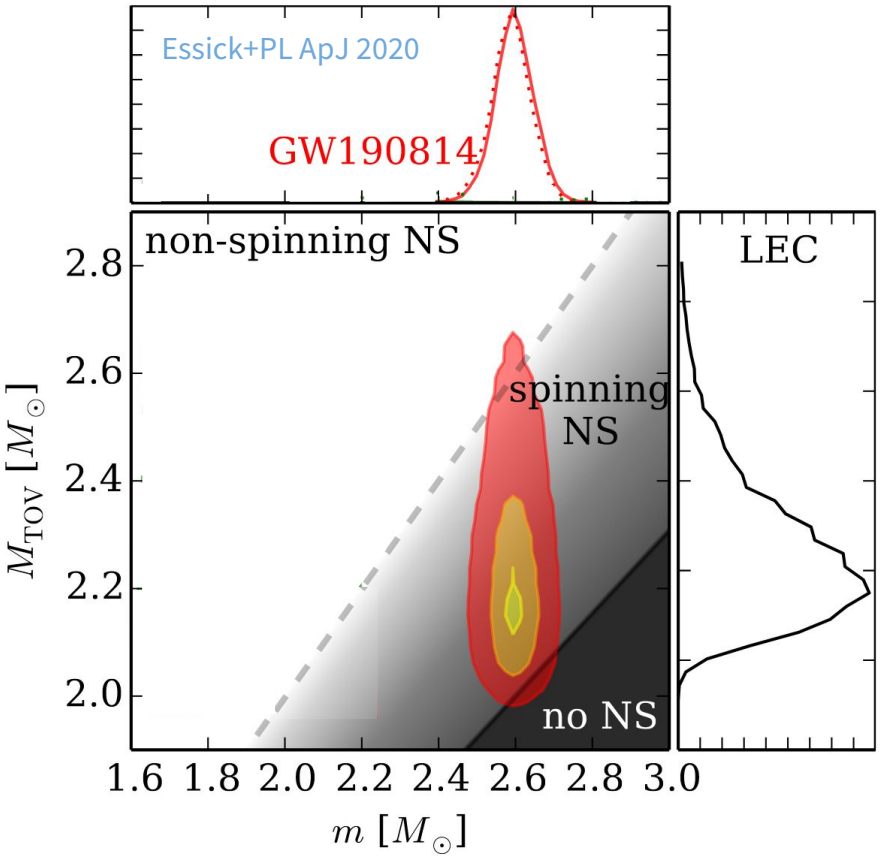
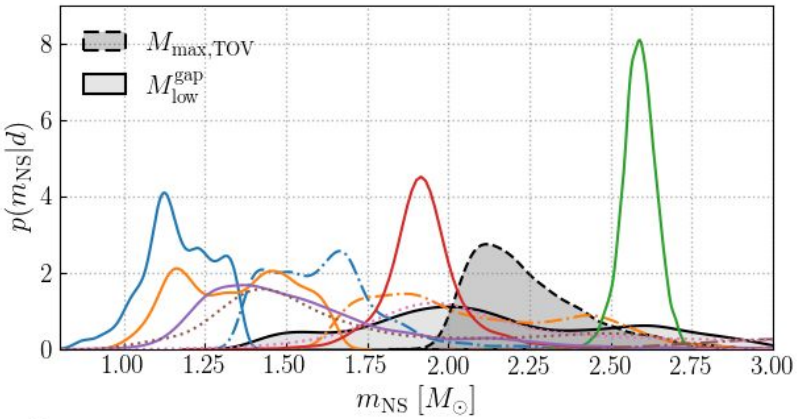


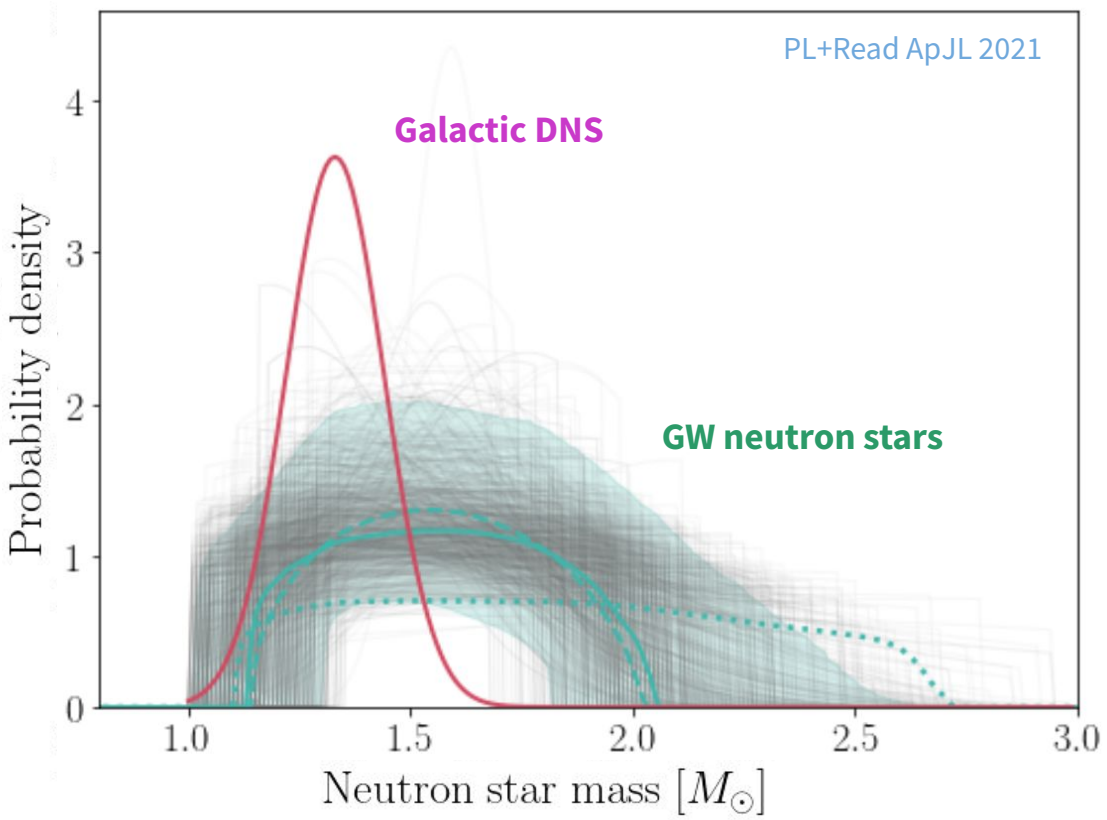
No tides or EM counterpart observed for these events

GW190814's secondary mass is above M_{TOV} – probably the lightest known black hole

LVK arXiv:2111.03634



Extragalactic neutron star mass distribution



Maximum mass in the population

PL+Read ApJL 2021

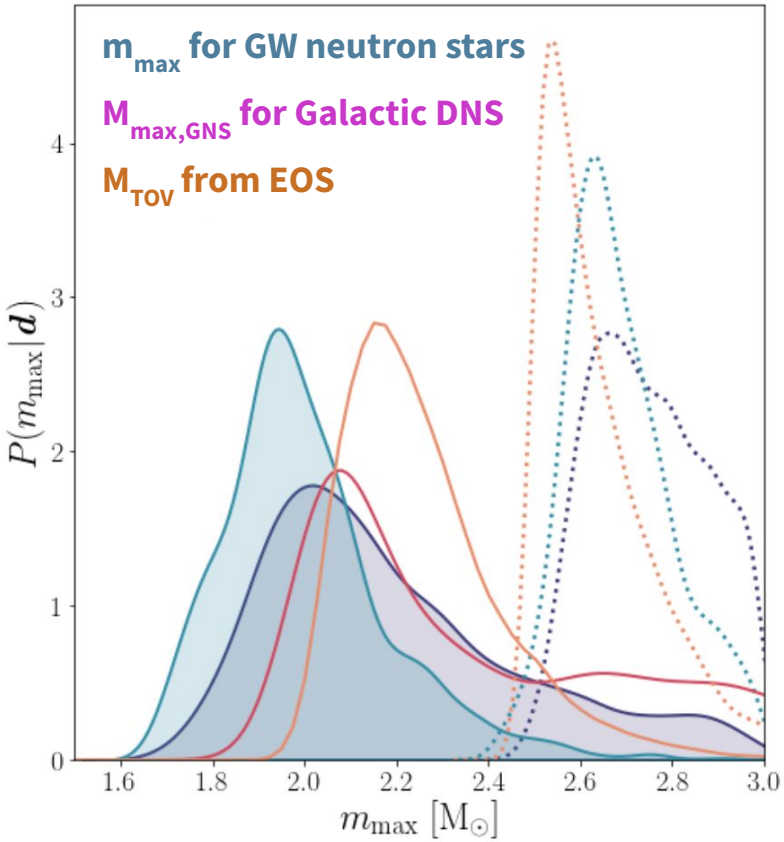
If $m_{max} < M_{TOV}$

↳ formation channel limits the neutron star mass spectrum

If $m_{max} < M_{max,GNS}$

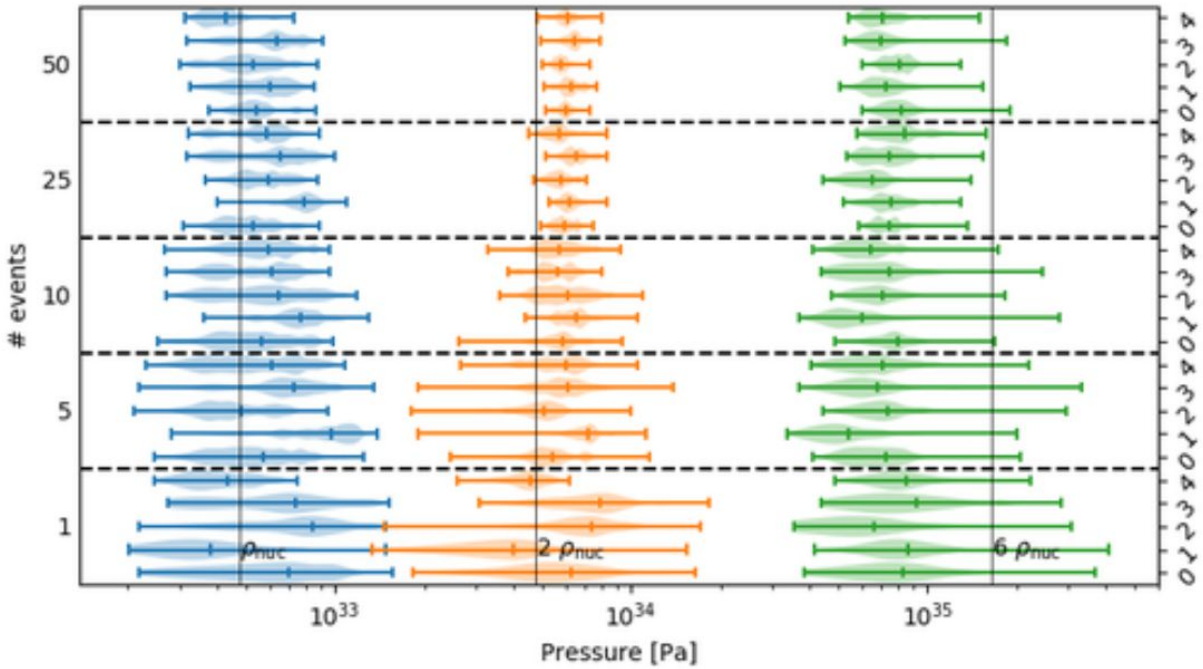
↳ binary evolution prevents heaviest neutron stars from merging

Neutron stars as heavy as can be supported by the EOS seem to end up in merging compact binaries.

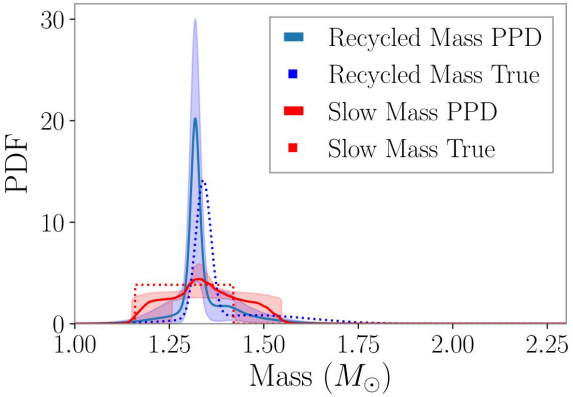


Mismodeling the neutron star population

Choosing wrong population-level mass prior **biases recovered EOS** after O(10) events
(Wysocki+ arXiv:2001.01747)



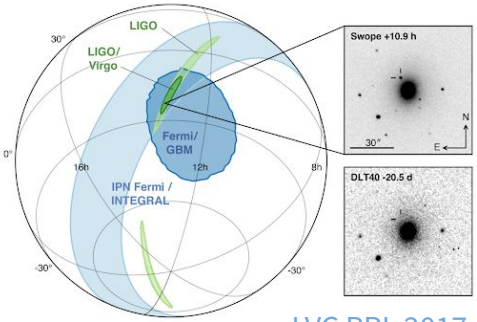
Converse also true:
mismodeling EOS biases recovered mass distribution
(Golomb+Talbot ApJ 2022)



3. Electromagnetic counterparts

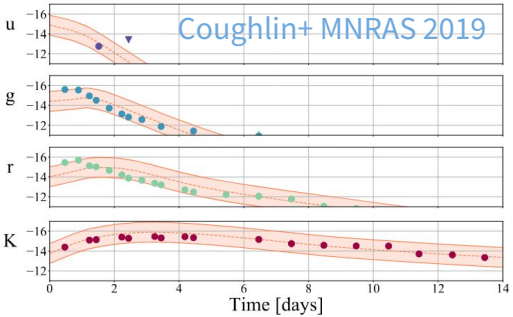
The bright counterparts to GW170817

BNSs identified as sGRB progenitors



LVC PRL 2017

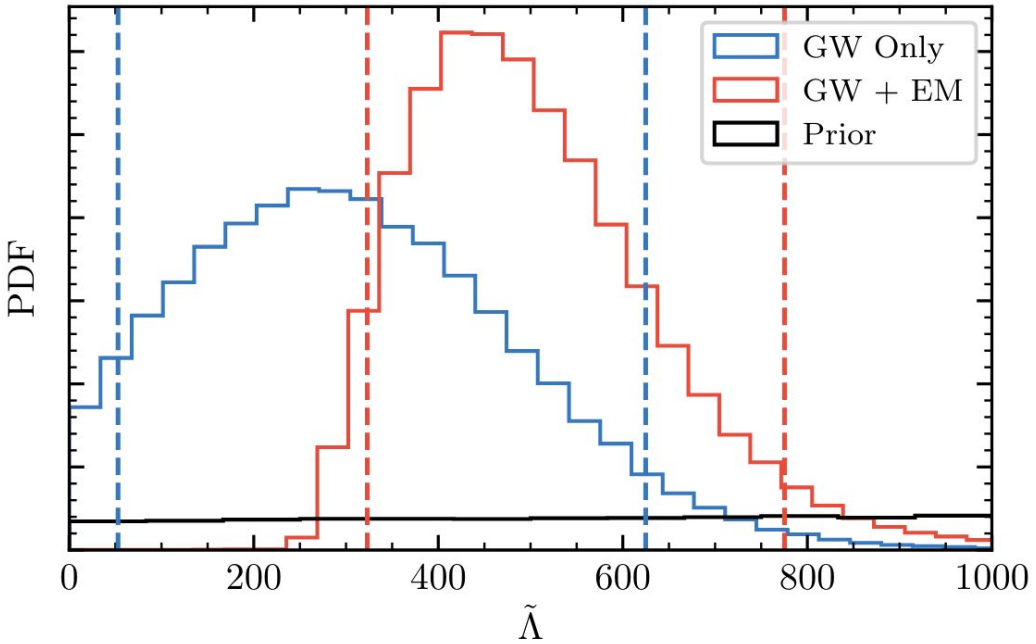
… and as sites for heavy element nucleosynthesis



Coughlin+ MNRAS 2019

Kilonova observations set lower bound on Λ
… but beware of lightcurve model systematics!

Radice+Dai EPJA 2019

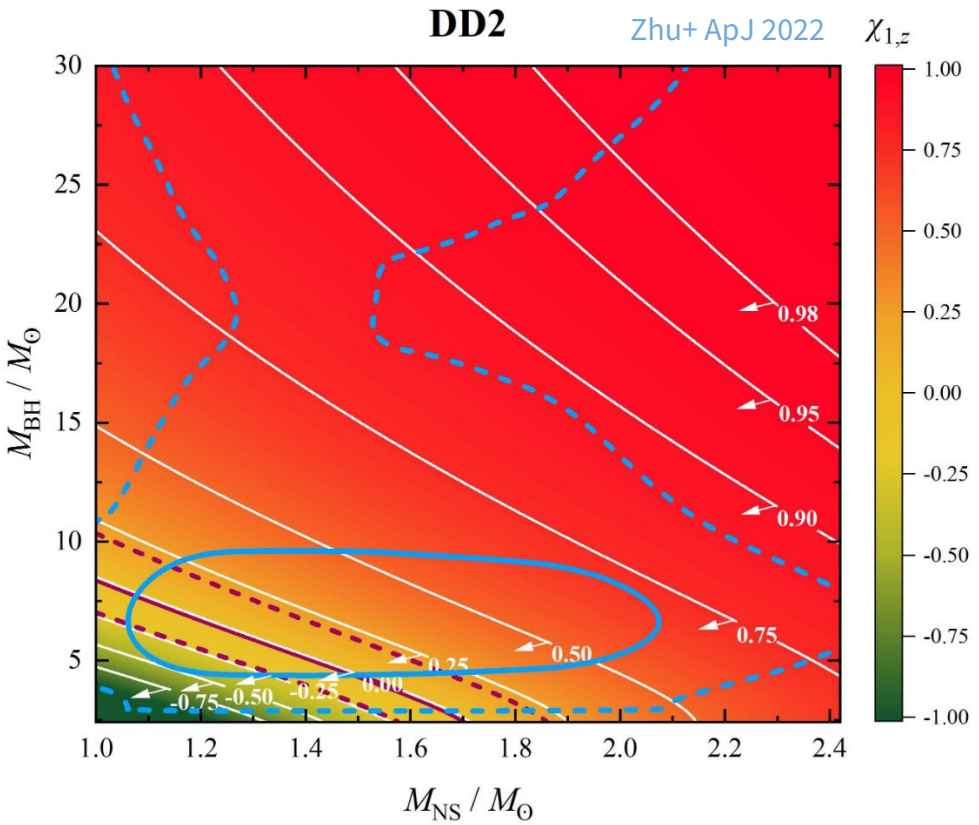


Tidal disruption in NSBHs: dimmer prospects

Observed NSBH population

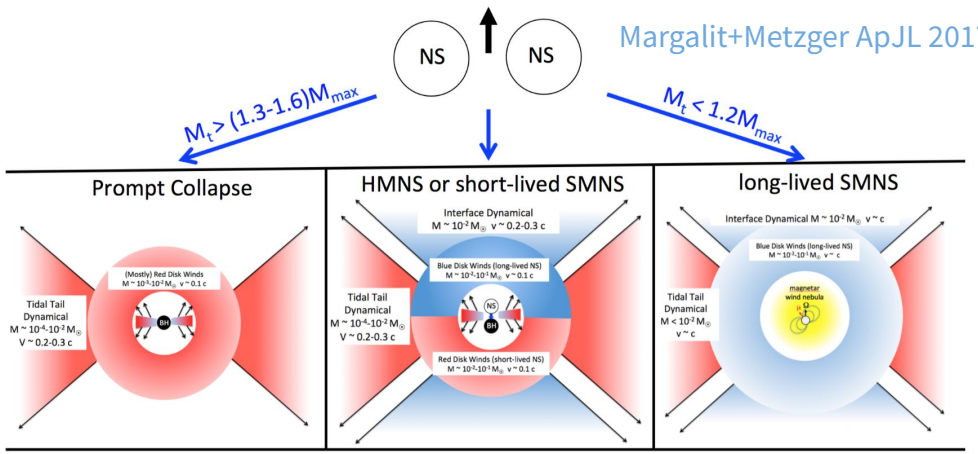
Observed BH spin distribution

Tidal disruption occurs only where NSBH population and BH spin contours overlap!



4. Postmerger remnant

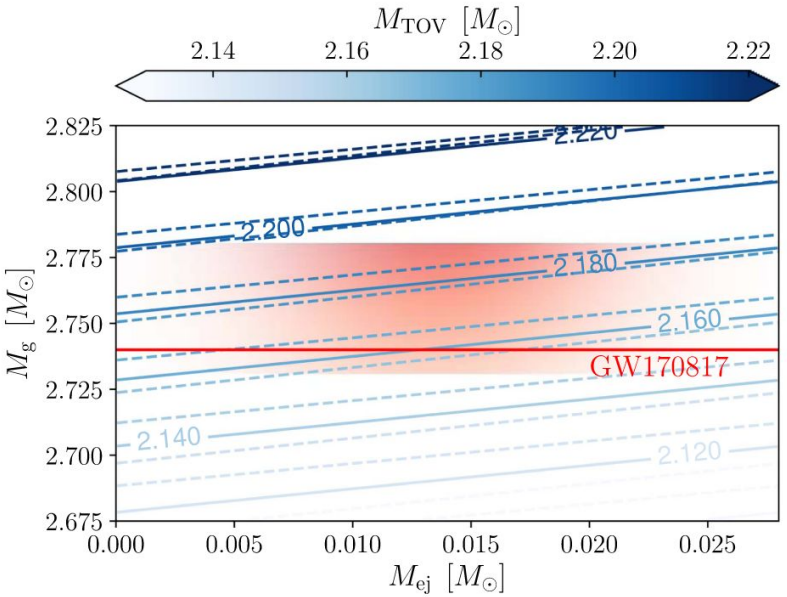
GW170817's remnant



Margalit+Metzger ApJL 2017

See also LVC CQG 2020, which finds $M_{TOV} < 2.3\ M_\odot$

Rezzolla+ ApJL 2018

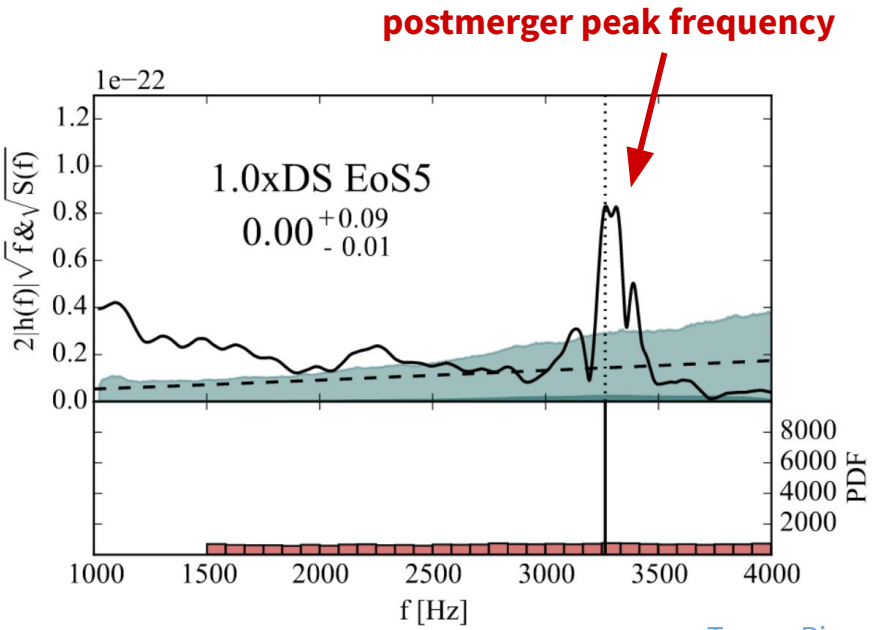


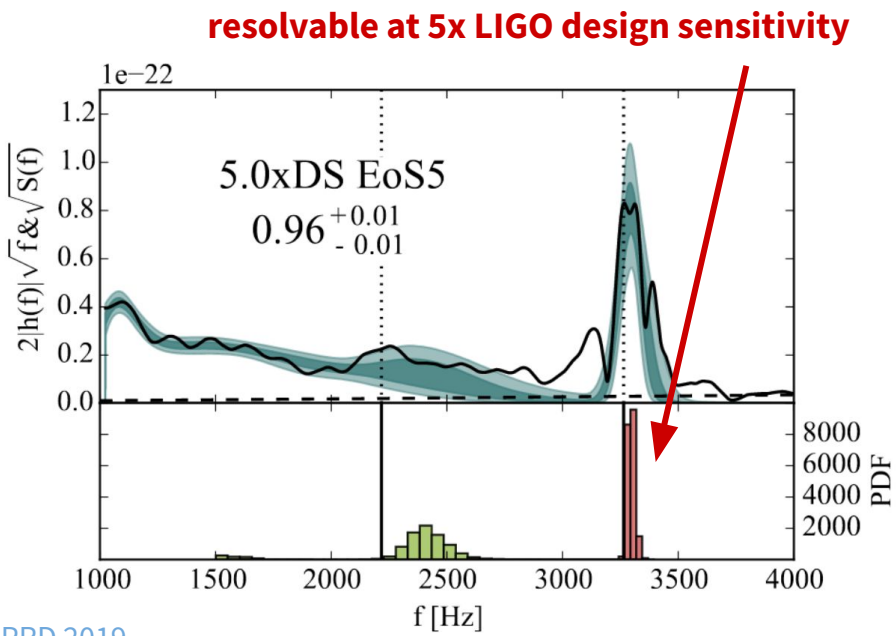
Electromagnetic observations suggest the merger remnant collapsed to a BH

This sets the threshold mass for collapse, which can be connected to M_{TOV} via simulations

Postmerger gravitational waves

No postmerger gravitational waves observed for GW170817, but possible with future sensitivity improvements



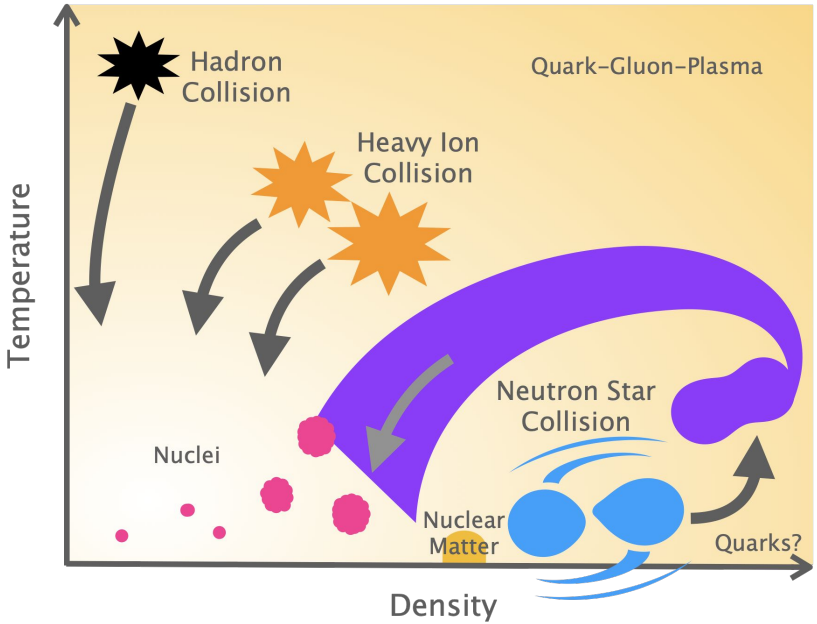


Torres-Rivas+ PRD 2019

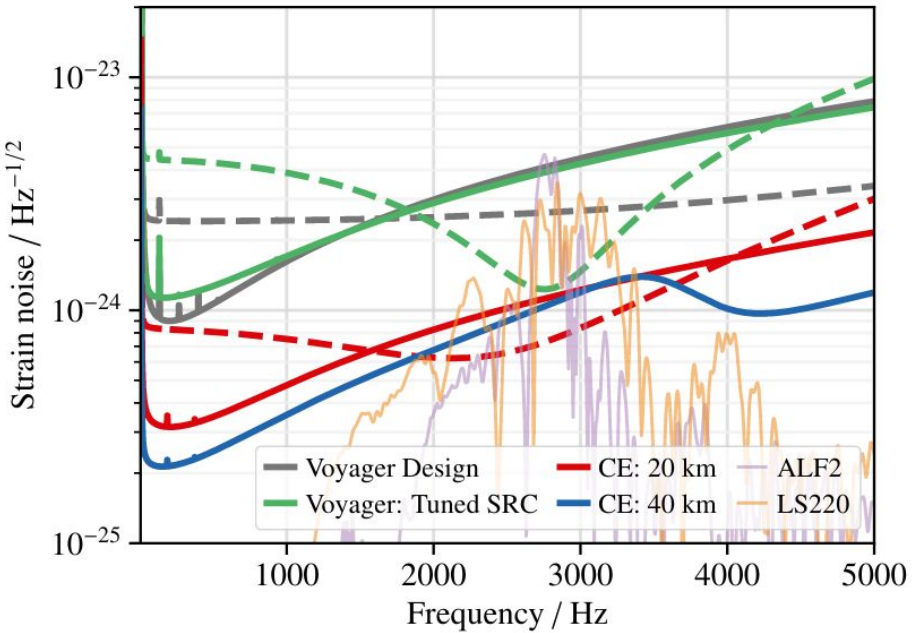
Postmerger gravitational waves

Postmerger gravitational waves probe matter in a different regime than inspiral – differences vs predictions are what will be interesting!

Evans+ (incl. PL) arXiv:2109.09882



Srivastava+ (incl. PL) arXiv:2201.10668



Matter effects: eos + waveform systematics? dynamical tides?

Masses: maximum neutron star mass? population + eos modeling?

Electromagnetic counterparts: lightcurve models? tidal disruption?

Postmerger remnant: detectability? finite temperature + microphysics?