Prospects and challenges for dense matter studies with gravitational waves

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ACFI workshop – 13 Oct 2022

Neutron stars in LVK O3

BNS rate of ~ 440 $Gpc^{-3}\ yr^{-1}$

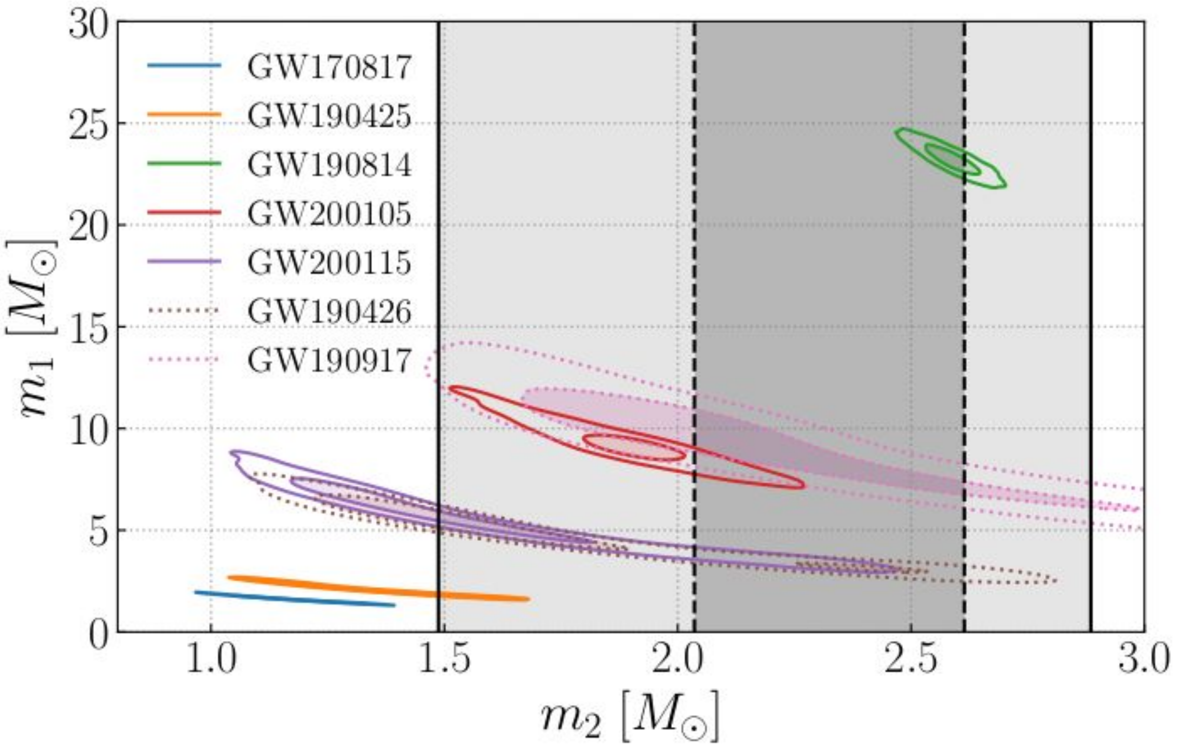
NSBH rate of ~ 60 $Gpc^{-3}\ yr^{-1}$

cf. post-GW170817 BNS rate estimate of ~ 3800 $Gpc^{-3}\ yr^{-1}$

or BBH rate of ~ 35 $Gpc^{-3}\ yr^{-1}$

LVK LRR 2020

LVK arXiv:2111.03634



What to expect in LVK O4?

BNS range of ~ 190 Mpc, search VT of ~ 0.016 Gpc^3 yr LVK LRR 2020

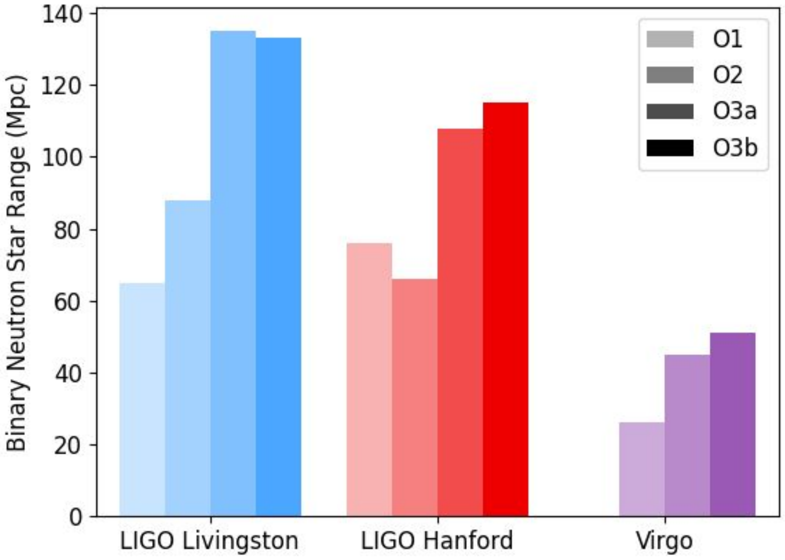
- ~ 7 expected BNS detections

NSBH range of ~ 330 Mpc, ~ 5x larger search VT but ~ 7x lower rate than BNSs

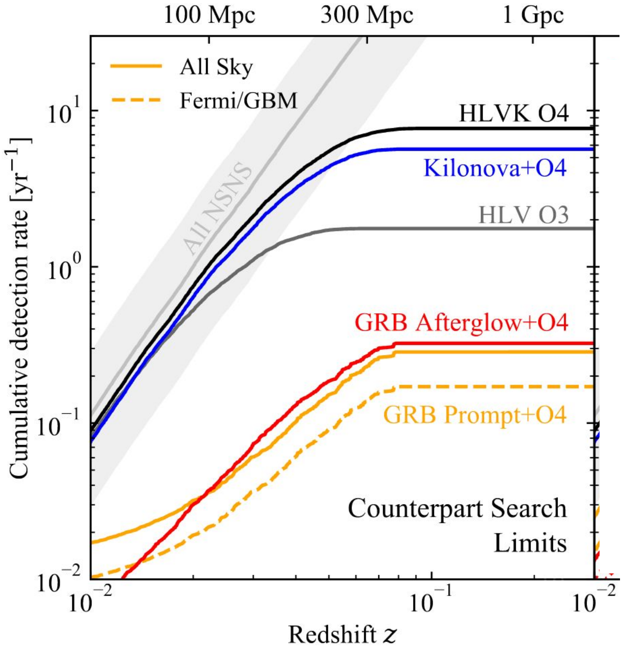
- ~ 5 expected NSBH detections

LVK O5 (ca. 2025) is projected to increase search VTs by another ~ 5x

LVK/Hannah Middleton/OzGrav



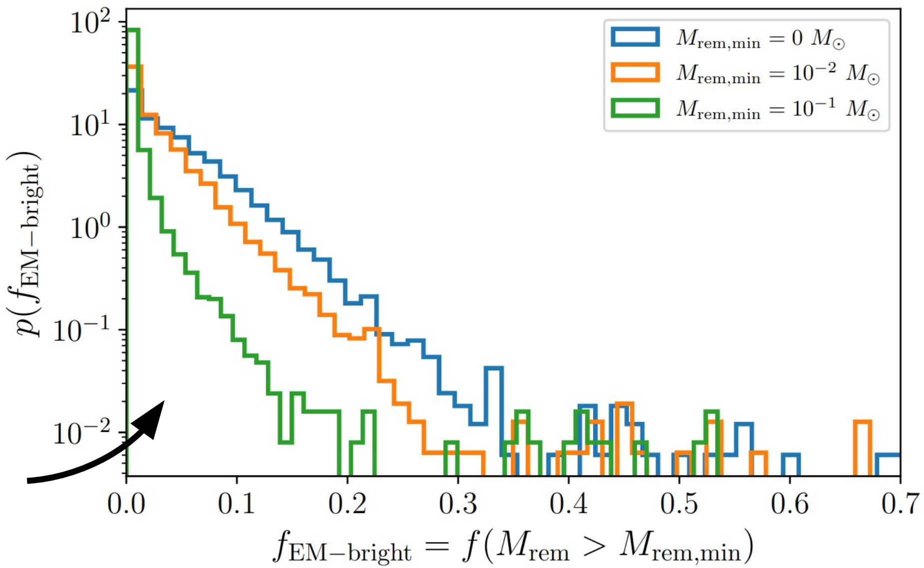
Multimessenger forecasting



80% of BNS mergers estimated to produce a kilonova, but only ~ 10% will be detectable → reasonable to expect 1 EM counterpart in O4

Colombo+ ApJ 2022, cf. Patricelli+ MNRAS 2022

Biscoveanu+PL+Vitale arXiv:2207.01568



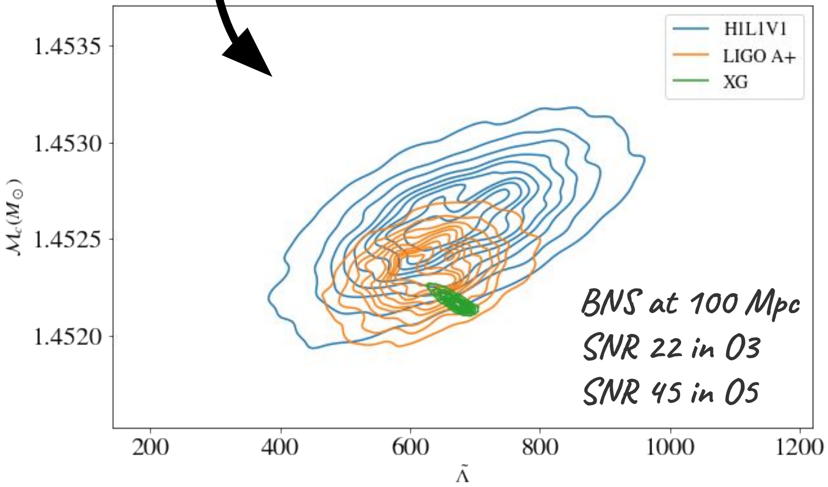
90% credible upper bound on fraction of NSBH population with any ejecta whatsoever is ~ 10%

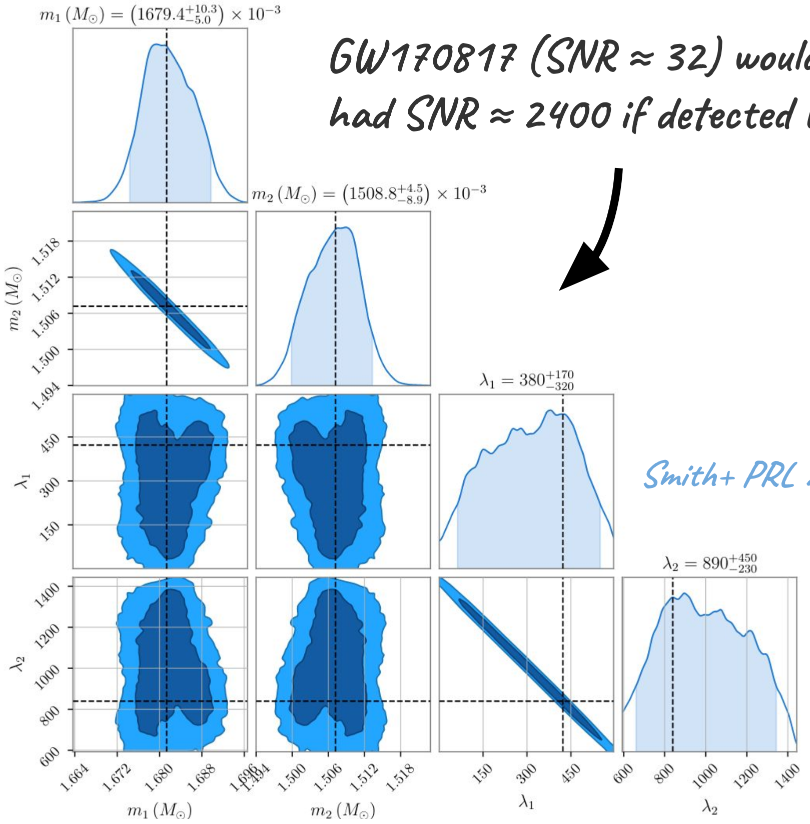
Future BNS tidal measurements

statistical error of ±100 in binary tidal deformability in O5

GW170817 (SNR ≈ 32) would have had SNR ≈ 2400 if detected in XG!

Wuchner+PL+Read (in prep)



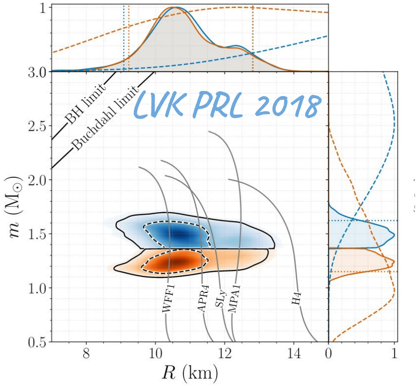


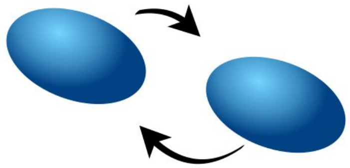
Smith+ PRL 2021

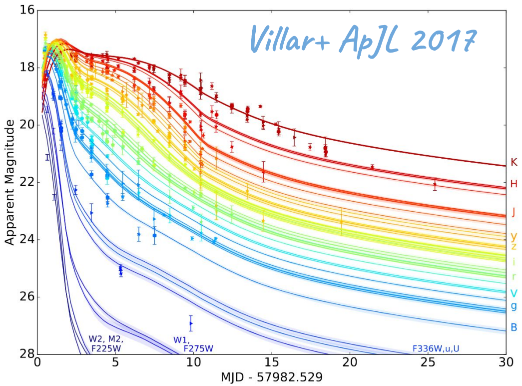
5PN tidal parameter $\tilde{\Lambda}$: measurable

6PN tidal parameter $\delta\tilde{\Lambda}$: not measurable!

Inferring dense matter properties from GWs







hierarchical Bayesian EOS inference from GW observations

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

EOS prior

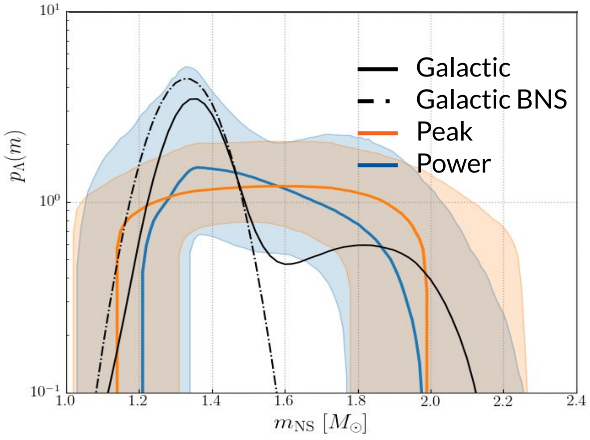
i^{th} GW likelihood

common prior on source properties

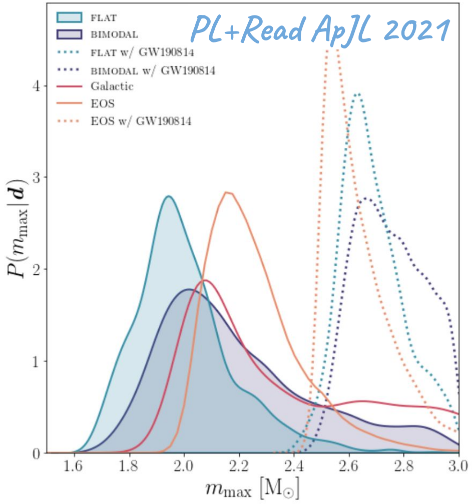
Astrophysical uncertainties

- *shape of the NS mass distribution: uniform or bimodal?*
- *BNS (or NSBH) pairing function: random or preferentially equal-mass?*
- *lower mass gap: disjoint, contiguous, or overlapping NS and BH mass spectra?*
- *maximum mass in the NS population: less than, equal to, or larger than M_{TOV}?*
- *NS spin distribution: fast or slow?*

LVK arXiv:2111.03634

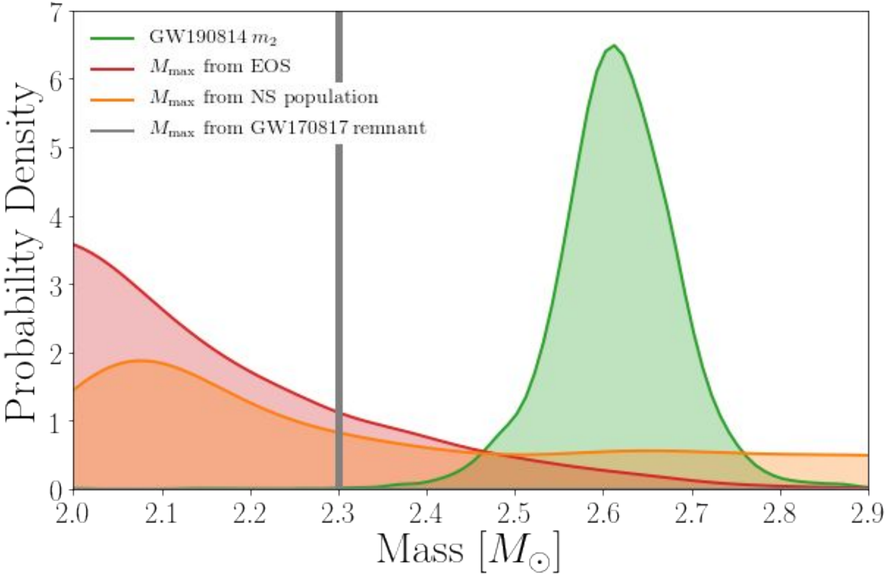


PL+Read ApJL 2021

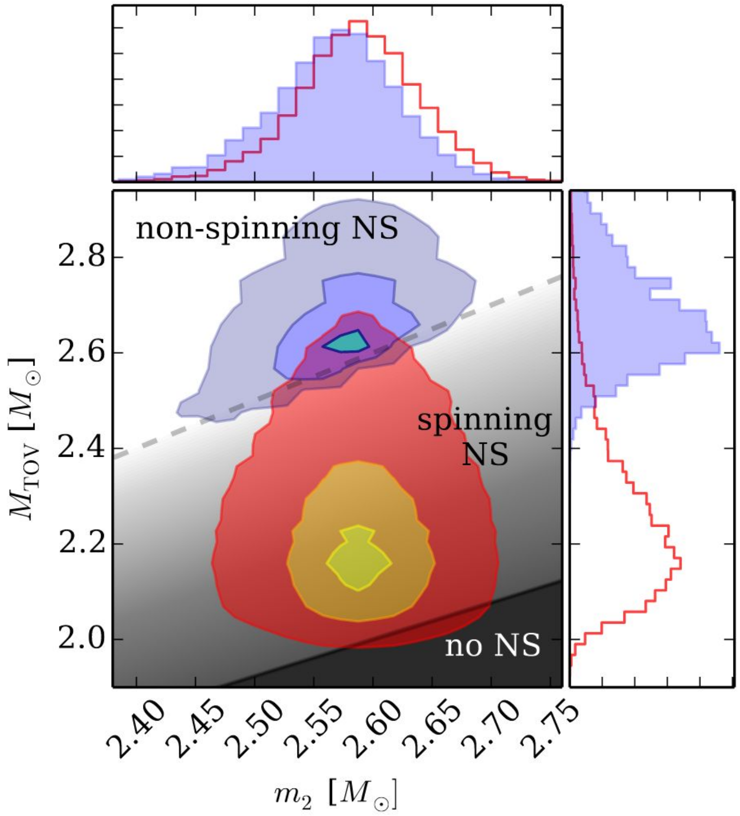


Does the population really matter?

population assumptions inform the classification of GW190814 as a NSBH or a BBH merger, and strongly impact the inferred maximum TOV mass



Essick+PL ApJ 2020



Population assumptions in EOS inference

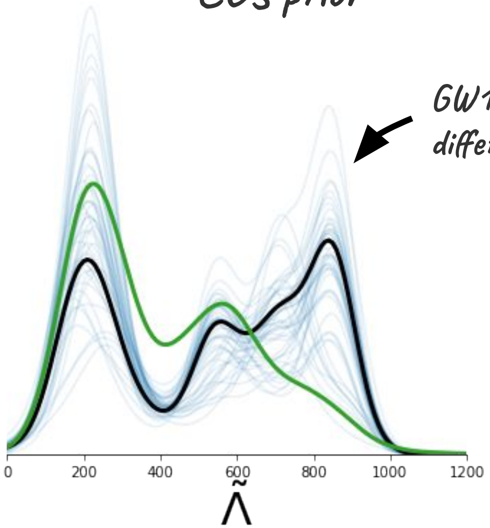
fixed (but uncertain) population model

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

EOS prior

i^{th} GW likelihood

common prior on source properties



GW170817 tides under different population priors

$$P(m^i_{1,2}, \Lambda^i_{1,2}|\,\text{eos, pop}) = P(m^i_{1,2}|\,\text{pop})\ \delta^{(2)}(\Lambda^i_{1,2} - \Lambda(m^i_{1,2}; \text{eos}))$$

mass distribution

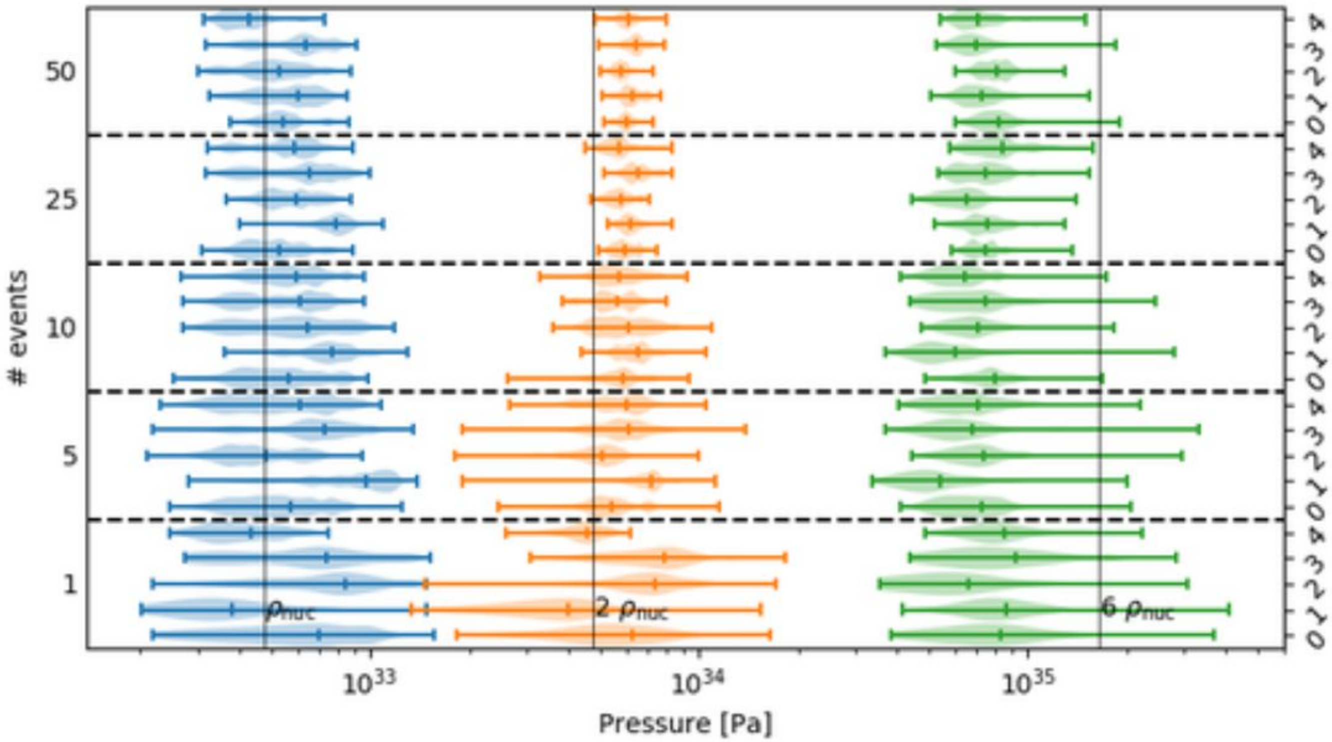
common EOS

Penuliar+PL+Read (in prep)

When does the population matter?

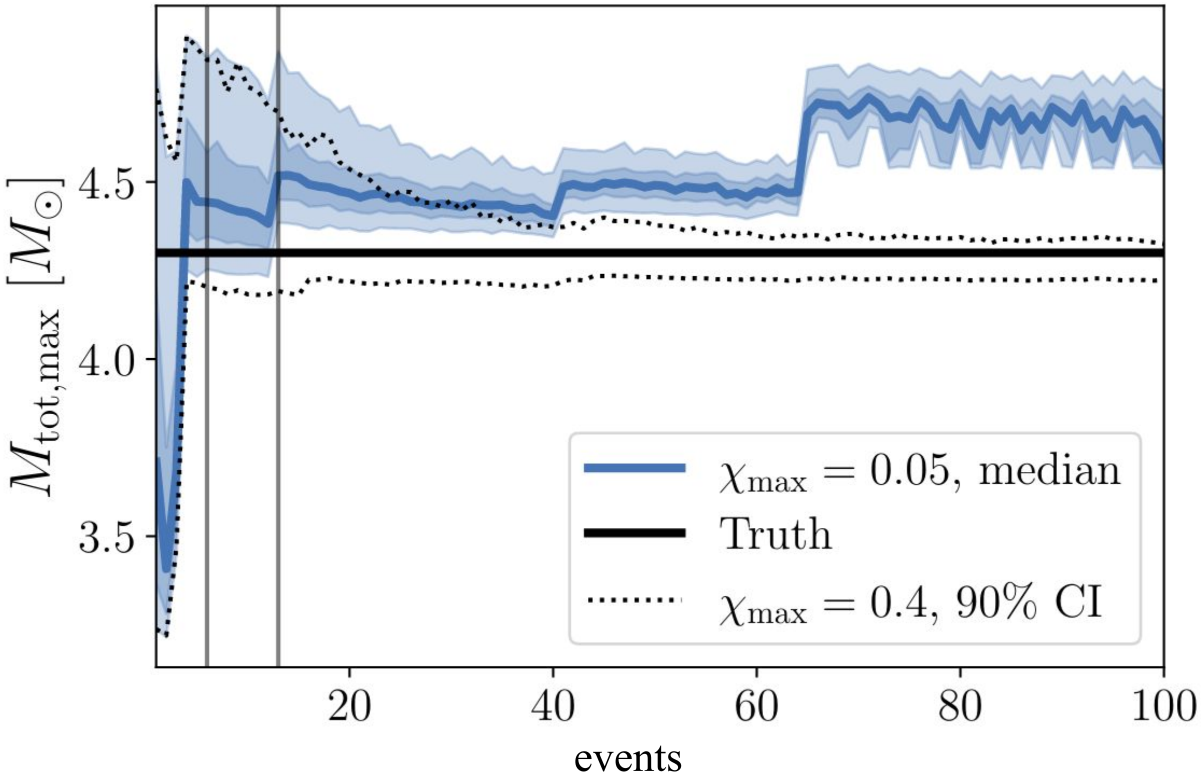
Wysocki+ arXiv:2001.01747

imposing the wrong population-level mass prior can bias the inferred EOS after O(10) BNS observations



When does the population matter?

Biscoveanu+Talbot+Vitale MNRAS 2022



incorrectly assuming NSs spin slowly can bias the inferred maximum mass in the population after O(10) BNS observations

Simultaneous EOS & population inference

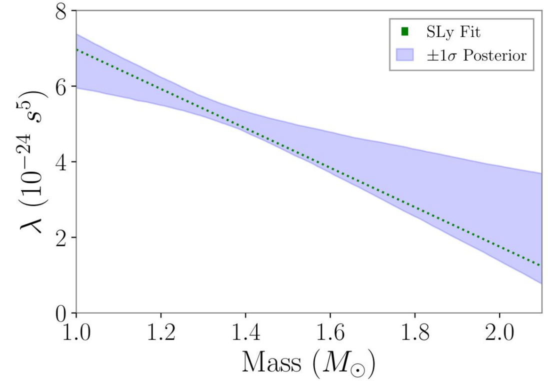
population model no longer fixed!

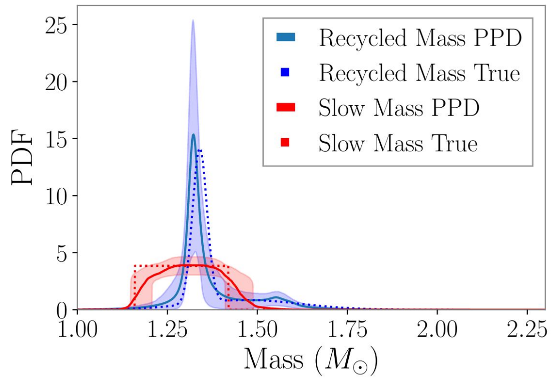
$$P(\text{eos}, \text{pop}|d) \propto P(\text{eos}, \text{pop}) \prod_i \beta(\text{pop})^{-1} \int P(d_i|m^i_{1,2}, \Lambda^i_{1,2}) P(m^i_{1,2}, \Lambda^i_{1,2}|\text{eos}, \text{pop}) dm^i_{1,2} d\Lambda^i_{1,2}$$

joint EOS + population prior — *selection effects* — *i^{th} GW likelihood* — *common prior on source properties*

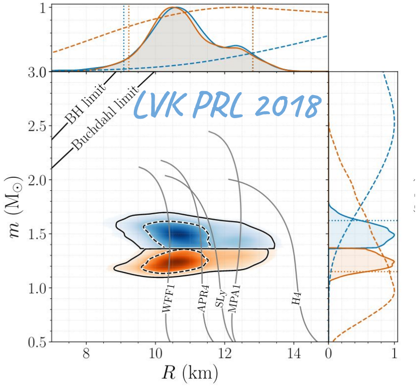
methods in development by several groups

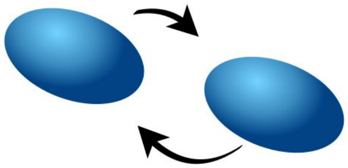
e.g. Golomb+Talbot ApJ 2022, Wysocki+ arXiv:2001.01747, Legred+ (incl. PL) (in prep)

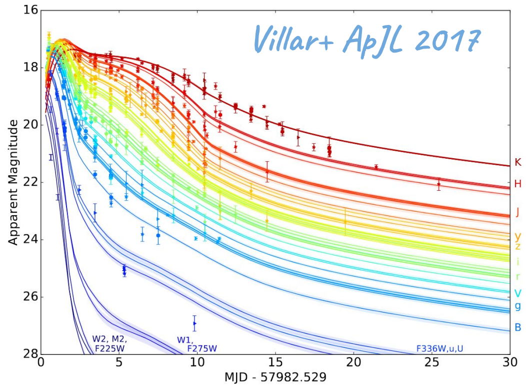




Inferring dense matter properties from GWs







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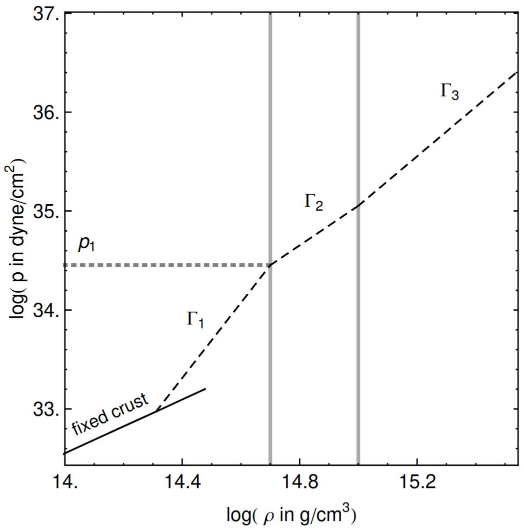
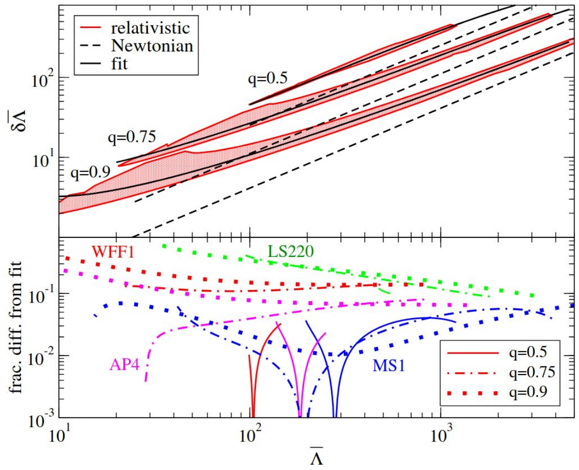
EOS modeling & uncertainty quantification

EOS parameterizations

e.g. piecewise polytropes Read+ PRD 2008,
spectral decomposition Lindblom PRD 2010,
sound speed parameterization Tews+ PRC 2018



Universal relations



e.g. binary Love relations Yagi+Yunes CQG 2016

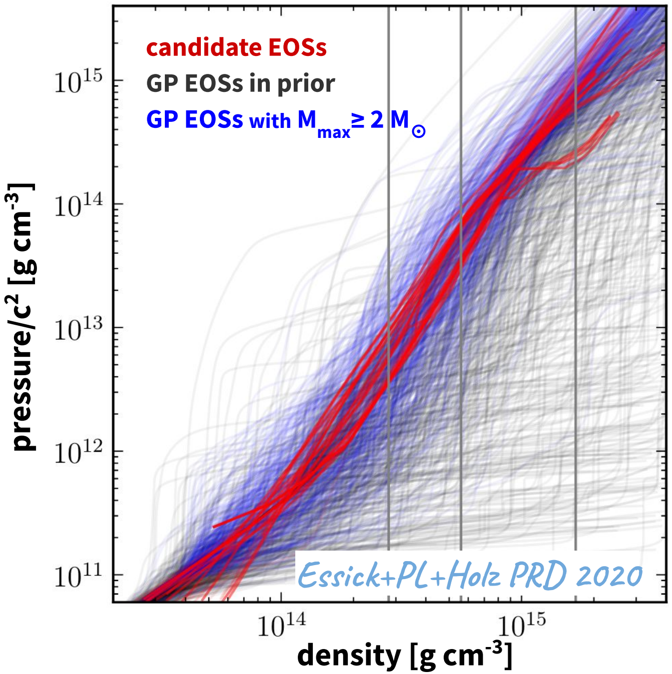
parametric models specify P(eos) via distributions over parameters; URs use fit + residuals to specify effective P(Λ(m))

EOS modeling & uncertainty quantification

Nonparametric representations

directly specify the distribution over functions that is P(eos)!

e.g. Gaussian processes PL+Essick PRD 2019, cf. Miller+ ApJL 2021, also machine learning models Morawski+Bejger A&A 2020, Han+ ApJ 2021



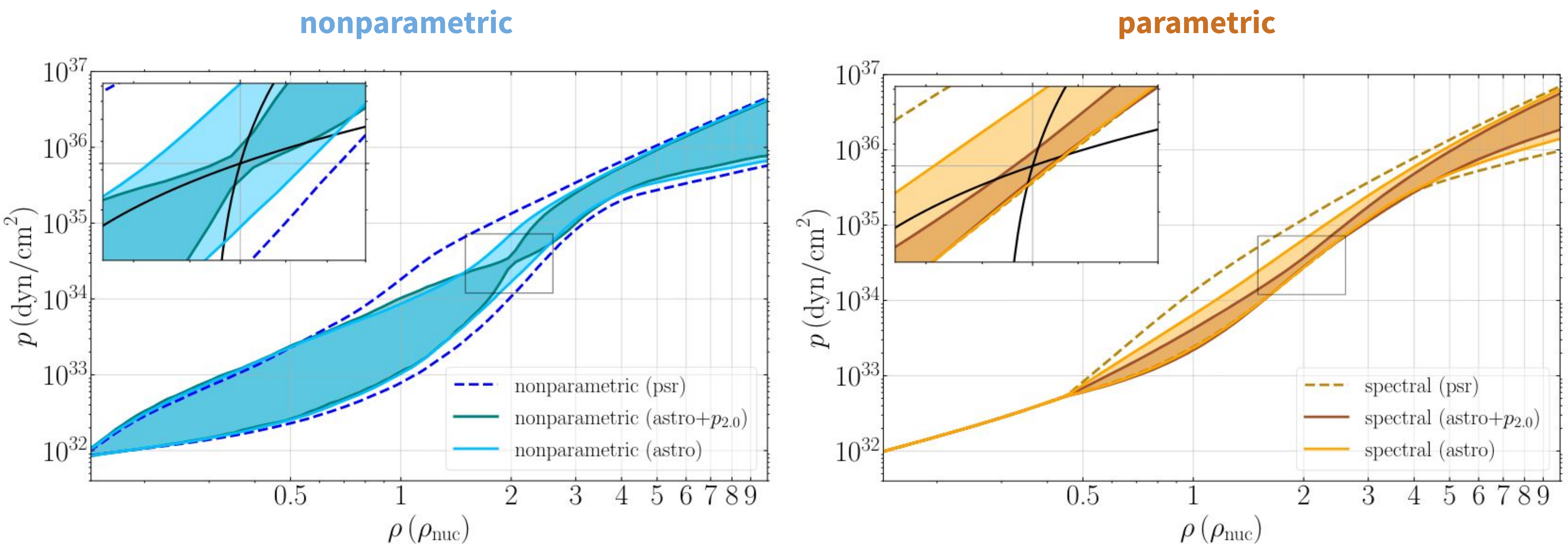
the Gaussian process for the EOS is a probability distribution over causal and thermodynamically stable functions $c_s^2(p)$ with Gaussian covariance kernel

$$K_{\rm se}(x_i, x_j; \sigma, l) = \sigma^2 \exp\left(-\frac{(x_i - x_j)^2}{2l^2}\right)$$

Designing phenomenological EOS priors

"data-driven" astrophysical EOS inference philosophy: prescribe prior spanning all physically allowed EOSs

beware: parametric EOS models can introduce artificial intra-density correlations Legred+ (incl. PL) PRD 2022



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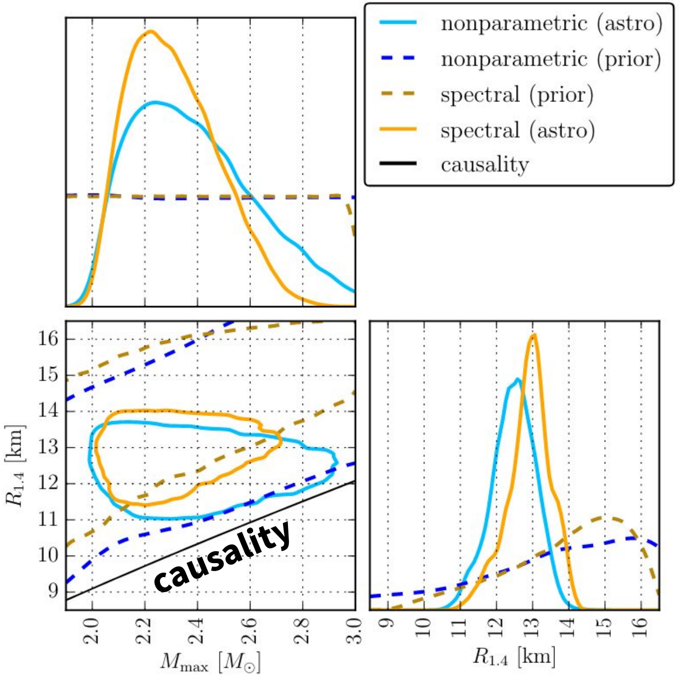
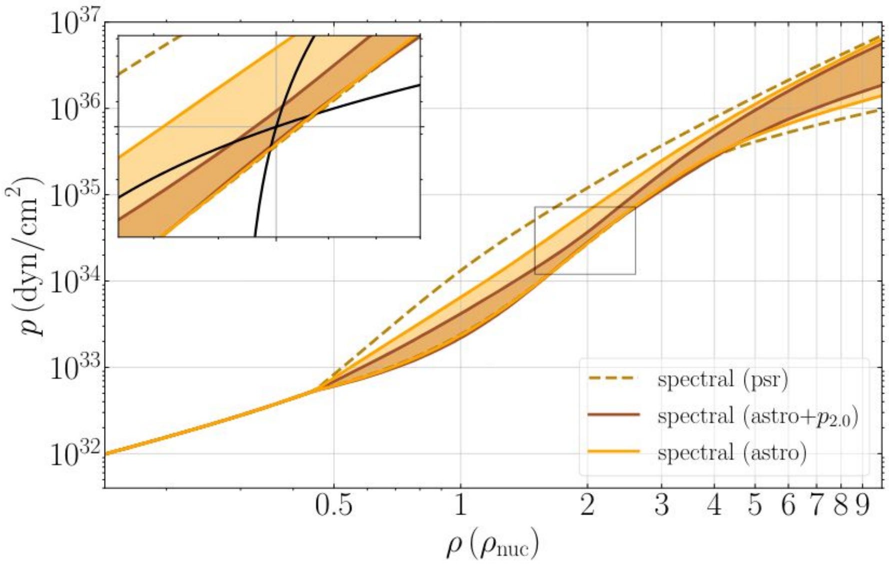
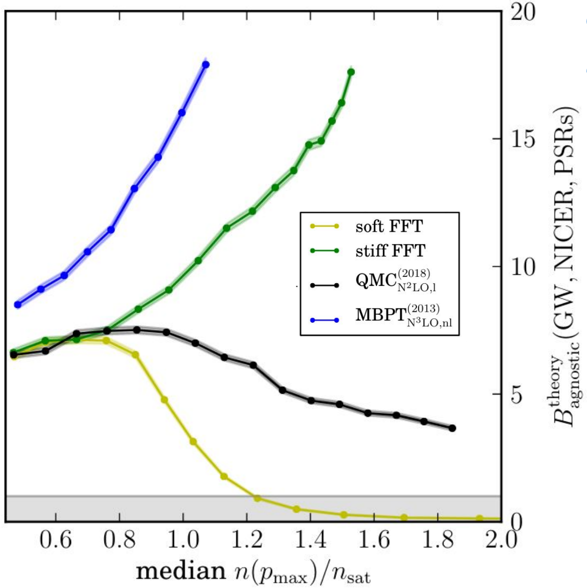


parametric

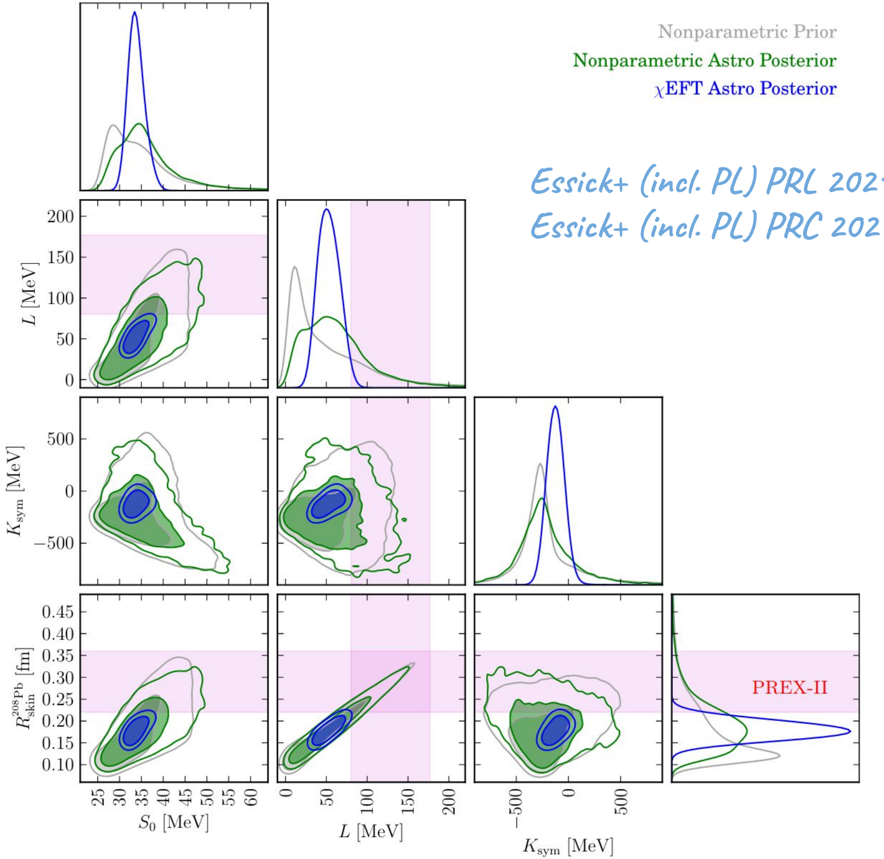


Beyond EOS phenomenology

condition a phenomenological EOS prior, like the Gaussian process model, on chiral EFT calculations at low densities

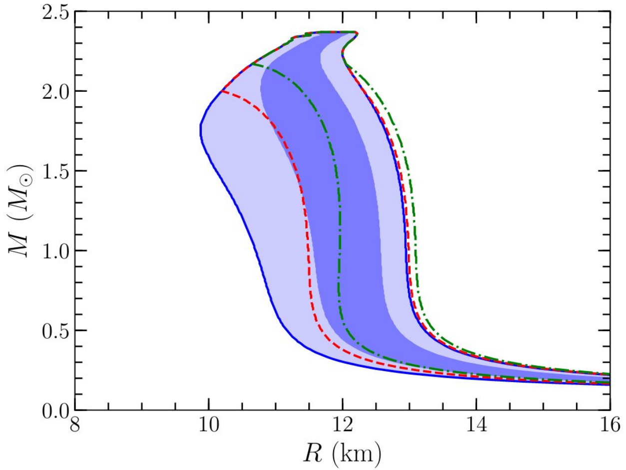


Essick+ (incl PL) PRC 2020



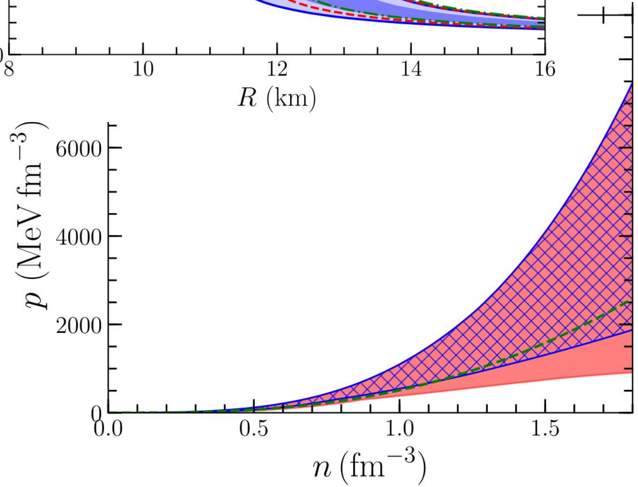
Essick+ (incl. PL) PRL 2021
Essick+ (incl. PL) PRC 2021

Beyond EOS phenomenology



parametric energy density functional model for EOS, constrained with chiral EFT and nuclear experiments

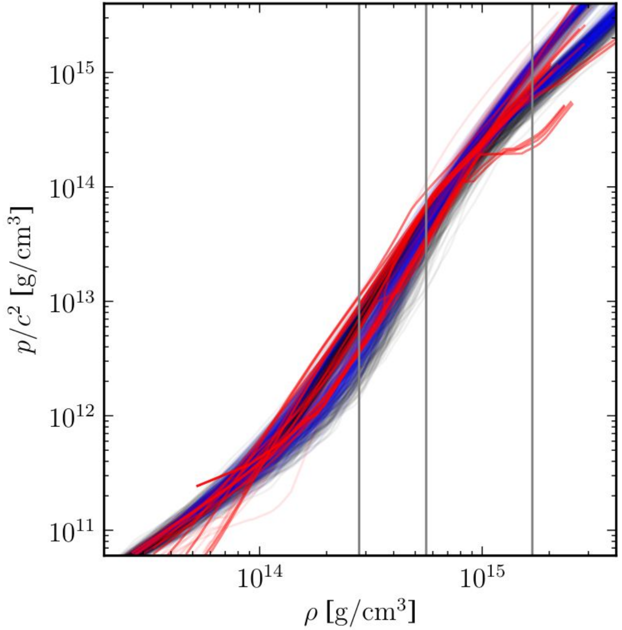
Lim+Holt EPJA 2019



Gaussian processes conditioned on candidate EOSs with different compositions

Essick+PL+Holz PRD 2020

$P(\text{Hadronic}\mid\text{data})$	$P(\text{Hyperonic}\mid\text{data})$	$P(\text{Quark}\mid\text{data})$
28%	16%	56%



Outlook

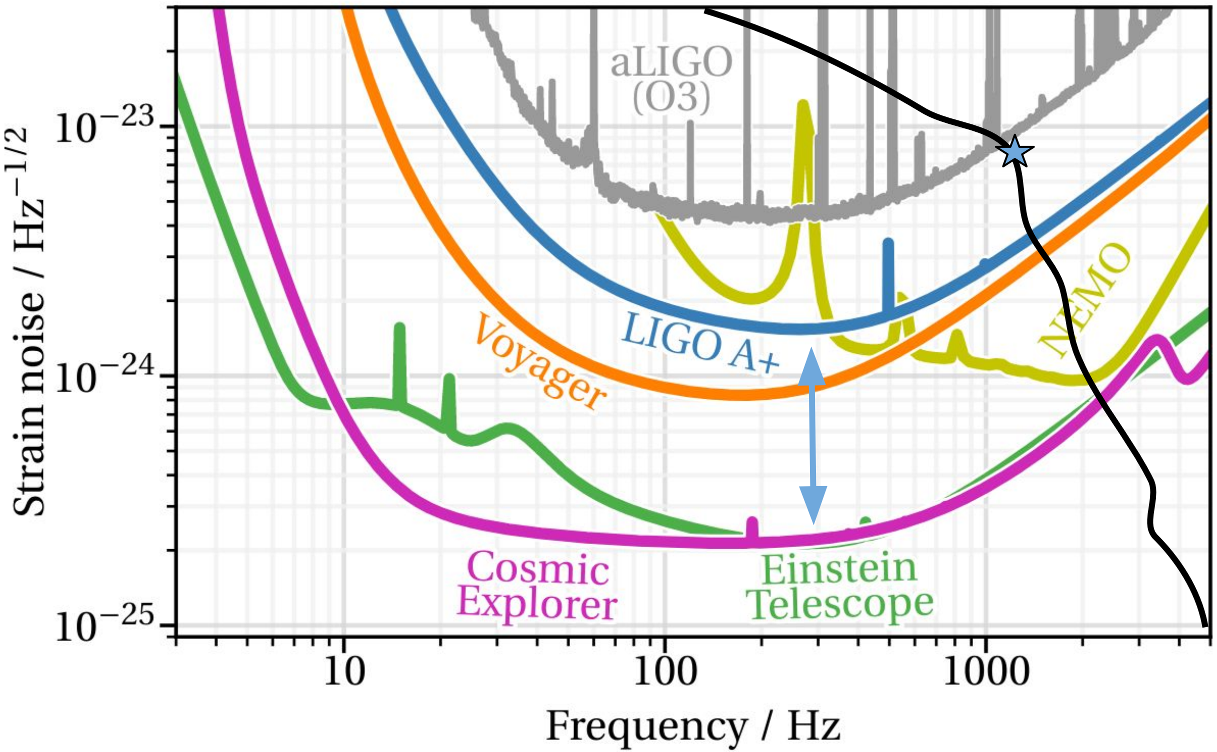
In the next campaign of LVK observations, we can hope for…

- *several BNS mergers with measurable tidal effects*
- *half a dozen more NSBH mergers*
- *maybe an EM counterpart or two*

In order to take full advantage of the dense-matter information these louder, more numerous signals will provide, we need…

- *more careful treatments of systematics in EOS modeling*
- *closer integration between nuclear theory/experiment and astrophysics*
- *simultaneous population and EOS inference*

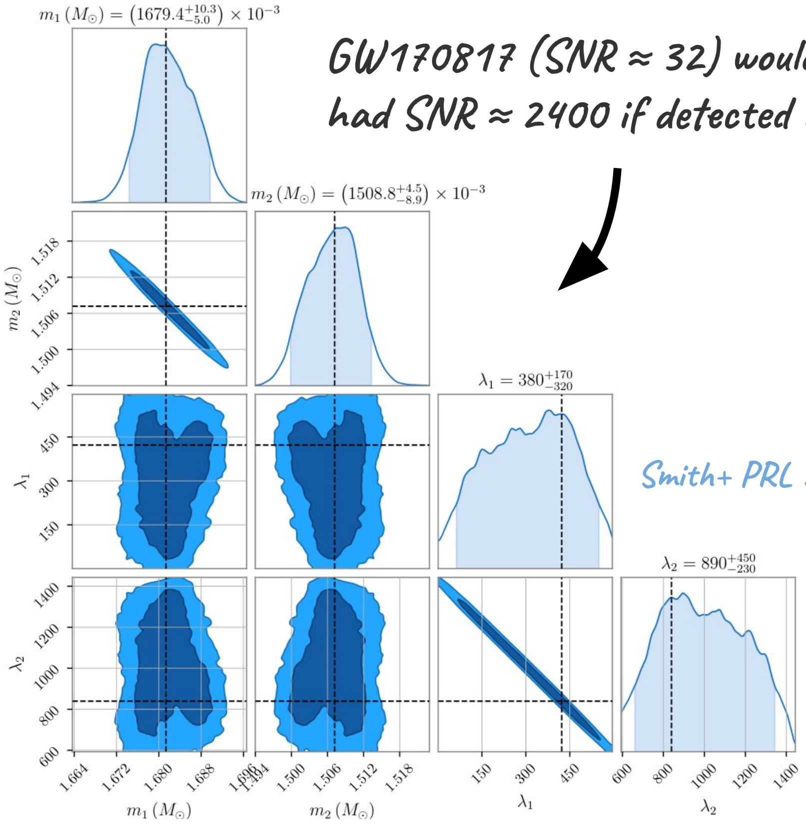
Bonus slide: XG sensitivity



Evans+ arXiv:2109.09882

XG gives 10x improvement in broadband sensitivity

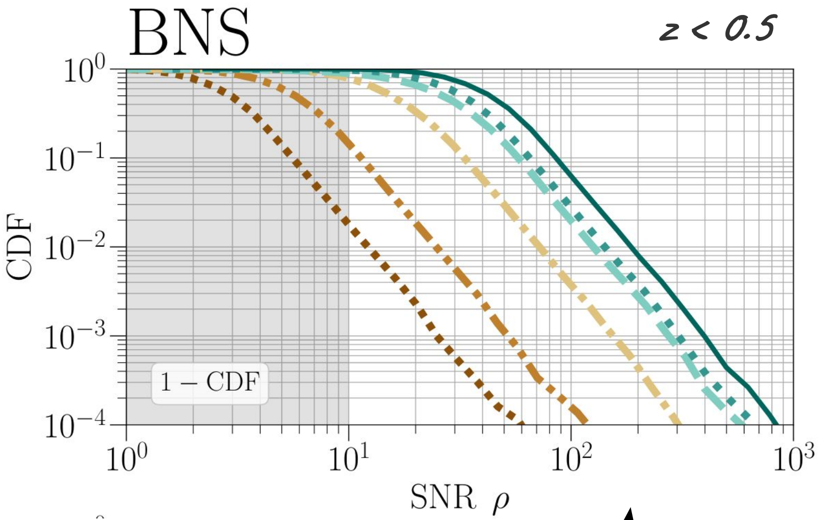
Bonus slide: XG BNS observations



GW170817 (SNR ≈ 32) would have had SNR ≈ 2400 if detected in XG!

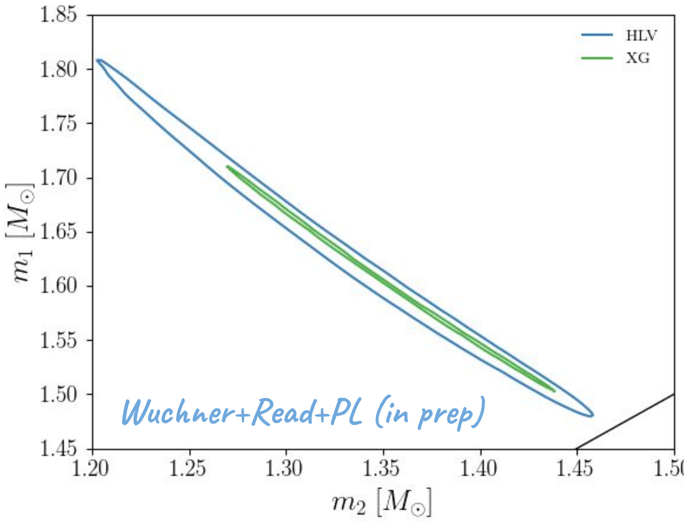
Smith+ PRL 2021

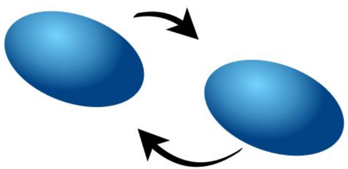
Borhanian+Sathyaprakash arXiv:2202.11048

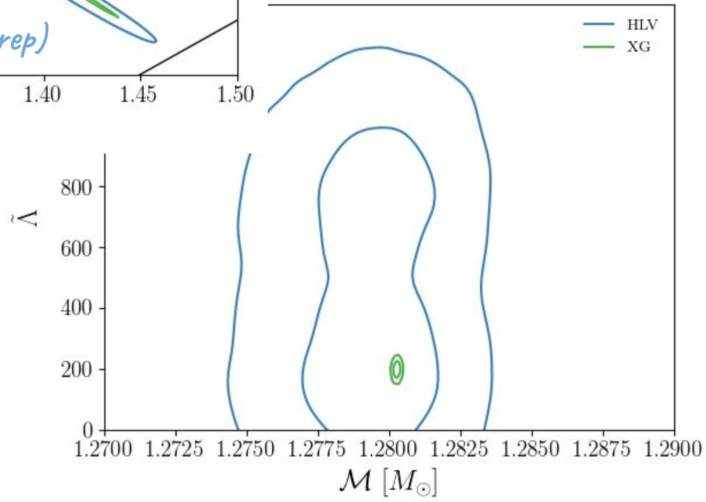


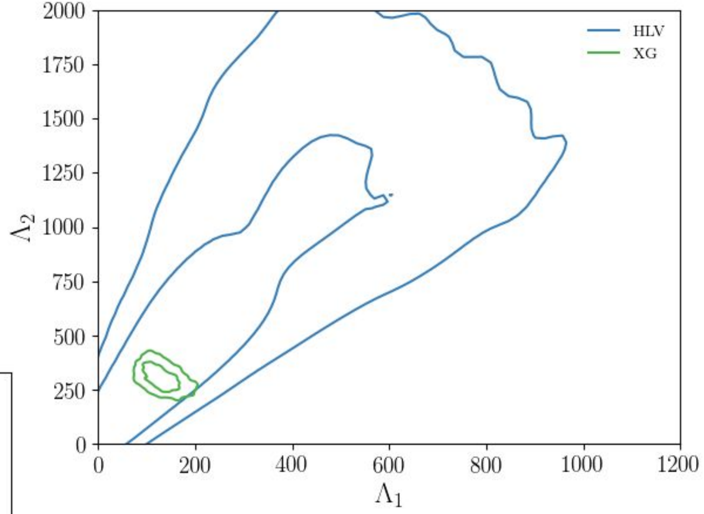
50% of nearby BNSs have SNR > 100 in XG

Bonus slide: XG tidal measurements







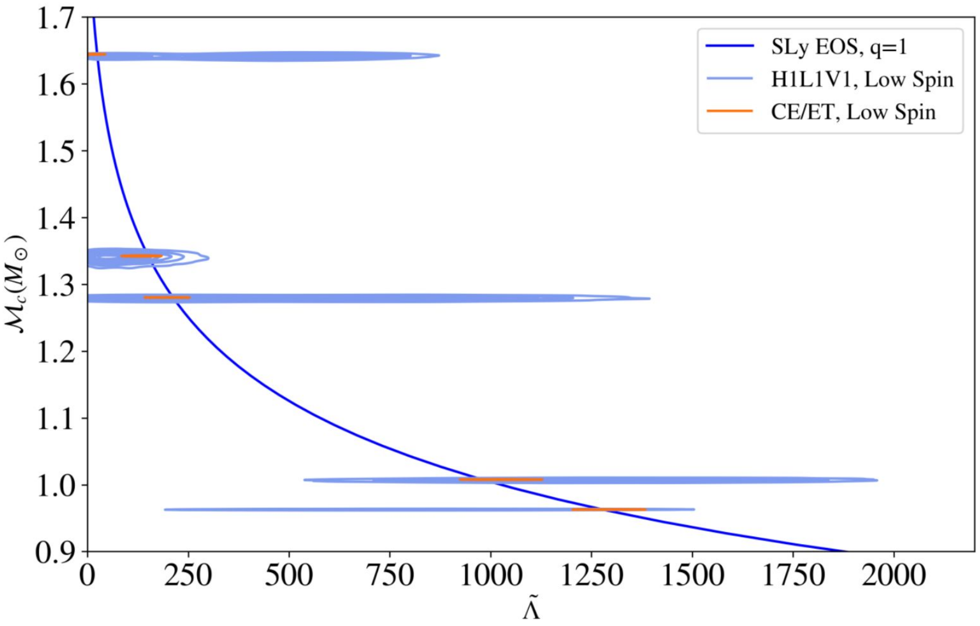


2.9 $M_\odot$ total mass
BNS at 110 Mpc:
SNR 15 in HLV,
SNR 400 in XG

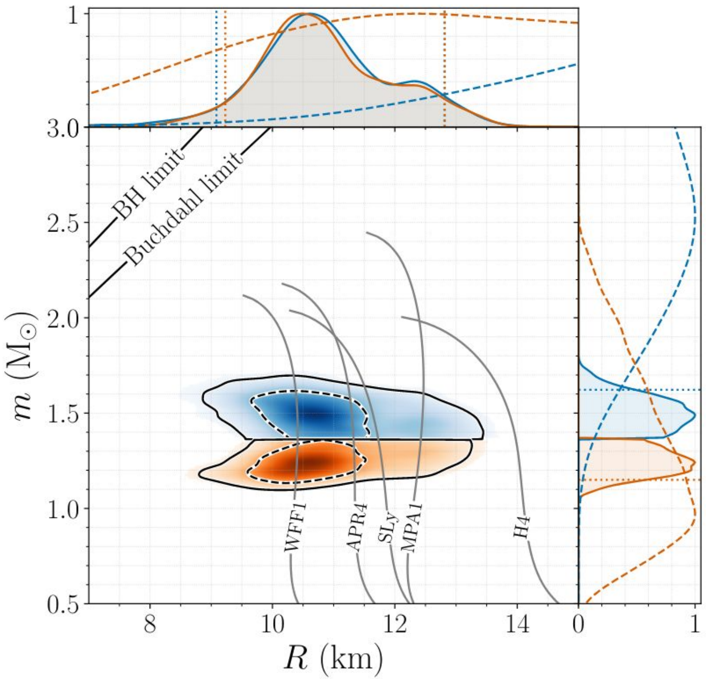
Λ measures tidal deformation;
$\tilde{\Lambda}$ is a mass-weighted average
of Λ_1 and Λ_2

Bonus slide: XG NS tides & radii

Wuchner+Read+PL (in prep)



LVK PRL 2018



correlations currently used to map between tides and radii break down in XG era!