The high-density equation of state and maximum mass of neutron stars

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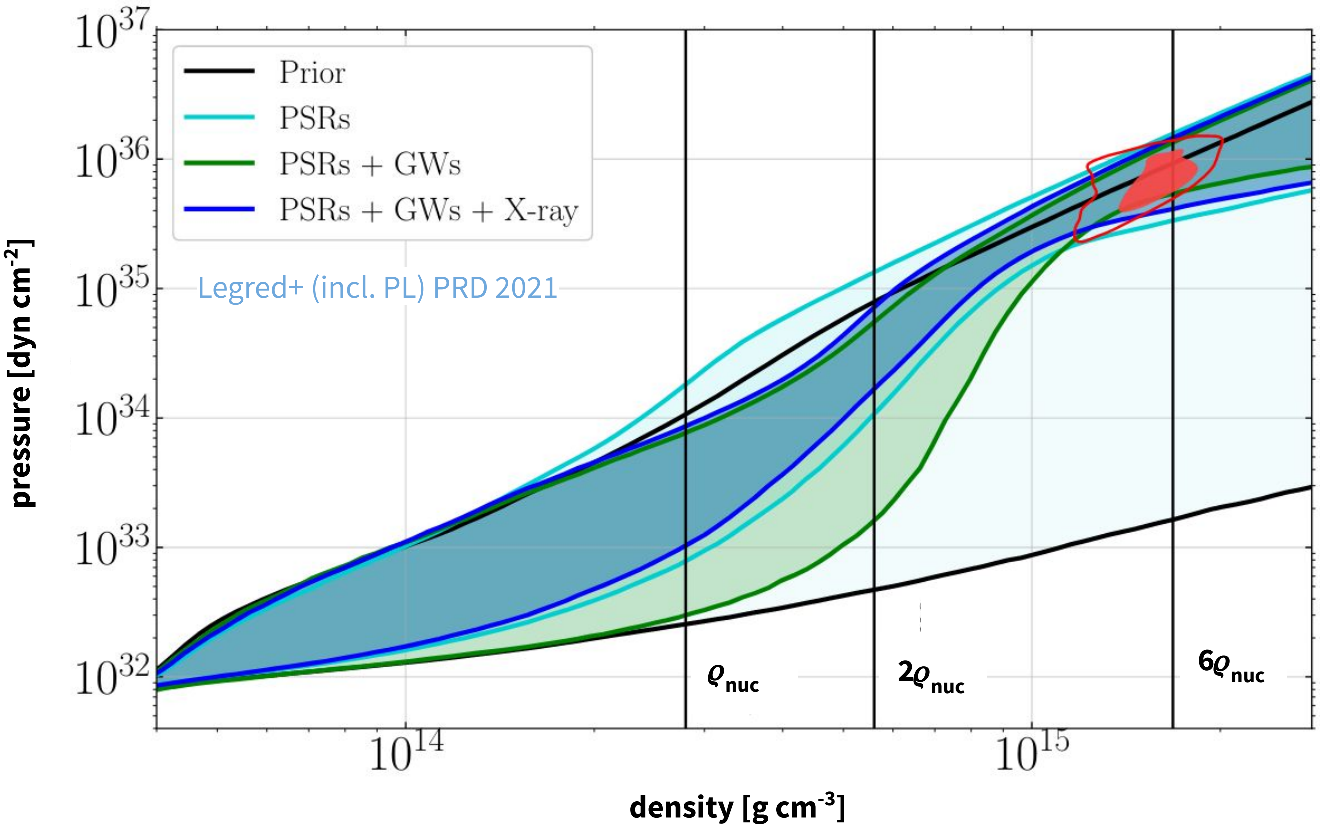
Legred, Chatziioannou, Essick, Han & Landry PRD 104 063003 (2021), arXiv:2106.05313

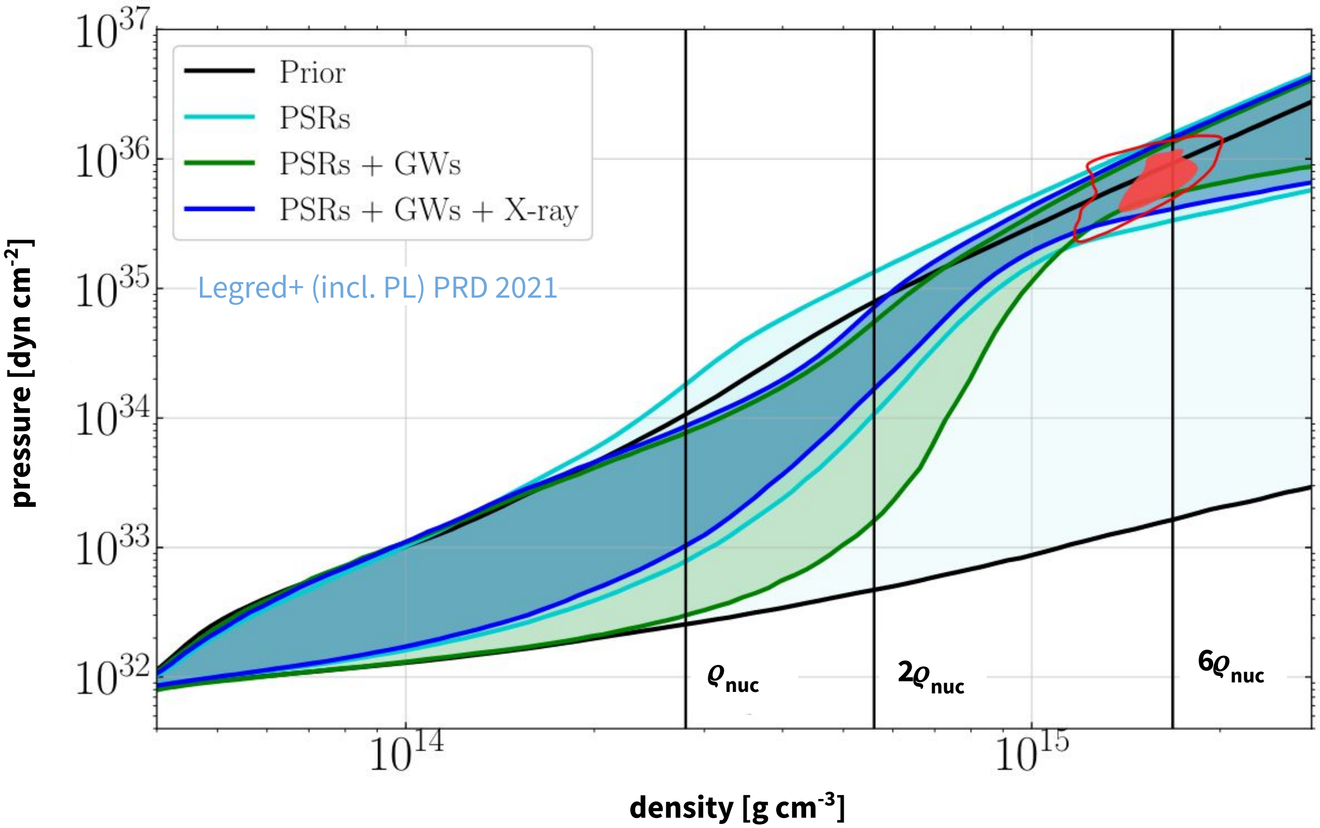
INT ◆ 24 May 2022

Observational constraints on the EOS



Current knowledge of the cold neutron star equation of state, with 90% credible error envelope

Observational constraints on the EOS



Current knowledge of the cold neutron star equation of state, with 90% credible error envelope

Causality + stability

(Chiral EFT + nuclear experiments)

Masses from radio PSRs

BNS tides with GWs

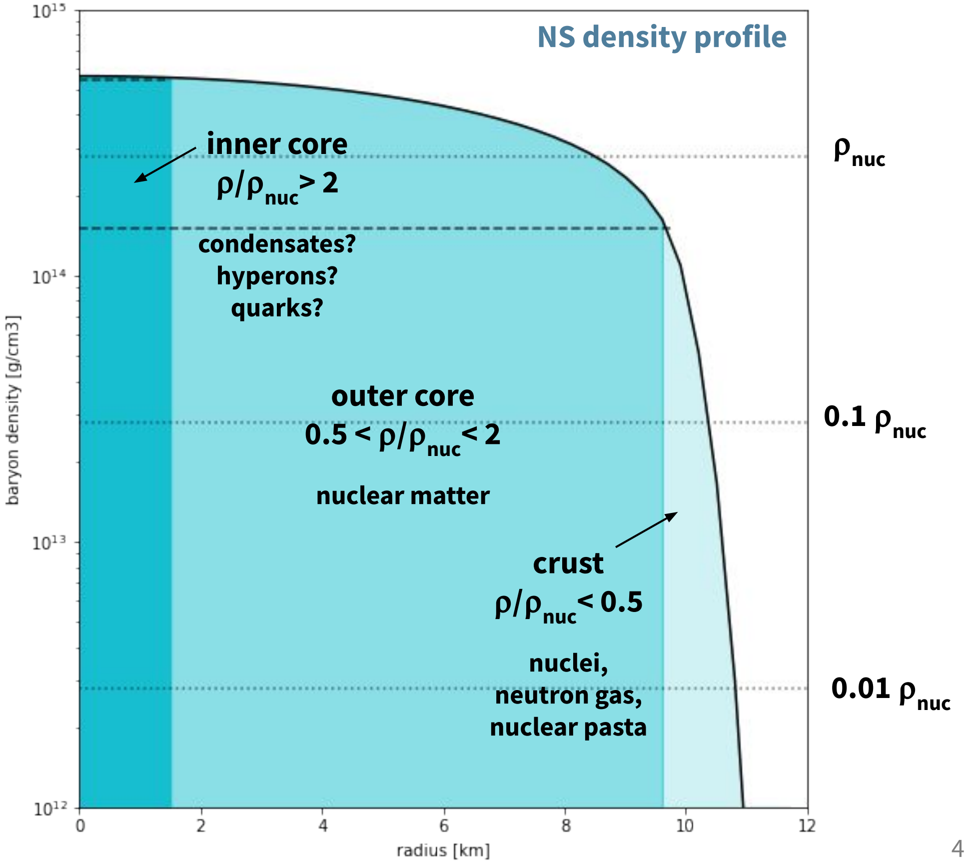
NS radii w/ X-ray hotspots

High-density neutron star matter

What pressures and densities are reached in neutron star cores?

What is the phase structure of matter inside neutron stars?

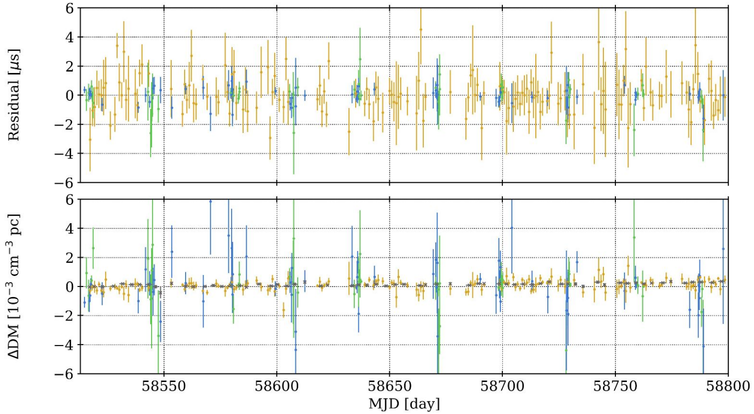
How much mass can be supported against gravitational collapse?



What's the maximum neutron star mass?

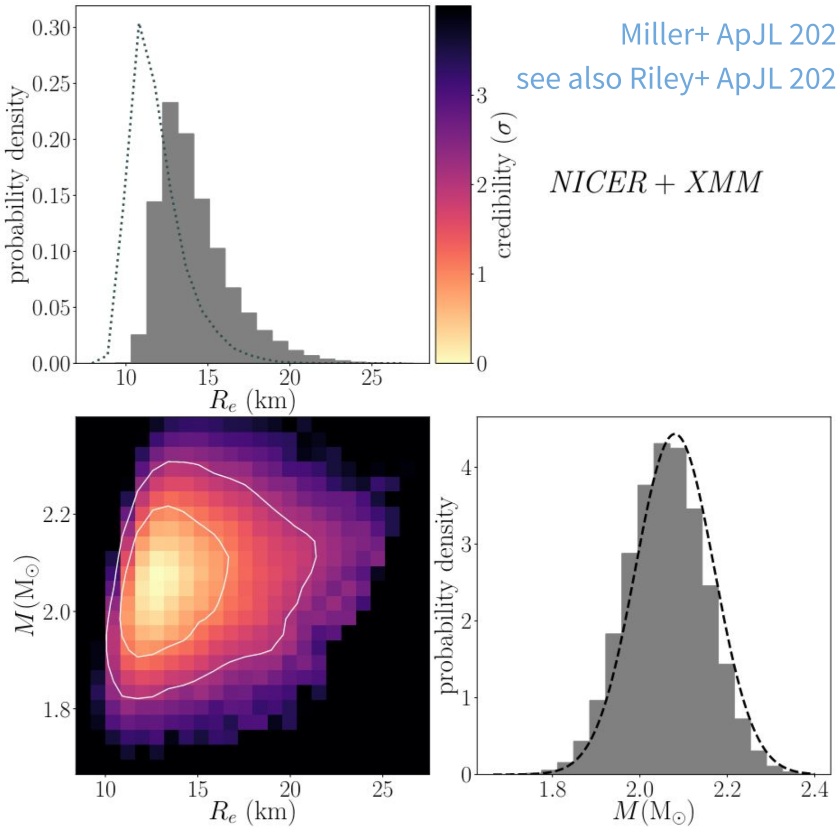
The heaviest known neutron star, PSR J0740+6620, has a mass of about 2.1 $M_\odot$.

Fonseca+ ApJL 2021



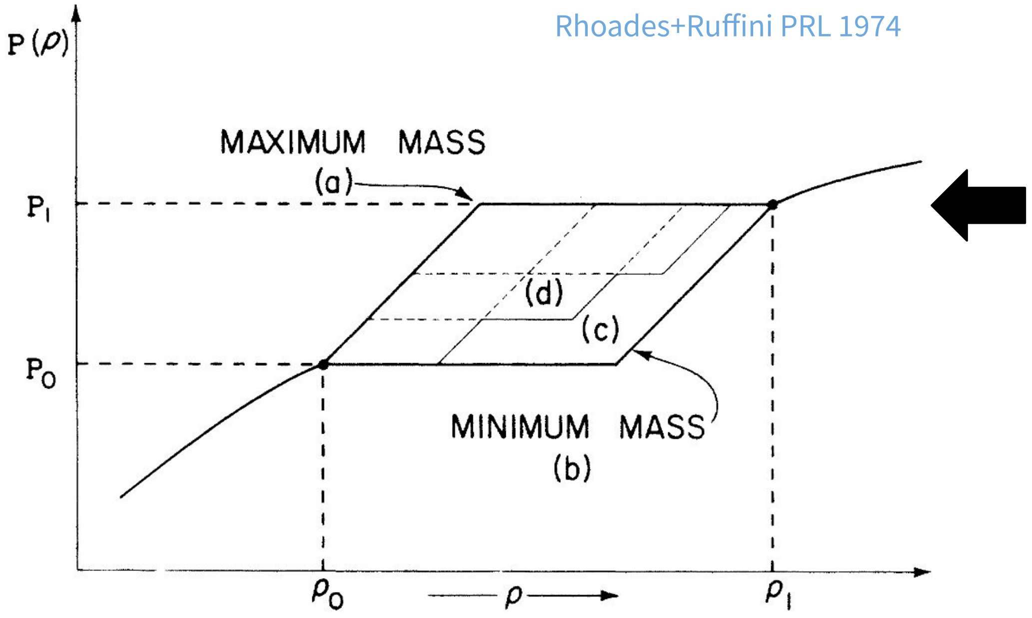
Pulsar mass measured via Shapiro delay of radio pulses:
$m = 2.08 \pm 0.07\ M_\odot$

Miller+ ApJL 2021
see also Riley+ ApJL 2021



What's the maximum neutron star mass?

For nonrotating neutron stars, causality considerations set an upper bound of about 3 $M_\odot$ on the maximum mass.

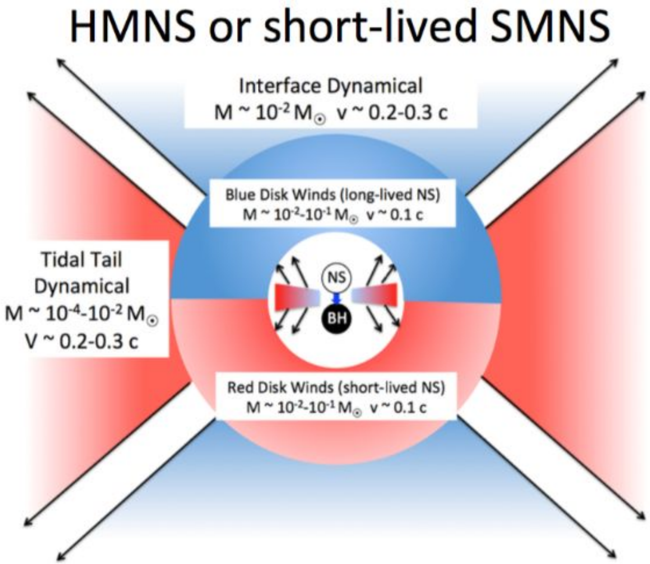


Rhoades+Ruffini PRL 1974

Neutron stars that exceed the Tolman-Oppenheimer-Volkoff (TOV) mass, M_{TOV}, are unstable against radial perturbations

What's the maximum neutron star mass?

GW170817's electromagnetic counterpart suggests that the merger remnant collapsed to a black hole, bounding the threshold mass for collapse below 2.7 $M_\odot$.



Margalit+Metzger ApJL 2017

LVC (incl. PL) PRX 2019

GW170817 remnant mass:

$$M_{tot} = 2.73^{+0.04}_{-0.01}\, M_\odot$$

Rotation can stabilize a neutron star up to 20% more massive than M_{TOV} Cook+ ApJ 1994

↓

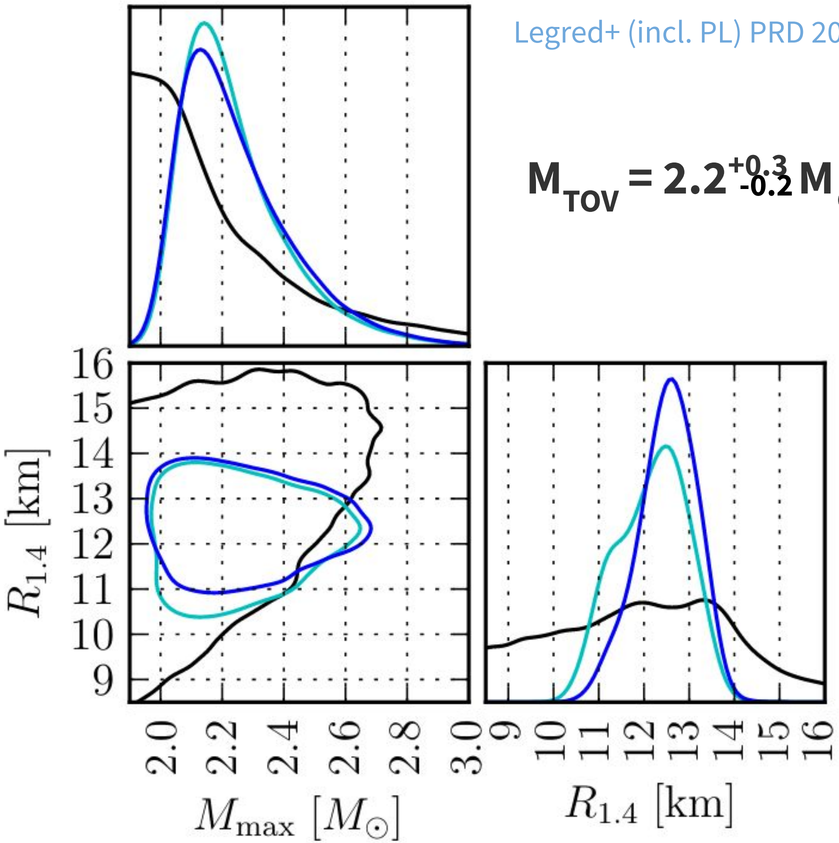
The threshold mass constraint maps to an upper bound of approximately 2.3 $M_\odot$ on M_{TOV}

LVC (incl. PL) CQG 2020

What's the maximum neutron star mass?

Inference of the equation of state from gravitational-wave and pulsar observations of neutron stars constrains M_{TOV} to be approximately 2.2 $M_{\odot}$.

Relies on an EOS model to extrapolate up to the high densities relevant for the maximum mass



Legred+ (incl. PL) PRD 2021

$M_{TOV} = 2.2^{+0.3}_{-0.2}\, M_{\odot}$

Modeling + inferring the EOS

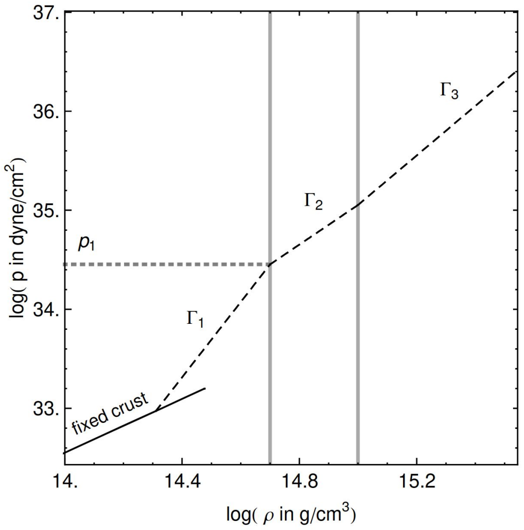
Hierarchical Bayesian inference of the EOS

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

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

One way to prescribe an EOS prior is via parameterization, e.g.

- ***Piecewise polytrope*** Read+ PRD 2008
- ***Spectral decomposition of Γ*** Lindblom PRD 2010
- ***Sound speed extension*** Tews+ PRC 2018
- ...



piecewise polytrope

Read+ PRD 2008

Modeling + inferring the EOS

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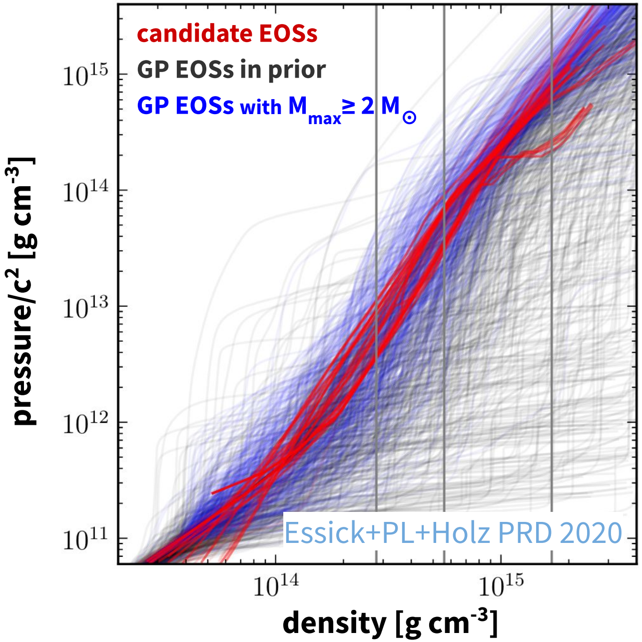
eos prior **gw likelihood** **prior on gw params**

Another approach is nonparametric, representing the EOS prior as a Gaussian process (GP) Landry+Essick PRD 2019

The GP is a probability distribution over causal and thermodynamically stable functions p(e) with Gaussian covariance kernel

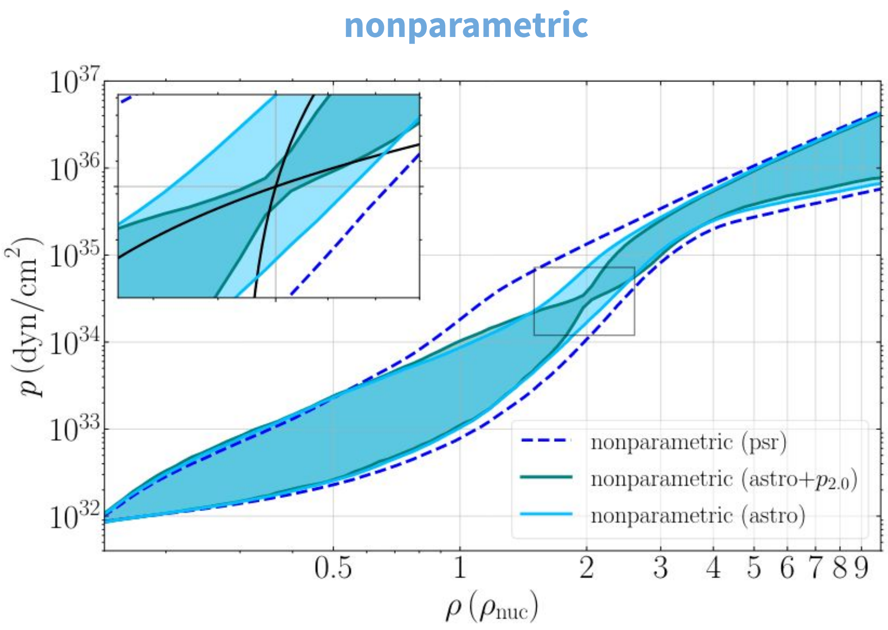
$$K_{\text{se}}(x_i, x_j; \sigma, l) = \sigma^2 \exp\left(-\frac{(x_i - x_j)^2}{2l^2}\right)$$

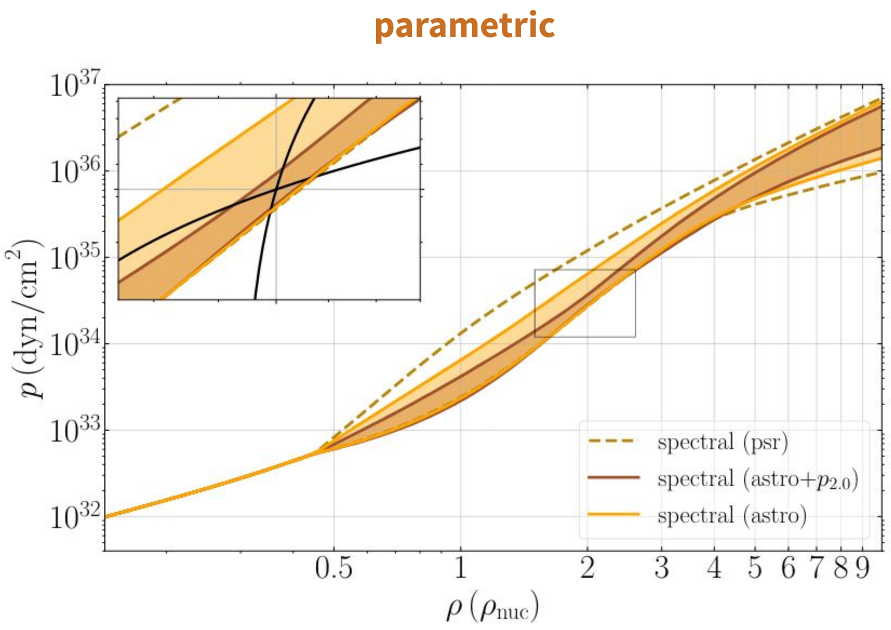


Modeling + inferring the EOS

Parametric EOS representations can introduce artificial correlations between different densities; mitigate this with EOSs generated from a Gaussian process

Legred+ (incl. PL) PRD 2022





EOS inference + the neutron star population

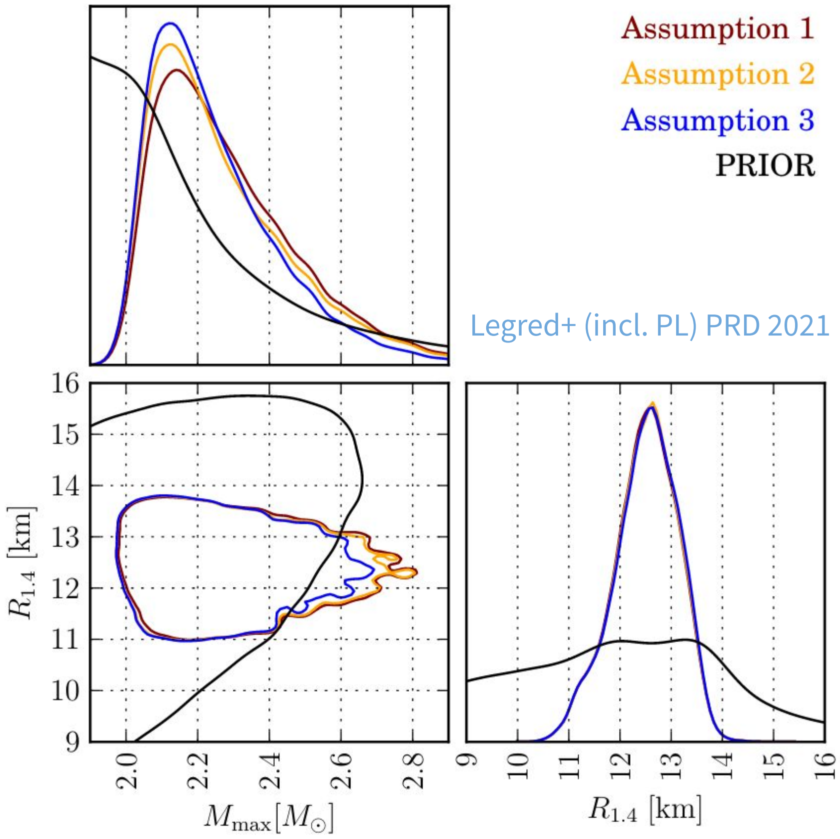
EOS inference relies (either explicitly or implicitly) on a choice of population model to prescribe the prior on source properties for each observation.

$$P\left(m|\text{eos}\right) = \frac{\Theta(M_{\text{lower}} \leq m)\Theta(m \leq M_{\text{upper}})}{M_{\text{upper}} - M_{\text{lower}}}$$

1. PSR J0740 may be a black hole

2. PSR J0740 is known to be a NS, but the heaviest NSs with masses near M_{TOV} aren't observable as pulsars

3. PSR J0740 is known to be a NS, and pulsar masses can be as large as M_{TOV}



Legred+ (incl. PL) PRD 2021

EOS inference + the neutron star population

Landry+Read ApJL 2021

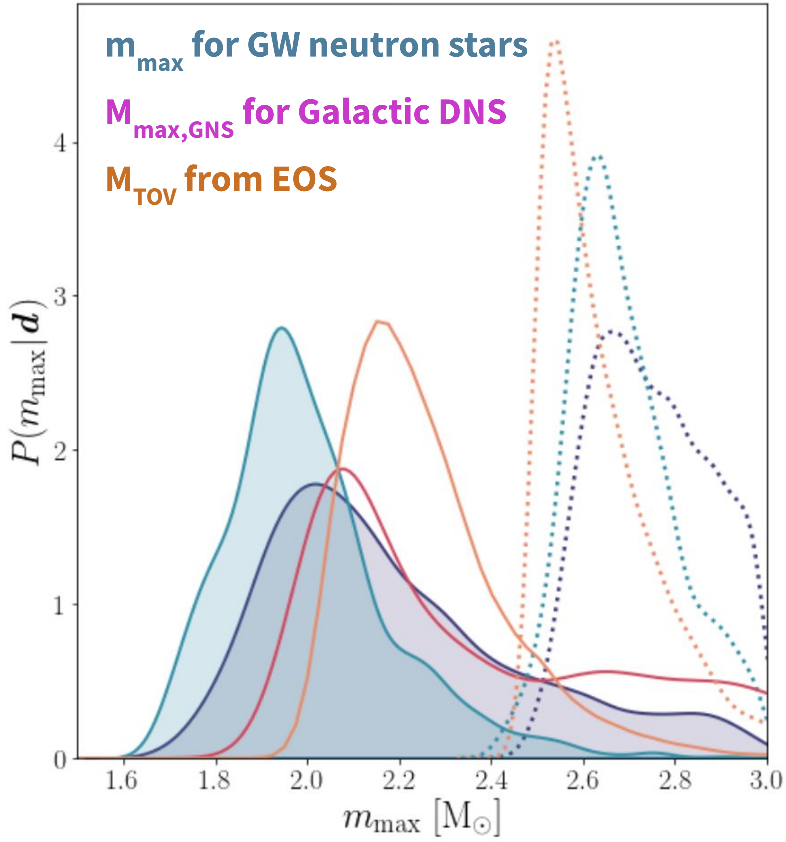
EOS inference relies (either explicitly or implicitly) on a choice of population model to prescribe the prior on source properties for each observation.

The correct approach is to simultaneously infer the neutron star population and the EOS!

1. PSR J0740 may be a black hole

2. PSR J0740 is known to be a NS, but the heaviest NSs with masses near M_{TOV} aren't observable as pulsars

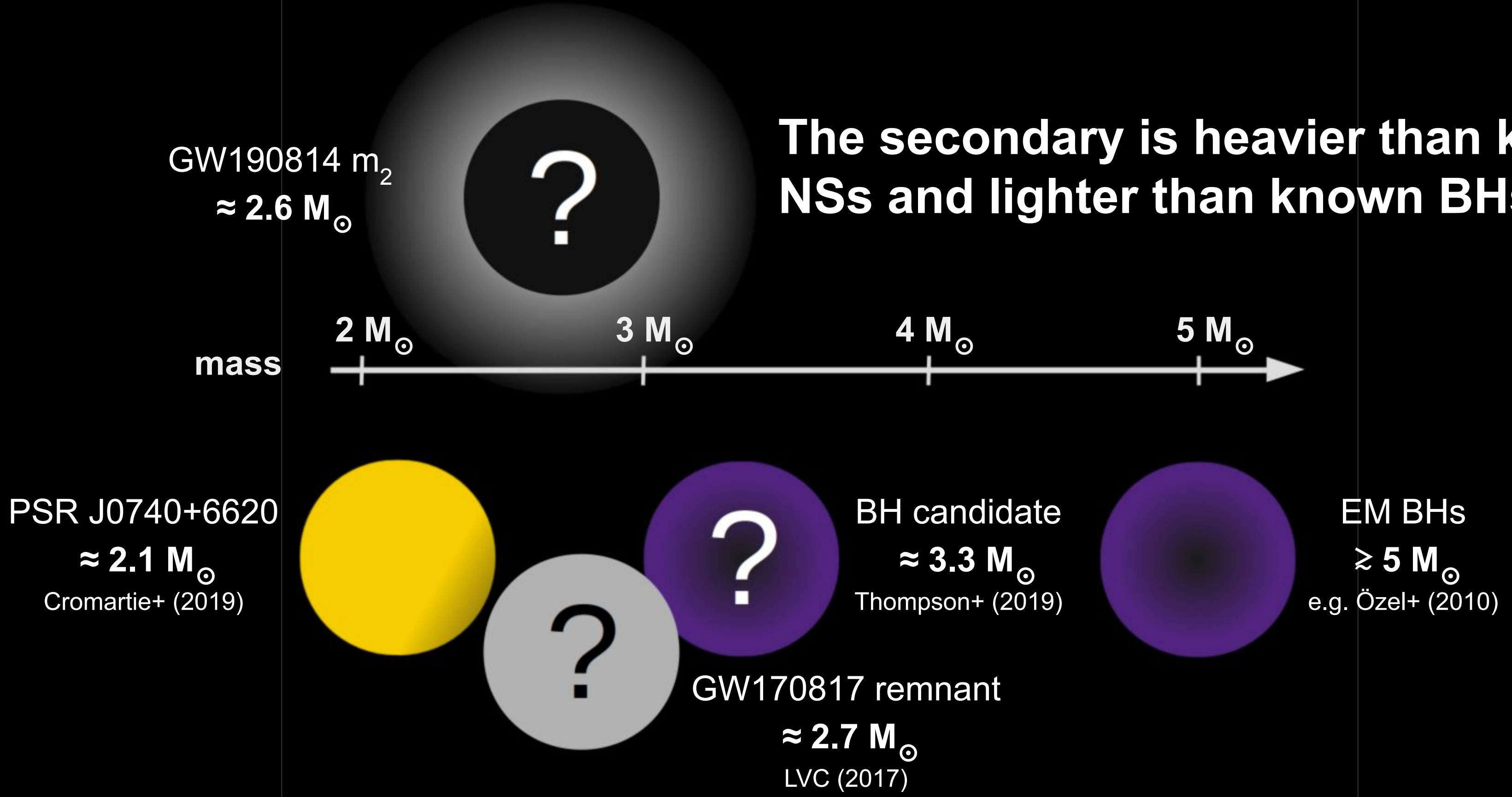
3. PSR J0740 is known to be a NS, and pulsar masses can be as large as M_{TOV}



What about GW190814?

LVC (incl. PL) ApJL 2020

The secondary is heavier than known NSs and lighter than known BHs.

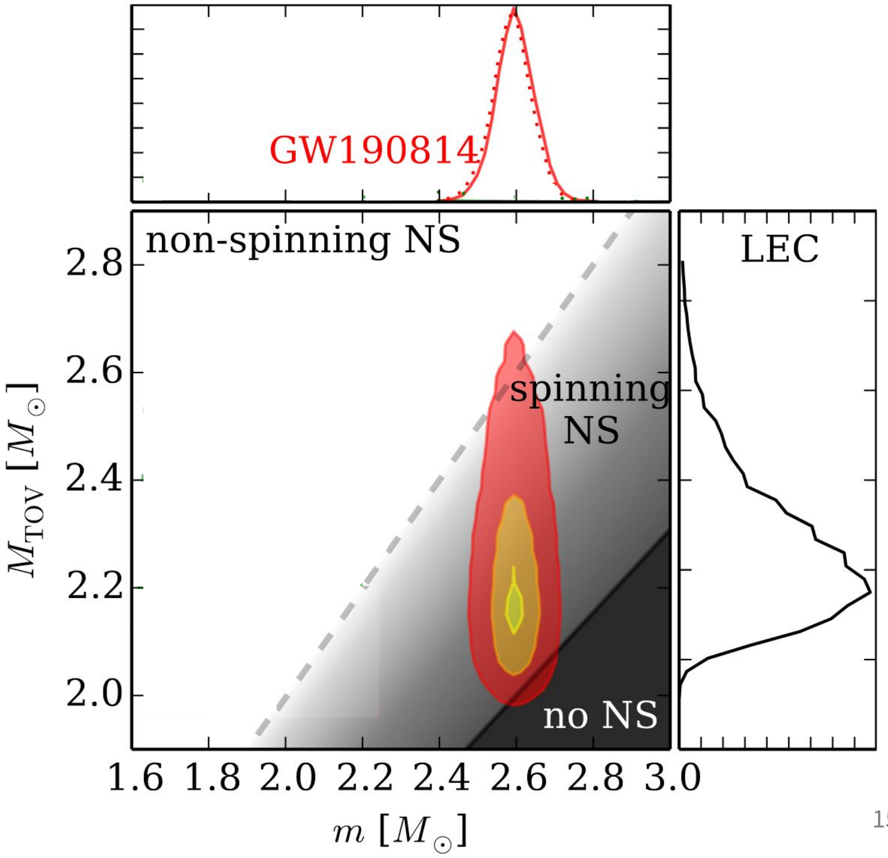


What about GW190814?

Essick+Landry ApJ 2020

Comparison with M_{TOV} indicates that GW190814's 2.59 ± 0.09 $M_\odot$ secondary is probably too heavy to be a nonrotating neutron star.

$$P(m_2 \leq M_{TOV}) \approx 5\%$$



Similar conclusions reached via

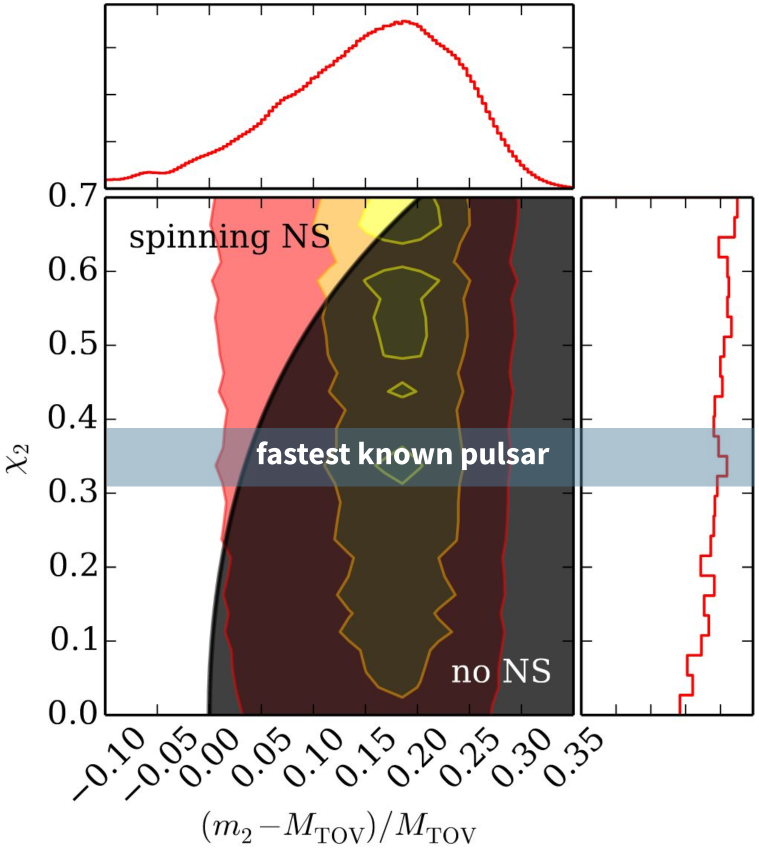
- ***Parametric EOS inference*** Godzieba+ ApJ 2021
- ***Density functional theory*** Fattoyev+ PRC 2020
- ***Chiral EFT*** Tews+ ApJL 2021
- ...

What about GW190814?

Many proposed alternatives to the black hole interpretation involve rapid rotation

- ***Super-fast pulsar*** Zhang+Li ApJ 2020
- ***Rotating NS, collapsed premerger*** Most+ MNRASL 2020
- ***Rotating quark star*** Dexheimer+ PRC 2021
- **...**

The fastest known pulsar spins at 716 Hz, or χ ~ 0.3-0.4 Hessels+ Sci 2006



Supporting 2.6 $M_\odot$ requires *very* rapid rotation that is difficult to explain from the astrophysical perspective.

Astrophysical observations favor a maximum nonrotating neutron star mass of about 2.3 $M_\odot$

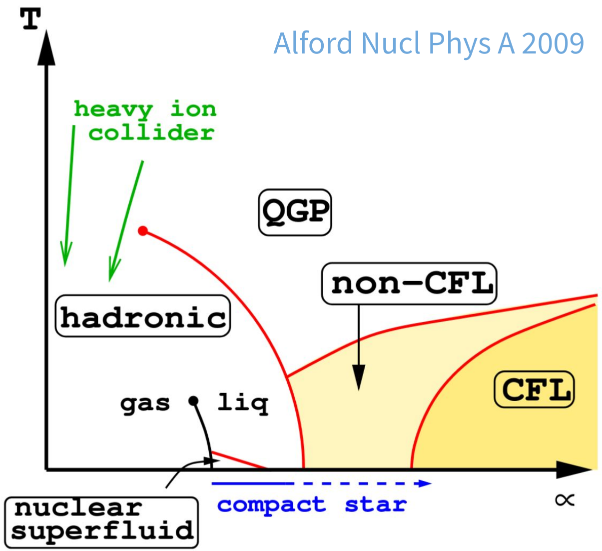
There is likely a subpopulation of light black holes with masses just above M_{TOV}

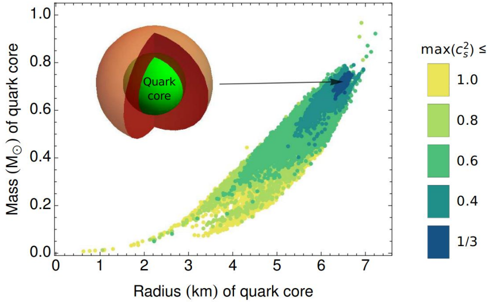
Exotic phases in neutron star cores?

At sufficiently high densities, non-hadronic degrees of freedom are expected to appear, e.g. hyperons and/or deconfined quarks

- ***Distinct hadronic and exotic phases may be separated by a strong first-order phase transition*** e.g. Alford+ PRD 2013
- ***Hadrons and exotic particles may coexist in mixed phase with smooth crossover*** e.g. Baym+ ApJ 2019

Alford Nucl Phys A 2009





Some predictions that quark cores appear generically in the heaviest neutron stars e.g. Annala+ Nat Phys 2020

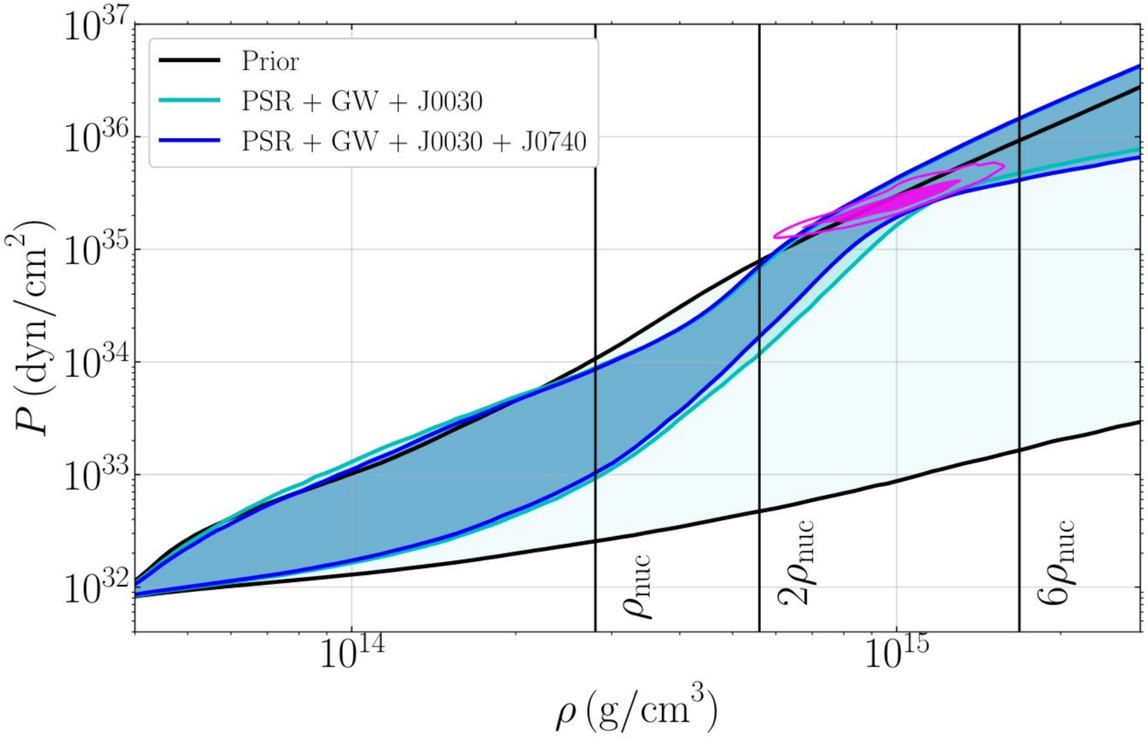
How dense can neutron stars get?

Inferred central pressure and density for PSR J0740+6620

central density

2.3 - 4.7 ρ_{nuc}

Legred+ (incl. PL) PRD 2021



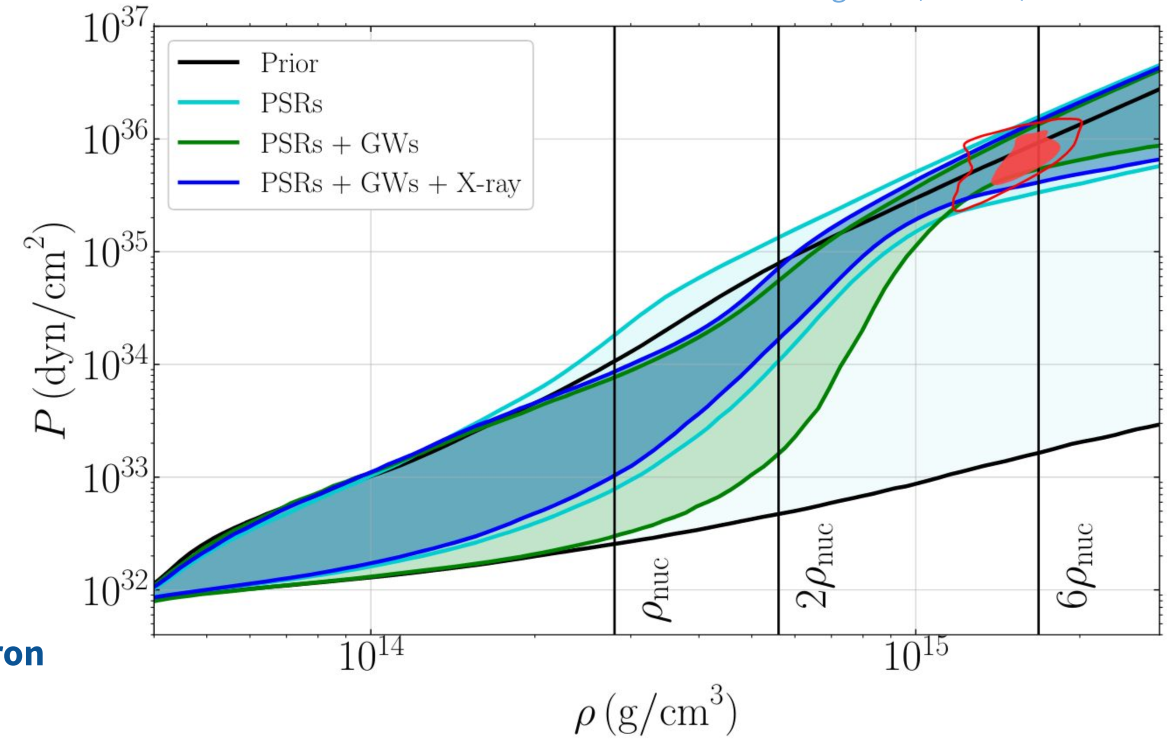
How dense can neutron stars get?

Legred+ (incl. PL) PRD 2021

Inferred central pressure and density for maximum-mass neutron stars

central density

3.9 - 6.4 ρ_{nuc}

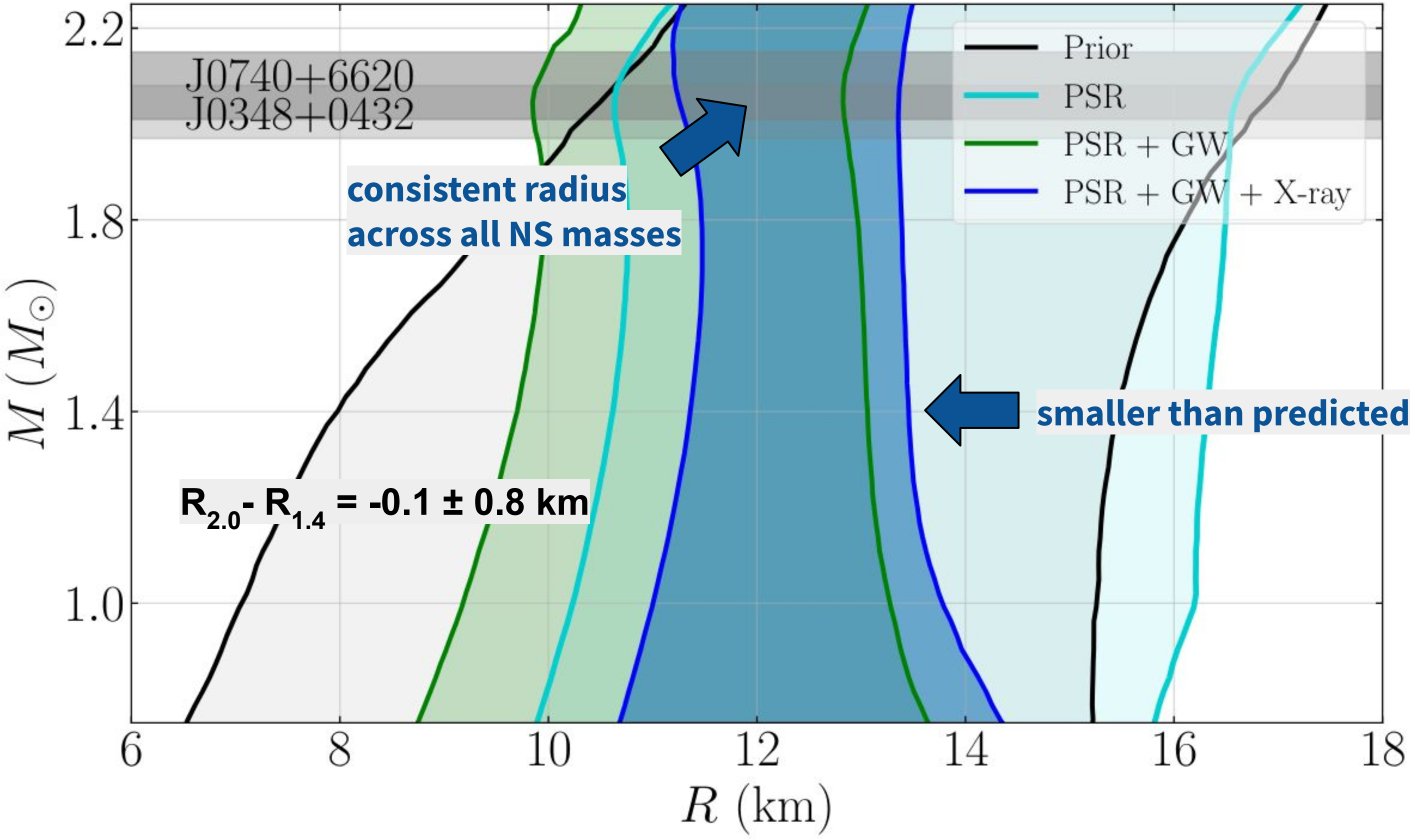


For exotic phases to occur in neutron star cores, phase transition onset must be below about 6 ρ_{nuc}

Neutron star radii at high and low masses

Legred+ (incl. PL) PRD 2021

small radius difference disfavors high-density softening of EOS associated with exotic phases



Similar radius for PSR J0740 and 1.4 $M_{\odot}$ neutron stars, less extreme central densities disfavor exotic cores

… but exotic phases by no means ruled out yet

Sound speed in neutron star matter

At asymptotically high densities, expect matter to be described by (perturbative) QCD calculations

- ***Sound speed of 1/√3 for ultra-relativistic massless particles***
- ***Sound speed reduced by finite particle masses, weak interactions***

Conjecture that sound speed in neutron star matter interpolates between low-density limit $c_s << 1$ and perturbative QCD limit $c_s = 1/\sqrt{3}$ Bedaque+Steiner PRL 2015

A sound speed above 1/√3 indicates strongly coupled, non-conformal matter

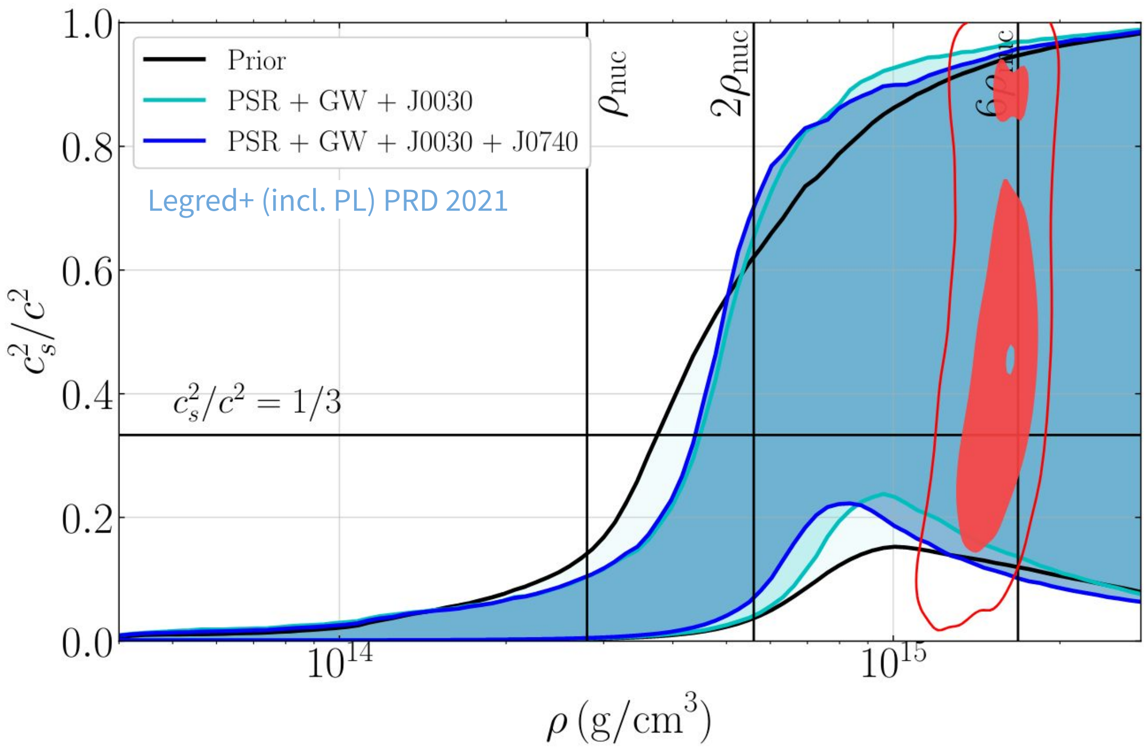
- ***E.g. quarkyonic matter*** McLerran+Reddy PRL 2019

2 $M_\odot$ pulsars are in tension with this conformal bound Bedaque+Steiner PRL 2015

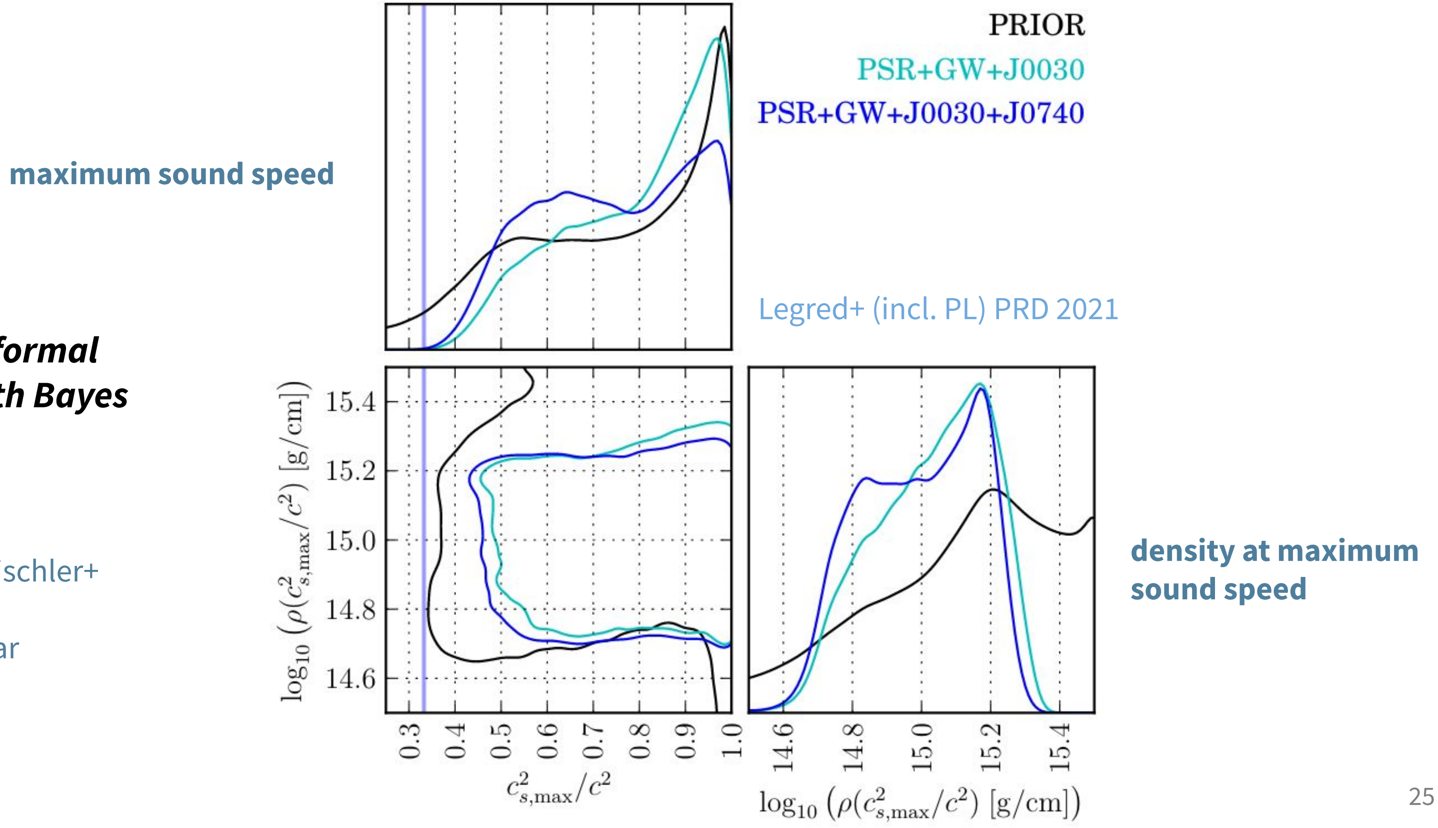
Sound speed in neutron star matter

central sound speed of maximum-mass star

EOSs that satisfy the conformal bound are disfavored relative to the prior



Sound speed in neutron star matter



EOSs that violate conformal limit are preferred with Bayes factor of O(1000)

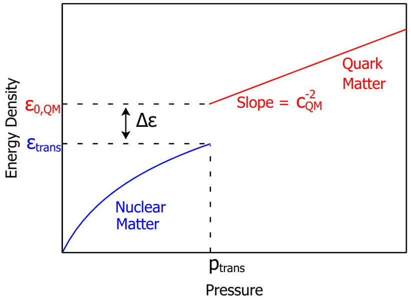
See Landry+ PRD 2020, Drischler+ PRC 2022, Altiparmak+ arXiv:2203.14974 for similar conclusions

Conjectured conformal bound on the sound speed likely violated inside neutron stars

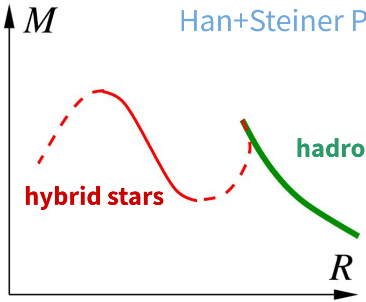
Possible indication of a strongly interacting phase

Hybrid stars and strong phase transitions

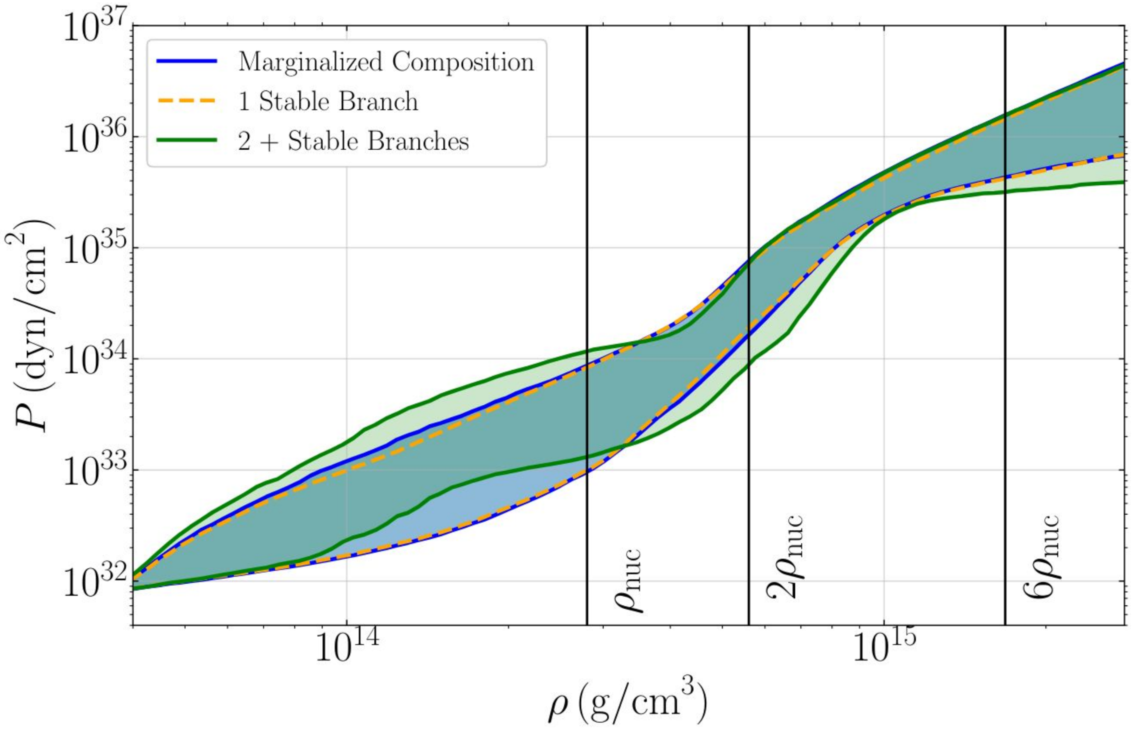
- Energy jump in the EOS from strong first-order phase transitions



- Large enough jumps produce a disconnected hybrid star branch

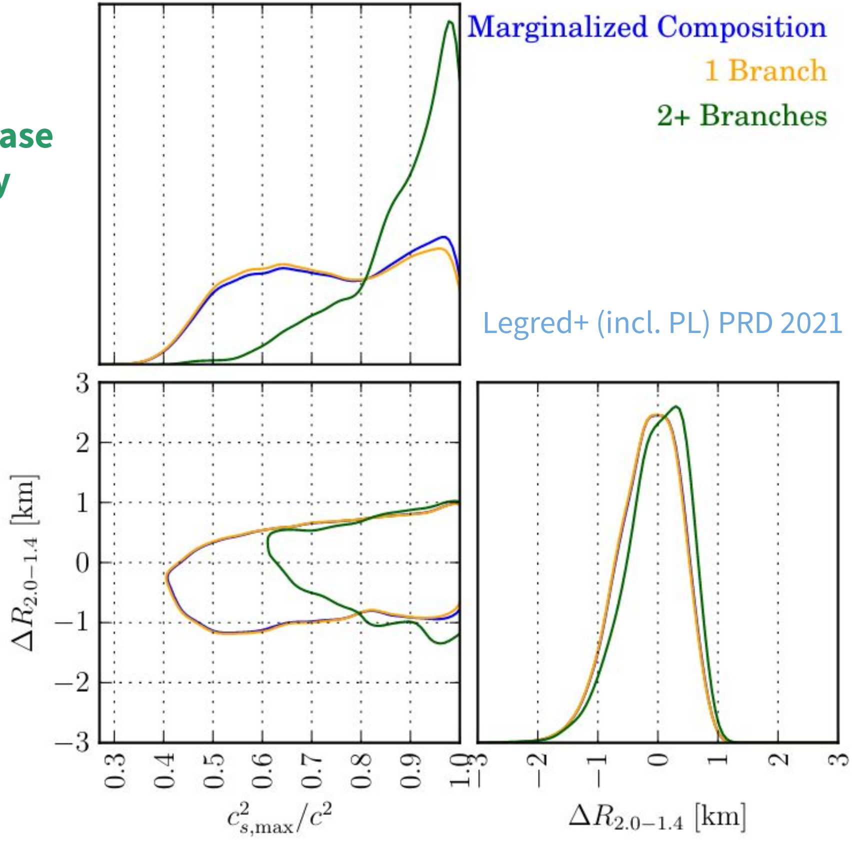


Legred+ (incl. PL) PRD 2021



Hybrid stars and strong phase transitions

EOSs with a strong phase transition reach a very large sound speed



Legred+ (incl. PL) PRD 2021

radius difference tightly constrained

EOSs that have a disconnected hybrid star branch are disfavored with a Bayes factor of 7

PSR J0740's radius measurement reduces the probability of a strong phase transition supporting a disconnected hybrid star branch relative to past results

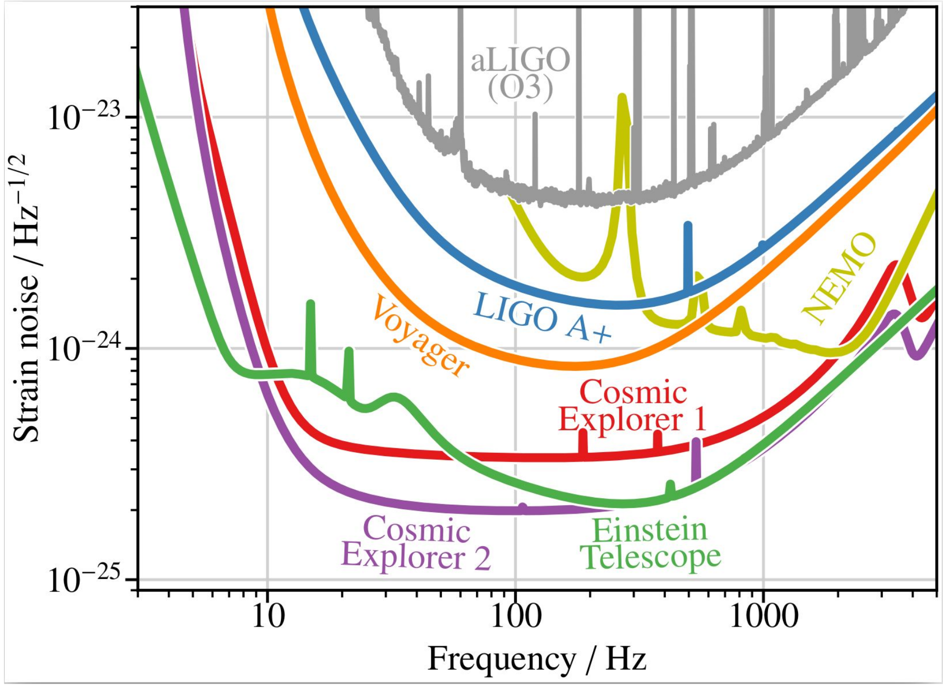
... but only mildly disfavored

LIGO A+ & 3G GW observatories

- During O4, at design sensitivity, LIGO & Virgo expected to detect ~ 4 BNSs with SNR > 20
- During O5, at A+ sensitivity, LIGO & Virgo expected to detect O(10) BNSs with SNR > 20
- Cosmic Explorer expected to detect O(100) BNSs with SNR > 100 per year
- CE will also capture complete BNS population out to z ~ 2, have a horizon of z ~ 10

CE Horizon Study: Evans+ (+PL) arXiv:2109.09882

Kuns+ 2020



LIGO A+ & 3G GW observatories

E. Hall, Cosmic Explorer Project

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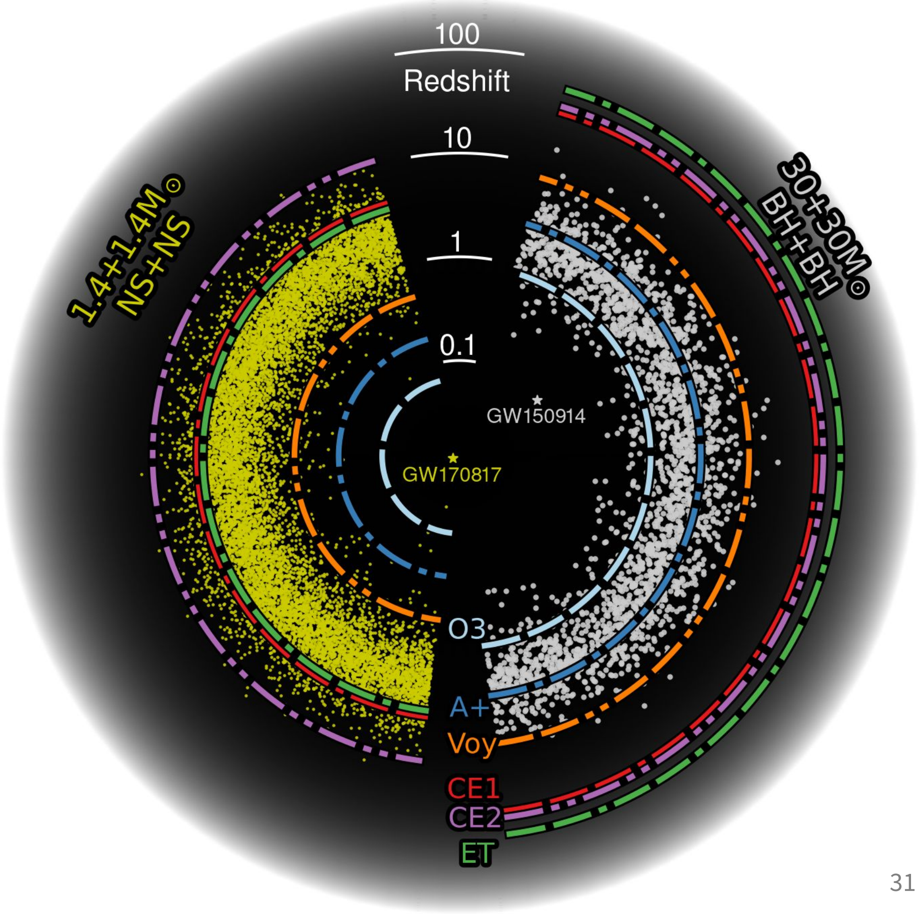
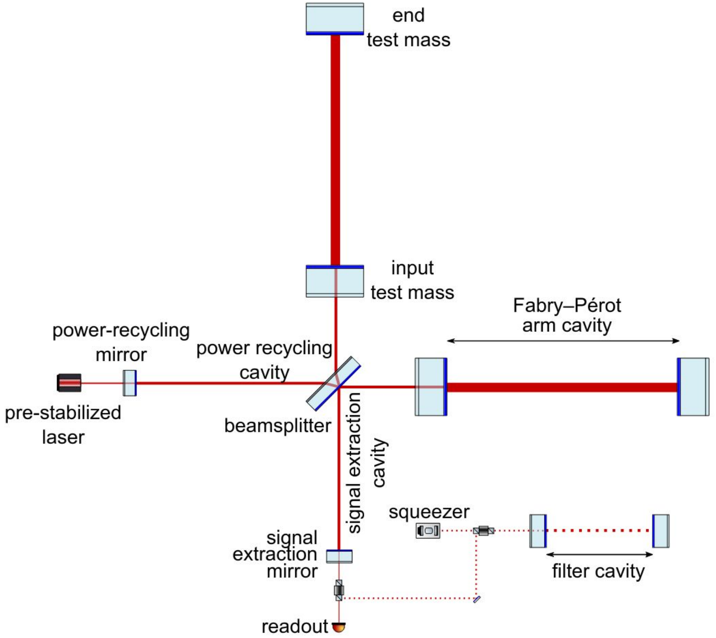
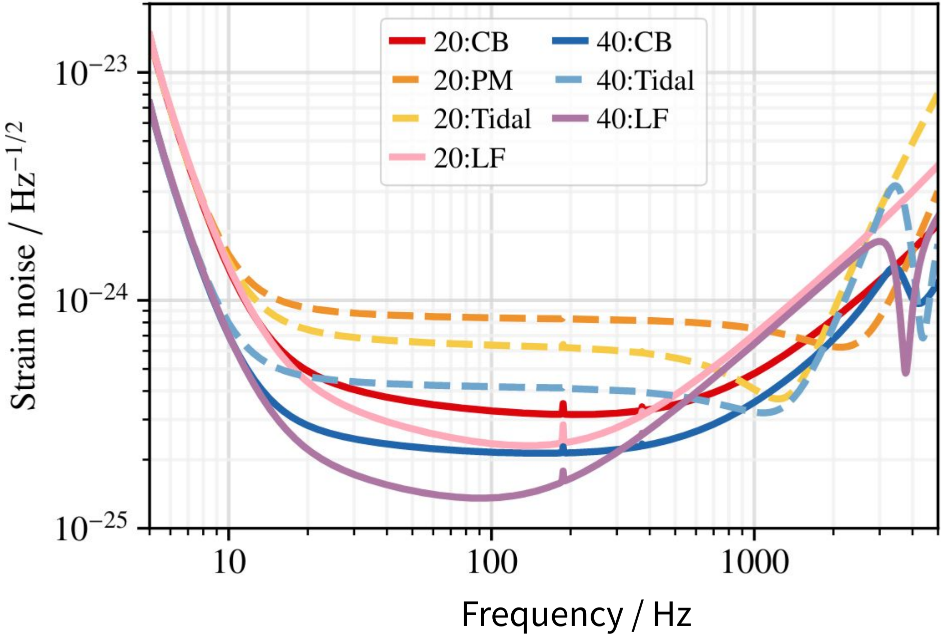


LIGO A+ & 3G GW observatories

It may be possible to tune the reflectivity of Cosmic Explorer's signal extraction mirror to improve sensitivity to binary neutron star inspirals (or postmerger gravitational waves). Srivastava+ (incl. PL) arXiv:2201.10668





The nonrotating maximum neutron star mass is approximately 2.3 $M_\odot$

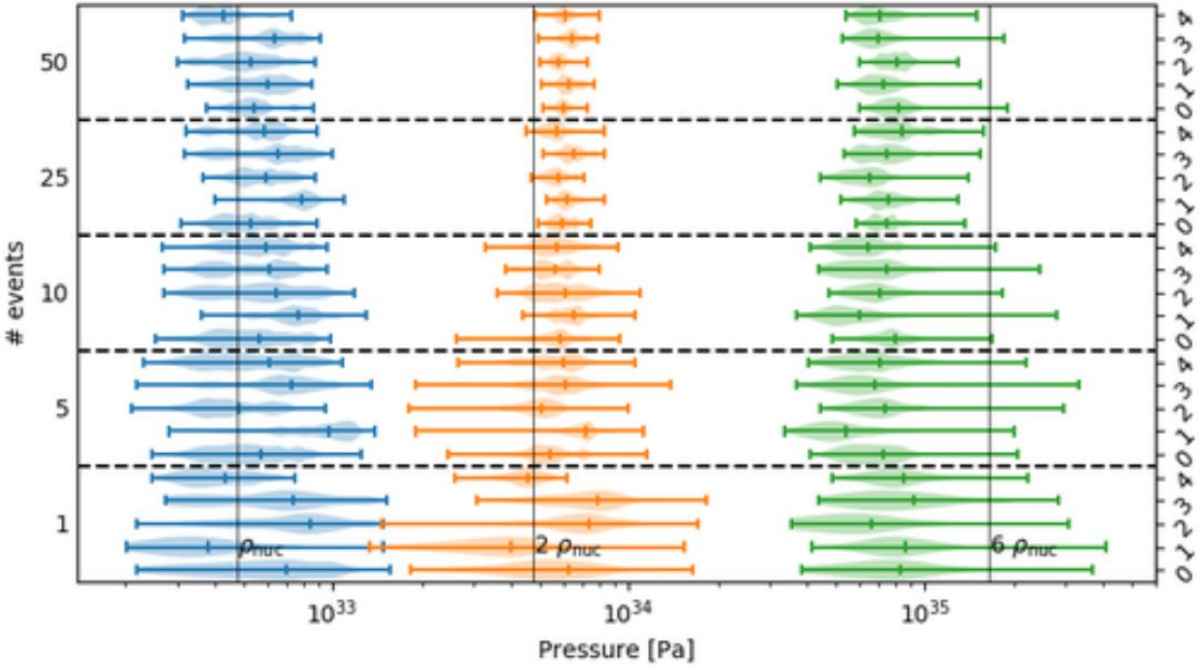
The matter density inside cold, nonrotating neutron stars likely does not exceed six times nuclear saturation density

There is strong evidence that the sound speed inside neutron stars exceeds the conjectured conformal bound

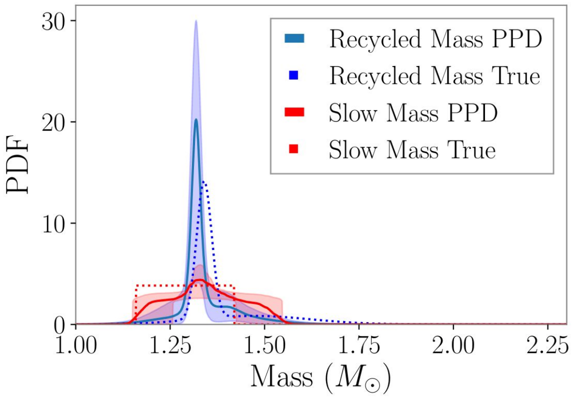
Strong phase transitions aren't necessary to explain current observations, but they aren't strongly disfavored either

Mismodeling the neutron star population

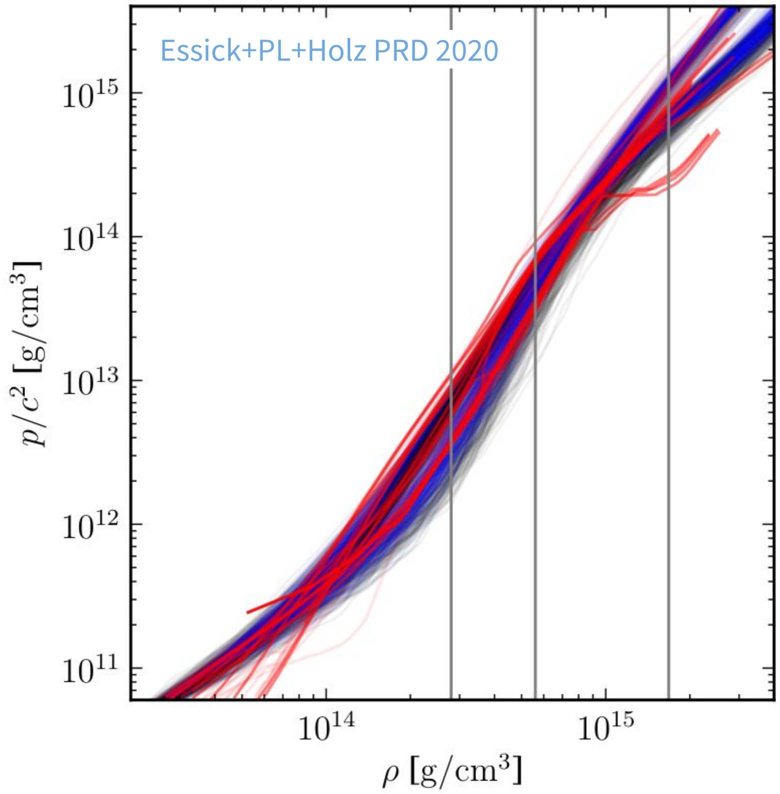
Choosing wrong population-level mass prior **biases recovered EOS** after O(10) events
Wysocki+ arXiv:2001.01747



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



Inferring neutron star composition



A Gaussian process model for the EOS allows for model comparison between different compositions for neutron star matter within a particular theoretical framework, e.g.

- ***Condition a GP on hadronic RMF models***
- ***Do the same with RMF models hyperons***
- ***Do the same with RMF models with quarks***

Prior $(\mathcal{H}_i)$	$P(\text{Hadronic}\|\text{data})$	$P(\text{Hyperonic}\|\text{data})$	$P(\text{Quark}\|\text{data})$
informed	28%	16%	56%