Prior Uncertainties in Inferring Neutron Star Masses and Radii from Observations

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Recent Collaborators:

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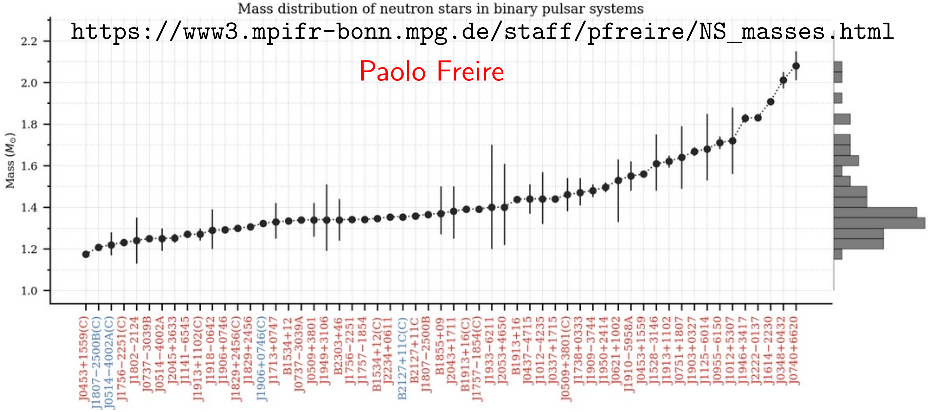
Masses of Pulsars in Binaries from Pulsar Timing

https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Paolo Freire



Largest: 2.08 ± 0.07 $M_\odot$
Smallest: 1.174 ± 0.004 $M_\odot$

Several other NS masses have been measured by other means, including some estimated to be more than $2M_\odot$ (e.g., black widow pulsars) and smaller than $1M_\odot$ (HESS J1731-347), but their mass uncertainties are generally large.

What is the Maximum Mass?

Minimum Maximum Mass

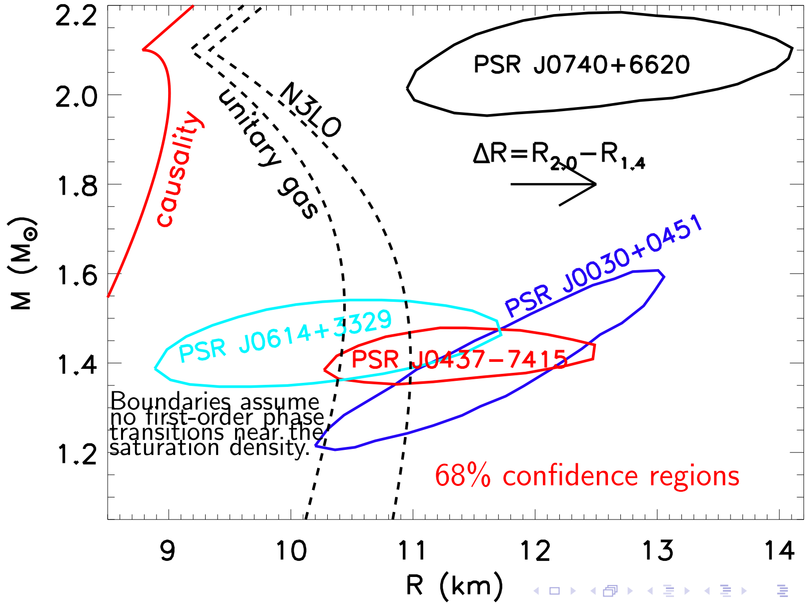
- PSR B1516+02B (Freire et al. 2008) $M = 2.08 \pm 0.19\ M_\odot$
- PSR J1614+2230 (Demorest et al. 2010) $M = 1.97 \pm 0.04\ M_\odot$
- PSR 1748-2021B (Clifford 2019) $M = 2.55^{+0.05}_{-0.08}\ M_\odot$ (total mass is $2.68 \pm 0.02 M_\odot$)
- PSR J0548+0432 (Antoniadis et al. 2013) $M = 2.01 \pm 0.04\ M_\odot$
- BPSR 1957+20 (van Kerkwijk 2010) $M = 2.4 \pm 0.3\ M_\odot$; black widow pulsar (BWP)
- PSR J1311-3430 (Romani et al. 2012) $M = 2.22 \pm 0.10 M_\odot$ BWP
- PSR J1544+4937 (Tang et al. 2014) $M = 2.06 \pm 0.56! M_\odot$ BWP
- PSR 2FGL J1653.6-0159 (Romani et al. 2014) $M > 1.96\ M_\odot$
- PSR J1227-4859 (de Martino et al. 2014) $M = 2.2 \pm 0.8\ M_\odot$ redback pulsar.
- PSR J0740+6620 (Fonseca et al. 2021) $M = 2.08 \pm 0.07\ M_\odot$
- PSR J0952-0607 (Romani et al. 2022) $M = 2.35 \pm 0.17 M_\odot$ BWP
- PSR J0514-4002E(C) (Barr et al. 2024) $M = 2.40 \pm 0.31\ M_\odot$ companion to $1.4 M_\odot$ pulsar

Maximum Maximum Mass from GW170817: $\simeq$ 2.2-2.3 $M_\odot$?

How Can a Neutron Star's Radius Be Measured?

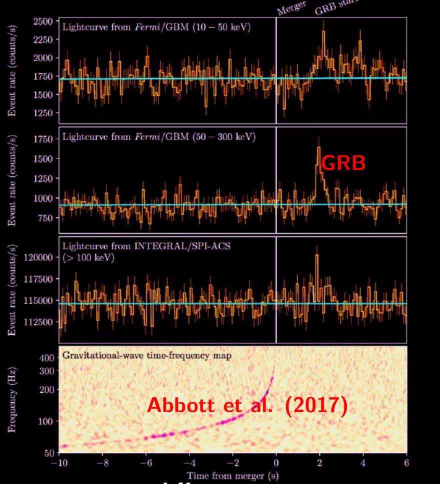
- X-ray observations of thermal emission from quiescent and bursting neutron stars
- X-ray phase-resolved spectroscopy of millisecond pulsars (NICER, NewAthena)
- Gravitational wave observations of merging neutron stars
- Pulsar timing of relativistic binary systems with spin-orbit coupling
- Gamma-ray bursters showing quasi-periodic oscillations
- Quasi-periodic oscillations seen in some accreting neutron star binaries

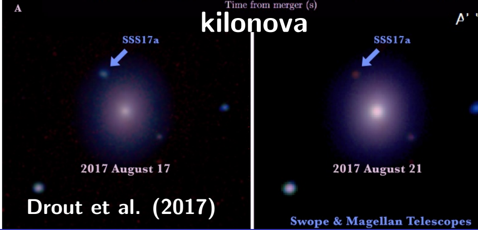
NICER Summary, with Minimum *R* Constraints



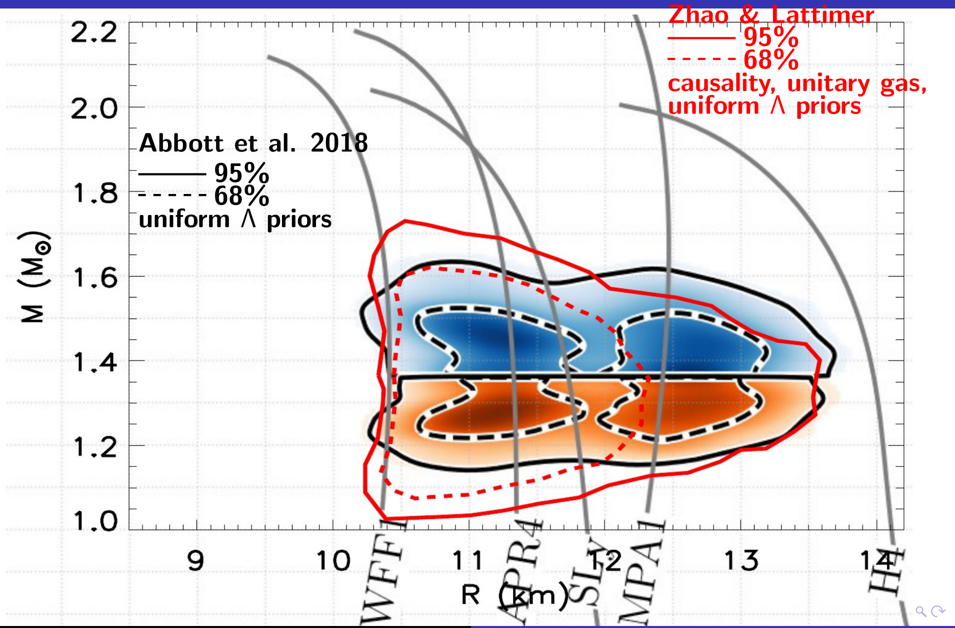
GW170817

- LVC detected a signal consistent with a BNS merger, followed 1.7 s later by a weak gamma-ray burst.
- $\sim$ 10100 orbits observed over 317 s.
- $\mathcal{M} = 1.186 \pm 0.001\ M_\odot$
- $M_{\rm T} = M_A + M_B \gtrsim 2^{6/5}\mathcal{M} = 2.725 M_\odot$
- $E_{\rm GW} > 0.025 M_\odot c^2$
- $D_L = 40^{+8}_{-14}$ Mpc
- $75 < \tilde\Lambda < 560$ (10.9 km$< \bar R < 13.3$ km)
- $M_{\rm ejecta} \sim 0.06 \pm 0.02\ M_\odot$
- Blue ejecta: $\sim 0.01 M_\odot$
- Red ejecta: $\sim 0.05 M_\odot$
- Highly opaque ejecta implies substantial r-process production
- M_T+Ejecta+GRB: $M_{max} \lesssim 2.22 M_\odot$

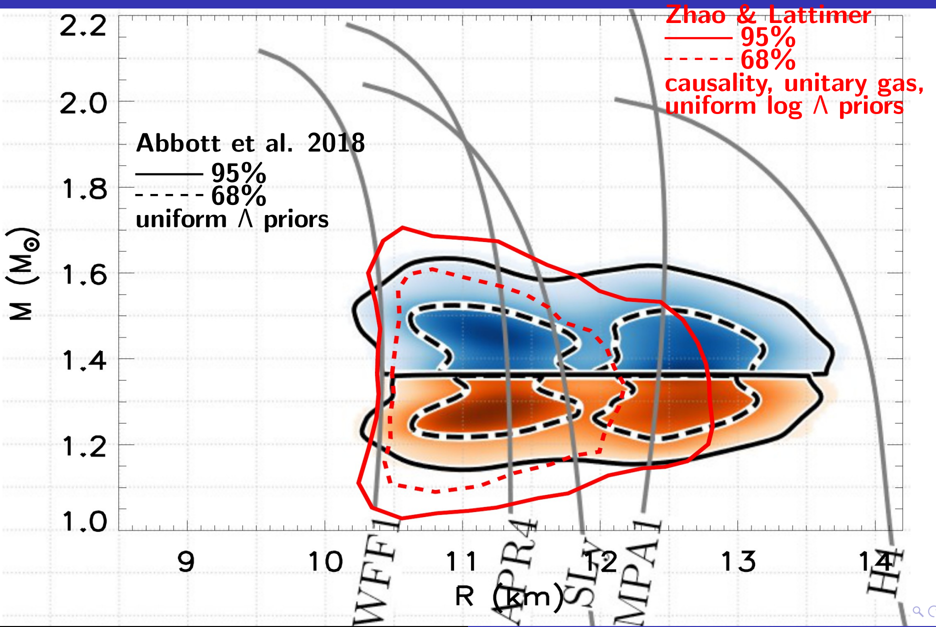




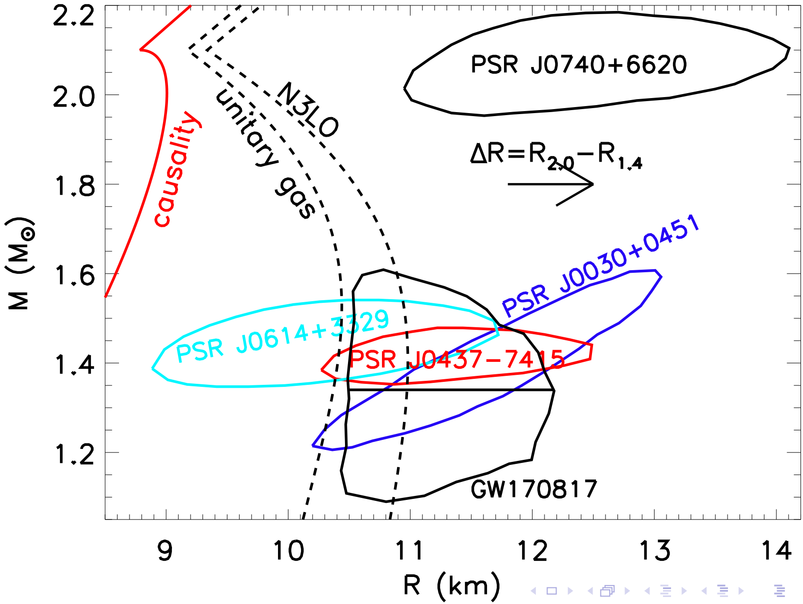
Systematic Biases in Deformability Extractions



Systematic Biases in Deformability Extractions



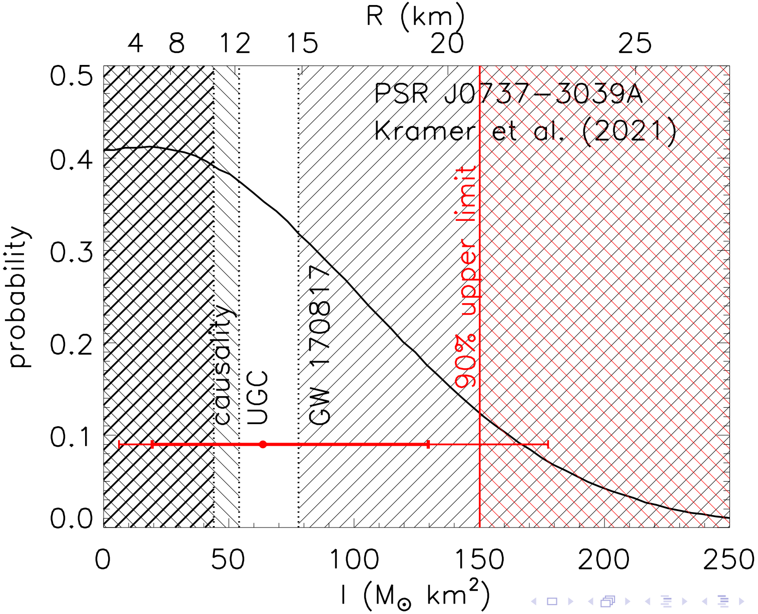
With NICER and GW170817 constraints



Moment of Inertia

- Spin-orbit coupling is of same magnitude as post-post-Newtonian effects (Barker & O'Connell 1975, Damour & Schaeffer 1988).
- Precession alters orbital inclination angle (observable if system is face-on) and periastron advance (observable if system is edge-on).
- More EOS sensitive than R: $I \propto MR^2$.
- Double pulsar PSR J0737-3037 ($P_b = 0.102$ d) is an edge-on candidate; $M_A = 1.338185 \pm 0.000004 M_\odot$.
- More relativistic systems have been found: PSR J1757-1854 ($M_A = 1.3412 \pm 0.0004 M_\odot$, $P_b = 0.164$ d) and J1946+2052 ($M_A < 1.31 M_\odot$, $P_b = 0.078$ d).
- Accurate ($\sim 10\%$) I measurements expected by 2030 for both PSR J0737-3037 and J1757-1854.

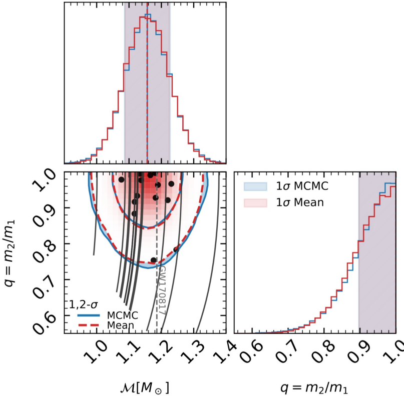
Current Moment of Inertia Measurement



GRB QPOs (modified from Guedes et al. 2025)

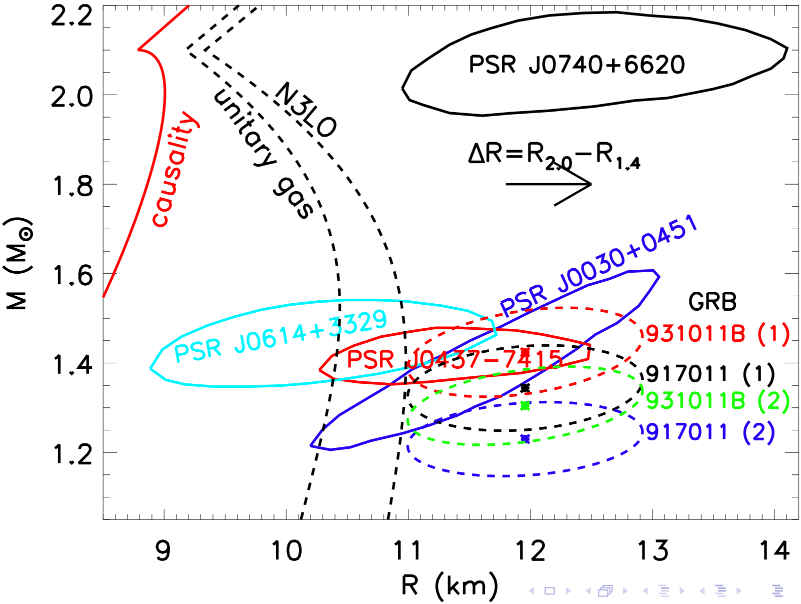
Quasi-periodic oscillations (QPOs) observed in 2 short gamma-ray bursts (s-GRBs) mimic radial and quadrupolar vibrations seen in simulations of post-merger hypermassive neutron stars.

The two observed frequencies obey semi-universal correlations with the binary's redshifted chirp mass $\mathcal{M}(1+z)$ and binary tidal deformability $\tilde{\Lambda}$. For GRB 910711 (931101B), these suggest $\tilde{\Lambda} = 1022 \pm 607$ (595 ± 204) and $\mathcal{M}(1+z) = 1.14 \pm 0.23 M_\odot$ ($1.36 \pm 0.23 M_\odot$), in ranges expected from galactic BNS.



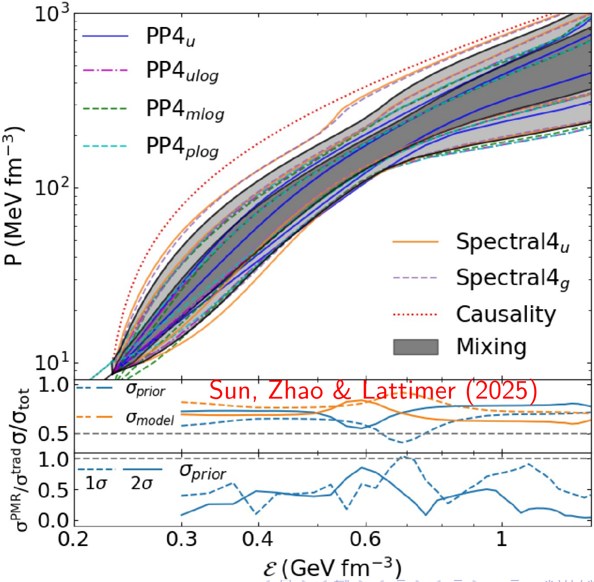
Priors for q and z taken from galactic BNS and s-GRBs ($\mathcal{P}(z) \propto z^3$, $\mathcal{P}(q) = \exp(-[q/0.2]^2)$). Furthermore, $\mathcal{M} \in [1.0, 1.30] M_\odot$ from galactic BNS, also, long-lived hypermassive neutron stars can't otherwise form. Also reasonable to assume all 4 neutron stars have a common radius R. A semi-universal relation (Zhao & Lattimer 2018), valid for $1.2 \leq M/M_\odot \leq 1.6$, is $\Lambda \simeq (0.0088 \pm 0.0008)(Rc^2/GM)^6$, then yields $R = 11.7 \pm 0.8$ km and masses $1.1 < M/M_\odot < 1.5$.

GRB QPO constraints

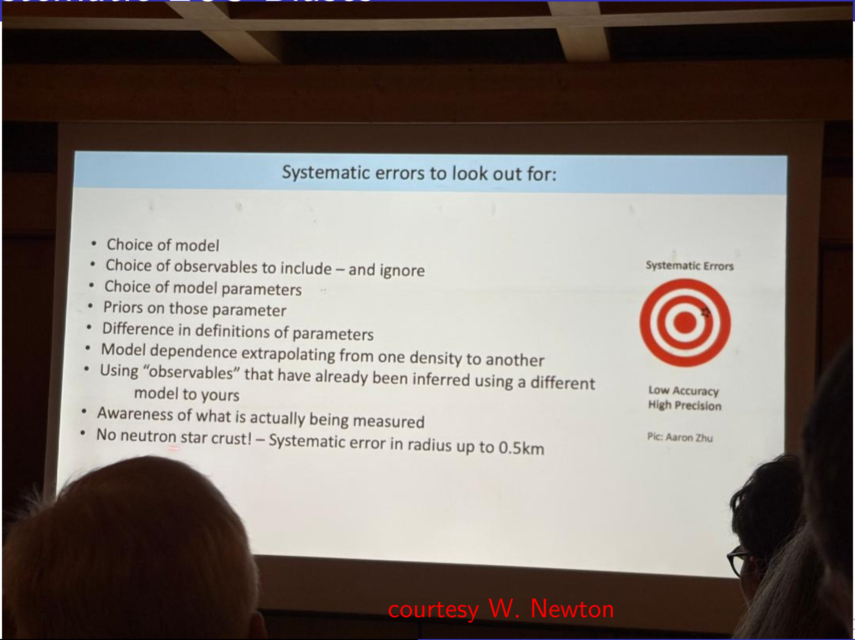


Inversion of *M-R* Data and Systematic EOS Biases

To infer the EOS from *M-R* data, the traditional approach involves Bayesian inversions beginning with *M-R* priors generated from millions of EOSs using EOS parameterizations, with parameters arbitrarily varied within causality and maximum mass bounds. The resulting EOS priors produce significant inference uncertainties, being at least as large as observational uncertainties.



Systematic EOS Biases



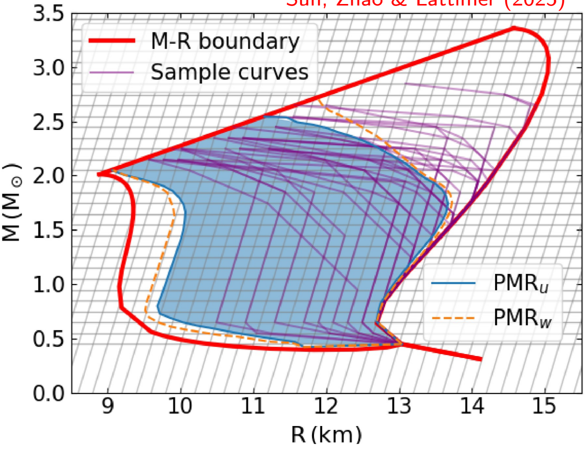
courtesy W. Newton

Parametrized *M*-*R* (PMR) Method

To avoid prior EOS uncertainties, the PMR method grids the allowed *M*-*R* space. The prior consists of *M*-*R* curves that satisfy an assumed M_{max} and are produced by connecting adjacent mass nodes with segments not violating causality or thermodynamic stability. A trapezoidal mesh prevents curves from bouncing back-and-forth in *R*. Direct analytic inversion of surviving *M*-*R* curves generate EOS data (see last year's talk). Bayesian methods with *M*-*R* observations assign weights to each *M*-*R* curve and its EOS reconstruction.

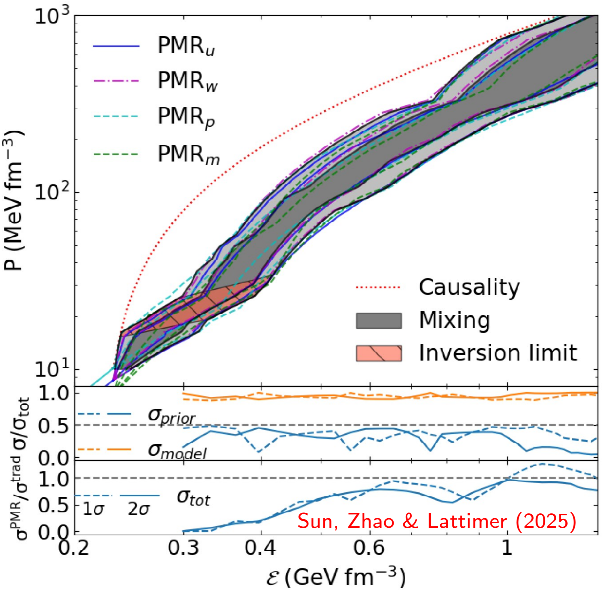
Blue region contains 68% of connected nodes

Sun, Zhao & Lattimer (2025)



Comparison of EOS Inferences

The PMR method is more natural since its priors and posteriors are both in *M-R* space, and its observational uncertainties dominate its prior uncertainties at all densities. In contrast, the uncertainties from the EOS priors in the traditional Bayesian framework are about as large as the observational uncertainties. The PMR method has a stiffer high-density EOS, and, at all but the highest densities, smaller absolute uncertainties.



Take Aways

- Novel predictions of neutron star properties are on the horizon, including moment of inertia measurements and observations of GRB QPOs.
- Systematic uncertainties affect both observational predictions of masses and radii and inferences of the underlying neutron star EOS.
- At the present time, using traditional Bayesian inference frameworks, these two types of uncertainties have approximately the same magnitude.
- Until precision (~ 0.1 km) measurements of radii are available, it is crucial to reduce systematic uncertainties in EOS inferences.
- The PMR method offers a novel approach that has better control of its systematic prior uncertainties, and, as a result, apparently smaller absolute uncertainties.