New Constraints on the Neutron Star Equation of State

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In collaboration with Sebastien Guillot, Anna Hensel, Lucien Mauviard, Achim Schwenk, Isak Svensson, Anna Watts (and many more people!)

European Research Council
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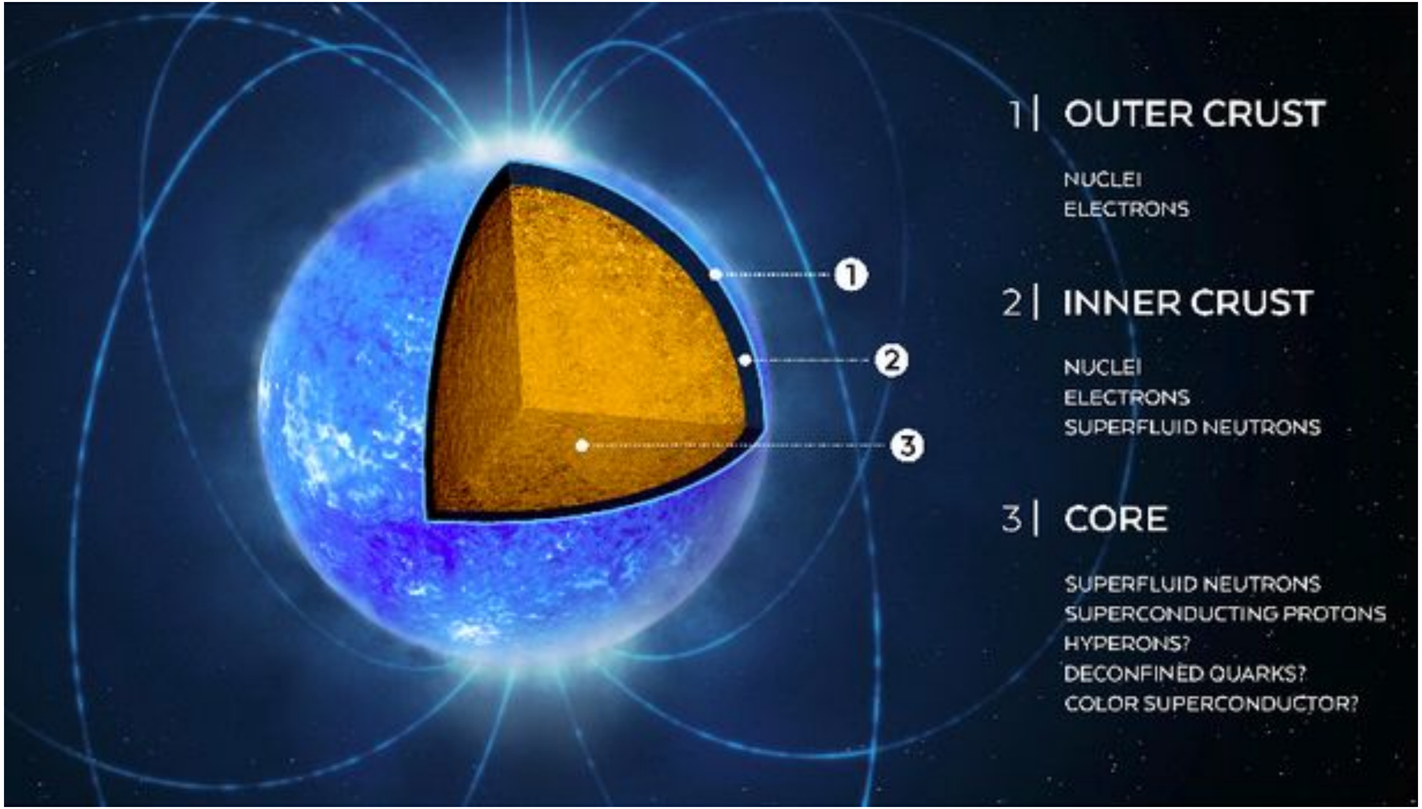
Neutron stars (NS)



The natural laboratory for the investigation of nuclear matter

Figure from Watts et al, Rev. Mod. Phys (2016), arxiv:1602.01081

Multimessenger astrophysics

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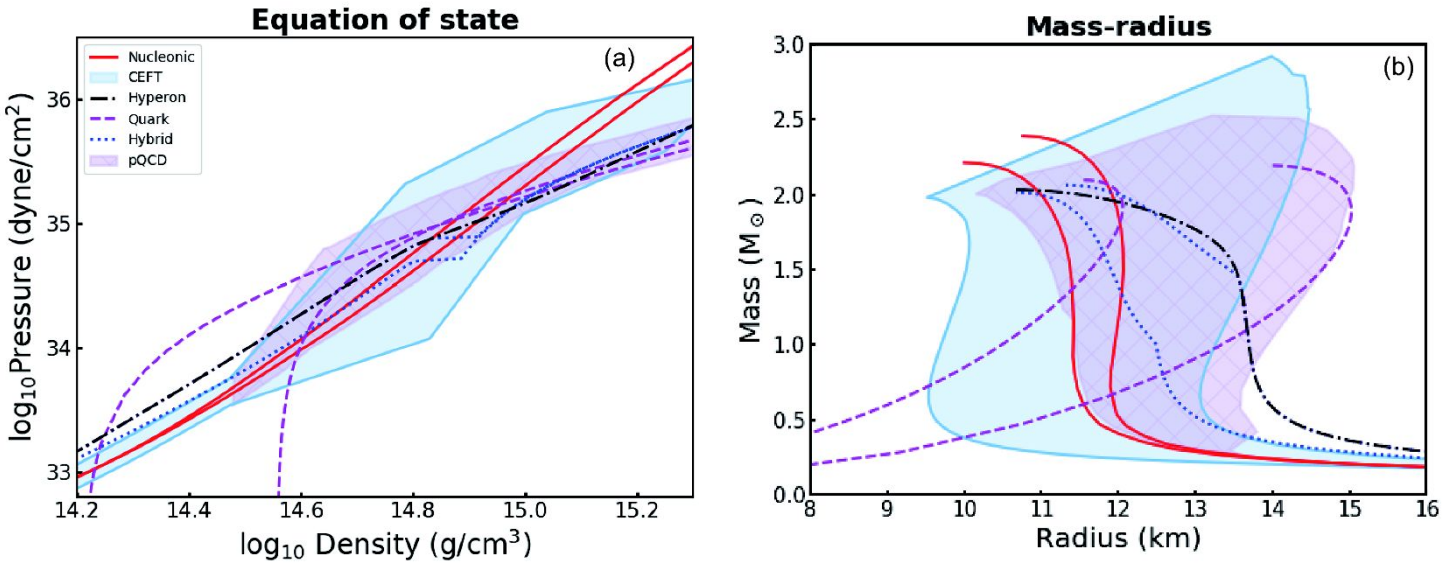
Recent (and future) observations provide unprecedentedly precise NS data

Modified figure from https://www.ligo.org/science/Publication-GWHEN-IceCube/index.php

Constraining equation of state and NS M-R curves



Astrophysical observations can constrain the nuclear matter EOS

Figure from Watts et al, Science China Physics, Mechanics & Astronomy (2019), arxiv:1812.04021

See Anthea Fantina's talk today

Pulse profile modeling

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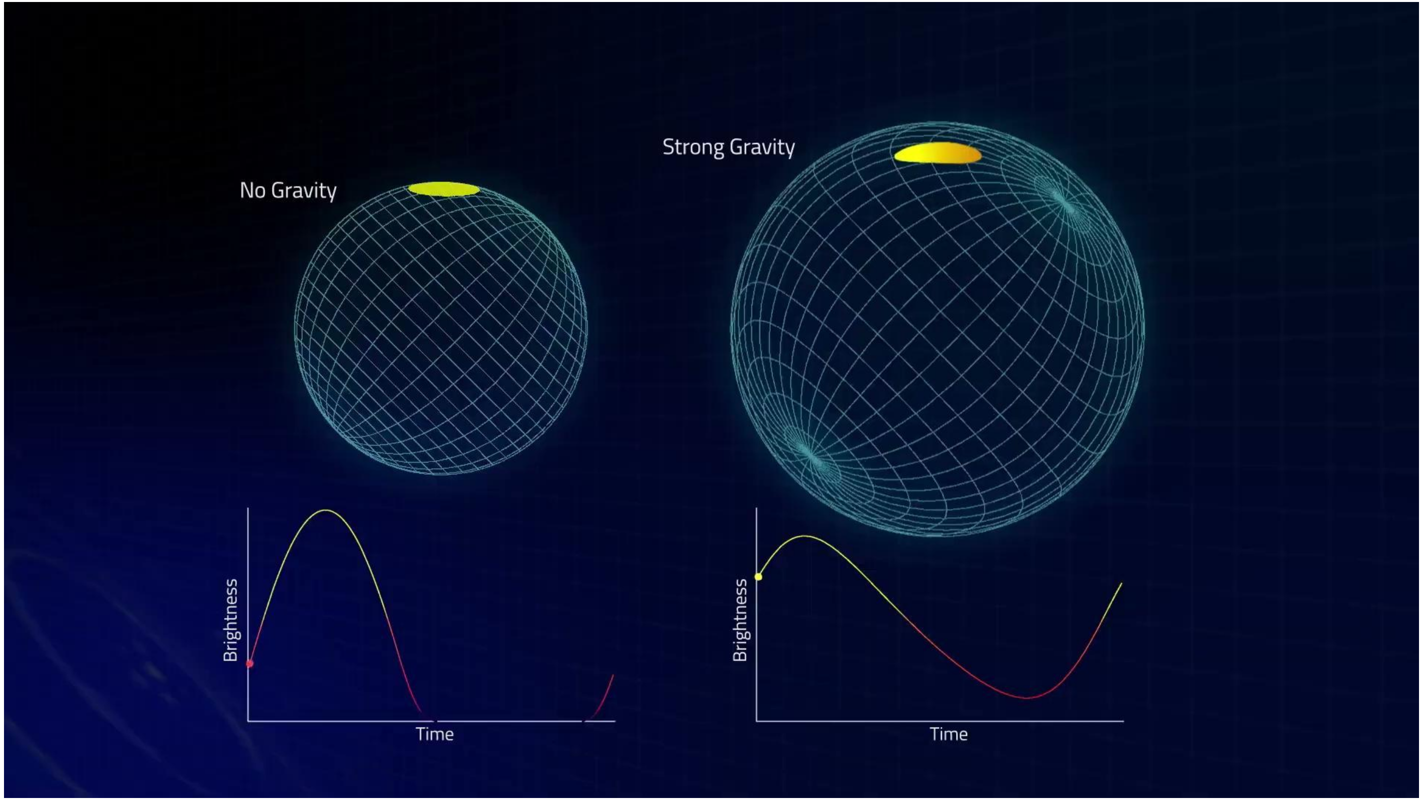
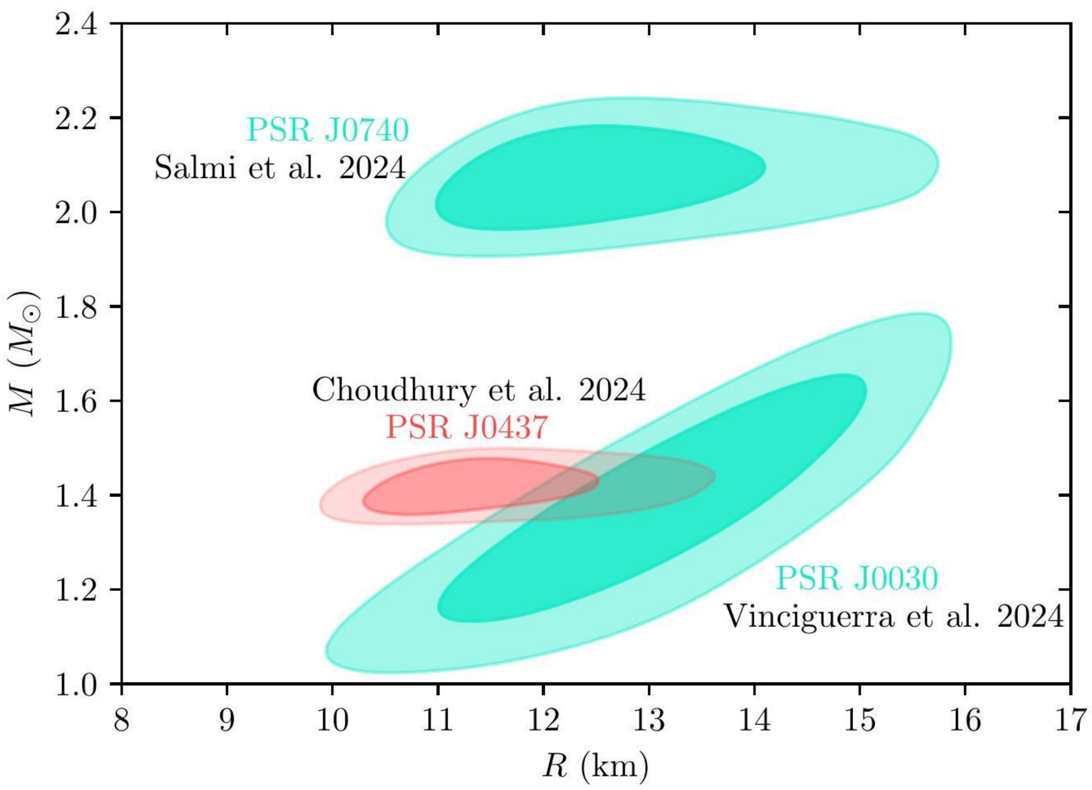


Proportional effect to the stars' compactness (M/R)

Simultaneous constraint on neutron star mass and radius

Animation from https://svs.gsfc.nasa.gov/vis/a020000/a020200/a020268/Lensing.1080.mp4

Recent data from NICER and GW



Already including mass constraints from radio observations and background constraints (when available)

Plus tidal deformabilities from GW170817 and GW190425

Modified figure from Rutherford, MM, Svensson et al, ApJL (2024), arxiv:2407.06790

Chiral effective field theory

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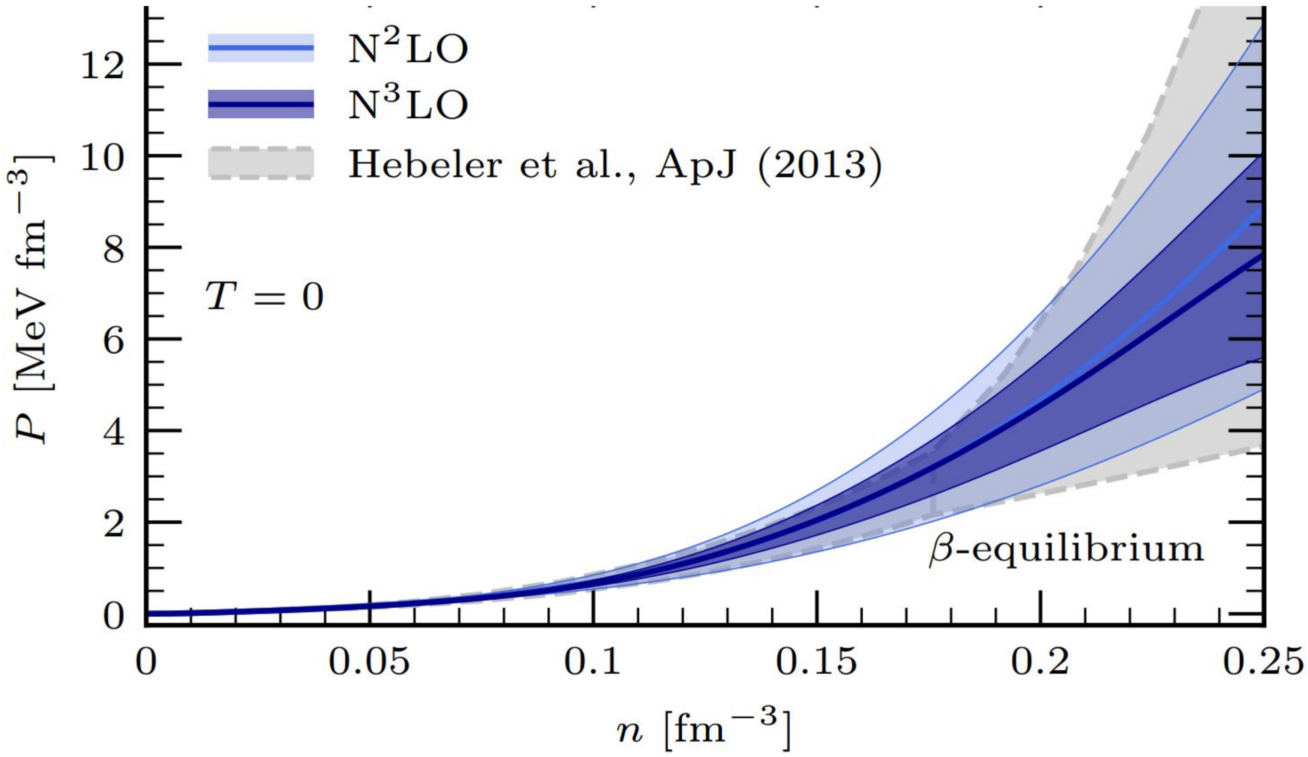
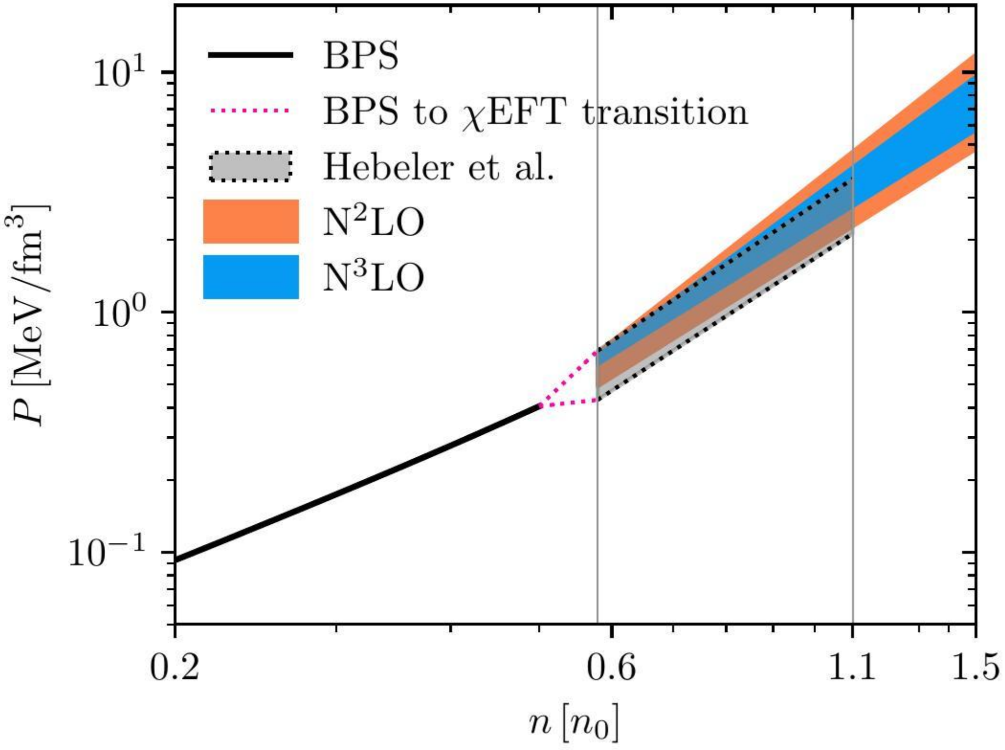


Based on asymmetric matter calculations and improved uncertainty quantification, for both next-to-next-to (N^2LO) and next-to-next-to-next-to (N^3LO) leading order

Figure from Keller et al, PRL (2023), arxiv:2204.14016

Crust and outer core

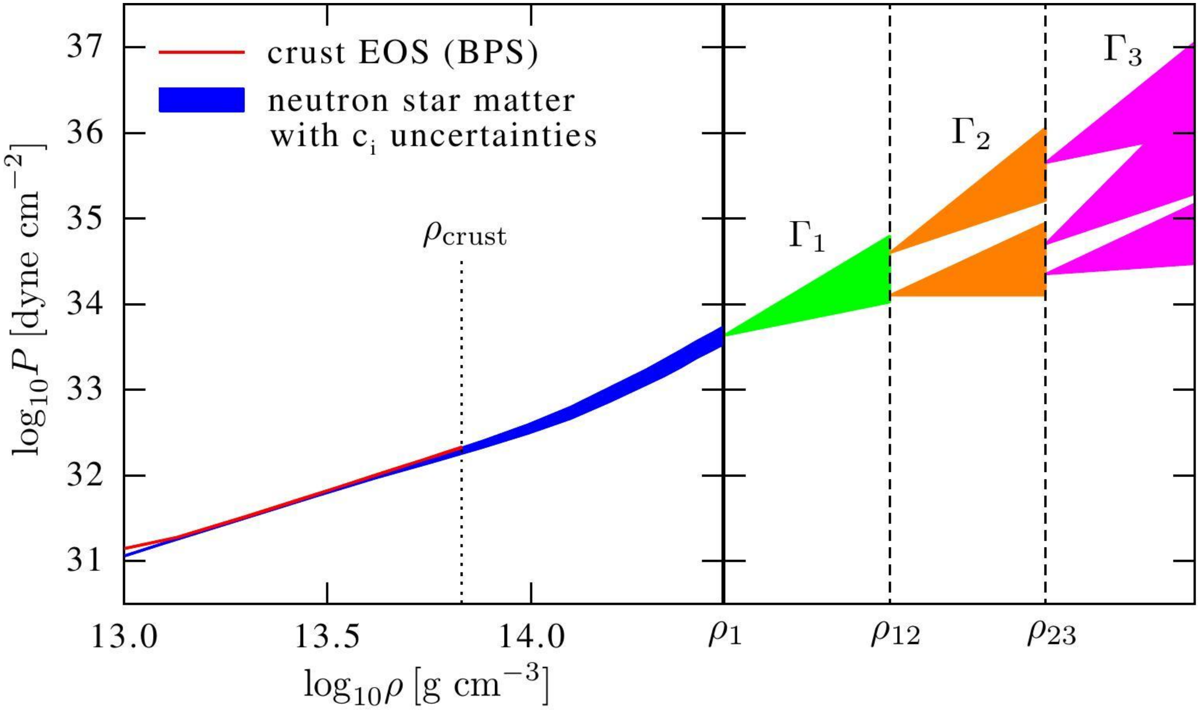


BPS EOS to model crust and polytropic fit ($P = K n^{\Gamma}$) for chiral EFT

Extended to both $1.1 n_{sat}$ and $1.5\ n_{sat}$

From Rutherford, MM, Svensson et al, ApJL (2024), arxiv:2407.06790

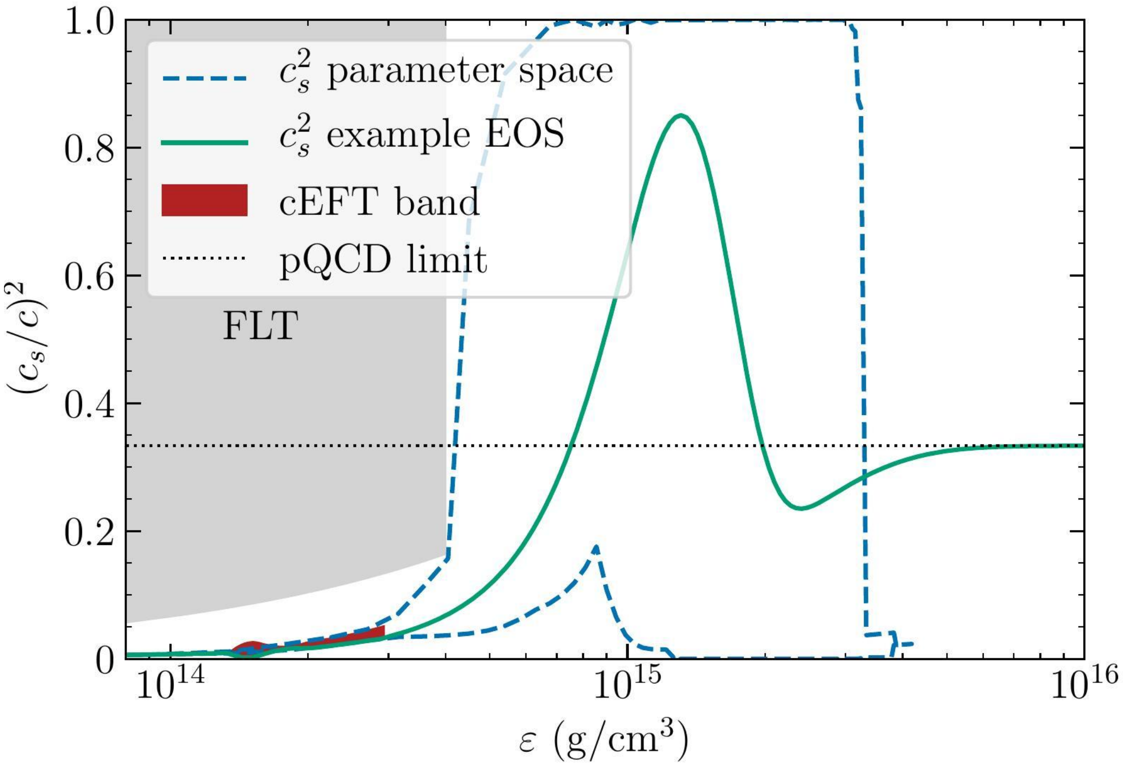
Piecewise polytropic parametrization (PP)



3 independent polytropes, respecting causality

Figure from Hebeler et al, ApJ (2013) arxiv:1303.4662

Speed of sound parametrization (CS)



Analytical expression to speed of sound, limited by

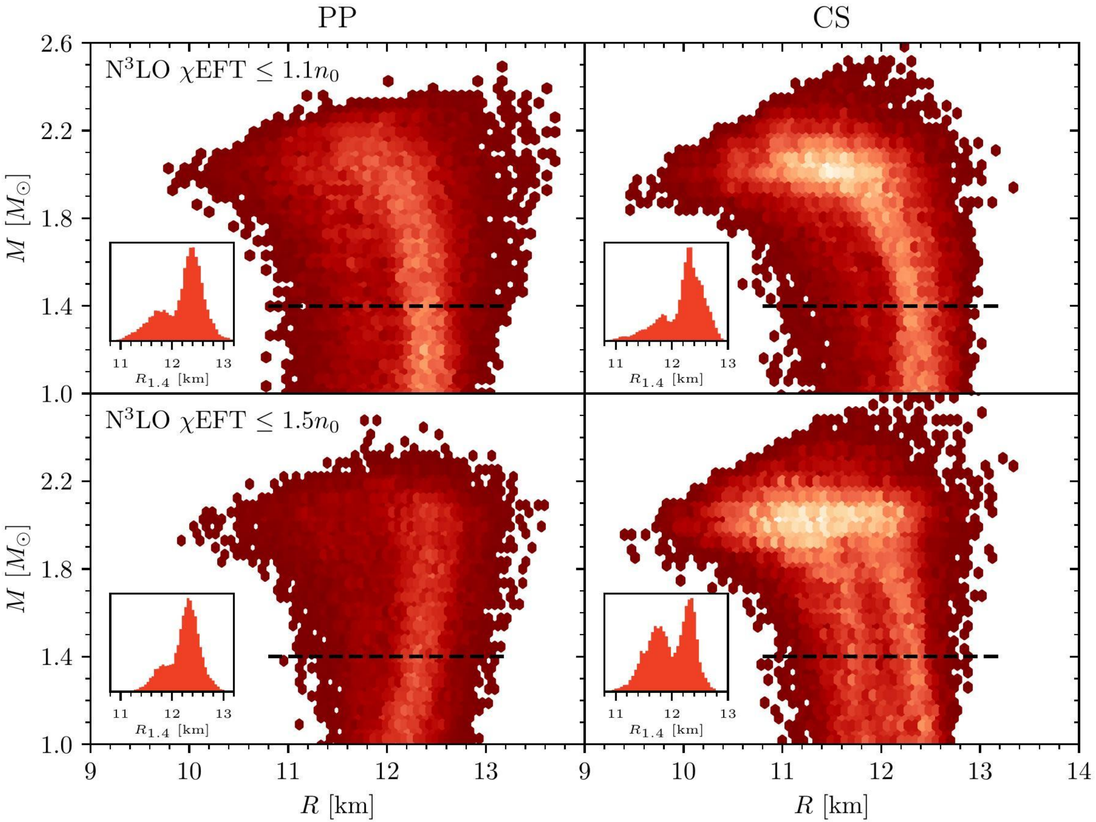
Fermi liquid theory

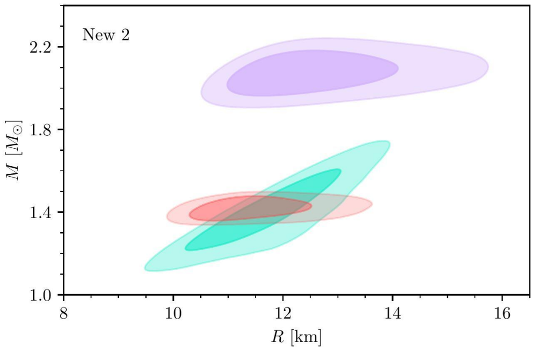
causality

$\lim_{n \geq 50\, n_{sat}} c_s^2 \rightarrow 1/3$

Figure from Greif et al, MNRAS (2019)
arxiv: 1812.08188

Most likely M-R



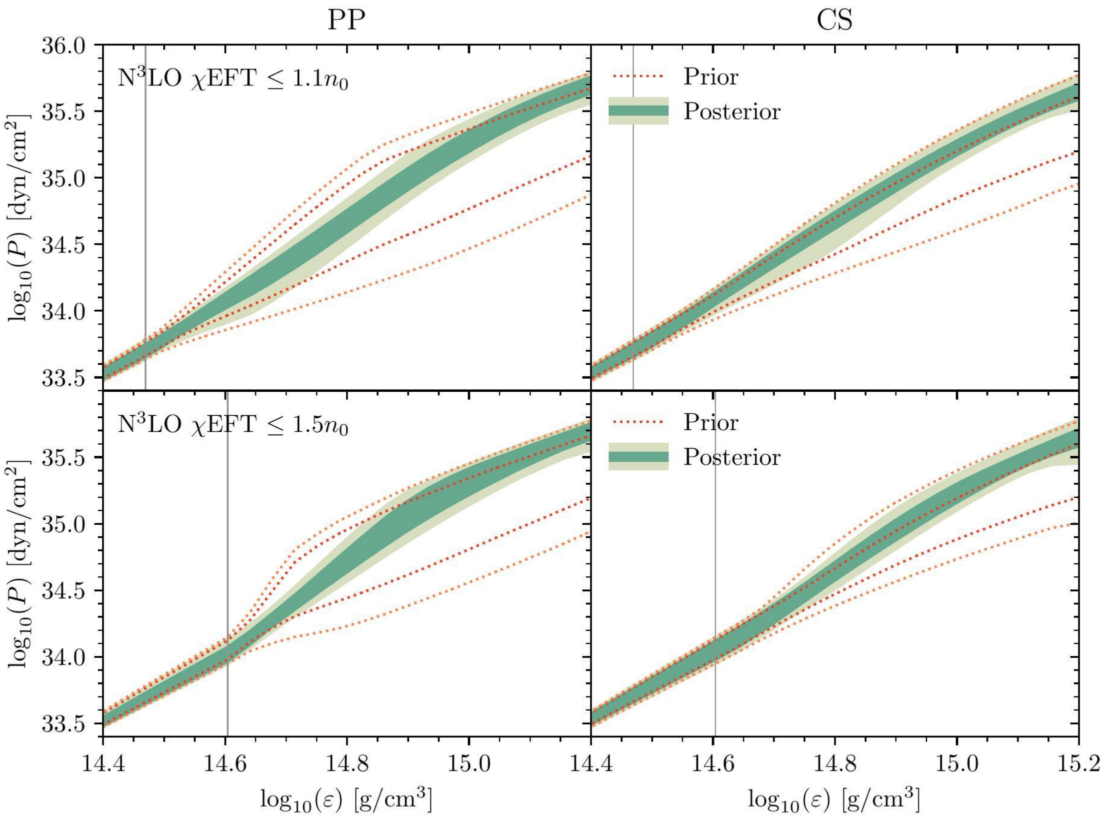


Consistent results for PP and CS parameterizations

Bimodal-like tendency for all posteriors

From Rutherford, MM, Svensson et al, ApJL (2024), arxiv:2407.06790

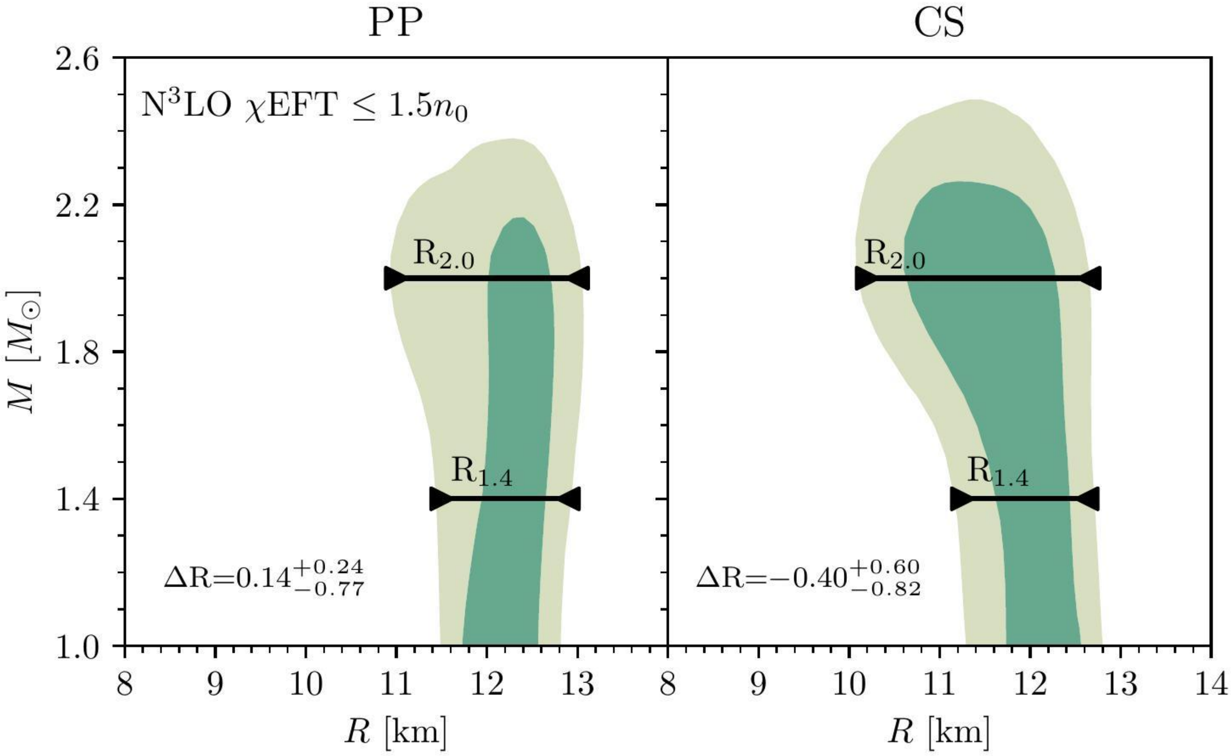
Corresponding P-E curves



Stiffening of EOS P-E curves at intermediate densities

From Rutherford, MM, Svensson et al, ApJL (2024) arxiv:2407.06790

Trends for dense matter EOS



We calculate

$\Delta R = R_{2.0} - R_{1.4}$

$\Delta R > 0$ suggests a stiffening of the EOS

Small dependence on high-density extension

From Rutherford, MM, Svensson et al, ApJL (2024), arxiv:2407.06790

Perturbative QCD (pQCD)

From A. Hensel thesis defended yesterday!

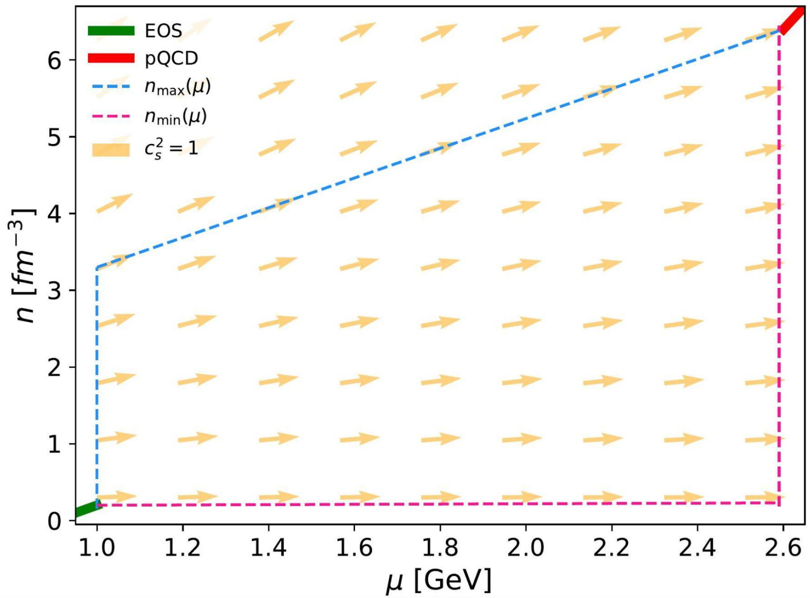
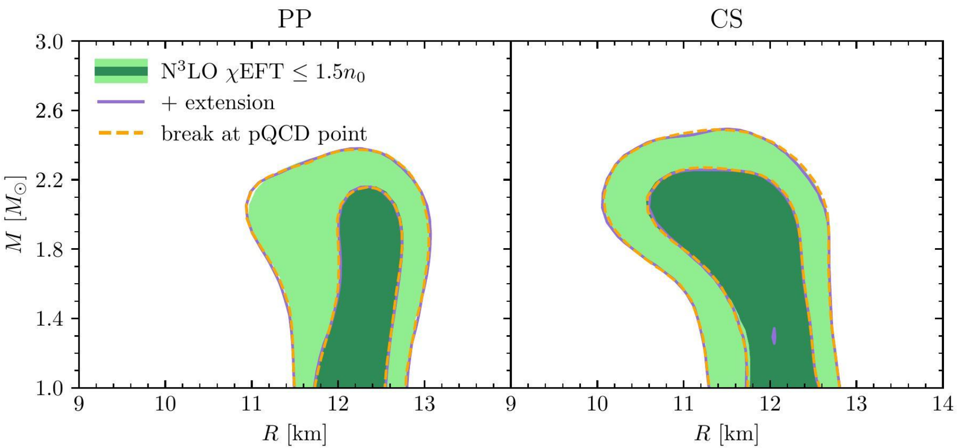


Figure modified from Komoltsev and Kurkela, PRL (2022), arxiv:2111.05350



High-density extensions implemented to all EOS previously incompatible with pQCD pressure constraints

Minor effects in the posteriors, already well constrained by PSR J0740

PSR J0614 M-R from NICER

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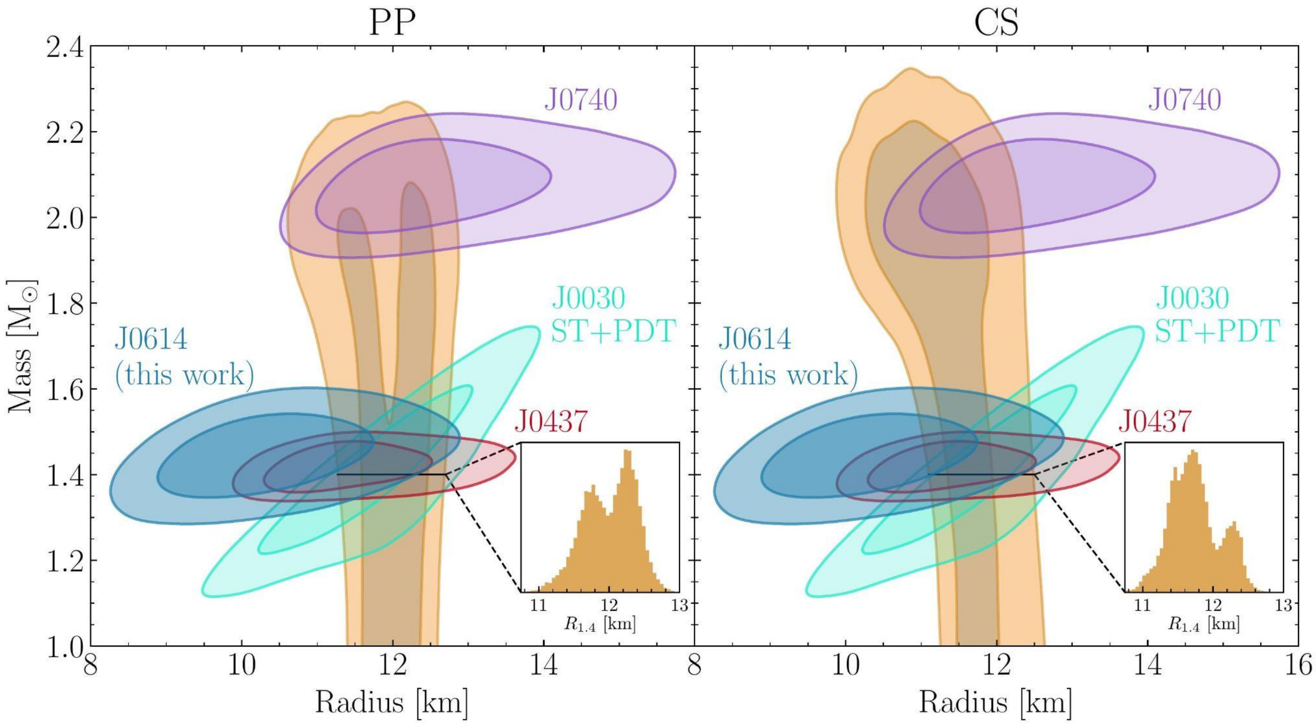
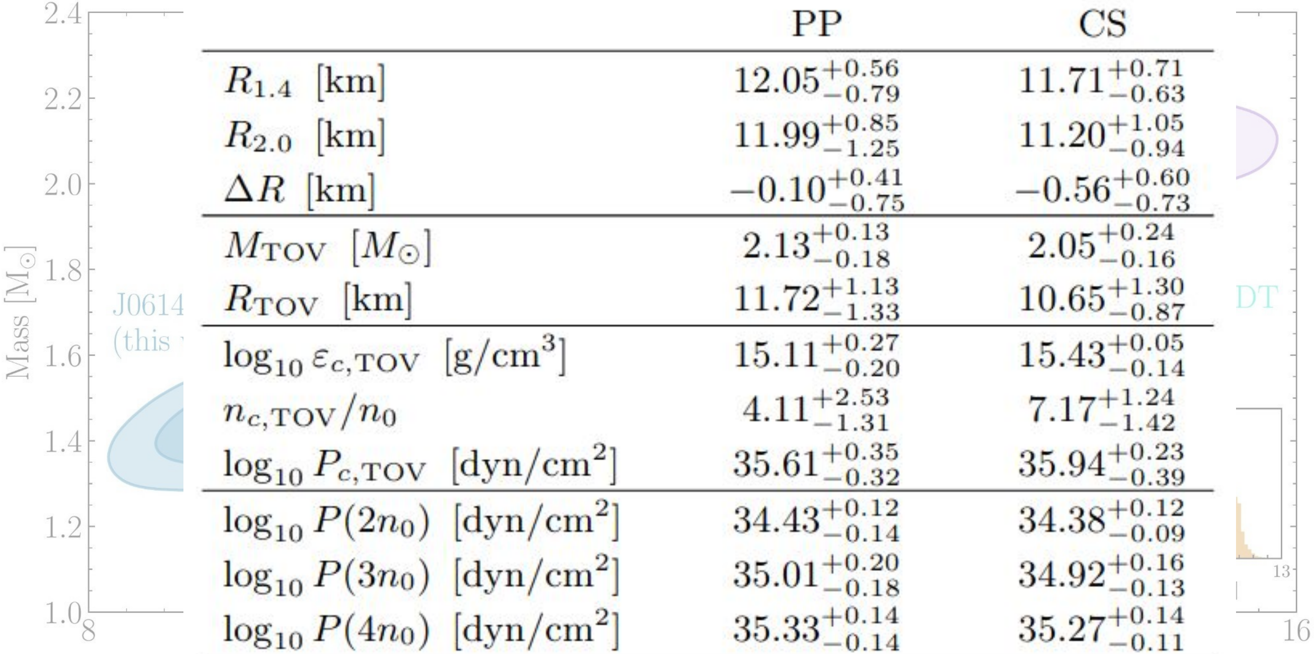


Bimodal-like structure present for both high-density extensions

Slight EOS softening compared to previous posteriors

Figure from Mauviard, Guillot et al, ApJ submitted (2025)
arxiv: 2506.14883

PSR J0614 M-R from NICER



	PP	CS
$R_{1.4}$ [km]	$12.05^{+0.56}_{-0.79}$	$11.71^{+0.71}_{-0.63}$
$R_{2.0}$ [km]	$11.99^{+0.85}_{-1.25}$	$11.20^{+1.05}_{-0.94}$
ΔR [km]	$-0.10^{+0.41}_{-0.75}$	$-0.56^{+0.60}_{-0.73}$
$M_{\rm TOV}$ $[M_\odot]$	$2.13^{+0.13}_{-0.18}$	$2.05^{+0.24}_{-0.16}$
$R_{\rm TOV}$ [km]	$11.72^{+1.13}_{-1.33}$	$10.65^{+1.30}_{-0.87}$
$\log_{10} \varepsilon_{c,\rm TOV}$ [g/cm^3]	$15.11^{+0.27}_{-0.20}$	$15.43^{+0.05}_{-0.14}$
$n_{c,\rm TOV}/n_0$	$4.11^{+2.53}_{-1.31}$	$7.17^{+1.24}_{-1.42}$
$\log_{10} P_{c,\rm TOV}$ [dyn/cm^2]	$35.61^{+0.35}_{-0.32}$	$35.94^{+0.23}_{-0.39}$
$\log_{10} P(2n_0)$ [dyn/cm^2]	$34.43^{+0.12}_{-0.14}$	$34.38^{+0.12}_{-0.09}$
$\log_{10} P(3n_0)$ [dyn/cm^2]	$35.01^{+0.20}_{-0.18}$	$34.92^{+0.16}_{-0.13}$
$\log_{10} P(4n_0)$ [dyn/cm^2]	$35.33^{+0.14}_{-0.14}$	$35.27^{+0.14}_{-0.11}$

Bimodal-like structure present for both high-density extensions

Slight EOS softening compared to previous posteriors

Figure from Mauviard, Guillot et al, ApJ submitted (2025) arxiv:2506.14883

Summary

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- NICER data significantly constraints the posteriors, especially PSR J0740

- Posteriors overall consistent for N^2LO, N^3LO, PP, CS, up to 1.1 n_0 or 1.5 n_0
  N^3LO and 1.5 n_0 more constrained

- Bimodal-like structure under further investigation, within the posteriors, no clear preference between softer or stiffer EOS

- Precision of observations only increases! More data expected soon

NEoST

Gracias!

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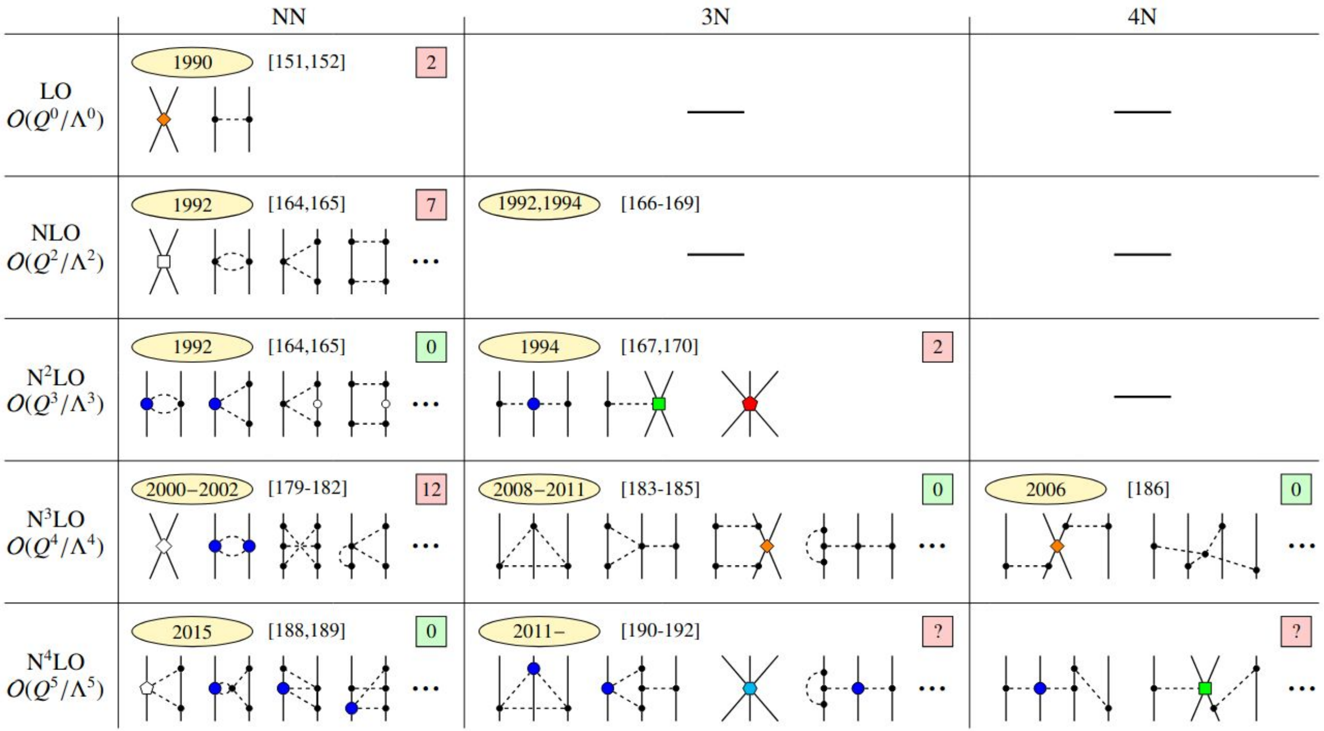
Additional slides

Chiral effective field theory



Ab-initio calculations can determine the EOS at low densities

Figure from Hebeler, Phys.Rept. (2021), arxiv:2002.09548

Non-trivial hot-spot modeling

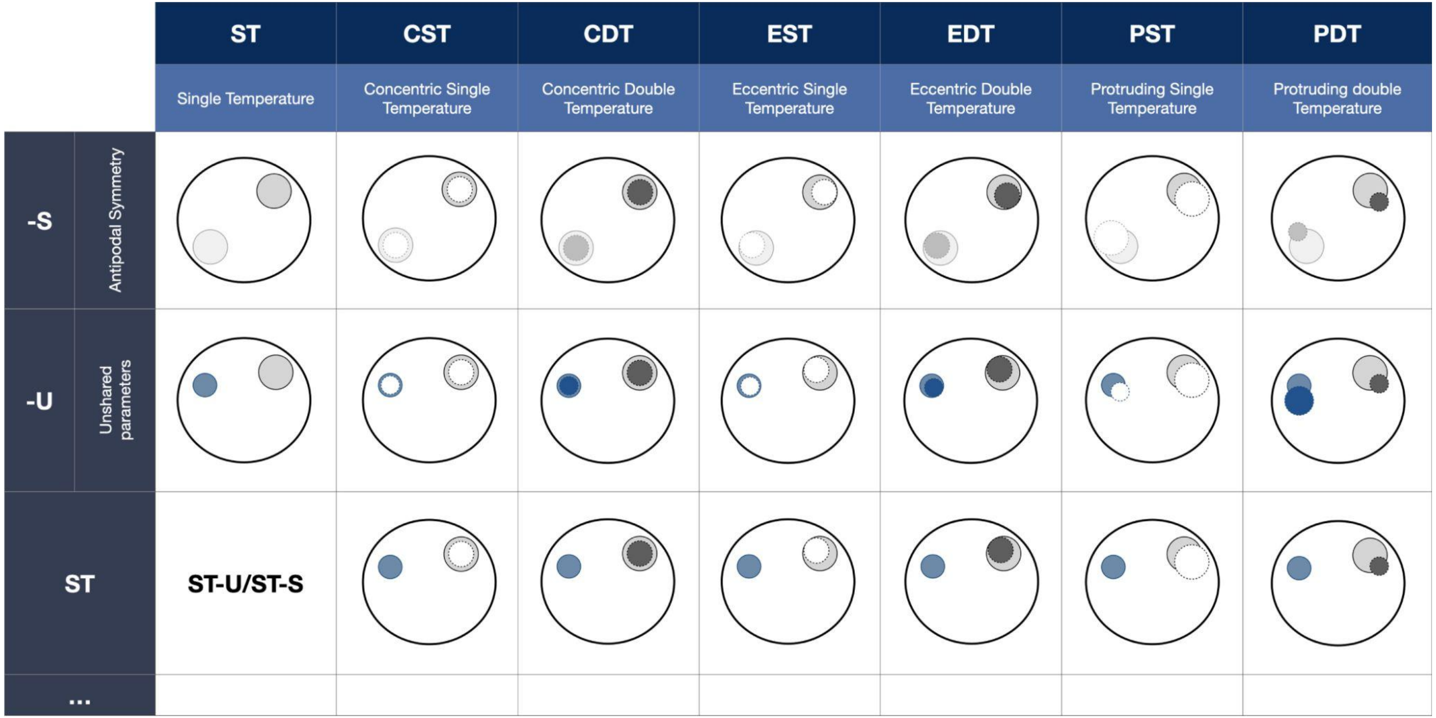


Figure from Vinciguerra et al, APJ (2023), arxiv:2308.08409

Recent data from NICER

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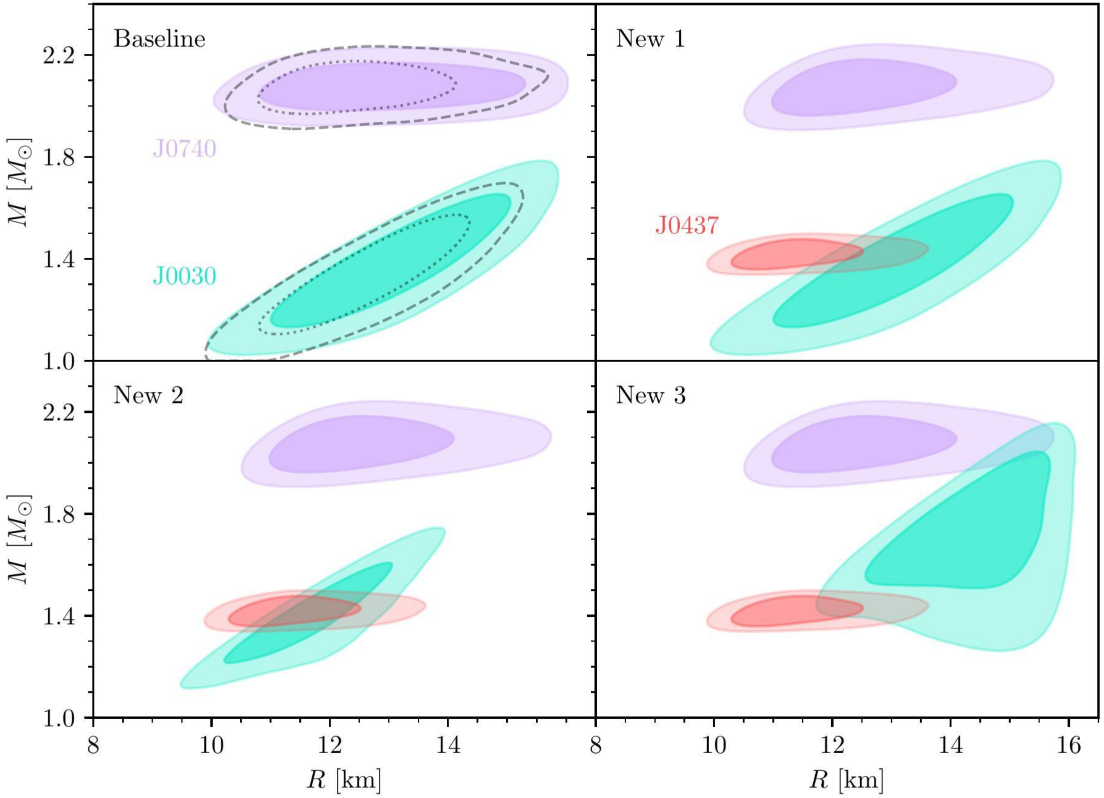

Some possible MR data contours for some neutron stars

From Rutherford, MM, Svensson et al, ApJL (2024), arxiv:2407.06790

Bayesian framework

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Following previous works, (Raaijmakers et al, 2020; 2019), posterior distributions of all EOS parameters (θ) and central energy density (ε):

$$p(\theta, \varepsilon \mid d, \mathbb{M}) \propto p(\theta \mid \mathbb{M})\ p(\varepsilon \mid \theta, \mathbb{M}) \times \prod_i p(\Lambda_{1,i}, \Lambda_{2,i}, q_i \mid \mathcal{M}_c, d_{\mathrm{GW},i}) \times \prod_l p_{\mathrm{new}}(M_l, R_l \mid d_{\mathrm{NICER(+radio)},l}),$$

with mass measurements of J0740, J0437 and J0614 included through NICER M-R likelihoods

See NEoST: **https://xpsi-group.github.io/neost/overview.html**

PP parametrization equation

Each polytrope given by $p(\rho) = K \rho^{\Gamma}$

such that $\varepsilon(p) = (1 + a)(p/K)^{1/\Gamma} + p/(\Gamma - 1)$

Parameter ranges are:

For χ_{EFT} up to $1.1n_0$,

Γ_1: [1, 4.5], Γ_2: [0, 8], Γ_3: [0.5, 8], ρ_{12}: [1.5, 8.3], ρ_{23}: [1.5, 8.3]

For χ_{EFT} up to $1.5n_0$,

Γ_1: [0, 8], Γ_2: [0, 8], Γ_3: [0.5, 8], ρ_{12}: [2, 8.3], ρ_{23}: [2, 8.3]

CS parametrization equation

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High density EOS given by

$$c_s^2(x)/c^2 = a_1 e^{-\frac{1}{2}(x-a_2)^2/a_3^2} + a_6 + \frac{\frac{1}{3} - a_6}{1 + e^{-a_5(x-a_4)}},$$

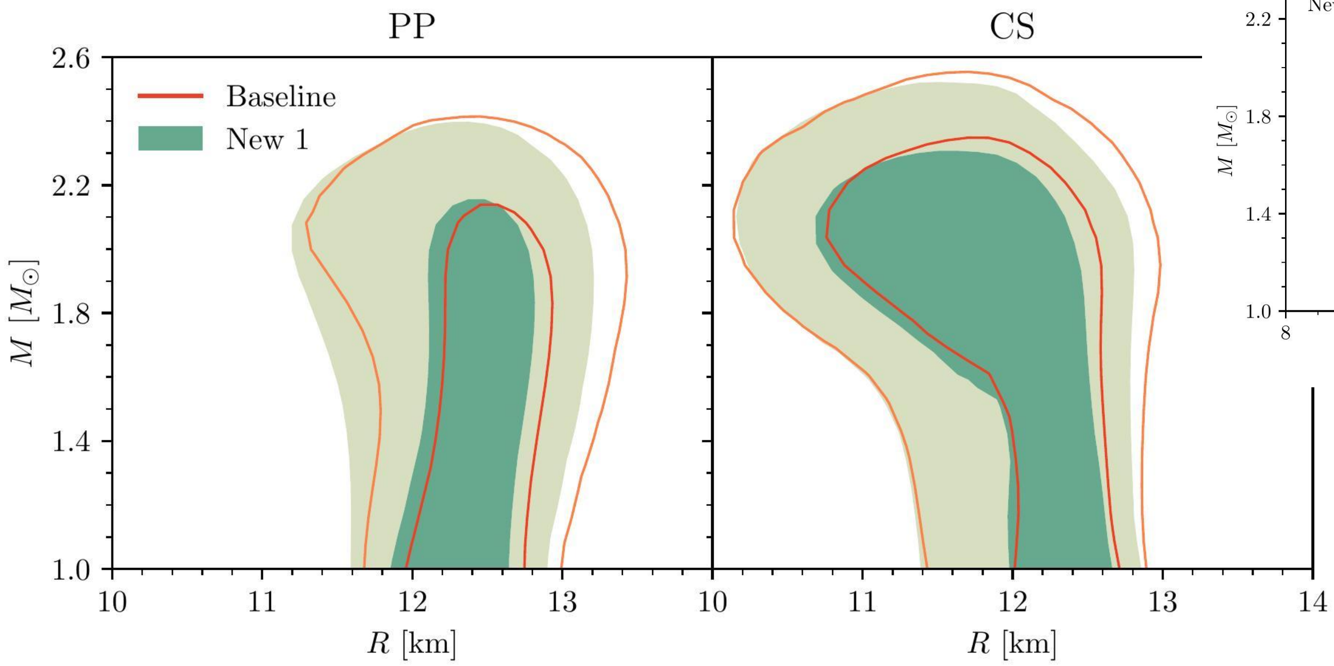
a_6 to match χ_{EFT} band.

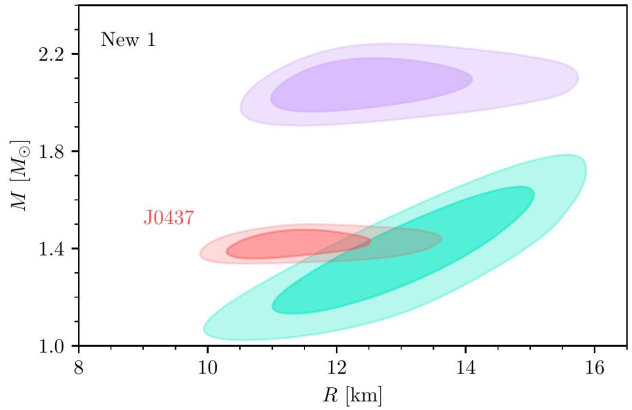
Fermi liquid theory (FLT) limit is c_s^2 FLT(1.5 n_0)/$c^2 \leq 1/m_N^2 (3\pi^2 n)^{2/3}$

With a_1:[0.1,1.5], a_2:[1.5,12], a_3:[0.05,2], a_4:[1.5,37], a_5:[0.1,1]

a_1 outside this range fails maximum mass constraint or causality

Other hot spot scenarios





From Rutherford, MM, Svensson et al, ApJL (2024), arxiv:2407.06790

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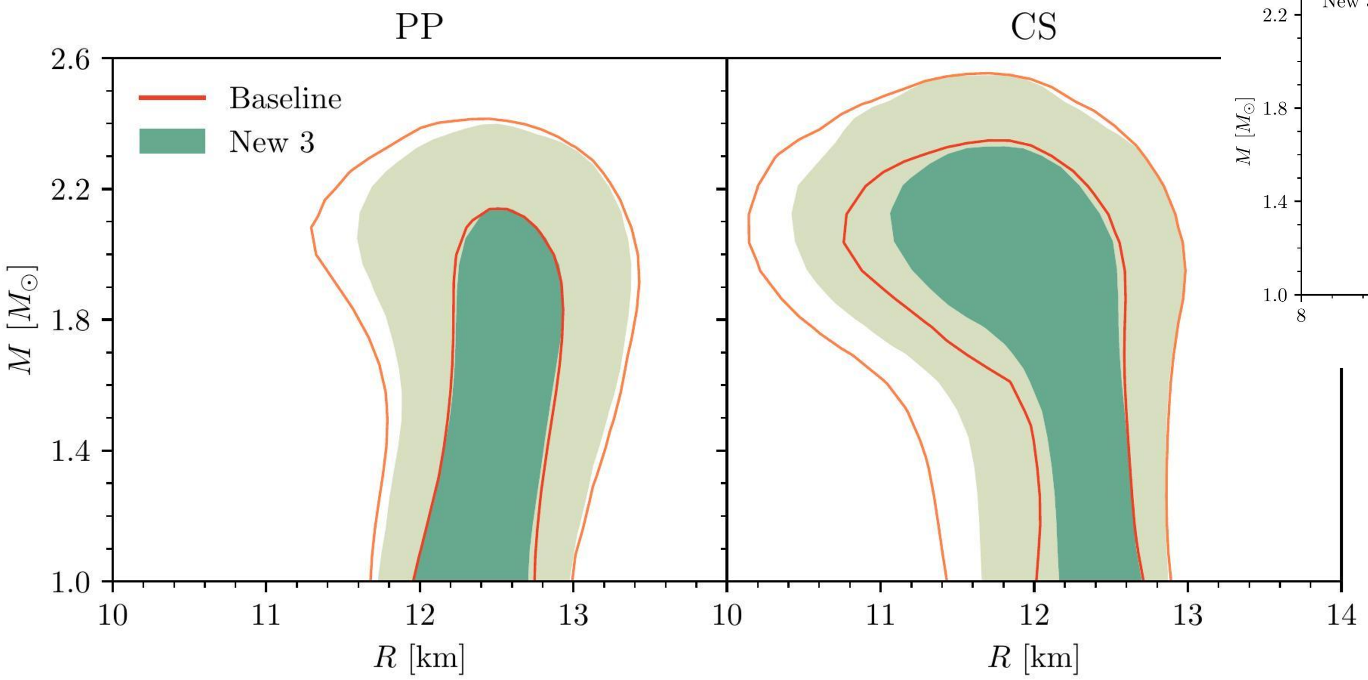

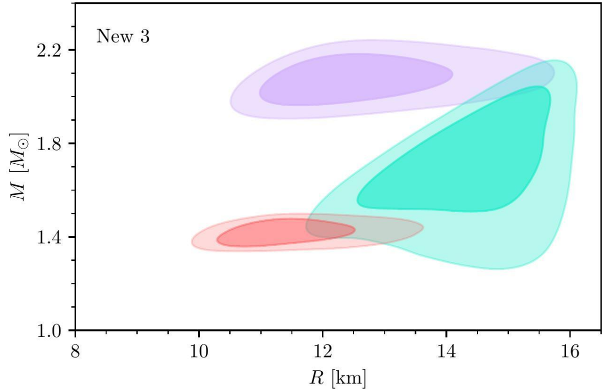

From Rutherford, MM, Svensson et al, ApJL (2024) arxiv:2407.06790

Other NICER released data

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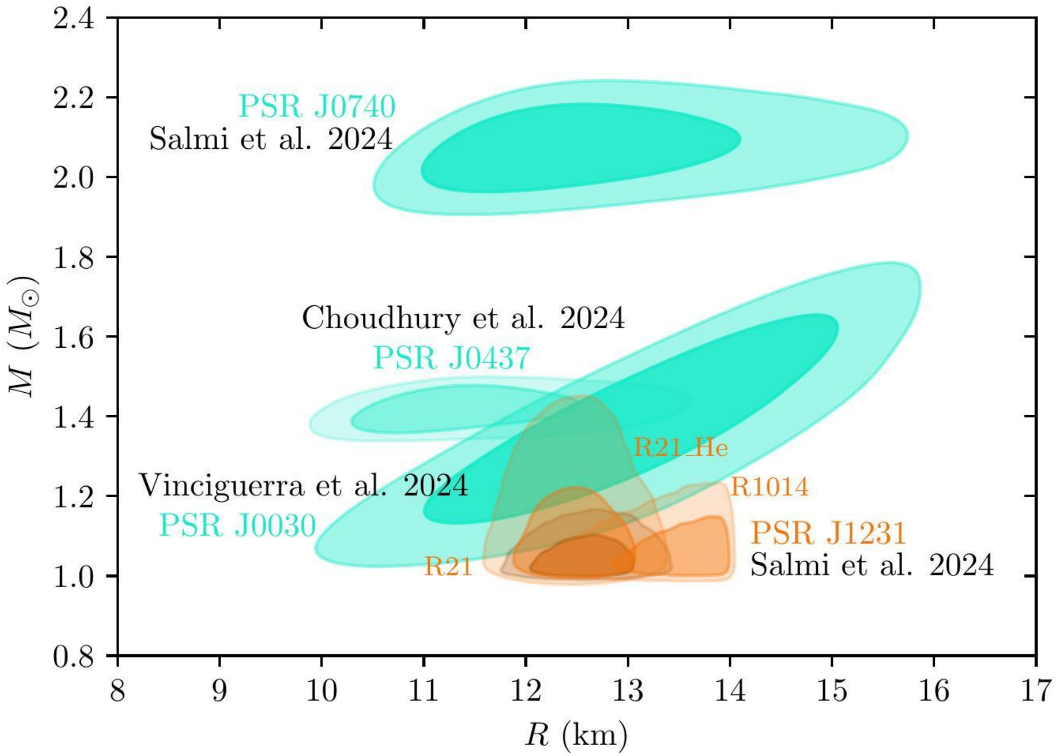

Other hot spot models for J0614

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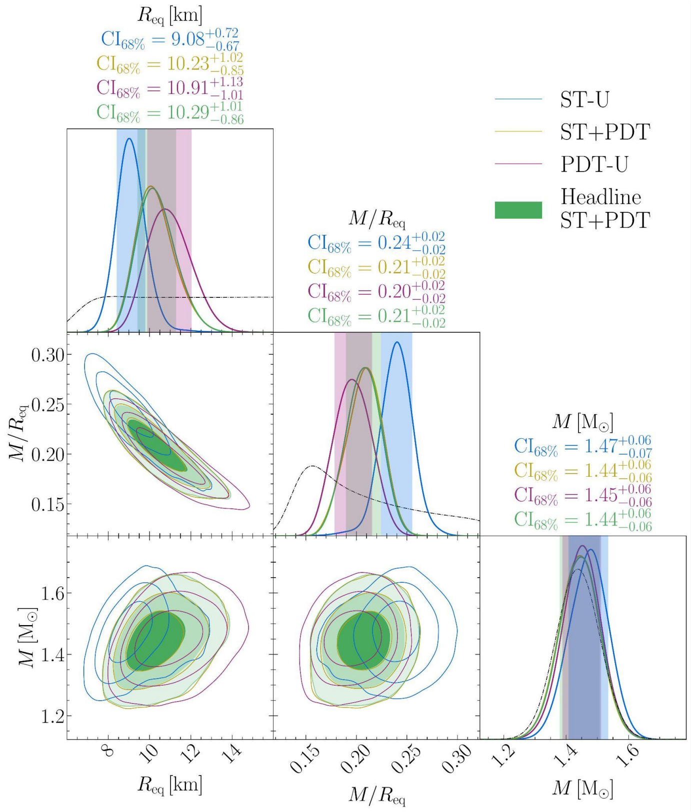

Figure from Mauviard, Guillot et al, ApJ submitted (2025), arxiv:2506.14883