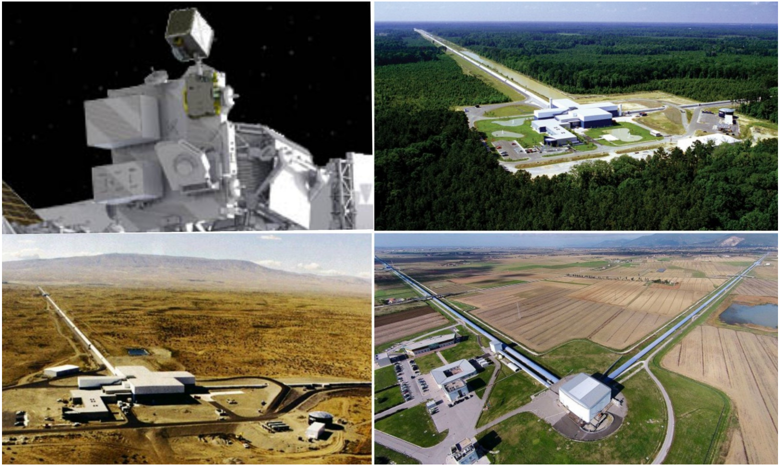
New Constraints on the Nuclear Equation of State

Melissa Mendes

TU Darmstadt

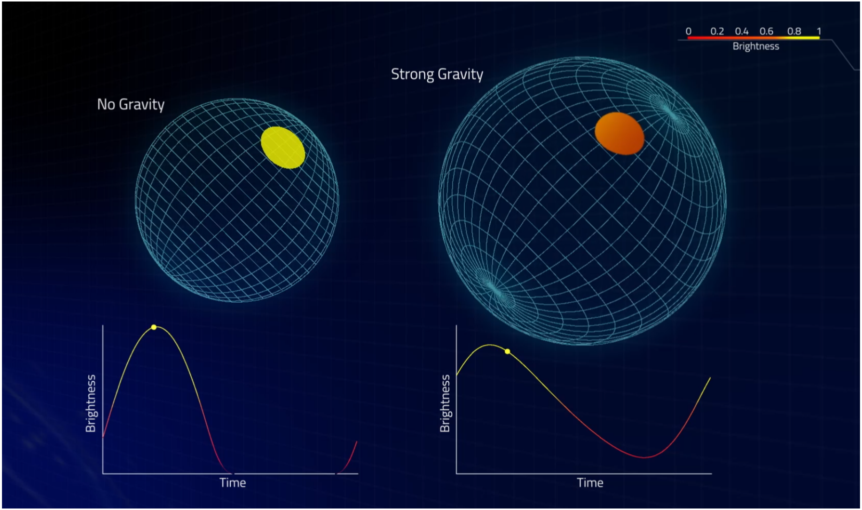
Multimessenger observations

NICER data for 3 neutron stars, gravitational wave constraints from LIGO/VIRGO



Modified from LIGO/NICER
(https://www.ligo.org/science/Publication-GWHEN-IceCube/index.php)

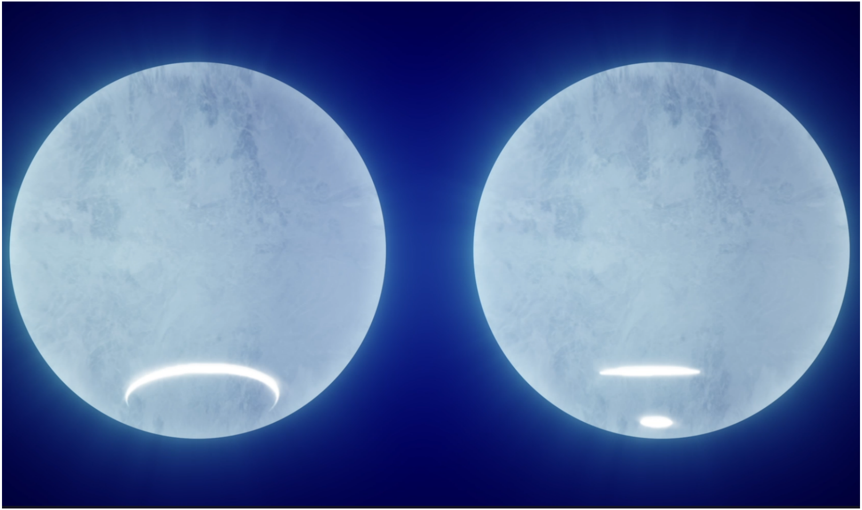
Pulse profile modelling (PPM)



Simulation of hot spot lensing effect

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

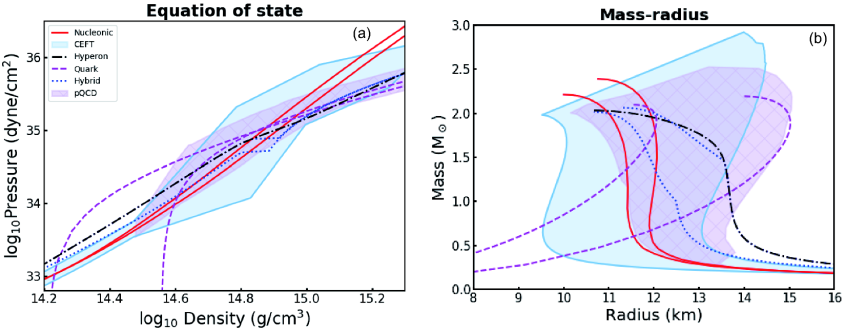
PPM PSR J0030



Hot spot configuration for PSR J0030
https://svs.gsfc.nasa.gov/vis/a010000/a013200/a013240/J0030_Model_Side-by-Side_1.mp4

Constraining equation of state and neutron star mass-radius

Astrophysical observations can constrain the EOS

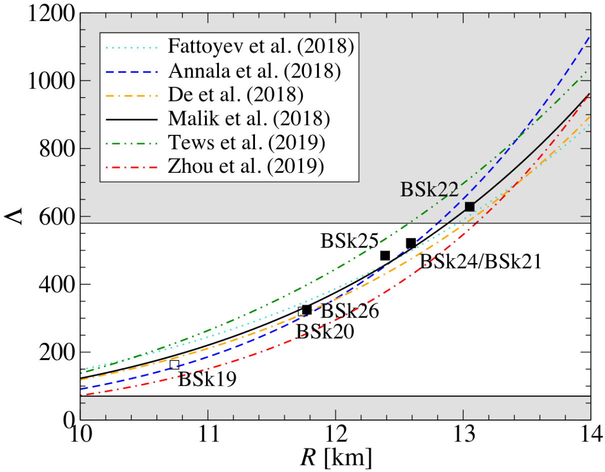


From Watts et al, 2019 (Science China Physics, Mechanics & Astronomy)

ArXiv: [1812.04021]

Constraining EOS and neutron star tidal deformability

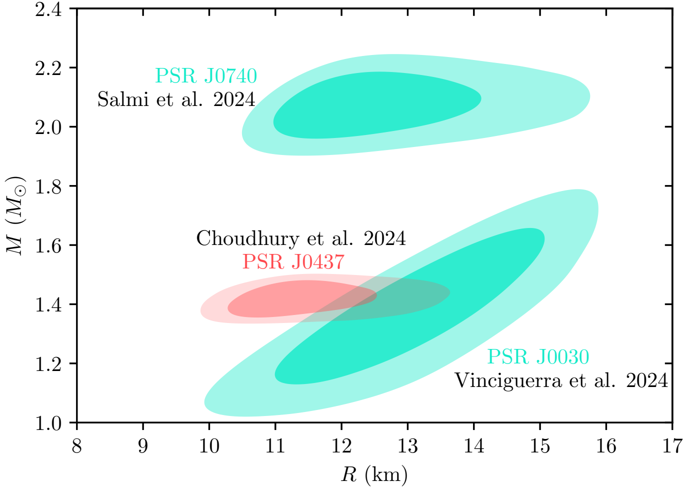
Gravitational wave measurements of NS mergers also constrain the EOS



From Perot et al, 2019 (Phys. Rev. C), ArXiv: [1910.13202]

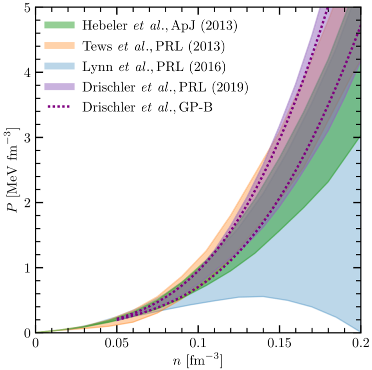
Recent NICER observations

Updated results for 2 neutron stars, new results for another one

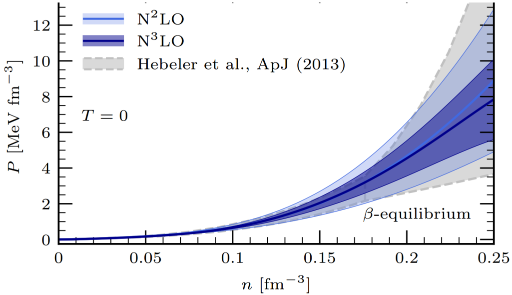


New χEFT calculations

Better understanding of matter interactions at low densities, expanding calculations to N^{2}LO/N^{3}LO



From Huth et al, 2021 (PRC)
ArXiv: [2009.08885]



From Keller et al, 2023 (PRL)
ArXiv: [2204.14016]

Outline

1. Methodology
   - New χEFT constraints
   - Prior distributions
   - Bayesian framework
   - Astrophysical data sets
2. Constraints on M-R and EOS
   - Posteriors for the "New 2" data contour
   - Implications for dense matter EOS
   - Implications for NS maximum mass

Based on Rutherford, MM, Svensson et al, 2024 (ApJL)
ArXiv: 2407.06790

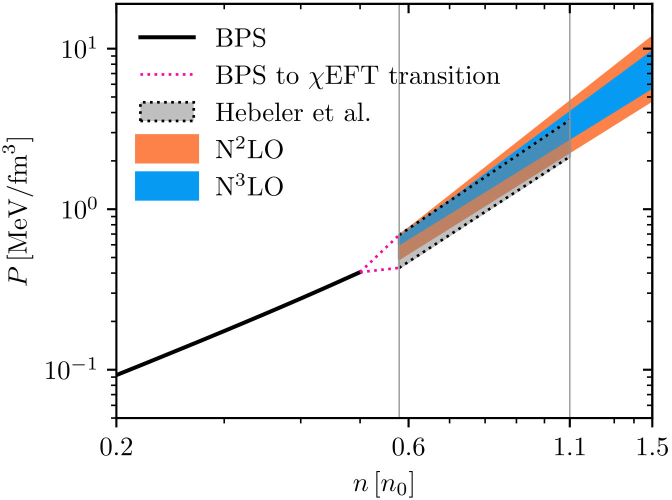
Outline

1. Methodology
   - New χEFT constraints
   - Prior distributions
   - Bayesian framework
   - Astrophysical data sets

2. Constraints on M-R and EOS
   - Posteriors for the “New 2” data contour
   - Implications for dense matter EOS
   - Implications for NS maximum mass

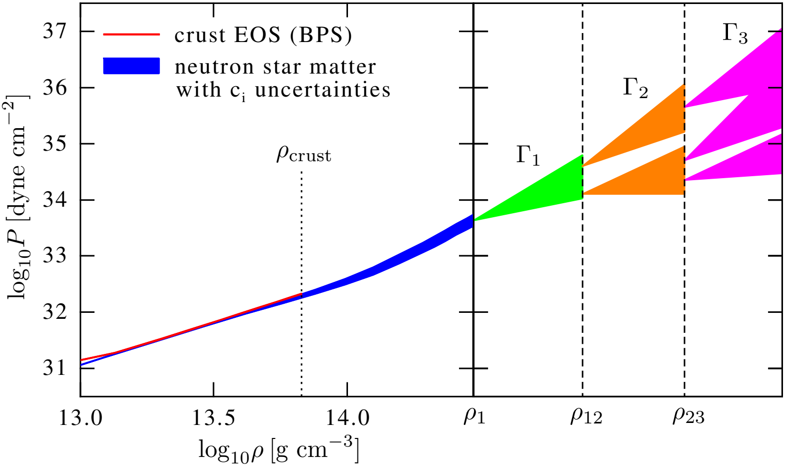
New χEFT bands

N^{2}LO or N^{3}LO extended up to 1.1 or 1.5n_0, $P = Kn^\Gamma$
BPS EOS at lower densities



Piecewise polytrope extension

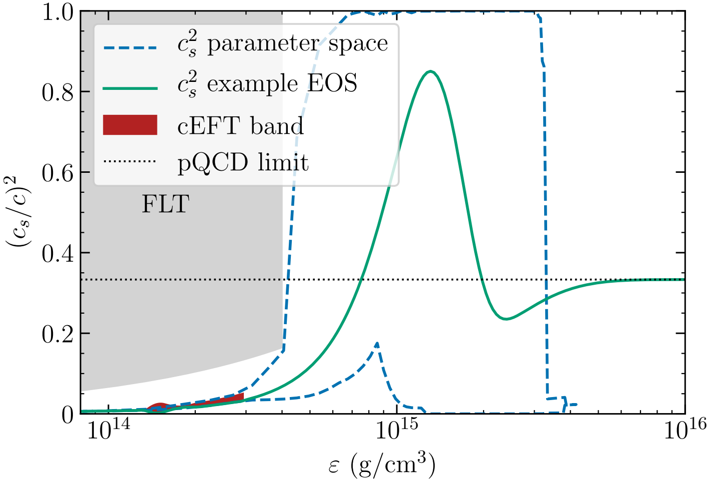
3 independent polytropes, varying Γ_1, Γ_2, Γ_3, ρ_{12} and ρ_{23}, constrained by causality



From Hebeler et al, 2013 (ApJ) [ArXiv: 1303.4662]

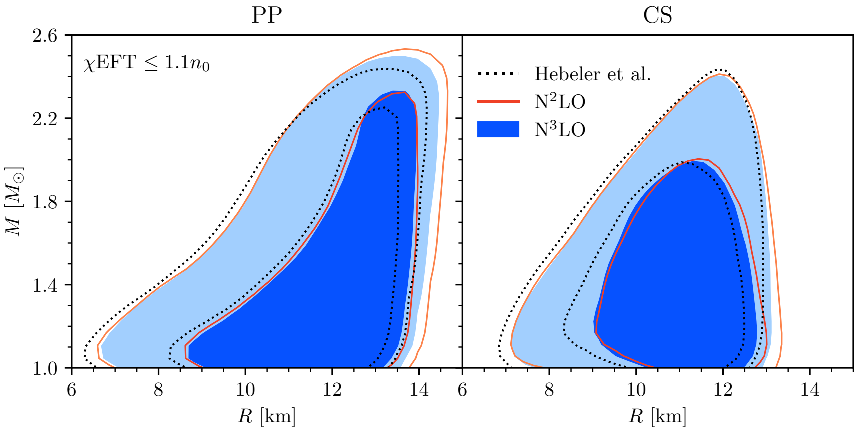
Speed of sound parametrization

Constrained by FLT, $0 \le c_s^2 \le c^2$, $\lim_{n \ge 50\, n_0} c_s^2 \to 1/3$ from below



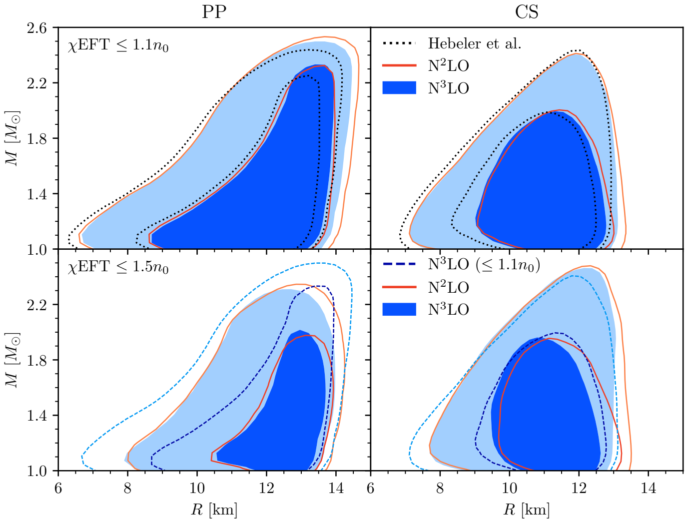
From Greif et al, 2019 (MNRAS) [ArXiv: 1812.08188]

Overall consistent
Radii around 11-13 km
New bands slightly favour larger radii
Different shapes for PP and CS, but similar maximum masses



Priors M - R for χEFT bands up to 1.5n$_0$

Contours more constrained, CS favours larger M_{TOV}



Bayesian framework

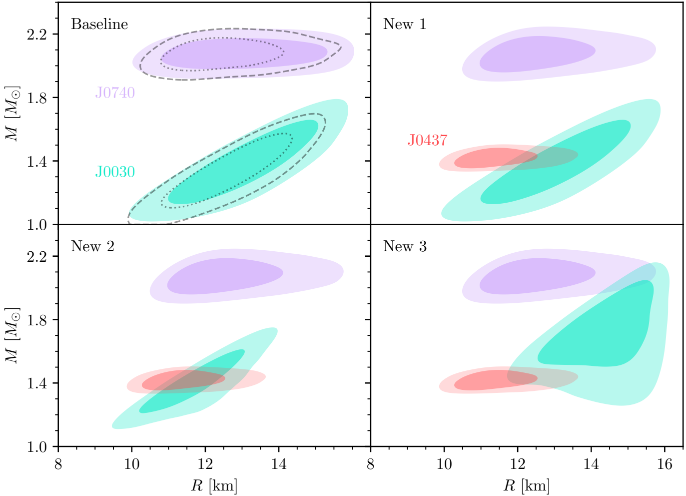
Following previous works (Raaijmakers et al, 2020; 2019), posterior distributions of all EOS parameters (θ) and central energy density (ε):

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

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

New astrophysical datasets

"Baseline" scenario includes previous NICER data
"New 1, 2, 3" include J0437 and different background analysis for J0740/J0030



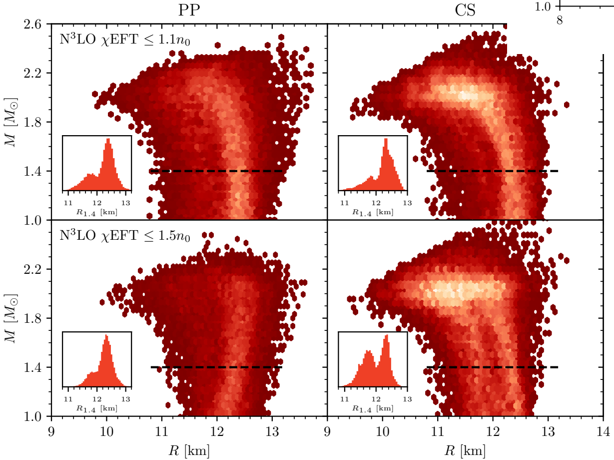
Outline

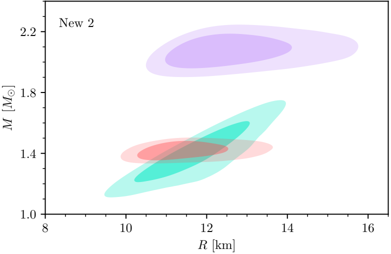
1. Methodology
   - New χEFT constraints
   - Prior distributions
   - Bayesian framework
   - Astrophysical data sets

2. Constraints on M-R and EOS
   - Posteriors for the "New 2" data contour
   - Implications for dense matter EOS
   - Implications for NS maximum mass

"New 2" data contour

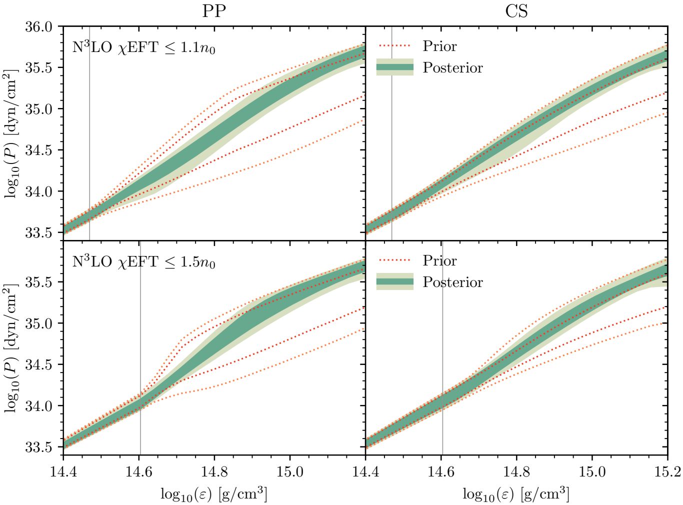
Suggestions of posterior bimodality





Corresponding P-ε posteriors

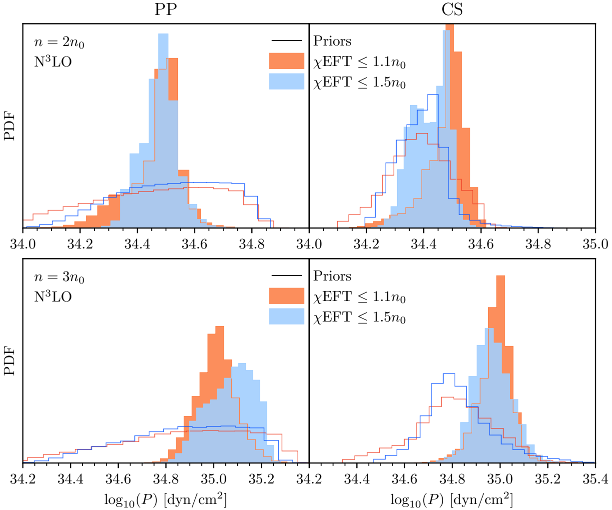
Posteriors well constrained
Stiffening at intermediate densities



Posteriors tightly constrained

PP and CS consistent and similar for $2n_0$ and $3n_0$

Posteriors clearly constrained by data

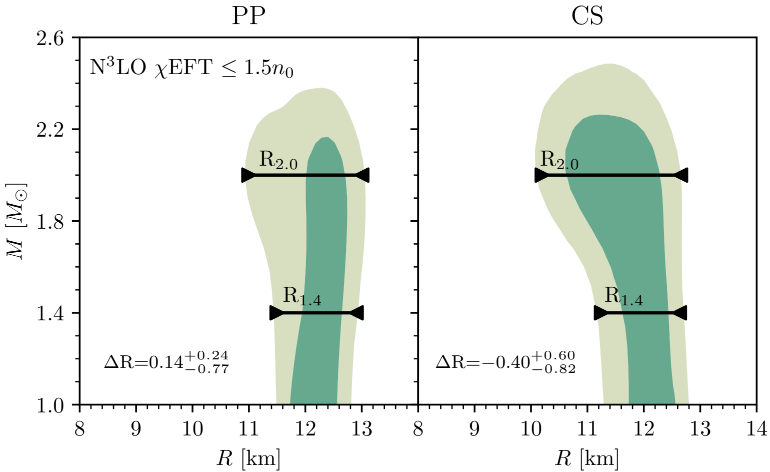


Trends for dense matter EOS

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

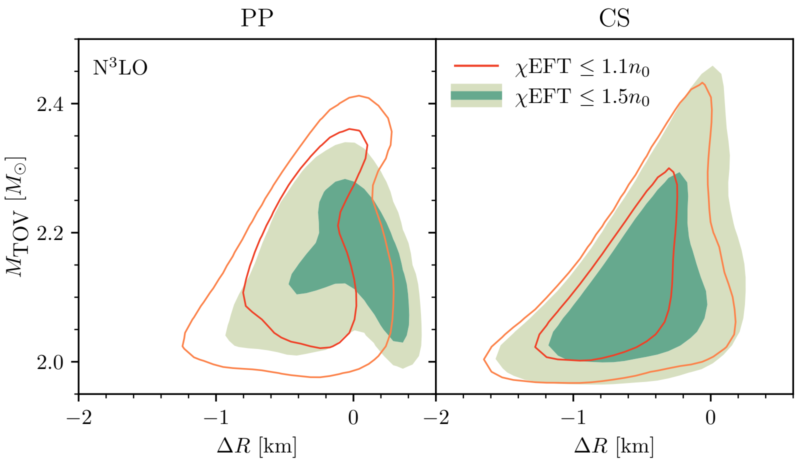
$\Delta R < 0\,(> 0)$ indicates EOS softens (stiffens) at high densities

(Drischler et al 2021, (PRC) ArXiv:[2009.06441])



NS maximum mass strongly dependent on J0740-like measurements

Increasing M_{TOV} with larger ΔR



Summary

- Posteriors overall consistent for PP, CS, up to $1.1n_0$ or $1.5n_0$; N^3LO and $1.5n_0$ more constraining
- New NICER data significantly constraints the posteriors, especially maximum mass
- 95% CI 1.4 $M_\odot$ (2.0 $M_\odot$): PP $12.28^{+0.50}_{-0.76}$ km ($12.33^{+0.70}_{-1.34}$ km)

  CS $12.01^{+0.56}_{-0.75}$ km ($11.55^{+0.94}_{-1.09}$ km)
- For favoured NICER dataset, bimodality observed under further investigation, no clear preference between soft or stiff EOS

Acknowledgments

TECHNISCHE UNIVERSITÄT DARMSTADT

European Research Council
Established by the European Commission

Thank you!

melissa.mendes@tu-darmstadt.de

SFB 1245

TOV equations I

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{\mathcal{E}(r)}{c^2}\frac{Gm(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{m(r)c^2}\right]\left[1-\frac{2Gm(r)}{c^2 r}\right]^{-1} ,$$

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2 \frac{\mathcal{E}(r)}{c^2} ,$$

$$\frac{\mathrm{d}y(r)}{\mathrm{d}r} = -\frac{y(r)^2}{r} - \frac{y(r)}{r}F(r) - rQ(r), \text{where}$$

$$F(r) = \left[1-4\pi r^2(\mathcal{E}(r)-P(r))\right]\left[1-\frac{2m(r)}{r}\right]^{-1},$$

$$Q(r) = 4\pi\left[5\mathcal{E}(r)+9P(r)+\frac{\mathcal{E}(r)+P(r)}{c_s^2(r)}-\frac{6}{r^2}\right]\left[1-\frac{2m(r)}{r}\right]^{-1}$$

$$-\frac{4m^2(r)}{r^4}\left[1+\frac{4\pi r^3 P(r)}{m(r)}\right]^2\left[1-\frac{2m(r)}{r}\right]^{-2}$$

With $y(R) = y_R$, calculate the tidal Love number $k_2\,(\xi, y_R)$,

$$
\begin{aligned}
k_2\,(\xi, y_R) = &\frac{1}{20}\xi^5(1-\xi)^2\left[(2-y_R)+(y_R-1)\,\xi\right]\left\{\left[(6-3y_R)+\frac{3}{2}\,(5y_R-8)\,\xi\right]\xi+\right.\\
&+\frac{1}{2}\left[(13-11y_R)+\frac{1}{2}\,(3y_R-2)\,\xi+\frac{1}{2}\,(1+y_R)\,\xi^2\right]\xi^3+\\
&\left.+3\left[(2-y_R)+(y_R-1)\,\xi\right](1-\xi)^2\ln(1-\xi)\right\}^{-1},
\end{aligned}
$$

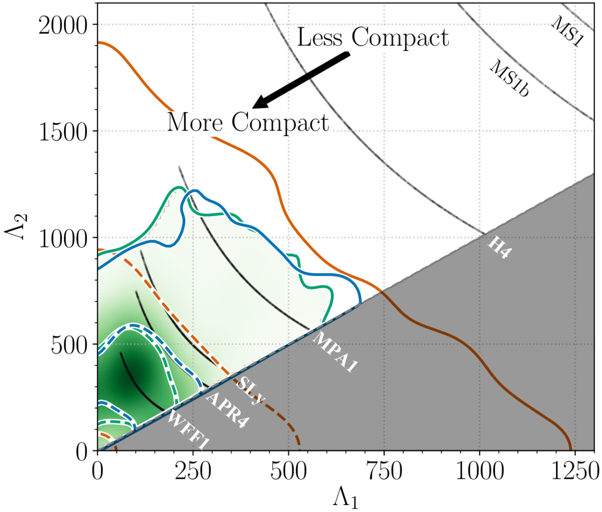
where $\xi = 2GM/Rc^2$. The dimensionless tidal deformability is

$$
\Lambda = \frac{2}{3}k_2\xi^{-5} = \frac{2}{3}k_2\left(\frac{Rc^2}{2GM}\right)^5
$$

but the actual observable is the mass-weighted tidal deformability:

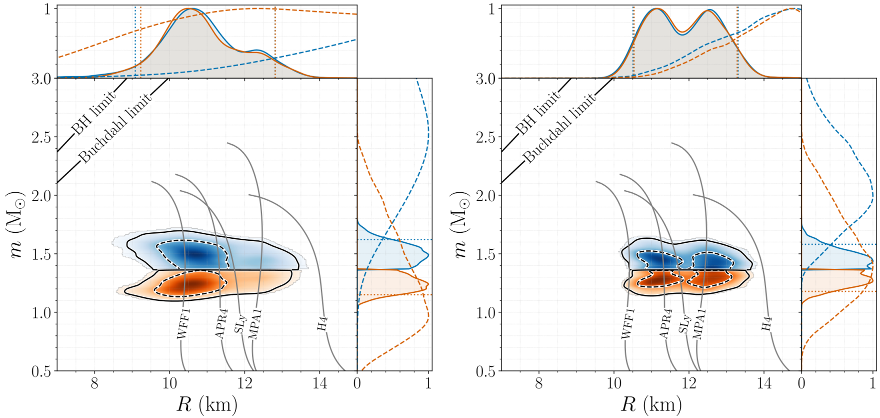
$$
\tilde{\Lambda} = \frac{16}{13}\frac{(M_1+12M_2)\,M_1^4\Lambda_1+(M_2+12M_1)\,M_2^4\Lambda_2}{(M_1+M_2)^5}.
$$

GW170817 tidal deformability contours



From LIGO/VIRGO Collaboration, 2018 (PRL) ArXiv: [1805.11581]

Corresponding GW170817 mass-radius contours



From LIGO/VIRGO Collaboration, 2018 (PRL) ArXiv: [1805.11581]

Speed of sound parametrization equation

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 χEFT band.

Fermi liquid theory (FLT) limit is $c^2_{s,\mathrm{FLT}}(1.5n_0)/c^2 \leq \frac{1}{m_N^2}\left(3\pi^2 n\right)^{\frac{2}{3}}$

With a1:[0.1,1.5], a2:[1.5,12], a3:[0.05,2], a4:[1.5,37], a5:[0.1,1]

a1 outside this range fails maximum mass constraint or causality

Piecewise polytrope parametrization equation

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

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

Parameter ranges are:

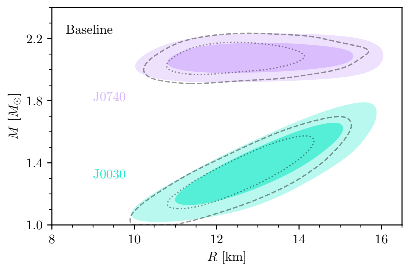
For χEFT up to $1.1\mathrm{n}_0$,

$\Gamma_1 : [1, 4.5], \Gamma_2 : [0, 8], \Gamma_3 : [0.5, 8], \rho_{12} : [1.5, 8.3], \rho_{23} : [1.5, 8.3]$

For χEFT up to $1.5\mathrm{n}_0$,

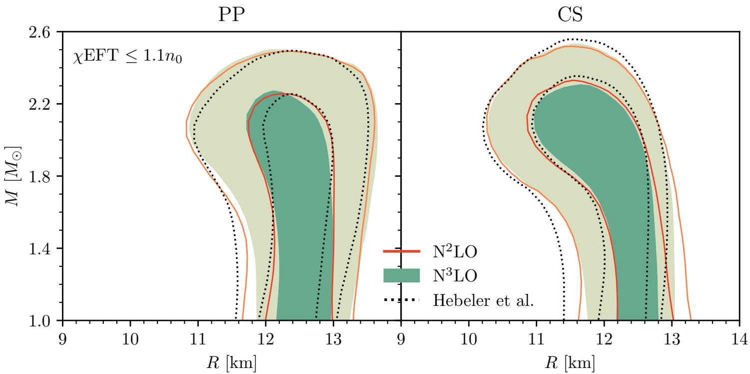
$\Gamma_1 : [0, 8], \Gamma_2 : [0, 8], \Gamma_3 : [0.5, 8], \rho_{12} : [2, 8.3], \rho_{23} : [2, 8.3]$

Impact of priors on "Baseline" run



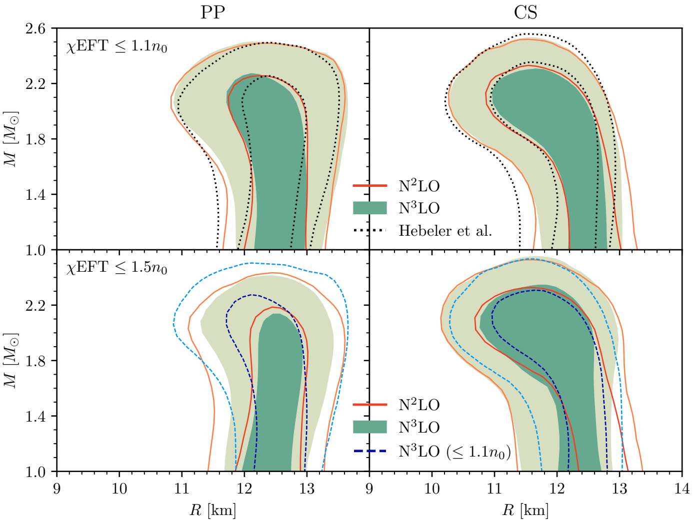
N^{2}LO and N^{3}LO favour larger radii

especially for low masses

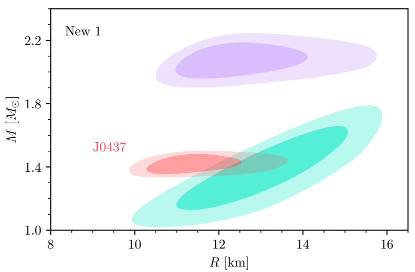


Comparing with χEFT bands up to 1.5 n_0

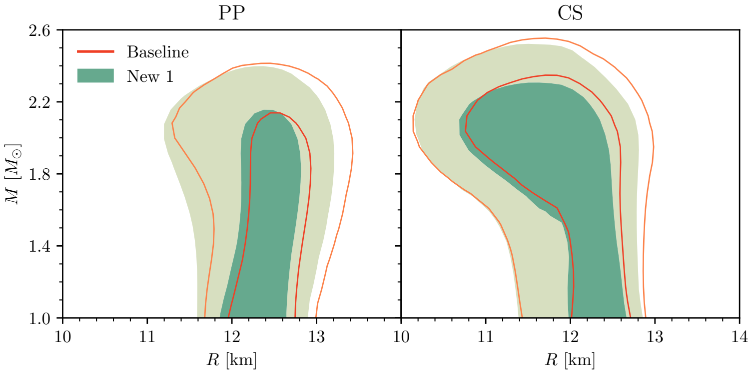
CS parametrization consistently prefers softer EOS



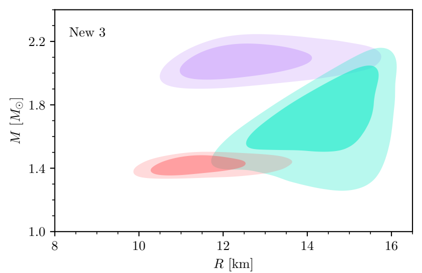
Including source J0437



Radii shifted to lower values



Including constraints to J0030



Radii shifted to larger values