Constraining the dense matter EOS with new NICER measurements and new chiral EFT inputs

Melissa Mendes

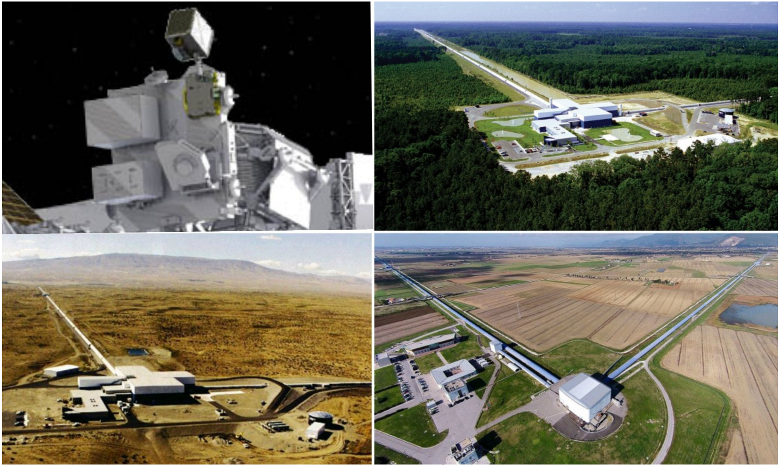
TU Darmstadt

European Research Council
Established by the European Commission

TECHNISCHE UNIVERSITÄT DARMSTADT

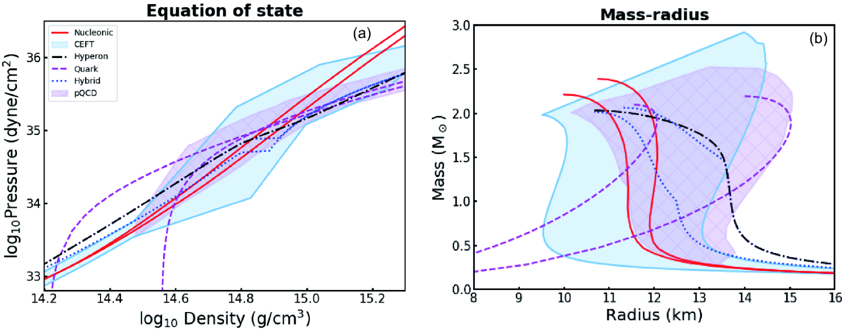
Multimessenger observations

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)

Astrophysical observations can constrain the EOS

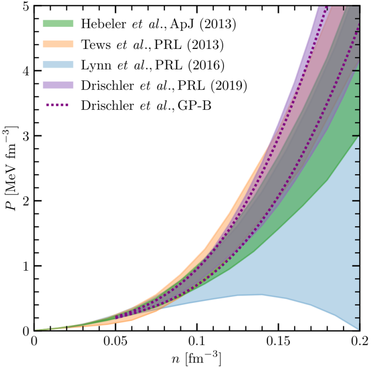


From Watts et al, 2019 (Science China Physics, Mechanics & Astronomy)

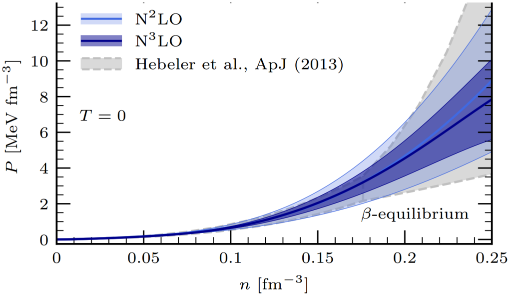
ArXiv: [1812.04021]

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
   - "Baseline" scenario
   - "New 1-3" scenarios
   - Implications for dense matter EOS
   - Implications for NS maximum mass
3. Summary

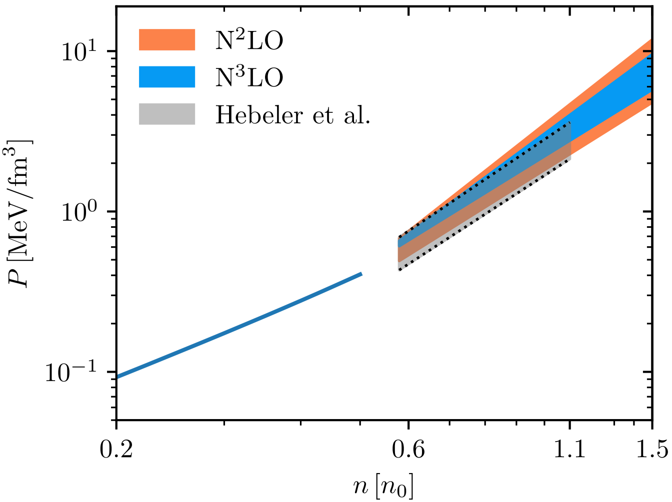
Based on Rutherford, MM, Svensson et al, 2024 (submitted APJL)

Outline

1. Methodology
   - New χEFT constraints
   - Prior distributions
   - Bayesian framework
   - Astrophysical data sets
2. Constraints on M-R and EOS
   - "Baseline" scenario
   - "New 1-3" scenarios
   - Implications for dense matter EOS
   - Implications for NS maximum mass
3. Summary

New χEFT bands

N^{2}LO or N^{3}LO extended up to 1.1 or 1.5 n$_0$, $P = Kn^\Gamma$
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

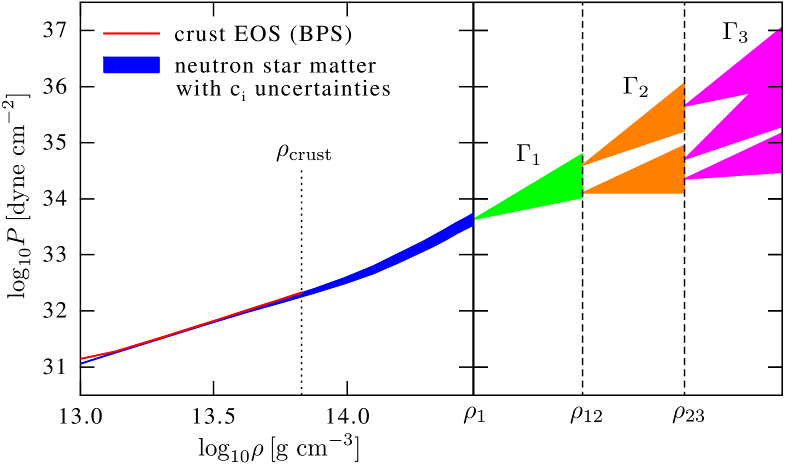


Figure: From Hebeler et al, 2013 (ApJ) [ArXiv: 1303.4662]

Speed of sound parametrization

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

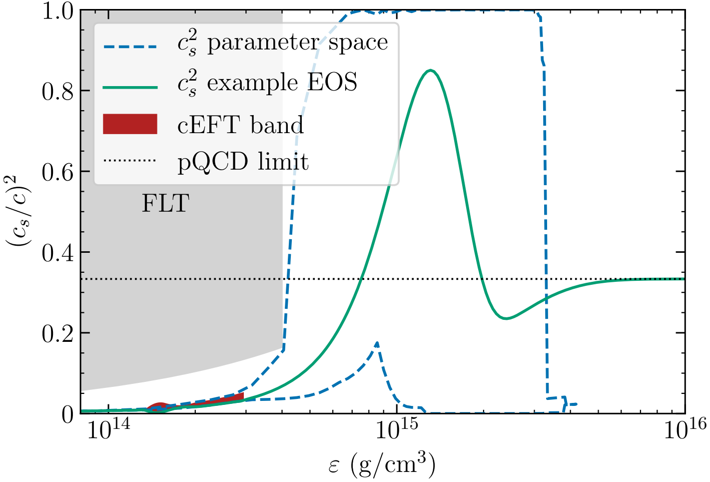
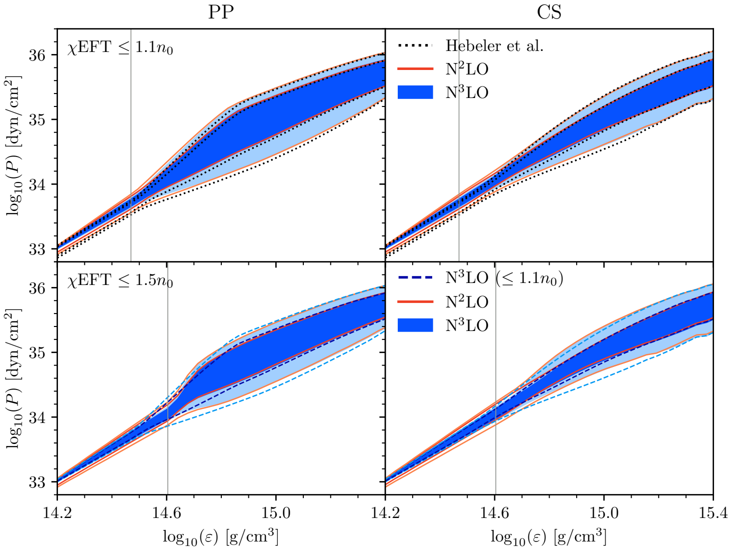


Figure: From Greif et al, 2019 (MNRAS) [ArXiv: 1812.08188]

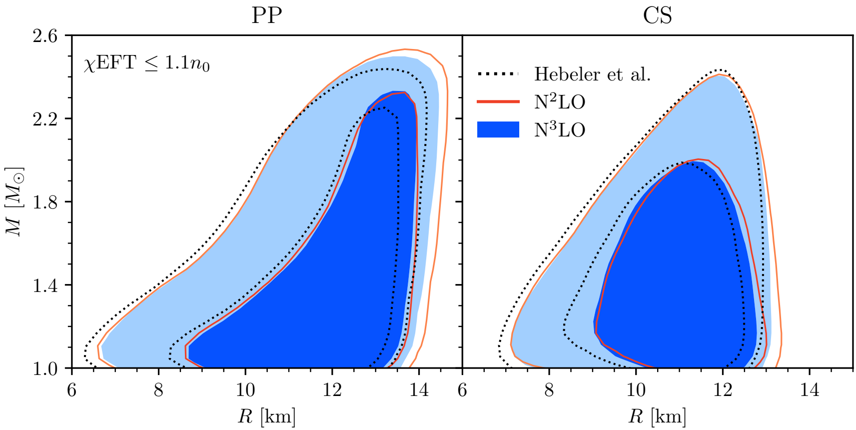
Priors for equations of state

Contours for 68% and 95% confidence intervals



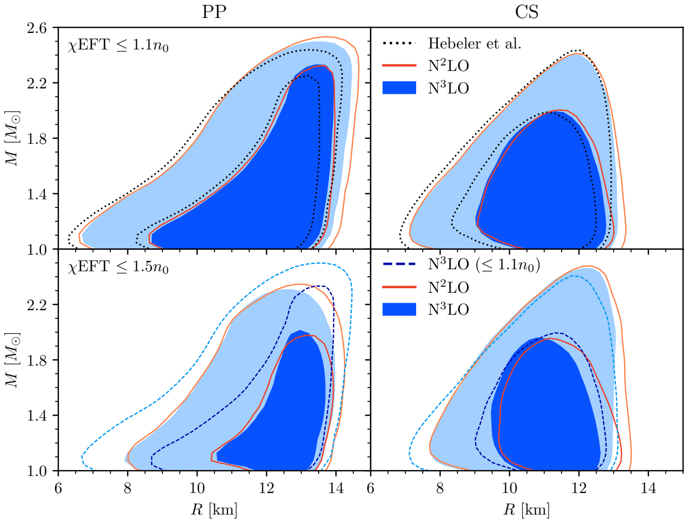
Priors $M \times R$ for χEFT bands up to 1.1 n_0

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



Priors $M \times R$ for χEFT bands up to 1.5 n_0

Contours more constrained, CS favours larger M_{TOV}



Bayesian framework

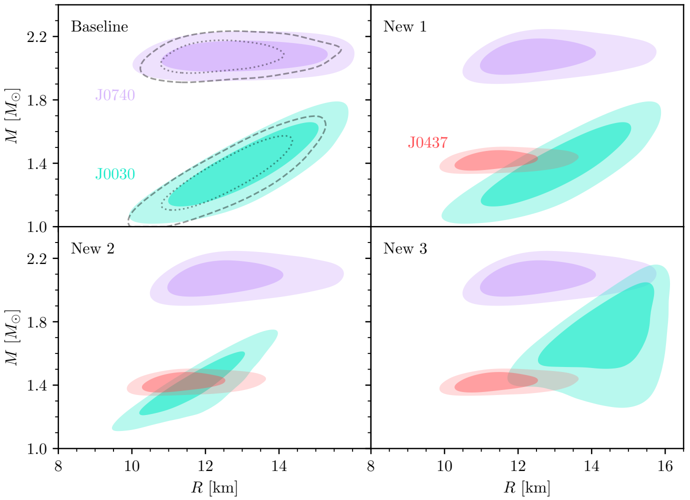
Following previous works (Raaijmakers et al, 2020; 2019), posterior distributions of all EOS parameters (θ) and central energy density (ε):

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

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



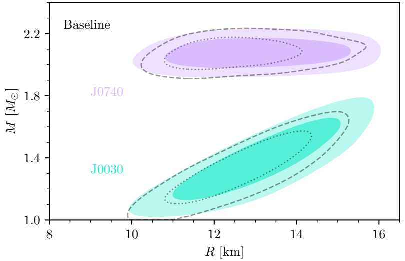
Outline

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

2. Constraints on M-R and EOS
   - "Baseline" scenario
   - "New 1-3" scenarios
   - Implications for dense matter EOS
   - Implications for NS maximum mass

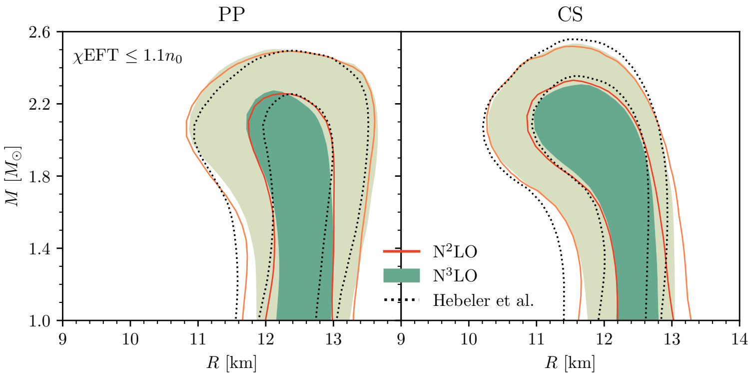
3. Summary

Impact of priors on "Baseline" run



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

especially for low masses

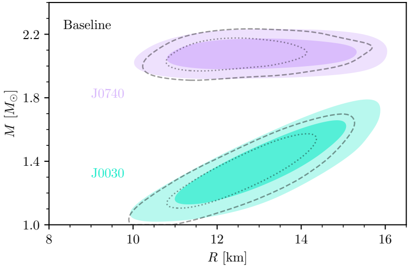


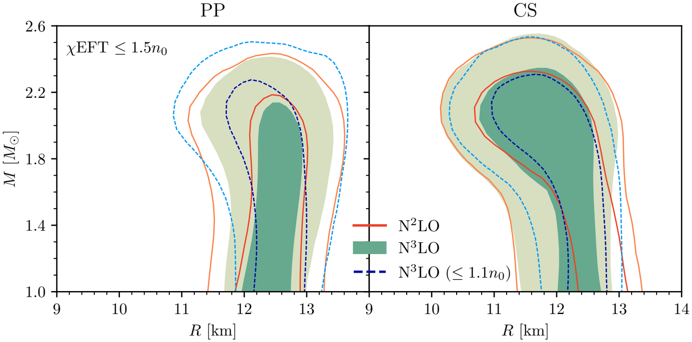
Comparison of PP x CS model, N^3LO to 1.5 n_0

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

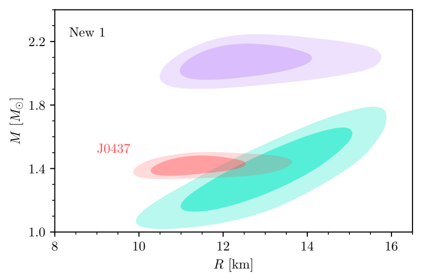
For N^3LO, PP: $\Delta R = 0.14^{+0.24}_{-0.77}$

CS: $\Delta R = -0.40^{+0.60}_{-0.82}$

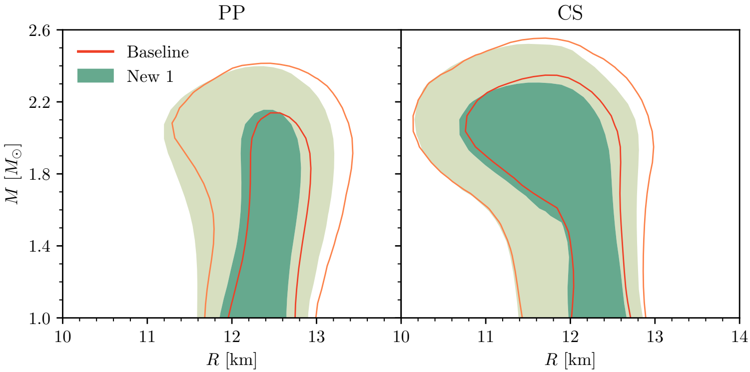




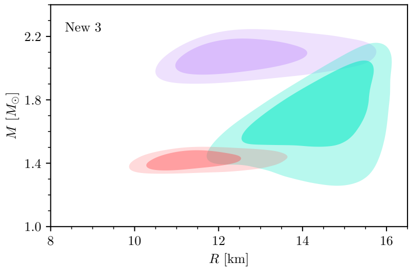
Including source J0437



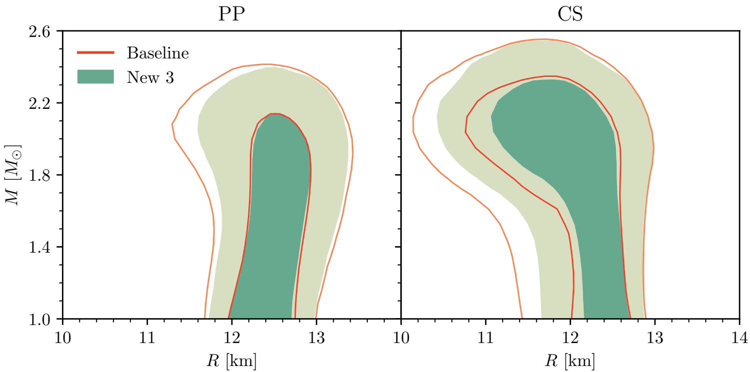
Radii shifted to lower values



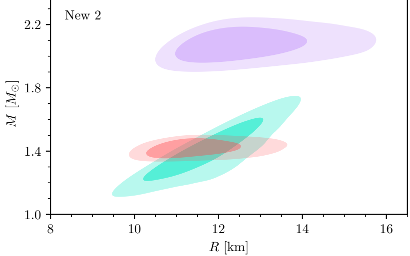
Including constraints to J0030



Radii shifted to larger values

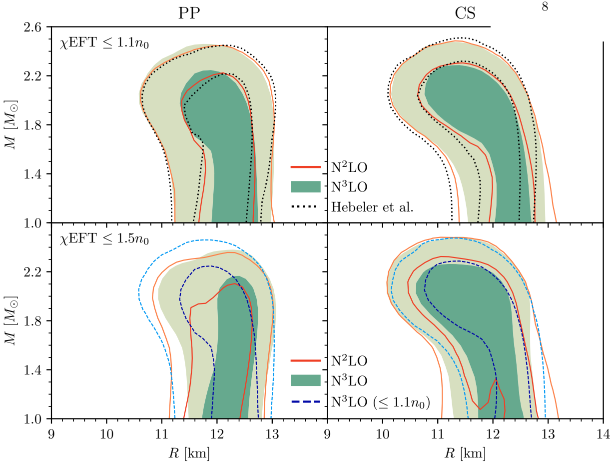


Alternative contour to J0030



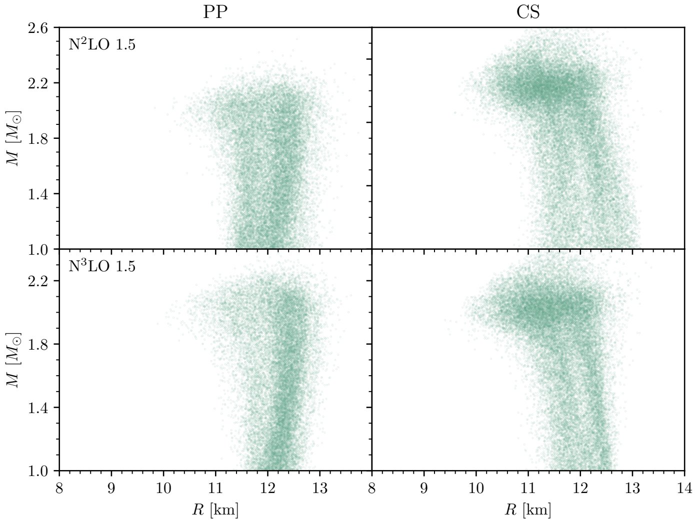
Posterior bimodality for all χEFT bands

Softer or stiffer EOS equally probable



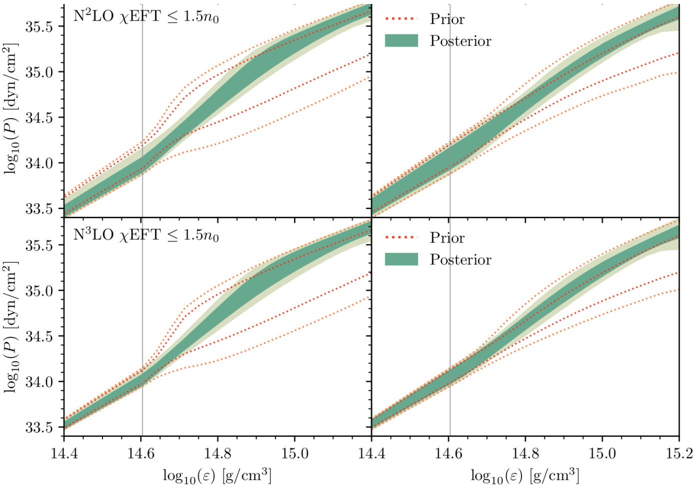
Bimodality driven by data contours

More clearly seen in scatter plots



Corresponding P-ε posteriors

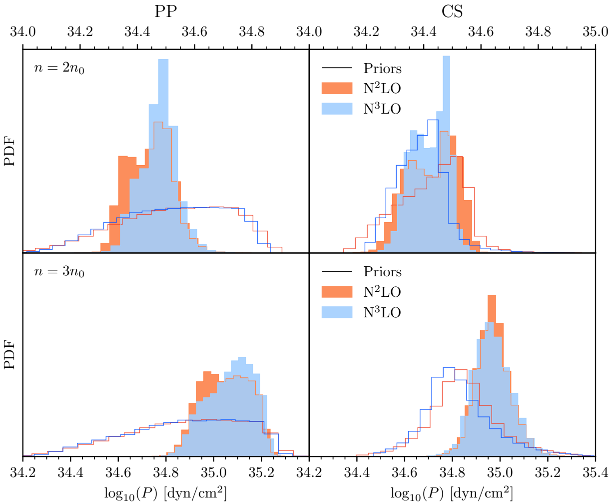
Posteriors well constrained
Stiffening at intermediate densities



Posteriors tightly constrained

Bimodality particularly around 2 n_0 for χEFT bands up to 1.5 n_0

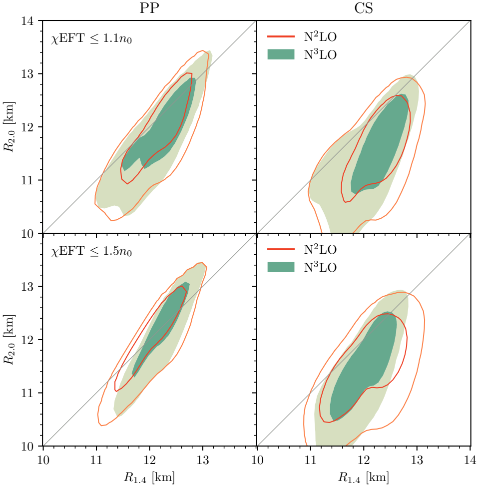
PP and CS consistent



$R_{1.4}$ and $R_{2.0}$ not necessarily correlated

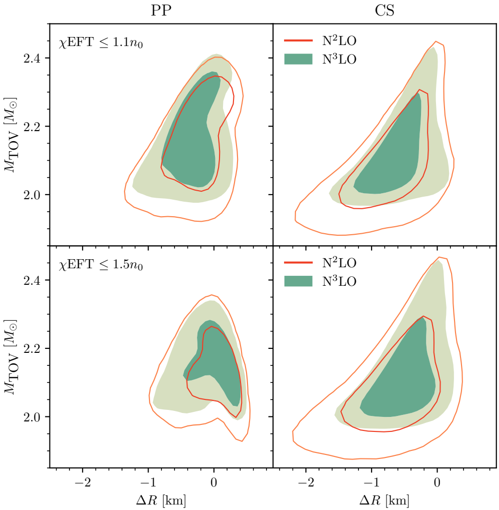
$\Delta R < 0 (> 0)$ indicates EOS softens (stiffens) at high densities
(Drischler et al 2021, (PRC) ArXiv:[2009.06441])

CS favours $\Delta R < 0$



NS maximum mass strongly dependent on J0740-like measurements

Increasing M_{TOV} with larger ΔR



Outline

1. Methodology
   - New χEFT constraints
   - Prior distributions
   - Bayesian framework
   - Astrophysical data sets
2. Constraints on M-R and EOS
   - "Baseline" scenario
   - "New 1-3" scenarios
   - Implications for dense matter EOS
   - Implications for NS maximum mass
3. Summary

Summary

- Posteriors overall consistent for N^{2}LO, N^{3}LO, PP, CS, up to 1.1 n_0 or 1.5 n_0; N^{3}LO and 1.5 n_0 more constrained
- 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 new 2 dataset, bimodality suggests soft or stiff EOS equally favoured

Acknowledgments

Thank you!

melissa.mendes@physik.tu-darmstadt.de

Constraining the dense matter equation of state with new NICER mass-radius measurements and new chiral effective field theory inputs

Nathan Rutherford,[1] Melissa Mendes,[2,3,4] Isak Svensson,[2,3,4] Achim Schwenk,[2,3,4] Anna L. Watts,[5] Kai Hebeler,[2,3,4] Jonas Keller,[2,3] Chanda Prescod-Weinstein,[1] Devarshi Choudhury,[5] Geert Raaijmakers,[6] Tuomo Salmi,[5] Patrick Timmerman,[5] Serena Vinciguerra,[5] Sebastien Guillot,[7,8] and James M. Lattimer[9]