Rising Researchers Seminar Series

The Rising Researchers Seminar Series is committed to creating an **environment which is welcoming and safe** for all speakers, attendees, organizers, and other affiliated persons, hereinafter ``participants''. It is the responsibility of all participants to foster such an environment.

Participants shall **treat each other professionally and respectfully**. Participants shall refrain from any inappropriate behaviour, including discriminatory actions and comments based on individual characteristics such as age, race, ethnicity, sexual orientation, gender identity, gender expression, marital status, nationality, immigration status, political affiliation, ability status, or educational background. Disruptive or harassing behavior will not be tolerated including but not limited to inappropriate or intimidating language and unwelcome jokes or comments.

Violations of this code of conduct should be reported to any member of the executive committee (see About Us page on the website). The Executive committee may also act of their own accord should they notice violations. Sanctions may range from verbal warning, to ejection from the meeting or, in severe cases, partial or total bans from future meetings.

References: This code of conduct is based heavily on that of the INT and the APS. We are also grateful to Roxanne Springer for valuable discussion and guidance.

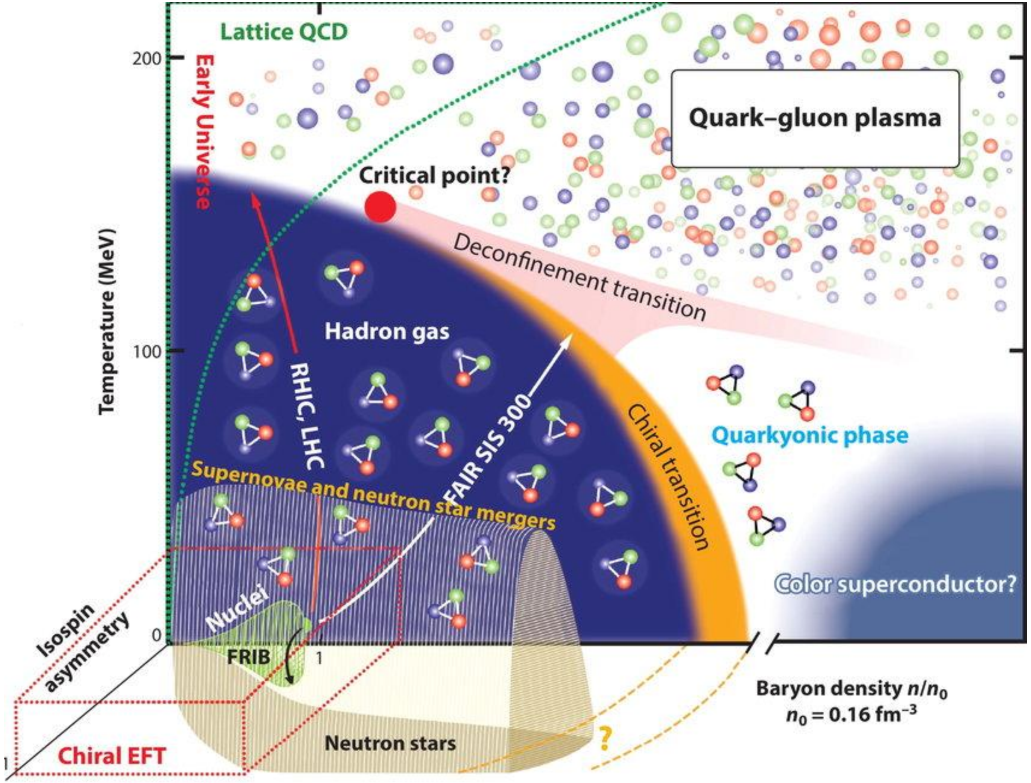
Updated constraints on the neutron star equation of state

Melissa Mendes - TU Darmstadt - 09/12

Updated constraints on the neutron star equation of state

Melissa Mendes
TU Darmstadt

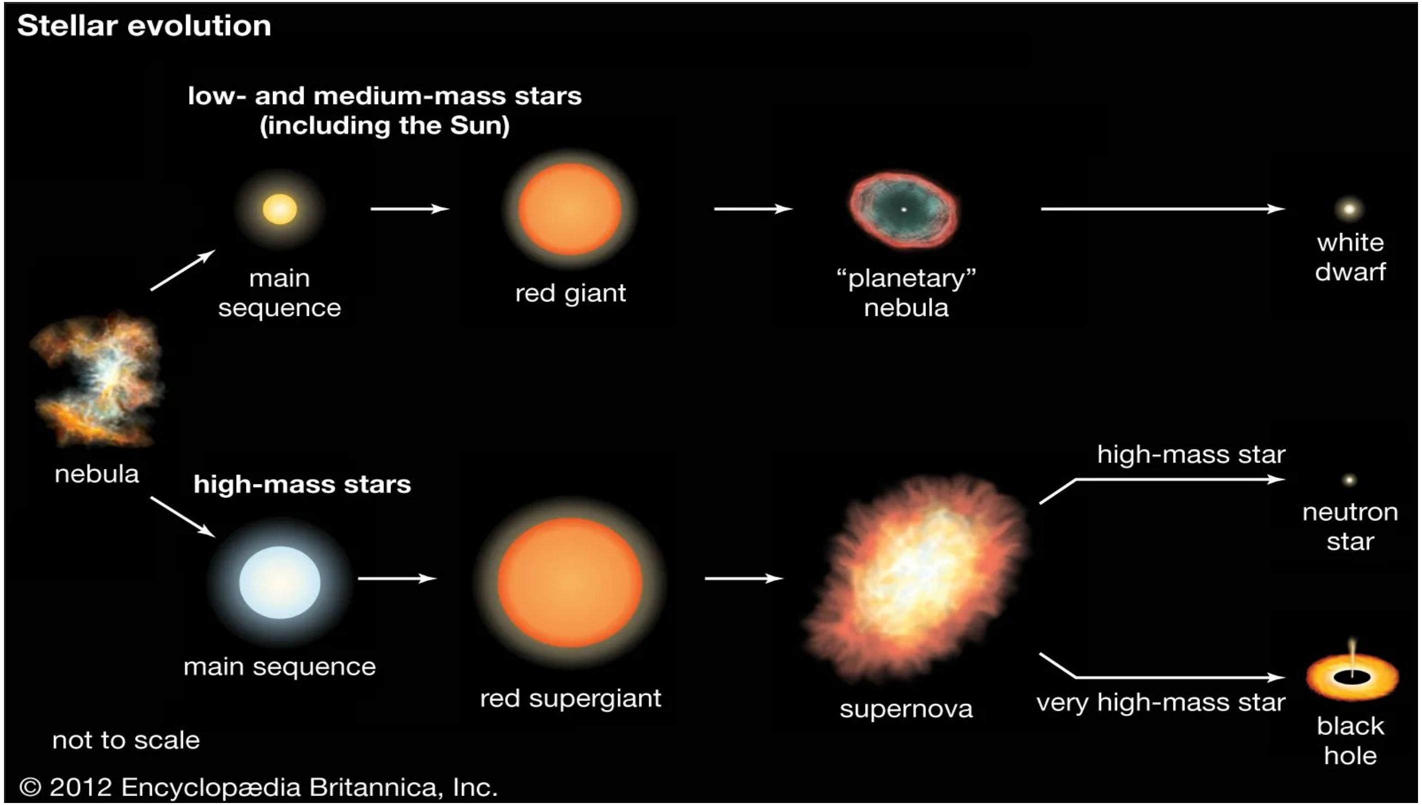
QCD phase diagram



Neutron stars are interesting systems to investigate the nuclear matter equation of state

Figure from Drischler et al, Annu. Rev. Nucl. Part. Sci. (2021), arxiv:2101.01709

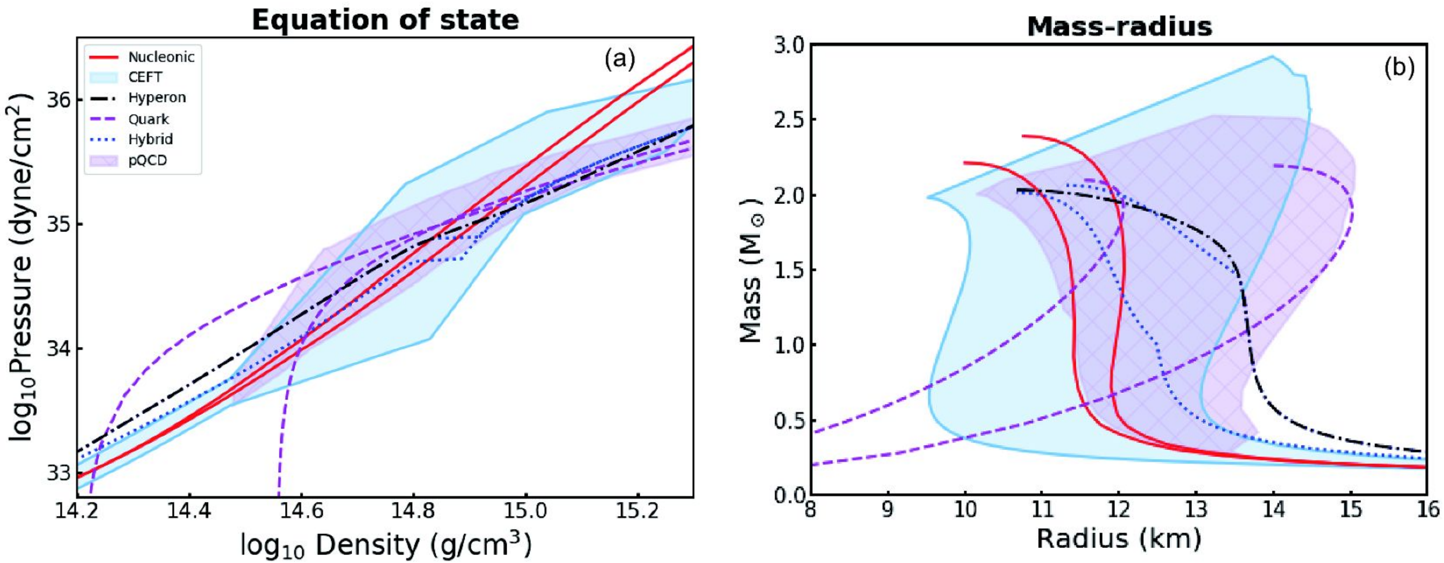
Neutron stars (NS)



The final stage of evolution of high-mass stars

Figure from Encyclopedia Britannica (2012)
https://www.britannica.com/science/star-astronomy/Subsequent-development-on-the-main-sequence

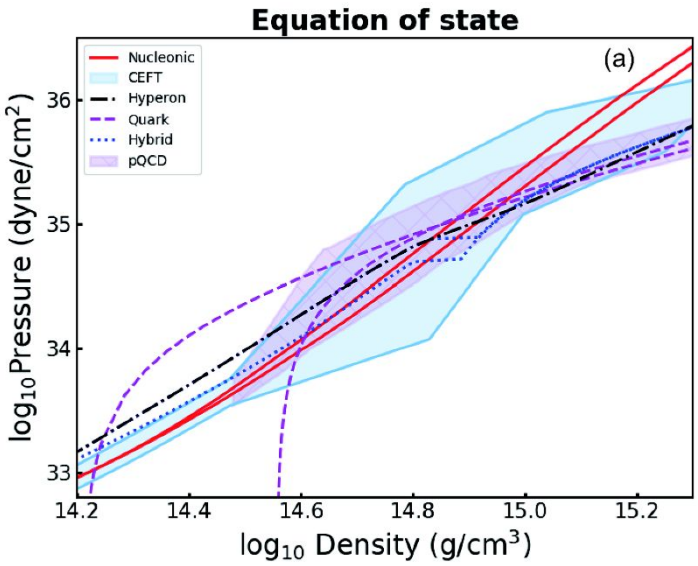
Constraining equation of state (EOS) with NS observables

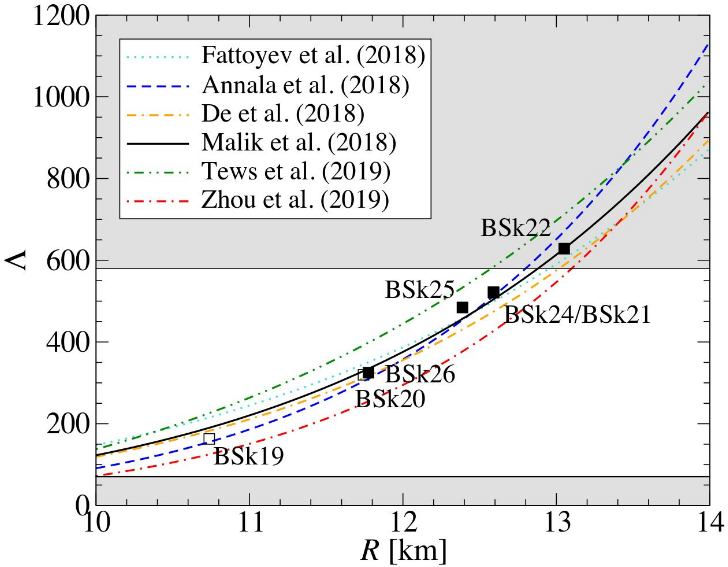


Mass-Radius observations can constrain the nuclear matter EOS (in beta-equilibrium)

Figure from Watts et al, Sci China Phys Mech Astron (2019), arxiv:1812.04021

Constraining equation of state (EOS) with NS observables





Tidal deformability -mass-radius observations can constrain the nuclear matter EOS (in beta-equilibrium)

Modified figure from Watts et al, Sci China Phys Mech Astron (2019), arxiv:1812.04021;

Perot et al, Phys. Rev. C (2019), arxiv: 1910.13202

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Primer on astro observational techniques
- Recent chiral effective field theory (χEFT) calculations
- Recent perturbative quantum chromodynamic (pQCD) calculations
- Bayesian framework and EOS construction
- Implications for dense matter EOS
- Inference of EOS parameters

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

Raaijmakers, …, **MM**, … et al, 2025 (JOSS), https://doi.org/10.21105/joss.06003

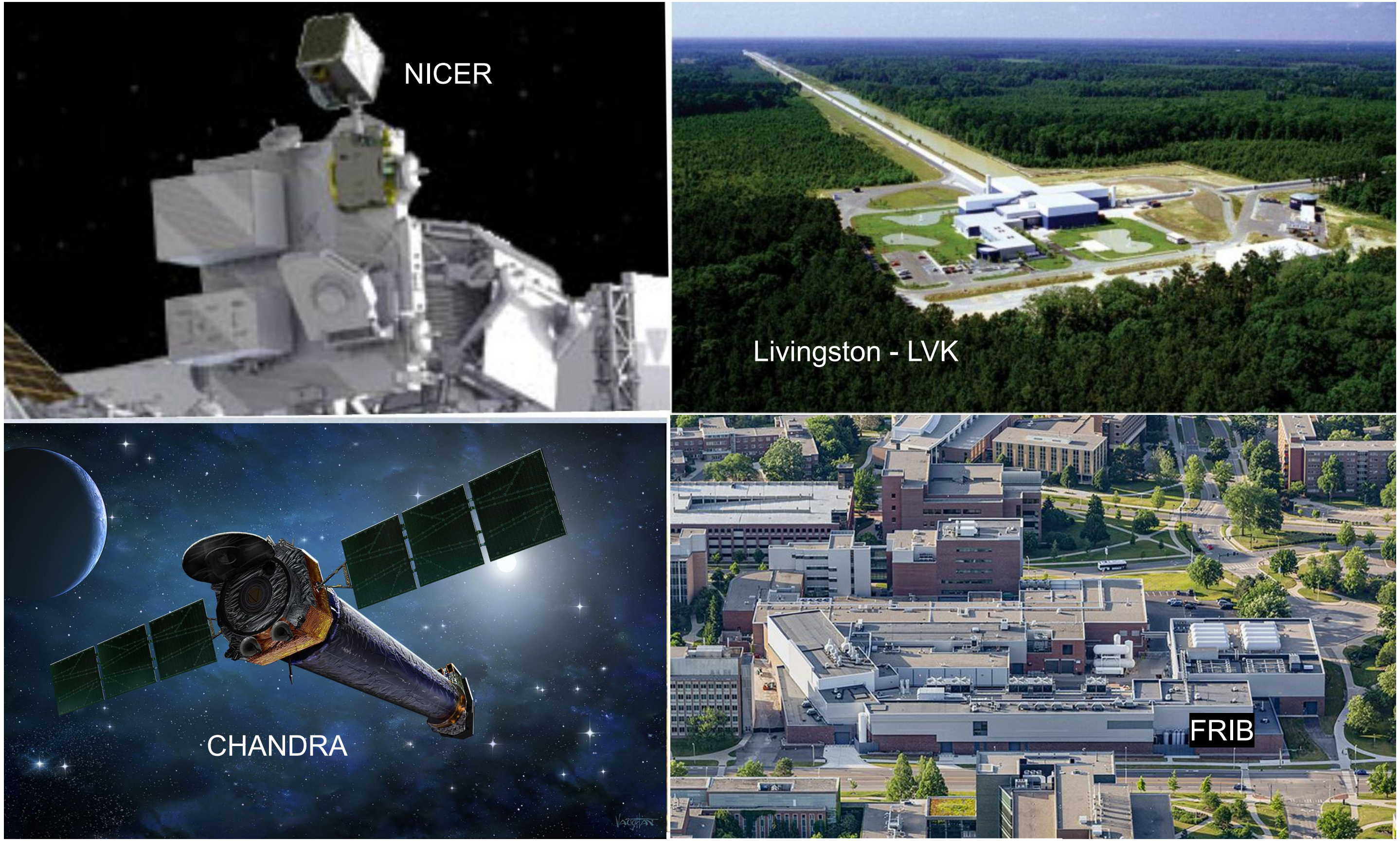
Mauviard, …, **MM,** … et al, 2025 (ApJ), arxiv: 2506.14883

Hoogkamer, …, **MM**, … et al, 2025 (Editor's suggestion PRD), arxiv: 2510.27619

MM et al, 2025 (in preparation)

NEoST

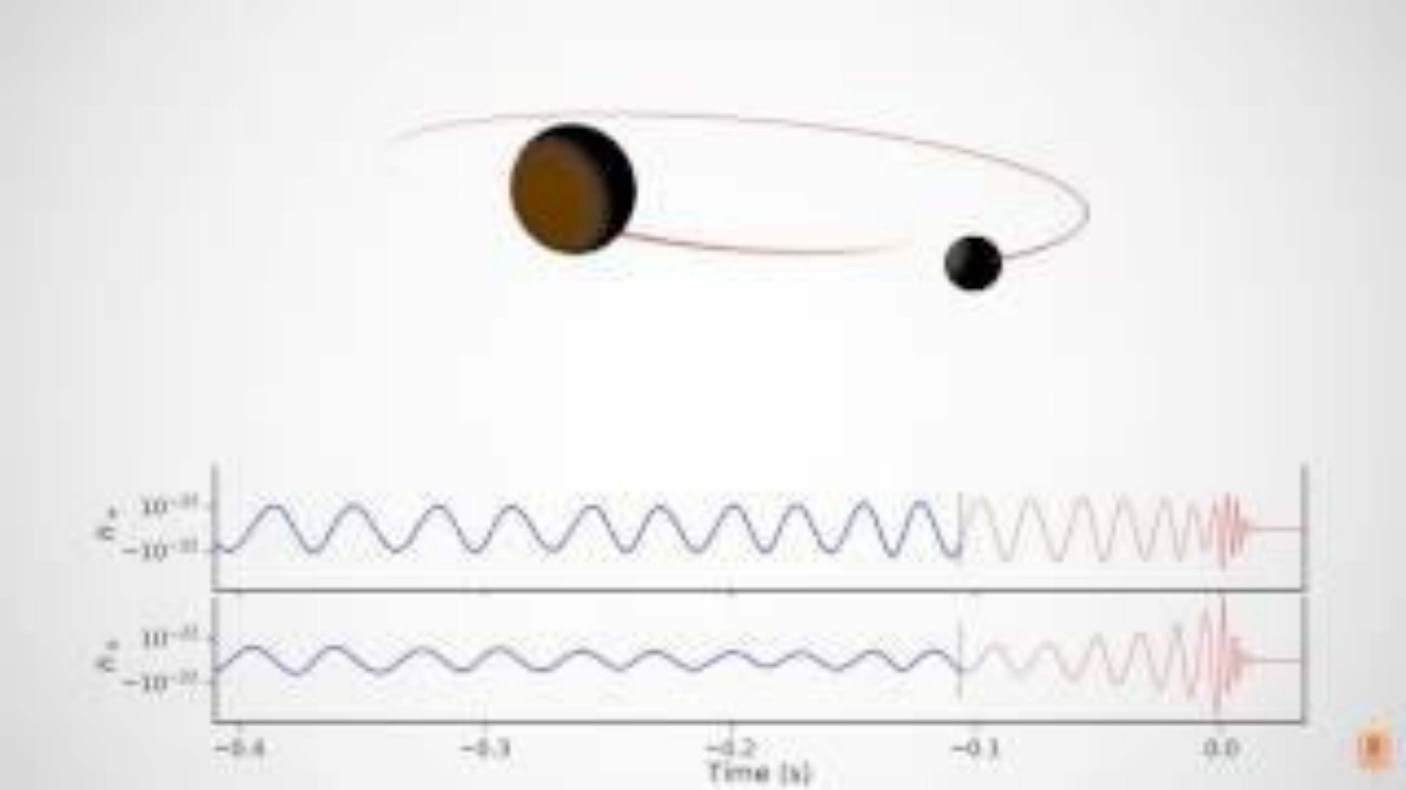
Data collection facilities



Recent (and future) observations provide unprecedentedly precise neutron star and nuclei data

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

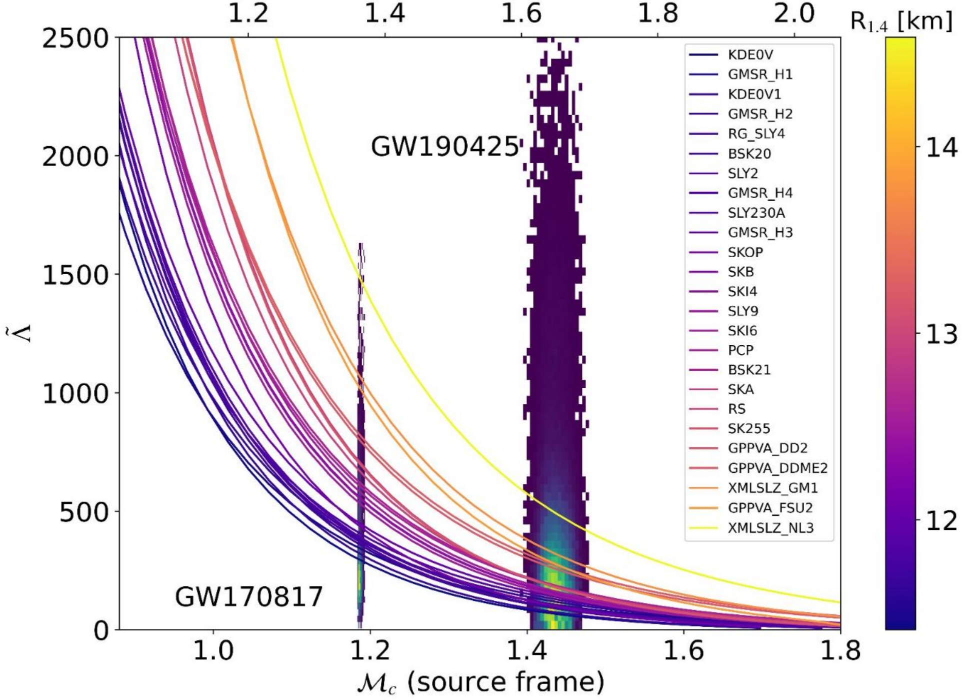
Gravitational waves



Waveform signals feature information about neutron star properties

Animation from https://www.ligo.caltech.edu/video/ligo20170601v2

Two binary NS merger events



GW170817 much more constraining

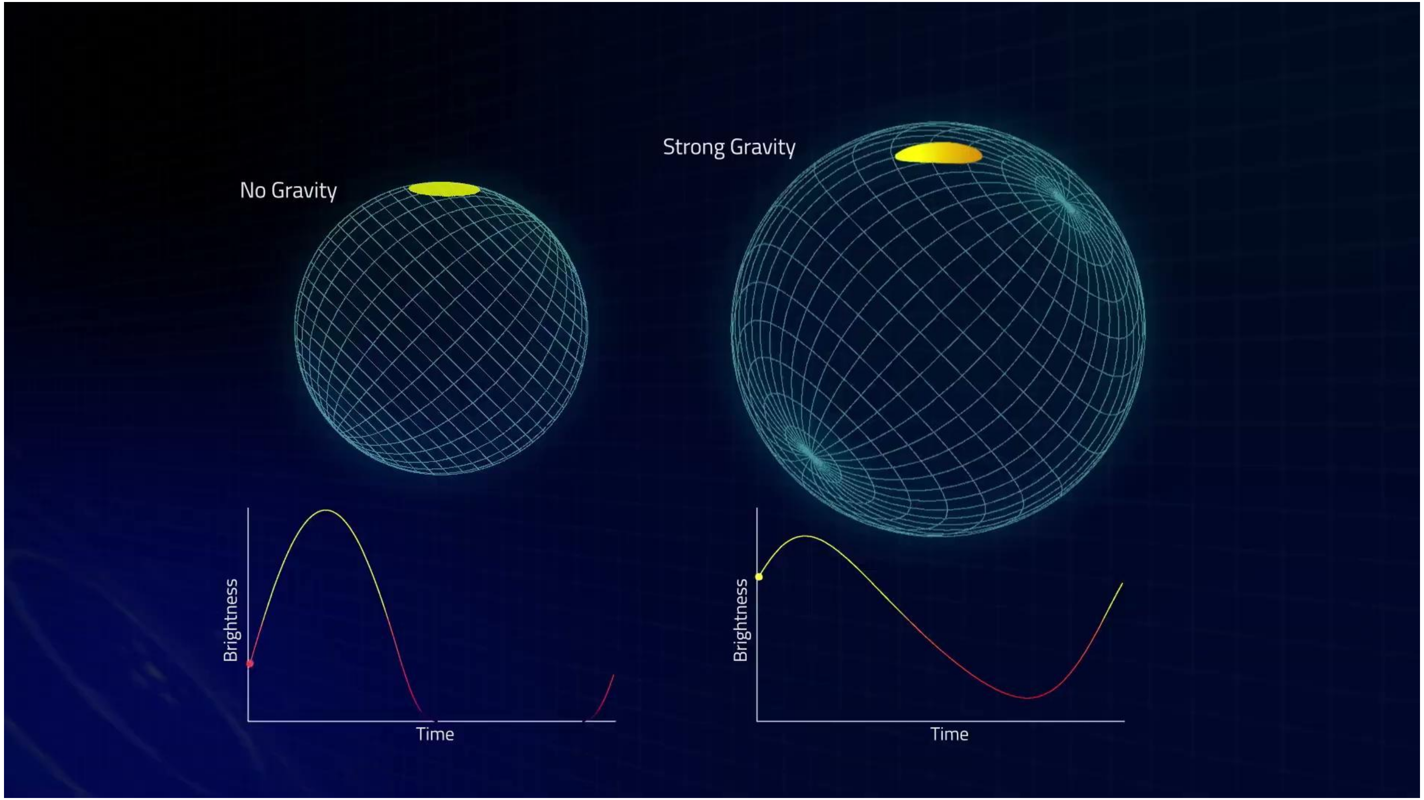
$$\tilde{\Lambda} = 300^{+420}_{-230}$$

GW190425 binary NS or NS-black hole merger still open question

$$\tilde{\Lambda} \leq 600$$

Figure from J. Read, L. Suleiman's slides on behalf of LVK collaboration at Nuclei in the Cosmos 2025 - https://indico.icc.ub.edu/event/341

Pulse profile modeling

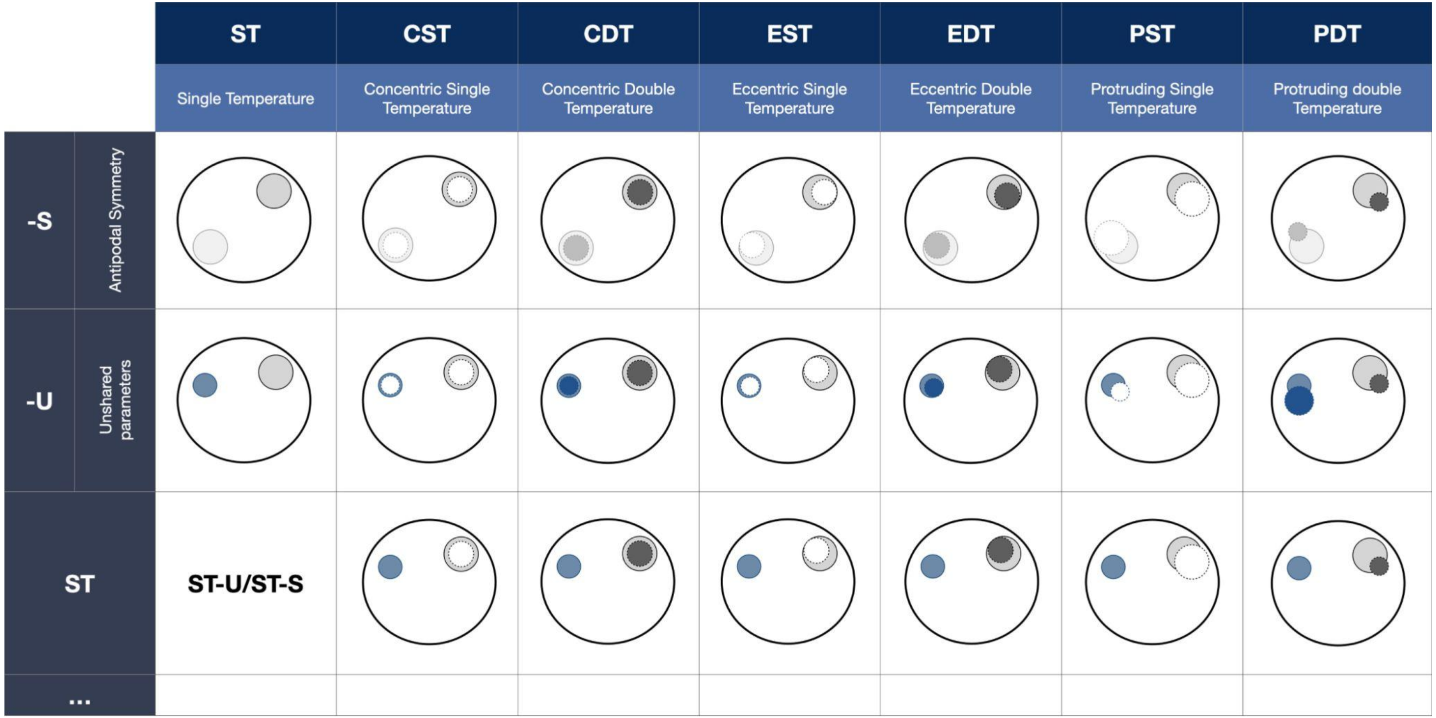


Proportional effect to the stars' compactness (M/R)

Simultaneous constraint on neutron star mass and radius

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

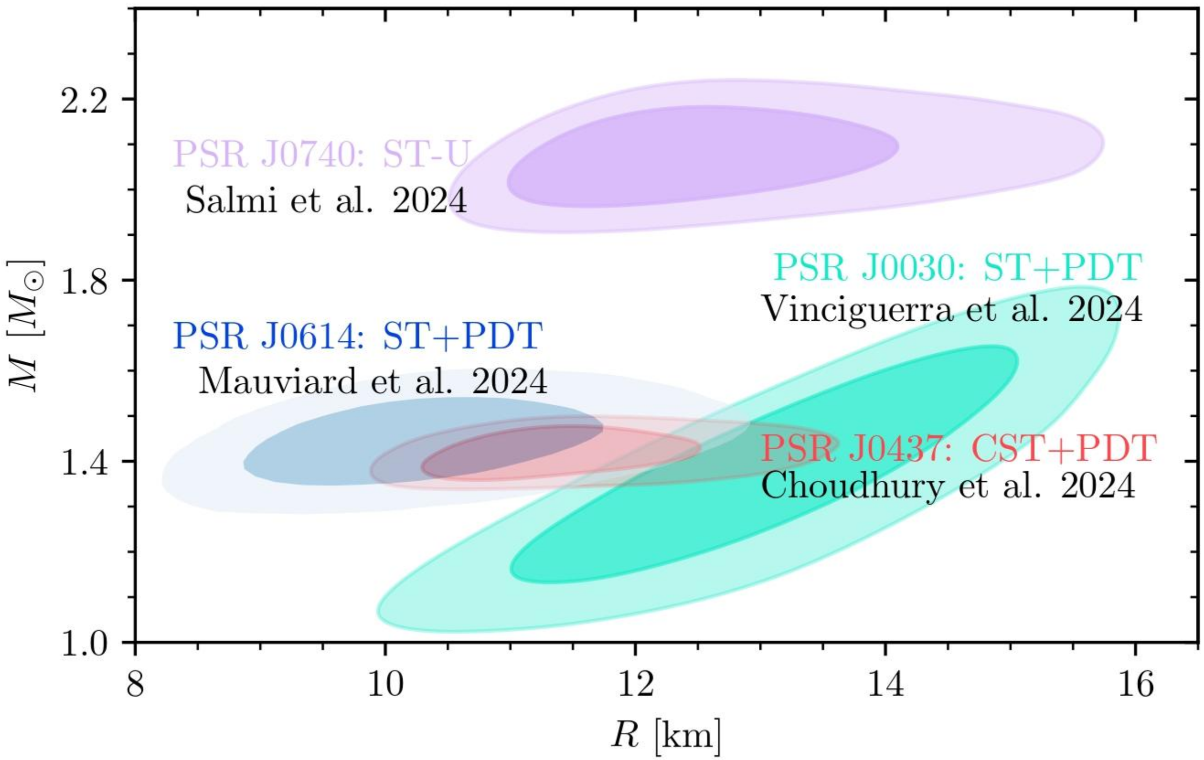
Non-trivial hot-spot modeling



Large number of parameters needed to describe hot spots

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

Recent data from NICER



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

Modified figure from Mauviard, …, **MM**, … et al, ApJ (2025), arxiv: 2506.14883

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Primer on astro observational techniques
- Recent chiral effective field theory (χEFT) calculations
- Recent perturbative quantum chromodynamic (pQCD) calculations
- Bayesian framework and EOS construction
- Implications for dense matter EOS
- Inference of EOS parameters

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

Raaijmakers, …, **MM**, … et al, 2025 (JOSS), https://doi.org/10.21105/joss.06003

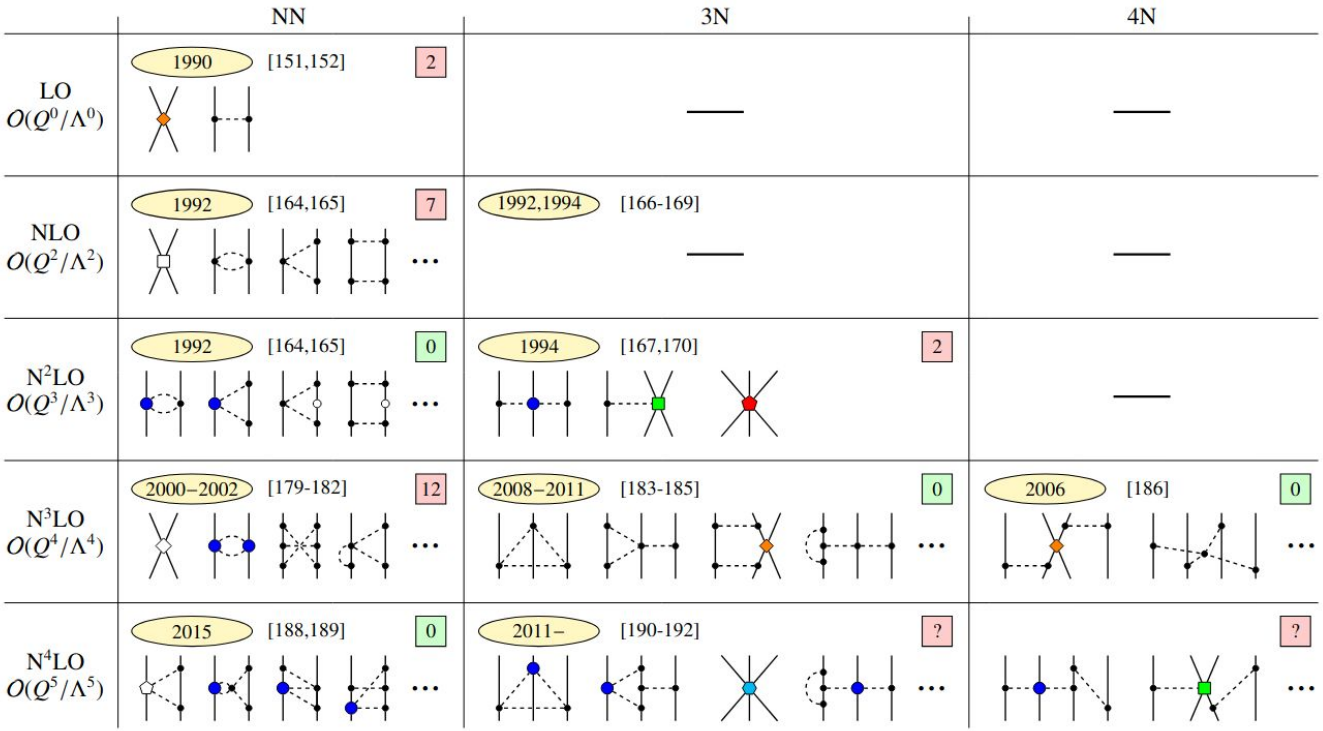
Mauviard, …, **MM,** … et al, 2025 (ApJ), arxiv: 2506.14883

Hoogkamer, …, **MM**, … et al, 2025 (Editor's suggestion PRD), arxiv: 2510.27619

MM et al, 2025 (in preparation)

NEoST

Chiral effective field theory

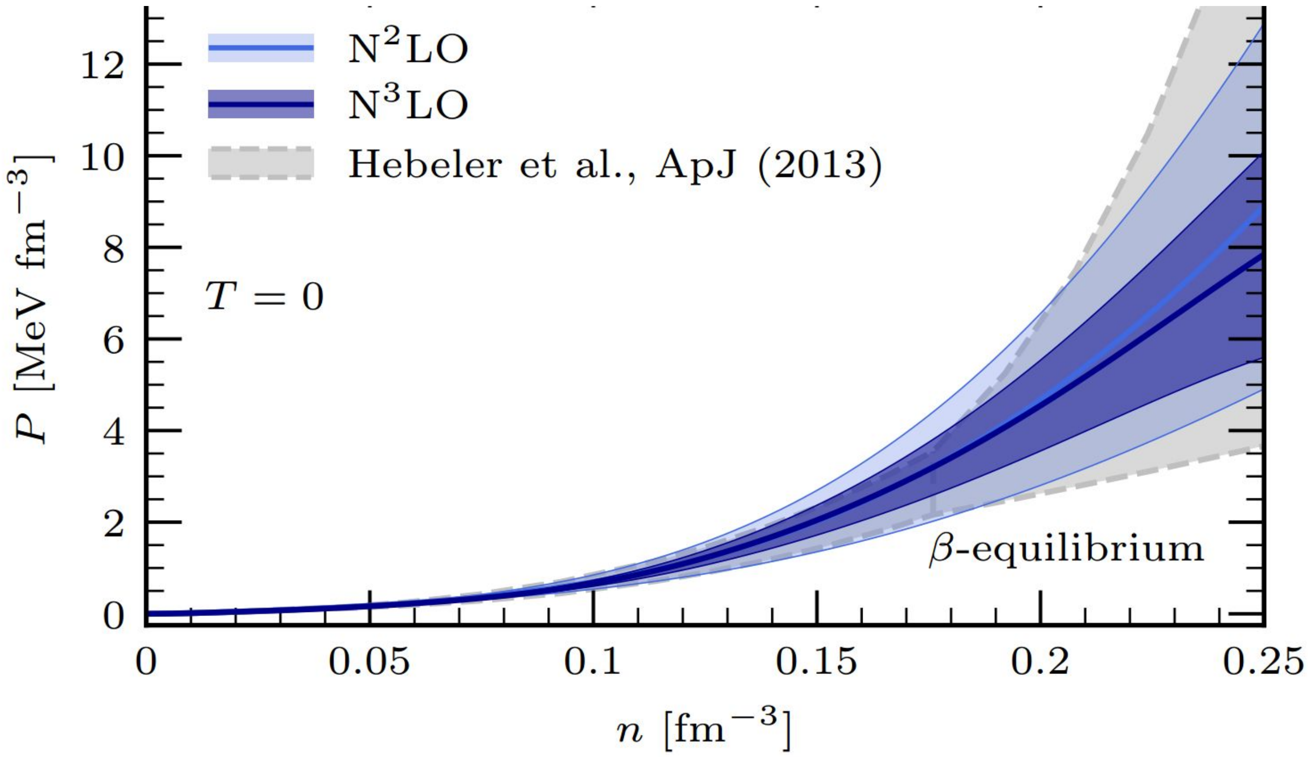


Ab initio calculations can determine the EOS at low densities

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

Recent χEFT EOS calculations

TECHNISCHE UNIVERSITÄT DARMSTADT



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

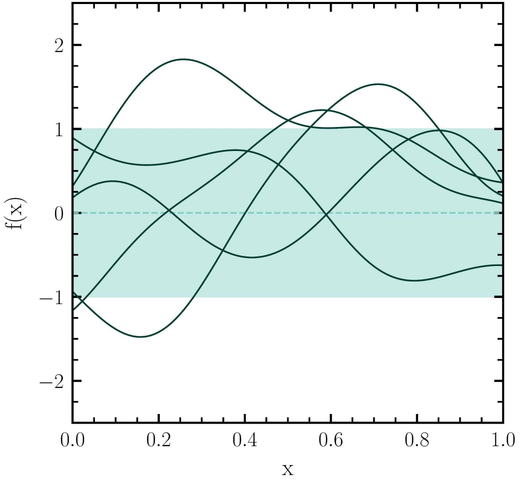
Figure from Keller et al, PRL (2023), arxiv:2204.14016

Gaussian processes (GP)

TECHNISCHE UNIVERSITÄT DARMSTADT

$$f(x) \sim GP\left[m(x), \kappa(x, x'; \theta)\right]$$

$$\kappa(x, x'; \theta) = \bar{c}^2 \exp\left[-\frac{1}{2}(x - x')^T L (x - x')\right]$$

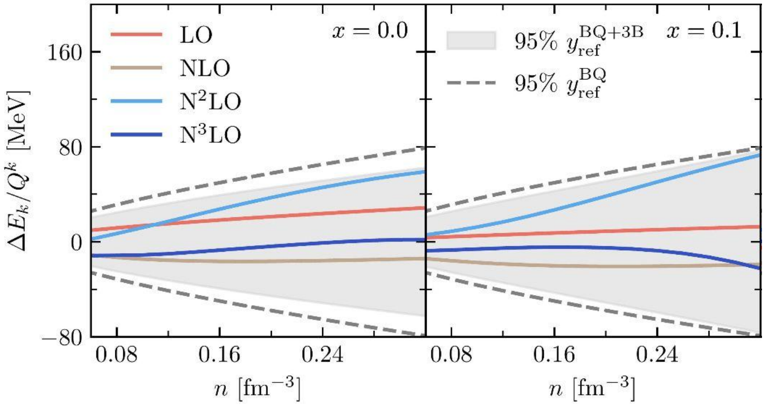


where

$$L = \begin{pmatrix} \ell_n^{-2} & 0 \\ 0 & \ell_x^{-2} \end{pmatrix}$$

hyperparameters $\bar{c}^2$, ℓ determined from expansion coefficients

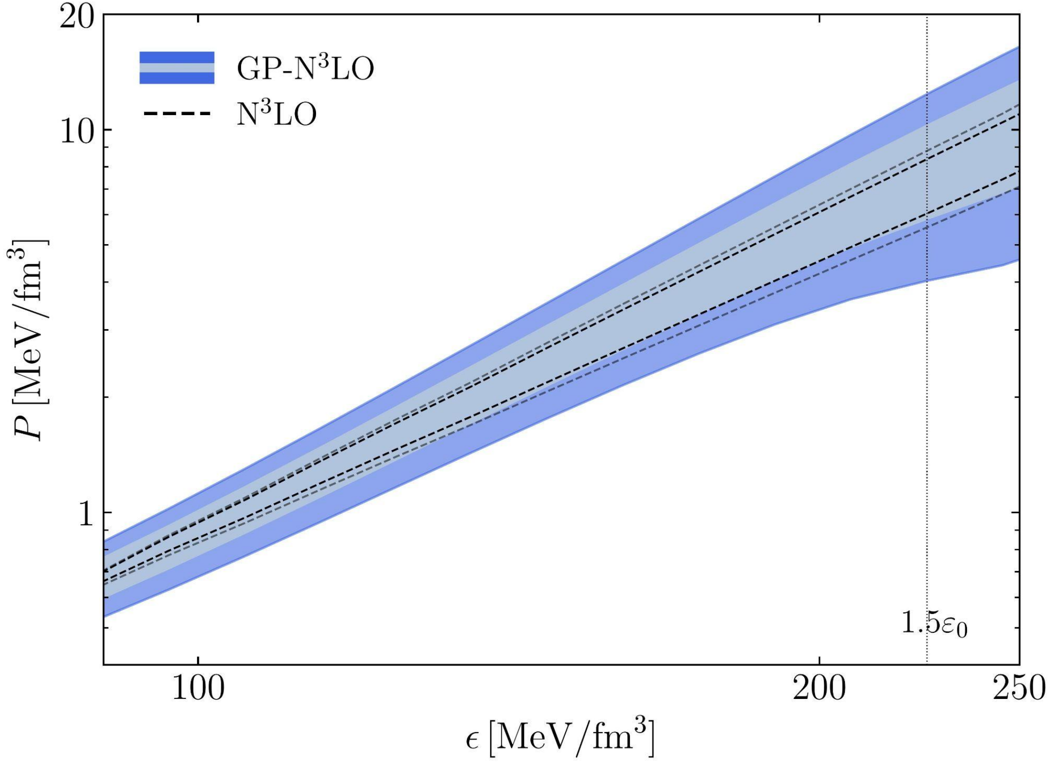
Calculations performed by H. Göttling



Modified figure from Göttling et al (2025), in preparation

GP for uncertainty quantification following Drischler et al., PRC (2020); Melendez et al., PRC (2019)

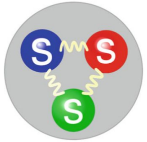
Recent χEFT EOS implementation



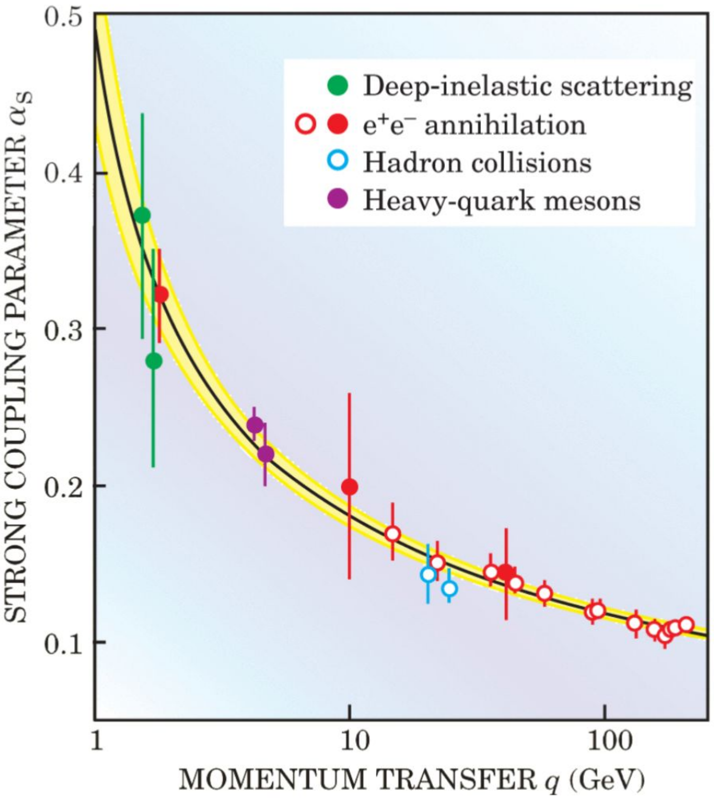
Broader pressure range covered with χEFT EOS with uncertainty quantification (GP-N³LO)

Modified figure from **MM** et al (2025), in preparation

Asymptotic freedom



Confinement at low q



Freedom at large q

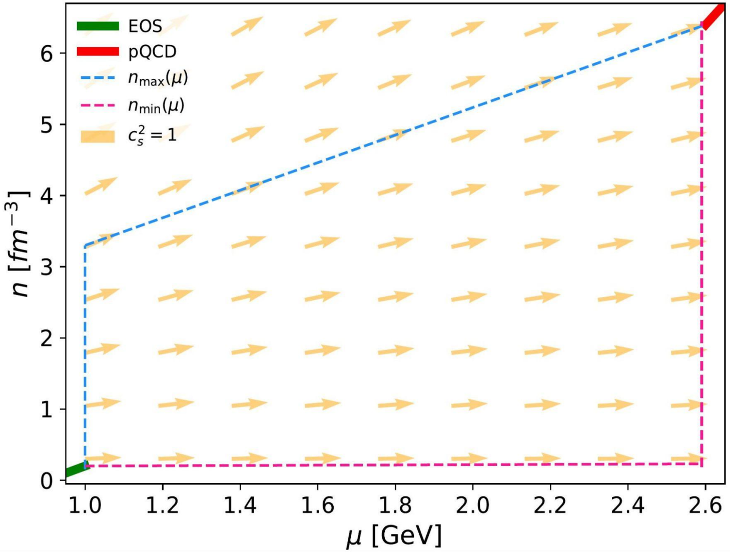
Perturbative QCD (pQCD) explores the region of smaller strong coupling constant

Modified figure from Fritzsch, H. (2018), Murray Gell-Mann and the Physics of Quarks, Springer

pQCD implementation

TECHNISCHE UNIVERSITÄT DARMSTADT

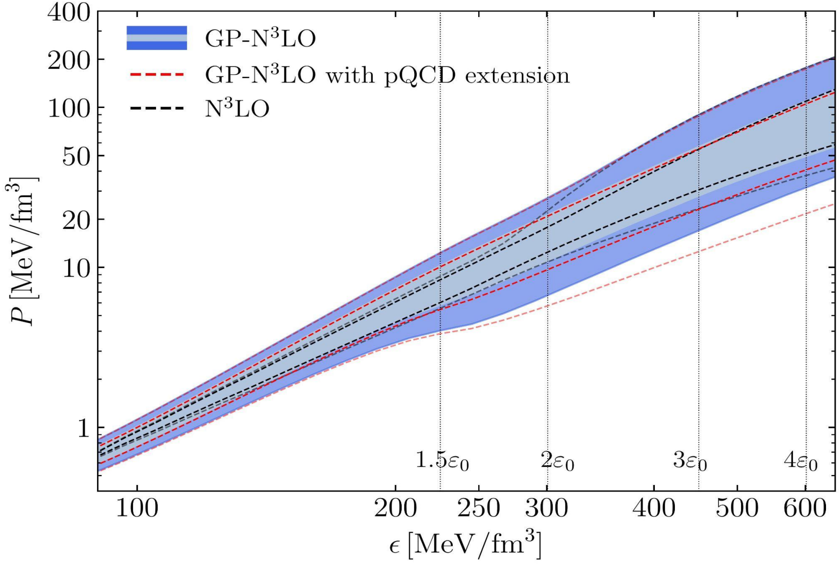
Extension procedure built by A. Hensel



Modified figure from Komoltsev and Kurkela, PRL (2022), arxiv:2111.05350

EOS extensions built to respect pQCD constraints

Further expands prior space, especially at high densities



Modified figure from **MM** et al (2025), in preparation

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Primer on astro observational techniques
- Recent chiral effective field theory (χEFT) calculations
- Recent perturbative quantum chromodynamic (pQCD) calculations
- Bayesian framework and EOS construction
- Implications for dense matter EOS
- Inference of EOS parameters

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

Raaijmakers, …, **MM**, … et al, 2025 (JOSS), https://doi.org/10.21105/joss.06003

Mauviard, …, **MM,** … et al, 2025 (ApJ), arxiv: 2506.14883

Hoogkamer, …, **MM**, … et al, 2025 (Editor's suggestion PRD), arxiv: 2510.27619

MM et al, 2025 (in preparation)

NEoST

Bayesian framework

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

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

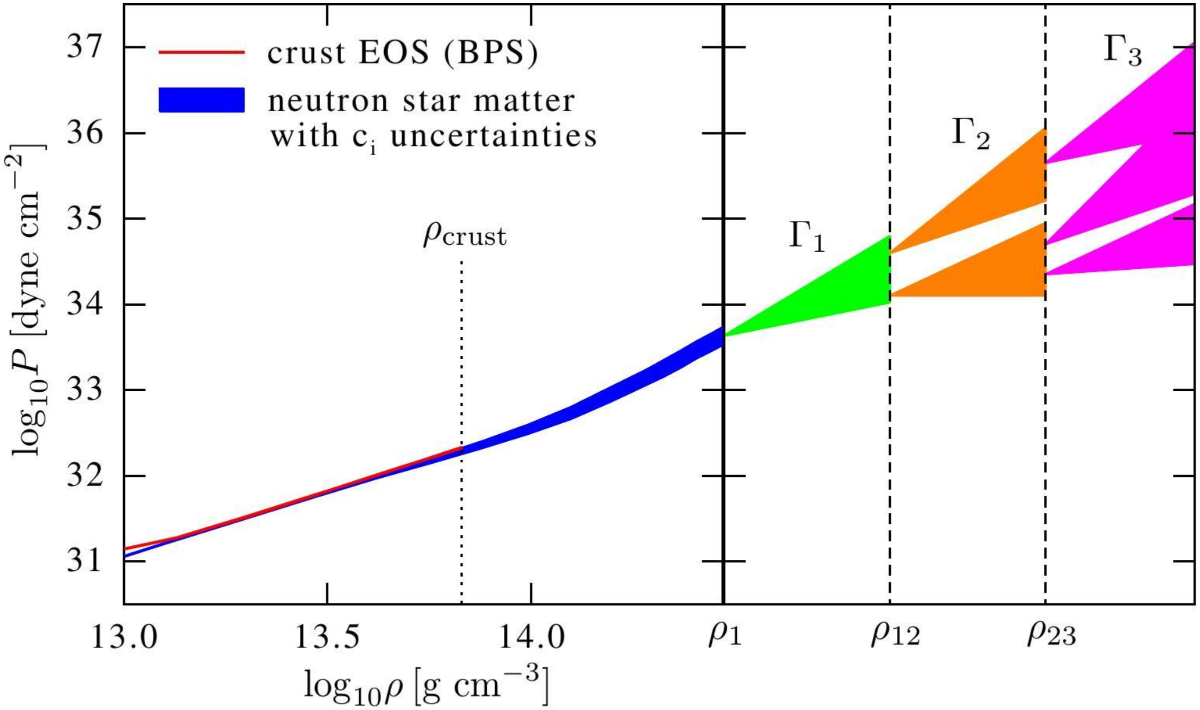
with radio mass measurements included through NICER M-R likelihoods when available

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

NEoST

Piecewise polytropic parametrization (PP)

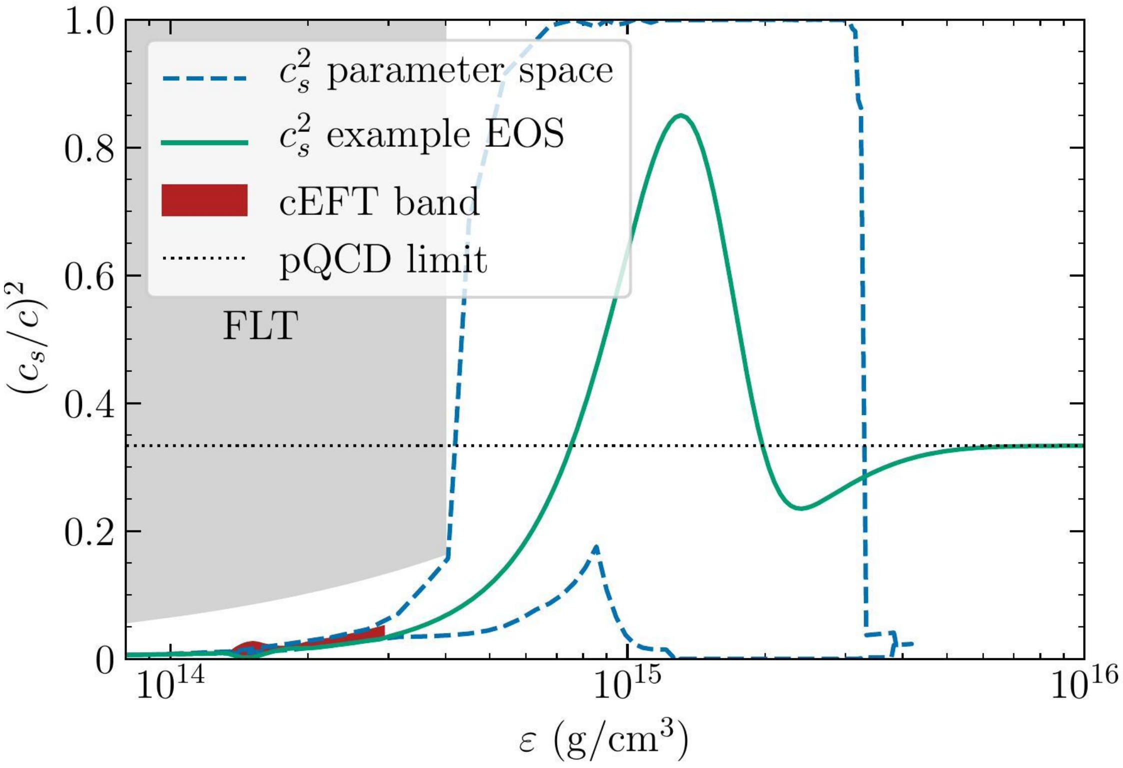
TECHNISCHE UNIVERSITÄT DARMSTADT



3 independent polytropes, respecting causality, following Read et al, PRD (2009), arxiv: 0812.2163

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

Speed of sound parametrization (CS)

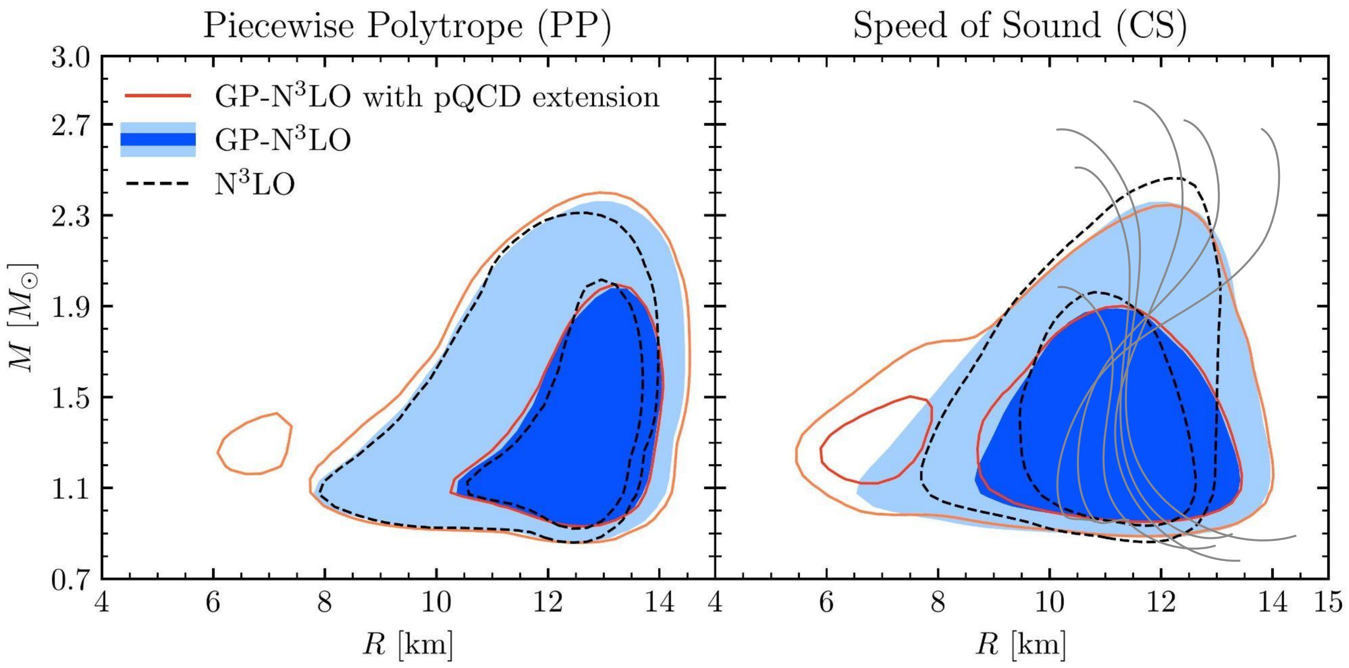


Analytical expression to speed of sound, limited by

- Fermi liquid theory
- causality
- $\lim_{n \geq 50\, n0} c_s^2 \rightarrow 1/3$

From Greif et al, MNRAS (2019)
arxiv: 1812.08188

Mass-Radius (MR) priors



Radii around 10-14 km

Both the new treatment of the cEFT EOS and pQCD extensions expand MR priors

From **MM** et al, in preparation (2025)

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Primer on astro observational techniques
- Recent chiral effective field theory (χEFT) calculations
- Recent perturbative quantum chromodynamic (pQCD) calculations
- Bayesian framework and EOS construction
- Implications for dense matter EOS
- Inference of EOS parameters

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

Raaijmakers, …, **MM**, … et al, 2025 (JOSS), https://doi.org/10.21105/joss.06003

Mauviard, …, **MM,** … et al, 2025 (ApJ), arxiv: 2506.14883

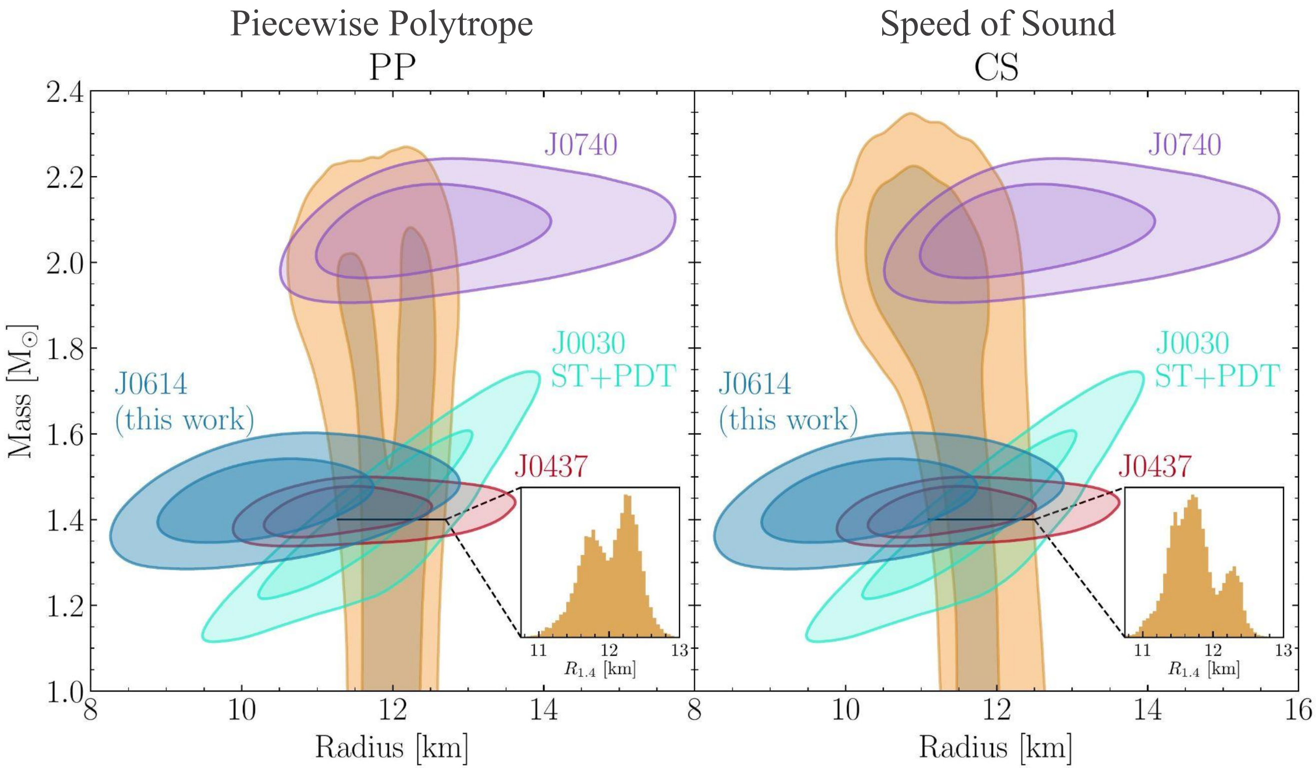
Hoogkamer, …, **MM**, … et al, 2025 (Editor’s suggestion PRD), arxiv: 2510.27619

MM et al, 2025 (in preparation)

NEoST

Most likely M-R, N^3LO only

TECHNISCHE UNIVERSITÄT DARMSTADT



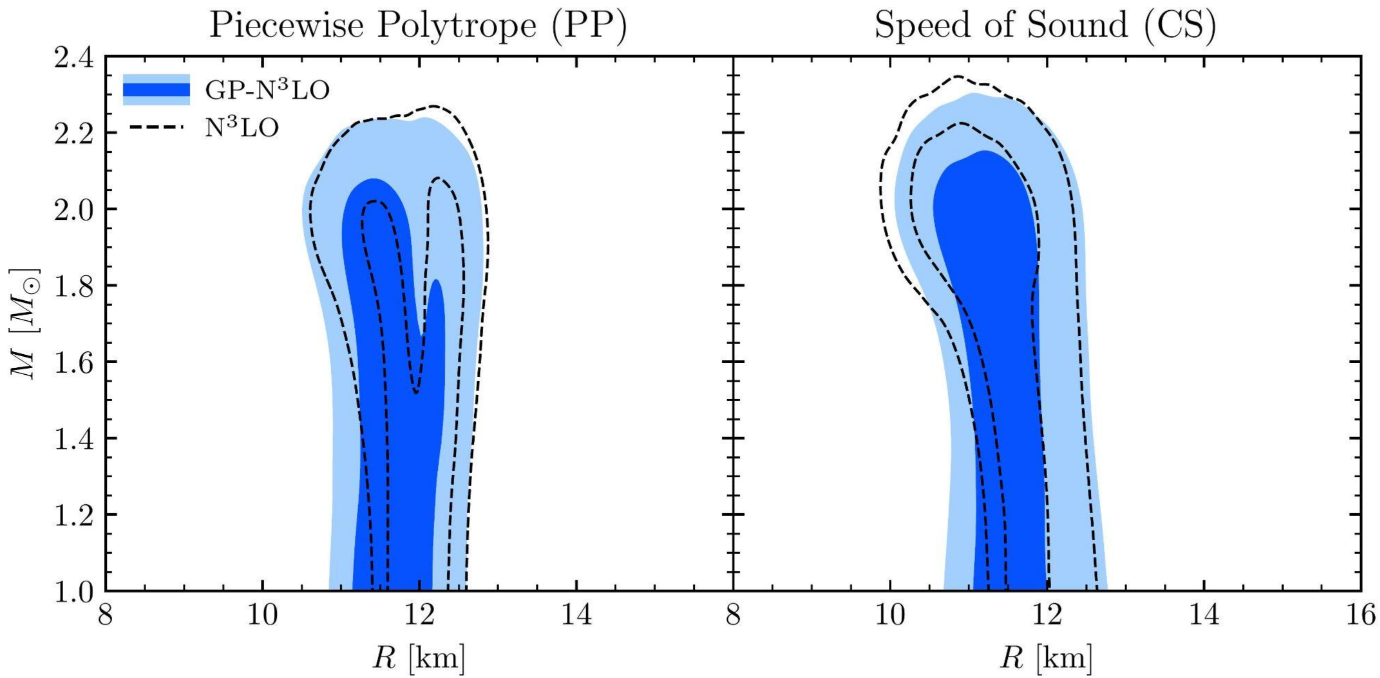
Consistent results for PP and CS parameterizations

Slight EOS softening compared to previous posteriors

Minimal impact on maximum mass

From Mauviard, …, **MM**, … et al, ApJ (2025), arxiv:2506.14883

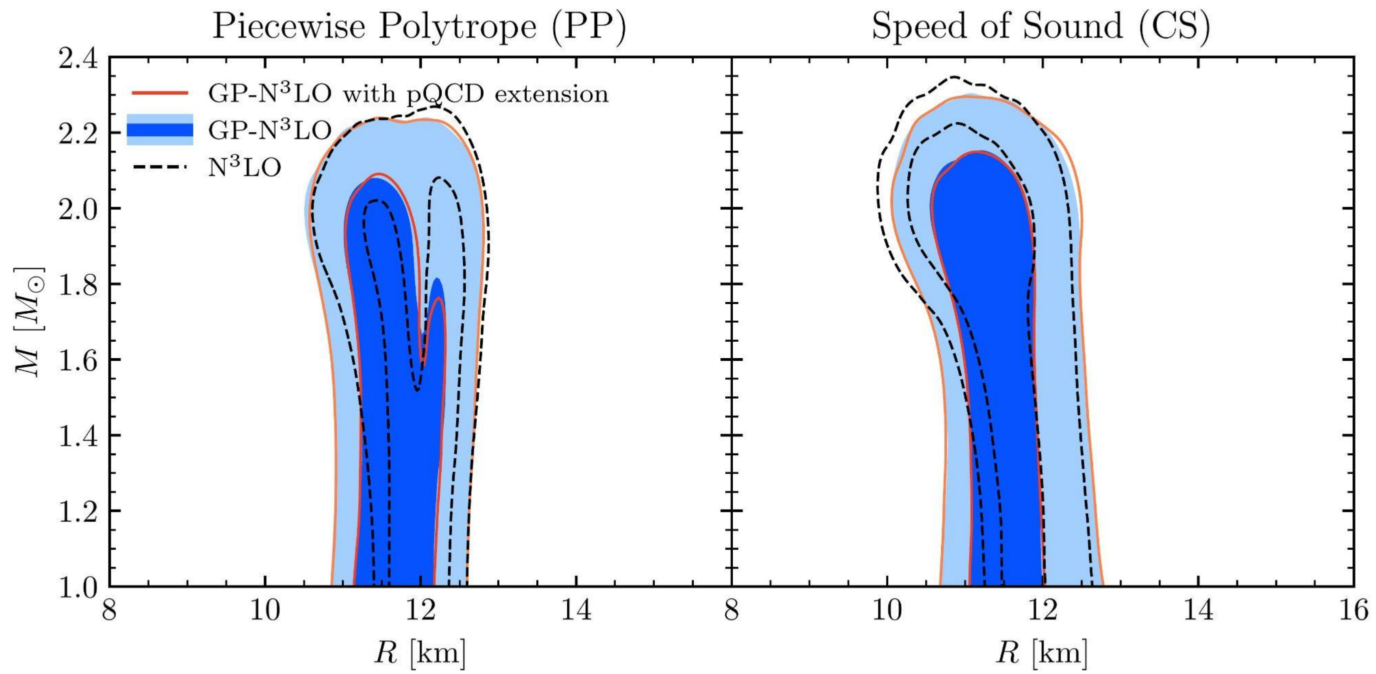
Most likely M-R with GP-N3LO



New cEFT implementation broadens the radius, especially for low mass stars

From **MM** et al, in preparation (2025)

With pQCD constraints

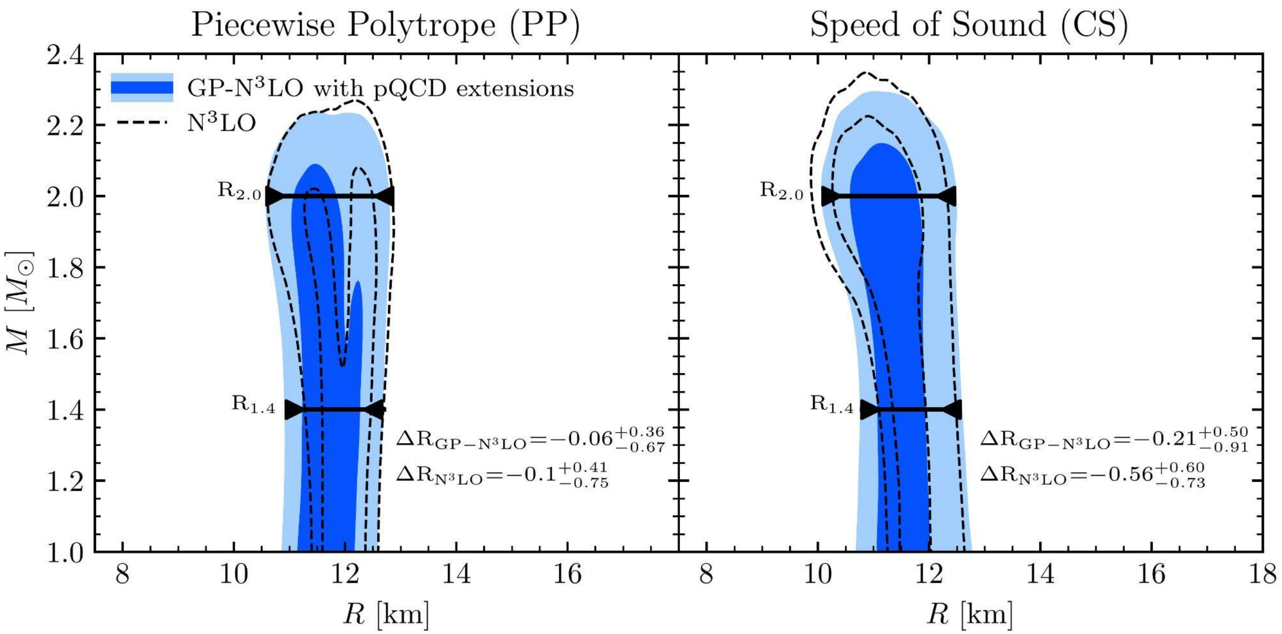


Minor differences to the posterior without pQCD constraints

PSR J0740 measurement more constraining for P_{max} extension

From **MM** et al, in preparation (2025)

Most likely M-R with GP-N3LO



We calculate

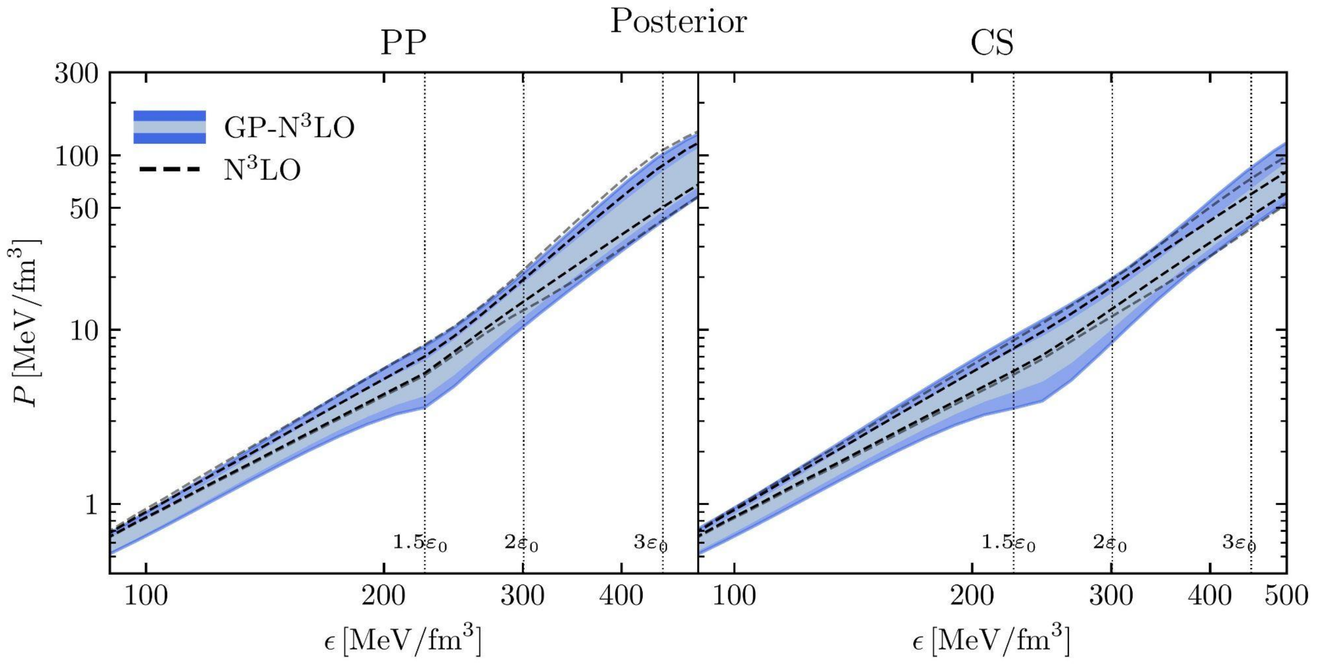
$\Delta R = R_{2.0} - R_{1.4}$

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

Small dependence on high-density extension

From **MM** et al, in preparation (2025)

Corresponding P-E curves



Broadening of pressure posterior beyond cEFT range

Minimal impact of pQCD extension

From **MM** et al, in preparation (2025)

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Primer on astro observational techniques
- Recent chiral effective field theory (χEFT) calculations
- Recent perturbative quantum chromodynamic (pQCD) calculations
- Bayesian framework and EOS construction
- Implications for dense matter EOS
- Inference of EOS parameters

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

Raaijmakers, …, **MM**, … et al, 2025 (JOSS), https://doi.org/10.21105/joss.06003

Mauviard, …, **MM,** … et al, 2025 (ApJ), arxiv: 2506.14883

Hoogkamer, …, **MM**, … et al, 2025 (Editor’s suggestion PRD), arxiv: 2510.27619

MM et al, 2025 (in preparation)

NEoST

EOS parametrization

$$E(n,\delta) = E_{\mathrm{SNM}}(n) + E_{\mathrm{sym}}(n)\cdot\delta^2 + \mathcal{O}\left(\delta^4\right), \;\; \delta = (n_{\mathrm{n}} - n_{\mathrm{p}})/n$$

with symmetry energy:

$$E_{\mathrm{sym}}(n) = J + L\left(\frac{n-n_0}{3n_0}\right) + \frac{1}{2}K_{\mathrm{sym}}\left(\frac{n-n_0}{3n_0}\right)^2 + \cdots$$

such that $L = 3P_{PNM}/n_0$

We explore the correlation between β-equilibrated matter and pure neutron matter to infer L

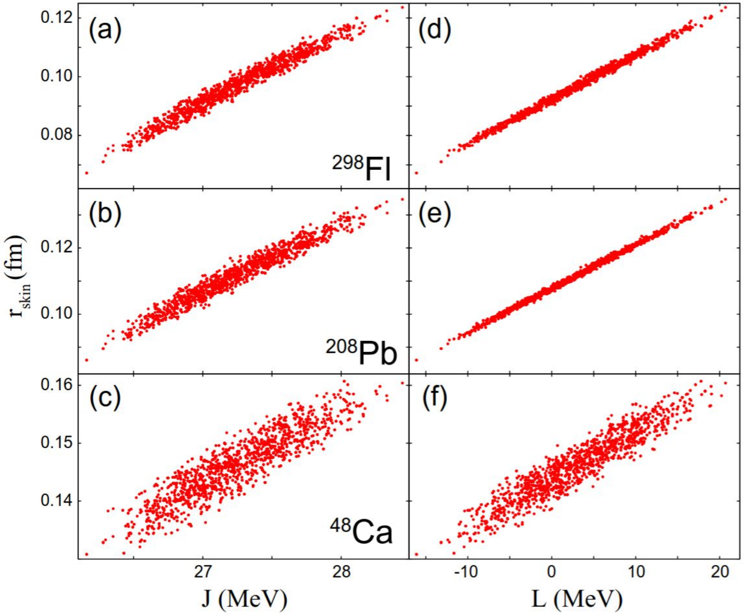
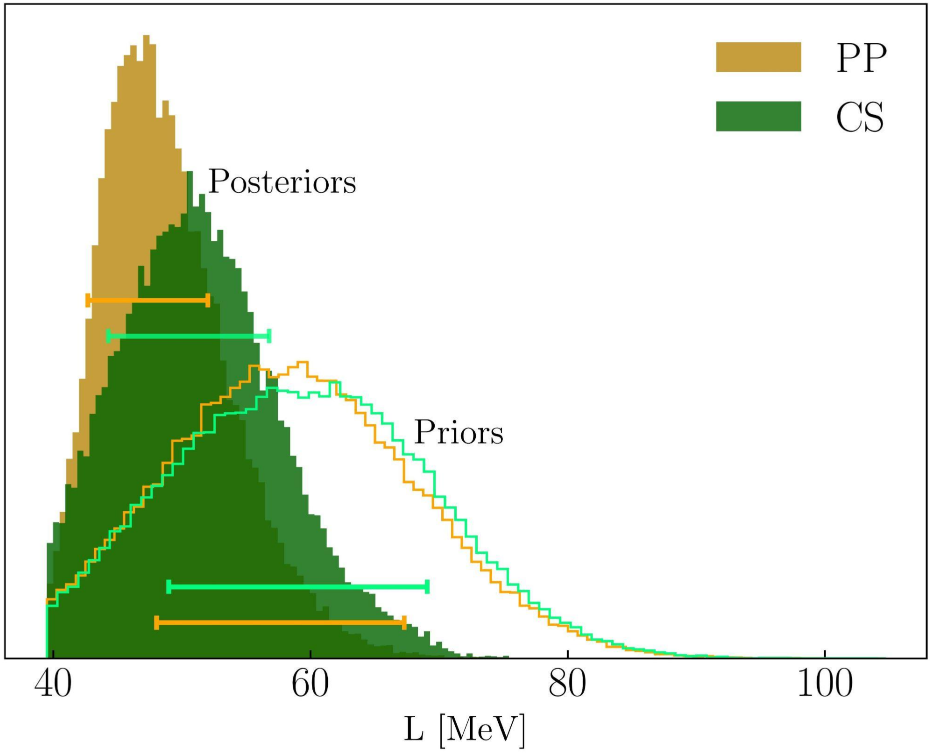


Figure from Reinhard and Nazarewicz, PRC (2016), arxiv:1601.06324

L parameter inference



Astrophysical data informs the value of L, the slope of symmetry energy

$L_{68\%\ PP}$ = 42.7 - 52.0 MeV

$L_{68\%\ CS}$ = 44.3 - 56.8 MeV

From **MM** et al, in preparation (2025)

Summary

TECHNISCHE UNIVERSITÄT DARMSTADT

- ❑ **Astrophysical data significantly constrains the EOS in high density, low temperature region**
- ❑ **Ab initio calculation updates can easily be integrated into EOS inference frameworks, including uncertainty quantification of cEFT EOS**
- ❑ **Inference of EOS parameters, such as L, statistically meaningful and astro informed**
- ❑ **Precision of observations only increases! More astrophysical and laboratory data expected soon**

Special thanks to A. Hensel, H. Göttling, I. Svensson, K. Hebeler, A. Schwenk

Thank you!

melissa.mendes@tu-darmstadt.de

Additional slides

NICER telescope primer

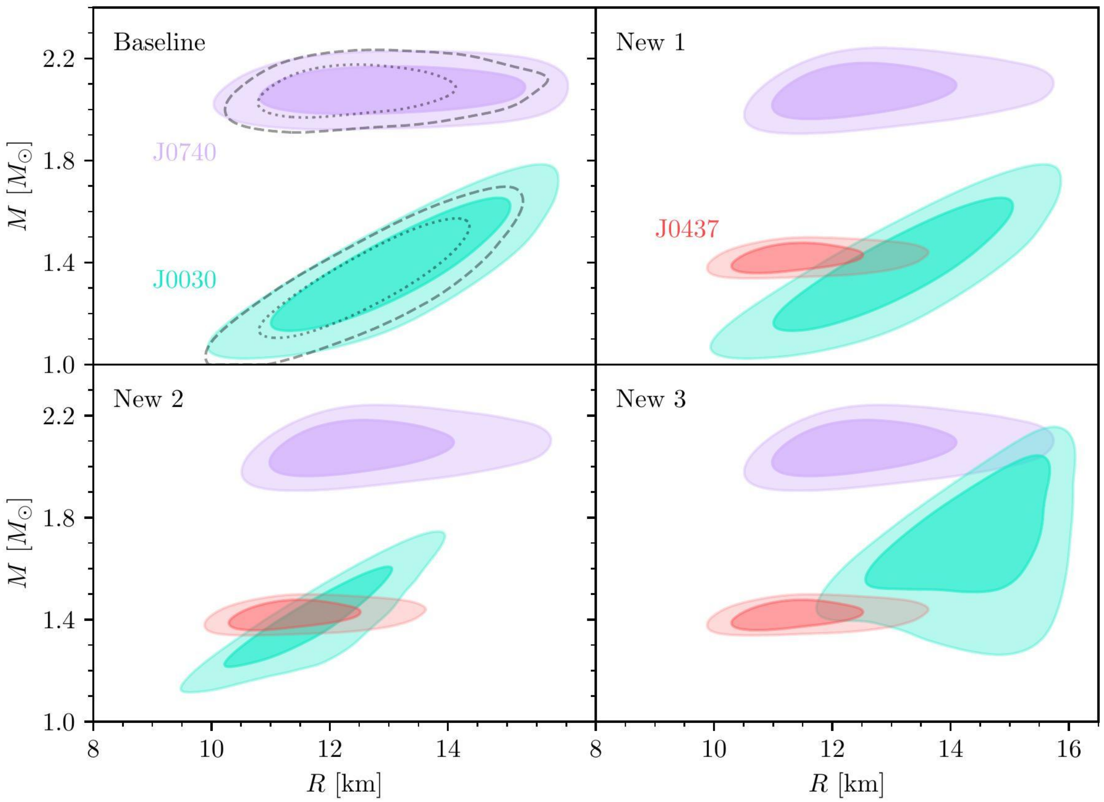
Neutron star Interior Composition ExploreR (NICER)

- X-ray telescope, aboard the International Space Station since 2017
- Needs rotating sources with f > 100 Hz
- Inferences depend on model for the surface emission, with free parameters:
  - mass, radius, spin rate, temperature distribution, beaming function or atmosphere model, observer inclination, distance, interstellar hydrogen column density and a background model

Targets:

- 5-10% precision level for PSR J0437-4715, PSR J0030+0451, PSR J1231+1411 and PSR J2124-3358
- Plus PSR J0614-3329, PSR J1614-2230, PSR J2124-3358, and others

Rutherford et al NICER data

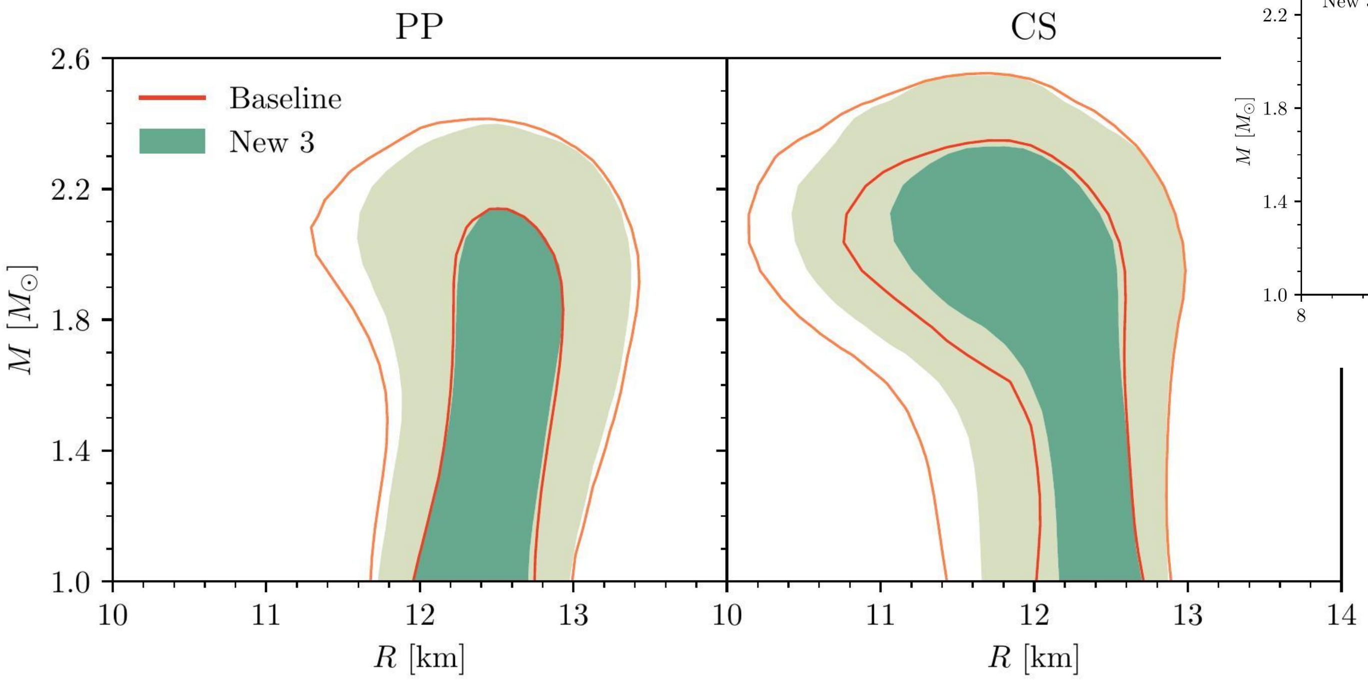


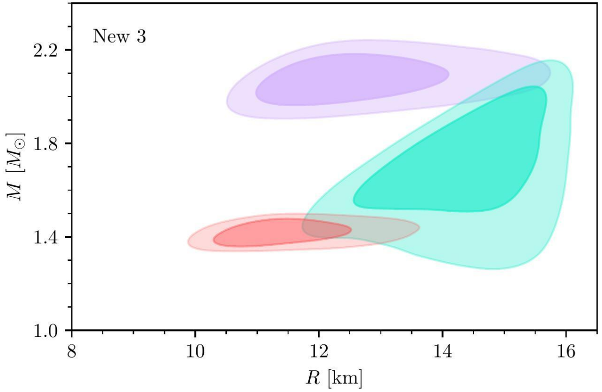
Some possible MR data contours depending on hot spot modelling

Plus GW170817 and GW190425

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

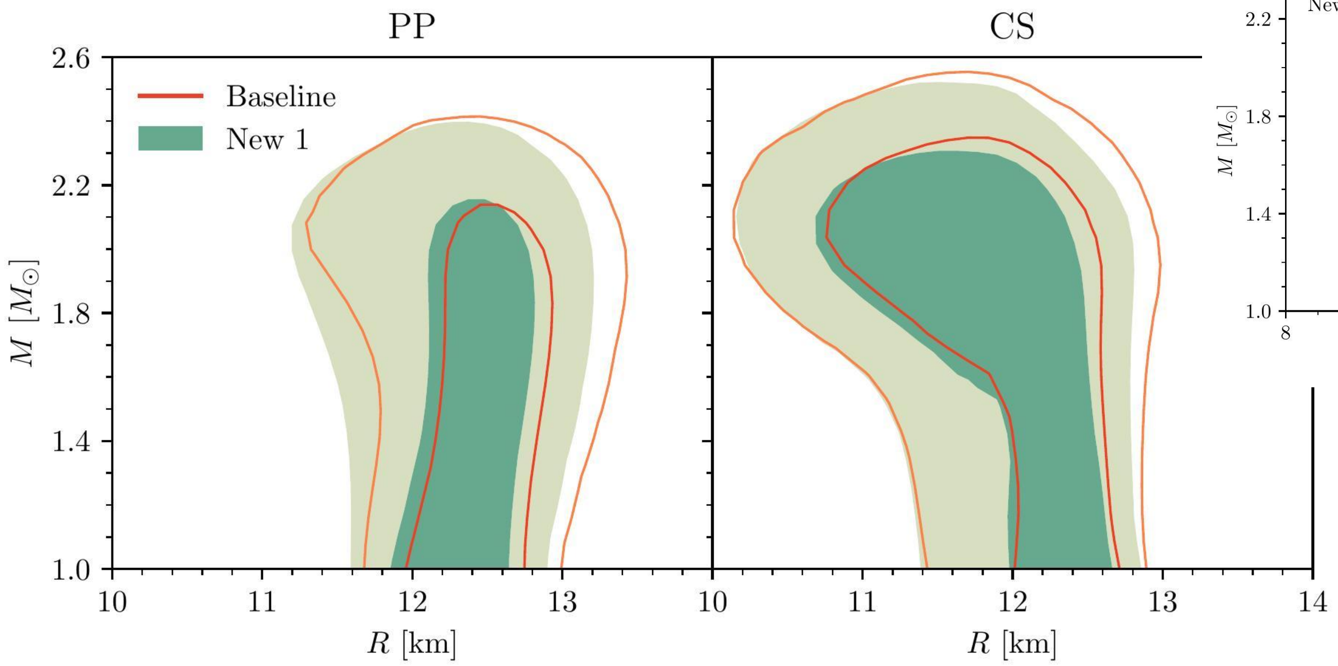
New 3 contours

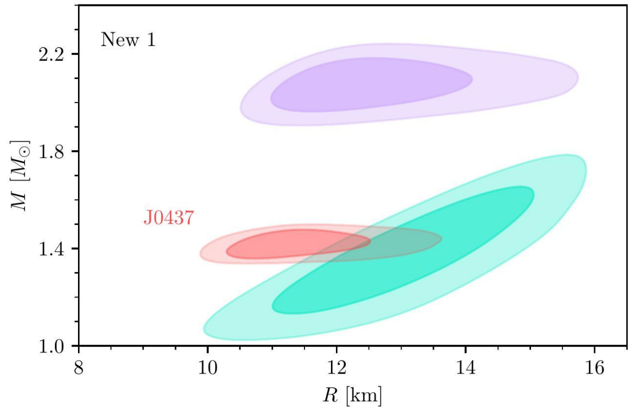




From Rutherford, **MM**, Svensson et al, ApJL (2024) arxiv:2407.06790

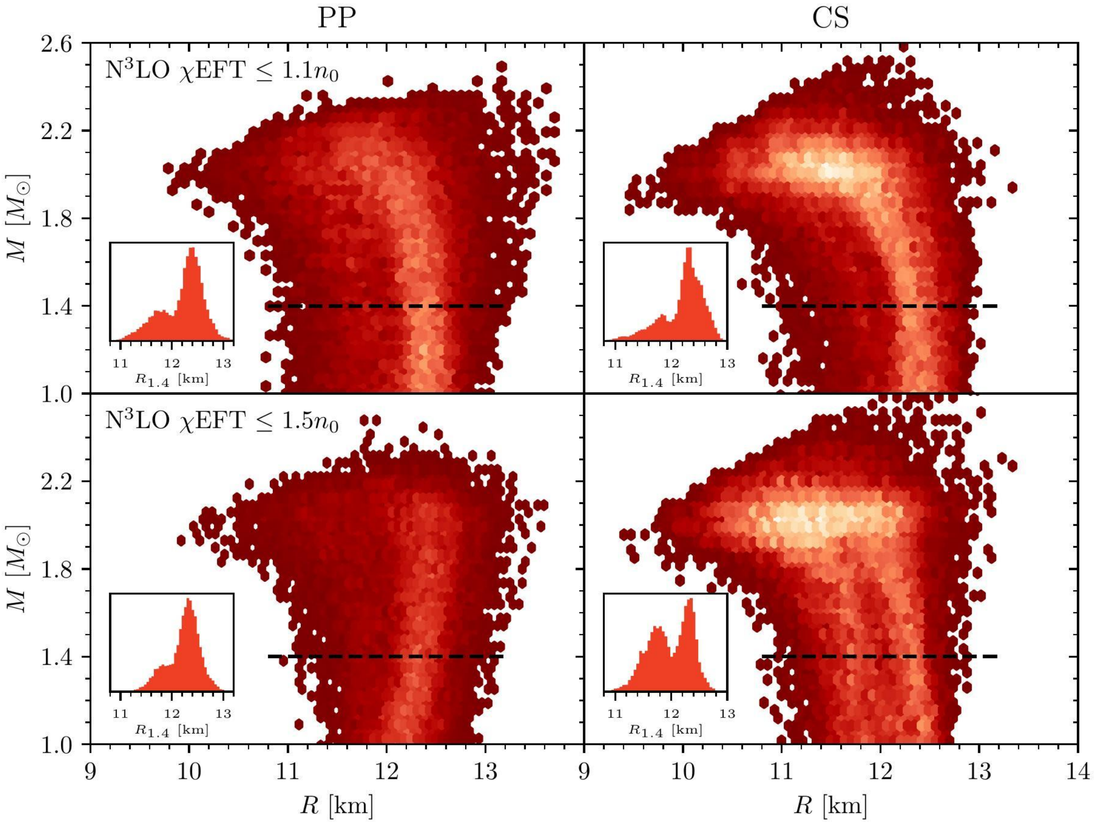
Other hot spot scenarios

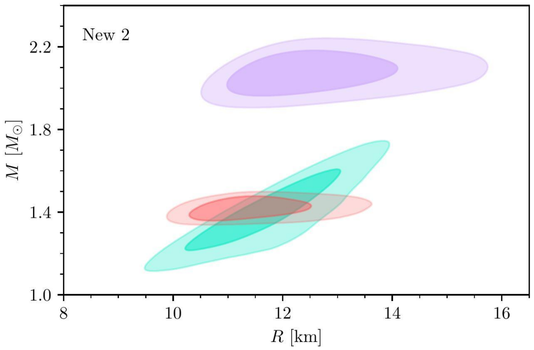




From Rutherford, **MM**, Svensson et al, ApJL (2024), arxiv:2407.06790

Most likely M-R





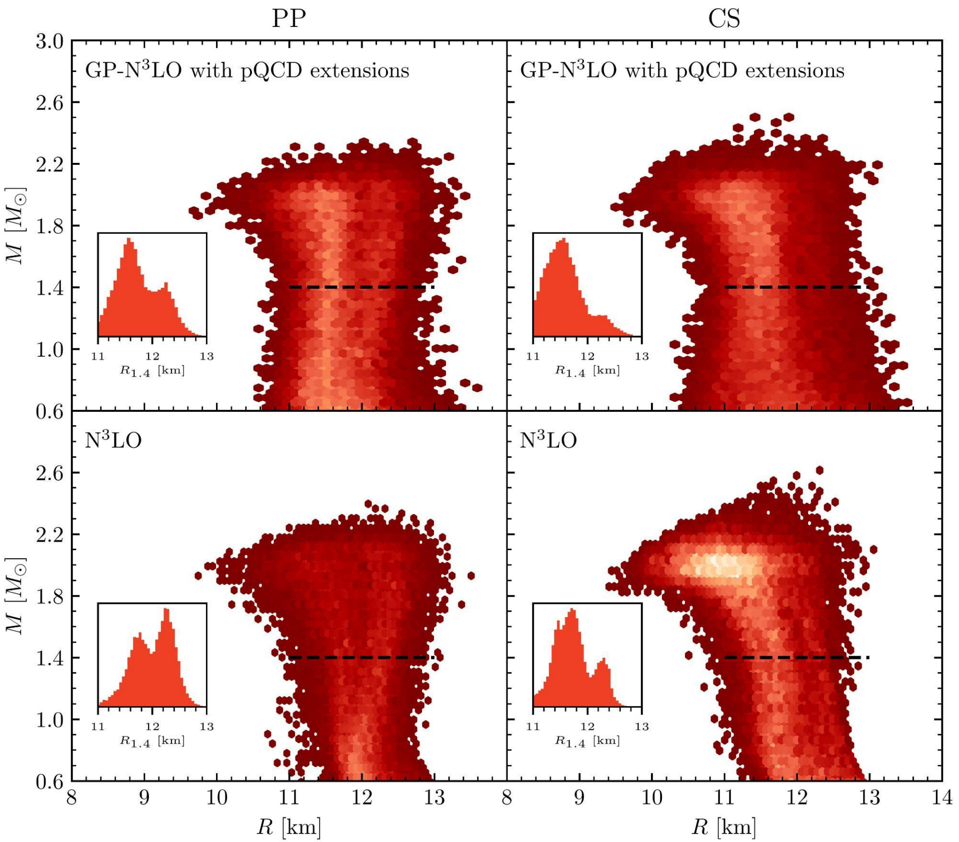
Consistent results for PP and CS parameterizations

Bimodal-like tendency for all posteriors

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

Most likely M-R

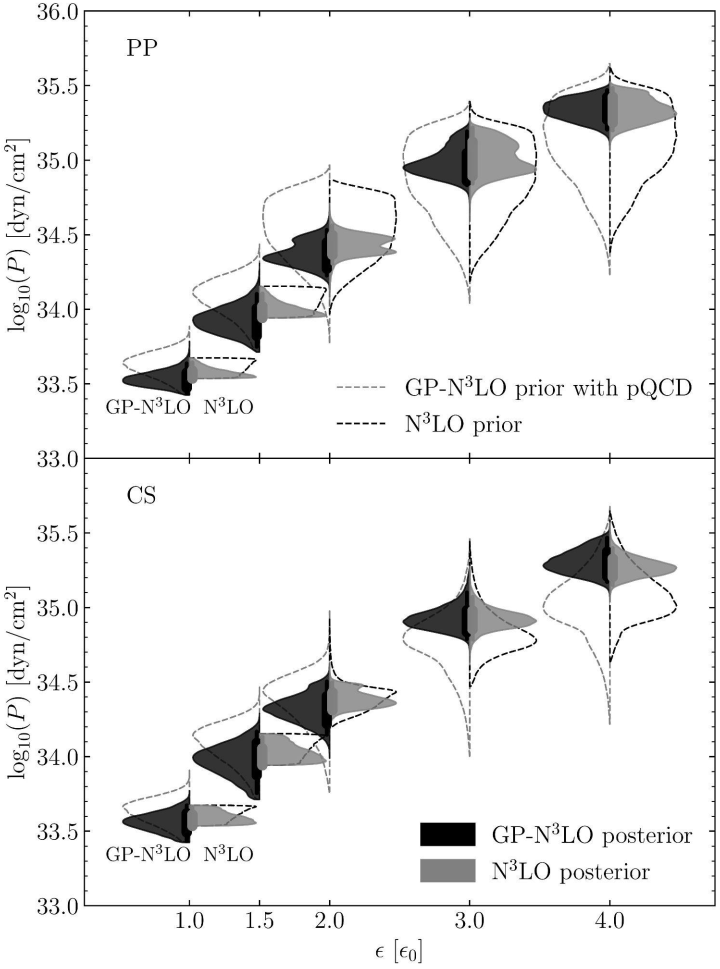
TECHNISCHE UNIVERSITÄT DARMSTADT



Bimodal-like tendency still present with new cEFT implementation and pQCD extensions

From **MM** et al (2025), in preparation

PxE



Consistent results for PP and CS parameterizations

Bimodal-like tendency for all posteriors

From **MM** et al (2025), in preparation

TOV equations I

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

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

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

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

$$Q(r) = 4\pi\left[5\mathcal{E}(r)+9P(r)+\frac{\mathcal{E}(r)+P(r)}{c_s^2(r)}-\frac{6}{r^2}\right]\left[1-\frac{2m(r)}{r}\right]^{-1}$$
$$-\frac{4m^2(r)}{r^4}\left[1+\frac{4\pi r^3 P(r)}{m(r)}\right]^2\left[1-\frac{2m(r)}{r}\right]^{-2}$$

TOV equations II

TECHNISCHE UNIVERSITÄT DARMSTADT

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

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

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:

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

PP parametrization equation

TECHNISCHE UNIVERSITÄT DARMSTADT

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

High density EOS given by

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

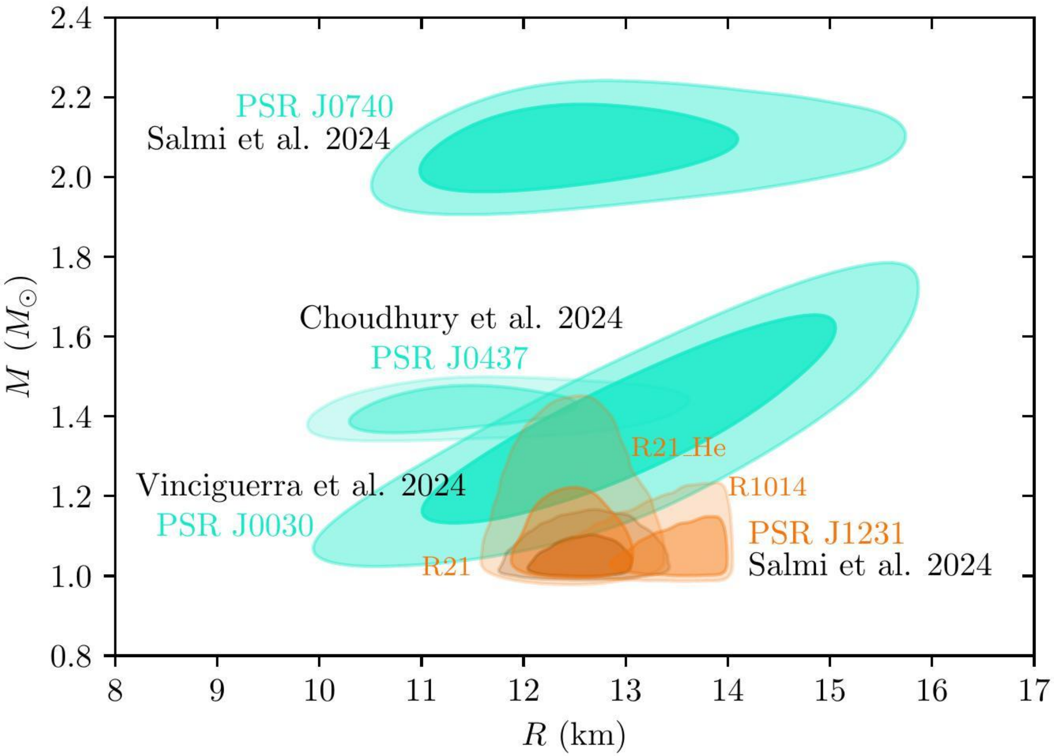
a_6 to match χ_{EFT} band.

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 NICER released data



Other hot spot models for J0614

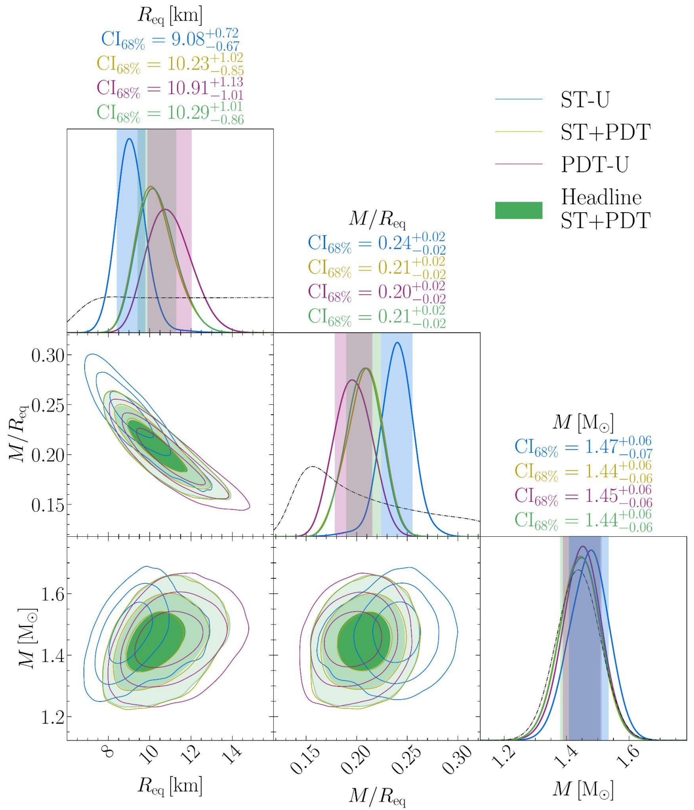
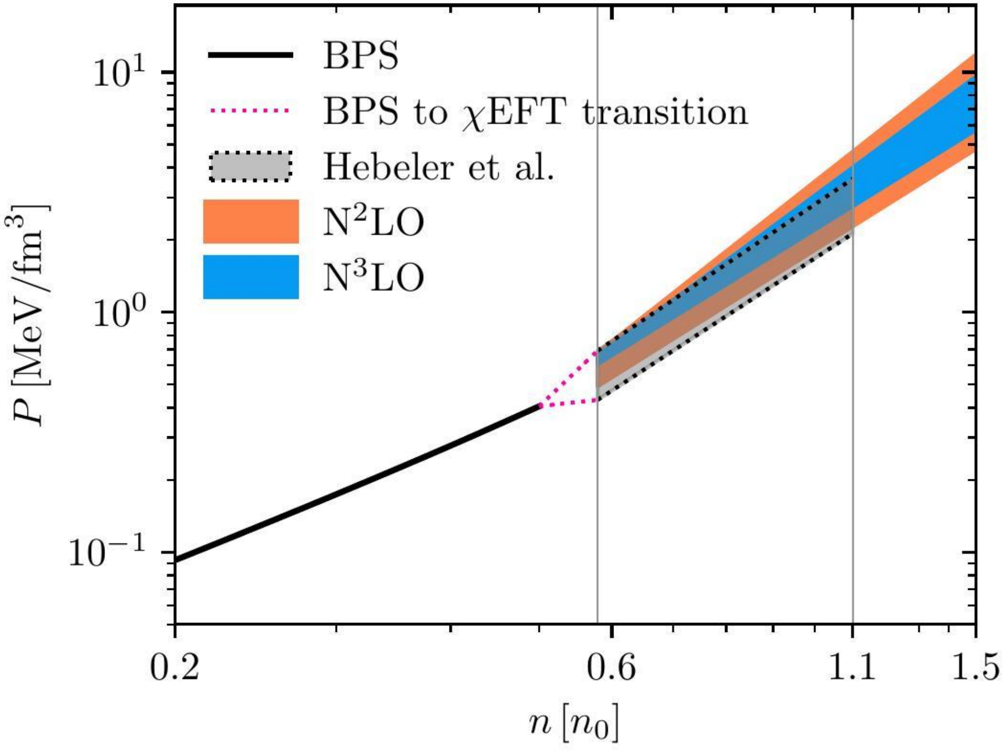


Figure from Mauviard, … **MM**, … et al, ApJ (2025), arxiv:2506.14883

Crust and outer core



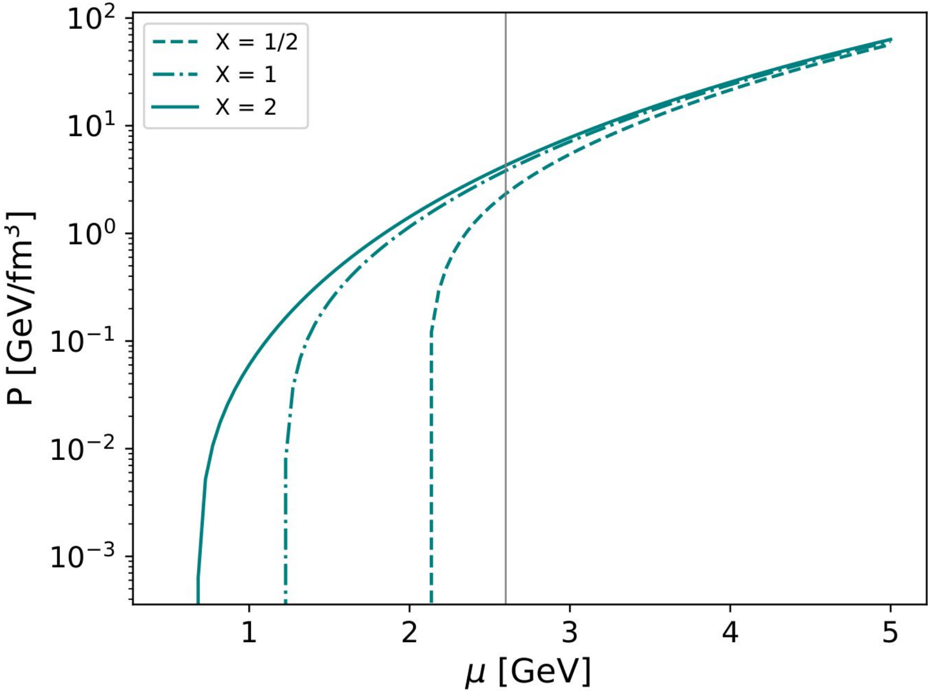
BPS EOS to model crust and polytropic fit ($P = K n^{\Gamma}$) for χEFT

Extended to both $1.1 n_0$ and $1.5 n_0$

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

pQCD implementation details

TECHNISCHE UNIVERSITÄT DARMSTADT



where $X \equiv 3\Lambda/(2\mu_B)$

with Λ renormalization scale

In NEoST, LogX uniformly sampled from [0.5, 2]

Figure from A. Hensel Master's thesis