Ab-initio nuclear matter equation of state

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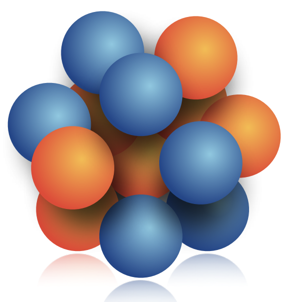
Introduction

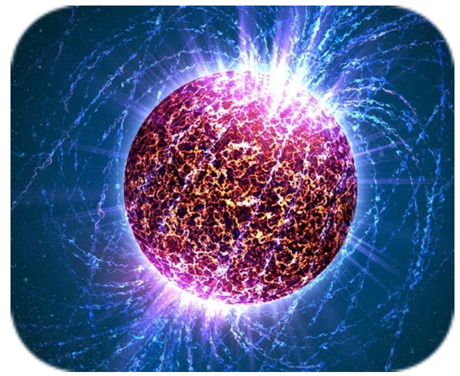
Goal: predict the emergence of nuclear properties and structure from first principles

nuclei



H ⟷

neutron stars



$R \sim 10^{-15}\,\mathrm{m}$

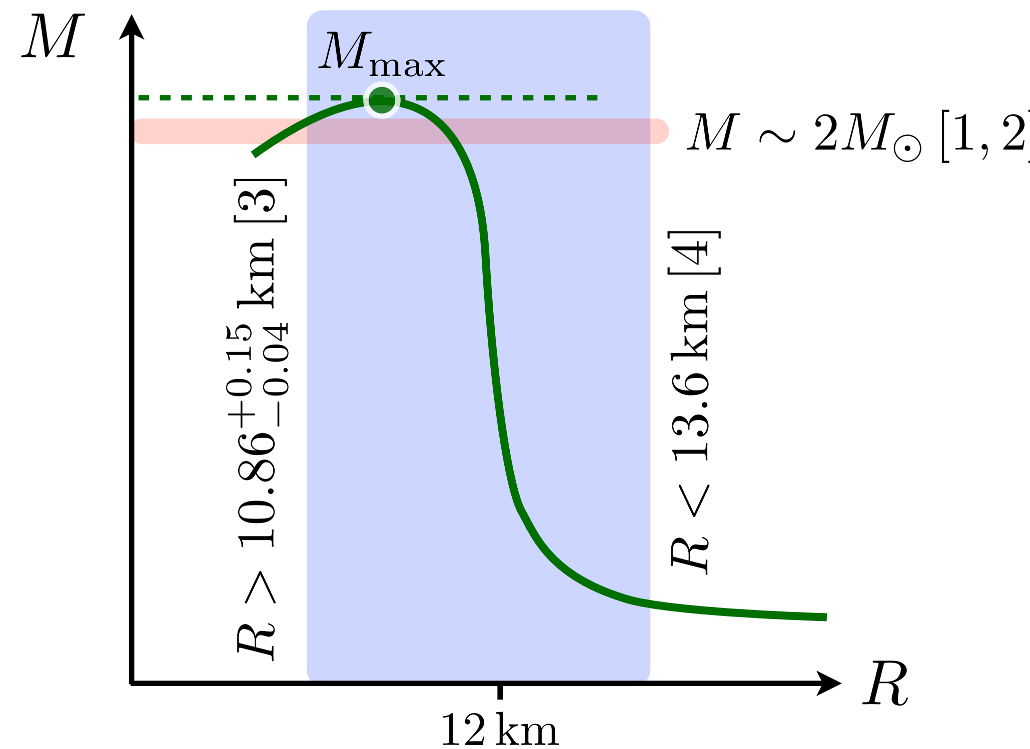
$M \sim 10^{-27}\,\mathrm{kg}$

$R \sim 10^{4}\,\mathrm{m}$

$M \sim 10^{30}\,\mathrm{kg}$

input: H

EoS $\xleftrightarrow{\text{TOV 1:1}}$ $M(R)$



Model: non-relativistic nucleons interacting with an effective nucleon-nucleon (NN) and three-nucleon interaction (NNN)

$$H = -\frac{\hbar^2}{2m_N}\sum_i \nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk} + \ldots$$

Question: is it possible to describe nuclei from microscopic nuclear Hamiltonians constructed to reproduce only few-body observables, while simultaneously predicting properties of matter?

[1] E. Fonseca *et al.*, ApJ **832**, 167 (2016)

[2] J. Antoniadis *et al.*, Science **340**, 1233232 (2013)

[3] A. Bauswein *et al.*, ApJ **850**, L34 (2017)

[4] E. Annala *et al.*, PRL **120**, 172703 (2017)

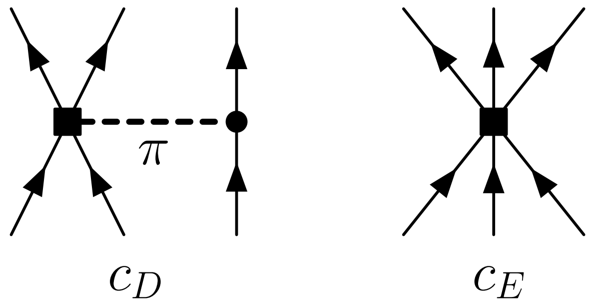
Nuclear Structure & Nuclear Dynamics

Interaction: χEFT potentials (Δ-less): coordinate-space, local @ N^{2}LO, local regulators

3b LECs (c_D, c_E) fit to:

- ^{4}He binding energy
- n-α scattering phase shifts

$\longrightarrow$ few-body observables

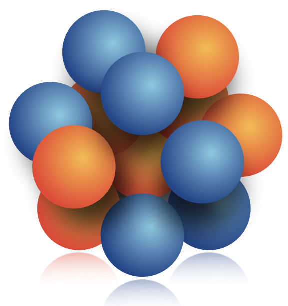


Method: quantum Monte Carlo (auxiliary field diffusion Monte Carlo, AFDMC)

Results: light and medium-mass nuclei

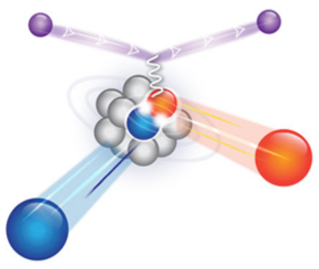
✓ *Nuclear structure* ($A \leq 16$) : binding energies, charge radii, charge form factors, r- and k-space 1- and 2-body densities

- D.L. *et al.*, PRL **120**, 122502 (2018)
- D.L. *et al.*, PRC **97**, 044318 (2018)
- D.L. *et al.*, PRC **98**, 014322 (2018)
- S. Gandolfi, D.L. *et al.*, Front. Phys. **8**, 117 (2020)



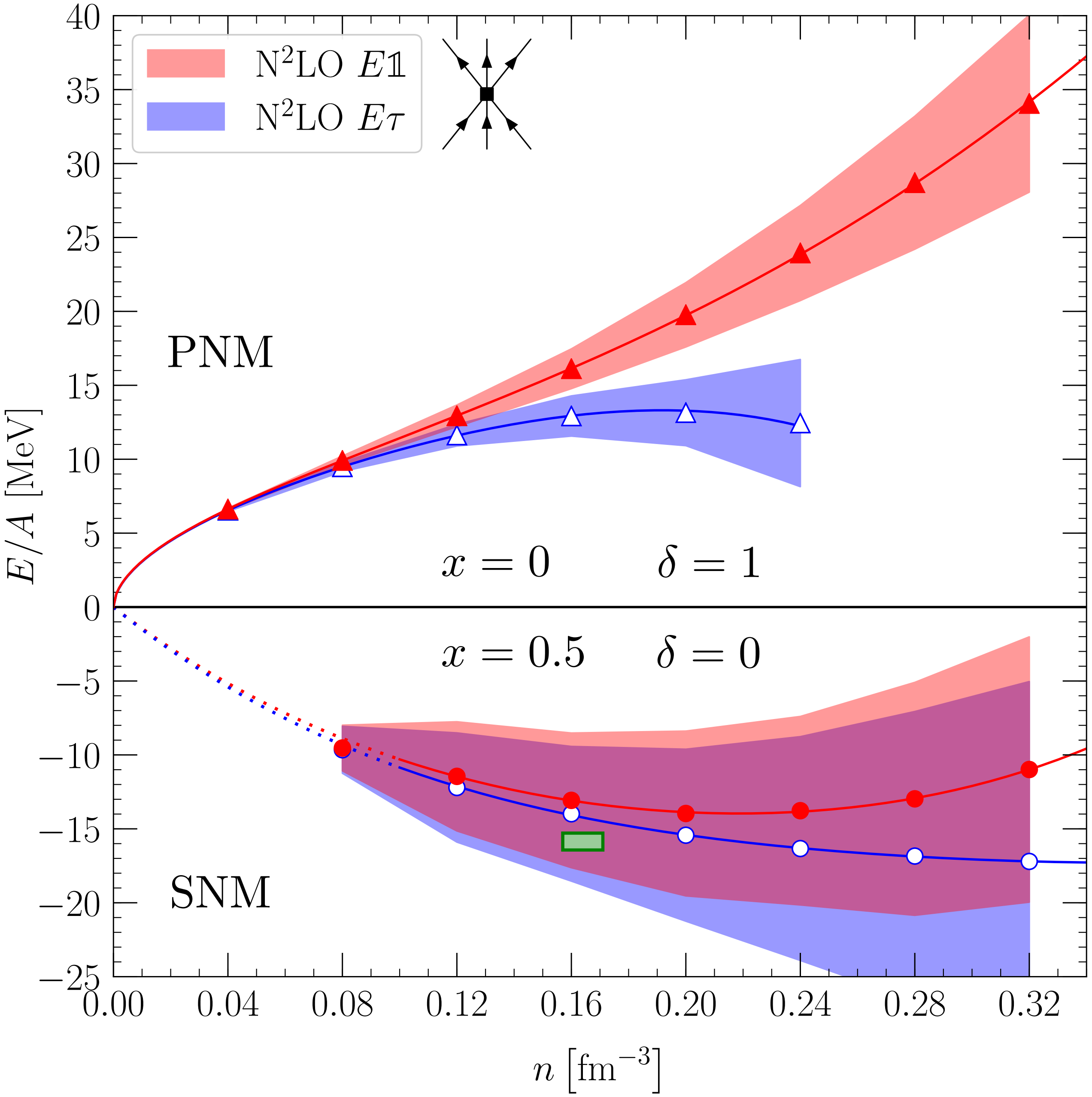
✓ *Nuclear dynamics* ($A \leq 40$) : short-range correlations, e-scattering experiments

- R. Cruz-Torres, D.L. *et al.*, PLB **797**, 134890 (2019)
- J.E. Lynn, D.L. *et al.*, JPG Nucl. Part. Phys. **47**, 045109 (2020)
- R. Cruz-Torres, D.L., *et al.*, arXiv1907.03658 (Nat. Phys. ?)



Nuclear and Neutron-Star Matter

D.L. *et al.*, Phys. Rev. Research **2**, 022033(R) (2020)



$$E_{\rm PNM}(n) = a\left(\frac{n}{n_{\rm sat}}\right)^{\alpha} + b\left(\frac{n}{n_{\rm sat}}\right)^{\beta}$$

$$E_{\rm SNM}(n) = E_0 + \frac{K_0}{2!}\left(\frac{n-n_0}{3n_0}\right)^2 + \frac{Q_0}{3!}\left(\frac{n-n_0}{3n_0}\right)^3 + \frac{Z_0}{4!}\left(\frac{n-n_0}{3n_0}\right)^4 + \mathcal{O}\left(\frac{n-n_0}{3n_0}\right)^5$$

Par.	N^{2}LO $E\mathbb{1}$	N^{2}LO $E\tau$	Empirical [1,2]
a	13.9(2) MeV	13.9(3) MeV	–
α	0.54(1)	0.54(2)	–
b	2.3(2) MeV	−1.0(4) MeV	–
β	2.6(1)	4(1)	–
n_0	0.22(1) fm^{-3}	0.36(1) fm^{-3}	0.164(7) fm^{-3}
E_0	−13.96(8) MeV	−17.29(9) MeV	−15.86(57) MeV
K_0	223(16) MeV	184(64) MeV	230(20) MeV
Q_0	252(390) MeV	1110(1491) MeV	300(400) MeV

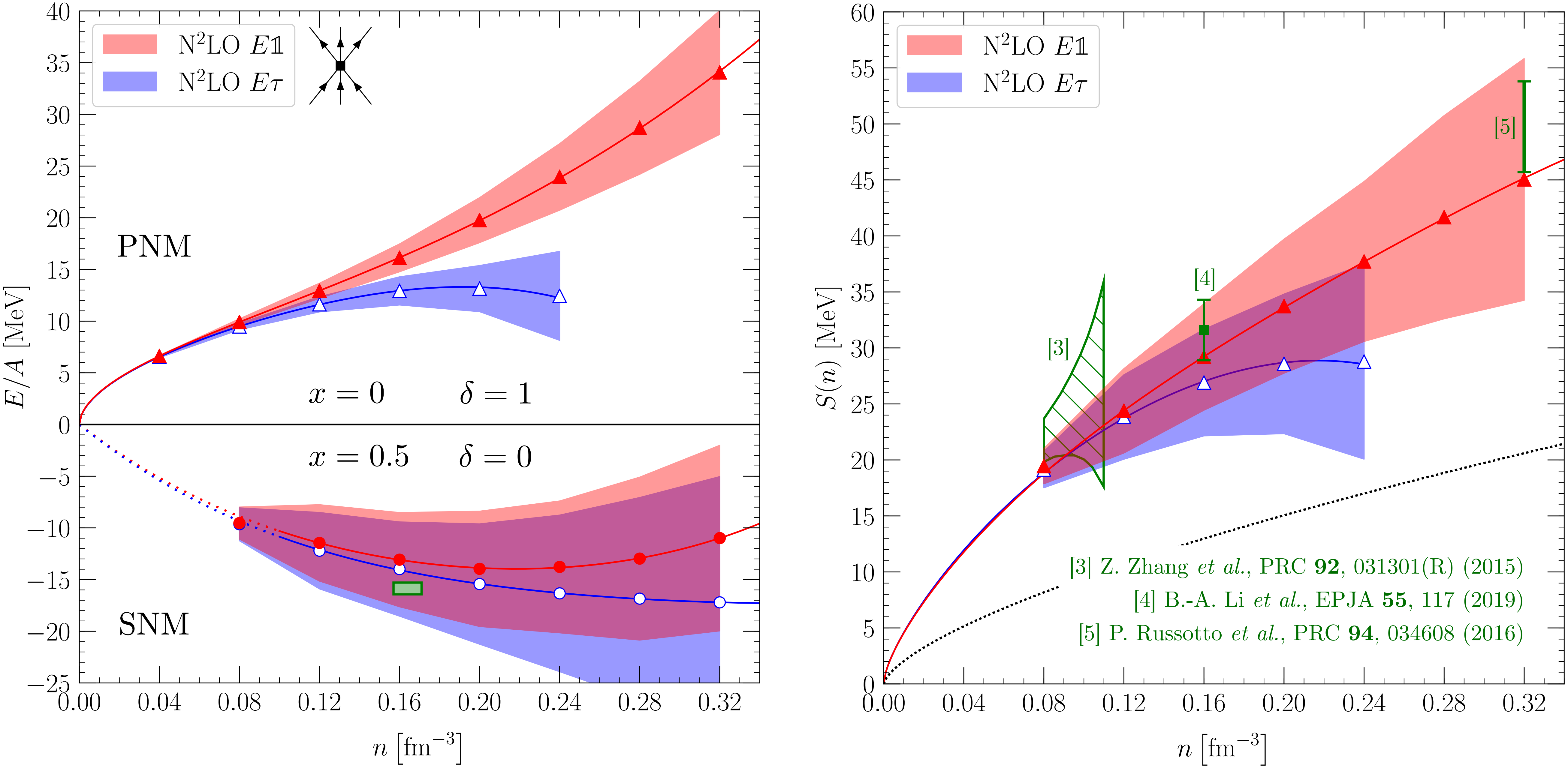
symmetry energy:

$$S(n) = E_{\rm PNM}(n) - E_{\rm SNM}(n)$$

[1] J. Margueron *et al.*, PRC **97**, 025805 (2018)
[2] N. Baillot d'Etivaux *et al.*, , ApJ **887**, 48 (2019)

Nuclear and Neutron-Star Matter

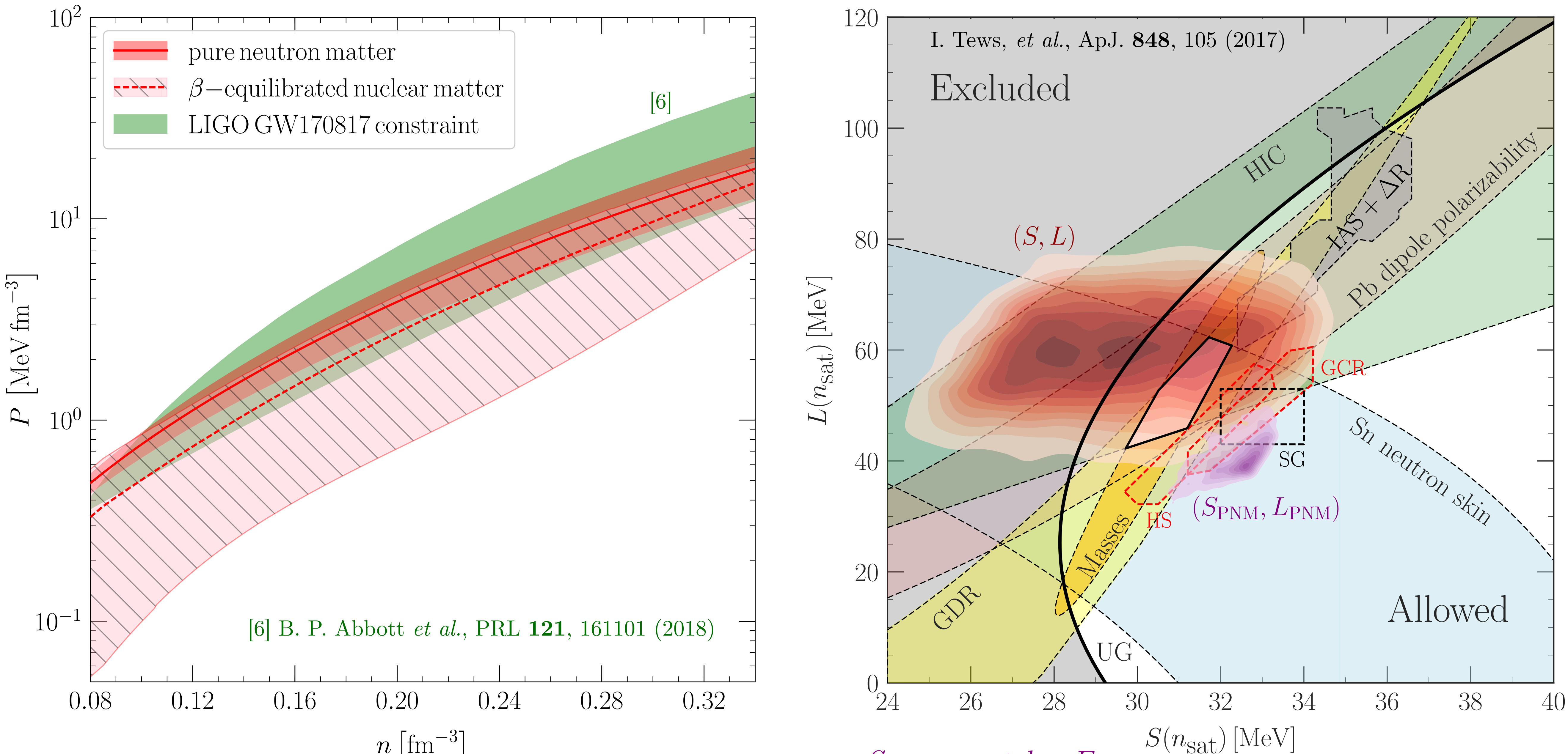
D.L. *et al.*, Phys. Rev. Research **2**, 022033(R) (2020)



Density	Obs.	N^{2}LO $E\mathbb{1}$	N^{2}LO $E\tau$	Empirical
n_{sat}	S	30(3)	27(3)	31.6(2.7) [4]
	L	59(9)	33(9)	58.9(16.0) [4]
$2n_{\text{sat}}$	S	45(5)	–	46 – 54 [5]
	L	67(44)	–	–

Nuclear and Neutron-Star Matter

D.L. *et al.*, Phys. Rev. Research **2**, 022033(R) (2020)



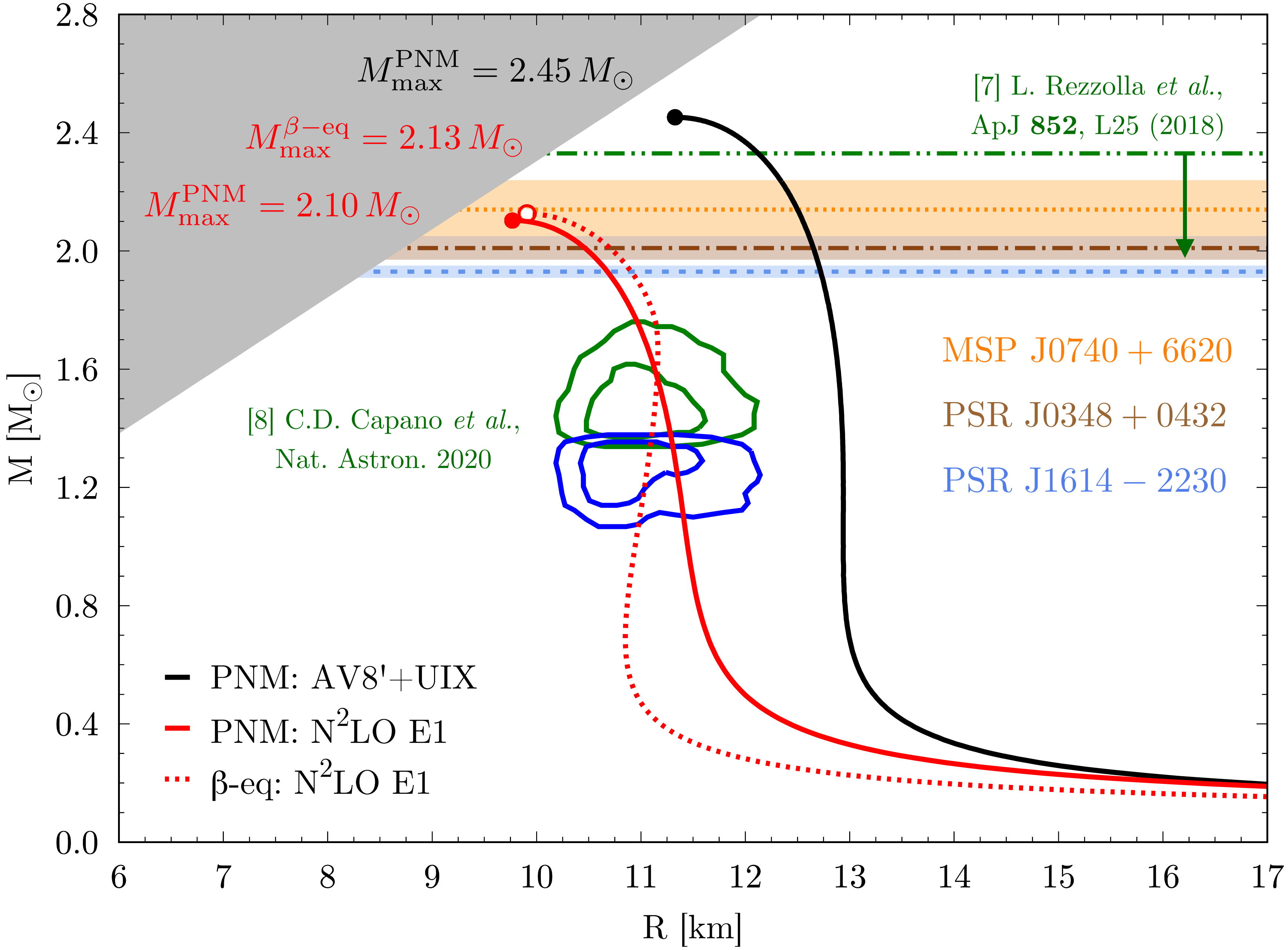
$S_{\mathrm{PNM}} = a + b - E_{\mathrm{sat}}$

$L_{\mathrm{PNM}} = 3\,(a\,\alpha + b\,\beta)$

local χEFT pot. @ N^{2}LO : fit to few-body observables $\longrightarrow$ good agreement with current constraints (both exp. and astro.)

Nuclear and Neutron-Star Matter

D.L., I. Tews: very preliminary!!



[7] combine constraints from:

- GW observations
- quasi-universal relations

$$1.97 \le M_{\max} \lesssim 2.33\, M_\odot$$

[8] combine constraints from:

- low-energy nuclear theory
- GW observations
- EM observations

$$R_{1.4\, M_\odot} = 11.0^{+0.9}_{-0.6}\,\text{km}$$

local χEFT pot. @ N^{2}LO : fit to few-body observables → good agreement with current constraints (both exp. and astro.)

Summary

- Local chiral interactions fit to few-body observables can describe ground-state properties of nuclei (at least) up to A=16 (structure and dynamics)
- The empirical saturation density and energy are reproduced within statistical and systematic uncertainties (the latter still large and dominant)
- The symmetry energy as a function of the density is in good agreement with available experimentally derived constraints at saturation and twice saturation density
- The pressure in β-equilibrated matter is in agreement with constraints extracted from gravitational waves of the neutron-star merger GW170817 by the LIGO-Virgo detection
- The neutron-star mass-radius relation is consistent with multi-source constraints

↓ future

- Application of QMC techniques to study neutron-rich light and medium-mass nuclei: ab-initio study of nuclei-matter correlations (nucleon skin, symmetry energy)
- Development of coordinate-space local chiral potentials with large cutoffs: reduction/ removal of regulator artifacts in nuclei and matter calculations
- Study of asymmetric nuclear matter and derivation of neutron star properties

Thank you!!