Neutron-Rich Systems:
Current Status of Ab Initio Predictions vs. Empirical Constraints

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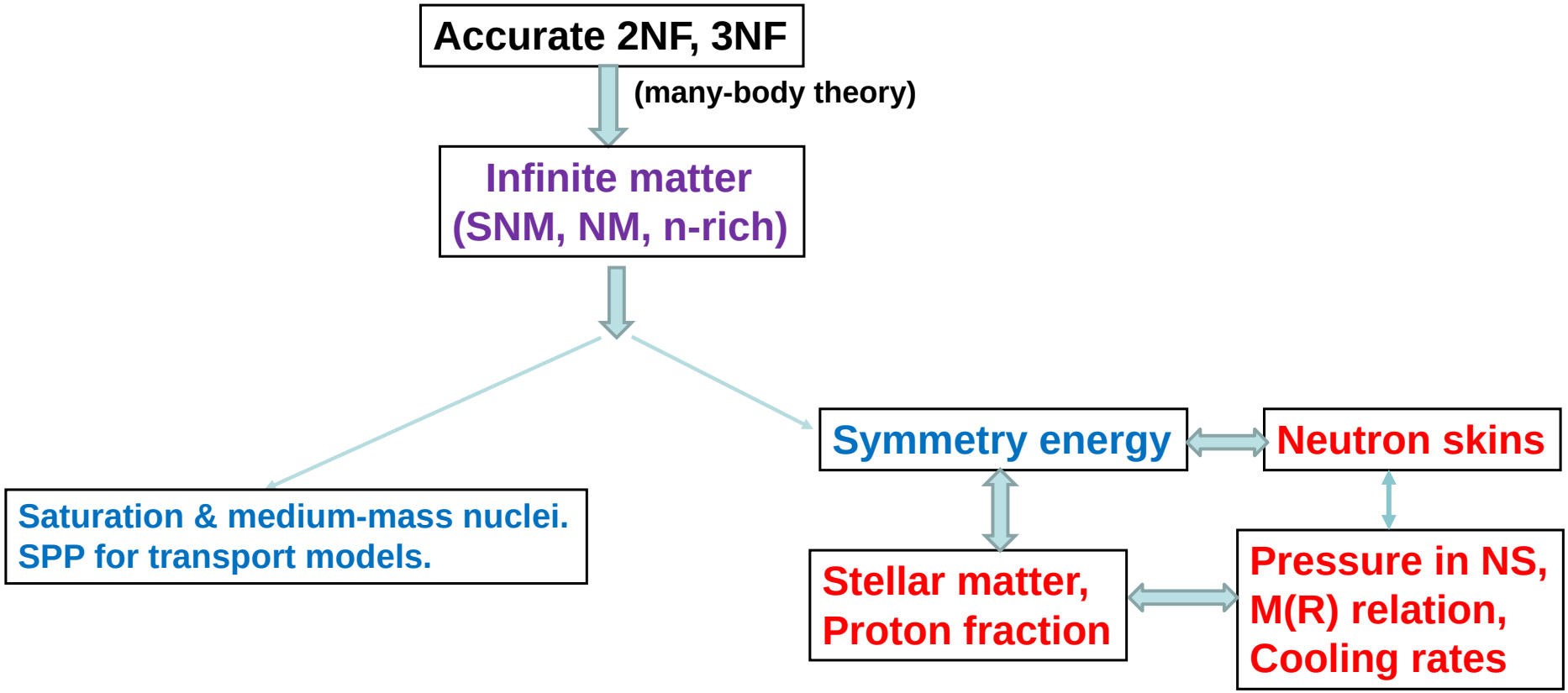
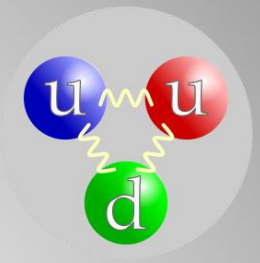
Dedicated to Rup, with everlasting love

Outline

- The "multiple personalities" of neutron matter (NM): From a nearly unitary system at low density to the main input for calculations of neutron stars (NS).
- Brief review of theoretical ingredients & our recent results for the symmetry energy, its density dependence, and related systems.
- **Neutron skins:** What can we learn from the recent measurement of the neutron skin in ^{48}Ca (CREX)?
- Conclusions and future prospects: Where do we go from here?..


Accurate 2NF, 3NF
(many-body theory)
Infinite matter
(SNM, NM, n-rich)
Saturation & medium-mass nuclei.
SPP for transport models.
Symmetry energy
Neutron skins
Stellar matter,
Proton fraction
Pressure in NS,
M(R) relation,
Cooling rates

Our (still incomplete) knowledge of the nuclear force is the result of decades of struggle.



Current understanding:
Scale determines the appropriate degrees of freedom.
This concept is central to the development of an Effective Field Theory.

We use:

2NF: high-quality NN chiral potentials at N^2LO and N^3LO (Entem, Machleidt, and Nosyk, 2017)

+

All leading (subleading) 3NF at the given order

These free-space interactions ⇒ nonperturbative particle-particle ladder with self-consistent single-particle spectrum

F.S. & Randy Millerson, PRC**104**, 034308
F.S. & Randy Millerson, PRC**104**, 064312

Our most recent predictions:

$e_{sym}(\rho_0)$ = 31.3 +/- 0.8 MeV

L = 50 +/- 8.0 MeV (a measure of the density dependence of the symmetry energy at saturation)

L is strongly correlated with the thickness of the neutron skin, measurable in terrestrial experiments.

Our prediction for ^{208}Pb:

S = (1.3 – 1.7) fm

$R_{1.4}$ = 11.96 +/- 0.80 km

From a Bayesian analysis of 300,000 EoS constrained by microscopic nuclear theory and nuclear experiments [Lin & Holt, EPJ **55**, 209 (2019)], the radius of a 1.4-solar masses is reported as:

$R_{1.4} = (11.36 - 12.48)$ km 1σ confidence level

$R_{1.4} = (10.26 - 12.87)$ km 2σ confidence level

On the larger side of these values:

...This result challenges our present understanding of the density dependence of the symmetry energy extracted from various experimental and theoretical analyses....

(Reed,Fattoyev, Horowitz, Piekarewicz, PRL126, 172503 (2021))

$J = 38.09 \pm 4.73\ MeV$

S = 0.283 ± 0.071 fm

L = 106 ±37 *MeV*

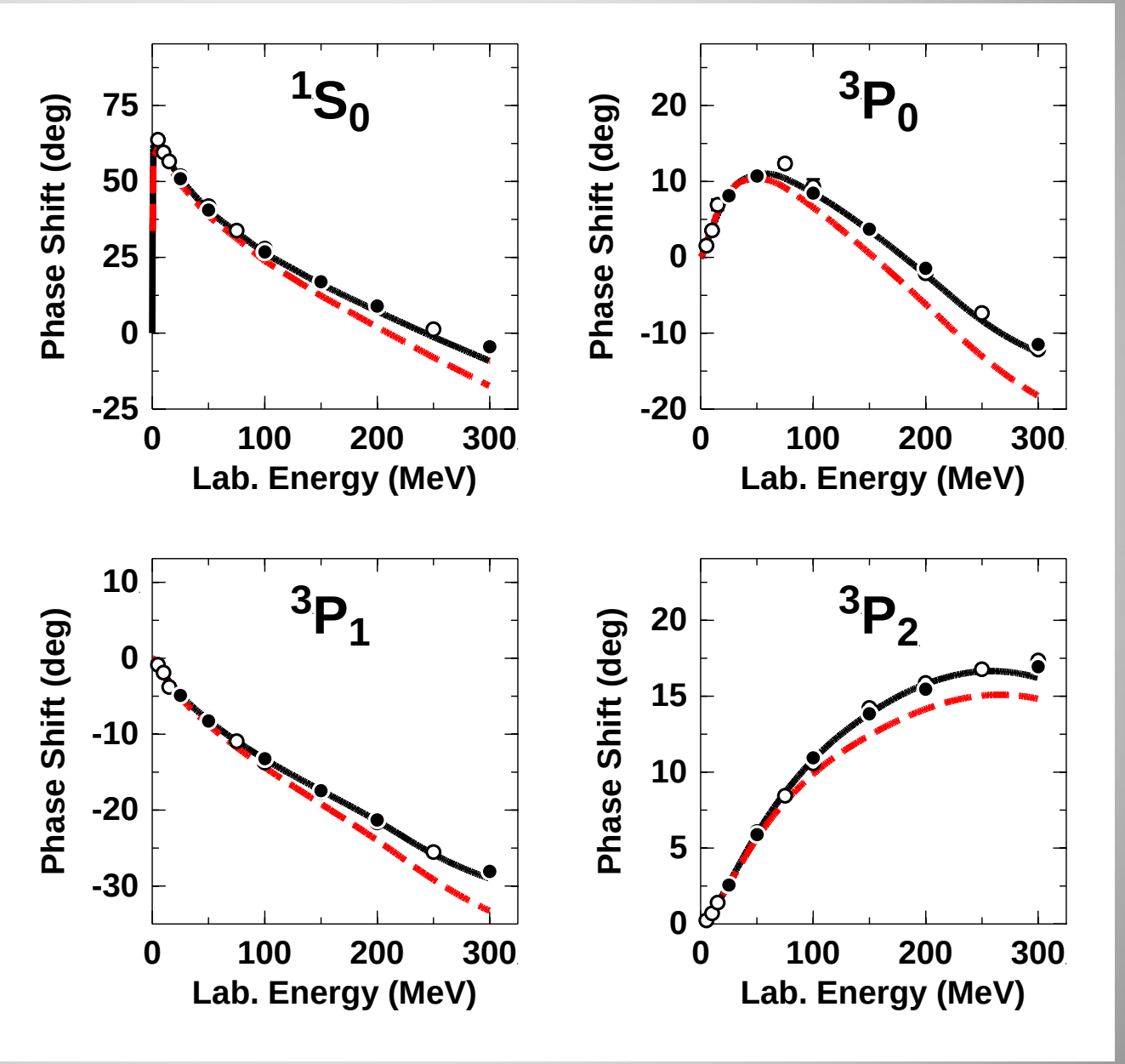
$R_{1.4}$ = (13.33 – 14.26) km

$J = e_{sym}(\rho_0)$

IMPACT OF THE ISOVECTOR PART OF THE FREE-SPACE NN FORCE:

Black: N3LO(450)

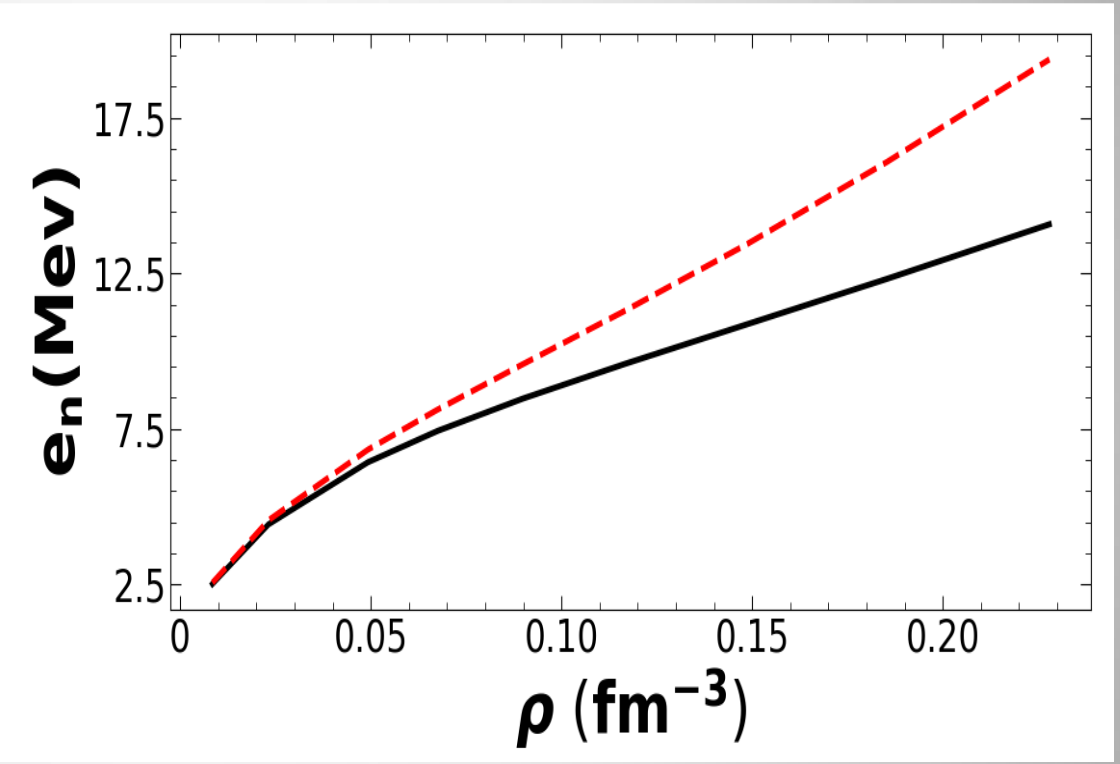
Red: N3LO(450) with intended deterioration of the fit in selected phase shifts.



Impact on the energy/neutron in NM from relaxing the constraint of accurate I=1 S and P waves:

Black: N3LO(450)

Red: "Modified" N3LO(450)



Evaluated at normal density

observable	N3LO(450)	Modified N3LO(450)
Energy/neutron (MeV)	11.11	13.88
Slope of the NM EoS (Mev/fm^{-3})	39.79	70.03
Pressure in NM (MeV/fm^{3})	0.956	1.68

NEWS from HALL A, JLab

Parity-violating experiment with ^{48}Ca is completed*

Extracted value of the neutron skin:

S = 0.121 +/- 0.026 +/- 0.024 fm

This would not be expected based on the PREX-II result

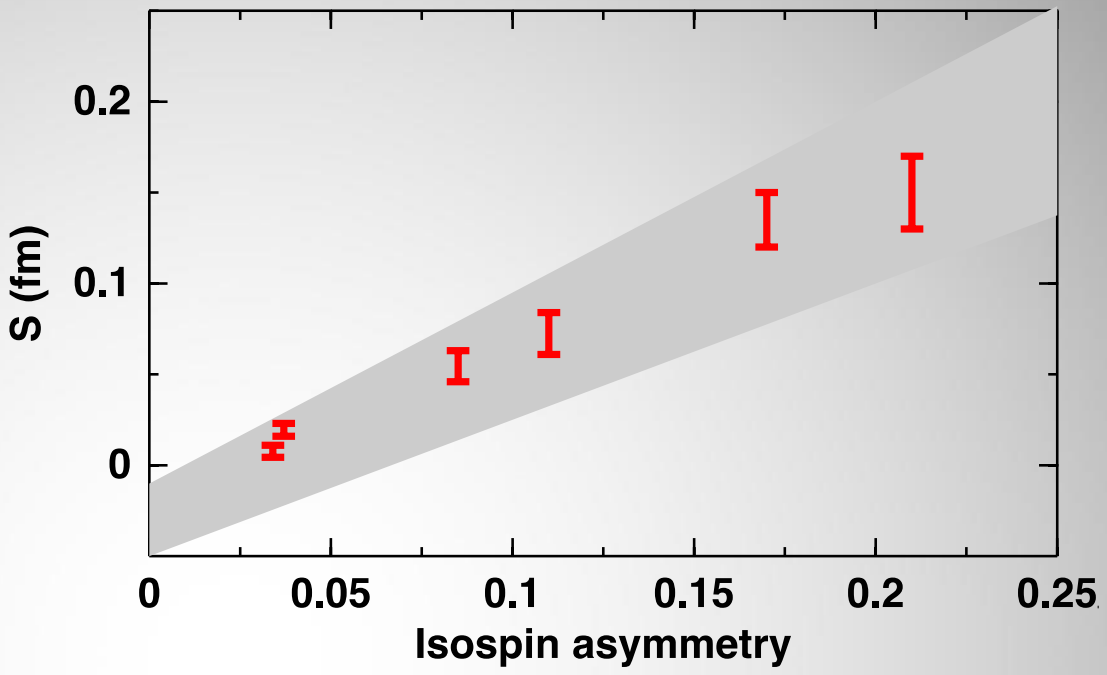
"…..the contrast between the two measurements is a bit surprising and provides a challenge to the theoretical description of nuclei."

K.D. Paschke

***CREX Collaboration, Hall A Jefferson Lab**
arXiv:2205.11593 [nucl-ex], PRL129, 042501 (2022)

Our findings for ^{208}Pb and ^{48}Ca are both on the smaller side):

S(^{48}Ca) = 0.12 – 0.15 fm
S(^{208}Pb) = 0.13 – 0.17 fm



Red bars: Neutron skin of ^{58}Ni, ^{27}Al, ^{59}Co, ^{90}Zr, ^{48}Ca, and ^{208}Pb [*]. The shaded area is bounded by linear fits to the data (Swiatecki *et al.)*

[*] F.S. PRC105, 064303 (2022)

Status of "microscopic" predictions

^{208}Pb

^{48}Ca

Hagen *et al*. Nat. Phys. 12, 186 (2016)

"…We show that the neutron skin …
is significantly smaller than previously thought…"

S = 0.12 – 0.15 fm
(with N^2LO_{sat})

Hu *et al*. Nat. Phys. 18, 1196 (2021)

S = 0.14 – 0.20 fm

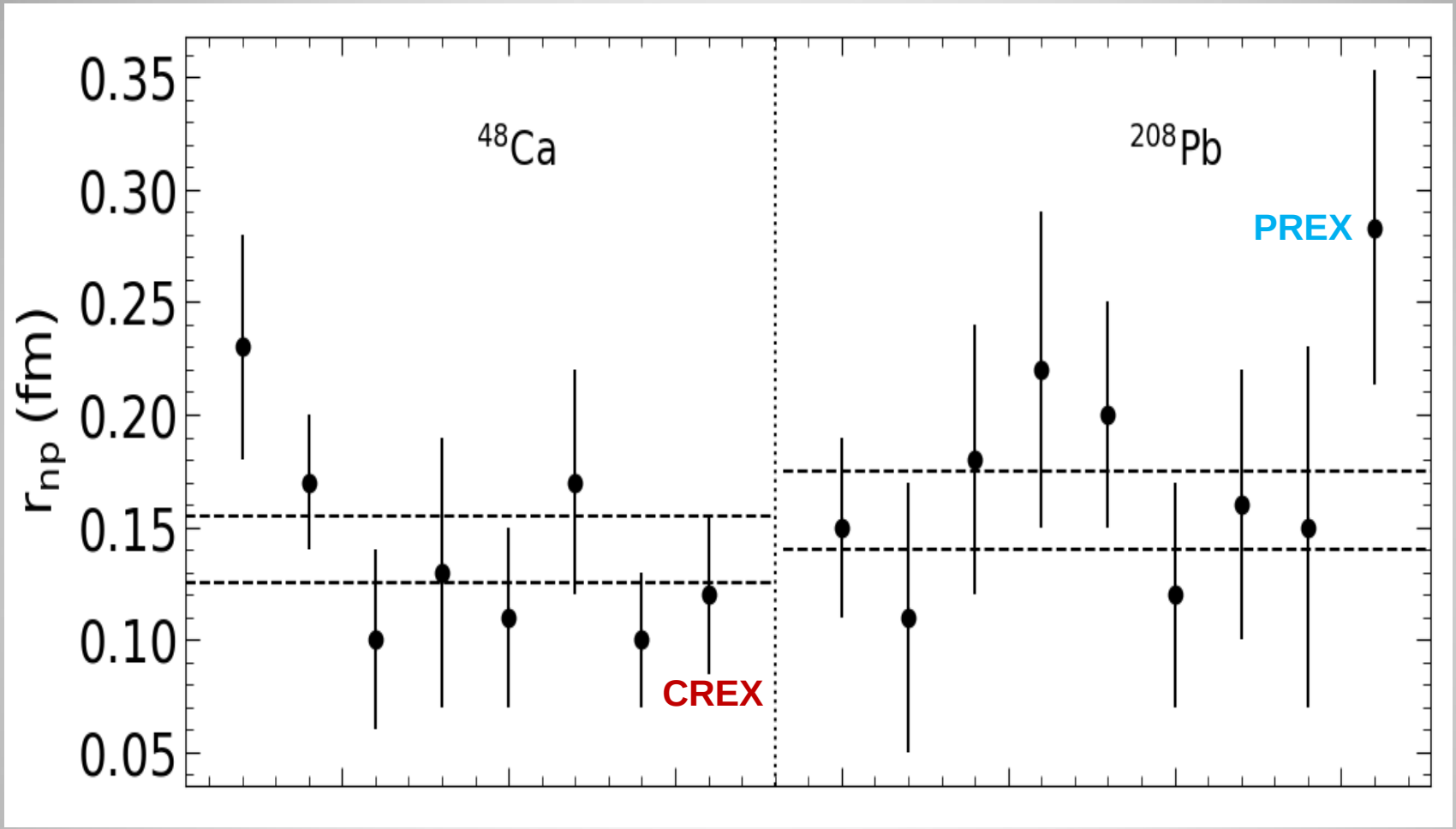
Novario *et al*. PRL 130, 032501 (2023)

S = 0.184 – 0.236 fm
(using linear regression obtained from lighter nuclei, S = 0.210 +/- 0.026)

Novario *et al*. PRL 130, 032501 (2023)

S = 0.114 – 0.186 fm
(with ΔN^2LO_{GO})

An overview of experimental constraints (J.M. Lattimer, *Particles* **2023**, *6*, 30) **



Sources: [70] – [76], [18] of [**]

Methods: elastic (polarized or not) p scattering, pionic atoms, pion scattering, α scattering

Sources: [70] – [73], [77]– [81], [17] of [**]

Methods: elastic (polarized or not) p scattering, pionic atoms, pion scattering, anti-p annihilation, coherent $\pi^0\gamma$ production

- **CREX and PREX-II outcomes are not consistent with each other. Developing more RMF models for the purpose of imposing a reconciliation of the two results is not the right path.** See, for instance, Kumar et al., "CREX- and PREX-II-motivated relativistic interactions and their implications ...." PRC107, 055801 (2023).

We anxiously await to hear from MREX (Mainz Radius Experiment) at the MESA accelerator!

The Mainz Radius EXperiment (MREX) will determine "...*the neutron-skin thickness of ^{208}Pb with ultimate precision*." arXiv:1802.04759 [nucl-ex]

PREX-I, PREX-II, CREX, MREX, ?REX...

What are the prospects of reaching a consensus based on reproducible evidence?

NS cooling data have the potential to provide robust constraints:

Symmetry Energy -> proton fraction -> direct Urca → NS cooling

When the proton fraction is about 1/9 (approximate threshold for direct Urca), the following relation can be derived:

$$e_{sym}(\rho_{dU}) = \hbar c\left(\frac{9}{28}\right)(\pi^2/3)^{1/3}\,(\rho_{dU})^{1/3}$$

Say, $\rho_{dU} = 1.5\,\rho_0$
$e_{sym}(\rho_0) = 38.1$ MeV

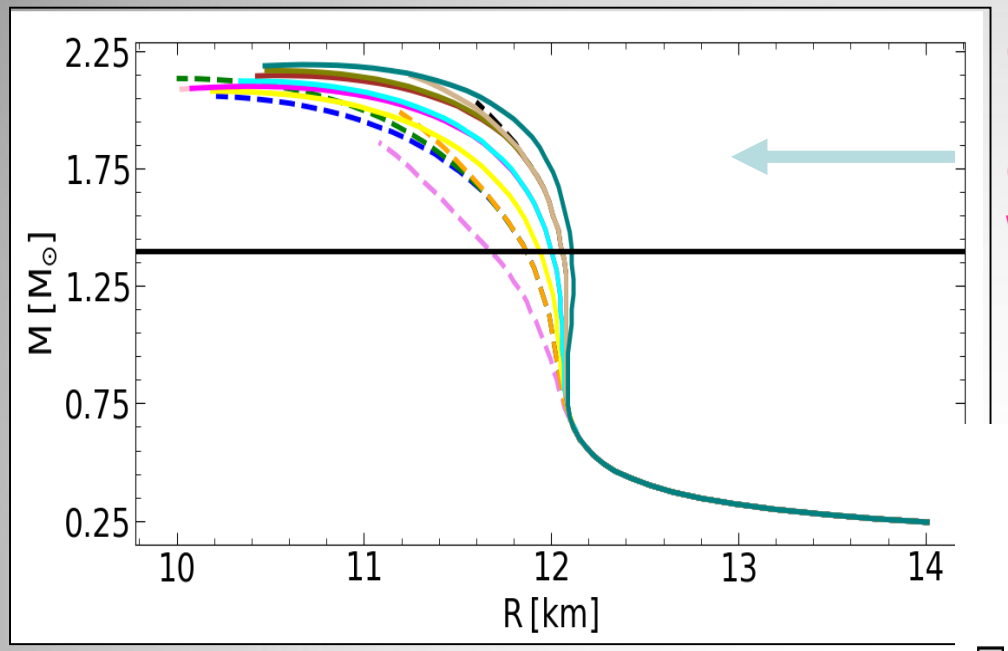
$e_{sym}(\rho_{dU}) = 58.6$ MeV

As suggested by PREX-II

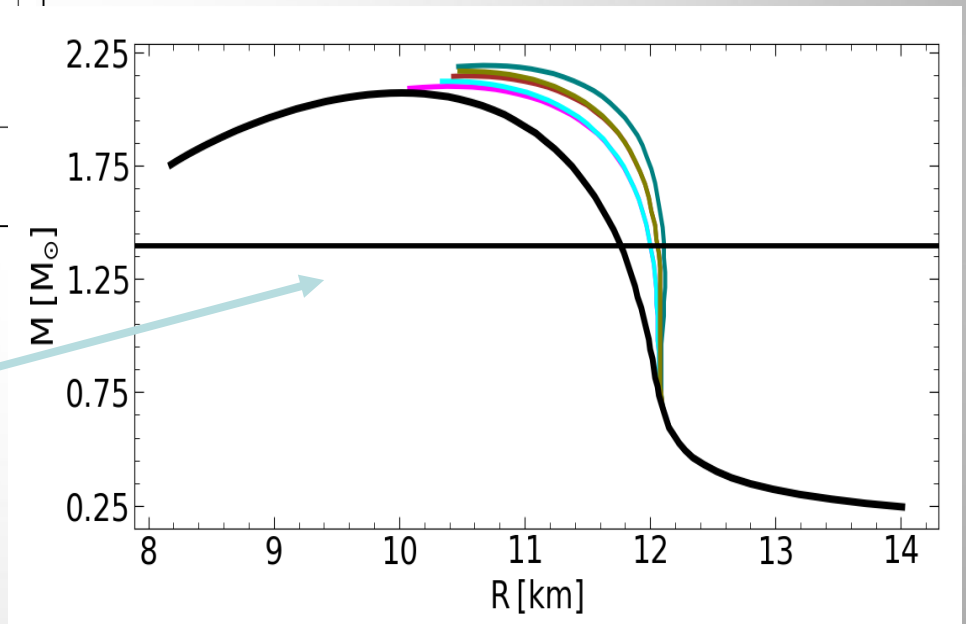
Evidence for such steep slope/rapid NS cooling?

Switching to a system larger than the neutron skin by 20 orders of magnitude….

Extension of the EoS to high densities and M(R) relations:



Continuation of the EoS.
Each of the colored curves is a combination of two polytropes with different adiabatic index.



Black: single parametrization in terms of the speed of sound.
Colored: some of the "best" polytropic combinations with respect to causality and max. mass constraints.

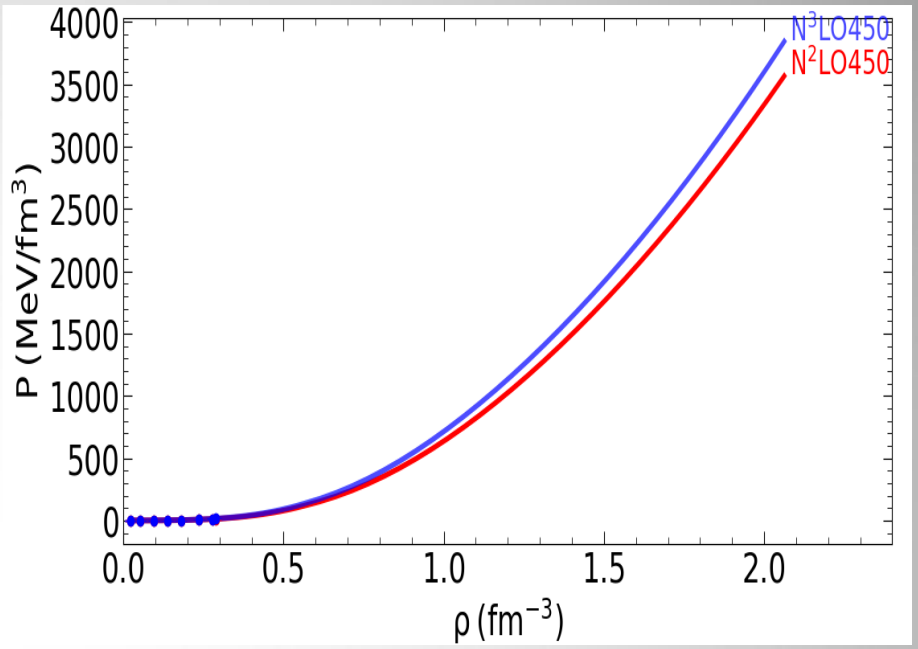
We find it best to join

Theory + relatively steep polytrope +

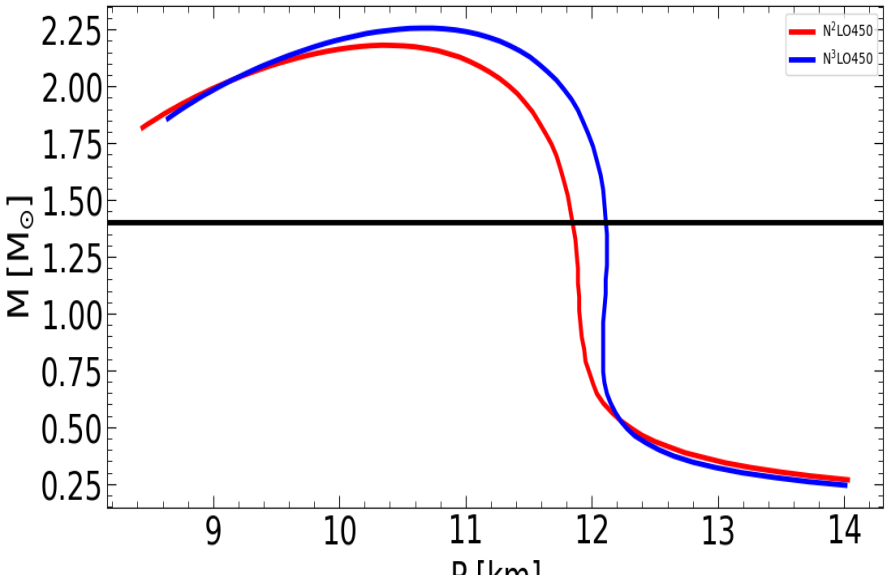
causality preserving piece

Pressure in beta-stable matter

PSR J0952-06
M = (2.35 +/- 0.17) M_{sun}
Romani et al. arXiv: 2207.05124



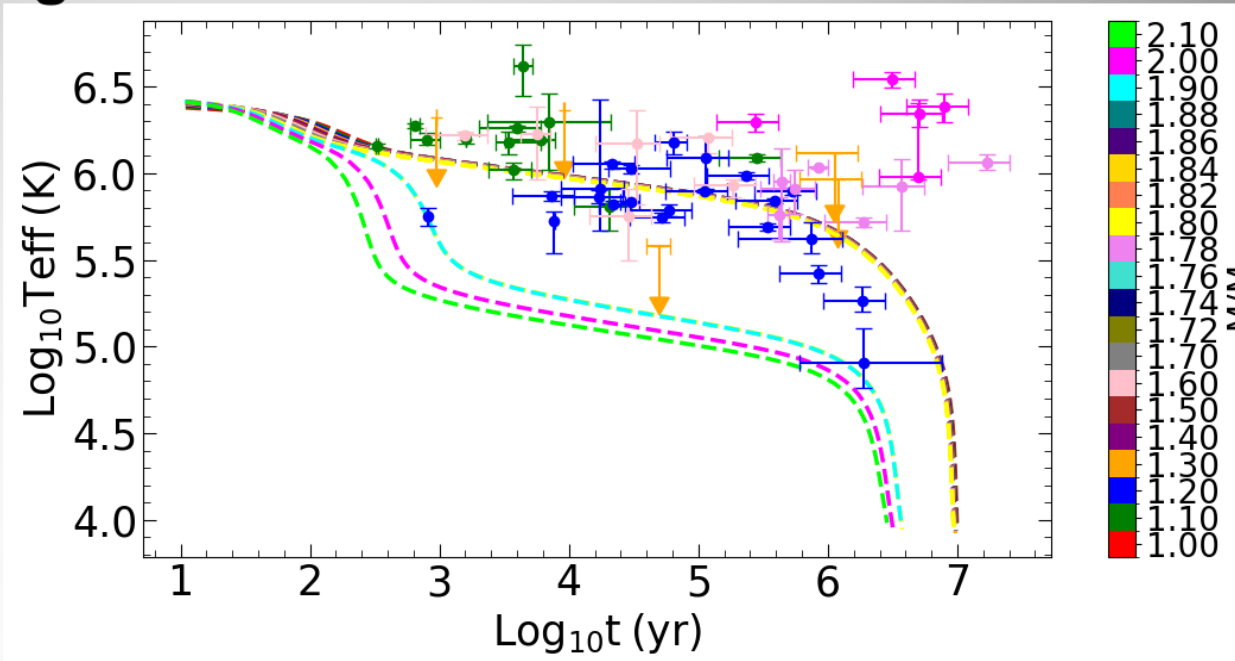
M_{max} = 2.18 solar masses
M_{max} = 2.26 solar masses

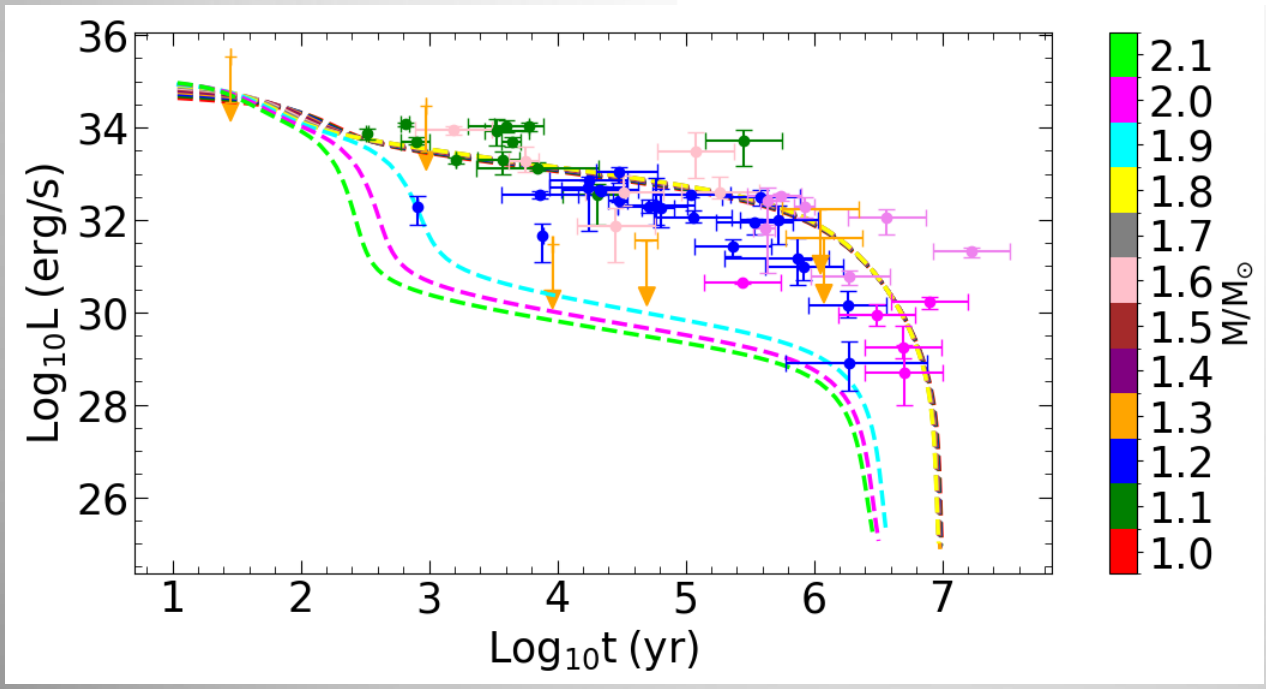


M(R) relation obtained with: Micro. EoS + polytrope (adiabatic index = 3.3) + causality preserving softer piece.

In progress: NS cooling

Data from:
Potekhin et al. (2020)





Next:

- **NM from low to high density: unique opportunities to test neutron forces.**

- **The density dependence of the symmetry energy continues to be debated. Results from the MREX experiment will be helpful.**

From the nuclear force standpoint:

- **Convergence at N3LO needs to be on robust ground.**

- **All chiral 3NFs at N^4LO should be calculated.**

- **3NF at N^4LO: additional non-locality, softness –> possibly the opportunity to solve one or more outstanding problems.**

WFM method, so far applied to lattice Monte Carlo simulations (S. Elhatisari et al. *Nature* 630, 59 (2024)

Chiral orders: unresolved issues

Problem with the regularized 3NF at N3LO (and higher orders) in all present nuclear structure calculations.

The N3LO 3NFs currently in use are regularized by a multiplicative regulator applied to the 3NF derived from dimensional regularization.

This approach leads to violation of chiral symmetry at N3LO and destroys the consistency between two- and three-nucleon forces.

Krebs and Epelbaum (2023) have pointed to a possible way to proceed.

Thank you