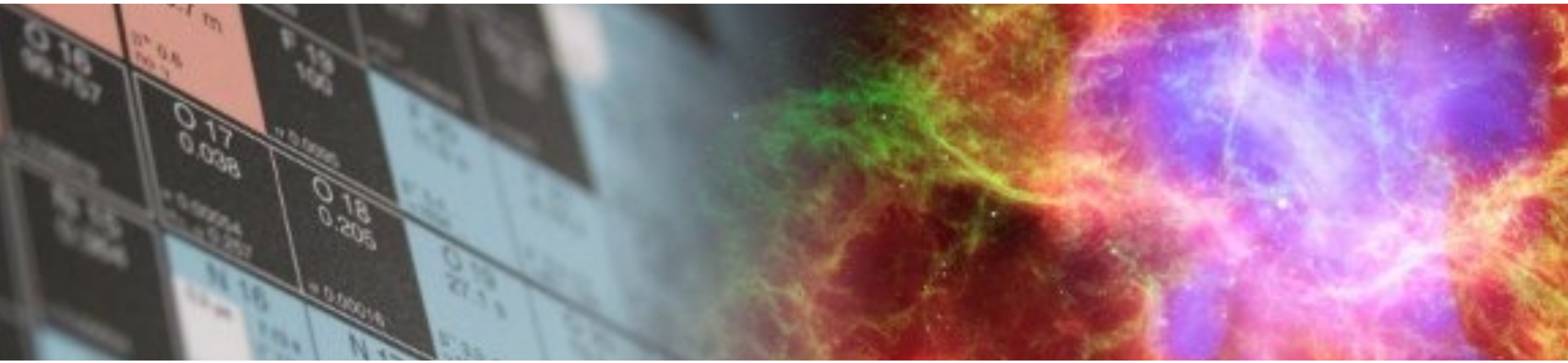
Dense matter from nuclear theory, experiments, and observations

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG



GSI-FAIR Colloquium, Dec. 16, 2025

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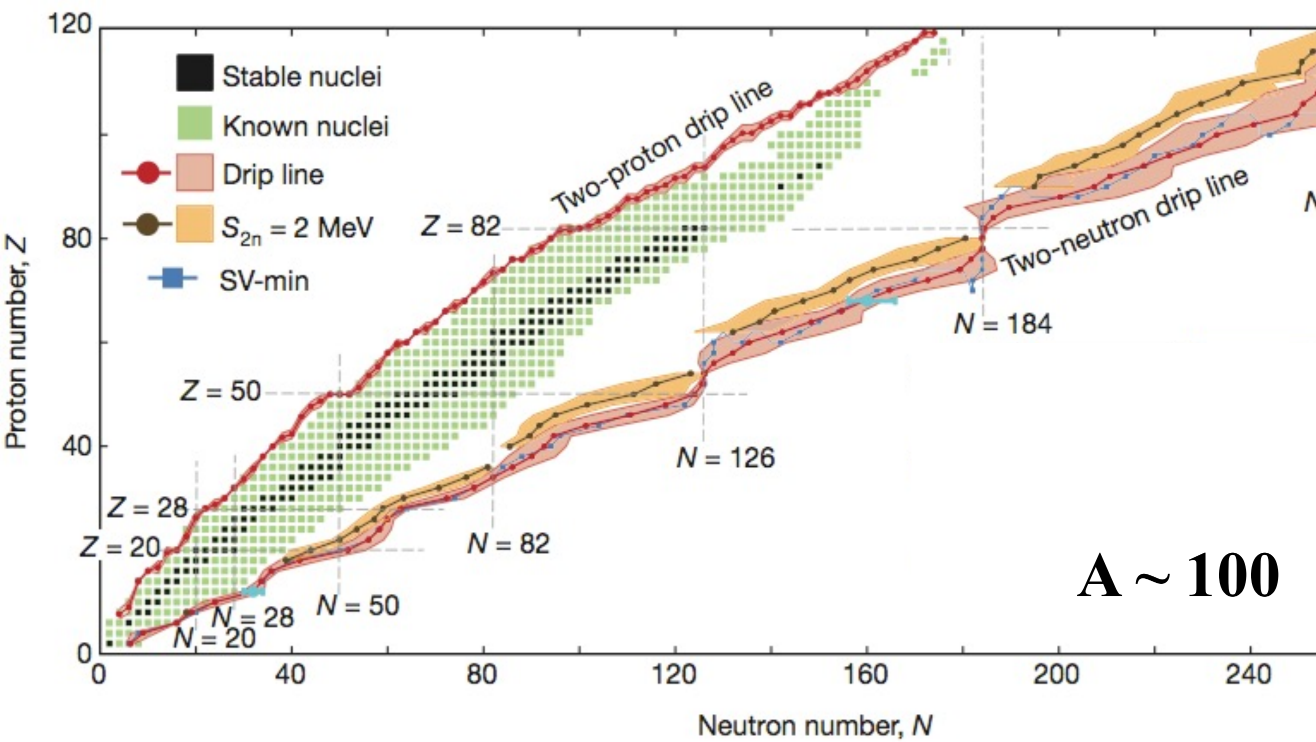
Structure of nuclei and dense matter in neutron stars

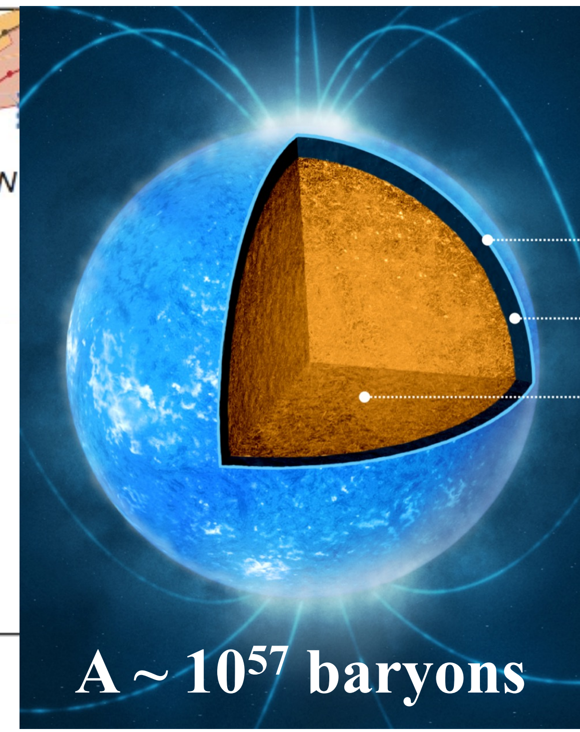
doi:10.1038/nature11188

The limits of the nuclear landscape

Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡

~ 4000±500 nuclei unknown, extreme neutron-rich





Extreme neutron-rich matter in neutron stars

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The limits of the nuclear landscape

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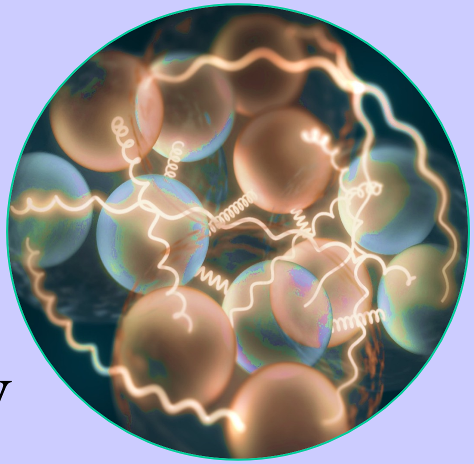
~ 4000±500 nuclei unknown, extreme neutron-rich

rich physics with nucleons
as degrees of freedom

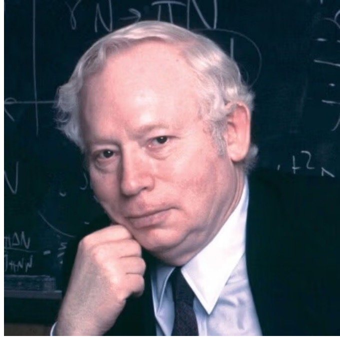
microphysics of nuclei
macrophysics of neutron stars

typical momenta Q ~ 200 MeV
~ **pion** mass m_π

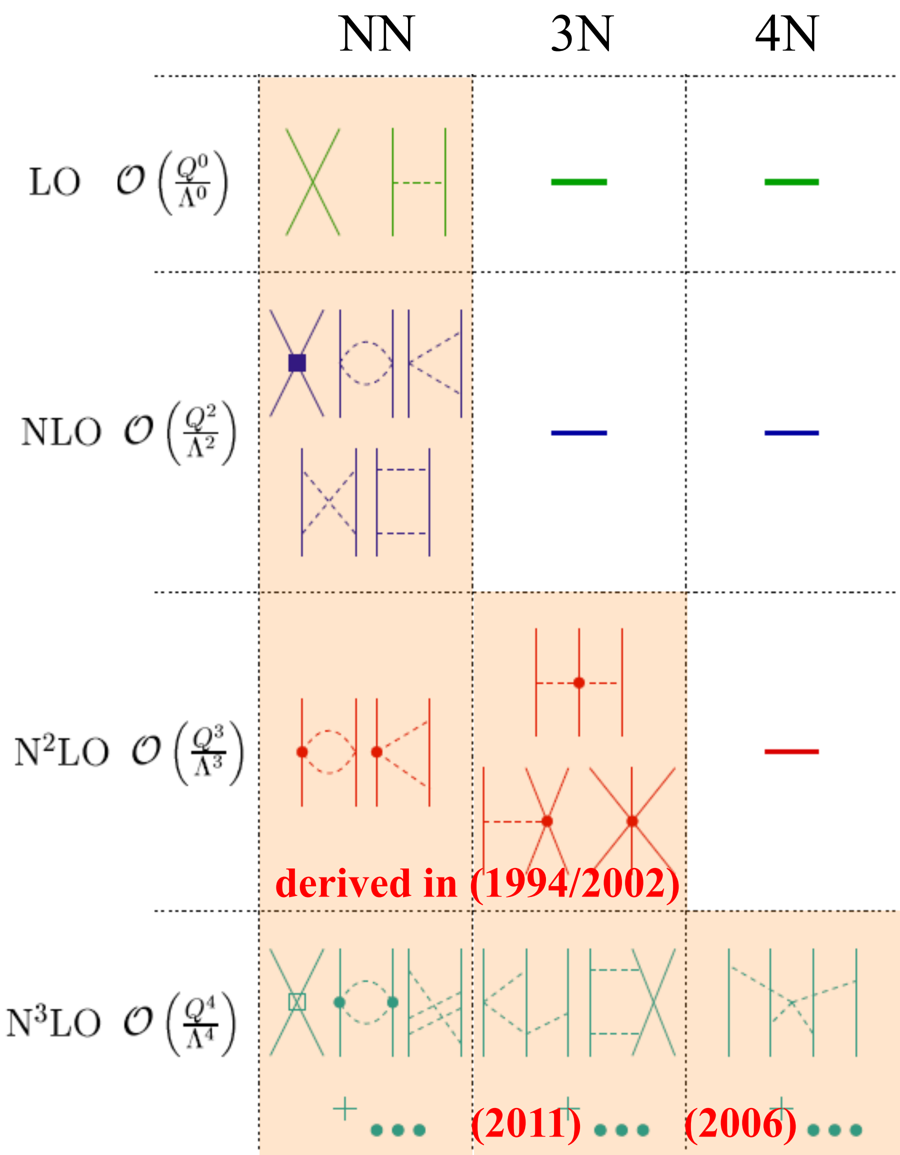


Extreme neutron-rich matter in neutron stars

Chiral effective field theory for nuclear forces



Systematic expansion in low momenta $(Q/\Lambda_b)^n$



based on symmetries of strong interaction (QCD)

long-range interactions governed by pion exchanges

powerful approach for many-body interactions

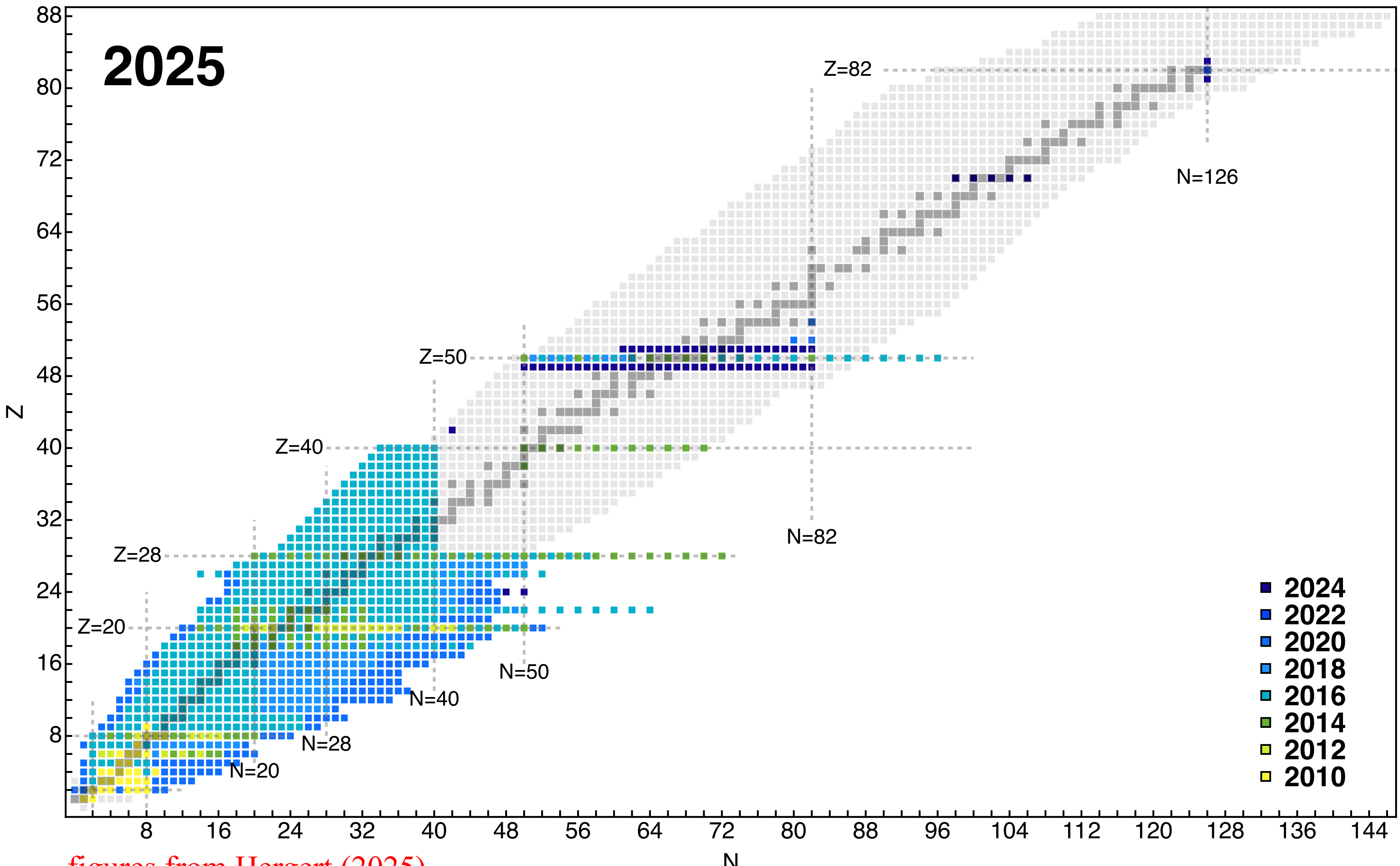
all 3- and 4-neutron forces predicted to N^3LO

Tews et al., PRL (2013)

Weinberg (1990,91), van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Meißner,…

Great progress in ab initio calculations of nuclei

systematic interaction expansion + systematic many-body expansion

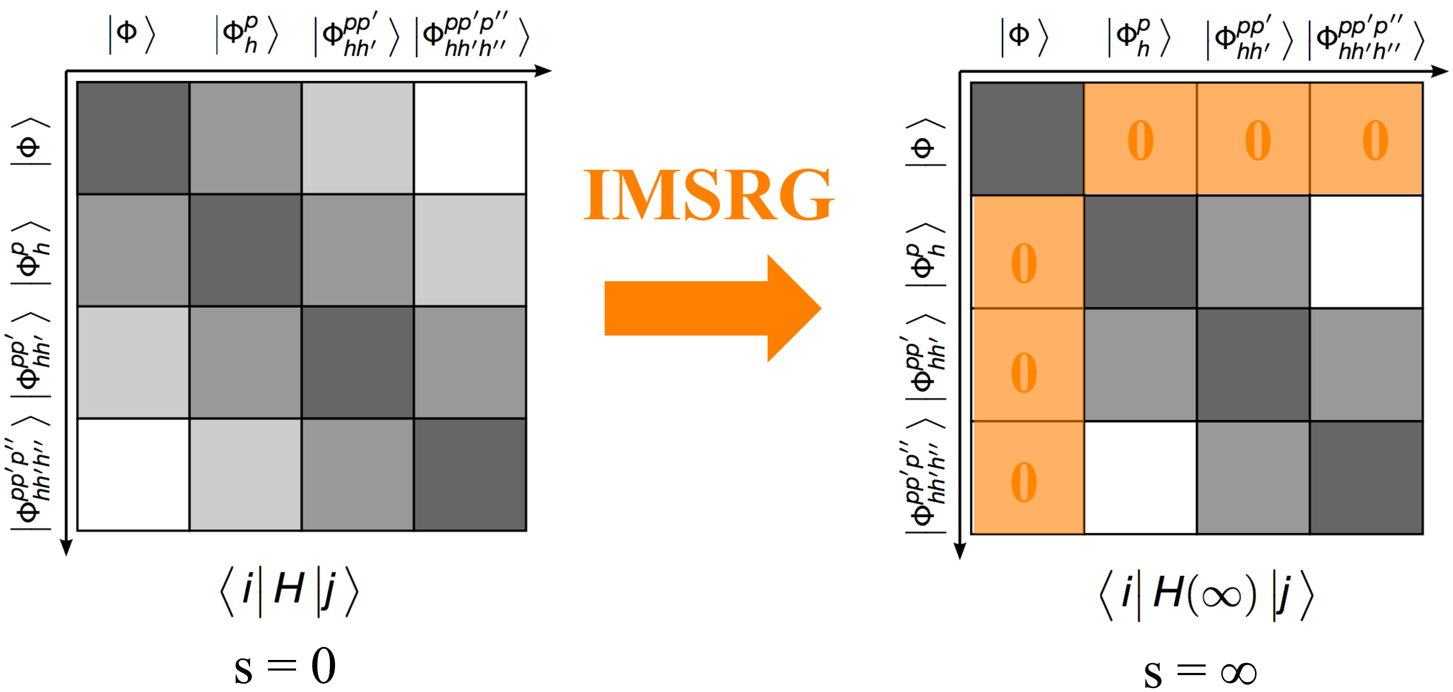


figures from Hergert (2025)

In-medium similarity renormalization group (IMSRG)

Tsukiyama, Bogner, AS, PRL (2011), Hergert et al., Phys. Rep. (2016), Stroberg et al., PRL (2017)

flow equations to decouple higher-lying particle-hole states ($s = 0 \rightarrow \infty$)



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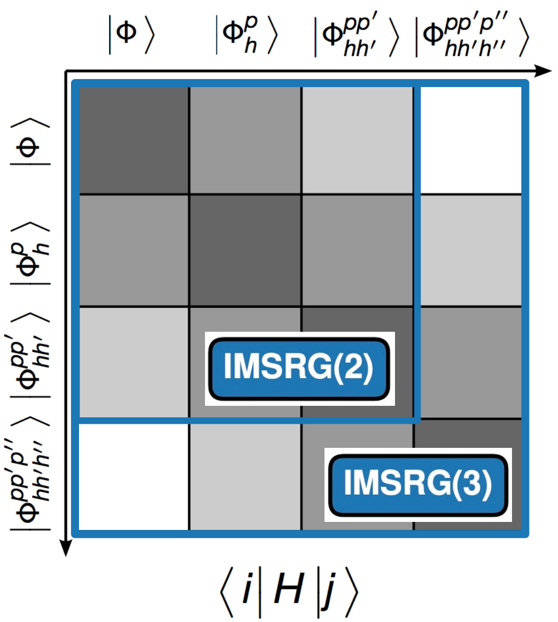
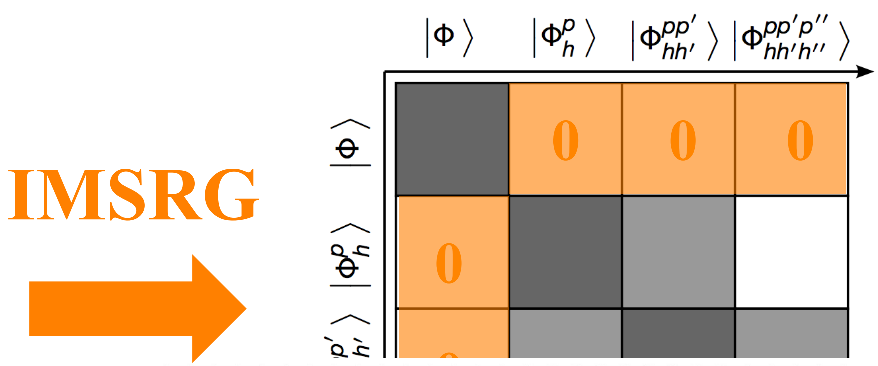
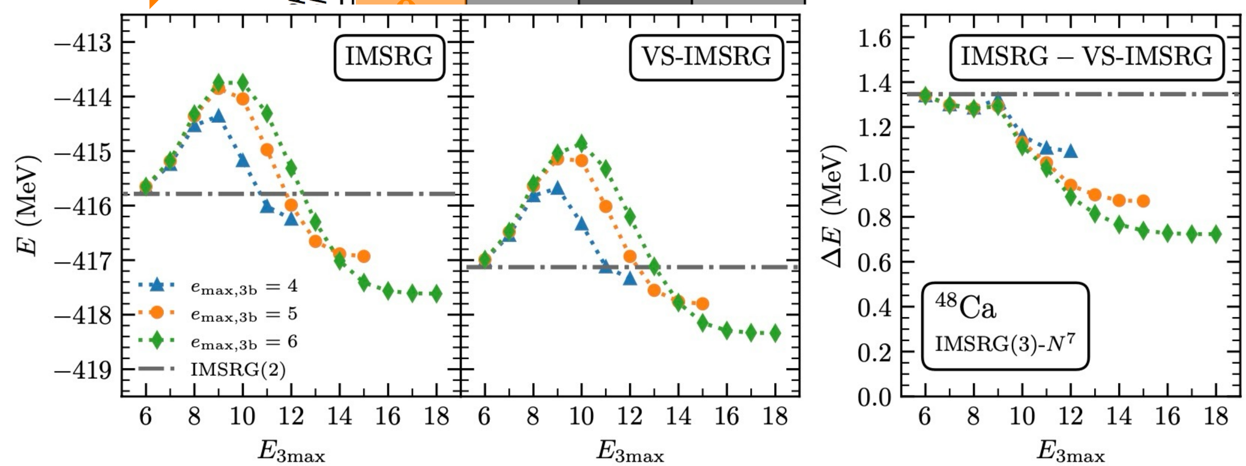




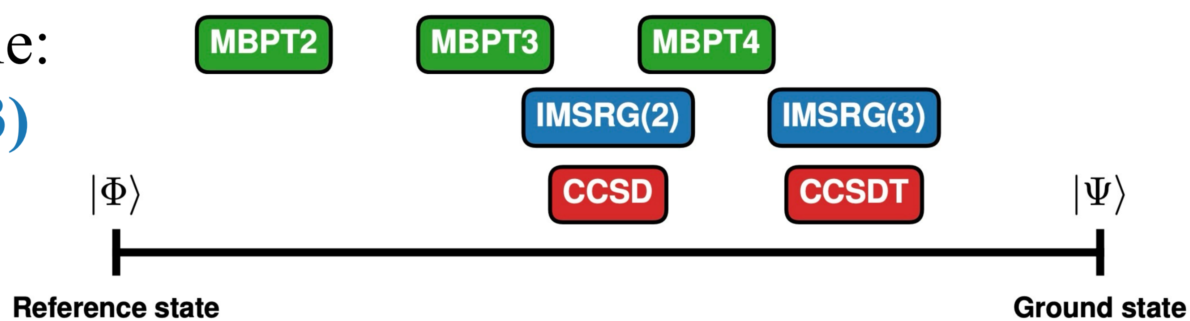


Systematically improvable:

IMSRG(2) → IMSRG(3)

Heinz et al., PRC (2021), (2025)

He, Stroberg, PRC (2024)



Great progress in ab initio calculations of nuclei

ARTICLES
https://doi.org/10.1038/s41567-022-01715-8

nature physics

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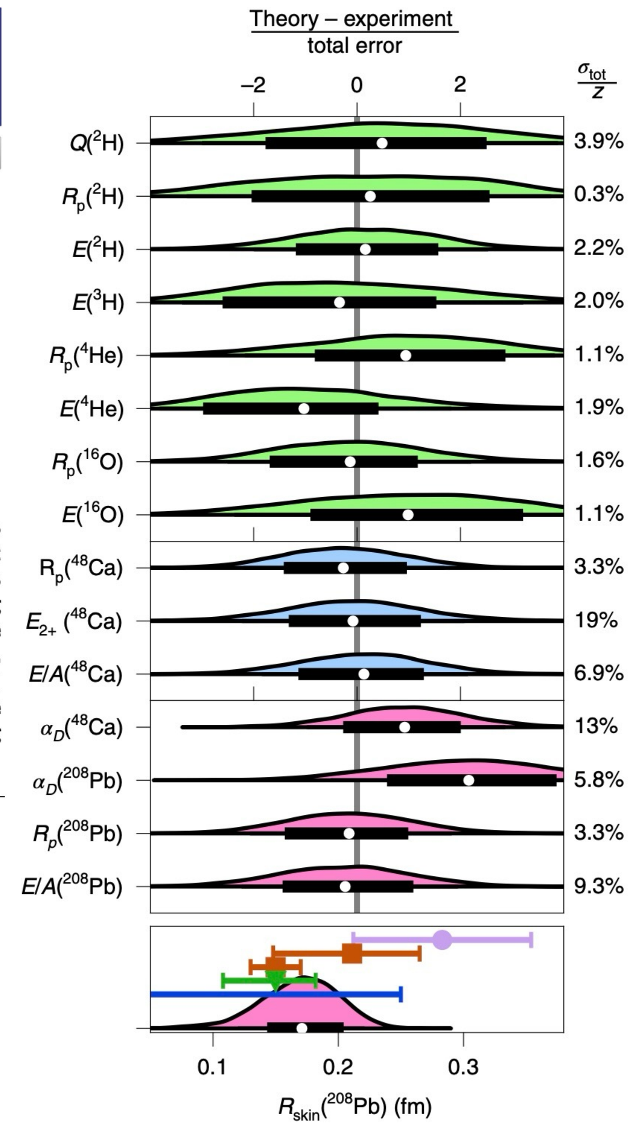
OPEN

Ab initio predictions link the neutron skin of ^{208}Pb to nuclear forces

Baishan Hu[1,11], Weiguang Jiang[2,11], Takayuki Miyagi[1,3,4,11], Zhonghao Sun[5,6,11], Andreas Ekström[2], Christian Forssén[2]✉, Gaute Hagen[1,5,6], Jason D. Holt[1,7], Thomas Papenbrock[5,6], S. Ragnar Stroberg[8,9] and Ian Vernon[10]

Heavy atomic nuclei have an excess of neutrons over protons, which leads to the formation of a neutron skin whose thickness is sensitive to details of the nuclear force. This links atomic nuclei to properties of neutron stars, thereby relating objects that differ in size by orders of magnitude. The nucleus ^{208}Pb is of particular interest because it exhibits a simple structure and is experimentally accessible. However, computing such a heavy nucleus has been out of reach for ab initio theory. By combining advances in quantum many-body methods, statistical tools and emulator technology, we make quantitative predictions for the properties of ^{208}Pb starting from nuclear forces that are consistent with symmetries of low-energy quantum chromodynamics. We explore 10^9 different nuclear force parameterizations via history matching, confront them with data in select light nuclei and arrive at an importance-weighted ensemble of interactions. We accurately reproduce bulk properties of ^{208}Pb and determine the neutron skin thickness, which is smaller and more precise than a recent extraction from parity-violating electron scattering



PHYSICAL REVIEW C **105**, 014302 (2022)

Converged *ab initio* calculations of heavy nuclei

T. Miyagi,[1,*] S. R. Stroberg,[2,†] P. Navrátil,[1,‡] K. Hebeler,[3,4,5,§] and J. D. Holt[1,6,∥]

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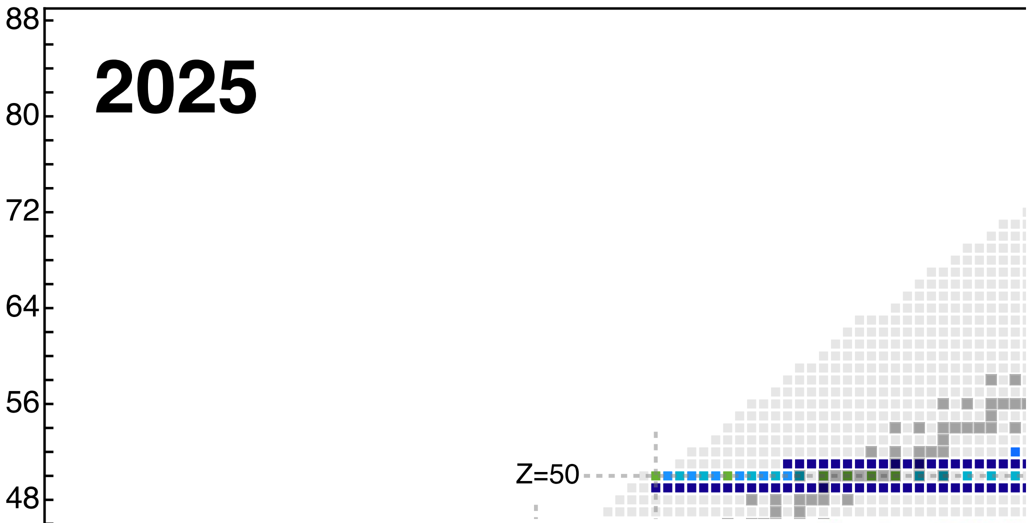
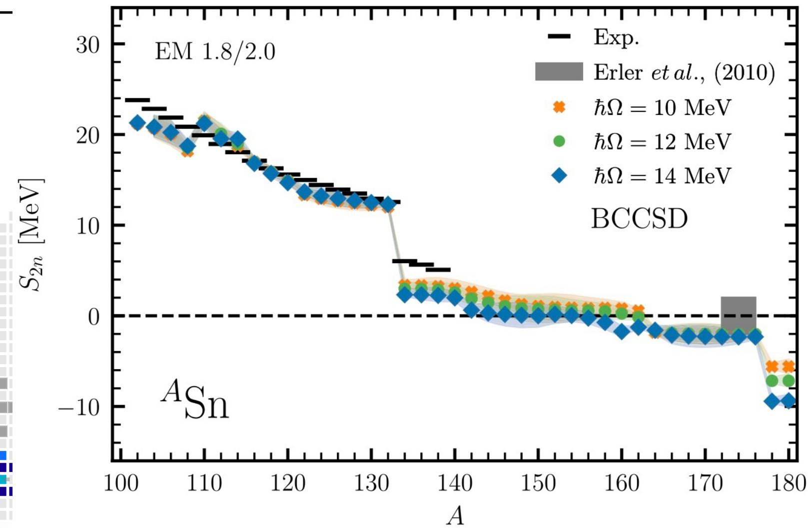
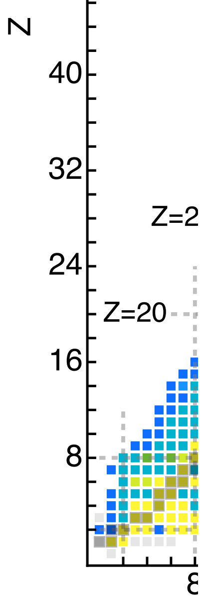
Great progress in ab initio calculations of nuclei





Phys. Lett. B 851 (2024) 138571



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Letter

Towards heavy-mass *ab initio* nuclear structure: Open-shell Ca, Ni and Sn isotopes from Bogoliubov coupled-cluster theory

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[e] *IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*

figures

Great progress in ab initio calculations of nuclei

PHYSICAL REVIEW LETTERS **132**, 232503 (2024)

Impact of Two-Body Currents on Magnetic Dipole Moments of Nuclei

T. Miyagi,[1,2,3,*,‡‡] X. Cao,[4,†] R. Seutin,[3,1,2,‡] S. Bacca,[5,6,§] R. F. Garcia Ruiz,[7,∥] K. Hebeler,[1,2,3,¶] J. D. Holt,[8,9,**] and A. Schwenk[1,2,3,††]

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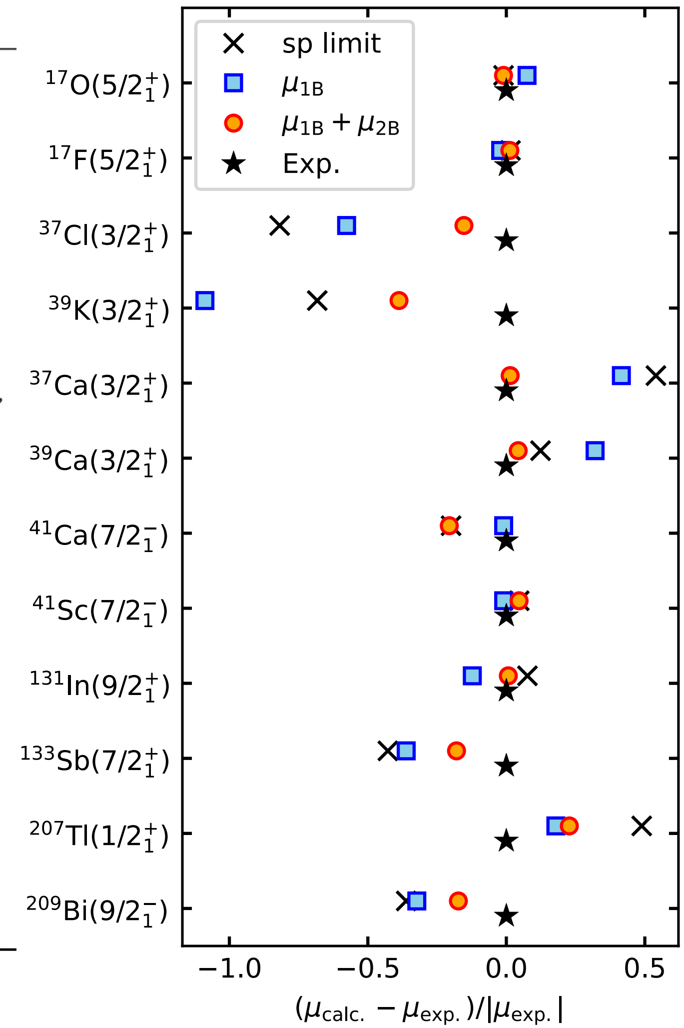
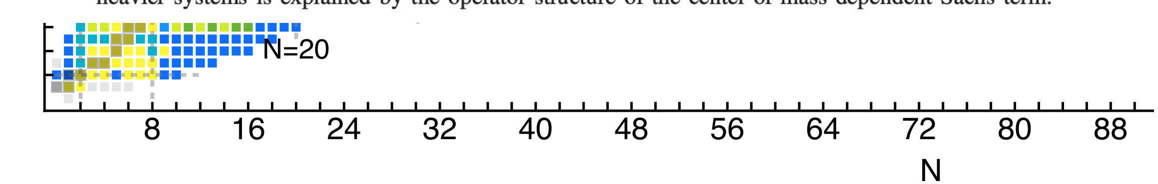
(Received 28 November 2023; revised 23 March 2024; accepted 25 April 2024; published 7 June 2024)

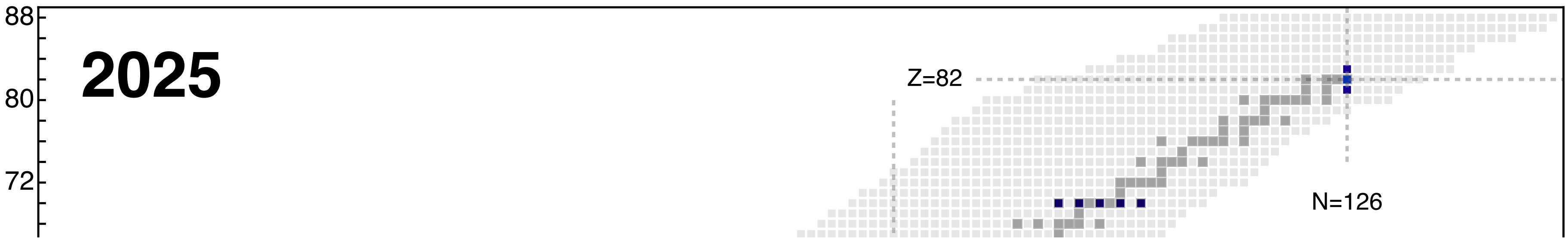
We investigate the effects of two-body currents on magnetic dipole moments of medium-mass and heavy nuclei using the valence-space in-medium similarity renormalization group with chiral effective field theory interactions and currents. Focusing on near doubly magic nuclei from oxygen to bismuth, we have found that the leading two-body currents globally improve the agreement with experimental magnetic moments. Moreover, our results show the importance of multishell effects for ^{41}Ca, which suggest that the $Z = N = 20$ gap in ^{40}Ca is not as robust as in ^{48}Ca. The increasing contribution of two-body currents in heavier systems is explained by the operator structure of the center-of-mass dependent Sachs term.



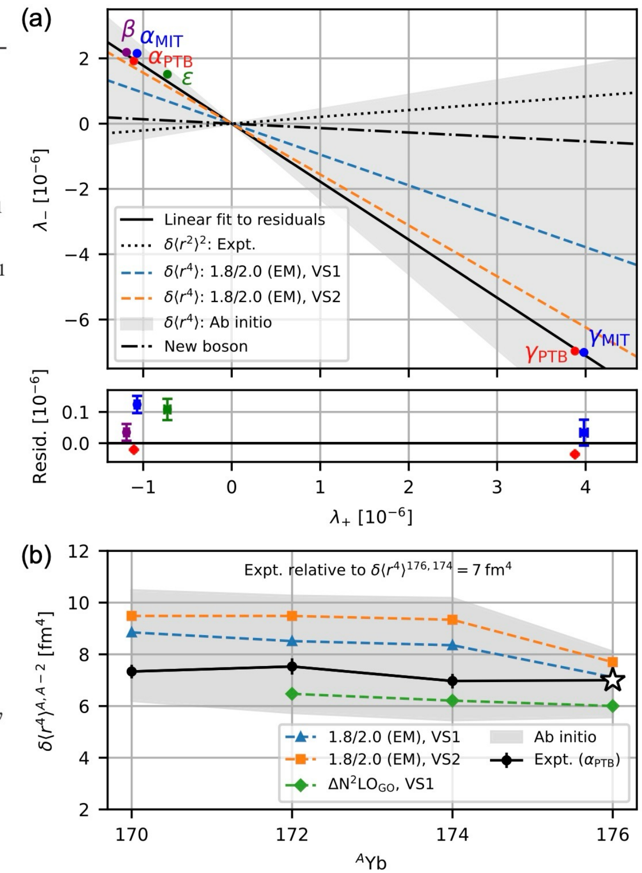


figures from Hergert (2025)

Great progress in ab initio calculations of nuclei



PHYSICAL REVIEW LETTERS **134,** 063002 (2025)



Probing New Bosons and Nuclear Structure with Ytterbium Isotope Shifts

Menno Door,[1,2,*,†] Chih-Han Yeh,[3,*,‡] Matthias Heinz,[4,5,1,§] Fiona Kirk,[3,6] Chunhai Lyu,[1] Takayuki Miyagi,[4,5,1] Julian C. Berengut,[7] Jacek Bieroń,[8] Klaus Blaum,[1] Laura S. Dreissen,[3,9] Sergey Eliseev,[1] Pavel Filianin,[1] Melina Filzinger,[3] Elina Fuchs,[3,6] Henning A. Fürst,[3,10] Gediminas Gaigalas,[11] Zoltán Harman,[1] Jost Herkenhoff,[1] Nils Huntemann,[3] Christoph H. Keitel,[1] Kathrin Kromer,[1] Daniel Lange,[1,2] Alexander Rischka,[1] Christoph Schweiger,[1] Achim Schwenk,[4,5,1] Noritaka Shimizu,[12] and Tanja E. Mehlstäubler[3,10,13]

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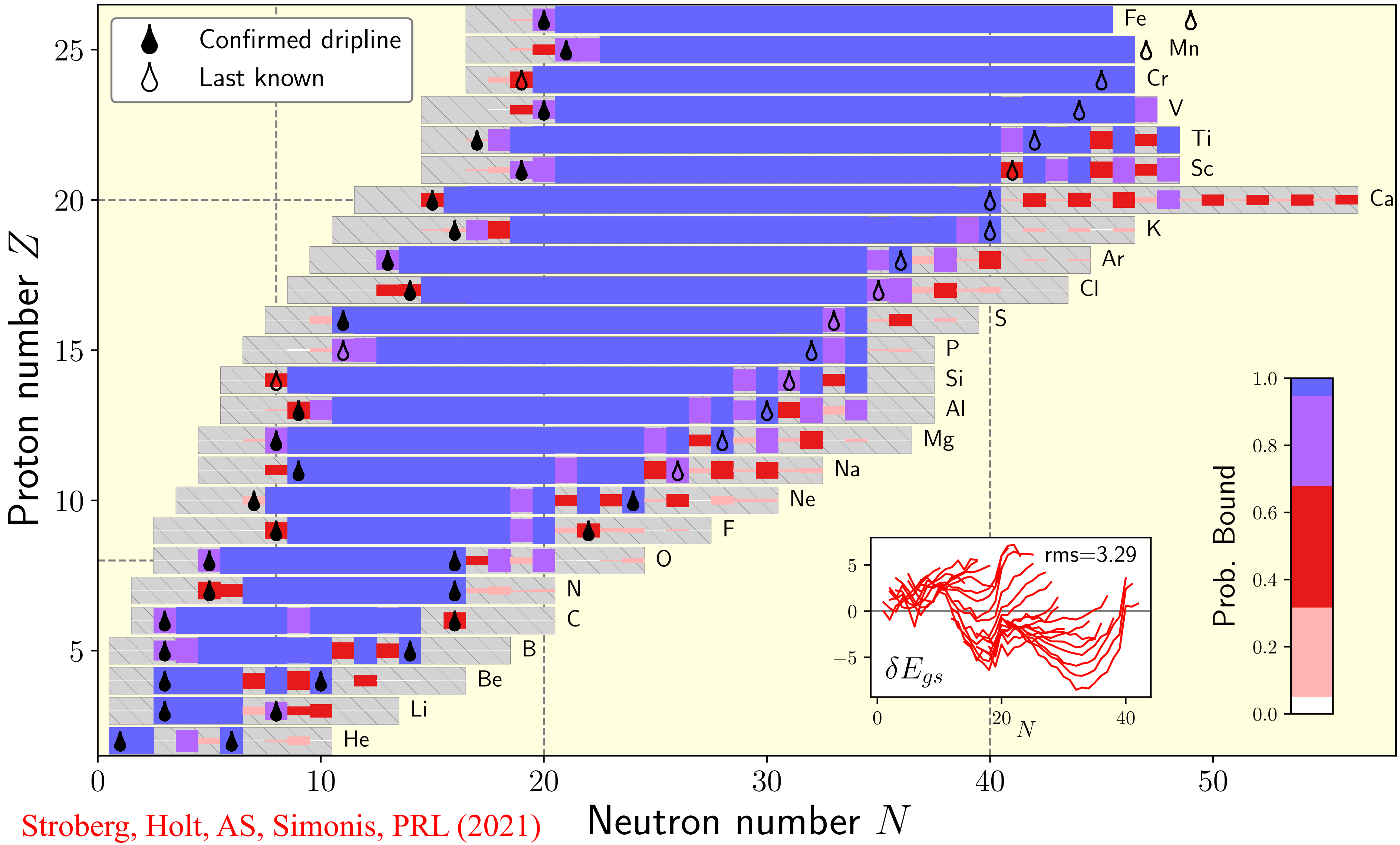
In this Letter, we present mass-ratio measurements on highly charged Yb^{42+} ions with a precision of 4×10^{-12} and isotope-shift measurements on Yb^+ on the $^2S_{1/2} \rightarrow {}^2D_{5/2}$ and $^2S_{1/2} \rightarrow {}^2F_{7/2}$ transitions with a precision of 4×10^{-9} for the isotopes ^{168,170,172,174,176}Yb. We present a new method that allows us to extract higher-order changes in the nuclear charge distribution along the Yb isotope chain, benchmarking *ab initio* nuclear structure calculations. Additionally, we perform a King plot analysis to set bounds on a fifth force in the keV/c^2 to MeV/c^2 range coupling to electrons and neutrons.

Great progress in ab initio calculations of nuclei



Stroberg, Holt, AS, Simonis, PRL (2021)

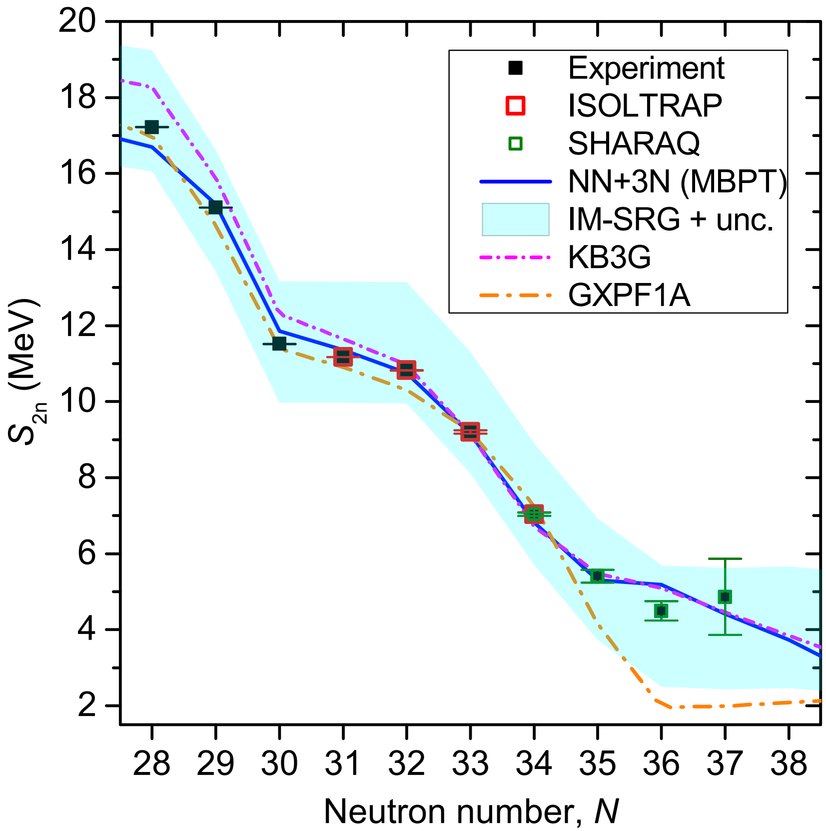
Lower nuclear landscape based on a chiral NN+3N interaction

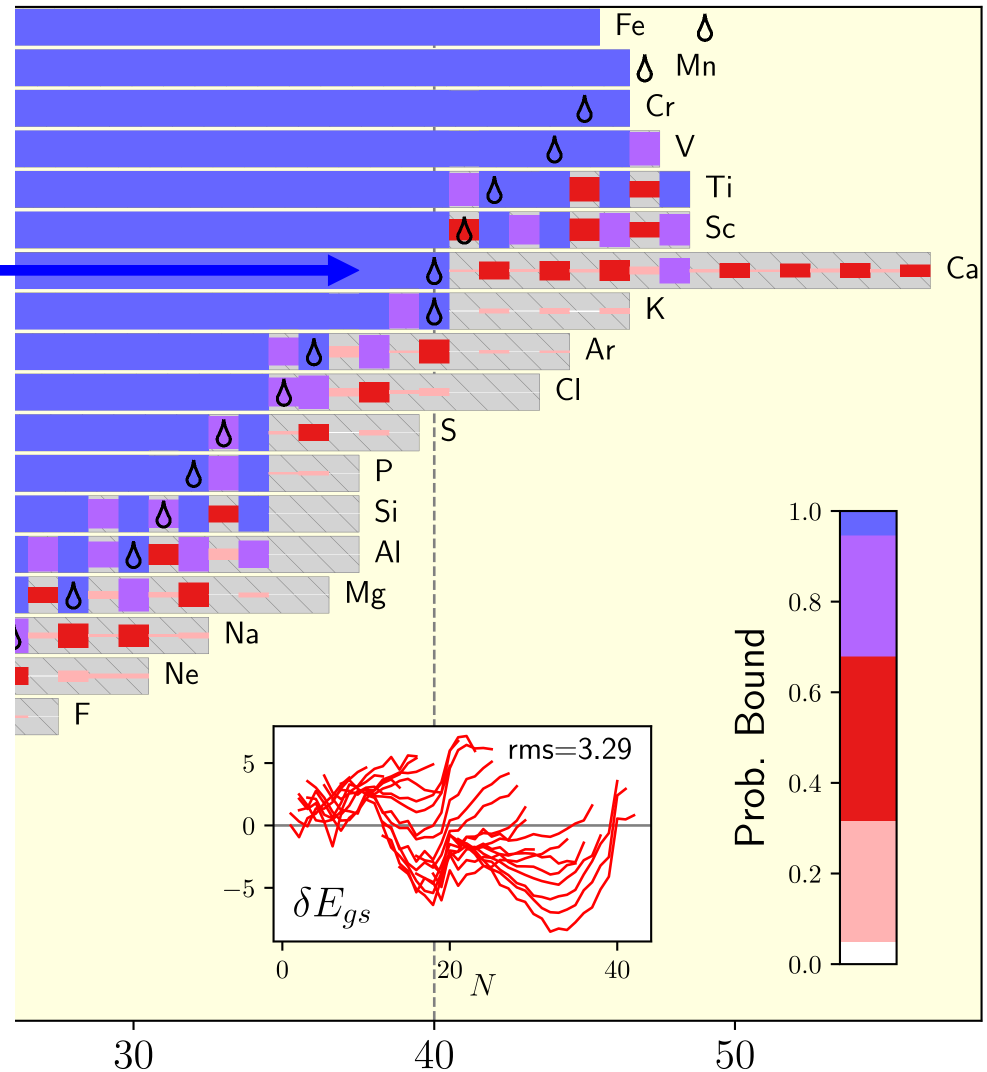
Neutron-rich calcium masses

active exp-theory collaborations for rare isotopes

pioneering $^{51\text{-}57}$Ca masses

Gallant et al., PRL (2012), Wienholtz et al., Nature (2013), Michimasa et al., PRL (2019)



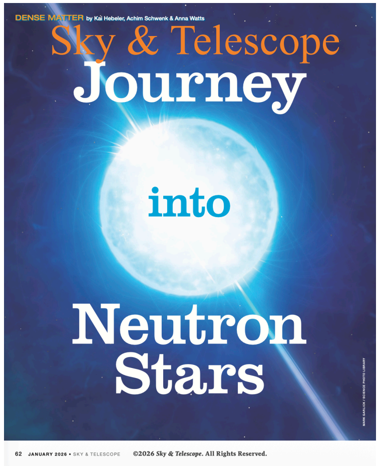


Extreme matter in neutron stars

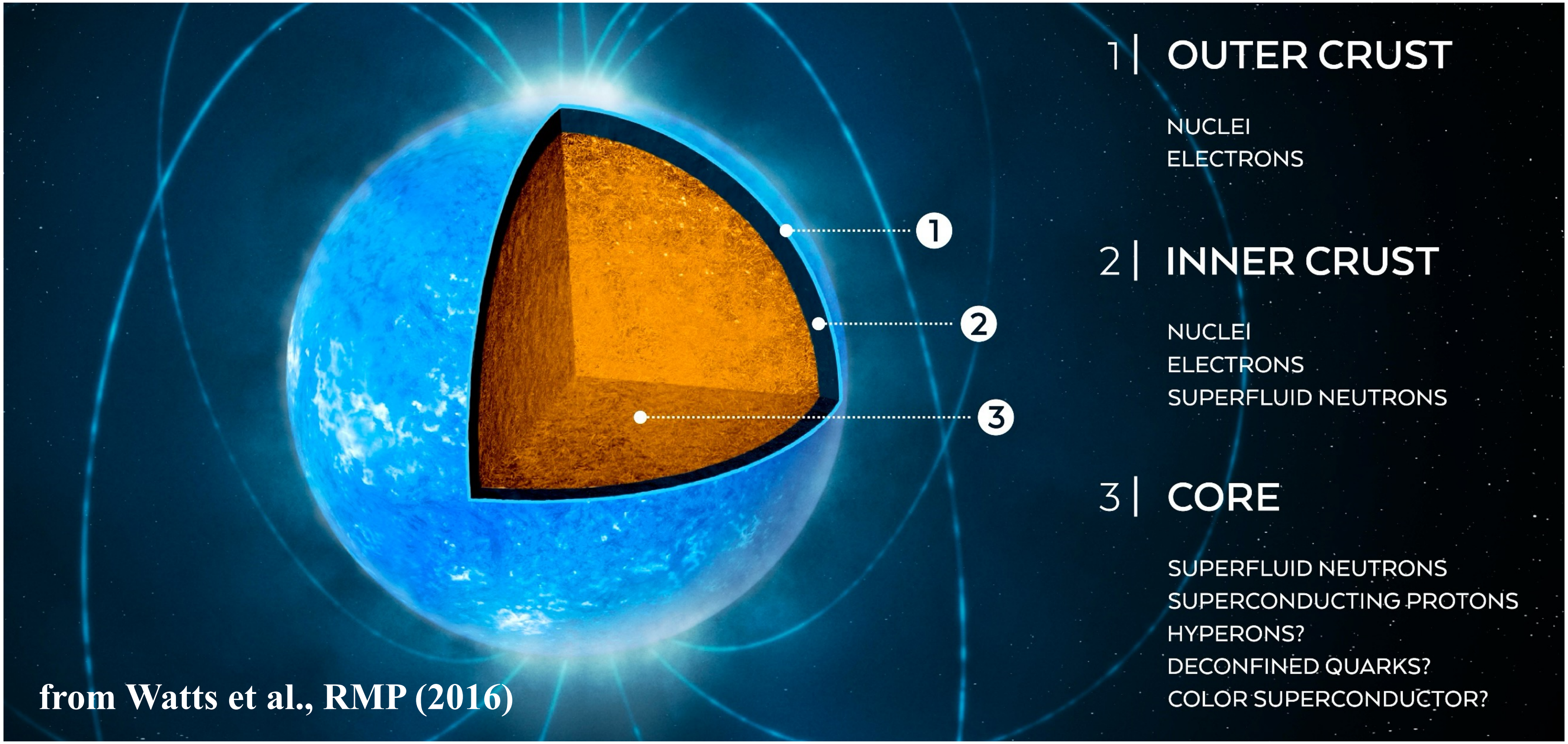
Dense matter up to ~ 5-8 n_0 (in heaviest neutron stars)

governed by strong interactions, up to few n_0: n,p,e,μ

When (do) degrees of freedom change?



Chiral EFT sets pressure of first few km Hebeler et al., PRL (2010), ApJ (2013)

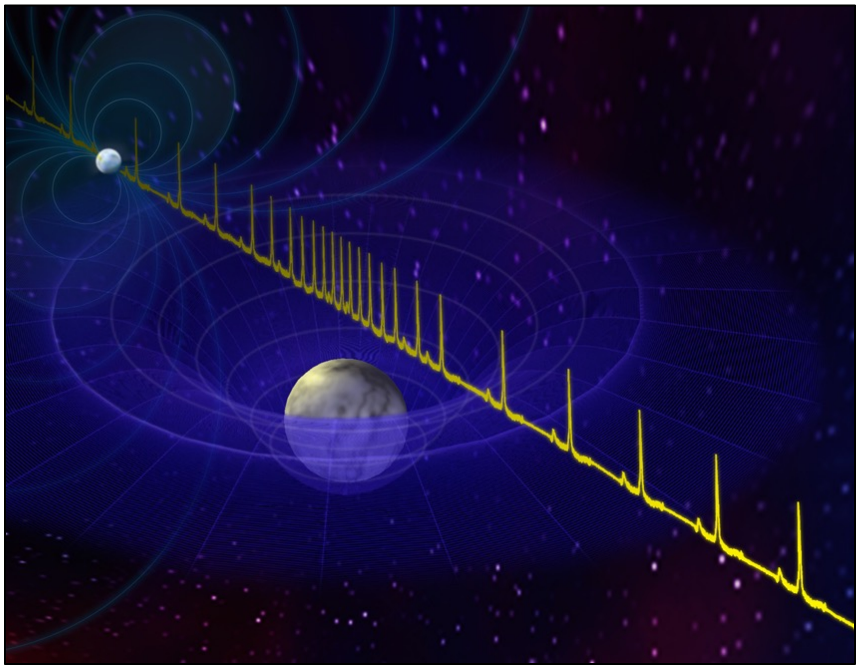


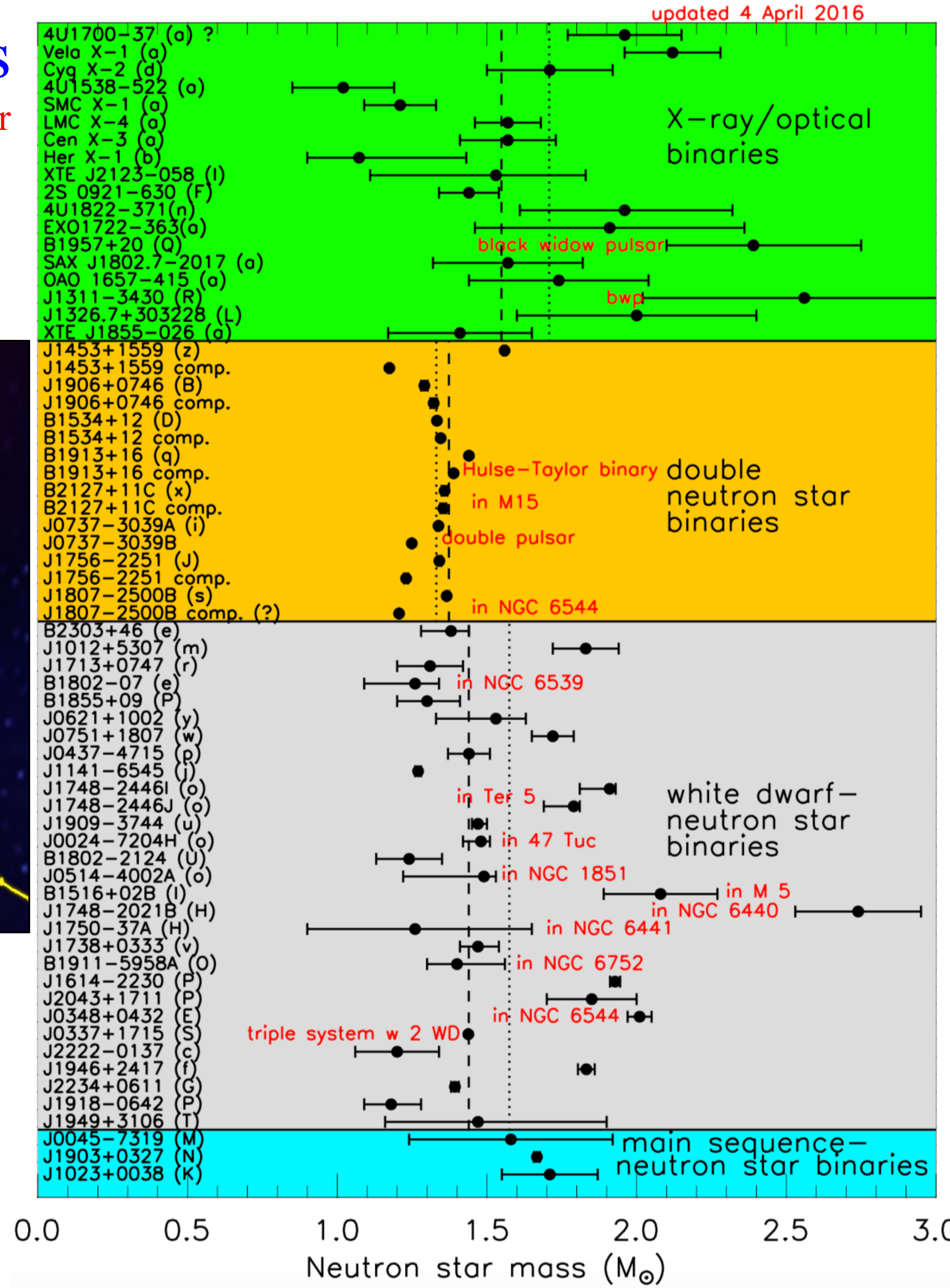
from Watts et al., RMP (2016)

Neutron star masses

from Jim Lattimer

mass measurements from radio pulsar timing





three 2 M_{sun} neutron stars obs.

J1614: Demorest et al., Nature (2010),

J0348: Antoniadis et al., Science (2013),

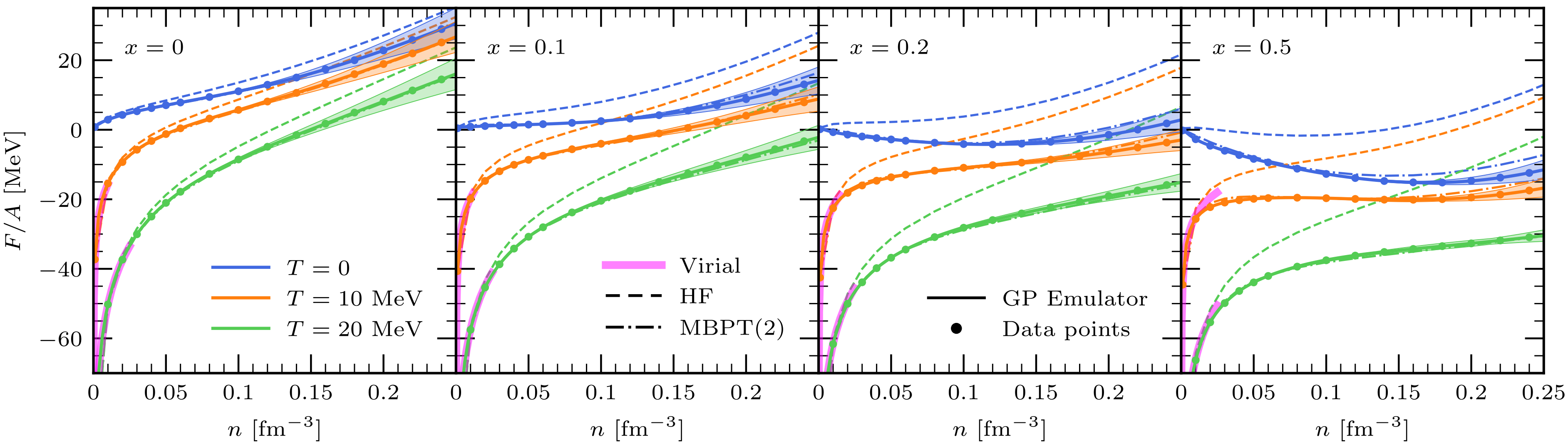
J0740: **2.08±0.07 M_{sun}** Fonseca et al., (2021)

EOS for arbitrary proton fraction and temperature

Keller, Hebeler, AS, PRL (2023)

based on chiral NN+3N interactions to N^3LO

order-by-order EFT uncertainties + (smaller) many-body uncertainties



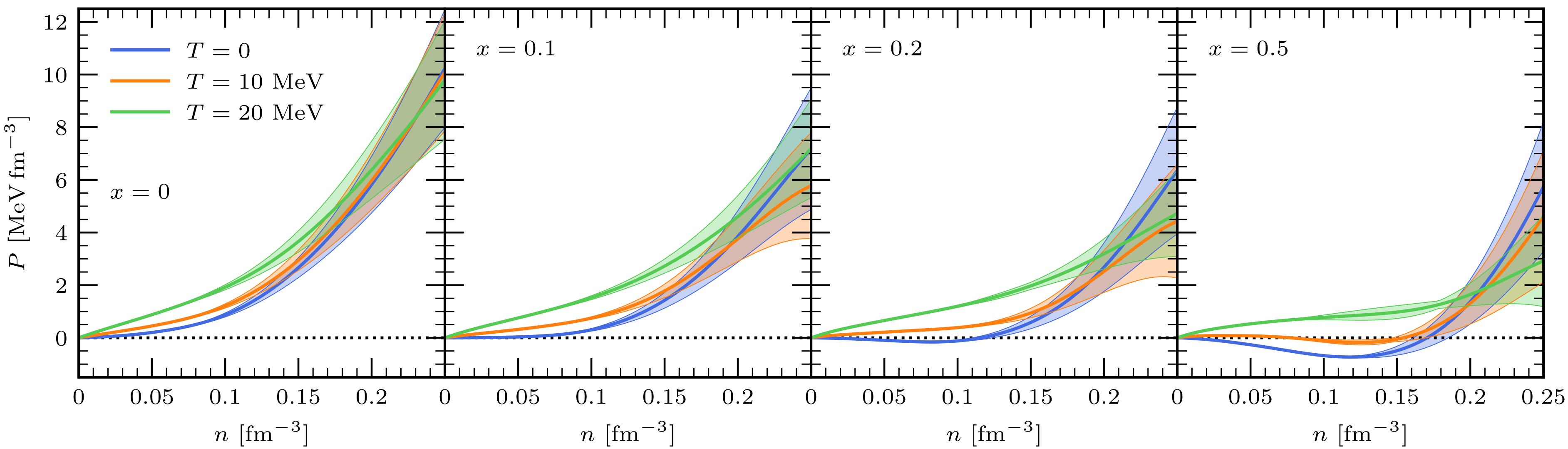
excellent reproduction of free energy data by Gaussian process (GP)

agrees with model-indep. virial EOS Horowitz, AS, NPA (2006) at low densities

EOS for arbitrary proton fraction and temperature

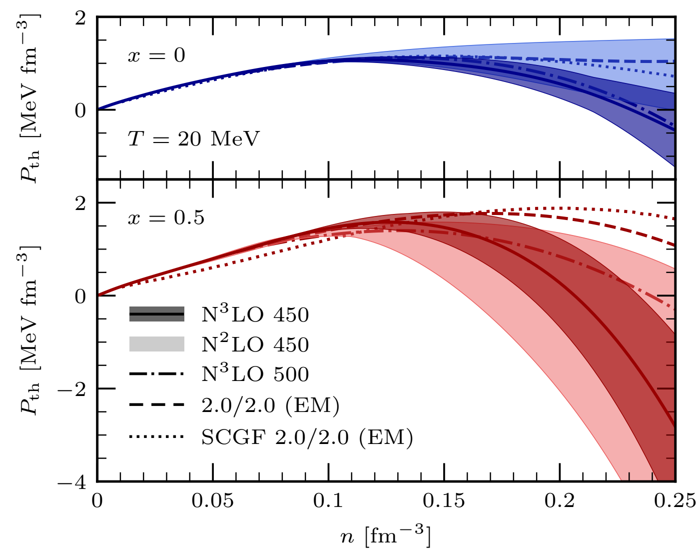
Keller, Hebeler, AS, PRL (2023)

GP emulator to calculate pressure (thermodyn. consistent derivatives)



pressure isothermals cross at higher densities
→ negative thermal expansion

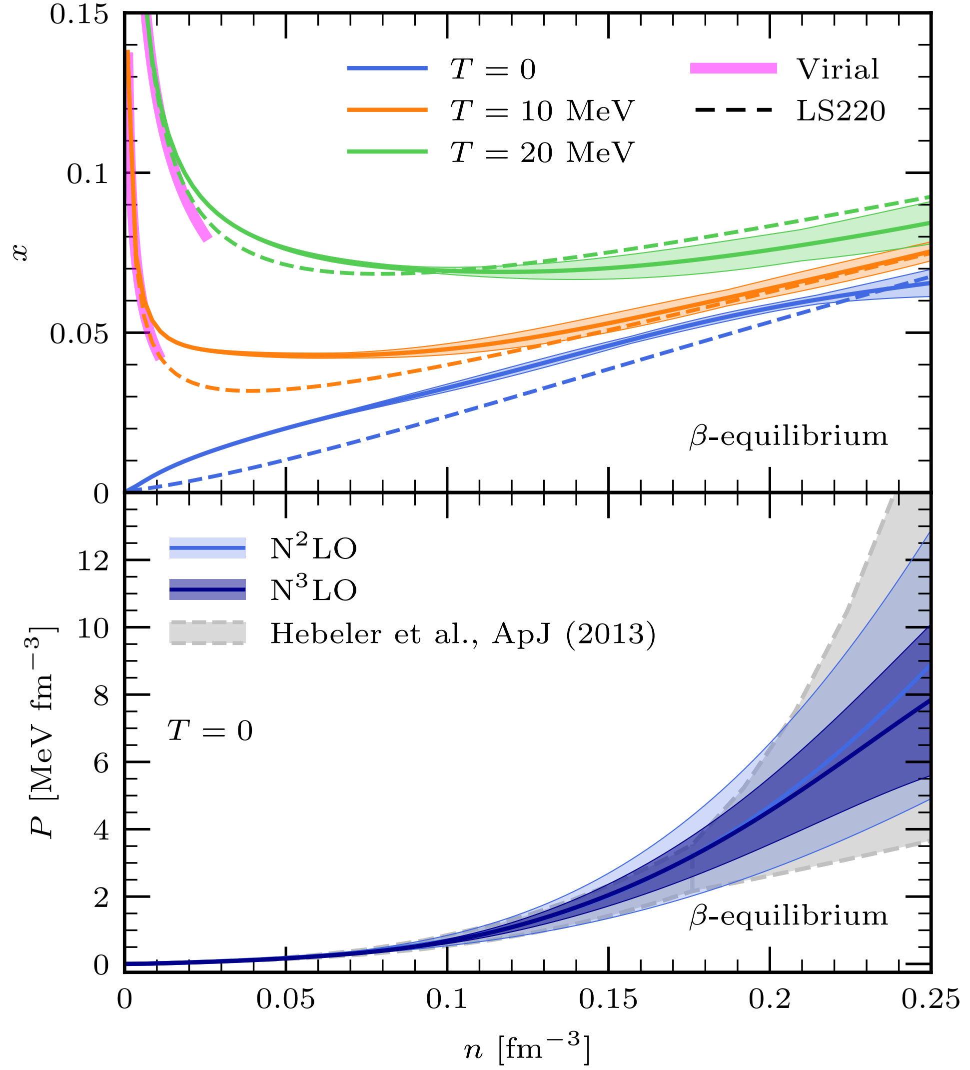
thermal part of pressure decreases with increasing density,
found for all chiral interactions studied



EOS for neutron star matter in beta equilibrium

Keller, Hebeler, AS, PRL (2023)

use GP emulator to access arbitrary proton fraction, solve for beta equilibrium



EOS of neutron star matter at N^2LO and N^3LO,

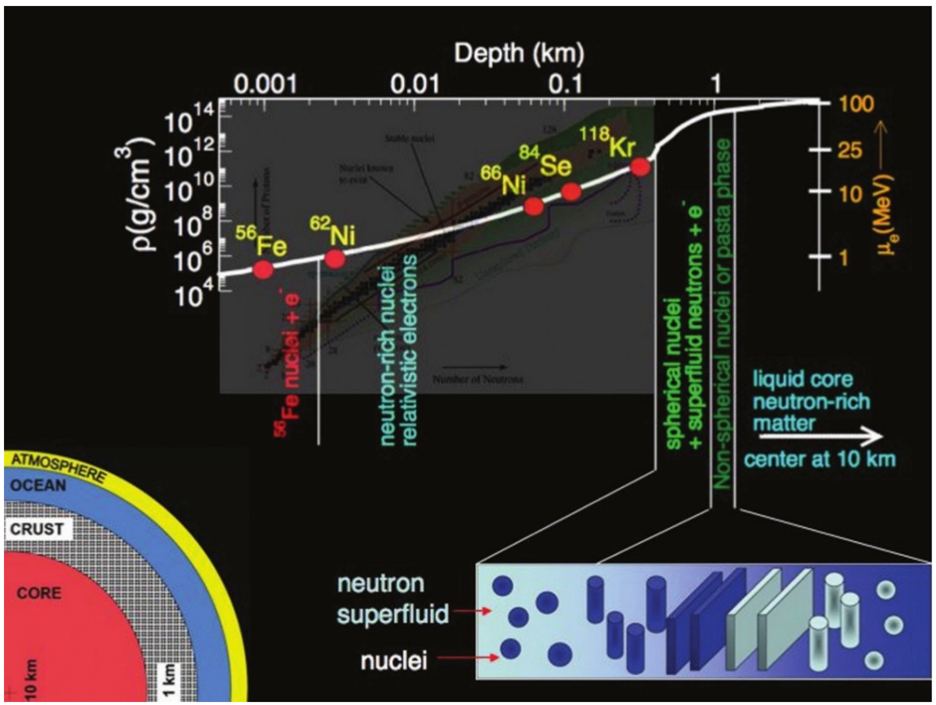
no indication of EFT breakdown

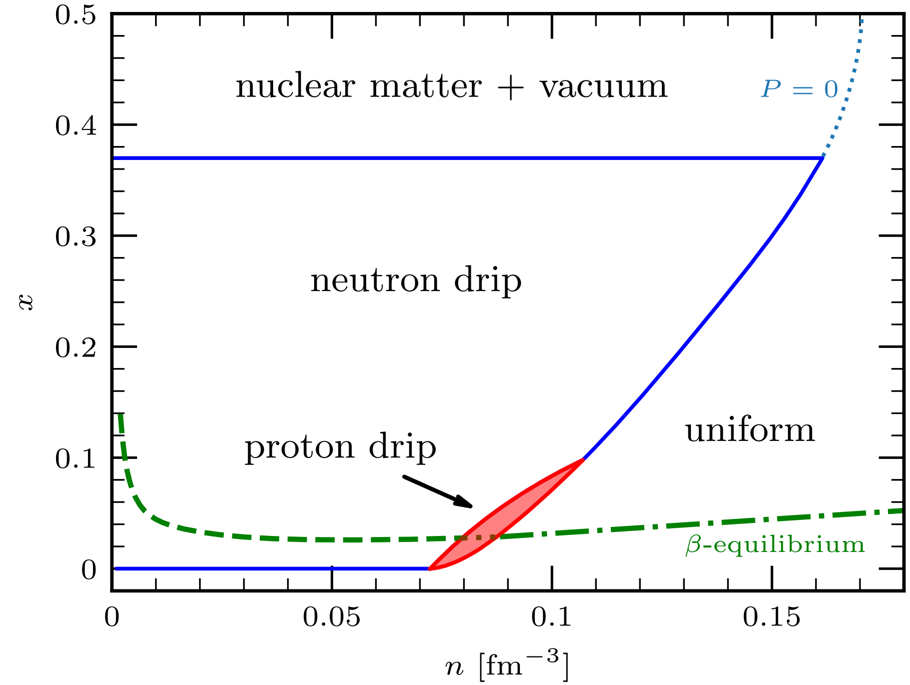
N^3LO band prefers higher pressures, improvement over older calculations

Subnuclear phase diagram of neutron star matter

~ 5% proton fraction in denser neutron matter

below ~ 0.5 n_0 possible pasta phases: clusters/structures of high density surrounded by neutron (and proton?) gas: neutron (and proton?) drip





Keller, Hebeler, Pethick, AS, PRL (2024)

Chiral EFT calculations establish proton drip:

robust for any reasonable EOS, proton drip aids pasta formation

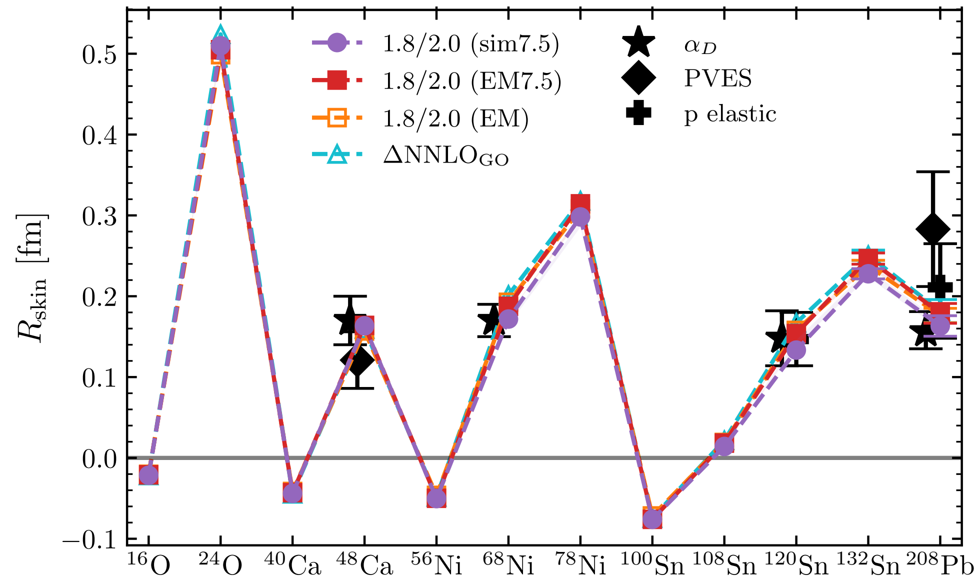
Constraints from neutron skins and related probes

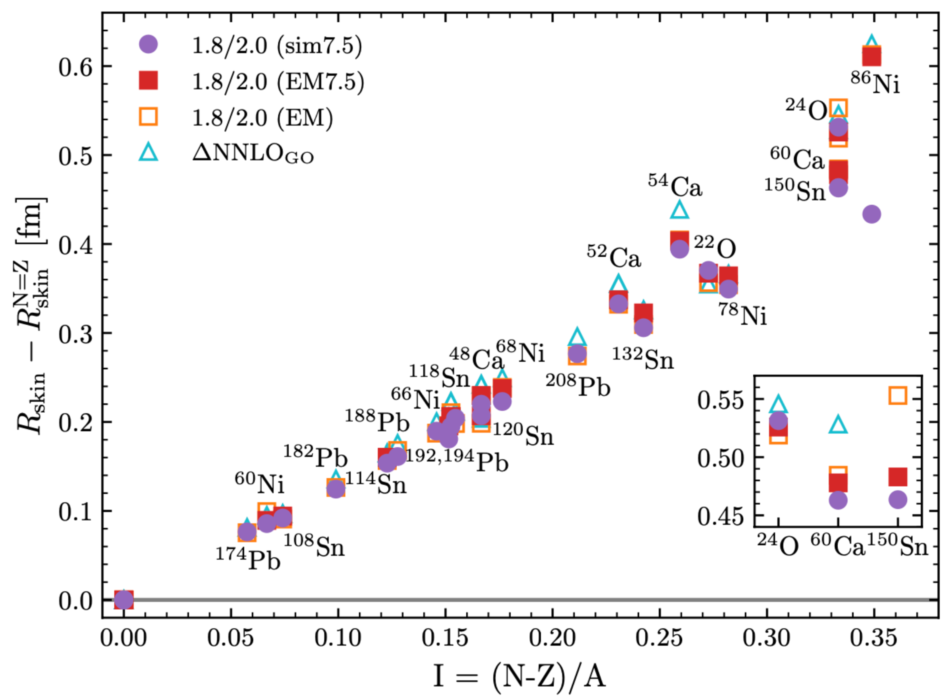
neutron skin = $R_n - R_p$
probes neutron matter pressure,
large pressure ~ larger skin

different experiments sensitive
to neutron skin, provides
constraints on matter around n_0

neutron skins tightly predicted
in chiral EFT calculations
Arthius et al., arXiv:2401.06675,
Novario et al., PRL (2023)

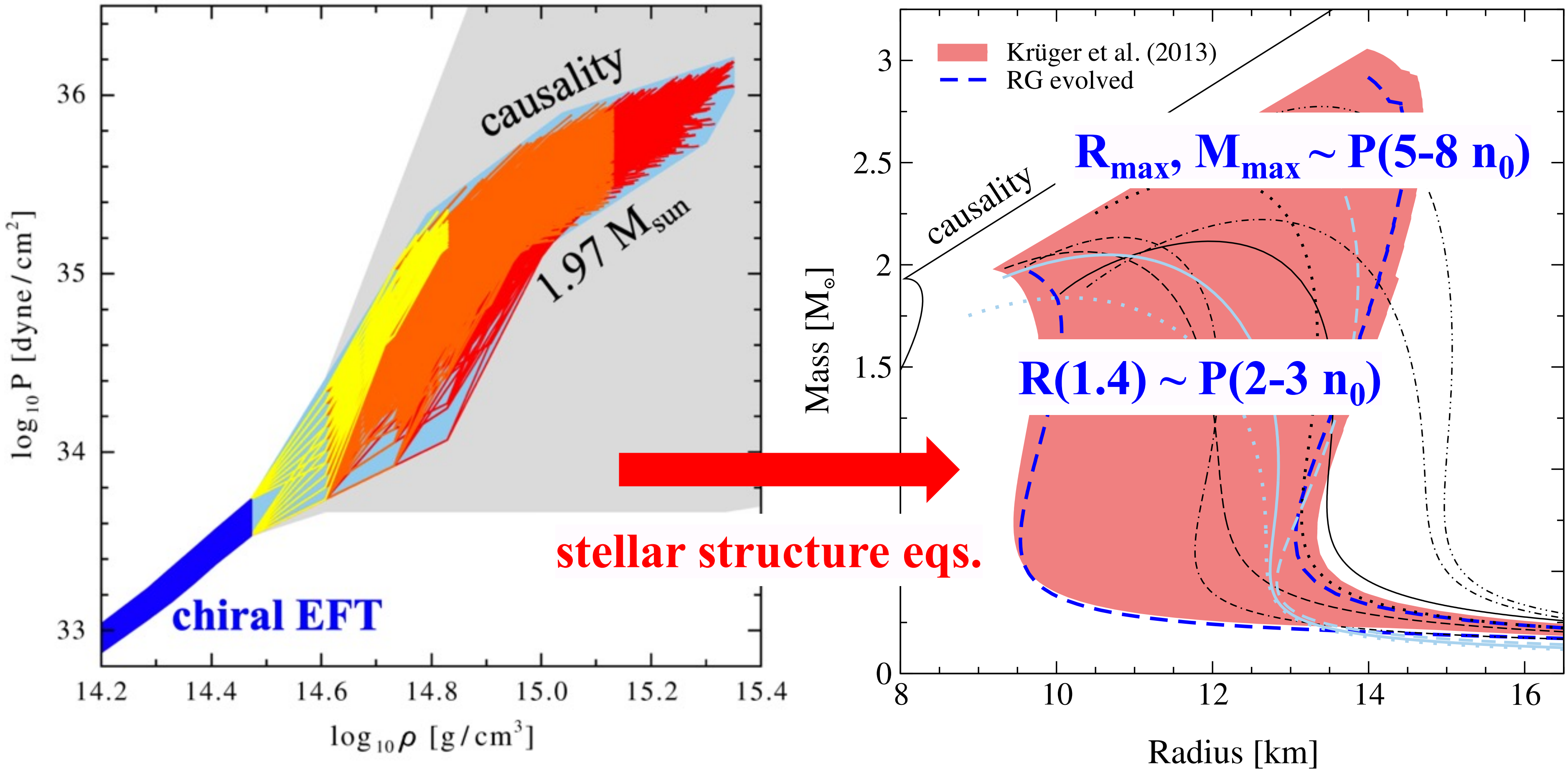
interesting predictions
for extreme n-rich nuclei





Impact on neutron stars Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

constrain high-density EOS by causality, require to support 2 M_{sun} star



piecewise polytropes (PP) includes phase transitions

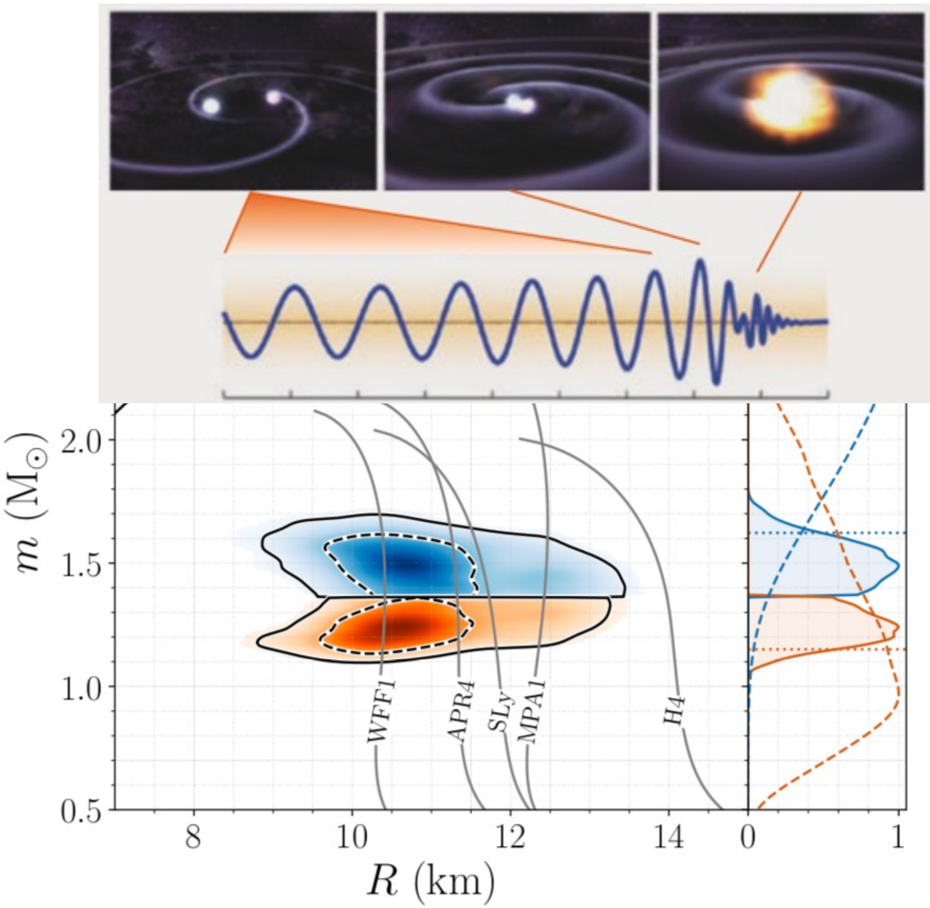
other high-density extensions use speed of sound parametrizations (CS), Gaussian processes, piecewise speed of sound,…

Neutron star radius information

from gravitational waves and pulse-profile modeling

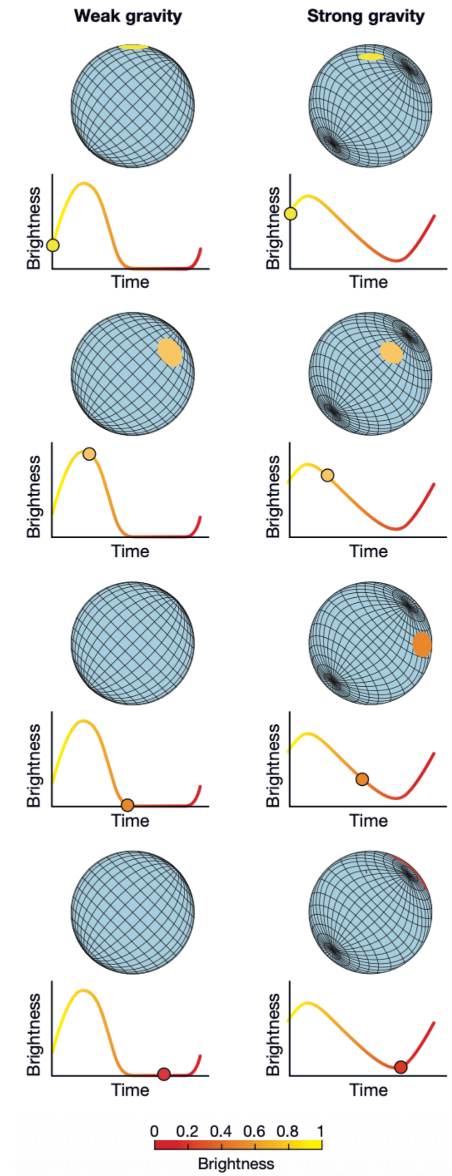
GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration



tidal deformability ~ R^5

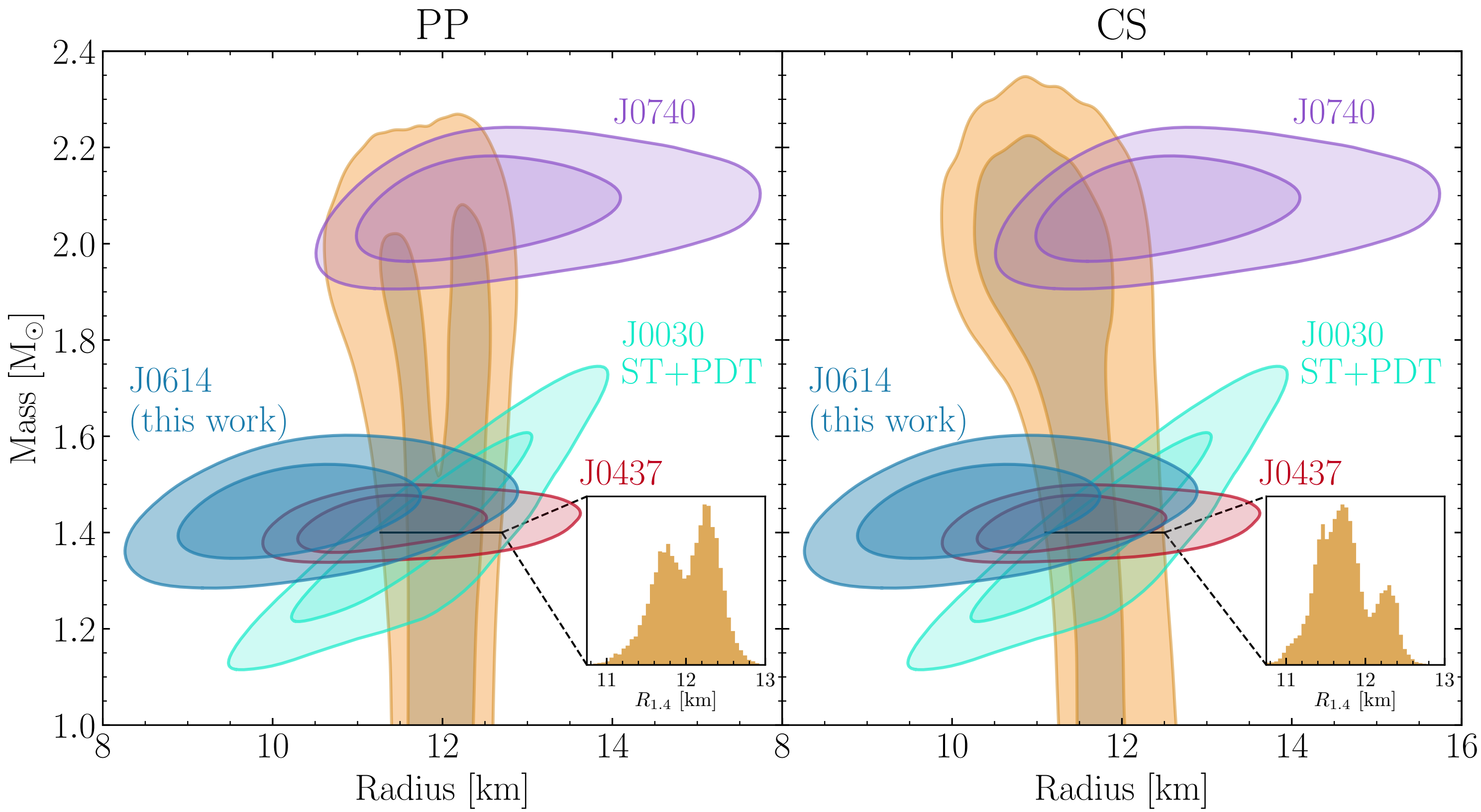
sensitive to compactness M/R



LIGO/Virgo and NICER results

chiral EFT up to $1.5n_0$ + general high-density extensions + causality

including information from GW170817 and 4 stars studied by NICER



Raaijmakers et al., ApJL (2020), (2021), Rutherford, Mendes, Svensson et al., ApJL (2024)
Mauviard-Haag et al., ApJ (2025)

posterior distributions very similar for PP/CS high-density extensions

Constraints at intermediate densities

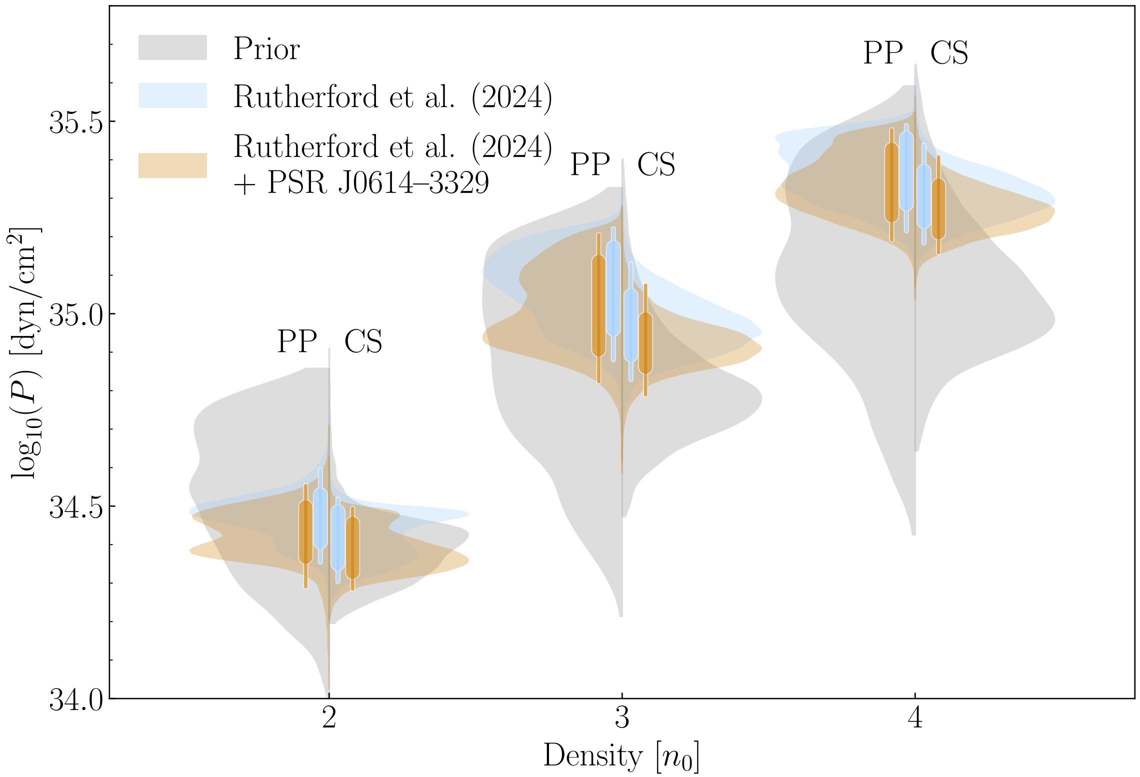
chiral EFT up to $1.5n_0$ + general EOS extrapolations + causality

including information from GW170817 and 4 stars studied by NICER

observations constrain pressure at intermediate densities

posteriors at $3\text{-}4n_0$ → astro prefers higher pressures

important to explore prior sensitivities

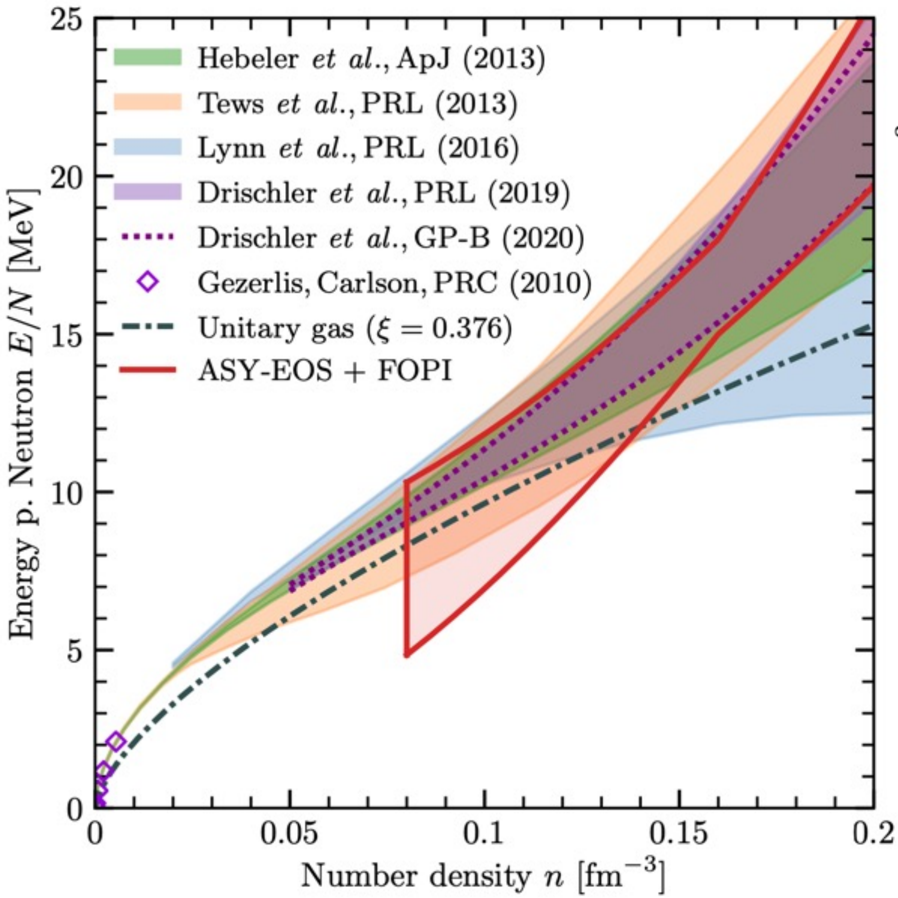


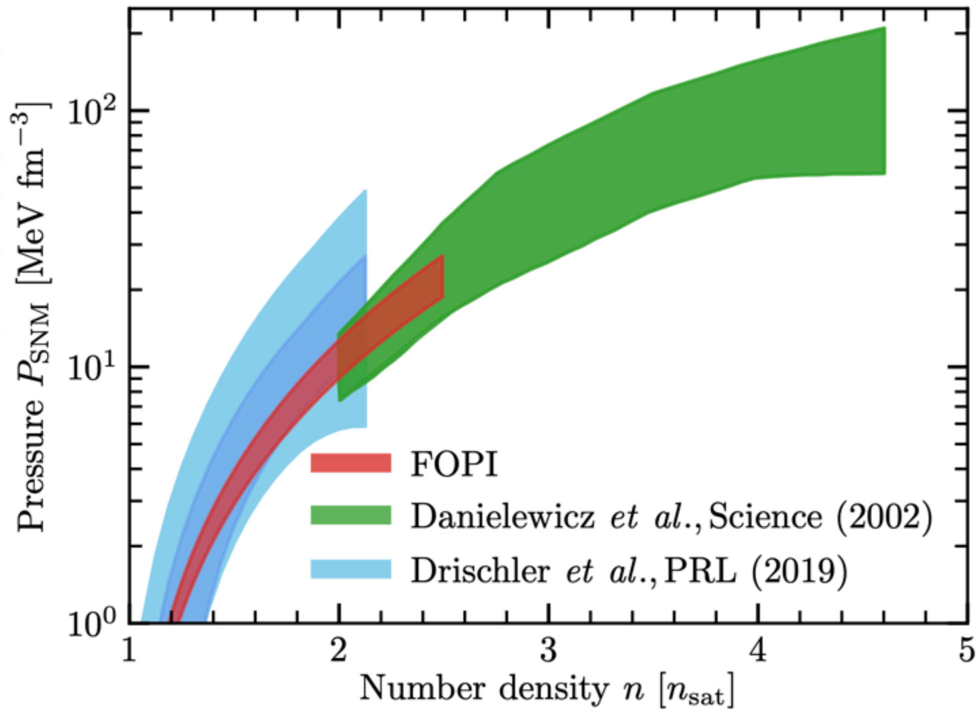
Rutherford, Mendes, Svensson et al., ApJL (2024)
Mauviard-Haag et al., ApJ (2025)

will be very constraining with more observations

Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

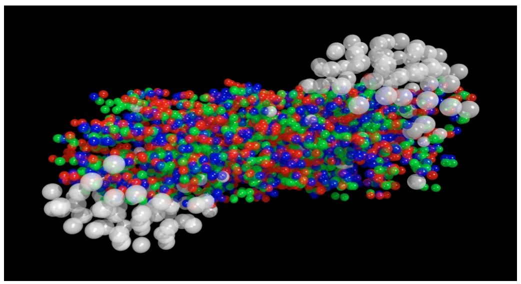
include in addition to chiral EFT: constraints from ASY-EOS and FOPI for neutron and symmetric matter

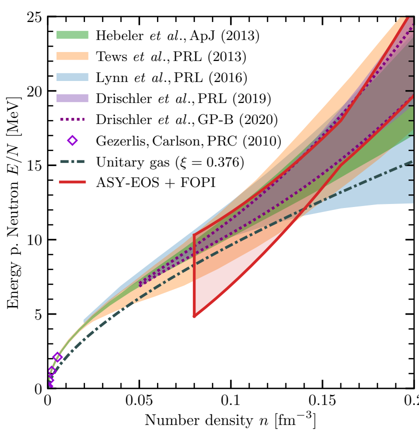


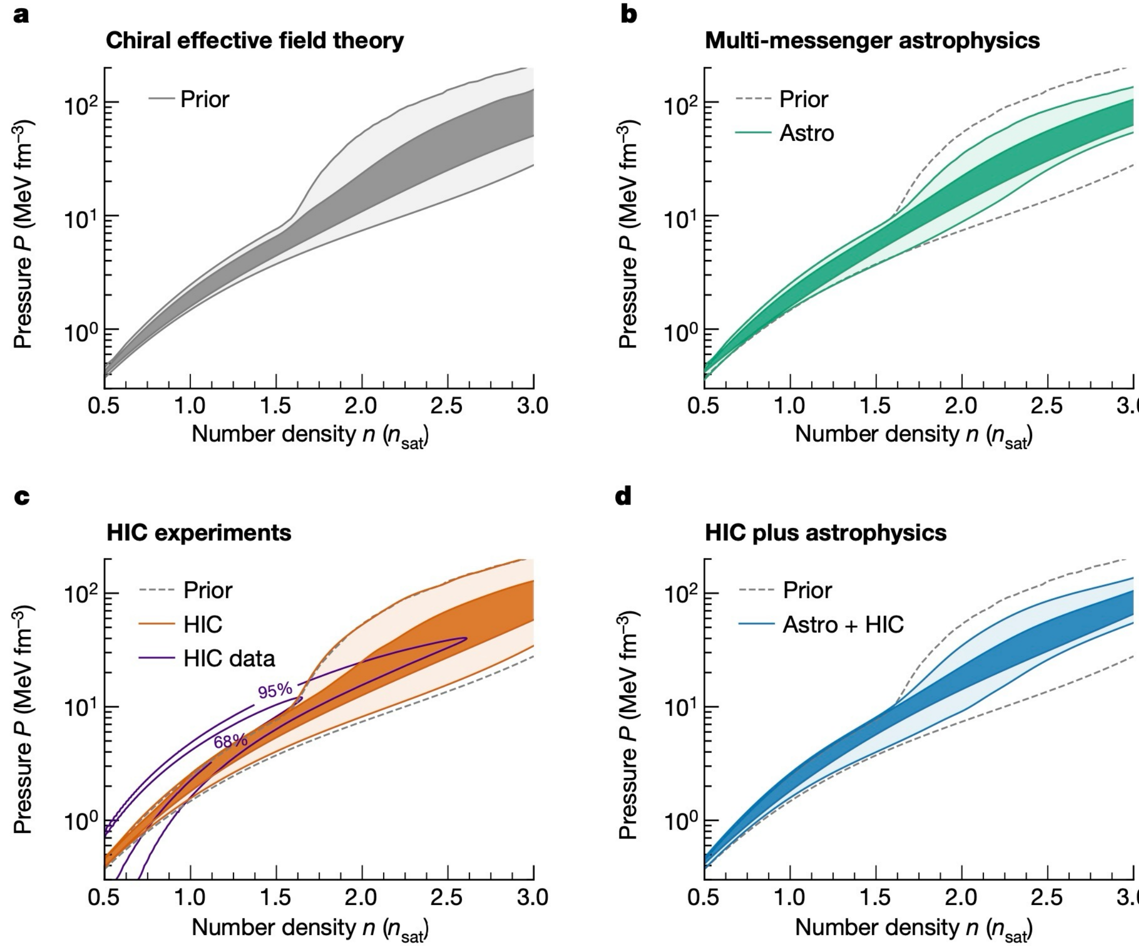


Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

inclusion of HIC constraints prefers higher pressures, similar to NICER, overall remarkable consistency with chiral EFT and astro constraints







future HIC constraints for intermediate densities very interesting

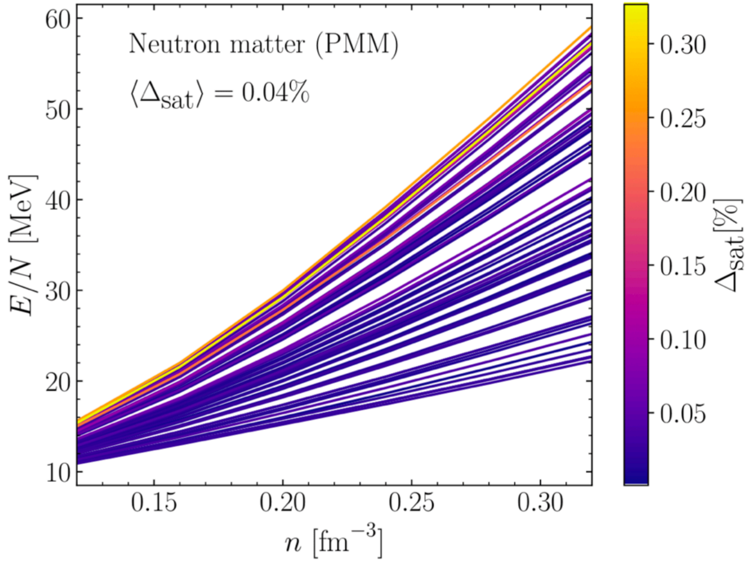
	Prior	Astro only	HIC only	Astro + HIC
$P_{1.5n_{sat}}$	$5.59^{+2.04}_{-1.97}$	$5.84^{+1.95}_{-2.26}$	$6.06^{+1.85}_{-2.04}$	$6.25^{+1.90}_{-2.26}$
$R_{1.4}$	$11.96^{+1.18}_{-1.15}$	$11.93^{+0.80}_{-0.75}$	$12.06^{+1.13}_{-1.18}$	$12.01^{+0.78}_{-0.77}$

Inferring 3N couplings from next generation observations

Somasundaram, Svensson et al., Nature Comm. (2025)

prior: assume 100% uncertainty in c_1 and c_3

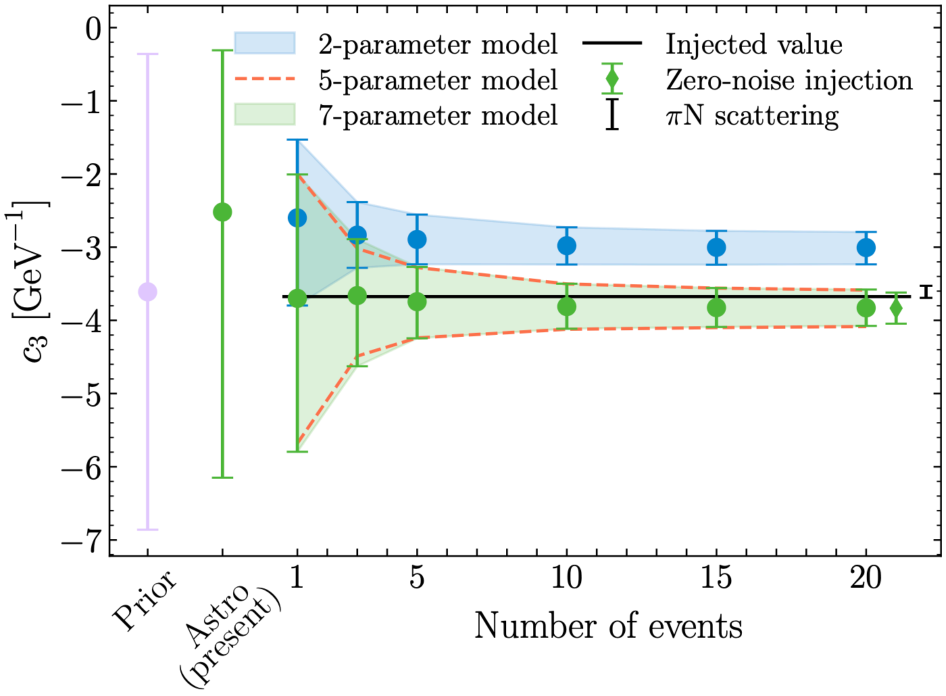
build emulator (parametric matrix model) for neutron matter



infer 3N couplings from astro data

present observations not very constraining

~20 future events will lead to interesting constraints for c_3

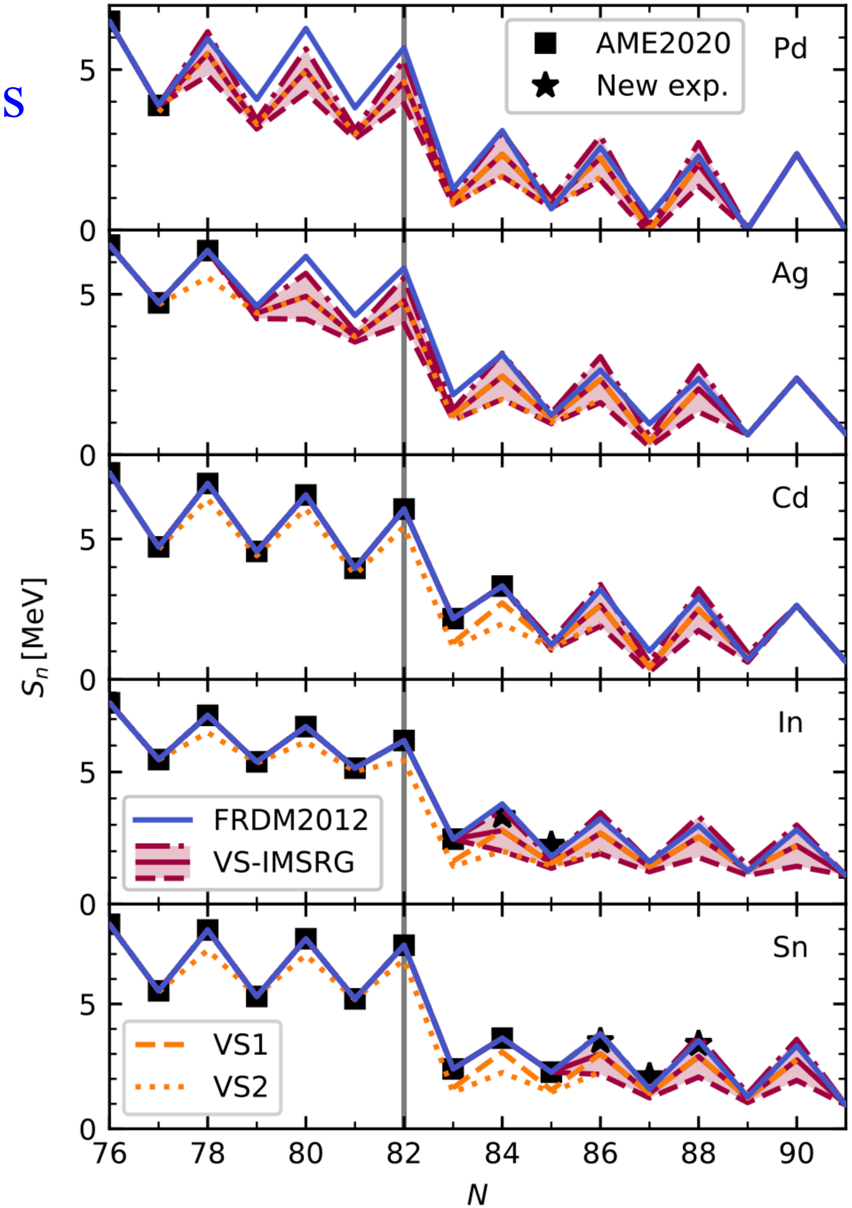


Nuclear masses around N=82 and r-process nucleosynthesis

Kuske, Miyagi, Arcones, AS, arXiv:2509.19131

nuclear masses from VS-IMSRG with interaction + valence space uncertainties around N=82 (for Sn, In, Cd, Ag, Pd)

incorporate uncertainties in baseline model AME2020 + FRDM2012



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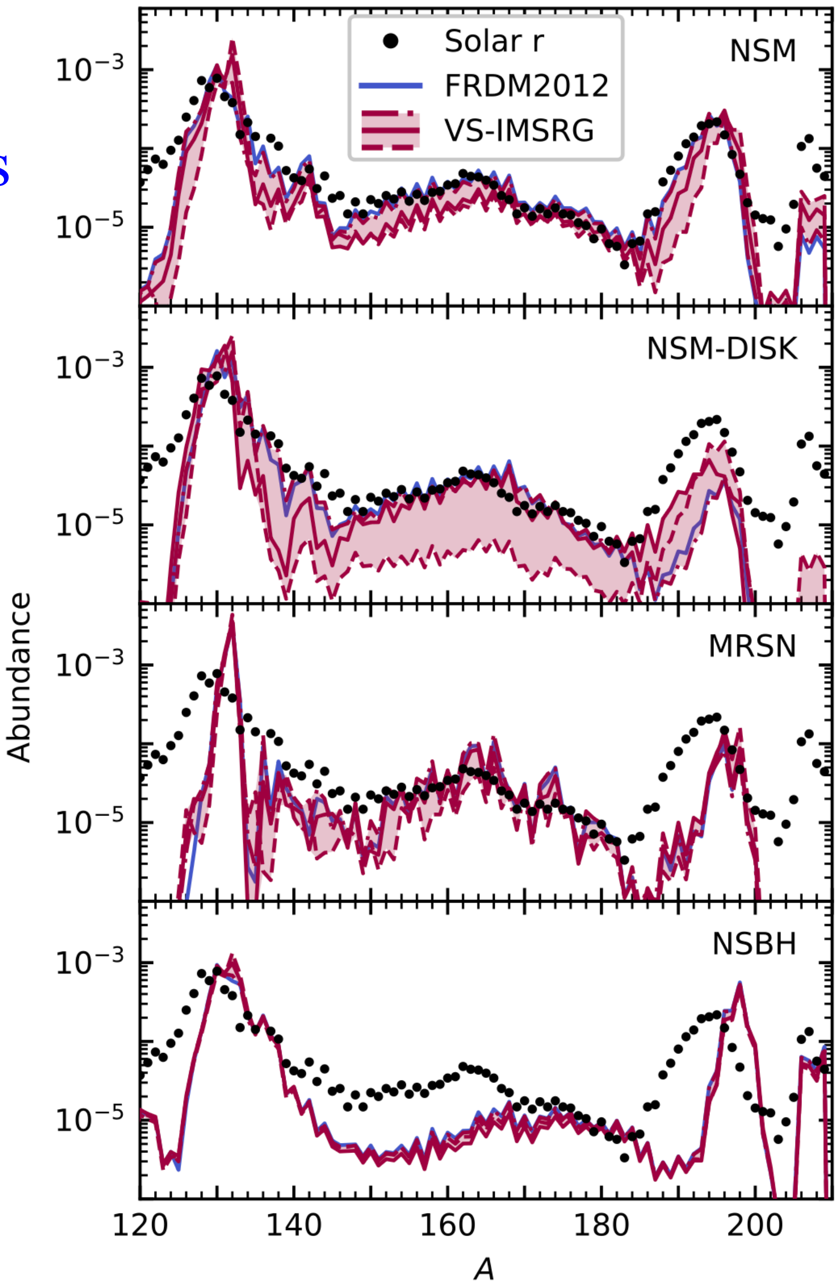
incorporate uncertainties in baseline model AME2020 + FRDM2012

explore r-process predictions for different astrophysics scenarios

largest effects for n-star mergers (NSM)

ab initio masses strengthen waiting point of 2nd peak, leading to slower nucleosynthesis flow, and important impact on 3rd peak



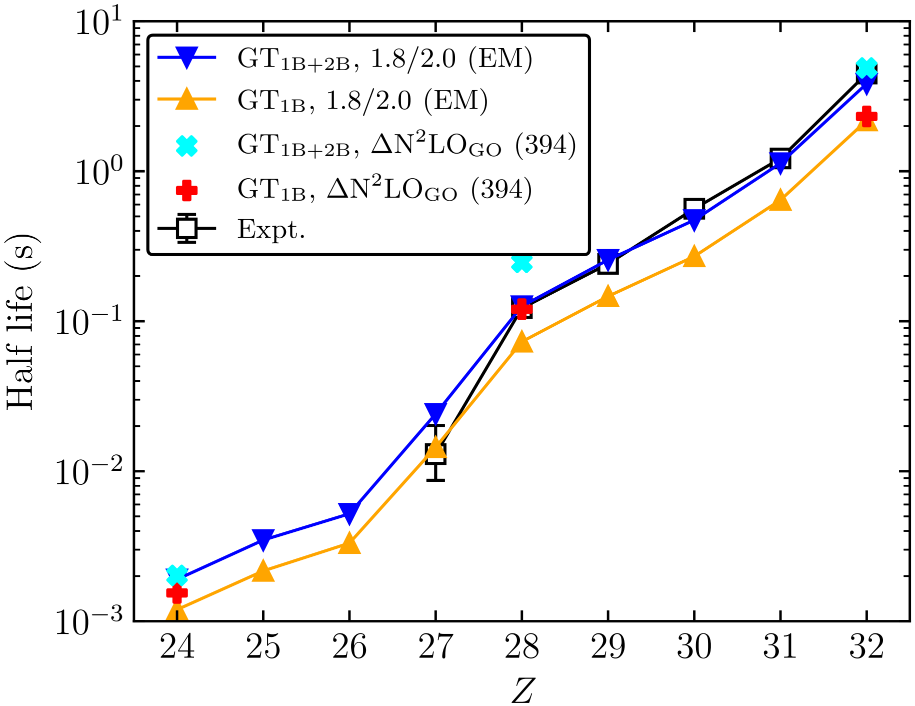
Gamow-Teller beta decays for N=50 nuclei

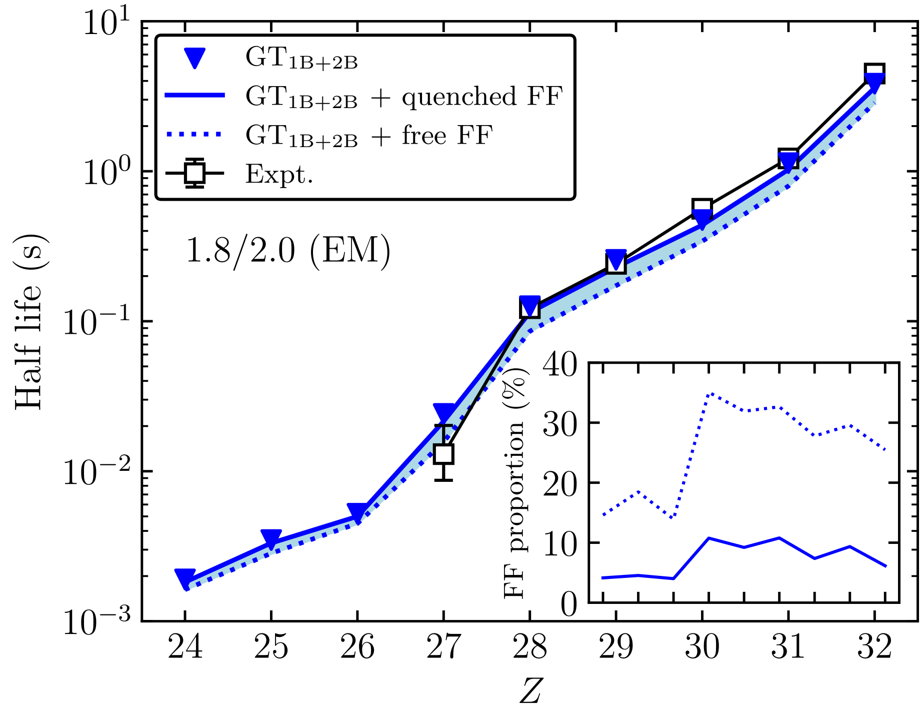
Li, Miyagi, AS, arXiv:2509.19131

VS-IMSRG calculations for valence space on top of ^{48}Ca core

1.8/2.0 (EM) and ΔN^2LO_{GO} interactions with 1-body + 2-body currents

very good agreement with experiment, without adjustments





+ contributions from first-forbidden (FF) transitions

Summary

Thanks to: ab initio: **P. Arthuis**, S. Bogner, **C. Brase**, **M. Companys**, K. Hebeler, H. Hergert, **M. Heinz**, J.D. Holt, **Z. Li**, **T. Miyagi**, **T. Plies**, **A. Porro**, R. Stroberg, **U. Vernik**, **A. Tichai**

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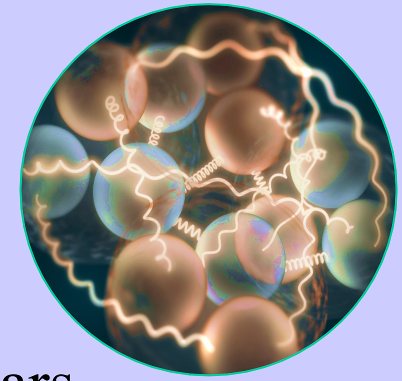
Chiral EFT + powerful many-body methods
→ great progress for ab initio calcs
of nuclei and dense matter



reliable EOS up to ~ 1-2 n_0
with controlled uncertainties
→ multimessenger era of neutron stars,
high-density constraints from astrophysics, HIC