Neutron-rich matter from chiral EFT, experiments, and observations

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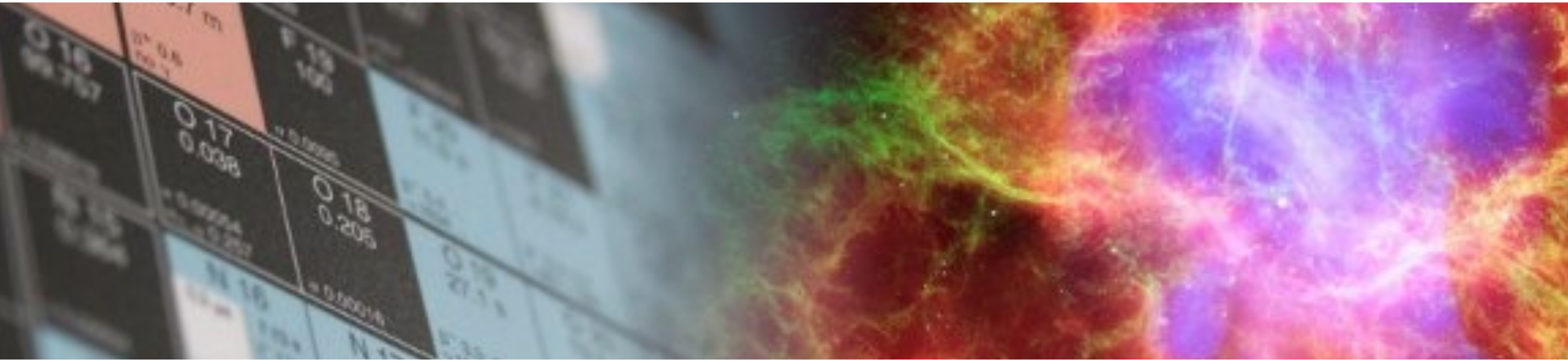
HEIDELBERG



TRIUMF PAINT Workshop, Feb. 25, 2026

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SFB 1245

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Hessens Zukunft

Nuclear masses around N=82 and r-process nucleosynthesis

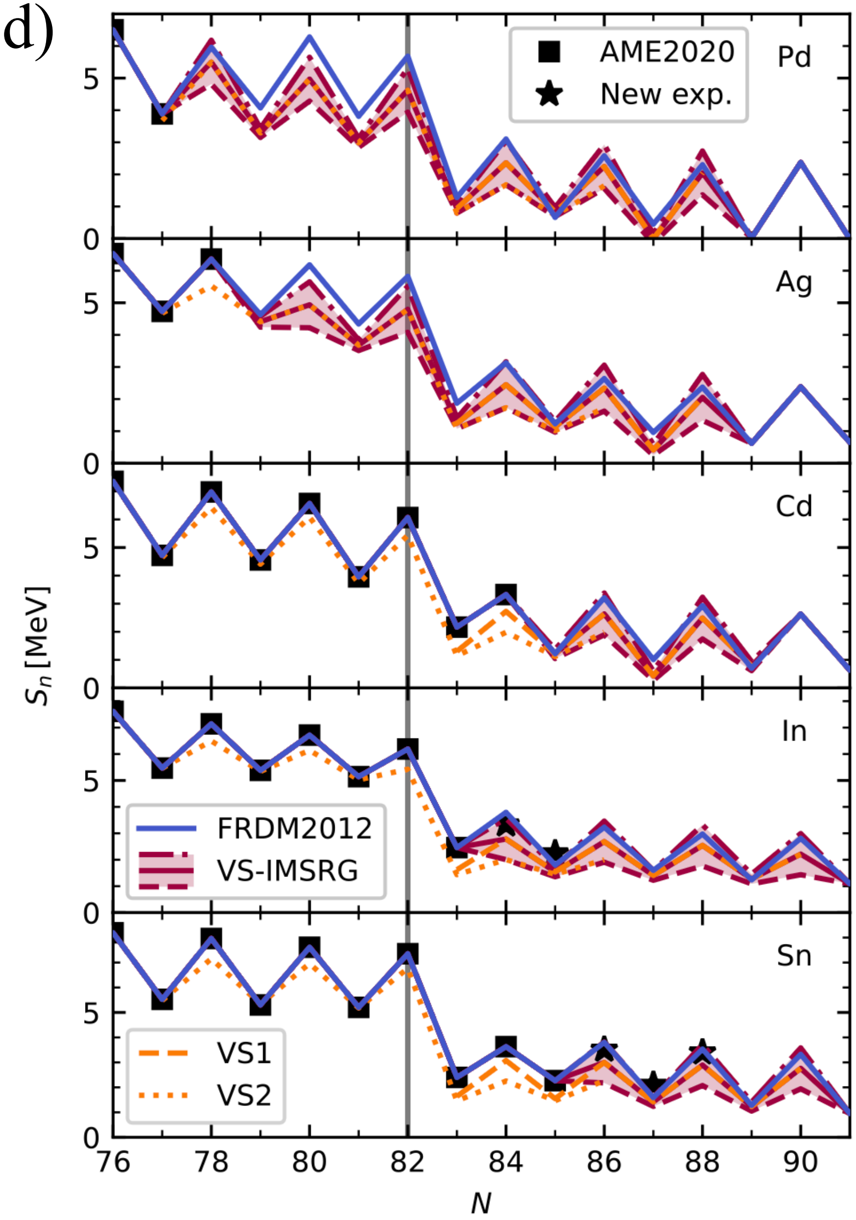
Kuske, Miyagi, Arcones, AS, arXiv:2509.19131

masses around N=82 (Sn, In, Cd, Ag, Pd)
→ interesting region at exp frontier

VS-IMSRG results with valence space
+ interaction uncertainties

separation energies have smaller uncertainties due to correlations; IMSRG(3f2) is within VS1, VS2

incorporate VS-IMSRG masses
with uncertainties (min/central/max)
in baseline AME2020 + FRDM2012



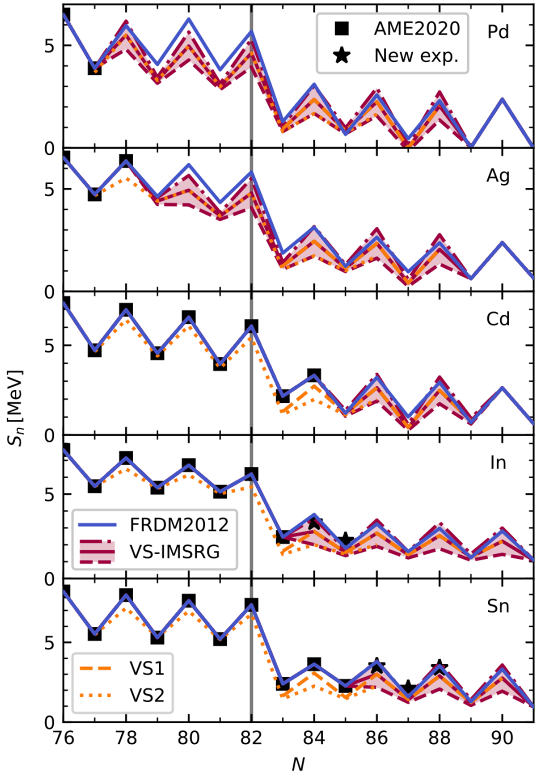
Nuclear masses around N=82 and r-process nucleosynthesis

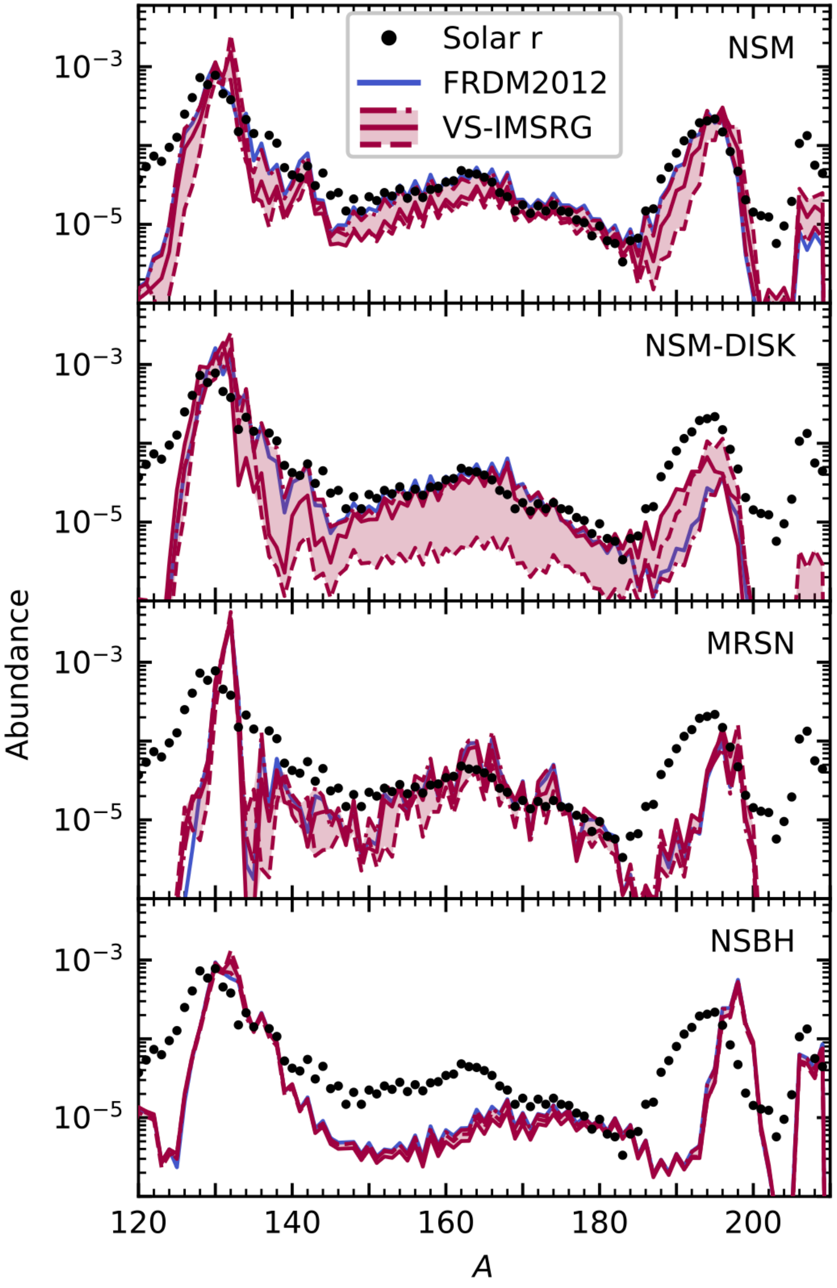
Kuske, Miyagi, Arcones, AS, arXiv:2509.19131

VS-IMSRG masses (min/central/max)

in baseline AME2020 + FRDM2012

explore r-process predictions for different astrophysics scenarios





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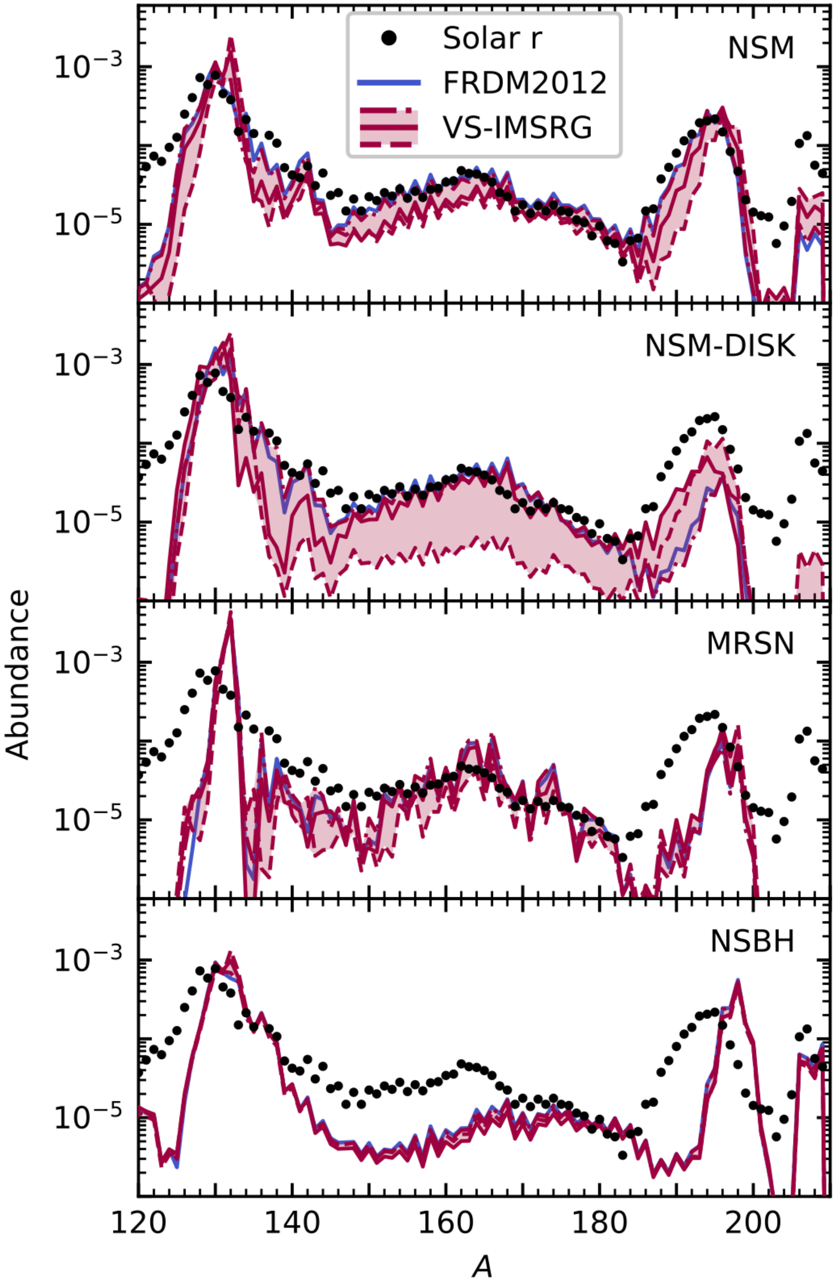
VS-IMSRG masses (min/central/max)
in baseline AME2020 + FRDM2012

explore r-process predictions for different astrophysics scenarios

largest effects for n-star mergers (NSM and NSM-DISK)

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



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explore r-process predictions for different astrophysics scenarios

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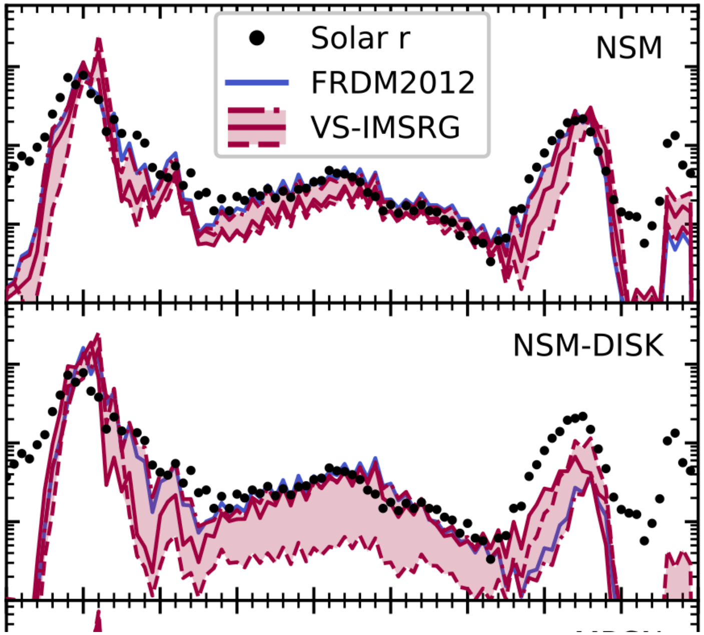
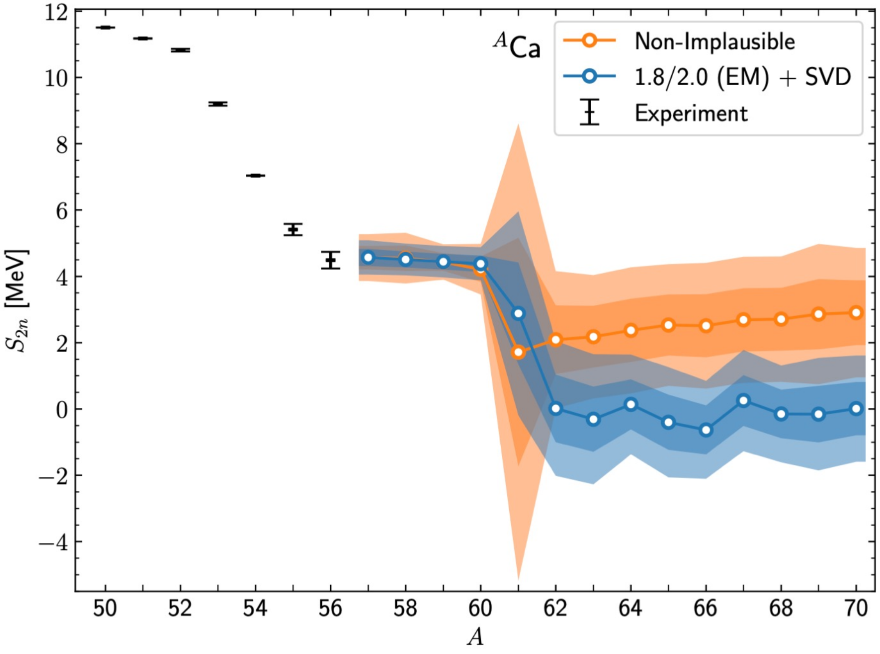
future: correlated ab-inito-based mass model see poster of Max Cincar

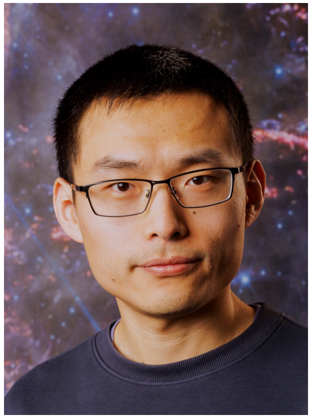


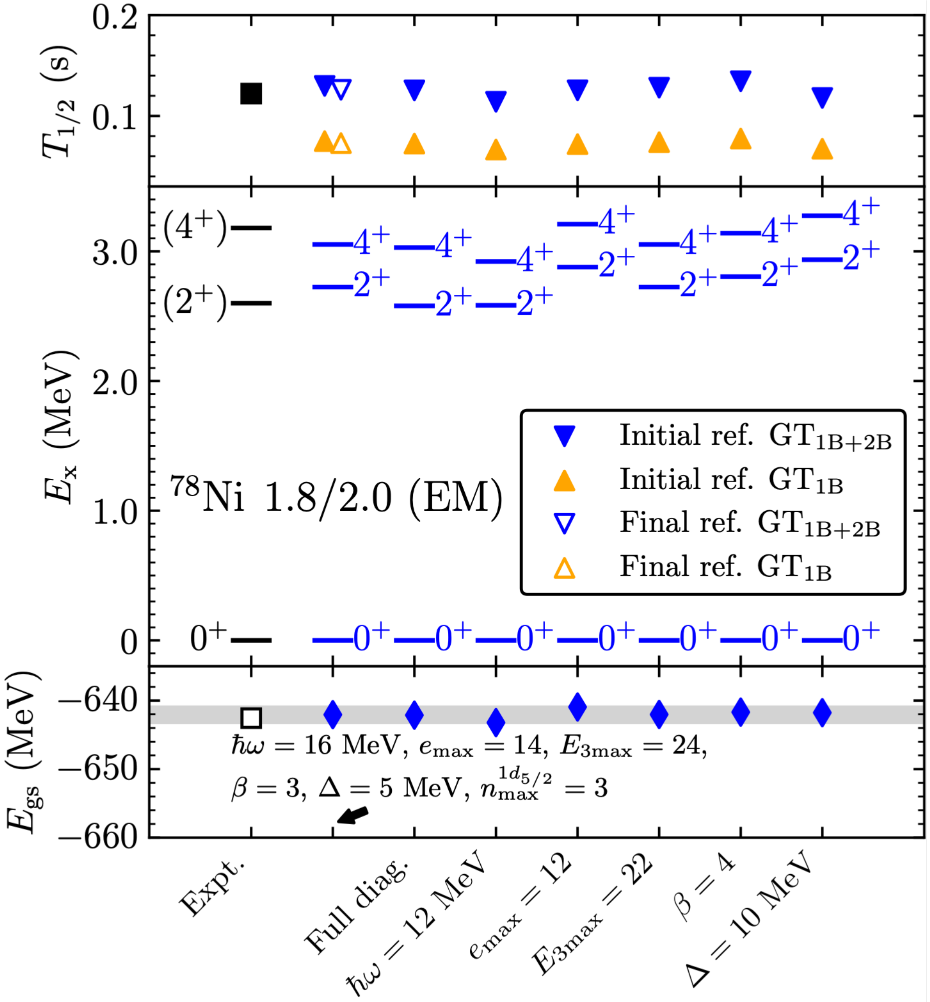


Gamow-Teller beta decays for N=50 nuclei

Zhen Li, Miyagi, AS, arXiv:2509.19131

VS-IMSRG calc for valence space on top of ^{48}Ca core
1.8/2.0 (EM) interaction with 1B + 2B currents,
test sensitivities to IMSRG + model space choices





very good agreement with exp
with 2B currents included,
weak sensitivities to theo choices

Gamow-Teller beta decays for N=50 nuclei

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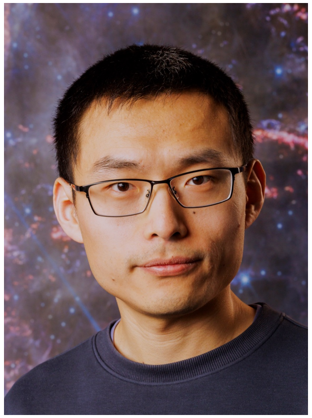
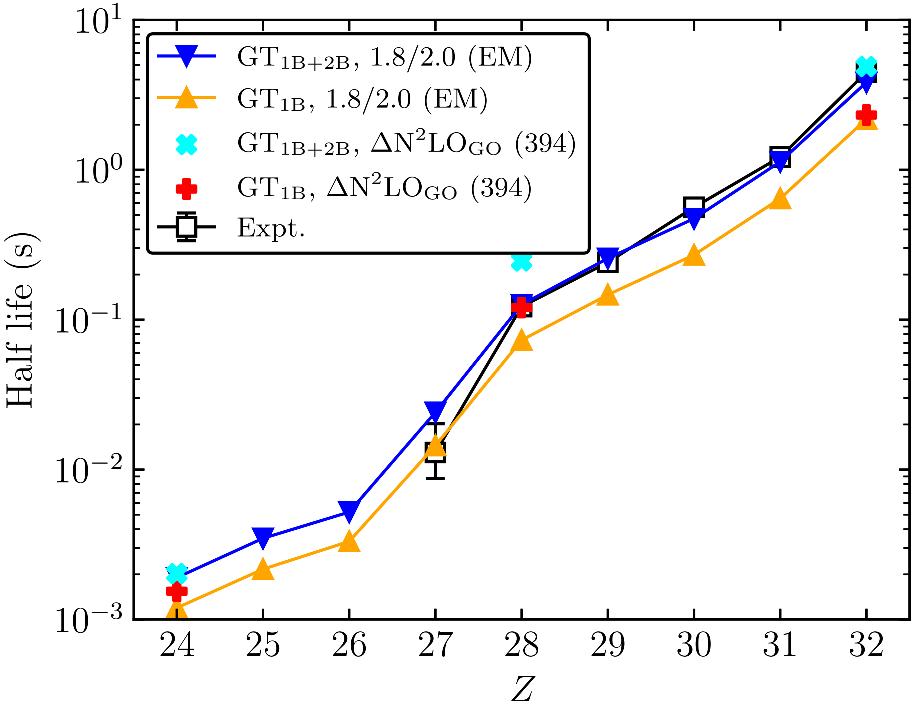


VS-IMSRG calc for valence space on top of ^{48}Ca core

1.8/2.0 (EM) interaction with 1B + 2B

for N=50 nuclei, explore in addition ΔN^2LO_{GO} interaction



overall good agreement with exp, without adjustments

Gamow-Teller beta decays for N=50 nuclei

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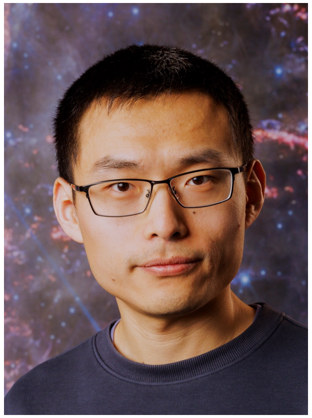

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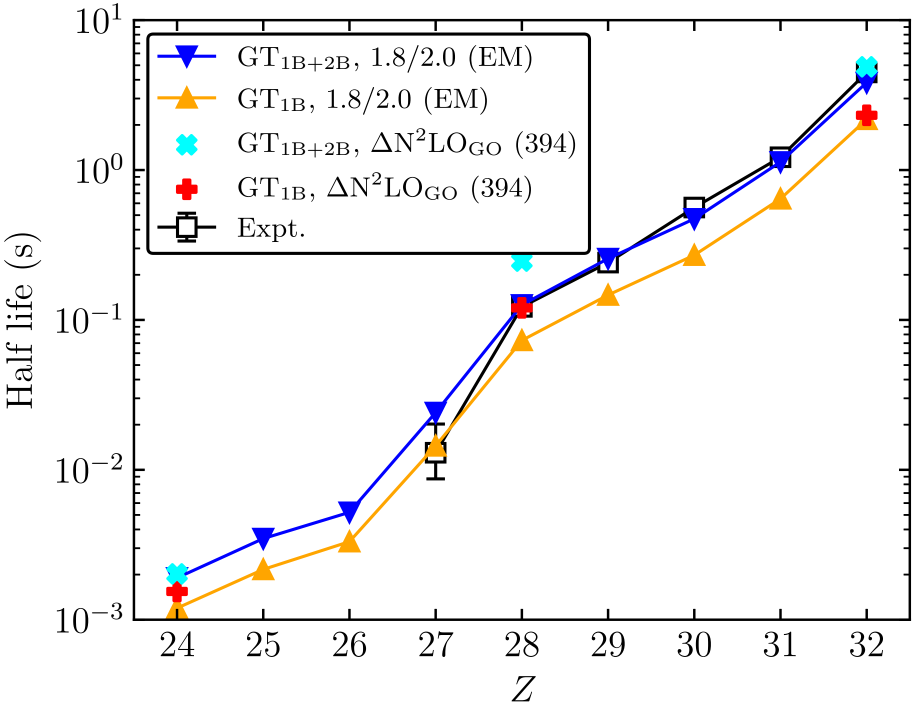

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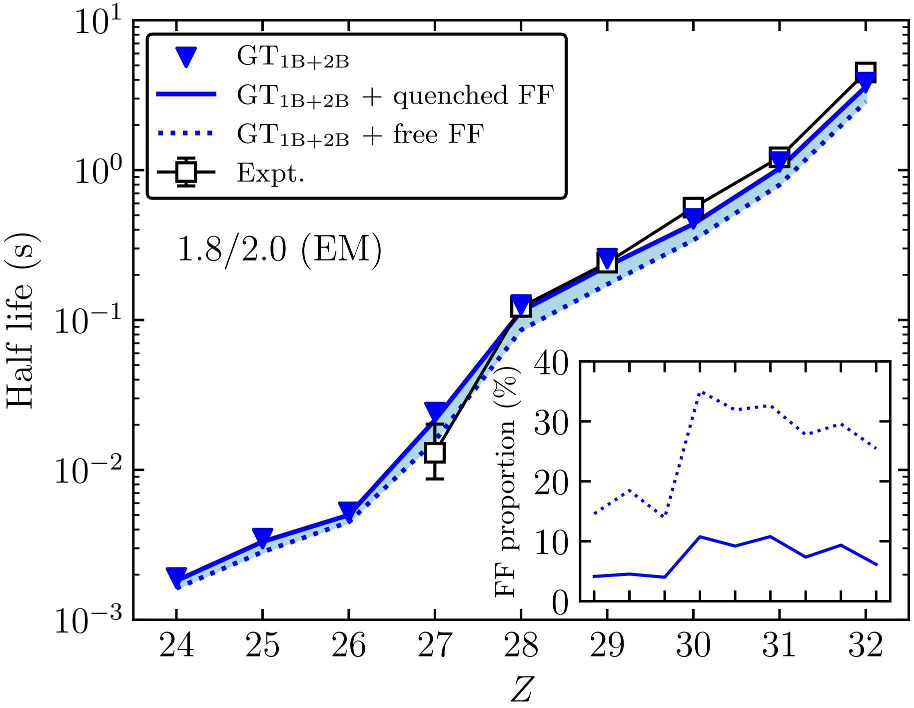


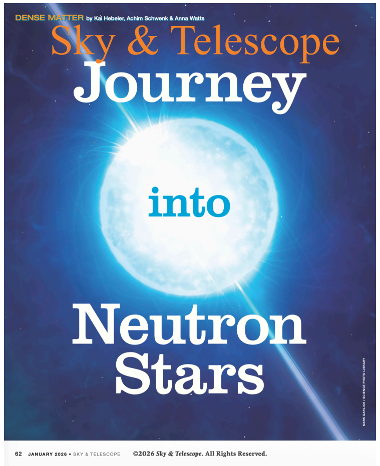
+ contributions from first-forbidden (FF) transitions

Extreme matter in neutron stars

Dense matter up to ~3-8 n_0 (95% CI, in heaviest n stars)

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

When (do) degrees of freedom change?



DENSE MATTER by Kai Hebeler, Achim Schwenk & Anna Watts

Sky & Telescope

Journey into Neutron Stars

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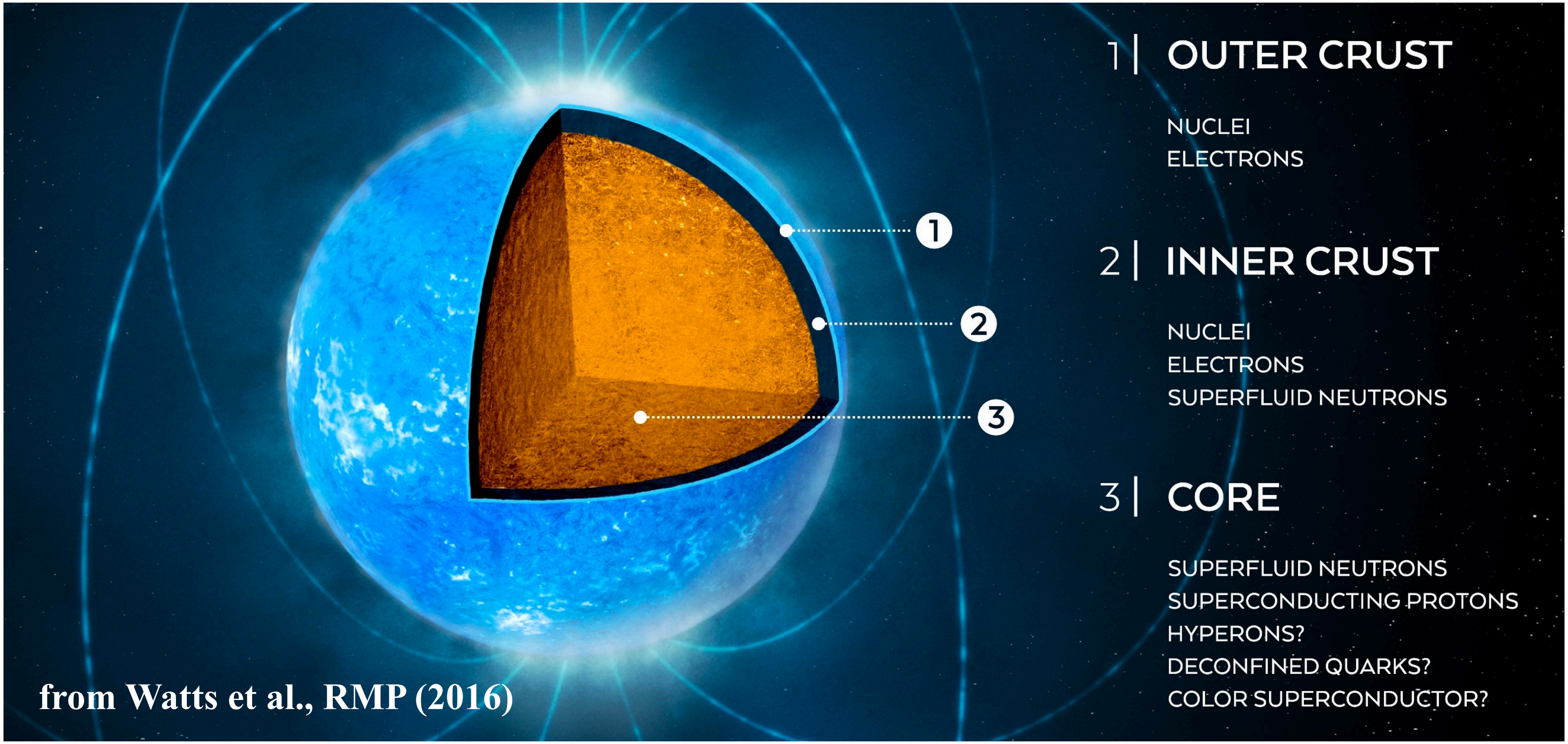
Chiral EFT sets pressure of first few km Hebeler et al., PRL (2010), ApJ (2013)

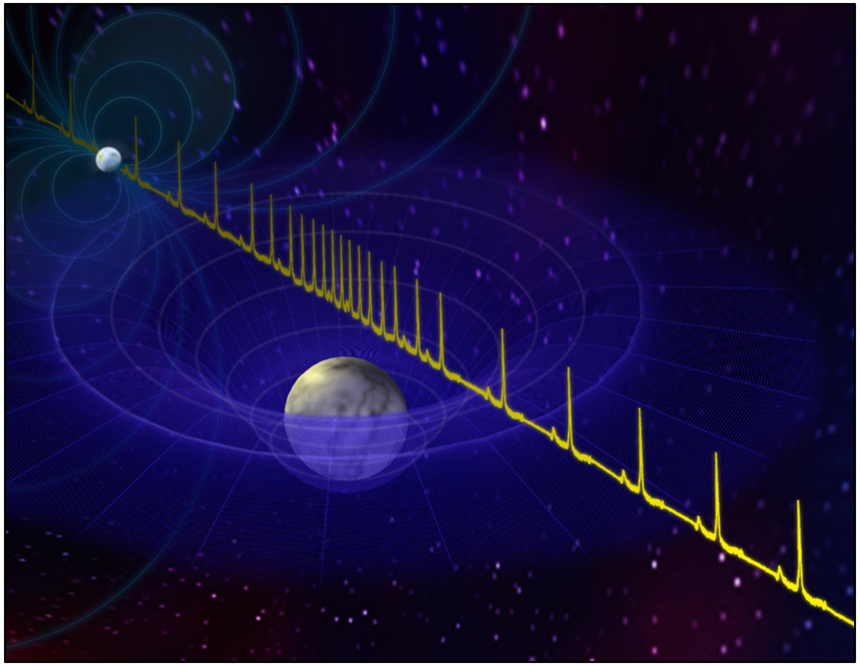


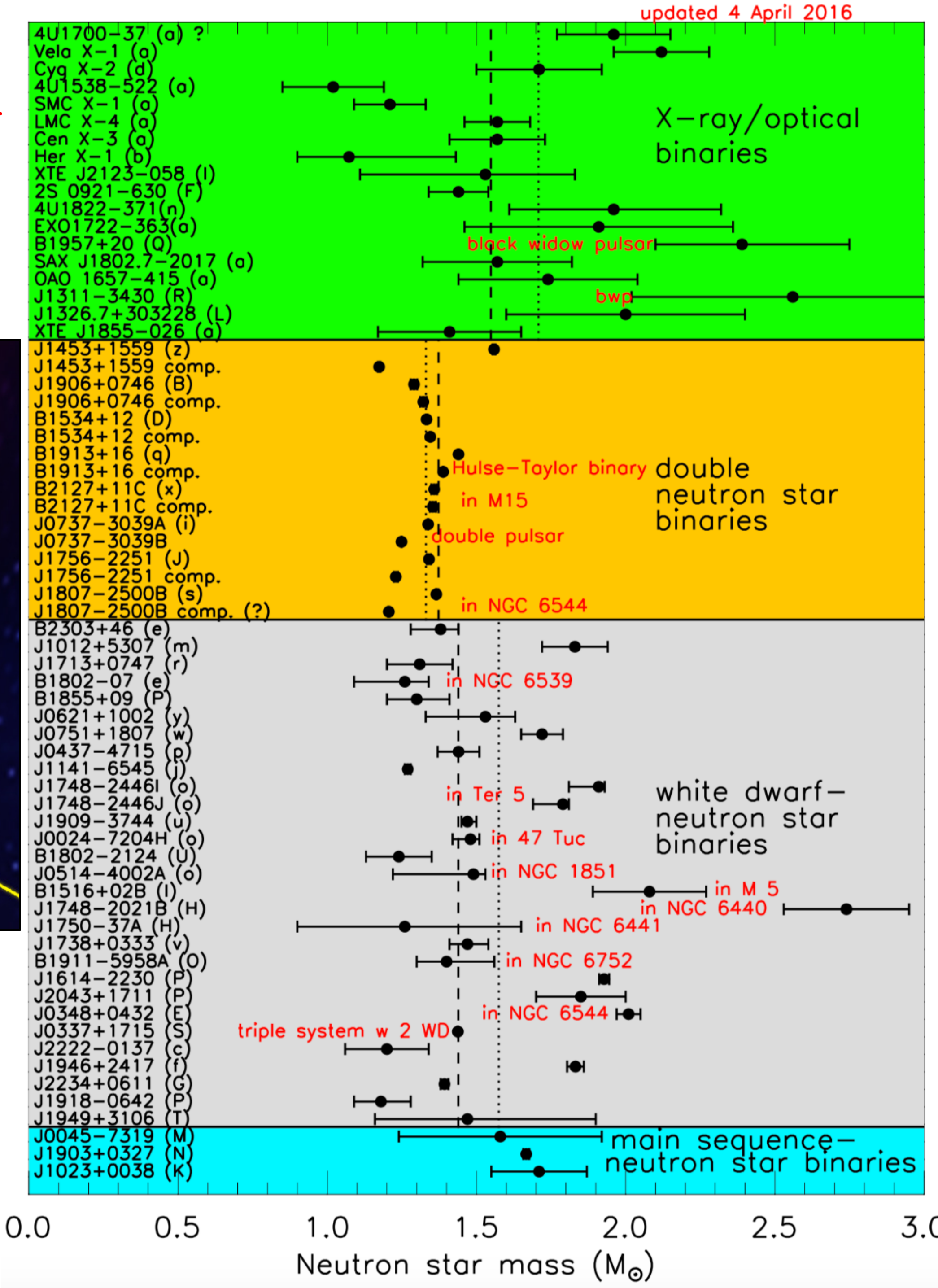
from Watts et al., RMP (2016)

Neutron star masses

from Jim Lattimer

mass measurements from
radio pulsar timing





three 2 M_{sun} n stars observed

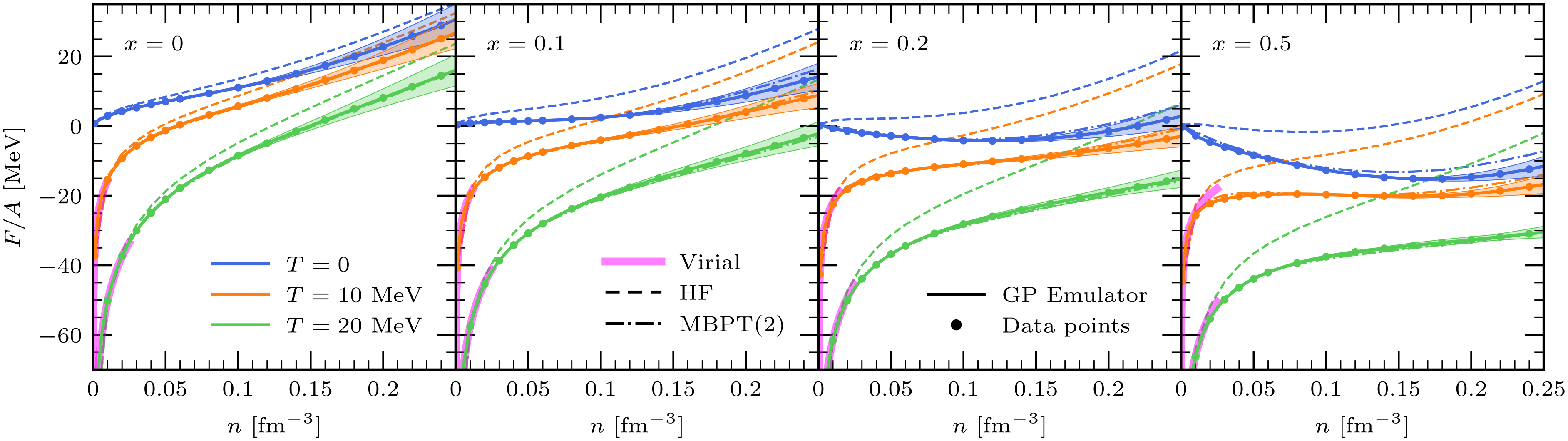
J1614: Demorest et al., Nature (2010),
J0348: Antoniadis et al., Science (2013),
J0740: **2.08±0.07 M_{sun}** Fonseca et al., (2021)

EOS for arbitrary proton fraction and temperature

Keller, Hebeler, AS, PRL (2023)

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

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



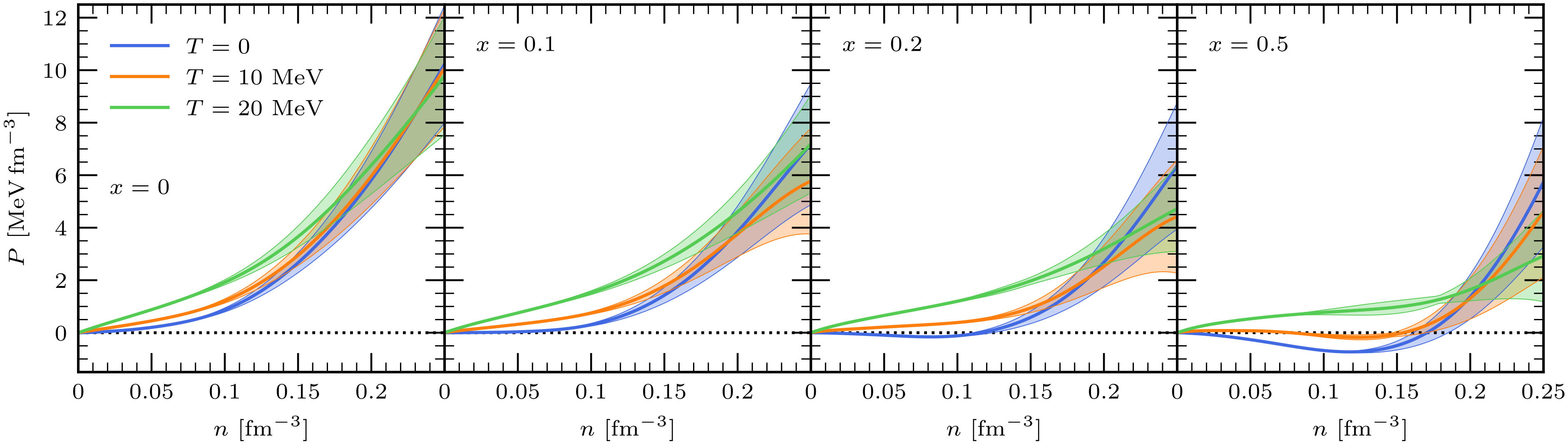
excellent reproduction of free energy data by Gaussian process (GP)

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

EOS for arbitrary proton fraction and temperature

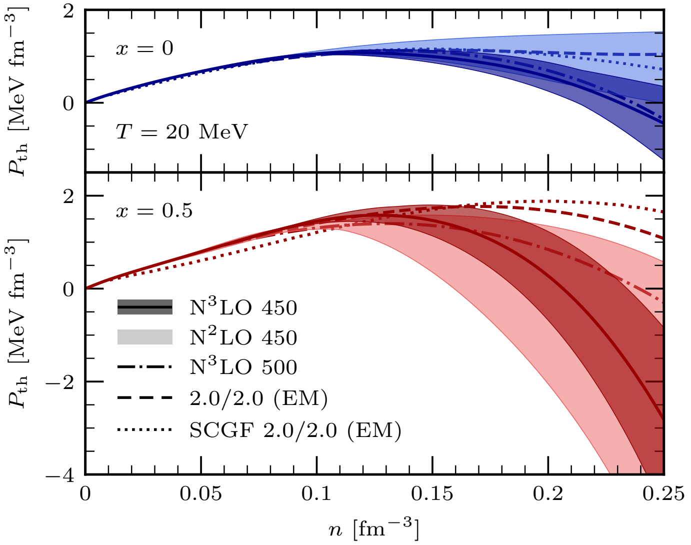
Keller, Hebeler, AS, PRL (2023)

GP emulator to calculate pressure (thermodyn. consistent derivatives)



pressure isothermals cross at higher densities
→ negative thermal expansion

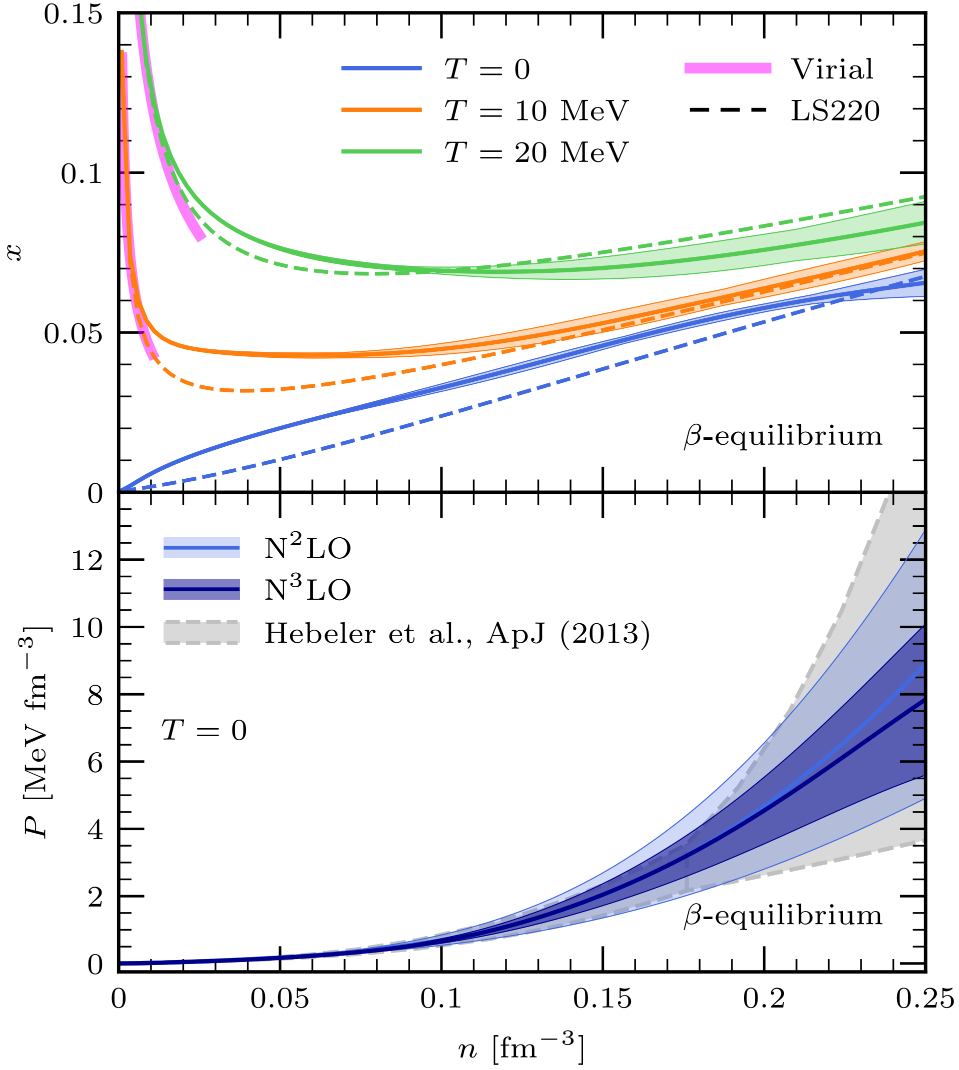
thermal part of pressure decreases with
increasing density,
found for all chiral interactions studied,
is related to density dep. of m* from 3N



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



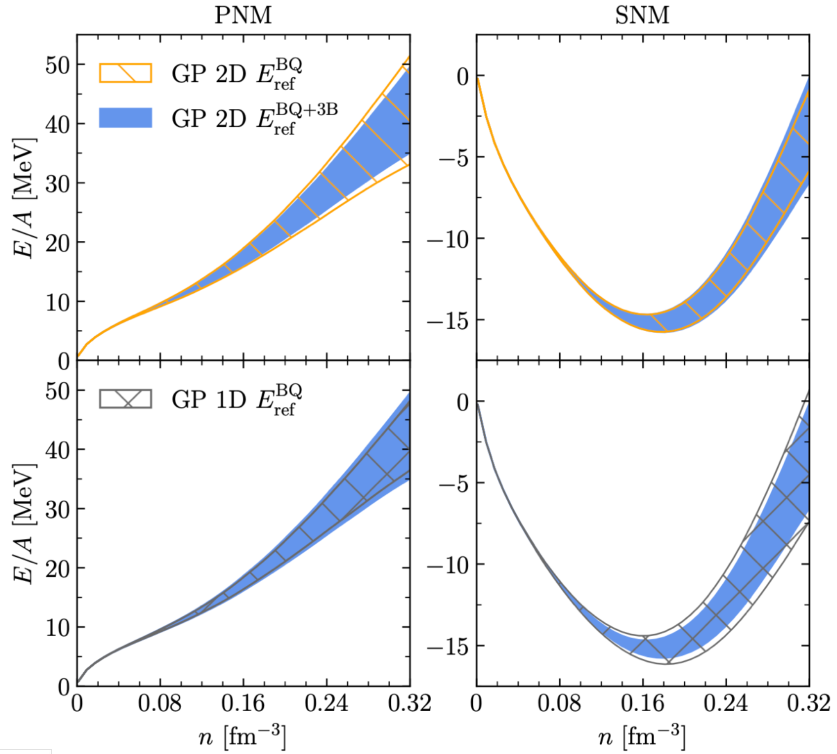
EOS of neutron star matter at N^{2}LO and N^{3}LO,
no indication of EFT breakdown

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

EFT truncation uncertainties from 2d GP

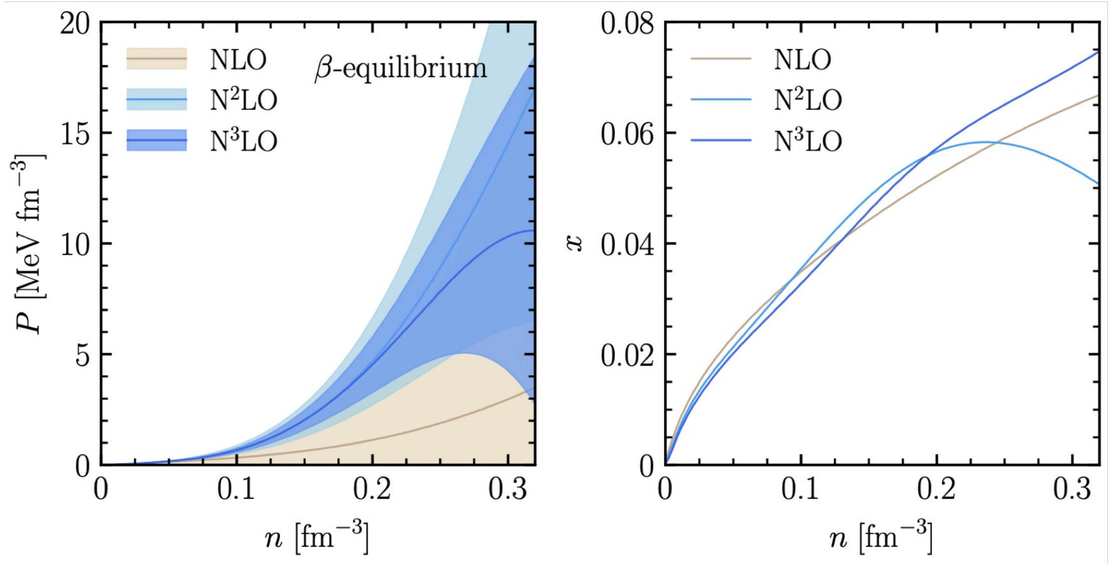
Göttling, Hoff, Hebeler, AS, arXiv:2512.19593

GP-Bayesian uncertainties from order-by-order analysis with 3-body-informed reference energy



agrees well with 1d GP from Drischler et al. for PNM and SNM

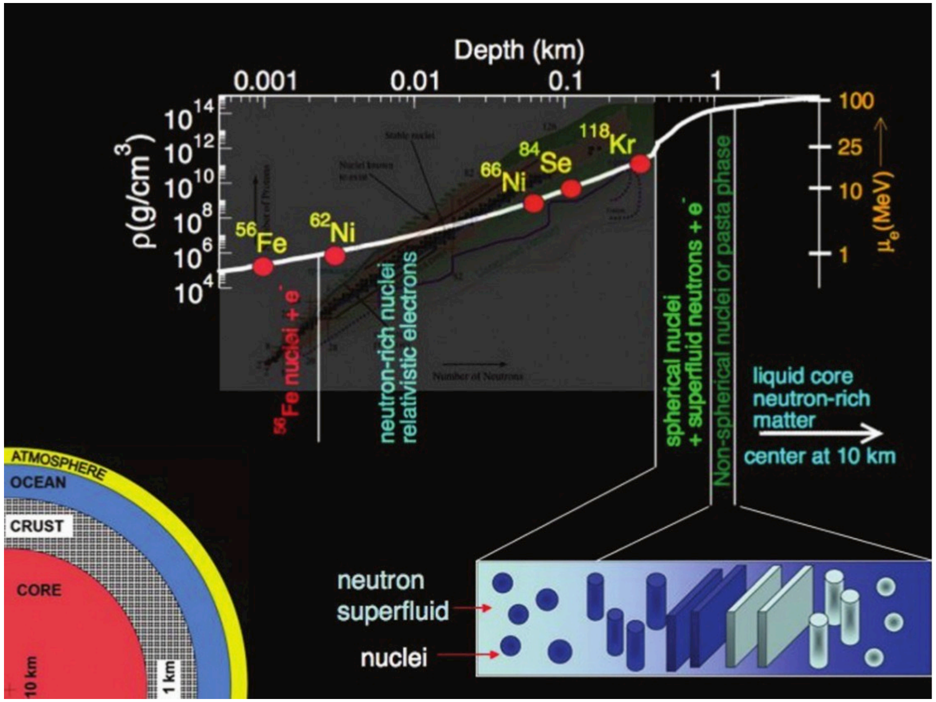
GP-Bayesian uncertainties for EOS in beta equilibrium

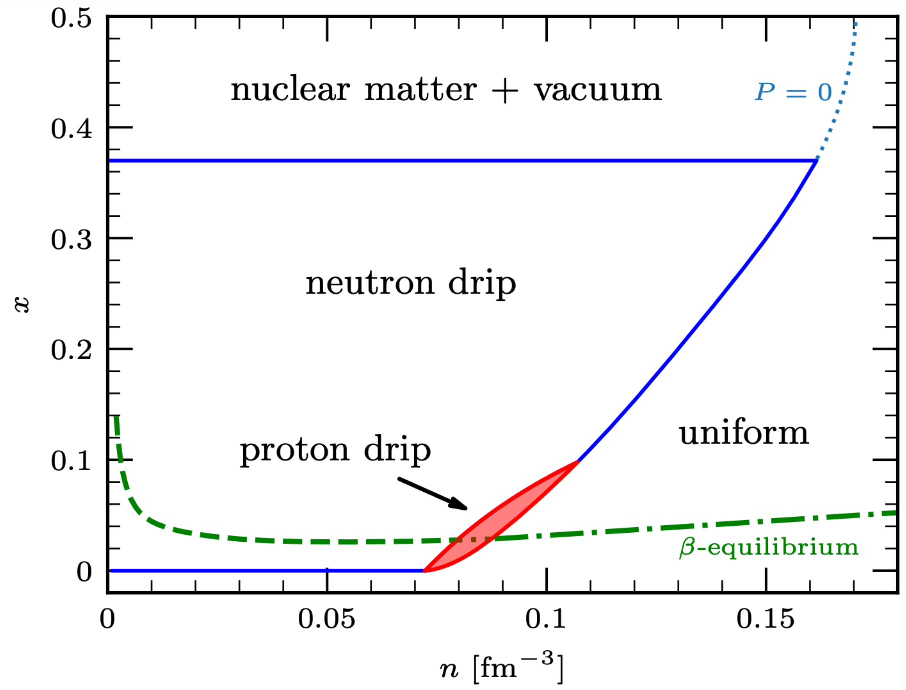


Subnuclear phase diagram of neutron star matter

~ 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:

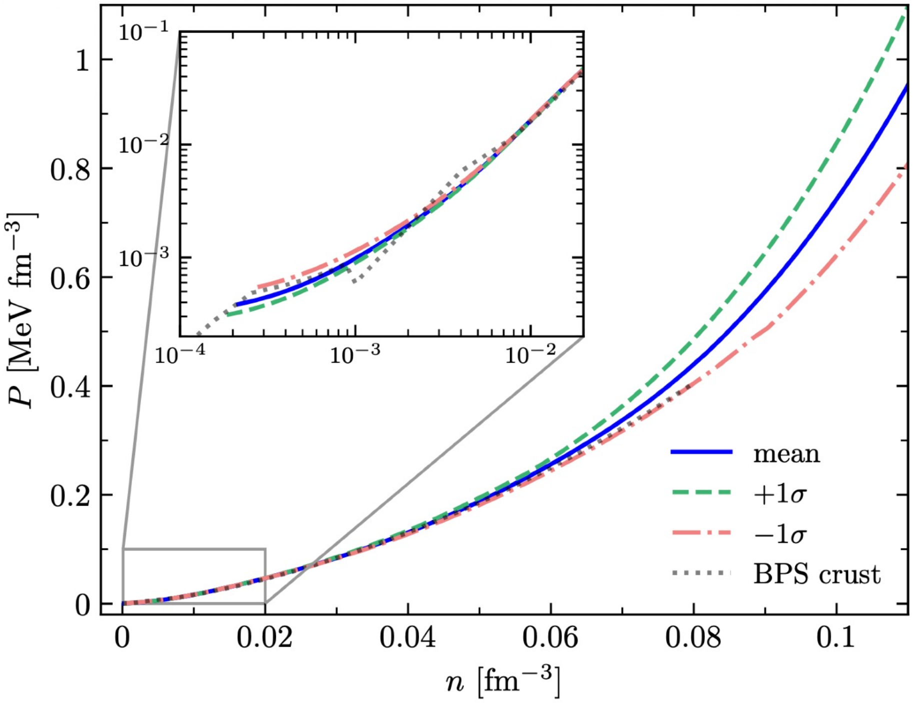
robust for any reasonable EOS, proton drip aids pasta formation

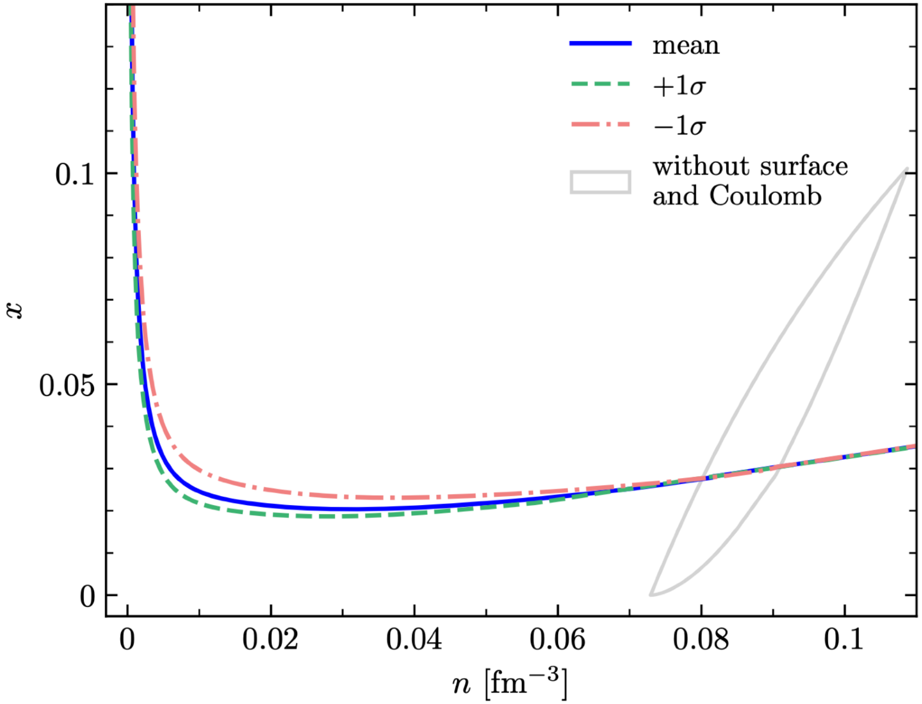
Consistent inner-crust EOS

Göttling, Hoff, Hebeler, AS, arXiv:2512.19593

construct inner-crust EOS consistent with uniform asymmetric matter calculations with EFT uncertainties at N^{3}LO

based on compressible liquid drop model
with surface tension and Coulomb effects (adjusted to exp. masses)



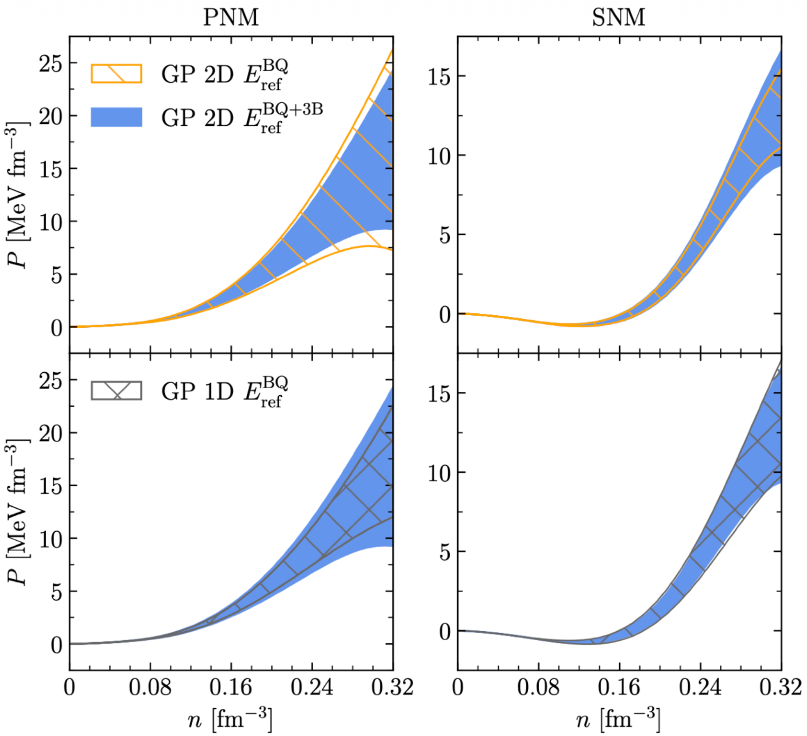


future: include in astrophysics inference framework

Constraints from neutron skins and related probes

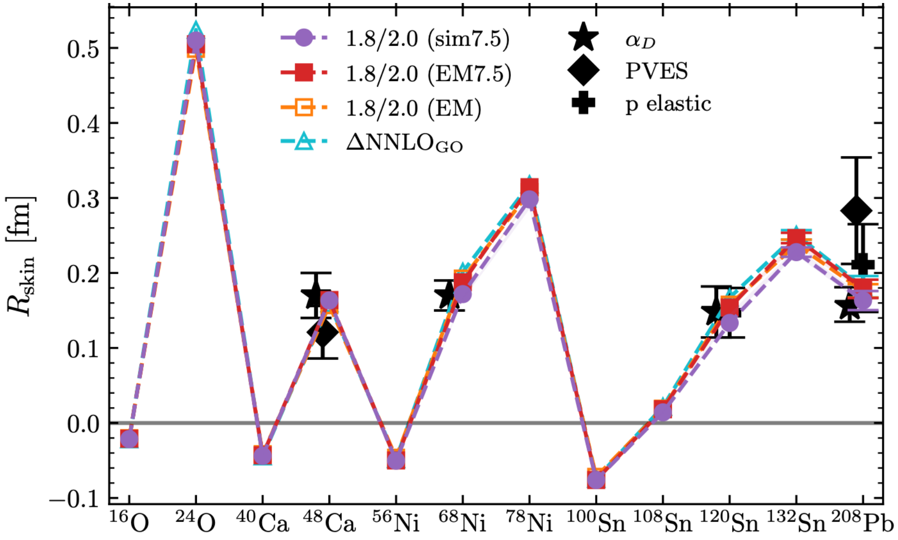
neutron skin = $R_n - R_p$
probes neutron matter pressure,
large pressure ~ larger skin

different experiments sensitive to neutron skin, probes matter below n_0 where chiral EFT uncertainties are smaller



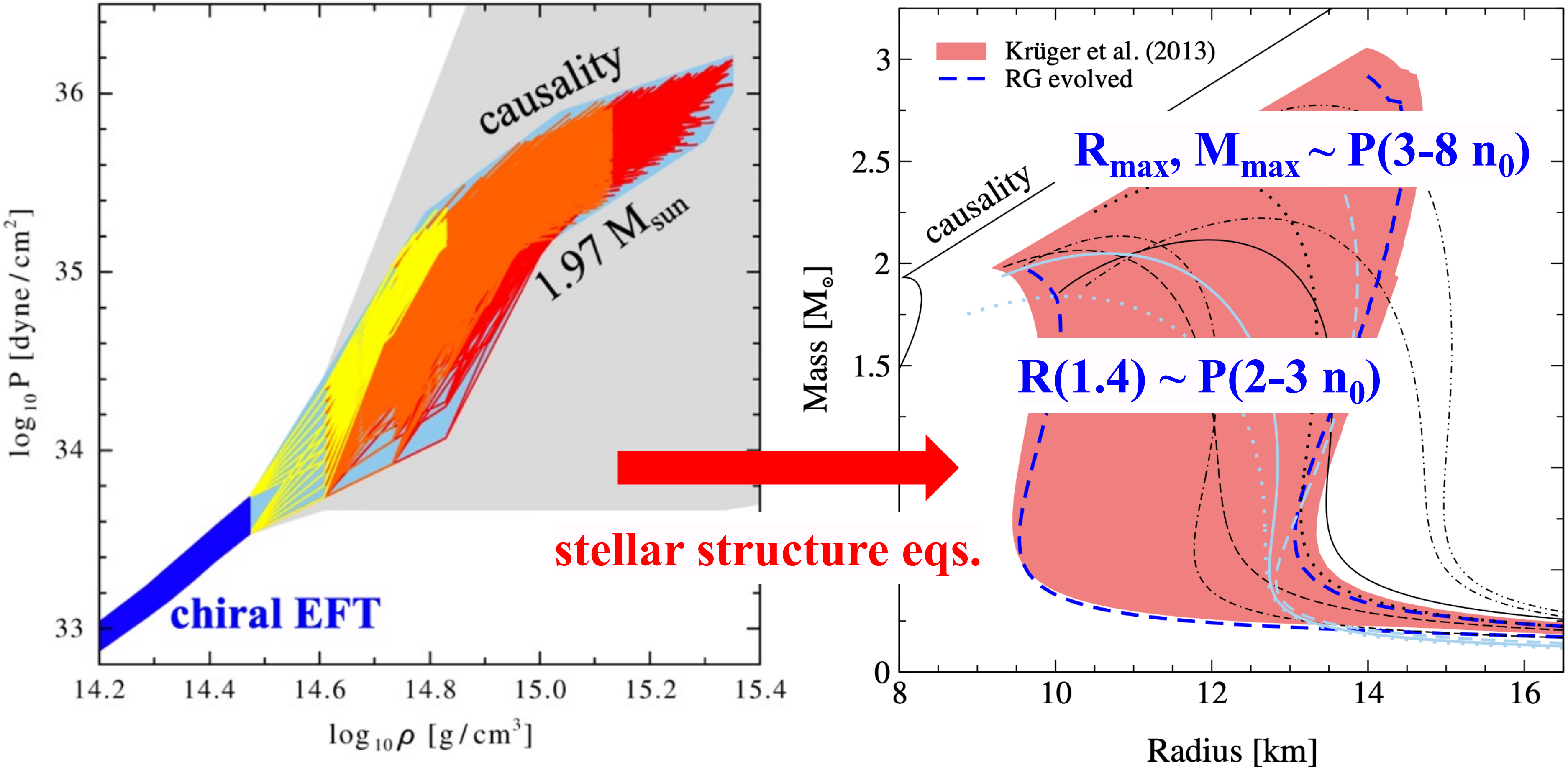
→ neutron skins tightly predicted in chiral EFT calculations

Arthius et al., arXiv:2401.06675,
Novario et al., PRL (2023)



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



R_{max}, M_{max} ~ P(3-8 n_0)

R(1.4) ~ P(2-3 n_0)

stellar structure eqs.

piecewise polytropes (PP) includes phase transitions

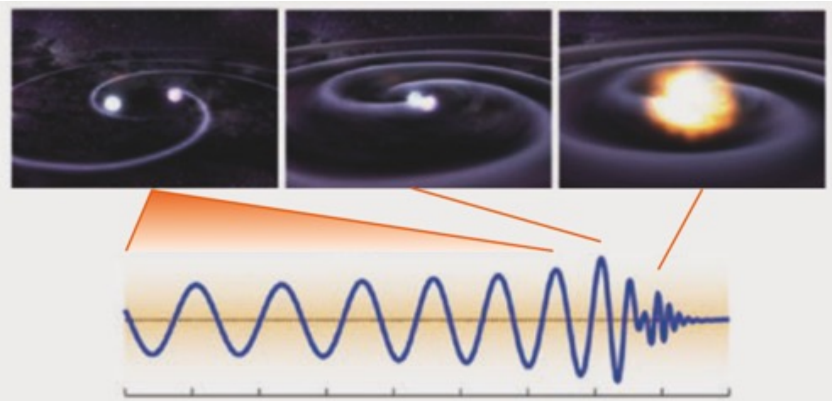
other high-density extensions use speed of sound parametrizations (CS), Gaussian processes, piecewise speed of sound,…

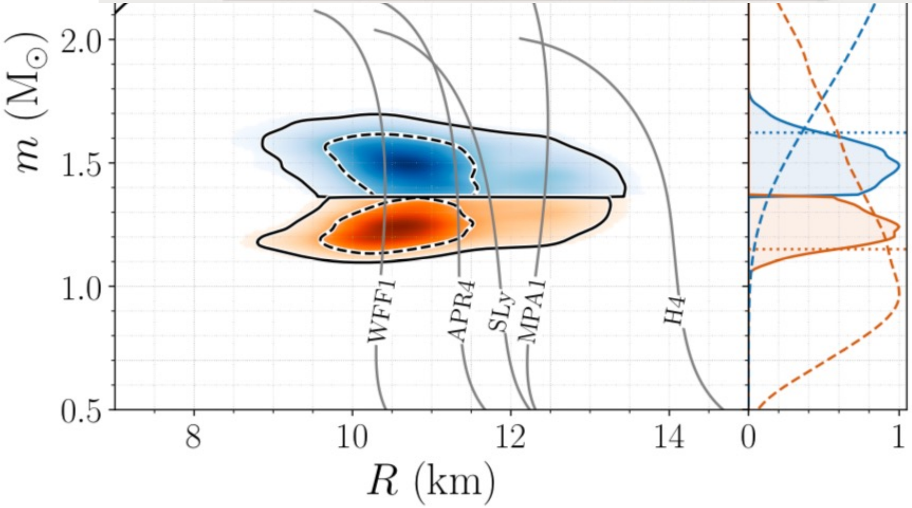
Neutron star radius information

from gravitational waves and pulse-profile modeling

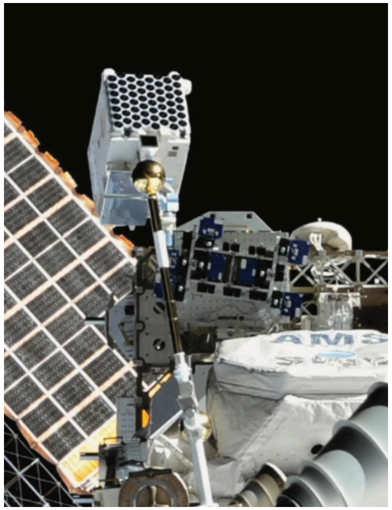
GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration



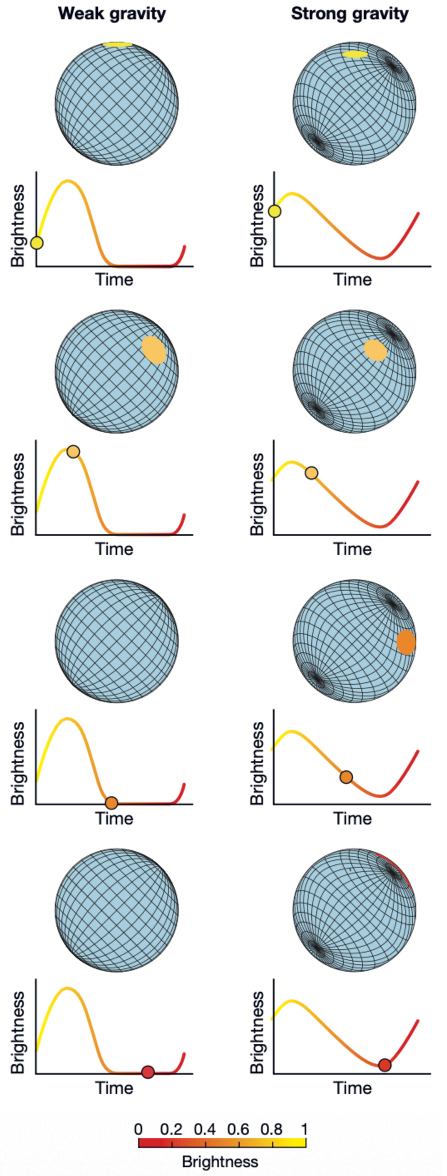


tidal deformability ~ R^5



sensitive to compactness

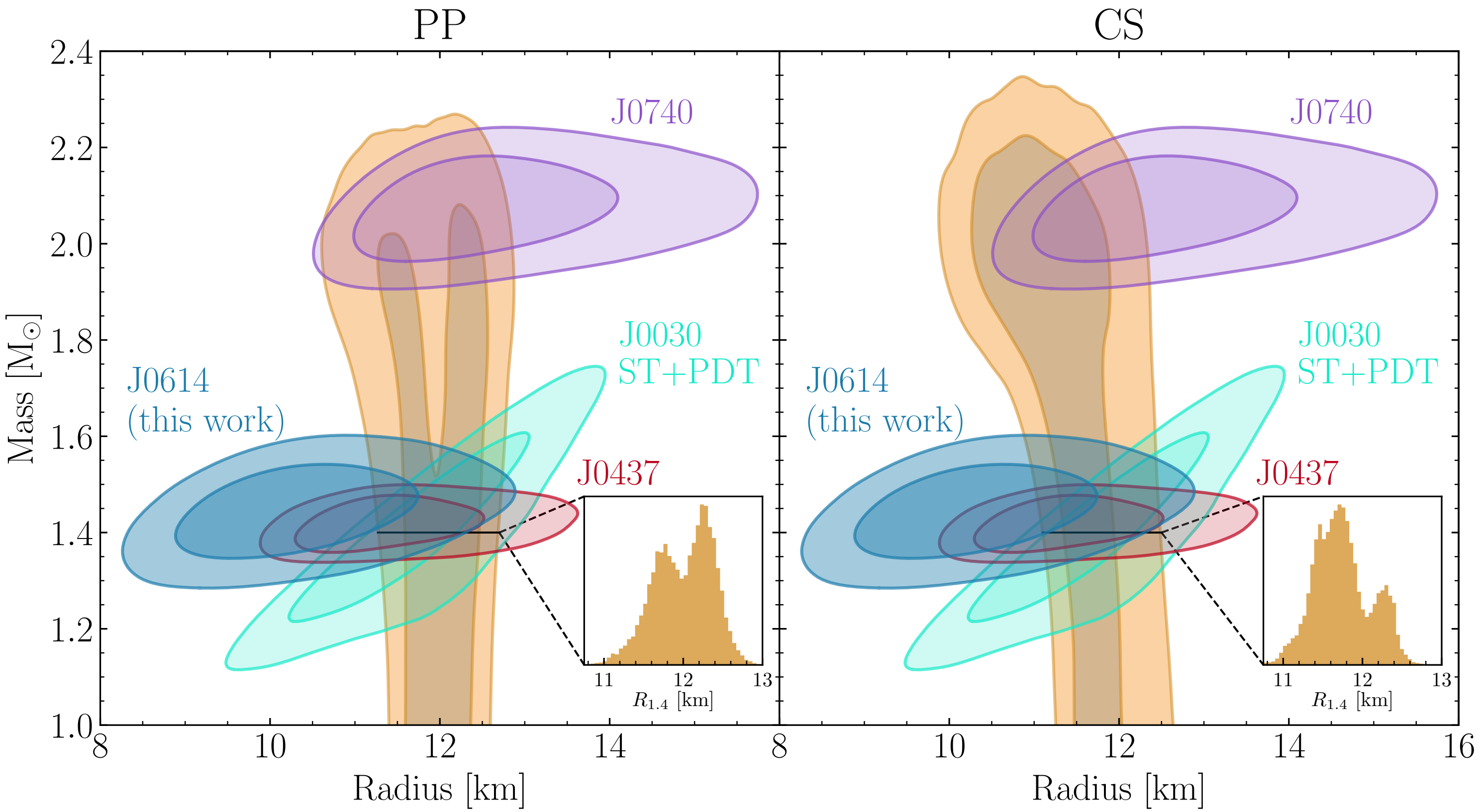
M/R



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 dist. ~12 km very similar for PP/CS high-density extensions

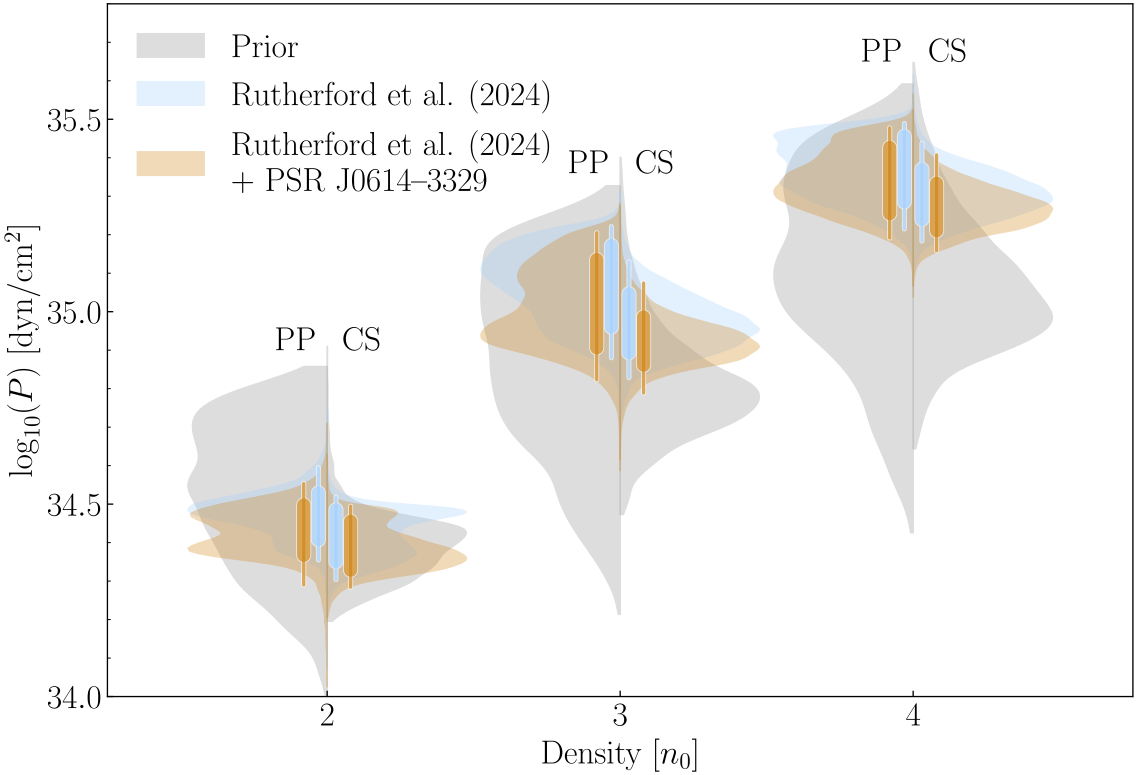
Constraints at intermediate densities

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

posters at 3-4n_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

Summary

Chiral EFT + powerful many-body methods

→ reliable predictions for neutron-rich nuclei for r-process

EOS up to ~1-2 n_0 with controlled uncertainties

← high-density constraints from multimessenger astrophysics

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