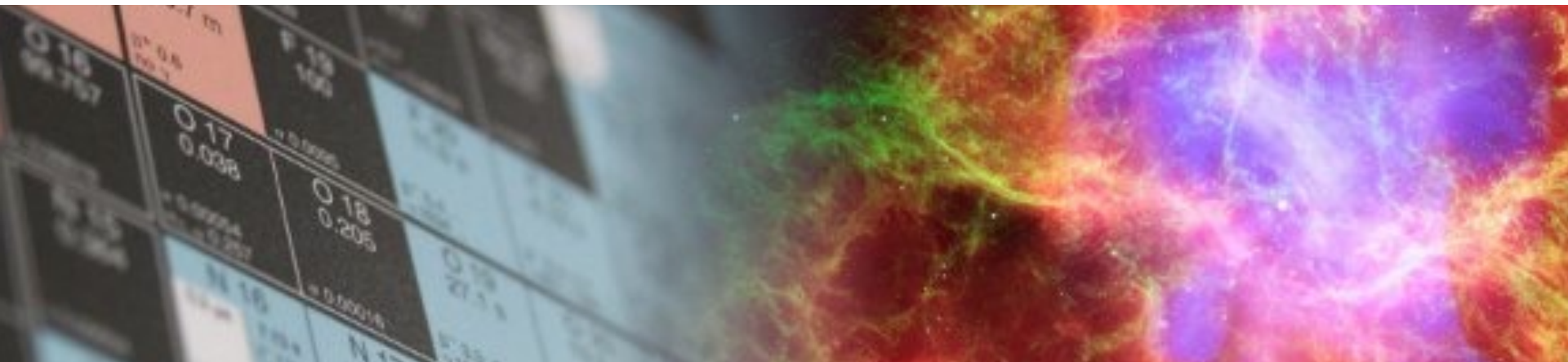


Neutron-rich matter from chiral EFT, experiments, and observations

Achim Schwenk



TECHNISCHE
UNIVERSITÄT
DARMSTADT



“Unlocking the QCD phase diagram”, Sept. 7, 2026



European Research Council
Established by the European Commission

ERC AdG EUSTRONG



LOEWE

Exzellente Forschung für
Hessens Zukunft

Happy 80th birthday, Peter!

with great thanks for EMMI

for bringing me to Darmstadt

for all your support

for meetings with time for physics

All the very best for many more
years to come!!



Happy 80th birthday, Peter!



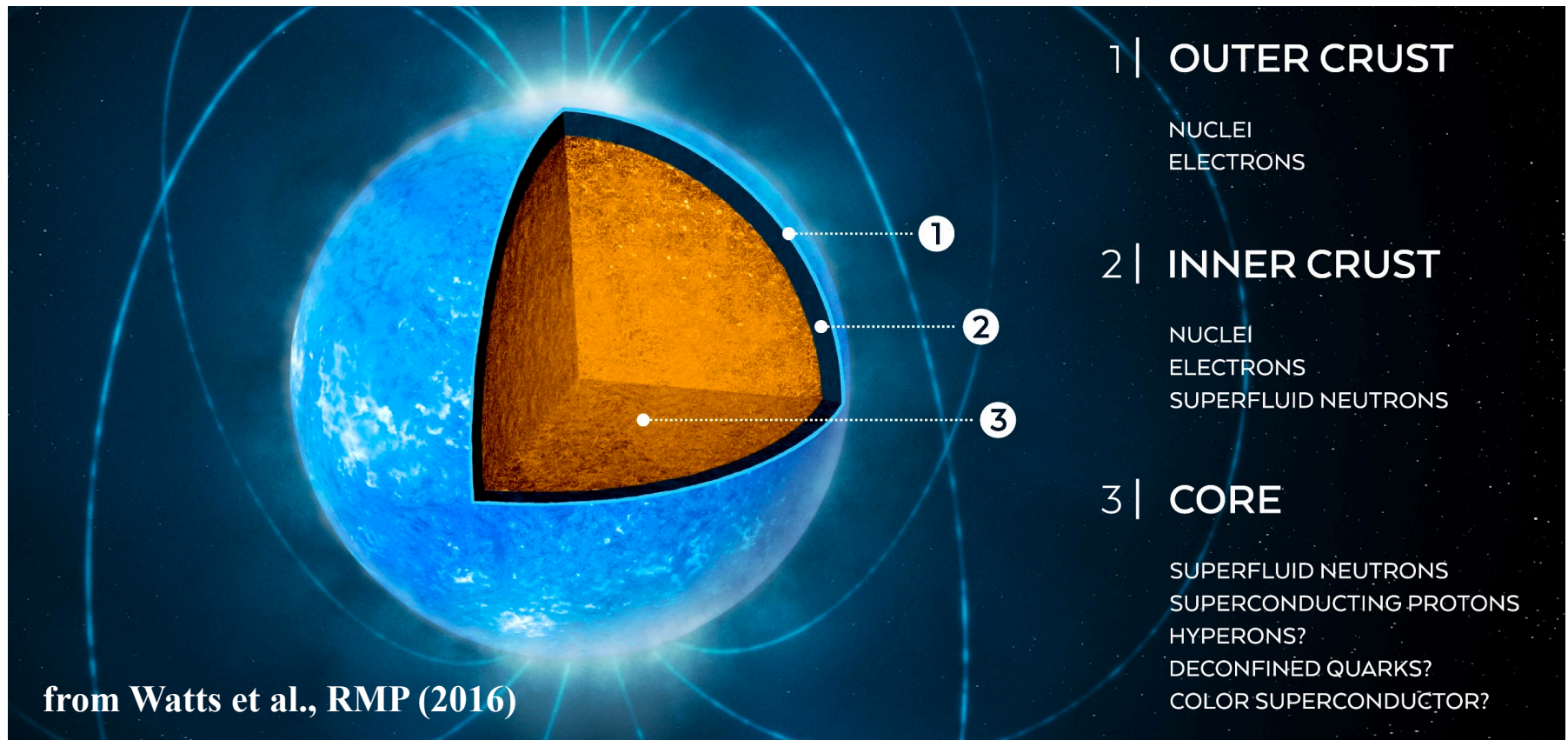
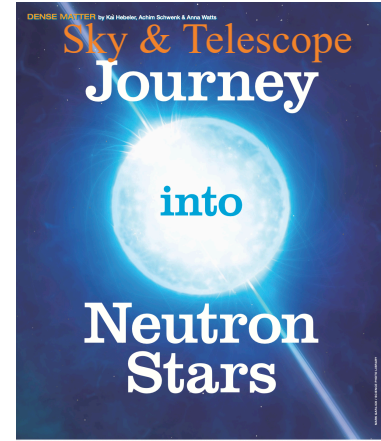
Extreme matter in neutron stars

Dense matter up to $\sim 3-8 n_0$ (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?

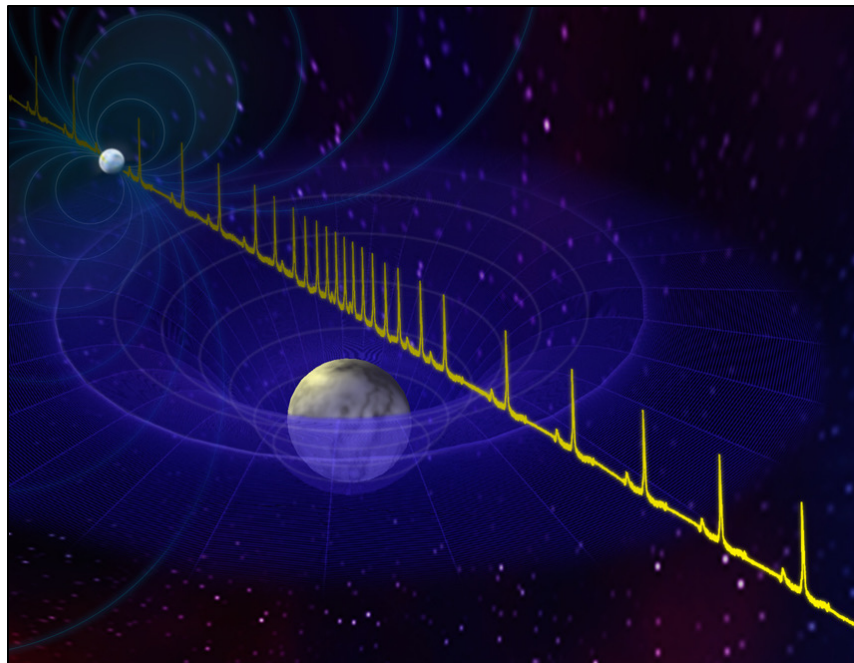
Chiral EFT sets pressure of first few km Hebeler et al., PRL (2010), ApJ (2013)



Neutron star masses

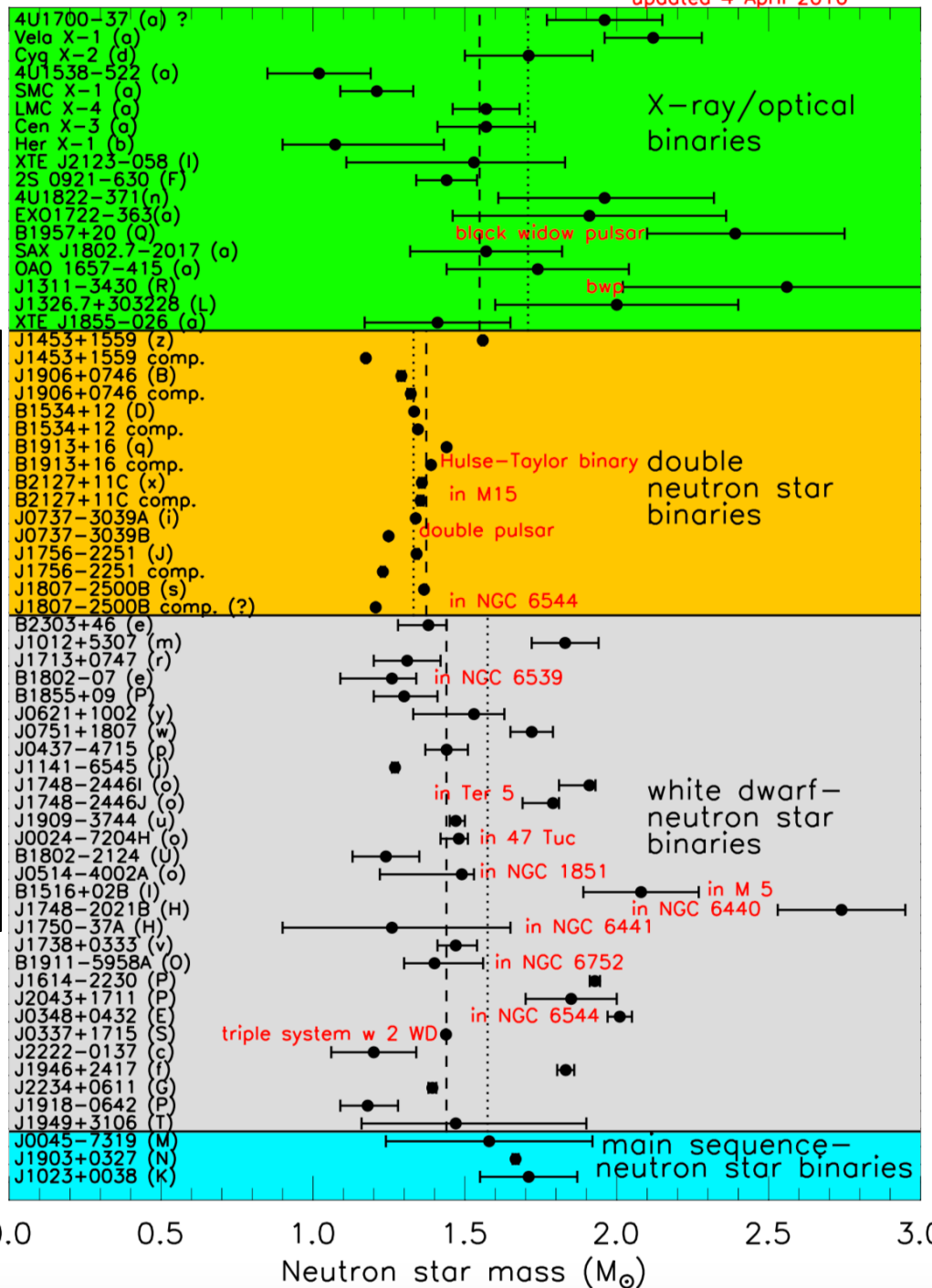
from Jim Lattimer

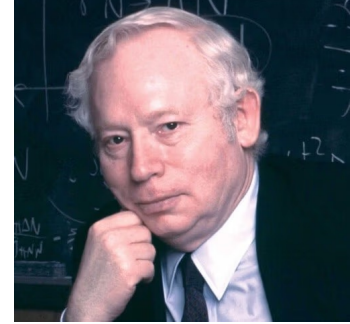
mass measurements from
radio pulsar timing



three $2 M_{\text{sun}}$ n stars observed

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





Chiral effective field theory for nuclear forces

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

	NN	3N	4N
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$			
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$			
N ² LO $\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$			
N ³ LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$			

derived in (1994/2002)

(2011)

(2006)

based on symmetries of strong interaction (QCD)

long-range interactions governed by pion exchanges

powerful approach for many-body interactions

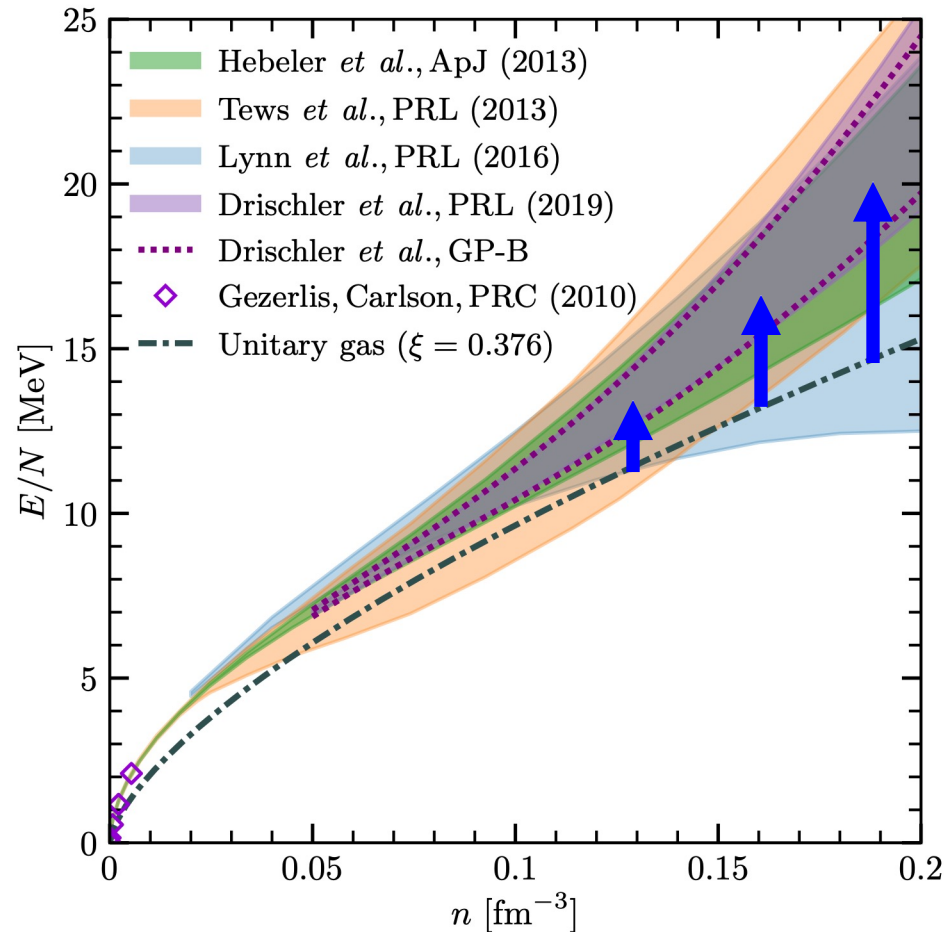
all 3- and 4-neutron forces predicted to N³LO

Tews et al., PRL (2013)

enables uncertainty quantification from higher orders and input data

Chiral EFT calculations of neutron matter

good agreement up to saturation density for neutron matter
including NN, 3N, 4N interactions up to $N^3\text{LO}$



slope determines pressure of
neutron matter

comparison to unitary Fermi gas
measured with cold atoms

stronger increase towards higher
densities (EOS becomes stiffer)
due to **repulsive 3N forces**

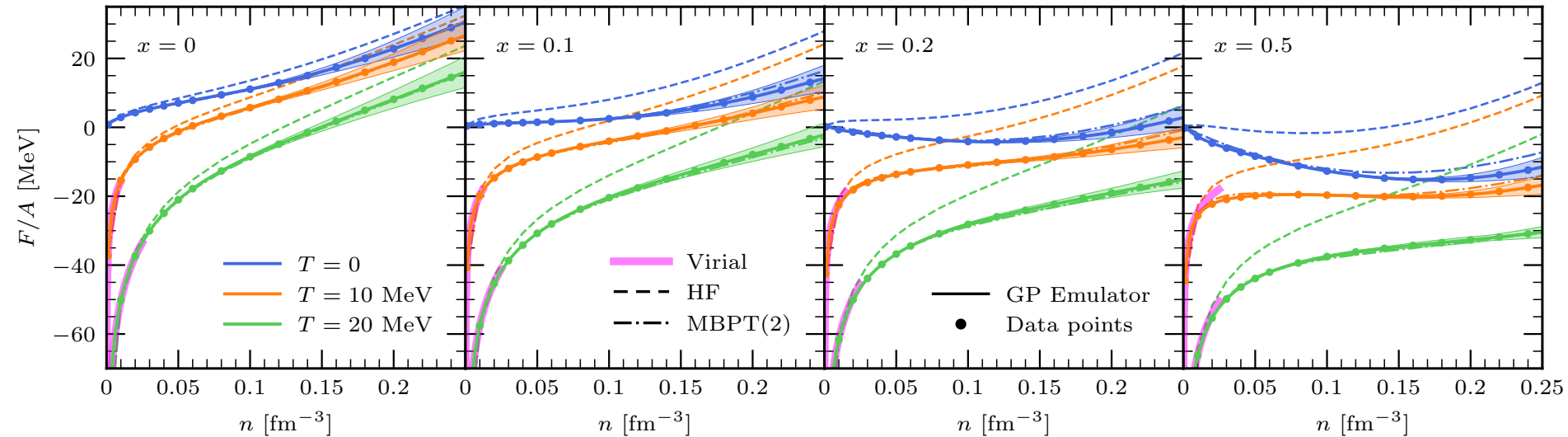
comparison from Huth *et al.*, PRC (2021)

EOS for arbitrary proton fraction and temperature

Keller, Hebeler, AS, PRL (2023)

based on chiral NN+3N interactions to N³LO

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



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

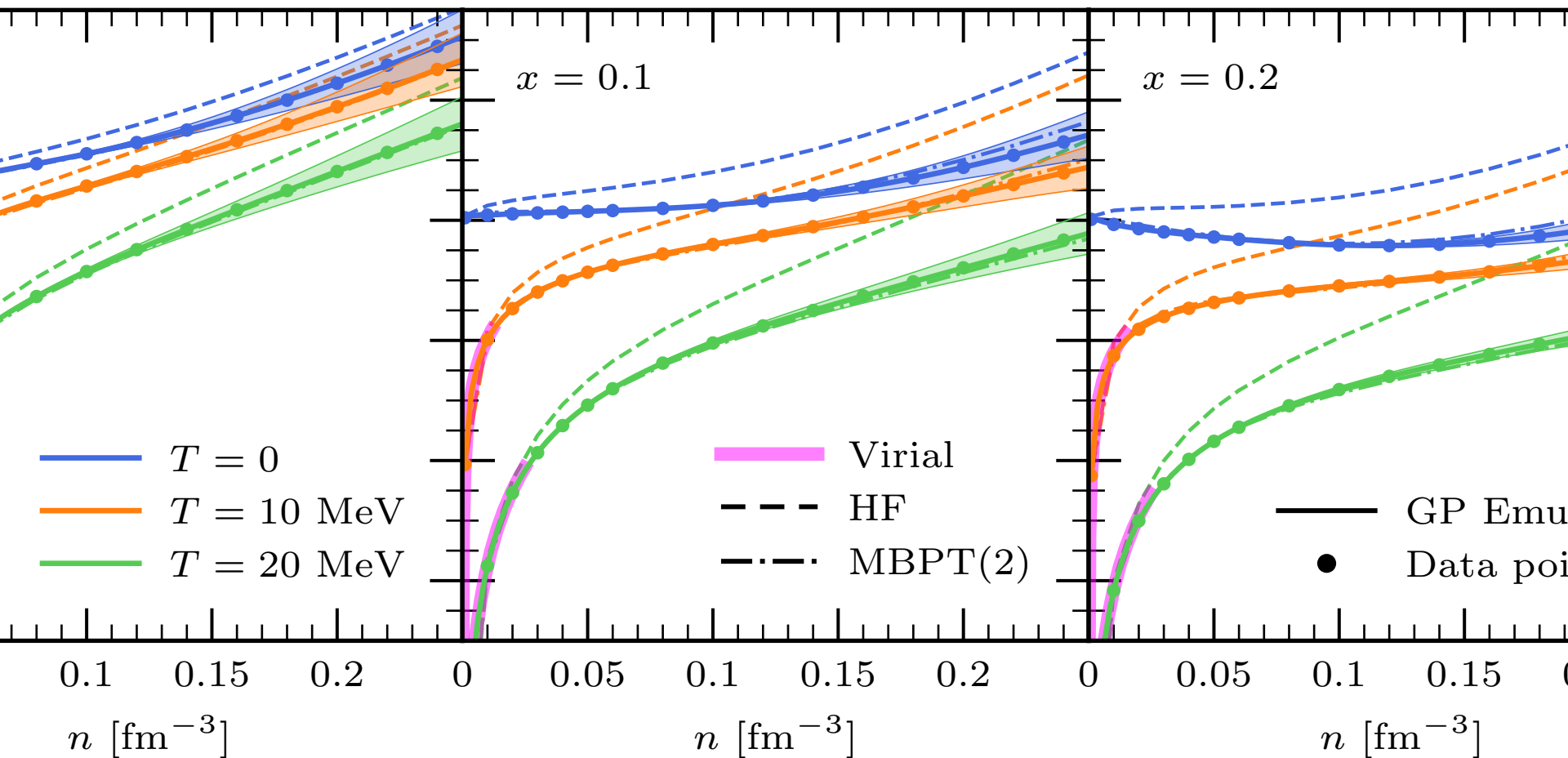
agrees with model-indep. virial EOS Horowitz, AS, NPA (2006) at low densities

EOS for arbitrary proton fraction and temperature

Keller, Hebeler, AS, PRL (2023)

based on chiral NN+3N interactions to N³LO

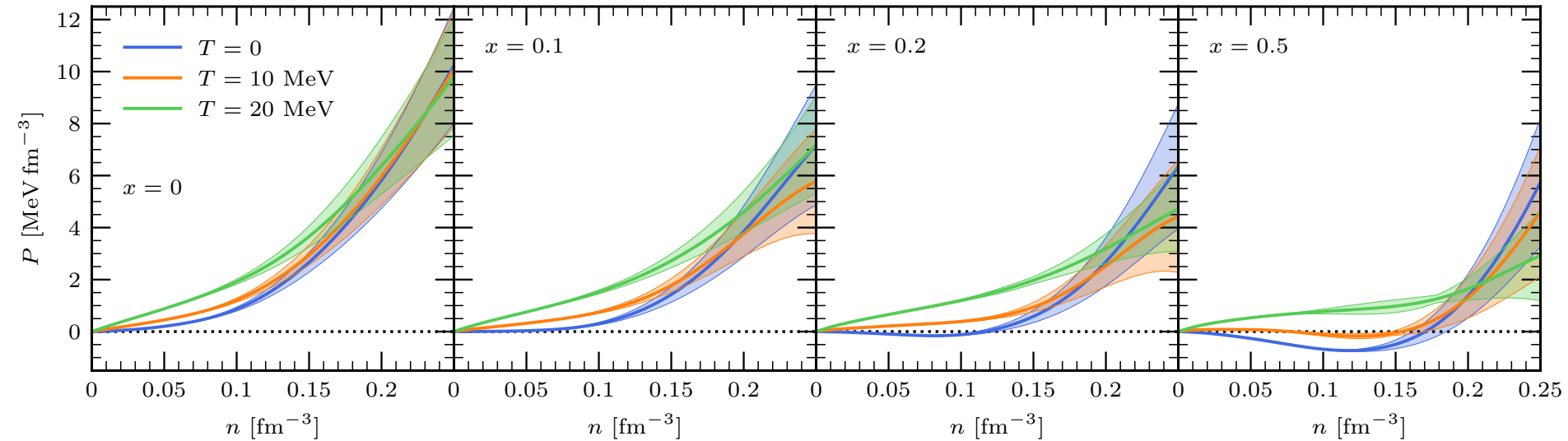
order-by-order EFT uncertainties + (smaller) many-body uncertainties



EOS for arbitrary proton fraction and temperature

Keller, Hebeler, AS, PRL (2023)

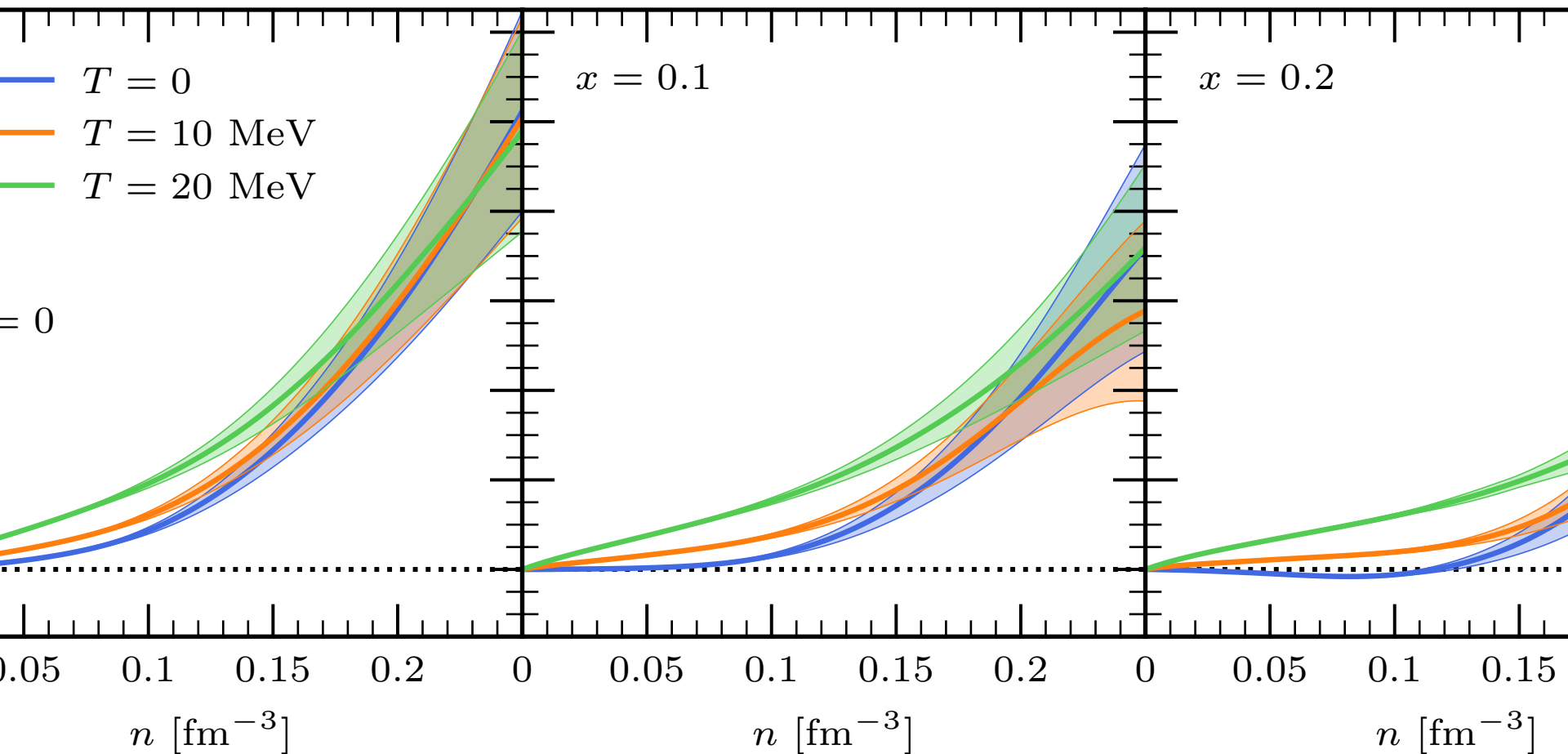
GP emulator to calculate **pressure** (thermodyn. consistent derivatives)



EOS for arbitrary proton fraction and temperature

Keller, Hebeler, AS, PRL (2023)

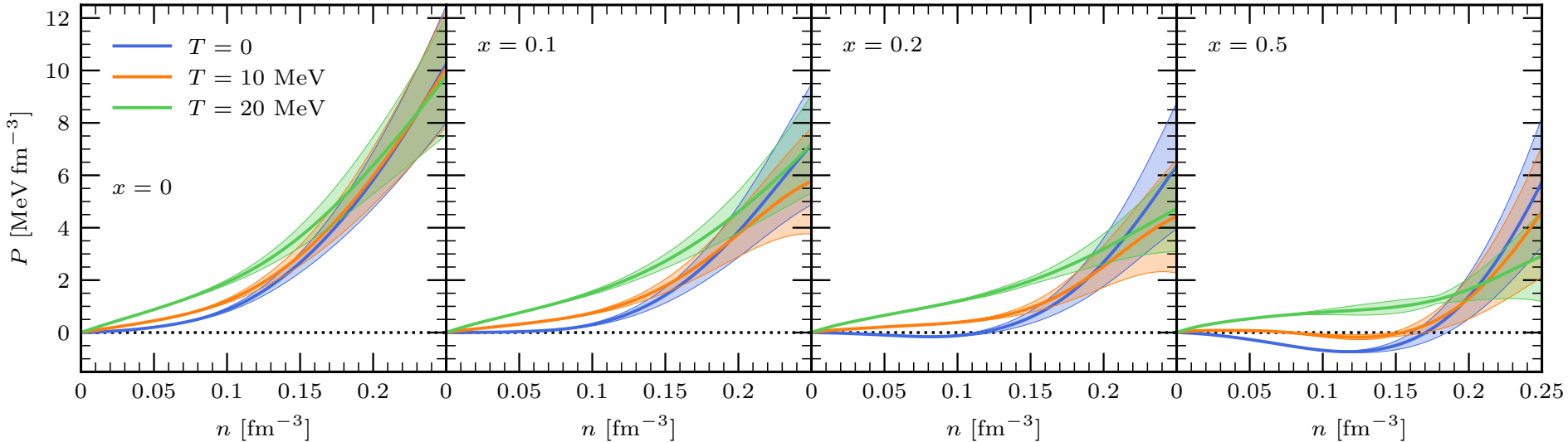
GP emulator to calculate **pressure** (thermodyn. consistent derivatives)



EOS for arbitrary proton fraction and temperature

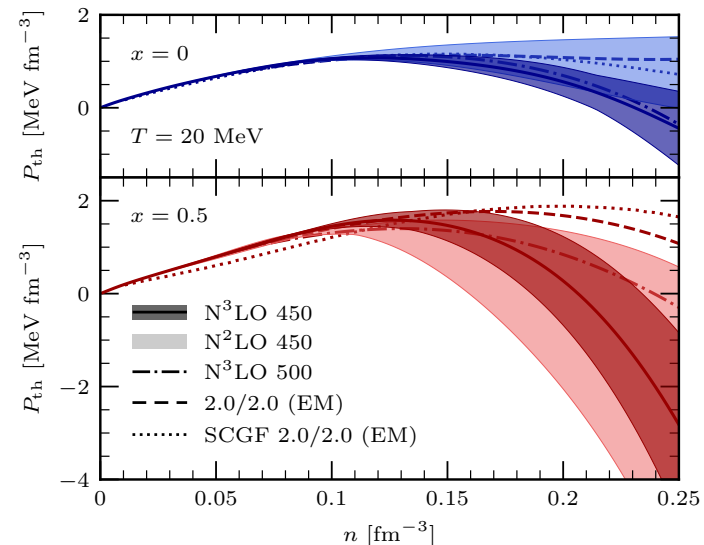
Keller, Hebeler, AS, PRL (2023)

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 $3N$

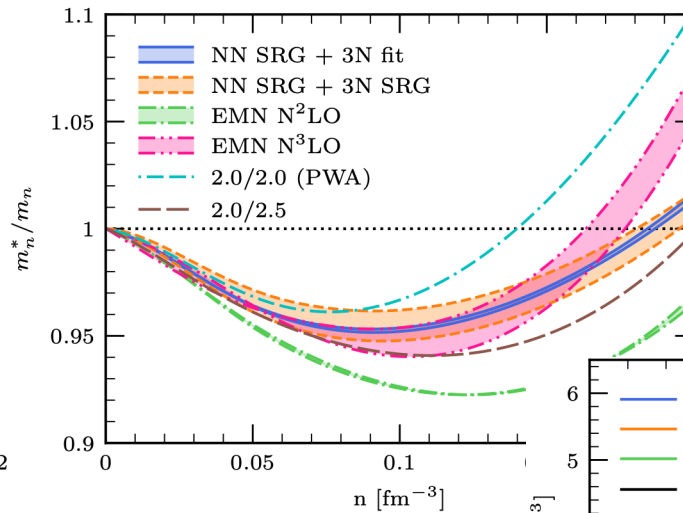
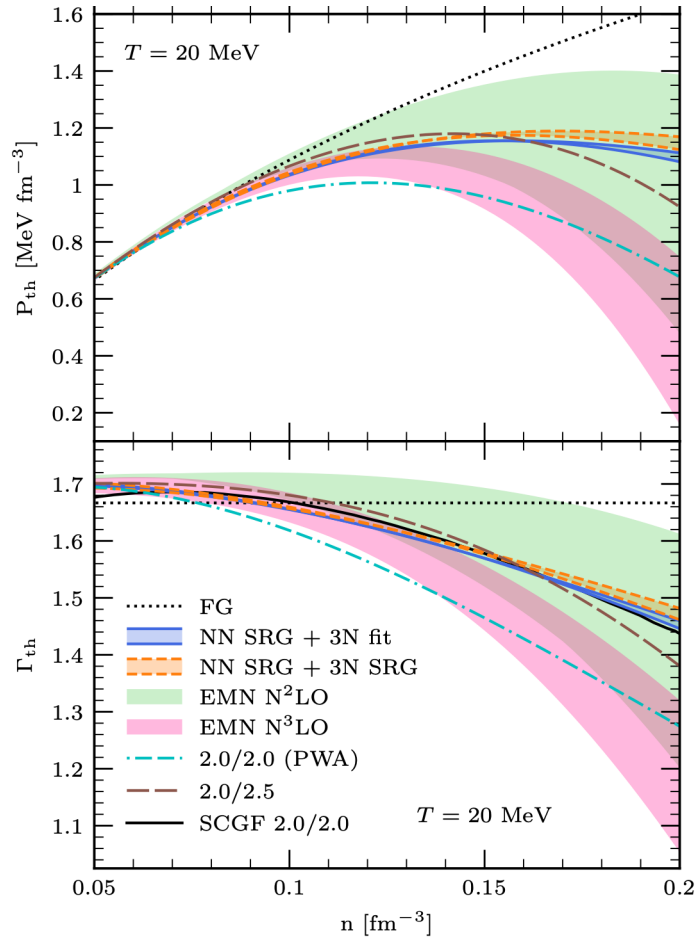


Thermal effects governed by effective mass

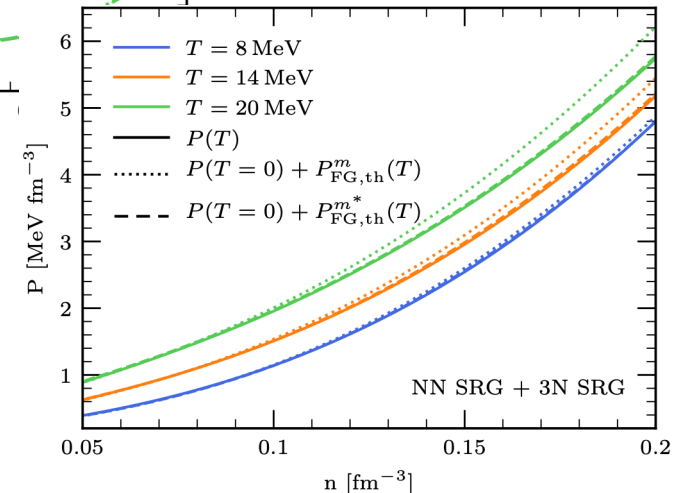
decreasing thermal pressure due to repulsive 3N contributions

increasing effective mass m^* beyond n_{sat}

$$\Gamma_{\text{th}}^*(n) = \frac{5}{3} - \frac{n}{m_n^*} \frac{\partial m_n^*}{\partial n}$$



$$\Gamma_{\text{th}}(T, n) = 1 + \frac{P_{\text{th}}(T, n)}{\mathcal{E}_{\text{th}}(T, n)}$$



Carbone, AS, PRC (2019)

Keller, Wellenhofer, Hebeler, AS, PRC (2021)

Impact on core-collapse supernova simulations

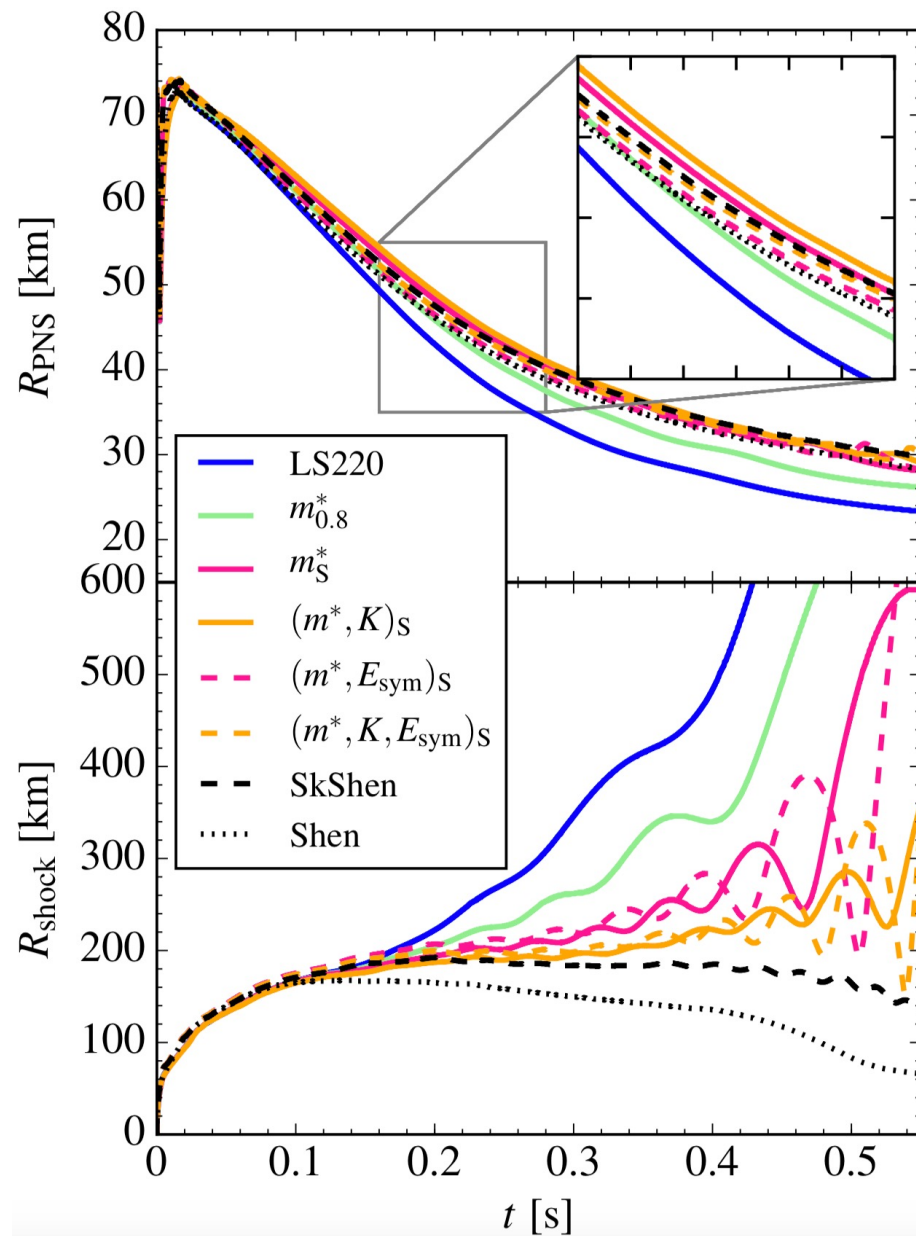
Yasin, Schäfer, Arcones, AS, PRL (2019)

constructed EOS that systematically vary nuclear matter properties between LS and Shen et al. EOS

	m^*/m	K	E_{sym}	L	n_0	B
LS220	1.0	220	29.6	73.7	0.155	16.0
Shen	0.634	281	36.9 ^a	110.8	0.145	16.3
Theo.	0.9(2)	215(40)	32(4)	51(19)	0.164(7)	15.86(57)

thermal contributions/ m^* are key for proto-neutron star contraction

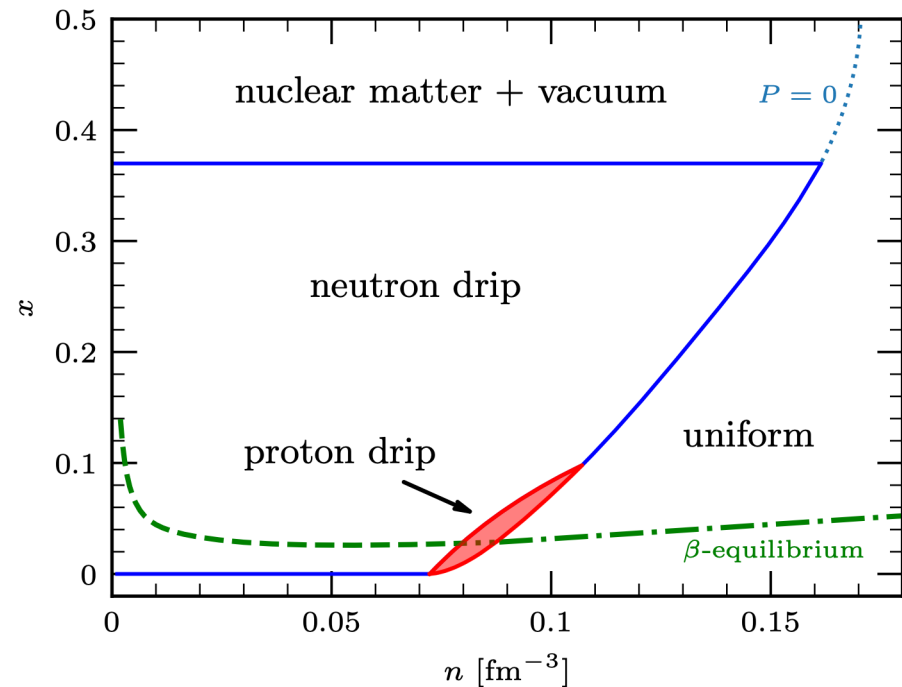
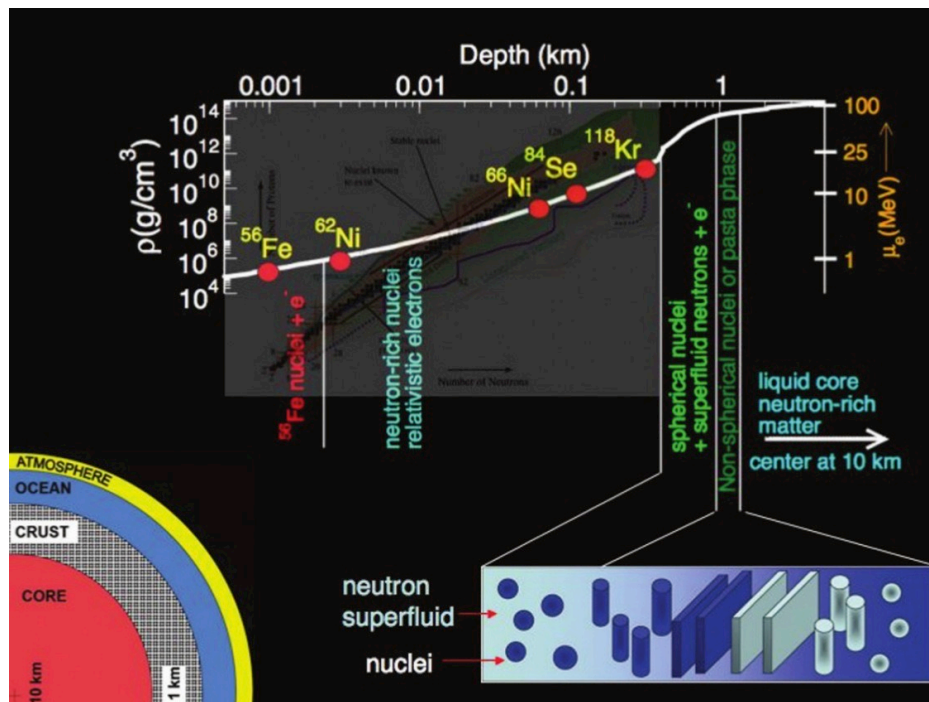
faster contraction aids supernova shock to more successful explosion



Subnuclear phase diagram of neutron star matter

~ 5% proton fraction in denser neutron matter

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



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

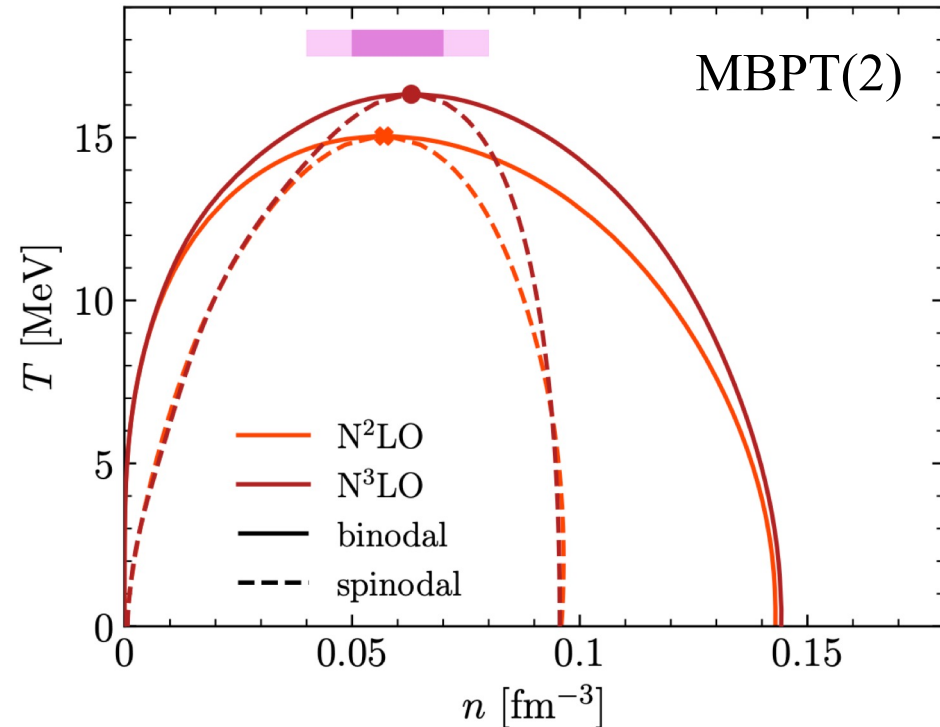
Chiral EFT calculations establish proton drip:

robust for any reasonable EOS, proton drip aids pasta formation

Phase diagram from chiral EFT

Hoff, M.Sc. Thesis, Götting, Hoff, Hebeler, AS, in preparation

construct liquid-gas phase diagram based on GP emulator of asymmetric matter calculations + GP-Bayesian EFT uncertainties



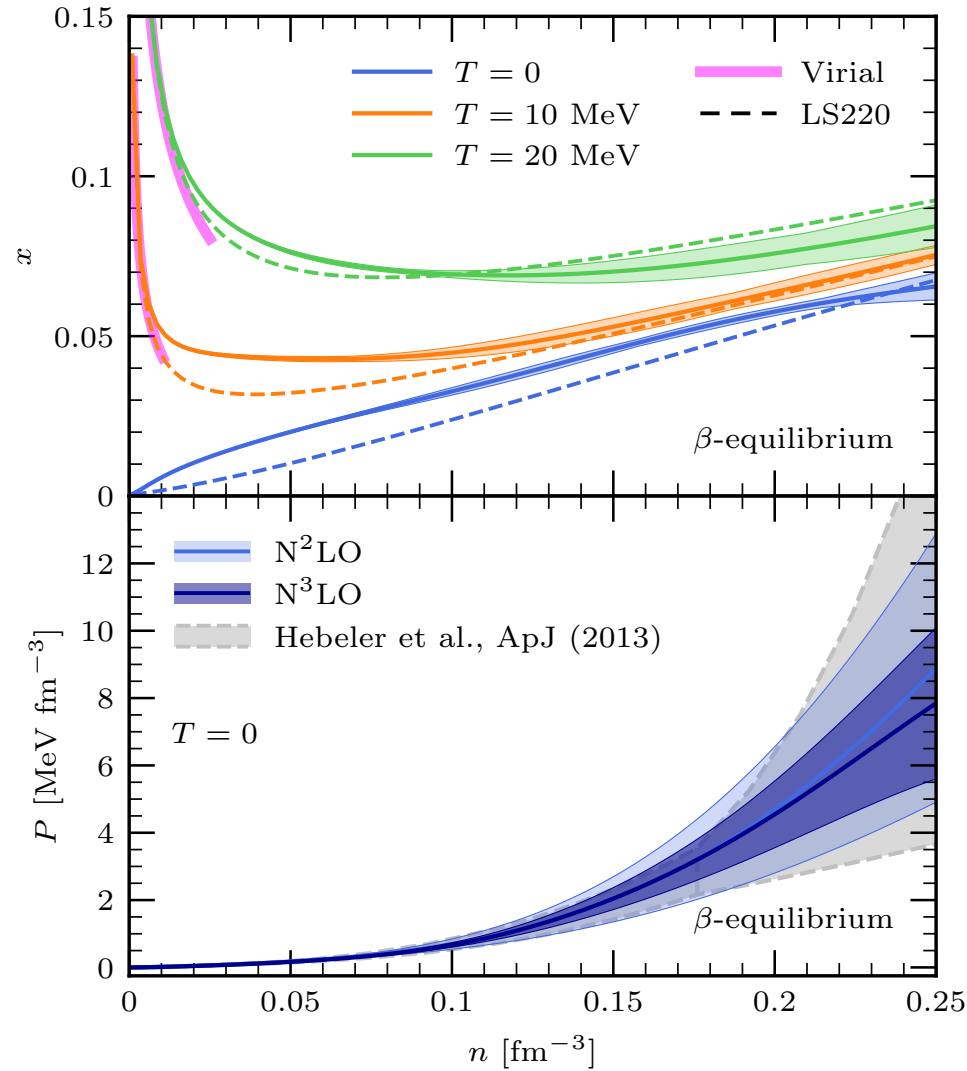
good reproduction of critical point at $N^2\text{LO}$ and $N^3\text{LO}$ at MBPT(2) level
see also review by Kaiser, Weise, arXiv:2602.09916

EOS for neutron star matter in beta equilibrium

Keller, Hebeler, AS, PRL (2023)

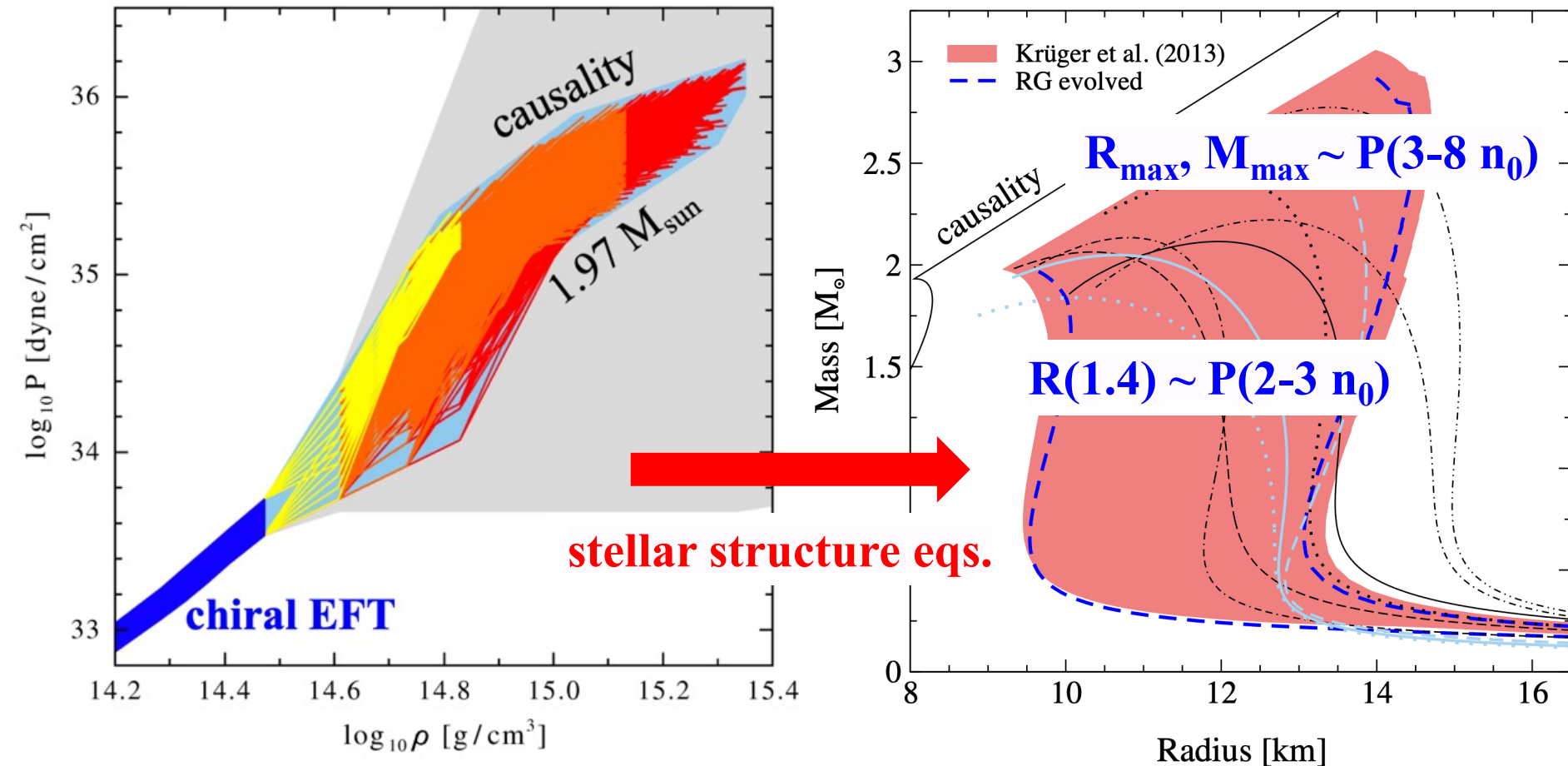
use GP emulator to access arbitrary
proton fraction,
solve for beta equilibrium

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



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

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



piecewise polytropes (PP) includes phase transitions

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

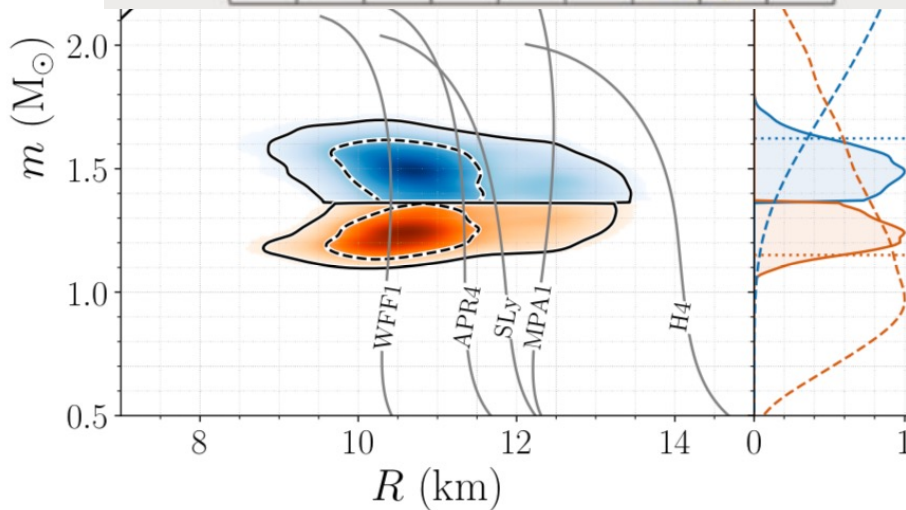
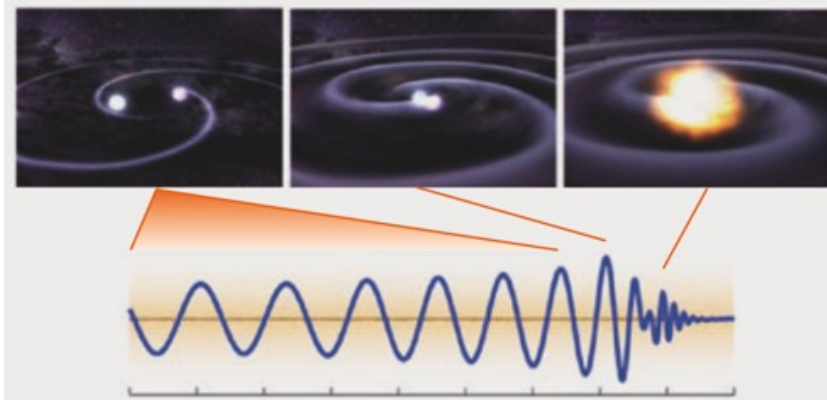
Neutron star radius information

from gravitational waves

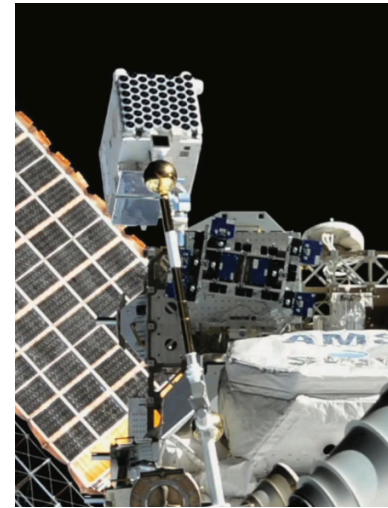
and pulse-profile modeling

GW170817: Measurements of neutron star radii and equation of state

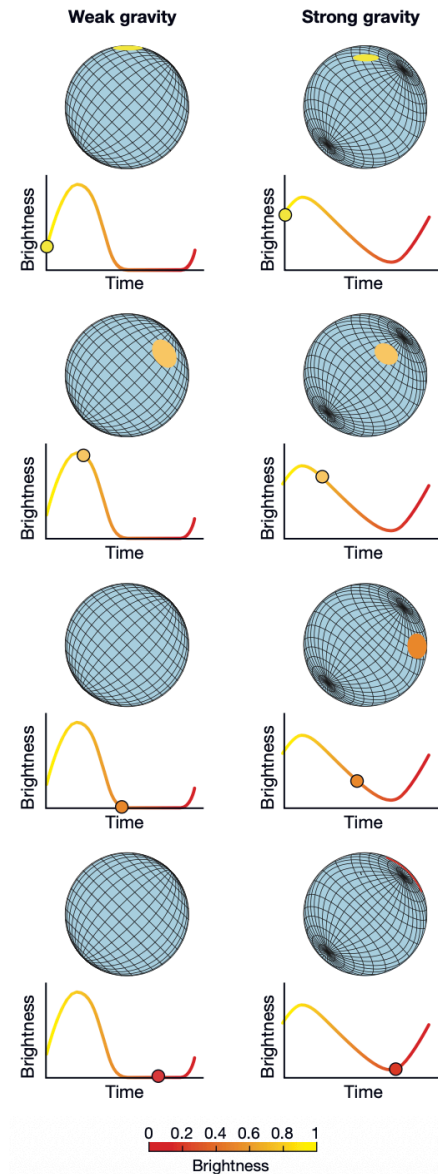
The LIGO Scientific Collaboration and The Virgo Collaboration



tidal deformability $\sim R^5$

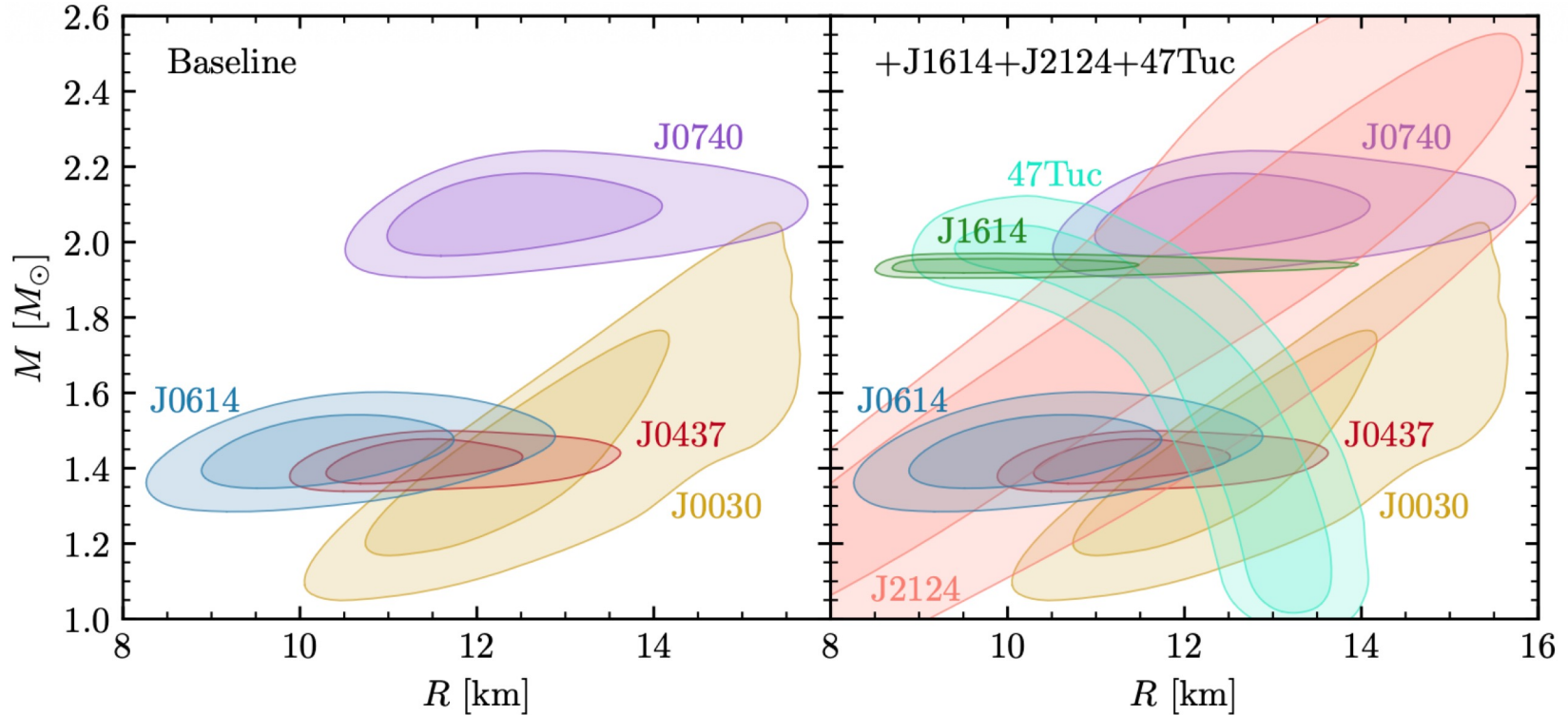


sensitive to
compactness
 M/R



LIGO/Virgo and NICER results

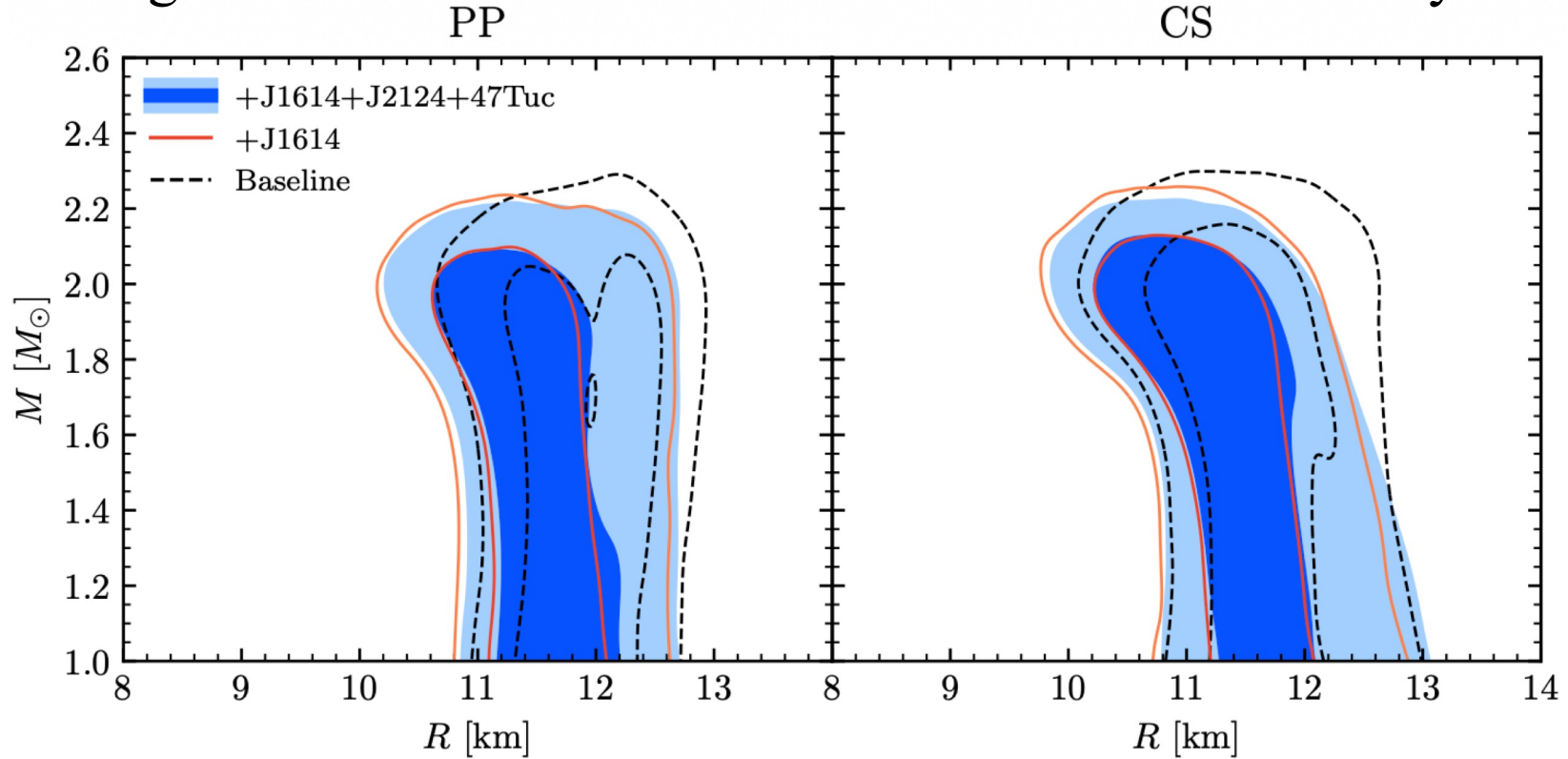
chiral EFT up to $1.5n_0$ + general high-density extensions + causality
including information from GW170817 and 6 stars studied by NICER



Raaijmakers et al., ApJL (2020), (2021), Rutherford, Mendes, Svensson et al., ApJL (2024)
Mauviard-Haag et al., ApJ (2025), Mendes, Svensson, Götting et al., arXiv:2609.00173

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Raaijmakers et al., ApJL (2020), (2021), Rutherford, Mendes, Svensson et al., ApJL (2024)
Mauviard-Haag et al., ApJ (2025), Mendes, Svensson, Götting et al., arXiv:2609.00173

posterior dist. 11-12 km very similar for PP/CS high-density extensions

Constraints at intermediate densities

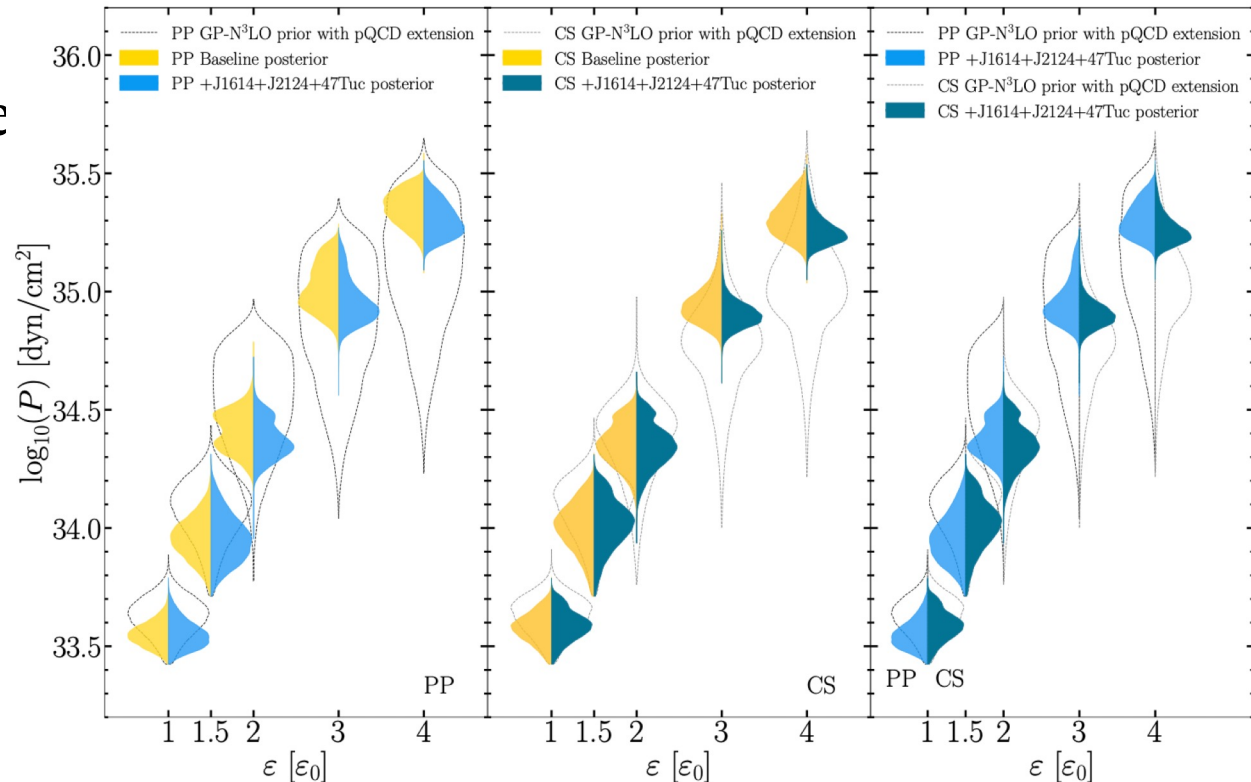
chiral EFT up to $1.5n_0$ + general EOS extrapolations + causality

including information from GW170817 and 6 stars studied by NICER

observations constrain
pressure at intermediate
densities

astro prefers soft to
stiff (relative to prior)
from below $2n_0$
to $3-4n_0$

important to explore
prior sensitivities



Rutherford, Mendes, Svensson et al., ApJL (2024)

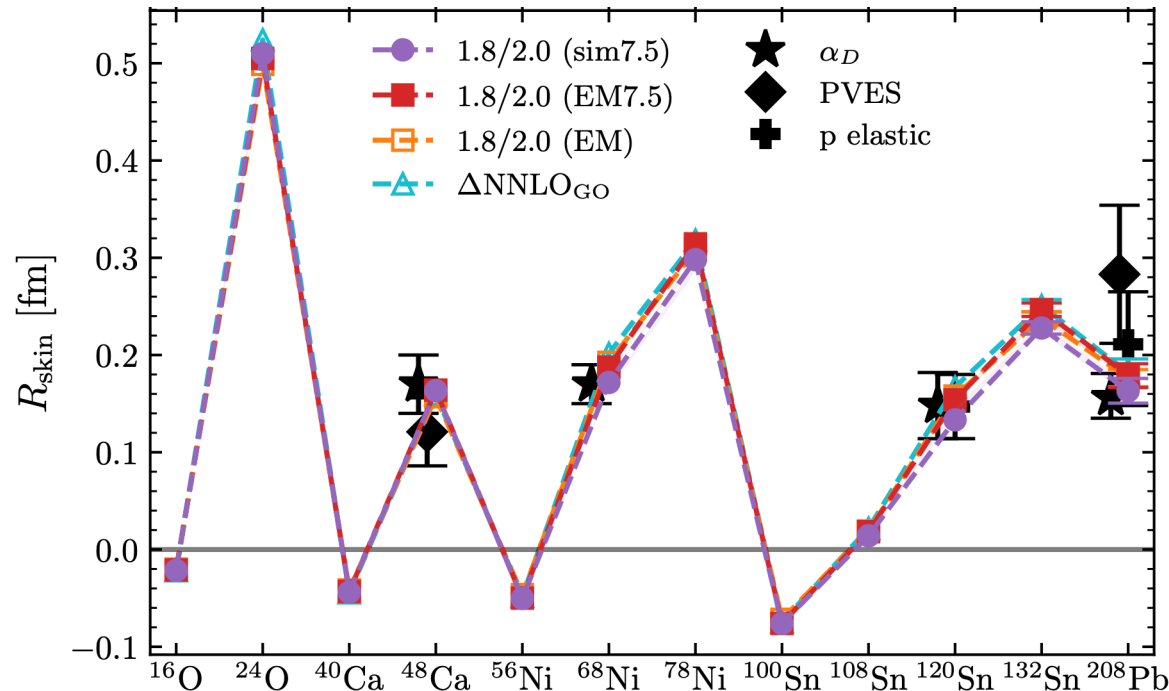
Mauviard-Haag et al., ApJ (2025), Mendes et al., arXiv:2609.00173

will be very constraining with more observations

Experimental constraints on neutron skin

from dipole polarizability, elastic proton scattering,
parity violating (PV) electron scattering,...

figure from Arthuis, Hebeler, AS (2024)



all experimental inferences are indirect (i.e., with some model dep.)

puzzle with large neutron skin (with large unc.) for ^{208}Pb by PREX

CREX has smaller unc. and is consistent with theory

PREX experiment

PHYSICAL REVIEW LETTERS **126**, 172502 (2021)

Editors' Suggestion

Featured in Physics

Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering

D. Adhikari,¹ H. Albataineh,² D. Androic,³ K. Aniol,⁴ D. S. Armstrong,⁵ T. Averett,⁵ C. Ayerbe Gayoso,⁵ S. Barcus,⁶ V. Bellini,⁷ R. S. Beminiwattha,⁸ J. F. Benesch,⁶ H. Bhatt,⁹ D. Bhatta Pathak,⁸ D. Bhetuwal,⁹ B. Blaikie,¹⁰ Q. Campagna,⁵

We report a precision measurement of the parity-violating asymmetry A_{PV} in the elastic scattering of longitudinally polarized electrons from ^{208}Pb . We measure $A_{\text{PV}} = 550 \pm 16(\text{stat}) \pm 8(\text{syst})$ parts per billion, leading to an extraction of the neutral weak form factor $F_W(Q^2 = 0.00616 \text{ GeV}^2) = 0.368 \pm 0.013$. Combined with our previous measurement, the extracted neutron skin thickness is $R_n - R_p = 0.283 \pm 0.071 \text{ fm}$. The result also yields the first significant interior weak density of ^{208}Pb : $\rho_W^0 = -0.0796 \pm 0.0036(\text{exp}) \pm 0.0013(\text{th})$ baryon density $\rho_b^0 = 0.1480 \pm 0.0036(\text{exp}) \pm 0.0013(\text{theo}) \text{ fm}^{-3}$. The measurement also yields the density dependence of the symmetry energy of nuclear matter near saturation for the size and composition of neutron stars.

uses tight correlations with selected density functionals (and other assumptions) to infer neutron skin

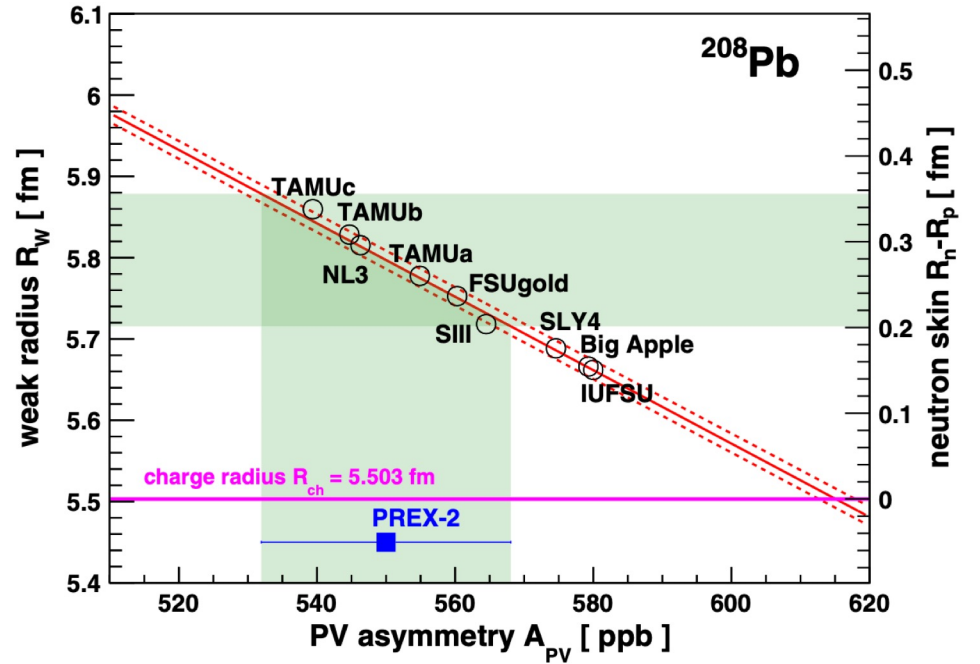


FIG. 3. Extraction of the weak radius (left vertical axis) or neutron skin (right vertical axis) for the ^{208}Pb nucleus. R_{ch} [46] is shown for comparison.

Ab initio calculation of A_{PV} based on 38 Hamiltonians

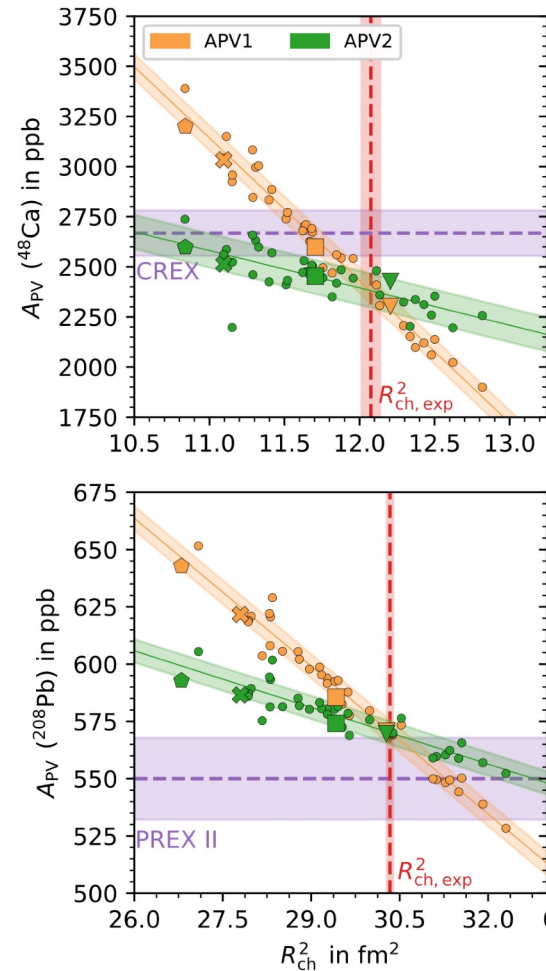
Noël, Heinz, Hoferichter, Miyagi, AS, arXiv:2606.25019

(not so tight) correlation of A_{PV} with charge radius and neutron skin

recommend APV2:

uses theoretical charge density
consistently from Hamiltonian
(APV1 uses exp. charge density)

ab initio “predictions” of
 A_{PV} based on exp. charge radius
agree with experiment within
exp. and theo. uncertainties



Ab initio calculation of A_{PV} based on 38 Hamiltonians

Noël, Heinz, Hoferichter, Miyagi, AS, arXiv:2606.25019

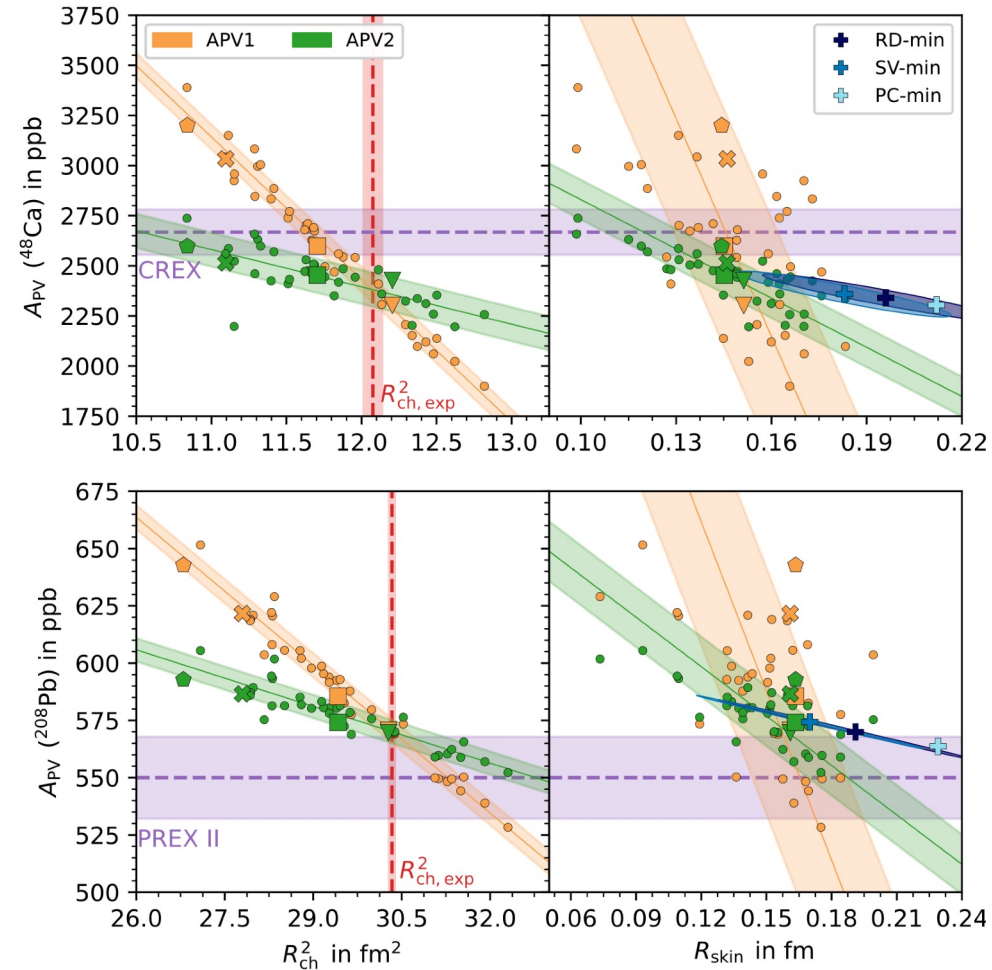
(not so tight) correlation of A_{PV} with charge radius and neutron skin

ab initio prediction (APV2) of neutron skin of ^{208}Pb is smaller than inferred from PREX

	Observable	This work	Experiment
^{48}Ca	A_{PV} [CREX, ppb]	2387(12)(82) ^a	2668(106)(40)
	$R_n - R_p$ [fm]	0.120(14)(12) ^b	0.121(26)(24)
		0.152(1)(18) ^a	
^{208}Pb	A_{PV} [PREX II, ppb]	570.1(0.6)(5.1) ^a	550(16)(8)
	$R_n - R_p$ [fm]	0.187(25)(18) ^b	0.278(78)(12)
		0.155(0)(24) ^a	

^a Predicted from correlation with R_{ch}^2 .

^b Inferred from correlation with A_{PV} .



Ab initio calculation of A_{PV} based on 38 Hamiltonians

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(not so tight) correlation of A_{PV} with charge radius and neutron skin

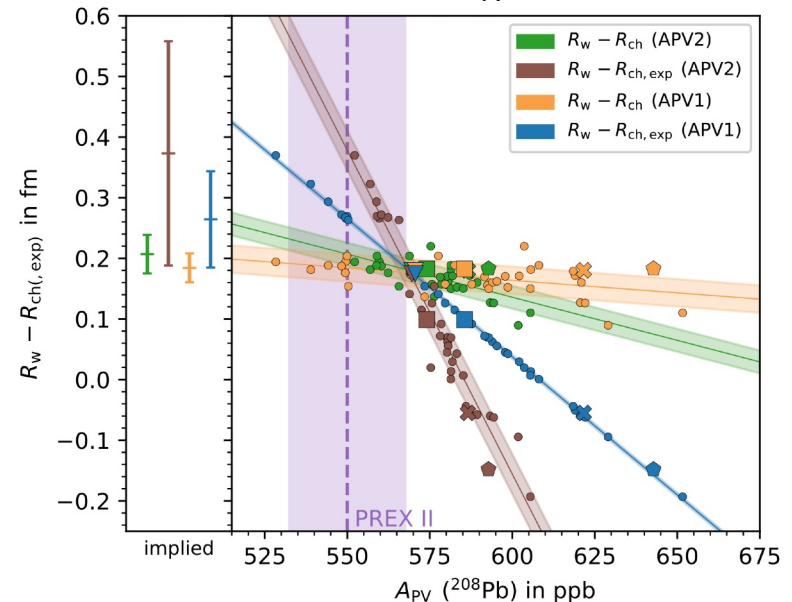
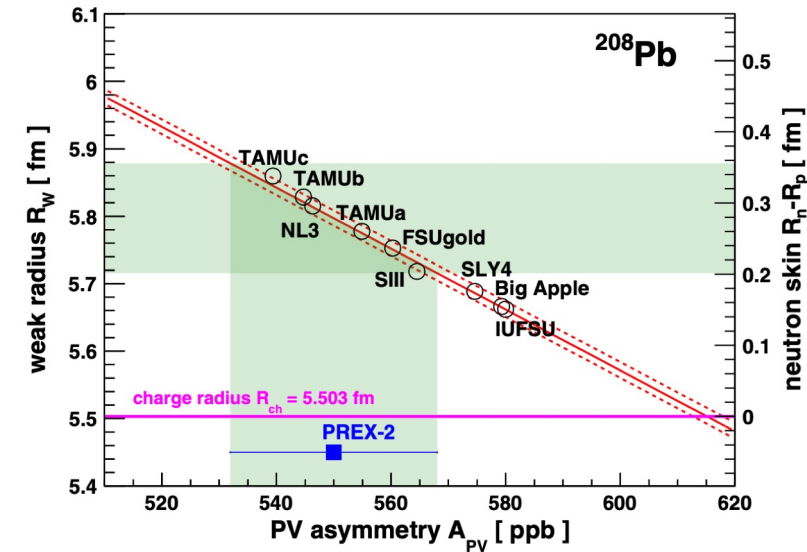
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		0.155(0)(24) ^a	

^a Predicted from correlation with R_{ch}^2 .

^b Inferred from correlation with A_{PV} .

keeping charge radius fixed to exp. value when using theoretical correlations gives large skin



Nuclear masses around N=82 and r-process nucleosynthesis

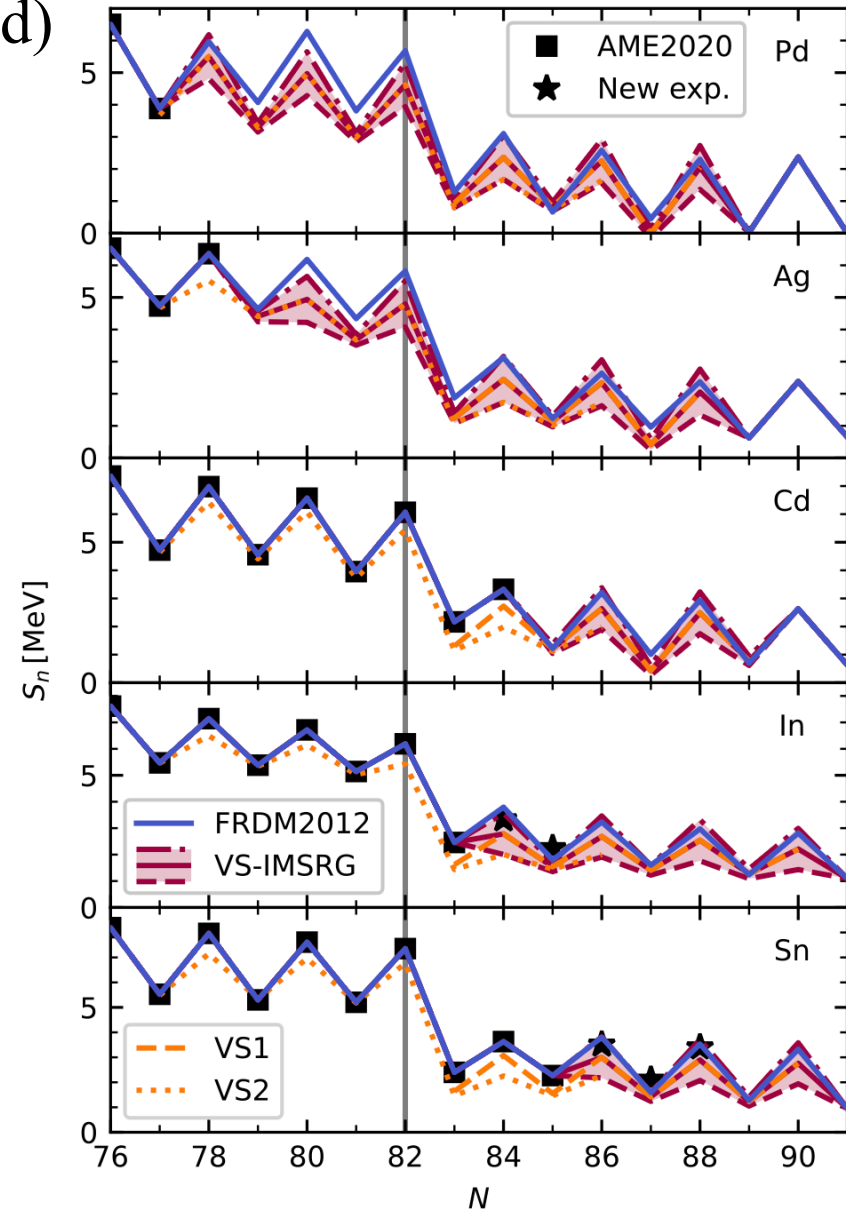
Kuske, Miyagi, Arcones, AS, PRL (2026)

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, PRL (2026)

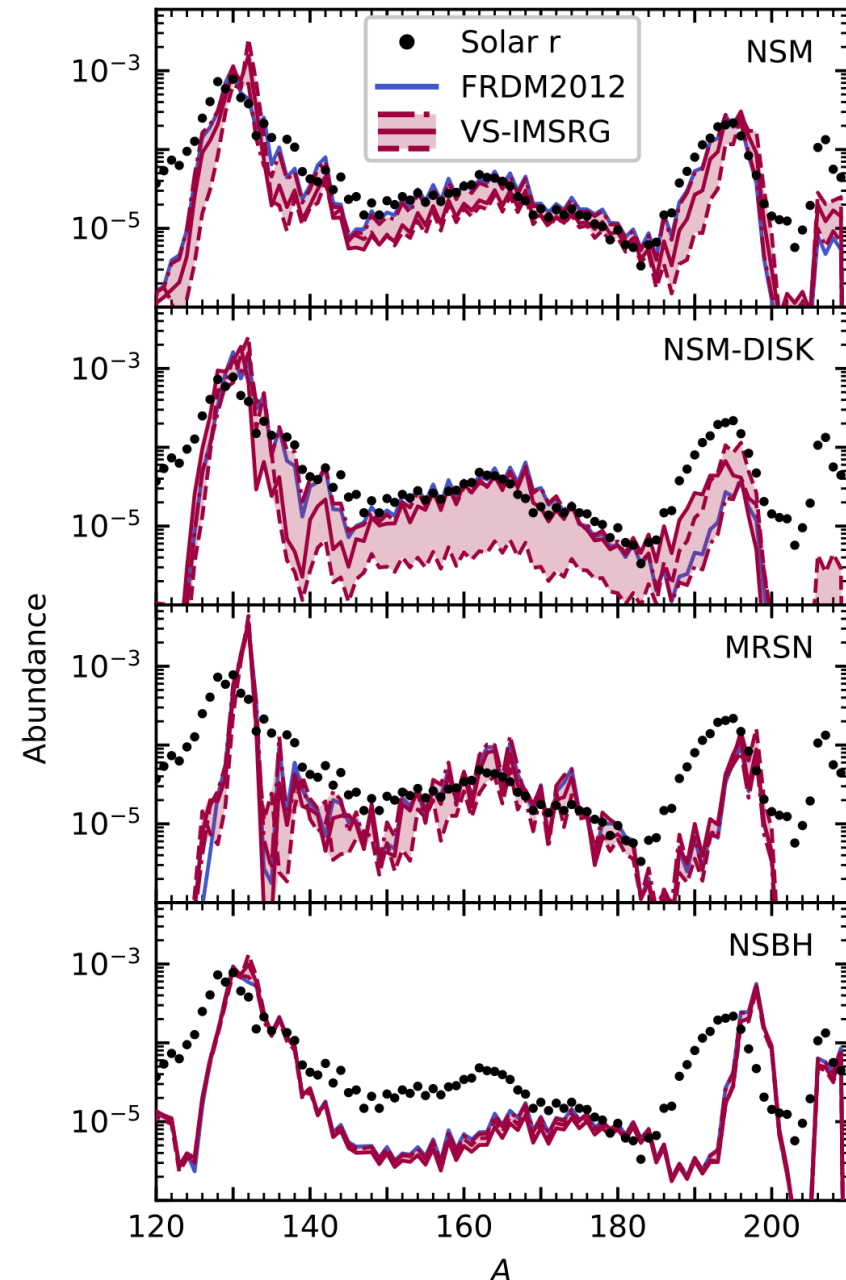
VS-IMSRG masses (min/central/max)
in baseline AME2020 + FRDM2012

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

future: use correlated ab-initio-based
mass model conditioned on data



Summary

Thanks to:

**F. Alp, Y. Dietz, C. Drischler,
H. Göttling, S. Guillot, J. Lattimer,
K. Hebeler, L. Hoff, J. Keller,
L. Mauviard, M. Mendes, C. Pethick, N. Rutherford,
R. Somasundaram, I. Svensson, I. Tews, A. Watts**



ab initio calculations based on chiral EFT interactions for nuclei and
dense matter: cold, finite temperature, arbitrary proton fraction,
density dependence of effective mass leads to decreasing P_{th}

reliable EOS up to $\sim 1-2 n_0$ with controlled EFT and many-body
uncertainties: key for multimessenger era of neutron stars,

high-density constraints from astrophysics: soft to stiff from $2n_0$ to $3-4n_0$

ab initio calculations of parity-violating asymmetry of ^{208}Pb and

nuclear masses for r-process Noël, Heinz, Hoferichter, Miyagi, AS, arXiv:2606.25019,
Kuske, Miyagi, Arcones, AS, PRL (2026)