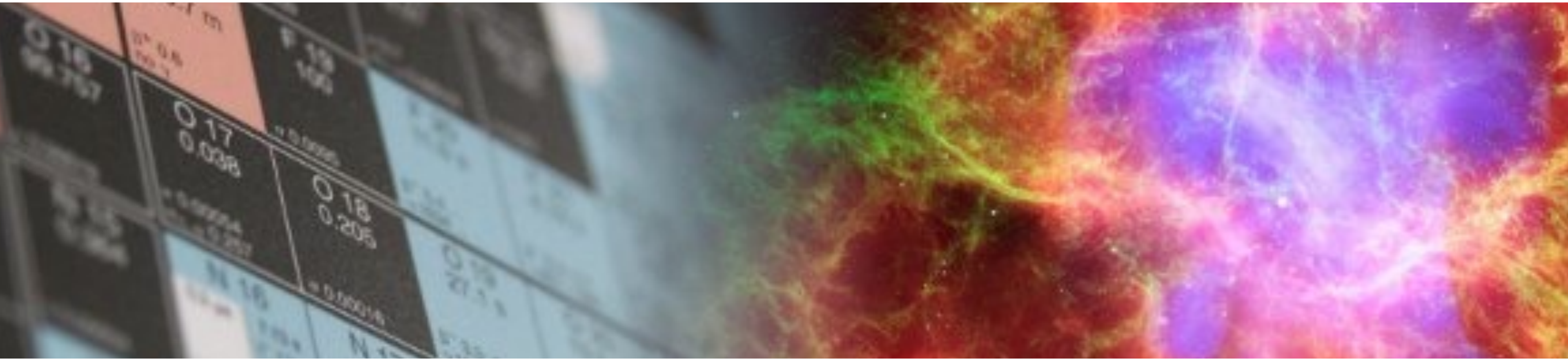
Equation of state developments for nuclear matter

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG



INT Program “Neutron Rich Matter on Heaven and Earth”, July 22, 2022

DFG

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European Research Council

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ERC AdG EUSTRONG

Bundesministerium für Bildung und Forschung

Outline

Chiral effective field theory for nuclear forces

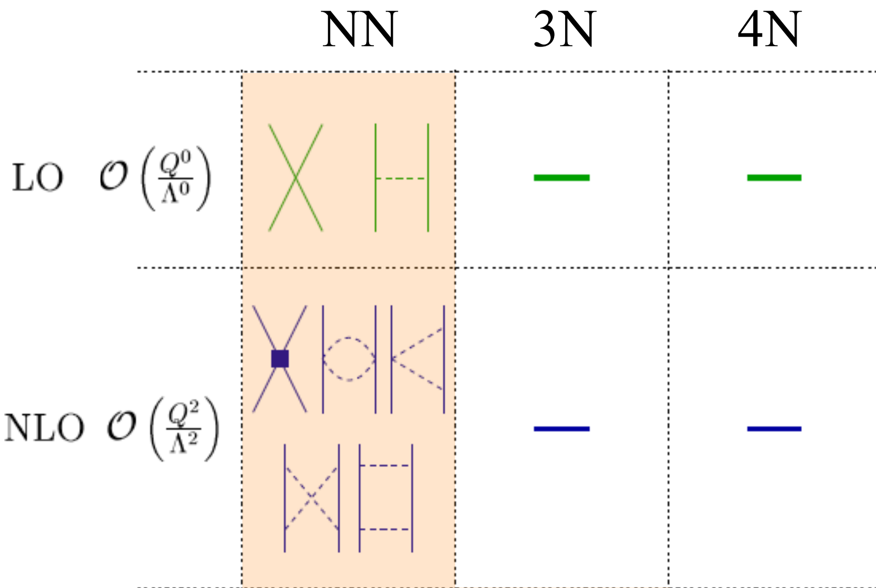
Ab initio calculations of nuclear matter:
cold, finite temperature and arbitrary proton fraction

Constraints at intermediate densities:
astro, heavy-ion collisions, functional RG

Nuclear experiments: dipole response, CREX, PREX

Chiral effective field theory for nuclear forces

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



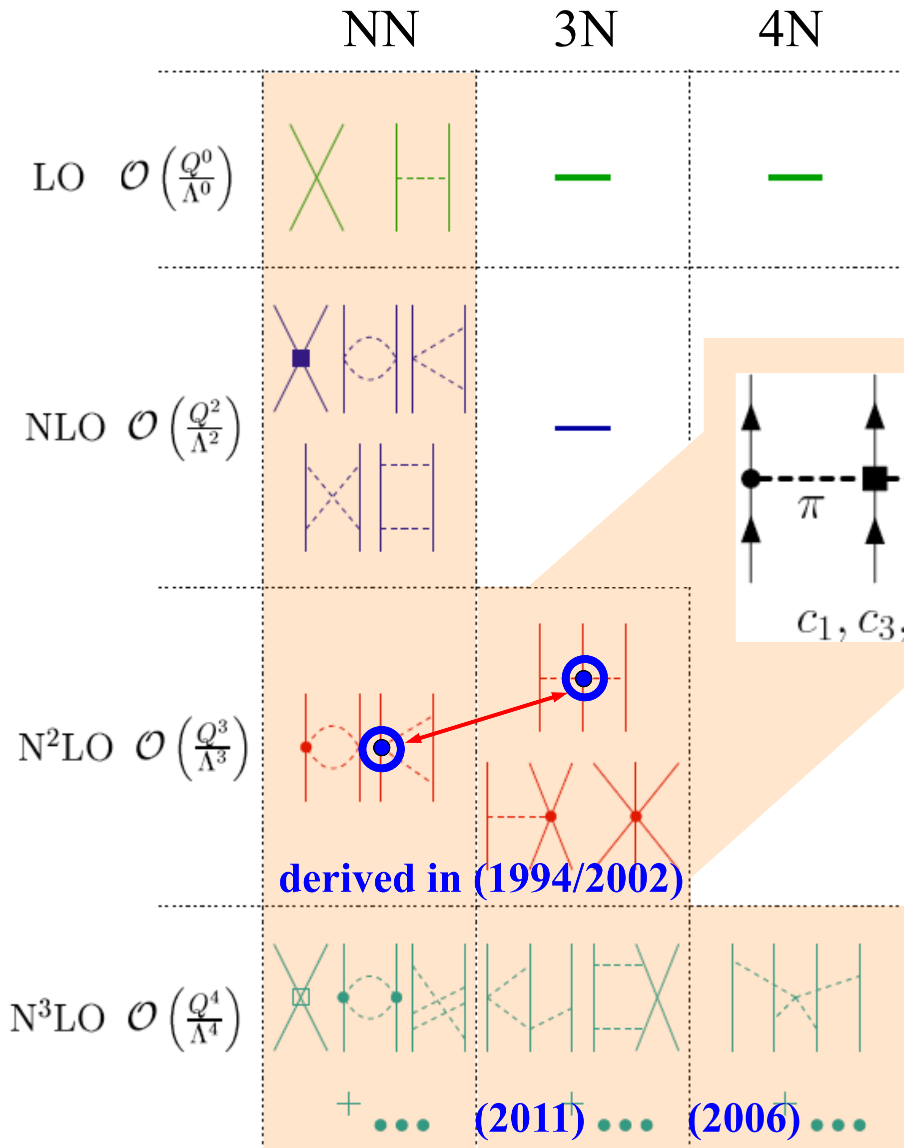
based on symmetries of strong interaction (QCD)

long-range interactions governed by pion exchanges

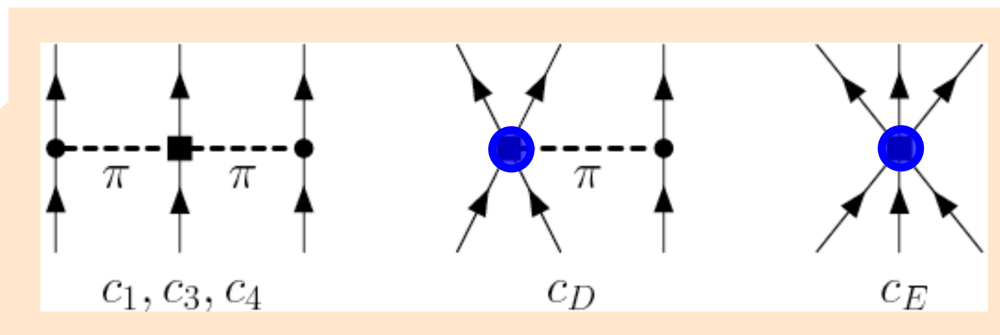
Weinberg (1990,91)

Chiral effective field theory for nuclear forces

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



powerful approach for
many-body interactions



only 2 new couplings at N^{2}LO

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

Hebeler, AS (2010), Tews, Krüger et al. (2013)

Weinberg, van Kolck (1992-1994), Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Meissner,…

Chiral effective field theory for nuclear forces

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

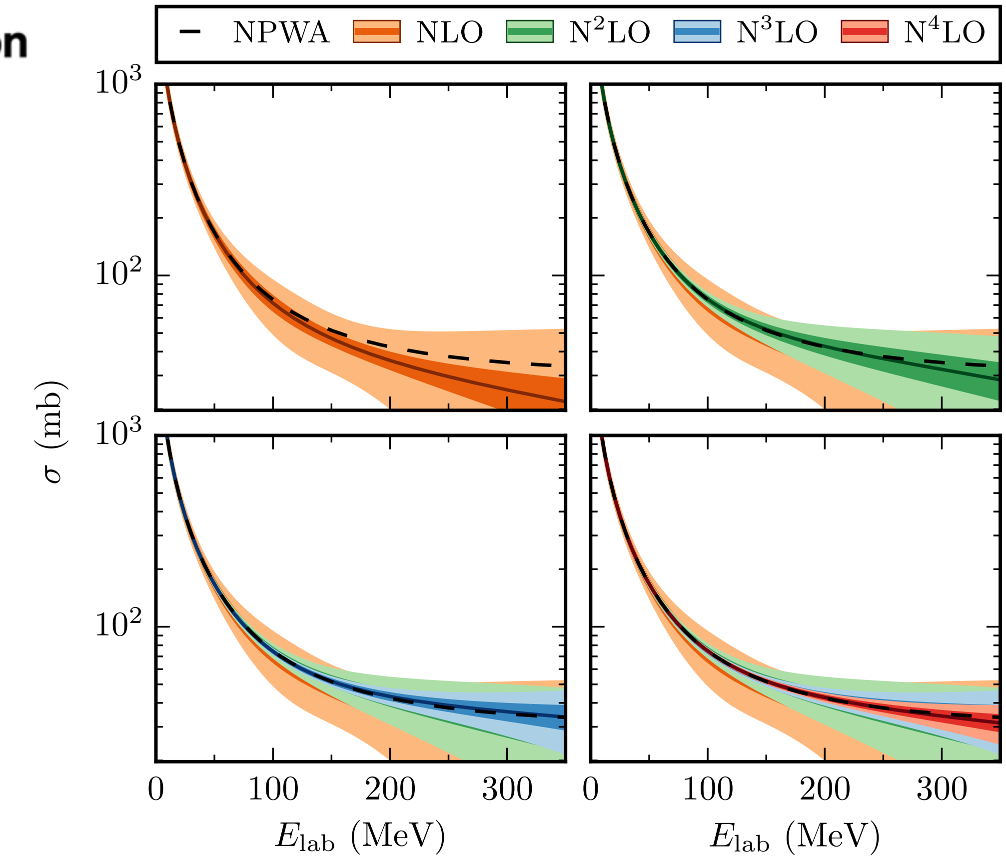
IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **42** (2015) 034028 (20pp) doi:10.1088/0954-3899/42/3/034028

A recipe for EFT uncertainty quantification in nuclear physics

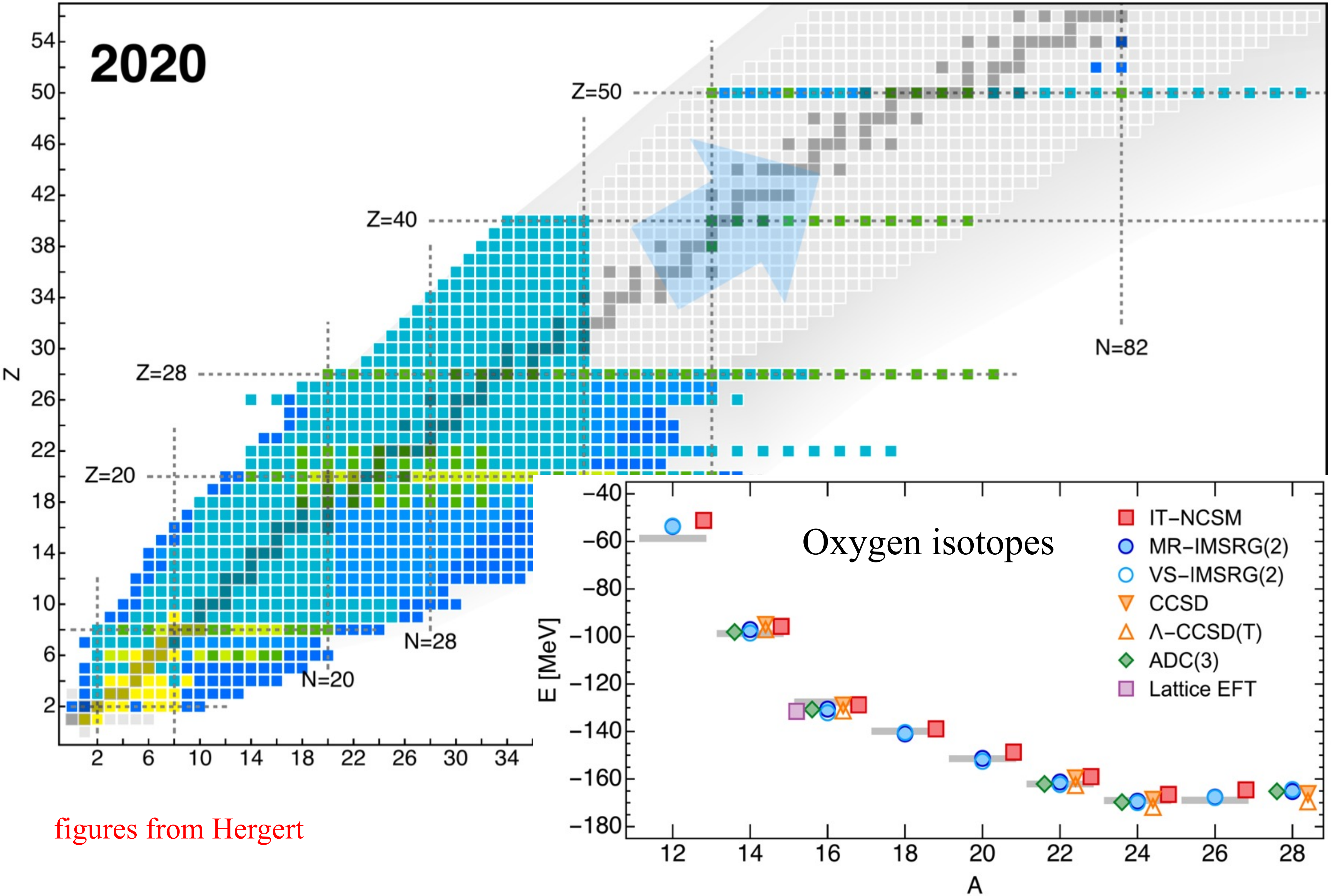
R J Furnstahl[1], D R Phillips[2] and S Wesolowski[1]

Bayesian uncertainty estimates and model checking



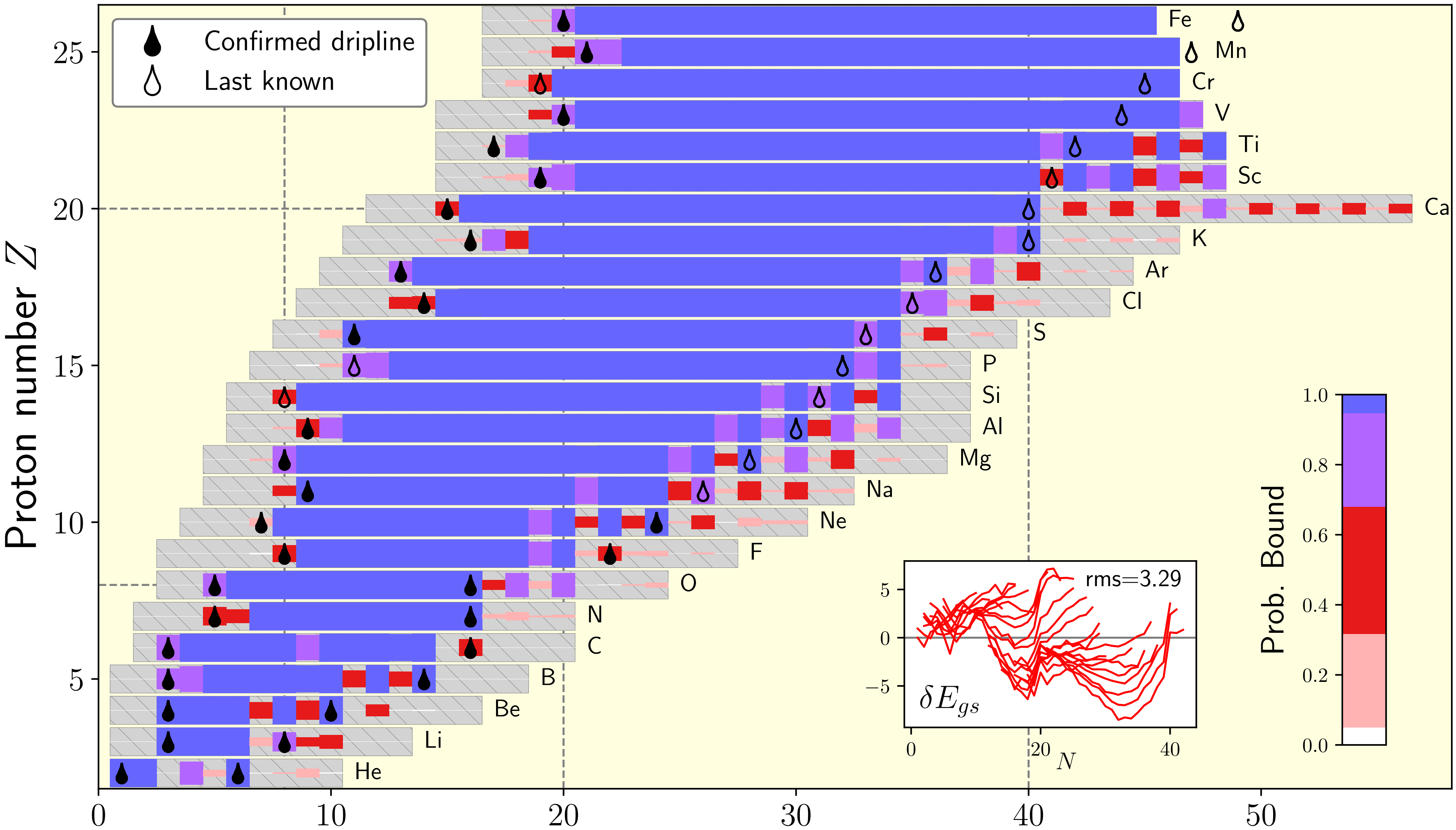
Furnstahl, Phillips, Klos, Wesolowski, Melendez (2015-)

Great progress in ab initio calculations of nuclei



figures from Hergert

Nuclear landscape based on a chiral NN+3N interaction



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

ab initio is advancing to global theories, limitations due to input NN+3N

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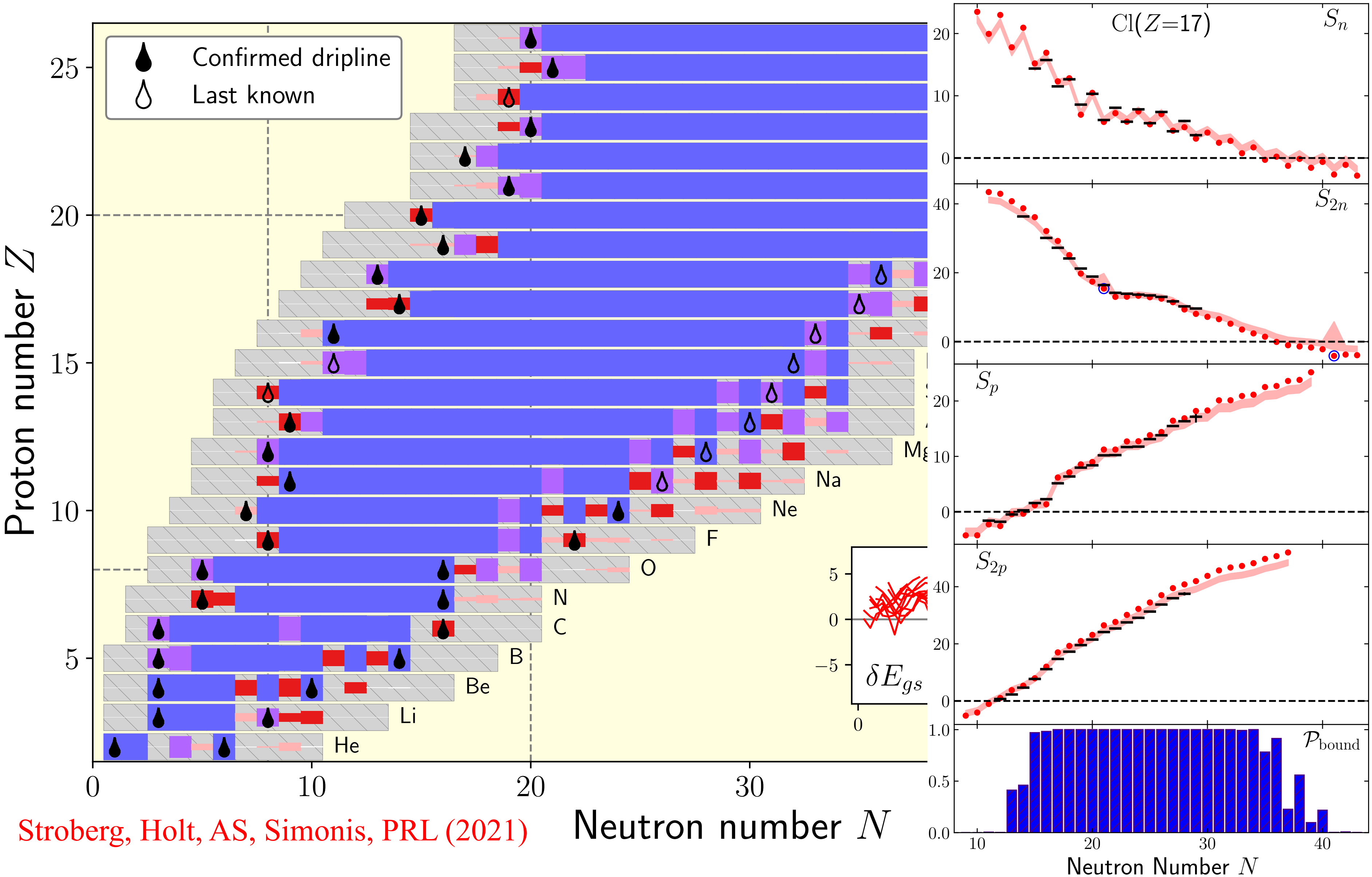


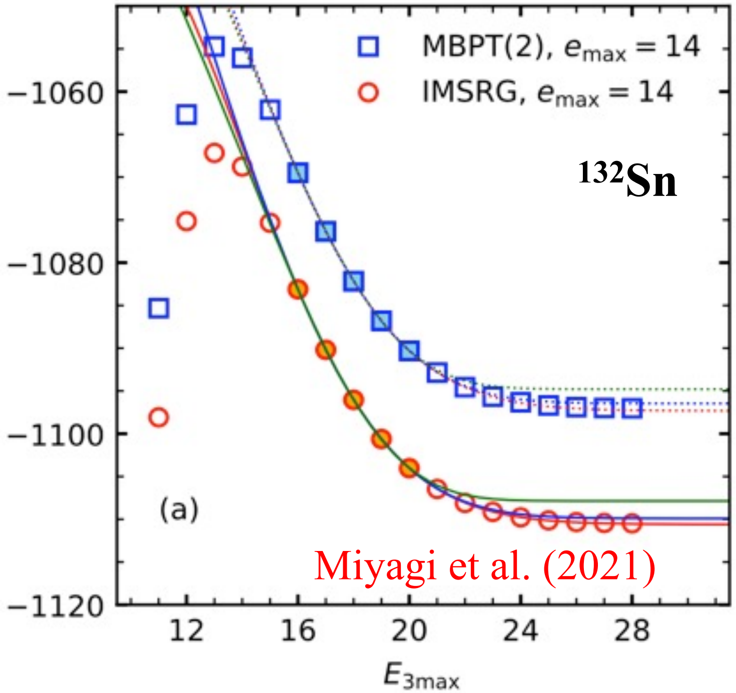
Stroberg, Holt, AS, Simonis, PRL (2021)

ab initio is advancing to global theories, limitations due to input NN+3N

First ab initio calculations of ^{208}Pb

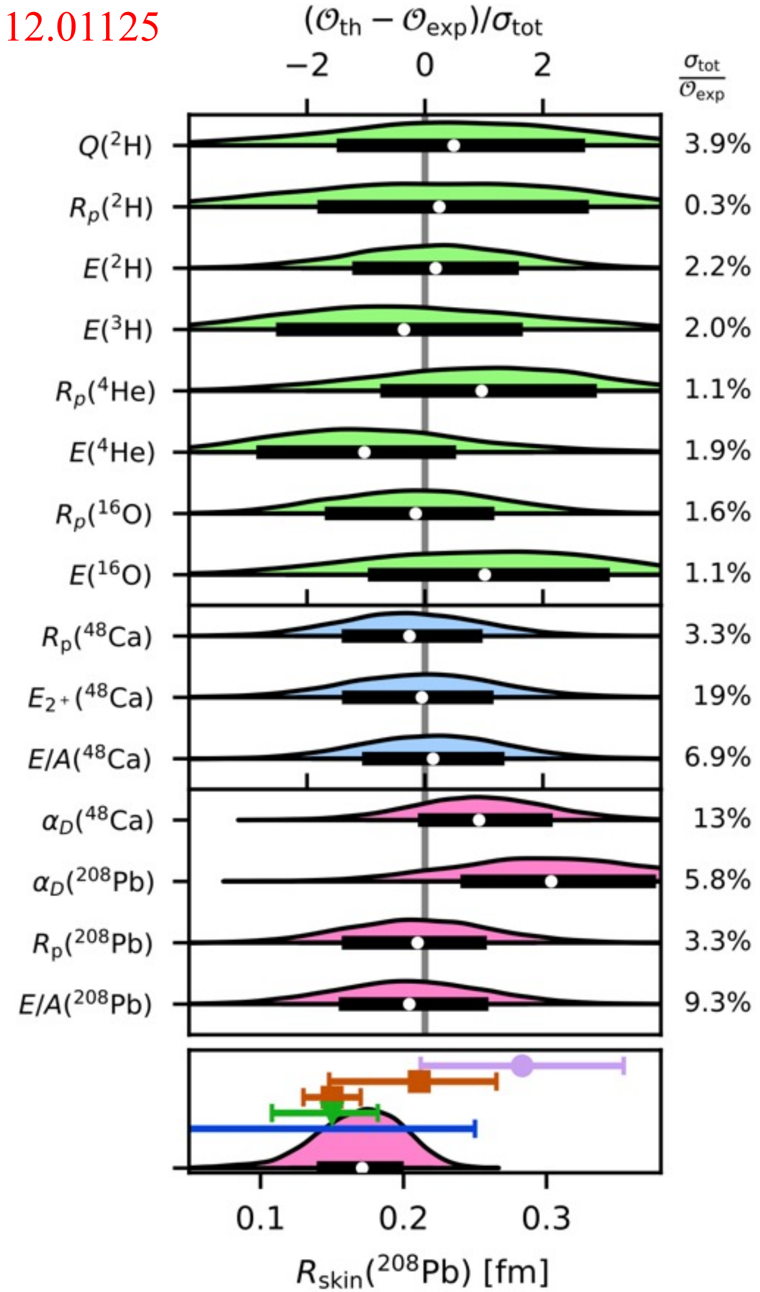
Hu, Jiang, Miyagi et al. [Chalmers, ORNL, TRIUMF], arXiv:2112.01125

enabled by 3N advances



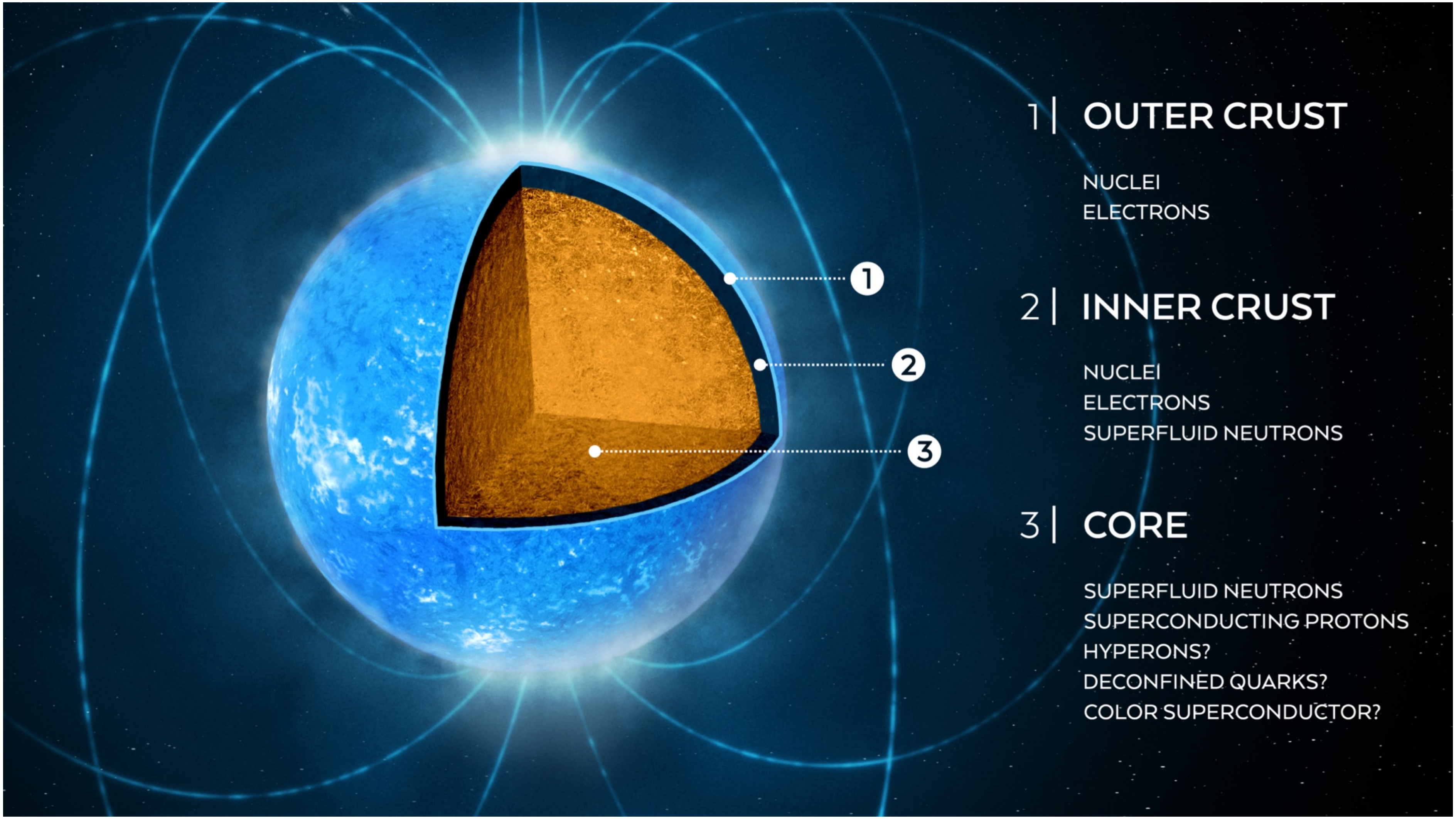
history matching to explore uncertainties in NN+3N interactions

predicted **neutron skin of ^{208}Pb**



Extreme matter in neutron stars

governed by the same strong interactions



Watts et al., RMP (2016)

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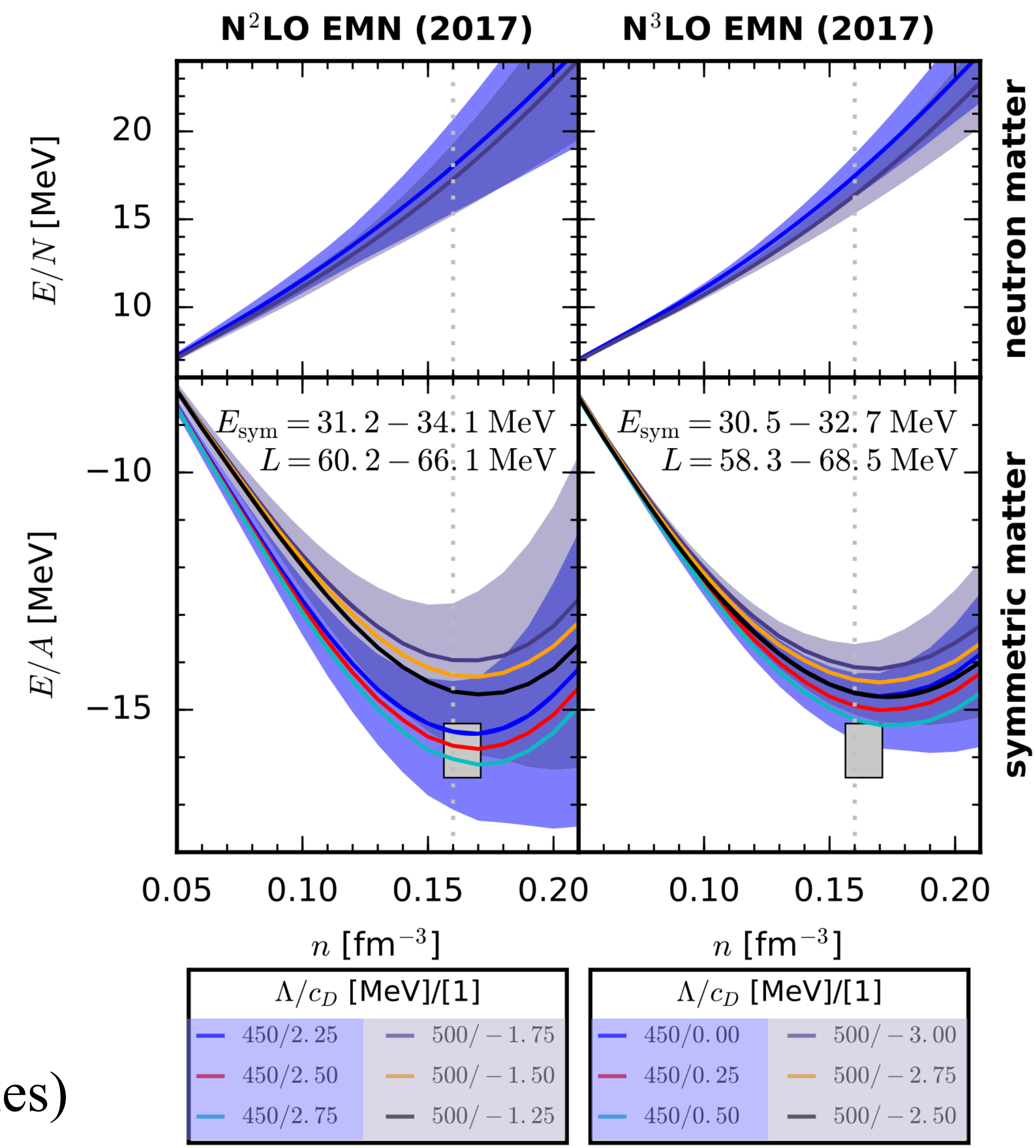
N³LO calculation of neutron matter and symmetric matter

Monte-Carlo evaluation
of energy diagrams
up to 4th order in MBPT
Drischler, Hebeler, AS, PRL (2019)

including NN, 3N, 4N
3N fit to saturation region

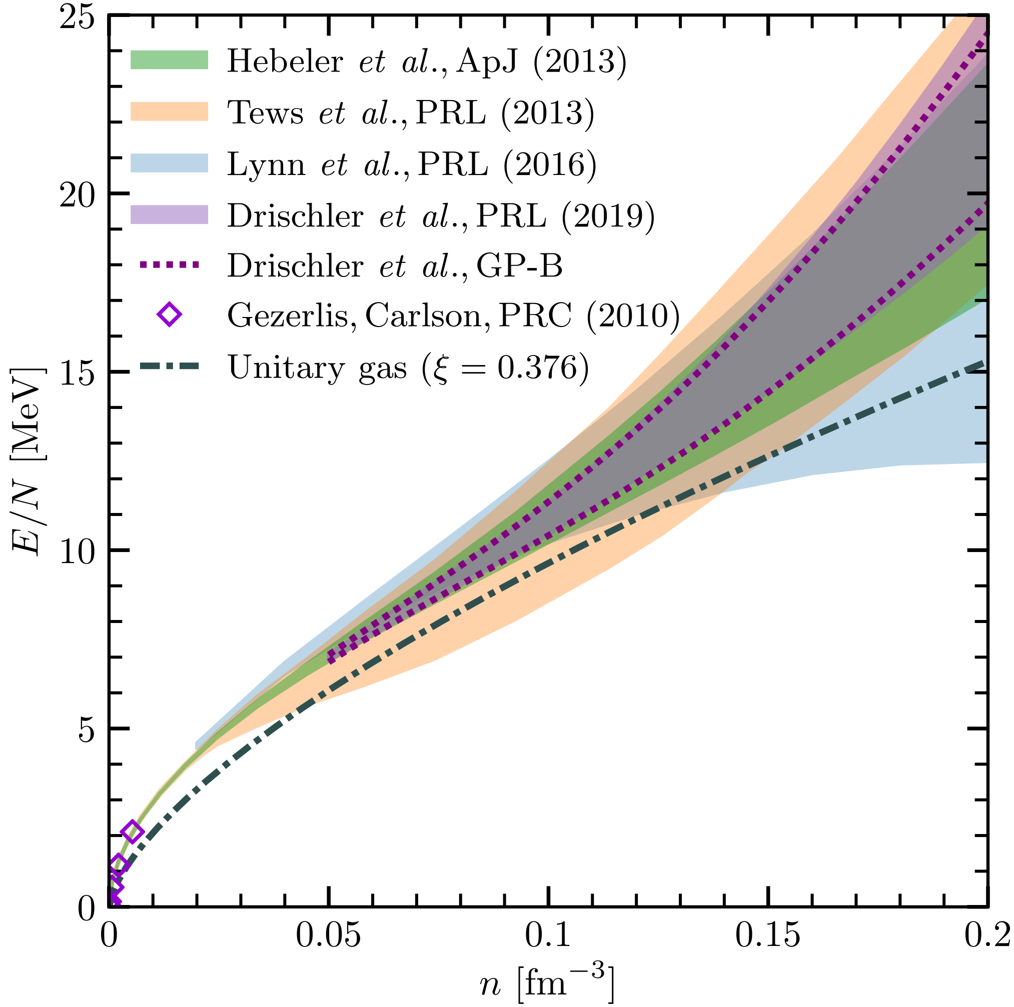
all many-body forces
to N³LO predicted for
neutron matter
Tews, Krüger, Hebeler, AS, PRL (2013)

systematic improvement
from N²LO to N³LO
(EFT uncertainties
+ cutoff, fit, reg uncertainties)



Chiral EFT calculations of neutron matter

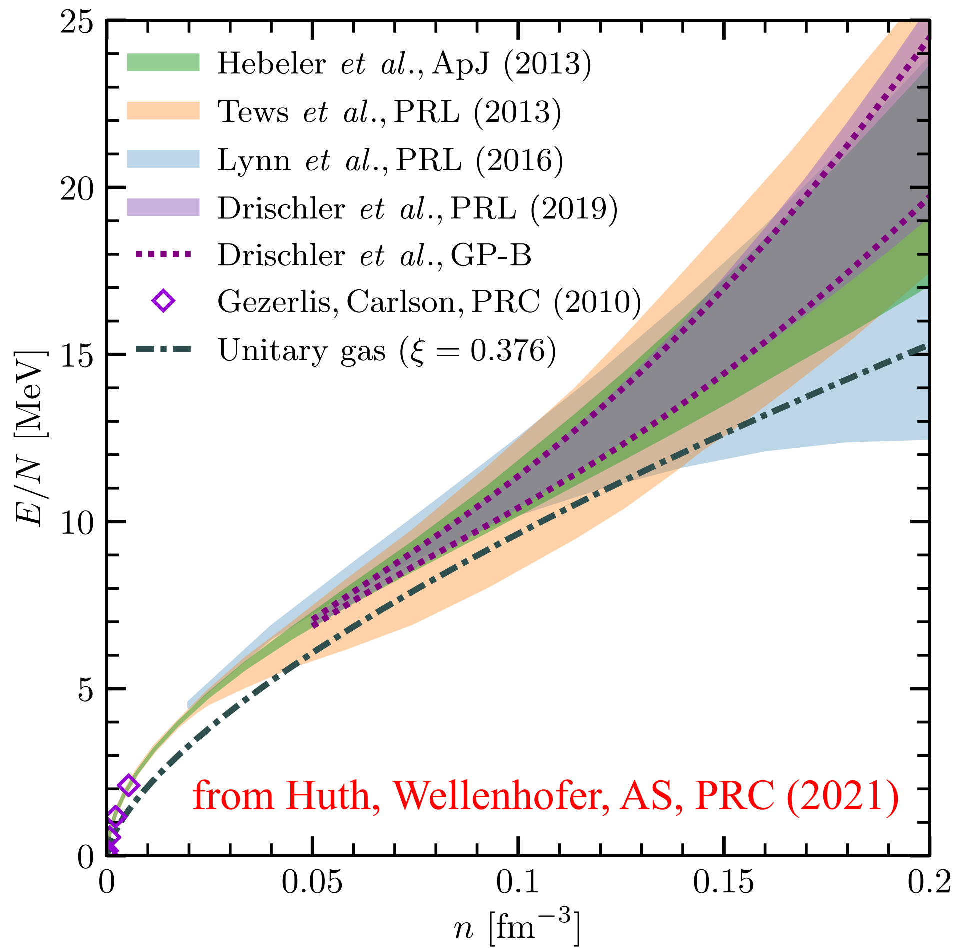
good agreement up to saturation density for neutron matter
nonlocal/local int. and different calcs. (MBPT, QMC, SCGF, CC)

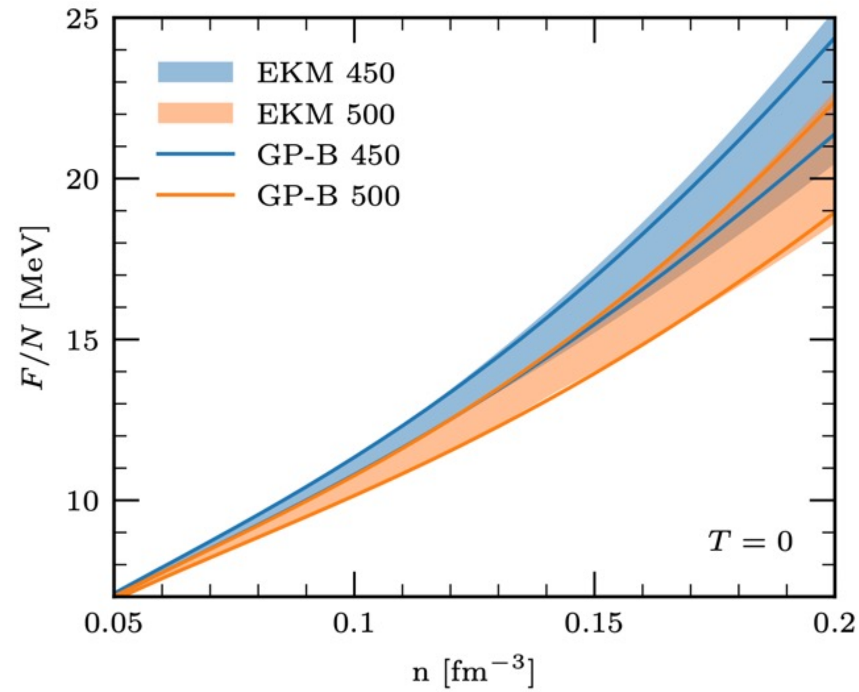


slope determines pressure of neutron matter

from Huth, Wellenhofer, AS, PRC (2021)

Chiral EFT calculations of neutron matter - Uncertainties



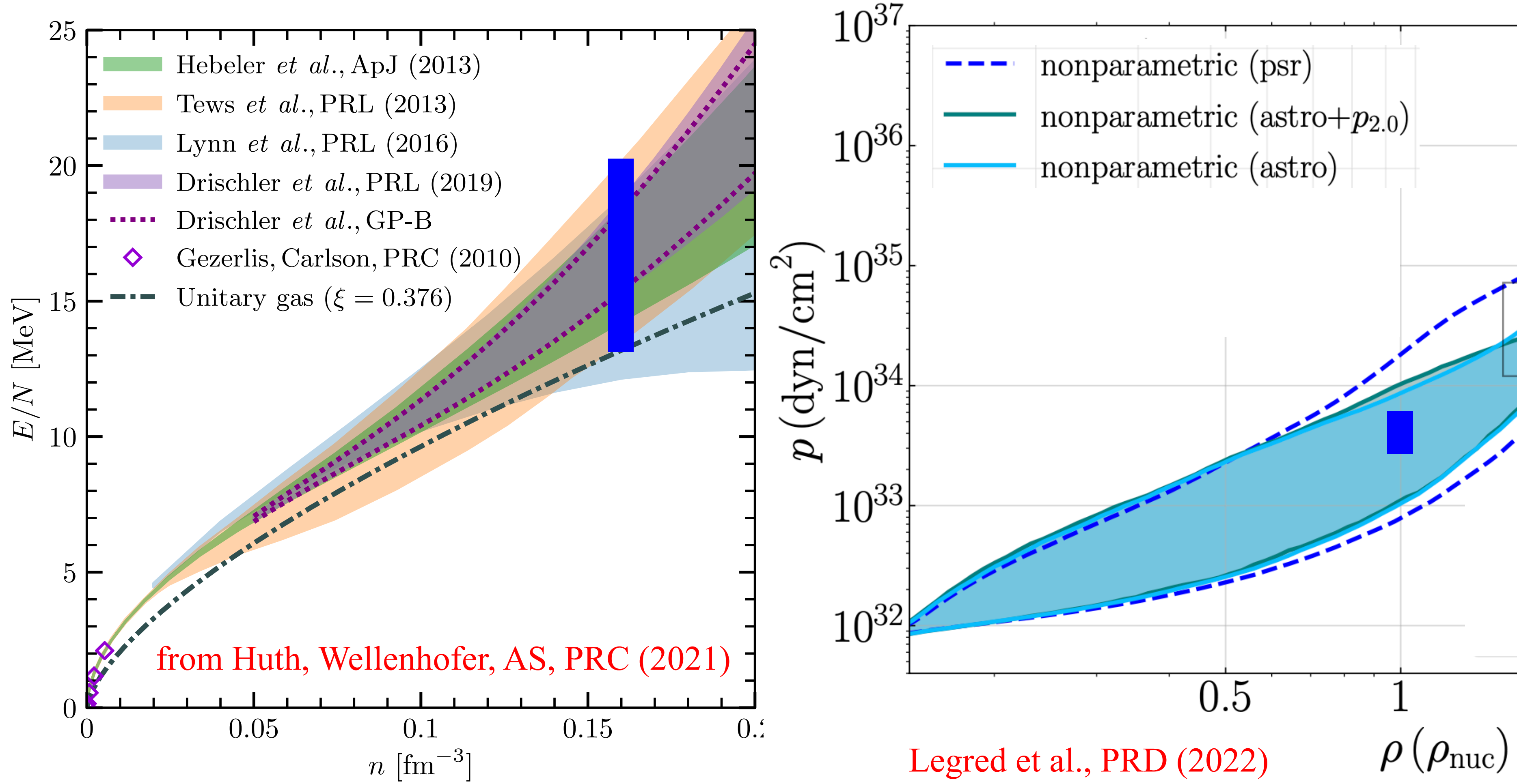


Keller, Wellenhofer, Hebeler, AS, PRC (2021)

GP-B (68%) gives similar bands as order-by-order EFT unc. (**EKM**) from Q/Λ_b expansion $\Delta X^{(j)} = Q \cdot \max\left(|X^{(j)} - X^{(j-1)}|, \Delta X^{(j-1)}\right)$

interaction choices (cutoffs, reg, fit) add to GP-B/EKM uncertainties

Chiral EFT calculations of neutron matter

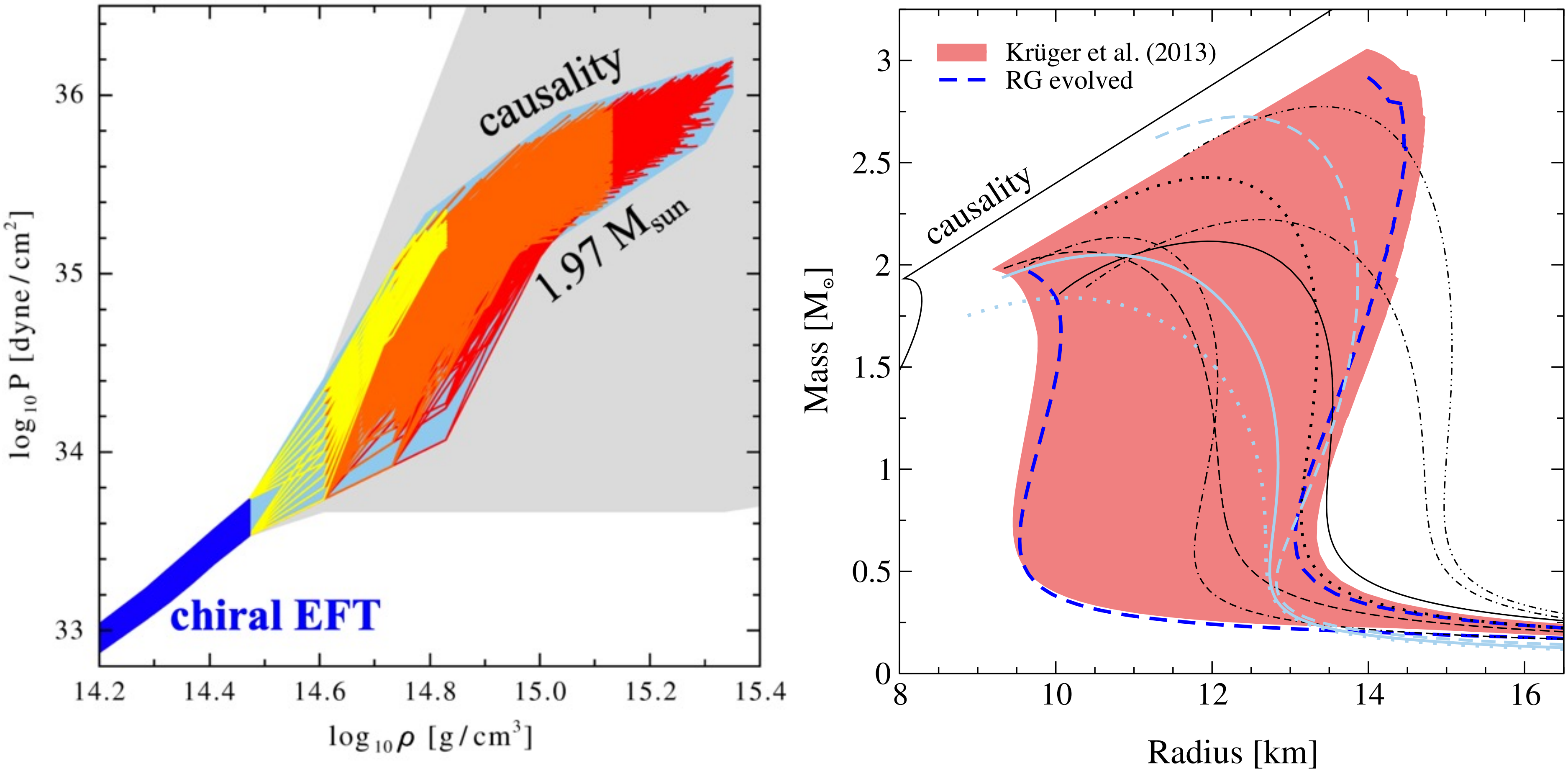


comparison to nonparametric EOS

suggests important nuclear physics constraints between nuclear crust at ~0.1 n_0 and saturation density

Impact on neutron stars (pre LIGO) Hebeler, Lattimer, Pethick, AS, ApJ (2013)

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



predicts neutron star radius: 9.7 - 13.9 km for M=1.4 M_{sun}

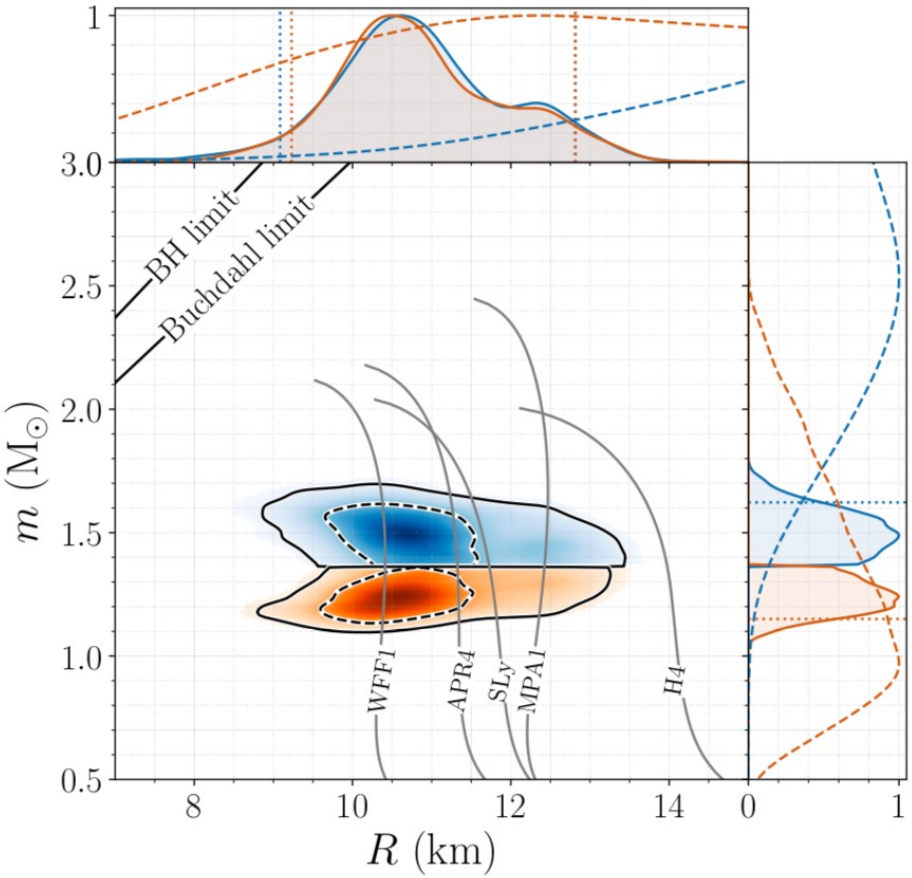
1.8 - 4.4 n_0 modest central densities

Neutron star radius from GW170817

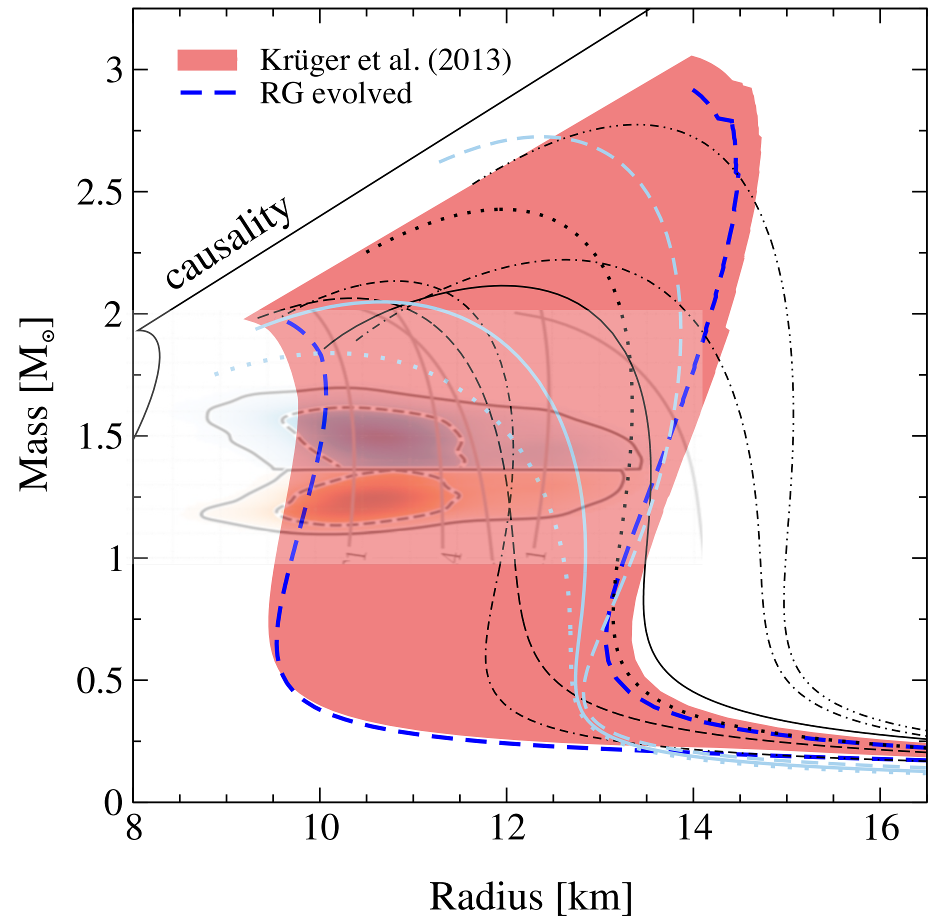
chiral EFT + general EOS extrapolation: 9.7 - 13.9 km for M=1.4 M_{sun}

GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration
(compiled 30 May 2018)



very consistent with
GW170817 from LIGO/Virgo

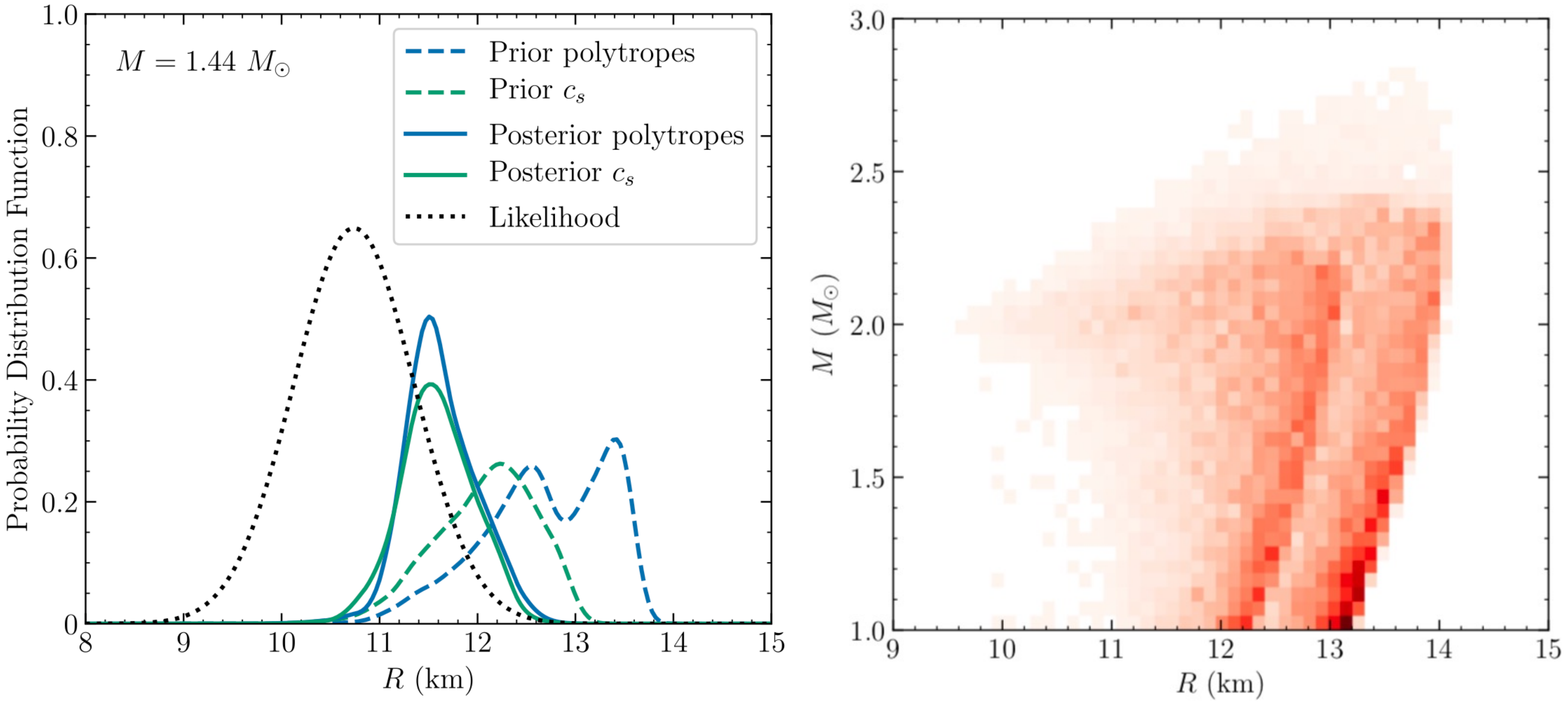


Neutron star radius from GW170817

chiral EFT + general EOS extrapolation: 9.7 - 13.9 km for M=1.4 M_{sun}

Bayesian inference vs. maximum extent, and prior sensitivities

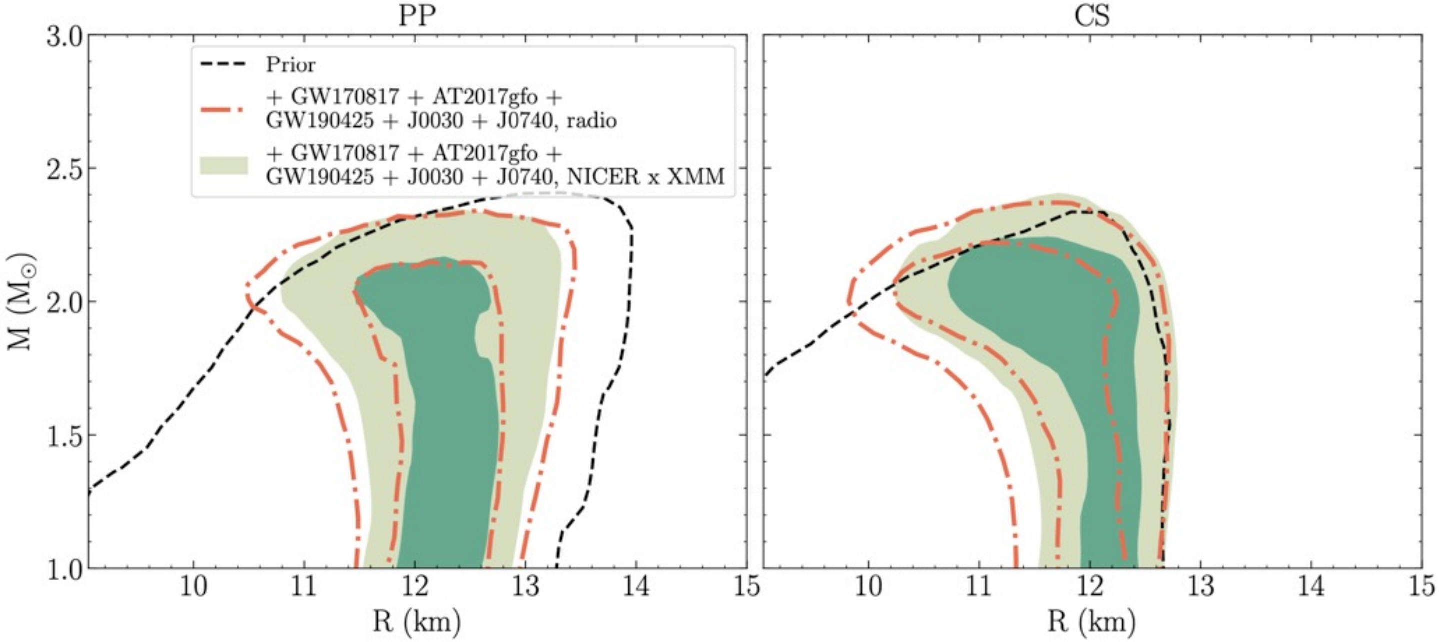
Greif, Raaijmakers et al., MNRAS (20219)



Combined merger and NICER constraints

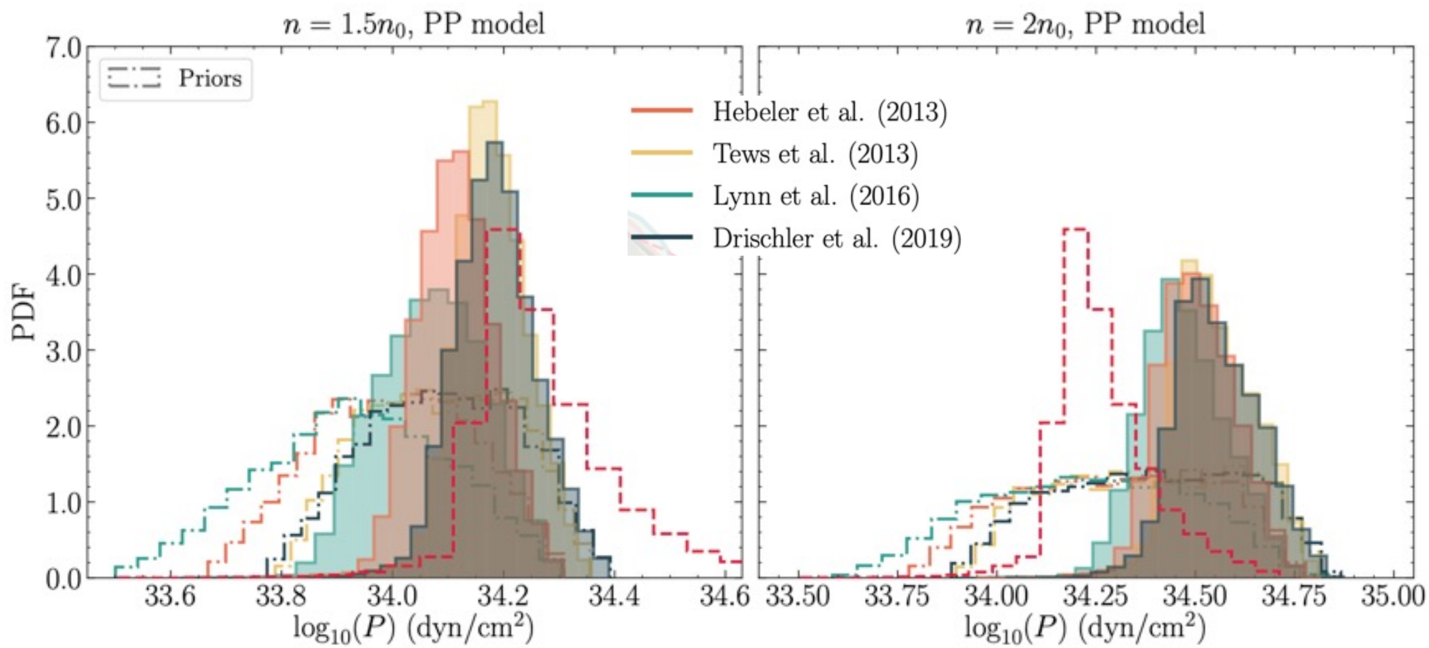
Raaijmakers et al., ApJL (2020), (2021)

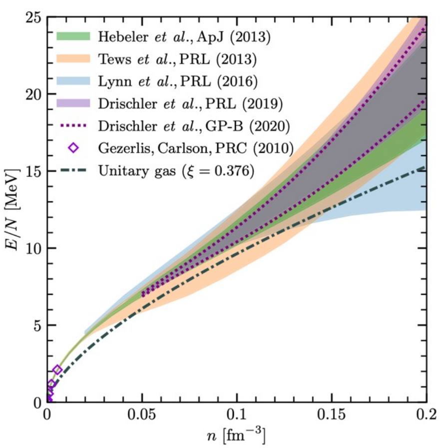
for mass-radius



equation of state at 1.5 and 2 n_0

astro prefers higher pressures





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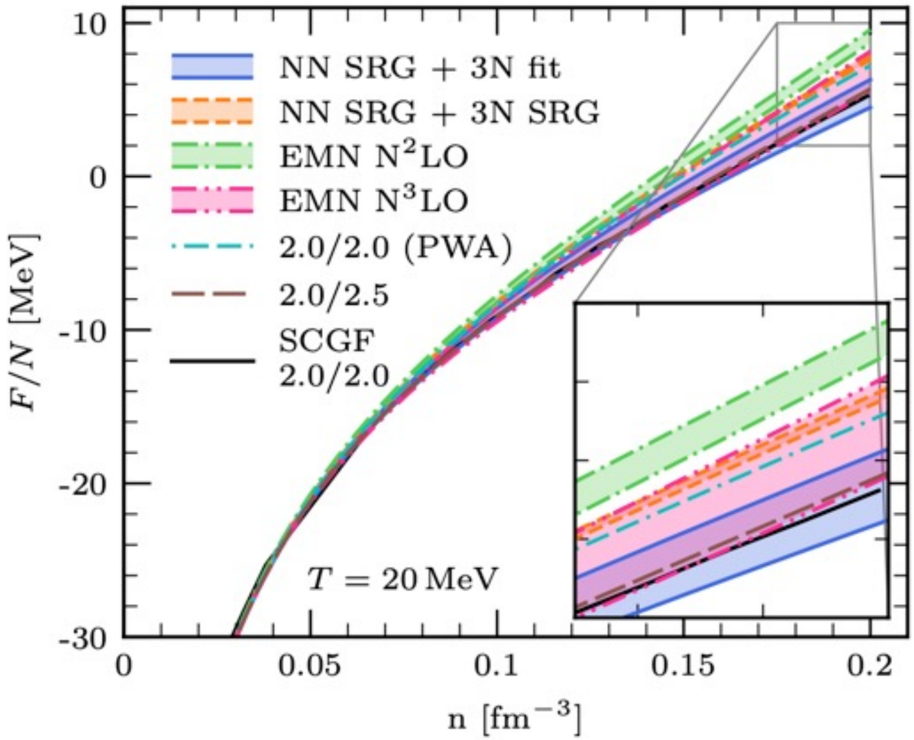
Nuclear experiments: dipole response, CREX, PREX

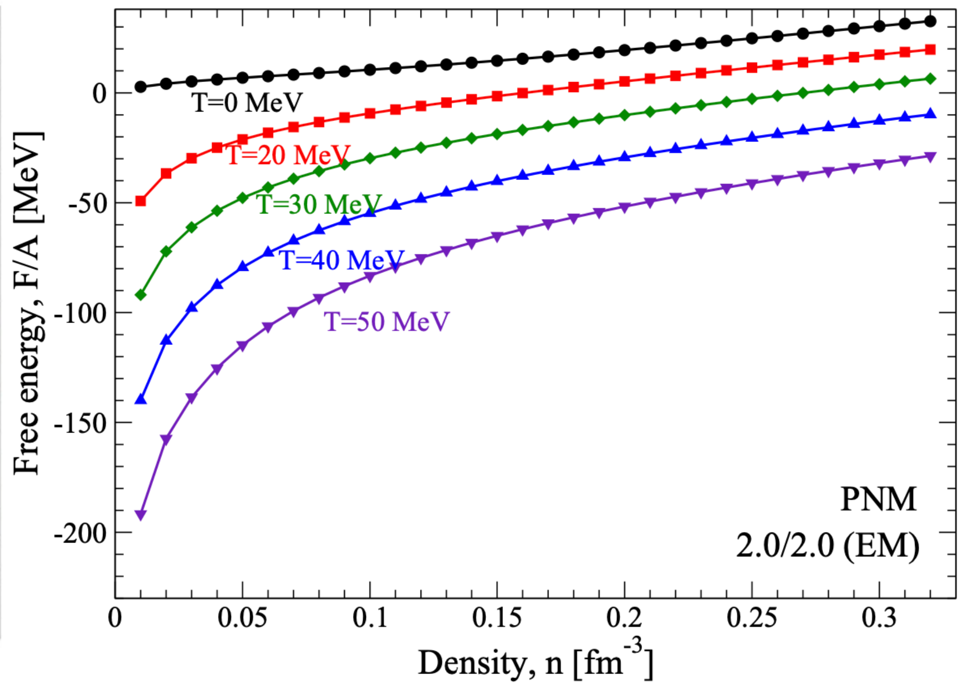
Neutron matter at finite temperature

similar thermal effects for different NN+3N interactions

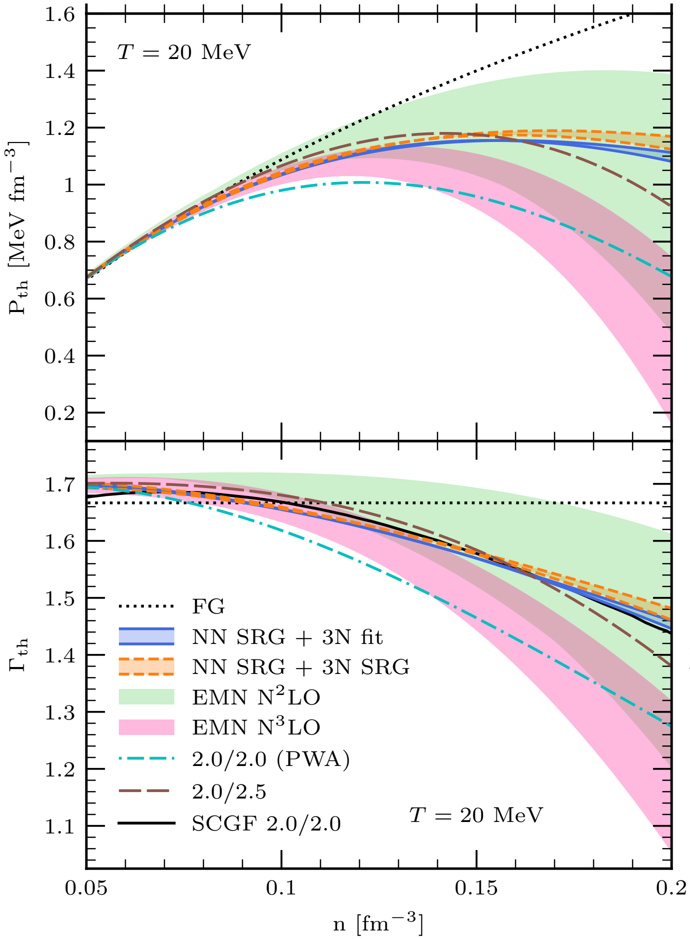
Keller, Wellenhofer, Hebeler, AS, PRC (2021)

SCGF (2.0/2.0): Carbone, AS, PRC (2019)





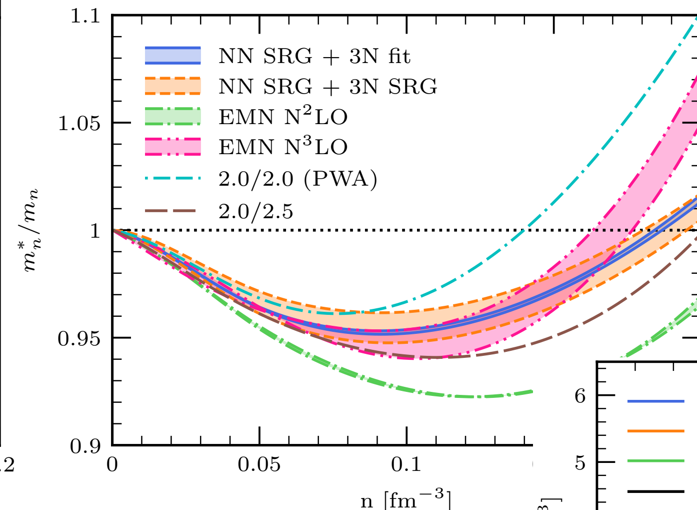
Thermal effects governed by effective mass

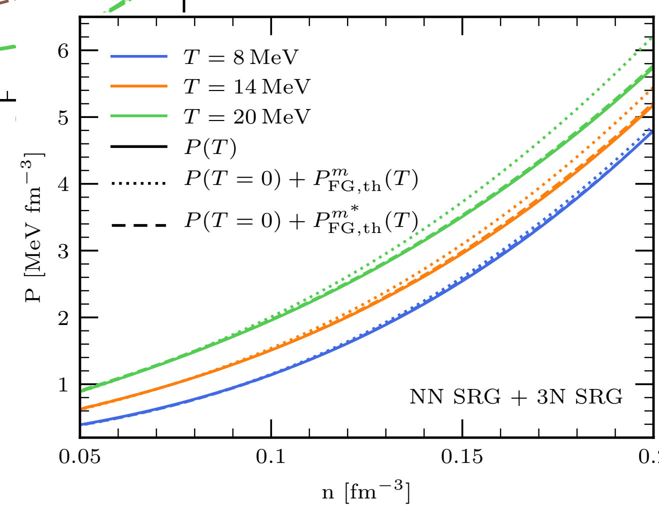


decreasing thermal pressure due to repulsive 3N contributions

increasing effective mass m^* beyond n_{sat}

$$\Gamma^*_{\rm th}(n) = \frac{5}{3} - \frac{n}{m^*_n}\frac{\partial m^*_n}{\partial n}$$





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

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

Impact on core-collapse supernova simulations

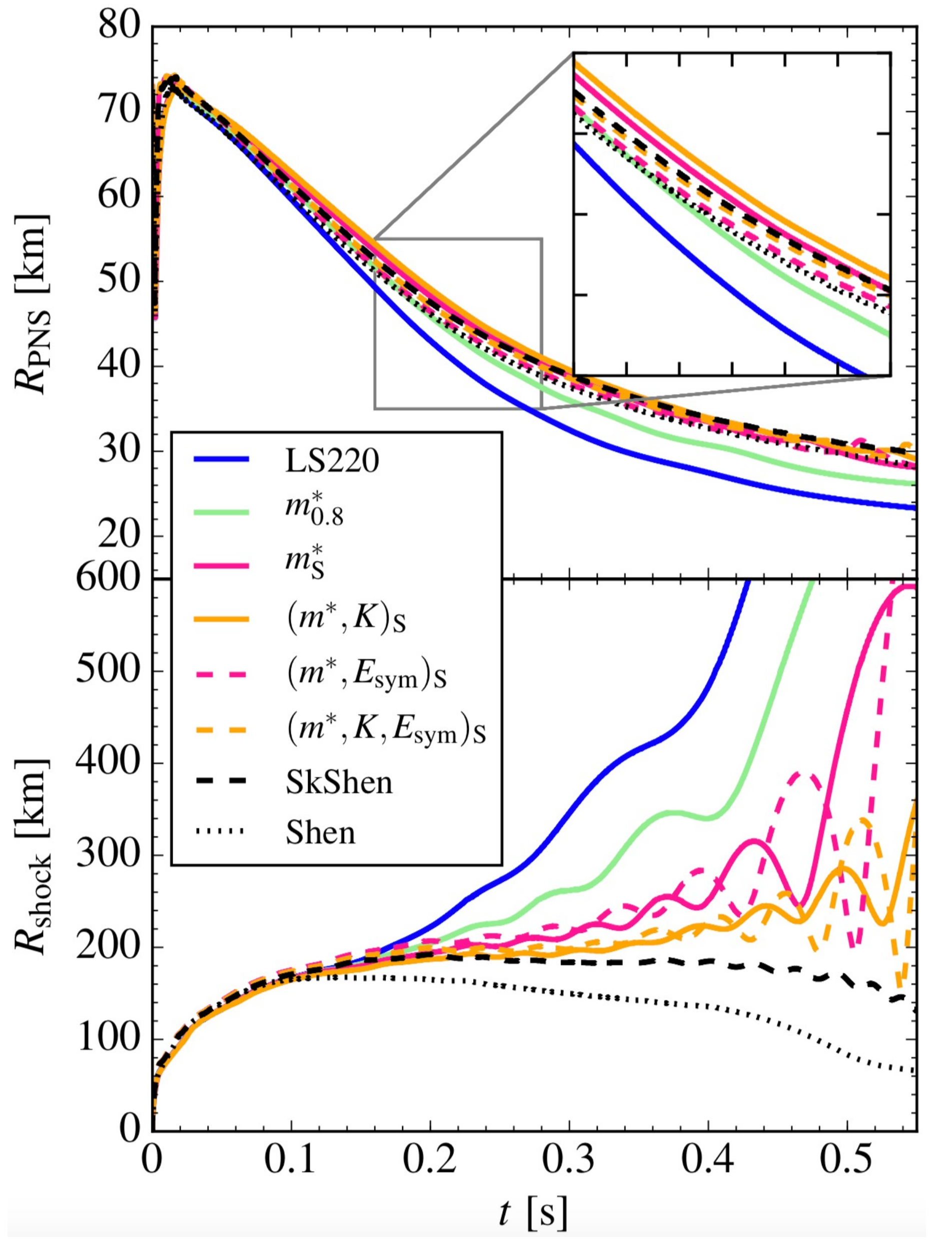
Yasin, Schäfer, Arcones, AS, PRL (2019)

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

	m^*/m	K	$E_{\rm sym}$	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



EOS for arbitrary proton fraction and temperature

Keller, Hebeler, AS, arXiv:2204.14016

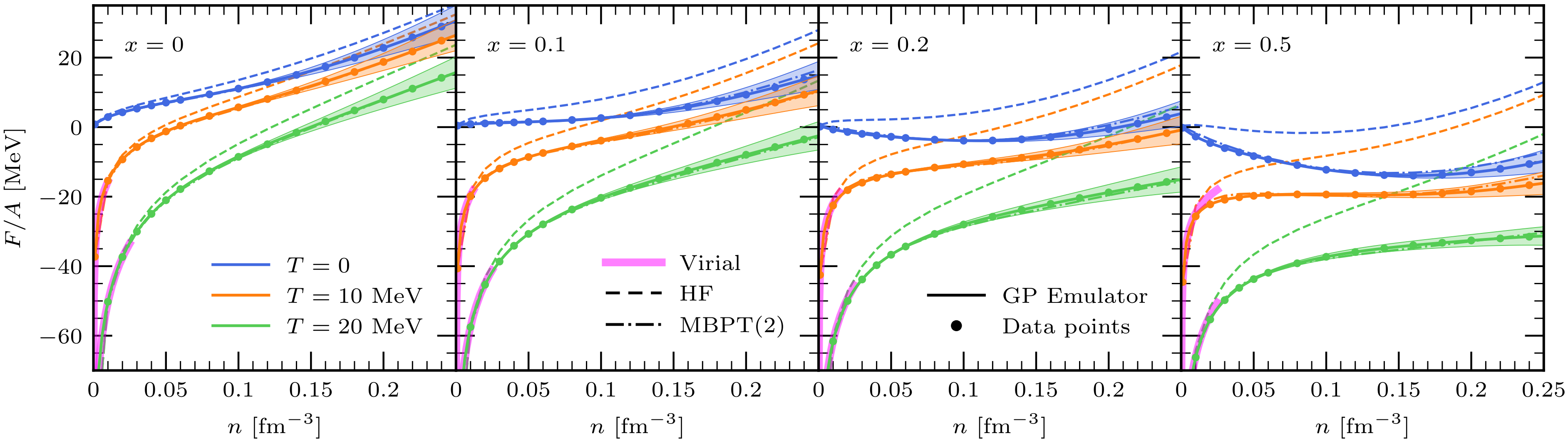
based on chiral EFT NN+3N interactions (EMN 450) to N^3LO

order-by-order EFT uncertainties $\Delta X^{(j)} = Q \cdot \max\left(|X^{(j)} - X^{(j-1)}|, \Delta X^{(j-1)}\right)$

(small) many-body uncertainties at MBPT(3)

excellent reproduction of free energy data by Gaussian process

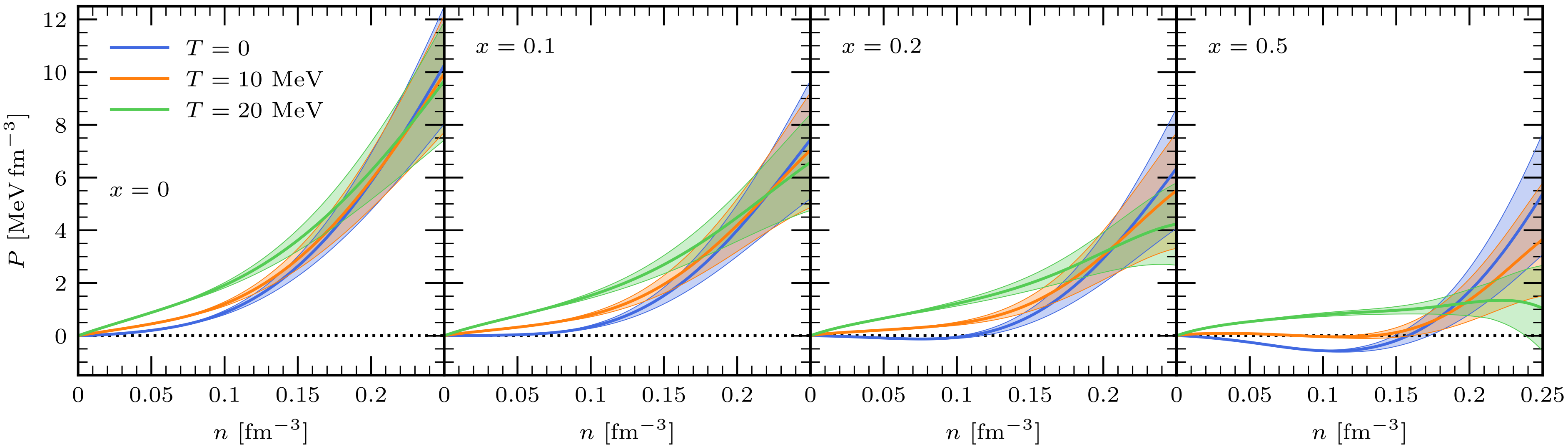
agrees with model-indep. virial EOS Horowitz, AS, NPA (2006) at low densities



EOS for arbitrary proton fraction and temperature

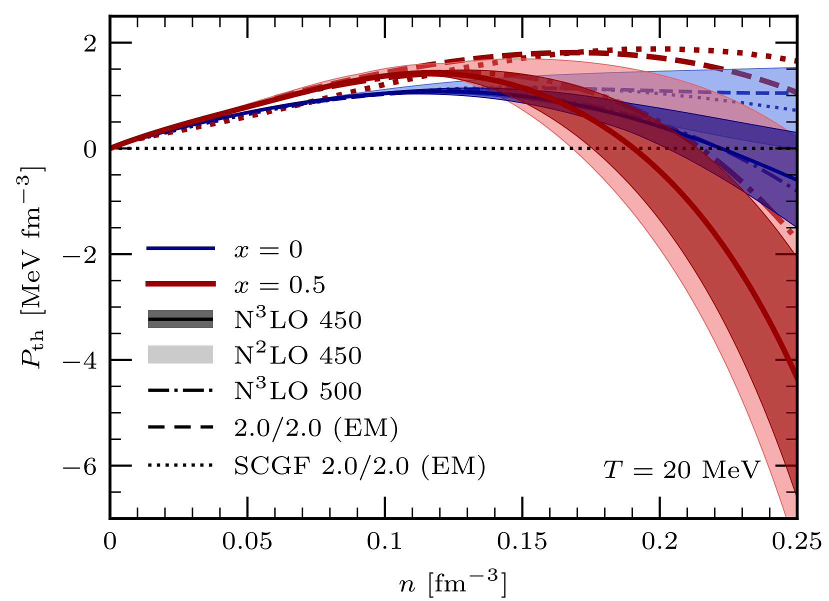
Keller, Hebeler, AS, arXiv:2204.14016

GP emulator to calculate pressure (thermodyn. consistent derivatives)



pressure isothermals cross at higher densities → negative thermal expansion

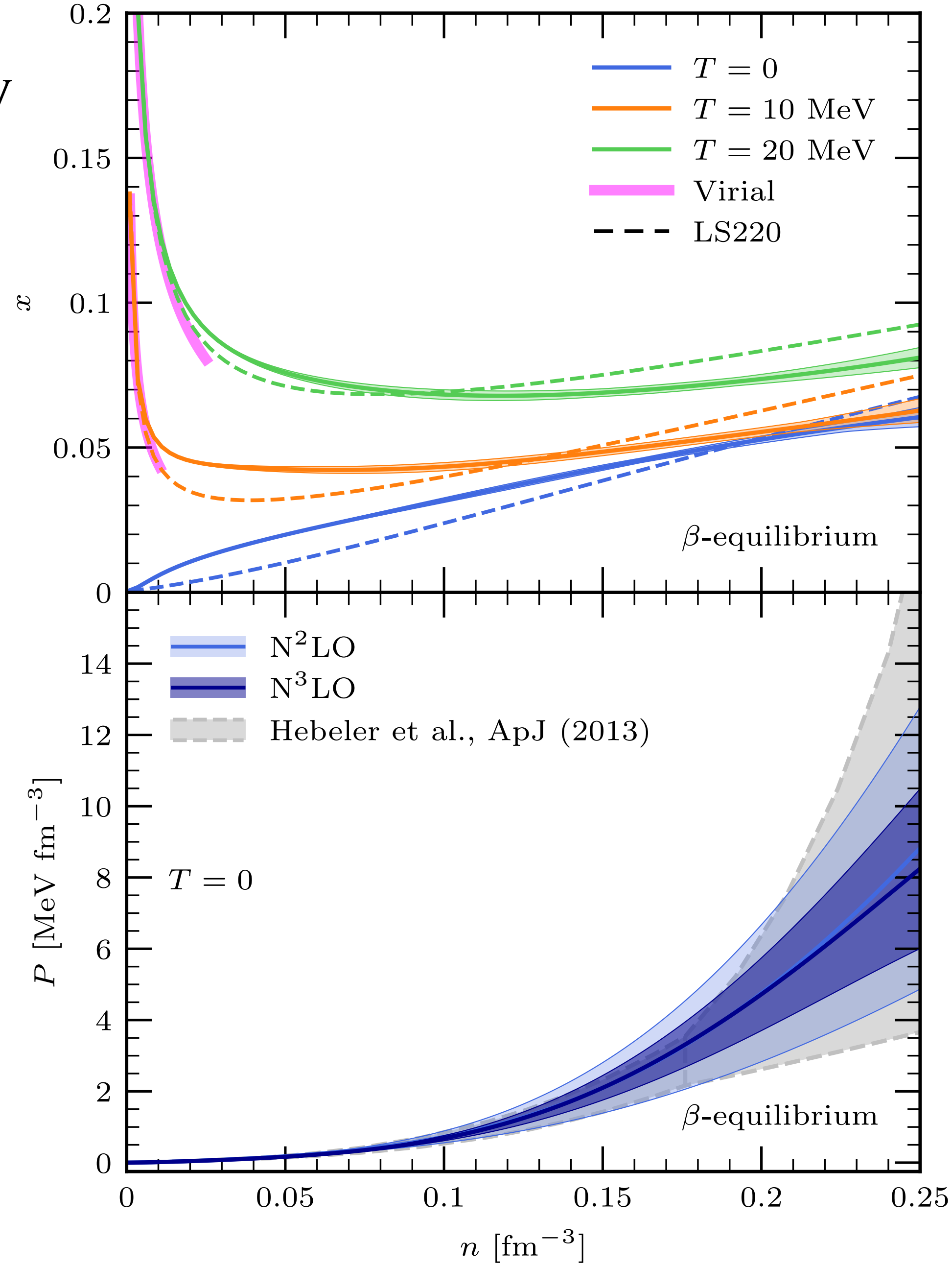
thermal part of pressure decreases with increasing density, observed for different chiral orders, cutoffs and interactions



EOS for neutron star matter in beta equilibrium

Keller, Hebeler, AS, arXiv:2204.14016

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

Applications to speed of sound and symmetry free energy

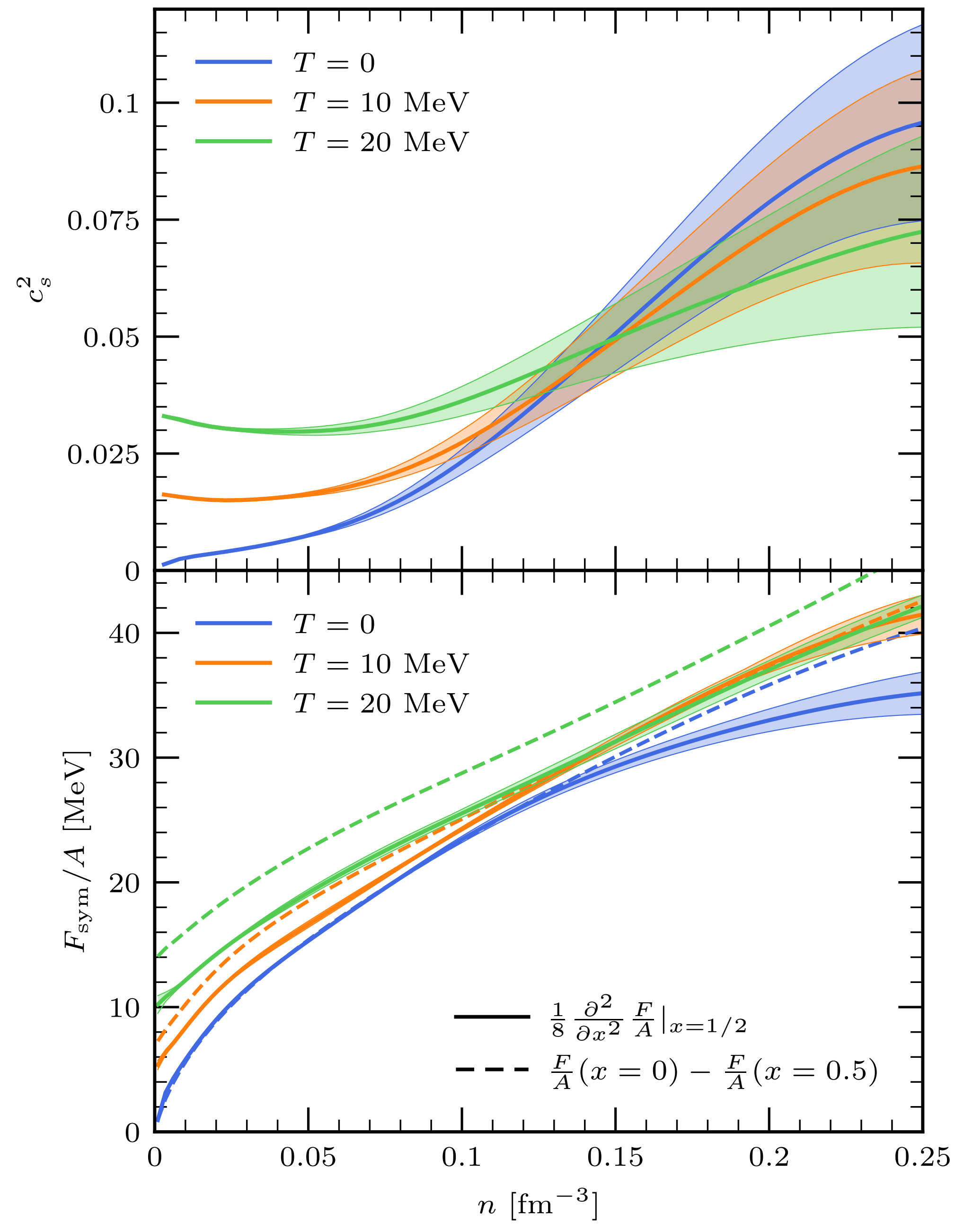
Keller, Hebeler, AS, arXiv:2204.14016

speed of sound for neutron matter at constant entropy

high-density behavior with increasing T similar to pressure

symmetry energy tightly constrained at fixed density

difference in definition mainly due to kinetic energy (m^*)



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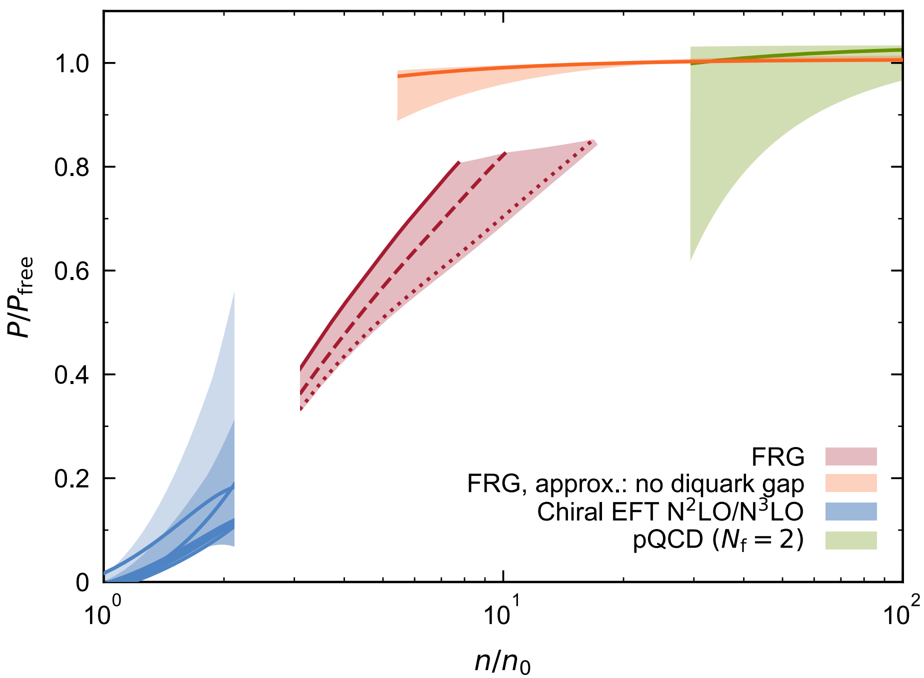
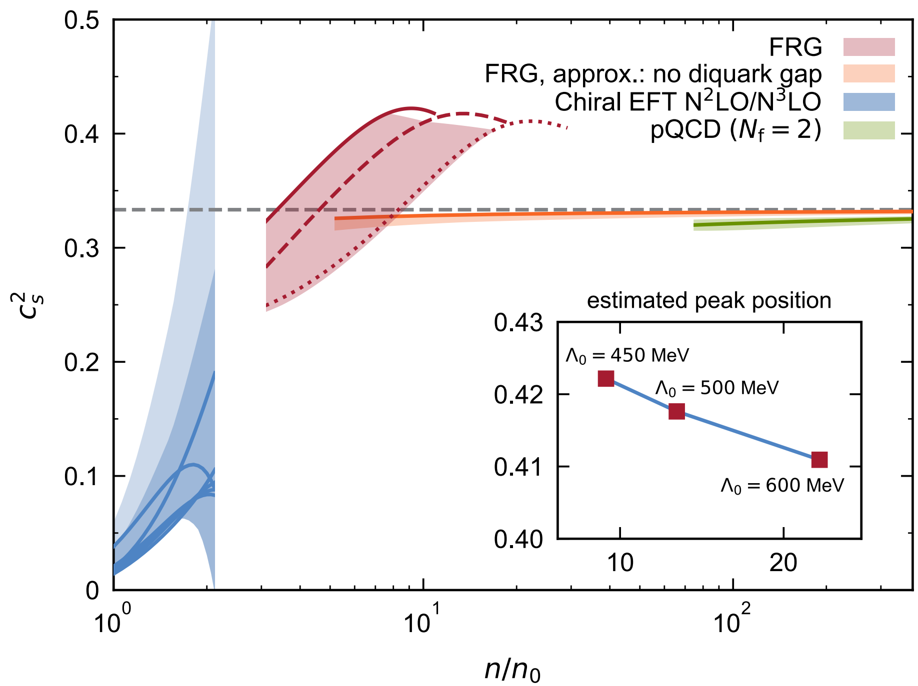
Functional RG: From QCD to intermediate densities

based on QCD at high densities

symmetric matter (m_u=m_d, no s quark, no electroweak interactions)

Leonhardt, Pospiech, Schallmo, Braun et al., PRL (2020)





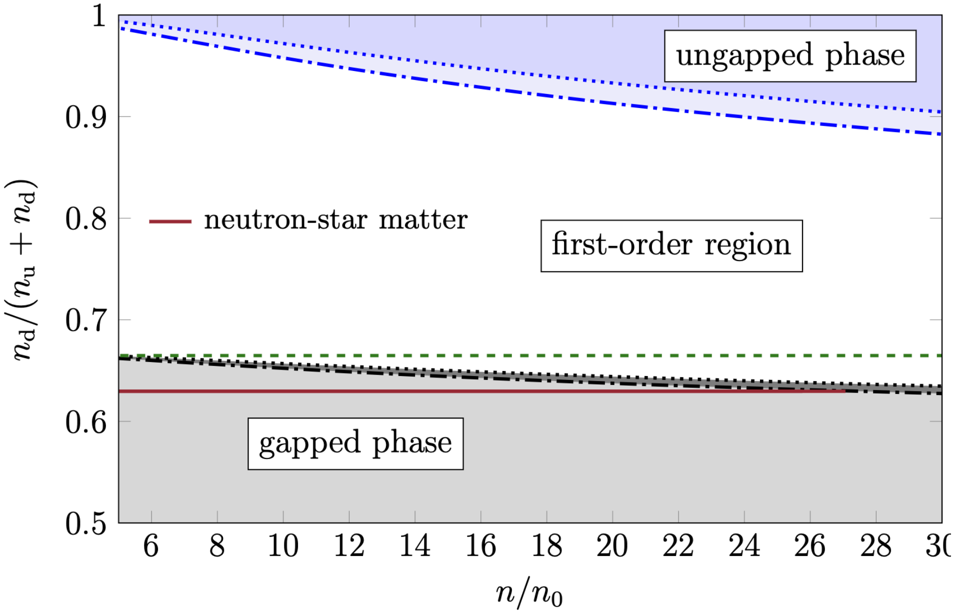
promising consistency between chiral EFT and FRG and pQCD

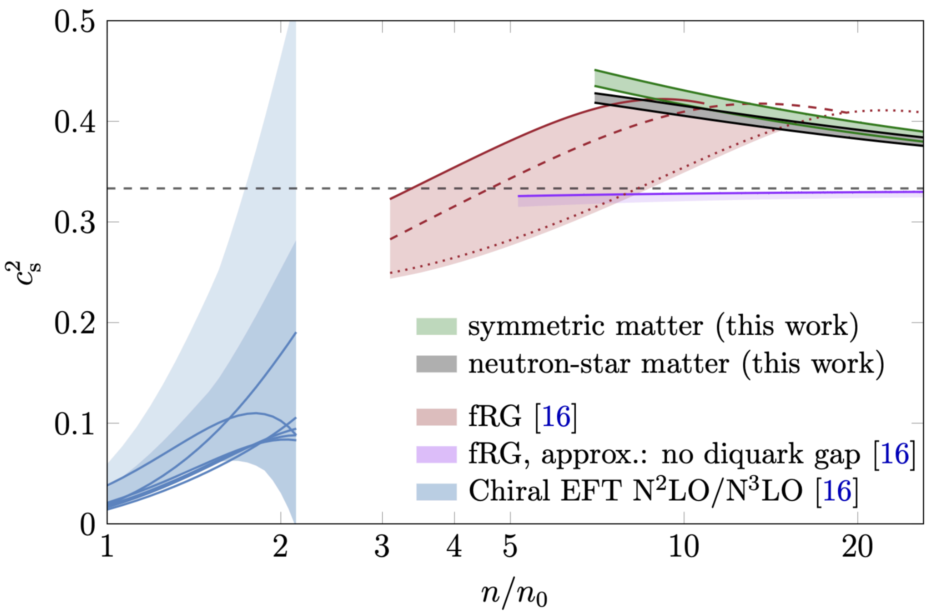
diquark correlations crucial for intermediate densities and high speed of sound

Functional RG: From QCD to intermediate densities

neutron star matter (m_u=m_d, no s quark)

Braun, Schallmo, arXiv:2204.00358





suggests ungapped quark matter phase is at very high densities

diquark gap gives large speed of sound up to high densities

may push validity of pQCD to higher densities

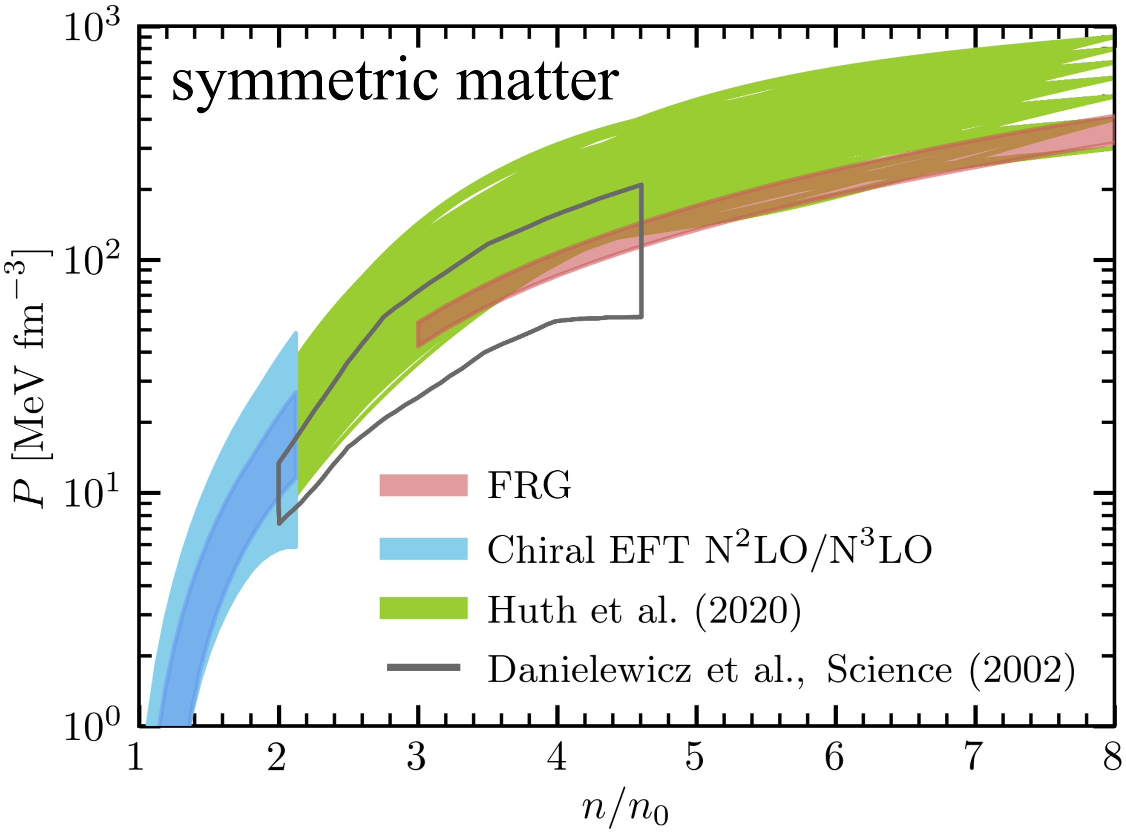
Symmetric matter: From chiral EFT to functional RG

comparison to **new EOS functionals** with 2 M_{sun} + LIGO/Virgo, NICER

Huth, Wellenhofer, AS, PRC (2021)

comparison to
heavy-ion constraint

Danielewicz et al., Science (2002)



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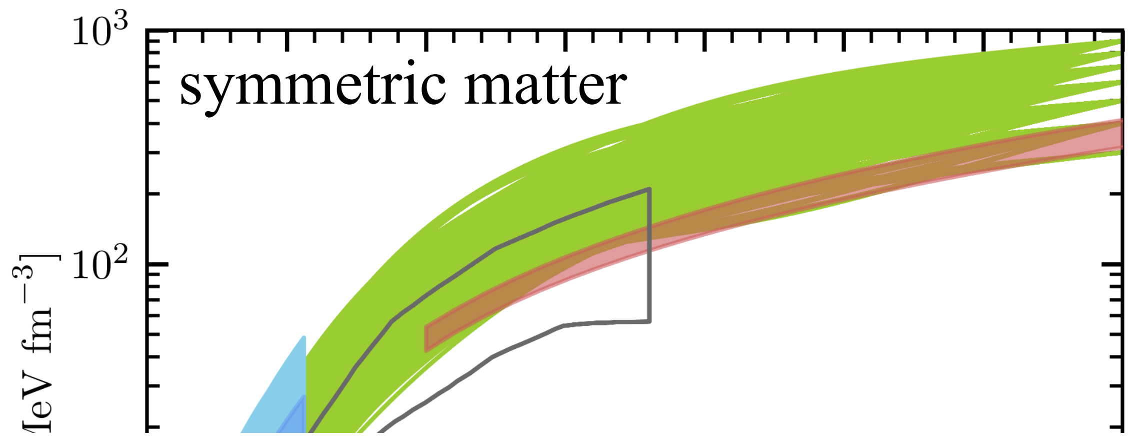
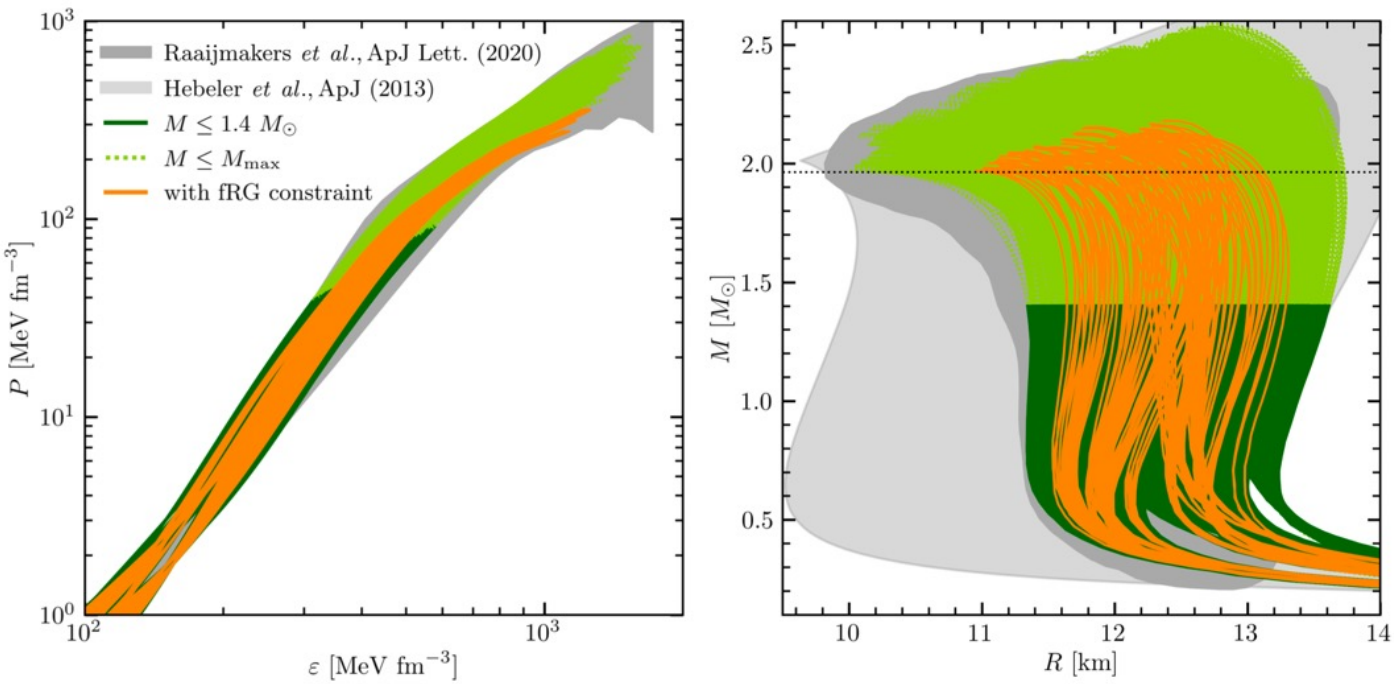
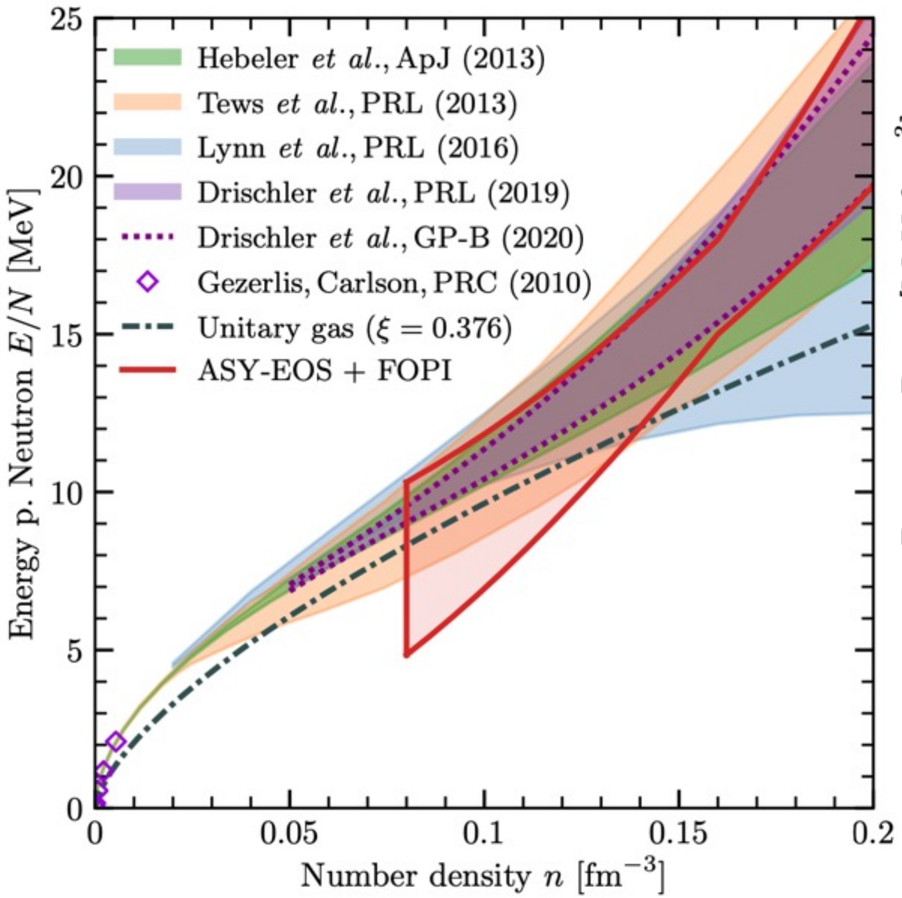
fRG provides interesting constraints at intermediate densities

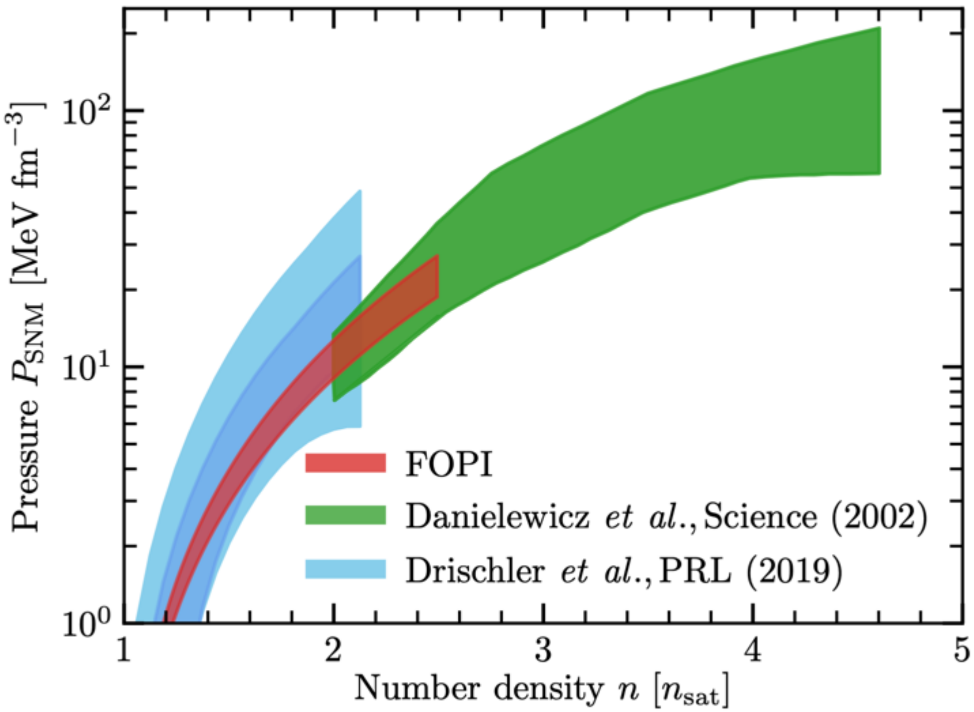




Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

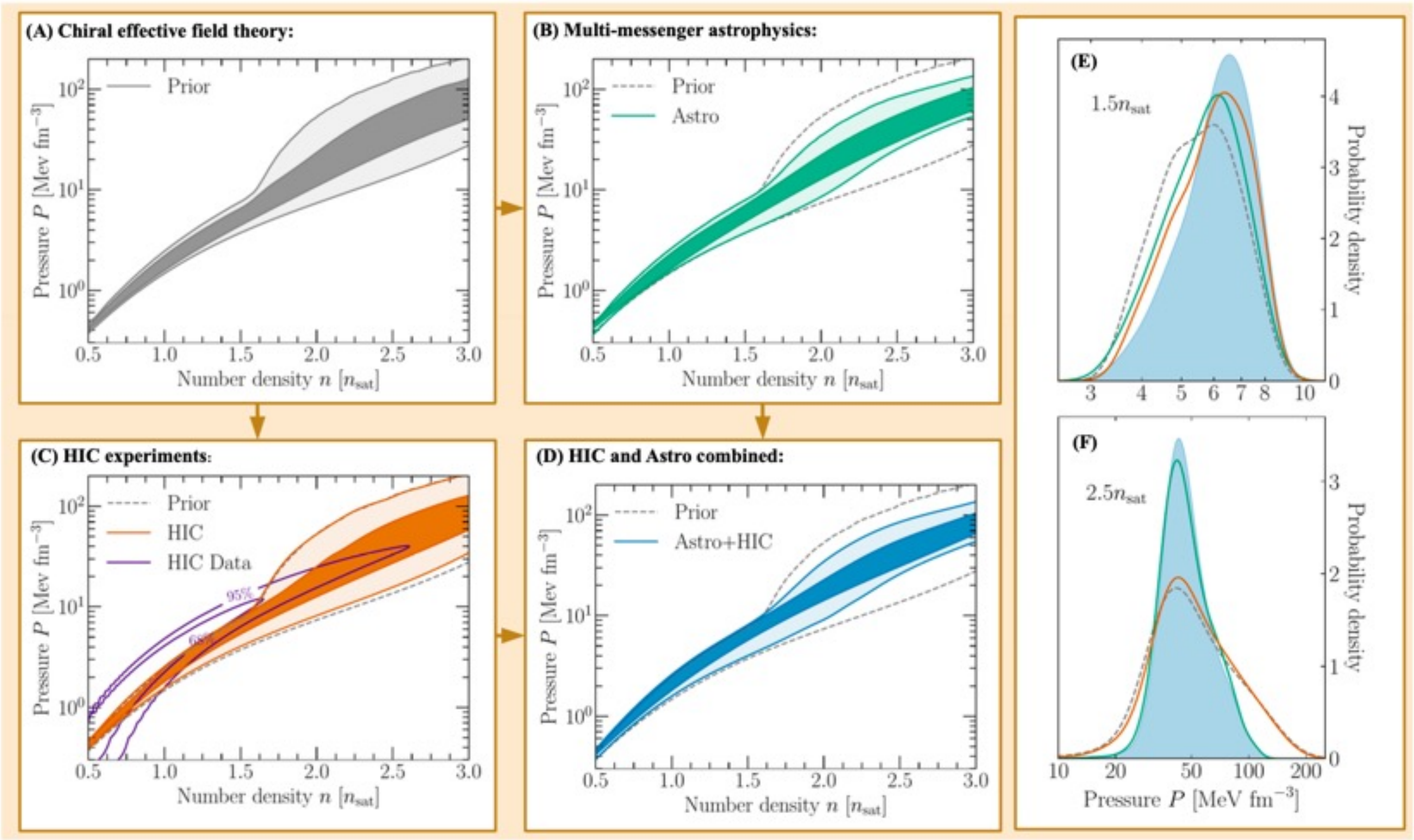
include in addition to chiral EFT: constraints from ASY-EOS and FOPI for neutron and symmetric matter with different functionals





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



improves HIC constraints for interm. densities very interesting

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

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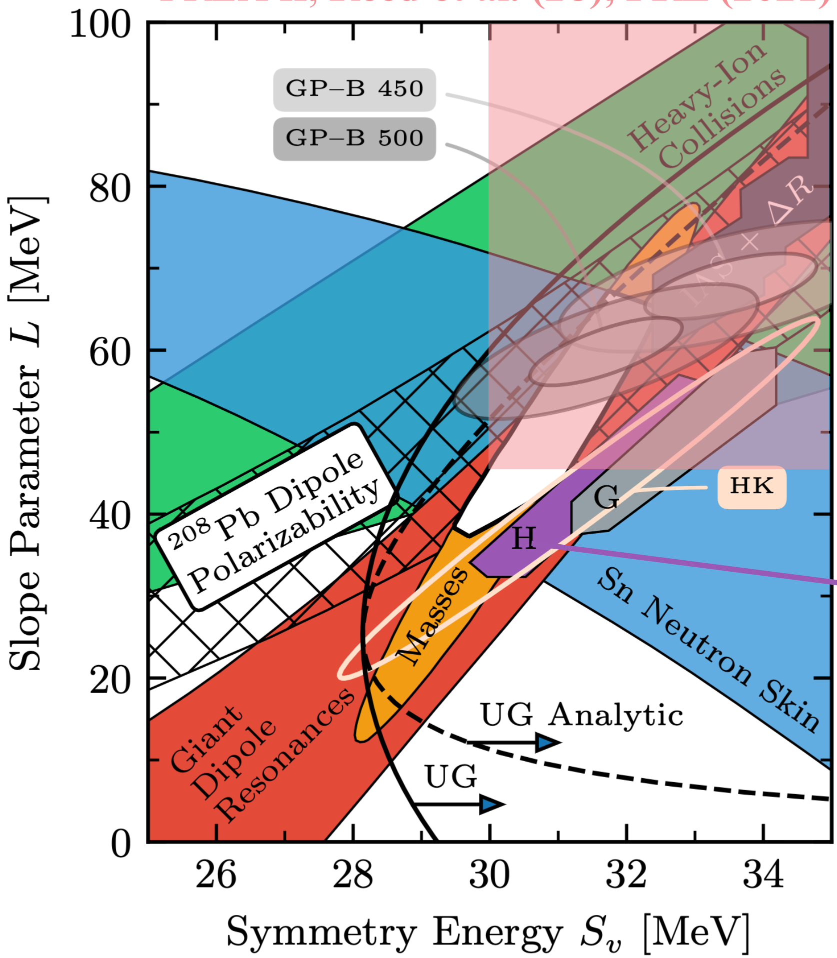
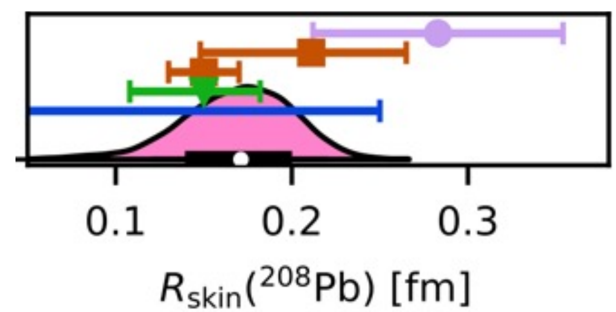
Symmetry energy vs. L parameter based on Lattimer, Lim, ApJ (2013)

PREX II, Reed et al. (2σ), PRL (2021)



Ab initio calc of ^{208}Pb neutron skin

Hu, Jiang, Miyagi et al., arXiv:2112.01125



Region H corresponds to ^{208}Pb neutron skin: 0.14-0.20 fm

Hebeler, Lattimer, Pethick, AS, PRL (2010)

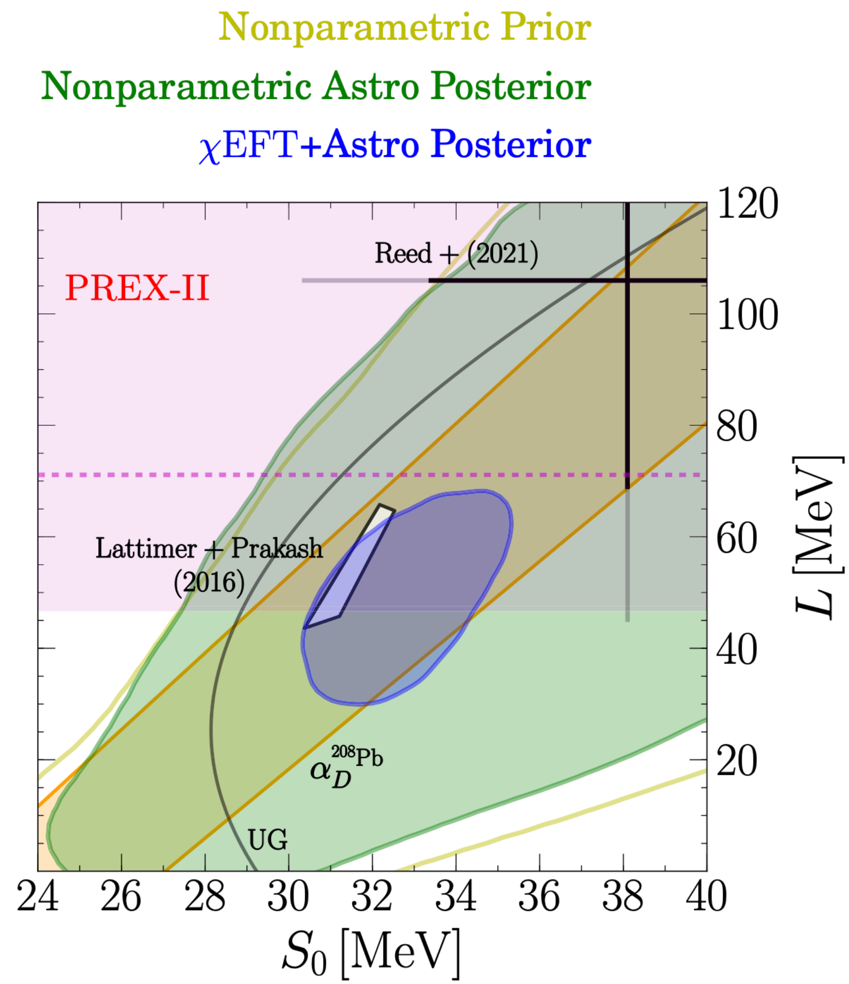
MREX precision goal ±0.03 fm very important (ideally better)

from Drischler, Holt, Wellenhofer, AS, ARNPS (2021)

Note: not all regions are at same saturation density

Impact of PREX and ^{208}Pb dipole polarizability

Essick, Landry, AS, Tews, PRL, PRC (2021)



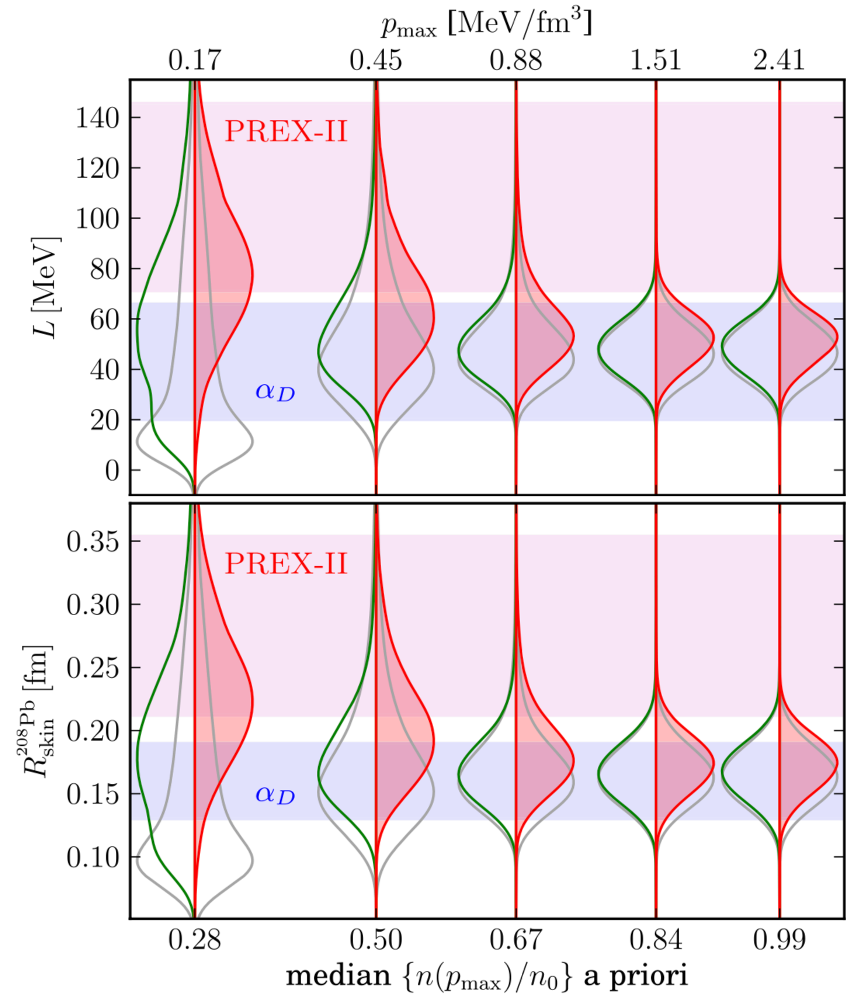


FIG. 2. Prior (gray, unshaded), Astro posterior (green, left-unshaded), and Astro + PREX-II posterior (red, right-shaded)

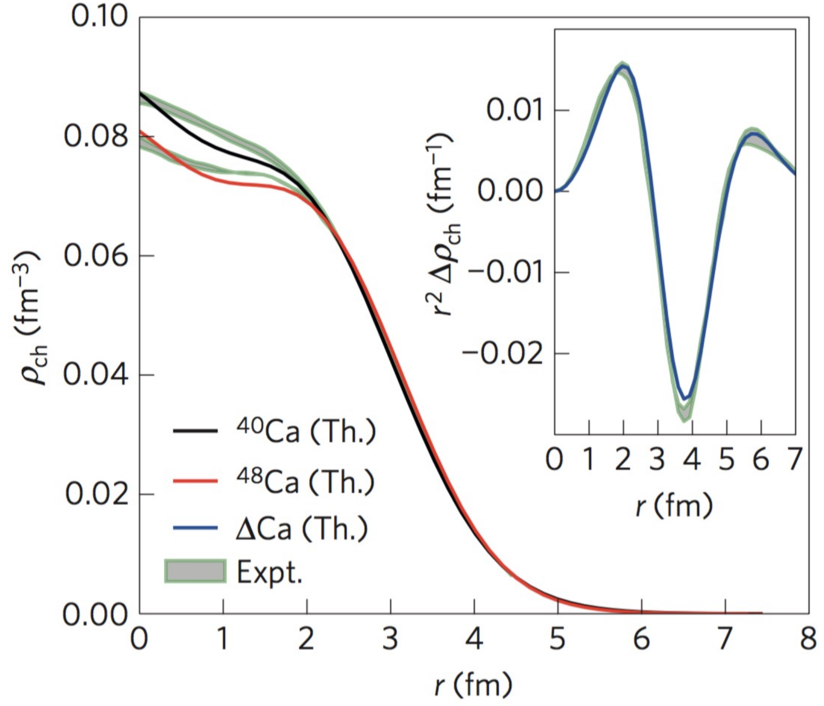
^{208}Pb dipole polarizability Tamii et al., PRL (2021)

very consistent with χEFT+Astro posterior

Neutron skin and dipole polarizability of ^{48}Ca

Hagen et al., Nature Phys. (2015)

ab initio calculations lead to charge distributions consistent with exp

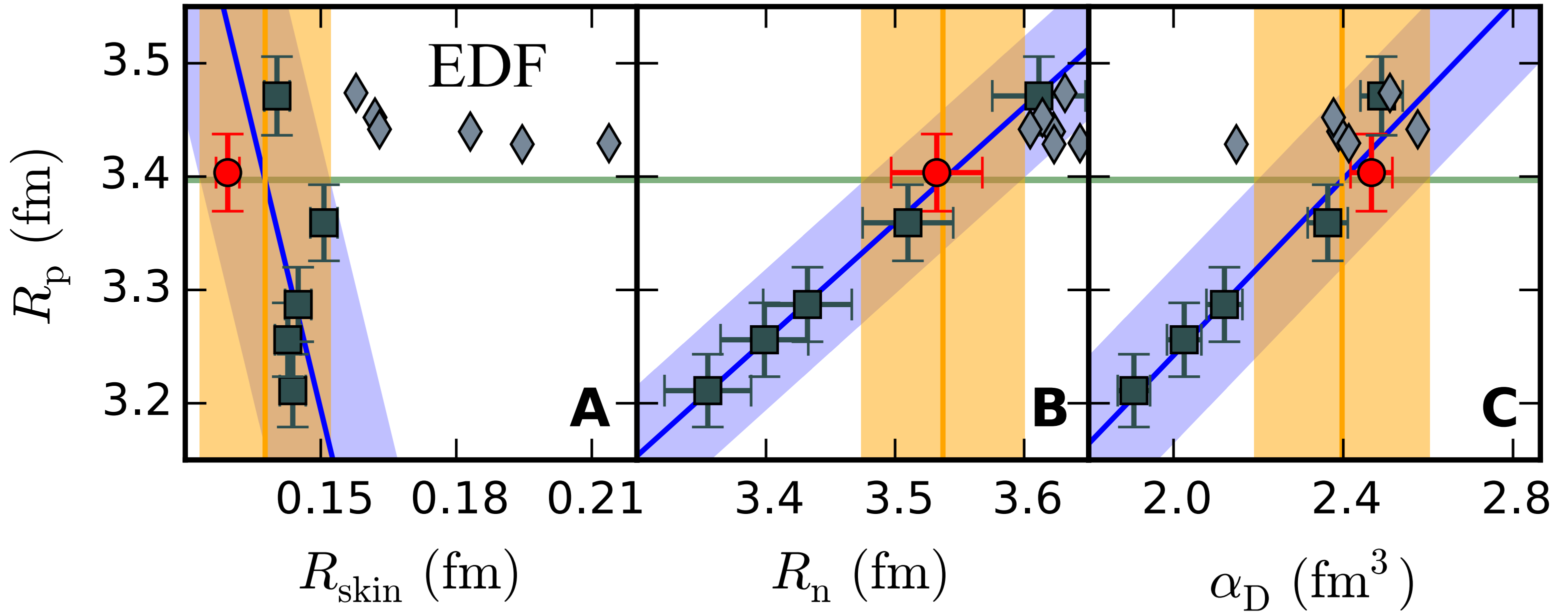


Neutron skin and dipole polarizability of ^{48}Ca

Hagen et al., Nature Phys. (2015)

ab initio calculations lead to charge distributions consistent with exp,

predict **small neutron skin** **dipole polarizability α_D**



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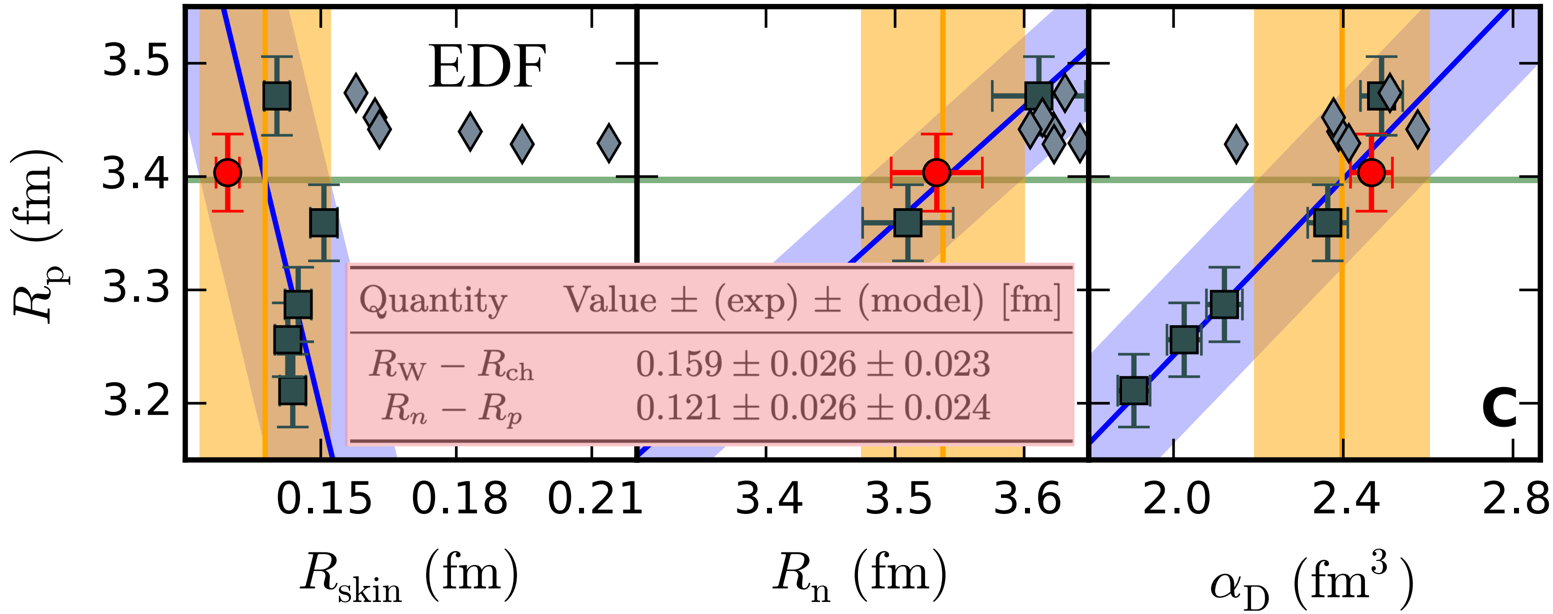
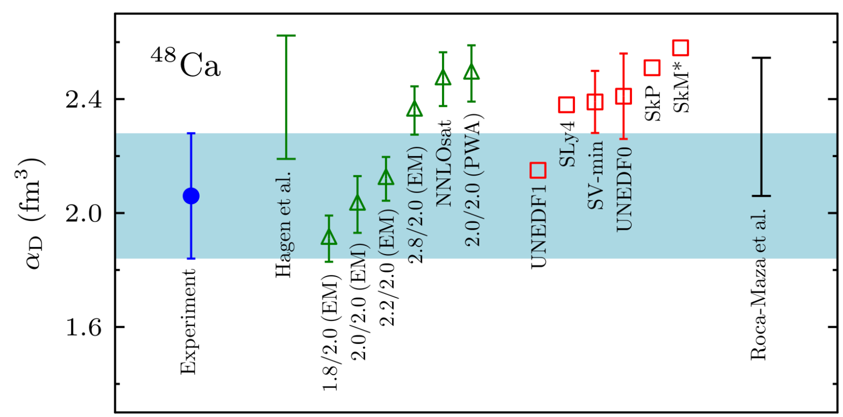


agrees with dipole polarizability from Darmstadt-Osaka exp Birkhan et al., PRL (2017)

+ with CREX result Adhikari et al., PRL (2022)



Summary

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ab initio calculations based on chiral EFT interactions for many nuclei and matter: cold, finite T, arbitrary proton fraction

reliable results up to 1-1.5 n_0 with controlled uncertainties: EFT truncation + systematic uncertainties

astro, heavy-ion collisions, functional RG provides insights to intermediate densities

chiral EFT agrees with many experiments for (n-rich) nuclei + ^{48}Ca dipole polarizability, CREX – precise PREX/MREX needed