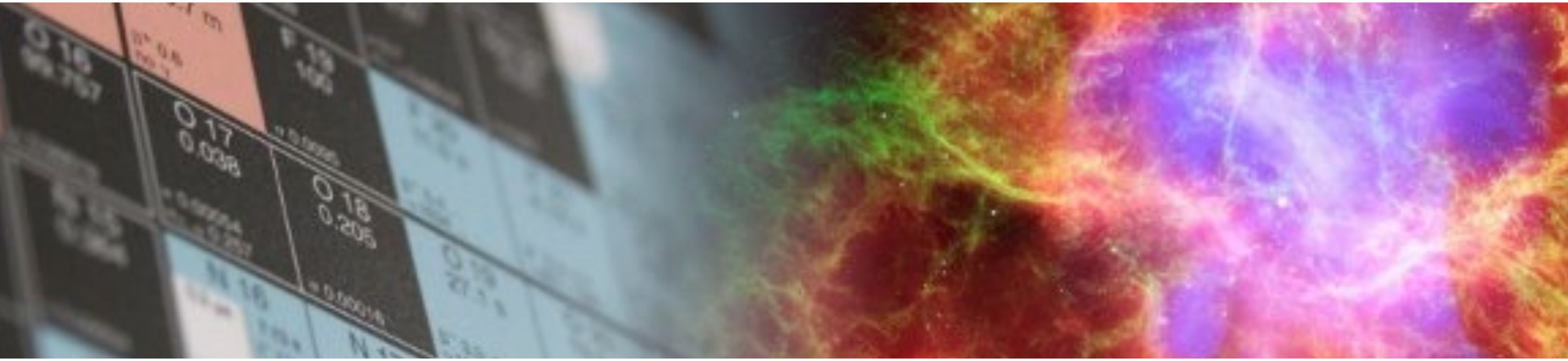
New equation of state developments for neutron star matter and for finite temperature

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG



INT Workshop "R-process and EOS after LIGO/Virgo", May 24, 2022

DFG

SFB 1245

erc
European Research Council
Established by the European Commission
ERC AdG EUSTRONG

Bundesministerium
für Bildung
und Forschung

Outline

Chiral effective field theory for nuclear forces

Ab initio calculations of nuclear matter

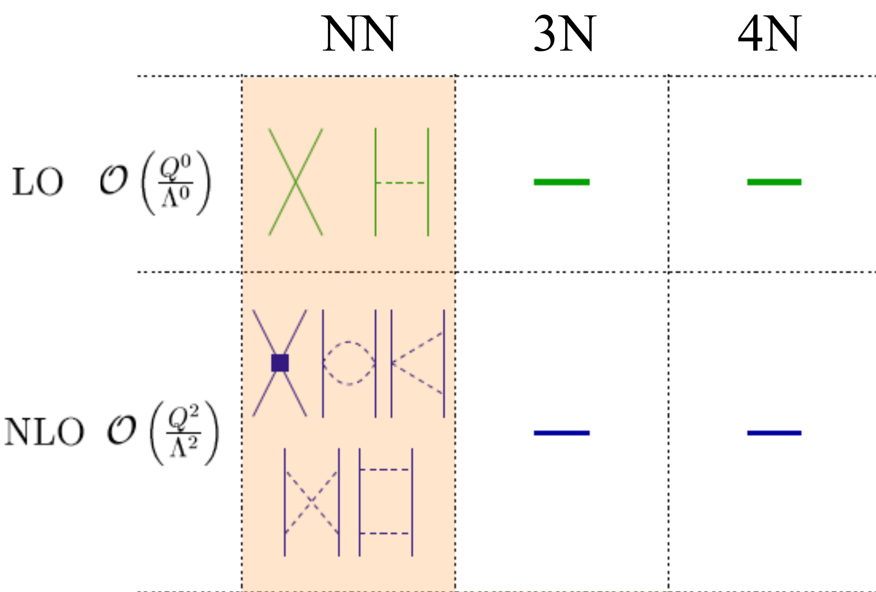
EOS constraints from chiral EFT and astrophysics

Constraints from heavy-ion collisions

EOS for arbitrary proton fraction and finite T

Chiral effective field theory for nuclear forces

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



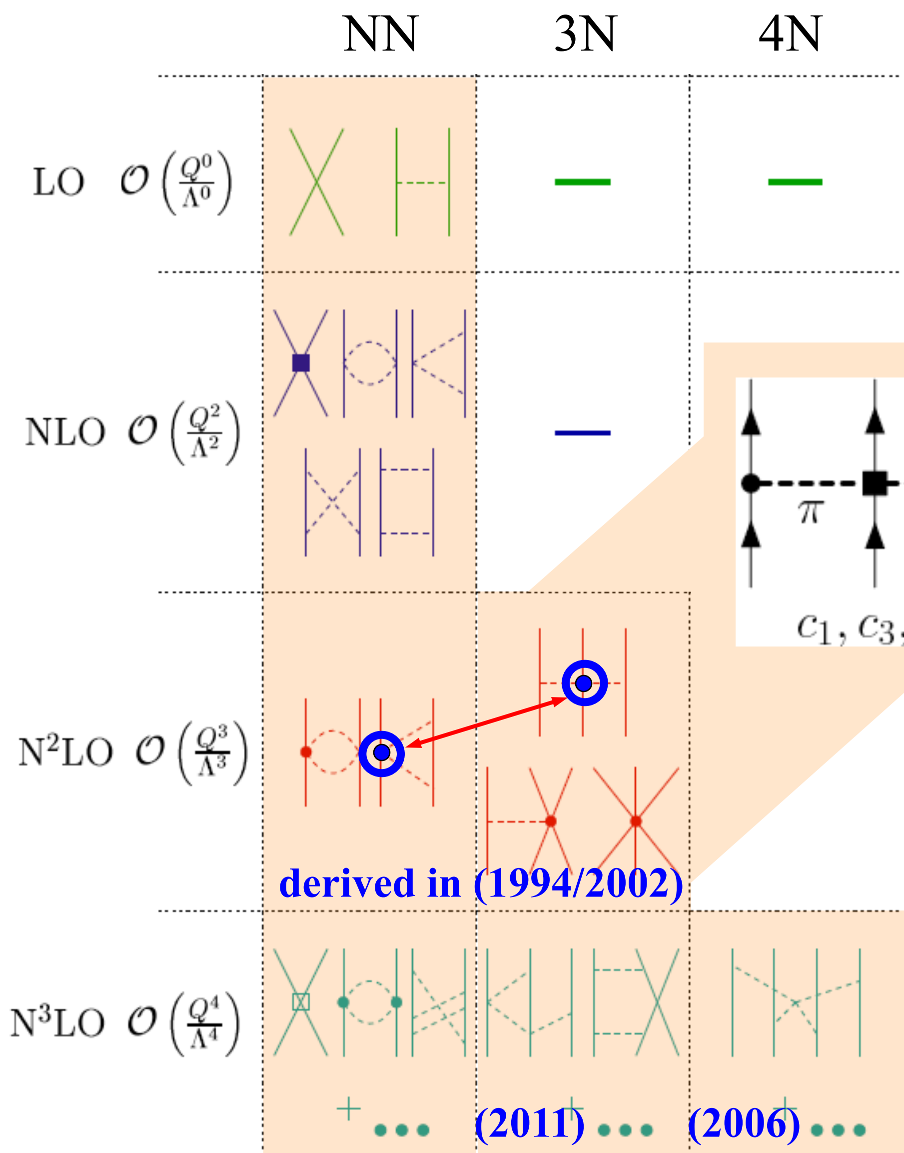
based on symmetries of strong interaction (QCD)

long-range interactions governed by pion exchanges

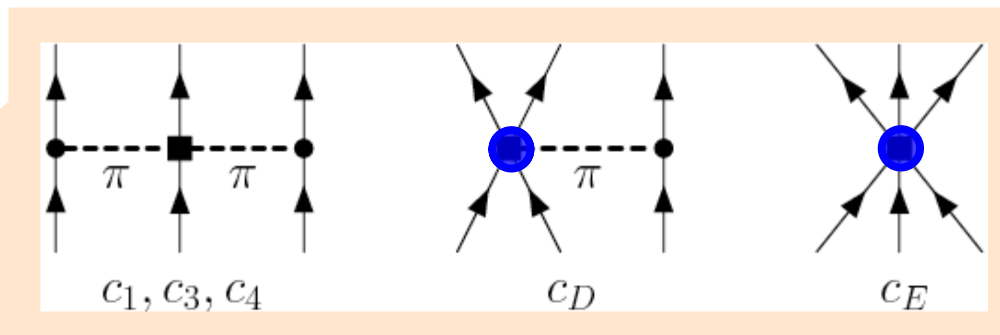
Weinberg (1990,91)

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

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

Chiral effective field theory for nuclear forces

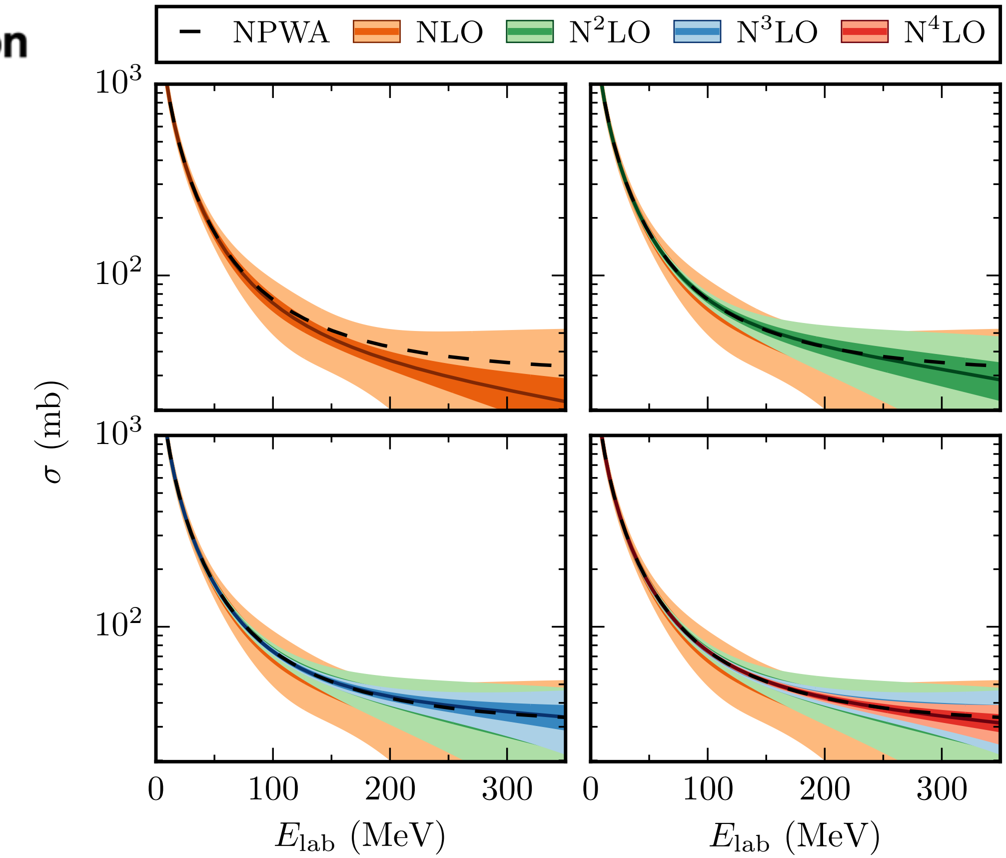
Systematic expansion (power counting) in low momenta $(Q/\Lambda_b)^n$

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

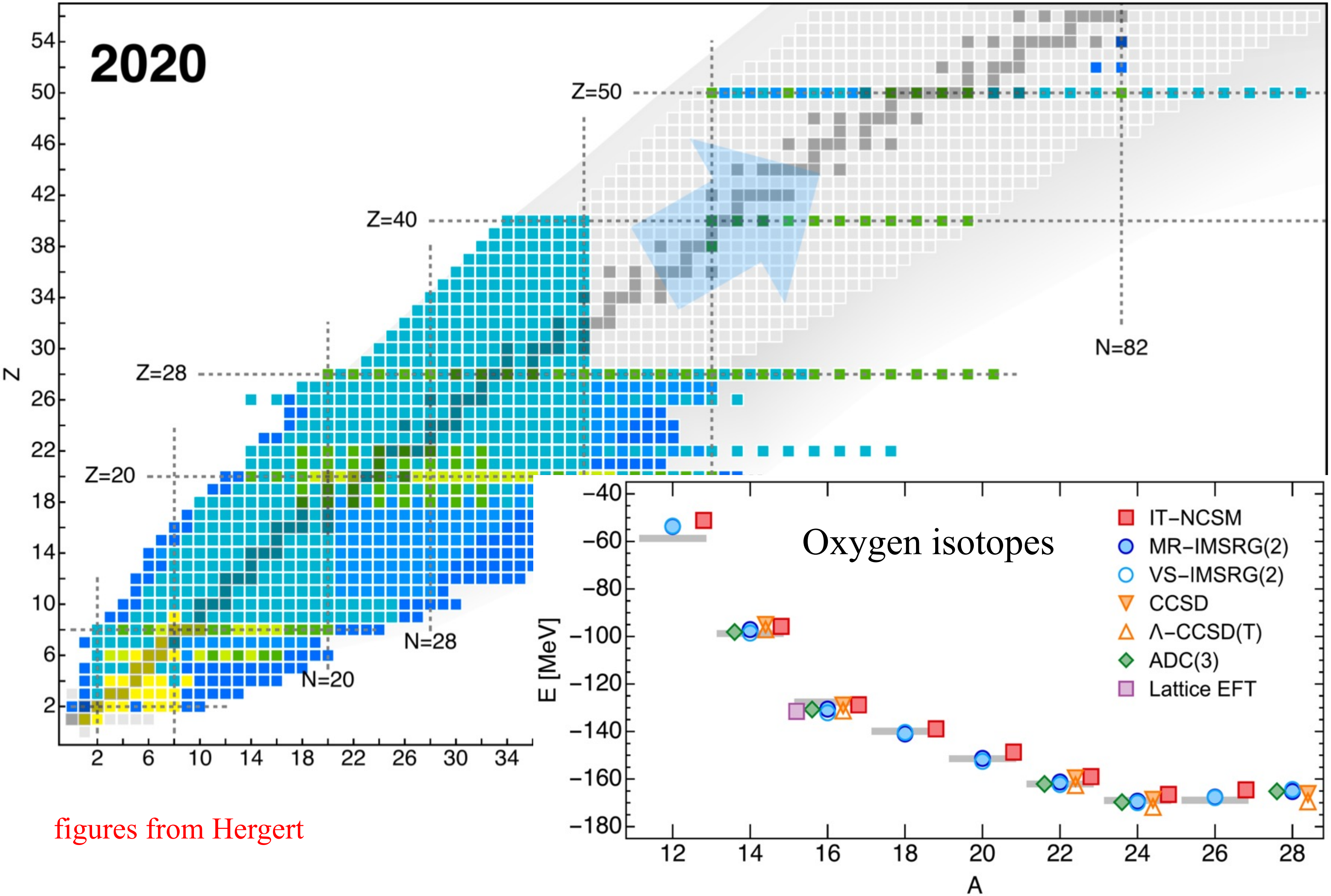
R J Furnstahl[1], D R Phillips[2] and S Wesolowski[1]

Bayesian uncertainty estimates and model checking



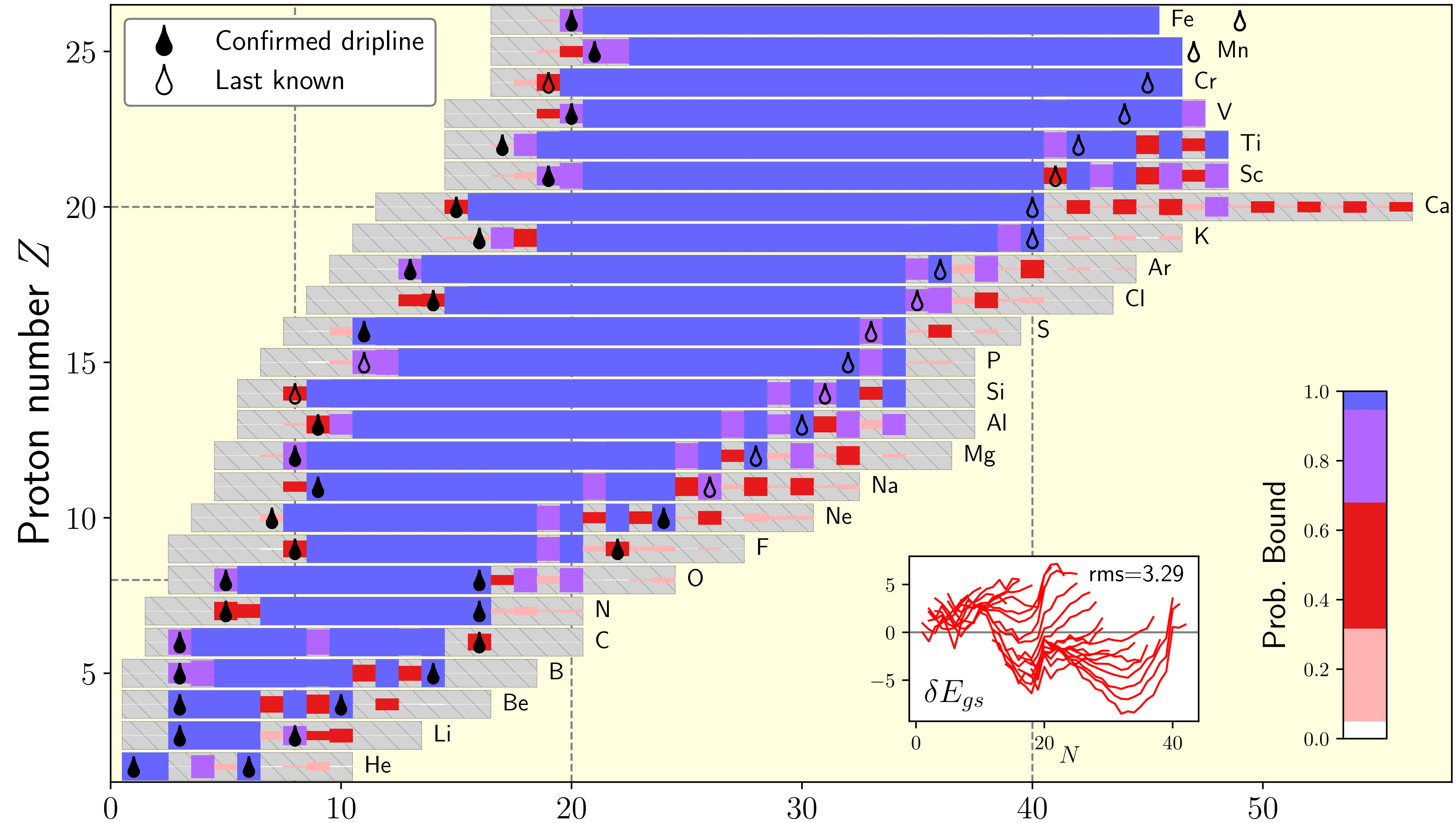
Furnstahl, Phillips, Klos, Wesolowski, Melendez (2015-)

Great progress in ab initio calculations of nuclei



figures from Hergert

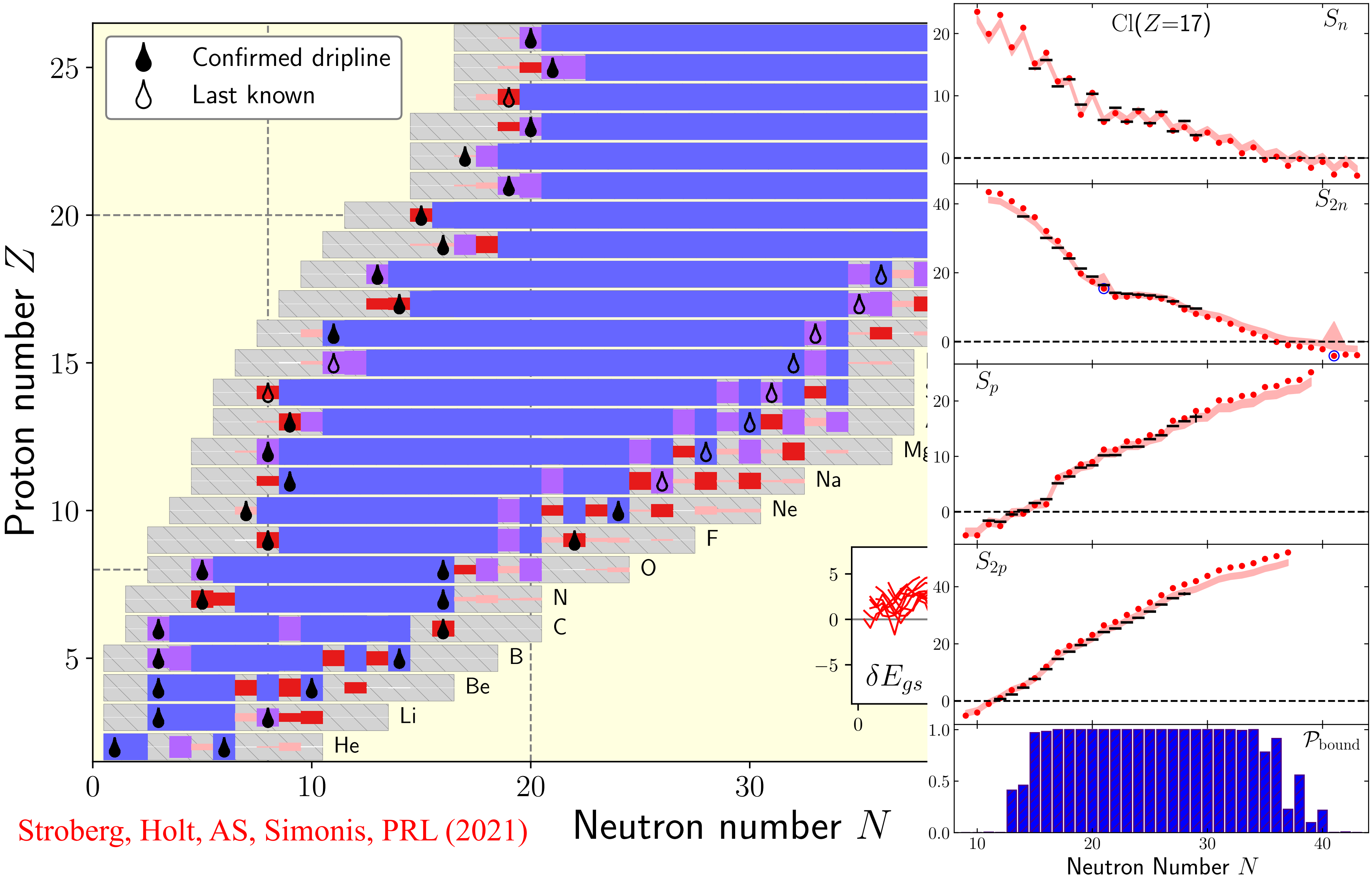
Nuclear landscape based on a chiral NN+3N interaction



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

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

Nuclear landscape based on a chiral NN+3N interaction

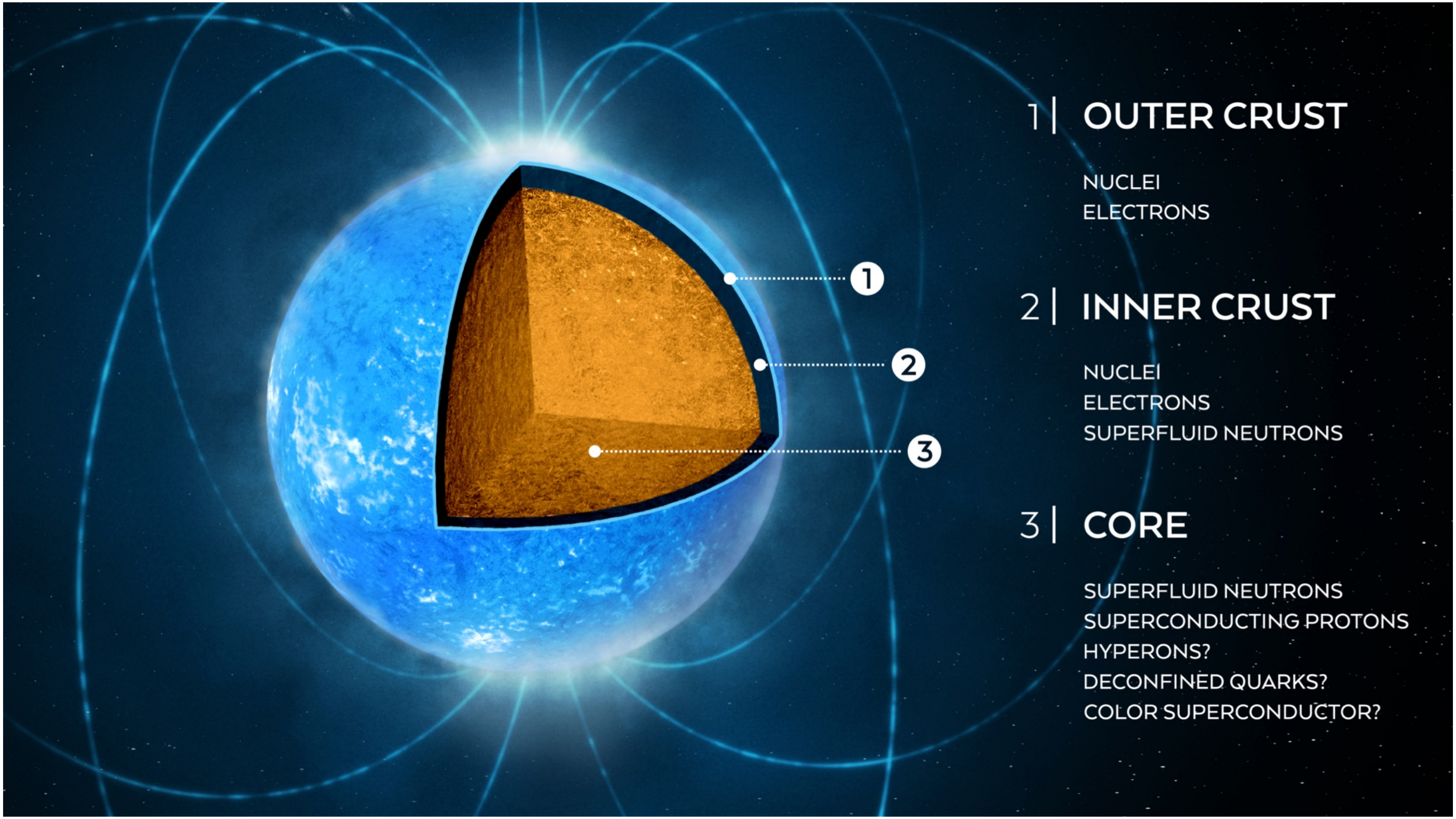


Stroberg, Holt, AS, Simonis, PRL (2021)

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

Extreme matter in neutron stars

governed by the same strong interactions



Watts et al., RMP (2016)

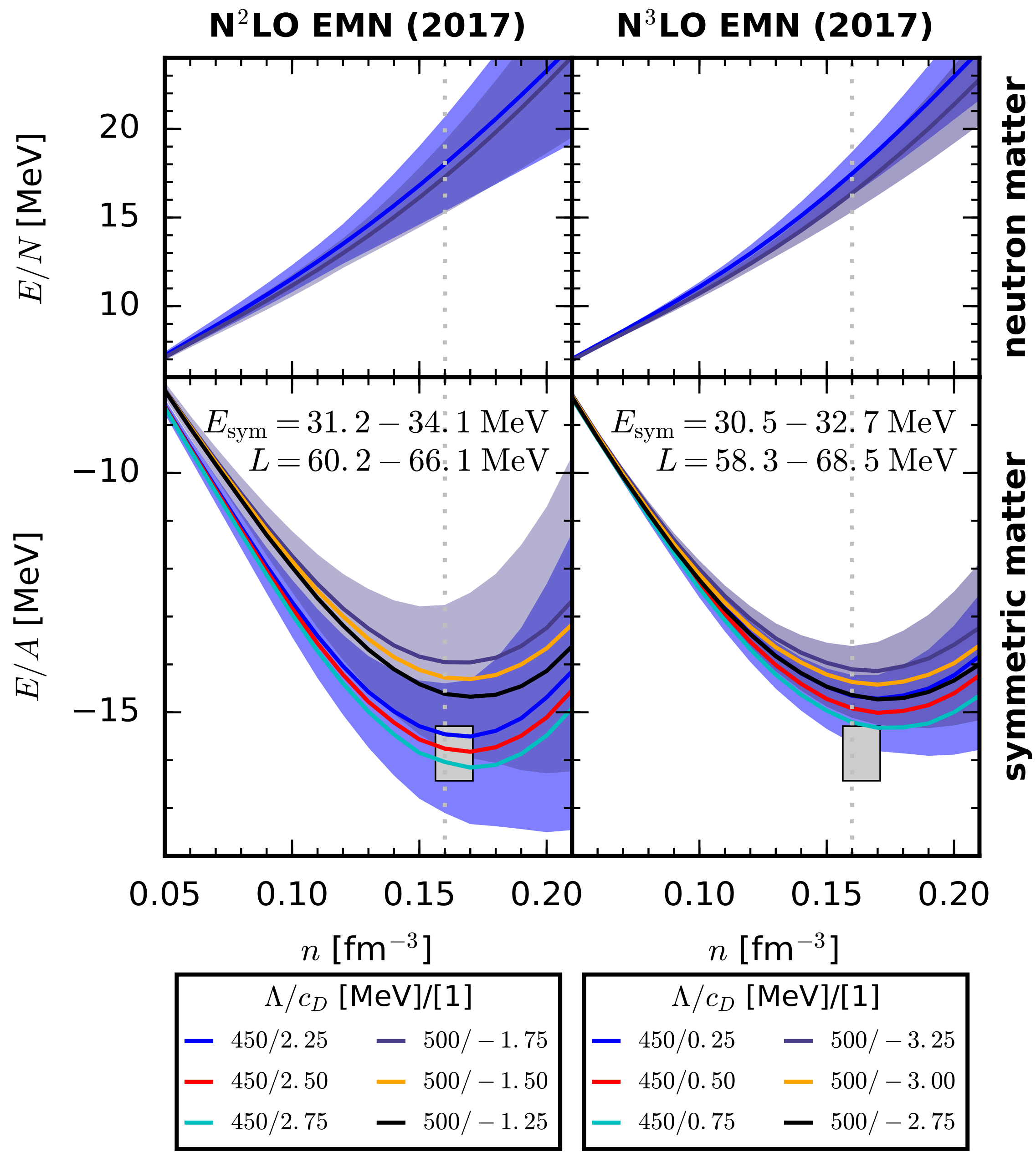
N^3LO calculation of neutron matter and symmetric matter

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

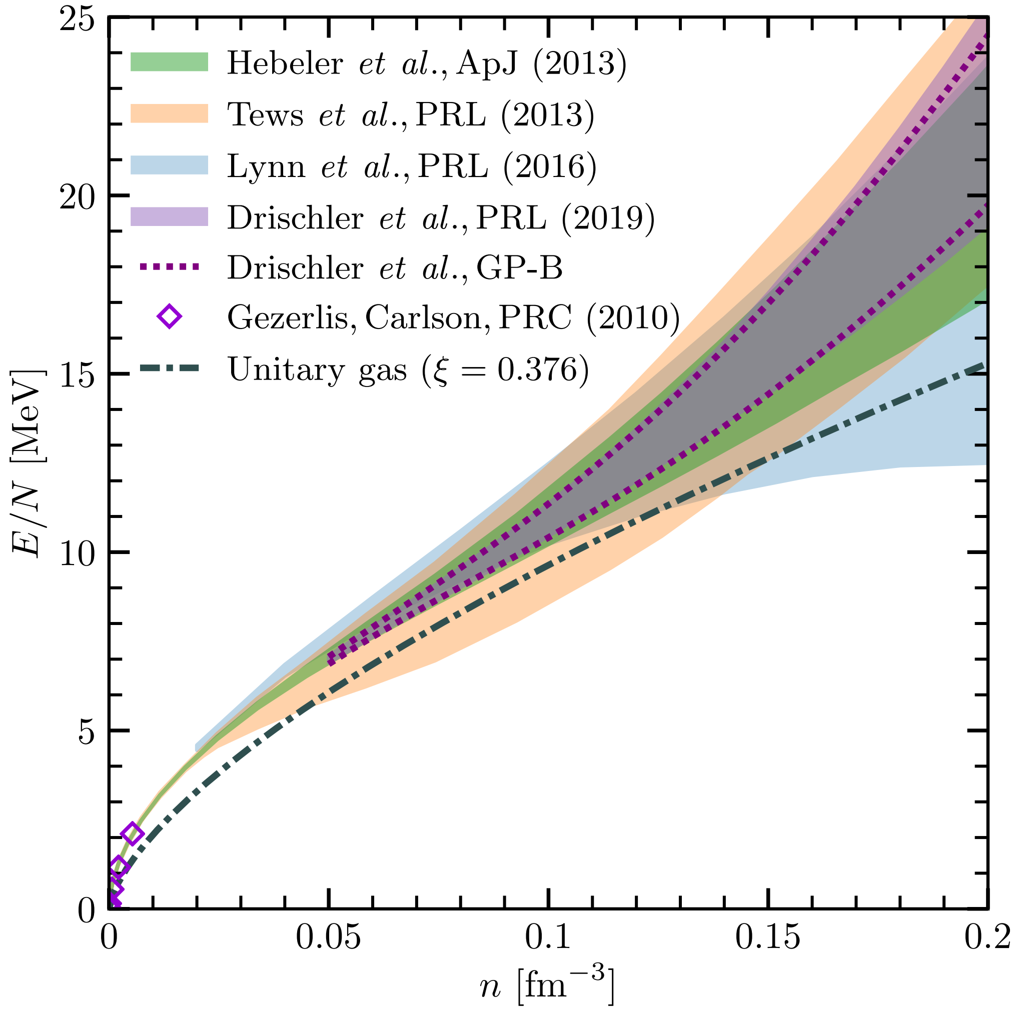
all many-body forces
to N^3LO predicted for
neutron matter
Tews, Krüger, Hebeler, AS, PRL (2013)

systematic improvement
from N^2LO to N^3LO



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)



from Huth, Wellenhofer, AS, PRC (2021)

slope determines pressure of neutron matter

GP-B (68%) gives similar band as simple EFT uncertainties

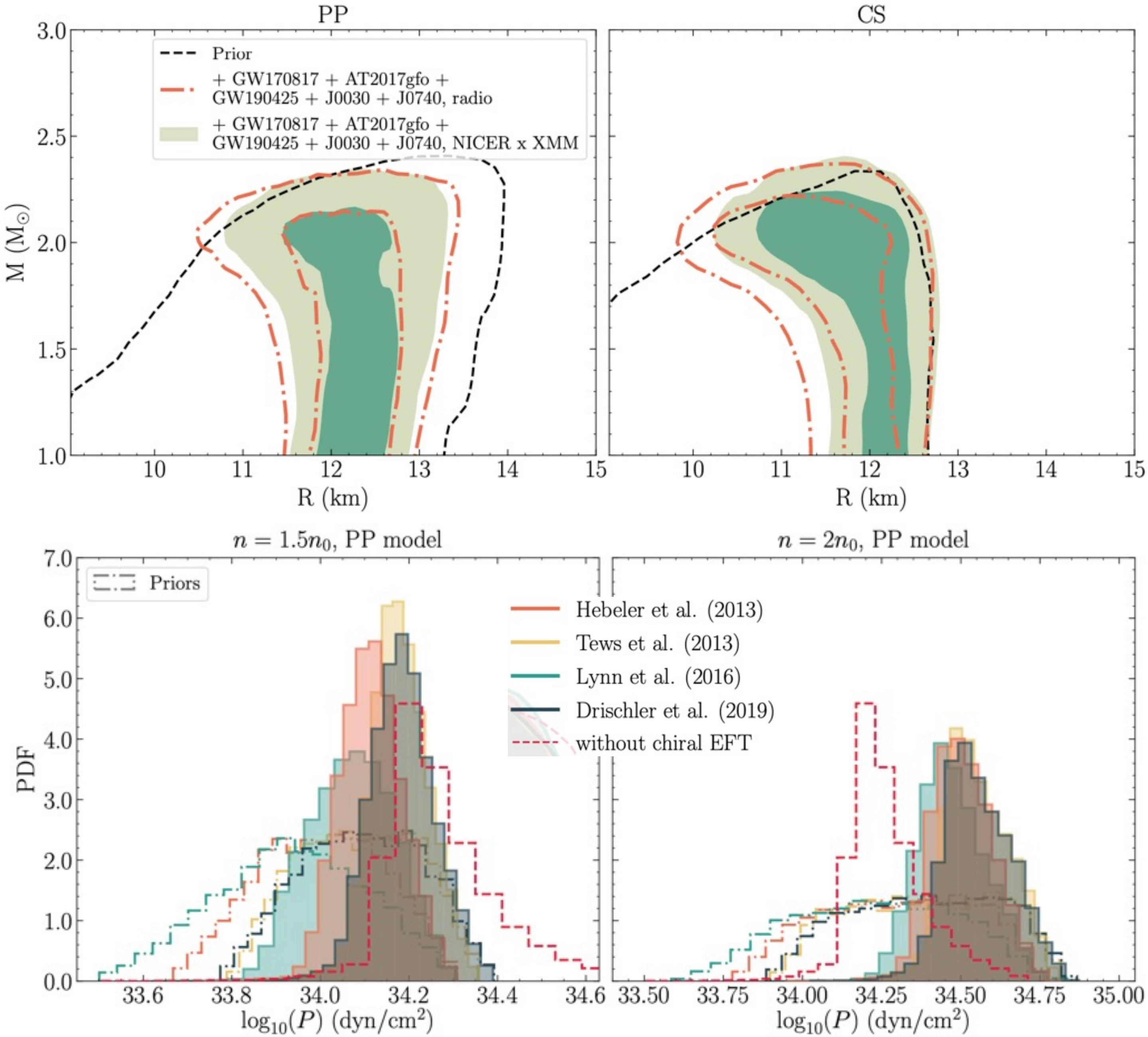
Combined merger and NICER constraints

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

for mass-radius

equation of state at 1.5 and 2 n_0

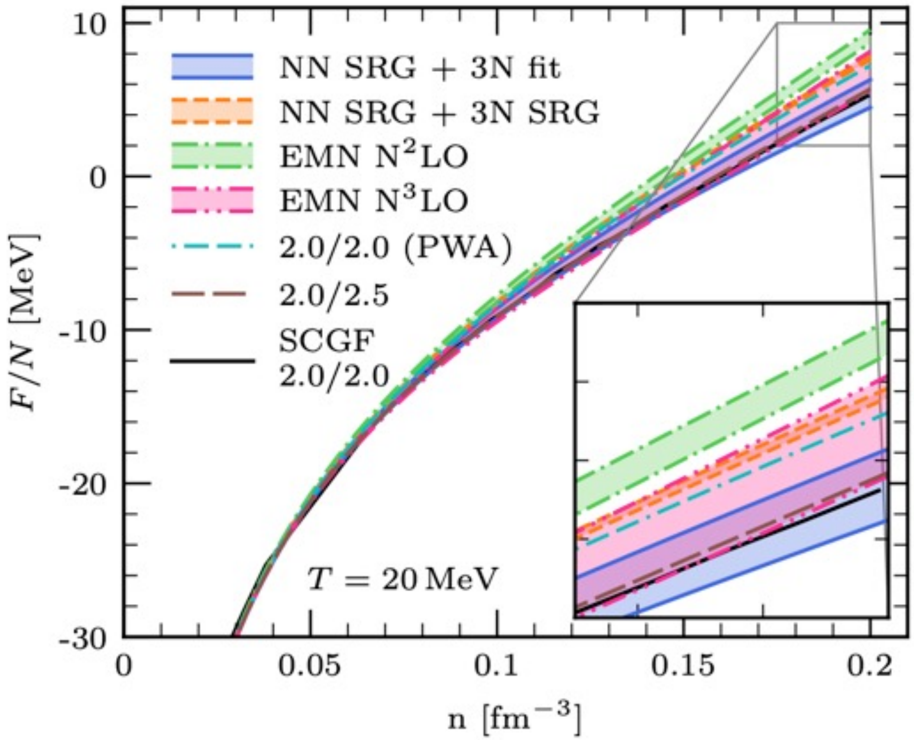
astro prefers higher pressures

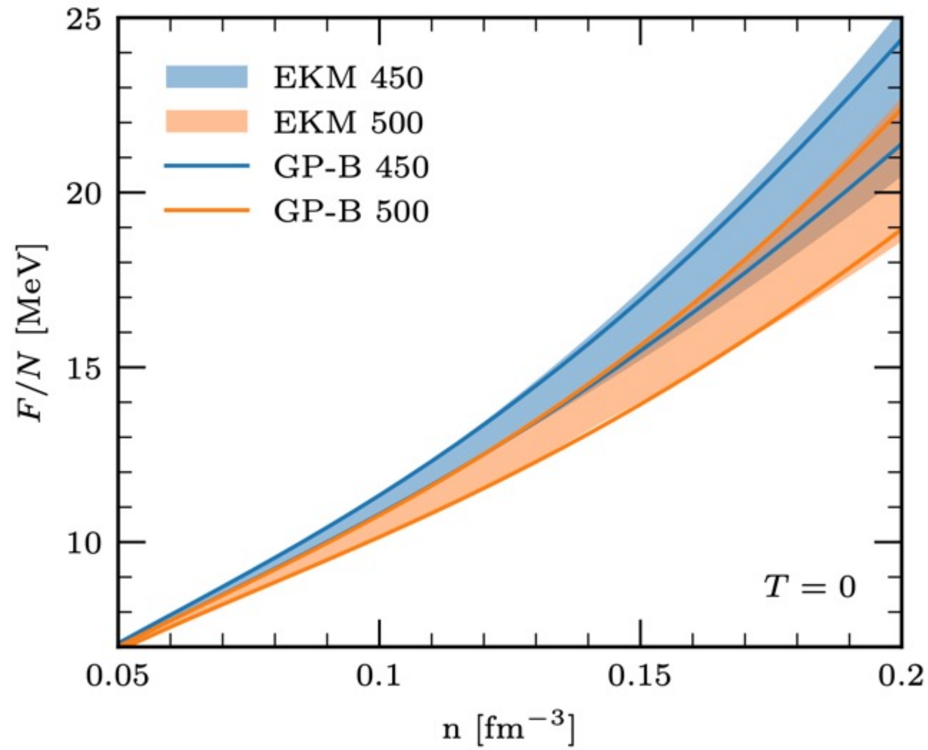


Neutron matter at finite temperature

similar thermal effects for different NN+3N interactions

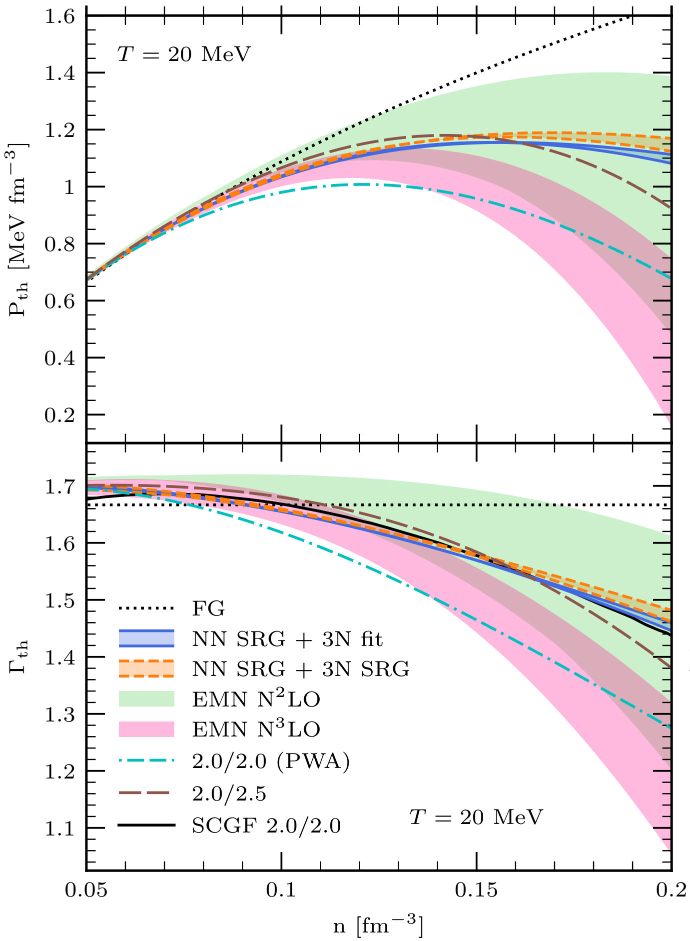
Keller, Wellenhofer, Hebeler, AS, PRC (2021)





EFT uncertainties (EKM) similar to GP-B (68%) Drischler et al. (2020)

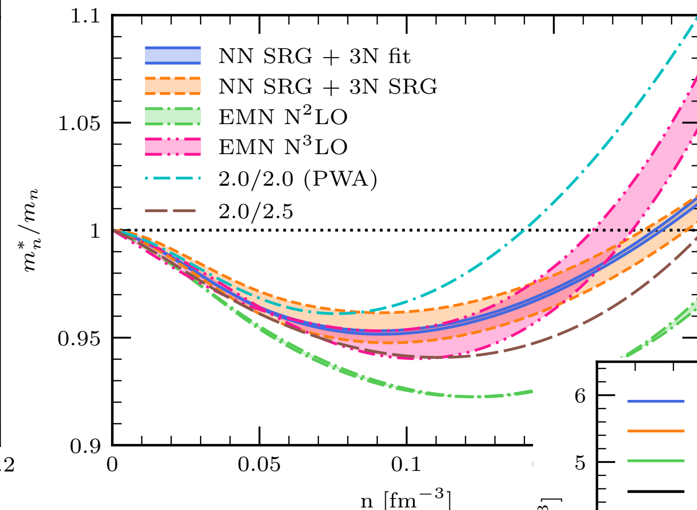
Thermal effects governed by effective mass

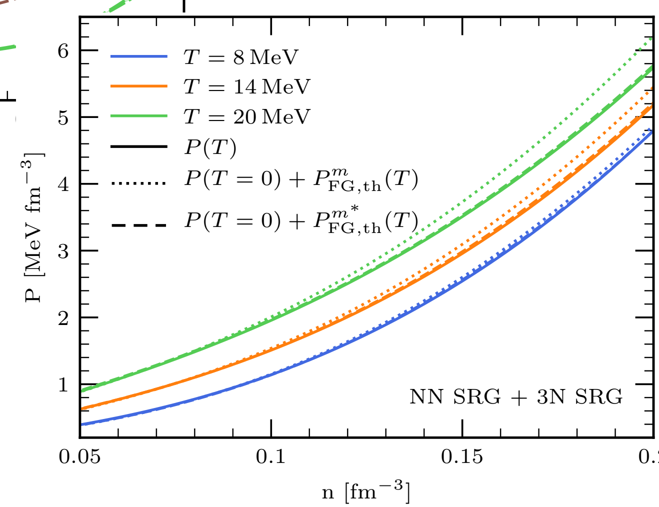


decreasing thermal pressure due to repulsive 3N contributions

increasing effective mass m^* beyond n_{sat}

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





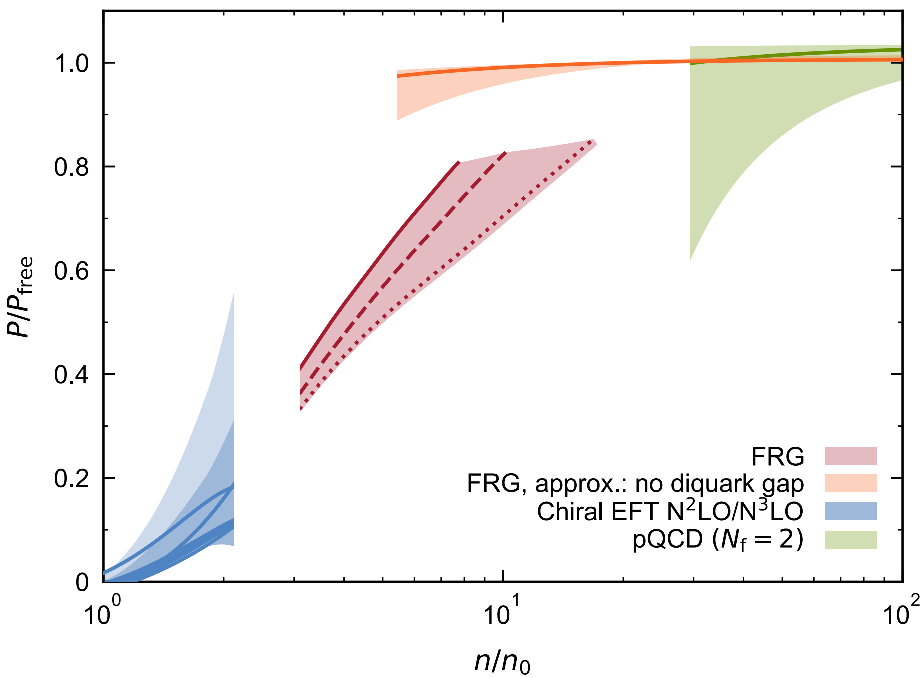
Keller, Wellenhofer, Hebeler, AS, PRC (2021)

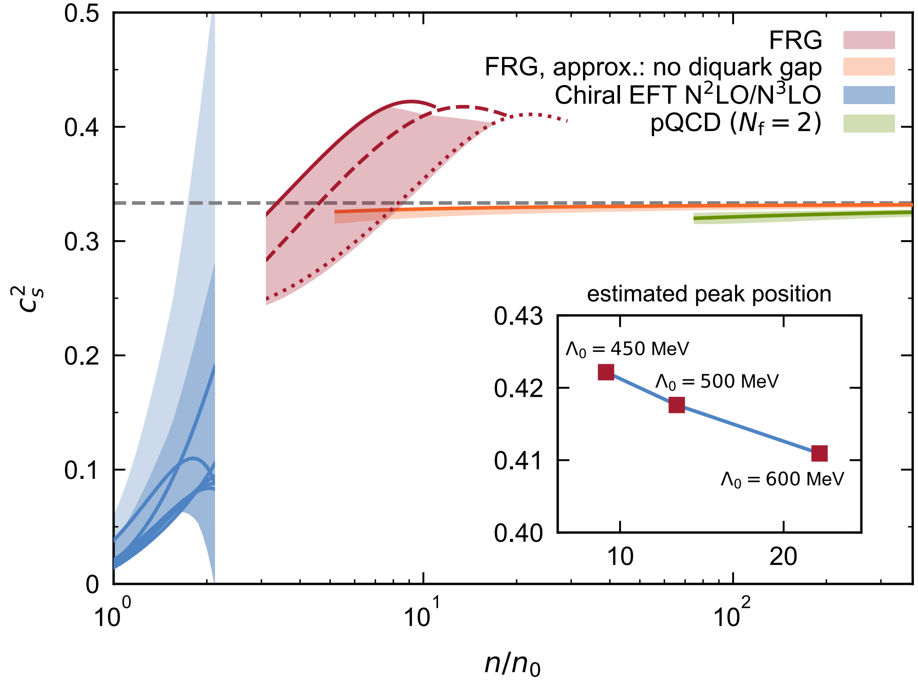
Functional RG: From QCD to intermediate densities

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

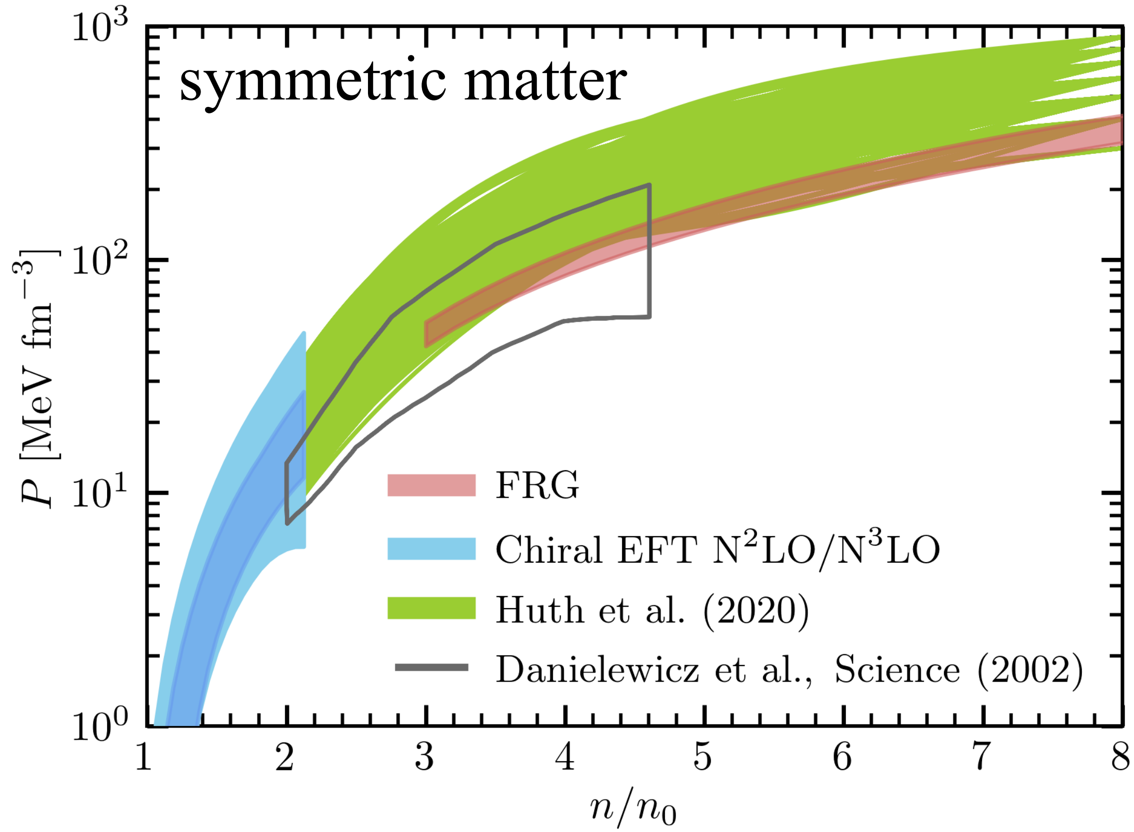
Symmetric matter: From chiral EFT to functional RG

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)



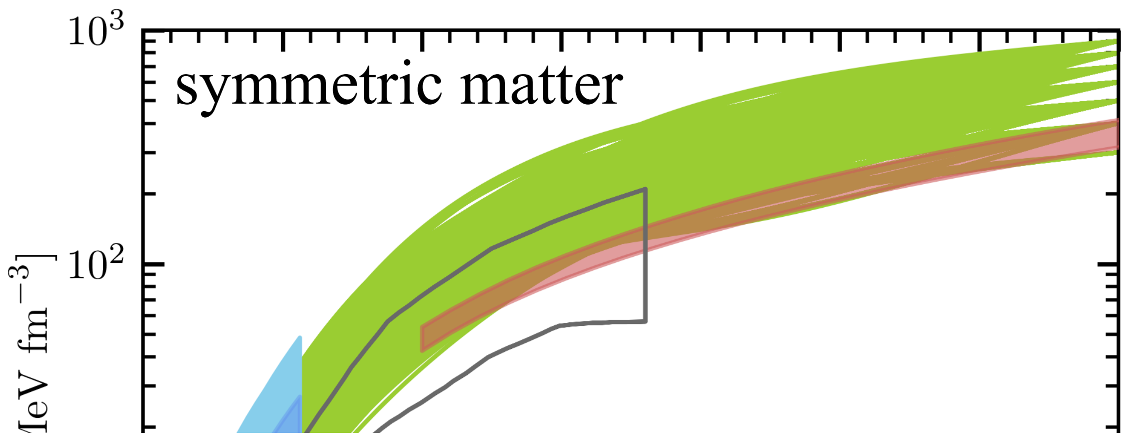
Symmetric matter: From chiral EFT to functional RG

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

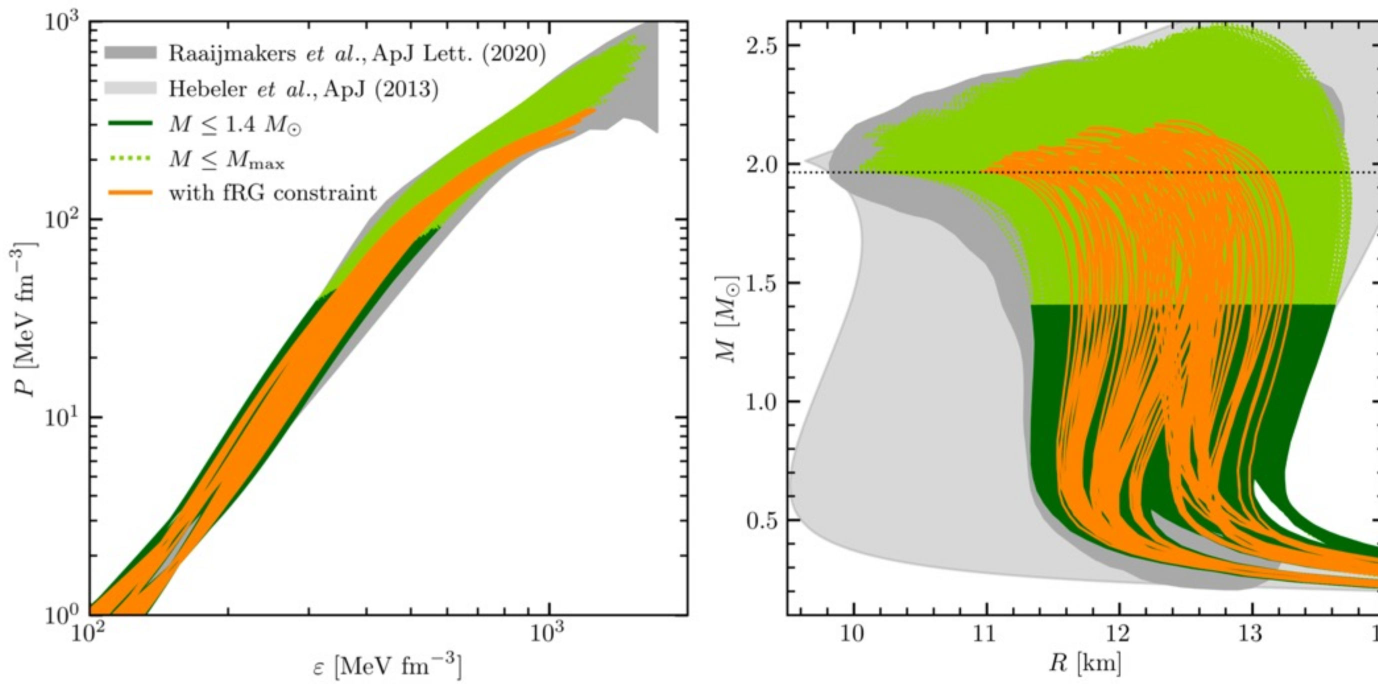
Huth, Wellenhofer, AS, PRC (2021)

comparison to heavy-ion constraint

Danielewicz et al., Science (2002)

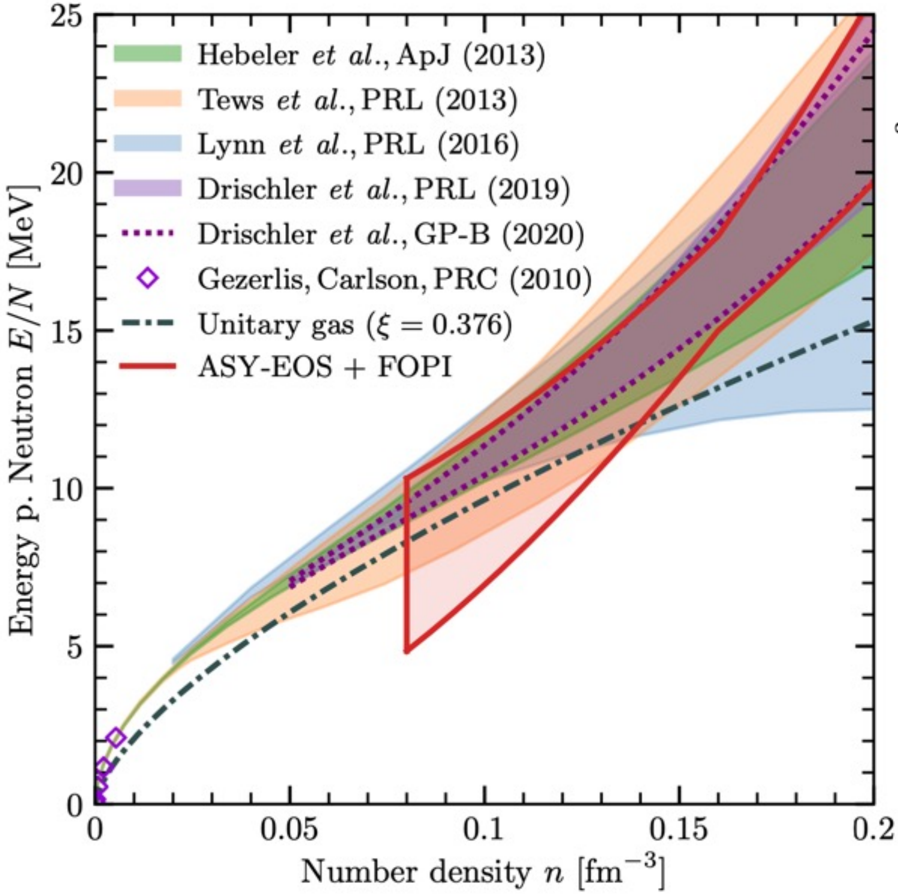


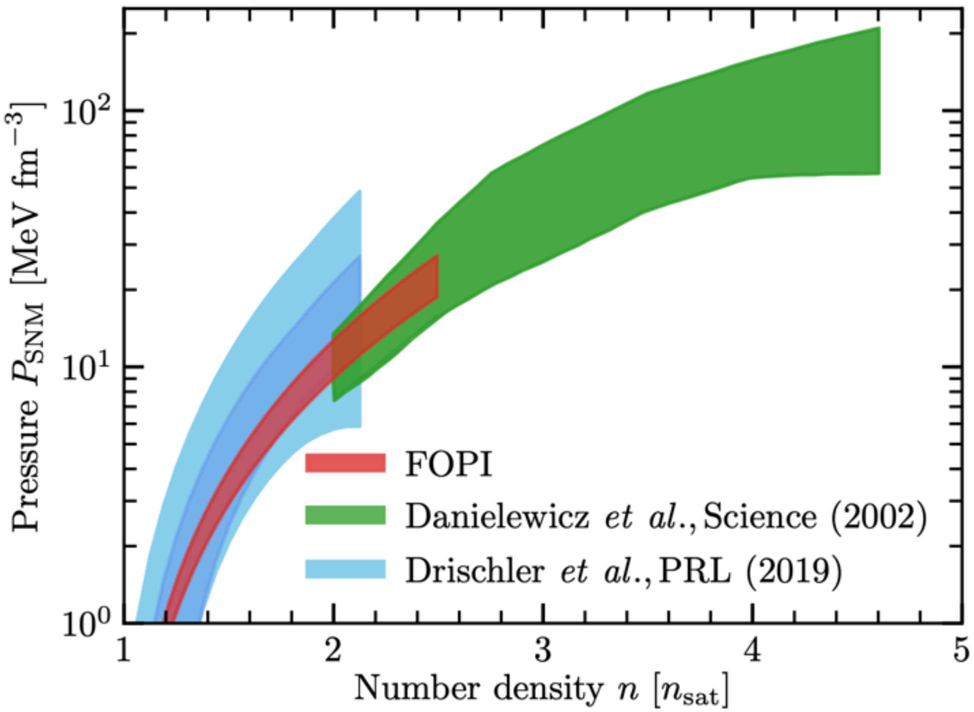
fRG provides interesting constraints at intermediate densities



Constraints from heavy-ion collisions Huth, Pang et al., arXiv:2107.06229

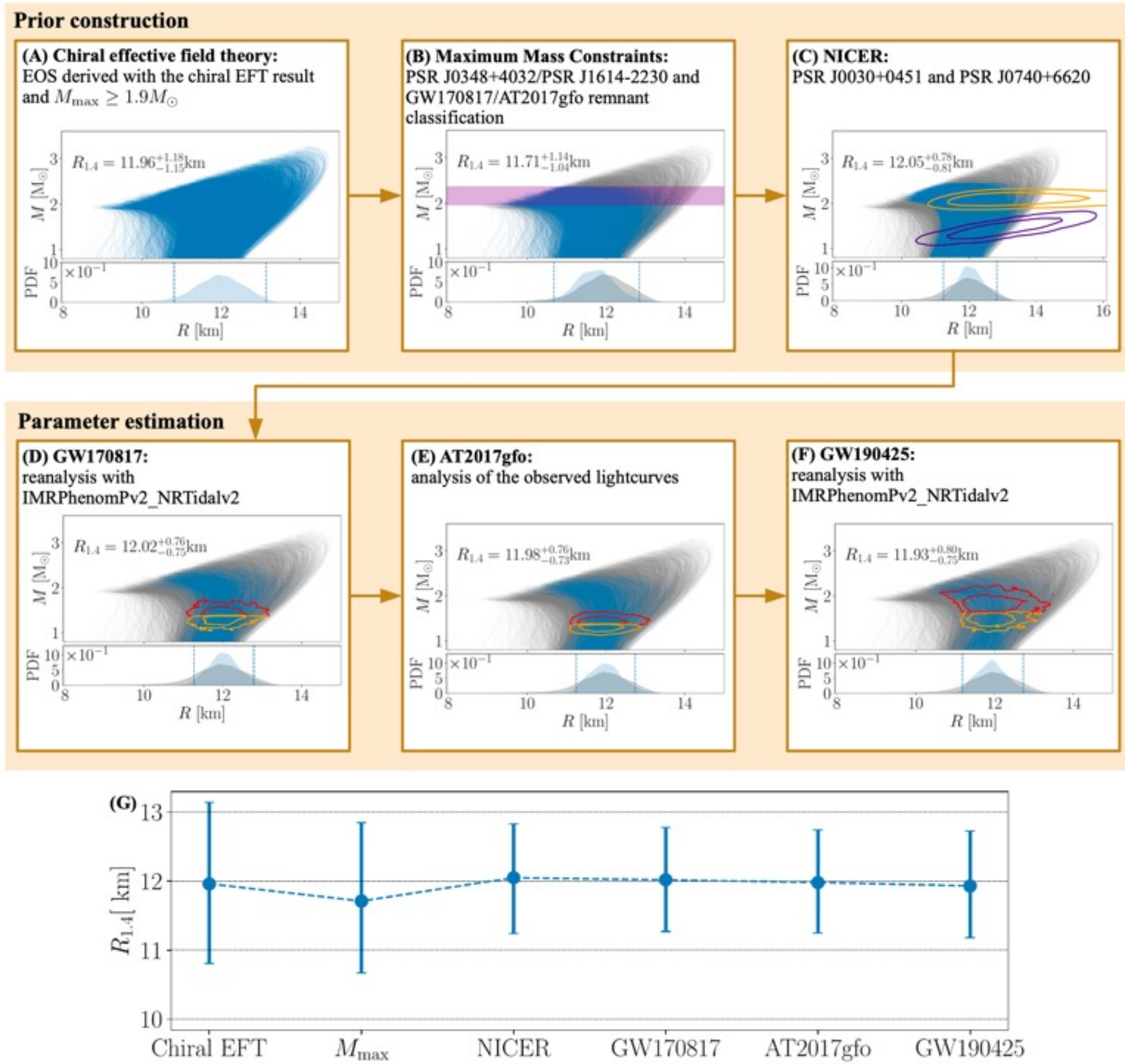
include in addition to chiral EFT: constraints from ASY-EOS and FOPI for neutron and symmetric matter with different functionals





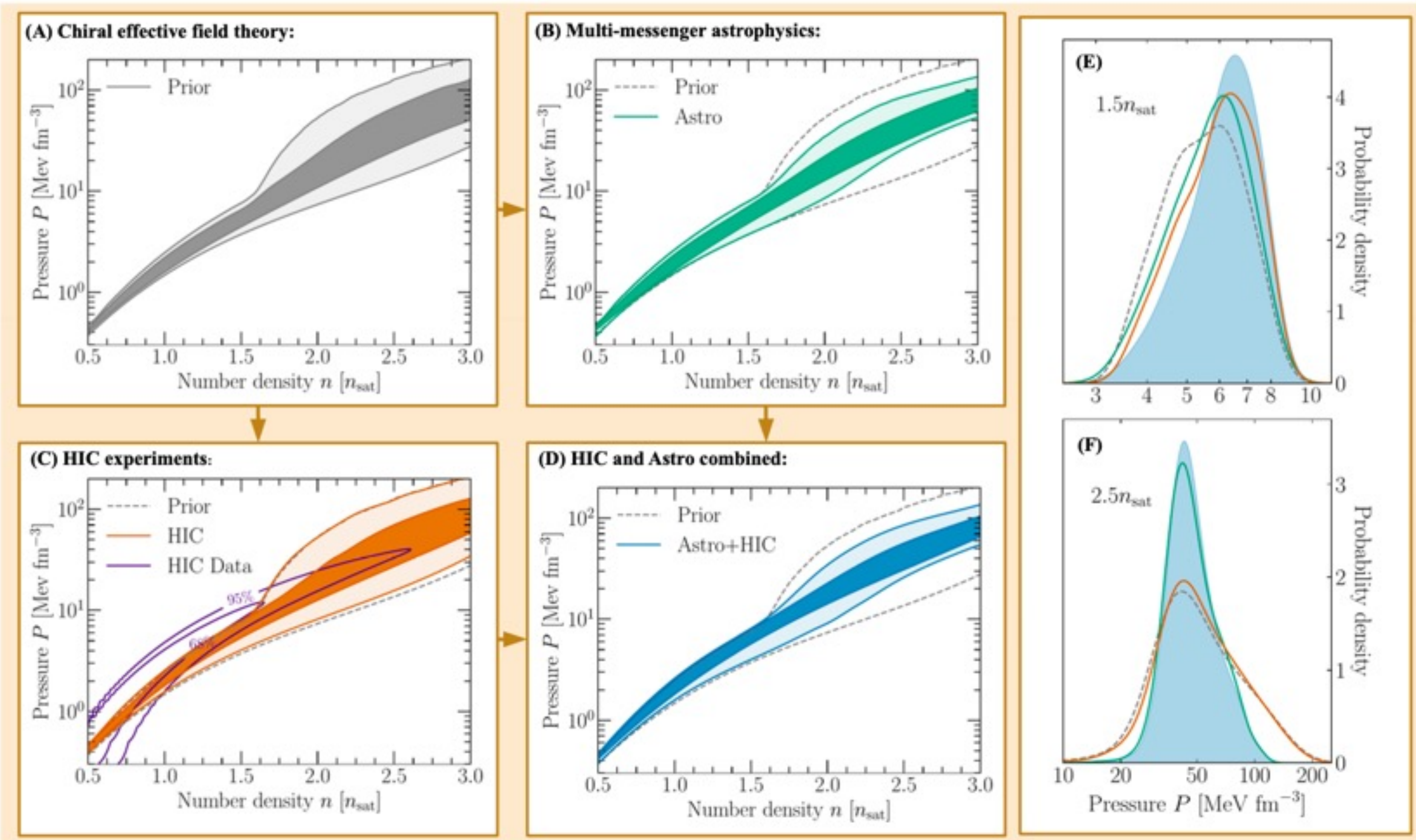
Constraints from heavy-ion collisions Huth, Pang et al., arXiv:2107.06229

Bayesian multi-messenger framework using EOS draws based on chiral EFT (QMC results) with c_s extension



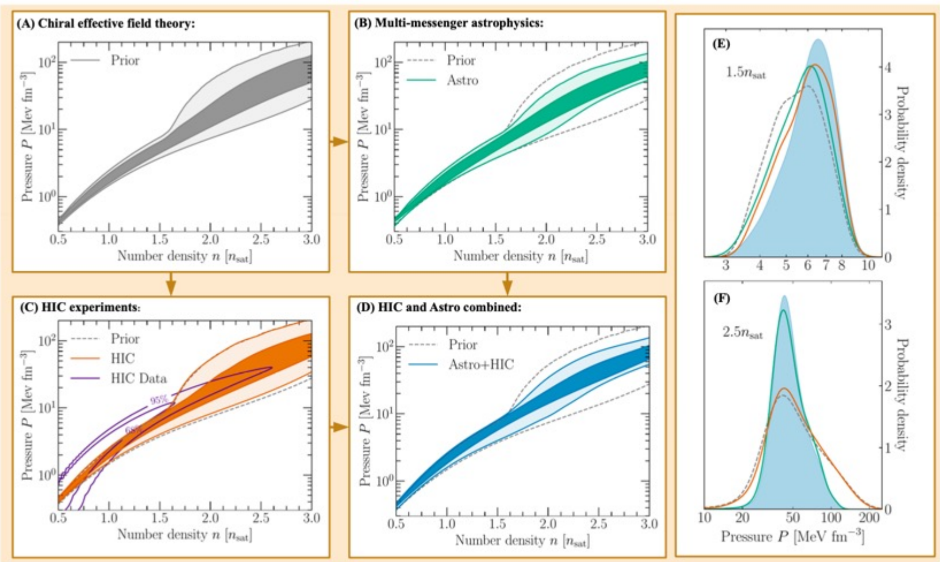
Constraints from heavy-ion collisions Huth, Pang et al., arXiv:2107.06229

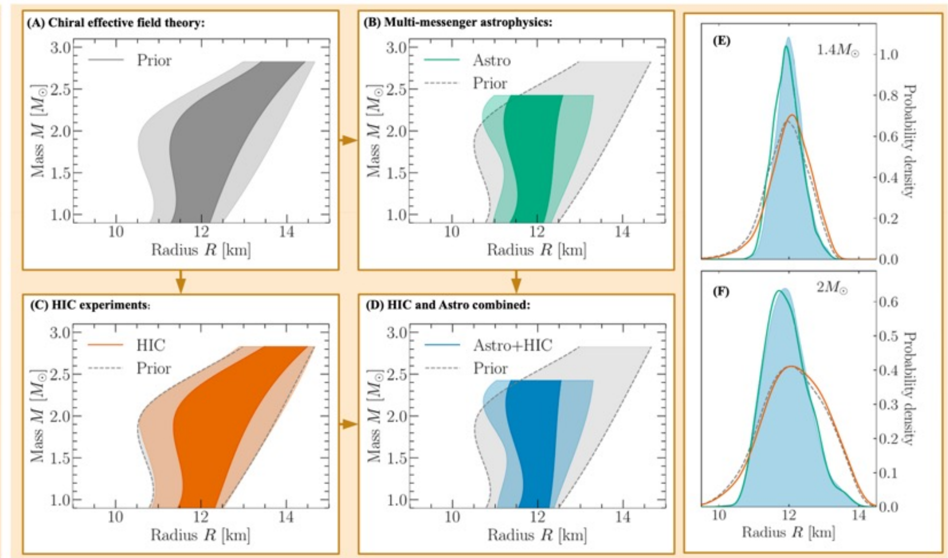
inclusion of HIC constraints prefers higher pressures, similar to NICER, overall remarkable consistency with chiral EFT and astro constraints



Constraints from heavy-ion collisions Huth, Pang et al., arXiv:2107.06229

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





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

more HIC information for intermediate densities very interesting

EOS for arbitrary proton fraction and temperature

Keller, Hebeler, AS, arXiv:2204.14016

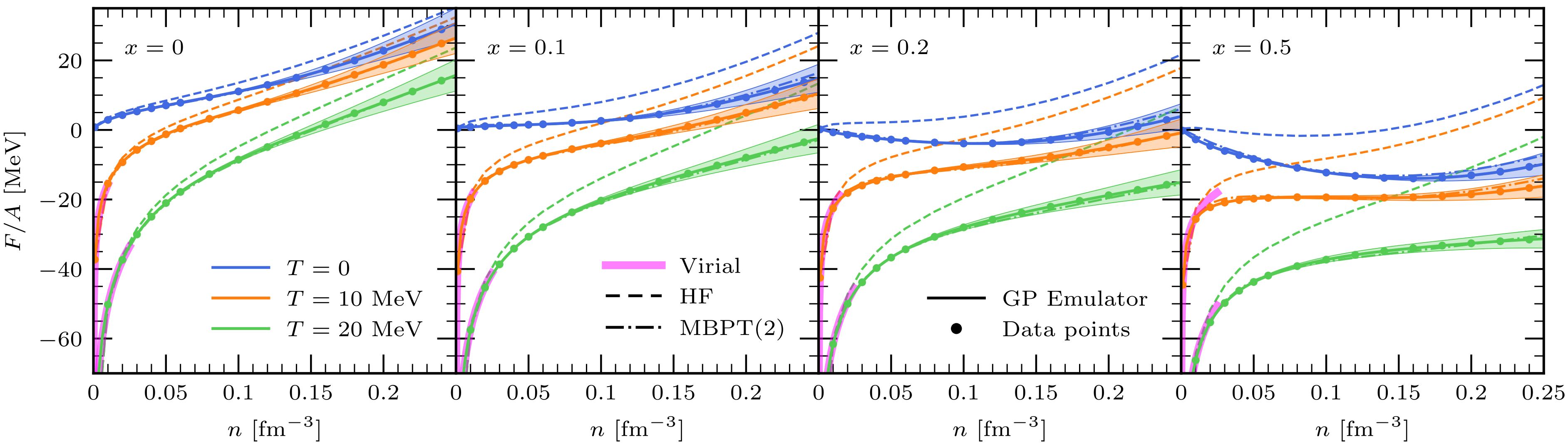
based on chiral EFT NN+3N interactions (EMN 450) to N^{3}LO

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

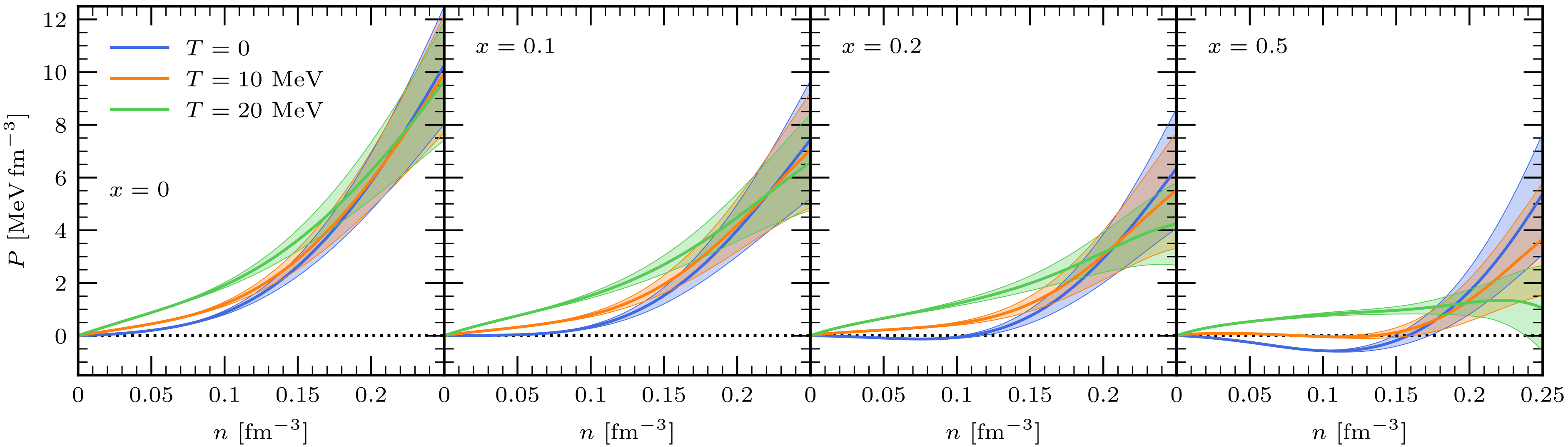
agreement with model-independent virial EOS at low densities



EOS for arbitrary proton fraction and temperature

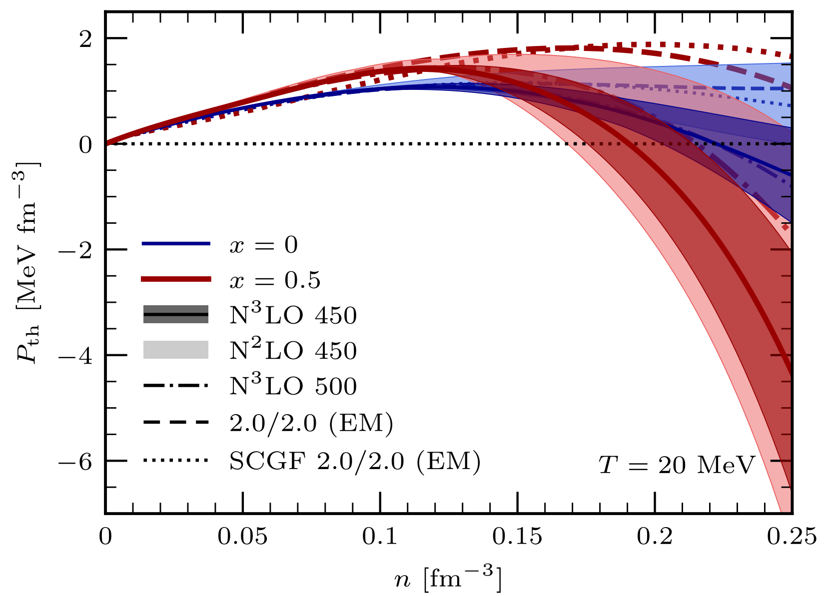
Keller, Hebeler, AS, arXiv:2204.14016

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



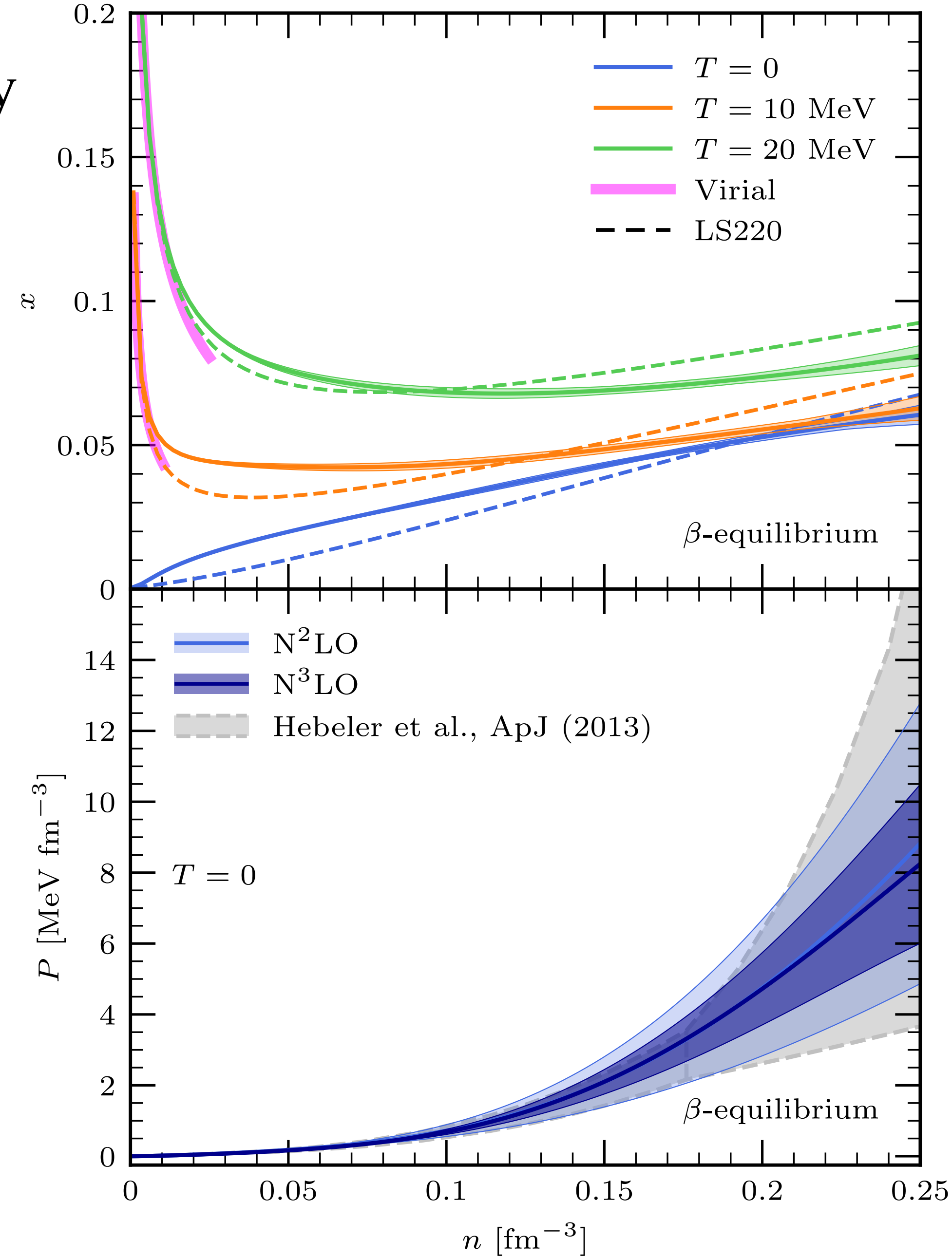
EOS for neutron star matter in beta equilibrium

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

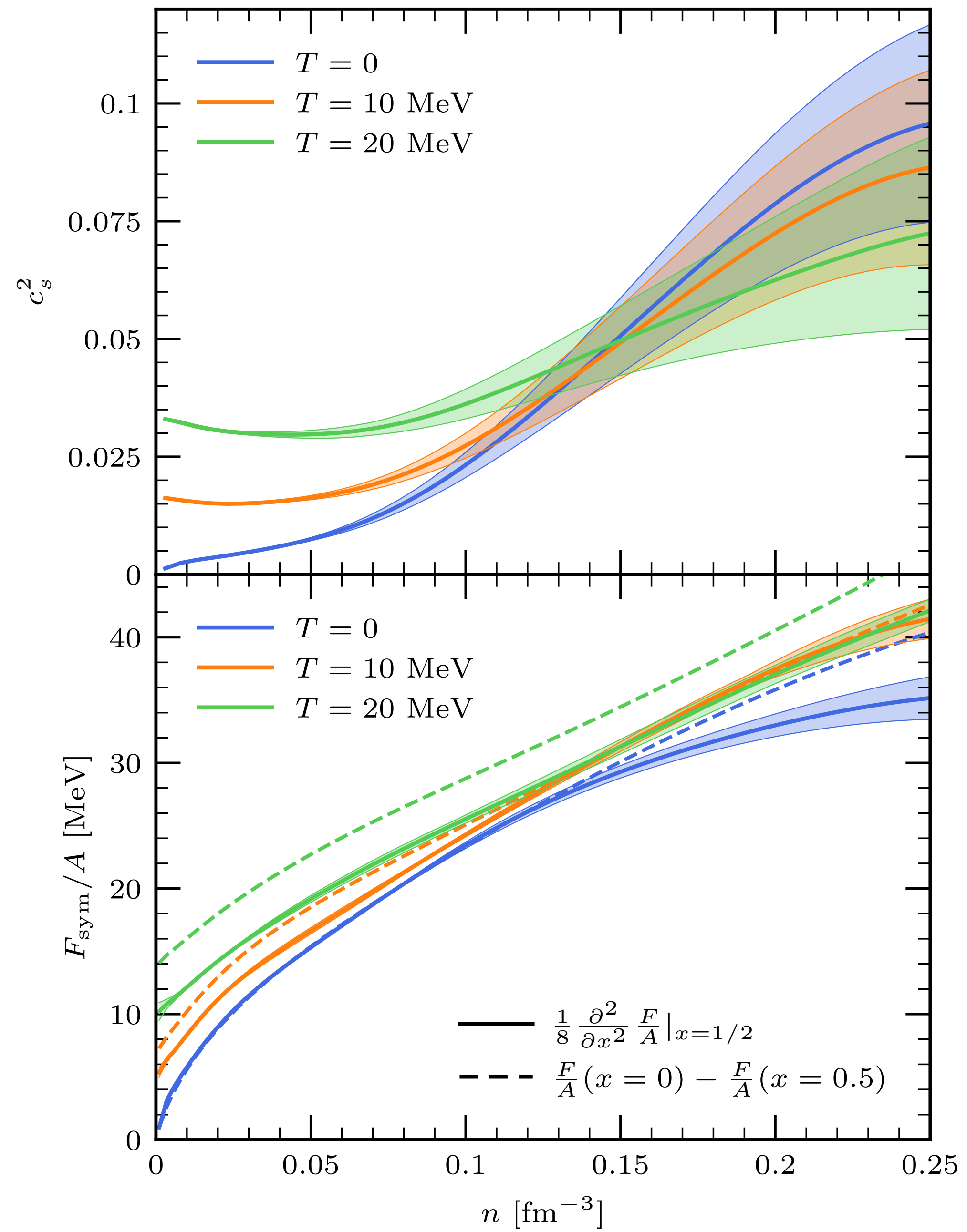
Keller, Hebeler, AS, arXiv:2204.14016

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*)



Summary

Thanks to: J. Braun, T. Dietrich, C. Drischler, S. Greif, K. Hebeler, **S. Huth**, J. Lattimer, A. Le Fèvre, **J. Keller**, **P. Pang**, C. Pethick, **G. Raaijmakers**, I. Tews, W. Trautmann, A. Watts, C. Wellenhofer

Chiral effective field theory for nuclear forces

Ab initio calculations of nuclear matter

EOS constraints from chiral EFT and astrophysics

Constraints from heavy-ion collisions

EOS for arbitrary proton fraction and finite T