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

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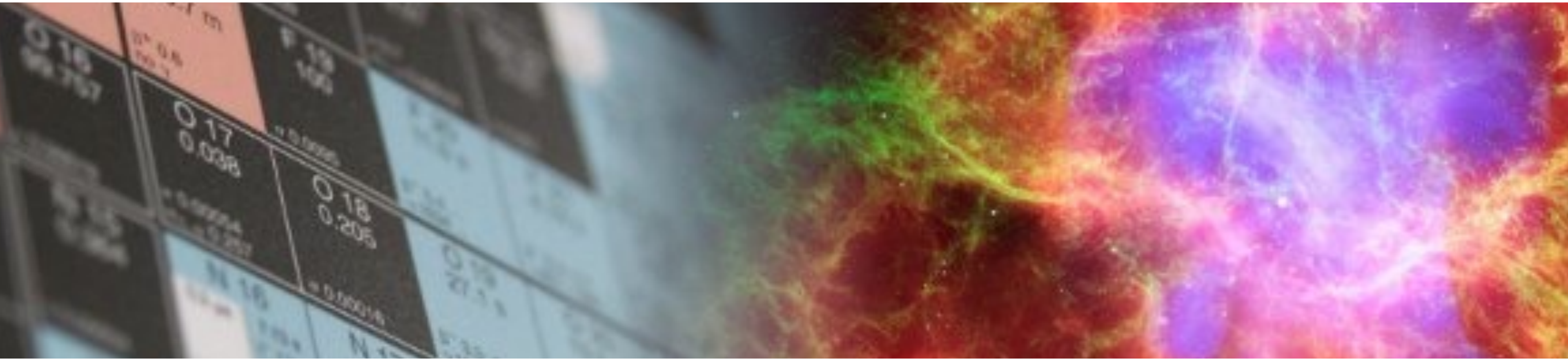

TRIUMF Ab Initio Workshop, Vancouver, March 3, 2023

DFG

SFB 1245

erc
European Research Council
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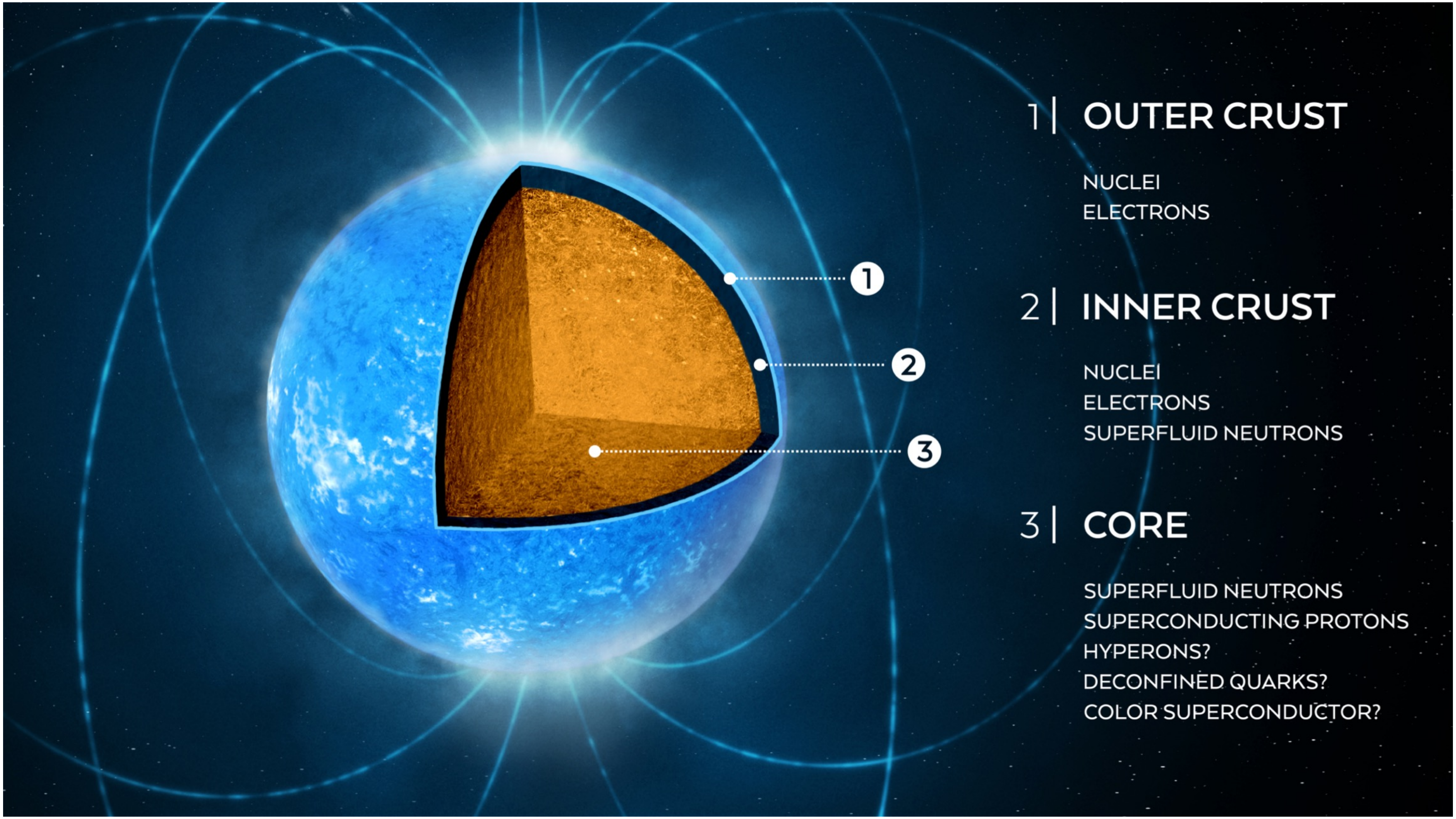
für Bildung
und Forschung

# Extreme matter in neutron stars

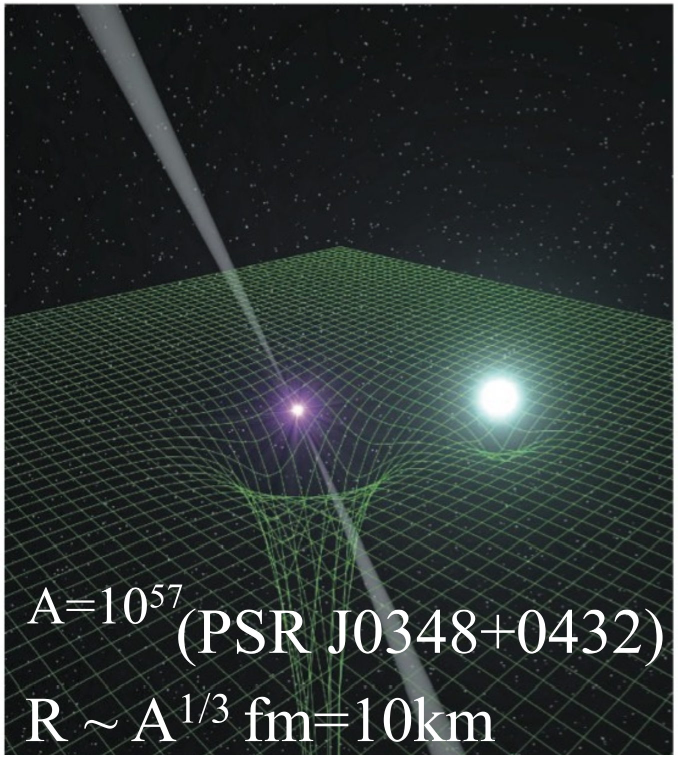
governed by the same strong interactions:
chiral EFT sets pressure of first few km to inside



Watts et al., RMP (2016)

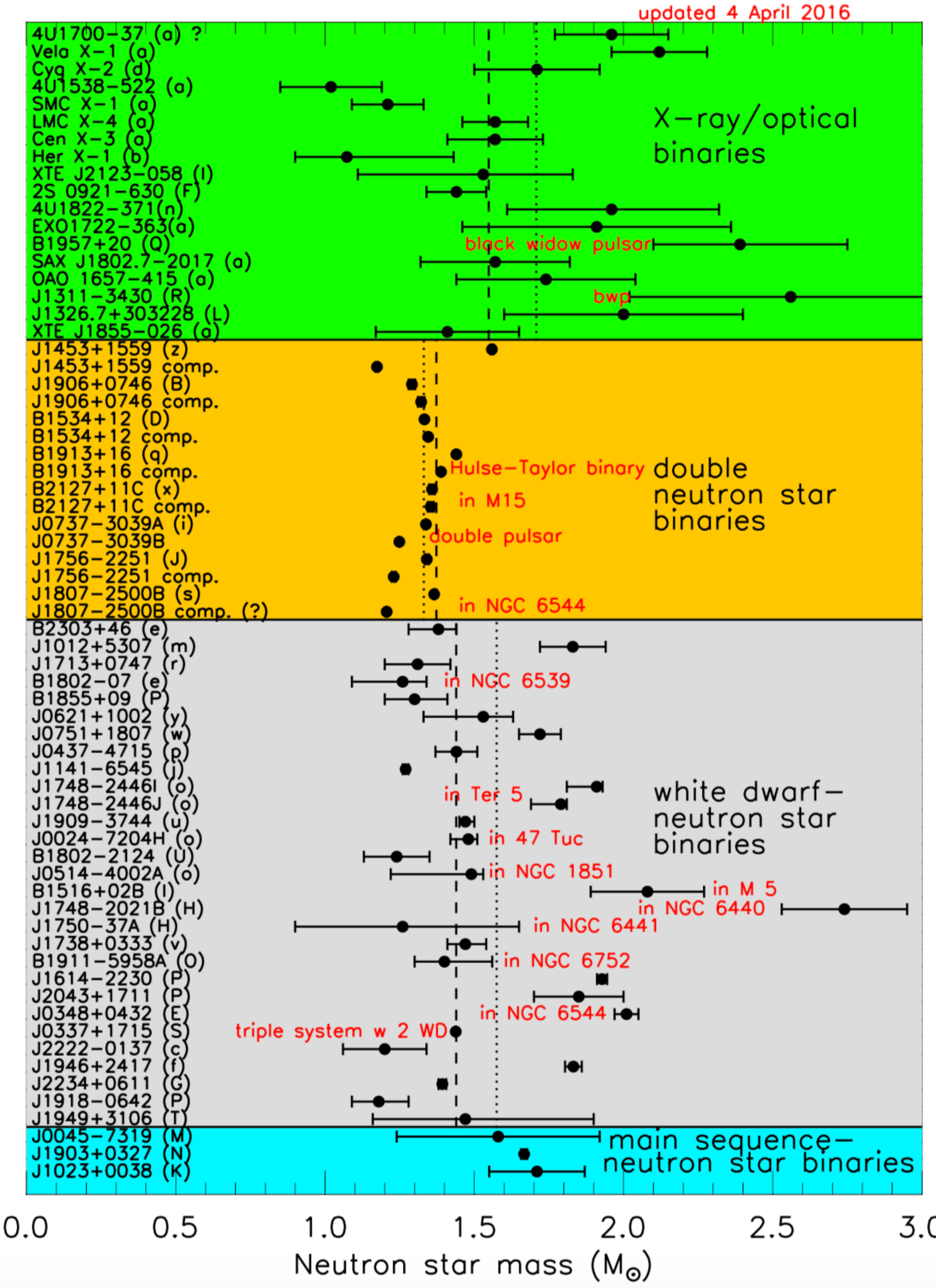
# Neutron star masses

from Jim Lattimer



$A=10^{57}$ (PSR J0348+0432)

$R \sim A^{1/3}$ fm=10km



three 2 $M_{\text{sun}}$ neutron stars obs.

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

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

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

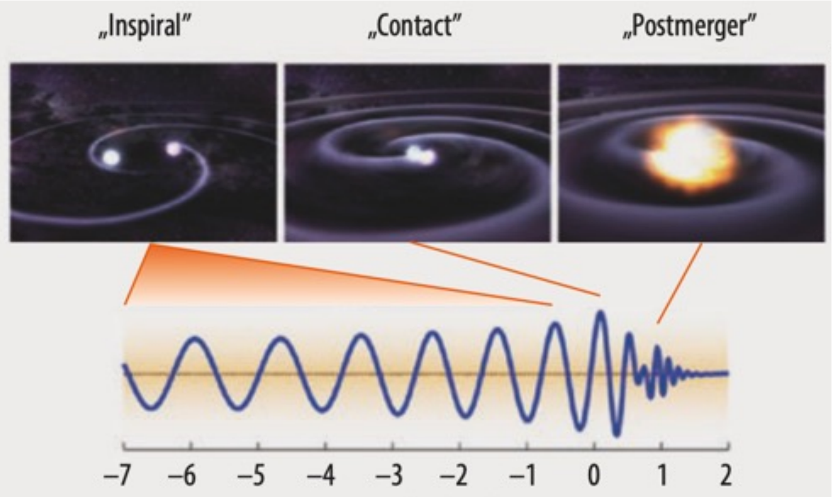
# Neutron star radius from GW170817

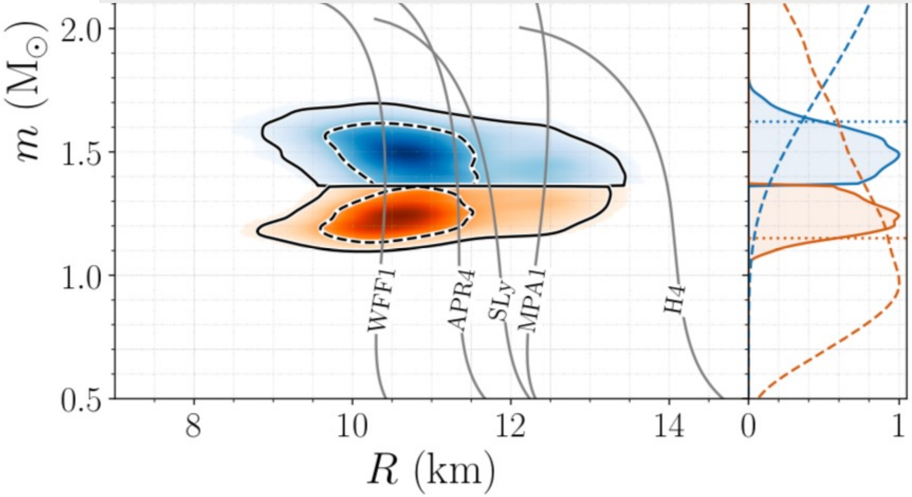
chiral EFT + general EOS extrapolation: 9.7 - 13.9 km for M=1.4 $M_{sun}$

Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

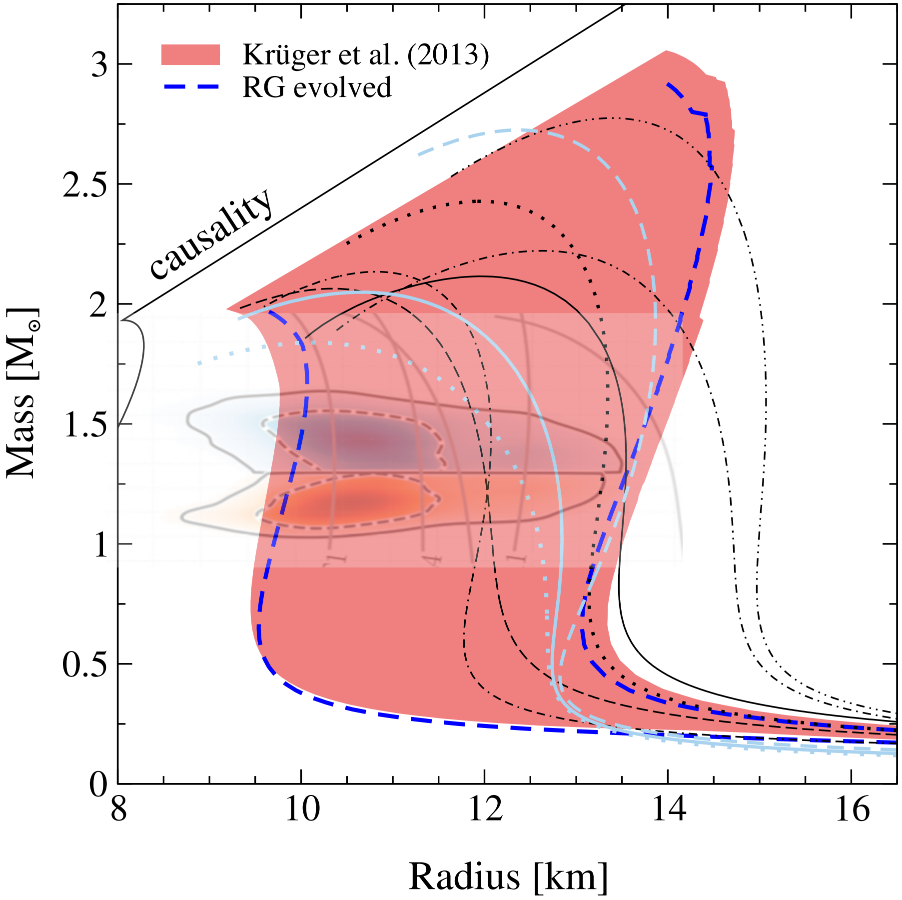
**GW170817: Measurements of neutron star radii and equation of state**

The LIGO Scientific Collaboration and The Virgo Collaboration

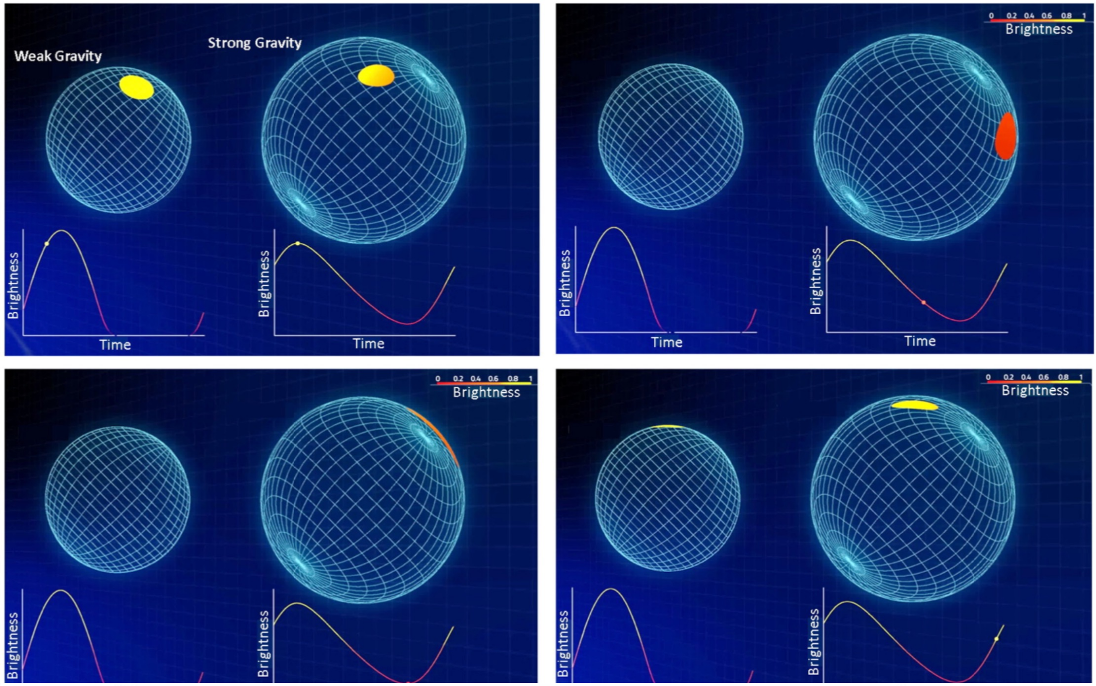




very consistent with
chiral EFT + causality + 2 $M_{sun}$



# NICER results



Neutron star radius from pulse profile modeling

J0030 and J0740
here: Amsterdam analysis
Riley et al., ApJL (2019), (2021)

similar results from Illinois-Maryland analysis
Miller et al., ApJL (2019), (2021)

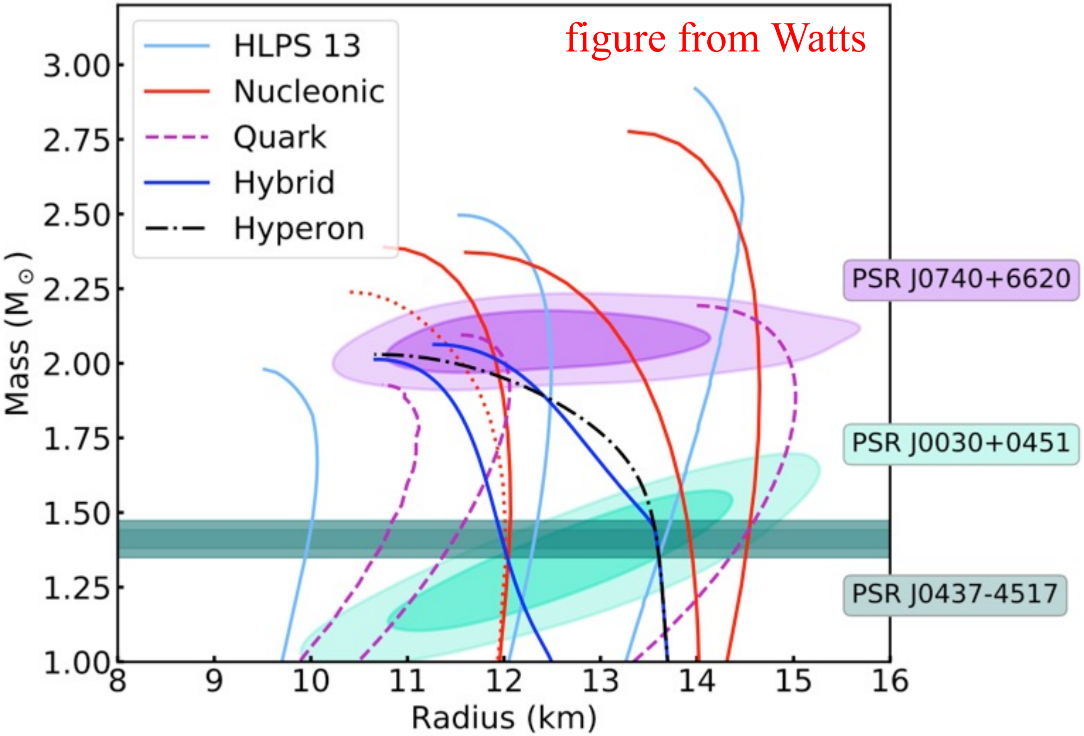


figure from Watts

# Outline

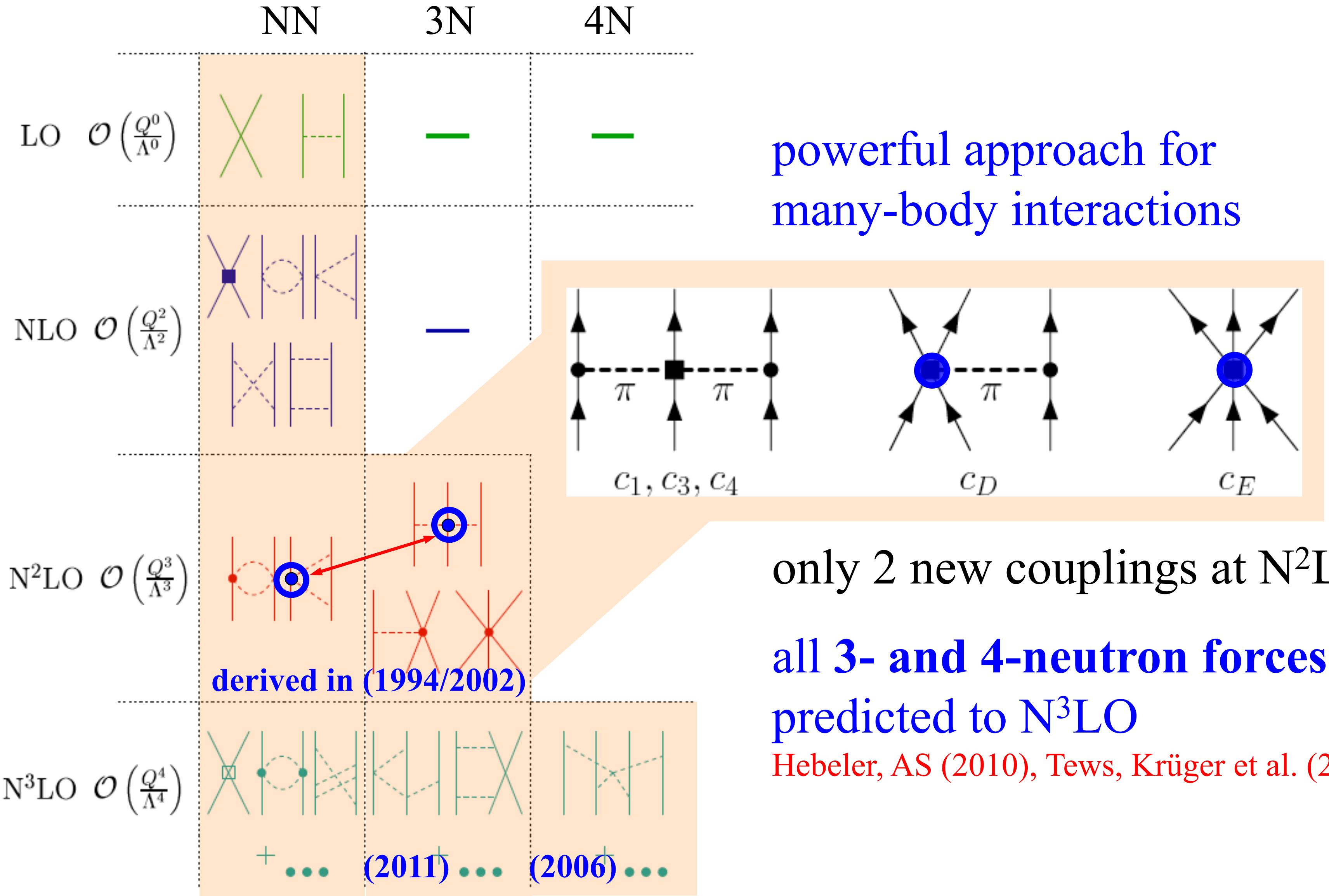
Ab initio calculations of nuclear matter

EOS for arbitrary proton fraction and finite temperature

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

# Chiral effective field theory for nuclear forces

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



derived in (1994/2002)

(2011)

(2006)

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,…

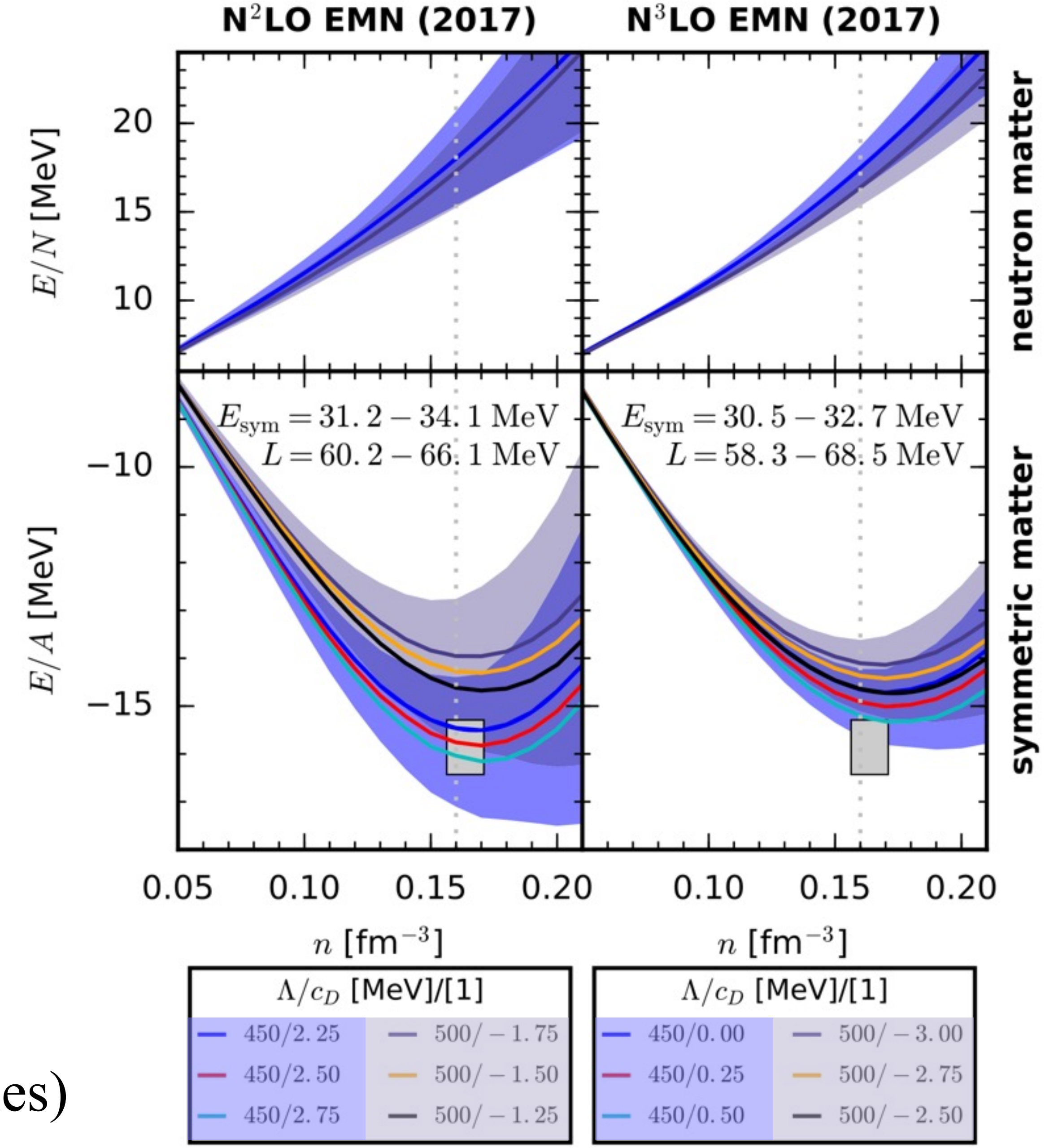
# $N^3LO$ calculation of neutron matter and symmetric matter

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

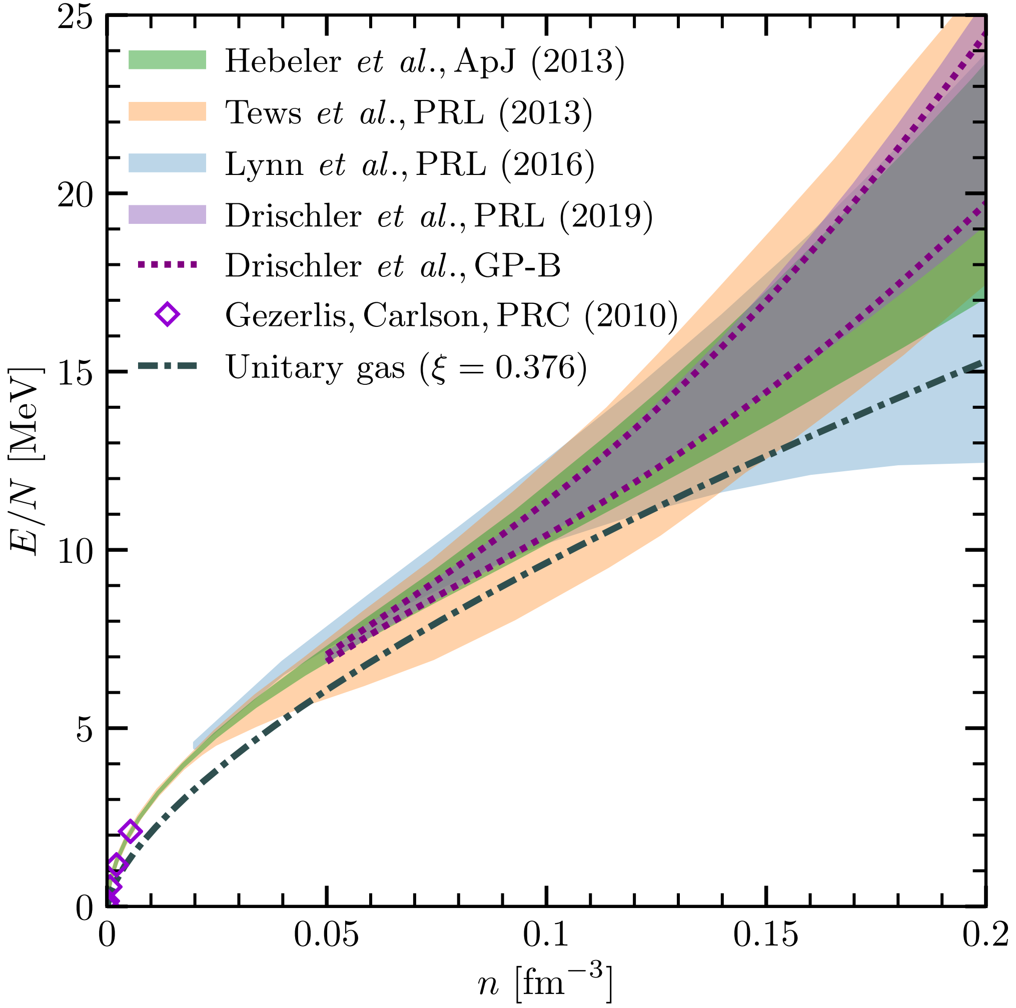
all many-body forces
to $N^3LO$ predicted for
neutron matter
Tews, Krüger, Hebeler, AS, PRL (2013)

systematic improvement
from $N^2LO$ to $N^3LO$
(EFT uncertainties
+ cutoff, fit, reg uncertainties)



# Chiral EFT calculations of neutron matter

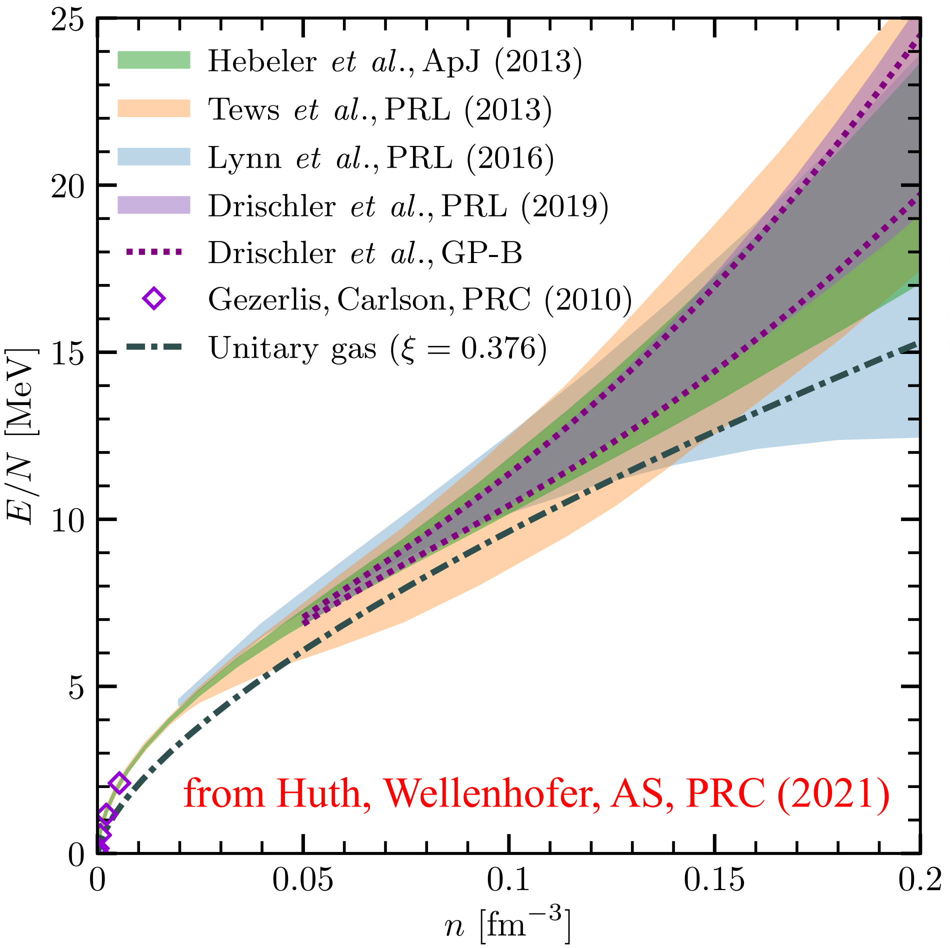
good agreement up to saturation density for neutron matter
nonlocal/local int. and different calcs. (MBPT, QMC, SCGF, CC)



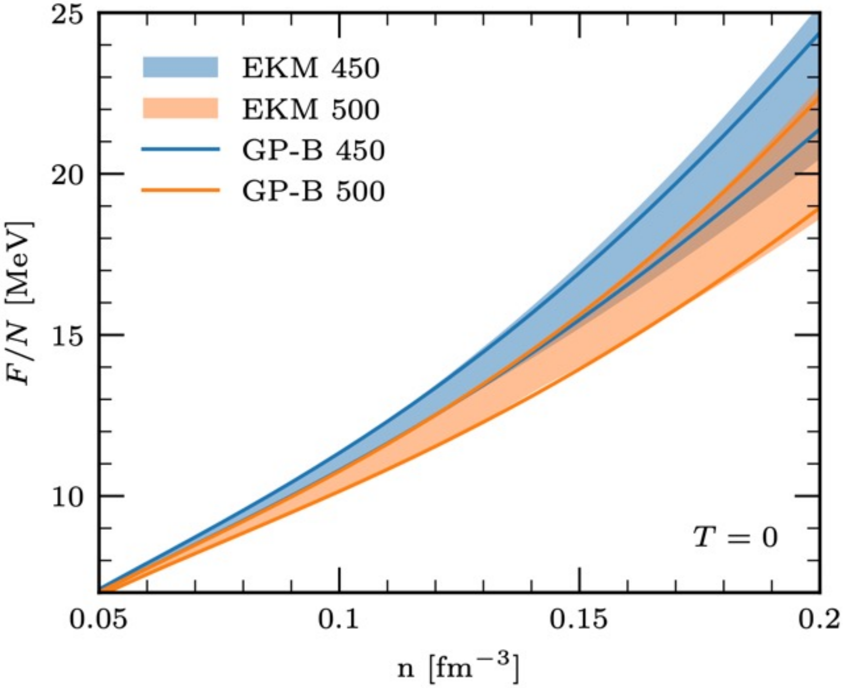
slope determines pressure of neutron matter

from Huth, Wellenhofer, AS, PRC (2021)

# Chiral EFT calculations of neutron matter - Uncertainties



from Huth, Wellenhofer, AS, PRC (2021)

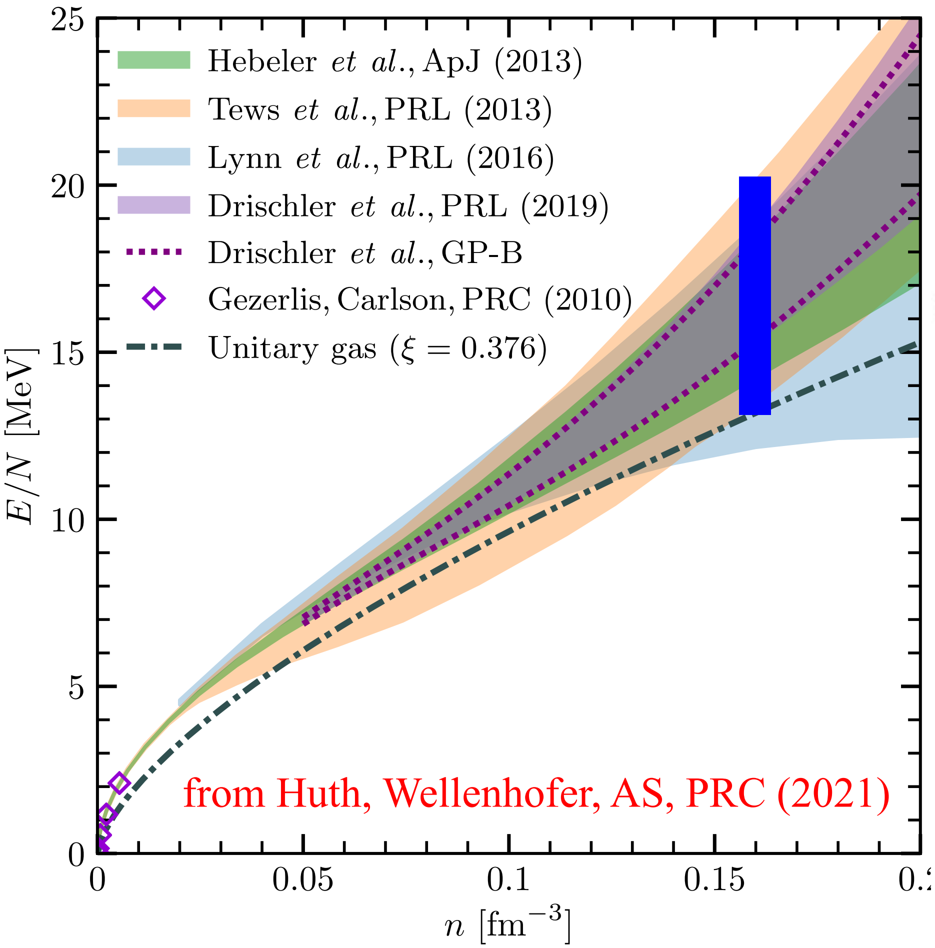


Keller, Wellenhofer, Hebeler, AS, PRC (2021)

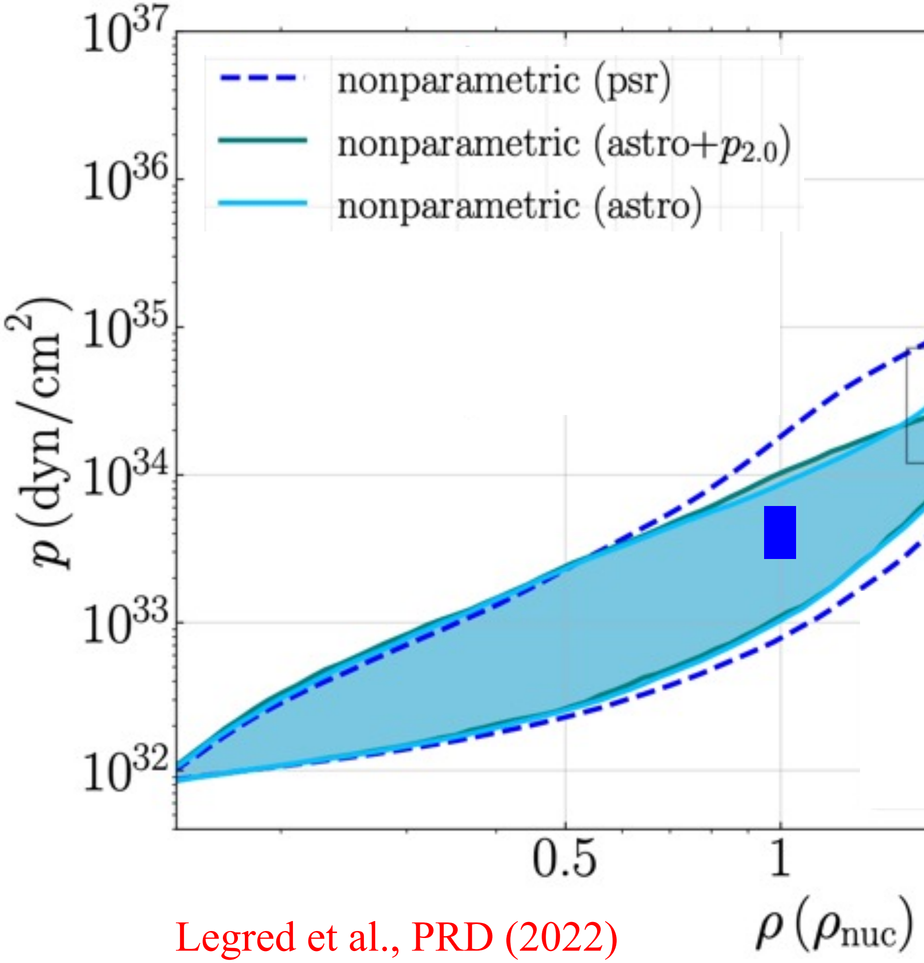
**GP-B** (68%) gives similar bands as order-by-order EFT unc. (**EKM**) from Q/$\Lambda_b$ expansion $\Delta X^{(j)} = Q \cdot \max\left(|X^{(j)} - X^{(j-1)}|, \Delta X^{(j-1)}\right)$

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

# Chiral EFT calculations of neutron matter



from Huth, Wellenhofer, AS, PRC (2021)



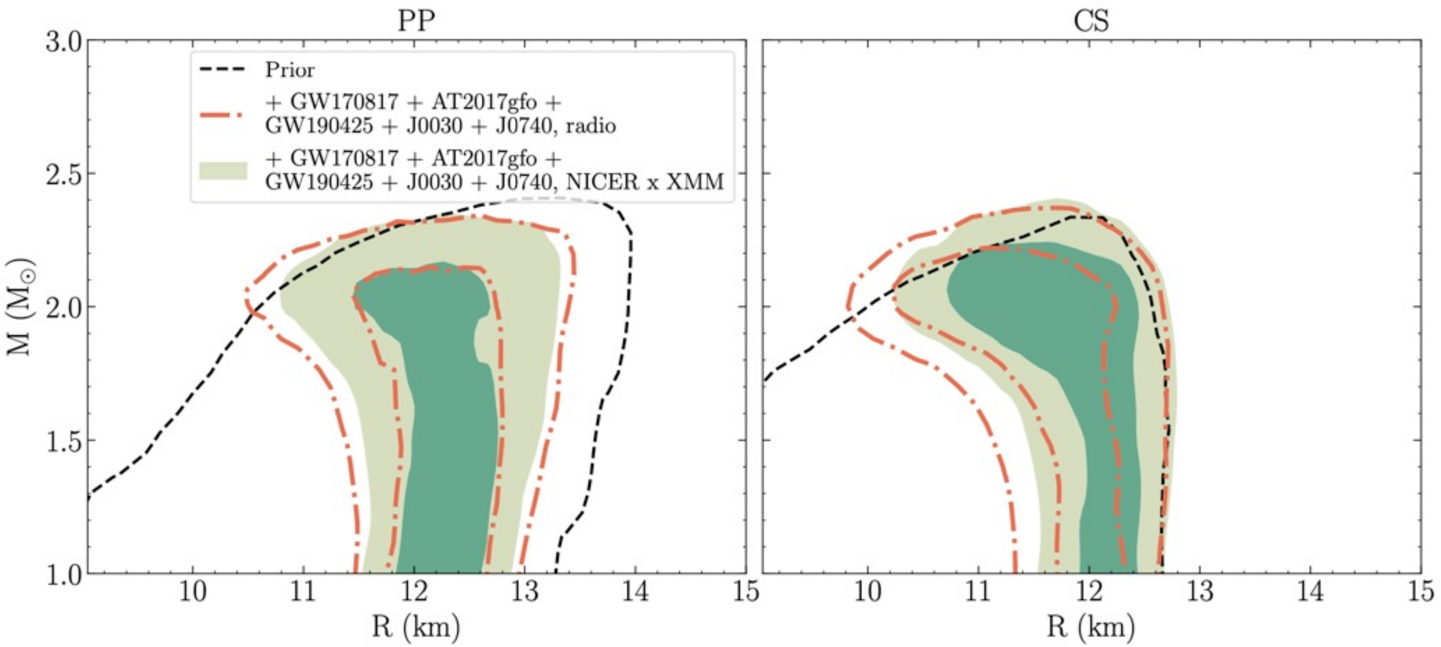
Legred et al., PRD (2022)

comparison to nonparametric EOS

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

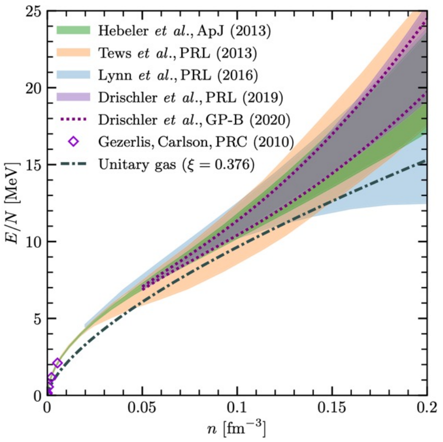
# Combined merger and NICER constraints

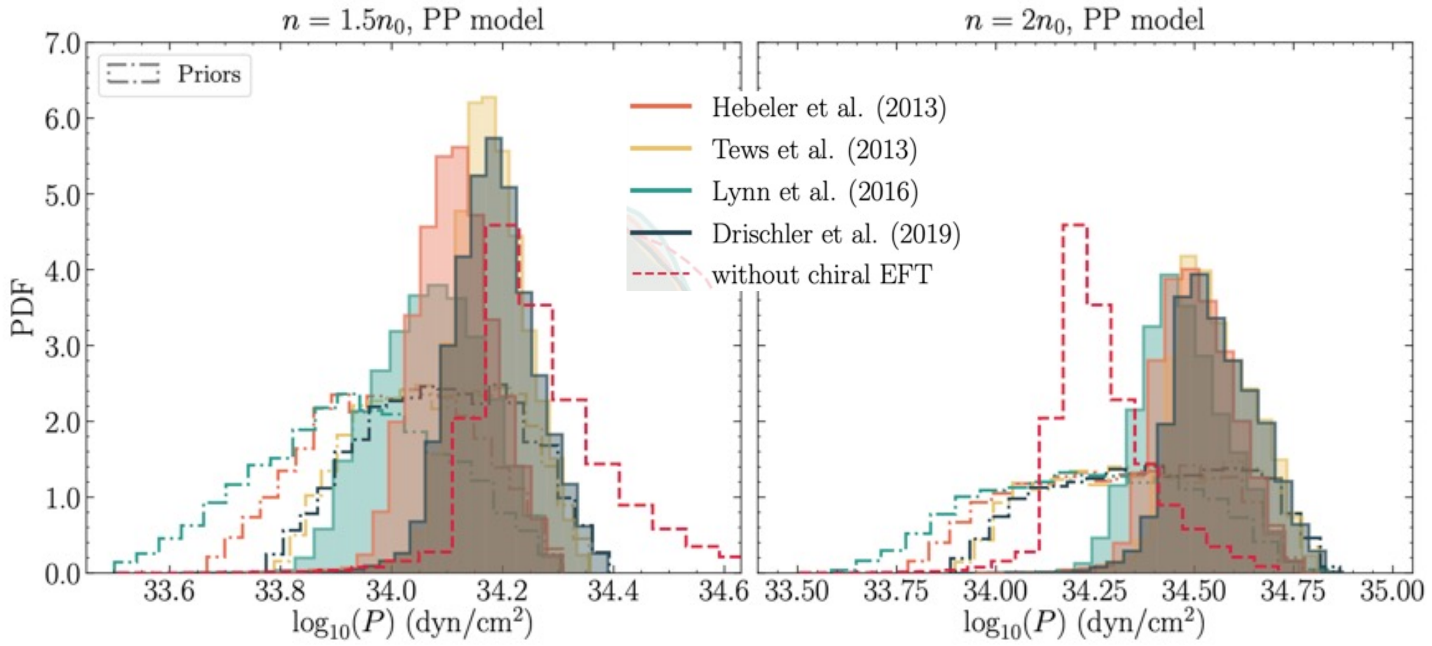
Raaijmakers et al.,
ApJL (2020), (2021)
for mass-radius



EOS at
1.5 and 2 $n_0$

astro prefers
higher pressures





# Outline

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**EOS for arbitrary proton fraction and finite T**

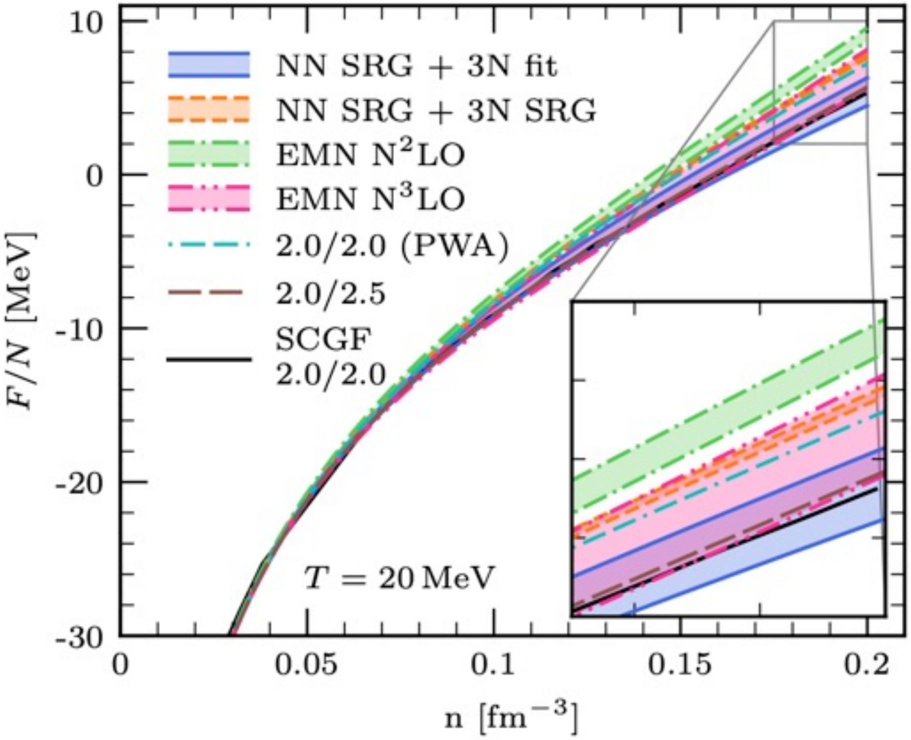
Constraints at intermediate densities:
astrophysics, heavy-ion collisions, functional RG

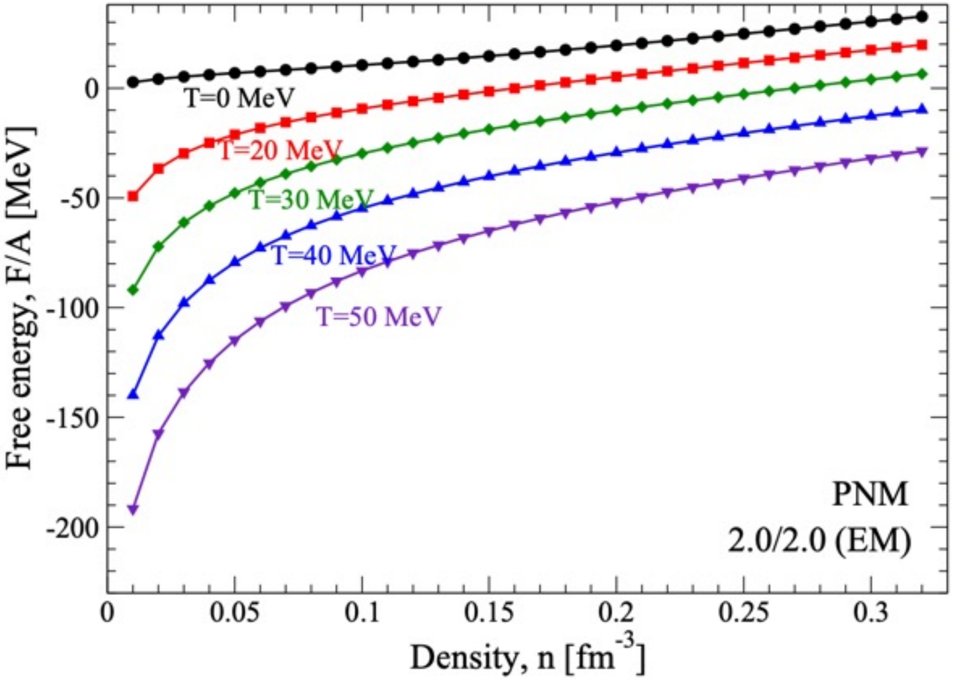
# Neutron matter at finite temperature

similar thermal effects for different NN+3N interactions

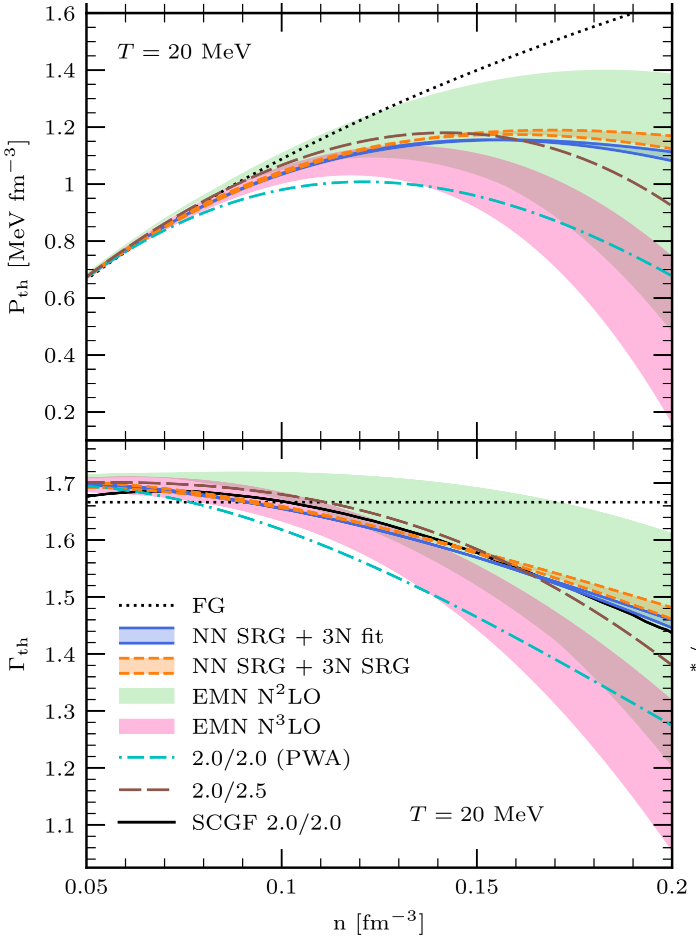
Keller, Wellenhofer, Hebeler, AS, PRC (2021)

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





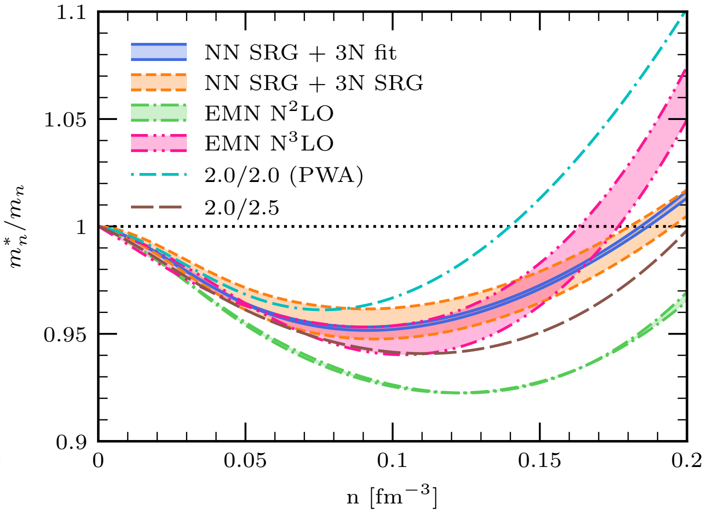
# Thermal effects governed by quasiparticles with eff. mass



decreasing thermal pressure due to repulsive 3N contributions

increasing effective mass m$^*$ beyond n$_{\rm sat}$

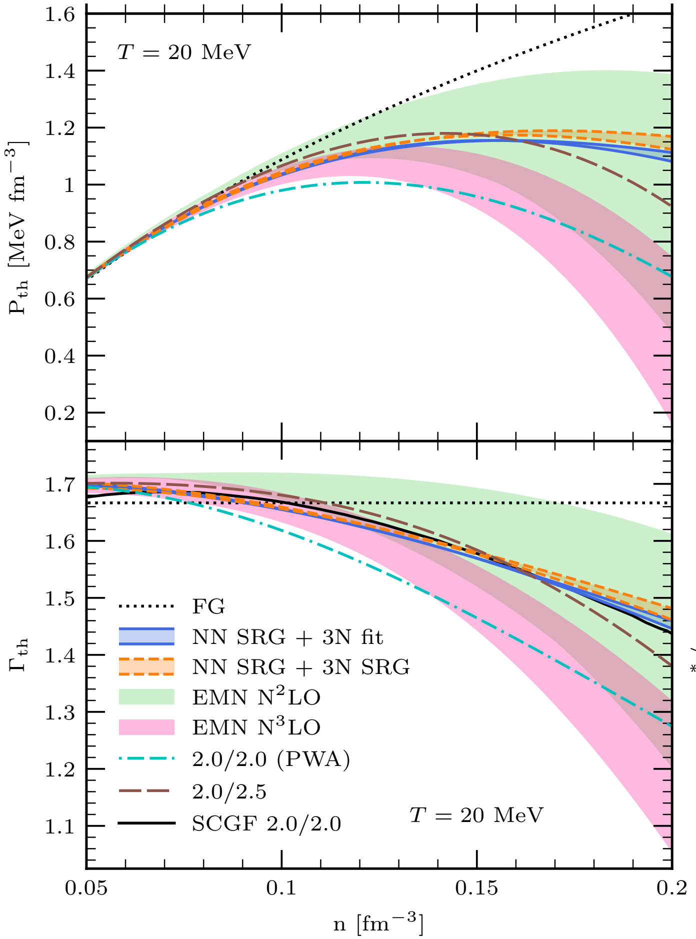
$$\Gamma^*_{\rm th}(n) = \frac{5}{3} - \frac{n}{m^*_n}\frac{\partial m^*_n}{\partial n}$$



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

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

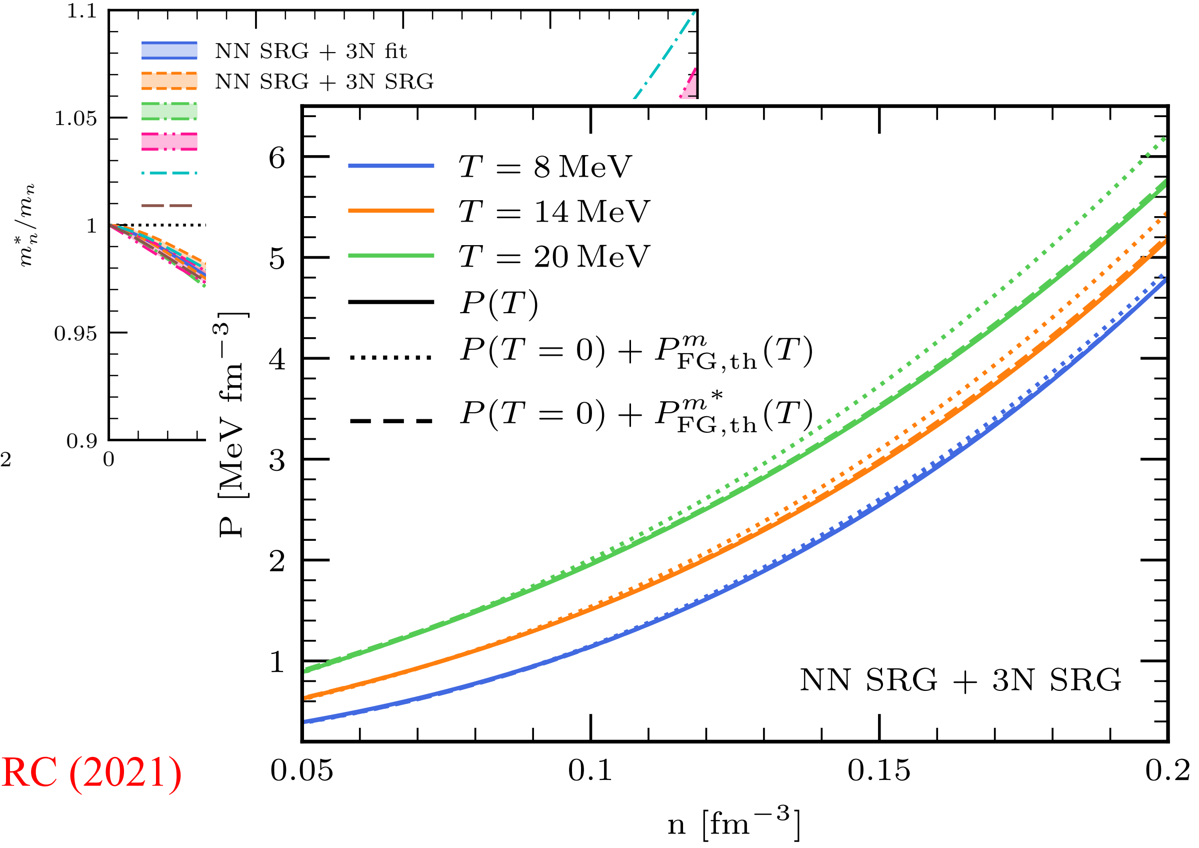
# Thermal effects governed by quasiparticles with eff. mass



decreasing thermal pressure due to repulsive 3N contributions

increasing effective mass $m^*$ beyond $n_{sat}$

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



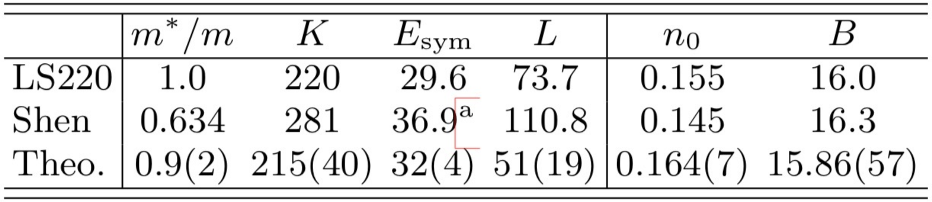
$$\Gamma_{th}(T,n) = 1 + \frac{P_{th}(T,n)}{\mathcal{E}_{th}(T,n)}$$

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

# Impact on core-collapse supernova simulations

Yasin, Schäfer/Huth, Arcones, AS, PRL (2020)

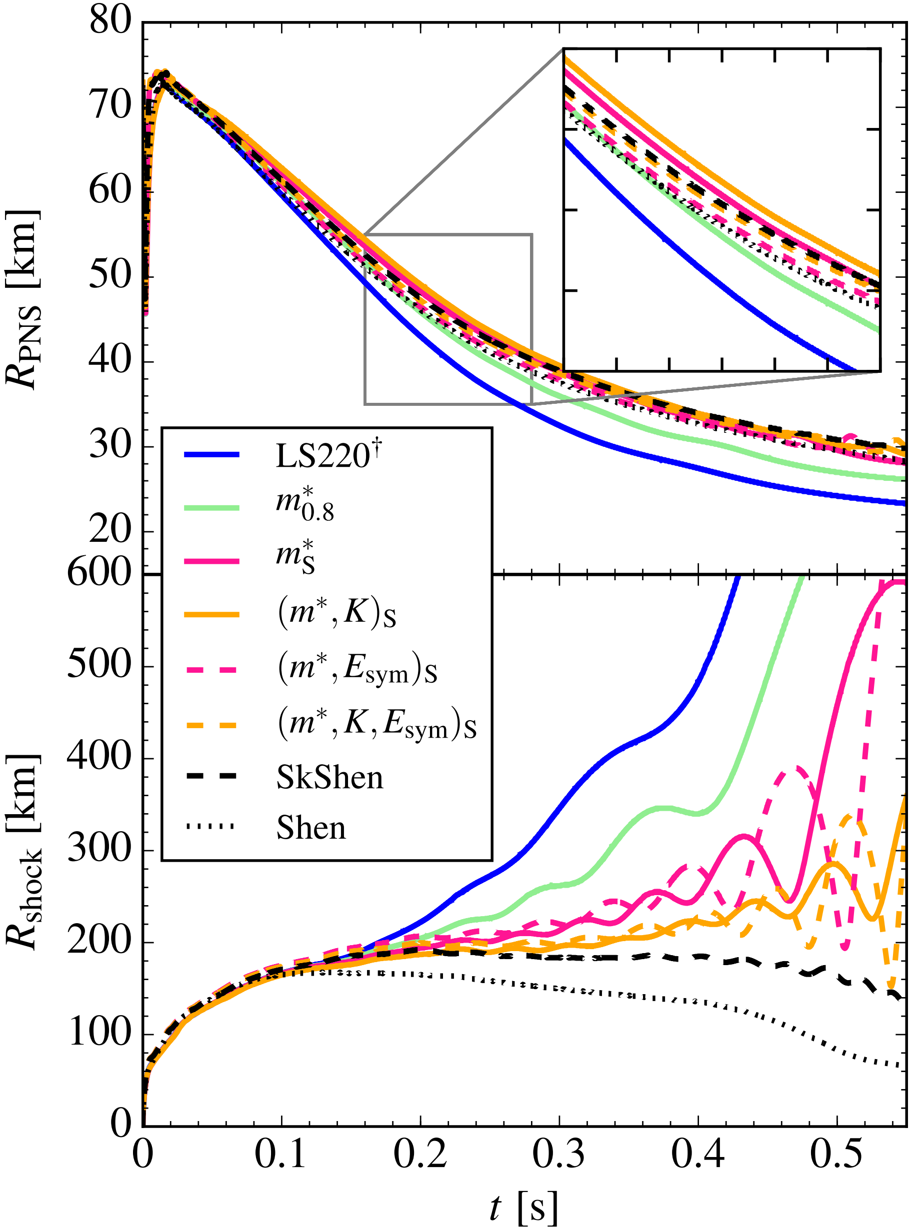
constructed EOS that systematically vary nuclear matter properties between LS and Shen et al. EOS



|  | $m^*/m$ | $K$ | $E_{\rm sym}$ | $L$ | $n_0$ | $B$ |
|---|---|---|---|---|---|---|
| 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

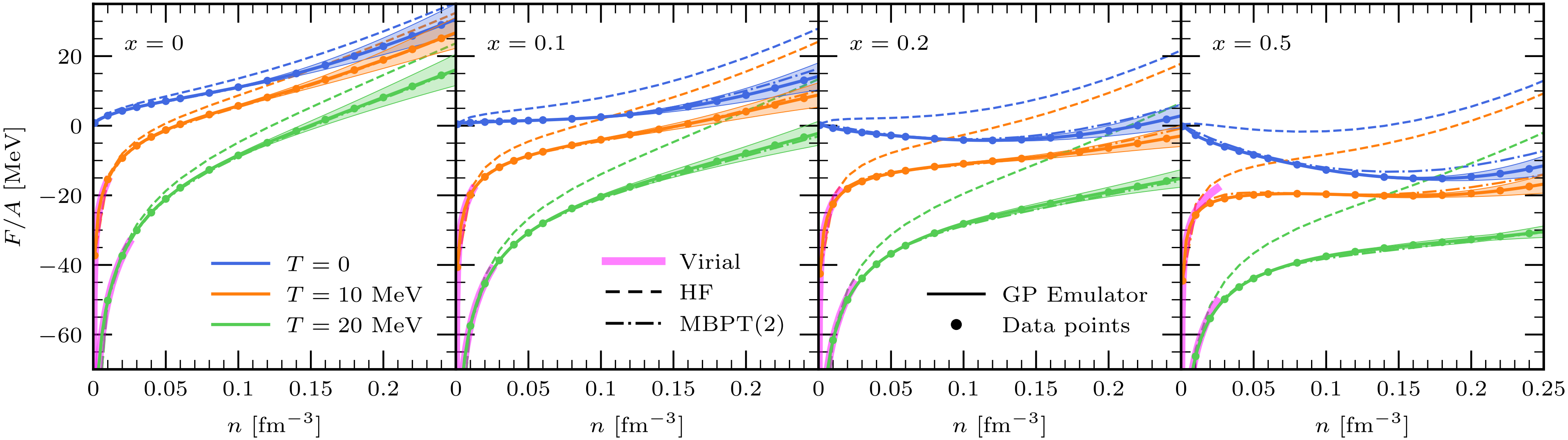
Keller, Hebeler, AS, PRL (2023)

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

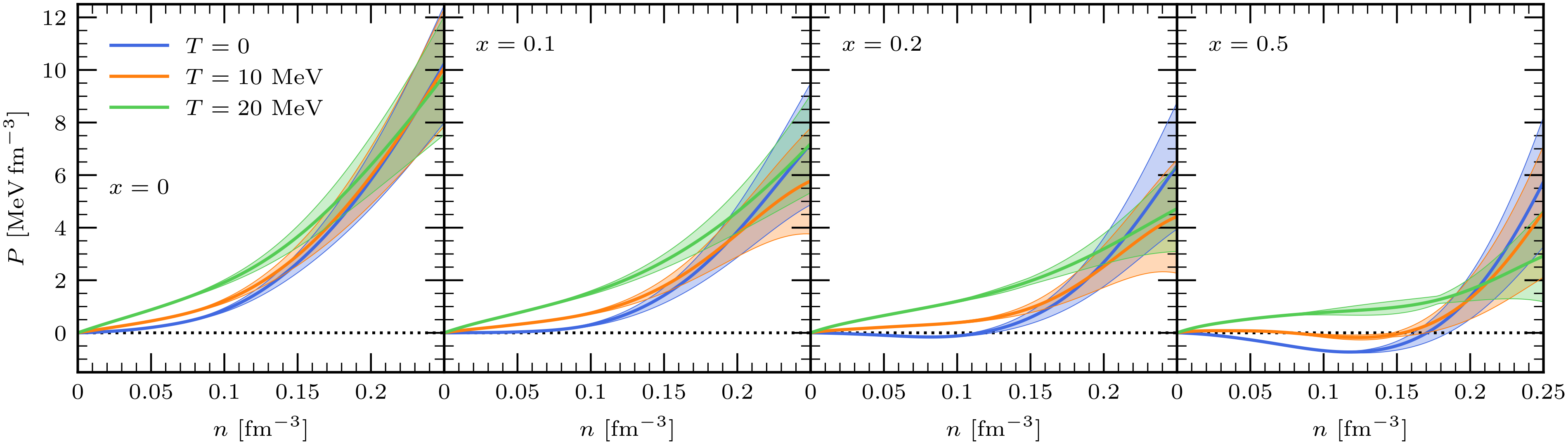
agrees with model-indep. virial EOS Horowitz, AS, NPA (2006) at low densities



# 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

see also Carbone et al., Wellenhofer et al.

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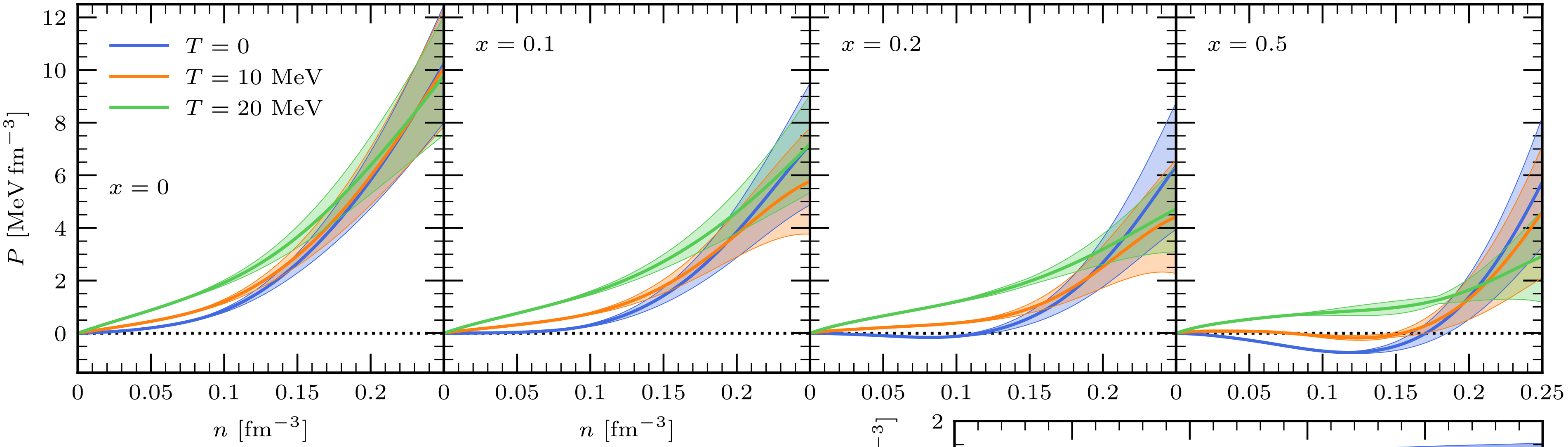

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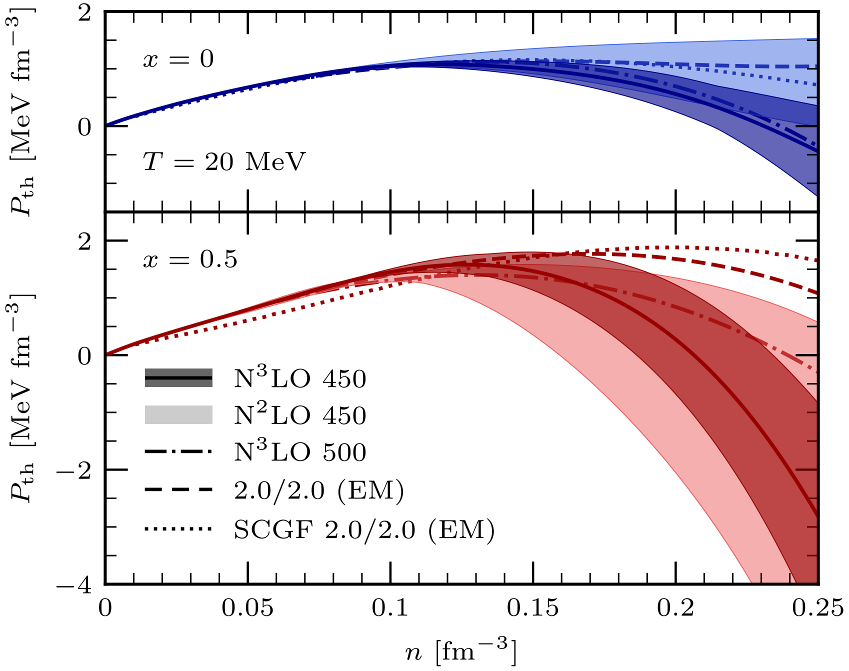
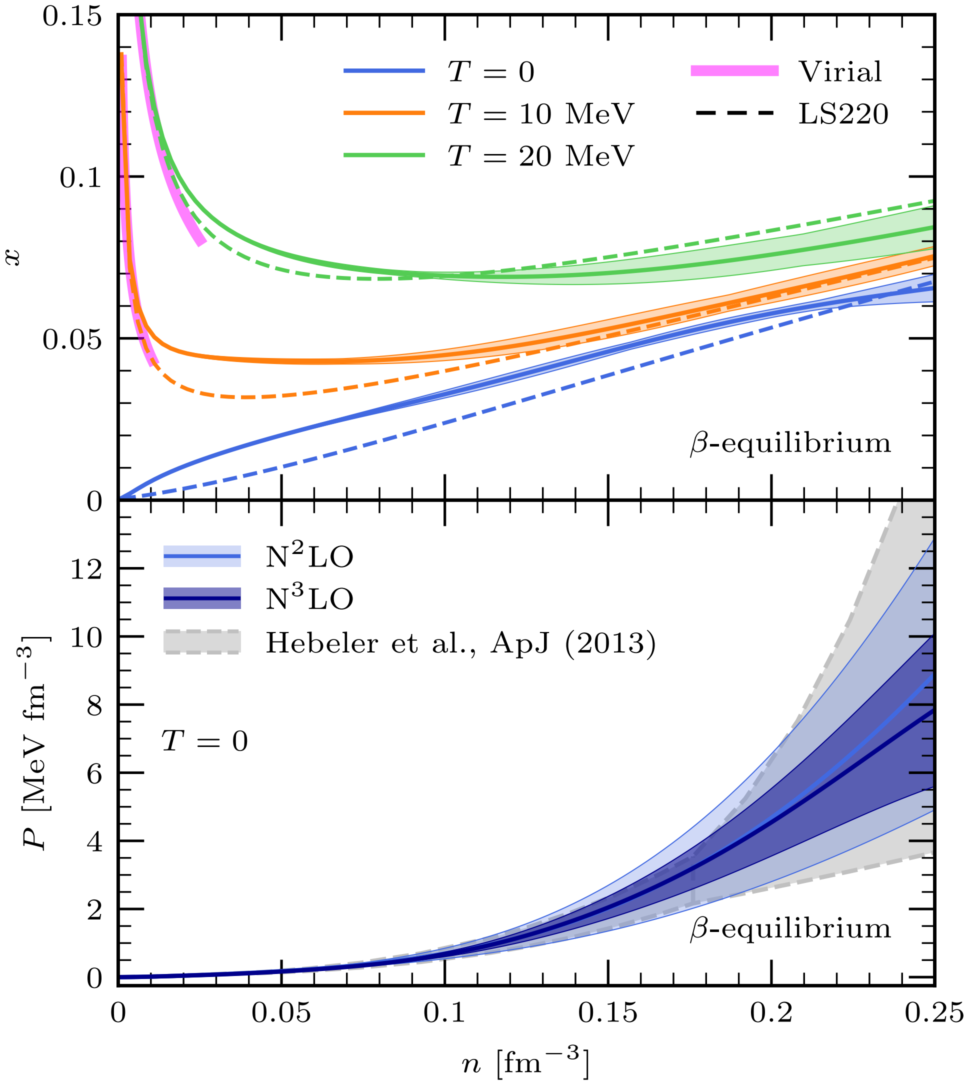


thermal part of pressure decreases with increasing density, observed for different chiral orders, cutoffs and interactions

# EOS for neutron star matter in beta equilibrium

Keller, Hebeler, AS, 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

# Outline

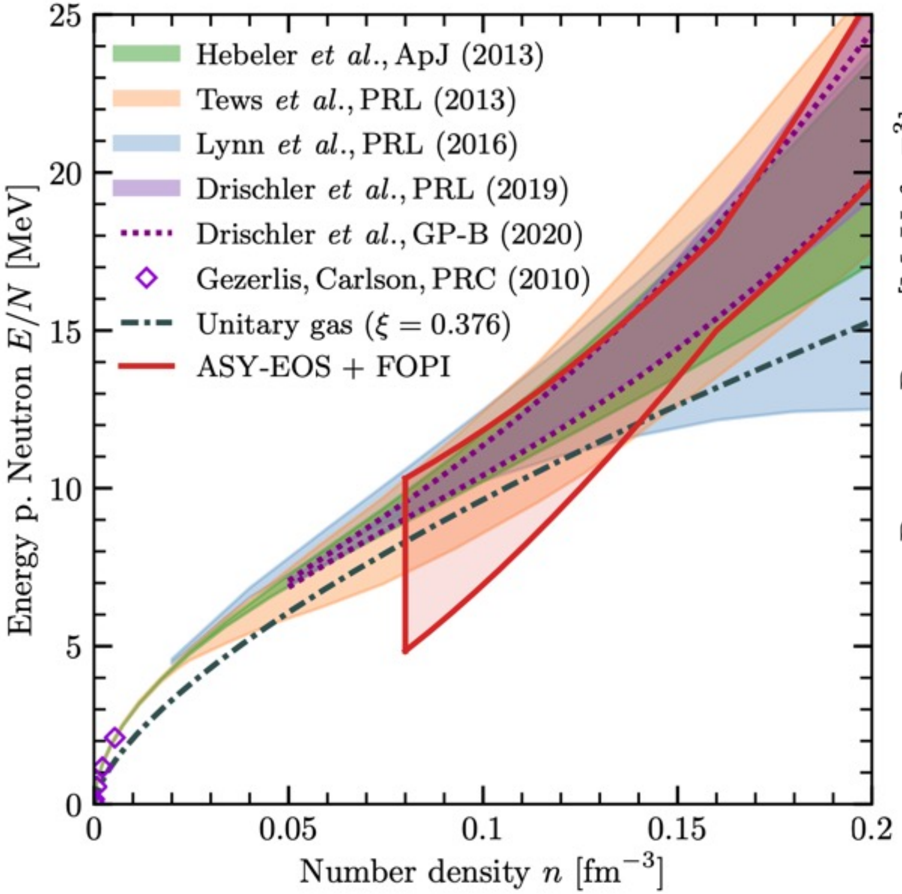
Ab initio calculations of nuclear matter

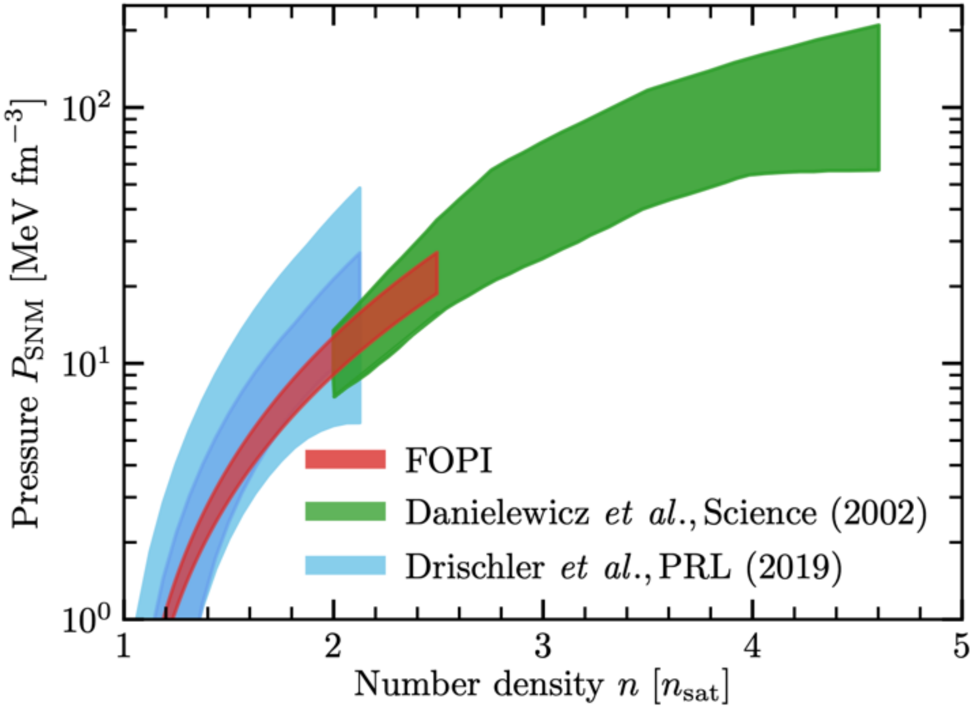
EOS for arbitrary proton fraction and finite temperature

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

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

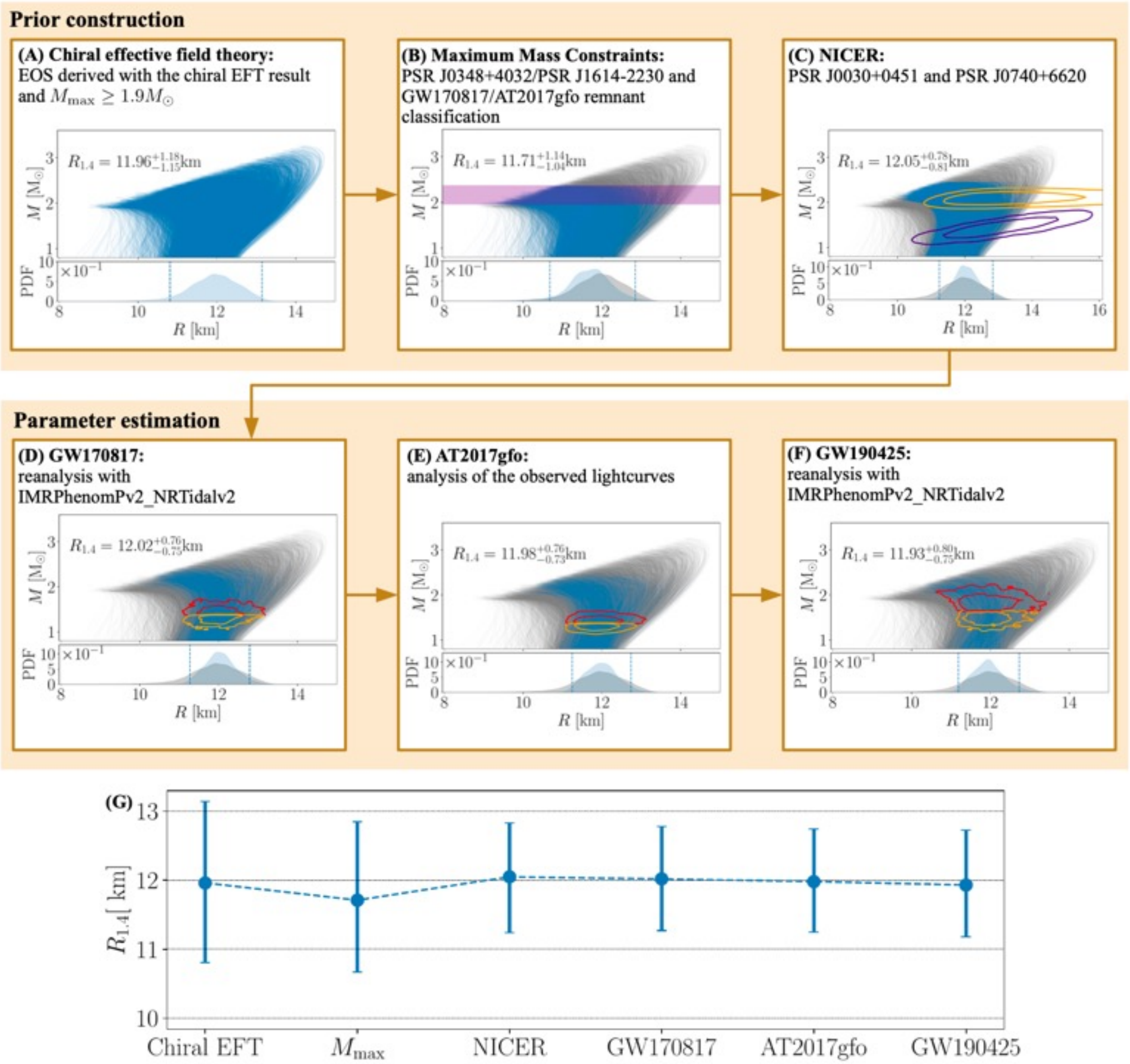
include constraints from heavy-ion collision experiments
**ASY-EOS and FOPI at GSI** for neutron-rich and symmetric matter





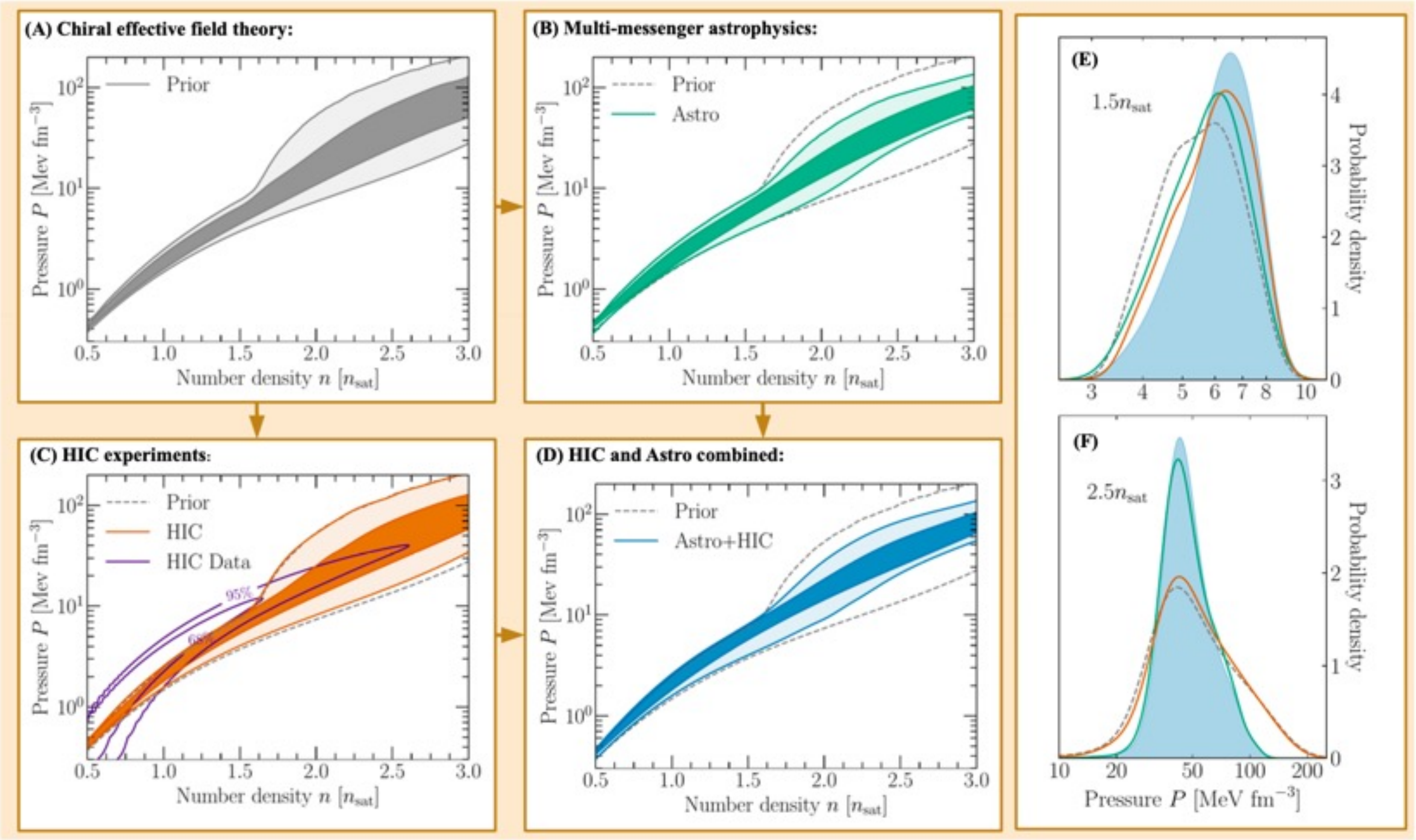
# Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

Bayesian multi-messenger framework using EOS draws based on chiral EFT



# 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



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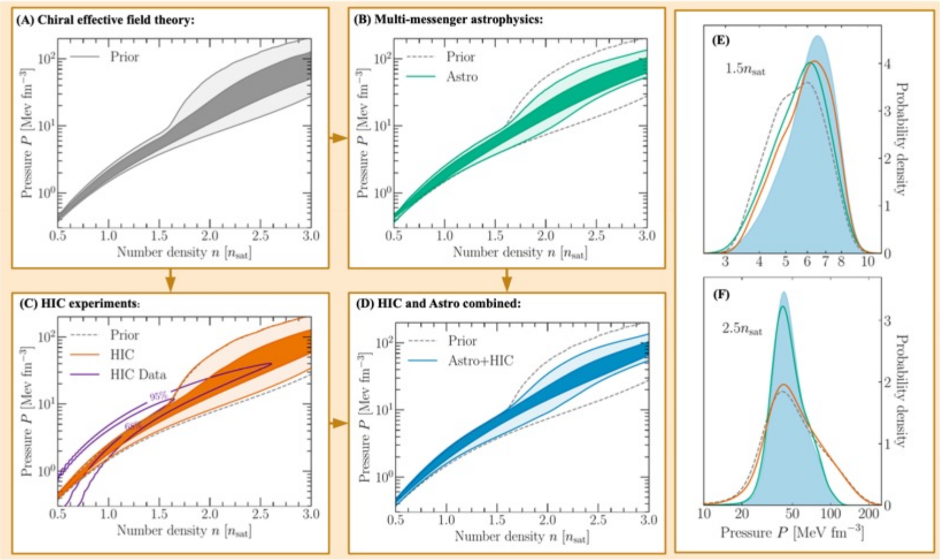
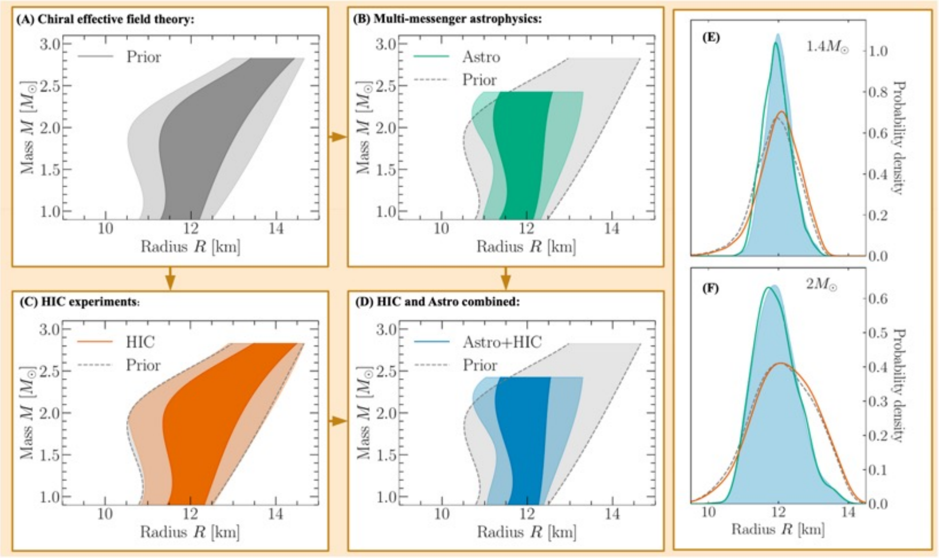




| | Prior | Astro only | HIC only | Astro + HIC |
|---|---|---|---|---|
| $P_{1.5n_{\rm sat}}$ | $5.59^{+2.04}_{-1.97}$ | $5.84^{+1.95}_{-2.26}$ | $6.06^{+1.85}_{-2.04}$ | $6.25^{+1.90}_{-2.26}$ |
| $R_{1.4}$ | $11.96^{+1.18}_{-1.15}$ | $11.93^{+0.80}_{-0.75}$ | $12.06^{+1.13}_{-1.18}$ | $12.01^{+0.78}_{-0.77}$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

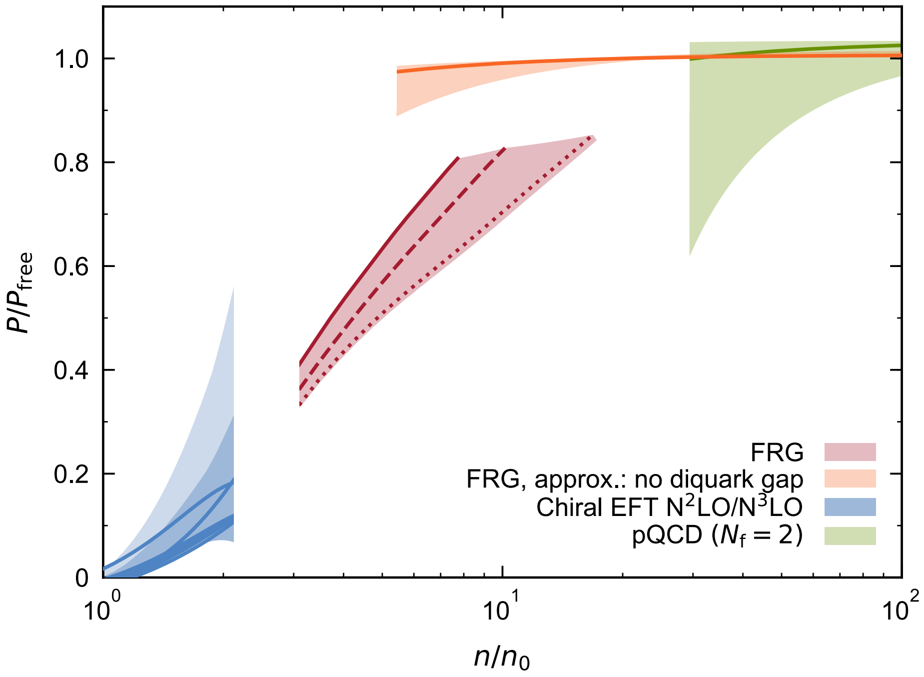
more HIC information for intermediate densities very interesting

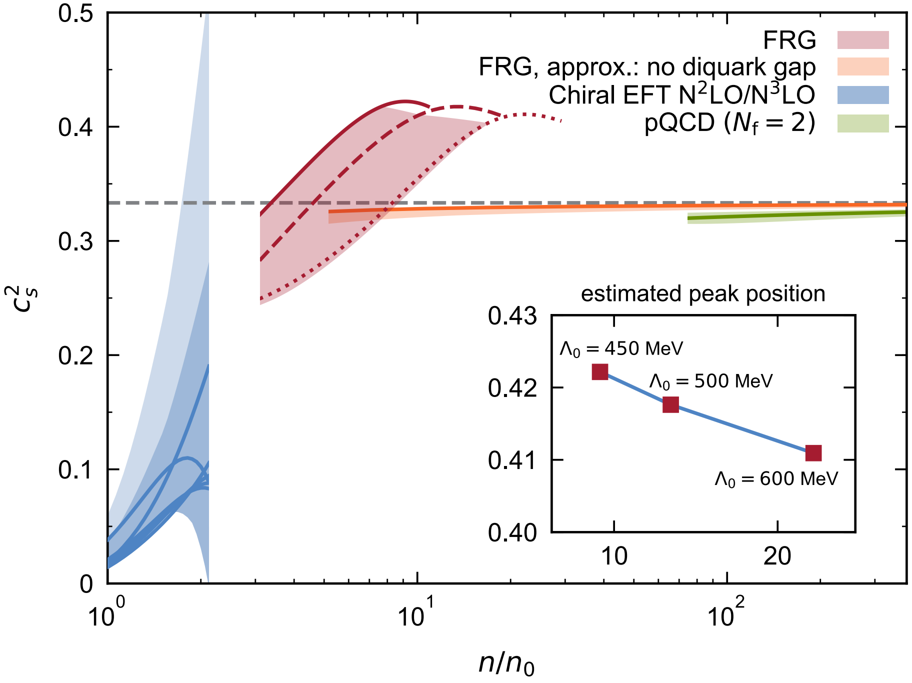
# Functional RG: From QCD to intermediate densities

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

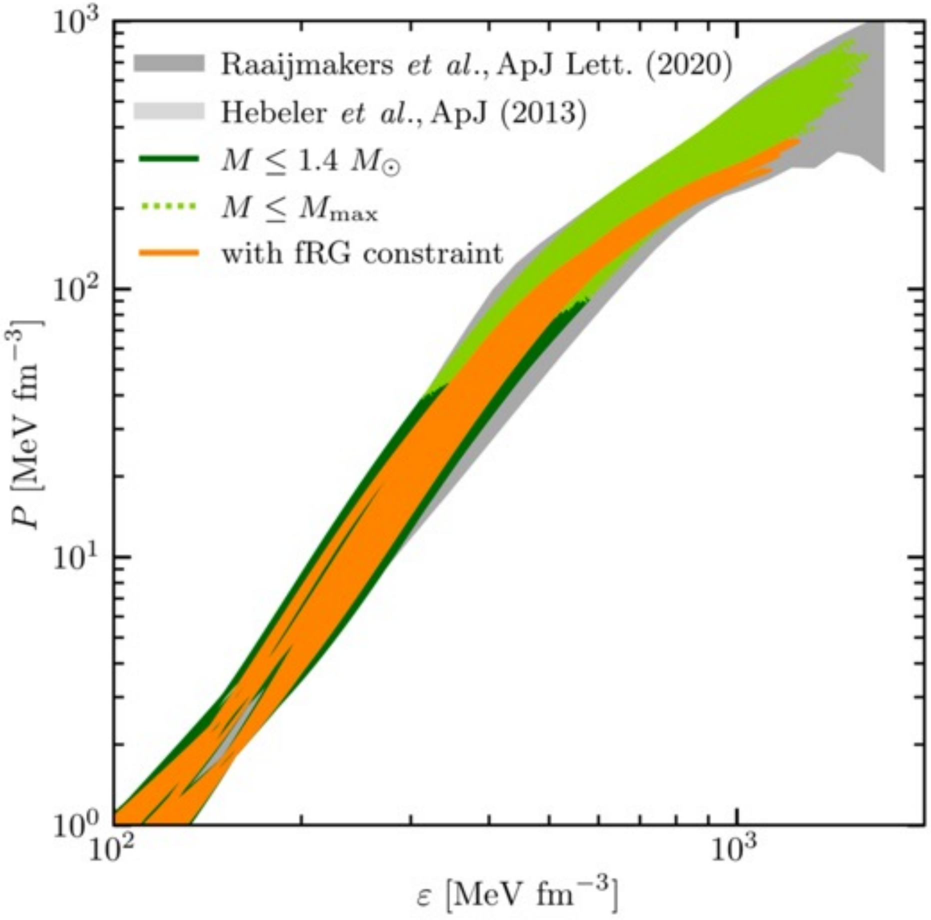
diquark correlations crucial for intermediate densities and high speed of sound

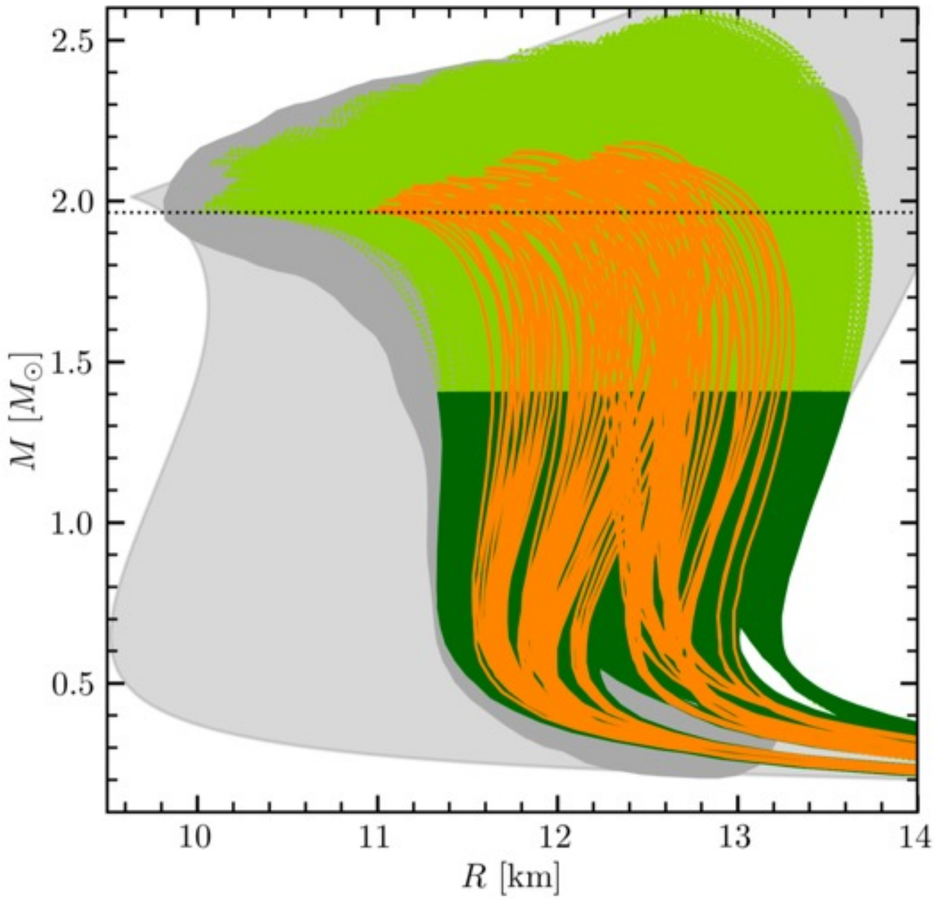
# Impact of functional RG for EOS and neutron stars

**new EOS functionals** constrained by chiral EFT +2 $M_{sun}$ + GW, NICER

Huth, Wellenhofer, AS, PRC (2021)

**FRG** provides interesting constraints at intermediate densities





# 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

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

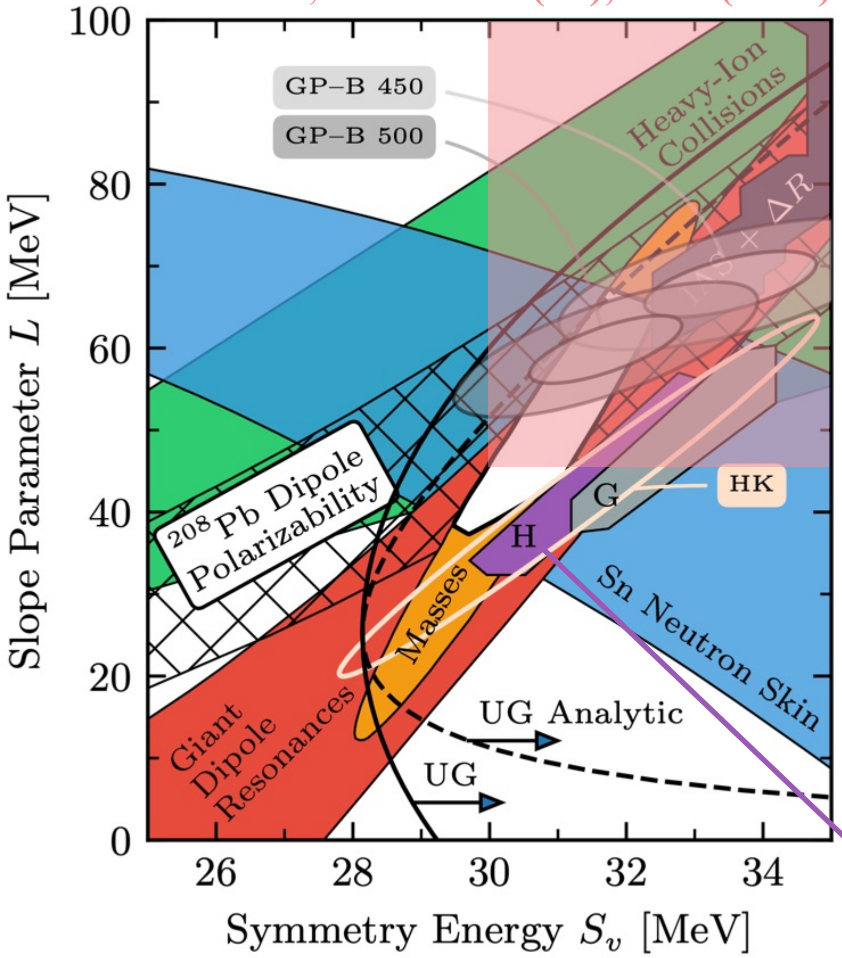
reliable EOS up to 1-1.5 $n_0$ with controlled uncertainties from EFT truncation + small many-body uncertainties

multimessenger astrophysics, heavy-ion collisions, functional RG provide insights to intermediate densities

# Symmetry energy vs. L parameter

based on Lattimer, Lim, ApJ (2013)

PREX II, **Reed et al. (2σ), PRL (2021)**



from Drischler et al., ARNPS (2021)

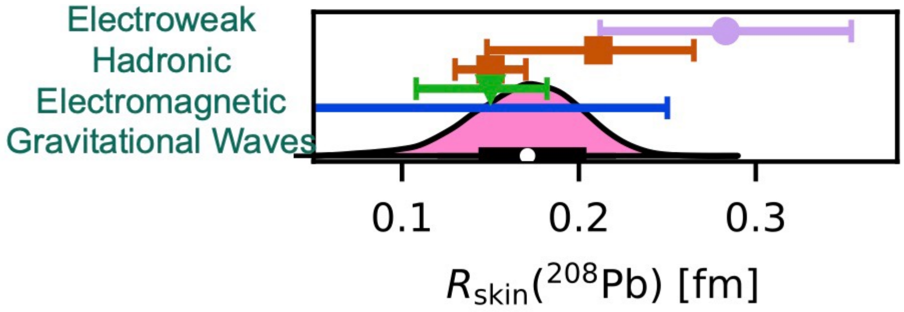
Note: not all regions are at same sat density

PREX obtained large neutron skin,

large pressure of neutron matter ~ L

ab initio calculation of $^{208}$Pb
gives neutron skin: 0.14-0.20 fm

Hu, Jiang, Miyagi, Sun et al., Nature Phys. (2022)



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

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

need to improve precision of PREX
(consistent with all calcs at 2σ level)