

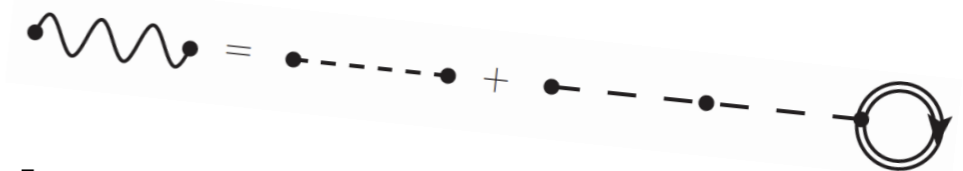


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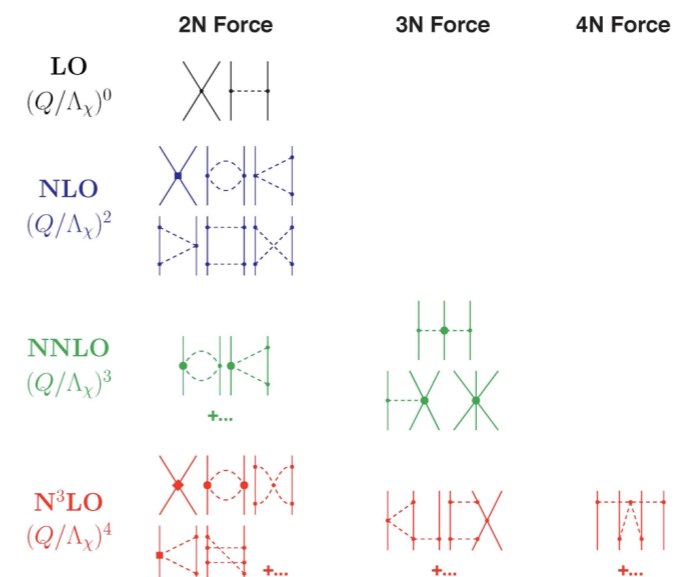
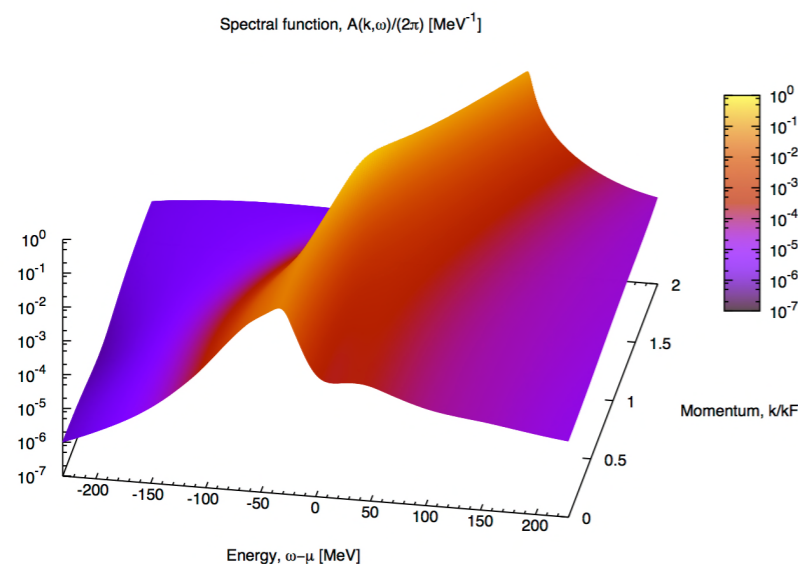
Alexander von Humboldt  
Stiftung/Foundation



# Nuclear matter at zero and finite temperatures based on chiral forces

Arianna Carbone - TU Darmstadt

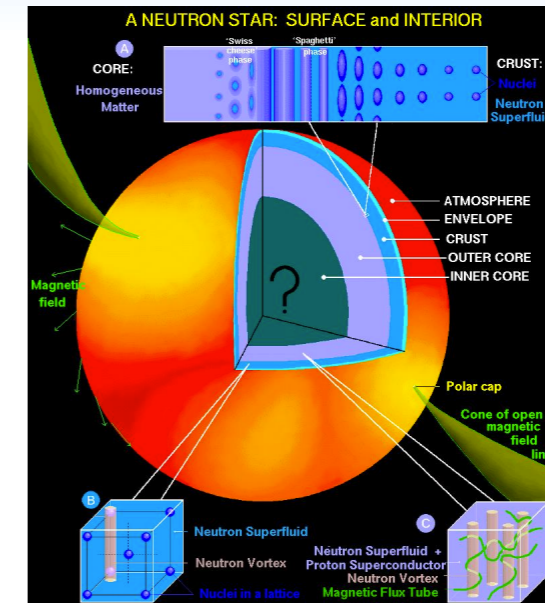
TH Institute "Neutron Stars" - CERN - 6 December 2016



# Nuclear theory: from nuclei to nuclear matter

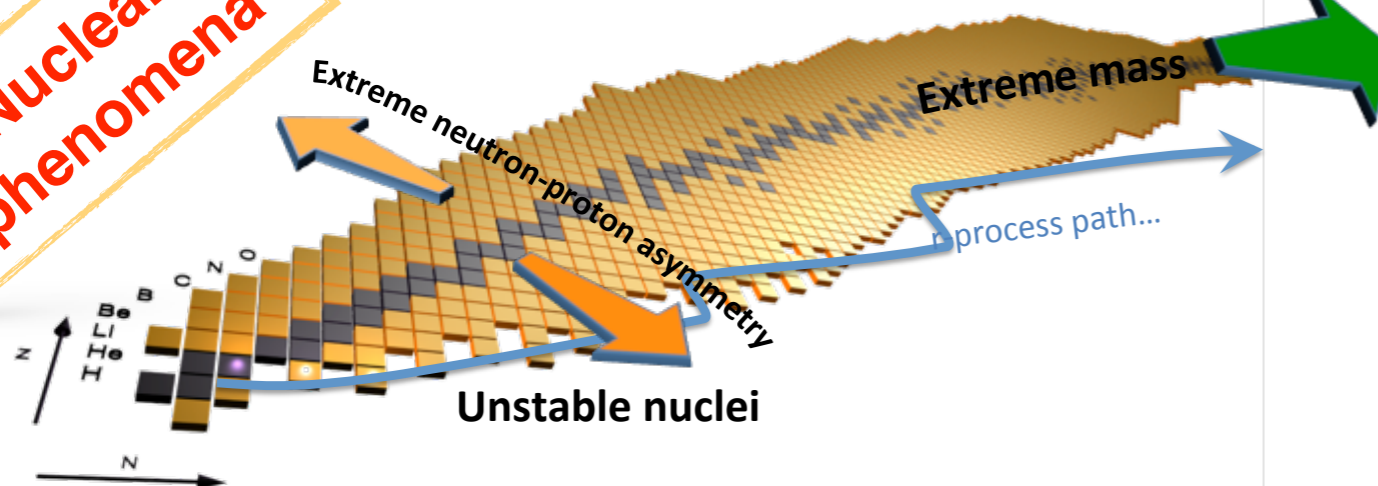
## The nuclear many-body problem

- Build reliable methods with predictive power
- Probe the limits of the nuclear landscape
- Constrain the EOS of neutron star matter

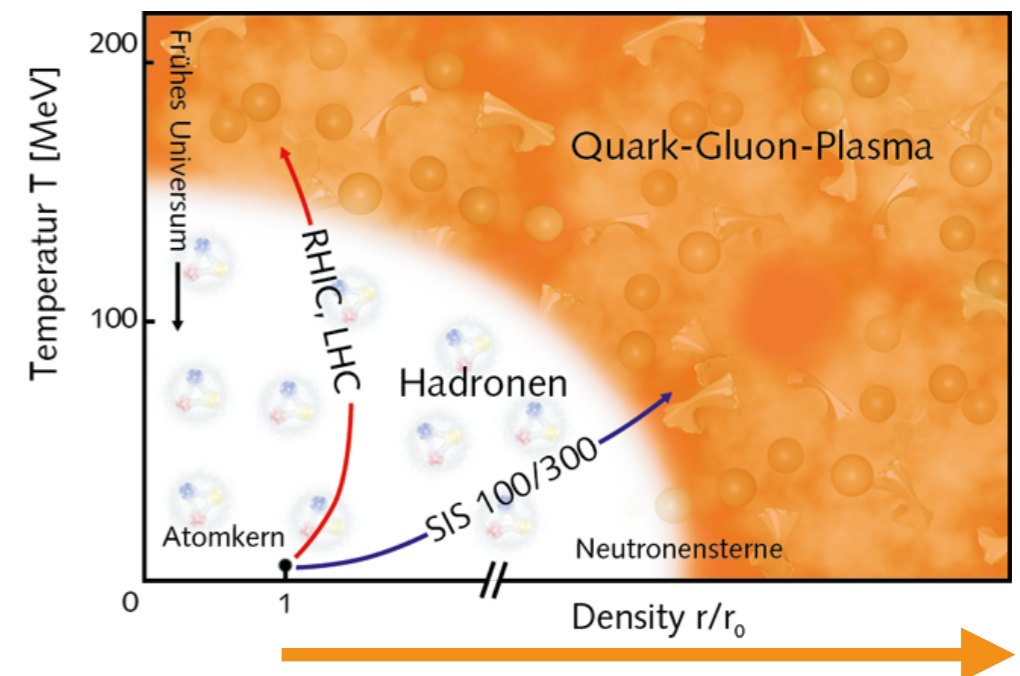


Astrophysics

Nuclear phenomena



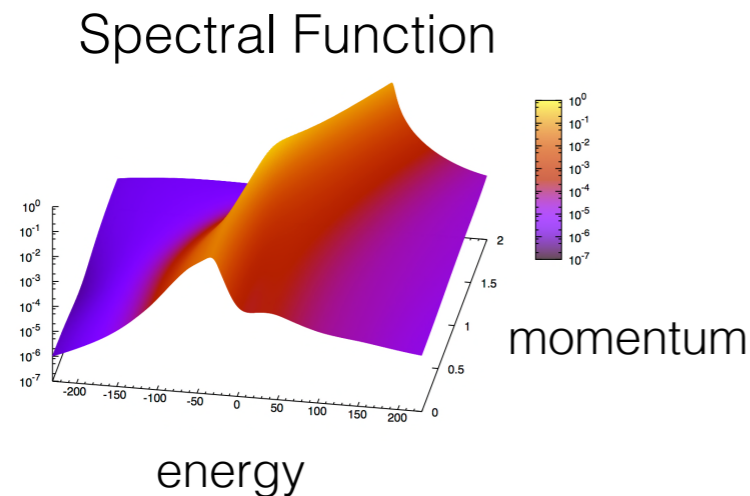
## The phase diagram of hadronic matter



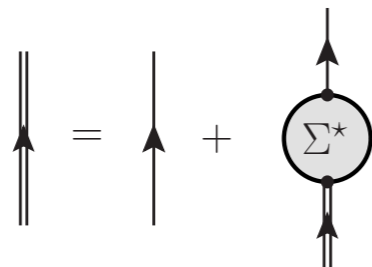
Radioactive beam facilities access this region at the extremes

# Solving the nuclear many-body problem

## Self-consistent Green's functions

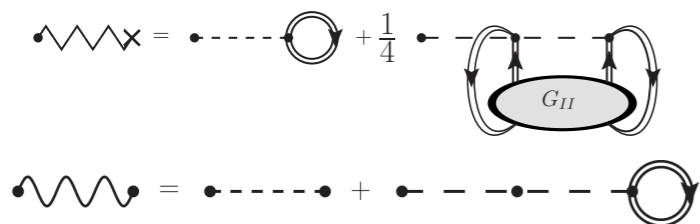


**Dyson equation**



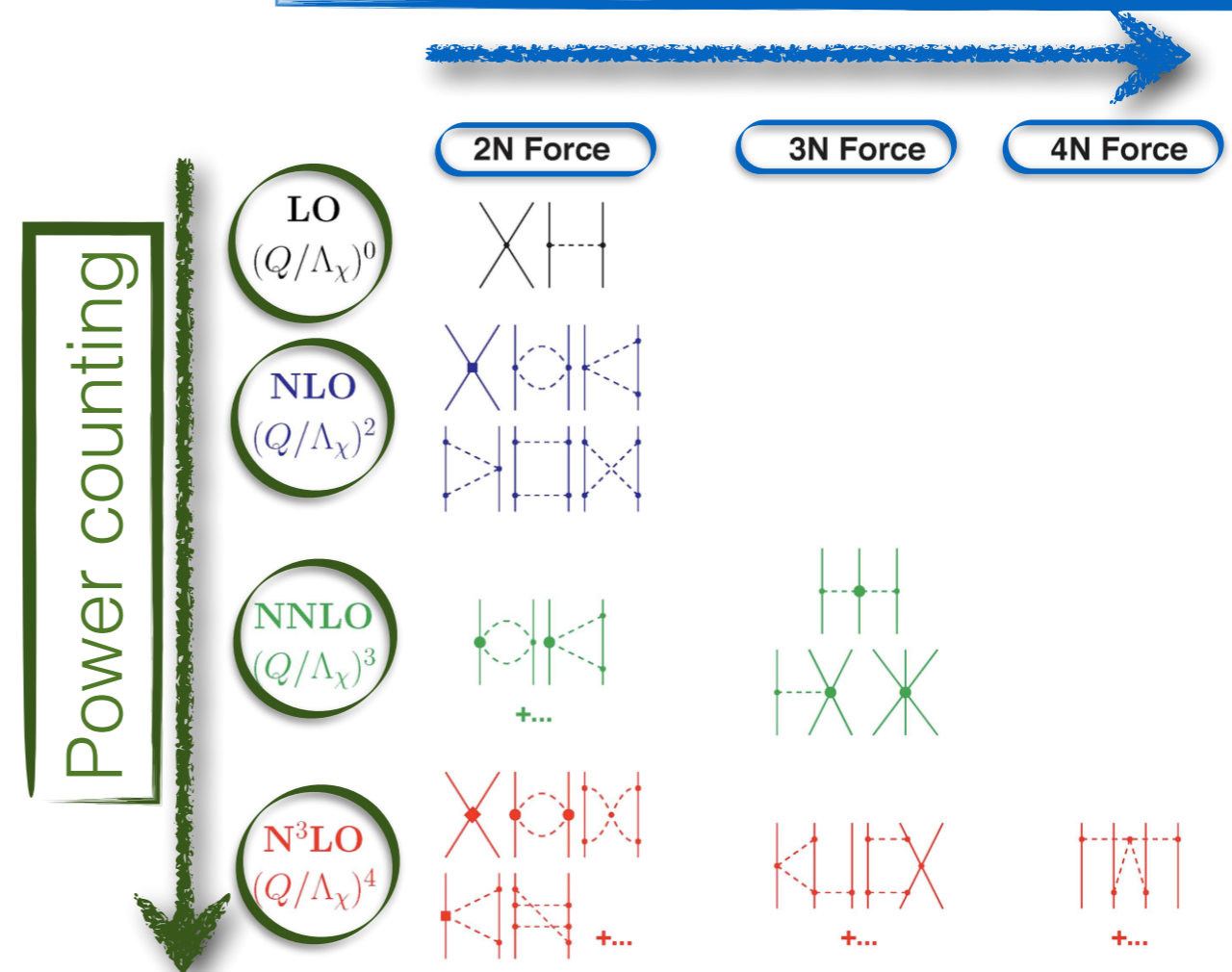
## Breakthrough: full formal extension to consistently include 3BFs

Carbone, Cipollone, Barbieri, Rios, Polls,  
PRC **88**, 054326 (2013)



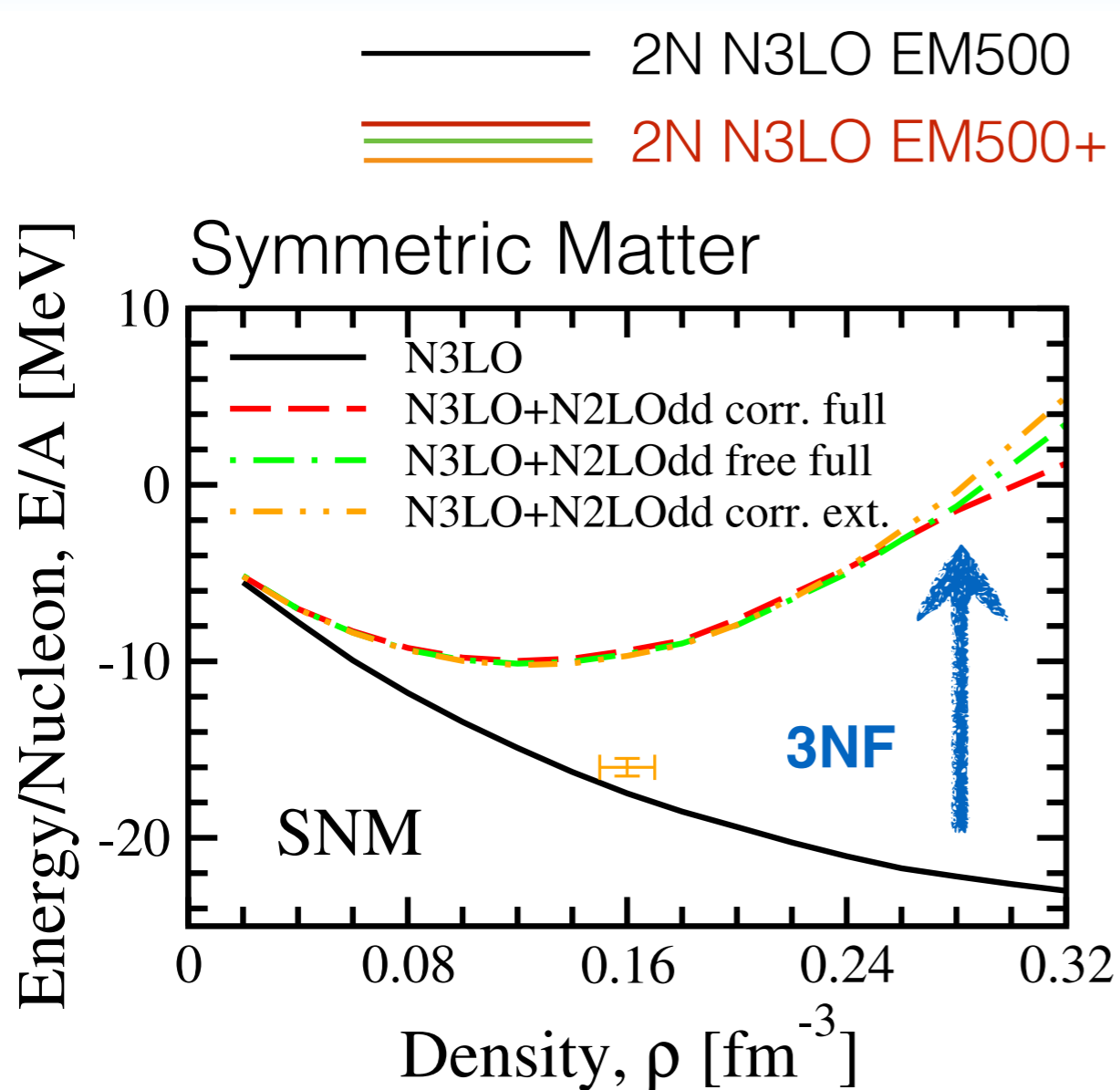
## Chiral Hamiltonian nucleons and pions

### Hierarchy of N-body forces



**theoretical uncertainties**

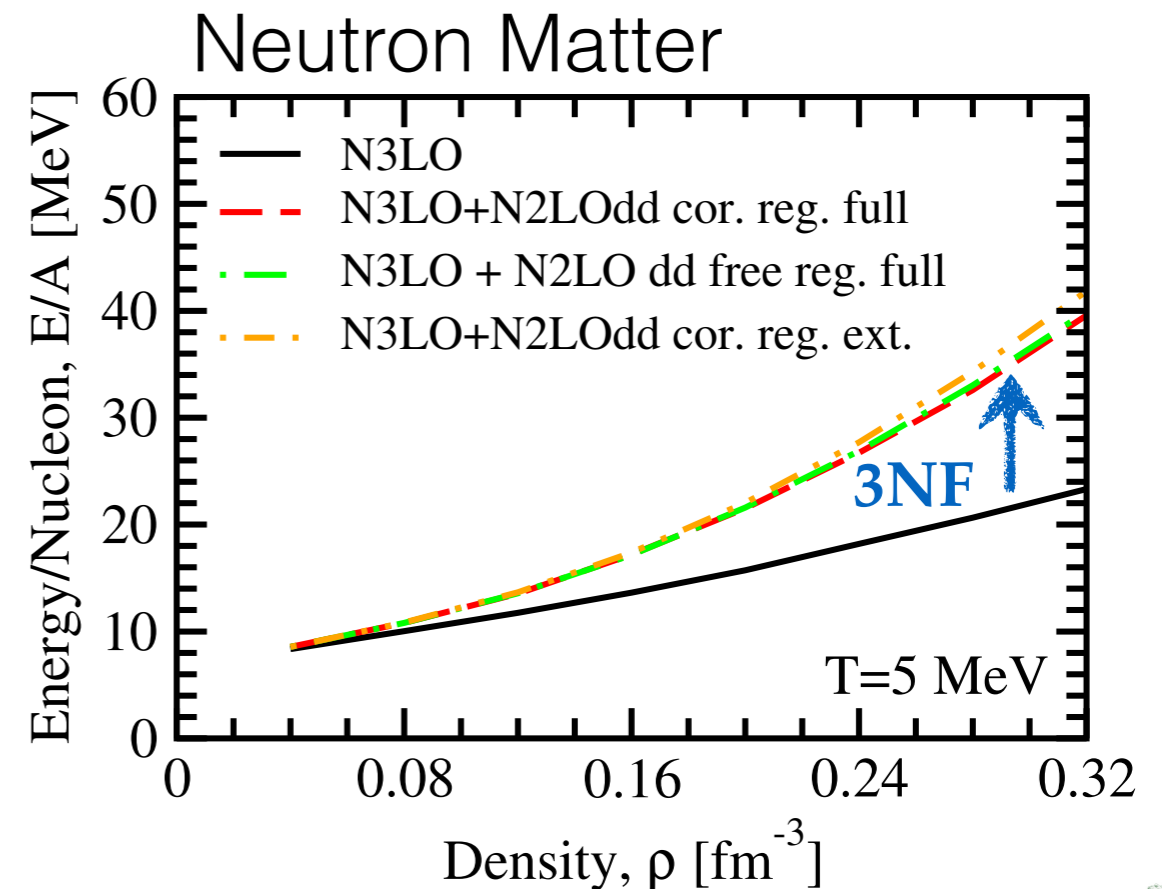
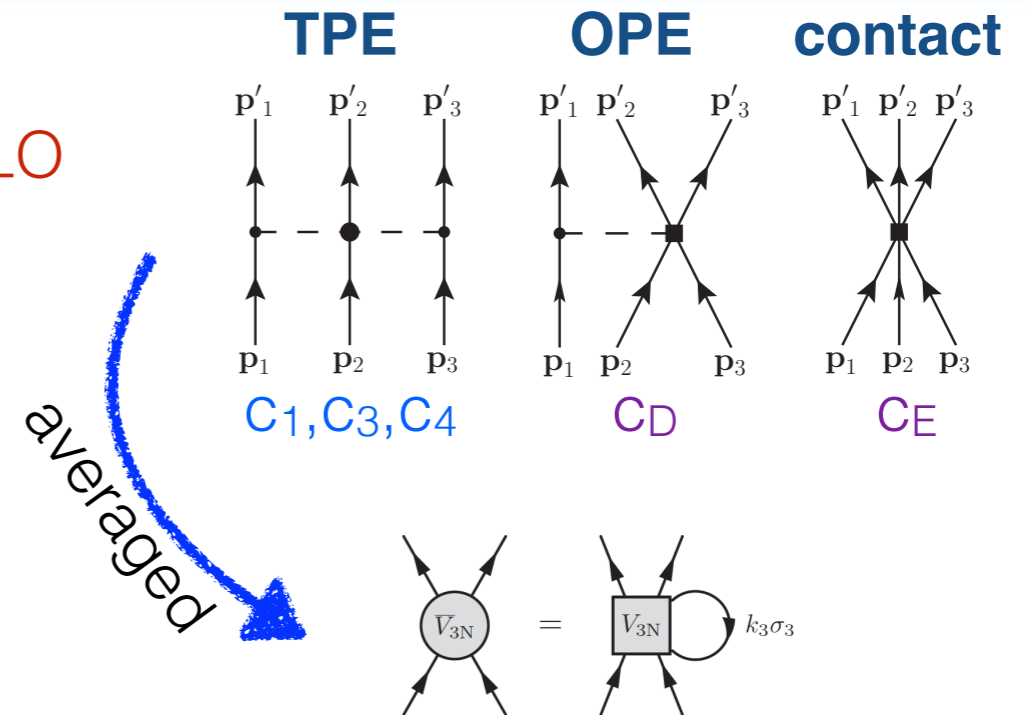
# The need for 3-body nuclear forces



- Improved prediction of saturation density
- Neutron matter energy stiffens

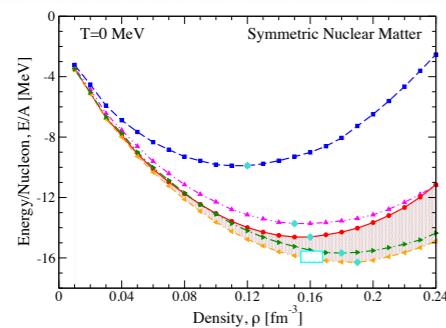
Carbone, Rios, Polls, PRC 88, 044302 (2013)

Carbone, Rios, Polls, PRC 90, 054322 (2014)

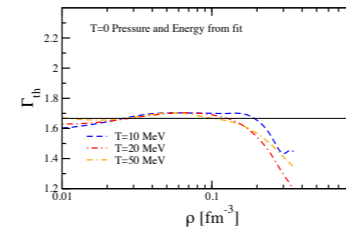


# What can we predict?

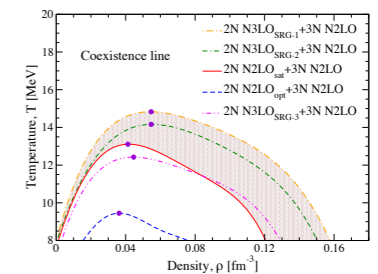
Saturation point  
& uncertainties



Thermal effects  
in the PNM EOS

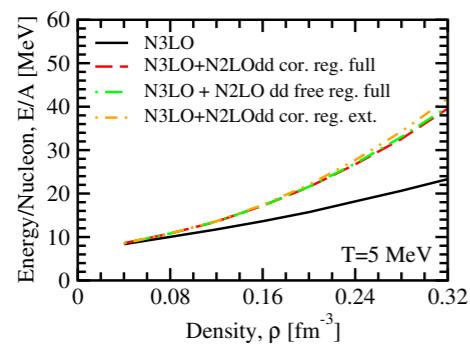


Finite-T & estimate of  
liquid-gas transition

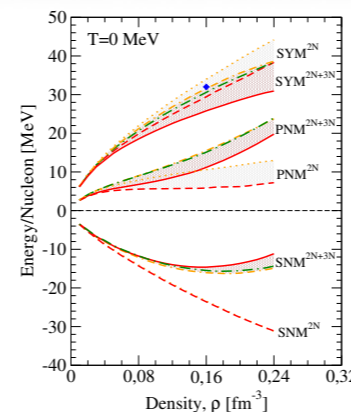


Many-Body approach  
+  
Chiral EFT

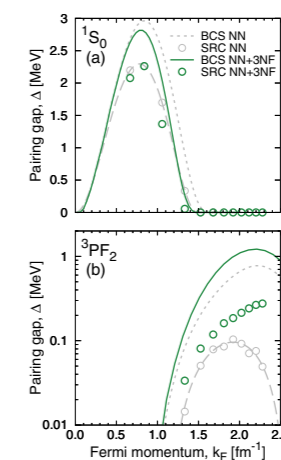
PNM equation of state



Symmetry energy  
& slope parameter

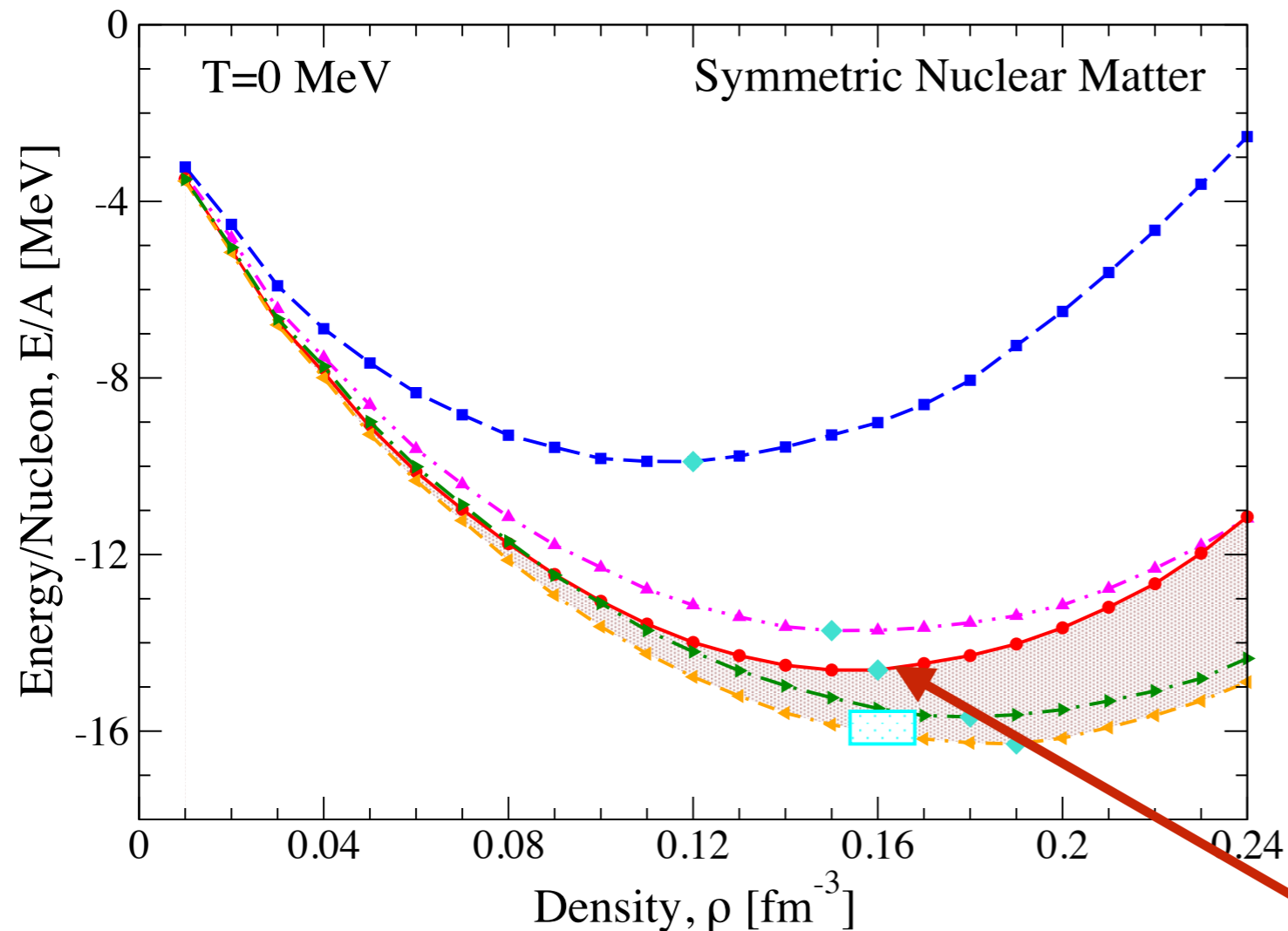


Pairing gap  
in PNM

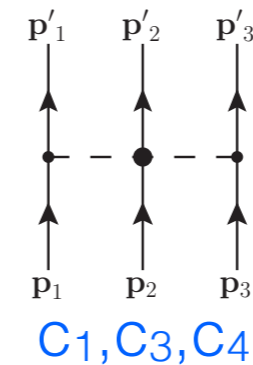


## Saturation point according to different Hamiltonians

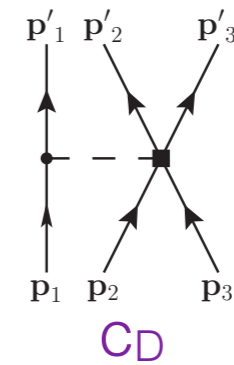
Carbone (in preparation)



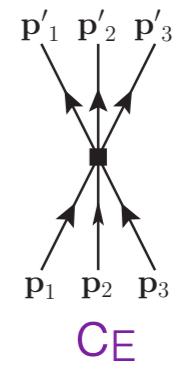
**TPE**



**OPE**



**contact**



Some low-energy constants are fit to few-body properties

- N3LO EM500SRG, 3NFs fit to  $^3\text{H}$  BEs,  $^4\text{He}$   $r_m$
- N2LOopt (POUNDERS), 3NFs fit to  $^3\text{H}$ ,  $^3\text{He}$  BEs
- N2LOsat (POUNDERS), NN+3N fit to  $^3\text{H}$ ,  $^3,^4\text{He}$ ,  $^{14}\text{C}$ ,  $^{16}\text{O}$  BEs,  $r_{ch}$

2N N3LO EM500 (SRG  $L=2.0\text{fm}^{-1}$ ) + 3N N2LO ( $L=2.0\text{fm}^{-1}$ ) ★

2N N3LO EM500 (SRG  $L=2.0\text{fm}^{-1}$ ) + 3N N2LO ( $L=2.5\text{fm}^{-1}$ ) ★

2N N3LO EM500 (SRG  $L=2.8\text{fm}^{-1}$ ) + 3N N2LO ( $L=2.0\text{fm}^{-1}$ )

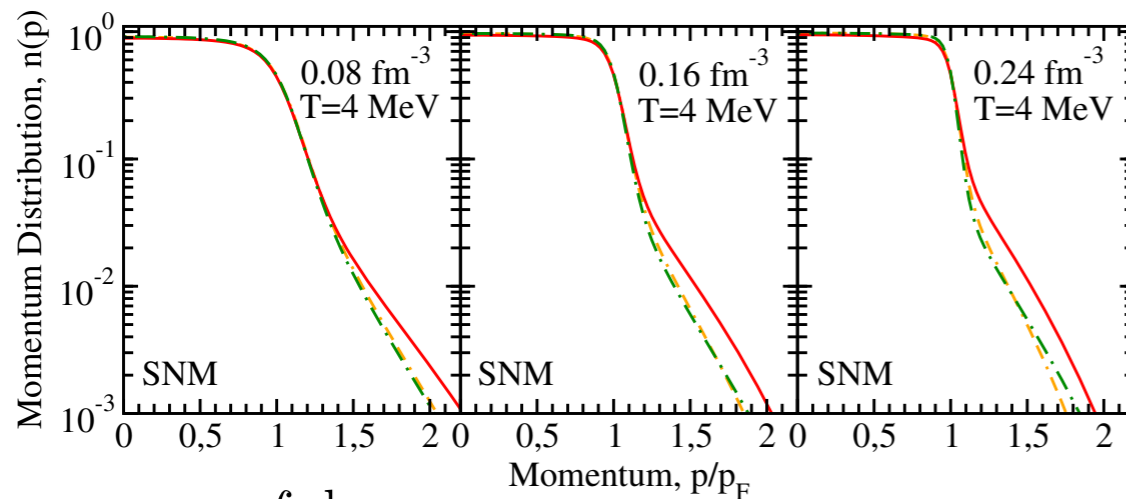
2N N2LOsat + 3N N2LO ★

2N N2LOopt + 3N N2LO

N2LOsat (NN+3N):  
predicts saturation density

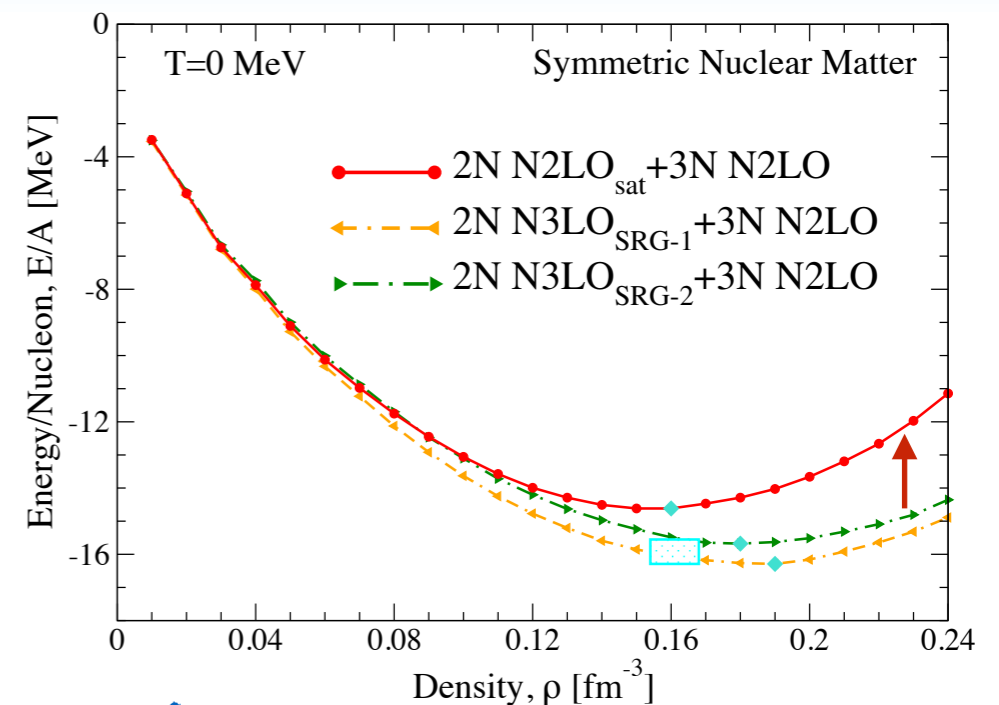
## From microscopic... to macroscopic: why N2LOsat saturates

The microscopic picture: momentum distribution



$$n(p) = \int \frac{d\omega}{2\pi} \mathcal{A}(p, \omega) f(\omega)$$

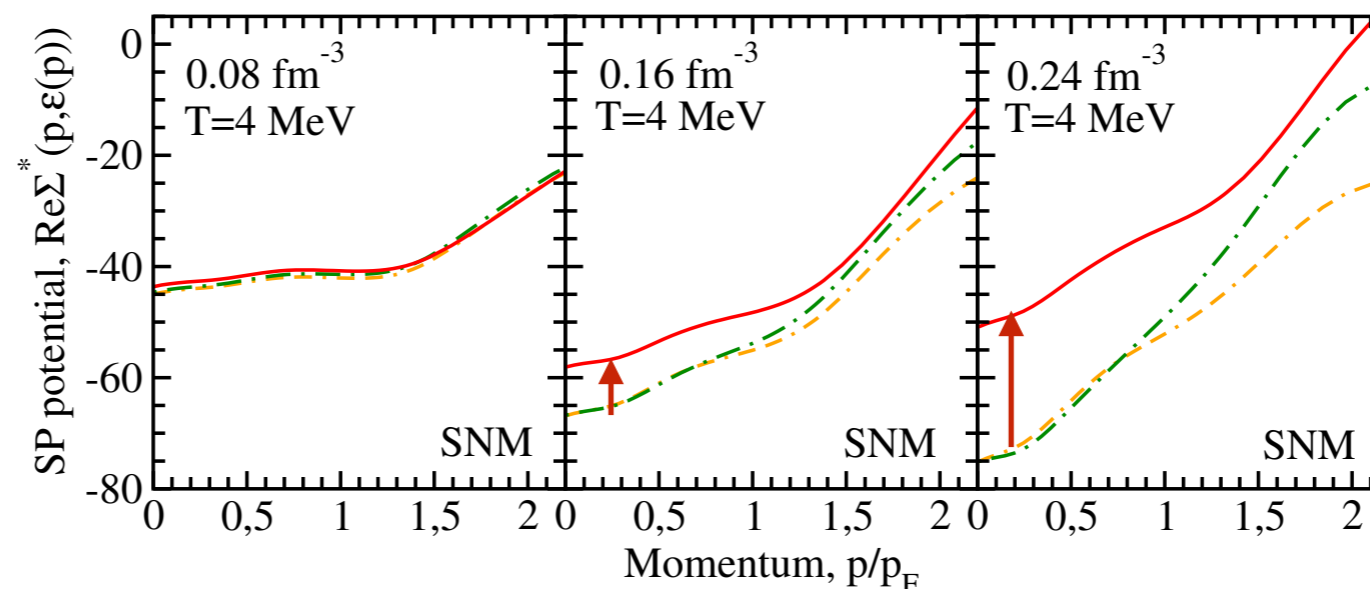
- N2LOsat high-momentum states



..the macroscopic picture:  
total energy more repulsive

...start seeing the big  
picture: the self-energy

$$\varepsilon_{qp}(p) = \frac{p^2}{2m} + \text{Re}\Sigma^*(p, \varepsilon_{qp}(p))$$



Carbone (in preparation)

- 3NF effects as density increases
- N2LOsat more repulsive

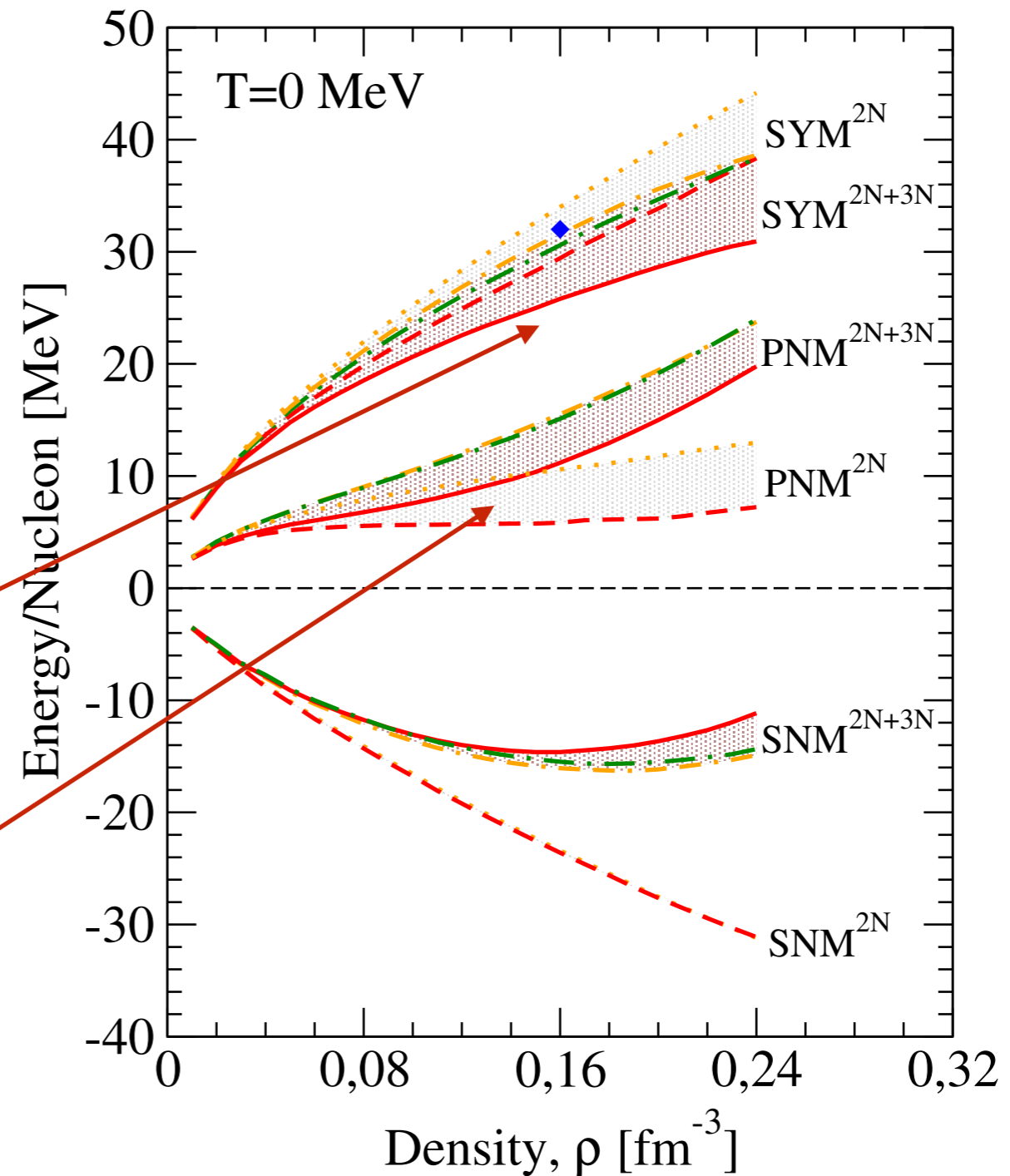
# Predictions for the Symmetry Energy and slope L

$$\frac{S}{A}(\rho) = \frac{E_{\text{PNM}}}{A}(\rho) - \frac{E_{\text{SNM}}}{A}(\rho)$$

	SRG1	SRG2	SAT
Sv (MeV)	31.6	30.6	25.8
L (MeV)	49.3	48.7	37.4

- N2LOsat small S/A and L
- N2LOsat PNM energy too attractive

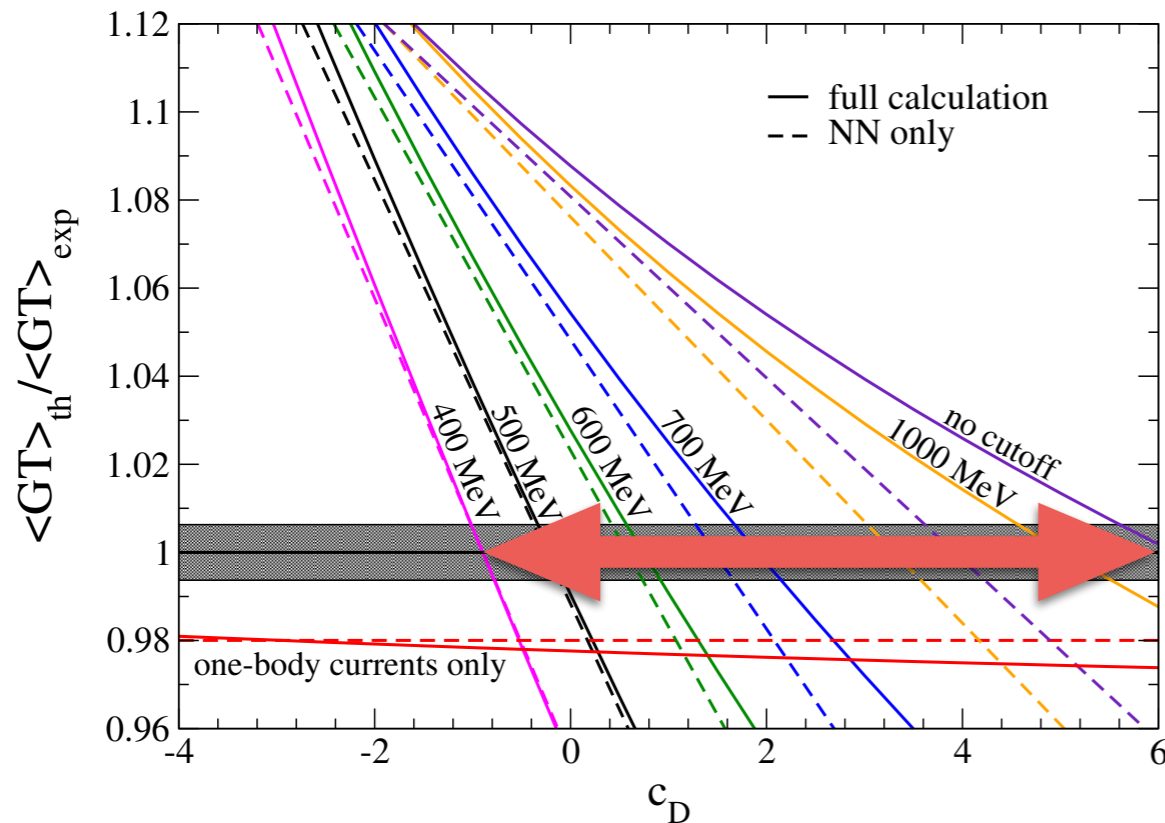
Necessity to check all infinite matter properties to judge the goodness of a potential



Carbone (in preparation)

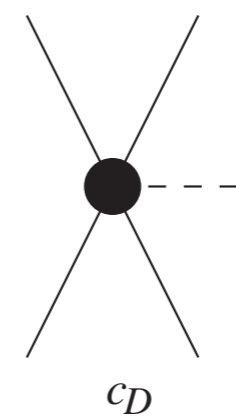
# Uncertainties due to fitting procedures

- Triton beta-decay is experimentally precisely known
- Constraints on the  $c_D$  coupling

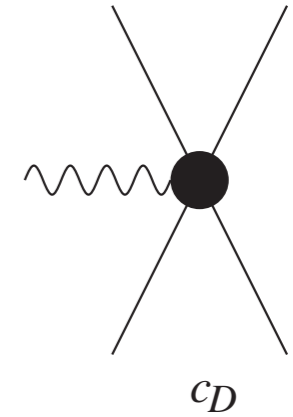


- **Visible effect on the prediction of the saturation point**
- Energy and density range:  
 $E \sim [-11; -21] \text{ MeV}$ ;  $\rho \sim [0.13-0.20] \text{ fm}^{-3}$

Understand new ways to fit the LECs

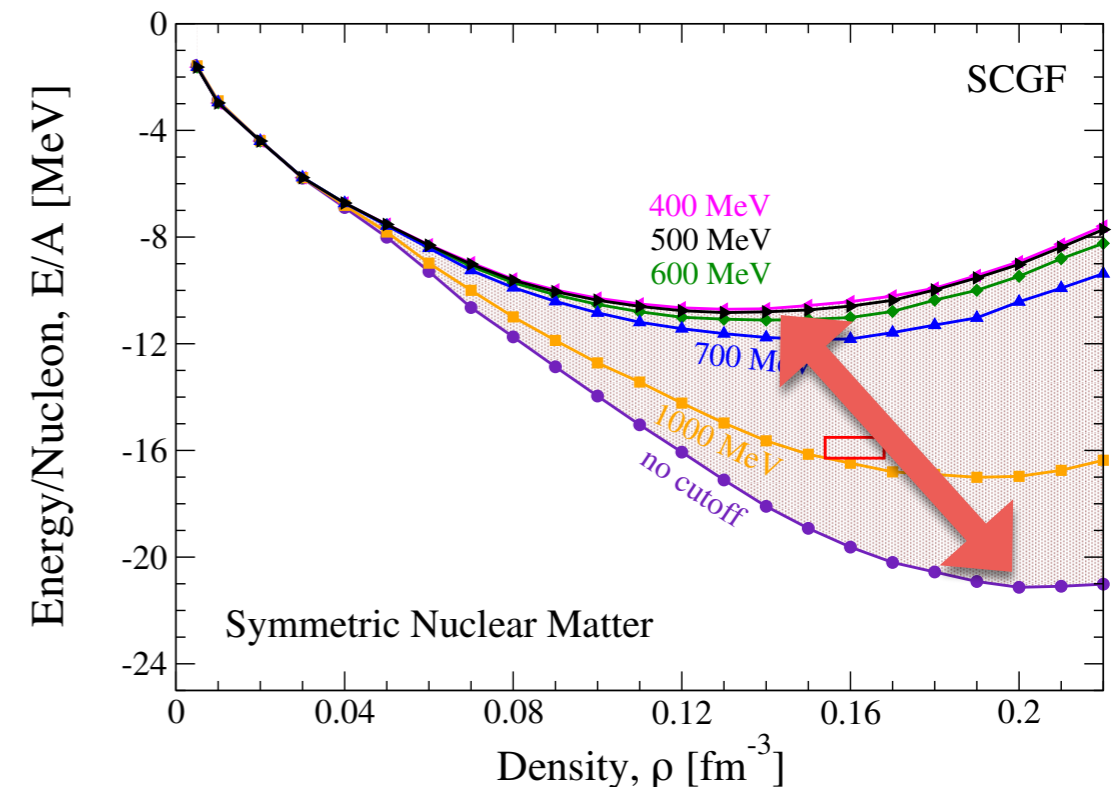


OPE 3N interaction



axial vector current

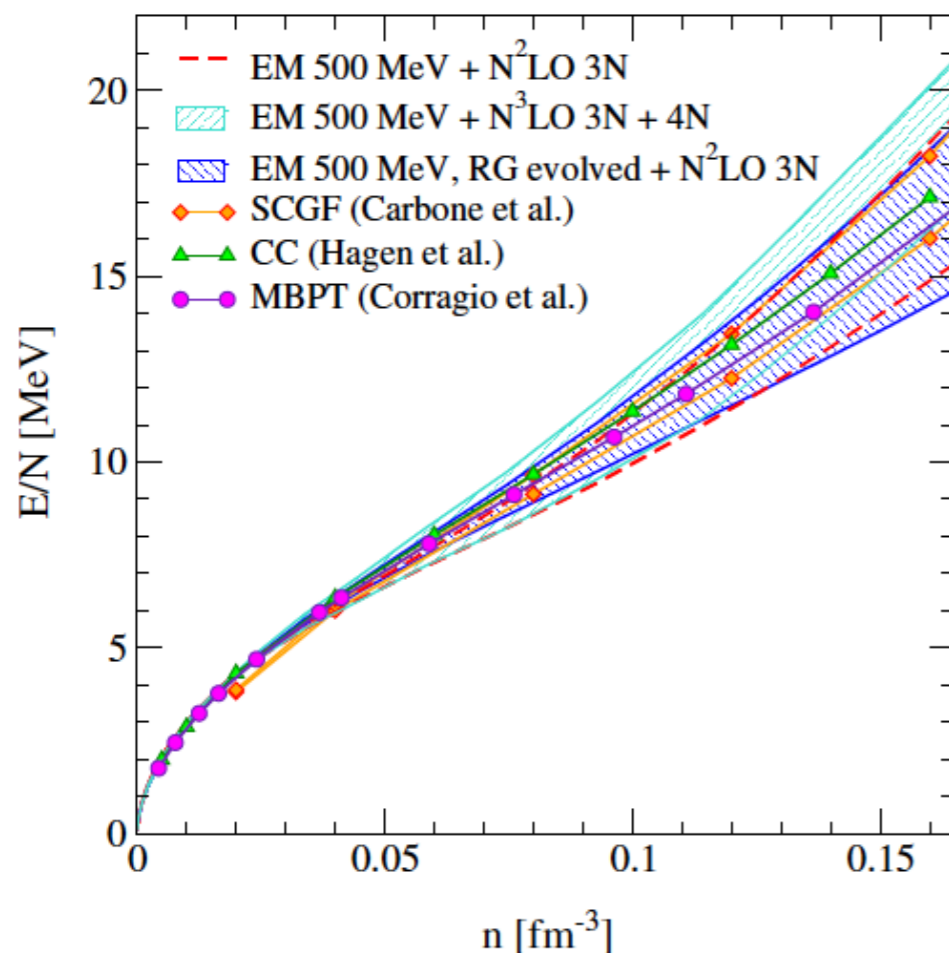
## Cutoff dependence on the current



Klos, Carbone, Hebeler, Menéndez, Schwenk (*in preparation*)

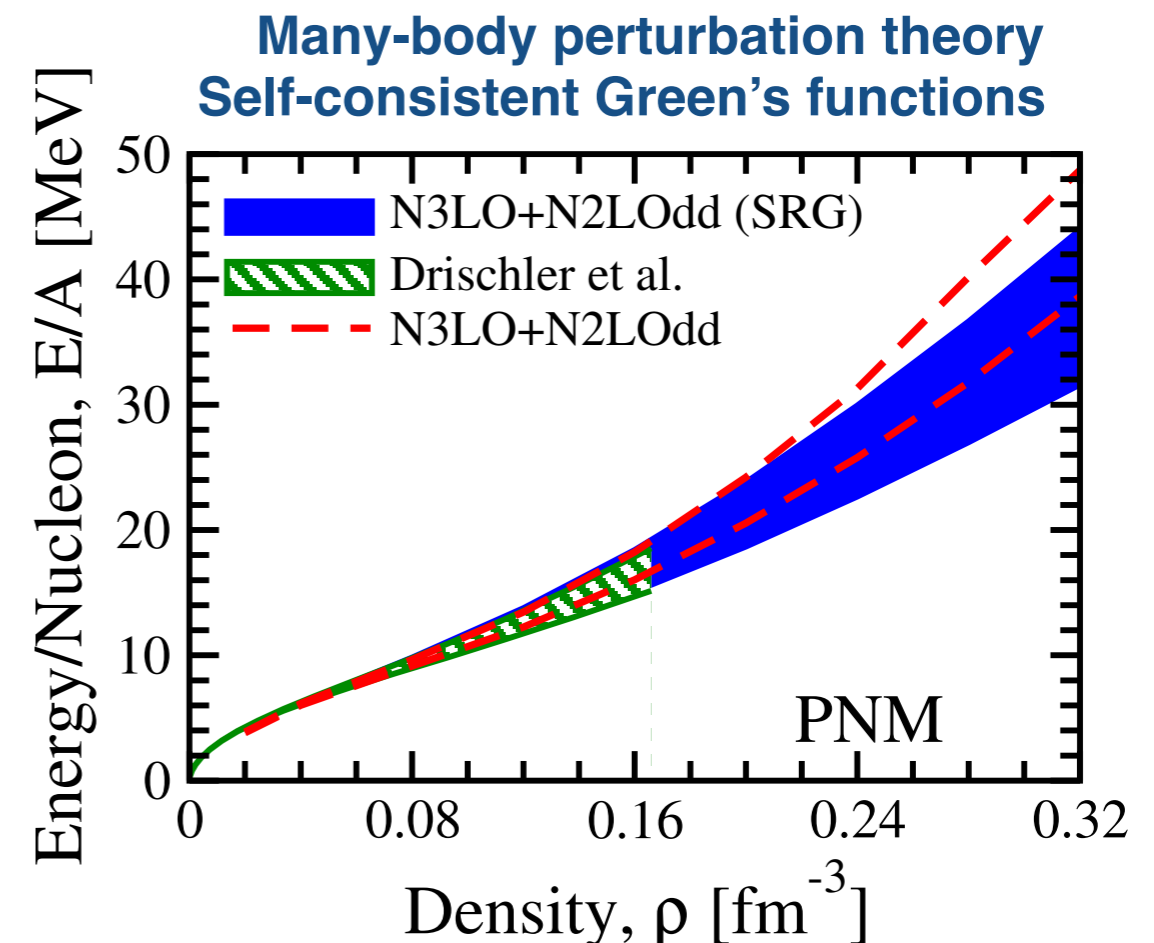
# Many-body methods comparison

Remarkable agreement between several many-body methods and different Hamiltonians



Hebeler *et al.*, Ann. Rev. Nucl. Part. Sci. 65, 457 (2015)

- Low-density neutron matter perturbative



Carbone, Rios, Polls, PRC 90, 054322 (2014)

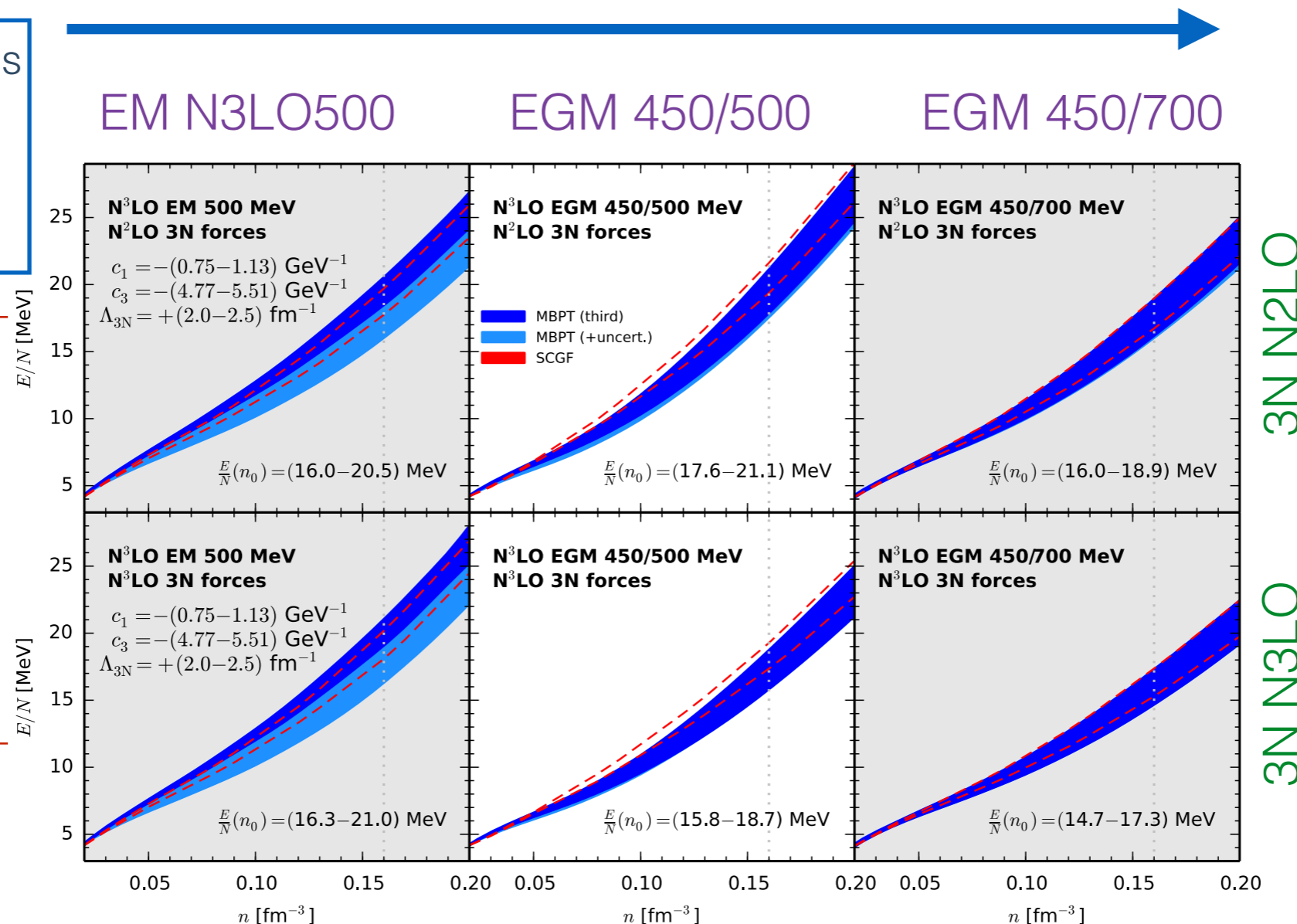
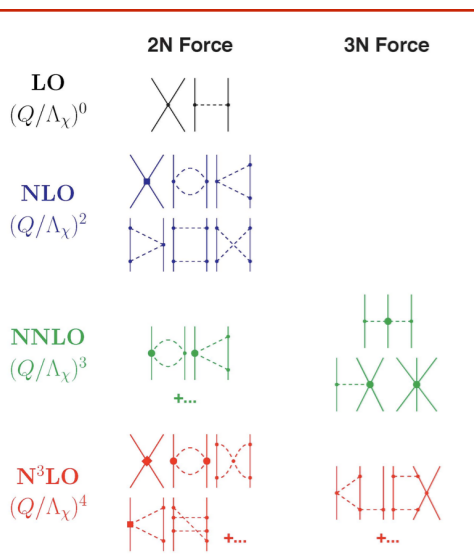
- Agreement up to  $0.20 \text{ fm}^{-3}$  with the use of different Hamiltonians
- Questionable validity of chiral EFT

# Pure neutron matter with 2N + 3N at N3LO

Improved 3NF matrix elements Hebeler et al. 2015  
Partial-wave based 3NF average Drischler 2014-2015

many-body approximation uncertainty

How perturbative is the potential:  
**MBPT** vs **SCGF**  
band shrinks

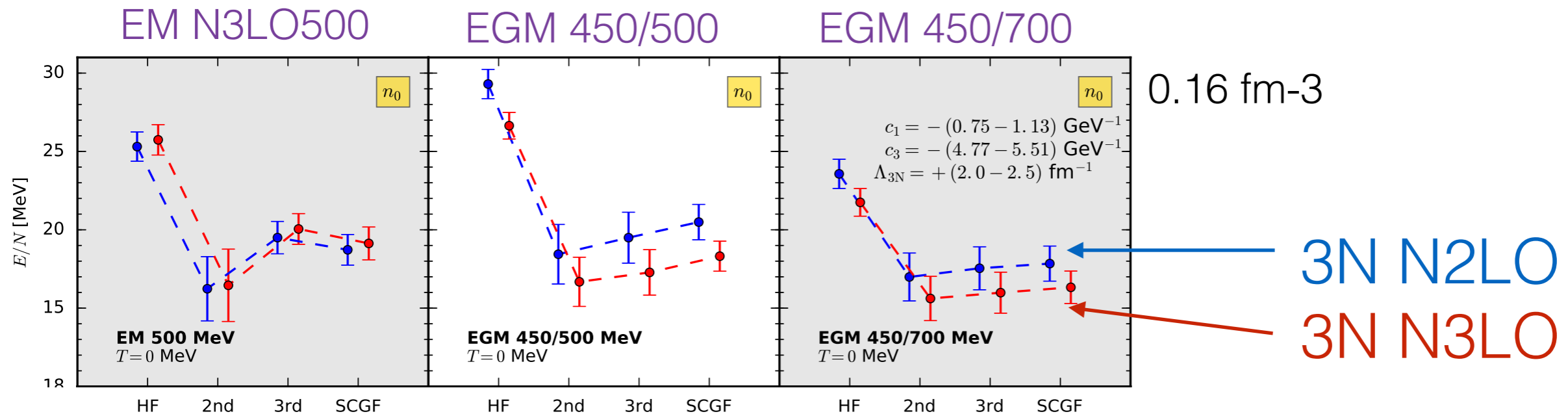


chiral forces uncertainty

N3LO 3NF shift in energy bands

Drischler, Carbone, Hebeler, Schwenk PRC94, 054307 (2016)

# Test the many-body convergence at full 2N+3N N3LO



many-body truncation  
attractive 2nd order  
repulsive 3rd order

understand the many-body convergence

test the chiral Hamiltonian convergence

EM N3LO500      EGM 450/500      EGM 450/700

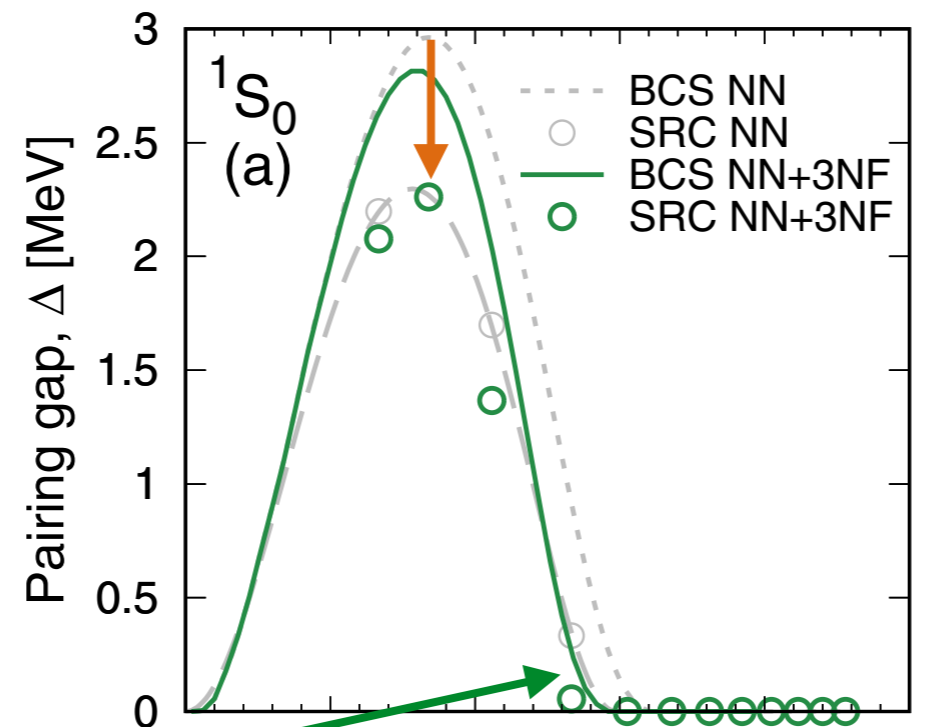
How perturbative is the potential: smaller beyond of 3rd order

Drischler, Carbone, Hebeler, Schwenk PRC94, 054307 (2016)

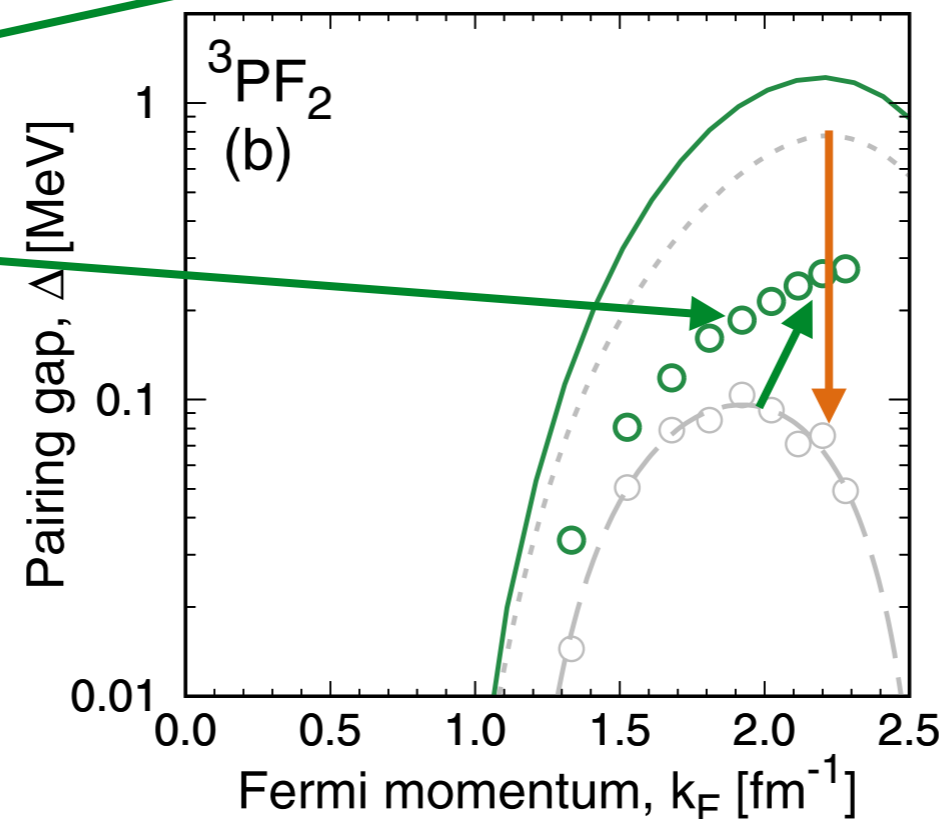
# The pairing gap in neutron matter

Beyond BCS:  
correlations  
strongly reduce  
gap

- effect of 3NFs:
  - $^1S_0$ : weaker, attractive, lower densities
  - $^3P_F2$ : stronger, repulsive, higher densities



- $^1S_0$  max 2.3 MeV, closes at  $\sim 1.5 \text{ fm}^{-1}$
- 3NFs repulsive, pairing smaller



- No closure for  $^3P_F2$  gap with 3N
- limits of applicability of chiral forces

Ding et al., PRC94, 025802 (2016)

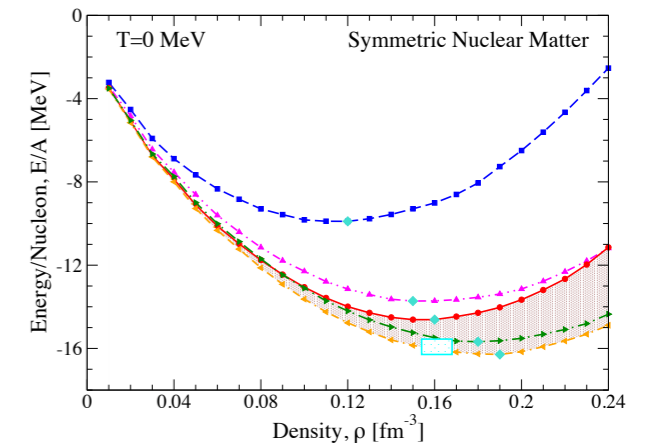
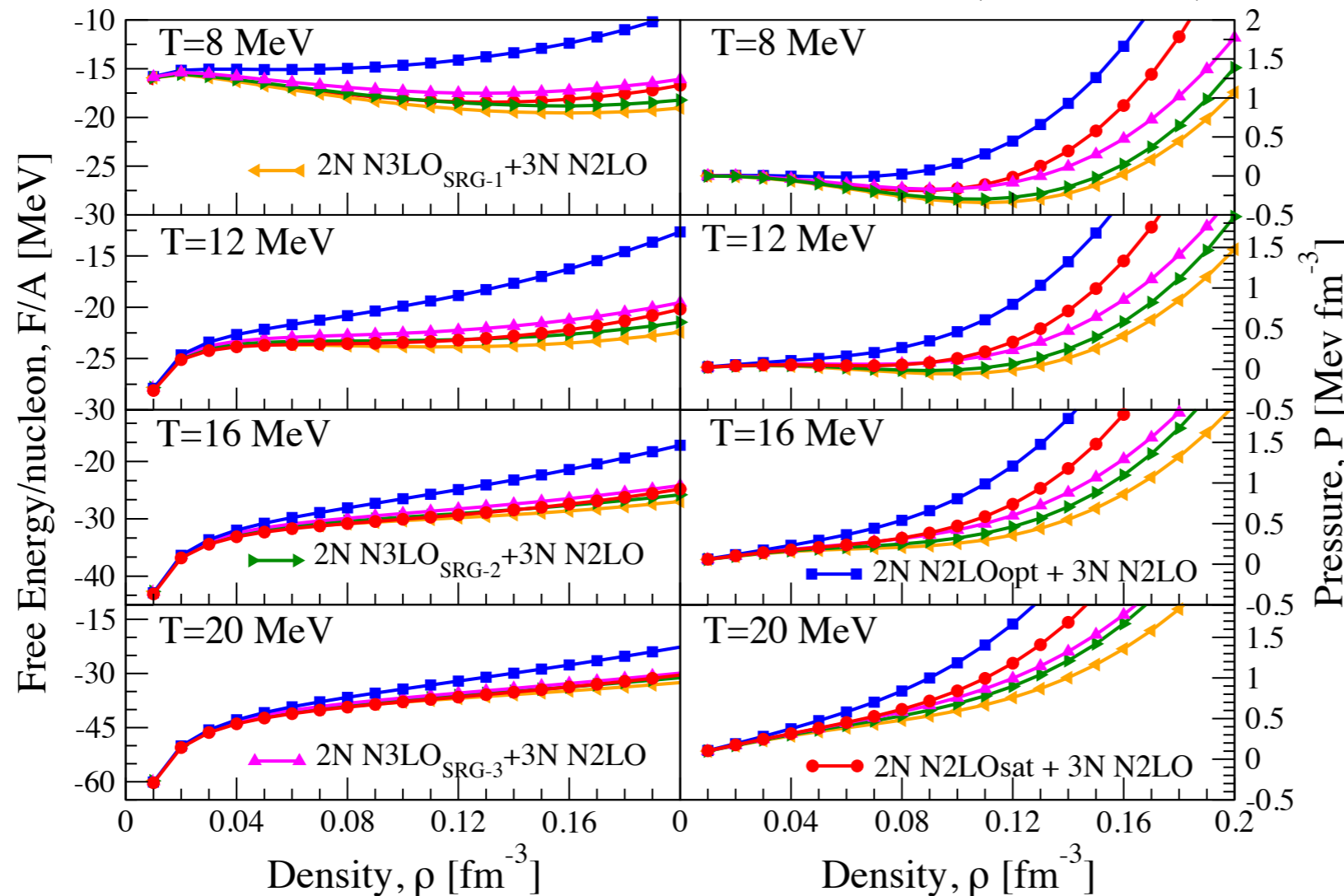
Drischler et al., arXiv:1610.05213v1 (2016)

# Free energy and pressure at varying temperature

$$F = E - TS$$

$$P = \rho(\mu - F)$$

increasing temperature



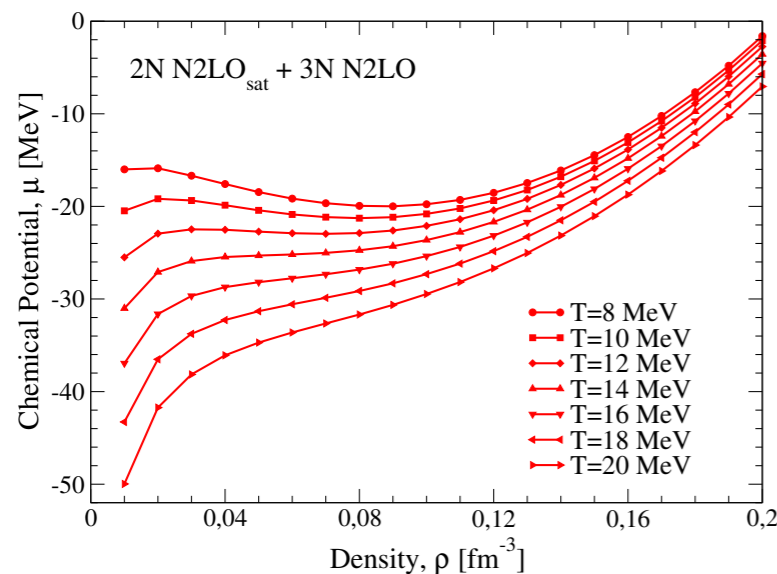
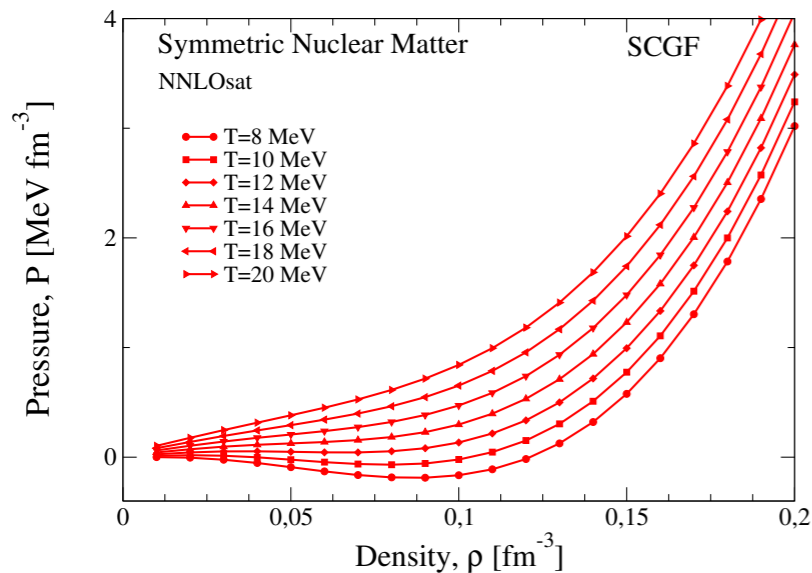
- similar behaviour to zero T energy
- N2LOopt most repulsive
- less difference between other potentials
- liquid-gas phase transition

2N N3LO EM500 (SRG  $L=2.0\text{fm}^{-1}$ ) + 3N N2LO ( $L=2.0\text{fm}^{-1}$ )  
 2N N3LO EM500 (SRG  $L=2.0\text{fm}^{-1}$ ) + 3N N2LO ( $L=2.5\text{fm}^{-1}$ )  
 2N N3LO EM500 (SRG  $L=2.8\text{fm}^{-1}$ ) + 3N N2LO ( $L=2.0\text{fm}^{-1}$ )  
 2N N2LOsat + 3N N2LO  
 2N N2LOopt + 3N N2LO

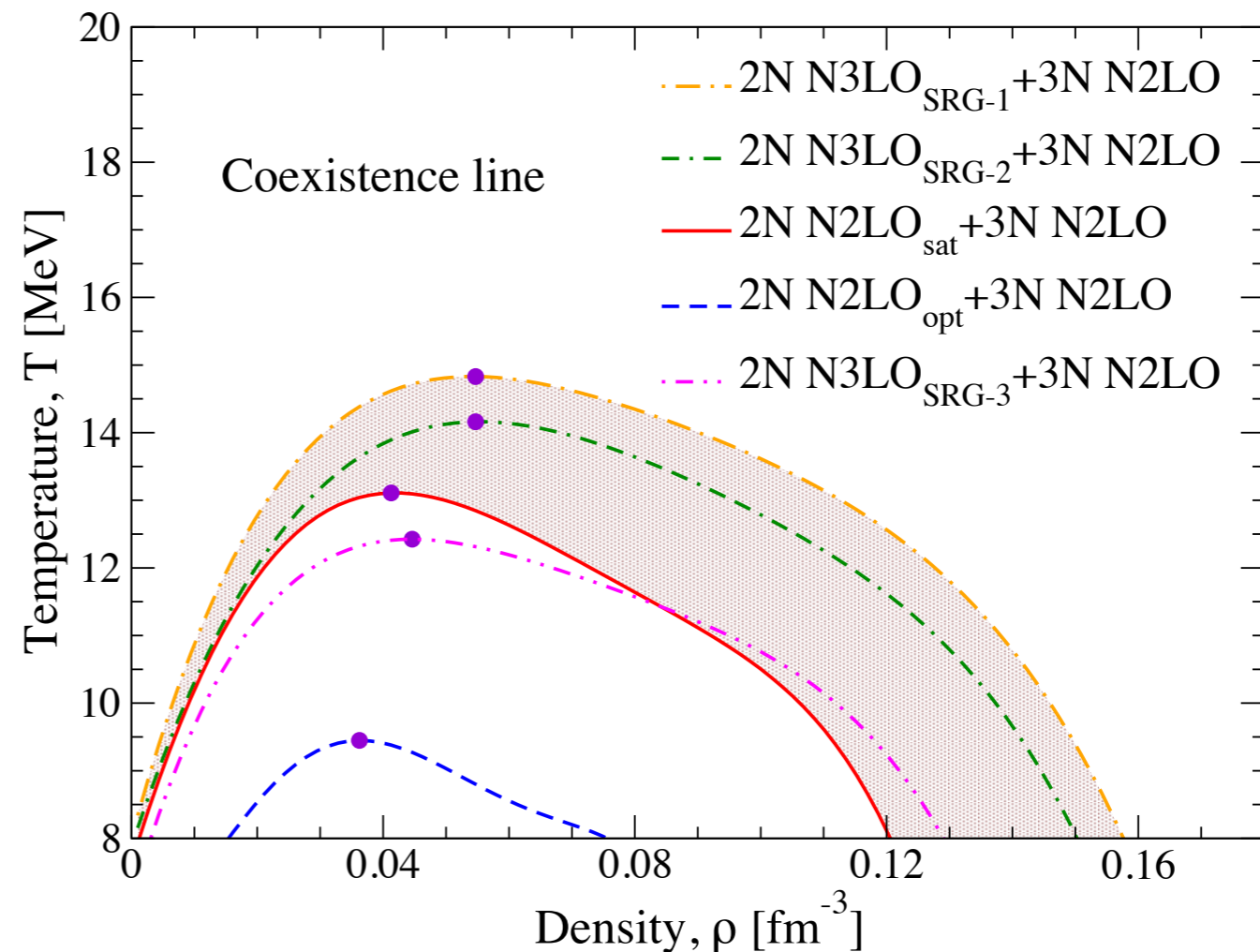
Carbone, Rios, Polls (*in preparation*)

## The liquid-gas phase transition and critical point

NN N2LO<sub>sat</sub>+3N N2LO



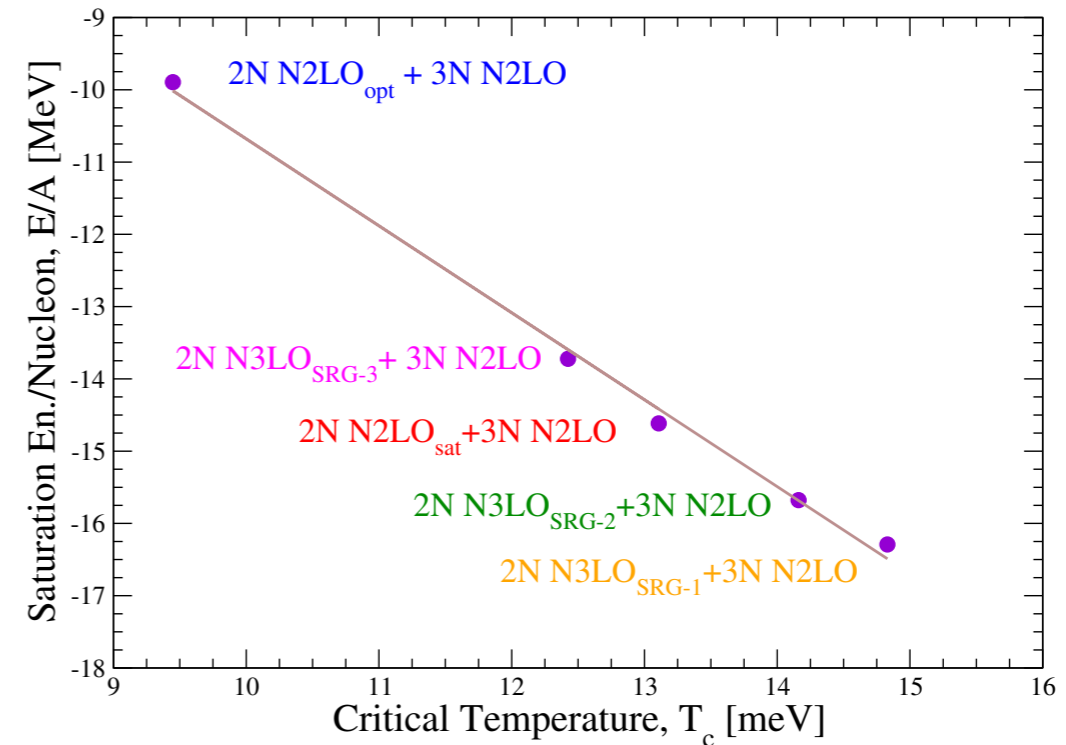
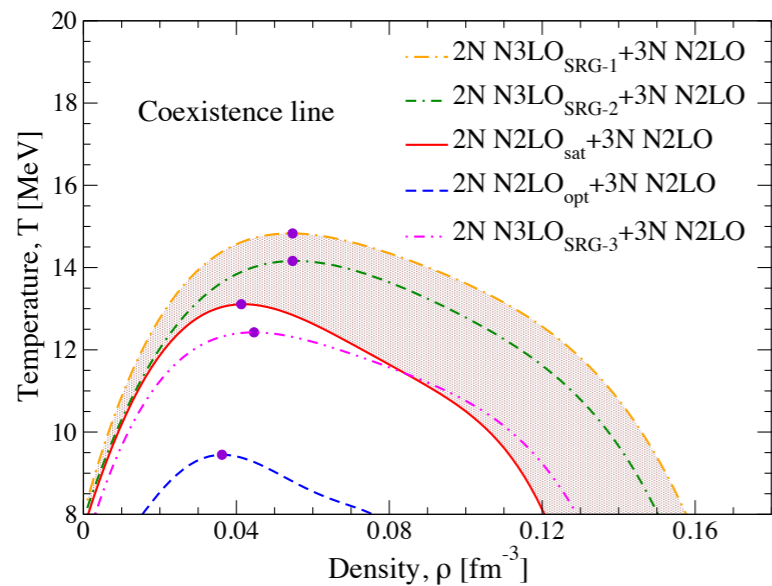
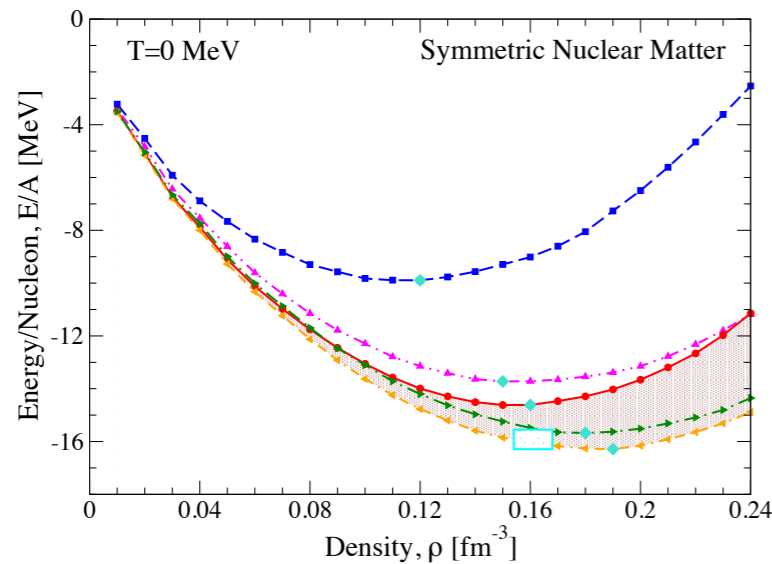
$$\mu(\rho_g) = \mu(\rho_l) \quad P(\rho_g) = P(\rho_l)$$



Carbone, Rios, Polls (*in preparation*)

- Coexistence line: equilibrium between a gas and a liquid phase
- Predicted critical temperature  $\sim T \sim [13-15]$  MeV (experimental  $\sim [15-20]$  MeV)
- Previous consistent results from Wellenhofer et al., PRC 89, 064009 (2014)

# Saturation Energy vs Critical Temperature



SCGF	$\rho_c$ [fm <sup>-3</sup> ]	$T_c$ [MeV]	$\rho_0$ [fm <sup>-3</sup> ]	$\frac{E_0}{N}$ [MeV]	$\frac{m^*}{m}$
N3LO <sub>SRG-1</sub>	0.05	14.8	0.19	-16.3	0.85
N3LO <sub>SRG-2</sub>	0.05	14.2	0.18	-15.7	0.81
N3LO <sub>SRG-3</sub>	0.04	12.4	0.15	-13.7	0.90
NNLO <sub>opt</sub>	0.04	9.4	0.12	-9.9	0.90
NNLO <sub>sat</sub>	0.04	13.1	0.16	-14.6	0.90

Carbone, Rios, Polls (*in preparation*)

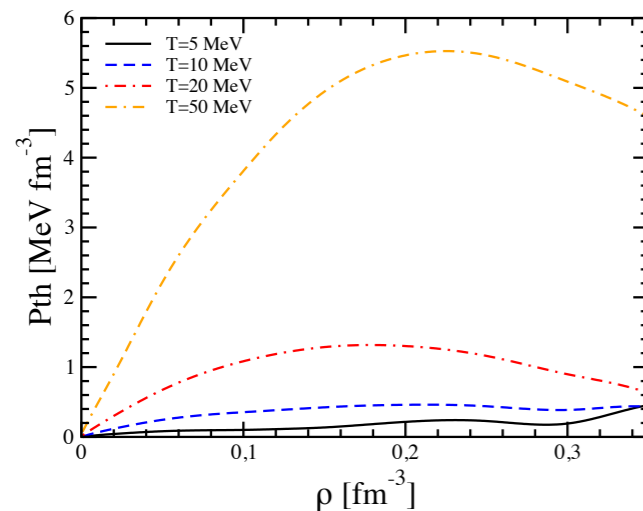
- Interesting linear correlation between saturation energy and critical temperature

# Thermal effects for astrophysical applications

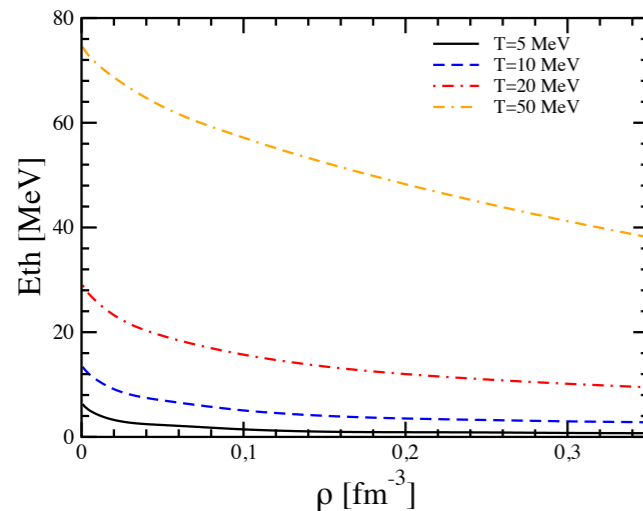
- Pressure calculated as: **Pcold+Pthermal**
- Thermal index considered **constant**

$$P_{th} = (\Gamma_{th} - 1) \rho E_{th}$$

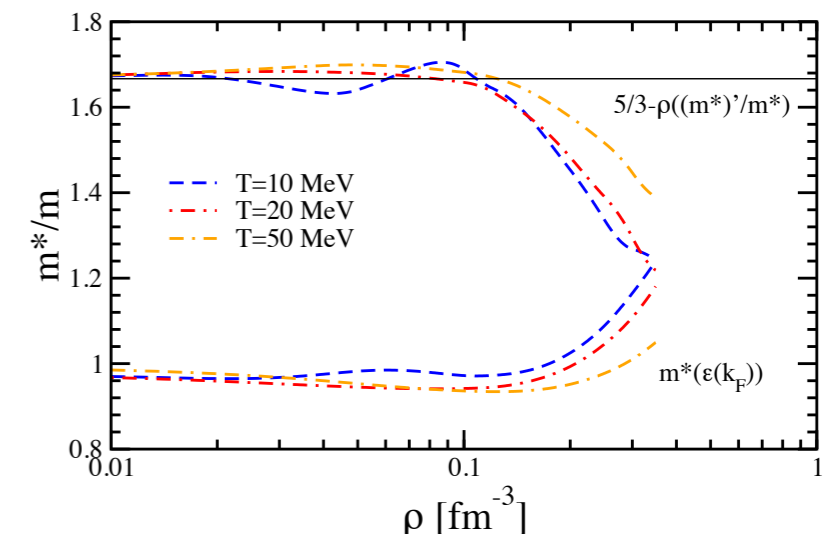
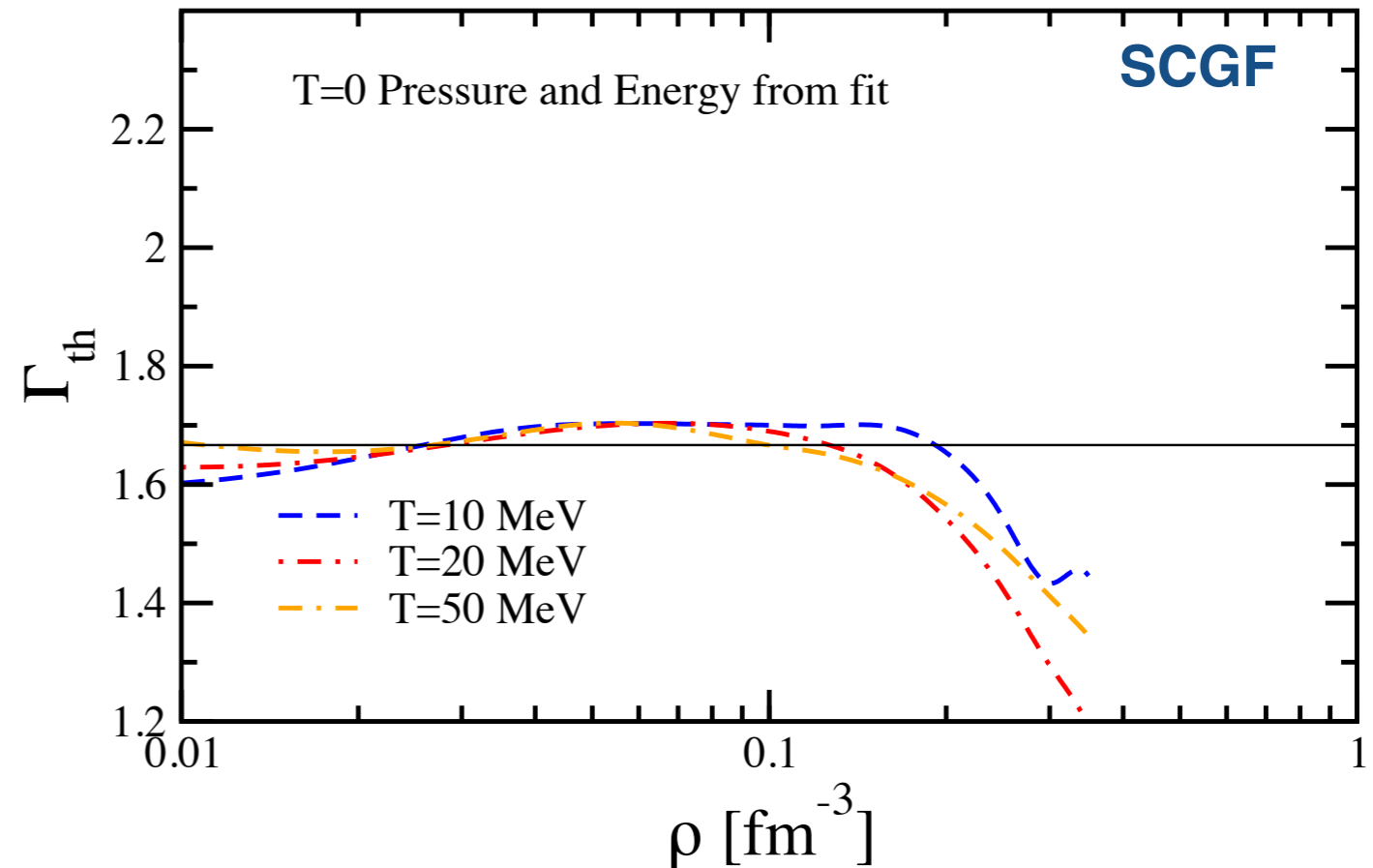
$$P_{th} = P(T) - E_0$$



$$E_{th} = E(T) - E_0$$

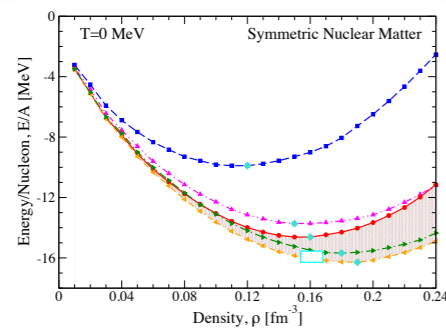


- $P_{th}$  decreases after certain density
- $E_{th}$  decreases monotonically
- Index increases then decreases after saturation density
- dependence on the effective mass derivative

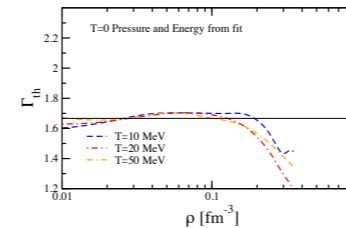


# What can we predict?

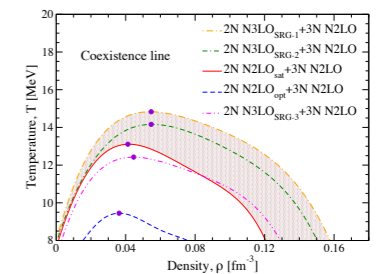
Saturation point  
& uncertainties



Thermal effects  
in the PNM EOS

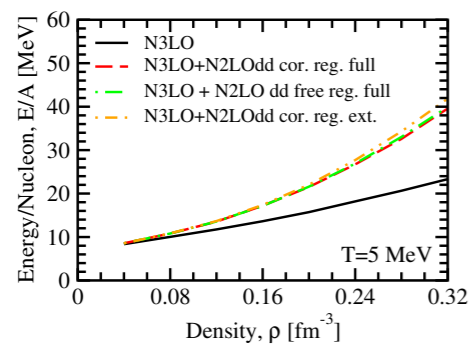


Finite-T & estimate of  
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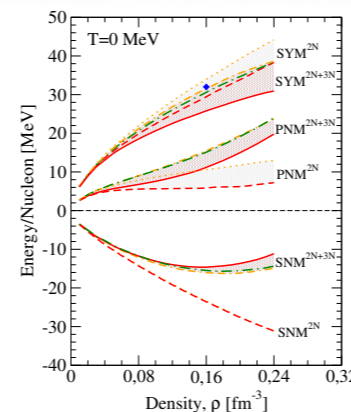


Many-Body approach  
+  
Chiral EFT

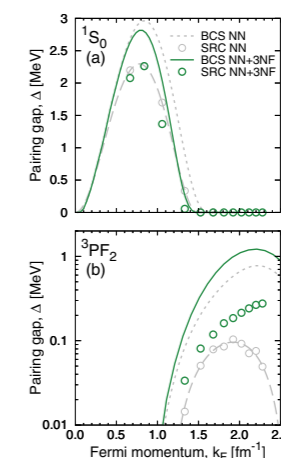
PNM equation of state



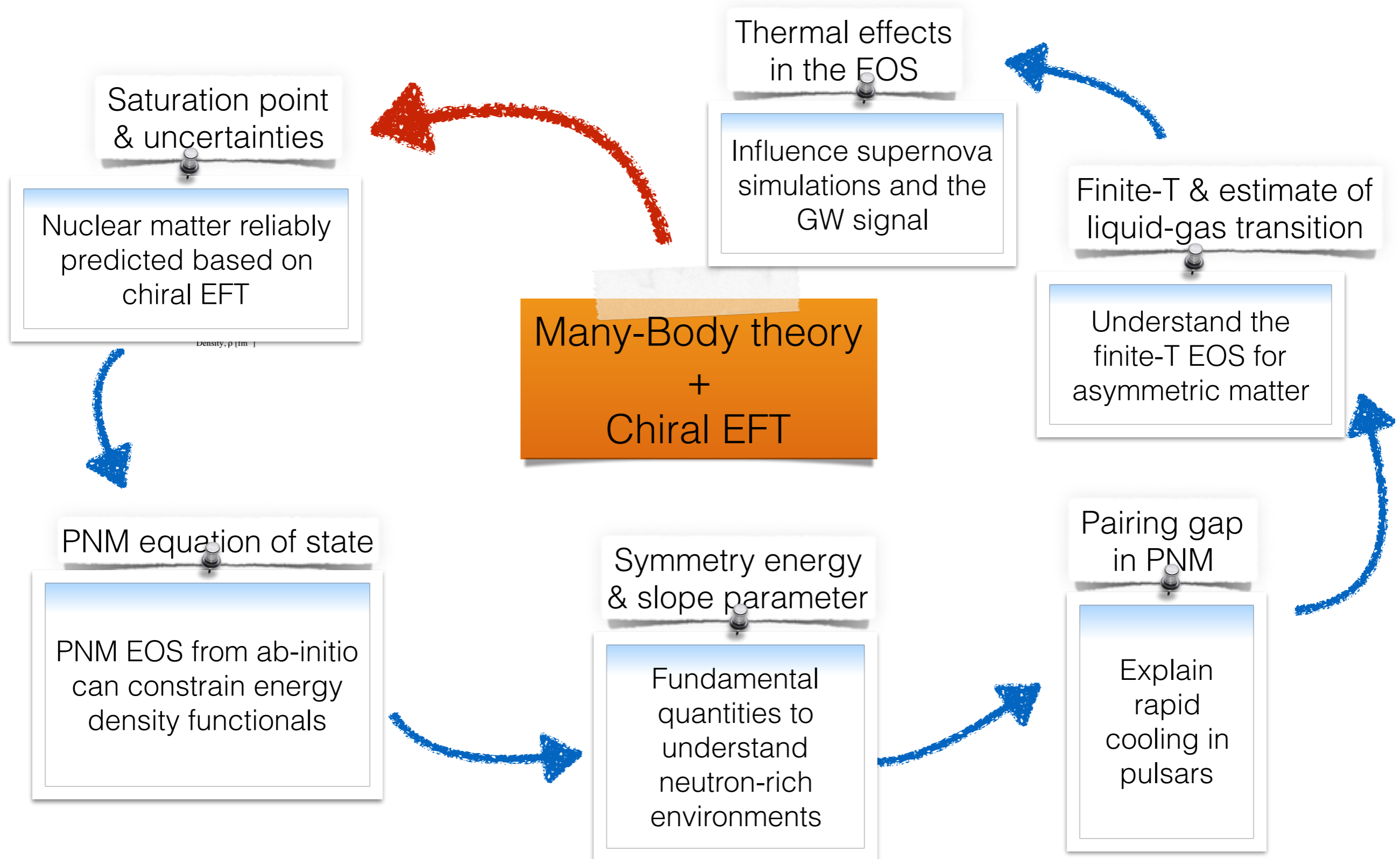
Symmetry energy  
& slope parameter



Pairing gap  
in PNM



# Summary and Impact of results



# Summary and Impact of results

Saturation point  
& uncertainties

Nuclear matter reliably  
predicted based on  
chiral EFT

Density,  $\rho$  [fm<sup>-3</sup>]

PNM equation of state

PNM EOS from ab-initio  
can constrain energy  
density functionals

thermal effects



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K. Hebeler, A. Schwenk



UNIVERSITY OF  
SURREY

A. Rios  
C. Barbieri



Universitat de Barcelona

A. Polls

Finite-T & estimate of  
liquid-gas transition

Interpret  
astrophysical  
scenarios at high T

Pairing gap  
in PNM

Explain  
rapid  
cooling in  
pulsars

neutron-rich  
environments

Thank you for your attention!