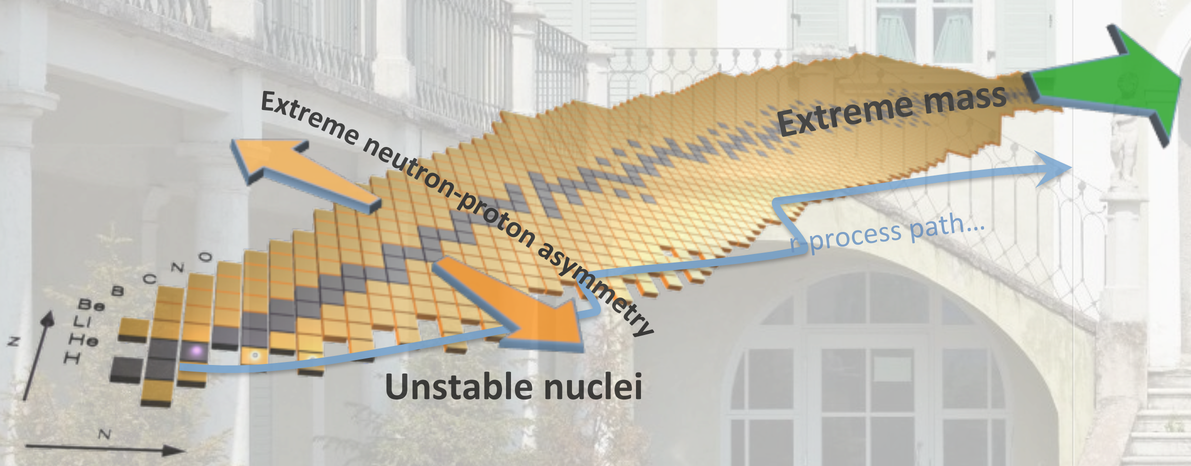
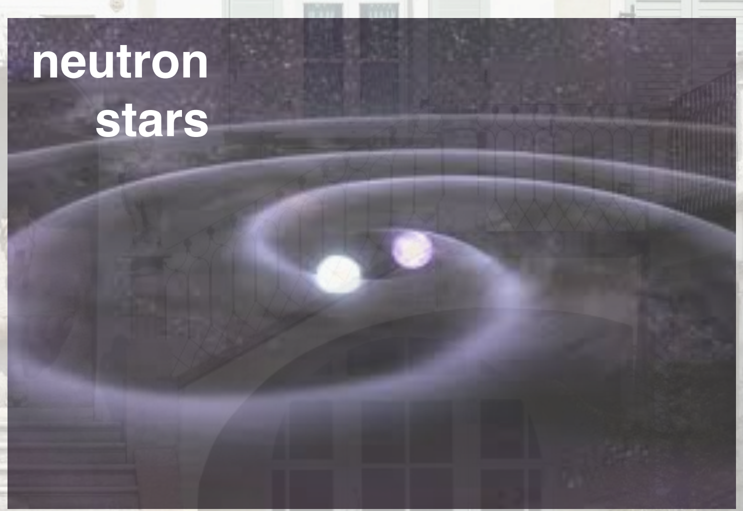
Ab initio studies of infinite matter from a Green's function approach

Arianna Carbone

NuSYM2018 - Busan, South Korea - 13 September 2018





FONDAZIONE BRUNO KESSLER

Predicting the symmetry energy from saturating potentials

Arianna Carbone

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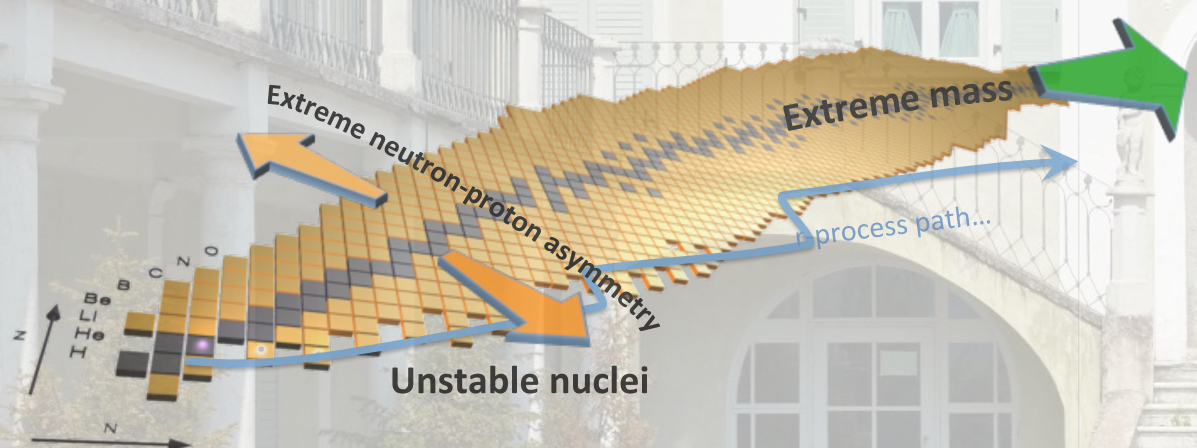


FONDAZIONE BRUNO KESSLER

Ab initio low-energy nuclear theory

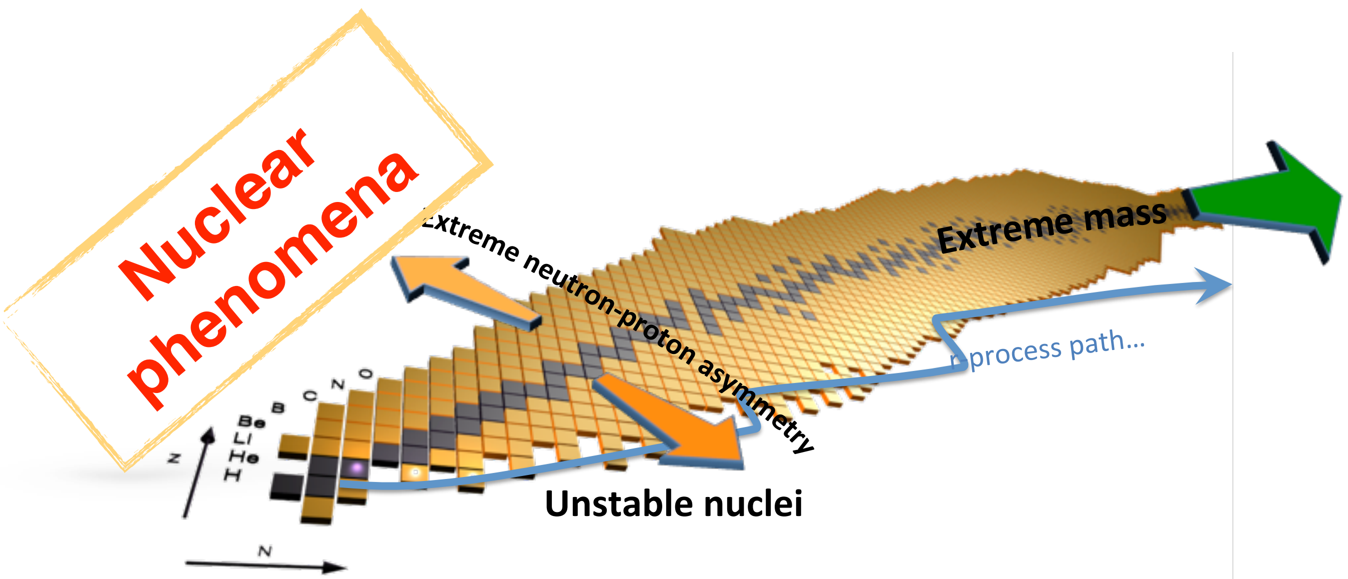
Solve the nuclear many-body problem from first principles

- Build reliable methods with predictive power

Ab initio low-energy nuclear theory

Solve the nuclear many-body problem from first principles

- Build reliable methods with predictive power
- Probe the limits of the nuclear landscape



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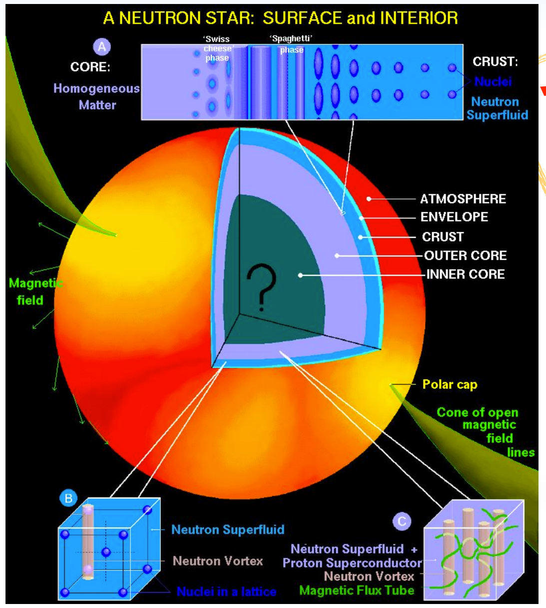
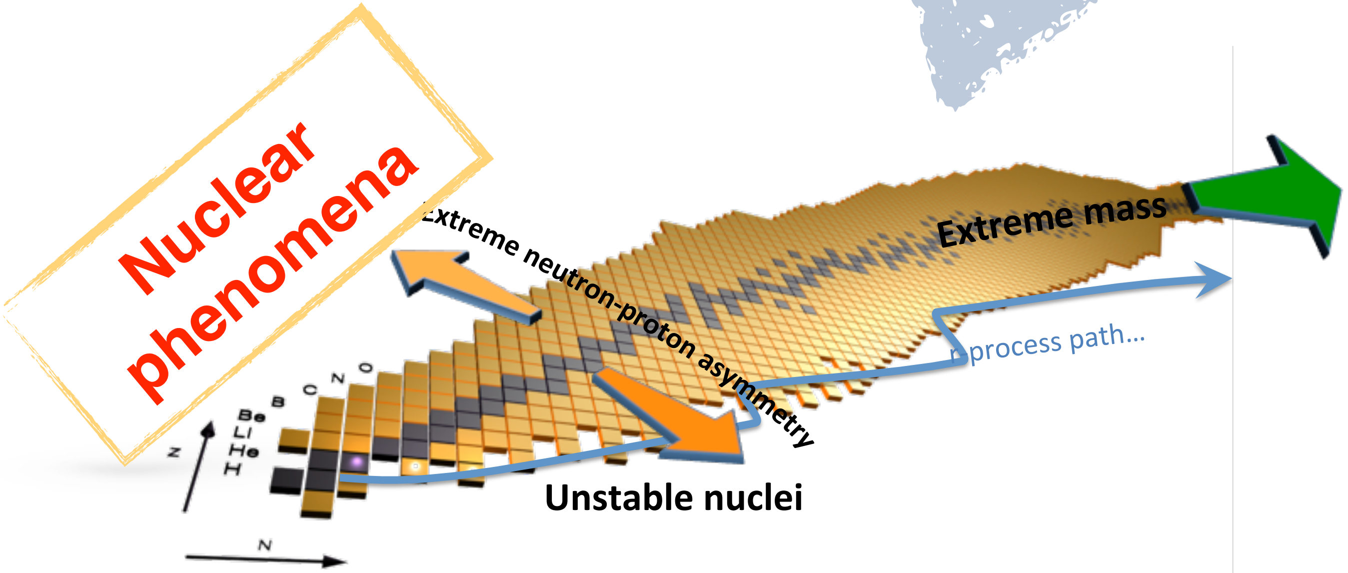
- Constrain the EOS of neutron star matter



Astrophysics



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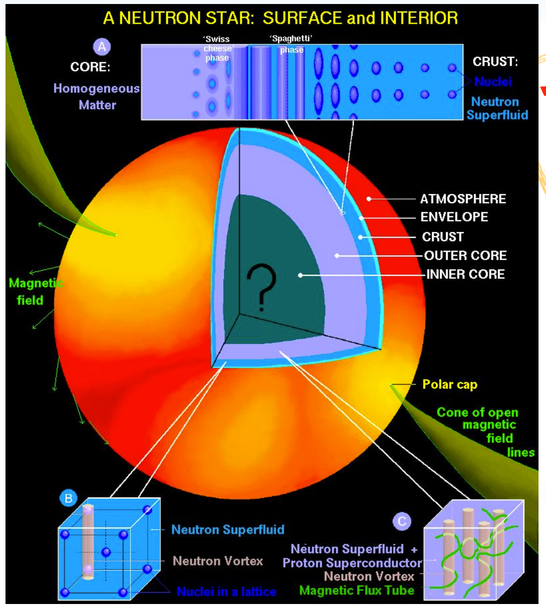
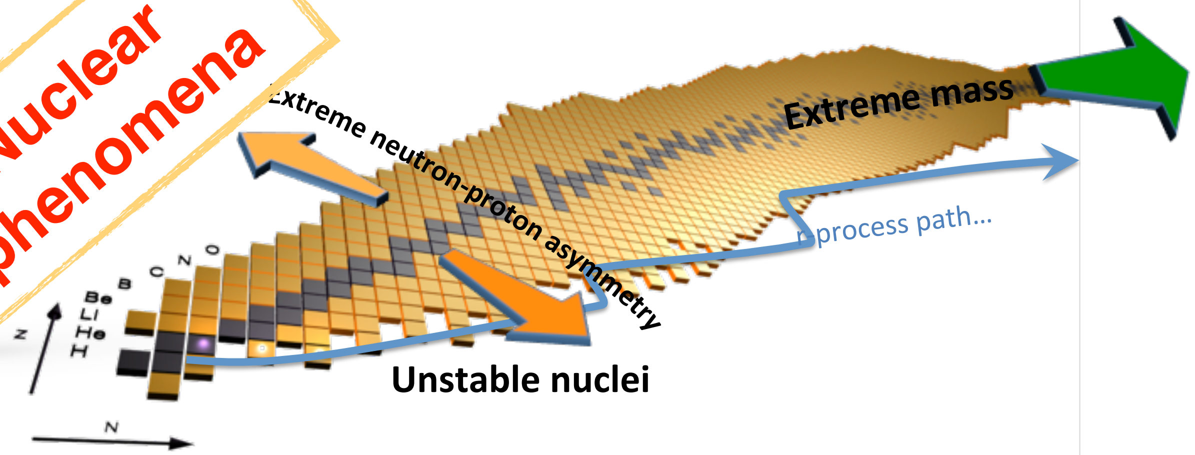
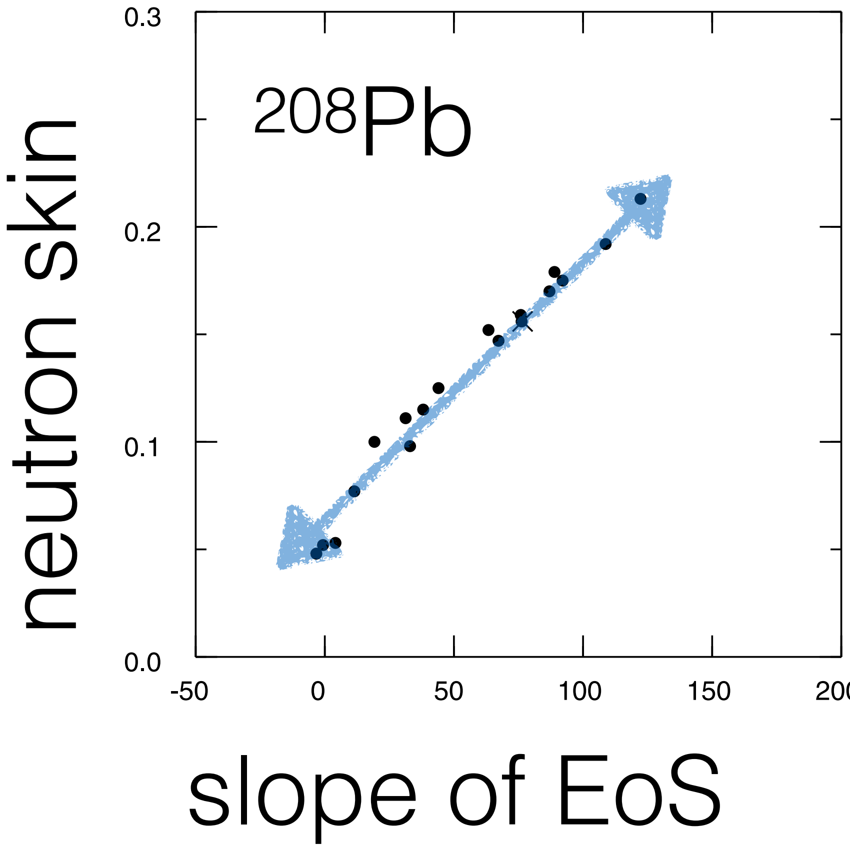


Astrophysics

Nuclear phenomena



Brown (2000)



neutron-rich nuclei and neutron matter: a strong correlation

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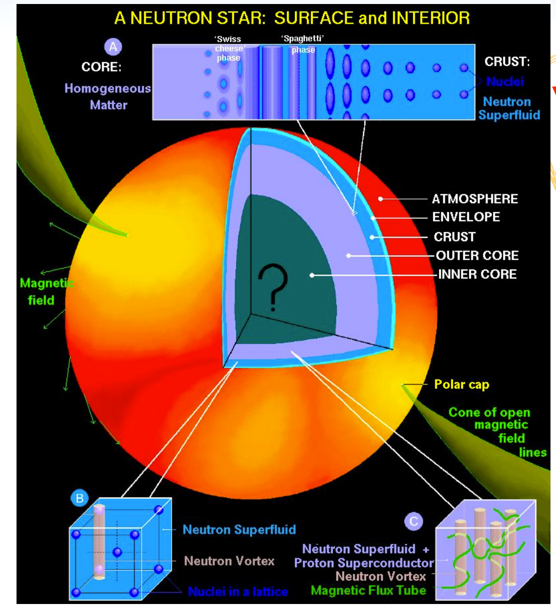

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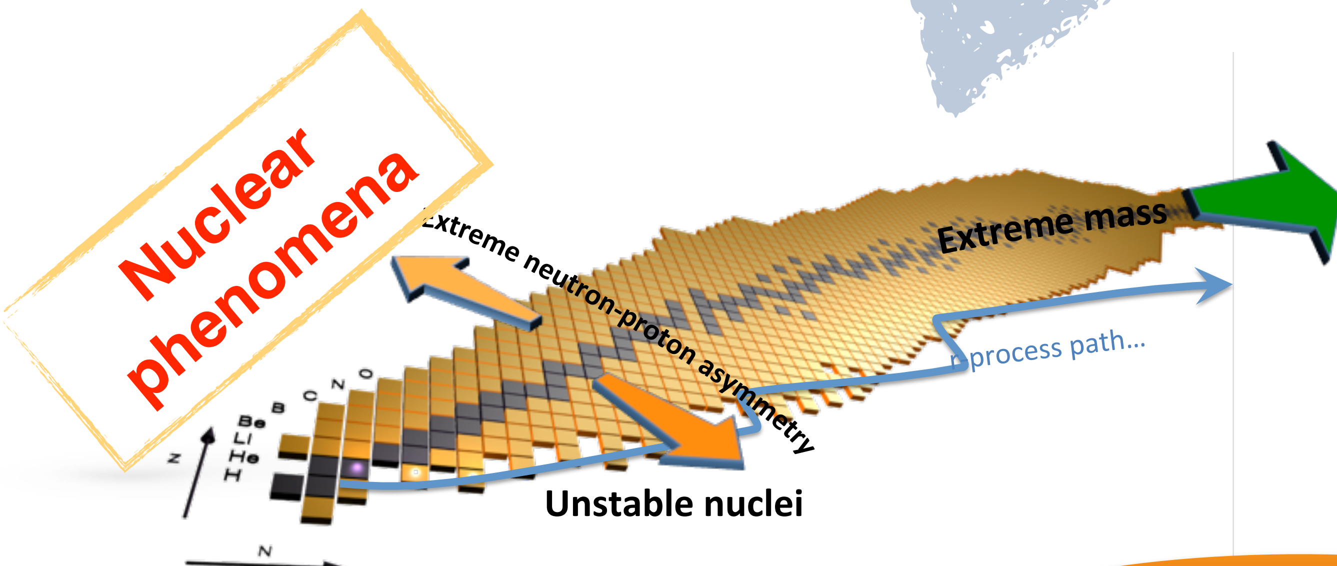

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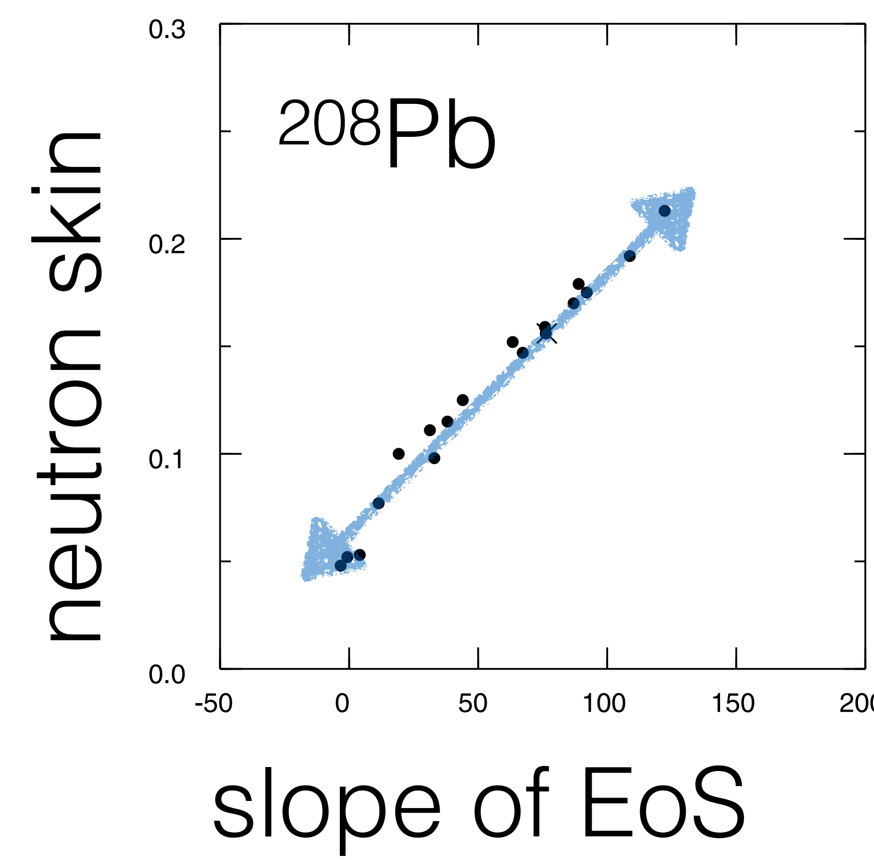


Predict infinite matter

neutron-rich nuclei and neutron matter: a strong correlation

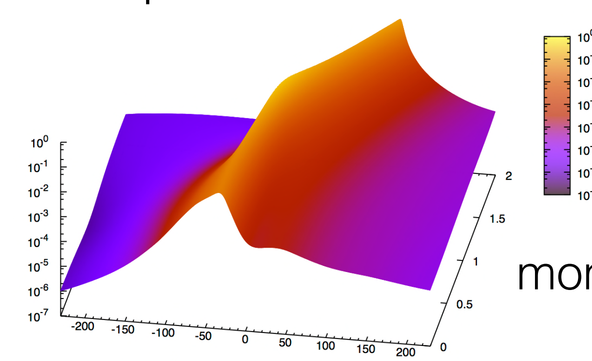
The self-consistent Green's function method

- Green's function: a tool to solve the nuclear many-body problem; **nonperturbative, correlations beyond mean field**

Dickhoff & Barbieri, PPNP 52 (2004) 377

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

Single-nucleon spectral function



momentum

energy

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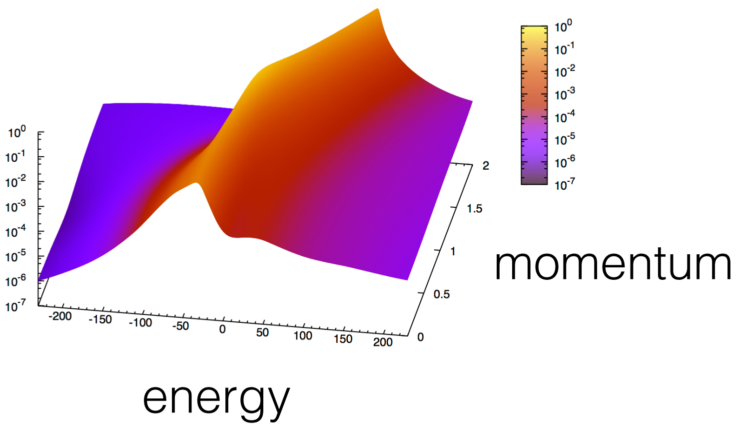

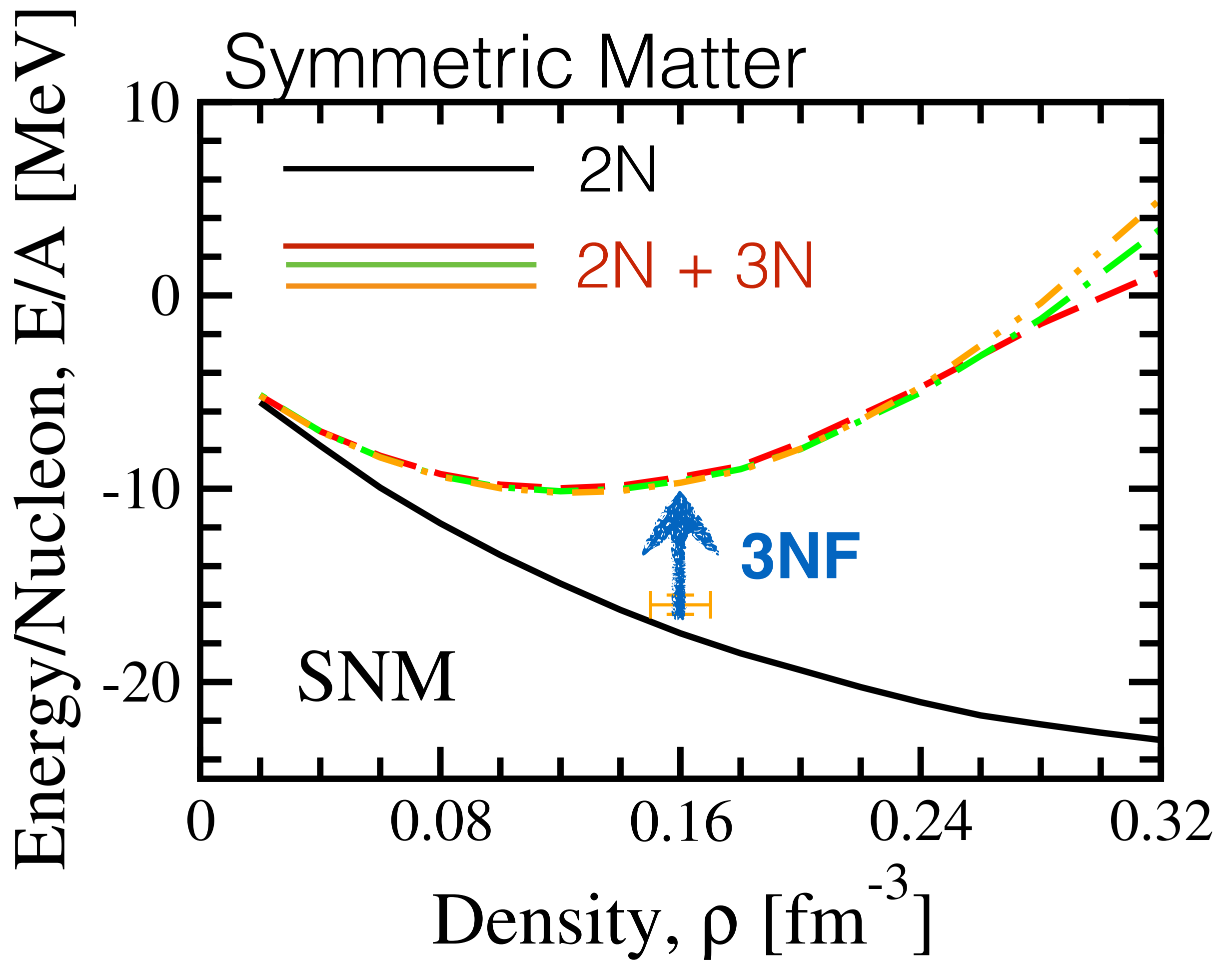

- Improved prediction of saturation density
  Carbone, Rios, Polls, PRC 88, 044302 (2013)
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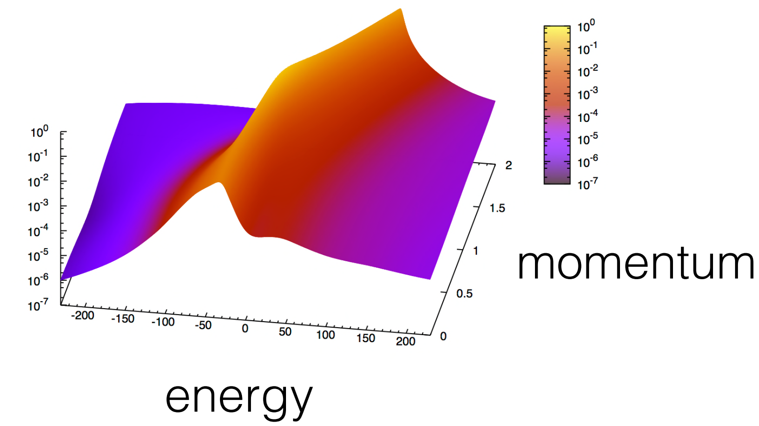
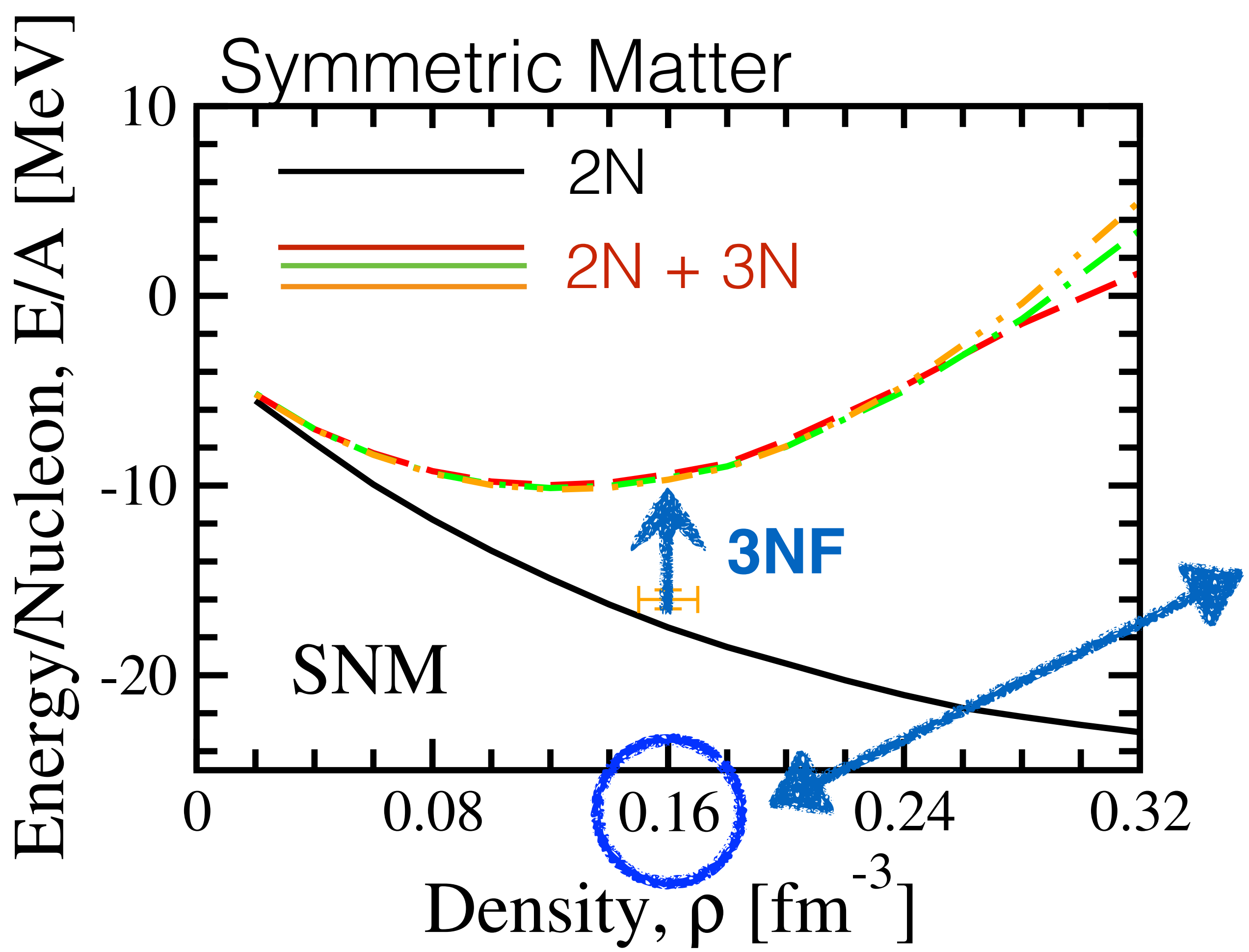
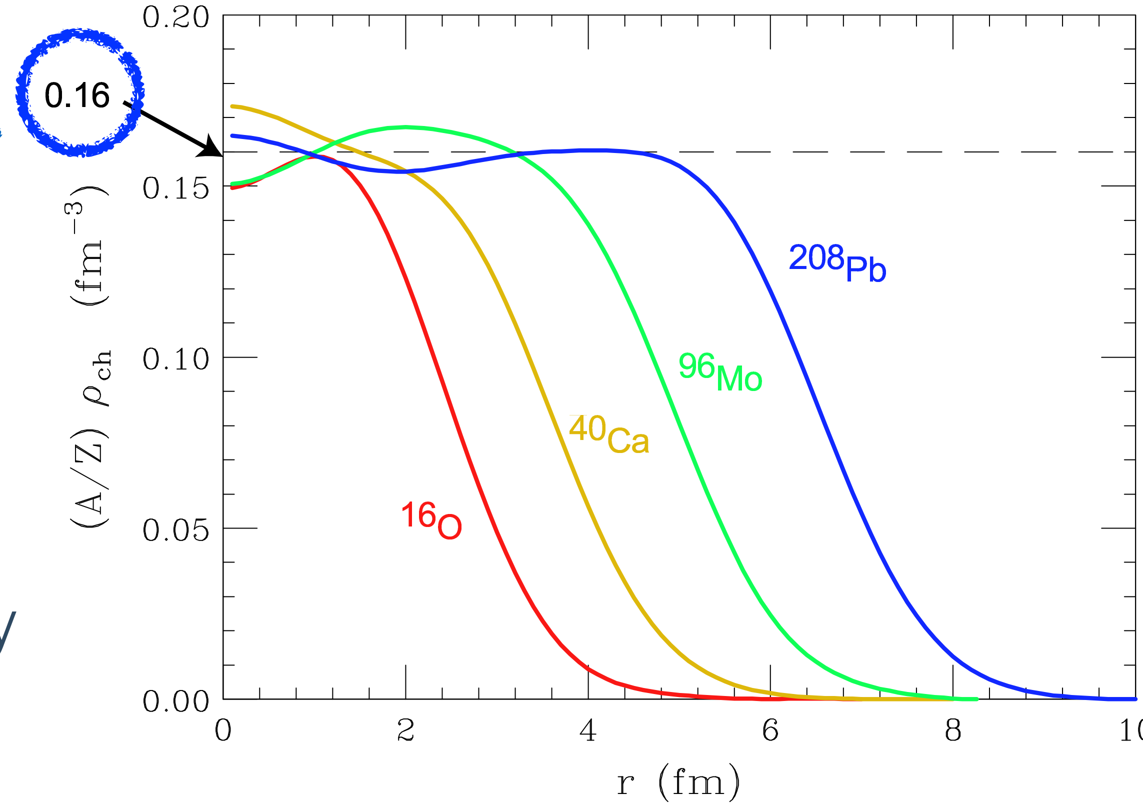


Symmetric Matter



nuclear charge density



Courtesy of O. Benhar

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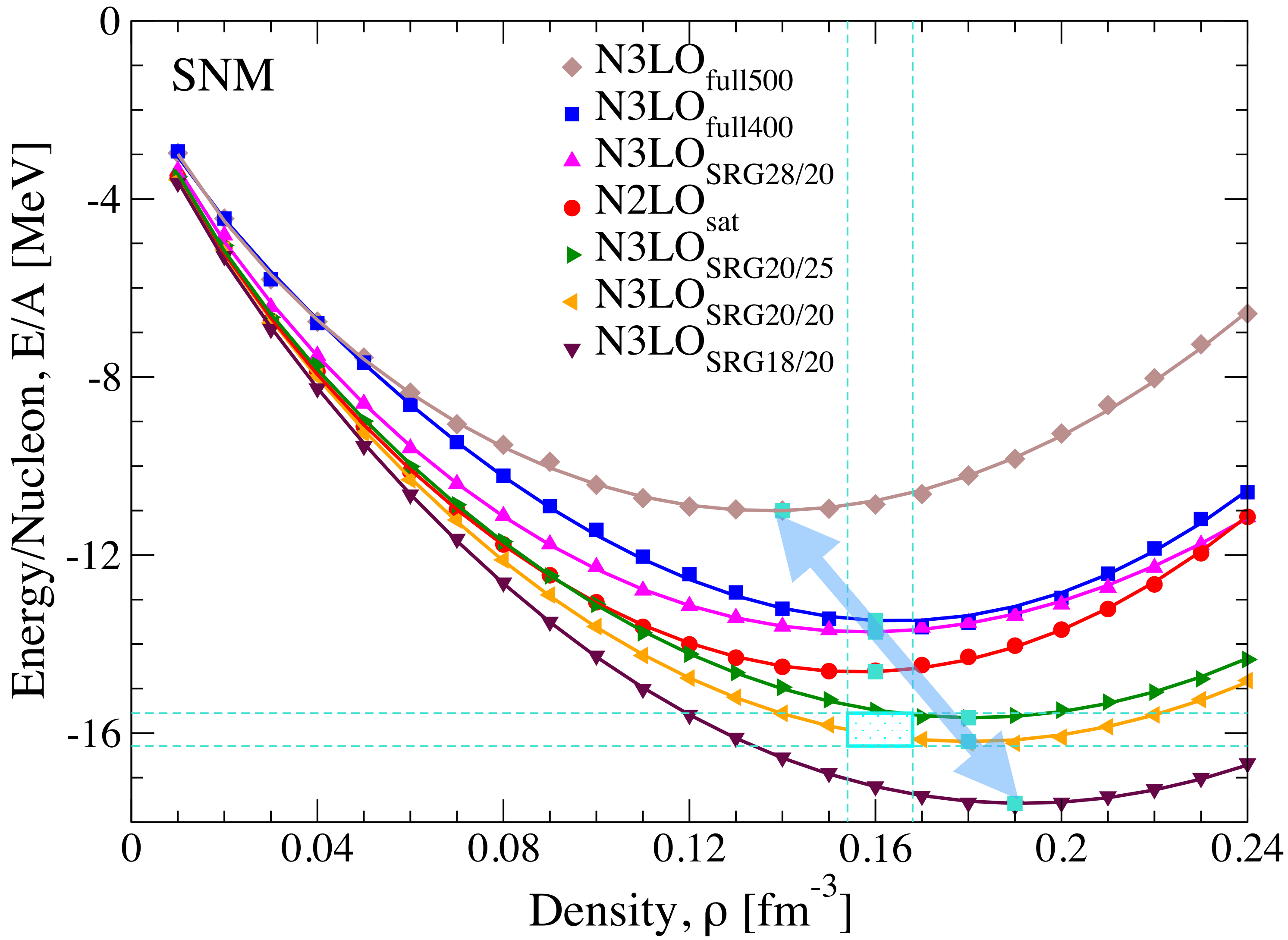
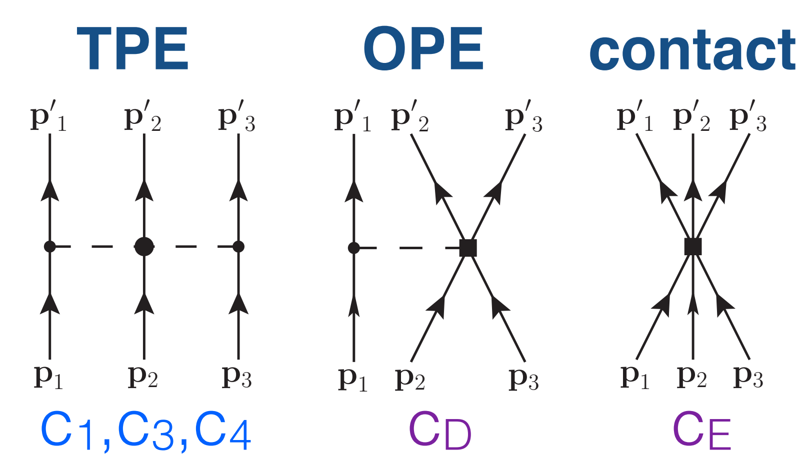
Saturation point according to different Hamiltonians

Carbone *(in preparation)*



Chiral hamiltonians



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

Theoretical uncertainty band

based on the nuclear hamiltonian

Saturation point according to different Hamiltonians

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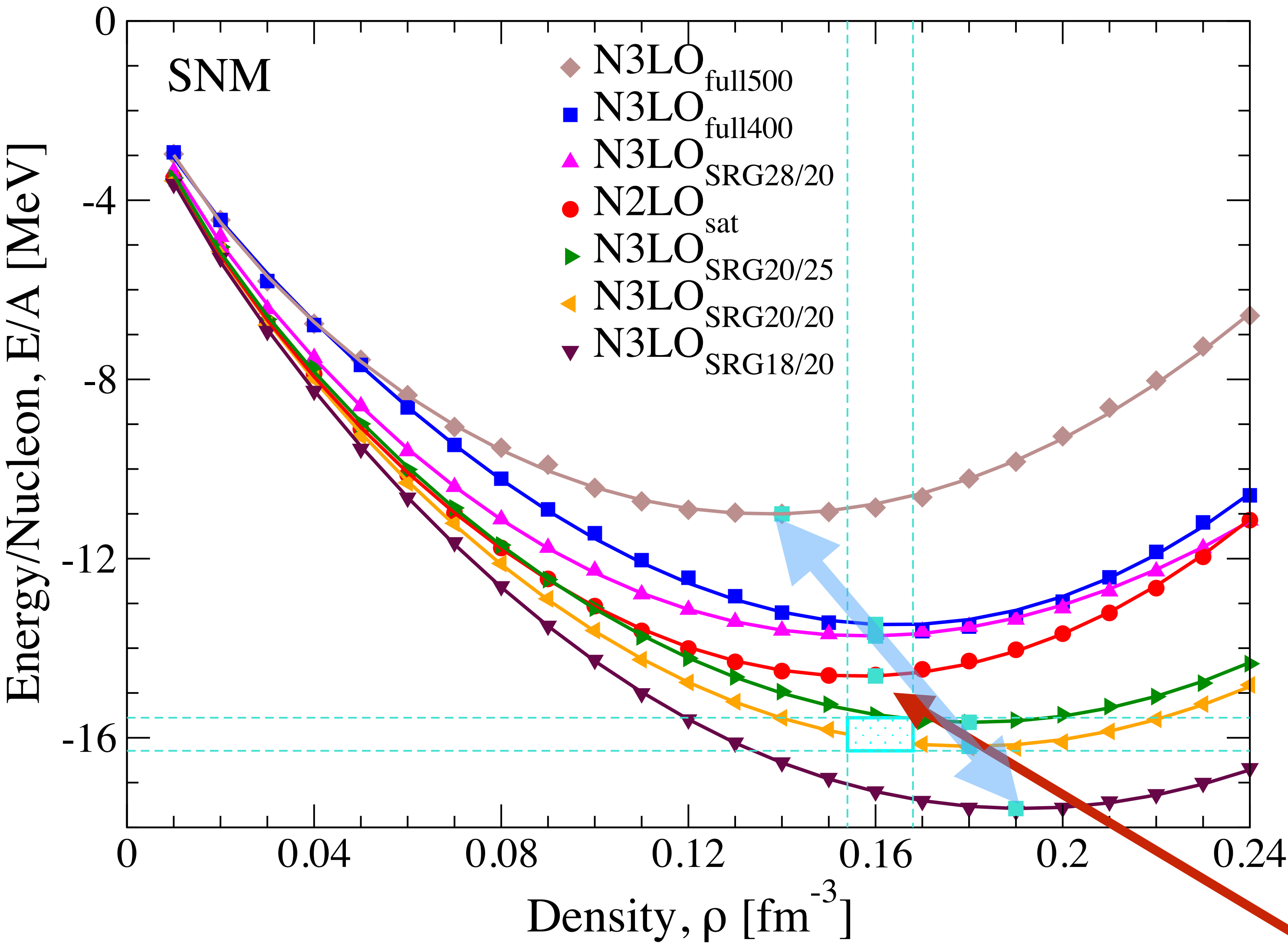

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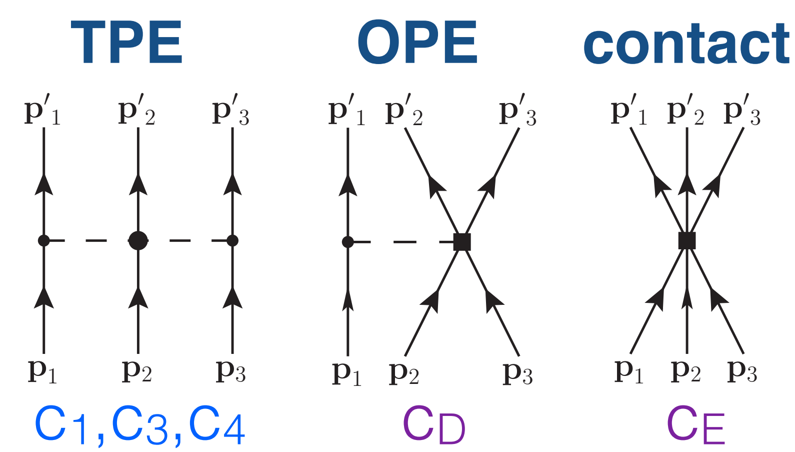

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N2LOsat (2N+3N): predicts saturation density fit to mid-mass nuclei too

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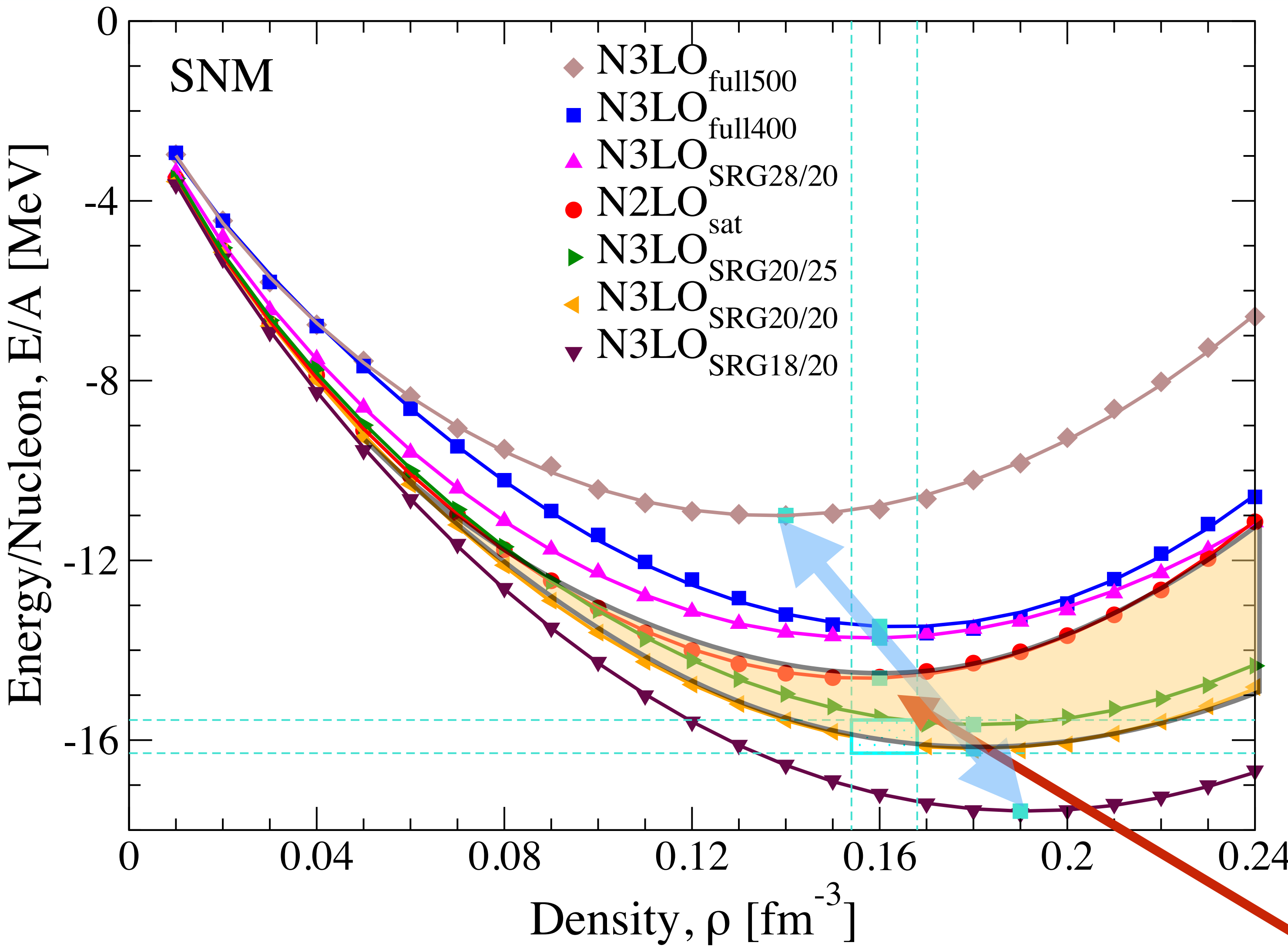
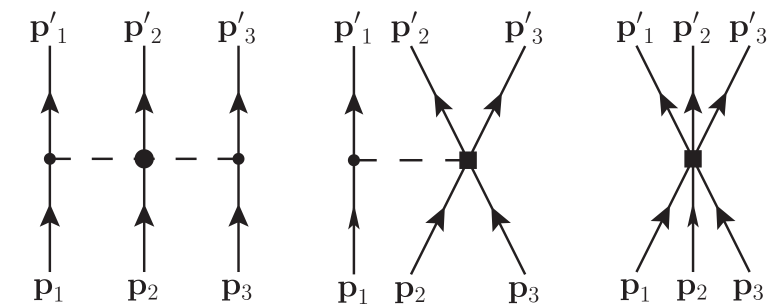


Chiral hamiltonians

TPE **OPE** **contact**



C_1, C_3, C_4 C_D C_E

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- 2N $N2LO_{sat}$+3N N2LO
- 2N $N3LO_{SRG-1}$+3N N2LO
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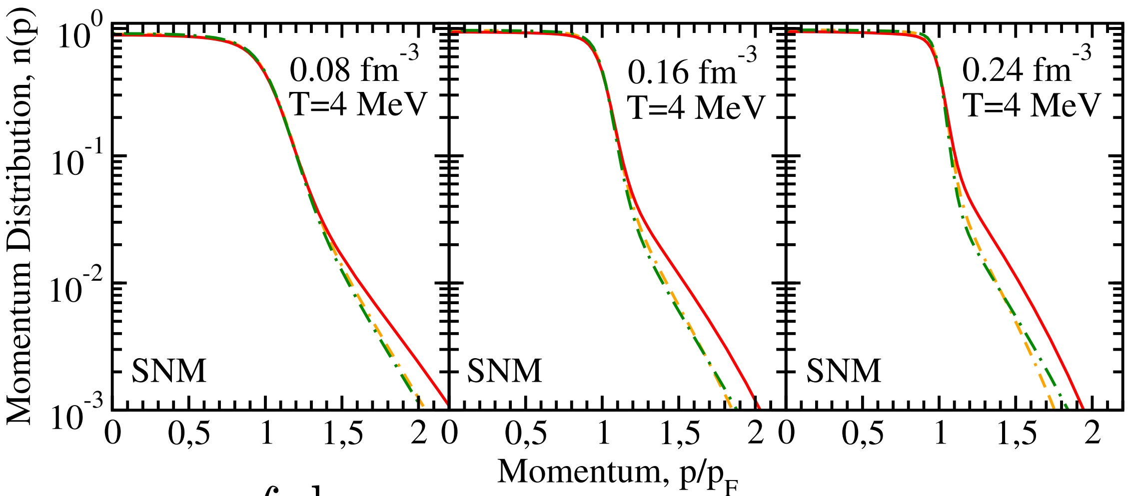
From microscopic… to macroscopic

Symmetric nuclear matter

Carbone *(in preparation)*

The microscopic picture: momentum distribution



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

- N2LOsat high-momentum states

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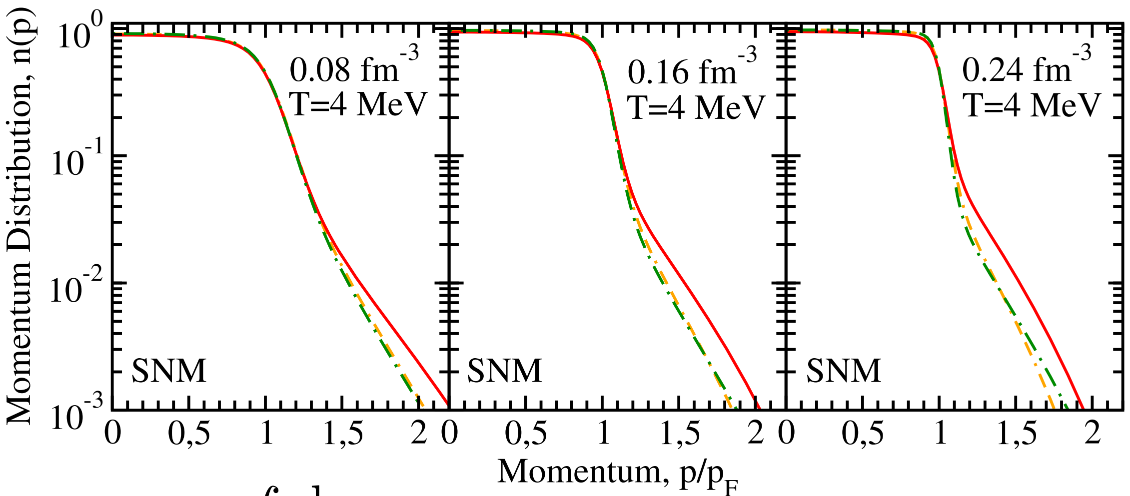

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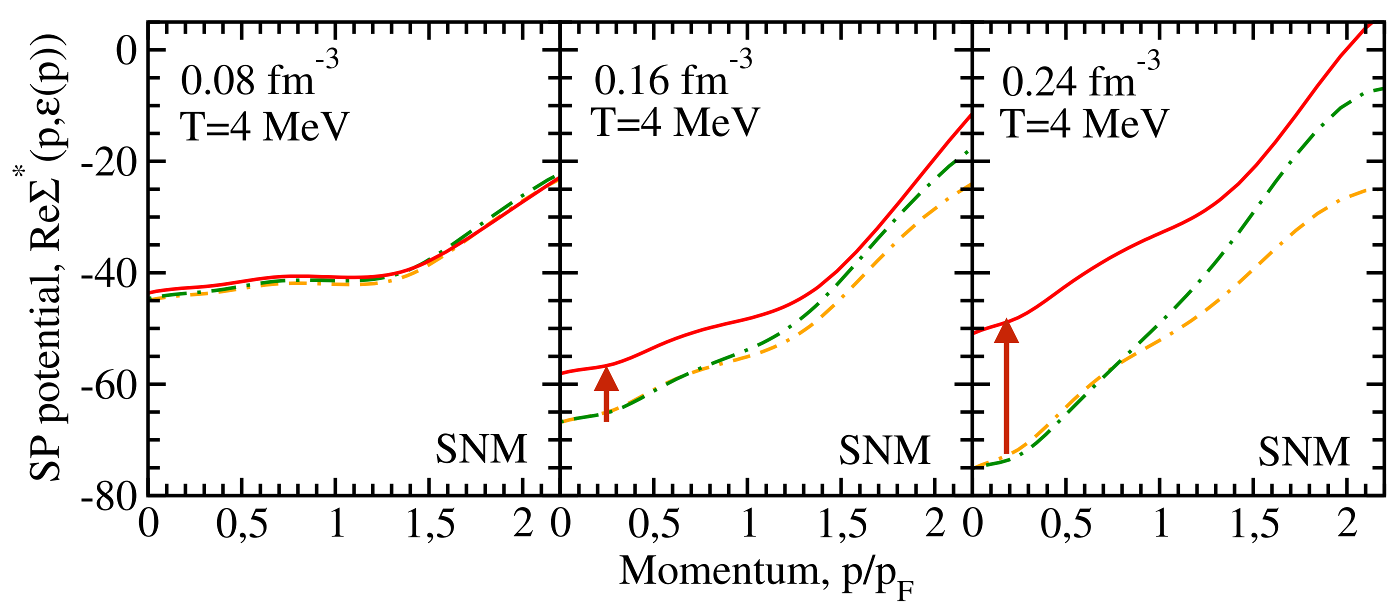
…start seeing the big picture: the self-energy

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



- 3NF effects as density increases
- N2LOsat more repulsive

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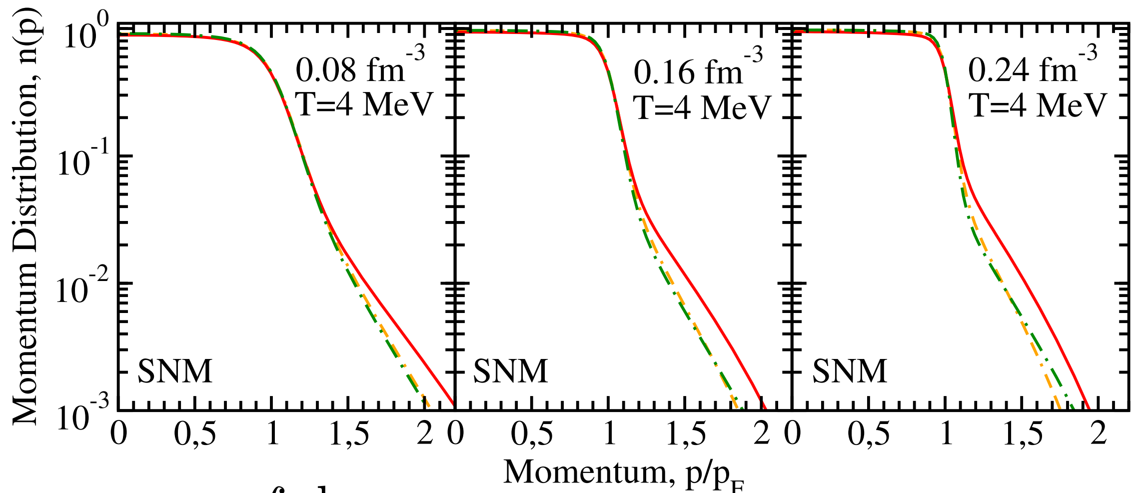

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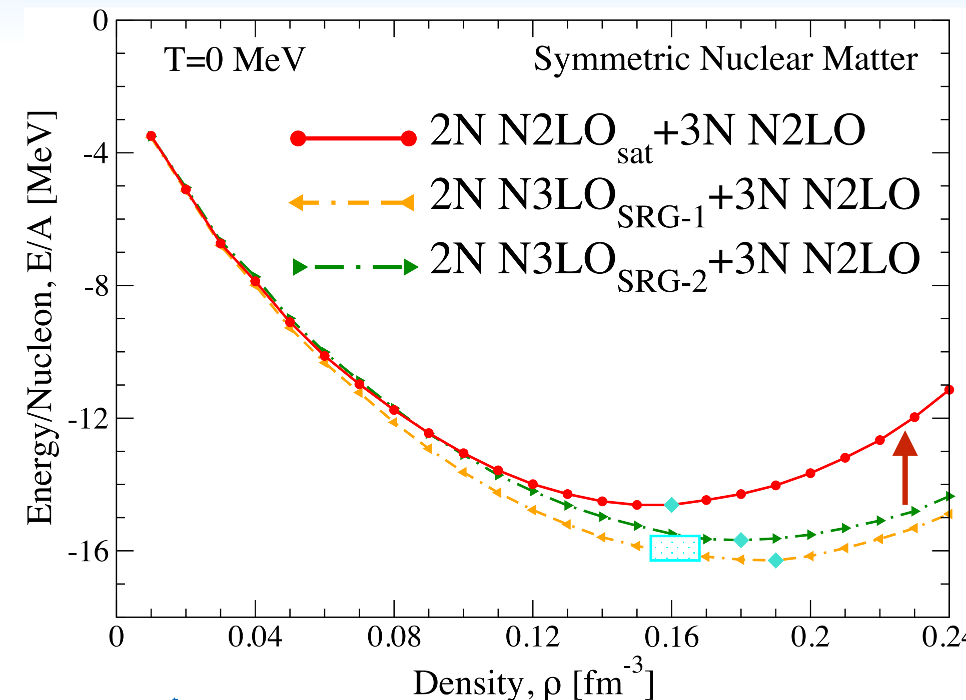

..the macroscopic picture: total energy more repulsive

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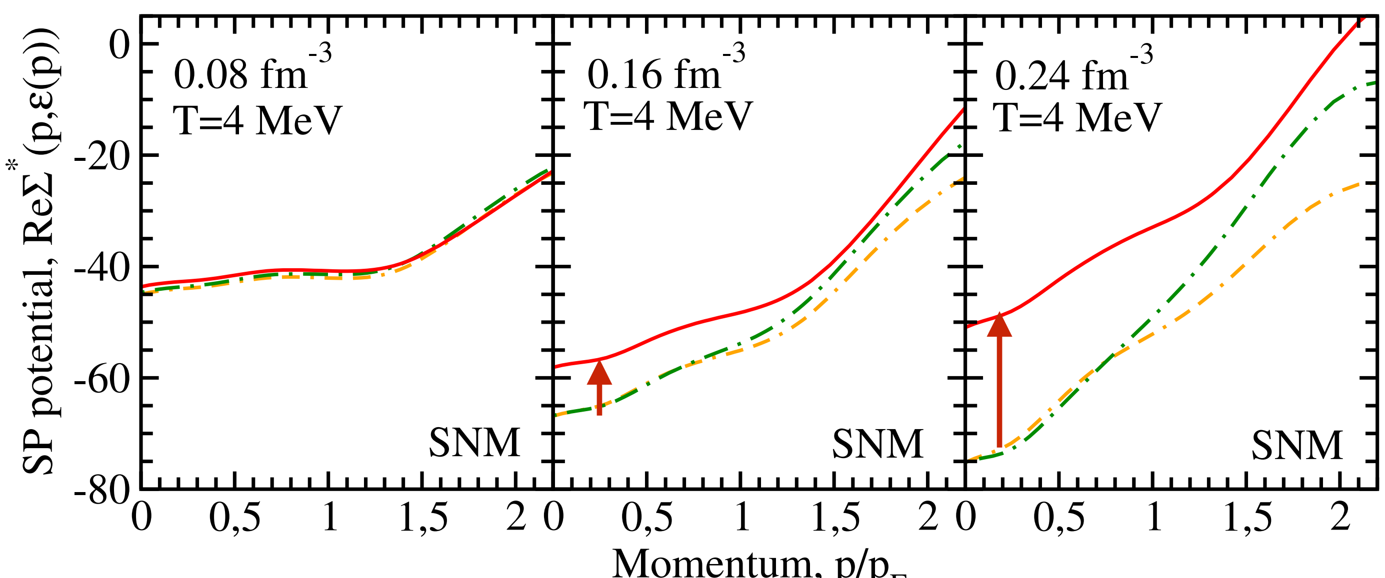

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Pure neutron matter

Carbone *(in preparation)*

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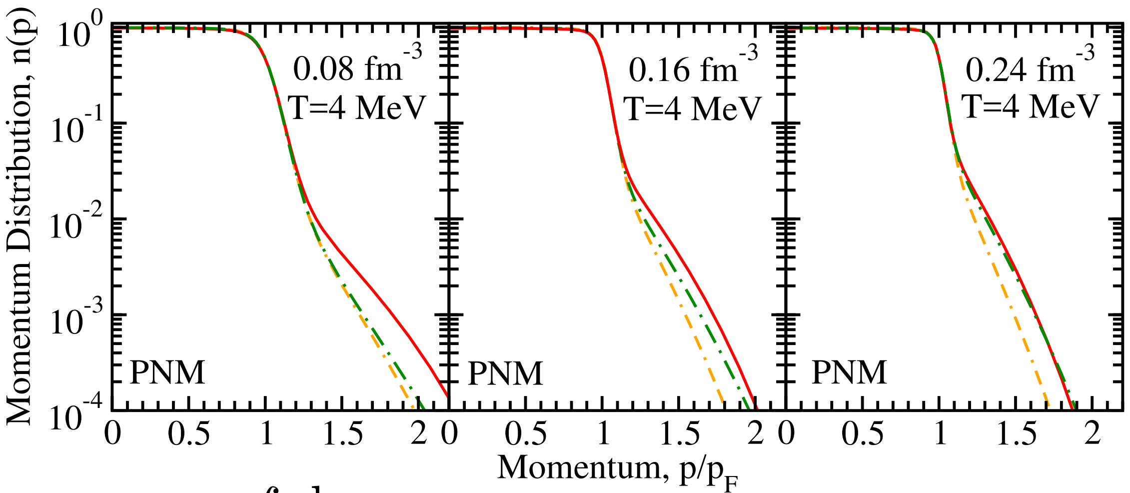

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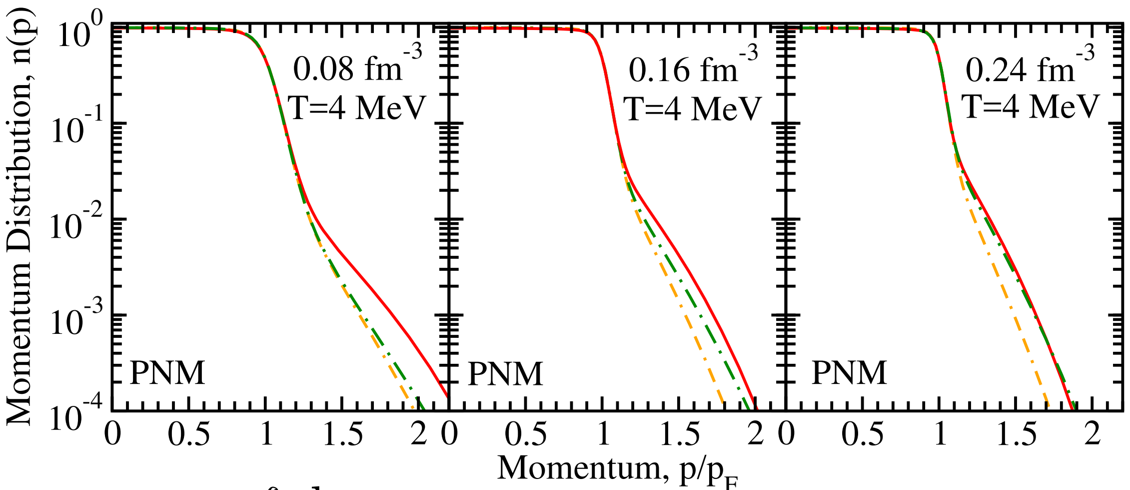

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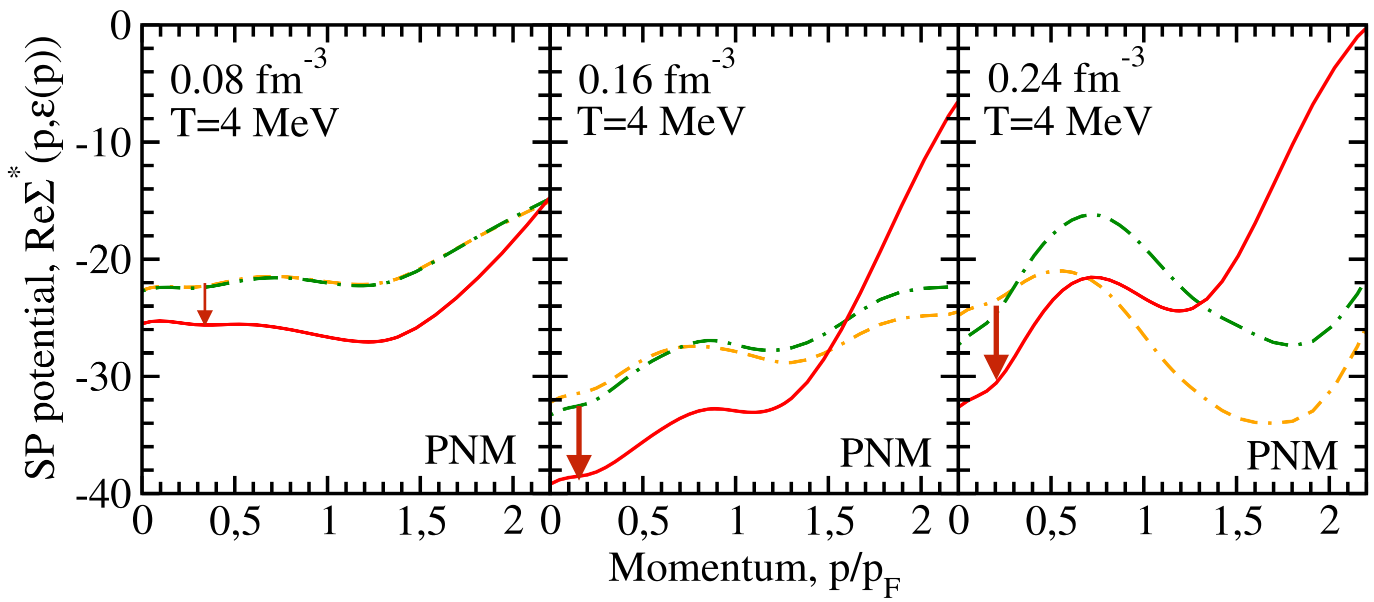

- 3NF effects are reversed
- N2LOsat more attractive

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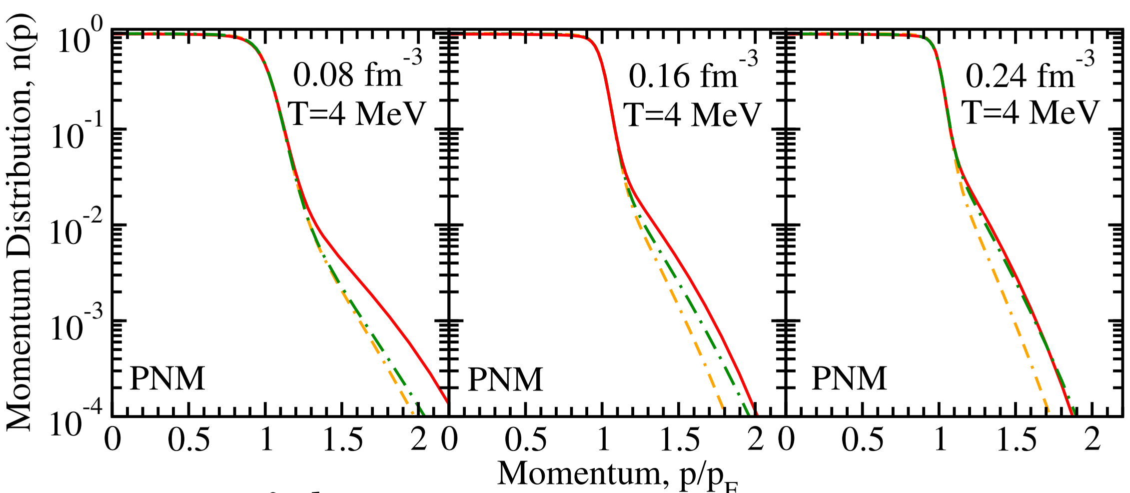

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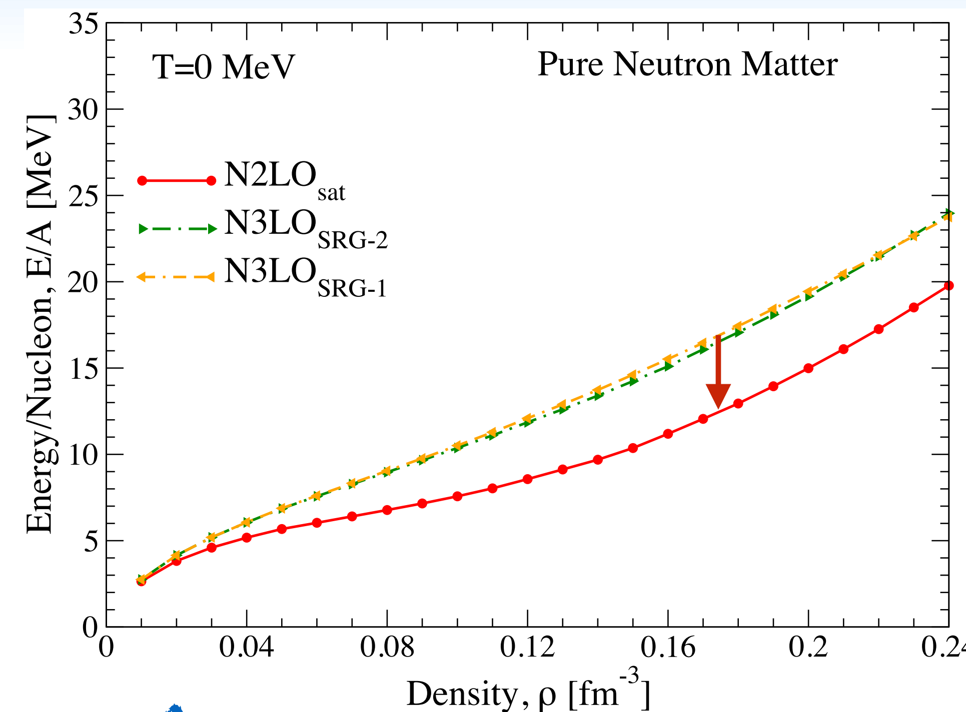

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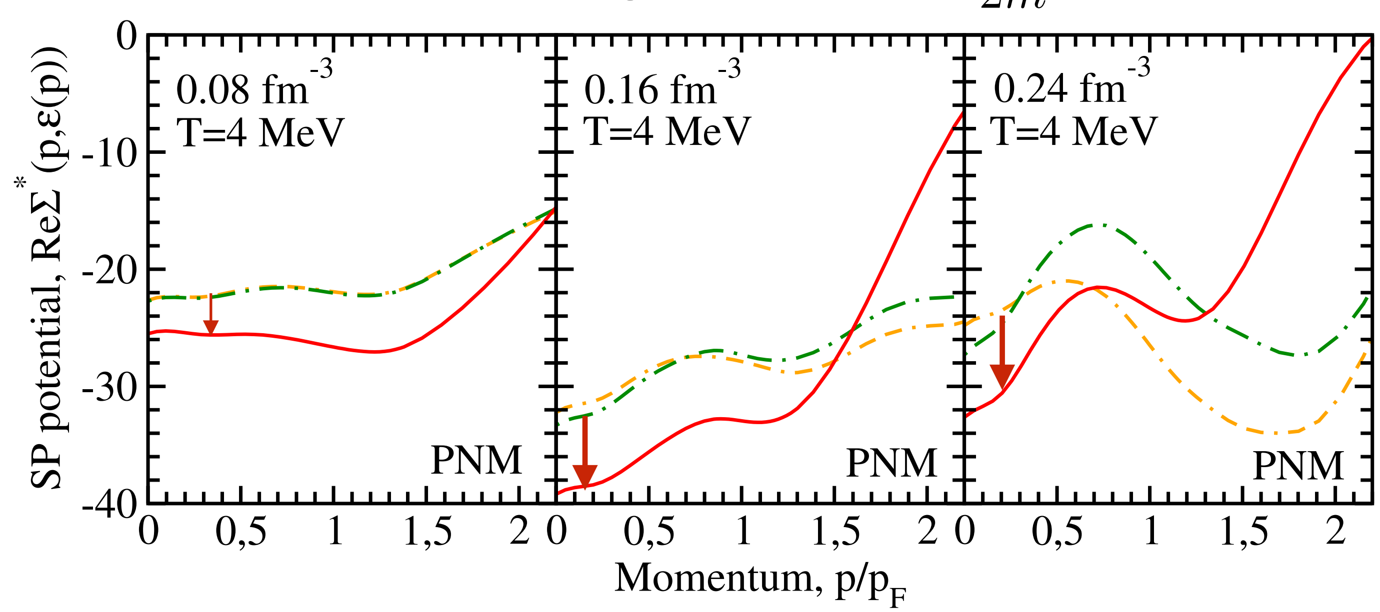

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Predictions for the Symmetry Energy and slope L

Carbone *(in preparation)*

Energy of asymmetric matter

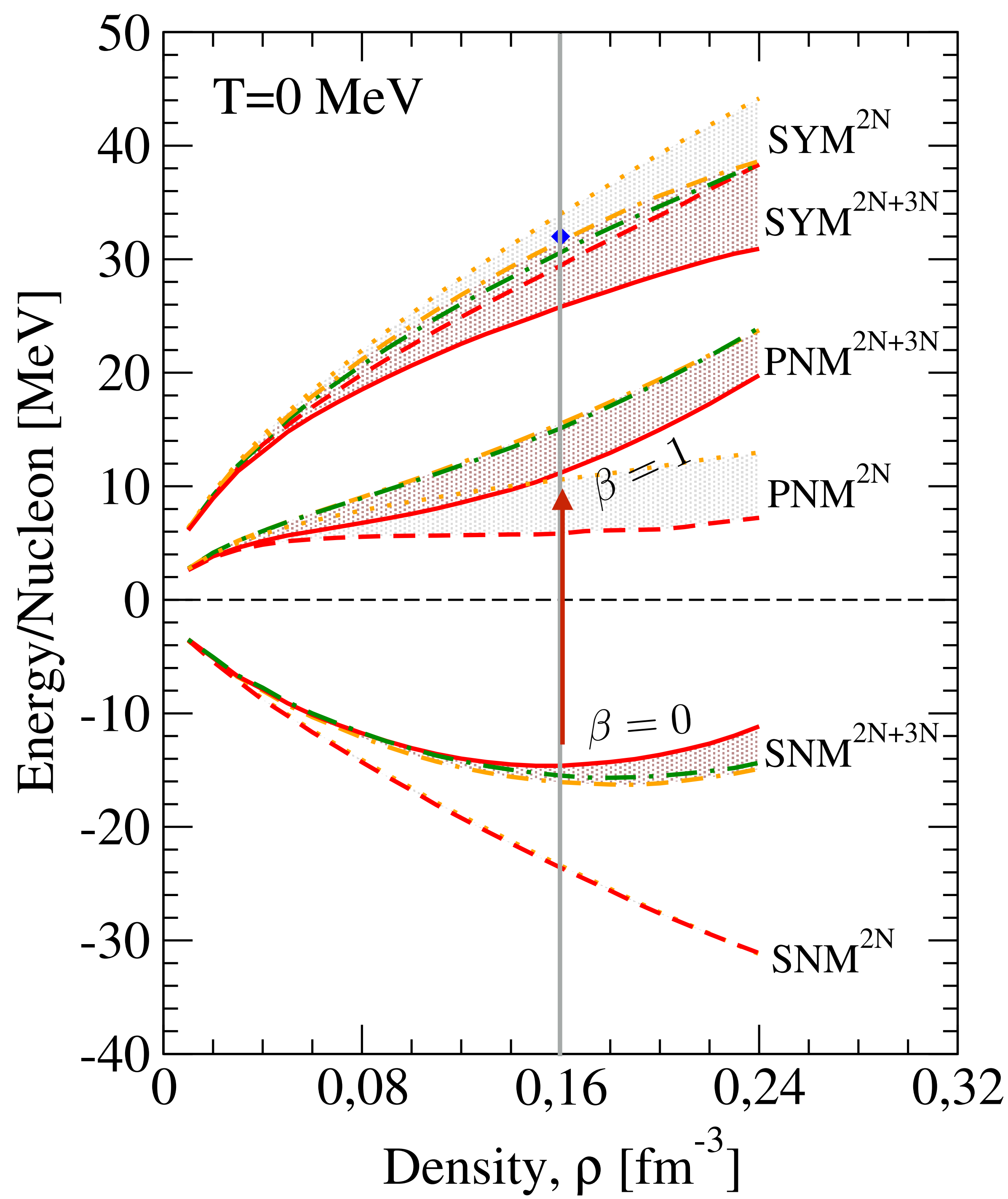
$$\frac{E}{A}(\rho,\beta) \simeq \frac{E_{\rm SNM}}{A}(\rho) + \frac{S}{A}(\rho)\beta^2$$

$\beta = 1$

$$\frac{S}{A}(\rho) \simeq \frac{E_{\rm PNM}}{A}(\rho) - \frac{E_{\rm SNM}}{A}(\rho)$$

Symmetry energy

	SRG1	SRG2	SAT
Sv (MeV)	31.6	30.6	25.8
L (MeV)	49.3	48.7	37.4
K (MeV)	290	270	213



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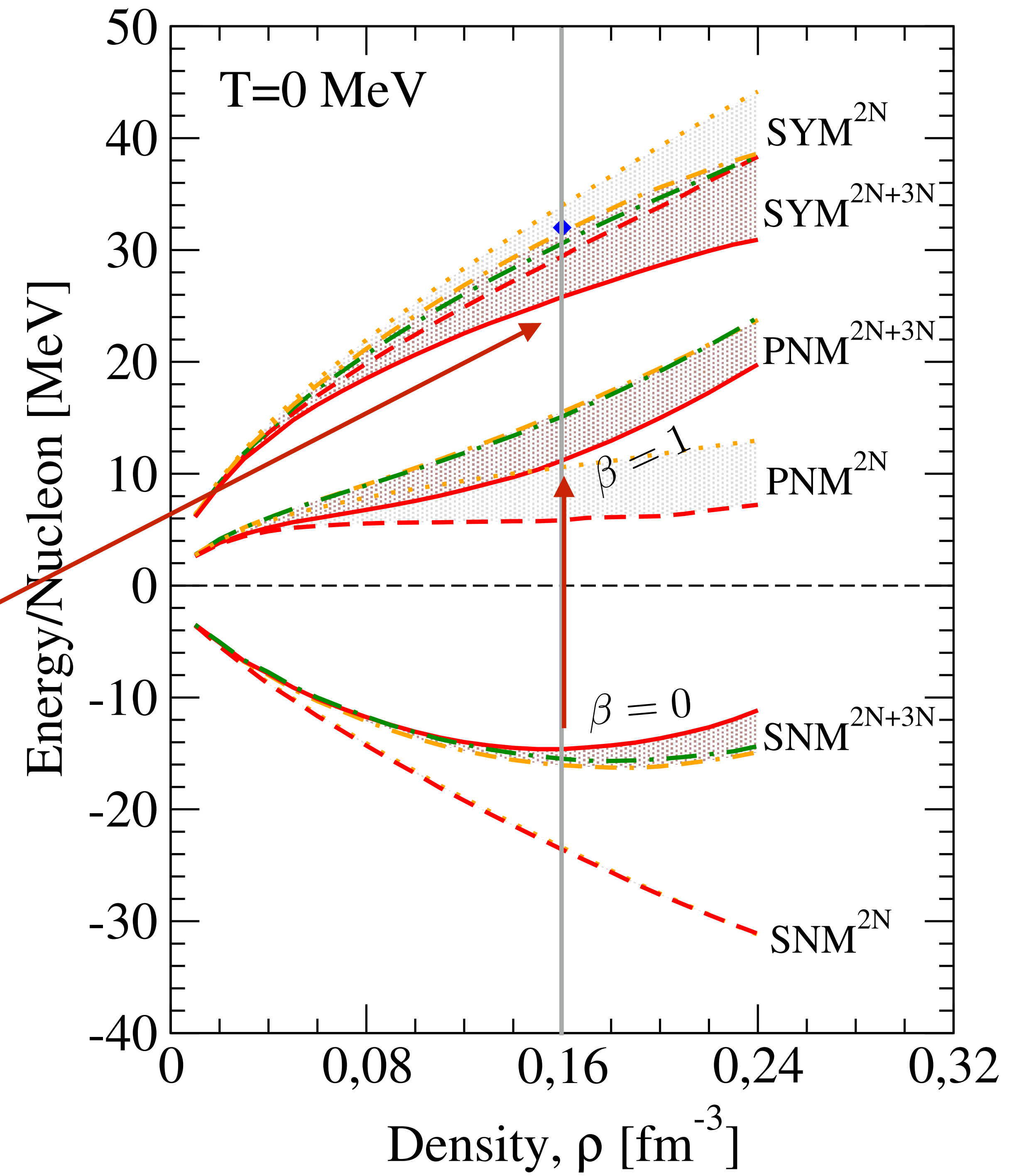

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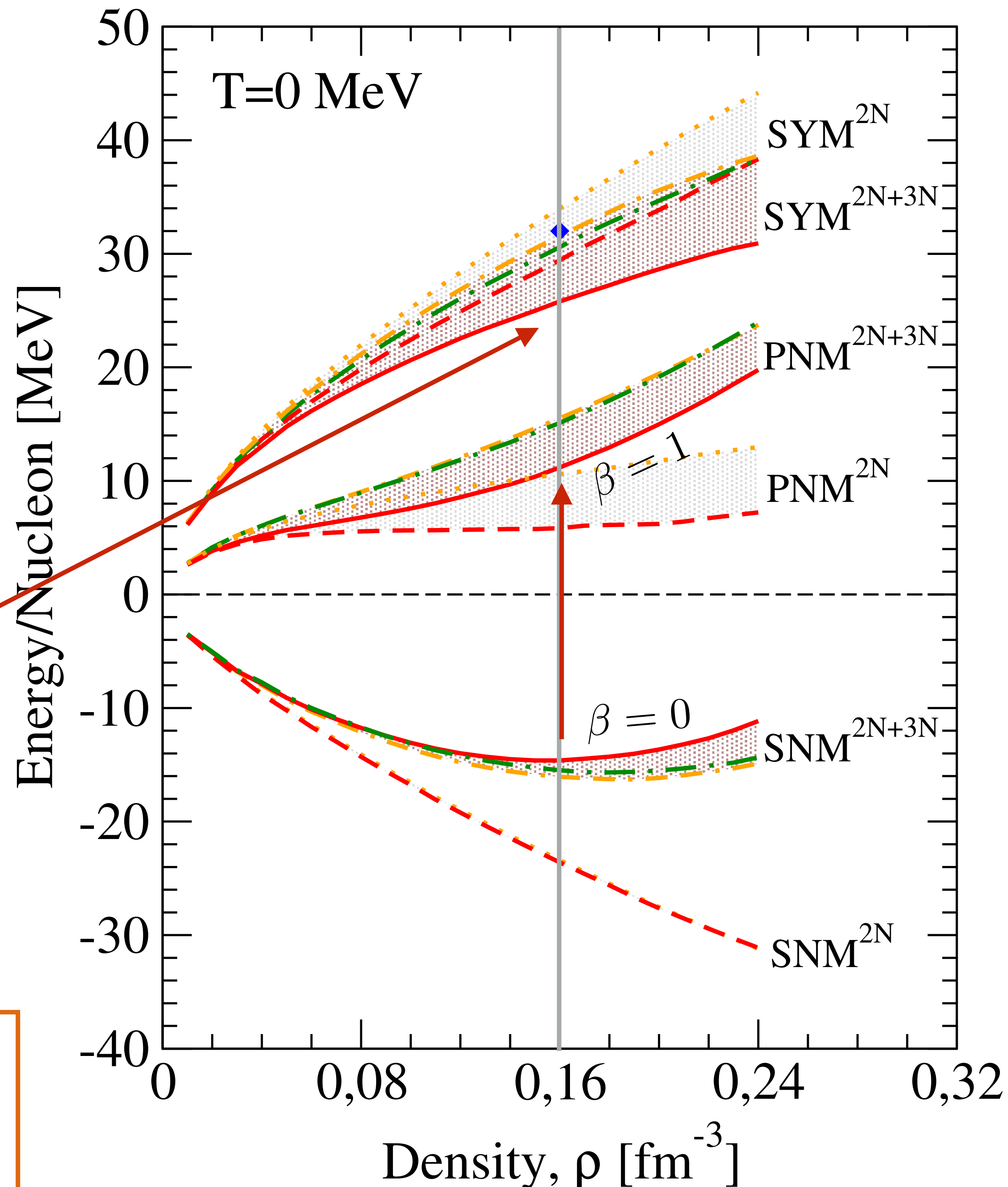


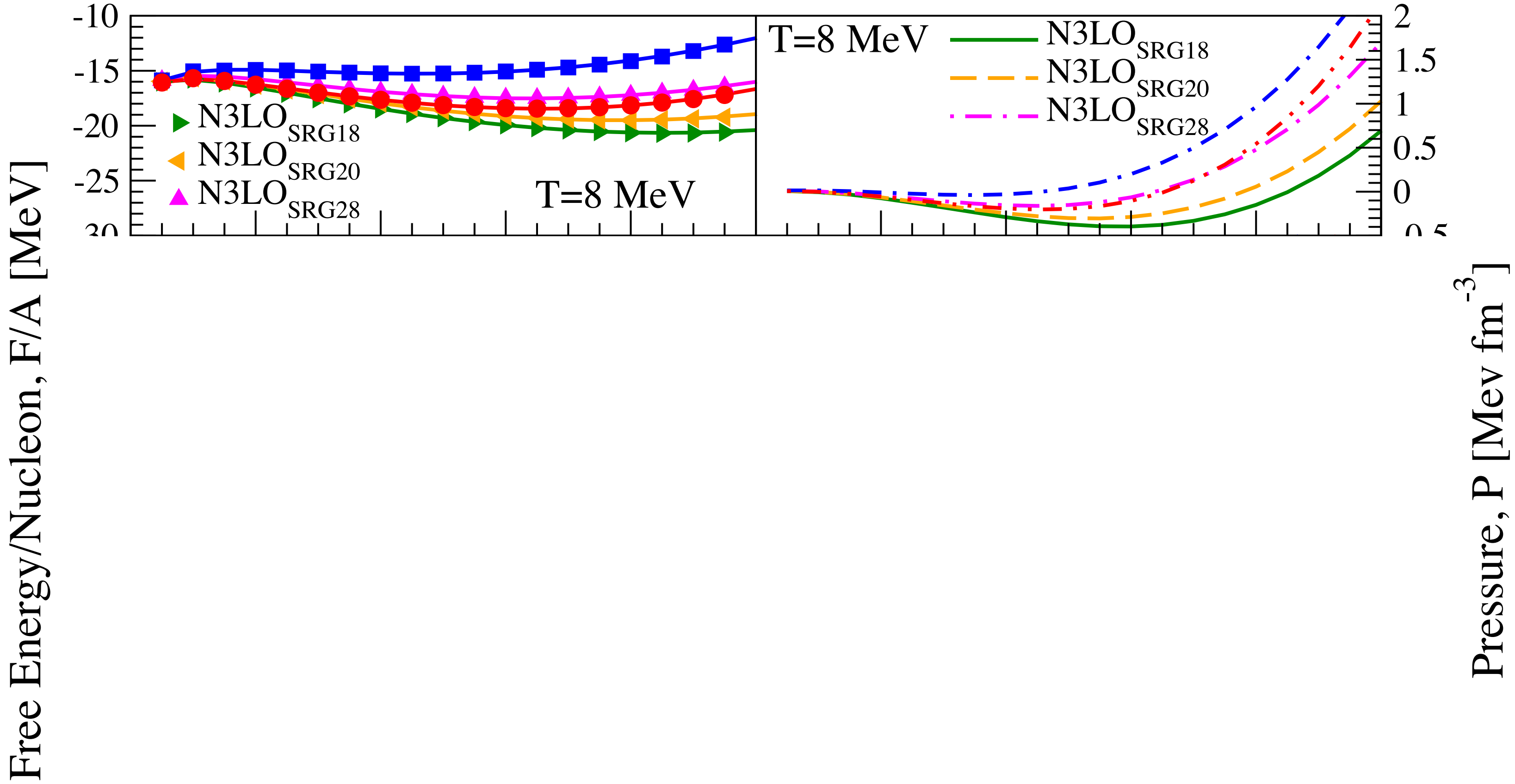
Check all infinite matter properties to judge the goodness of a potential

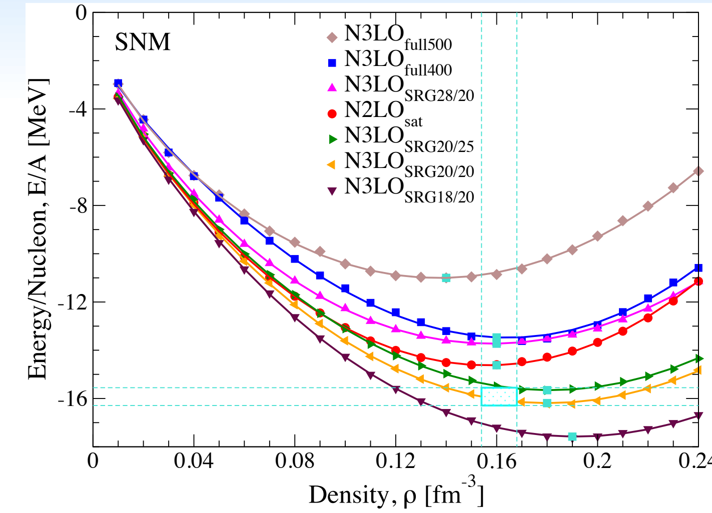
Free energy and pressure at varying temperature

Free-energy
$$F = E - TS$$

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

increasing temperature





- similar behaviour to zero T energy
- liquid-gas phase transition

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

Carbone, Polls, Rios PRC 98 025804 (2018)

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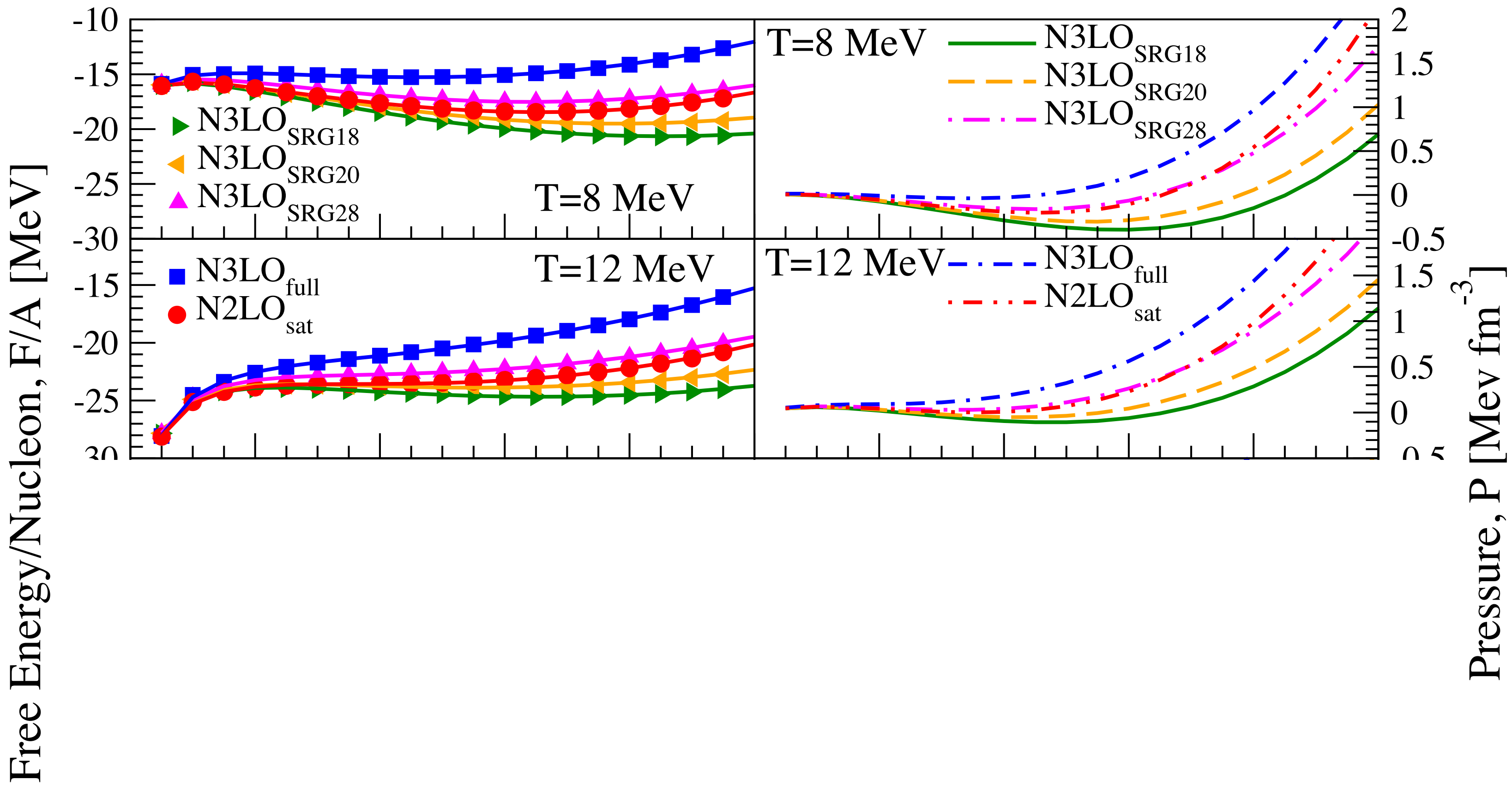

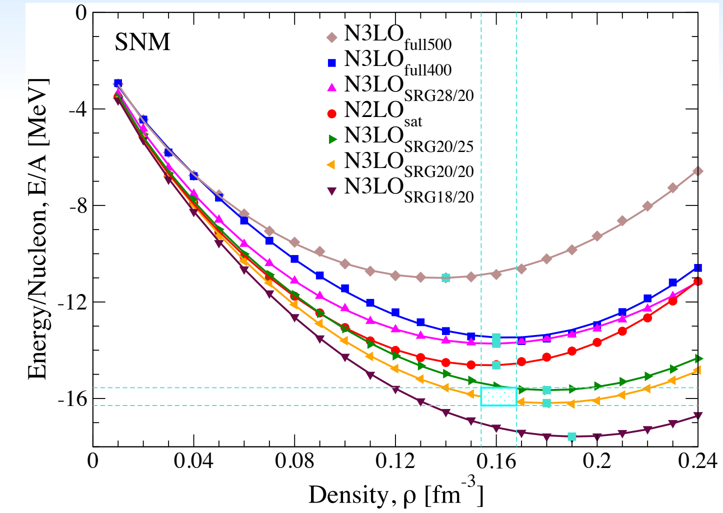

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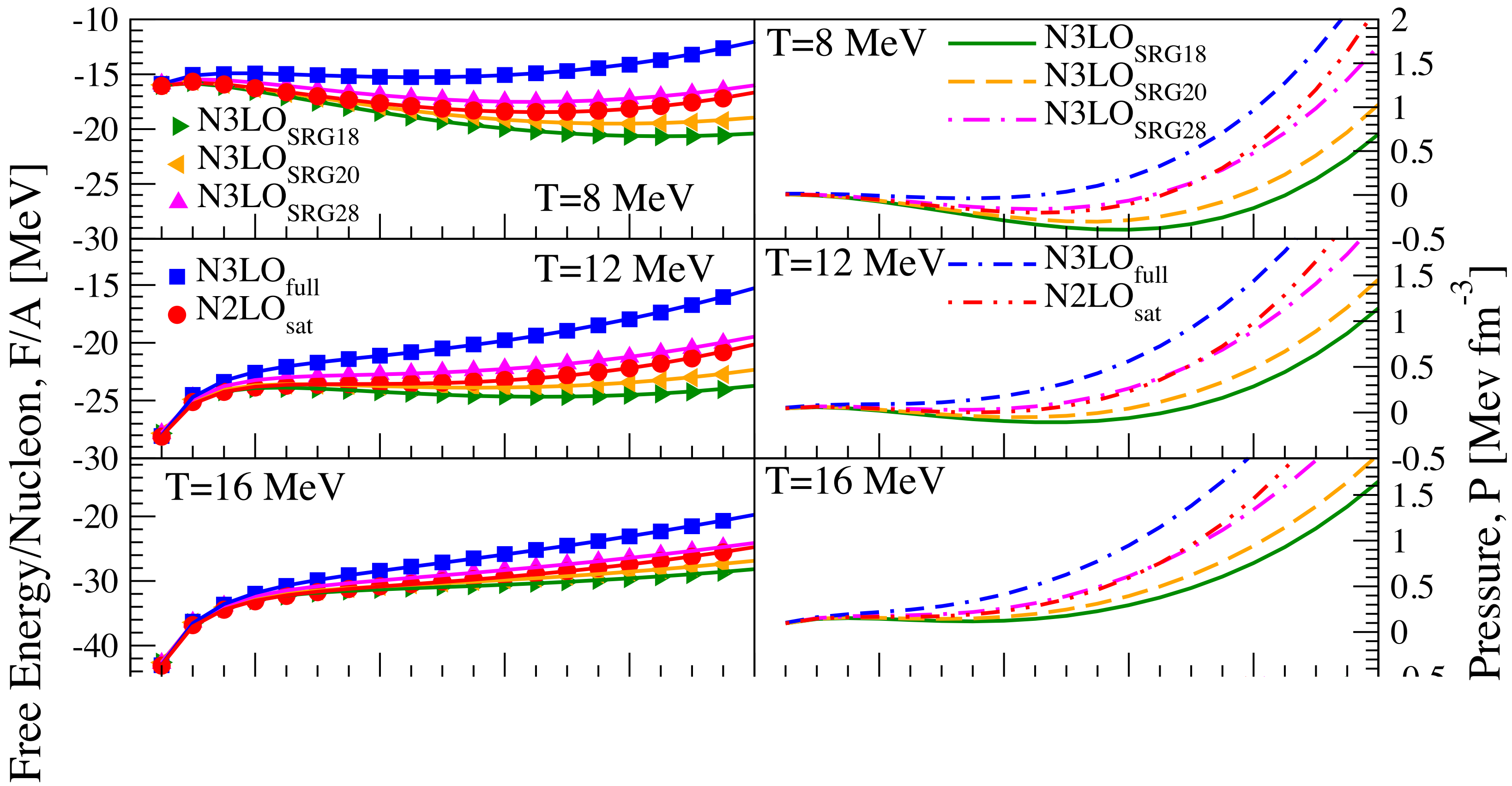

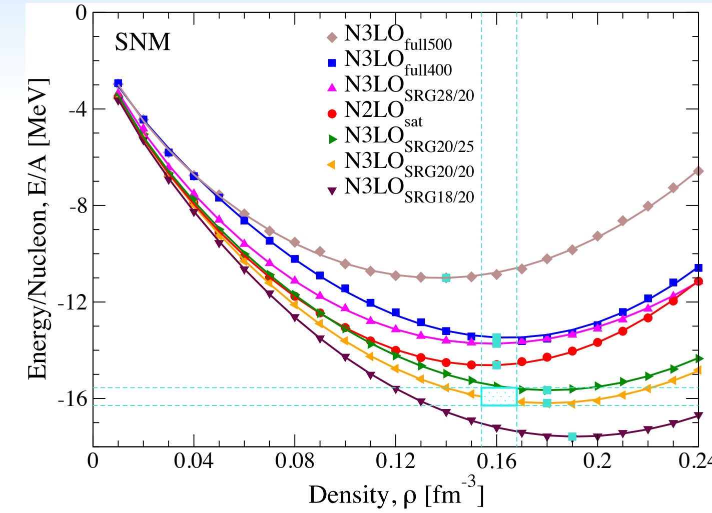

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Carbone, Polls, Rios PRC 98 025804 (2018)

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Symmetric nuclear matter

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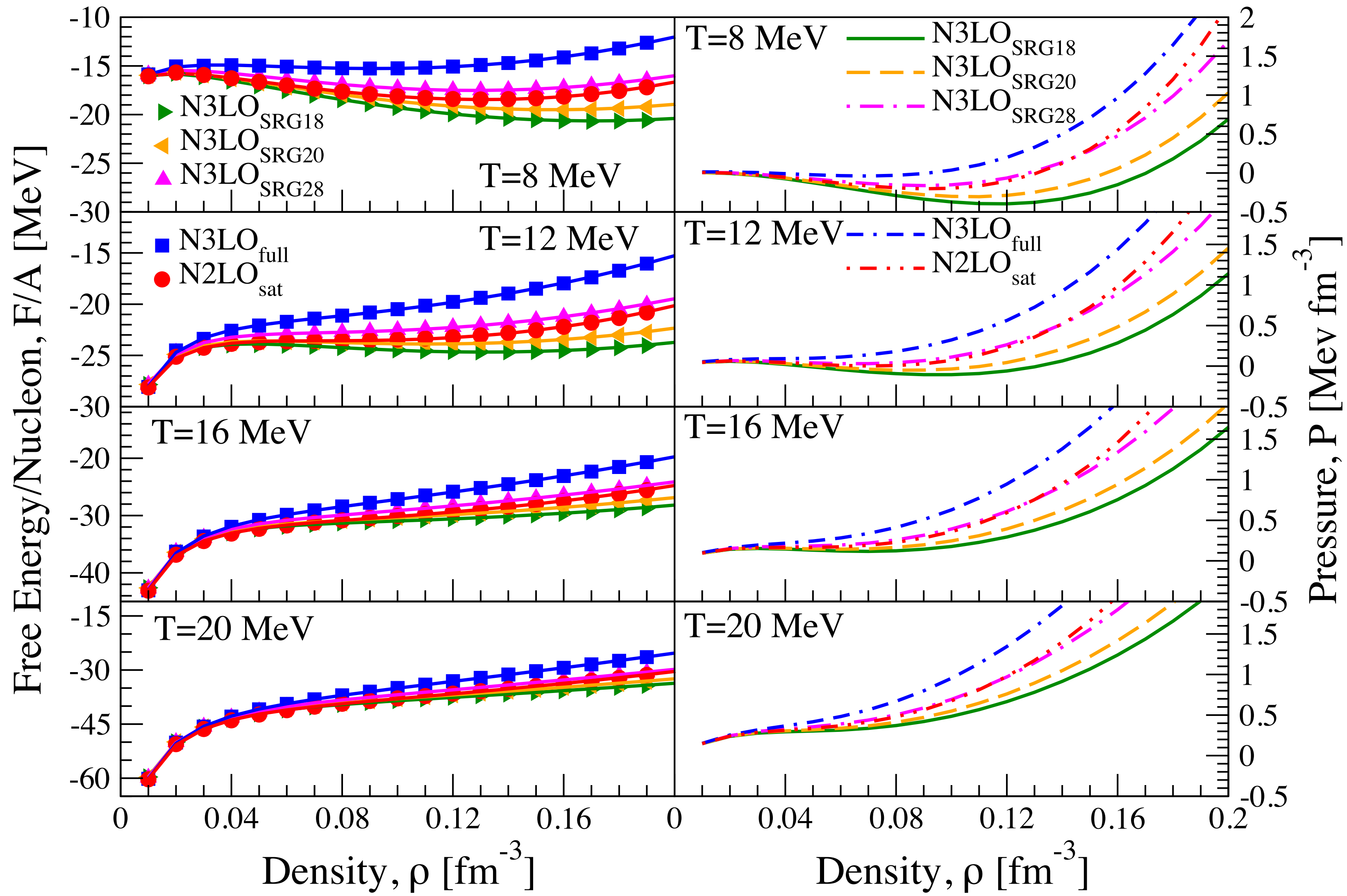

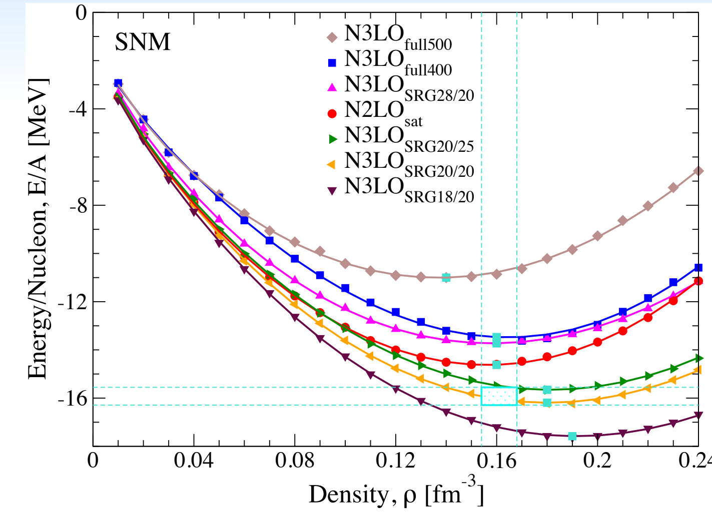

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N2LOsat 2N + 3N

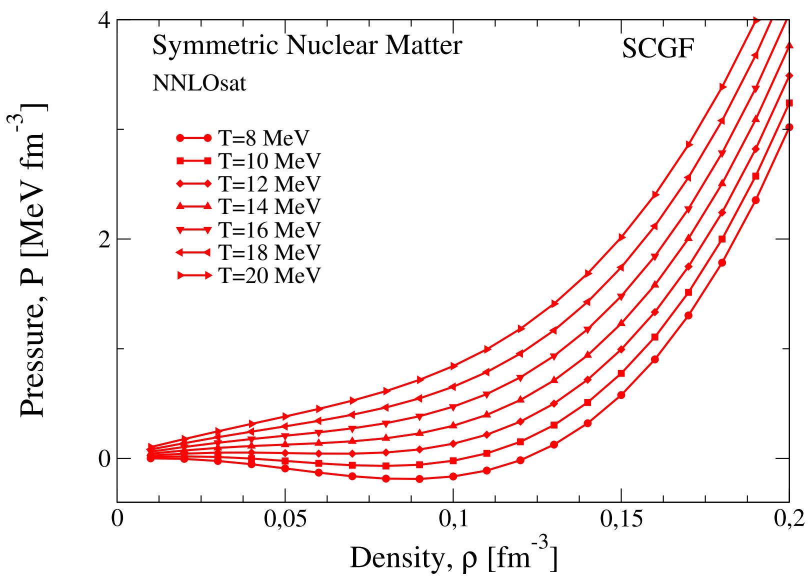
2N N2LOopt + 3N N2LO

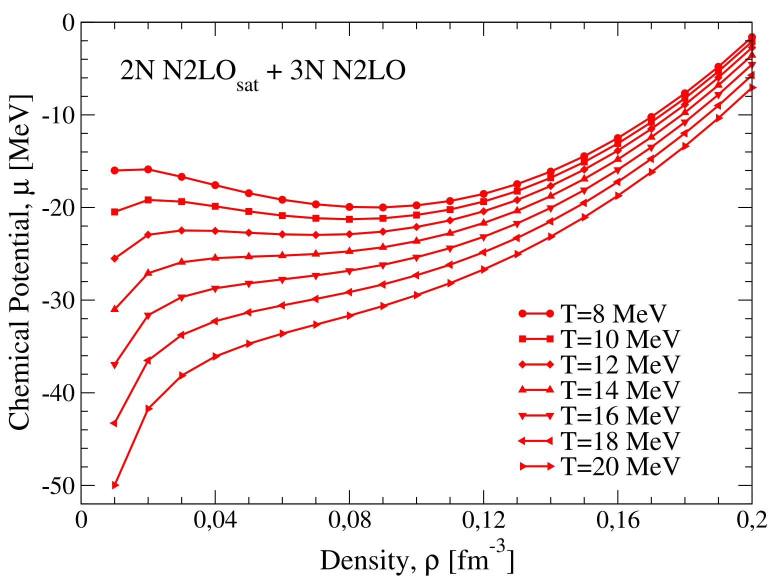
Carbone, Polls, Rios PRC 98 025804 (2018)

The liquid-gas phase transition and critical point

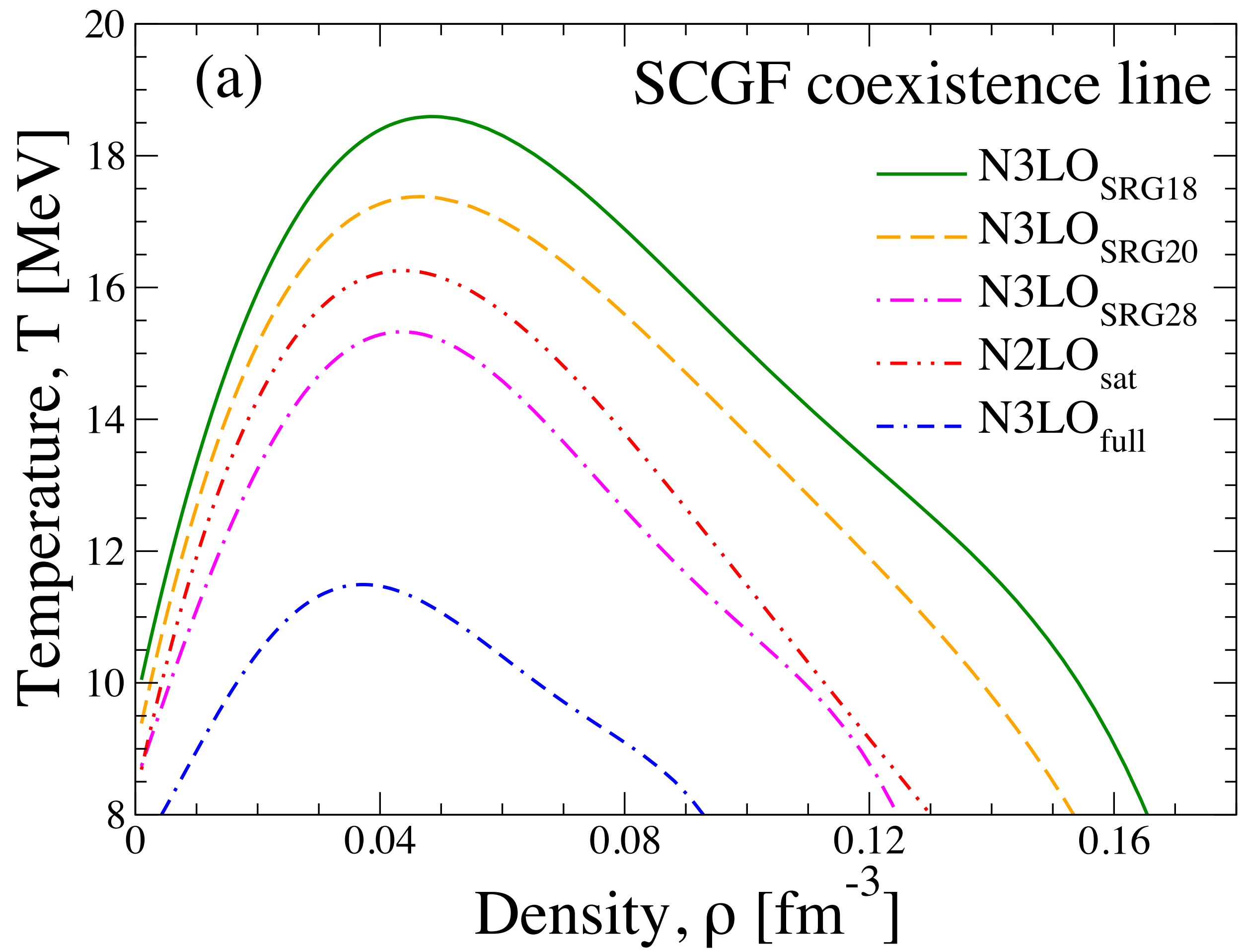
Carbone, Polls, Rios PRC 98 025804 (2018)

N2LOsat 2N+3N





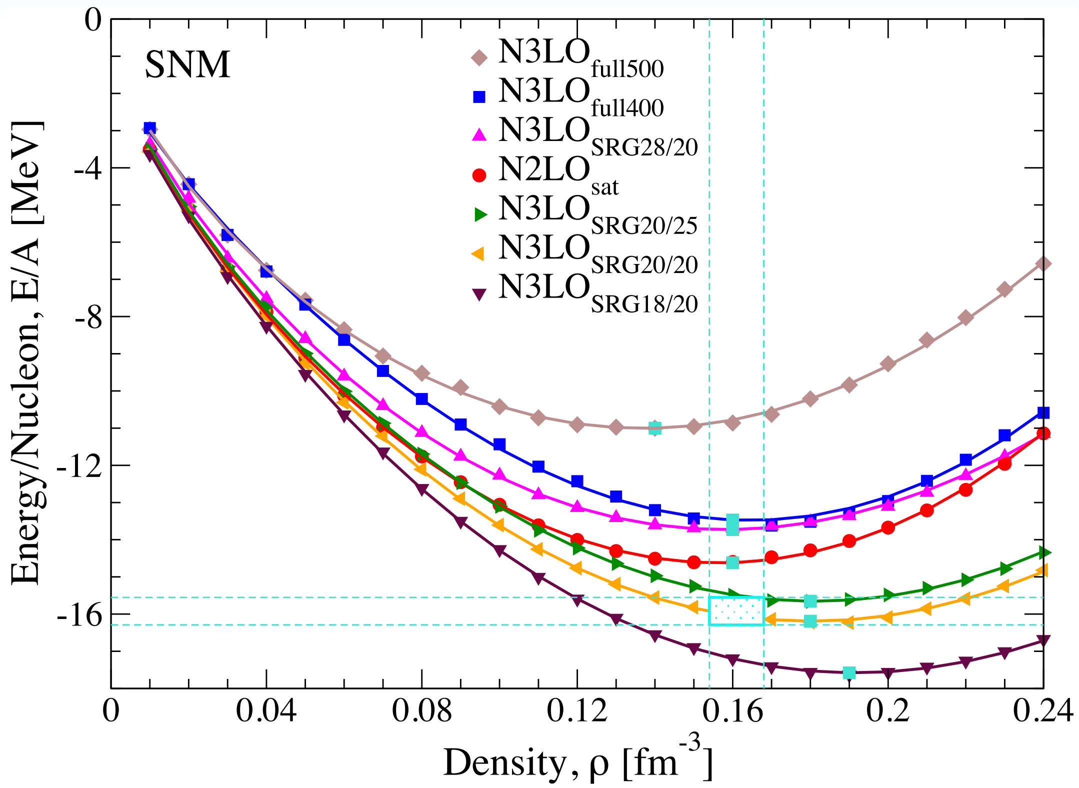
$$\mu(\rho_g) = \mu(\rho_l) \qquad P(\rho_g) = P(\rho_l)$$

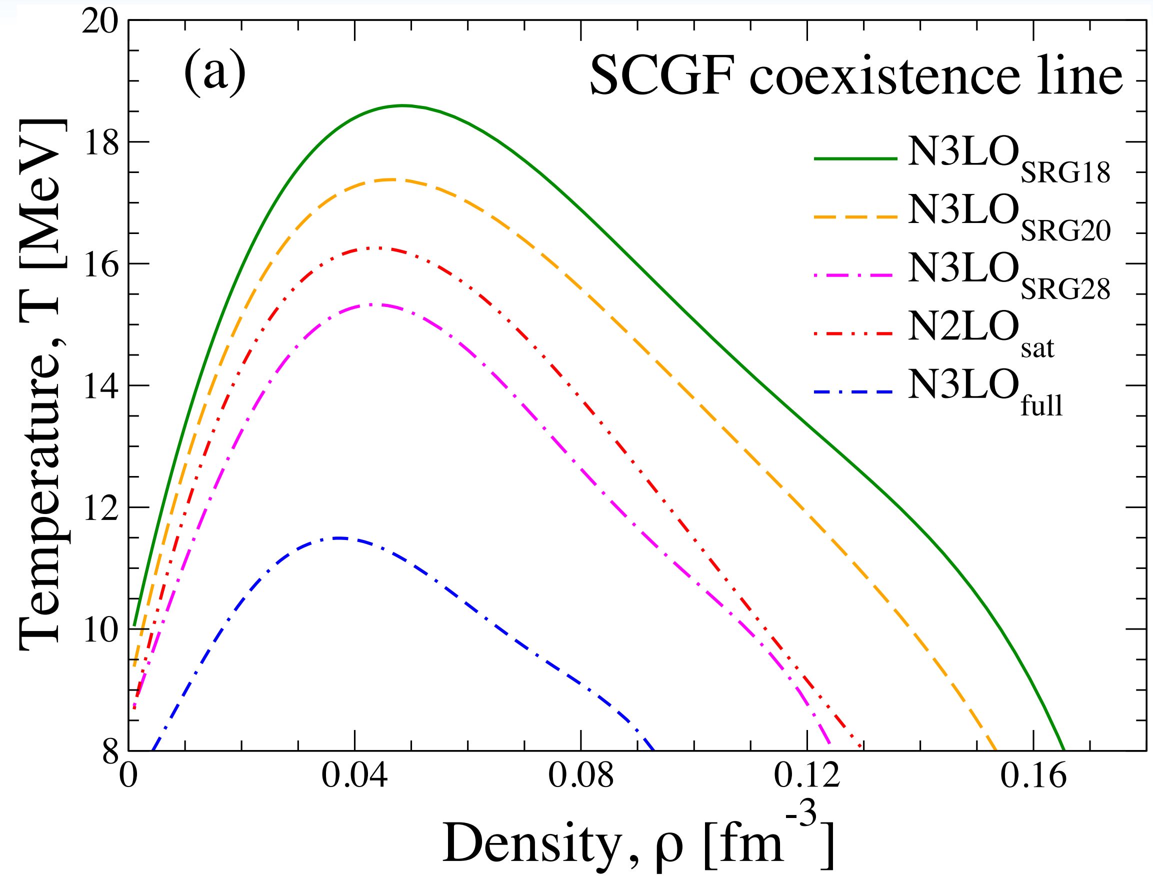


- Coexistence line: equilibrium between a gas and a liquid phase
- Predicted critical temperature ~ T=~[15-19] MeV (experimental ~[15-20] MeV)
- Previous consistent results from Wellenhofer et al., PRC 89 ,064009 (2014)

The saturation energy vs the critical temperature

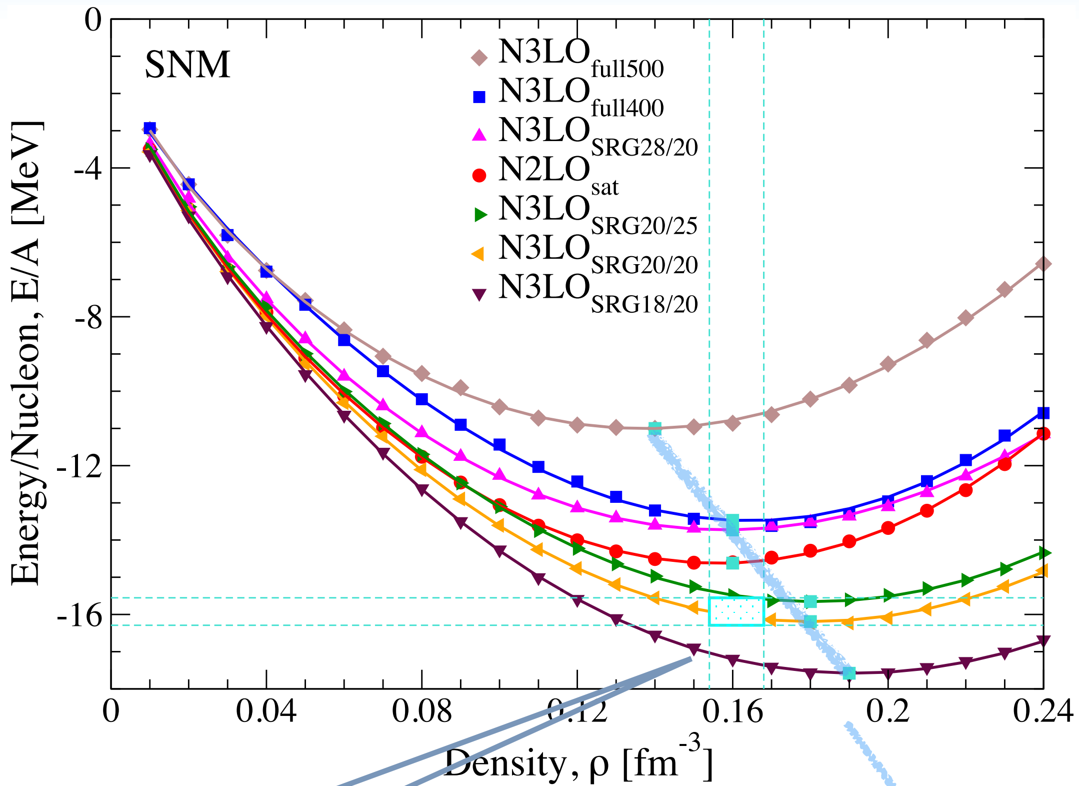
Carbone, Polls, Rios PRC 98 025804 (2018)

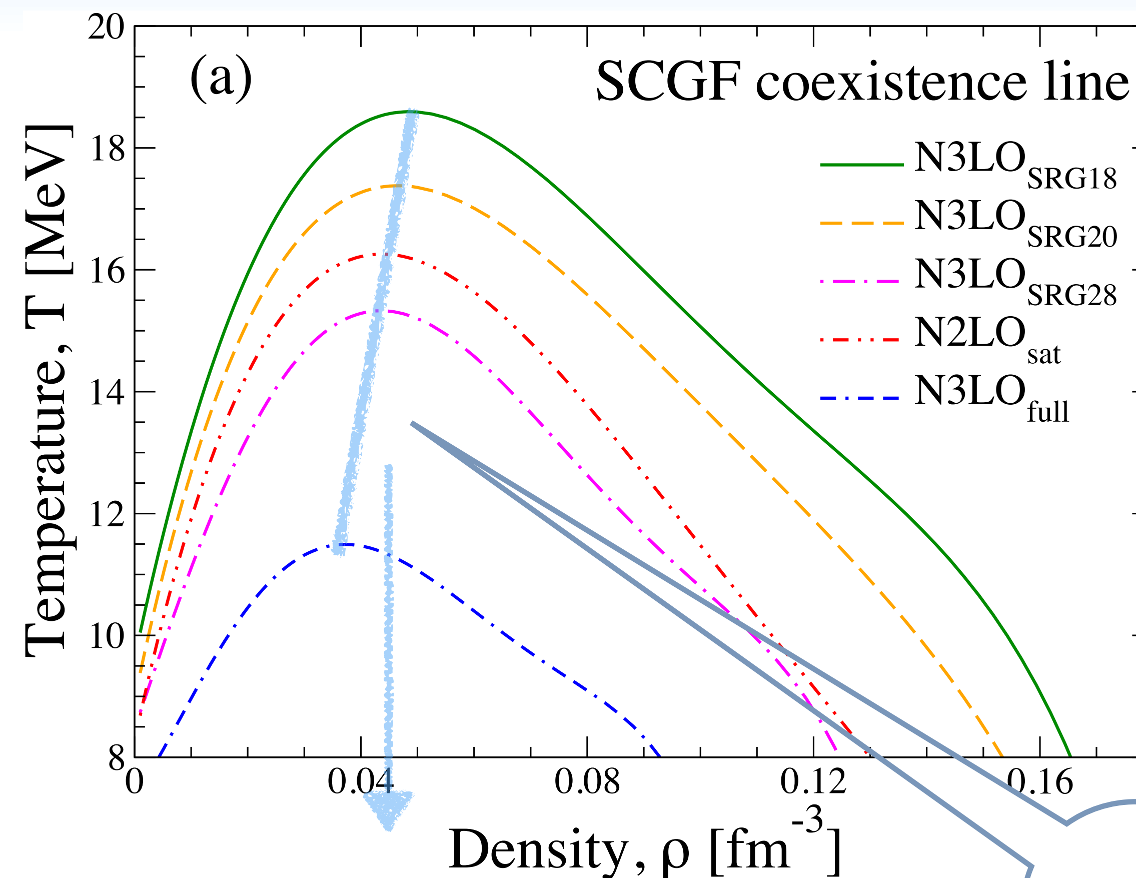




The saturation energy vs the critical temperature

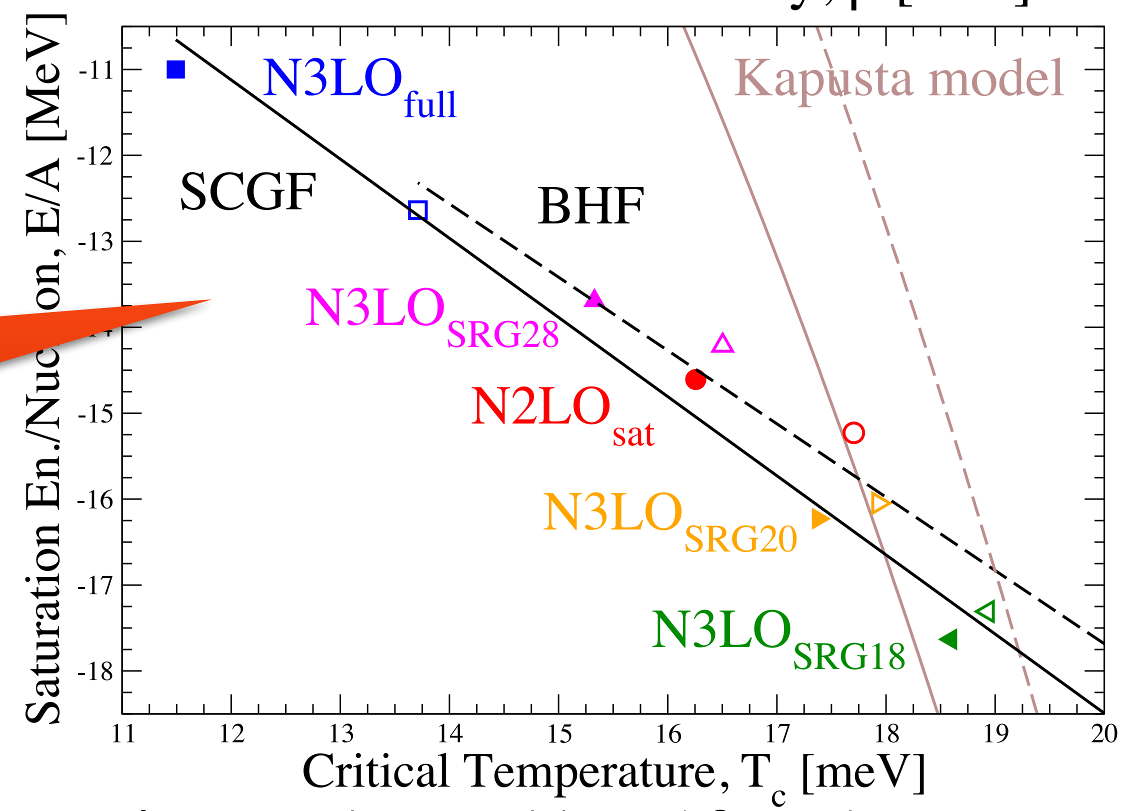
Carbone, Polls, Rios PRC 98 025804 (2018)





Esat

Tc



theoretical uncertainty bands correlate: helpful in pinning down the critical temperature

Thermal effects in EoS for astrophysical simulations

$P_{\text{cold}} + P_{\text{thermal}}$ → $P_{\text{th}} = (\Gamma_{\text{th}} - 1)\rho E_{\text{th}}$ Constant value

Astrophysical EoS

Carbone & Schwenk *(in preparation)*

Thermal effects in EoS for astrophysical simulations

$$P_{\text{cold}} + P_{\text{thermal}} \longrightarrow P_{\text{th}} = (\Gamma_{\text{th}} - 1)\rho E_{\text{th}}$$

Constant value

Astrophysical EoS

$$\Gamma_{\text{th}} = 1 + \frac{P_{\text{th}}}{\rho E_{\text{th}}}$$

$$E_{\text{th}} = E(T) - E_0$$
$$P_{\text{th}} = P(T) - E_0$$

Carbone & Schwenk *(in preparation)*

Thermal effects in EoS for astrophysical simulations

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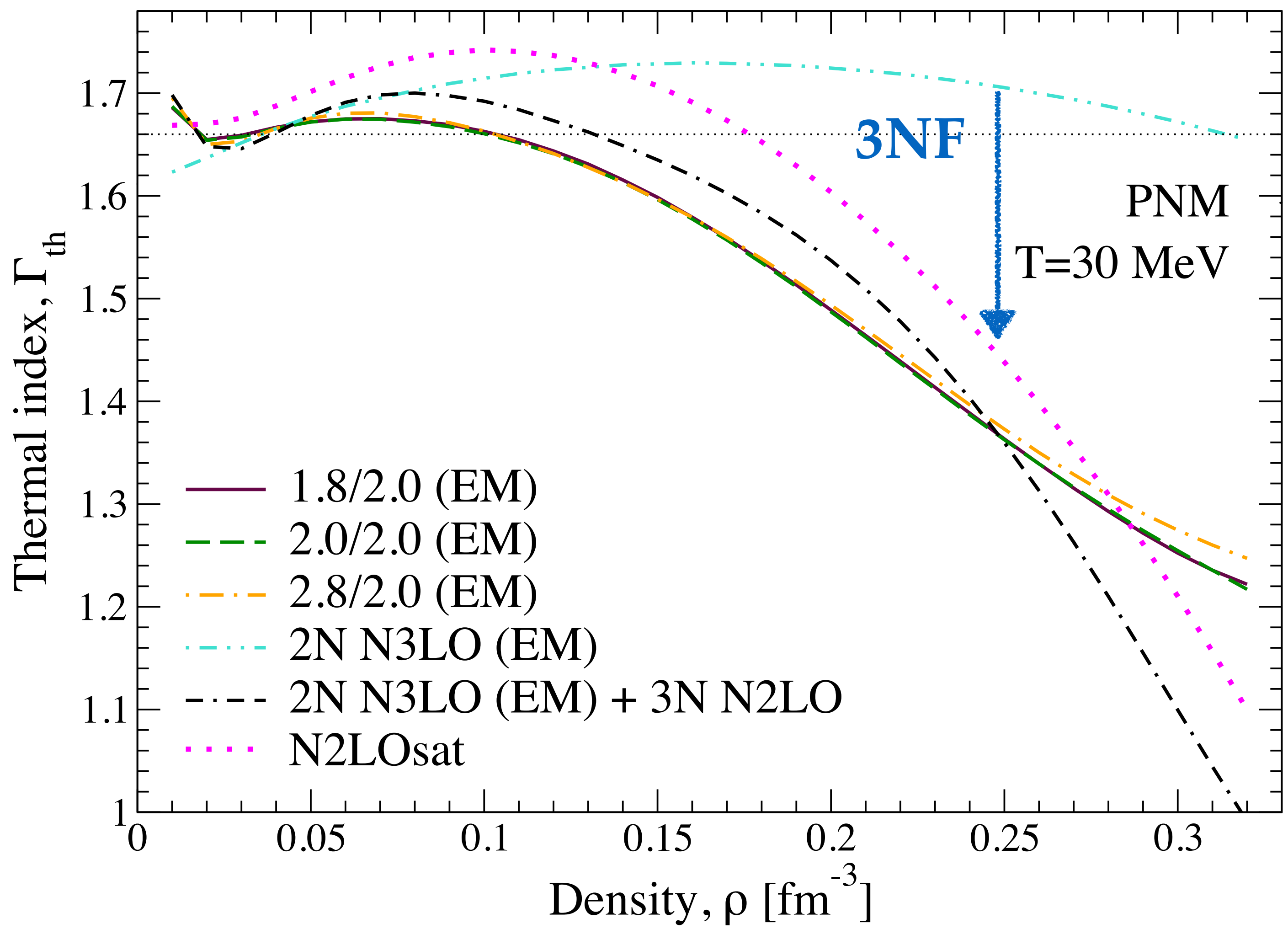

suppression due to 3-body forces

Carbone & Schwenk *(in preparation)*

Thermal effects in EoS for astrophysical simulations

$$P_{\rm cold} + P_{\rm thermal} \longrightarrow P_{\rm th} = (\Gamma_{\rm th} - 1)\rho E_{\rm th}$$ Constant value

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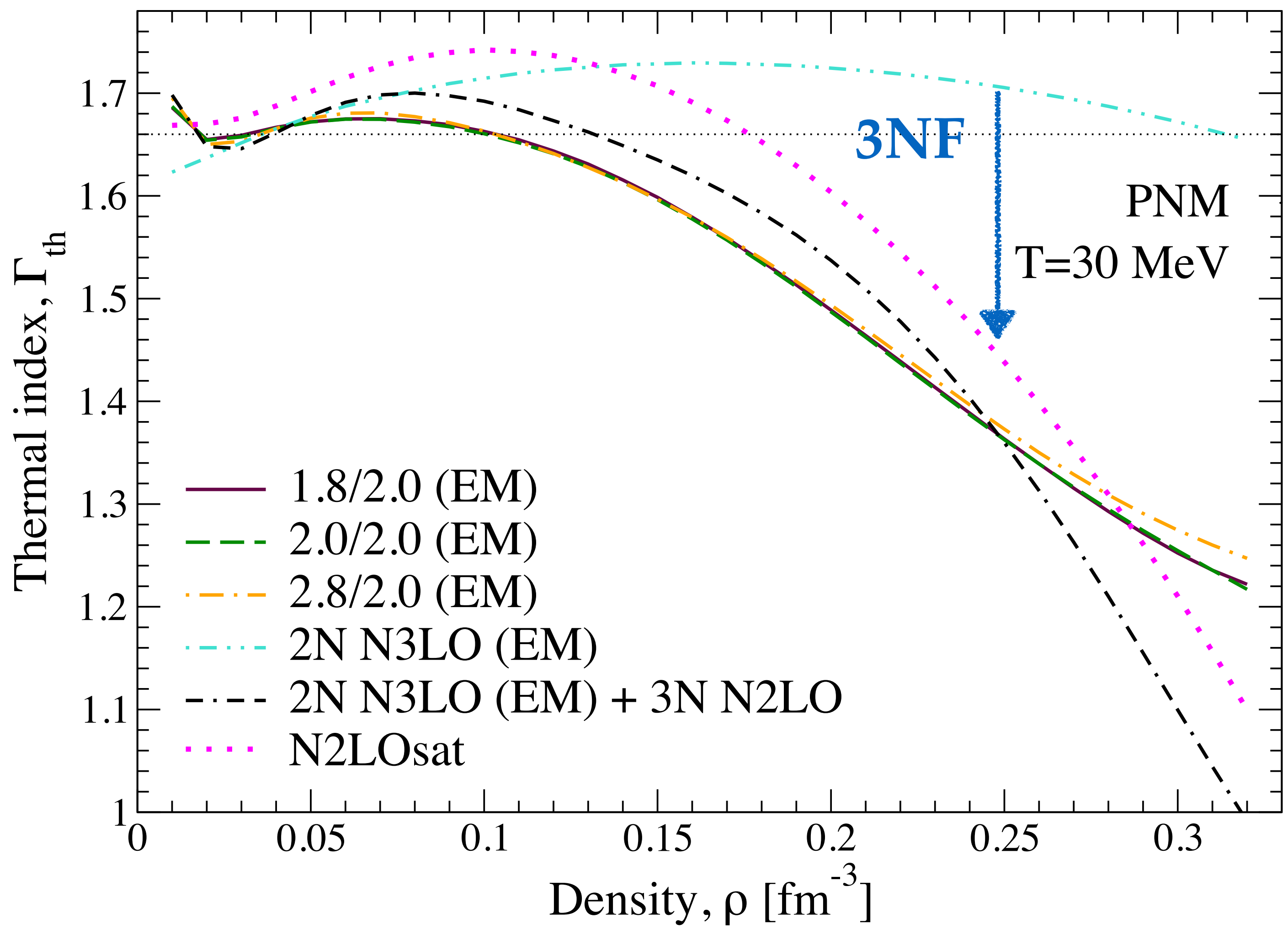
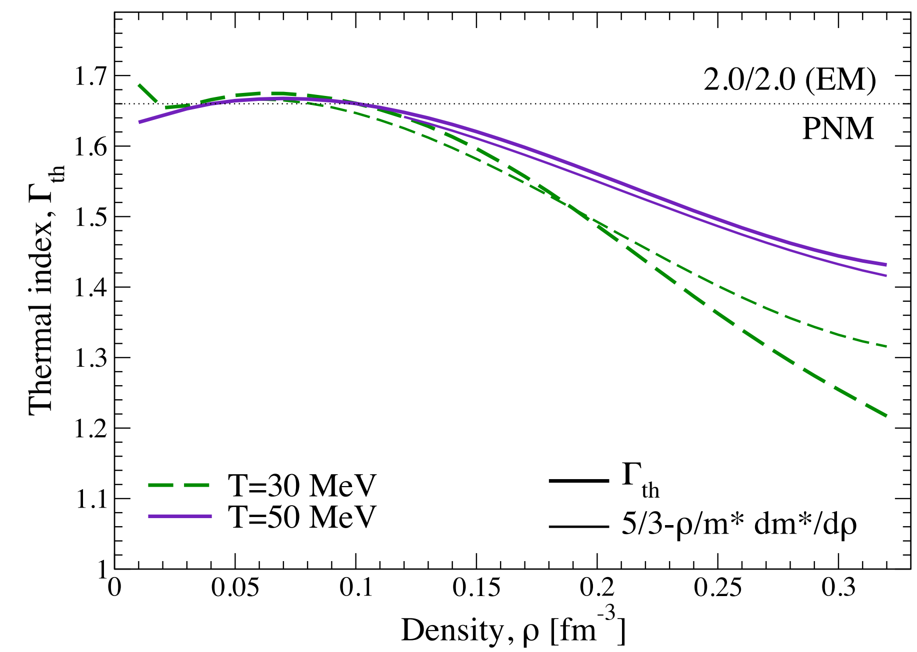
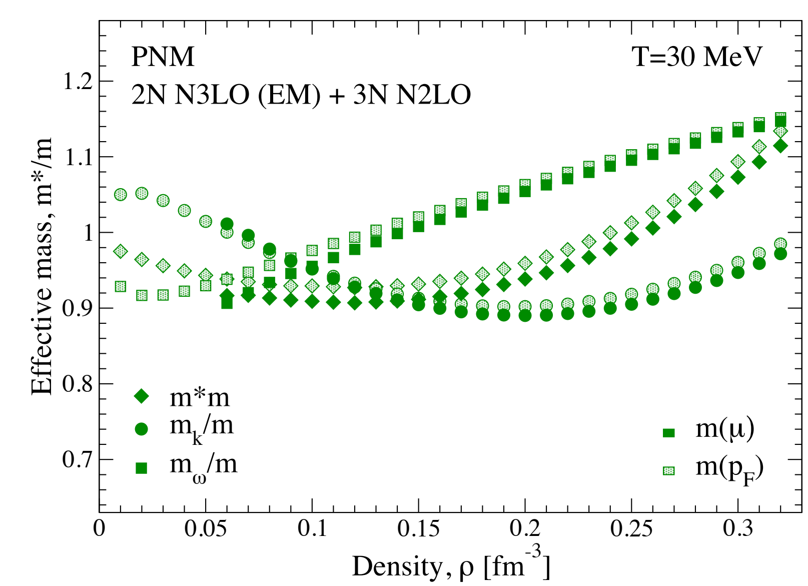






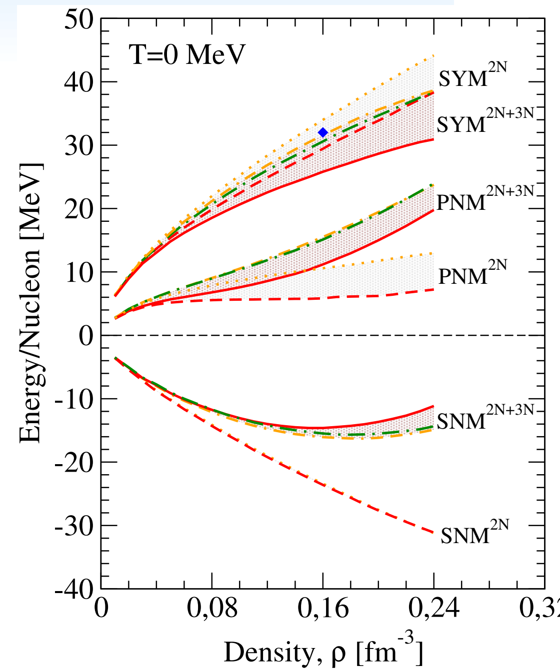
suppression due to 3-body forces

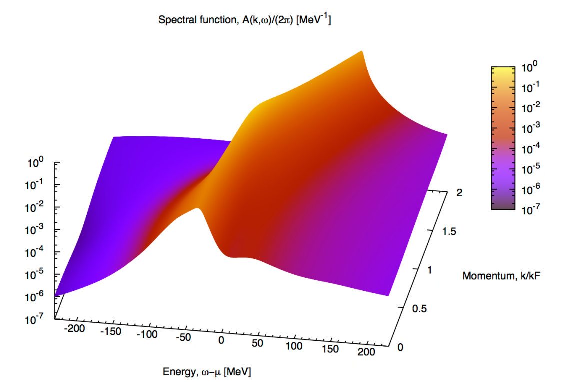
Carbone & Schwenk *(in preparation)*

Conclusions

Conclusions

★ Predict the symmetry energy from first principles

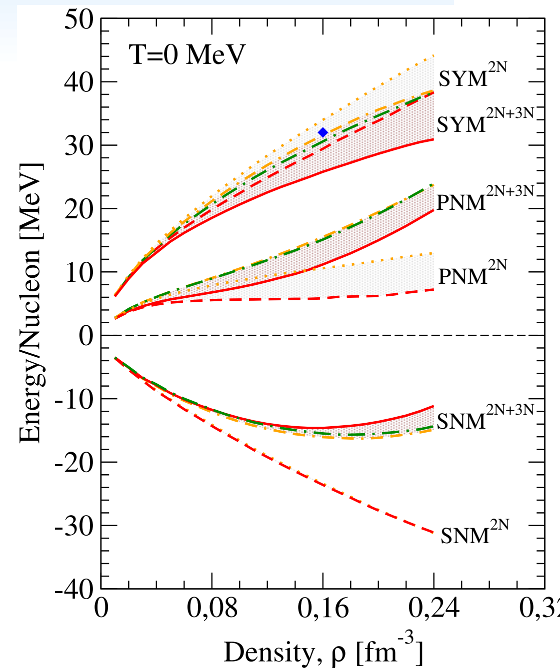


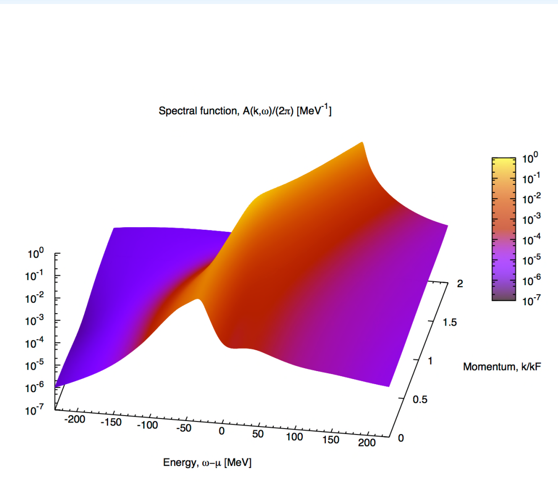


Conclusions

★ Predict the symmetry energy from first principles

★ Pinning saturation point is not enough for reasonable predictions



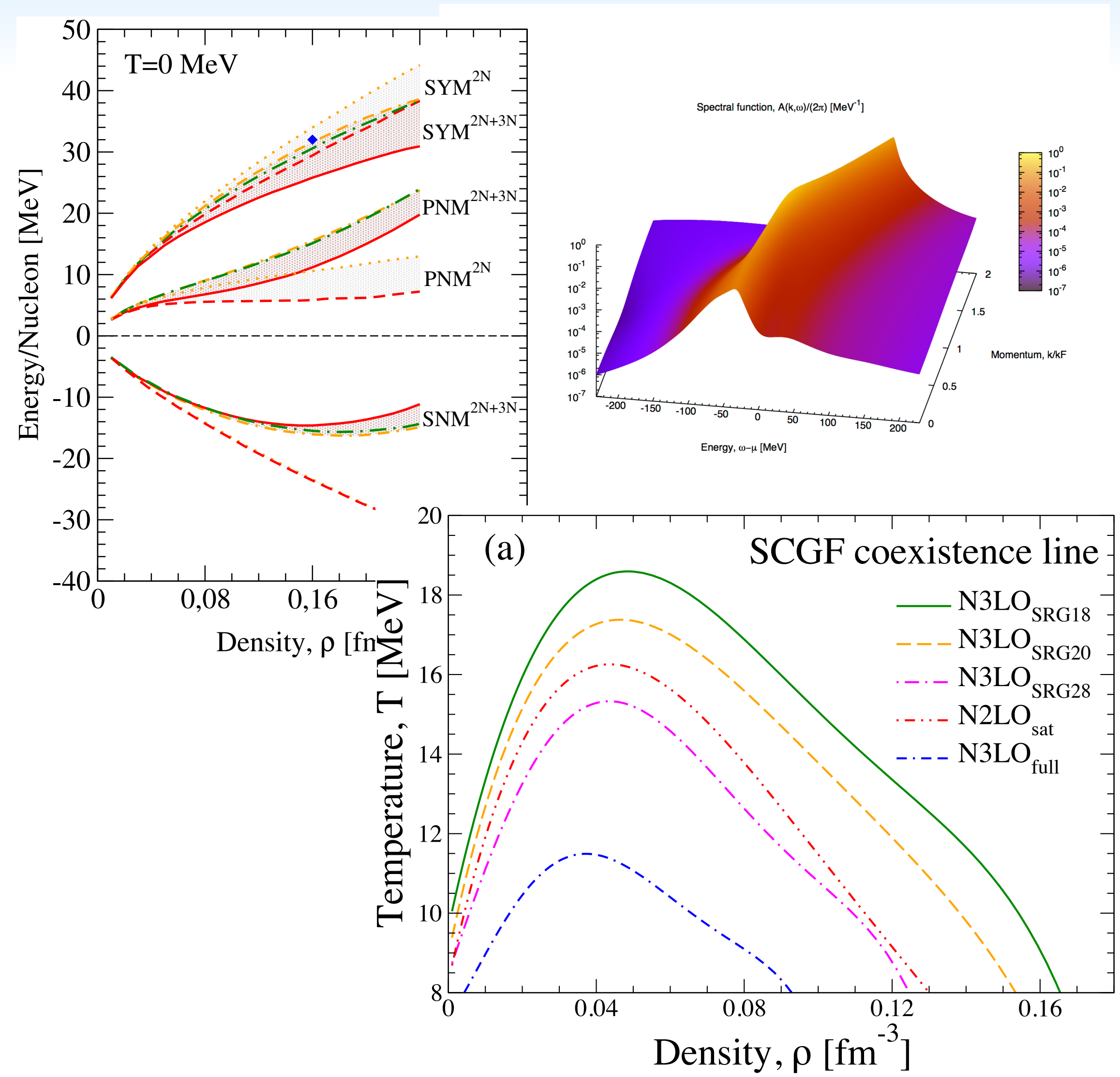


Conclusions

★ Predict the symmetry energy from first principles

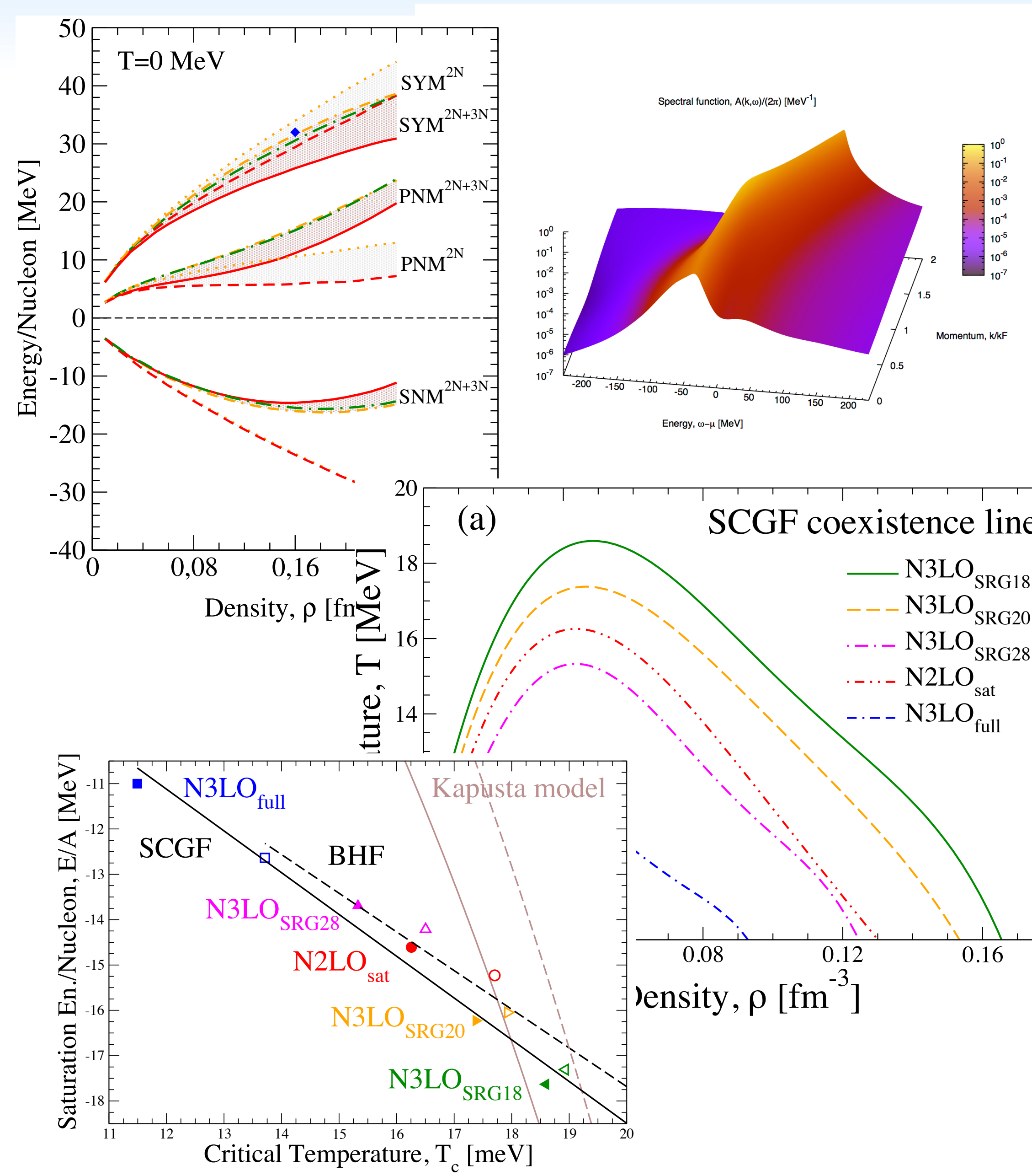
★ Pinning saturation point is not enough for reasonable predictions

★ Acceptable results for the liquid-gas critical temperature



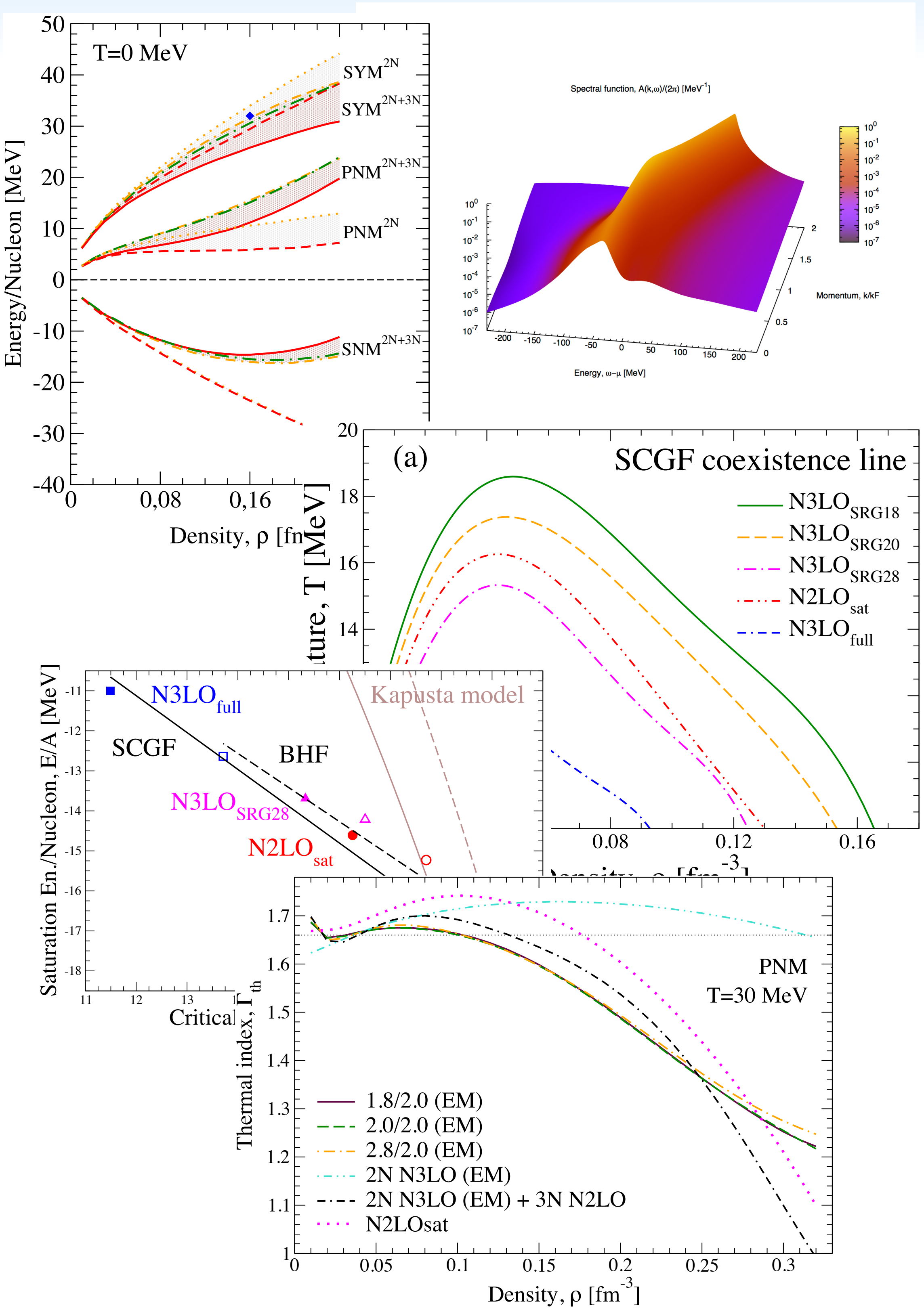
Conclusions

- ★ Predict the symmetry energy from first principles
- ★ Pinning saturation point is not enough for reasonable predictions
- ★ Acceptable results for the liquid-gas critical temperature
- ★ Correlations between Esat and Tc



Conclusions

- ⋆ Predict the symmetry energy from first principles
- ⋆ Pinning saturation point is not enough for reasonable predictions
- ⋆ Acceptable results for the liquid-gas critical temperature
- ⋆ Correlations between Esat and Tc
- ⋆ Thermal effects are important for astro EoS



Conclusions

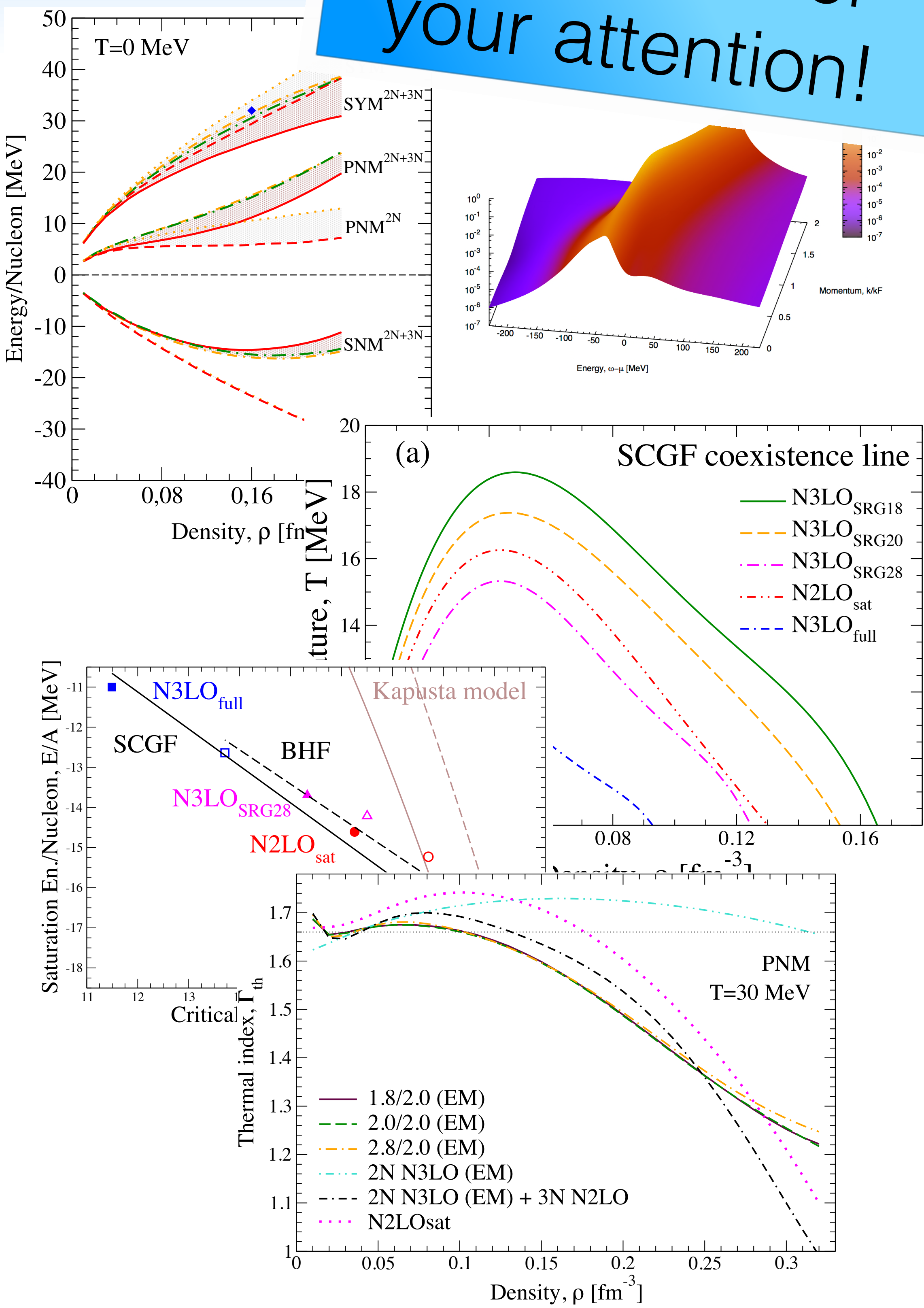
Thank you for your attention!

- ★ Predict the symmetry energy from first principles
- ★ Pinning saturation point is not enough for reasonable predictions
- ★ Acceptable results for the liquid-gas critical temperature
- ★ Correlations between Esat and Tc
- ★ Th… tant for as…

TECHNISCHE UNIVERSITÄT DARMSTADT — C. Drischler, P. Klos, K. Hebeler, A. Schwenk

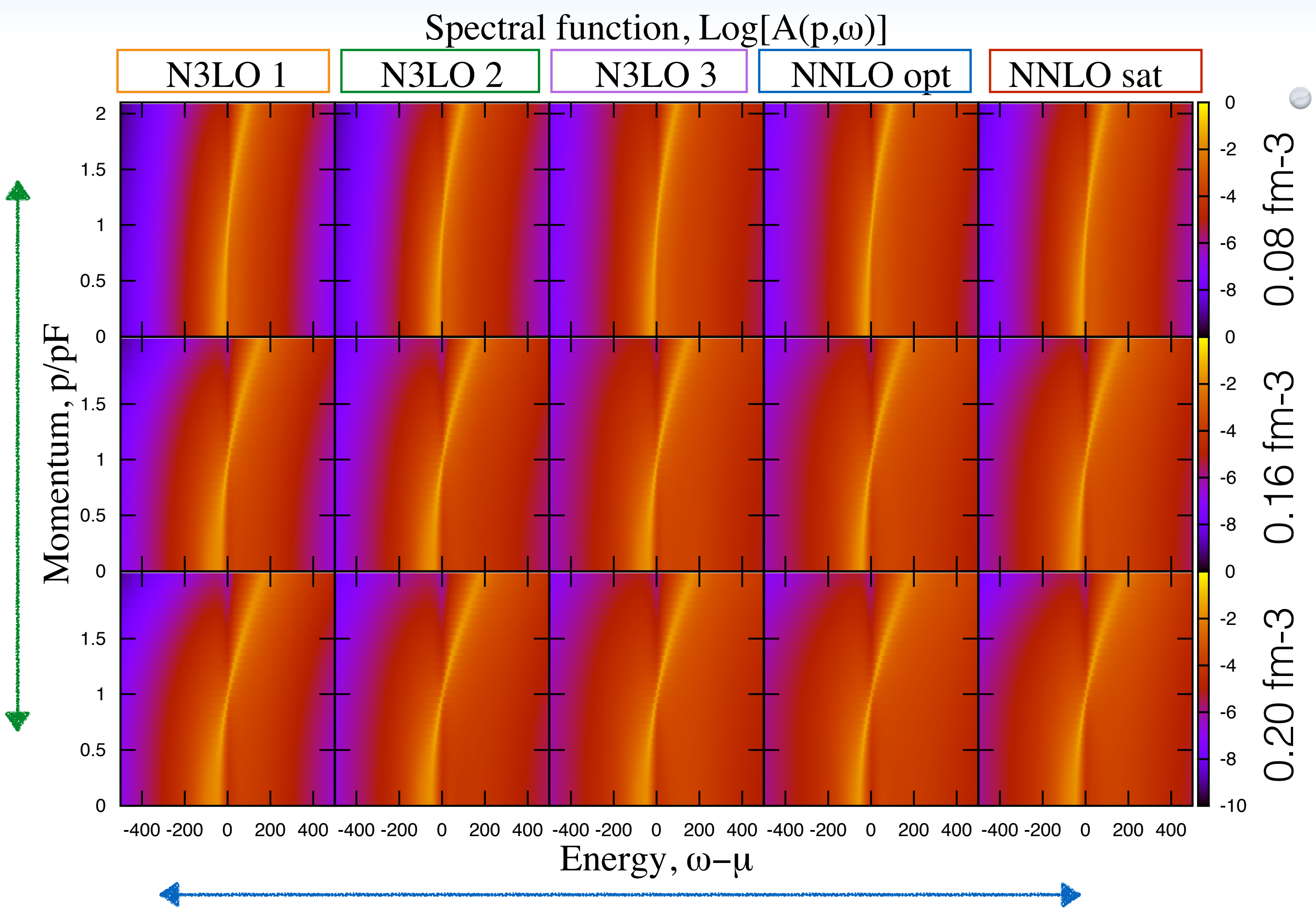
UNIVERSITY OF SURREY — A. Rios, C. Barbieri

Universitat de Barcelona — A. Polls

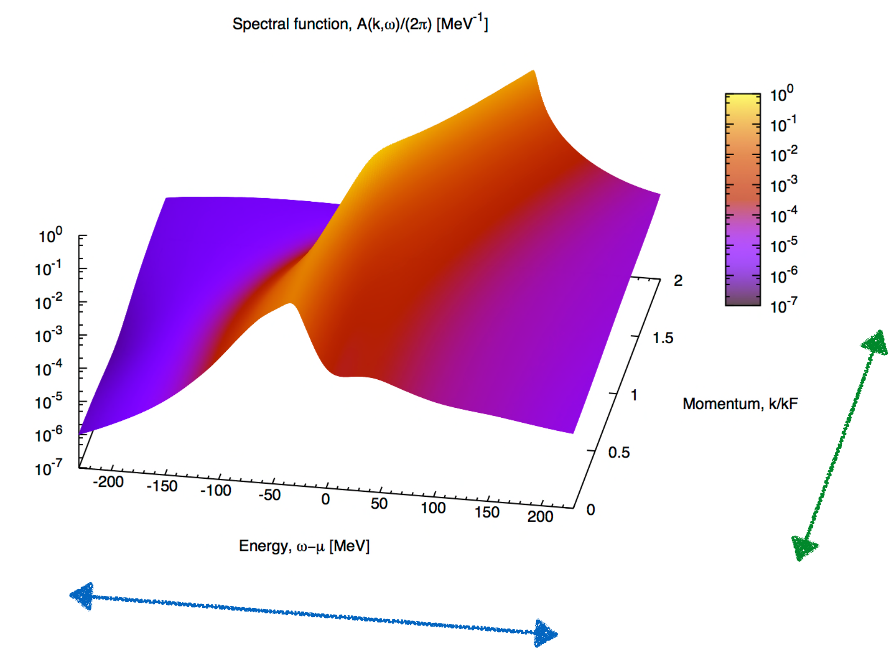


Backup

Microscopic properties according to different Hamiltonians

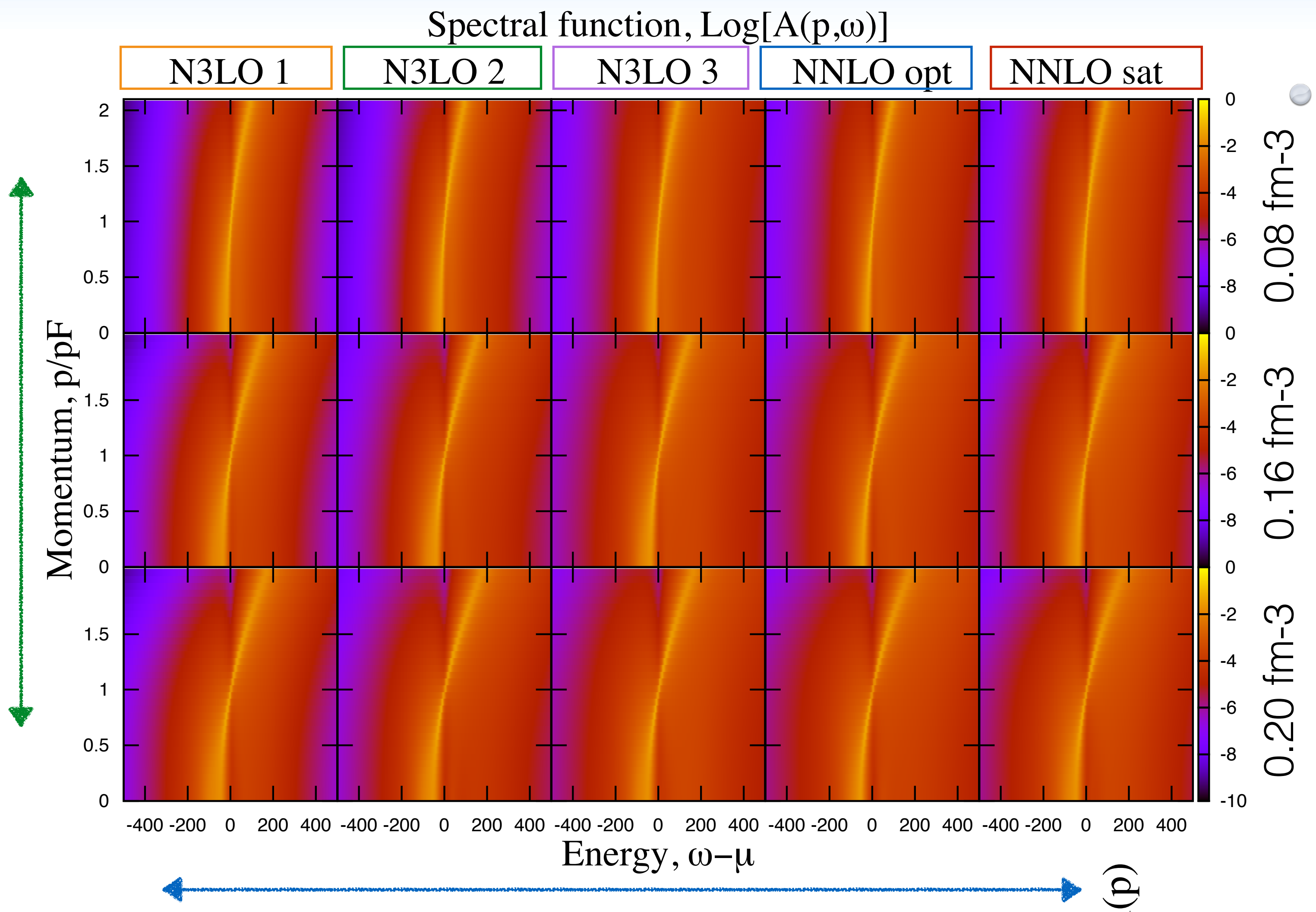


- full description beyond quasiparticle

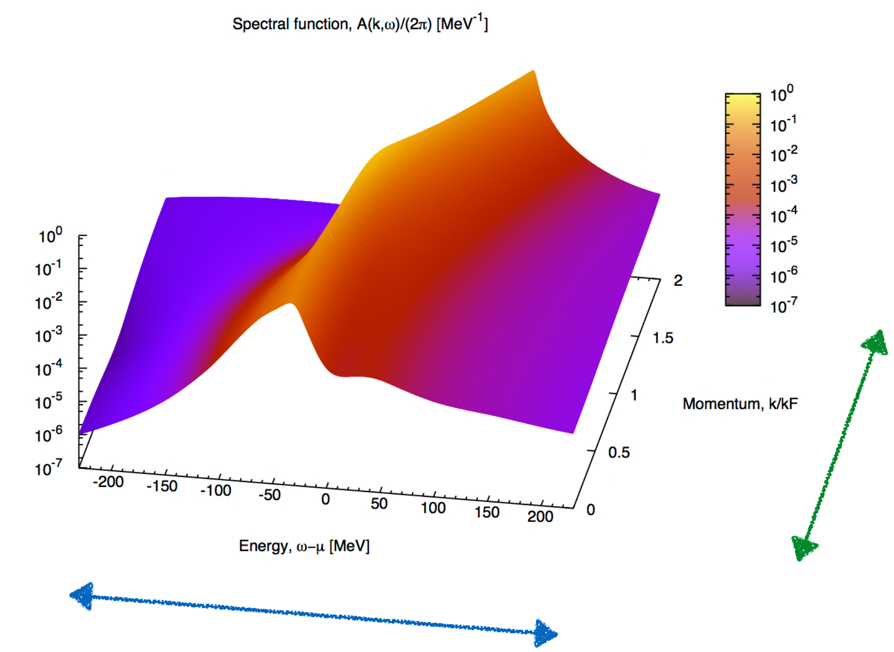


- energy tails affected by the cutoff on the NN force
- high-momentum region also affected by cutoff and density dependence
- effects clearly visible in momentum distribution

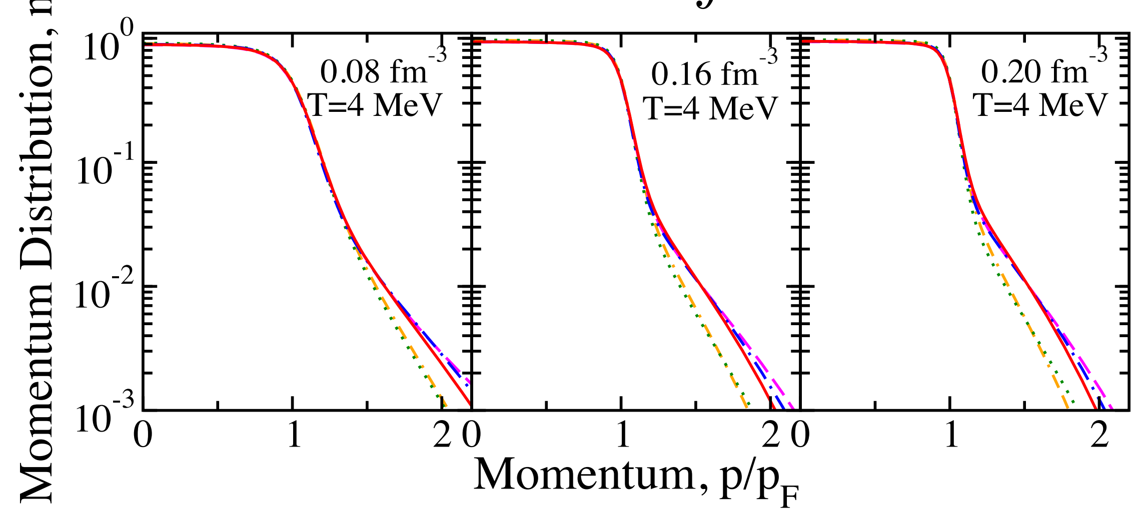
Microscopic properties according to different Hamiltonians



- full description beyond quasiparticle



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



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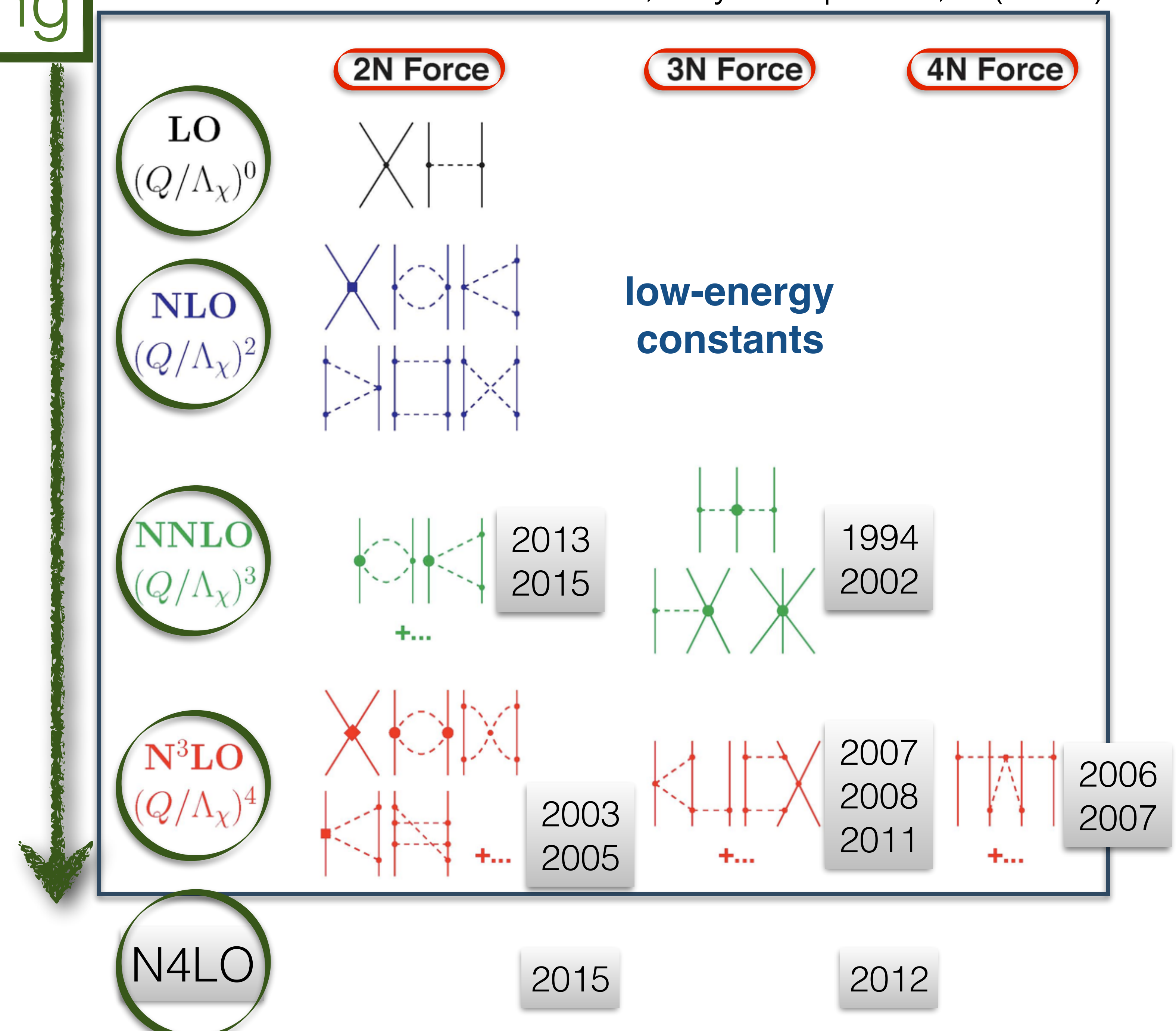
- high-momentum region also affected by cutoff and density dependence
- effects clearly visible in momentum distribution

Why nuclear matter from chiral EFT?

Epelbaum *et al.*, Rev. Mod. Phys. 81, 1773(2009)
Machleidt *et al.*, Phys. Rep. 503, 1 (2011)

Power counting

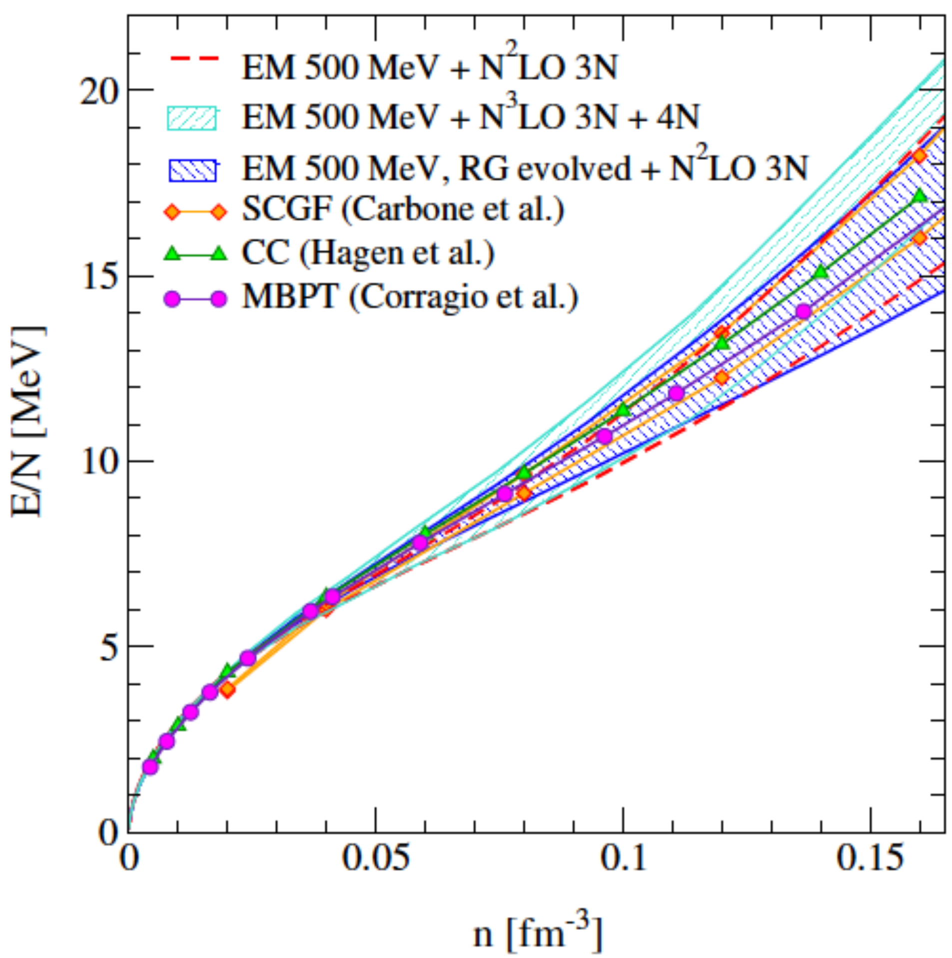


- Effective theory of QCD
- Nucleons & pions as d.o.f.
- Power counting expansion
- Hierarchy of many-body forces
- Theoretical uncertainties

<u>Over 20 years of ongoing improvement</u>

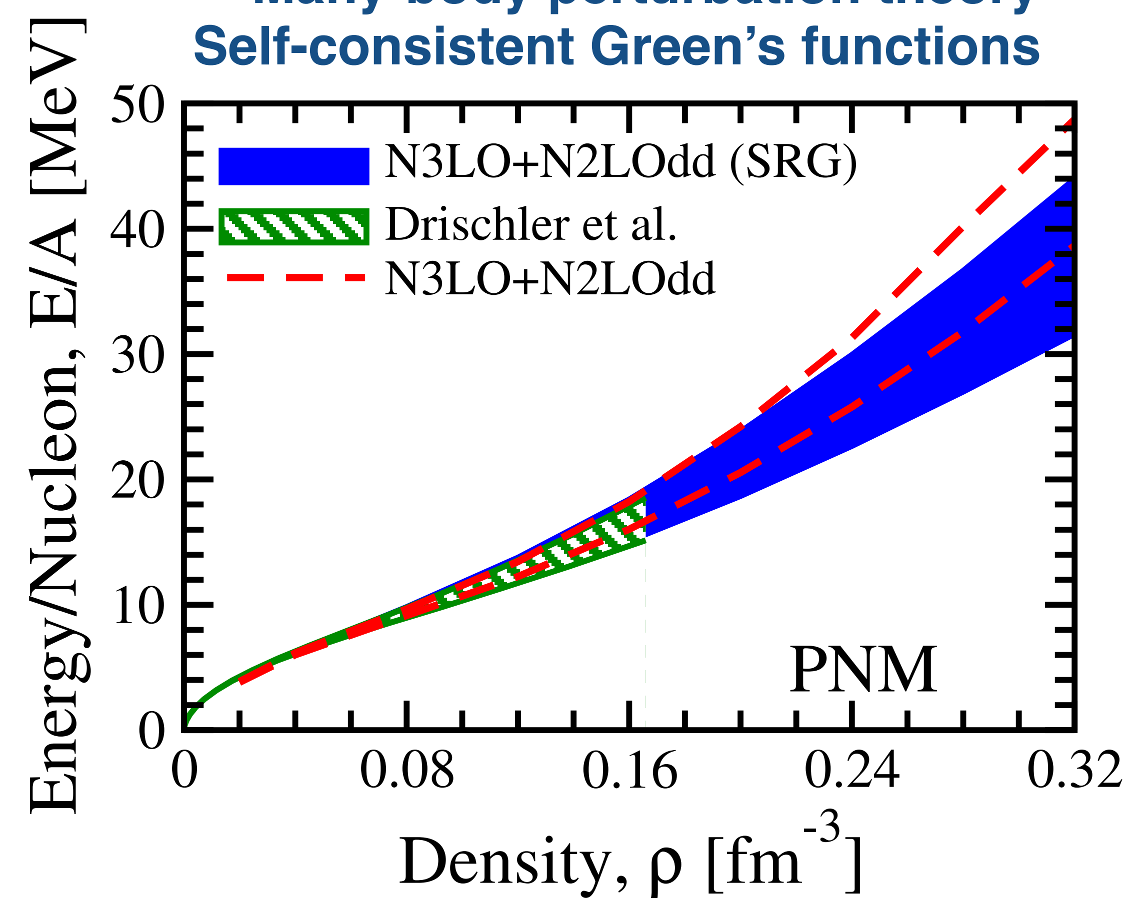
Many-body methods comparison

Remarkable agreement between several many-body methods and different Hamiltonians



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

Many-body perturbation theory
Self-consistent Green's functions

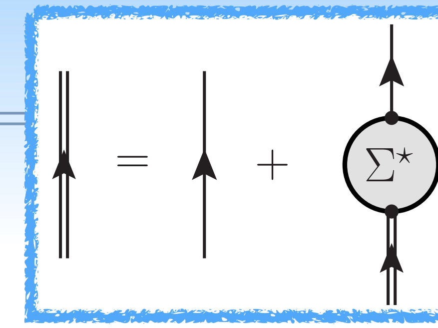


Carbone, Rios, Polls, PRC 90, 054322 (2014)

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

- Low-density neutron matter perturbative

Extended SCGF approach

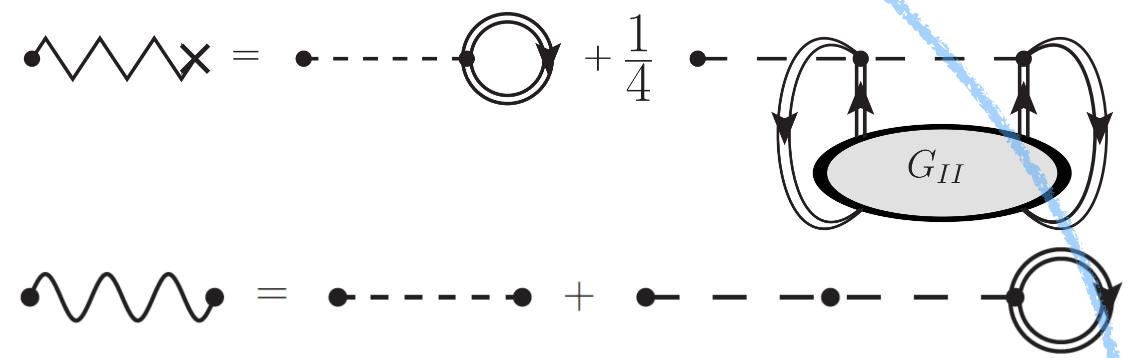


Carbone, Cipollone, Barbieri, Rios, Polls, PRC **88**, 054326 (2013)

2B → **2B + 3B**

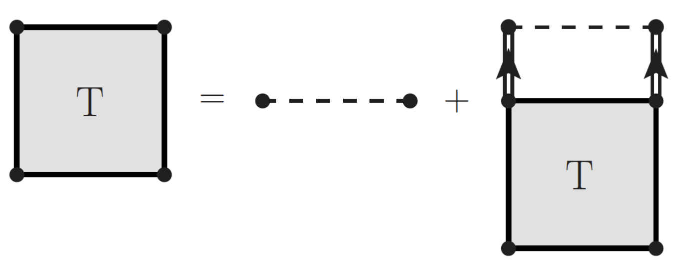
1. define **effective interactions** to include correctly 3B terms, **dressed normal ordering**:

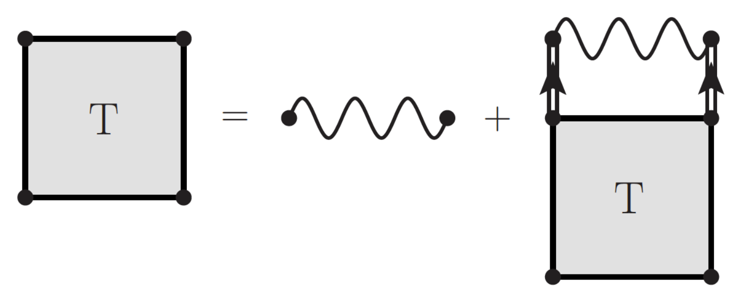
Interaction



2. calculate T-matrix with effective 2B term, **modified ladder approximation**:

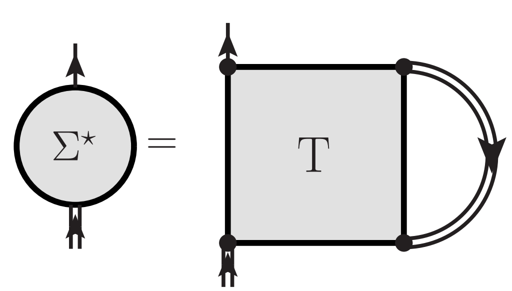
T-matrix

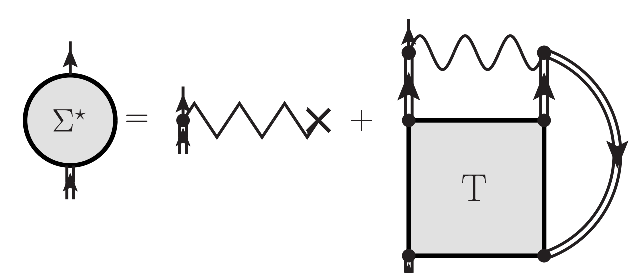




3. calculate self-energy distinguishing the effective terms, **correct diagrams counting**:

Self-energy

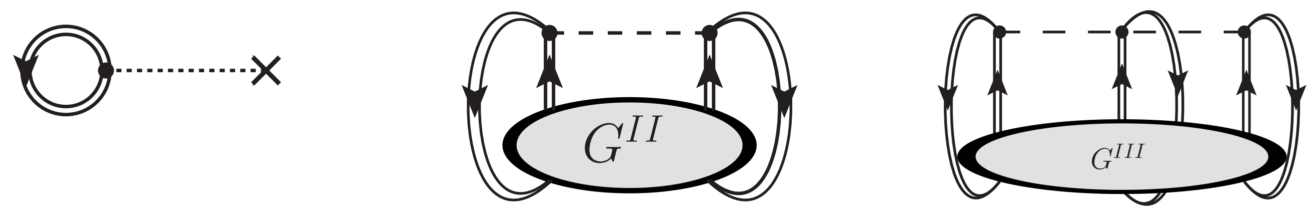




Define a new sum rule

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

$$E^N = \langle\Psi^N|\hat{H}|\Psi^N\rangle = \langle\Psi^N|\hat{T}|\Psi^N\rangle + \langle\Psi^N|\hat{V}|\Psi^N\rangle + \langle\Psi^N|\hat{W}|\Psi^N\rangle$$



- Galitskii-Migdal-Koltun sumrule modified:

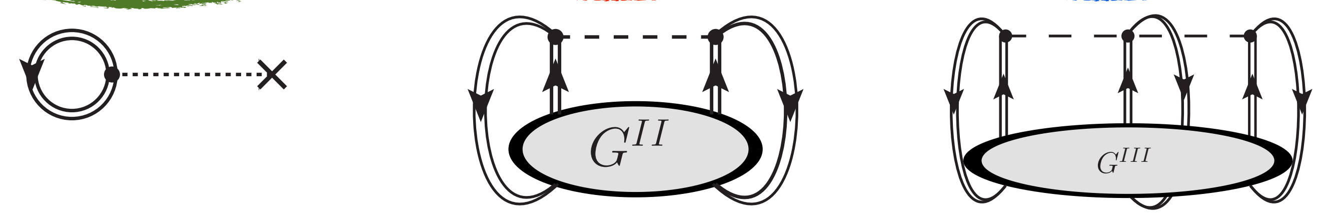
$$\sum_\alpha \int_{-\infty}^{E^N - E^{N-1}} \mathrm{d}\omega\, \omega \frac{1}{\pi} \mathrm{Im}\, G_{\alpha\alpha}(\omega) = \langle\Psi^N|\hat{T}|\Psi^N\rangle + 2\langle\Psi^N|\hat{V}|\Psi^N\rangle + 3\langle\Psi^N|\hat{W}|\Psi^N\rangle$$

$$\boxed{\frac{E}{A} = \frac{\nu}{\rho} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \int \frac{\mathrm{d}\omega}{2\pi} \frac{1}{2} \left\{ \frac{p^2}{2m} + \omega \right\} \mathcal{A}(p,\omega) f(\omega) - \frac{1}{2}\langle\Psi^N|\hat{W}|\Psi^N\rangle}$$

Define a new sum rule

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

$$E^N = \langle \Psi^N | \hat{H} | \Psi^N \rangle = \langle \Psi^N | \hat{T} | \Psi^N \rangle + \langle \Psi^N | \hat{V} | \Psi^N \rangle + \langle \Psi^N | \hat{W} | \Psi^N \rangle$$



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Backup

- Plot of pressure of PNM (to compare with Tsang, Danielewicz paper 2018)
- Plot of symmetry energy as T-dependance
- slide with diagrams and formula of GMK sumrule
- figure of pnm with many approaches