Recent advances in infinite matter based on chiral nuclear forces

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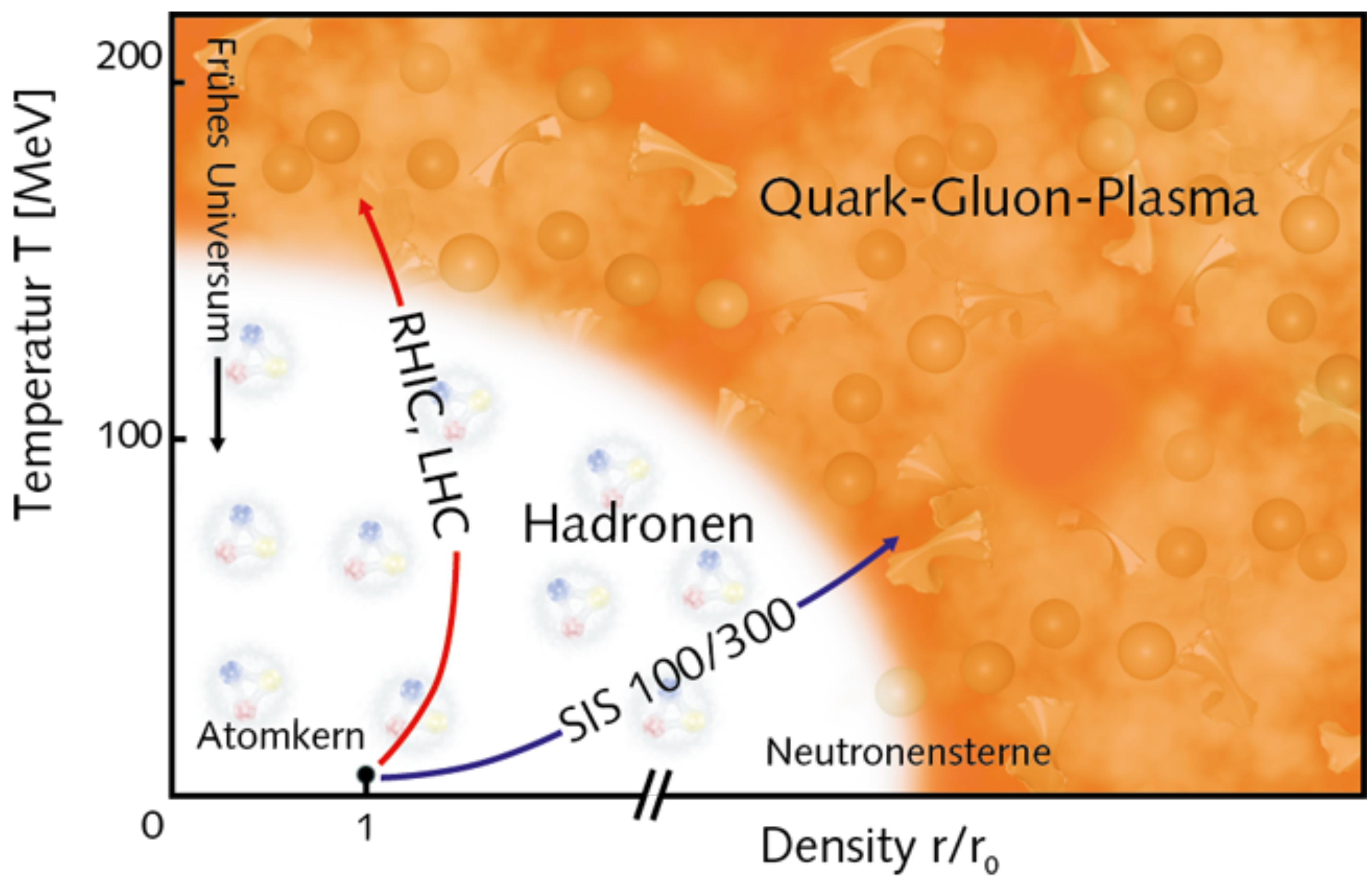
Nuclear matter covers wide ranges of density and temperature

The phase diagram of **hadronic matter**

High T, low rho early universe



https://www.gsi.de/en/start/fair/forschung_an_fair/kernmateriephysik.htm

Question about a transition to a QG plasma phase

Low T, high rho neutron-rich systems

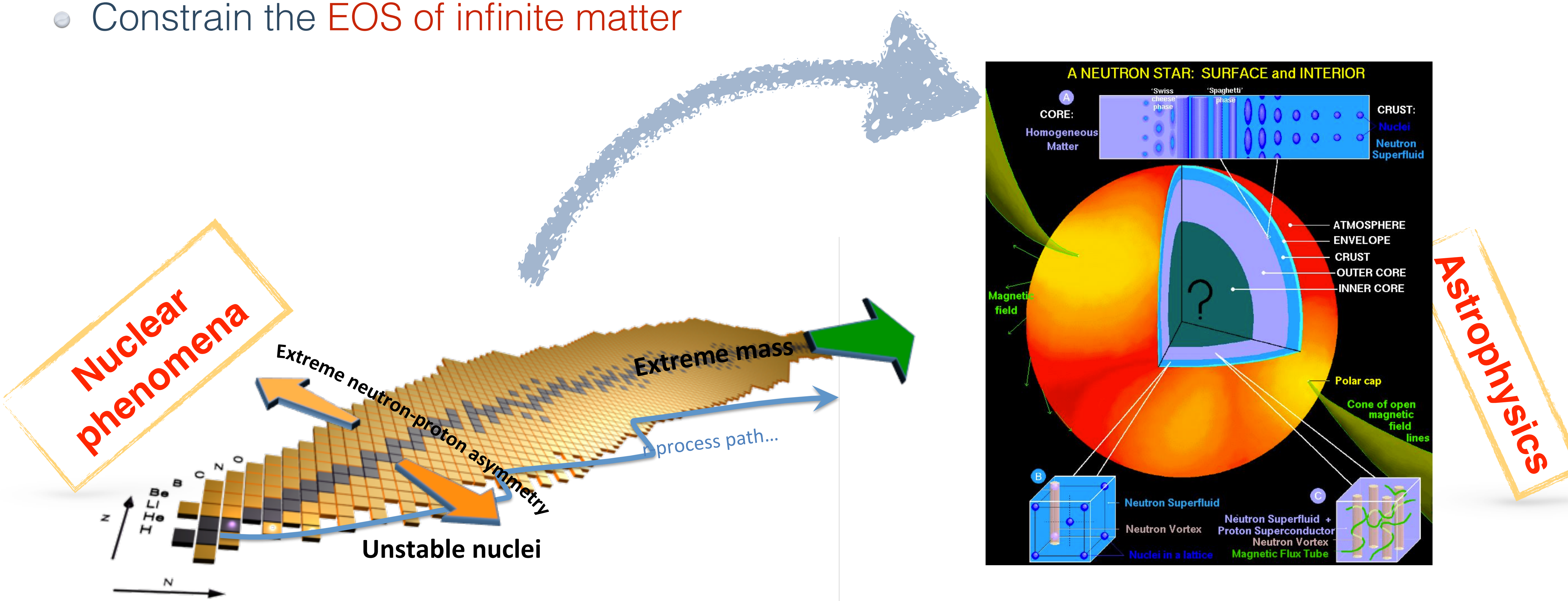
Radioactive beam facilities will access this region at the extremes

How can nuclear theory help experiment understand the QCD phase diagram?

The nuclear many-body problem

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

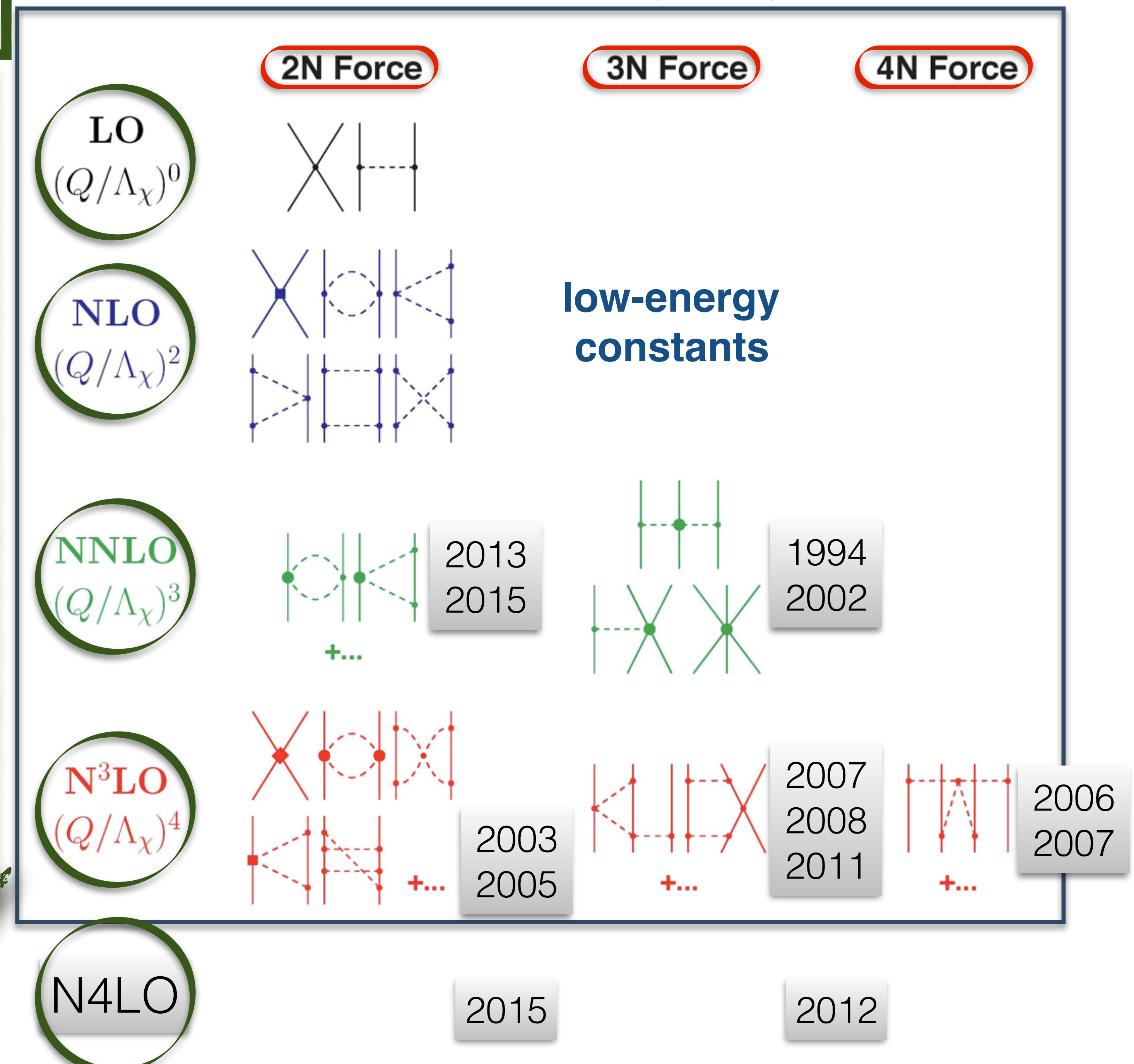
From nuclei to nuclear matter



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

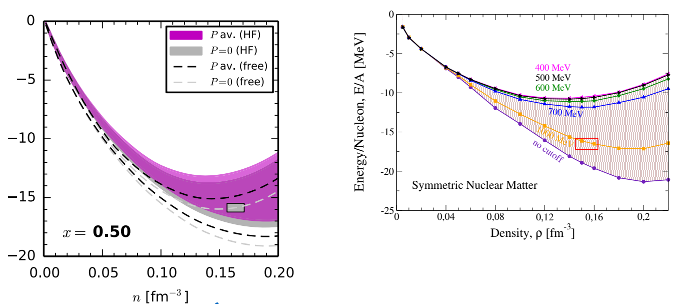


- Effective theory of QCD
- Nucleons & pions as d.o.f.
- Power counting expansion
- Hierarchy of many-body forces
- Theoretical uncertainties

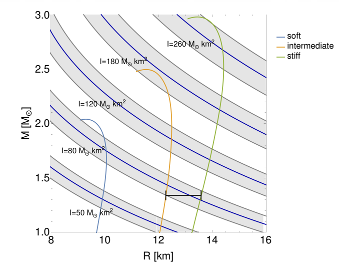
Over 20 years of ongoing improvement

What can we predict?

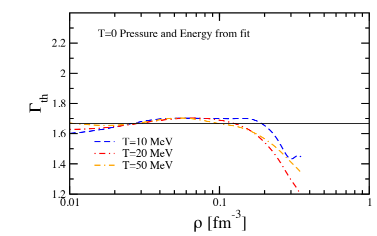
Saturation point & uncertainties



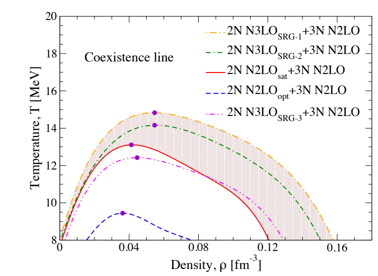
Neutron star moment of inertia



Thermal effects in the PNM EOS

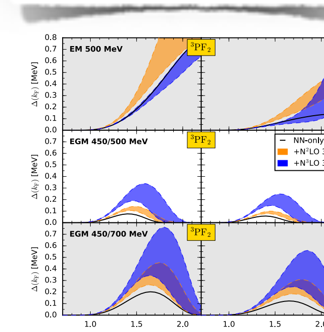


Finite-T & estimate of liquid-gas transition

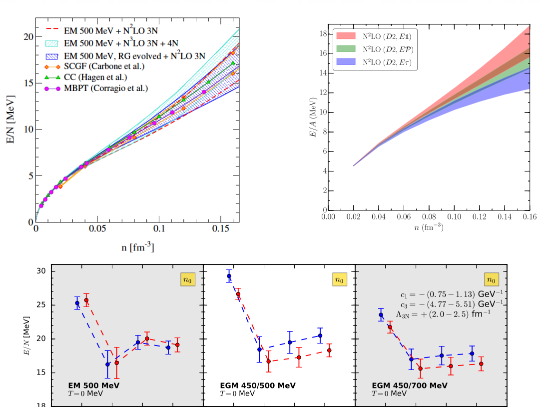


Many-Body approaches + Chiral EFT

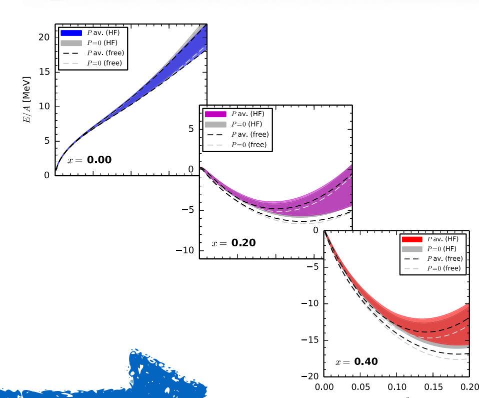
Pairing gap in PNM



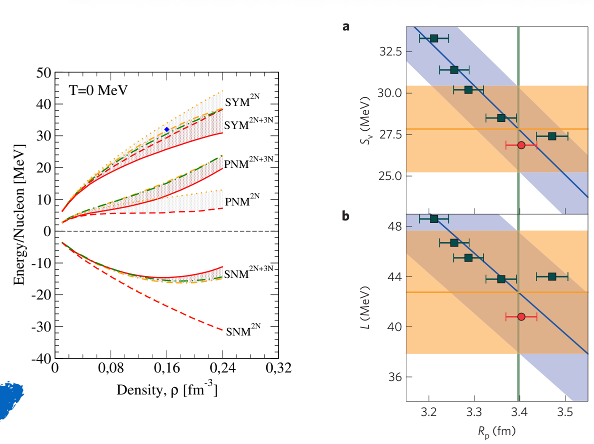
PNM equation of state



Asymmetric matter



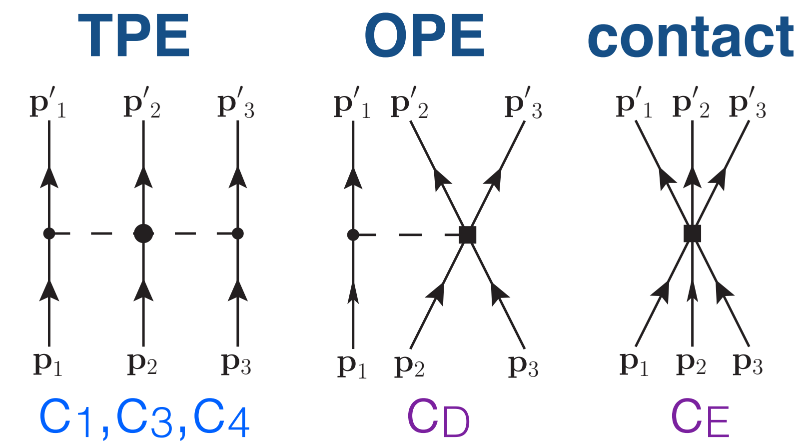
Symmetry energy & slope parameter



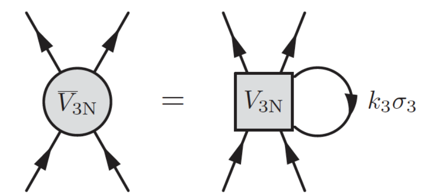
Saturation point according to different Hamiltonians

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

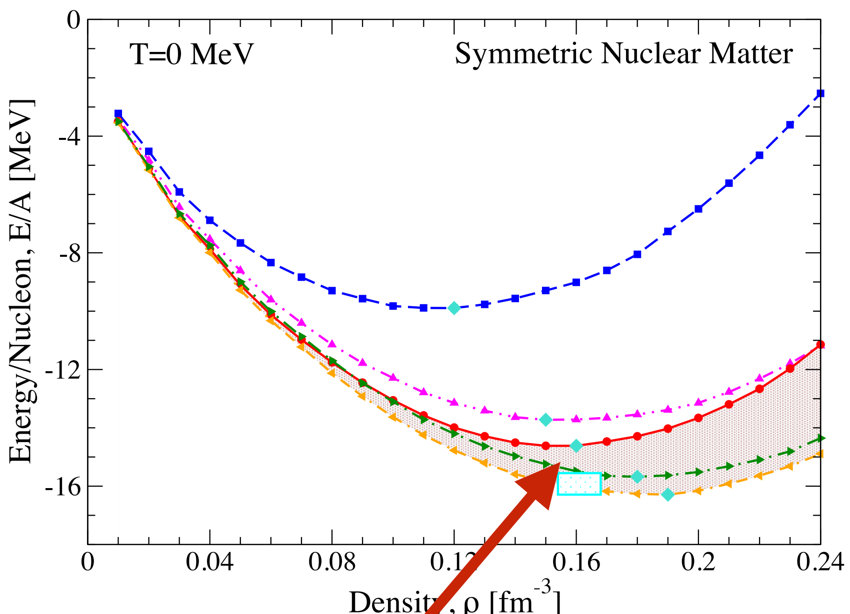
- N3LO EM500 or EGM+SRG, 3NFs fit to ^{3}H BEs, ^{4}He r_m
- N2LOopt (POUNDERS), 3NFs fit to ^{3}H, ^{3}He BEs
- N2LOsat (POUNDERS), NN+3N fit to ^{3}H, ^{3,4}He, ^{14}C, ^{16}O BEs, r_{ch}



average



SCGF

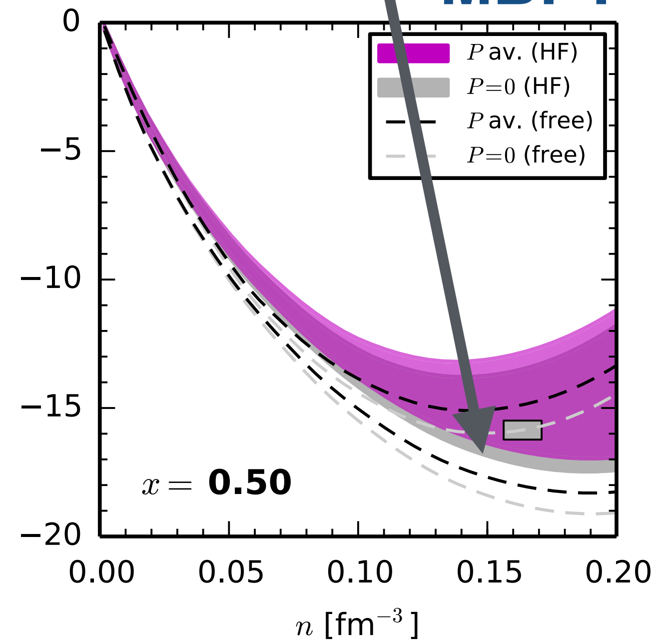


Carbone *(in preparation)*

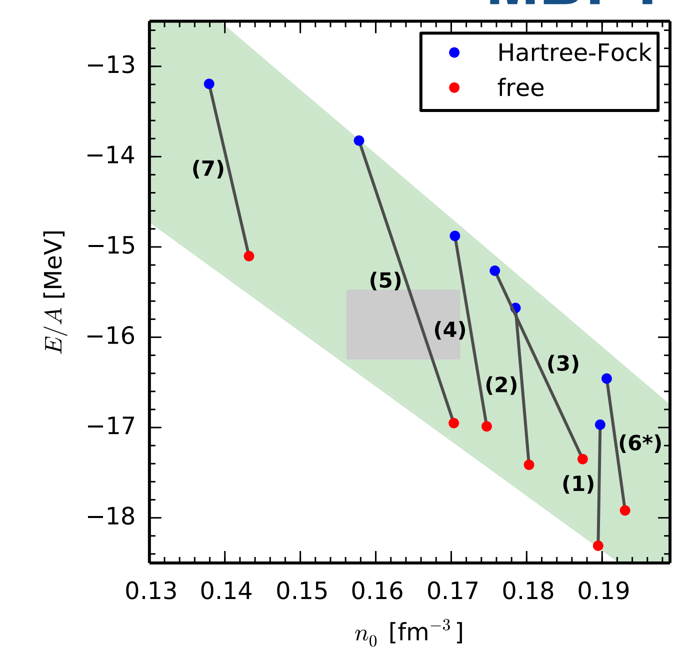
N2LOsat: predicts saturation density

average uncertainty

MBPT



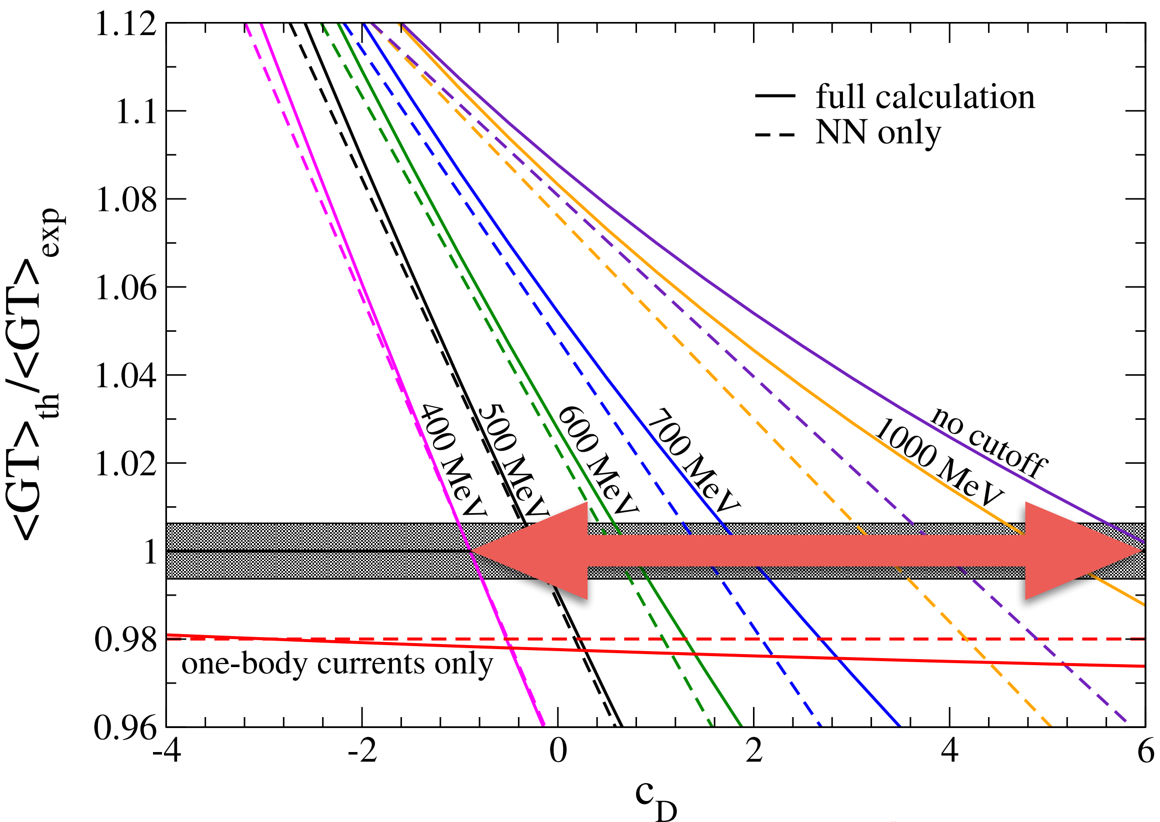
MBPT

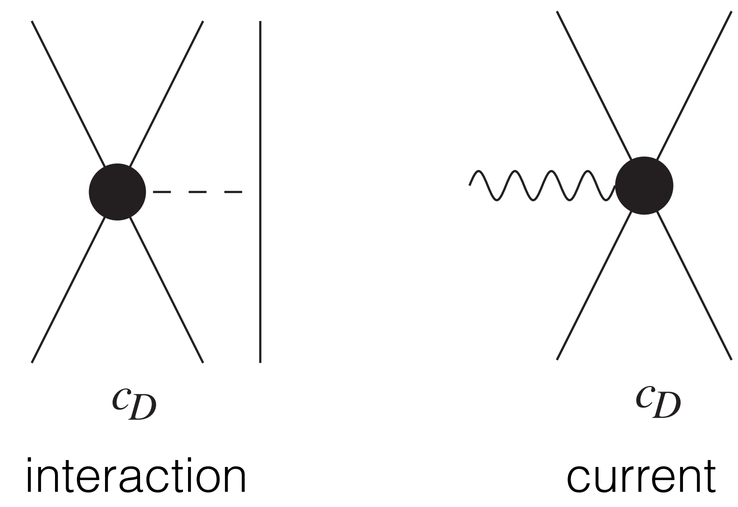


Drischler, Hebeler, Schwenk PRC93, 054314 (2016)

Uncertainties due to fitting procedures

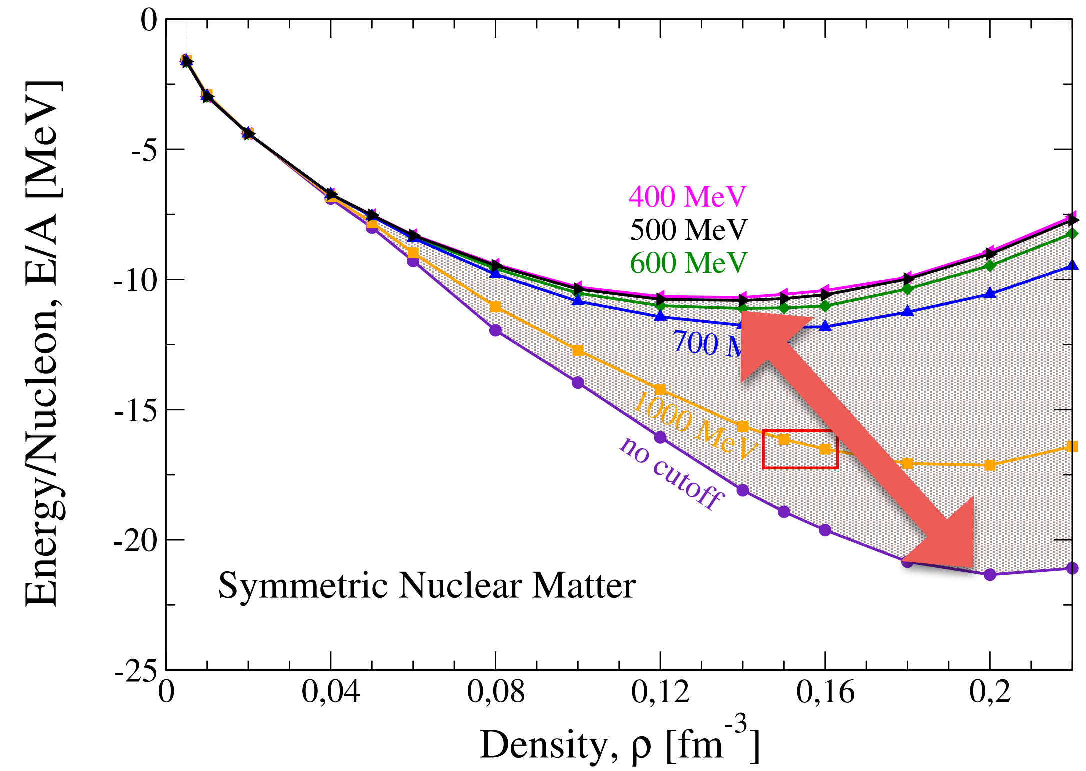
- Triton beta-decay is exp. precisely known
- Constraints on the cD coupling





Cutoff dependence on the current

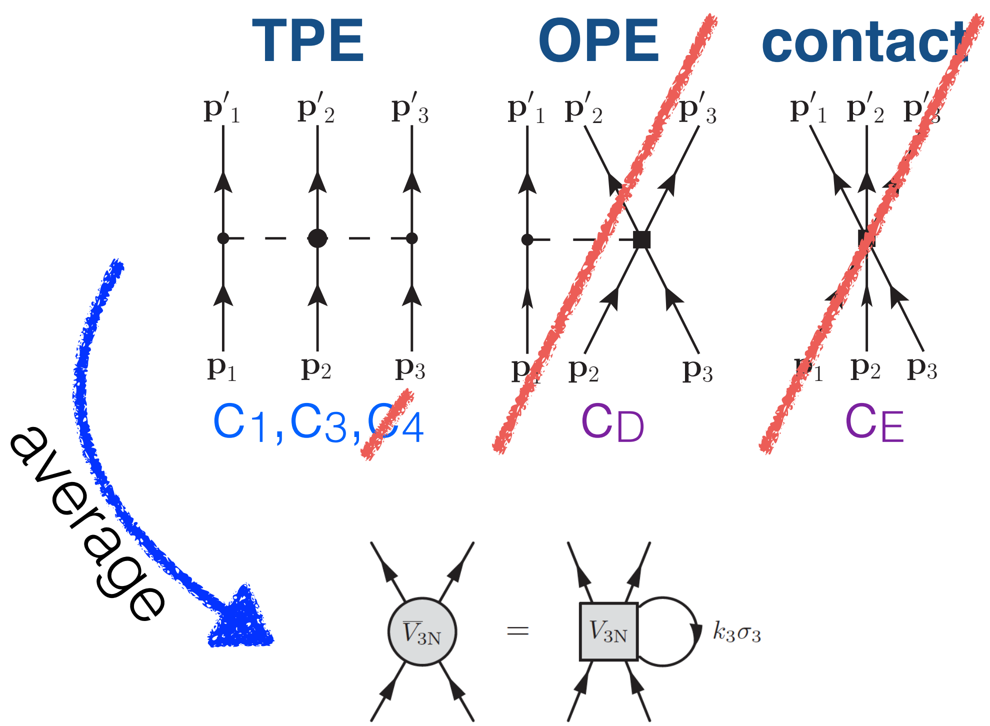
SCGF



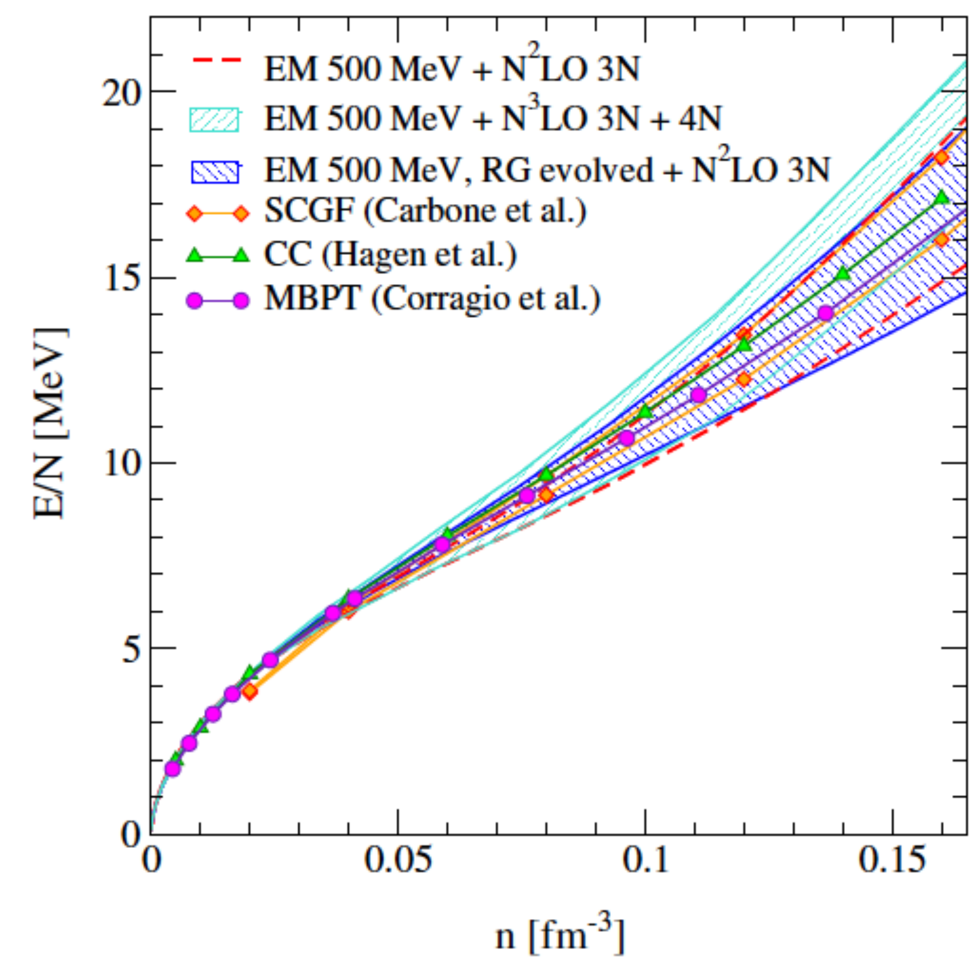
- **Visible effect on the prediction of the saturation point**
- Energy and density range:
  E=[-11;-20]MeV; r=[0.14-0.20]fm^{-3}

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

Many-body methods comparison



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



- Low-density neutron matter perturbative
- Bands from c1 and c3 uncertainties
- First calculations including N3LO 3N at HF

Remarkable agreement between many-body methods and different Hamiltonians

Further results:

AFDMC - Gezerlis et al., PRC 90, 054323 (2014)

Lattice EFT - Epelbaum et al., EPJA 40, 199 (2009)

In-medium Chiral PT - J.W. Holt et al., PPNP 73, 35 (2013),

Lacour et al., Ann. Phys. 326, 241 (2011)

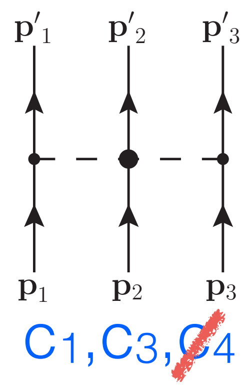
MBPT Wellenhofer et al, PRC 92, 015801 (2015)

Pure neutron matter

Quantum Monte Carlo and local chiral forces

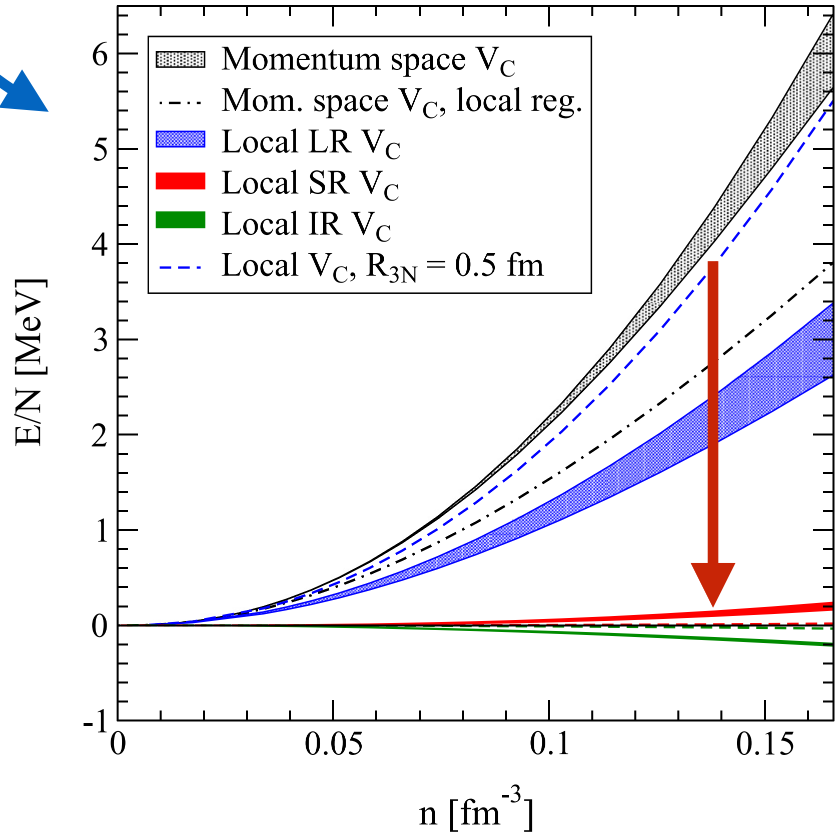
- Fourier transformed nonlocal TPE translates into a long-range + intermediate-range+ short-range local coordinate space interaction

TPE



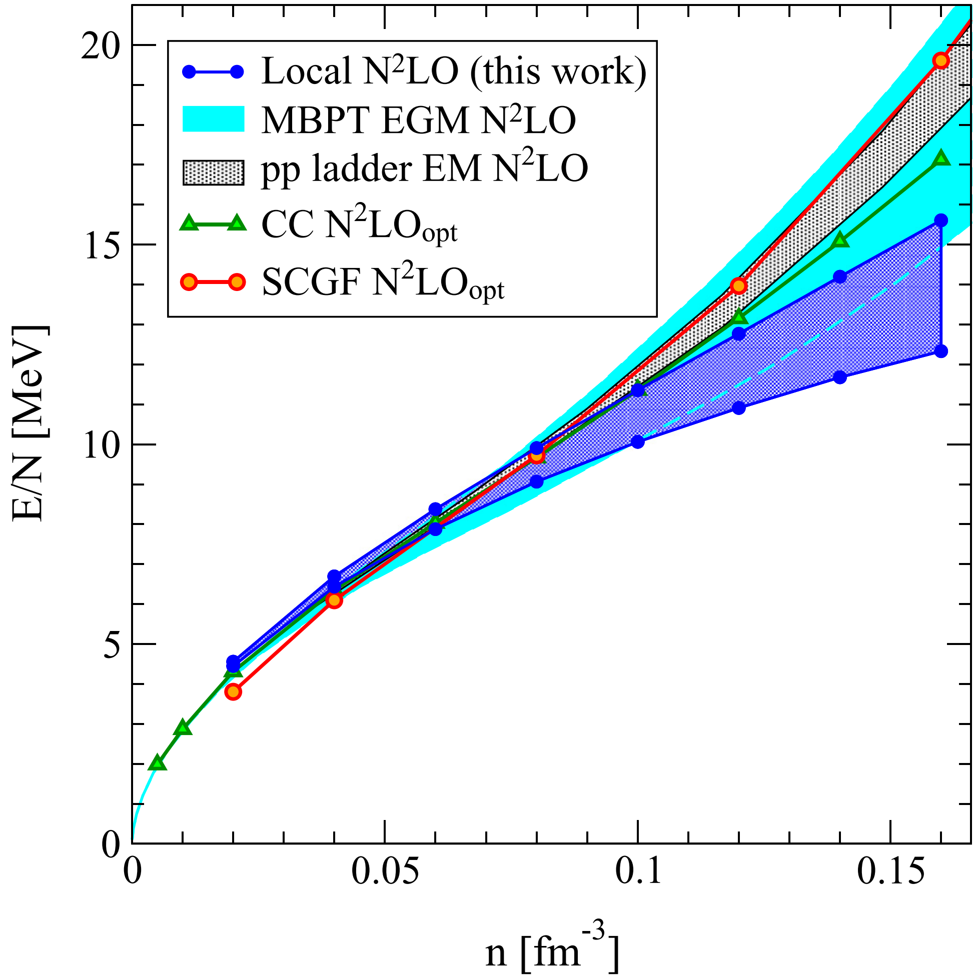
TPE

Hartree-Fock



local vs nonlocal 3NF repulsion can drastically change

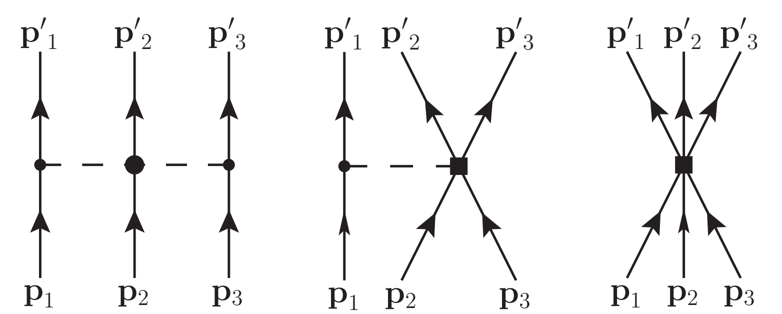
AFDMC



Tews et al. PRC93, 024305 (2016)

Quantum Monte Carlo and local chiral forces

TPE **OPE** **contact**



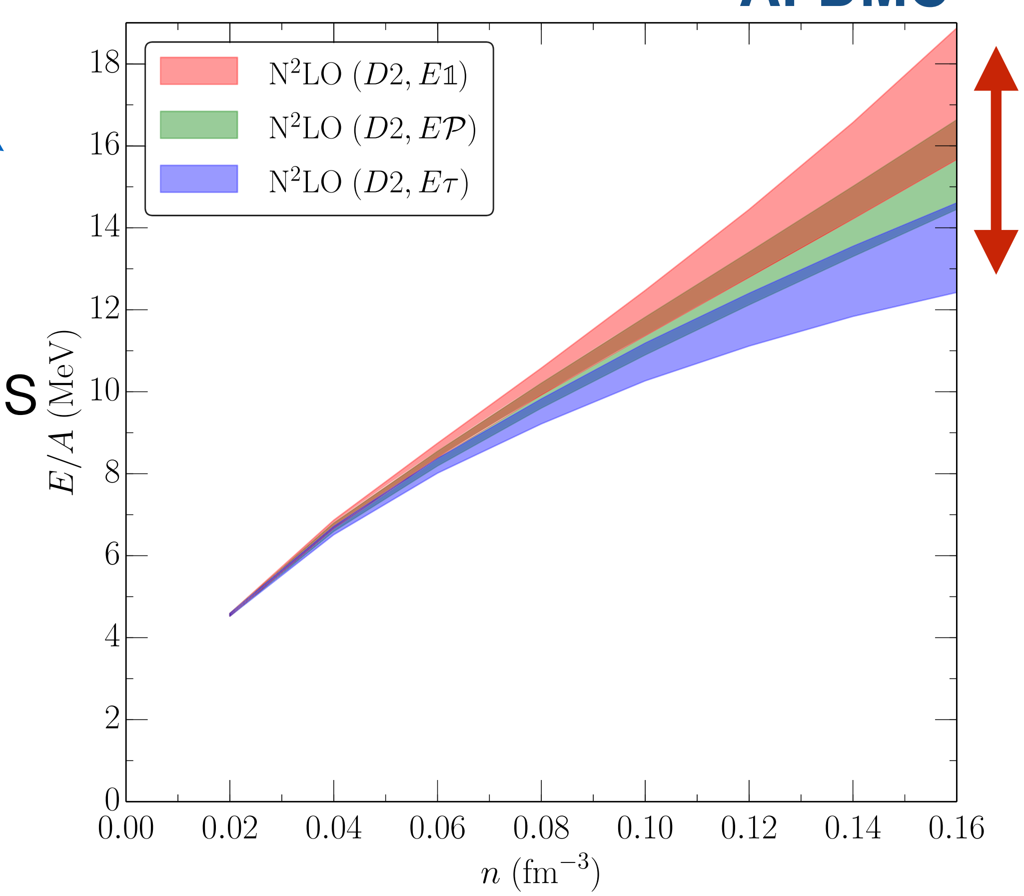
C1,C3,C4 — CD: D1, D2 — CE: Et, E1, EP

OPE & contact

Uncertainty in the Hamiltonian definition

different combinations of OPE and contact local forces provide additional uncertainty

AFDMC



Lynn et al. PRL116, 062501 (2016)

NN+3N local coordinate space chiral forces

- Fourier transformed shot-range topologies are ambiguous: two cD and three cE terms
- Fits to ^{4}He BE and P-wave n-alpha scattering

Pure neutron matter at 2N + 3N at N3LO

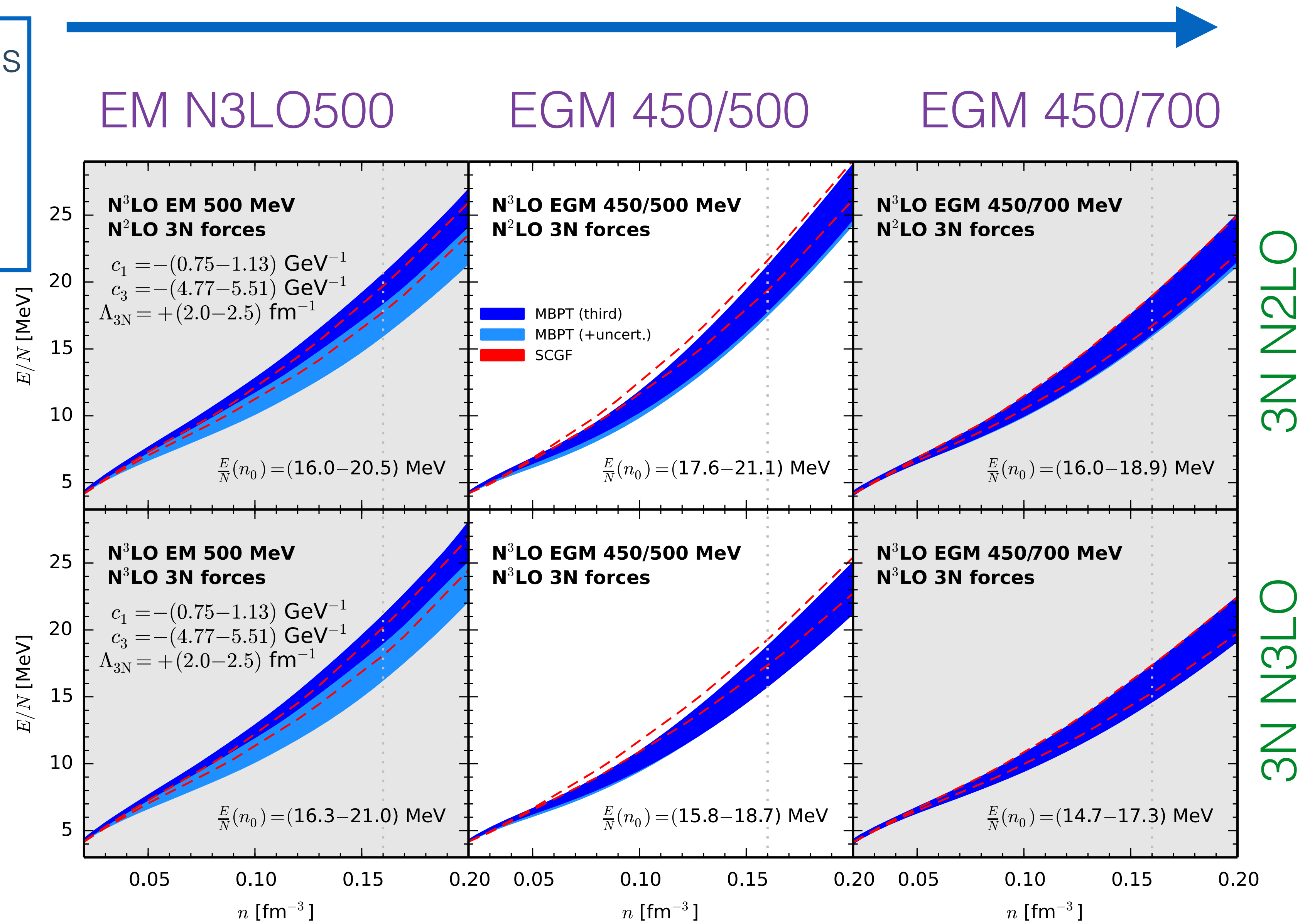
Improved 3NF matrix elements Hebeler et al. 2015
Partial-wave based average Drischler 2014-2015

many-body approximation uncertainty

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

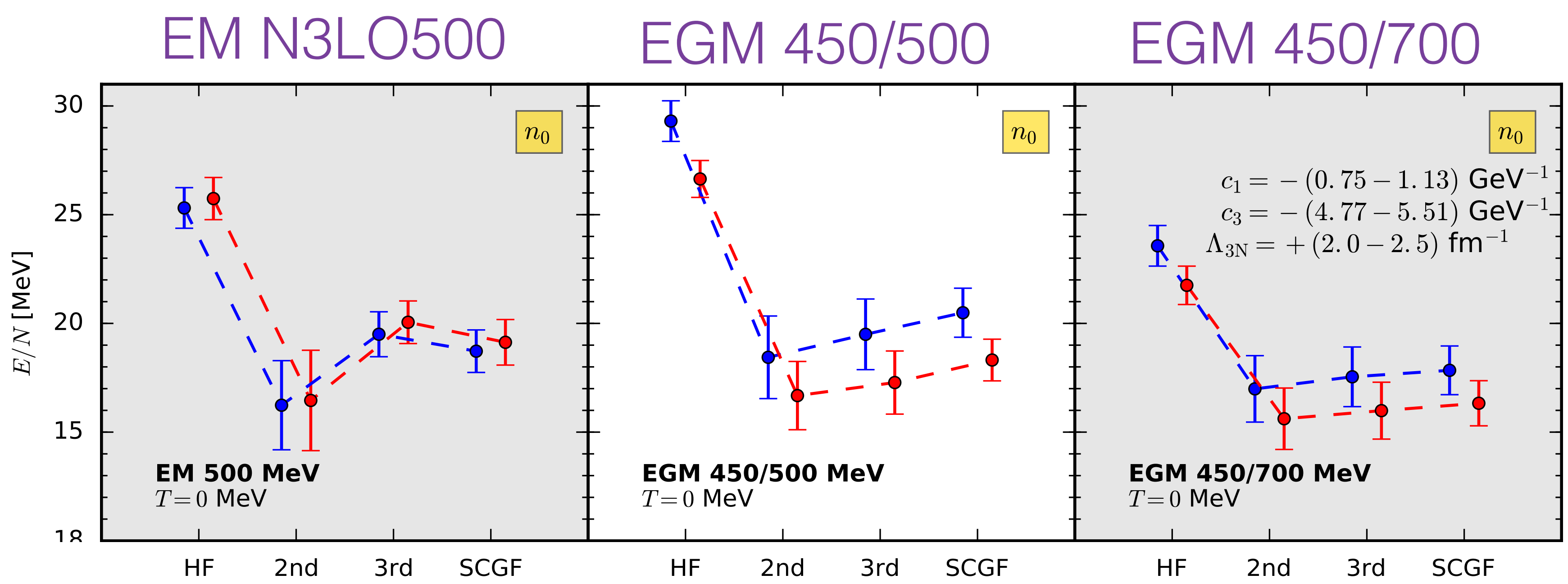
chiral forces uncertainty

N3LO 3NF shift in energy bands



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

Pure neutron matter at N3LO: many-body convergence



0.16 fm-3

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

- EM500 less perturbative
- 3rd order MBPT very well converged for EGMs
- **3NN2LO** vs **3NN3LO:** shift due 3NN3LO

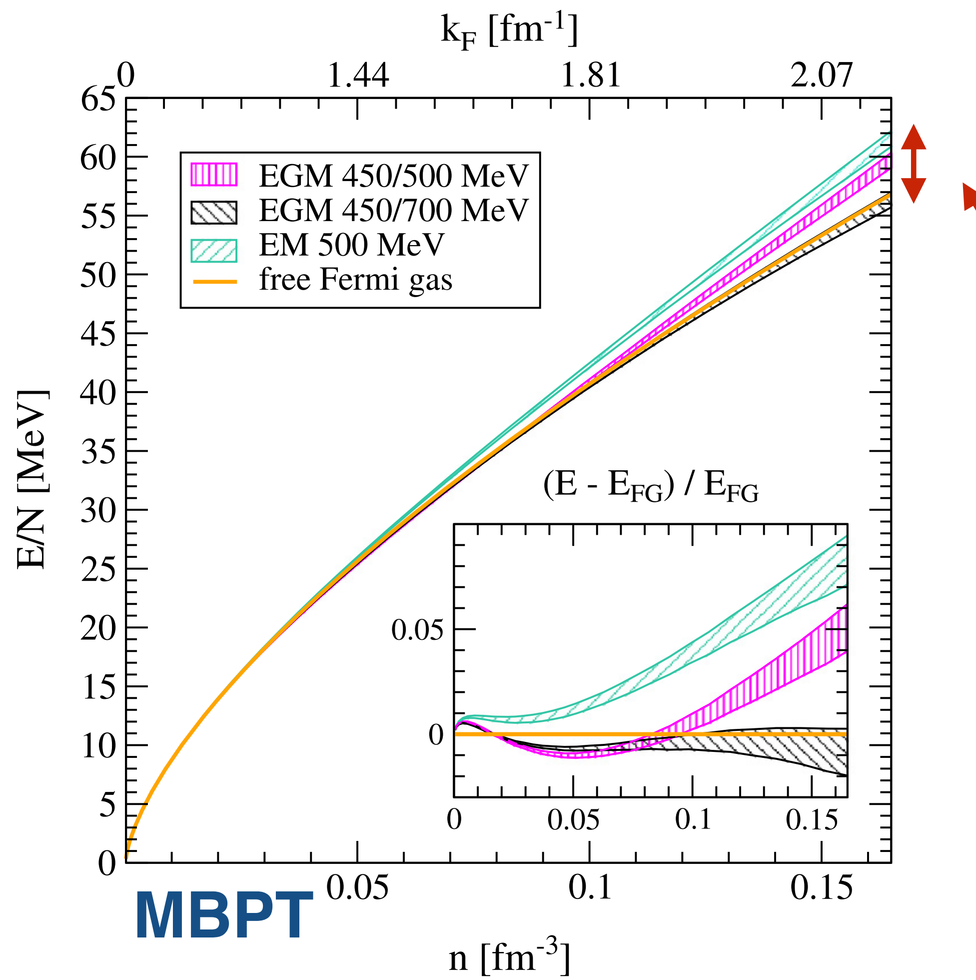
EM N3LO500 EGM 450/500 EGM 450/700

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

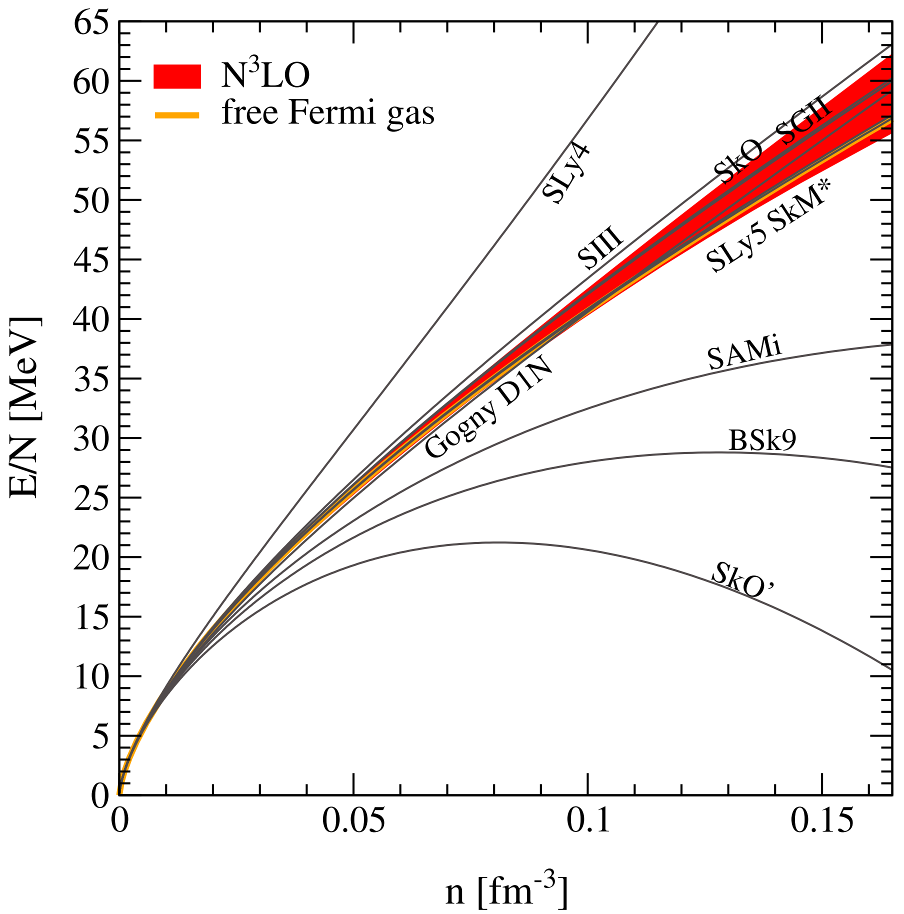
Drischler, Carbone, Hebeler, Schwenk PRC94, 054307 (2016)

Pure neutron matter

Spin-polarized neutron matter vs free Fermi gas



- good agreement between EDFs and FFG at low n
- significant deviations at higher n
- microscopic results constrain EDFs

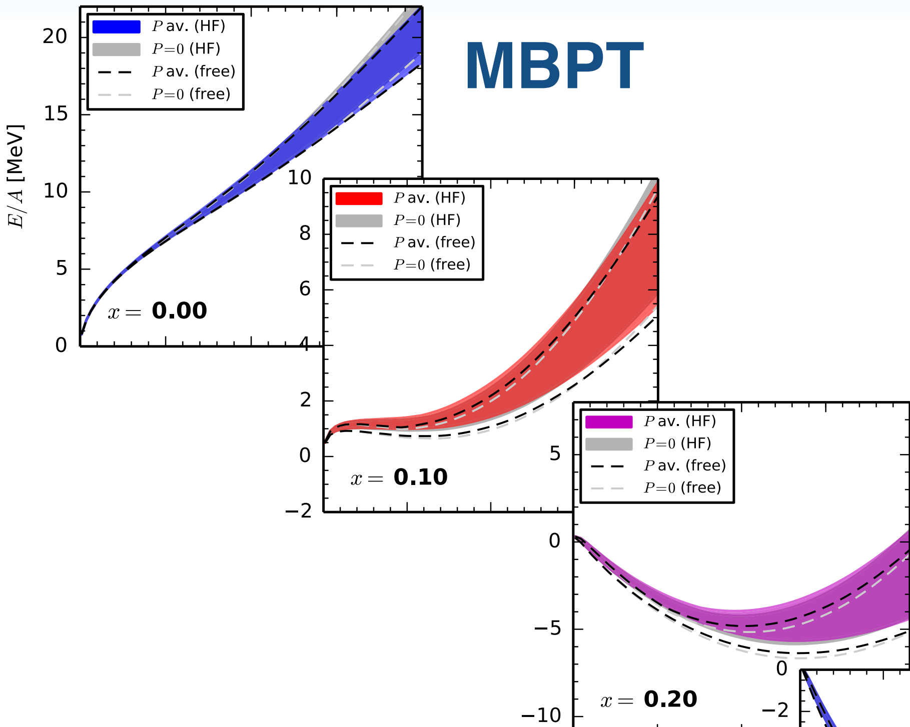


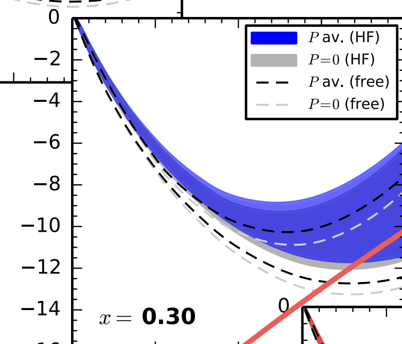
Krüger, Hebeler, Schwenk PLB744, 18 (2015)

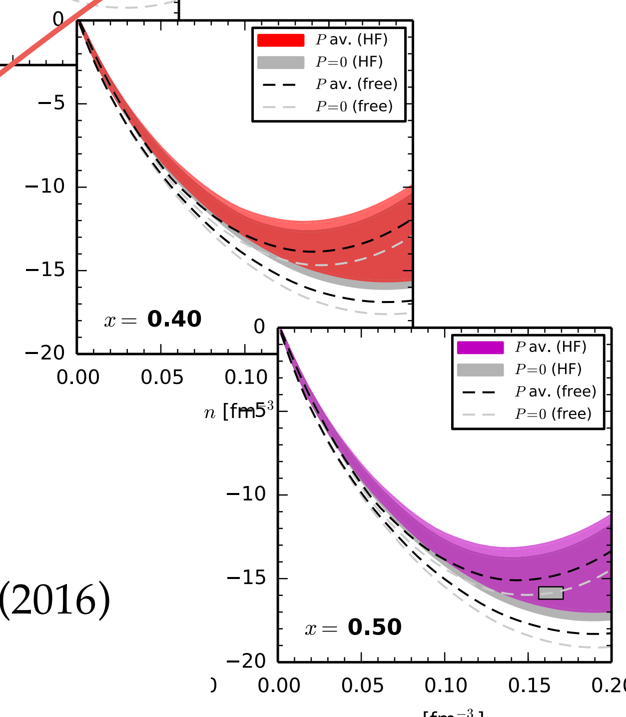
- energy very close to a FFG
- dependence on NN interaction
- comparing to PNM, transition to ferromagnetic state only at $n>n_0$

Asymmetric matter and the symmetry energy

MBPT





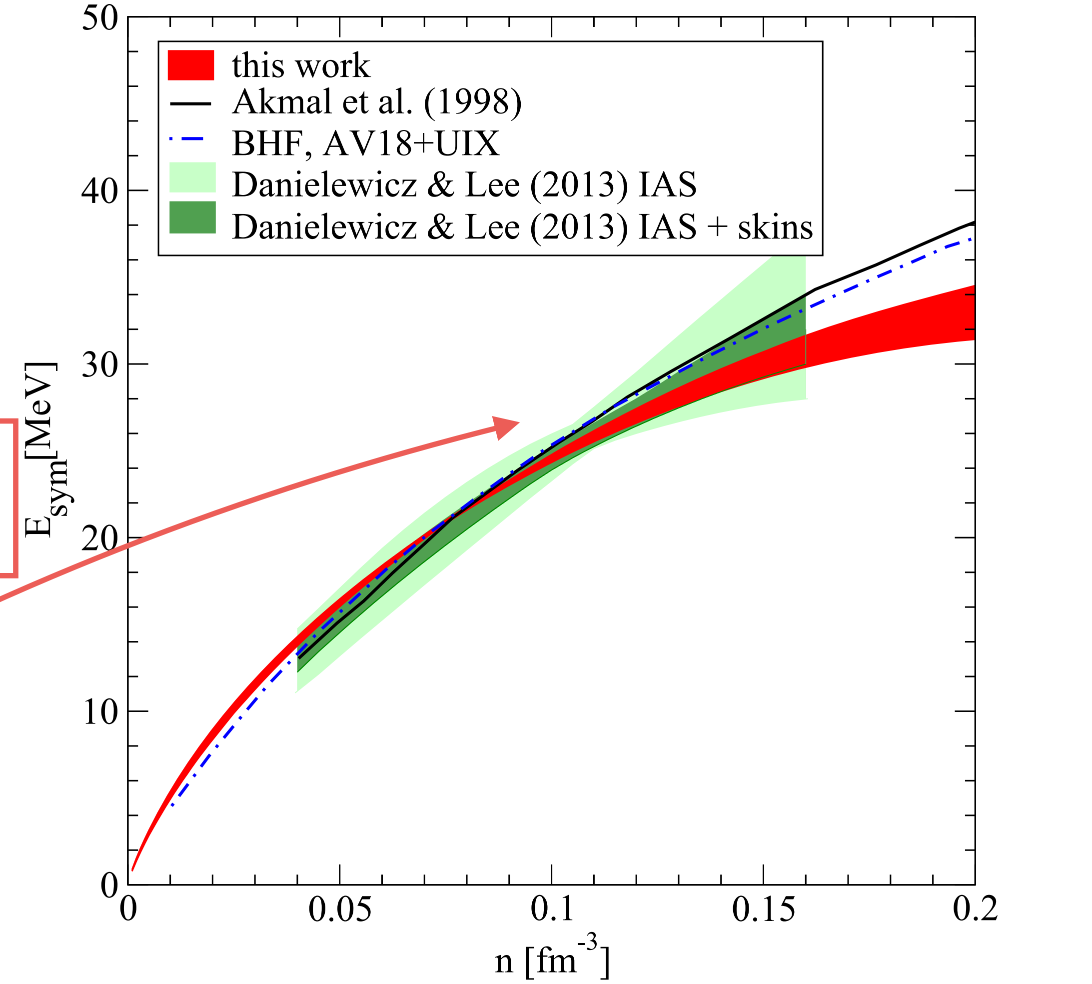


- Reasonable quadratic app. in the asymmetry, however quartic terms are being investigated.

$$\frac{E(n,\beta)}{A} = \frac{E(n,\beta=0)}{A} + S_v(n)\beta^2 + \mathcal{O}(\beta^4)$$

Drischler, Hebeler, Schwenk PRC93, 054314 (2016)

Predict the symmetry energy



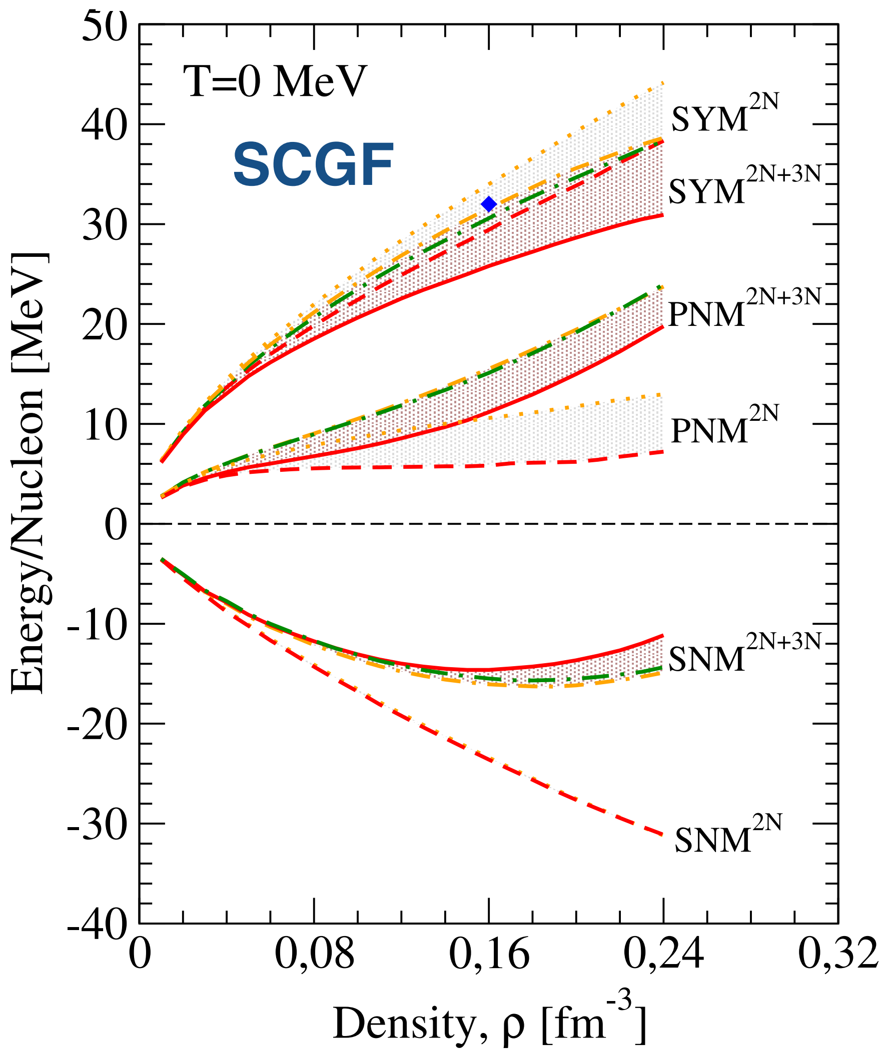
Consistent with previous calculation and IAS results

Drischler, Somà, Schwenk PRC89, 025806 (2014)

Symmetry Energy and slope parameter L

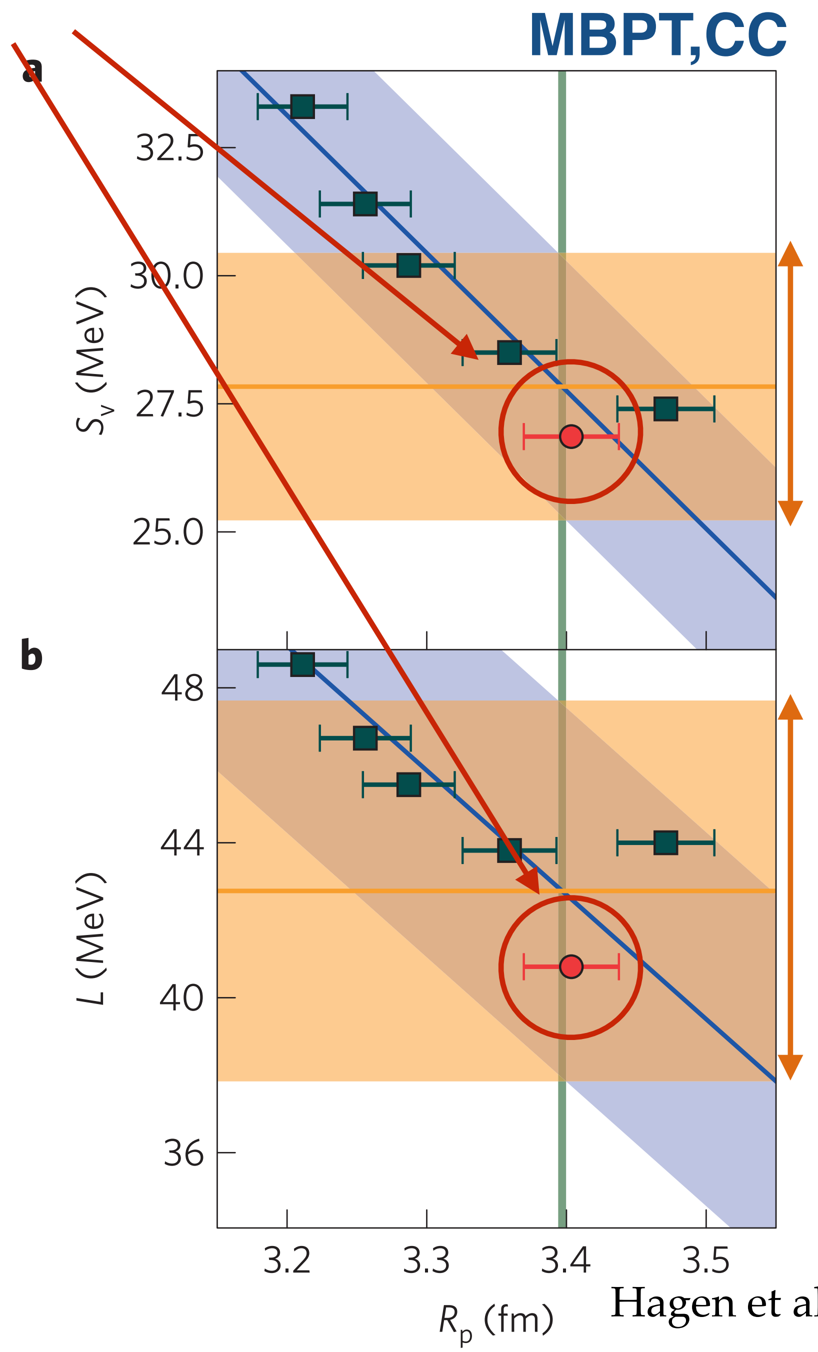
$$\frac{S}{A}(\rho) = \frac{E_{\rm PNM}}{A}(\rho) - \frac{E_{\rm SNM}}{A}(\rho)$$

	SRG1	SRG2	SAT
Sv (MeV)	31.57	30.59	25.81
L (MeV)	49.27	48.69	32.70



Carbone *(in preparation)*

- N2LOsat predicts a small Sv and L with different calculations



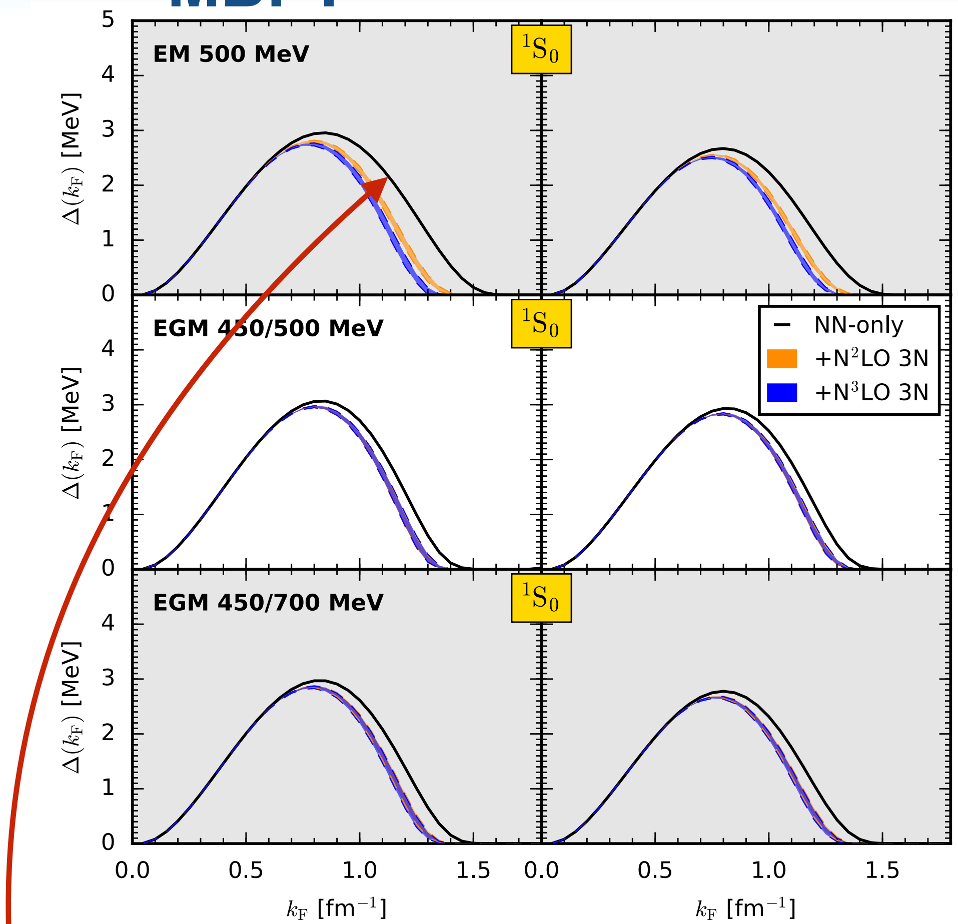
Hagen et al, Nature Pays 12, 186 (2016)

- Sv and L can be constrained by the point-proton radius of Ca48

Sv [25.2-30.4]MeV
L [37.8-47.7]MeV

The pairing gap in neutron matter

MBPT

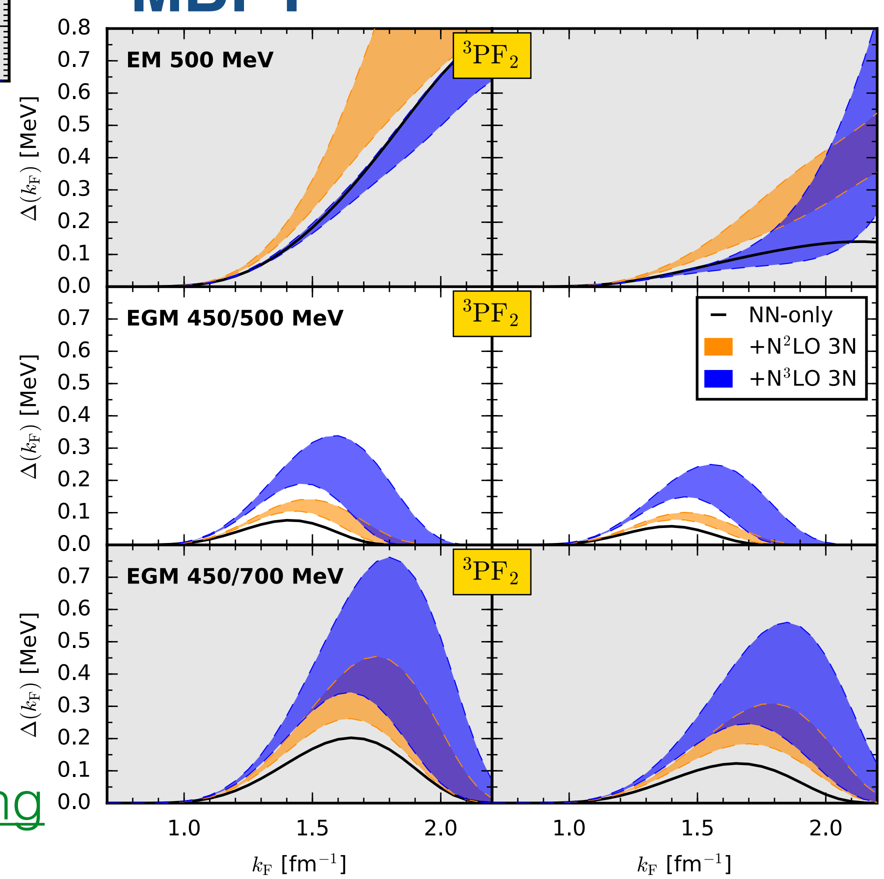


- BCS approx. gap
- 1S0 max 3 MeV, closes at ~1.5 fm-1
- 3NFs repulsive, pairing smaller

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

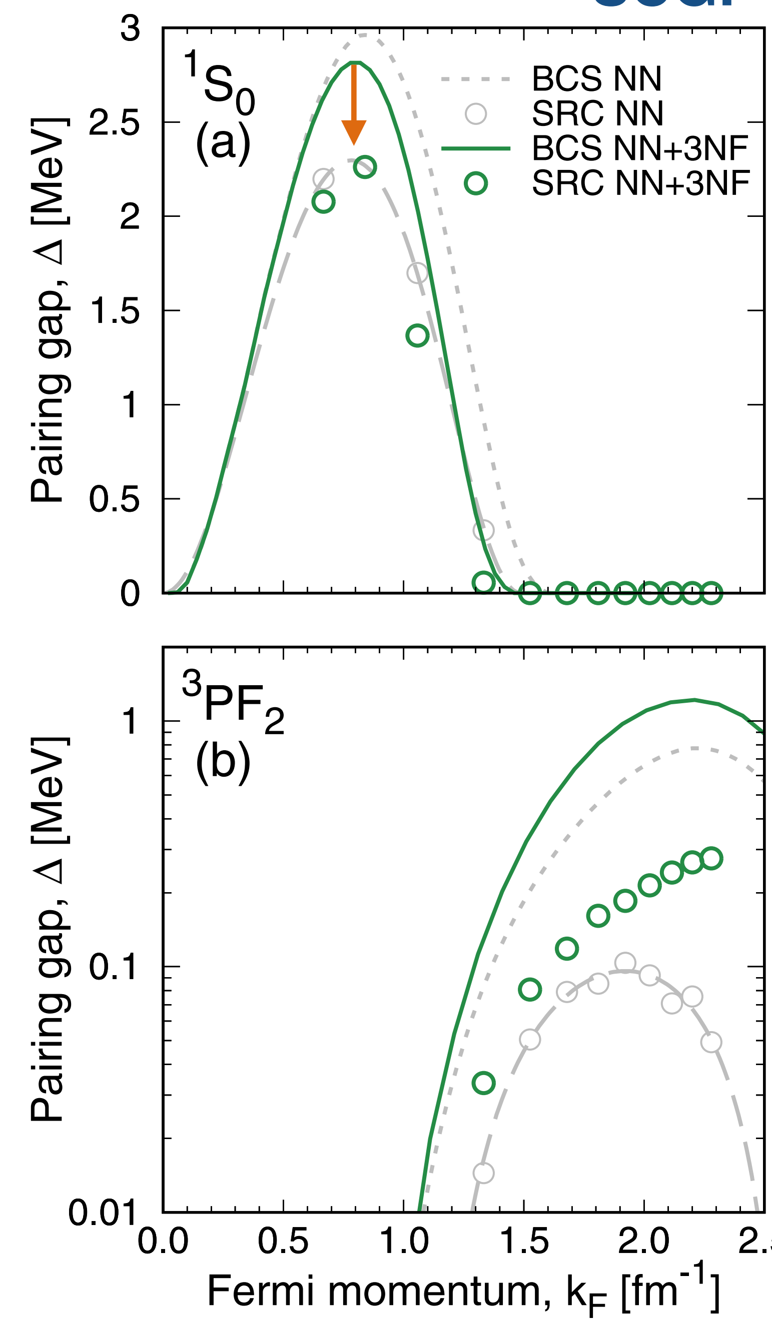
- 3PF2 depends on the interaction
- 3NFs attractive, enhancing of the pairing

MBPT



- Beyond BCS: correlations strongly reduce gap
- No closer for 3PF2 gap with EM500
- limits of applicability of chiral forces

SCGF



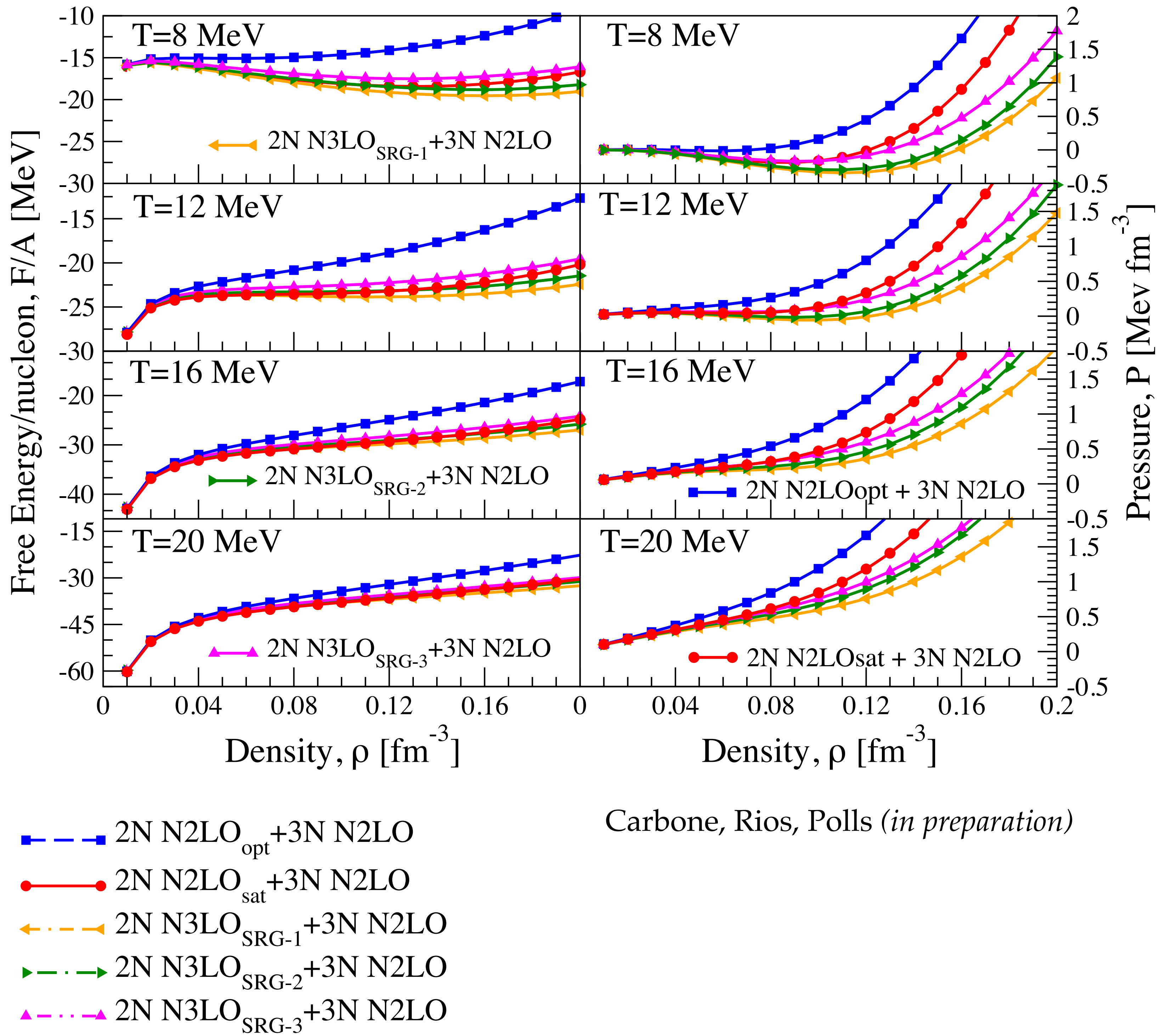
Ding et al., PRC94, 025802 (2016)

Symmetric nuclear matter

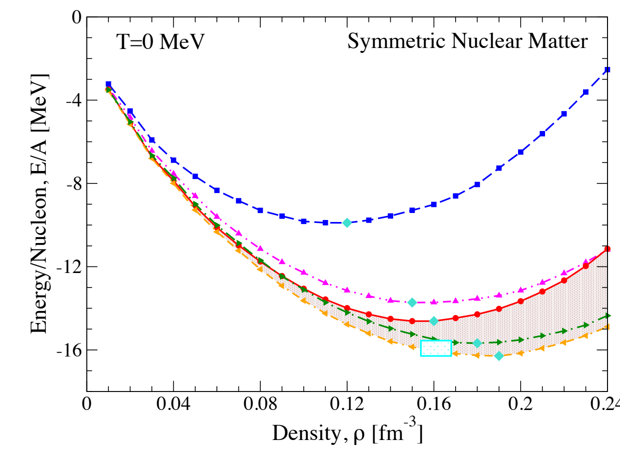
Free energy and pressure at varying temperature

SCGF $F = E - TS$ $P = \rho(\mu - F)$

increasing temperature



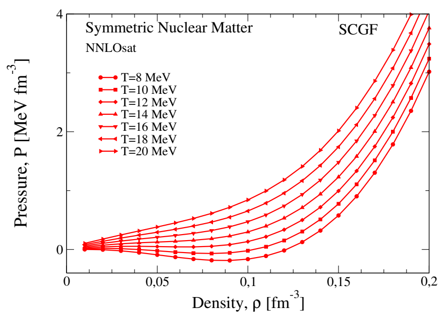
Carbone, Rios, Polls *(in preparation)*

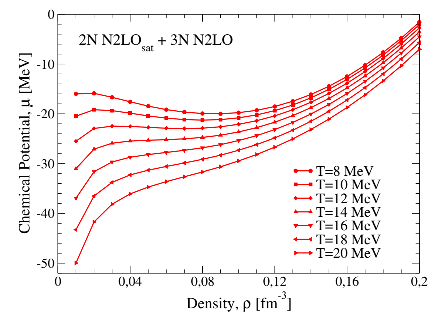


- similar behaviour to zero T energy
- N2LOopt most repulsive
- less difference between other potentials
- liquid-gas phase transition

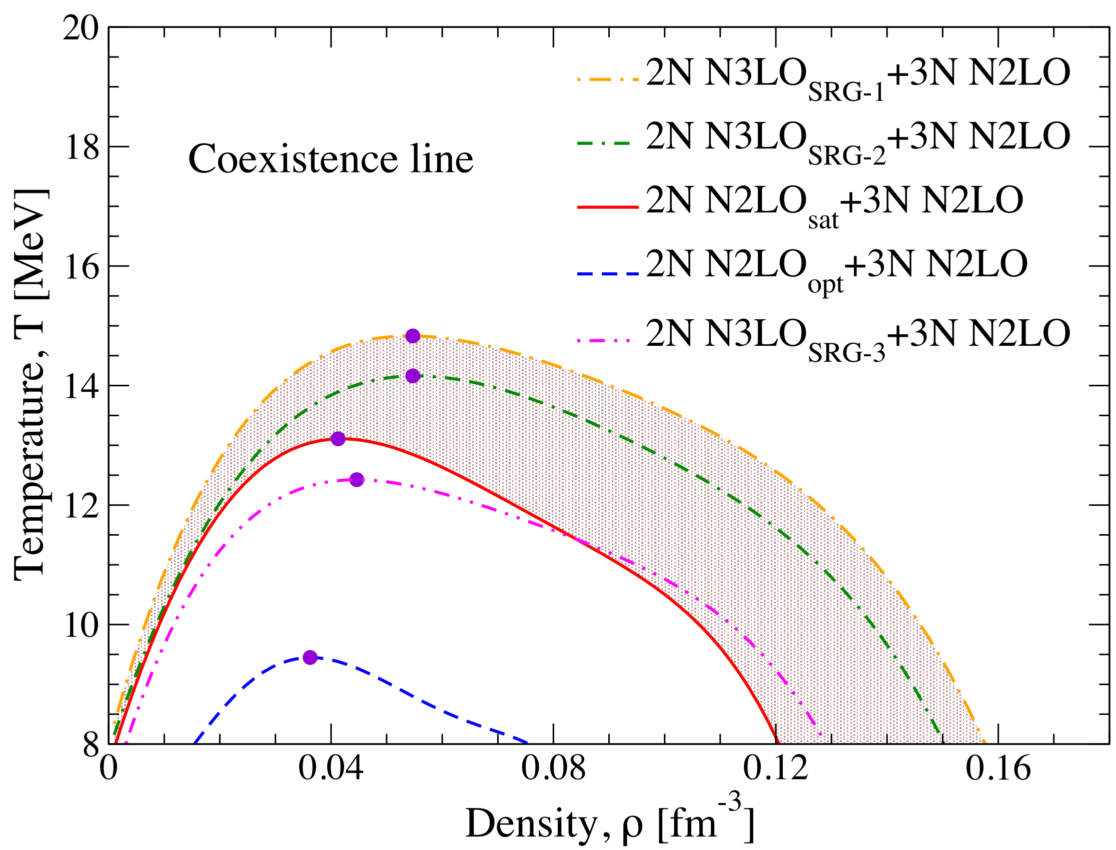
Saturation Energy vs Critical Temperature

SCGF

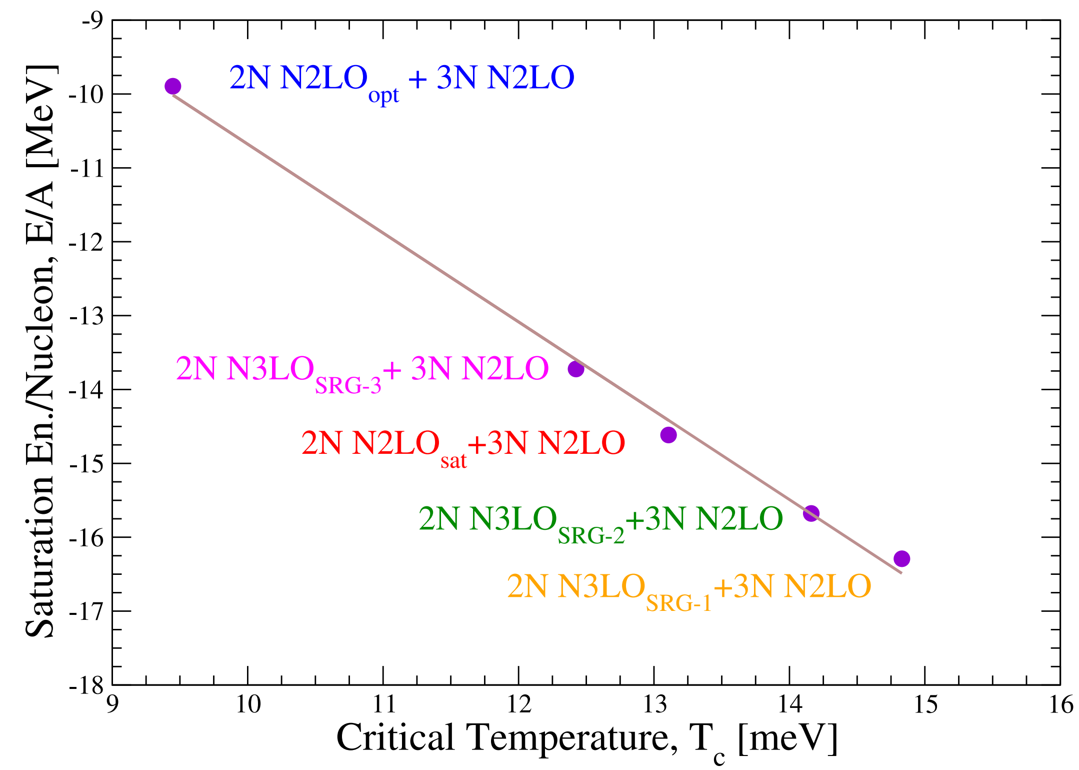




$$\mu(\rho_g) = \mu(\rho_l) \quad P(\rho_g) = P(\rho_l)$$



- Remarkable linear correlation between saturation energy and critical temperature



SCGF	ρ_c [fm^{-3}]	T$_c$ [MeV]	ρ_0 [fm^{-3}]	$\frac{E_0}{N}$ [MeV]	$\frac{m^*}{m}$
N3LO$_{SRG-1}$	0.05	14.8	0.19	-16.3	0.85
N3LO$_{SRG-2}$	0.05	14.2	0.18	-15.7	0.81
N3LO$_{SRG-3}$	0.04	12.4	0.15	-13.7	0.90
NNLO$_{opt}$	0.04	9.4	0.12	-9.9	0.90
NNLO$_{sat}$	0.04	13.1	0.16	-14.6	0.90

- Coexistence line: equilibrium between a gas and a liquid phase
- Lower critical temperature respect to estimated experimental value ~ T=18 MeV

Carbone, Rios, Polls *(in preparation)*

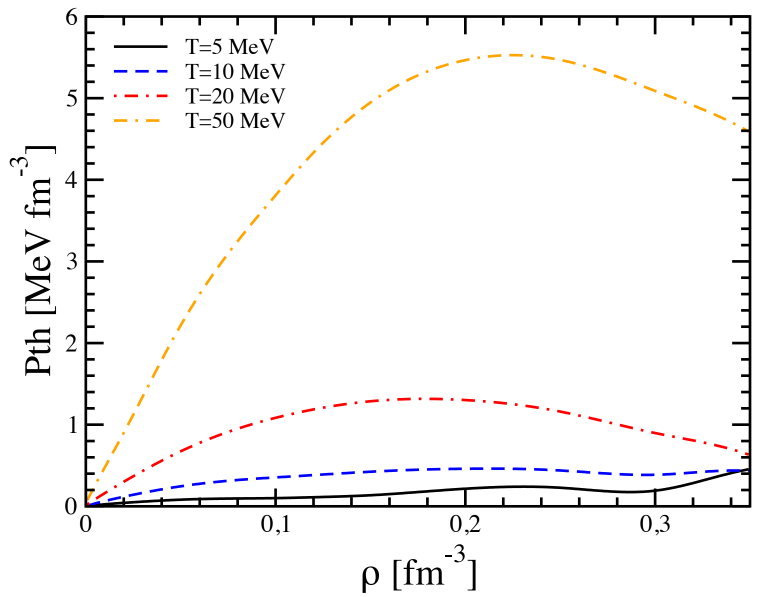
Pure neutron matter

Thermal effects for supernovae simulations

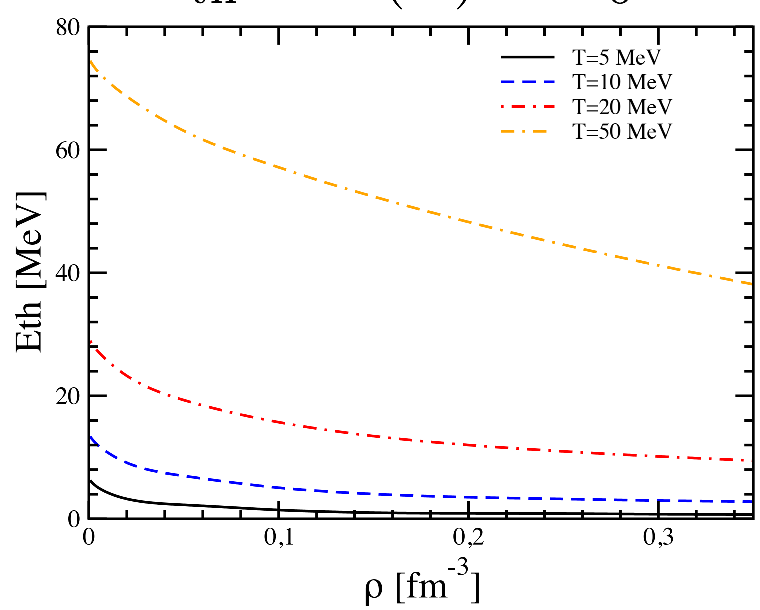
- Pressure calculated as: **Pcold+Pthermal**
- Thermal index considered **constant**

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

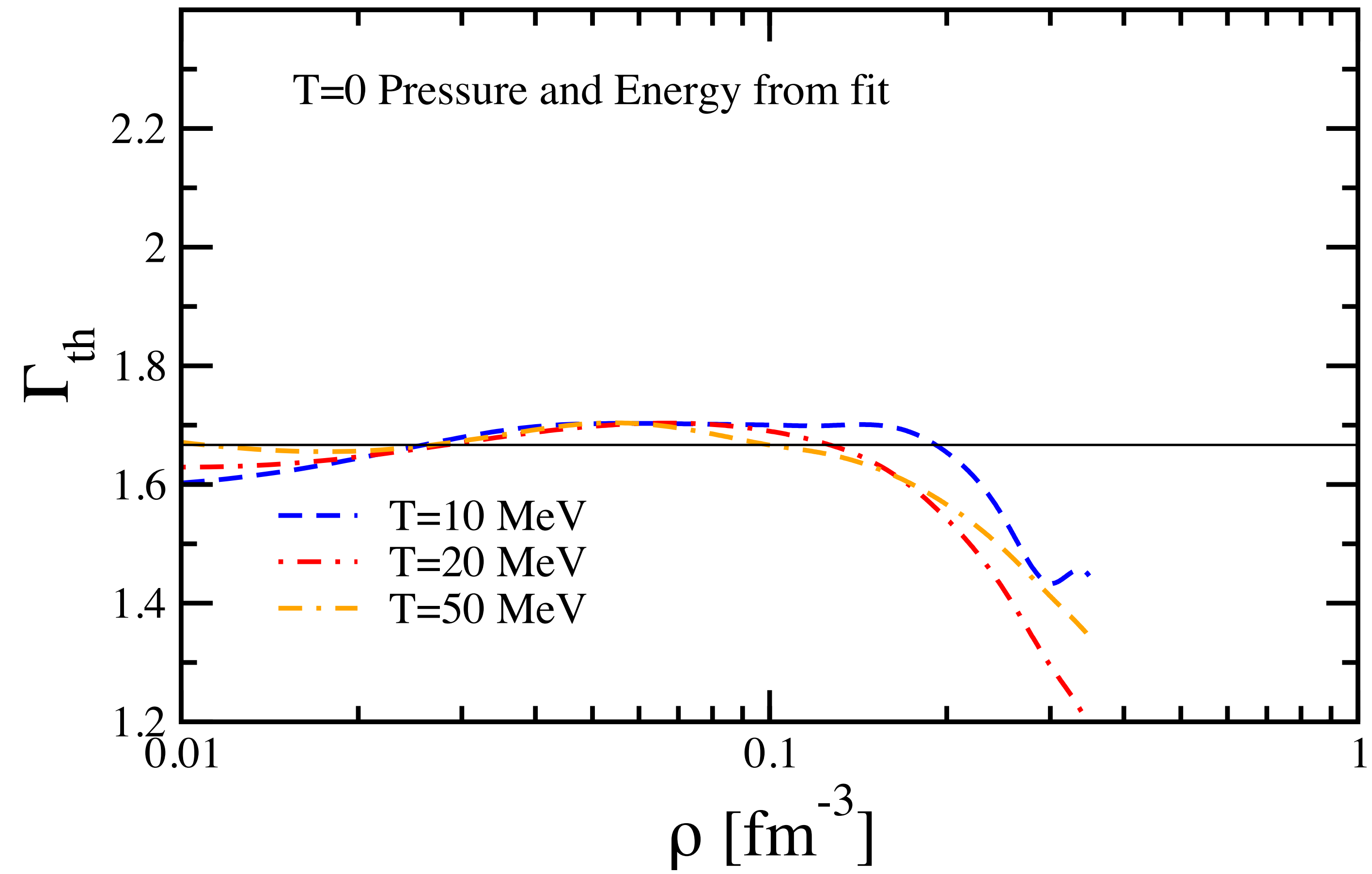
$$P_{\rm th} = P(T) - E_0$$



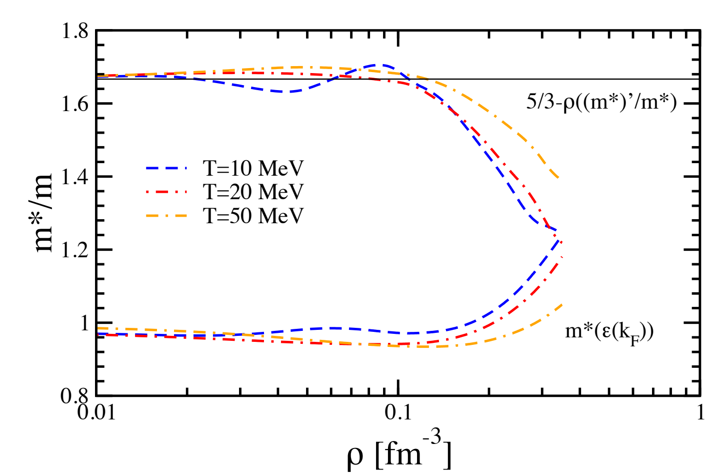
$$E_{\rm th} = E(T) - E_0$$



SCGF



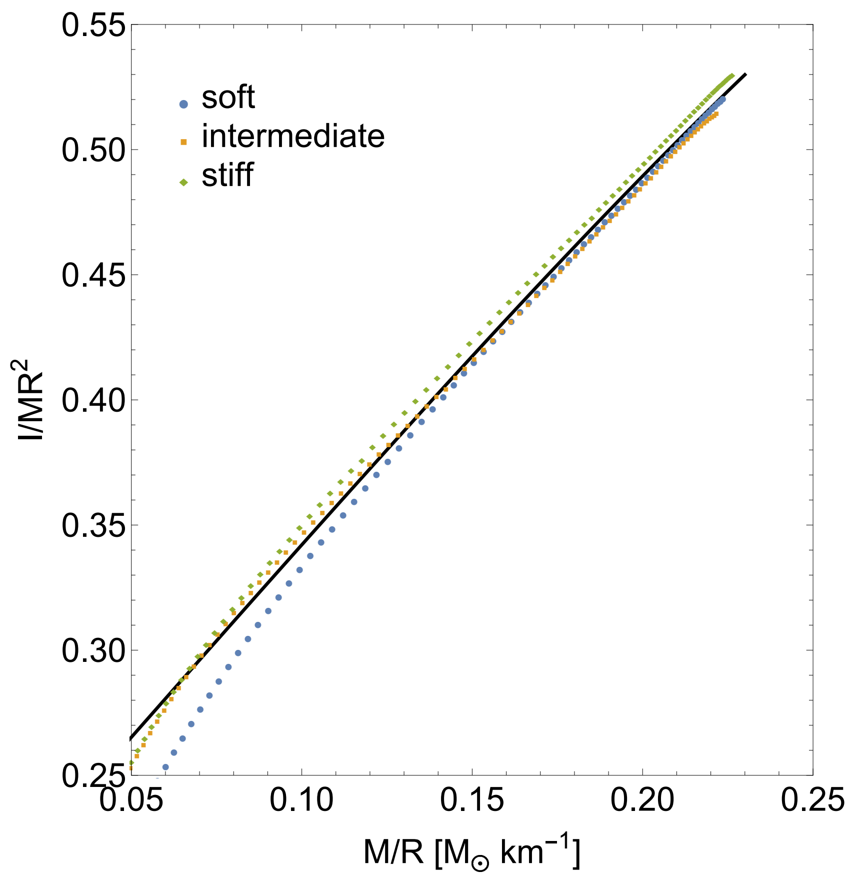
- Pth decreases after certain density
- Eth decreases monotonically
- Index increases then decreases after sat. density
- dependence on the effective mass derivative

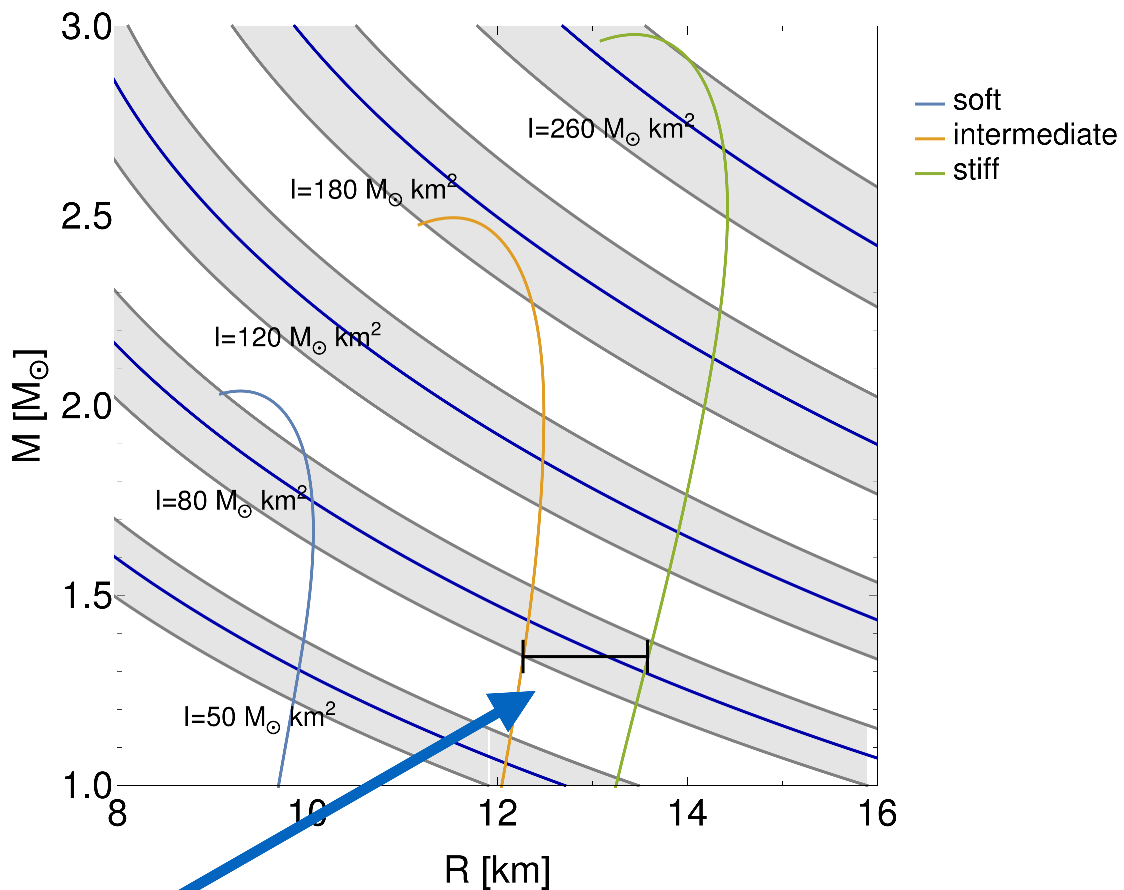


Pure neutron matter

Momenta of inertia constraints for neutron star radius

- NS Mass and radius can constrain the EOS of NSmatter
- Radius is poorly constrained



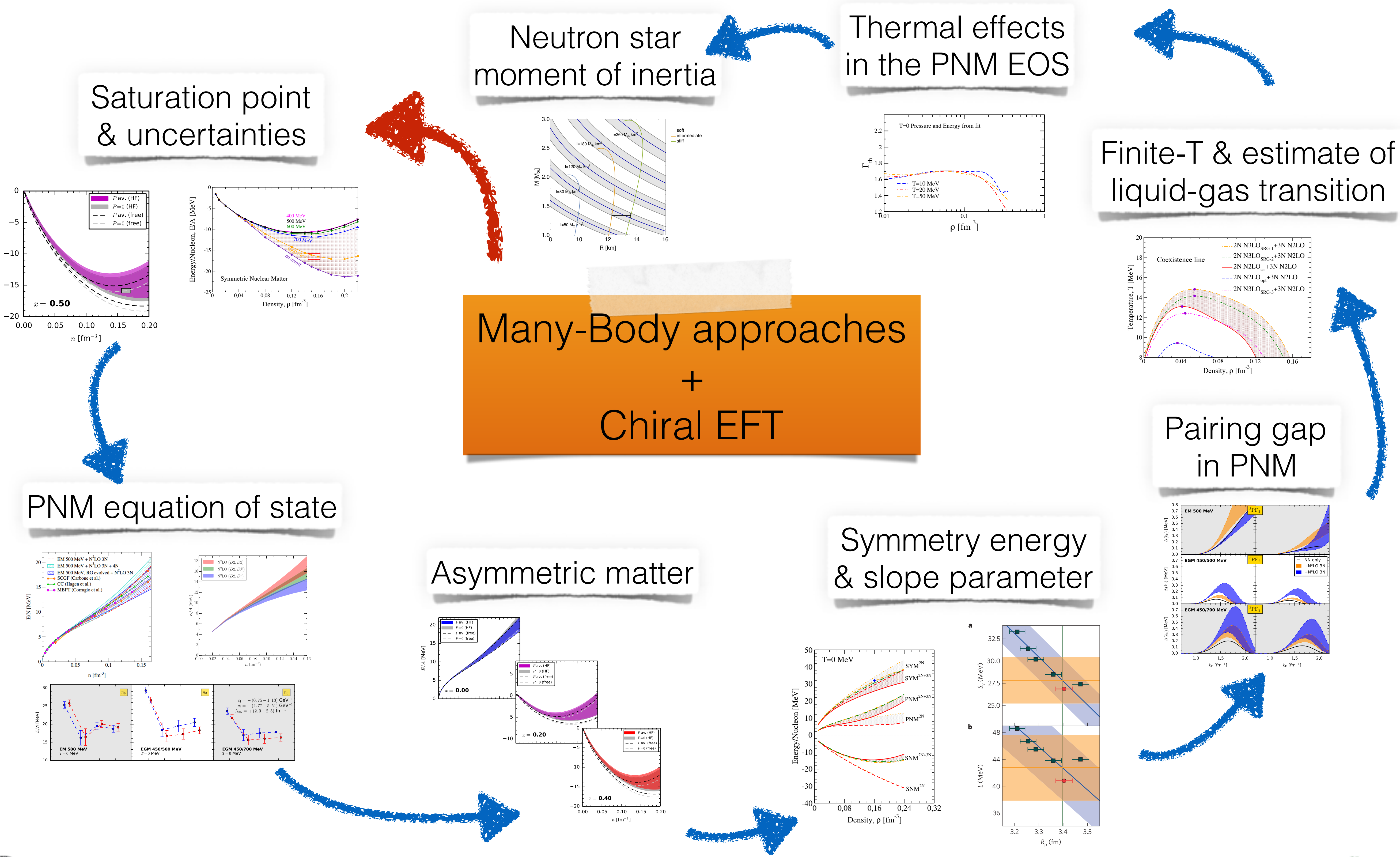


I [$M_\odot$ km^2]	ΔI [%]	R [km]	ΔR [km]
70	10	11.3 − 12.7	1.4
	20	10.4 − 13.5	3.1
80	10	12.3 − 13.5	1.2
	20	11.4 − 13.5	2.1

Greif Master Thesis (2016)

- relation between IM and M/R of NSs
- A measurement of the IM could constrain R and thus the EOS

What can we predict?



Summary and Impact of results

Many-Body approaches + Chiral EFT

Saturation point & uncertainties
Nuclear matter reliably predicted based on chiral EFT

Neutron star moment of Inertia
NS radius constraints from IM

Thermal effects in the PNM EOS
Influence supernova simulations and the GW signal

Finite-T & estimate of liquid-gas transition
Interpret astrophysical scenarios at high T

Pairing gap in PNM
Explain rapid cooling in pulsars

Symmetry energy & slope parameter
Fundamental quantities to understand neutron-rich environments

Asymmetric matter
Microscopic calculation drive the Mass/Radii relation

PNM equation of state
PNM EOS from ab-initio can constrain energy density functionals

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Thank you for your attention!