Correlated isospin asymmetric systems

Short-range and tensor correlation effects

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NUSYM14, Liverpool, 8 July 2014

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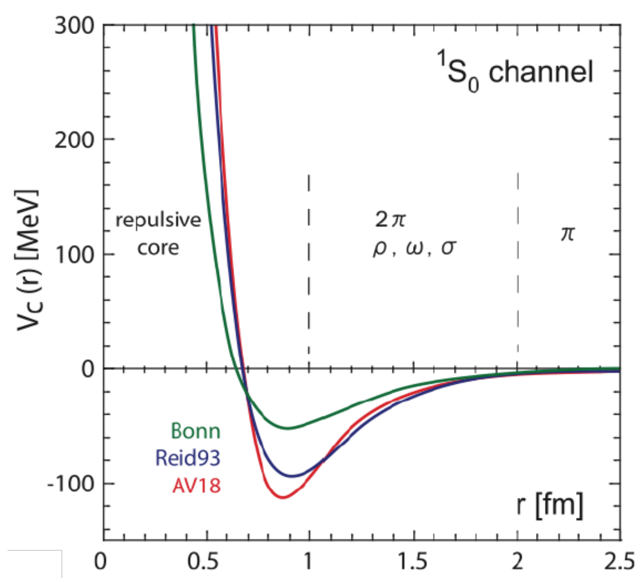
Origin of correlations in nuclear physics

~5-10 %	~5-10 %	~15-25 %

Short-range

Short-distance structure of NN force

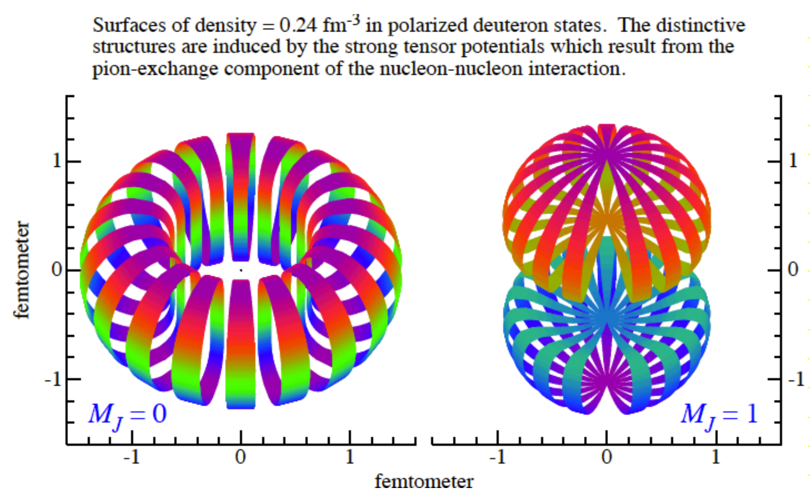


Ishii, PRL 99, 022001 (2007)

- Fit of NN phase-shift
- Indications from Lattice QCD
- Beyond mean-field needed!

Tensor

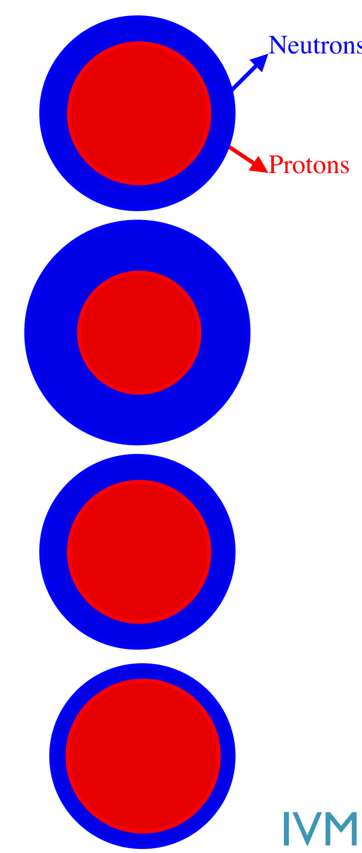
Deuteron density



Argonne Theory Group

- Deuteron quadrupole moment
- One-pion exchange
- Total energy & saturation
- Nuclear structure

Long-range



IVMR

- Coupling to low-lying phonons
- Nuclear oscillations
- Finite-size effects

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Short-range	**Tensor**	~~**Long-range**~~

Short-range

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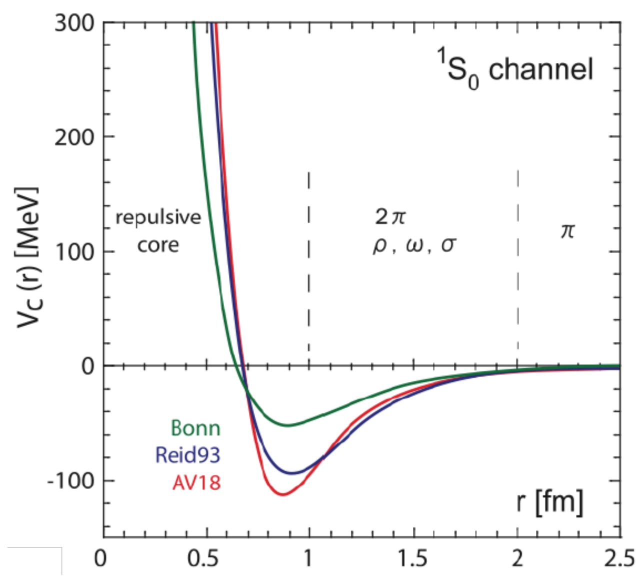

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Tensor

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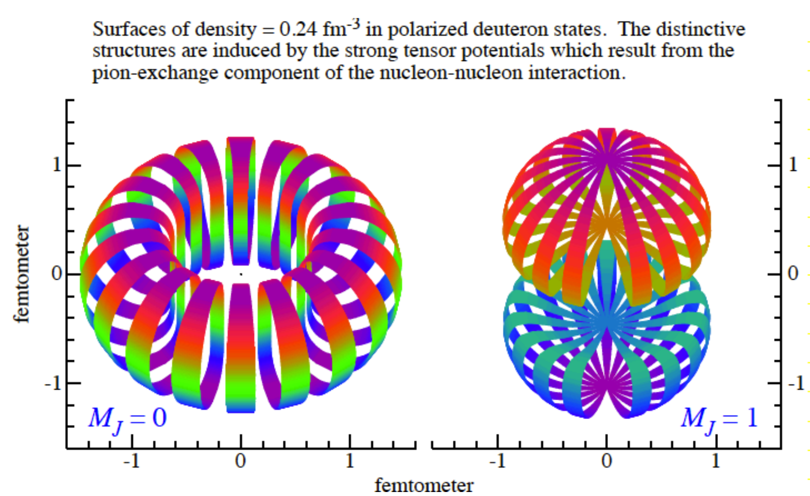

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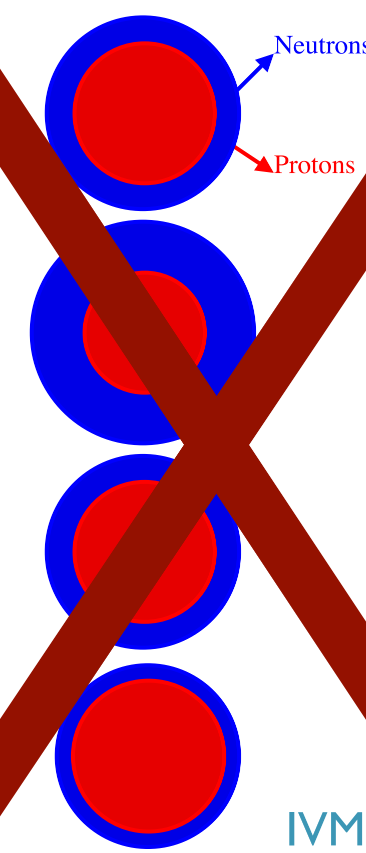

IVMR

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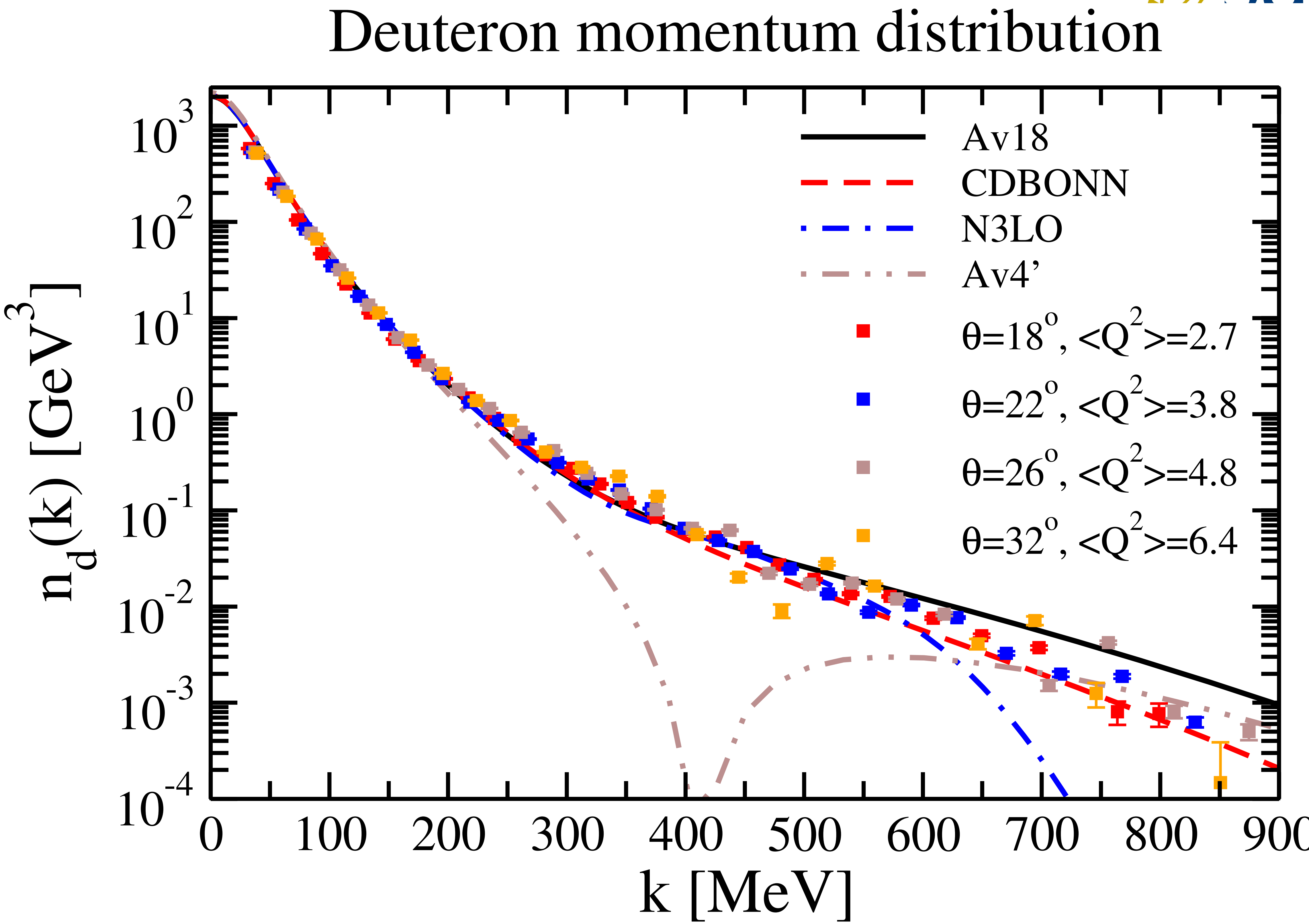
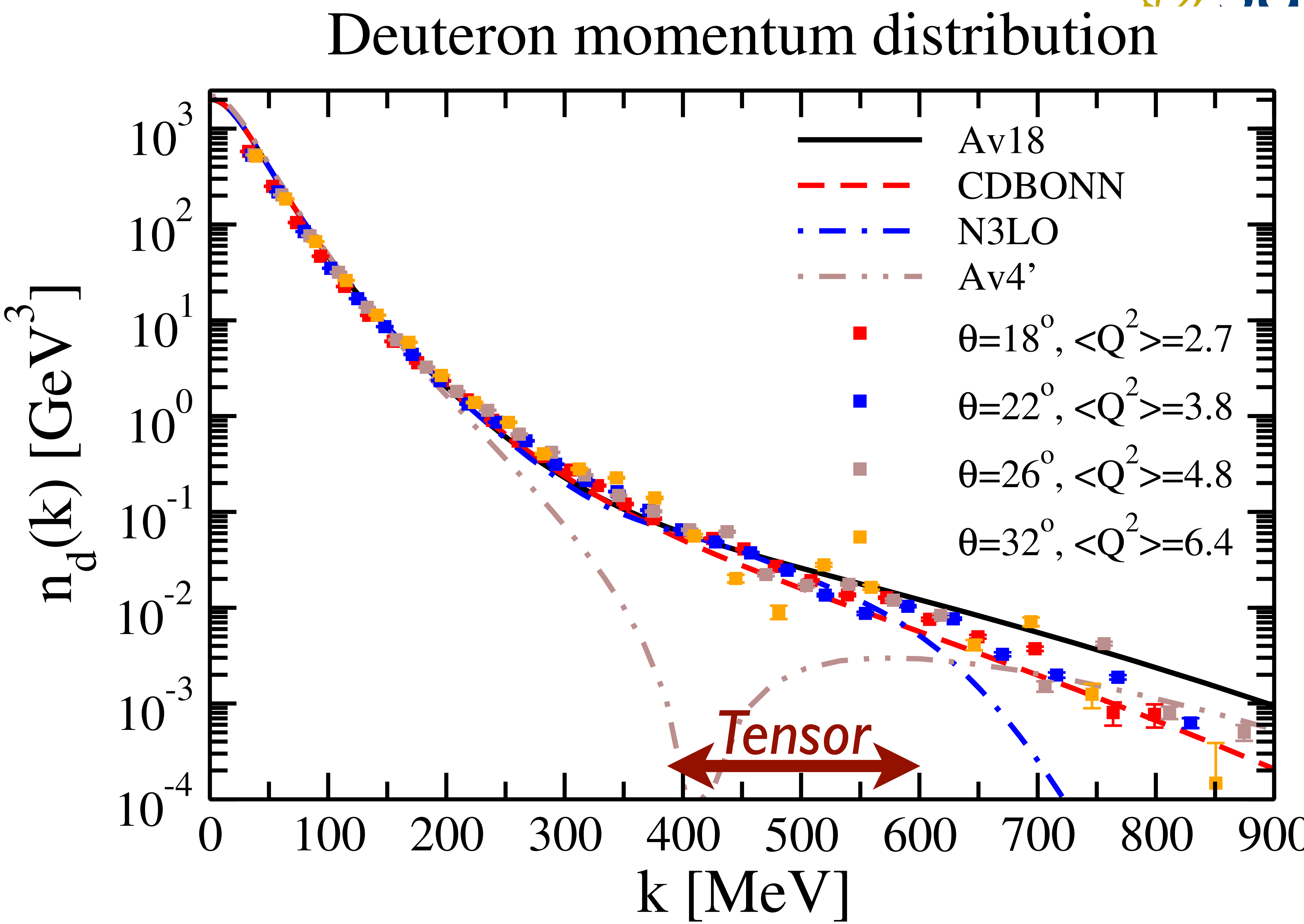
Why short-range correlations?



Fomin et al., PRL **108** 092502 (2012)

Inclusive quasi-elastic e⁻ scattering vs NN potential theory

Why short-range correlations?



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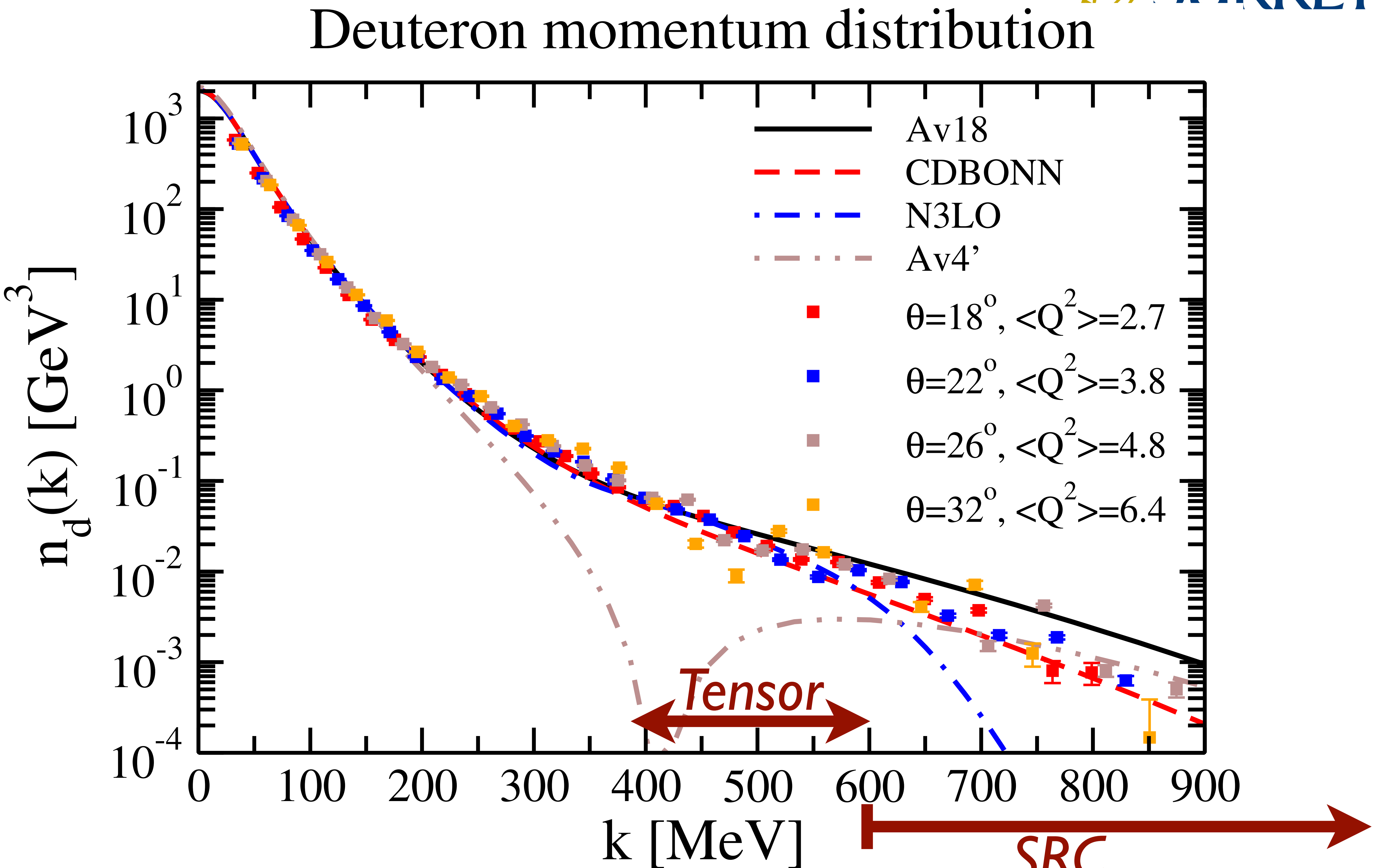
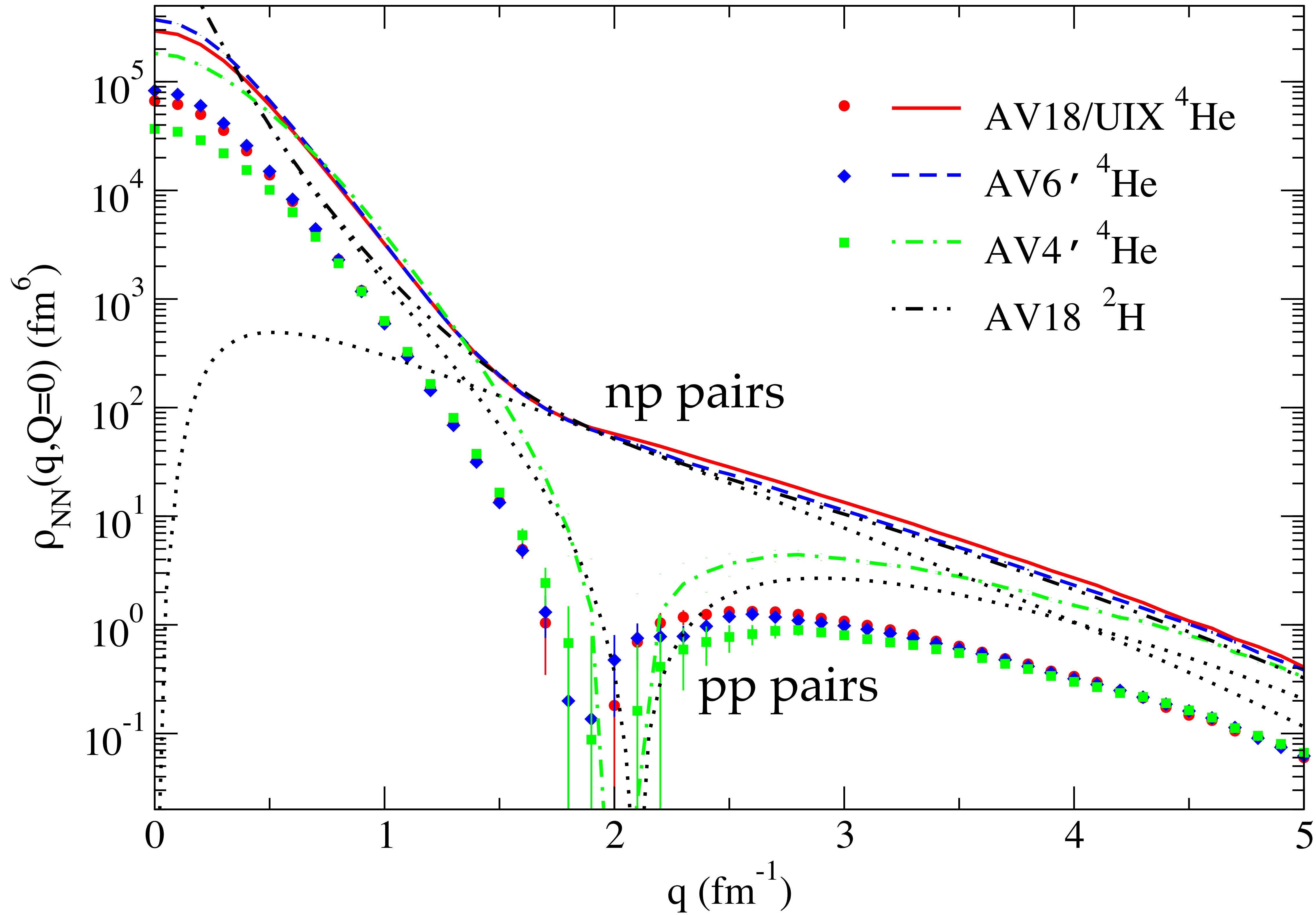


Fomin et al., PRL **108** 092502 (2012)

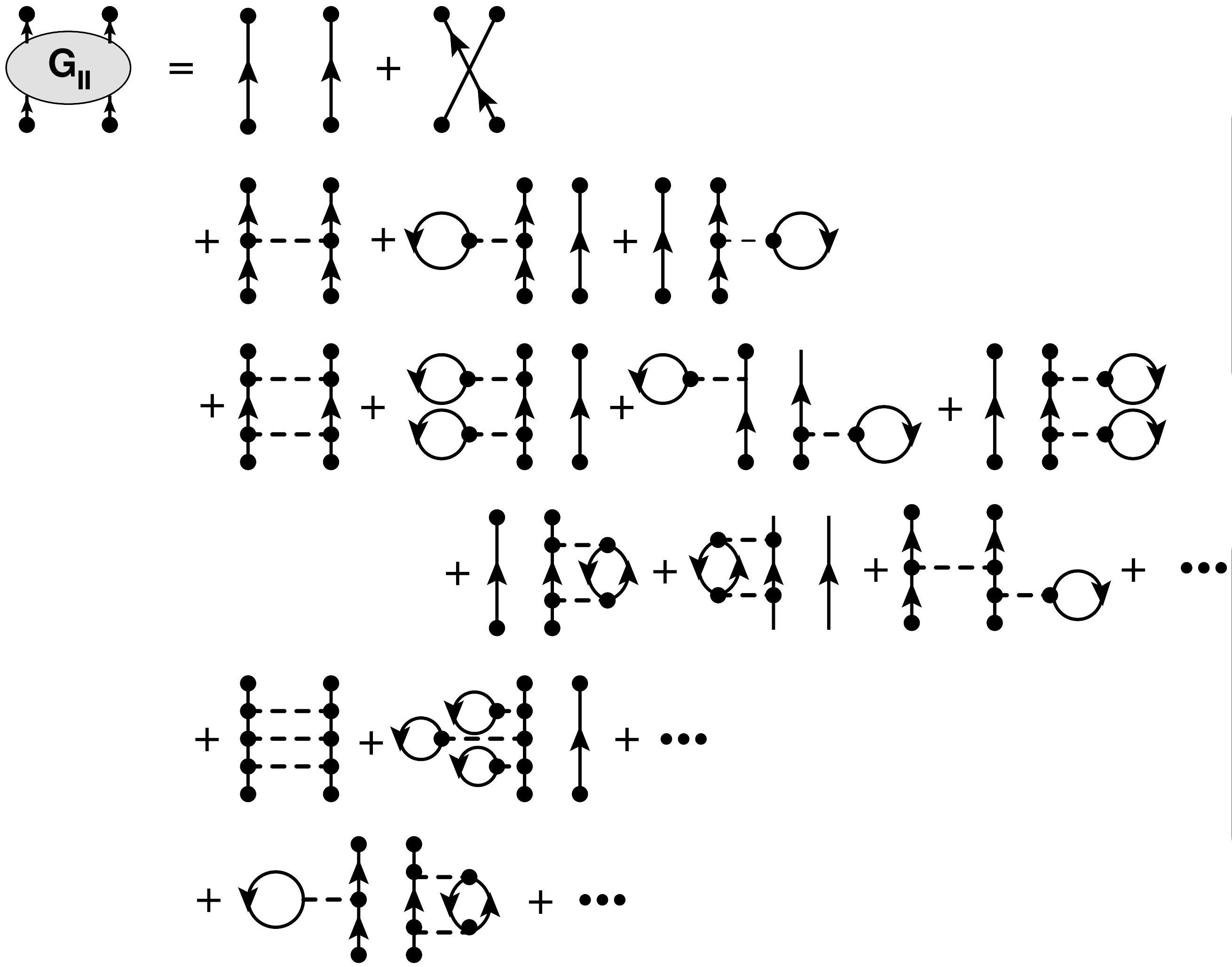
Inclusive quasi-elastic e^- scattering vs NN potential theory

Two-body momentum distribution

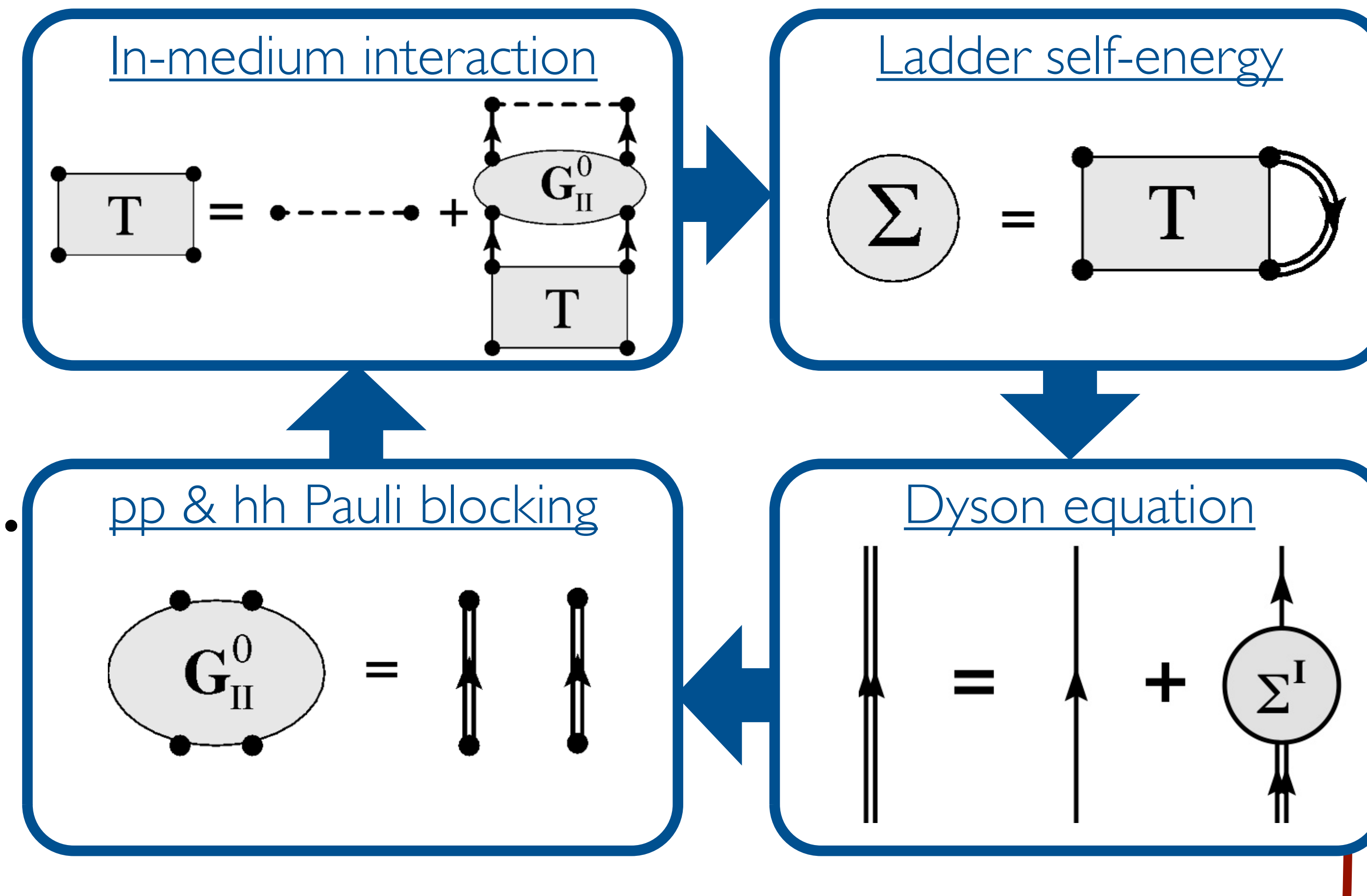
VMC theoretical calculations

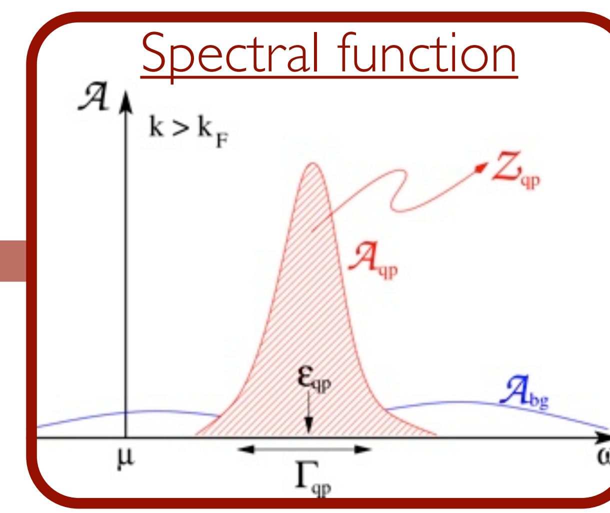


Schiavilla & Wiringa, *PRL* **98** 132501 (2007)



Ladder approximation within SCGF





One-body properties
Momentum distribution
Thermodynamics & EoS
Transport

Ramos, Polls & Dickhoff, NPA **503** 1 (1989)
Alm *et al.*, PRC **53** 2181 (1996)
Dewulf *et al.*, PRL **90** 152501 (2003)
Frick & Muther, PRC **68** 034310 (2003)
Rios, PhD Thesis, U. Barcelona (2007)
Soma & Bozek, PRC **78** 054003 (2008)

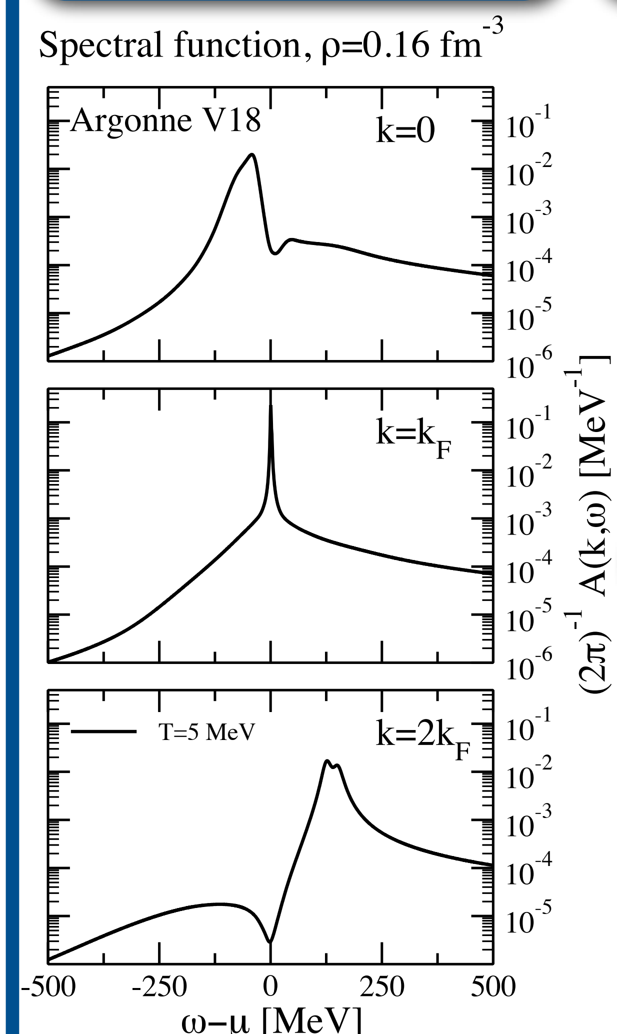
Self-consistency, pp+hh & full off-shell effects

Finite temperature

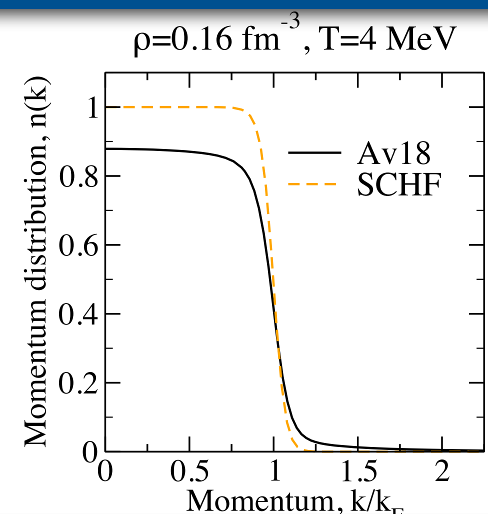
Self-consistent Green's functions

Microscopic properties

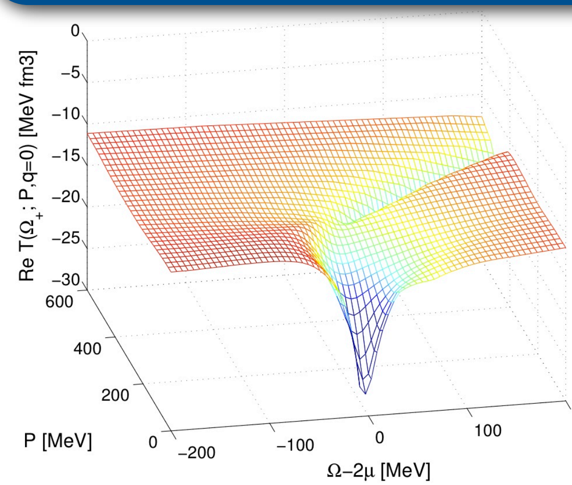
Spectral function



Momentum distribution

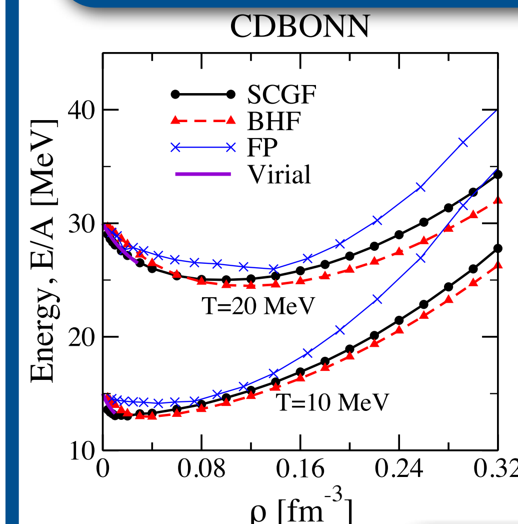


In-medium interaction

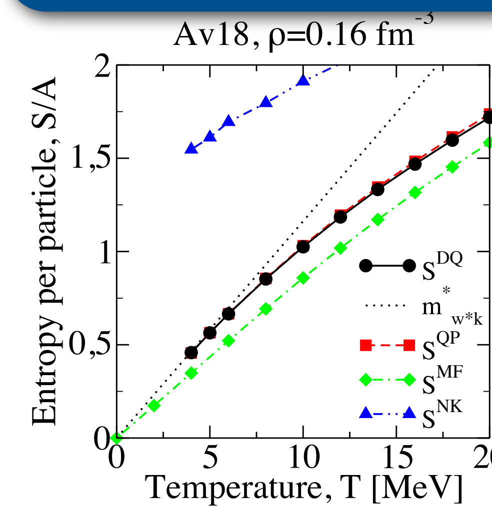


Bulk properties

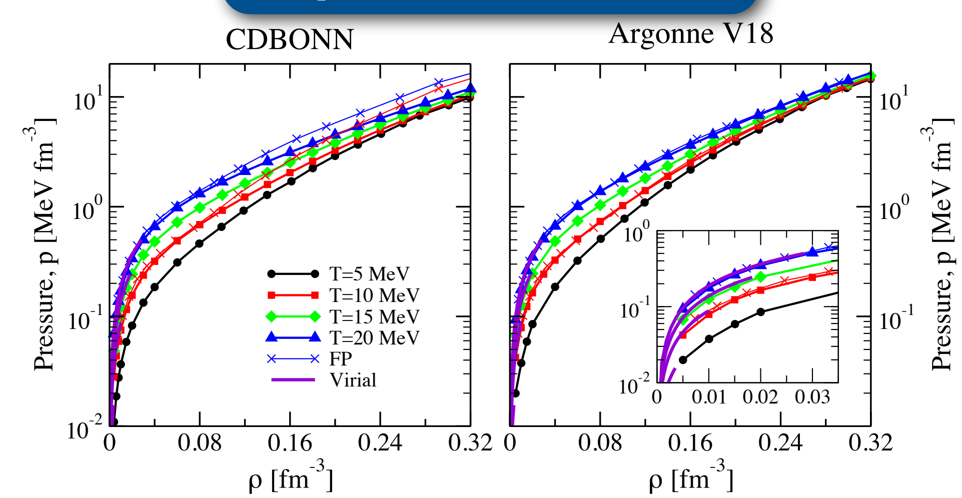
Total Energy



Entropy



Equation of State

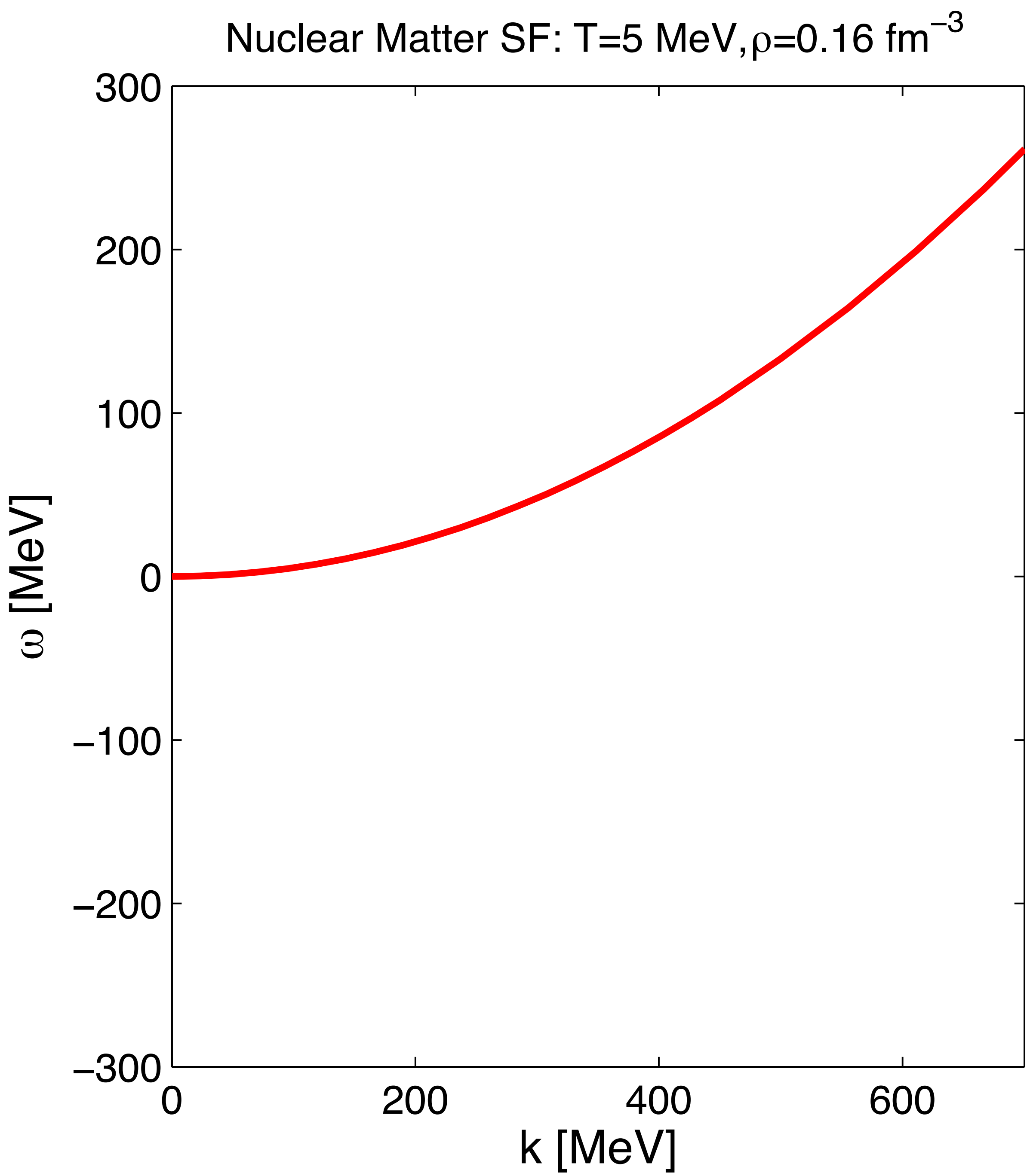


+ Transport

Quasi-particles vs spectral functions

$$\varepsilon_k = \frac{k^2}{2m}$$

$$n(k) = \frac{1}{1+e^{\frac{\varepsilon_k-\mu}{T}}}$$

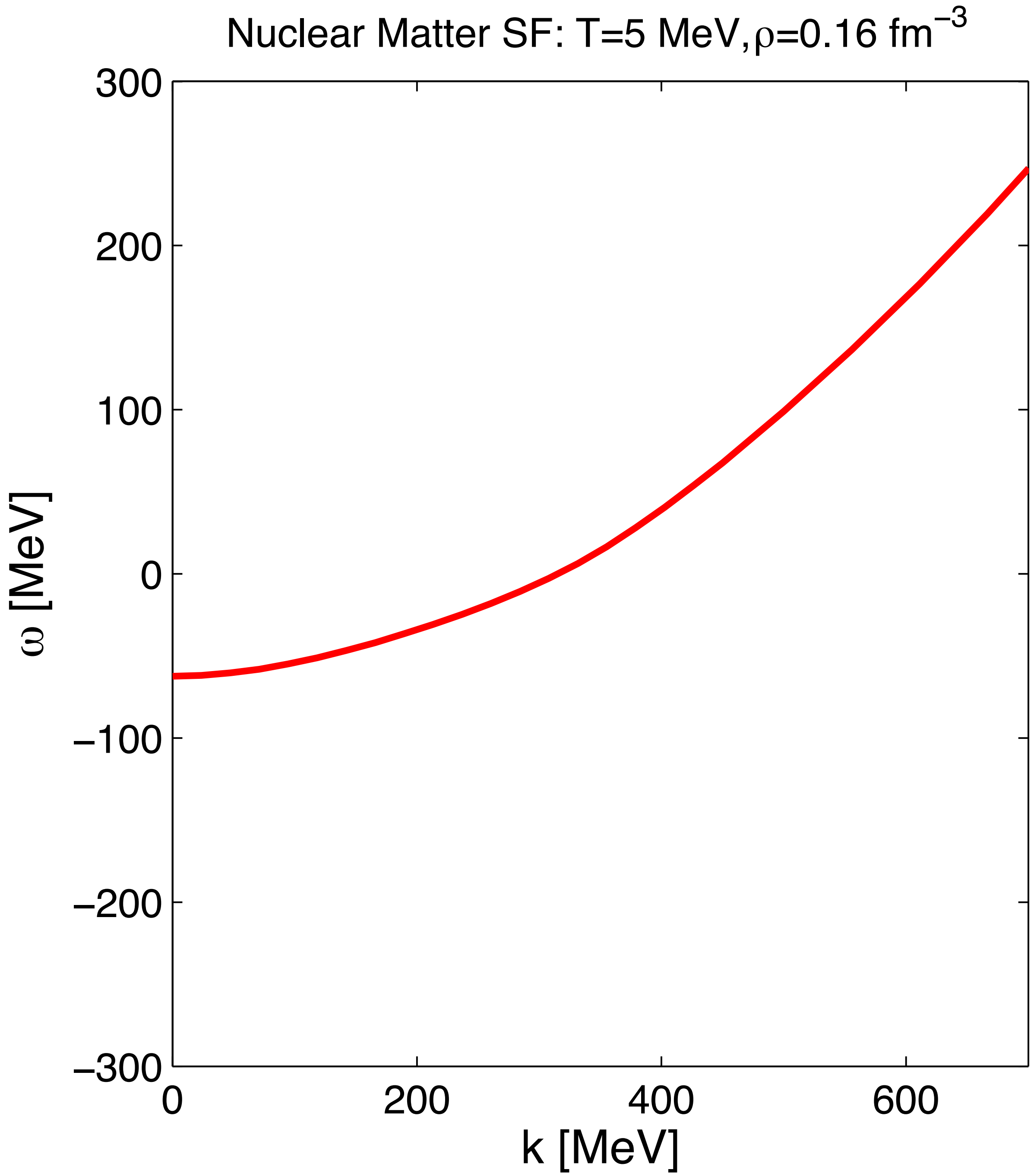


- Free fermions

Quasi-particles vs spectral functions

$$\varepsilon_k = \frac{k^2}{2m} + U(k)$$

$$n(k) = \frac{1}{1 + e^{\frac{\varepsilon_k - \mu}{T}}}$$

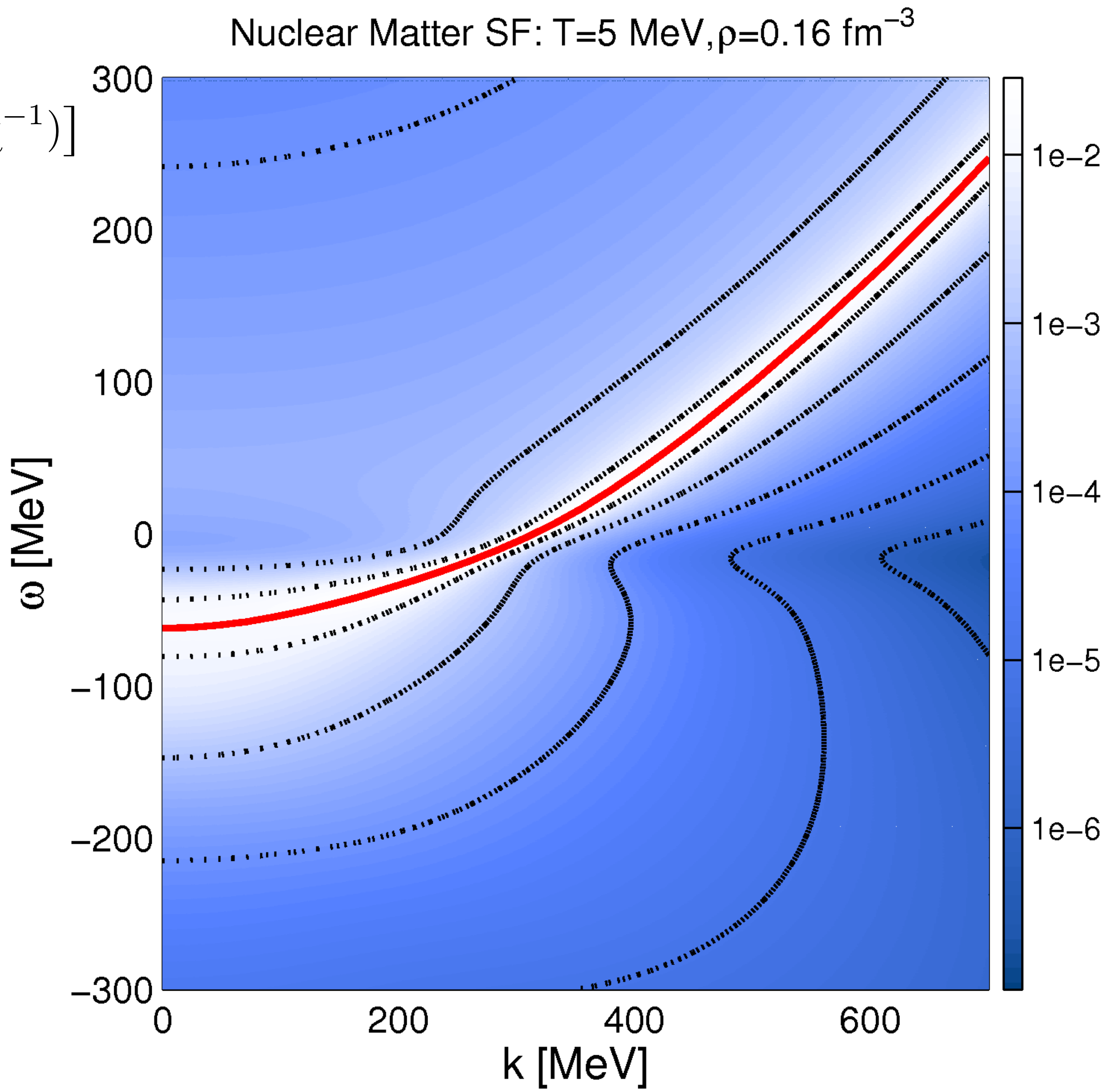


- Free fermions
- Mean-field quasiparticles

Quasi-particles vs spectral functions

$$A^<(k,\omega) = \sum_{n,m} \frac{e^{-\beta(E_n-\mu A)}}{Z} \left|\langle m|a_{\boldsymbol{k}}|n\rangle\right|^2 \delta[\omega - (E_n^A - E_m^{A-1})]$$

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



- Free fermions
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- Correlated case

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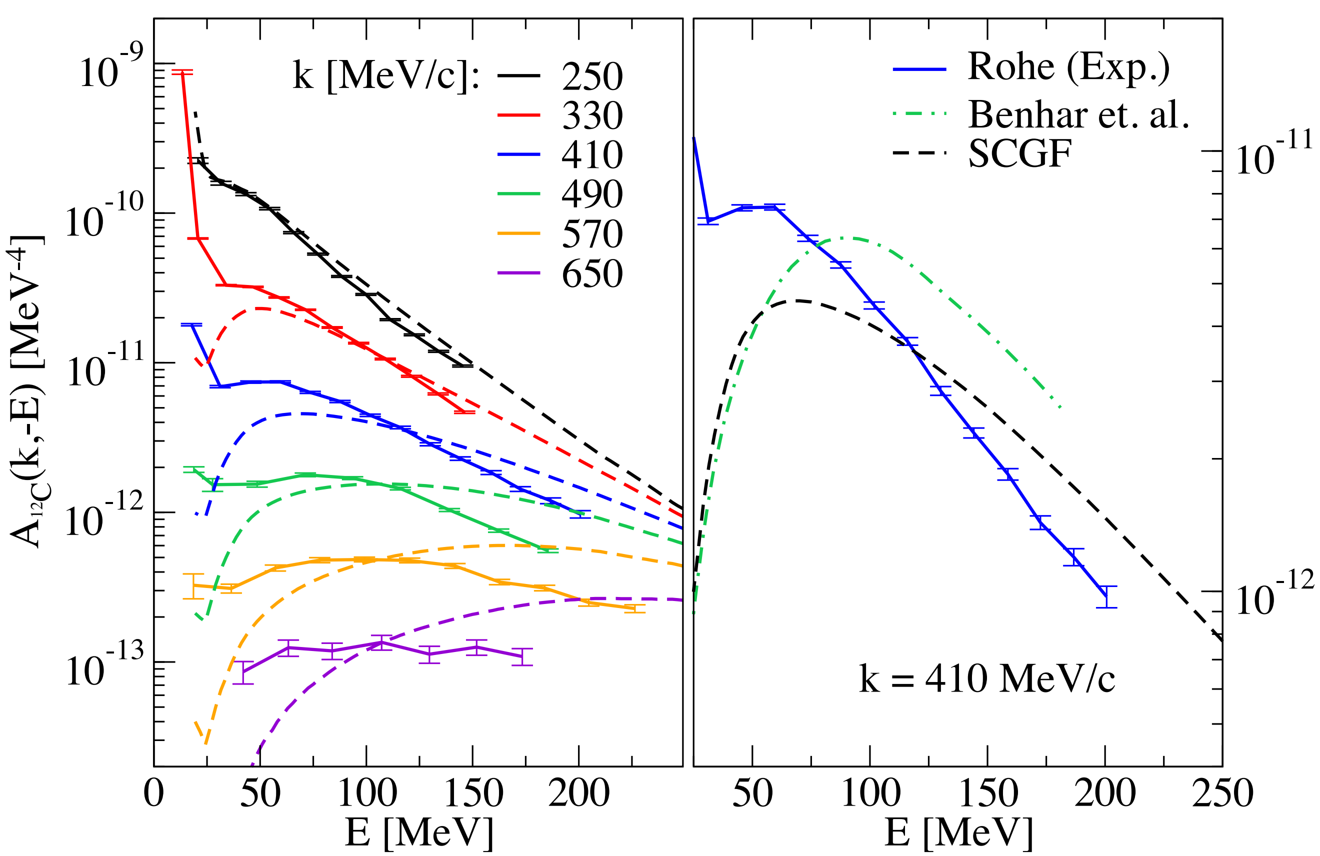
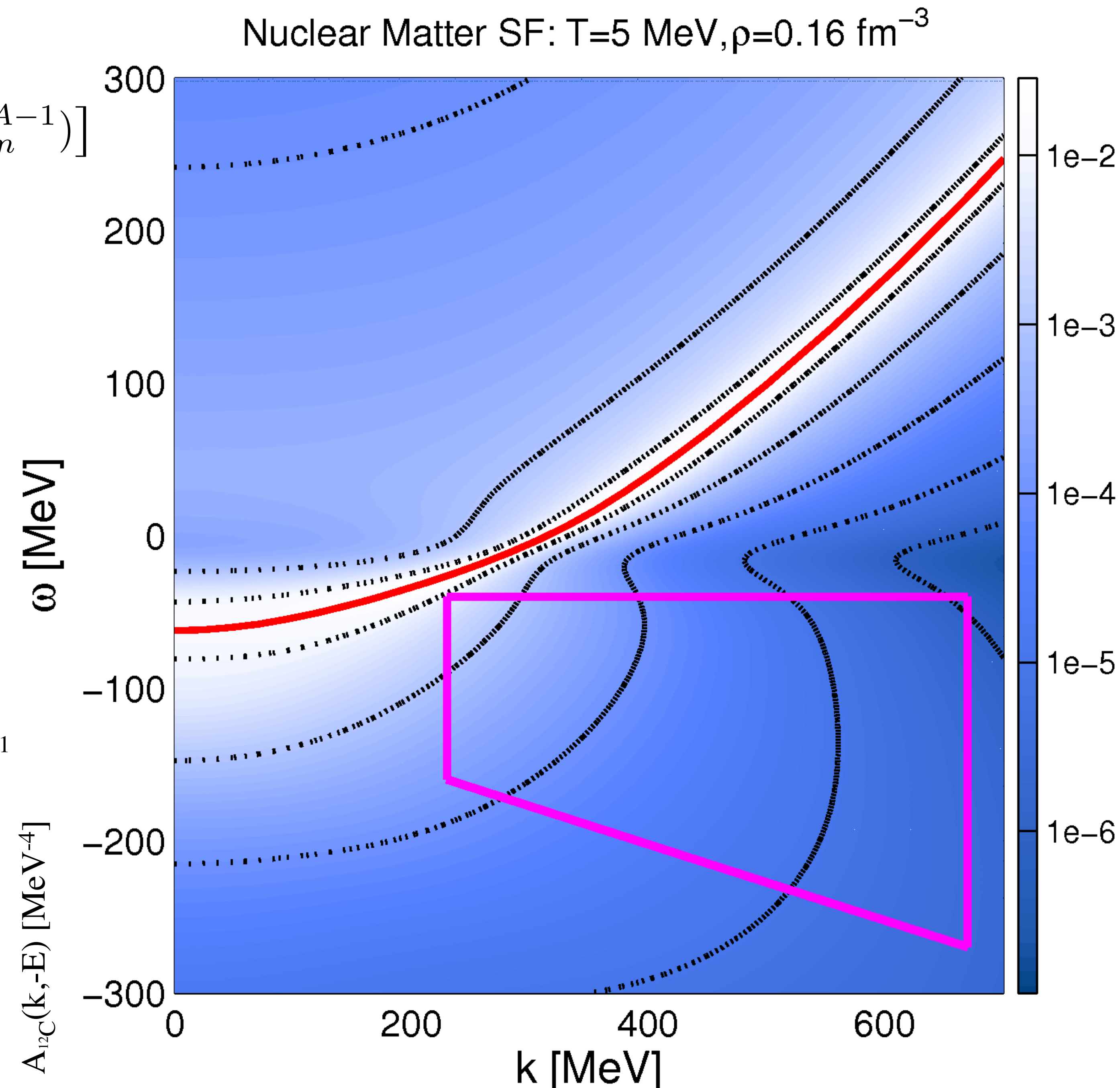


Rohe et al., PRL **93** 182501 (2004)



- Free fermions
- Mean-field quasiparticles
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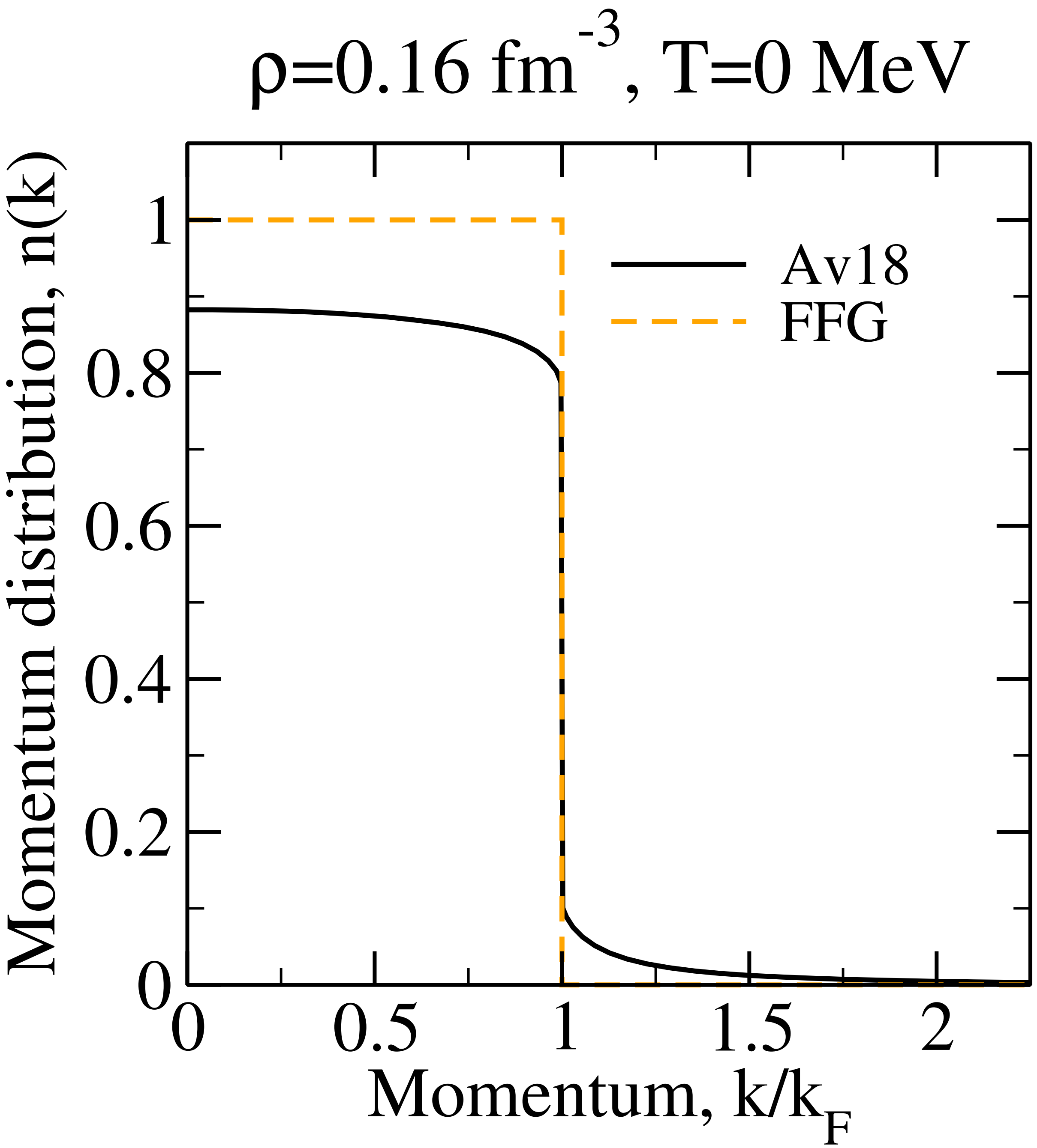
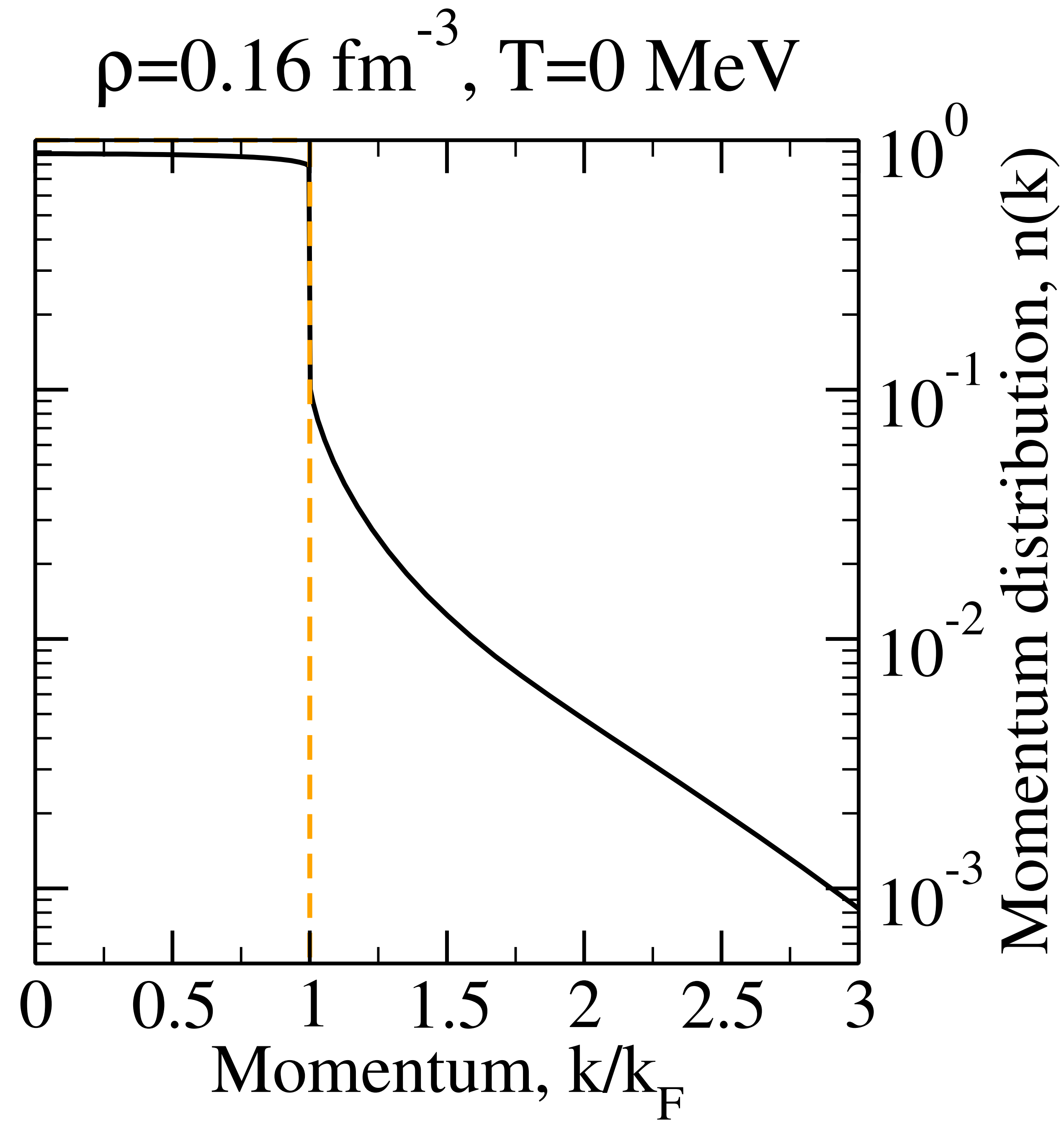
Momentum distribution

Single-particle occupation

$$n(k) = \left\langle a_k^\dagger a_k \right\rangle \qquad \nu \int \frac{d^3k}{(2\pi)^3} n(k) = \rho$$





- 11-13% depletion at low k, population at high k

Momentum distribution

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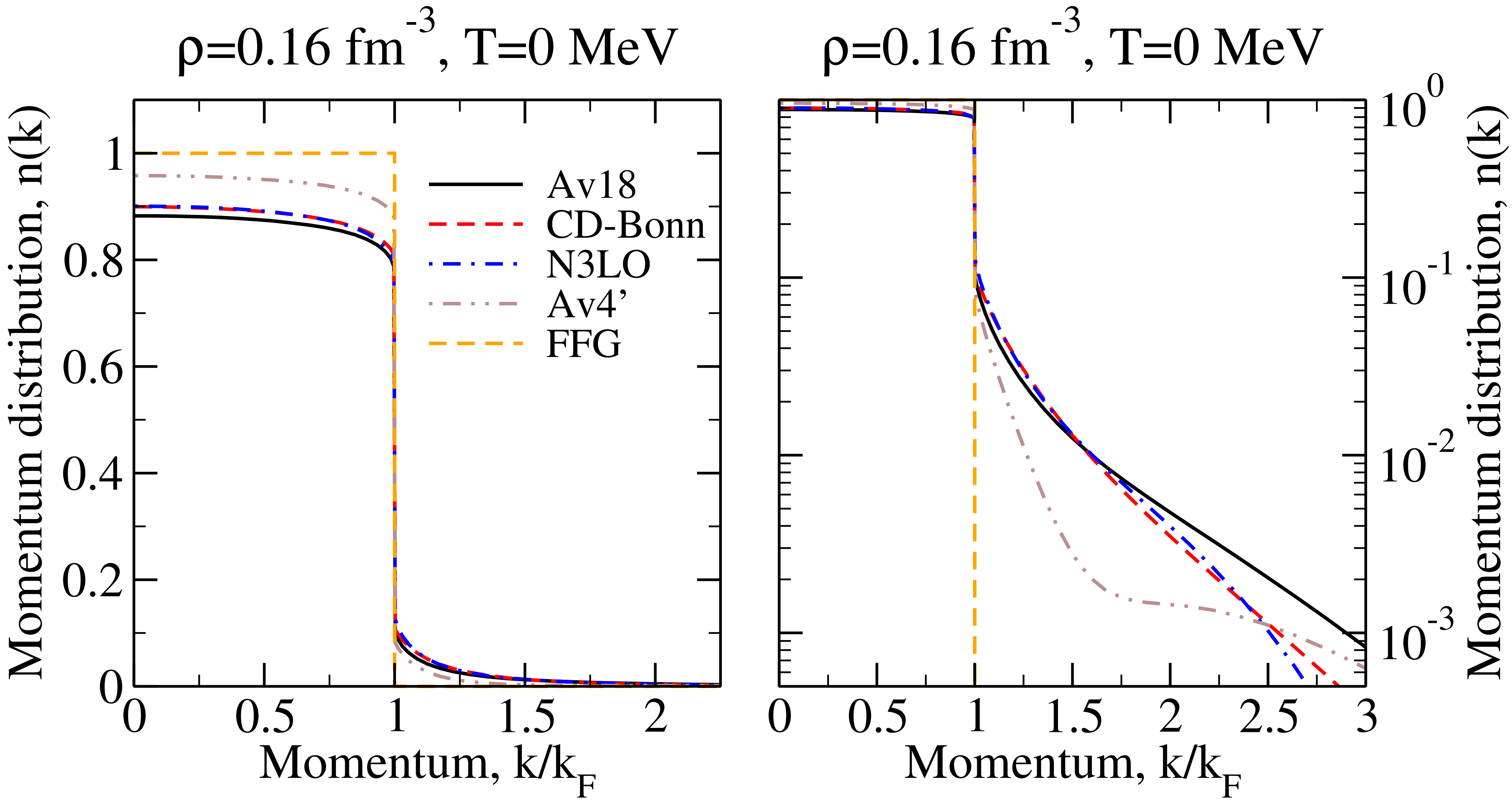

- 11-13% depletion at low k, population at high k
- Dependence on NN interaction under control

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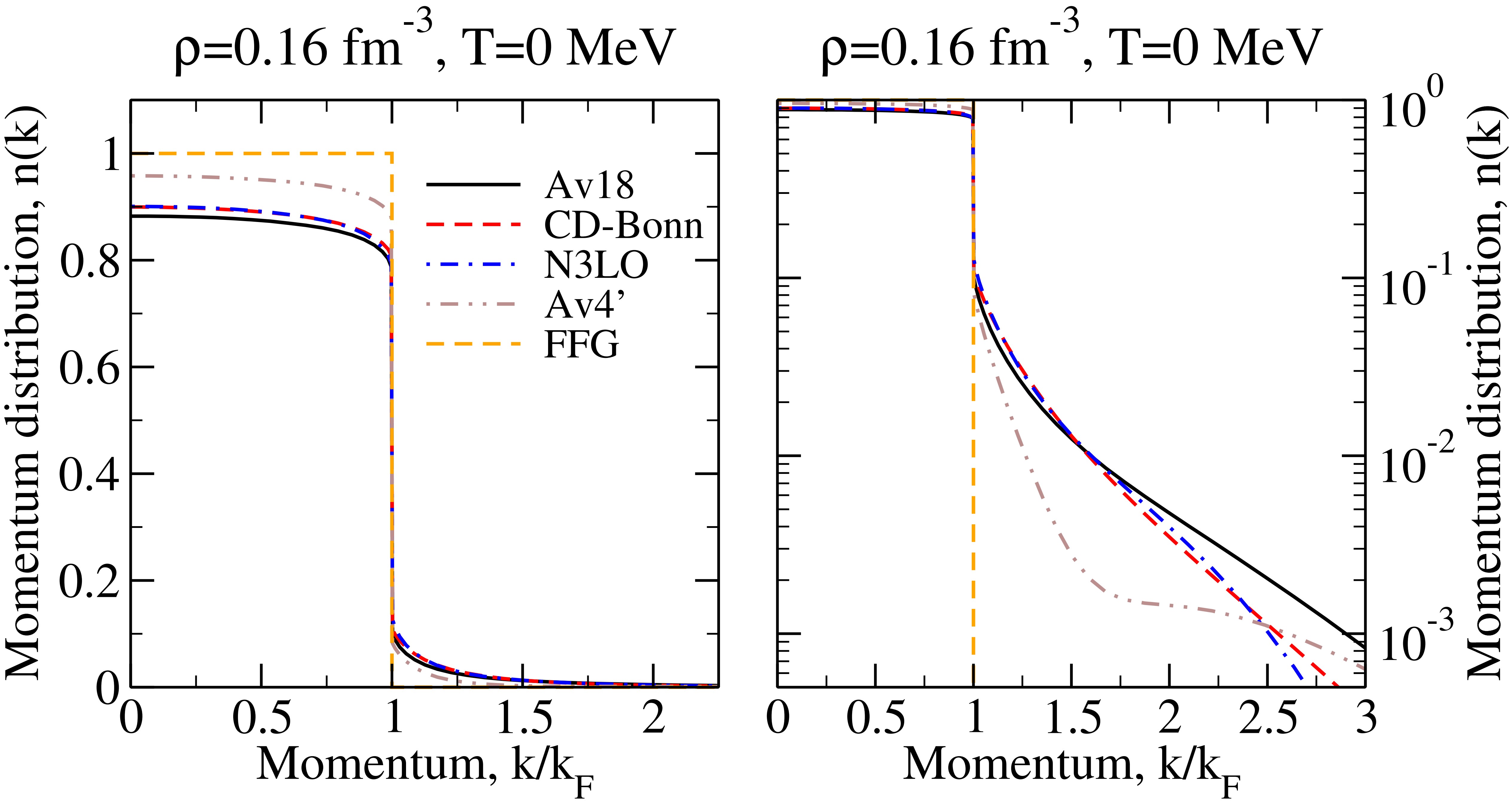

- 11-13% depletion at low k, population at high k
- Dependence on NN interaction under control
- T=0 extrapolated from finite T

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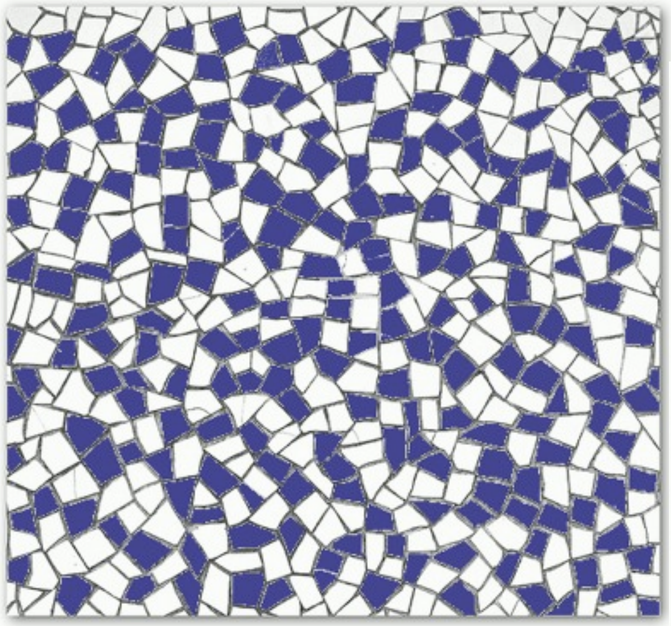
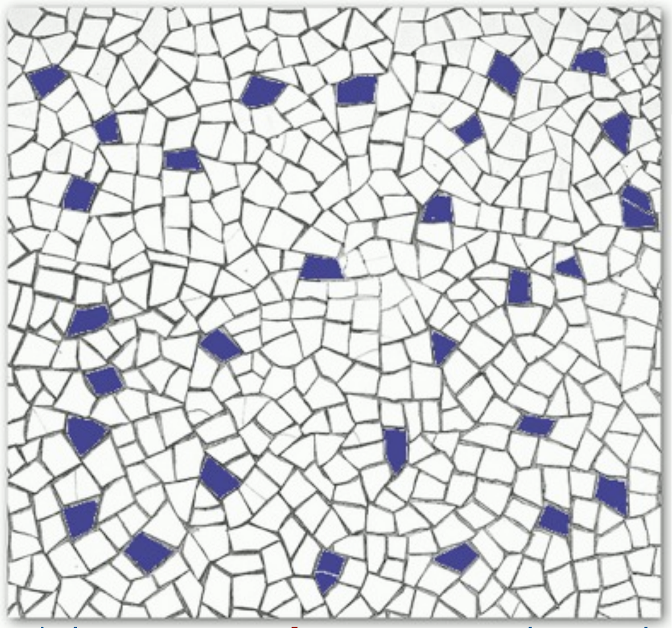
Nuclear "trencadís"

β=0
Symmetric matter



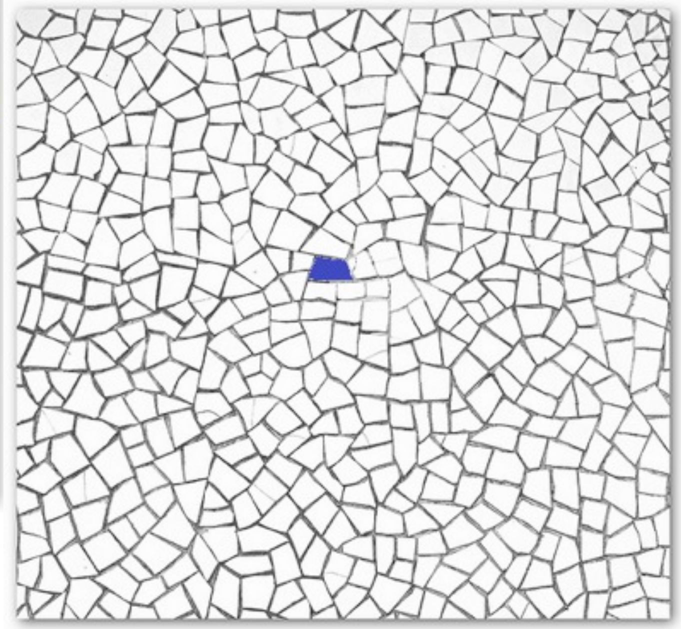
SR+Tensor correlations

β≠0
Asymmetric matter



*Neutrons **less** correlated*
*Protons **more** correlated*

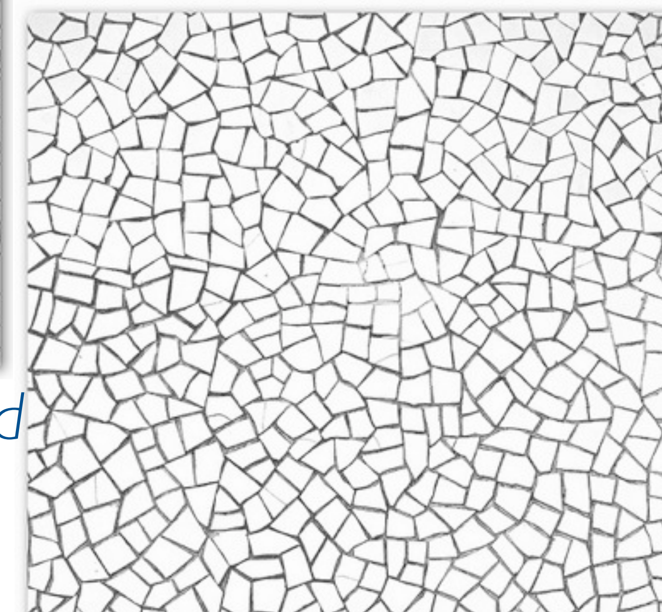
β≈1
Polaron



*Protons **maximally** correlated*
***Hyper**-impurities?*

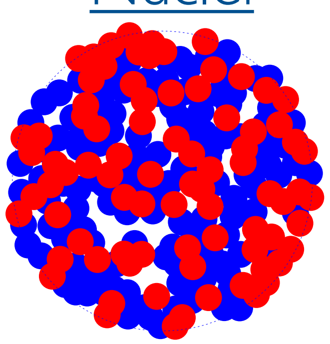
Neutron stars

β=1
Neutron matter



SR correlations

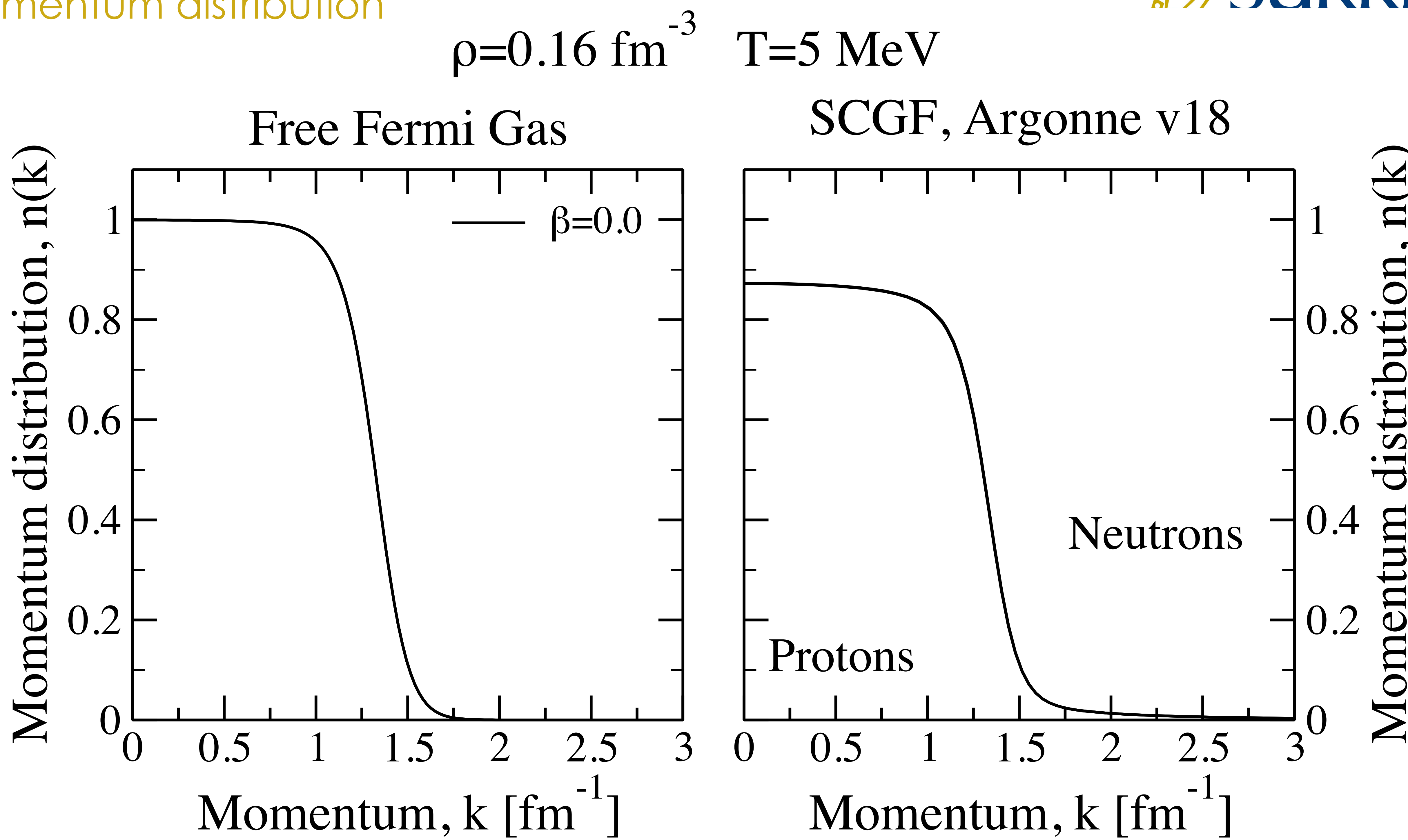
Nuclei



$$\beta = \frac{N-Z}{N+Z}$$

Frick, Rios et al. PRC **71**, 014313 (2005)
Rios et al. PRC **79**, 064308 (2009)
Carbone et al. EPL **97** 22001 (2012)

Asymmetric matter
Momentum distribution



- Correlations affect depletion ⇒ non-perturbative effect
- Neutrons become less correlated
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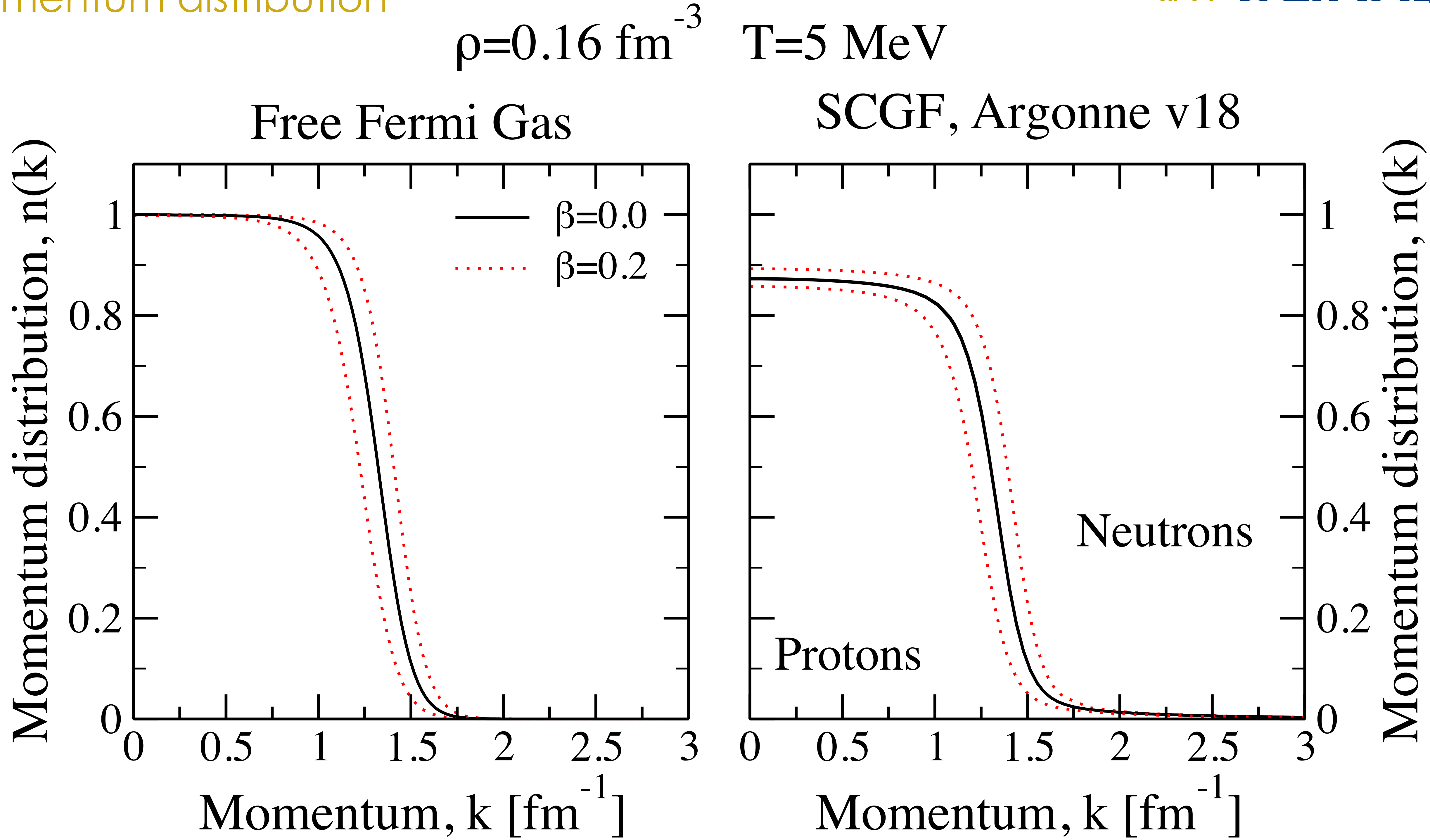
A. Rios et al., PRC **79** 064308 (2009)

Asymmetric matter
Momentum distribution



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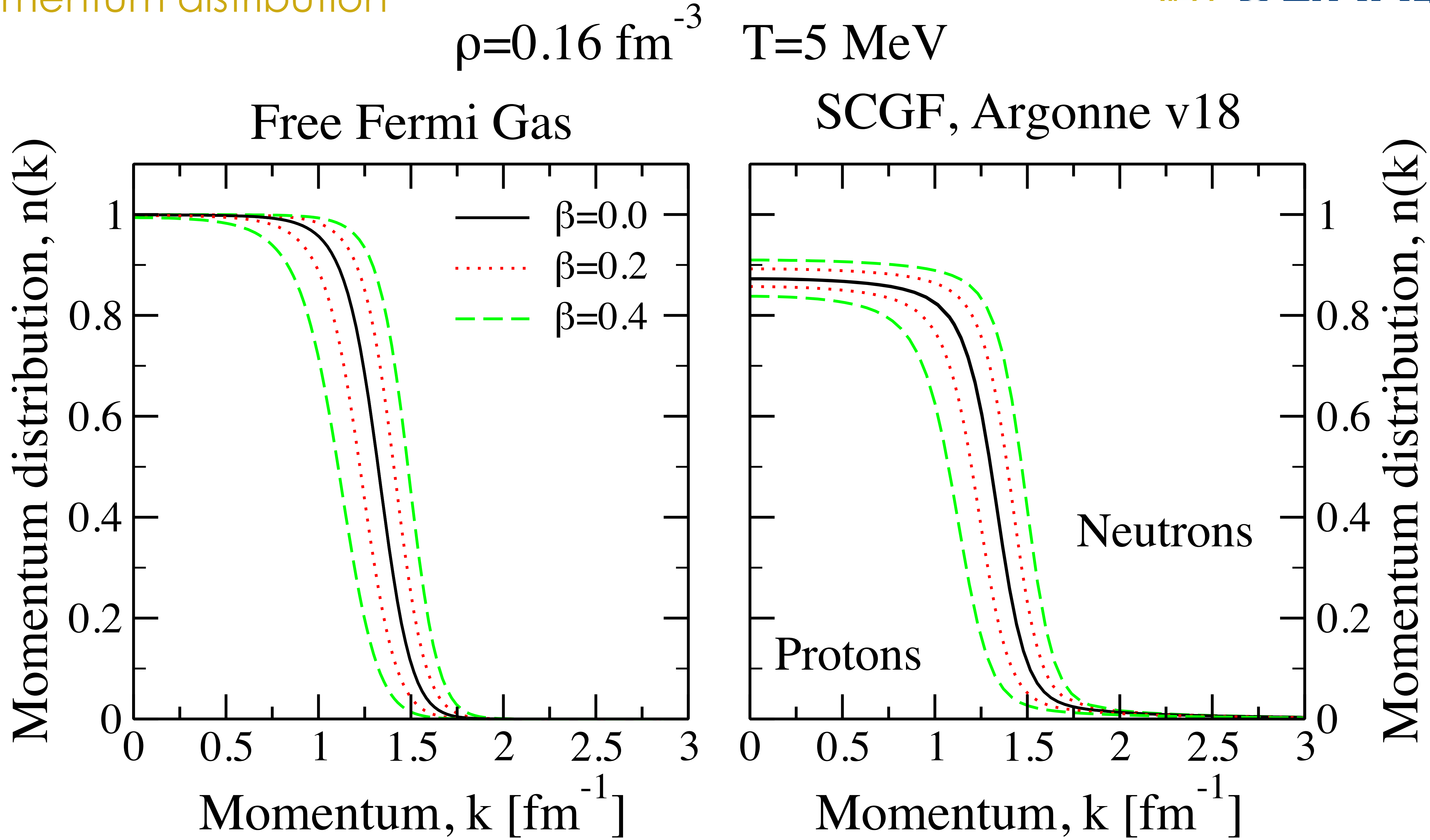

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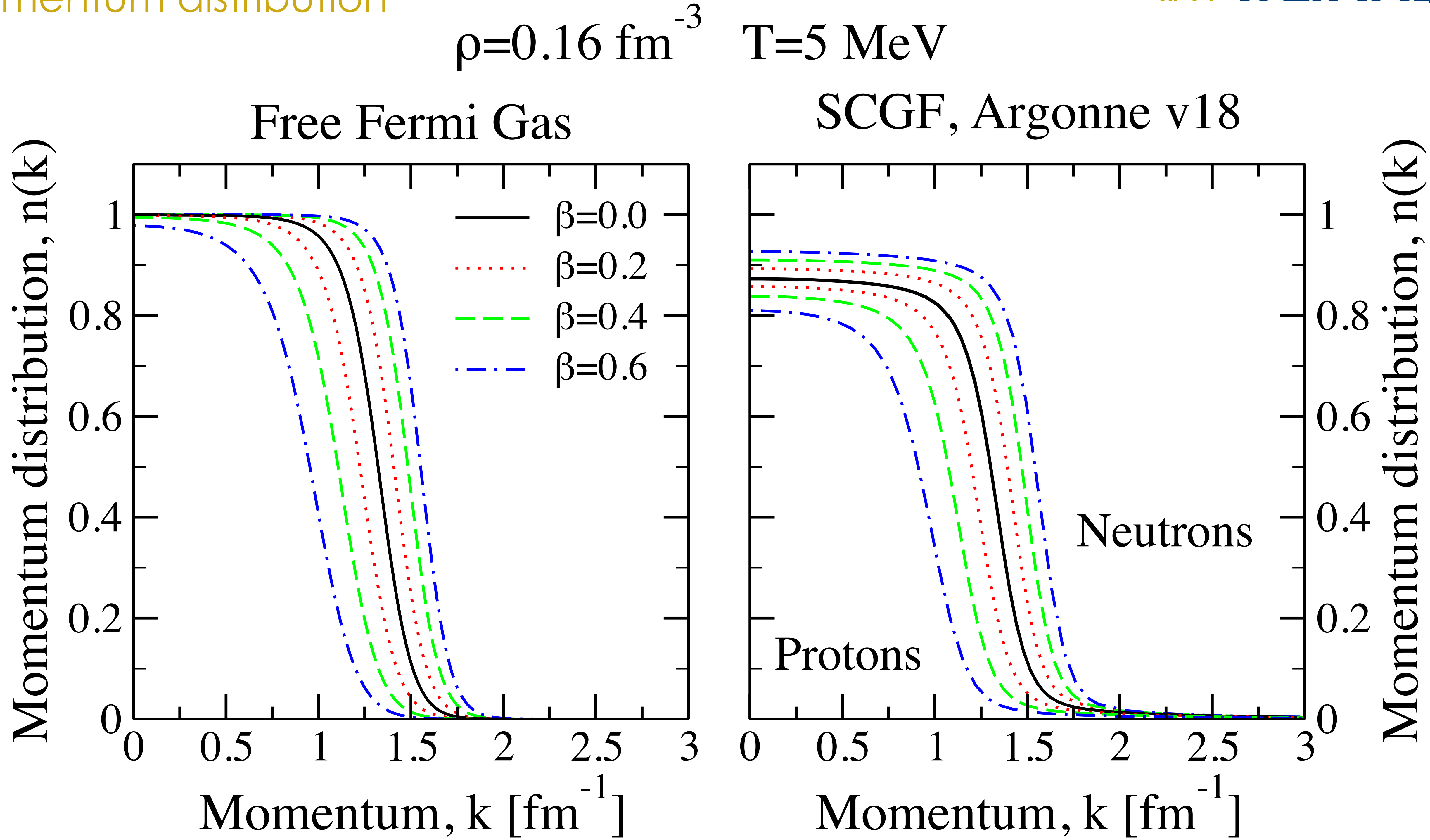

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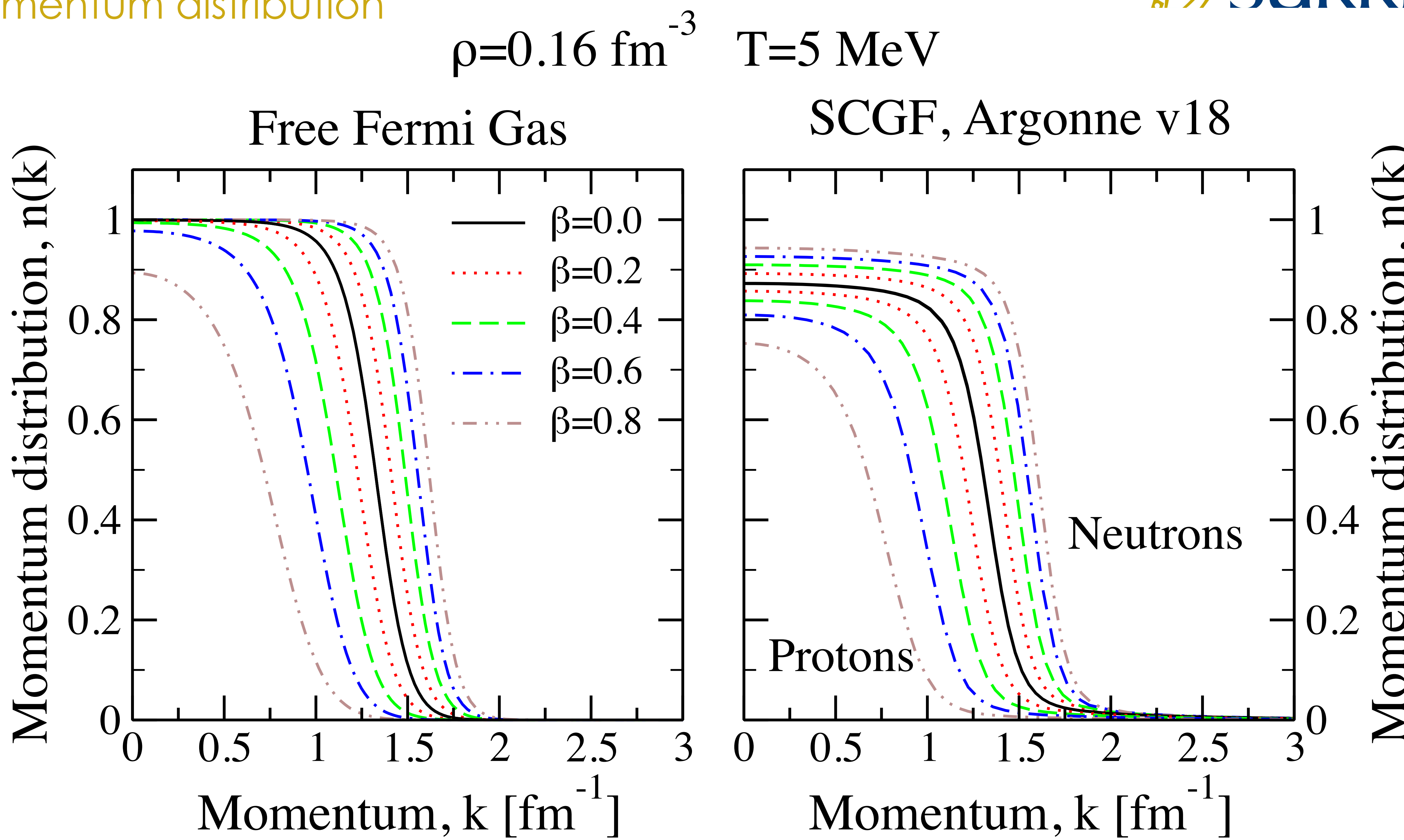

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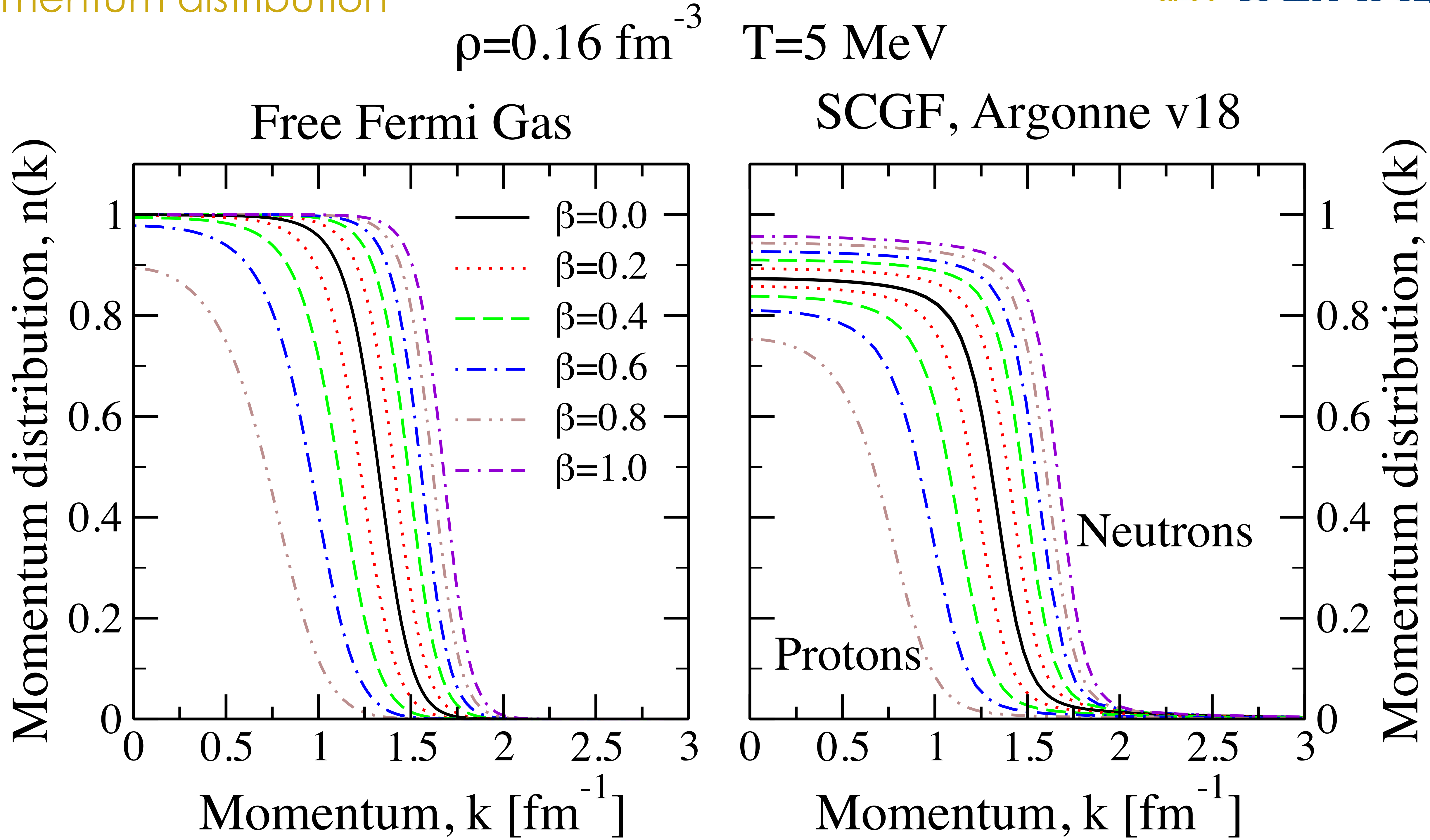

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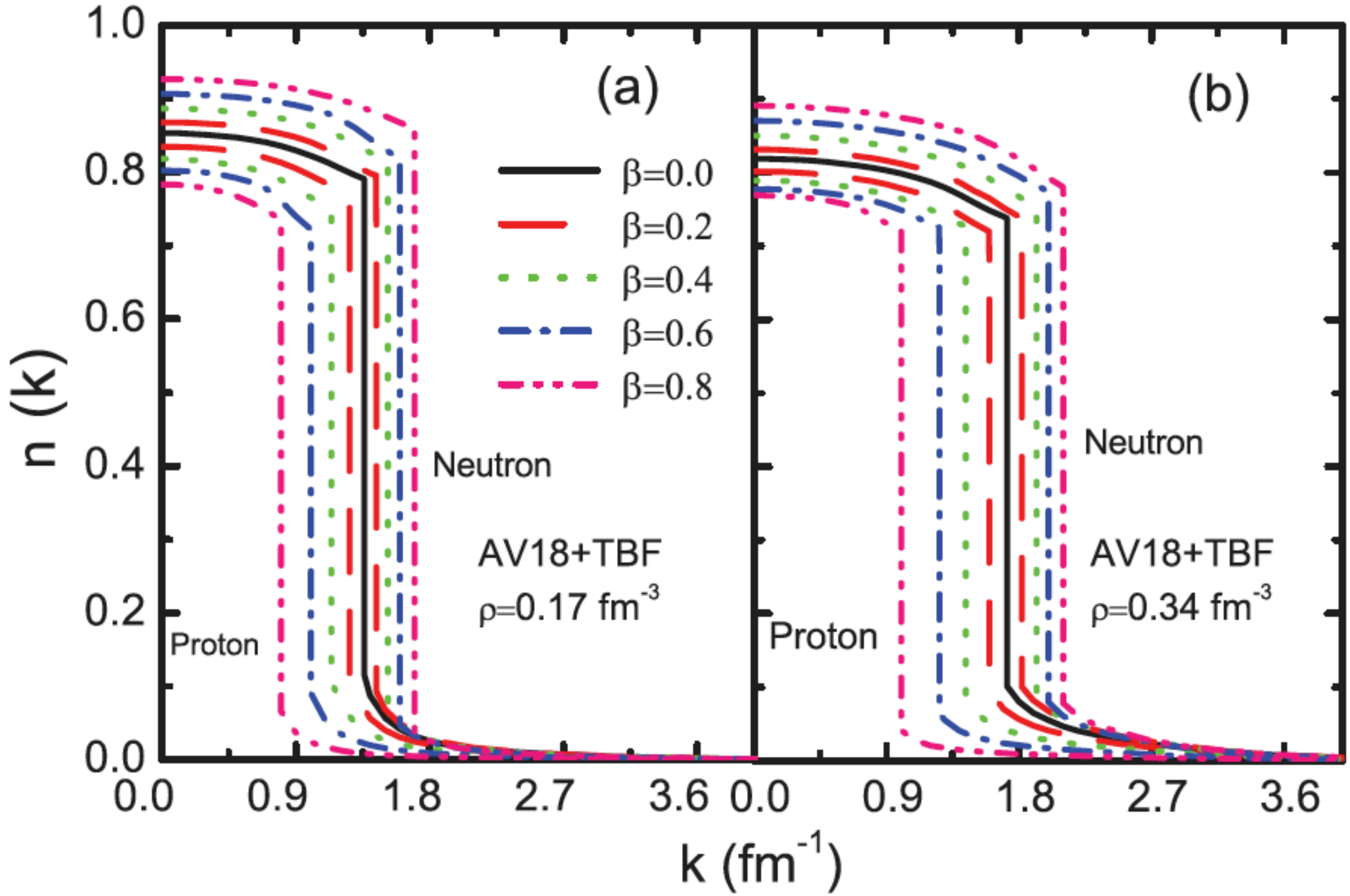
A. Rios et al., PRC **79** 064308 (2009)

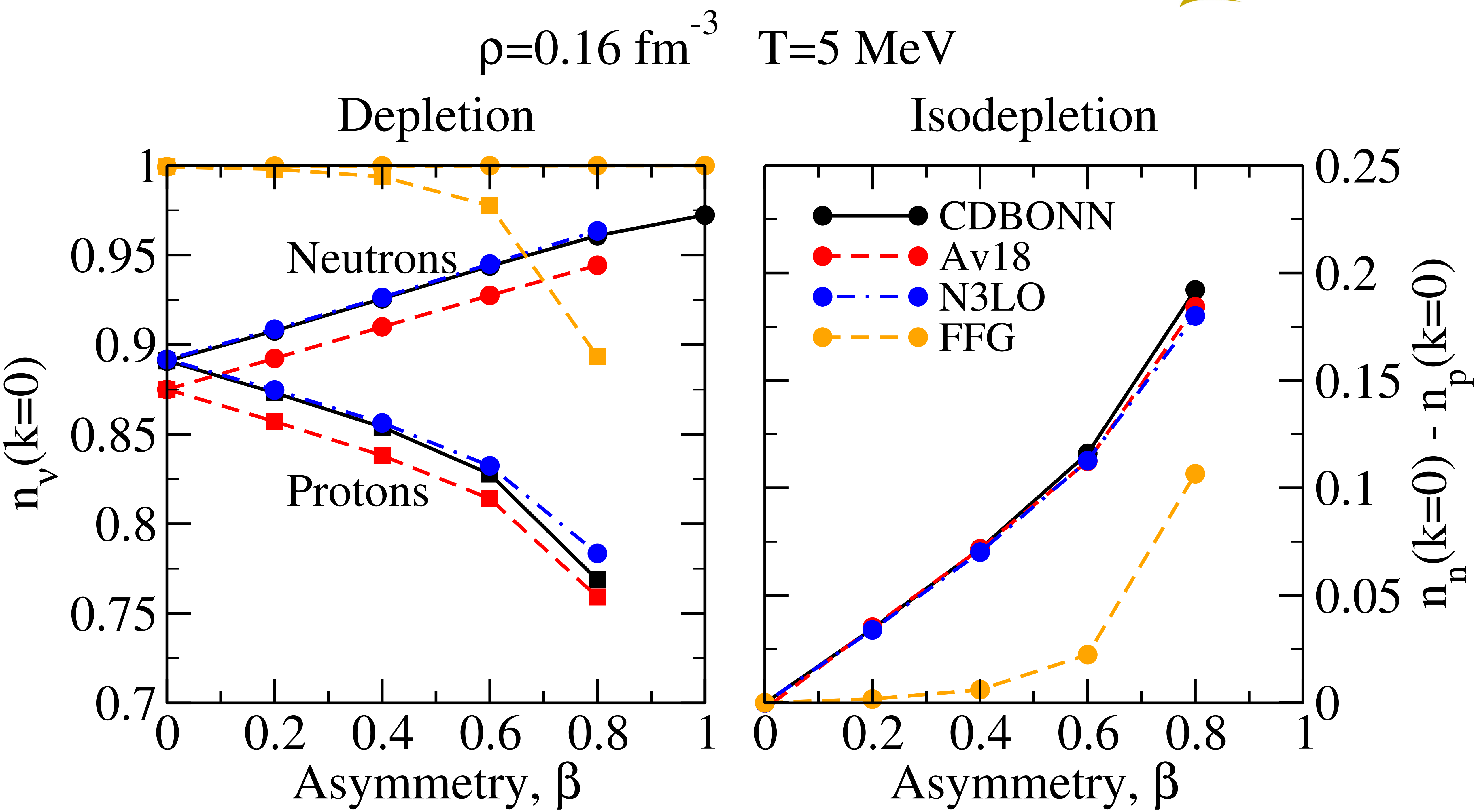
Theoretical confirmation

Asymmetric matter momentum distribution
EBHF calculation, T = 0



Yin, Li, Wang & Zuo, PRC **87** 014314 (2013)

Universality at k=0



- Correlations vs asymmetry
- All potentials lie in a narrow iso-depletion band

A. Rios et al., PRC **79** 064308 (2009)

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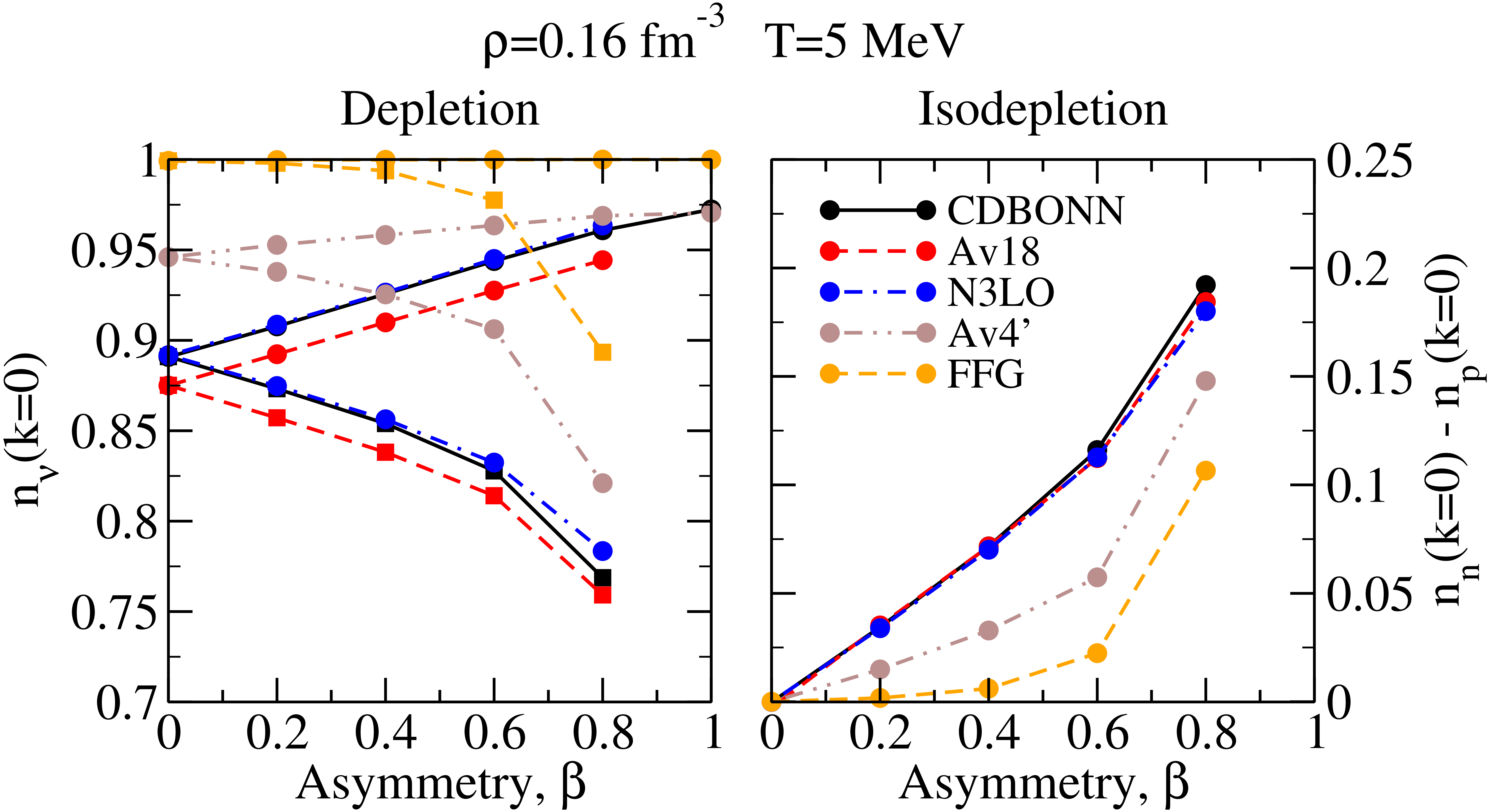
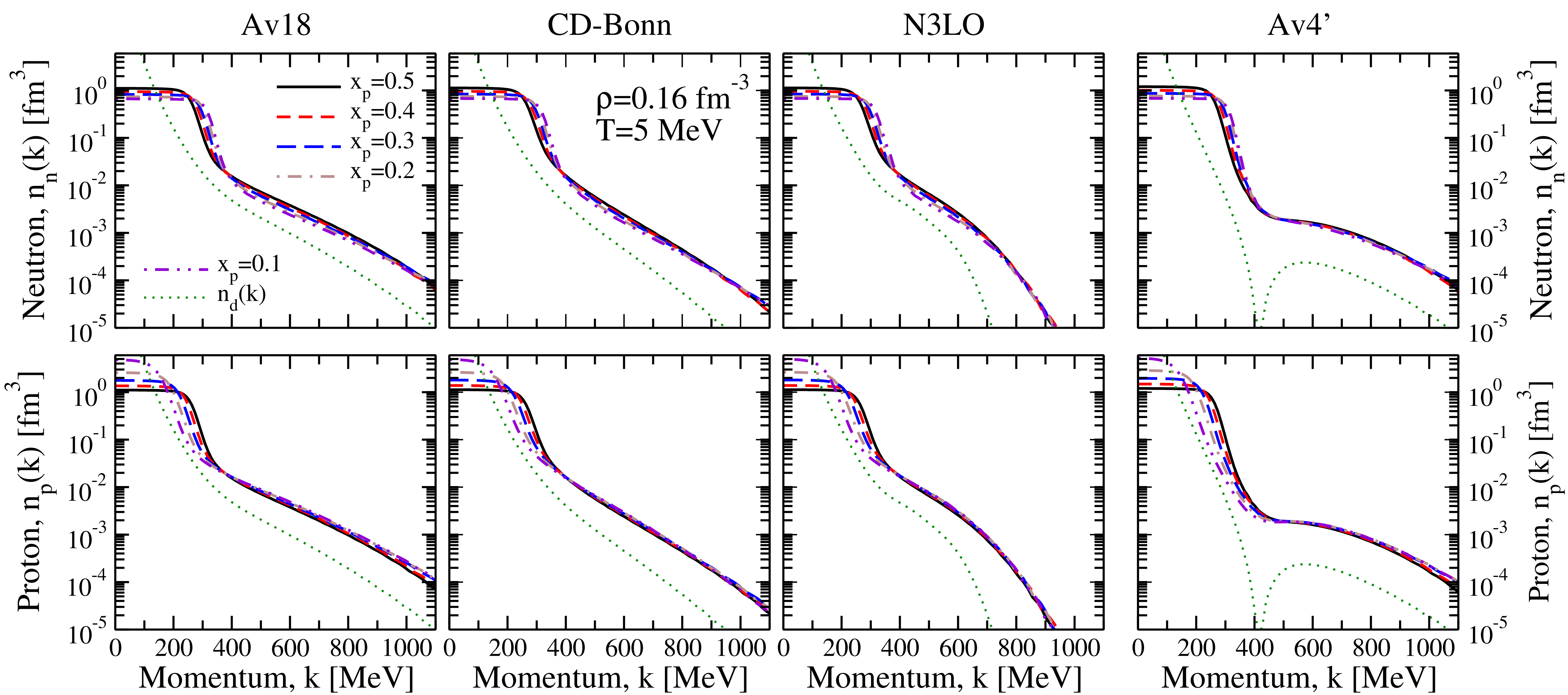


- Correlations vs asymmetry
- All potentials lie in a narrow iso-depletion band
- Tensor needed!

A. Rios et al., PRC **79** 064308 (2009)

Quantifying tensor-like correlations

$$4\pi\int_0^\infty \mathrm{d}k k^2\, n(k) = 1$$



- SNM vs deuteron momentum distribution
- Very similar in tensor-like area
- Compare to empirical estimates Arrington et al. PPNP 67 898 (2012)

A. Rios, A. Polls & W.H. Dickhoff, PRC **89**, 044303 (2014)

Quantifying tensor-like correlations

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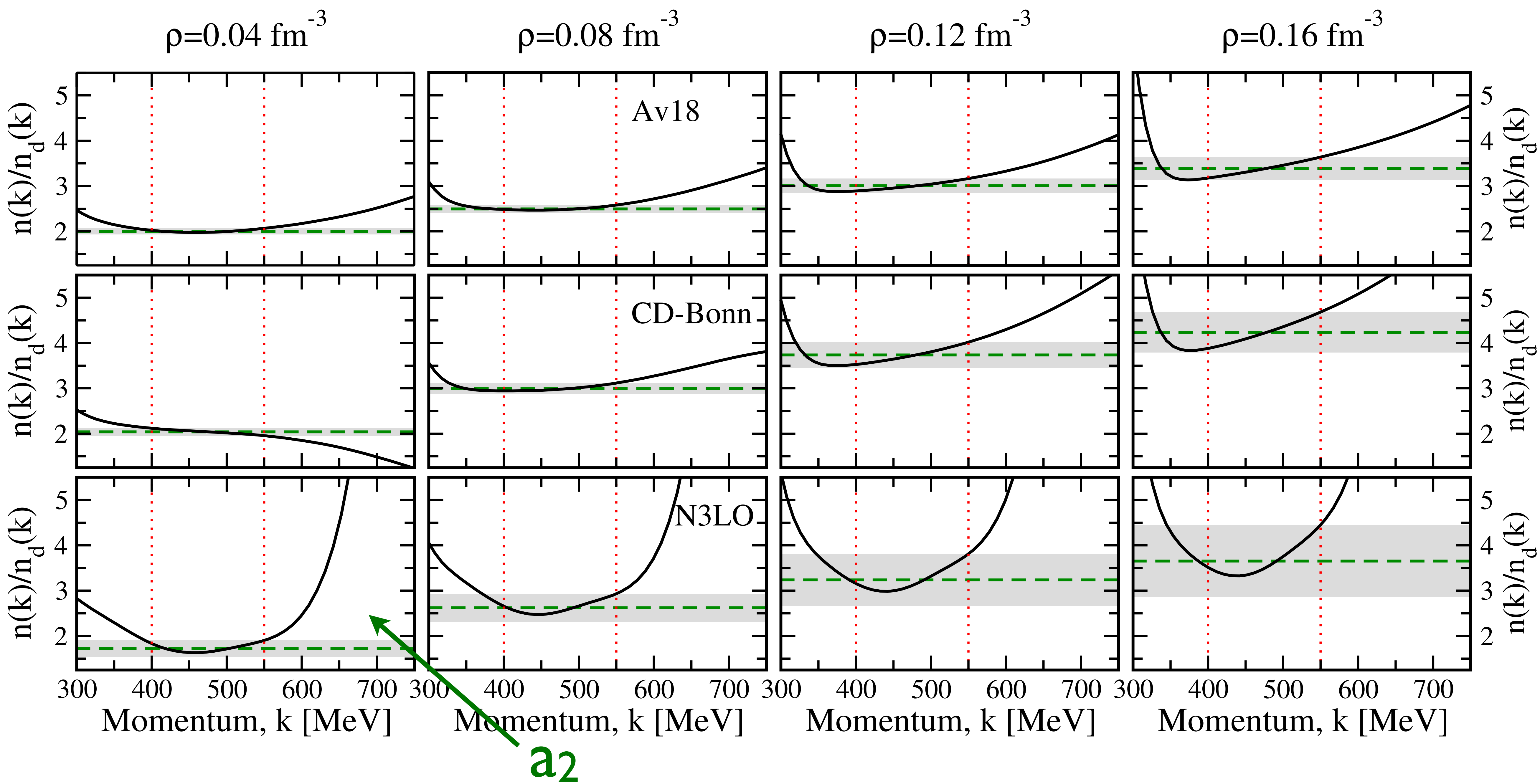

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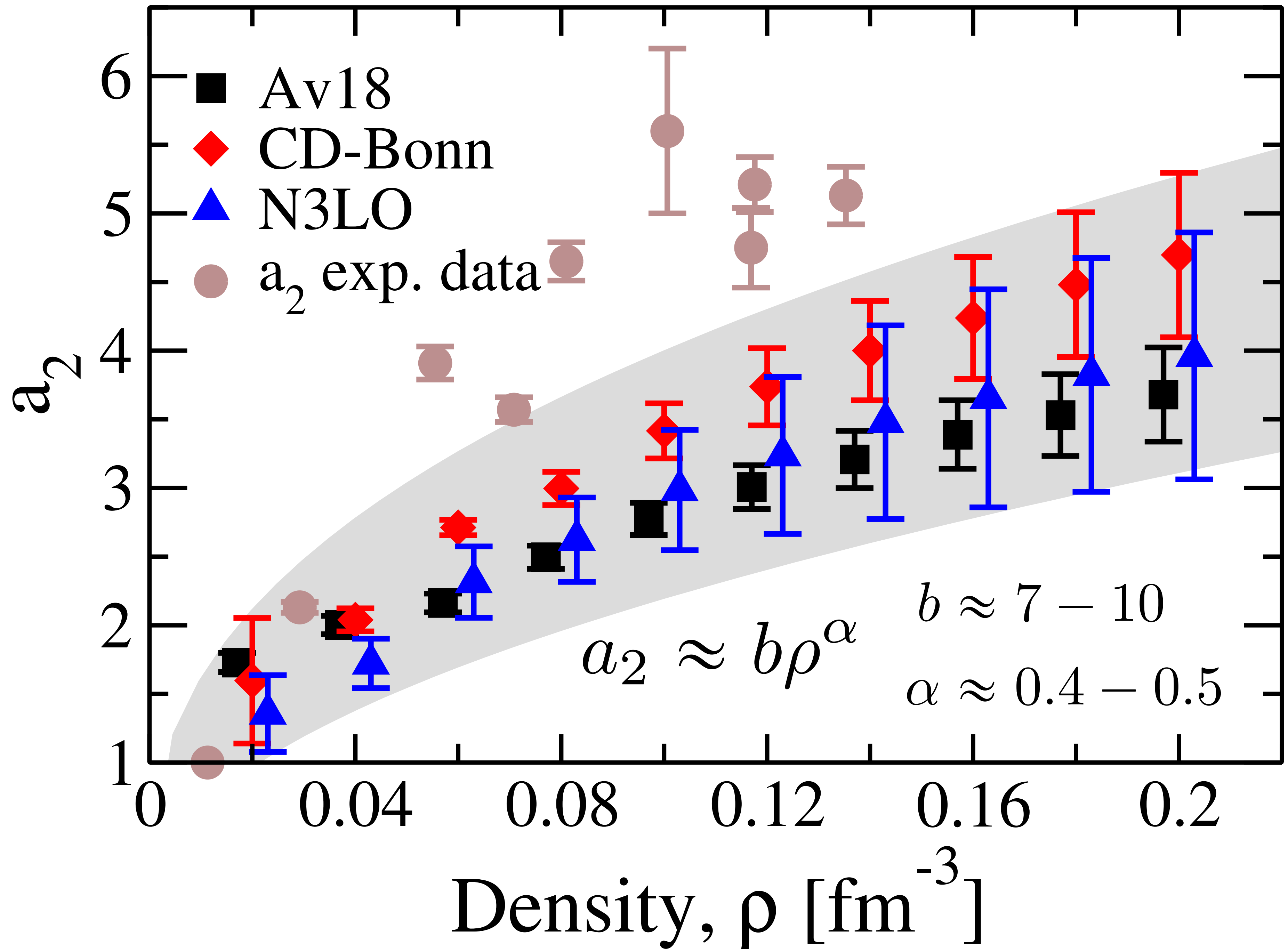

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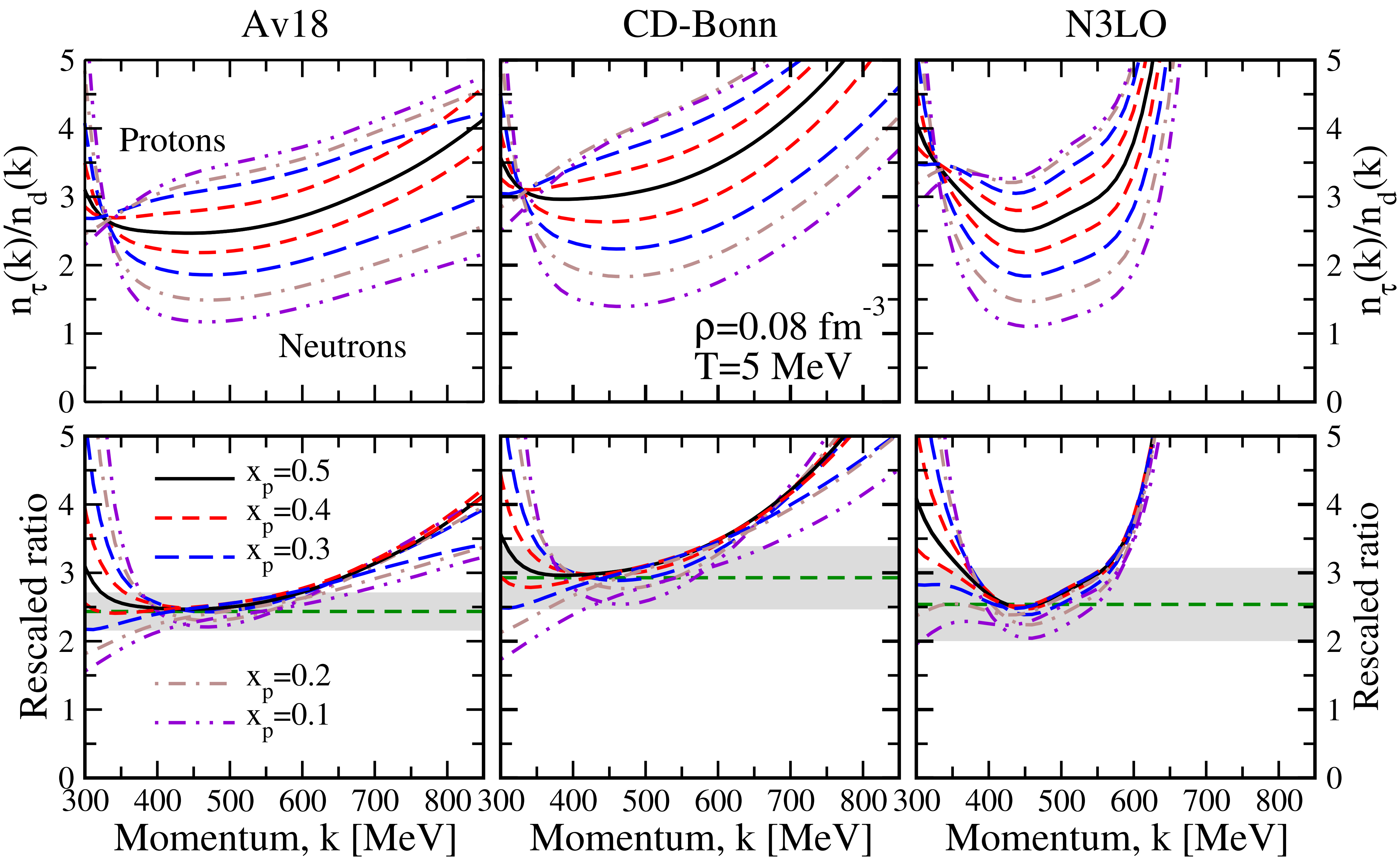
Quantifying tensor-like correlations II

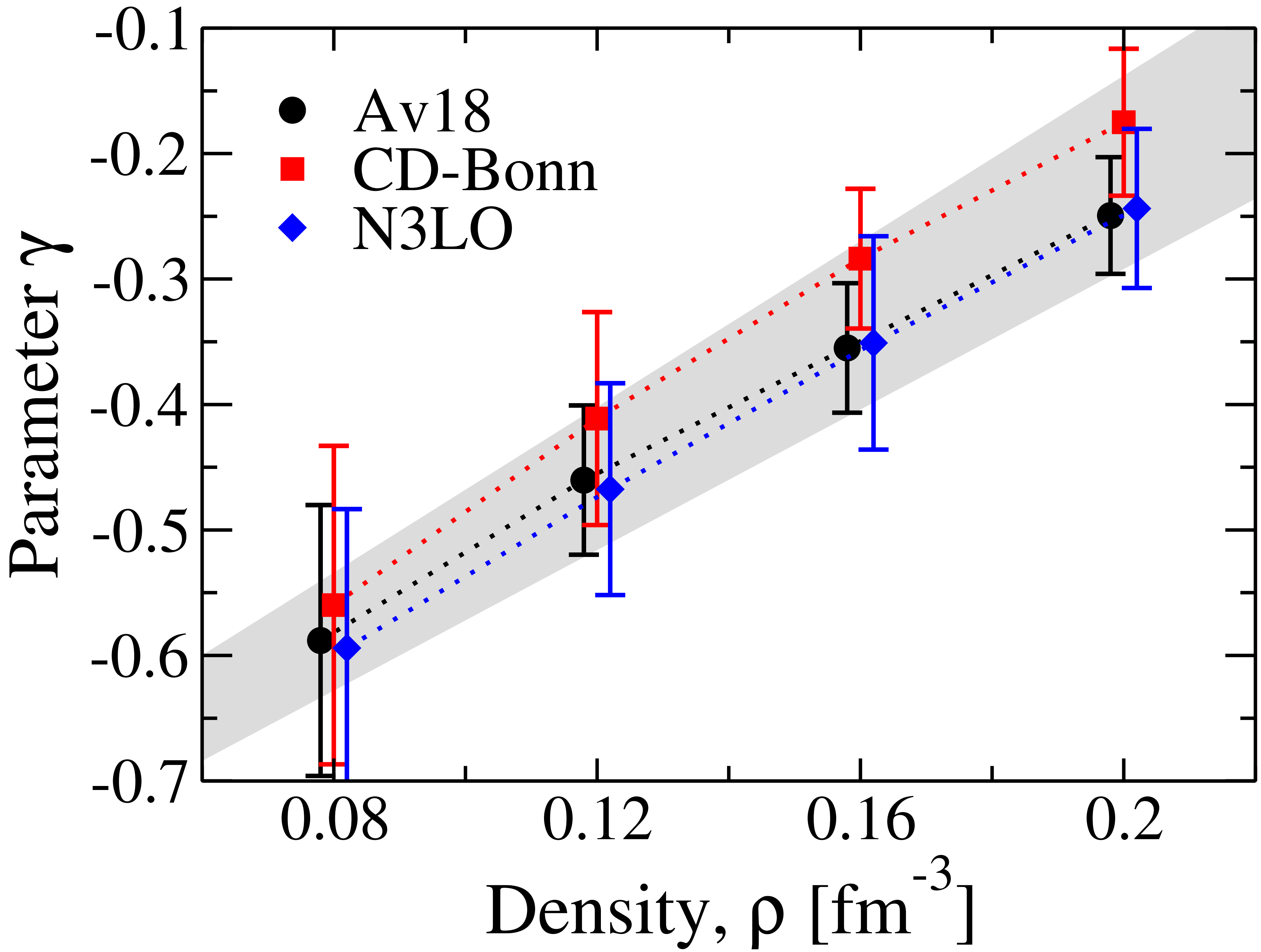


$$a_2 \approx b \left[1 \pm \gamma\beta\right] \rho^{\alpha}$$

Asymmetry dependence inspired by DFG model

A. Rios, A. Polls & W.H. Dickhoff, PRC **89**, 044303 (2014)

Quantifying tensor-like correlations II



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Asymmetry dependence inspired by DFG model

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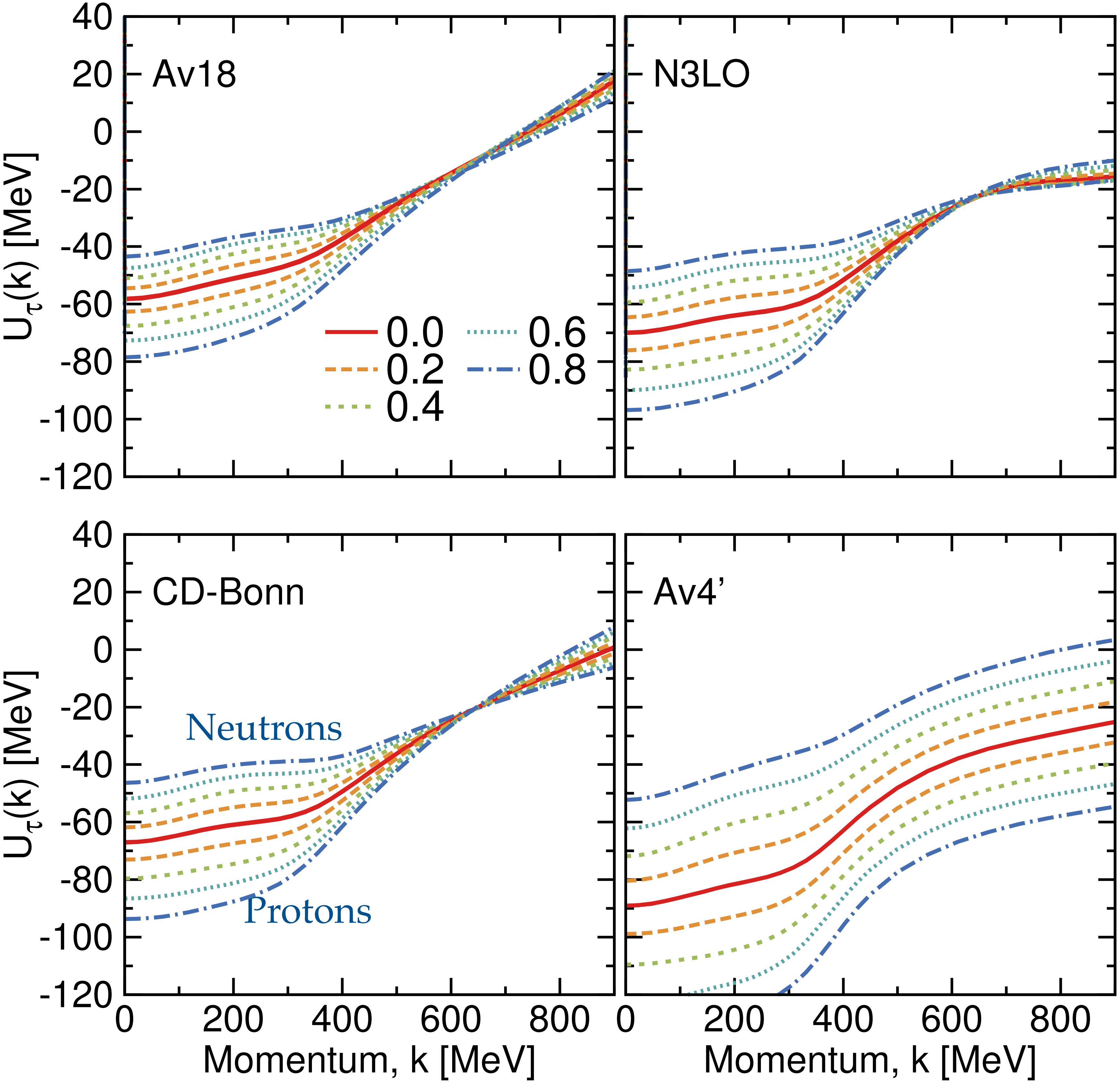
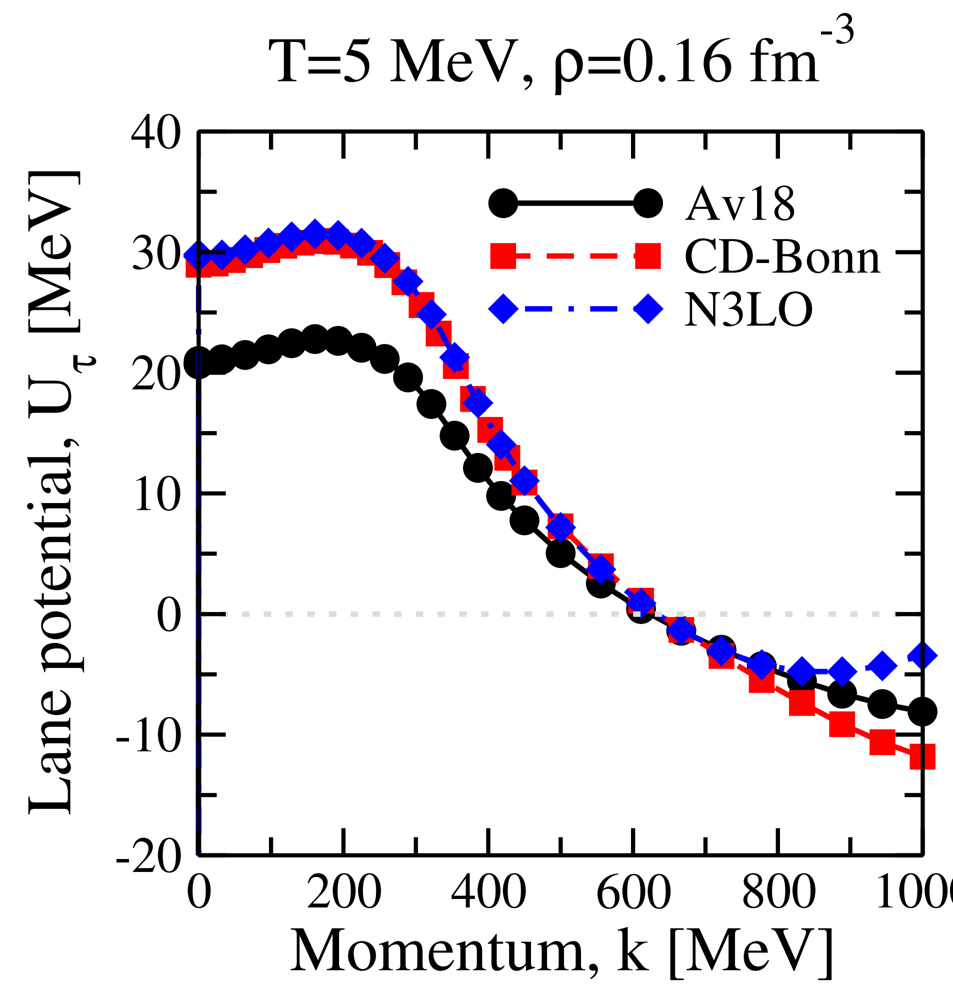
Single-particle potentials



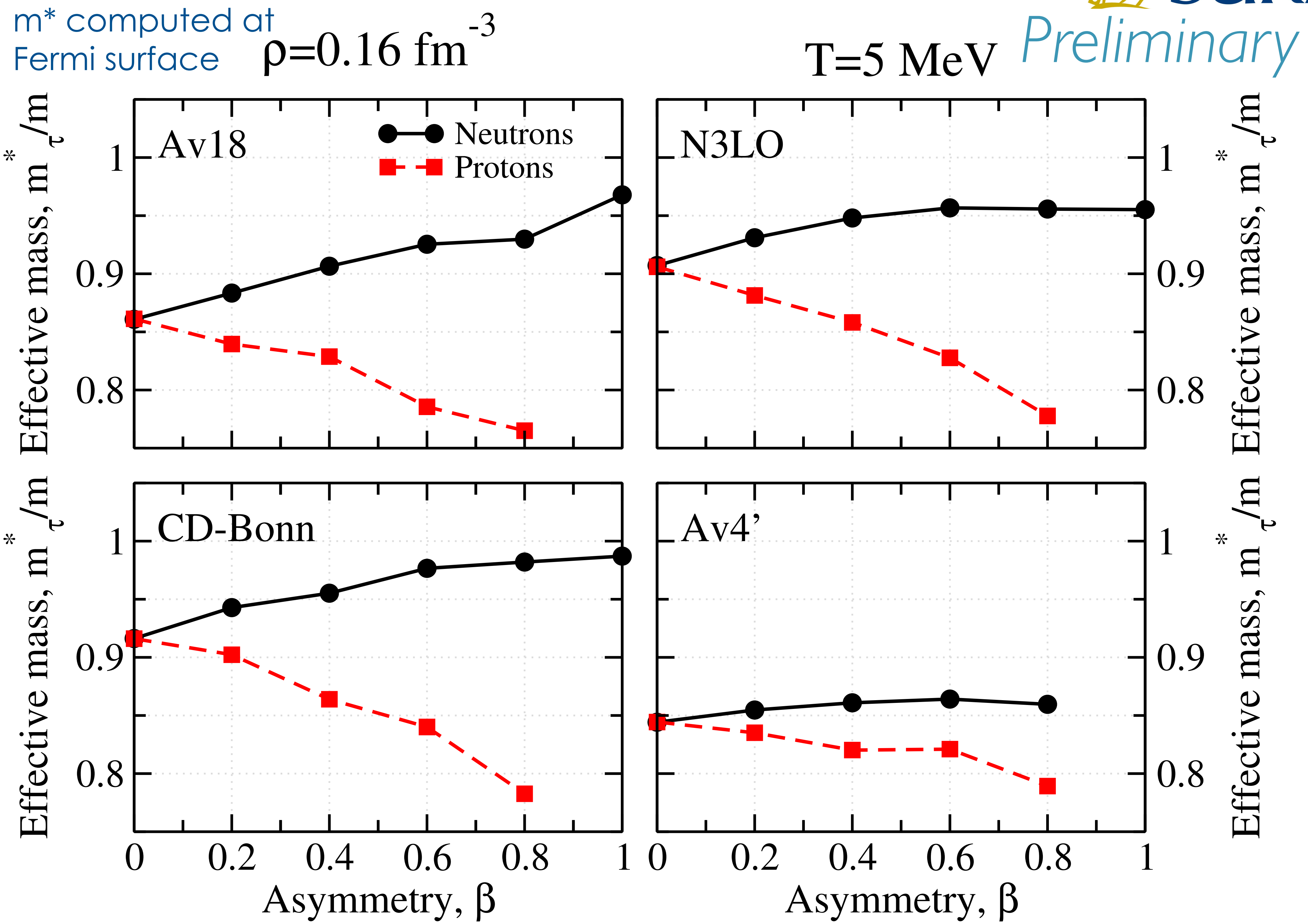
s.f. peaks

$$\varepsilon_k^\tau = \frac{k^2}{2m_\tau} + \underbrace{\mathrm{Re}\Sigma^\tau(k,\omega=\varepsilon_k^\tau)}_{U^\tau(k)}$$



Effective mass splitting

m* computed at Fermi surface

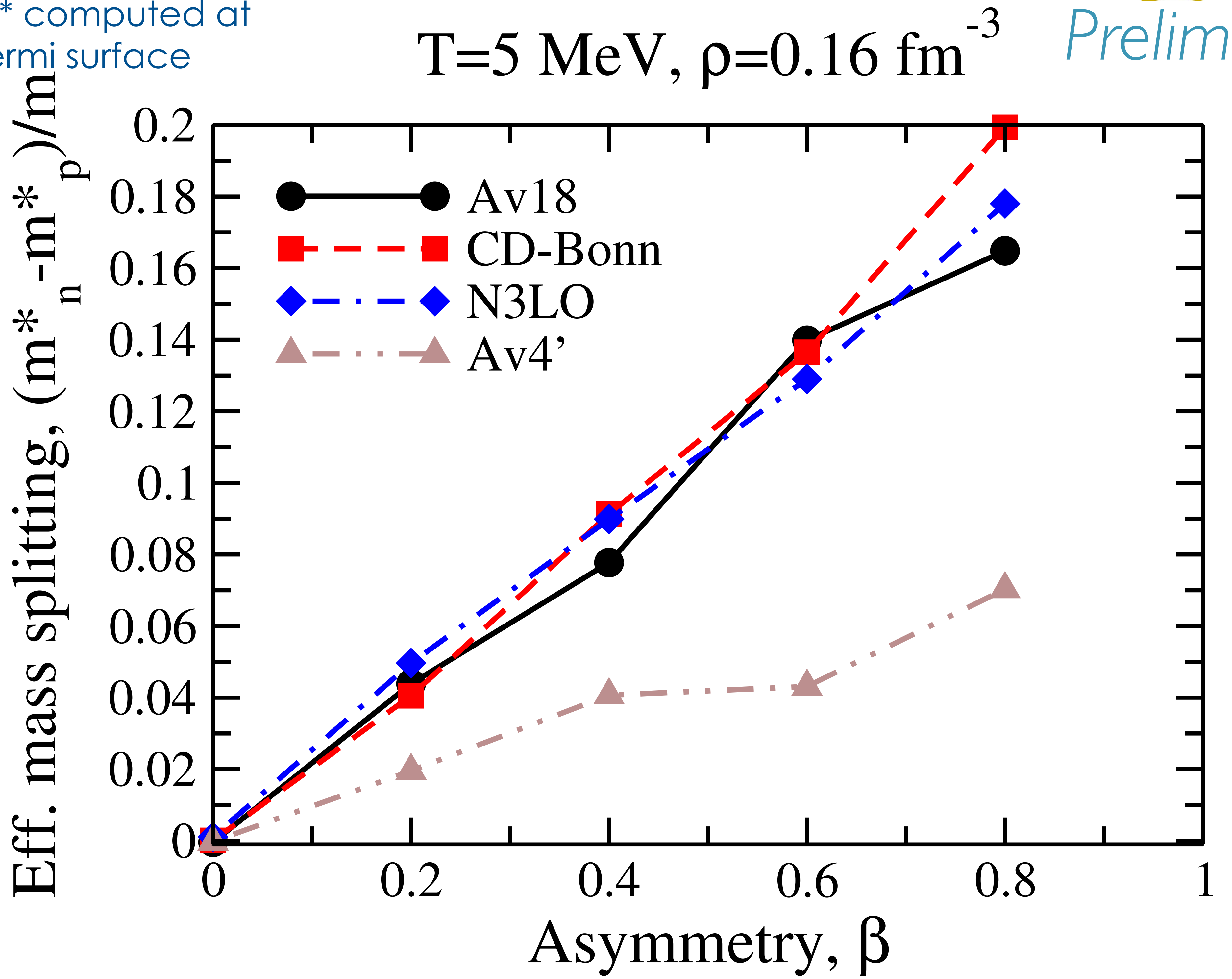


- Neutron-proton splitting is constrained
- Different masses (m^*_k, m^*_ω) can be computed
- 2NF only, could change with 3NF?

Effective mass splitting

m* computed at Fermi surface

Preliminary



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Effective mass splitting

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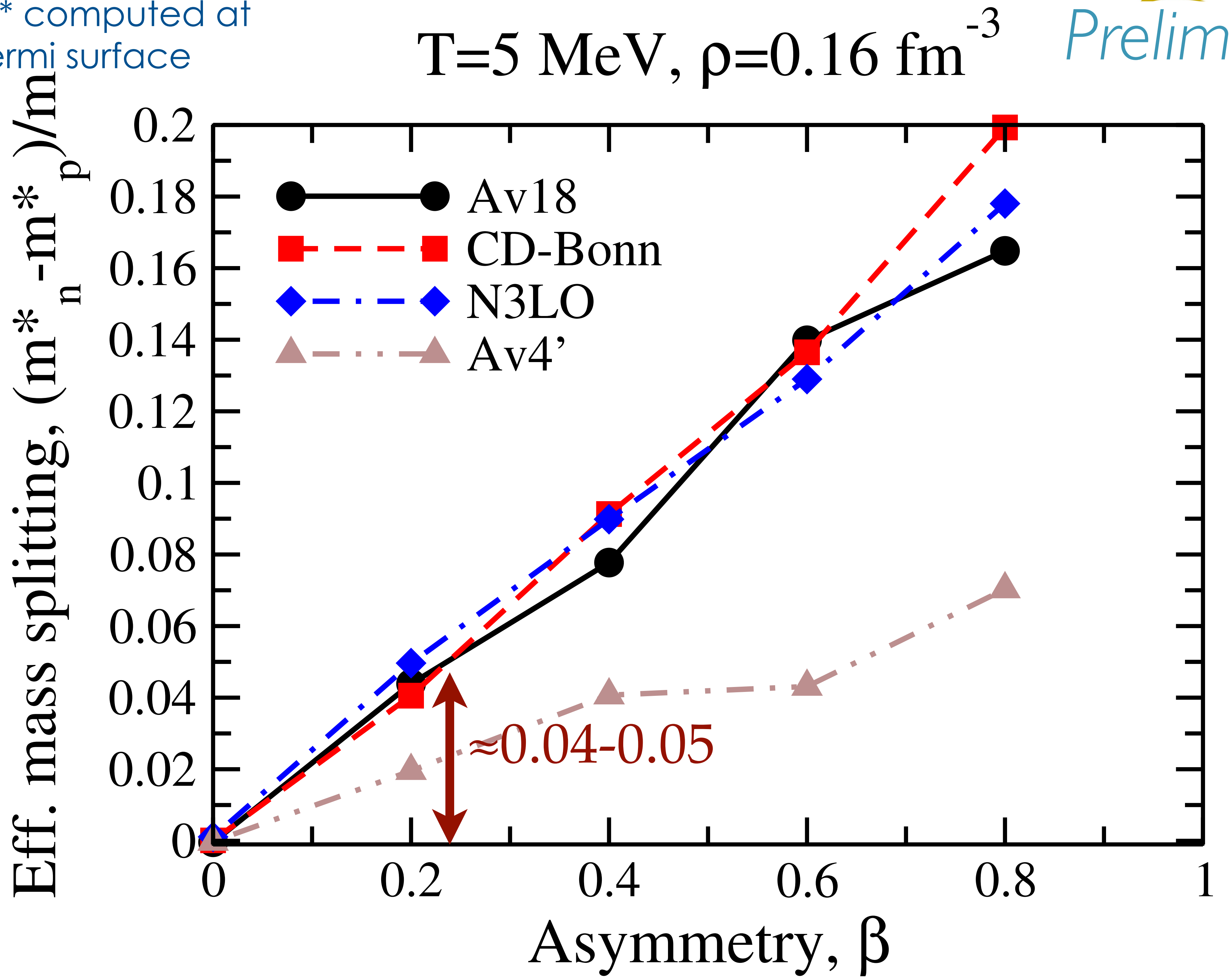
Fermi surface

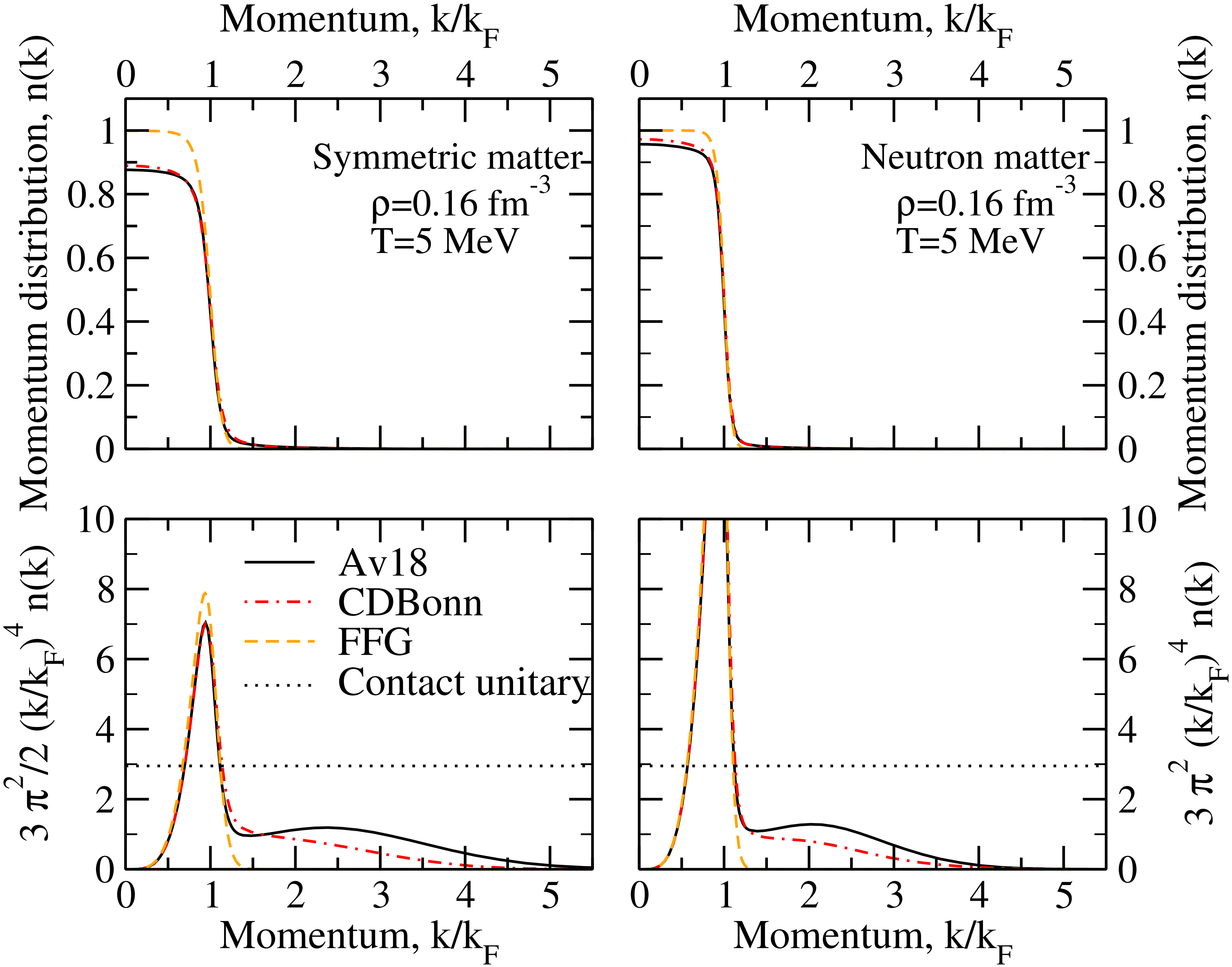
Preliminary



- Neutron-proton splitting is constrained
- Different masses (m^*_k,m^*_ω) can be computed
- 2NF only, could change with 3NF?

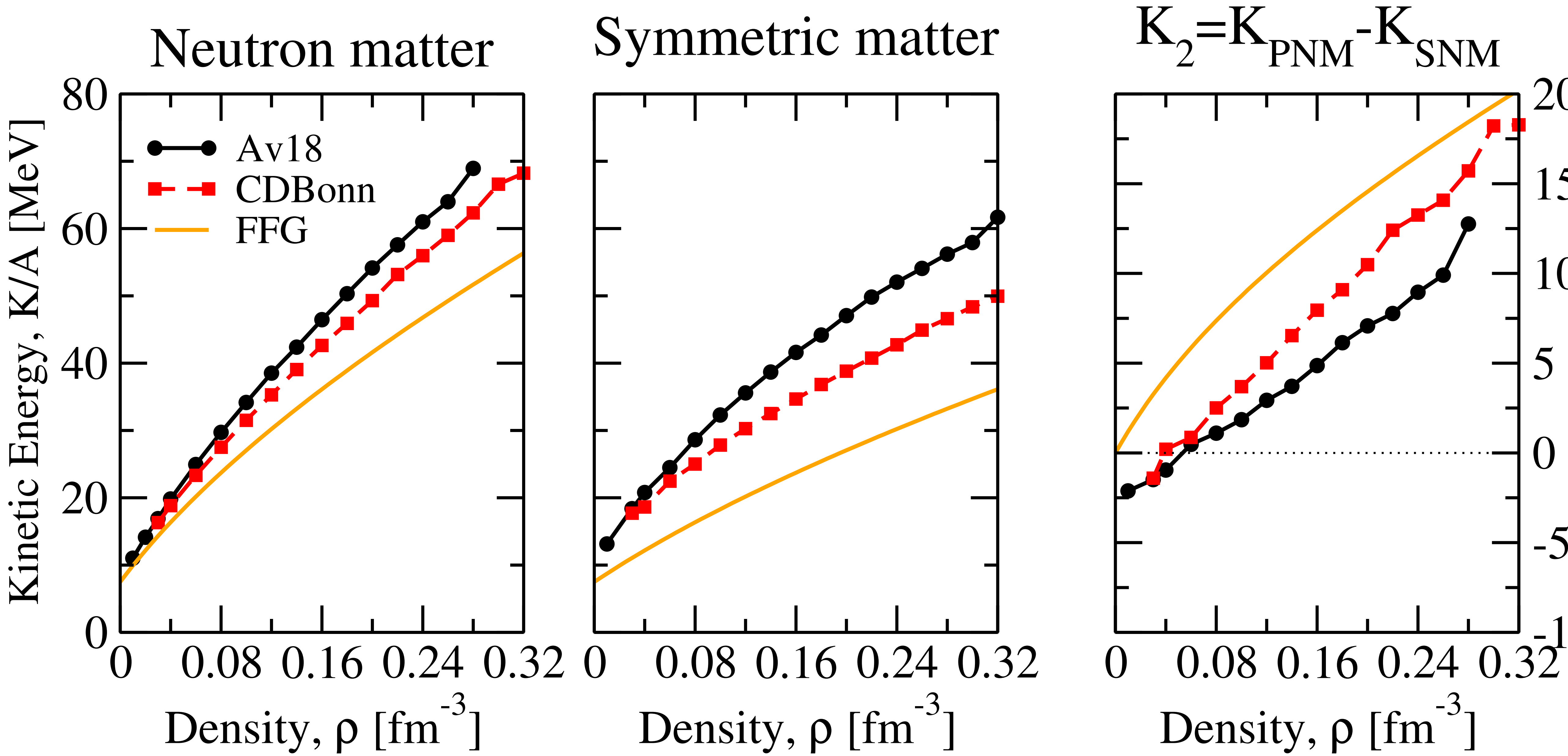
Kinetic symmetry energy I

$$\frac{K}{A} \approx \int \frac{d^3k}{(2\pi)^3} \frac{k^2}{2m} n(k) \approx \int_0^\infty dk k^4 n(k)$$



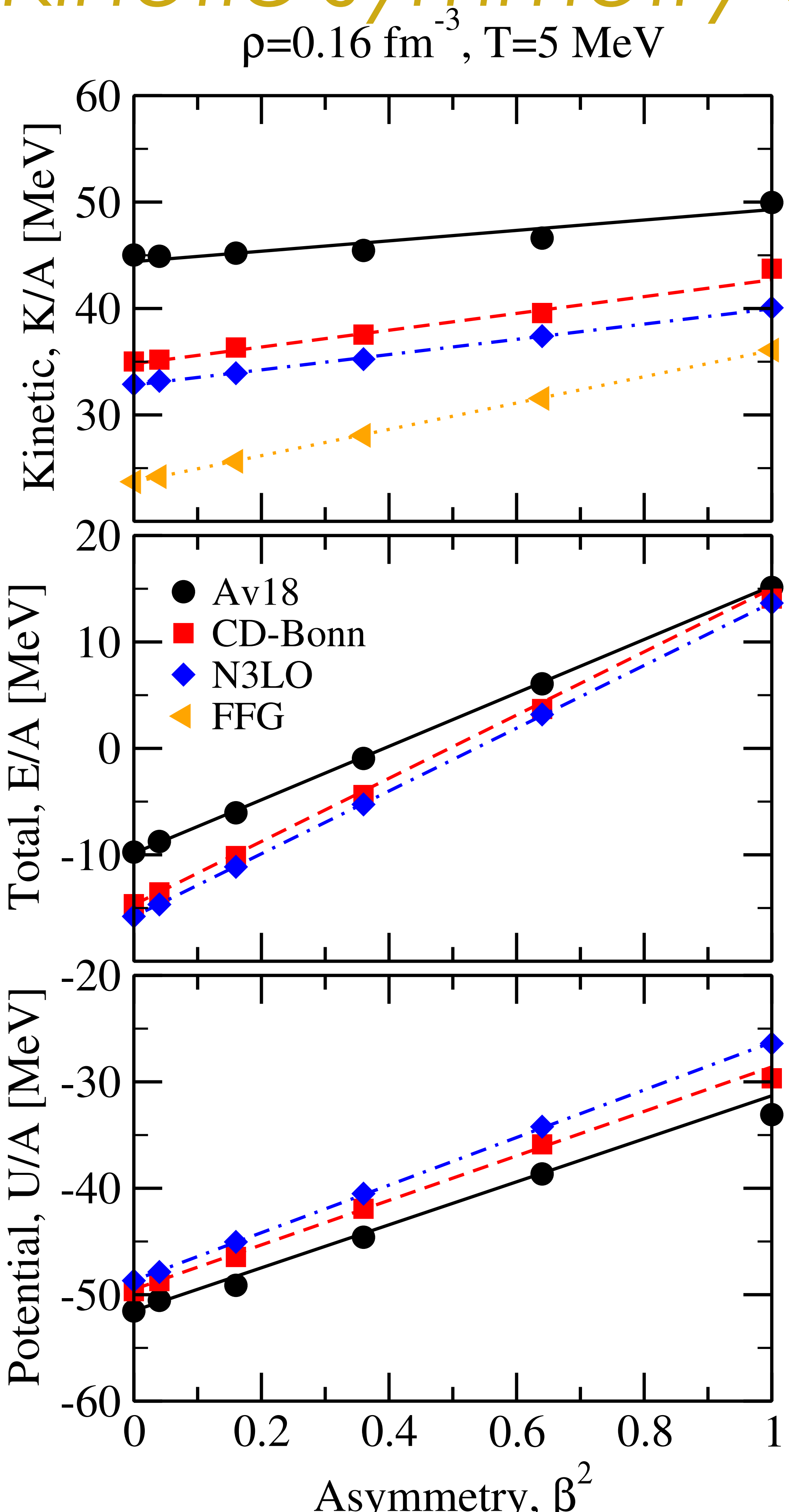
A. Carbone, A. Polls and A. Rios EPL **97** 22001 (2012)

Symmetry energy consequences



- Kinetic component is reduced by correlations
- Implications for observables?

Kinetic symmetry energy II

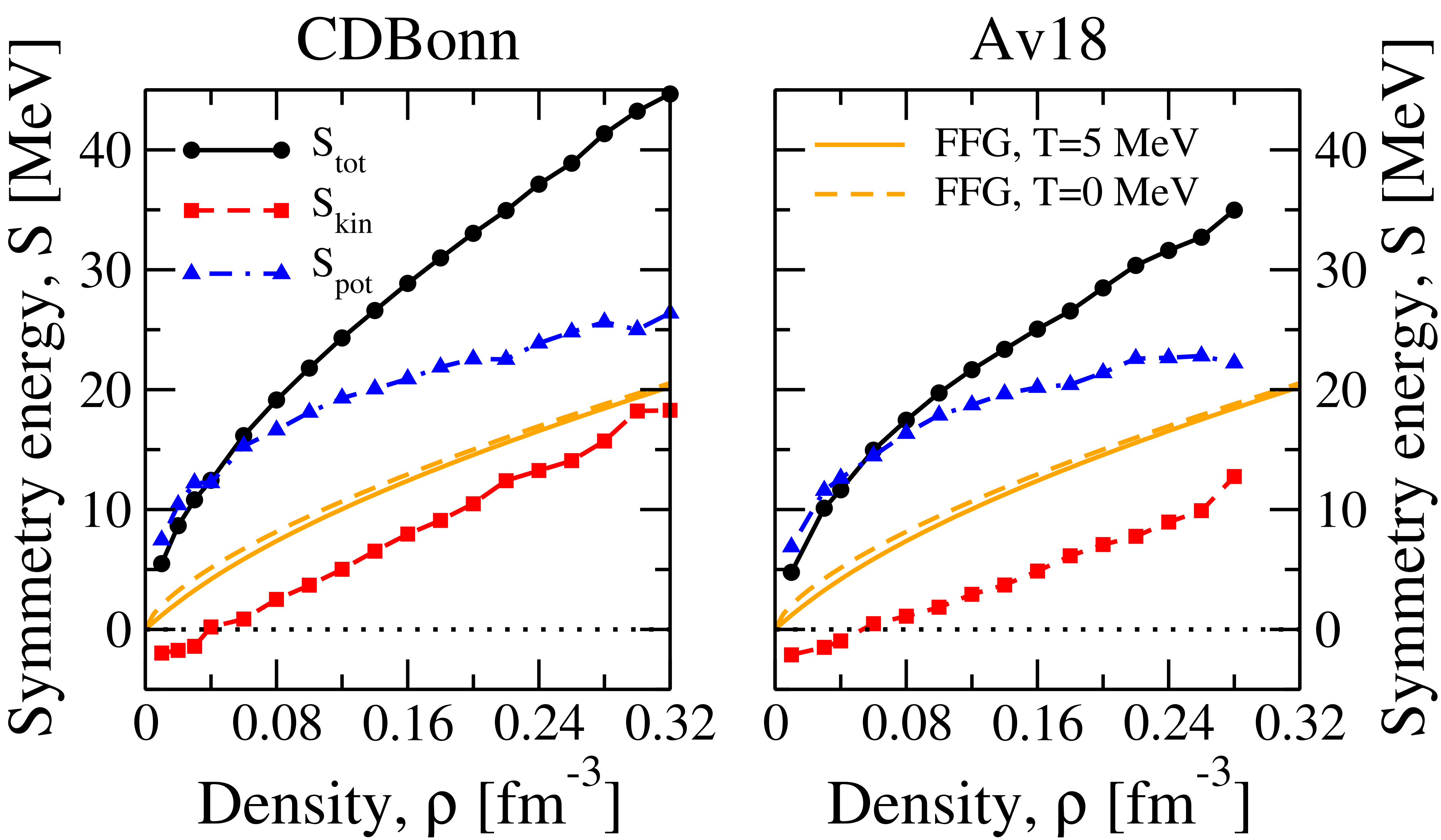


$$e(\rho,\beta) \approx e(\rho,0) + S(\rho)\beta^2$$

	Kinetic	Potential	Total
FFG	12.3	-	12.3
Mean-field	12.3	20	32.3
Av18	4.9	20.2	25.1
CDBonn	7.9	20.9	28.8
N^3LO	7.2	22.4	29.7

A. Carbone, A. Polls and A. Rios EPL **97** 22001 (2012)

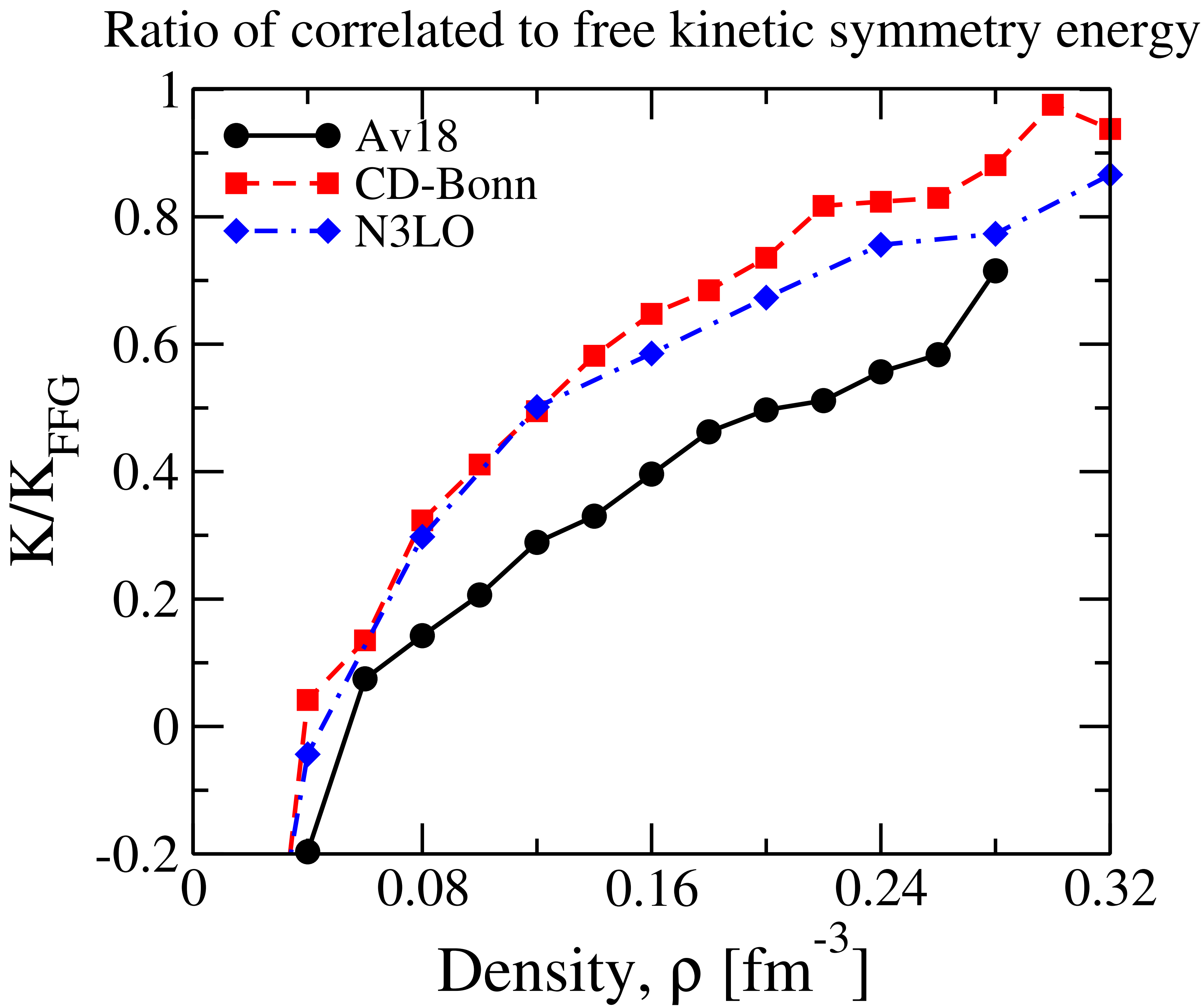
Symmetry energy



- Kinetic component is reduced by correlations
- Implications for observables? See **Bao-An**'s talk

Symmetry energy

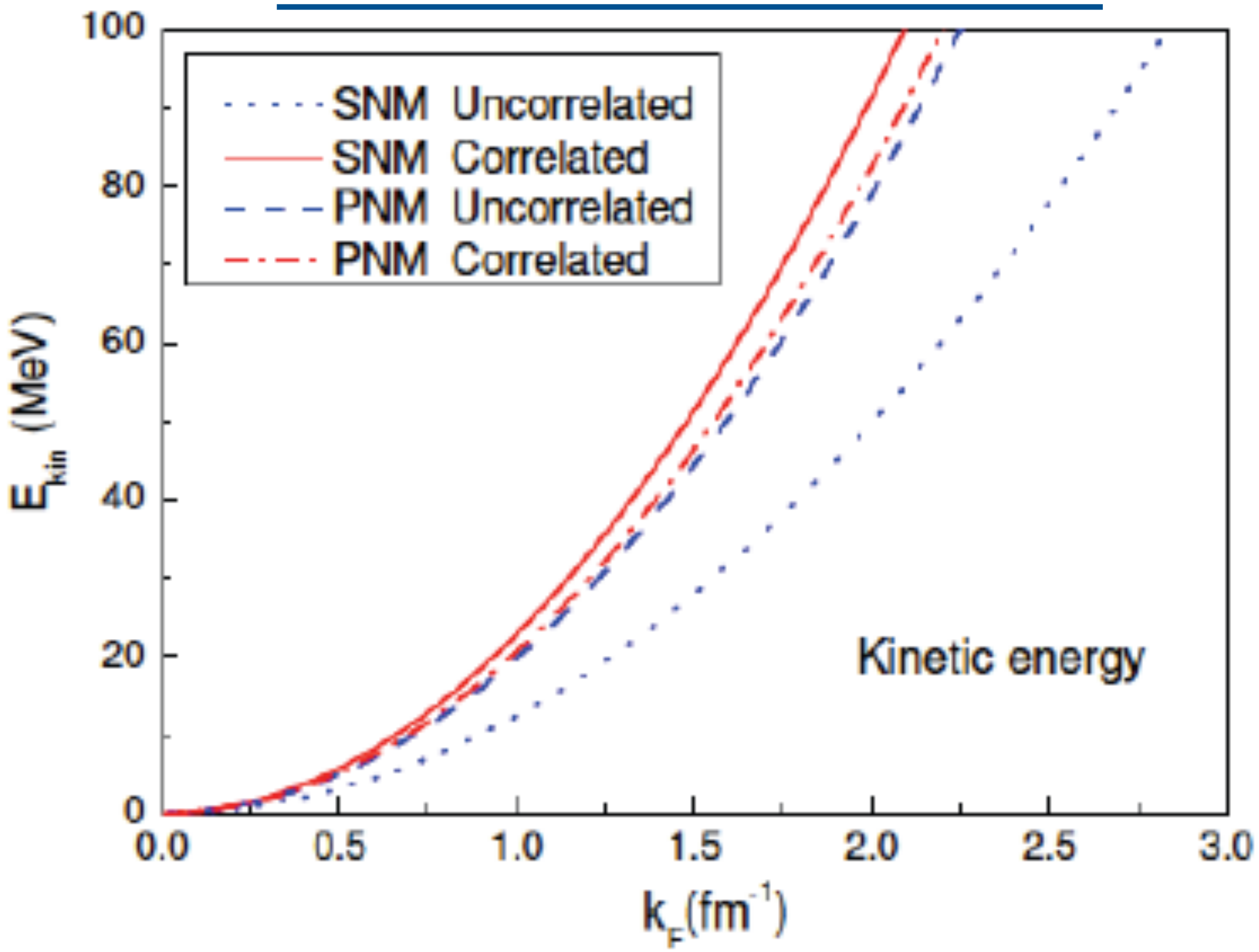
Preliminary



- Kinetic component is reduced by correlations
- Implications for observables? See **Bao-An**'s talk

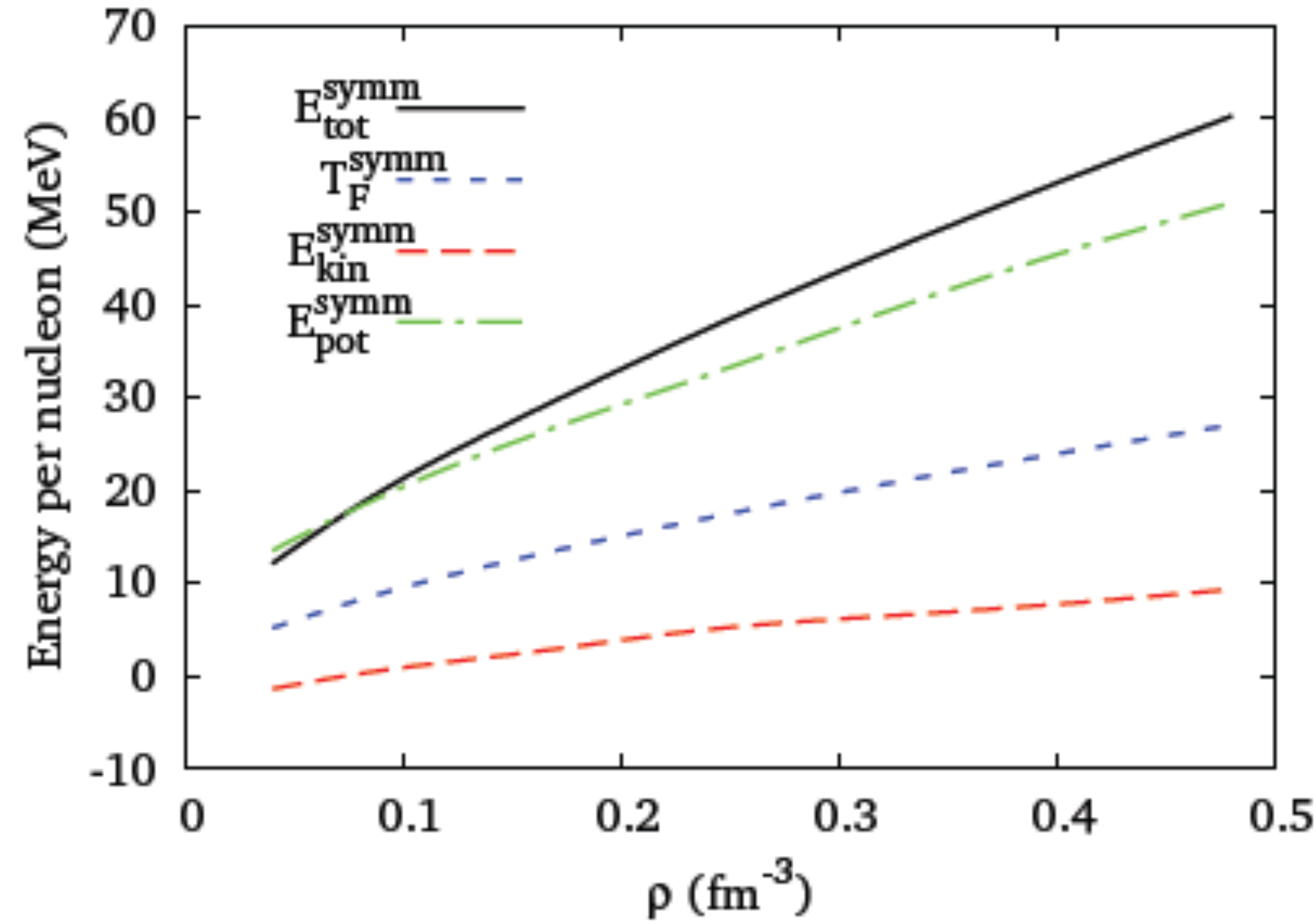
Confirmed by other approaches

Schematic model



Xu & Li, arxiv:1104.2075

FHNC



A. Lovato, private communication

Av18+3BF, $\rho = 0.16\ \mathrm{fm}^{-3}$

BHF + Hellman-Feynman theorem

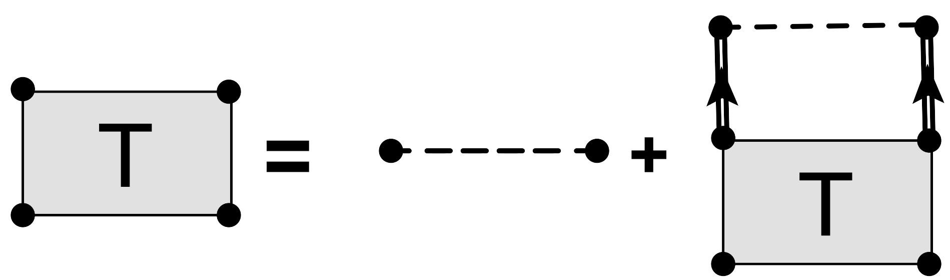
	E_{PNM}	E_{SNM}	S_{tot}	L
K/A	53.3	54.3	-1.0	14.9
U/A	-34.2	-69.5	35.3	51.6
Total	19.1	-15.2	34.3	66.5

A. Carbone, et al. EPJA **50** 13 (2014)

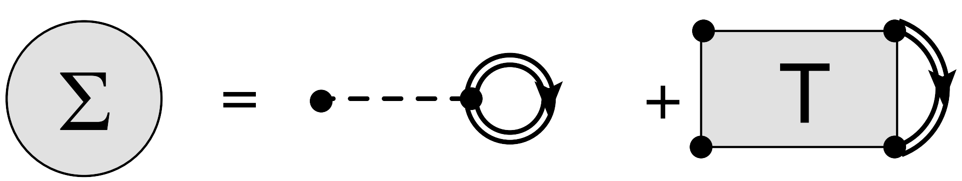
Ladder approximation with 3BF

Two-body interaction

In-medium T-matrix

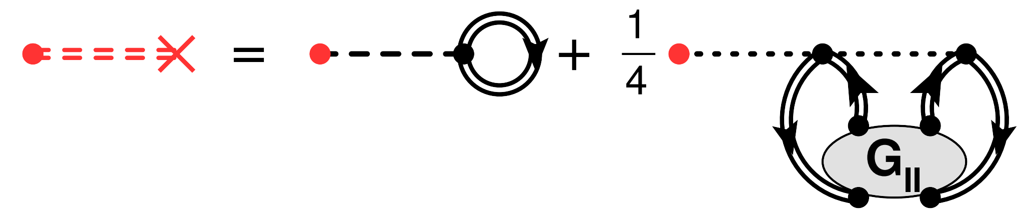


Self-energy

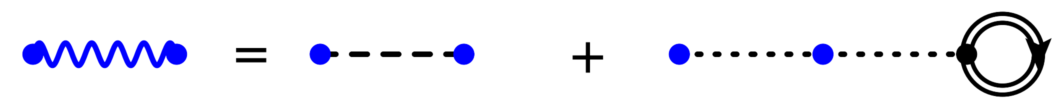


Effective interactions

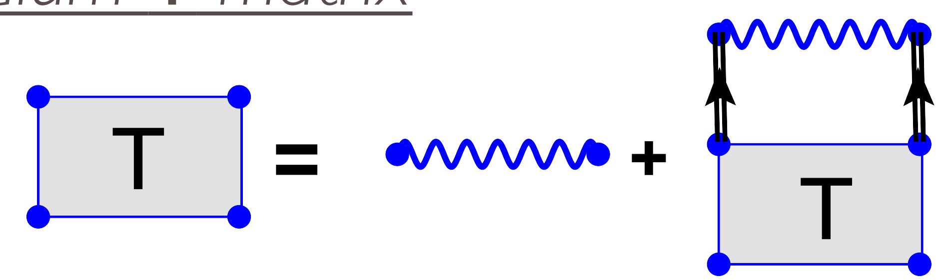
Effective one-body force



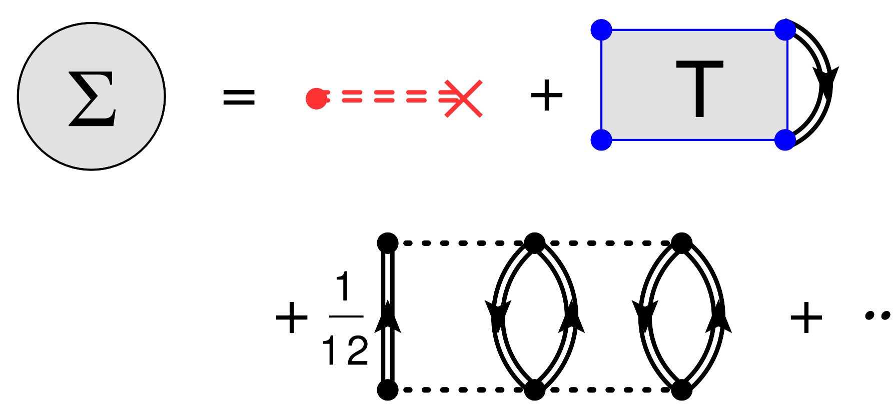
Effective two-body force



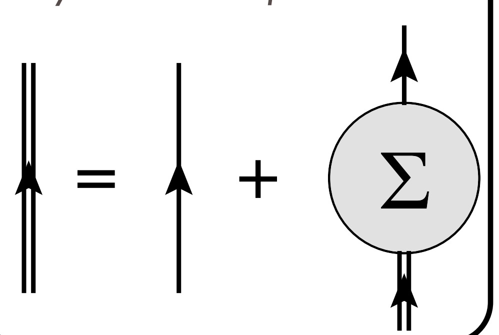
In-medium T-matrix



Self-energy



Dyson equation

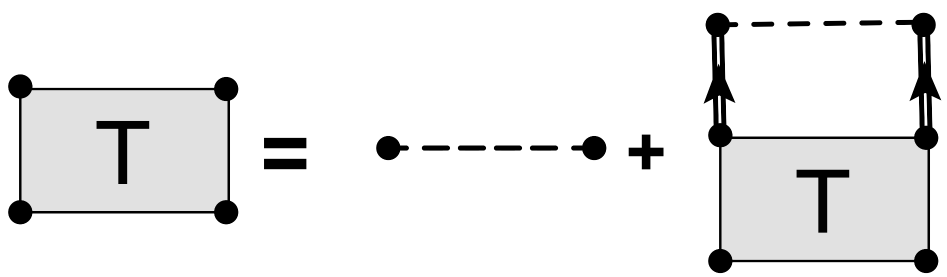


Carbone *et al.*, *PRC* **88** 054326 (2013)

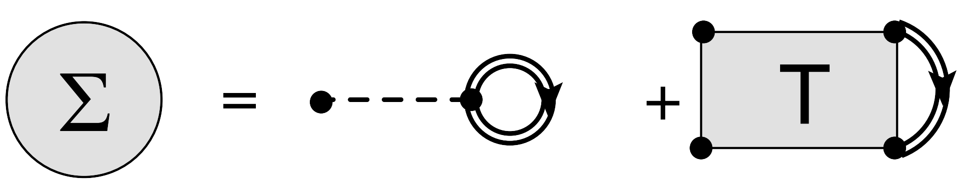
Ladder approximation with 3BF

Two-body interaction

In-medium **T**-matrix

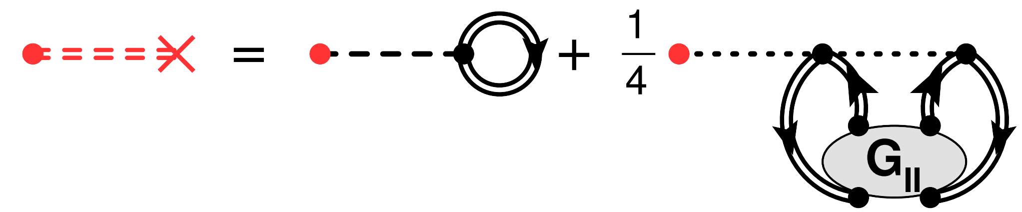


Self-energy

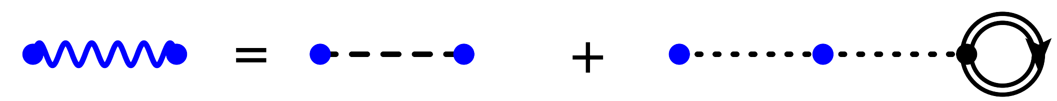


Effective interactions

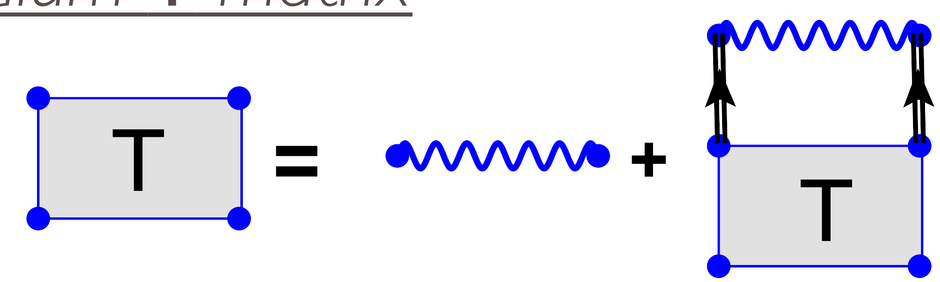
Effective one-body force



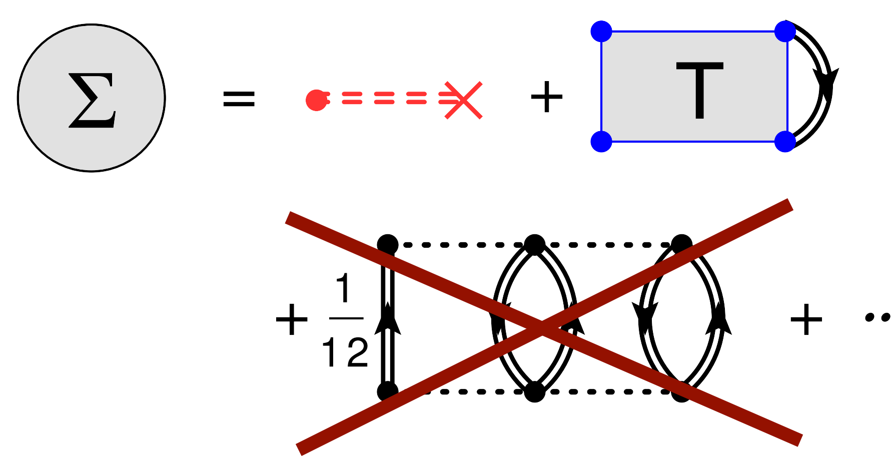
Effective two-body force



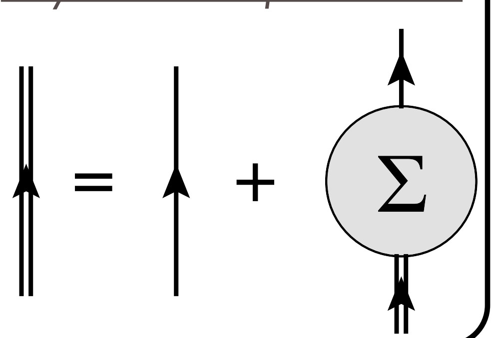
In-medium **T**-matrix



Self-energy



Dyson equation

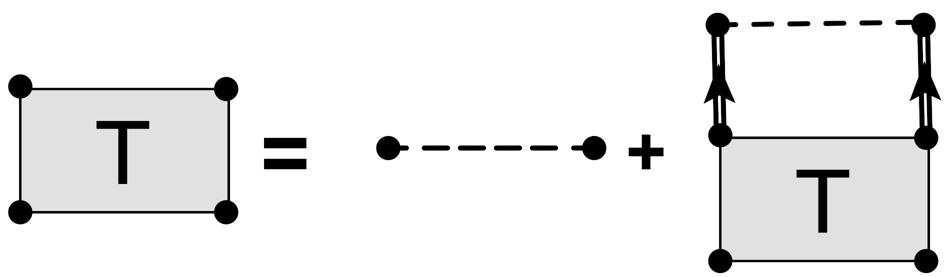


Carbone *et al.*, *PRC* **88** 054326 (2013)

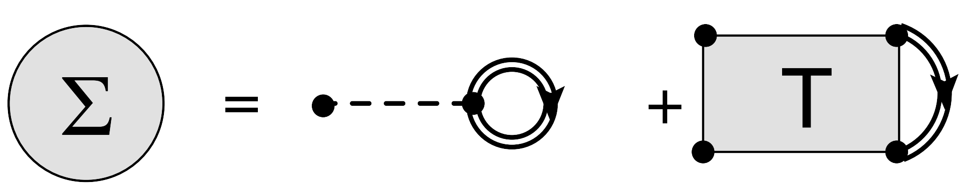
Ladder approximation with 3BF

Two-body interaction

In-medium T-matrix

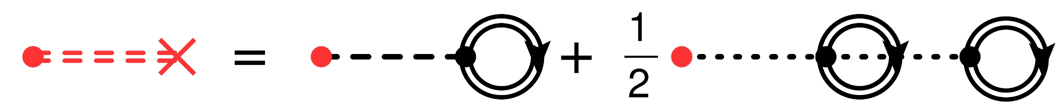


Self-energy



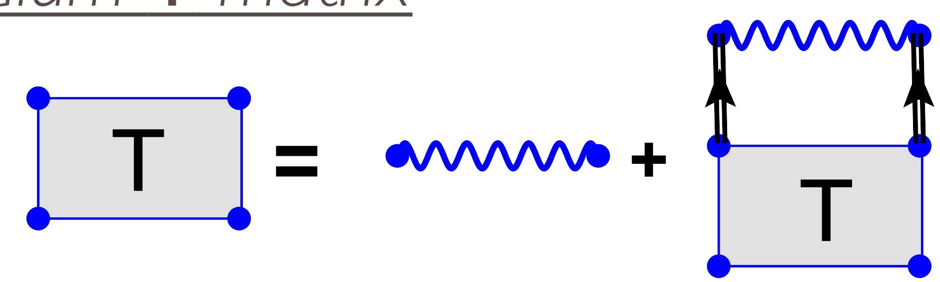
Effective interactions

Effective one-body force

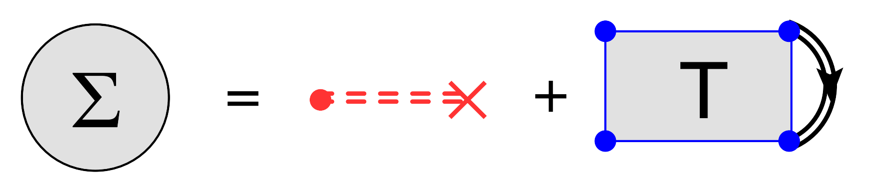


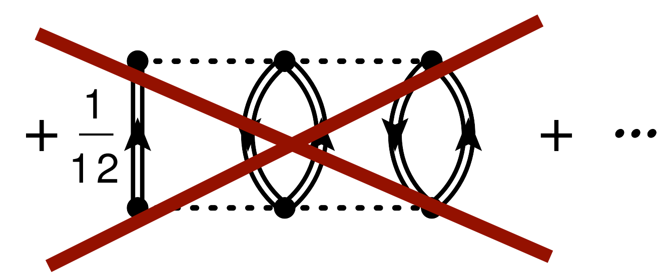
Effective two-body force

In-medium T-matrix

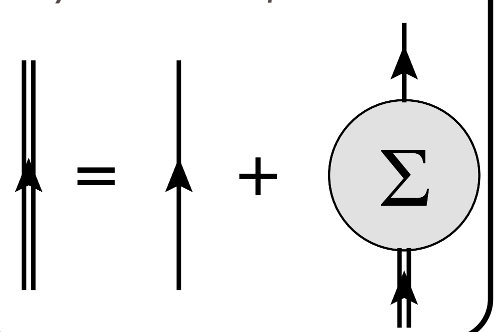


Self-energy





Dyson equation

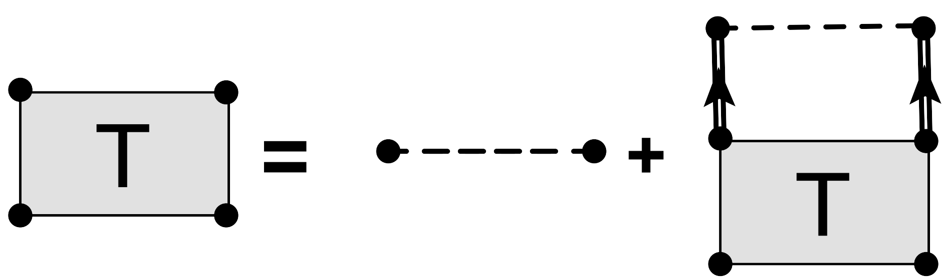


Carbone *et al.*, *PRC* **88** 054326 (2013)

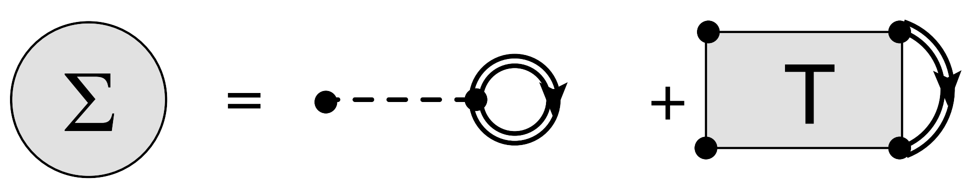
Ladder approximation with 3BF

Two-body interaction

In-medium T-matrix

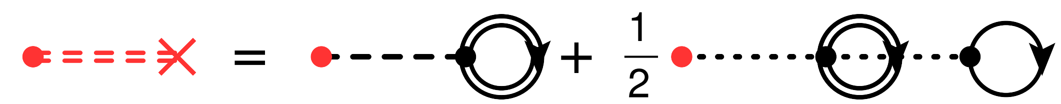


Self-energy



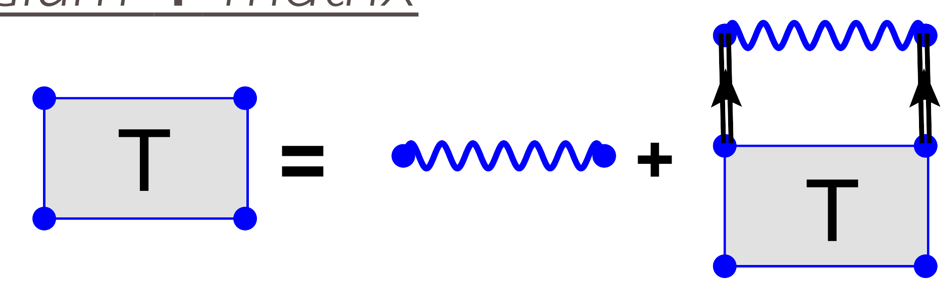
Effective interactions

Effective one-body force

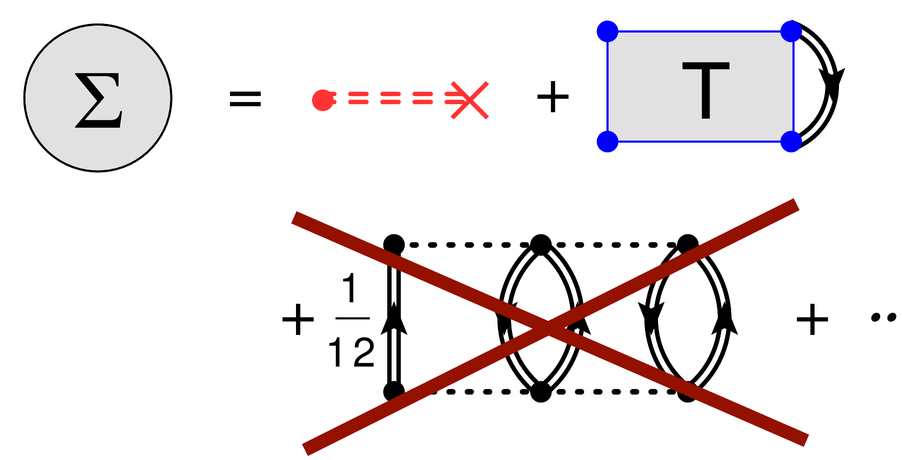


Effective two-body force

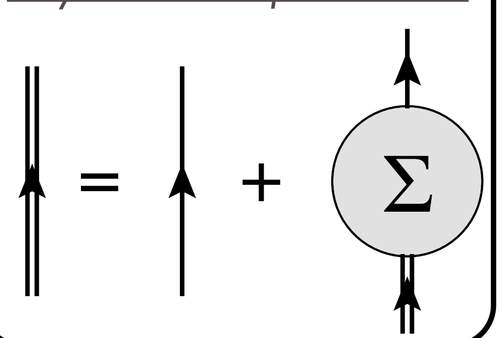
In-medium T-matrix



Self-energy



Dyson equation

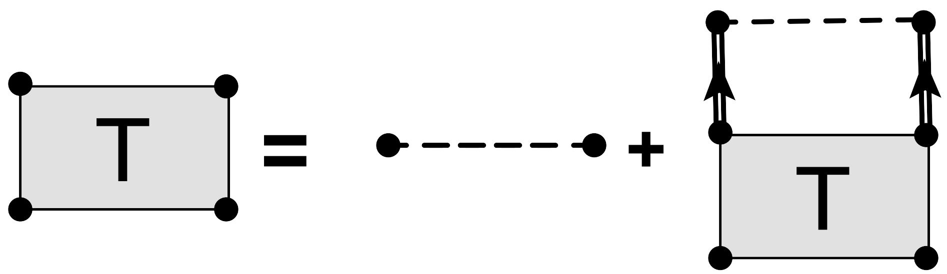


Carbone *et al.*, *PRC* **88** 054326 (2013)

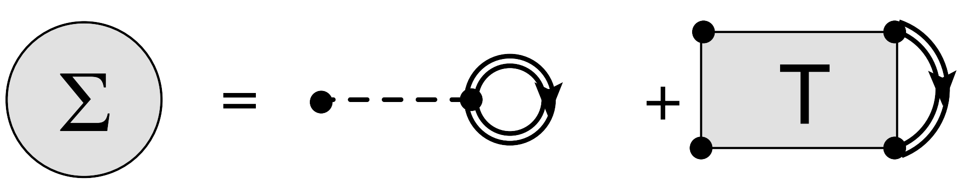
Ladder approximation with 3BF

Two-body interaction

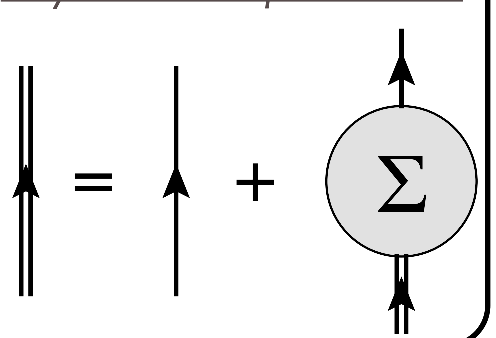
In-medium **T**-matrix



Self-energy

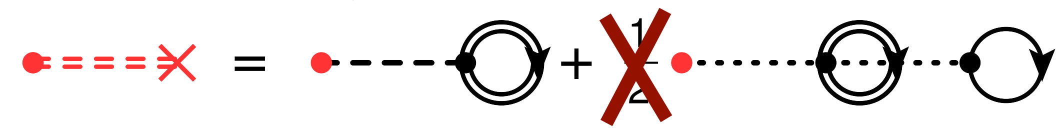


Dyson equation



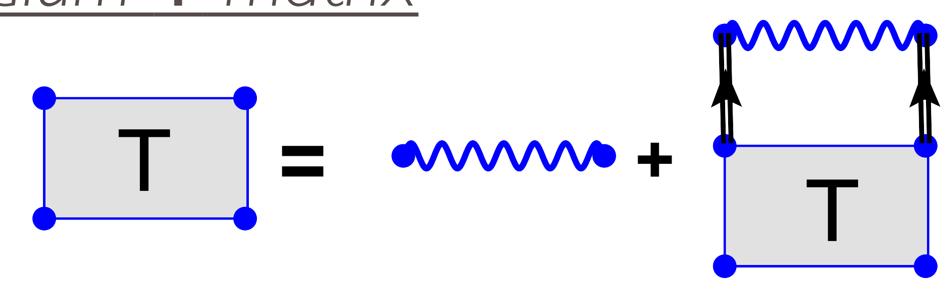
Effective interactions

Effective one-body force

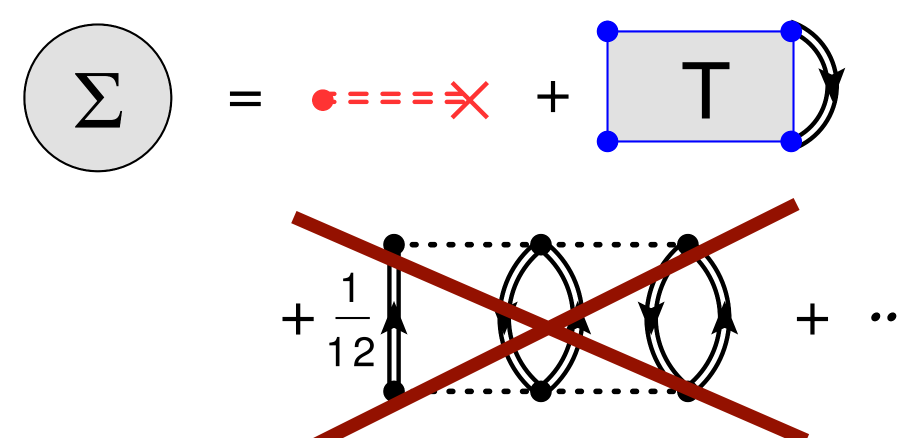


Effective two-body force

In-medium **T**-matrix



Self-energy



Symmetric matter
Theoretical uncertainties: Chiral expansion

Two-body N3LO

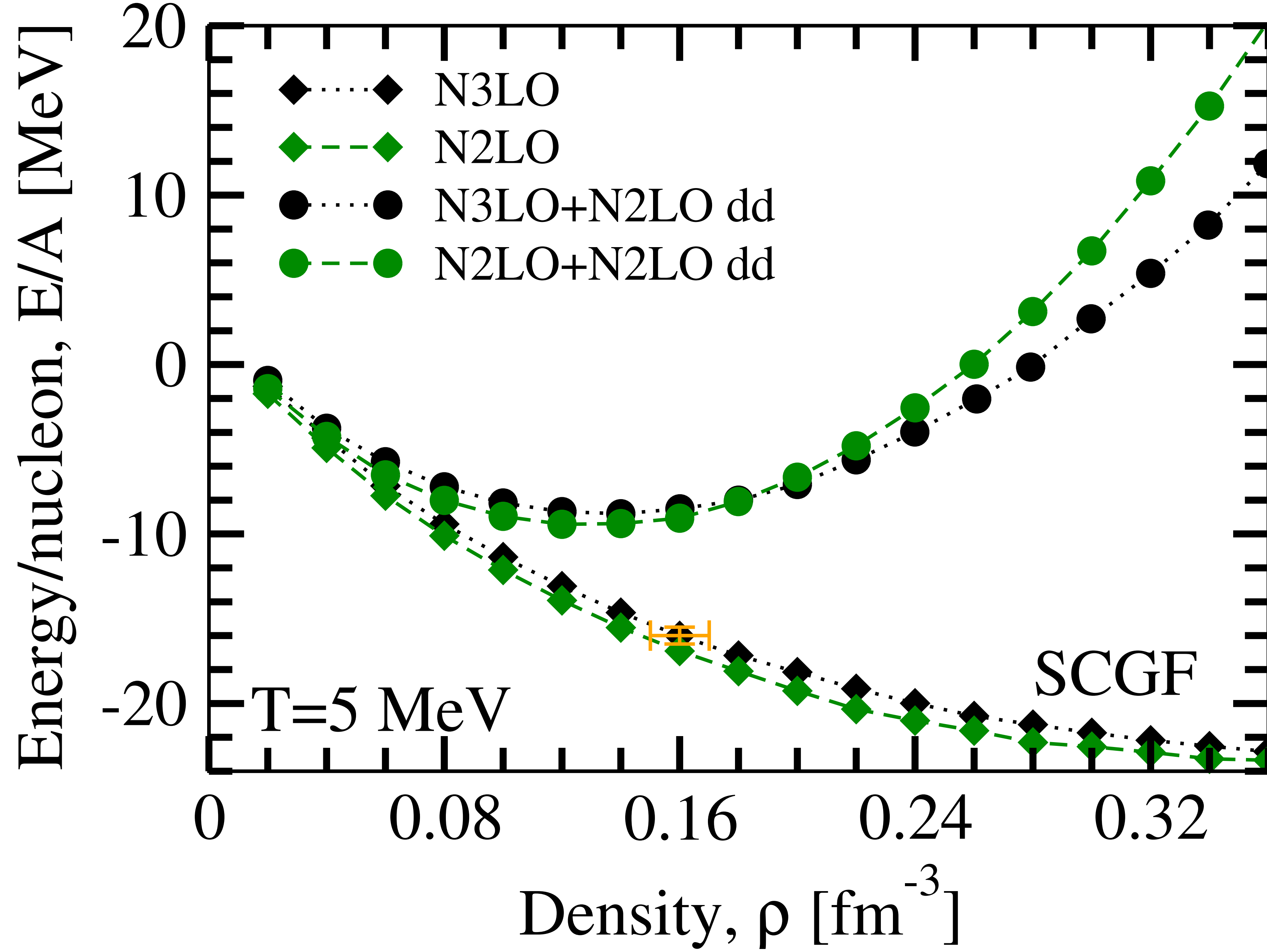
Uncorrelated average

LECs

c_D=-1.11

c_E=-0.66

K_0~60 MeV



- 3NF result is still *underbound*
- Small difference in infinite matter for N3LO & N2LO...
- In contrast to finite nuclei!

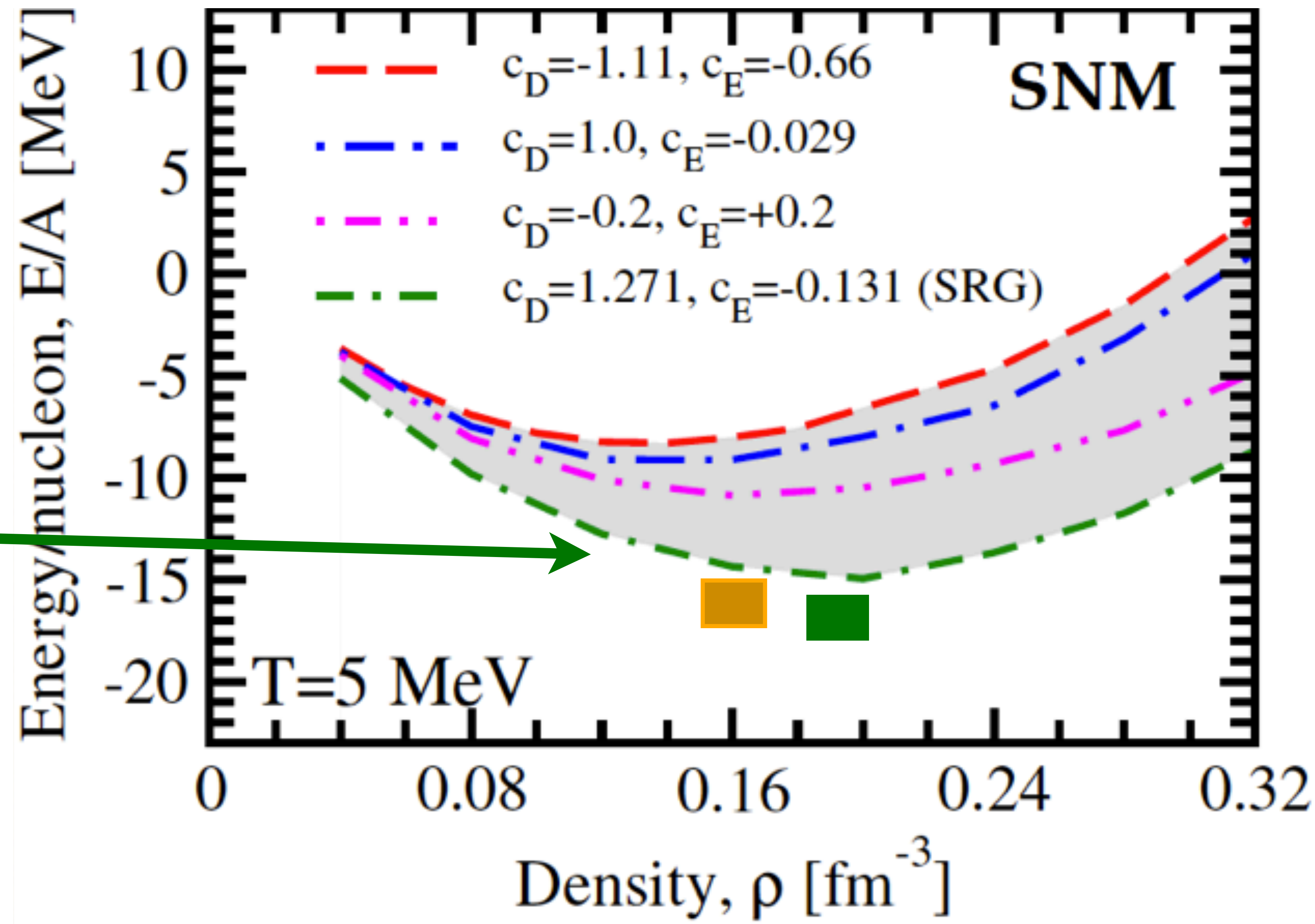
[1]*Carbone, Polls & Rios, PRC **88** 044302 (2014)*

Symmetric matter
Theoretical uncertainties: NN force

Uncorrelated average

Λ=2 fm^{-1} SRG
well below c_D,c_E uncertainty

<u>*Equation of state: LEC dependence*</u>



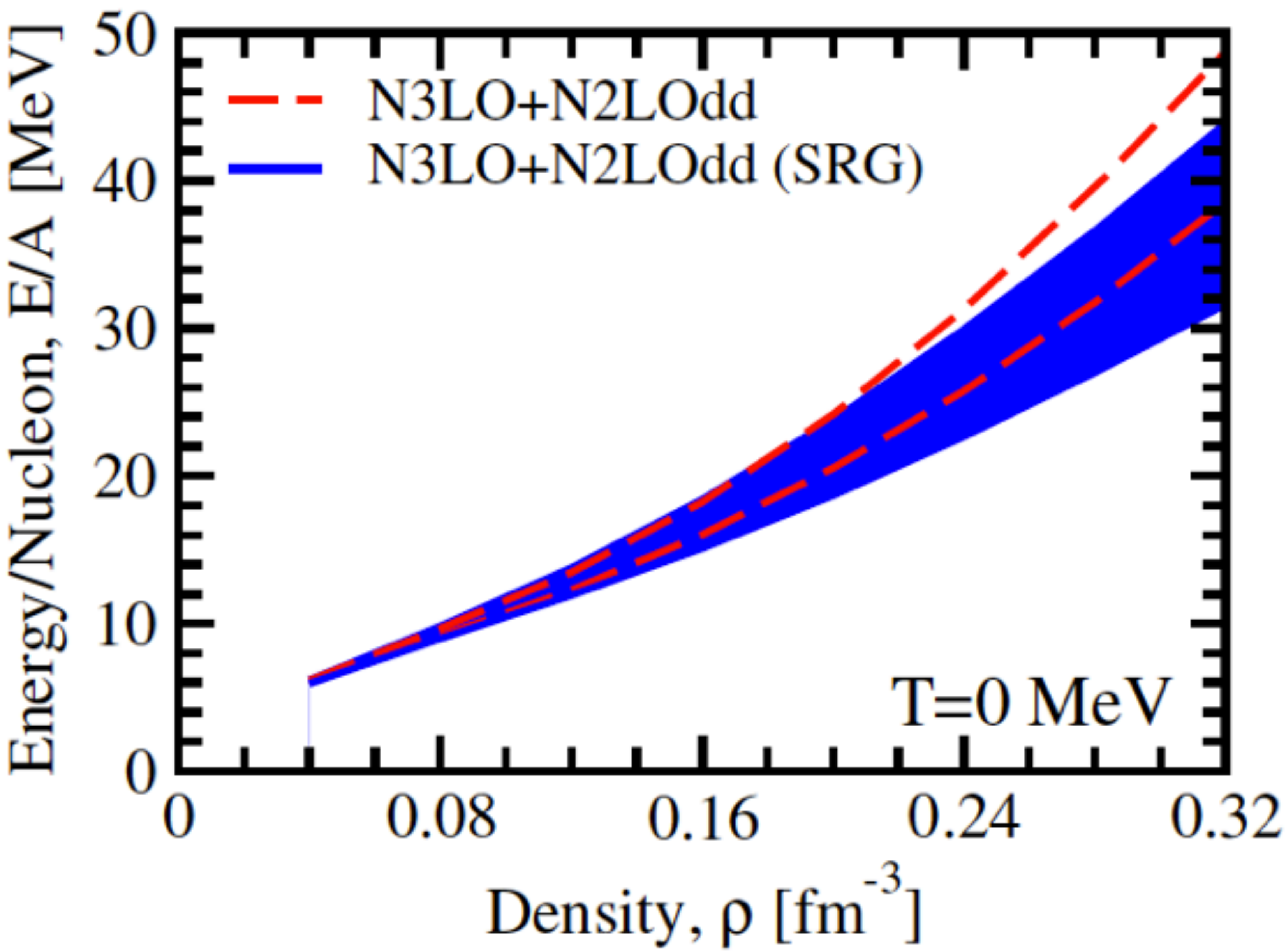
- LECs dependence is <u>*strong*</u>
- Renormalization via SRG: nuclear structure calculations?
- Small 3NF effects with larger saturation densities ⇒ smaller radii

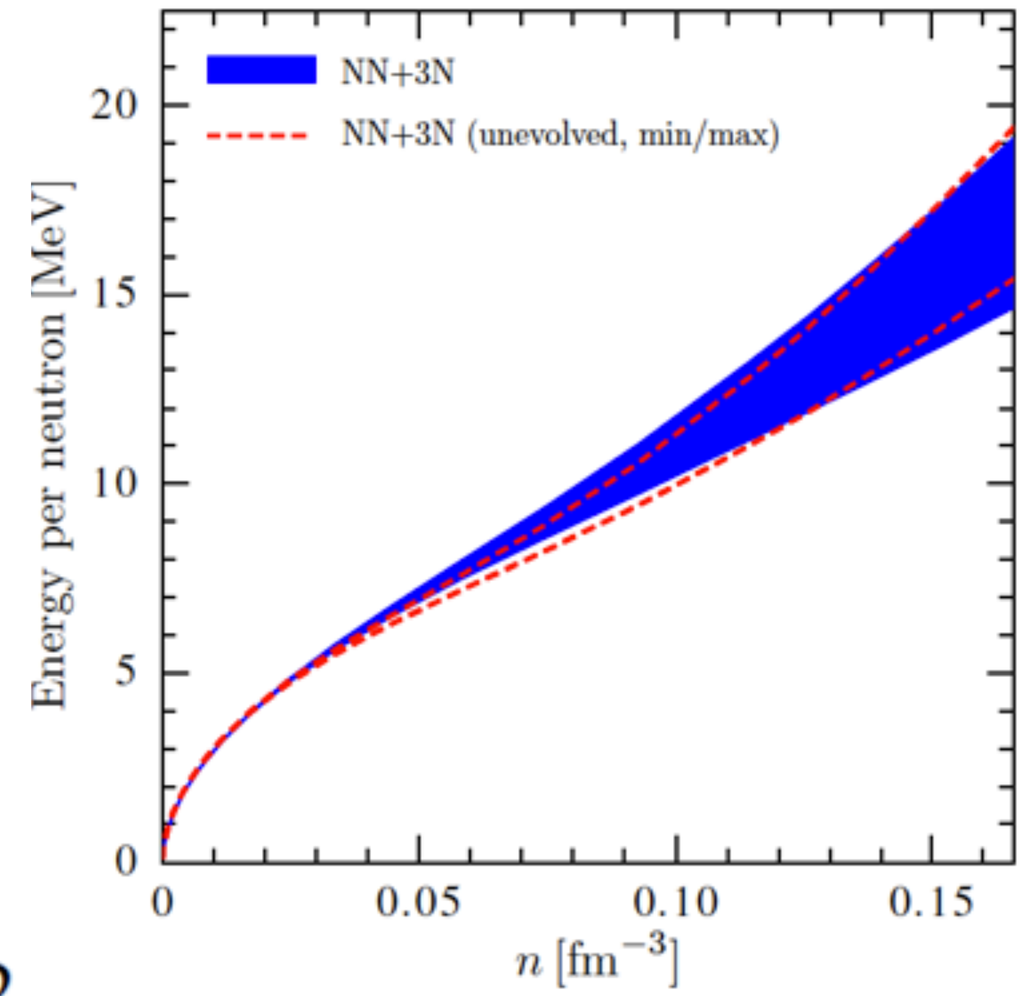
[1]*Carbone, Polls & Rios, PRC* ***88*** *044302 (2014)*

Neutron matter

UNIVERSITY OF SURREY

EoS for neutron matter: SRG





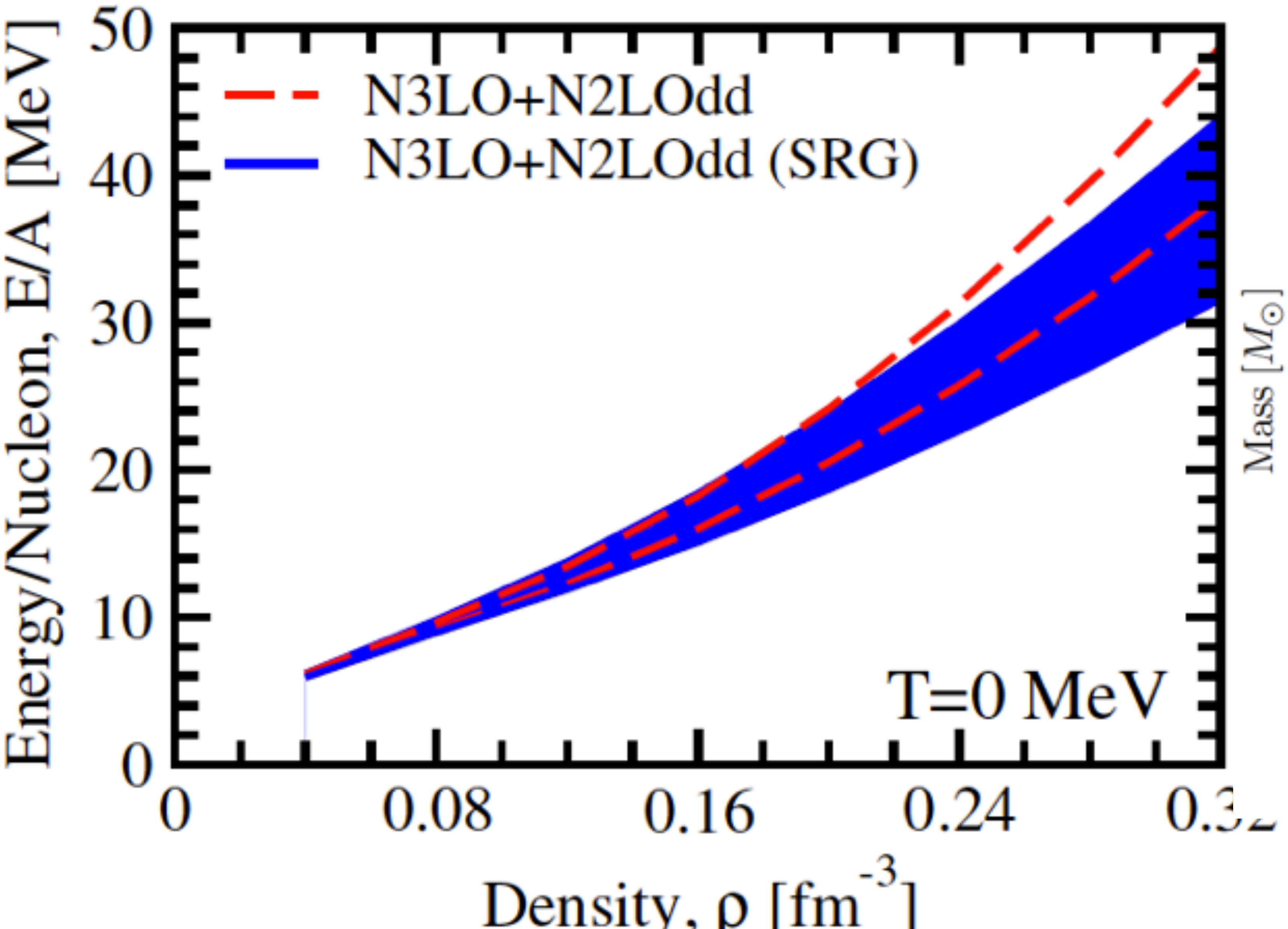
Hebeler, Lattimer, Pethick, Schwenk
ApJ **773** 11 (2013)

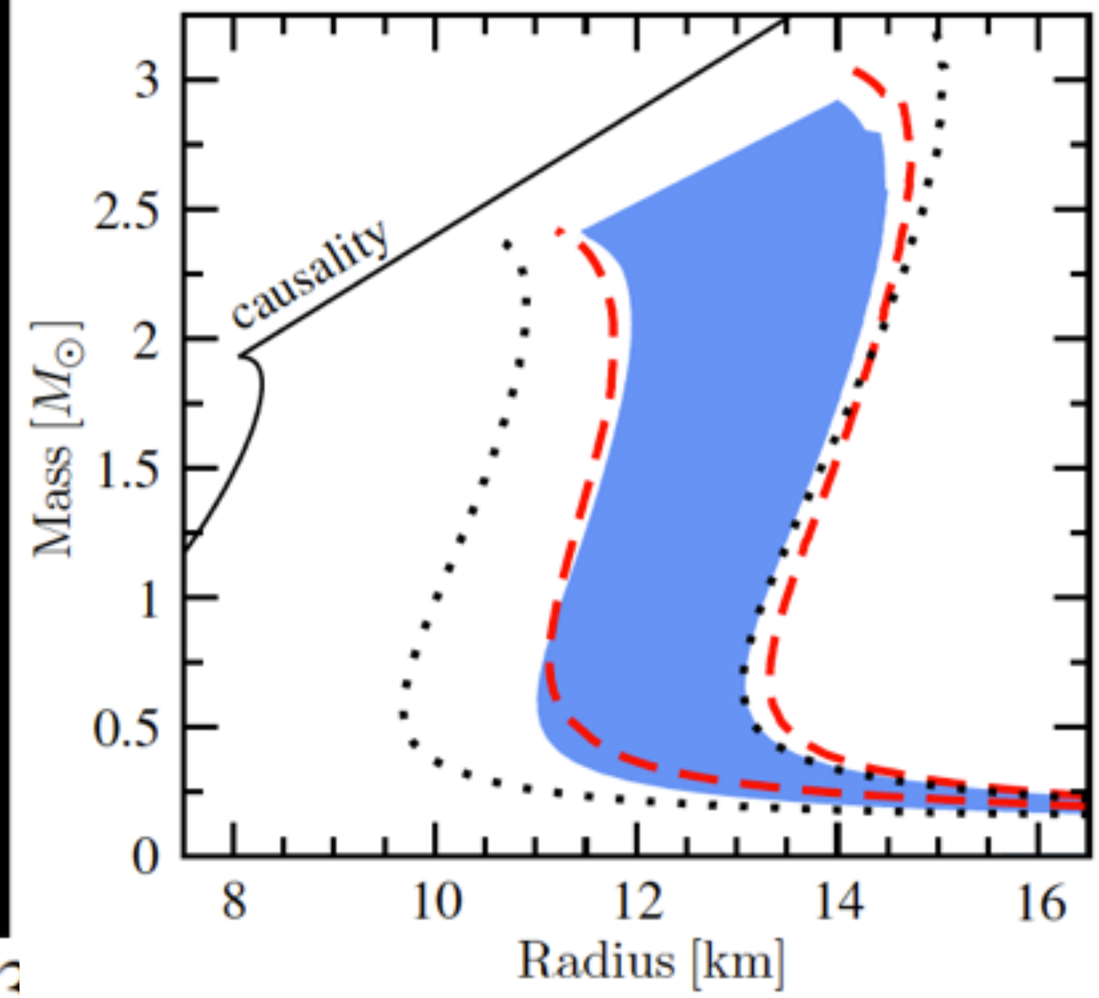
- Error band from unknown ChPT c_1, c_3 parameters
- Finite temperature & higher densities available

Carbone, Polls & Rios, *in preparation;* A. Carbone, PhD thesis

Neutron matter

EoS for neutron matter: SRG





Hebeler, Lattimer, Pethick, Schwenk
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- Error band from unknown ChPT c_1, c_3 parameters
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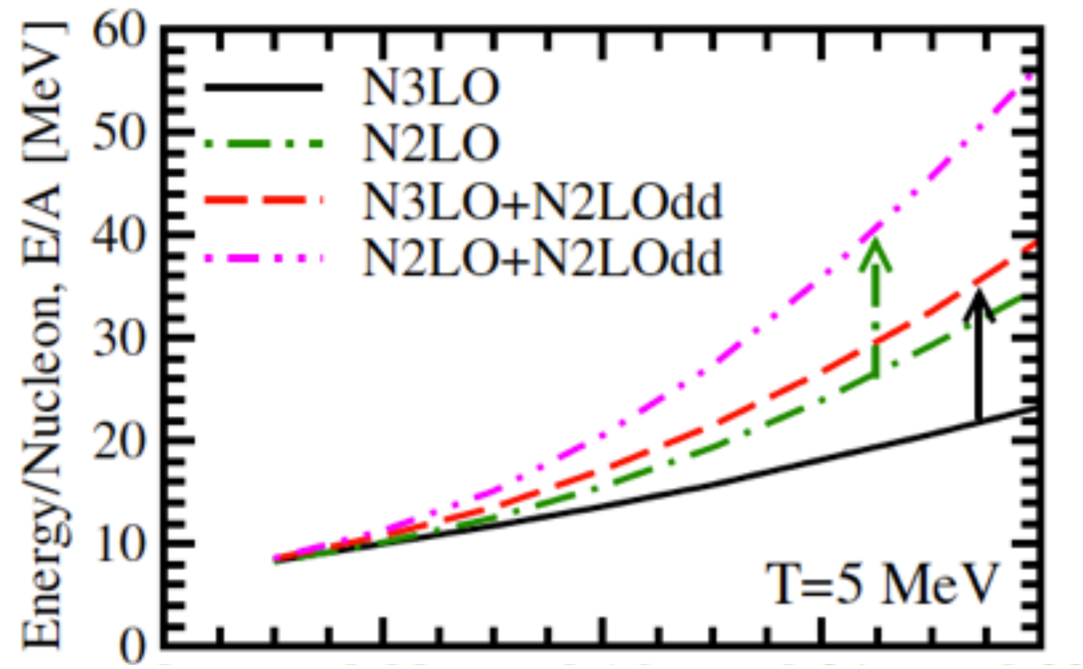
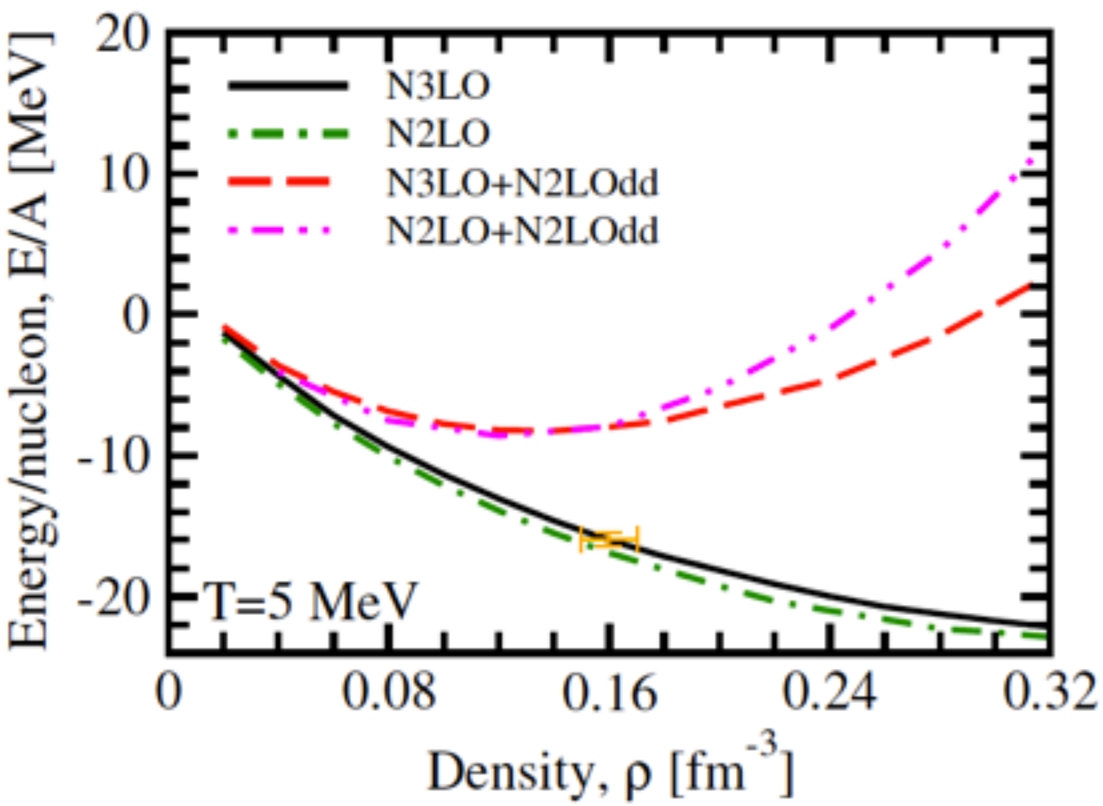
Carbone, Polls & Rios, *in preparation;* A. Carbone, PhD thesis

Isovector properties

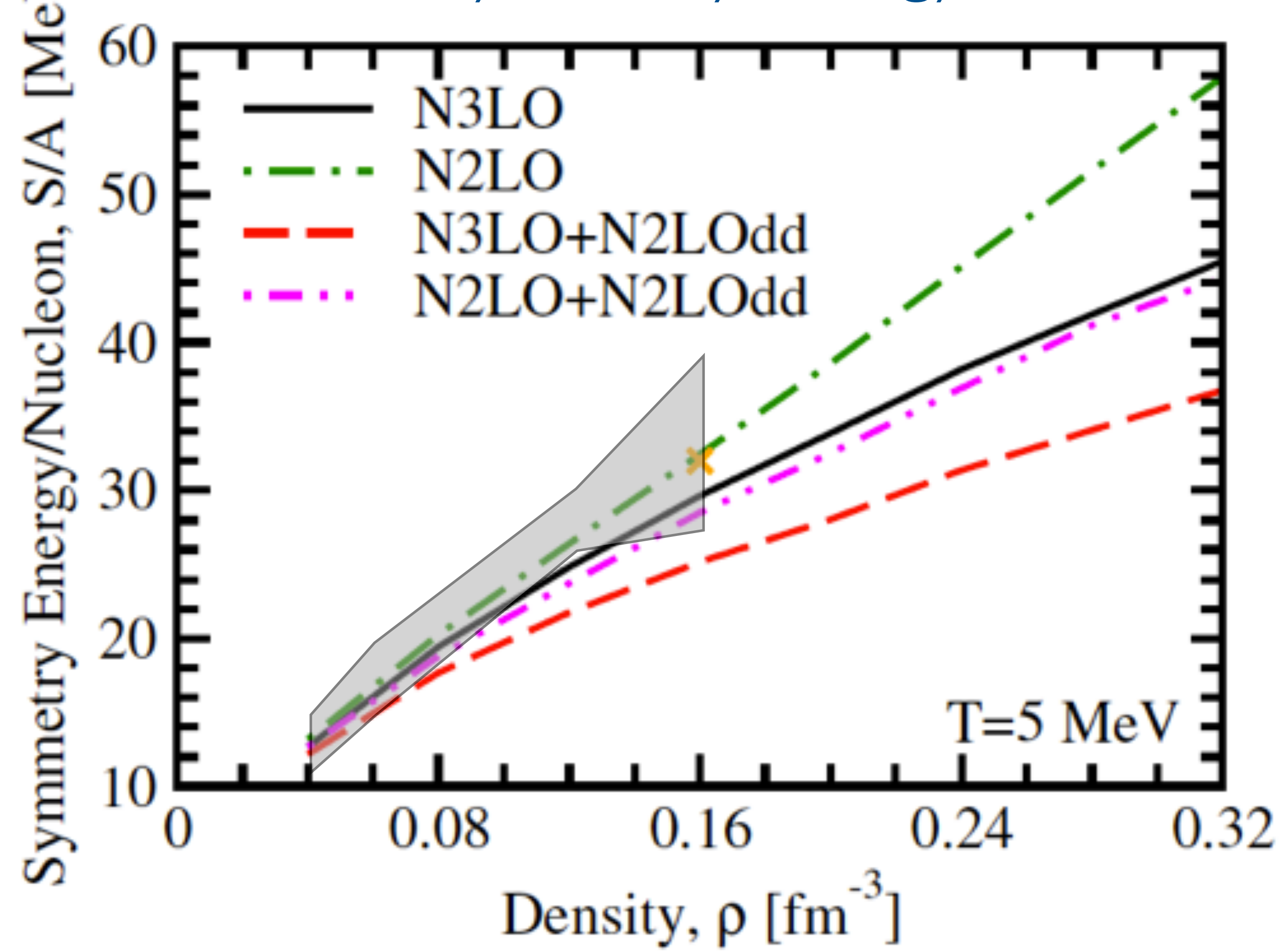
EoS for SNM & PNM





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

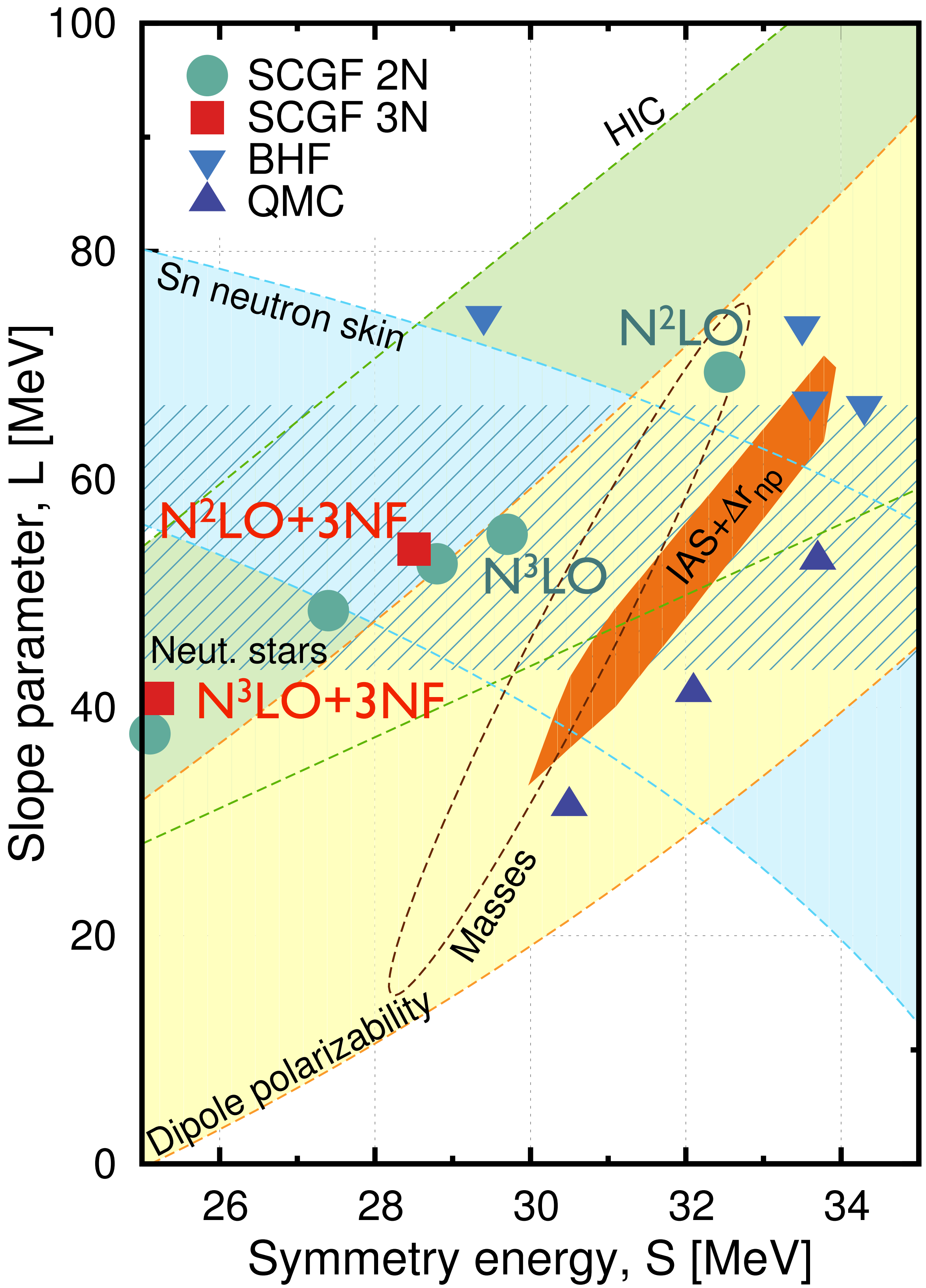
Symmetry energy



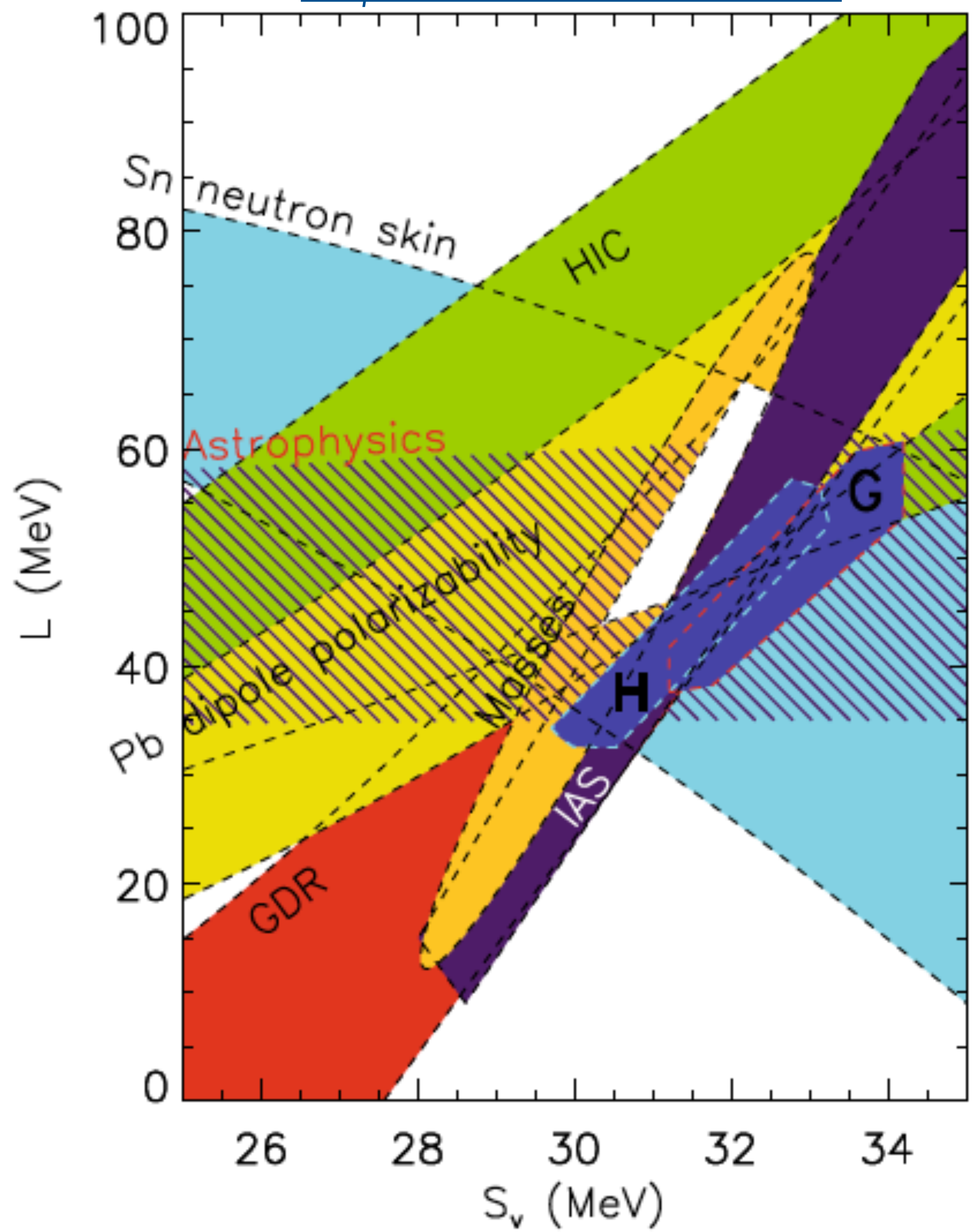
$\rho_0 = 0.16\text{fm}^{-3}$	E_{PNM}/A	E_{SNM}/A	S/A	L
N3LO	13.6	-16.0	29.6	52.9
N2LOopt	15.6	-16.9	32.5	69.4
N3LO+N2LOdd	17.2	-7.99	25.2	40.8
N2LOopt+N2LOdd	20.5	-7.96	28.5	53.9

Carbone, Polls & Rios, *in preparation;* A. Carbone, PhD thesis

Comparison to phenomenology

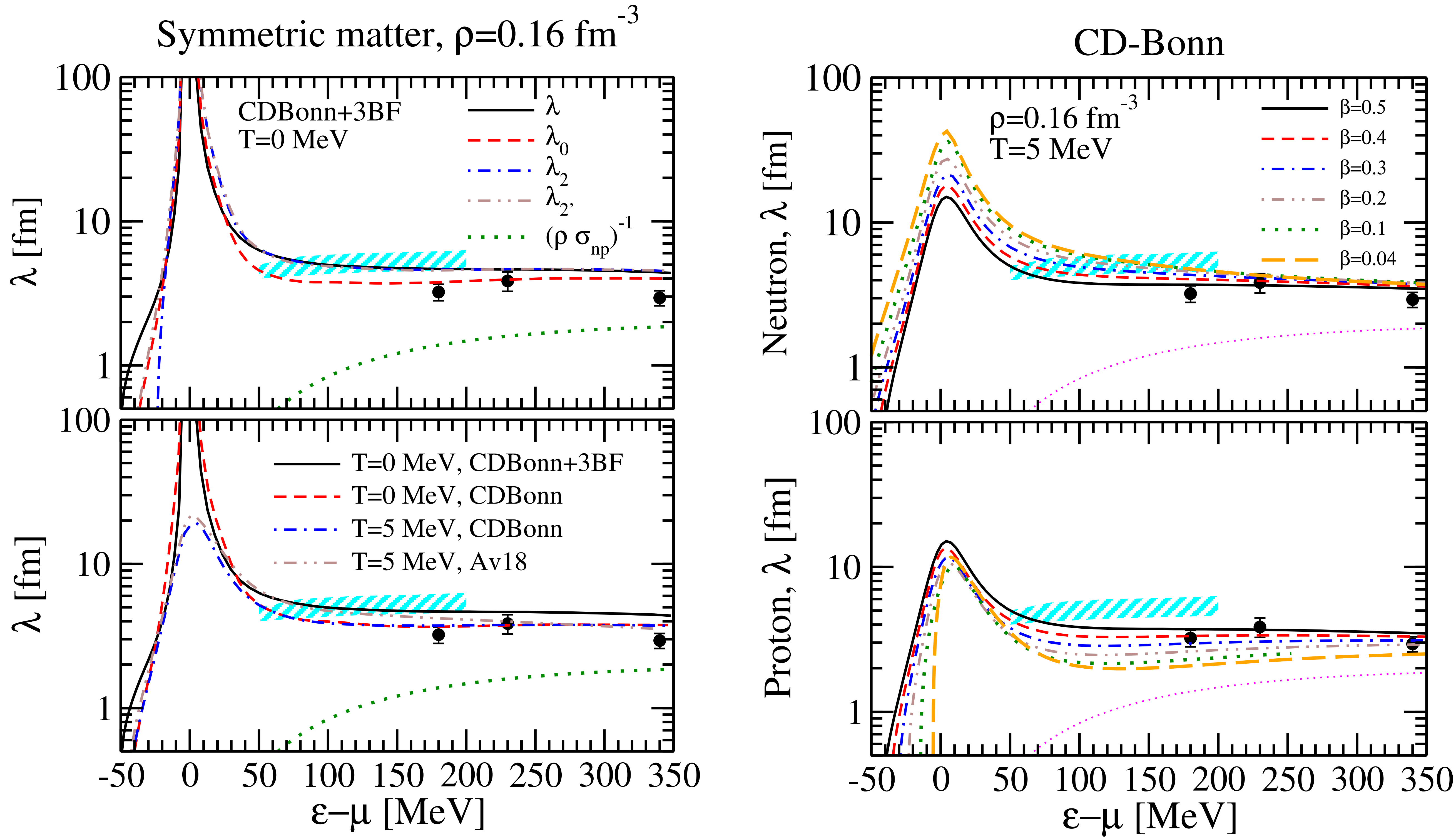


Experimental constrains



Lattimer & Lim, *ApJ* **771** 51 (2013)
Lattimer & Steiner EPJA Spec. Vol. (2014)

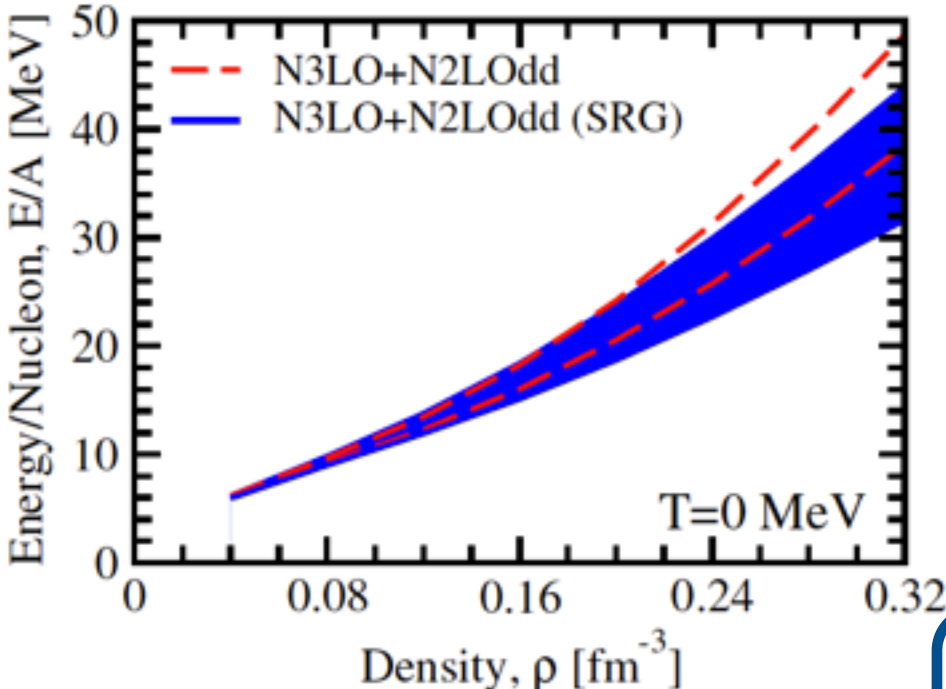
Transport properties
Nucleon mean-free path

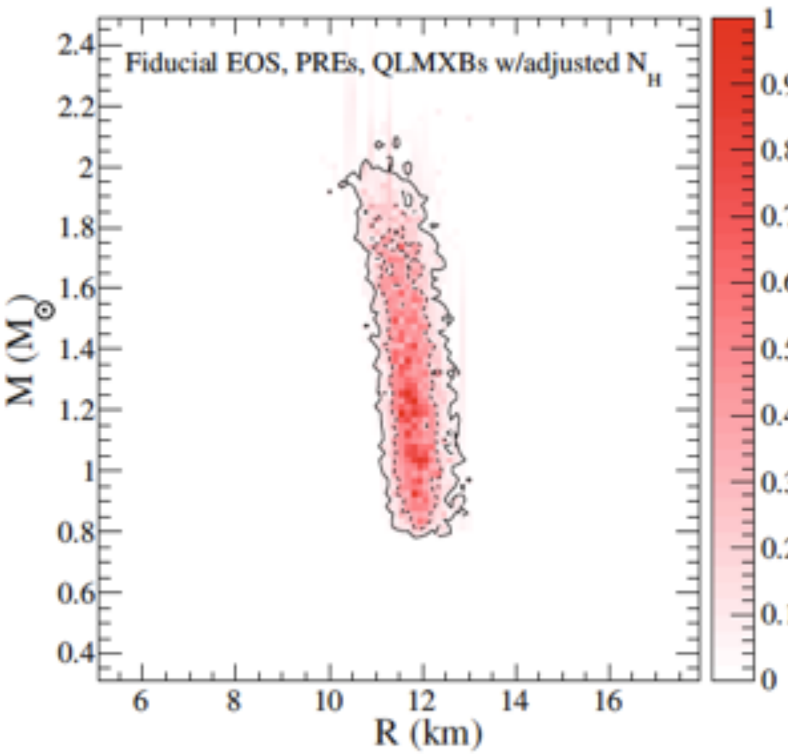


- Compatible with pA experiments
- Small model dependence & isospin dependence

Chiral EoS & pairing gaps

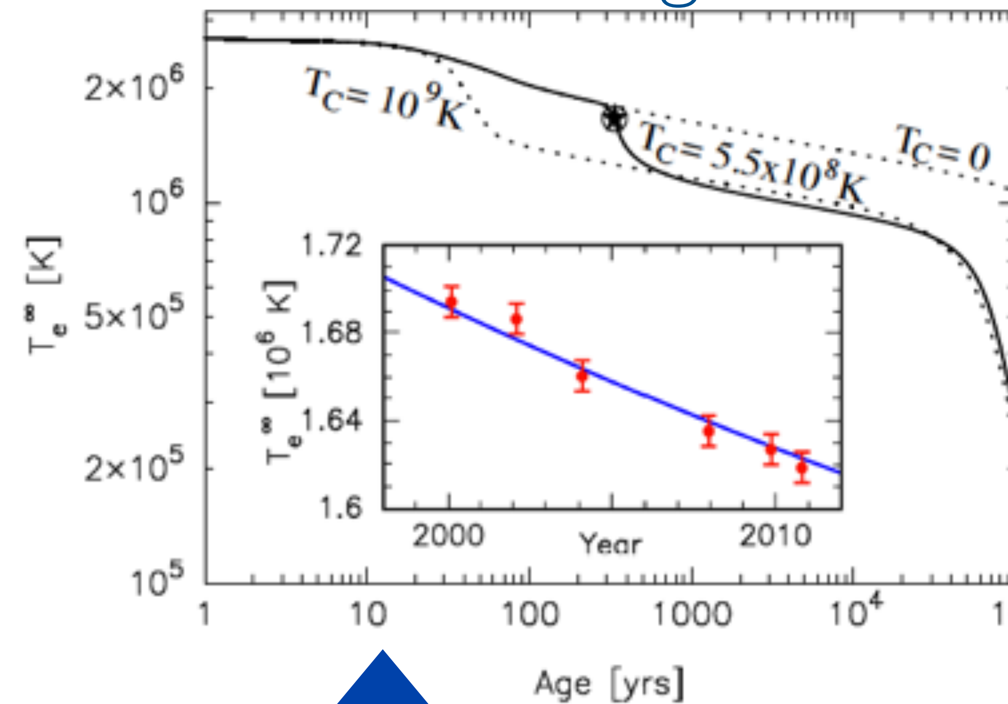
N^{3}LO EoS with 3BFs





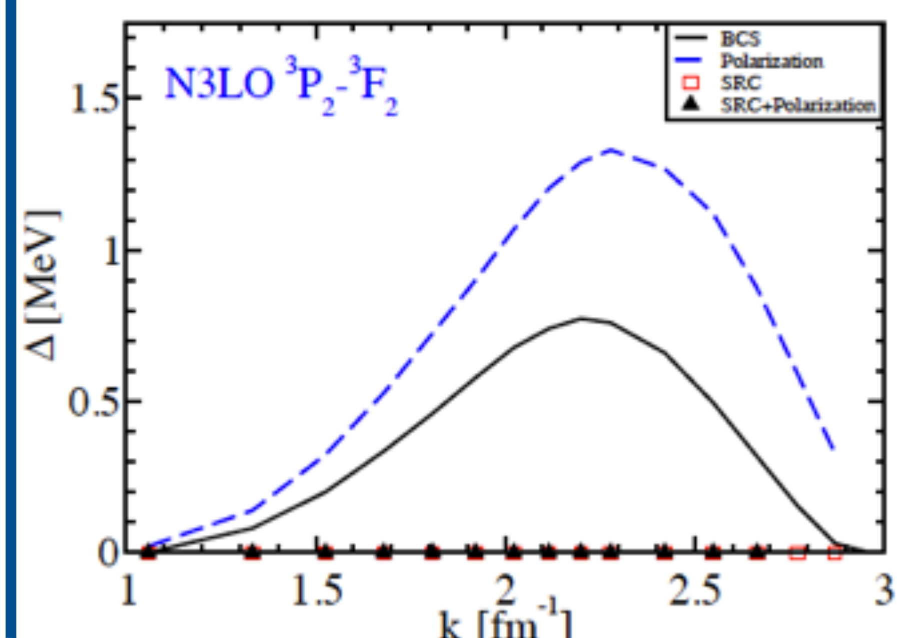
Steiner & Lattimer, EPJA **50** 49 (2014)

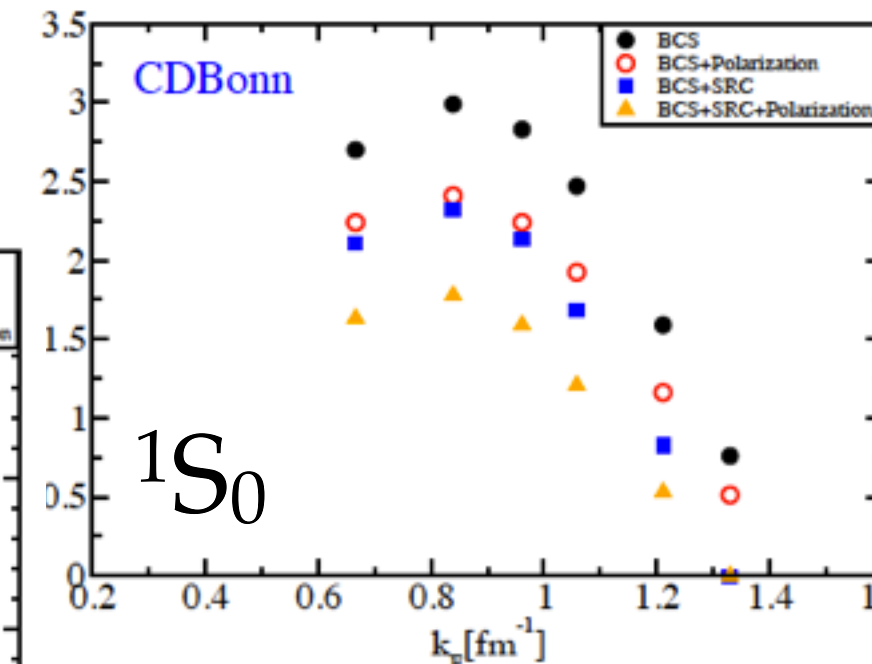
CasA cooling curve



PRL **106** 081101 (2011)

Pairing gap beyond BCS



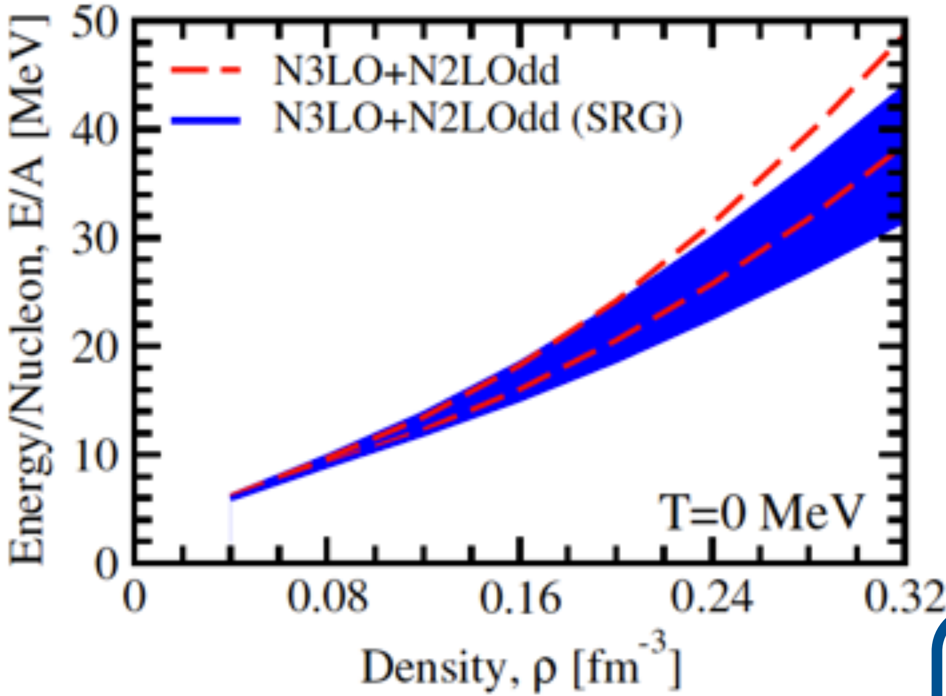


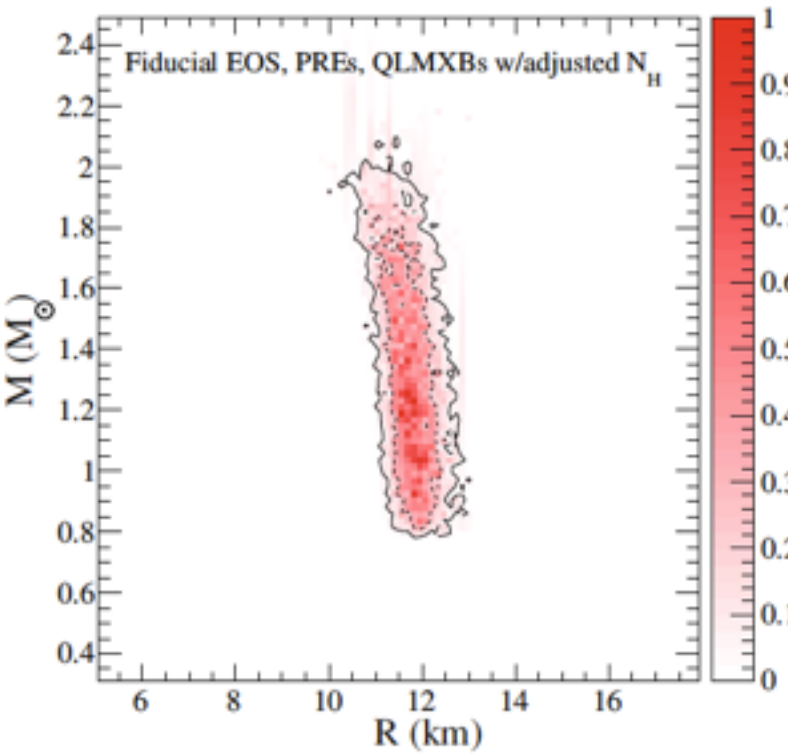
Preliminary

Ding, Witte, Dickhoff, Hussan, Rios & Polls, *arxiv:1406.7789*

Chiral EoS & pairing gaps

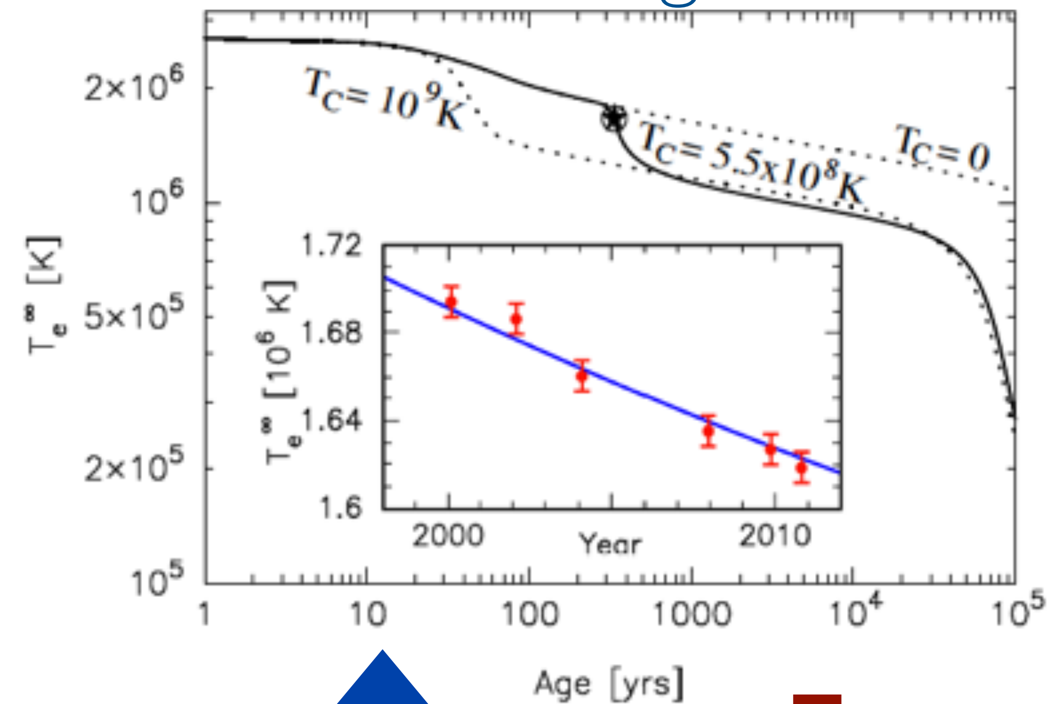
N^{3}LO EoS with 3BFs





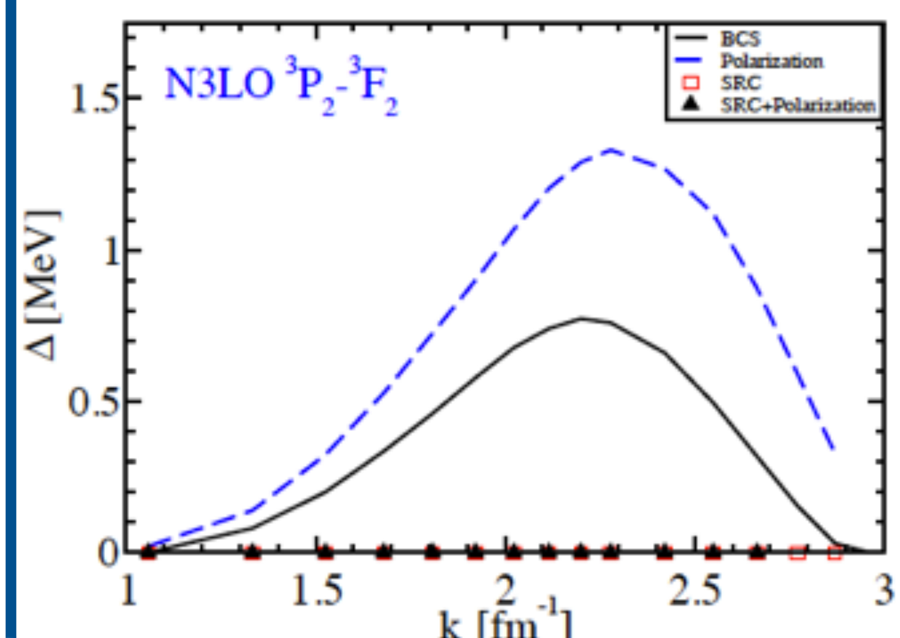
Steiner & Lattimer, *EPJA* **50** 49 (2014)

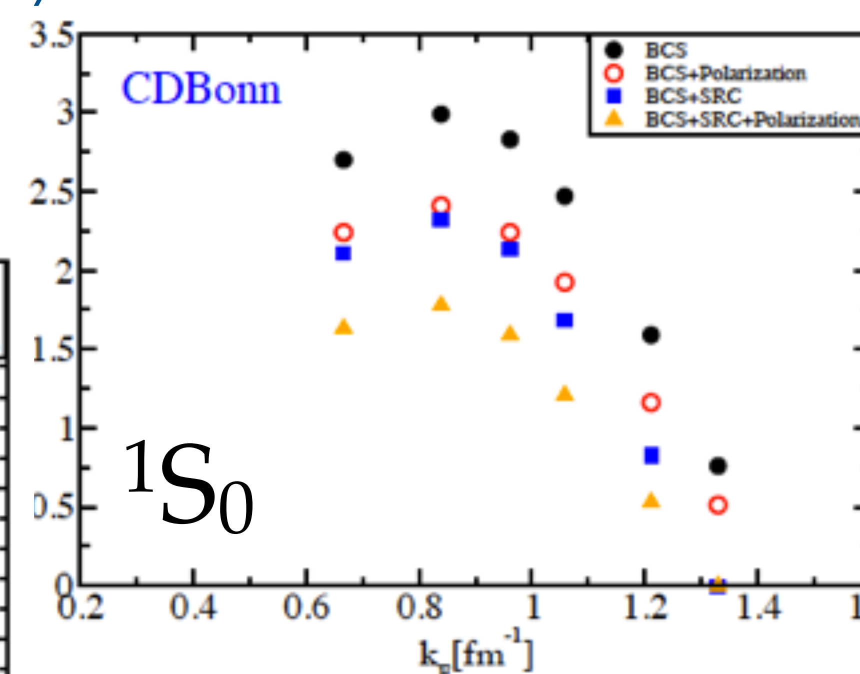
CasA cooling curve



PRL **106** 081101 (2011)

Pairing gap beyond BCS





Preliminary

Ding, Witte, Dickhoff, Hussan, Rios & Polls, *arxiv:1406.7789*

Conclusions

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- Ab initio nuclear theory to treat asymmetric systems
- Asymmetry dependence of SRC is universal
- Micro, macro properties handled
- Transport, pairing properties on-going
- Many-body forces can now be accessed
- Two-body properties?