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Density & isospin asymmetry dependence of correlations

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Summary

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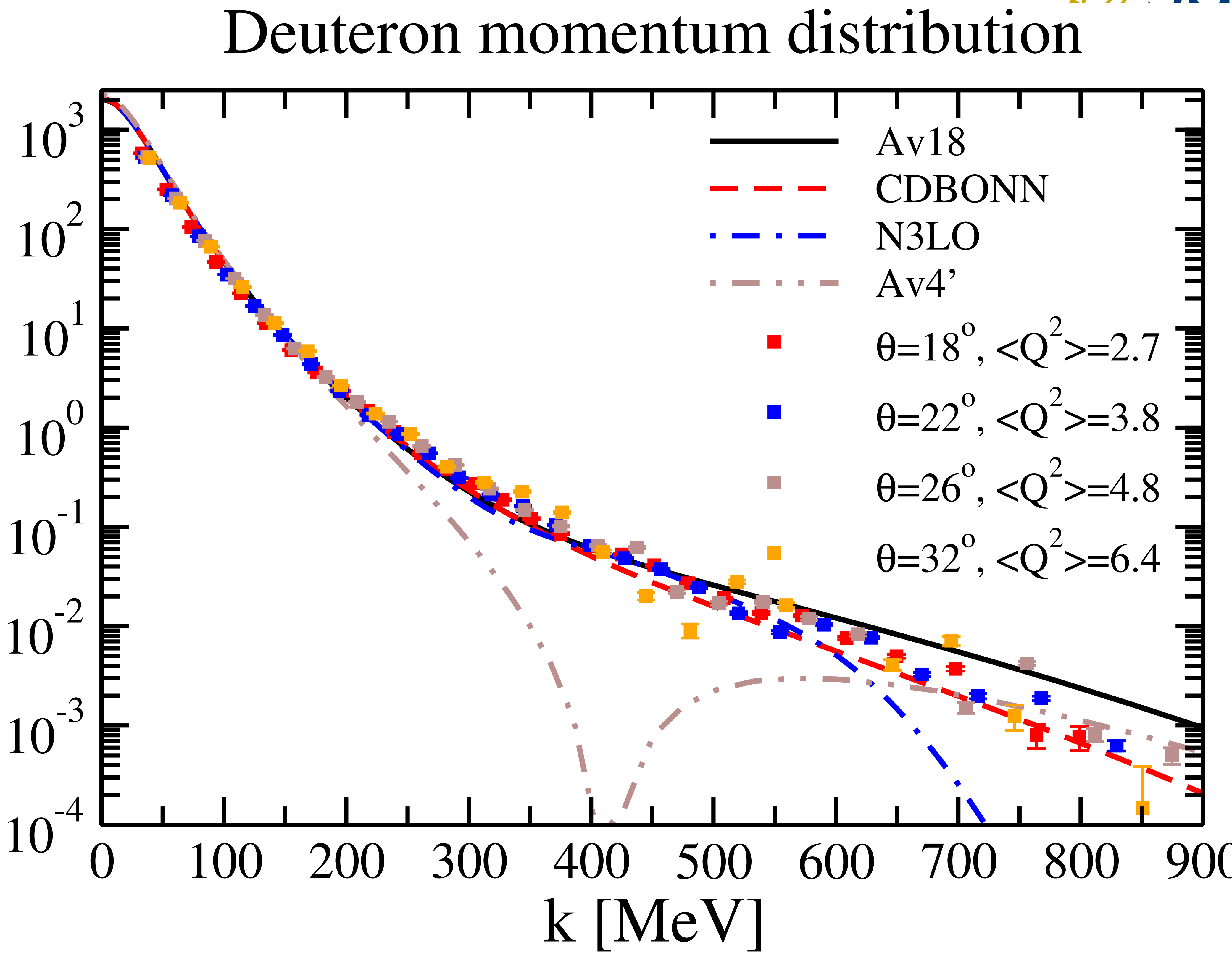
1. Depletion of the nuclear Fermi sea
2. High-momentum components
3. Implications for symmetry energy
4. Pairing in neutron stars

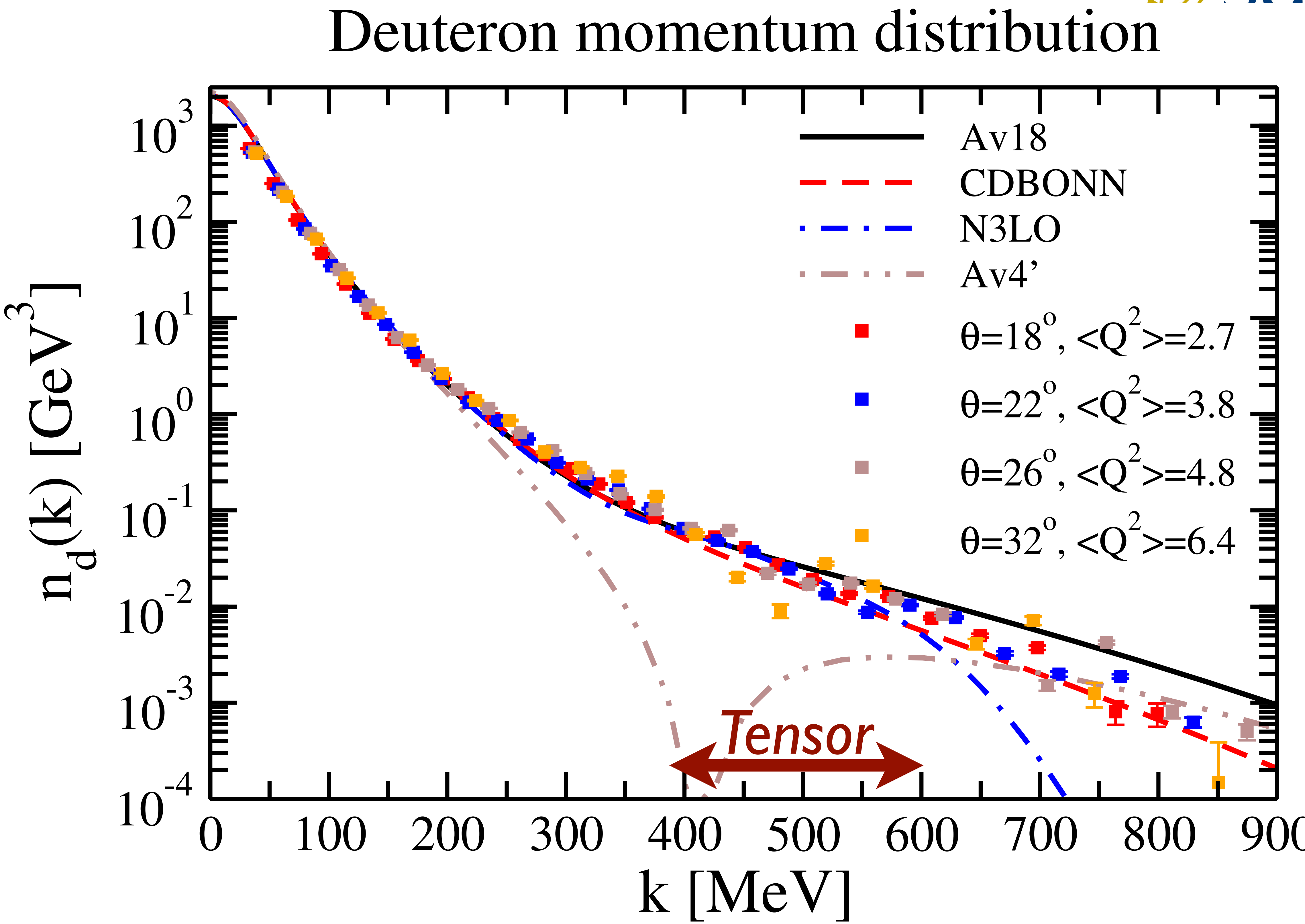
Why short-range correlations?



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

Inclusive quasi-elastic e⁻ scattering vs NN potential theory

Why short-range correlations?



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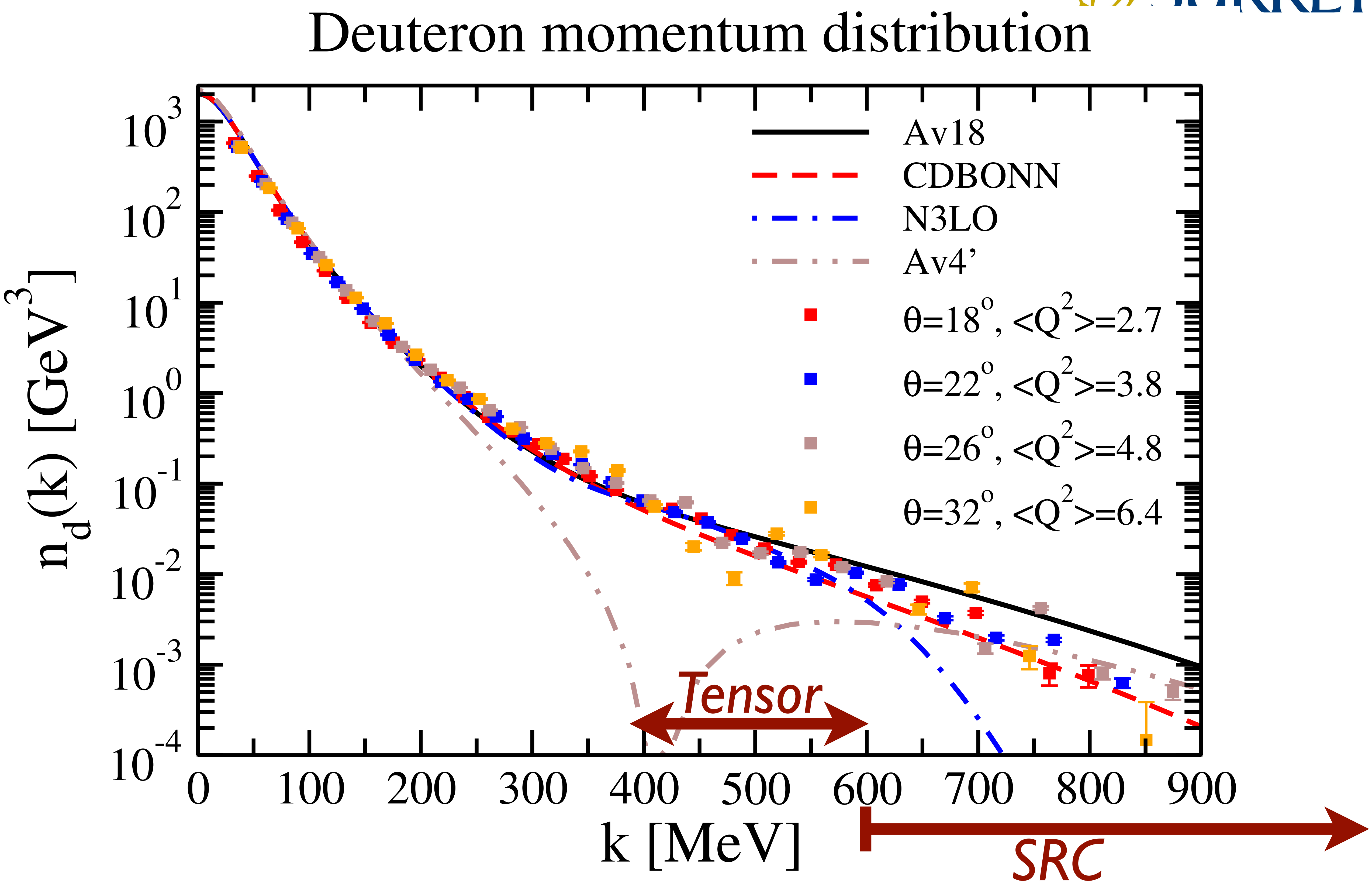


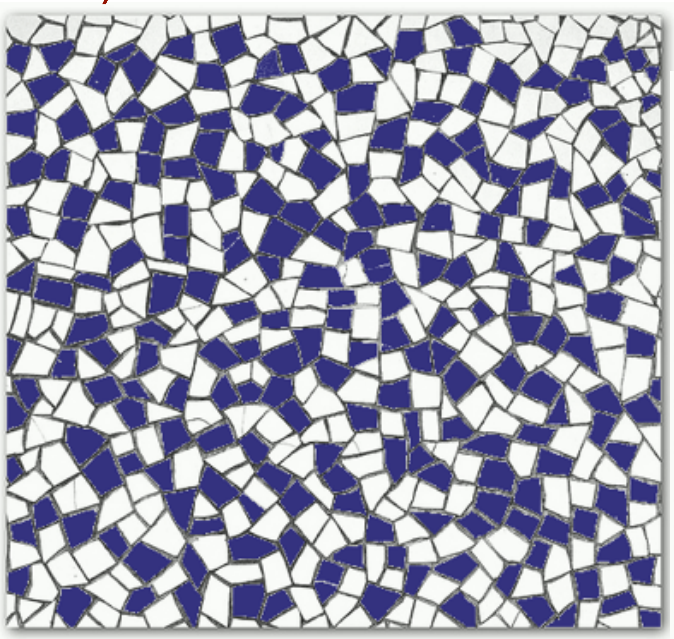
Fomin et al., PRL **108** 092502 (2012)

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

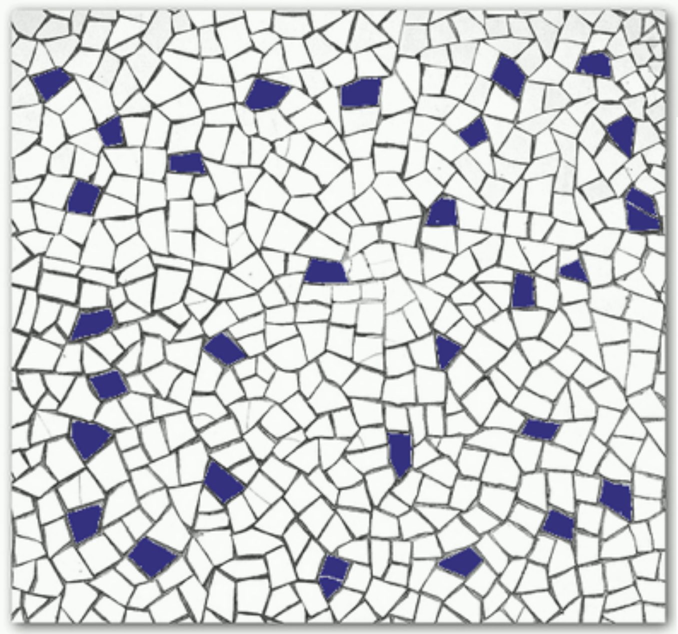
Nuclear vs neutron matter

Nuclear "trencadís"

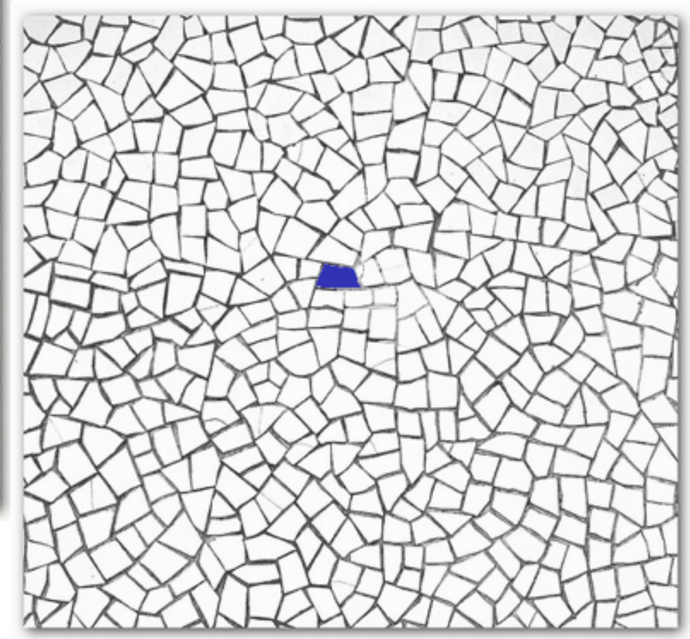
N=Z, β=0, x_p=0.5
Symmetric matter



$\beta \neq 0$, x_p<0.5
Asymmetric nuclei

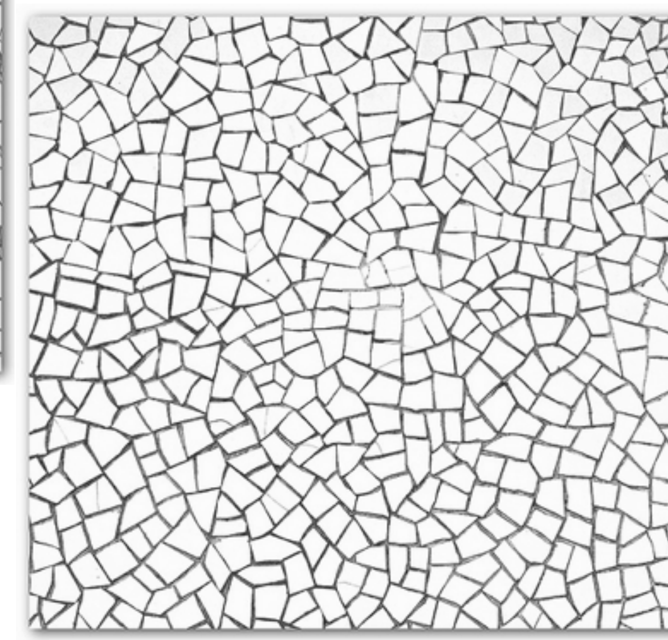


$\beta \approx 1$, $x_p \approx 0$
Polaron



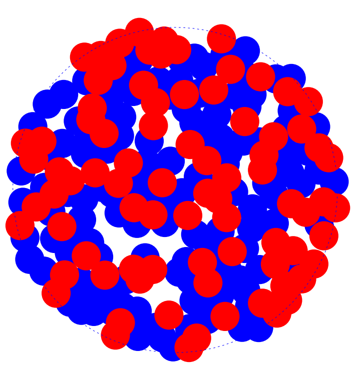
Neutron stars

β=1, x_p=0
Neutron matter



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

Nuclei

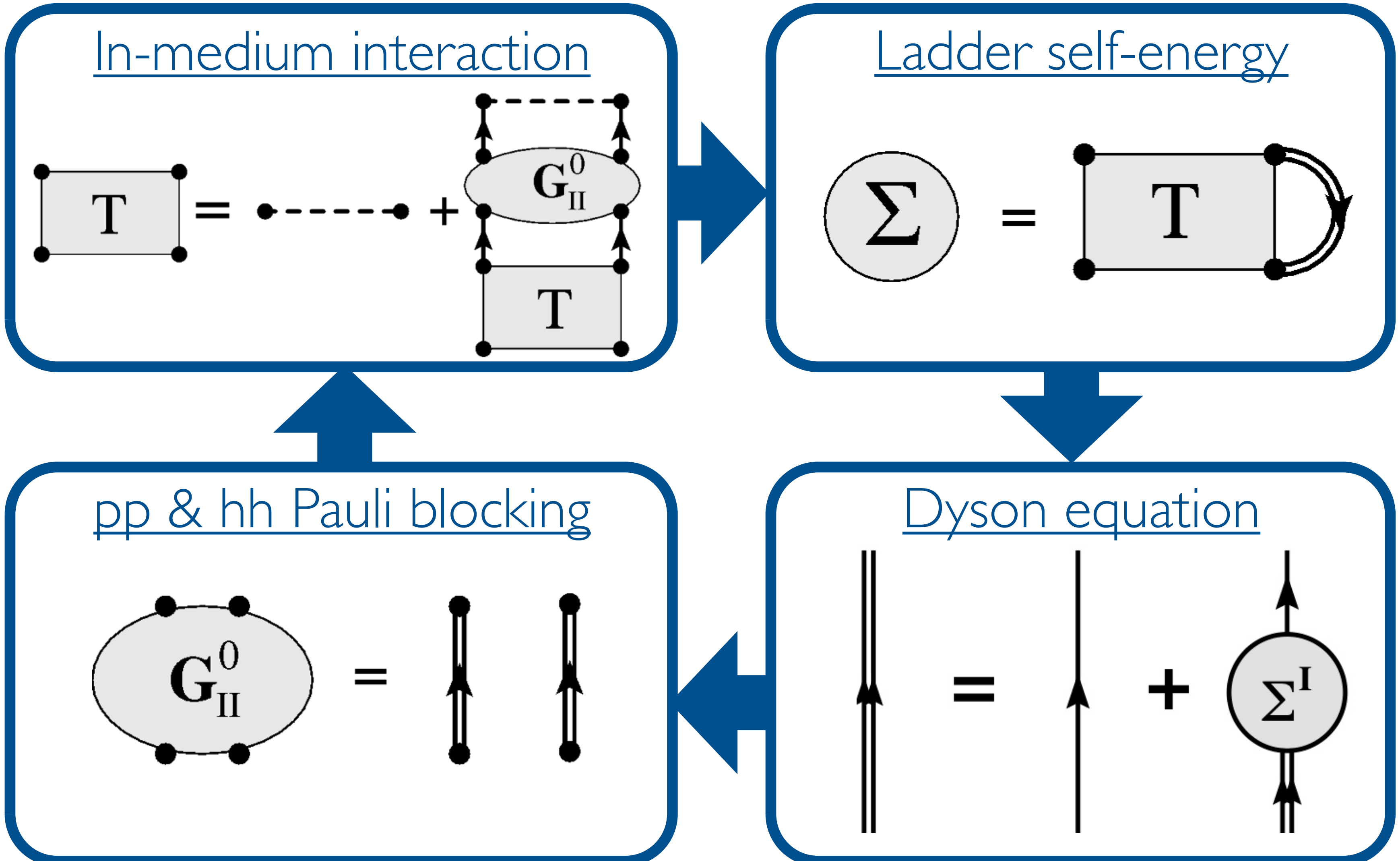


Lead 208
β=(126-82)/208=0.2
x_p=82/208=0.39

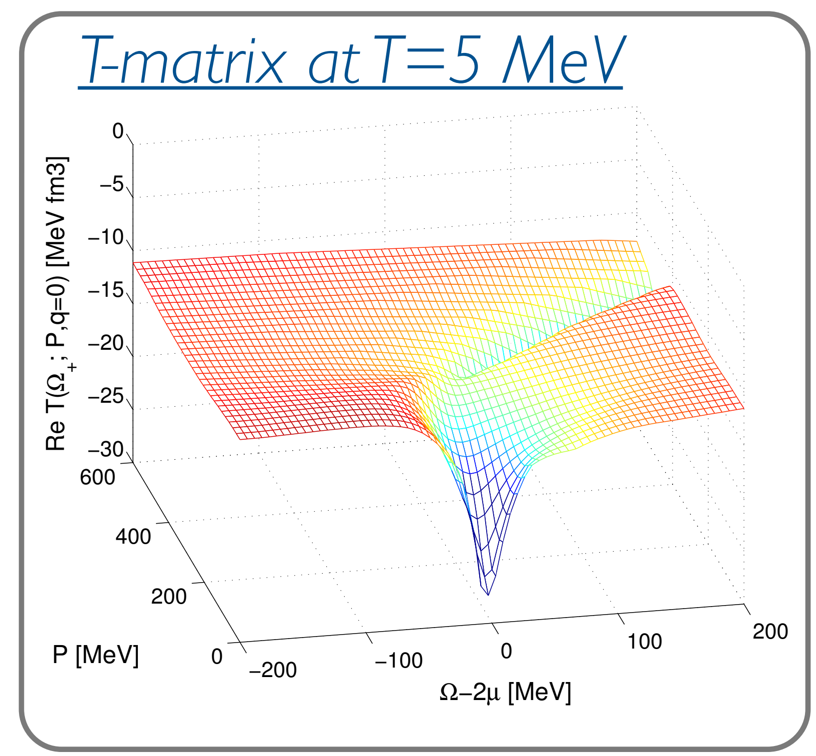
$$x_p = \frac{Z}{N+Z}$$

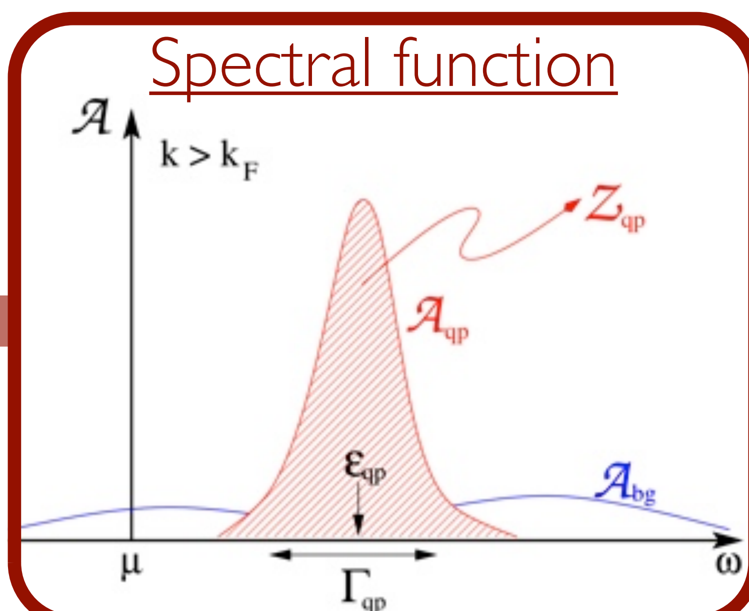
Experimentally unknown!

SCGF Ladder approximation



- Self-consistent resummation
- Energy and momentum integral
- @Finite T (Matsubara)

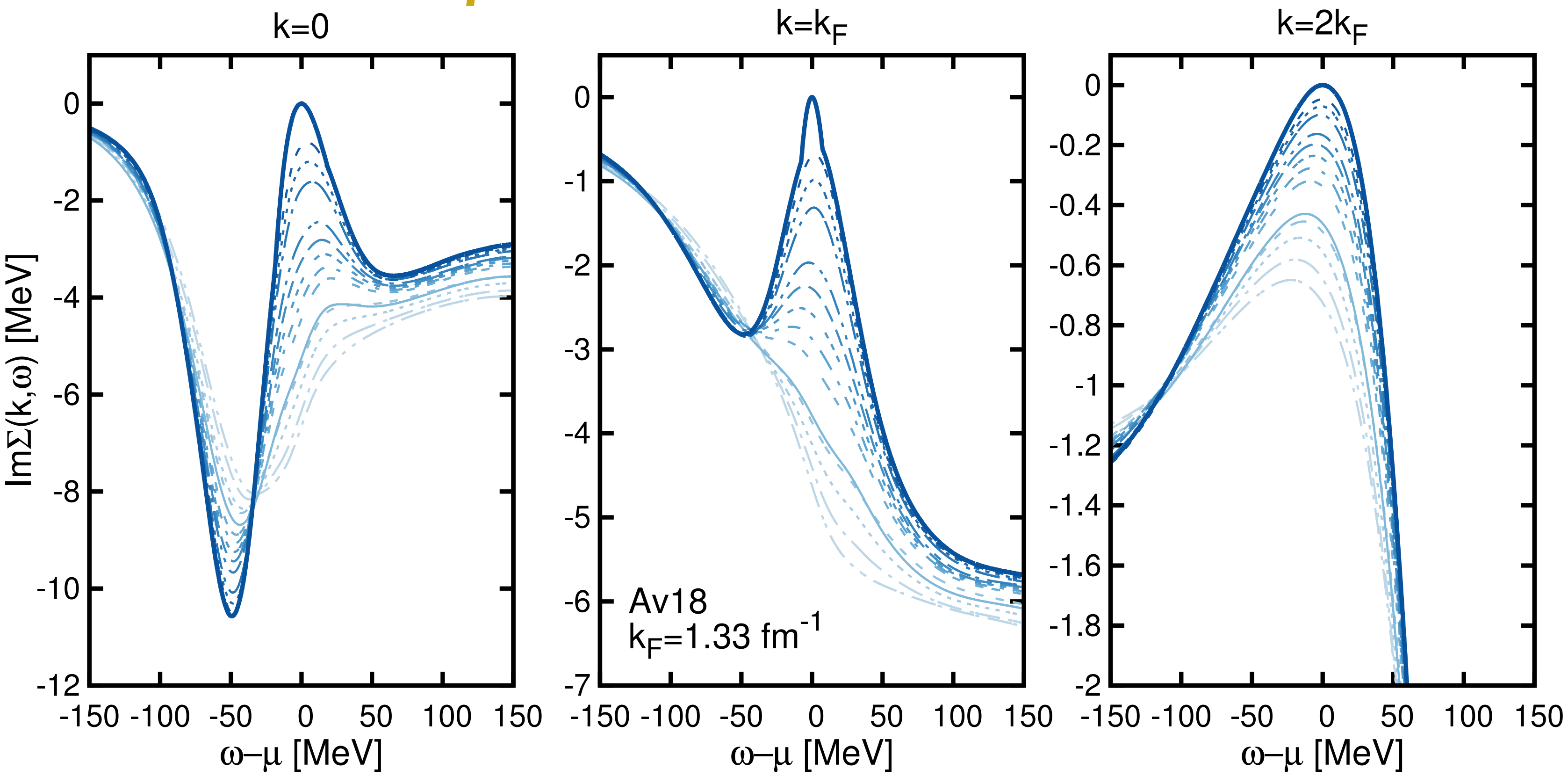


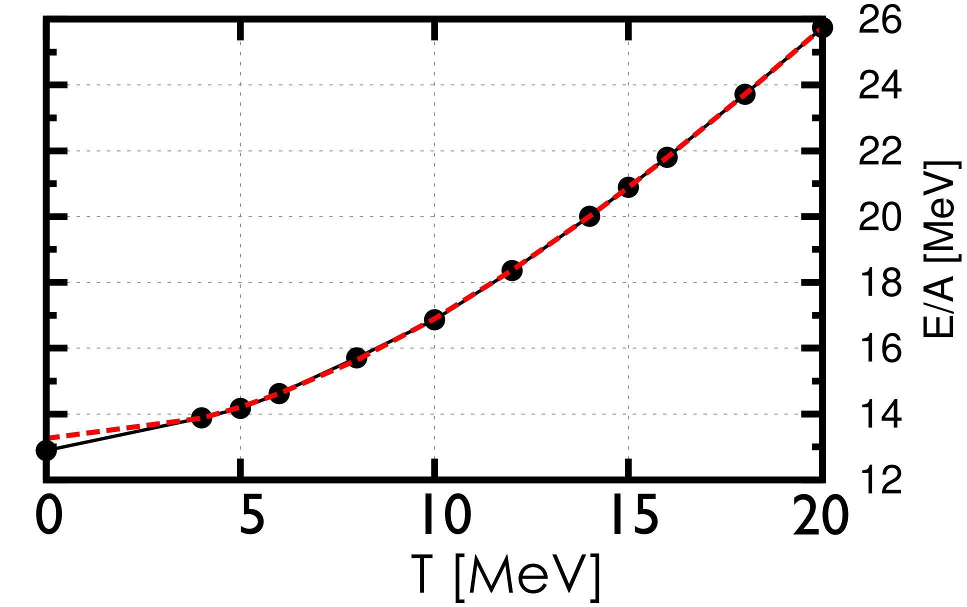


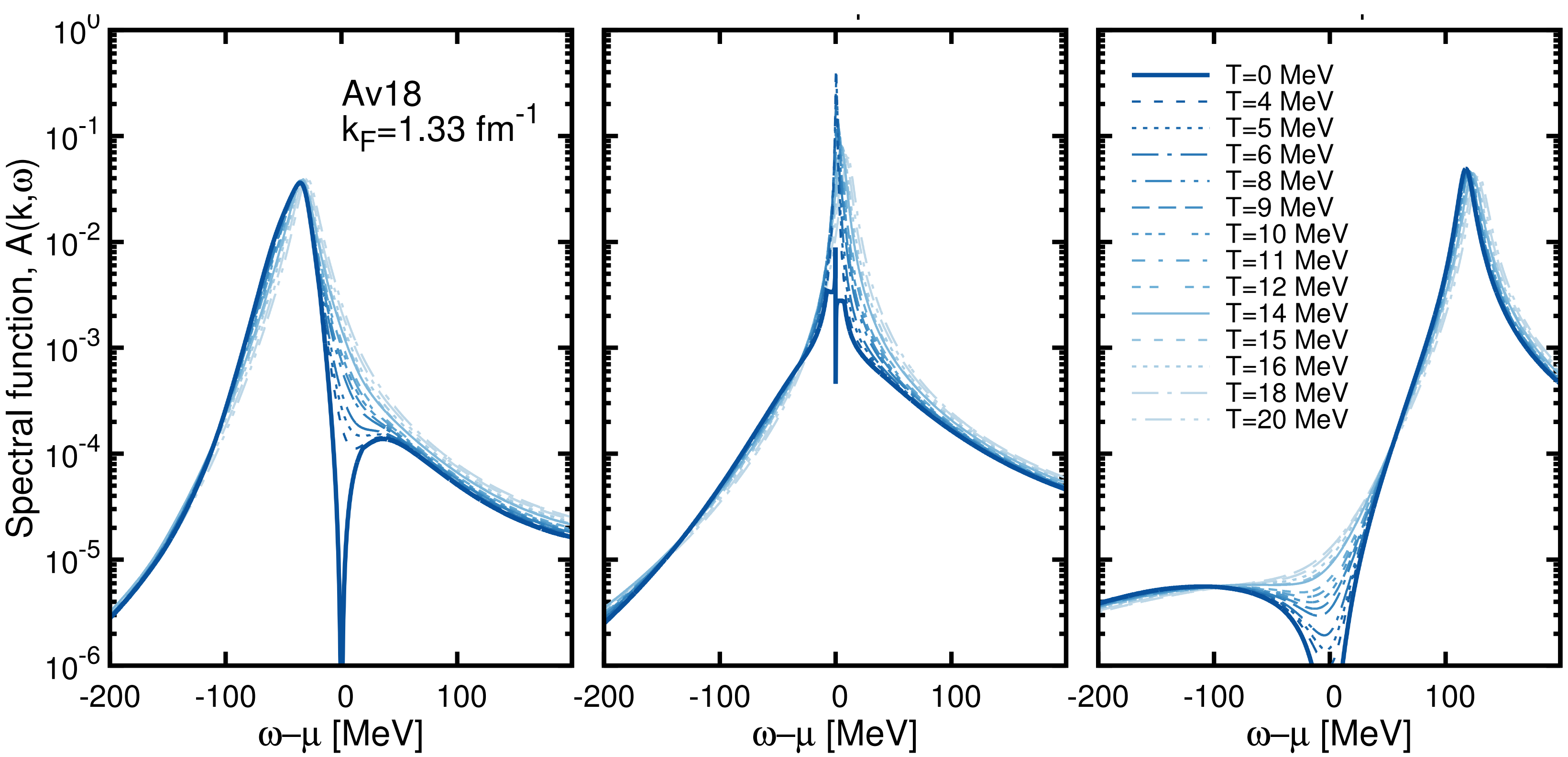
One-body properties
Momentum distribution
Thermodynamics & EoS
Transport

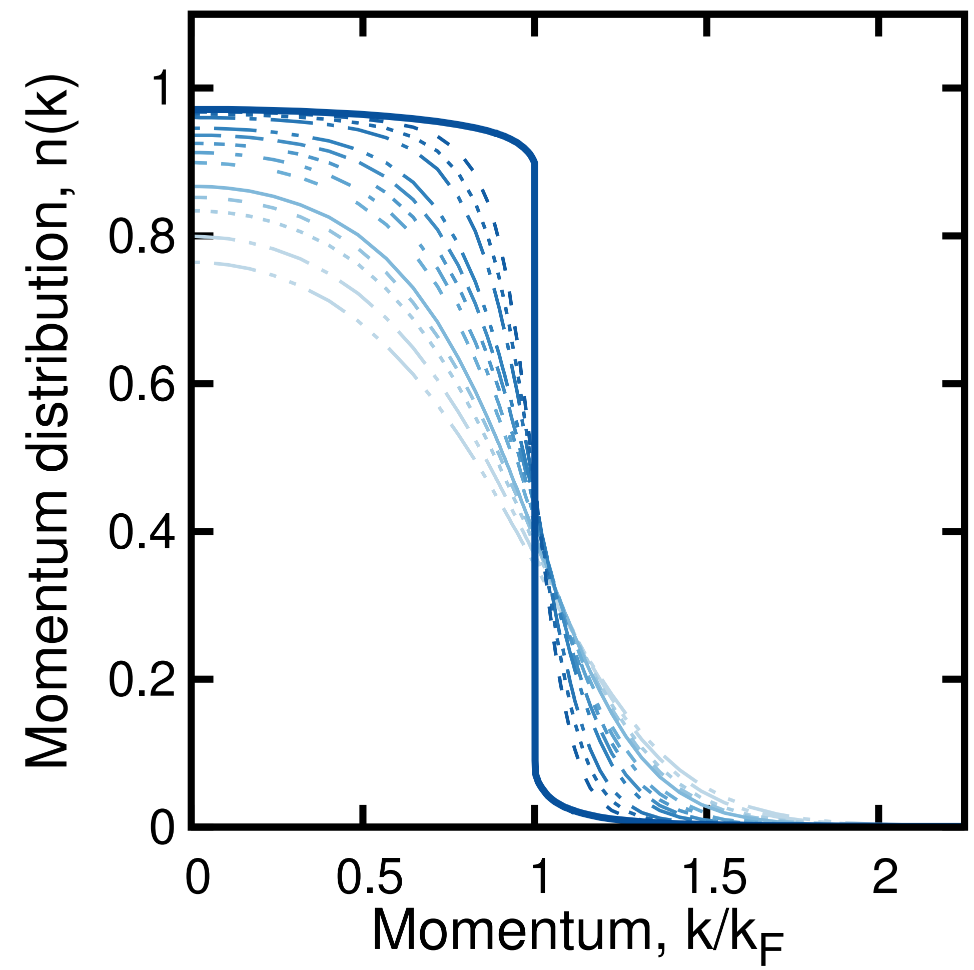
Ramos, Polls & Dickhoff, NPA **503** 1 (1989)
Alm *et al.*, PRC **53** 2181 (1996)
Dewulf *et al.*, PRL **90** 152501 (2003)
Frick & Muther, PRC **68** 034310 (2003)
Rios, PhD Thesis, U. Barcelona (2007)
Soma & Bozek, PRC **78** 054003 (2008)
Rios & Soma PRL **108** 012501 (2012)

T=0 extrapolations





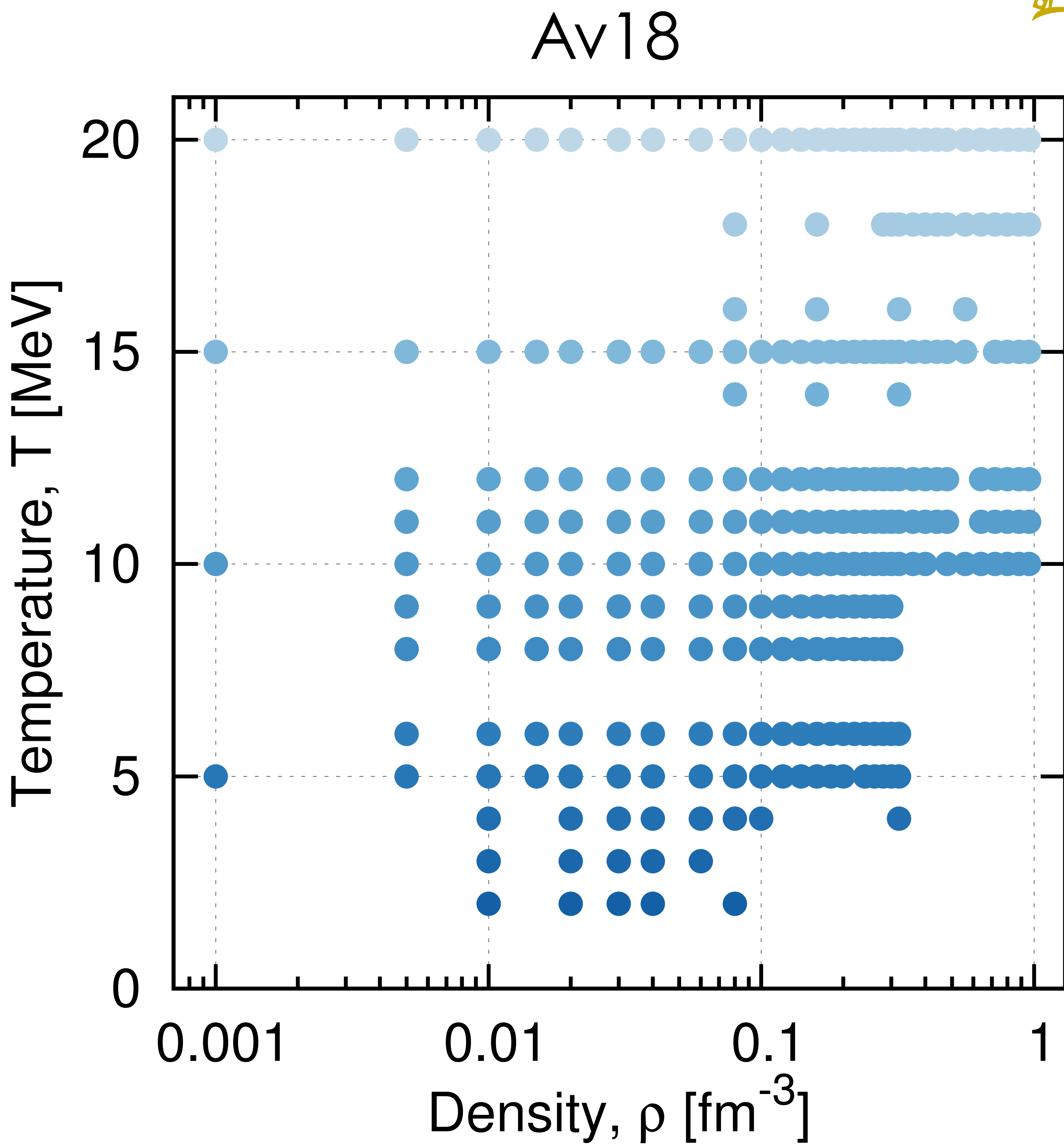




- **Extrapolate** $\Sigma(k,\omega;T)$ (13 Gb worth data)
- **Constraining** with **macroscopic** properties

A. Rios, *in preparation*

Available data



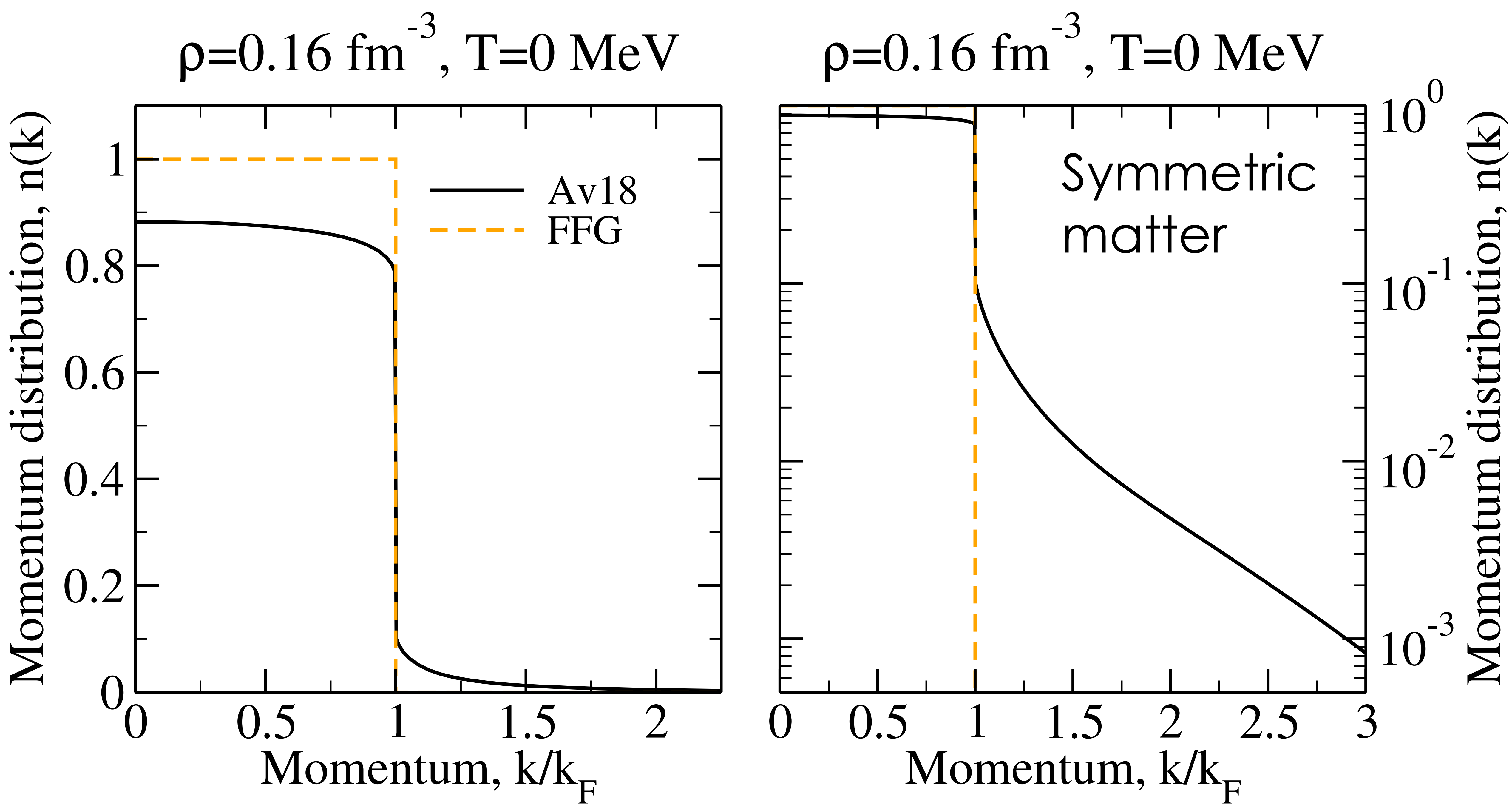
Self-energy, spectral function & thermodynamics

- **Advantages**
  - **All** kinds of NN interactions ✔
  - **3N** interactions too (Arianna's talk) ✔
  - Short-range & tensor **correlations** ✔
  - Density & **isospin** dependence ✔
  - Access to **off-shell** spectral function ✔
  - **No** artificial **separation** of MF vs correlations ✔
  - **Thermodynamically** consistent ✔
- **Limitations**
  - Non-relativistic ✘
  - Missing diagrams? ✘
  - No real-space picture (e.g. correlators) ✘
  - No nuclear surface ✘

Momentum distribution

Single-particle occupation

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



- SNM: 11-13% depletion at low k, population at high k
- Dependence on NN interaction under control
- PNM: 4-5% depletion at low k

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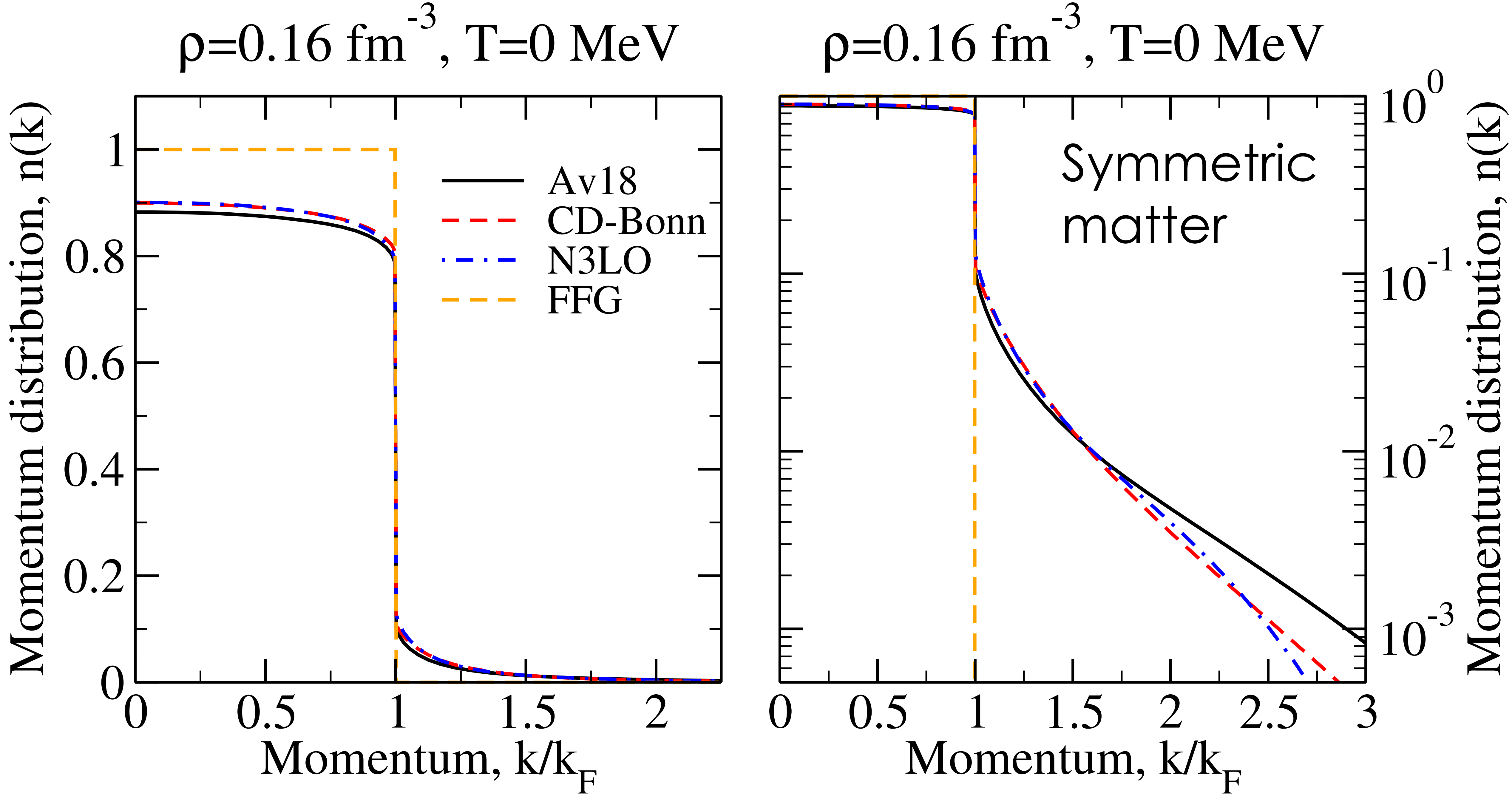

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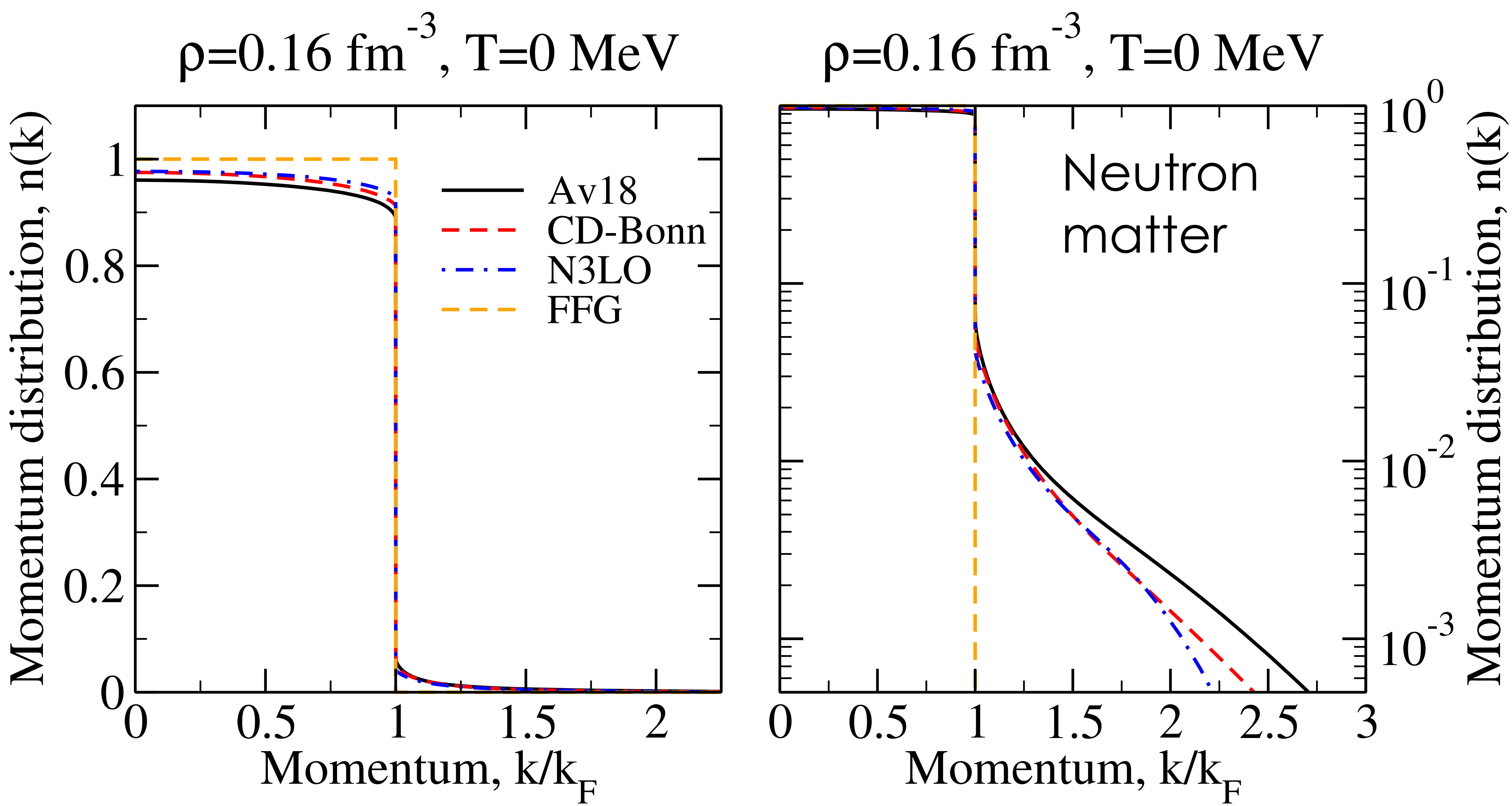

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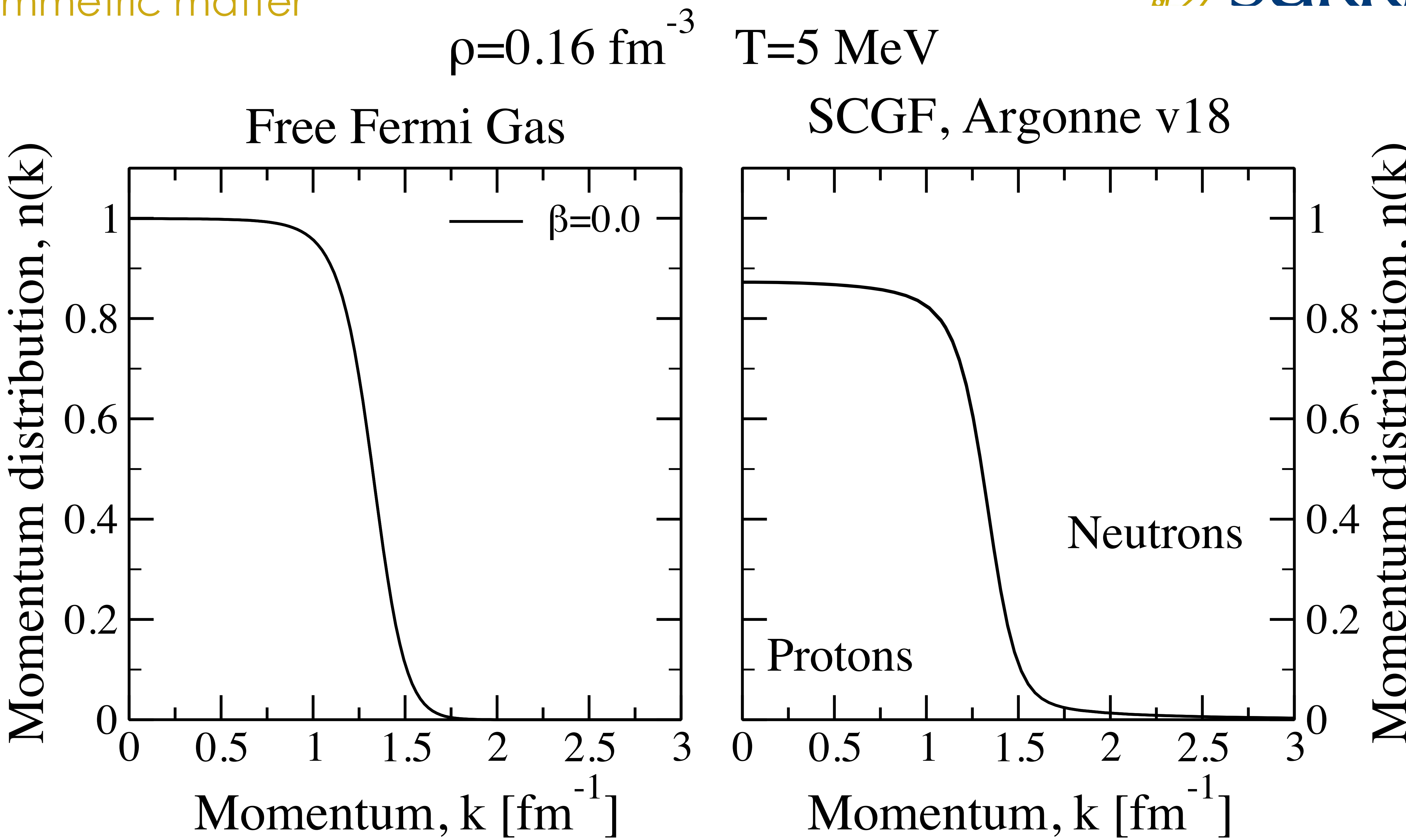
Momentum distribution
Asymmetric matter



- Correlations affect depletion ⇒ non-perturbative effect

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

Momentum distribution
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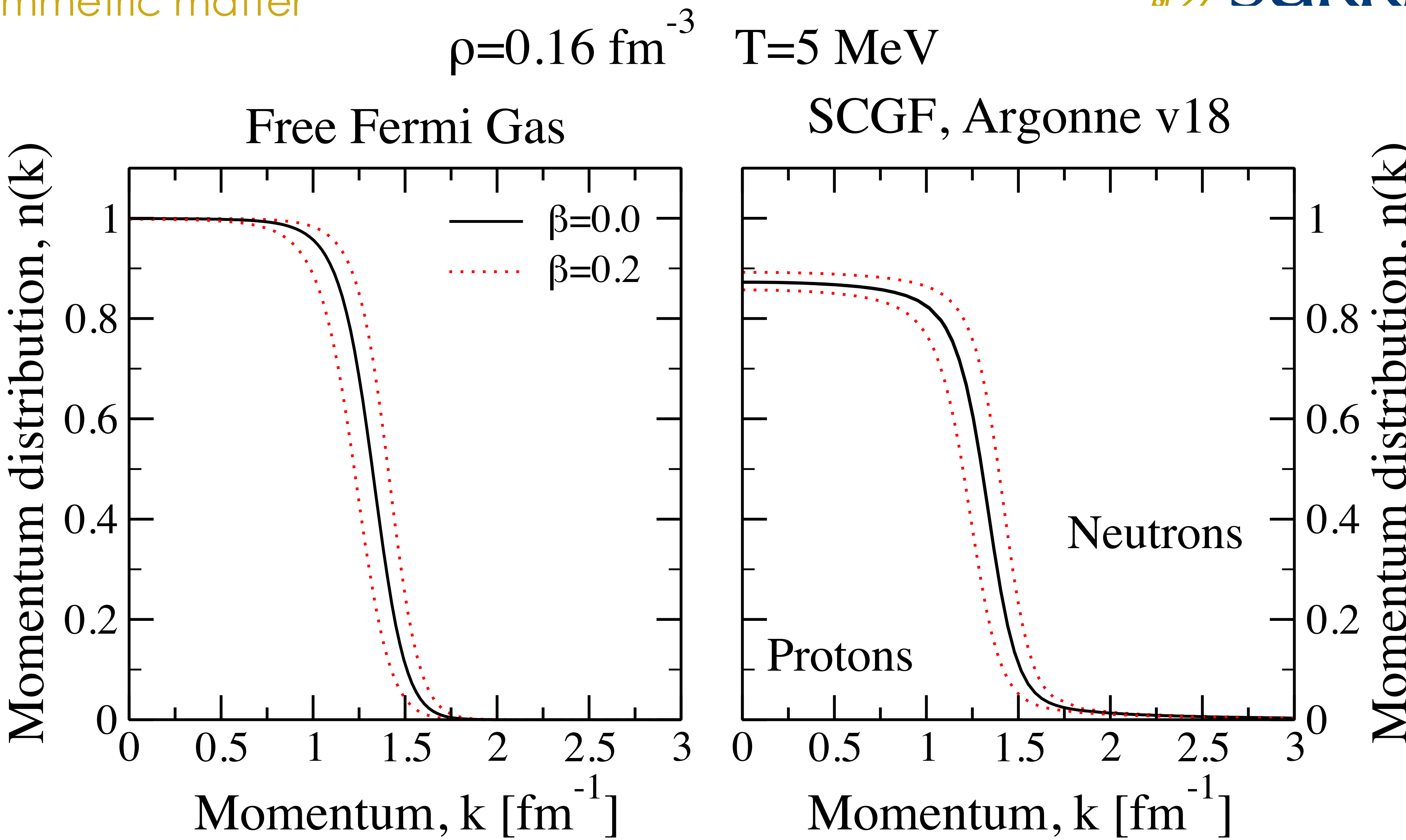

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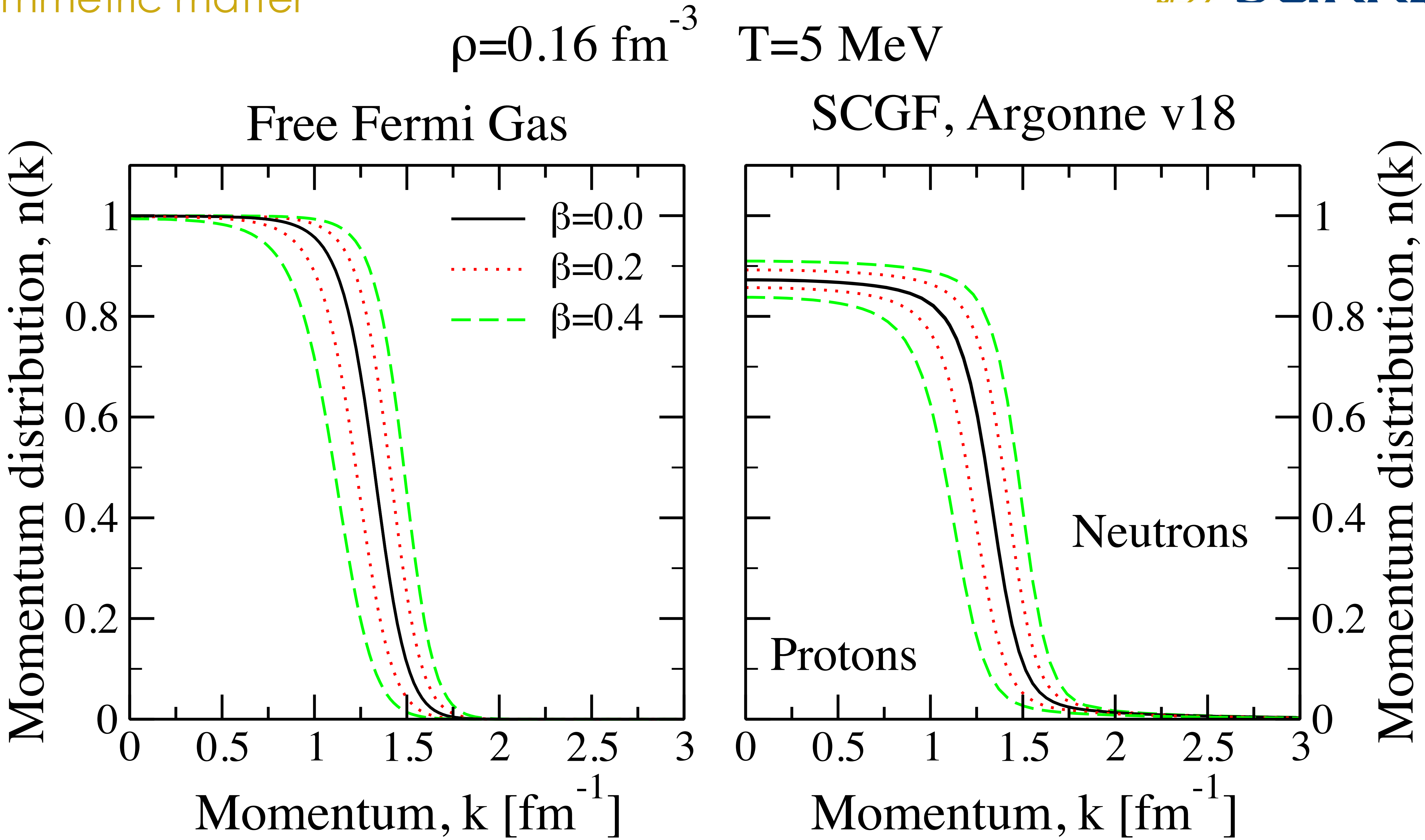

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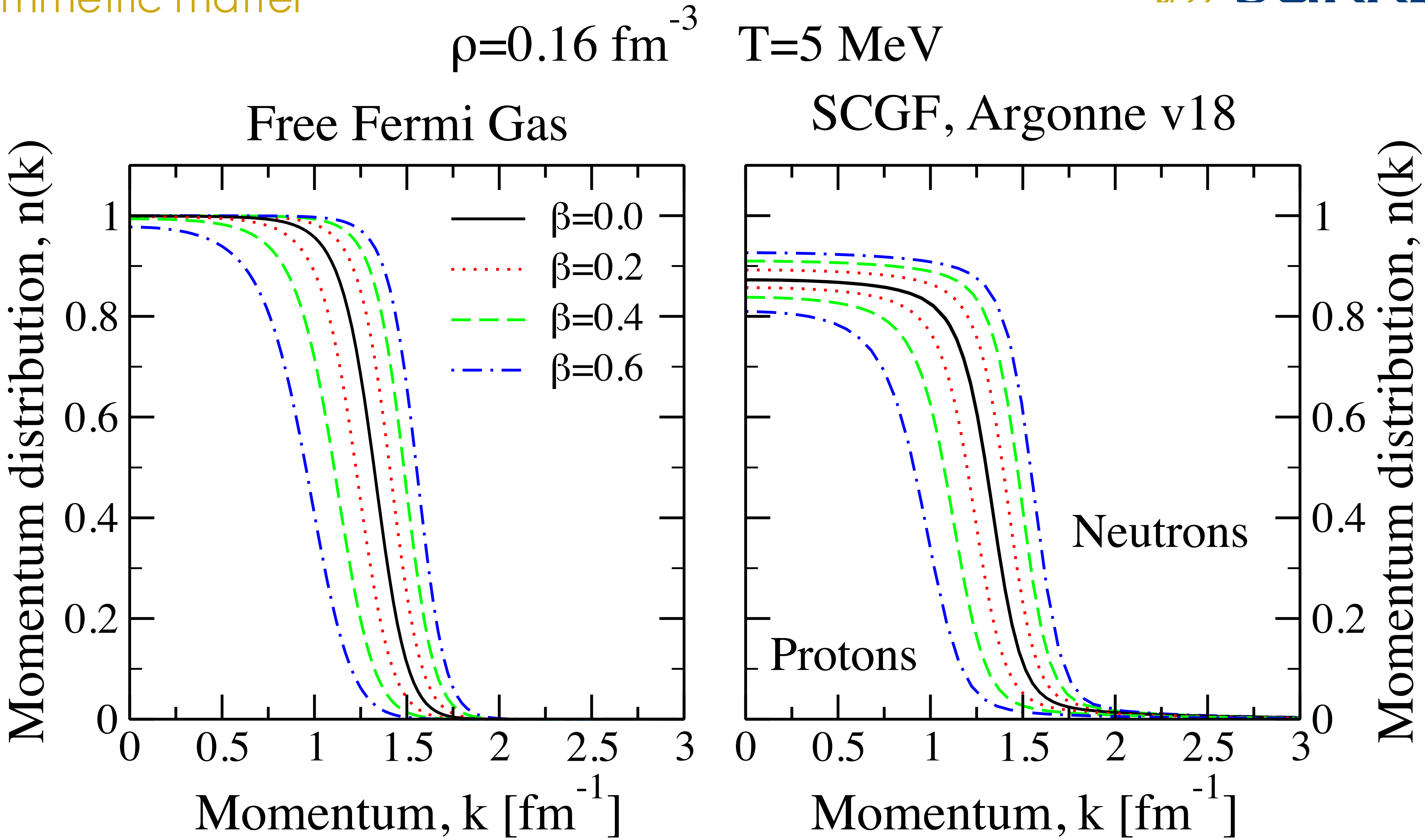

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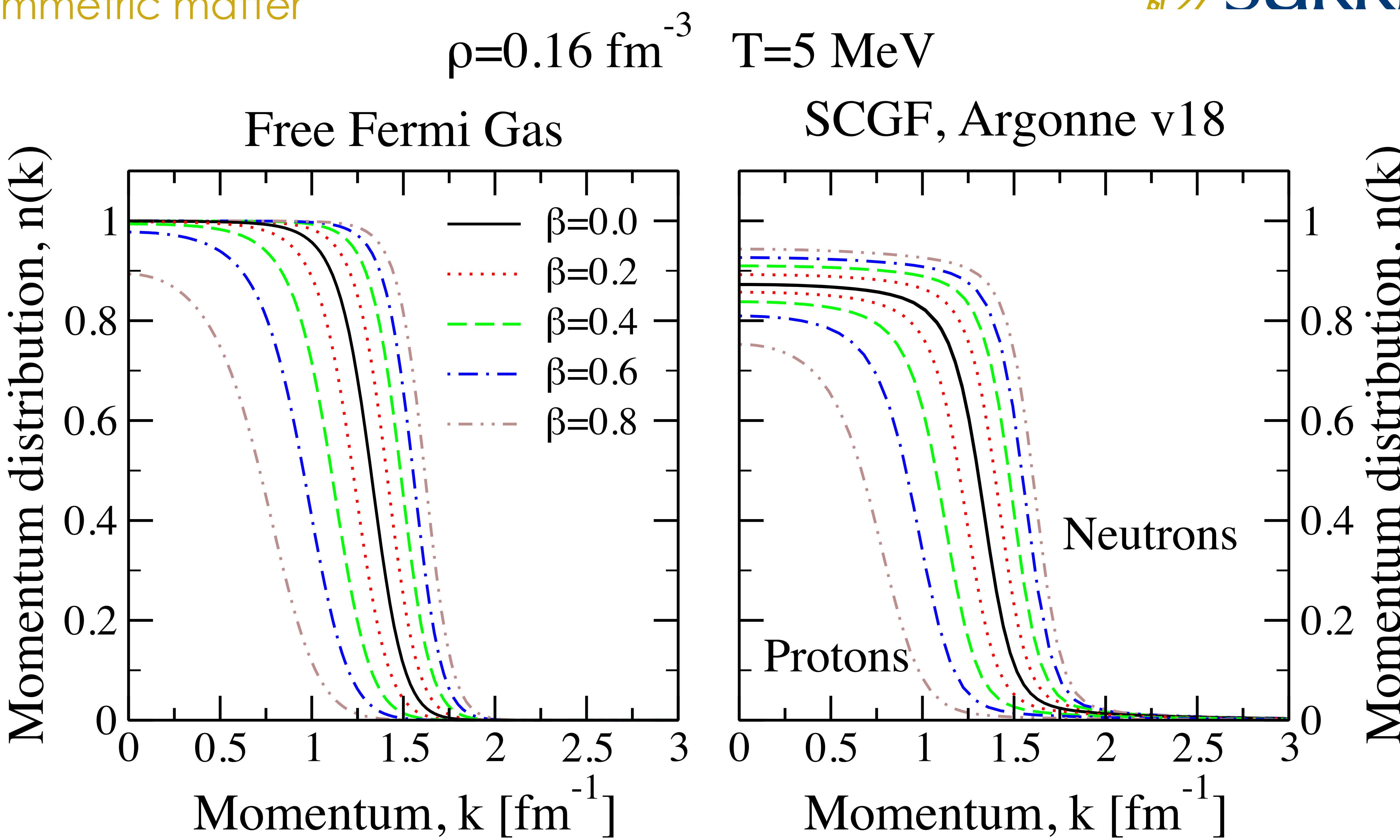

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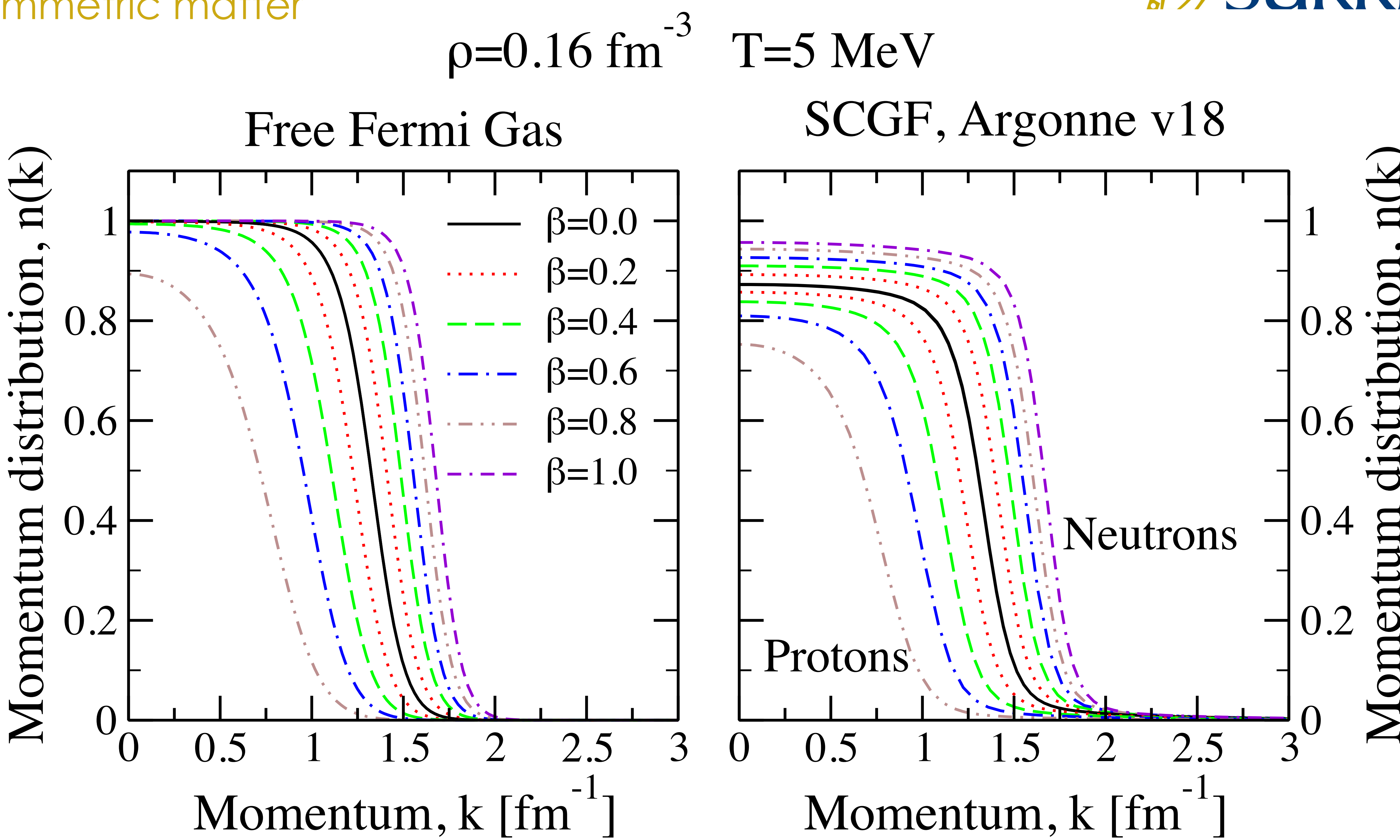
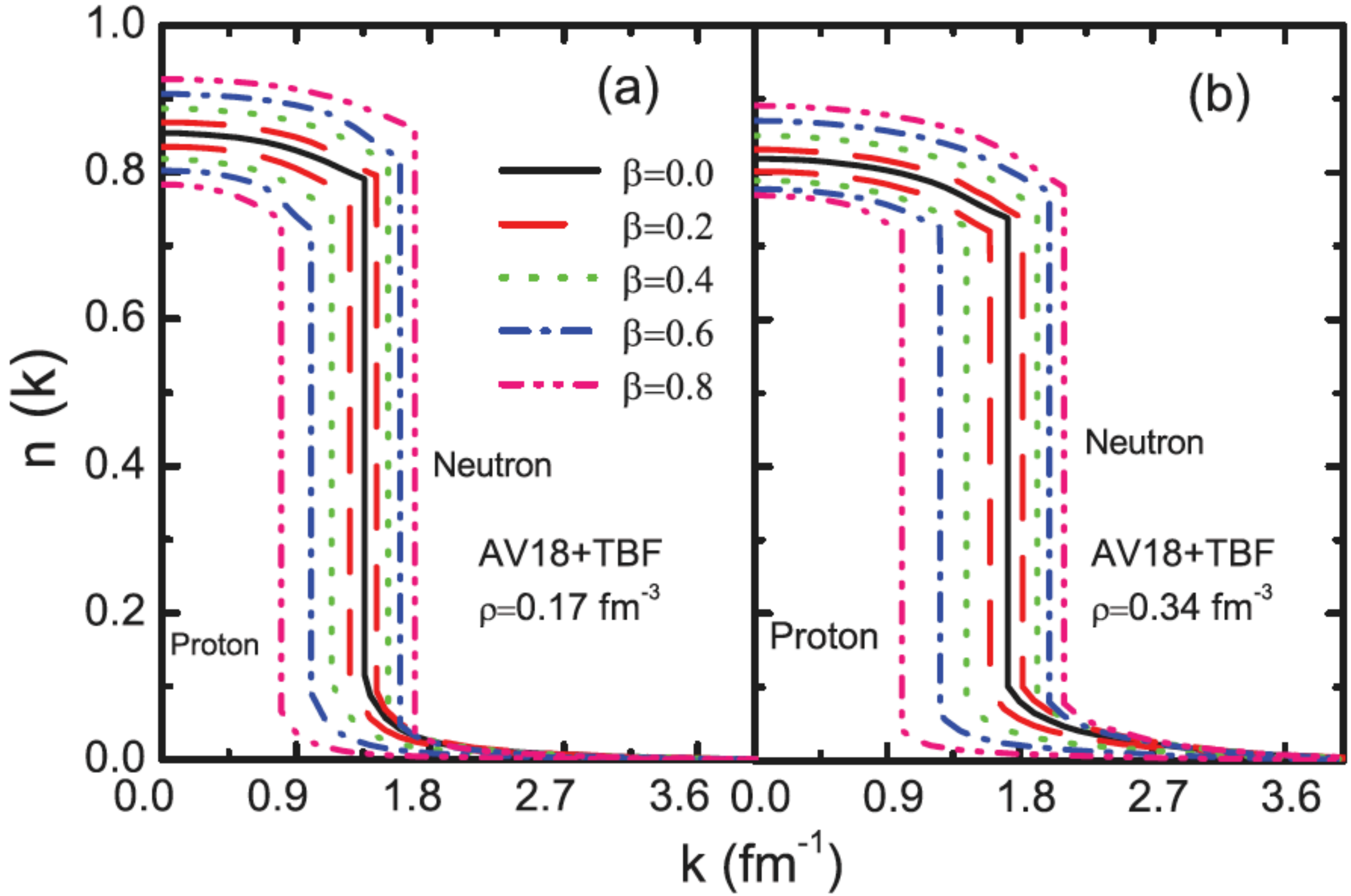


- Correlations affect depletion ⇒ non-perturbative effect
- Neutrons become less correlated
- Protons become more correlated

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

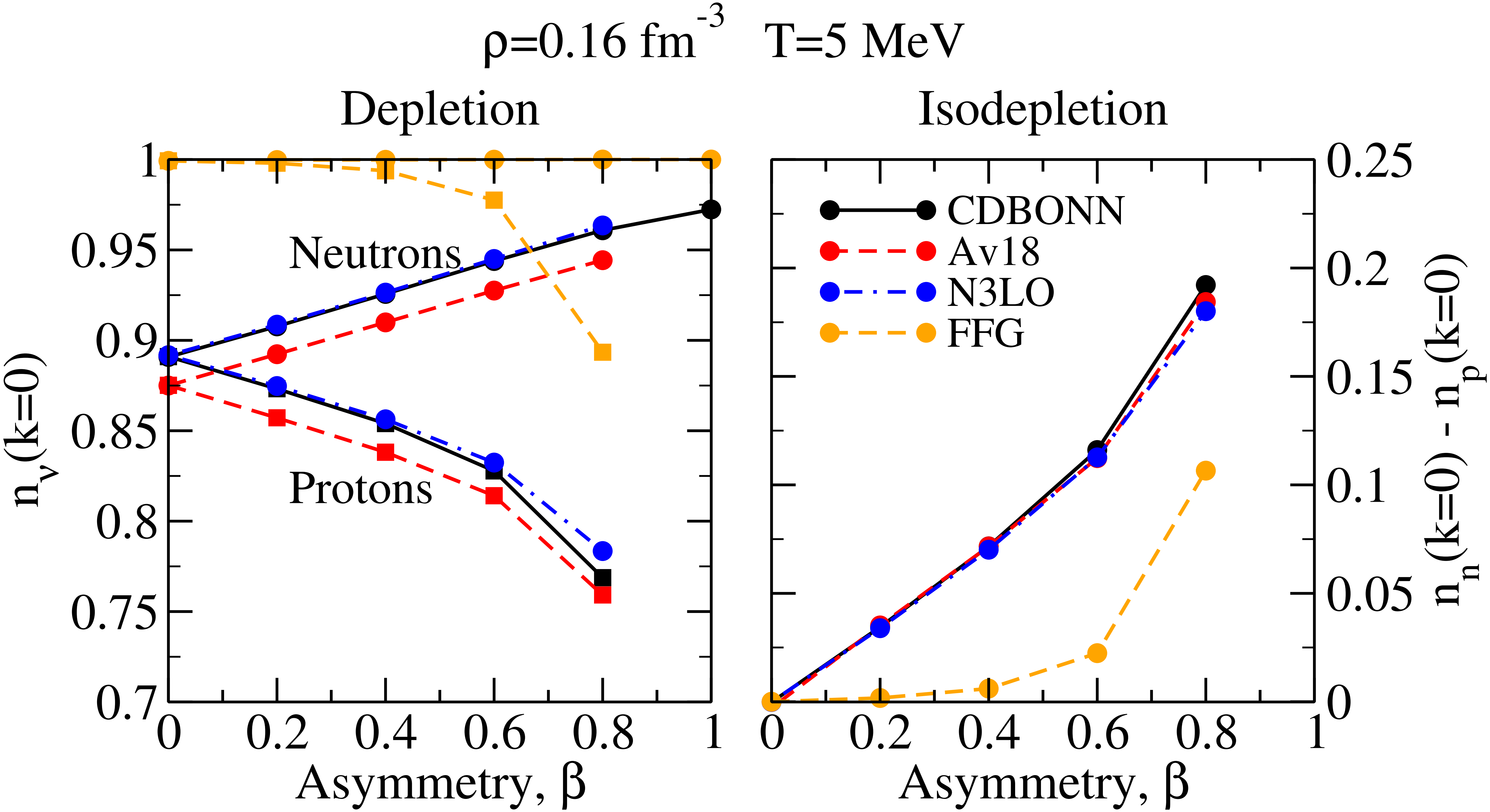
Theoretical confirmation

Asymmetric matter momentum distribution
EBHF calculation, T = 0



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

Behaviour at low momentum



- Correlations vs asymmetry

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

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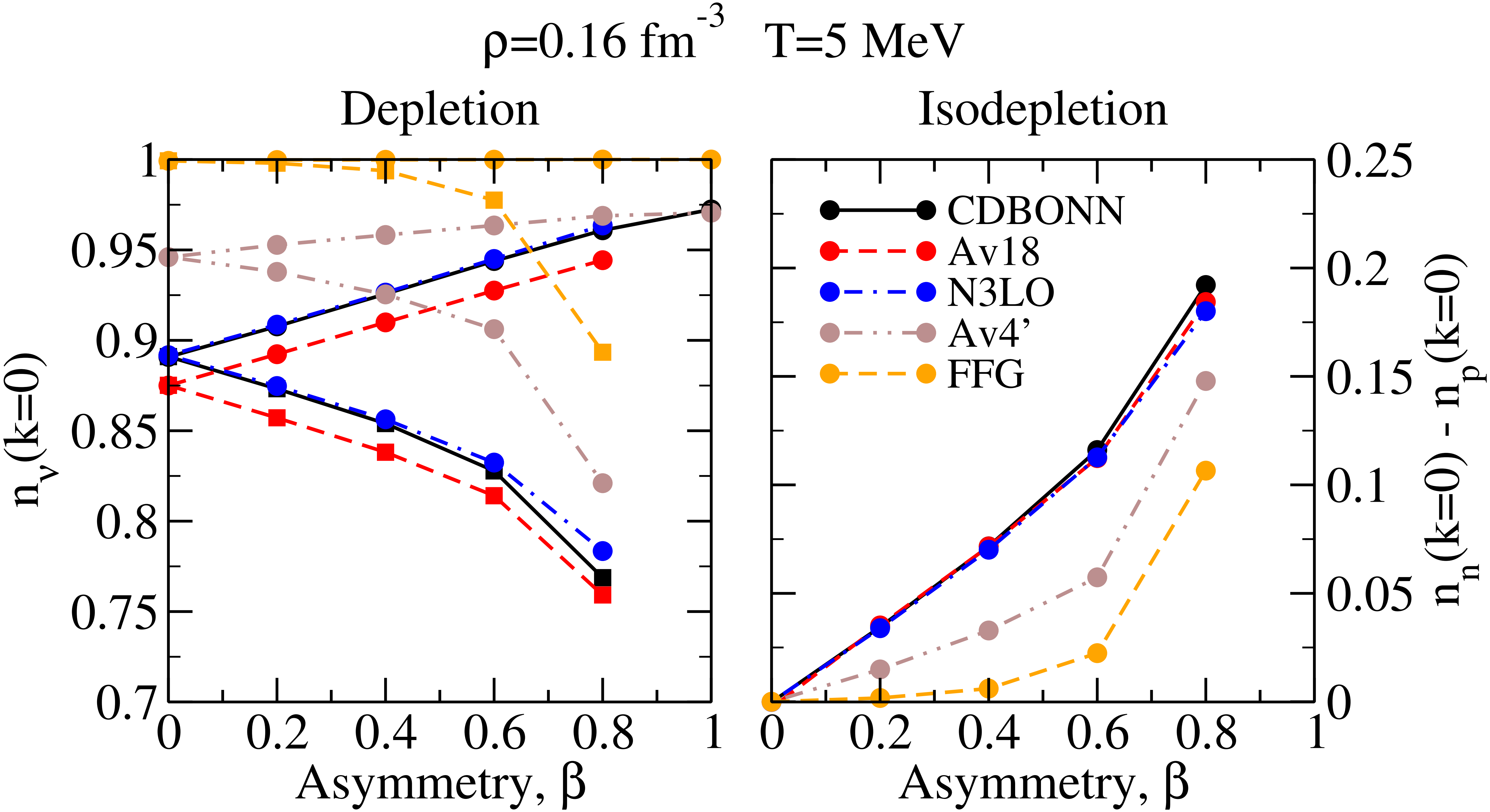
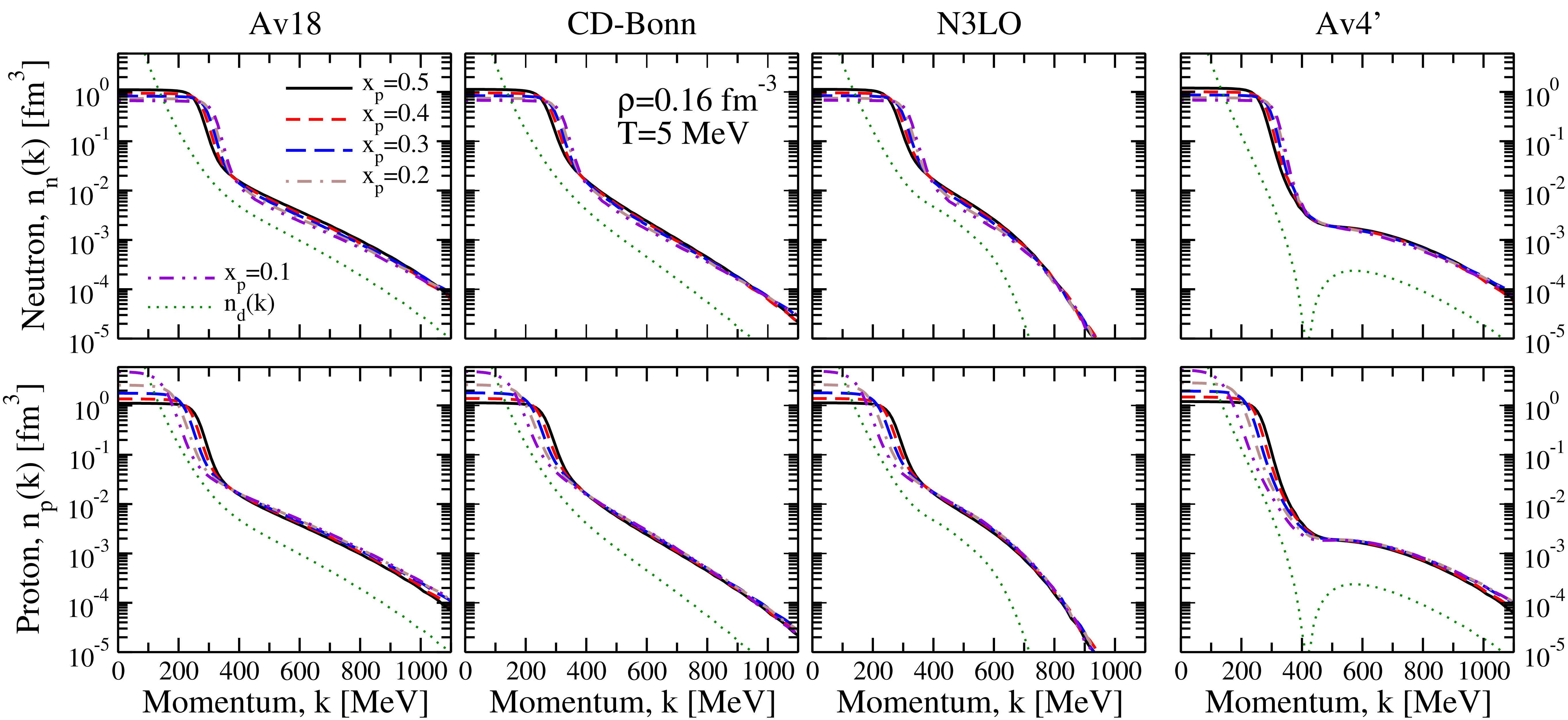


- Correlations vs asymmetry
- All potentials lie in a narrow iso-depletion band
- Tensor needed!

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)

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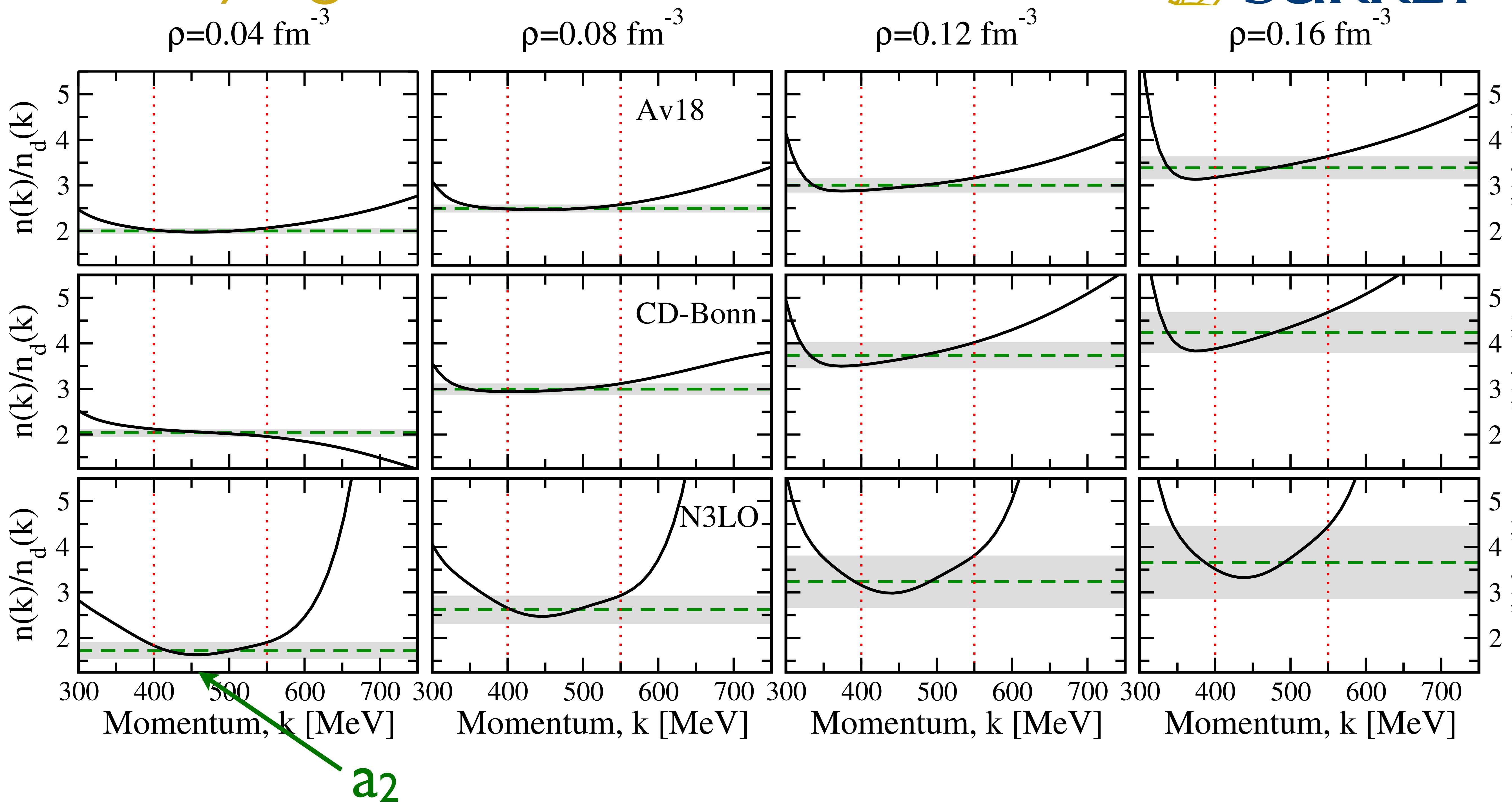

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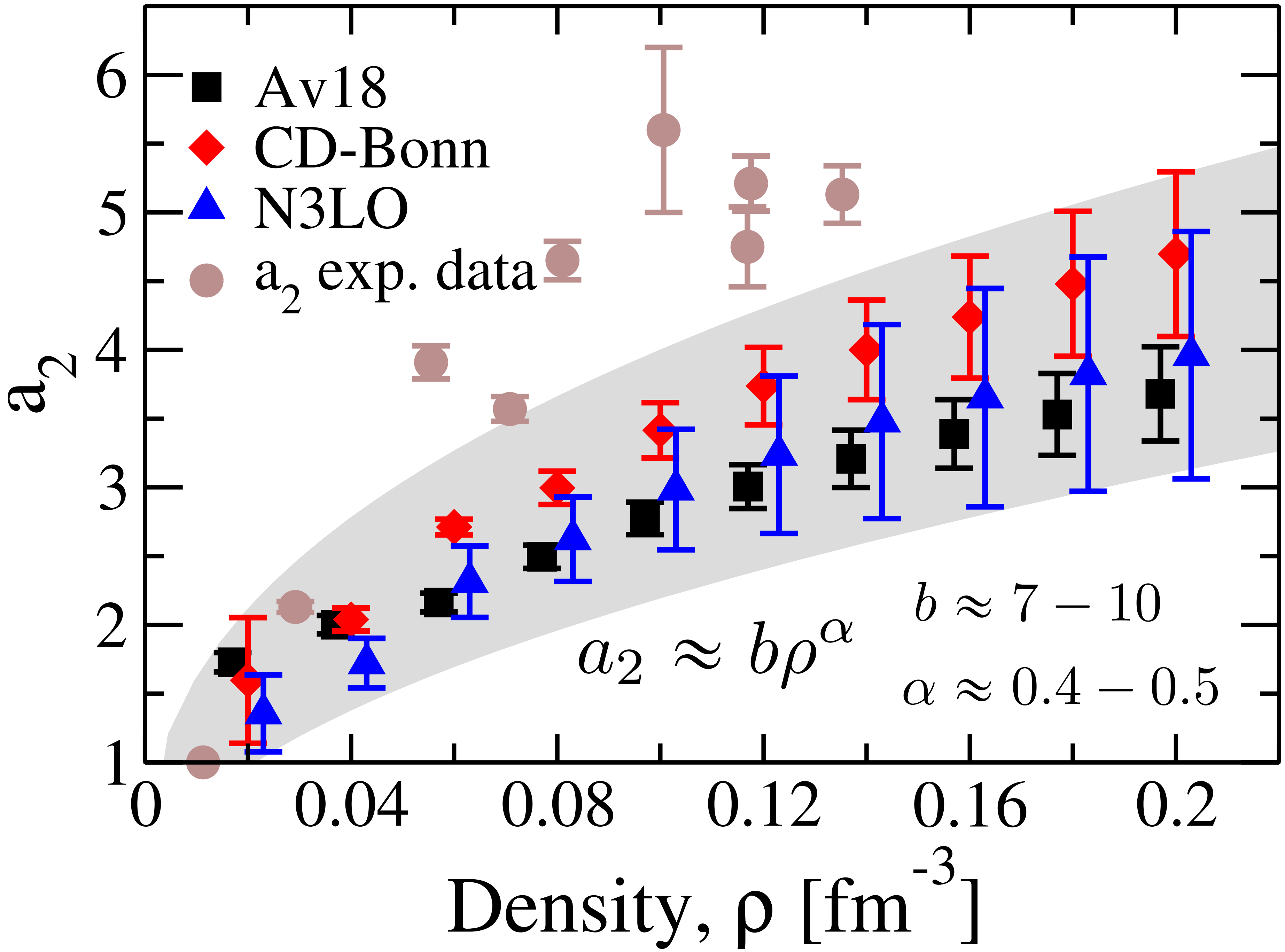

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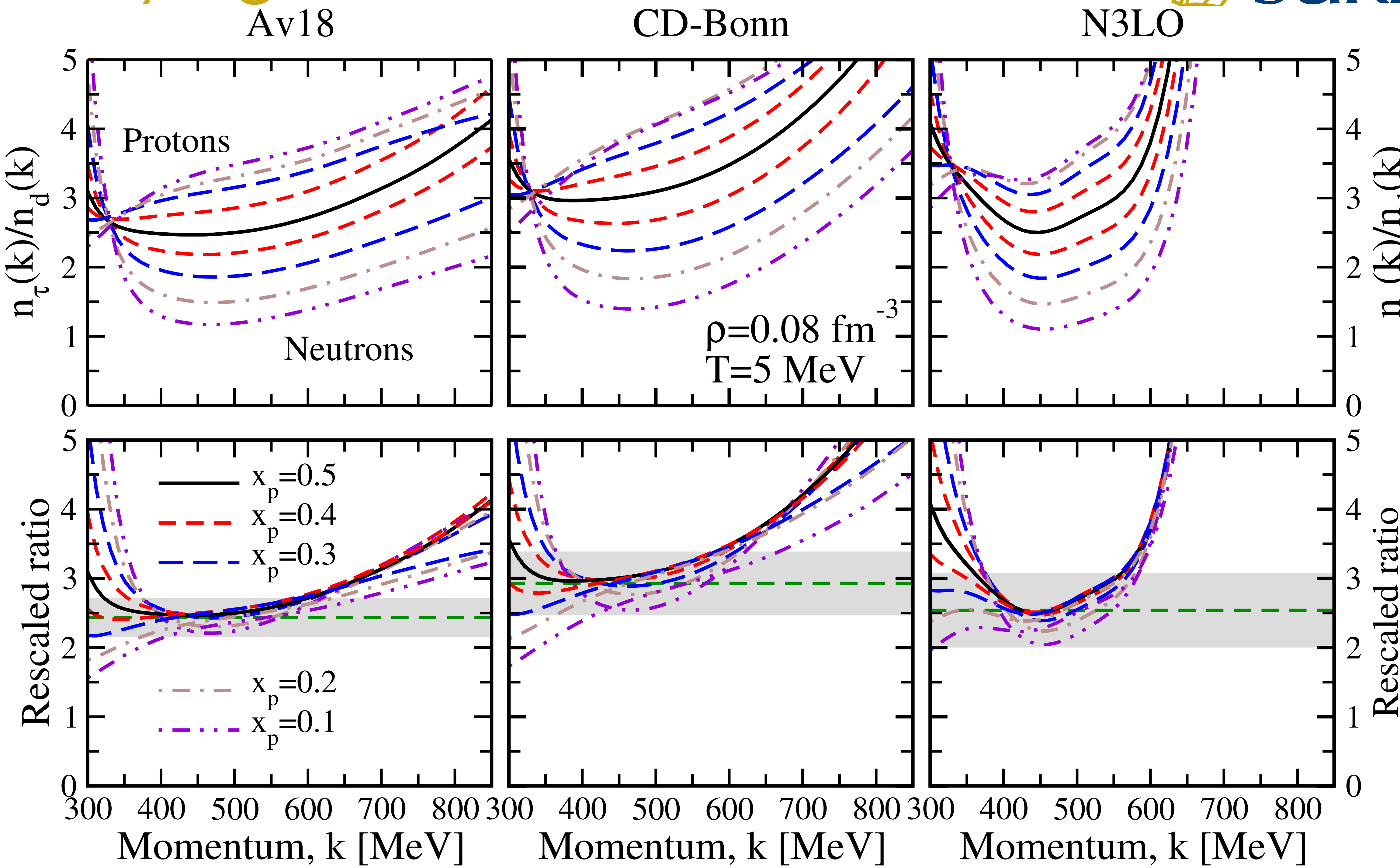
A. Rios, A. Polls & W.H. Dickhoff, PRC **89**, 044303 (2014)

Quantifying tensor-like correlations II



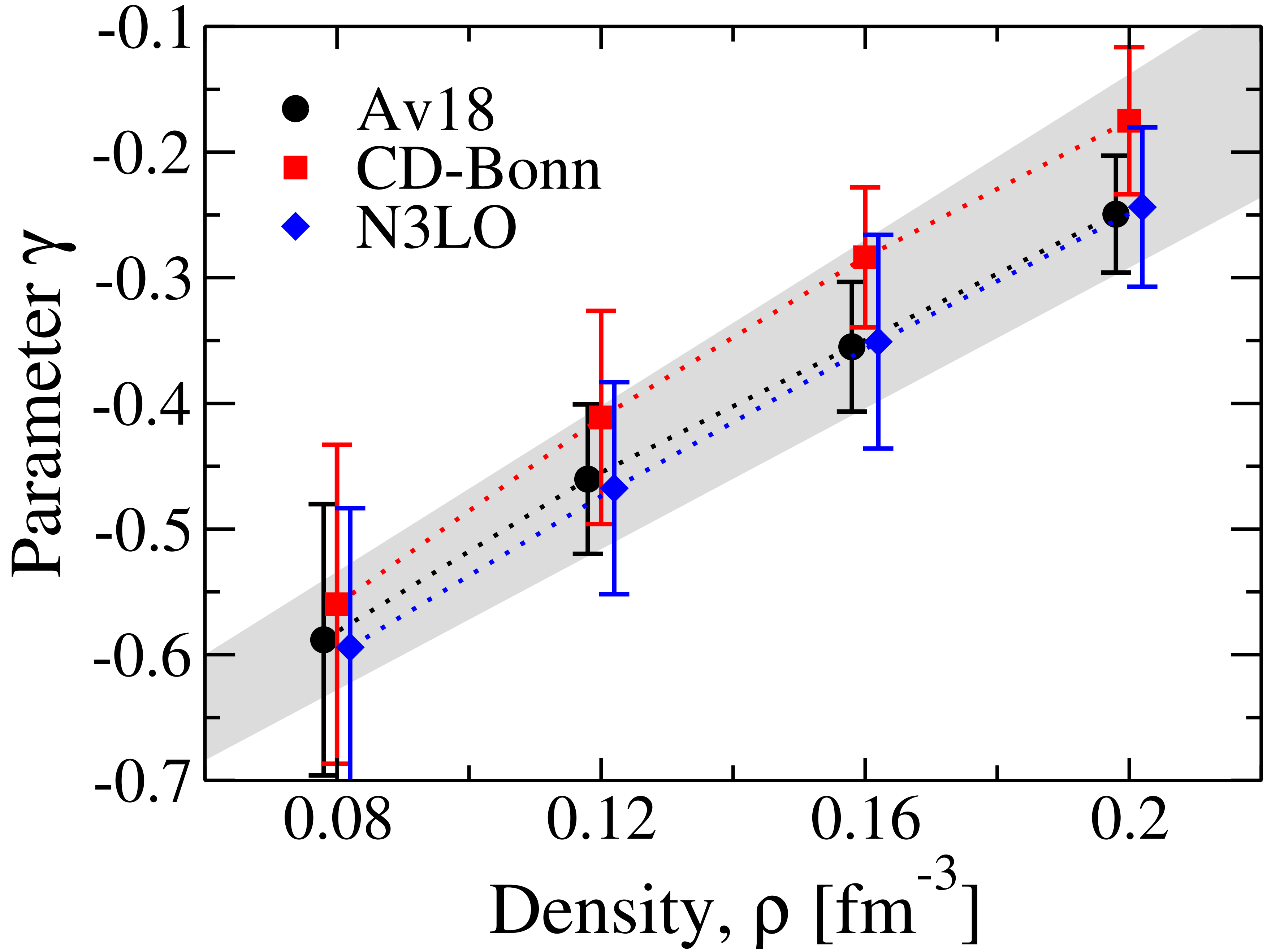
$$a_2^\tau(\rho,\beta) = a_2^\tau(\rho,0)\left[1 \mp \gamma(\rho)\beta\right]$$

Asymmetry dependence factorizes

Predicted by DFG (Lee-Yang) model $\gamma = \frac{a_{nn}^2 - 2a_{np}^2}{a_{nn}^2 + 2a_{np}^2}$

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

Quantifying tensor-like correlations II



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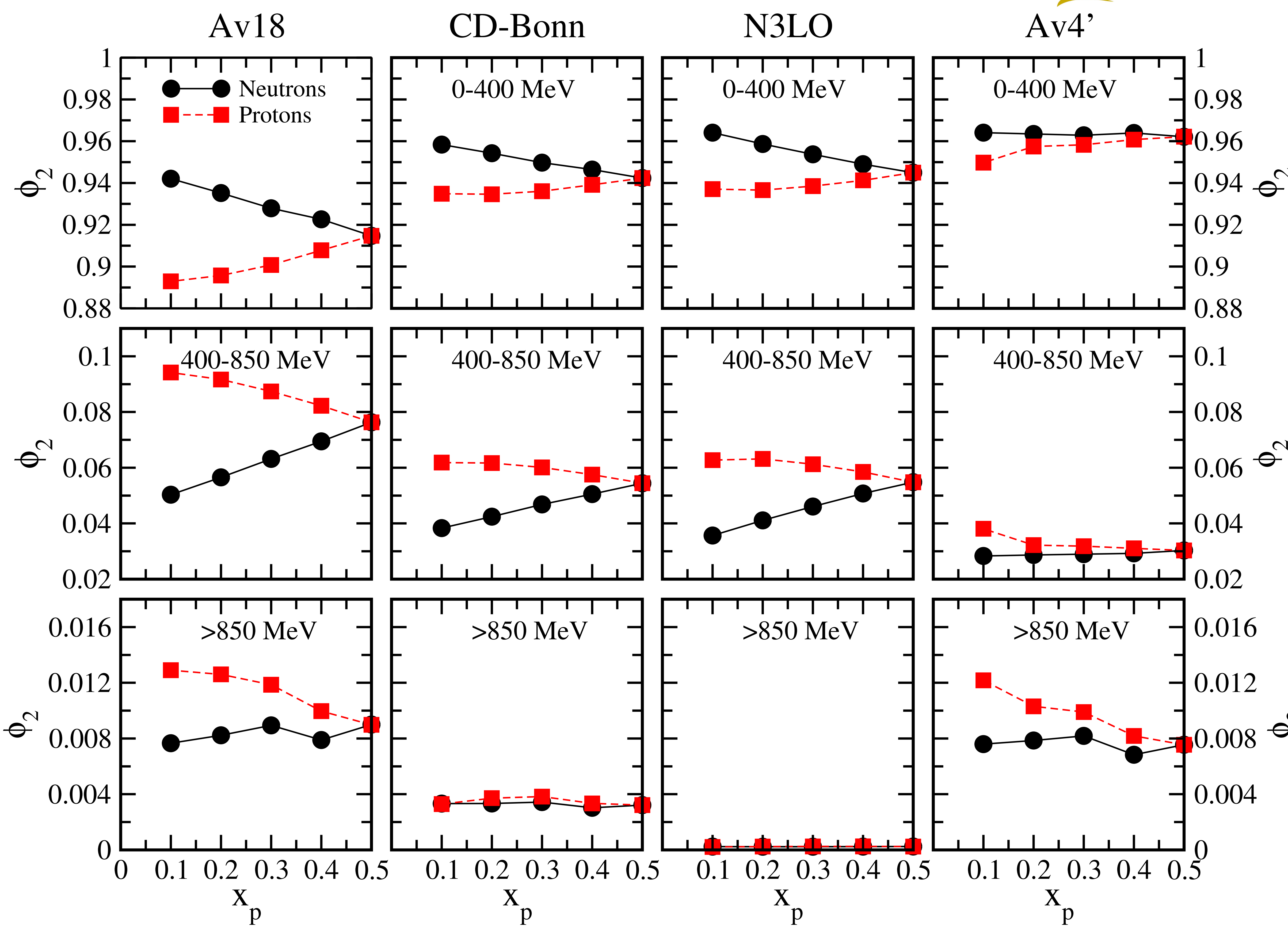
A. Rios, A. Polls & W.H. Dickhoff, PRC **89**, 044303 (2014)

Minority protons KE?



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

But are protons more energetic?

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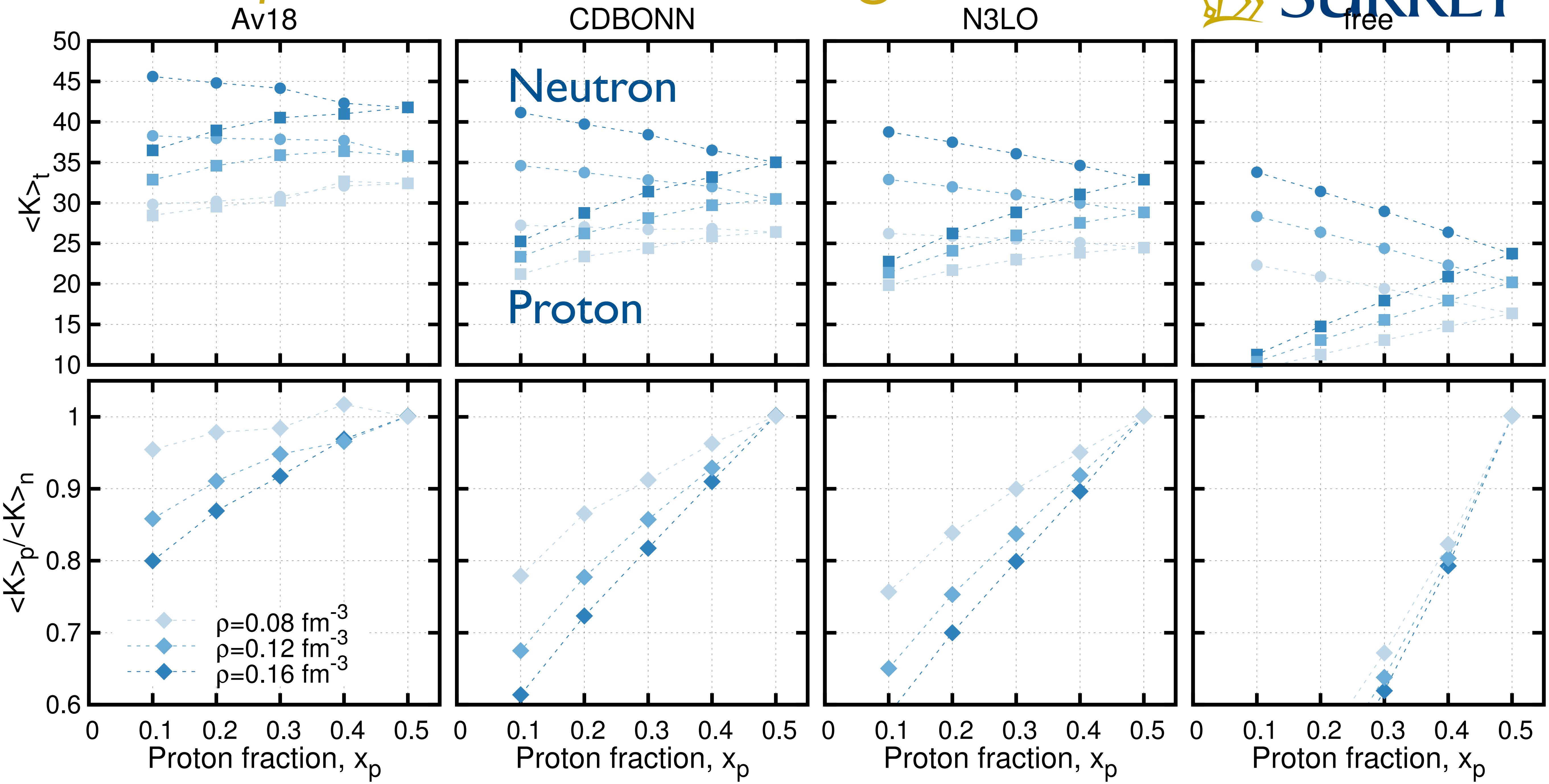

	x_p	0.5	0.4	0.3	0.2	0.1
Av18	K_n	41.8	42.3	44.2	44.8	45.6
	K_p	41.8	41.0	40.5	39.0	36.5
CD-Bonn	K_n	35.0	36.5	38.4	39.8	41.2
	K_p	35.0	33.2	31.4	28.7	25.3
N3LO	K_n	32.9	34.6	36.1	37.5	39.0
	K_p	32.9	31.1	28.8	26.2	22.7

10% effect in 208Pb

PRC **89**, 044303 (2014)

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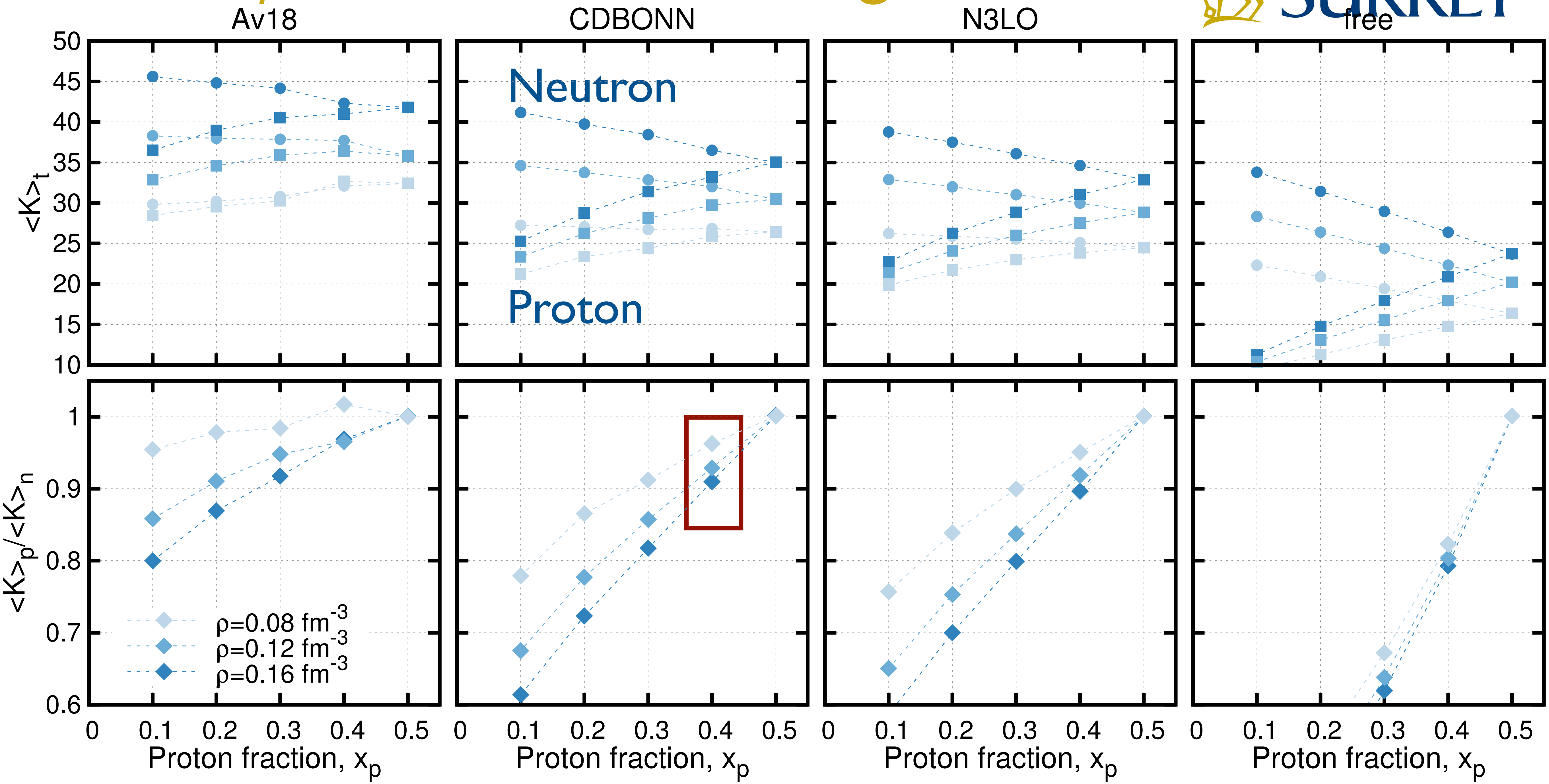

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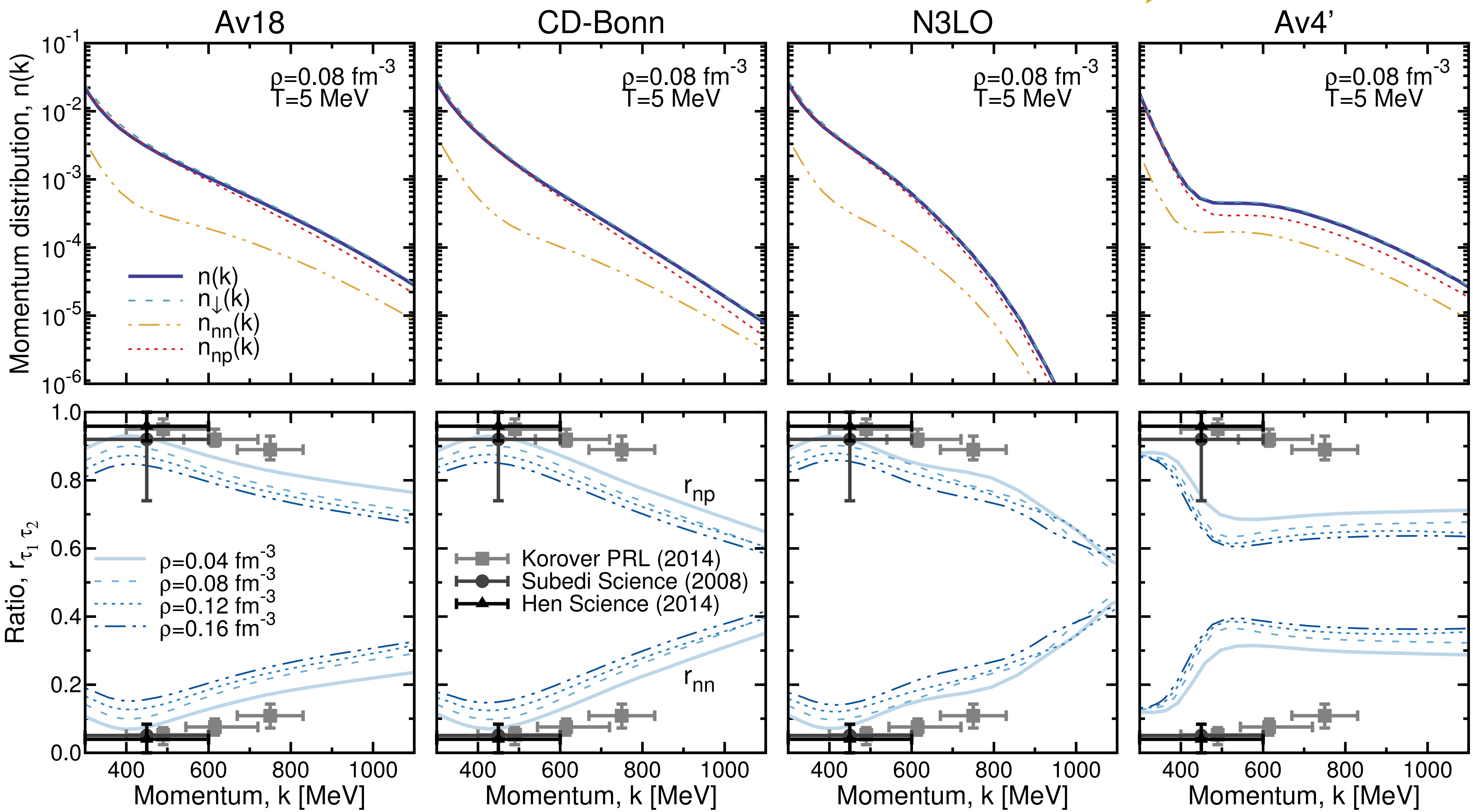
PRC **89**, 044303 (2014)

np vs nn components



$$n_{\downarrow}(k) \approx \partial_{\omega}\mathrm{Re}\Sigma_{\uparrow}(k,\omega)|_{\omega=\varepsilon(k)}$$

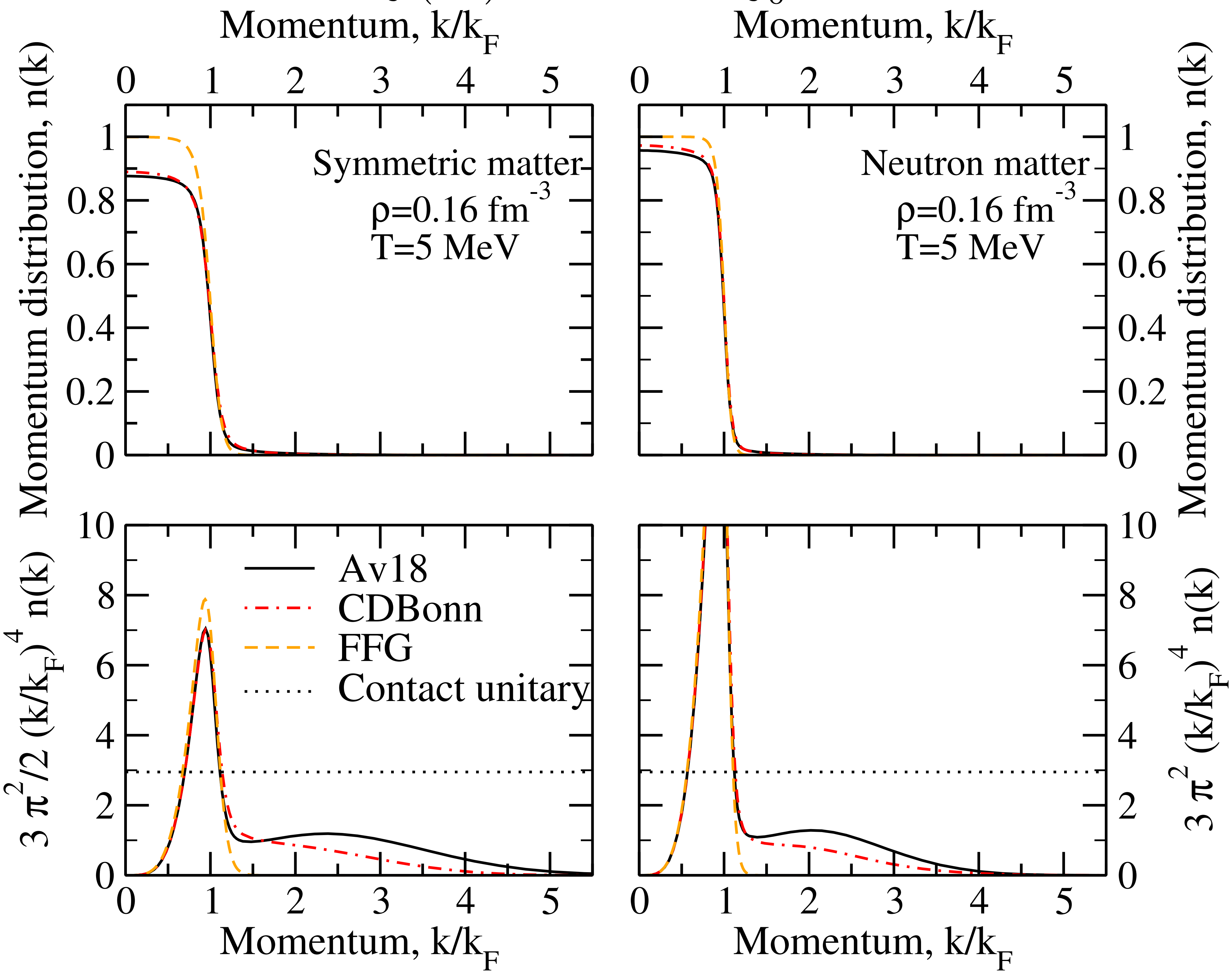
$$\mathrm{Re}\Sigma_{\uparrow}(k,\omega) = \mathrm{Re}\Sigma_{\uparrow}^{nn}(k,\omega) + \mathrm{Re}\Sigma_{\uparrow}^{np}(k,\omega)$$

$$r_{\tau_1\tau_2} = \frac{n_{\tau_1\tau_2}(k)}{n(k)}$$

A. Rios, in preparation

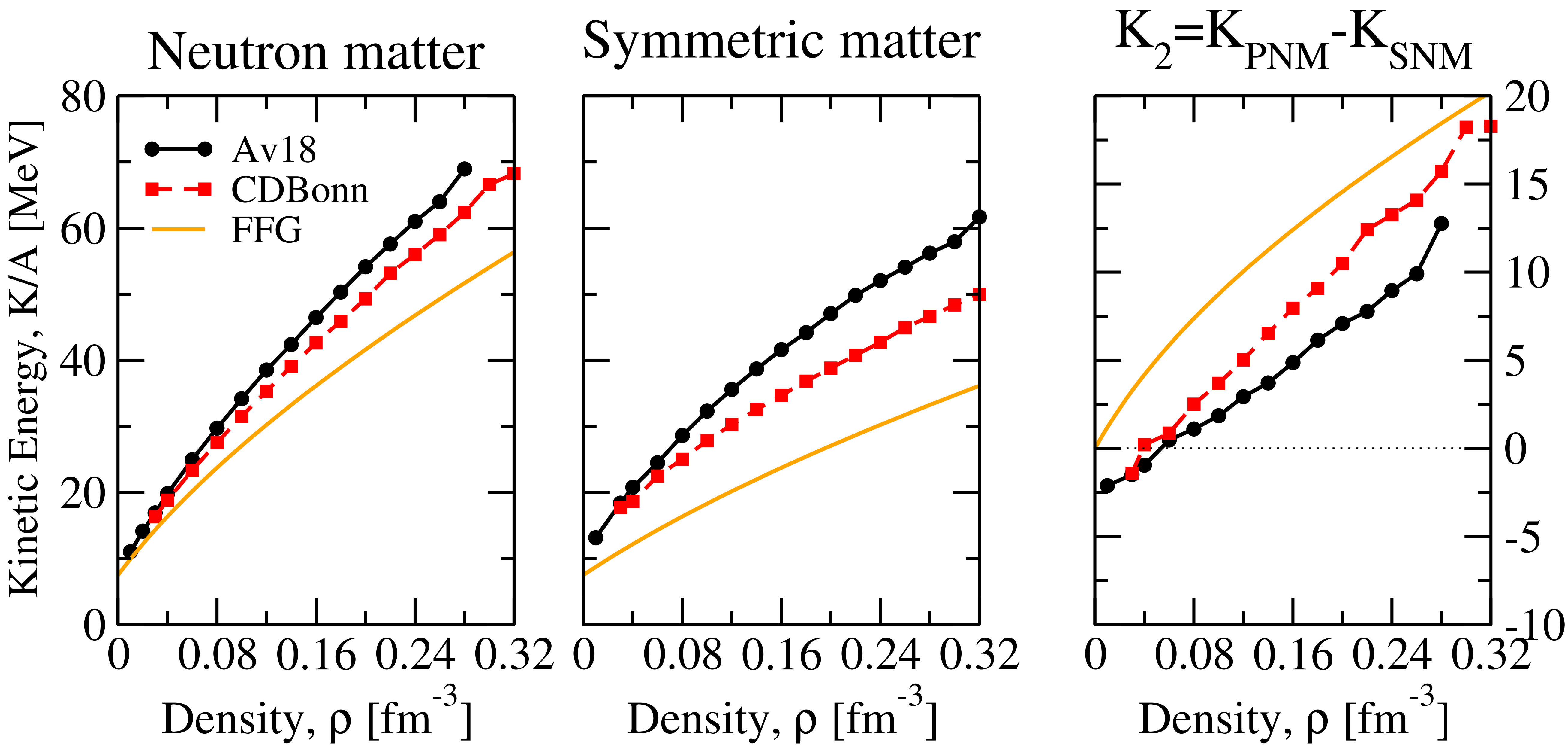
Kinetic symmetry energy I

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



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

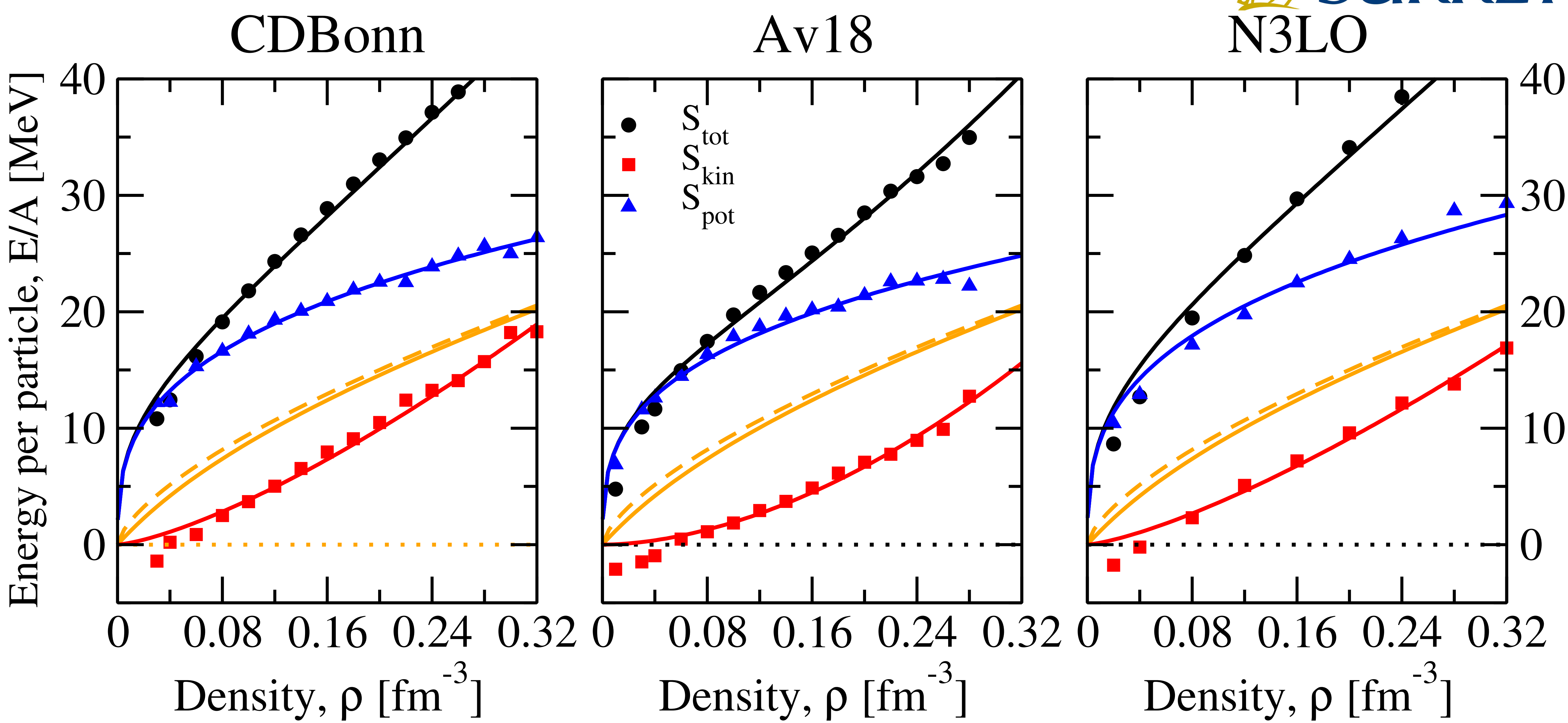
Symmetry energy consequences



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

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

Symmetry energy



$$S(\rho) = S_k \left(\frac{\rho}{\rho_0}\right)^{\alpha} + S_p \left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

S_k=4.5 - 7.5 MeV α=1.3 - 1.8

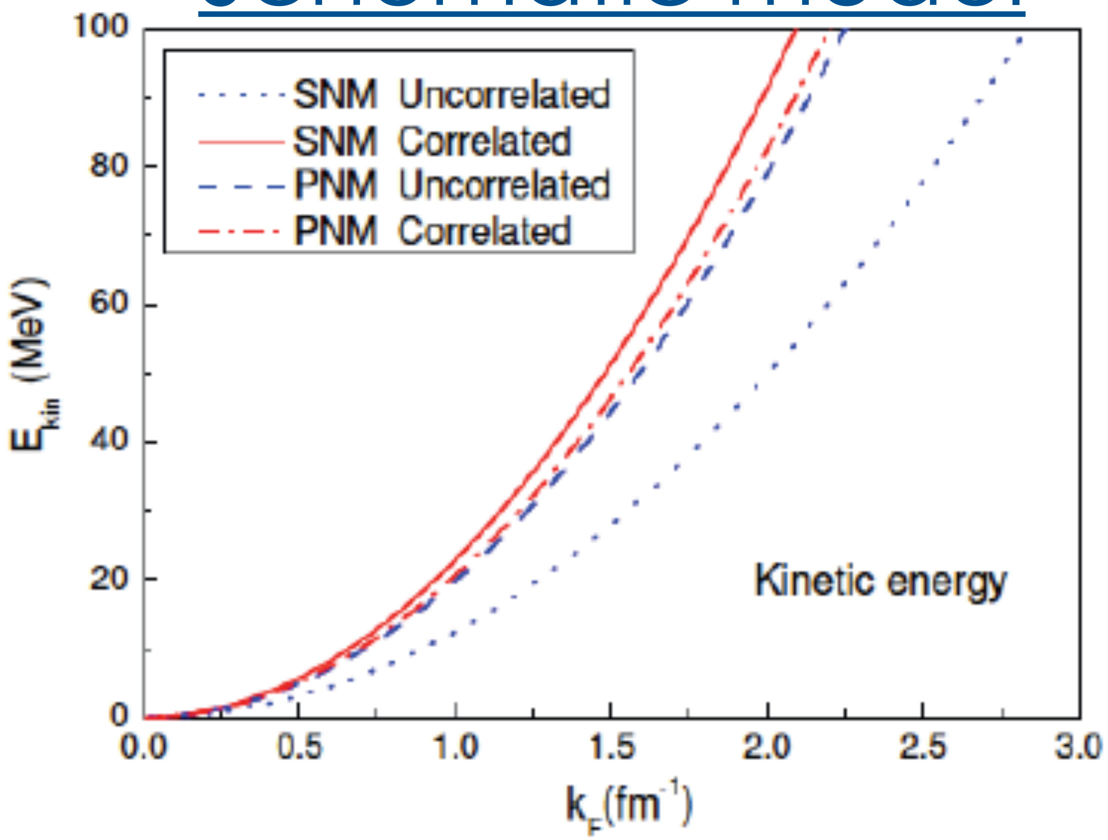
S_p=20 - 22.5 MeV γ=0.33

- Arbitrary / non-observable separation of energies
- Implications for observables? See **Or's** and **Bao-An**'s talk

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

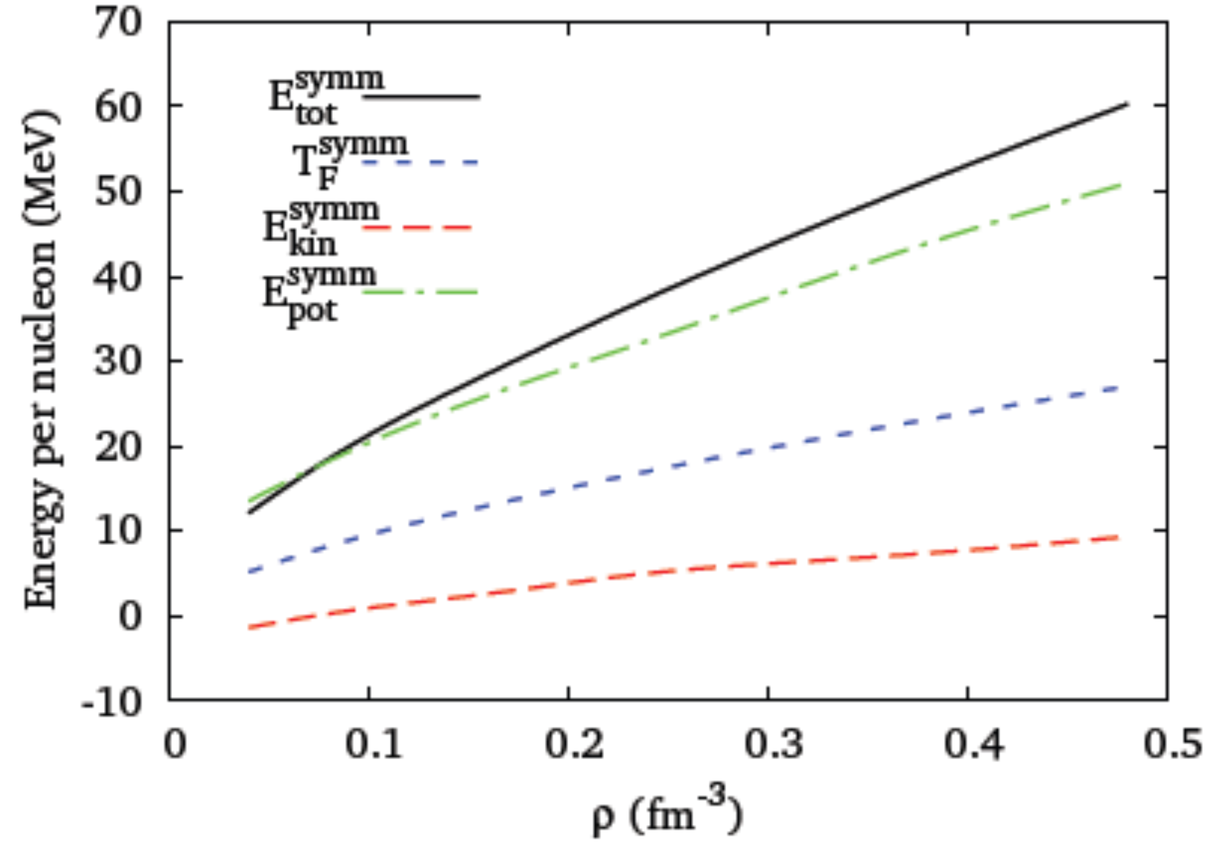
Confirmed by other approaches

Schematic model

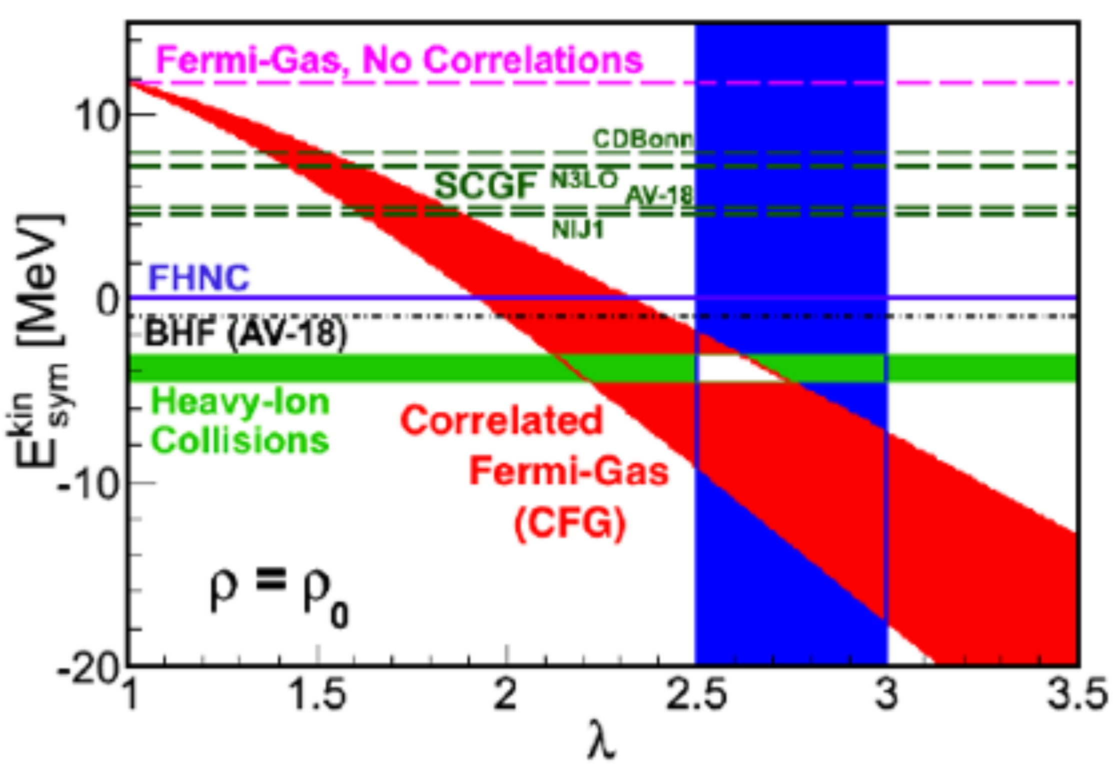


Xu & Li, arxiv:1104.2075

FHNC



A. Lovato, private communication



Hen et al., arxiv:1408.0772

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

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)

Comparison to phenomenology

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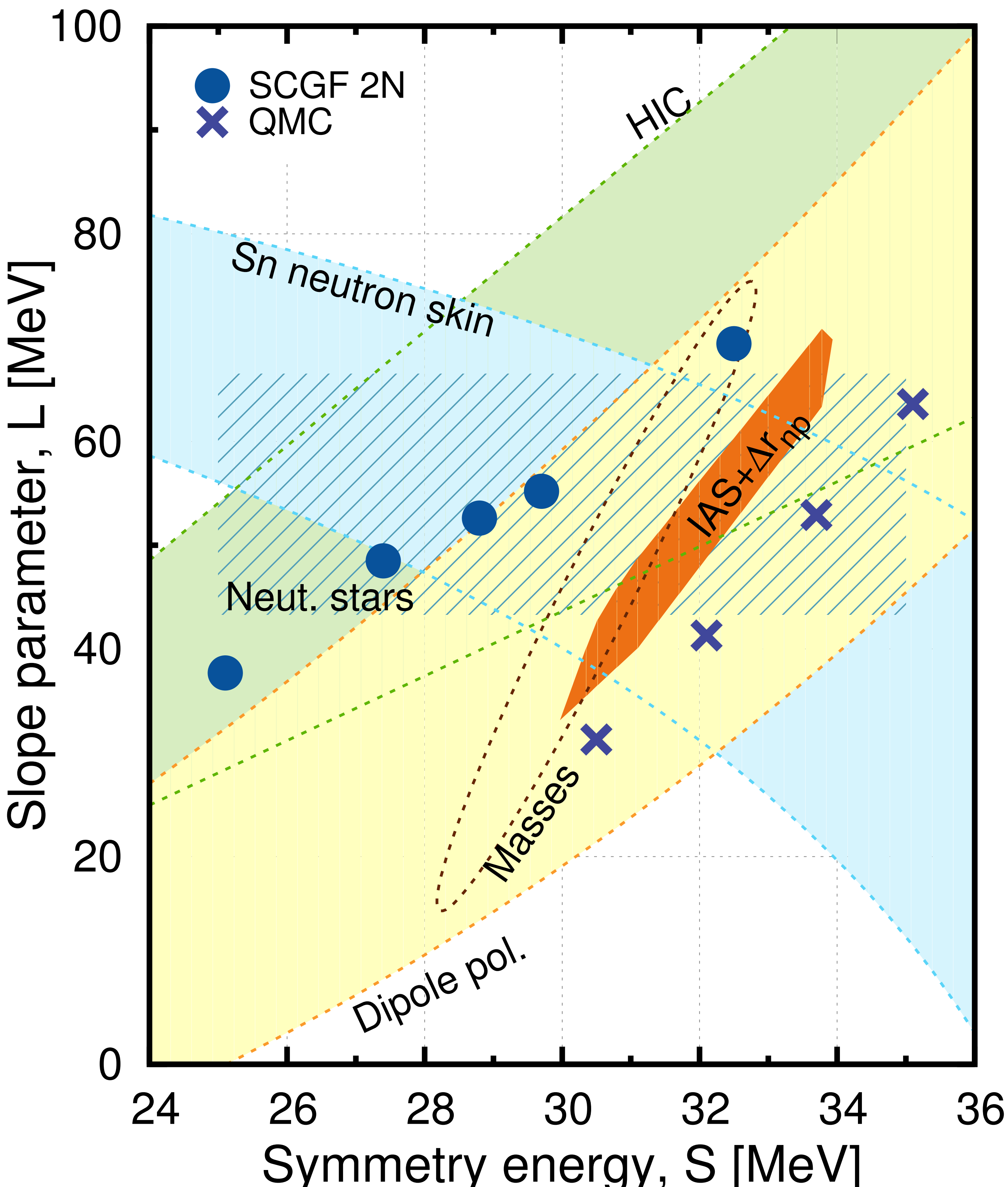
Experimental constrains



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

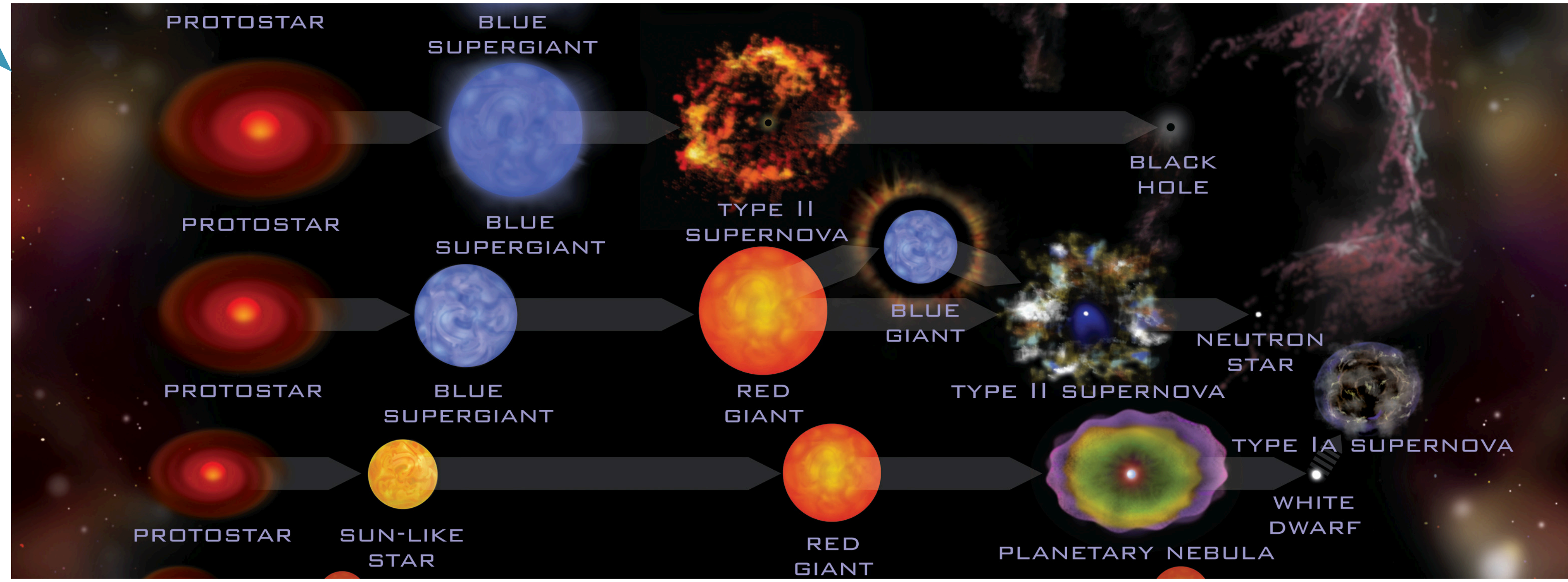
What is a neutron star?

Progenitor mass

25-50 $M_\odot$

8-25 $M_\odot$

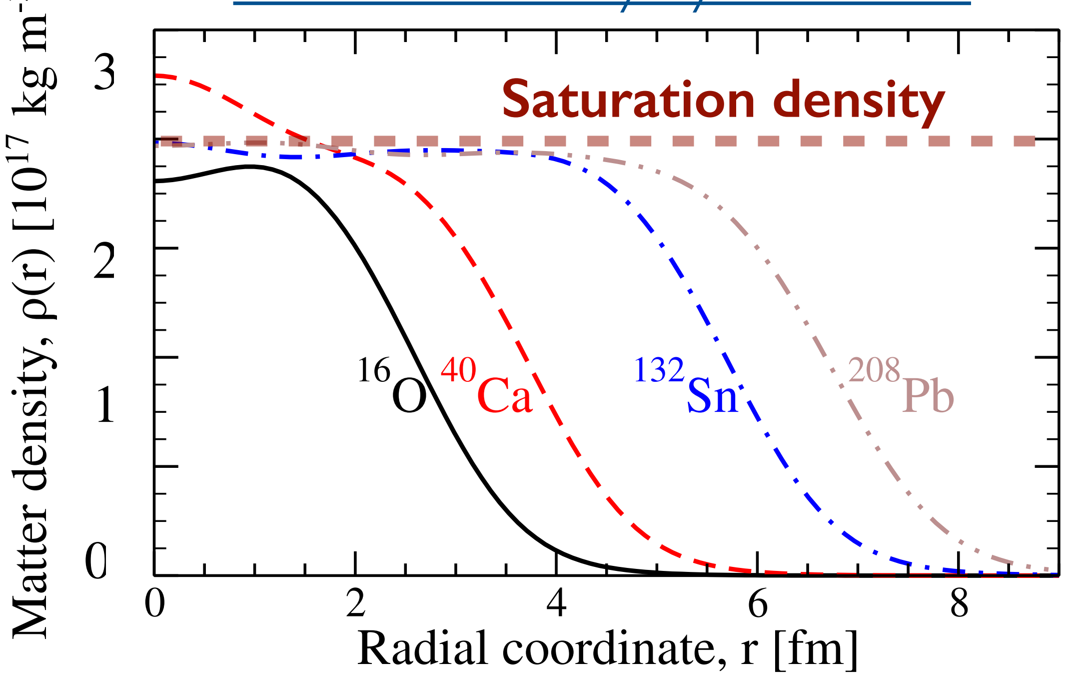
0.4-8 $M_\odot$

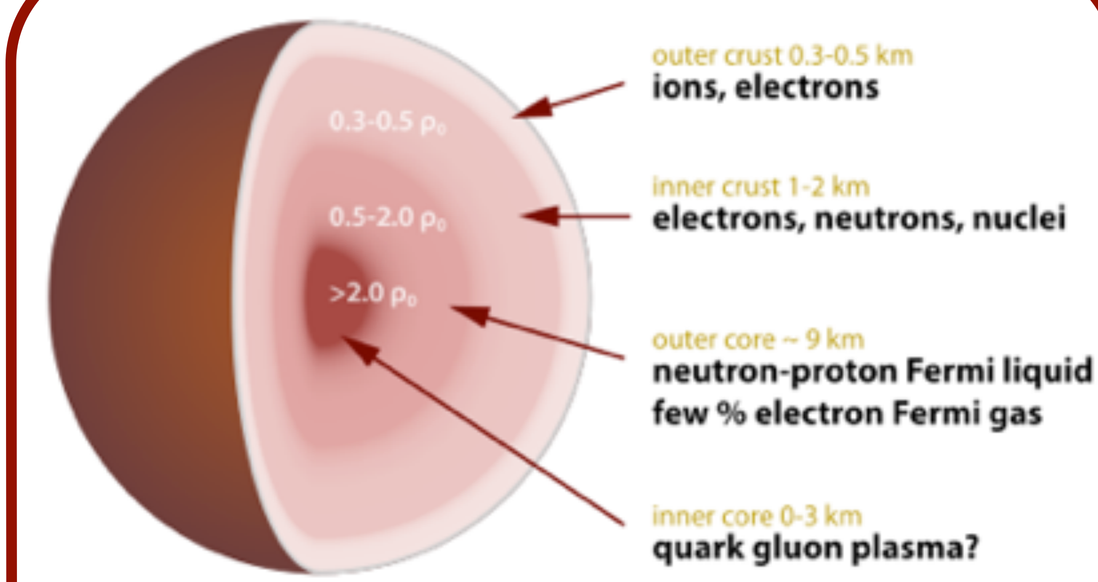


Mass $$M \sim 1.5 M_\odot = 3 \times 10^{30}\ \mathrm{kg}$$

Mass density $$\rho = \frac{M}{V} \approx 7.5 \times 10^{17}\ \mathrm{kg\ m^{-3}}$$

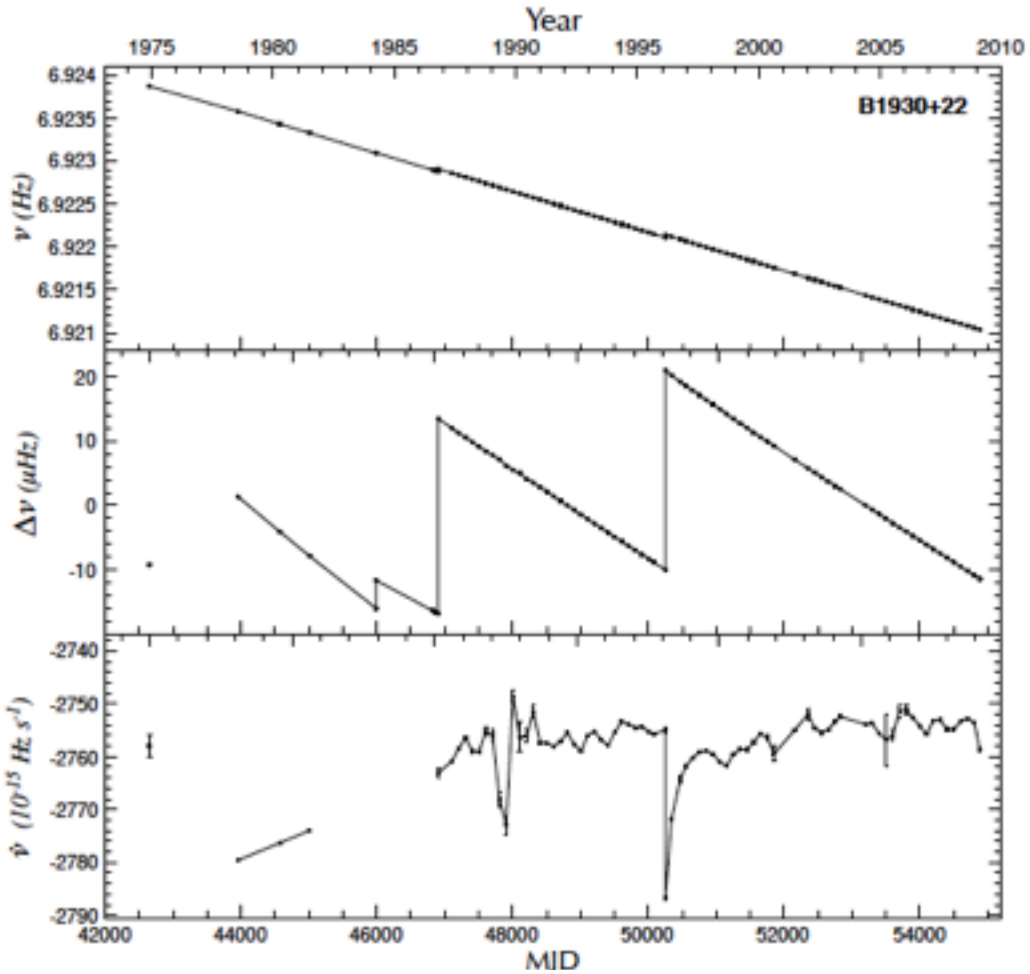
Nuclear density systematics



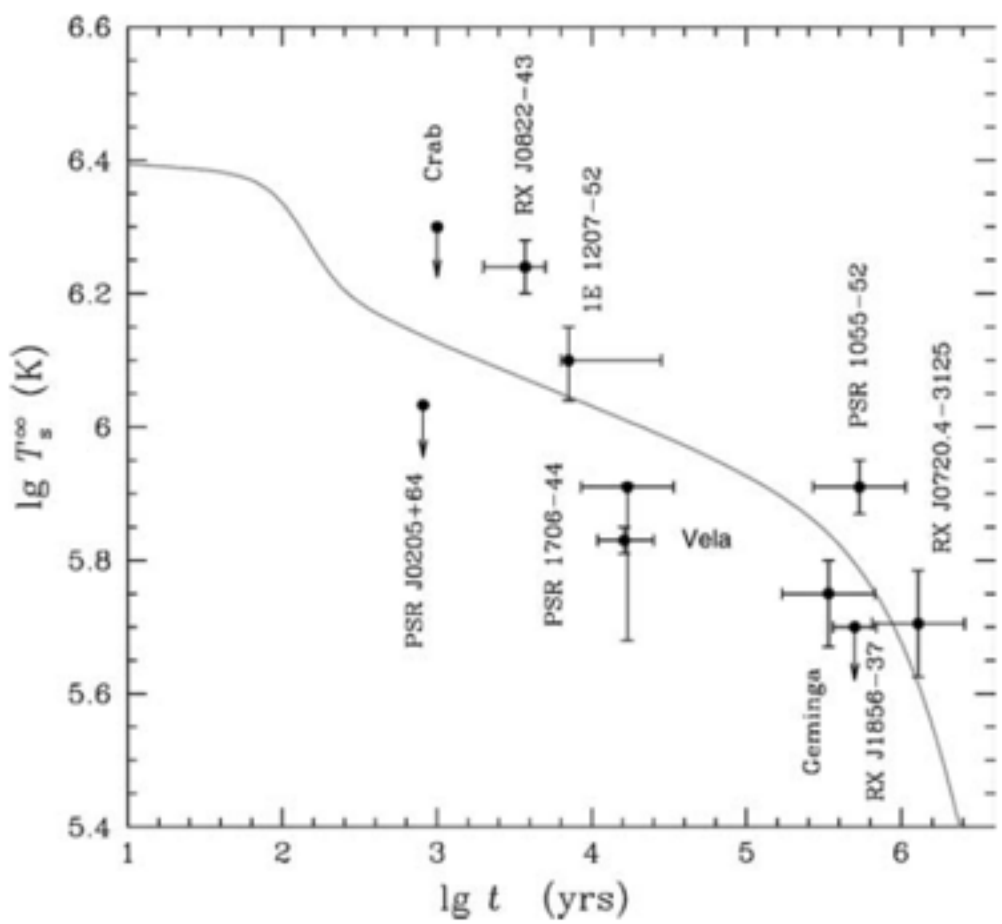


R~10 km

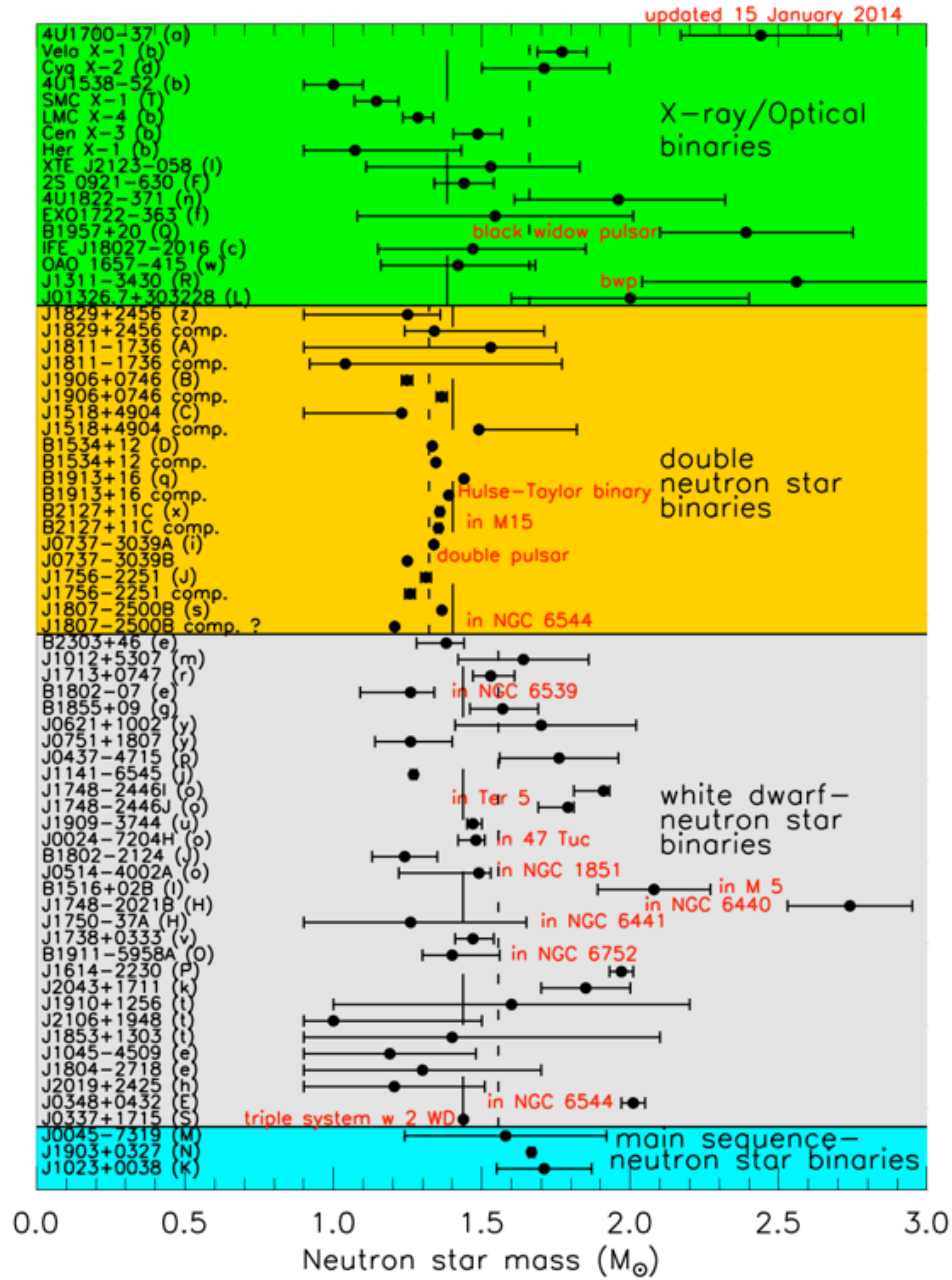
NS data!



Year
1975 1980 1985 1990 1995 2000 2005 2010
B1930+22
ν (Hz)
6.924 6.9235 6.923 6.9225 6.922 6.9215 6.921
$\Delta\nu$ (μHz)
20 10 0 -10
$\dot{\nu}$ (10^{-15} Hz s^{-1})
-2740 -2750 -2760 -2770 -2780 -2790
42000 44000 46000 48000 50000 52000 54000
MJD



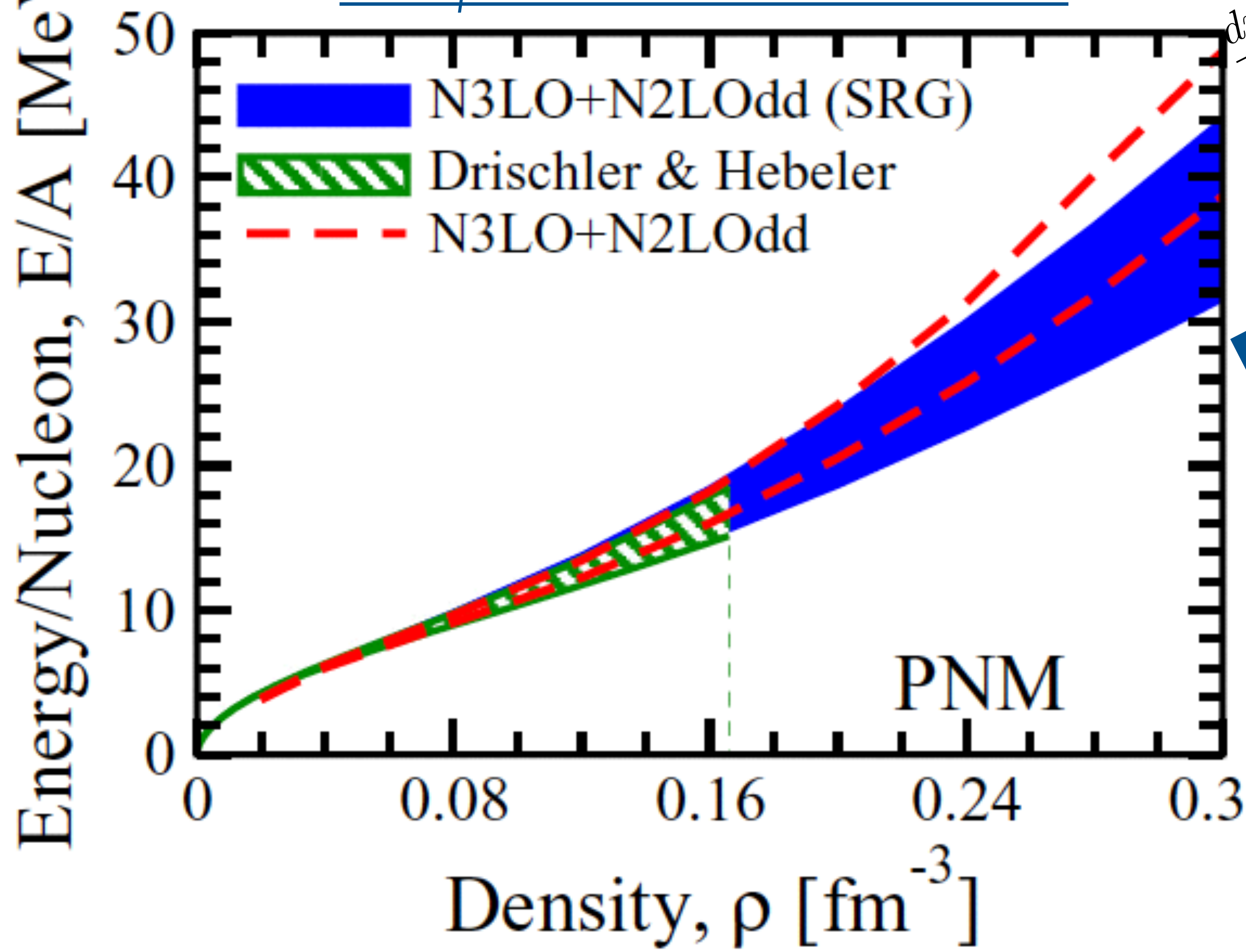
lg T_s^∞ (K)
6.6 6.4 6.2 6 5.8 5.6 5.4
1 2 3 4 5 6
lg t (yrs)
Crab
RX J0822-43
1E 1207-52
PSR J0205+64
PSR 1706-44
Vela
PSR 1055-52
RX J0720.4-3125
Geminga
RX J1856-37



updated 15 January 2014
4U1700-37 (a)
Vela X-1 (b)
Cyg X-2 (d)
4U1538-52 (b)
SMC X-1 (T)
LMC X-4 (b)
Cen X-3 (b)
Her X-1 (b)
XTE J2123-058 (l)
2S 0921-630 (F)
4U1822-371 (n)
EXO1722-363 (f)
B1957+20 (Q)
IFE J18027-2016 (c)
OAO 1657-415 (w)
J1311-3430 (R)
J01326.7+303228 (L)
X-ray/Optical binaries
black widow pulsar
bwp
J1829+2456 (z)
J1829+2456 comp.
J1811-1736 (A)
J1811-1736 comp.
J1906+0746 (B)
J1906+0746 comp.
J1518+4904 (C)
J1518+4904 comp.
B1534+12 (D)
B1534+12 comp.
B1913+16 (q)
B1913+16 comp.
B2127+11C (x)
B2127+11C comp.
J0737-3039A (i)
J0737-3039B
J1756-2251 (J)
J1756-2251 comp.
J1807-2500B (s)
J1807-2500B comp. ?
double neutron star binaries
Hulse-Taylor binary
in M15
double pulsar
in NGC 6544
B2303+46 (e)
J1012+5307 (m)
J1713+0747 (r)
B1802-07 (e)
B1855+09 (g)
J0621+1002 (y)
J0751+1807 (y)
J0437-4715 (p)
J1141-6545 (j)
J1748-2446I (o)
J1748-2446J (o)
J1909-3744 (u)
J0024-7204H (o)
B1802-2124 (J)
J0514-4002A (o)
B1516+02B (I)
J1748-2021B (H)
J1750-37A (H)
J1738+0333 (v)
B1911-5958A (O)
J1614-2230 (P)
J2043+1711 (k)
J1910+1256 (t)
J2106+1948 (t)
J1853+1303 (t)
J1045-4509 (e)
J1804-2718 (e)
J2019+2425 (h)
J0348+0432 (E)
J0337+1715 (S)
in NGC 6539
in Ter 5
in 47 Tuc
in NGC 1851
in M 5
in NGC 6440
in NGC 6441
in NGC 6752
in NGC 6544
triple system w 2 WD
white dwarf-neutron star binaries
J0045-7319 (M)
J1903+0327 (N)
J1023+0038 (K)
main sequence-neutron star binaries
0.0 0.5 1.0 1.5 2.0 2.5 3.0
Neutron star mass ($M_\odot$)

Neutron matter

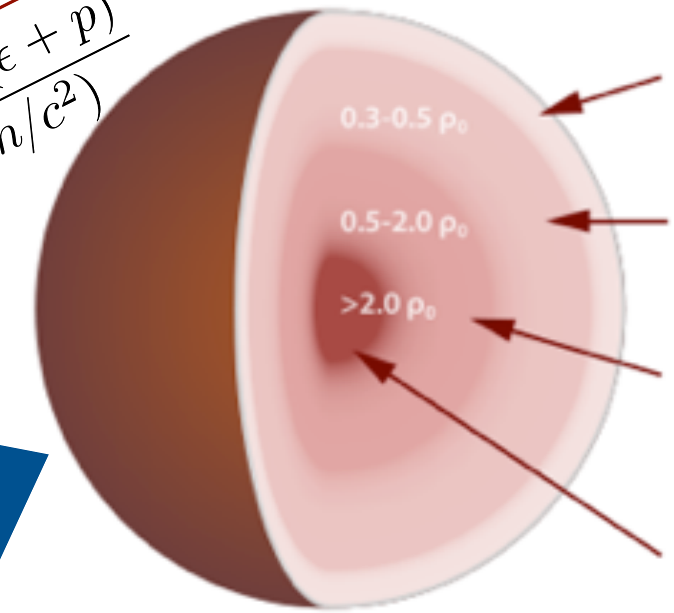
EoS for neutron matter: SRG

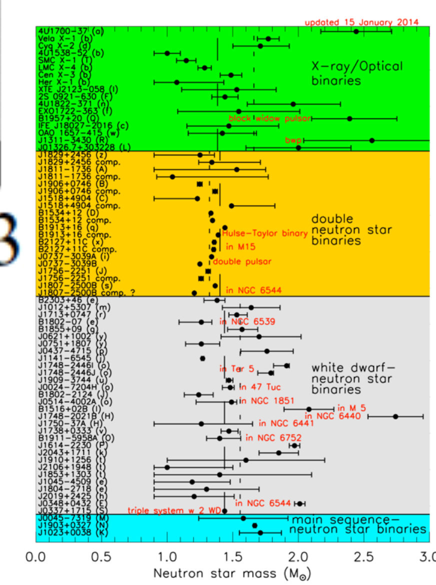


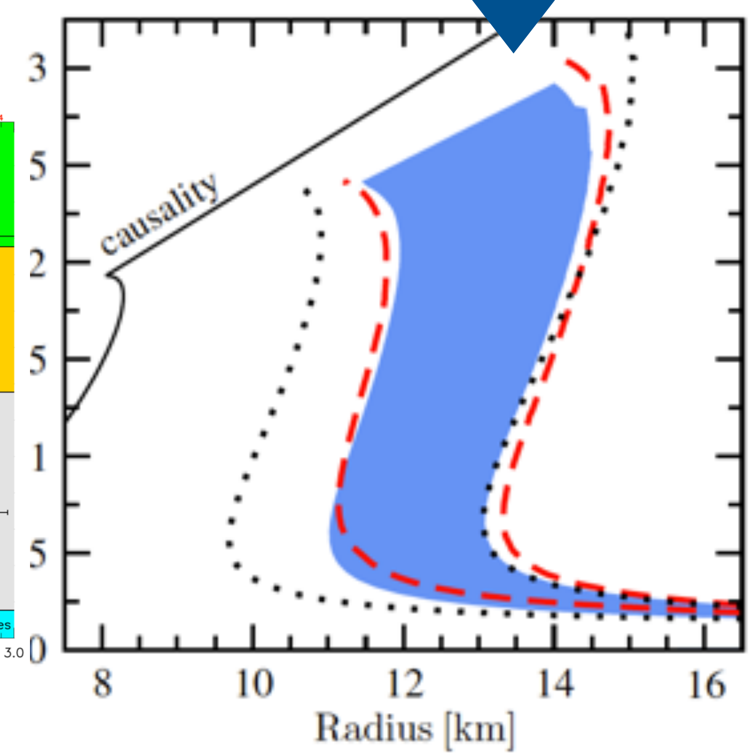
Tolman-Oppenheimer-Volkov

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m + 4\pi p r^3)(\epsilon + p)}{r(r - 2Gm/c^2)}$$

$$\frac{dm}{dr} = \frac{4\pi}{c^2}\epsilon r^2$$







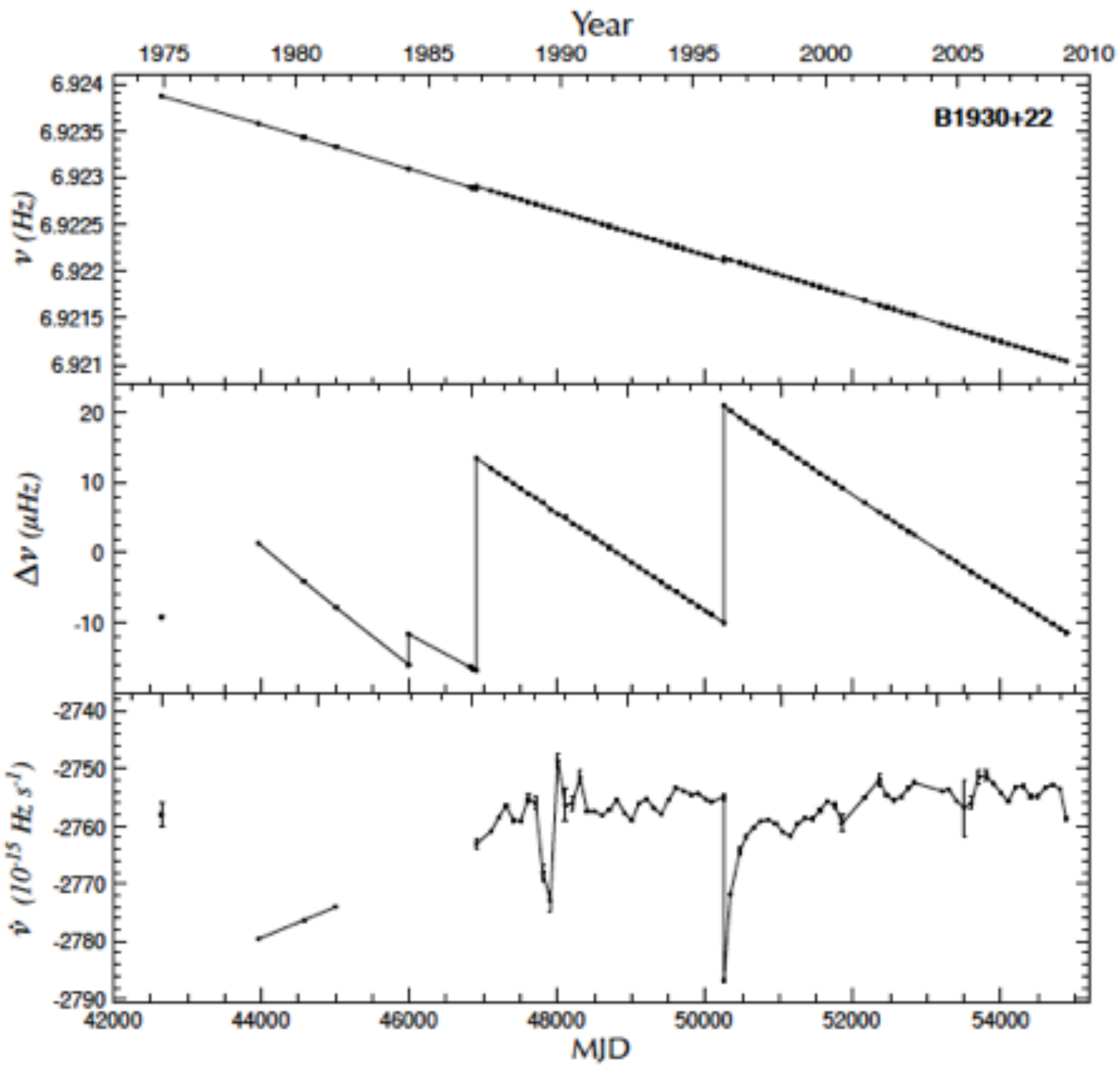
Hebeler, Lattimer, Pethick, Schwenk
ApJ **773** 11 (2013)

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

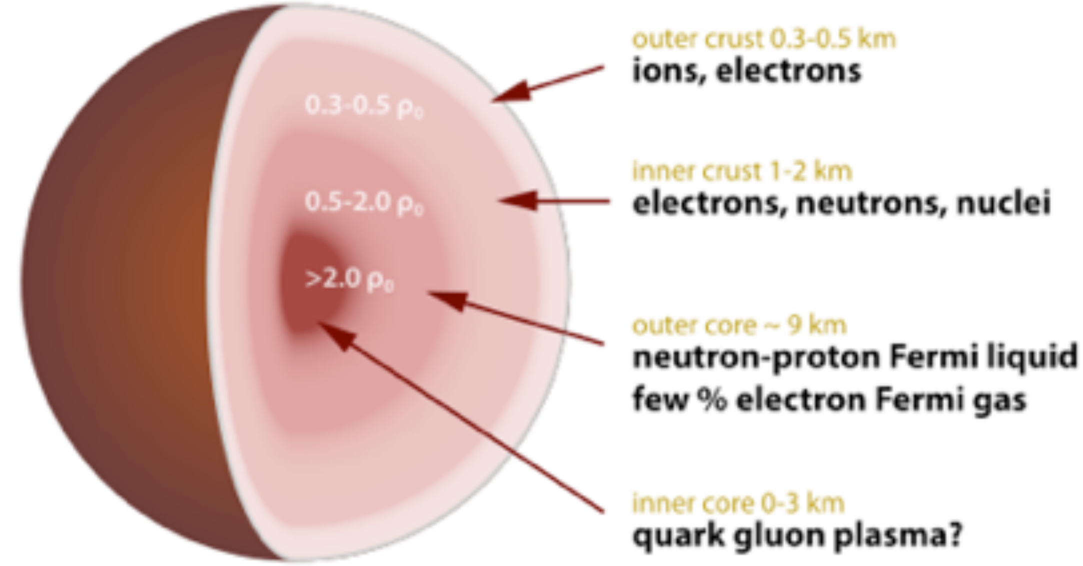
Schwenk talk, Arianna's talk tomorrow!

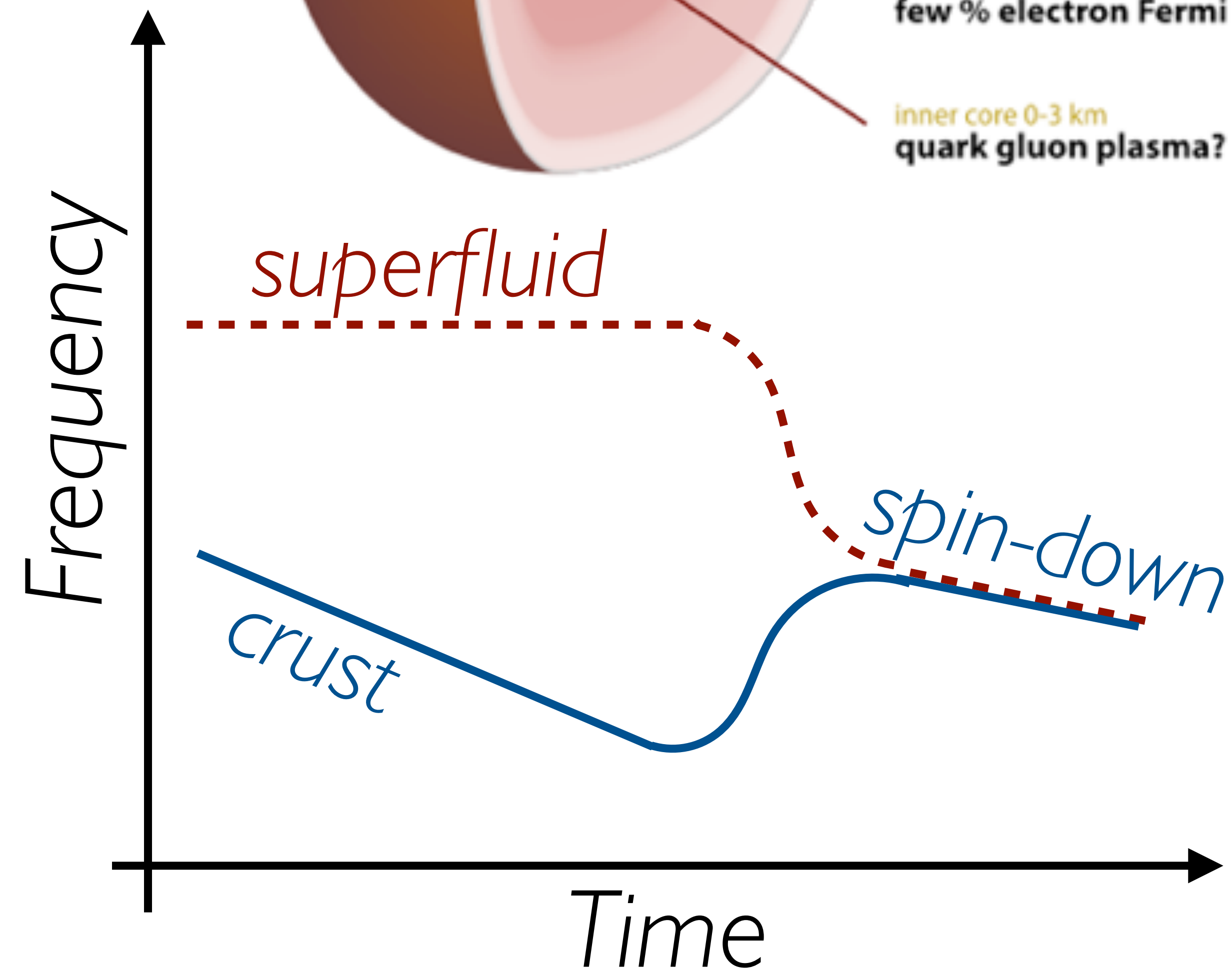
Carbone, Polls & Rios, *PRC* **90** 054322 (2014); A. Carbone, PhD thesis

Pulsar glitches



Espinoza, Lyne, Stappers & Kramer
MNRAS **414** 1679 (2011)





- **Crystalline** crust + dripped neutron **superfluid**
- Crust **slows down** due to magnetic braking
- **Superfluid** can only spin if **vortices** move out
- If vortices are **pinned** to nuclear lattice, they experience a time lag
- At some critical **pile-up**, a lot of vortices are **released** and crust spins up

Haskell & Melatos, *Int. J. Mod. Phys. D* 1530008 (2015); *arxiv:1502.07062*

Superfluid in the core

RESEARCH ARTICLE

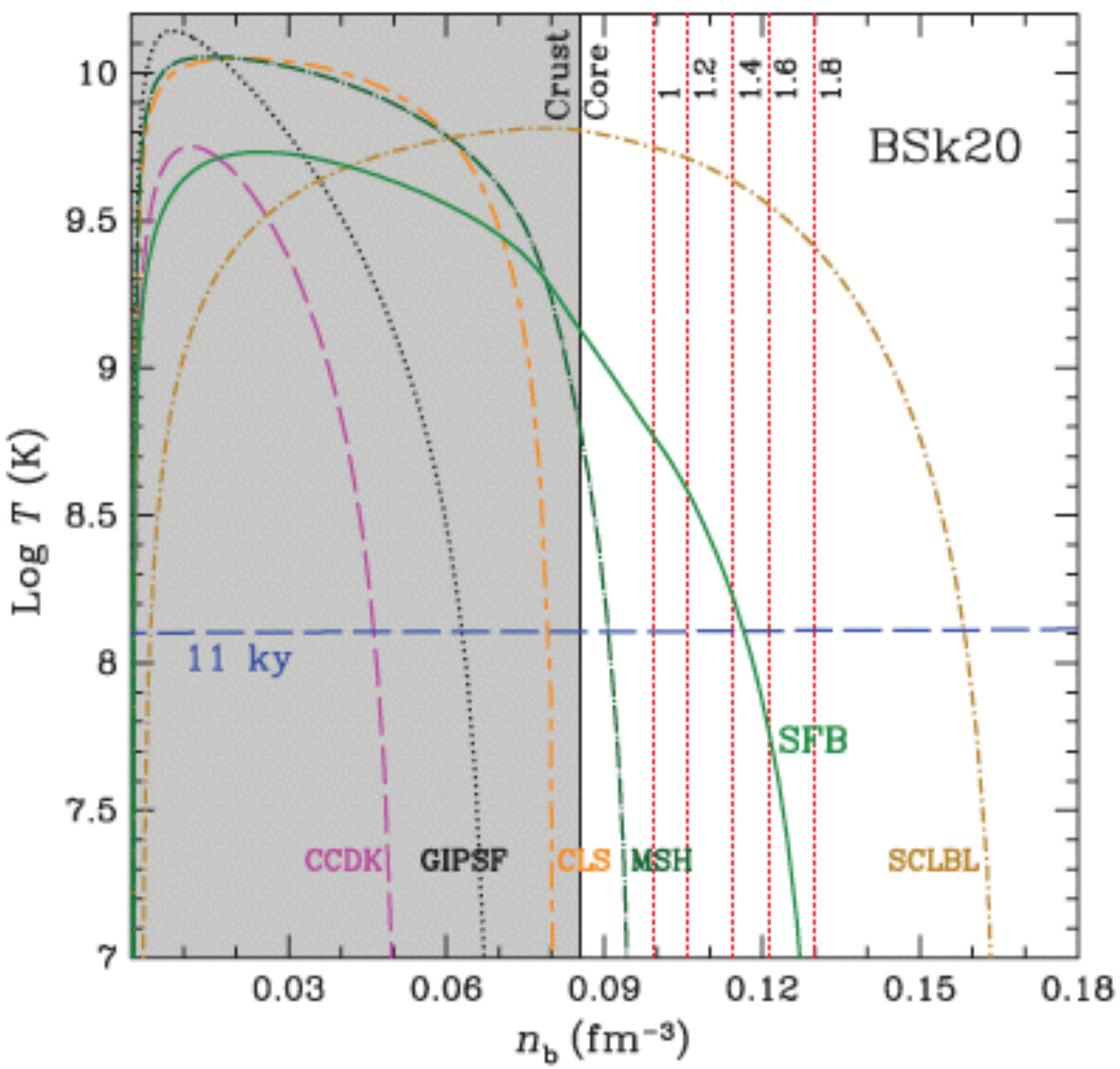


Fig. 2. Temperature dependence of neutron superfluid models as a function of baryon number density for the BSk20 nuclear equation of state. Thick curved lines are the superfluid critical temperature for the (labeled) models from (*23*). The vertical solid line indicates the separation between the crust (shaded region) and the core. Vertical dotted lines denote the density at which the superfluid moment of inertia (using the SFB superfluid model) is 1.6% of the total stellar moment of inertia for neutron stars of different mass (labeled in units of solar mass). The (nearly horizontal) dashed line is the temperature of a 1.4 M_{Sun} neutron star at an age of 11,000 years.

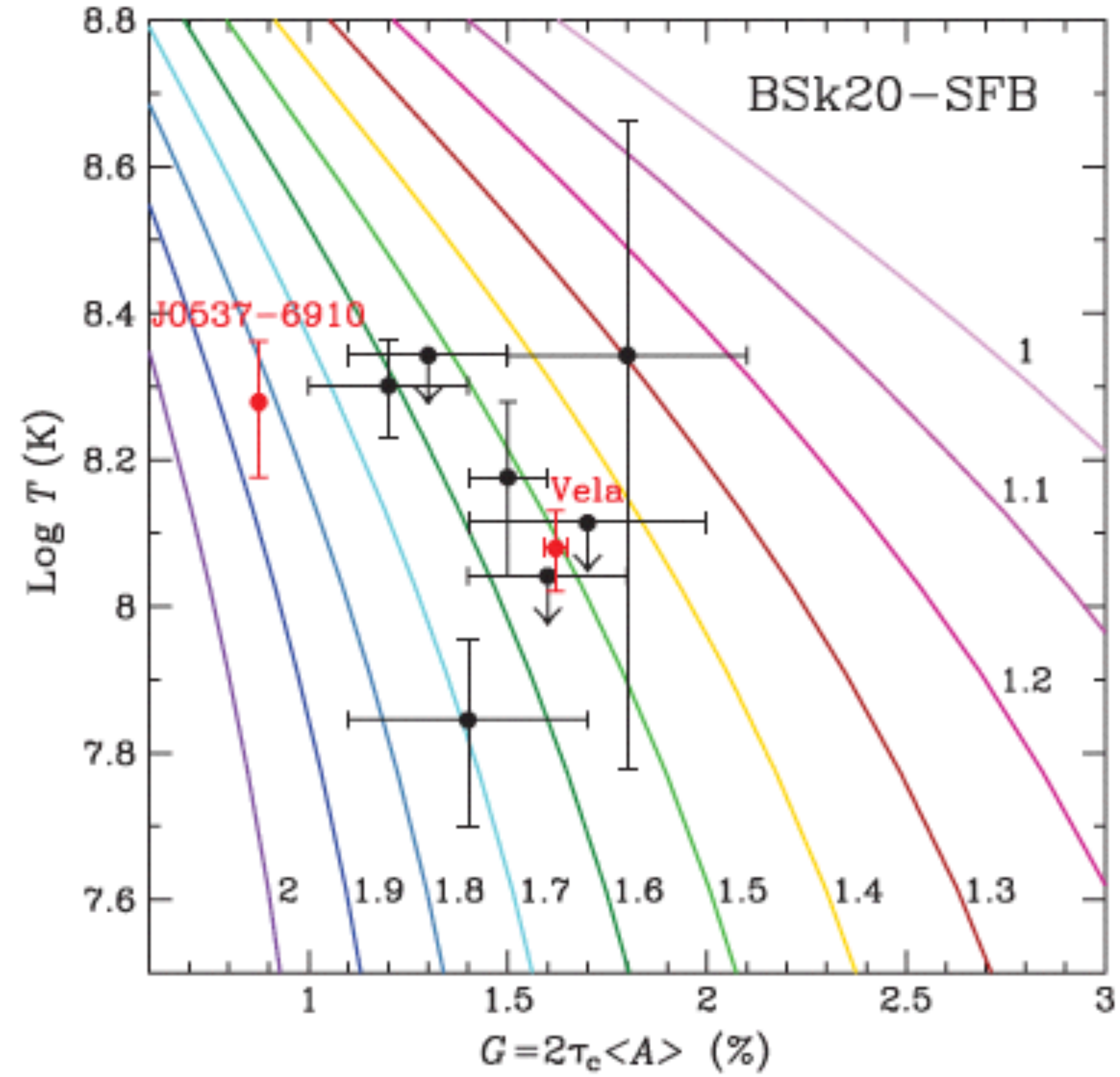
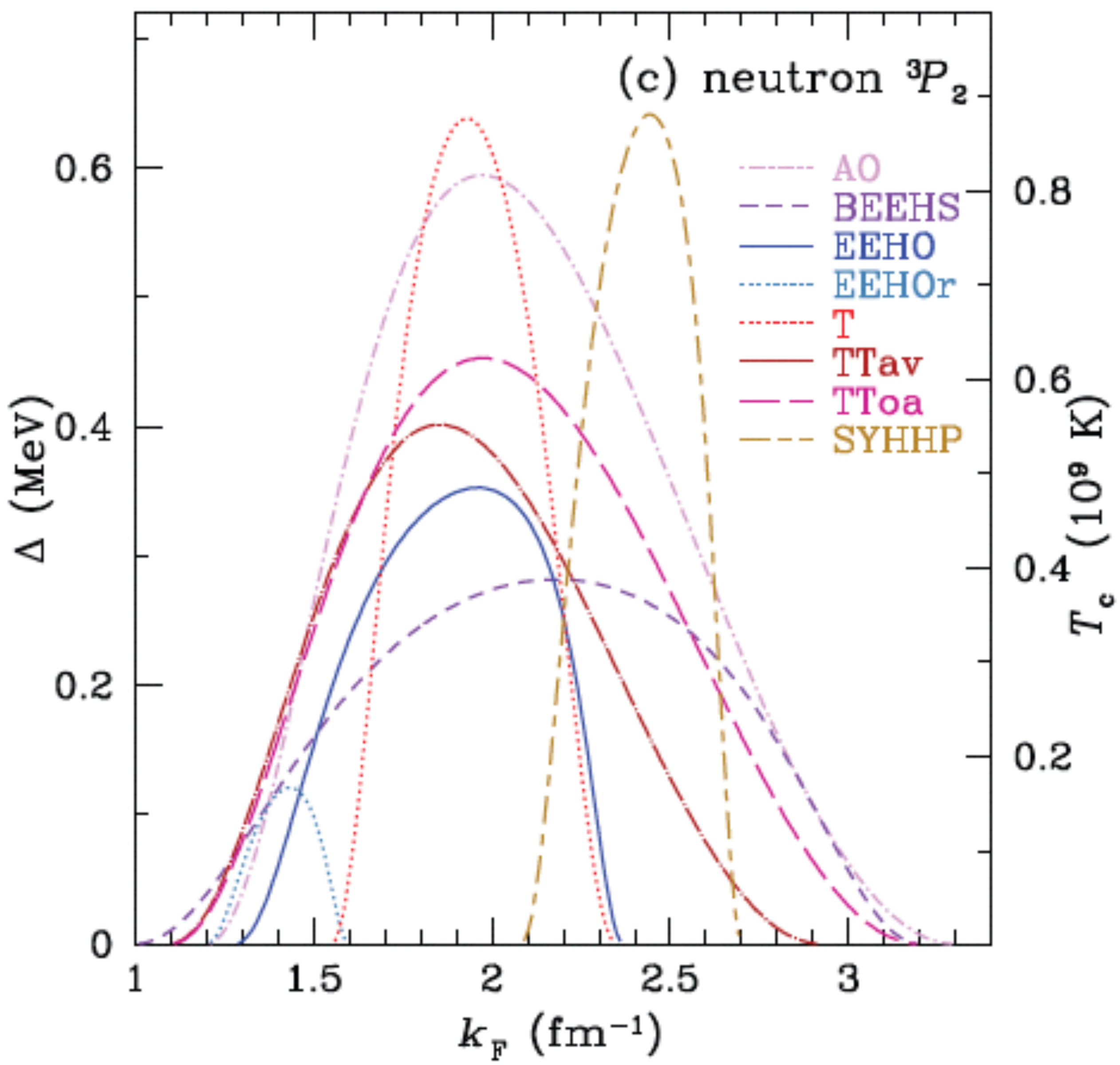
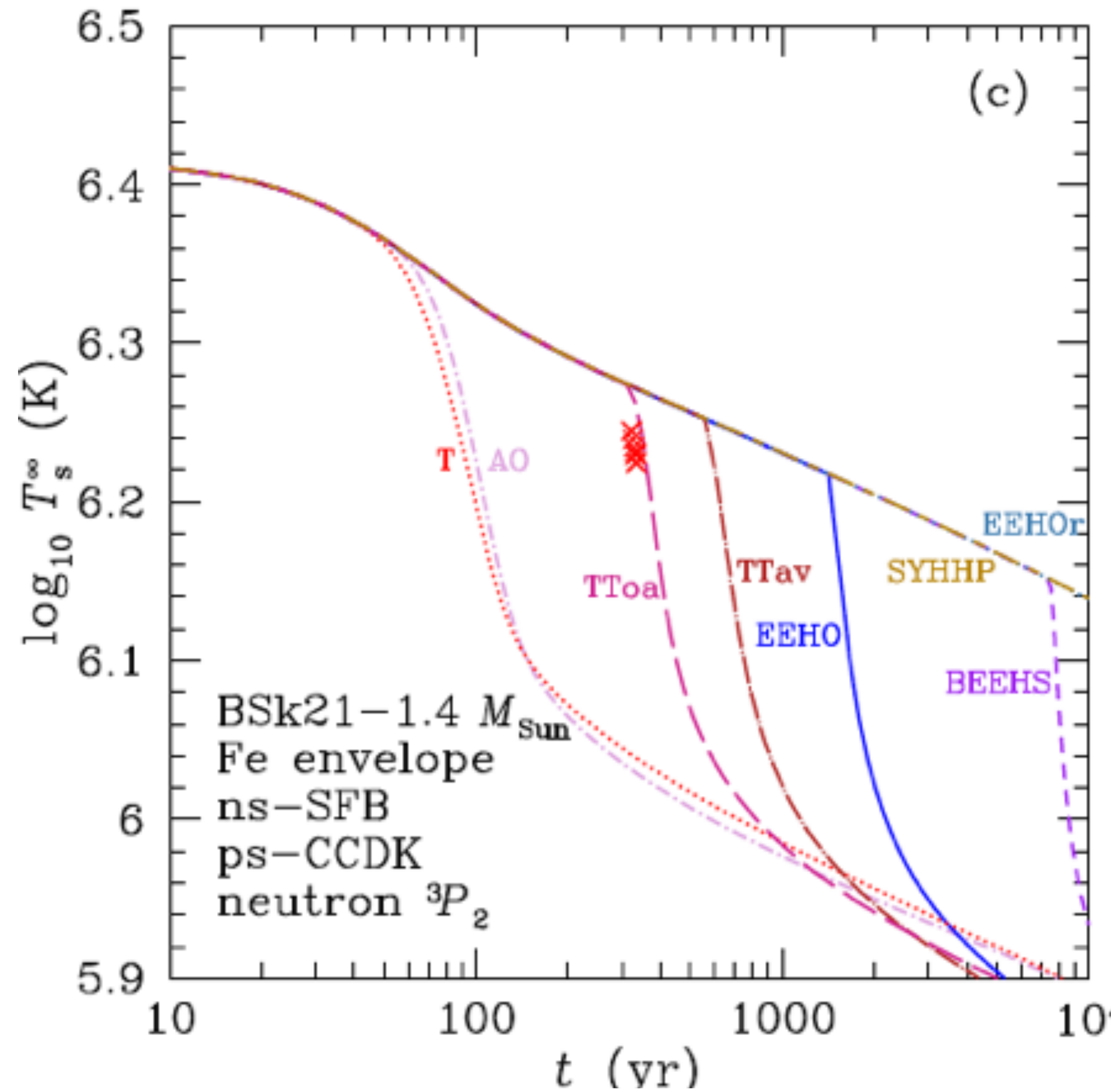


Fig. 3. Neutron star mass from pulsar observables *G* and interior temperature *T*. Data points are for pulsars with measured *G* from glitches and *T* from an age or surface temperature observation (see Table 1). Lines (labeled by neutron star mass, in units of solar mass) are the theoretical prediction for *G* and *T* using the BSk20 nuclear equation of state and SFB neutron superfluid models.

pulsar; dashed line) for a 1.4 M_{Sun} neutron star built using the BSk20

Cooling of Cassiopea A





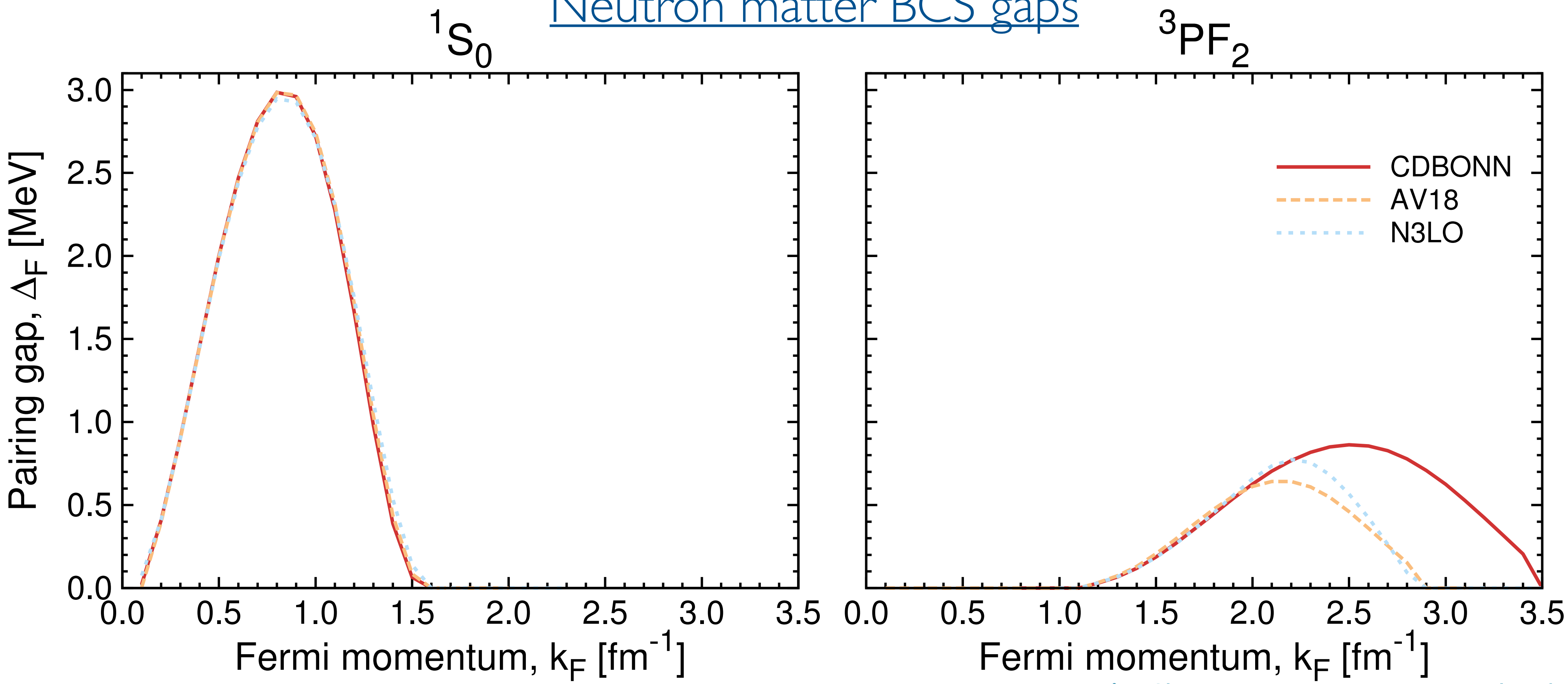
Name	Process	Emissivity (erg cm^{-3} s^{-1})
Modified Urca (neutron branch)	$n+n \to n+p+e^- + \bar{\nu}_e$ $n+p+e^- \to n+n+\nu_e$	$\sim 2\times10^{21}\, R\, T_9^8$
Modified Urca (proton branch)	$p+n \to p+p+e^- + \bar{\nu}_e$ $p+p+e^- \to p+n+\nu_e$	$\sim 10^{21}\, R\, T_9^8$
Bremsstrahlungs	$n+n \to n+n+\nu+\bar{\nu}$ $n+p \to n+p+\nu+\bar{\nu}$ $p+p \to p+p+\nu+\bar{\nu}$	$\sim 10^{19}\, R\, T_9^8$
Cooper pair	$n+n \to [nn]+\nu+\bar{\nu}$ $p+p \to [pp]+\nu+\bar{\nu}$	$\sim 5\times10^{21}\, R\, T_9^7$ $\sim 5\times10^{19}\, R\, T_9^7$
Direct Urca (nucleons)	$n \to p+e^- + \bar{\nu}_e$ $p+e^- \to n+\nu_e$	$\sim 10^{27}\, R\, T_9^6$

Ingredients

(a) Mass of pulsar
(b) EoS (determines radius)
(c) Internal composition
(d) **Pairing gaps** ($^1S_0$ & $^3PF_2$ channels)
(e) Atmosphere composition

Bardeen-Cooper-Schrieffer pairing

Neutron matter BCS gaps



Dean & Hjorth-Jensen, *Rev. Mod. Phys.* **75** 607 (2003)

BCS equation

$$\Delta_k^L = -\sum_{L'} \int_{k'} \frac{\langle k | V_{nn}^{LL'} | k' \rangle}{2\sqrt{\chi_{k'}^2 + |\Delta_{k'}|^2}} \Delta_{k'}^{L'} \quad \mathbf{+} \qquad \chi_k = \varepsilon_k - \mu$$

- Single-particle spectrum choice: $\varepsilon_k = \frac{k^2}{2m} + U(k) - \mu$
- Angular gap dependence: $|\Delta_k|^2 = \sum_L |\Delta_k^L|^2$

Maurizio, Holt & Finelli, *Phys. Rev. C* **90**, *044003* (2014)

Bardeen-Cooper-Schrieffer pairing

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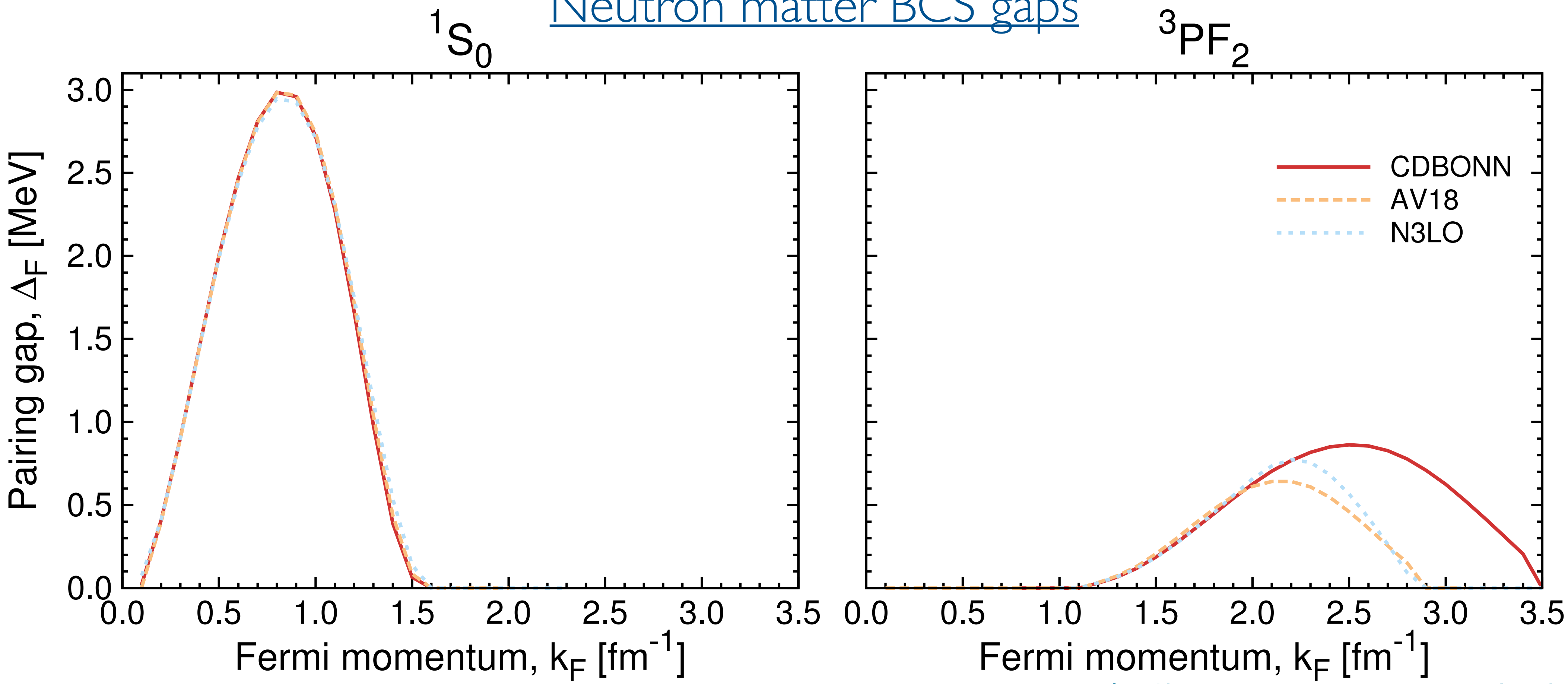
Neutron matter BCS gaps



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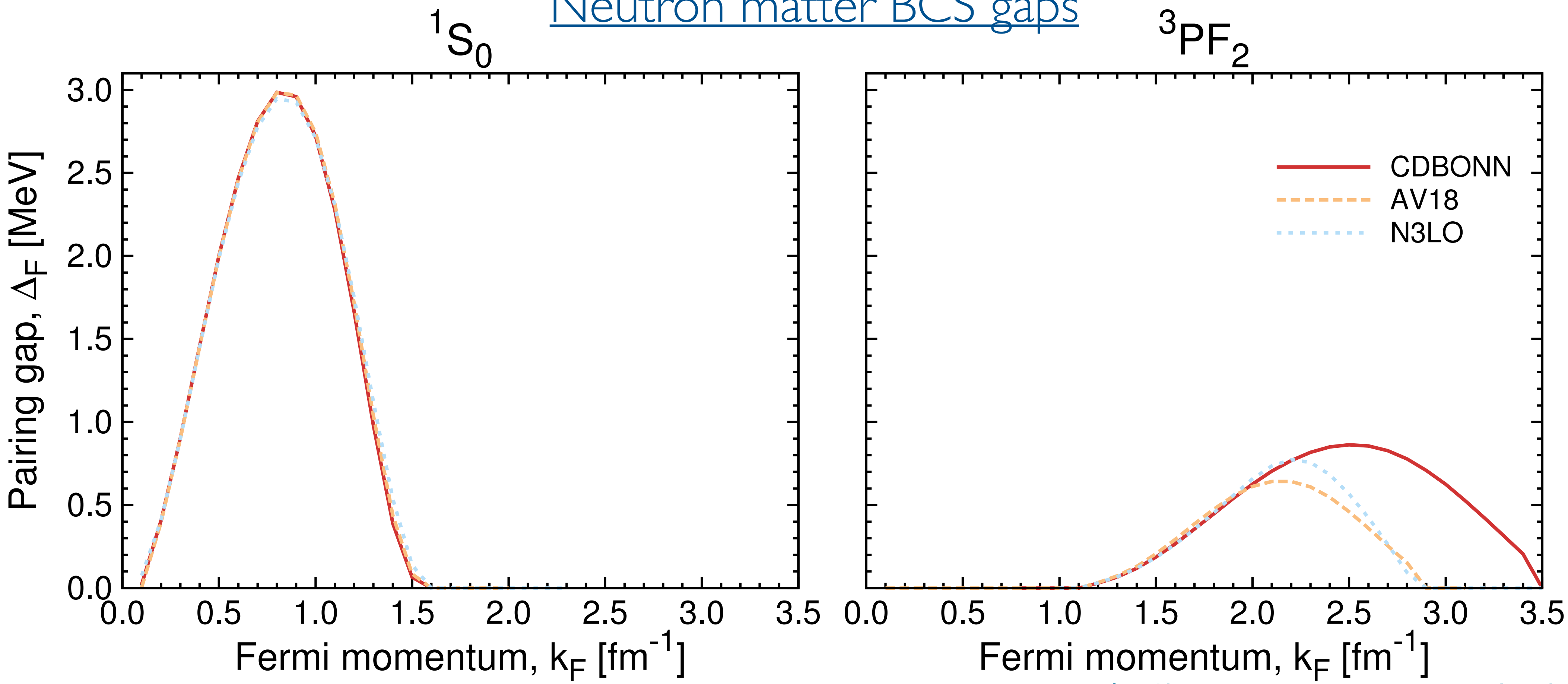

Dean & Hjorth-Jensen, *Rev. Mod. Phys.* **75** 607 (2003)

BCS equation

$$\boxed{\Delta_k^L = -\sum_{L'} \int_{k'} \frac{\langle k | V_{nn}^{LL'} | k' \rangle}{2\sqrt{\chi_{k'}^2 + |\Delta_{k'}|^2}} \Delta_{k'}^{L'} \; \mathbf{+} \qquad \chi_k = \varepsilon_k - \mu}$$

- Single-particle spectrum choice: $\varepsilon_k = \frac{k^2}{2m} + \cancel{U(k)} - \mu$
- Angular gap dependence: $|\Delta_k|^2 = \sum_L |\Delta_k^L|^2 \approx |\Delta_k^L|^2$

Maurizio, Holt & Finelli, *Phys. Rev. C* **90**, *044003* (2014)

Beyond BCS 101: SRC

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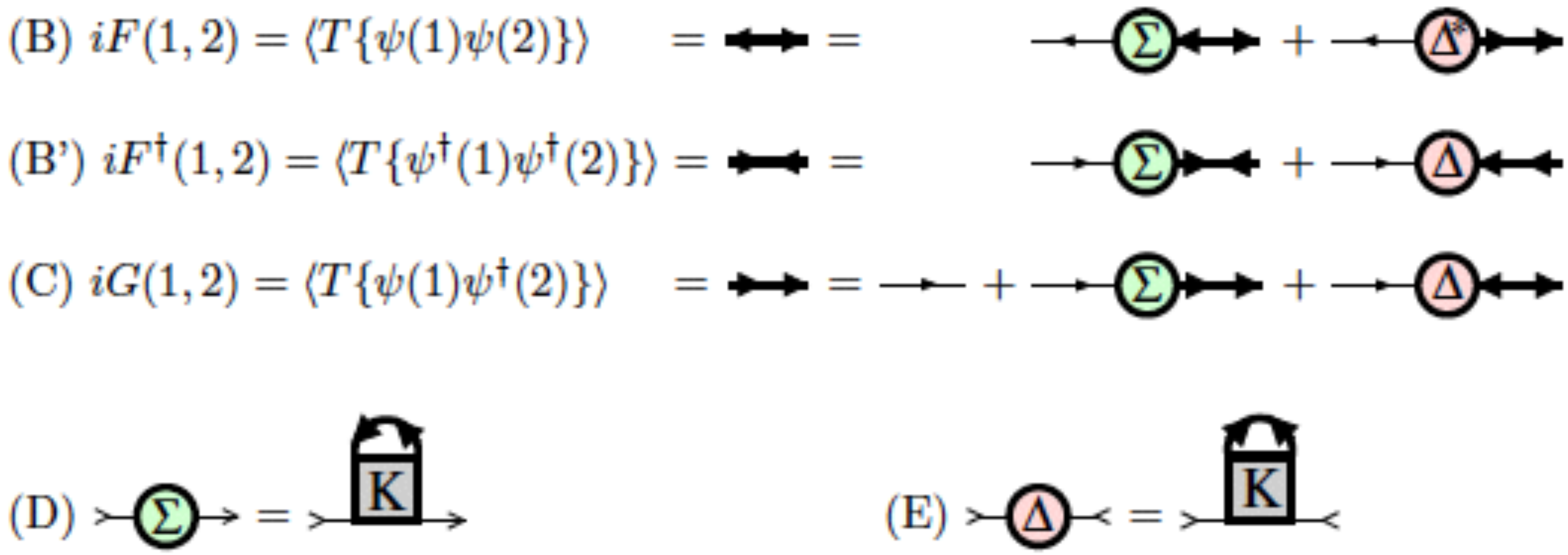
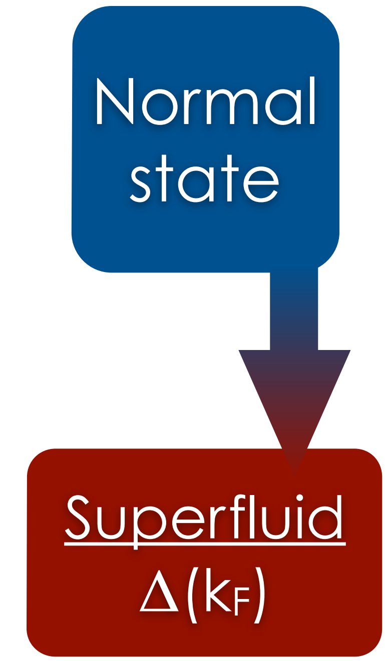




BCS+SRC equation

$$\Delta_k^L = -\sum_{L'} \int_{k'} \frac{\langle k | V_{nn}^{LL'} | k' \rangle}{2\sqrt{\bar{\chi}_{k'}^2 + |\Delta_{k'}|^2}} \Delta_{k'}^{L'} \;\boldsymbol{+}$$

$$\frac{1}{2\chi_k} = \int_\omega \int_{\omega'} \frac{1 - f(\omega) - f(\omega')}{\omega + \omega'} A(k,\omega) A_s(k,\omega')$$

- **BCS** is *lowest order* in Gorkov Green's function expansion
- T-matrix can be extended to paired systems
- But full self-consistency is still missing

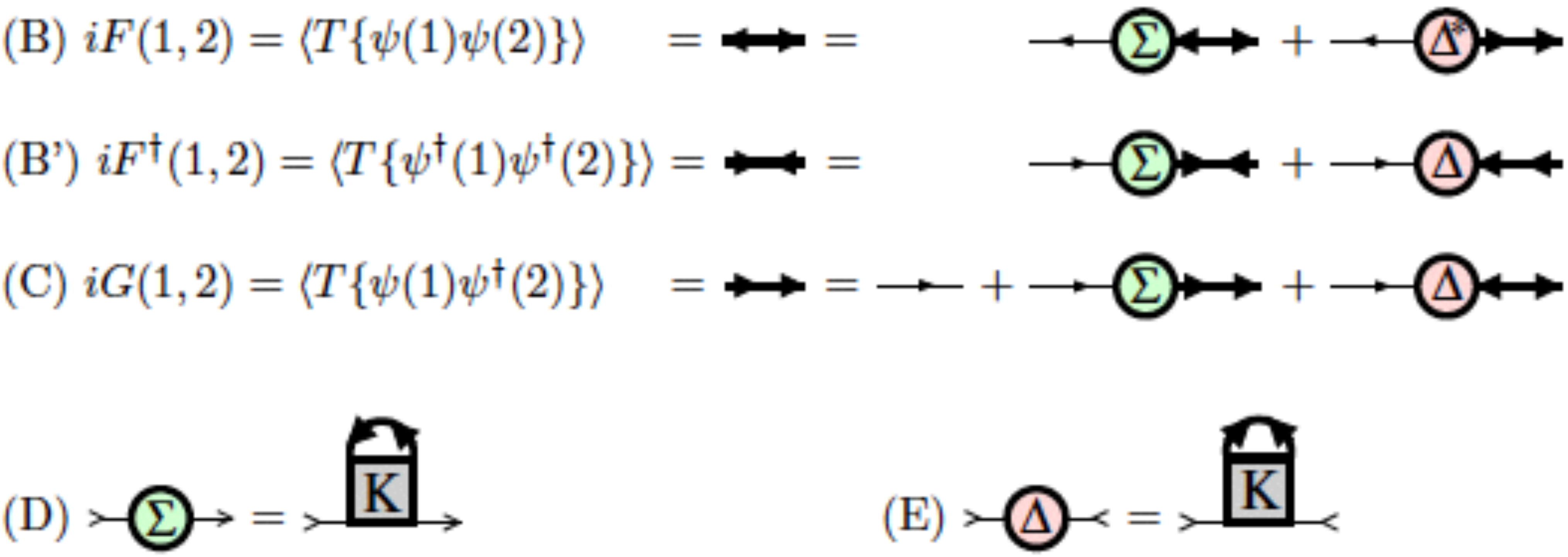
Bozek, *Phys. Rev. C* **62** 054316 (2000); Muether & Dickhoff, *Phys. Rev. C* **72** 054313 (2005)

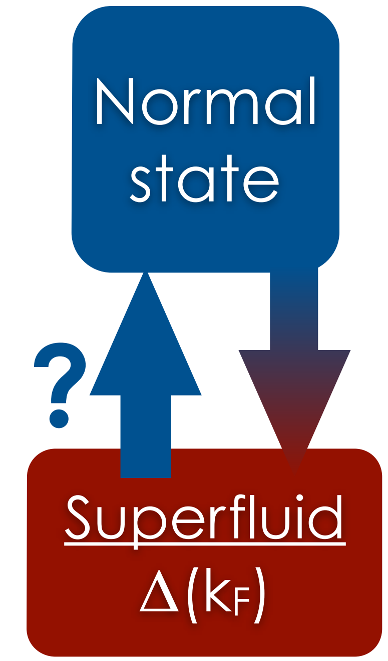
Beyond BCS 101: SRC

(B) $iF(1,2) = \langle T\{\psi(1)\psi(2)\}\rangle$

(B') $iF^\dagger(1,2) = \langle T\{\psi^\dagger(1)\psi^\dagger(2)\}\rangle$

(C) $iG(1,2) = \langle T\{\psi(1)\psi^\dagger(2)\}\rangle$





BCS+SRC equation

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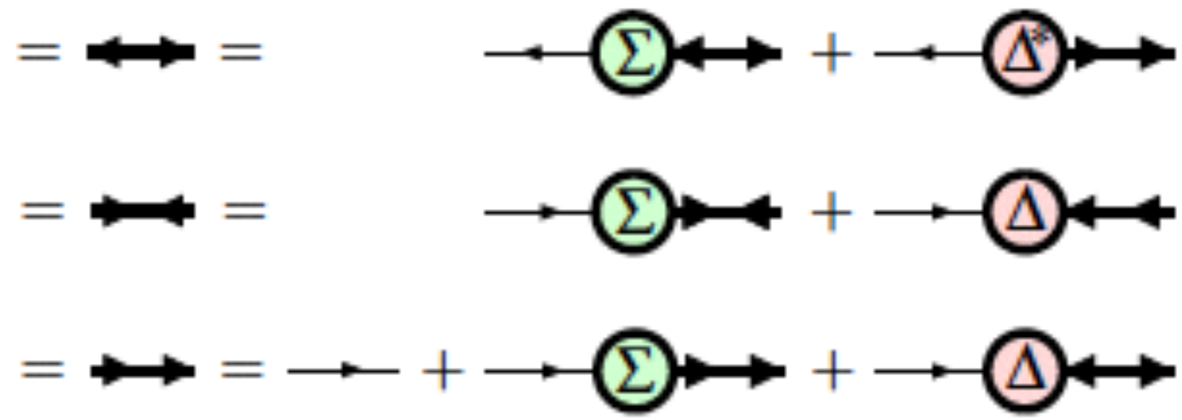
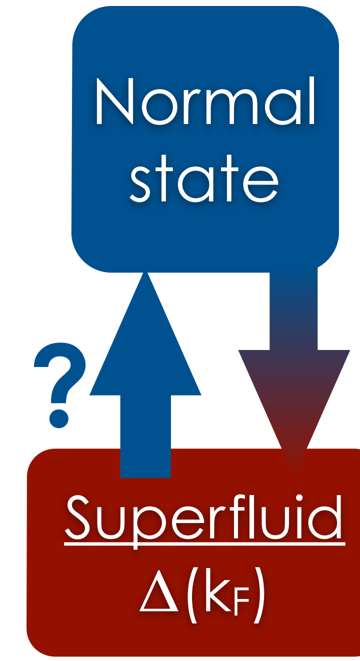
(C) $iG(1,2) = \langle T\{\psi(1)\psi^\dagger(2)\}\rangle$



(D)



BCS+SRC equation

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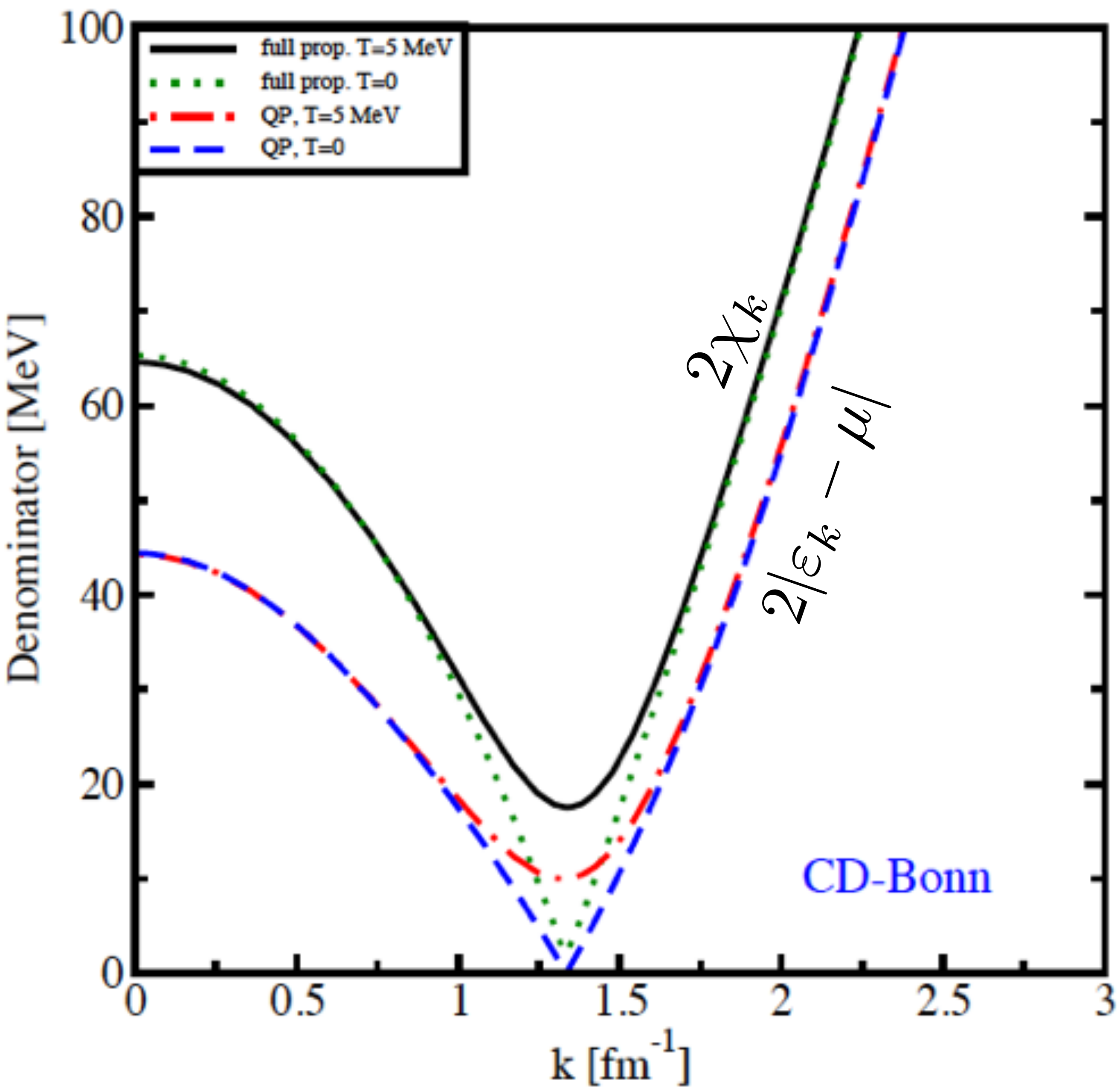
Bozek, *Phys. Rev. C* **62** 054316 (2000); Muether & Dickhoff, *Phys. Rev. C* **72** 054313 (2005)

Beyond BCS 101: SRC

Nuclear matter, ρ=0.16 fm^{-3}



Quasi-particle ⇔ BCS

$$\frac{1}{2\bar{\chi}_k} = \frac{1}{2|\varepsilon_k - \mu|}$$

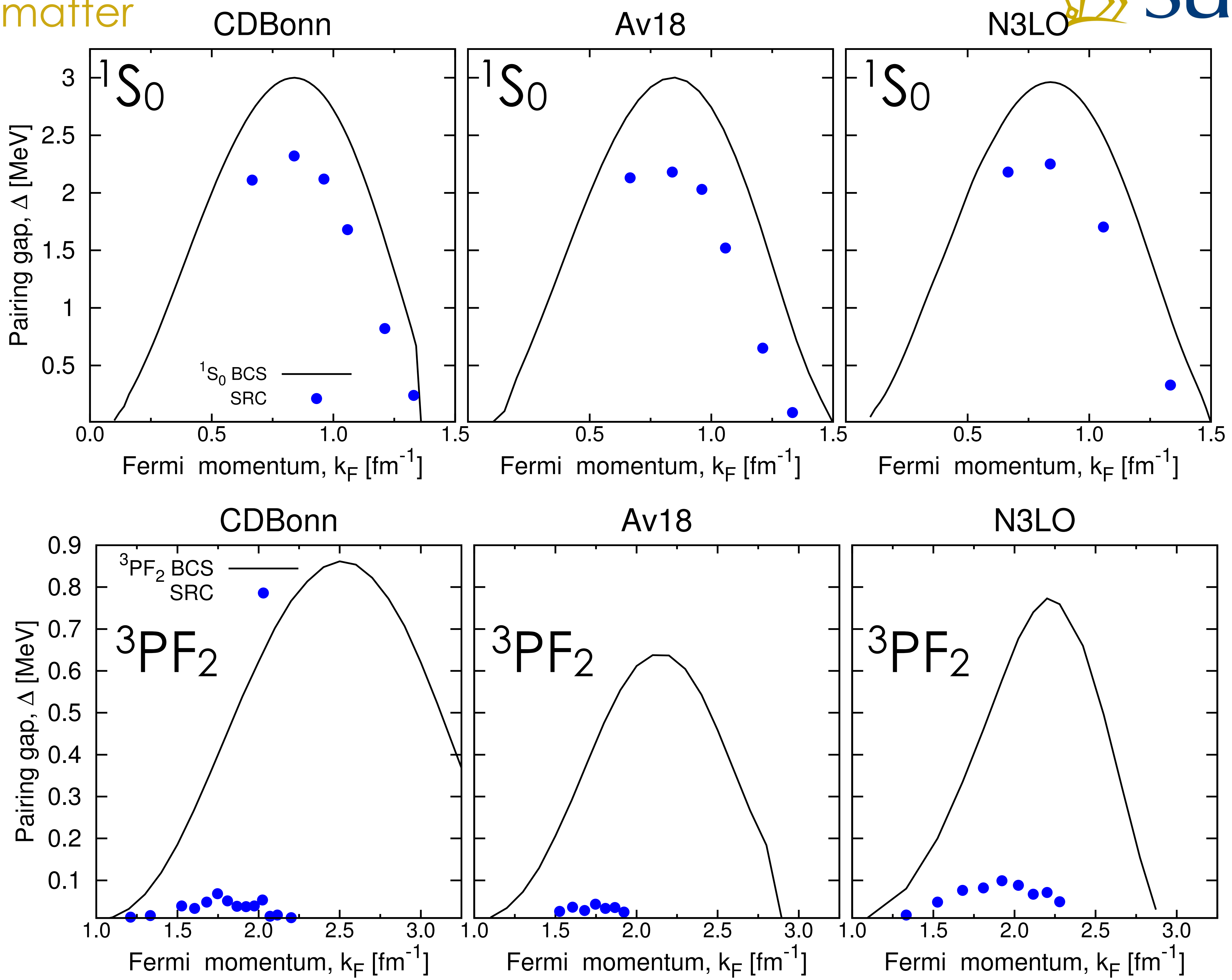
Full off-shell

$$\frac{1}{2\bar{\chi}_k} = \int_\omega \int_{\omega'} \frac{1 - f(\omega) - f(\omega')}{\omega + \omega'} A(k,\omega)A(k,\omega')$$

- How does **removal** of **strength** affect pairing?
- Necessarily **decreases** gap
- We use **normal** properties throughout

Beyond BCS 101: SRC

Neutron matter



BCS+SRC

$$\Delta_k^L = -\sum_{L'} \int_{k'} \frac{\langle k|V_{nn}^{LL'}|k'\rangle}{2\sqrt{\bar{\chi}_{k'}^2 + |\Delta_{k'}|^2}} \Delta_{k'}^{L'} \quad + \quad \frac{1}{2\chi_k} = \int_\omega \int_{\omega'} \frac{1-f(\omega)-f(\omega')}{\omega+\omega'} A(k,\omega) A_{\cancel{s}}(k,\omega')$$

Beyond BCS 201: LRC

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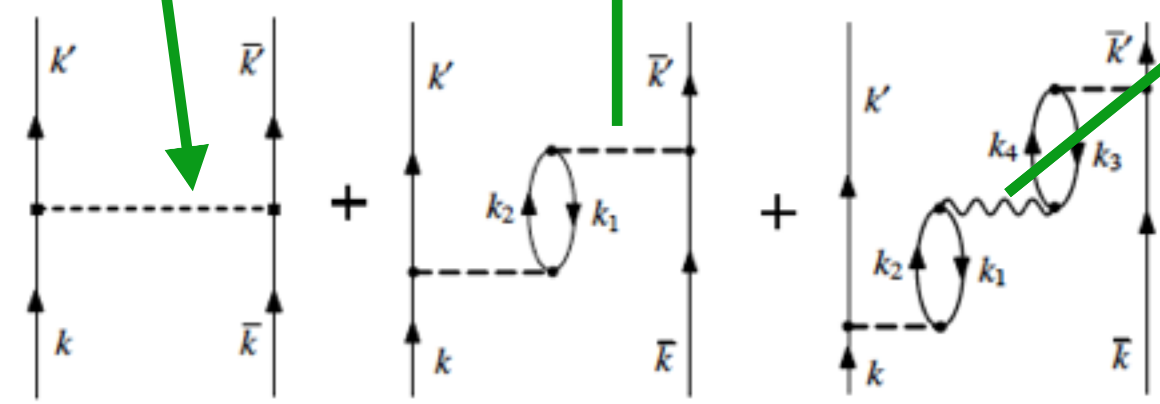
$$\Delta_k^L = -\sum_{L'}\int_{k'} \frac{\boxed{\langle k|V_{nn}^{LL'}|k'\rangle}}{2\sqrt{\boxed{\chi_{k'}^2}+|\Delta_{k'}|^2}}\Delta_{k'}^{L'}$$

ph recoupled G-matrix

Effective Landau parameters

$\mathcal{V}_{\text{pair}} =$



(a) (b) (c)

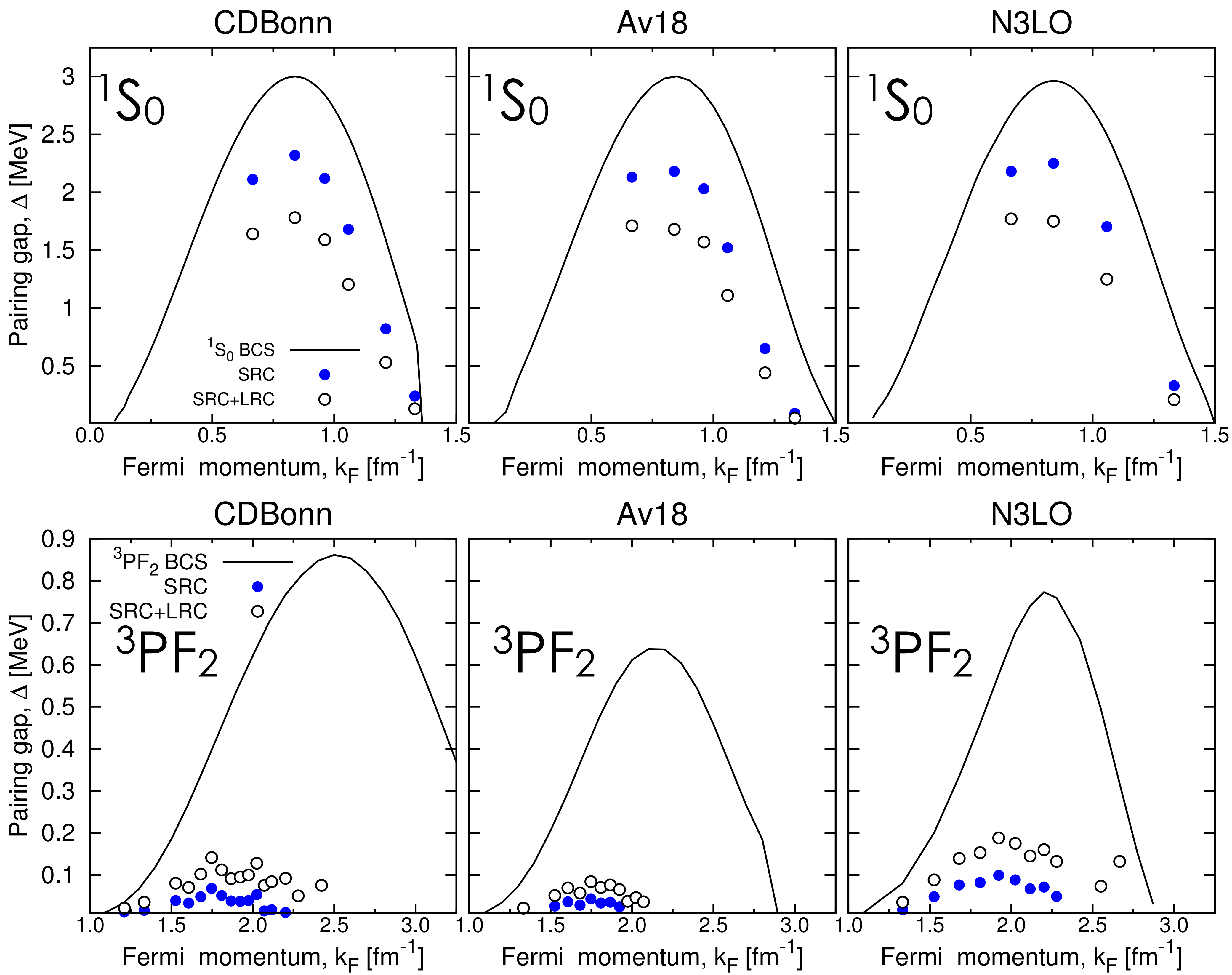
$$\langle 1\bar{1}|\mathcal{V}|1\bar{1}\rangle = \frac{1}{4}\sum_{2,2'}\sum_{S,T}(-)^S(2S+1)\langle 12|G_{ST}^{\text{ph}}|1'2'\rangle_A\langle 2'\bar{1}|G_{ST}^{\text{ph}}|2\bar{1}'\rangle_A\Lambda(22')$$

$$\Lambda_{ST}(q) = \frac{\Lambda_{ST}^0(q)}{1-\Lambda_{ST}^0(q)\times F_{ST}}$$

- Bare NN potential only is not the only possible interaction
- Diagram (a): nuclear interaction
- Diagram (b): in-medium interaction, density and spin fluctuations
- Diagram (c): included by Landau parameters

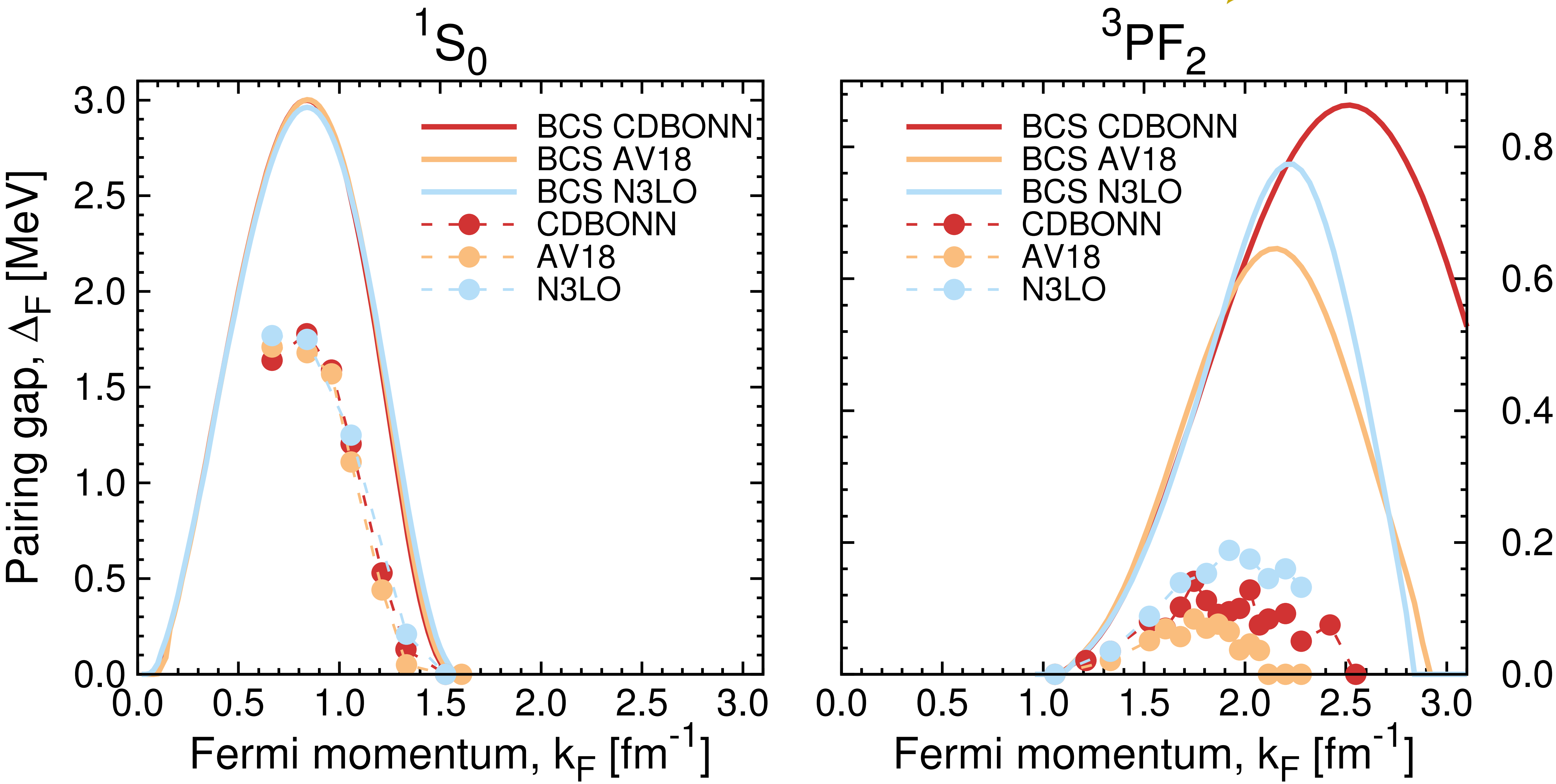
Beyond BCS 201: results $^1S_0$

Neutron matter



- LRC $^1S_0$ ($^3PF_2$) produces (anti-)screening

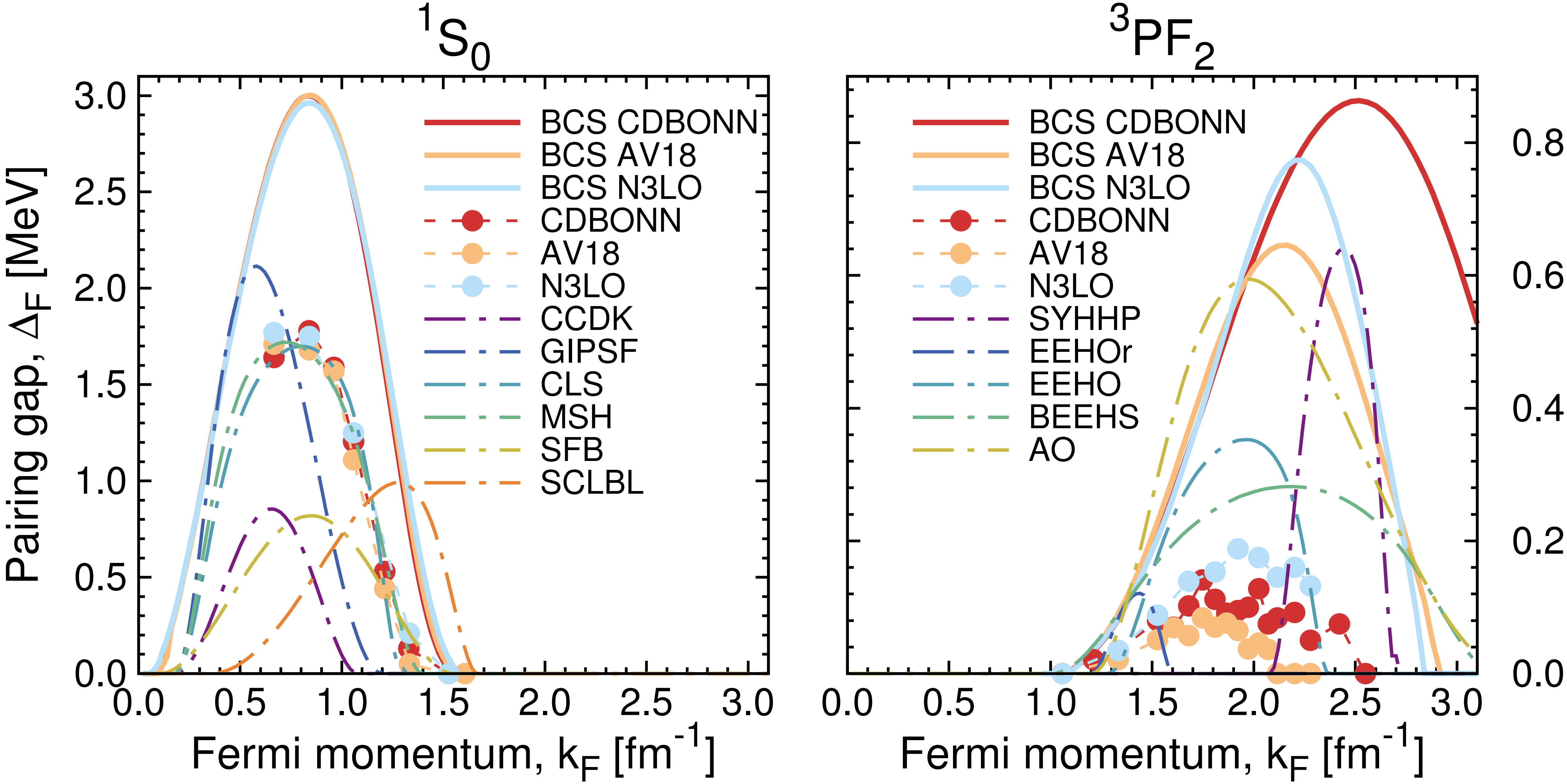
Beyond BCS 201: overview



- Effect is **robust**: independent of NN potential
- 3NF effect **not** included in SRC, BCS indicates **small**
- **Singlet** channel under control in **astrophysical** situations

Ho, Elshamouty, Heinke, Potekhin, *PRC **91** 015806 (2015)*

Beyond BCS 201: overview



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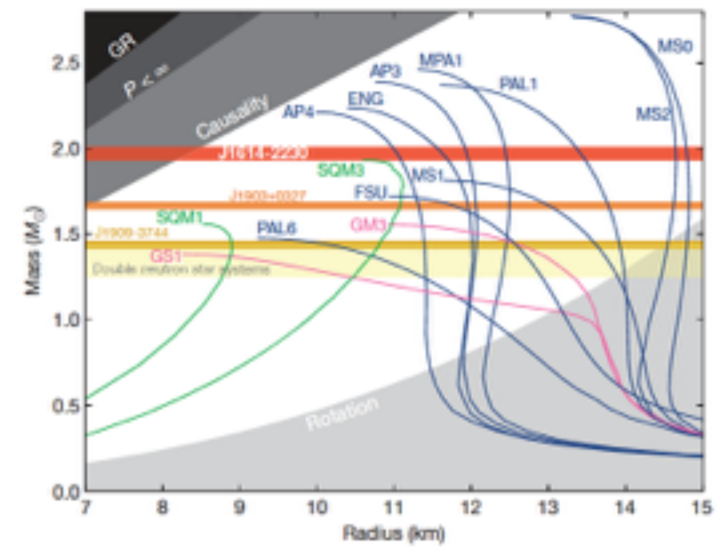
Ho, Elshamouty, Heinke, Potekhin, *PRC* ***91*** *015806 (2015)*

Neutron star modeling

Input #1
EoS

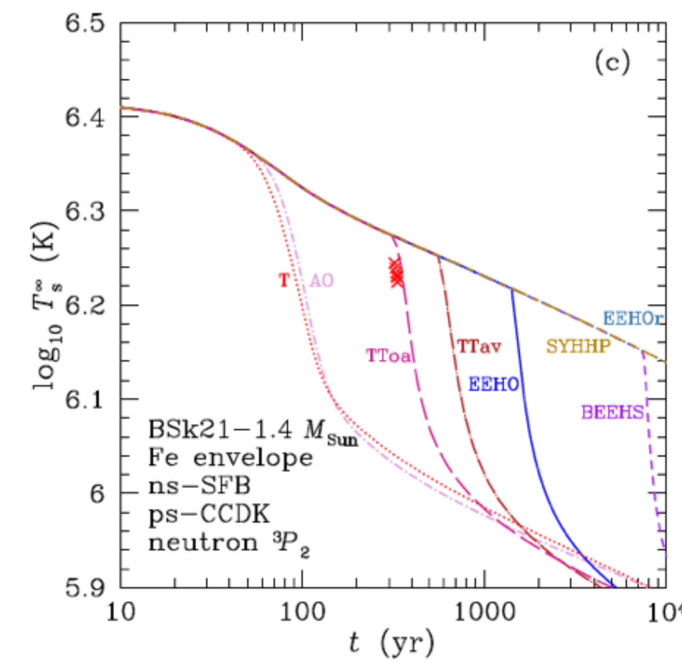
Observable #1
Mass-Radius relation

See Arianna's talk



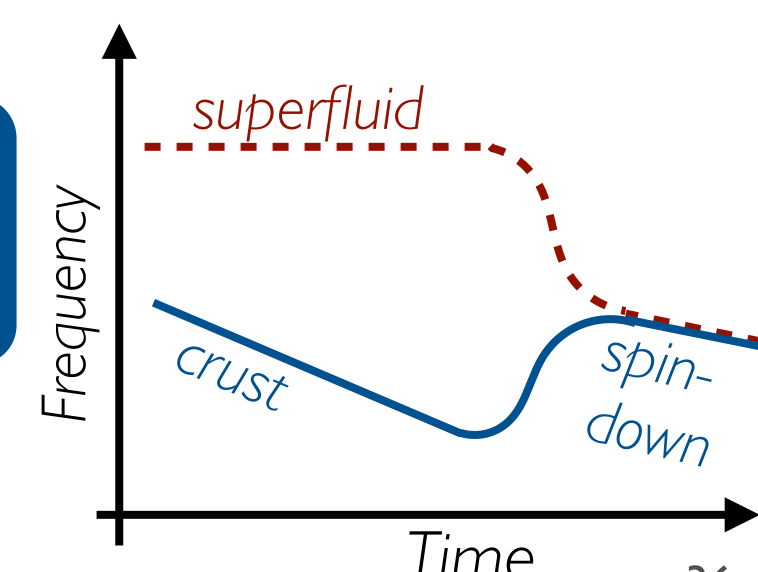
Input #2
Pairing gap

Observable #2
Cooling curve



Input #3
Crust-core

Observable #3
Glitching

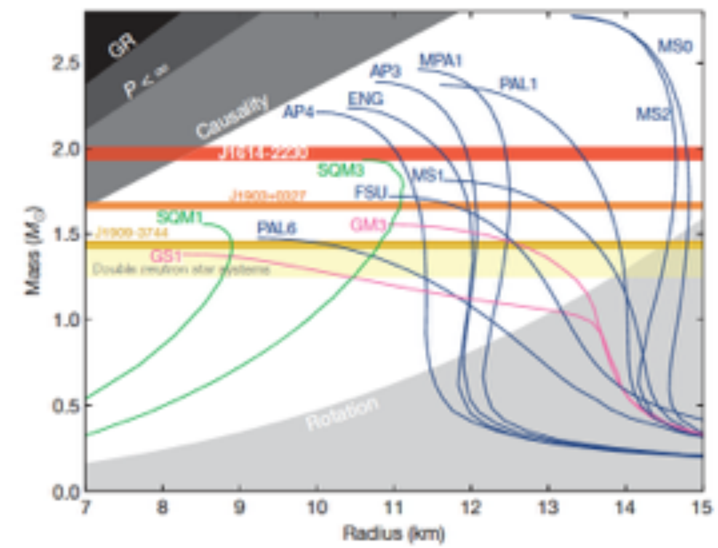


Neutron star modeling

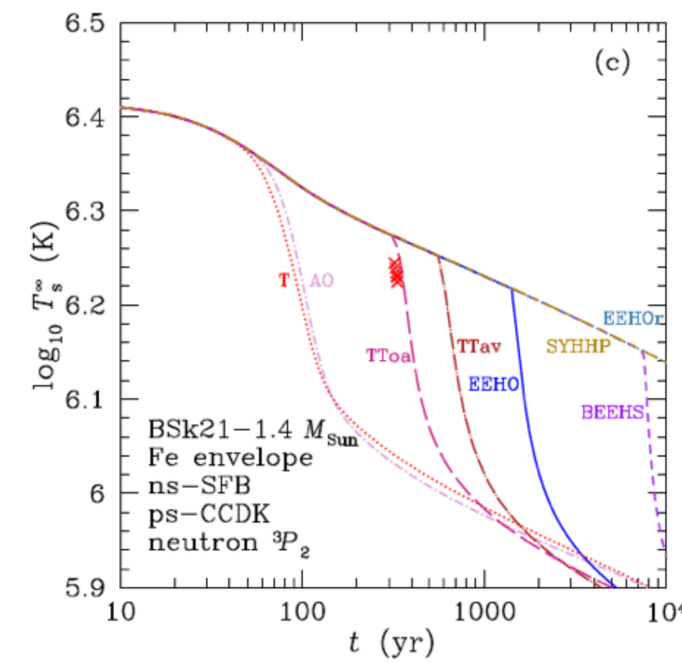
Input
Consistent many-body theory

Observable #1
Mass-Radius relation

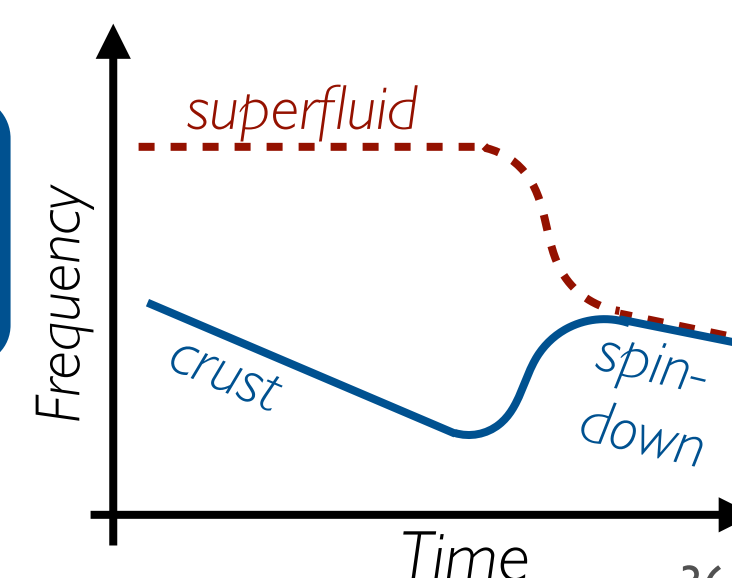
See Arianna's talk



Observable #2
Cooling curve



Observable #3
Glitching



Collaborators

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+C. Barbieri

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Conclusions

- Ab initio nuclear **theory** to treat **correlations**
- **Talk** to us if you need **quantitative** answers!

- **Different** NN forces give robust predictions
- Approximations introduced **meaningfully**

- Challenges ahead:
  - **2 body** propagators and momentum distributions
  - **Pairing** in isospin **asymmetric** matter
  - **Consistent** treatment of **cooling**, **glitch** & **EoS**

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