Green's functions for nuclear matter

Correlations, equation of state and pairing gaps

+A. Carbone

+D. Ding, W. H. Dickhoff, H. Dussan
arXiv:1502.05673

+A. Polls

+C. Barbieri

Arnau Rios Huguet
STFC Advanced Fellow
Department of Physics
University of Surrey

Saclay, 2 April 2015

Outline

➡ ***Motivation***

➡ *Nuclear matter: Equation of state with 3NFs*

➡ *Neutron matter: beyond-BCS pairing*

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Nuclei

- Finite size ⇒ (N,Z)
- Surface effects
- Single-particle wavefunction?

Nuclear matter

- Infinite matter ⇒ ρ
- No surface
- Plane waves
- Thermodynamic limit

Nuclear matter
Subtitle

Nuclei

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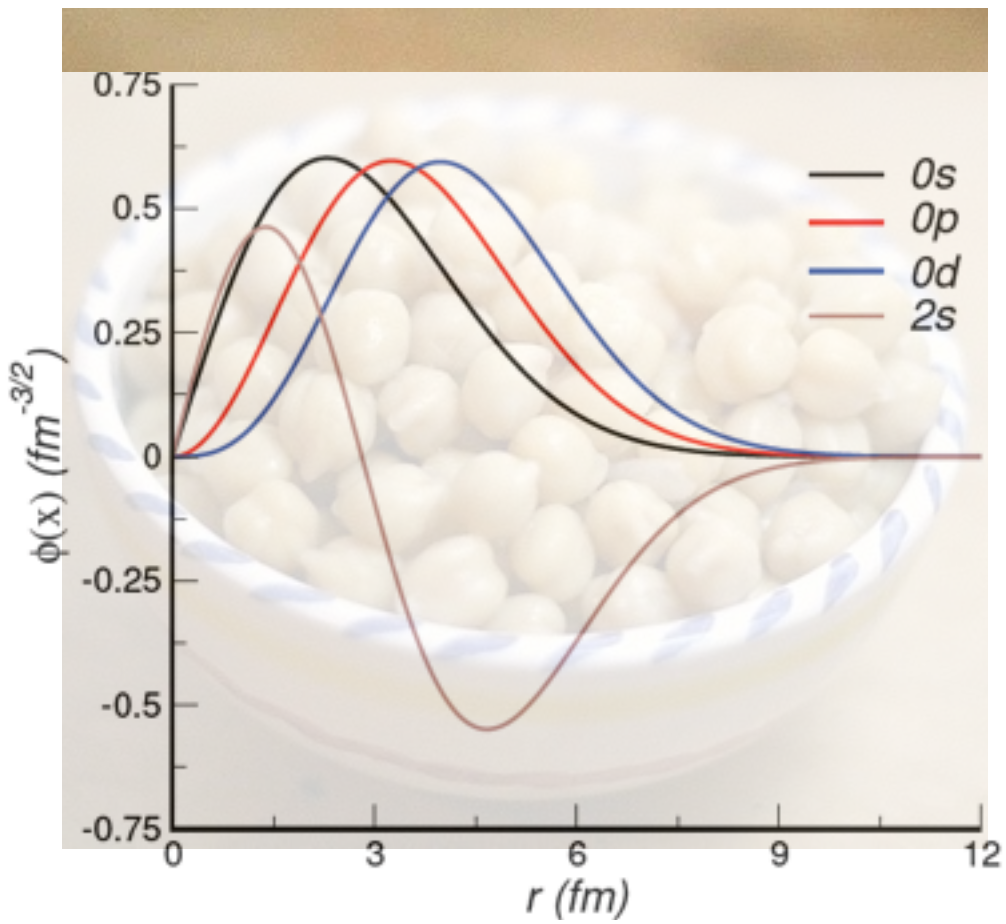
Nuclei



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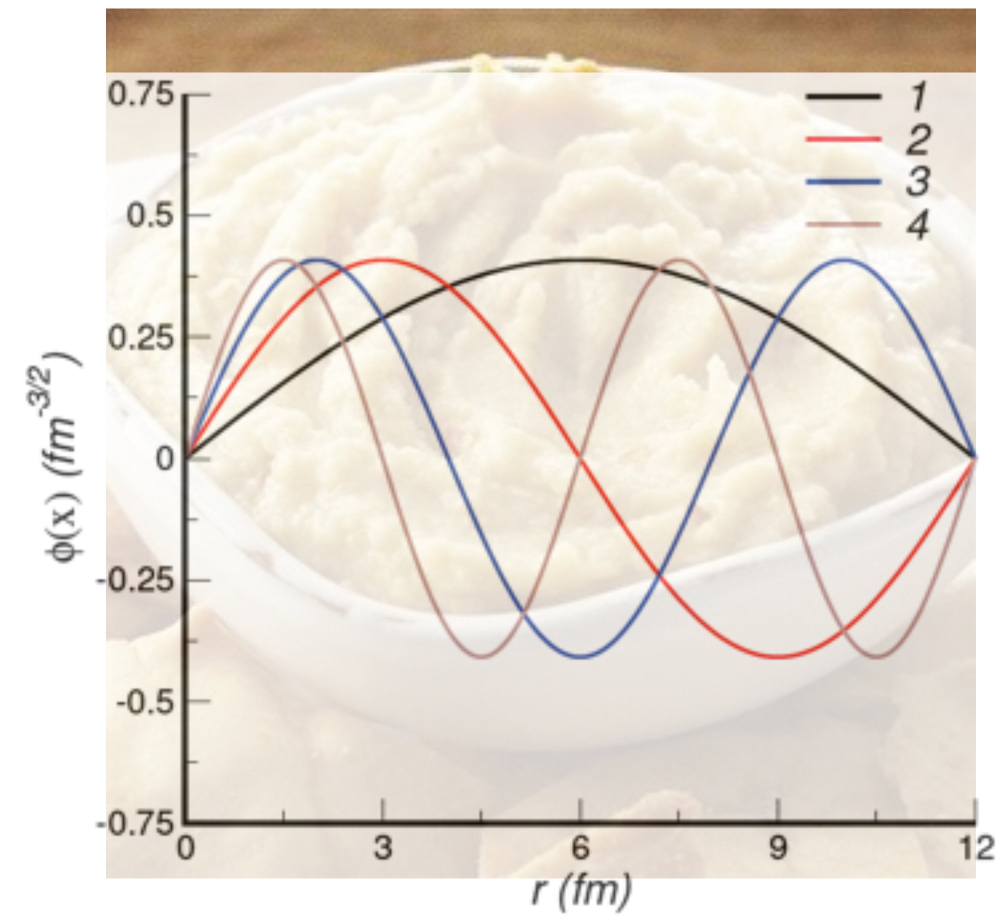
Nuclear matter



- Infinite matter ⇒ ρ
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Nuclear vs neutron matter

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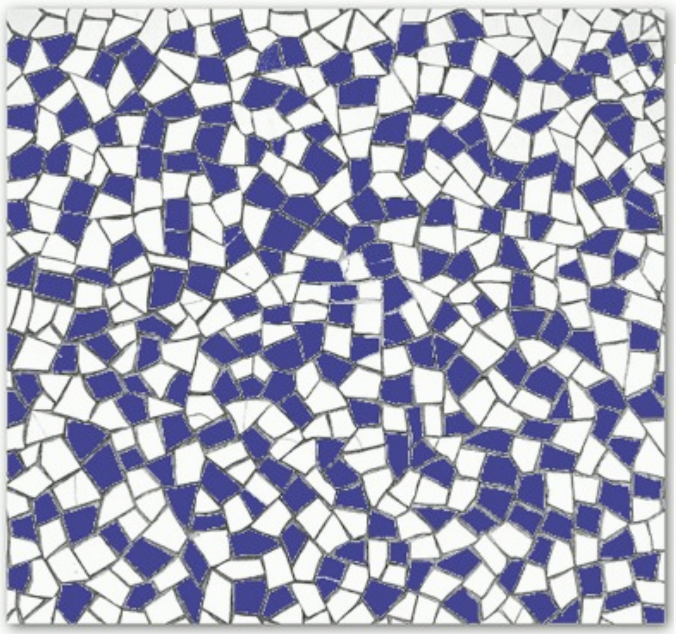
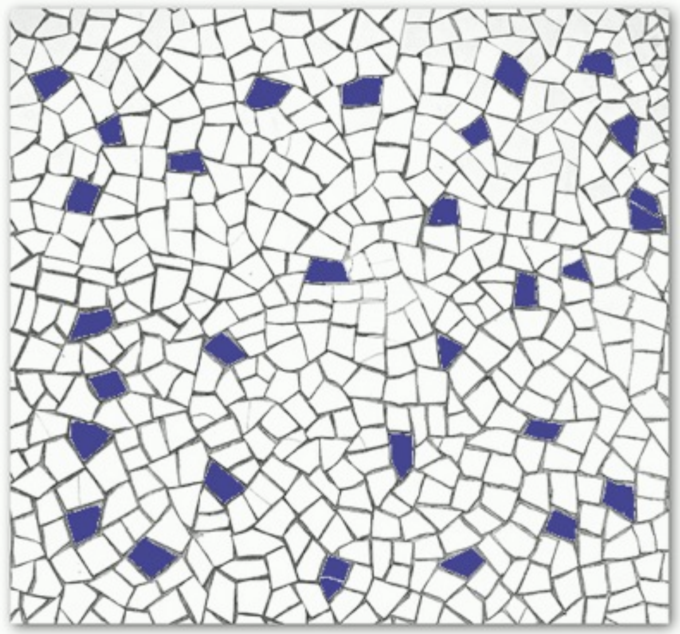
Nuclear "trencadís"

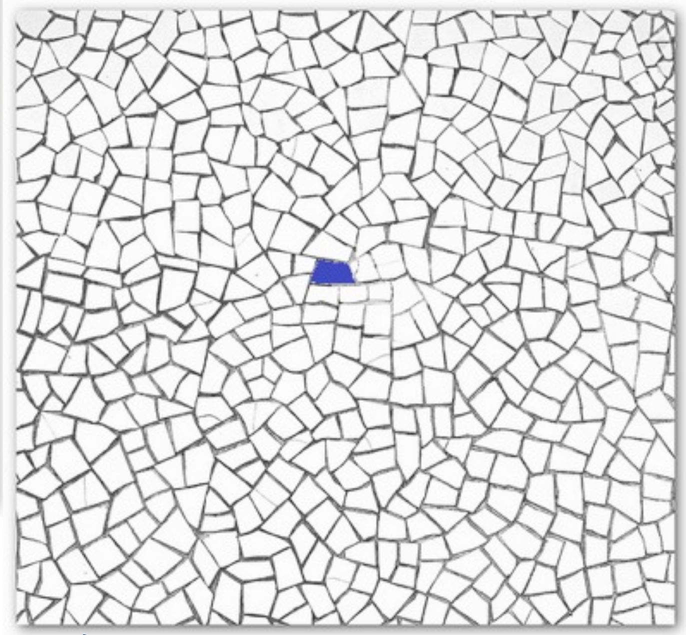
N=Z, β=0
Symmetric matter



β≠0
Asymmetric nuclei

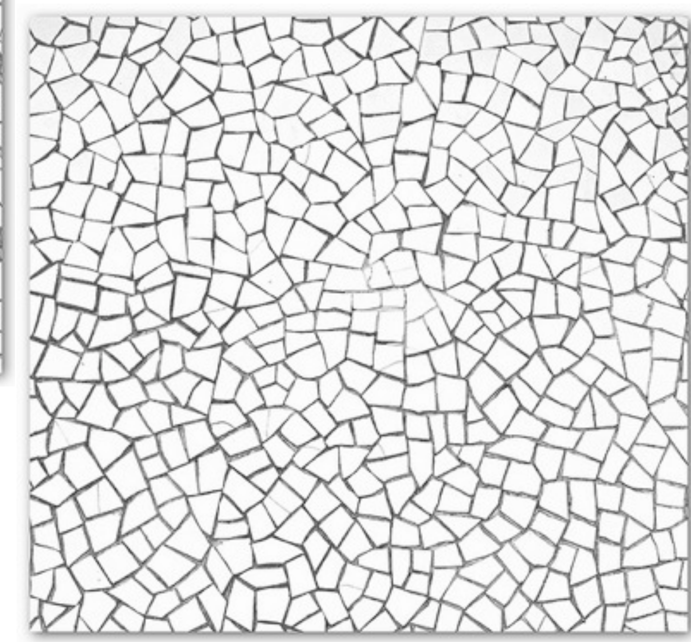


β≈1
Polaron



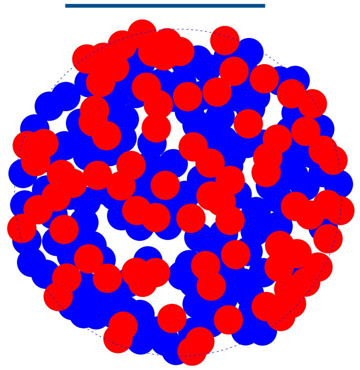
Neutron stars

β=1
Neutron matter



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

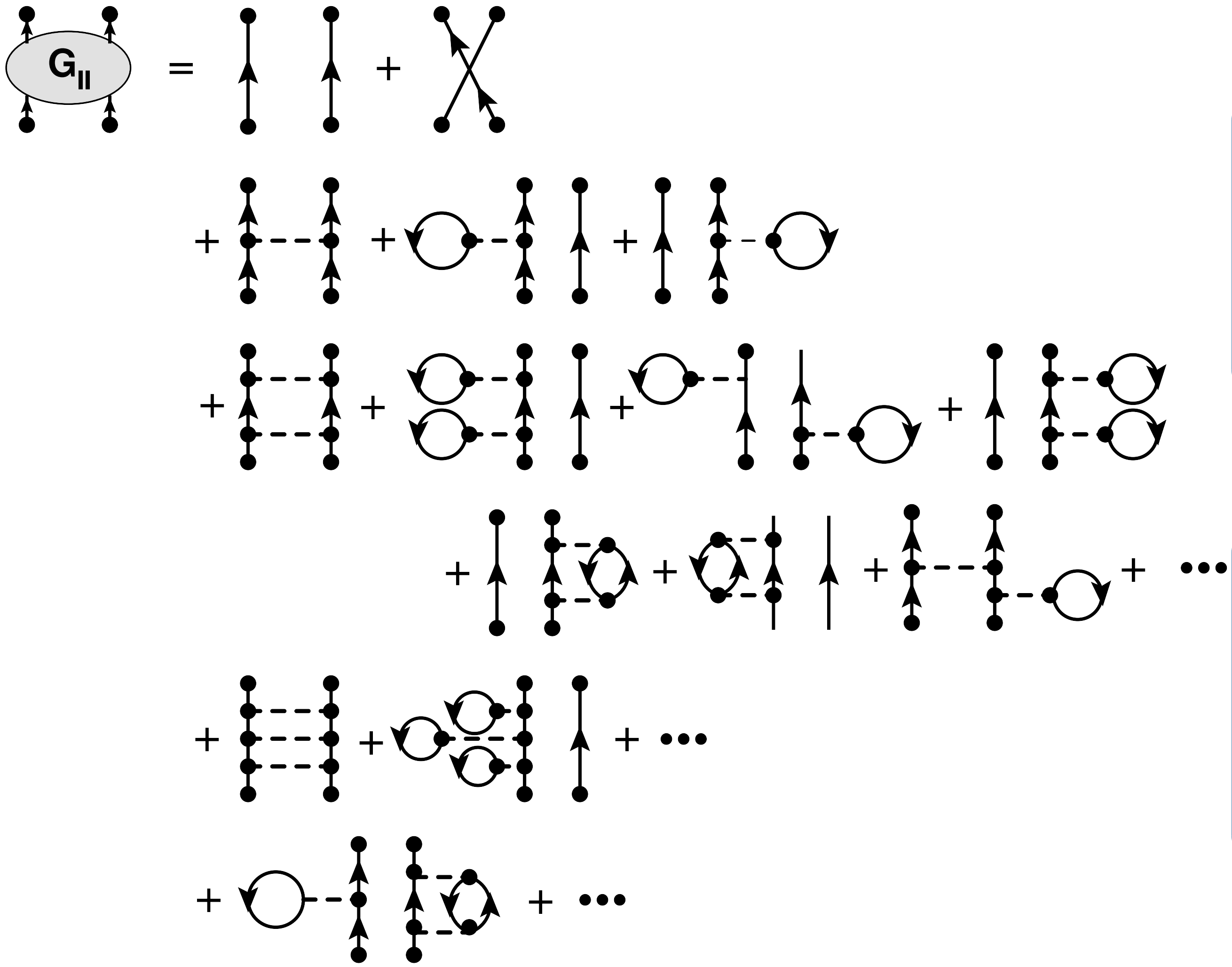
Nuclei



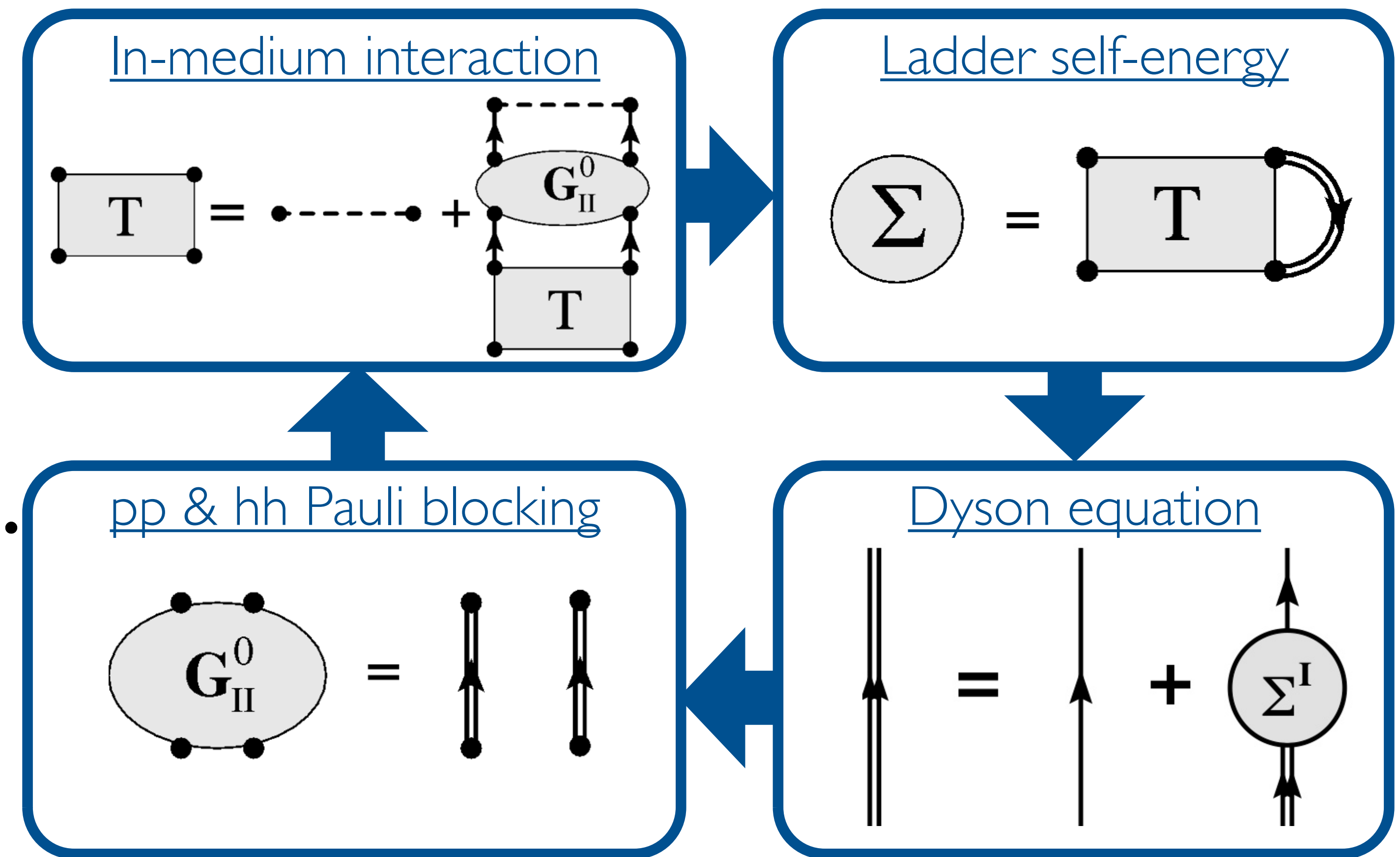
Lead 208
β=(126-82)/208=0.2

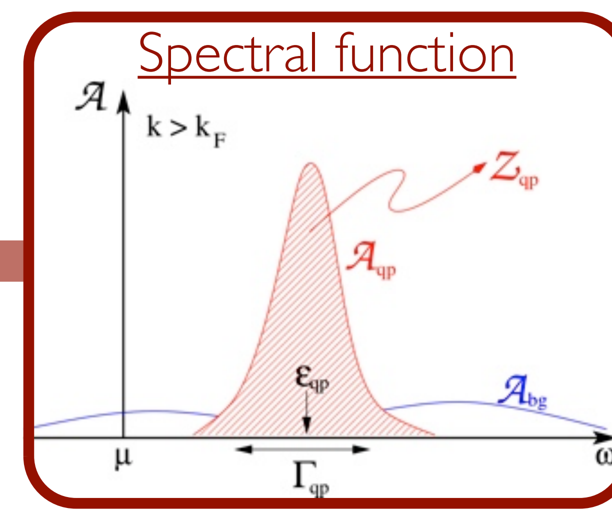
Experimentally unknown!

Self-consistent Green's functions



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)

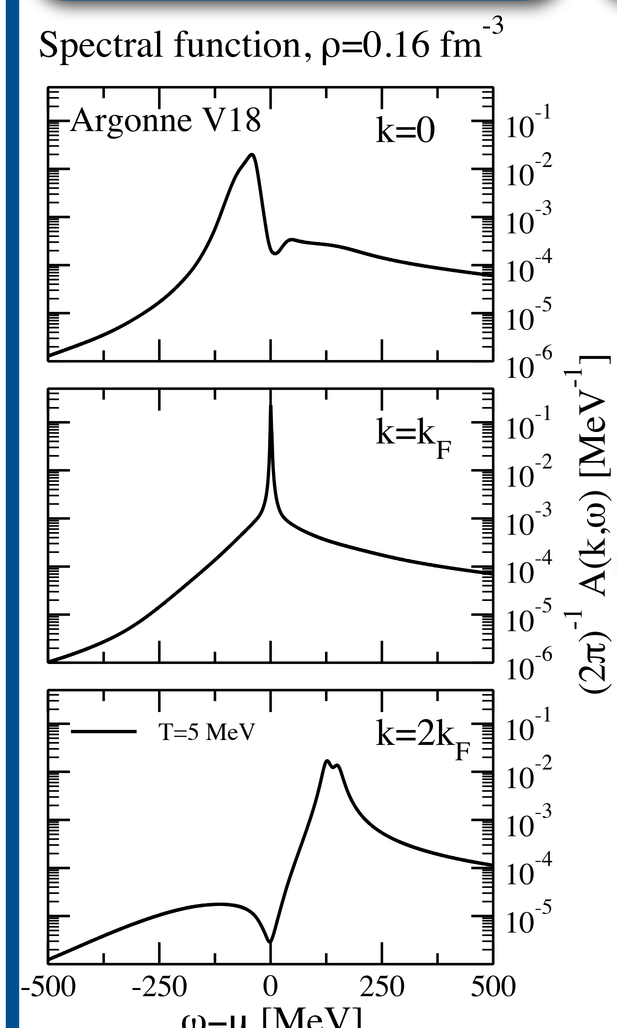
Self-consistency, pp+hh & full off-shell effects
Finite temperature

Self-consistent Green's functions

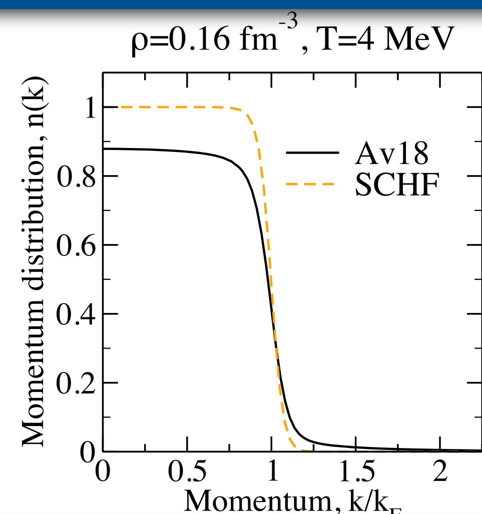
Microscopic properties

Bulk properties

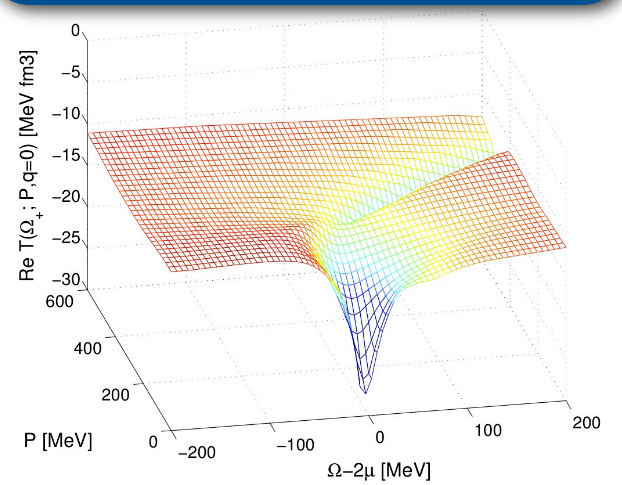
Spectral function



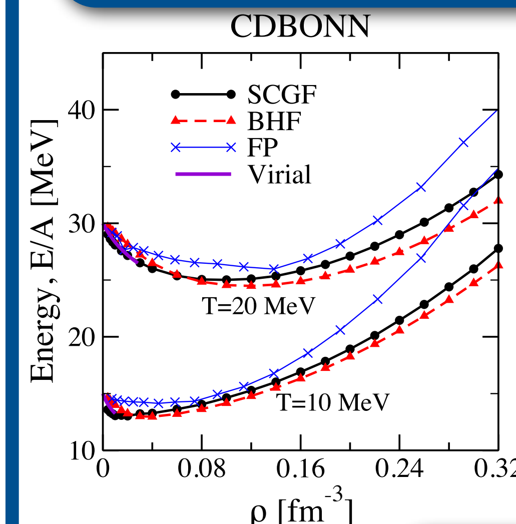
Momentum distribution



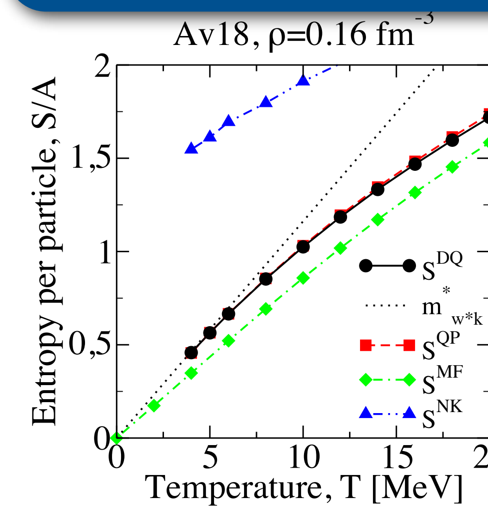
In-medium interaction



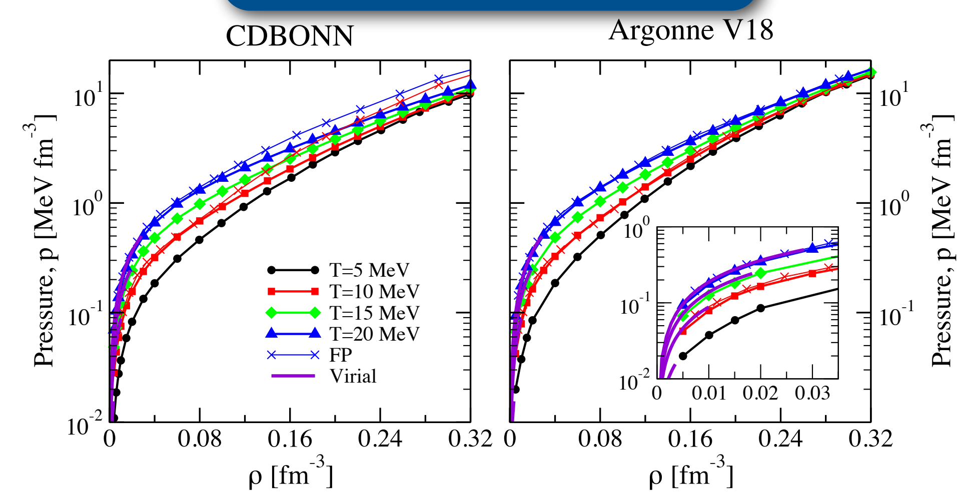
Total Energy



Entropy



Equation of State

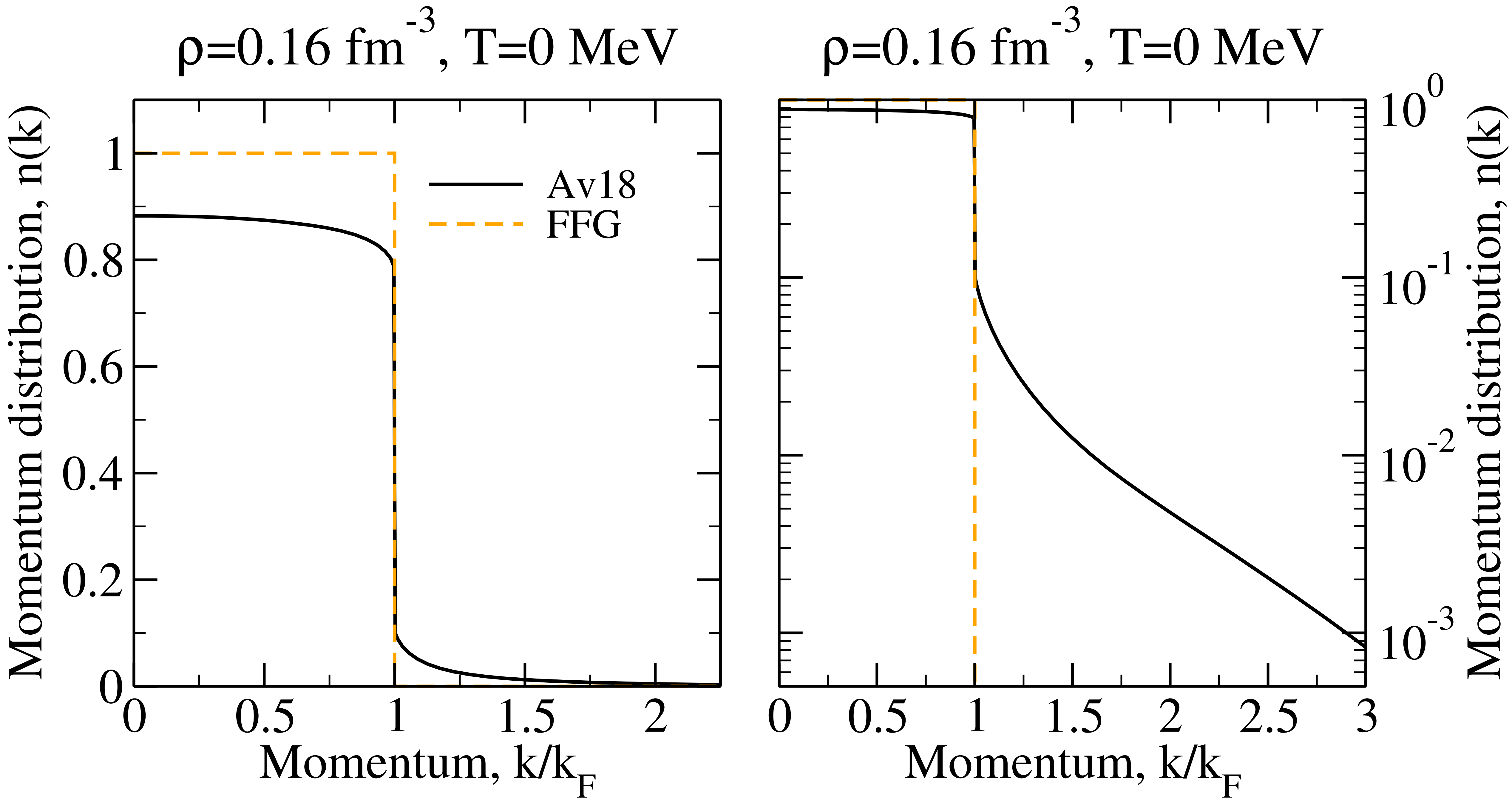


+ Transport

Momentum distribution in SNM

Single-particle occupation

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



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

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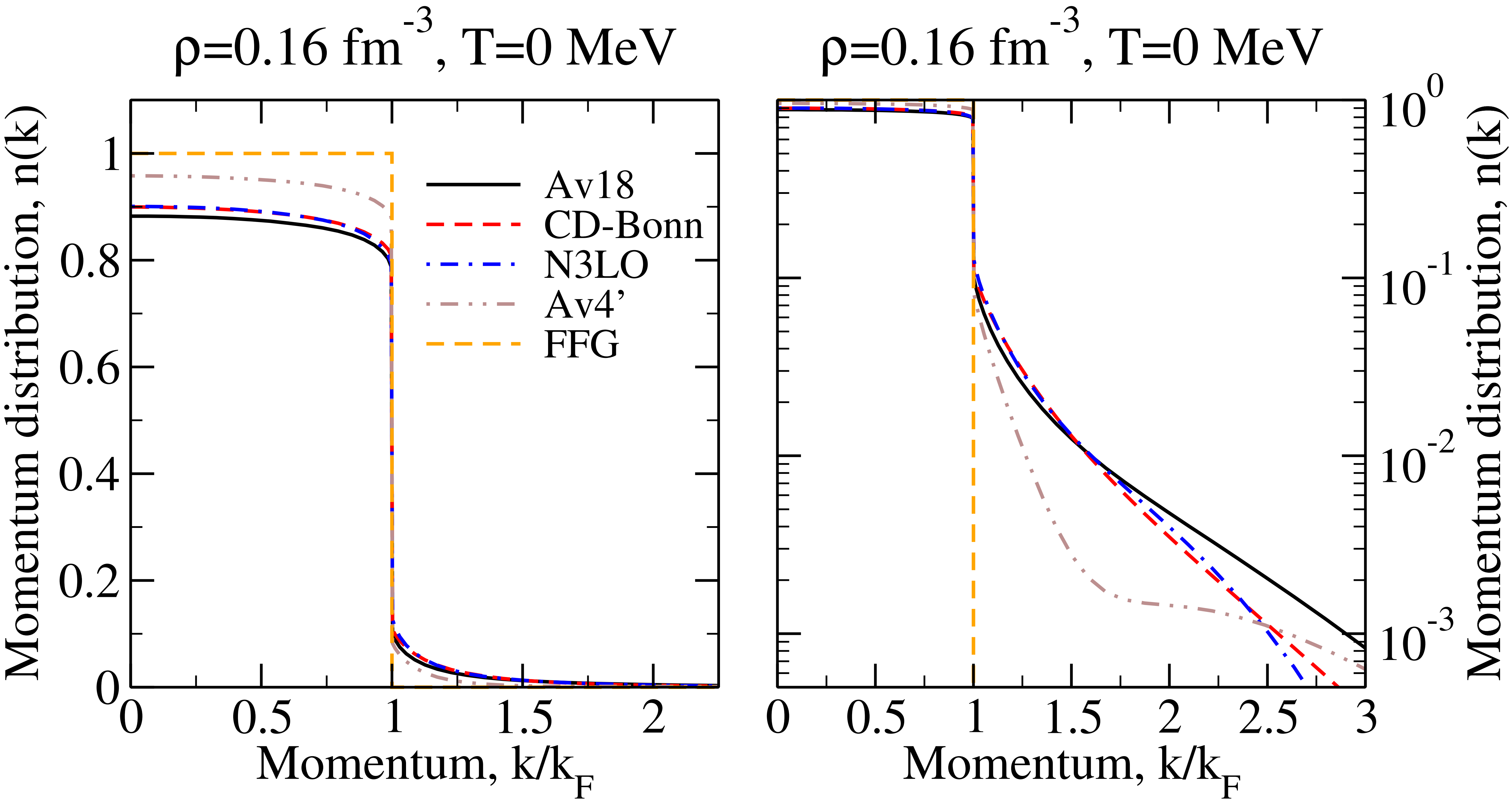

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- Dependence on NN interaction under control

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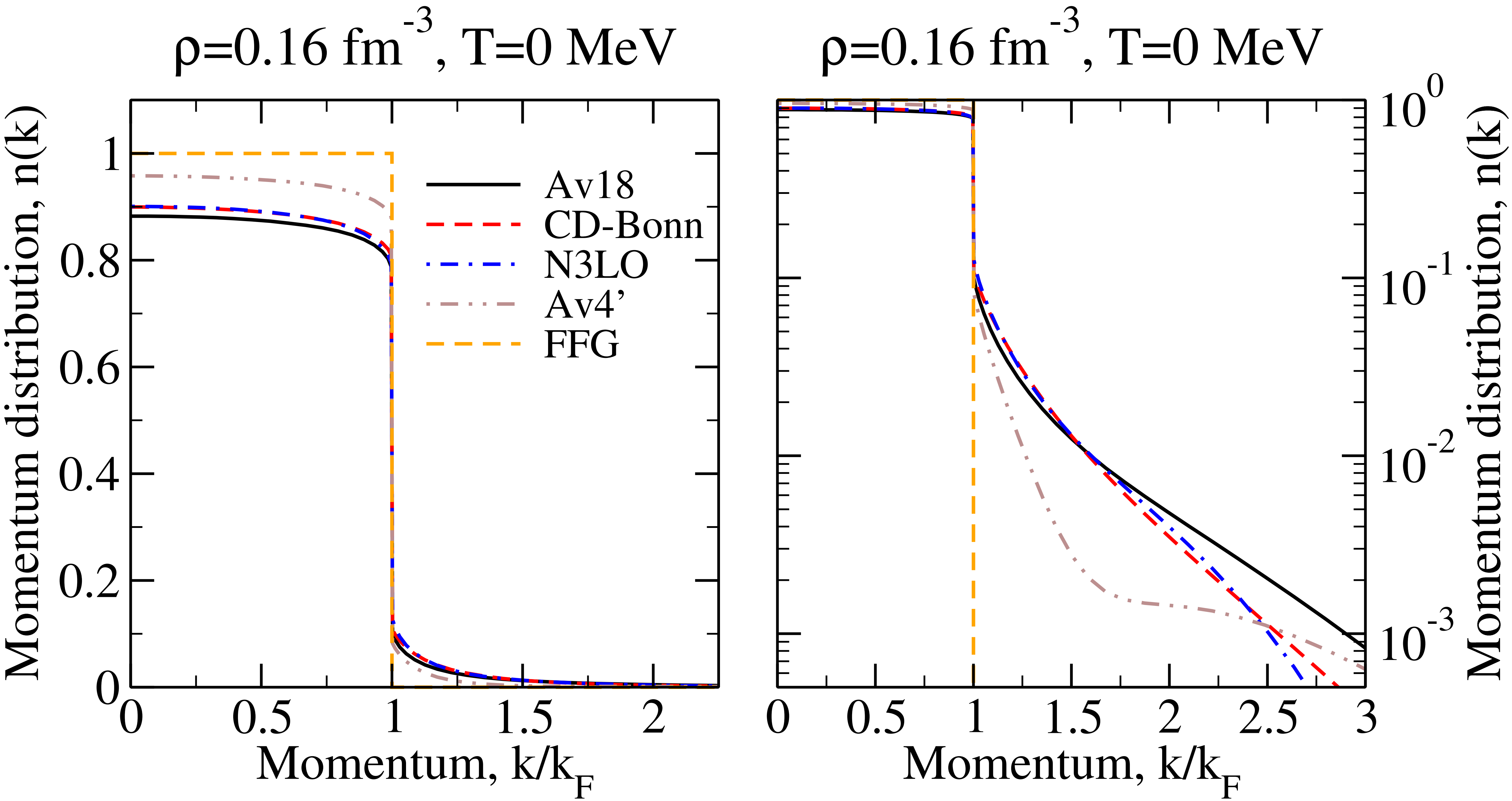
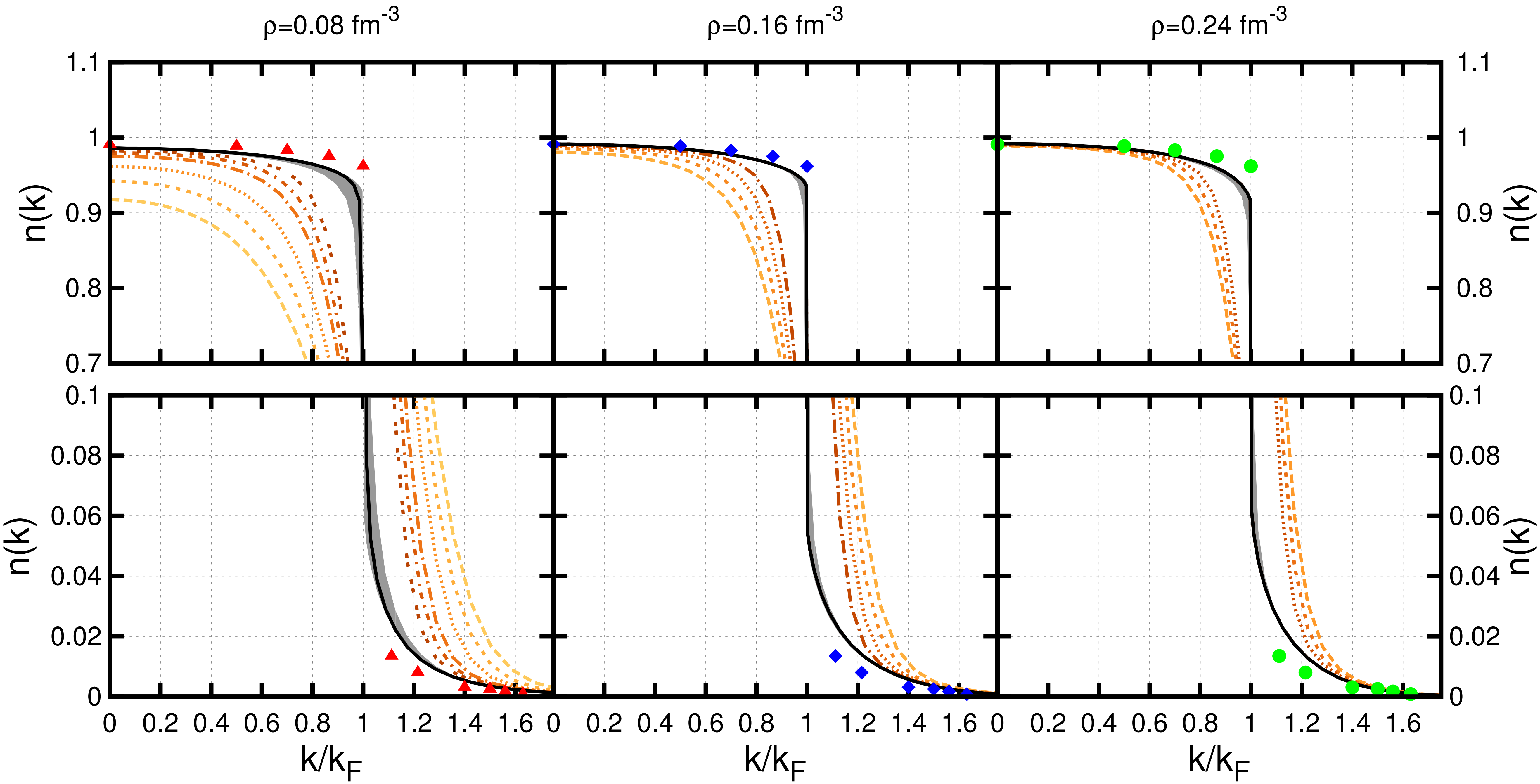


- 11-13% depletion at low k, population at high k
- Dependence on NN interaction under control
- T=0 extrapolated from finite T

Momentum distribution in PNM

CIMC vs SCGF



- Good agreement far from k_F
- Almost uncorrelated system at low density
- $NNLO_{opt}$ potential

Roggero, Mukherjee, Pederiva *PRL* **112**, 221103 (2014)

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The reach of ab initio: 2014

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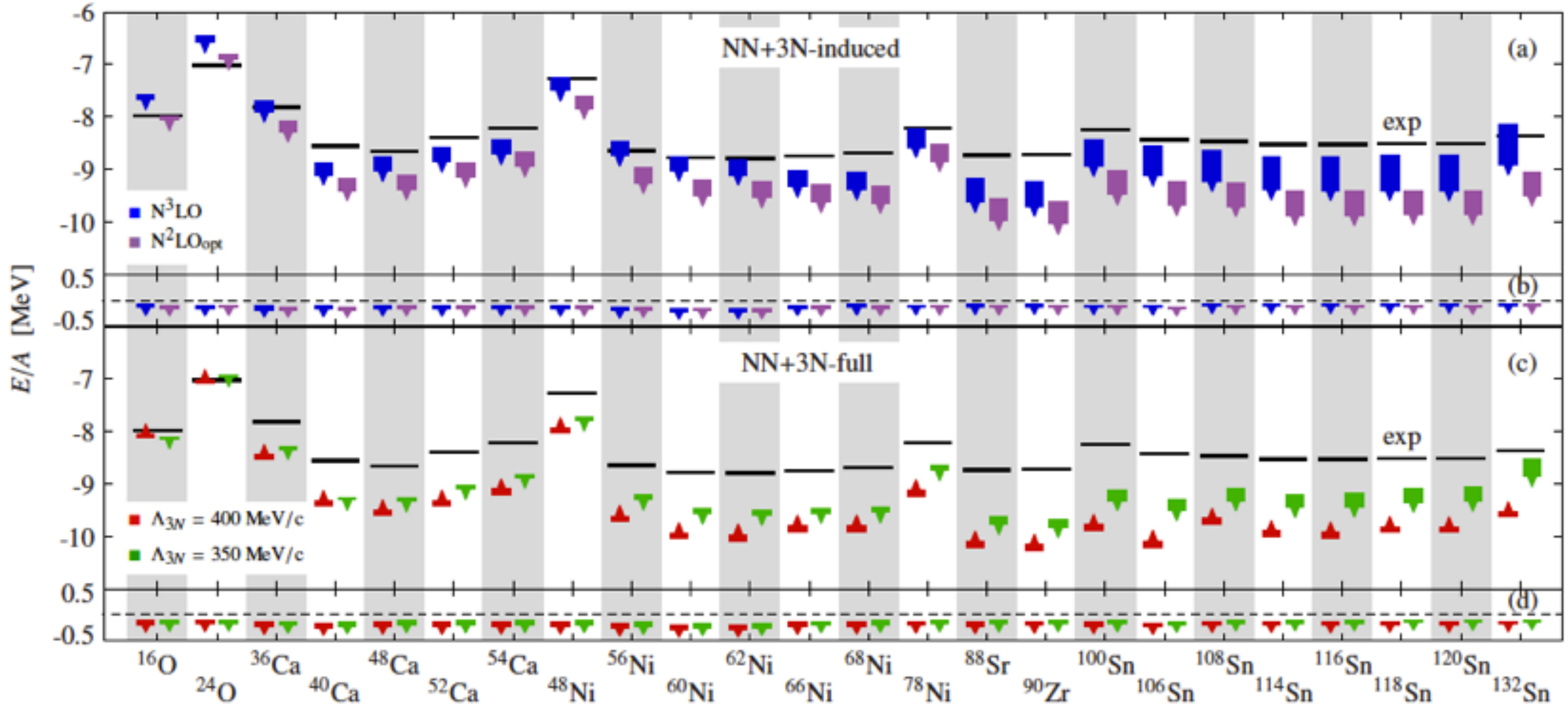

Binder, Langhammer, Calci & Roth, *PLB* ***736*** *119 (2014)*

- Consistent calculations up to A=132
- Many-body (CC) errors under control
- Overbinding even when 3NF included
- Radii are **too** small

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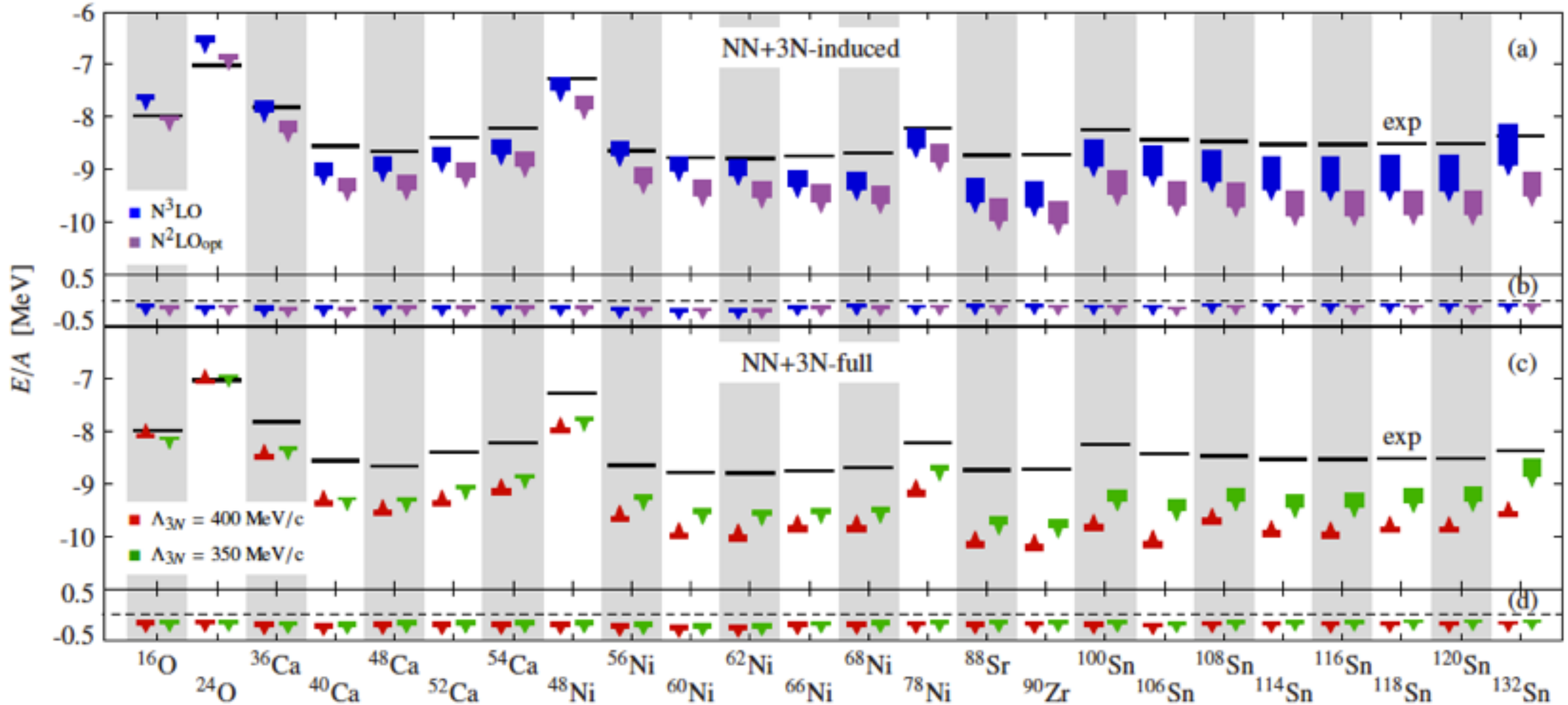
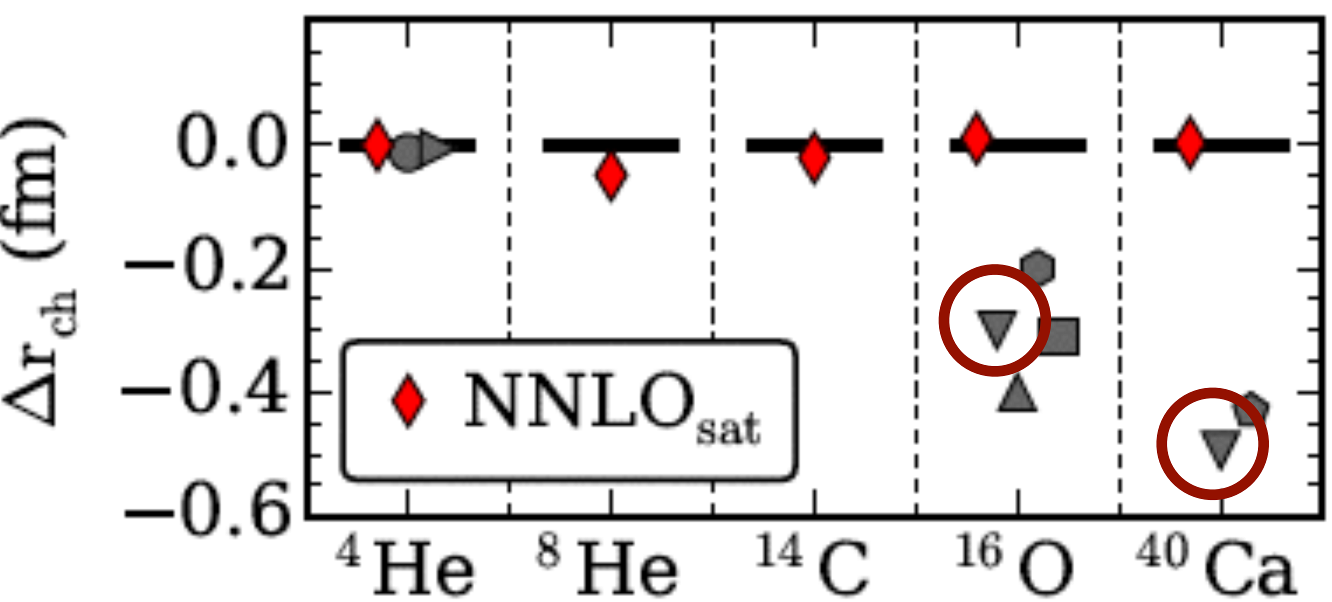


Binder, Langhammer, Calci & Roth, *PLB* ***736*** *119 (2014)*



Ekstrom, et al. arXiv:1502.04682

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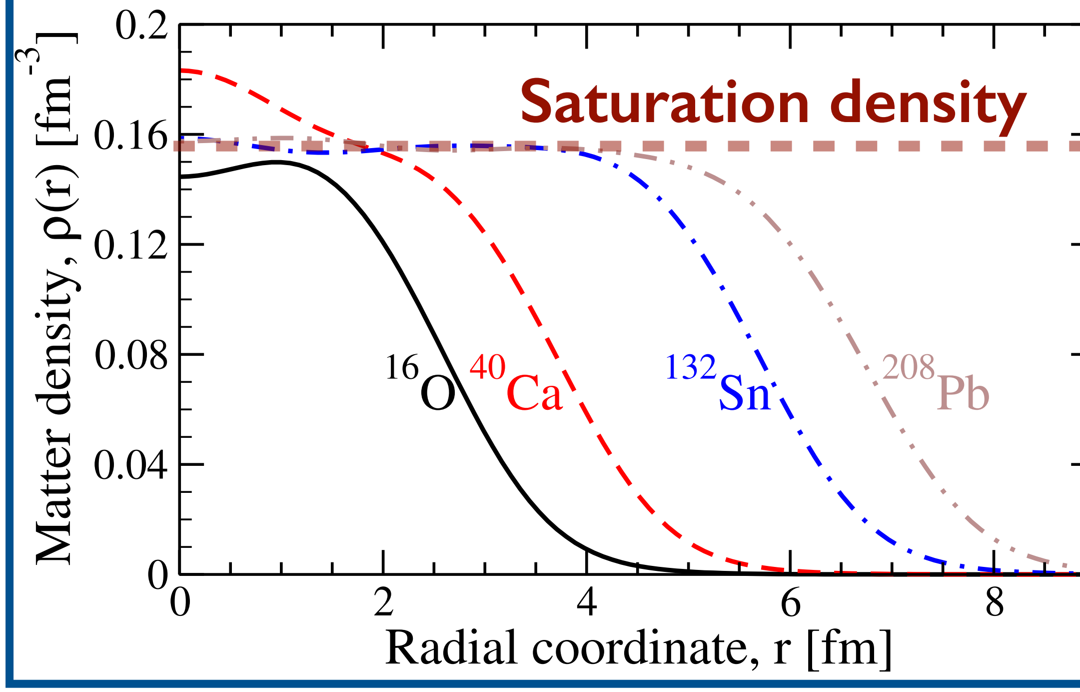
Nuclear matter

Bethe-Weiszacker Formula

$$\frac{B}{A} = a_V + a_s A^{-1/3} + \mathcal{O}(A^{-1})$$

+

Nuclear density systematics



$$R \approx 1.2 \left(\frac{0.16}{\rho_0}\right)^{1/3} A^{-1/3}\ \text{fm}$$

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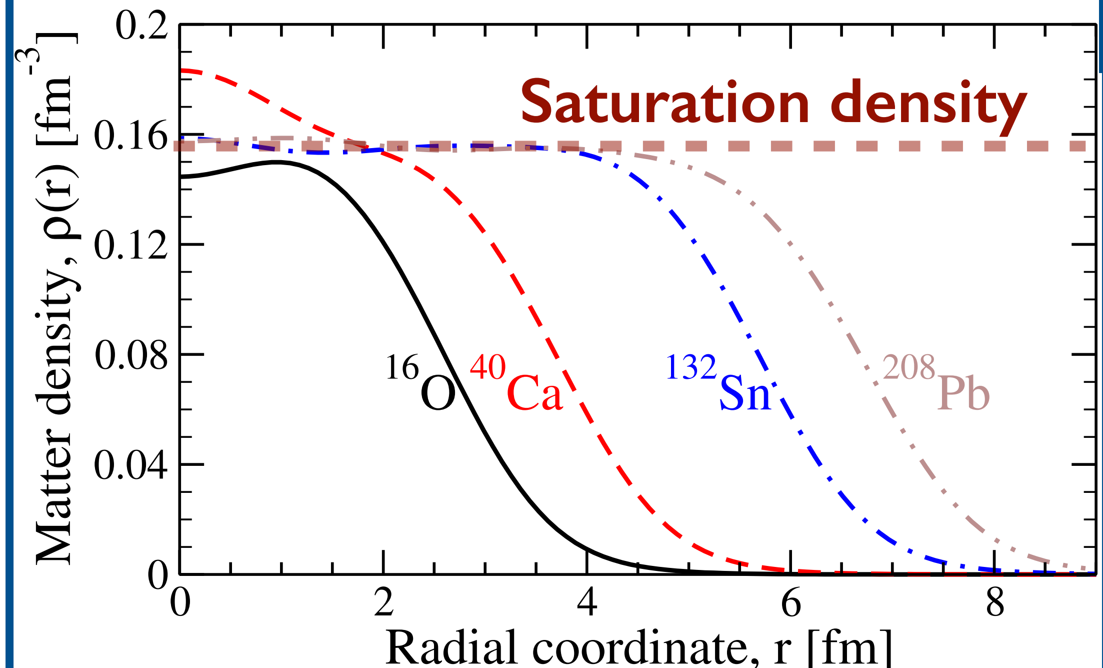

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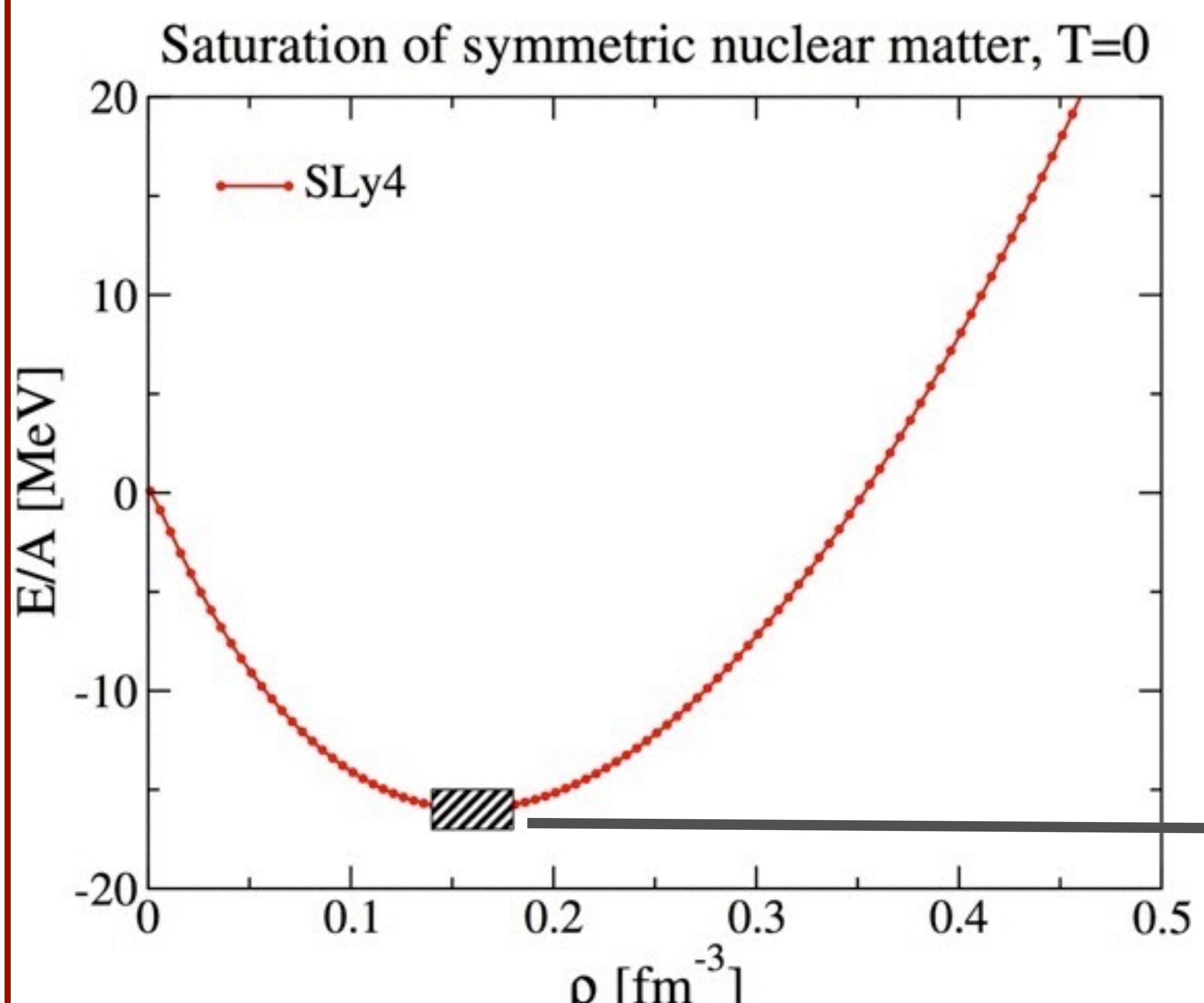

<u>Saturation point</u>

$$\rho_0 = 0.16 \text{ fm}^{-3}$$

$$\frac{E}{A} = -16 \text{ MeV}$$

$$K = 210 \text{ MeV}$$

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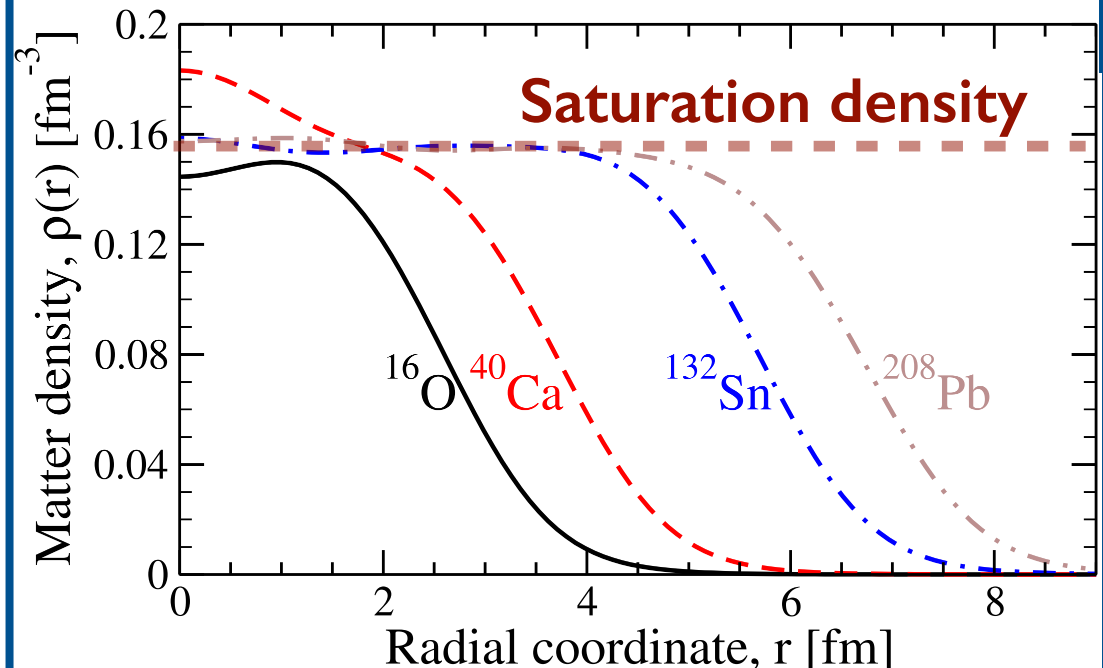

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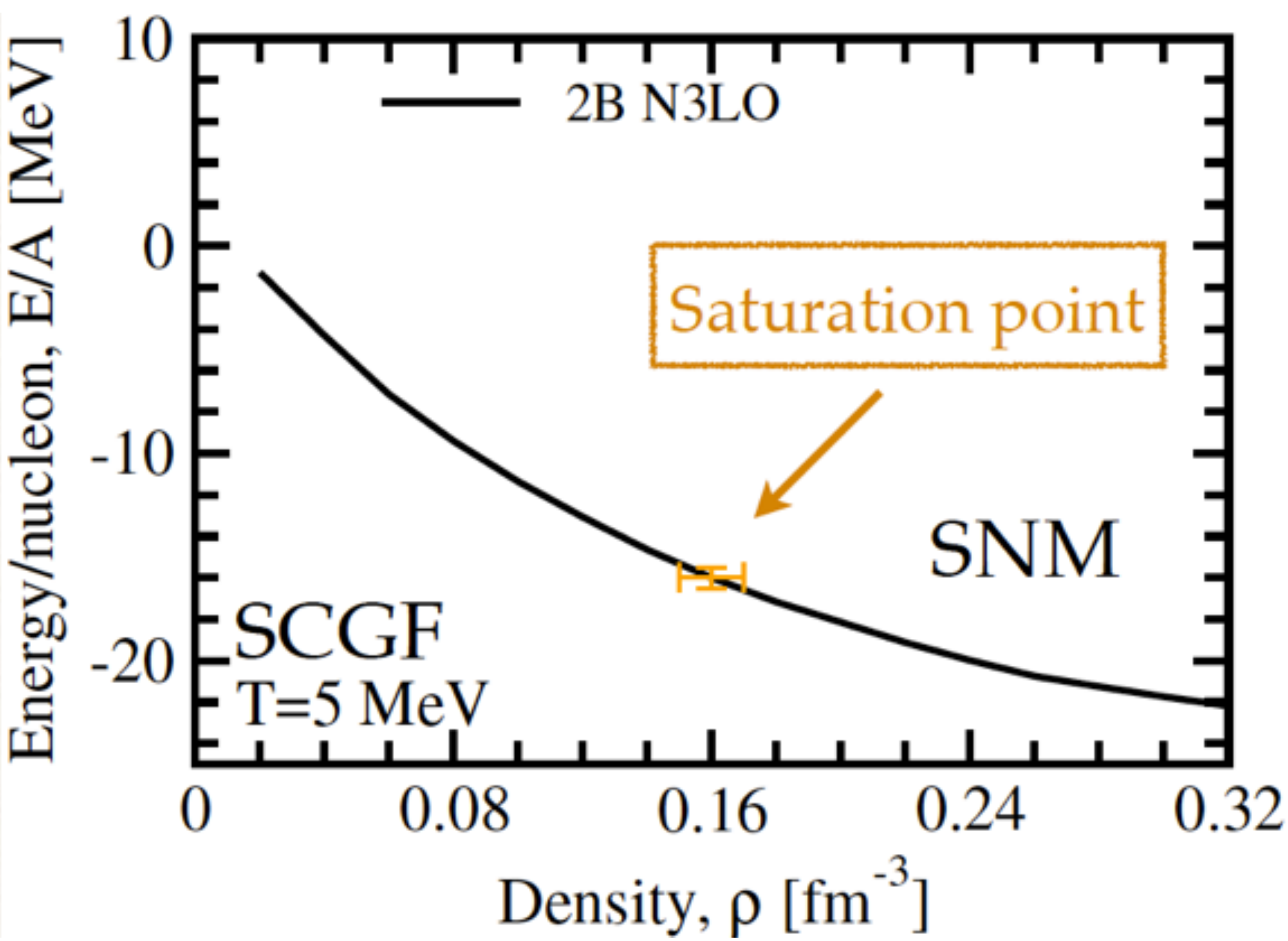

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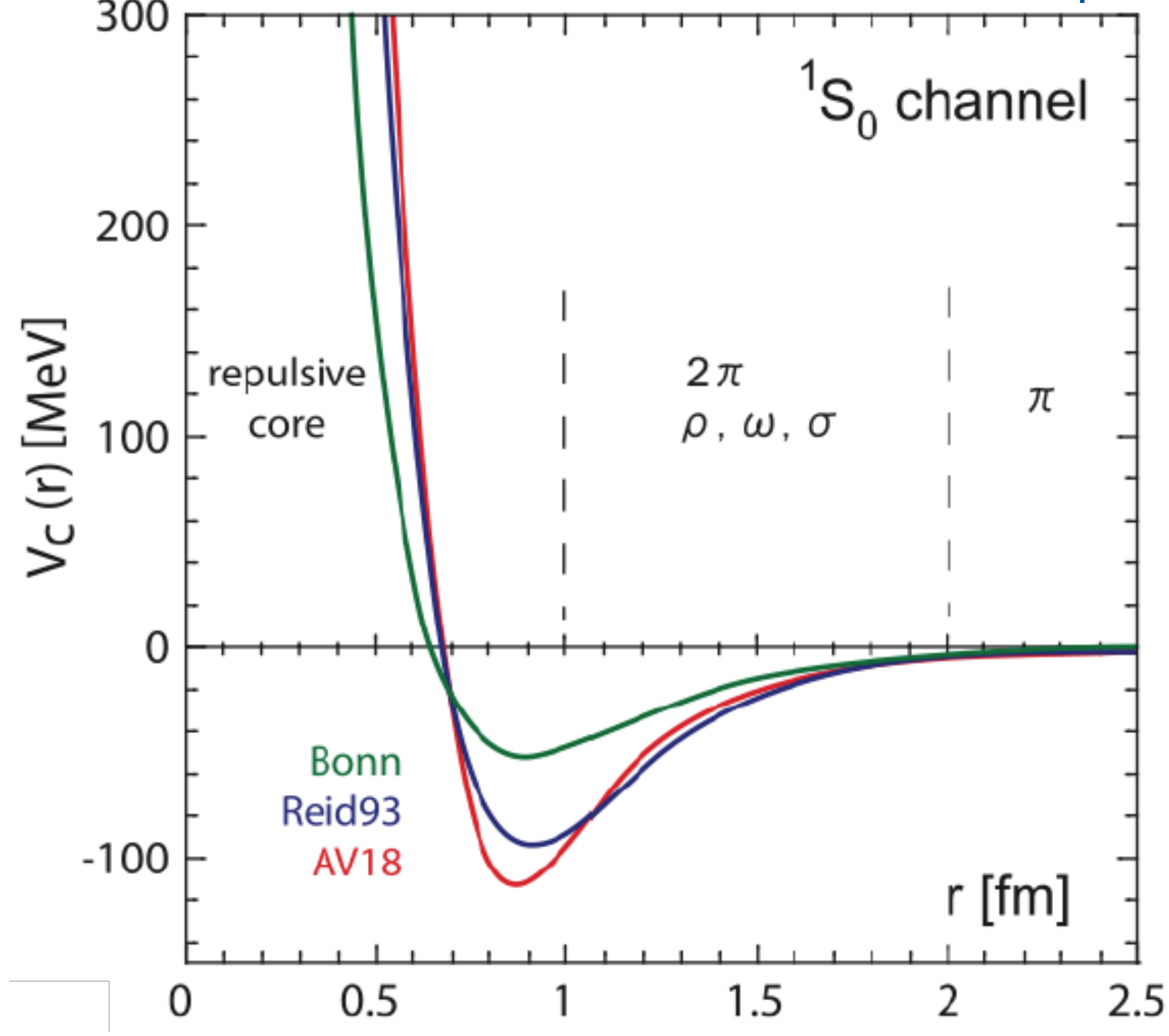
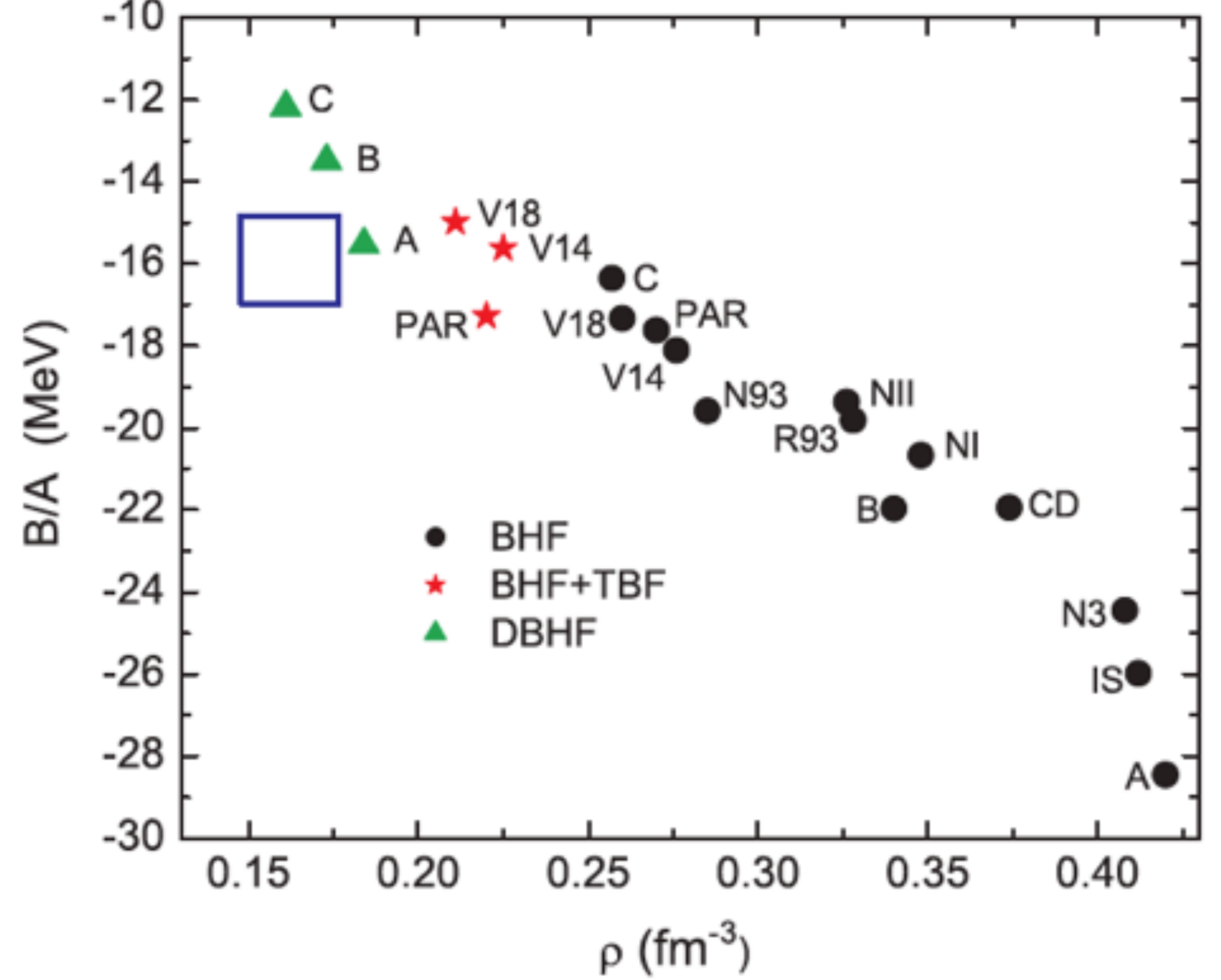
Complications

NN interaction is not unique



S. Aoki, et al. *Comput. Sci. Dis.* **1** 015009 (2008)

Saturation point of nuclear matter

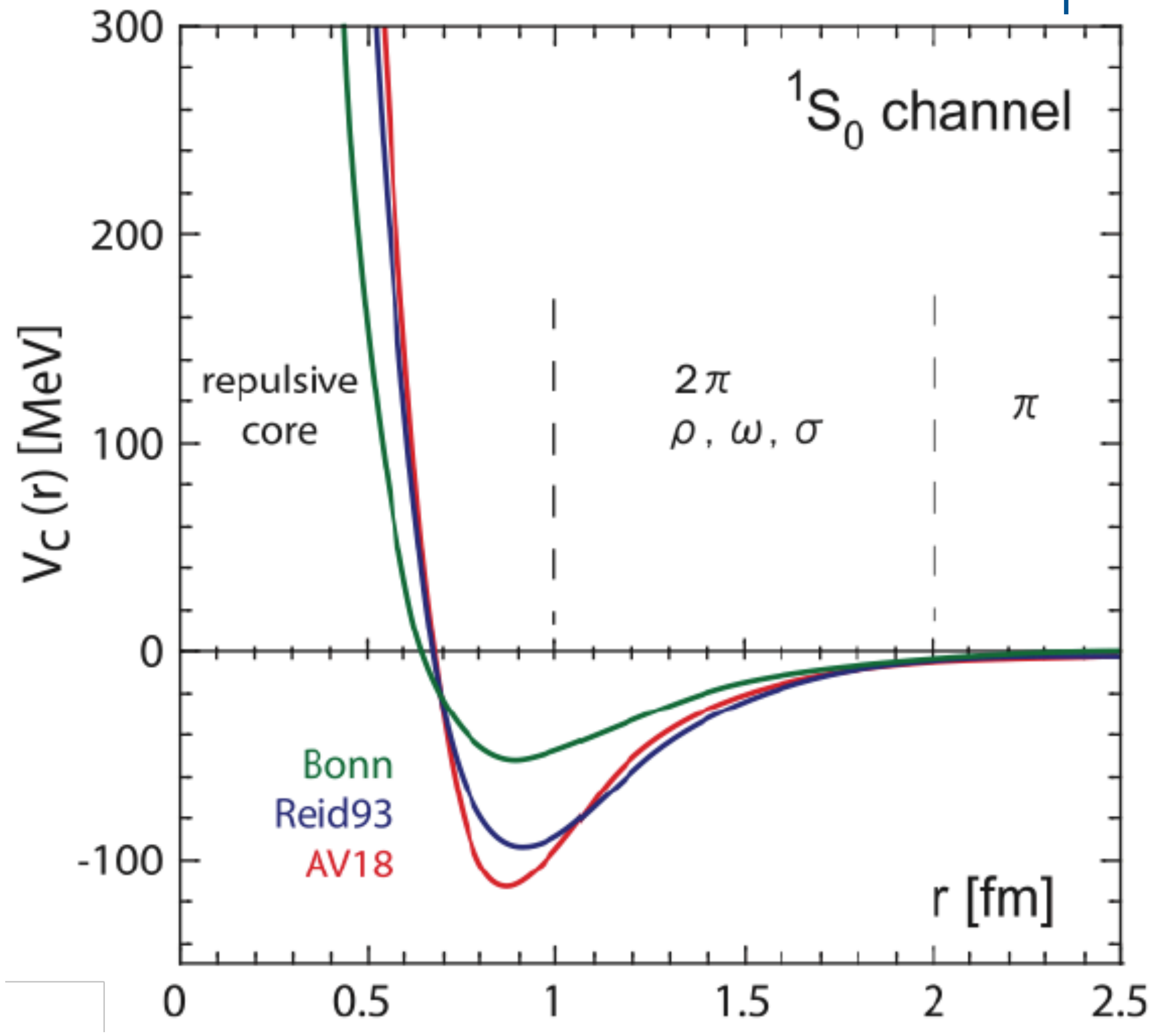


Li, Lombardo, Schulze et al. *PRC* **74** 047304 (2006)

- Three-body forces needed for saturation ✘

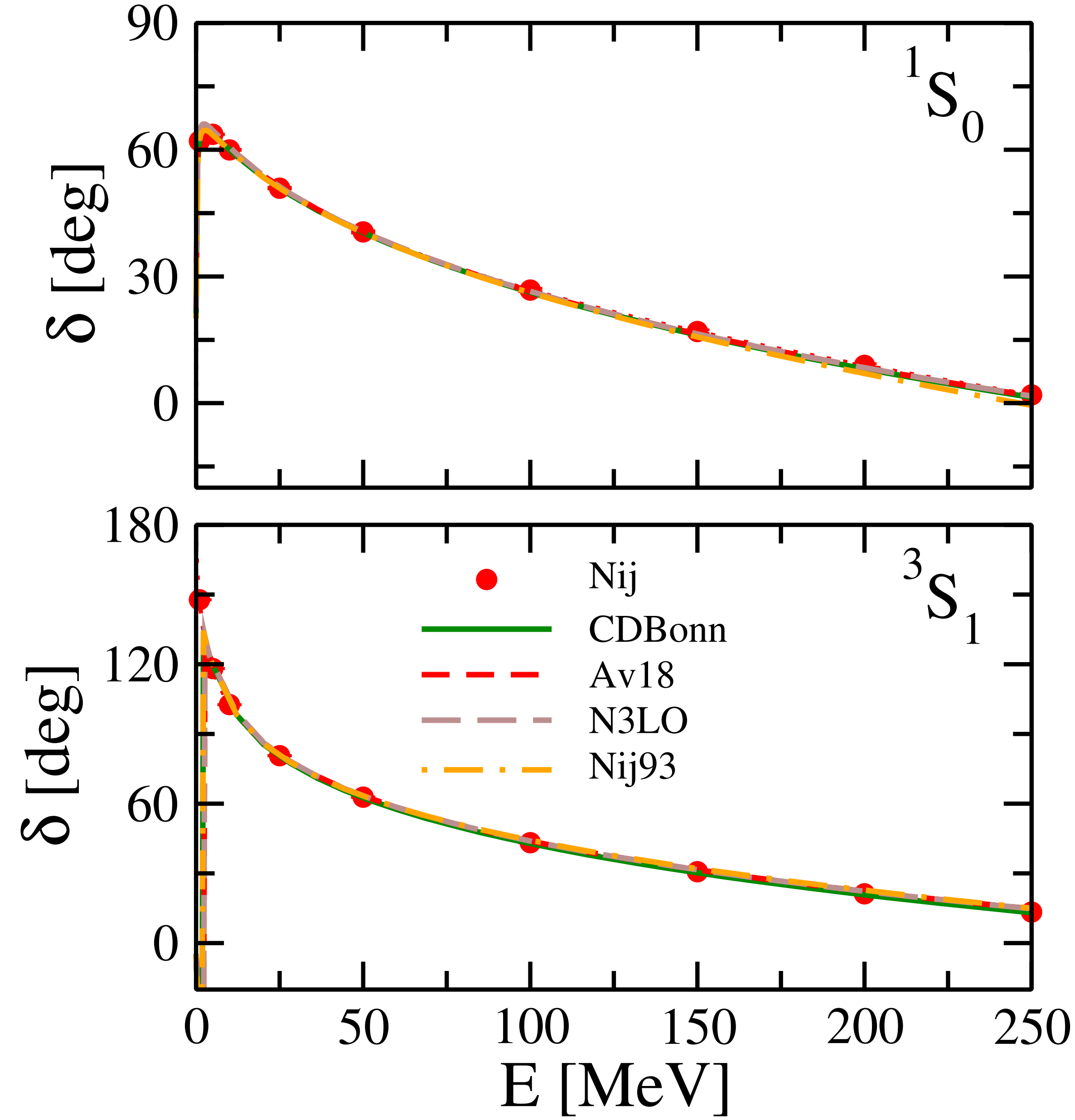
Complications

NN interaction is not unique



S. Aoki, et al. *Comput. Sci. Dis.* **1** 015009 (2008)

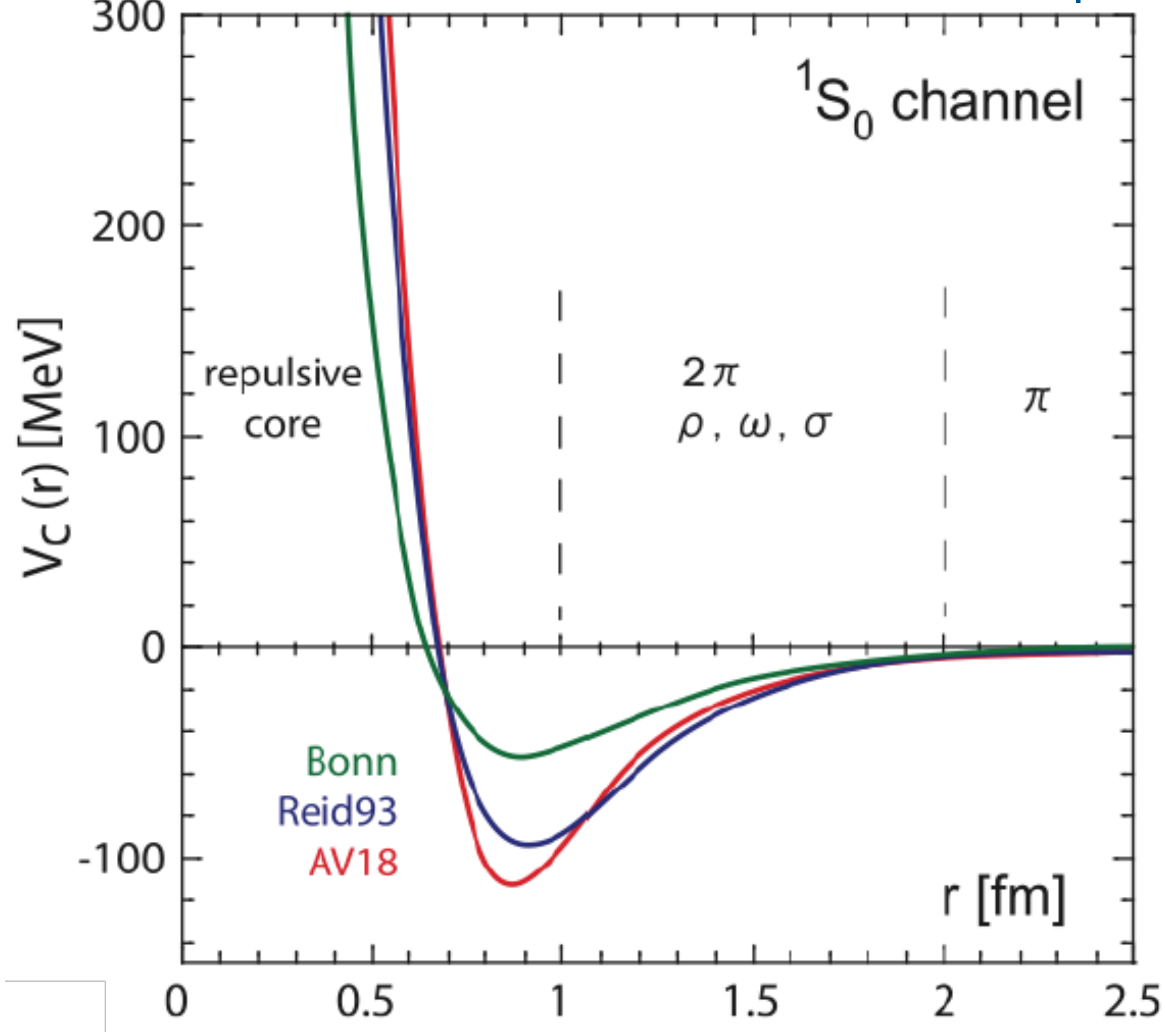
...but phase-shift equivalent!



- Three-body forces needed for saturation ✘
- Non-uniqueness of nucleon forces ✘

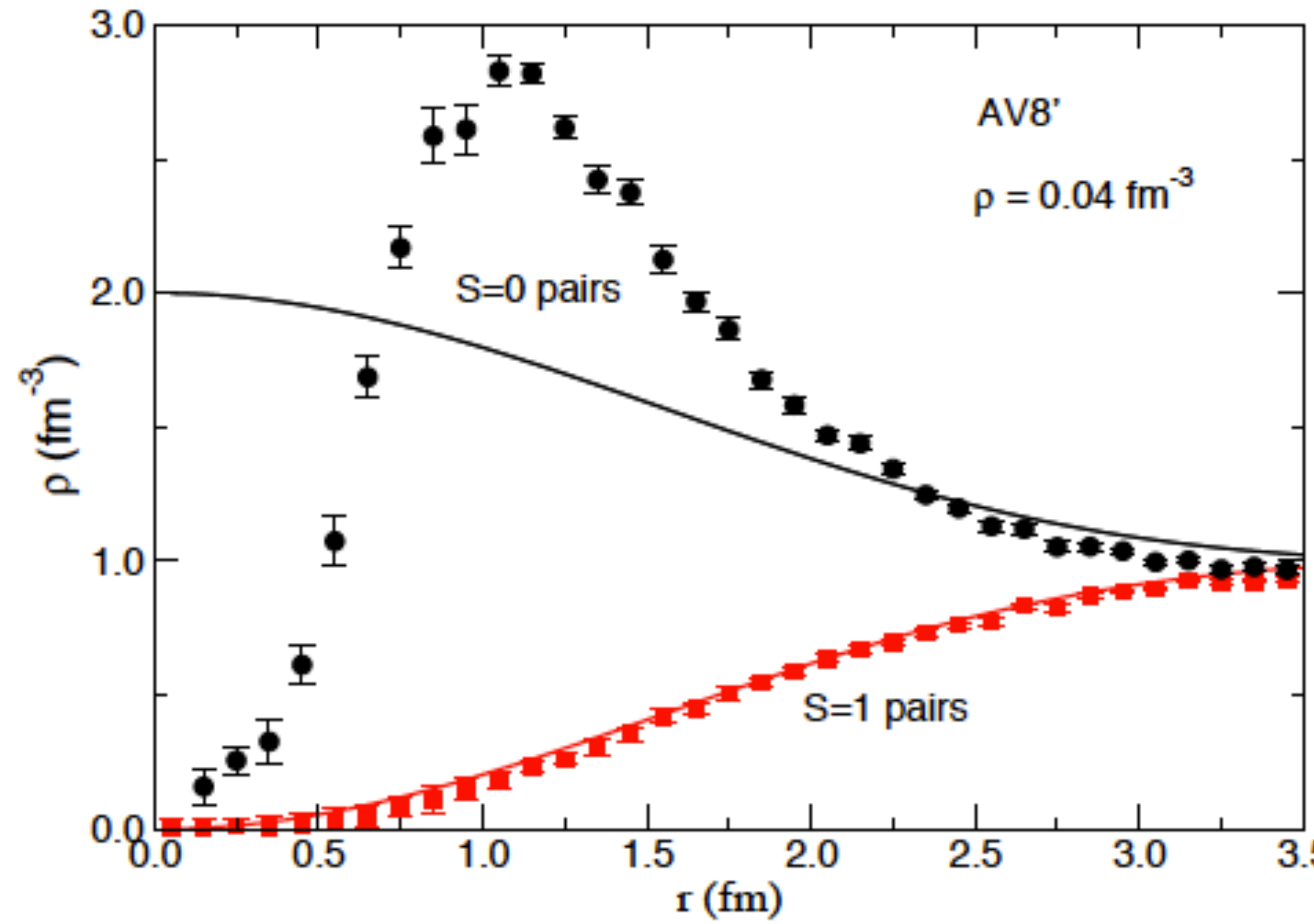
Complications

NN interaction is not unique



S. Aoki, et al. *Comput. Sci. Dis.* **1** 015009 (2008)

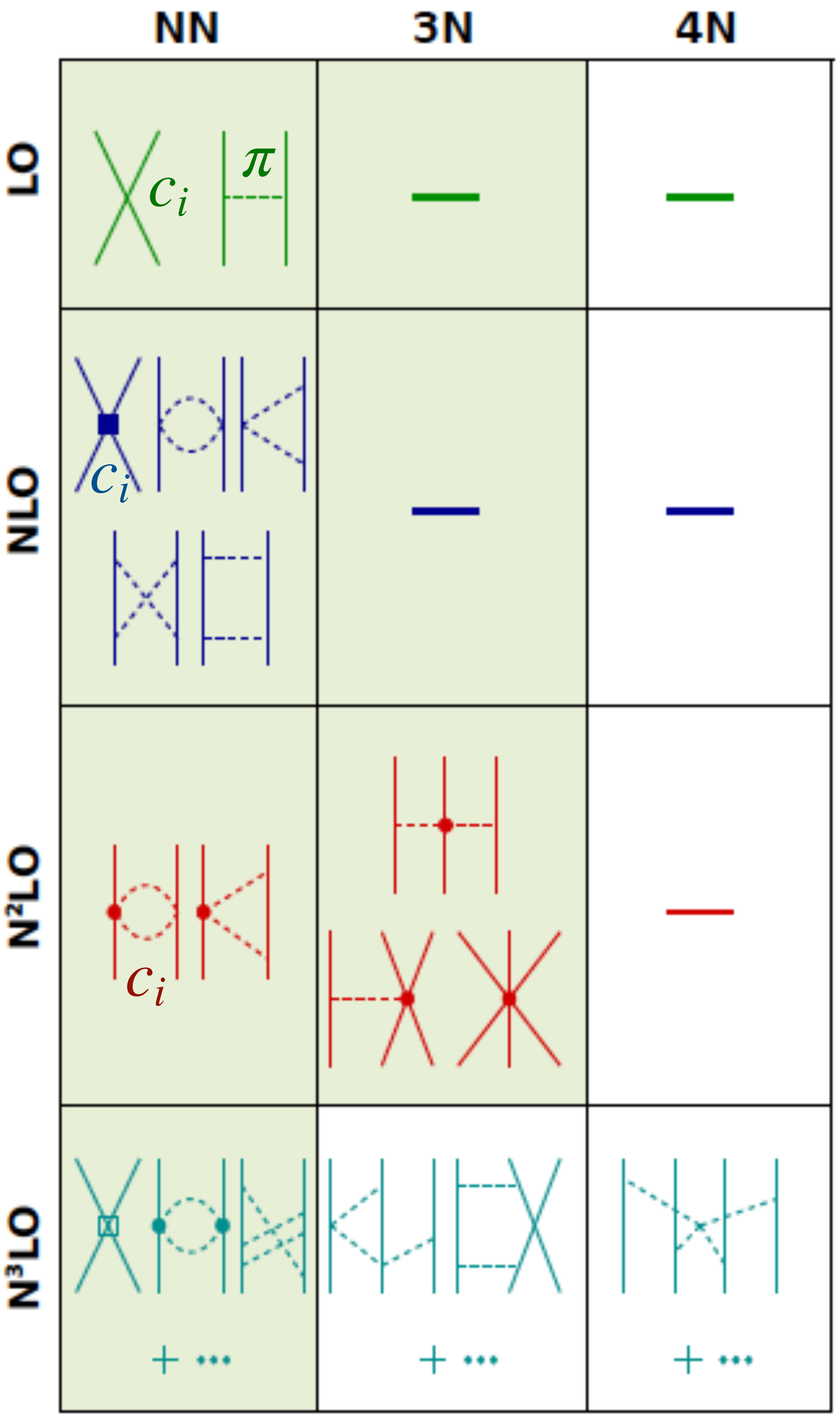
Strong short-range correlations



Carlson et al., *Phys. Rev. C* **68** 025802 (2003)

- Three-body forces needed for saturation ✘
- Non-uniqueness of nucleon forces ✘
- Short-range core needs many-body treatment ✘

NN forces from EFTs of QCD



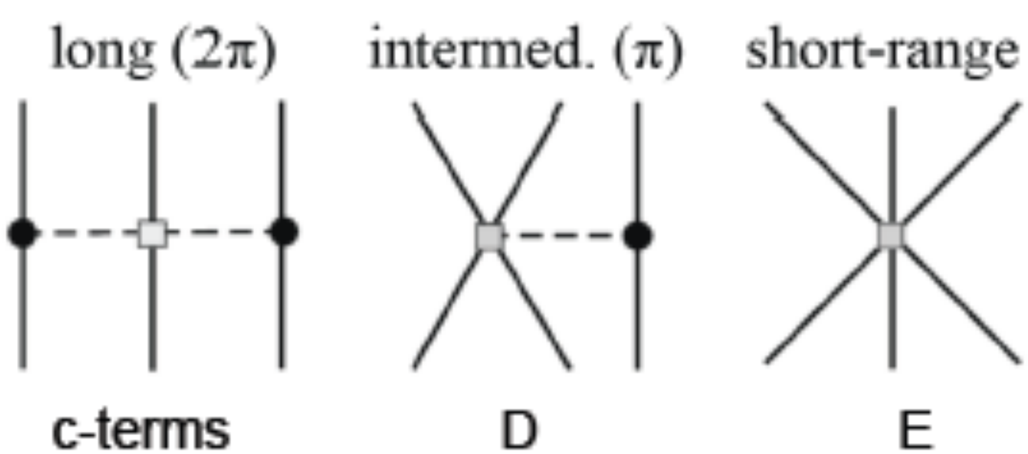
Robert Roth – TU Darmstadt – 04/2013

Chiral perturbation theory

- π and N as dof
- Systematic expansion
- 2N at N^{3}LO - LECs from πN, NN
- 3N at N^{2}LO - 2 more LECs
- (Often further renormalized)

$$\mathcal{O}\left(\frac{Q}{\Lambda}\right)$$

$$\Lambda \sim 1\ \mathrm{GeV}$$

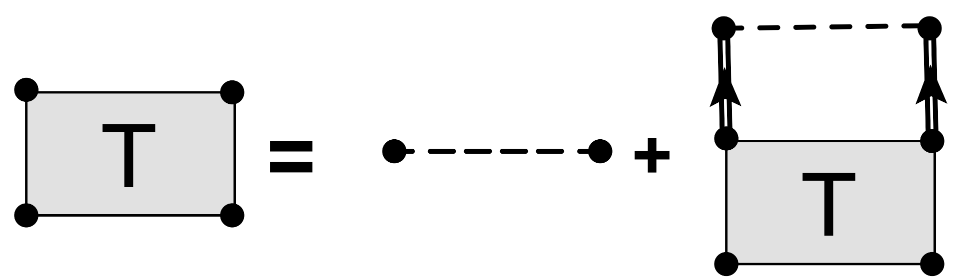


Weinberg, *Phys. Lett. B* **251** 288 (1990), *Nucl. Phys. B* **363** 3 (1991)
Entem & Machleidt, *Phys. Rev. C* **68**, 041001(R) (2003)
Tews, Schwenk *et al.*, *Phys. Rev. Lett.* **110**, 032504 (2013)

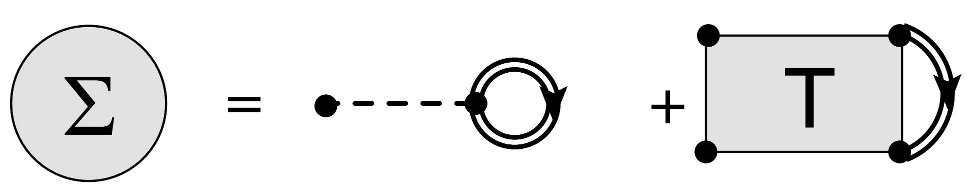
Ladder approximation with 3BF

Two-body interaction

In-medium T-matrix

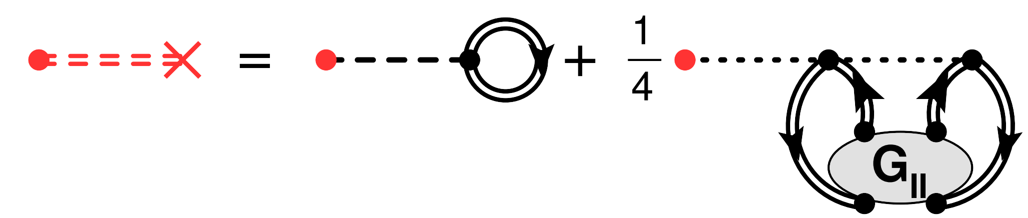


Self-energy



Effective interactions

Effective one-body force



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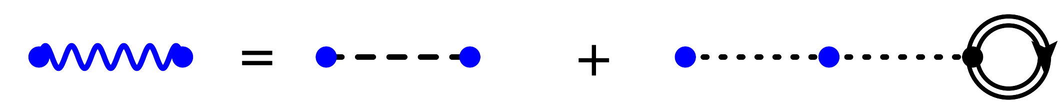
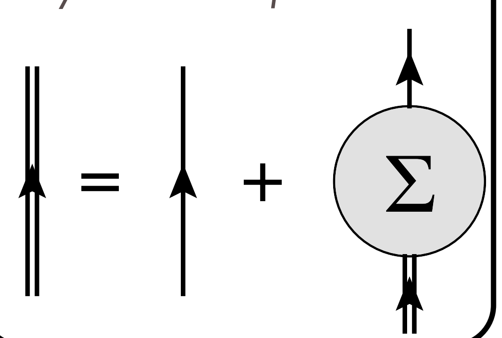


Dyson equation



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

Ladder approximation with 3BF

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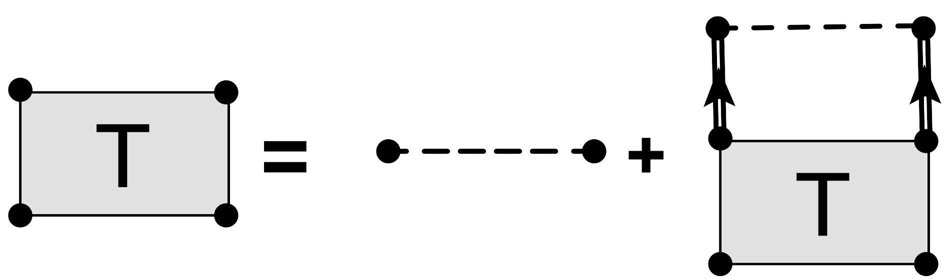
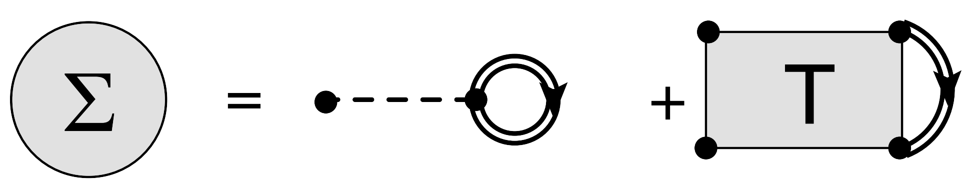


Self-energy



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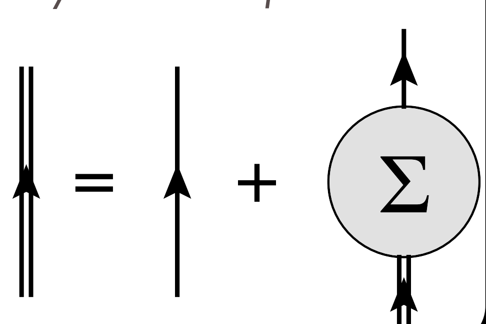

Effective interactions

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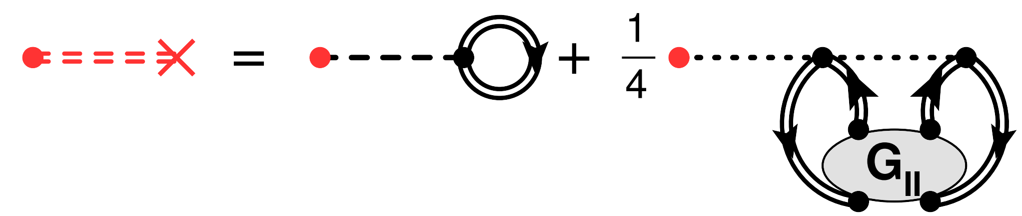

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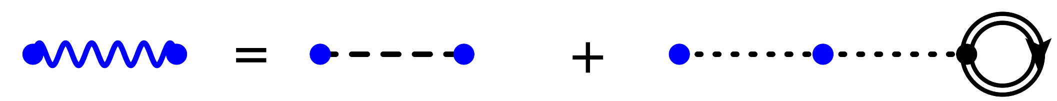

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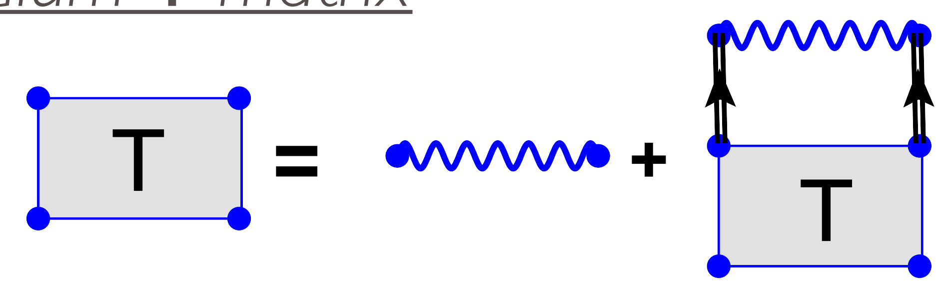

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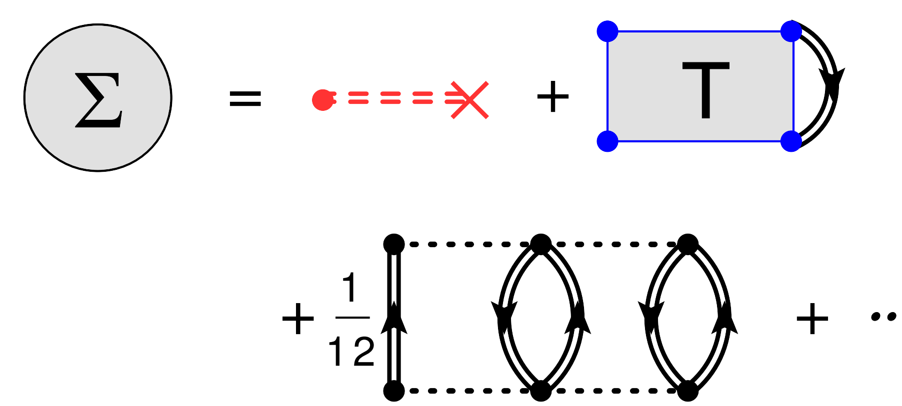

Carbone *et al.*, *PRC* **88** 054326 (2013)

Ladder approximation with 3BF

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Two-body interaction

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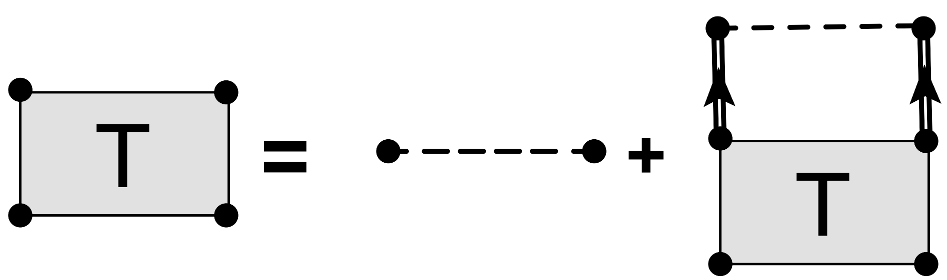

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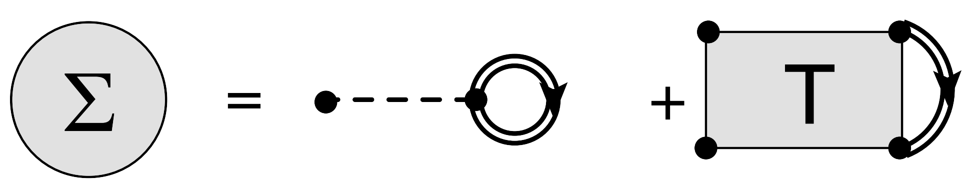

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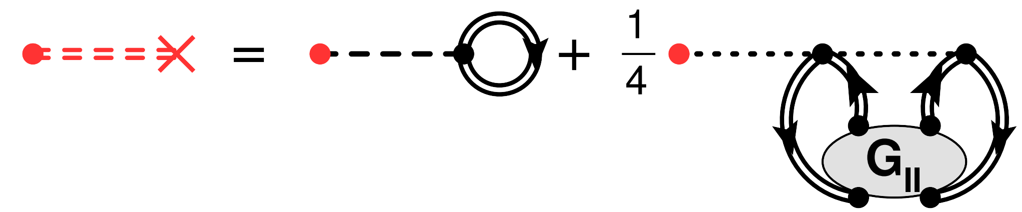

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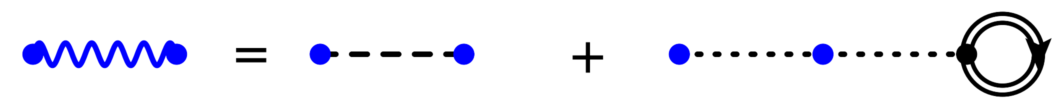

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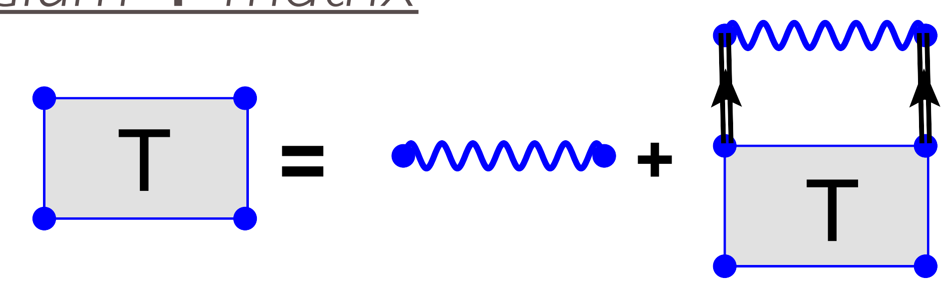

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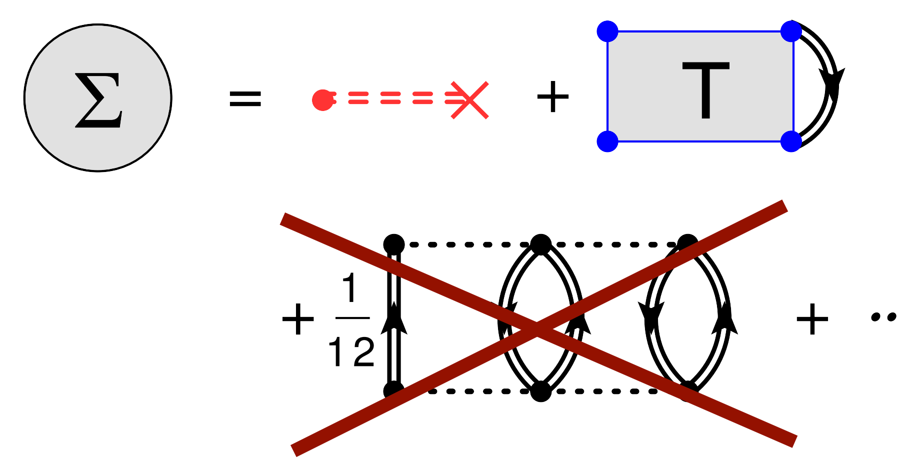
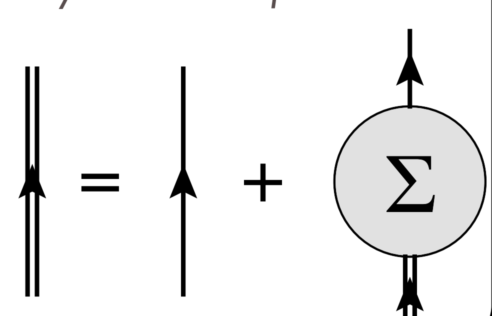


Dyson equation

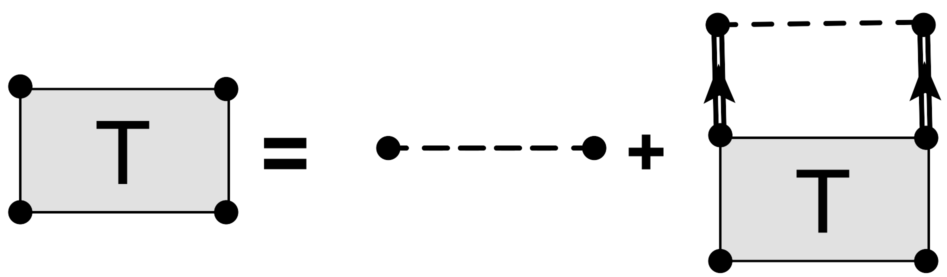


Carbone *et al.*, *PRC* **88** 054326 (2013)

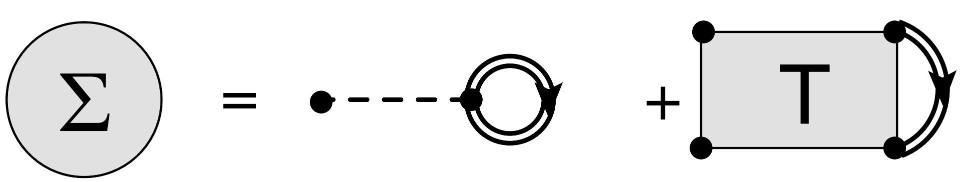
Ladder approximation with 3BF

Two-body interaction

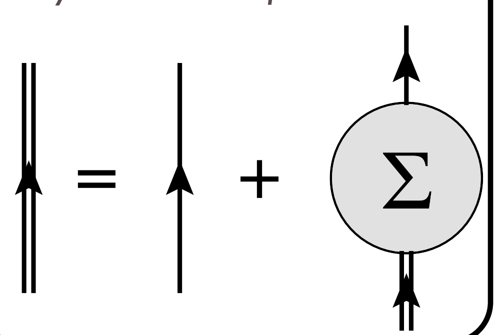
In-medium **T**-matrix



Self-energy

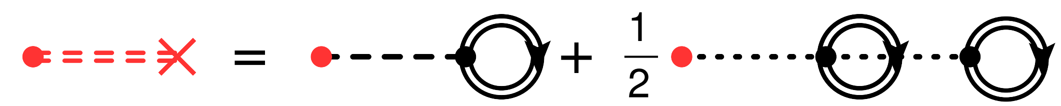


Dyson equation



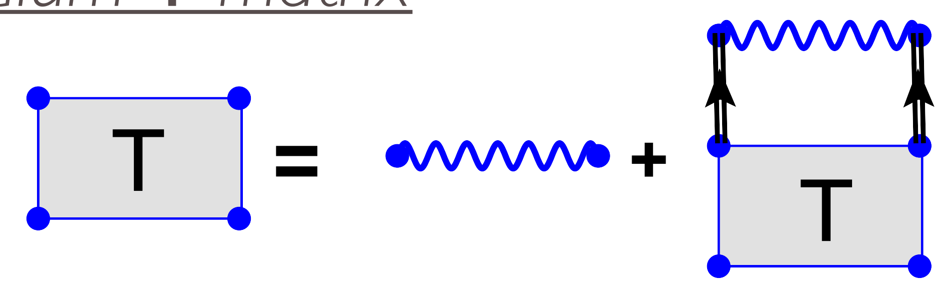
Effective interactions

Effective one-body force



Effective two-body force

In-medium **T**-matrix



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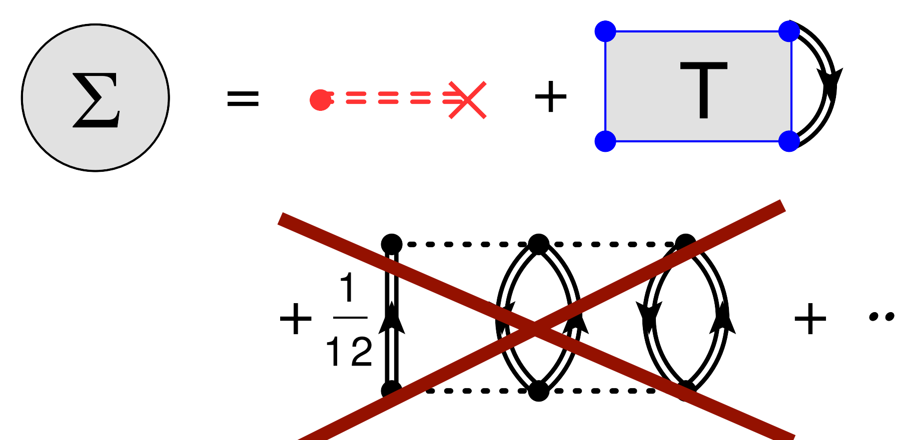

Carbone *et al.*, *PRC* **88** 054326 (2013)

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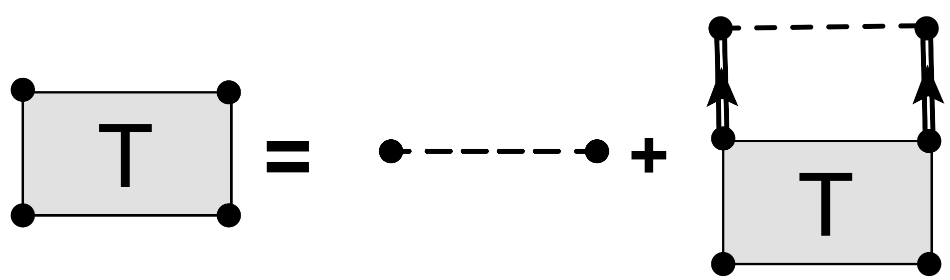
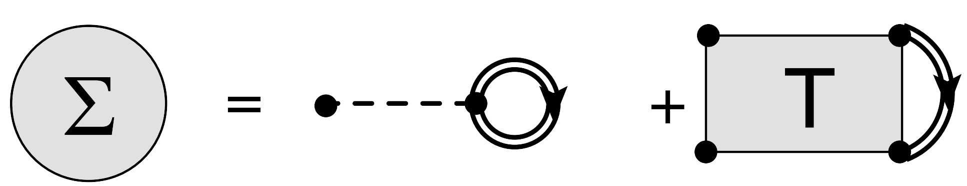


Self-energy



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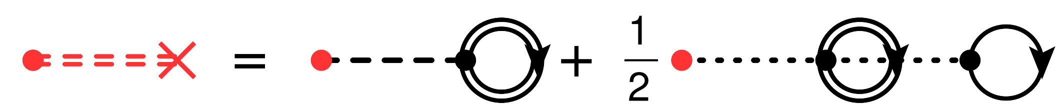

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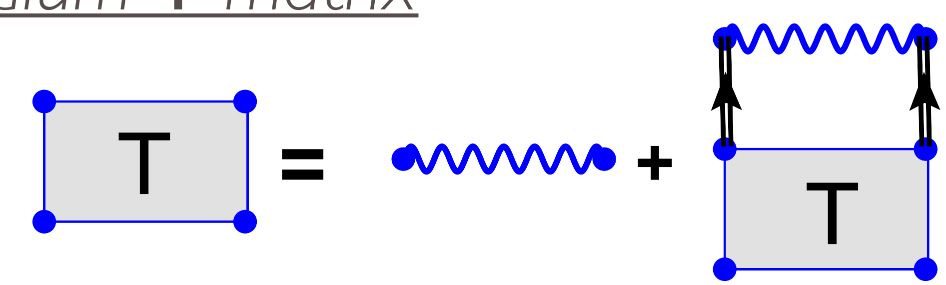
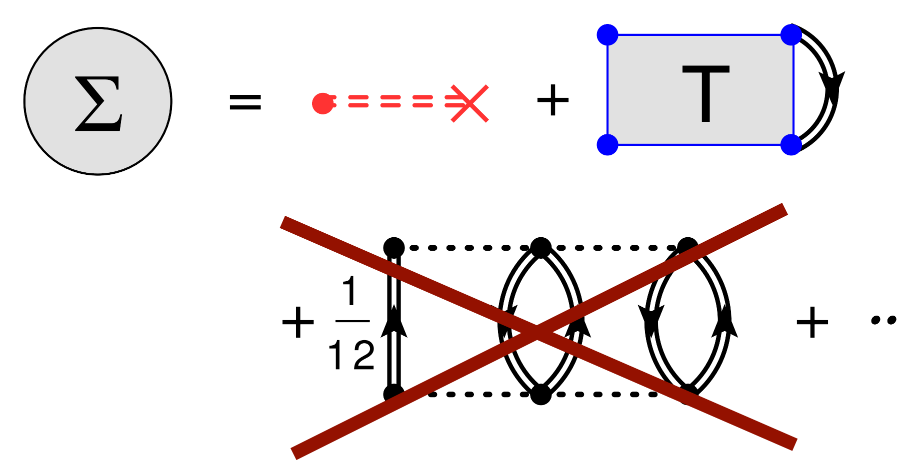
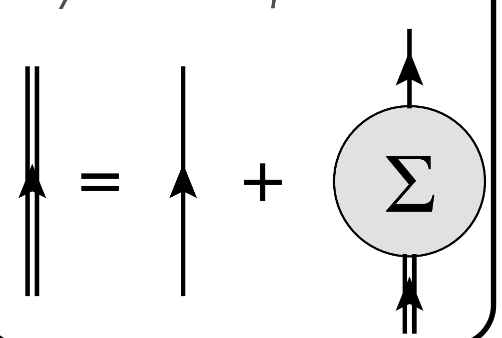


Self-energy



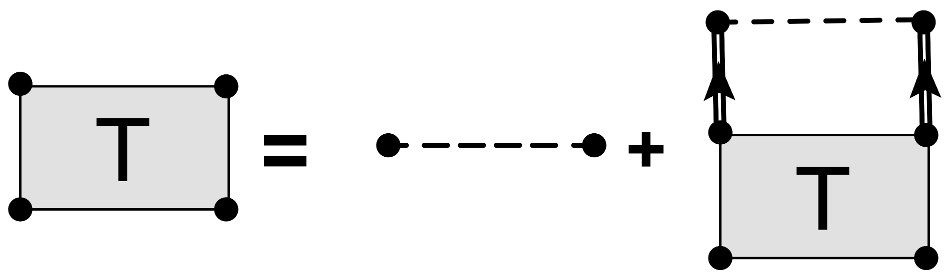
Dyson equation



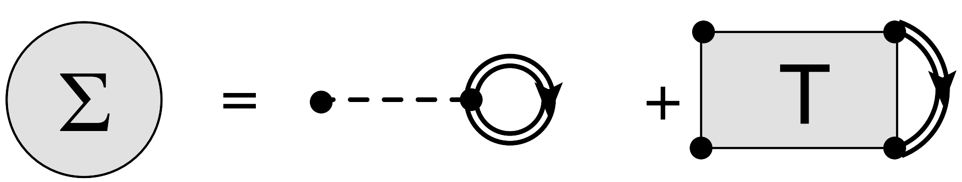
Ladder approximation with 3BF

Two-body interaction

In-medium T-matrix

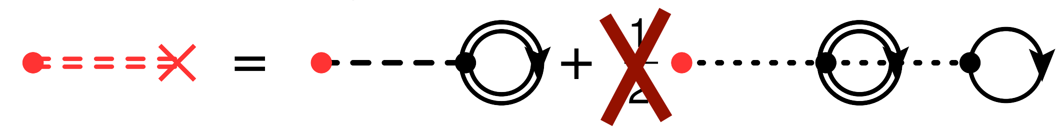


Self-energy



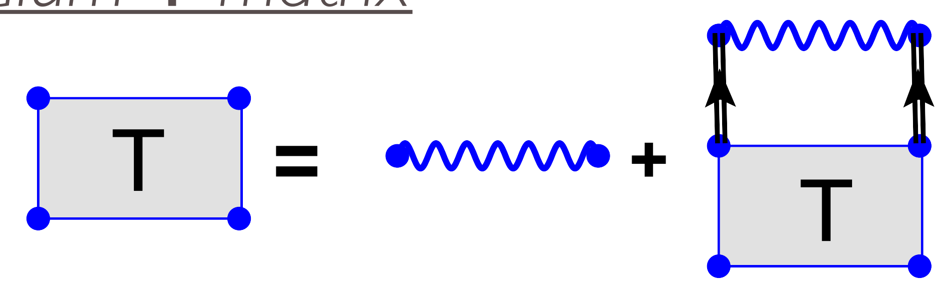
Effective interactions

Effective one-body force

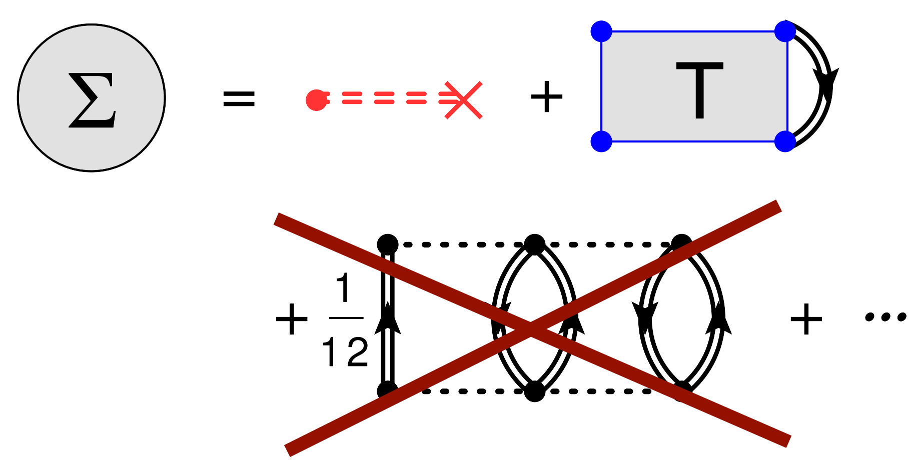


Effective two-body force

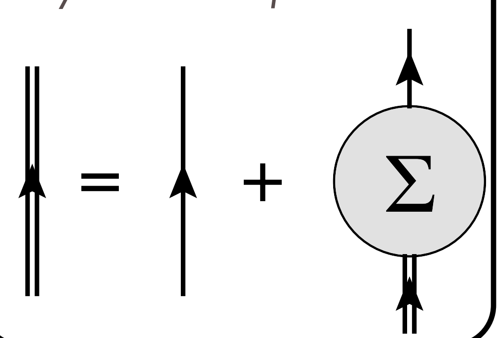
In-medium T-matrix



Self-energy



Dyson equation



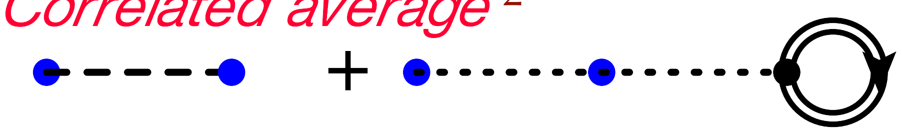
Density-dependent interaction

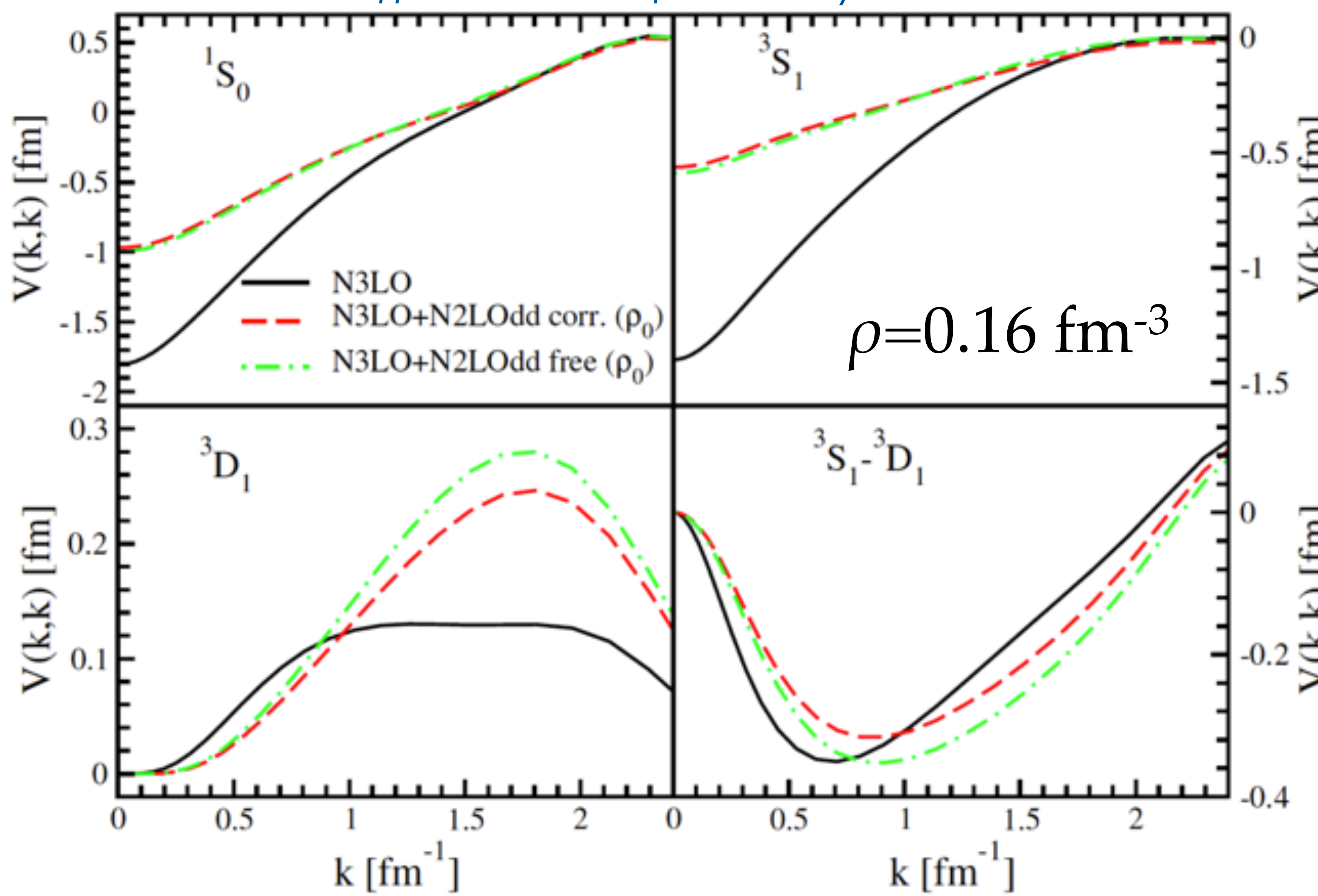
Chiral NN effective 2B forces: symmetric matter

Two-body N3LO

Uncorrelated average [1]

Correlated average [2]





LECs

c_D=-1.11

c_E=-0.66

$$k \neq k' \Rightarrow \frac{1}{2}(k+k')$$

- 3NF bring repulsion: correlated & uncorrelated averages are similar
- Correlated average brings small corrections to 1/2 of terms
- Diagonal k=k' matrix elements computed
- Off-diagonal extrapolated & regulated

[1] Holt *et al. Phys. Rev. C* **81** 024002 (2010)

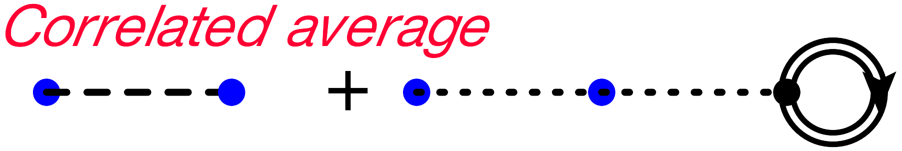
[2] Carbone, Polls & Rios, *PRC* **90**, 054322 (2014); A. Carbone, PhD thesis

Symmetric matter
Theoretical uncertainties: average procedure

Two-body N3LO

Uncorrelated average

Correlated average



<u>*LECs*</u>

c_D=-1.11

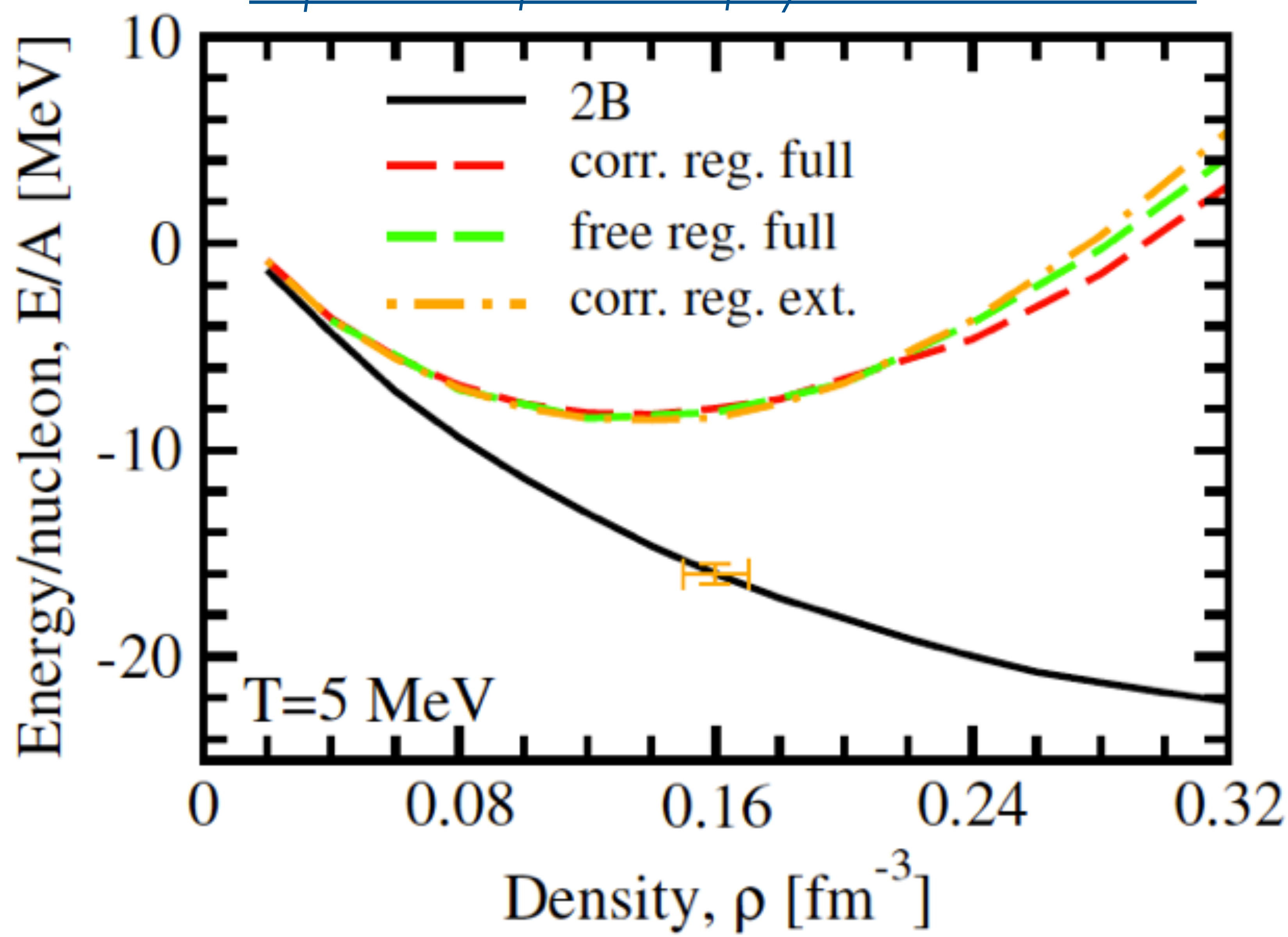
c_E=-0.66

K_0~60 MeV

Energy from GMK sum-rule

... with 3N corrections[1] ...

<u>Equation of state of symmetric matter</u>



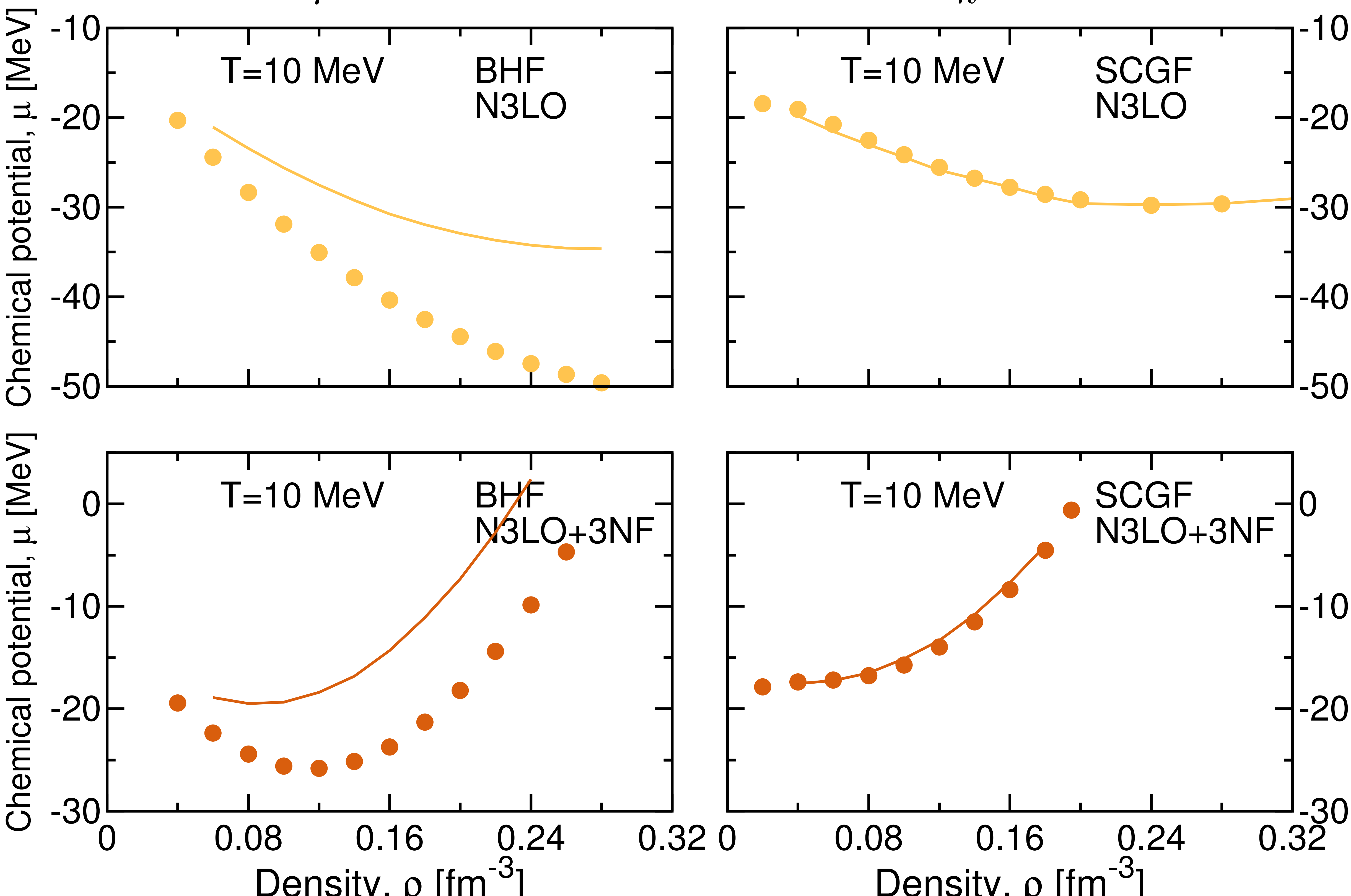
- Cor. reg. full=best we can do now is <u>*underbound*</u>
- Previous work with uncorrelated averages is validated
- Regulation at high momentum is irrelevant

[1]Carbone, Polls & Rios, *PRC* **88** 044302 (2013)

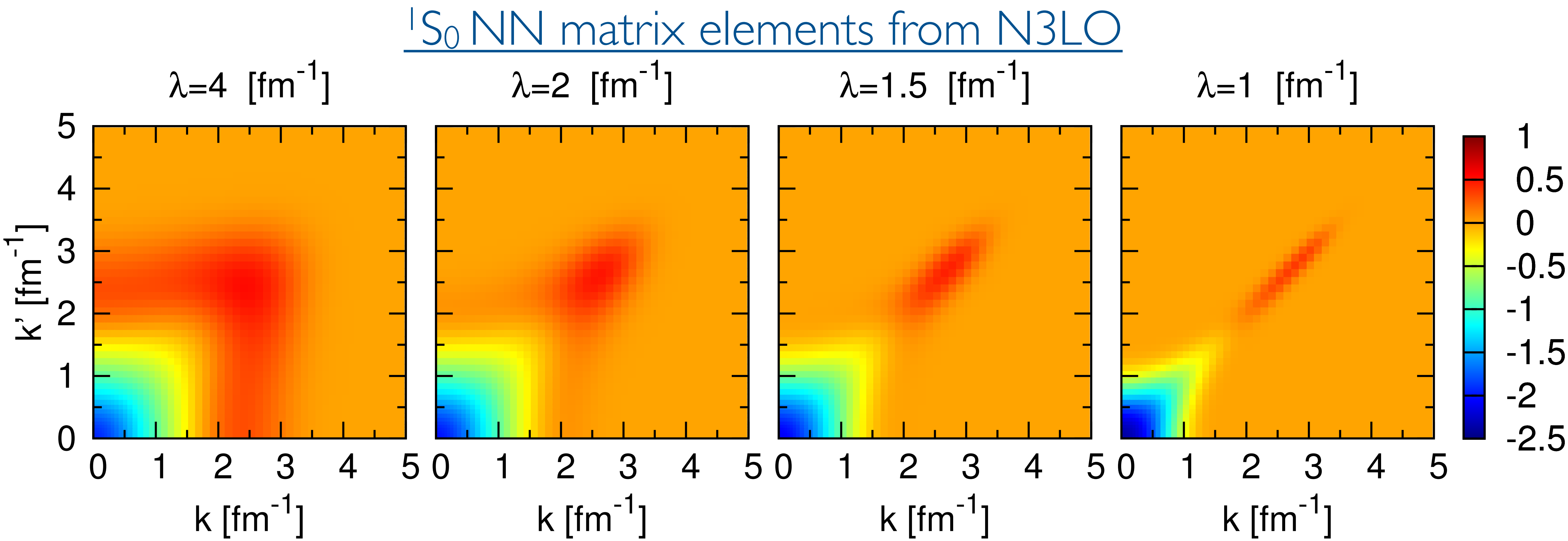
[2]Carbone, Polls & Rios, *PRC* **90** 054322 (2014); A. Carbone, PhD thesis

Thermodynamical consistency

$$\mu = \frac{\partial E/\Omega}{\partial \rho} \quad \longleftrightarrow \quad \rho = \sum_k n(k;\tilde{\mu})$$



Further renormalizations



$$\frac{dH_s}{ds} = [[T_{rel}, H_s], H_s] \Leftrightarrow \lambda = s^{-1/4}$$

- Series of unitary transformation
- Observables unaltered, but force becomes perturbative
- Induces 3-, 4- and up to A-body forces...
- If these can be treated perturbatively, calculation is easier

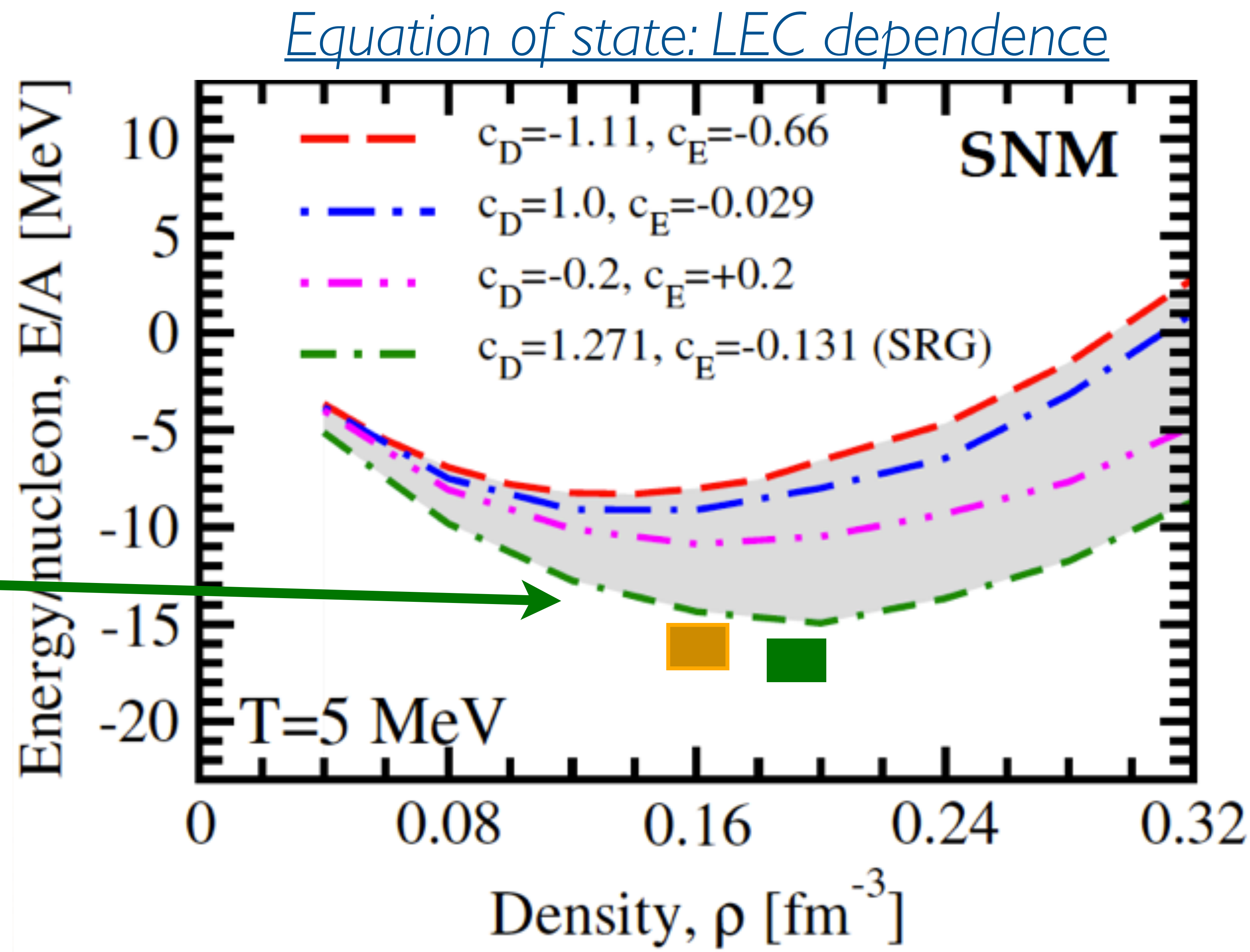
Bogner, Furnstahl, Schwenk, *Prog. Part. Nucl. Phys.* **65** 94 (2010)

Symmetric matter

Theoretical uncertainties: NN force

Uncorrelated average

Λ=2 fm⁻¹ SRG
well below c_D,c_E uncertainty

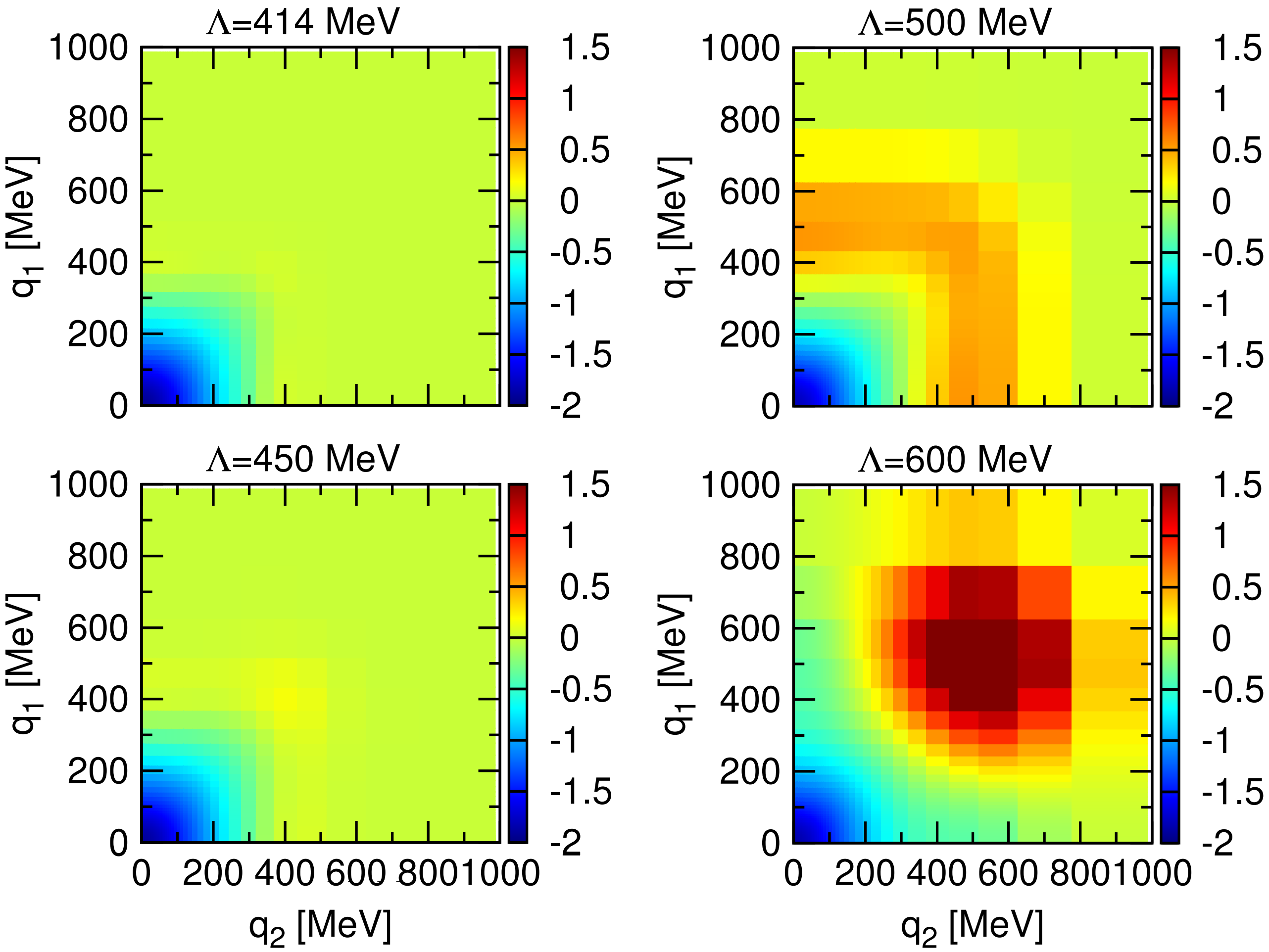


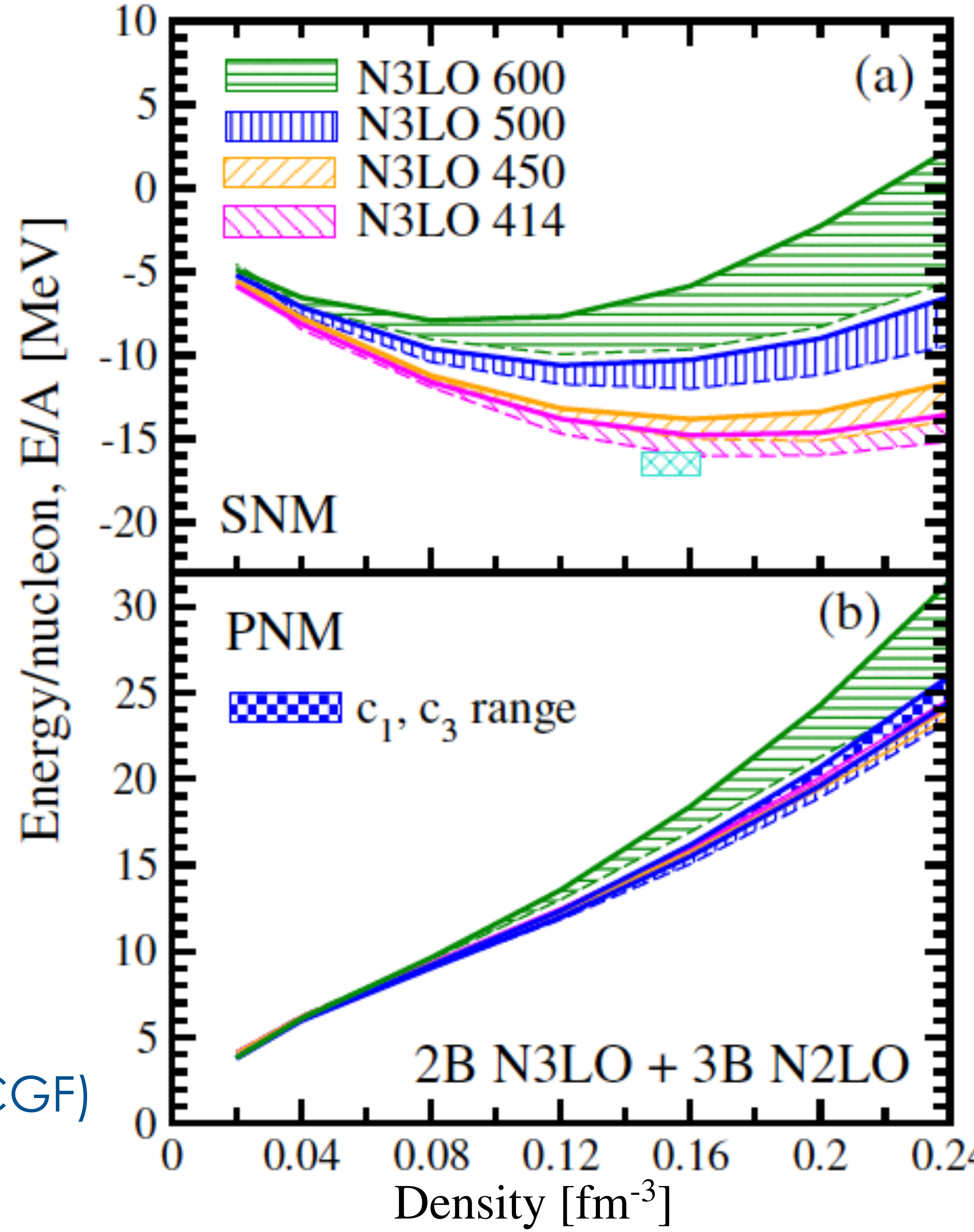
- LECs dependence is *strong*
- Renormalization via SRG: nuclear structure calculations?
- Small 3NF effects with larger saturation densities ⇒ smaller radii

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

Many-body uncertainty

Idaho chiral NN forces





- N3LO forces with **different** cut-offs
- (c_D, c_E) fitted to few-body, no SRG
- Explore **error** in *many-body* (BHF vs SCGF)
- Neutron matter is **more perturbative**

Carbone, Polls & Rios, *in preparation*

Outline

- ➡ *Motivation*
- ➡ *Nuclear matter: Equation of state with 3NFs*
- ➡ ***<u>Neutron matter:</u> beyond-BCS pairing***

What is a neutron star?
Why care?

Mass

$>100\ M_\odot$

$50\text{-}100\ M_\odot$

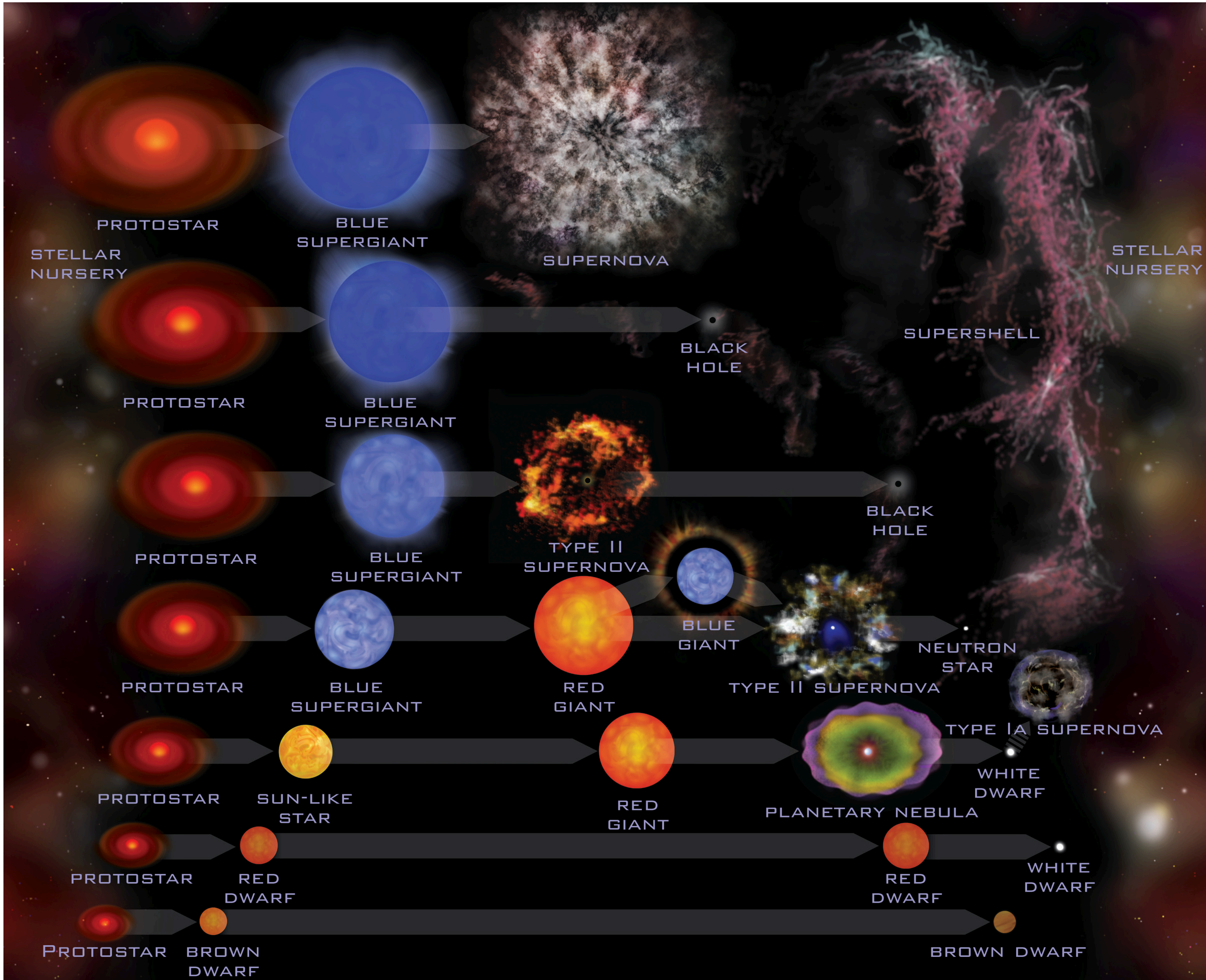
$25\text{-}50\ M_\odot$

$8\text{-}25\ M_\odot$

$0.4\text{-}8\ M_\odot$

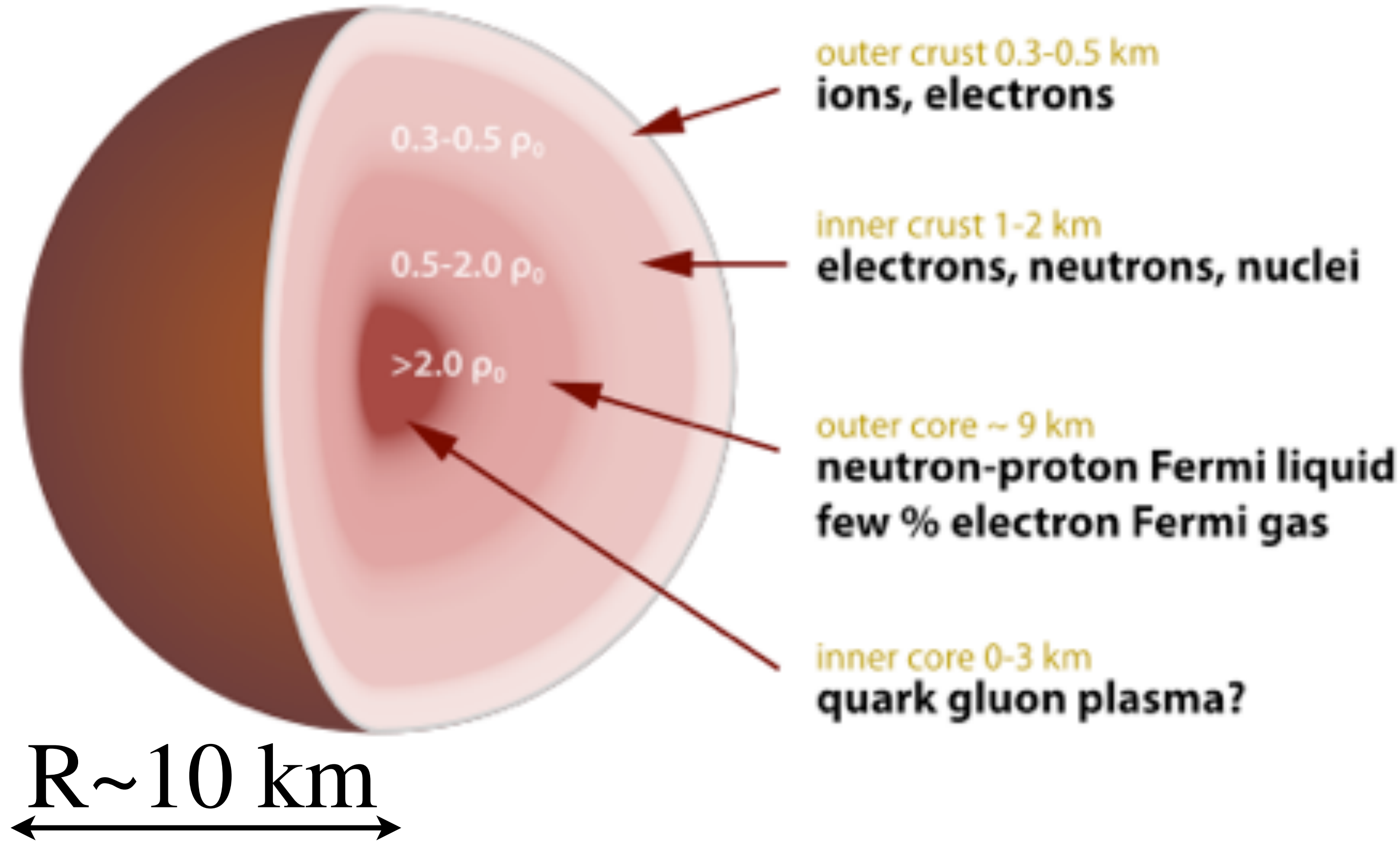
$0.08\text{-}0.4\ M_\odot$

$< 0.08\ M_\odot$



Prialnik, *Stellar Structure and Evolution*

Neutron star 101



Mass

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

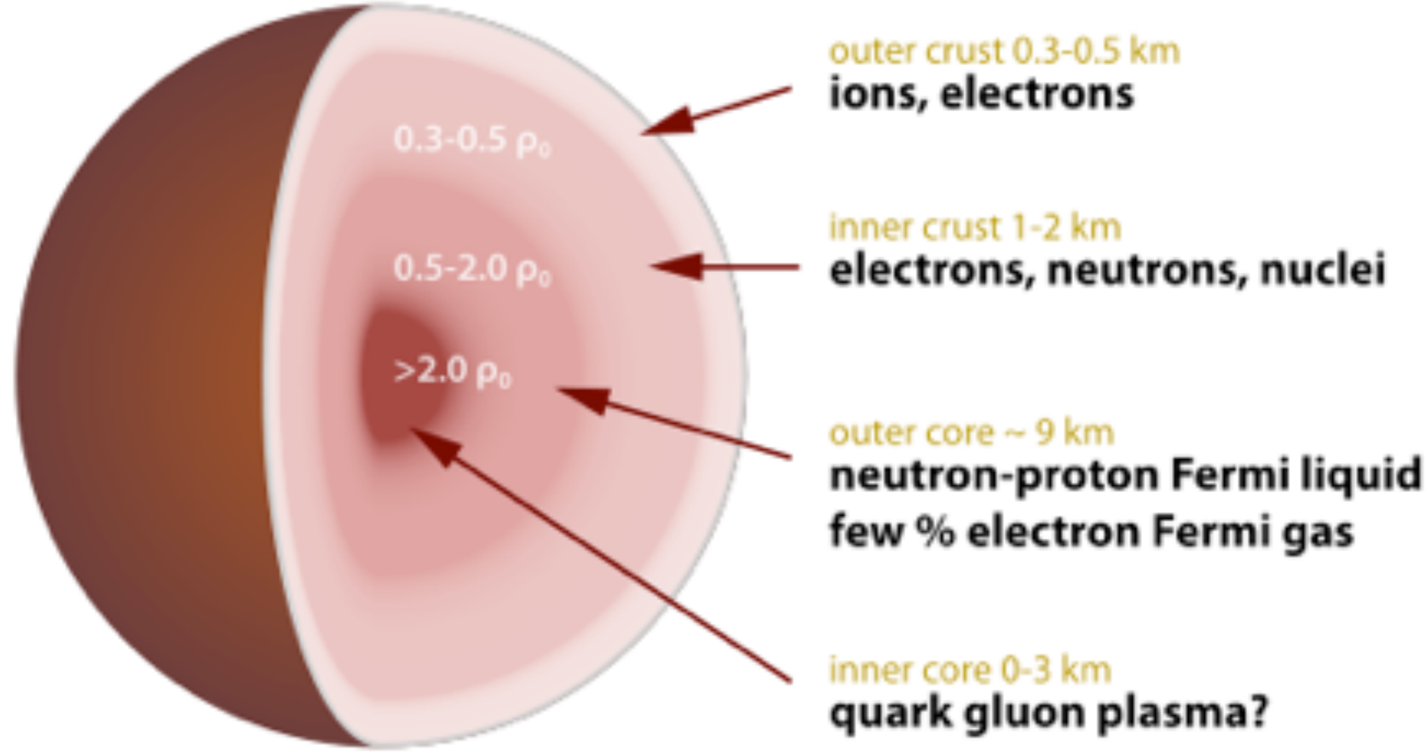
Radius

$$R \approx 10 \text{ km}$$

Mass density

$$\rho = \frac{M}{V}$$

Neutron star 101



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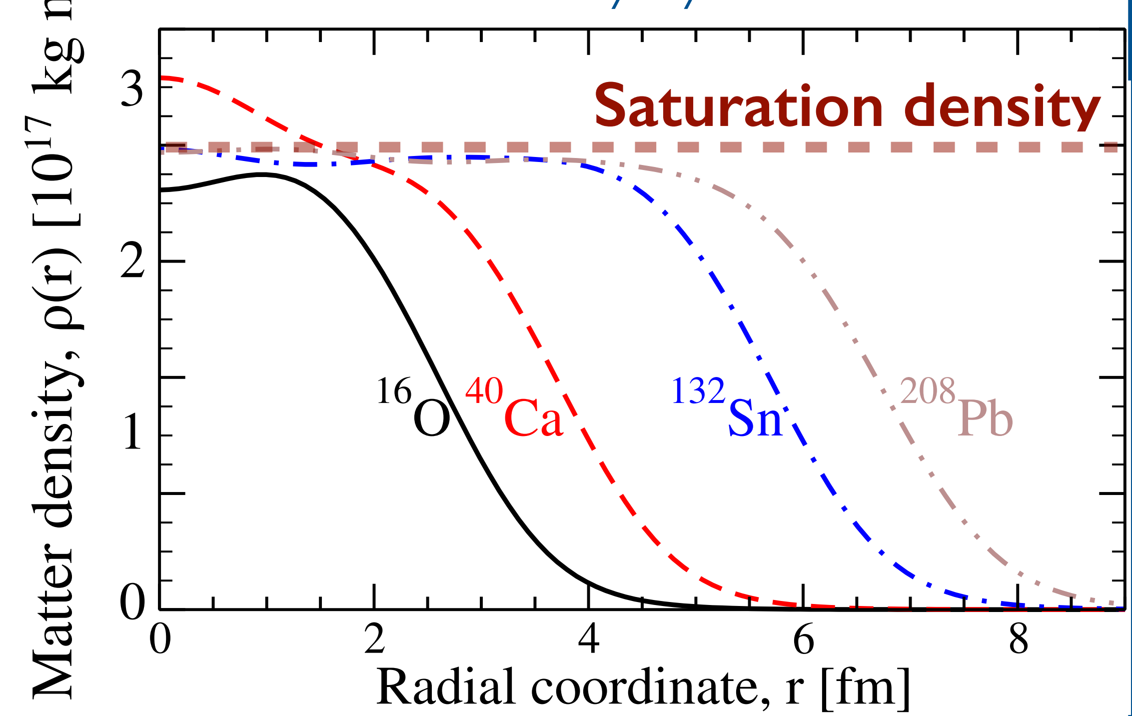
R~10 km

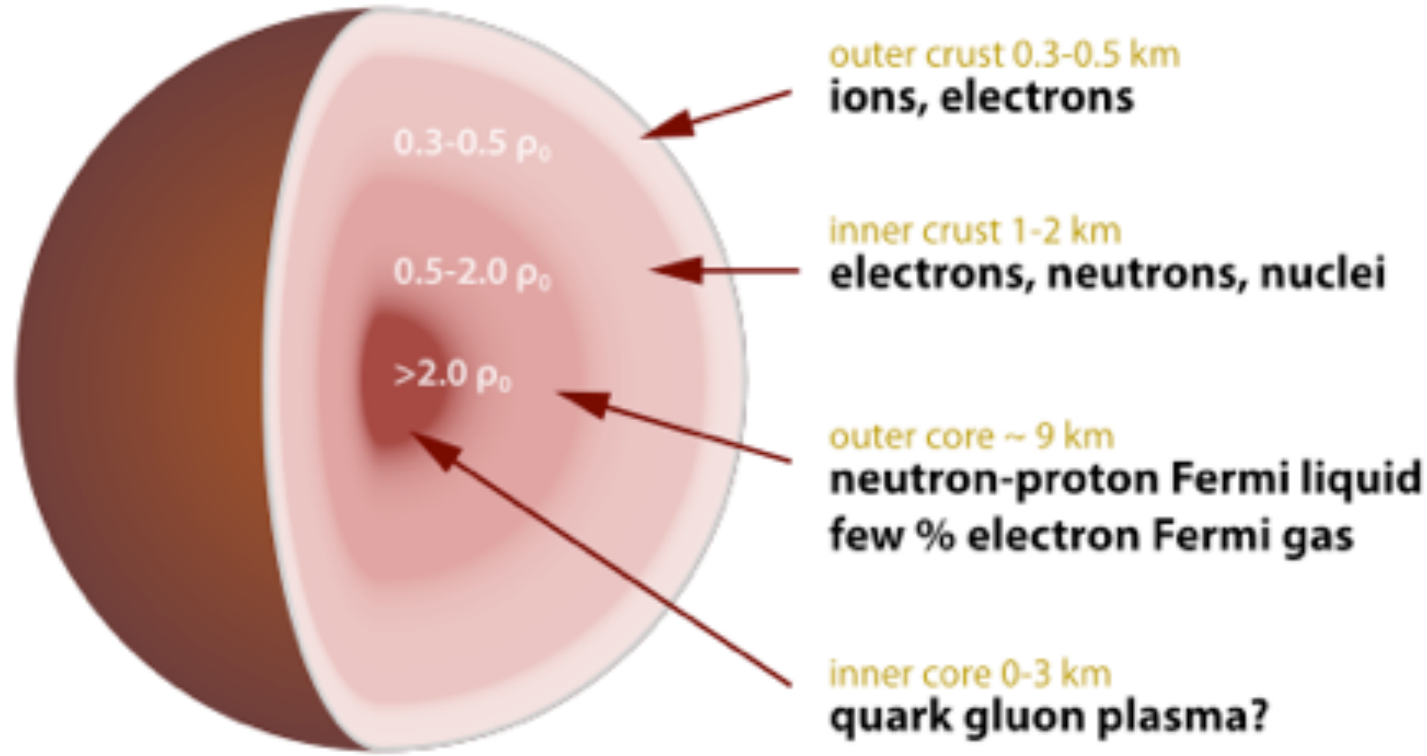
Mass density

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

Nuclear density systematics



Neutron star 101



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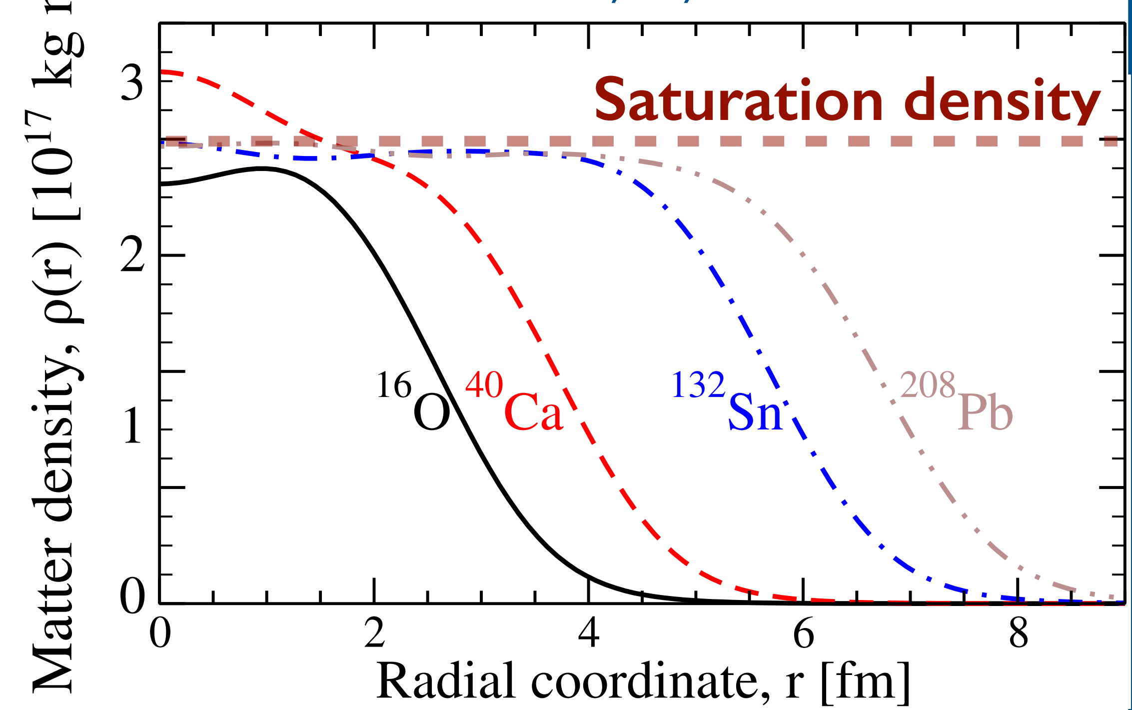
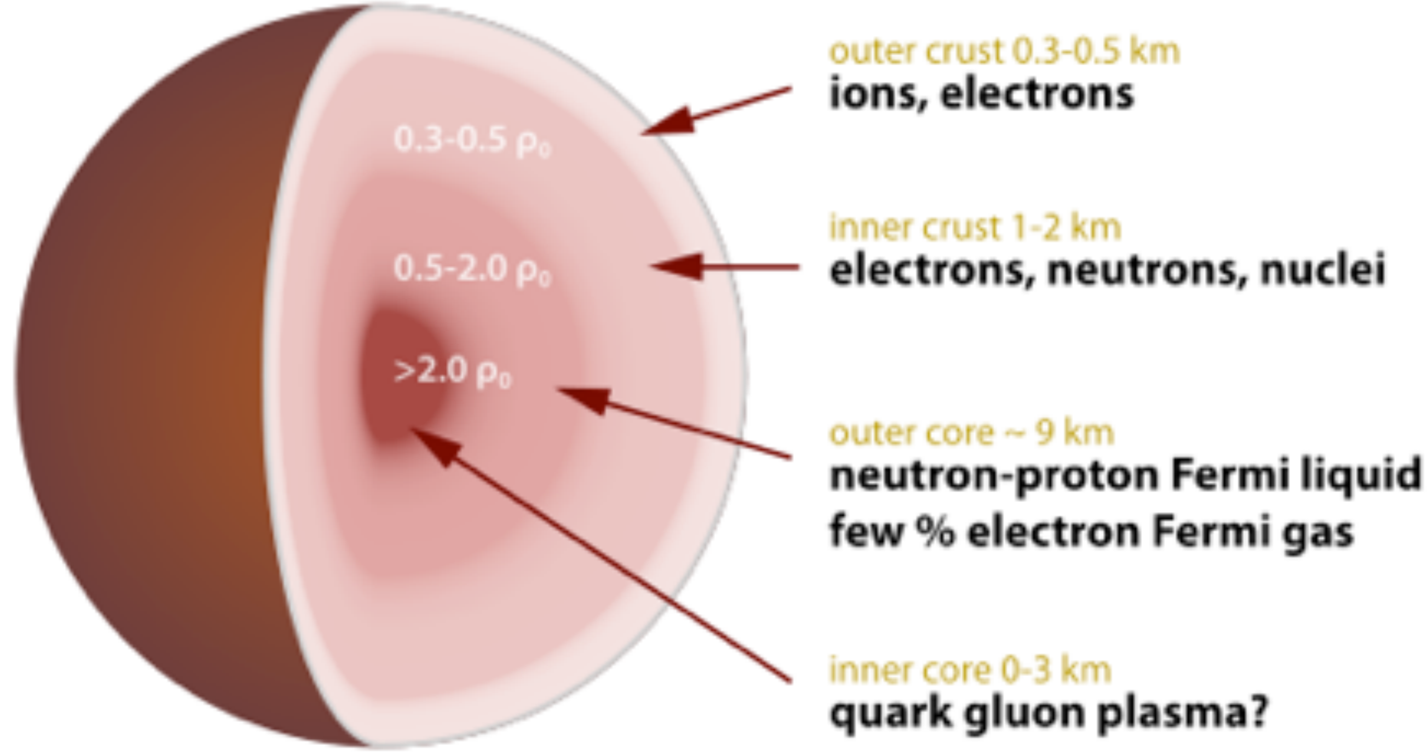
A teaspoon weights a billions of tons!

Nuclear density systematics



Neutron star 101



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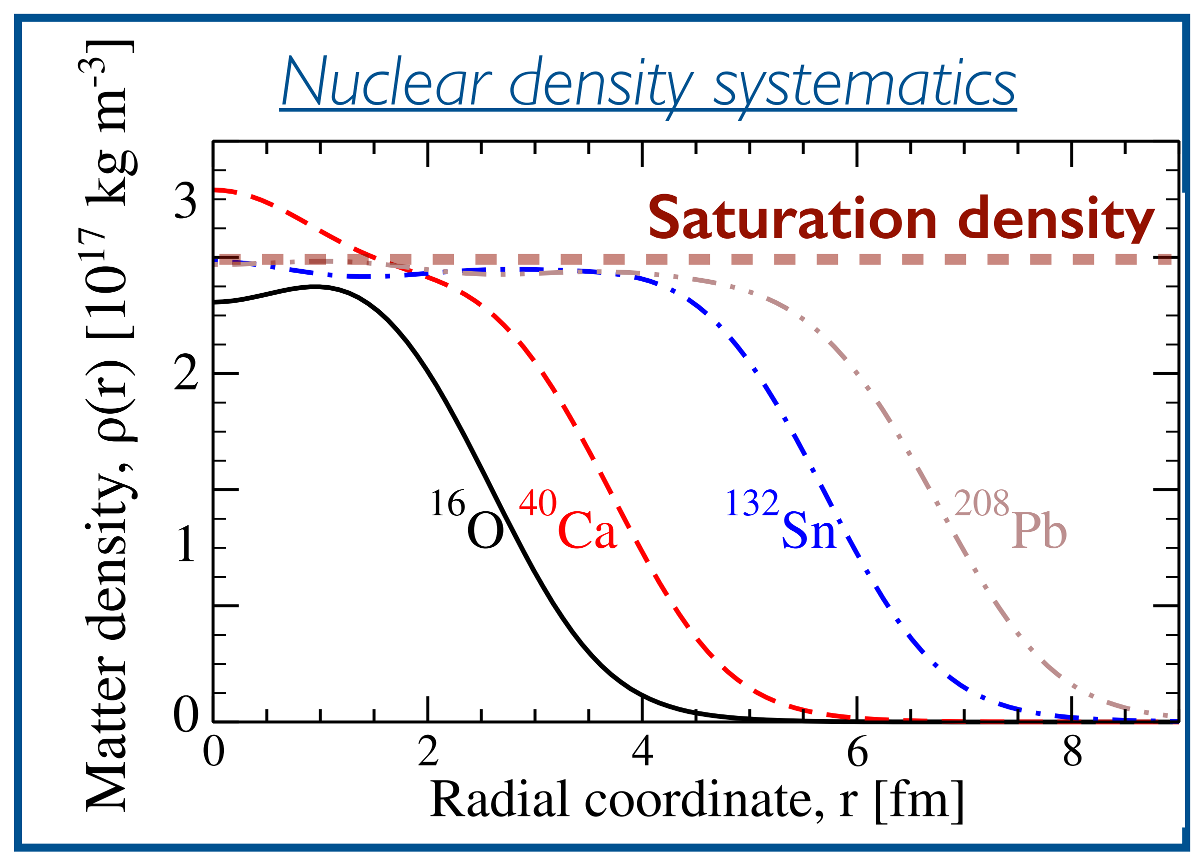


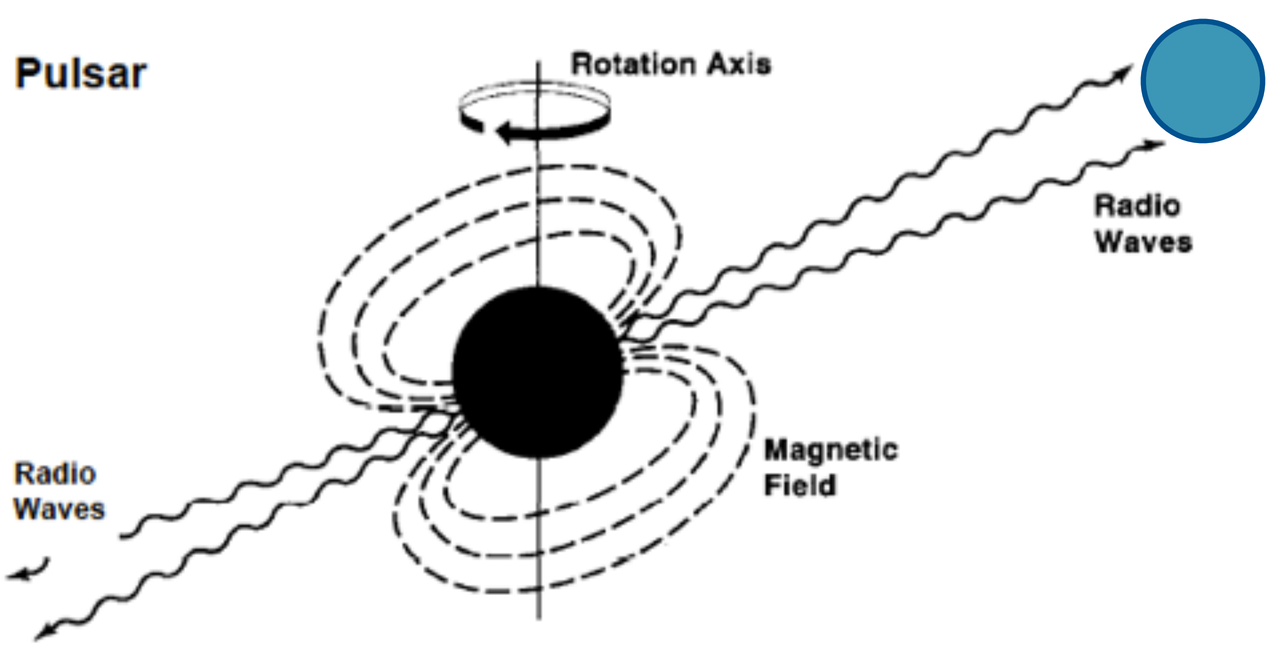
Escape velocity

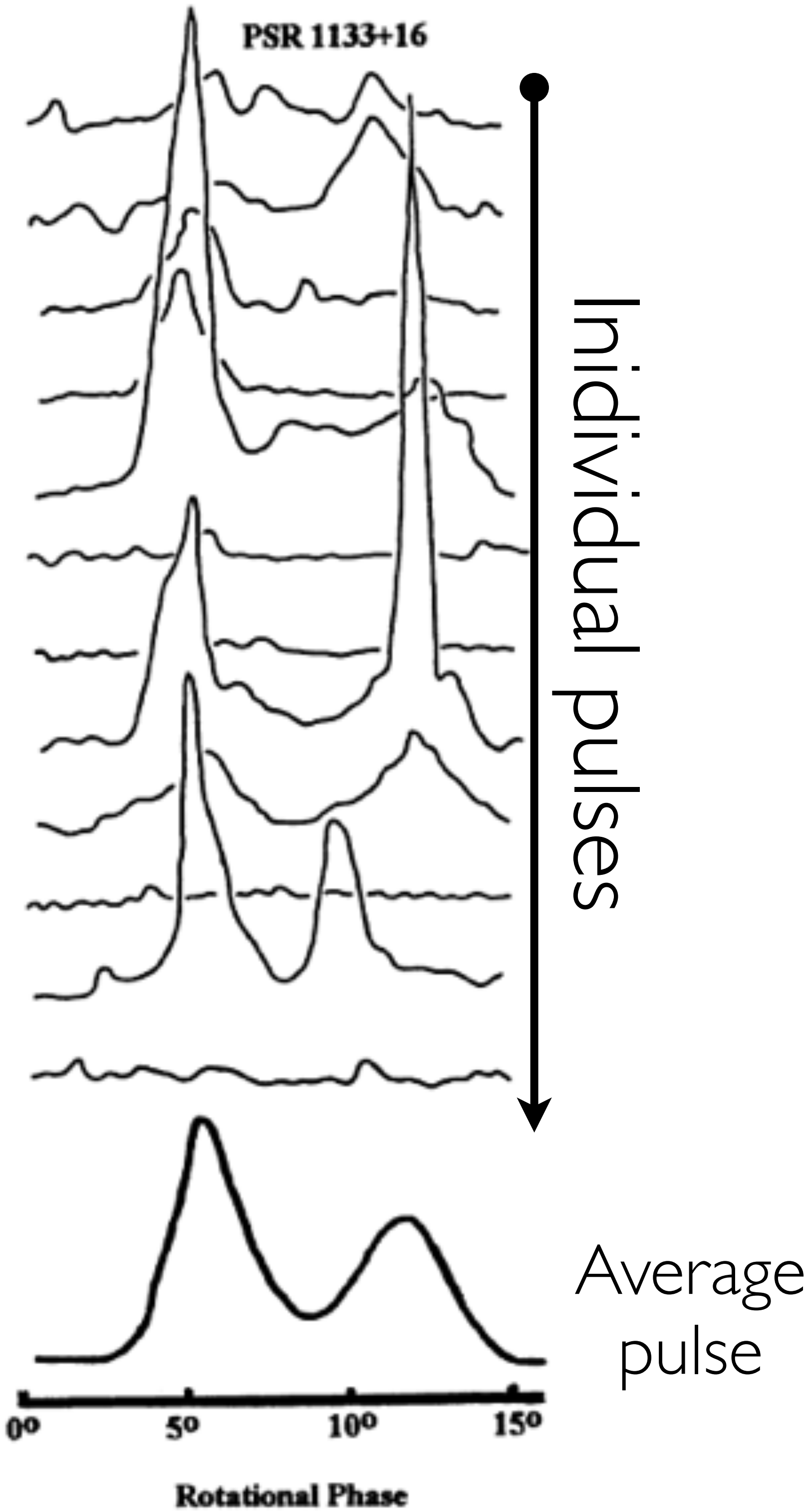
$$v = \sqrt{\frac{2GM}{R}} \sim 0.5c$$

How do we find them?

Sketch of a pulsar

Earth





- **Highest** magnetic fields in nature: 10^{16} G
- Particles **accelerated** along field lines
- Rotation is **fast** and **accurate**, unique of each pulsar
- Radio & X-ray bursts point our way

How do we find them?

Sketch of a pulsar

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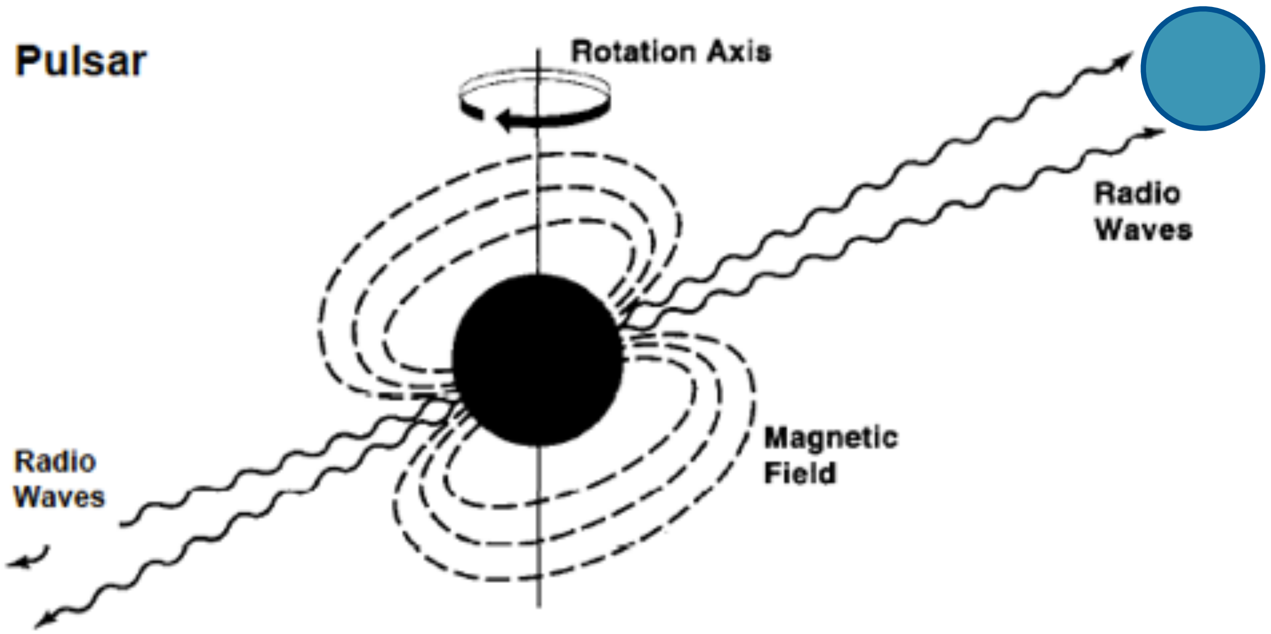
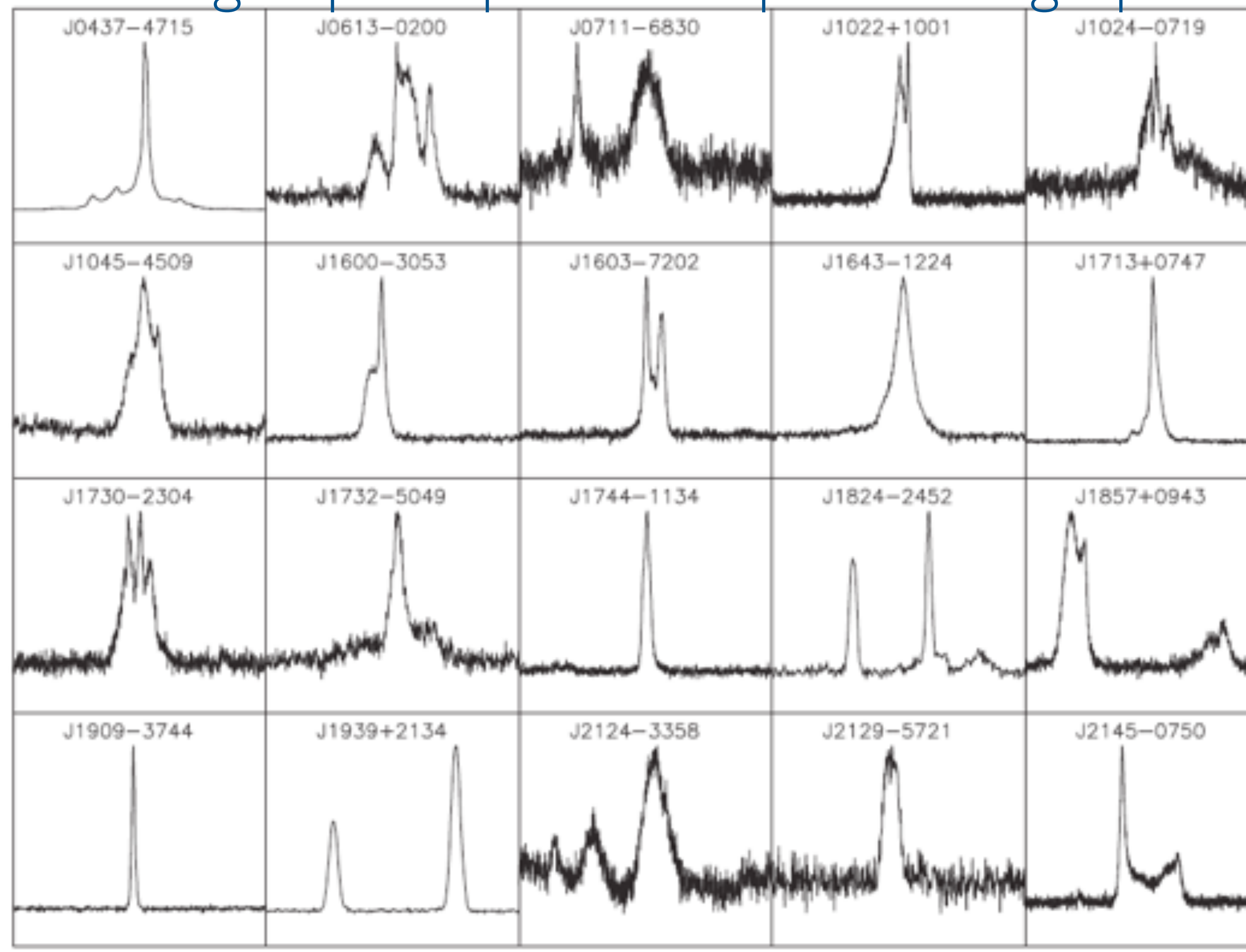


Averaged pulse profile - a pulsar's fingerprint



Hobbs et al., Pub. Astr. Soc. Aust. 202, 28 (201

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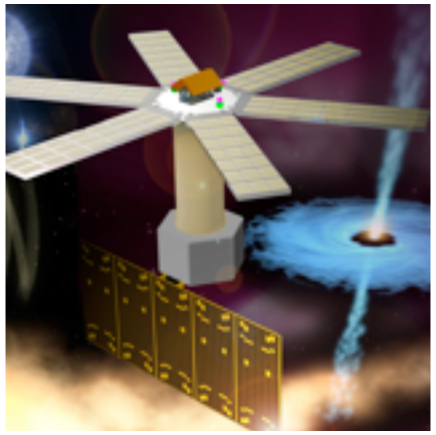
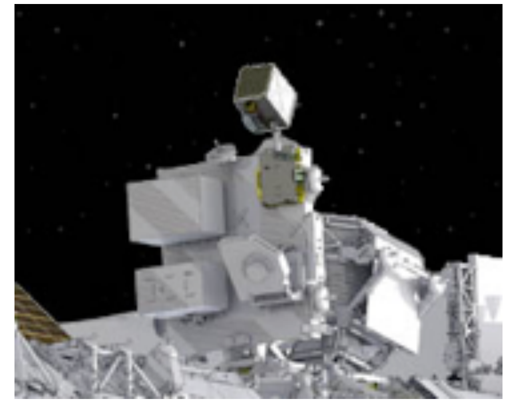
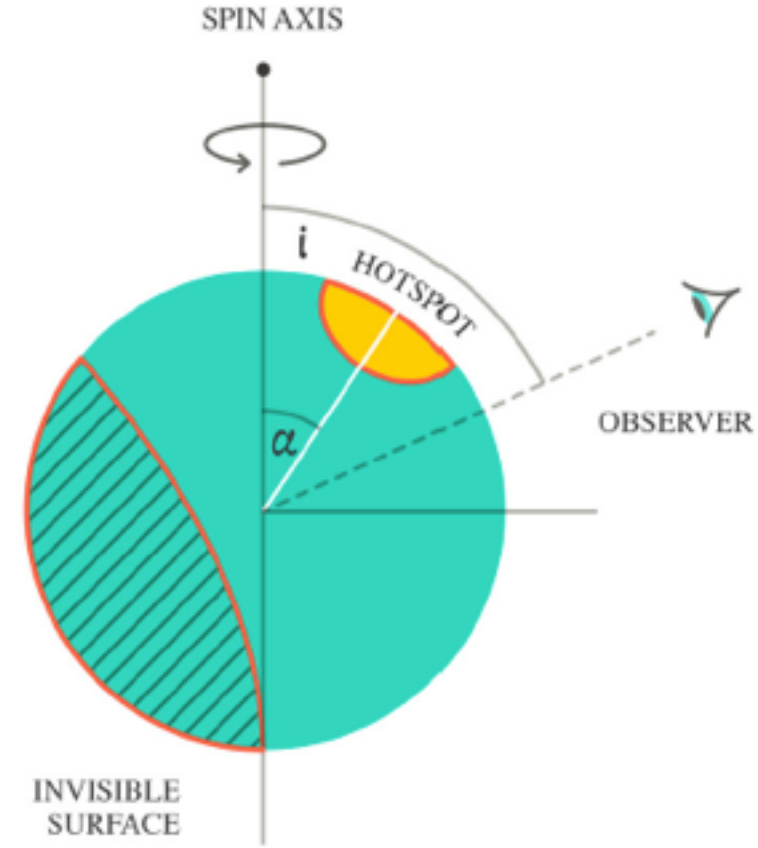
EoS from future observations
X-rays

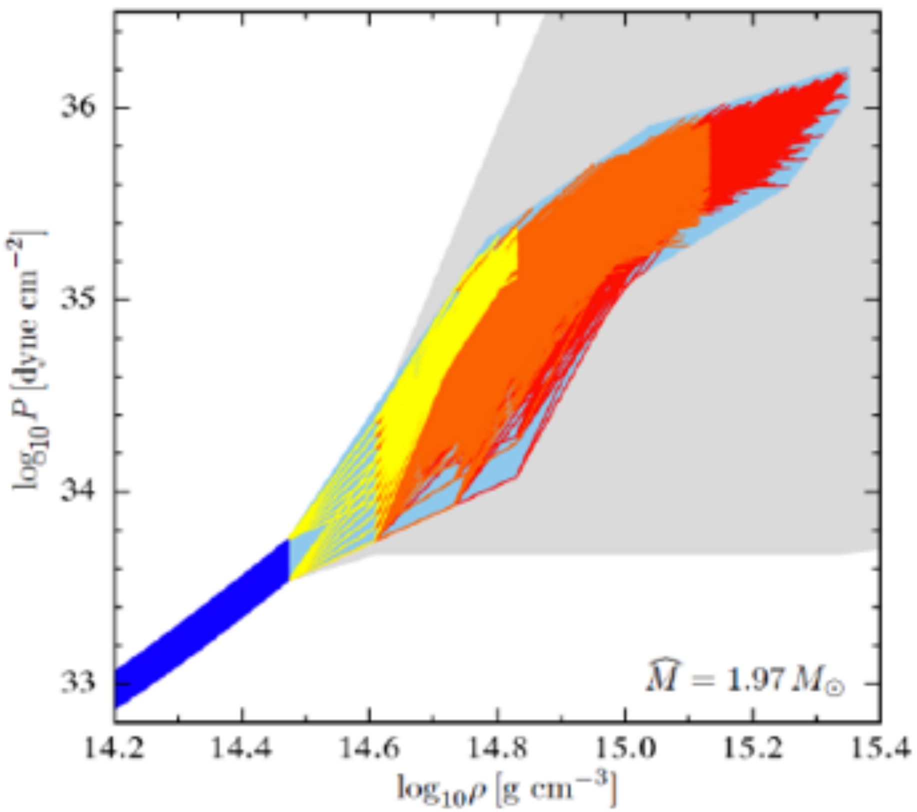


LOFT

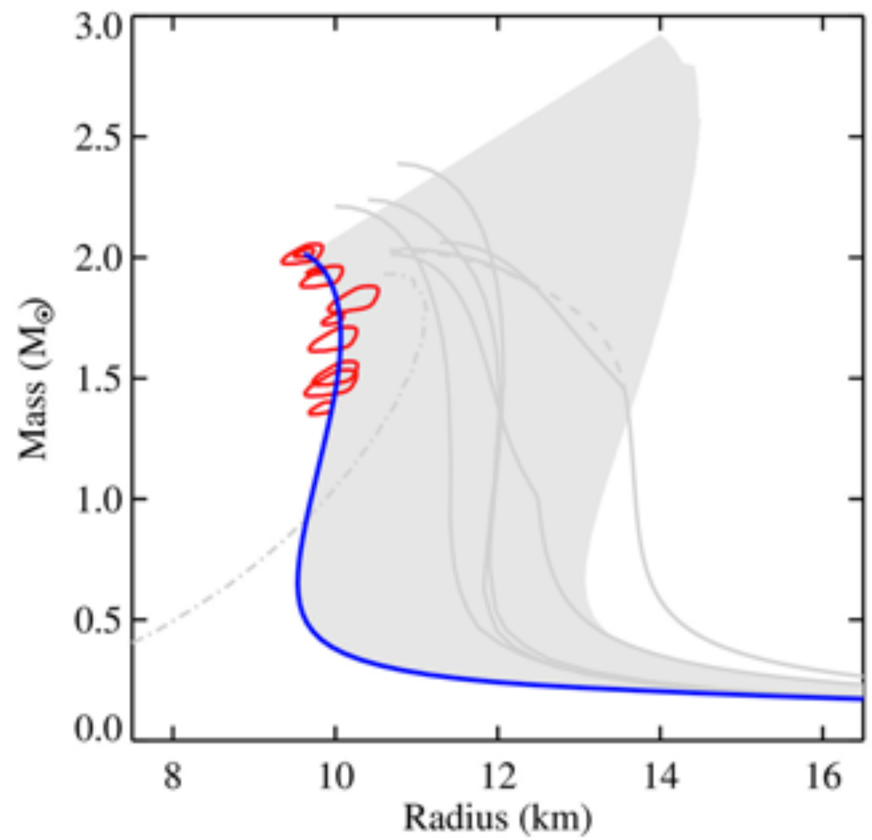


NICER

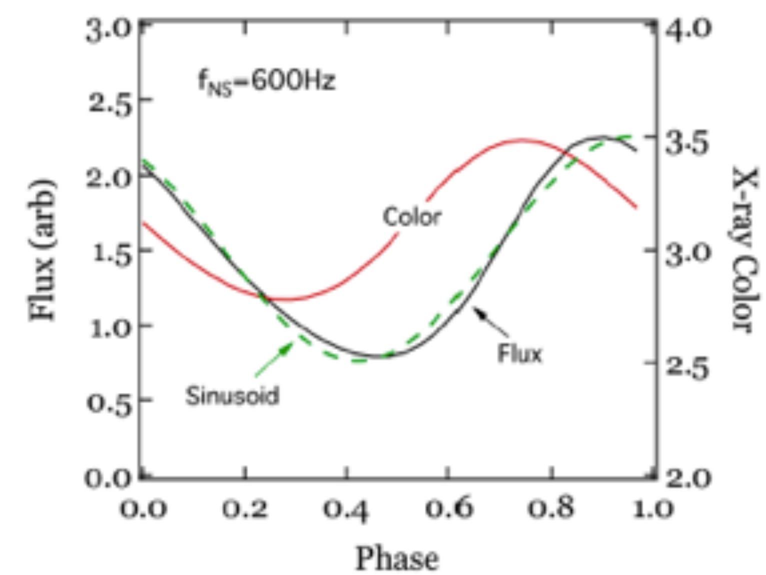




Hebeler et al. 2013

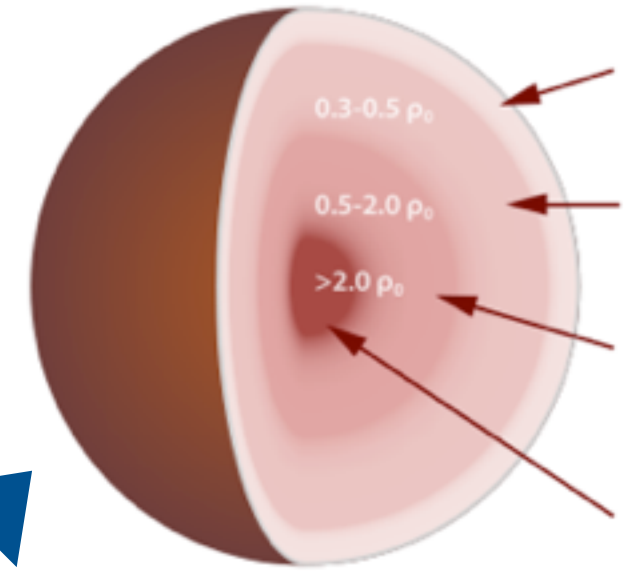


LOFT Yellow Book



- ESA X-ray observatory with dense matter program
- Burst oscillation of known sources will yield M-R to few % level
- Did not make it as M3... Might be put forward as M4?

Neutron matter mass and radius



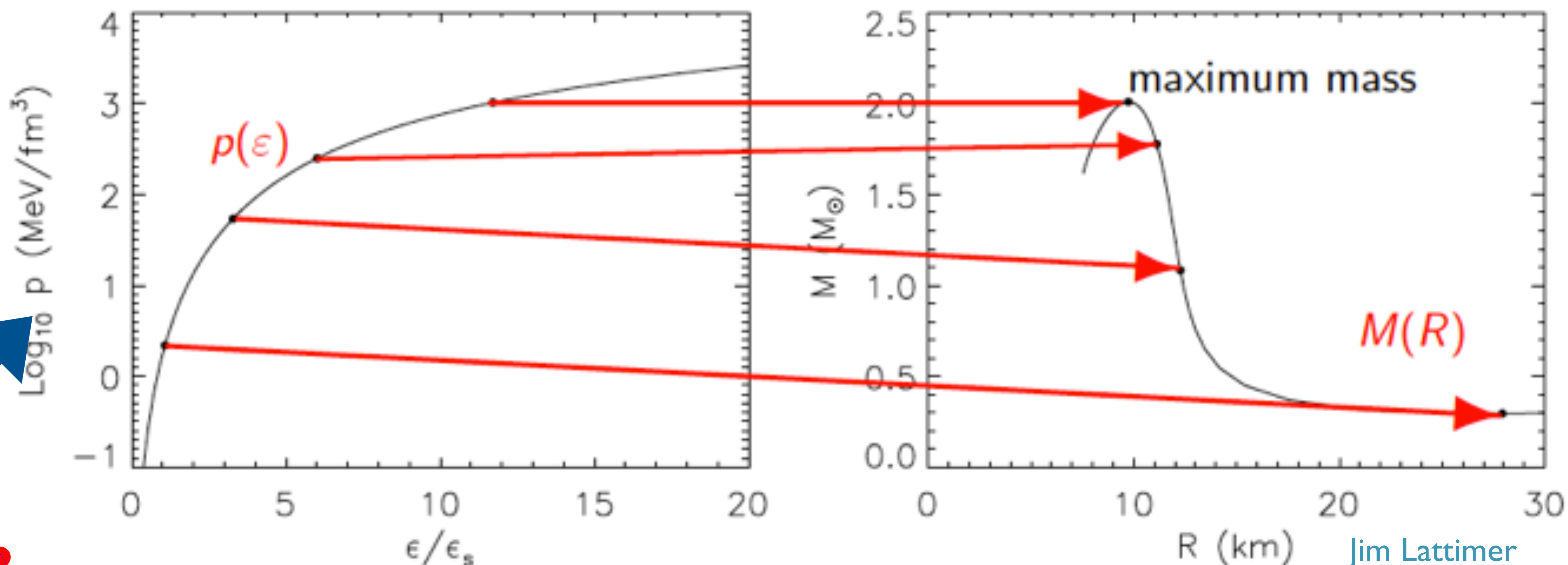
Tolman-Oppenheimer-Volkov equations

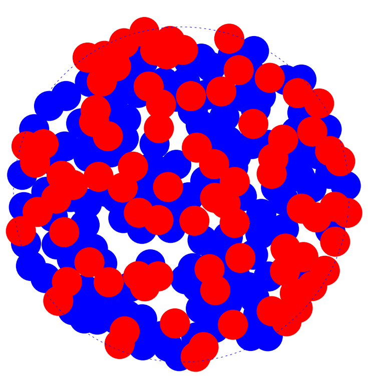
$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m + 4\pi p r^3)(\epsilon + p)}{r(r - 2Gm/c^2)}$$

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

Equation of State

Mass-Radius relation





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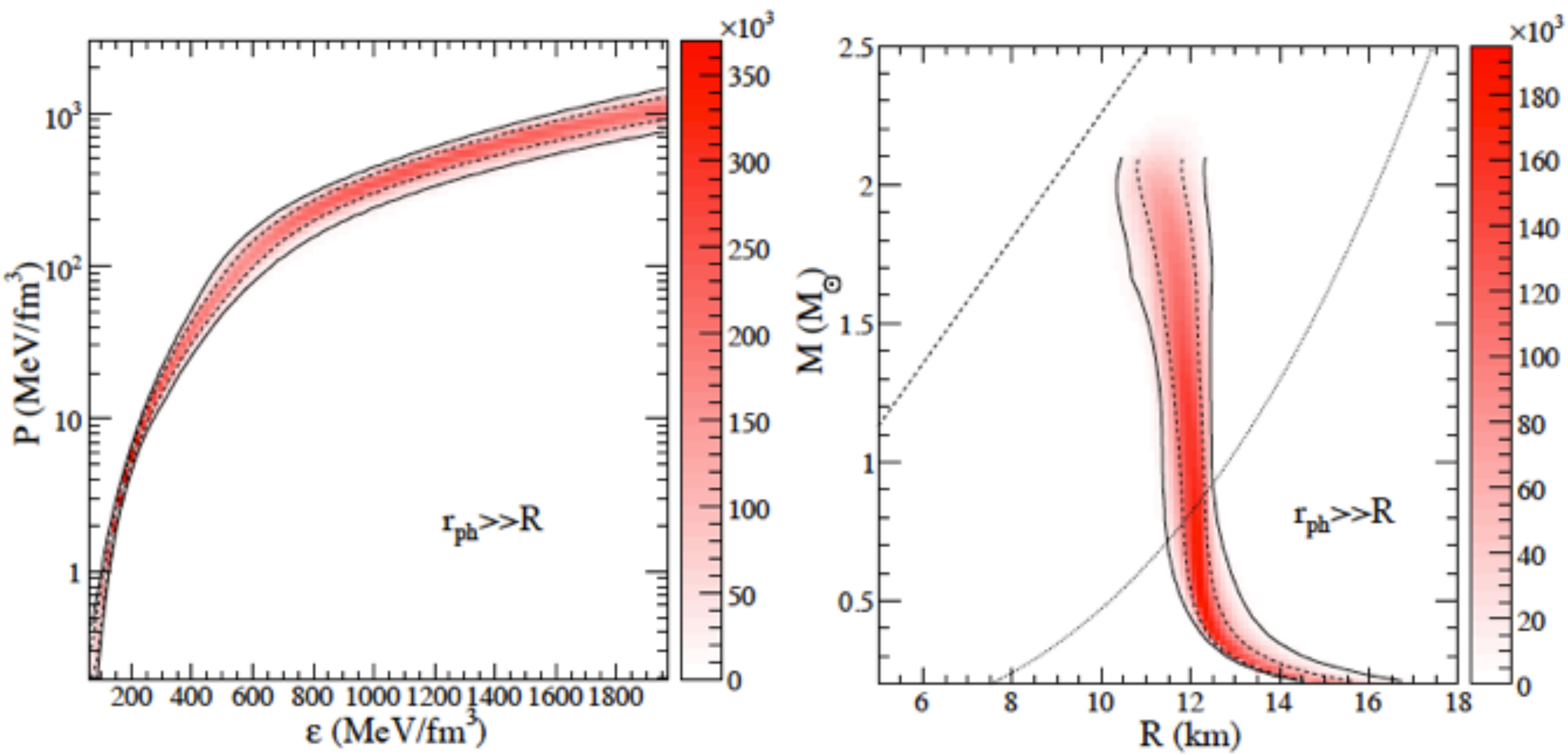
Inferred EoS and M-R relation from observations



Steiner, Lattimer & Brown, ApJ **722**, 33 (2010)

3 X-ray bursts, 3 X-ray binaries & 1 isolated NS

Neutron matter mass and radius

Tolman-Oppenheimer-Volkov equations

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

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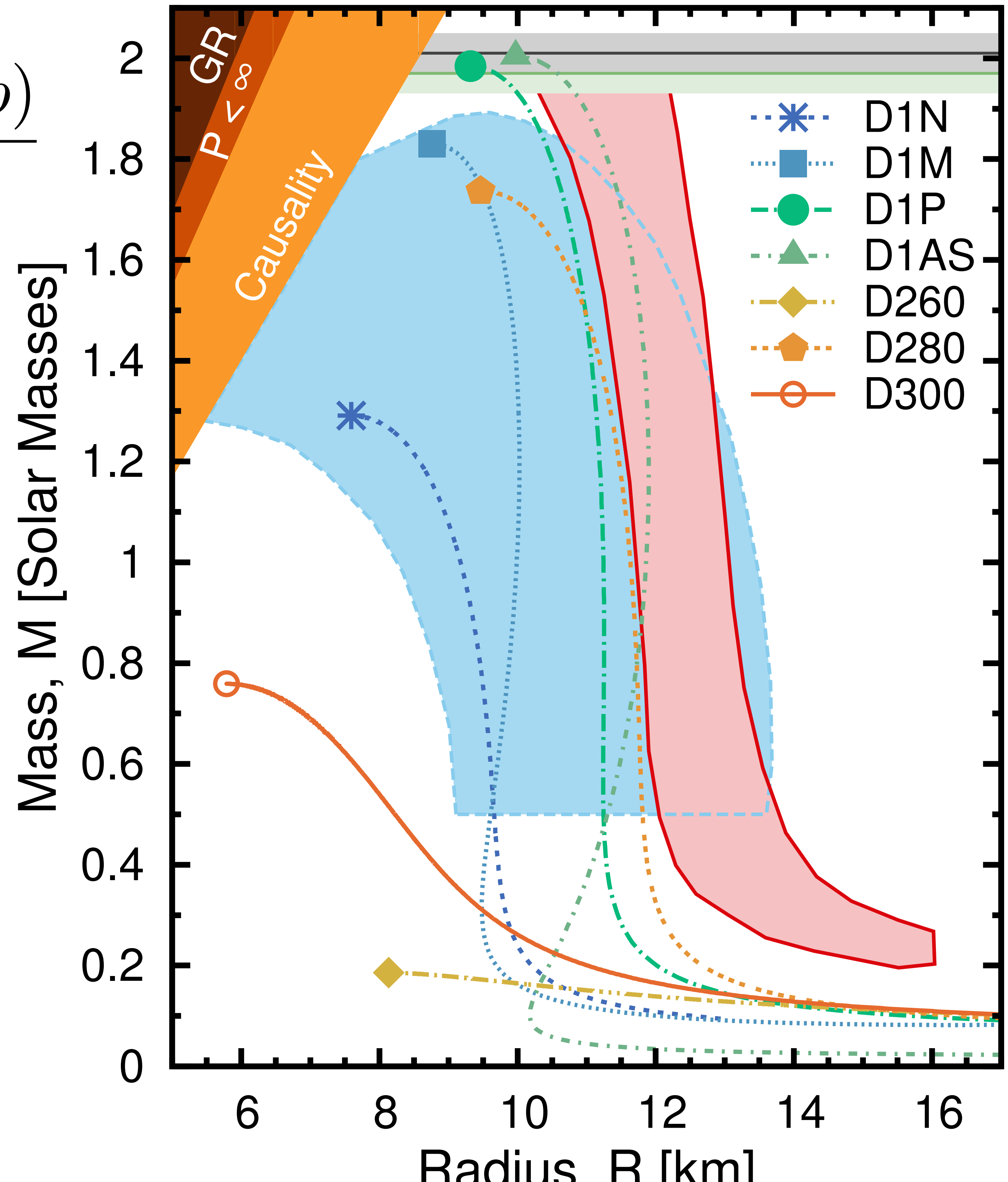
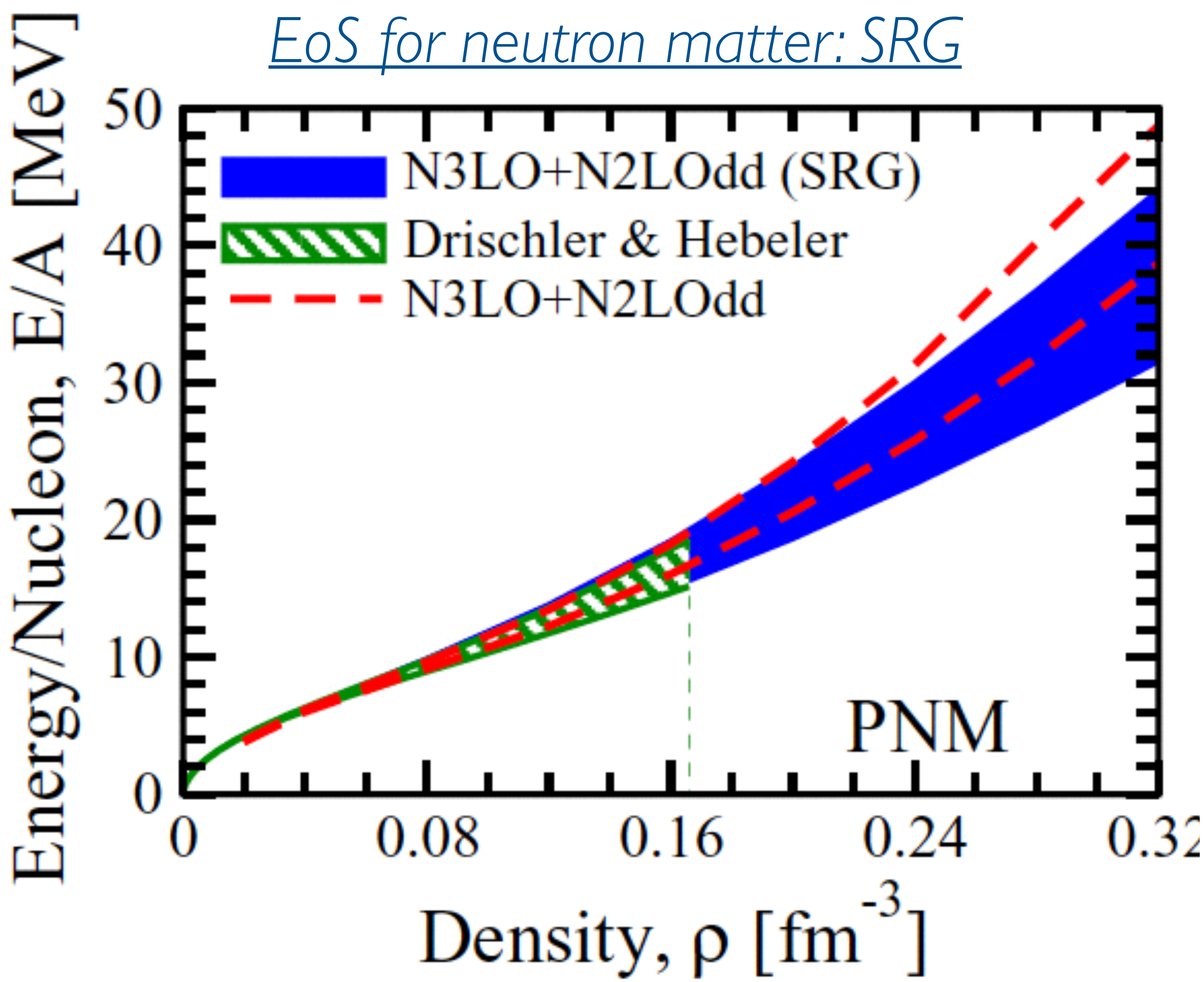
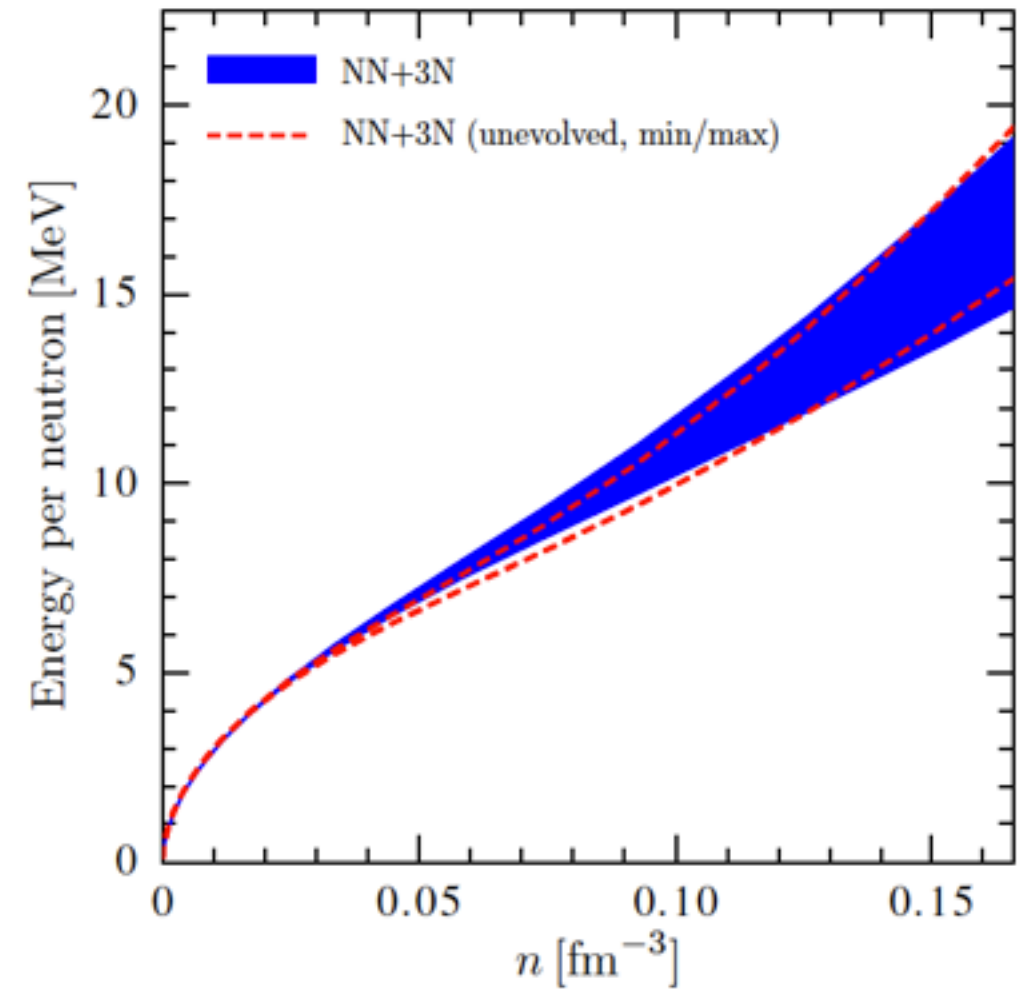


R. Sellahewa & A. Rios, *Phys. Rev. C* **90**, 054327 (2014)

Neutron matter





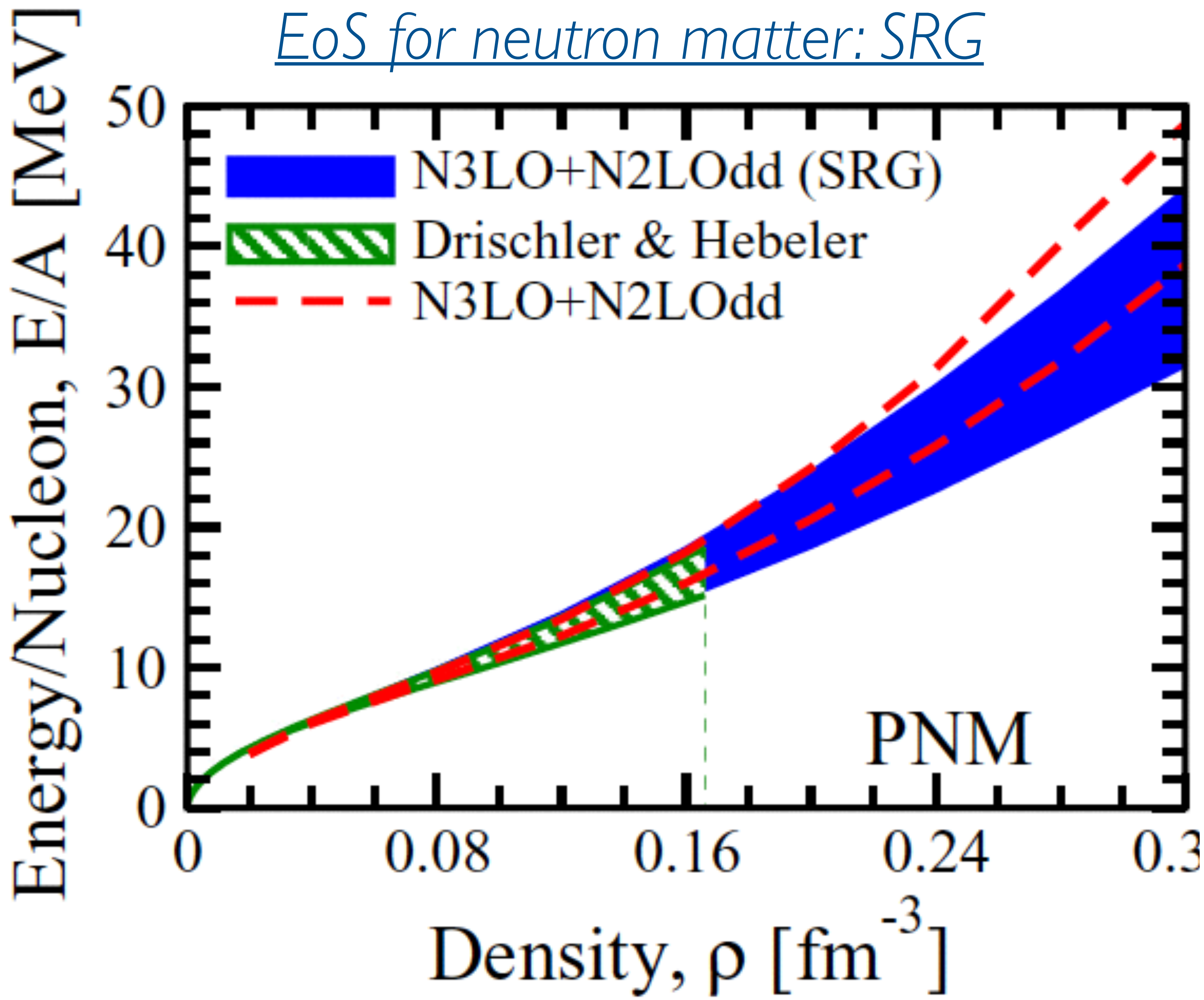
Hebeler, Lattimer, Pethick, Schwenk
ApJ **773** 11 (2013)

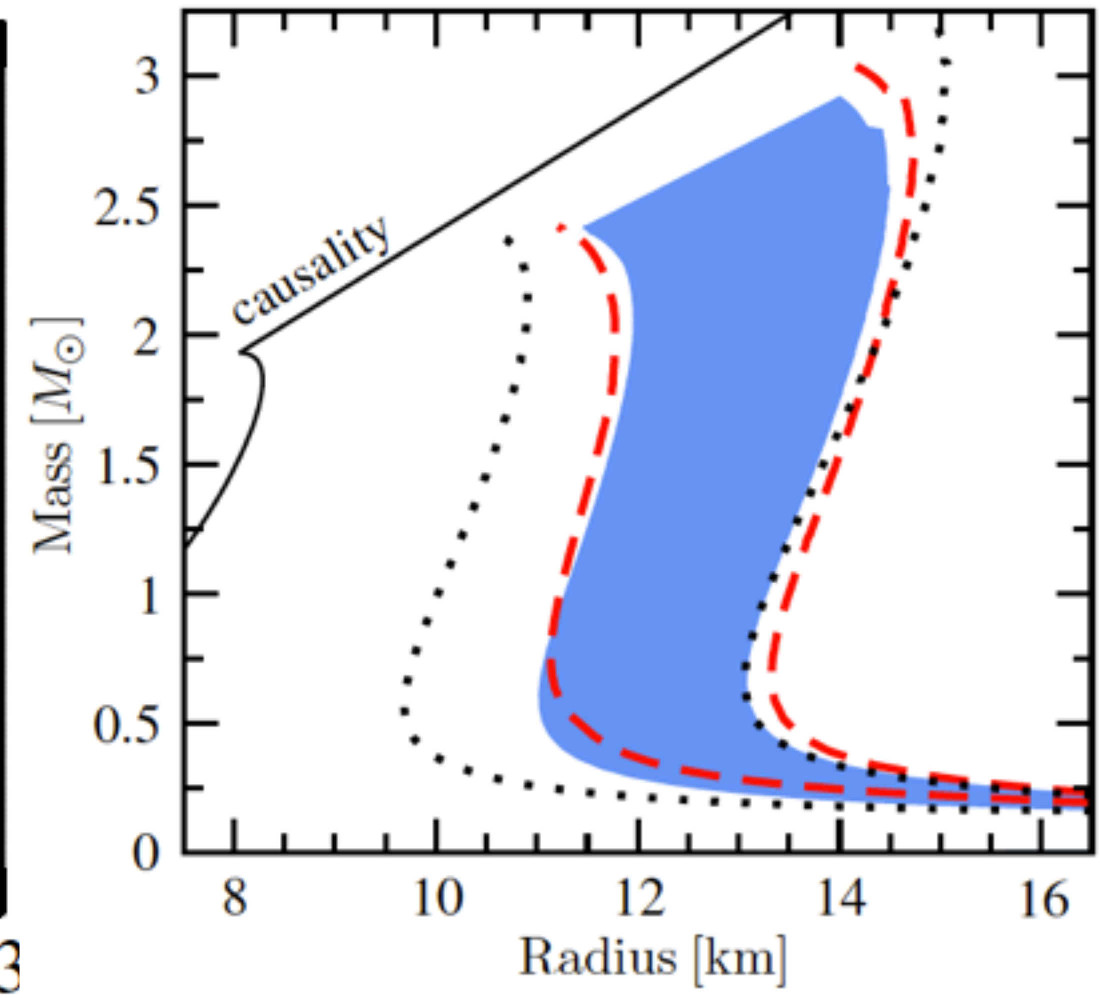
- Error band from unknown ChPT c_1, c_3 parameters
- Finite temperature & higher densities available

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

Neutron matter

EoS for neutron matter: SRG





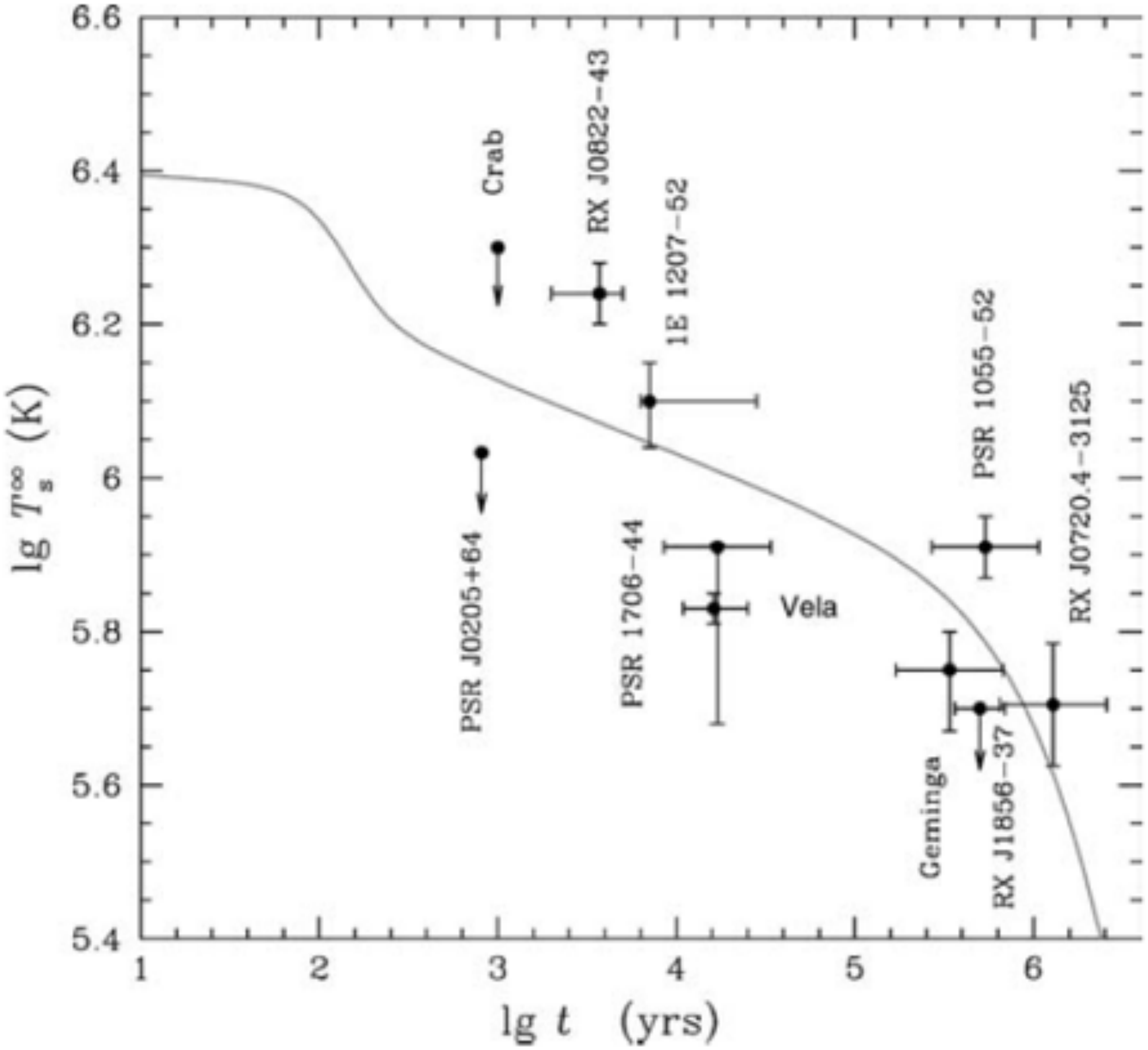
Hebeler, Lattimer, Pethick, Schwenk
ApJ **773** 11 (2013)

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

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

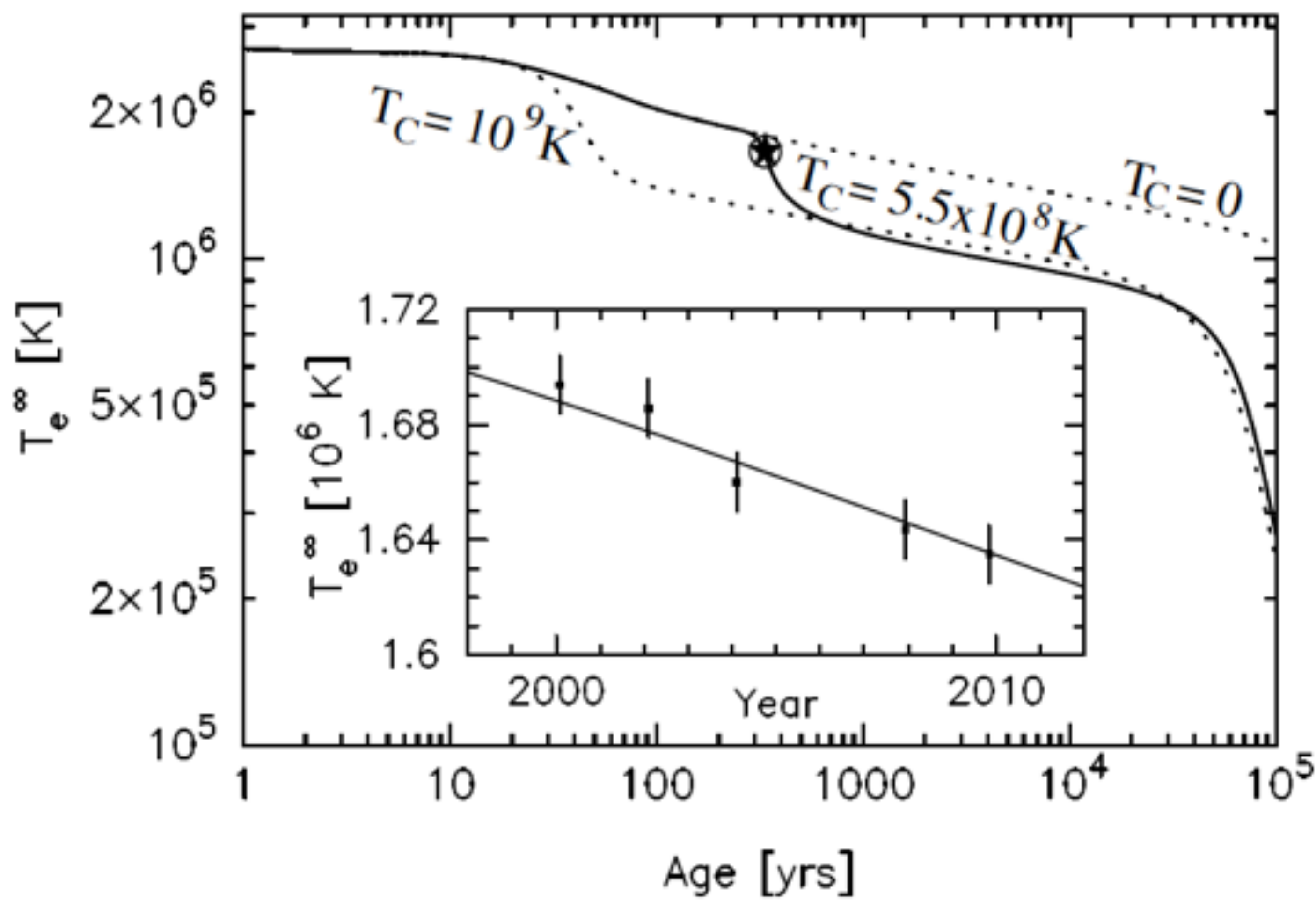
Cooling of neutron stars

NS cooling curves ($M=1.3M_\odot$)



Yakovlev & Pethick,ARAA **42** 169 (2004)

$^3PF_2$ pairing & CasA

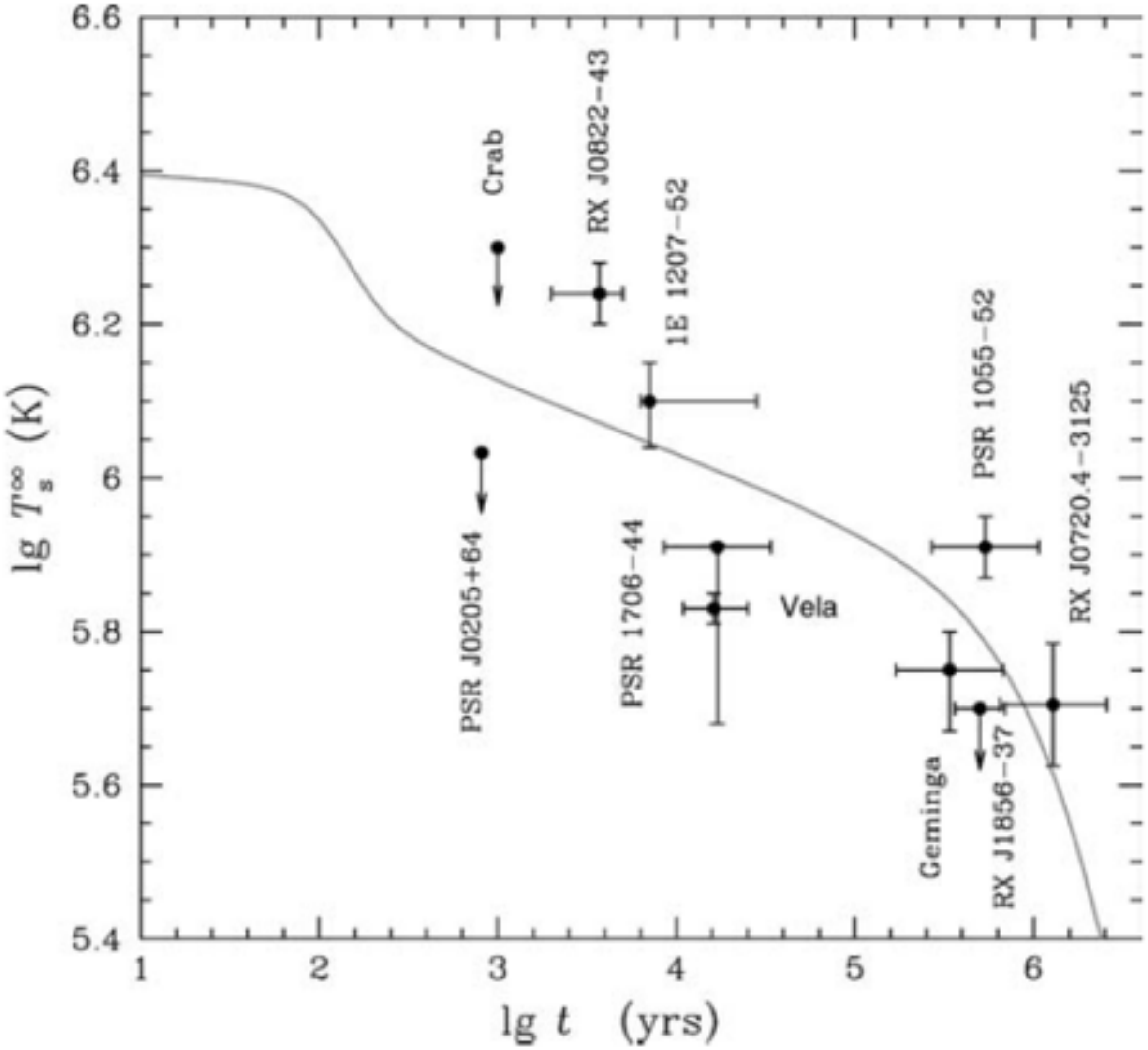


Page et al., *PRL* **106** 081101 (2011)

- Observational data available for a handful of systems
- Sensitive to **interior** physics!

Cooling of neutron stars

NS cooling curves (M=1.3M⊙)



Yakovlev & Pethick,ARAA **42** 169 (2004)

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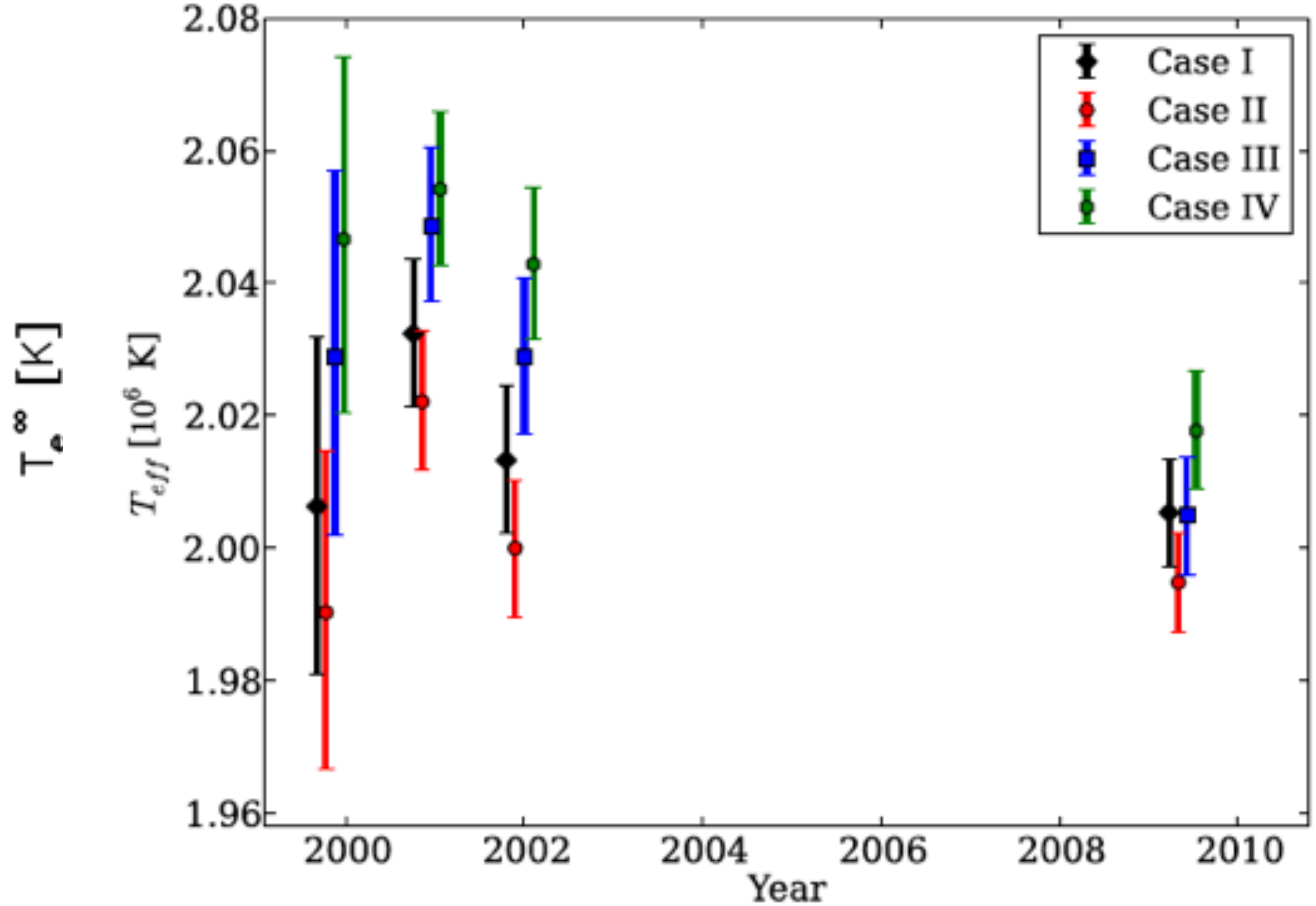
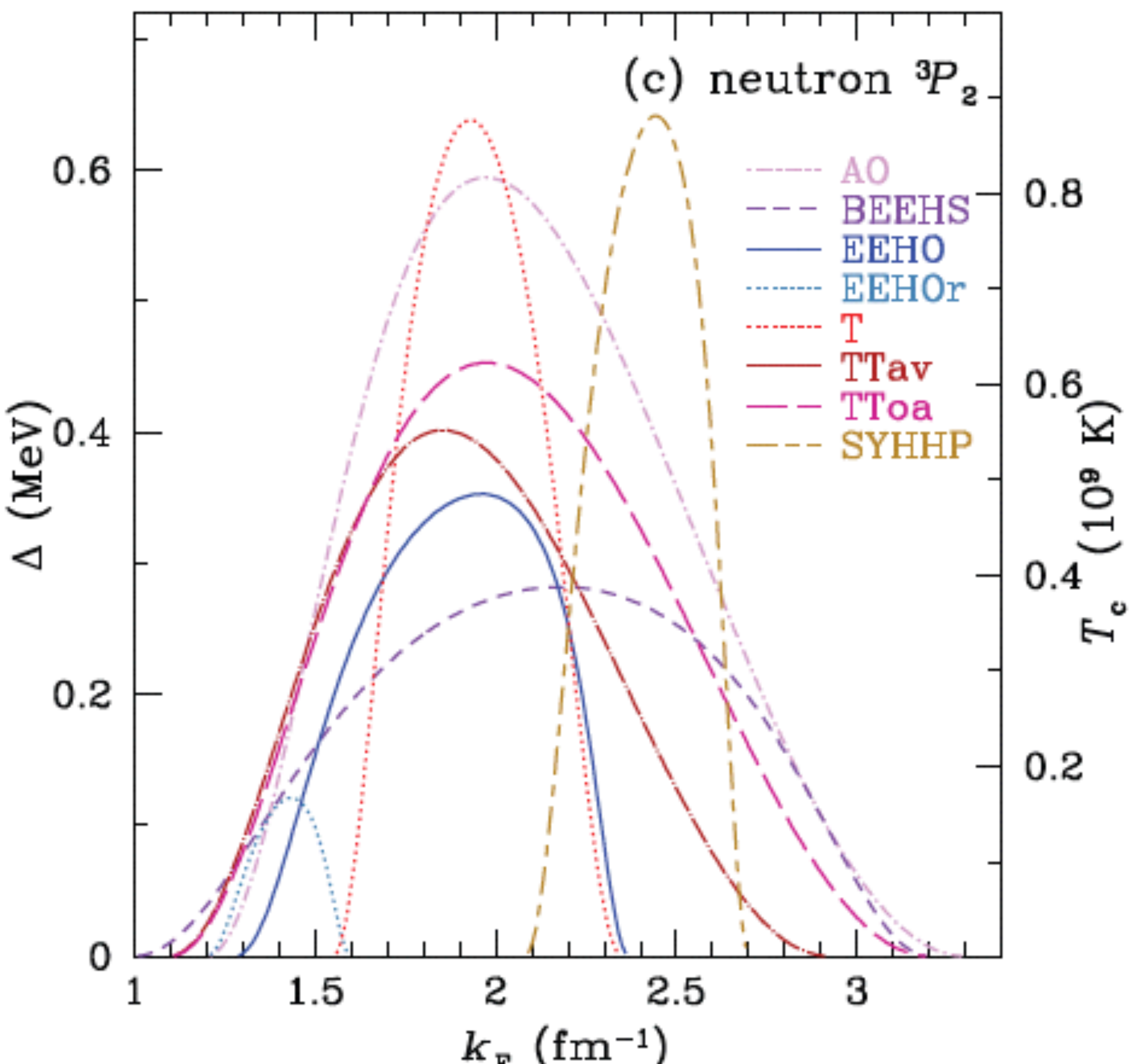
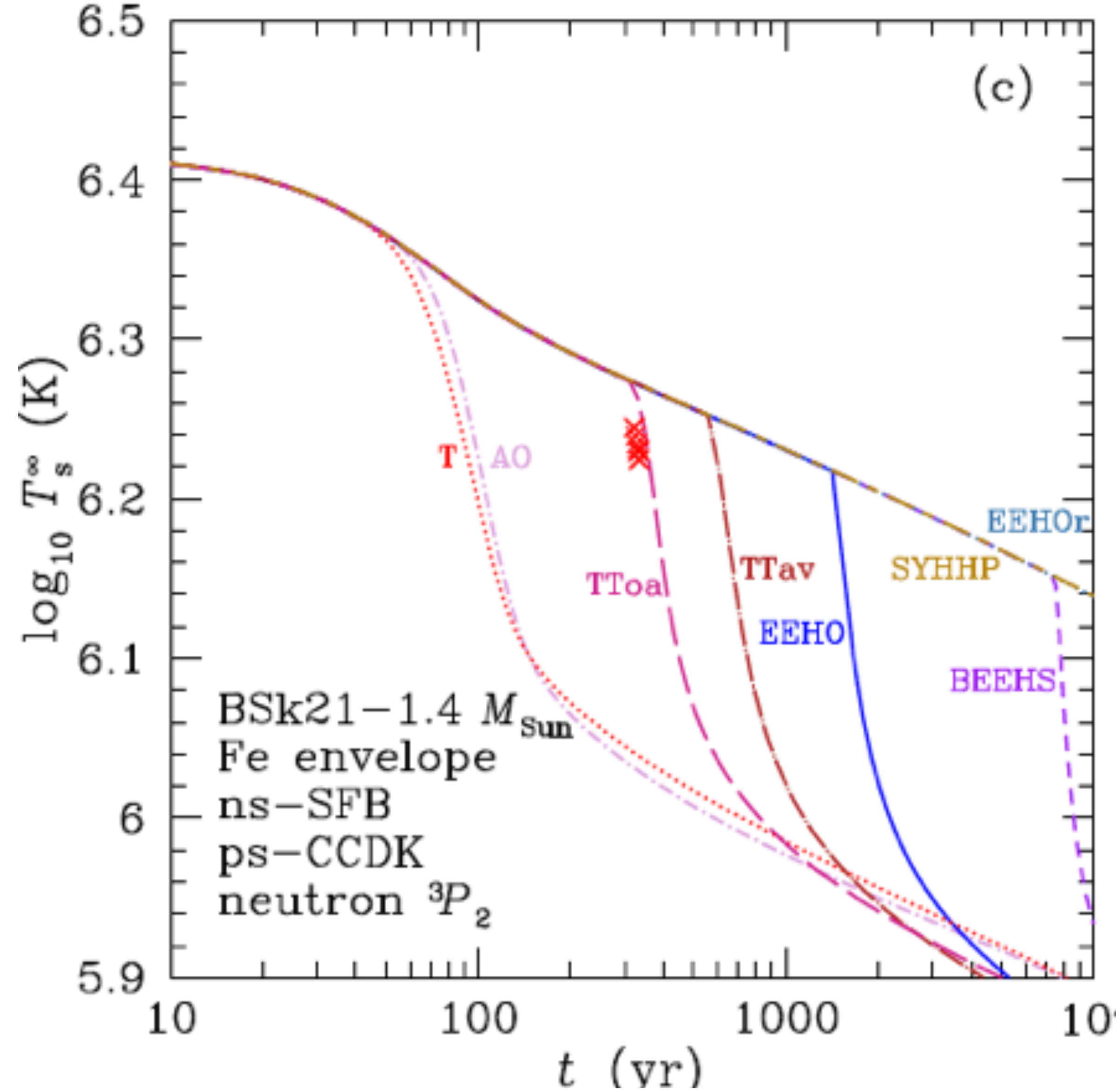


Figure 2. Inferred temperatures from HRC-S count rates for the NS in Cas A with different cases of source and background extraction regions (see Table 1 for case definitions). Cases II–IV have been shifted by a small offset in time (+0.1, +0.2, +0.3, respectively) to make them easier to distinguish. The temperature decline over 10 yr, for different cases, ranges from 0.9% $\pm$ 0.6% ($\chi^2 = 2.7$ for 2 dof) to 2% $\pm$ 0.7% ($\chi^2 = 1.3$ for 2 dof). Our preferred value for comparison with other detectors, Case I, exhibits a temperature decline of 1.0% $\pm$ 0.7% ($\chi^2 = 1.8$ for 2 dof).

- Observational data available for a handful of systems
- Sensitive to **interior** physics!

Cooling of Cassiopea A





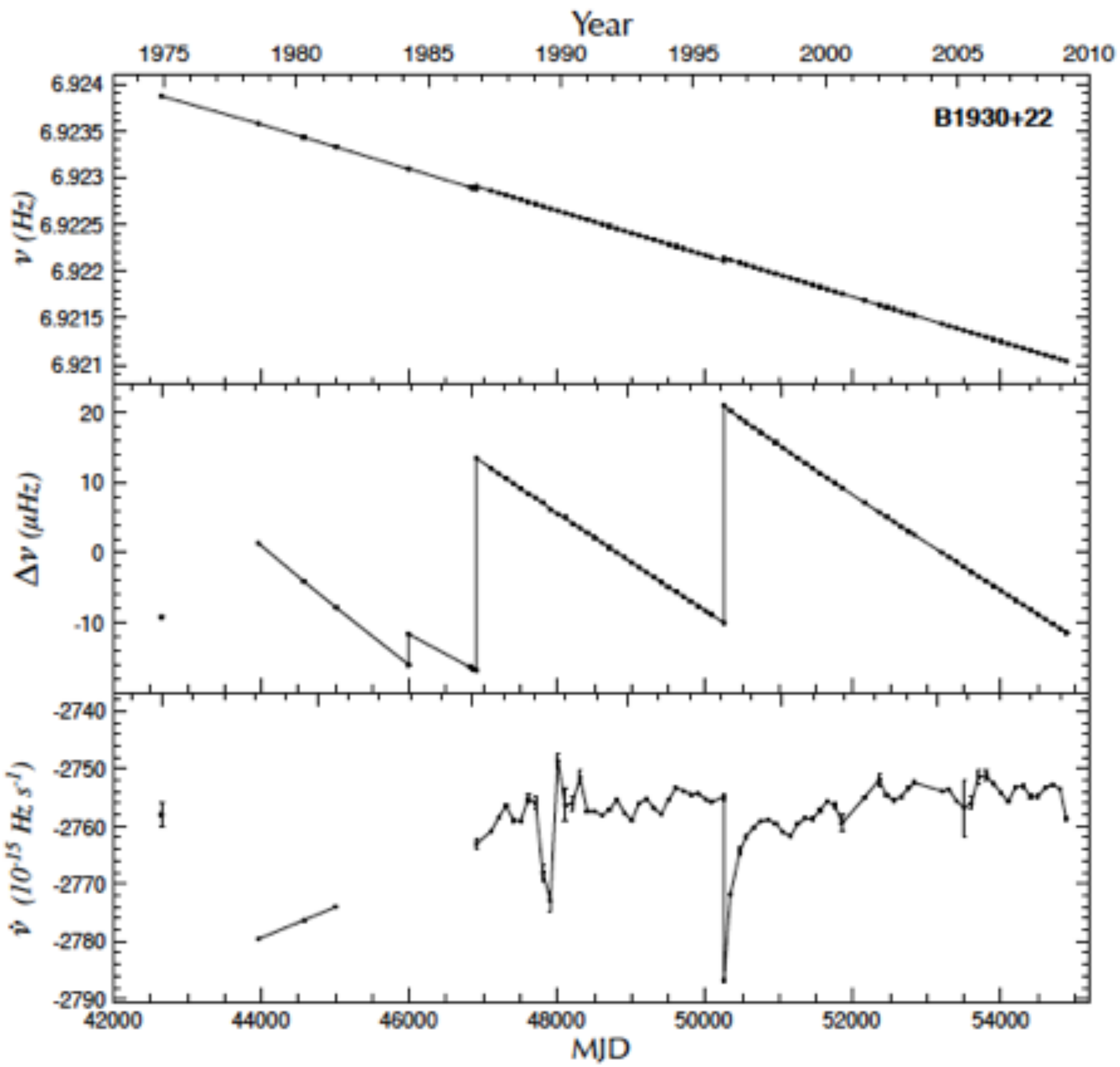
Ho, Elshamouty, Heinke, Potekhin
*PRC **91** 015806 (2015)*

Ingredients

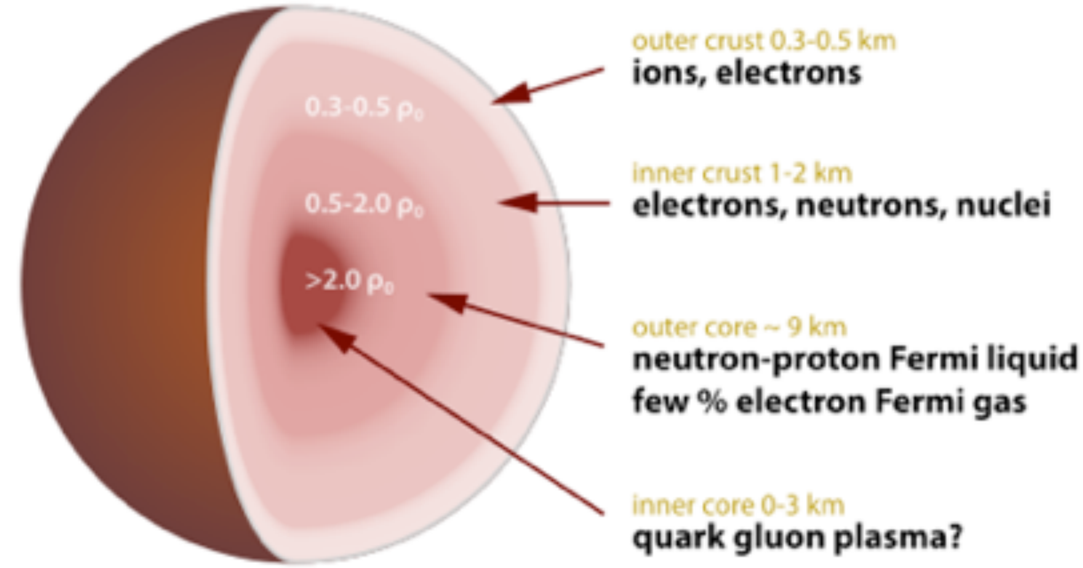
(a) Mass of pulsar
(b) EoS (determines radius)
(c) Internal composition
(d) Pairing gaps ($^1S_0$ & $^3PF_2$ channels)
(e) Atmosphere composition

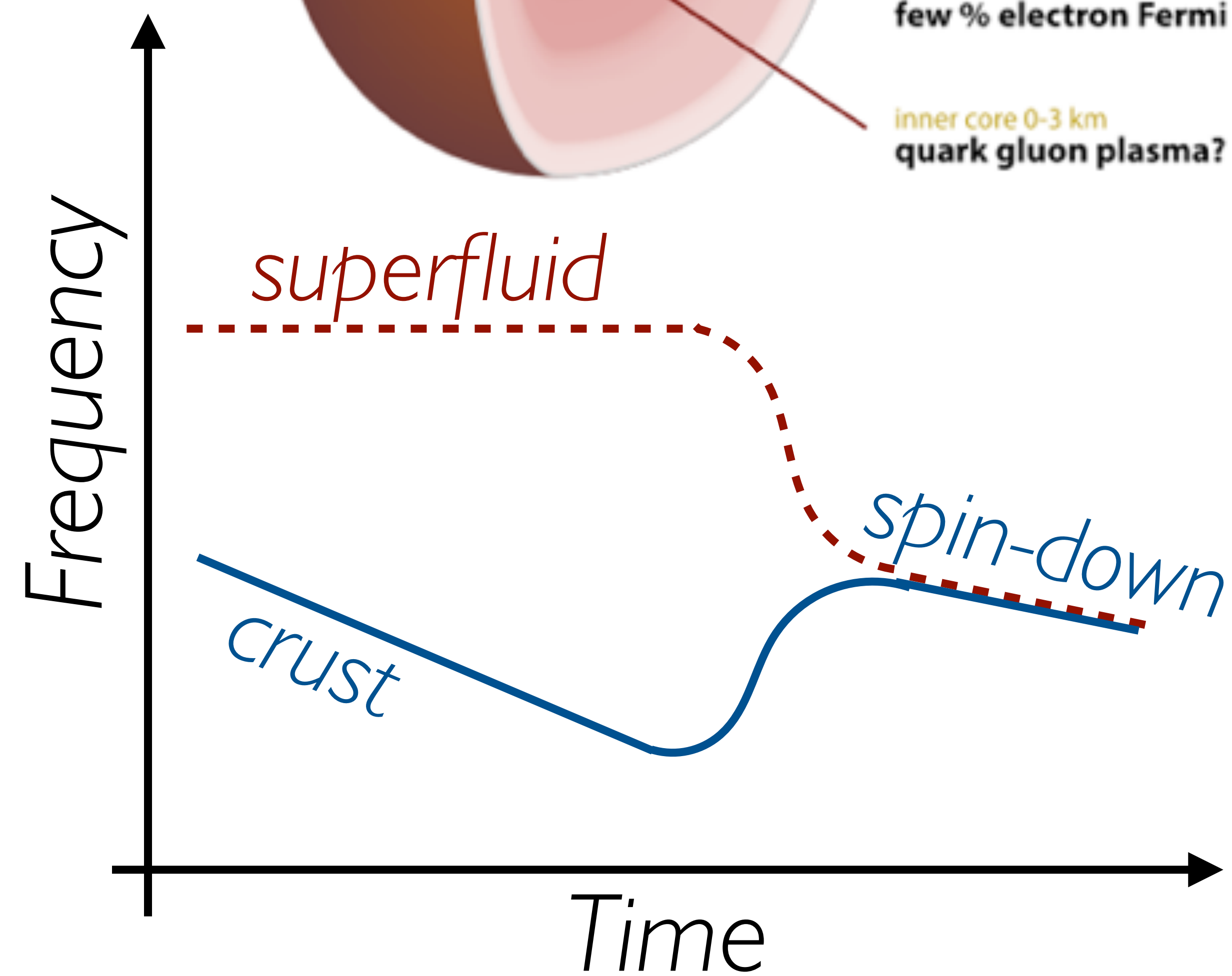
Name	Process	Emissivity (erg cm^{-3} s^{-1})
Modified Urca (neutron branch)	$n+n \to n+p+e^- + \bar{\nu}_e$ $n+p+e^- \to n+n+\nu_e$	$\sim 2\times10^{21}\, R T_9^8$
Modified Urca (proton branch)	$p+n \to p+p+e^- + \bar{\nu}_e$ $p+p+e^- \to p+n+\nu_e$	$\sim 10^{21}\, R T_9^8$
Bremsstrahlungs	$n+n \to n+n+\nu+\bar{\nu}$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

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, *arxiv:1502.07062*

Bardeen-Cooper-Schrieffer pairing

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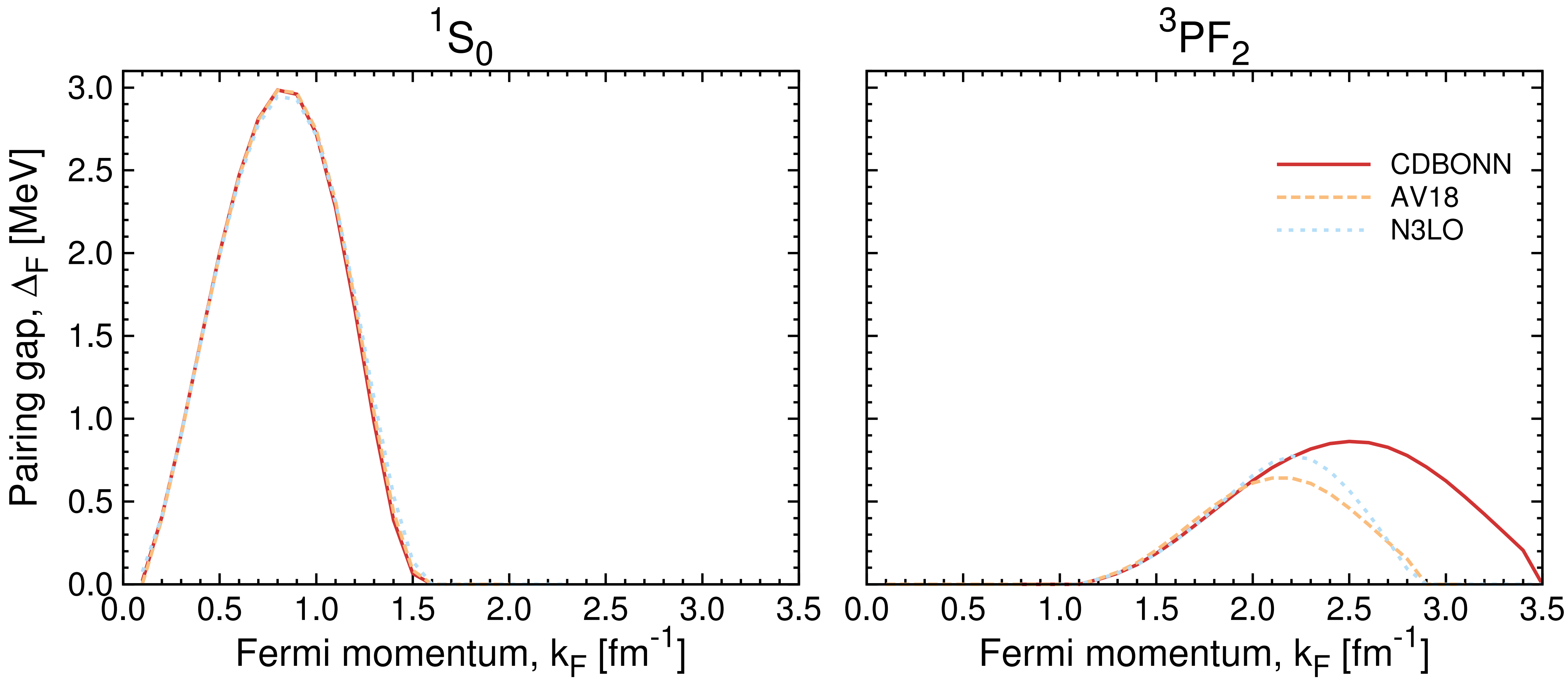
Neutron matter BCS gaps



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

BCS equation

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

- 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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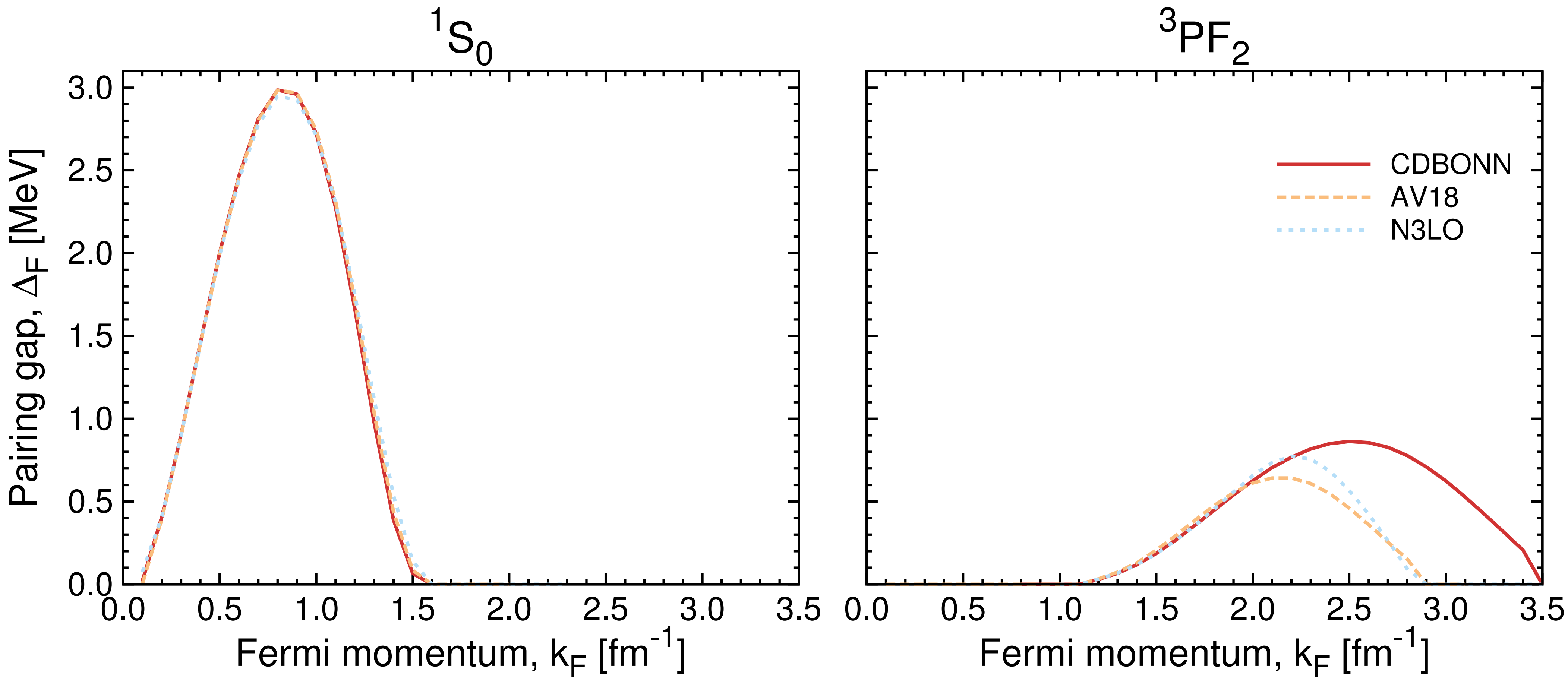
Neutron matter BCS gaps



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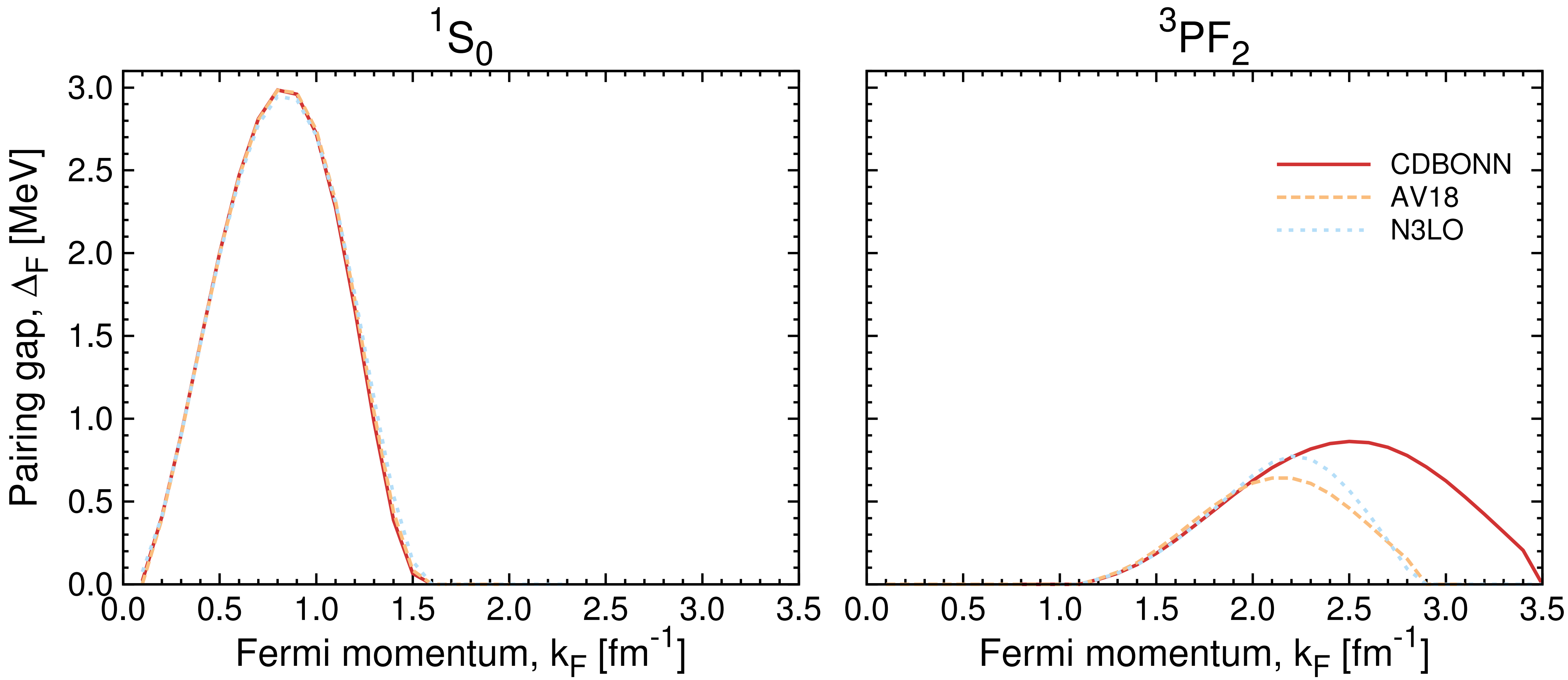

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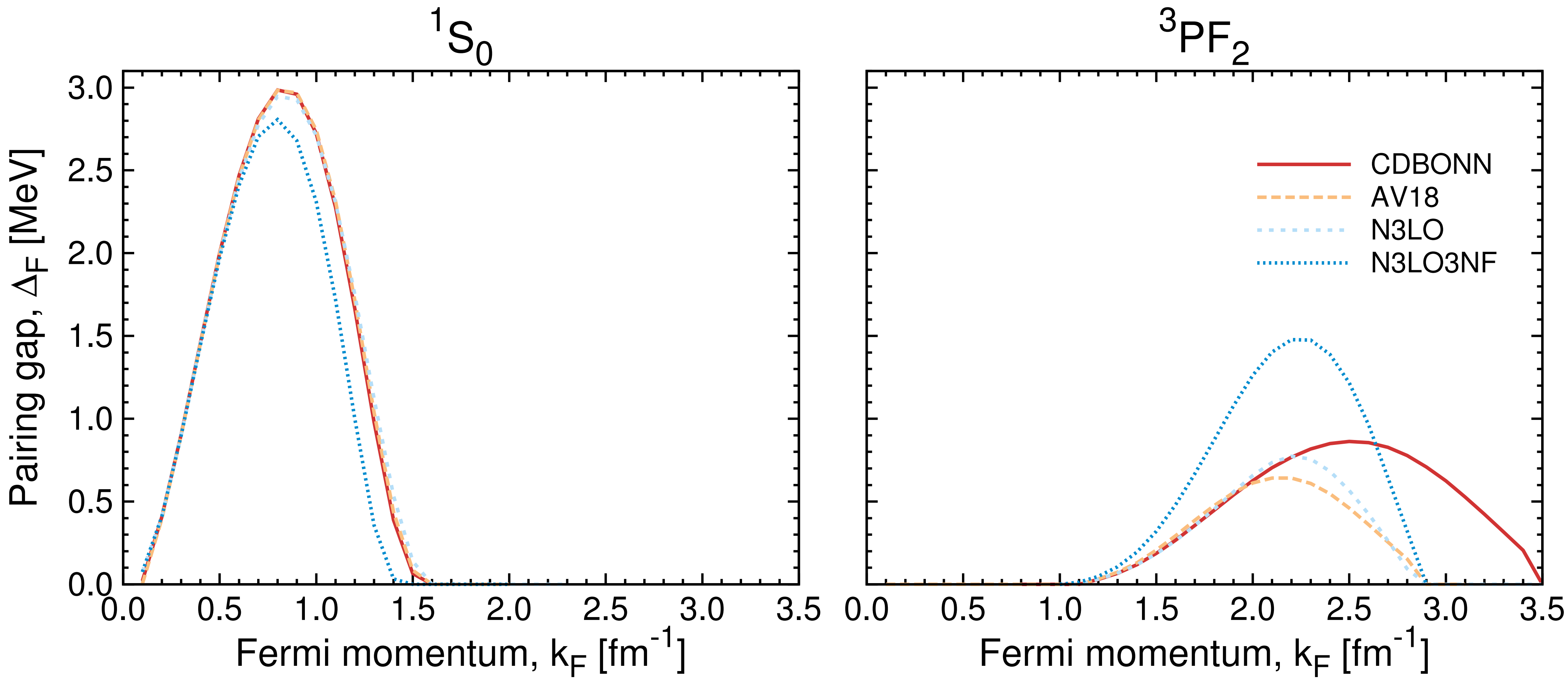
Neutron matter BCS gaps



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

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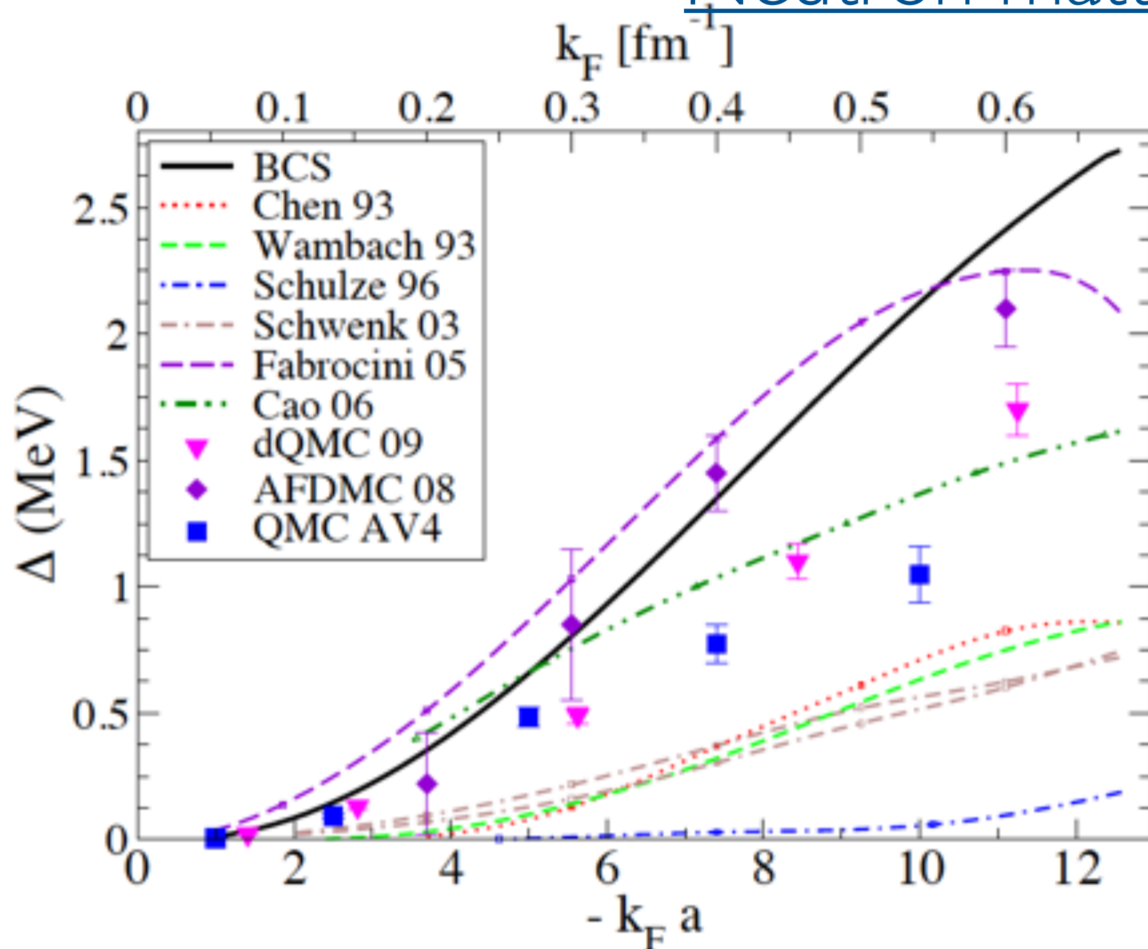
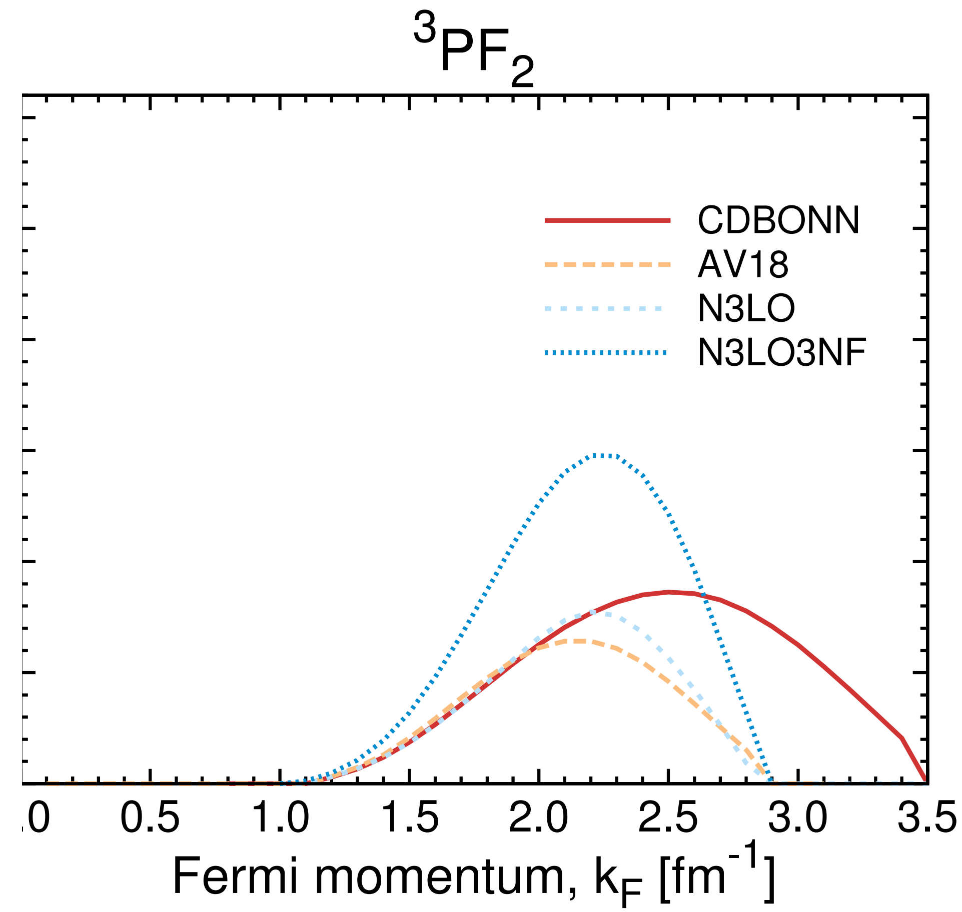
Neutron matter BCS gaps





Gandolfi, Gezerlis & Carlson, *arxiv:1501.05675, Annu. Rev. Nucl. Part.Sci.*

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

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

Beyond BCS 101: results SNM $^3SD_1$

Symmetric matter

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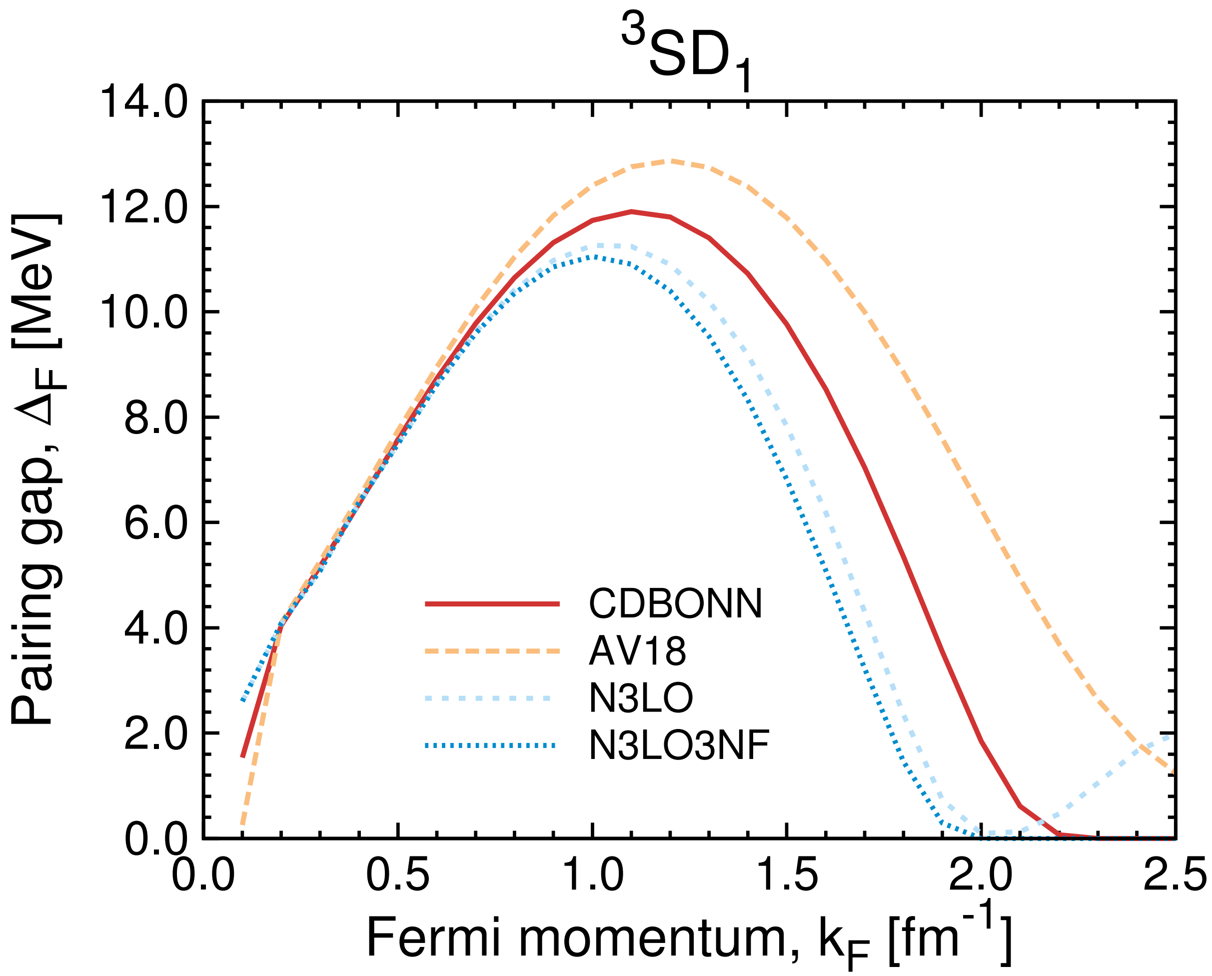
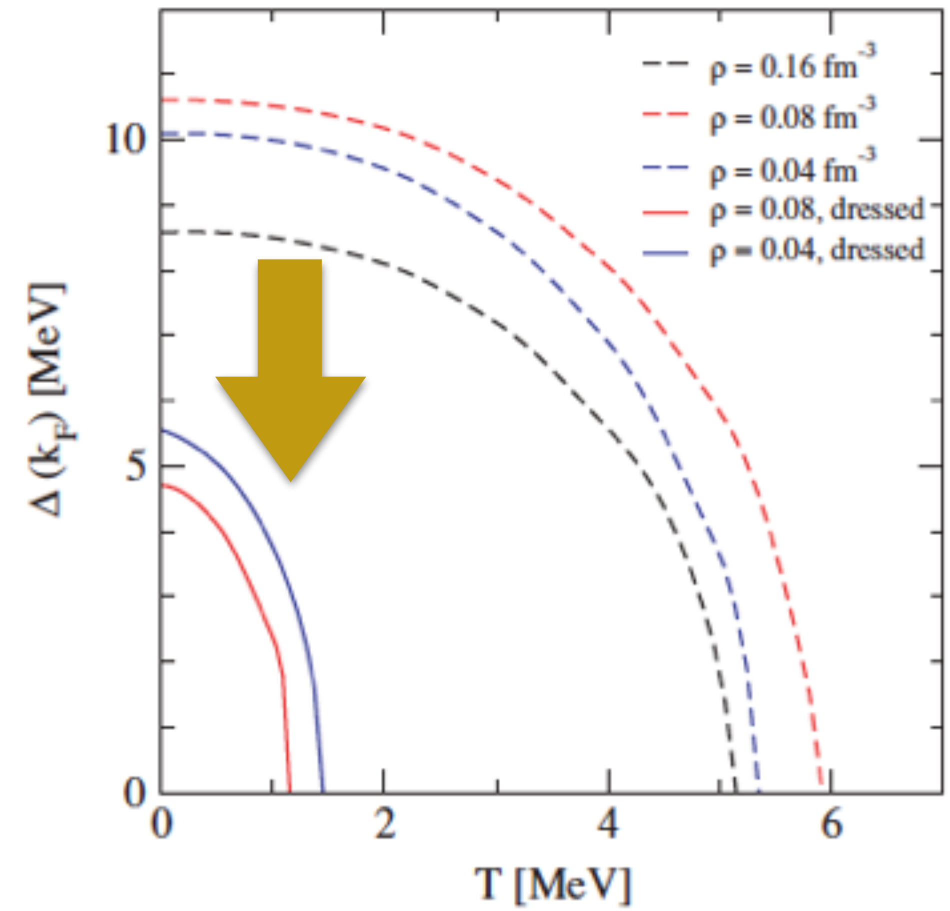
$^3SD_1$ nuclear matter BCS gaps



Maurizio, Holt & Finelli, *PRC* ***90**, 044003* (2014)

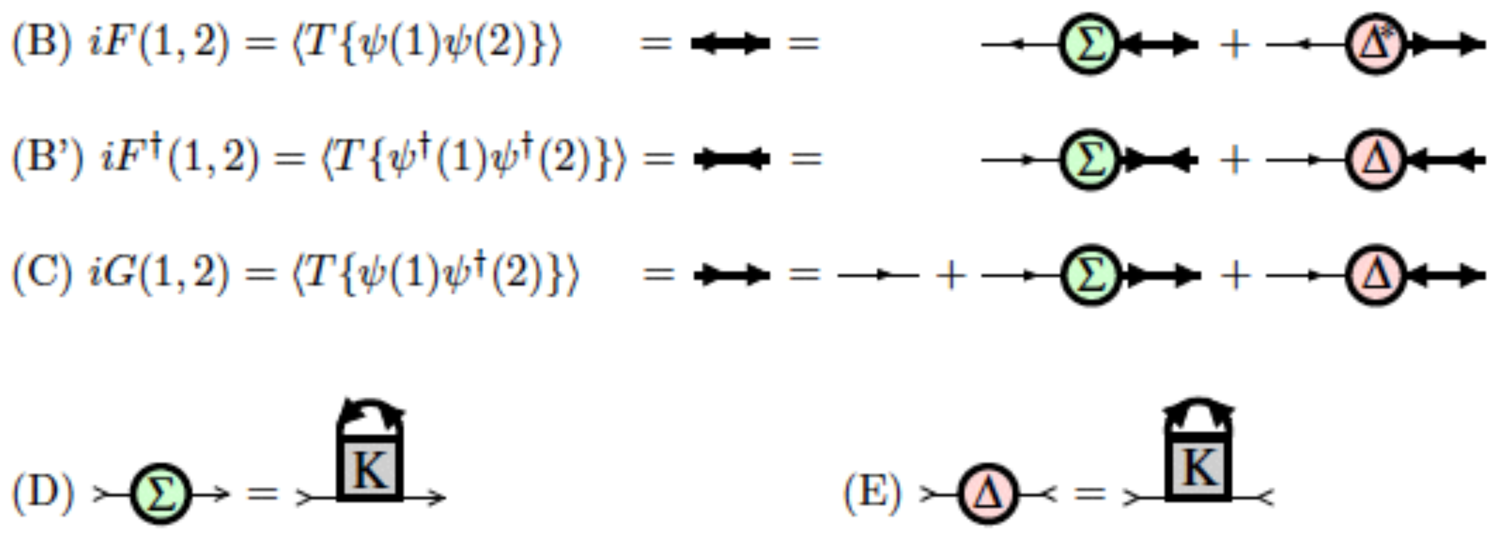
SRC-depleted $^3SD_1$ gaps

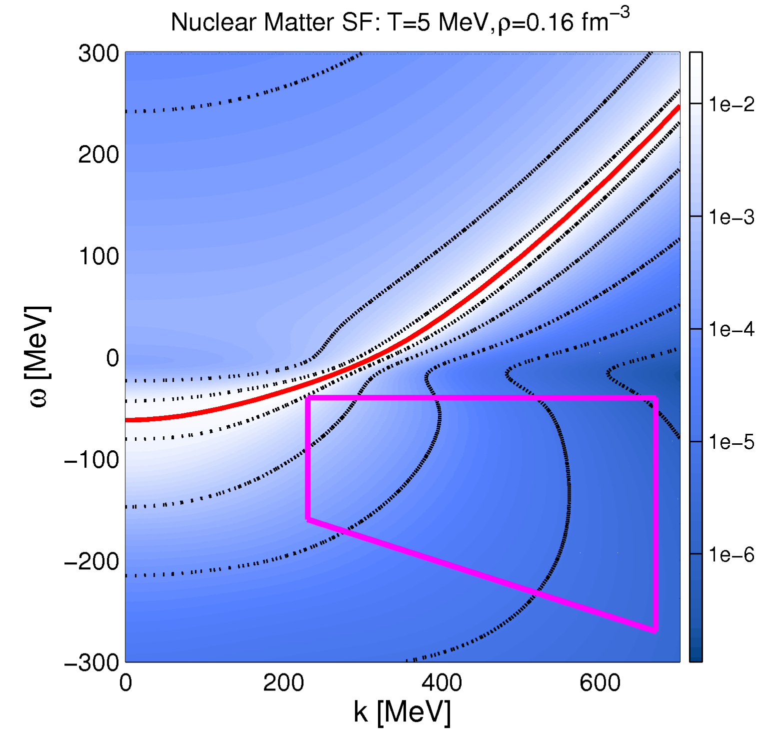


Muether & Dickhoff, *PRC* **72** 054313 (2005)

- **Massive** gaps ^{3}**SD$_1$** channel but…
- **No** evidence of strong *np* nuclear pairing
- Short-range correlations **deplete** gap
- 3BF effect? Short-range effects?

Beyond BCS 101: SRC





BCS+SRC equation

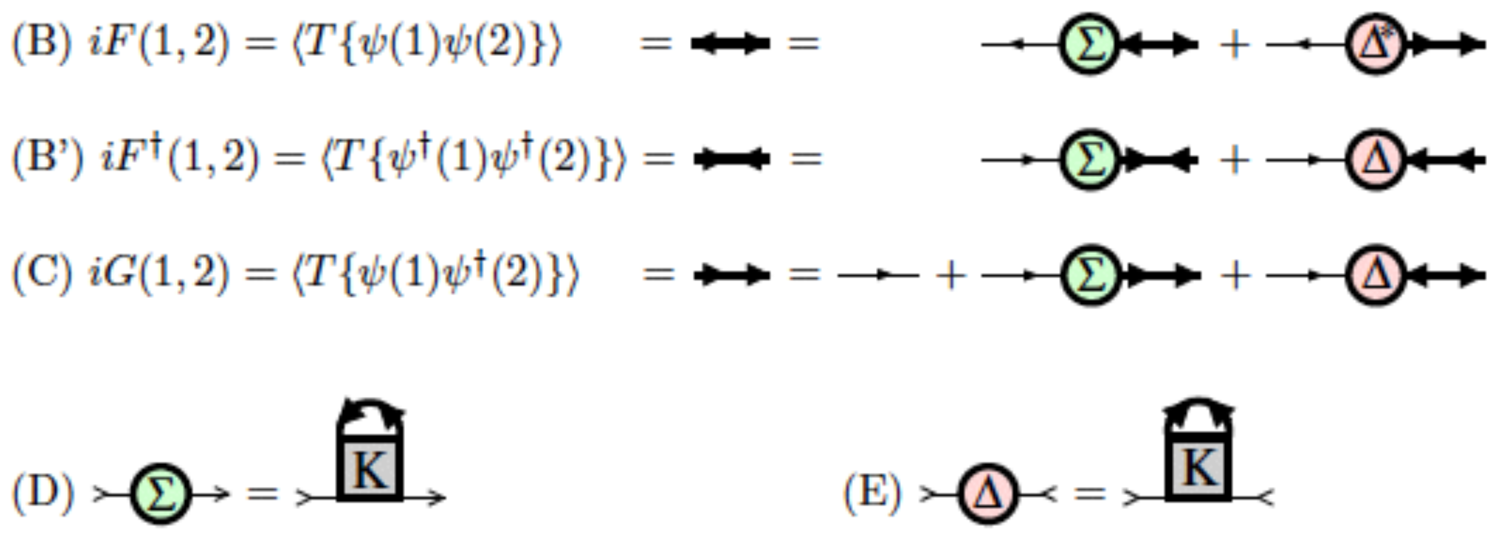
$$\Delta_k^L = -\sum_{L'}\int_{k'} \frac{\langle k|V_{nn}^{LL'}|k'\rangle}{2\chi_{k'}}\Delta_{k'}^{L'} \quad +$$

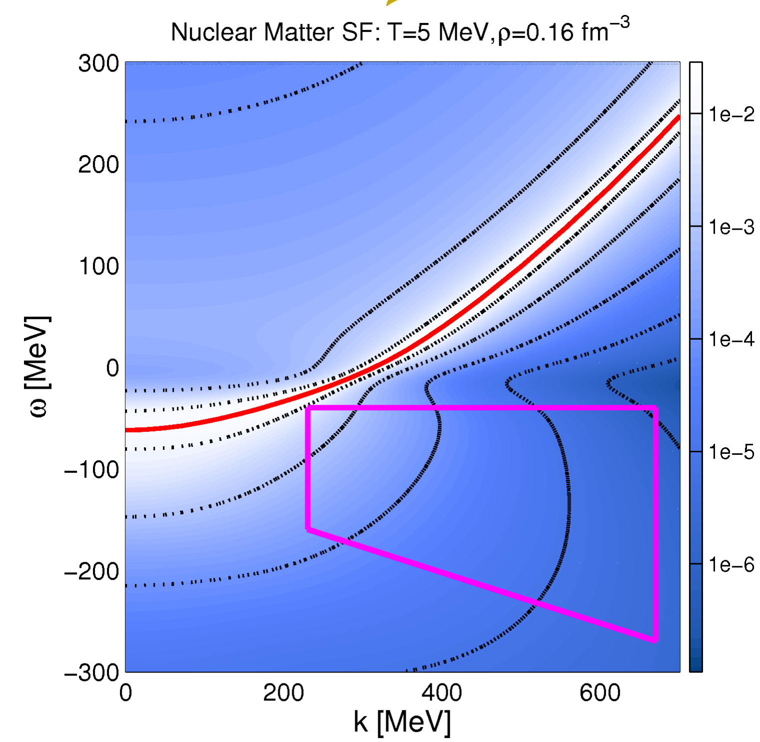
$$\frac{1}{2\chi_k} = \int_\omega\int_{\omega'} \frac{1-f(\omega)-f(\omega')}{\omega+\omega'} A(k,\omega)A_s(k,\omega')$$

- **BCS** is *lowest order* in Gorkov Green's function expansion
- How does **removal** of **strength** affect pairing?
- Effective replacement of denominator

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

Beyond BCS 101: SRC





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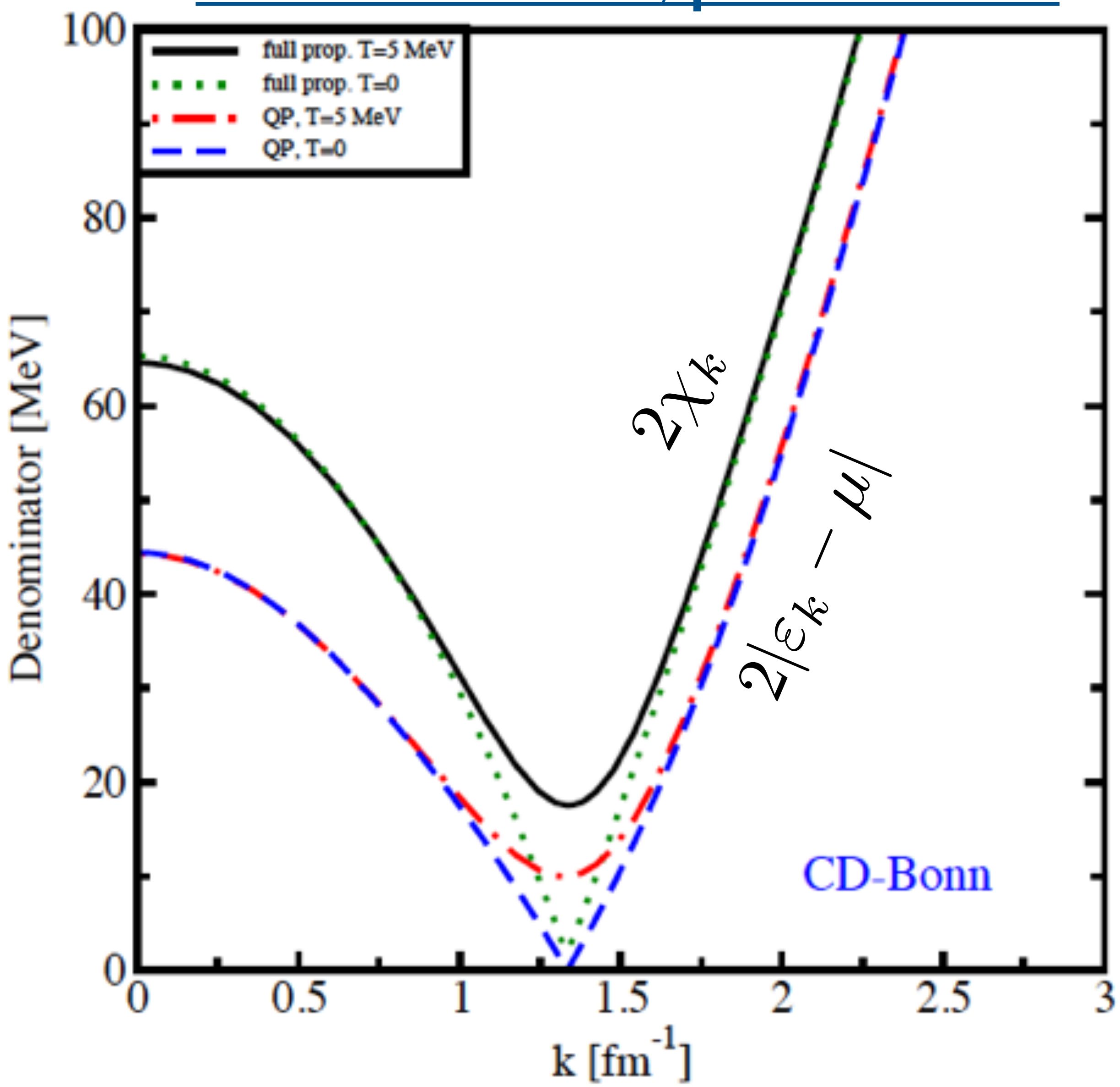
Bozek, *Phys. Rev. C* **62** 054316 (2000); Muether & Dickhoff, *Phys. Rev. C* **72** 054313 (2005)

Beyond BCS 101: SRC

Nuclear matter, ρ=0.16 fm^{-3}



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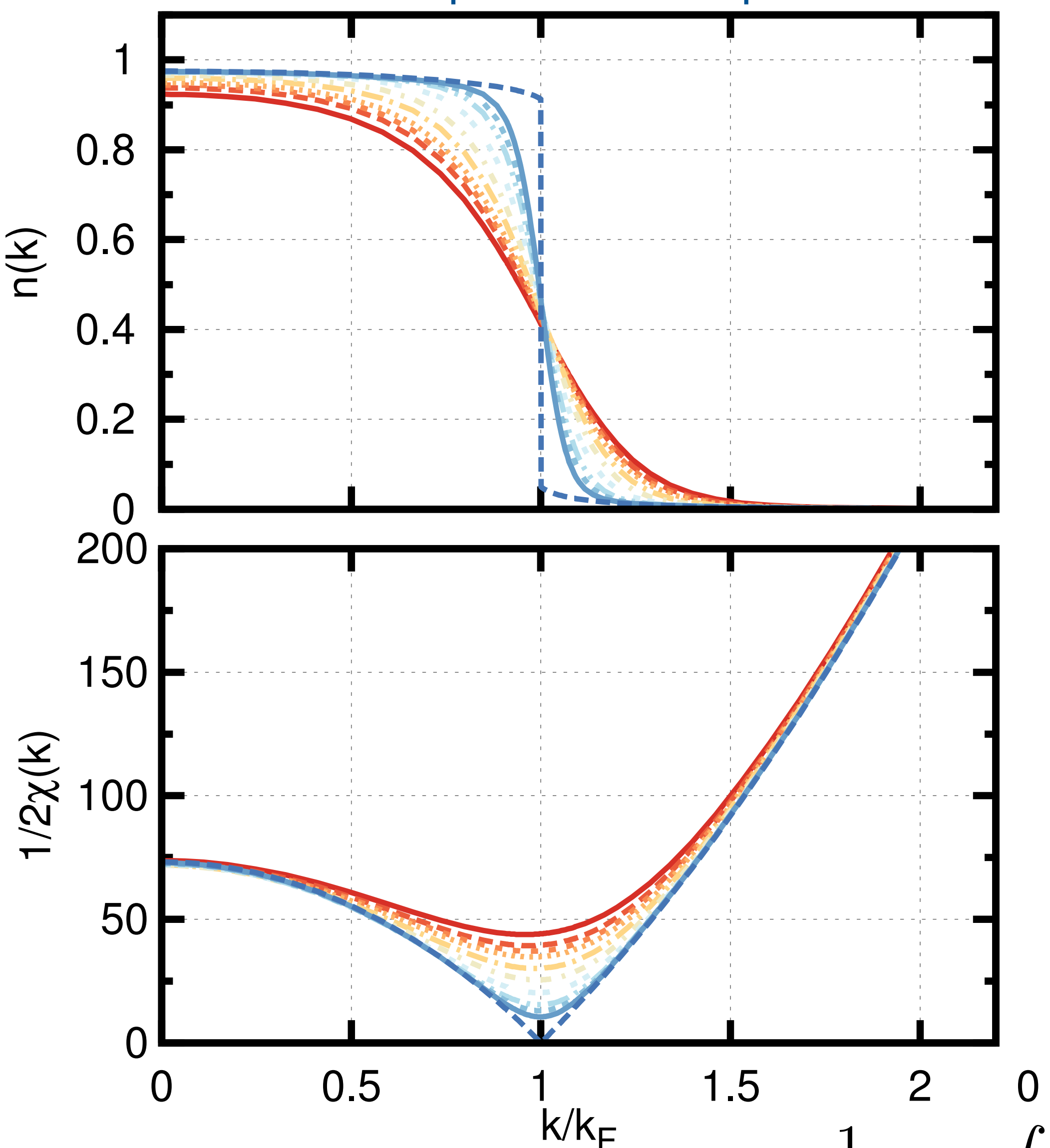
- Effective replacement of denominator

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

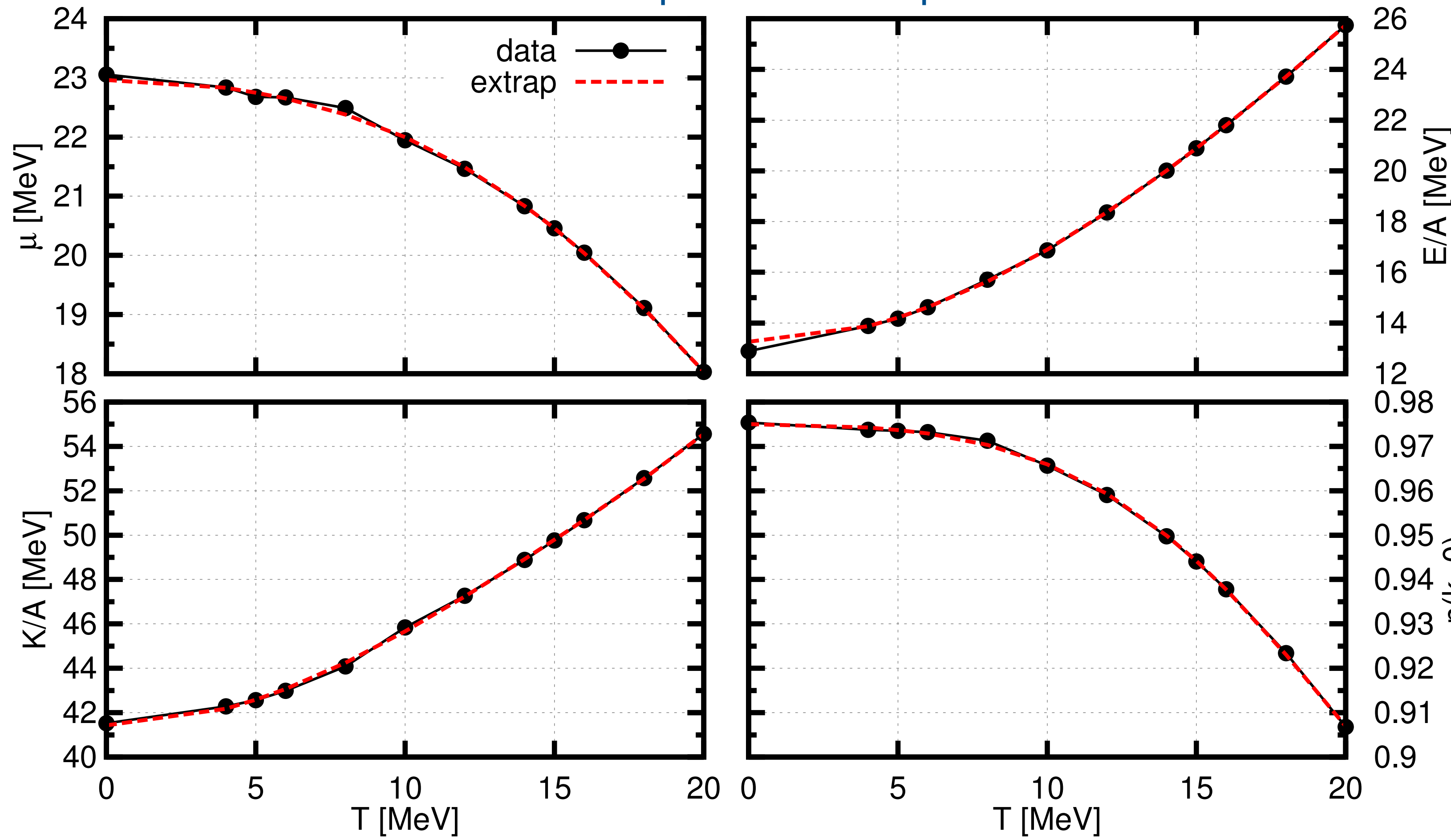
Denominator

CDBonn, PNM, ρ=0.16 fm^{-3}

Microscopic extrapolation



Macroscopic extrapolation



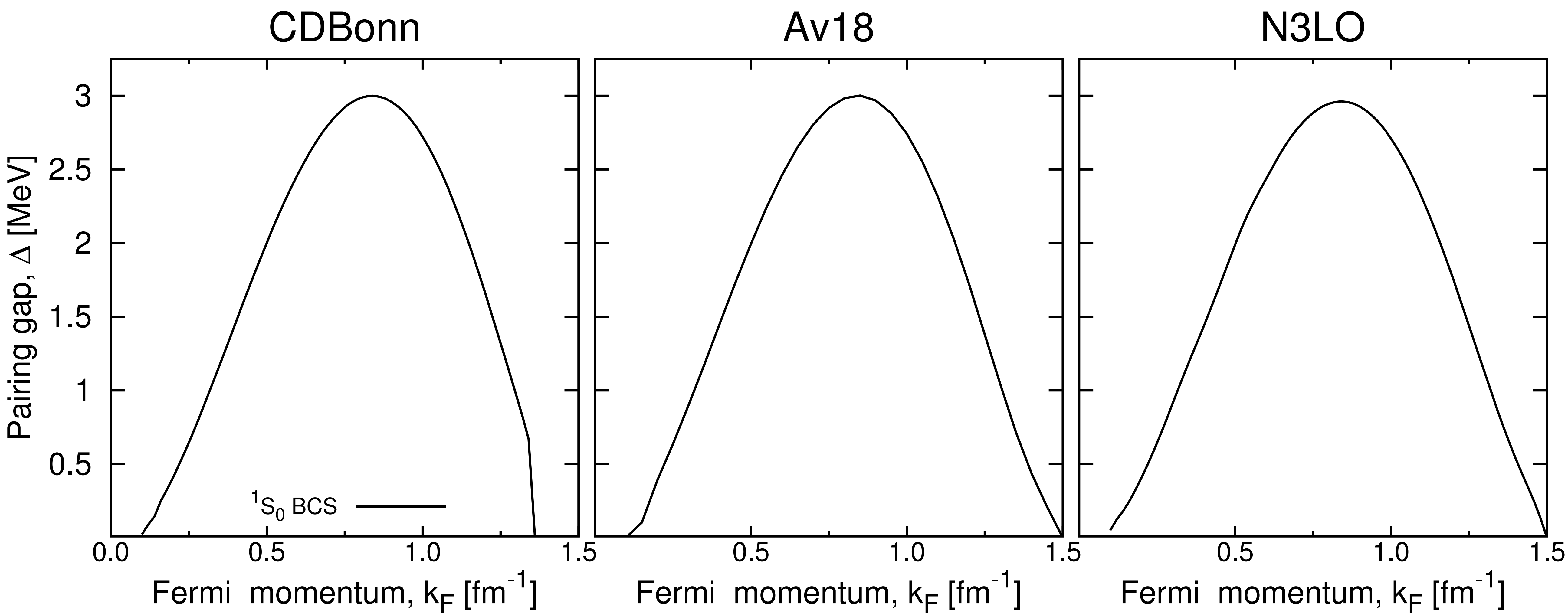
$$\frac{1}{2\chi_k} = \int_{\omega}\int_{\omega'} \frac{1 - f(\omega) - f(\omega')}{\omega + \omega'} A(k,\omega)A(k,\omega')$$

- Similar to G_2 component at finite T… but need T=0 **data**!
- **Extrapolate** $\Sigma(k,\omega;T)$ (13 Gb worth data)
- **Constraining** with **macroscopic** properties

A. Rios, *to be published*

Beyond BCS 101: results $^1S_0$

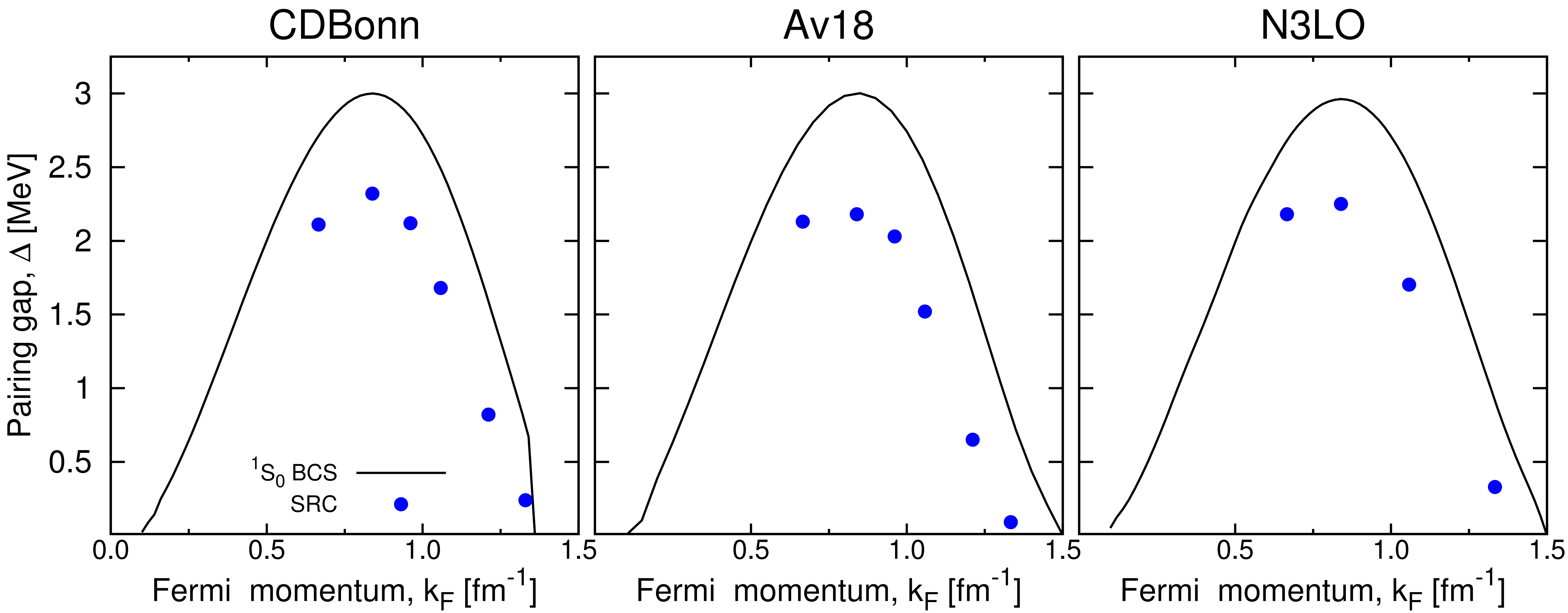
Neutron matter



- **Moderate** screening due to SRC: $\Delta_{max} \approx 2.5$ MeV
- Effect is **robust**: independent of NN potential
- **Similar** gap closure

Beyond BCS 101: results $^1S_0$

Neutron matter



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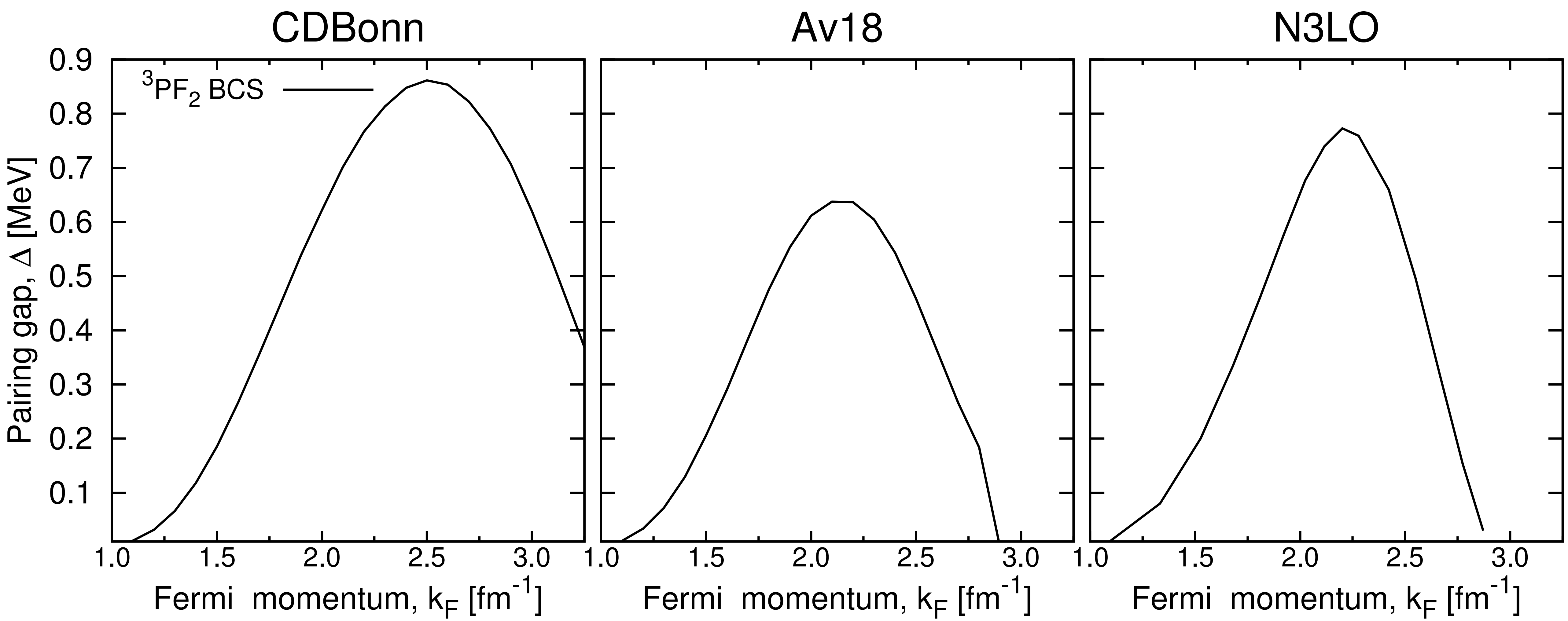
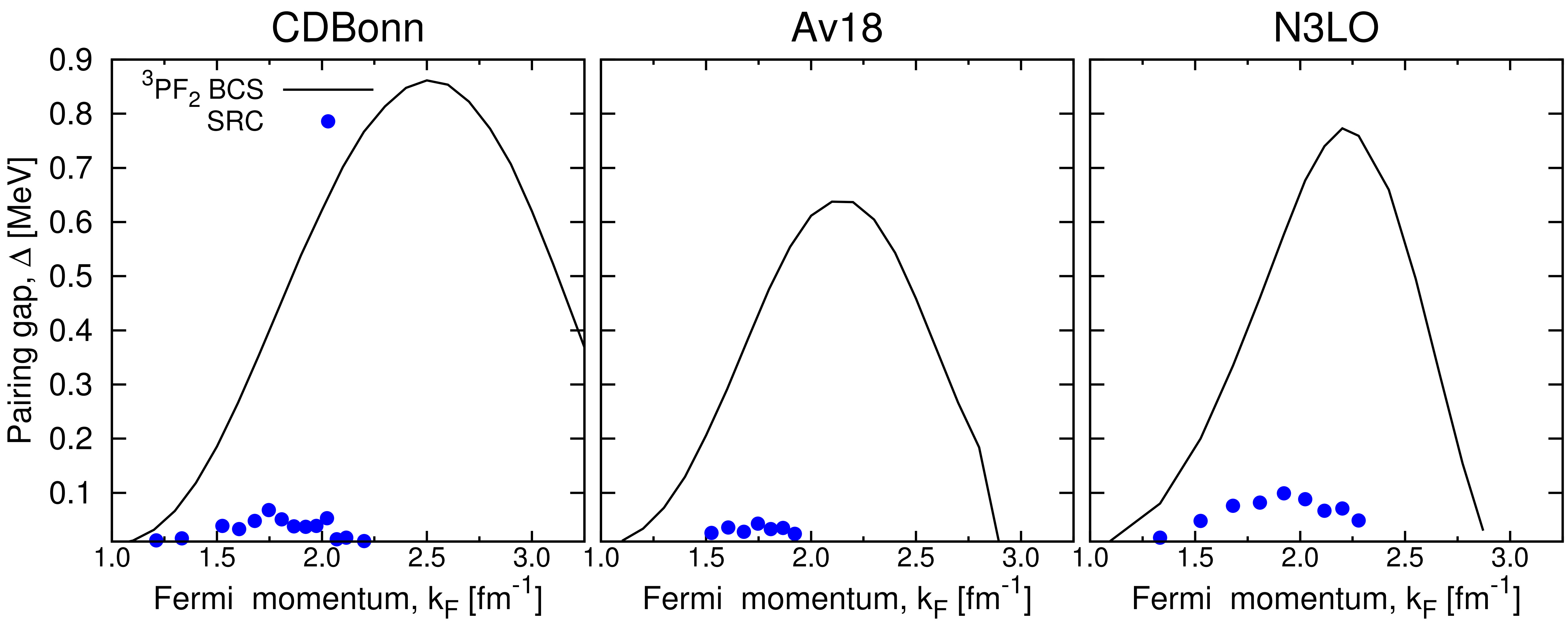
Beyond BCS 101: results $^3PF_2$

Neutron matter



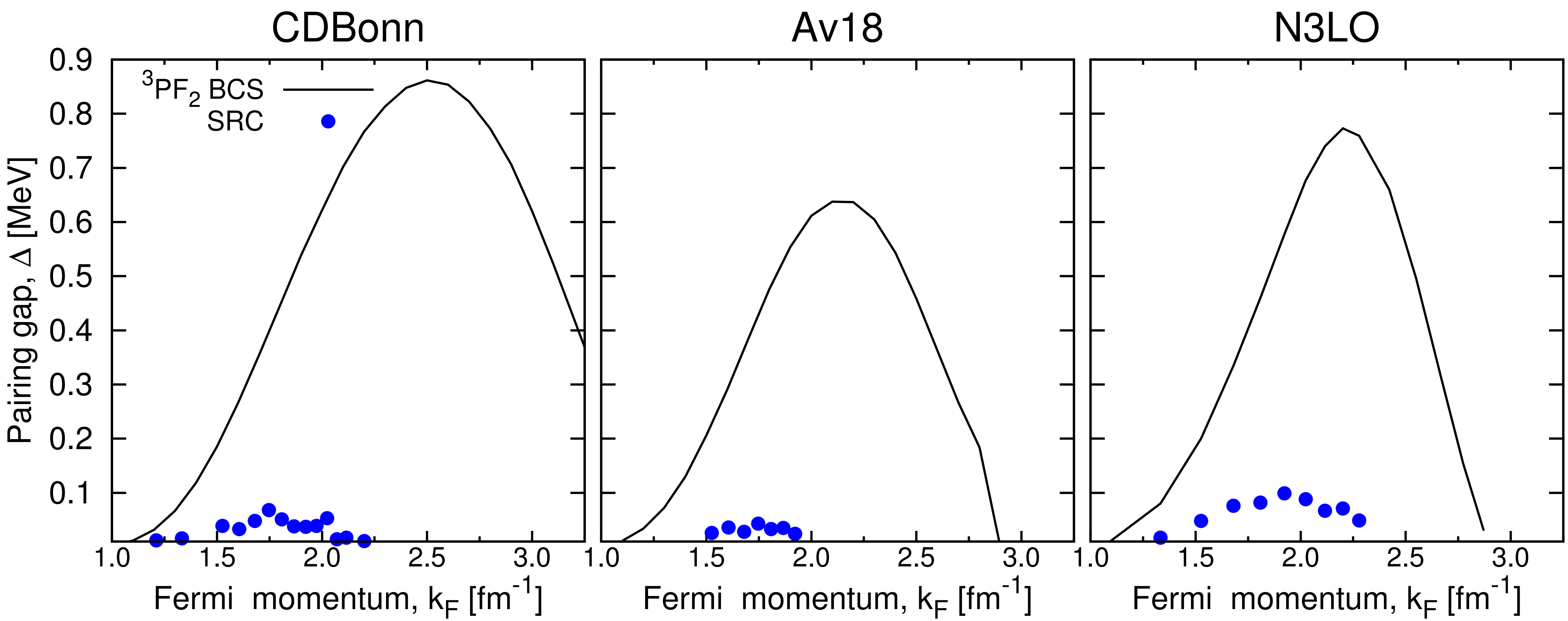
- **BCS** gaps are different in **size** and **extent**

Beyond BCS 101: results $^3PF_2$
Neutron matter



- **BCS** gaps are different in **size** and **extent**
- **Large** screening due to **SRC**: $\Delta \approx 0.1\text{-}0.05$ MeV
- **Lower** gap **closure**

Beyond BCS 101: results $^3PF_2$
Neutron matter



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- **Lower** gap **closure**
- Effect is **robust**: <u>independent</u> of NN potential

Beyond BCS 201: LRC

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

- Bare NN potential only is not the only possible interaction

Gao, Lombardo & Schuck, *Phys Rev C* **74** 064301 (2006)

Beyond BCS 201: LRC

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

?

✔

- Bare NN potential only is not the only possible interaction

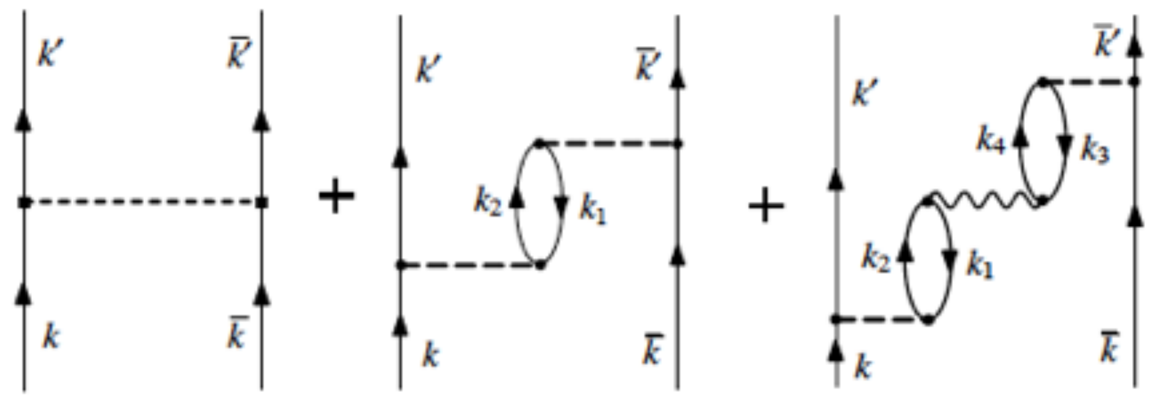
Gao, Lombardo & Schuck, *Phys Rev C* **74** 064301 (2006)

Beyond BCS 201: LRC

?

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

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



(a) (b) (c)

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Gao, Lombardo & Schuck, *Phys Rev C* **74** 064301 (2006)

Beyond BCS 201: LRC

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?

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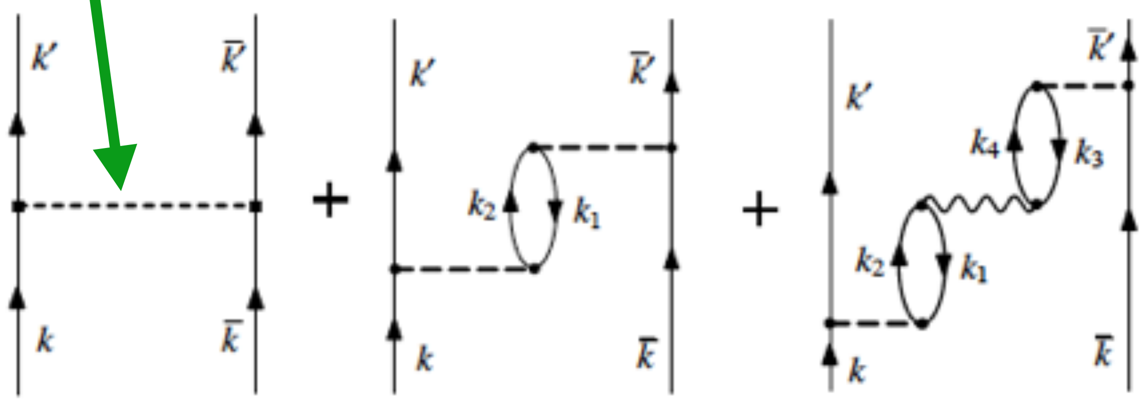


(a) (b) (c)

- Bare NN potential only is not the only possible interaction
- Diagram (a): nuclear interaction

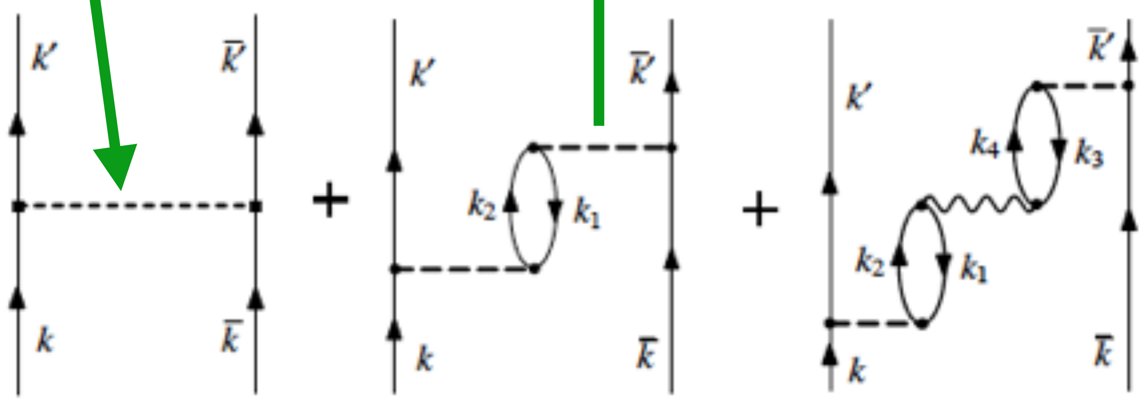
Beyond BCS 201: LRC

?

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

ph recoupled
G-matrix

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



(a) (b) (c)

$$\langle 1\bar{1}|\mathcal{V}|1\bar{1}\rangle = \frac{1}{4}\sum_{2,2'}\sum_{S,T}(-)^S(2S+1)\langle 12|G_{ST}^{\text{ph}}|1'2'\rangle_A \langle 2'\bar{1}|G_{ST}^{\text{ph}}|2\bar{1}'\rangle_A \Lambda^0(22')$$

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

Gao, Lombardo & Schuck, *Phys Rev C* **74** 064301 (2006)

Beyond BCS 201: LRC

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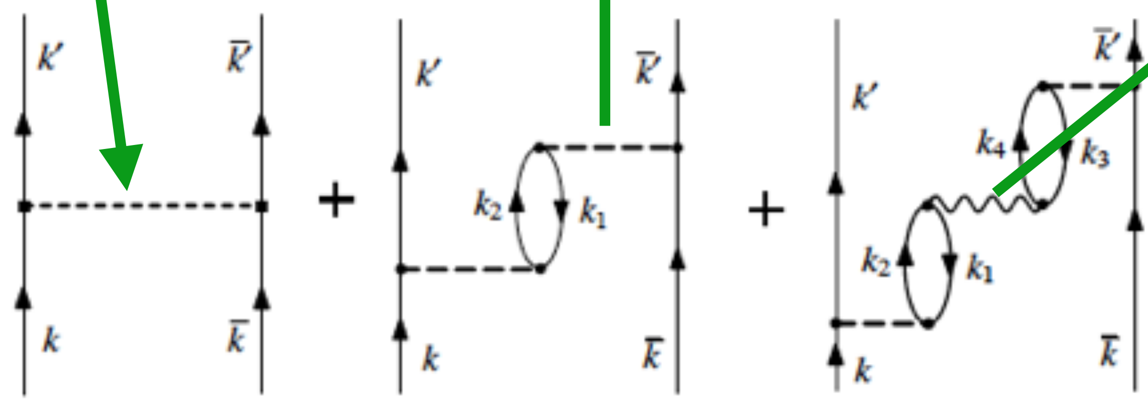
?

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

ph recoupled G-matrix

Effective Landau parameters

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



(a) (b) (c)

$$\langle 1\bar{1}|\mathcal{V}|1\bar{1}\rangle = \frac{1}{4}\sum_{2,2'}\sum_{S,T}(-)^S(2S+1)\langle 12|G_{ST}^{\text{ph}}|1'2'\rangle_A\langle 2'\bar{1}|G_{ST}^{\text{ph}}|2\bar{1}'\rangle_A\Lambda^0(22')$$

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

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

Gao, Lombardo & Schuck, *Phys Rev C* **74** 064301 (2006)

Beyond BCS 201: LRC

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

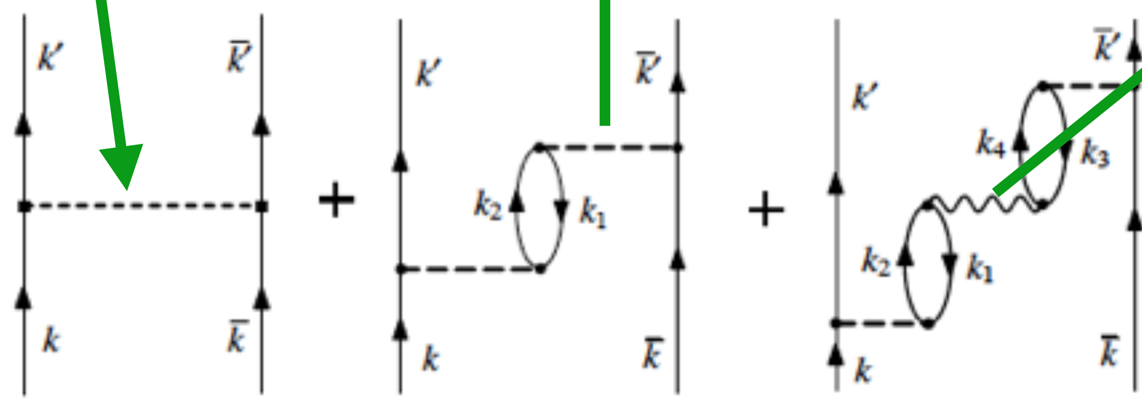
?

✔

ph recoupled G-matrix

Effective Landau parameters

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



(a) (b) (c)

$$\langle 1\bar{1} | \mathcal{V} | 1\bar{1} \rangle = \frac{1}{4} \sum_{2,2'} \sum_{S,T} (-)^S (2S+1) \langle 12 | G_{ST}^{\text{ph}} | 1'2' \rangle_A \langle 2'\bar{1} | G_{ST}^{\text{ph}} | 2\bar{1}' \rangle_A \Lambda^0(22')$$

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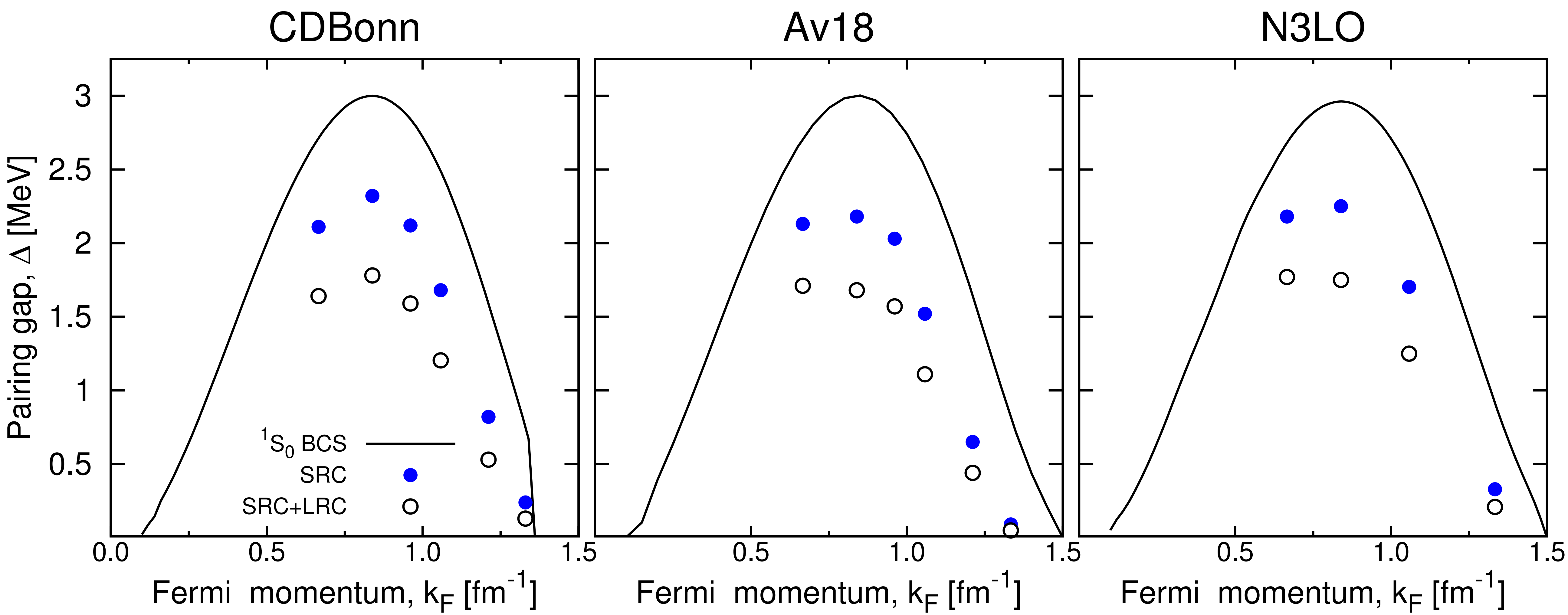
- Bare NN potential only is not the only possible interaction
- Diagram (a): nuclear interaction
- Diagram (b): in-medium interaction, density and spin fluctuations
- Diagram (c): included by Landau parameters

Gao, Lombardo & Schuck, *Phys Rev C* **74** 064301 (2006)

Beyond BCS 201: results $^1S_0$

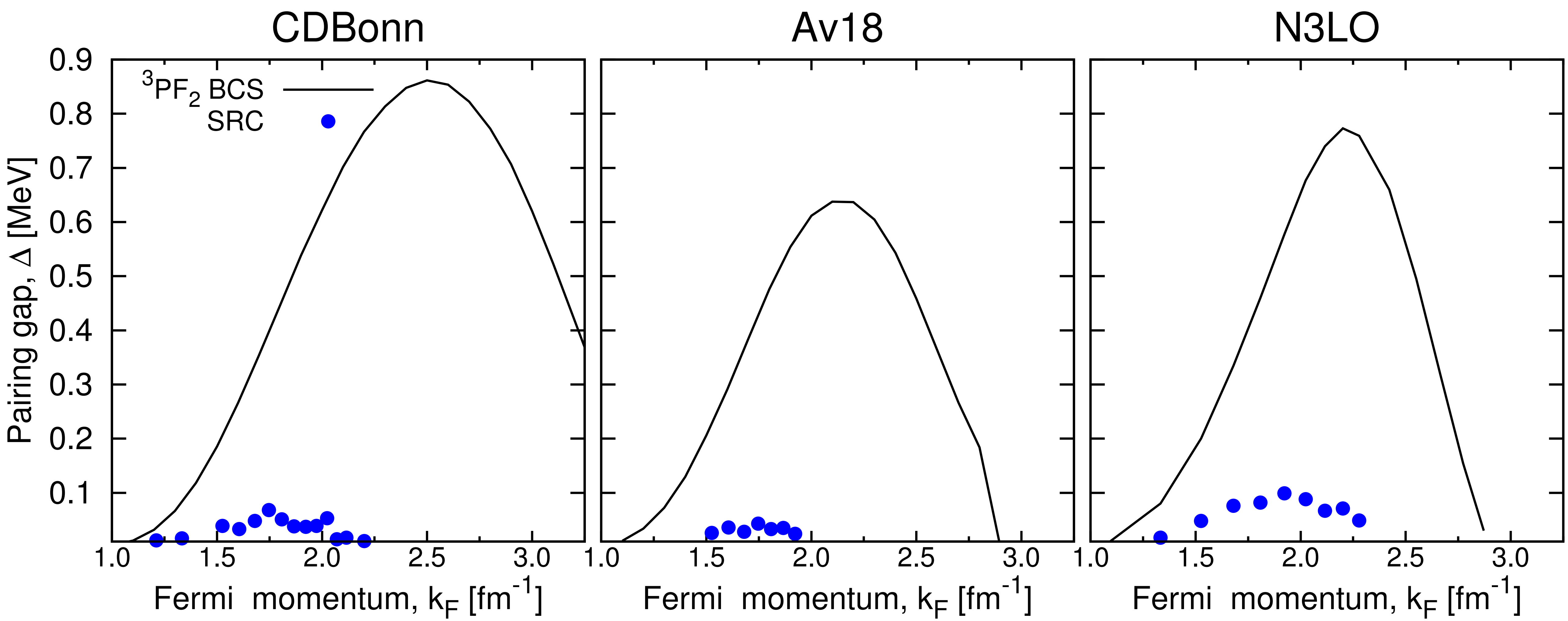
Neutron matter



- **Moderate** screening due to SRC: $\Delta_{max} \approx 2.5$ MeV
- **Additional** screening due to LRC: $\Delta_{max} \approx 2$ MeV
- Effect is **robust**: independent of NN potential
- **Similar** gap closure

Beyond BCS 201: results $^3PF_2$

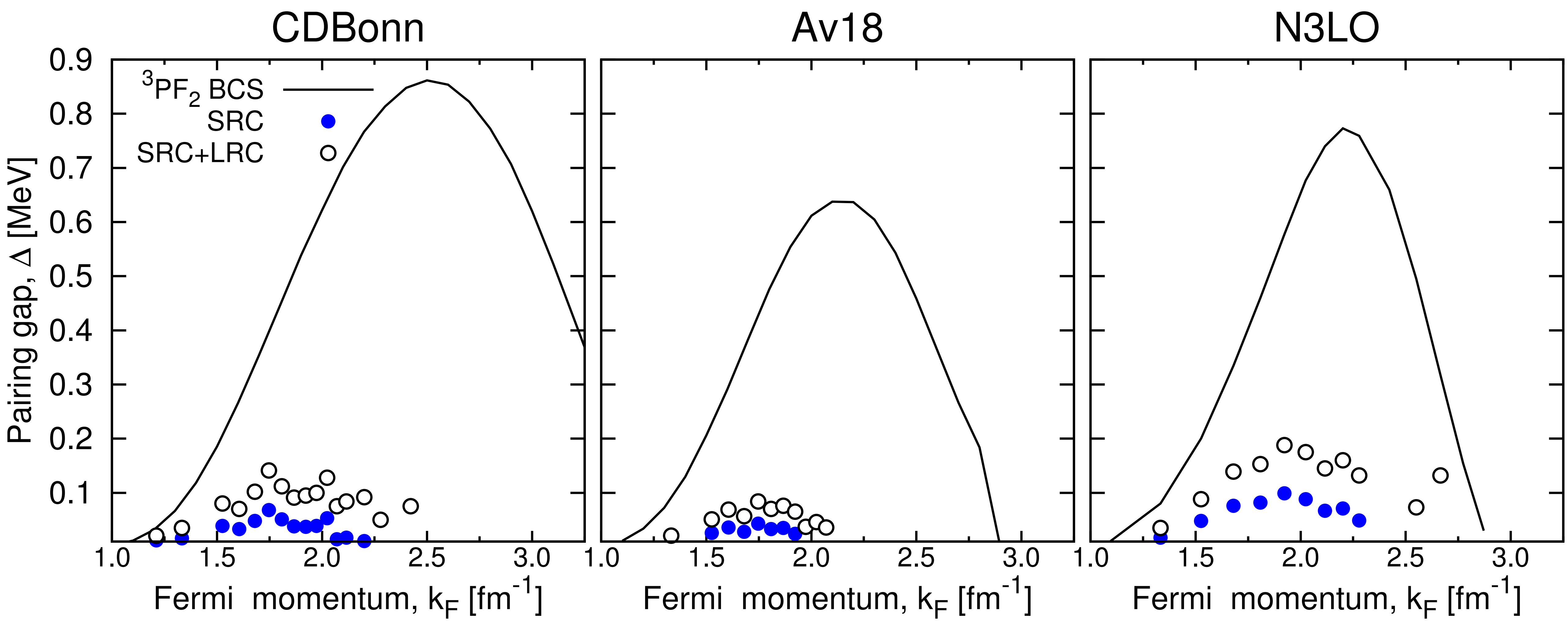
Neutron matter



- **Anti-**screening induced by **SRC**: $\Delta \approx 0.15\text{-}0.20$ MeV
- **Lower** gap **closure**
- Effect is **robust**: independent of NN potential

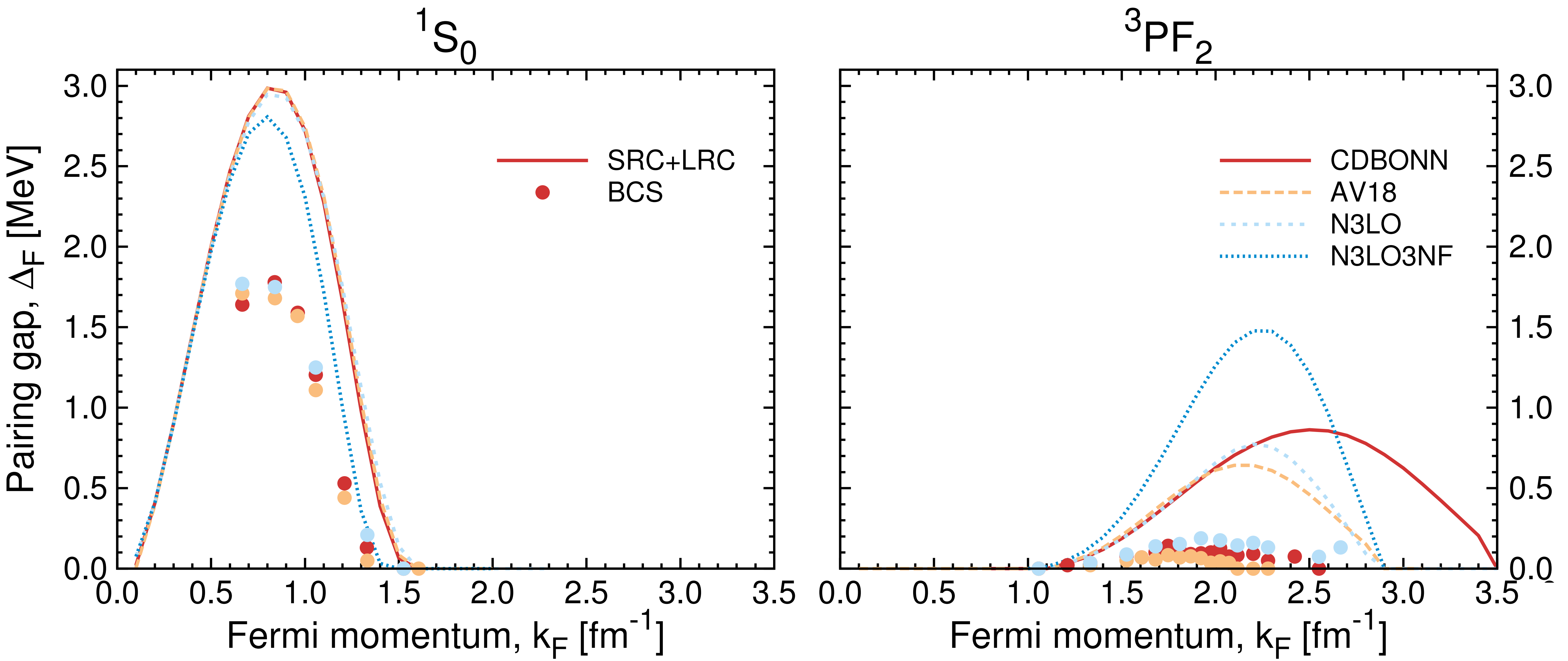
Beyond BCS 201: results $^3PF_2$

Neutron matter



- **Anti-**screening induced by **SRC**: $\Delta \approx 0.15$-0.20 MeV
- **Lower** gap **closure**
- Effect is **robust**: <u>independent</u> of NN potential

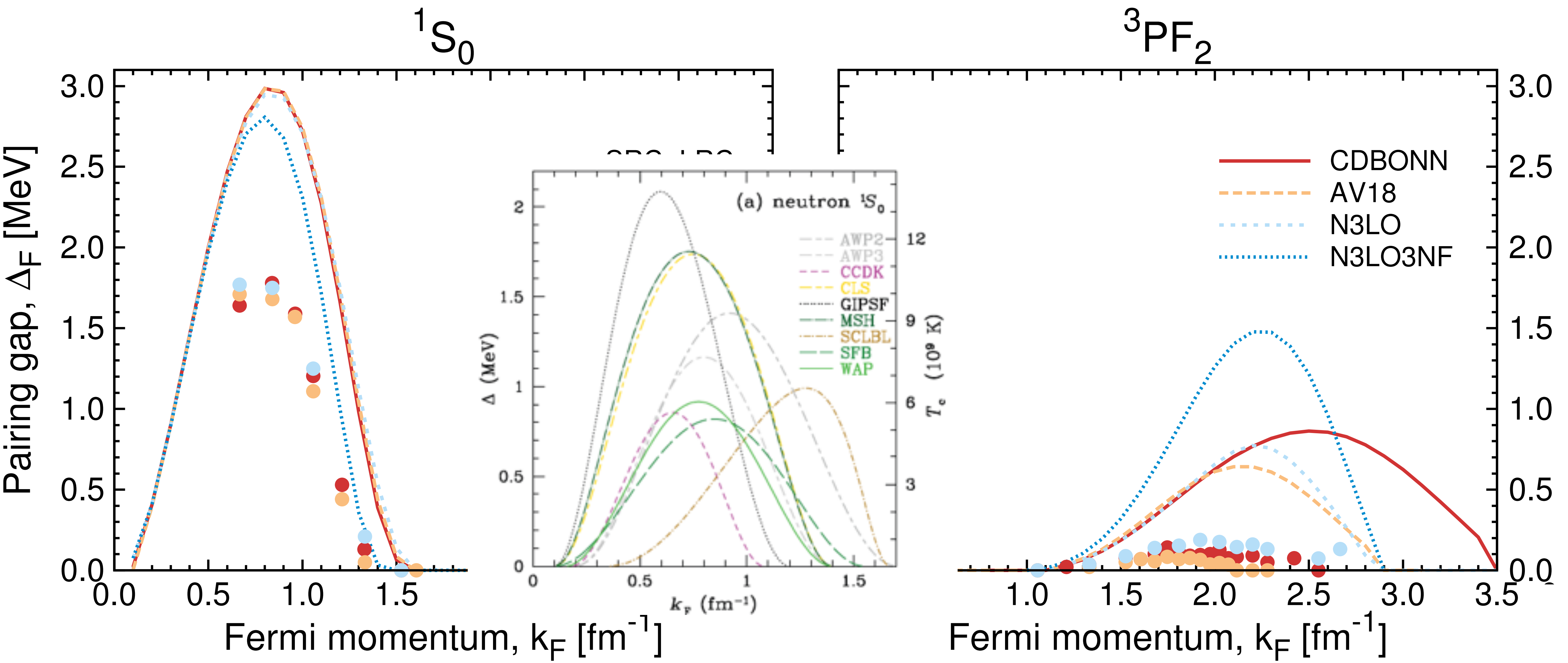
Beyond BCS 201: overview



- Effect is **robust**: <u>independent</u> of NN potential
- 3NF effect **not** included in SRC yet
- BCS indicates effects is **smaller** than correlations

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

Beyond BCS 201: overview



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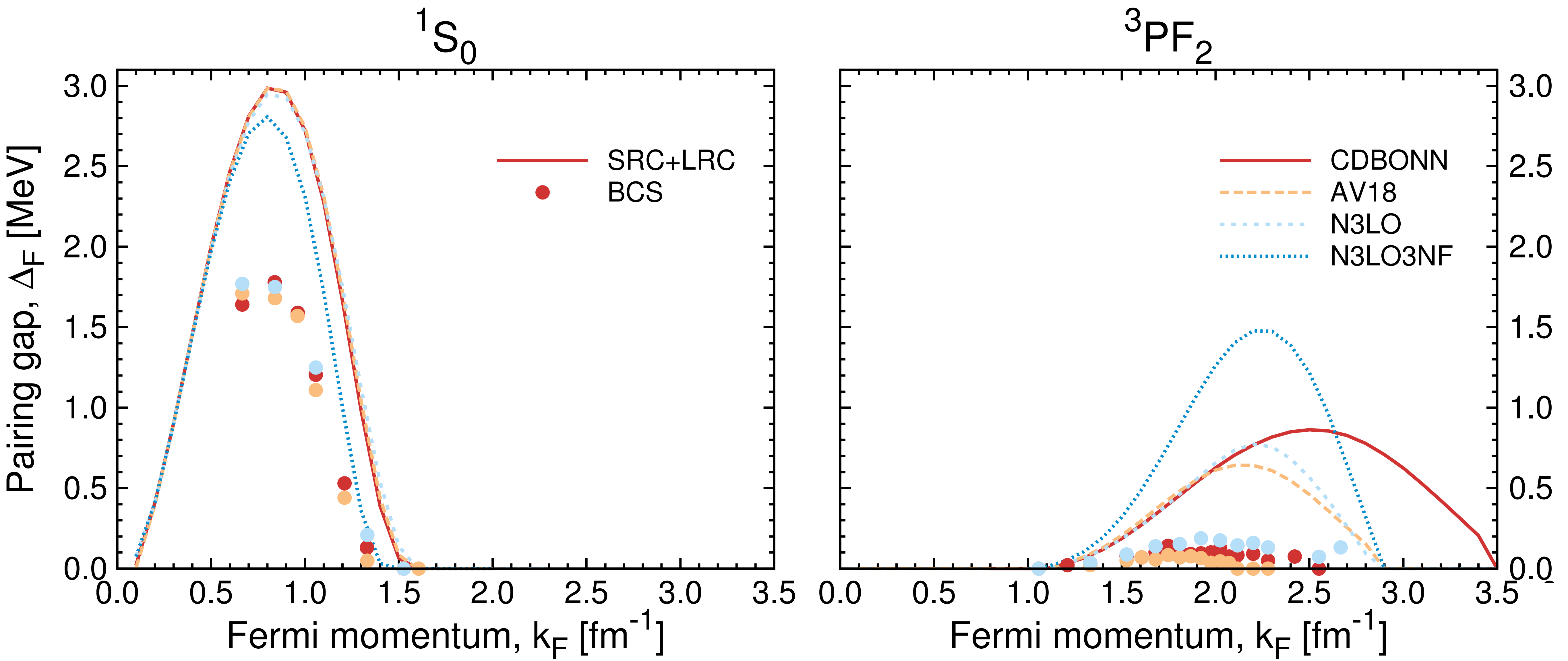
Ho, Elshamouty, Heinke, Potekhin, *PRC **91** 015806 (2015)*

Beyond BCS 201: overview



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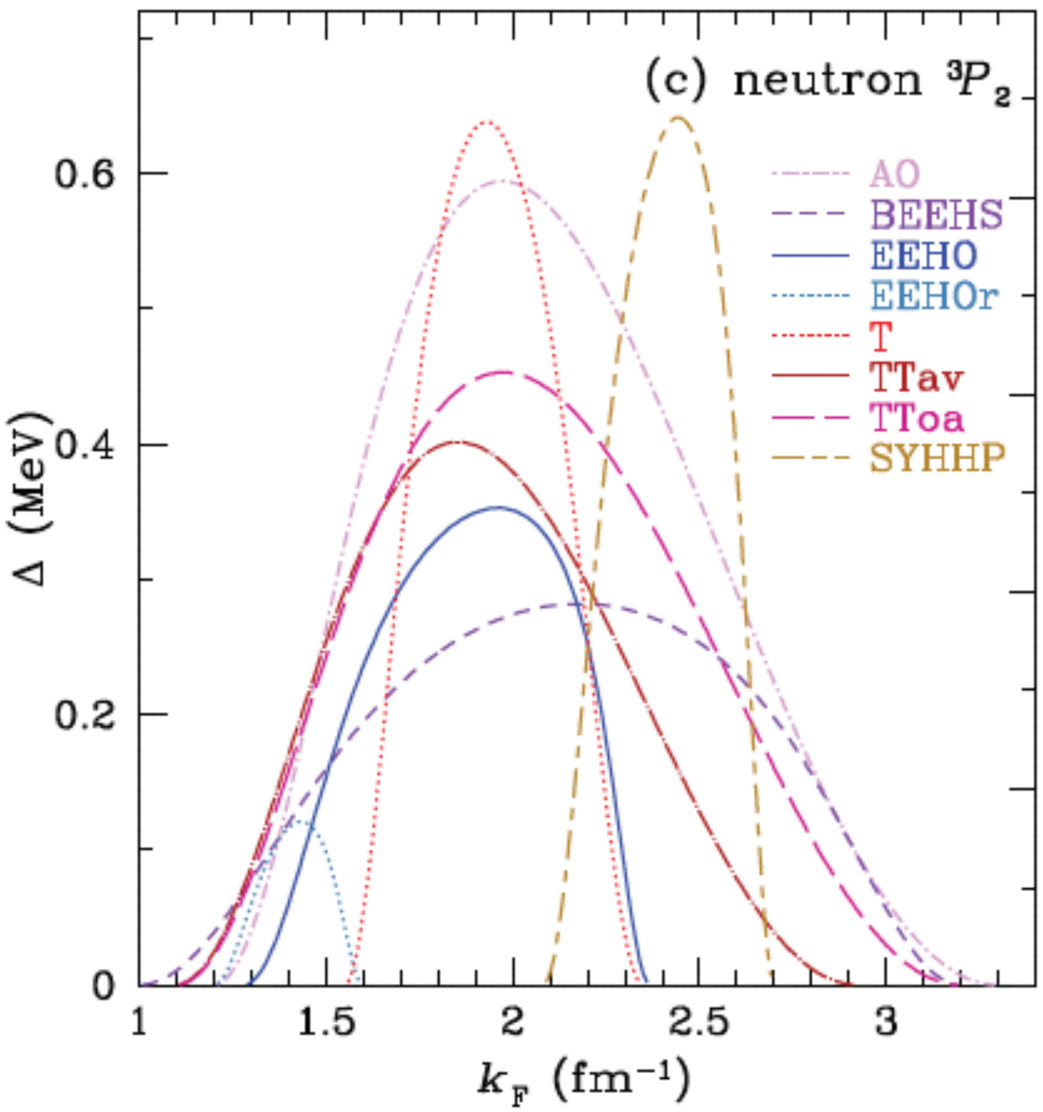
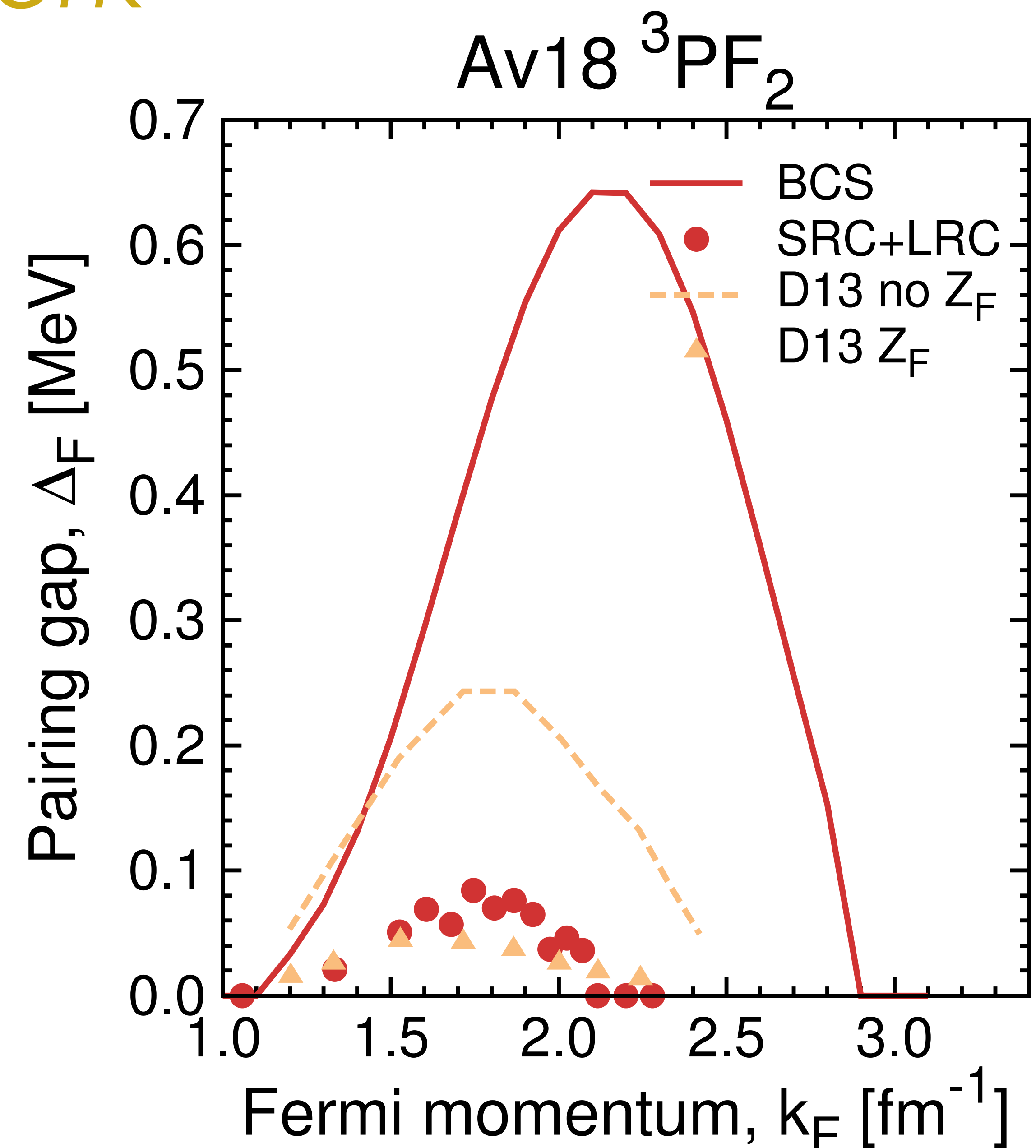
Ho, Elshamouty, Heinke, Potekhin, *PRC **91** 015806 (2015)*

Comparison to other work



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



Dong, Lombardo, Zuo
PRC **87** 062801(R) (2013)

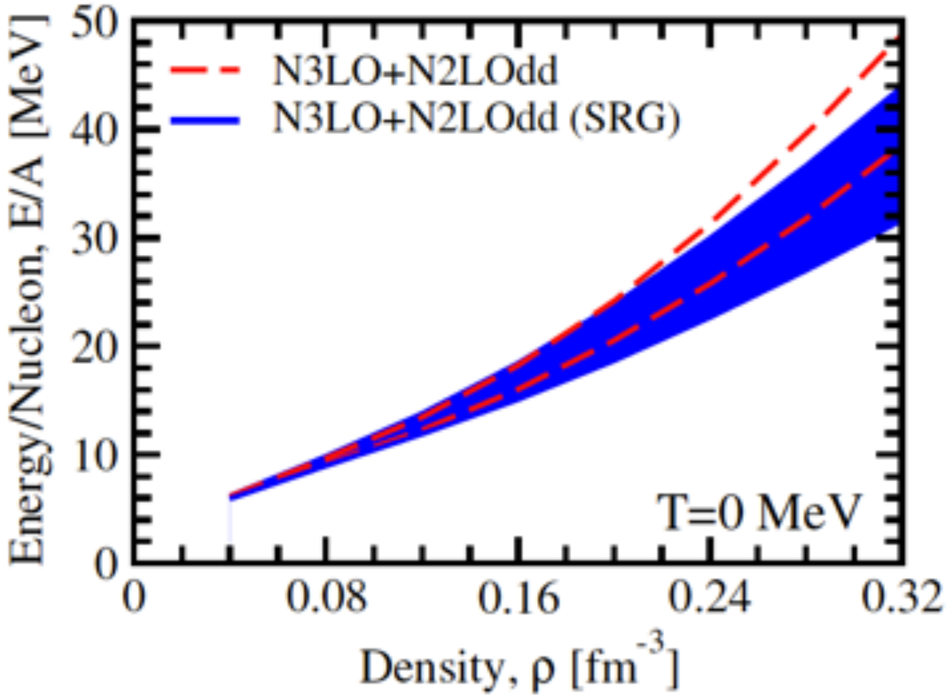
BCS+Z-factor equation

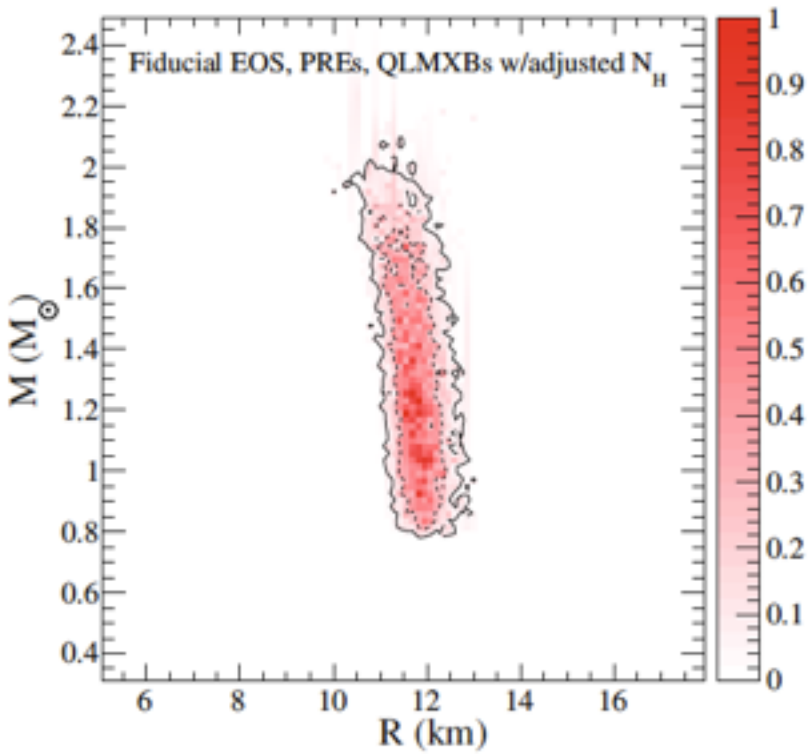
$$\Delta_k^L = Z_k \sum_{L'} \int_{k'} Z_{k'} \frac{\langle k|V_{nn}^{LL'}|k'\rangle}{2\chi_{k'}} \Delta_{k'}^{L'} \quad + \quad \chi_k = \sqrt{\varepsilon_k^2 + |\Delta_k|^2}$$

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

Chiral EoS & pairing gaps

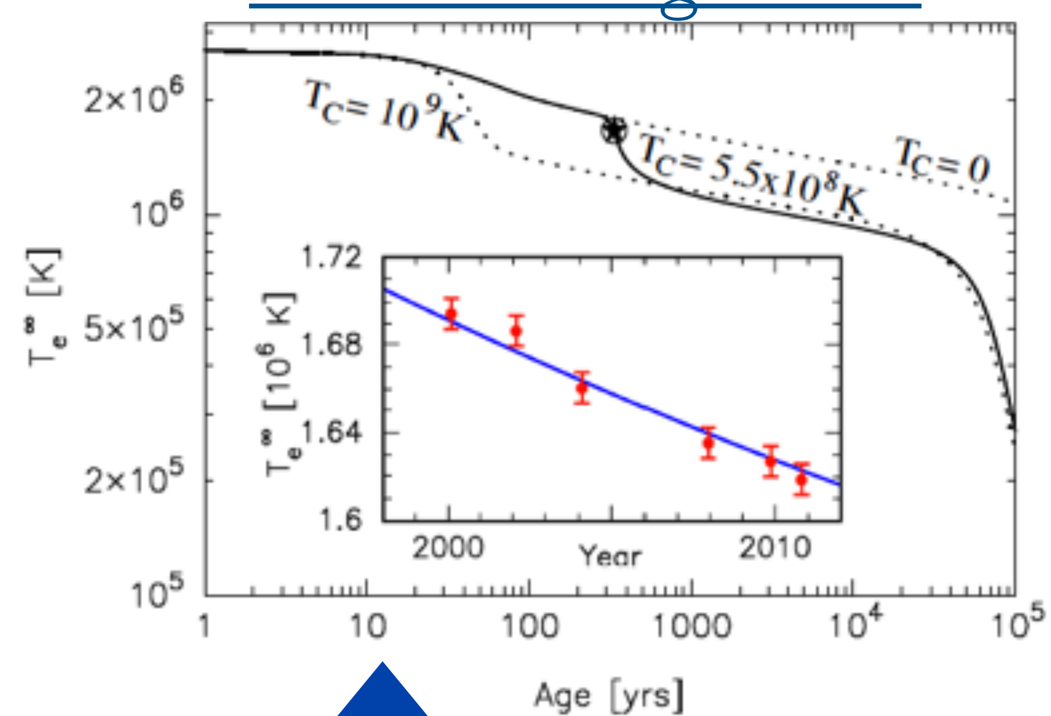
N^{3}LO EoS with 3BFs





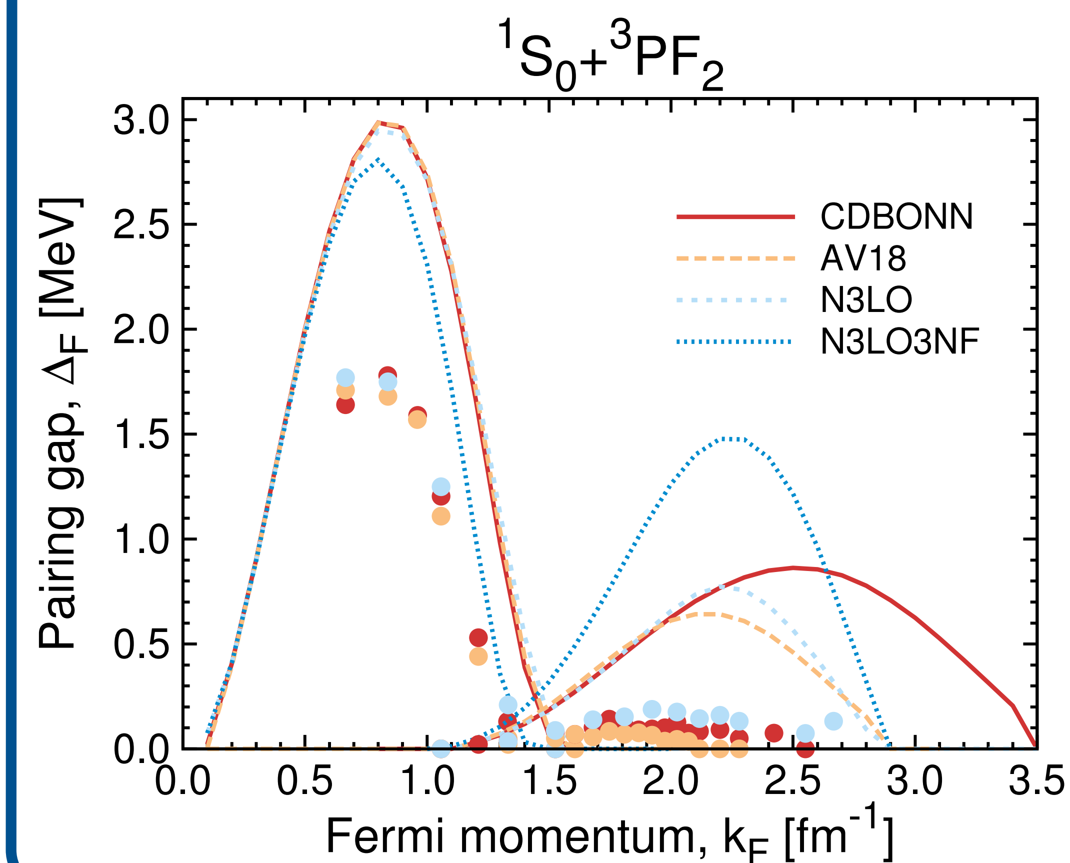
Steiner & Lattimer, *EPJA* **50** 49 (2014)

CasA cooling curve



PRL **106** 081101 (2011)

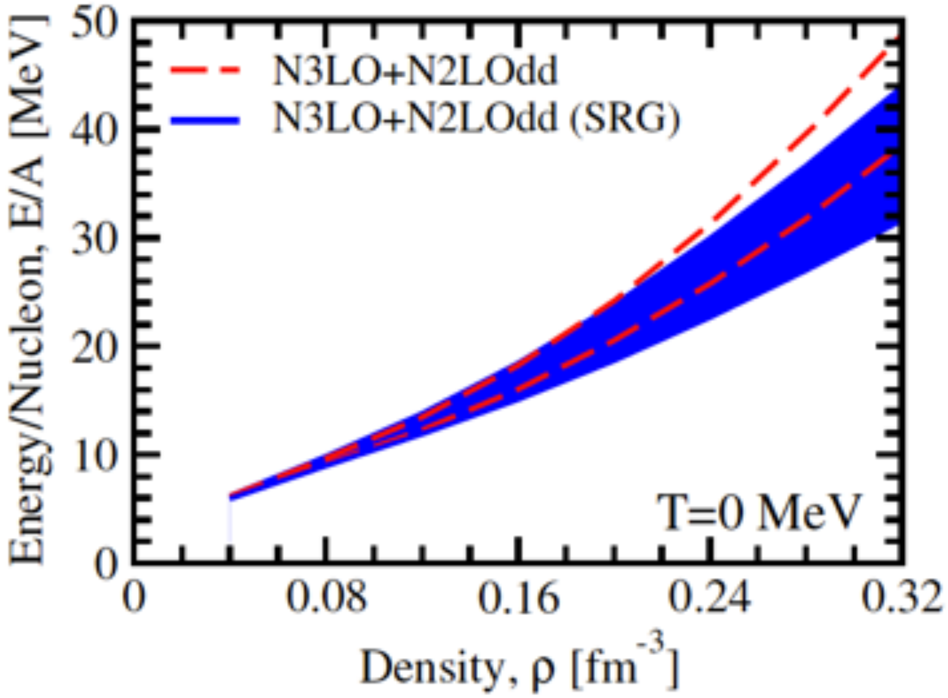
Pairing gap beyond BCS

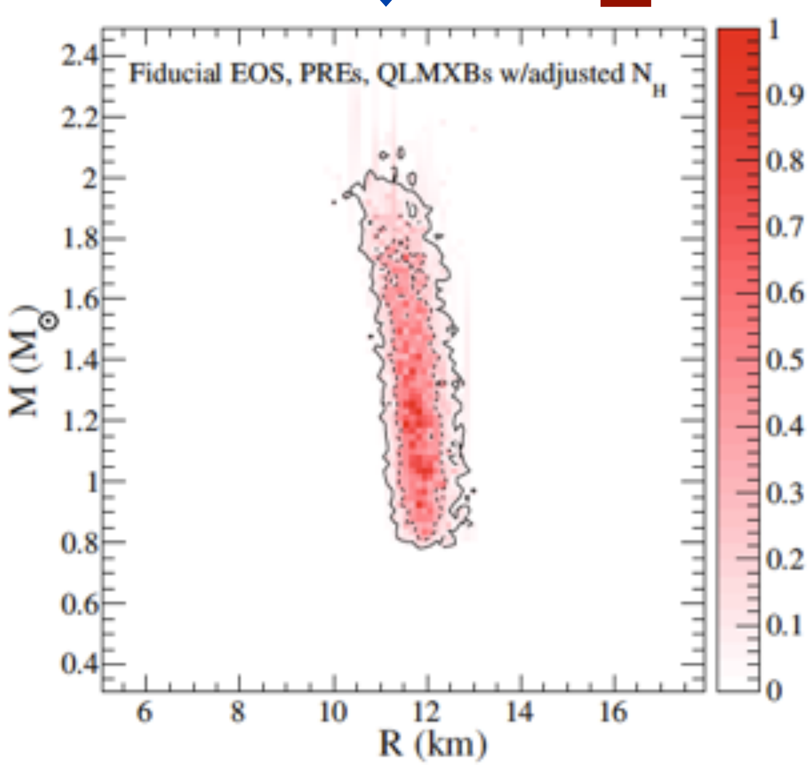


Ding, Witte, Dickhoff, Hussan, Rios & Polls, *arXiv:1502.05673*.

Chiral EoS & pairing gaps

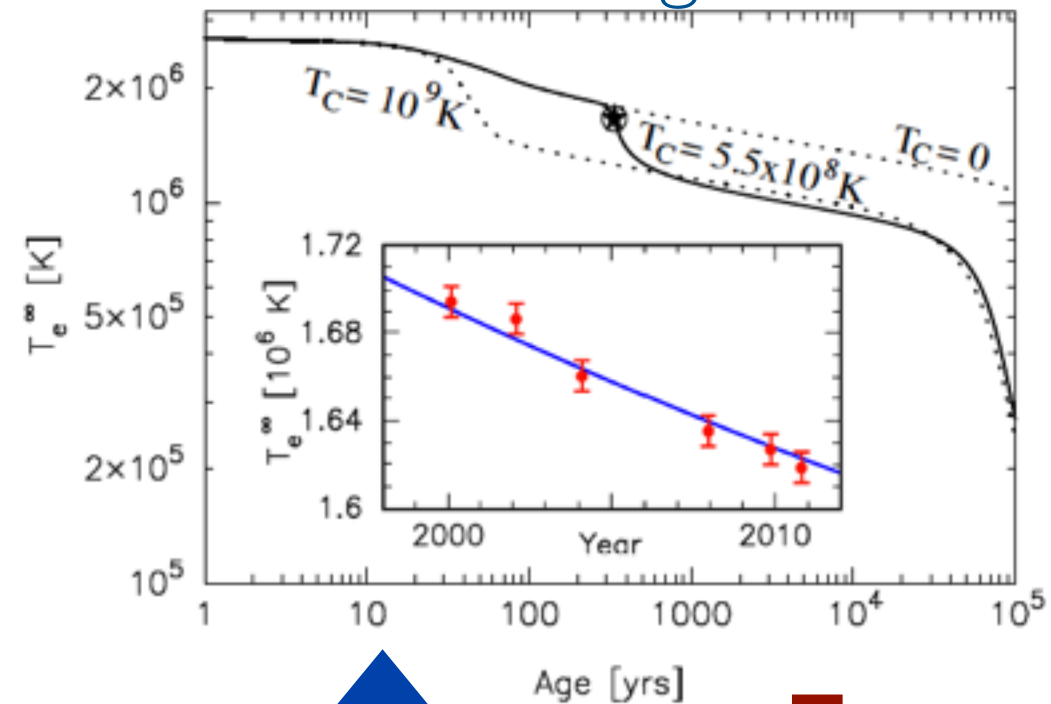
N^{3}LO EoS with 3BFs





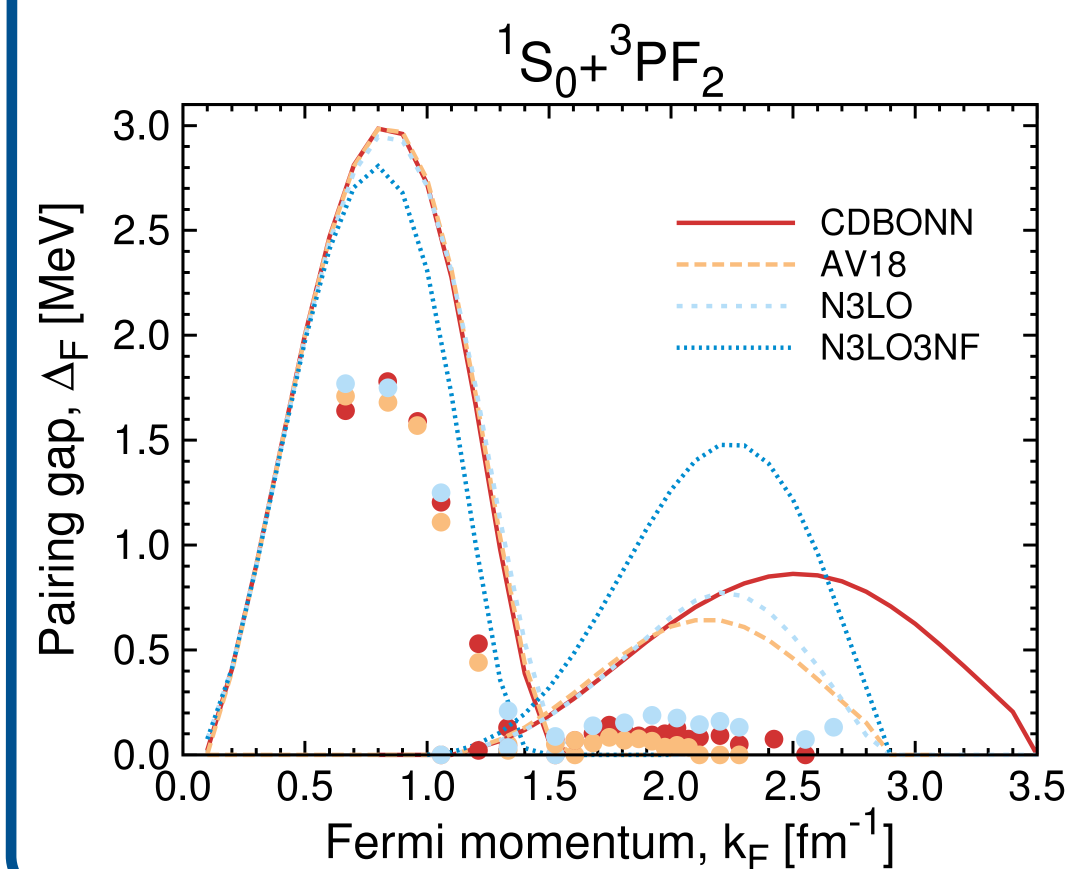
Steiner & Lattimer, *EPJA* **50** 49 (2014)

CasA cooling curve



PRL **106** 081101 (2011)

Pairing gap beyond BCS



Ding, Witte, Dickhoff, Hussan, Rios & Polls, *arXiv:1502.05673*.

Conclusions

- Ab initio nuclear **theory** to treat **pairing** systems

- **Different** NN forces give robust predictions
- Approximations introduced in a **meaningful** way

- Challenges ahead:
  - **pp** pairing?
  - isospin **asymmetric** matter?
  - **Cooling?**

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