# Nuclear matter with chiral three-nucleon forces

A. Carbone, A. Rios and A. Polls
In collaboration with A. Cipollone and C. Barbieri

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University of Surrey

# Outline:

- Nuclear matter & the importance of adding three-nucleon forces (3NF)
- Our approach to nuclear matter:
  - the self-consistent Green's functions (SCGF) approach with 3NF
  - include 3NF as a density dependent 2NF
- Results
- Conclusions & Outlooks

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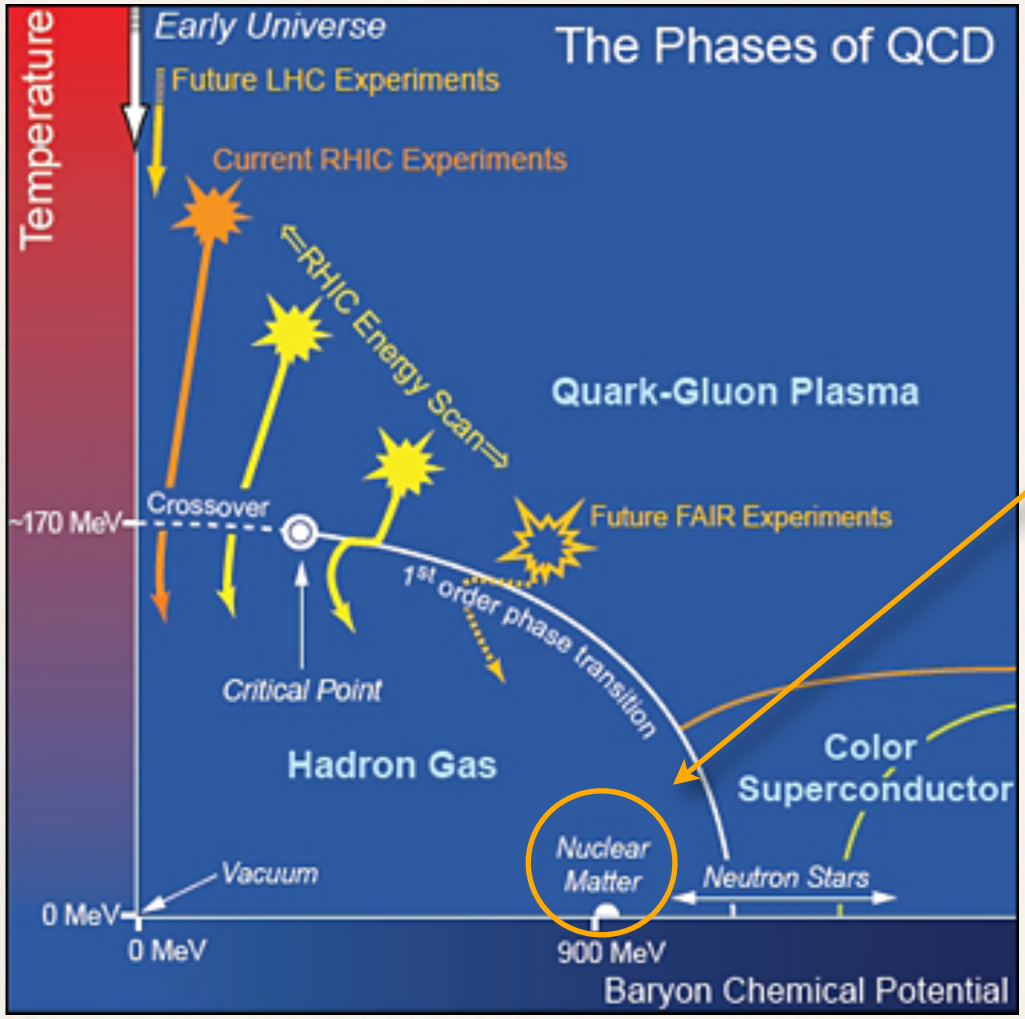
# Nuclear Matter




http://www.bnl.gov/newsroom/news.php?a=21870

What do we know about it?

Empirical saturation properties
$E_0$ = -16 MeV, $\varrho_0$ = 0.16 $fm^{-3}$

Symmetry Energy
S ≈ 30 MeV

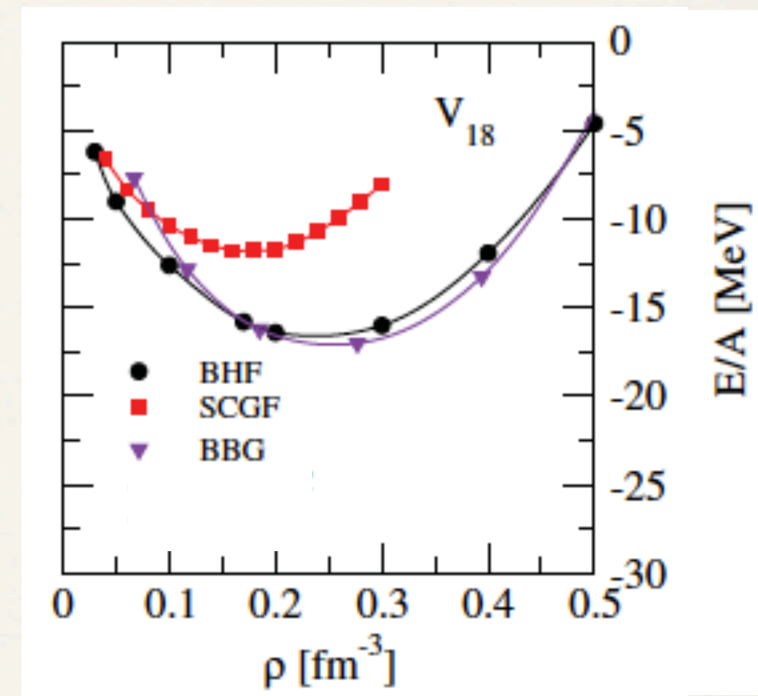
Compressibility
K ≈ 200/250 MeV

2solar mass neutron star observed
(Demorest *et al.* Nature 467, 1081, 2010)

# The importance of adding 3NF

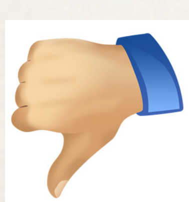
- During the past decades several <u>realistic nucleon-nucleon</u> (NN) <u>interactions</u> have been developed:

  - Paris potentials, *Lacombe et al.* 1980
  - Nijmegen potentials, *Stocks et al.* 1994
  - Argonne potentials, *Wiringa et al.* 1995
  - Bonn potentials, *Machleidt et al.* 1996




Baldo *et al.*, PRC 86, 064001 (2012)

<u>Good thing</u>: reproduce data from Nijmegen database

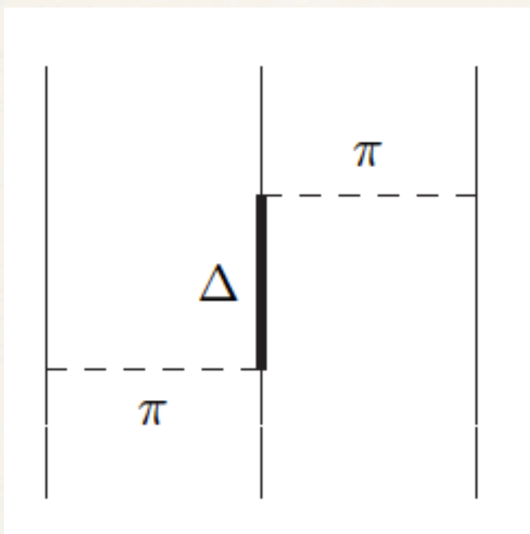


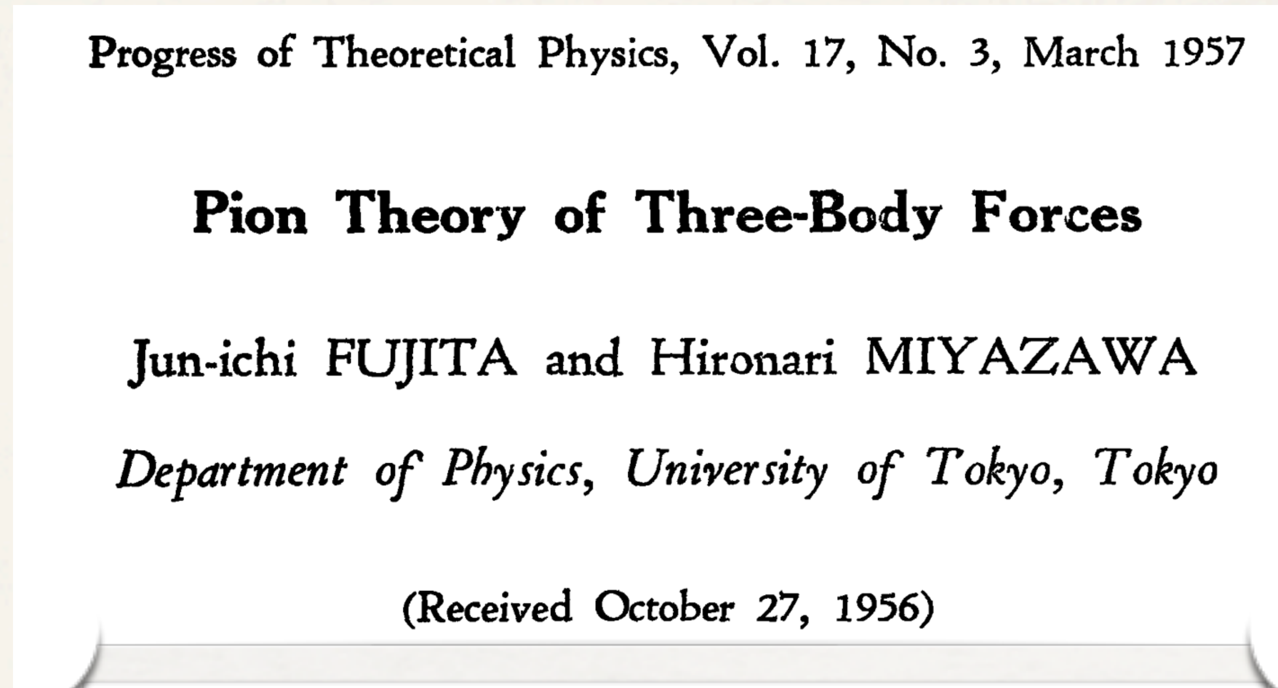
<u>Bad thing</u>: don't reproduce nuclei binding energies nor **saturation properties of nuclear matter**

# The importance of adding 3NF

Going back in time:

2-pion exchange attractive term



Progress of Theoretical Physics, Vol. 17, No. 3, March 1957

**Pion Theory of Three-Body Forces**

Jun-ichi FUJITA and Hironari MIYAZAWA

*Department of Physics, University of Tokyo, Tokyo*

(Received October 27, 1956)

helps overcome underbinding of nuclei,
worsens overbinding of SNM

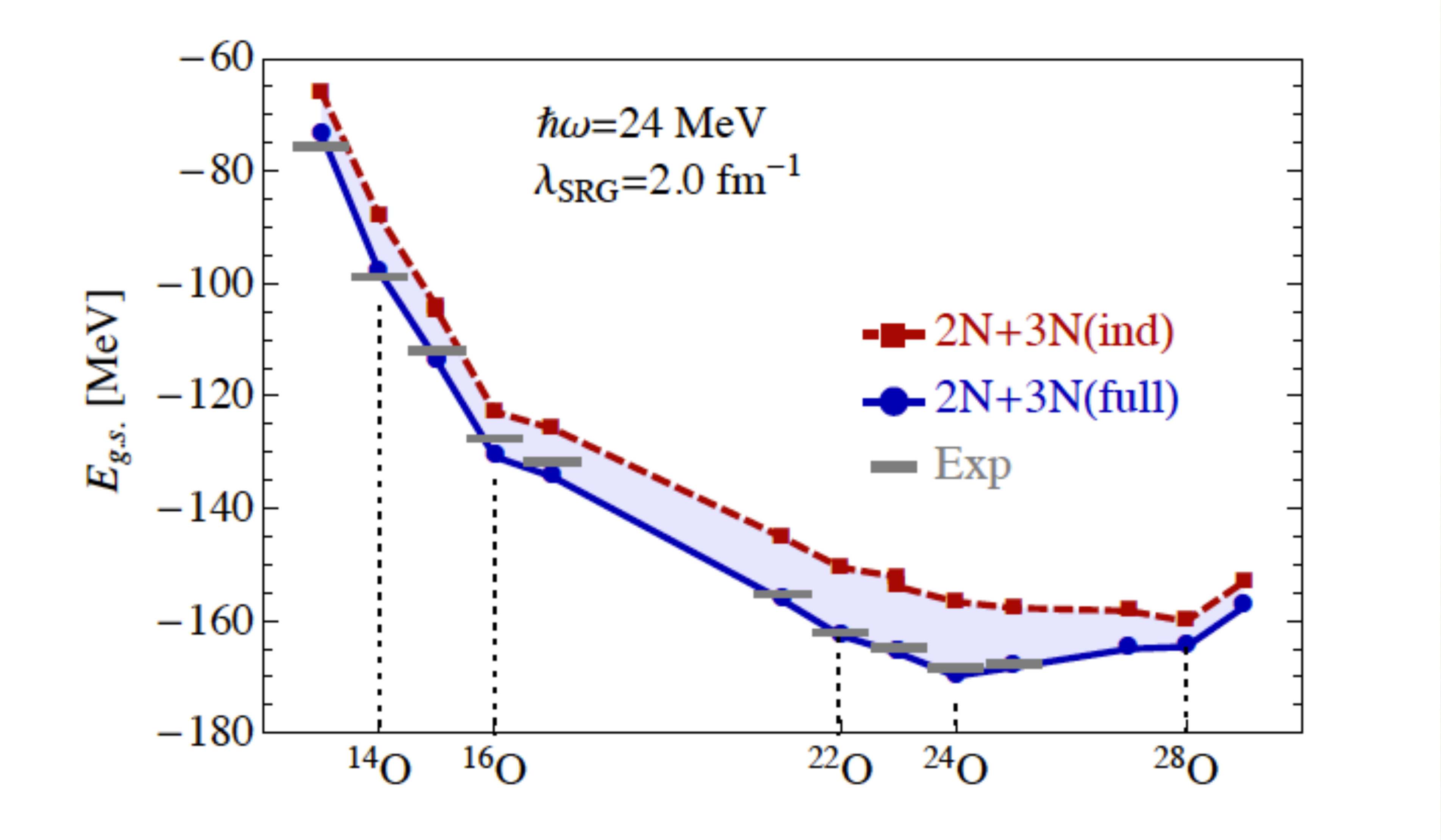
Other 3NF potentials came afterwards:

- Tucson-Melbourn potentials, *Coon et al.* 1979
- TNI potentials, *Lagaris et al.* 1981
- Urbana and Illinois potentials, *Carlson et al.* 1983

2-pion exchange attractive term
+
repulsive phenomenological term

# The importance of adding 3NF.... in nuclei

- SCGF theory for finite nuclei using SRG evolved chiral NN + 3NF forces:

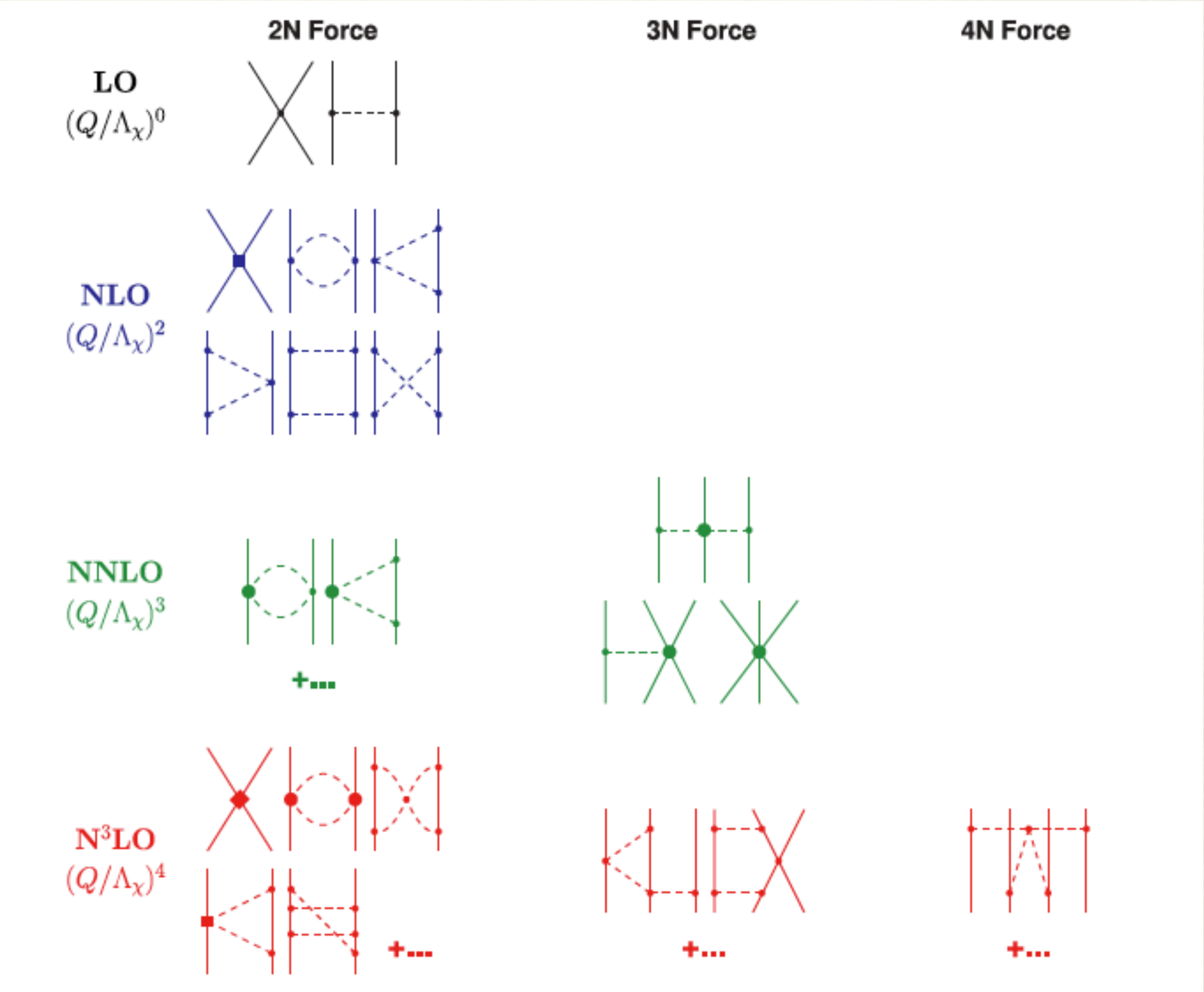



Cipollone *et al.* arxiv:1303.4900v1

See also H. Hergert *et al.* arxiv:1302.7294

# The importance of adding 3NF... a chiral approach

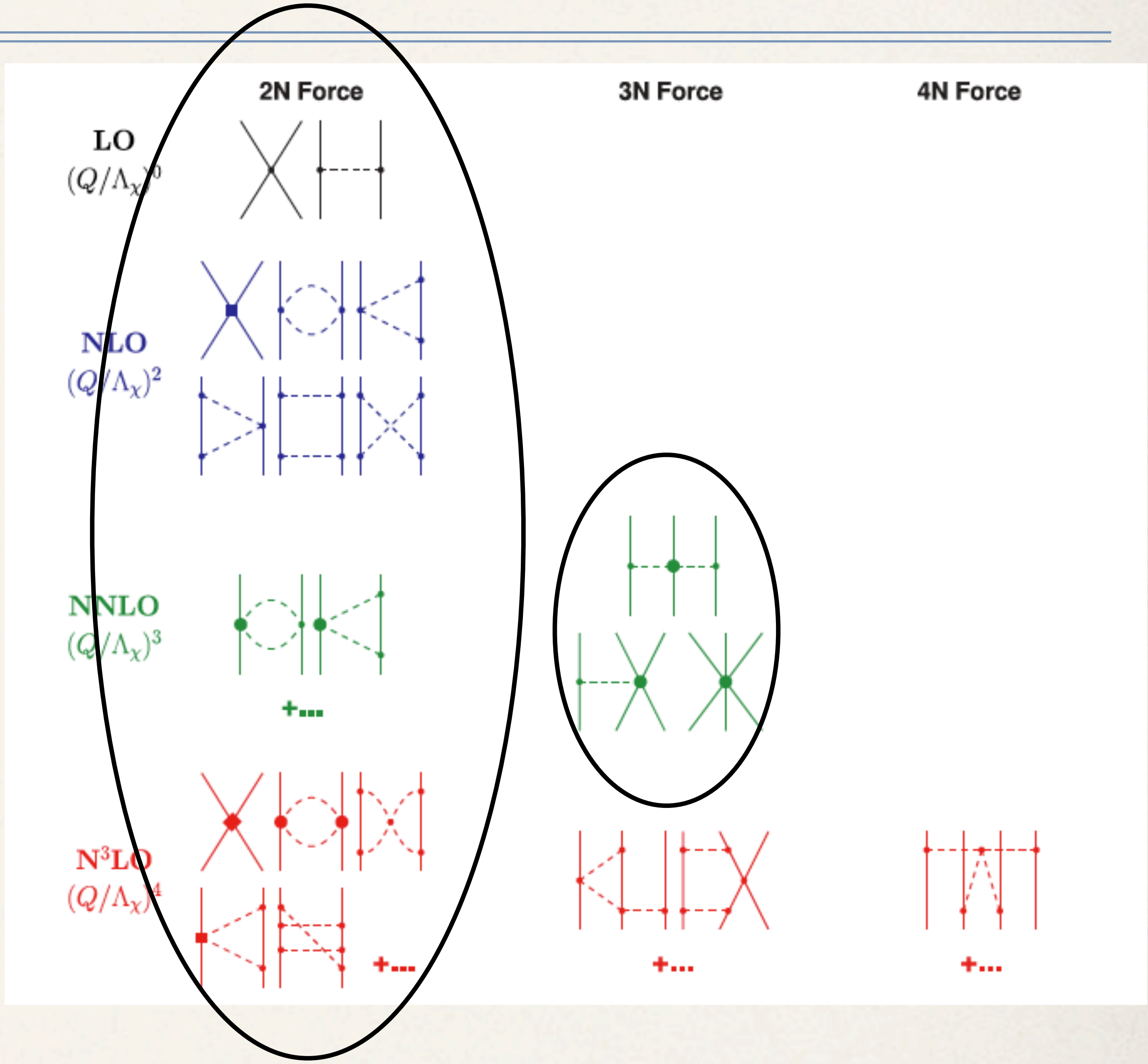
- Chiral EFT generates consistently the NN force and many-body forces
- State-of-the-art of 2NF chiral force:
    - N3LO (EM 2003, EGM 2005)
    - optimized version of N2LO recently published (Ekström *et al.* arXiv: 1303.4674v1)
- State-of-the-art of 3NF chiral force:
    - N2LO (ENGKMW 2004)
    - N3LO (IR 2007, BEKM 2008,2011)
    - N4LO (KGE 2012)




Machleidt, Phys. Rep. 503, 1 (2011)

# The importance of adding 3NF... a chiral approach

- In the present work we use:
  - 2NF N3LO (Entem and Machleidt, PRC 68, 041001, 2003)
  - 3NF N2LO (Epelbaum *et al.* PRC 70, 061002, 2004) in a density dependent form developed by Holt *et al.* PRC 81, 024002 (2010)
  - Low-energy constants are fit to NN and pi-N data;
  - Two constants appearing in the one-pion and contact term of the 3NF remain free

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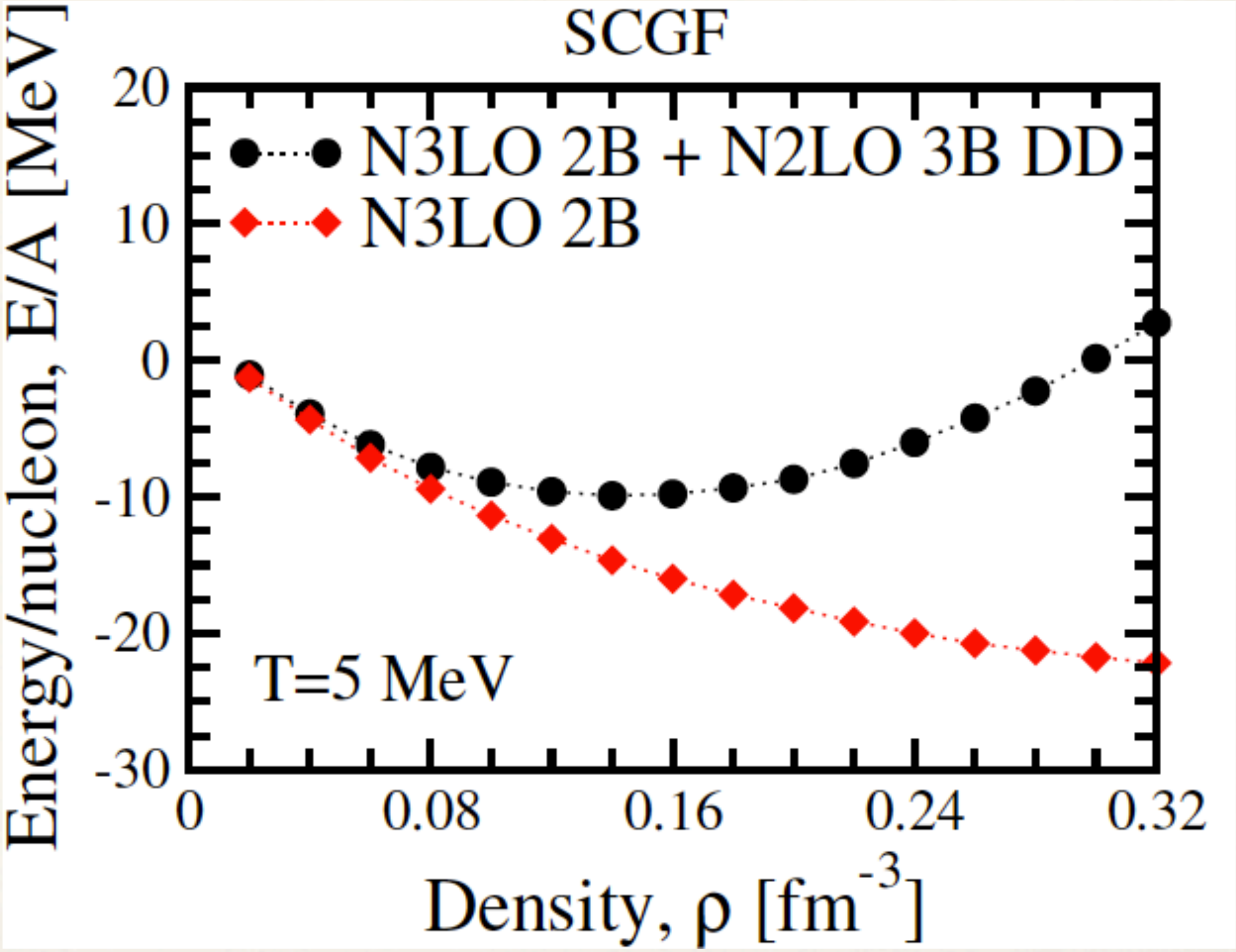
# The importance of adding 3NF.... in nuclear matter

- SCGF theory for nucler matter using chiral NN + 3NF forces:

Saturation values:
density = 0.14 fm$^{-3}$
energy = -9.91 MeV



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# The SCGF approach in very few words

- A non-relativistic quantum many-body theory originally developed in the 1950's
- Applyed to atomic, condensed matter, electron gas, **nuclei and nuclear matter** physics (reviews: Dickhoff & Barbieri, PPNP 52, 377, 2004; Müether & Polls, PPNP 45, 243, 2000)
- It is based on the use of the Green's function or single-particle (SP) propagator :

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- It is based on the use of the Green's function or single-particle (SP) propagator :

$$G_{\alpha\alpha'}(E) = \sum_m \frac{\langle \Psi_0^N | a_\alpha | \Psi_m^{N+1} \rangle \langle \Psi_m^{N+1} | a^\dagger_{\alpha'} | \Psi_0^N \rangle}{E - (E_m^{N+1} - E_0^N) + i\eta} + \sum_n \frac{\langle \Psi_0^N | a^\dagger_{\alpha'} | \Psi_n^{N-1} \rangle \langle \Psi_n^{N-1} | a_\alpha | \Psi_0^N \rangle}{E - (E_0 - E_n^{N-1}) + i\eta}$$

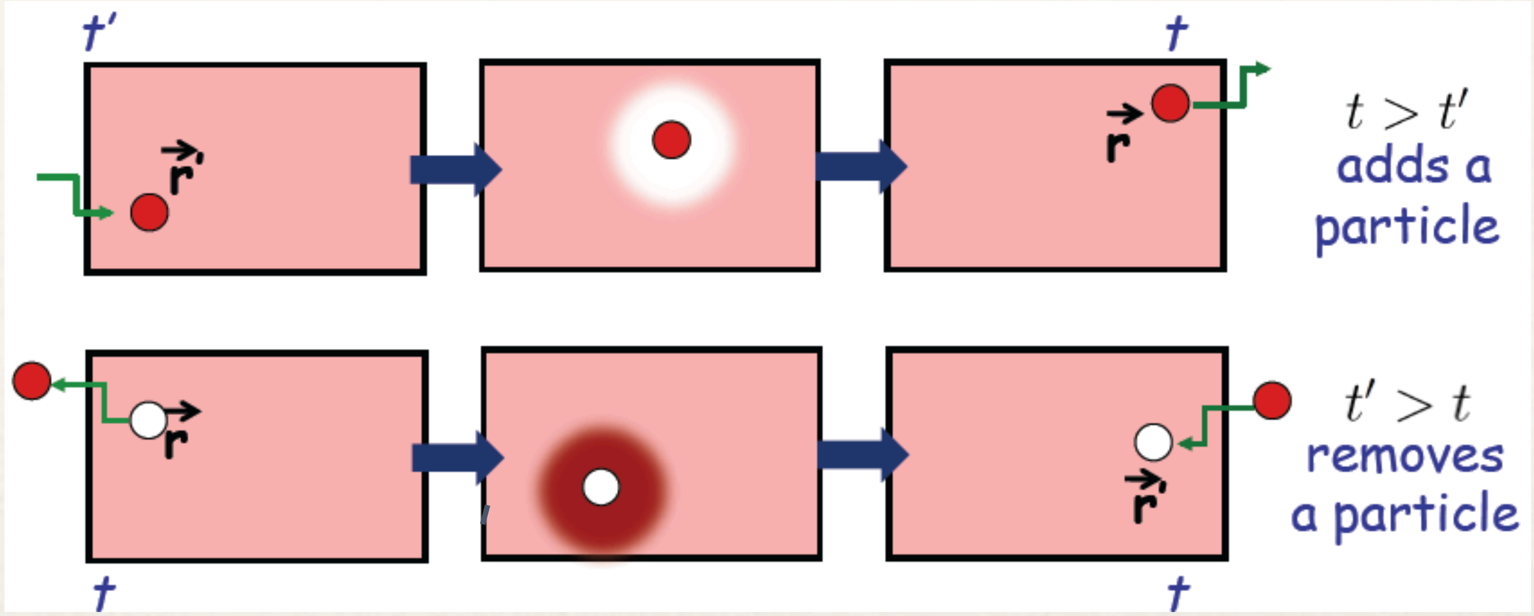
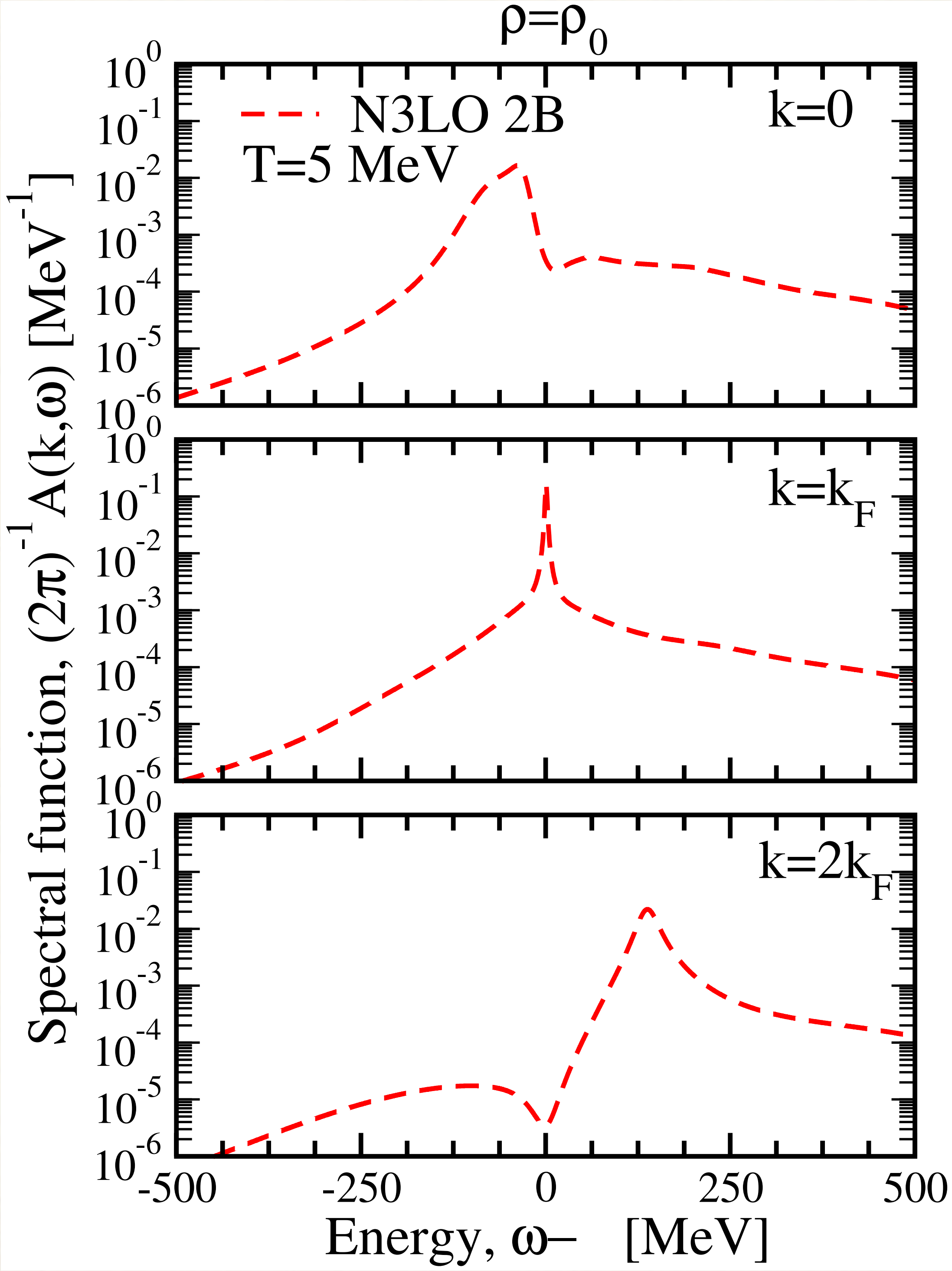



Figure by C. Barbieri

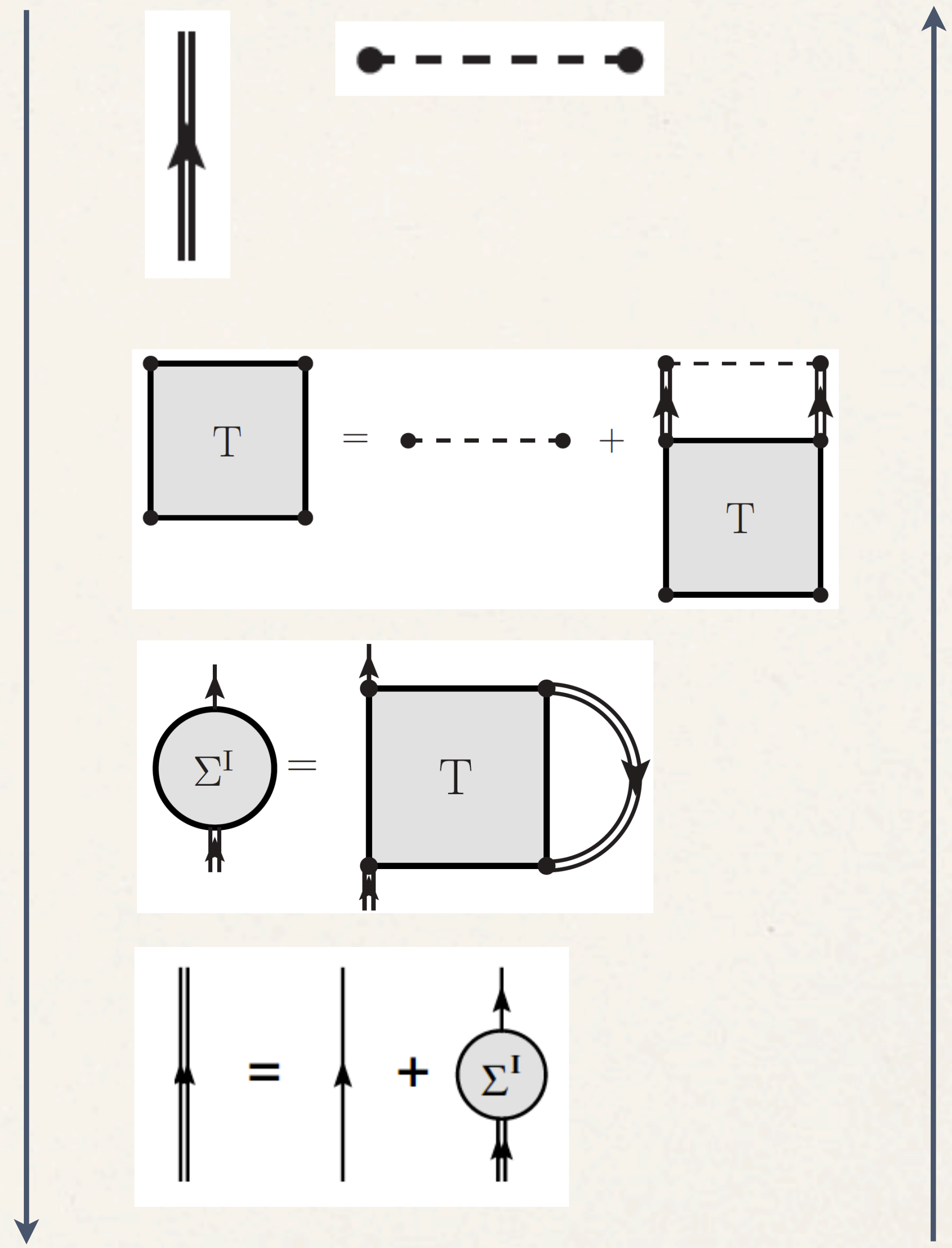
# The SCGF approach in very few words

- The SP propagator is directly connected to the spectral function:
  - defines the nucleon distribution in momentum/energy space



# The SCGF approach for SNM

- Start with a given spectral function, hence a SP propagator, and an NN interaction
- Construct an effective interaction in the medium, the T matrix, summing up iteratively the so called *ladder diagrams*
- Calculate the SP self-energy and other microscopic properties
- Calculate once again the SP propagator through Dyson's equation




- Procedure is repetead until self-consistency is achieved

# The SCGF approach with and without 3NF

*What changes……* Paper in preparation: A.C., A. Cipollone, C. Barbieri, A. Rios, A. Polls

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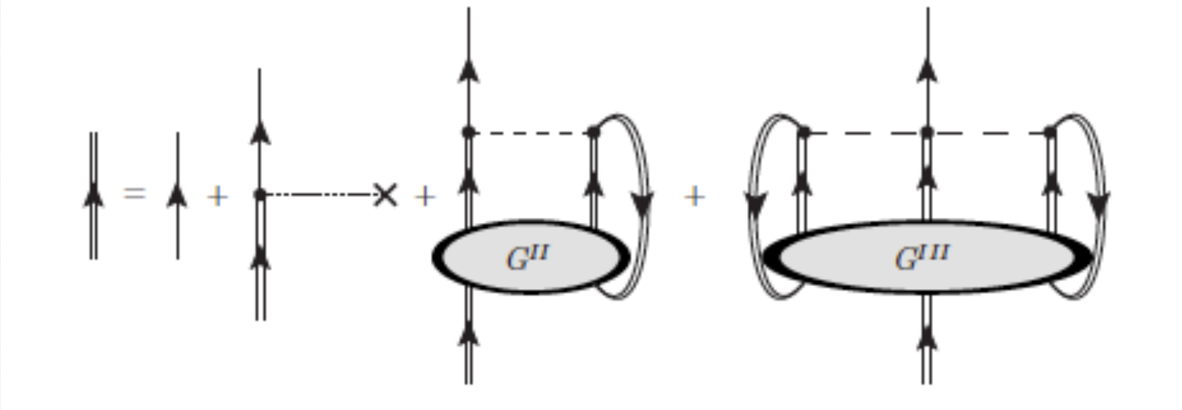

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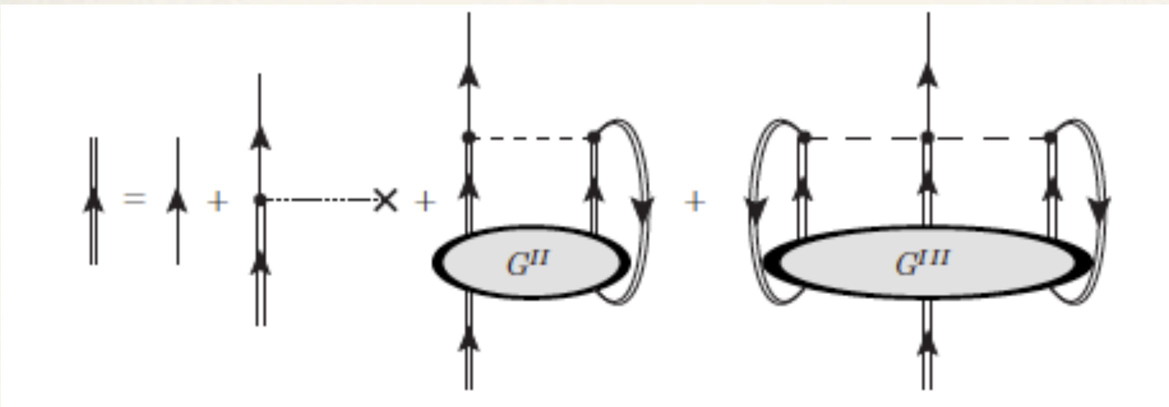


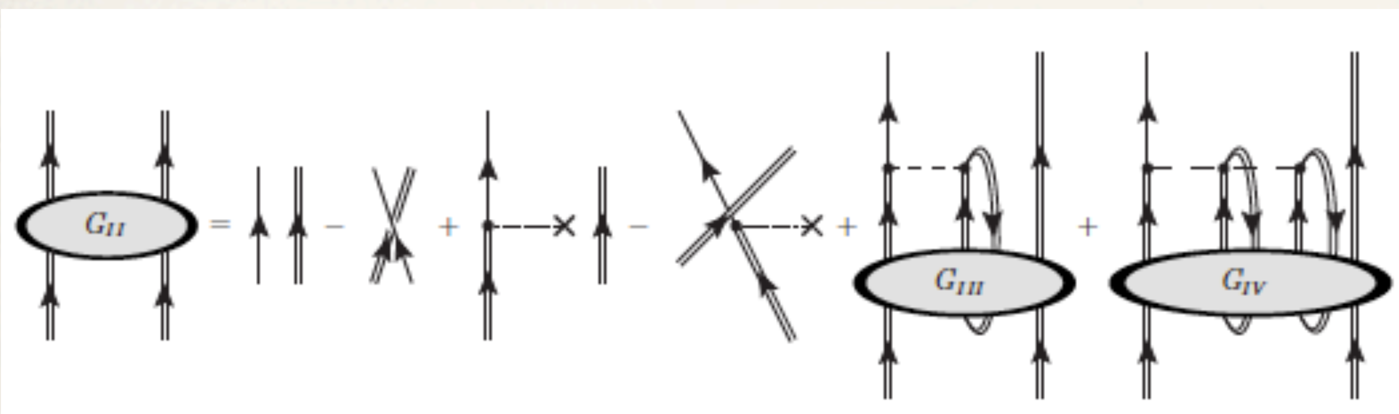

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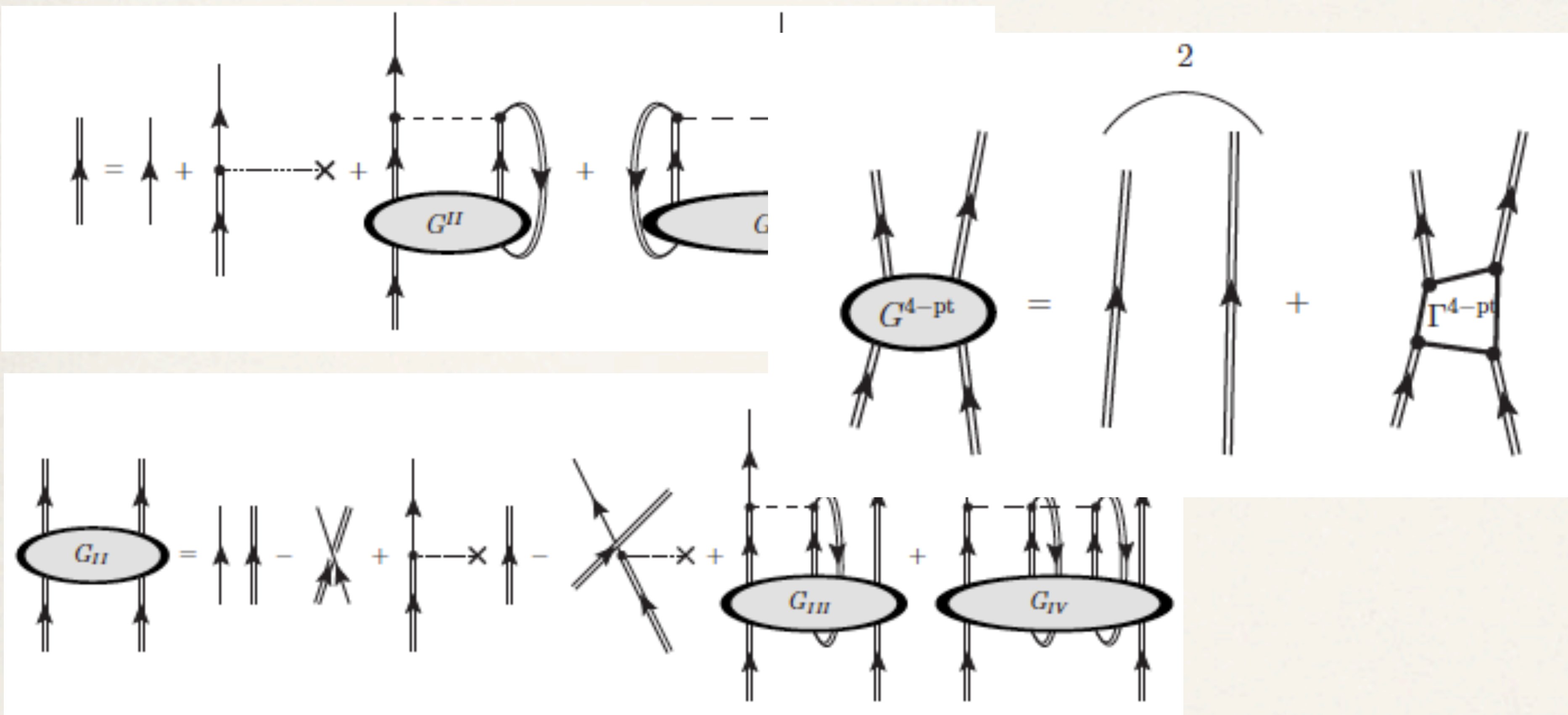

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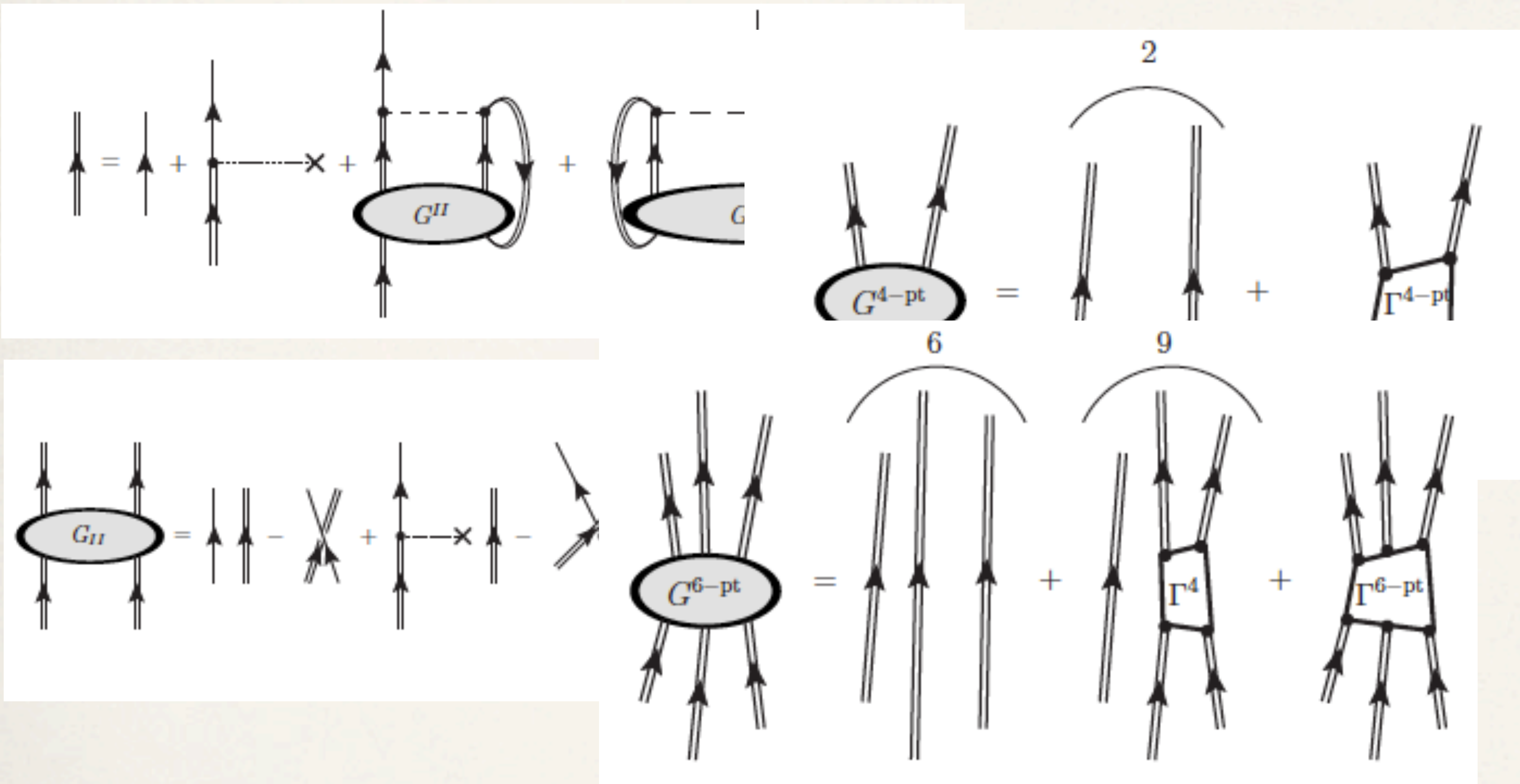

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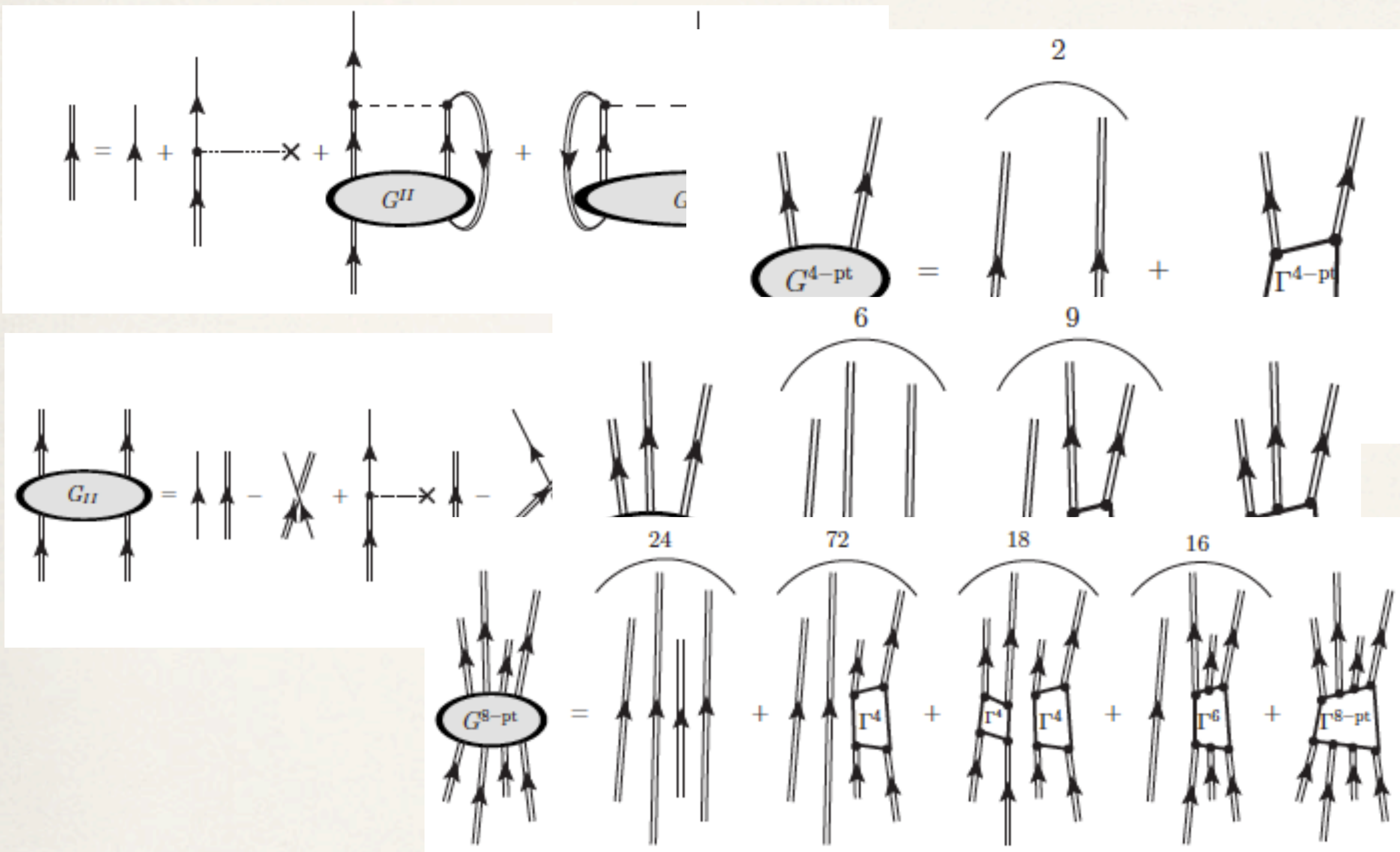

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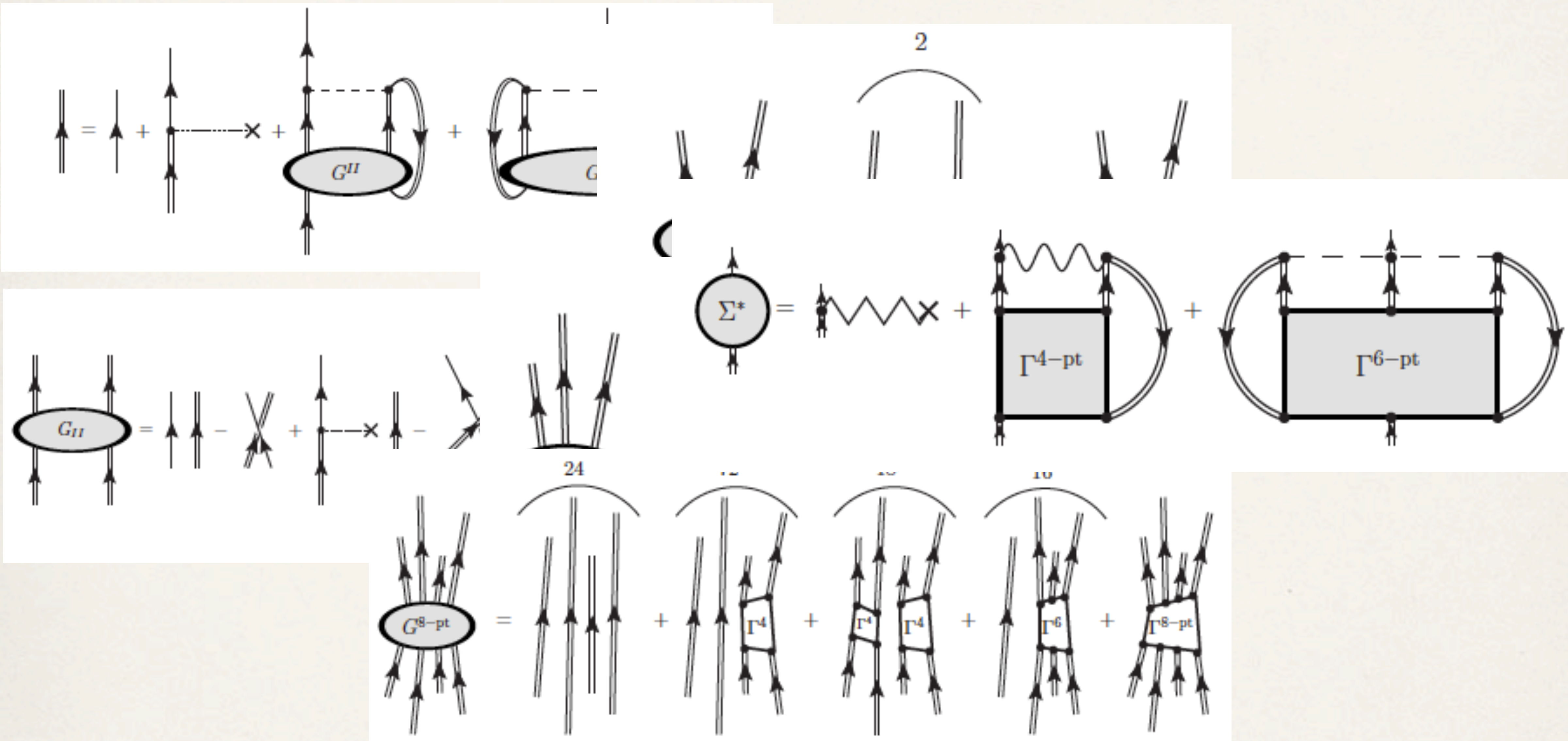

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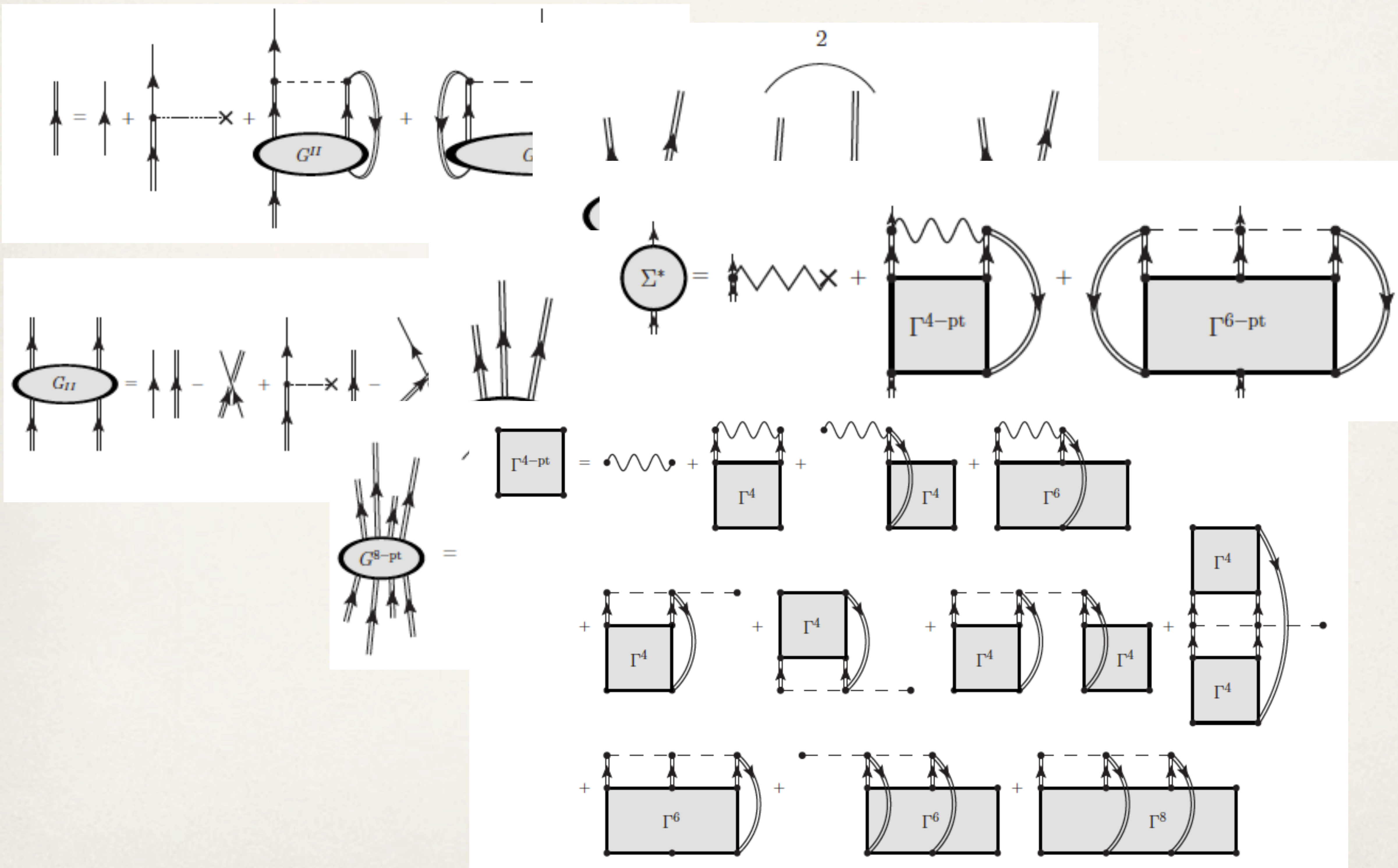

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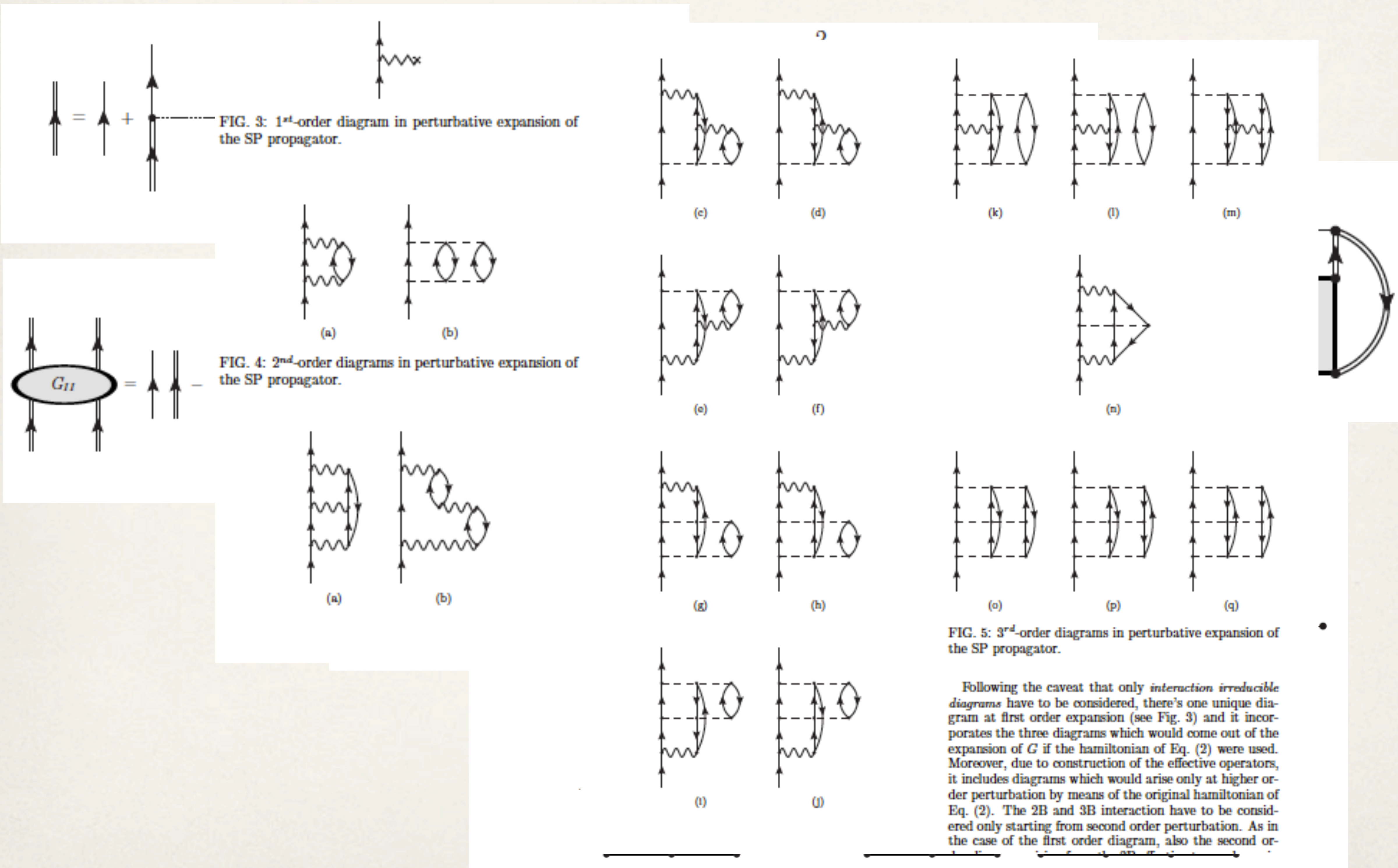


FIG. 3: $1^{st}$-order diagram in perturbative expansion of the SP propagator.

FIG. 4: $2^{nd}$-order diagrams in perturbative expansion of the SP propagator.

FIG. 5: $3^{rd}$-order diagrams in perturbative expansion of the SP propagator.

Following the caveat that only *interaction irreducible diagrams* have to be considered, there's one unique diagram at first order expansion (see Fig. 3) and it incorporates the three diagrams which would come out of the expansion of $G$ if the hamiltonian of Eq. (2) were used. Moreover, due to construction of the effective operators, it includes diagrams which would arise only at higher order perturbation by means of the original hamiltonian of Eq. (2). The 2B and 3B interaction have to be considered only starting from second order perturbation. As in the case of the first order diagram, also the second or-

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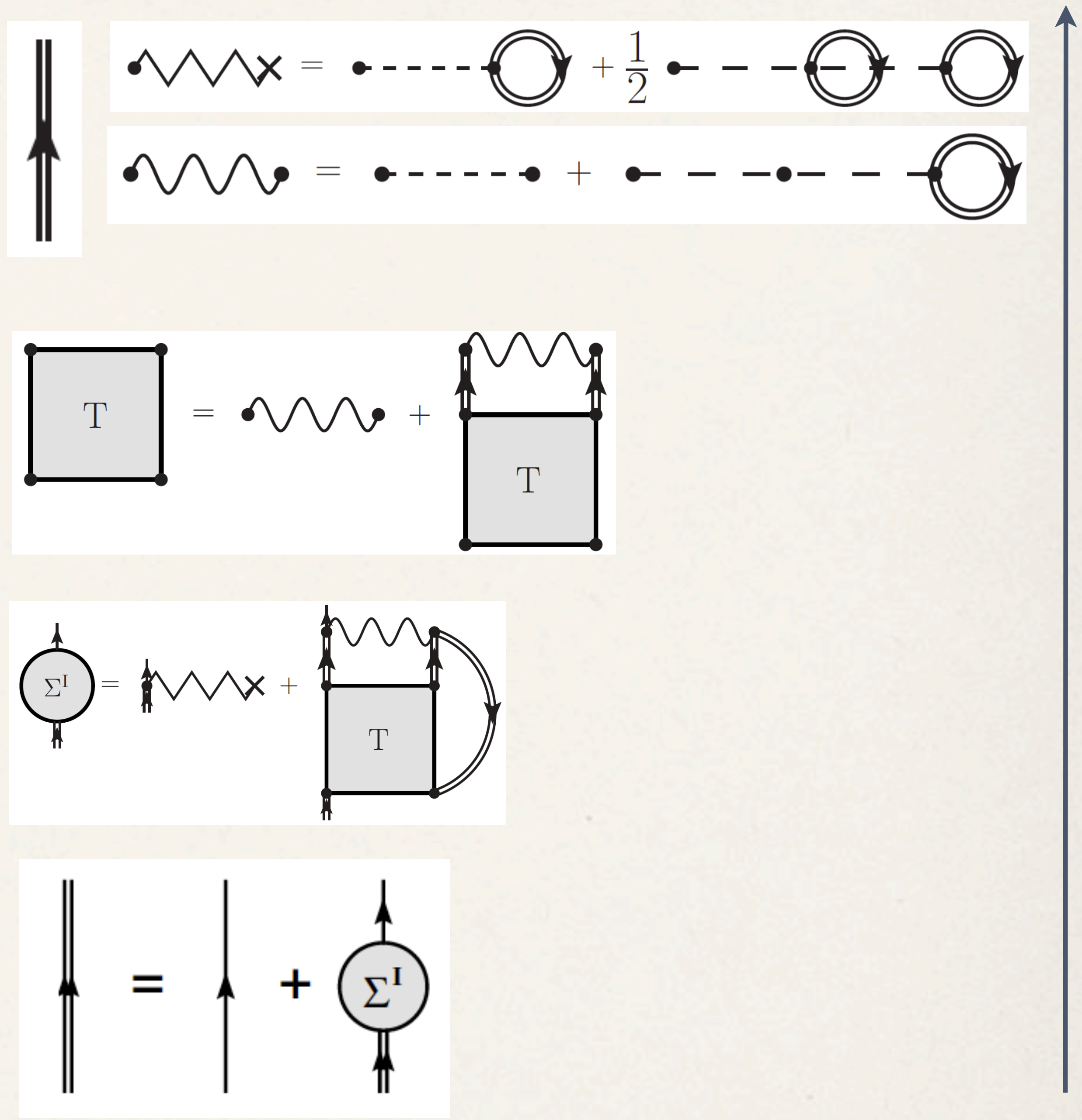


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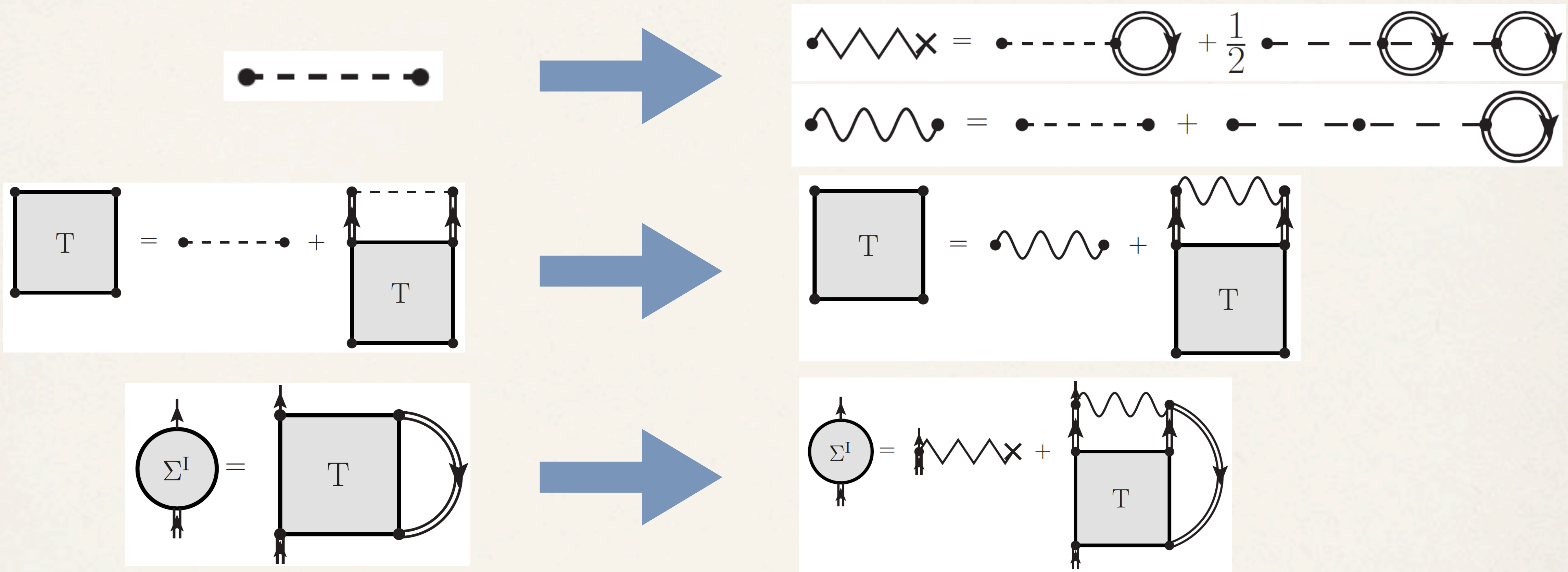

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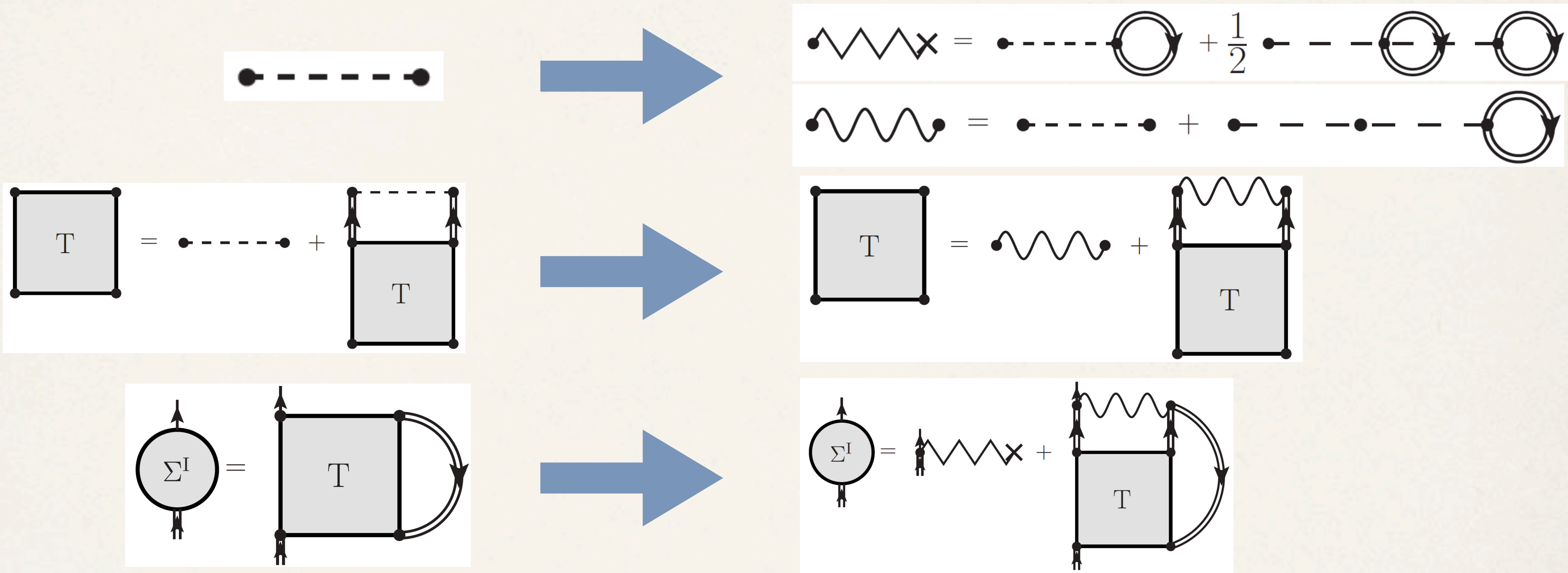


The main message: <u>you can't define an effective two-body interaction and include it right away in your many-body theory!</u>

(Bogner *et al.* PPNP 65, 94, 2010; Hebeler *et al.* PRC 82, 014314, 2010)

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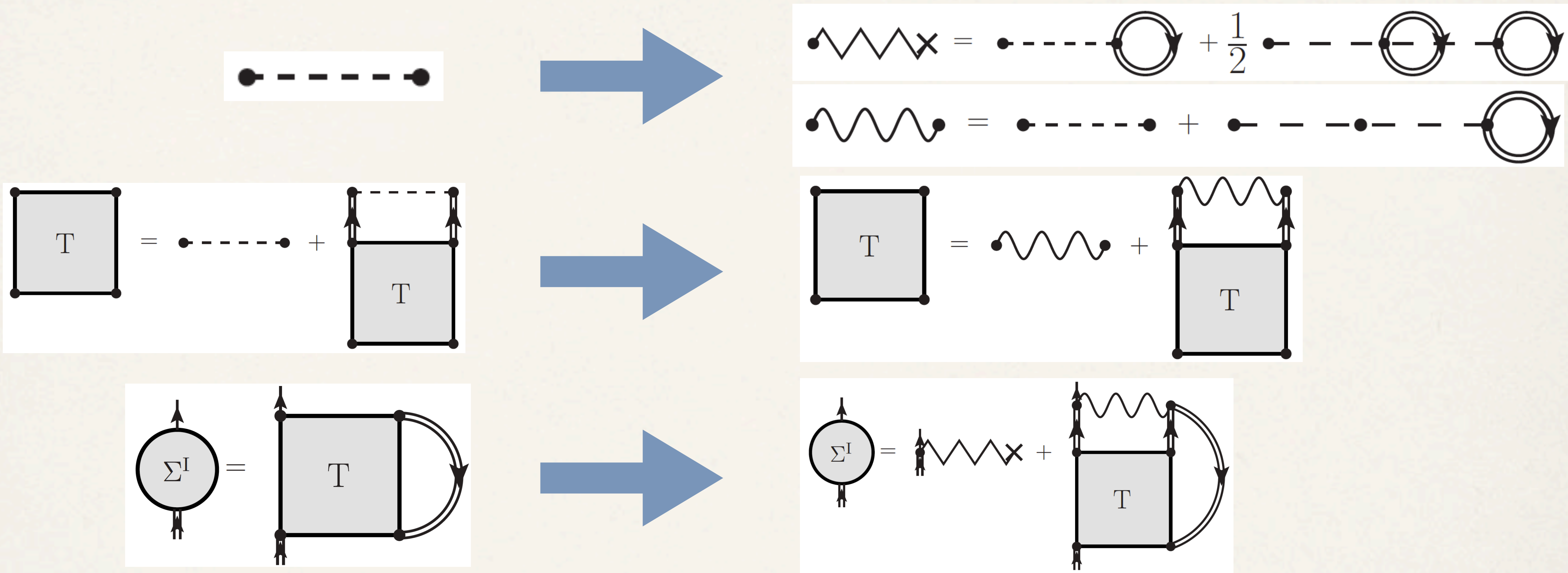
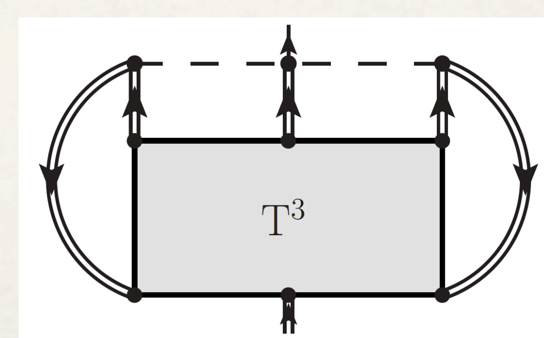



All 3-body interaction irreducible diagrams are omitted in this approach, i.e. those coming from a $T^3$ matrix



# The Koltun sumrule for the energy

- We need to calculate the total energy of the system:

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

- We have the Koltun sumrule to calculate the total energy of the system: first developed by Galitskii and Migdal (1958), later applied to finite system by Koltun ('70s)

$$\sum_\alpha \langle \Psi^N | a^\dagger_\alpha [a_\alpha, \hat{H}] | \Psi^N \rangle = \langle \Psi^N | \hat{T} | \Psi^N \rangle + 2 \langle \Psi^N | \hat{V} | \Psi^N \rangle$$

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The spectral function

$$\frac{E}{A} = \frac{\nu}{\rho} \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \int \frac{\mathrm{d}\omega}{2\pi} \frac{1}{2} \left\{ \frac{k^2}{2m} + \omega \right\} \mathcal{A}(k, \omega) f(\omega)$$

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- How does the Koltun sumrule change with 3NF?

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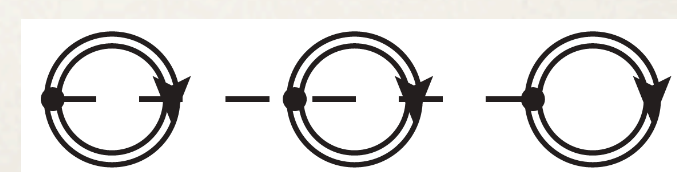
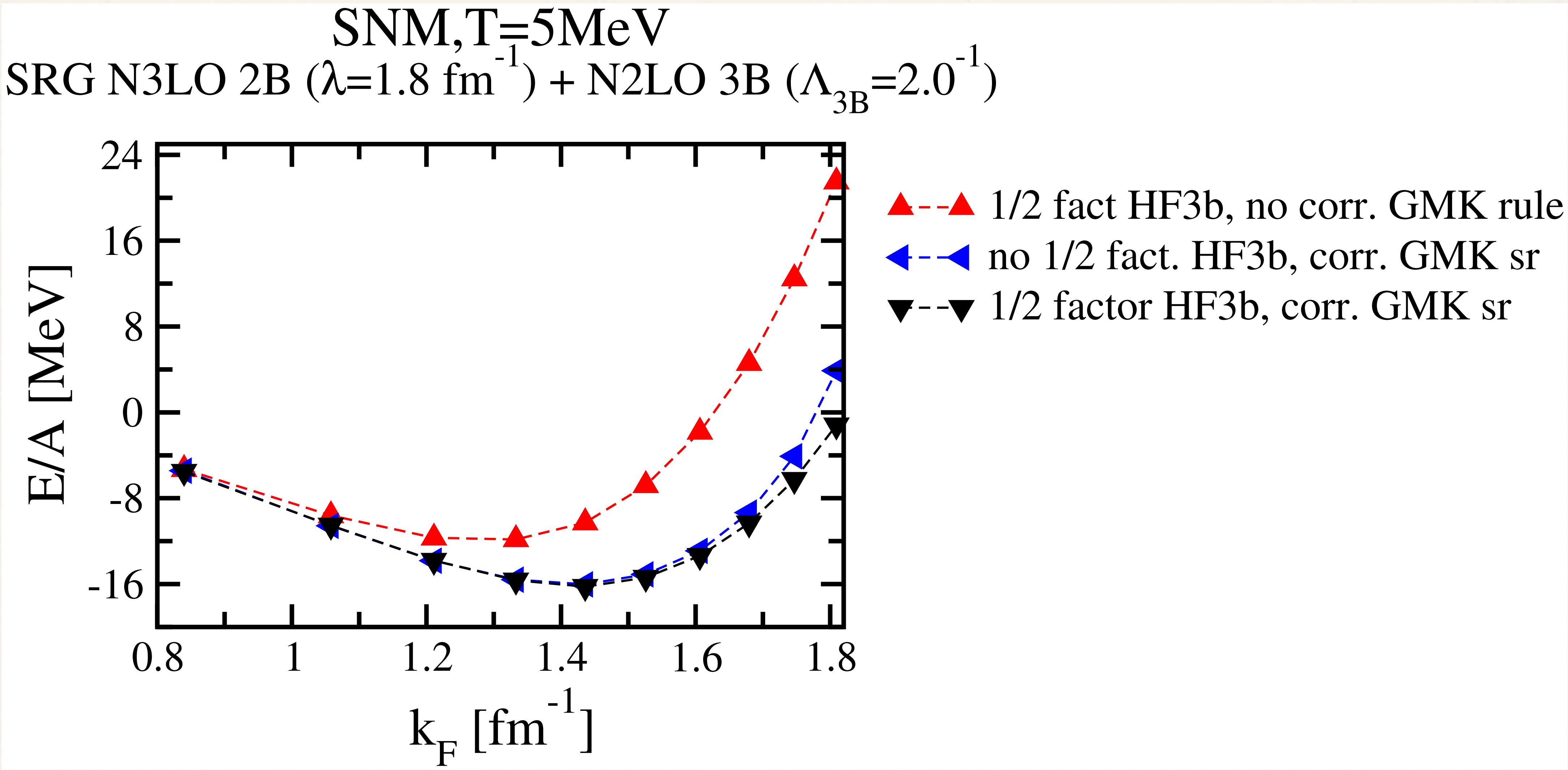
$$\sum_\alpha \langle \Psi^N | a_\alpha^\dagger [a_\alpha, \hat{H}] | \Psi^N \rangle = \sum_\alpha \int_{-\infty}^{E^N - E^{N-1}} \mathrm{d}E \, E \frac{1}{\pi} \mathrm{Im} \, G(\alpha, \alpha'; E)$$

The spectral function

$$\frac{E}{A} = \frac{\nu}{\rho} \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \int \frac{\mathrm{d}\omega}{2\pi} \frac{1}{2} \left\{ \frac{k^2}{2m} + \omega - \frac{1}{3} \Sigma_{HF}^{3NF}(k) \right\} \mathcal{A}(k, \omega) f(\omega)$$

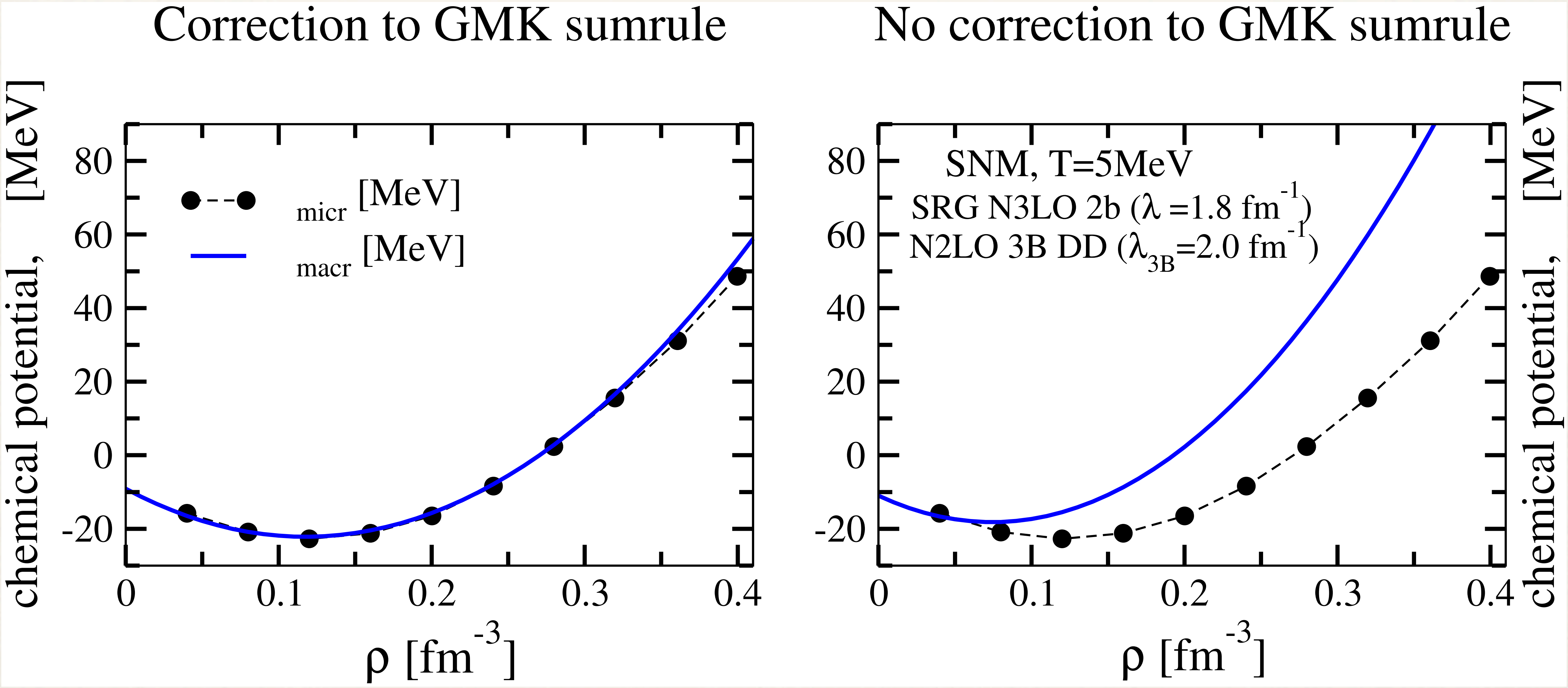


# The Koltun sumrule for the energy with 3NF



# The Koltun sumrule for the energy with 3NF

Thermodynamic consistency:



# Outline:

- Nuclear matter & the importance of adding three-nucleon forces (3NF)
- Our approach to nuclear matter:
  - the self-consistent Green's functions (SCGF) approach with 3NF
  - <u>include 3NF as a density dependent 2NF</u>
- Results
- Conclusions & Outlooks

# 3NF as a density dependent 2NF

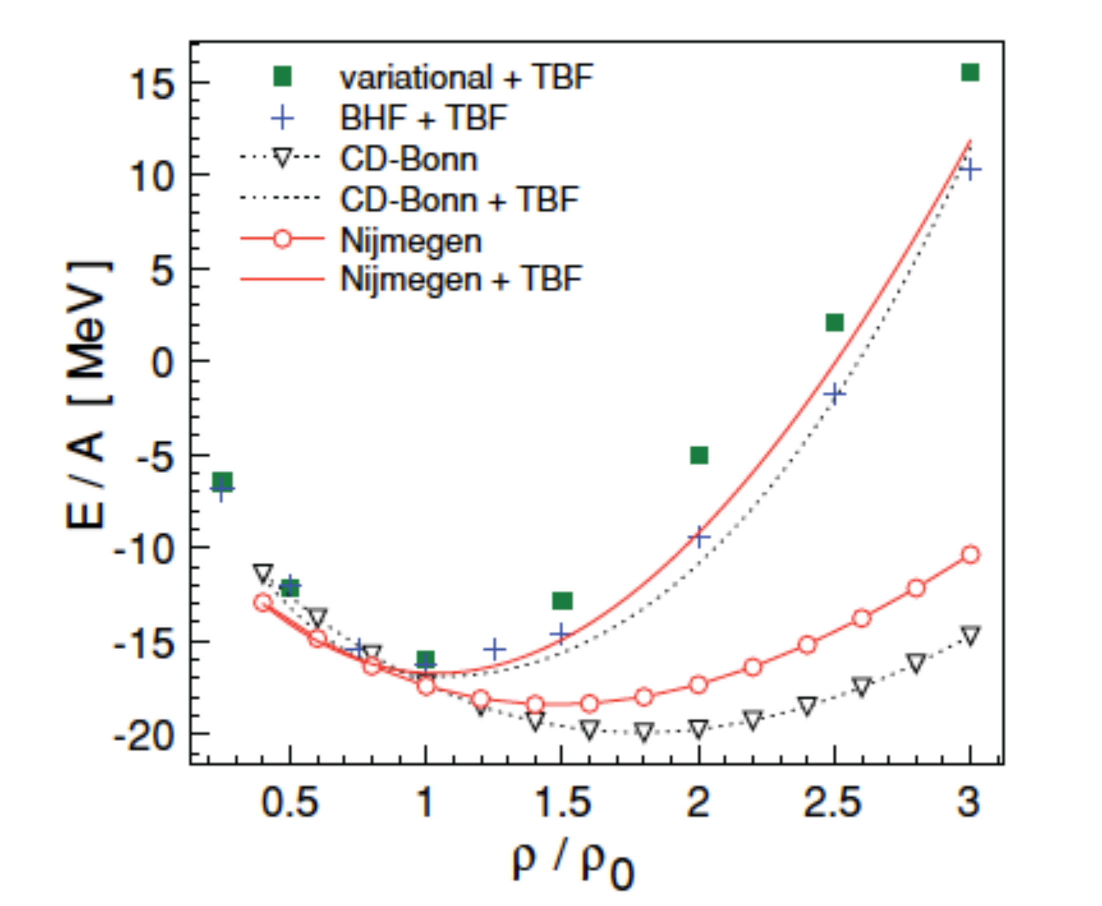
- Density dependent potentials obtained from:
  - Two-meson exchange potential (Grangé *et al*. PRC 40, 1040 (1989)):
    - used in BHF calculations (Li *et al*. PRC 77, 034316 (2008) , Vidaña *et al*. PRC 80, 045806 (2009))
    - average accounts for correlations; not correctly included in many-body theory
  - UIX potential (Pudliner *et al*. PRL 74, 4396 (1995)):
    - used in FHNC calculations Lovato *et al*., PRC 83, 054003 (2011)
    - average accounts for correlations on a statistical and dynamical level; correctly included in many-body theory

# 3NF as a density dependent 2NF....in SCGF

- Density dependent potentials obtained from:

  - UIX potential (Pudliner *et al*. PRL 74, 4396 (1995):

- used in SCGF calculations, Somá and Bozek, PRC 78, 054003 (2008)
- average is performed with a dressed SP propagator; not correctly included in many-body theory

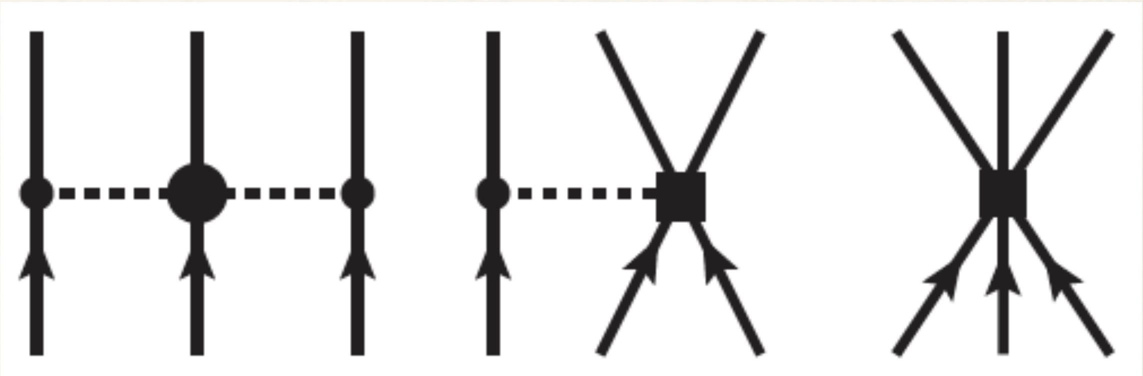


# 3NF as a density dependent 2NF

- Density dependent potentials obtained from:
  - chiral N2LO 3NF potential:
    - Holt *et al*. PRC 81, 024002, (2010);
    - Hebeler *et al*. PRC 82, 014314 (2010);
    - average is performed over the filled Fermi sea; correctly included in the many-body theory
    - Li *et al*. PRC 85, 064002 (2012);
    - average accounts for correlations; not correctly included in the many-body theory

# 3NF as a density dependent 2NF

- <u>Our approach to include a 3NF as a density dependent 2NF:</u>
    - Holt's definition of the density dependent 2NF, as detailed in Holt *et al.* PRC 81, 024002, 2010
    - Values of the low-energy constants $c_1, c_3, c_4$ fitted to NN and pi-N data (Entem & Machleidt PRC 68, 041001, 2003)
    - Values of low-energy constants which remain free, $c_D$ and $c_E$, fitted to 3H and 4He g.s. (Navratil FBS 41, 117, 2007)



$c_1, c_3, c_4$ $\quad$ $c_D$ $\quad$ $c_E$

# 3NF as a density dependent 2NF

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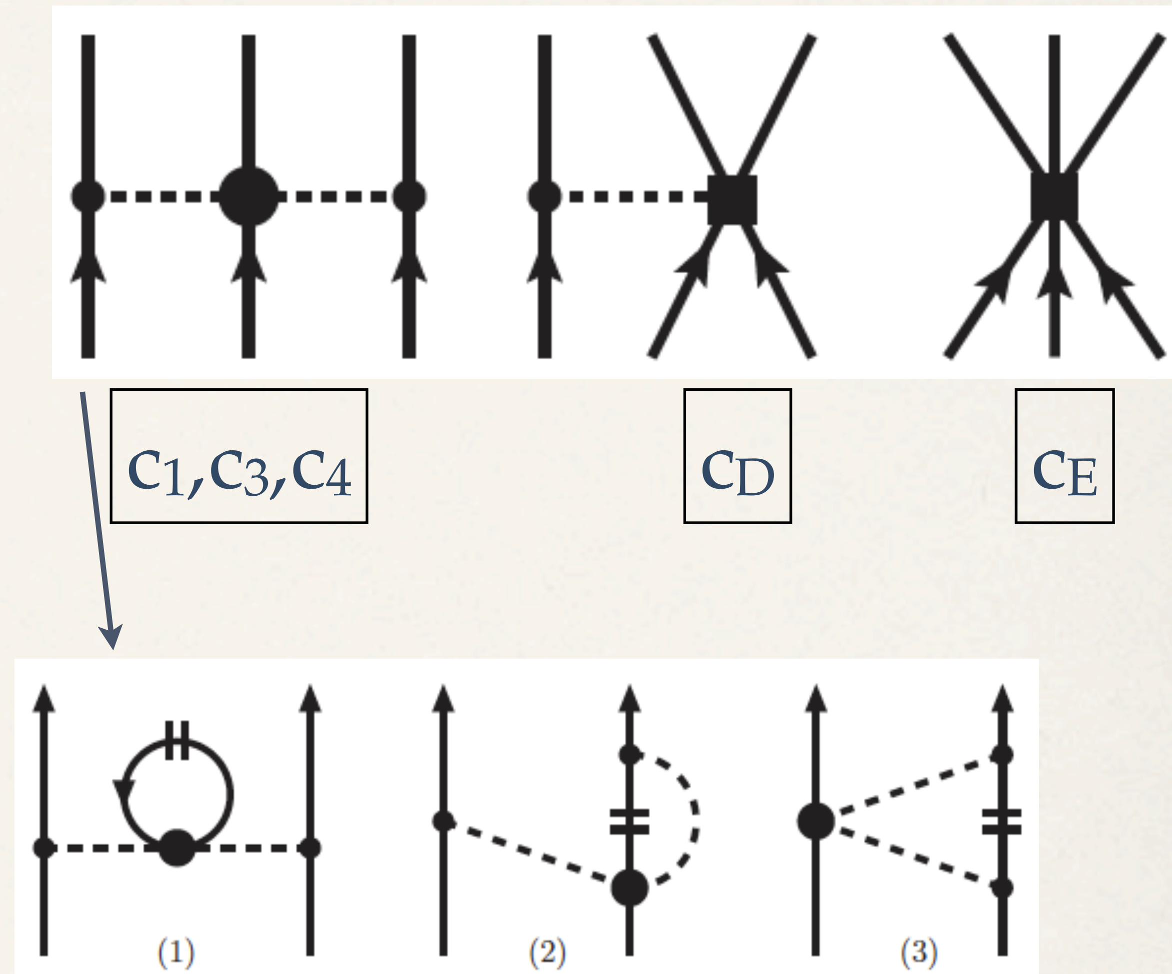

# 3NF as a density dependent 2NF

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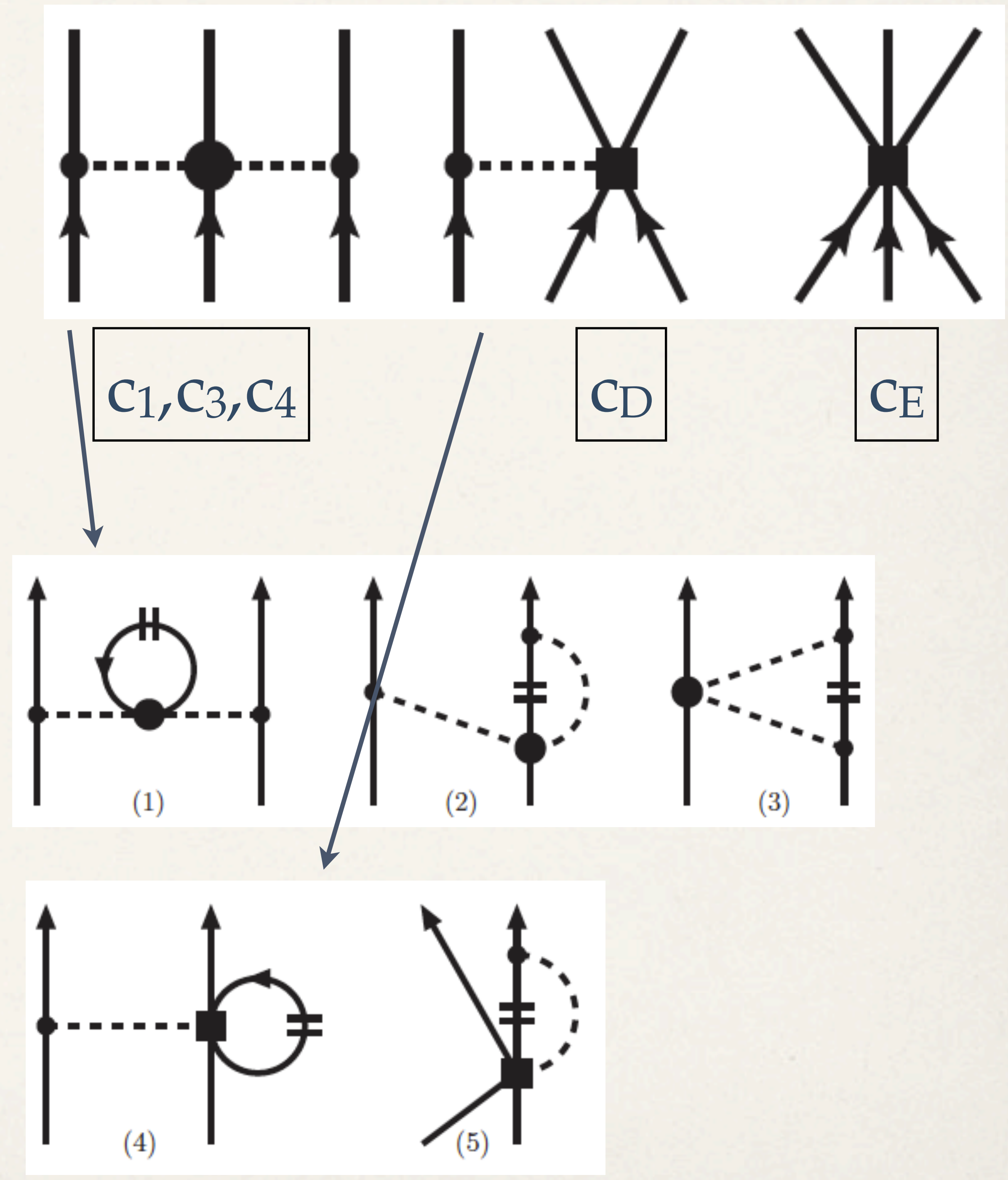

# 3NF as a density dependent 2NF

- Our approach to include a 3NF as a density dependent 2NF:
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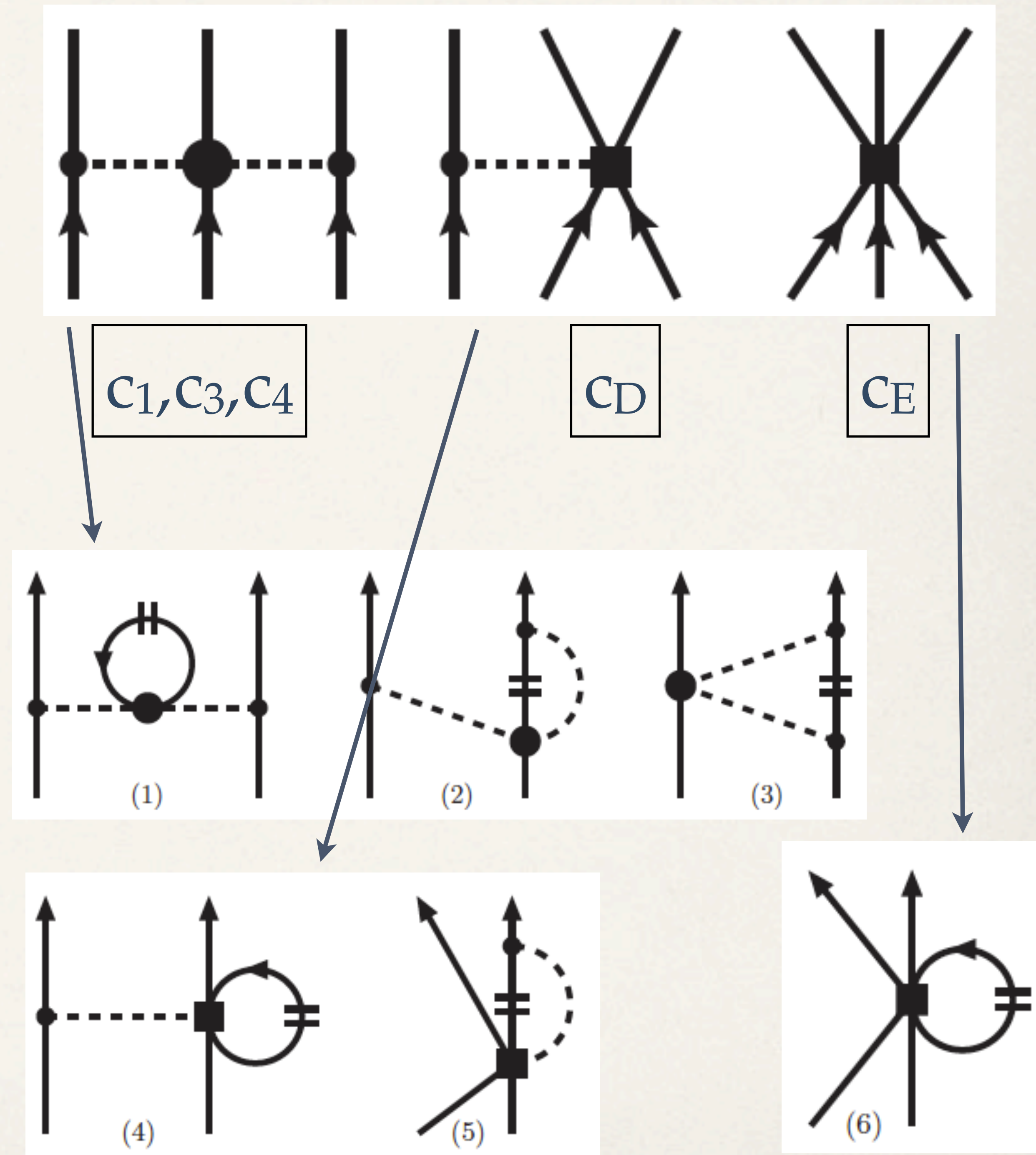

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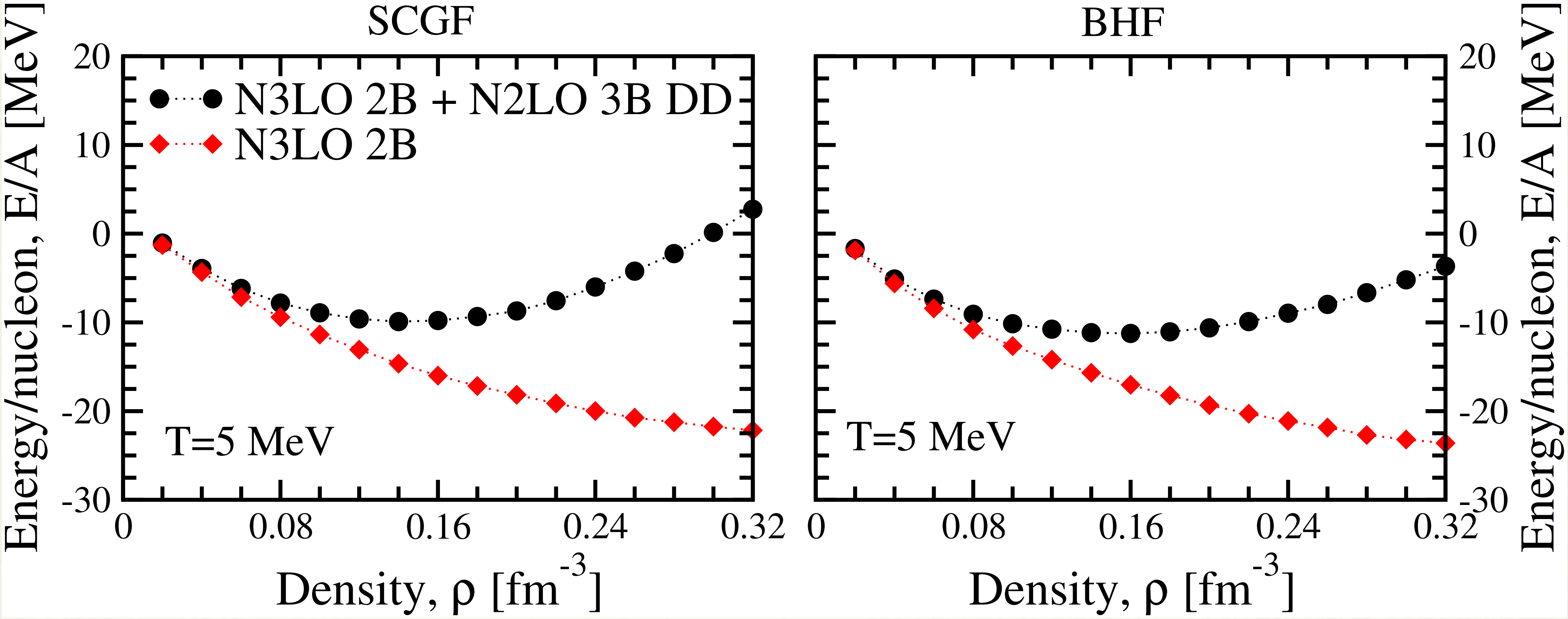
# Results: macroscopic properties

- Nuclear matter energy per nucleon with the SCGF and BHF approach:

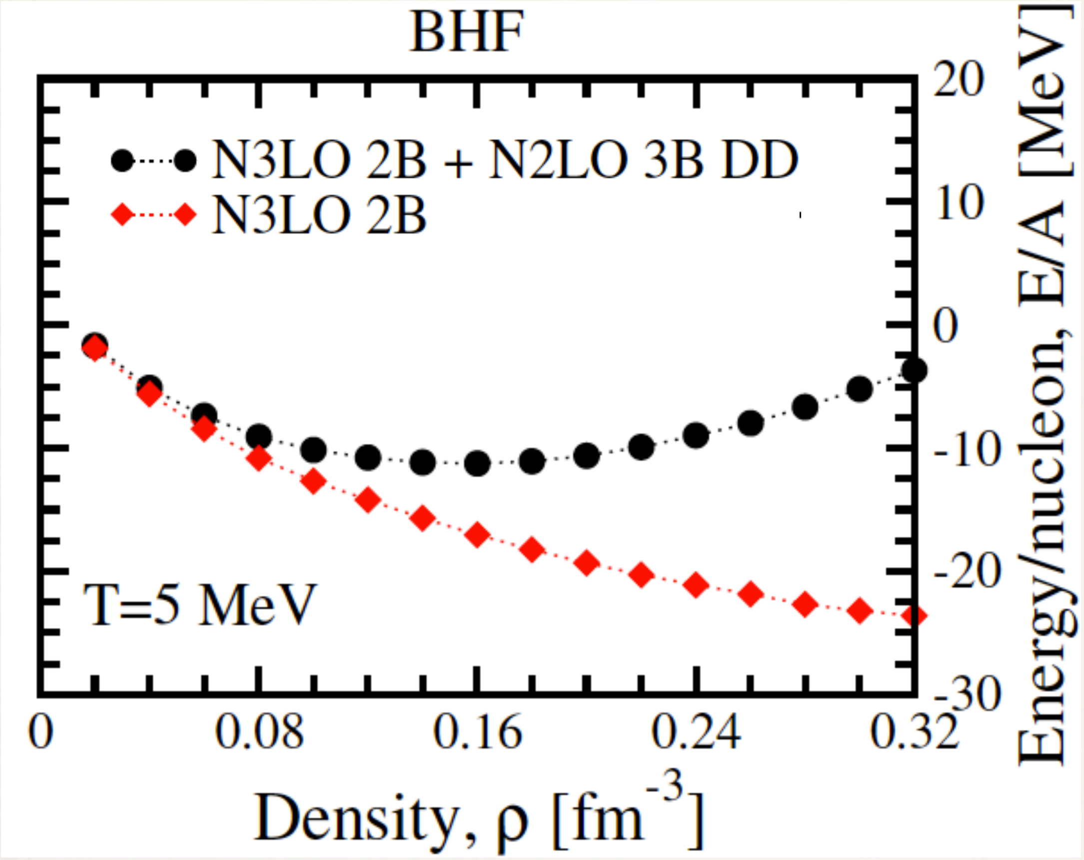


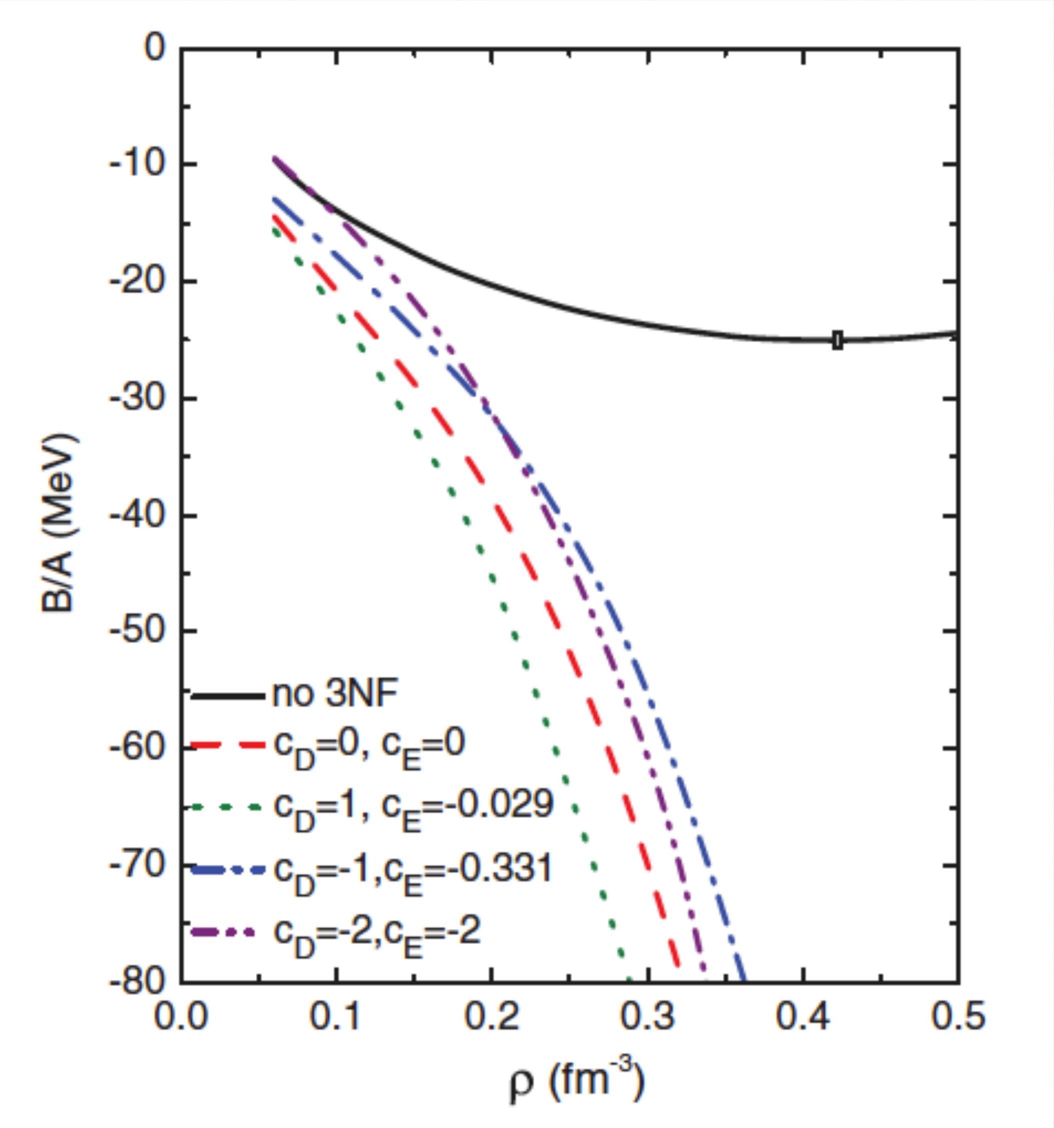

| Saturation values: |
|---|
| density = 0.14 $fm^{-3}$ |
| energy = -9.91 MeV |

| Saturation values: |
|---|
| density = 0.16 $fm^{-3}$ |
| energy = -11.25 MeV |

# Results: macroscopic properties

- Nuclear matter energy per nucleon with the BHF approach:




Saturation values:
density = 0.16 $fm^{-3}$
energy = -11.25 MeV

Li and Schulze, PRC 85, 064002, 2012

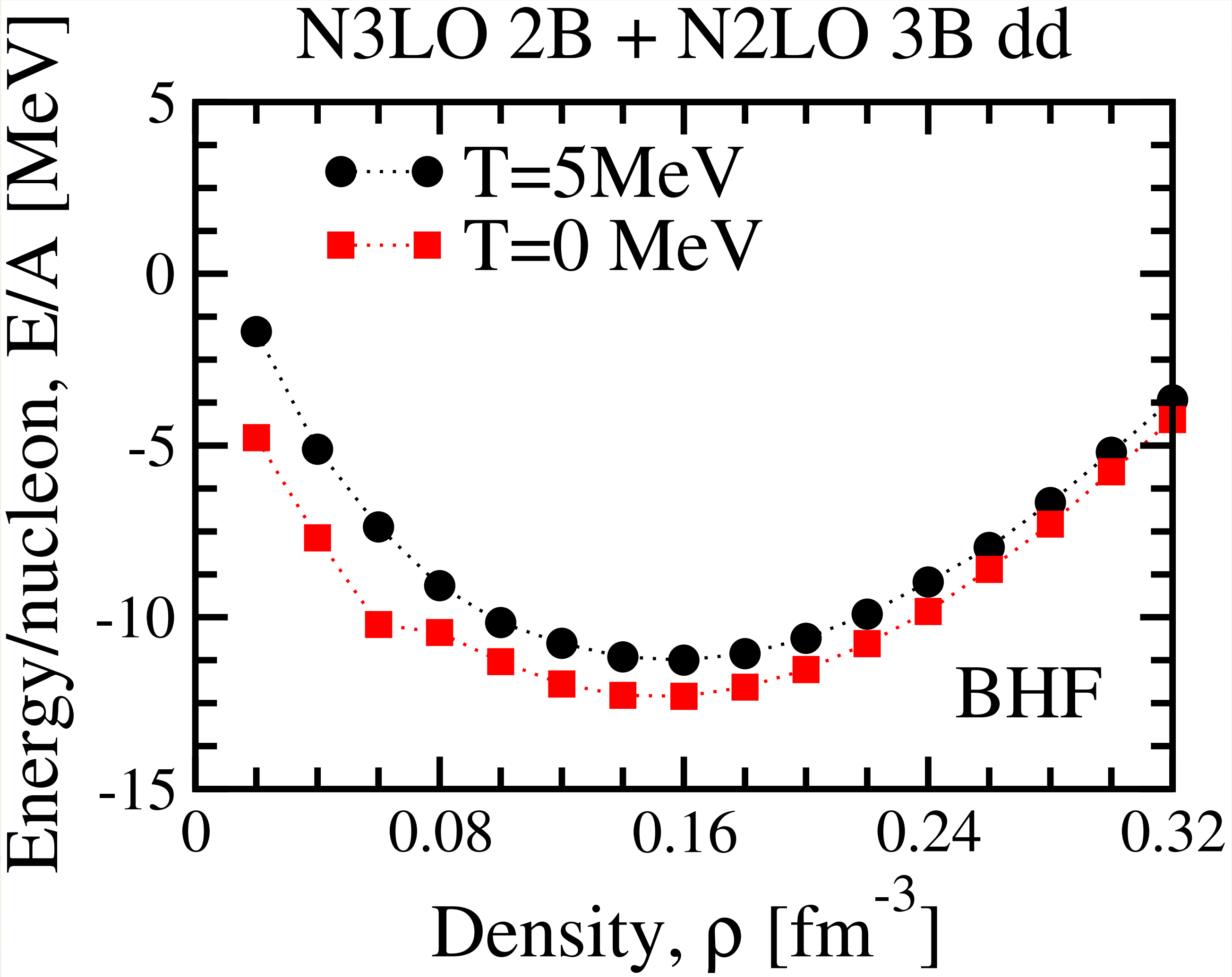
# Results: macroscopic properties

- Pin down thermal effects using the BHF approach:

Main effect at low density; T dependency is predictable and extrapolation to T=0 is under control

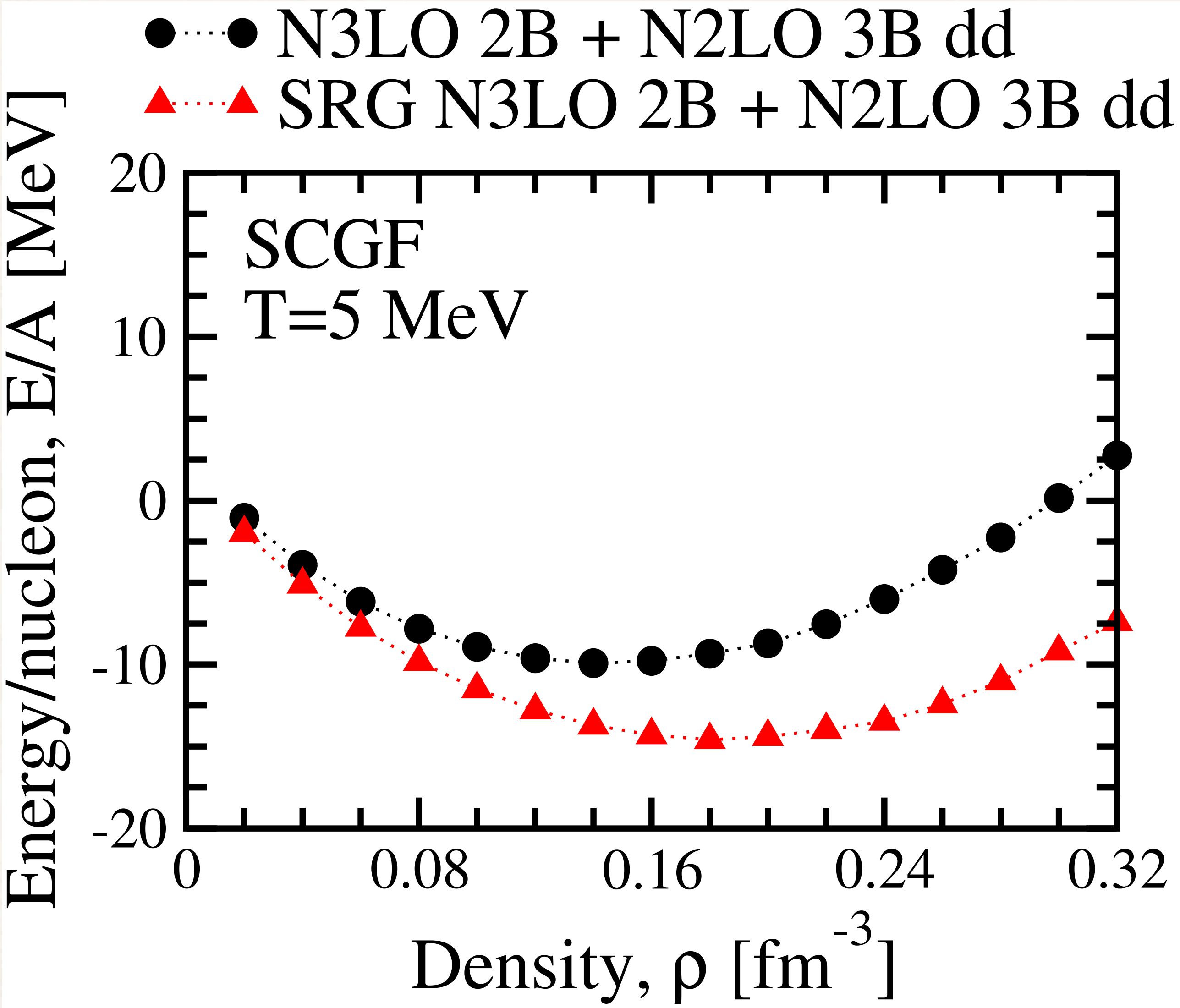
Saturation values:
density = 0.16 $fm^{-3}$
energy = -11.25 MeV

Saturation values:
density = 0.16 $fm^{-3}$
energy = -12.30 MeV



# Results: macroscopic properties

- Nuclear matter energy per nucleon, comparison with curve obtained using SRG evolved N3LO 2B, with $\lambda$=2.0 fm$^{-1}$ / $\Lambda_{3B}$=2.5 fm$^{-1}$:

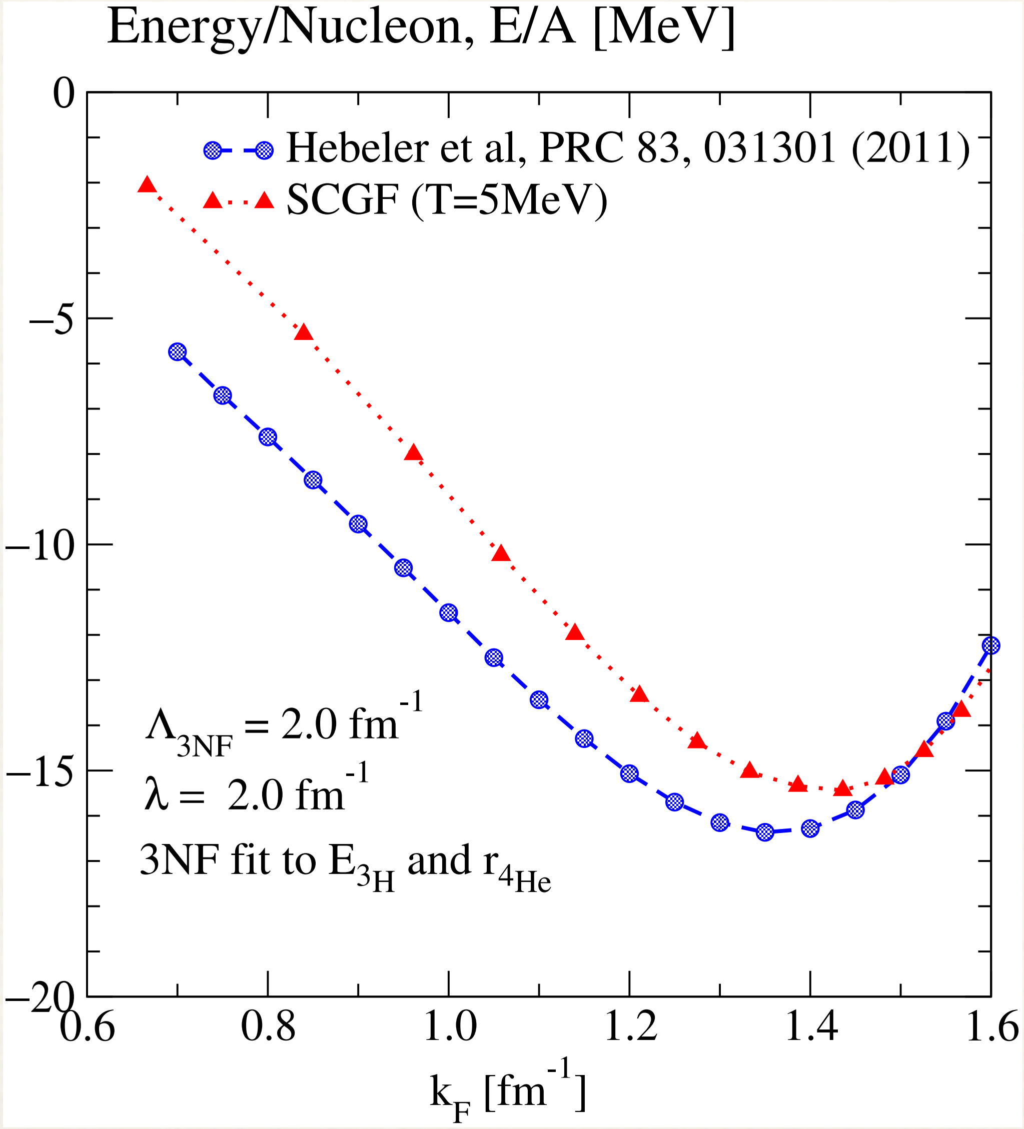



Saturation values:
density = 0.14 fm$^{-3}$
energy = -9.91 MeV

Saturation values:
density = 0.18 fm$^{-3}$
energy = -14.59 MeV

# Results: macroscopic properties

- Nuclear matter energy per nucleon, comparison with curve obtained using SRG evolved 2B N3LO with $\lambda$=2.0 fm$^{-1}$ / $\Lambda_{3B}$=2.0 fm$^{-1}$ by Hebeler *et al.* PRC 83, 031301 (2011):

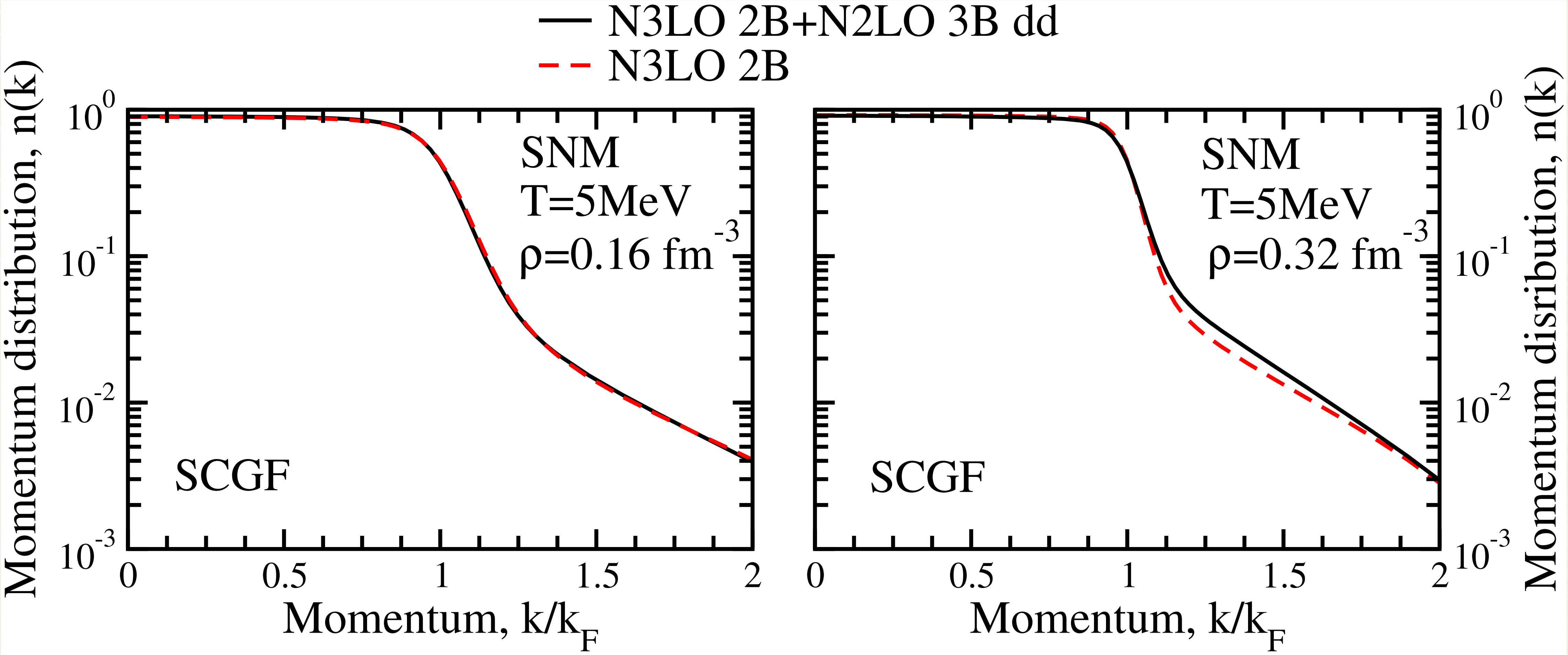



Saturation values:
density = 1.44 fm$^{-1}$
energy = -15.43 MeV

Saturation values:
density = 1.35 fm$^{-1}$
energy = -16.36 MeV

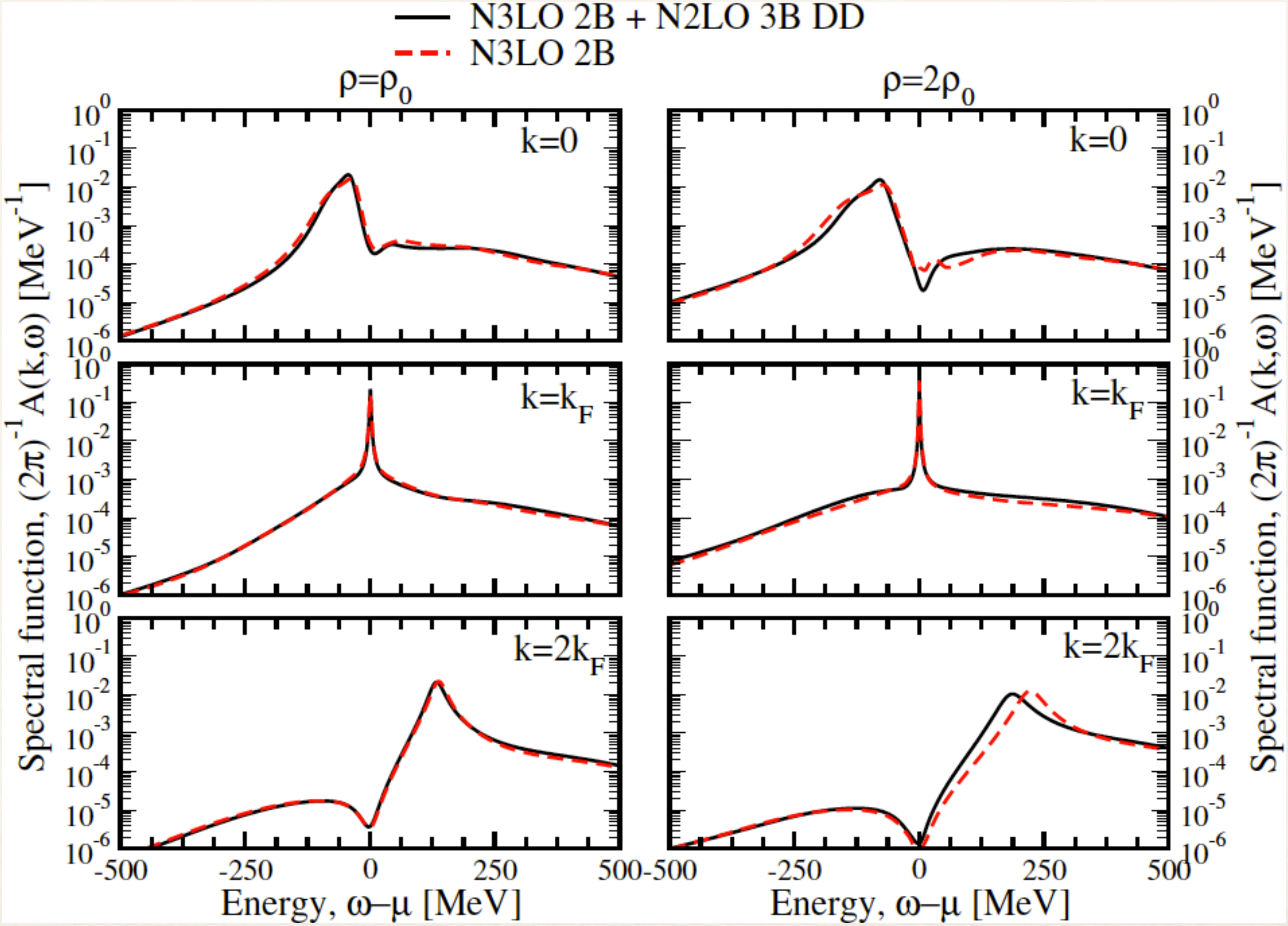
# Results: microscopic properties

- Momentum distribution at finite temperature:



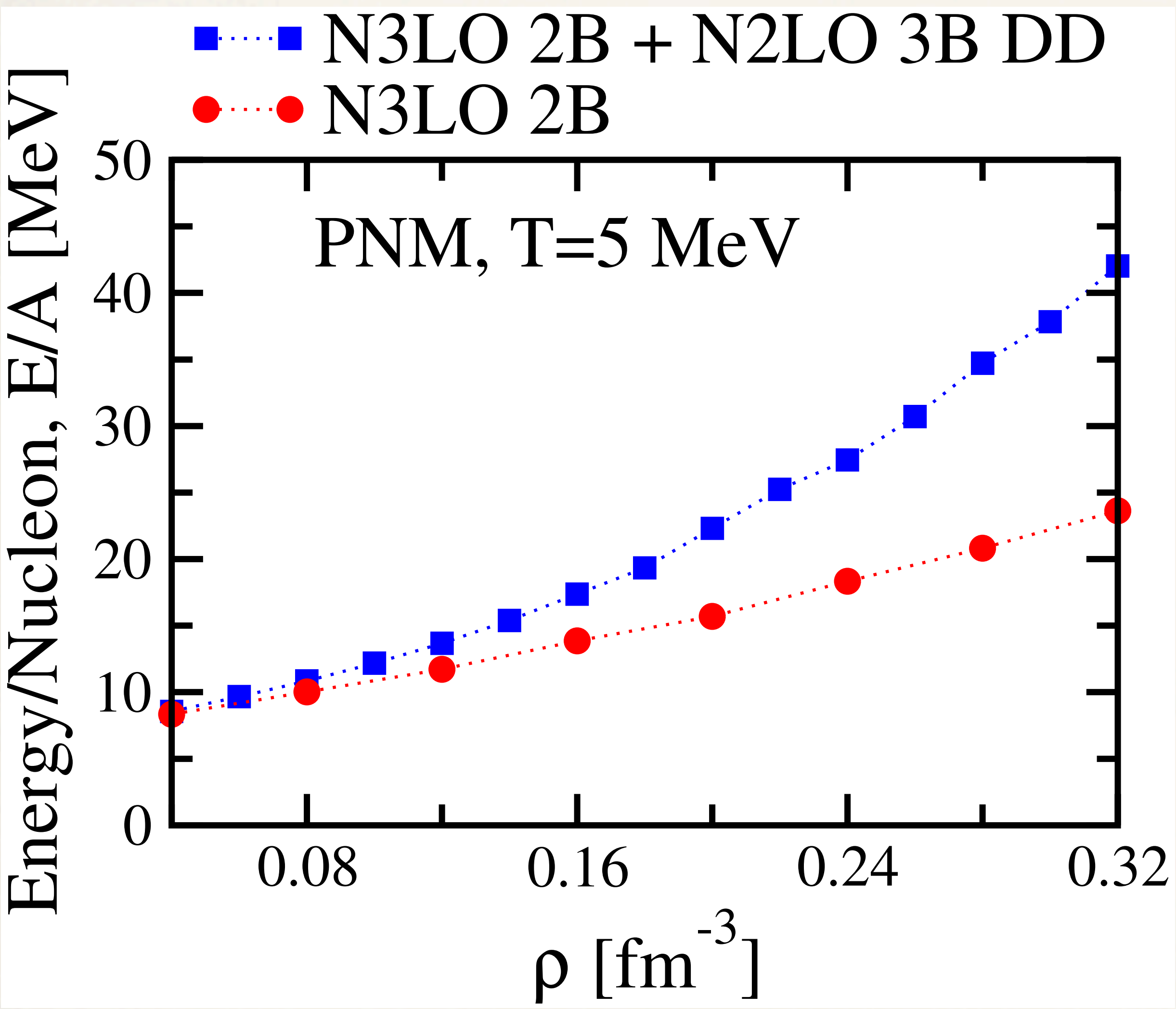
# Results: microscopic properties

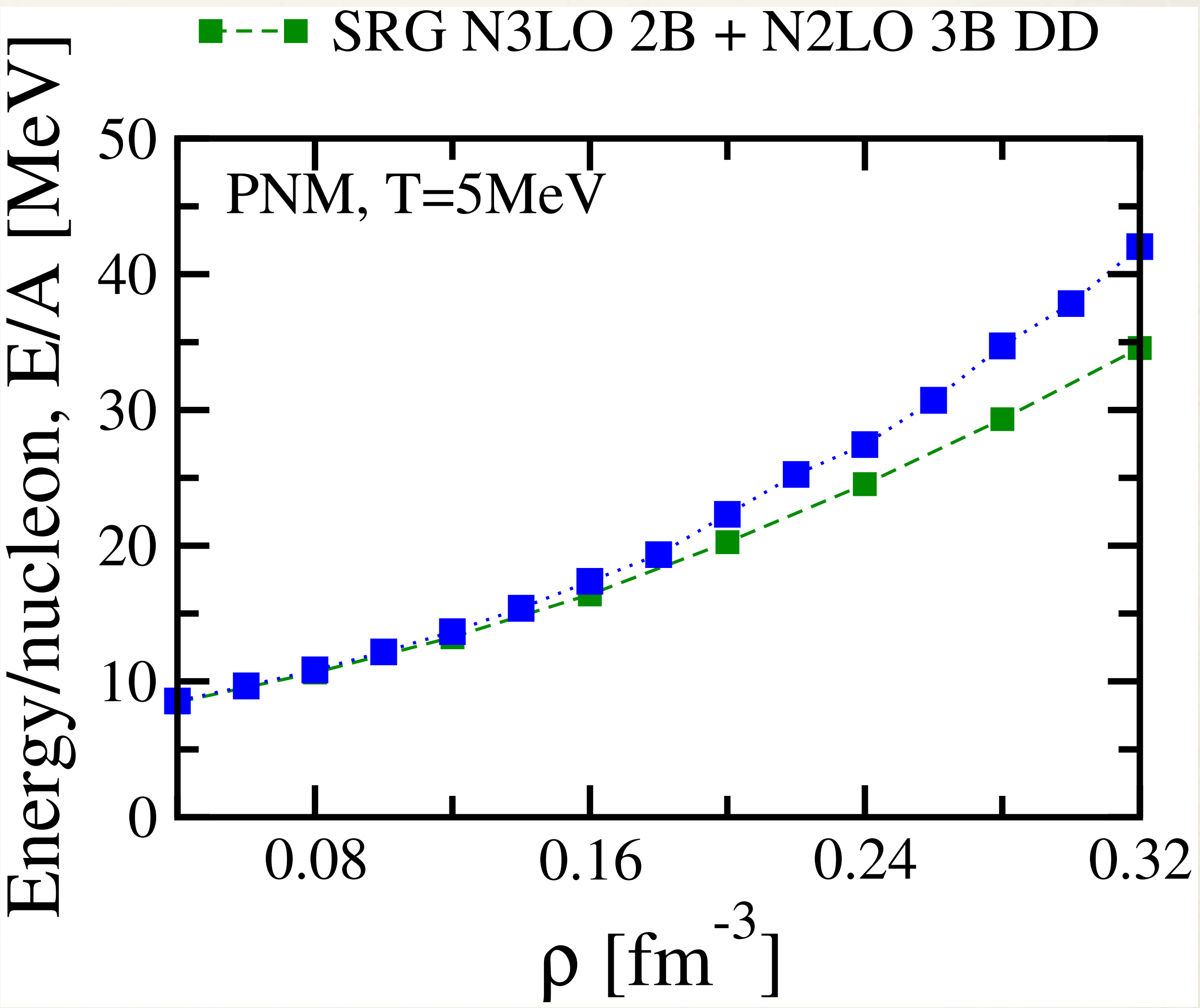
- Spectral function at finite temperature:



# Results: neutron matter

- <u>Neutron matter energy per nucleon</u> with the SCGF approach:



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# Conclusions & Outlooks

- We used the SCGF approach to calculate microscopic and macroscopic properties of symmetric nuclear matter
- We included 2B force up to N3LO and 3B up to N2LO in the density dependent prescription by J.W. Holt
- We obtained consistent results for the saturation energy of nuclear matter, comparing also with the SRG evolved case
- We also used the BHF approach and obtained realistic results with respect to other cases presented in the literature

# Conclusions & Outlooks

- Perform average of N2LO 3NF with a dressed propagator; work is in progress at the moment
- Include missing 3NF diagrams
- Improve correction of Koltun sumrule
- Evaluate neutron and asymmetric matter cases
- Encounter a way to avoid pairing instability and perform calculations at T=0 MeV

Thank you for your attention!