The neutron star equation of state

Chiral forces in the Green's functions formalism

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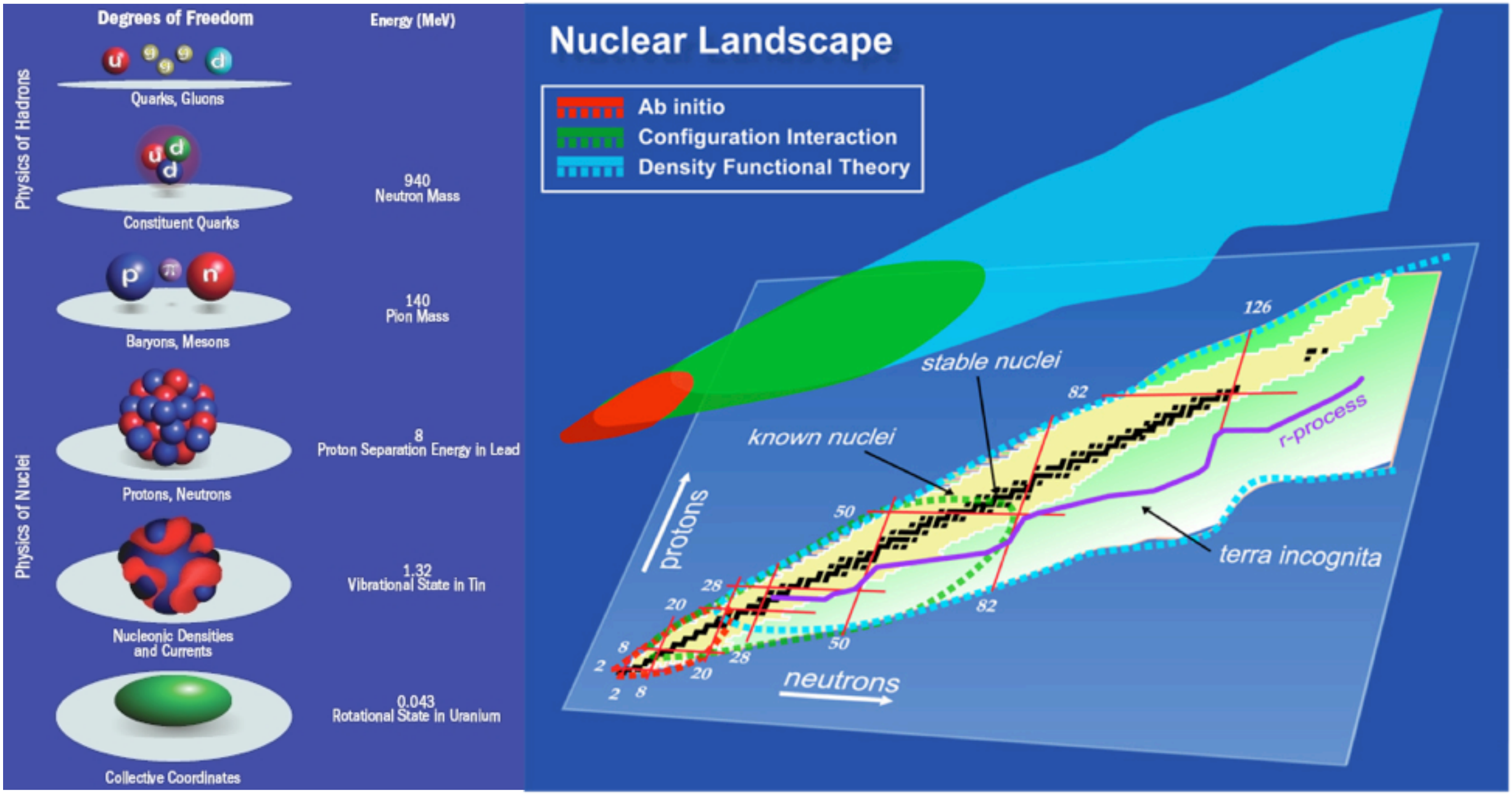
Compstar Conference, Florence, 25 March 2014

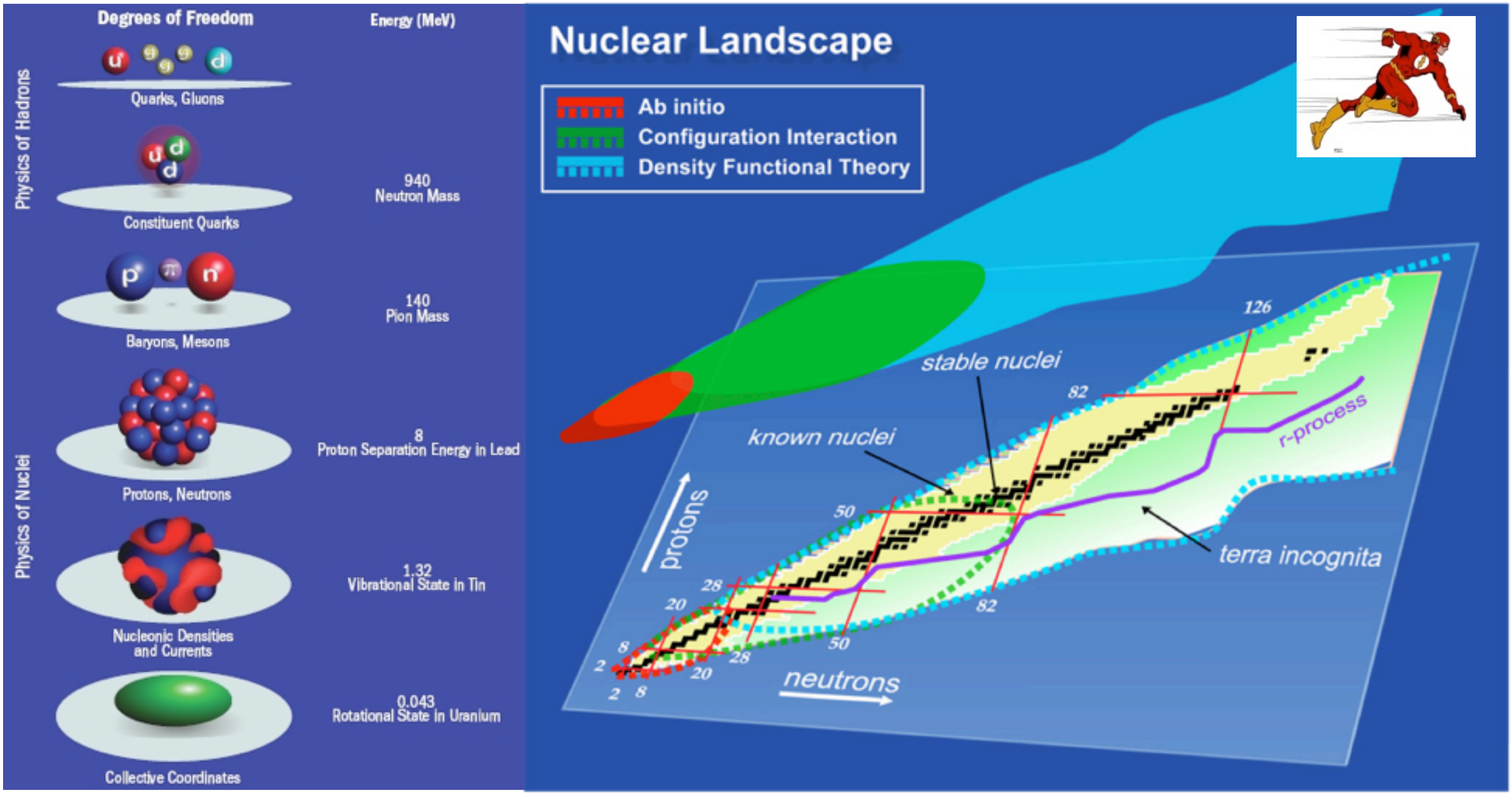
Theoretical nuclear physics



DOE/NSF Nuclear Science Advisory Committe, The Frontiers of Nuclear Science: A Long-Range Plan, 2007.

Two philosophies

Theoretical nuclear physics



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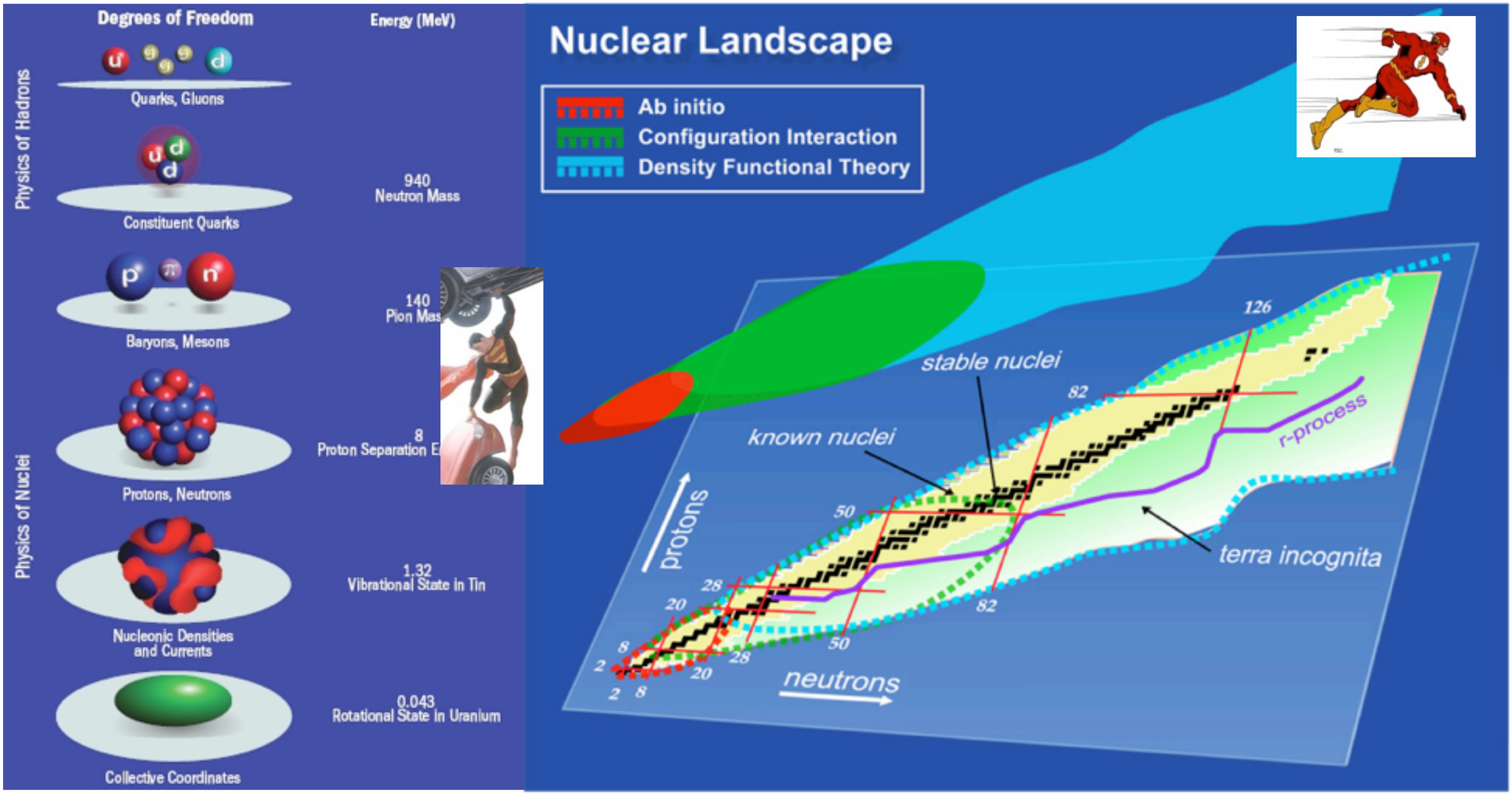
Two philosophies

- Phenomenological: nuclear properties from *energy density functional.*

Theoretical nuclear physics



DOE/NSF Nuclear Science Advisory Committe, The Frontiers of Nuclear Science: A Long-Range Plan, 2007.

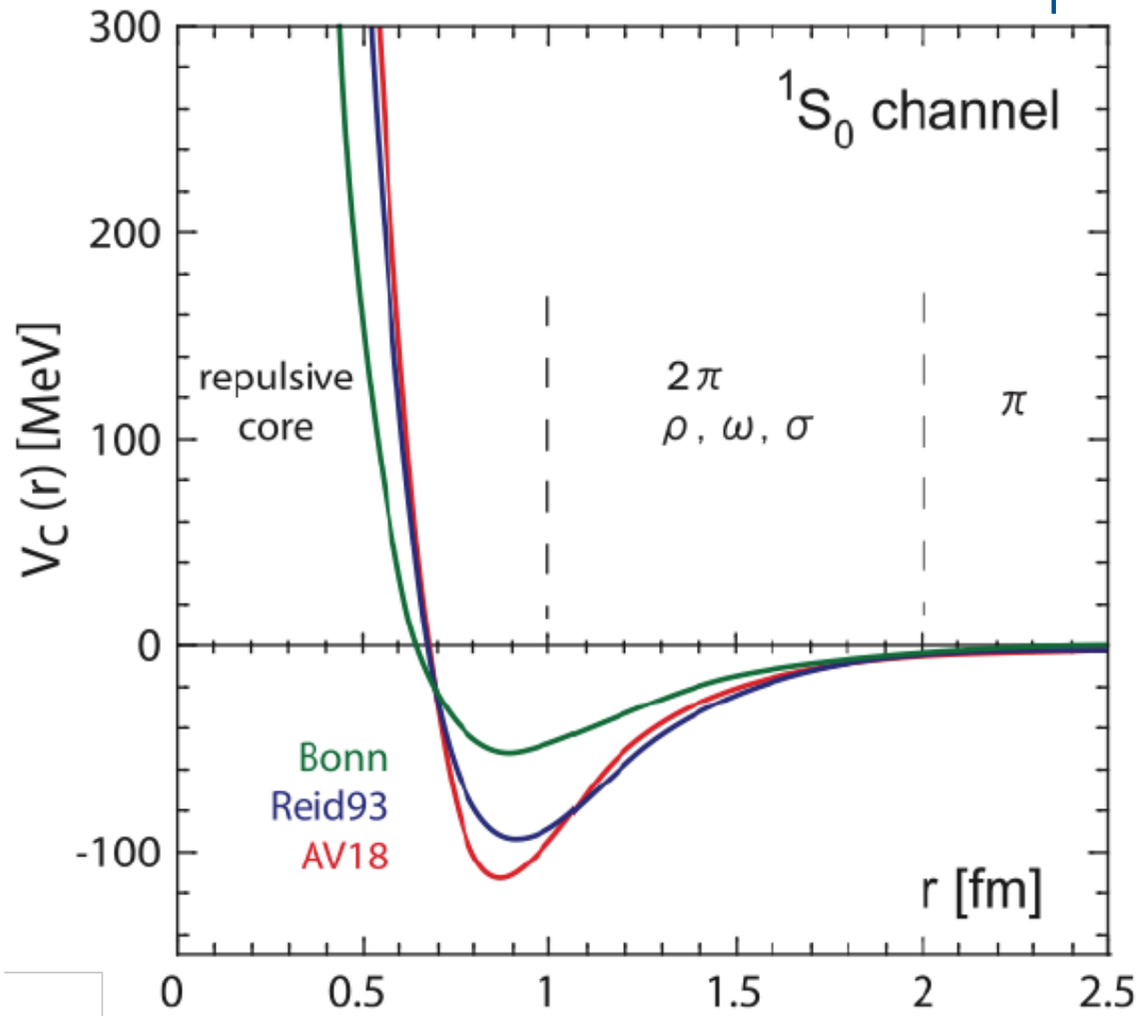
Two philosophies

- Phenomenological: nuclear properties from *energy density functional.*
- Ab initio: from QCD nucleon-nucleon force to nuclei?

Barbieri, Hagen, Roth, Schwenk, Bogner

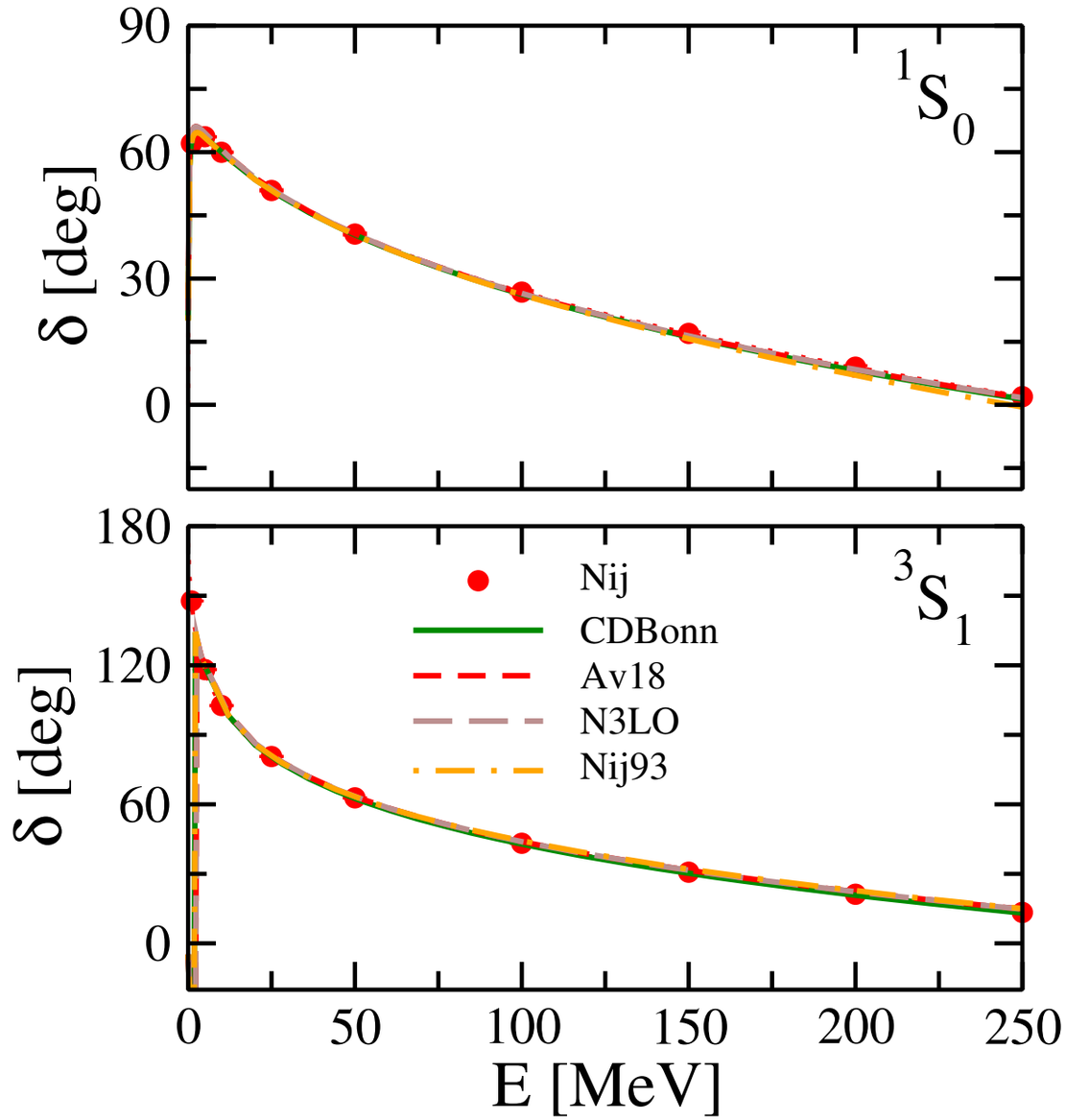
Complications

NN interaction is not unique



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

...but phase-shift equivalent!



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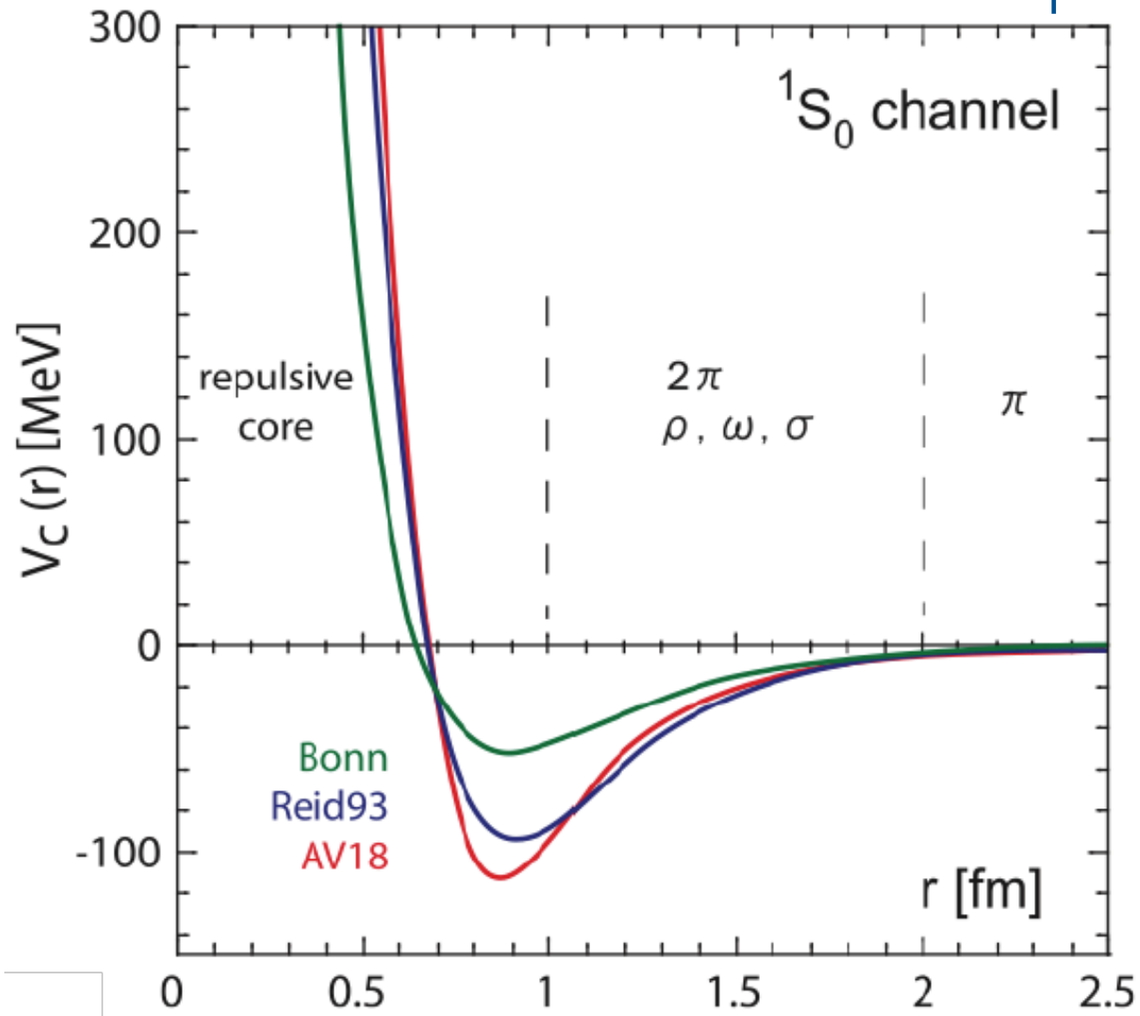

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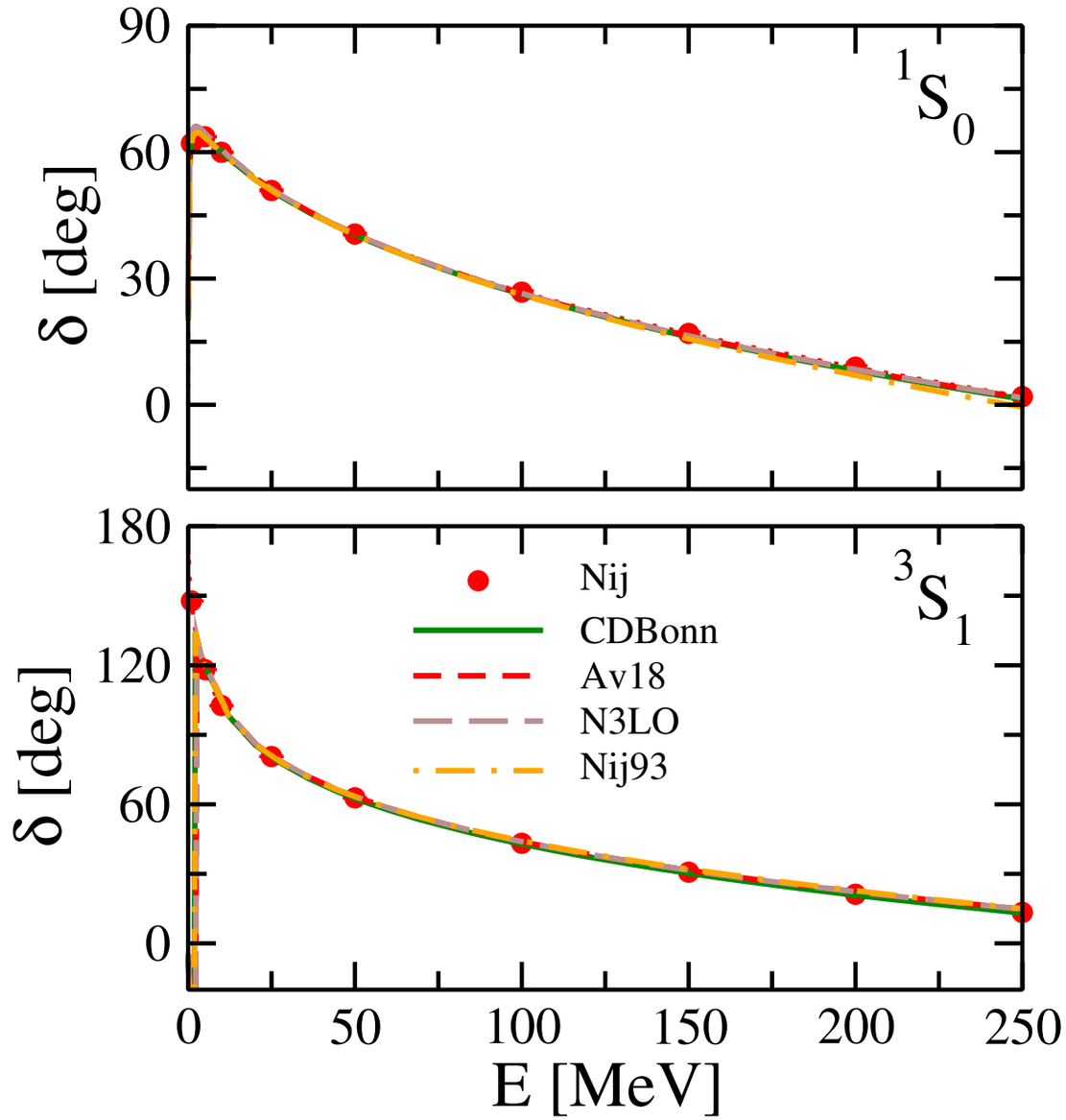

- Non-uniqueness of nucleon forces ✘

Complications

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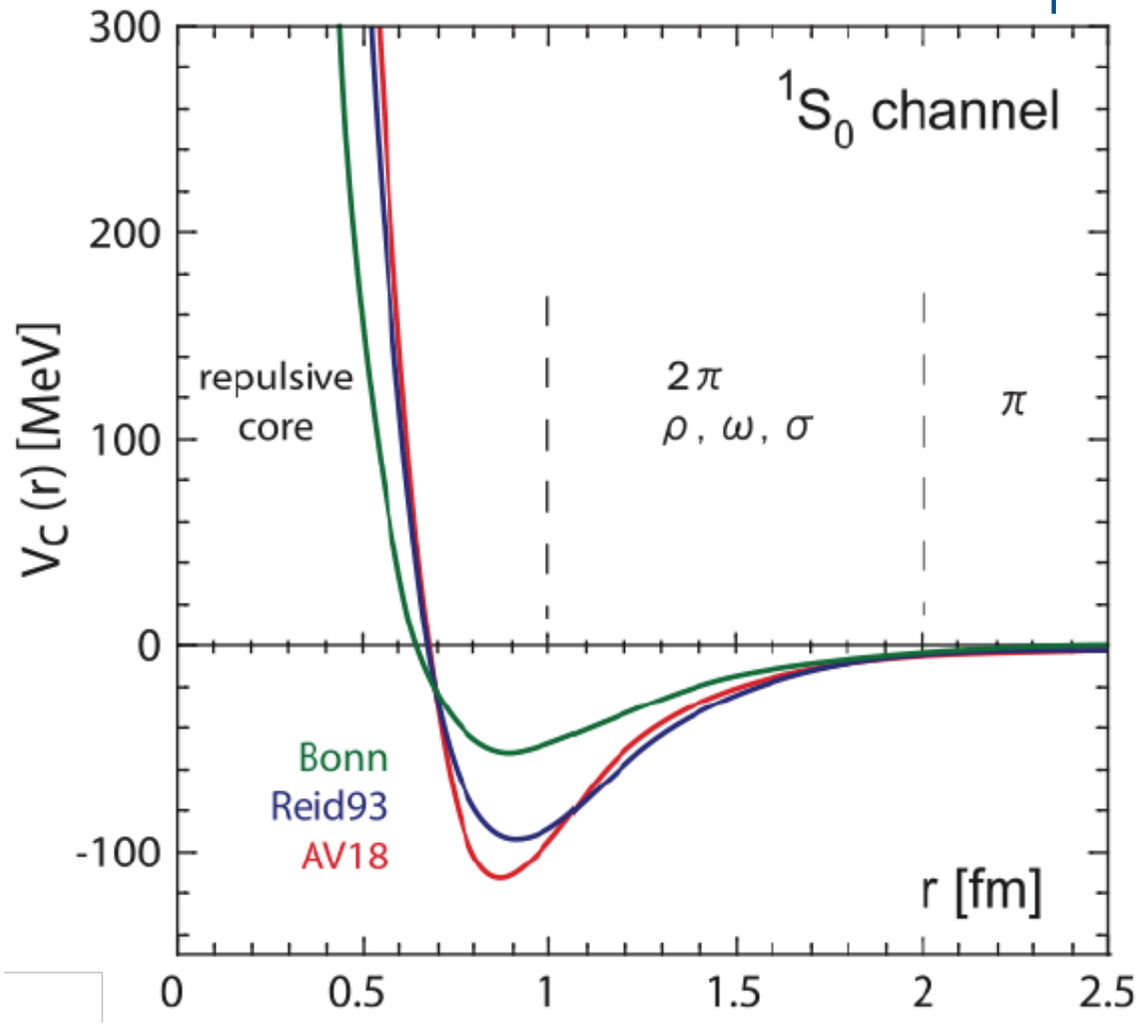
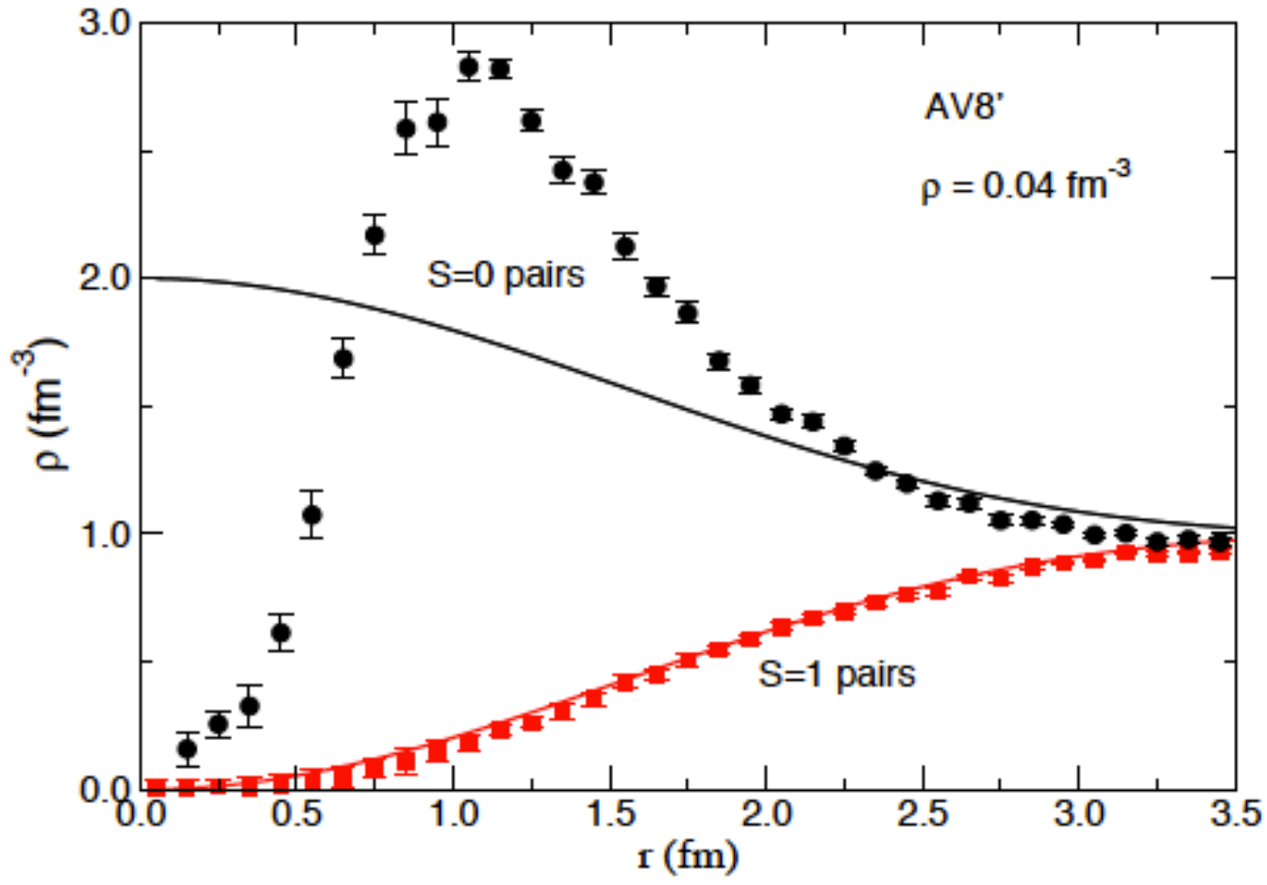


S. Aoki, et al. *Comput. Sci. Dis.* **1** 015009 (2008)

Strong short-range correlations

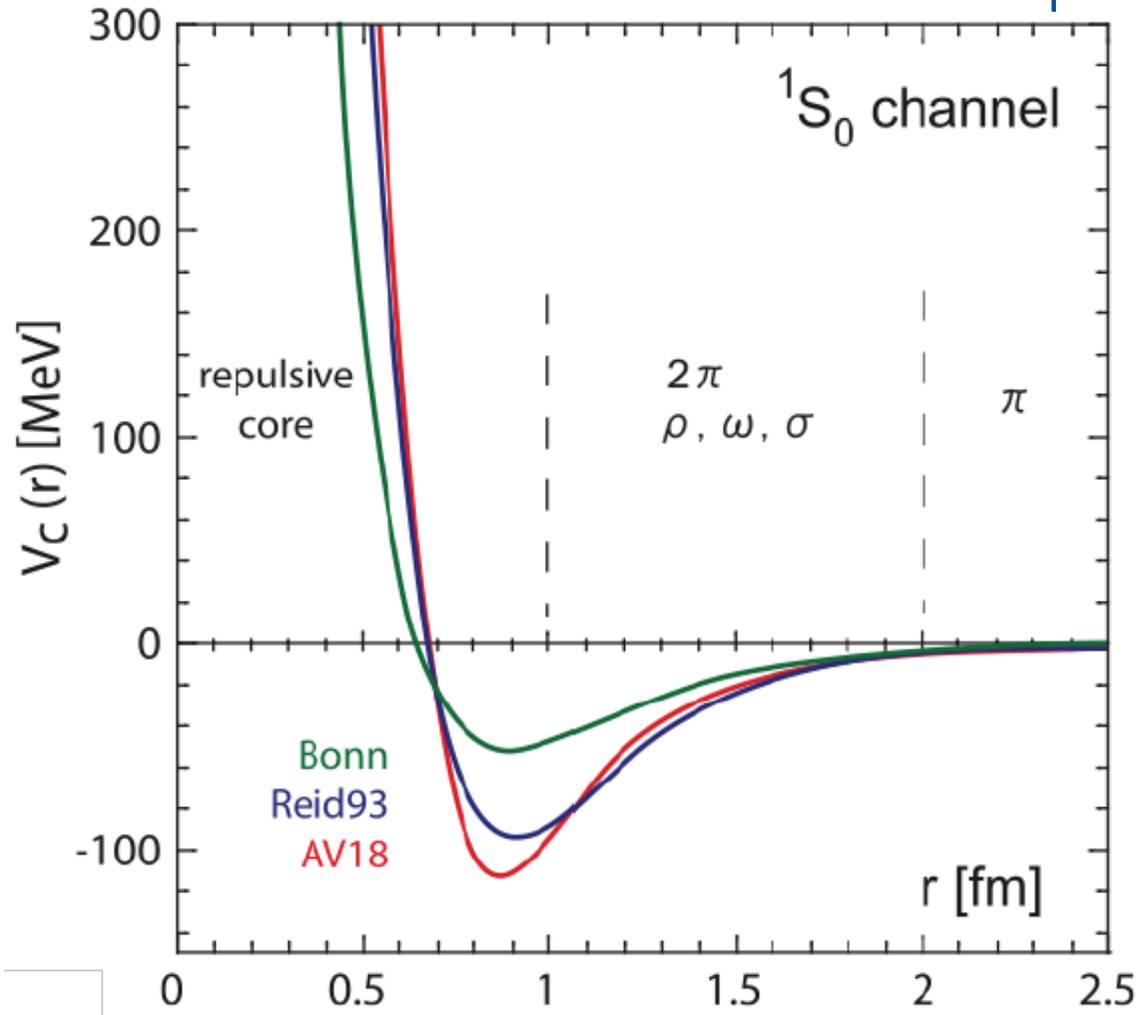


Carlson et al., *Phys. Rev. C* **68** 025802 (2003)

- Non-uniqueness of nucleon forces ✘
- Short-range core needs many-body treatment ✘

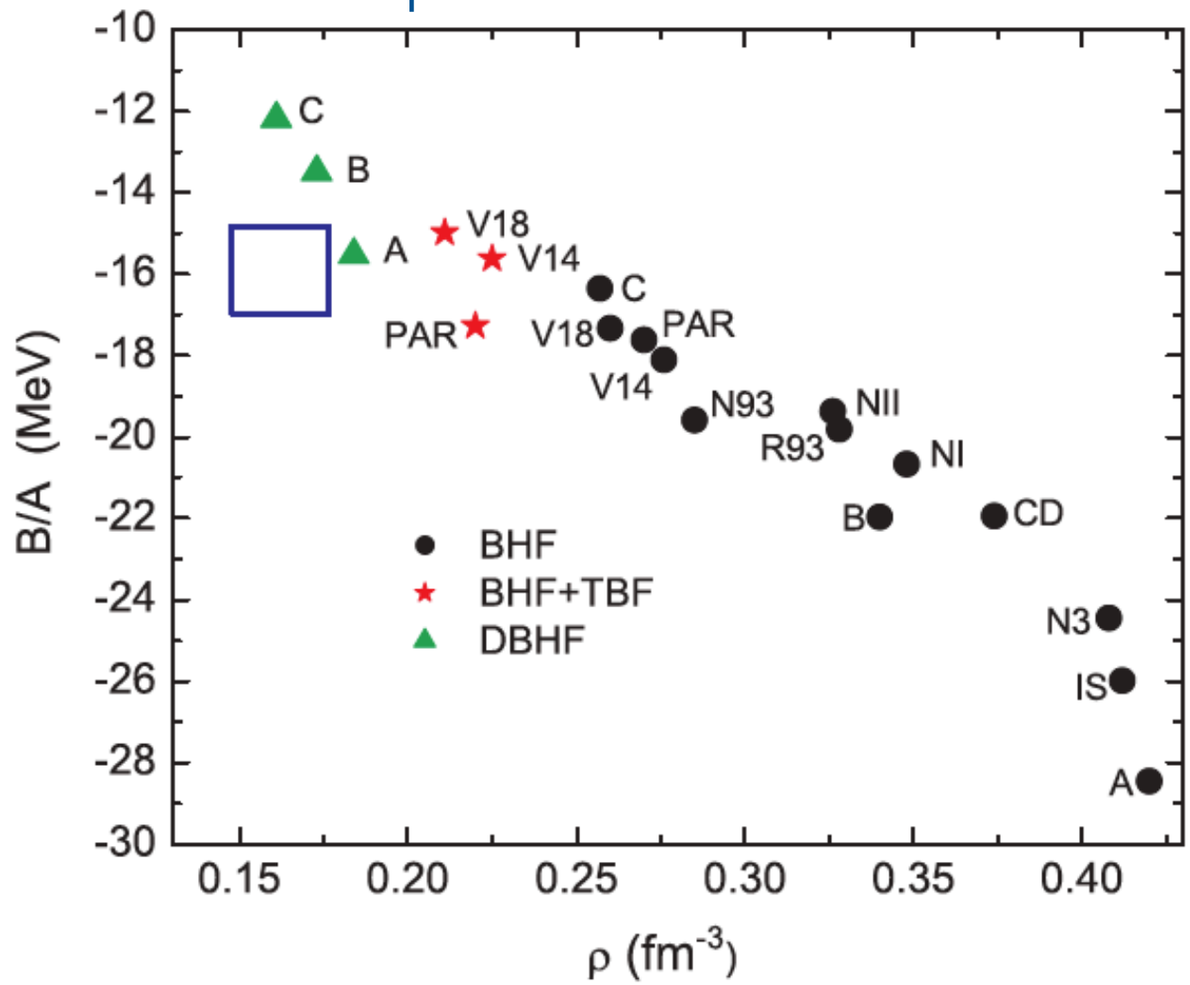
Complications

NN interaction is not unique



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

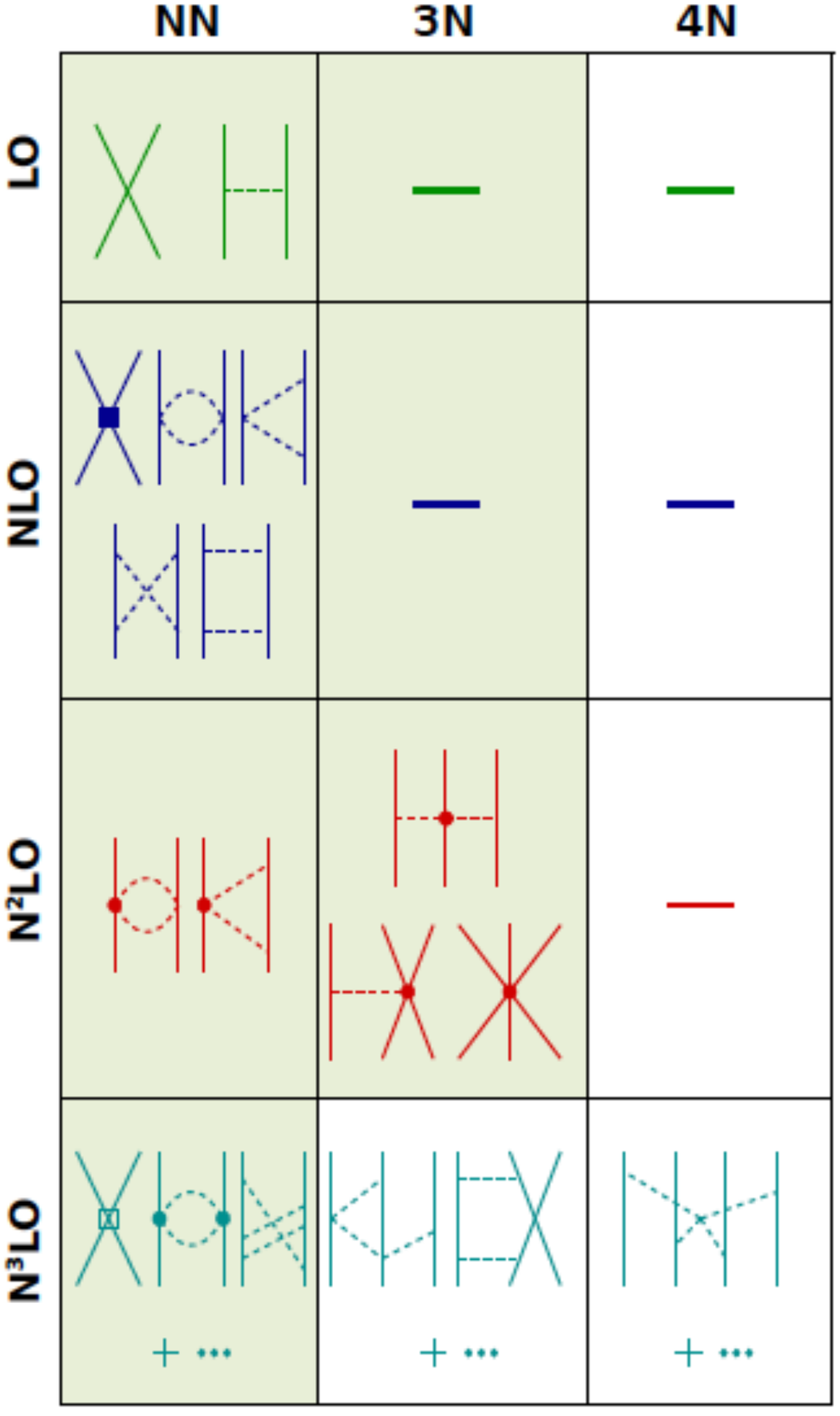
Saturation point of nuclear matter



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

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

NN forces from EFTs of QCD



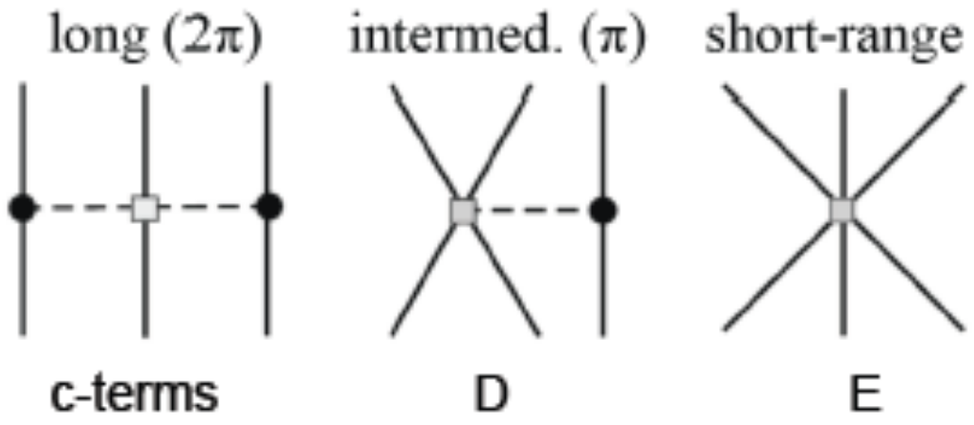
Robert Roth – TU Darmstadt – 04/2013

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

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

Chiral perturbation theory

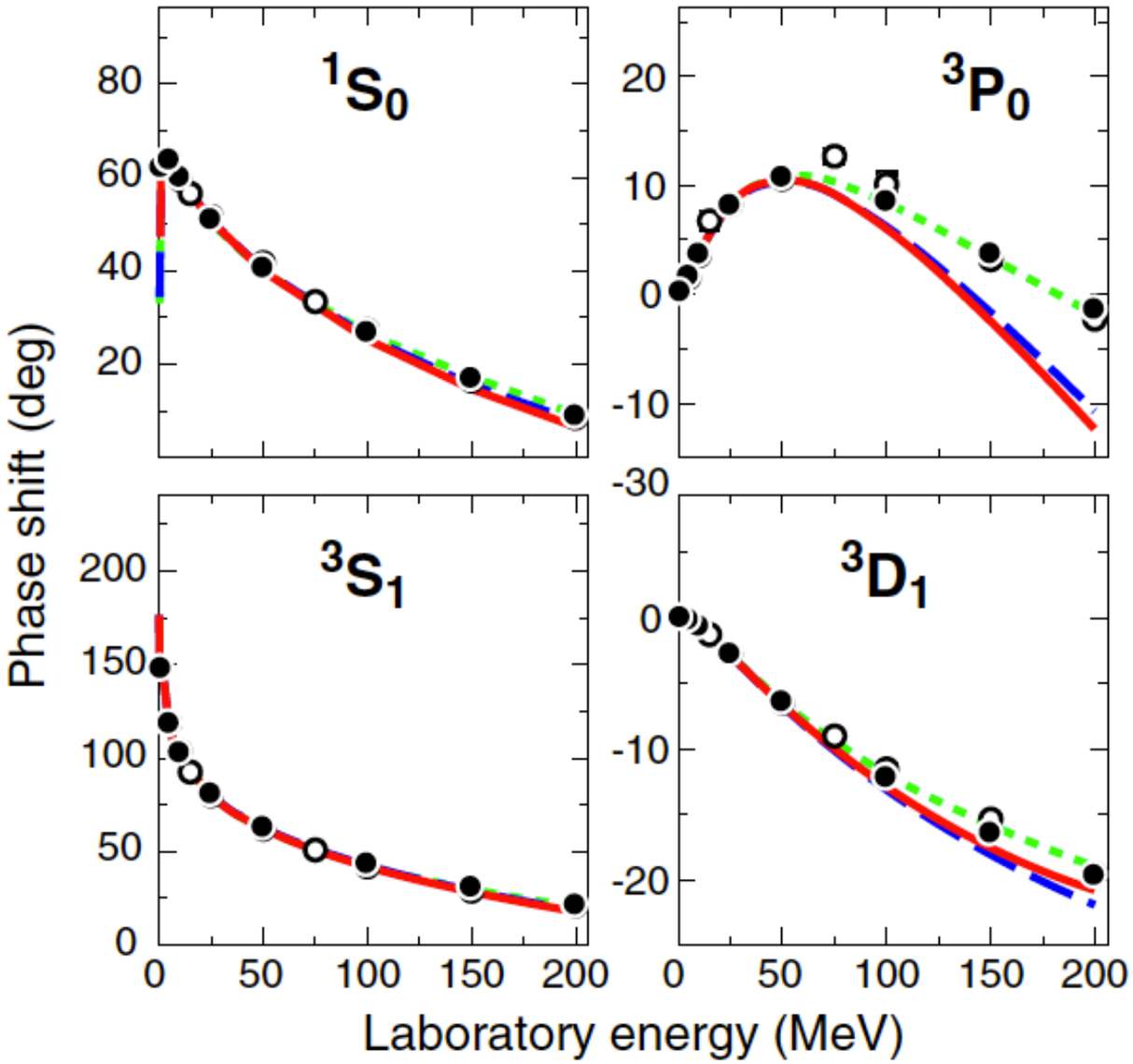
- π and N as dof
- Systematic expansion
- 2N at N³LO - LECs from πN, NN
- 3N at N²LO - 2 more LECs
- (Often further renormalized)



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)

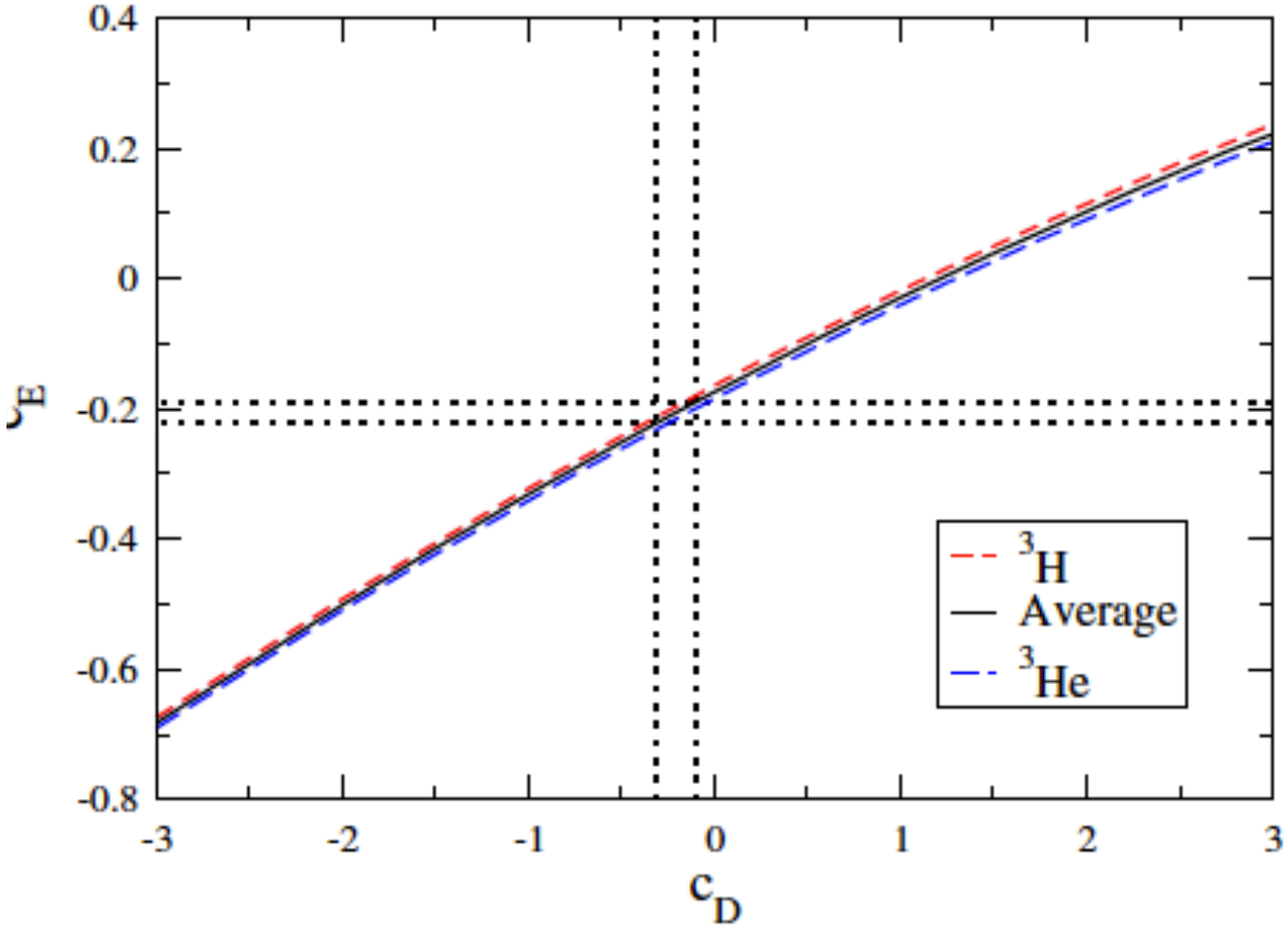
LECs fitting

2NF constants: deuteron + phase-shifts



N^{3}LO: Entem & Machleidt, *Phys. Rev. C* **68** 041001(2003)
N^{2}LO: Ekstrom et al., *PRL* **110** 192502 (2013)

3NF constants: A=3 + β decay



Nogga et al., *Phys. Rev. C* **73** 064002 (2006)
Gazit et al., *PRL* **103** 102502 (2009)

- Non-uniqueness now is quantifiable!

Further renormalizations

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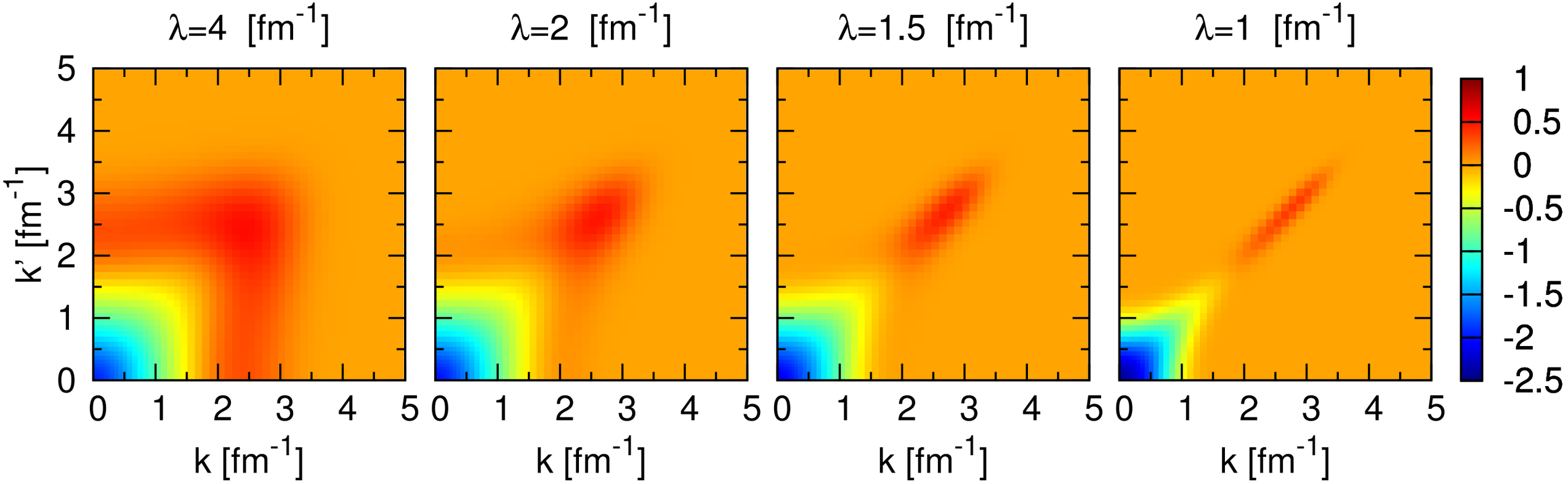
$^1S_0$ NN matrix elements from N3LO

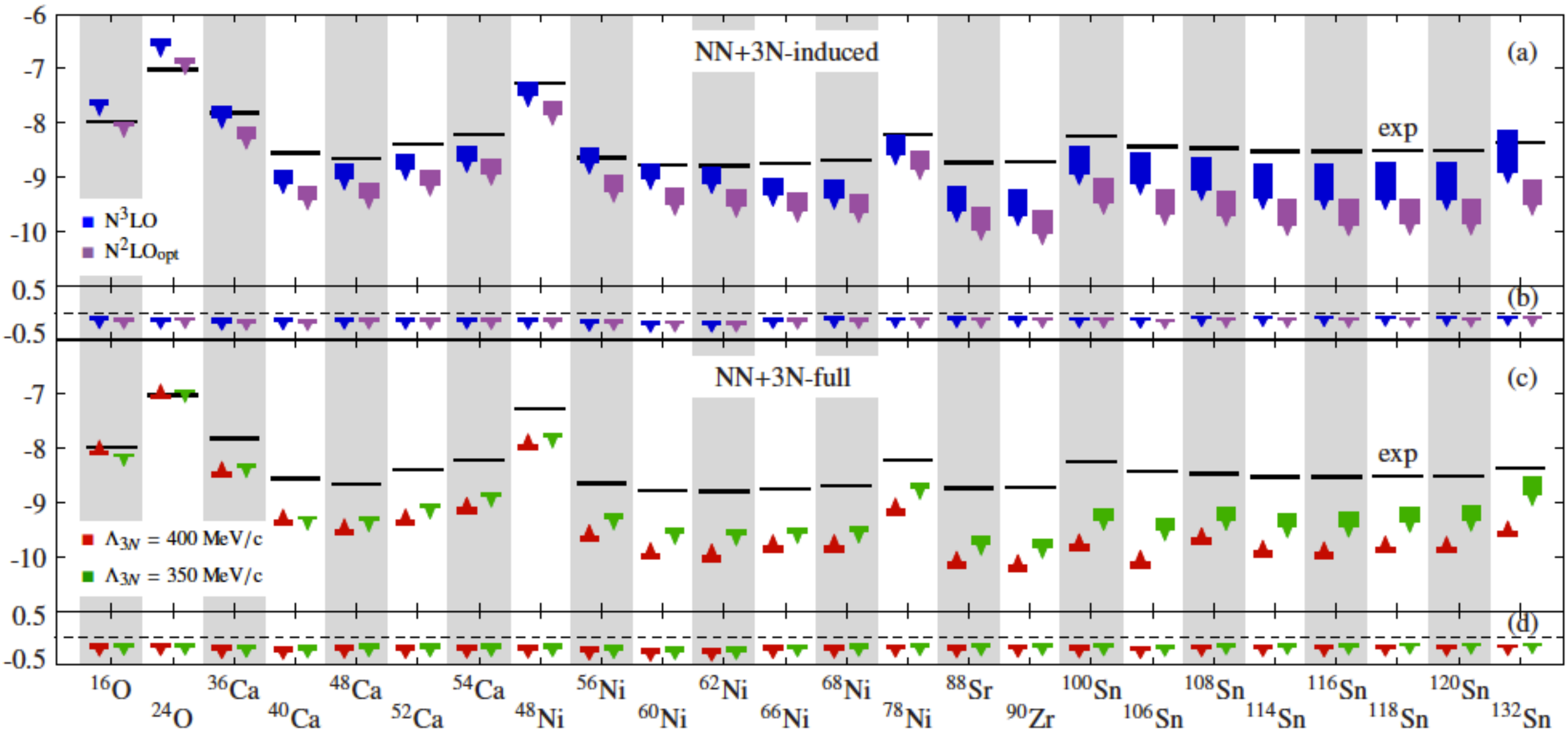


$$\frac{dH_s}{ds} = [[T_{rel}, H_s], H_s] \Leftrightarrow \lambda = s^{-1/4}$$

- 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)

The reach of ab initio: 2014



Binder, Langhammer, Calci & Roth, *arxiv:1312.5685*

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

Hypernuclei!

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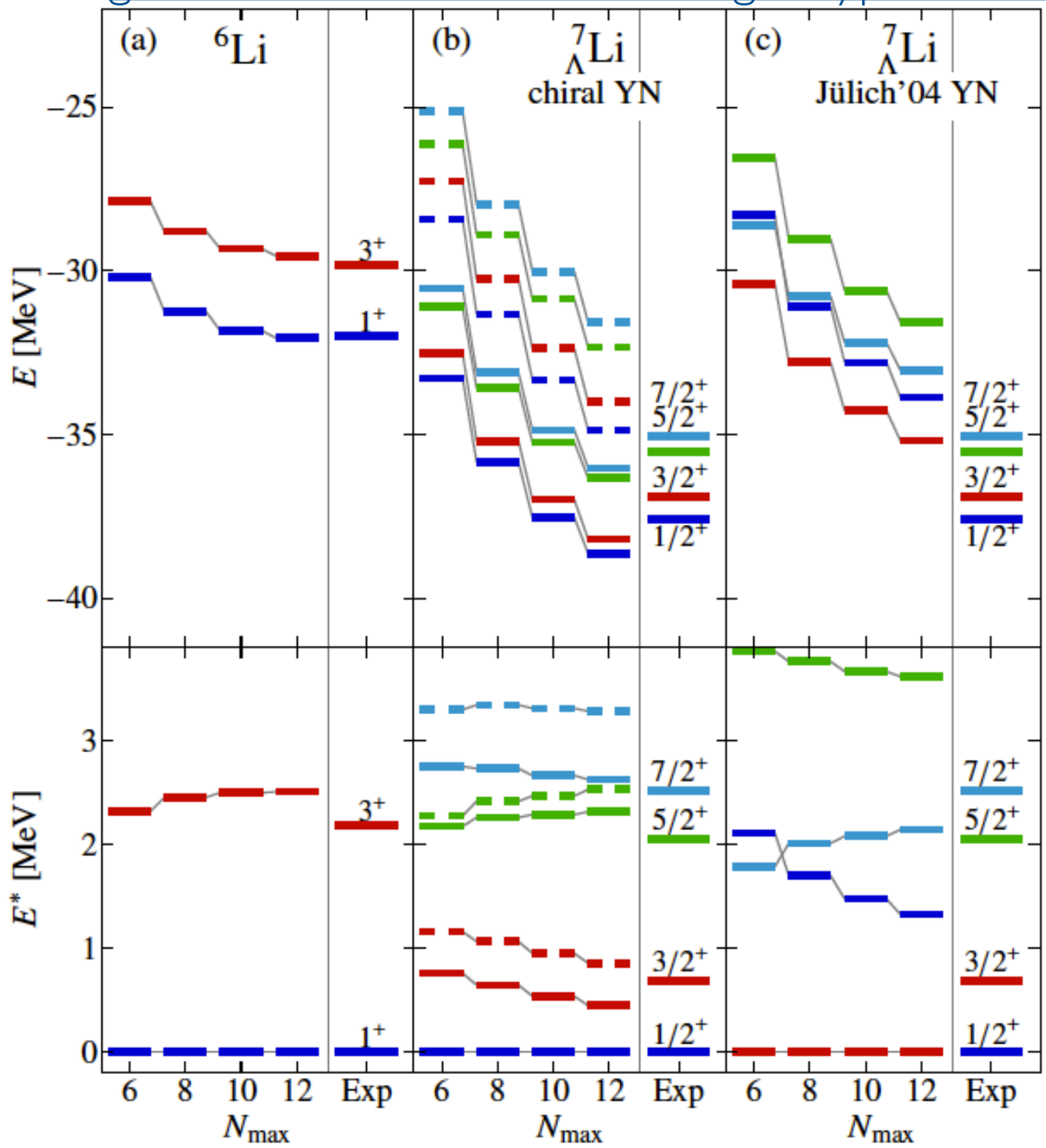
ground and excited states of light hypernuclei



- IT-NCSM with chiral NN & different YN forces
- Hypernuclear structure hints at nonperturbative YNN

Wirth, Garda, Navratil, Roth, et al. *arxiv:1403.3067*

SCGF: diagrammatic expansion

N-body Green's function

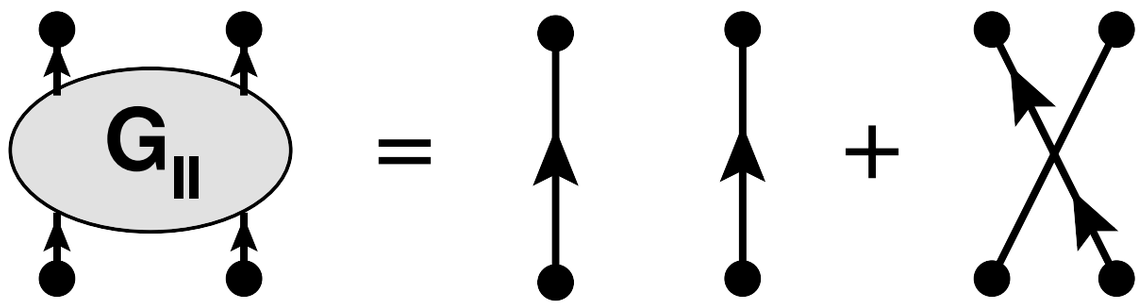
$$i^N G(\mathbf{1},\ldots,\mathbf{N};\mathbf{1}',\ldots,\mathbf{N}') = \left\langle \mathcal{T}\left\{a(\mathbf{1})\cdots a(\mathbf{N})a^\dagger(\mathbf{N}')\cdots a^\dagger(\mathbf{1}')\right\}\right\rangle$$

$\langle\cdot\rangle \rightarrow$ average over states

$\mathcal{T} \rightarrow$ some sort of time ordering (real, imaginary, on a contour...)

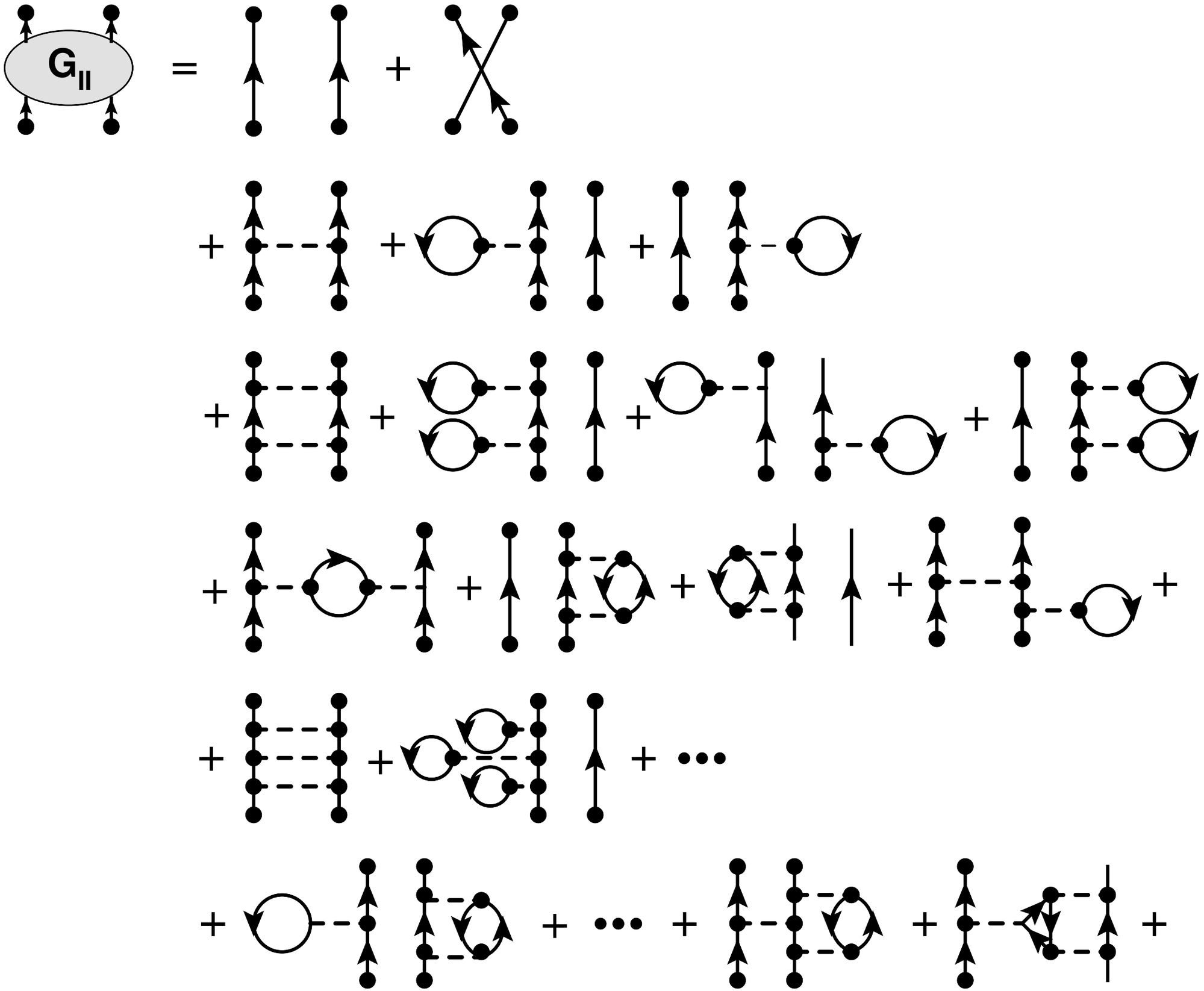
$\mathbf{1} \rightarrow \mathbf{r}_1, t_1, \sigma_1, \tau_1$

Two-body GF, lowest order diagrams

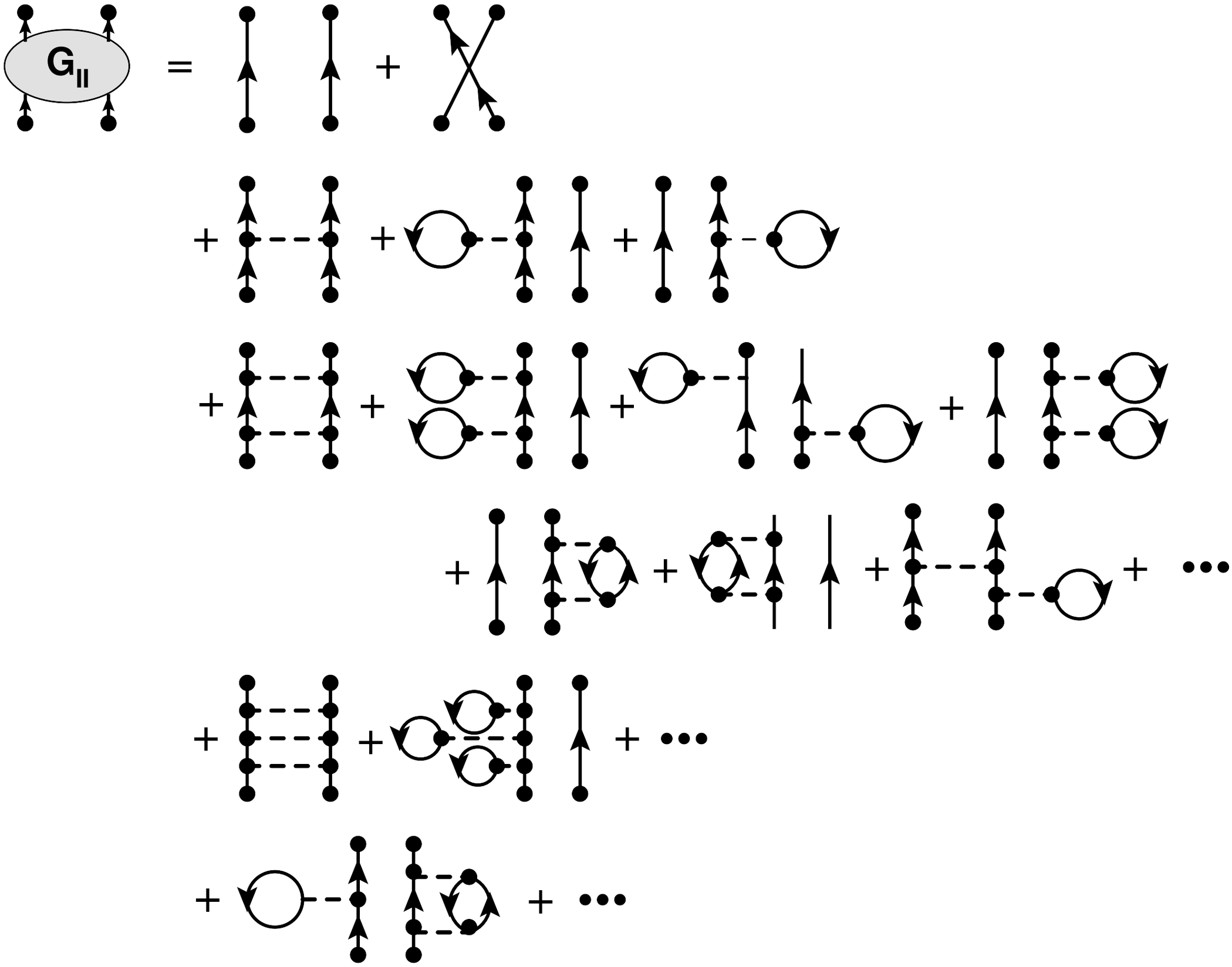


$$G_{II}(1,2;1',2') = G(1,1')G(2,2') - G(1,2')G(1',2)$$

SCGF: diagrammatic expansion



SCGF: diagrammatic expansion



Ladder approximation with 3BF

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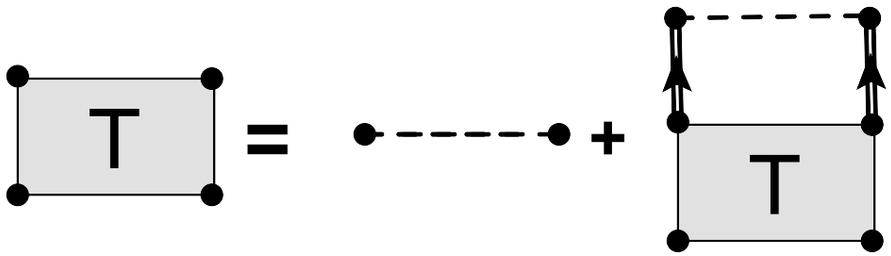
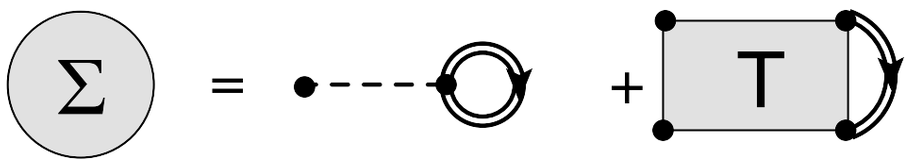
Two-body interaction

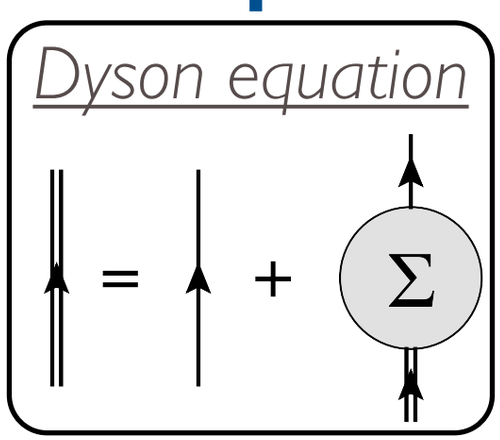
In-medium T-matrix



Self-energy

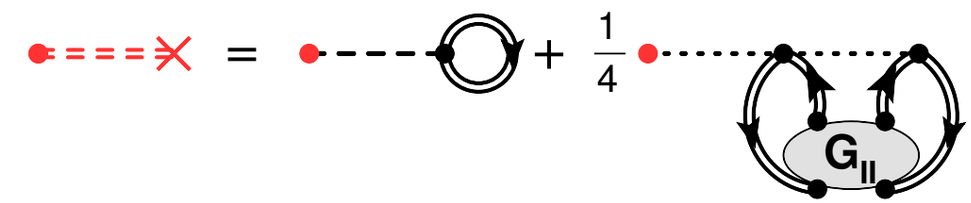


Dyson equation



Effective interactions

Effective one-body force



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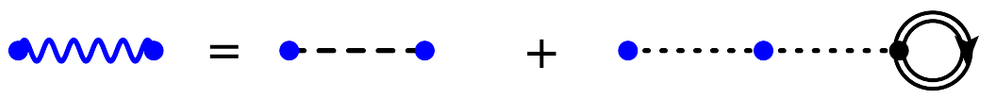
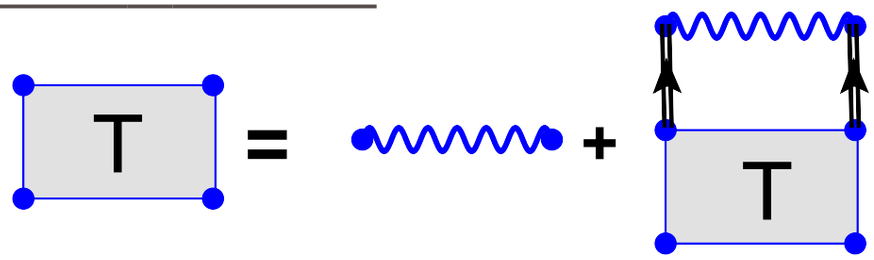


In-medium T-matrix



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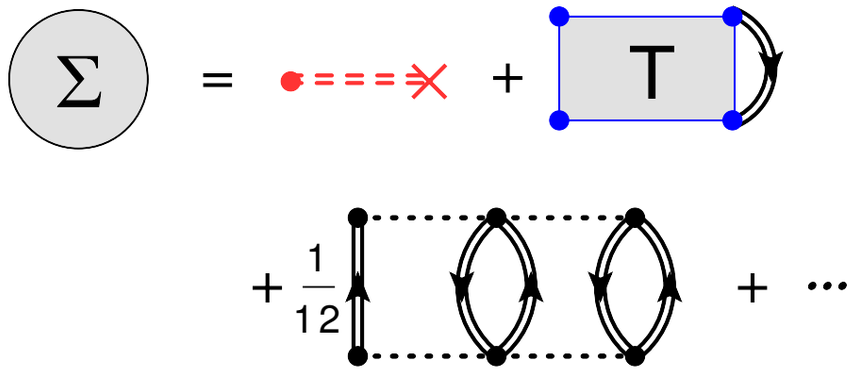

Carbone *et al.*, *Phys. Rev. C* **88** 054326 (2013)

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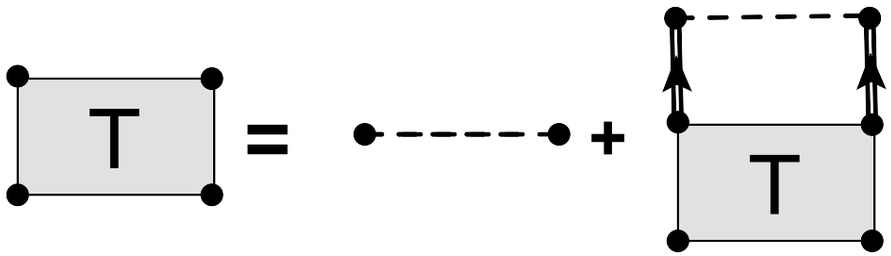

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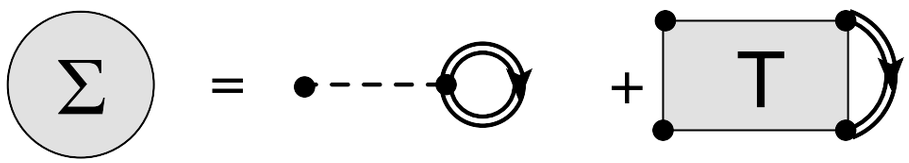

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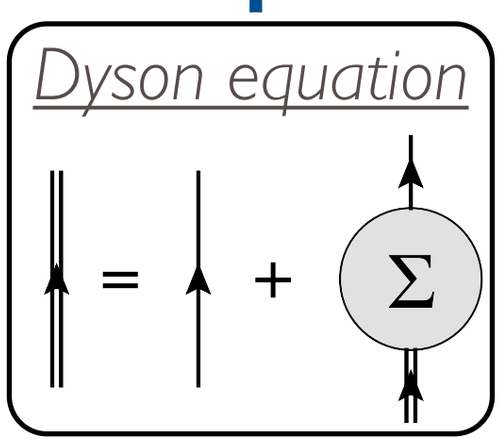

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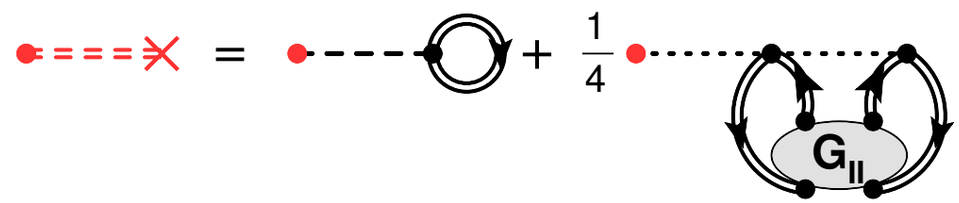

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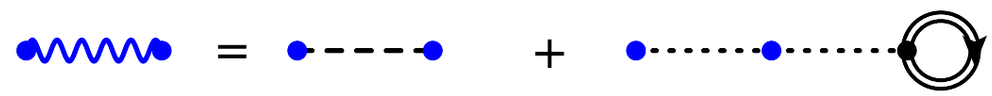

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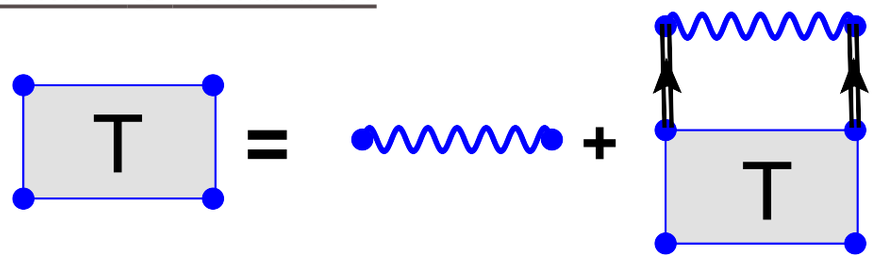

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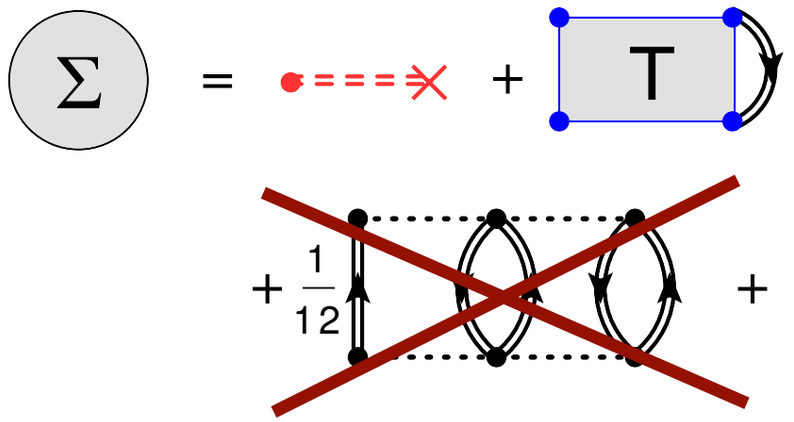

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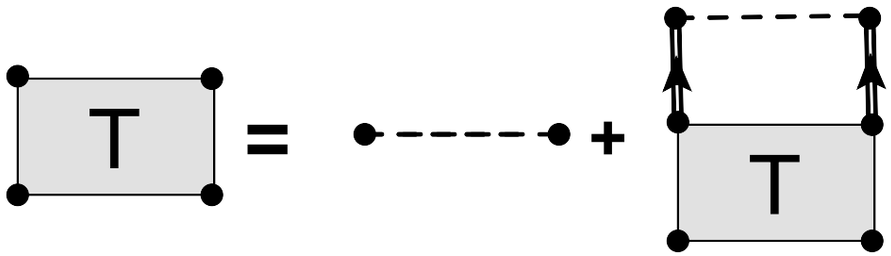

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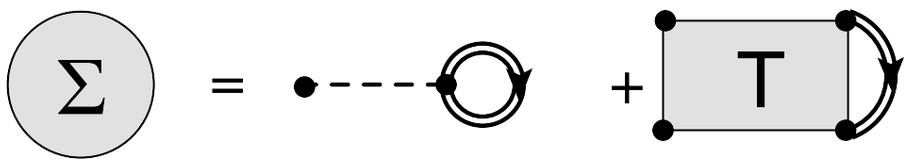

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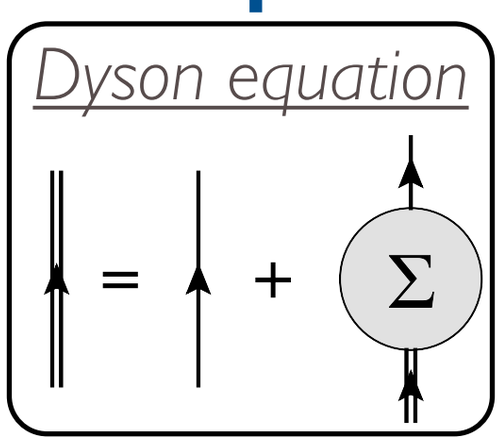

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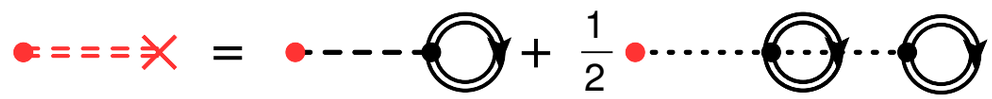

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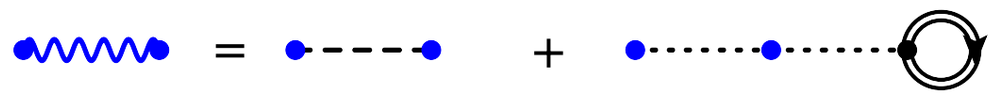

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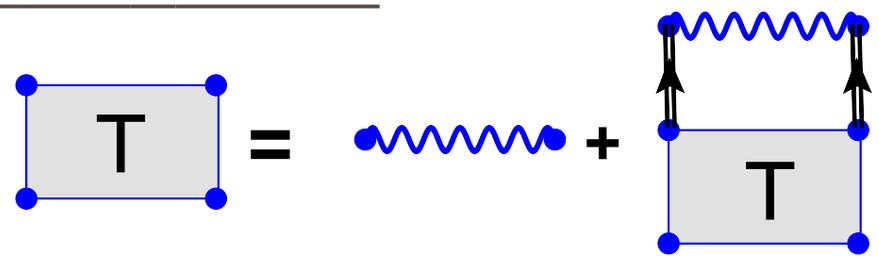

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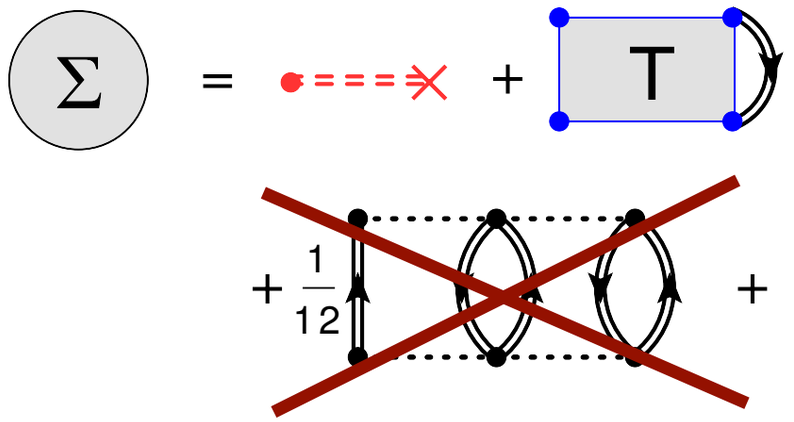

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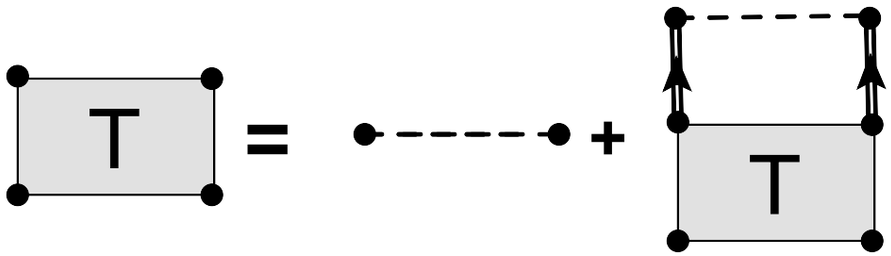

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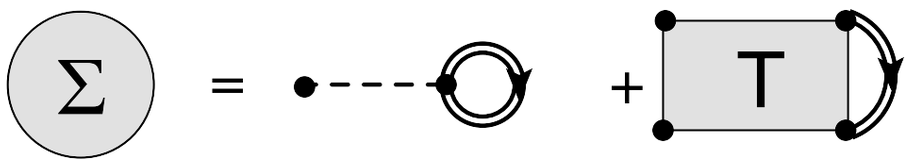

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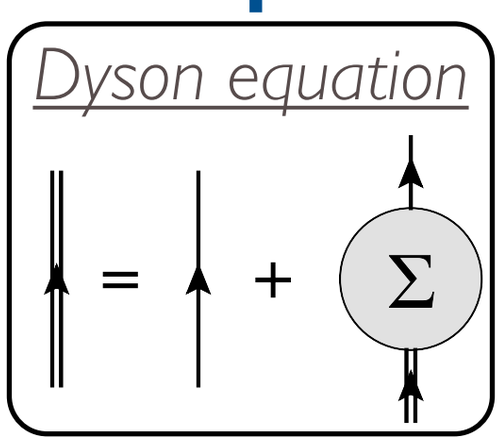

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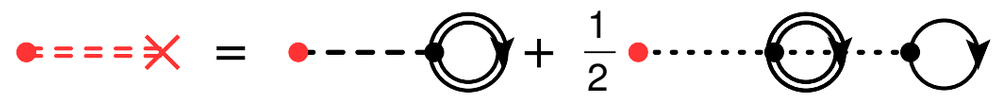

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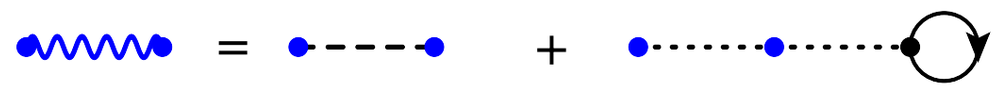

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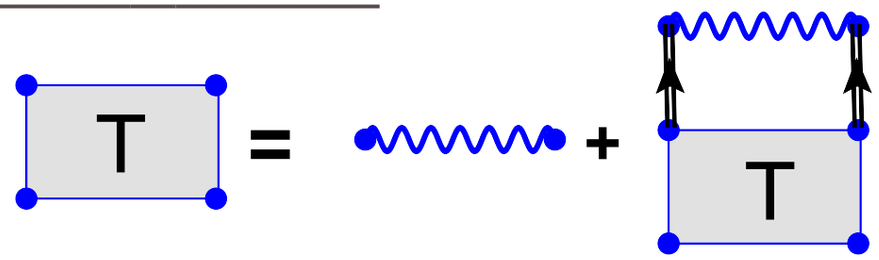

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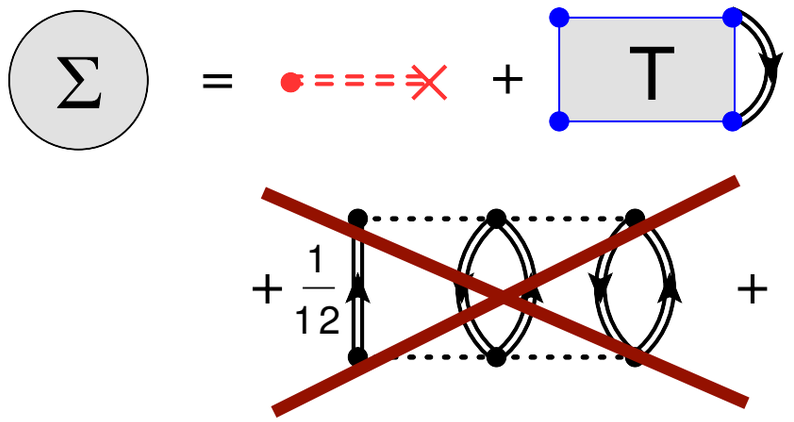

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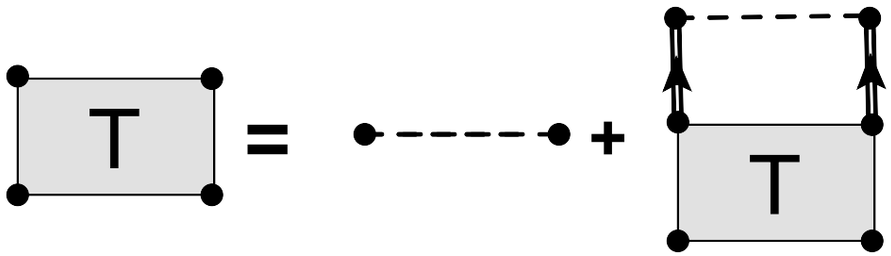
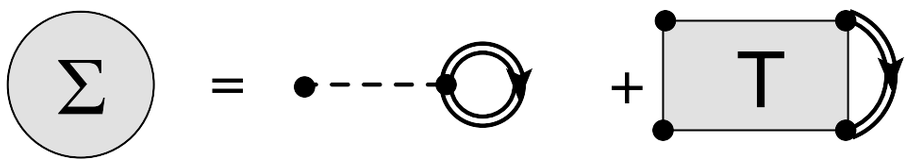
Ladder approximation with 3BF

Two-body interaction

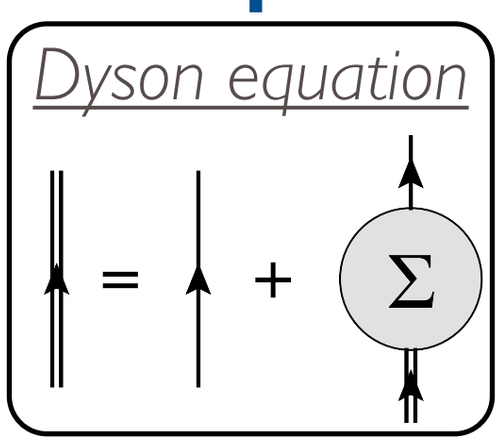
In-medium T-matrix



Self-energy

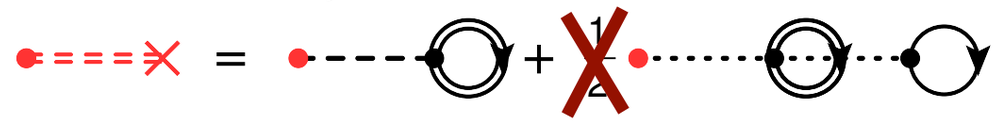


Dyson equation

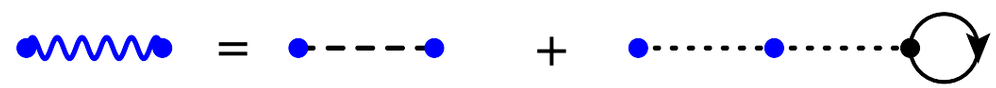


Effective interactions

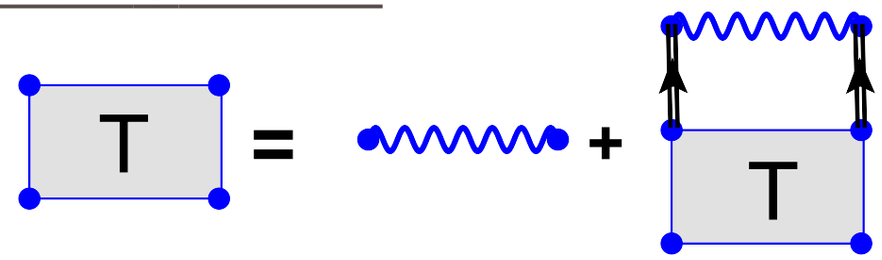
Effective one-body force



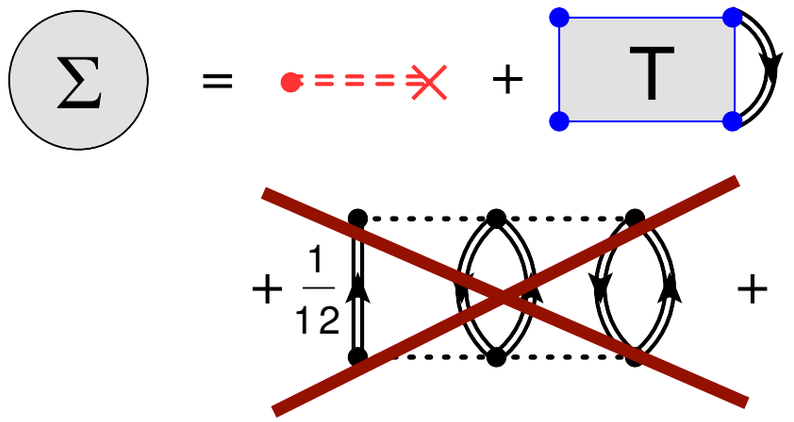
Effective two-body force



In-medium T-matrix



Self-energy



Carbone *et al.*, *Phys. Rev. C* **88** 054326 (2013)

Density-dependent interaction

Two-body N3LO

Uncorrelated average [1]

Correlated average [2]

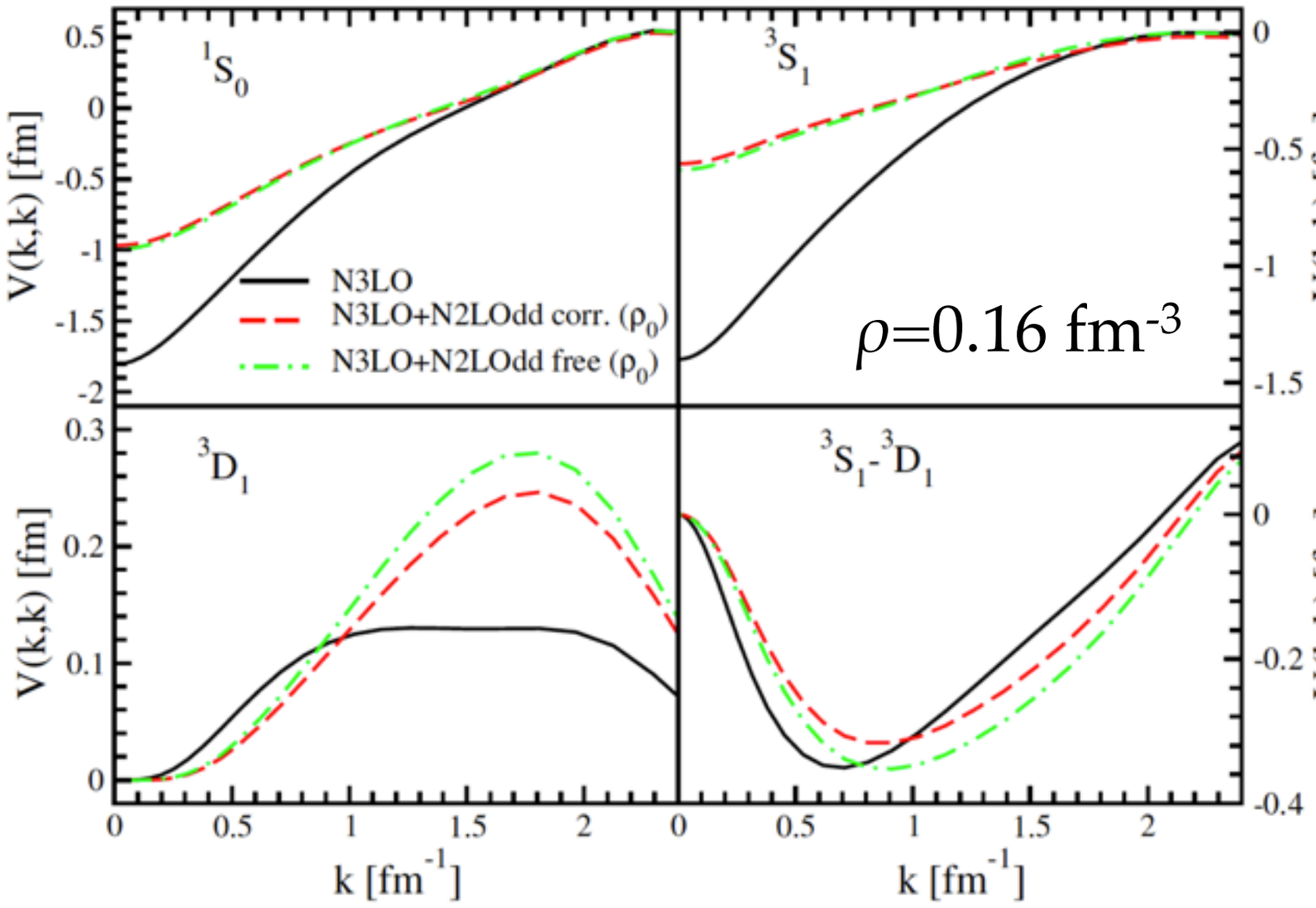
LECs

c_D=-1.11

c_E=-0.66

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

Chiral NN effective 2B forces: symmetric matter



- 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, *in preparation;* A. Carbone, PhD thesis

Symmetric matter

Theoretical uncertainties: average procedure

Two-body N3LO

Uncorrelated average

Correlated average

LECs

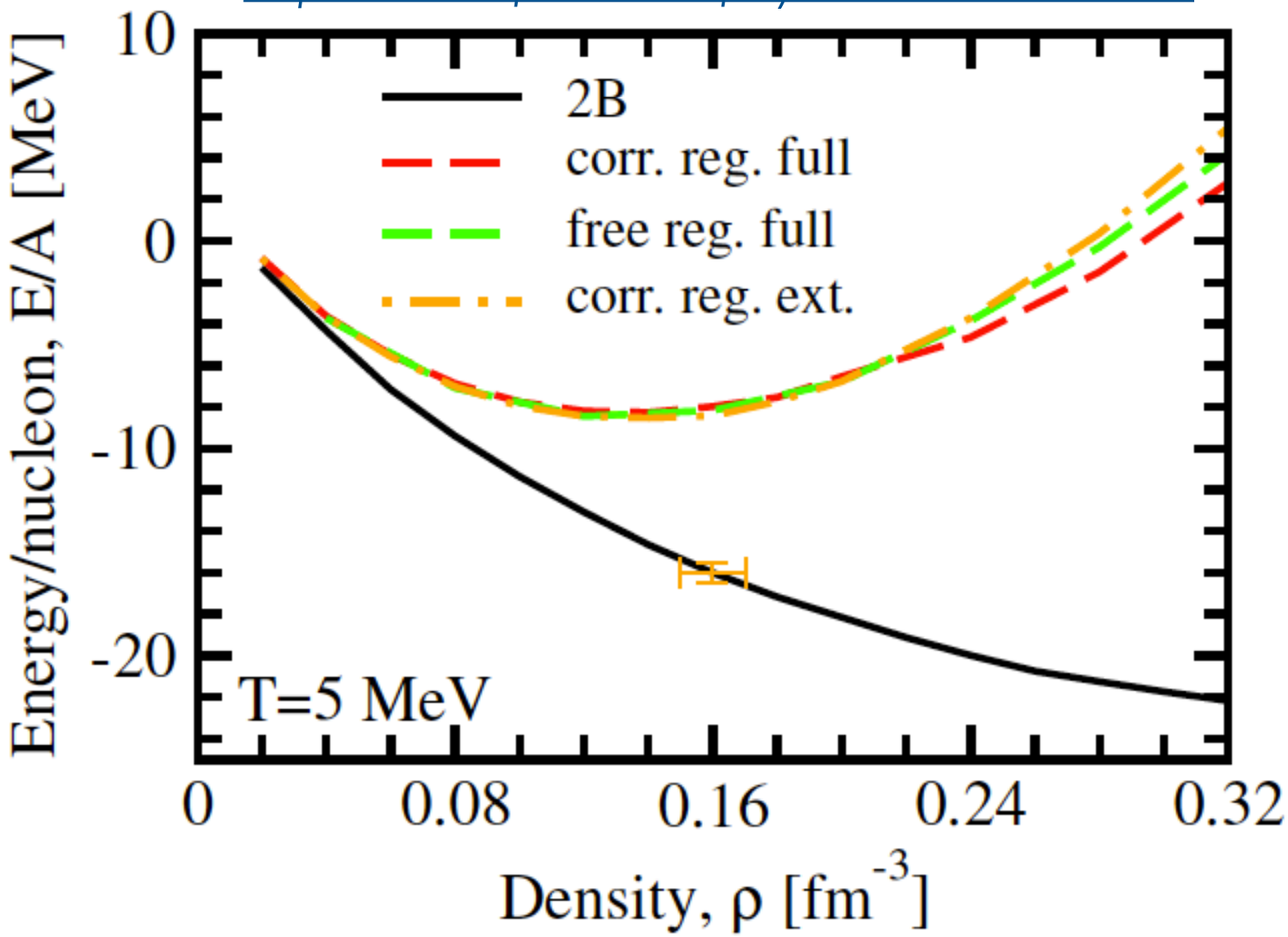
c_D=-1.11

c_E=-0.66

Energy from GMK sum-rule

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

Equation of state of symmetric matter



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

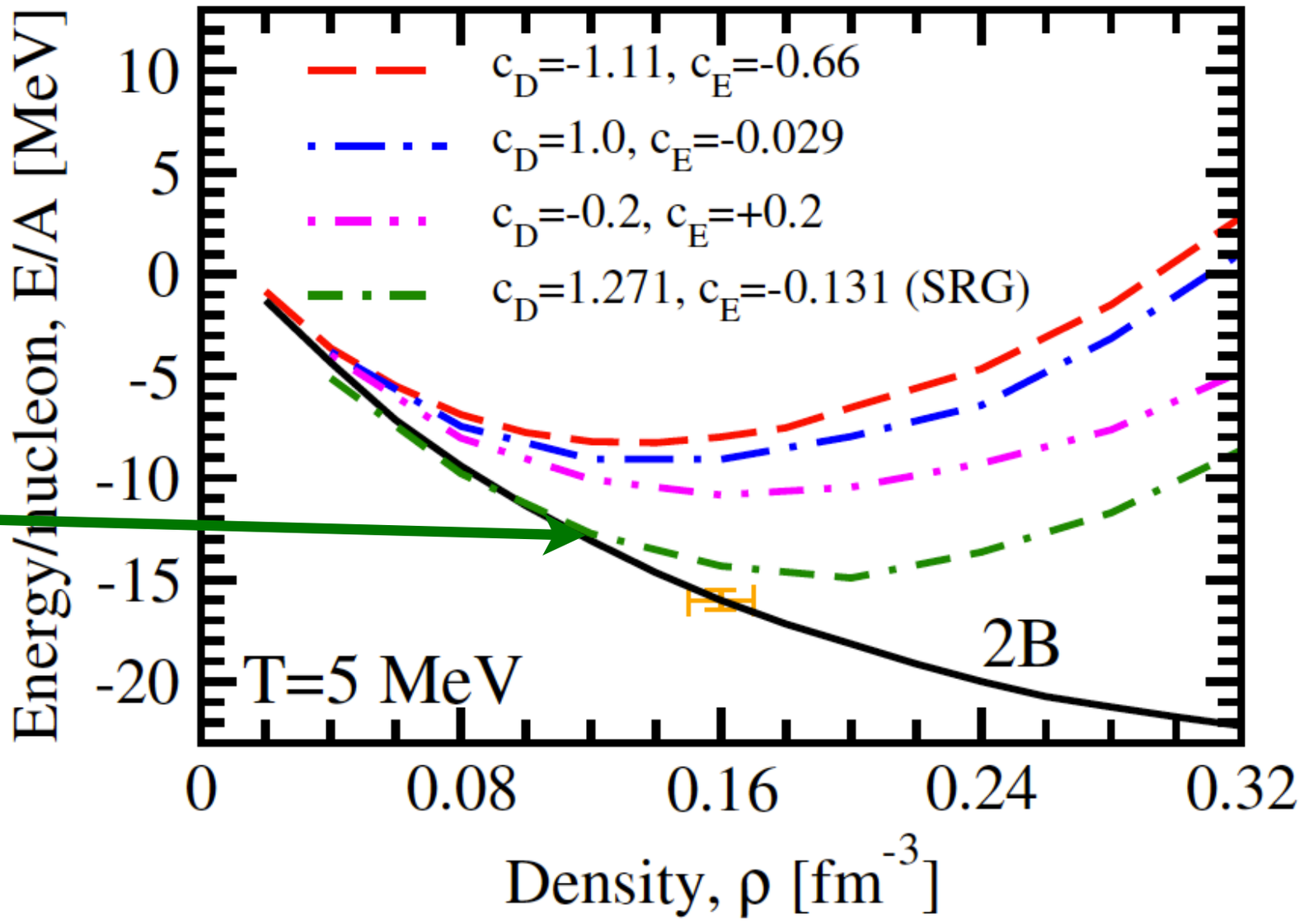
[1] Carbone, Polls & Rios, *Phys, Rev. C* **88** 044302 (2014)
Carbone, Polls & Rios, *in preparation;* A. Carbone, PhD thesis

Symmetric matter

Theoretical uncertainties: NN force

Uncorrelated average

Equation of state: LEC dependence



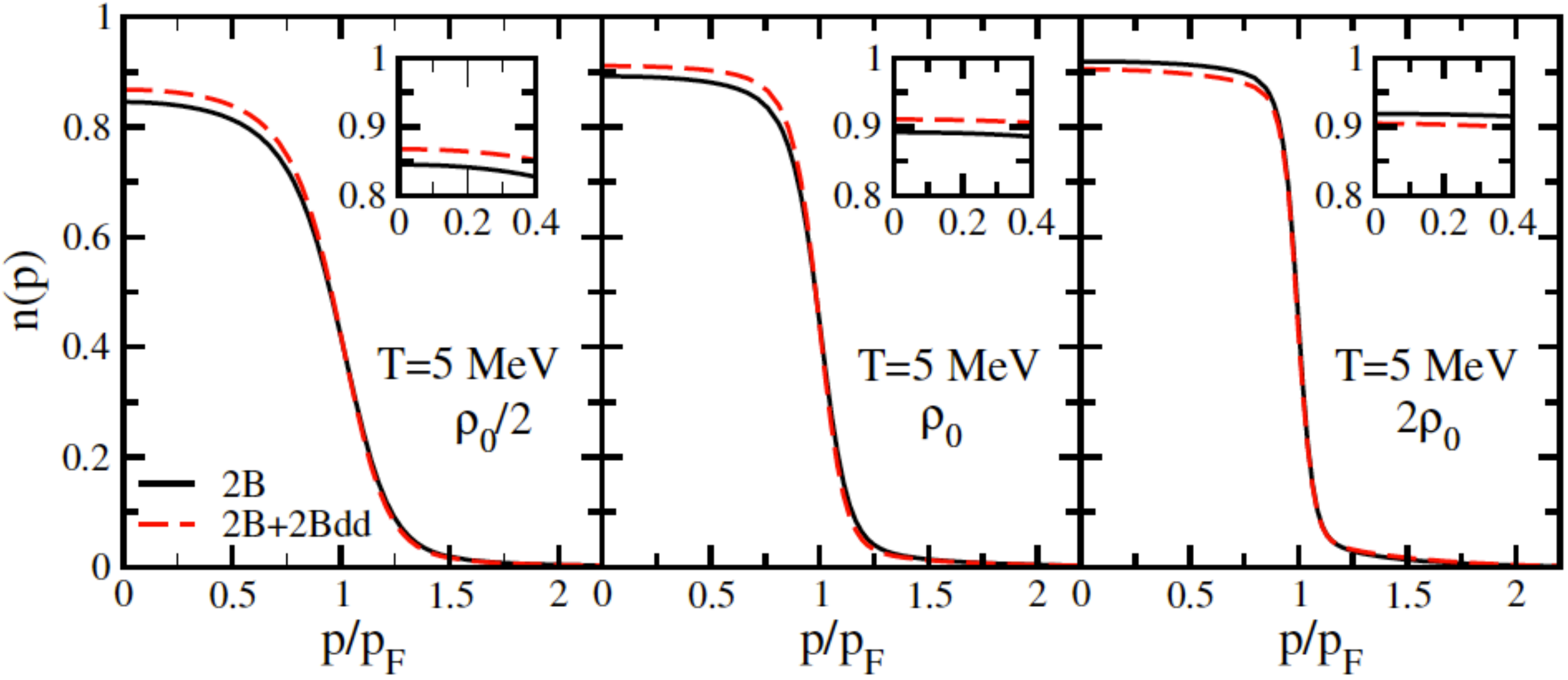
Further renormalized NN force
Nuclear structure calculations

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

Carbone, Polls & Rios, *Phys, Rev. C* **88** 044302 (2014)

Microscopic properties

Correlated momentum distribution

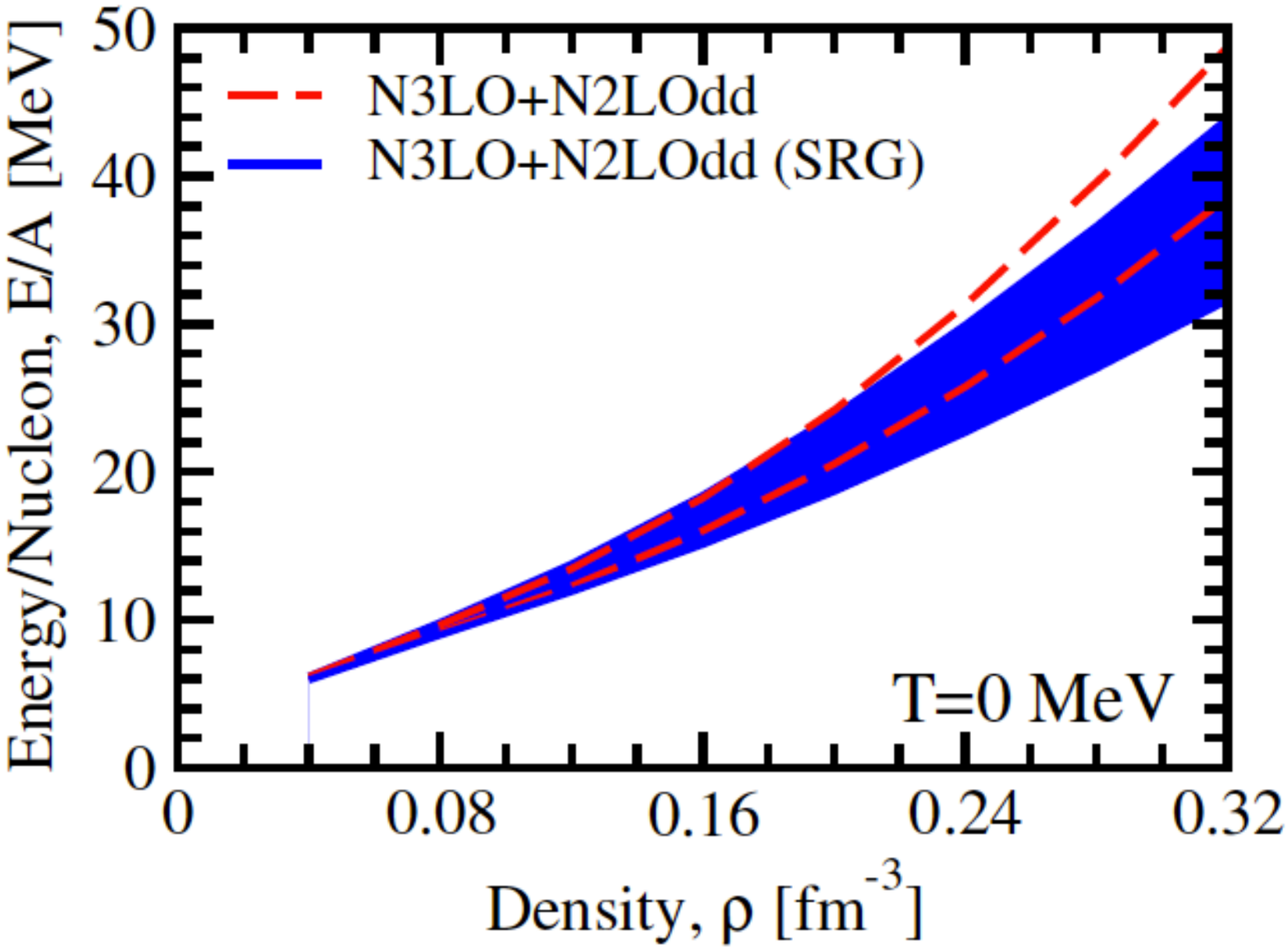


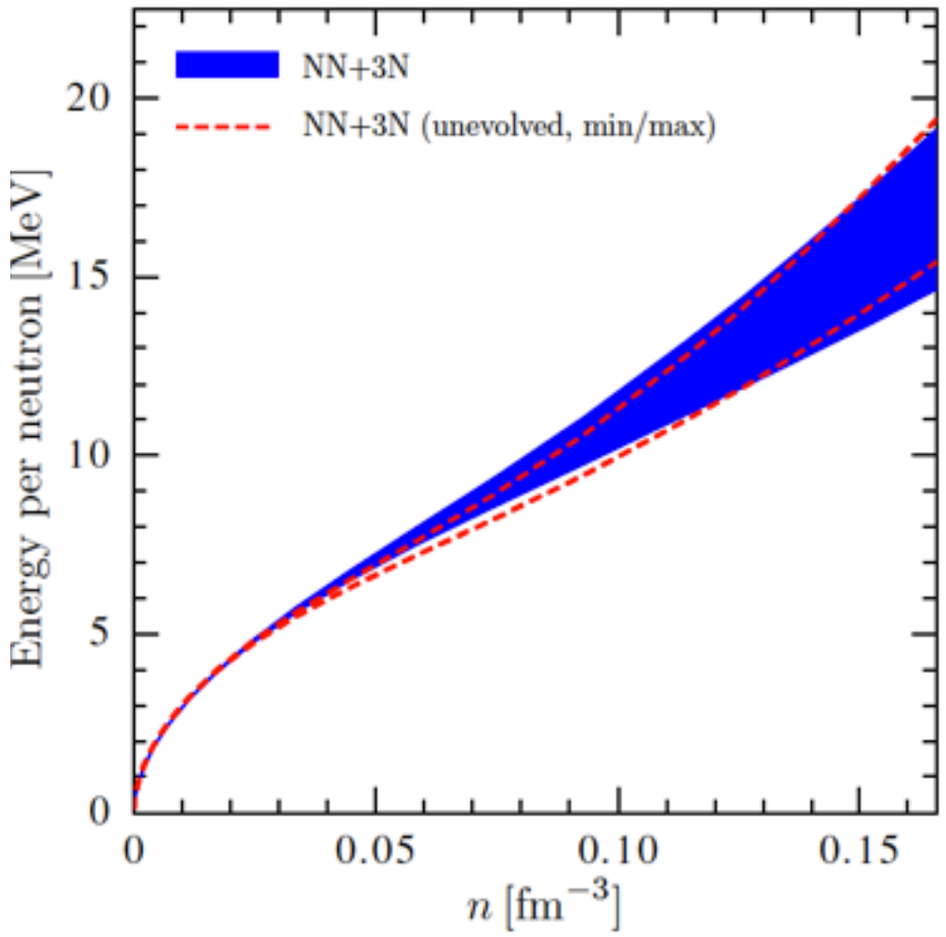
- 3NFs induce different density dependence
- Error band from unknown ChPT parameters
- Finite temperature & higher densities available

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

Neutron matter

EoS for neutron matter: SRG





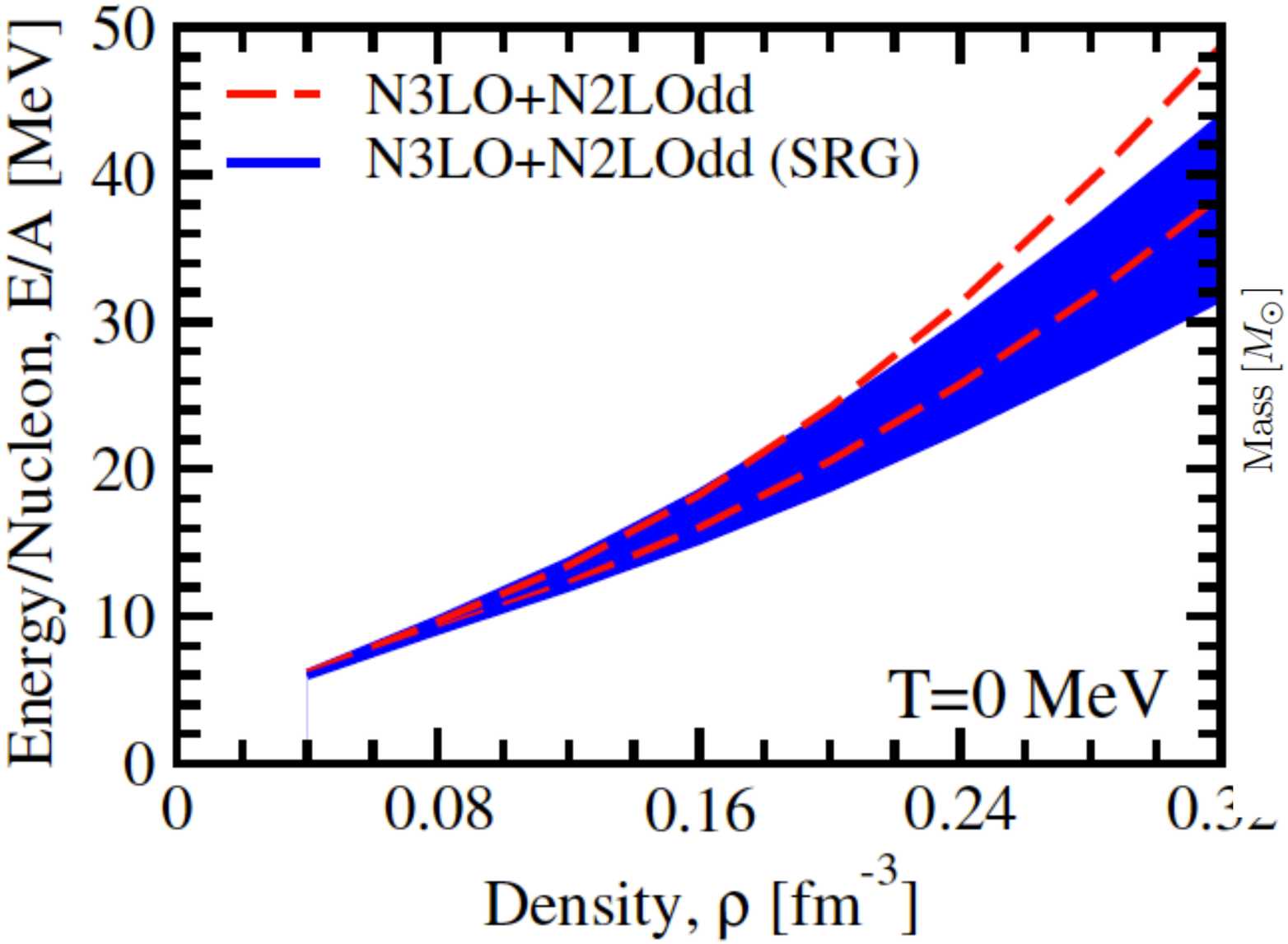
Hebeler, Lattimer, Pethick, Schwenk
ApJ **773** 11 (2013)

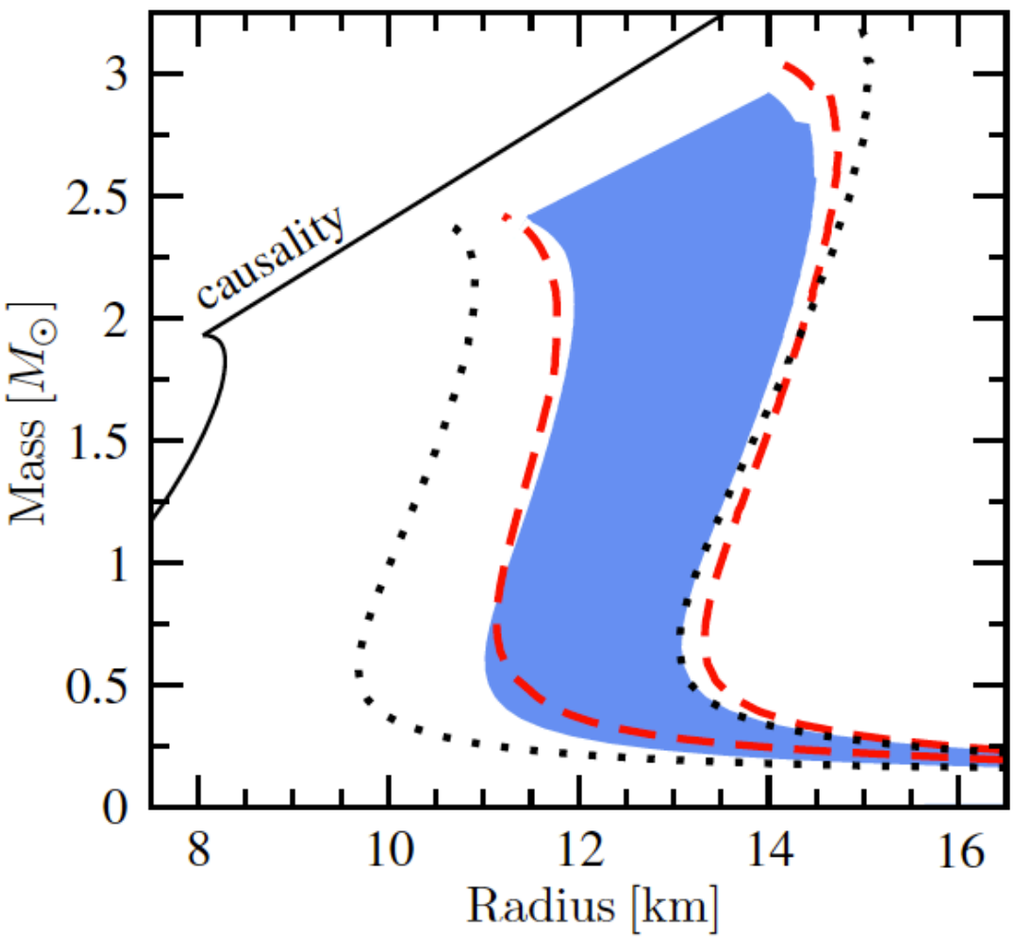
- Error band from unknown ChPT c_1, c_3 parameters
- Finite temperature & higher densities available

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

Neutron matter

EoS for neutron matter: SRG





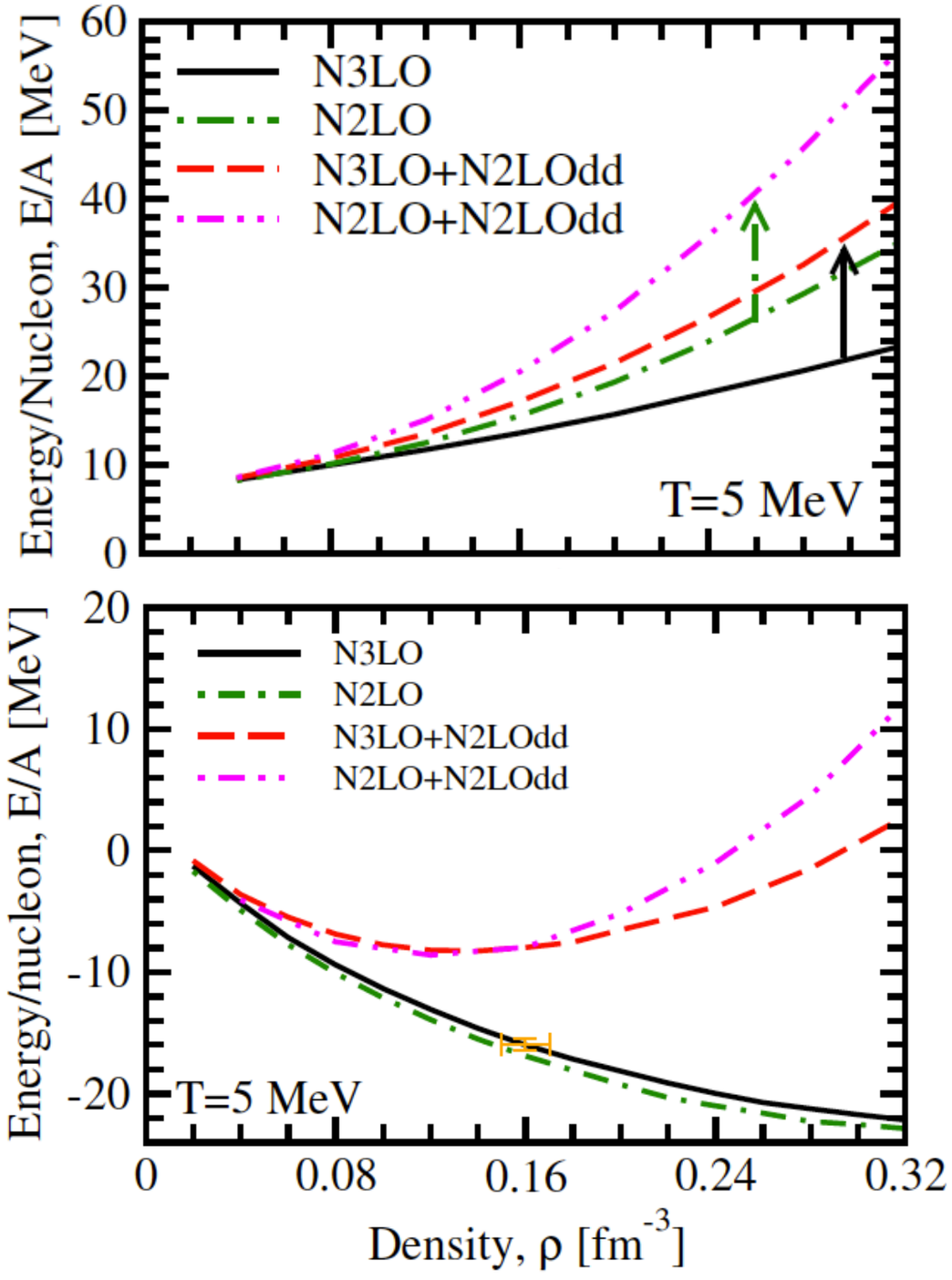
Hebeler, Lattimer, Pethick, Schwenk
ApJ **773** 11 (2013)

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

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

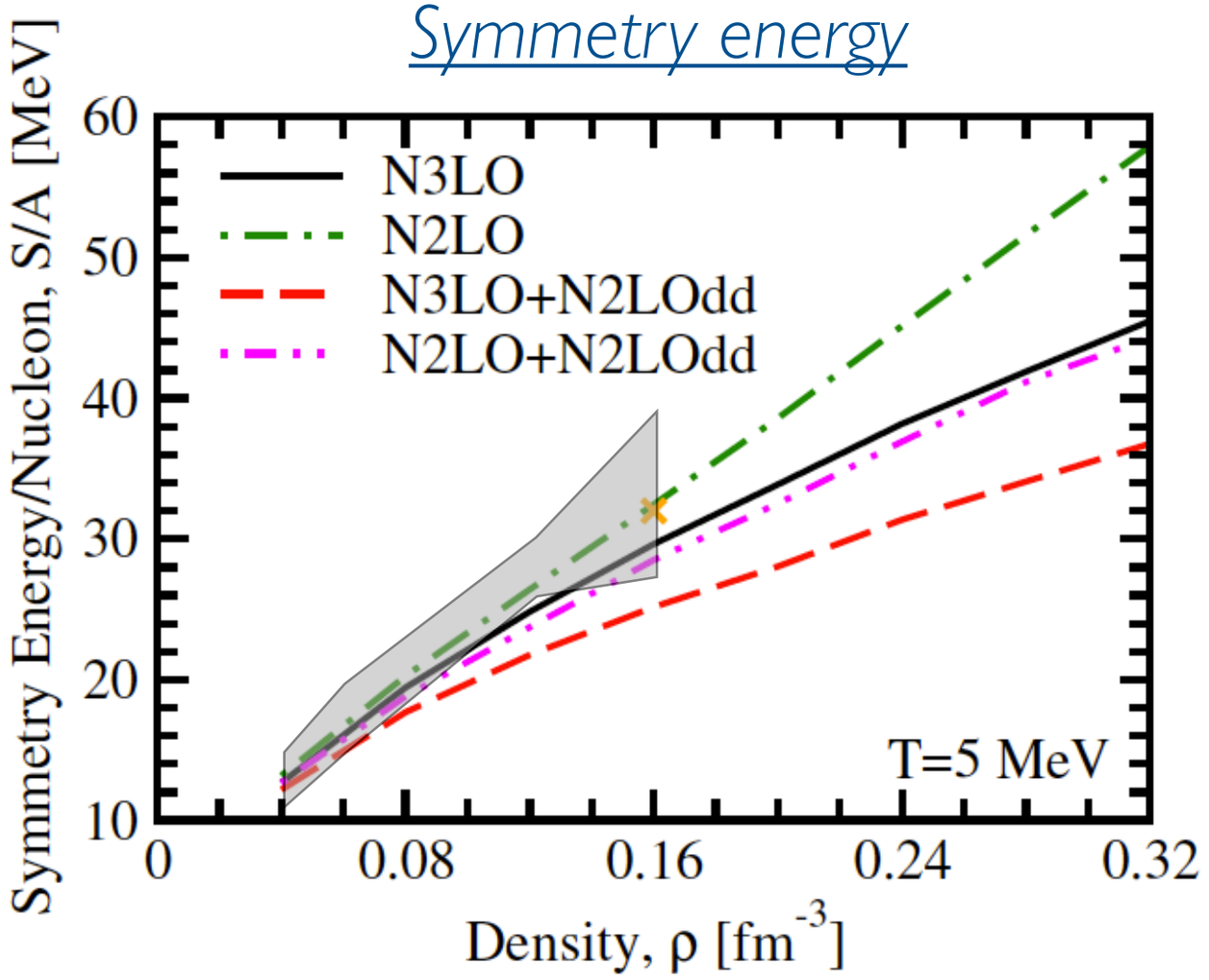
Isovector properties

EoS for SNM & PNM



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

Symmetry energy



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

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

Comparison to phenomenology

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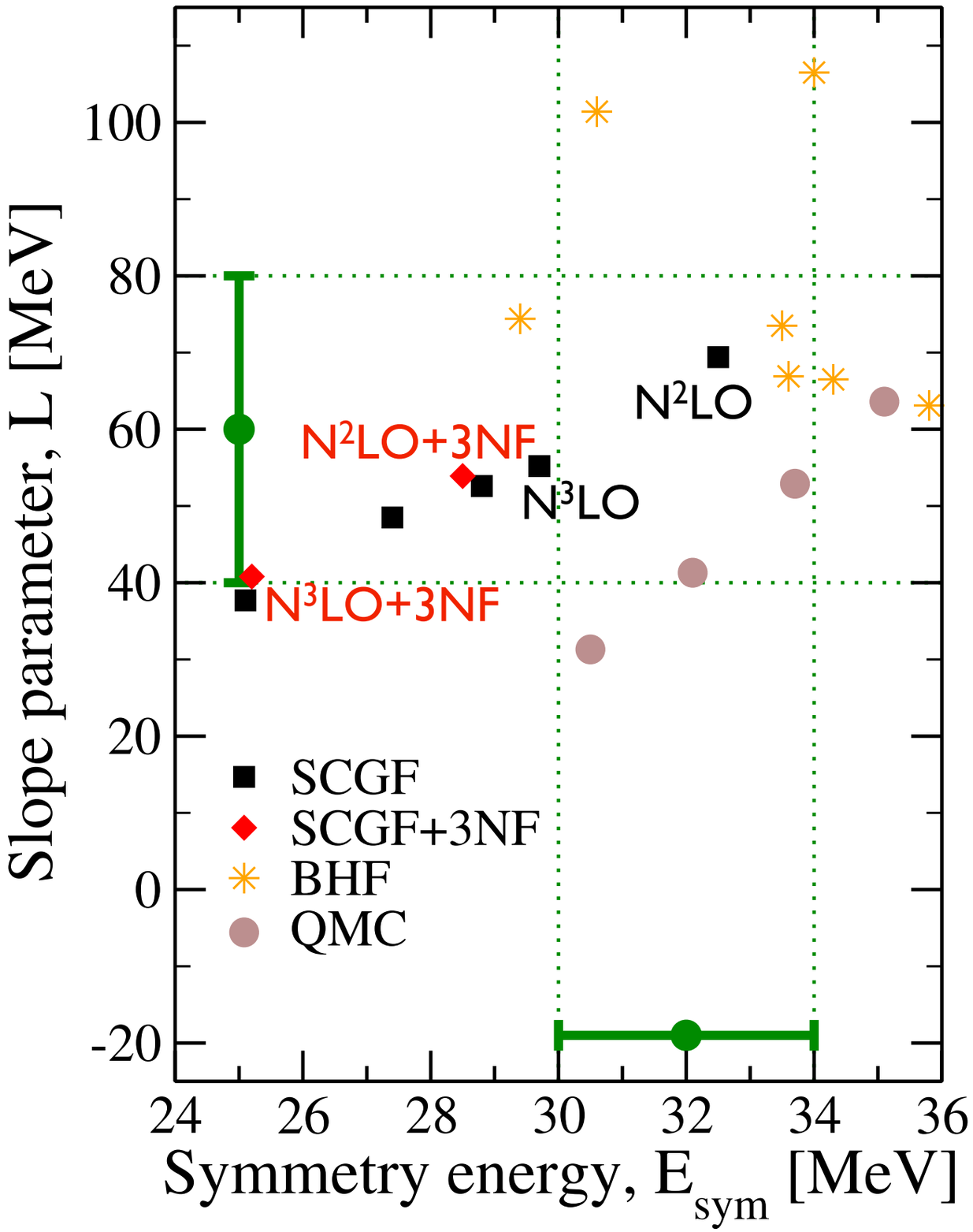
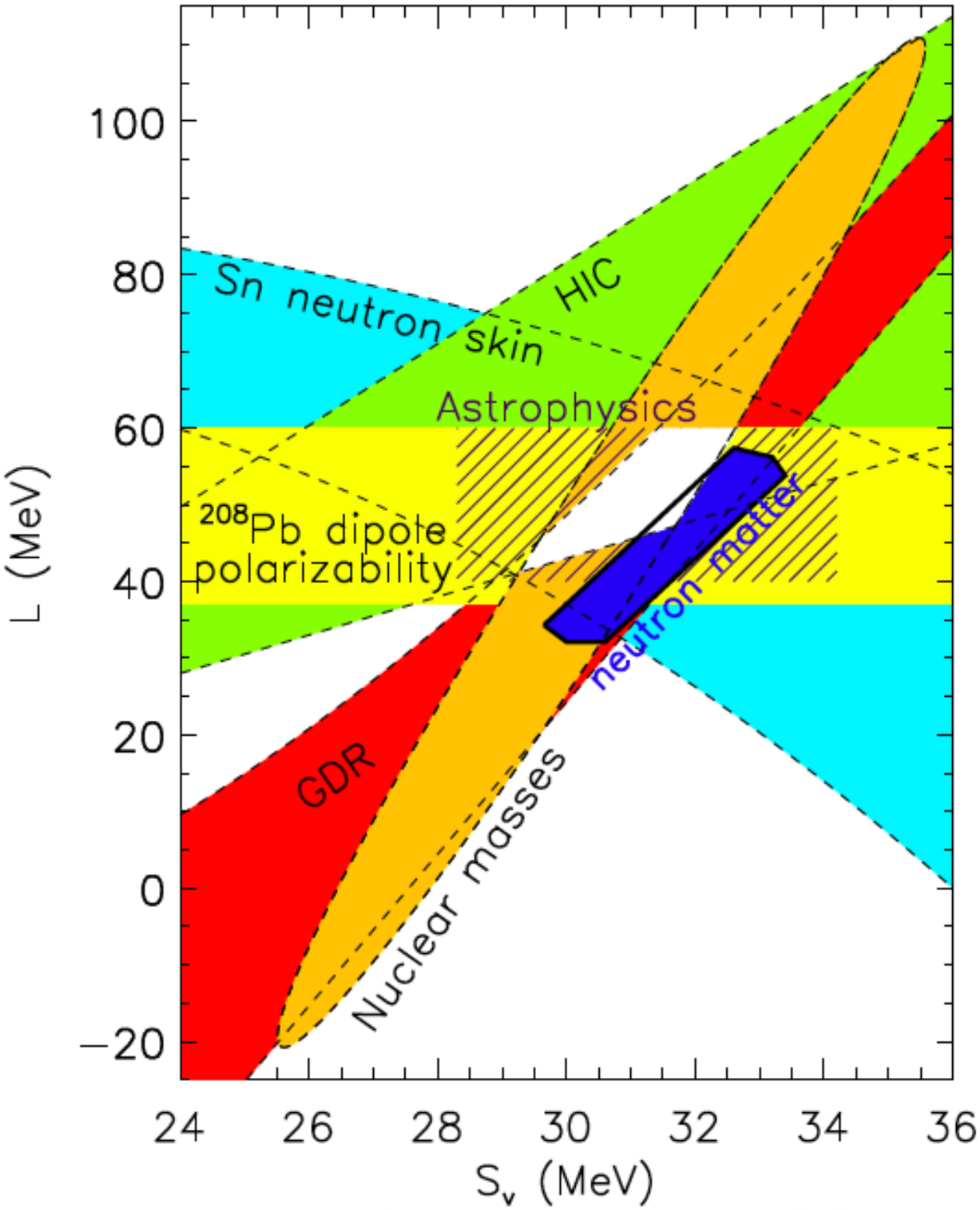
Correlations from nuclear theory



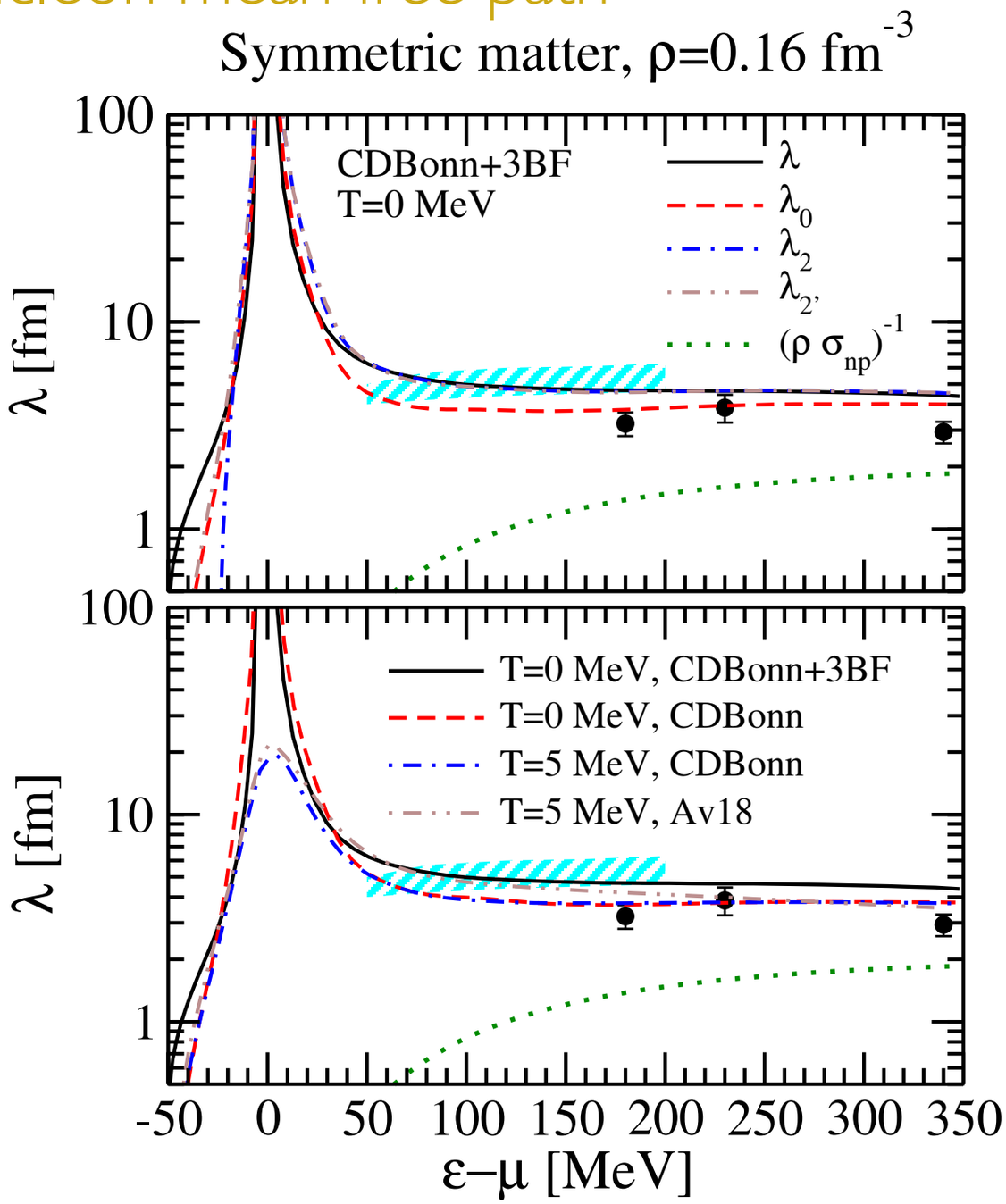
Experimental constrains

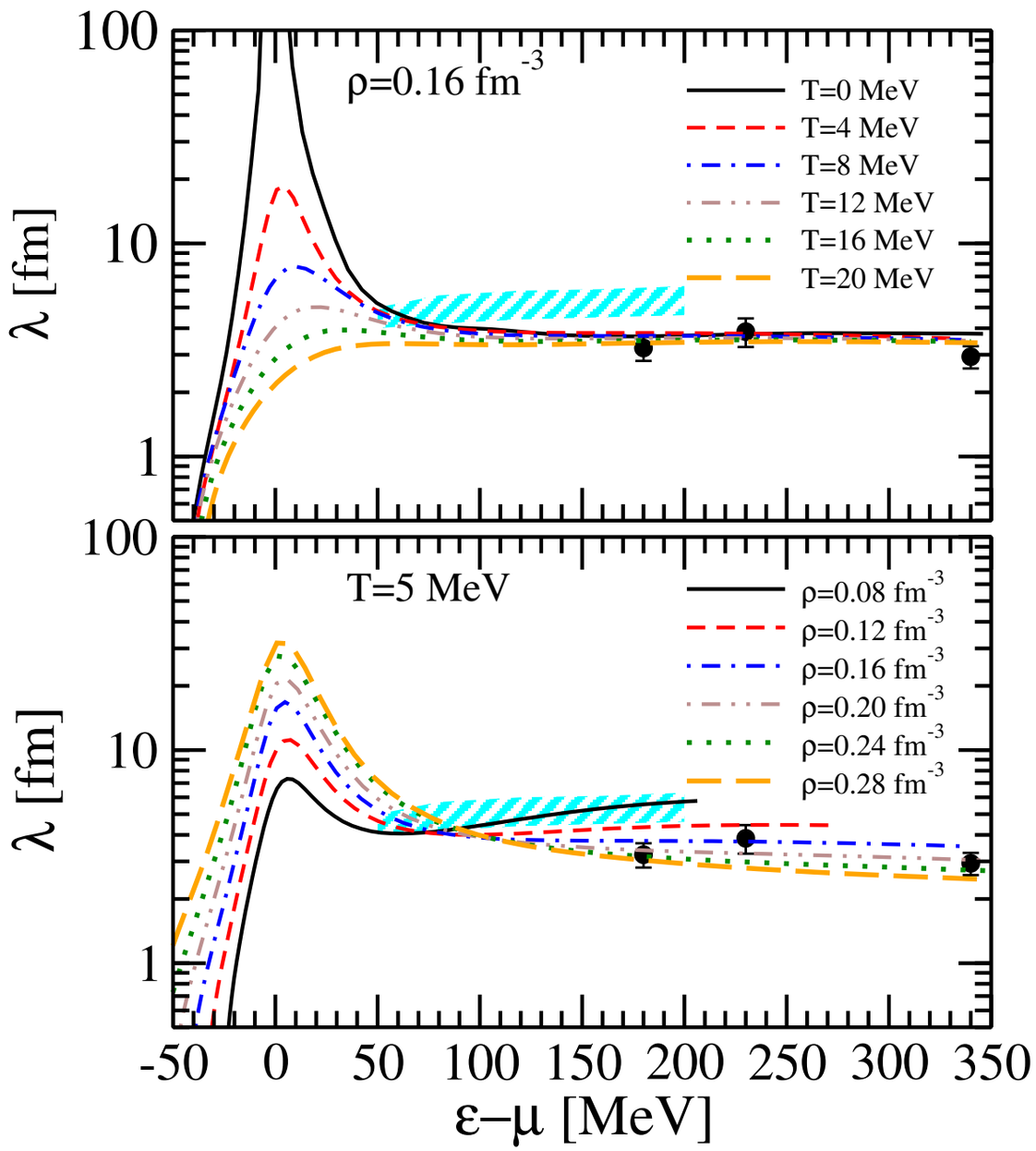


Lattimer & Lim, *ApJ* **771** 51 (2013)

Transport properties

Nucleon mean-free path



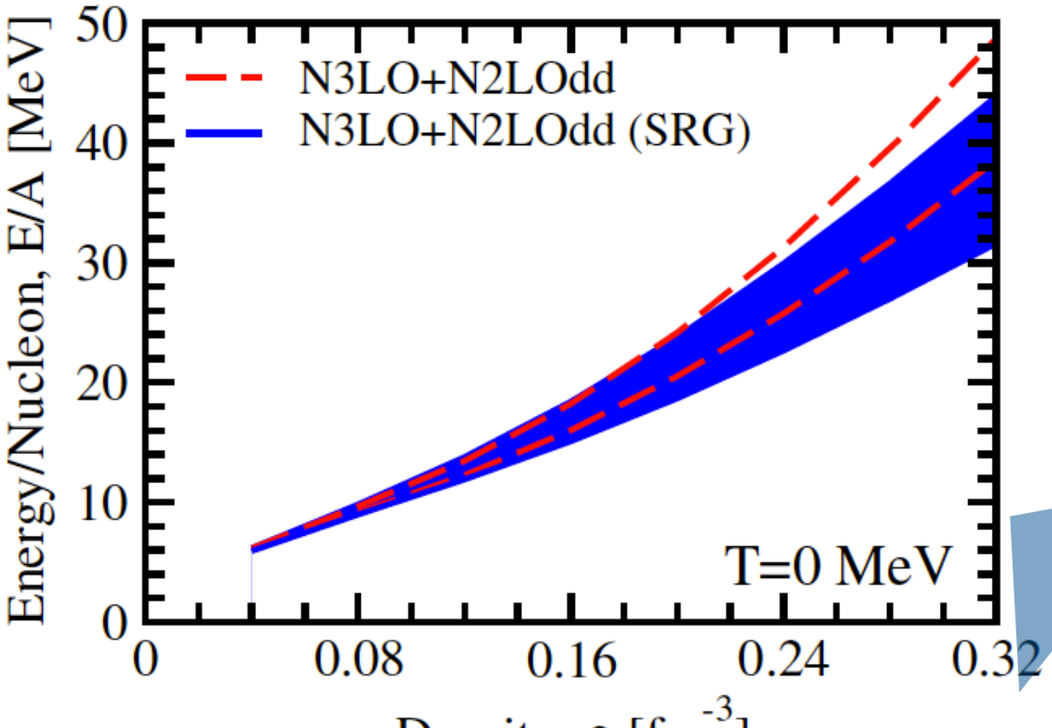


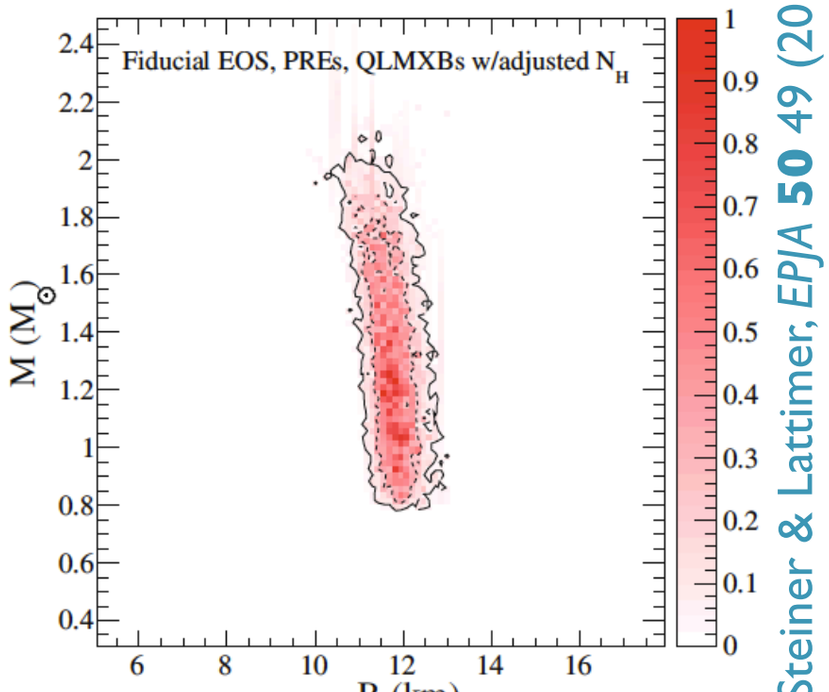
- Compatible with pA experiments
- Small model dependence

Rios & Soma, *PRL* **108** 012501 (2013)

Chiral EoS & pairing gaps

N^3LO EoS with 3BFs

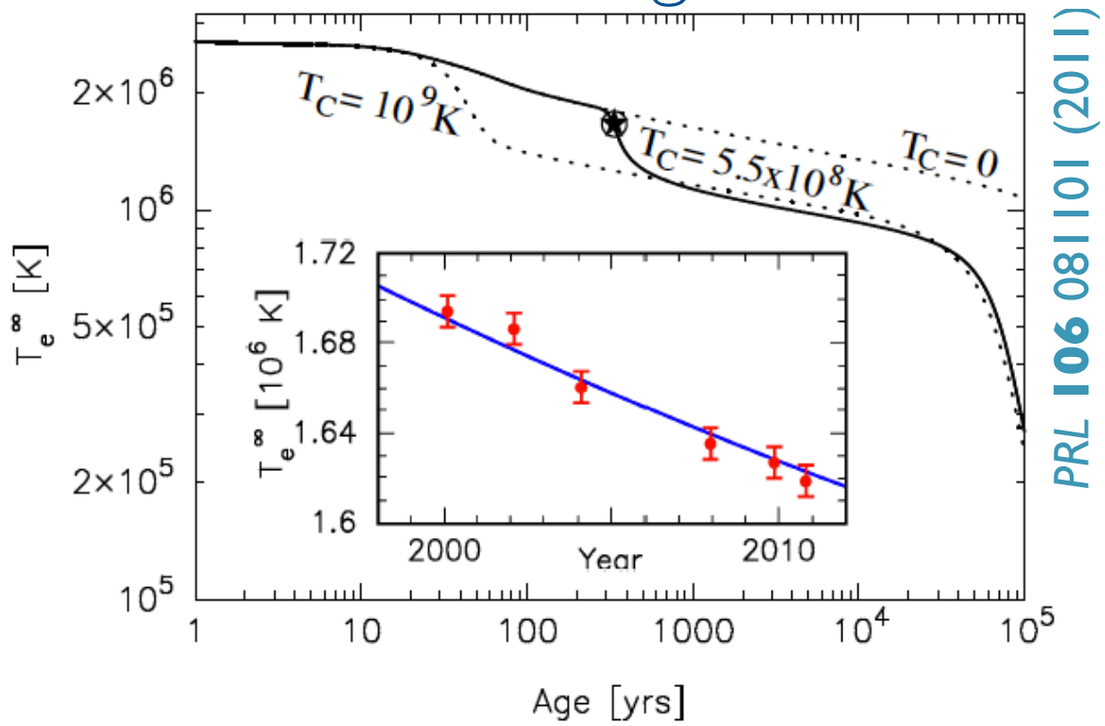




Steiner & Lattimer, *EPJA* **50** 49 (2014)

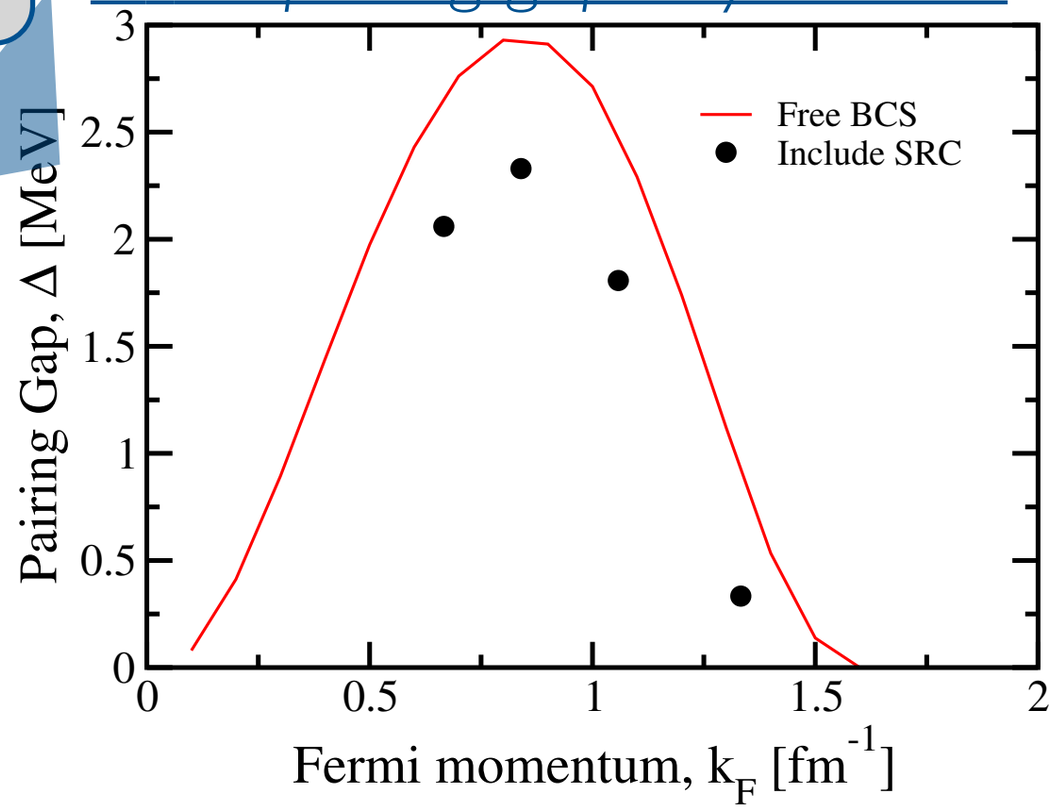
Chiral NN & 3N forces

CasA cooling curve



PRL **106** 081101 (2011)

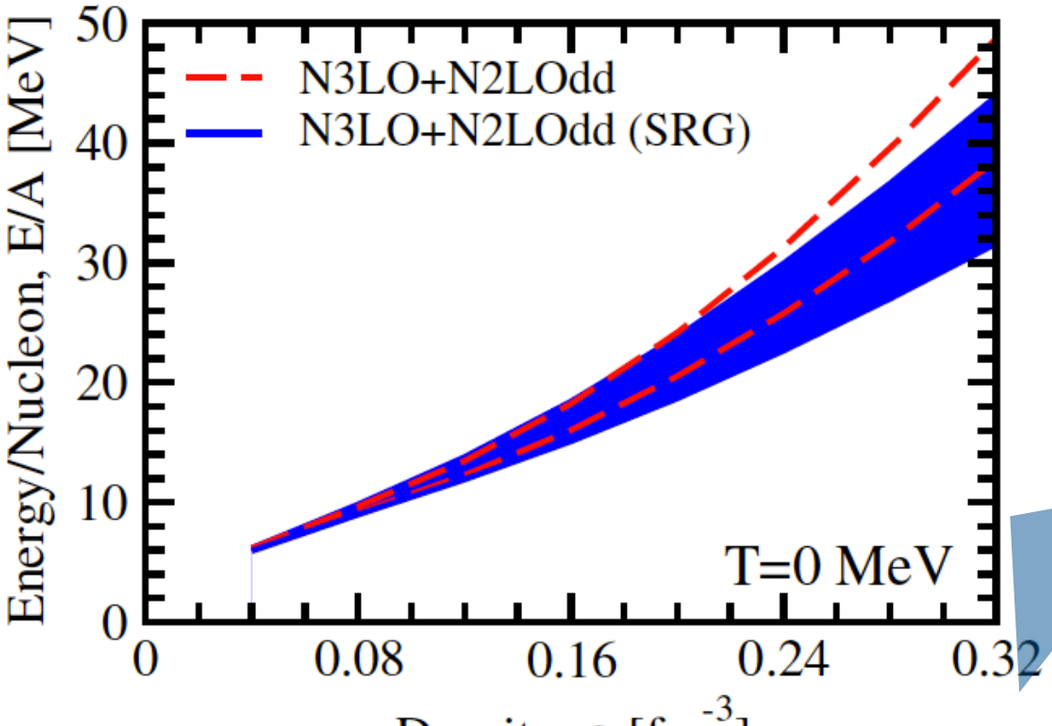
N^3LO pairing gap: beyond BCS

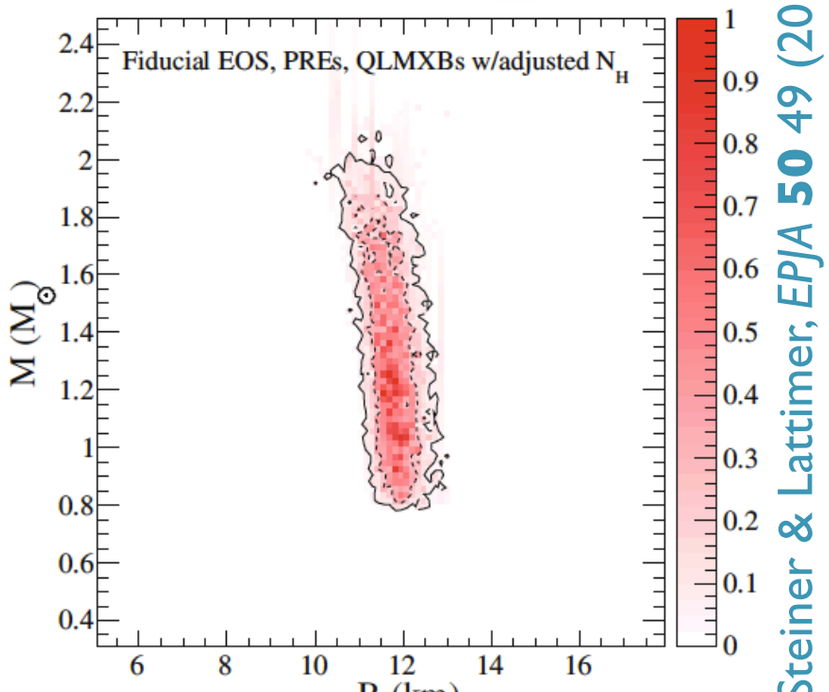


Dickhoff, Rios *et al., in preparation*

Chiral EoS & pairing gaps

N^3LO EoS with 3BFs

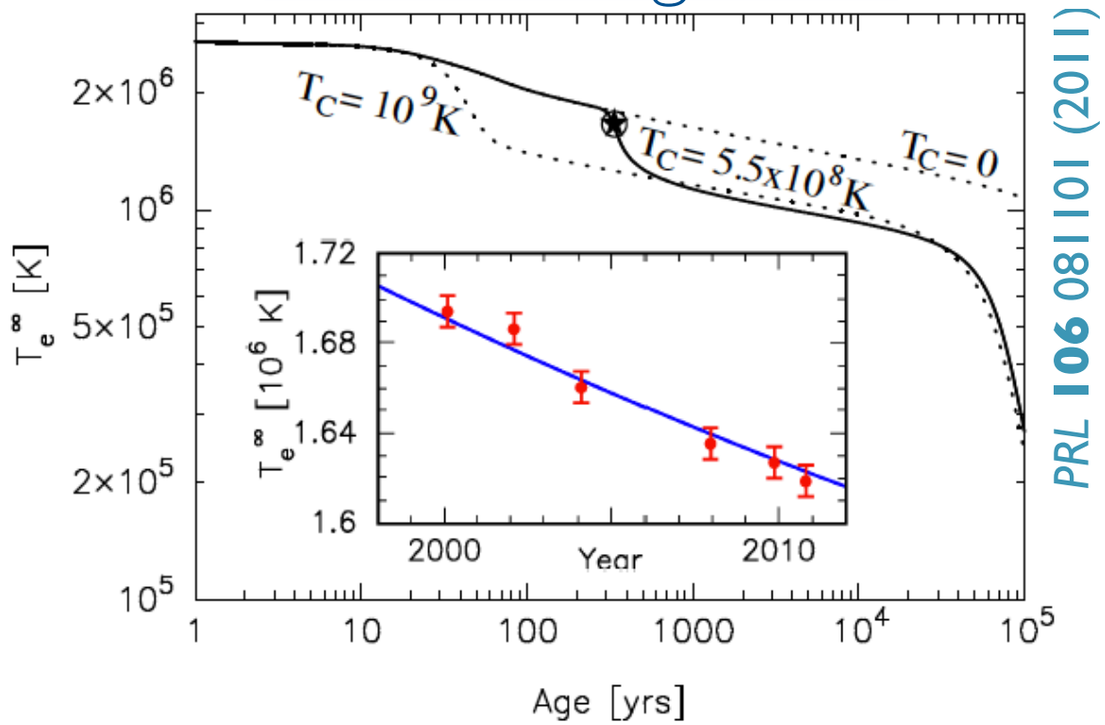




Steiner & Lattimer, *EPJA* **50** 49 (2014)

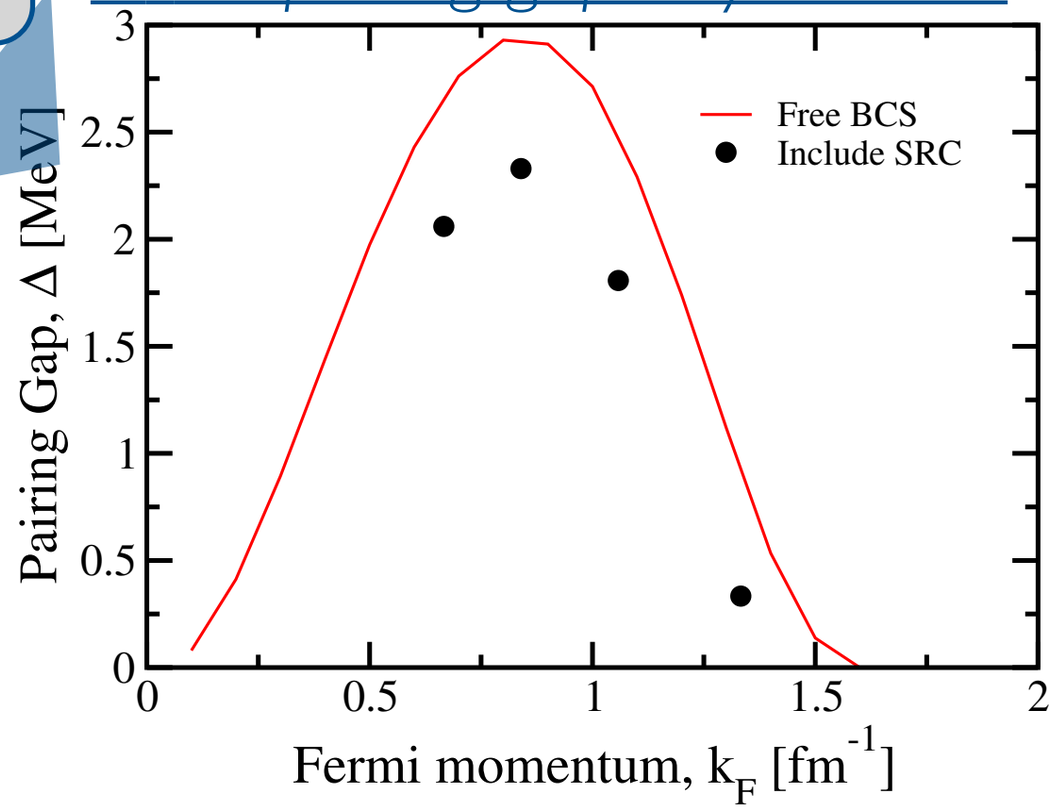
Chiral NN & 3N forces

CasA cooling curve



PRL **106** 081101 (2011)

N^3LO pairing gap: beyond BCS



Dickhoff, Rios *et al., in preparation*

Conclusions

- Ab initio nuclear theory is expanding
- Neutron star physics is relevant for this endeavor
- Many-body forces can now be accessed
- Micro, macro, transport, pairing properties on-going
- Hopefully a coherent picture will come out!

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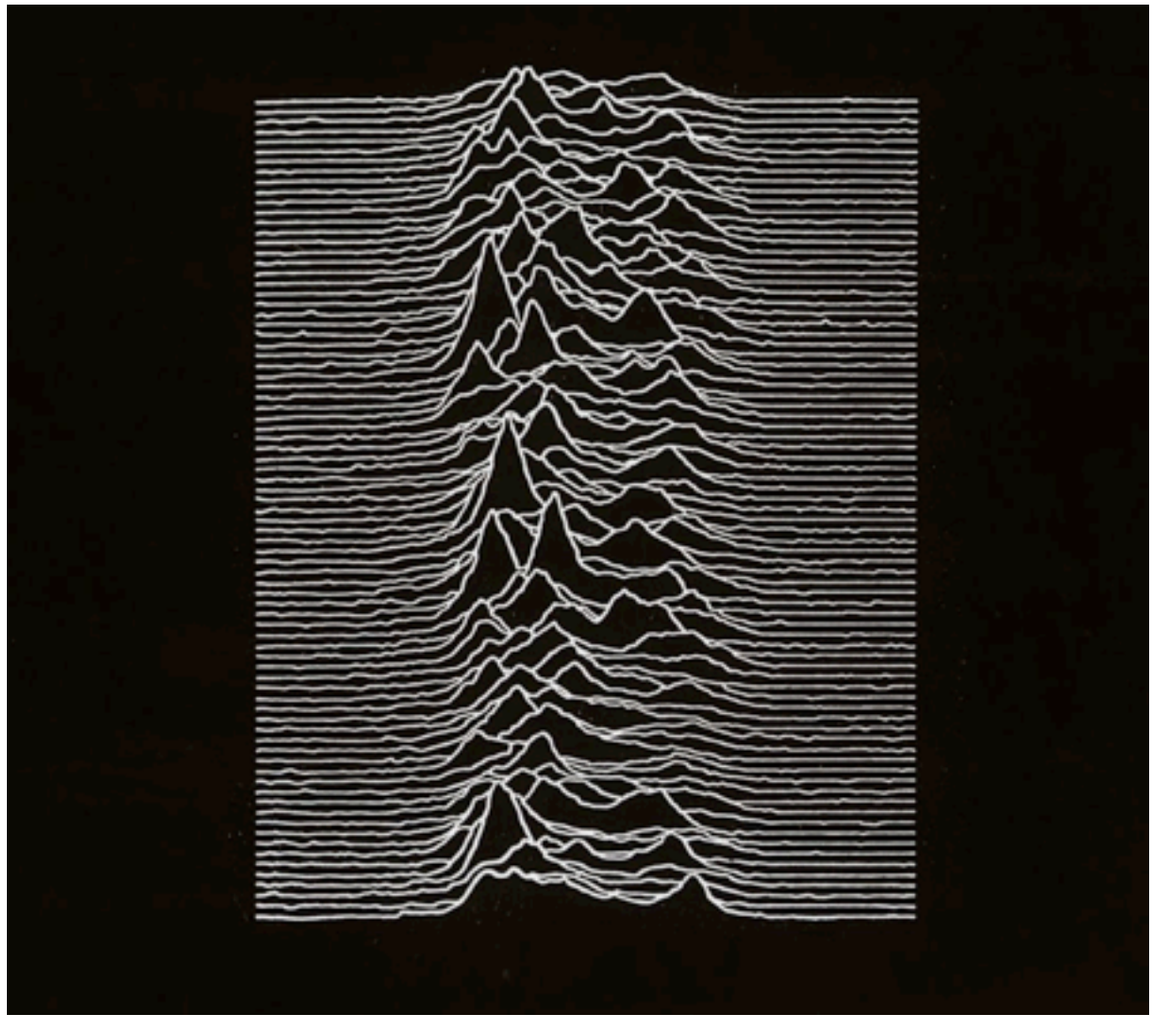
Thank you!



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