# Neutron matter with chiral EFT: Perturbative and first QMC calculations

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TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

**Nuclear Theory in the Supercomputing Era - 2013**

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Bundesministerium für Bildung und Forschung

# Happy birthday James!

# Outline

Chiral EFT and **many-body forces**

**Neutron matter** from chiral EFT interactions
**K. Hebeler, T. Krüger, I. Tews,** J.M. Lattimer, C.J. Pethick

need for nonperturbative benchmark,
which parts of chiral EFT interactions are perturbative?

**QMC calculations with chiral EFT interactions**
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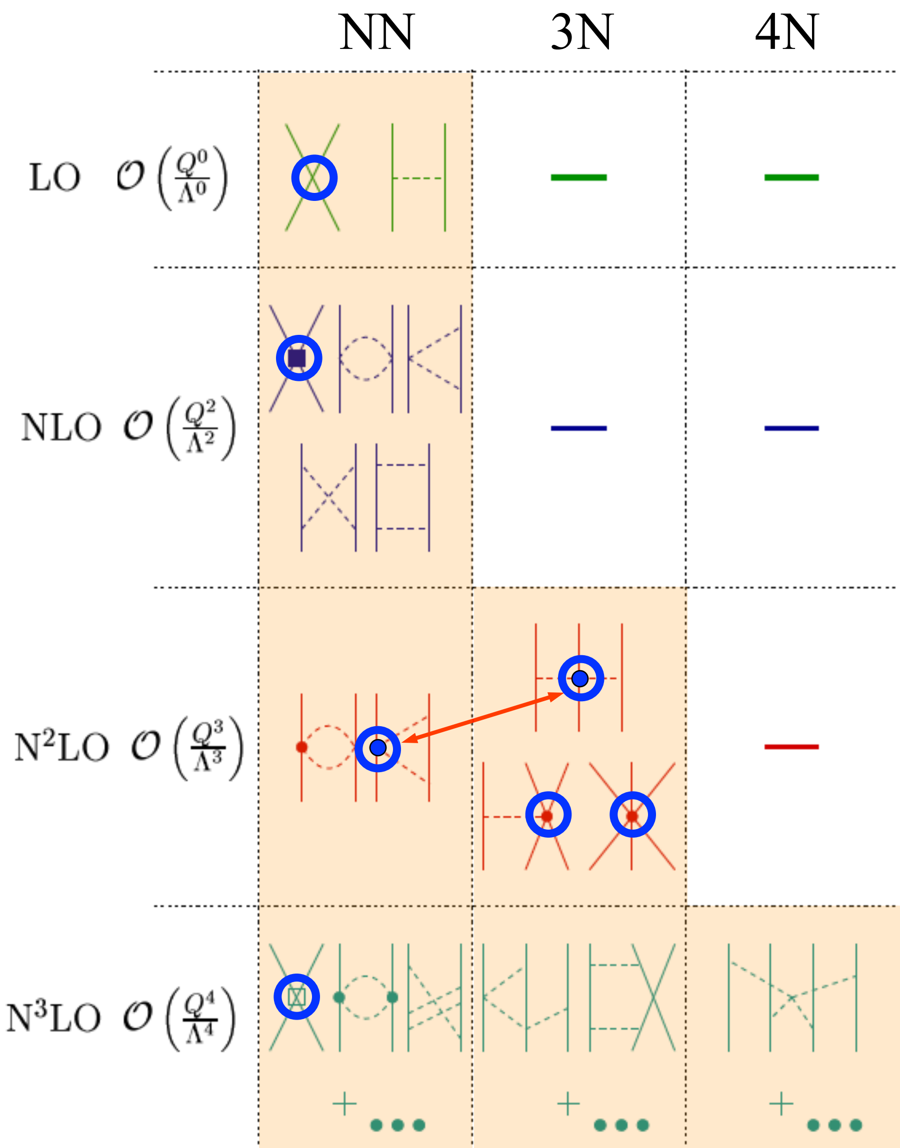
# **Chiral effective field theory** for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV




limited resolution at low energies,
can expand in powers $(Q/\Lambda_b)^n$

expansion parameter ~ 1/3 for nuclei

include long-range pion physics

few short-range couplings,
fit to experiment once

systematic: can work to desired
accuracy and obtain **error estimates**

consistent **electroweak interactions**
and **matching to lattice QCD**

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

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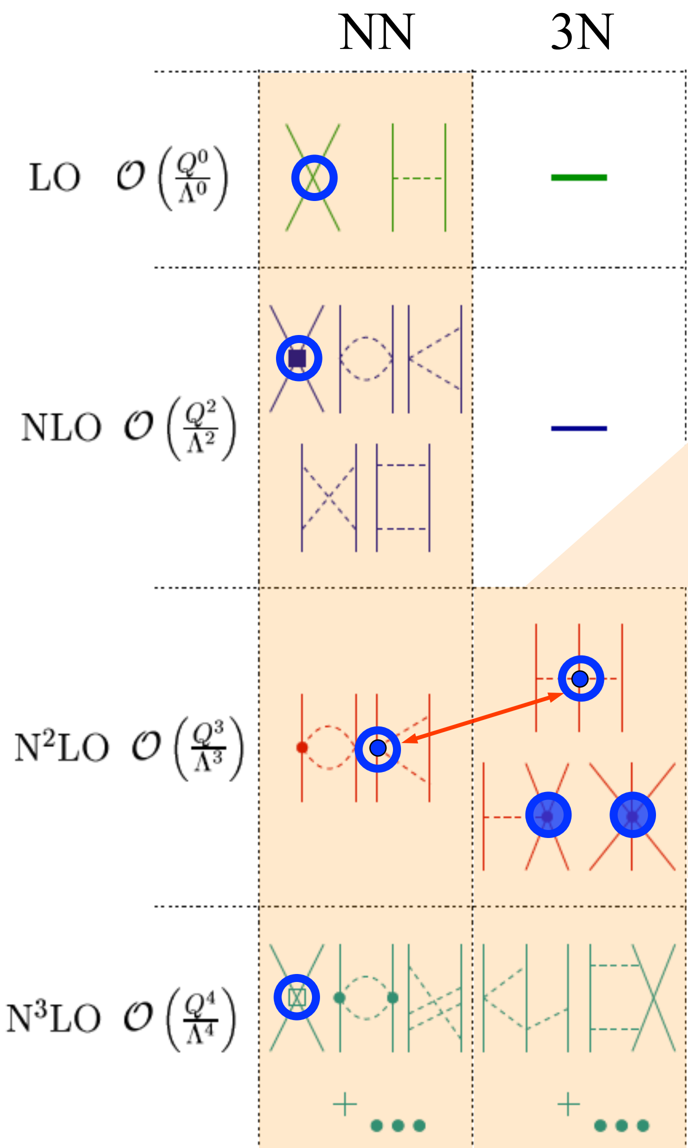
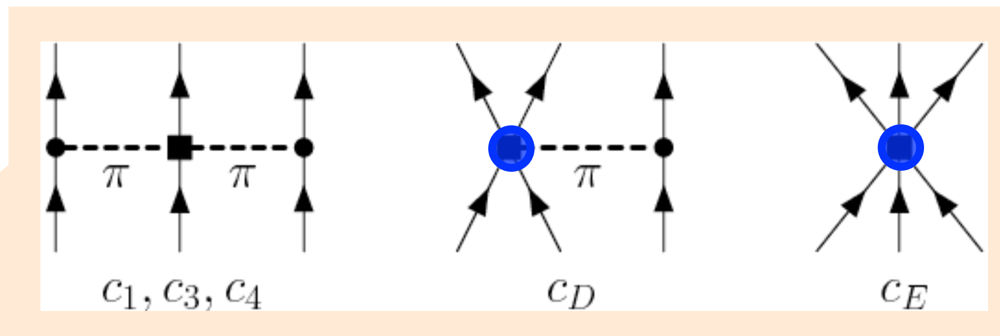



consistent NN-3N interactions

3N,4N: only 2 new couplings to $N^3LO$




$c_i$ from πN and NN Meissner et al. (2007)

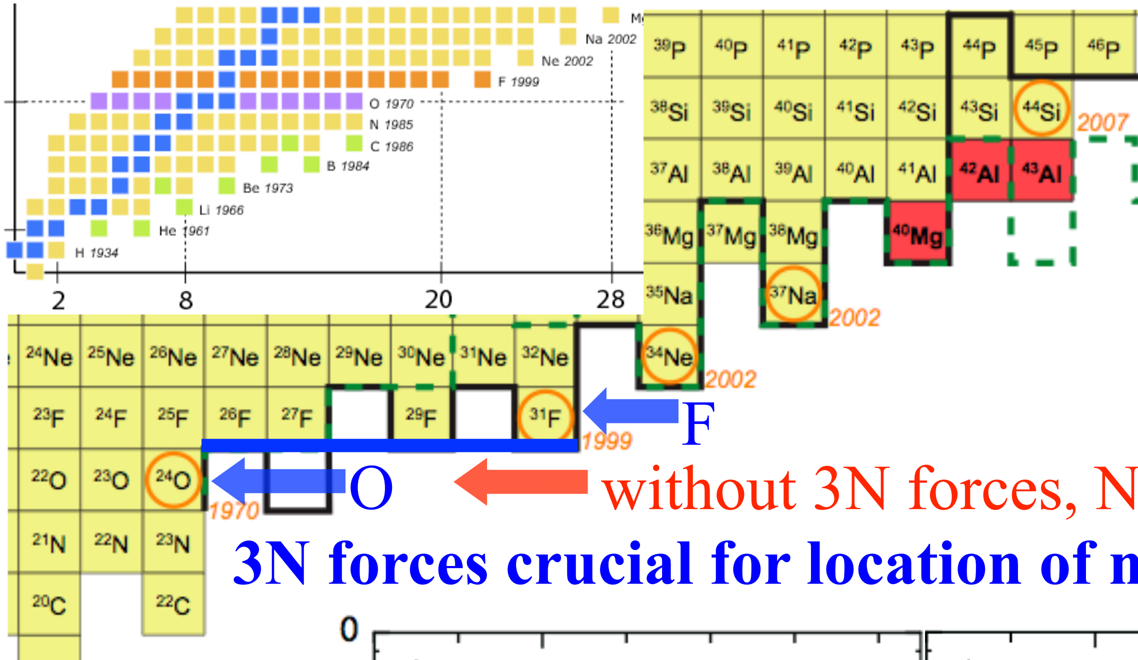
$$c_1 = -0.9^{+0.2}_{-0.5}\,,\ c_3 = -4.7^{+1.2}_{-1.0}\,,\ \ c_4 = 3.5^{+0.5}_{-0.2}$$

single-Δ: $c_1=0$, $c_3=-c_4/2=-3\ \text{GeV}^{-1}$

$c_D$, $c_E$ fit to $^3H$, $^4He$ properties only

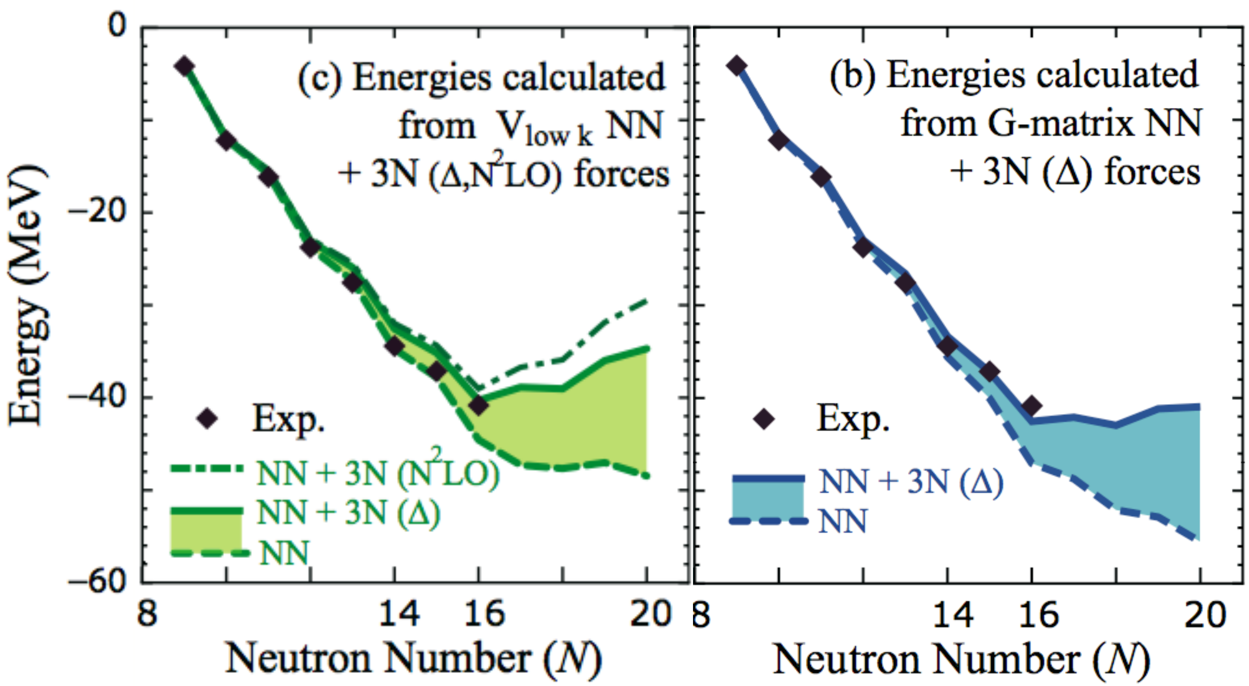
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

# The oxygen anomaly Otsuka et al. (2010)




without 3N forces, NN interactions too attractive

**3N forces crucial for location of neutron dripline**



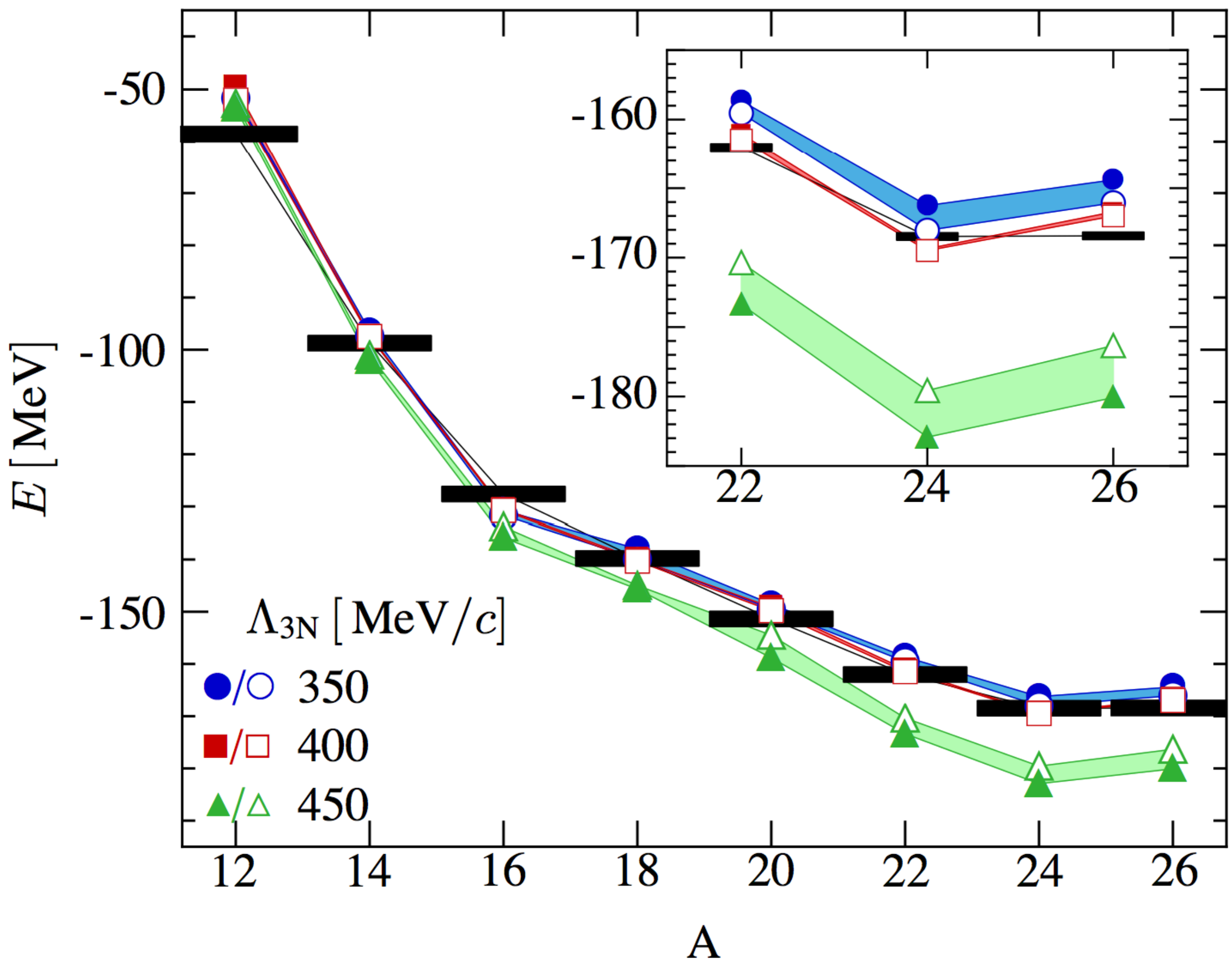
# New ab-initio methods extend reach

impact of 3N forces confirmed in large-space calculations:

Coupled Cluster theory with phenomenological 3N forces Hagen et al. (2012)

In-Medium Similarity RG based on chiral NN+3N Hergert et al. (2013)

Green's function methods based on chiral NN+3N Cipollone et al. (2013)

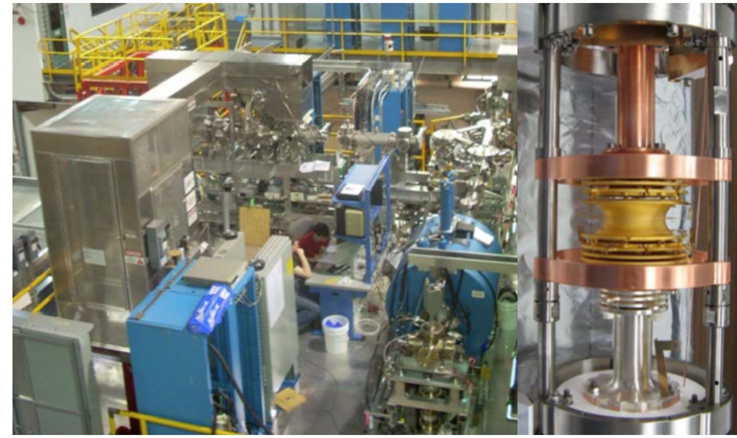


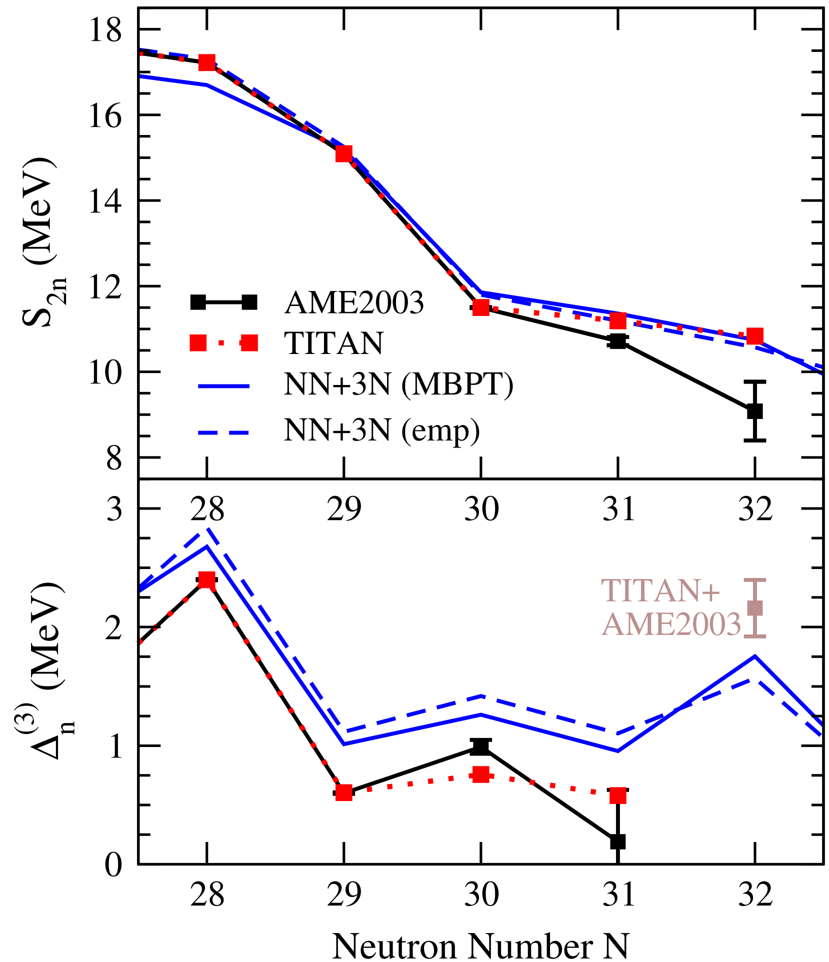
# new $^{51,52}$Ca TITAN measurements

$^{52}$Ca is 1.75 MeV more bound compared to atomic mass evaluation
Gallant et al. (2012)

behavior of 2n separation energy $S_{2n}$ agrees with NN+3N predictions

$^{53,54}$Ca masses measured at ISOLTRAP
accepted for publication in Nature





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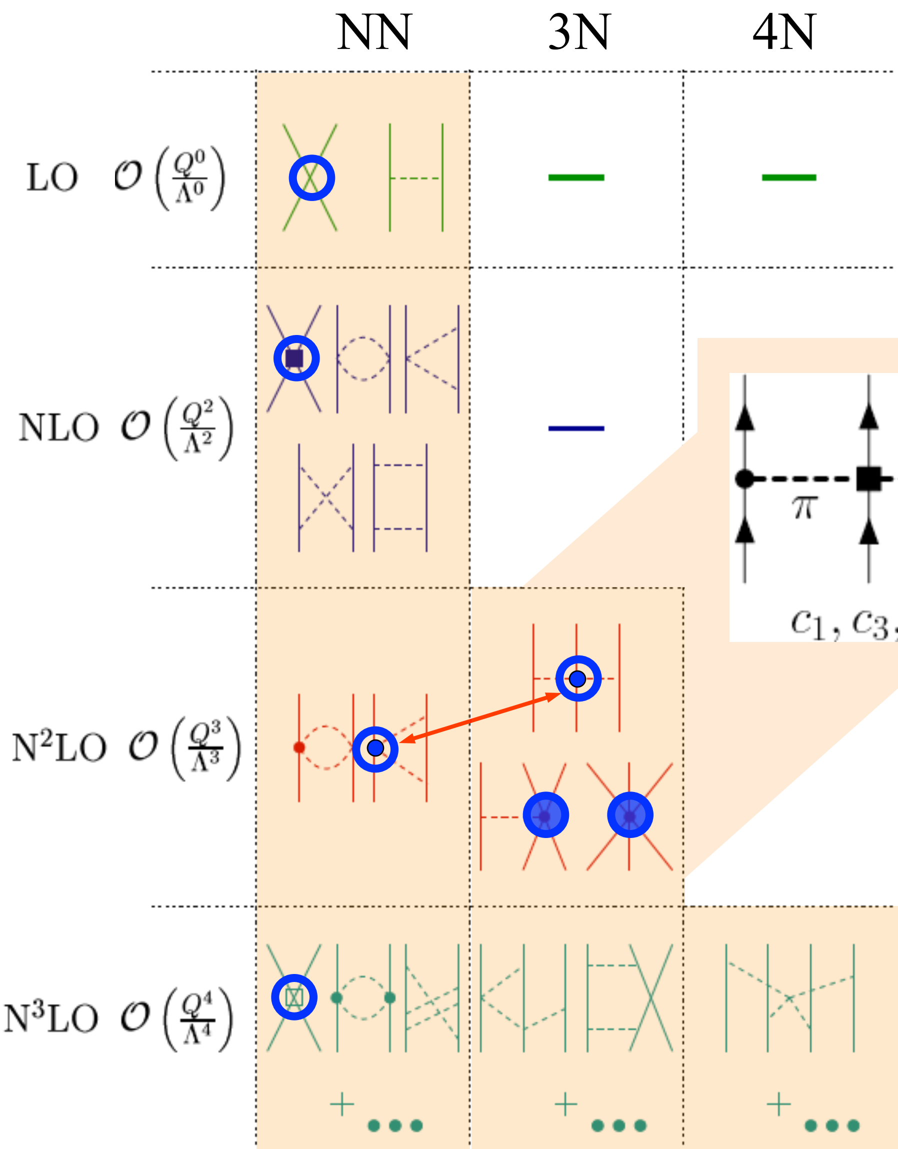
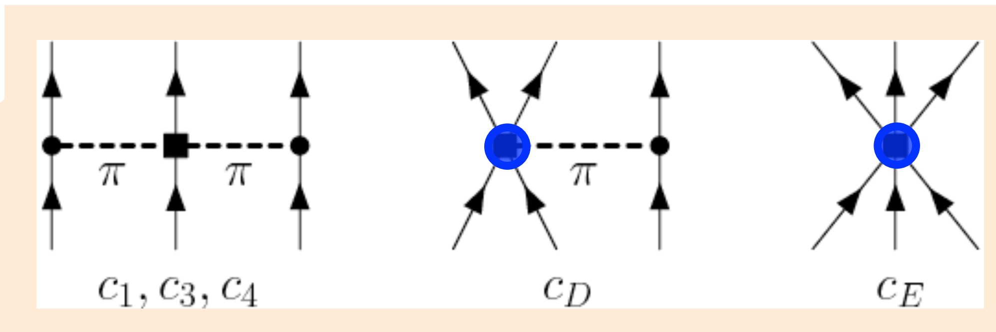



$c_D$, $c_E$ don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for $c_4$

Hebeler, AS (2010)




all 3- and 4-neutron forces are predicted to N$^3$LO!

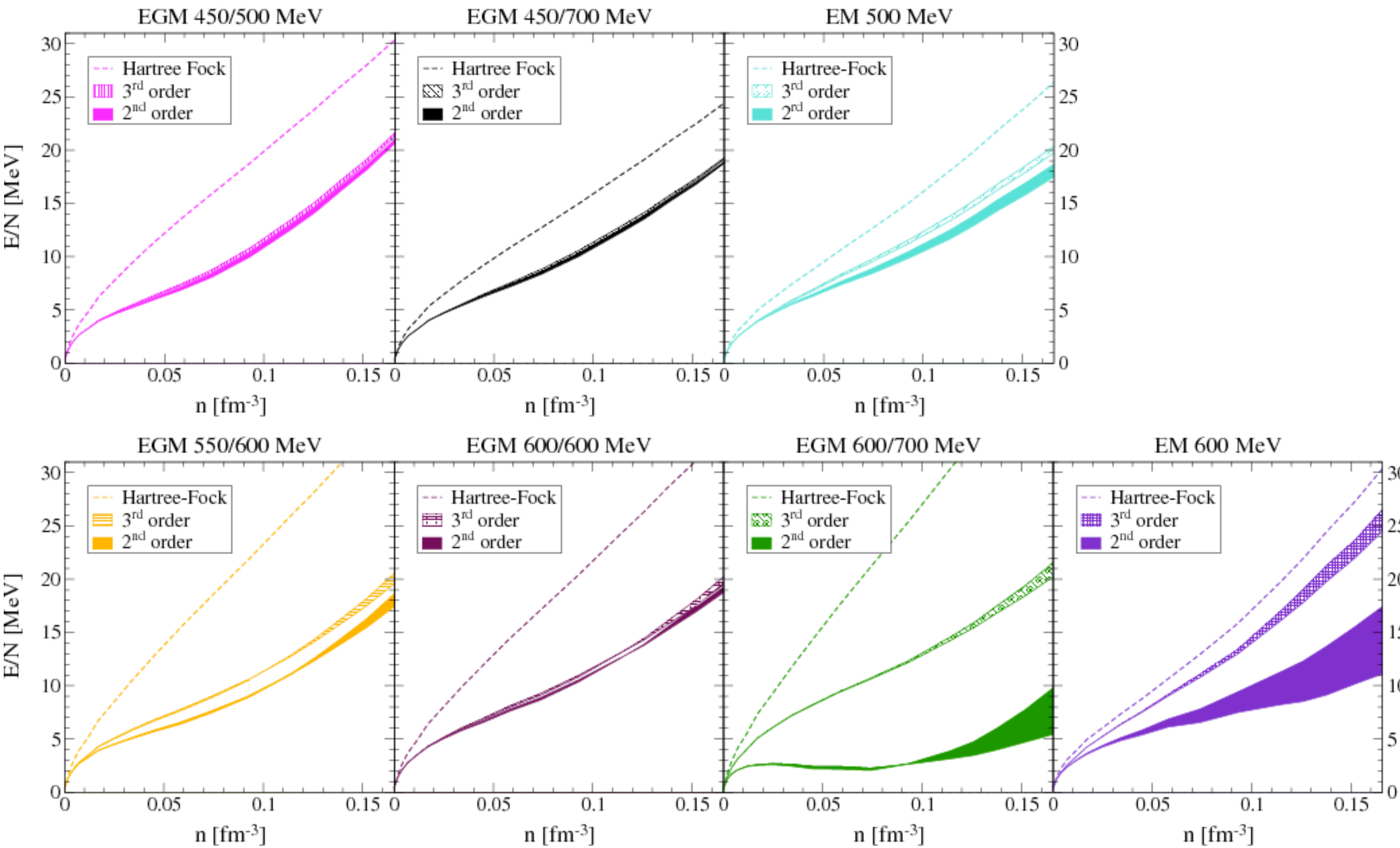
**study 3N and 4N in neutron matter**

Tews, Krüger, Hebeler, AS (2013)

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

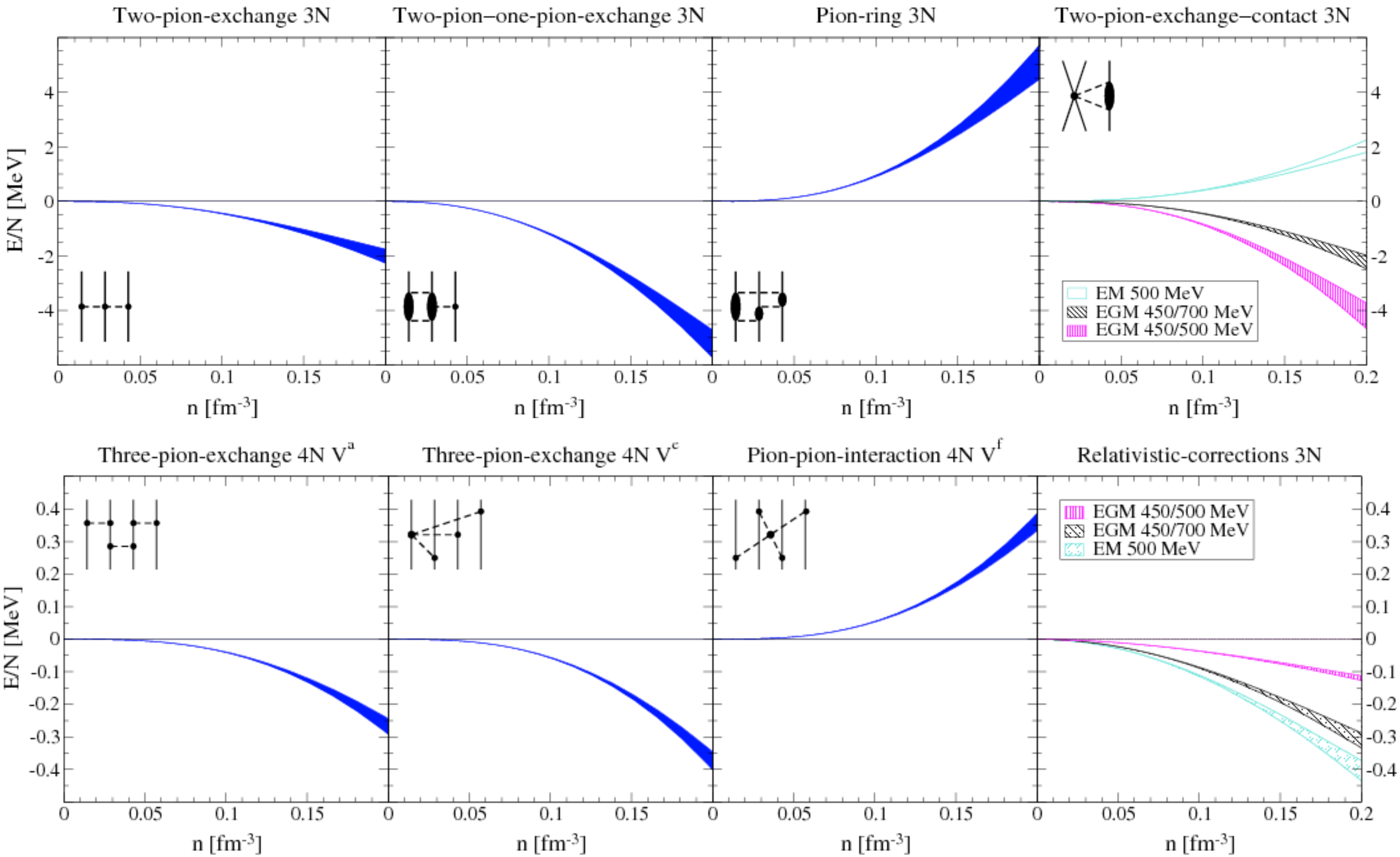
# Neutron matter from chiral EFT interactions

direct calculations without RG/SRG evolution, 3N to $N^2LO$ only



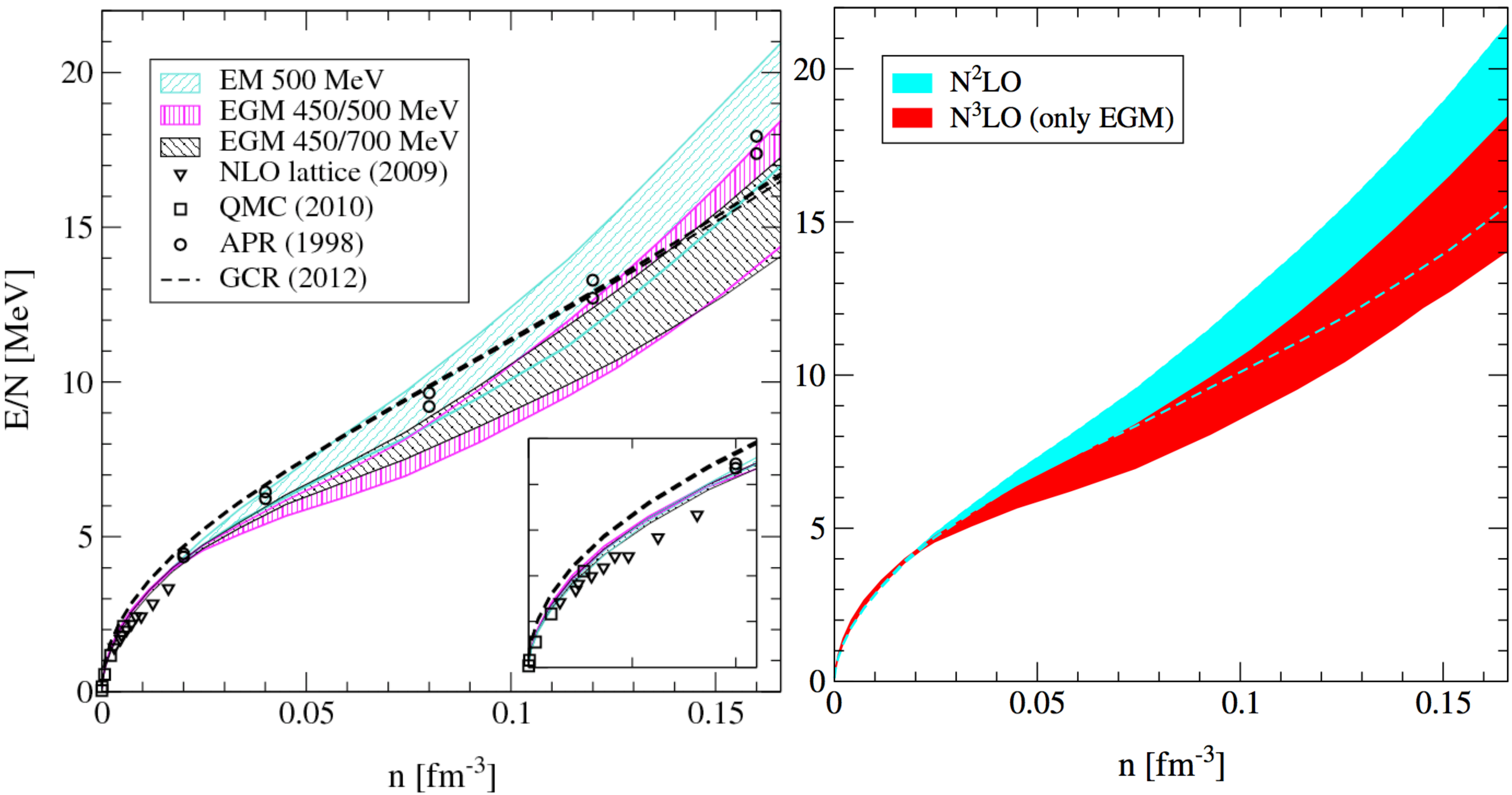
# $N^3LO$ 3N and 4N interactions in neutron matter

evaluated at Hartree-Fock level



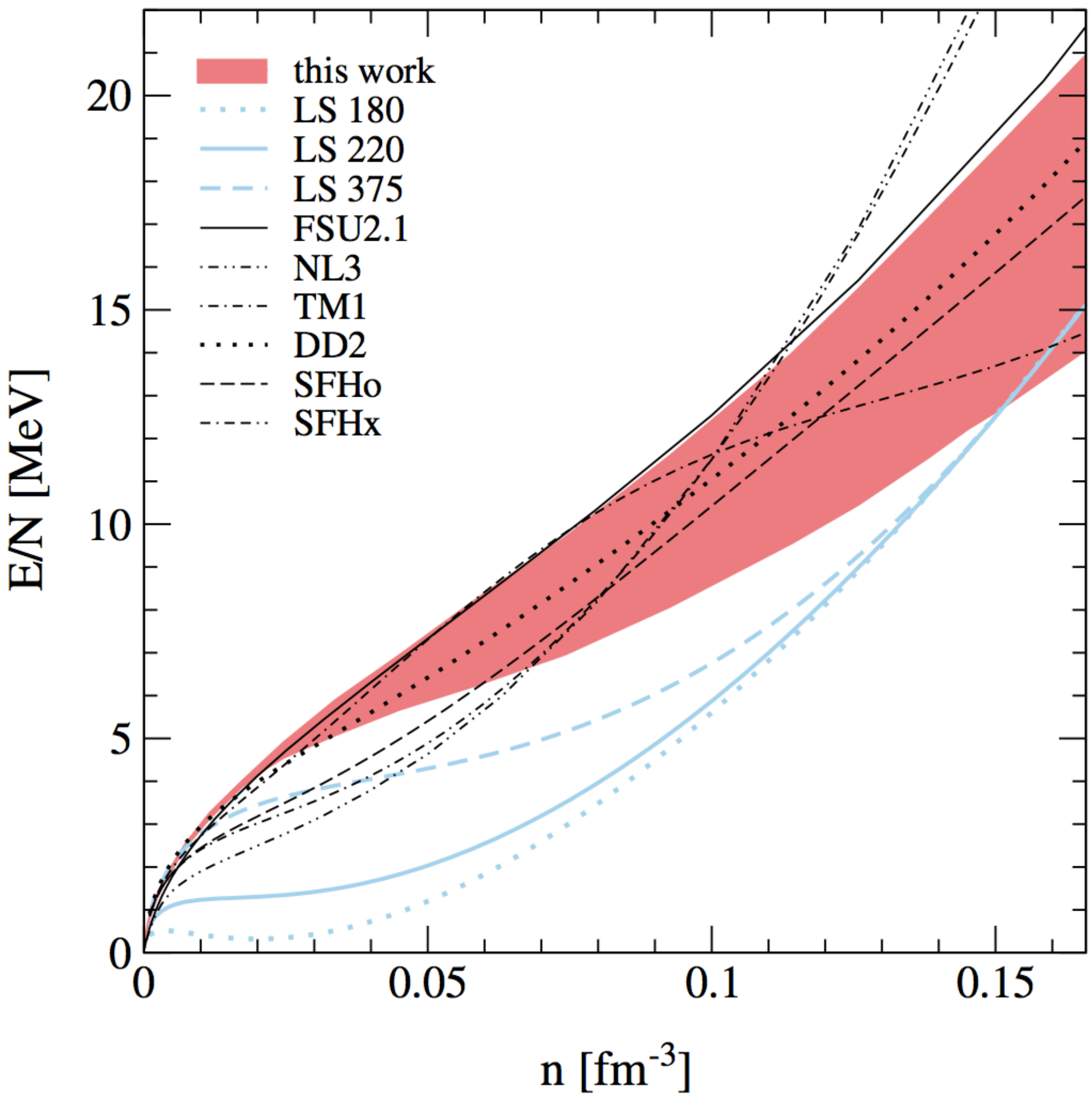
# Complete N$^3$LO calculation of neutron matter

first complete N$^3$LO result, Hartree-Fock +2nd order +3rd order (pp+hh)
includes uncertainties from NN, 3N (dominates), 4N



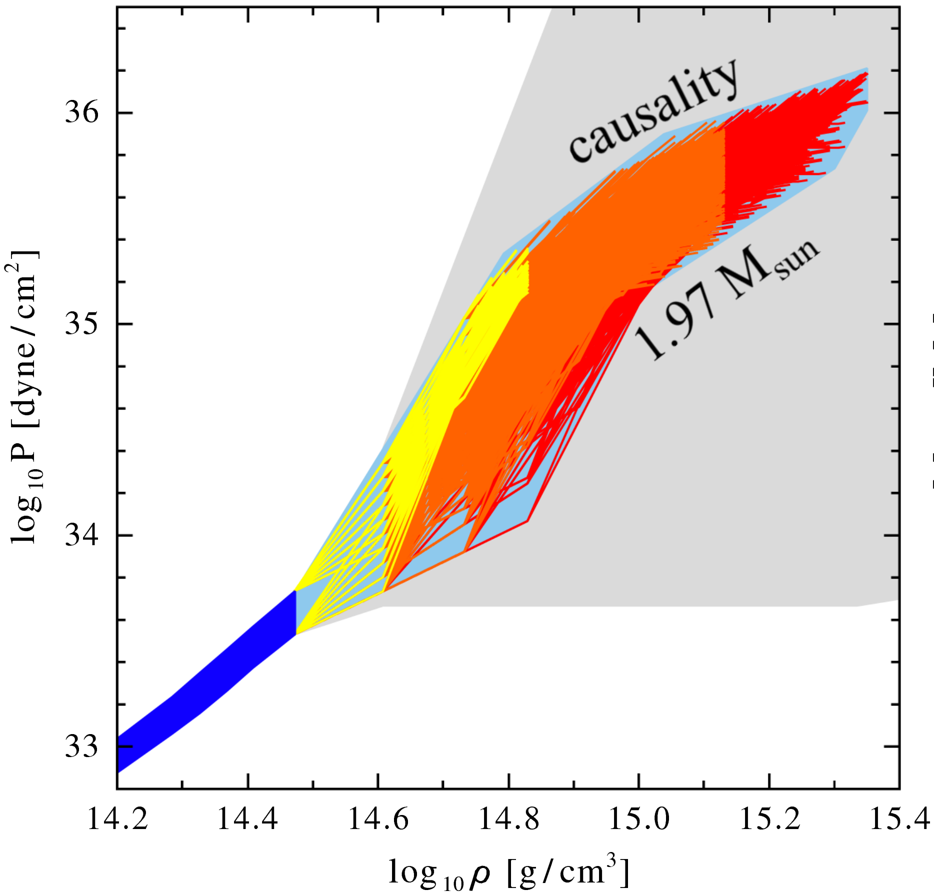
# Comparisons to equations of state in astrophysics

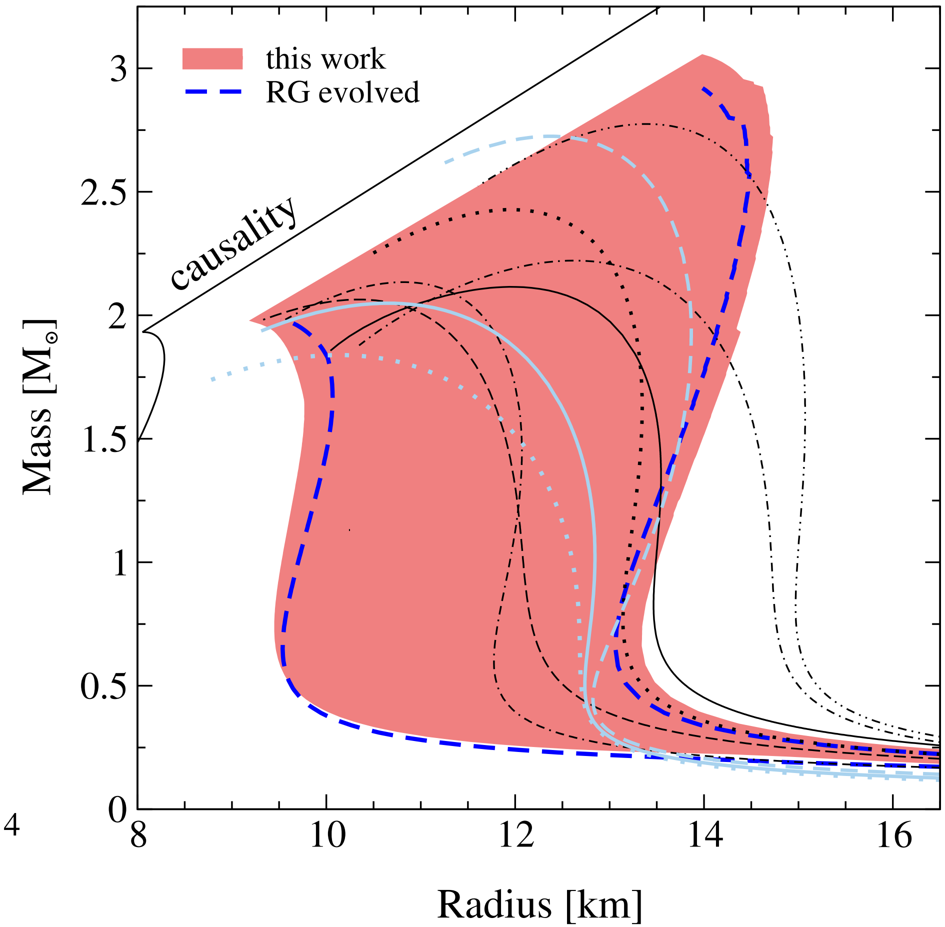
many equations of state used in supernova simulations not consistent with neutron matter results



# Impact on neutron stars Hebeler, Lattimer, Pethick, AS (2010, 2013)

constrain high-density EOS by causality, require to support 1.97 $M_{sun}$ star




low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

predicts neutron star radius: 9.7-13.9 km for M=1.4 $M_{sun}$ (±18% !)

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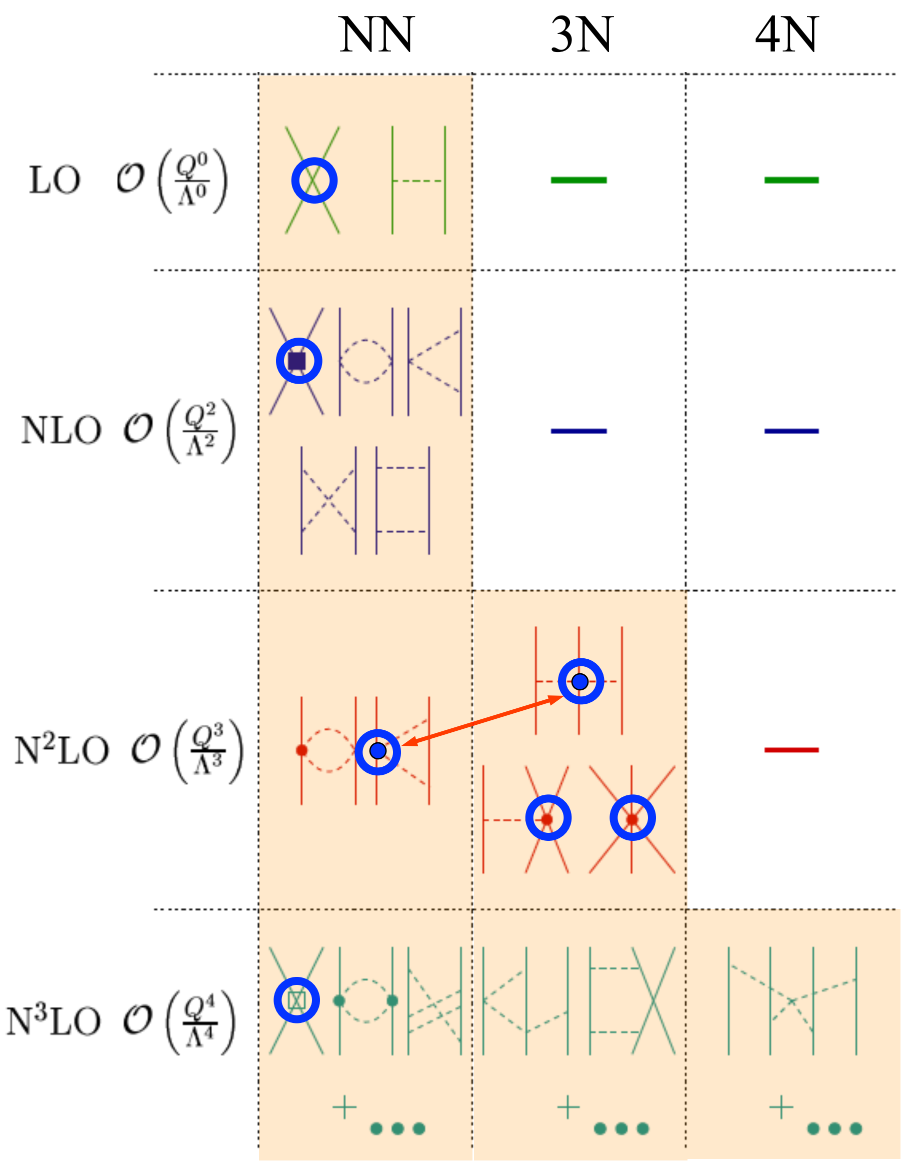
# QMC with chiral EFT interactions - challenges




EFT includes nonlocal interactions

caused by usual regulator
on relative momenta

and k-dependent contact interactions
k=mom. transfer in exchange channel

pion exchanges to $N^2LO$ local
except for regulator

strategies so far:
try directly in QMC
Lynn, Schmidt

separate local + nonlocal parts
and treat nonlocal perturbatively
Furnstahl, Wendt

# Local chiral EFT interactions

keep pion exchanges to $N^2LO$ local

regulate in coordinate space $f_{\rm long}(r) = 1 - e^{-(r/R_0)^4}$

construct local contact interactions $C_S + C_T\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$

with regulator on momentum transfer $\int \frac{d\mathbf{q}}{(2\pi)^3}\, C_{S,T}\, f_{\rm local}(q^2)\, e^{i\mathbf{q}\cdot\mathbf{r}} = C_{S,T}\, \frac{e^{-(r/R_0)^4}}{\pi\Gamma\left(\frac{3}{4}\right) R_0^3}$

at NLO use freedom to treat $k^2$ operators for isospin dependence

$$
\begin{aligned}
V_{\rm short}^{\rm NLO} &= C_1\, q^2 + C_2\, q^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \\
&+ \left(C_3\, q^2 + C_4\, q^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\right) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \\
&+ i\, \frac{C_5}{2}\, (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \mathbf{q} \times \mathbf{k} \\
&+ C_6\, (\boldsymbol{\sigma}_1 \cdot \mathbf{q})(\boldsymbol{\sigma}_2 \cdot \mathbf{q}) \\
&+ C_7\, (\boldsymbol{\sigma}_1 \cdot \mathbf{q})(\boldsymbol{\sigma}_2 \cdot \mathbf{q})\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\,,
\end{aligned}
$$

TABLE I. Short-range couplings for $R_0 = 1.2$ fm at LO, NLO, and $N^2LO$ (with a spectral-function cutoff $\widetilde{\Lambda} = 800$ MeV) [30]. The couplings $C_{1-7}$ are given in $\text{fm}^4$ while the rest are in $\text{fm}^2$.

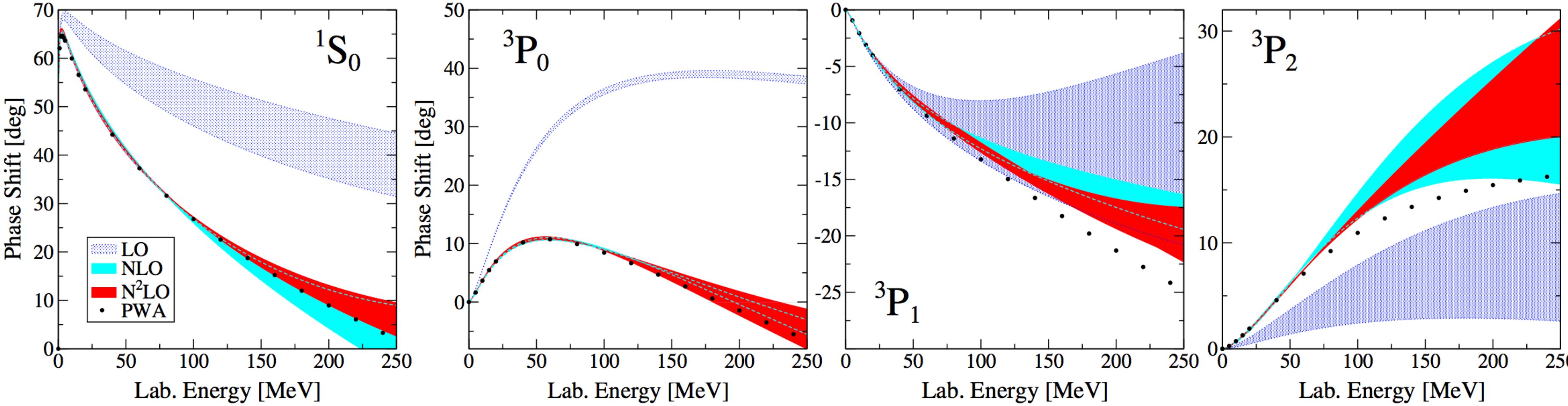
| | LO | NLO | $N^2LO$ |
|---|---|---|---|
| $C_S$ | −1.83406 | −0.64687 | 1.09225 |
| $C_T$ | 0.15766 | 0.58128 | 0.24388 |
| $C_1$ | | 0.18389 | −0.13784 |
| $C_2$ | | 0.15591 | 0.07001 |
| $C_3$ | | −0.13768 | −0.13017 |
| $C_4$ | | 0.02811 | 0.02089 |
| $C_5$ | | −1.99301 | −1.82601 |
| $C_6$ | | 0.26774 | 0.18700 |
| $C_7$ | | −0.25784 | −0.24740 |
| $C_{nn}$ | | | 0.05009 |

M. Freunek, Diploma Thesis (2007)

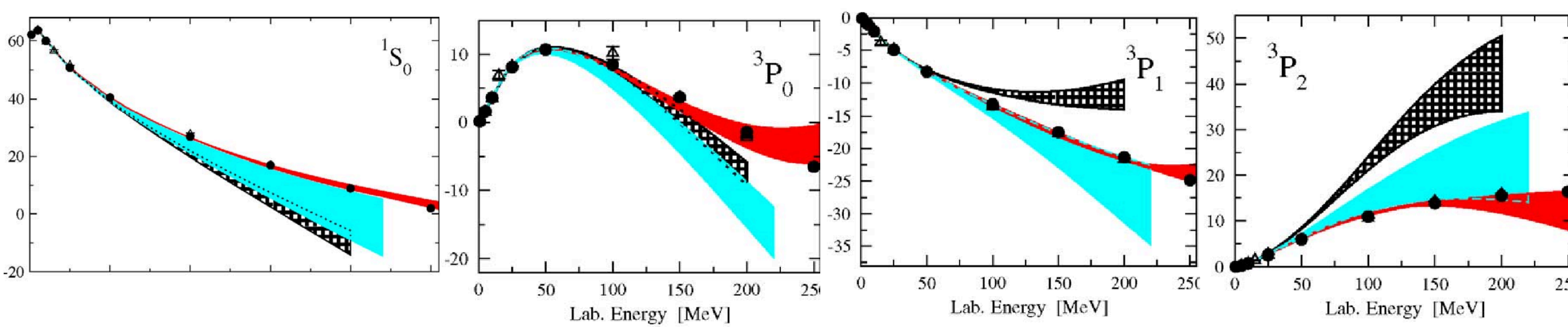
# Phase shift fits

fit to $E_{lab}$=1, 5, 10, 25, 50, 100 MeV, SF cutoff = 800 MeV

vary $R_0$ from 0.8-1.2 fm, corresponds to ~600-400 MeV




considerably better than EGM N$^2$LO potentials



# Auxiliary Field Diffusion Monte Carlo

A. Gezerlis, S. Gandolfi

AFDMC: Hubbard-Stratonovich transformation using auxiliary fields to change quadratic spin-isospin operator dependences to linear

include full interaction at LO, NLO, and $N^2LO$ in propagator
NN interactions only, next:3N

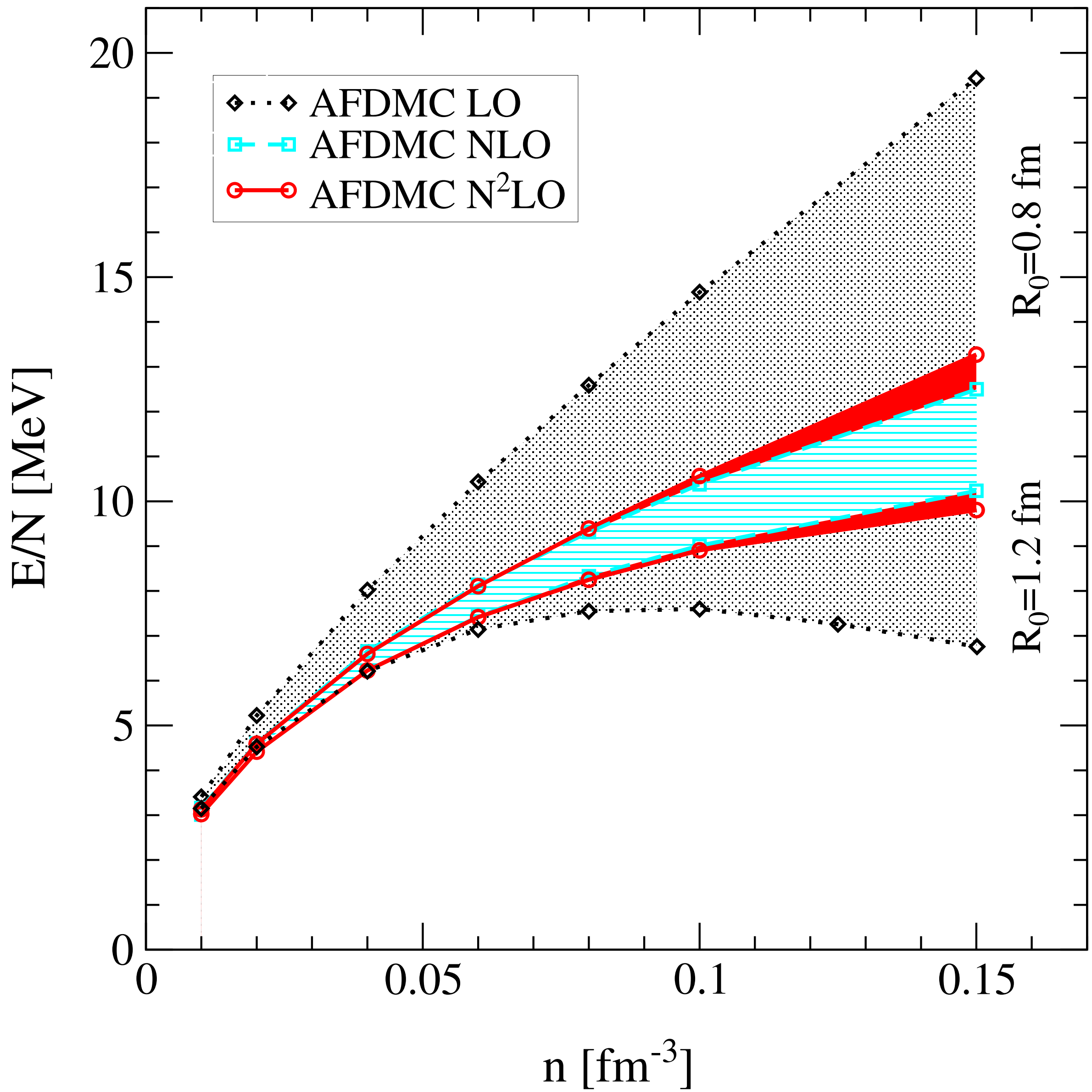
next: test which parts of chiral EFT interactions are perturbative ($N^3LO$ contributions will have nonlocal parts)

optimal number of 66 particles,
include contributions from 26 neighboring cells of simulation box

statistical uncertainty smaller than points
no to full Jastrow: 0.1-0.5 MeV (1-5%) for $R_0$=1.2-0.8 fm

# AFDMC results for neutron matter

order-by-order convergence up to saturation density

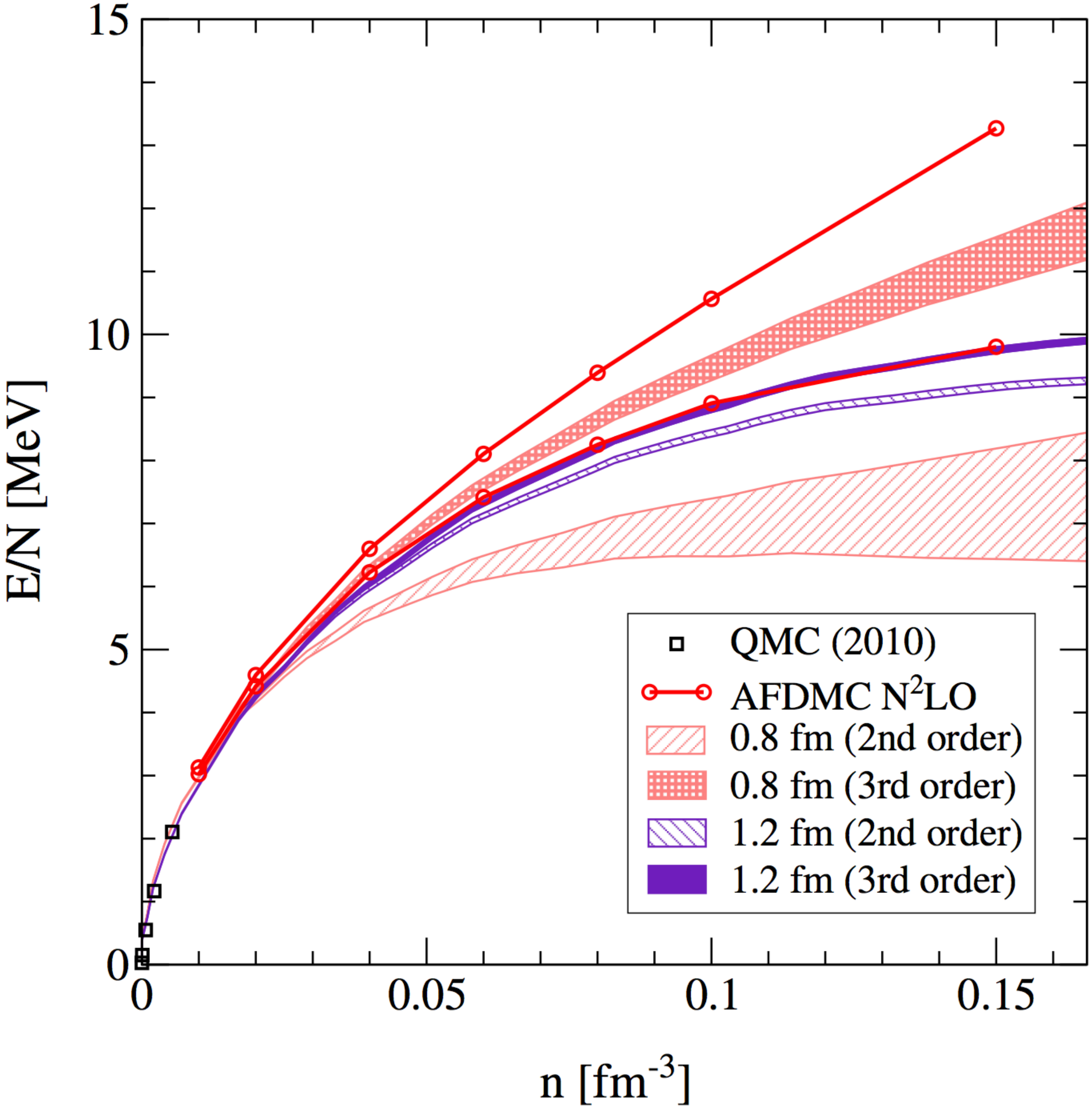



bands similar to phase shift bands

NLO ~ N$^2$LO due to large $c_i$

# Comparison to perturbative calculations at N$^2$LO

Hartree-Fock +2nd order +3rd order (pp+hh), same as for N$^3$LO calcs.




band at each order from free to HF spectrum

low cutoffs (400 MeV) 3rd order corr. small, excellent agreement with AFDMC

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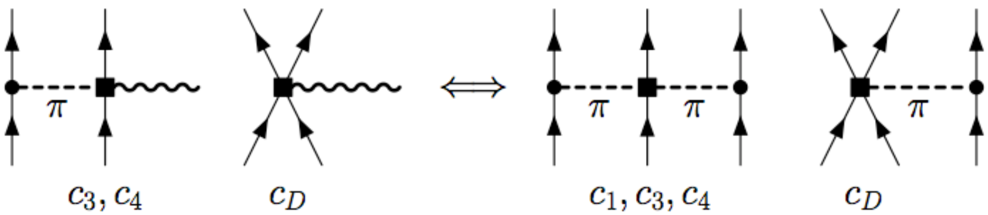
# Electroweak interactions and 3N forces

weak axial currents couple to spin, similar to pions

two-body currents predicted by NN, 3N couplings to $N^3LO$

Park et al., Phillips,…




two-body analogue of Goldberger-Treiman relation

explored in light nuclei, but not for larger systems

dominant contribution to Gamow-Teller transitions,
important in nuclei (Q~100 MeV)

3N couplings predict quenching of $g_A$ (dominated by long-range part)
and predict momentum dependence (weaker quenching for larger p)

Menendez, Gazit, AS (2011)

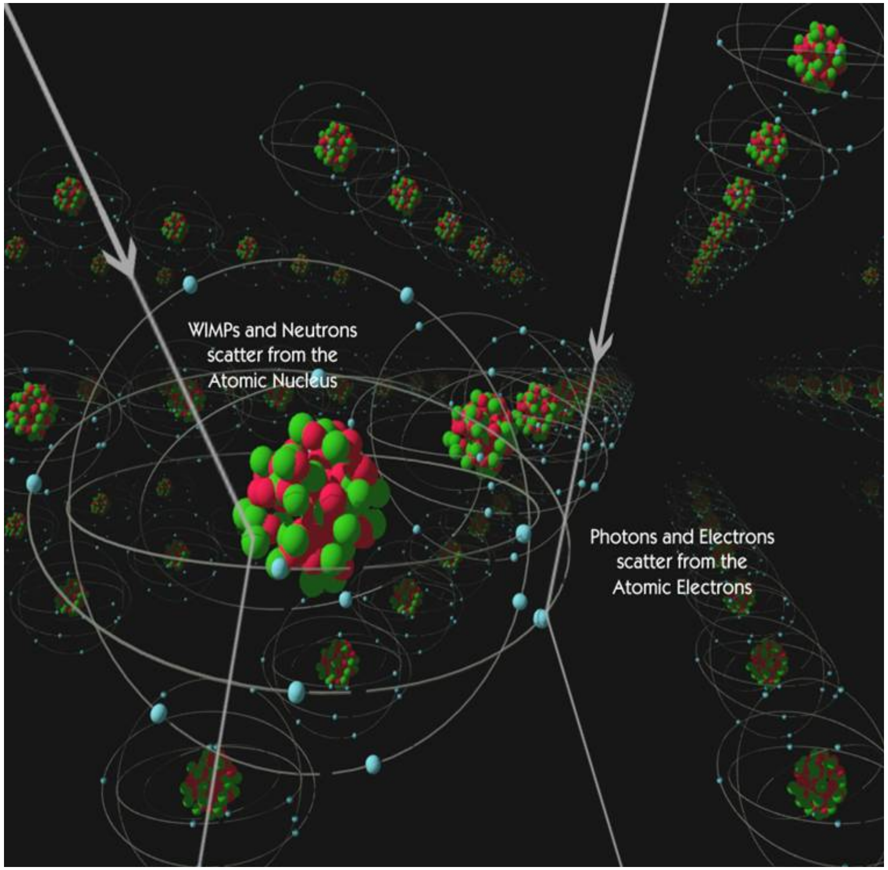
# Nuclear physics of direct dark matter detection

direct dark matter detection needs **nuclear structure factors** as input, particularly sensitive to nuclear structure for spin-dependent couplings

relevant momentum transfers ~ $m_\pi$

**calculate systematically with chiral EFT**
Menendez et al. (2012)

dark matter response may be complex
Haxton et al. (2012)

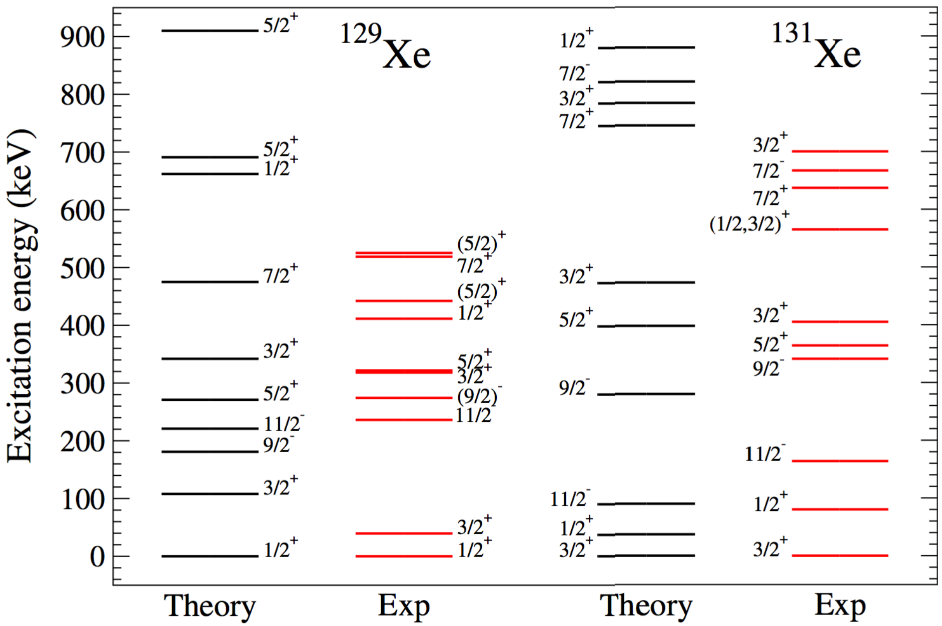


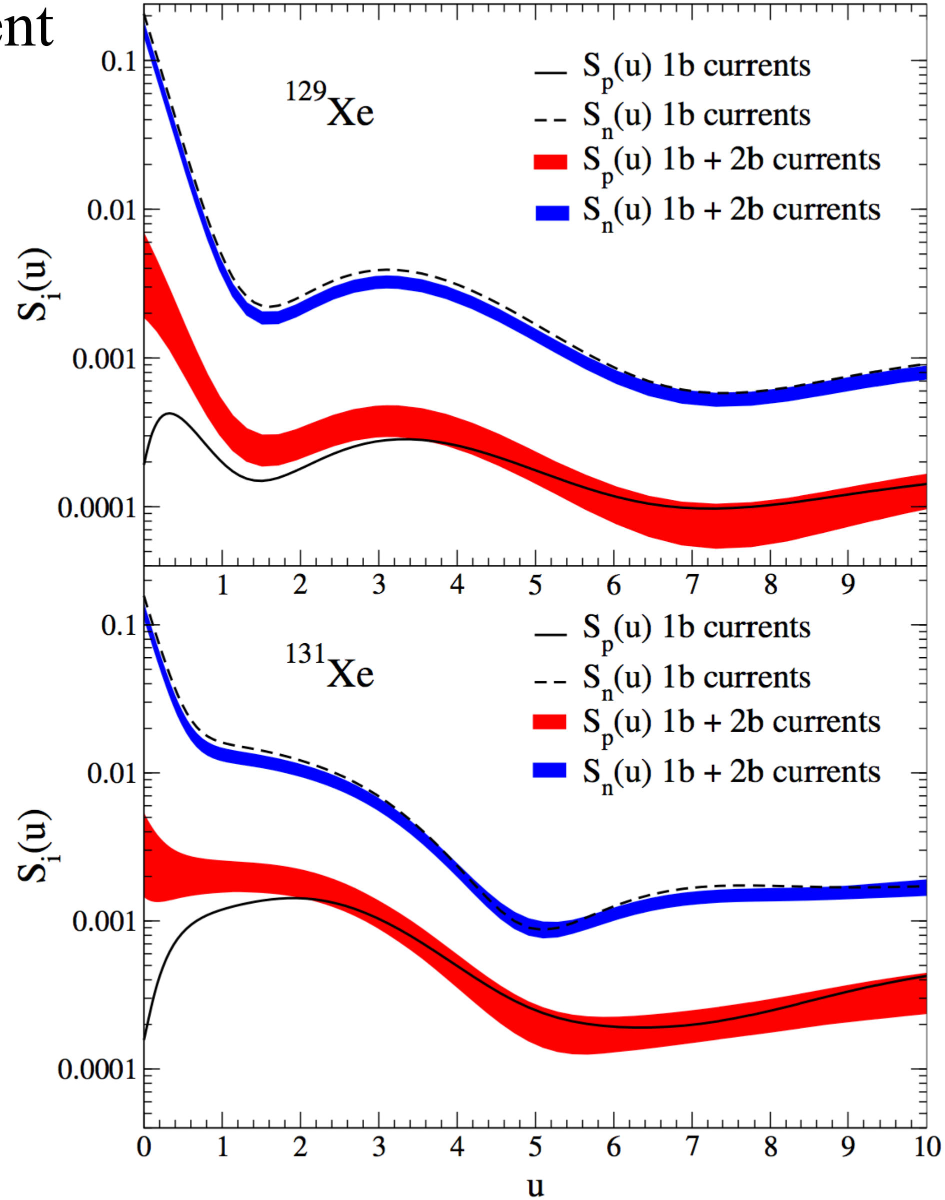
# Spin-dependent WIMP scattering off nuclei

spin-dependent WIMP-nucleon interactions
= isospin rotation of weak axial current

include chiral 2-body currents
and state-of-the-art interactions
Menendez, Gazit, AS (2012)

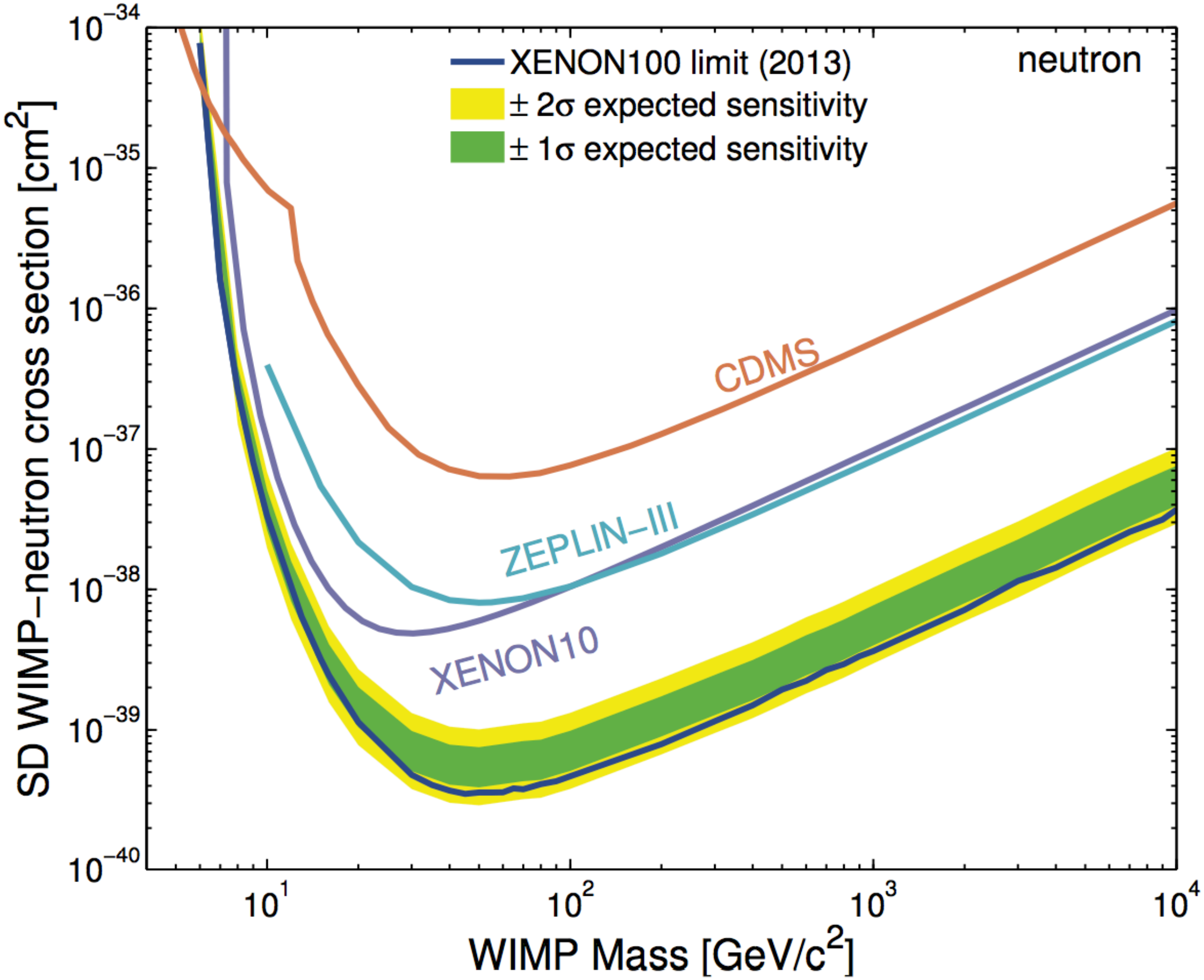
enhances coupling to even-species



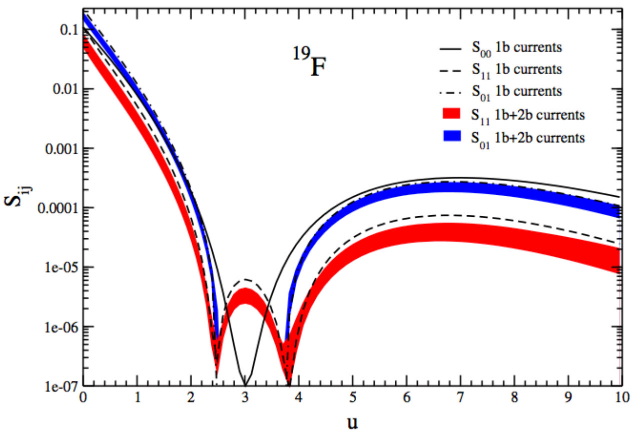
# Limits on SD WIMP-neutron interactions

best limits from XENON100 Aprile et al., 1301.6620
uses Javier Menendez' calculation

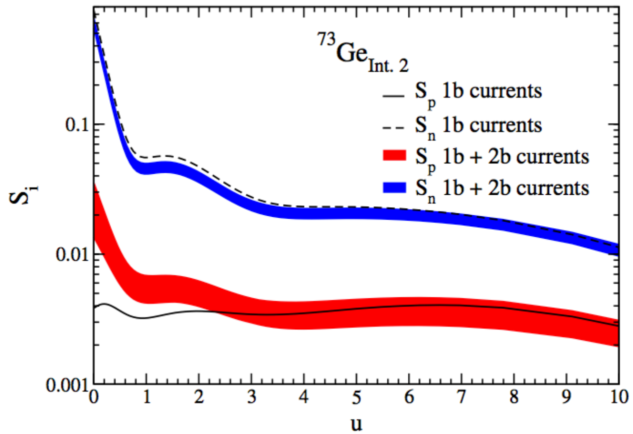


# Spin-dependent WIMP-nucleus response for $^{19}$F, $^{23}$Na, $^{27}$Al, $^{29}$Si, $^{73}$Ge, $^{127}$I

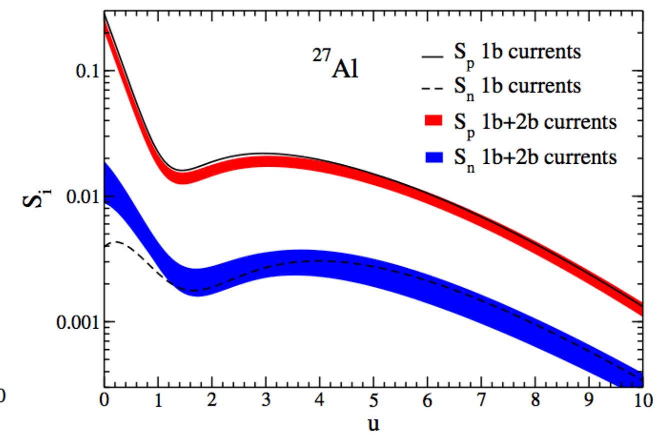
Klos, Menendez, Gazit, AS (2013)




PICASSO, COUPP, SIMPLE




CDMS, EDELWEISS, EURECA

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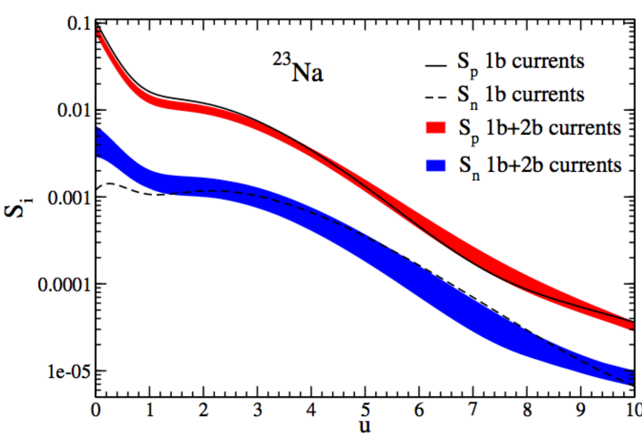
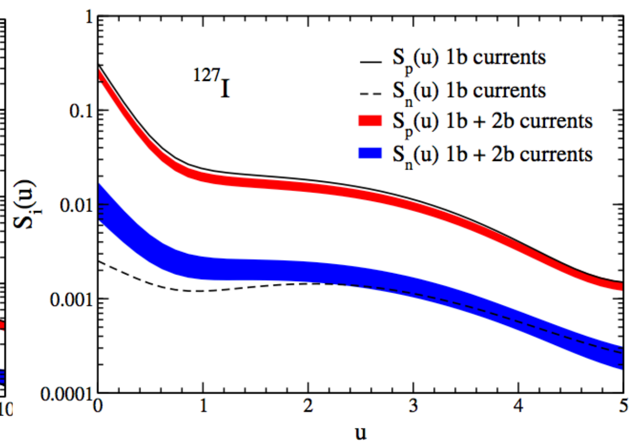
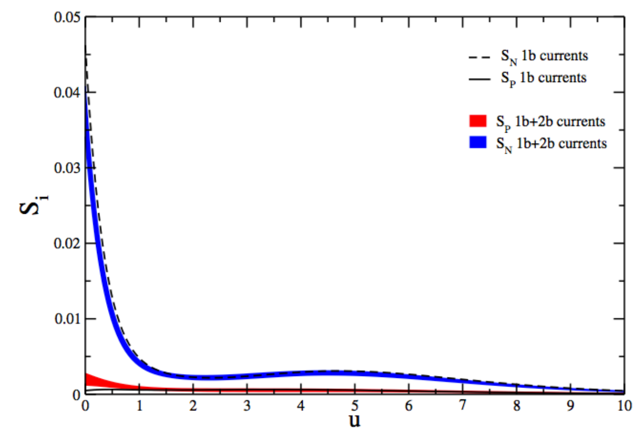



DAMA, ANAIS, DM-Ice




DAMA, ANAIS, DM-Ice, KIMS




CDMS-II

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