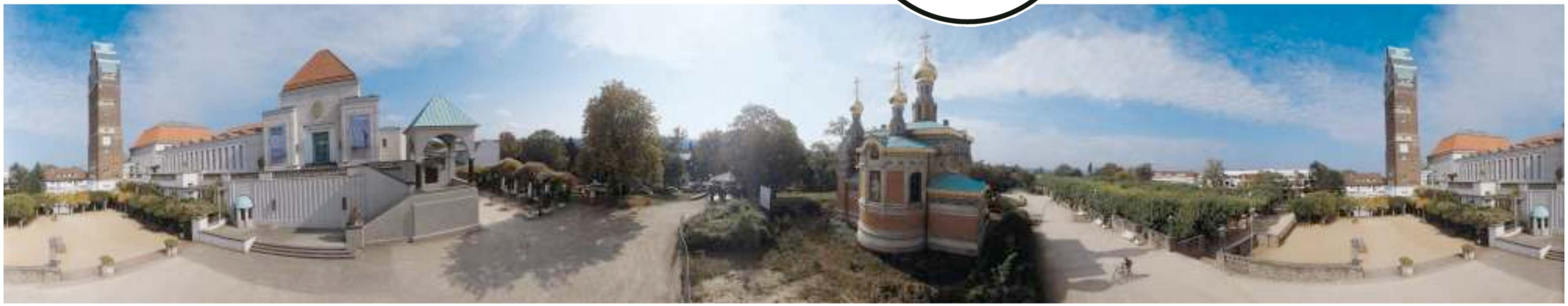
Chiral effective field theory and neutron-rich matter

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI



Block Course "Aspects of QCD at Finite Density"
University of Bielefeld, Sept. 22/23, 2011

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Minerva Stiftung

Bundesministerium für Bildung und Forschung


P

Outline

Chiral effective field theory for nuclear forces

Epelbaum, Hammer, Meissner, Rev. Mod. Phys. 81, 1773 (2009). Overview.
Epelbaum, Prog. Part. Nucl. Phys. 57, 654 (2006). Many useful details.
Bogner, Furnstahl, AS, Prog. Part. Nucl. Phys. 65, 94 (2010). Renormalization Group.

3N forces and neutron-rich nuclei

Otsuka, Suzuki, Holt, AS, Akaishi, Phys. Rev. Lett. 105, 032501 (2010).
Holt, Otsuka, AS, Suzuki, arXiv:1009.5984.
Holt, AS, arXiv:1108.2680.

3N forces and neutron matter, impact on neutron stars

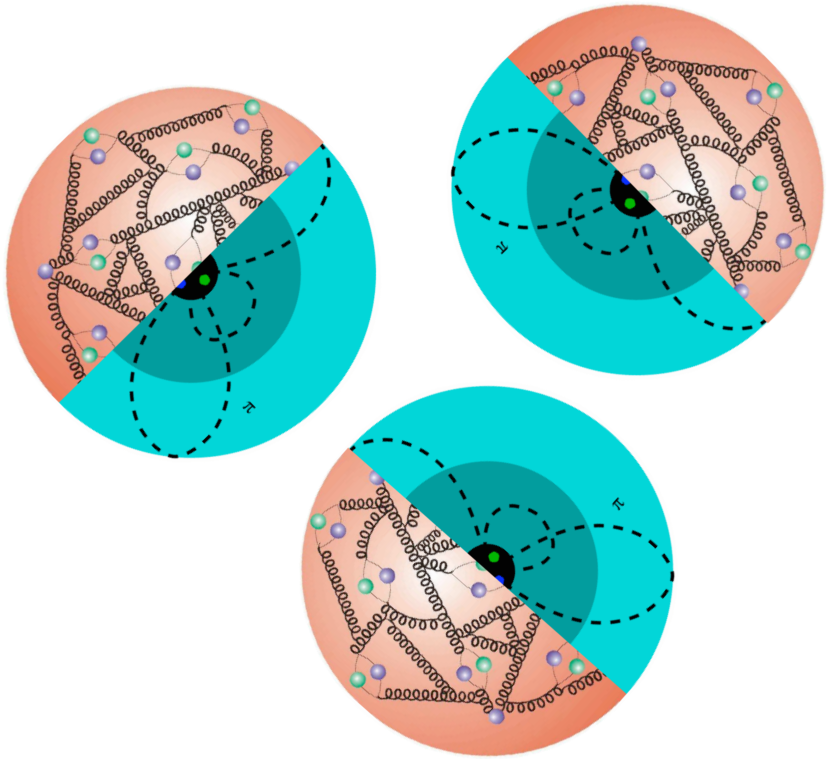
Hebeler, AS, Phys. Rev. C 82, 014314 (2010).
Hebeler, Lattimer, Pethick, AS, Phys. Rev. Lett. 105, 161102 (2010).

3N forces and electroweak currents

Menendez, Gazit, AS, Phys. Rev. Lett. 107, 062501 (2011).

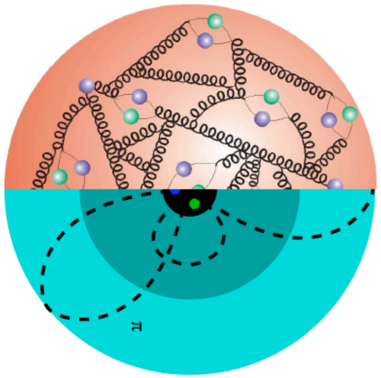
Contact: schwenk@physik.tu-darmstadt.de

The nuclear forces frontier

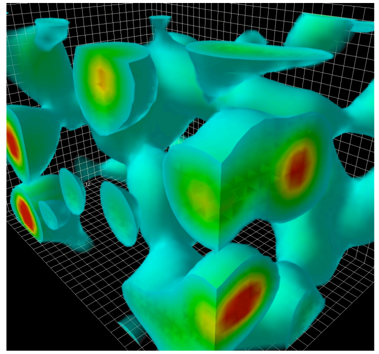


Λ / Resolution dependence

with high-energy probes:
quarks+gluons



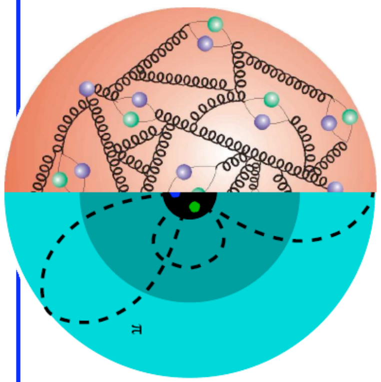
at low energies:
complex QCD vacuum



lowest energy excitations:
pions, nearly massless, m_π=140 MeV
'phonons' of QCD vacuum

Λ / Resolution dependence of nuclear forces

with high-energy probes:
quarks+gluons



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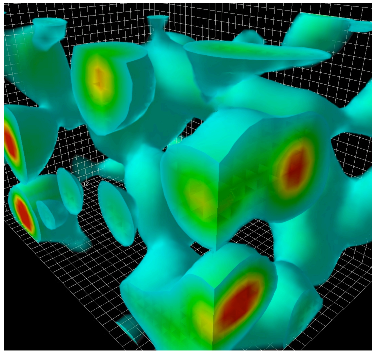
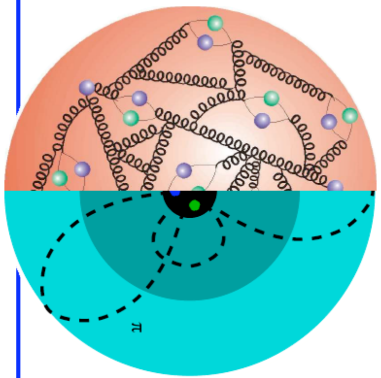


lowest energy excitations:
pions, nearly massless, m_π=140 MeV
'phonons' of QCD vacuum

Λ_{chiral}
momenta $Q \sim \lambda^{-1} \sim m_\pi$

$\Lambda_{\text{pionless}}$
momenta $Q \ll m_\pi$

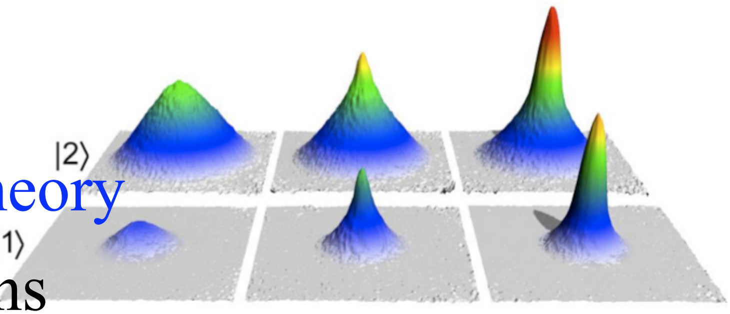
Λ / Resolution dependence of nuclear forces



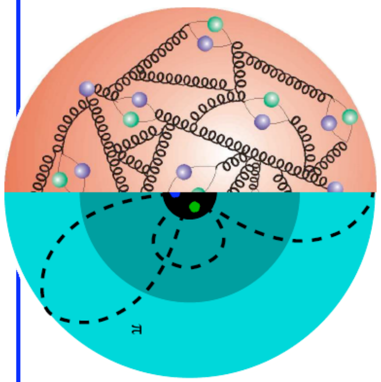
$\Lambda_{\text{pionless}}$

momenta $Q \ll m_\pi$: pionless effective field theory

large scattering length physics and corrections



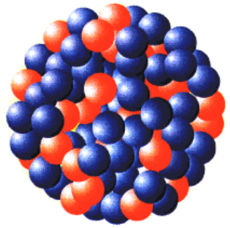
Λ / Resolution dependence of nuclear forces



Λ_{chiral}

momenta $Q \sim \lambda^{-1} \sim m_\pi$: chiral effective field theory

neutrons and protons interacting via pion exchanges
and shorter-range contact interactions

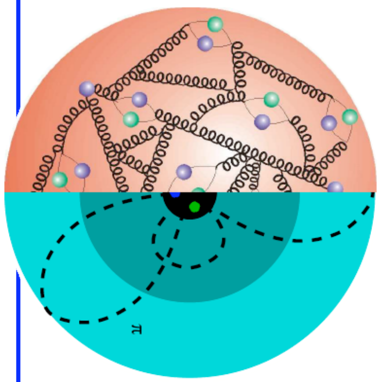


typical momenta in nuclei $\sim m_\pi$

$\Lambda_{pionless}$

momenta $Q \ll m_\pi$

Λ / Resolution dependence of nuclear forces



Effective theory for NN, 3N, many-N interactions and electroweak operators: resolution scale/Λ-dependent

$$H(\Lambda) = T + V_{\mathrm{NN}}(\Lambda) + V_{3\mathrm{N}}(\Lambda) + V_{4\mathrm{N}}(\Lambda) + \ldots$$

$\Lambda_{\mathrm{chiral}}$

momenta $Q \sim \lambda^{-1} \sim m_\pi$: chiral effective field theory

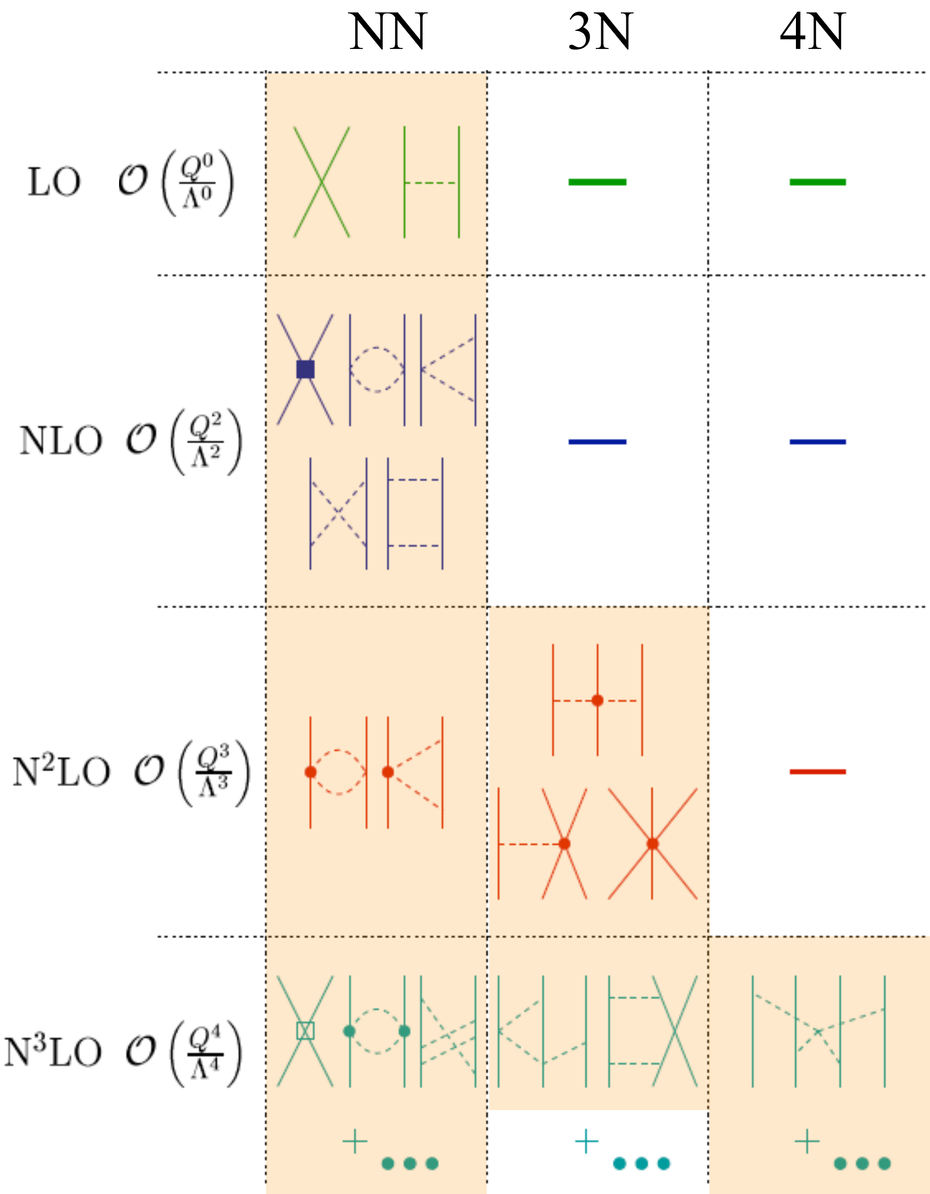
$\Lambda \downarrow$

$\Lambda_{\mathrm{pionless}}$

momenta $Q \ll m_\pi$

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 $(Q/\Lambda_b)^n$

LO, n=0 - leading order,
NLO, n=2 - next-to-leading order,…

expansion parameter ~ 1/3

(compare to multipole expansion
for a charge distribution)

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

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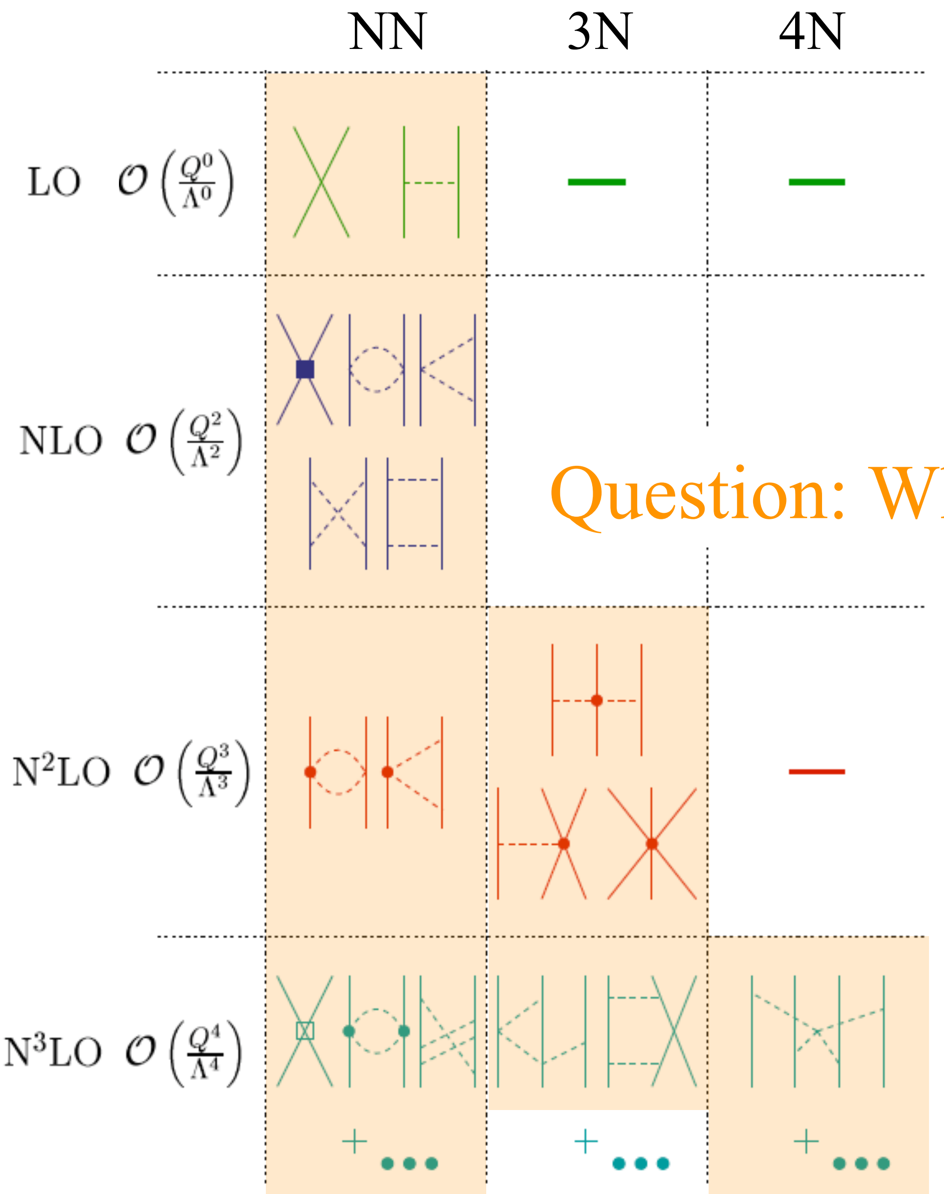

limited resolution at low energies, can expand in powers $(Q/\Lambda_b)^n$

LO, n=0 - leading order,
NLO, n=2 - next-to-leading order,…

Question: Why is there no n=1 contribution?

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

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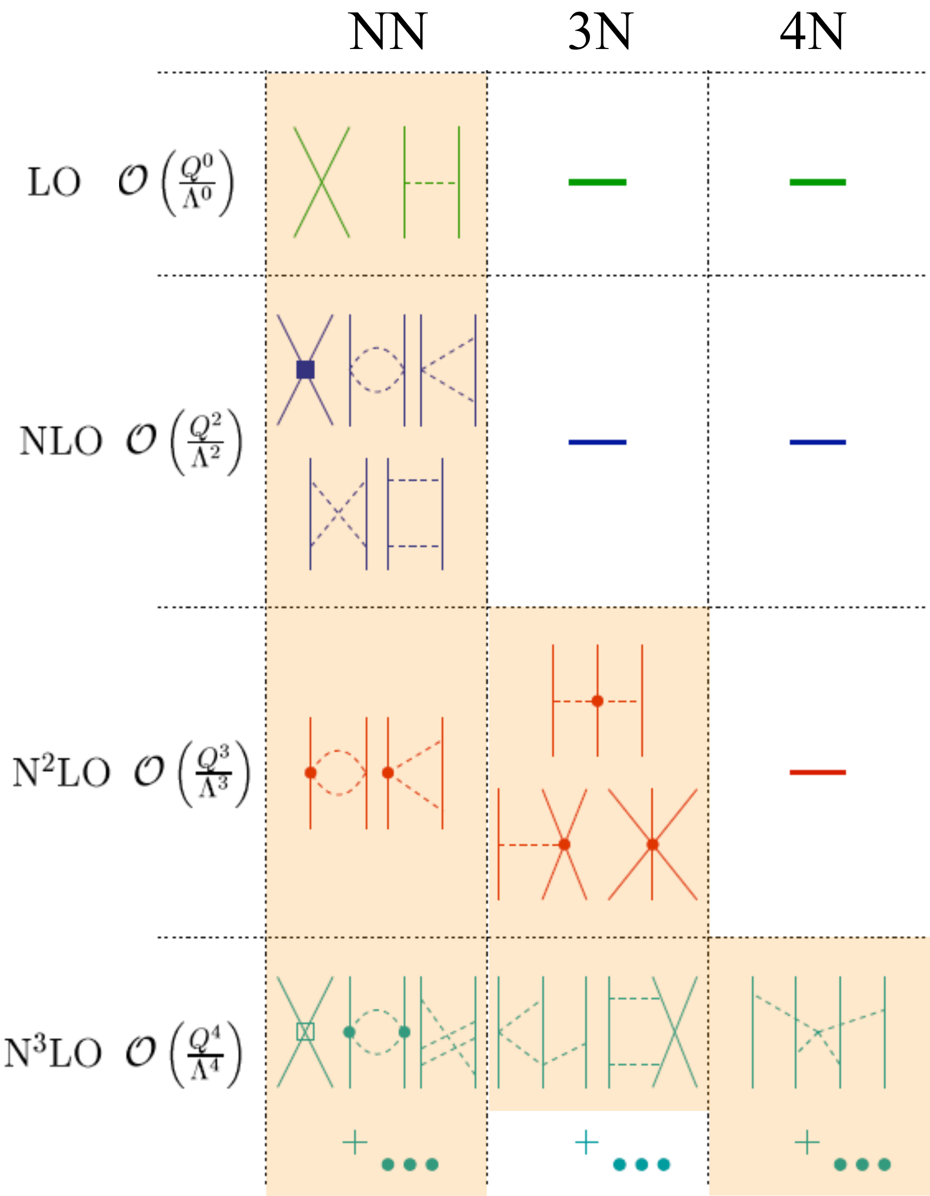

include long-range pion physics

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

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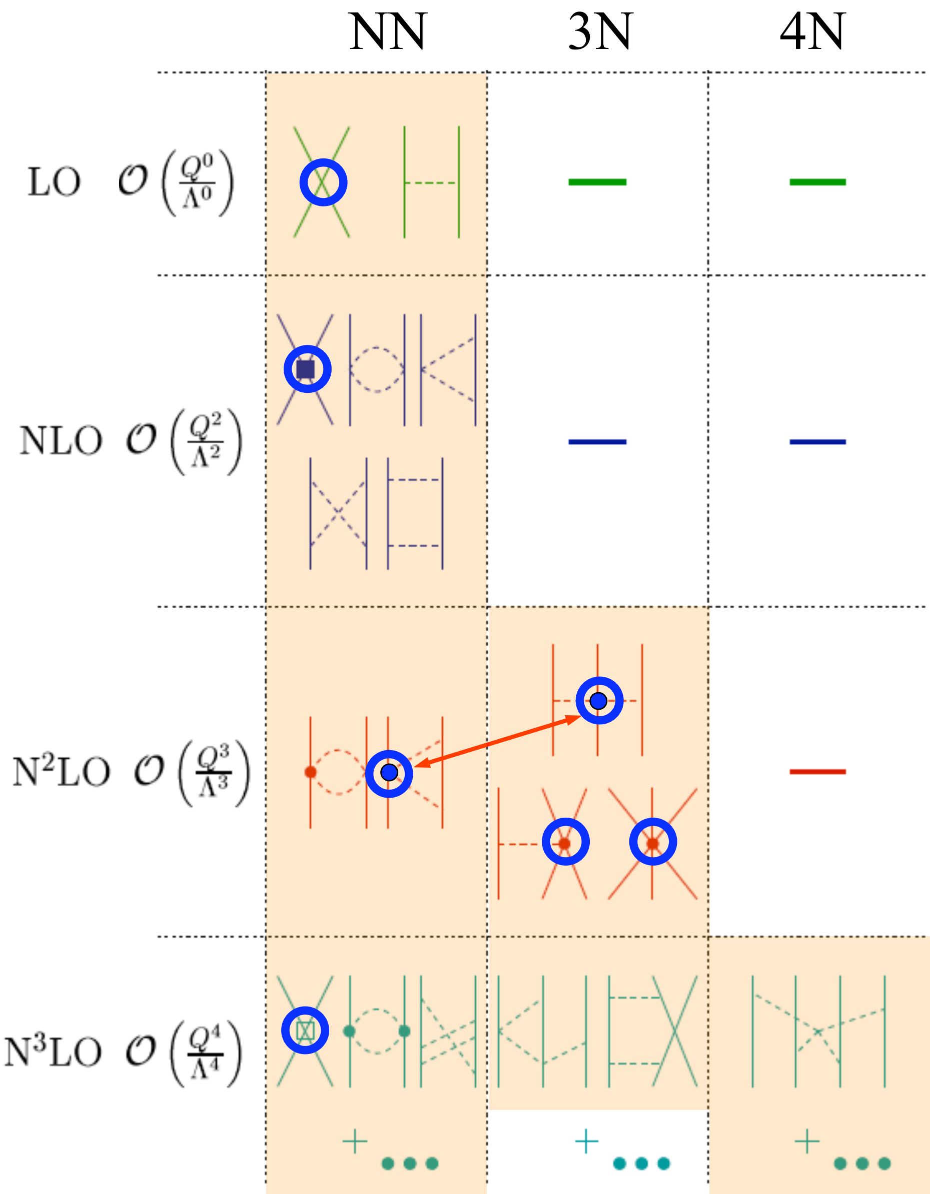


include long-range pion physics

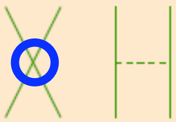
details at short distance not resolved

capture in few short-range couplings,
fit to experiment once, Λ-dependent

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

Chiral Effective Field Theory for nuclear forces

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

		NN	3N	4N
LO	$\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$		—	—

Question: What is V(r) for NN interactions at LO?

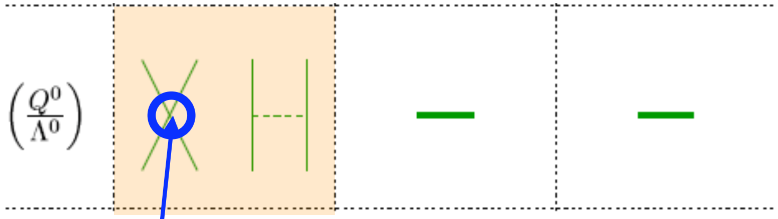
Hint: One-pion exchange + contact interaction
but with resolution scale Λ~500 MeV (cutoff on momenta)

Chiral Effective Field Theory for nuclear forces

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

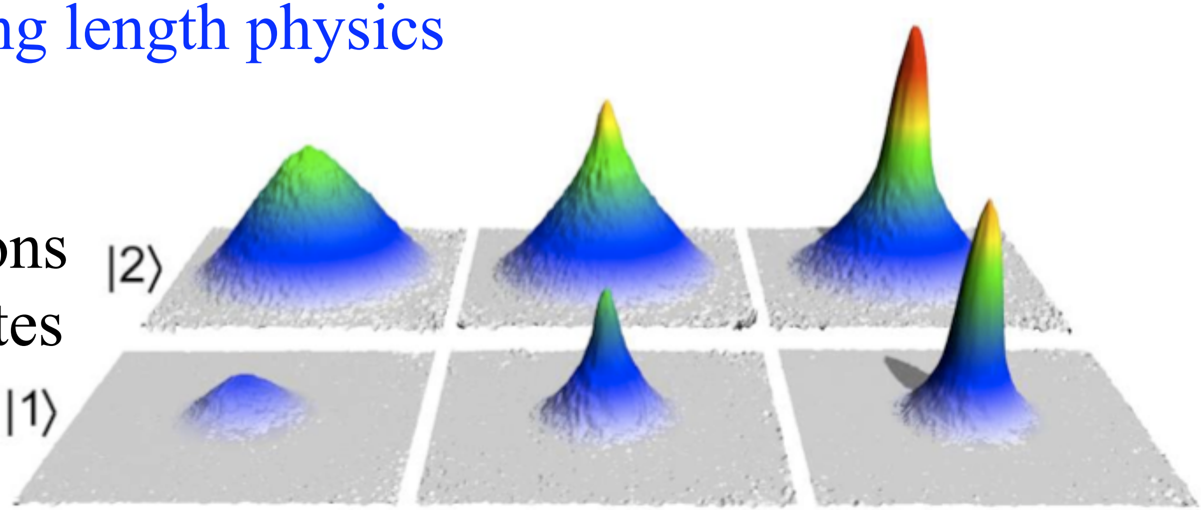
NN 3N 4N

LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$



large scattering length physics

^{6}Li fermions
2 spin states



from M. Zwierlein

neutrons with same density and temperature
have the same properties!

Chiral Effective Field Theory for nuclear forces

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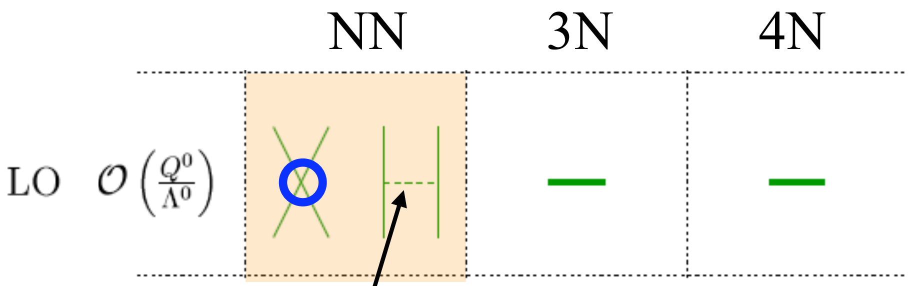
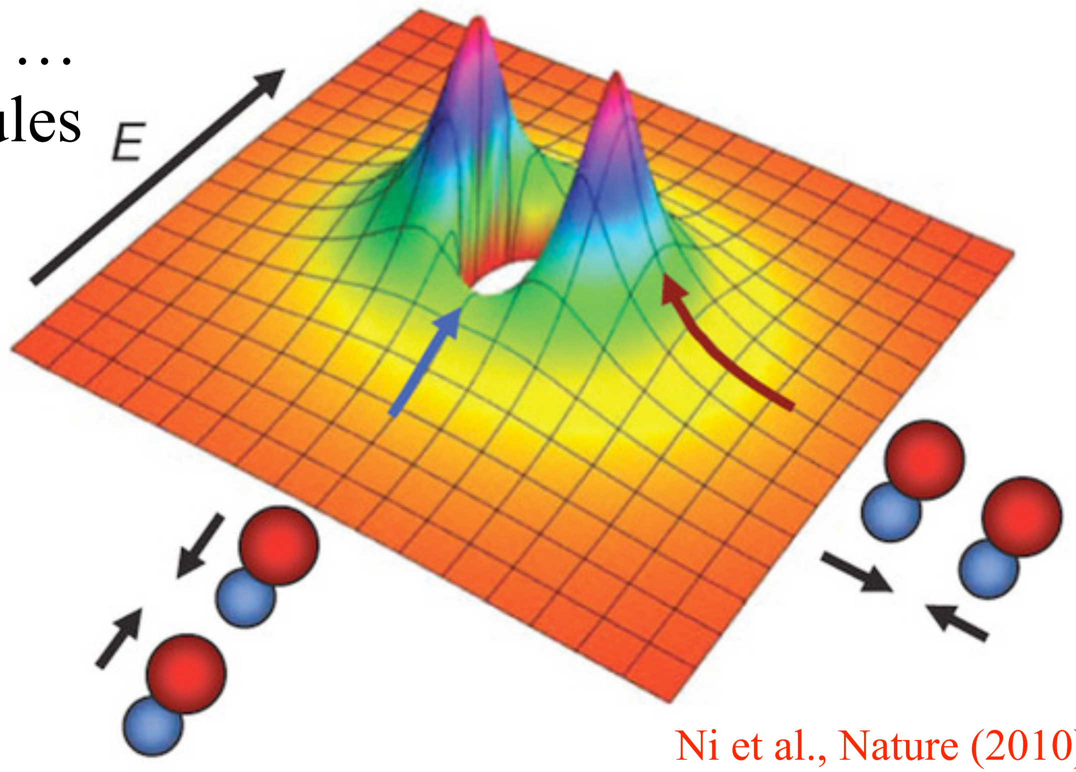


pion tensor/dipole interactions + …

→ compare to cold polar molecules



Ni et al., Nature (2010)

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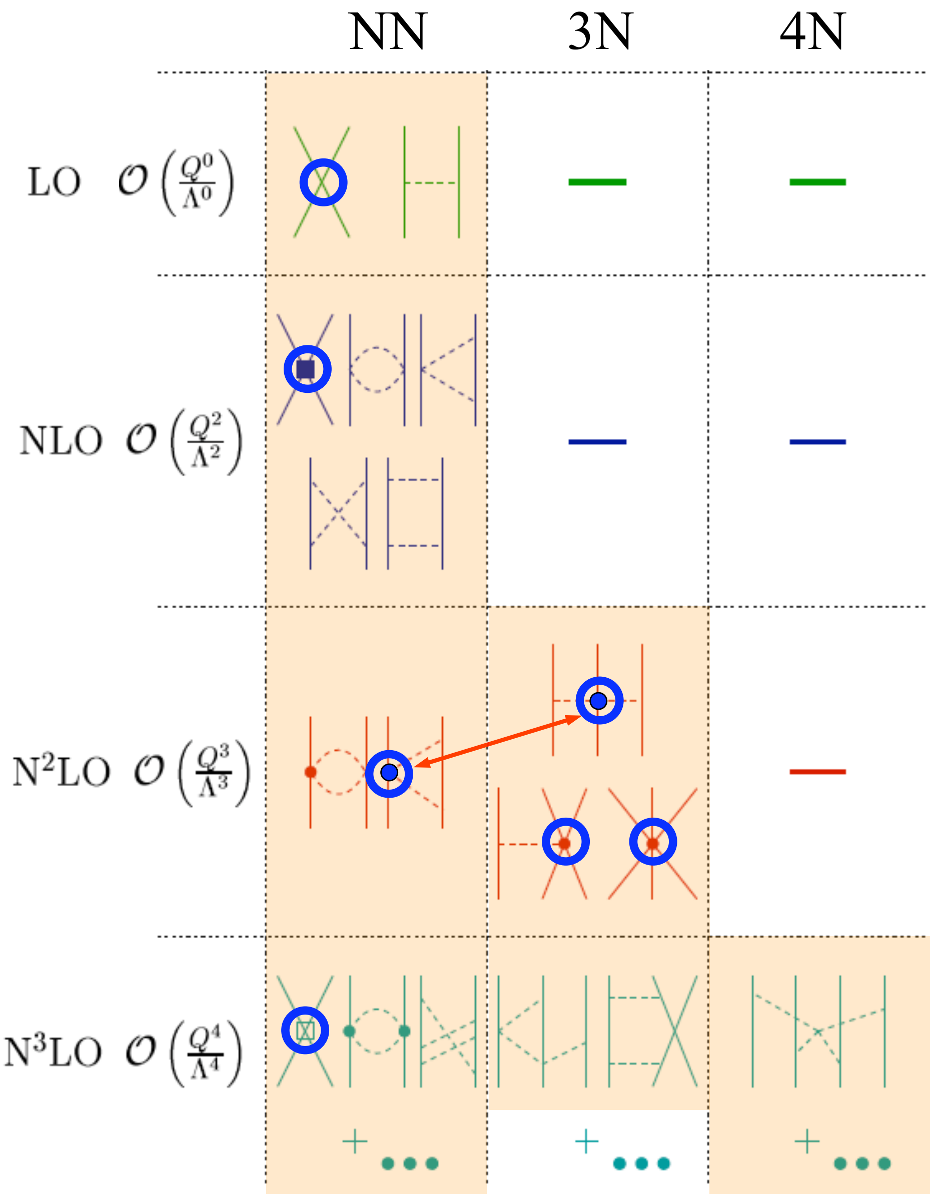
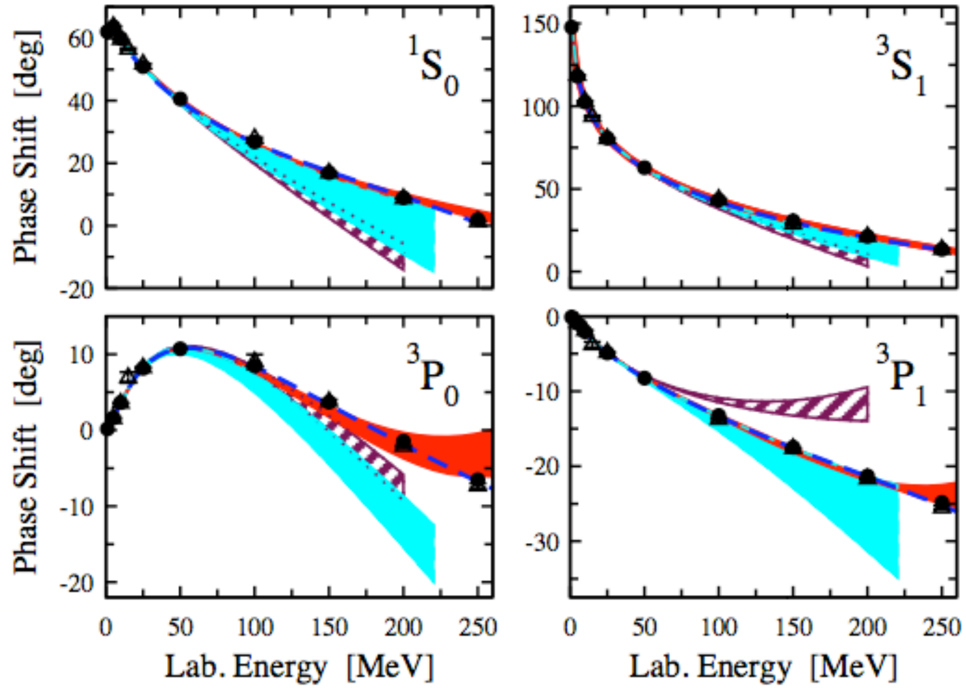


systematic: can work to desired accuracy and obtain error estimates from truncation order and Λ variation

accurate reproduction of
low-energy NN scattering at N^{3}LO

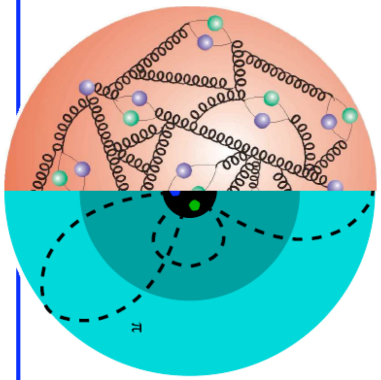


Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Nuclear forces and the Renormalization Group (RG)

RG evolution to lower resolution/cutoffs Bogner, Kuo, AS, Furnstahl,…

$$H(\Lambda) = T + V_{\rm NN}(\Lambda) + V_{\rm 3N}(\Lambda) + V_{\rm 4N}(\Lambda) + \ldots$$



$\Lambda_{\rm chiral}$

Λ

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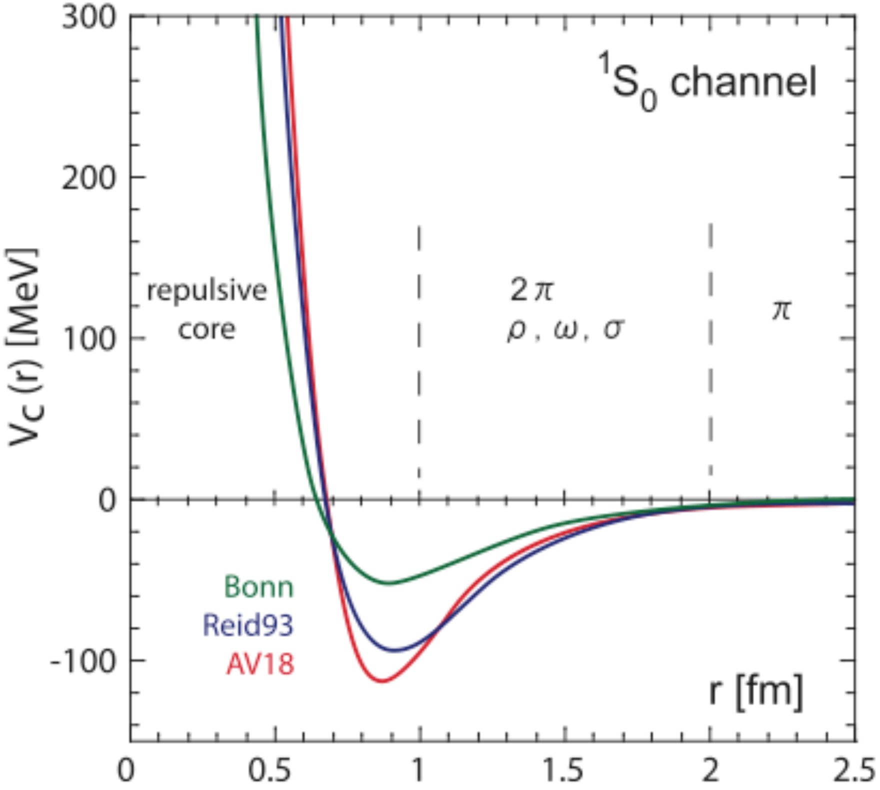
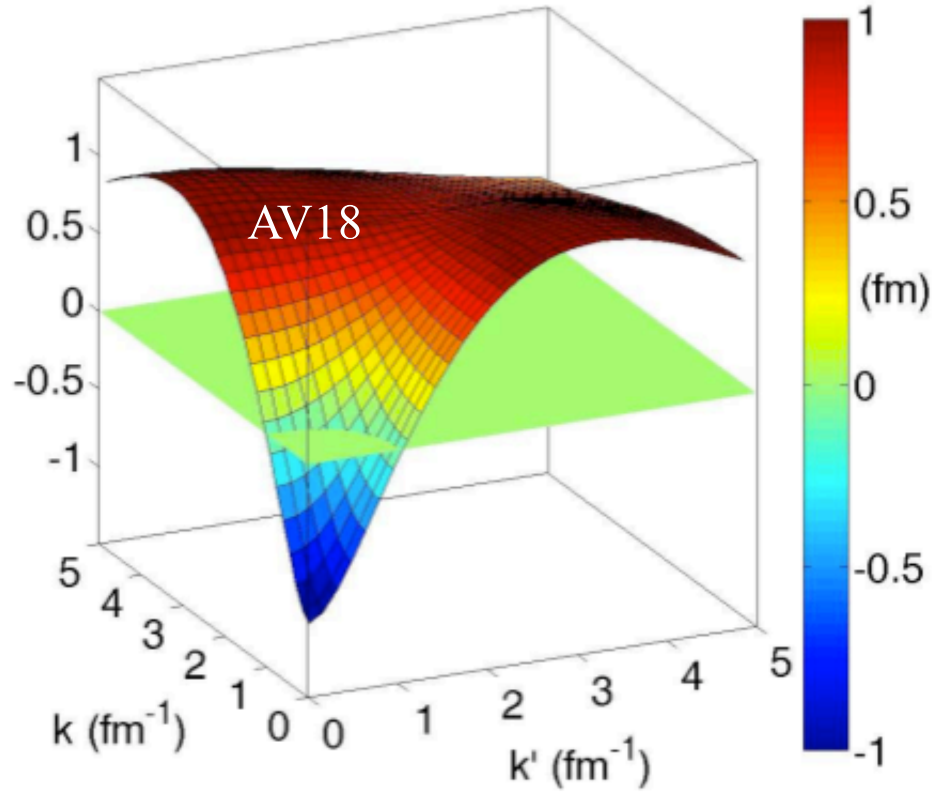
for NN interactions (preserves NN observables)





red = short-range repulsion

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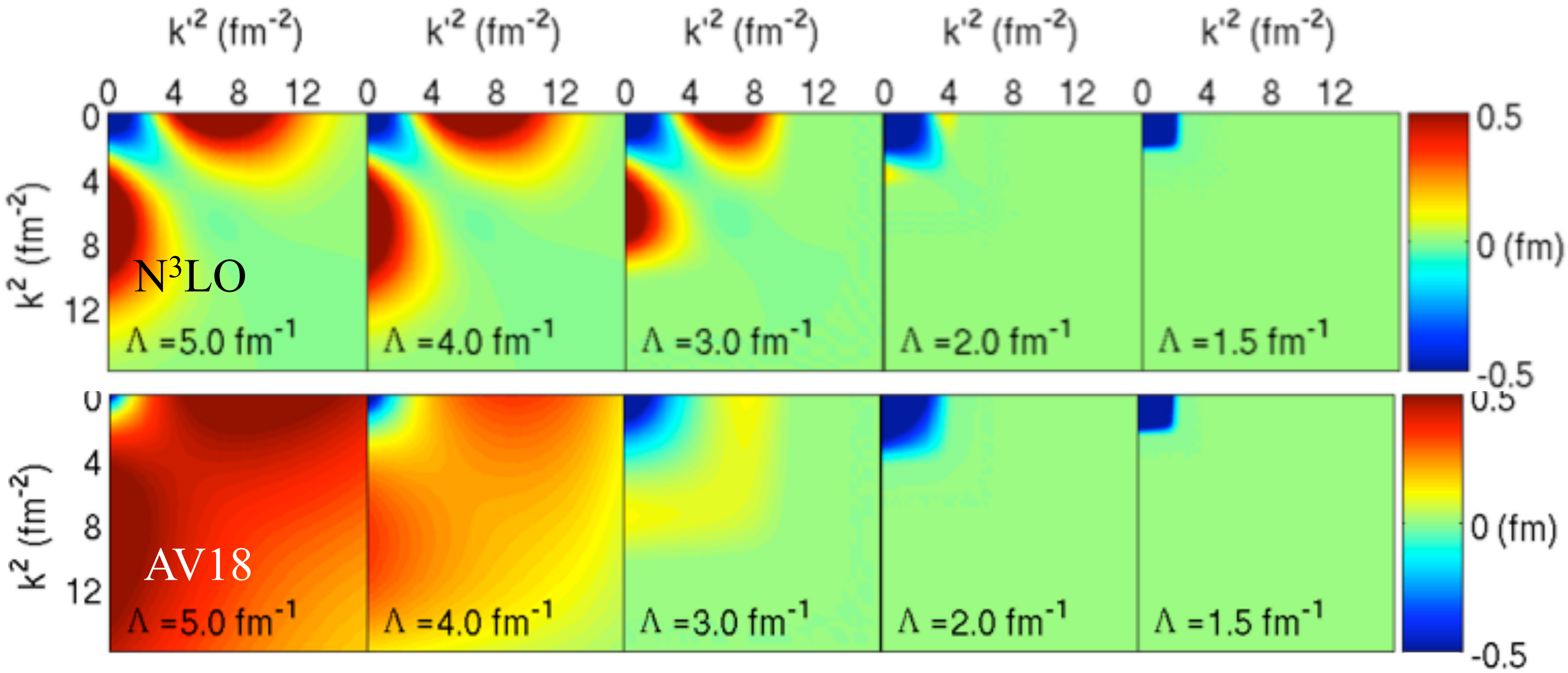

low-momentum interactions $V_{\mathrm{low}\,k}(\Lambda)$

RG decouples low-momentum physics from high momenta

Nuclear forces and the Renormalization Group (RG)

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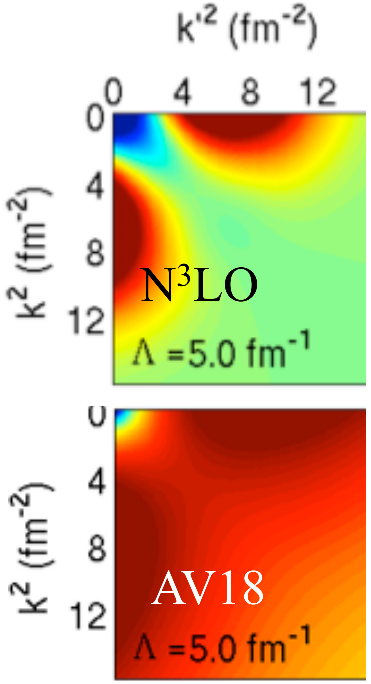
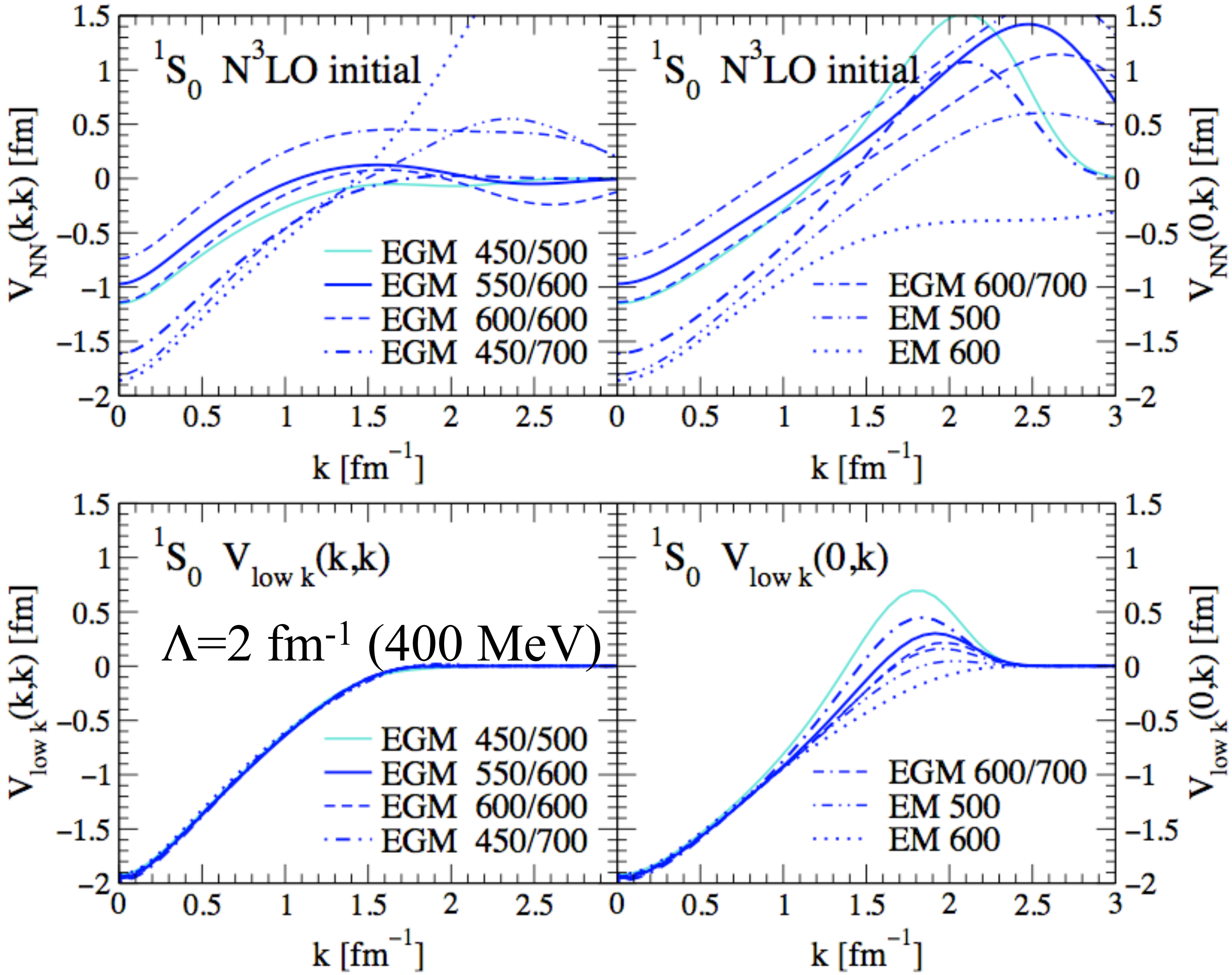




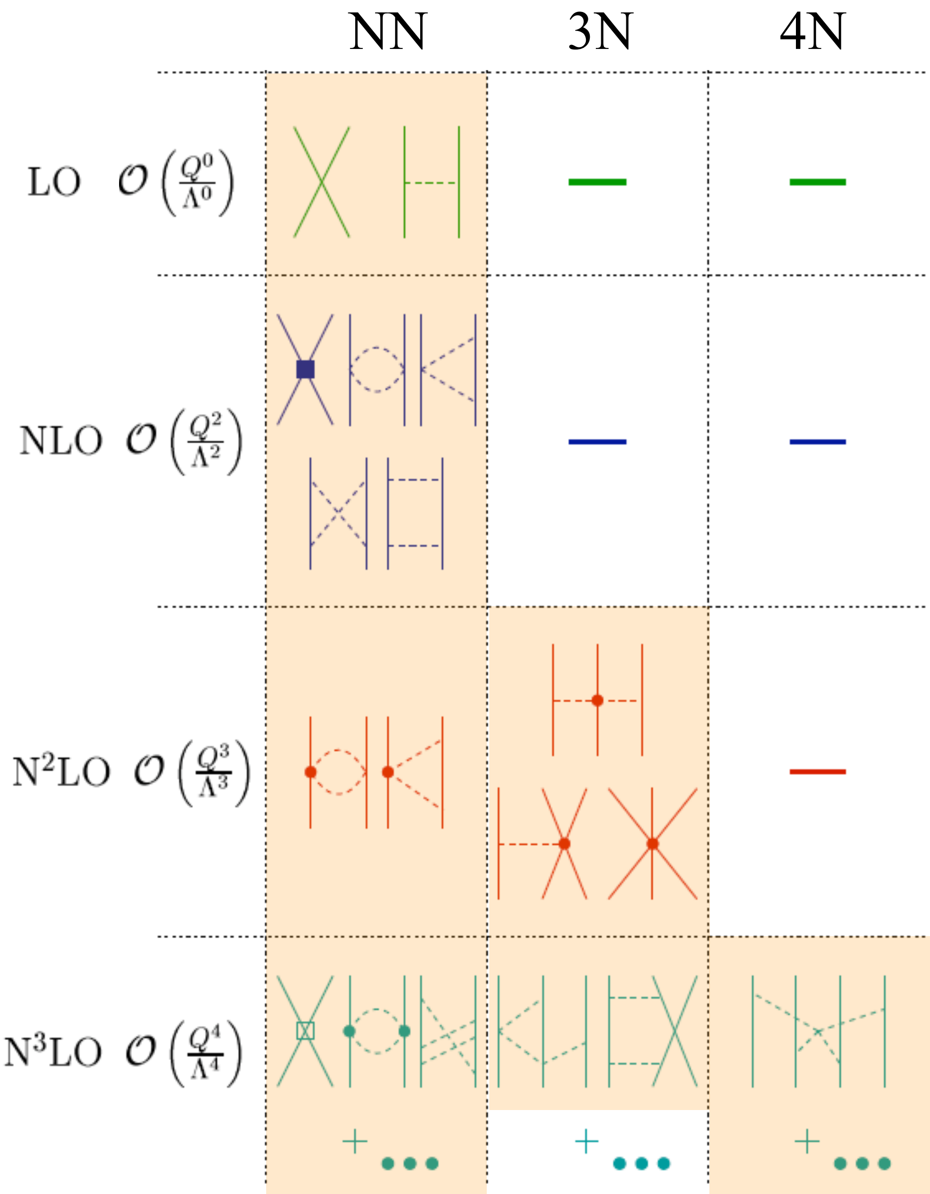
low-momentum i

RG decouples lov

low-momentum universality from different chiral N^{3}LO potentials

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 $(Q/\Lambda_b)^n$

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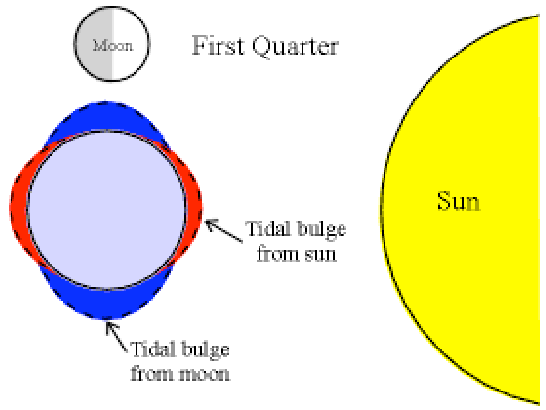
expansion parameter ~ 1/3

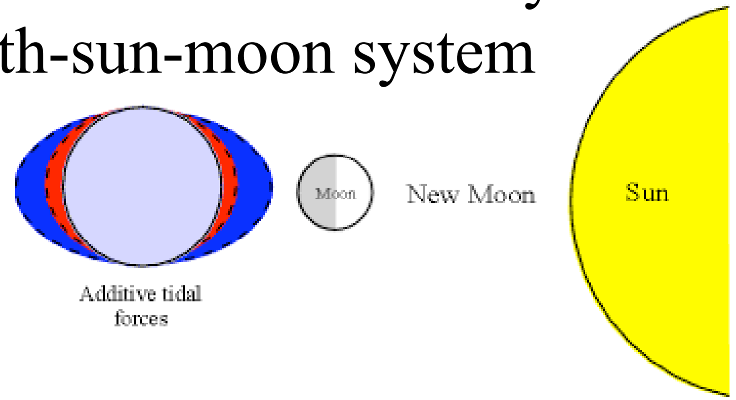
(compare to multipole expansion for a charge distribution)

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

Why are there three-body forces?

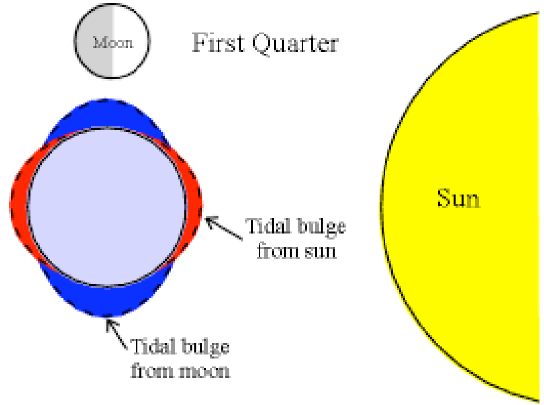


tidal effects lead to 3-body forces
in earth-sun-moon system

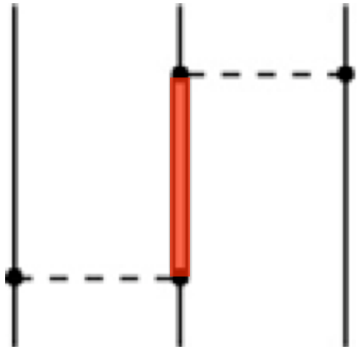


Why are there three-nucleon (3N) forces?

Nucleons are finite-mass composite particles,
can be excited to resonances



dominant contribution from Δ(1232 MeV)



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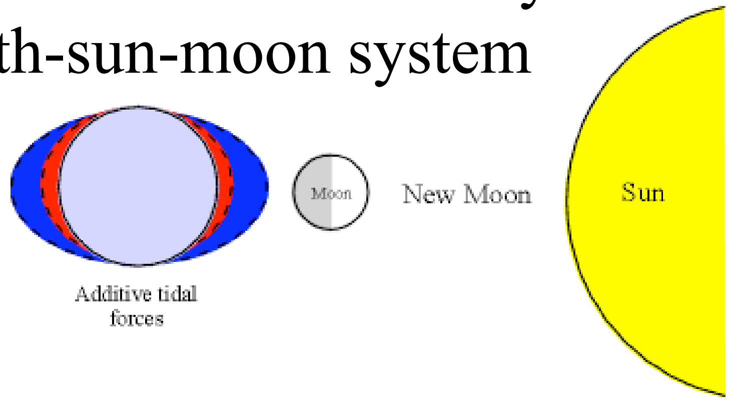
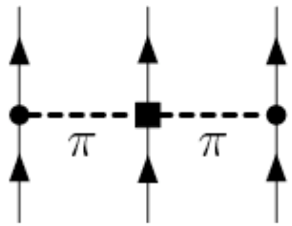
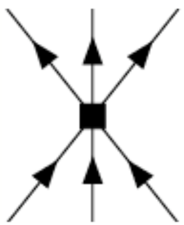


+ many shorter-range parts

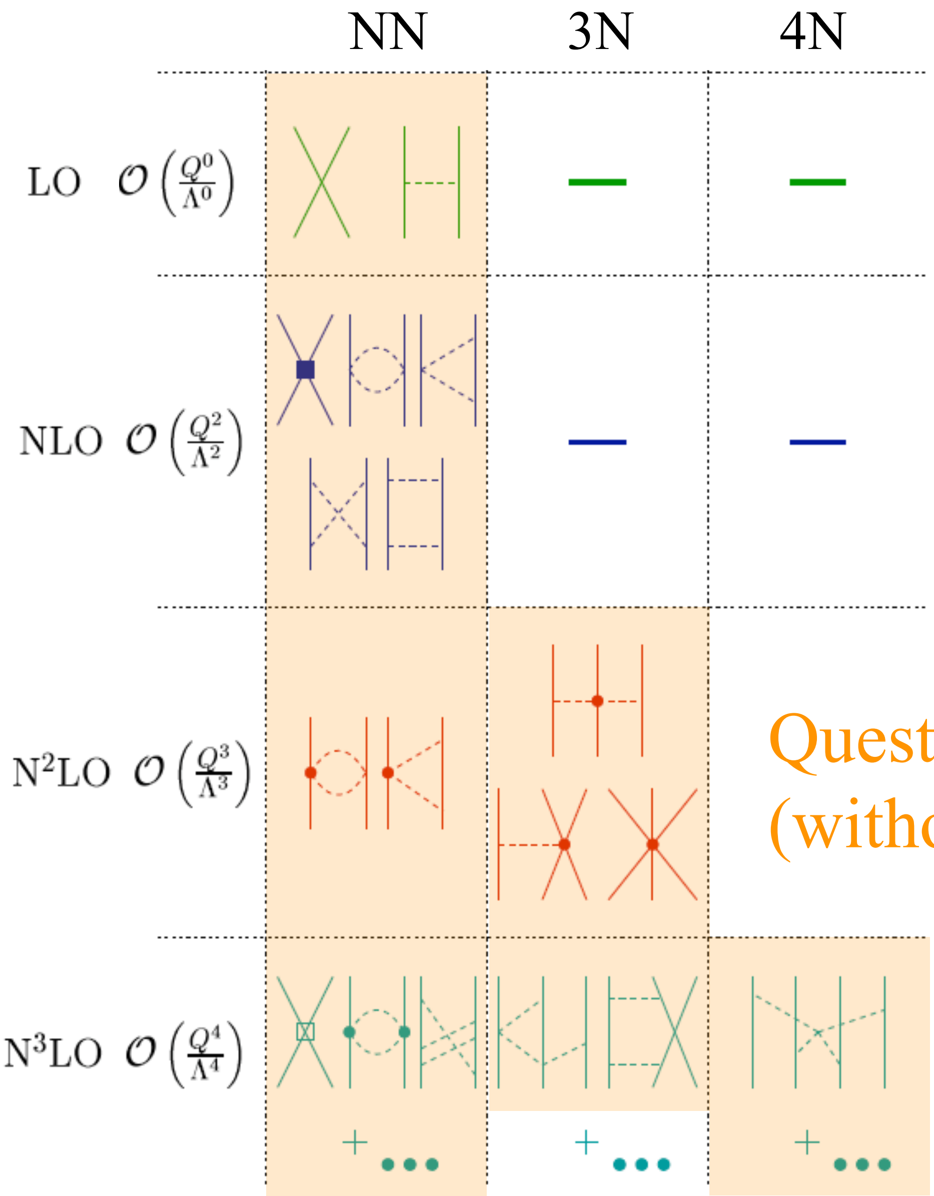
in chiral EFT (Delta-less): 

+ shorter-range parts

in pionless EFT:  + higher-order parts

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 $(Q/\Lambda_b)^n$

LO, n=0 - leading order,
NLO, n=2 - next-to-leading order,…

Question: Why do 3N forces start at n=3
(without explicit Deltas)?

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

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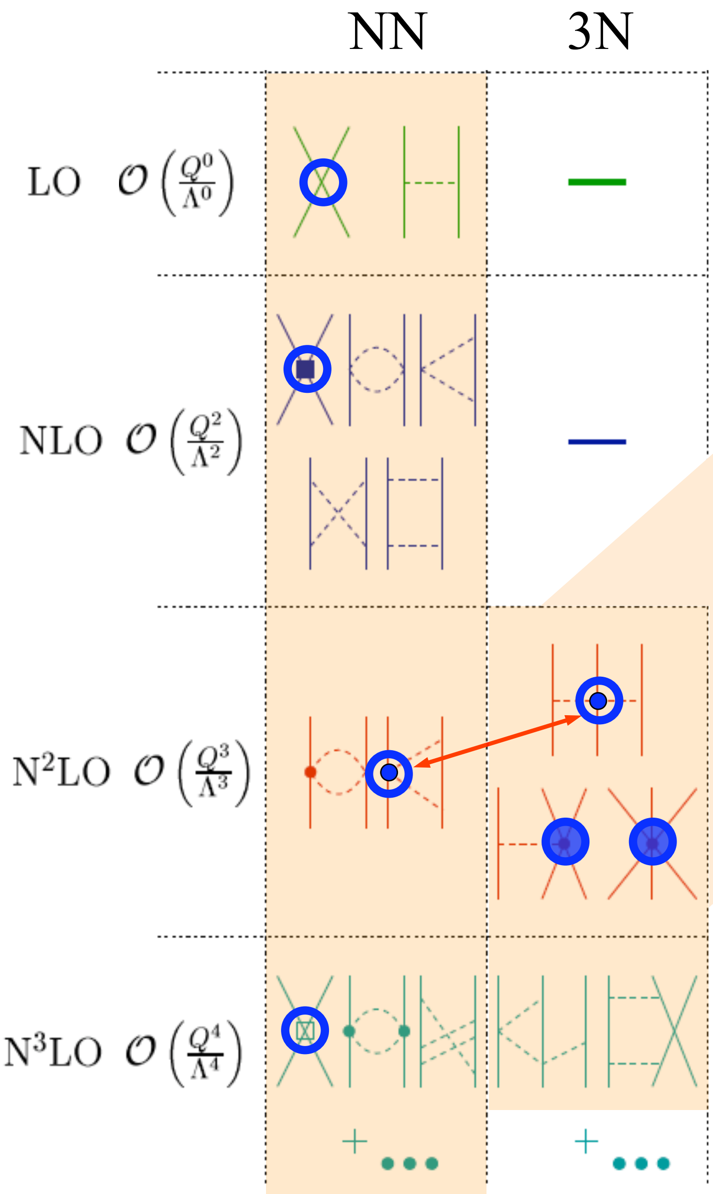
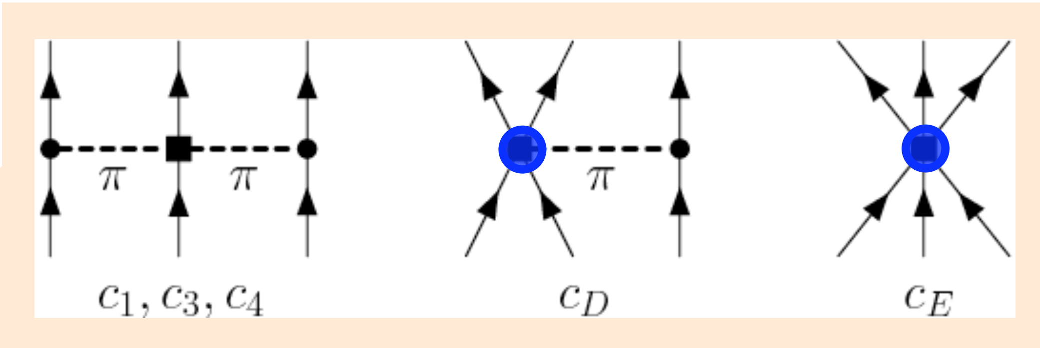


consistent NN-3N interactions

3N,4N: only 2 new couplings to N³LO



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

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

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

c_D, c_E fit to ^{3}H binding energy and ^{4}He radius (or ^{3}H beta decay half-life)

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

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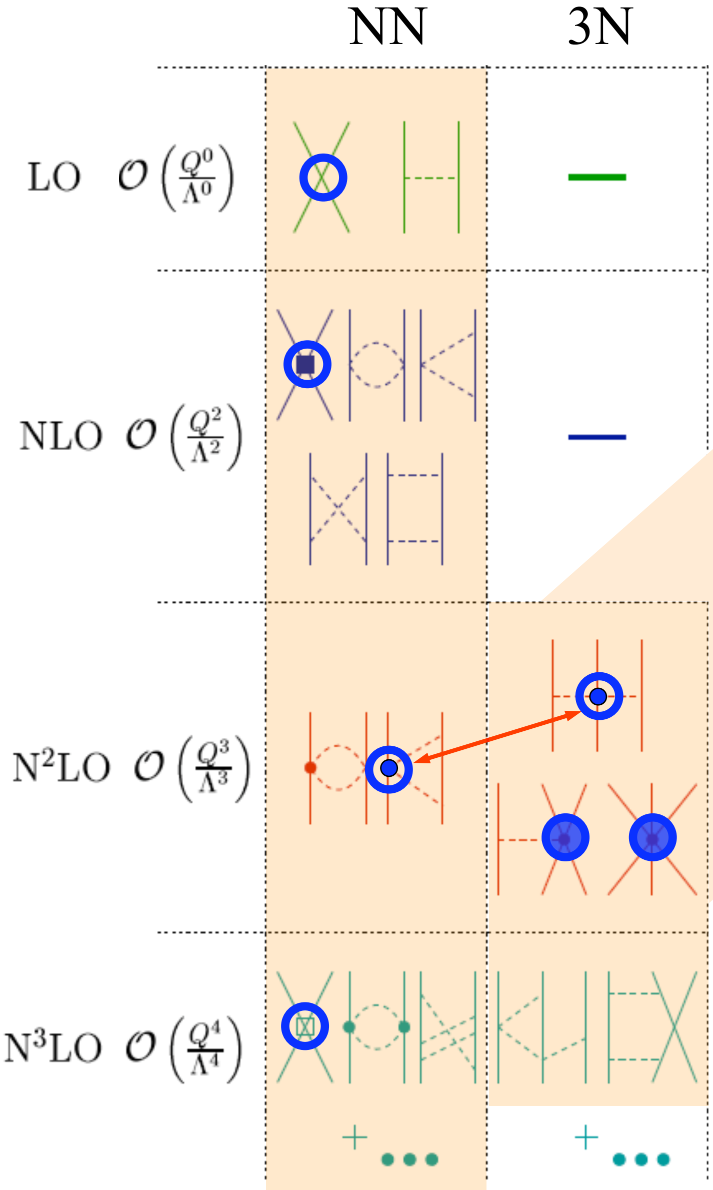

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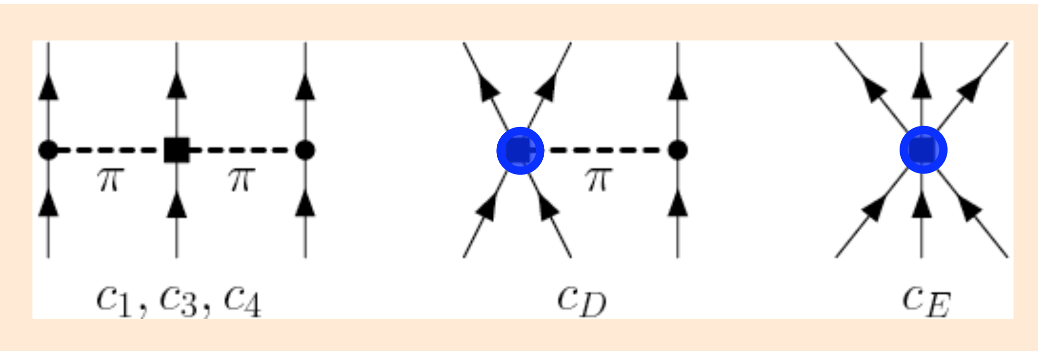


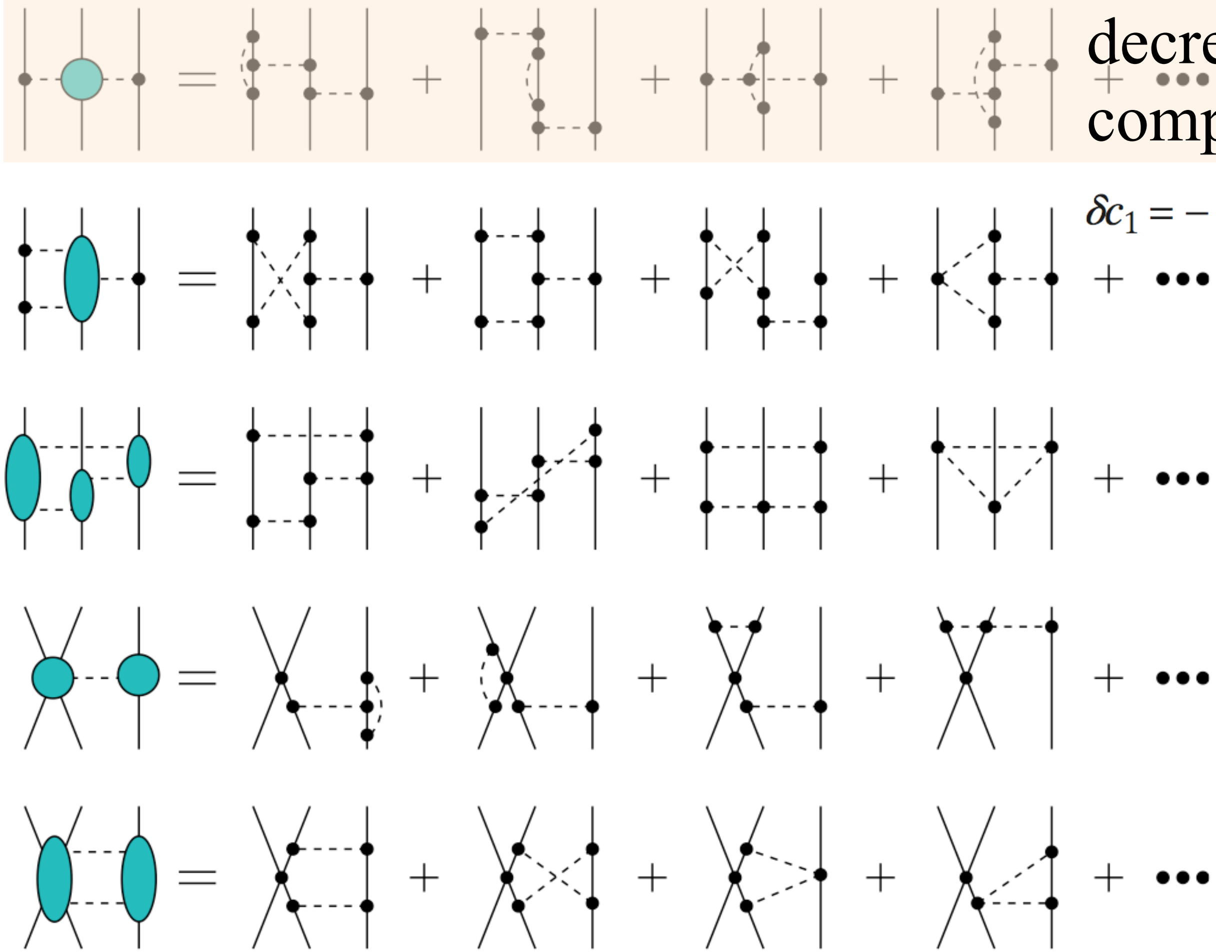
Question: Why are the next order
3N forces (n=4) parameter-free
(without new 3N contact interactions)?

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

Subleading chiral 3N forces

parameter-free N^{3}LO from Epelbaum et al.; Bernard et al. (2007), Ishikawa, Robilotta (2007)

one-loop contributions:
2π-exchange, 2π-1π-exchange, rings, contact-1π-, contact-2π-exchange



decrease c_i strengths
comparable to N^{2}LO uncertainty

$\delta c_1 = -g_A^2 M_\pi / 64\pi F_\pi^2$, $\delta c_3 = -\delta c_4 = g_A^4 M_\pi / 16\pi F_\pi^2$

$\delta c_3 = -\delta c_4 = 1\ \mathrm{GeV}^{-1}$

1/m corrections: spin-orbit parts, interesting for A_y puzzle

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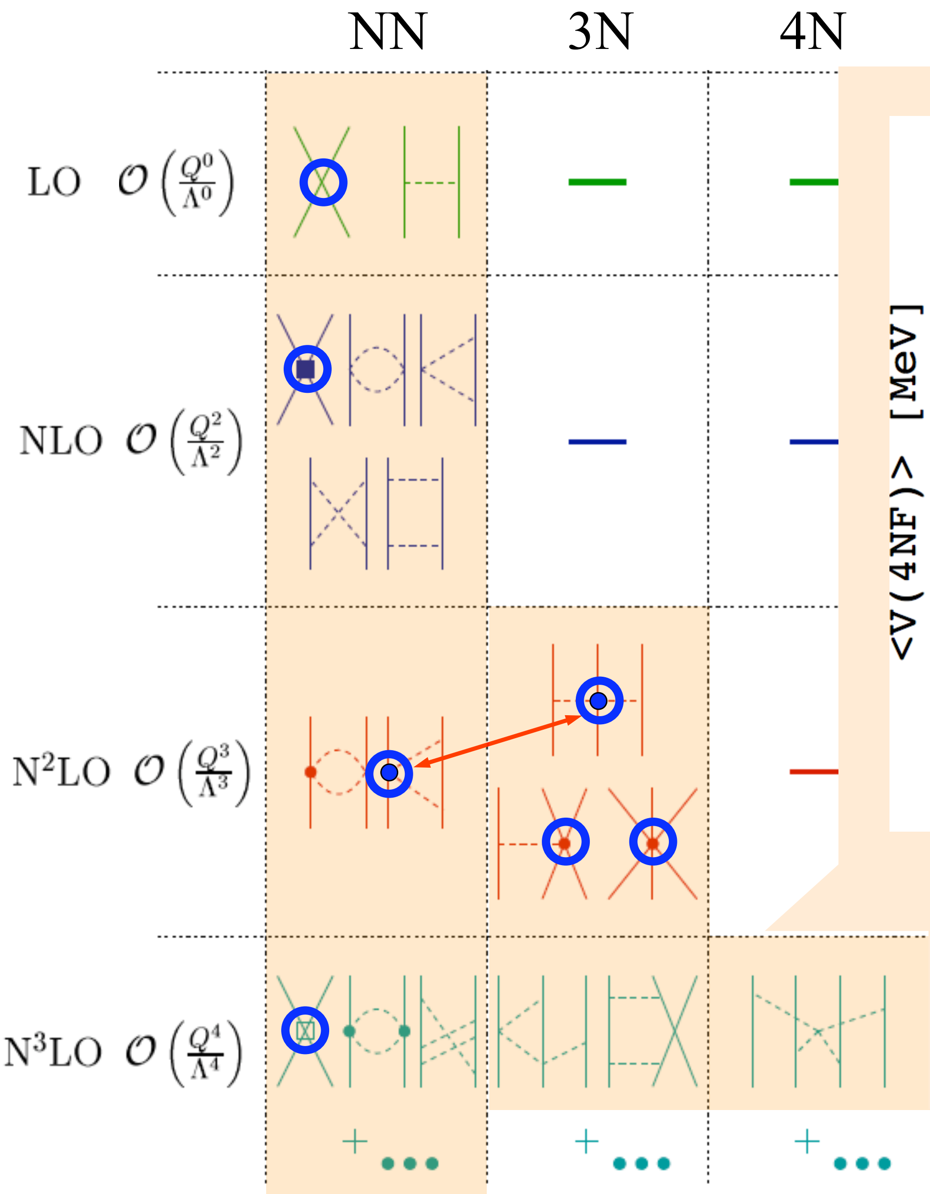

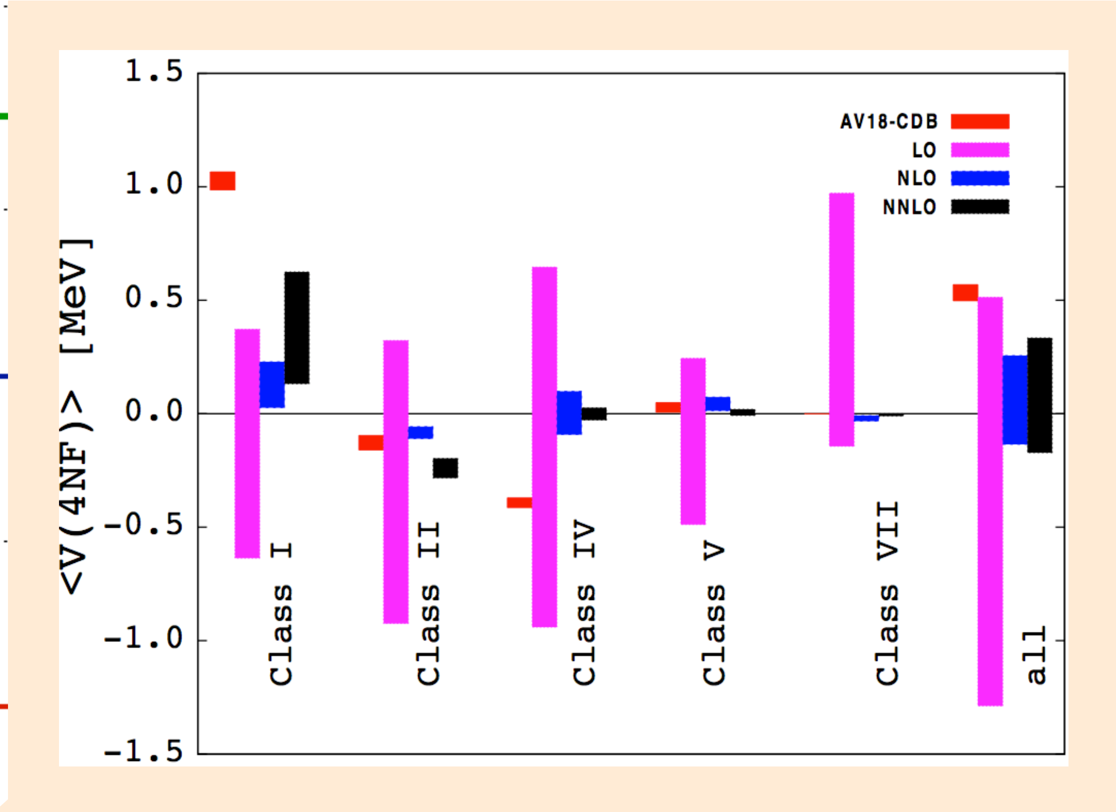

first perturbative estimate of 4N forces Nogga et al. (2010)

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

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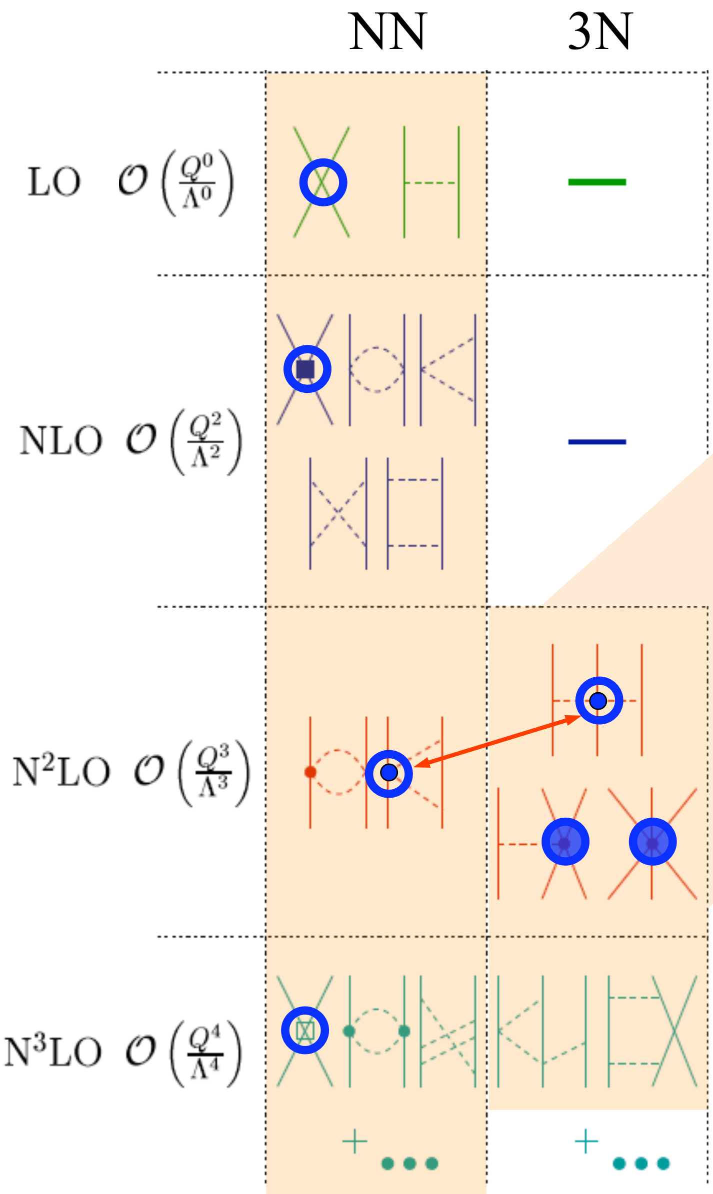

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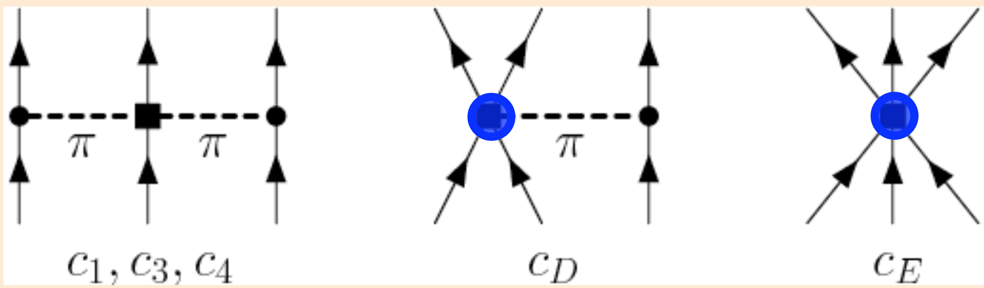

c_i from πN and NN Meissner et al. (2007)

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c_D, c_E fit to ^{3}H binding energy and ^{4}He radius (or ^{3}H beta decay half-life)

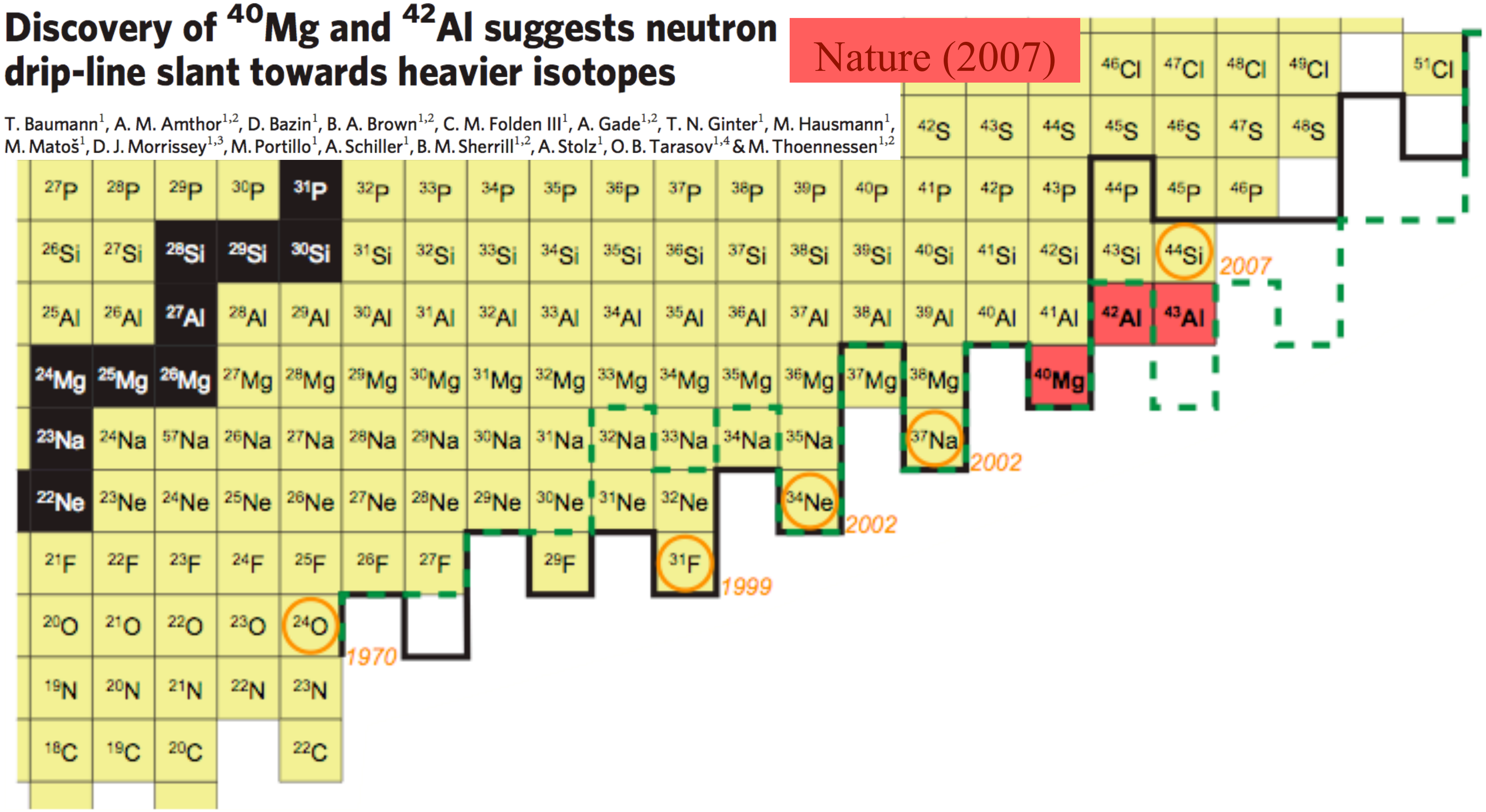
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Towards the limits of existence - the neutron drip-line

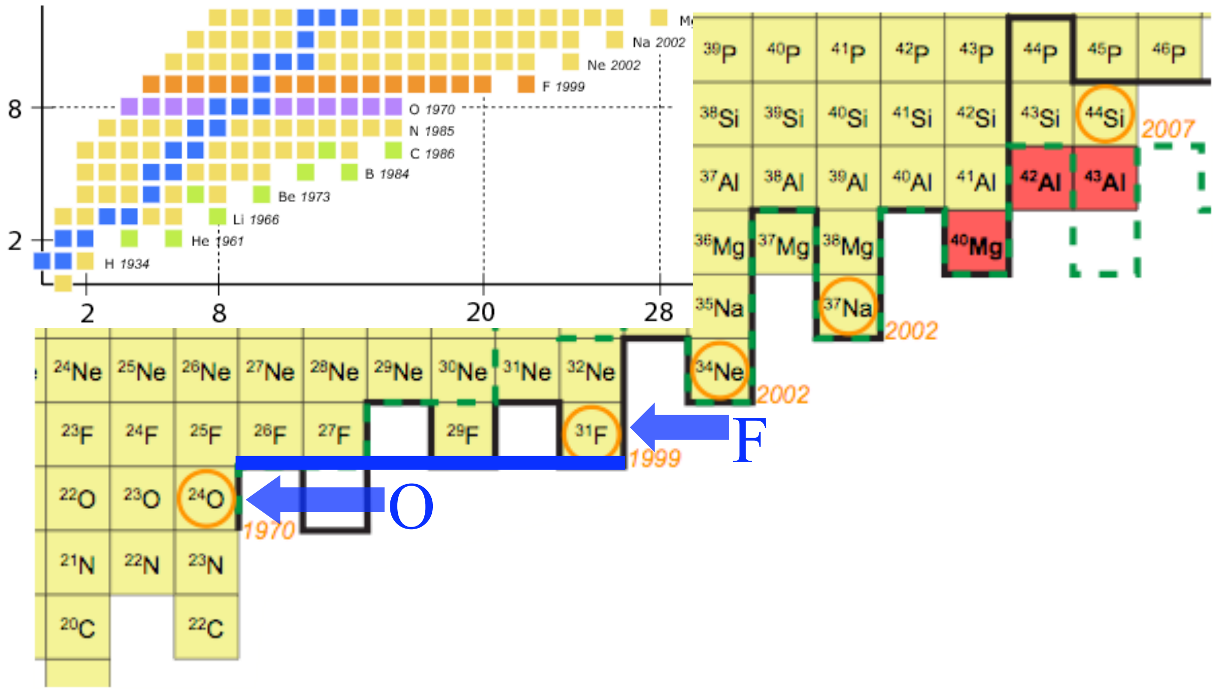
Discovery of ^{40}Mg and ^{42}Al suggests neutron drip-line slant towards heavier isotopes

Nature (2007)

T. Baumann[1], A. M. Amthor[1,2], D. Bazin[1], B. A. Brown[1,2], C. M. Folden III[1], A. Gade[1,2], T. N. Ginter[1], M. Hausmann[1], M. Matoš[1], D. J. Morrissey[1,3], M. Portillo[1], A. Schiller[1], B. M. Sherrill[1,2], A. Stolz[1], O. B. Tarasov[1,4] & M. Thoennessen[1,2]



The oxygen anomaly



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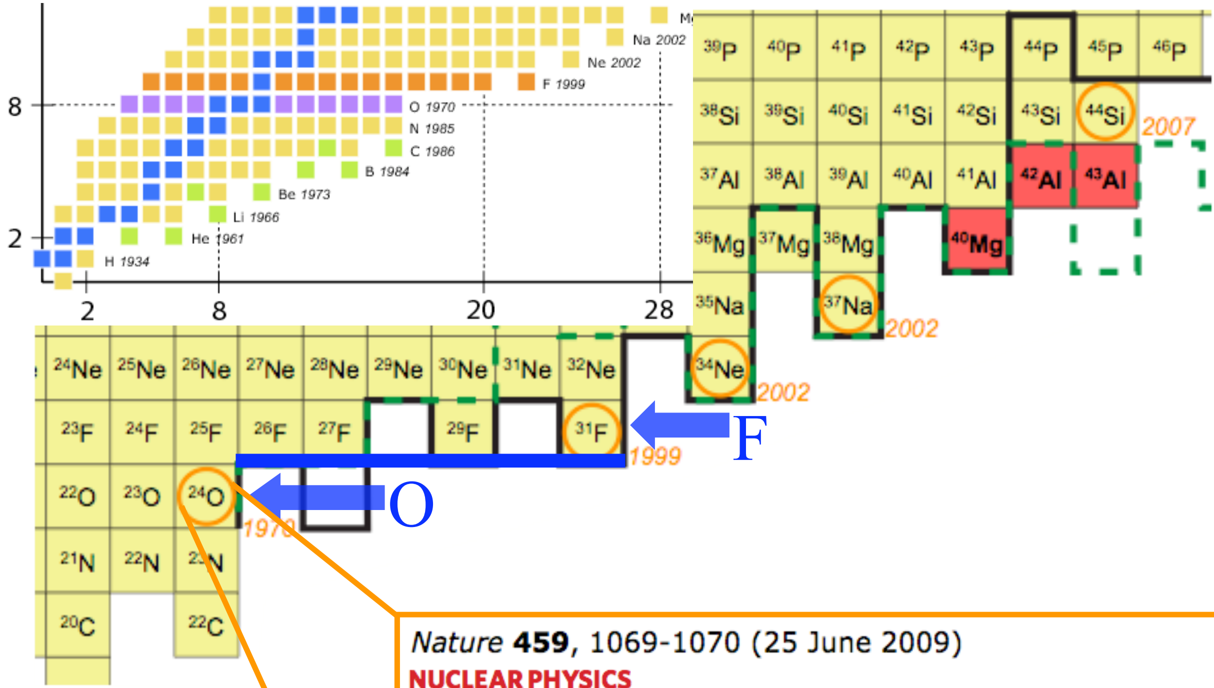


Nature **459**, 1069-1070 (25 June 2009)

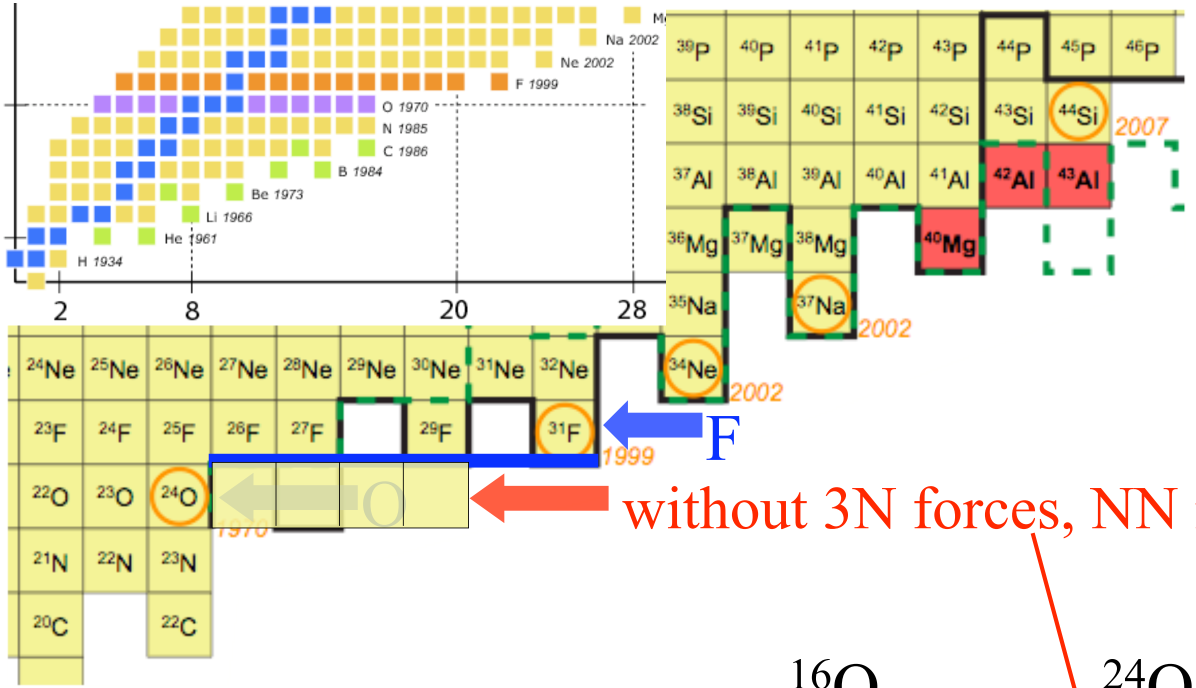
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

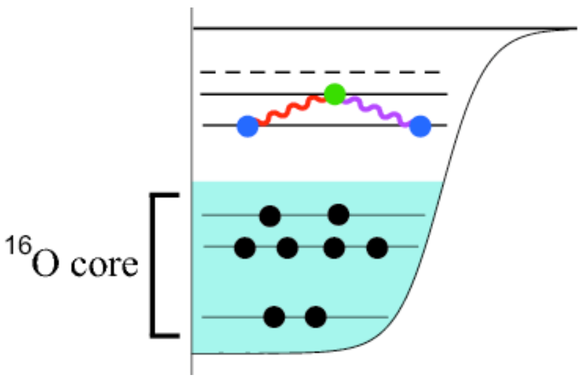
Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

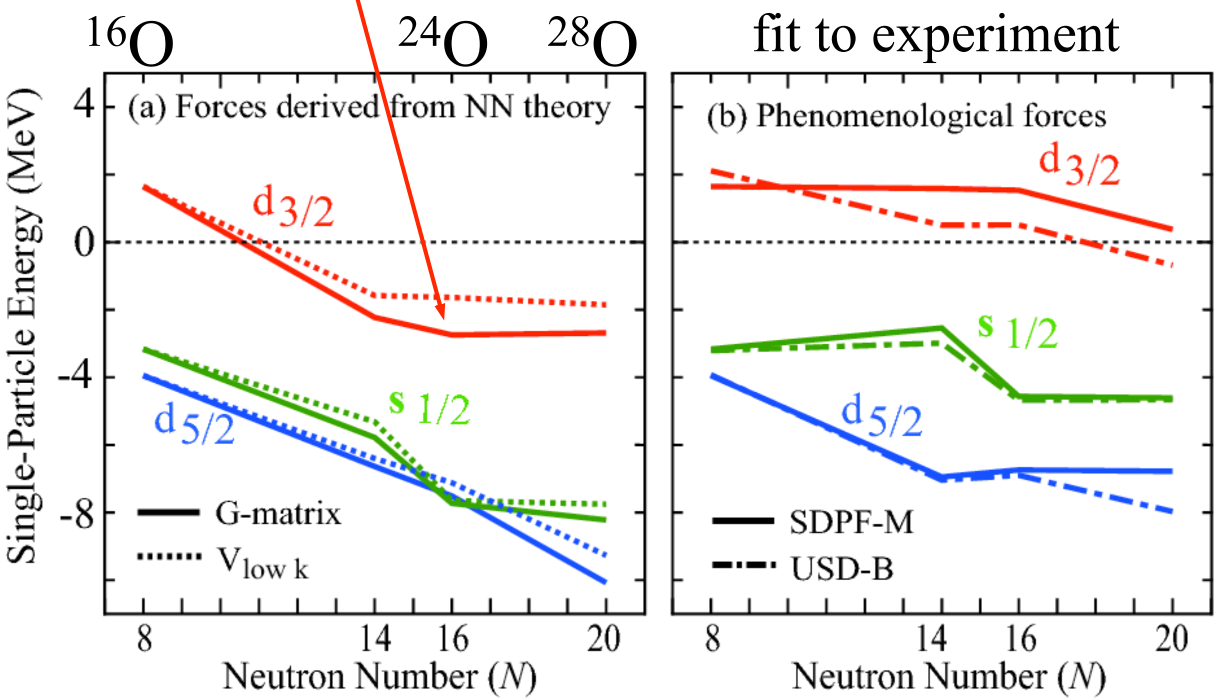
The oxygen anomaly - not reproduced without 3N forces



without 3N forces, NN interactions too attractive

many-body theory based on two-nucleon forces:
drip-line incorrect at ^{28}O





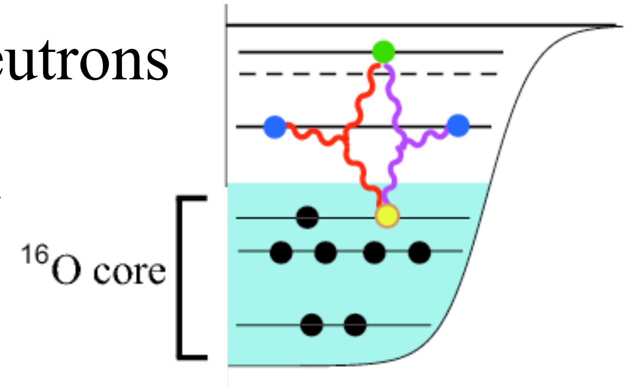
The oxygen anomaly - impact of 3N forces

include ‘normal-ordered’ 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons

contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$

Friman, AS, arXiv:1101.4858.



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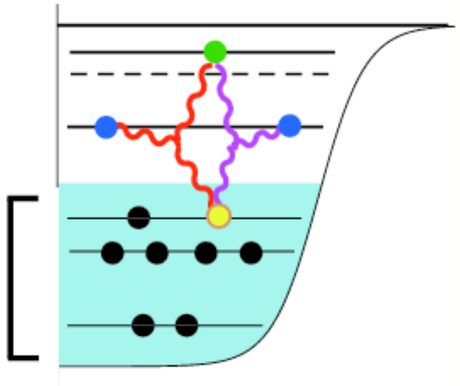
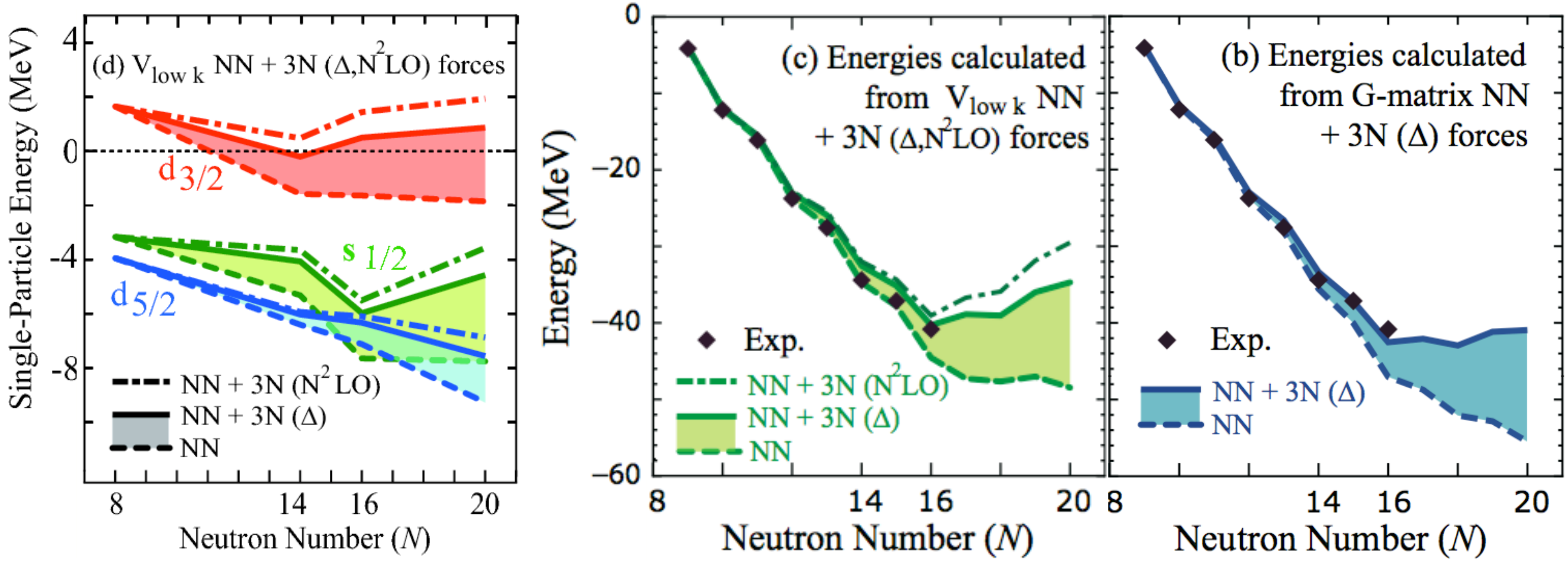


$d_{3/2}$ orbital remains unbound from ^{16}O to ^{28}O



microscopic explanation of the oxygen anomaly Otsuka et al., PRL (2010)

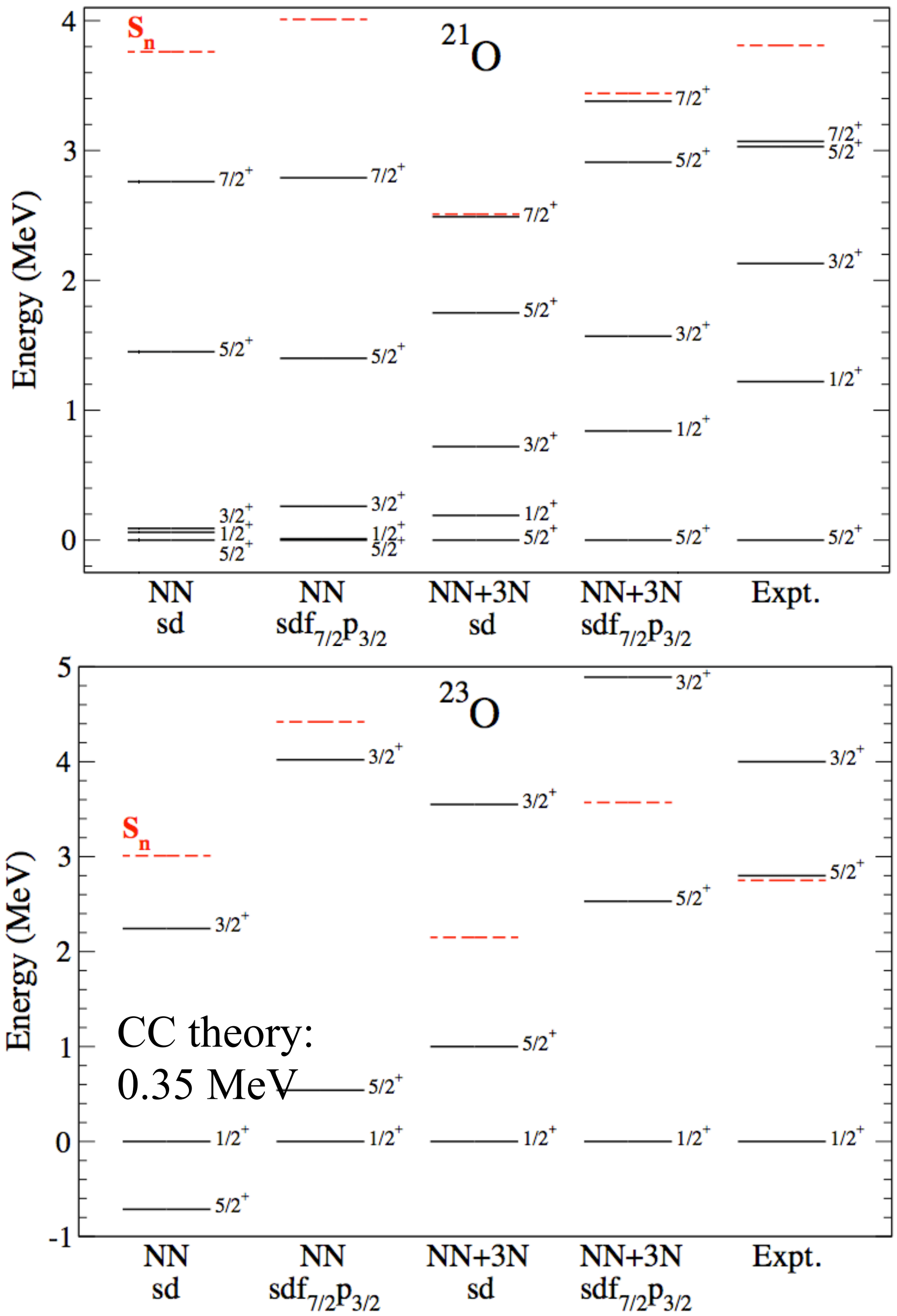
Oxygen spectra

focused on bound excited states

Holt, AS, arXiv:1108.2680.

NN only too compressed

3N contributions and extended valence space are key to reproduce excited states

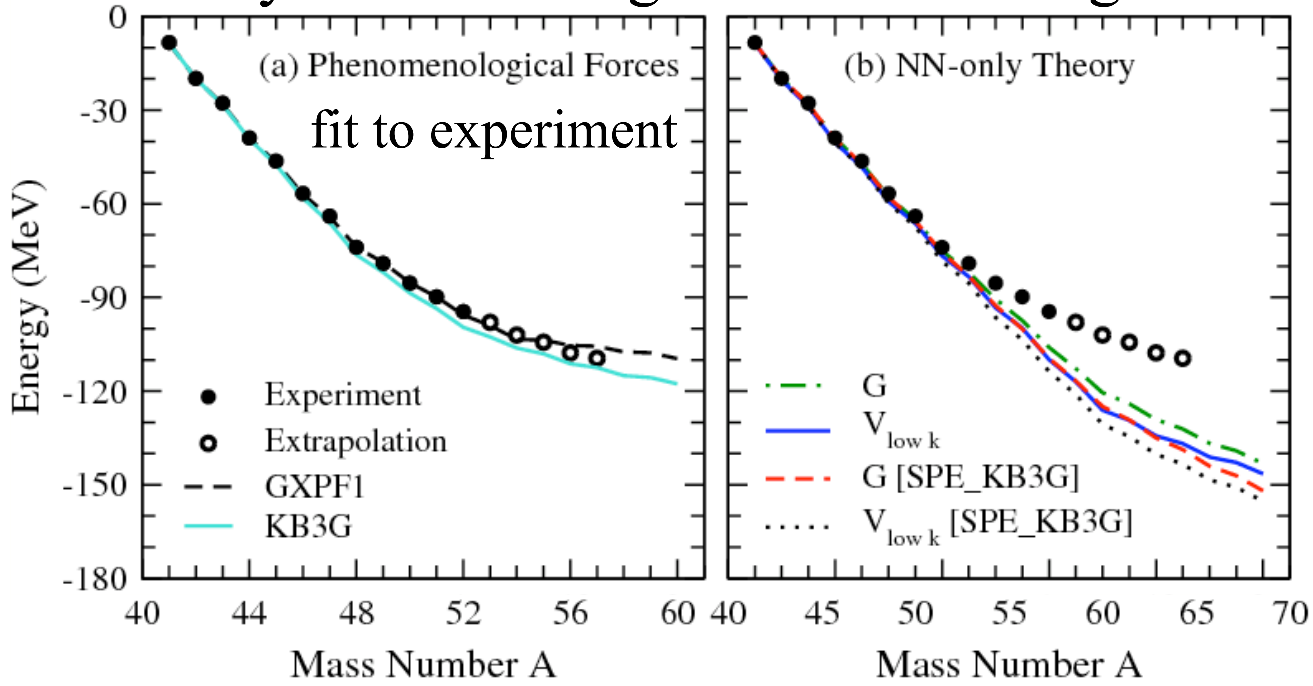


Evolution to neutron-rich calcium isotopes

repulsive 3N contributions also key for calcium ground-state energies

Holt et al., arXiv:1009:5984

mass measured to ^{52}Ca
shown to exist to ^{58}Ca



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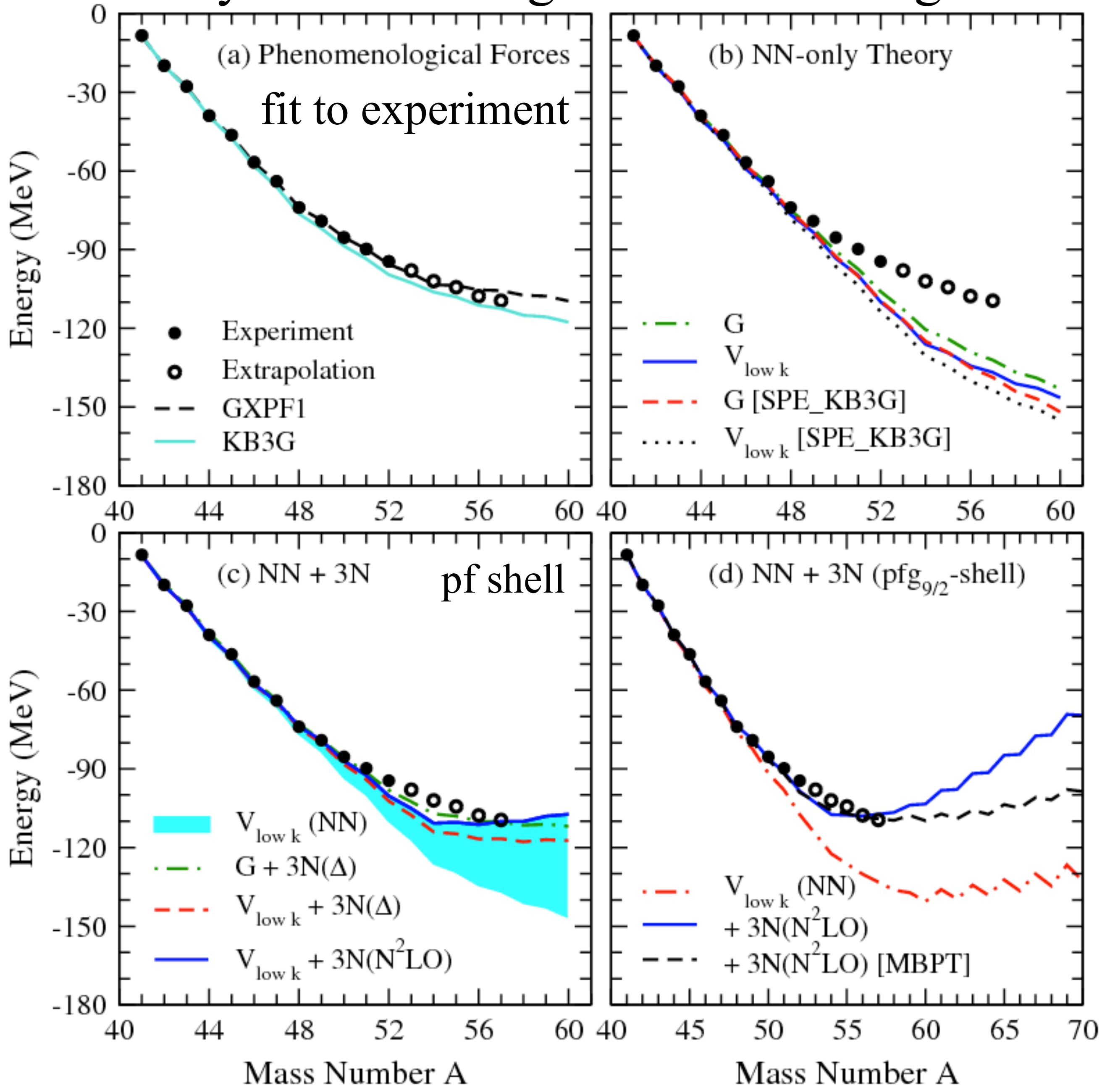
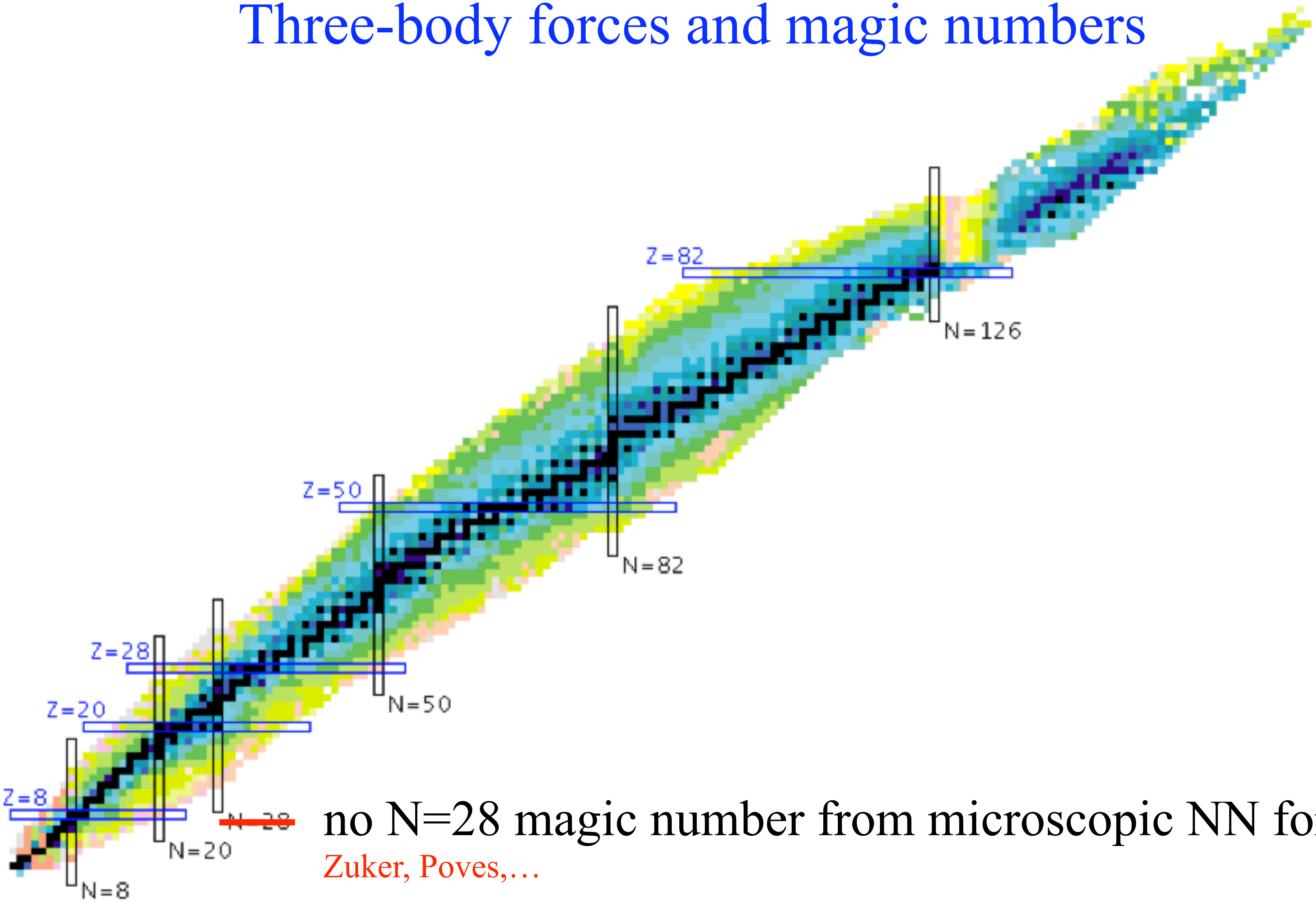
predict drip-line around ^{60}Ca, continuum contributions will be key



Three-body forces and magic numbers



no N=28 magic number from microscopic NN forces

Zuker, Poves,…

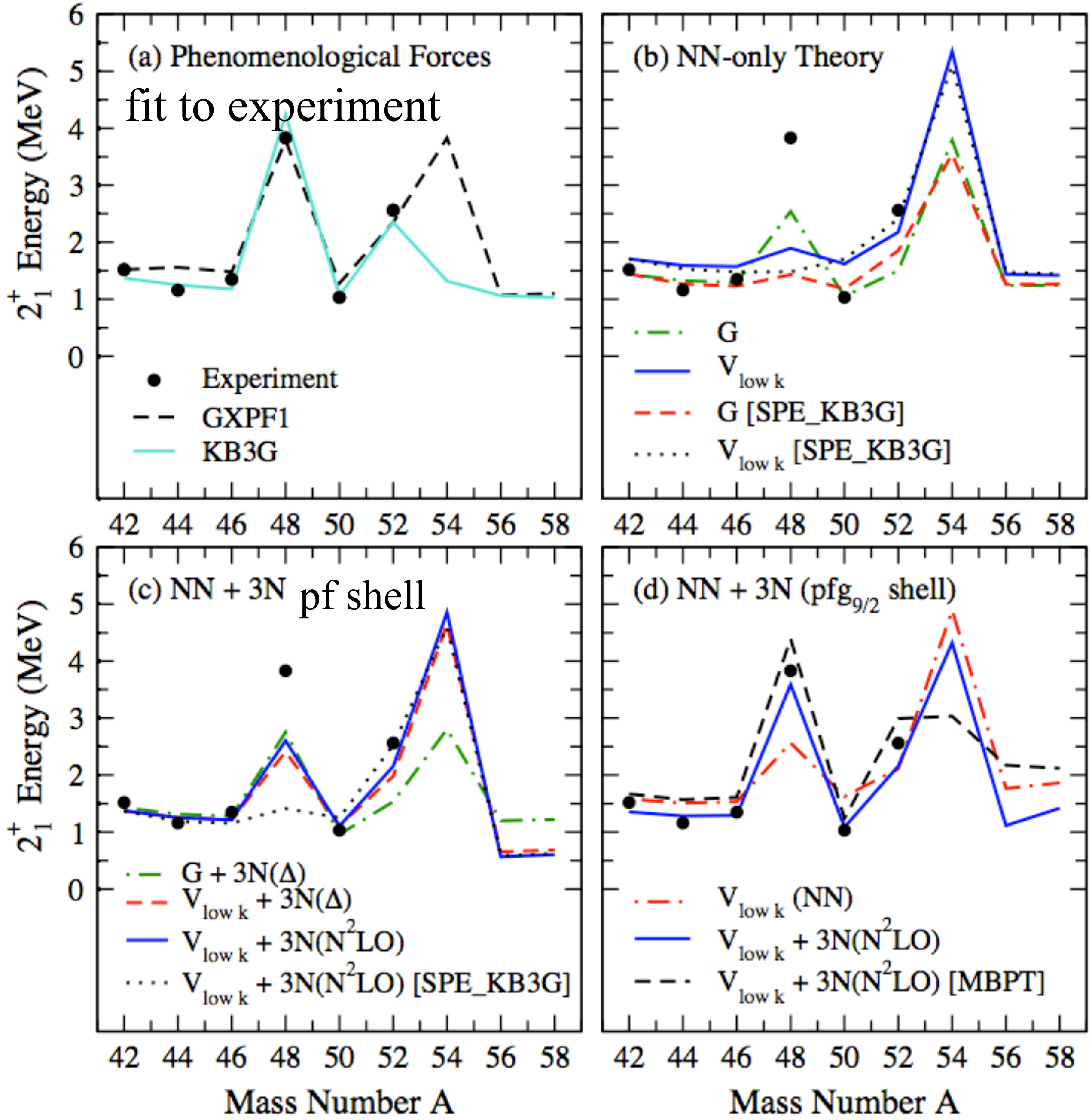
Three-body forces and magic numbers

3N mechanism important for shell structure

Holt et al., arXiv:1009:5984

N=28 shell closure due to 3N forces and single-particle effects (^{41}Ca)

N=34: predict high 2^+ excitation energy in ^{54}Ca at 3-5 MeV




P

Outline

Chiral effective field theory for nuclear forces

Epelbaum, Hammer, Meissner, Rev. Mod. Phys. 81, 1773 (2009). Overview.
Epelbaum, Prog. Part. Nucl. Phys. 57, 654 (2006). Many useful details.
Bogner, Furnstahl, AS, Prog. Part. Nucl. Phys. 65, 94 (2010). Renormalization Group.

3N forces and neutron-rich nuclei

Otsuka, Suzuki, Holt, AS, Akaishi, Phys. Rev. Lett. 105, 032501 (2010).
Holt, Otsuka, AS, Suzuki, arXiv:1009.5984.
Holt, AS, arXiv:1108.2680.

3N forces and neutron matter, impact on neutron stars

Hebeler, AS, Phys. Rev. C 82, 014314 (2010).
Hebeler, Lattimer, Pethick, AS, Phys. Rev. Lett. 105, 161102 (2010).

3N forces and electroweak currents

Menendez, Gazit, AS, Phys. Rev. Lett. 107, 062501 (2011).

Contact: schwenk@physik.tu-darmstadt.de

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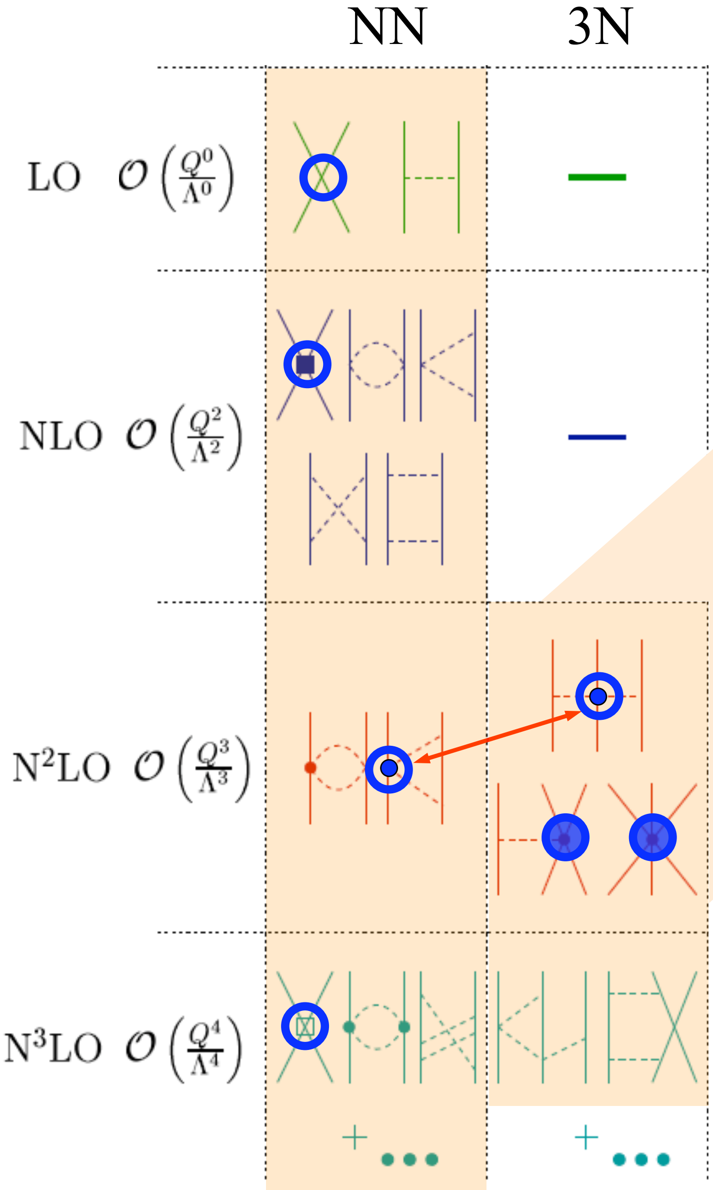

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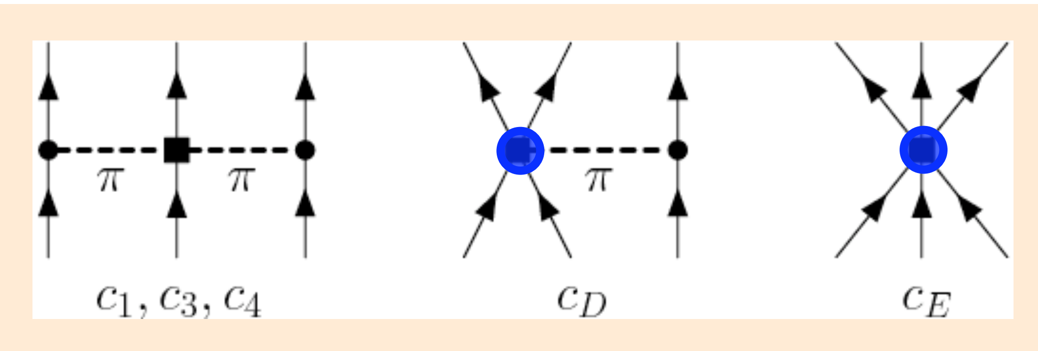

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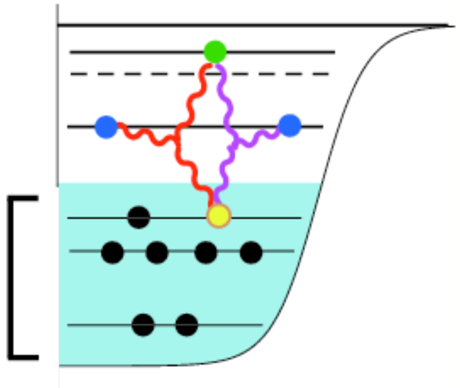

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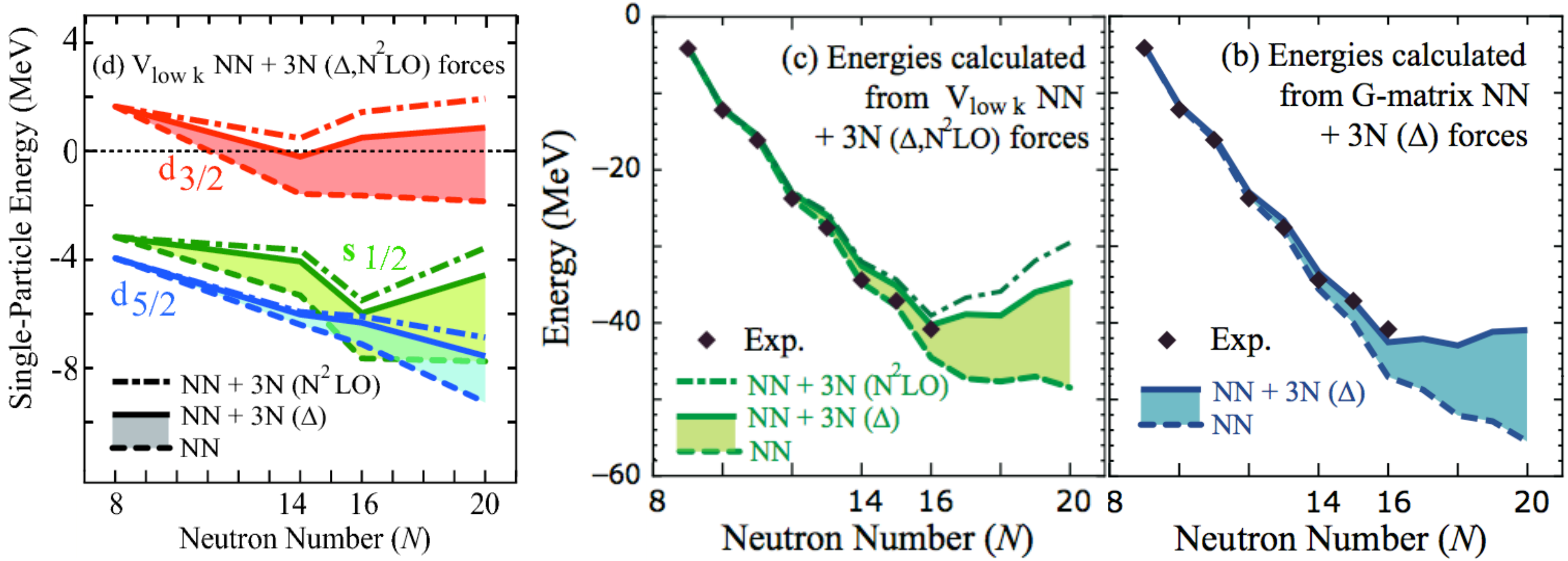

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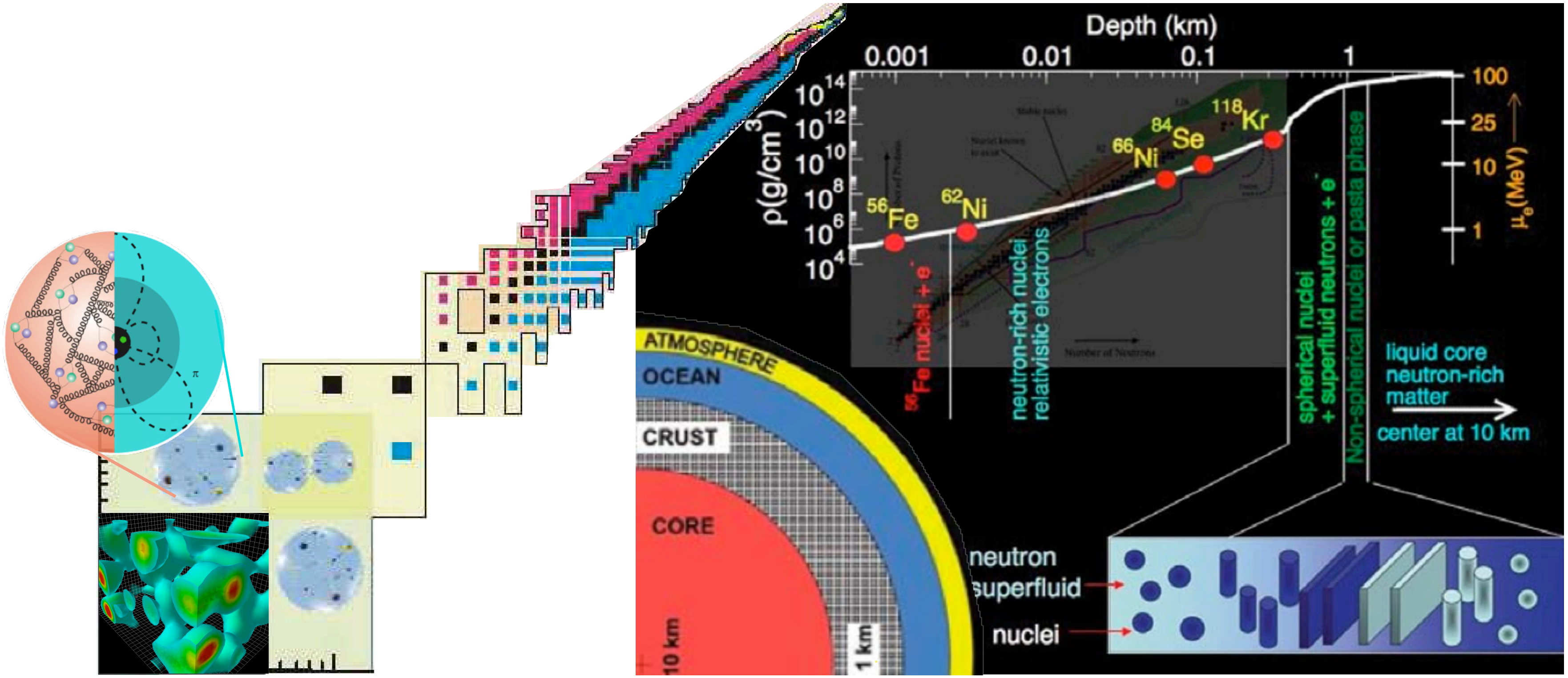
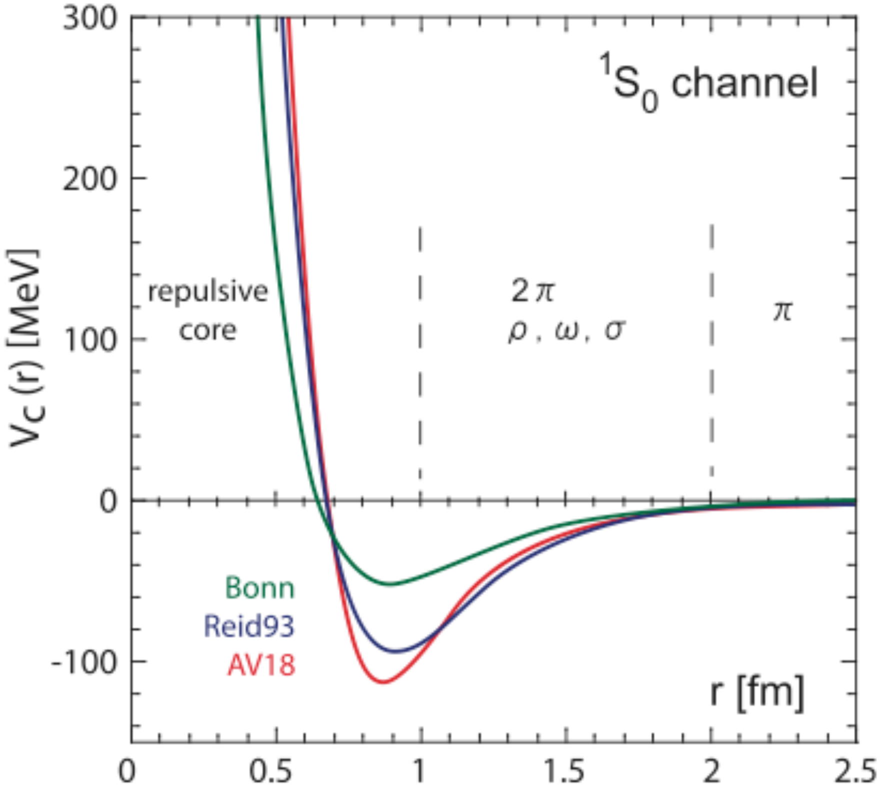
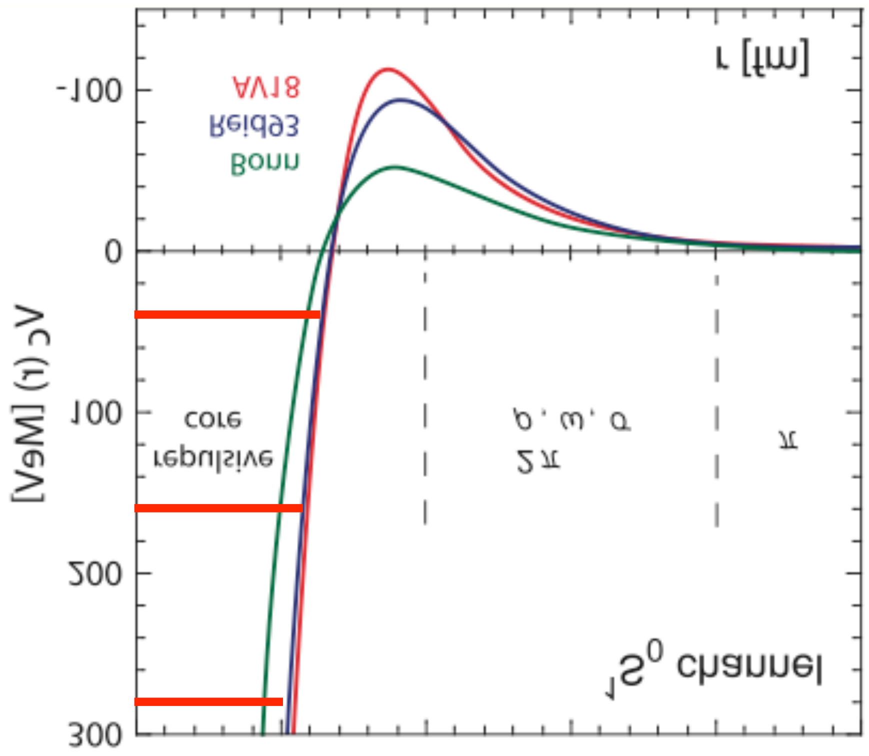
Extreme neutron-rich matter in stars



Convergence with low-momentum interactions

large cutoffs lead to flipped-potential bound states, even for small $-\lambda V$
requires nonperturbative expansion, leads to slow convergence for nuclei





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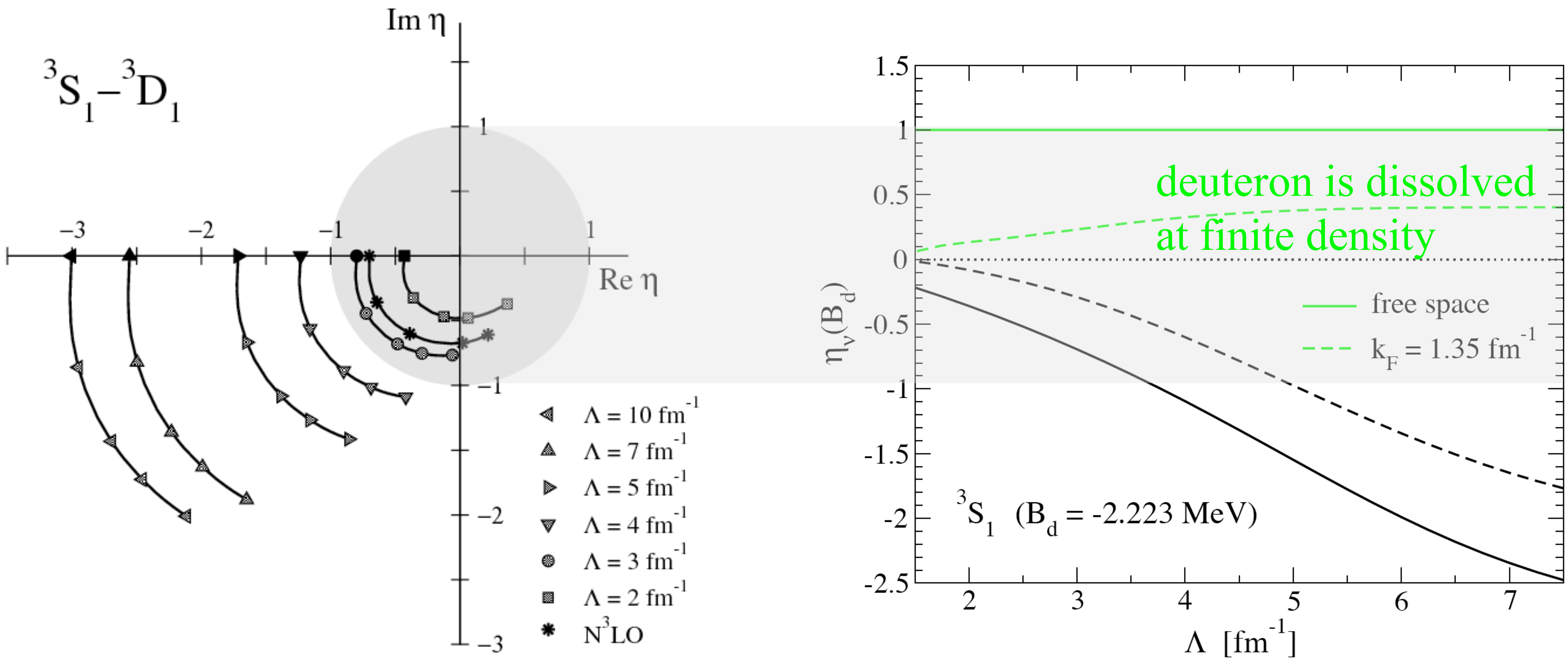
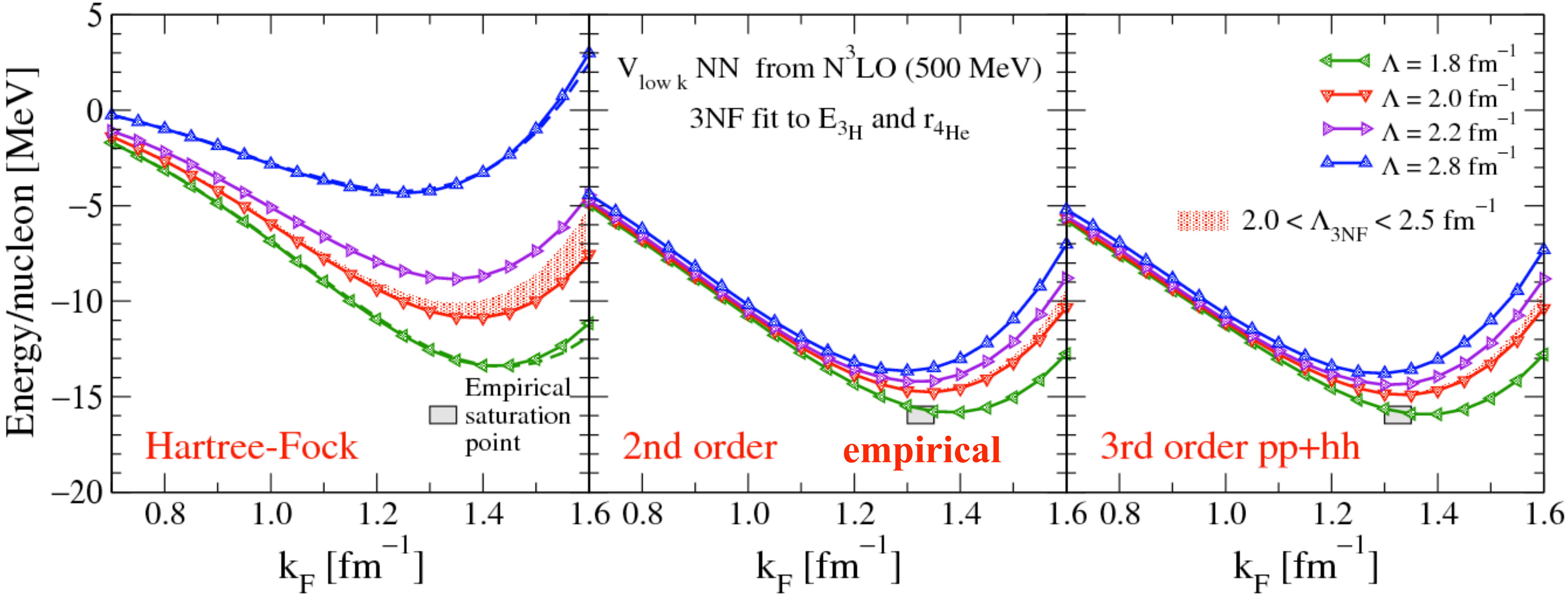


Weinberg eigenvalue analysis: two-body scattering becomes perturbative after RG evolution, except in channels with bound states

EFT and RG leads to improved convergence for nuclei and nuclear matter

Advances in nuclear matter theory

Is nuclear matter perturbative with chiral EFT and RG evolution?



Hebeler, Bogner, Furnstahl, Nogga, AS (2009, 2010)

exciting: empirical saturation with theoretical uncertainties

improved 3N treatment see also Holt, Kaiser, Weise (2010)

input to develop a universal energy density functional for all nuclei

UNEDF SciDAC Collaboration

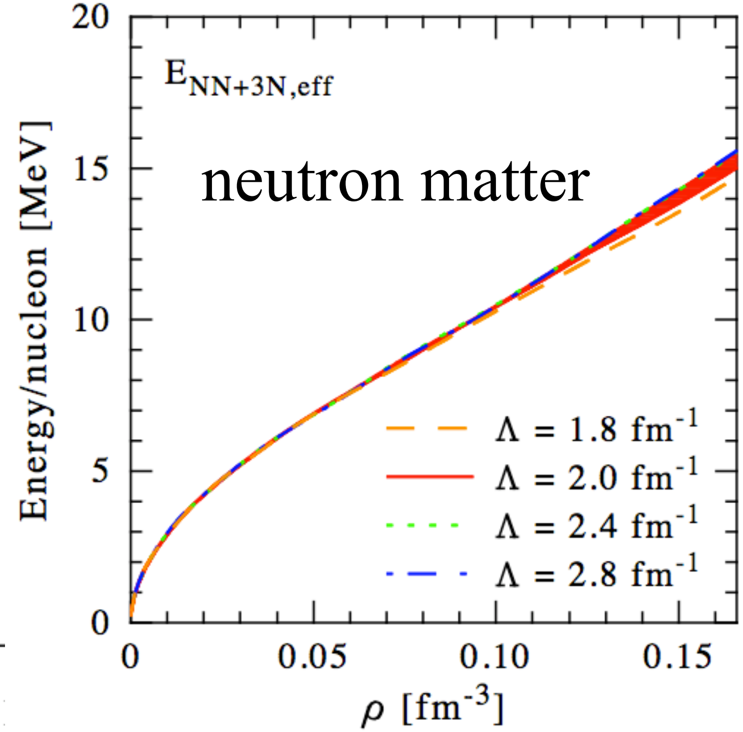
Universal Nuclear Energy Density Functional

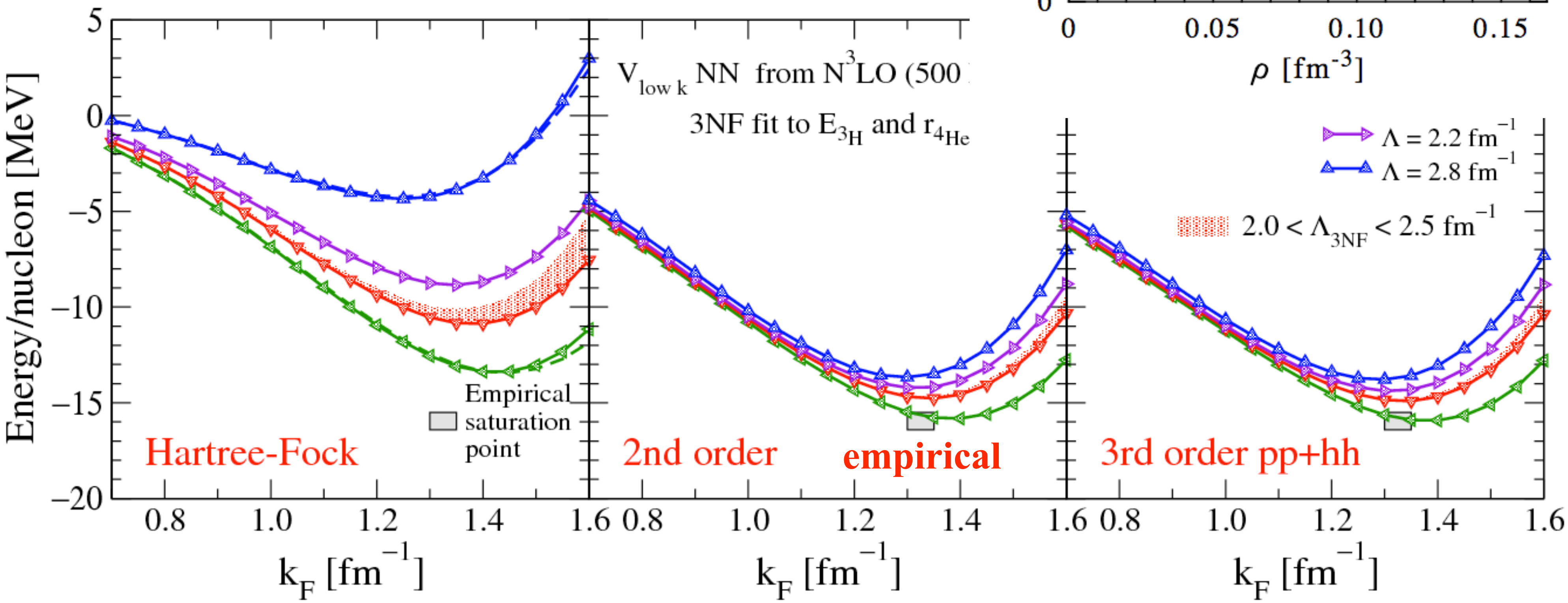
Impact of 3N forces on neutron matter

Hebeler, AS (2010); Tolos, Friman, AS (2007)

only long-range parts of 3N forces contribute to neutron matter (c_1 and c_3)

neutron matter: many-body forces are predicted to N^{3}LO!





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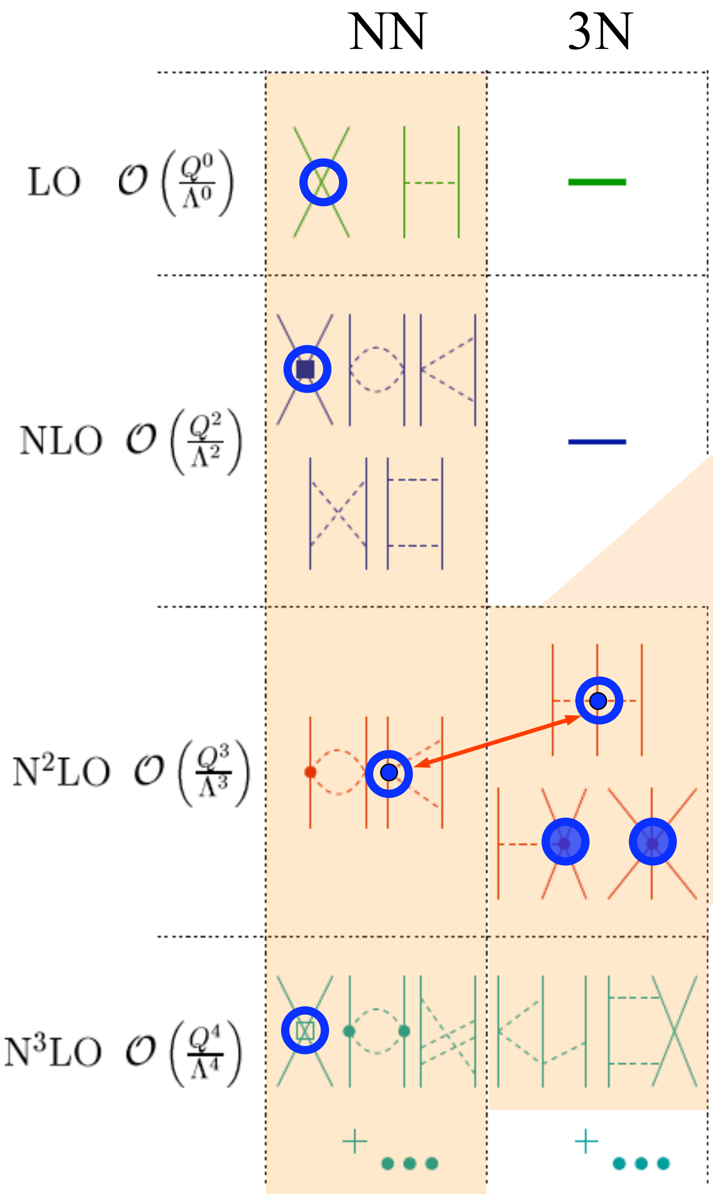

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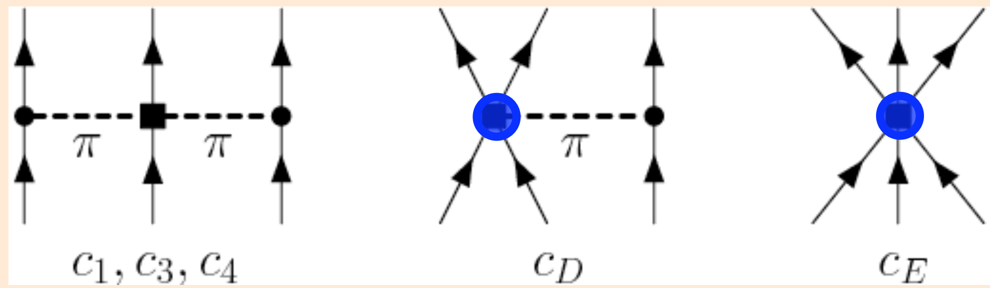

Question: Why do the c_D and c_E terms not contribute to neutron matter?

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

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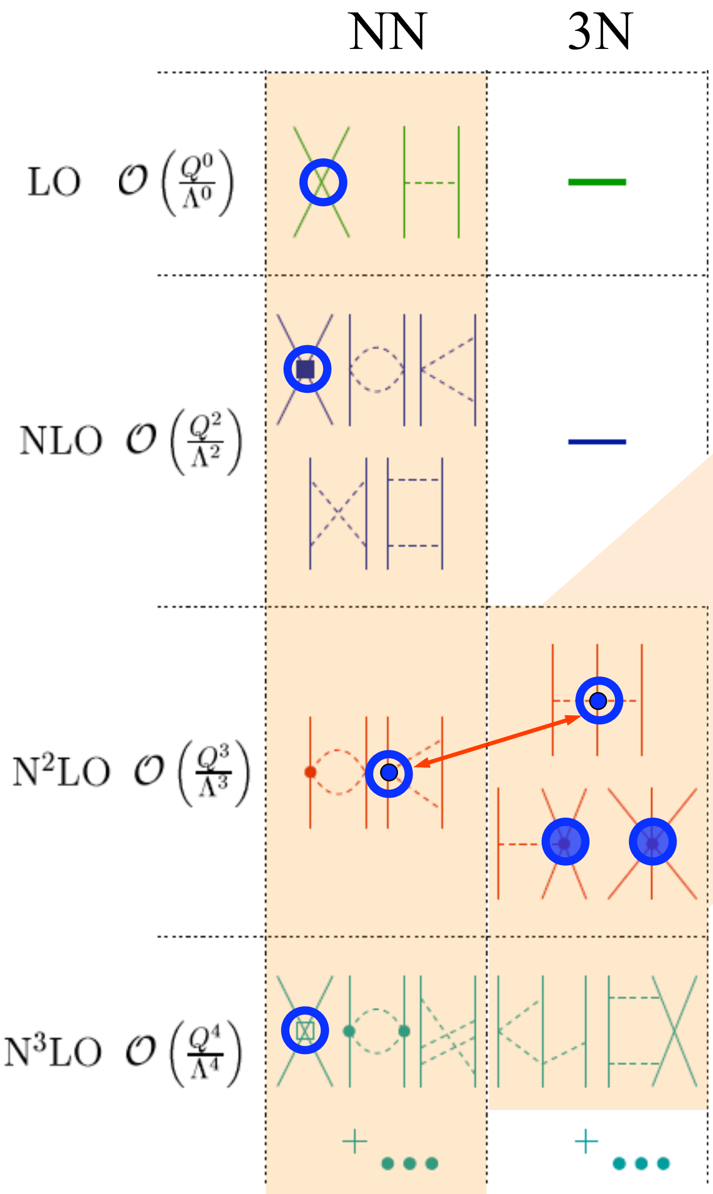

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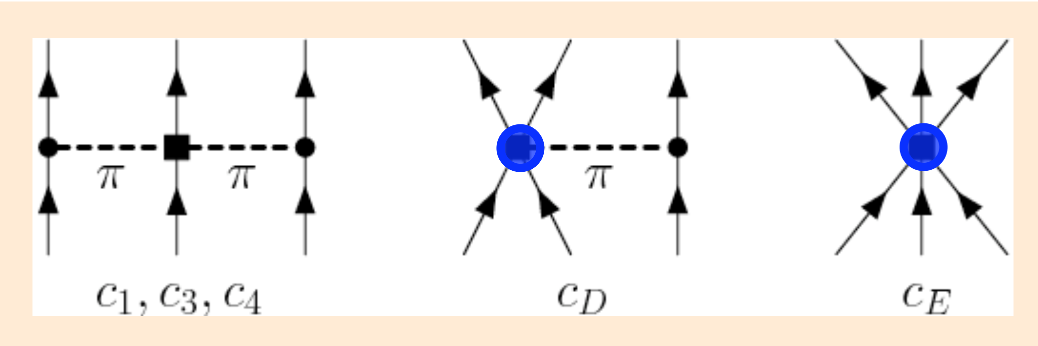

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Impact of 3N forces on neutron matter

Hebeler, AS (2010); Tolos, Friman, AS (2007)

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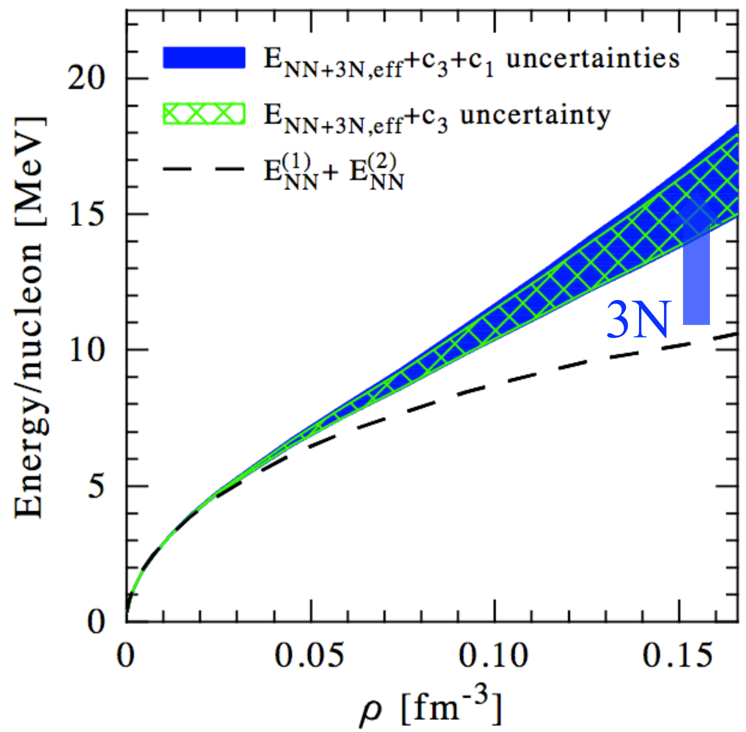

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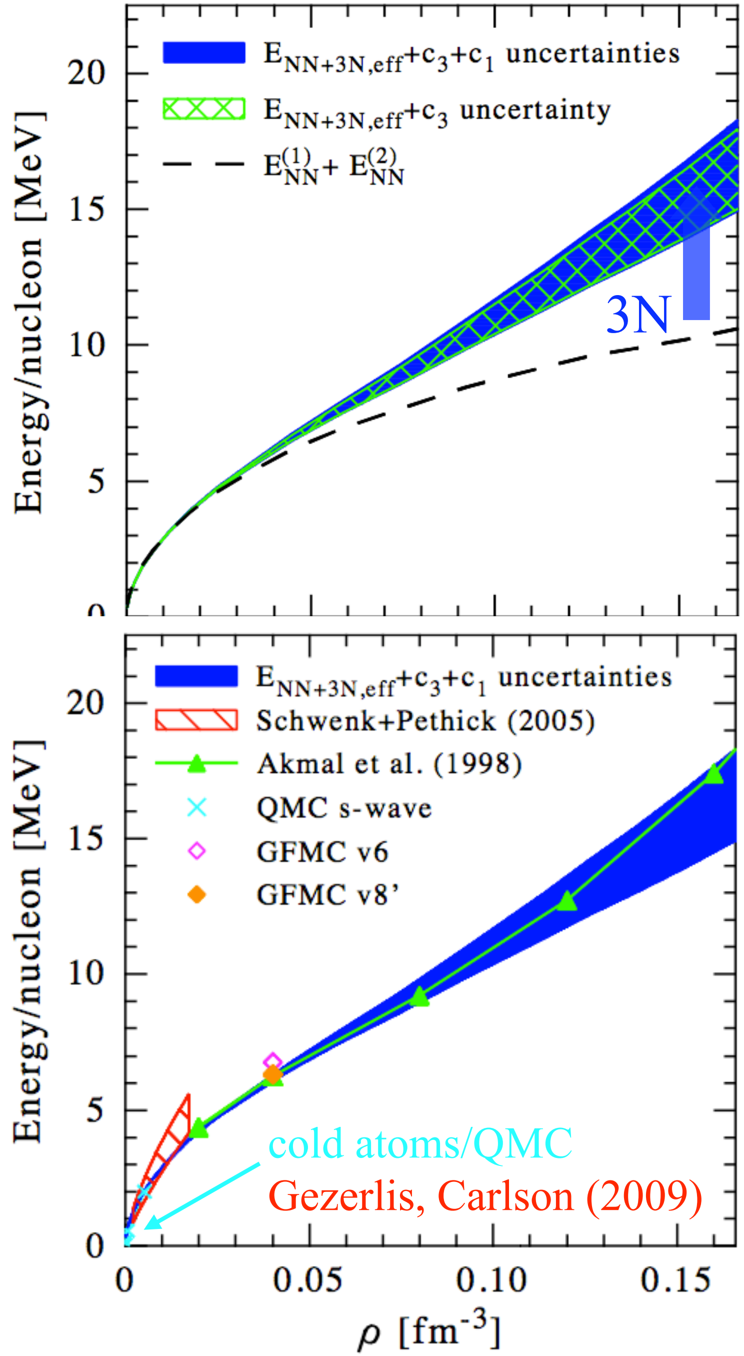
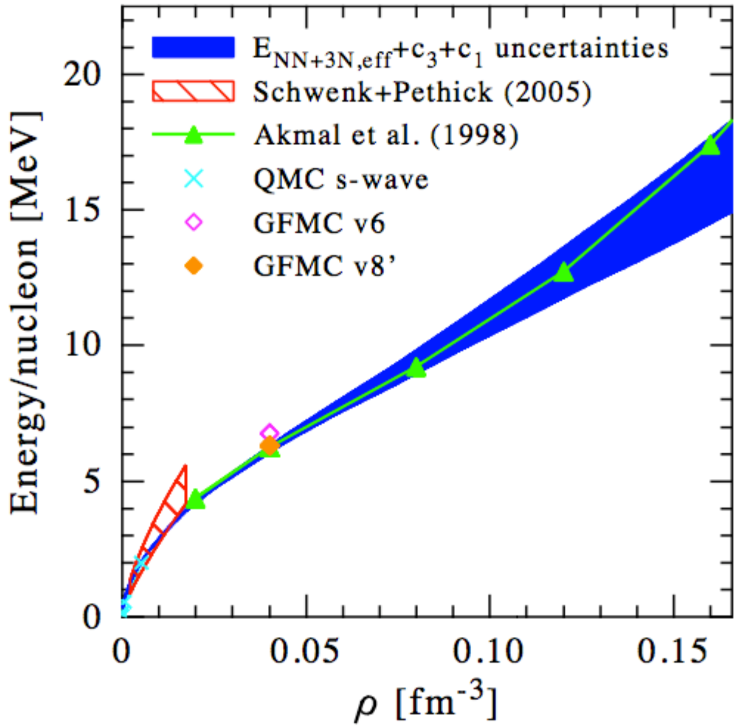
microscopic calculations within band



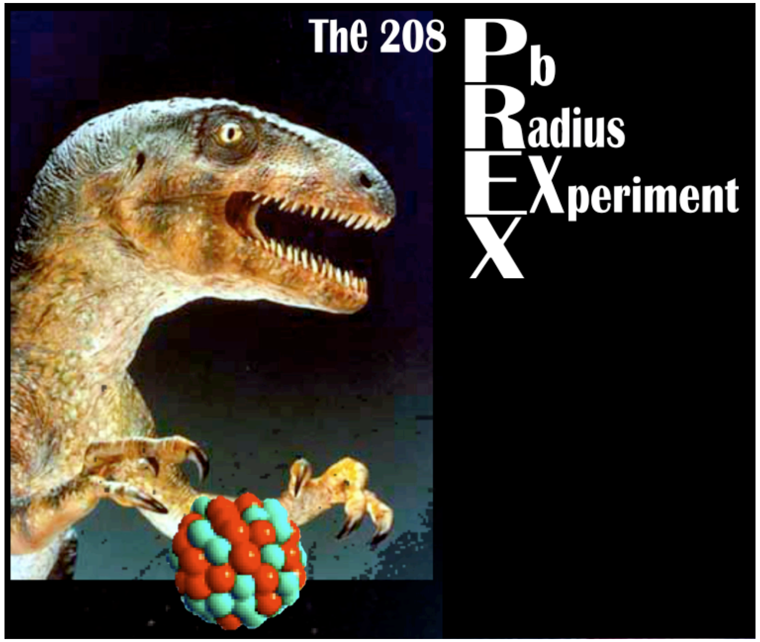
Symmetry energy and neutron skin Hebeler et al. (2010)

neutron matter band predicts range for symmetry energy 30.1-34.4 MeV

c_1 [GeV^{-1}]	c_3 [GeV^{-1}]	$\overline{S}_2$ [MeV]
-0.7	-2.2	30.1
-1.4	-4.8	34.4
NN-only EM		26.5
NN-only EGM		25.6



and neutron skin of ^{208}Pb to 0.17±0.03 fm



compare to ±0.05 fm future PREX goal
first result: 0.34+0.15-0.17 fm

from complete E1 response
0.156+0.025-0.021 fm Tamii et al., PRL (2011).

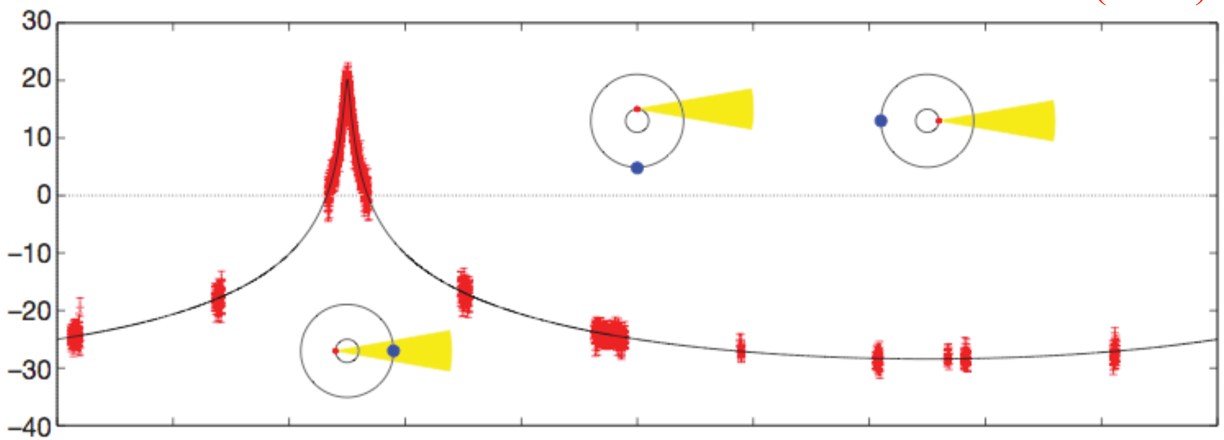
Discovery of the heaviest neutron star

A two-solar-mass neutron star measured using Shapiro delay

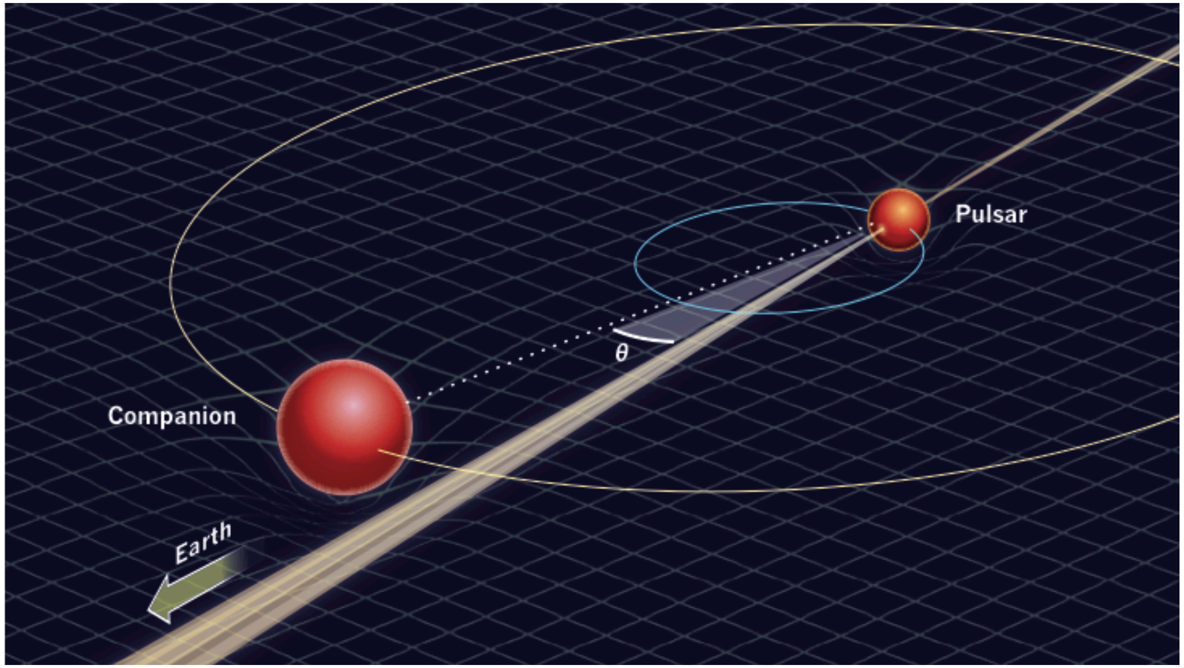
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature (2010)

direct measurement of neutron star mass from increase in signal travel time near companion



J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})



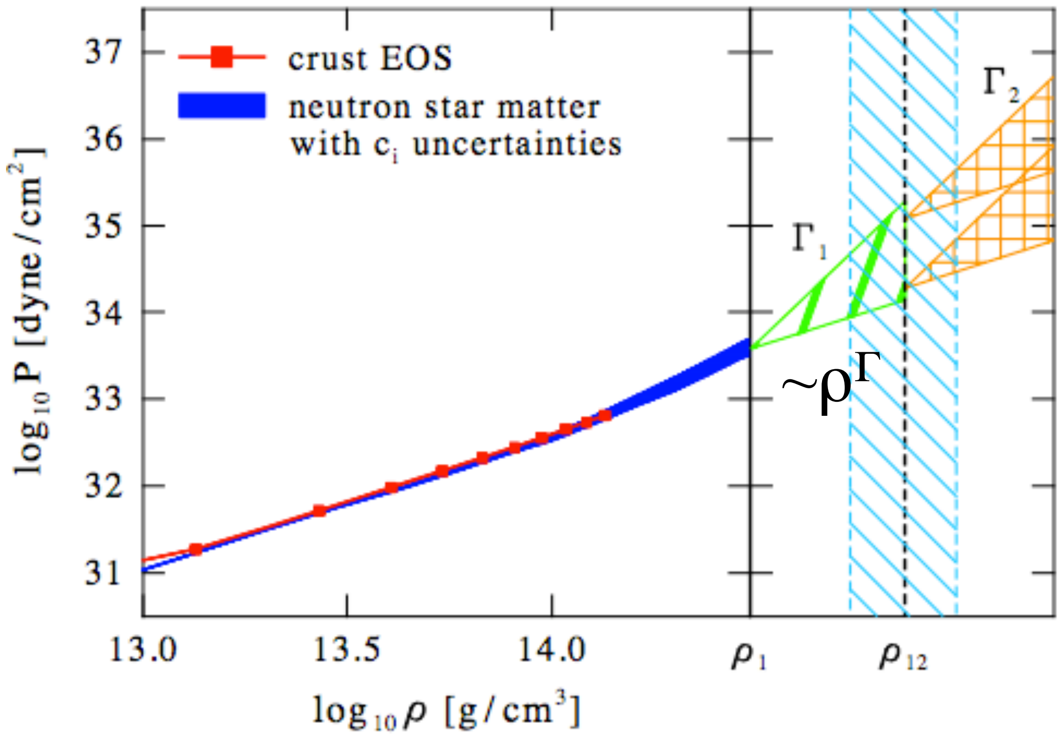
heaviest neutron star with 1.97±0.04 M_{sun}

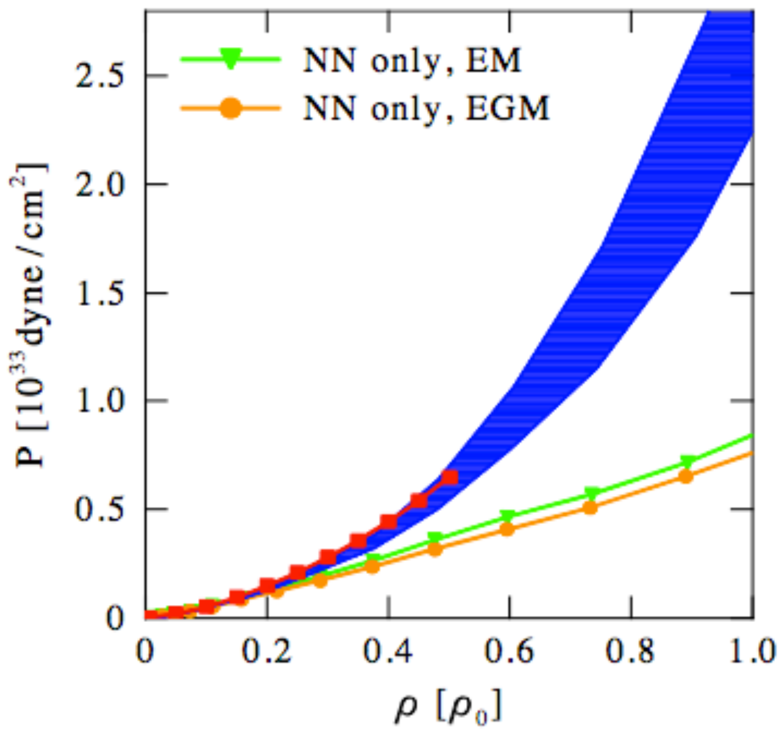
Impact on neutron stars

Neutron star structure determined by Tolman-Oppenheimer-Volkov eqn

$$\frac{dP}{dr} = -\frac{GM\epsilon}{r^2}\left[1+\frac{P}{\epsilon c^2}\right]\left[1+\frac{4\pi r^3 P}{Mc^2}\right]\left[1-\frac{2GM}{c^2 r}\right]^{-1}$$

with equation of state/pressure for neutron-star matter Hebeler et al., (2010)



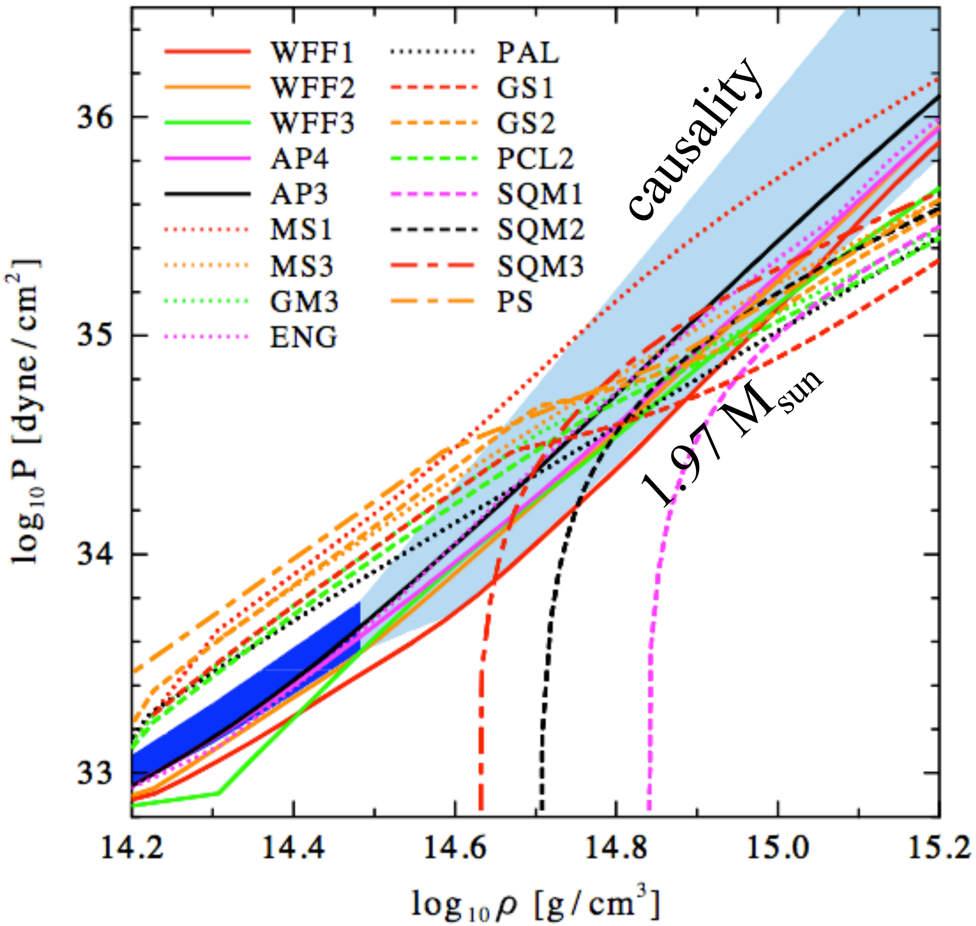


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

extend uncertainty band to higher densities using piecewise polytropes

Pressure of neutron star matter Hebeler et al. (2010)

constrain polytropes by causality and 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

Neutron star radius constraints Hebeler et al. (2010)

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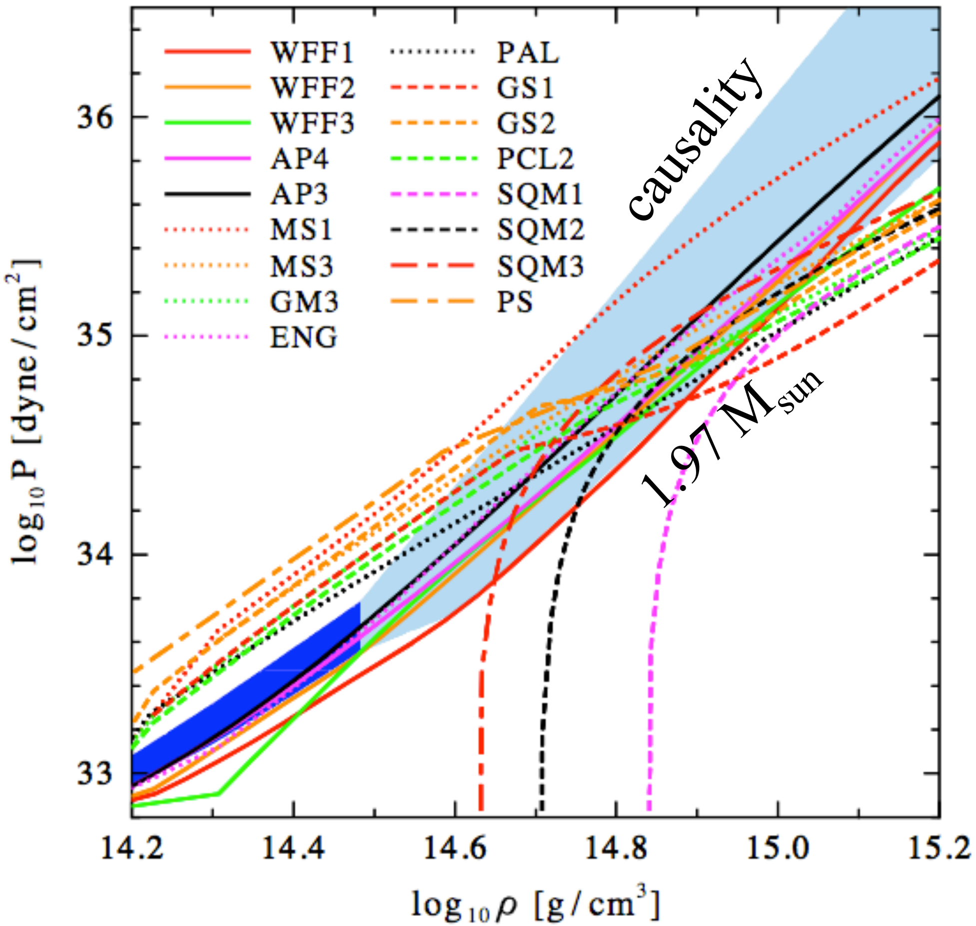

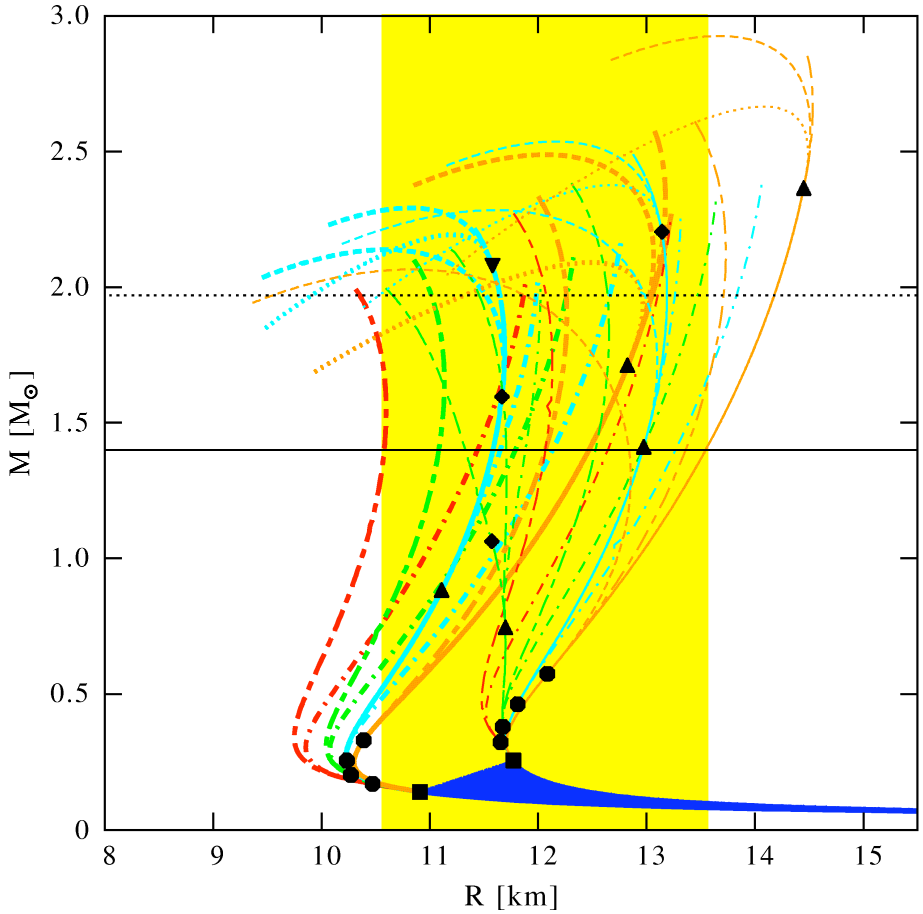

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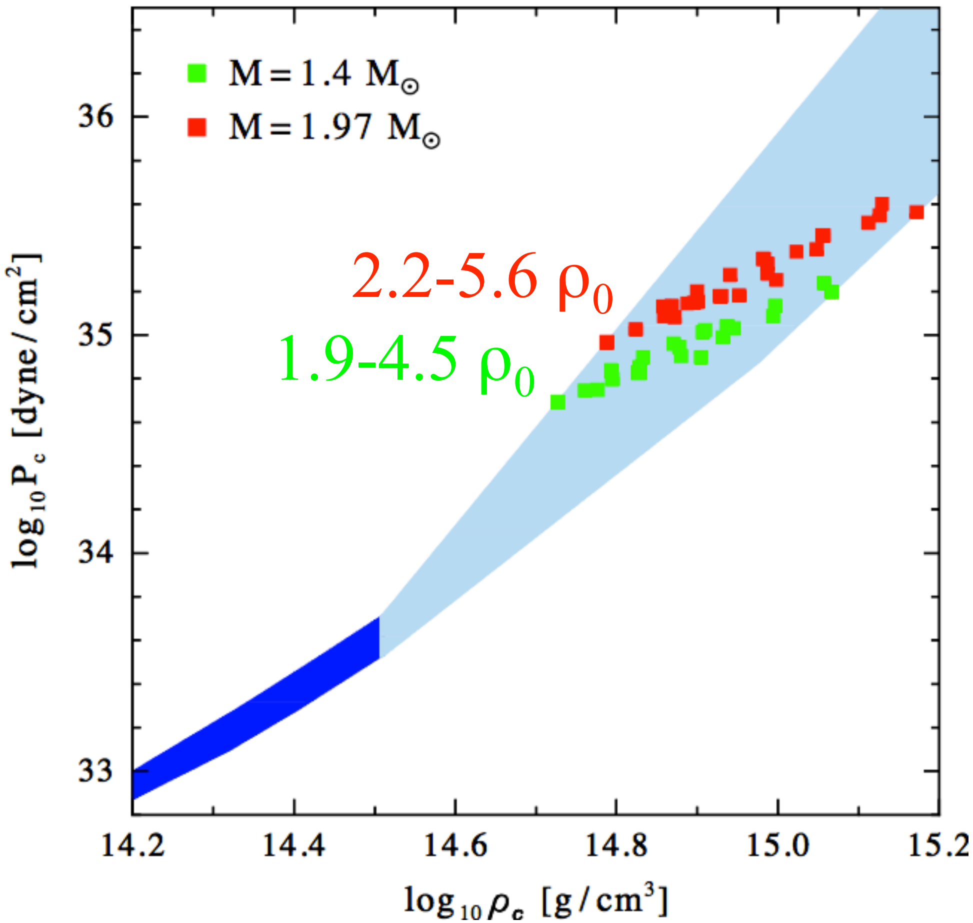

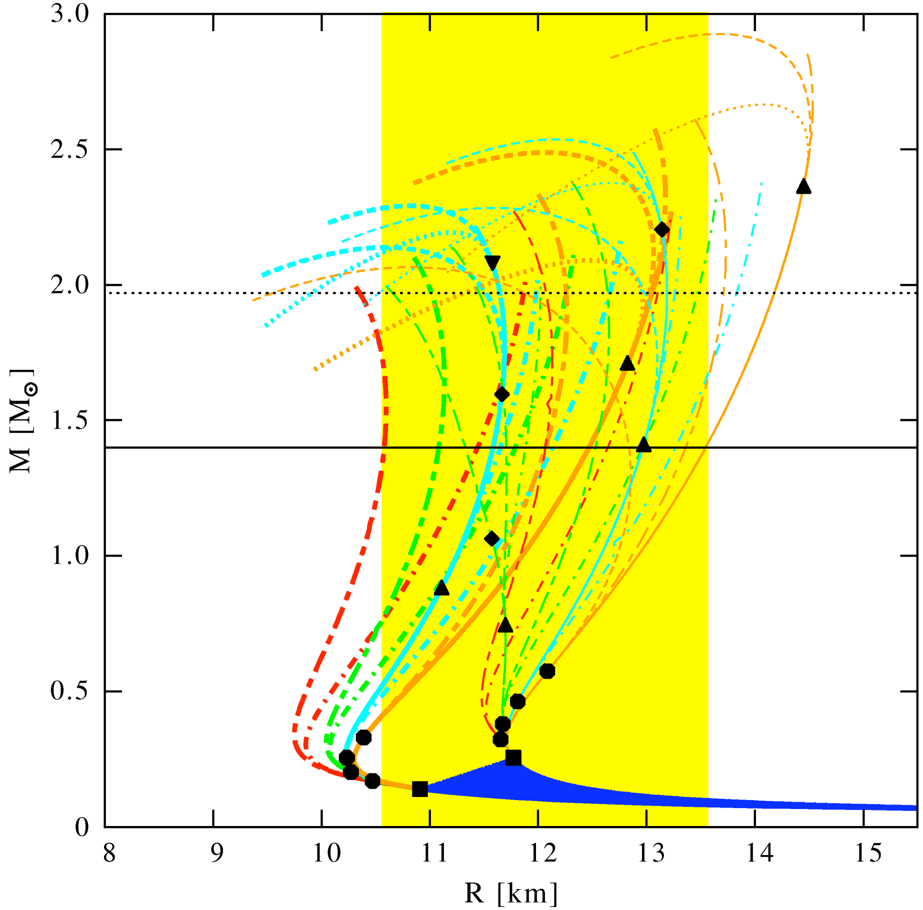

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Comparison to astrophysics

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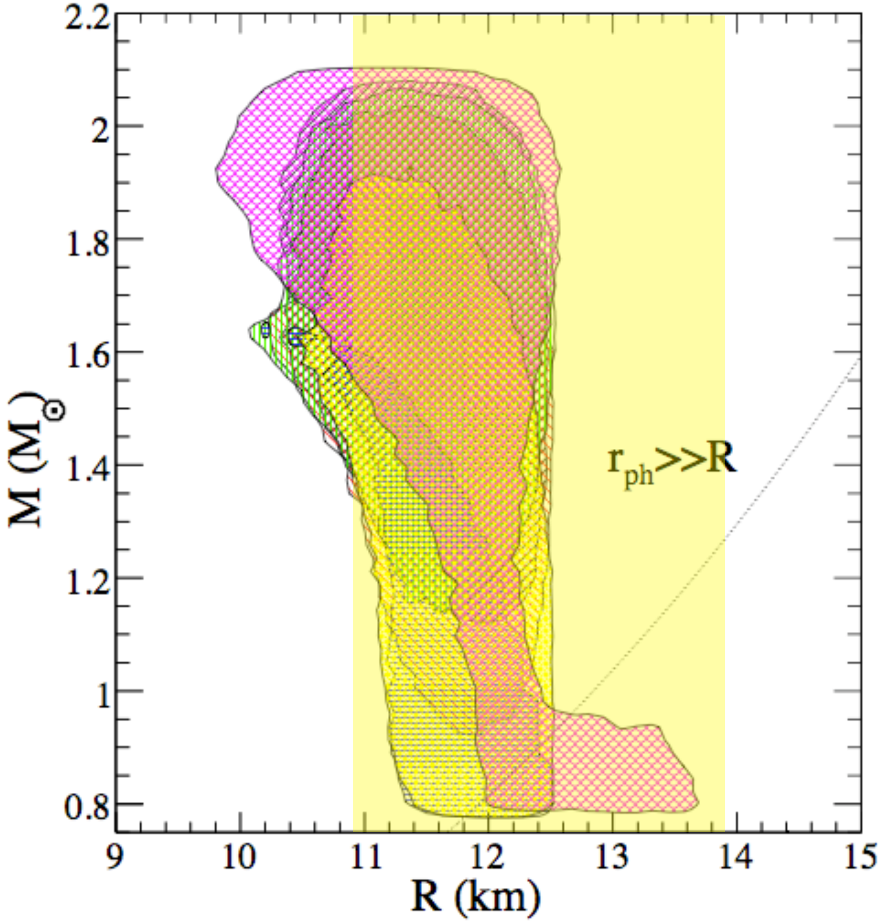

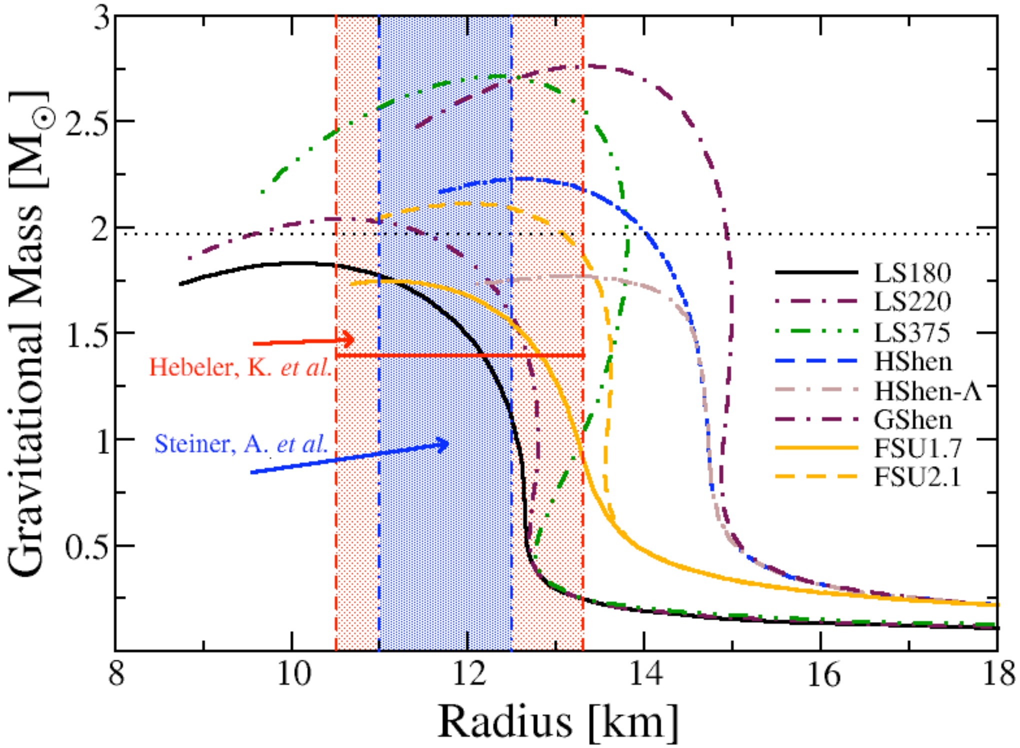

from Evan O' Connor

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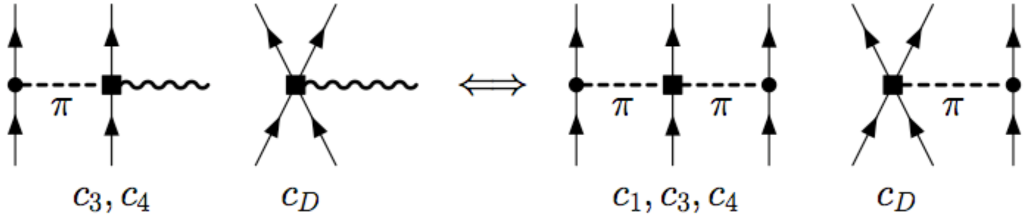
consistent with extraction from X-ray burst sources Steiner et al., ApJ (2010)
provides important constraints for EOS for core-collapse supernovae

Chiral EFT for electroweak transitions Menendez, Gazit, AS (2011).

two-body currents lead to important contributions in nuclei (Q~100 MeV) especially for Gamow-Teller transitions

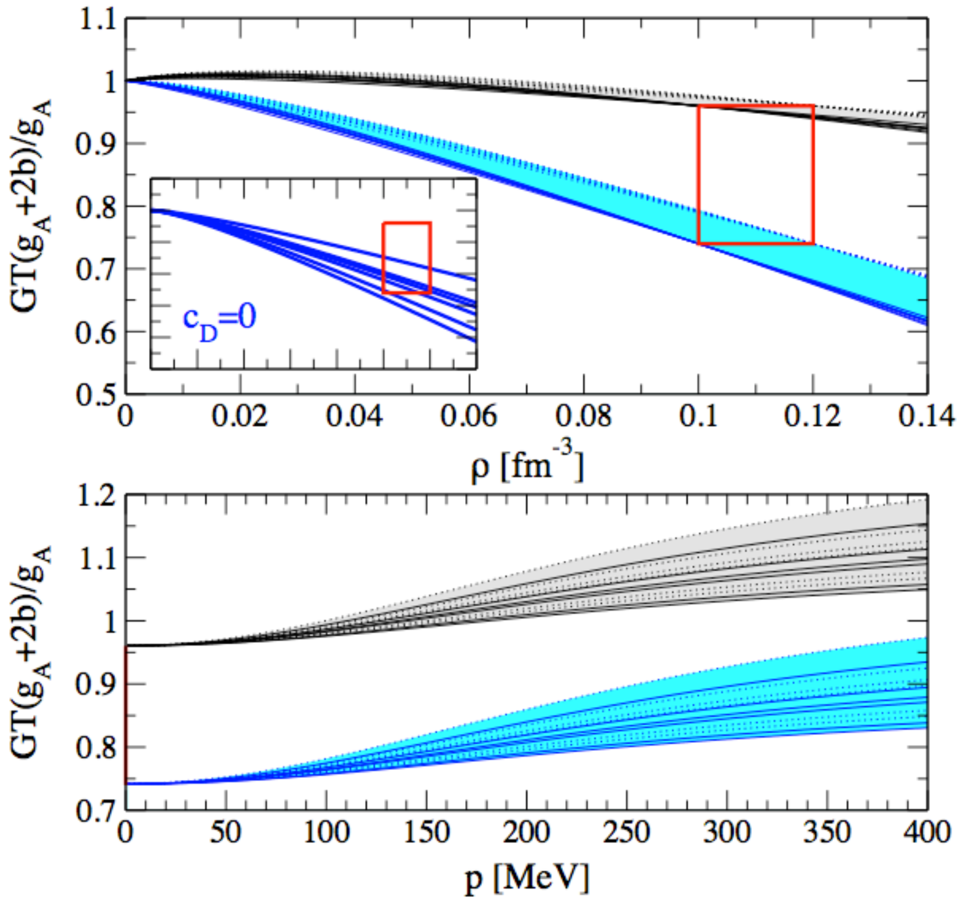
two-body currents determined by NN, 3N couplings to N^3LO

Park et al., Phillips,…



explains part of quenching of g_A (dominated by long-range part)

+ predict momentum dependence (weaker quenching for larger p)



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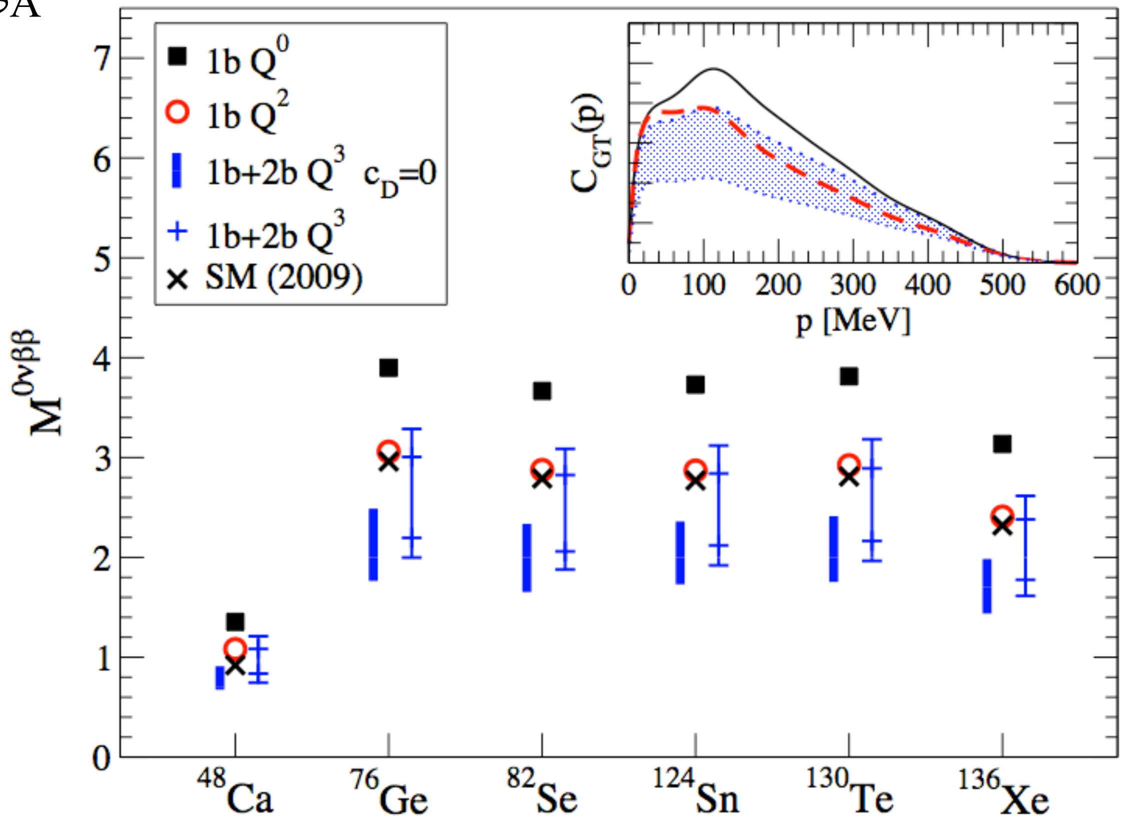

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Summary

Exciting era with advances on many fronts:
development of effective field theory and the renormalization group

enables a unified description from nuclei to matter in astrophysics

3N forces are a frontier for neutron-rich nuclei/matter:

key to explain why ^{24}O is the heaviest oxygen isotope

Ca isotopes and N=28 magic number, key for neutron-rich nuclei

dominant uncertainty of neutron (star) matter below nuclear densities,
constraints on neutron star radii

exciting interactions with experiments and observations!