Lattice QCD input for nuclear structure

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Bundesministerium für Bildung und Forschung

Outline

Chiral EFT and **c_i uncertainties**

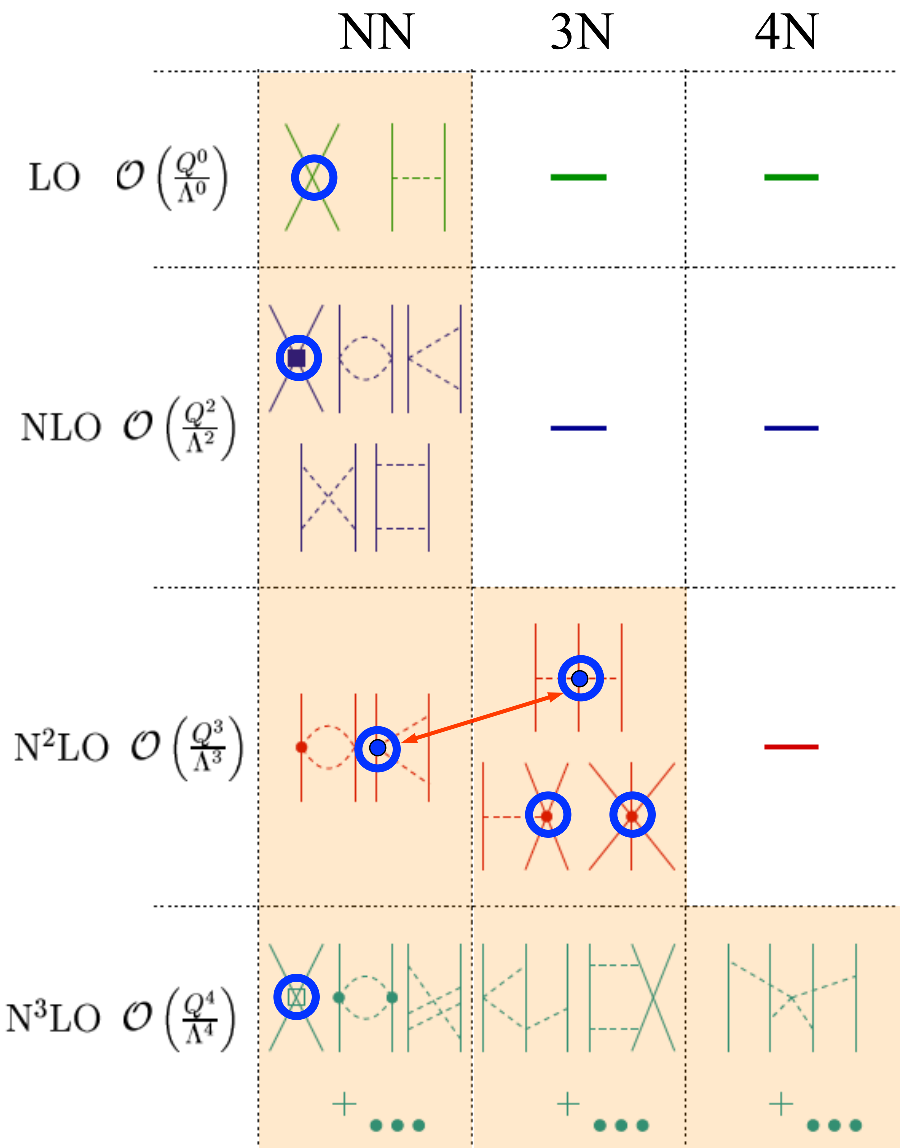
T=3/2 components of 3N forces: 3n, 4n systems, neutron-rich nuclei

Neutron matter is easier to calculate than n,p matter, provides tight constraints for neutron-rich matter
Is neutron matter easier in lattice QCD?

Lattice QCD for fundamental symmetries:
- neutrinoless double-beta decay, nn to pp matching problem?
- **WIMP-nucleon couplings** for dark matter response of nuclei

Chiral Effective Field Theory for nuclear forces

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



include long-range pion physics

few short-range couplings,
fit to experiment once

systematic: can work to desired accuracy and obtain error estimates

Open problems: Power counting and renormalization. **Can lattice QCD provide guidance?**

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

Chiral Effective Field Theory and many-body forces

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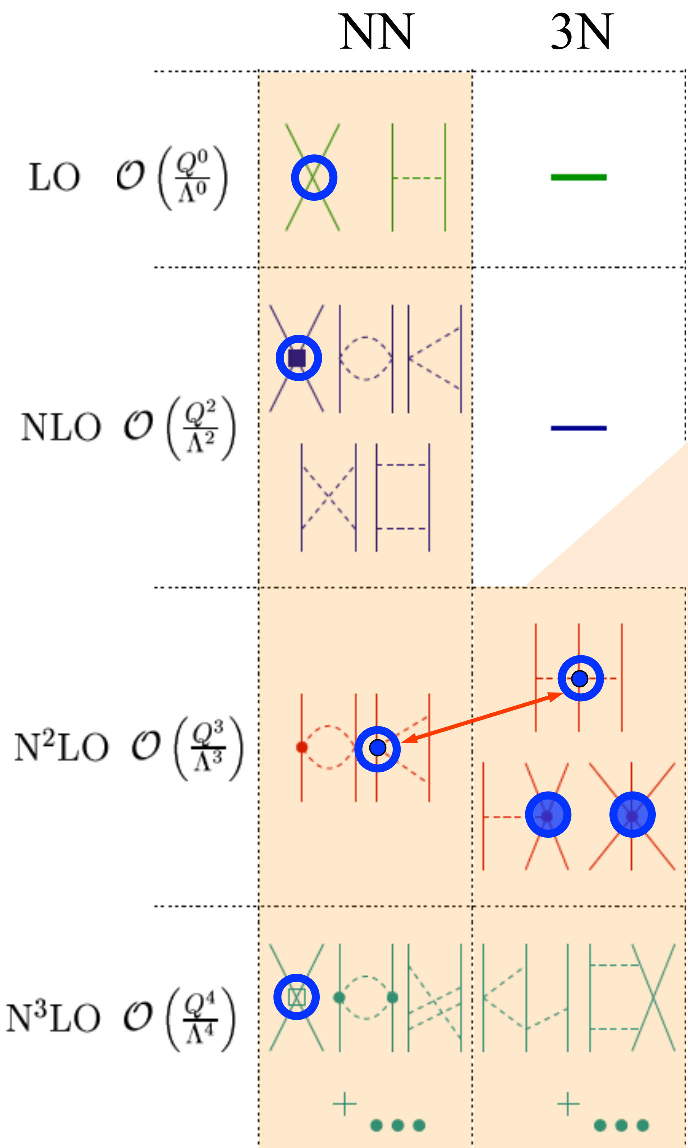
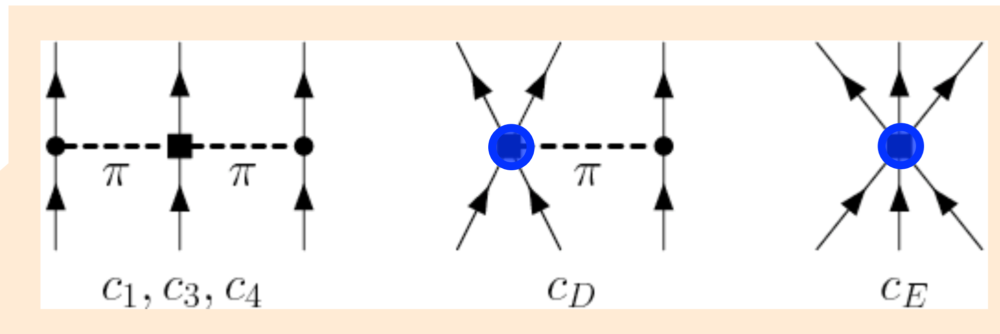


consistent NN-3N interactions

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



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

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

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

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

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

Range of c_i couplings

Uncertainty range

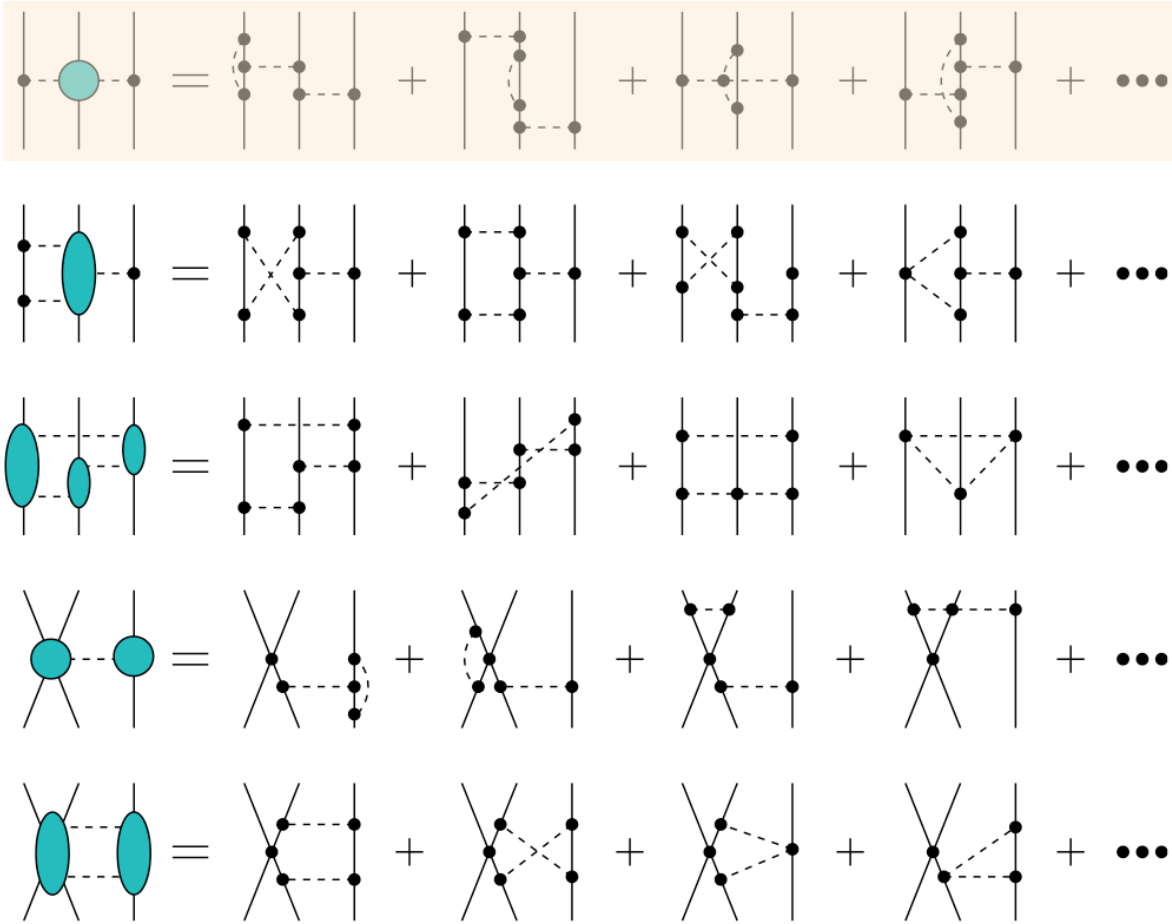
	c_1	c_3	c_4	
Fettes *et al.* (1998) (Fit 1)	-1.2	-5.9	3.5	πN
Büttiker and Meißner (2000)	-0.8	-4.7	3.4	πN
Meißner (2007)	-0.9	-4.7	3.5	πN
Rentmeester *et al.* (2003)	-0.8	-4.8	4.0	NN
Entem and Machleidt (2002)	-0.8	-3.4	3.4	NN
Entem and Machleidt (2003)	-0.8	-3.2	5.4	NN
Epelbaum *et al.* (2005)	-0.8	-3.4	3.4	NN
Bernard *et al.* (1997)	-0.9	-5.3	3.7	res

Subleading chiral 3N forces

parameter-free N^3LO Bernard et al. (2007,2011), Ishikawa, Robilotta (2007)

one-loop contributions:

2π-exchange, 2π-1π-exchange, rings, contact-1π-, contact-2π-exchange



decrease c_i strengths

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

comparable to

N^2LO uncertainty

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

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High-order analysis Krebs et al. (KGE) (2012)

	c_1 [GeV^{-1}]	c_3 [GeV^{-1}]
N^{2}LO/N^{3}LO EGM NN [31, 32]	-0.81	-3.40
N^{3}LO EM NN [33, 34]	-0.81	-3.20
N^{2}LO KGE [39]	$-(0.26-0.58)$	$-(2.80-3.14)$
'N^{2}LO' KGE (recom.) [39]	$-(0.37-0.73)$	$-(2.71-3.38)$
N^{3}LO KGE [39]	$-(0.75-1.13)$	$-(4.77-5.51)$

both ~10%

Can lattice QCD provide better constraints on c_i?

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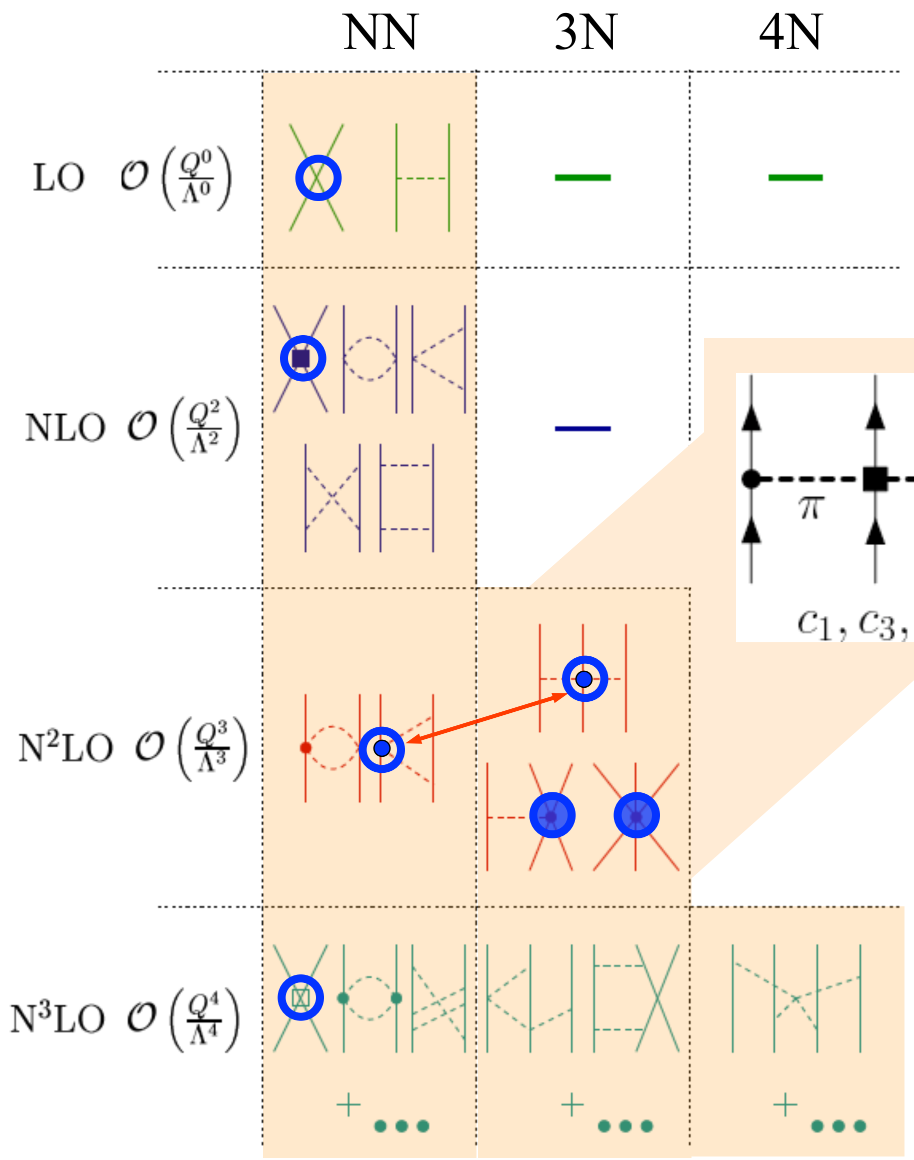
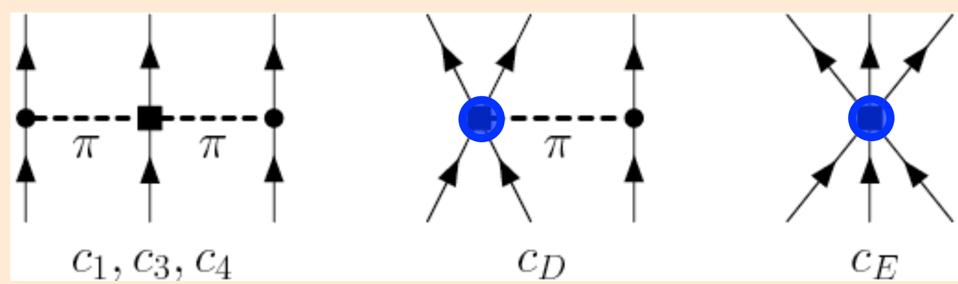


c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)

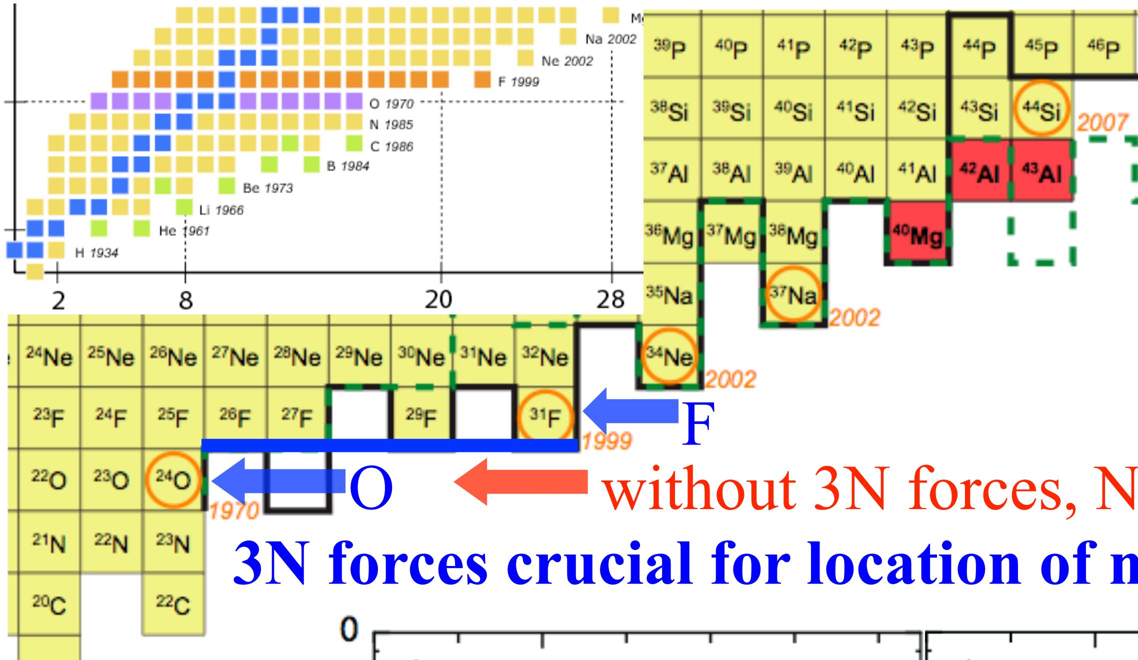


all 3- and 4-neutron forces are predicted to N³LO!

can predict 3n, 4n resonances, experiment feasible

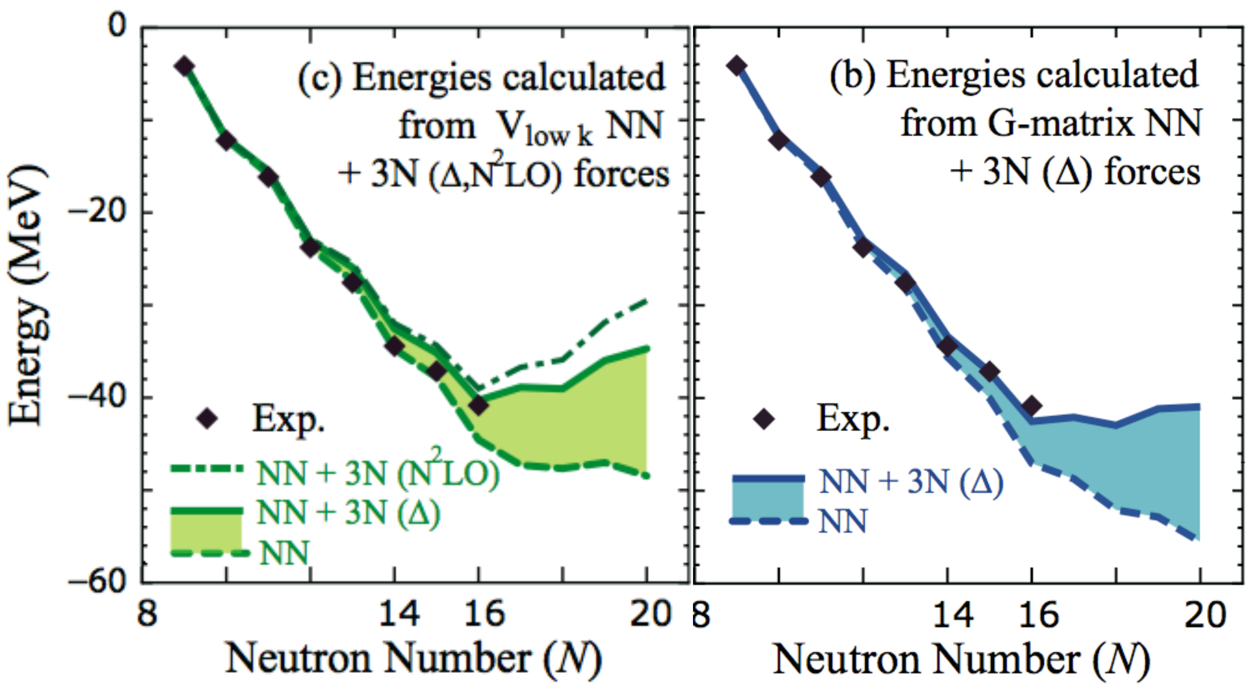
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

The oxygen anomaly



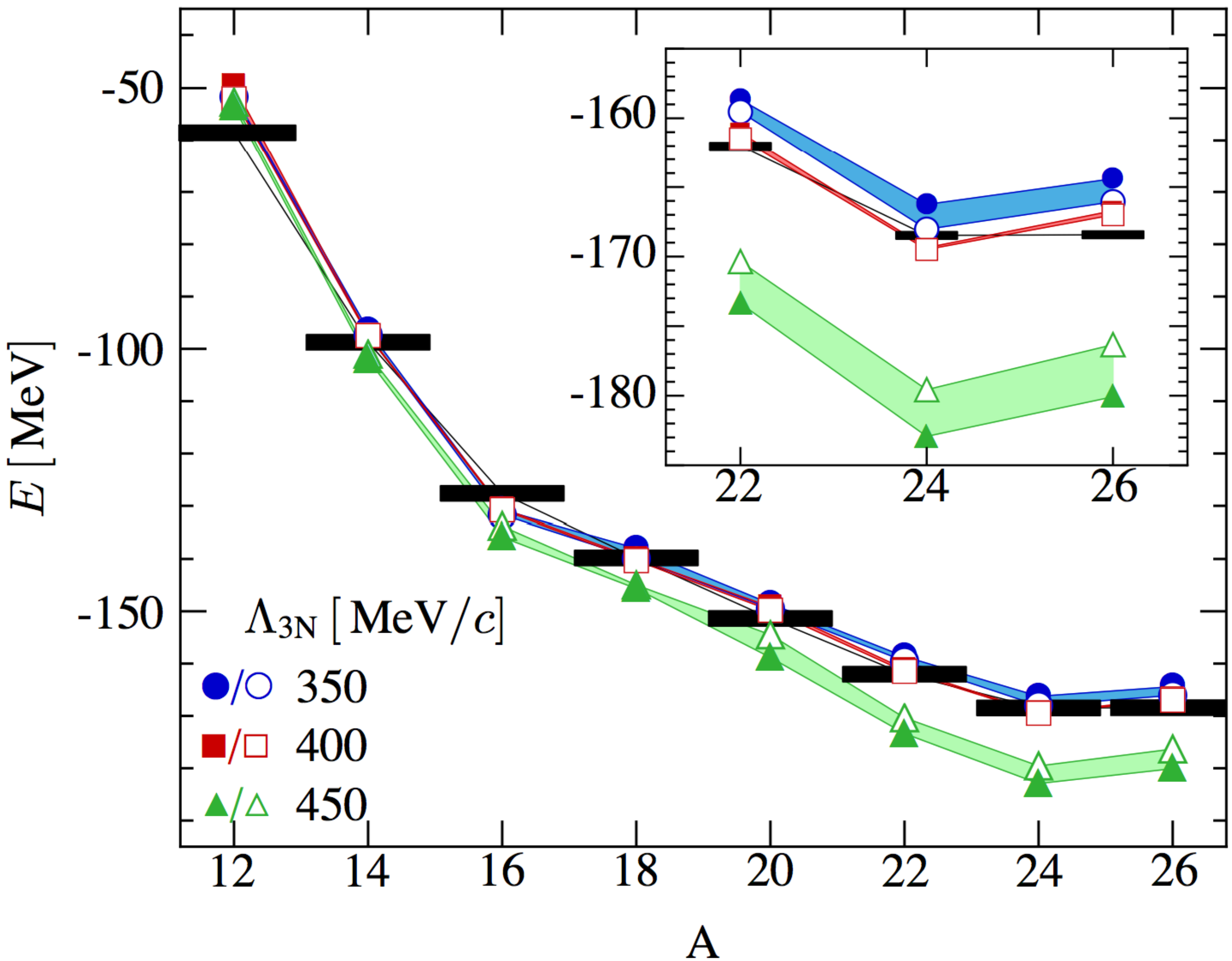
without 3N forces, NN interactions too attractive

3N forces crucial for location of neutron dripline

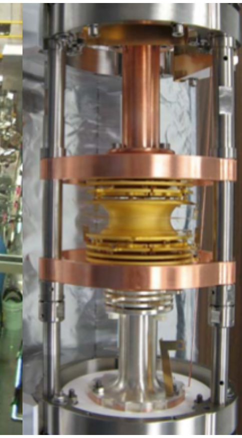


The oxygen anomaly

impact of 3N forces confirmed in ab-initio calculations:
CC with phenomenological forces Hagen et al. (2012)
In-Medium SRG based on NN+3N Hergert et al. (2013)

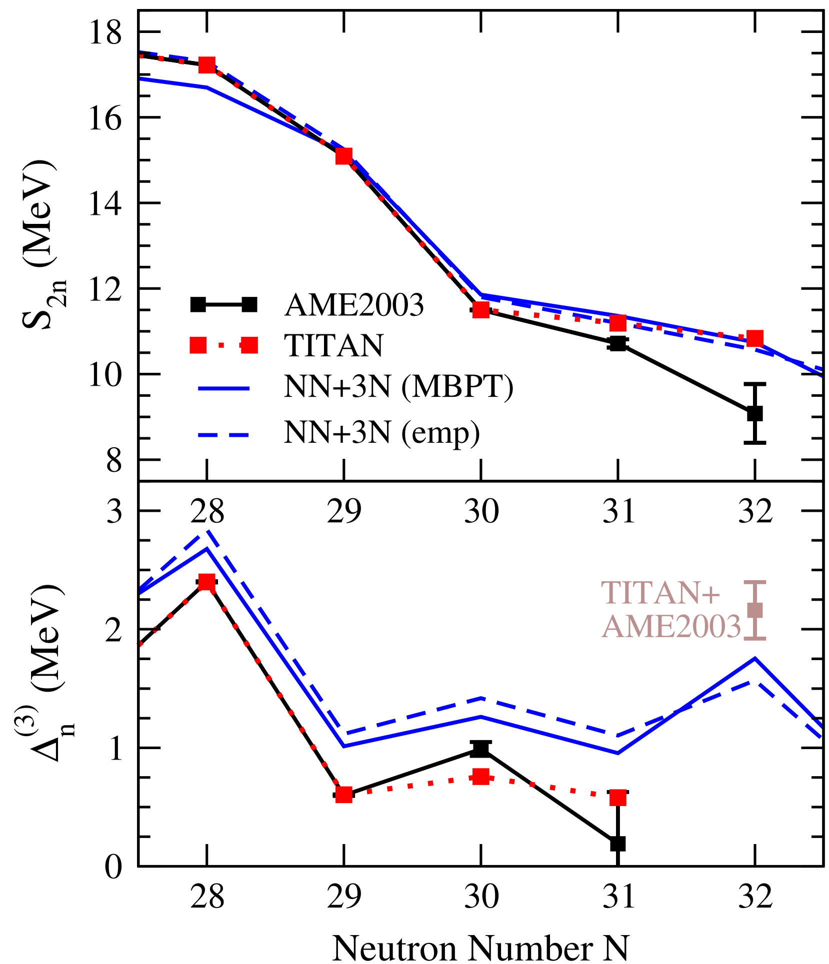


new ^{51,52}Ca TITAN measurements



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

behavior of two-neutron separation energy S_{2n} and odd-even staggering Δ_n agrees with NN+3N predictions



more neutron-rich isotopes at ISOLDE, RIKEN and NSCL

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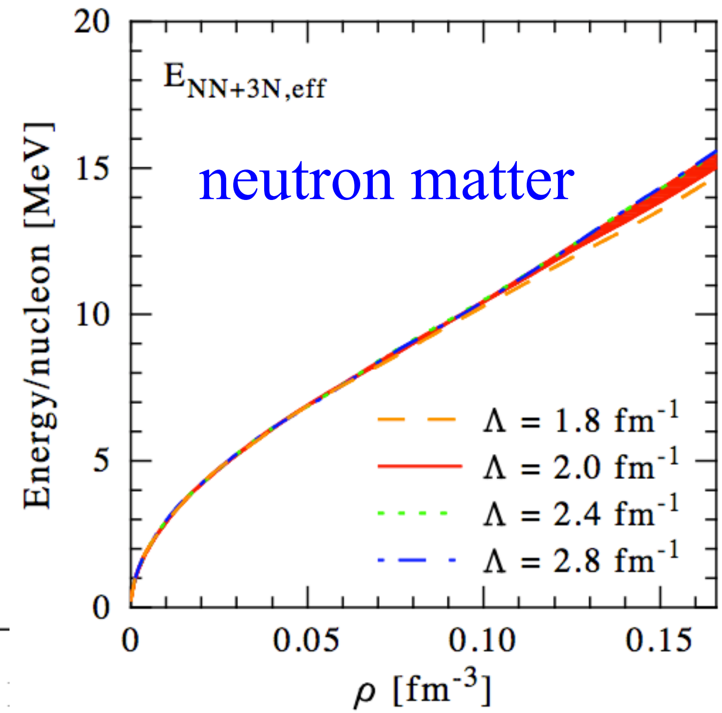
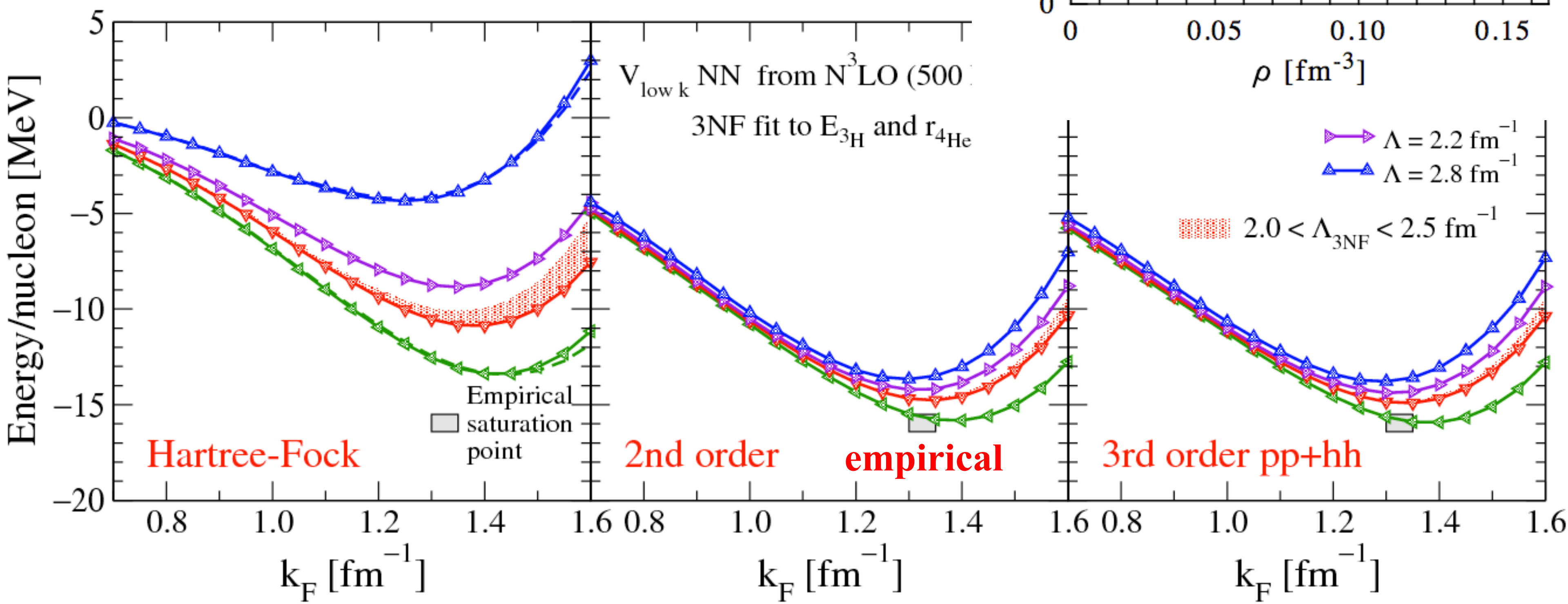
Impact of 3N forces on neutron matter

neutron matter is simpler system, only long-range parts of 3N forces contribute (c_1 and c_3)

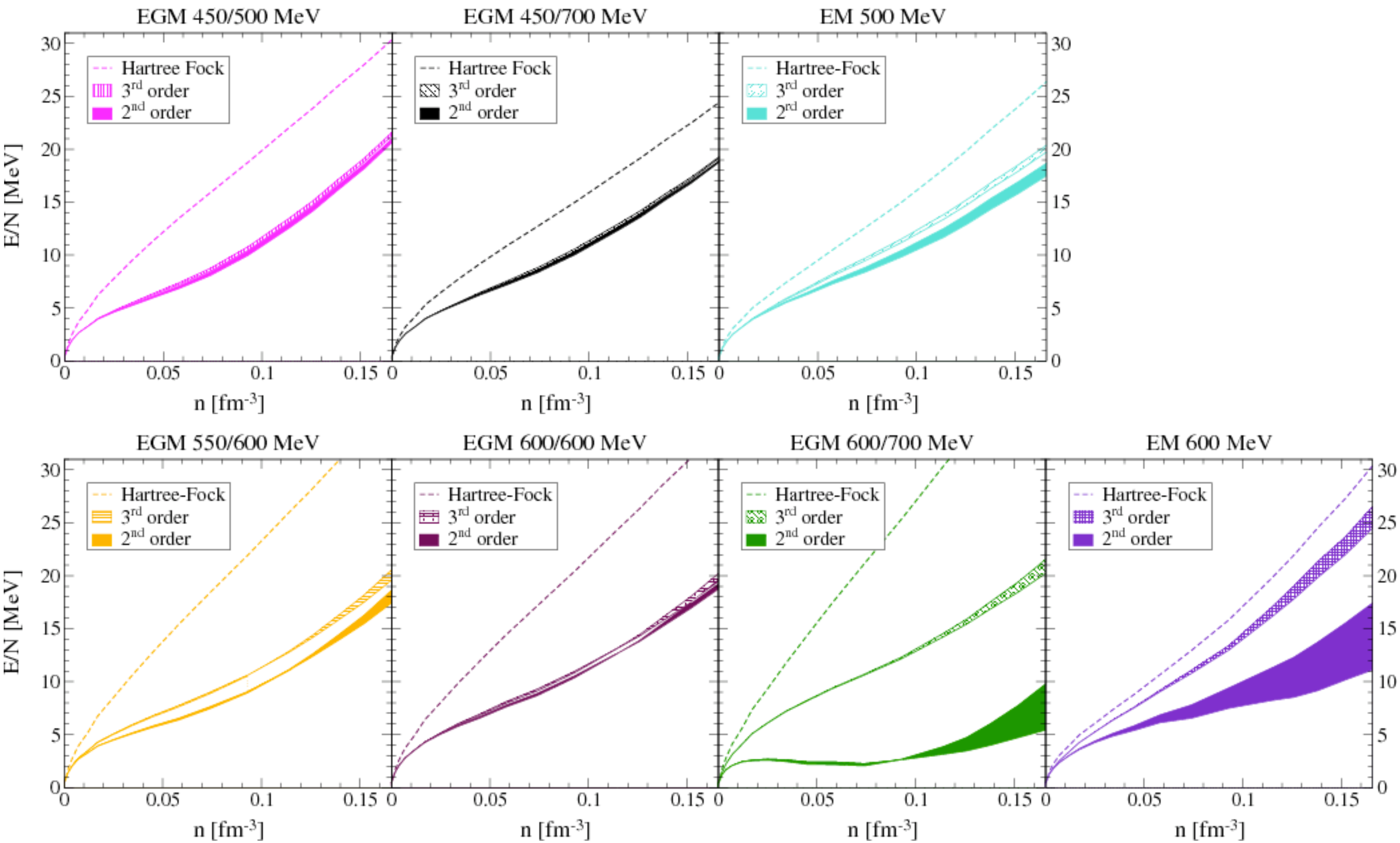
Hebeler, AS (2010)





Neutron matter from chiral EFT interactions

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



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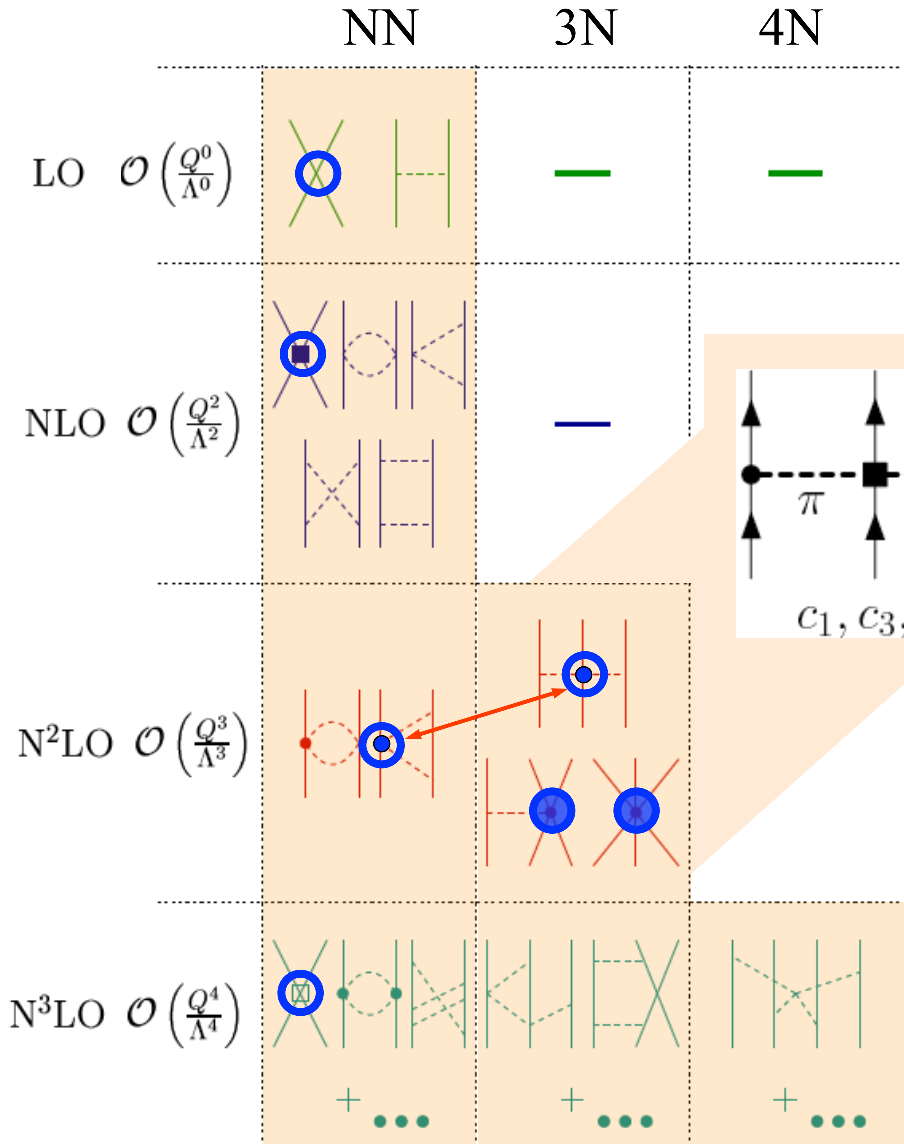

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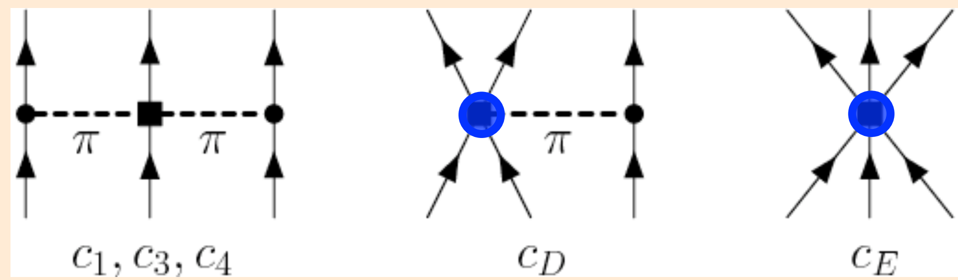


all 3- and 4-neutron forces are predicted to N³LO!

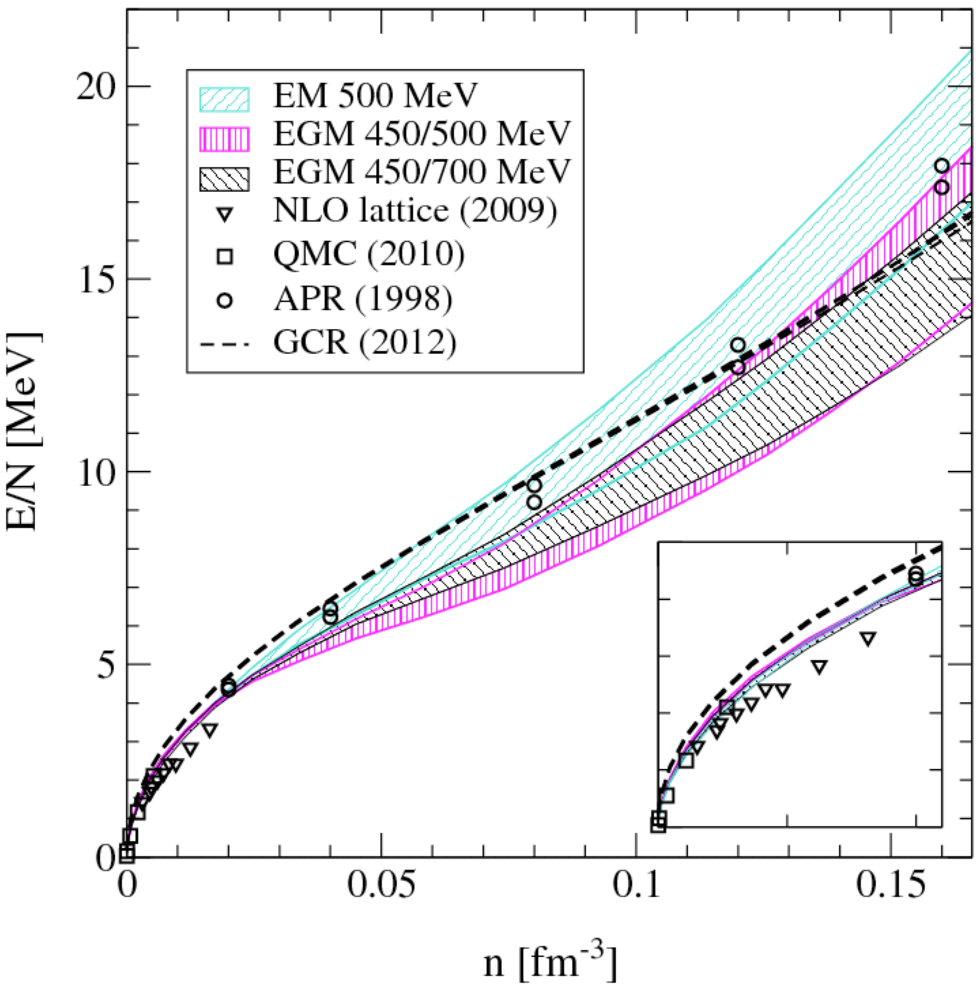
study 3N and 4N in neutron matter

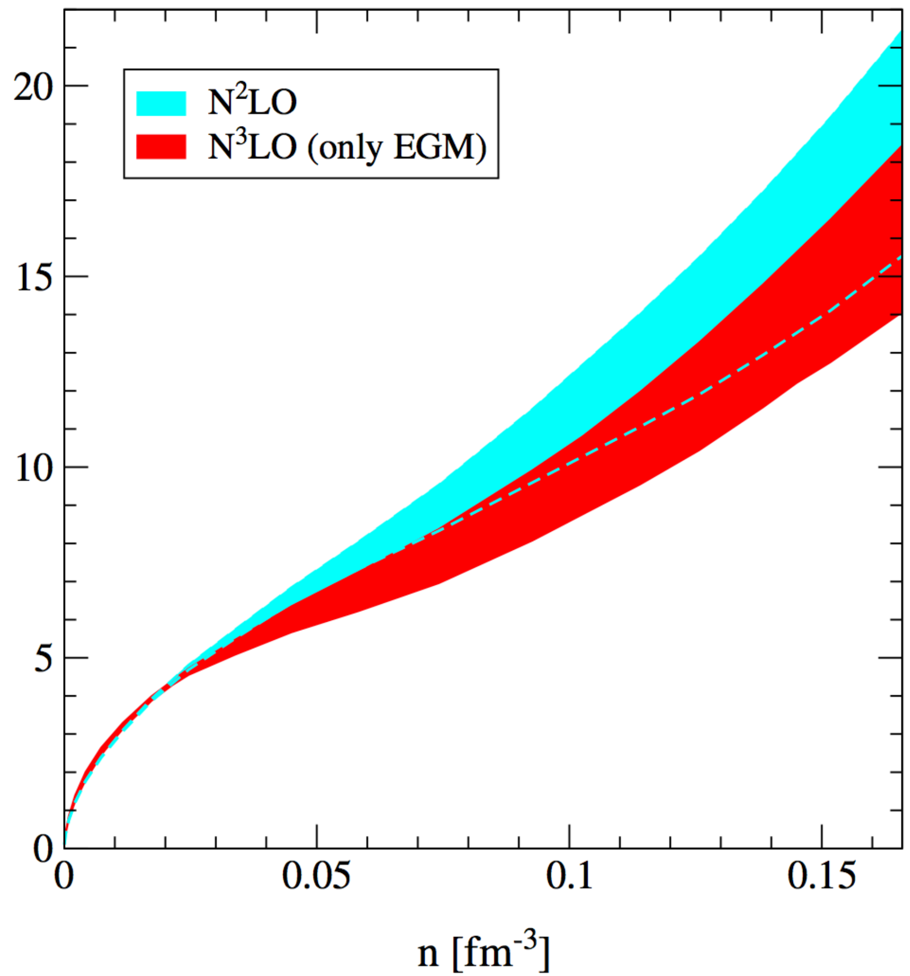
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Complete N^3LO calculation of neutron matter

first complete N^3LO result Tews, Krüger, Hebeler, AS (2013)

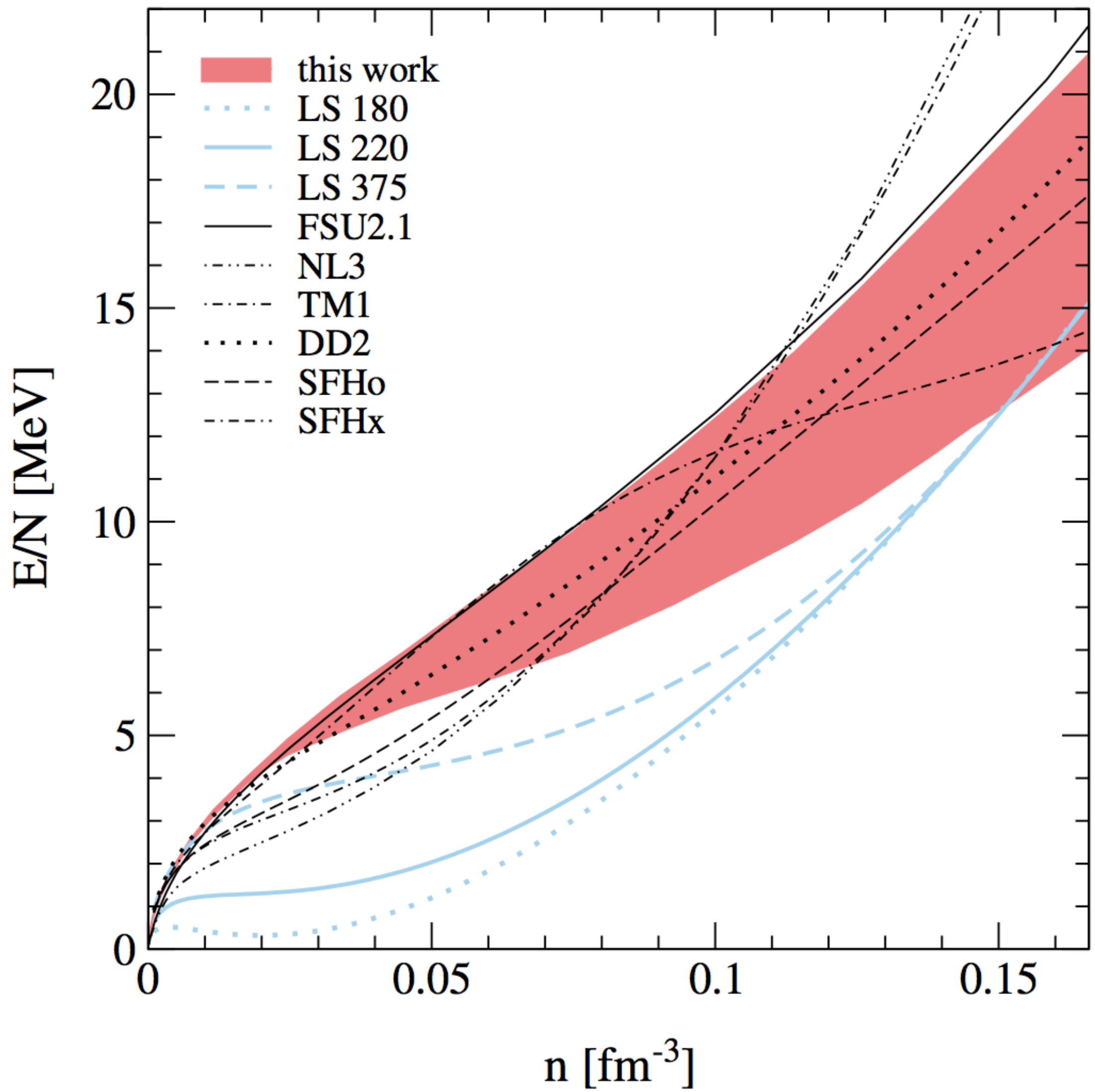
includes uncertainties from bare NN, 3N, 4N





Comparisons to equations of state in astrophysics

many equations of state not consistent with neutron matter results



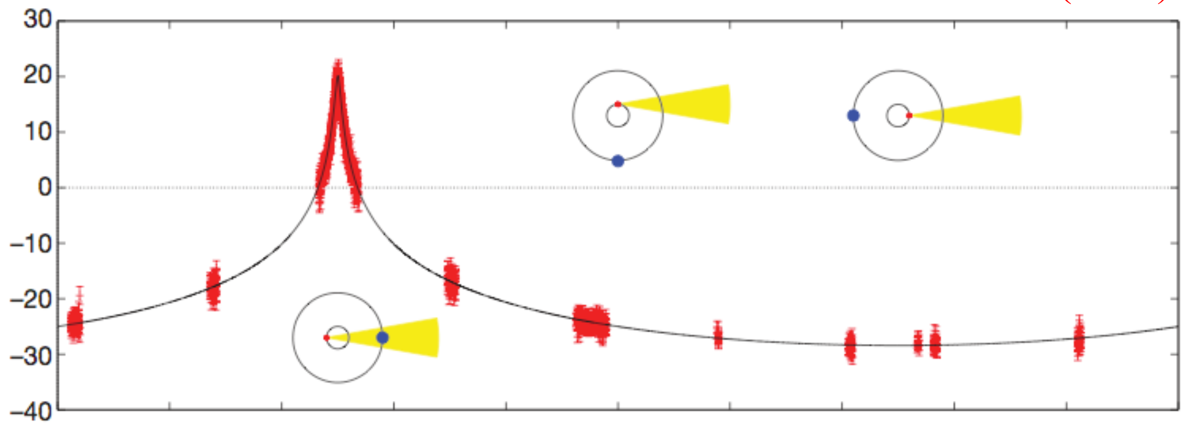
Discovery of the heaviest neutron star

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

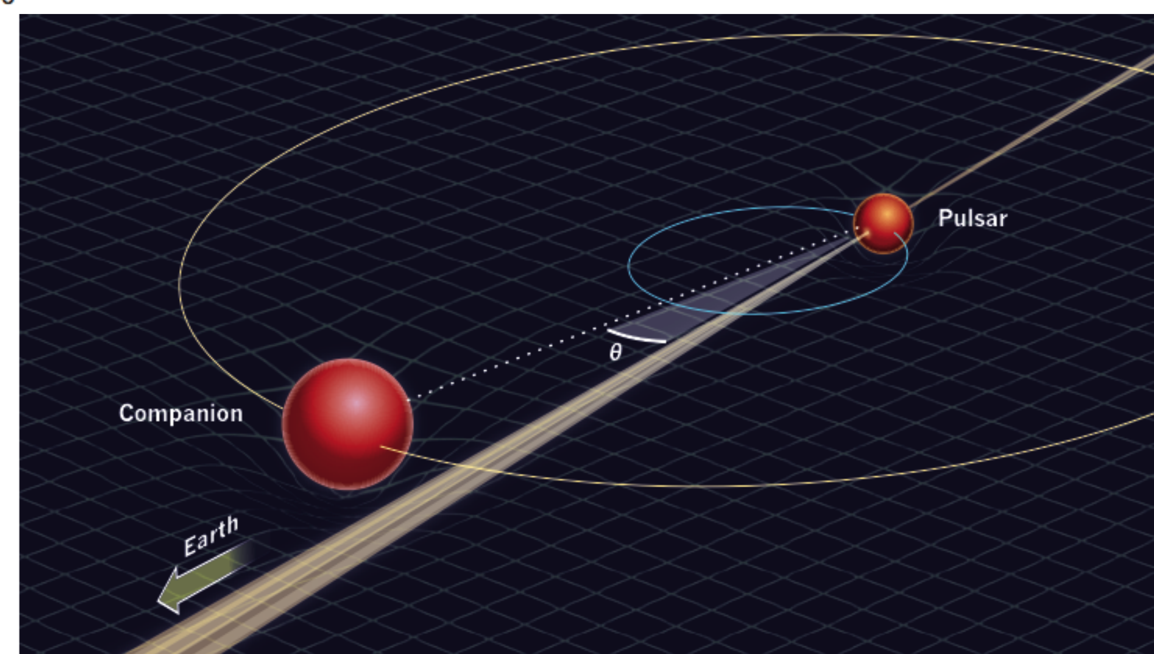
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature (2010)

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



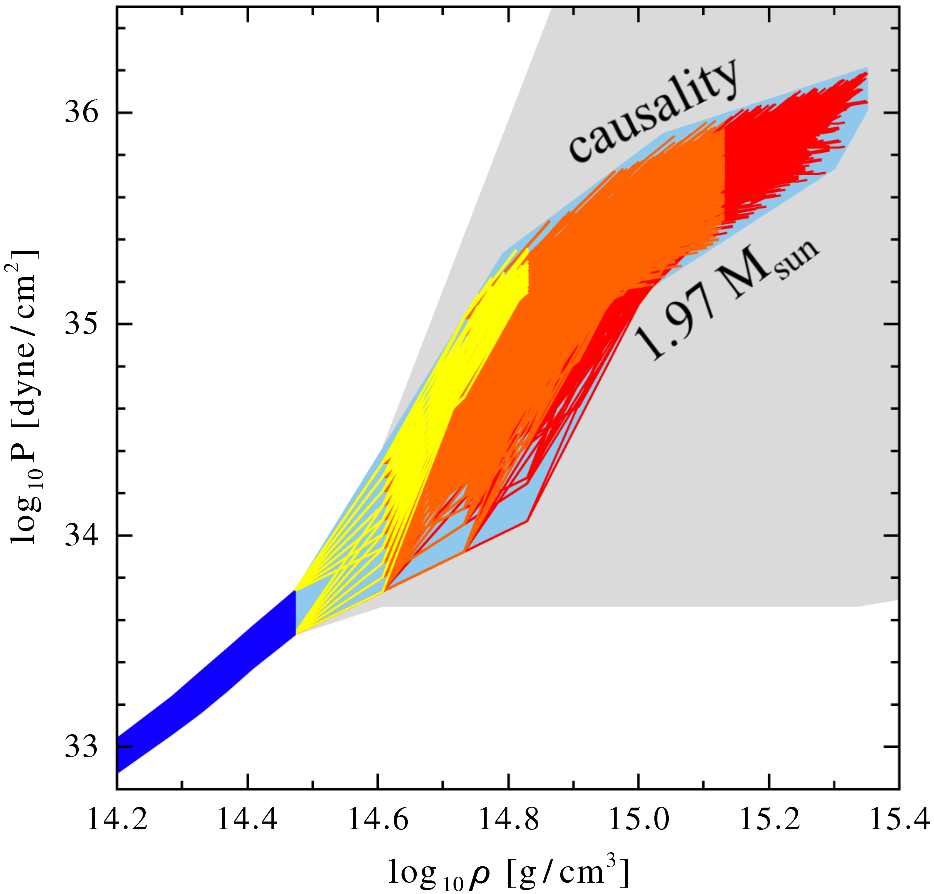
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})

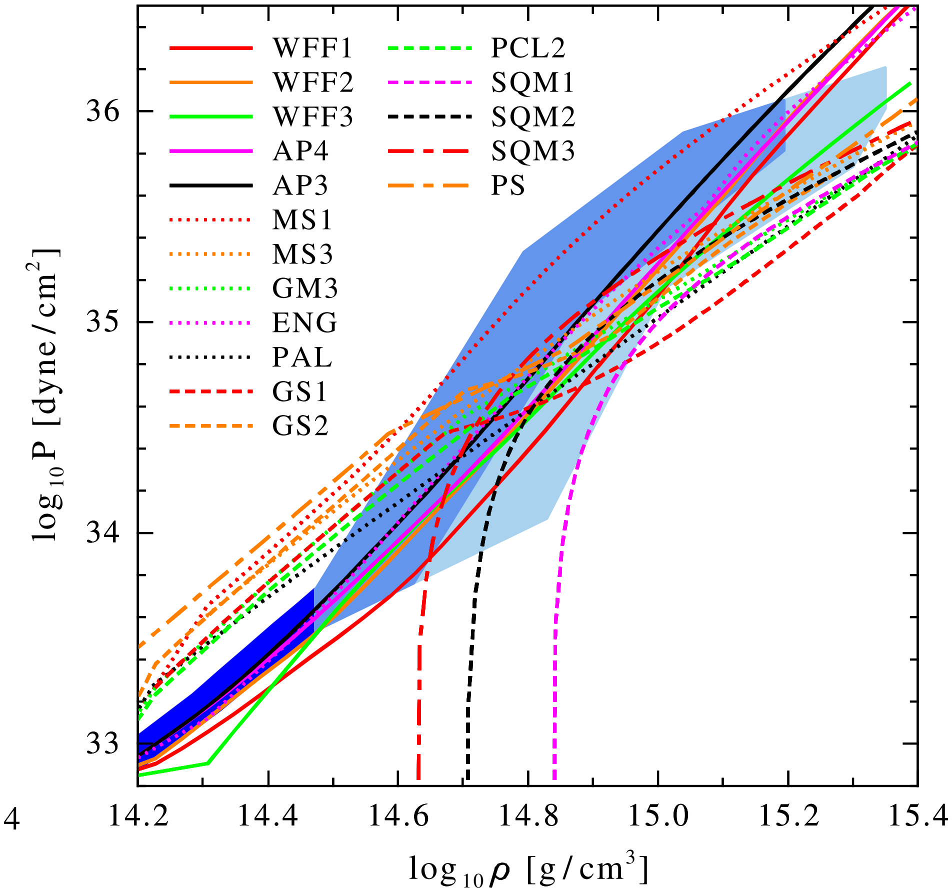


heaviest neutron star with 1.97±0.04 M_{sun}

Equation of state of neutron star matter

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

predicts neutron star radius: 9.7-13.9 km for M=1.4 M_{sun} (±15% !)

Neutron-star mergers and gravitational waves

explore sensitivity to neutron-rich matter in neutron-star merger and gw signal

Bauswein, Janka (2012), Bauswein, Janka, Hebeler, AS (2012).

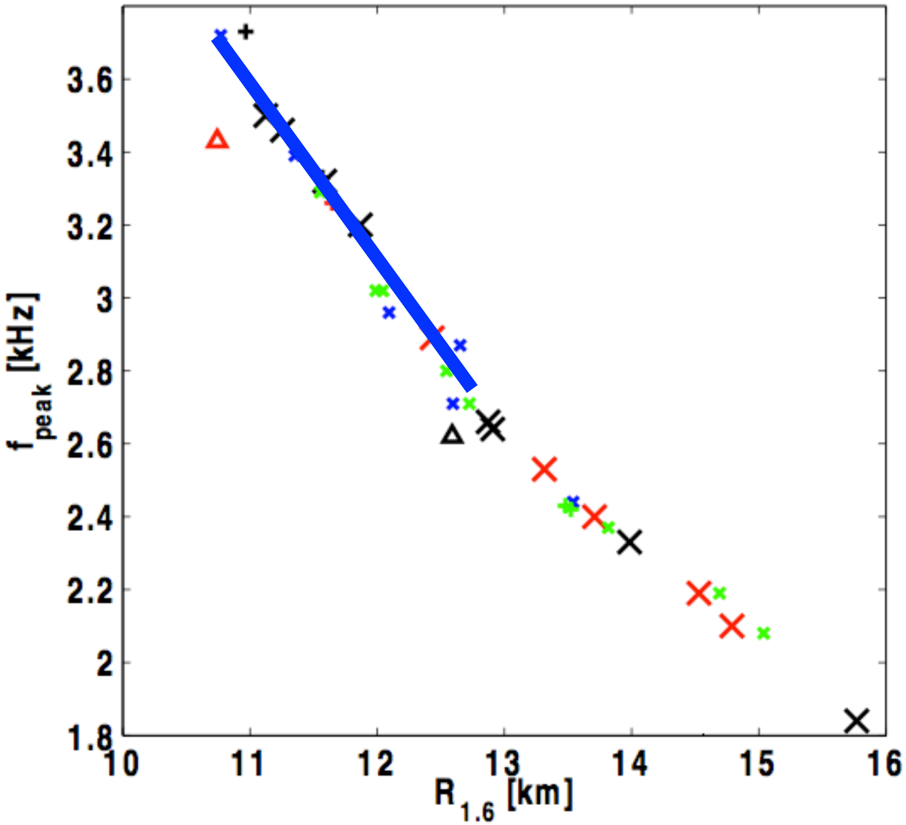


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.

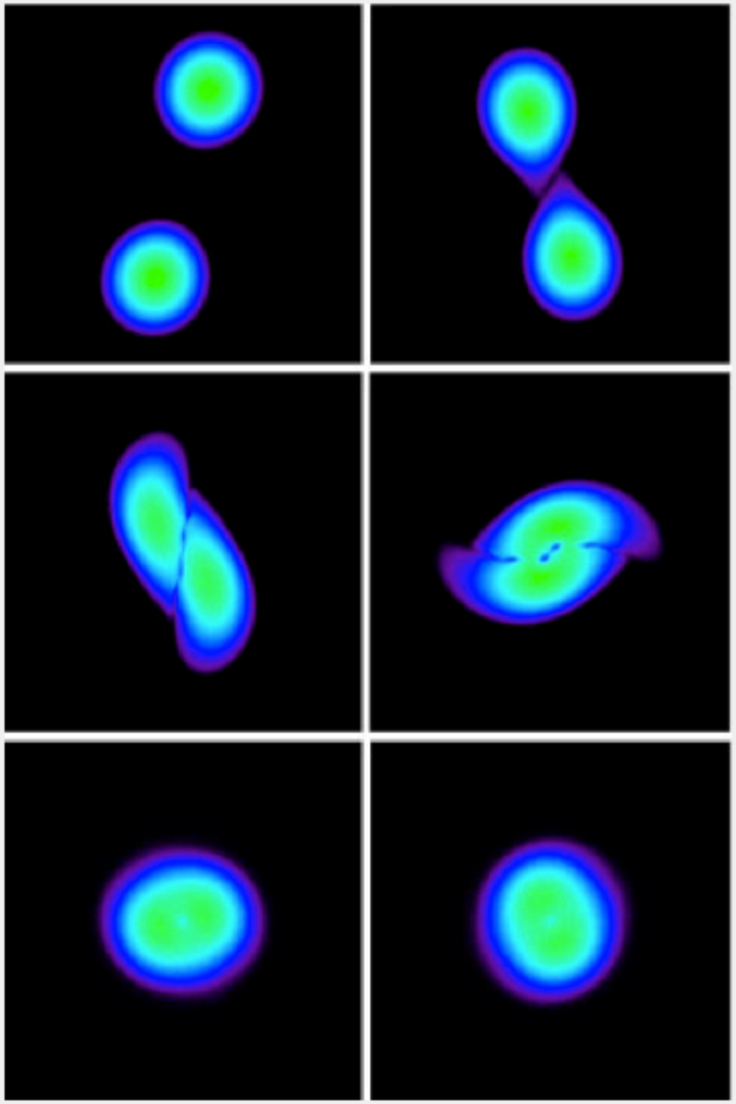


Fig. 1: Various snapshots of the collision of two neutron stars initially revolving around each other. The sequence simulated by the computer covers only 0.03 seconds. The two stars orbit each other counterclockwise (top left) and quickly come closer (top right). Finally they collide (centre left), merge (centre right), and form a dense, superheavy neutron star (bottom). Strong vibrations of the collision remnant are noticeable as deformations in east-west direction and in north-south direction (bottom panels). (Simulation: Andreas Bauswein and H.-Thomas Janka/MPA)

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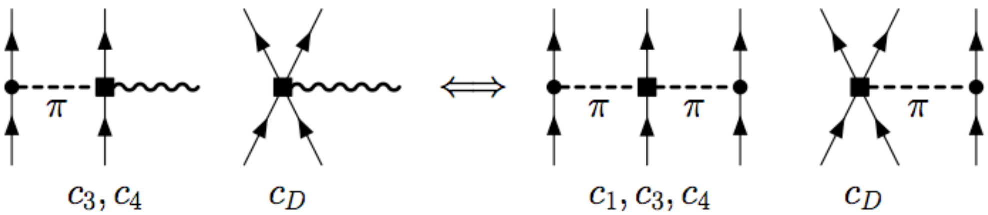
Electroweak interactions and 3N forces

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)

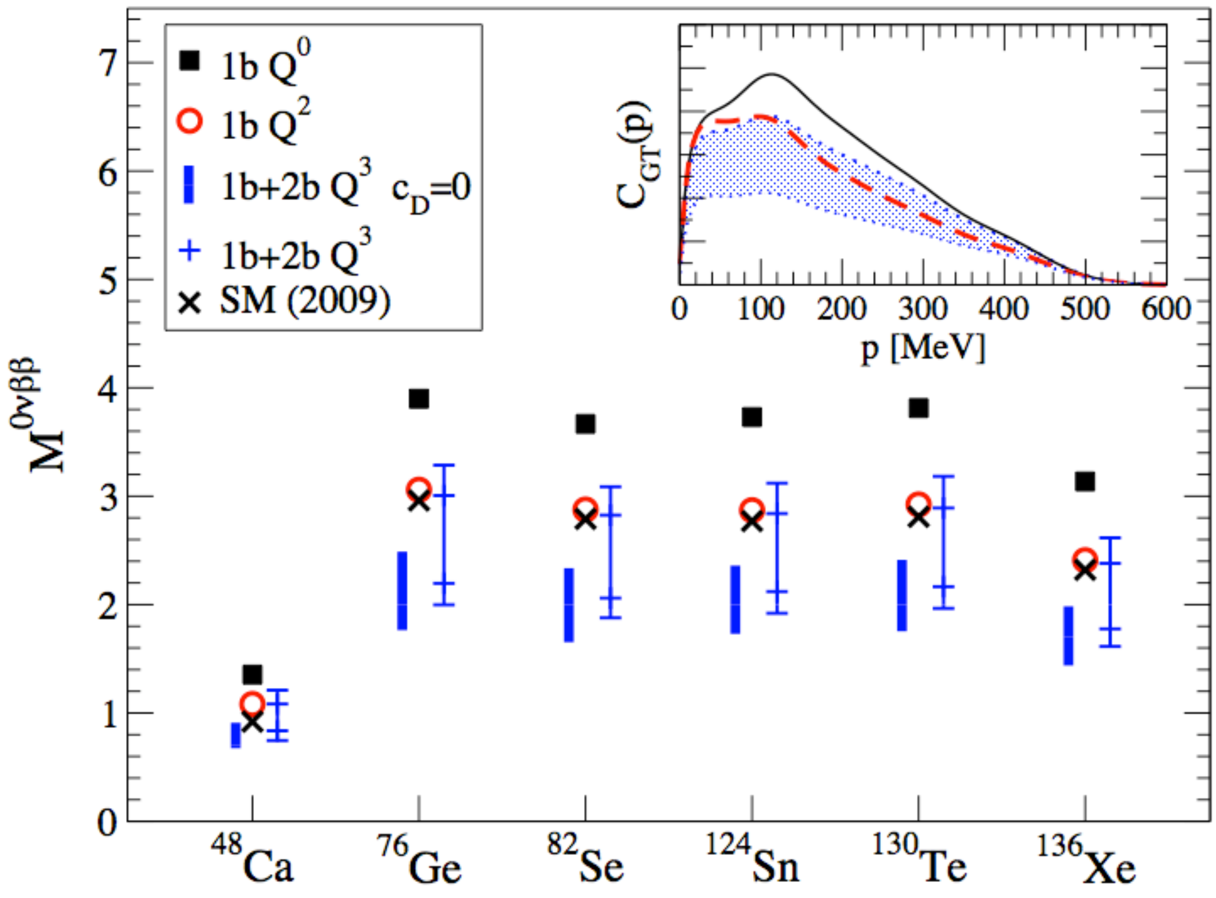
Menendez, Gazit, AS (2011)

Chiral EFT and $0\nu\beta\beta$ decay

Nuclear matrix elements for $0\nu\beta\beta$ decay based on chiral EFT operator

Menendez, Gazit, AS (2011)

Modest quenching because $0\nu\beta\beta$ decay probes higher momentum transfer



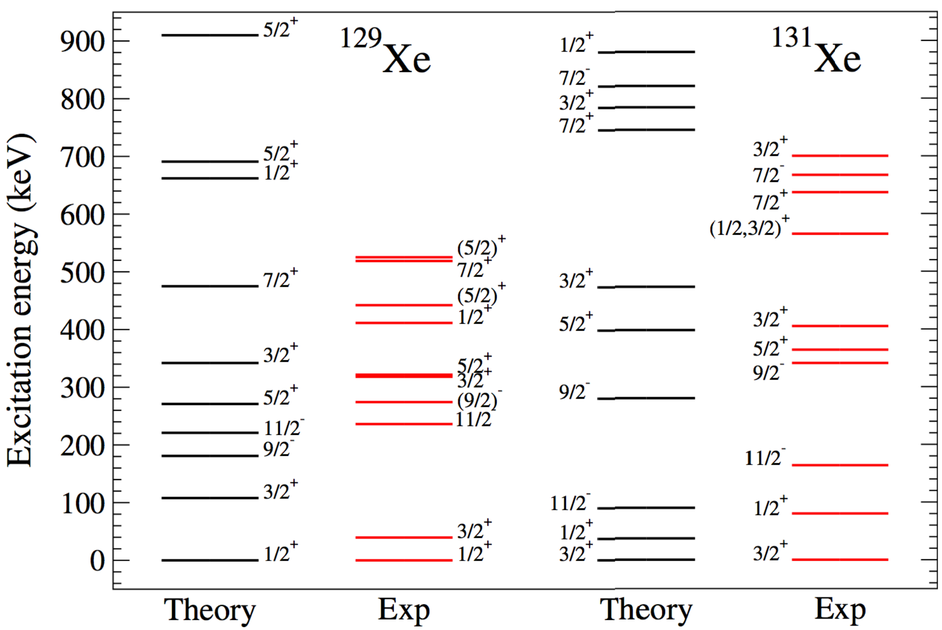
Is it possible to set up nn to pp matching problem with lattice QCD?

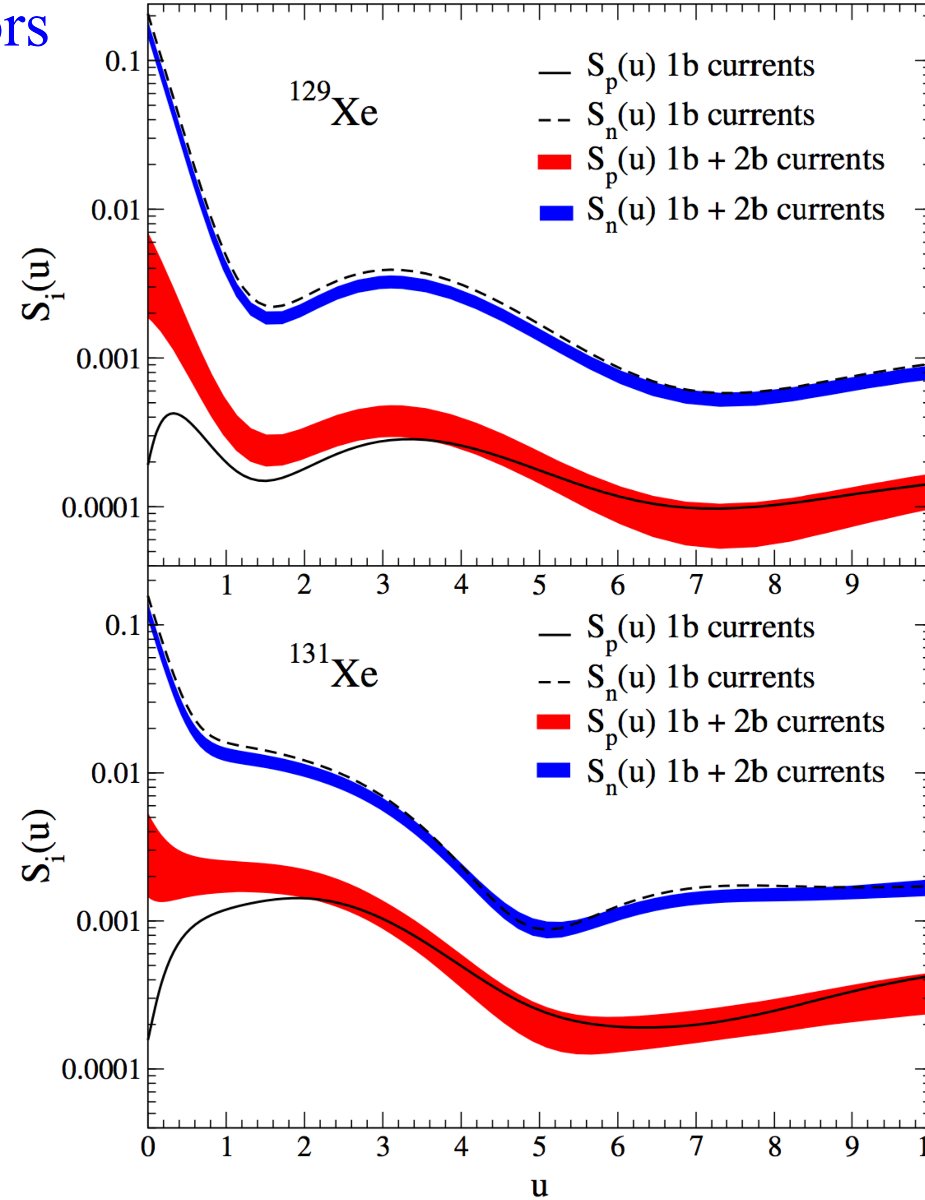
Direct detection of dark matter WIMPs by scattering off nuclei

spin-dependent WIMP-nucleon interaction is particularly sensitive to nuclear structure: spin structure factors

SD WIMP-nucleon coupling is isospin rot. of weak axial current, include long-range 2-body currents

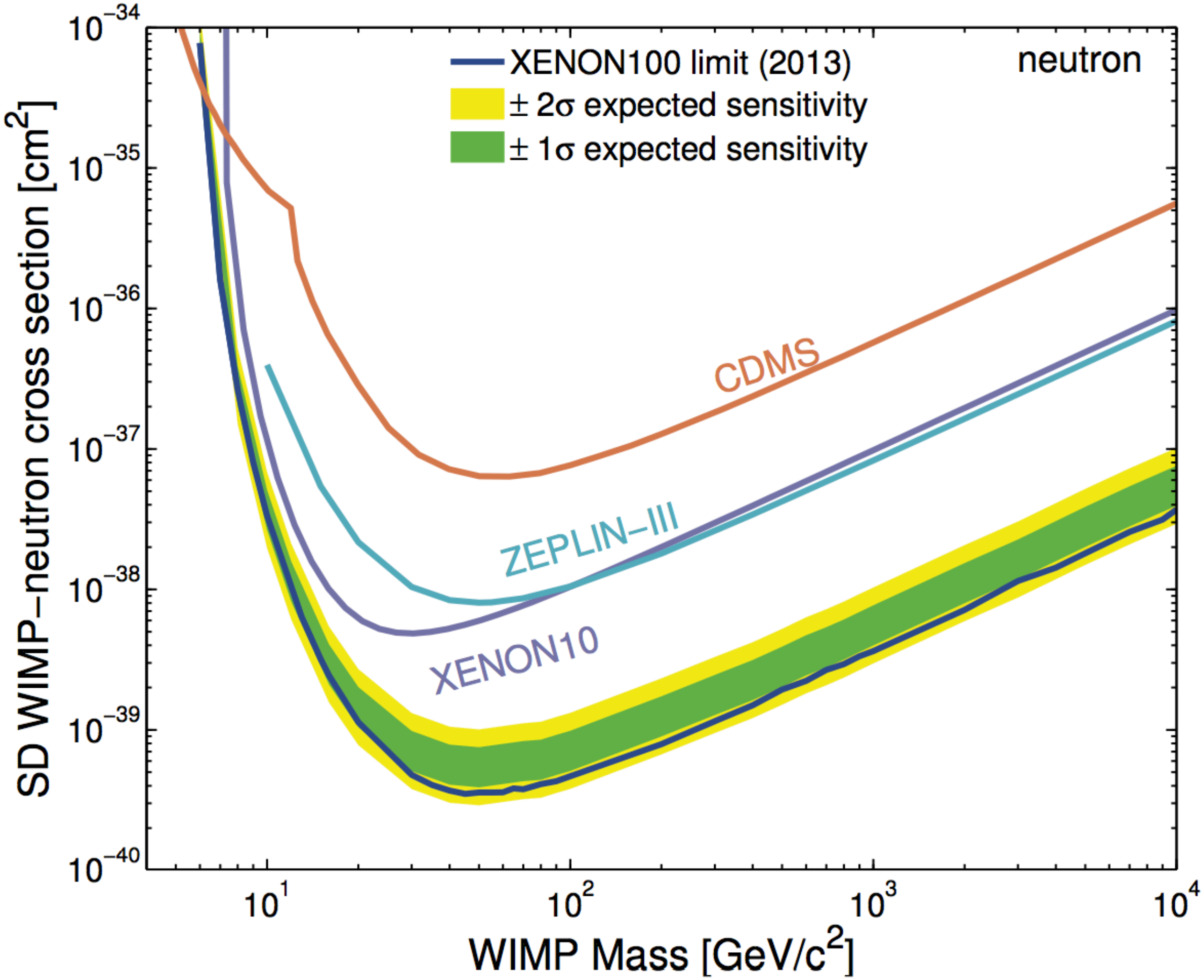
Menendez, Gazit, AS (2012)





Limits on SD WIMP-neutron interactions

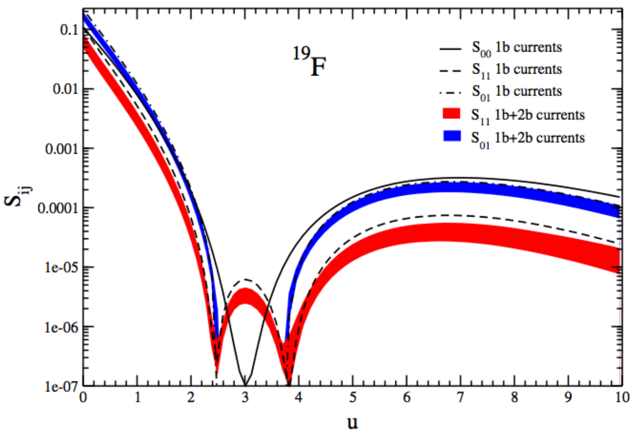
best limits from XENON100 Aprile et al., 1301.6620
uses Javier Menendez' calculation



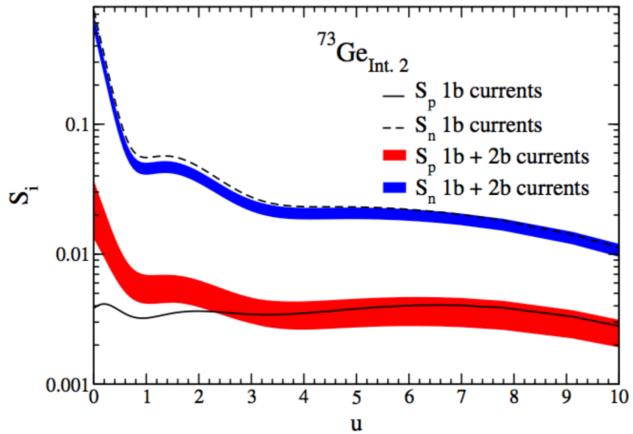
WIMP coupling to 1- and 2-nucleons from lattice QCD?

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

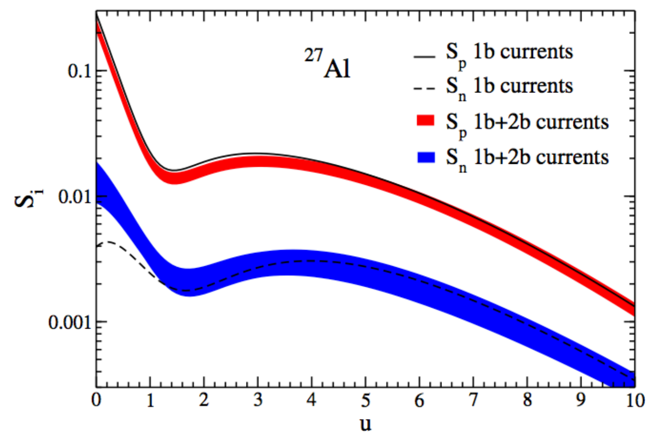
Klos, Menendez, Gazit, AS, in prep.



PICASSO, COUPP, SIMPLE



CDMS, EDELWEISS, EURECA



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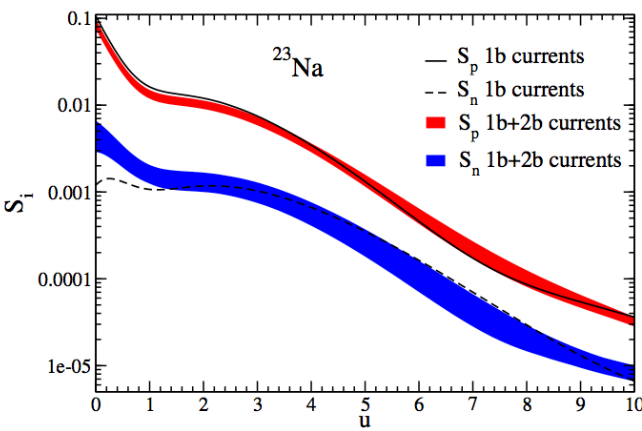
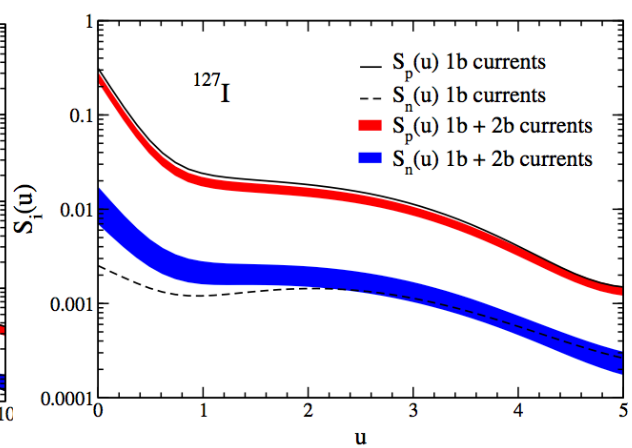
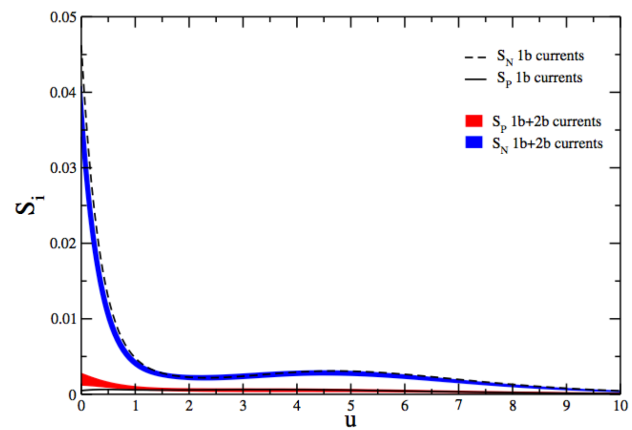


DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS



CDMS-II

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