Nuclear astrophysics and electron beams

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TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

Physics Opportunities with Intense, Polarized Electron Beams

MIT, March 14, 2013

S-DALINAC

DFG

erc

HELMHOLTZ ASSOCIATION

Minerva Stiftung

ARCHES

Award for Research Cooperation and High Excellence in Science

Bundesministerium für Bildung und Forschung

Outline

Chiral effective field theory
nuclear forces and electroweak interactions,
systematic EFT for energies below ~300 MeV!

Nuclear structure frontiers

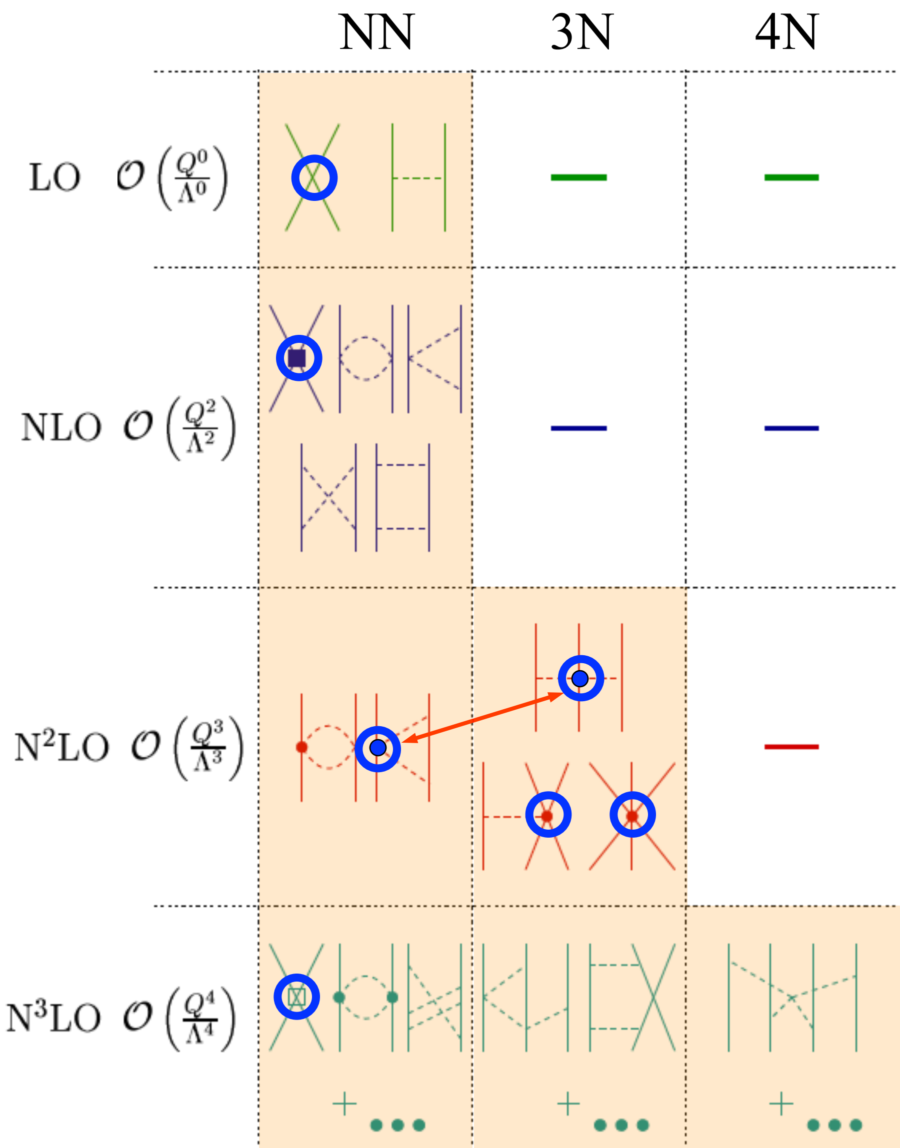
3N forces predict **neutron skin** and constrain **neutron stars**

Nuclear reactions for astrophysics and electron beams

Dark matter response of nuclei,
Is it possible to simulate/constrain this with electrons?

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**

talk by W. Delmold

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

Chiral effective field theory and **many-body forces**

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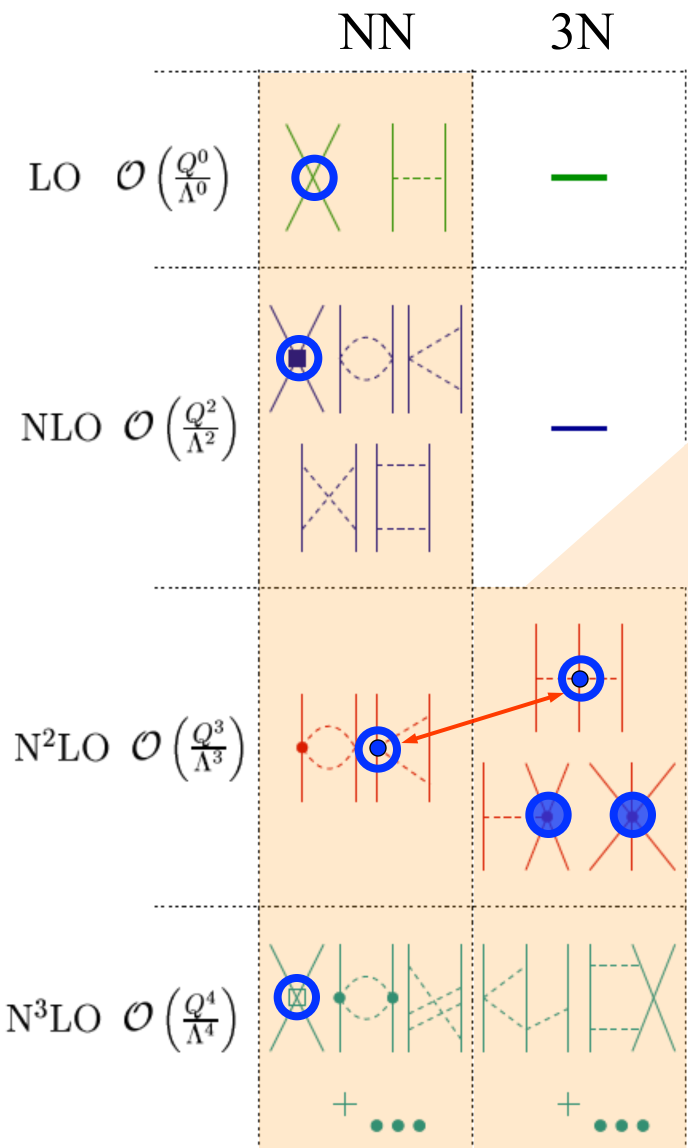
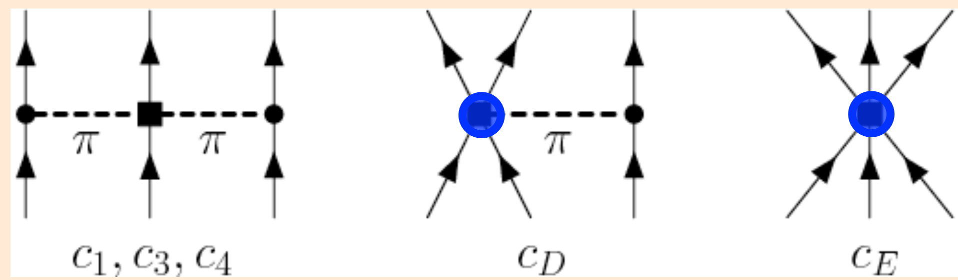


consistent NN-3N interactions

3N,4N: only 2 new couplings to N^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: $c_1=0$, $c_3=-c_4/2=-3$ GeV^{-1}

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

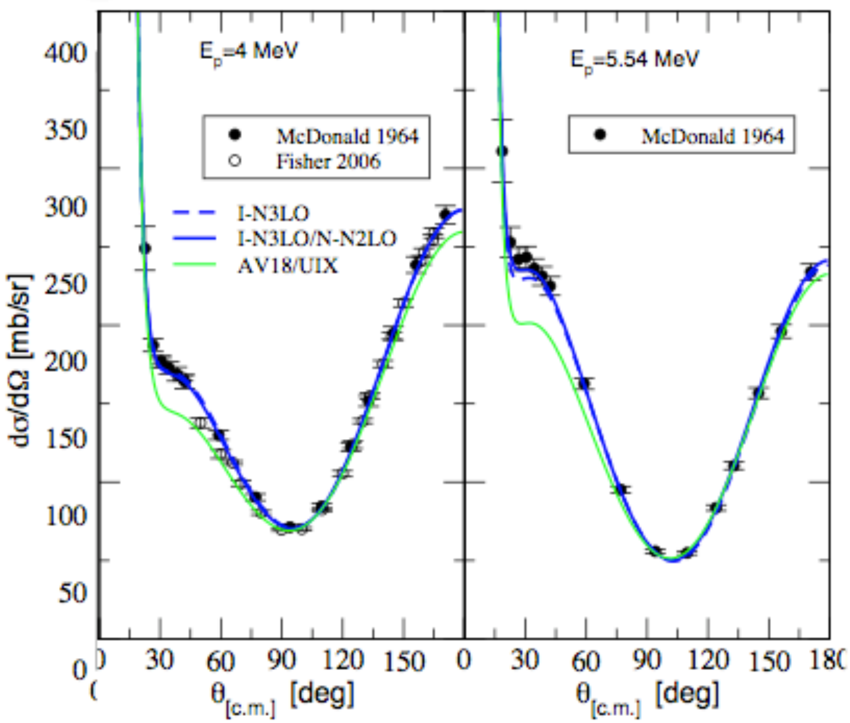
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Chiral effective field theory and few-body scattering

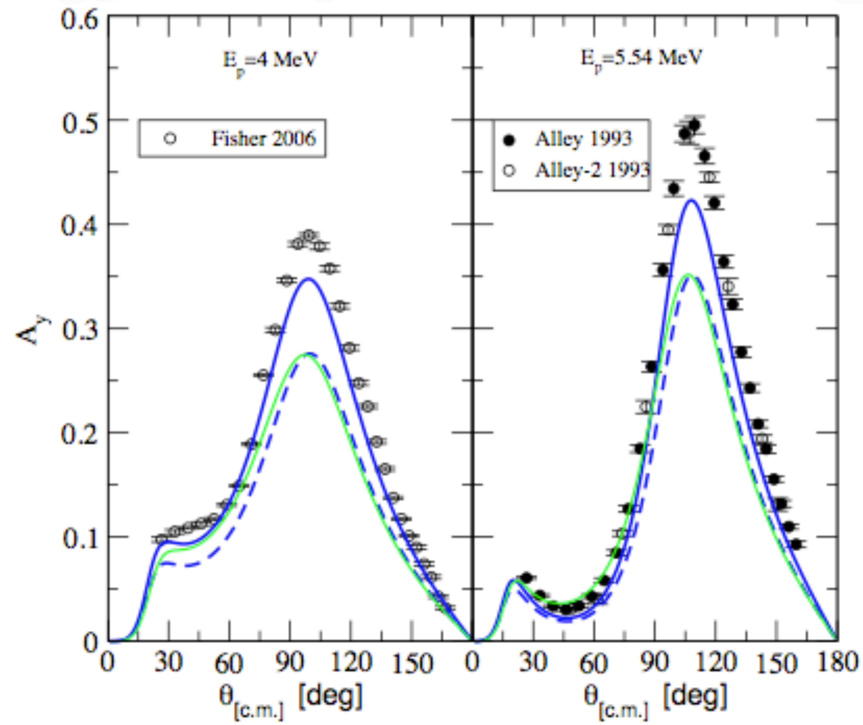
Chiral 3NF and 4N scattering

Viviani, Girlanda, Kievsky, Marcucci, Rosatti arXiv:1004.1306

p-^{3}He differential cross section



A_y-puzzle in p-^{3}He elastic scattering



(the LECs D,E are tuned to the ^{3}H and ^{4}He binding energies)

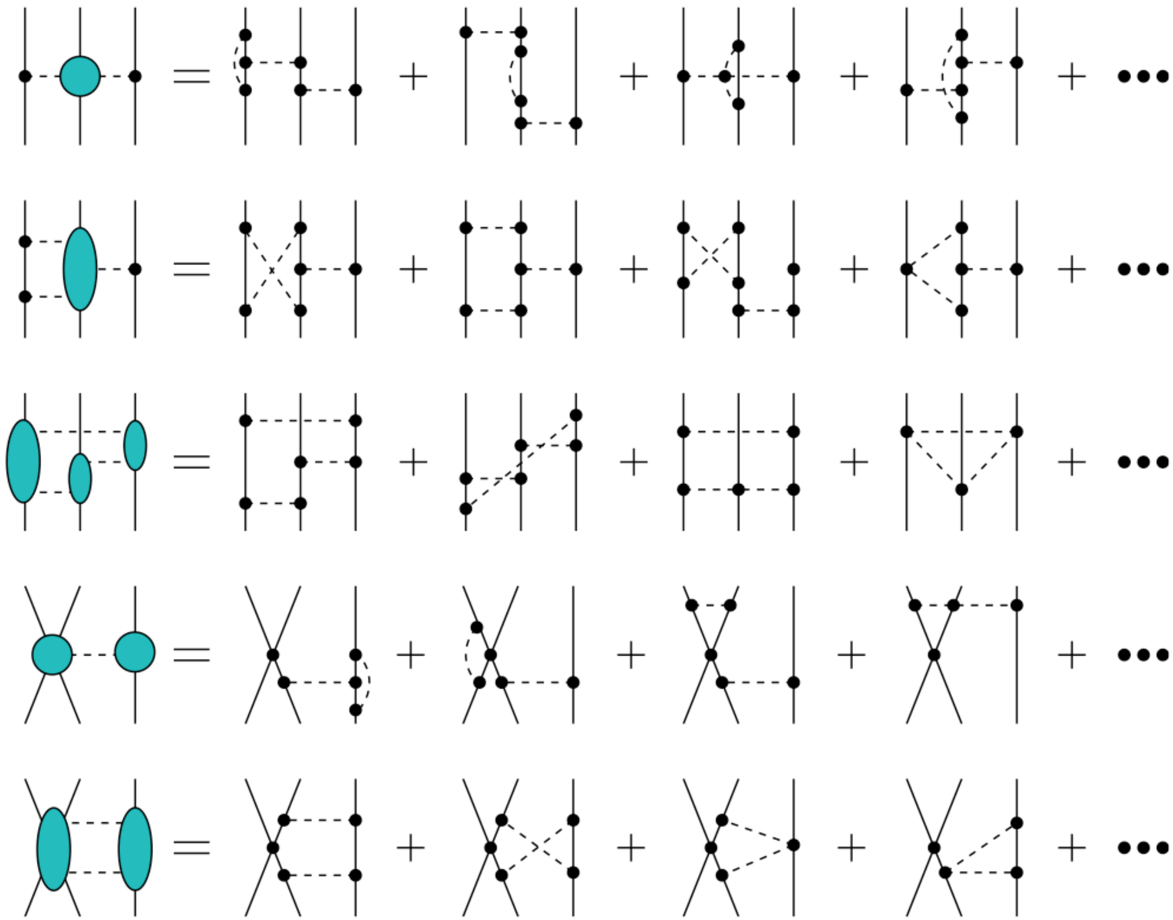
Leading 3N forces systematically improve few-body scattering

Subleading chiral 3N forces

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

many new structures!

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



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

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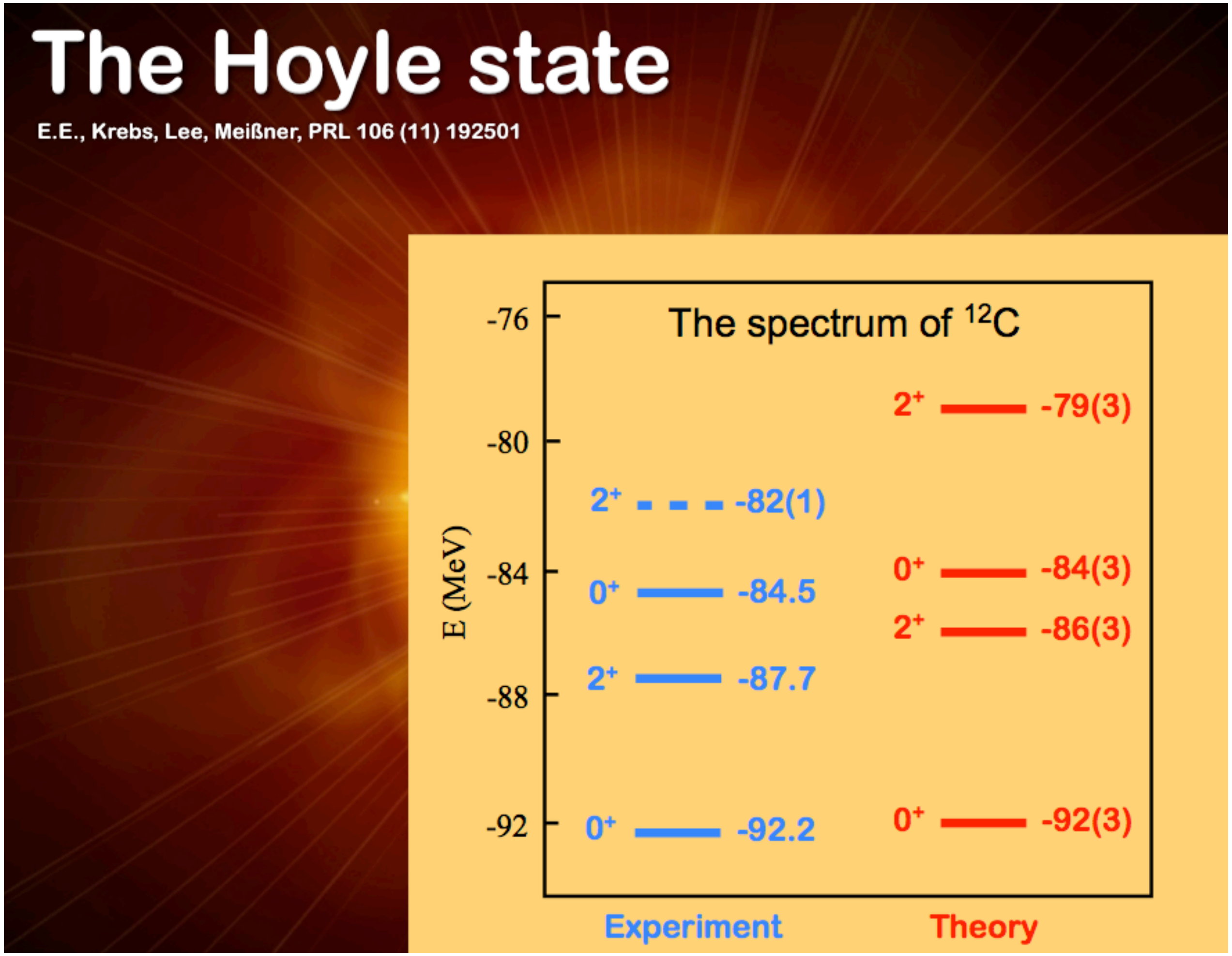
Nuclear lattice simulations of light N~Z nuclei

based on chiral EFT interactions on the lattice

Epelbaum, Krebs, Lee, Meissner (2011-)



structure of Hoyle state probed by electron scattering at S-DALINAC

Chernyk, Richter et al. (2007-) talk by J. Enders

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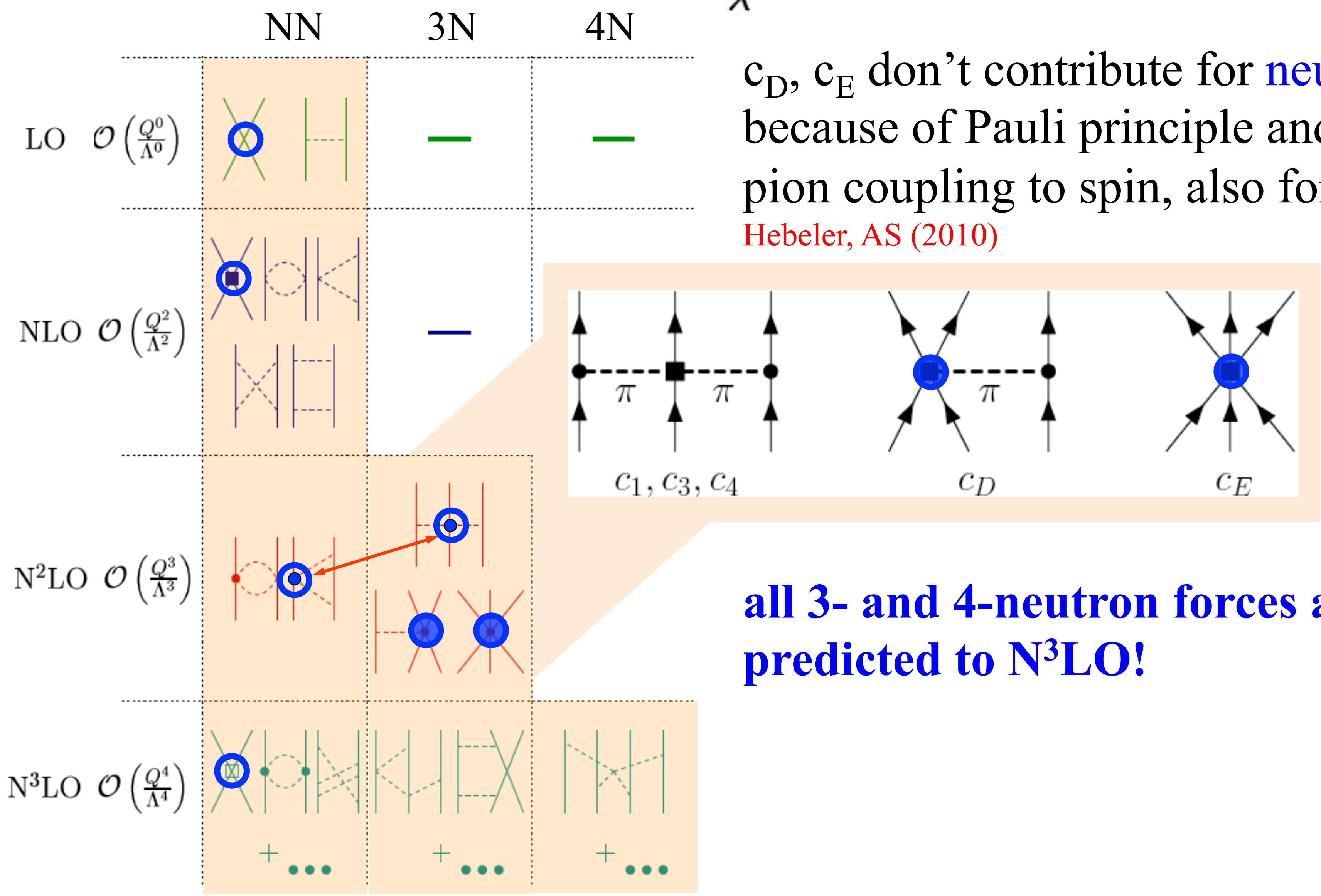


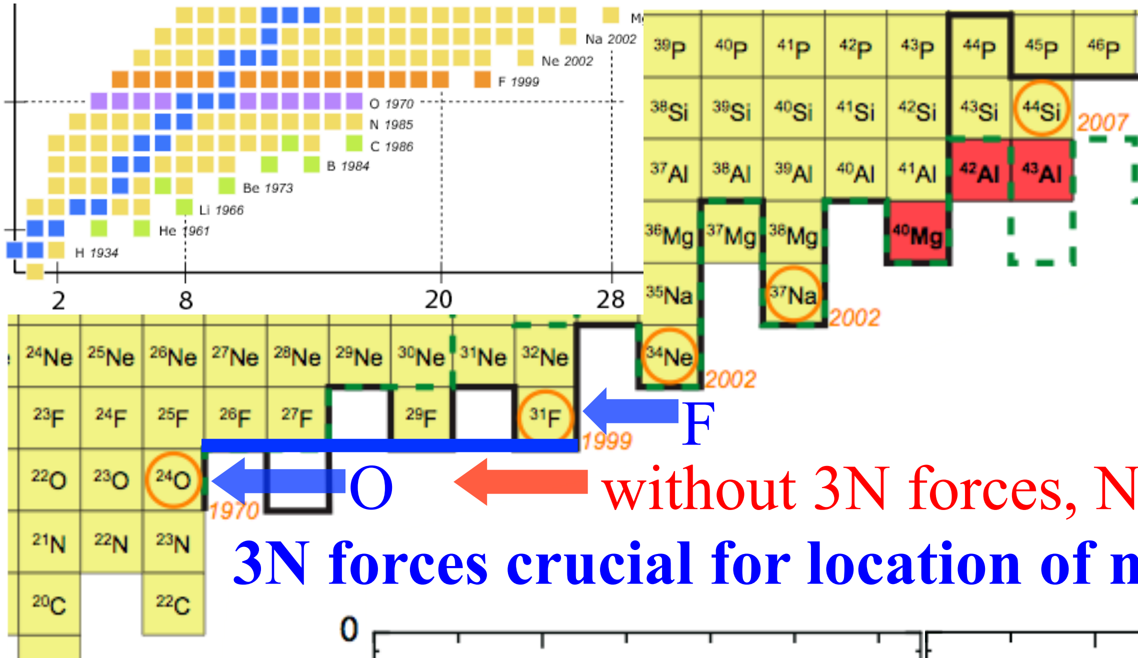
c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)

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

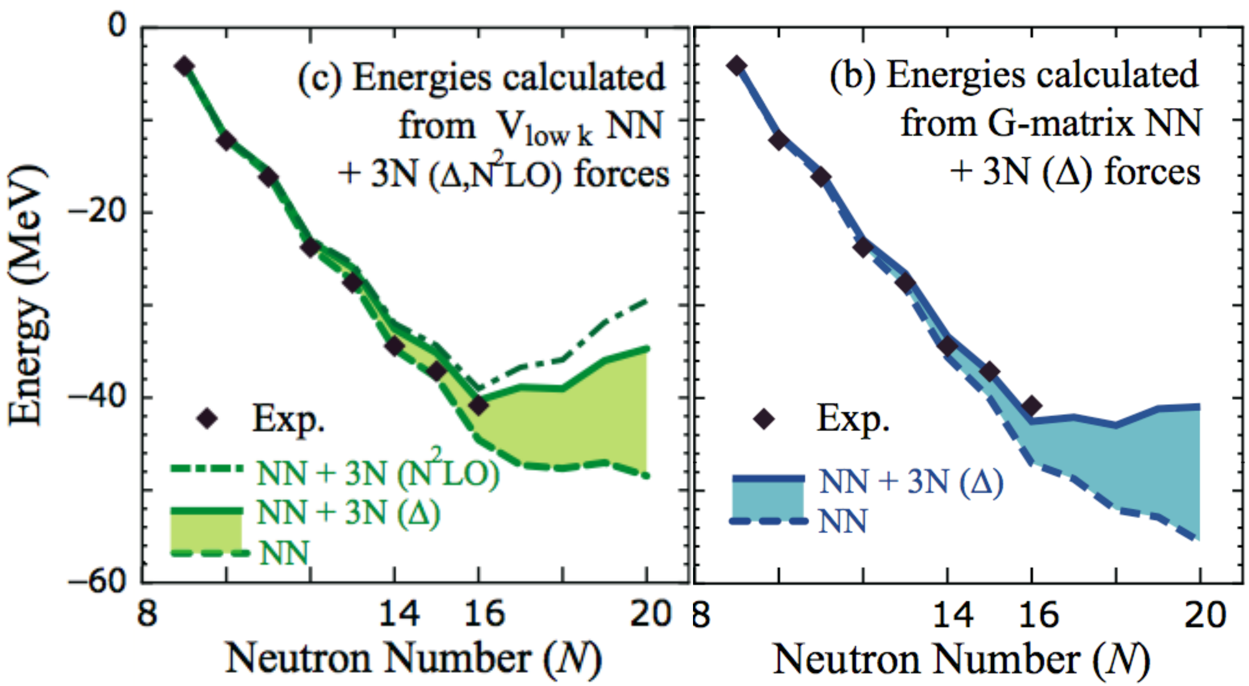
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

The oxygen anomaly Otsuka et al. (2010)



without 3N forces, NN interactions too attractive

3N forces crucial for location of neutron dripline

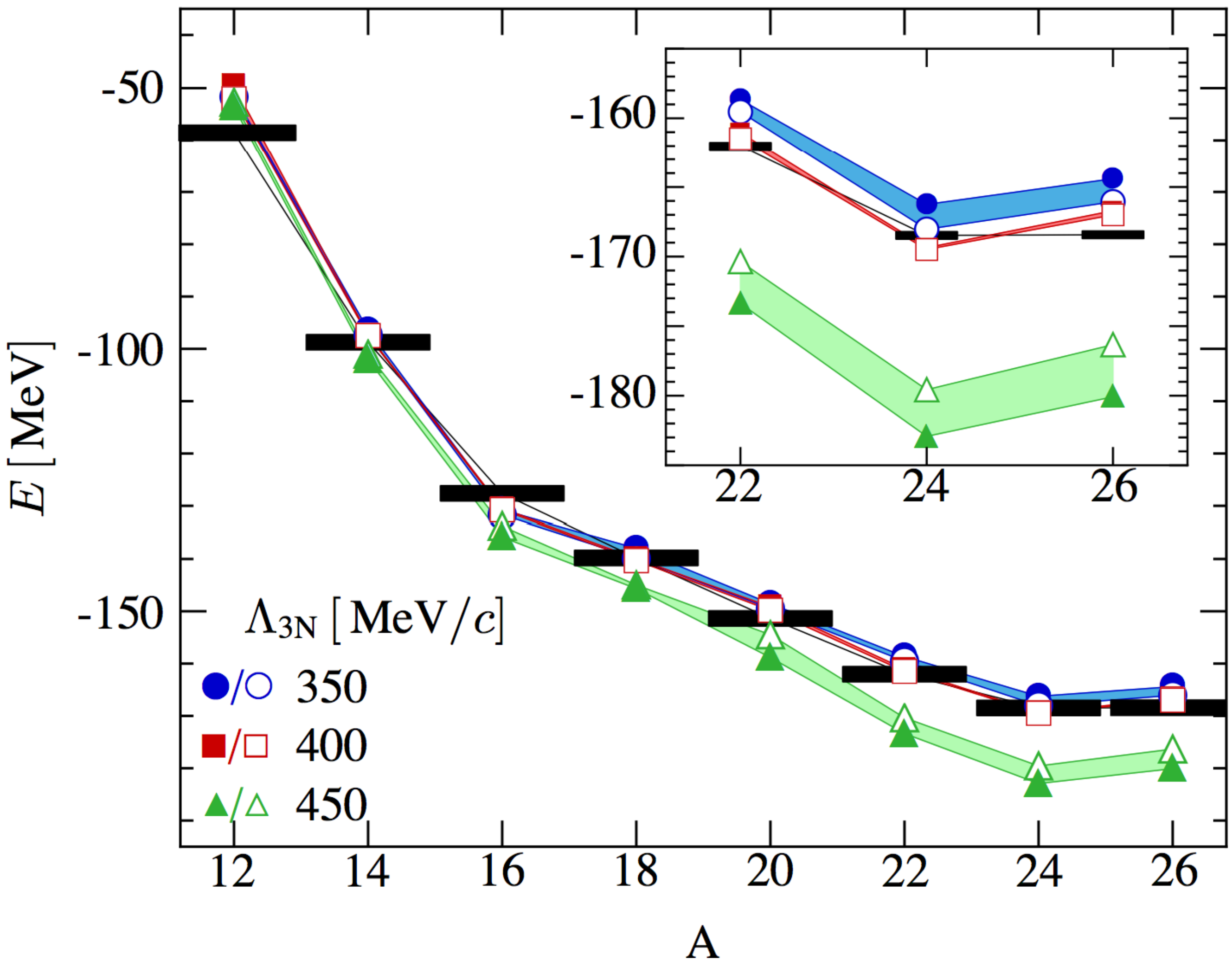


New ab-initio methods extend reach

impact of 3N forces confirmed in ab-initio 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)

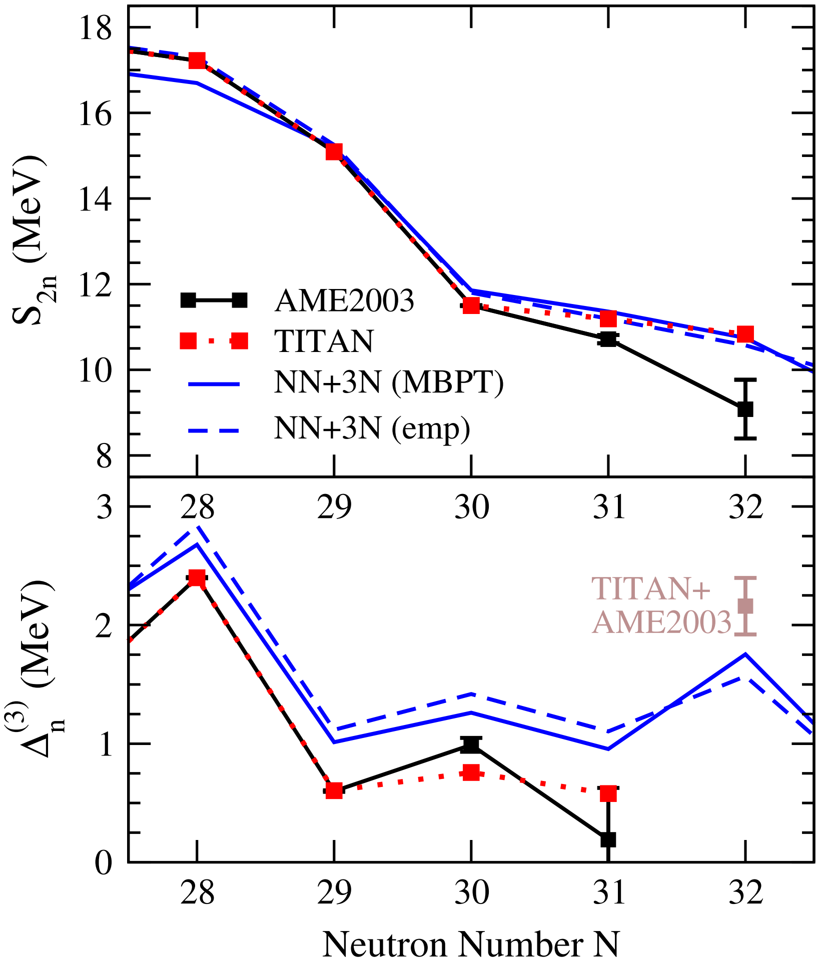


new ^{51,52}Ca TITAN measurements

^{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



more neutron-rich isotopes at ISOLDE, RIKEN and NSCL

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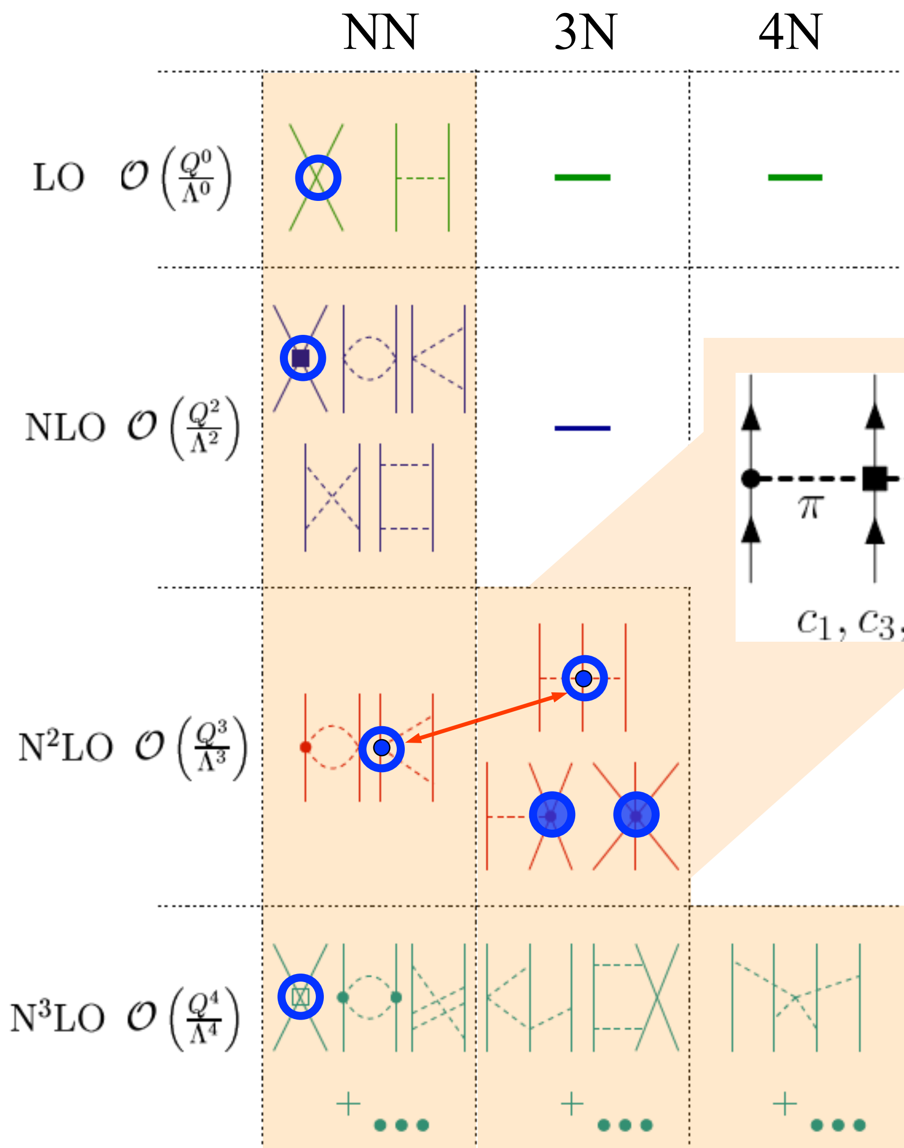

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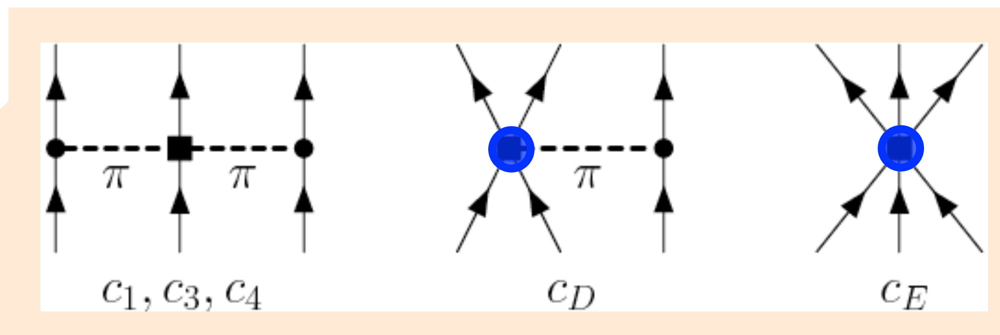
Hebeler, AS (2010)



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

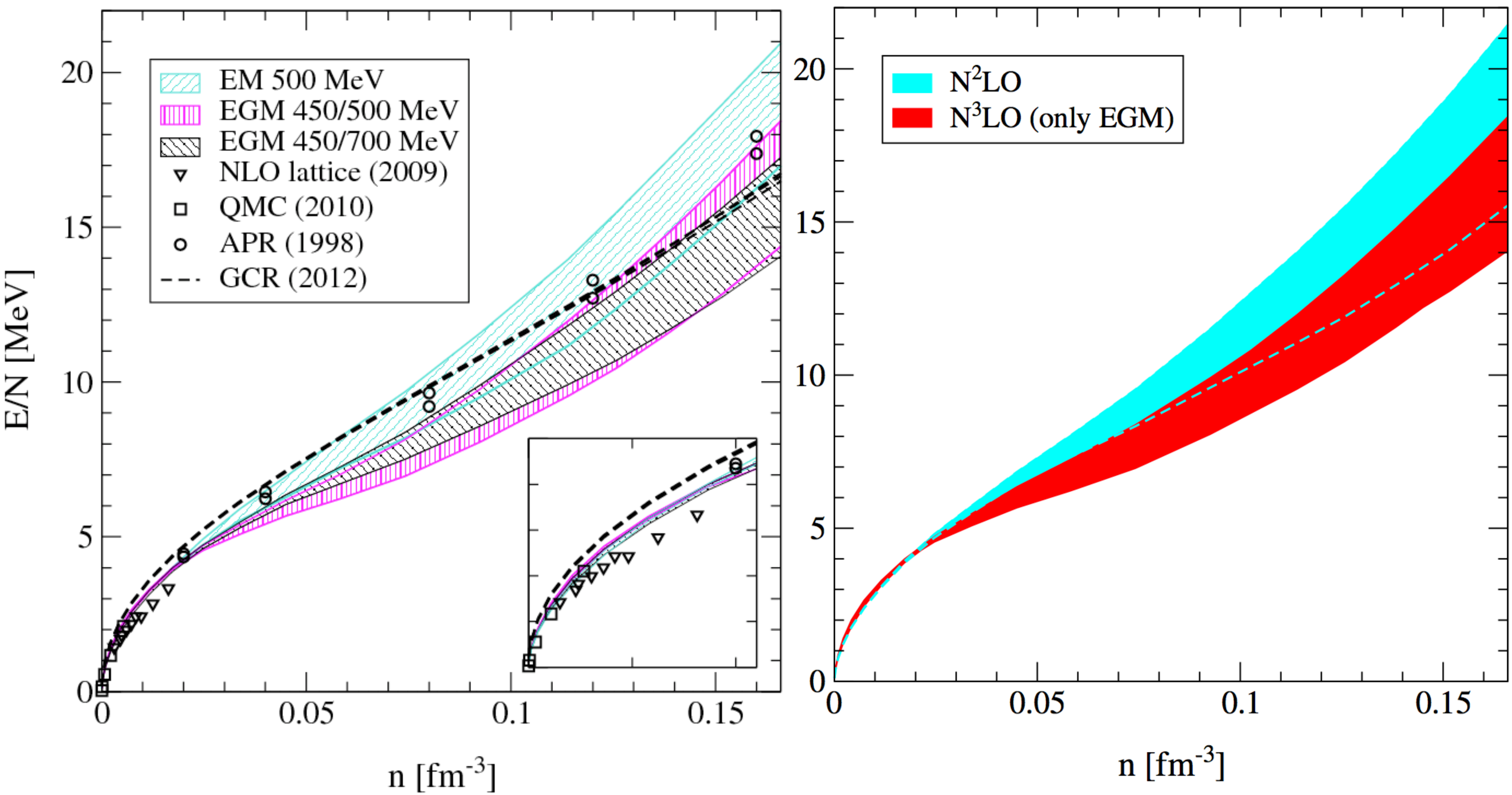
study 3N and 4N in neutron matter

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

Complete N^3LO calculation of neutron matter

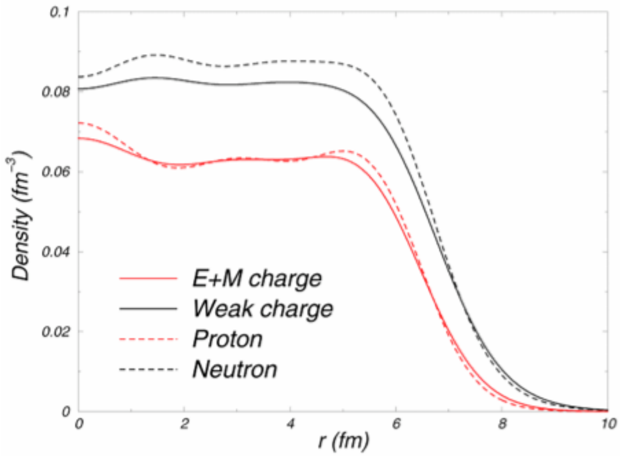
first complete N^3LO result Tews, Krüger, Hebeler, AS (2013)

includes uncertainties from NN, 3N (dominates), 4N



Neutron skin of ^{208}Pb

probes neutron matter energy/pressure,
neutron matter band predicts
neutron skin of ^{208}Pb: 0.17±0.03 fm (±18% !)
Hebeler et al. (2010)



talks by C. Sfienti, J. Piekarewicz and M. Dalton

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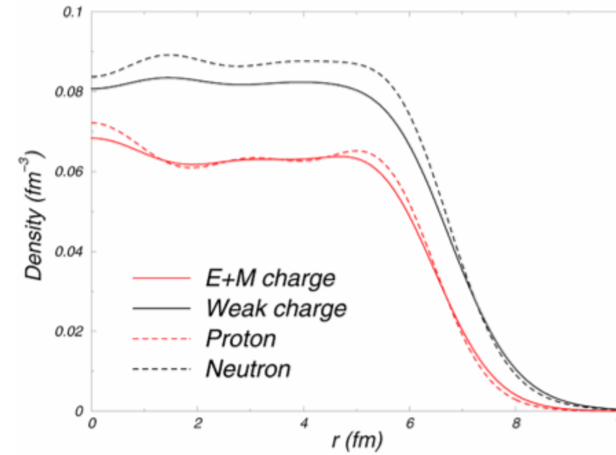


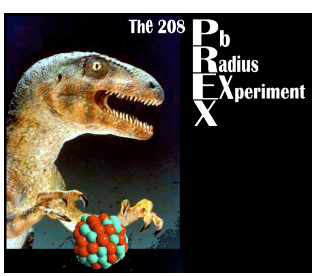
in excellent agreement with extraction from complete E1 response
0.156+0.025-0.021 fm

PRL **107**, 062502 (2011) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2011

Complete Electric Dipole Response and the Neutron Skin in ^{208}Pb

A benchmark experiment on ^{208}Pb shows that polarized proton inelastic scattering at very forward angles including 0° is a powerful tool for high-resolution studies of electric dipole ($E1$) and spin magnetic dipole ($M1$) modes in nuclei over a broad excitation energy range to test up-to-date nuclear models. The extracted $E1$ polarizability leads to a neutron skin thickness $r_{\rm skin} = 0.156^{+0.025}_{-0.021}$ fm in ^{208}Pb derived within

PREX: neutron skin from parity-violating electron-scattering at JLAB
electron exchanges Z-boson, couples preferentially to neutrons
goal II: ±0.06 fm



PRL **108**, 112502 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

Measurement of the Neutron Radius of ^{208}Pb through Parity Violation in Electron Scattering

We report the first measurement of the parity-violating asymmetry $A_{\rm PV}$ in the elastic scattering of polarized electrons from ^{208}Pb. $A_{\rm PV}$ is sensitive to the radius of the neutron distribution (R_n). The result $A_{\rm PV} = 0.656 \pm 0.060({\rm stat}) \pm 0.014({\rm syst})$ ppm corresponds to a difference between the radii of the neutron and proton distributions $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nucleus.

Symmetry energy and pressure of neutron matter

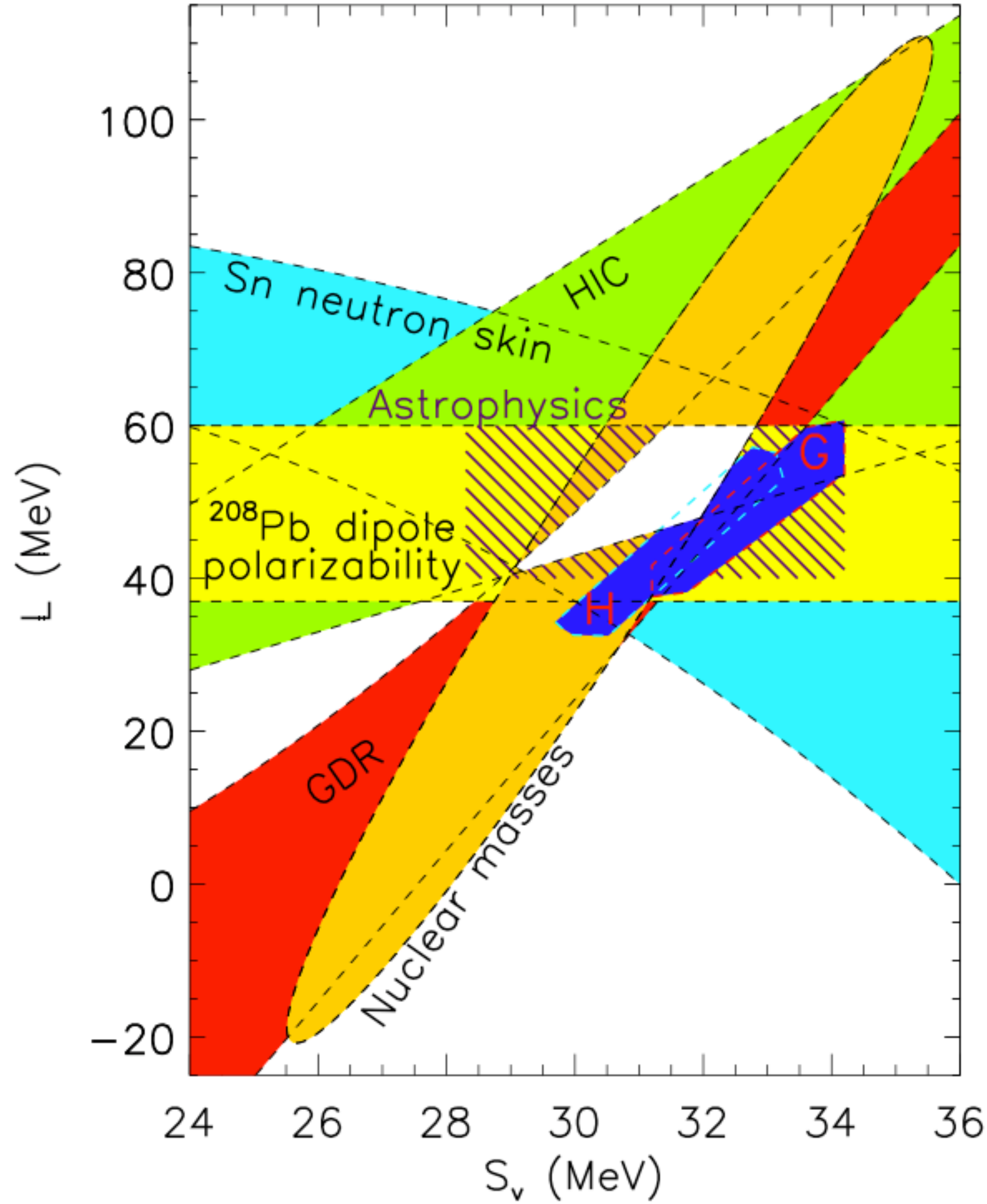
neutron matter band predicts symmetry energy S_v and its density derivative L

comparison to experimental and observational constraints
Lattimer, Lim (2012)

neutron matter constraints
H: Hebeler et al. (2010) and in prep.

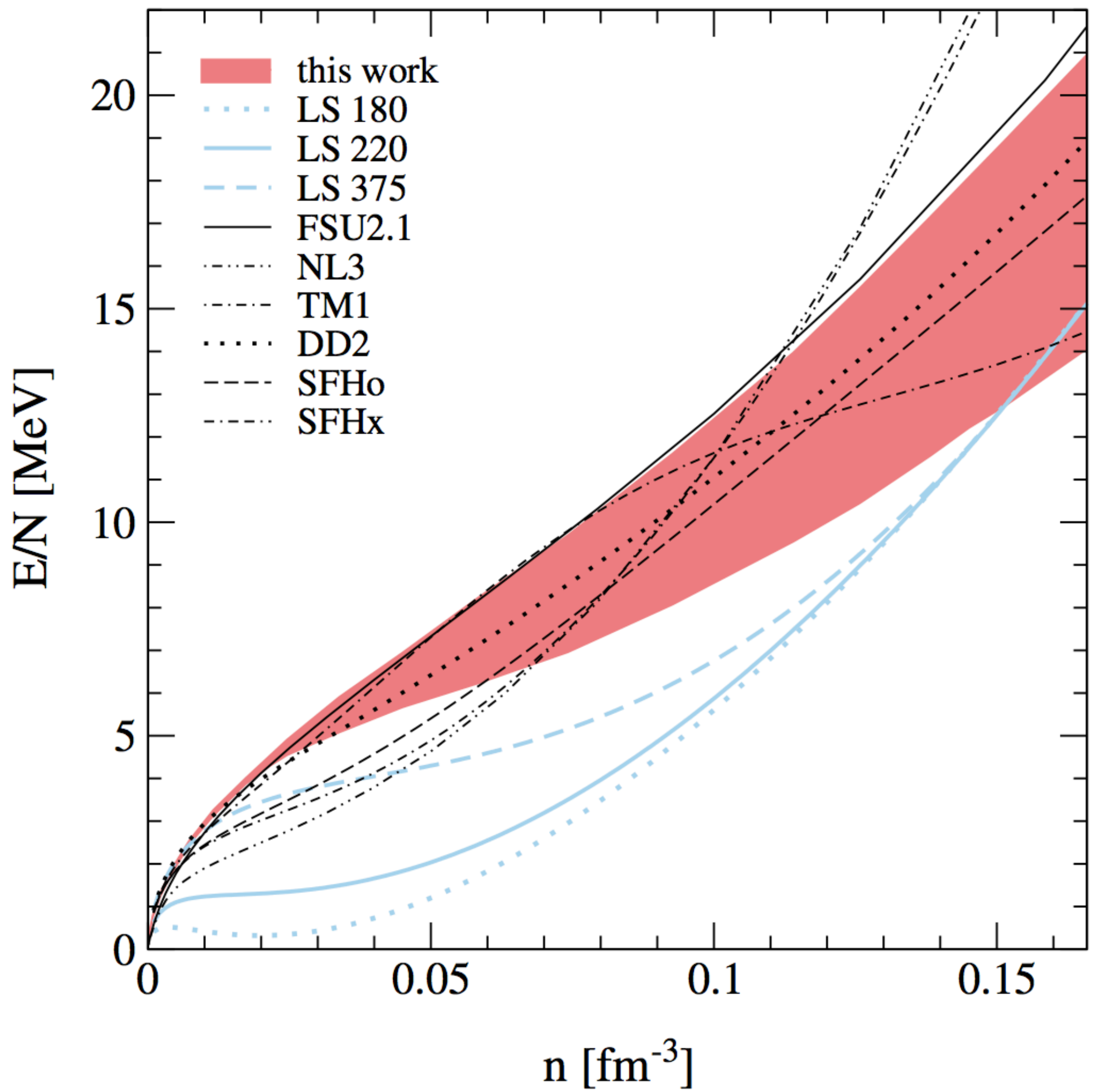
G: Gandolfi et al. (2011)

microscopic calculations provide tight constraints!



Comparisons to equations of state in astrophysics

many equations of state used in supernova simulations not consistent with neutron matter results Krüger, Tews, Hebeler, AS, in prep.



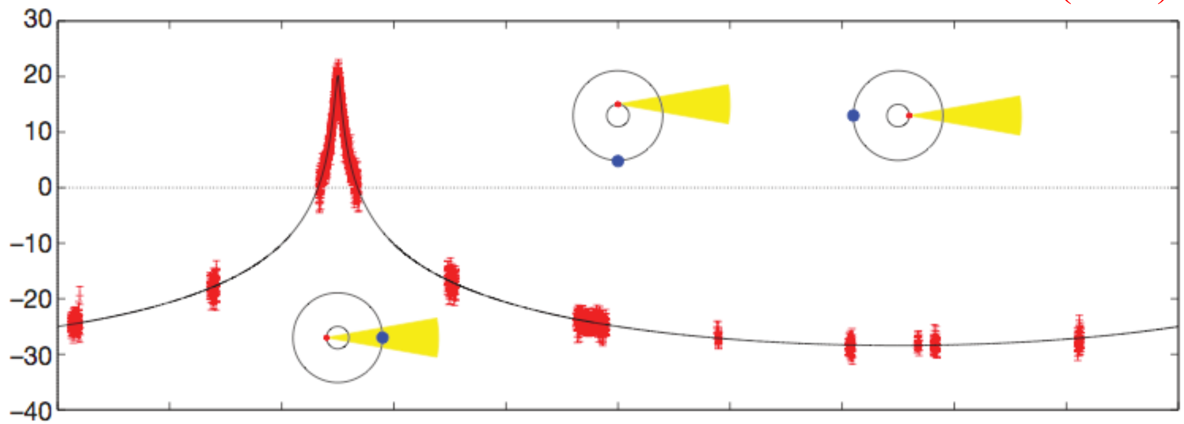
Discovery of the heaviest neutron star

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

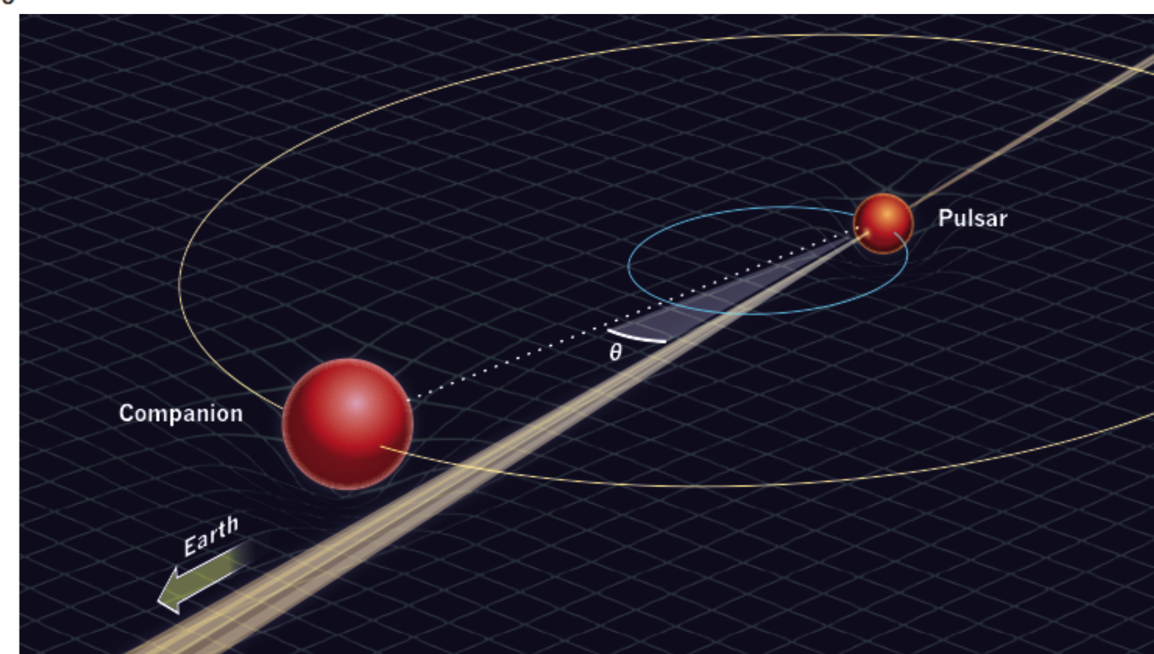
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature (2010)

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



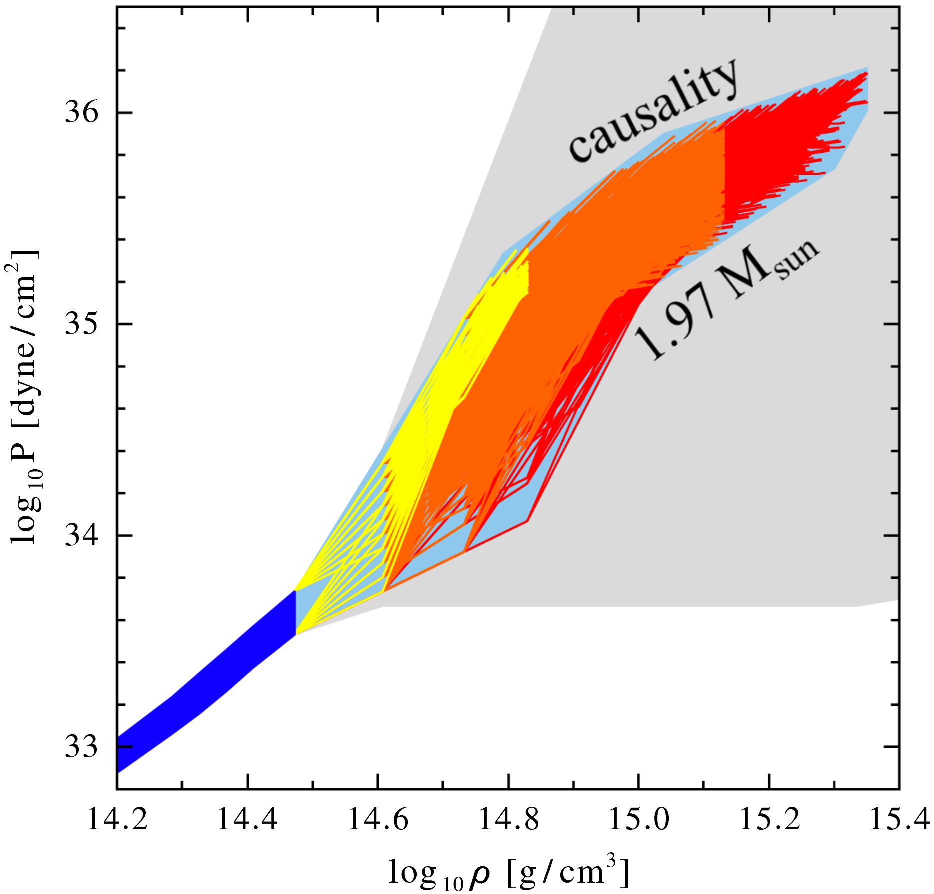
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})

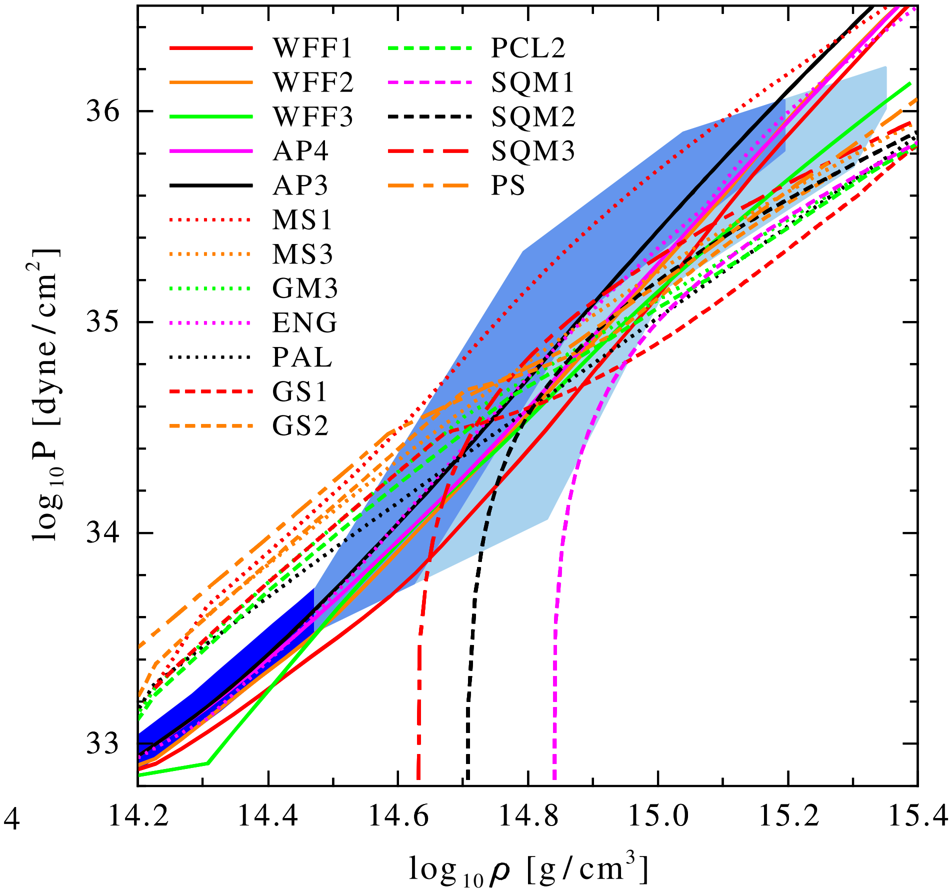


heaviest neutron star with 1.97±0.04 M_{sun}

Impact on neutron stars Hebeler, Lattimer, Pethick, AS (2010) and in prep.

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% !)

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).

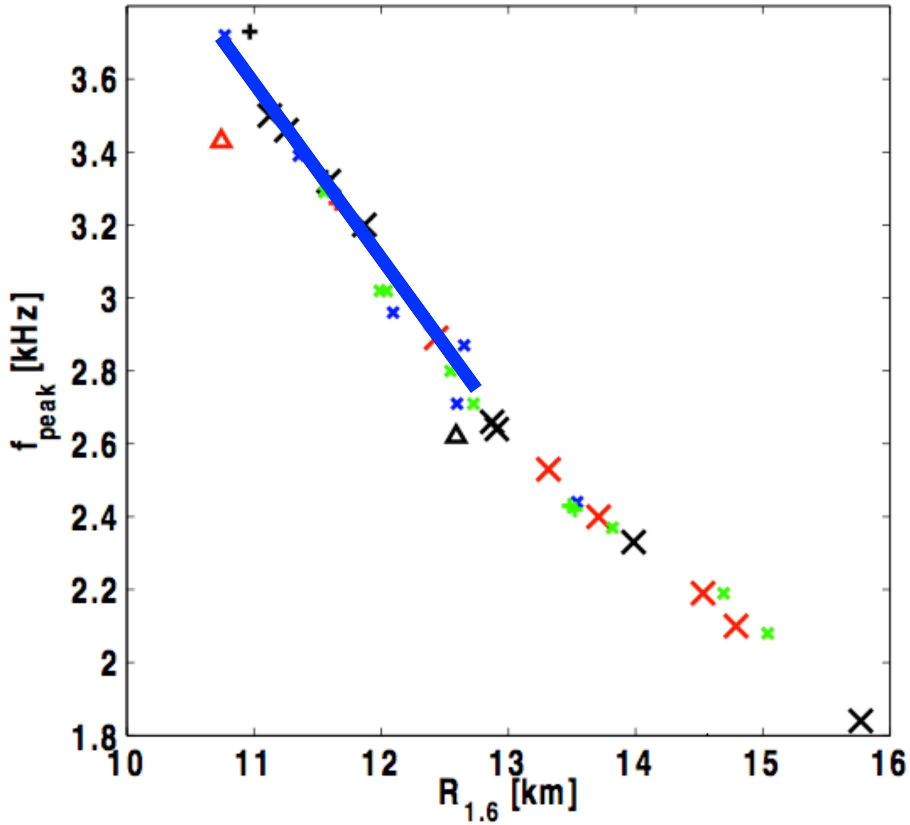


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.

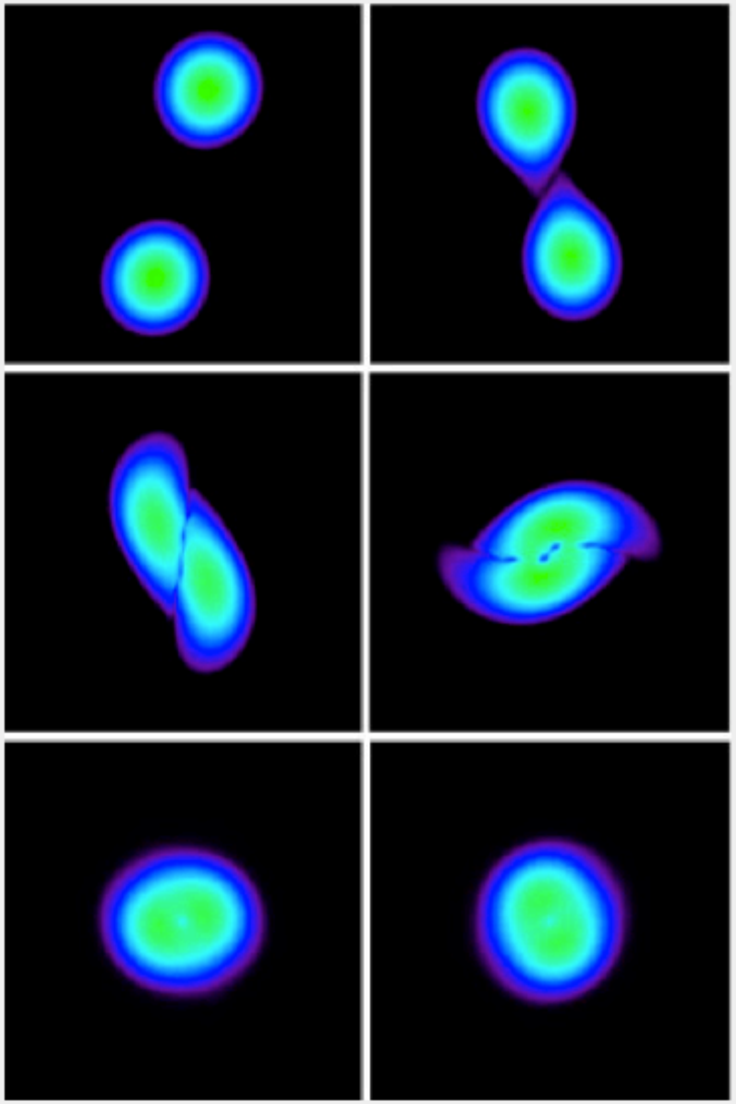


Fig. 1: Various snapshots of the collision of two neutron stars initially revolving around each other. The sequence simulated by the computer covers only 0.03 seconds. The two stars orbit each other counterclockwise (top left) and quickly come closer (top right). Finally they collide (centre left), merge (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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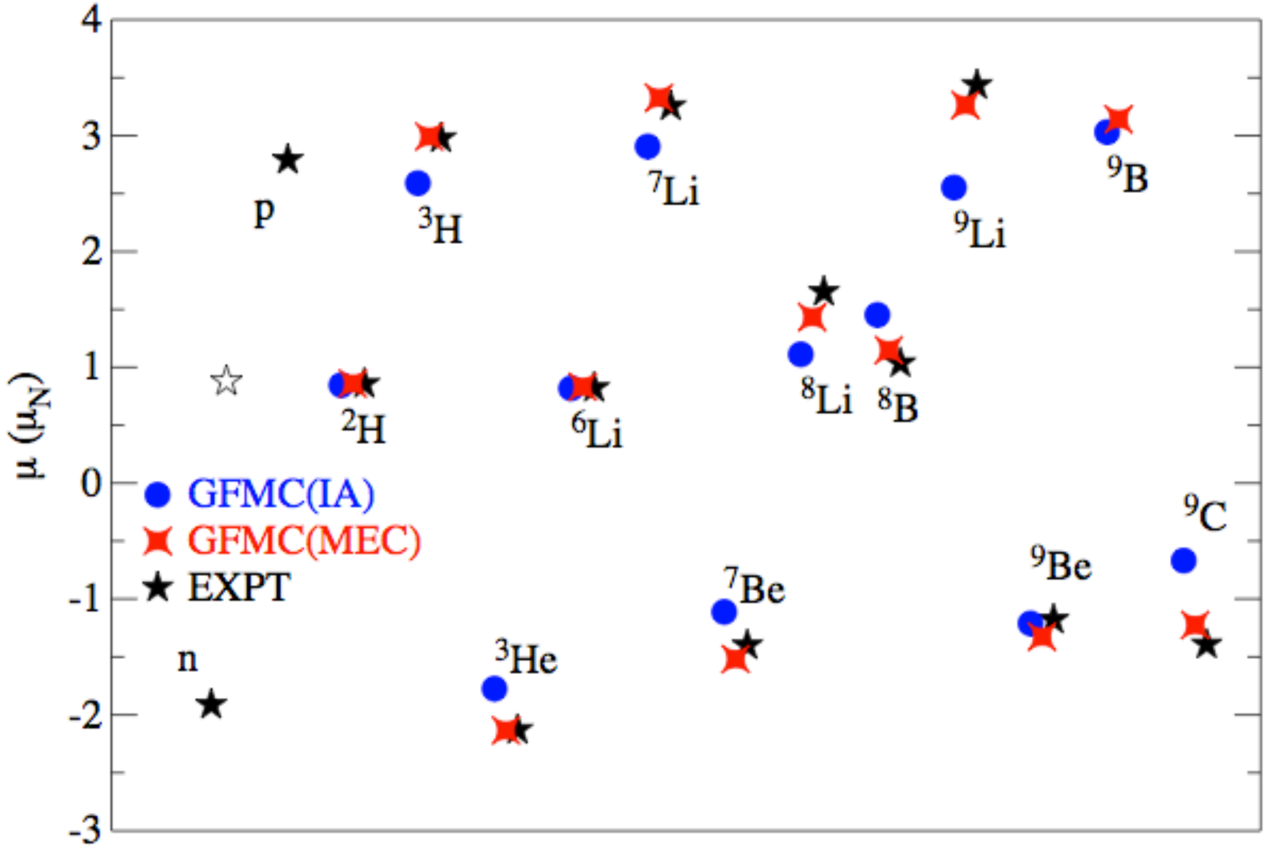
Chiral EFT currents and electroweak interactions

predicts consistent 1- and 2-body currents

GFMC calcs of magnetic moments in light nuclei Pastore et al. (2012)
2-body currents (meson-exchange currents) are key!



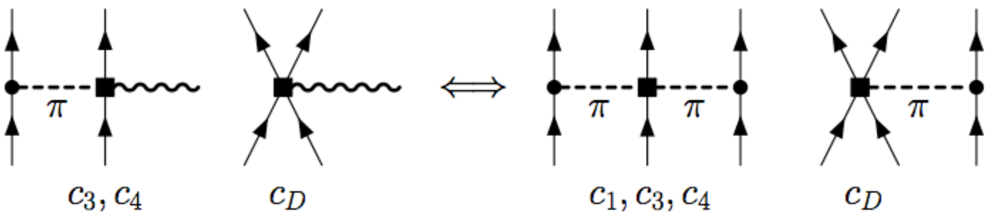
few-body electromagnetic reactions to test chiral EFT currents
talk by H. Griesshammer, related talk by D. Dutta

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)

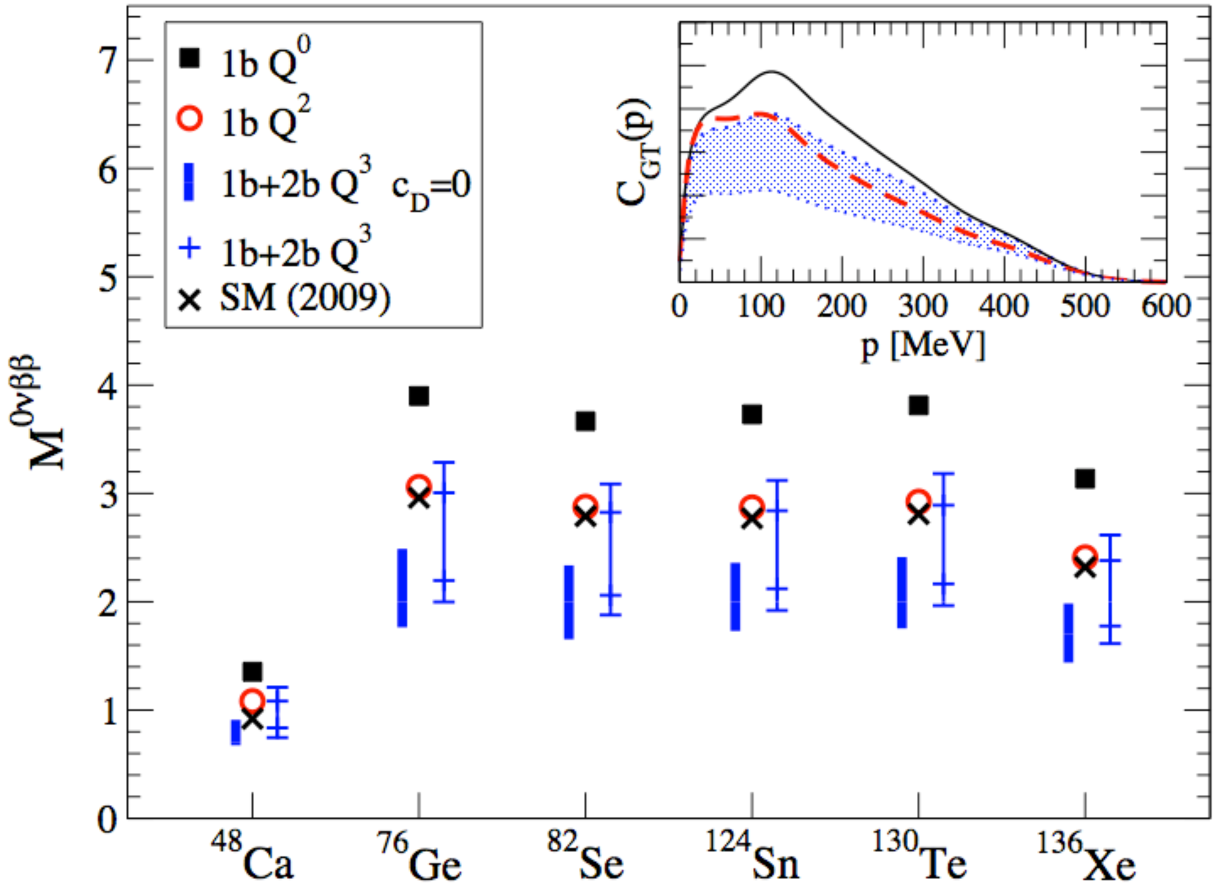
3N couplings predict quenching of g_A (dominated by long-range part)
and predict momentum dependence (weaker quenching for larger p)

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



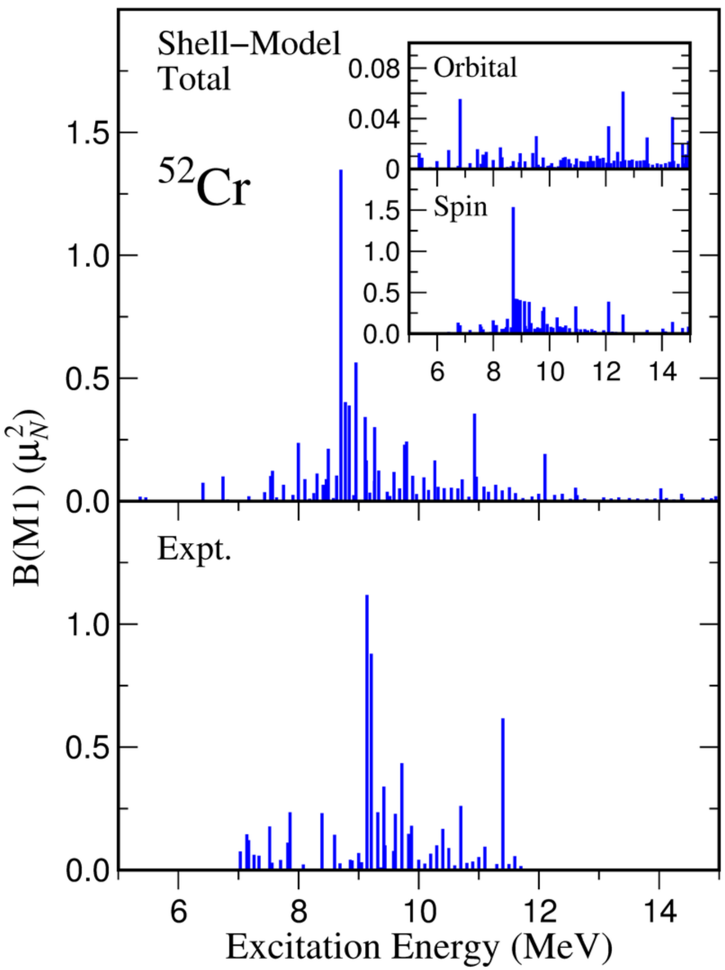
Can electron beams test operator and nuclear structure?

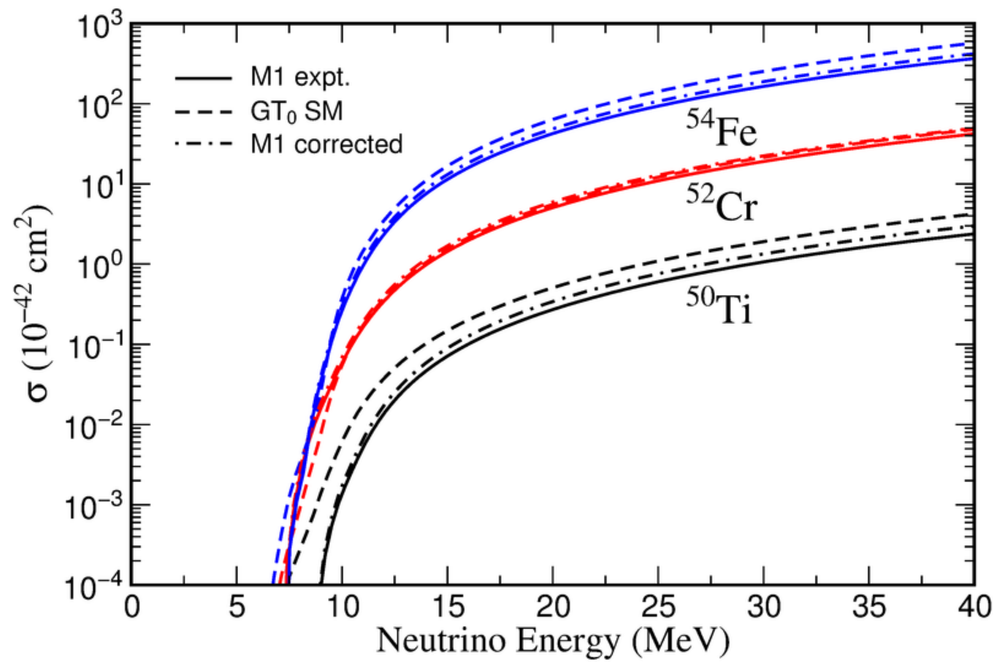
Simulating neutrino reactions with electrons Langanke et al. (2004)

inelastic neutrino scattering is relevant for supernova and nucleosynthesis

cross section mainly determined by GT response

constrained by S-DALINAC (e,e') M1 data (corr. for orbital contribution)

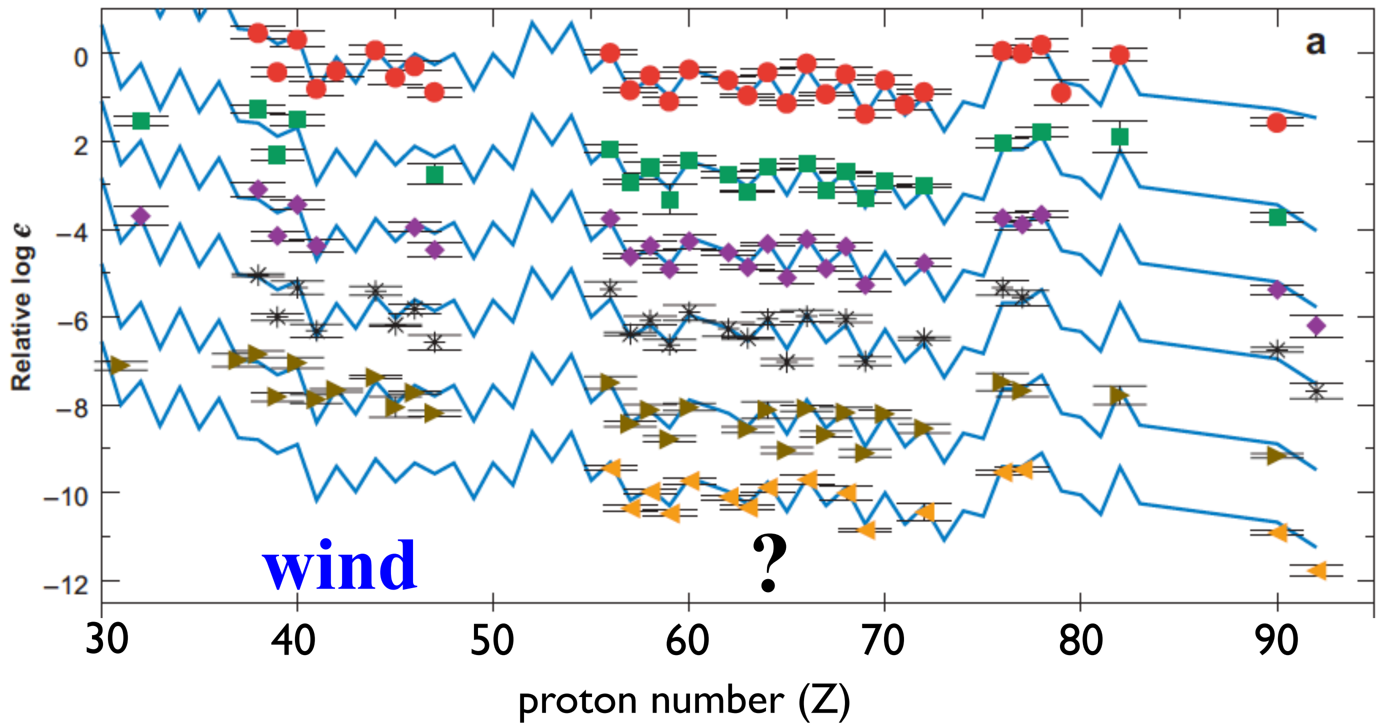


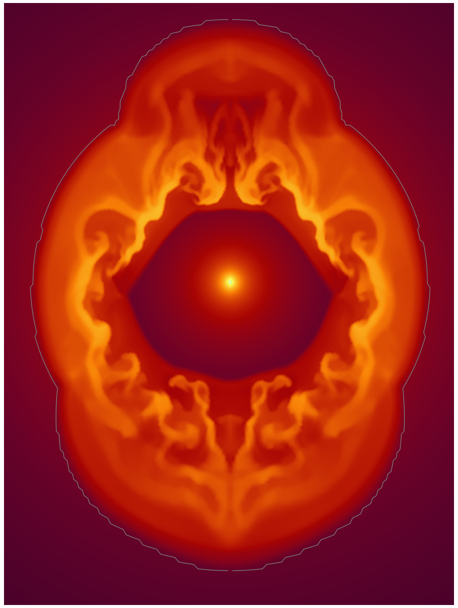


Nucleosynthesis in core-collapse supernovae

exciting observations of ultra metal-poor stars Cowan, Sneden, Christlieb, Frebel,…
probe early chemical evolution

light (Sr to Ag) + robust heavy r-process elements suggest several sites





Sr to Ag produced in neutrino-driven wind, for n- or p-rich conditions
Arcones, Montes (2011)

relevant reactions closer to stability, can be probed by electron beams

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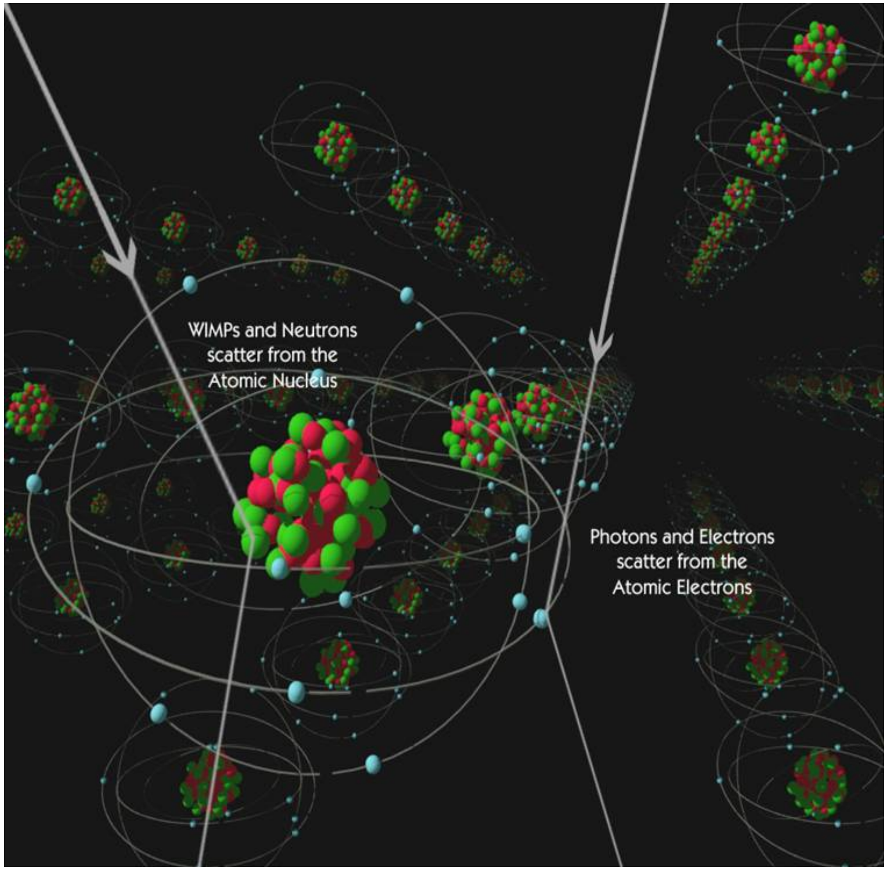
Nuclear physics of direct dark matter detection

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

relevant momentum transfers ~ m_π

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



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

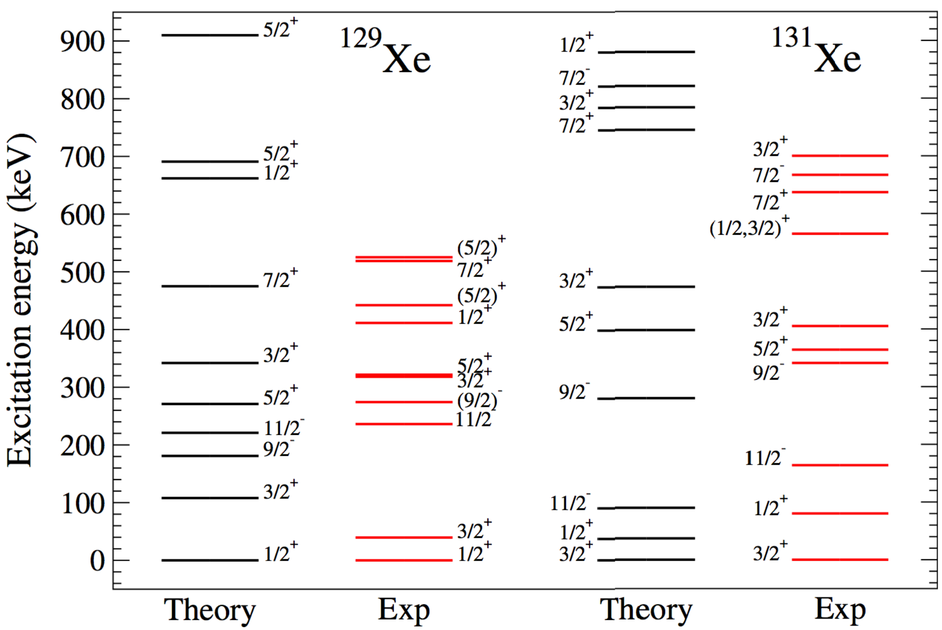
Is it possible to simulate/constrain dark matter response with electrons?

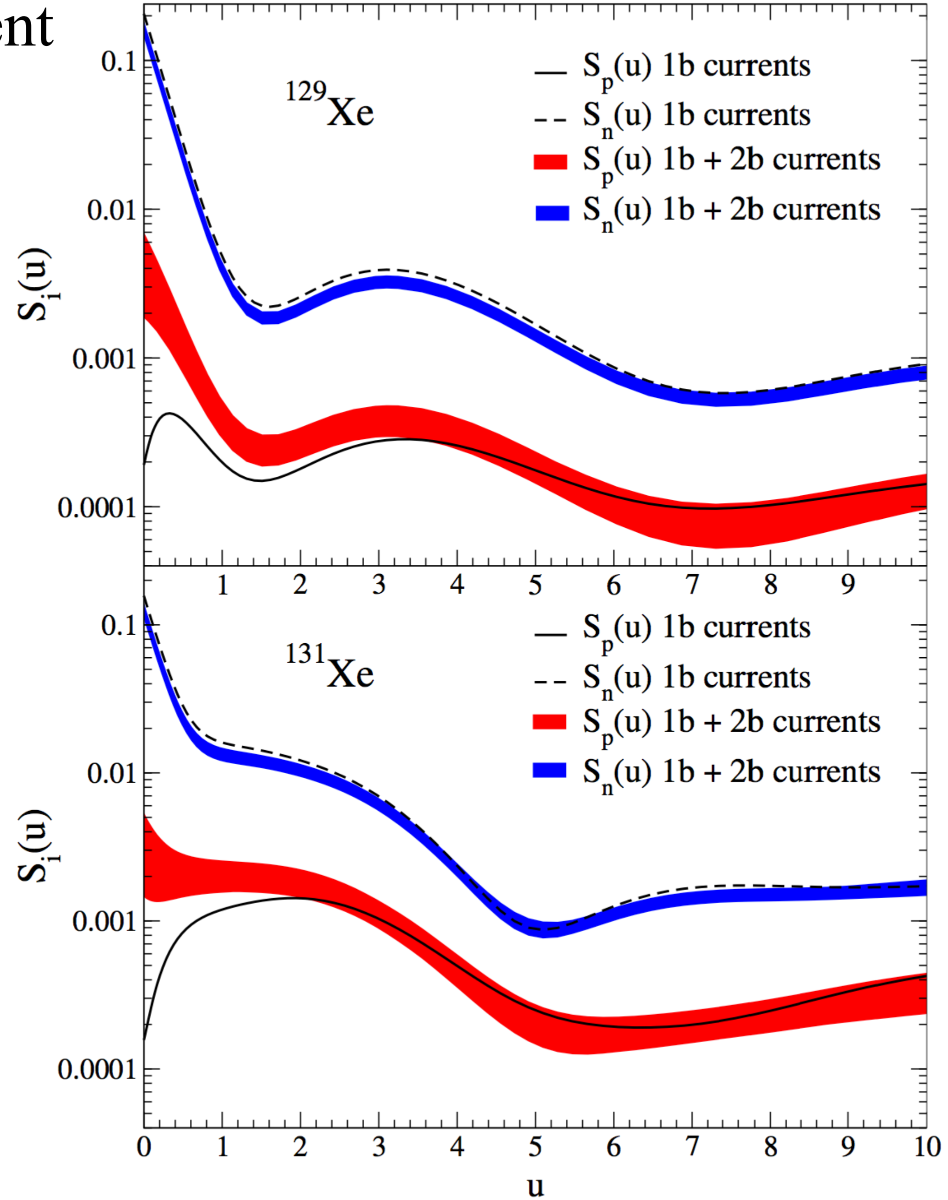
Spin-dependent WIMP scattering off nuclei

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

include chiral 2-body currents
and state-of-the-art interactions

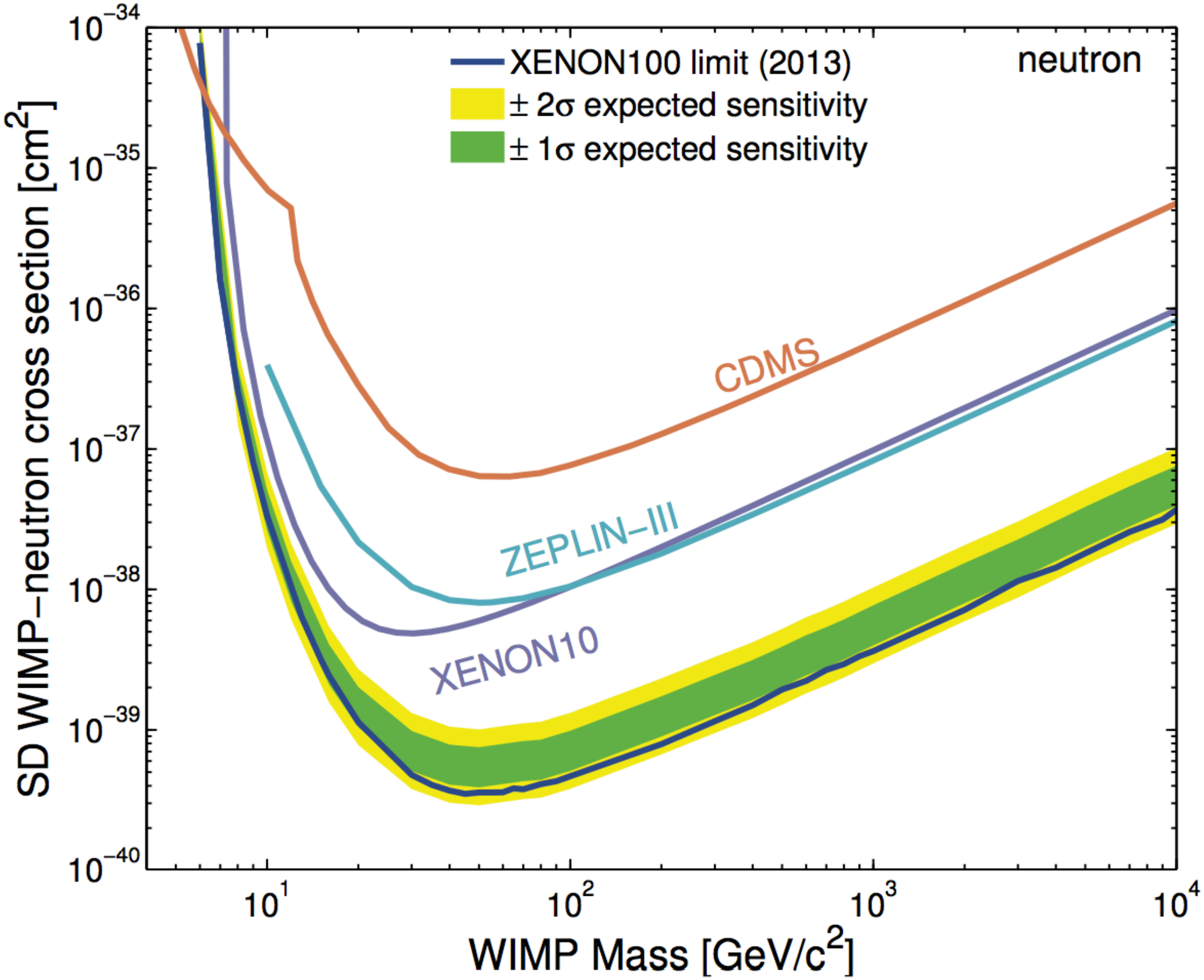
Menendez, Gazit, AS (2012)





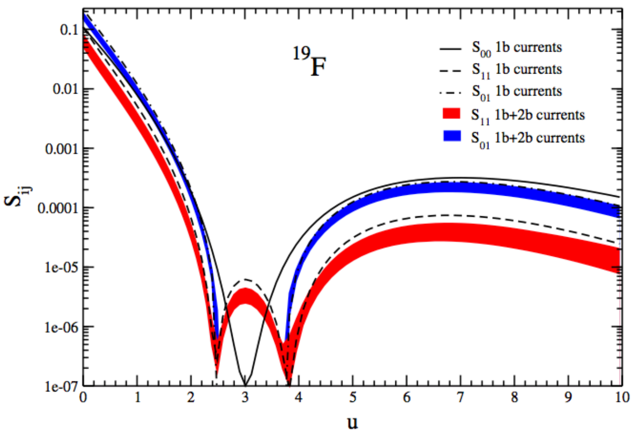
Limits on SD WIMP-neutron interactions

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

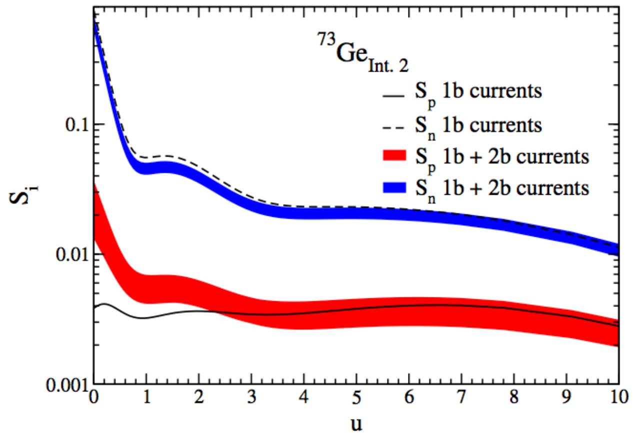


Spin-dependent WIMP-nucleus response for ^{19}F, ^{23}Na, ^{27}Al, ^{29}Si, ^{73}Ge, ^{127}I

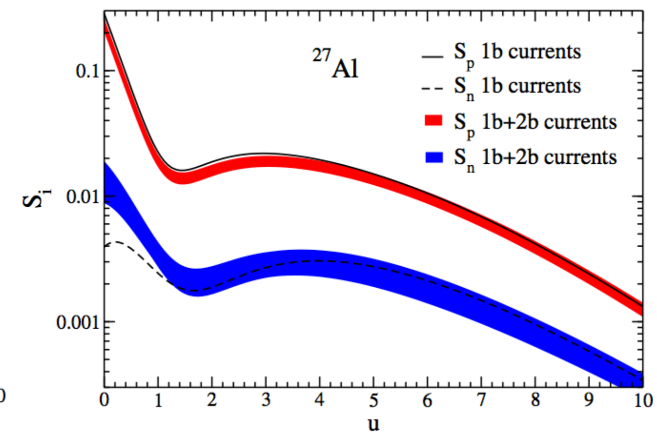
Klos, Menendez, Gazit, AS, in prep.



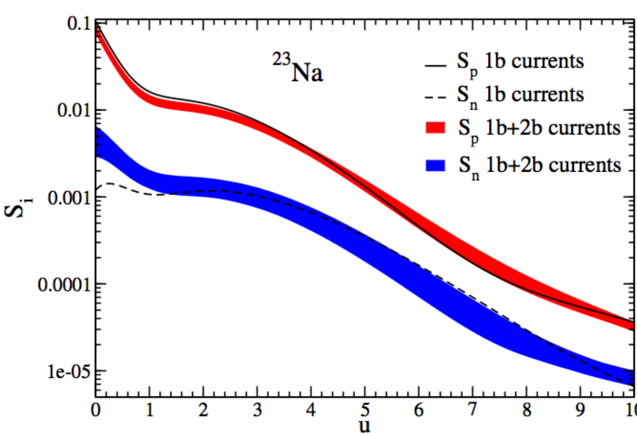
PICASSO, COUPP, SIMPLE



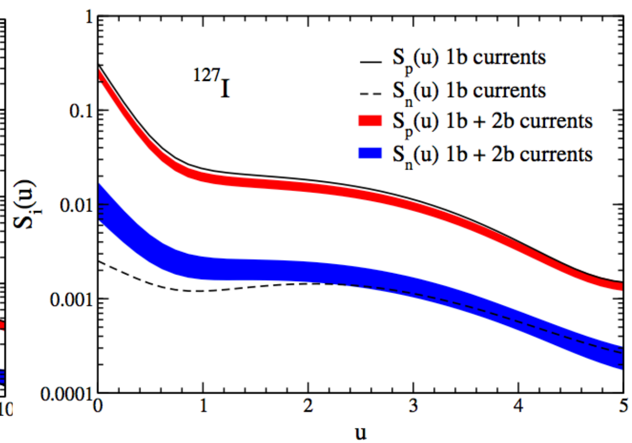
CDMS, EDELWEISS, EURECA



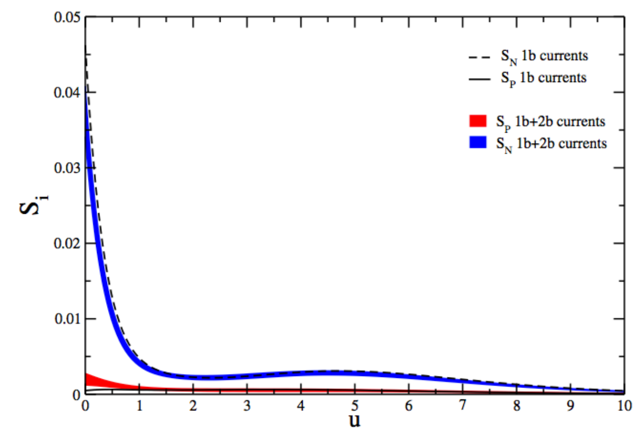
CRESST



DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS



CDMS-II

Thanks to collaborators!

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Summary

Chiral effective field theory
nuclear forces and electroweak interactions,
systematic EFT for energies below ~300 MeV!

Nuclear structure frontiers

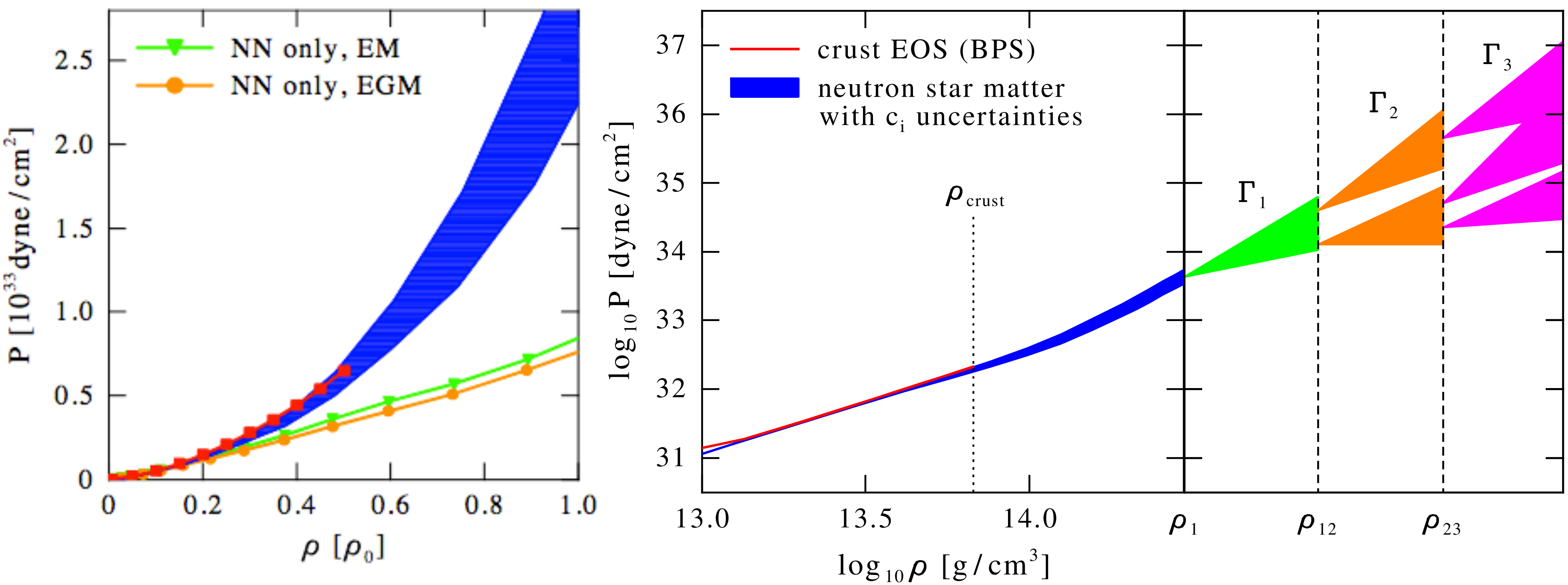
3N forces predict **neutron skin** and constrain **neutron stars**

Nuclear reactions for astrophysics and electron beams

Dark matter response of nuclei,
Is it possible to simulate/constrain this with electrons?

Impact on neutron stars Hebeler, Lattimer, Pethick, AS (2010) and in prep.

Equation of state/pressure for neutron-star matter (includes small $Y_{e,p}$)



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 allow for soft regions