Nuclear forces and their impact on matter at neutron-rich extremes

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TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

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Bundesministerium für Bildung und Forschung

Main message

3N forces and neutron-rich nuclei

with S.K. Bogner, **H. Hergert, J.D. Holt, J. Menéndez**, T. Otsuka, **J. Simonis**, T. Suzuki

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Masses of exotic calcium isotopes pin down nuclear forces

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Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

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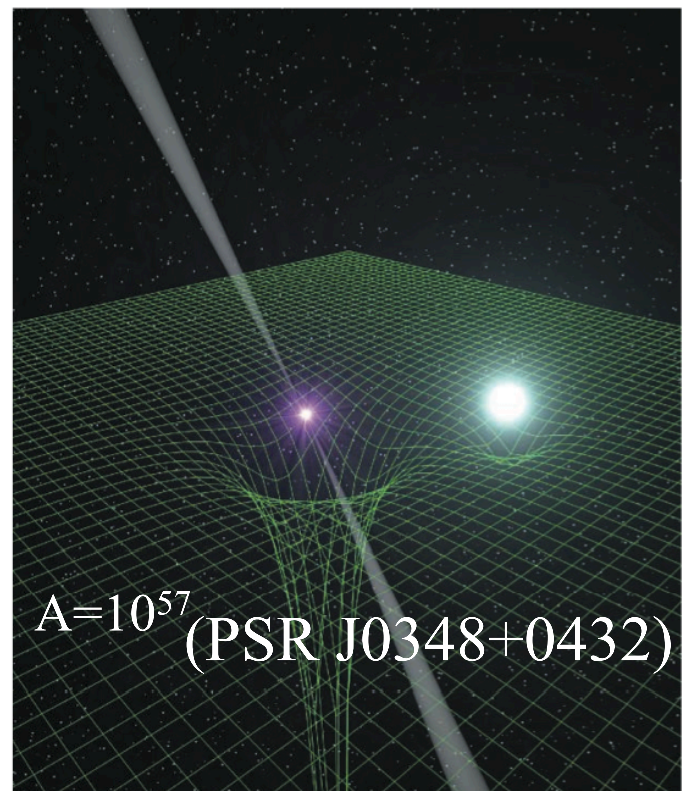
3N forces and neutron stars

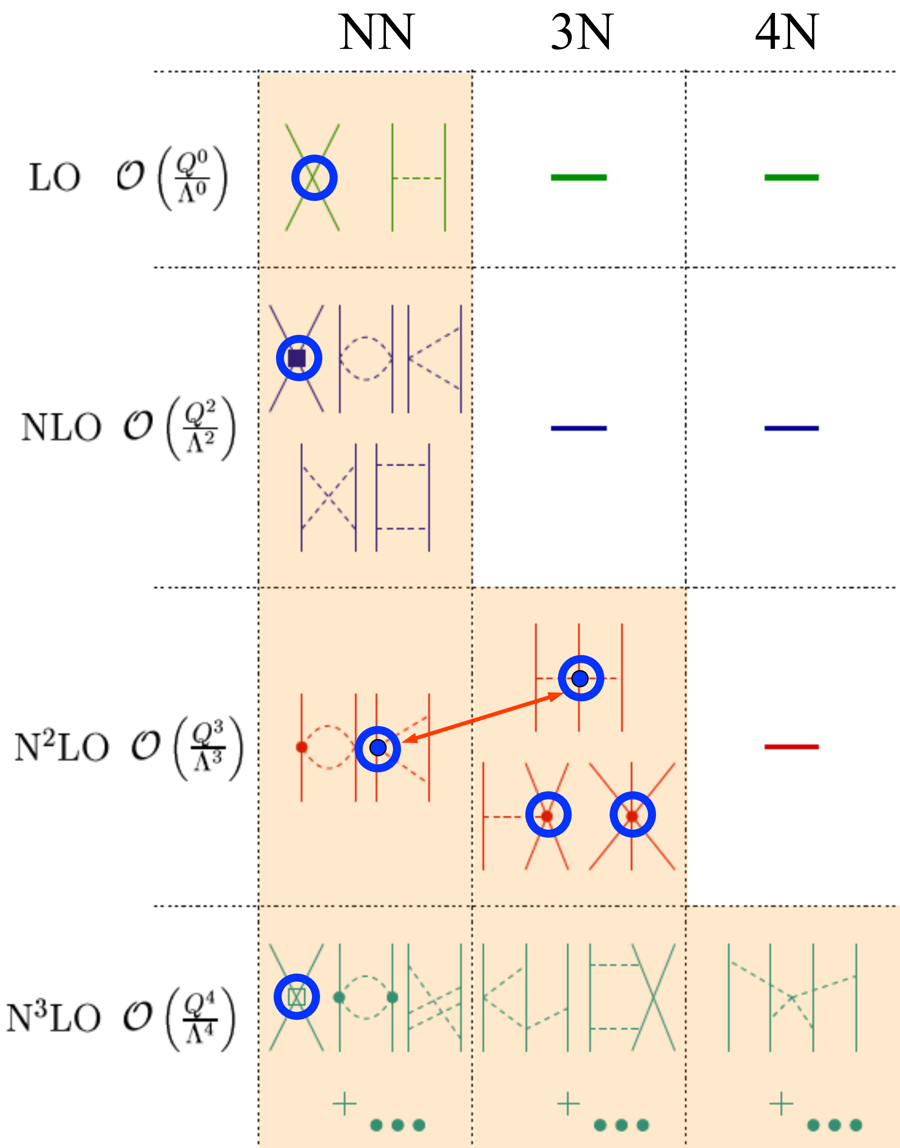
with C. Drischler, K. Hebeler, T. Krüger, J.M. Lattimer, C.J. Pethick, **V. Somá, I. Tews**



based on same strong interactions!

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**

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

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

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

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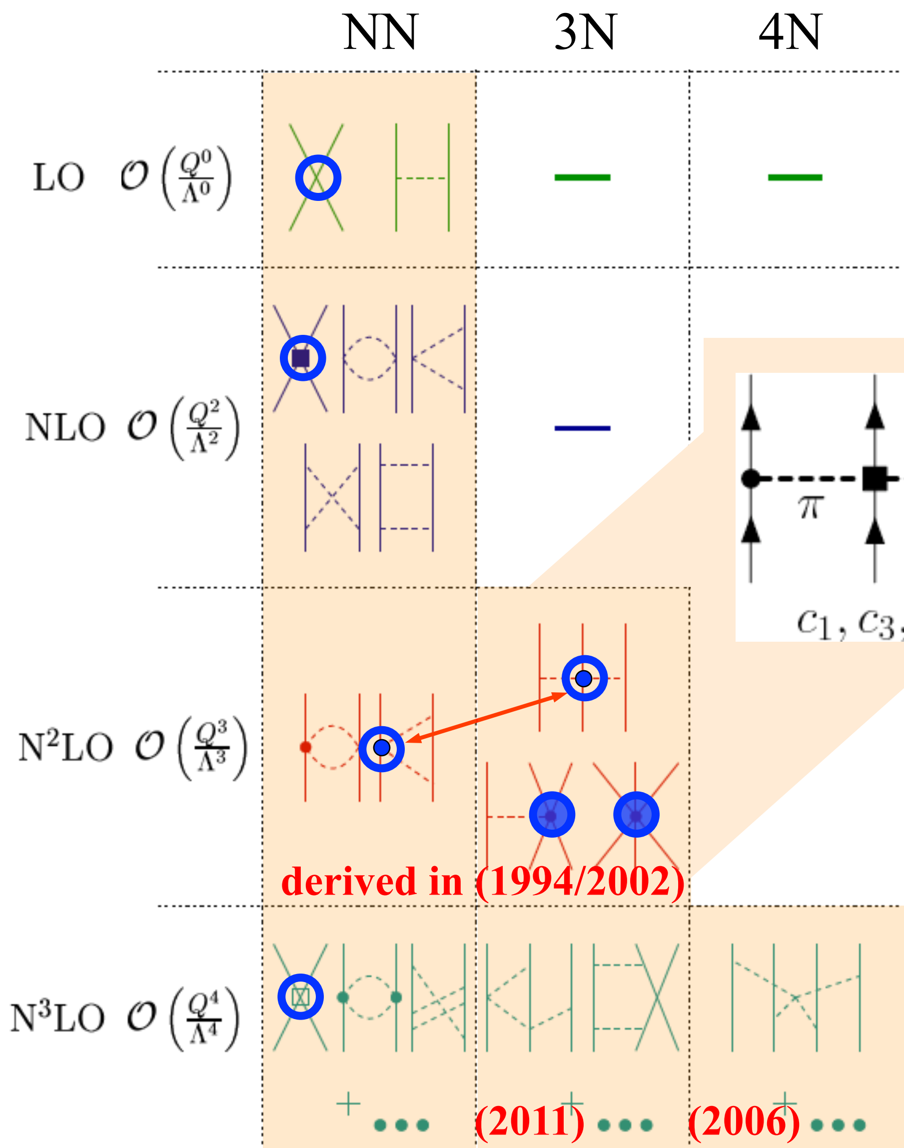
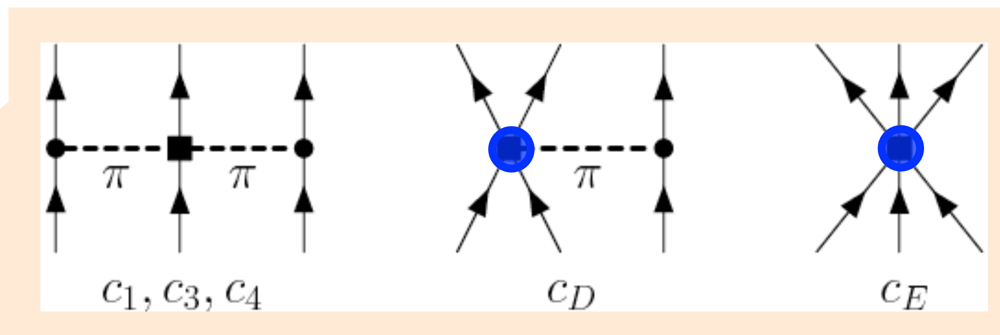


consistent NN-3N-4N interactions

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

+ no new couplings for neutrons



c_i from πN and NN Meissner, LAT 2005

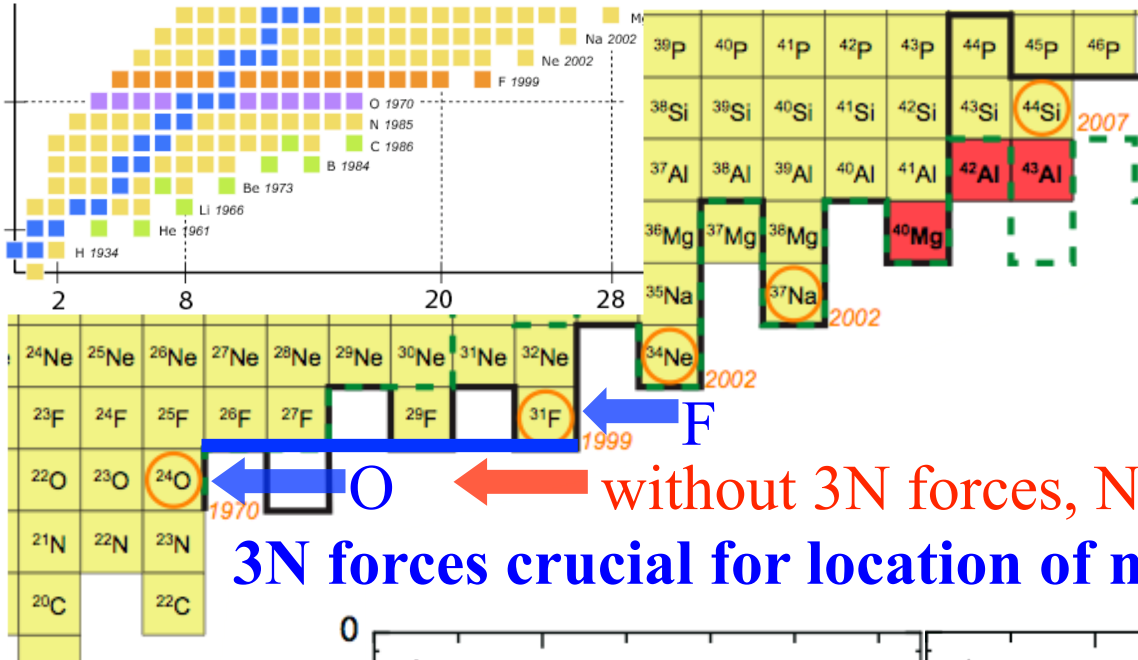
$$c_1 = -0.9^{+0.2}_{-0.5}\,, \quad c_3 = -4.7^{+1.2}_{-1.0}\,, \quad c_4 = 3.5^{+0.5}_{-0.2}$$

c_D, c_E fit to light nuclei only

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

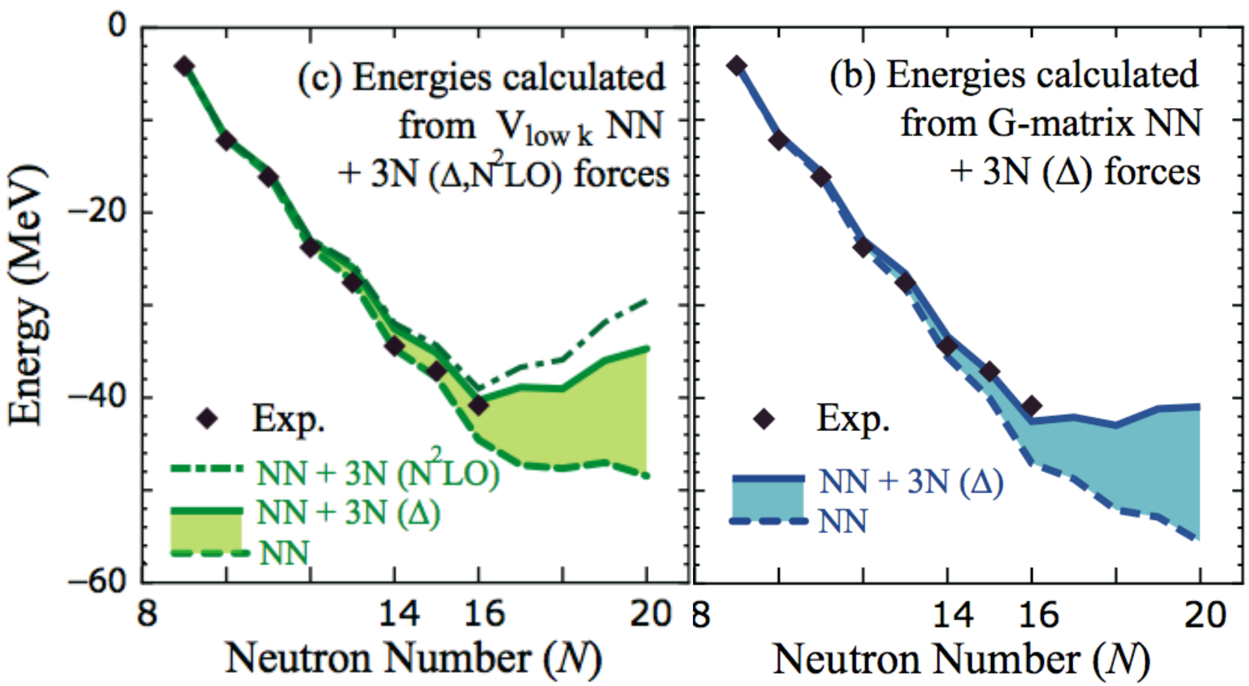
The oxygen anomaly

Otsuka, Suzuki, Holt, AS, Akaishi, PRL (2010)



without 3N forces, NN interactions too attractive

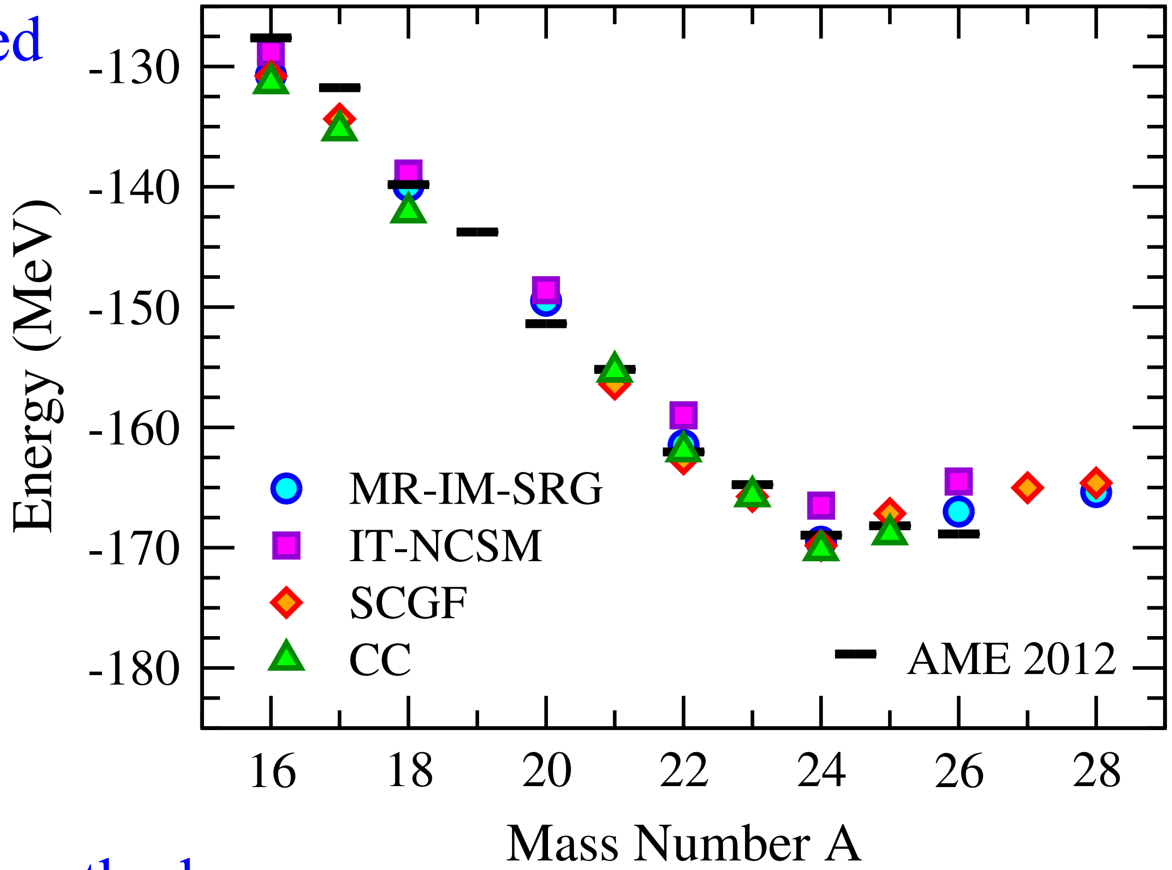
3N forces crucial for location of neutron dripline



Ab initio calculations of the oxygen anomaly

impact of 3N forces confirmed in large-space calculations

based on same SRG-evolved NN+3N interactions



using different many-body methods:

Coupled Cluster theory/CCEI Hagen et al., PRL (2012), Jansen et al., PRL (2014)

Multi-Reference In-Medium SRG and IT-NCSM Hergert et al., PRL (2013)

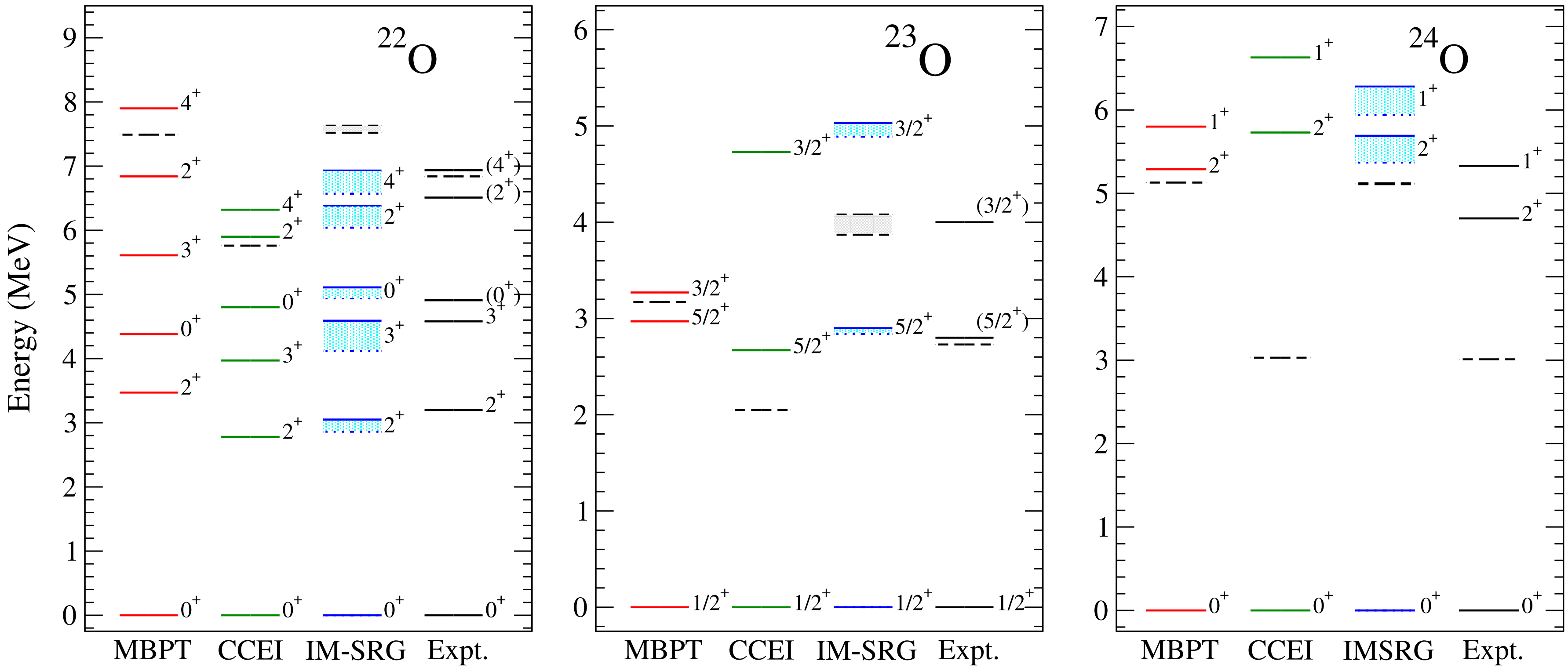
Self-Consistent Green's Function methods Cipollone et al., PRL (2013)

Ab initio calculations going open shell

In-Medium SRG to derive valence-shell interactions

Tsukiyama, Bogner, AS, PRL (2011), PRC (2012); Bogner et al., PRL (2014)

Coupled Cluster for effective interactions (CCEI) Jansen et al., PRL (2014)



Experiments at GANIL, GSI, NSCL, RIBF: ^{22}O and ^{24}O doubly magic

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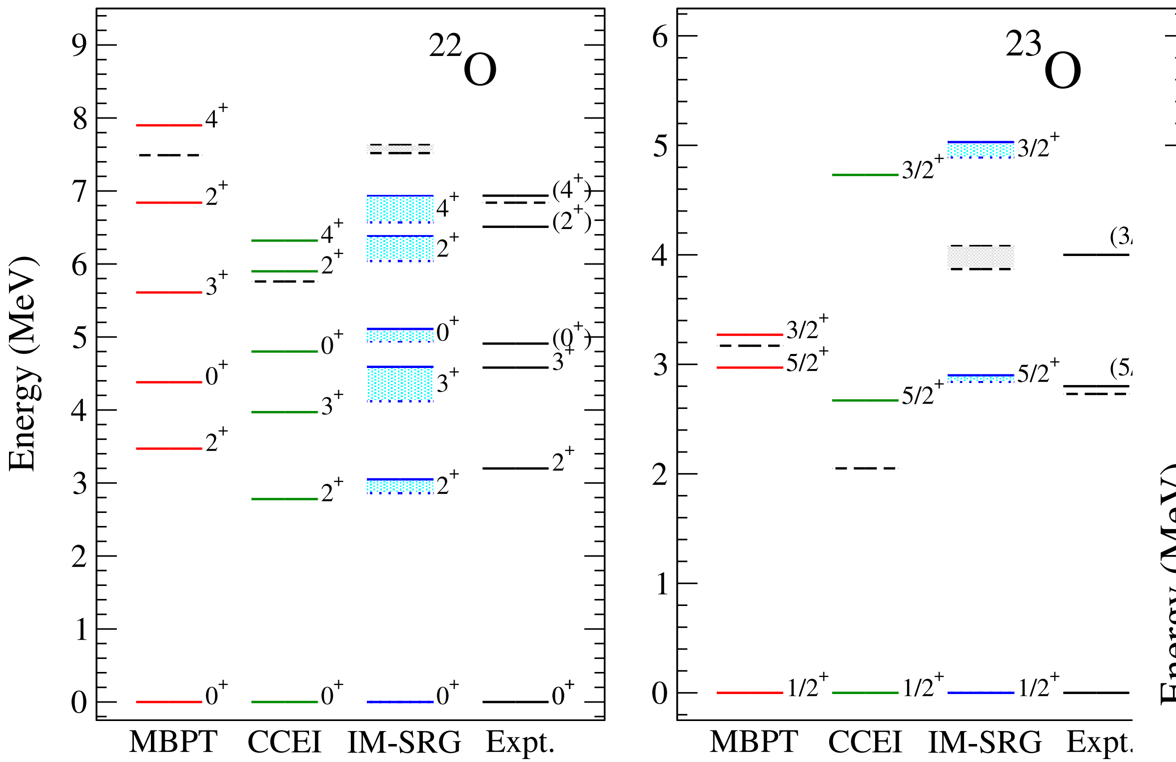
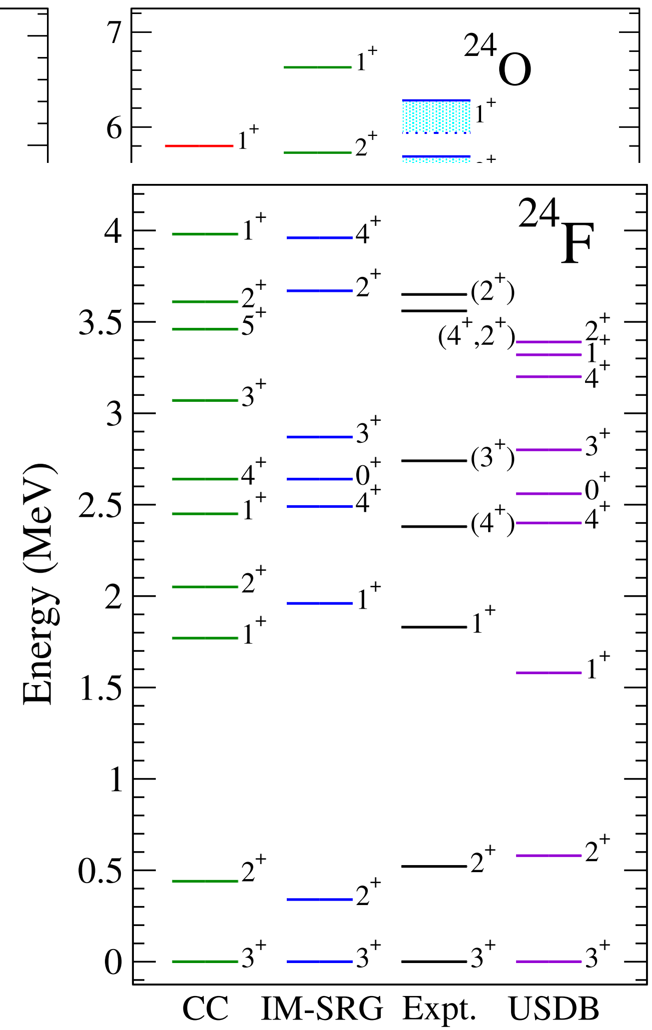


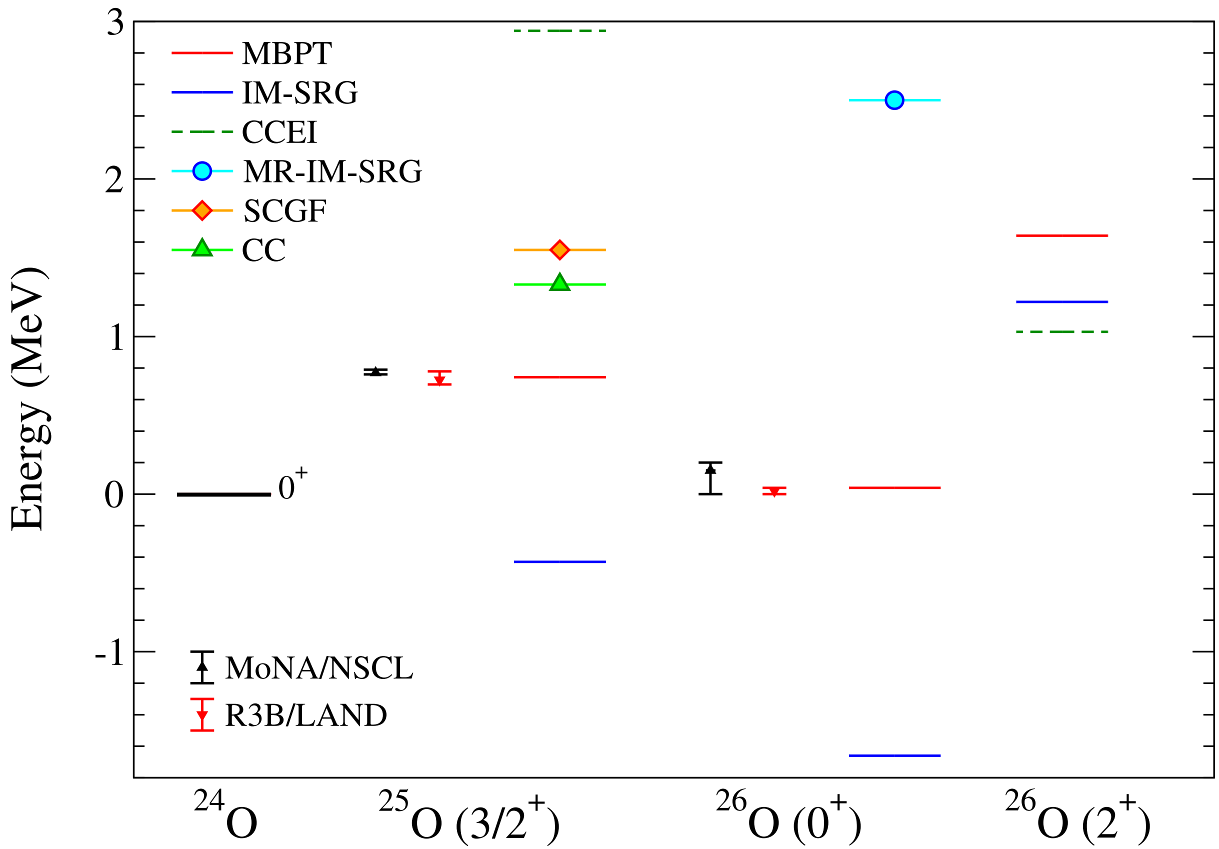


Experiments at GANIL, GSI, NSCL, RIBF

Spectrum of ^{24}F Cáceres et al., 1501.01166

Beyond the neutron dripline in oxygen

Pioneering experiments with MoNA/NSCL, R3B-LAND and at RIBF



calculations with NN+3N forces, continuum needs to be included

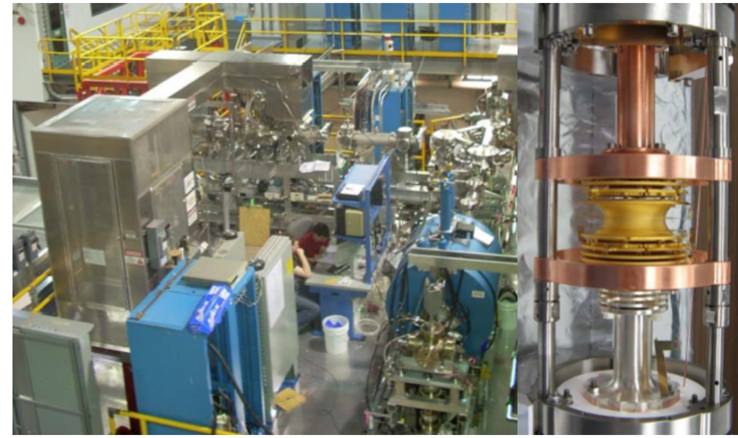
MBPT includes residual 3N forces, more important with N Simonis et al (2013)

challenging and large sensitivity to method and NN+3N forces

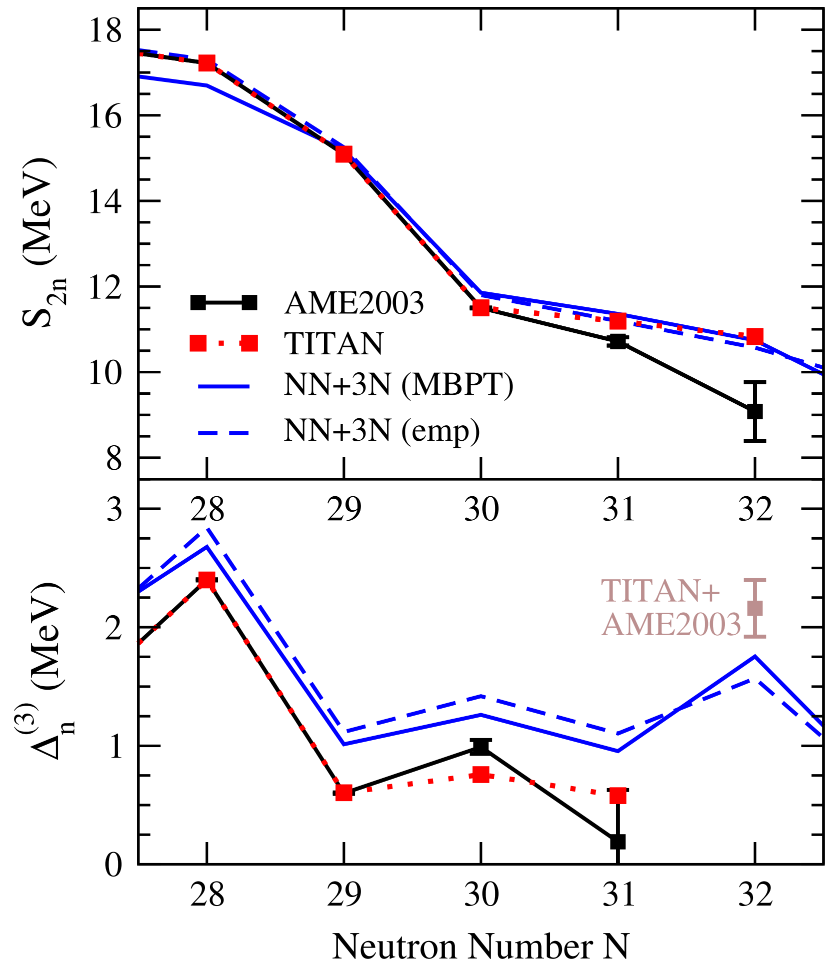
new $^{51,52}Ca$ TITAN measurements

^{52}Ca is 1.74 MeV more bound compared to atomic mass evaluation

Gallant et al., PRL (2012)



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



Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

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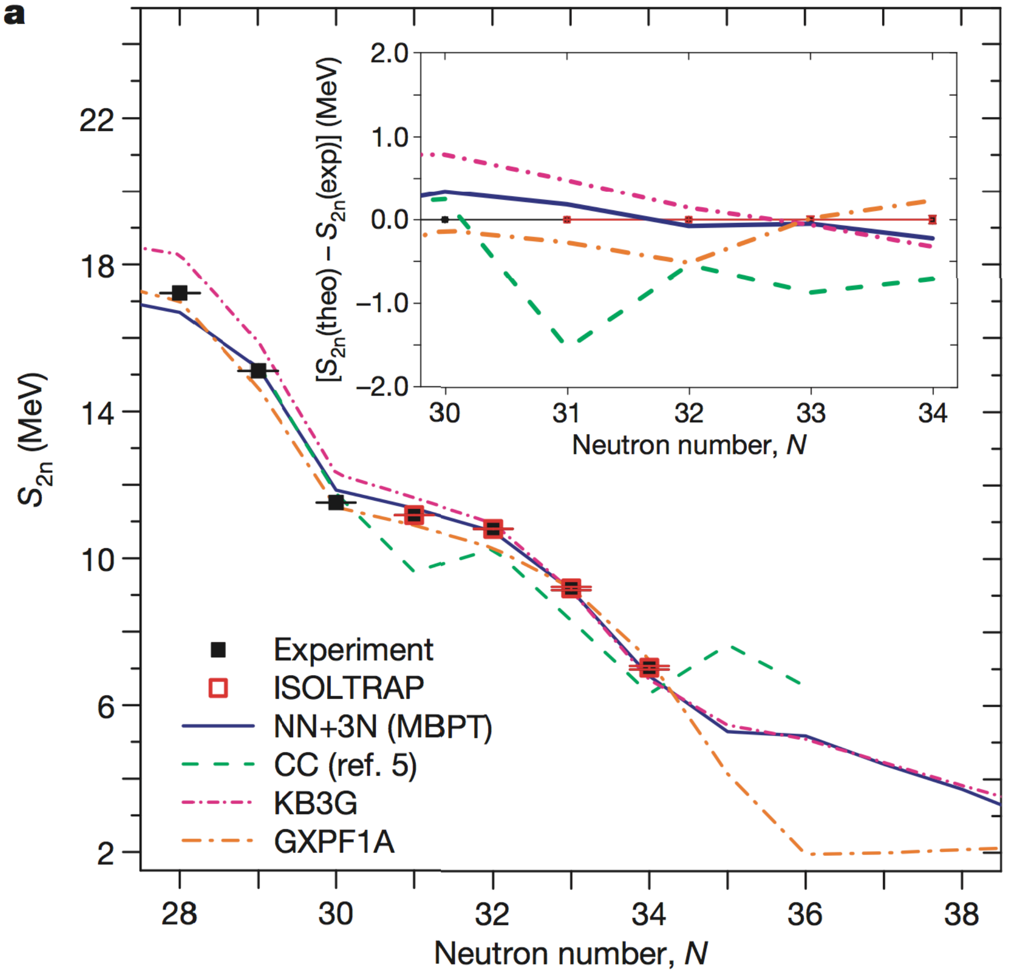
^{53,54}Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

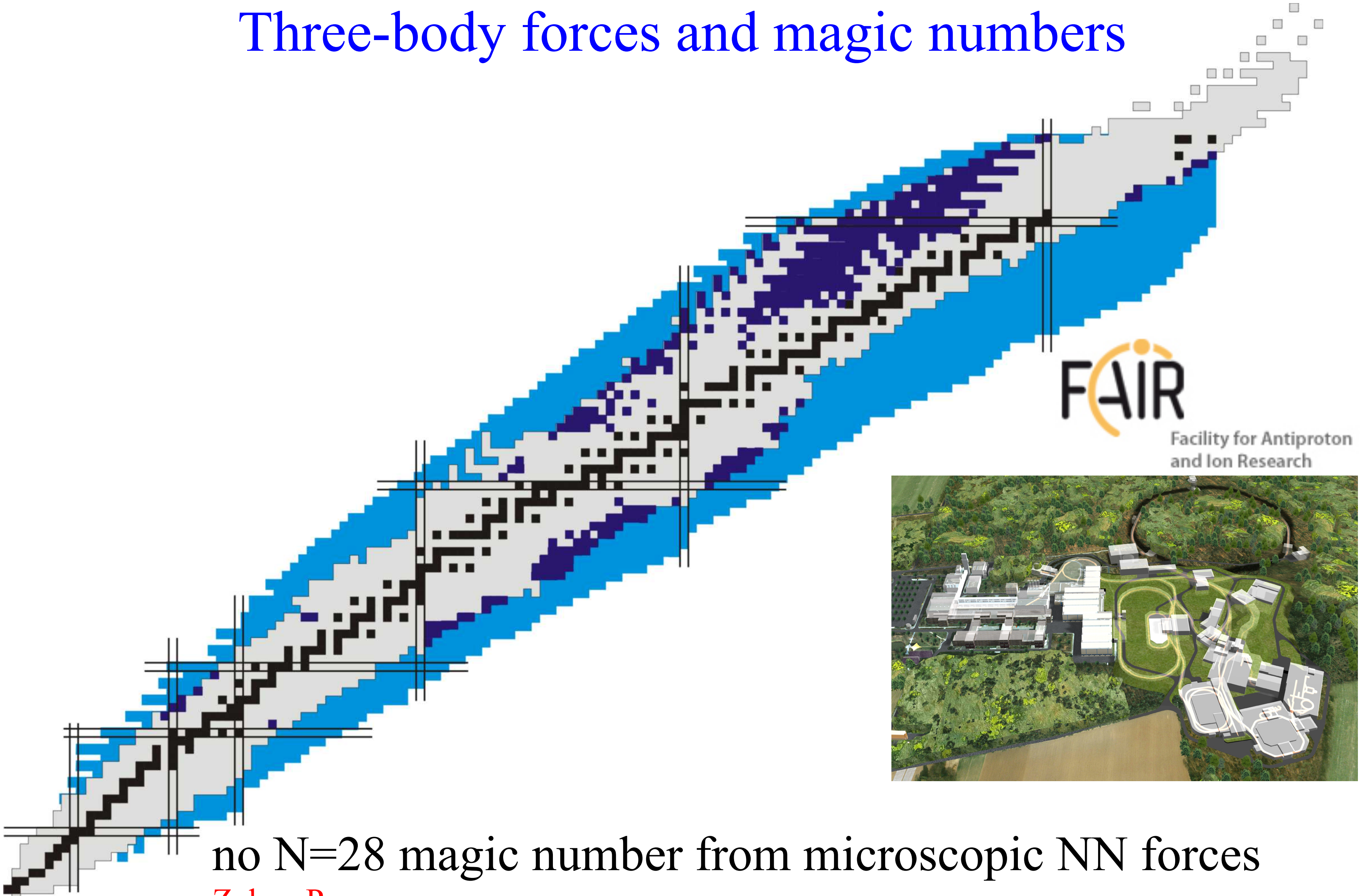
establish prominent N=32 shell closure in calcium

excellent agreement with theoretical NN+3N prediction

a



Three-body forces and magic numbers

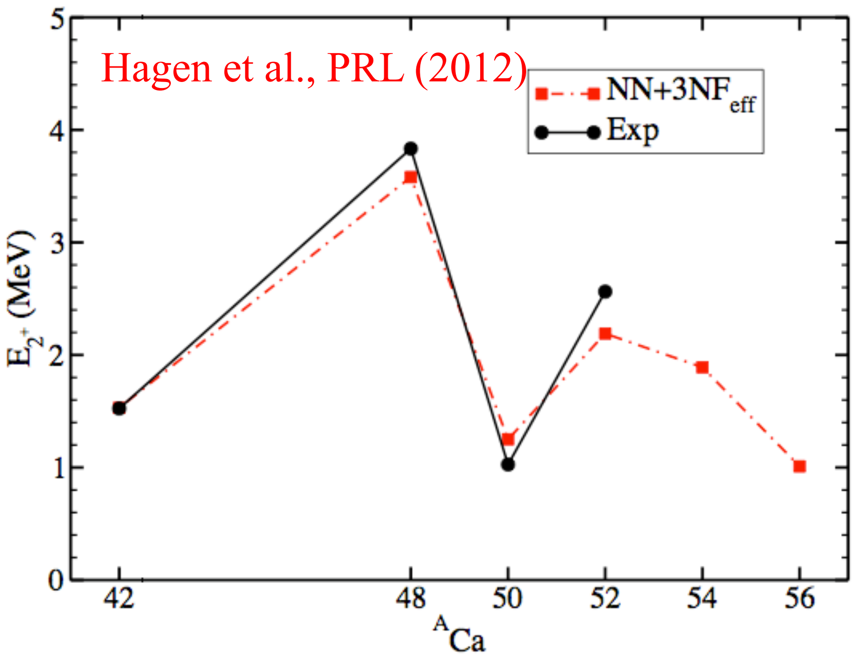


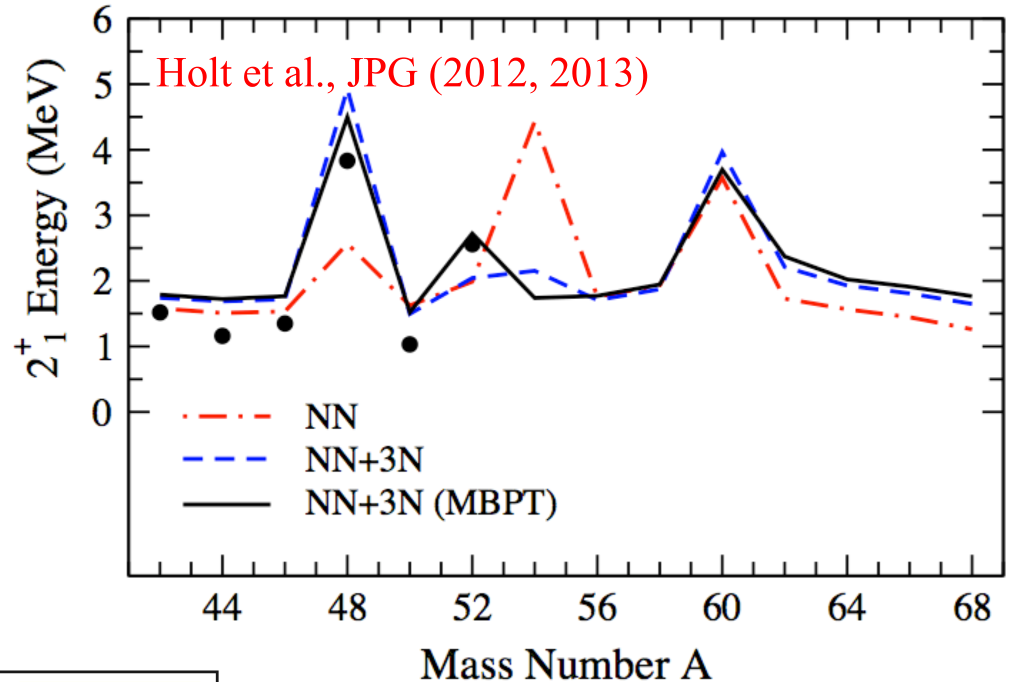
FAIR
Facility for Antiproton
and Ion Research

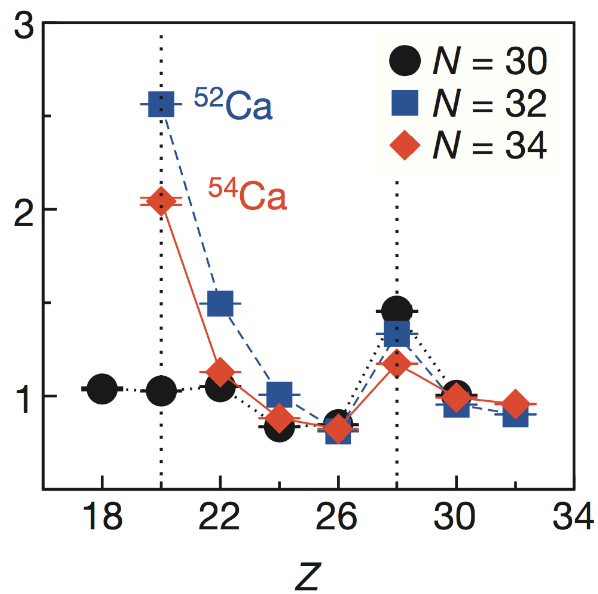
no N=28 magic number from microscopic NN forces

Zuker, Poves,…

3N forces and magic numbers







2^+ energy measured at RIBF suggests magic number N=34

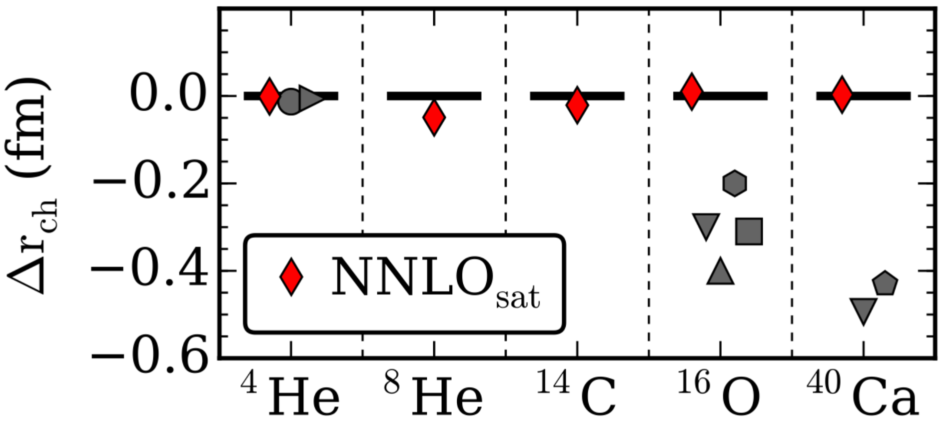
Steppenbeck et al., Nature (2013)

Resolution of radius problems

good saturation properties essential for radii

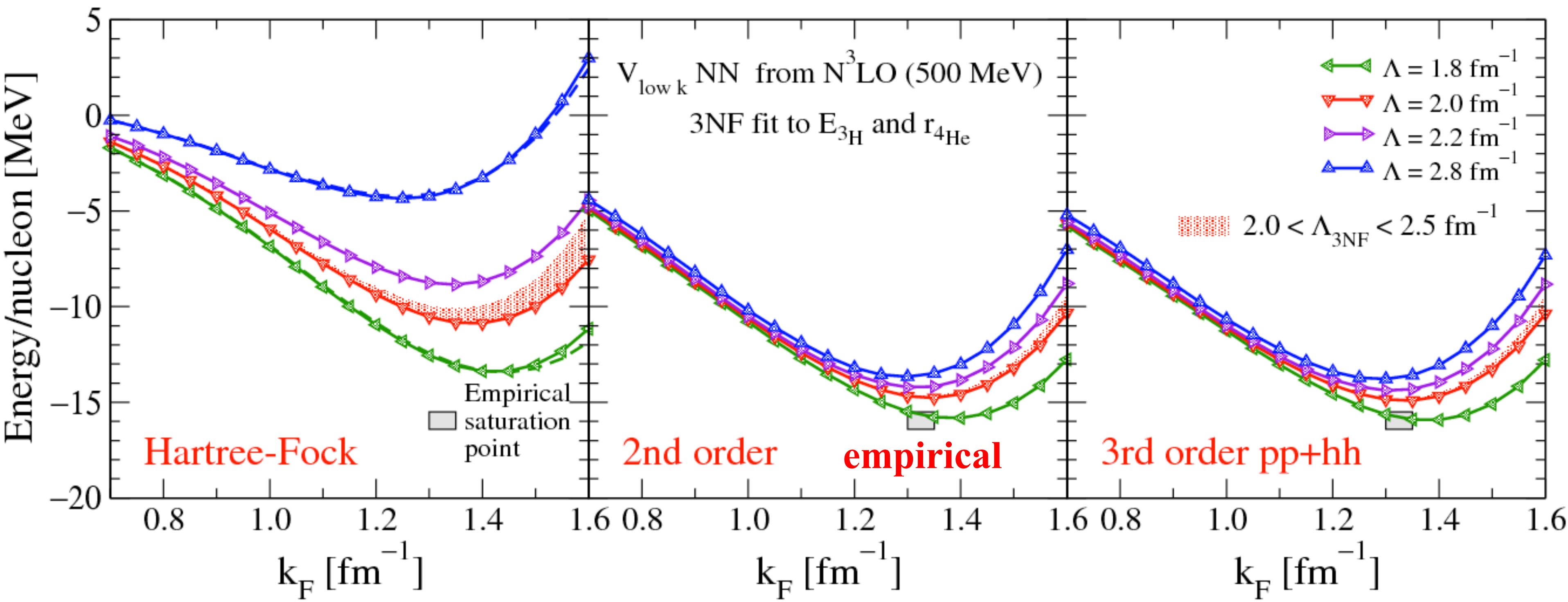
new N^2LOsat potential fit to selected nuclei up to A=24

Ekström et al. (2015)



Nuclear forces and nuclear matter

chiral 3N forces fit to light nuclei predict nuclear matter saturation
with theoretical uncertainties Hebeler et al. (2011), Bogner et al. (2005)



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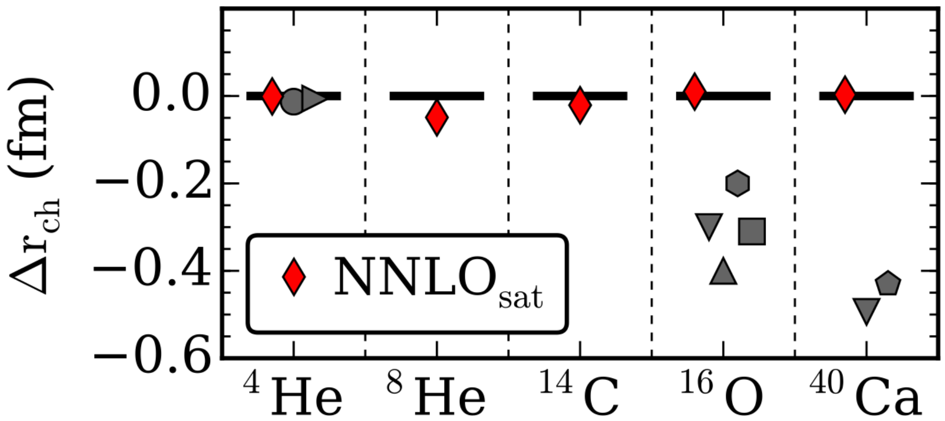
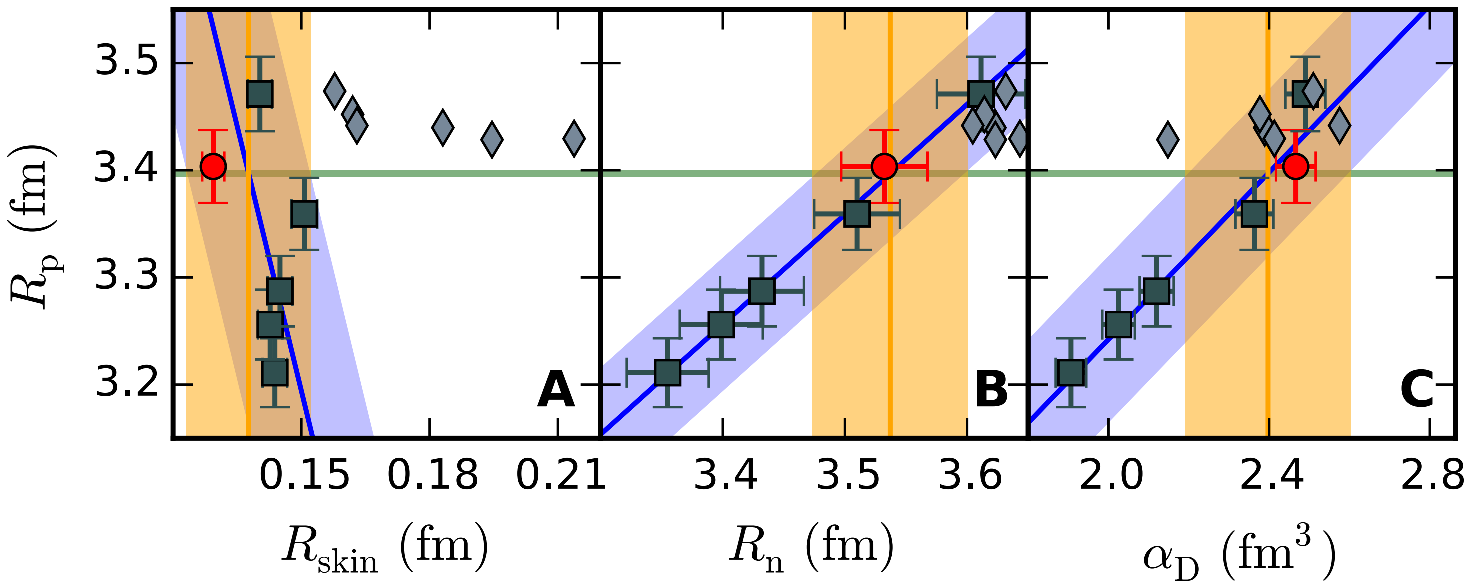


NN+3N interactions that predict

nuclear matter saturation (only fit to light nuclei, but nonlocal 3N regulators)

lead to radii consistent with experiment G. Hagen et al. results for ^{48}Ca



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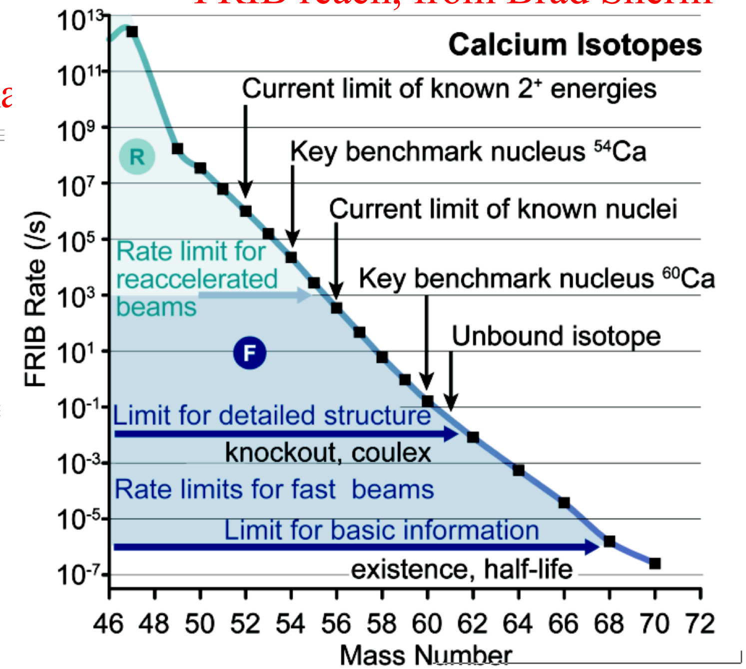
FRIB reach, from Brad Sherill



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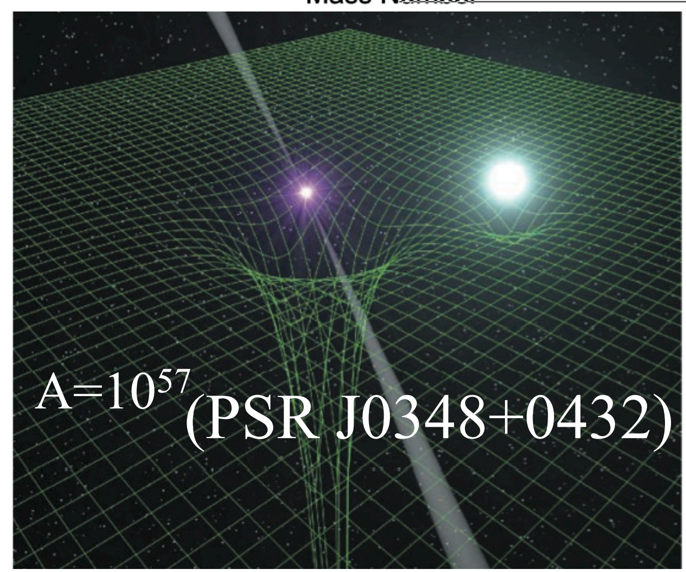

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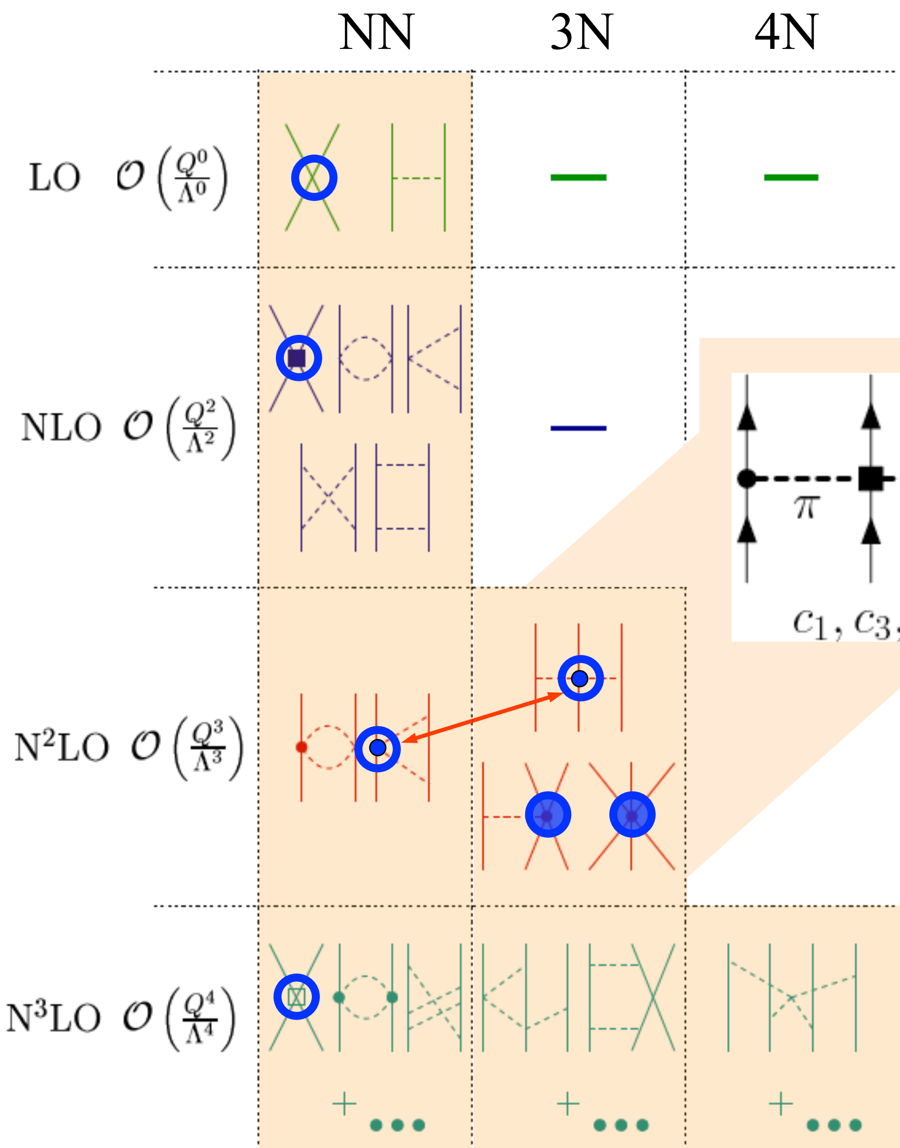
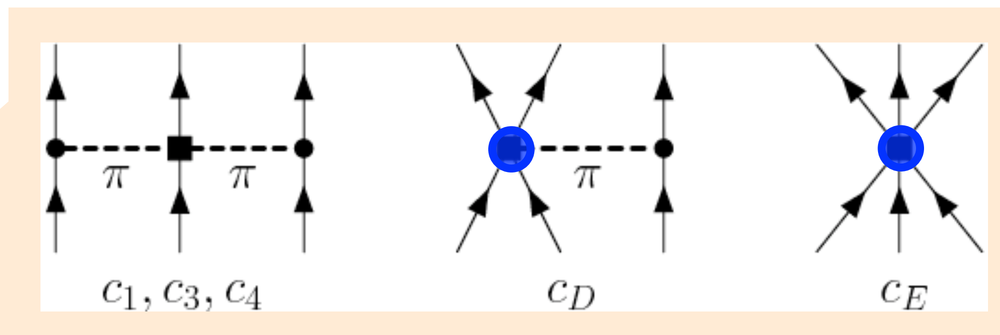


c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)



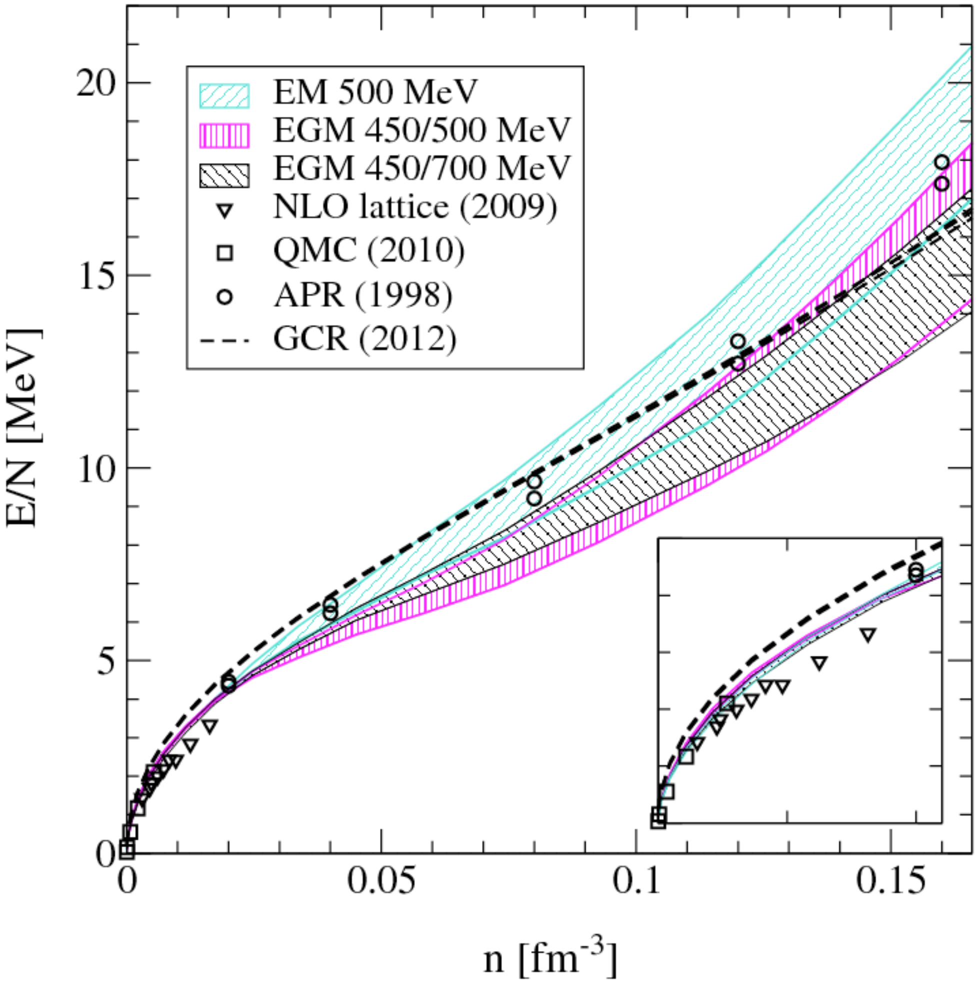
all 3- and 4-neutron forces are predicted to N³LO!

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

Complete N^3LO calculation of neutron matter

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

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



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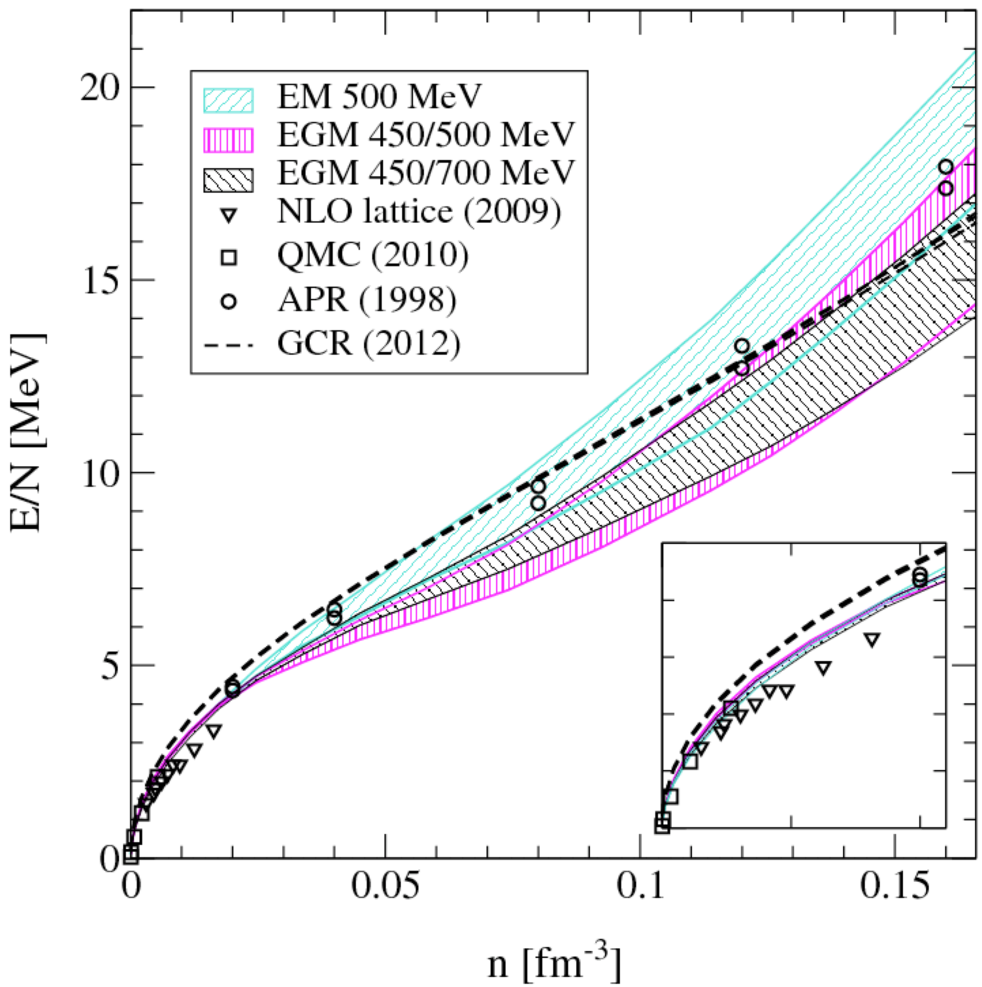
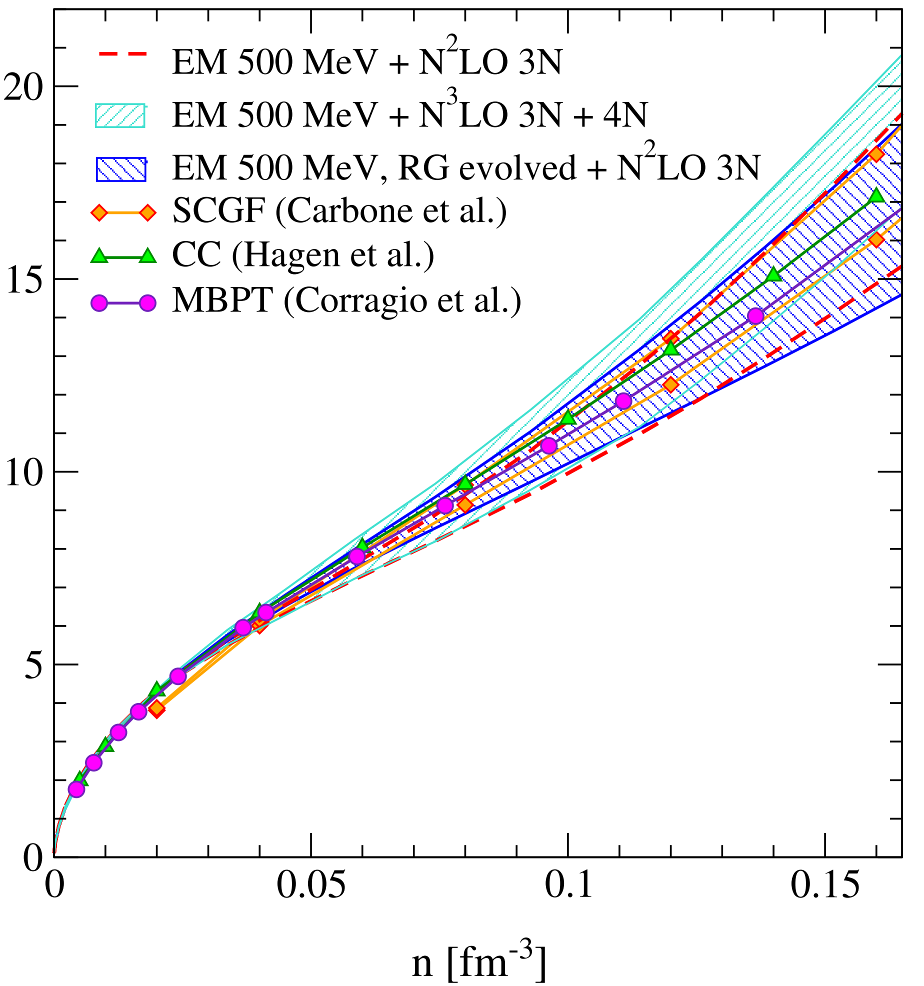


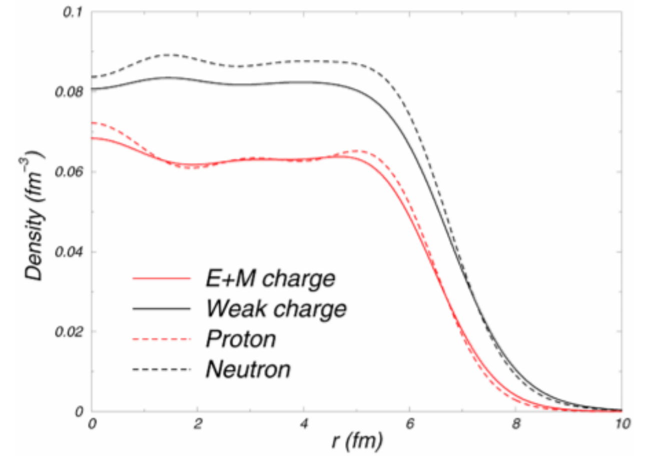


excellent agreement with other methods!

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, Lattimer, Pethick, AS, PRL (2010)



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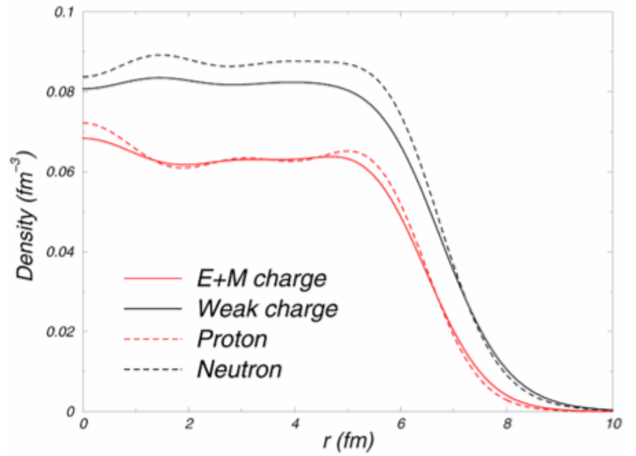

in excellent agreement with extraction from dipole polarizability
0.156+0.025-0.021 fm Tamii et al., PRL (2011)

PREX: neutron skin from parity-violating electron-scattering at JLAB
goal II: ±0.06 fm Abrahamyan et al., PRL (2012)

MAMI: coherent pion photoproduction
0.15+0.04-0.06 fm Tabert et al., PRL (2014)

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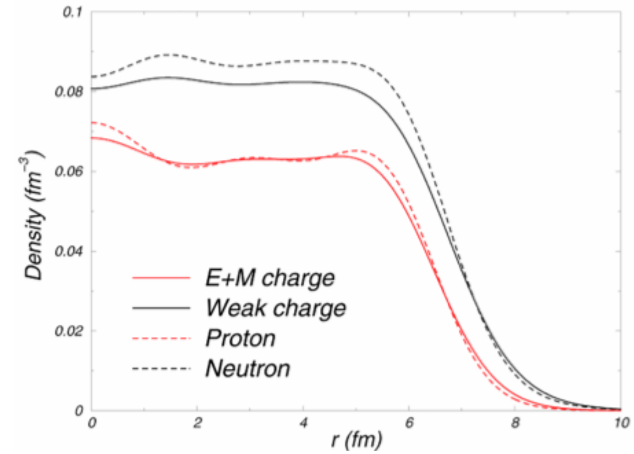
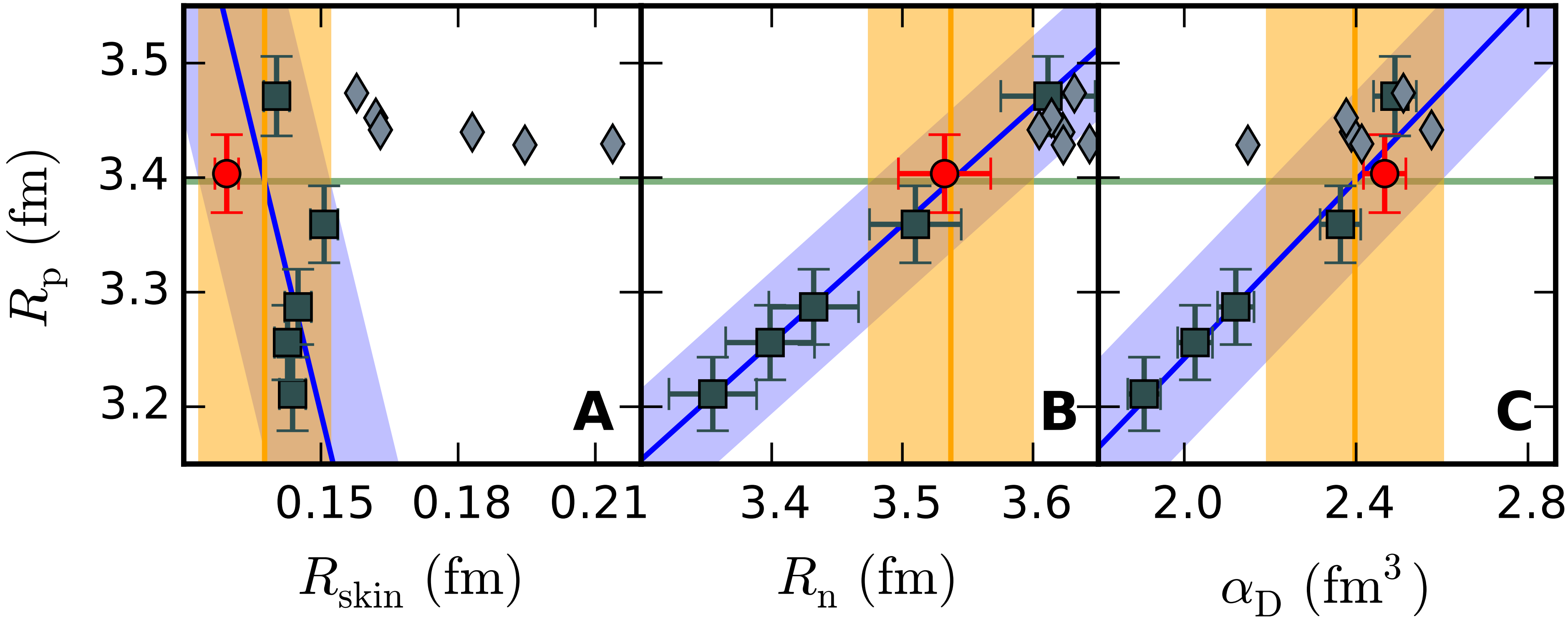




ab initio results for neutron skin and dipole polarizability of ^{48}Ca Hagen et al.

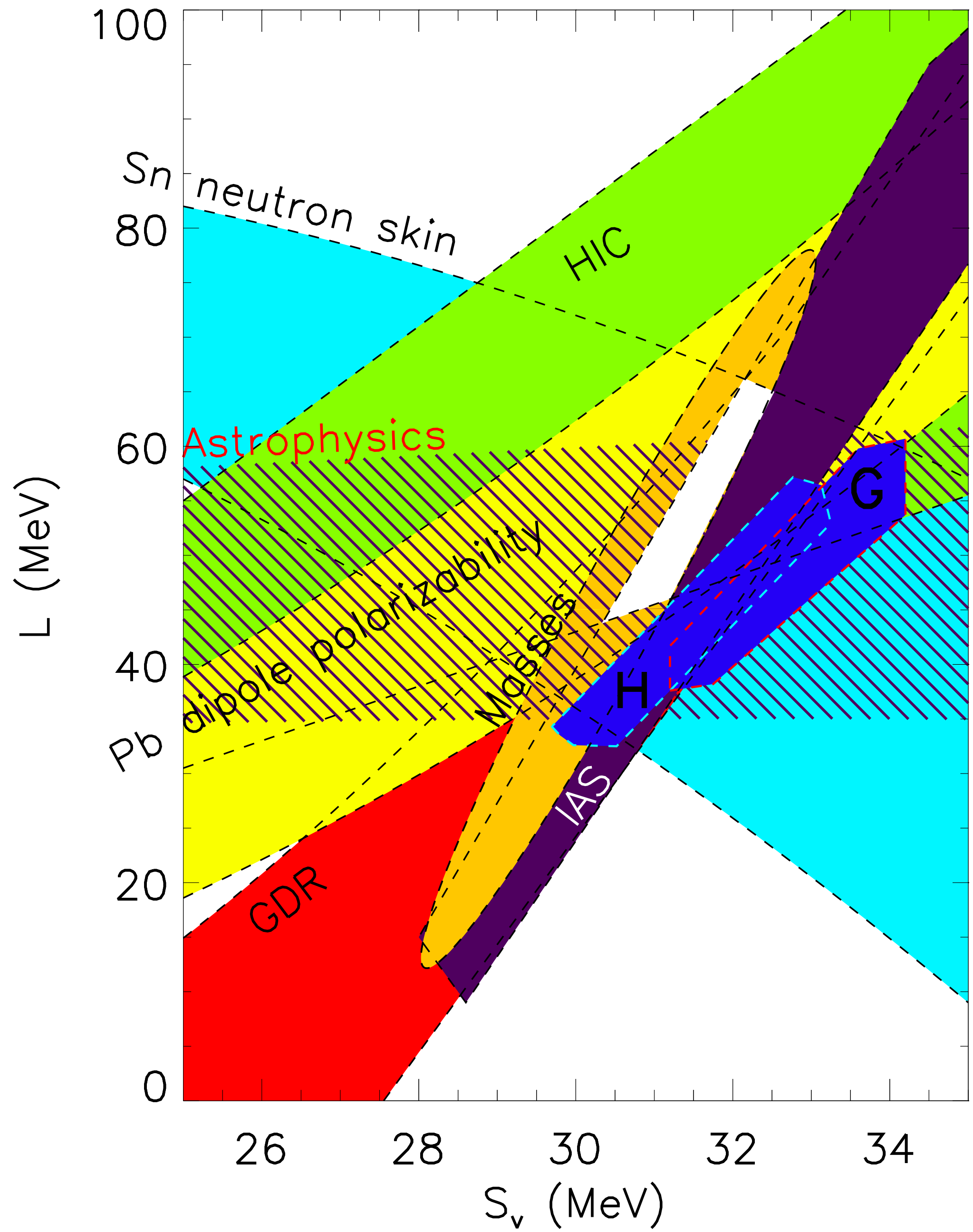
Symmetry energy and pressure of neutron matter

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

comparison to experimental
and observational constraints
Lattimer, Lim, ApJ (2012), EPJA (2014)

neutron matter constraints
H: Hebeler et al. (2010)
G: Gandolfi et al. (2011)
provide tight constraints!

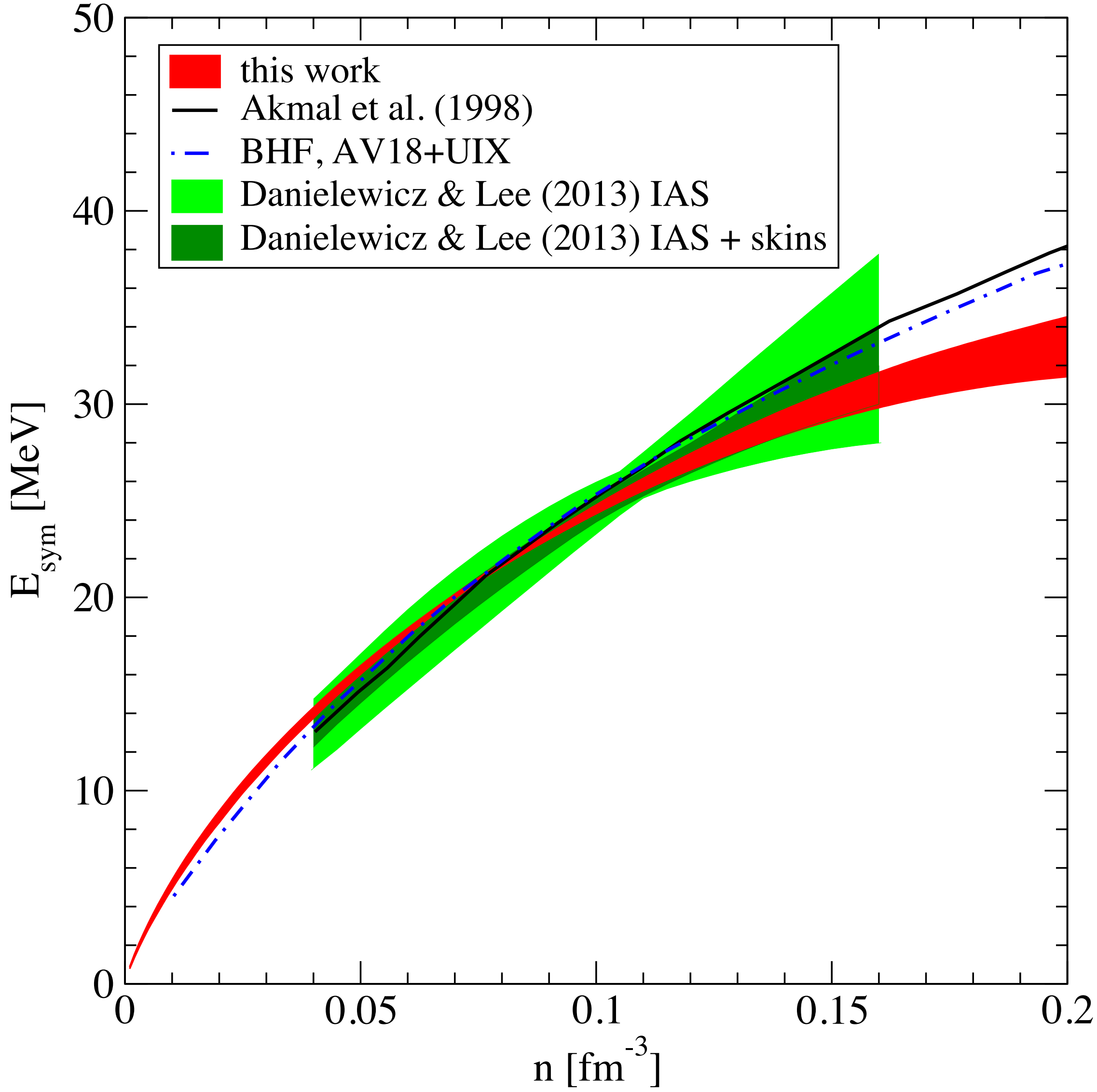
combined with Skyrme EDFs
predicts neutron skin
^{208}Pb: 0.182(10) fm
Brown, AS (2014)



Calculations of asymmetric matter Drischler, Soma, AS, PRD (2014)

E_{sym} comparison with extraction from isobaric analogue states (IAS)

3N forces fit to ^{3}H, ^{4}He properties only



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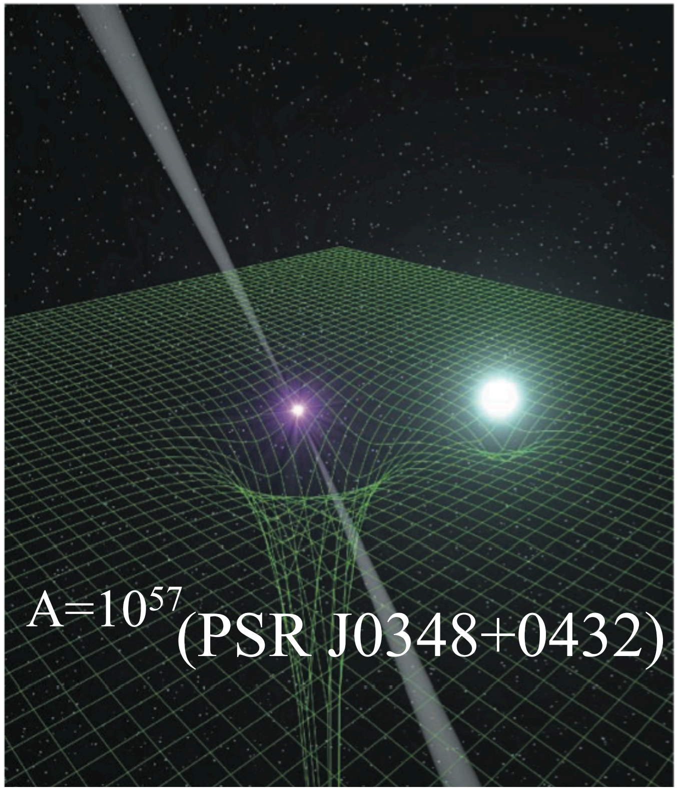

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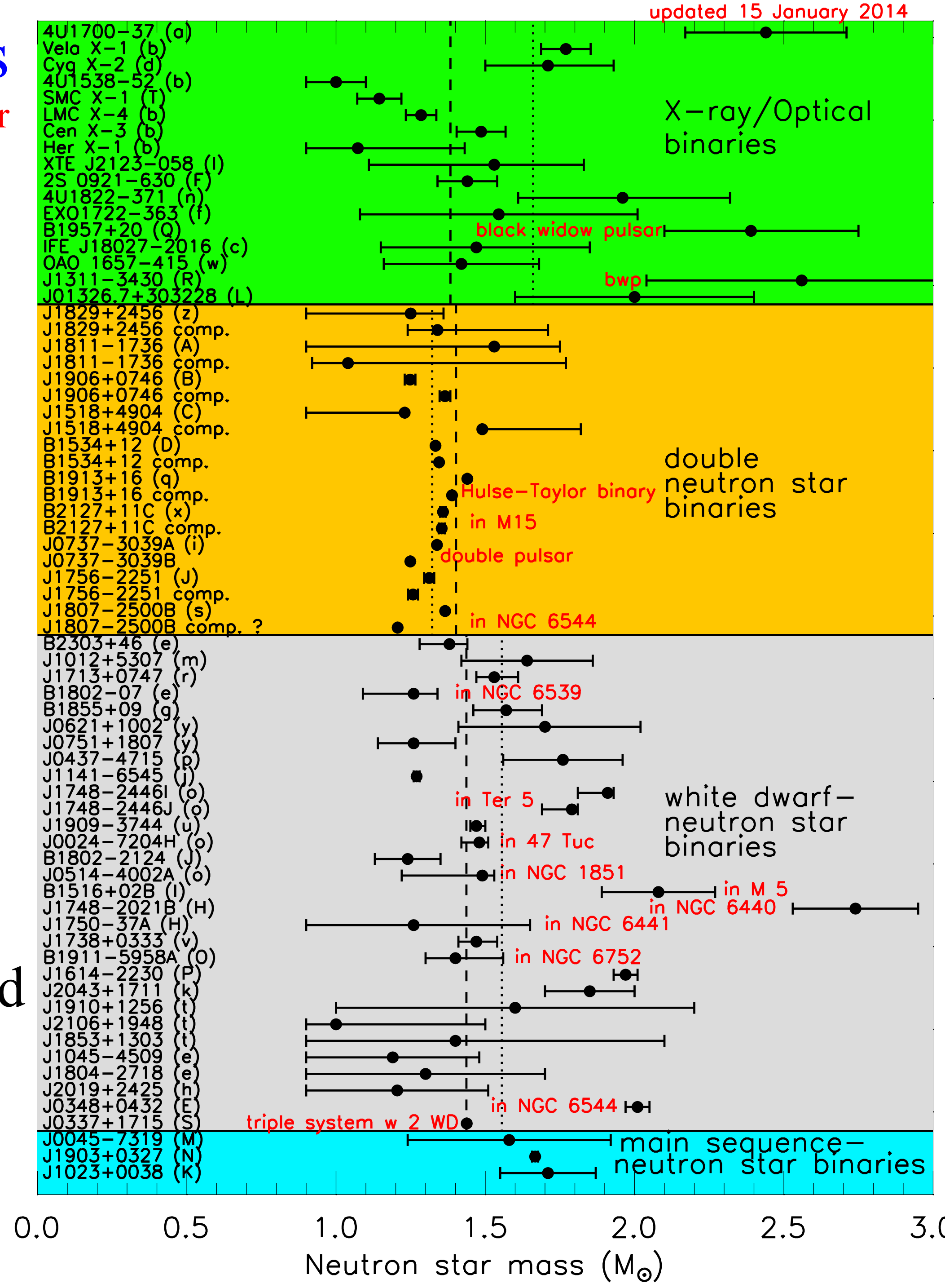
based on same strong interactions!

Chart of neutron star masses

from Jim Lattimer



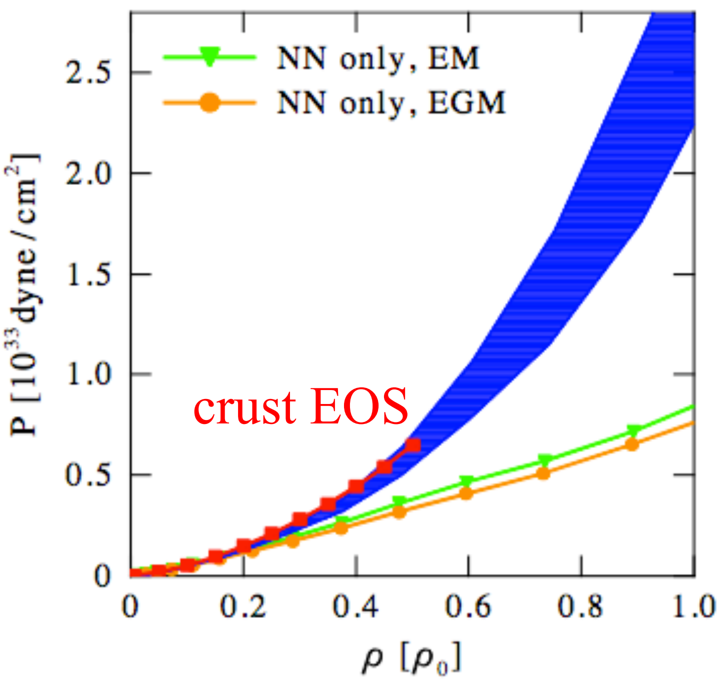
two 2 M_{sun} neutron stars observed

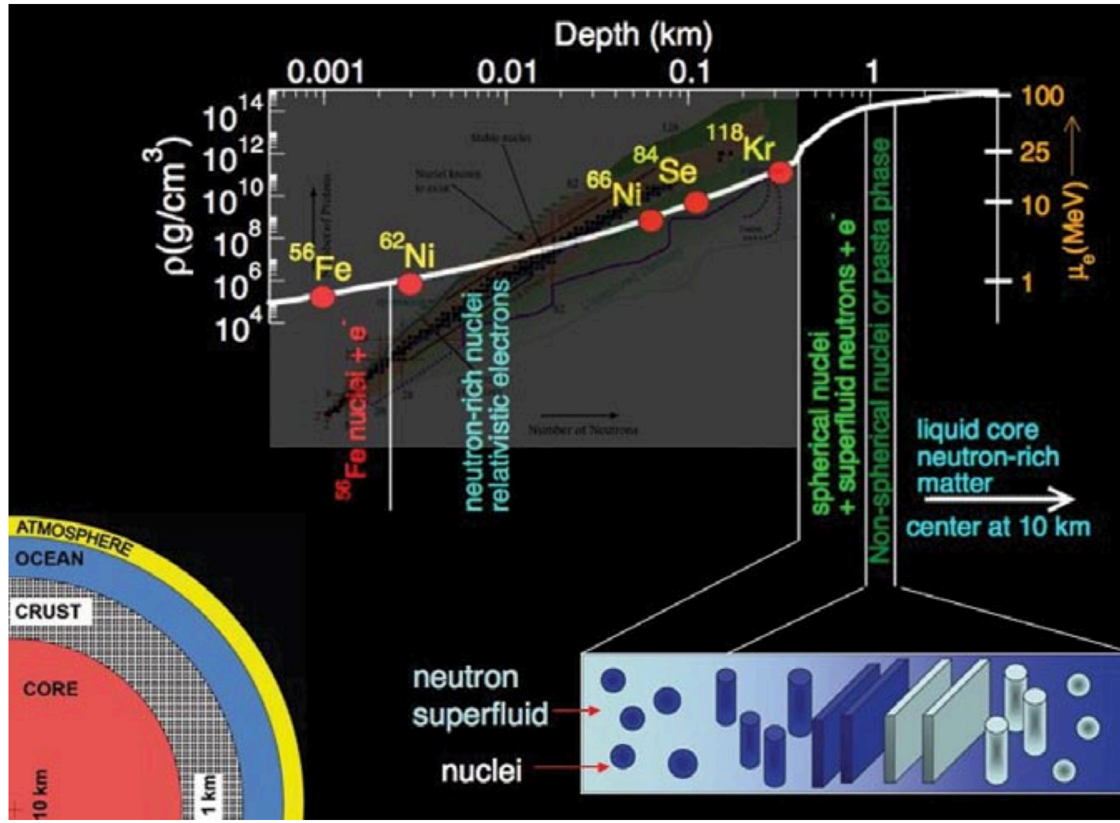
Demorest et al, Nature (2010),

Antoniadis et al., Science (2013)

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

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

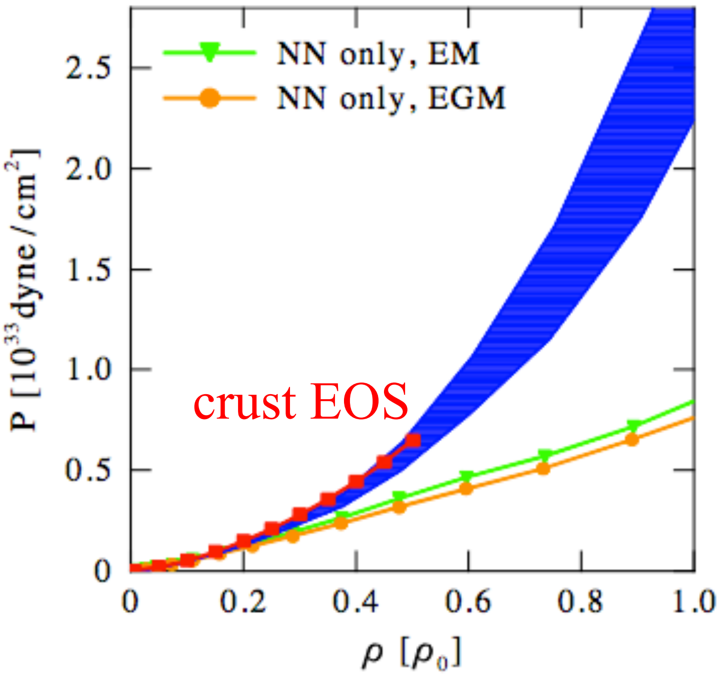


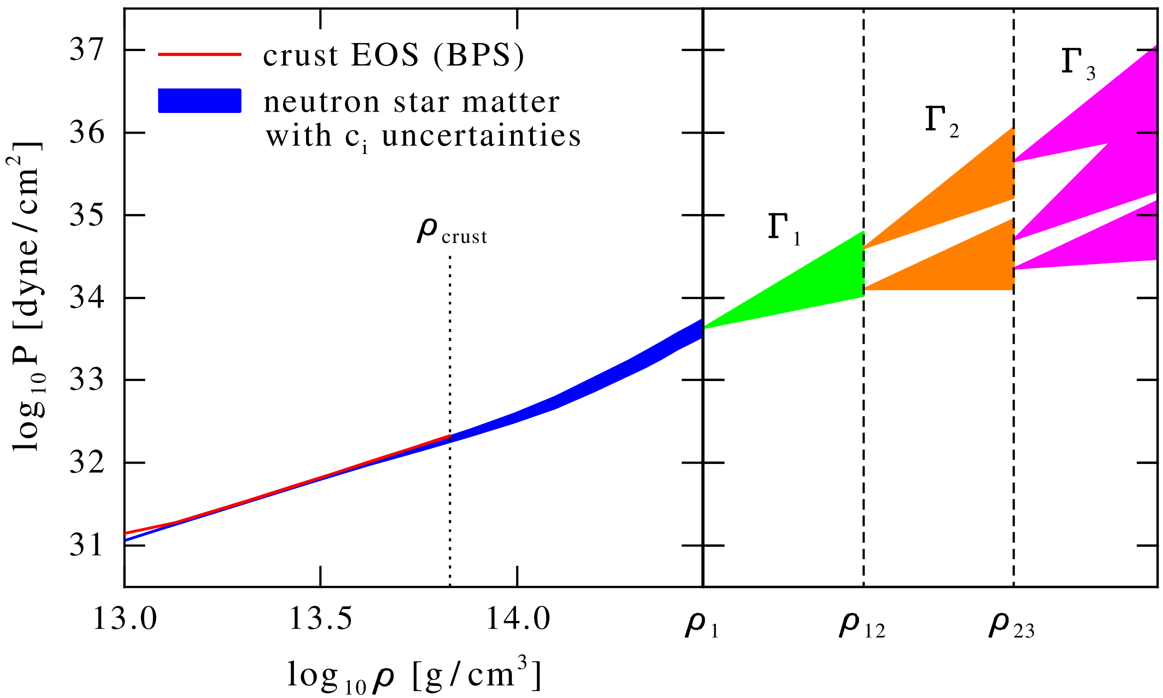


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

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



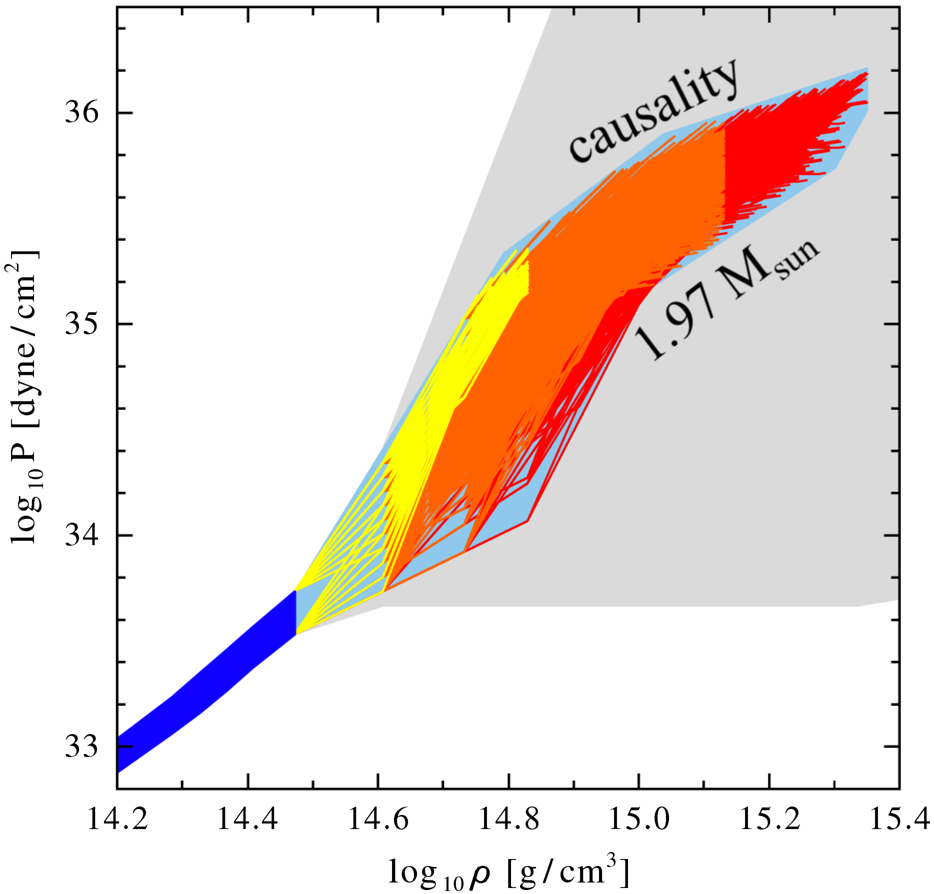


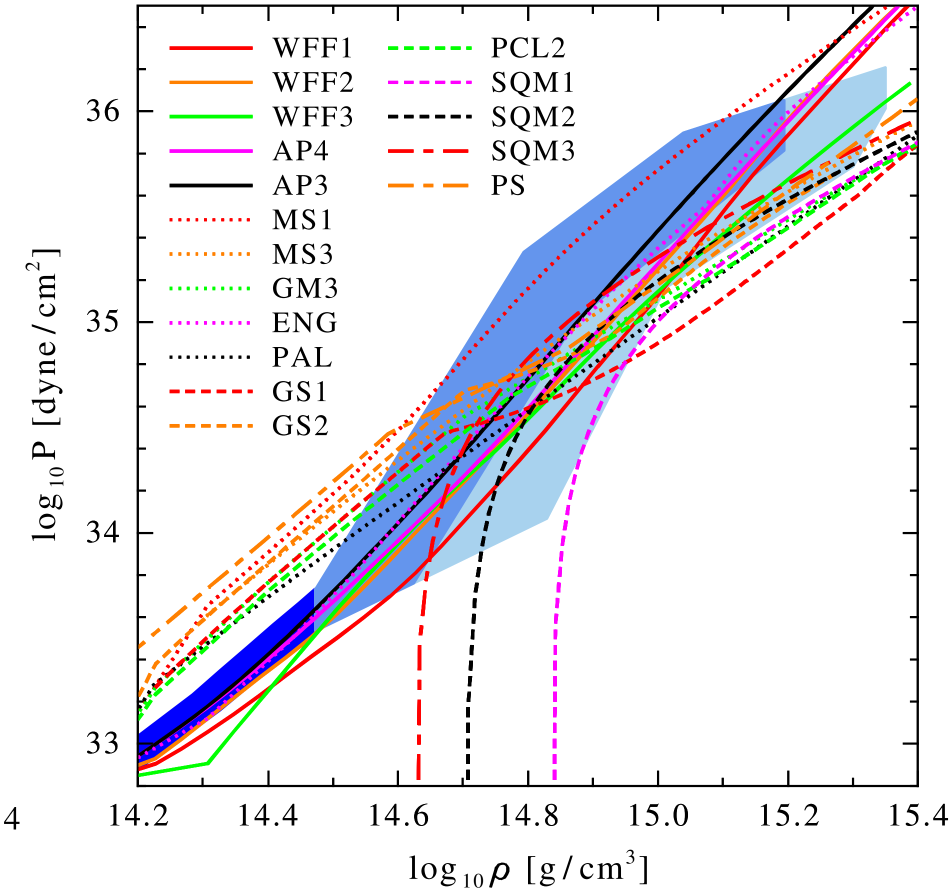
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

extend uncertainty band to higher densities using piecewise polytropes allow for soft regions

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

constrain high-density EOS by causality, require to support 2 M_{sun} star

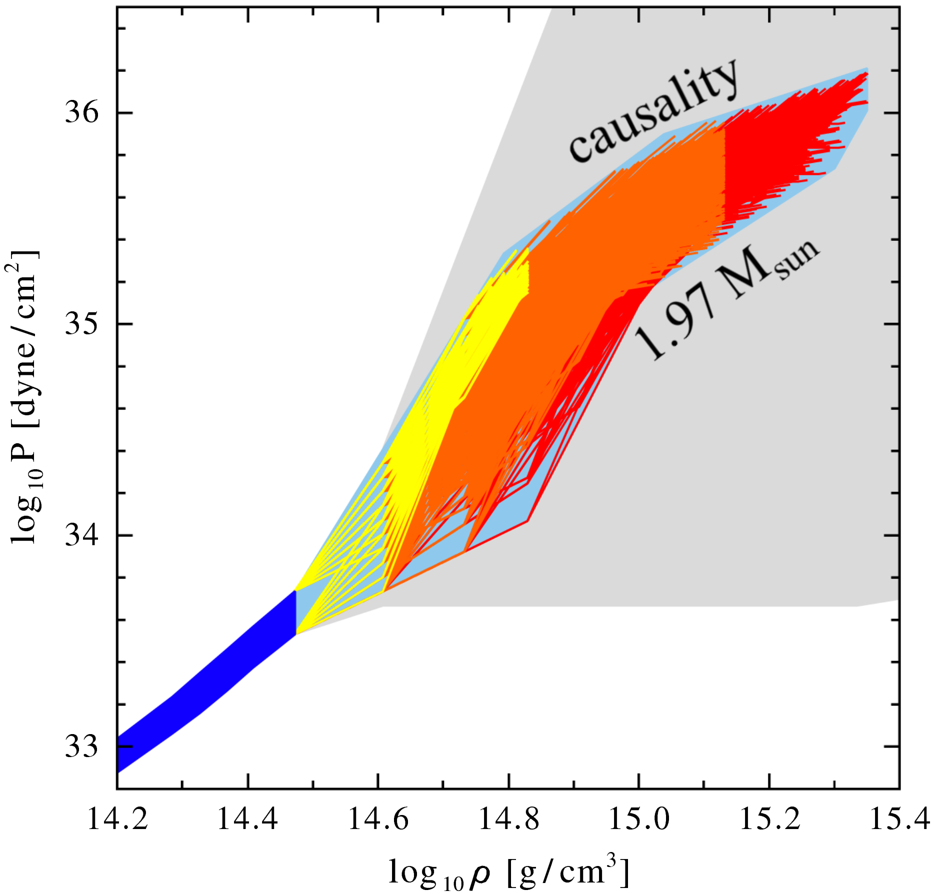


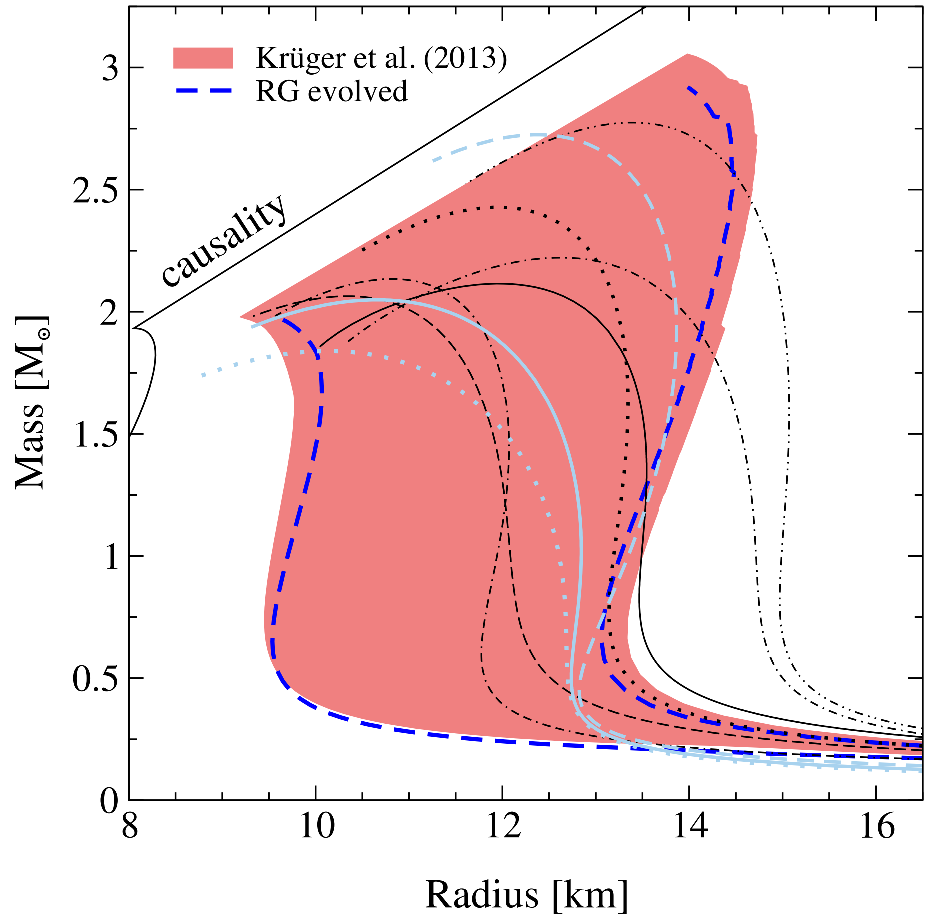


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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

constrain high-density EOS by causality, require to support 2 M_{sun} star



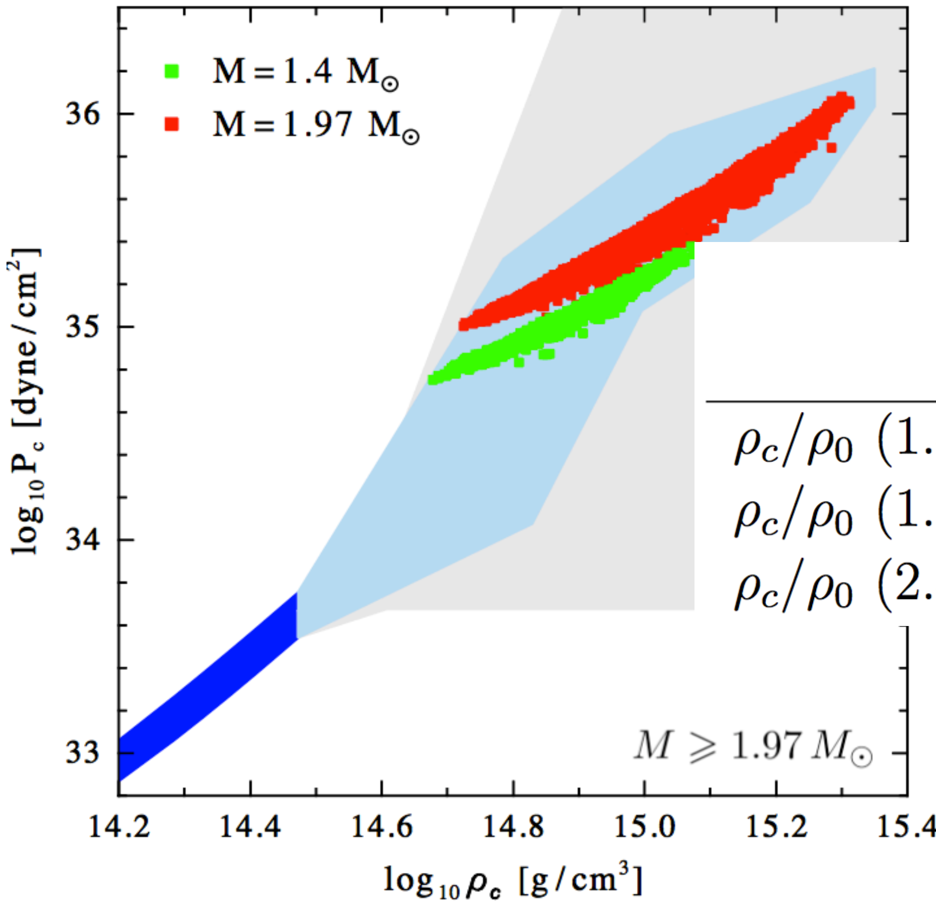


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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

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

constrain high-density EOS by causality, require to support 2 M_{sun} star



	$\widehat{M} = 1.97\,M_\odot$ min	max	$\widehat{M} = 2.4\,M_\odot$ min	max
ρ_c/ρ_0 $(1.4\,M_\odot)$	1.8	4.4	1.8	2.7
ρ_c/ρ_0 $(1.97\,M_\odot)$	2.0	7.6	2.0	3.4
ρ_c/ρ_0 $(2.4\,M_\odot)$			2.2	5.4

central densities
for 1.4 M_{sun} star: 1.8-4.4 ρ_0

not very high momenta!

Neutron-star mergers and gravitational waves

explore sensitivity to neutron-rich matter in neutron-star merger predictions for gravitational-wave signal, including NP uncertainties

Bauswein, Janka, PRL (2012)
Bauswein, Janka, Hebeler, AS, PRD (2012)

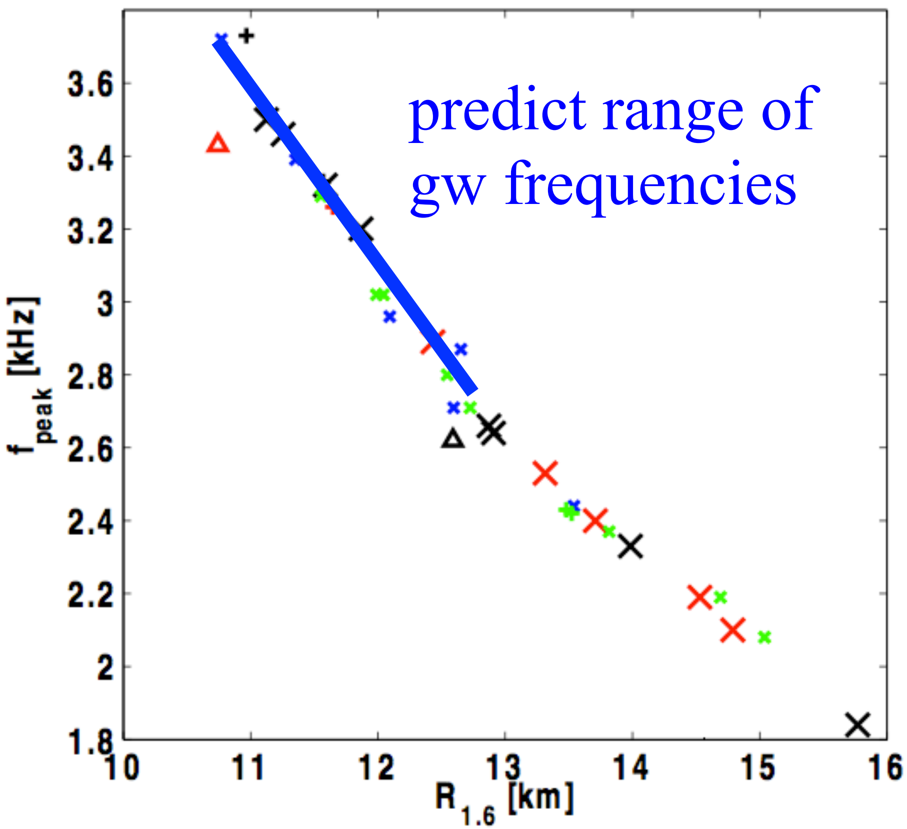
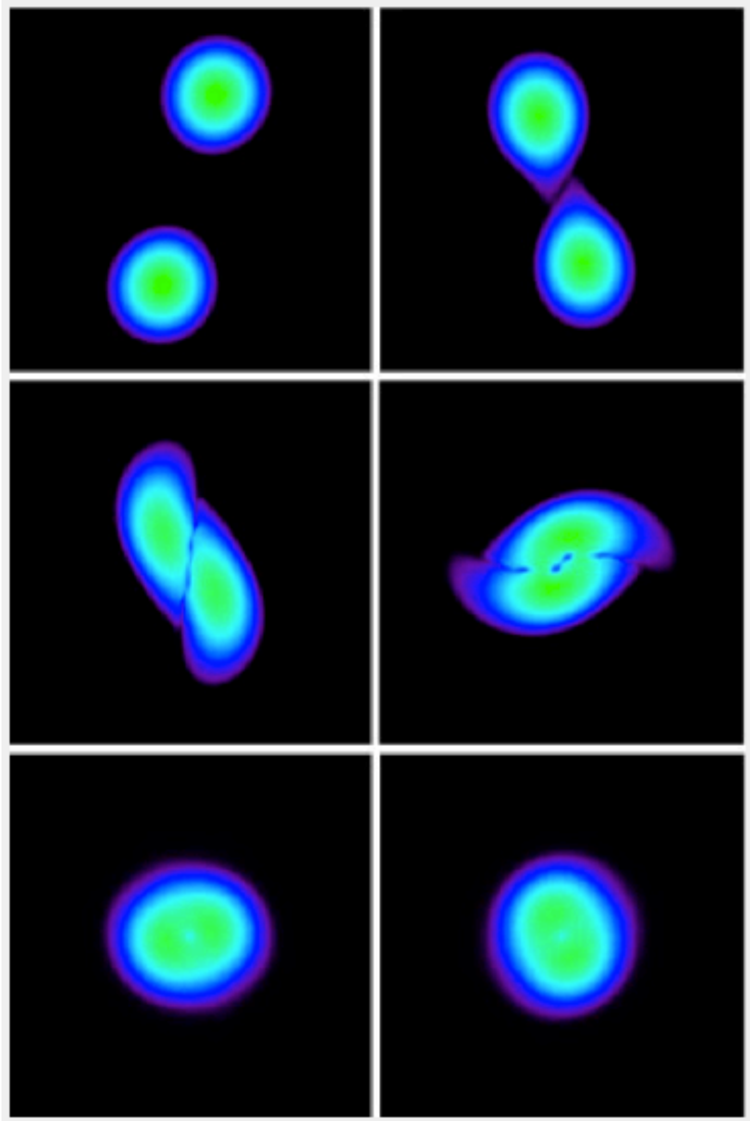


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_{\odot}$ for different EoSs. Symbols have the same meaning as in Fig. 8.



Dark matter direct detection

WIMP scattering off nuclei needs **nuclear structure factors** as input

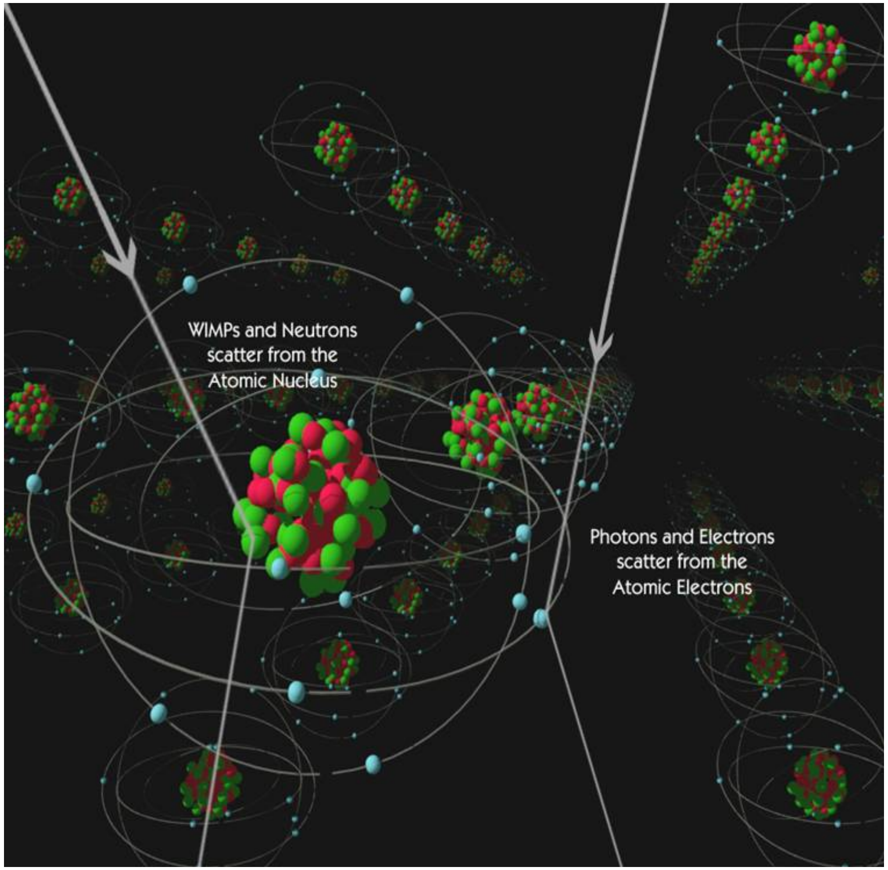
particularly sensitive to nuclear physics for **spin-dependent** or general WIMP-nucleon interactions

relevant momentum transfers ~ m_π

calculate systematically
with chiral effective field theory

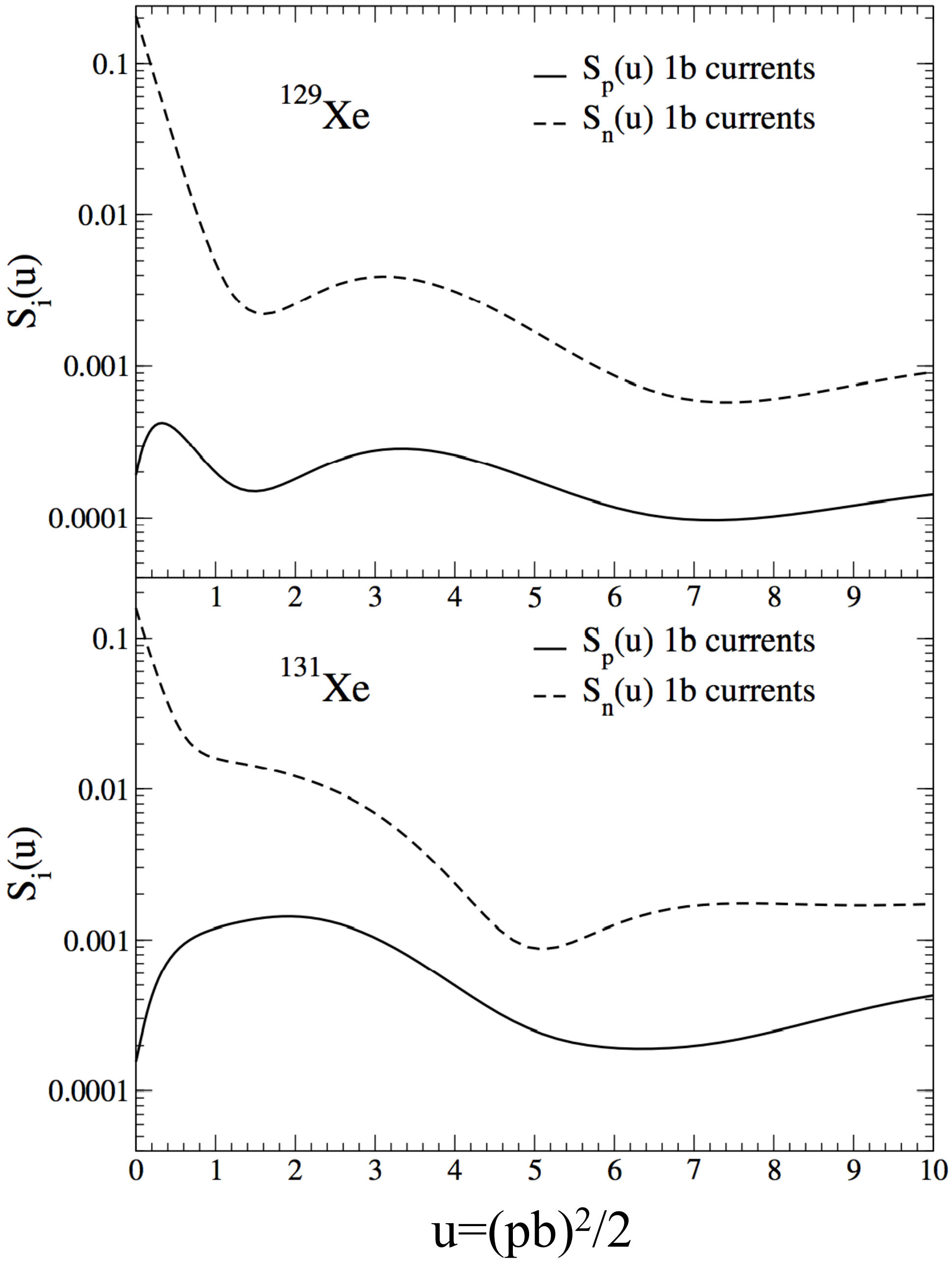
Menéndez, Gazit, AS, PRD (2012),
Klos, Menéndez, Gazit, AS, PRD (2013),
Baudis et al., PRD (2013),
Vietze et al., PRD (2015),
Hoferichter, Klos, AS, PLB (2015).

incorporate what we know
about QCD/nuclear physics



from CDMS collaboration

Spin structure factors for xenon

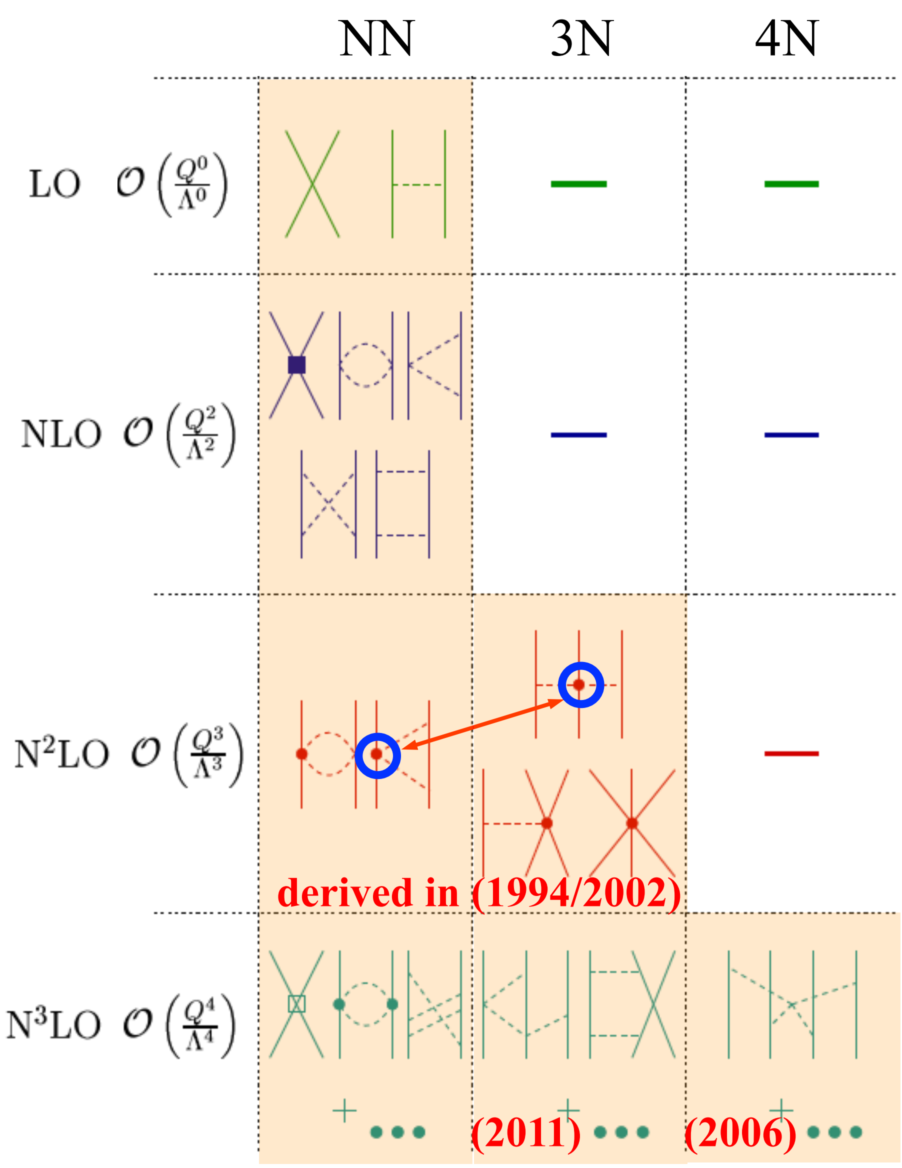


^{129,131}Xe are even Z, odd N,
spin is carried mainly by neutrons

at p=0 structure factors
at the level of one-body currents
dominated by "neutron"-only

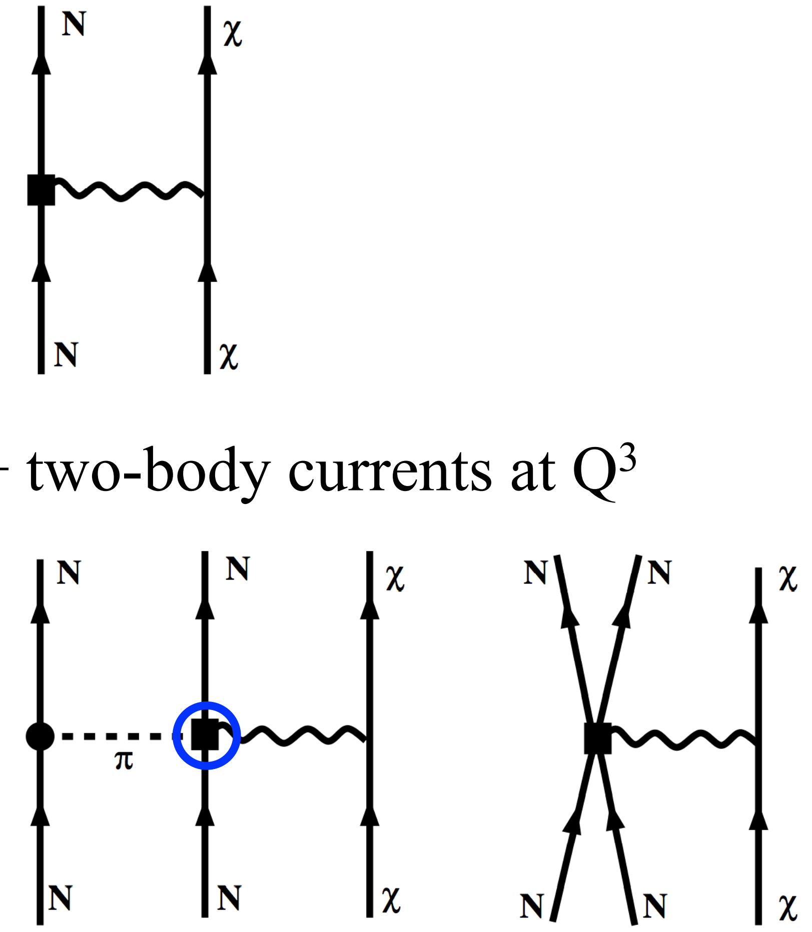
$$S_A = \frac{(2J+1)(J+1)}{\pi J} \left| a_p \langle S_p \rangle + a_n \langle S_n \rangle \right|^2$$

Chiral EFT for spin-dependent WIMP currents in nuclei



one-body currents at Q^0 and Q^2

+ two-body currents at Q^3

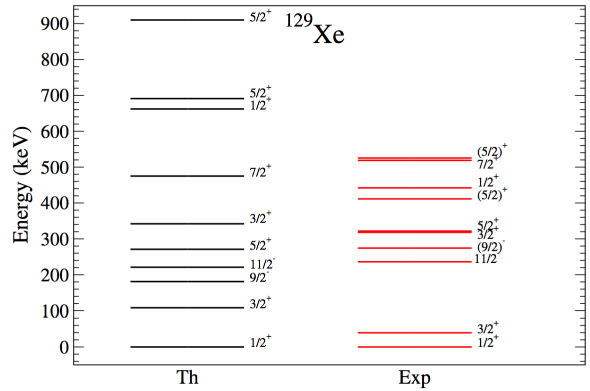


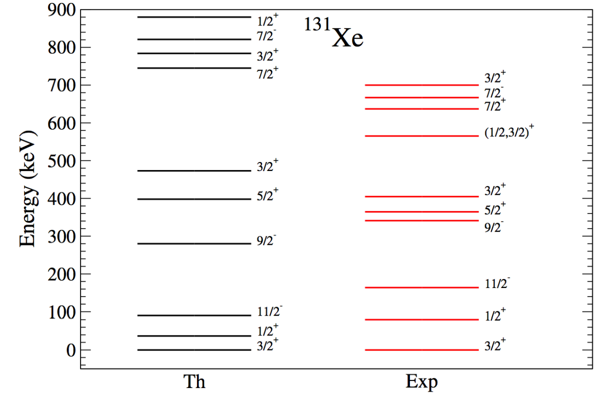
same couplings in forces and currents!

Nuclear structure for direct detection

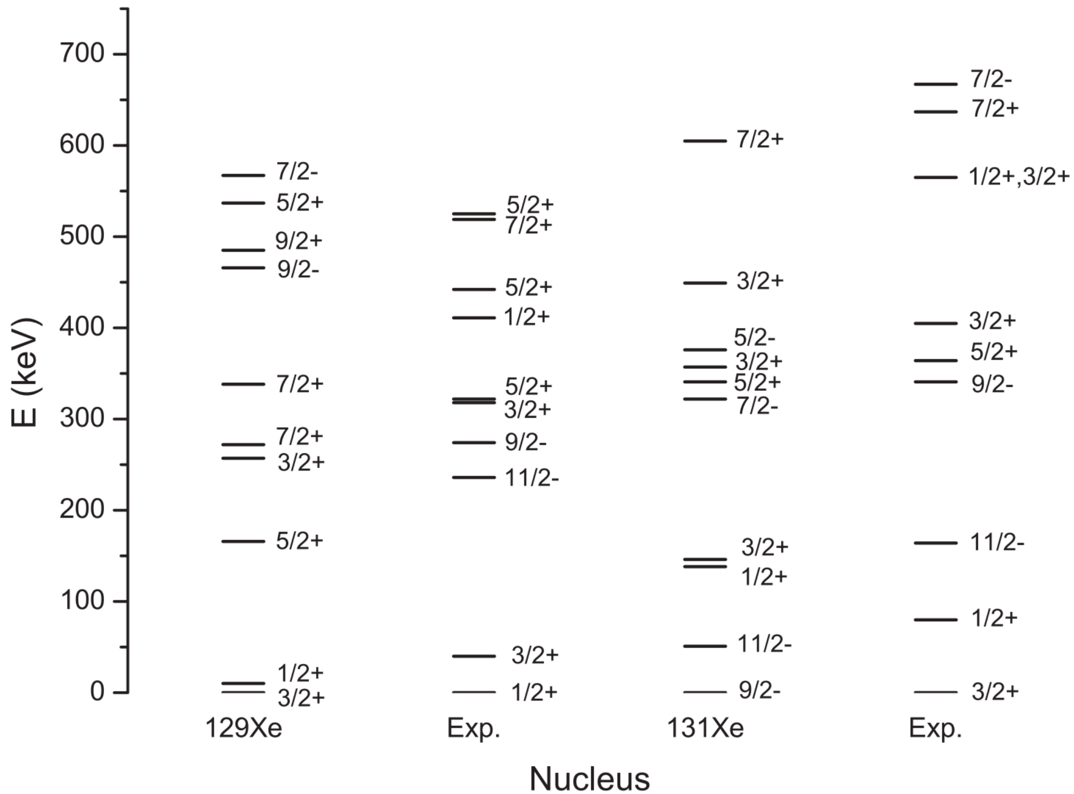
very good agreement for spectra; ordering and grouping well reproduced

Menendez, Gazit, AS, PRD (2012)

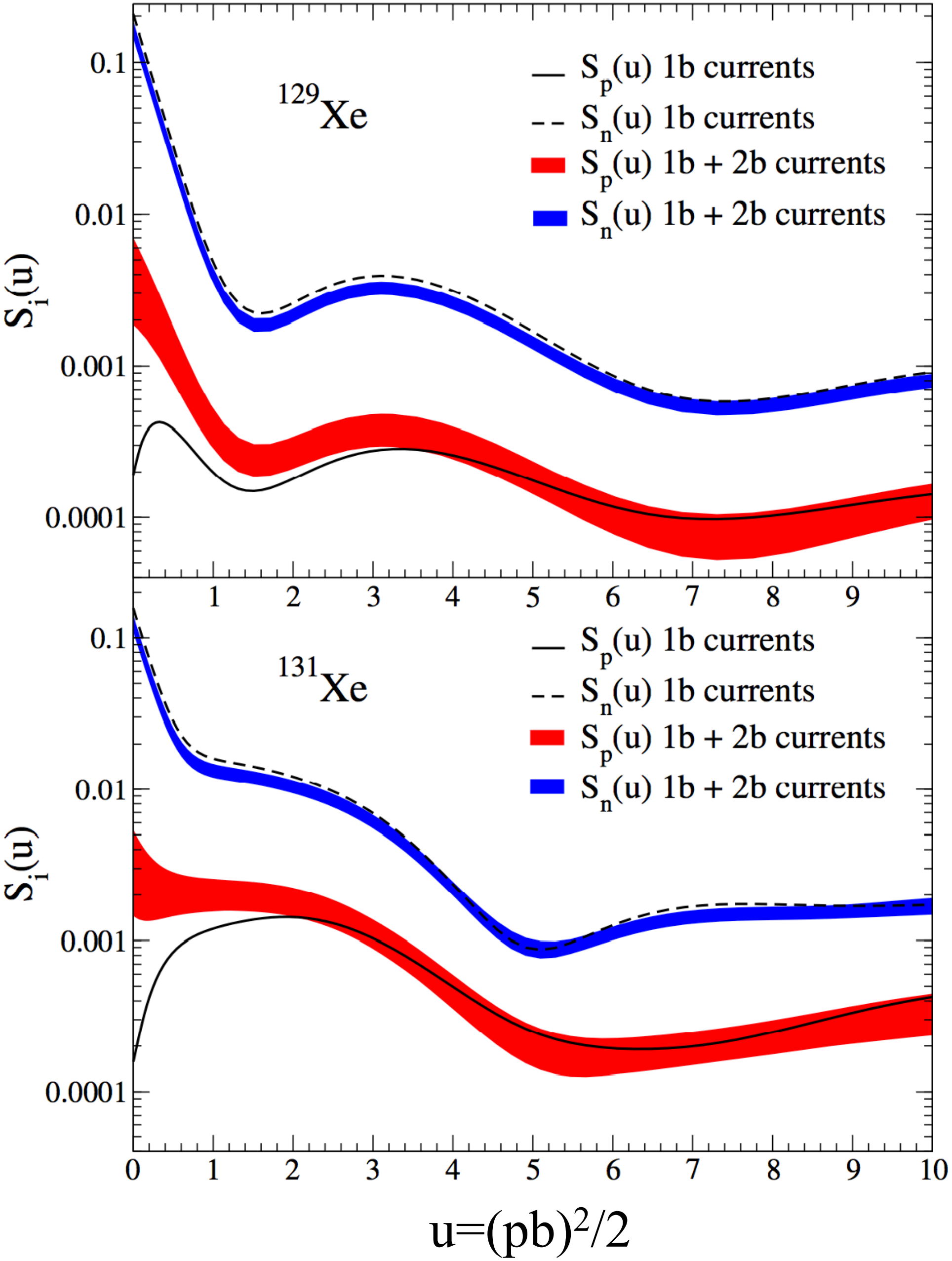




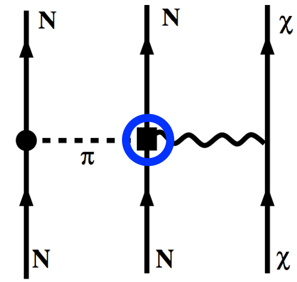
compare to other calculations for WIMP scattering



Xenon response with 1+2-body currents



two-body currents due to strong interactions among nucleons



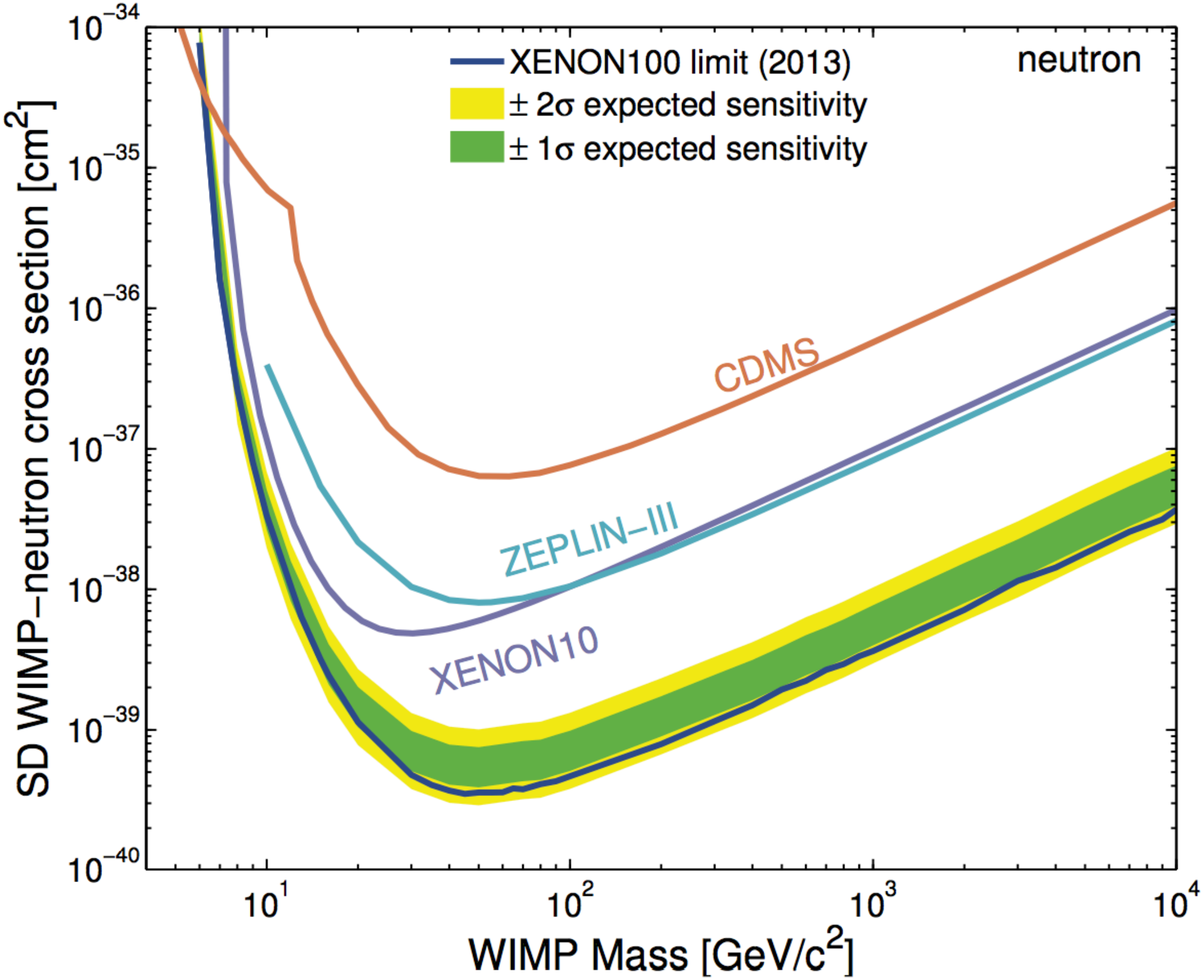
WIMPs couple to neutrons and protons at the same time

enhances coupling to even species in all cases (protons for Xe)

Limits on SD WIMP-neutron interactions

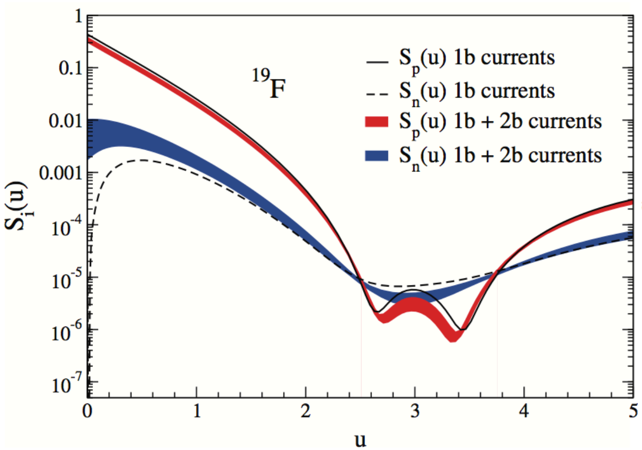
best limits from XENON100 Aprile et al., PRL (2013)

used our calculations with uncertainty bands for WIMP currents in nuclei

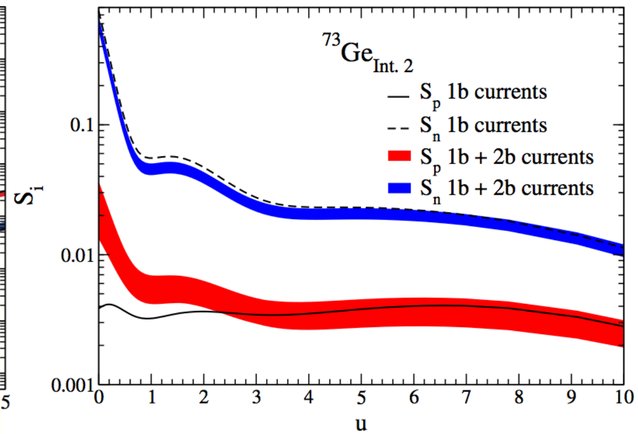


Spin-dependent WIMP-nucleus response for ^{19}F, ^{23}Na, ^{27}Al, ^{29}Si, ^{73}Ge, ^{127}I

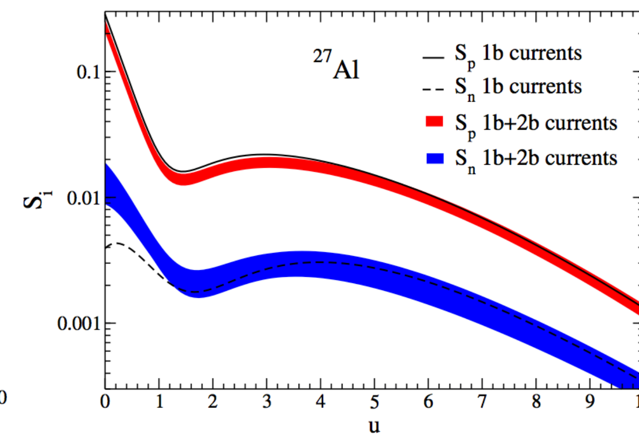
Klos, Menéndez, Gazit, AS, PRD (2013) includes structure factor fits for all isotopes



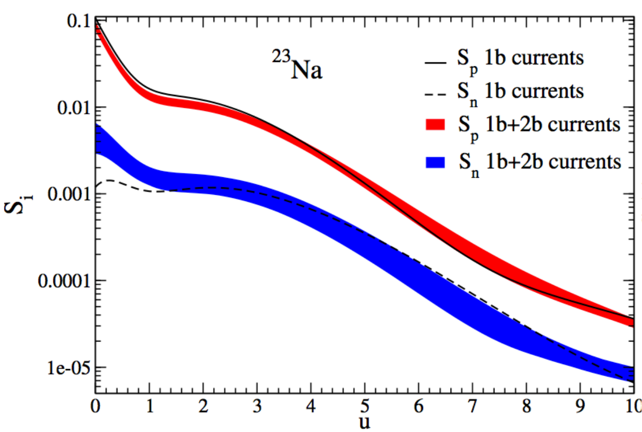
PICASSO, COUPP, SIMPLE



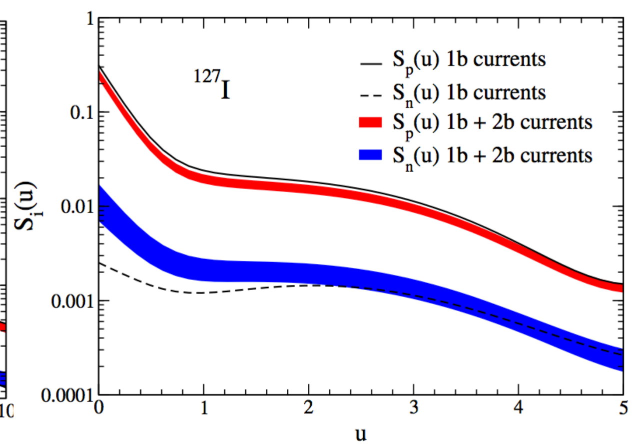
CDMS, EDELWEISS, EURECA



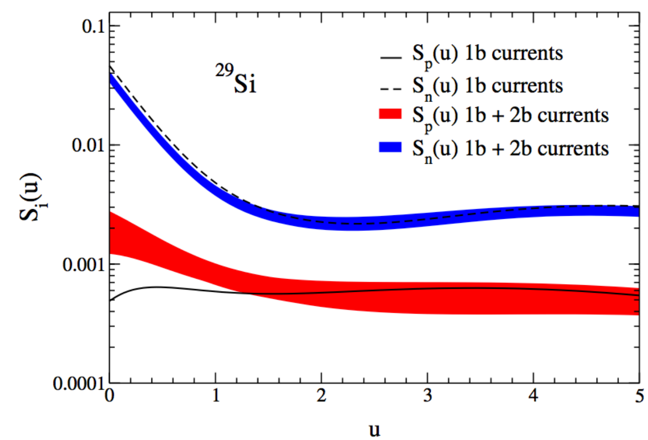
CRESST



DAMA, ANAIS, DM-Ice



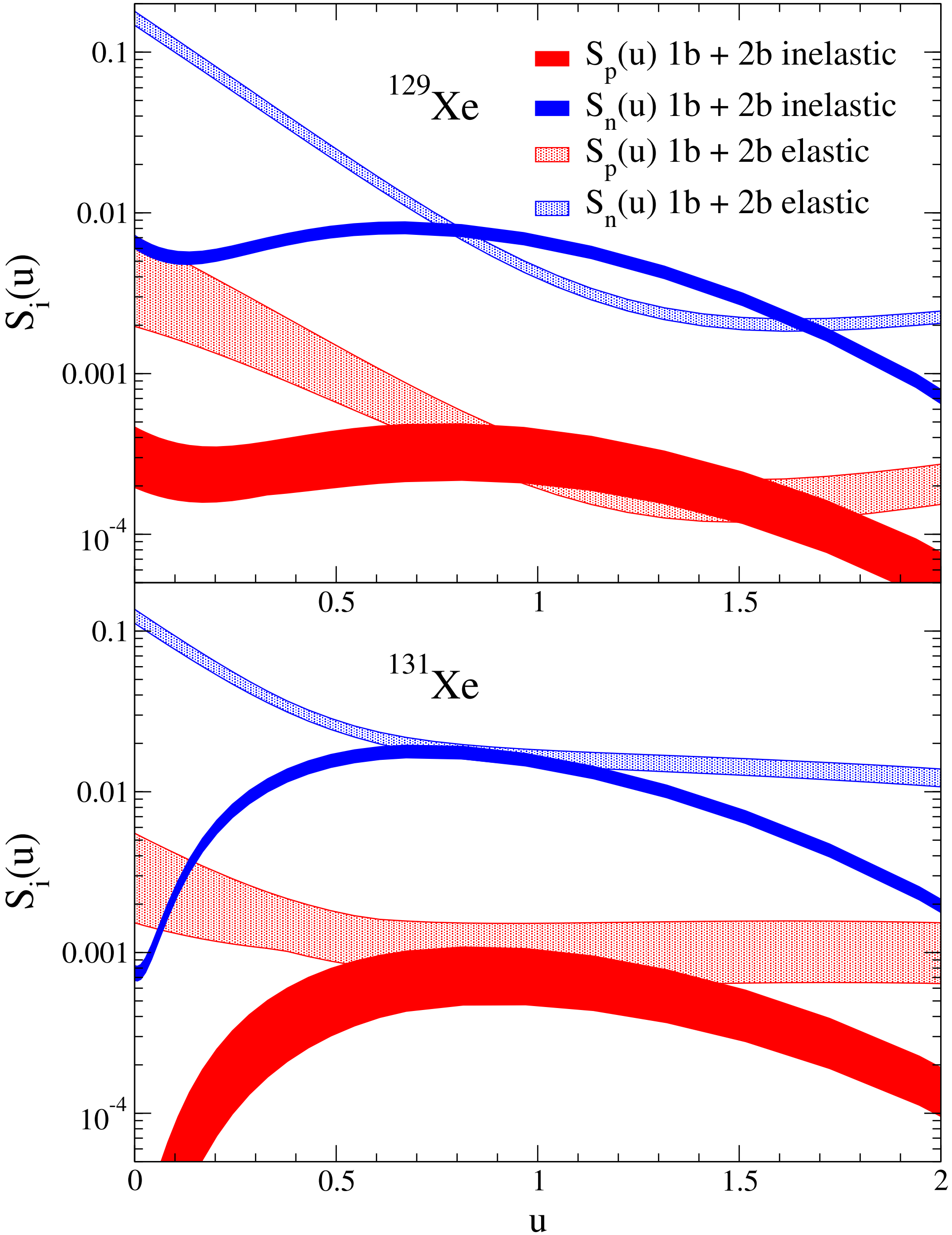
DAMA, ANAIS, DM-Ice, KIMS



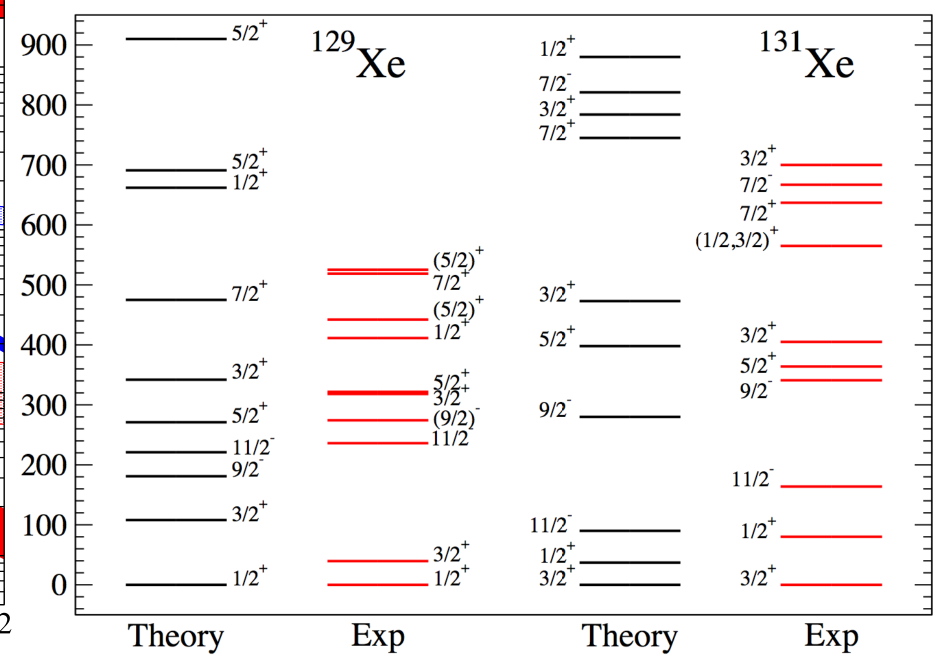
CDMS-II

Inelastic WIMP scattering to 40 and 80 keV excited states

Baudis, Kessler, Klos, Lang, Menéndez, Reichard, AS, PRD (2013)



inelastic channel comparable/ dominates elastic channel for p ~ 150 MeV

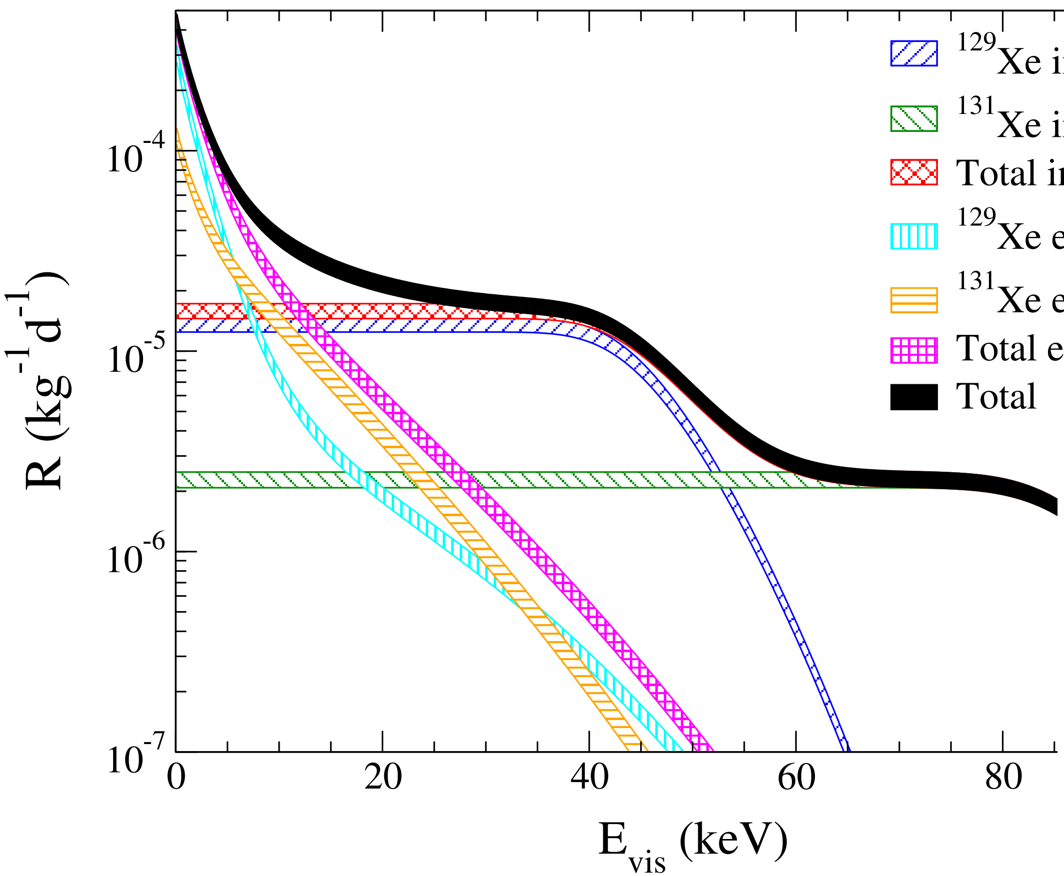


Signatures for **inelastic** WIMP scattering

elastic recoil **+ promt γ from de-excitation**

combined information from elastic and inelastic channel will allow to **determine dominant interaction channel** in one experiment

inelastic excitation sensitive to WIMP mass

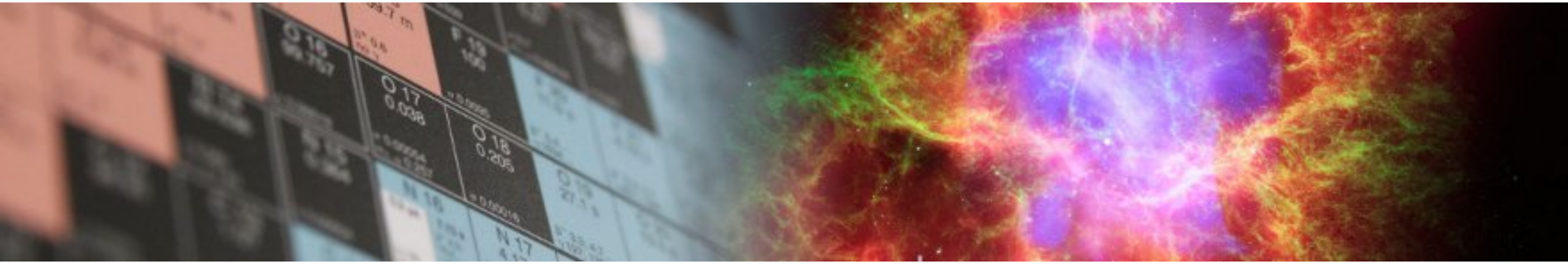


Mass [GeV]	^{129}Xe	^{131}Xe	Total
10	–	–	–
25	5	–	5
50	7	17	9
100	7	24	12
250	9	32	19
500	11	35	24

TABLE II. Minimum energy E_{vis} in keV above which the observed inelastic spectrum for ^{129}Xe, ^{131}Xe and for the total spectrum starts to dominate the elastic one for various WIMP masses.

Main message

Chiral EFT opens up unified description of matter from lab to cosmos



3N force are an exciting frontier for nuclear physics and astrophysics

Nuclear forces and their impact on neutron-rich nuclei

S.K. Bogner, **H. Hergert, J.D. Holt, J. Menéndez**, T. Otsuka, **J. Simonis**, T. Suzuki

on neutron-rich matter and neutron stars

C. Drischler, K. Hebeler, T. Krüger, J.M. Lattimer, C.J. Pethick, **V. Somá, I. Tews**

future: consistent electroweak interactions from chiral EFT

lattice QCD to connect chiral EFT to QCD