Nuclear forces, neutron-rich nuclei and matter

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EMMI

45 years of nuclear theory at Stony Brook –
A tribute to Gerry Brown

DFG

erc

HELMHOLTZ ASSOCIATION

Minerva Stiftung
ARCHES
Award for Research Cooperation and High Excellence in Science

Bundesministerium für Bildung und Forschung

in memory of Gerry

Outline

Three-nucleon (3N) forces

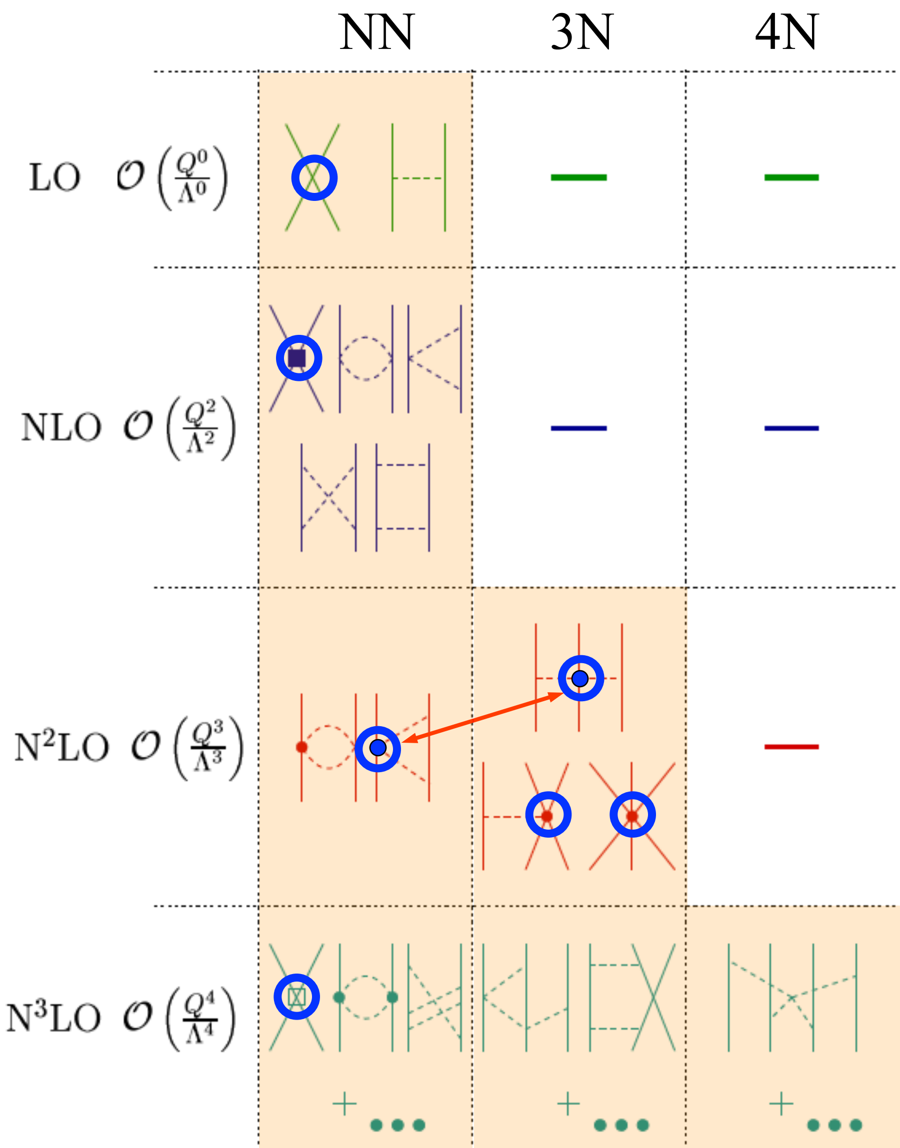
3N forces and neutron-rich nuclei

3N forces and neutron matter/stars

Dark matter response of nuclei

Chiral effective field theory for nuclear forces see talk by Ulf Meissner

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

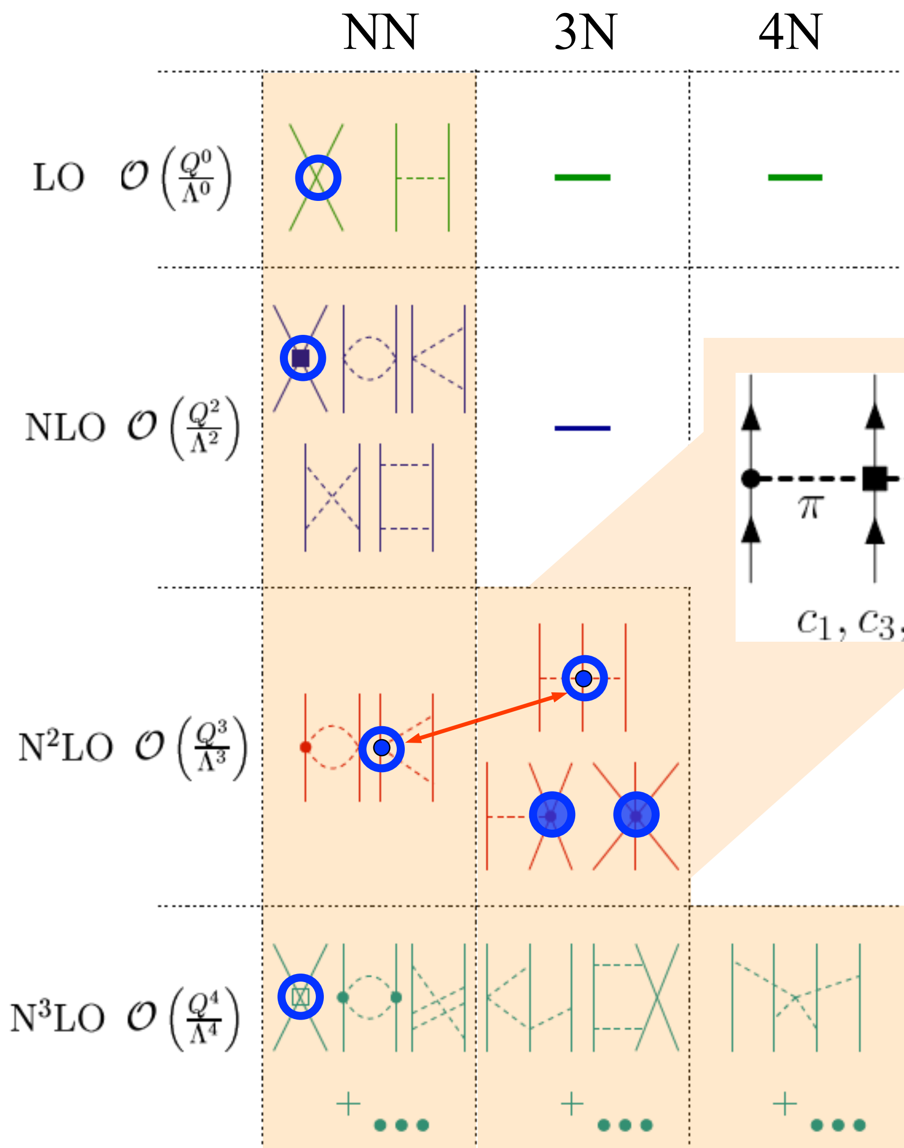
systematic: can work to desired
accuracy and obtain **error estimates**

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

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

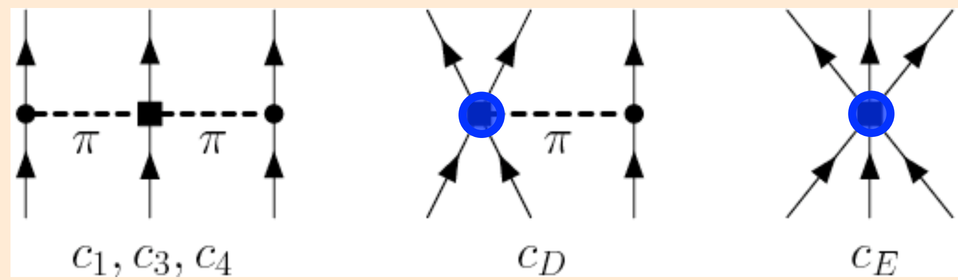
Chiral effective field theory and **many-body forces**

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



consistent NN-3N-4N interactions

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



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

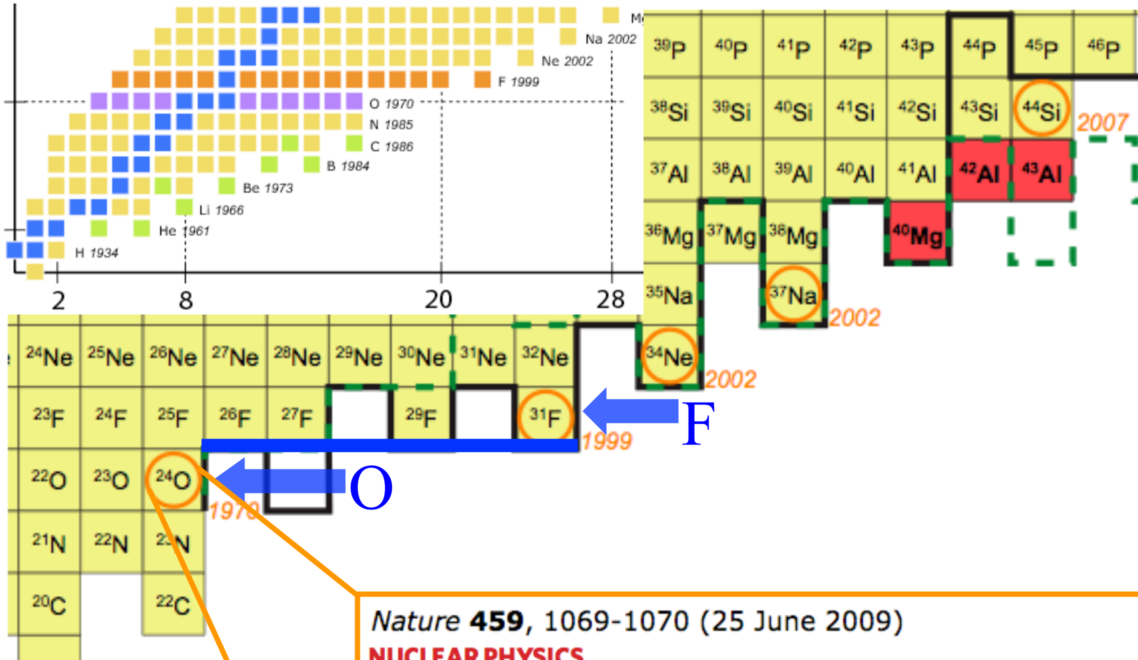
$$c_1 = -0.9^{+0.2}_{-0.5}\,,\; c_3 = -4.7^{+1.2}_{-1.0}\,,\; c_4 = 3.5^{+0.5}_{-0.2}$$

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, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

The oxygen anomaly



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

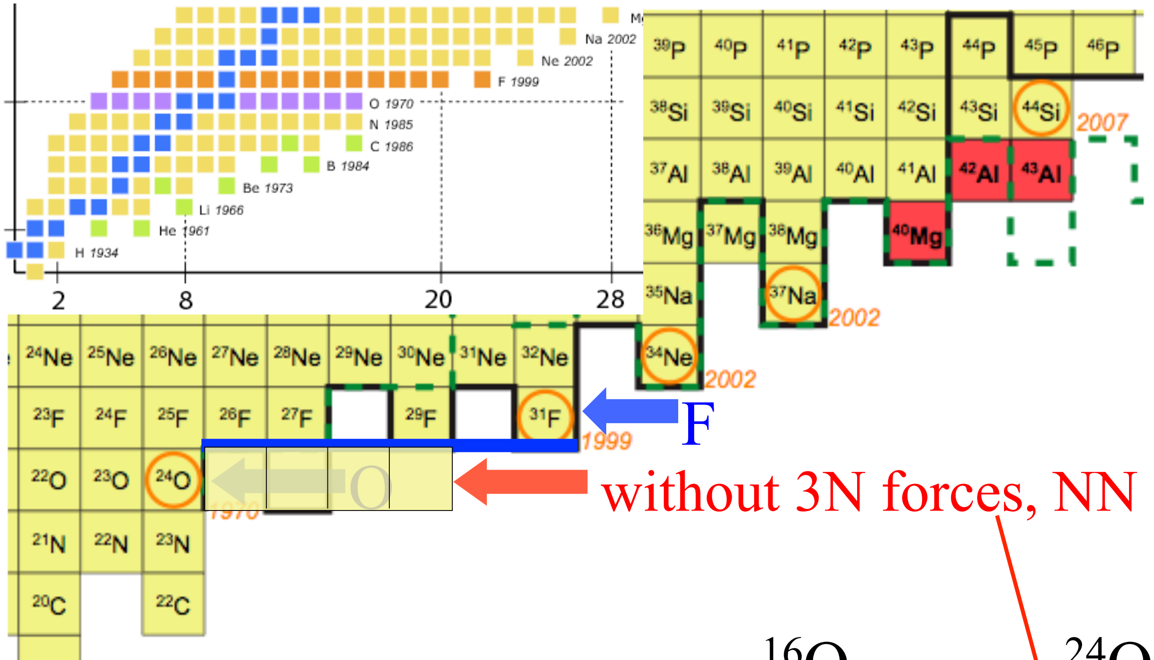
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

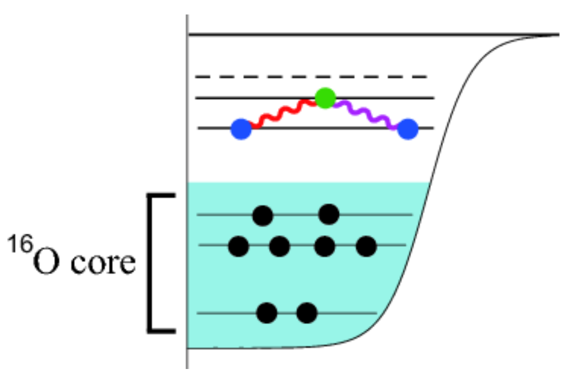
Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

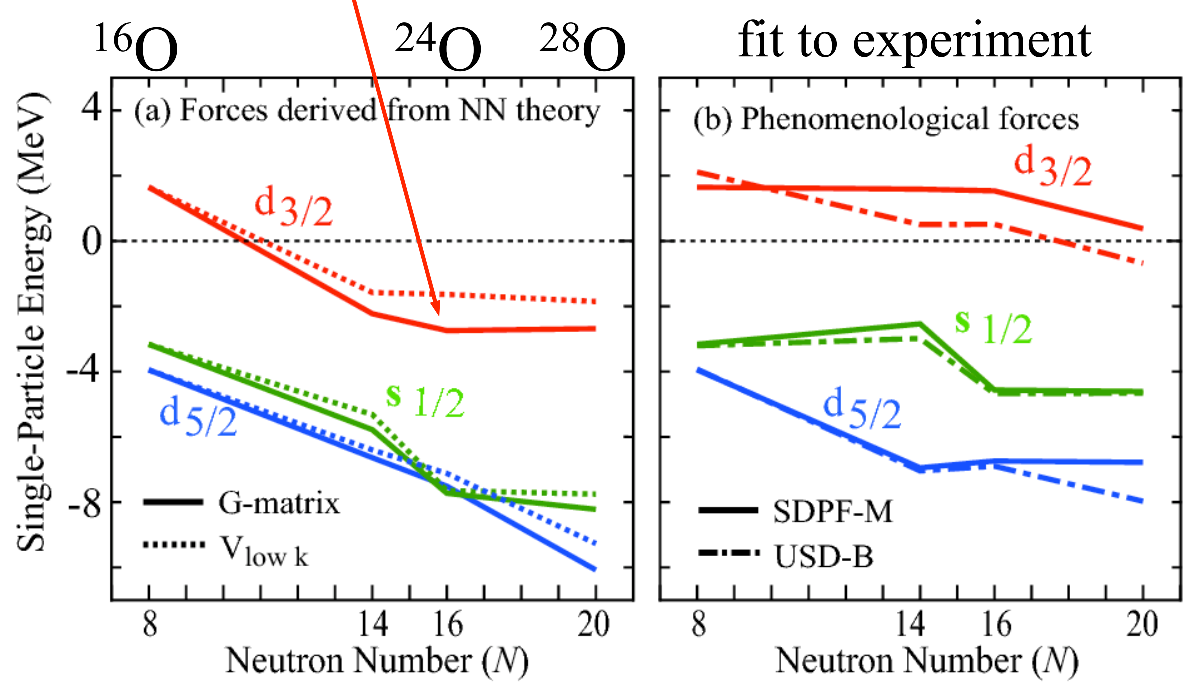
The oxygen anomaly - not reproduced without 3N forces



without 3N forces, NN interactions too attractive

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

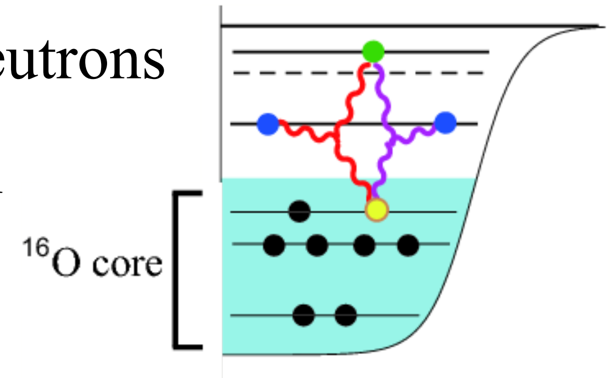




The shell model - impact of 3N forces

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 (2011)

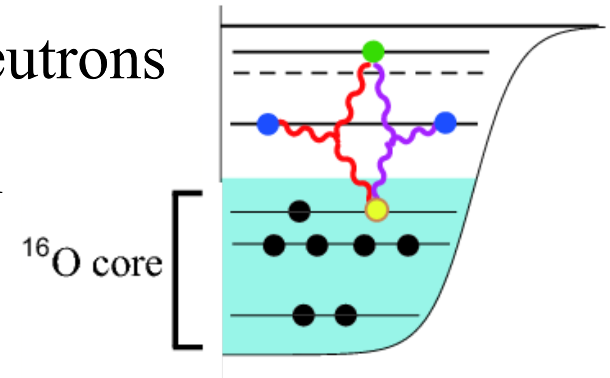
Oxygen isotopes - impact of 3N forces

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

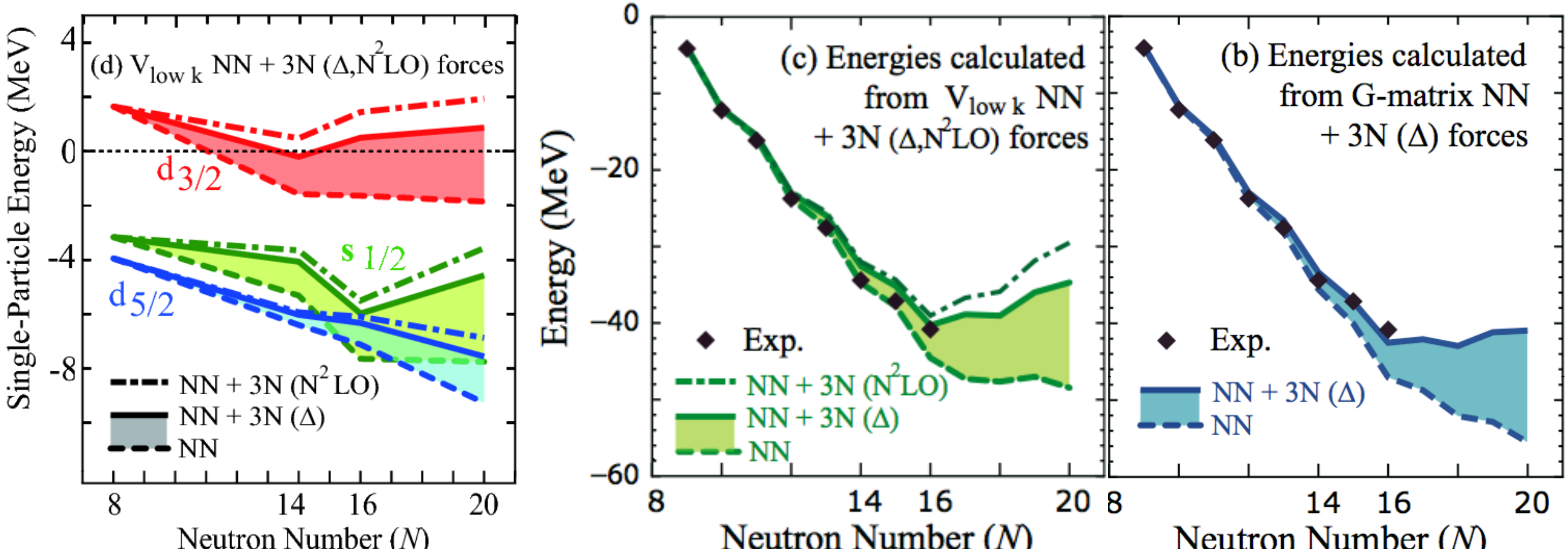
leads to repulsive interactions between valence neutrons

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

Friman, AS (2011)



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

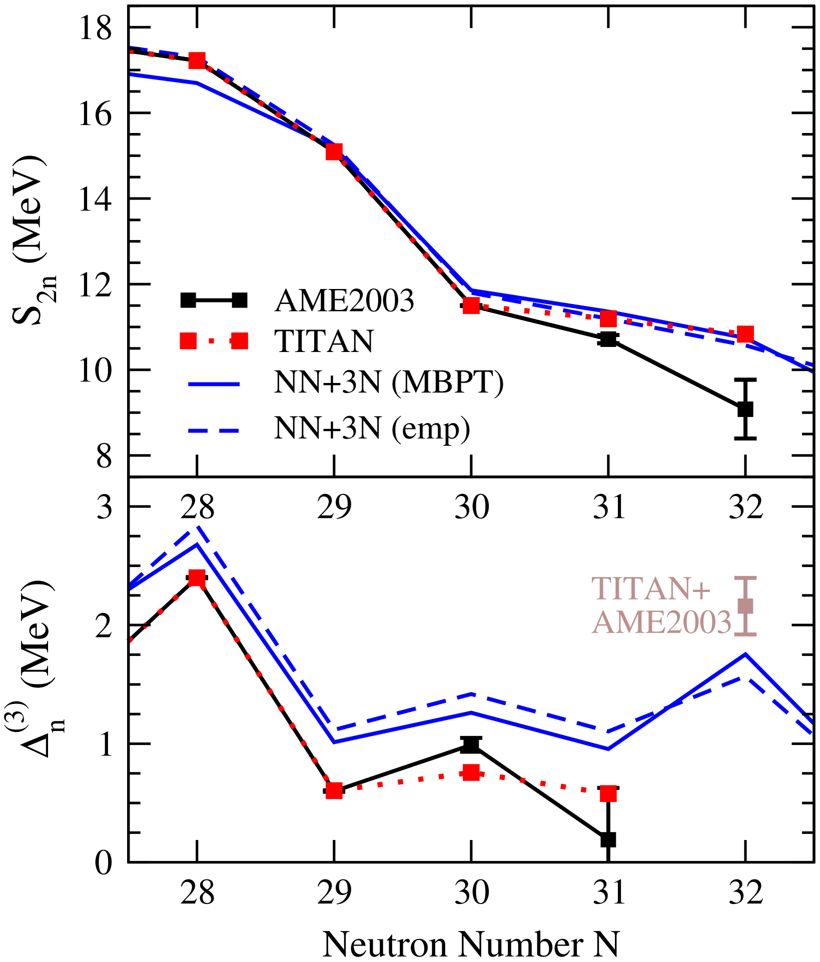


first explanation of the oxygen anomaly Otsuka, Suzuki, Holt, AS, Akaishi, PRL (2010)

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

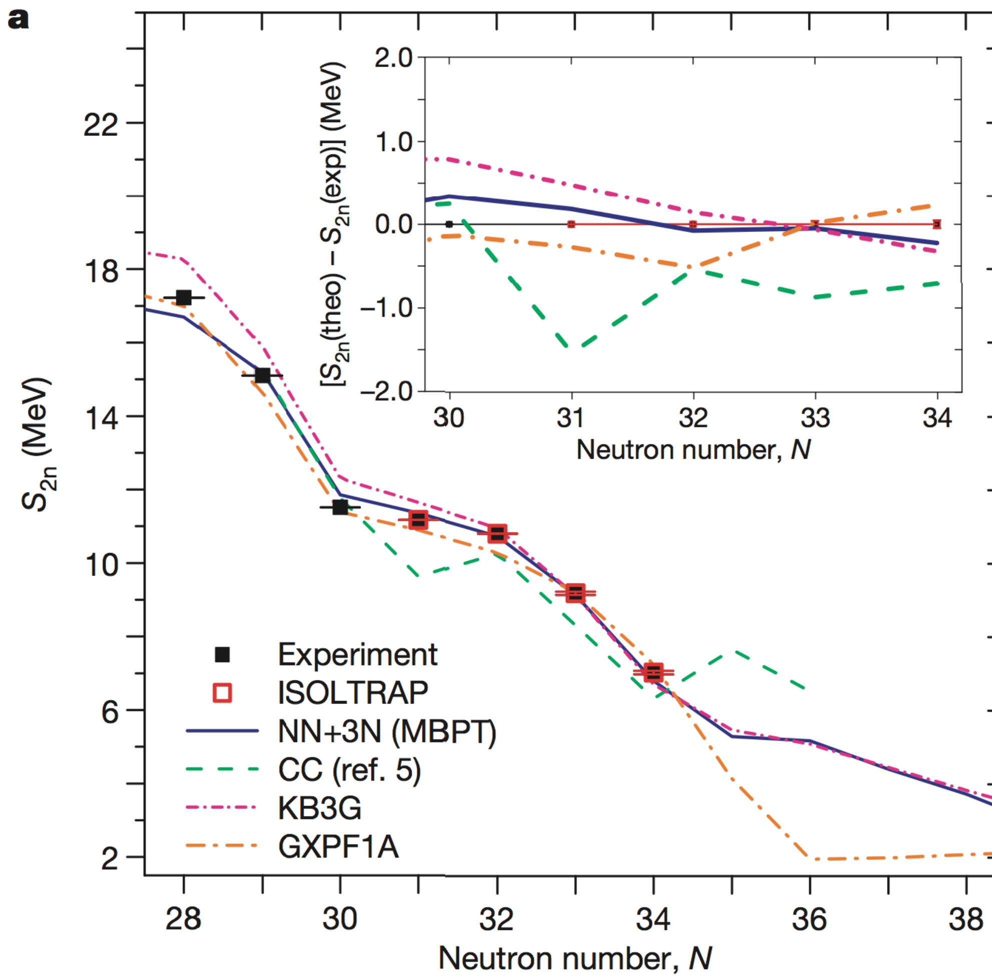
Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

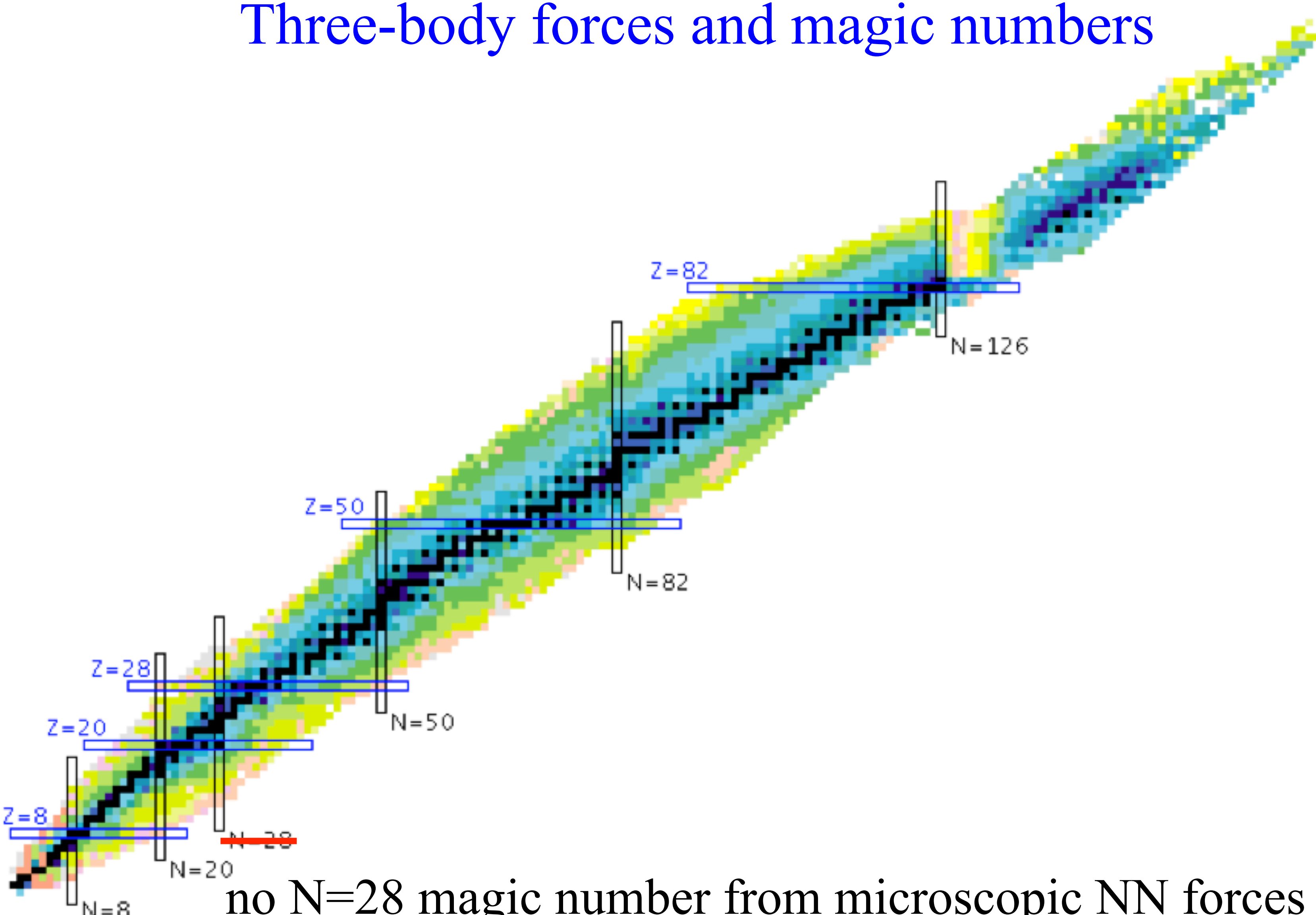
^{53,54}Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

establish prominent N=32 shell closure in calcium

excellent agreement with theoretical NN+3N prediction



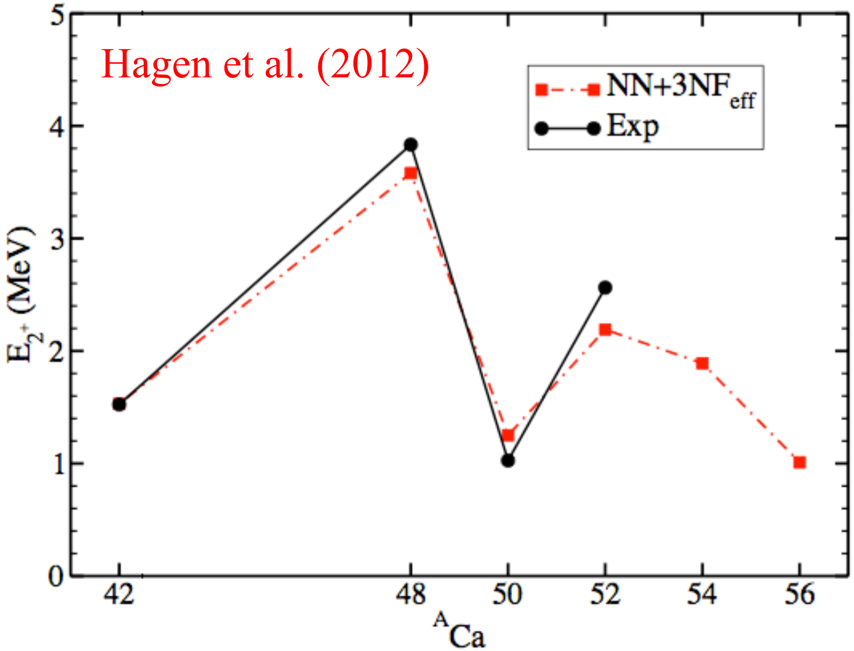
Three-body forces and magic numbers

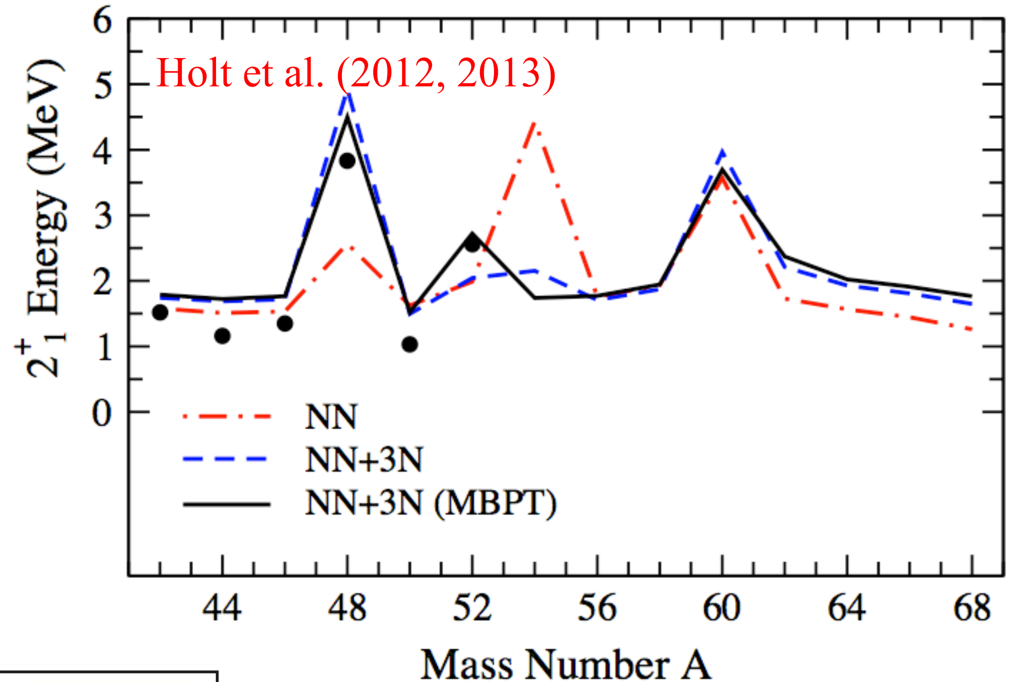


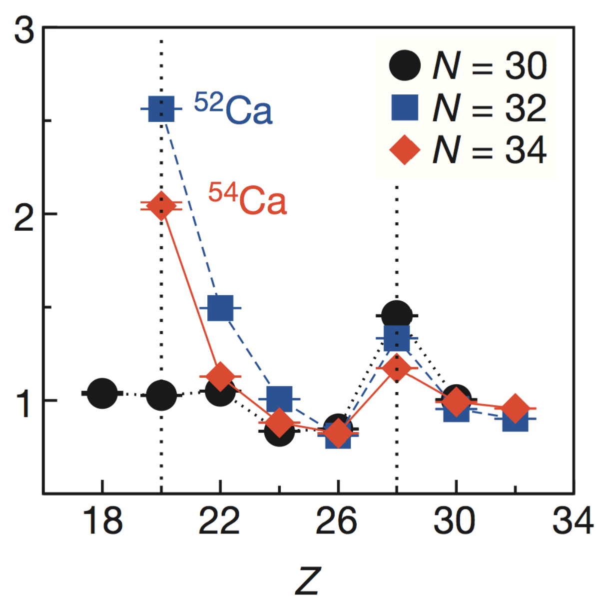
no N=28 magic number from microscopic NN forces

Zuker, Poves,…

Three-body forces and magic numbers



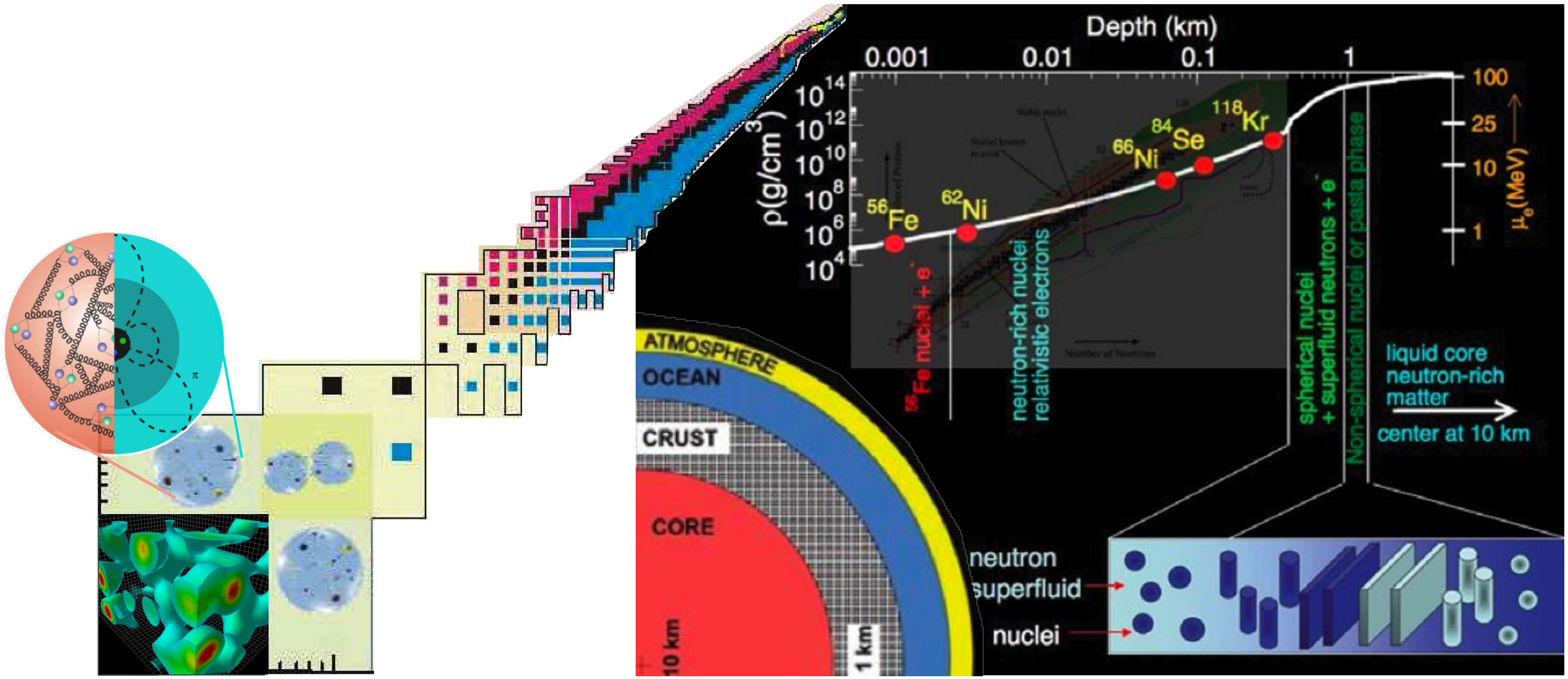




2^+ energy measured at RIBF suggests magic number N=34

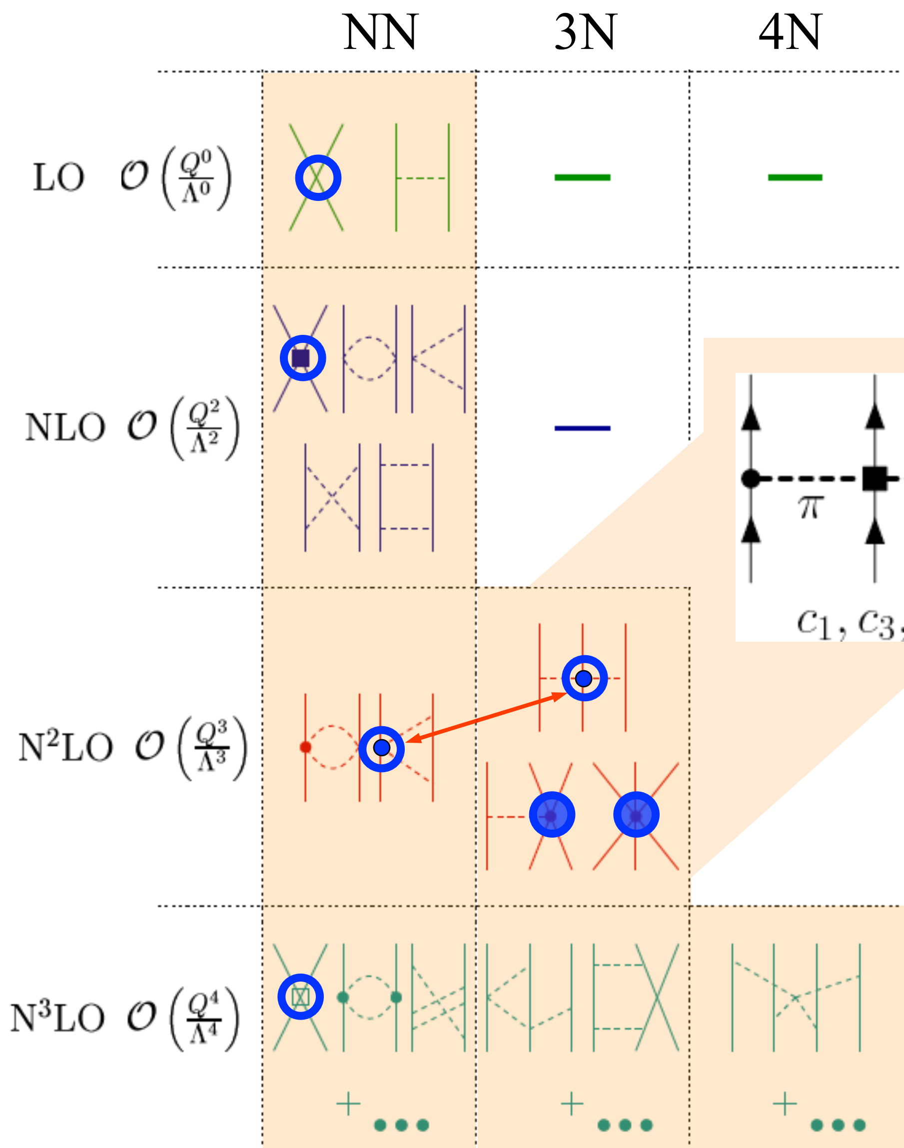
Steppenbeck et al., Nature (2013)

Neutron matter and neutron stars



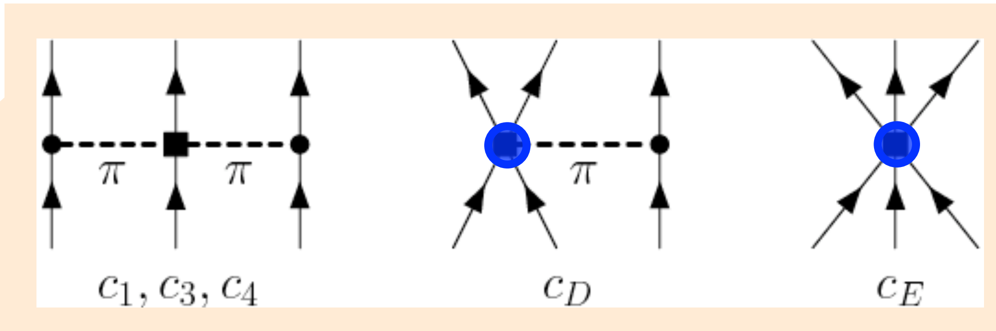
Chiral effective field theory for nuclear forces

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



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

Hebeler, AS (2010)



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

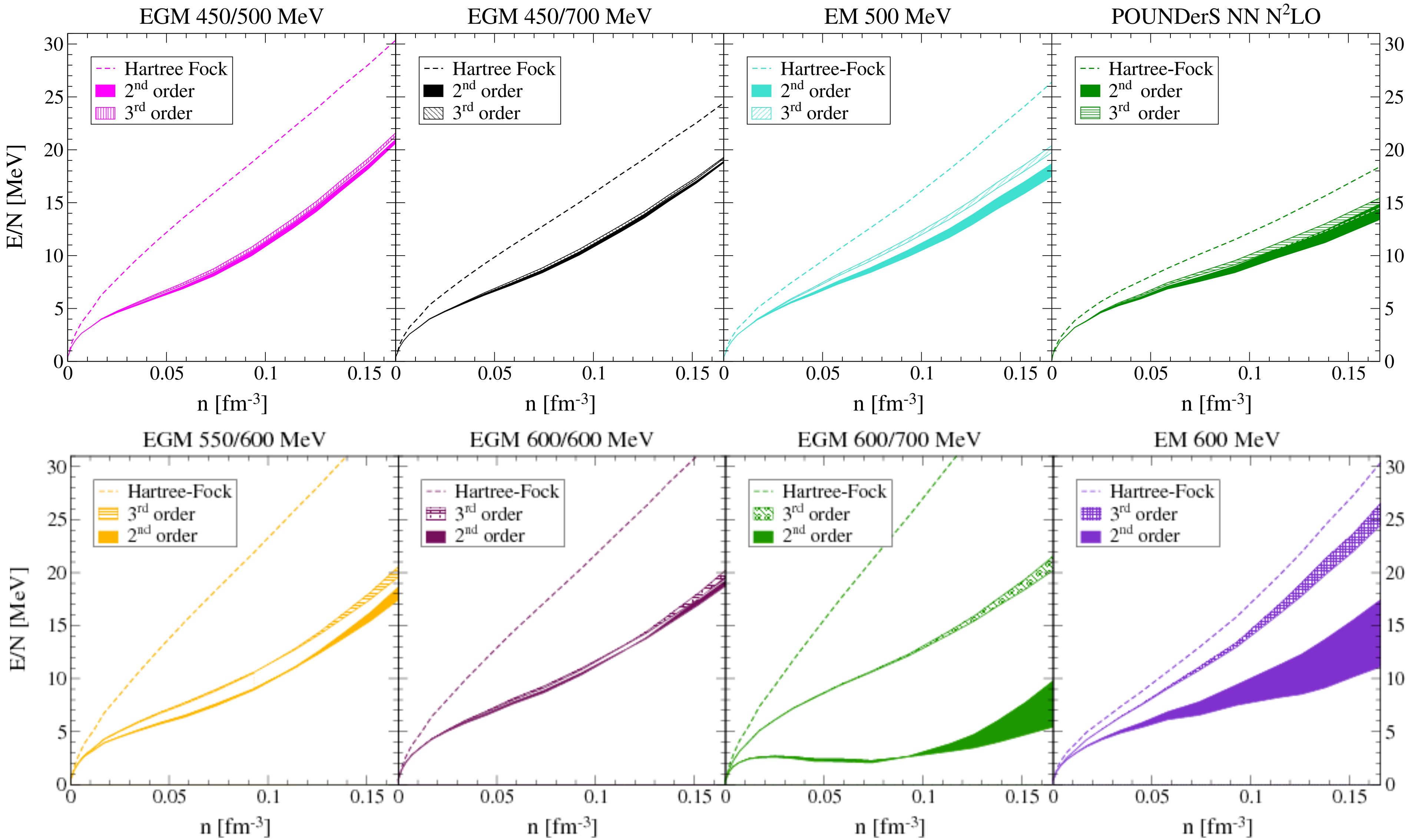
study 3N and 4N in neutron matter

Tews, Krüger, Hebeler, AS, PRL (2013)

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

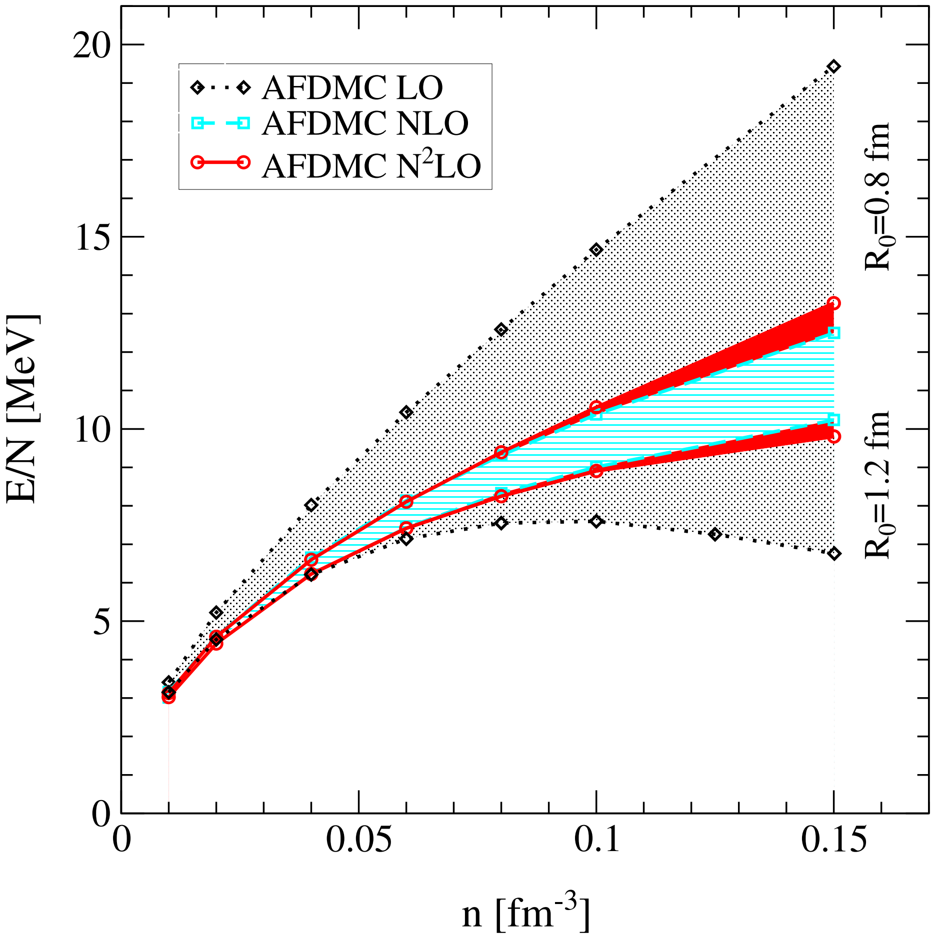
Neutron matter from chiral EFT interactions

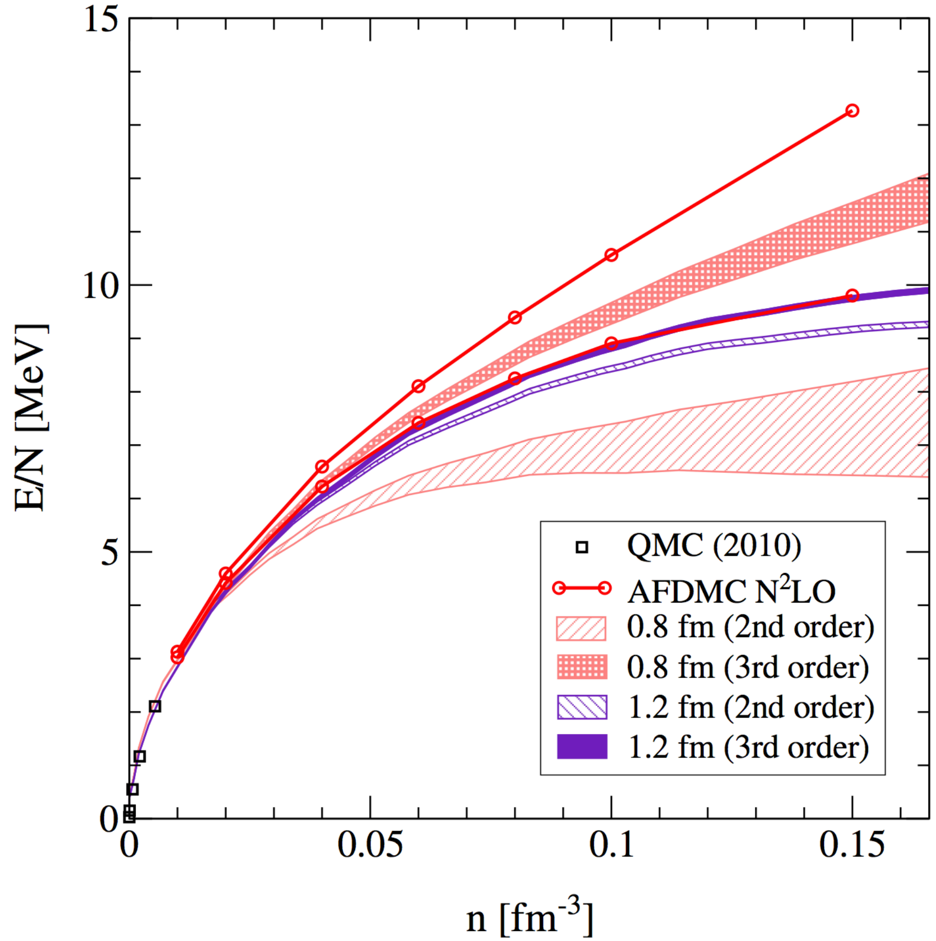
perturbative calculations, well converged for lower cutoffs



AFDMC results for neutron matter Gezerlis, Tews, et al., PRL (2013)

based on local chiral EFT potentials,
order-by-order convergence up to saturation density



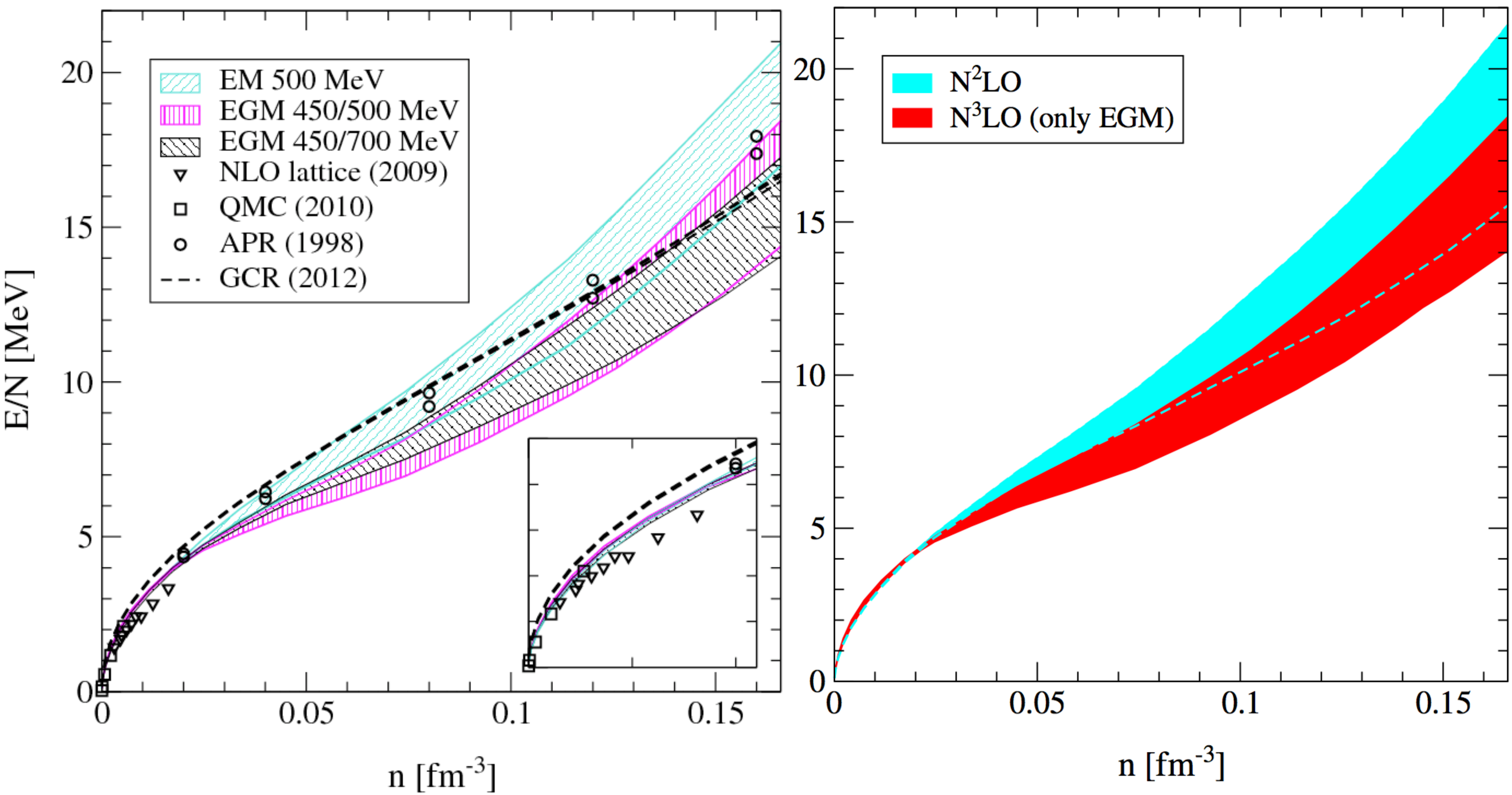


excellent agreement with perturbative calcs for low cutoffs (~400 MeV)

Complete N^{3}LO calculation of neutron matter

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

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



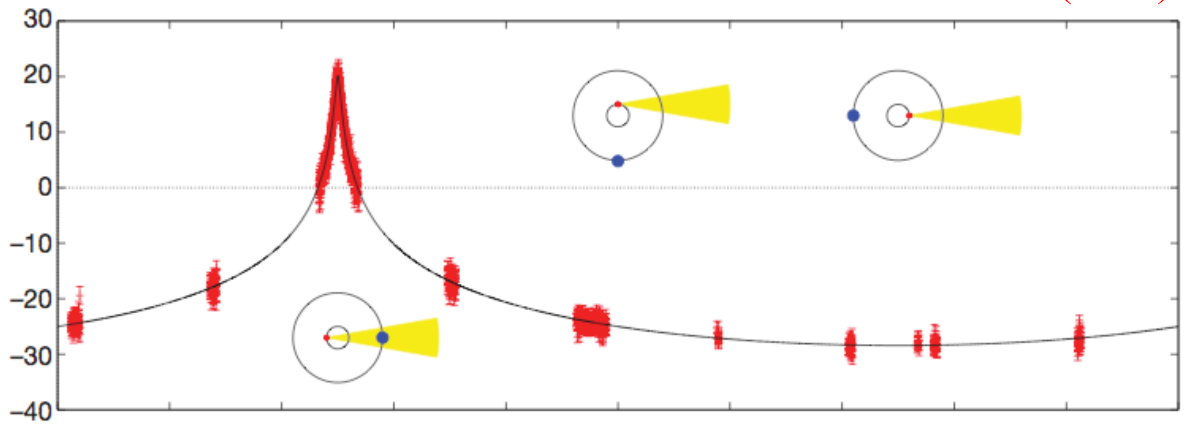
Discovery of the heaviest neutron star

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

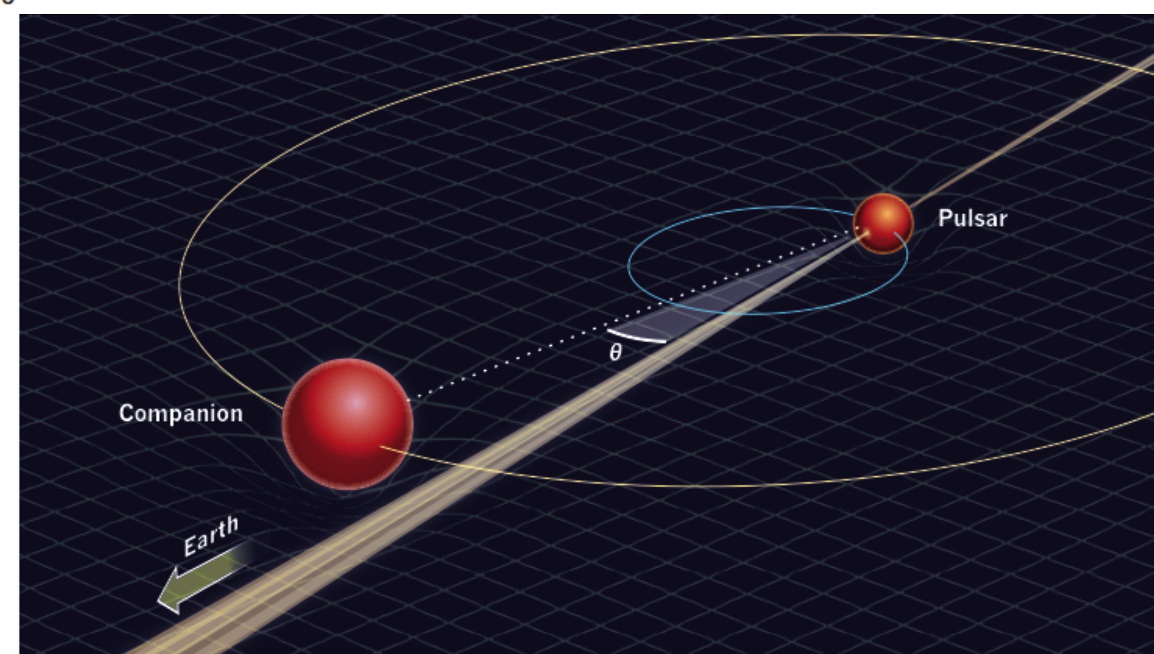
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

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}

Discovery of the heaviest neutron star (2013)

RESEARCH ARTICLE SUMMARY

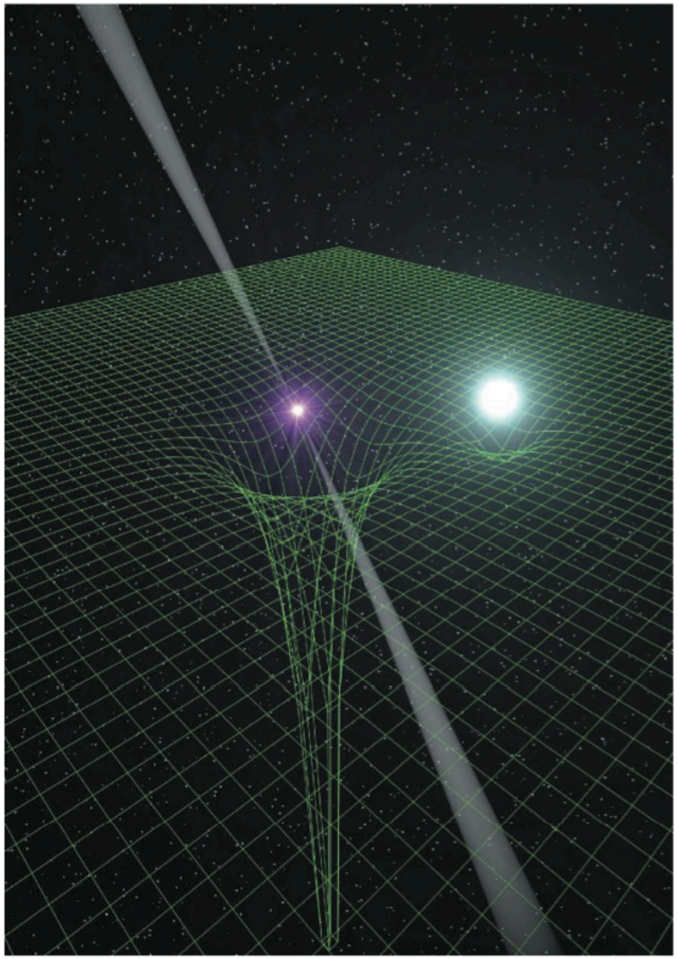
A Massive Pulsar in a Compact Relativistic Binary

John Antoniadis,* Paulo C. C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, Marten H. van Kerkwijk, Michael Kramer, Cees Bassa, Vik S. Dhillon, Thomas Driebe, Jason W. T. Hessels, Victoria M. Kaspi, Vladislav I. Kondratiev, Norbert Langer, Thomas R. Marsh, Maura A. McLaughlin, Timothy T. Pennucci, Scott M. Ransom, Ingrid H. Stairs, Joeri van Leeuwen, Joris P. W. Verbiest, David G. Whelan

Introduction: Neutron stars with masses above 1.8 solar masses ($M_\odot$), possess extreme gravitational fields, which may give rise to phenomena outside general relativity. Hitherto, these strong-field deviations have not been probed by experiment, because they become observable only in tight binaries containing a high-mass pulsar and where orbital decay resulting from emission of gravitational waves can be tested. Understanding the origin of such a system would also help to answer fundamental questions of close-binary evolution.

Methods: We report on radio-timing observations of the pulsar J0348+0432 and phase-resolved optical spectroscopy of its white-dwarf companion, which is in a 2.46-hour orbit. We used these to derive the component masses and orbital parameters, infer the system's motion, and constrain its age.

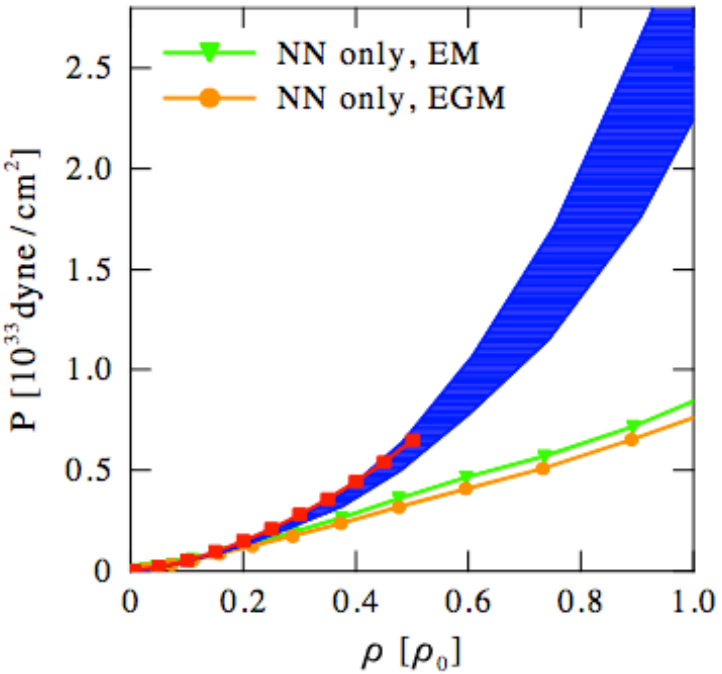
Results: We find that the white dwarf has a mass of $0.172 \pm 0.003\ M_\odot$, which, combined with orbital velocity measurements, yields a pulsar mass of $2.01 \pm 0.04\ M_\odot$. Additionally, over a span of 2 years, we observed a significant decrease in the orbital period, $\dot{P}_b^{obs} = -8.6 \pm 1.4\ \mu s\ year^{-1}$ in our radio-timing data.

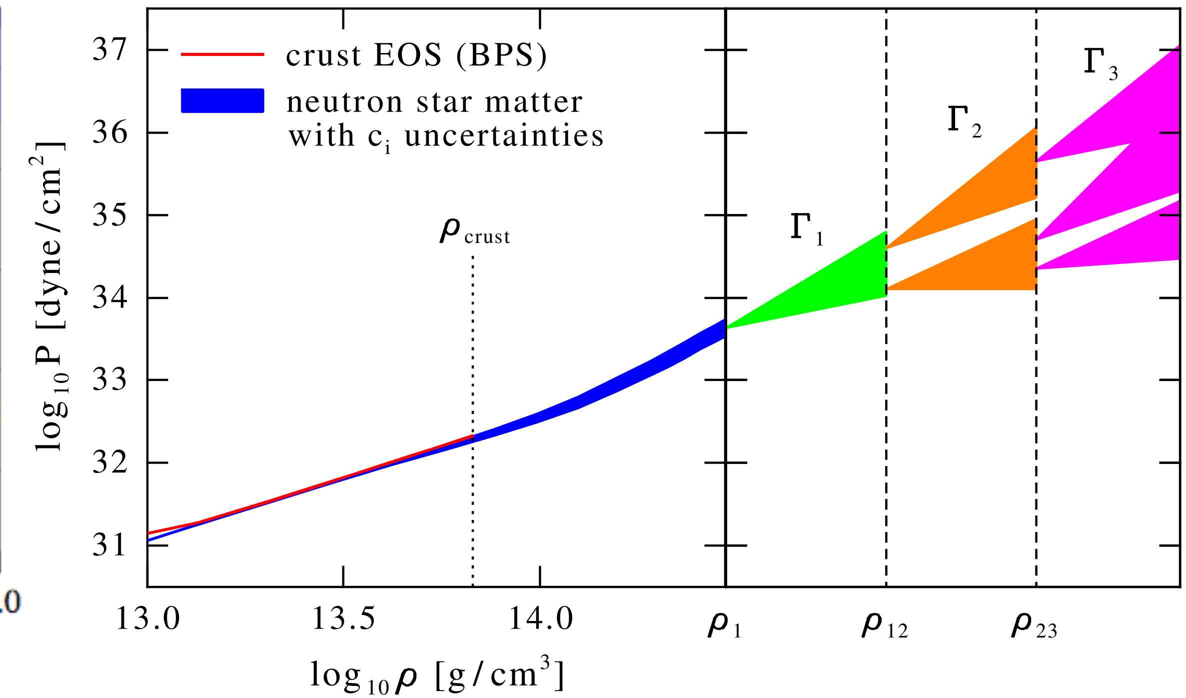


Artist's impression of the PSR J0348+0432 system. The compact pulsar (with beams of radio emission) produces a strong distortion of spacetime (illustrated by the green mesh). Conversely, spacetime around its white dwarf companion (in light blue) is substantially less curved. According to relativistic theories of gravity, the binary system is subject to energy loss by gravitational waves.

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

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



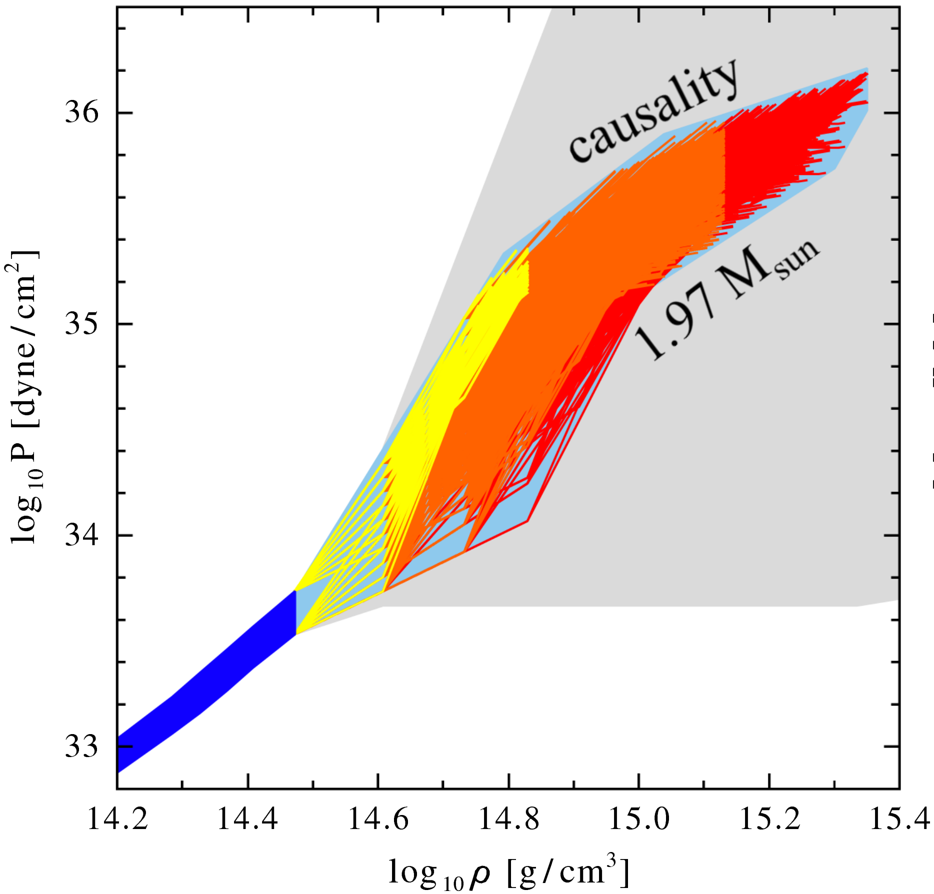


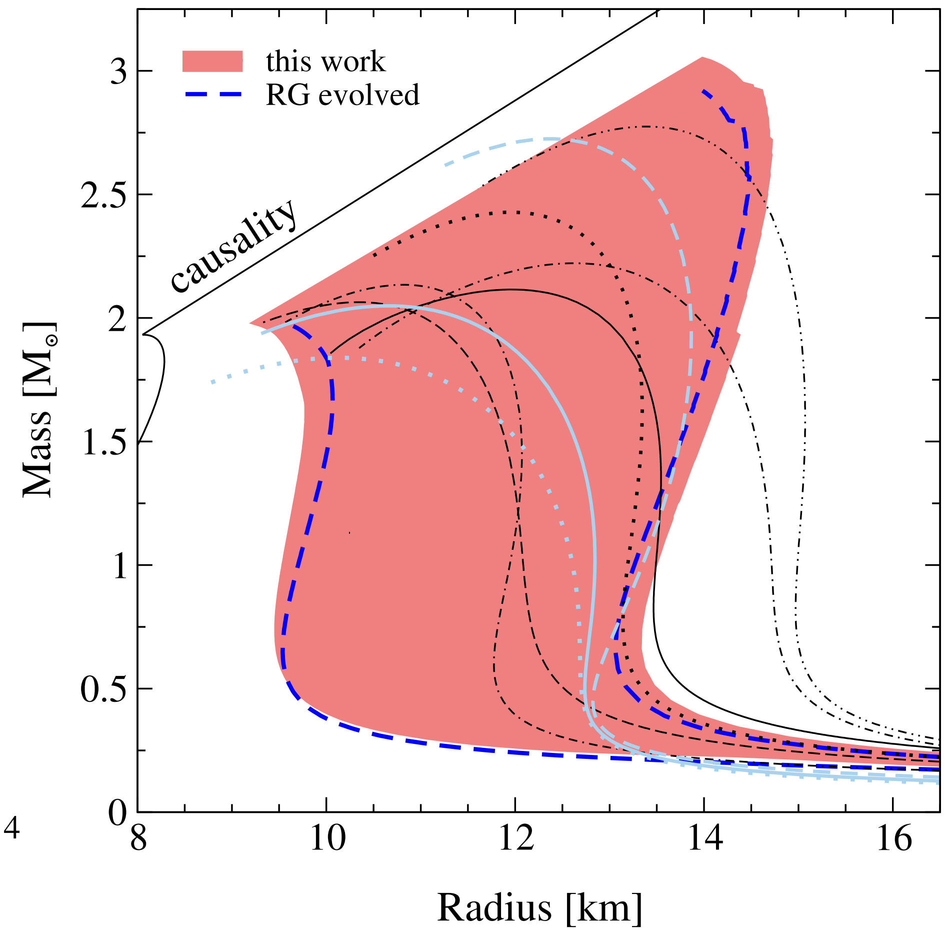
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

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

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





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

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

Direct dark matter detection

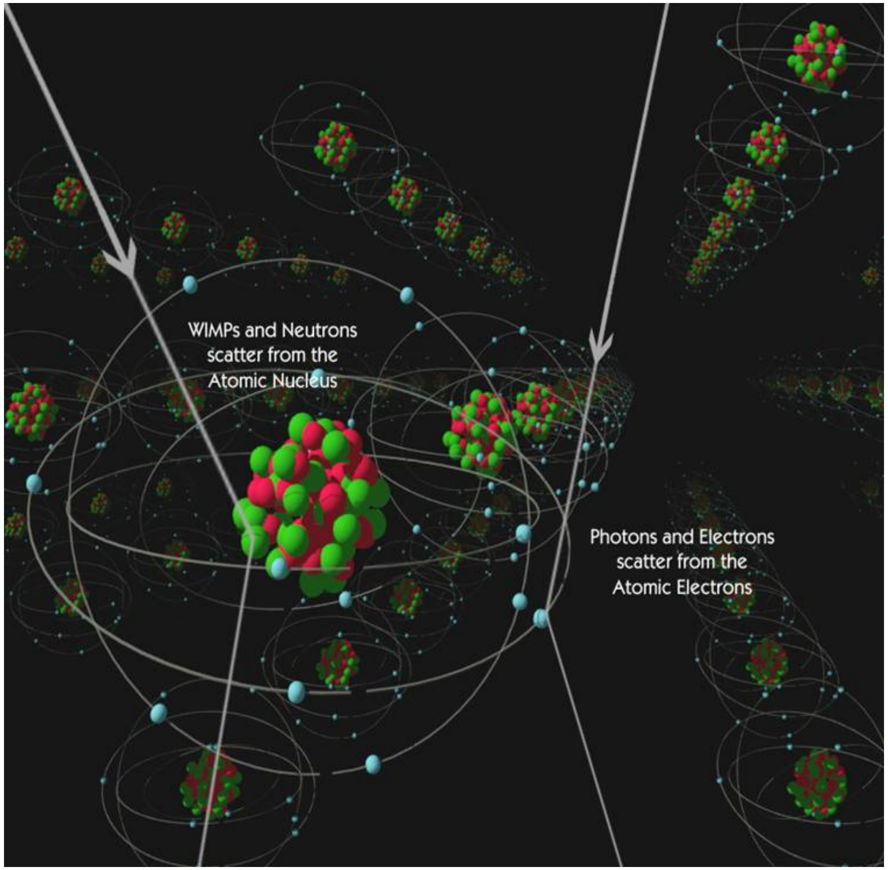
WIMP scattering off nuclei needs **nuclear structure factors** as input

particularly sensitive to nuclear physics for **spin-dependent** couplings

relevant momentum transfers ~ m_π

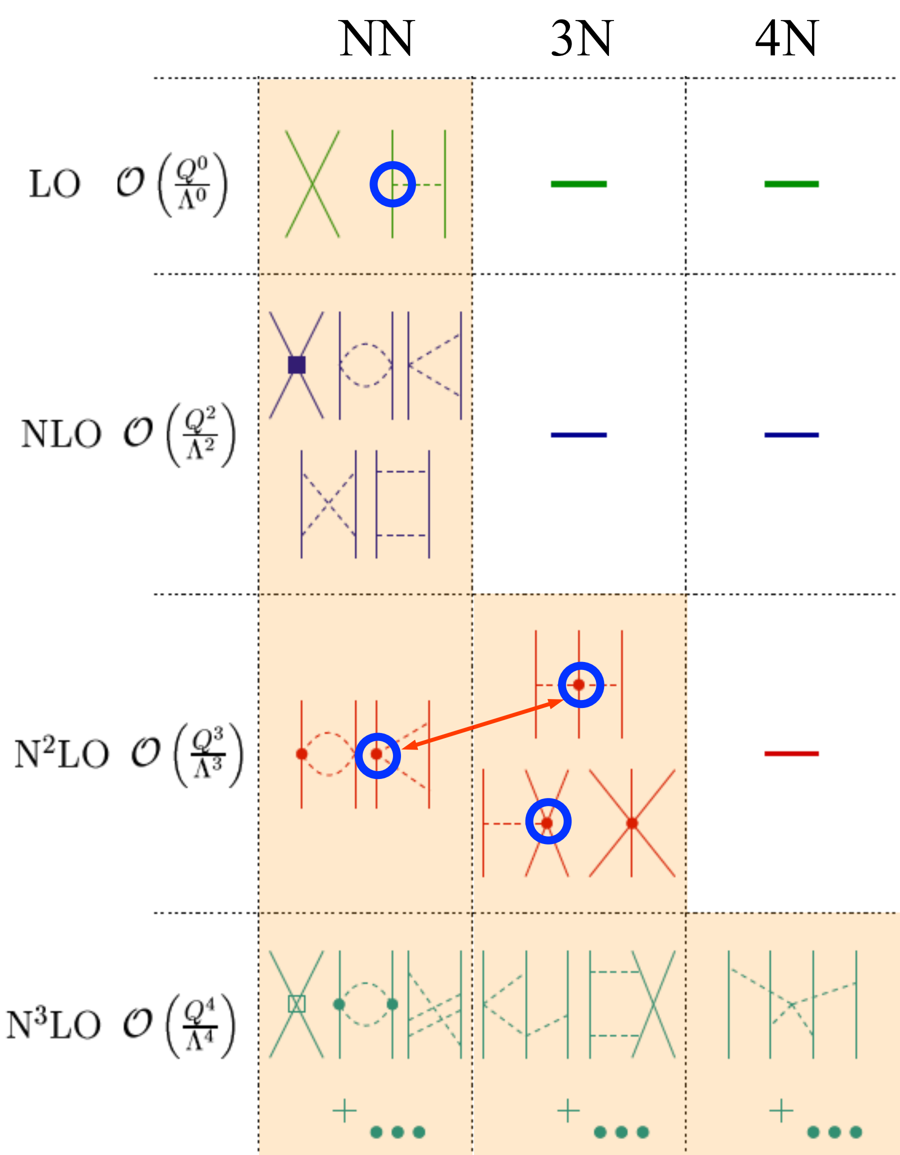
calculate systematically with chiral EFT

Menendez, Gazit, AS (2012),
Klos, Menendez, Gazit, AS (2013)

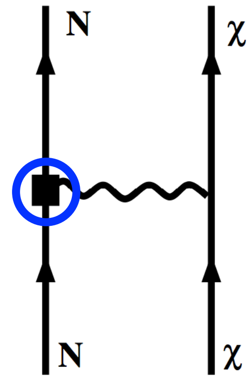


from CDMS collaboration

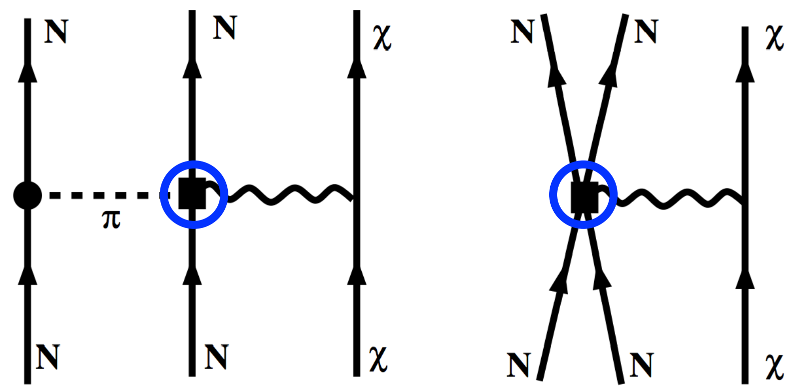
Chiral EFT for WIMP currents in nuclei



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

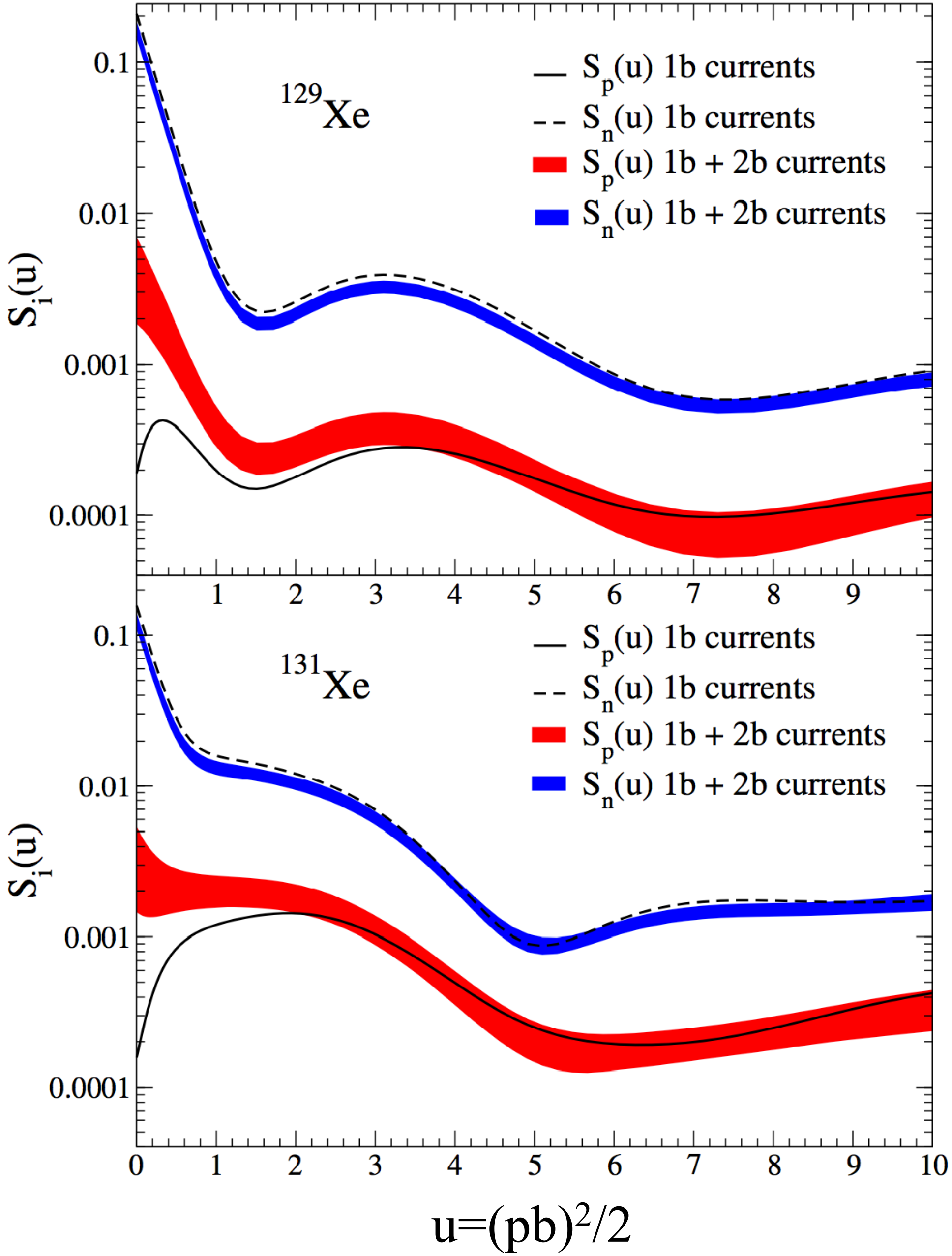


+ two-body currents at Q^3

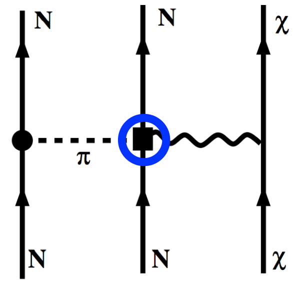


same couplings in forces and currents!

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

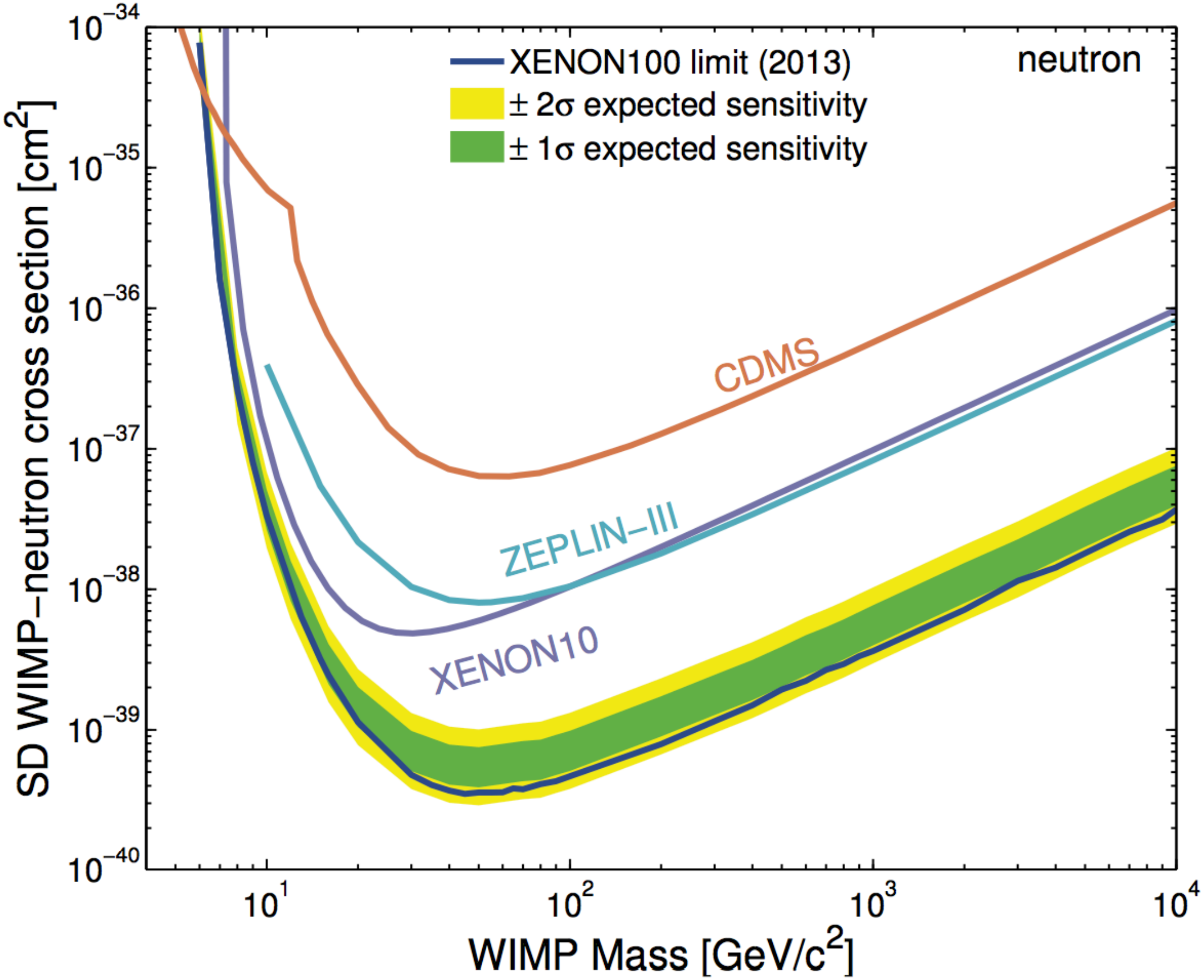
enhances coupling to even species in all cases (protons for Xe)

first calculations with chiral EFT currents and state-of-the-art nuclear interactions

Limits on SD WIMP-neutron interactions

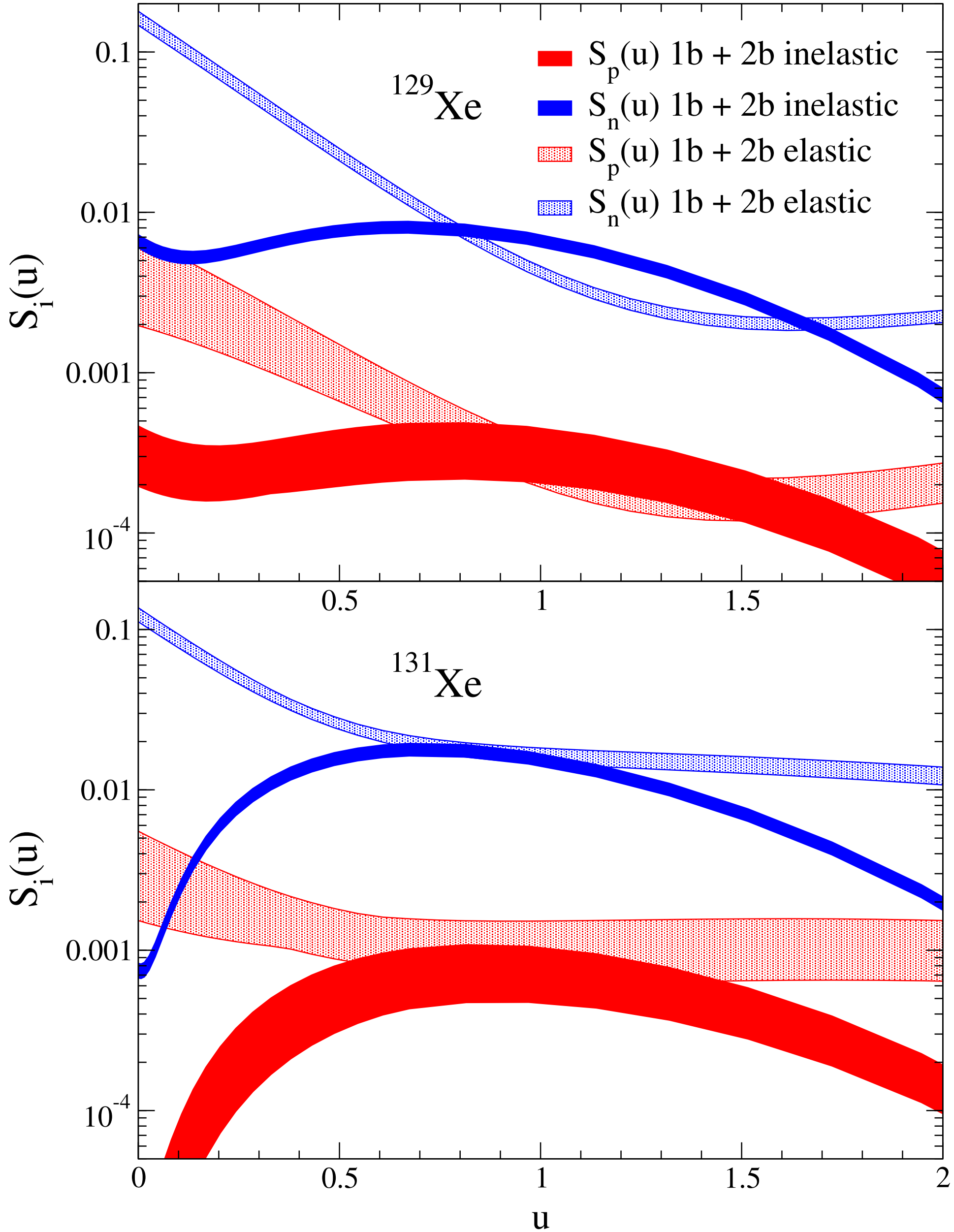
best limits from XENON100 Aprile et al., PRL (2013)

used our calculations with uncertainty bands for WIMP currents in nuclei

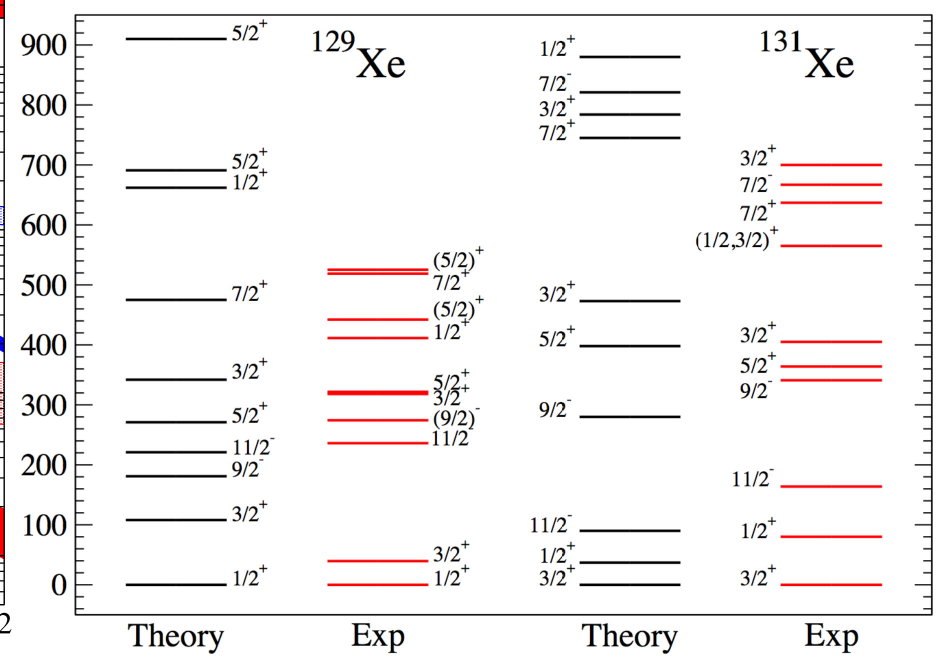


Inelastic WIMP scattering to 40 and 80 keV excited states

Baudis, Kessler, Klos, Lang, Menendez, Reichard, AS, PRD in press, arXiv:1309.0825



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

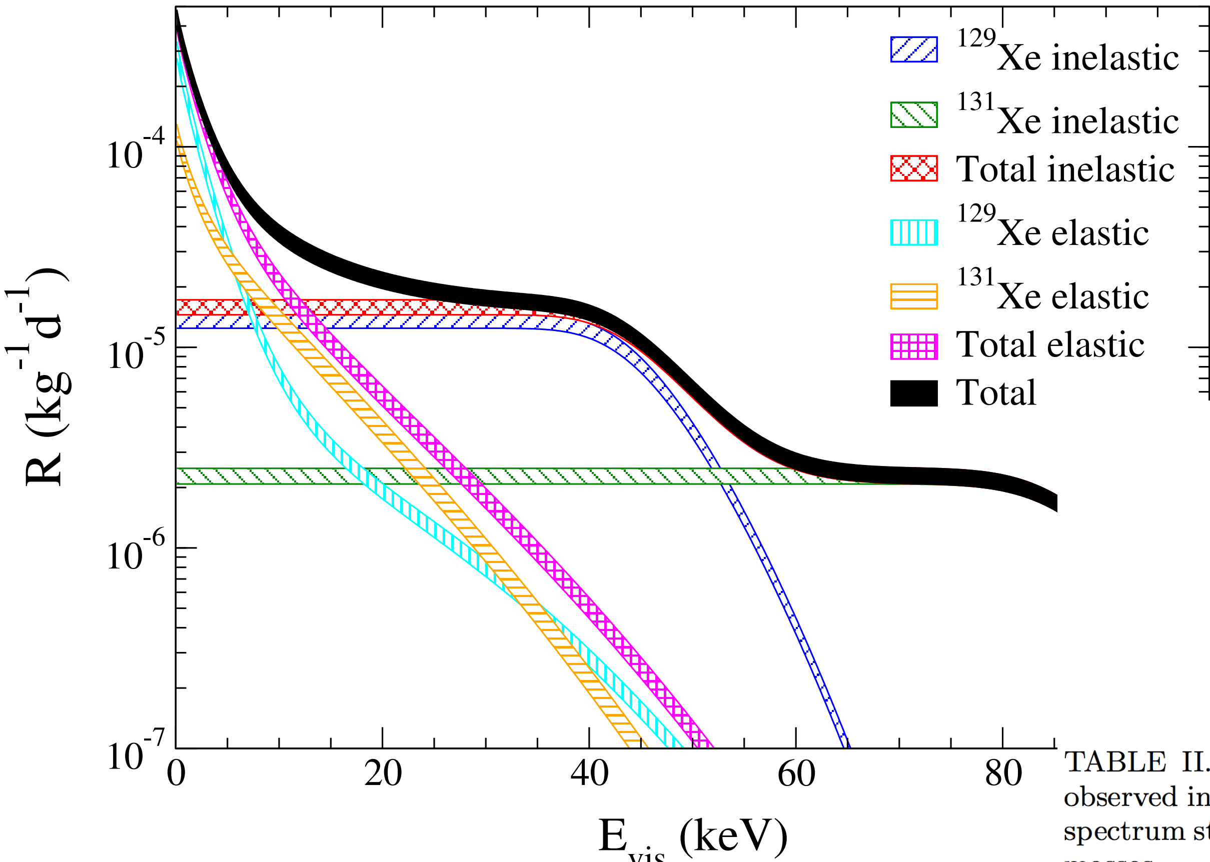


Signatures for **inelastic** WIMP scattering

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 $E_{\rm vis}$ 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.

Summary

3N forces are a frontier

key for neutron-rich nuclei

J.D. Holt, J. Menéndez, T. Otsuka, J. Simonis, T. Suzuki

and neutron-rich matter/stars

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

dark matter response of nuclei and two-body currents

J. Menéndez, P. Klos, D. Gazit

I owe a lot to Gerry and
would not be in physics without him!