From neutron-rich nuclei to matter in astrophysics

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

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Bundesministerium für Bildung und Forschung

Main message

3N forces and neutron-rich nuclei

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

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]

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

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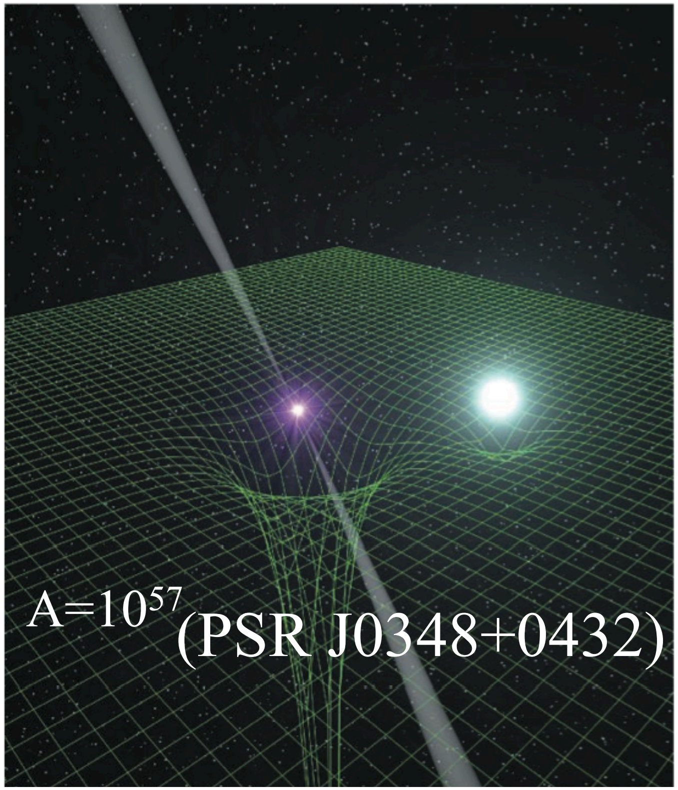
3N forces and neutron stars

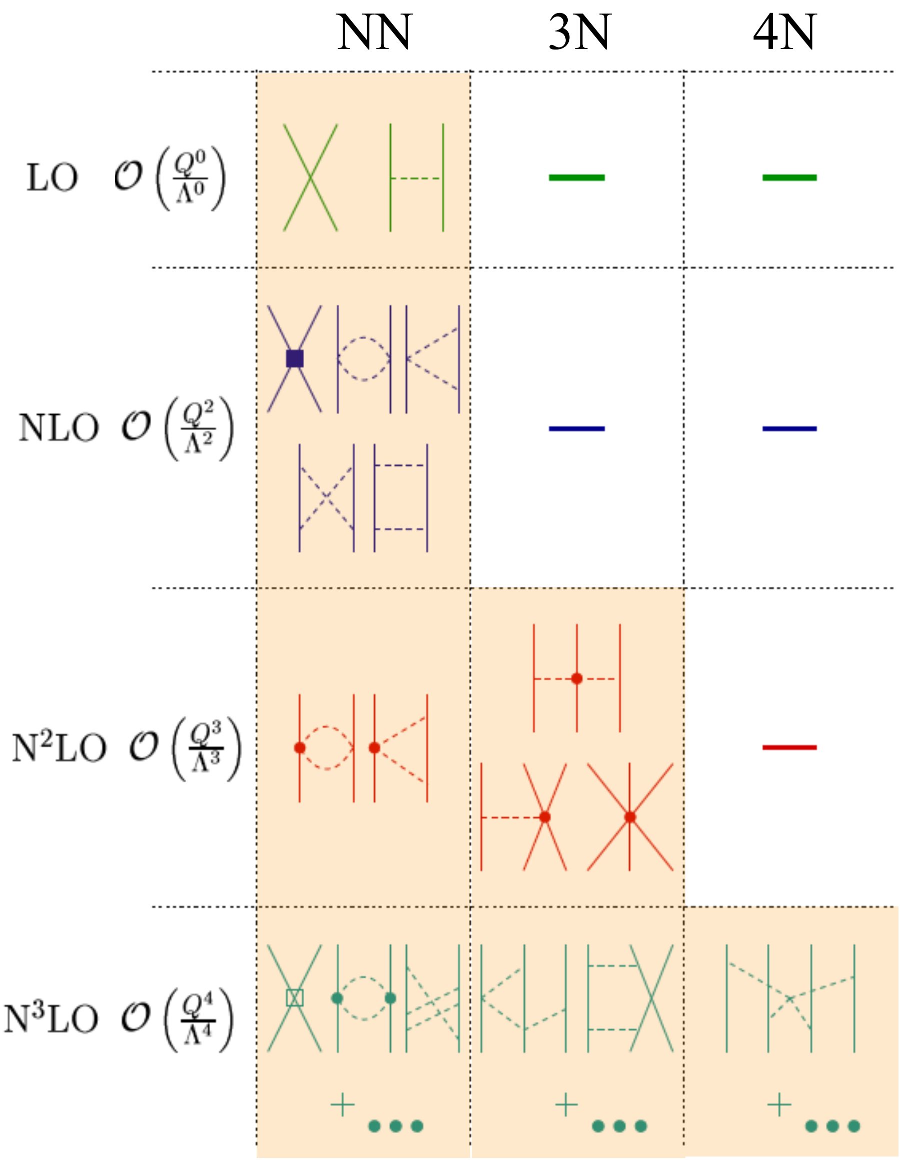
with C. Drischler, K. Hebeler, T. Krüger, J.M. Lattimer, C.J. Pethick, **V. Somá, I. Tews**



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



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

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

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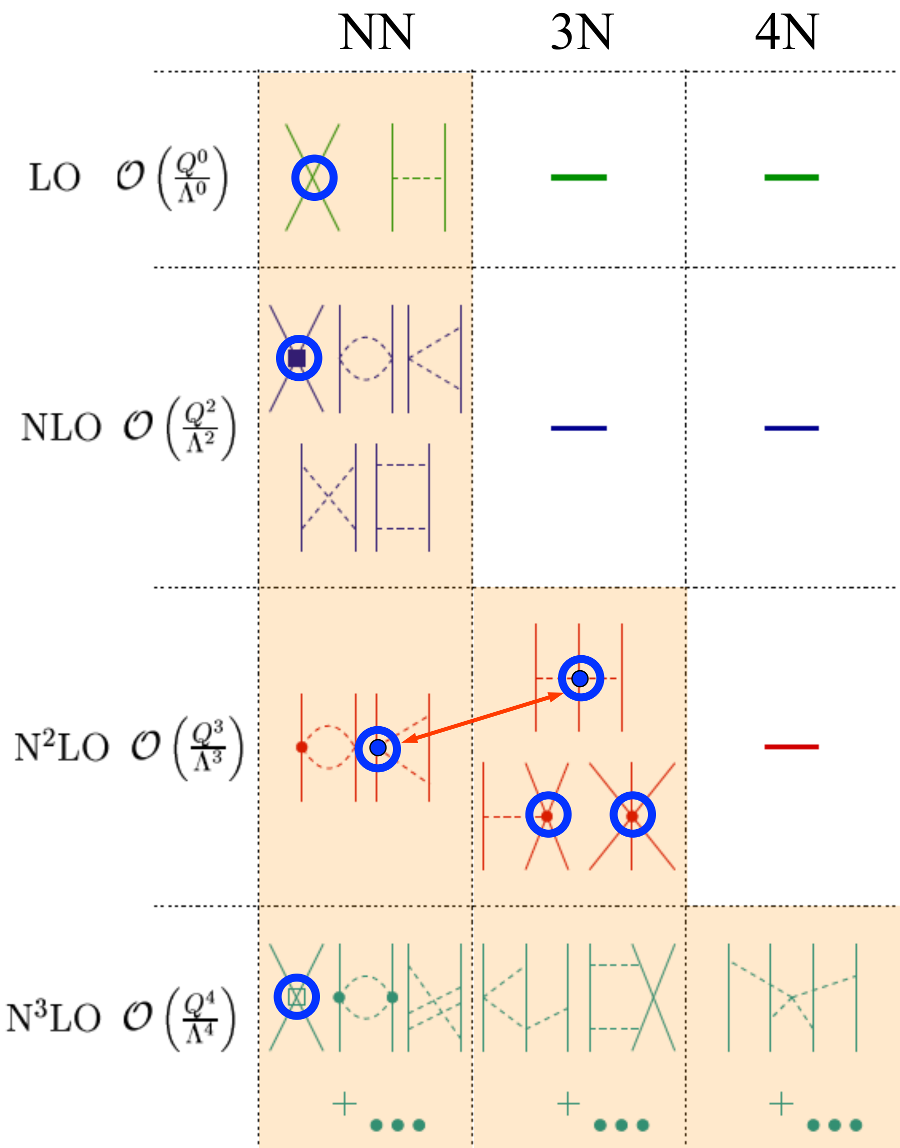


include long-range pion physics

few short-range couplings,
fit to experiment once

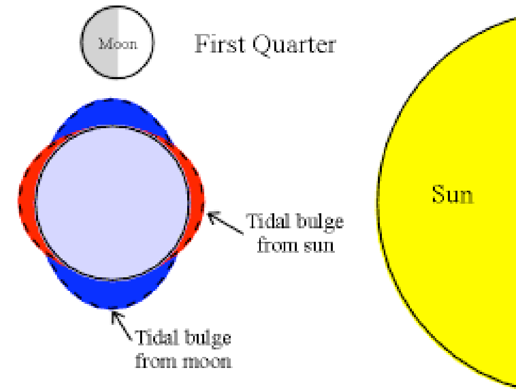
systematic: can work to desired accuracy and obtain **error estimates**

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

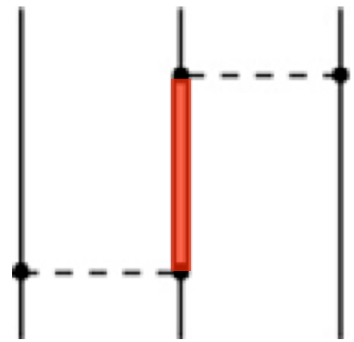
Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

Why are there 3N forces?

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

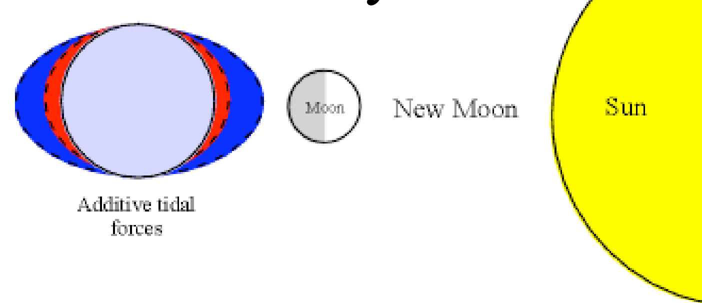


dominant contribution from Δ(1232 MeV)

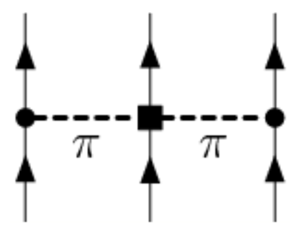


+ many shorter-range parts

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



chiral effective field theory (EFT)
Delta-less (Δ is treated as heavy):

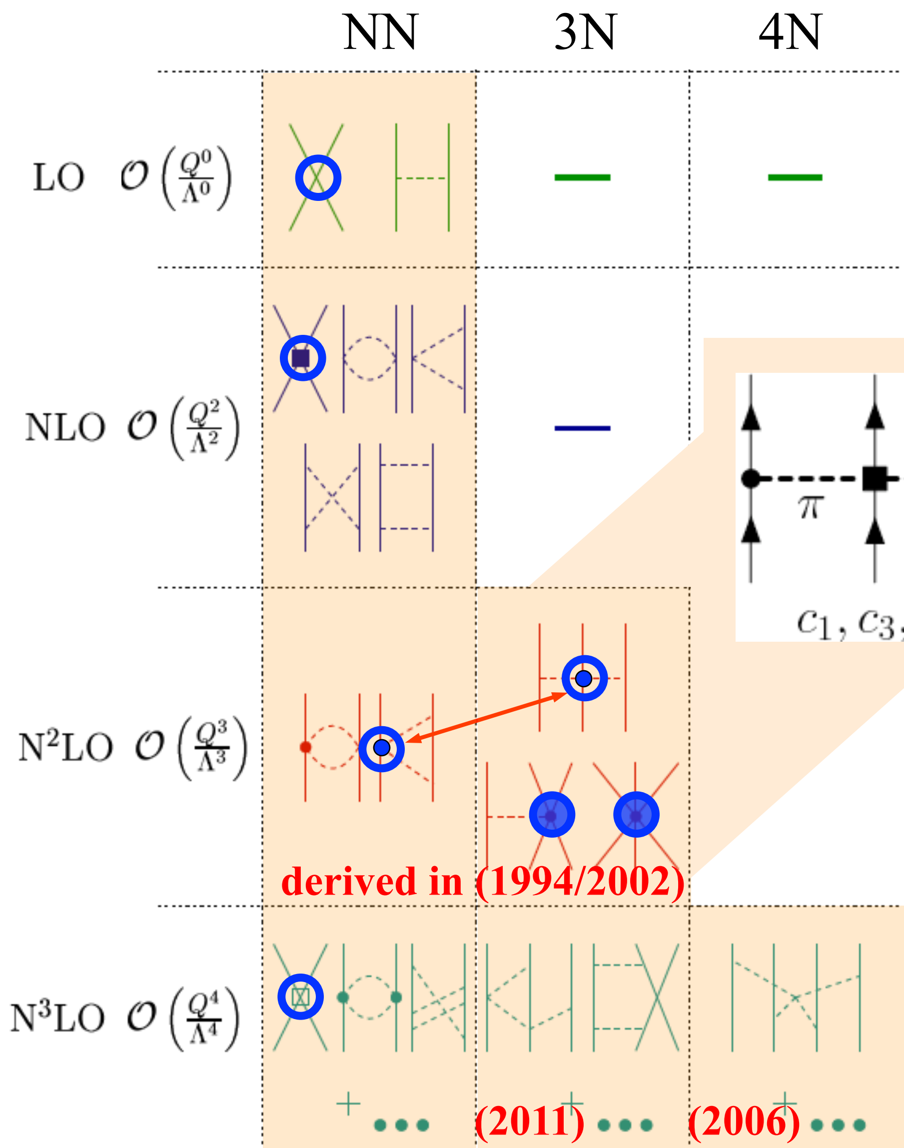


+ shorter-range parts

EFT provides a systematic and powerful approach for 3N forces

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

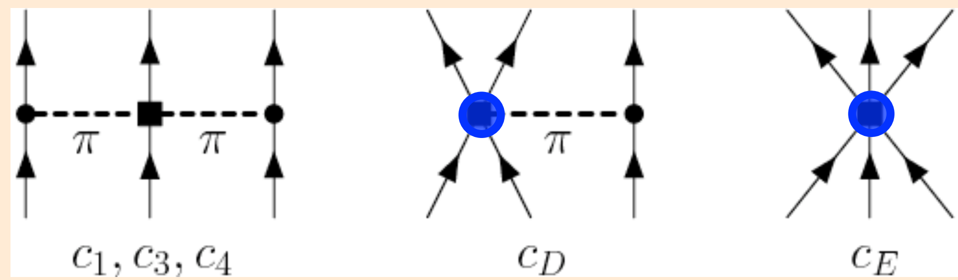
Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



consistent NN-3N-4N interactions

3N,4N: **2 new couplings to N³LO**

+ no new couplings for neutrons



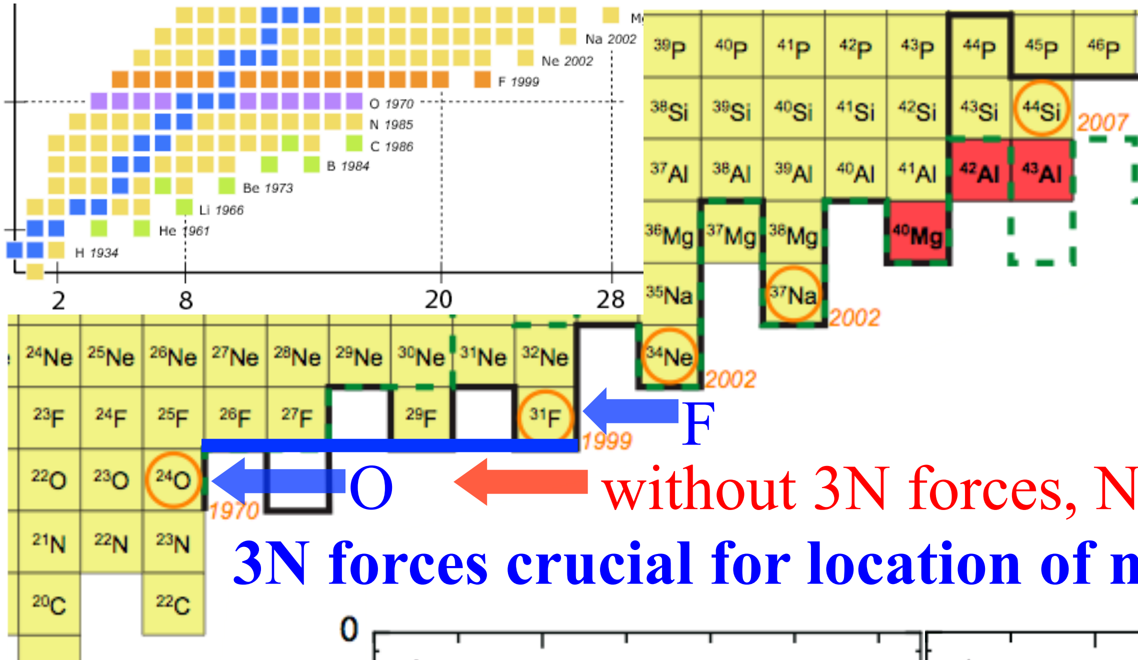
c_i from πN and NN Meissner, LAT 2005

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

c_D, c_E fit to light nuclei only

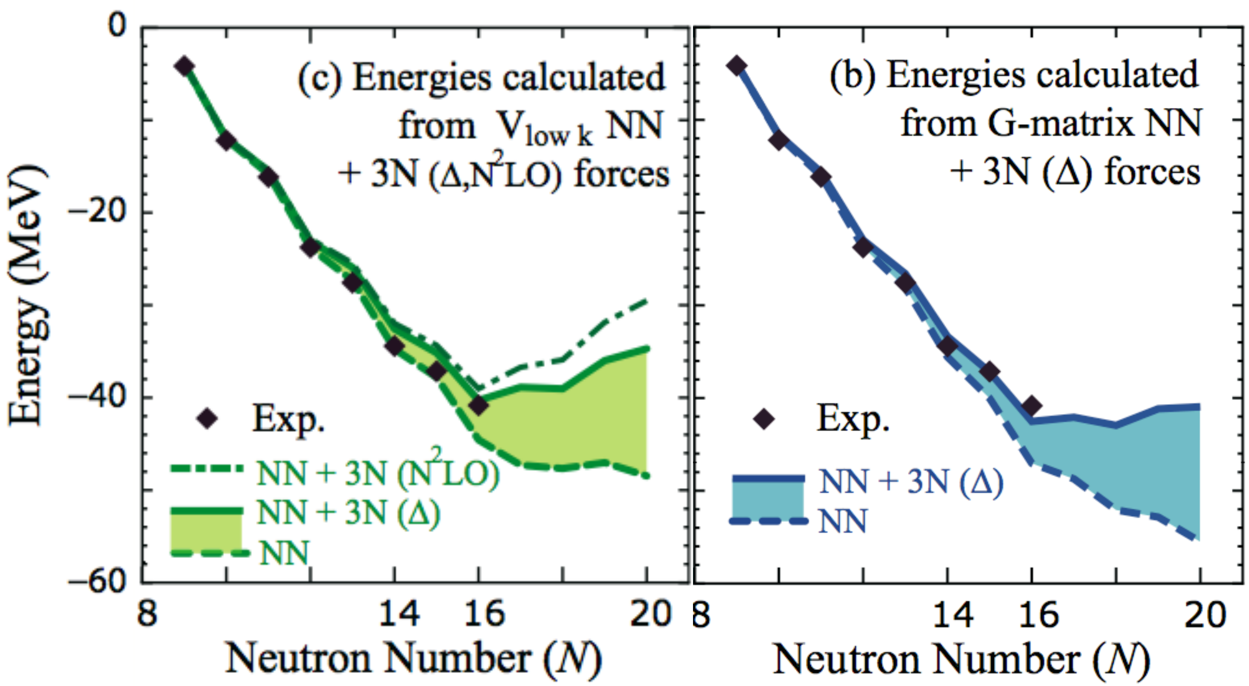
Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

The oxygen anomaly Otsuka, Suzuki, Holt, AS, Akaishi, PRL (2010)



without 3N forces, NN interactions too attractive

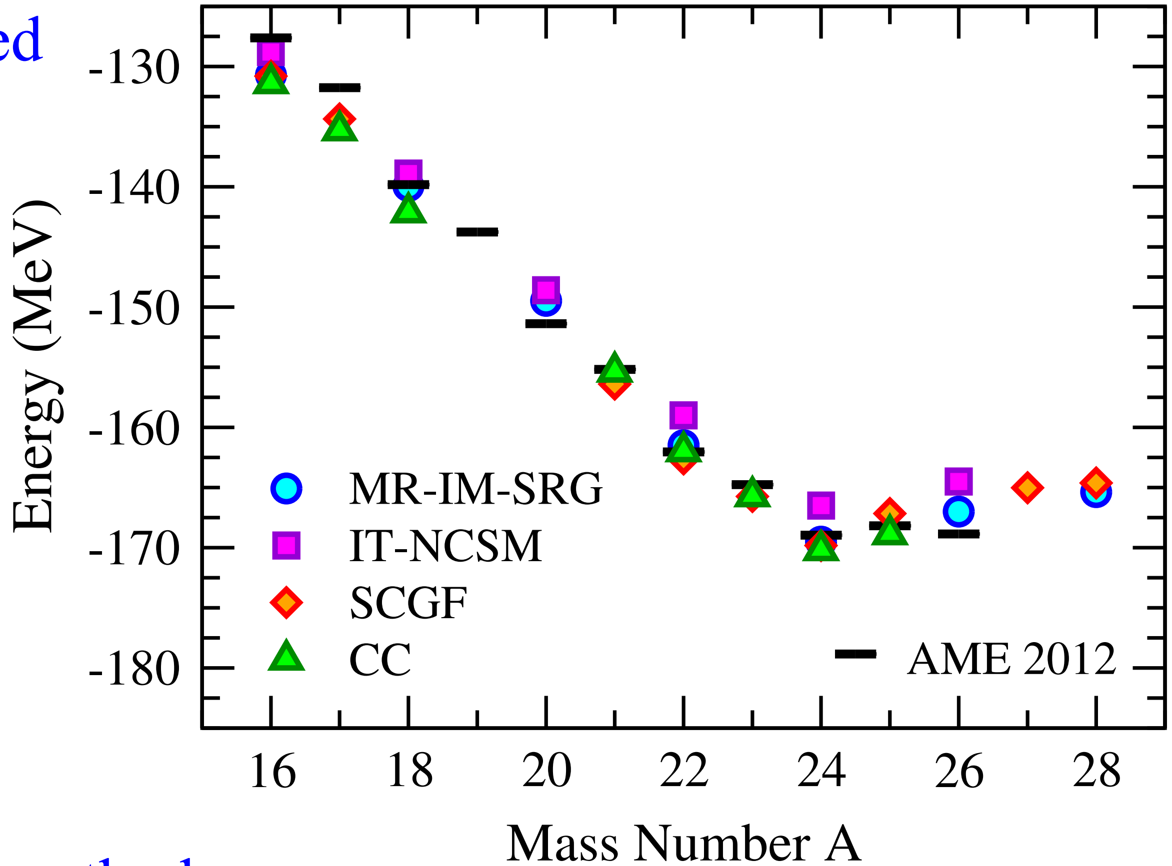
3N forces crucial for location of neutron dripline



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)

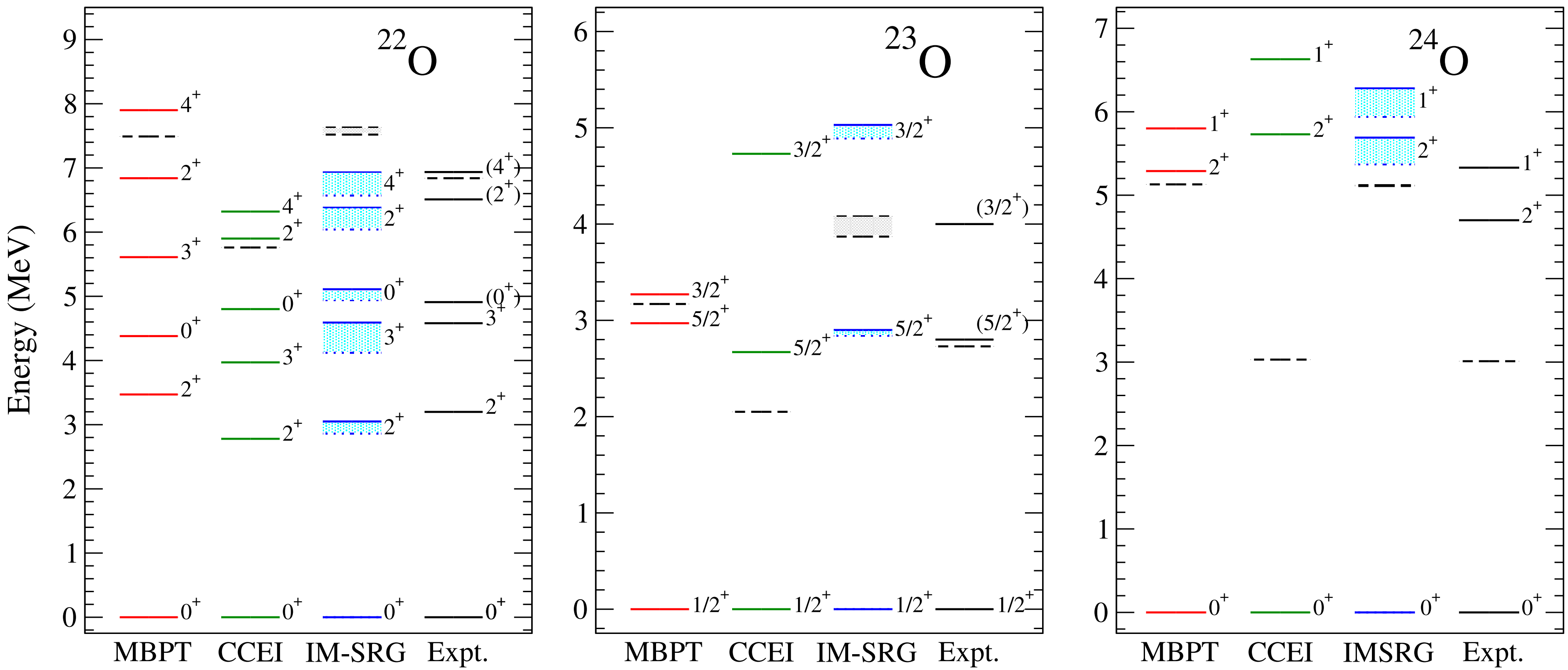
Self-Consistent Green's Function methods Cipollone et al., PRL (2013)

Ab initio calculations going open shell

In-Medium SRG to derive valence-shell interactions

Tsukiyama, Bogner, AS, PRL (2011), PRC (2012); Bogner, Hergert, Holt, AS 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

Ab initio calculations going open shell

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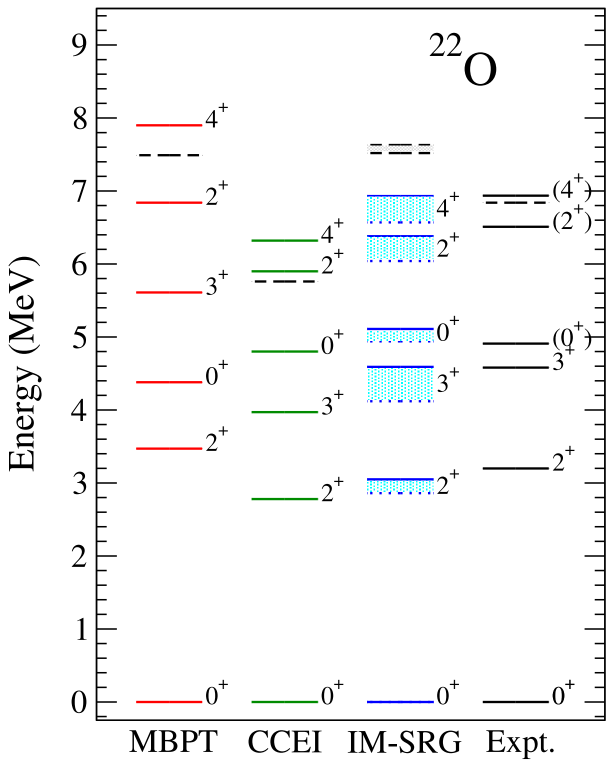
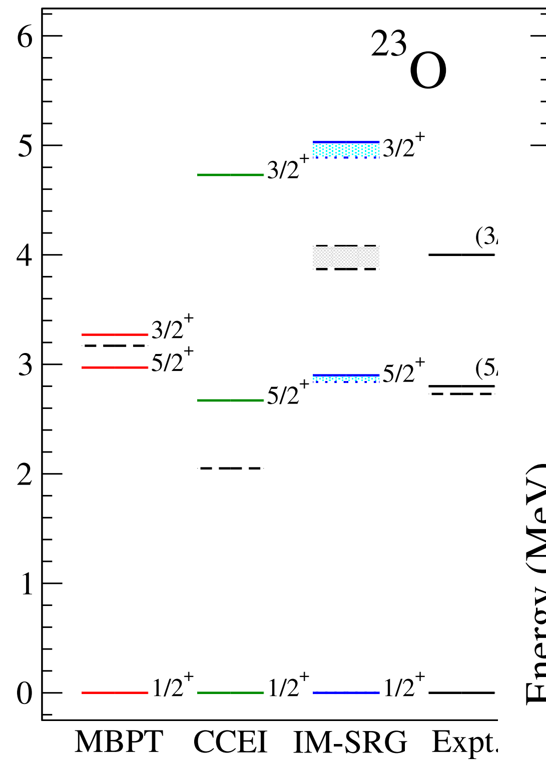
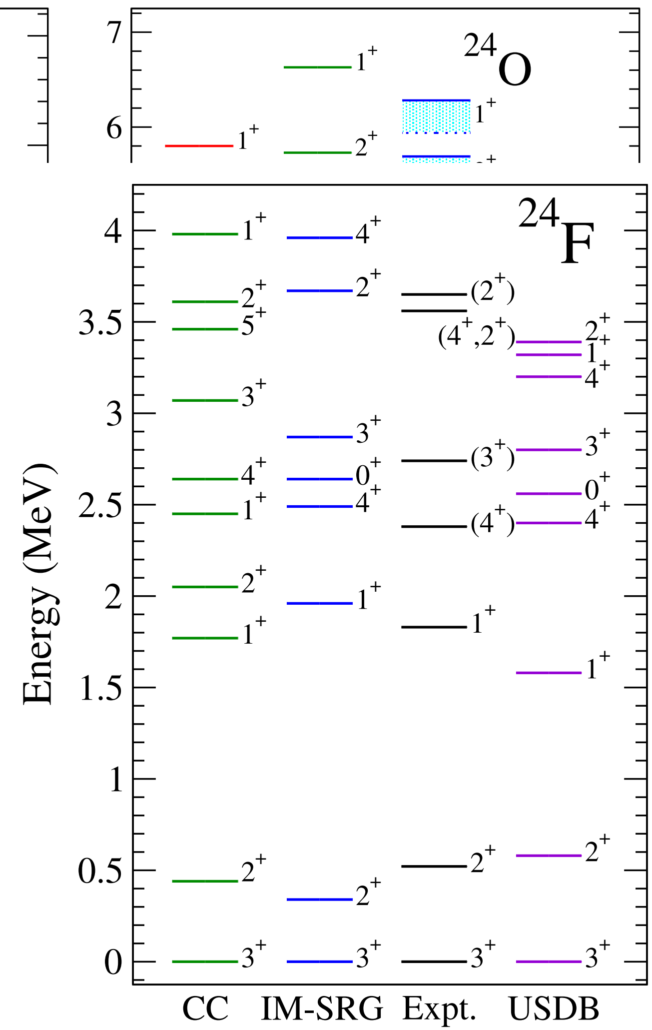




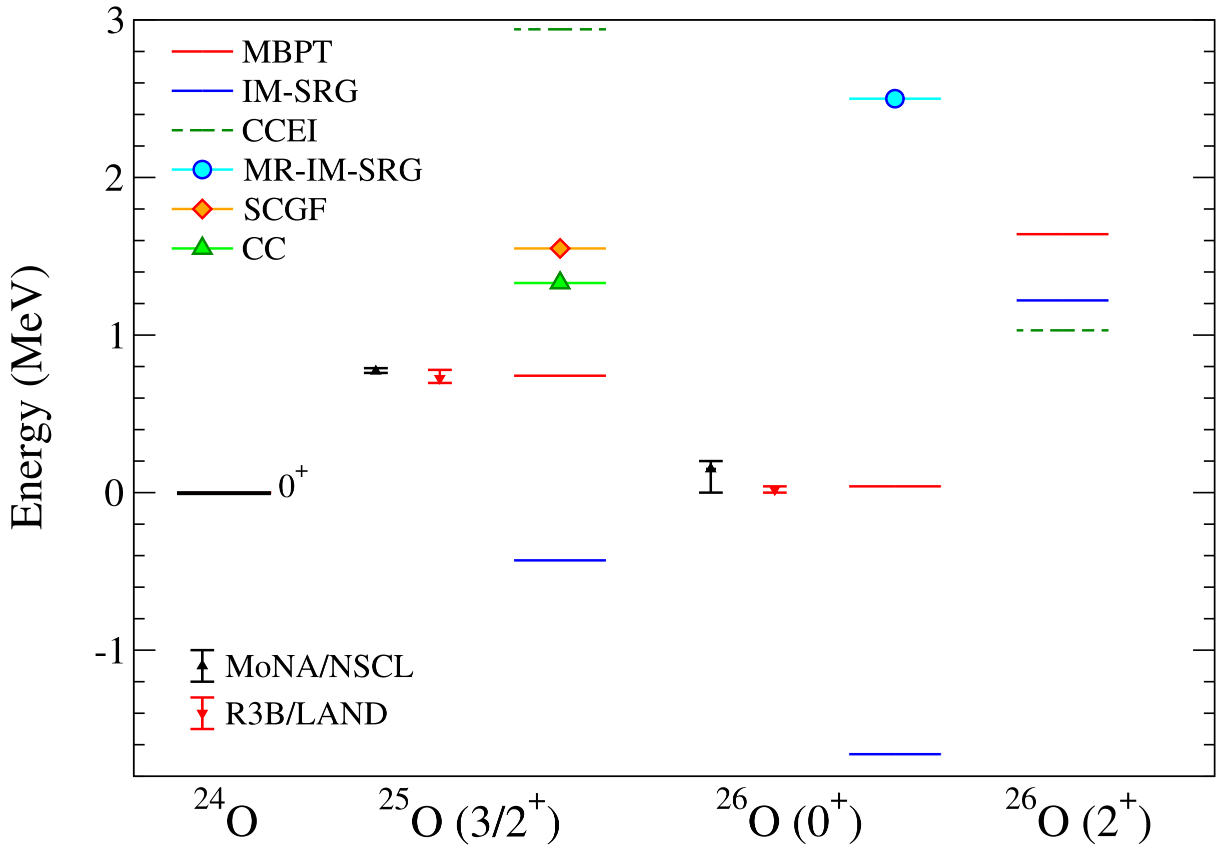


Experiments at GANIL, GSI, NSCL, RIBF

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

Frontier of ab initio calculations at A~50

doi:10.1038/nature12226

Masses of exotic calcium isotopes pin down nuclear forces

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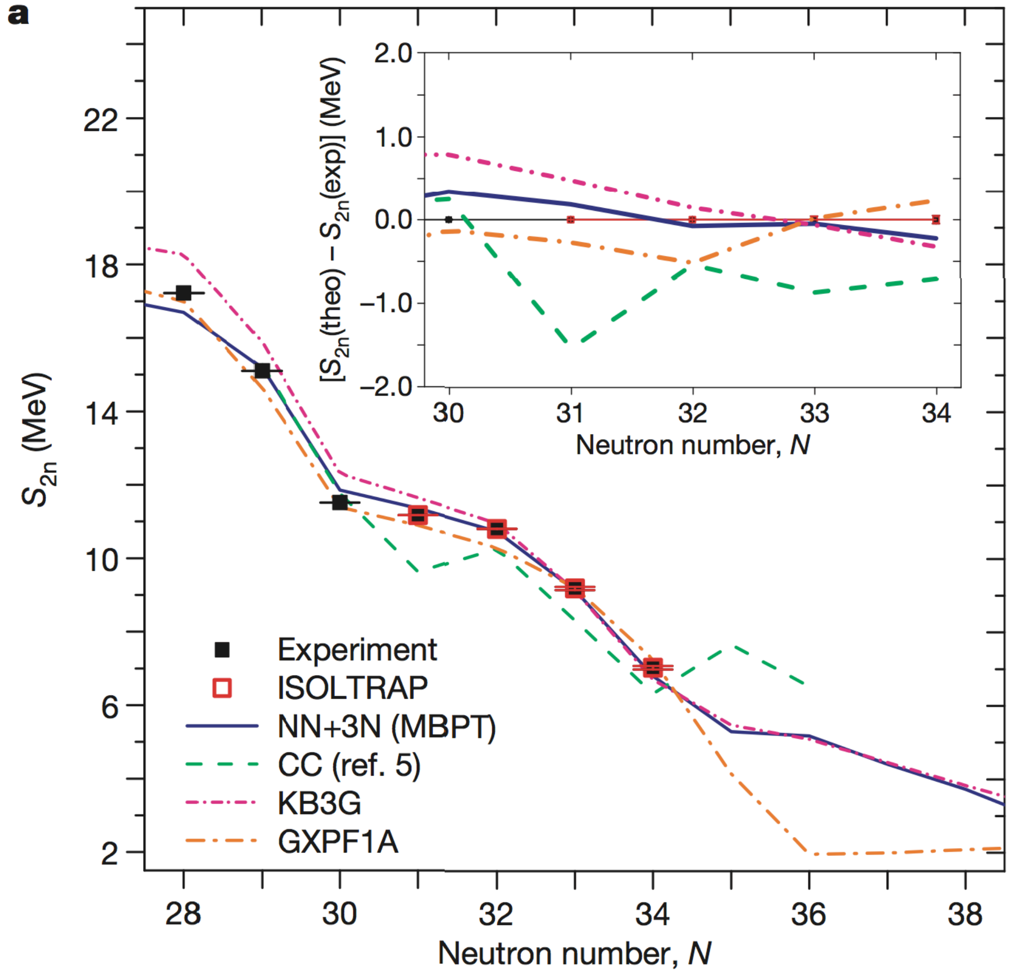
^{51,52}Ca masses at TITAN

Gallant et al., PRL (2012)

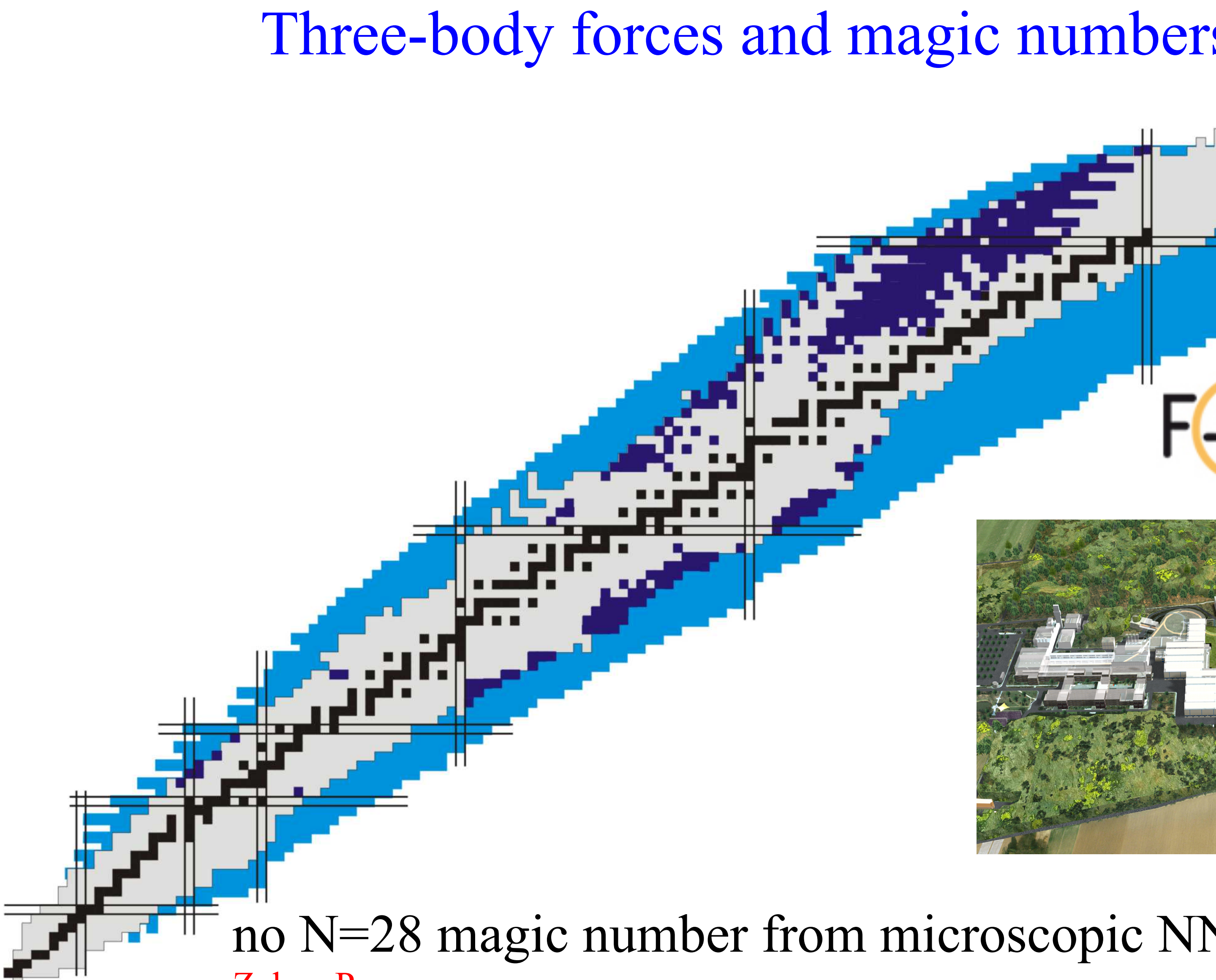
^{53,54}Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

establish prominent N=32 shell closure in calcium

excellent agreement with theoretical NN+3N prediction



Three-body forces and magic numbers

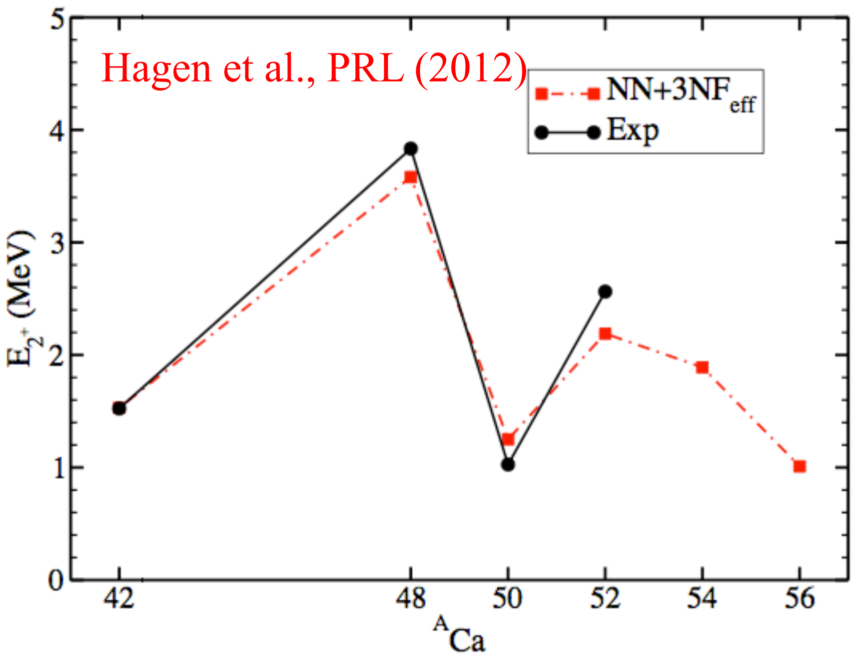


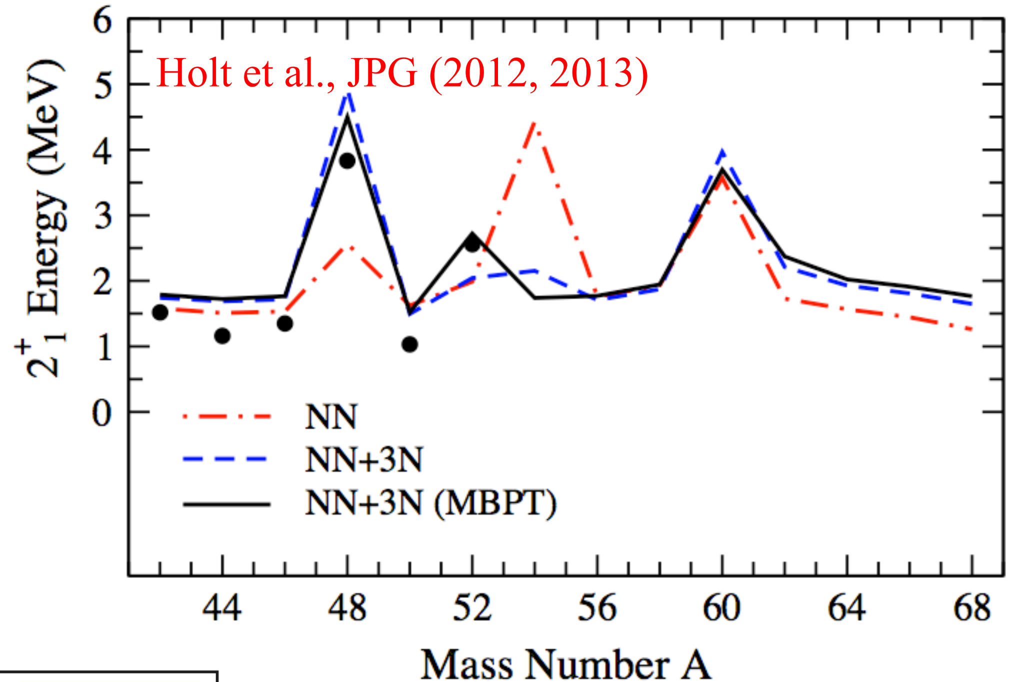
FAIR
Facility for Antiproton and Ion Research

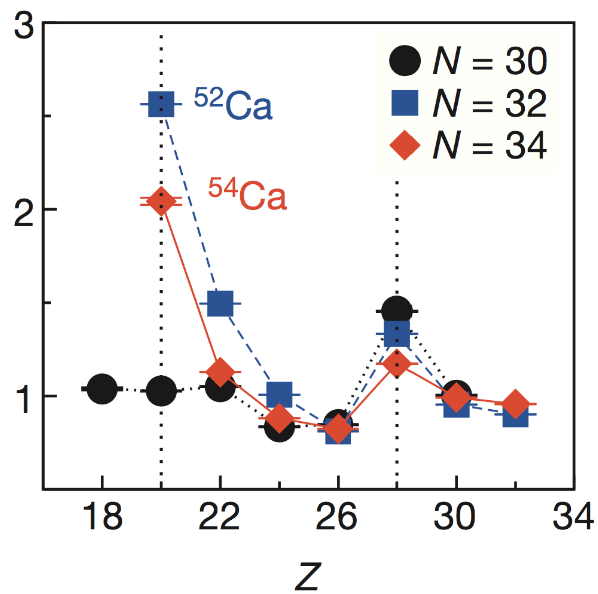
no N=28 magic number from microscopic NN forces

Zuker, Poves,…

3N forces and magic numbers





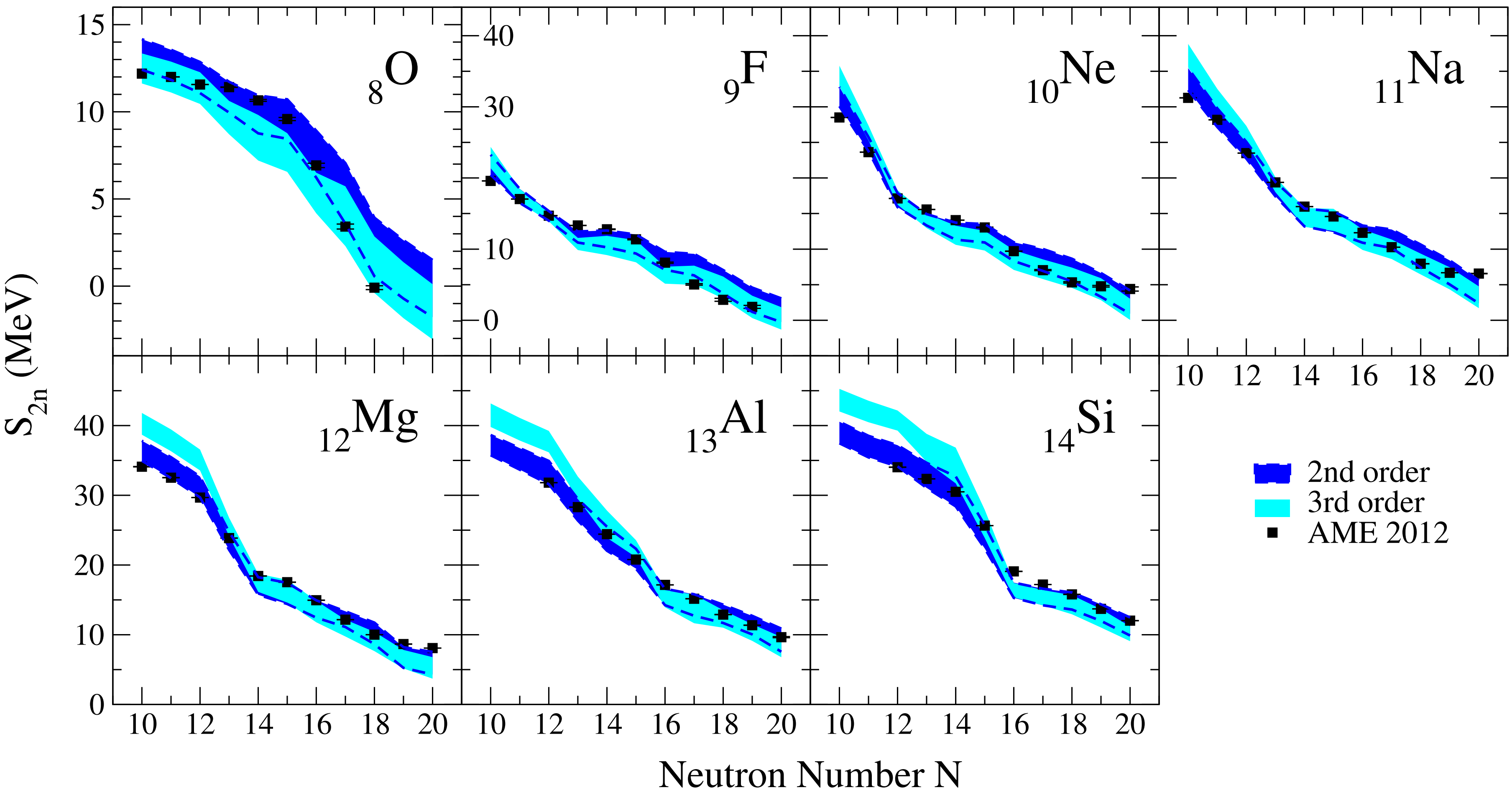


2^+ energy measured at RIBF suggests magic number N=34

Steppenbeck et al., Nature (2013)

Towards theoretical uncertainties **Simonis**, Holt, Hebeler, Menendez, AS, in prep.

based on NN+3N interactions (sd shell)
that predict nuclear matter saturation within uncertainties



Theoretical uncertainties dominated by uncertainties in nuclear forces!

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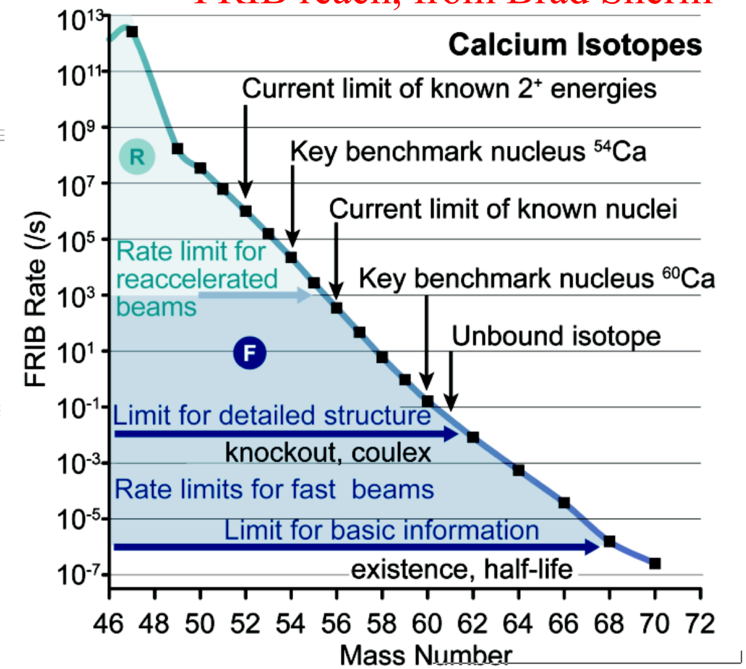
FRIB reach, from Brad Sherill



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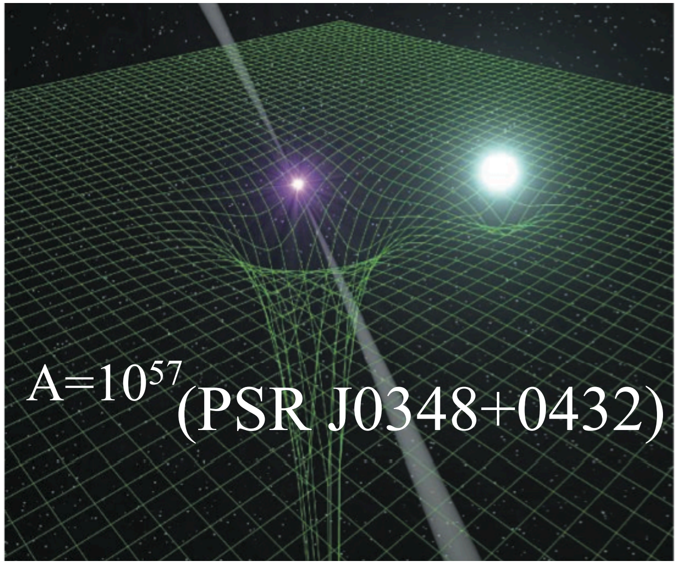

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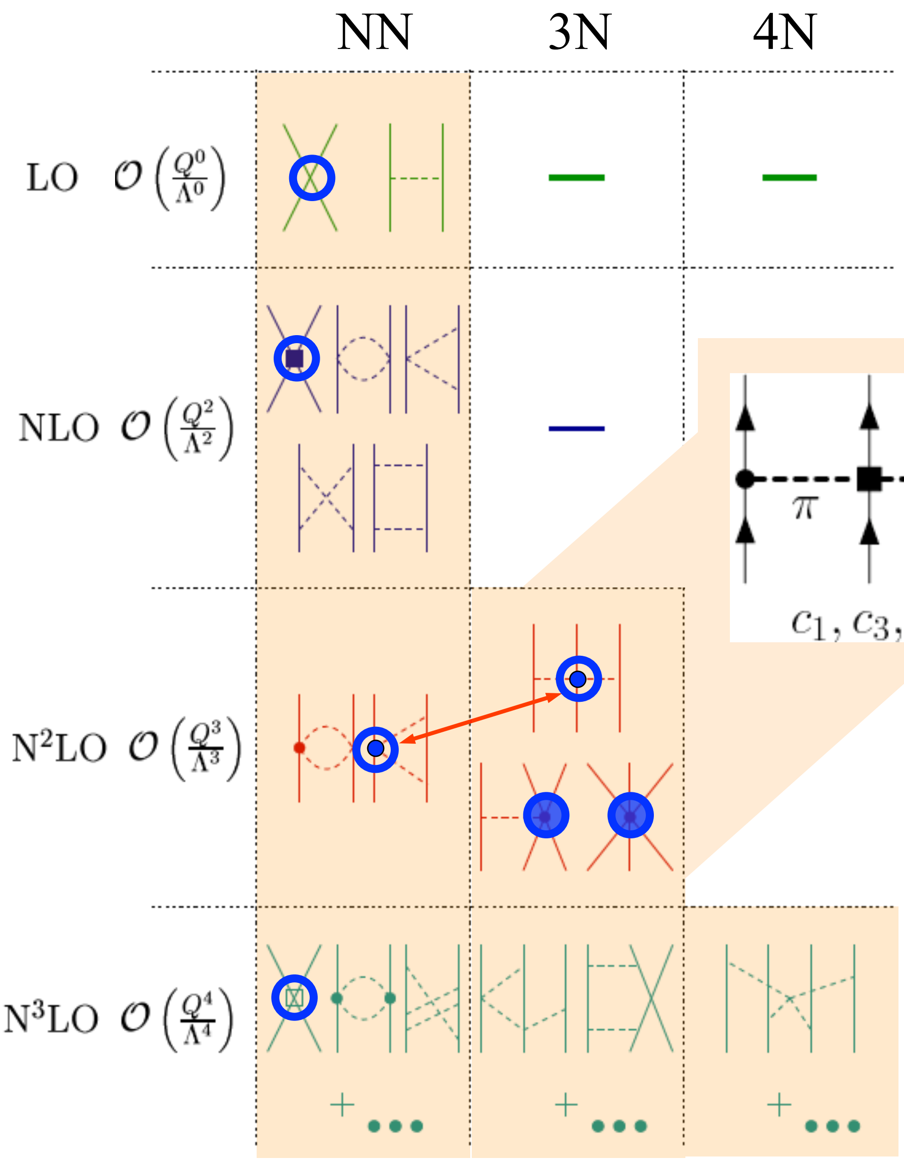
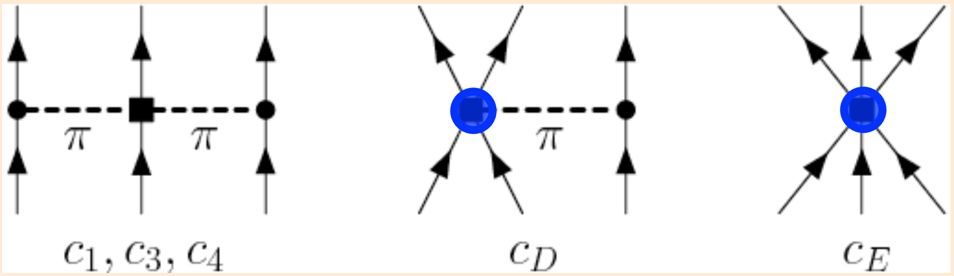


c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)



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

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

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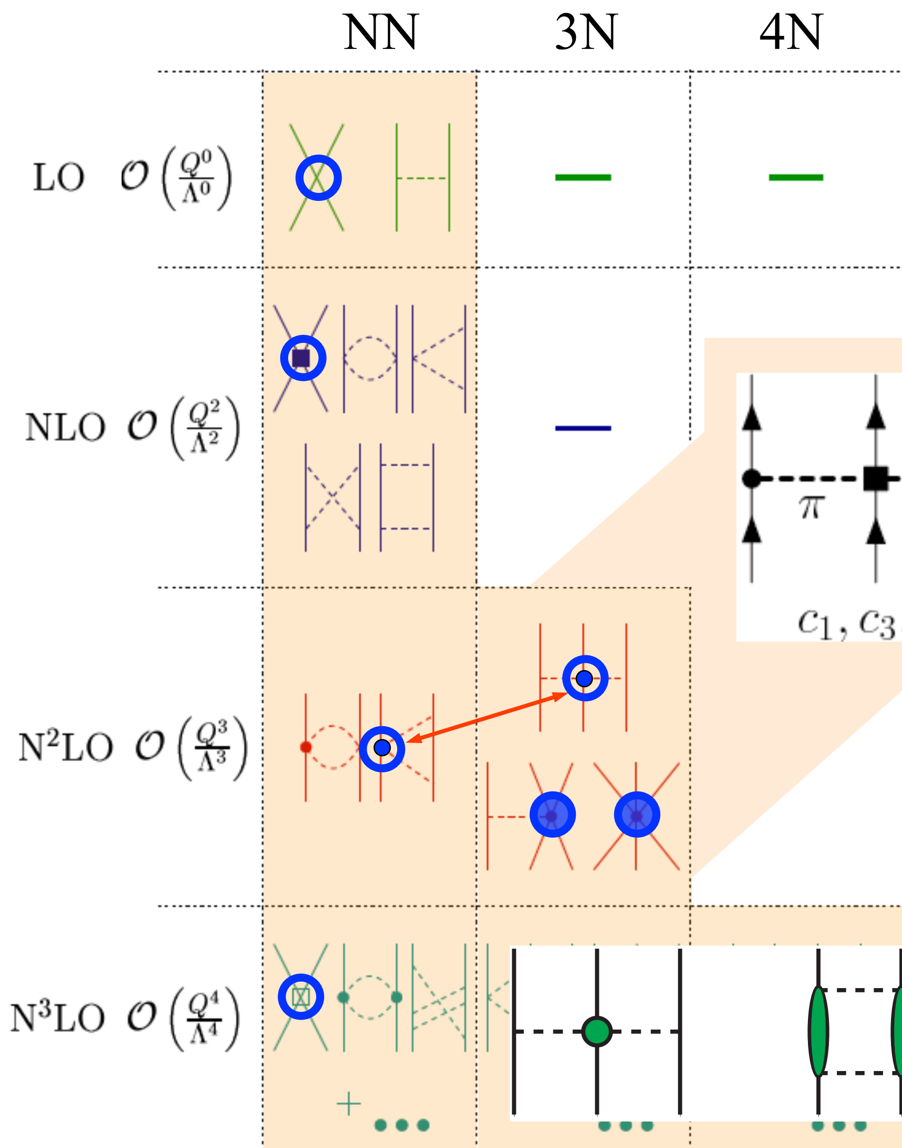

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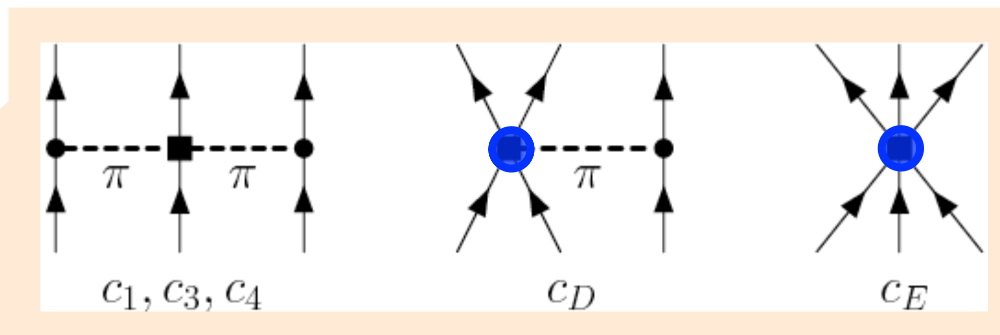

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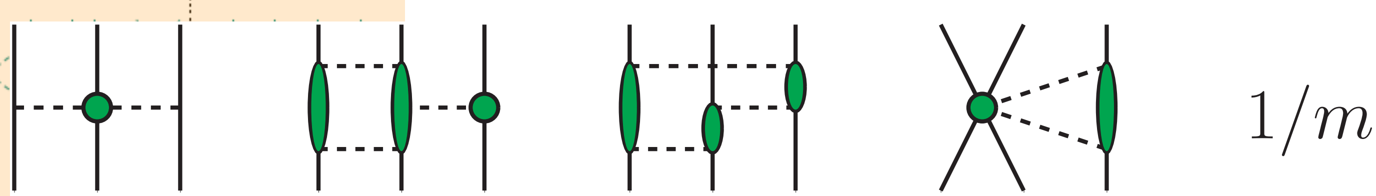
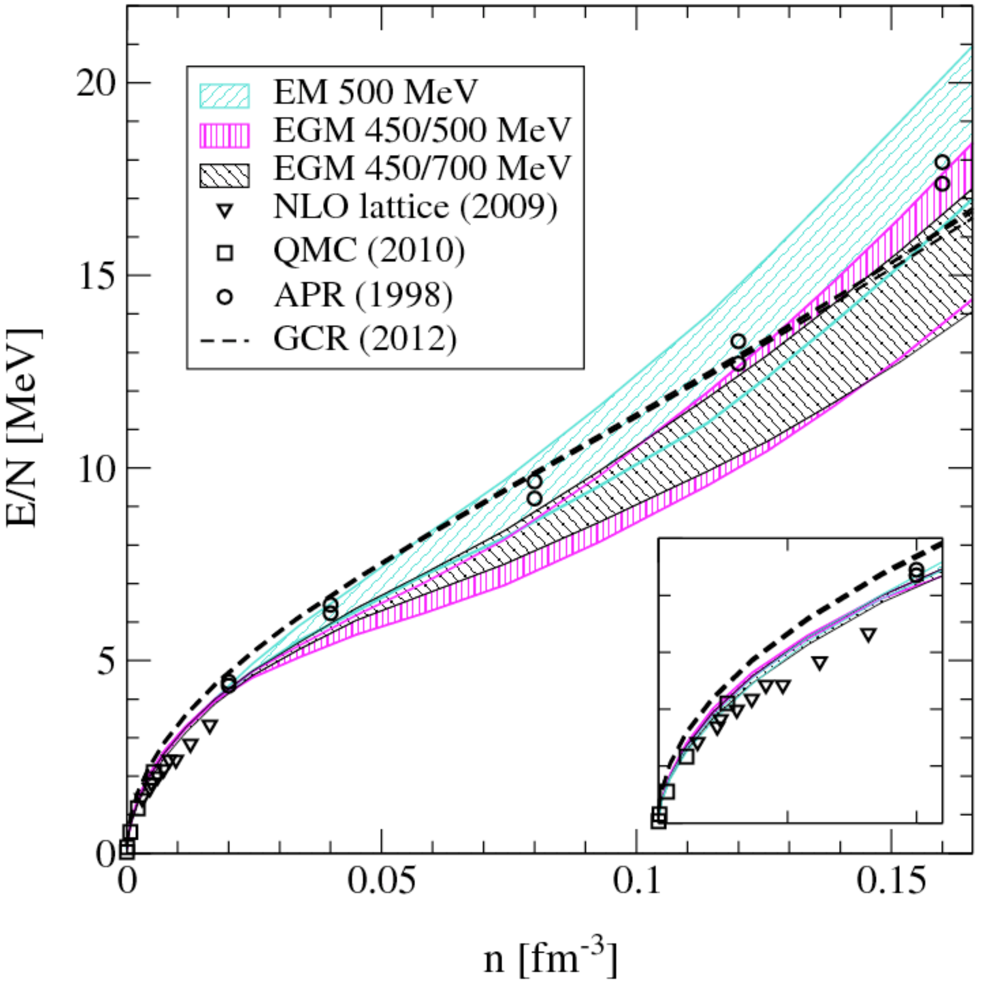


Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

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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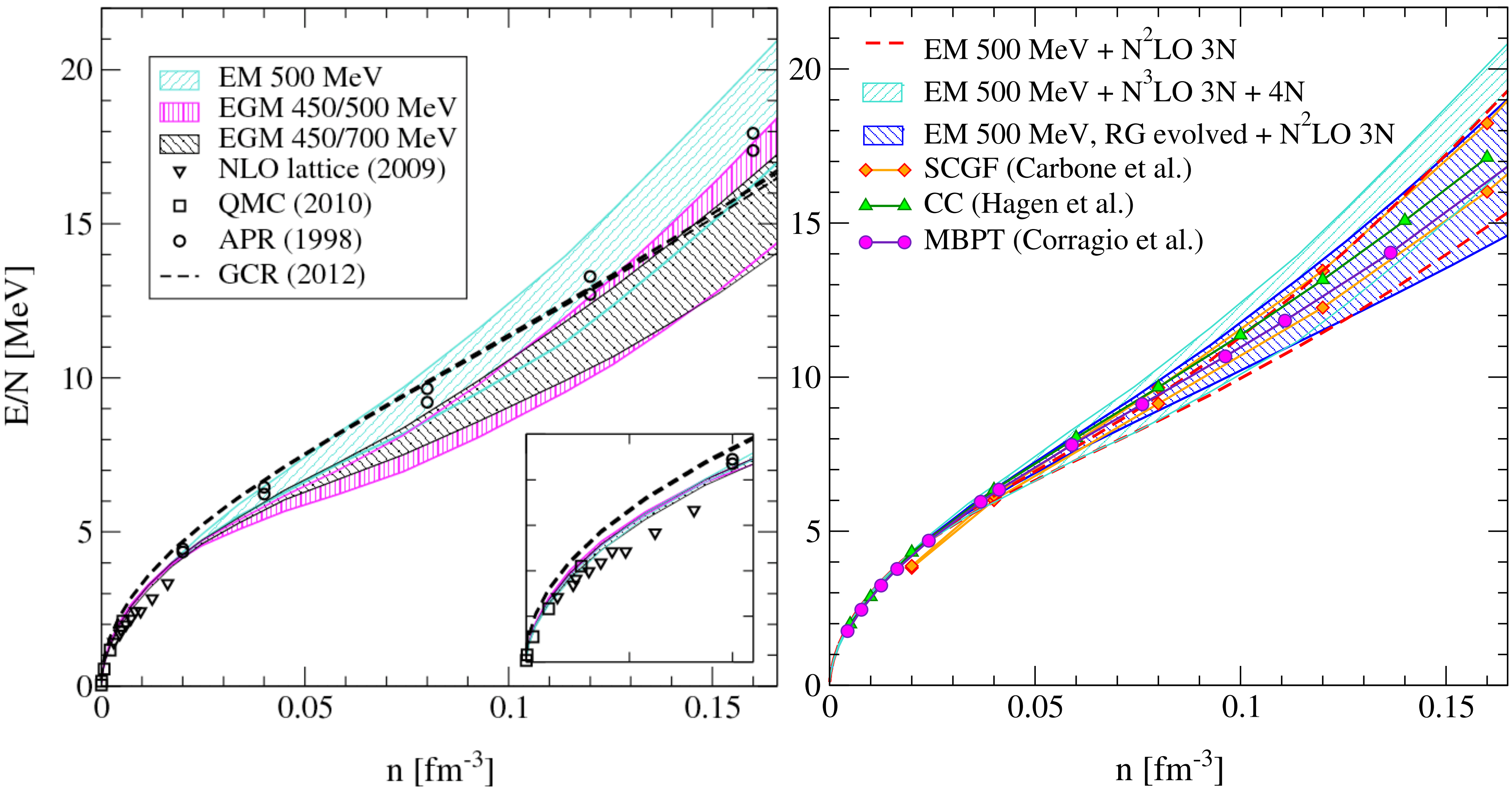


excellent agreement with other methods!

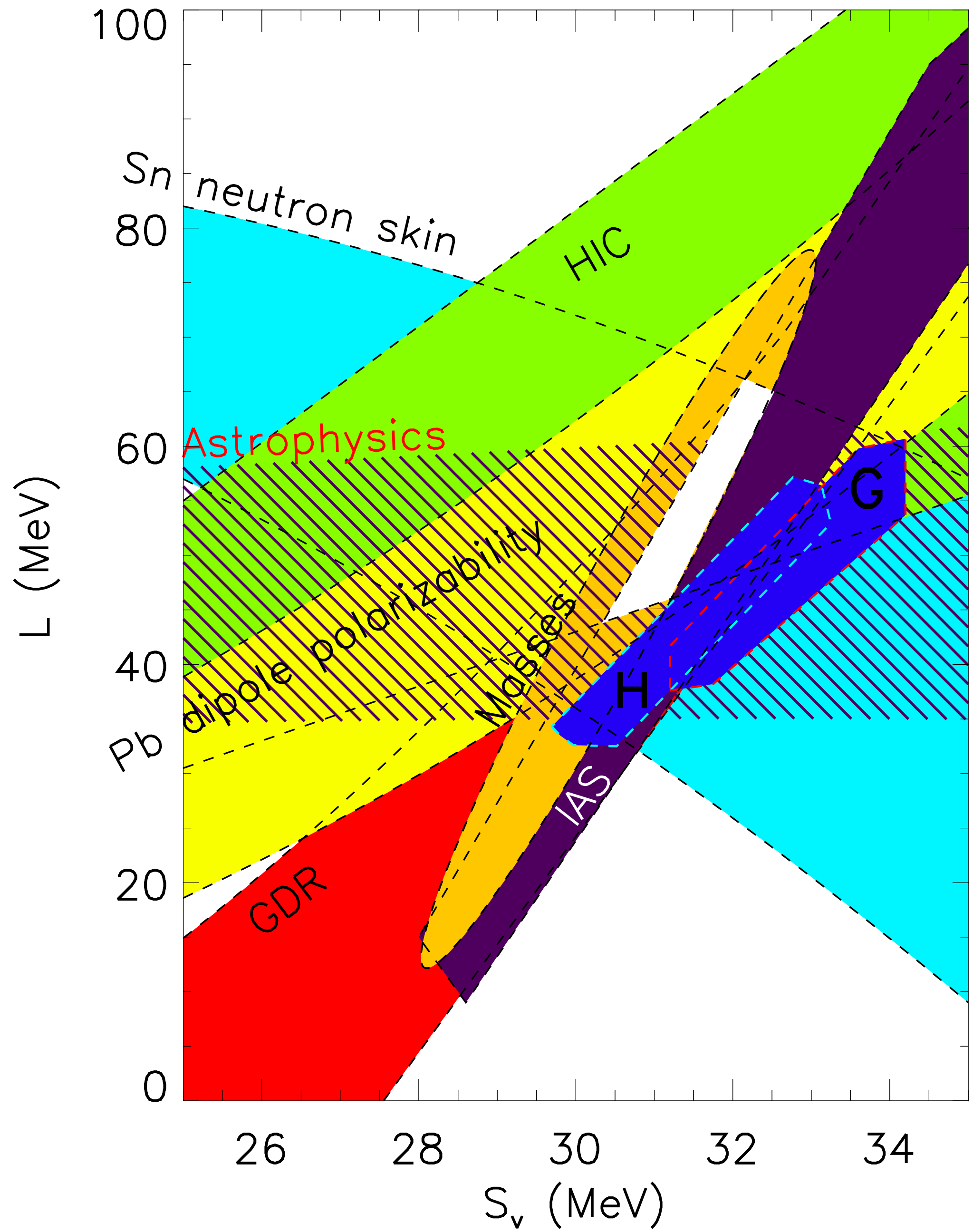
Symmetry energy and pressure of neutron matter

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!

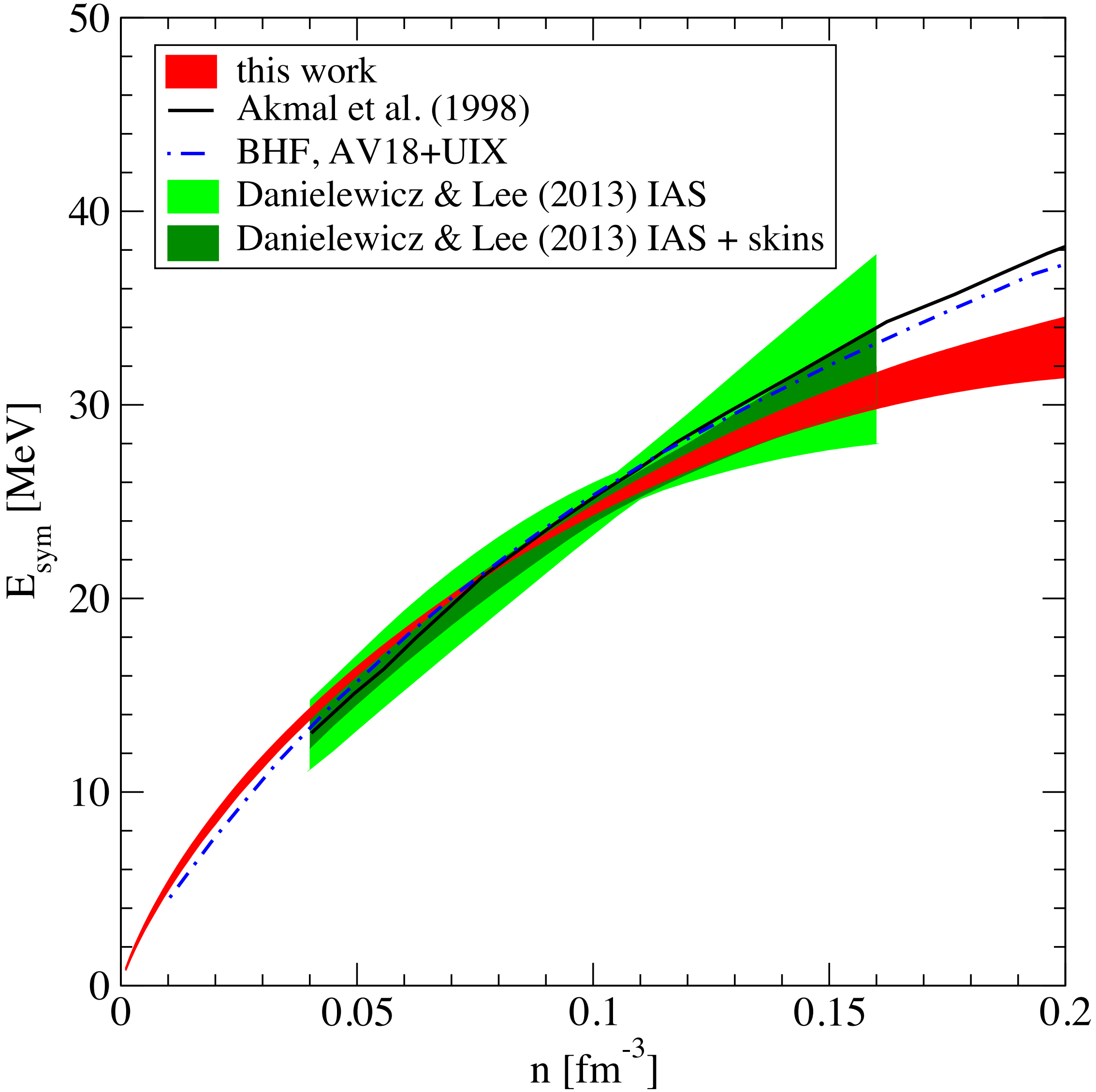
combined with Skyrme EDFs predicts neutron skin
^{208}Pb: 0.182(10) fm
^{48}Ca: 0.173(5) fm
Brown, AS, PRC (2014)



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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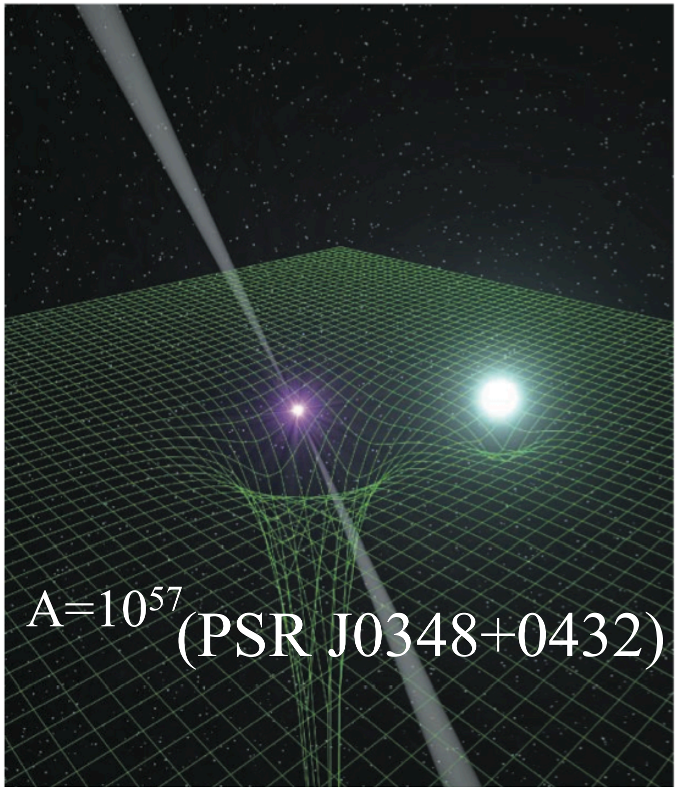
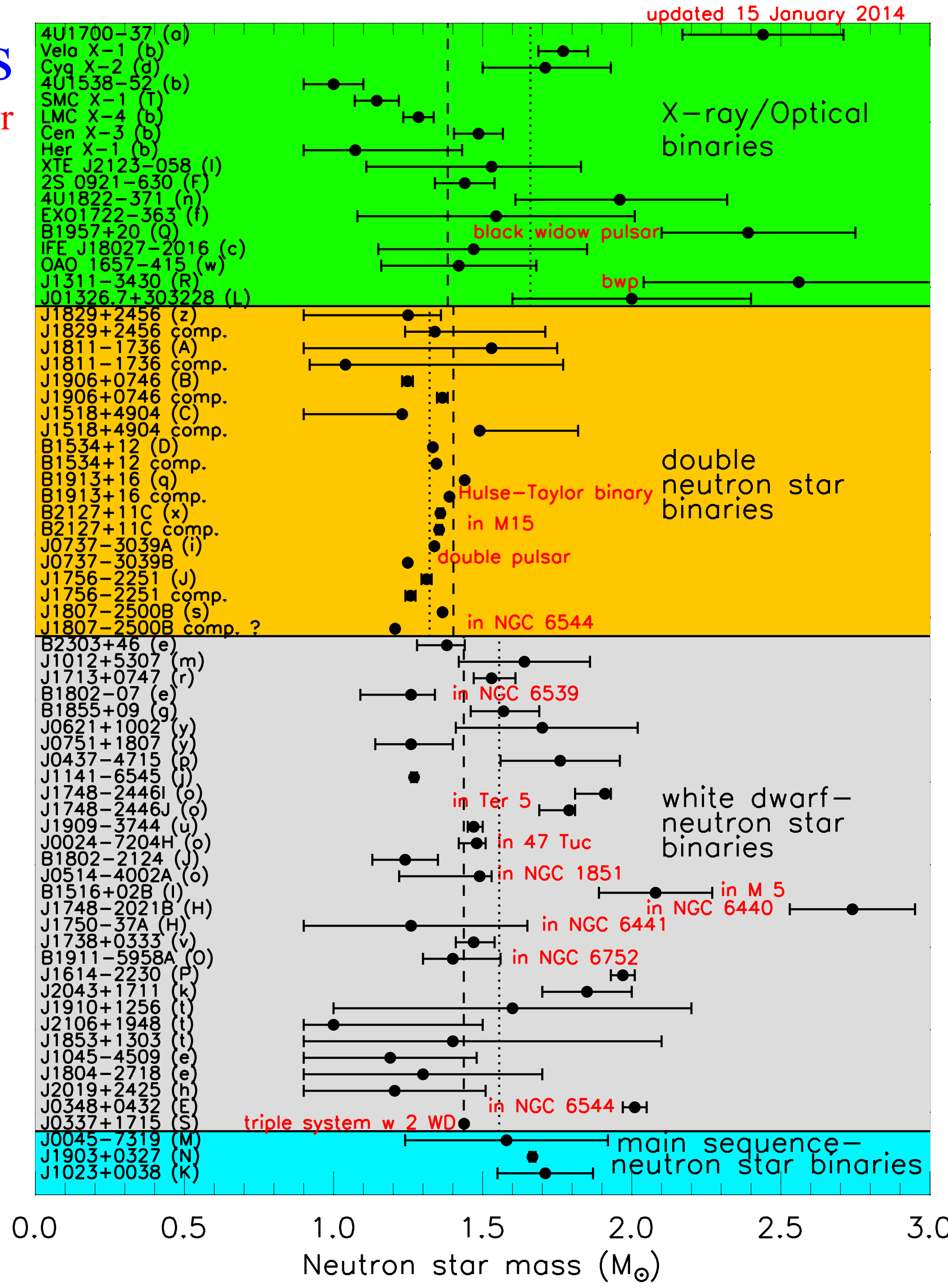


Chart of neutron star masses

from Jim Lattimer



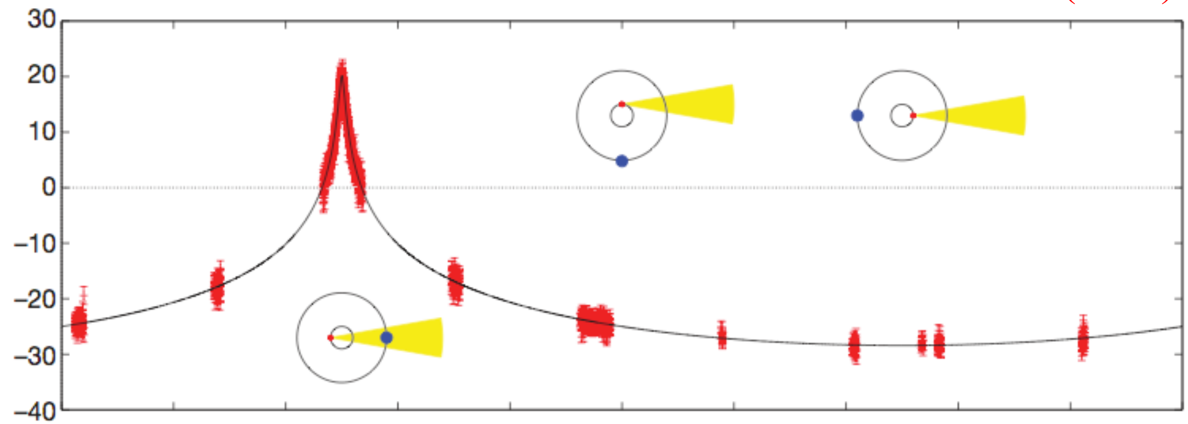
Discovery of the heaviest neutron star

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

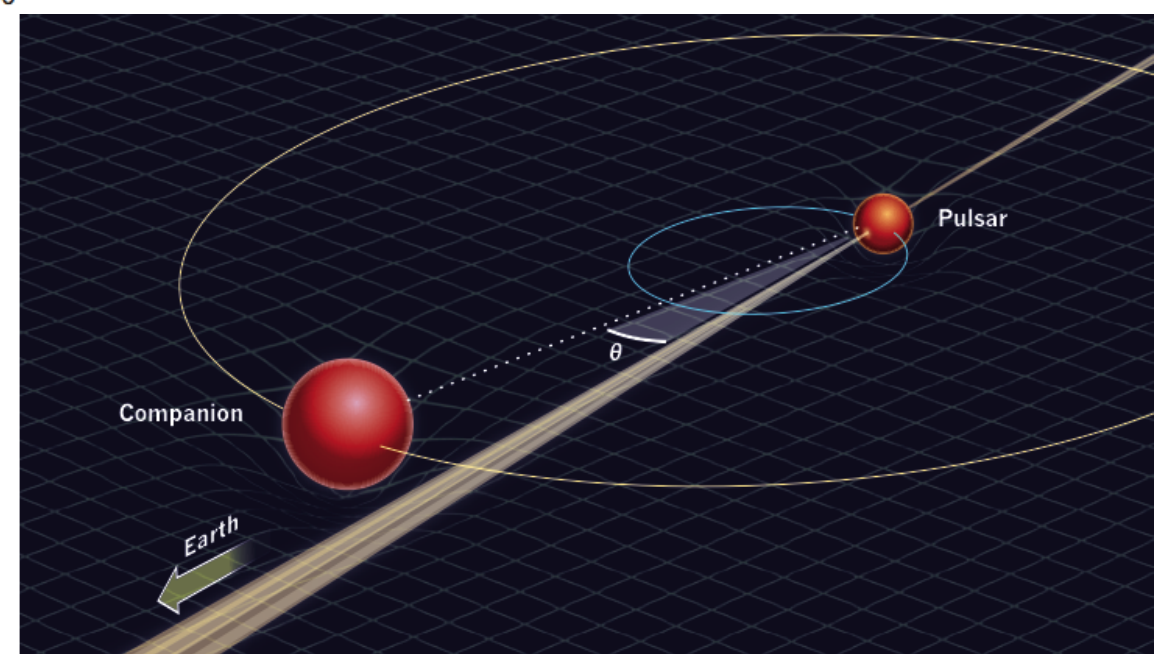
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

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 Science (2013)

RESEARCH ARTICLE SUMMARY

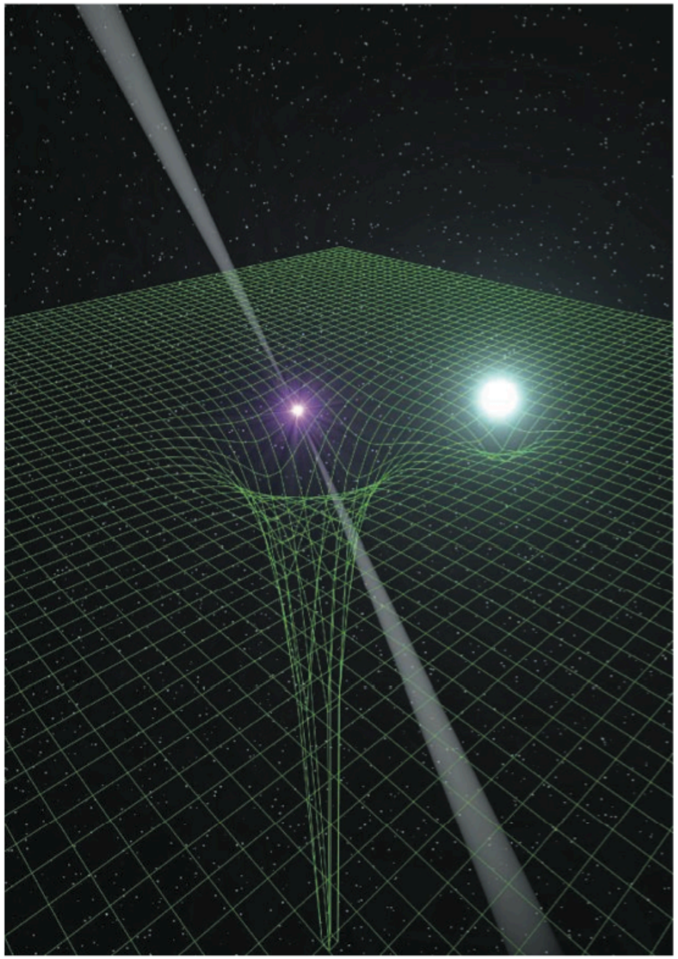
A Massive Pulsar in a Compact Relativistic Binary

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, $\dot{P}_b^{obs} = -8.6 \pm 1.4$ μs year^{-1} in our radio-timing data.

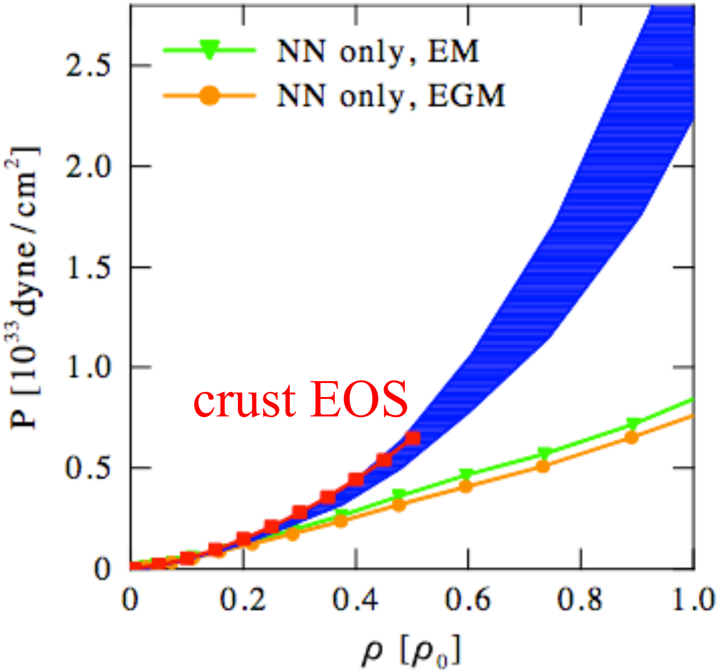


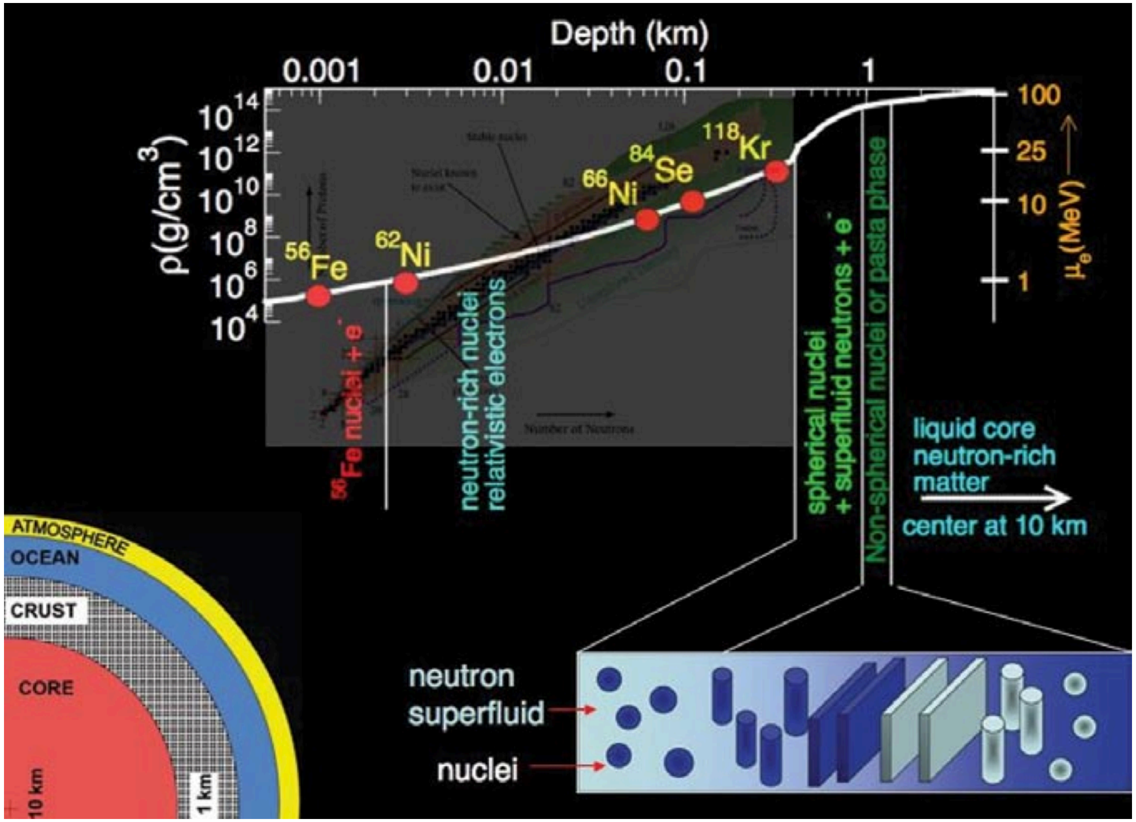
Artist's impression of the PSR J0348+0432 system. The compact pulsar (with beams of radio emission) produces a strong distortion of spacetime (illustrated by the green mesh). Conversely, spacetime around its white dwarf companion (in light blue) is substantially less curved. According to relativistic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

Impact on neutron stars

Hebeler, Lattimer, Pethick, AS, 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

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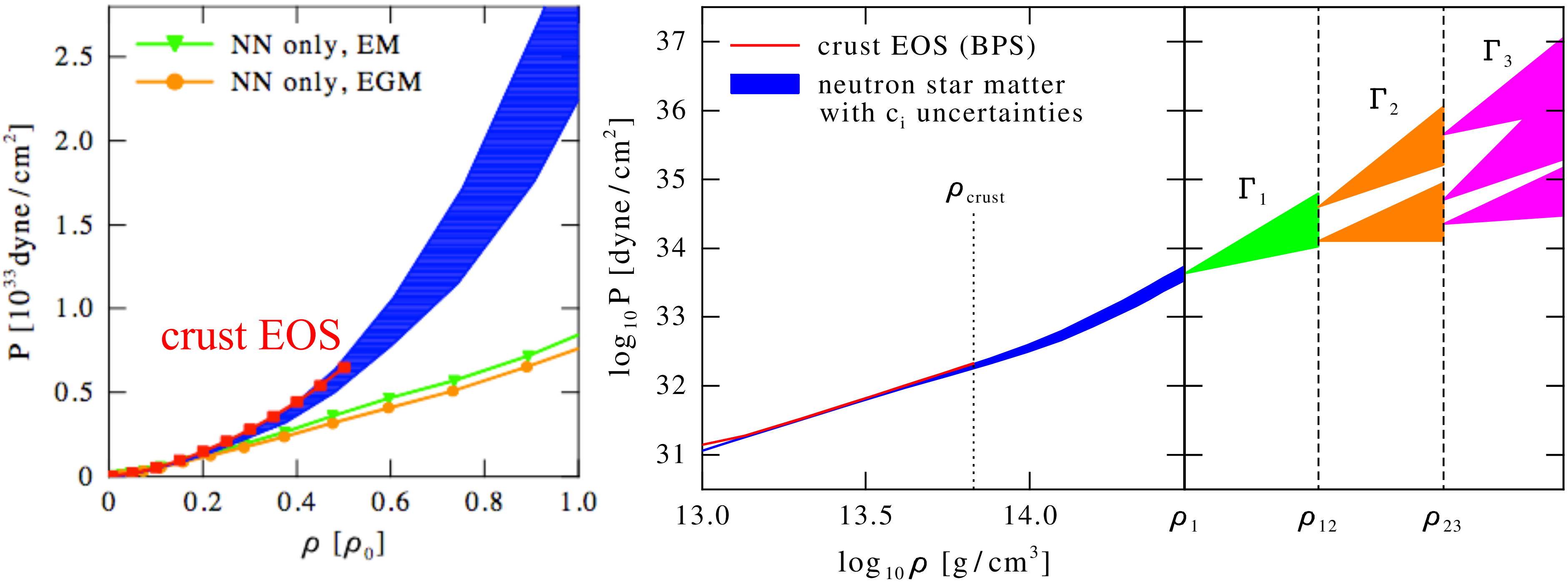
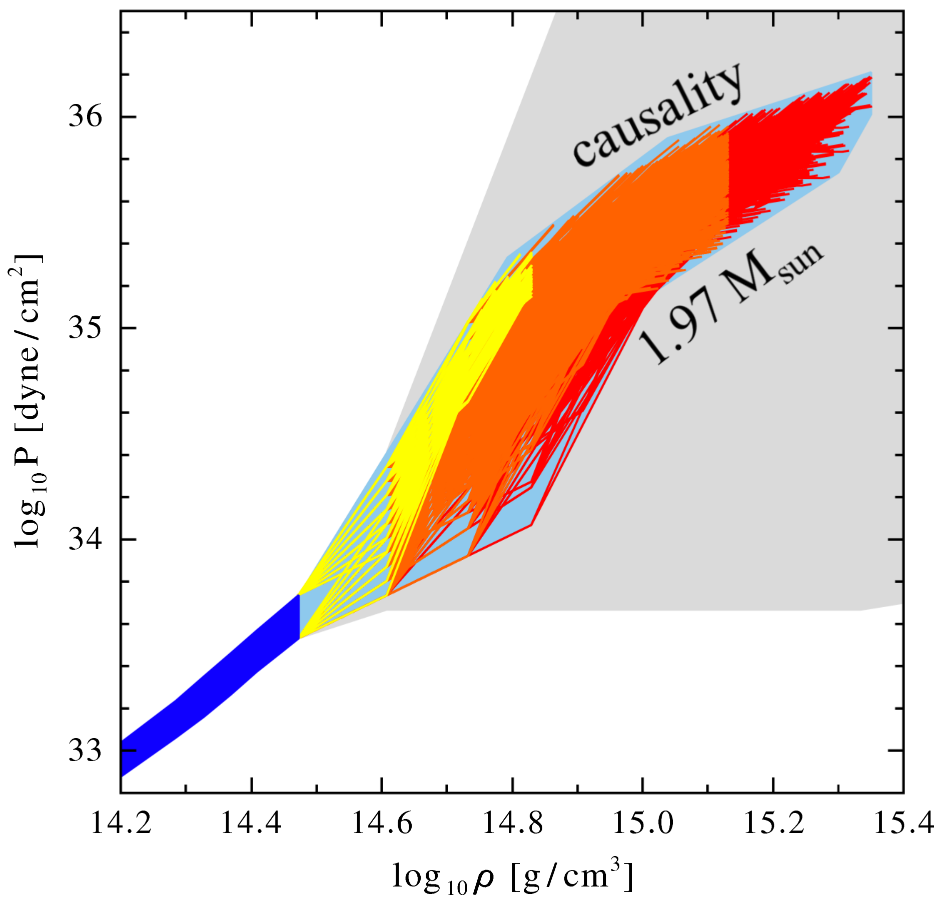


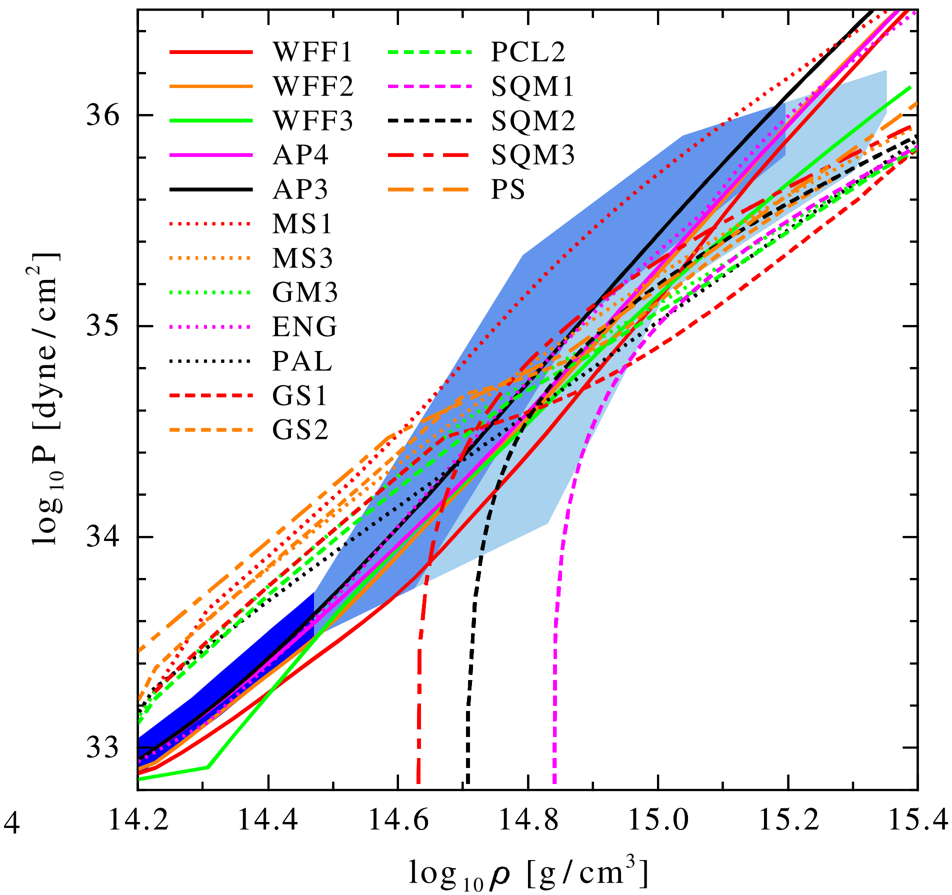
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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

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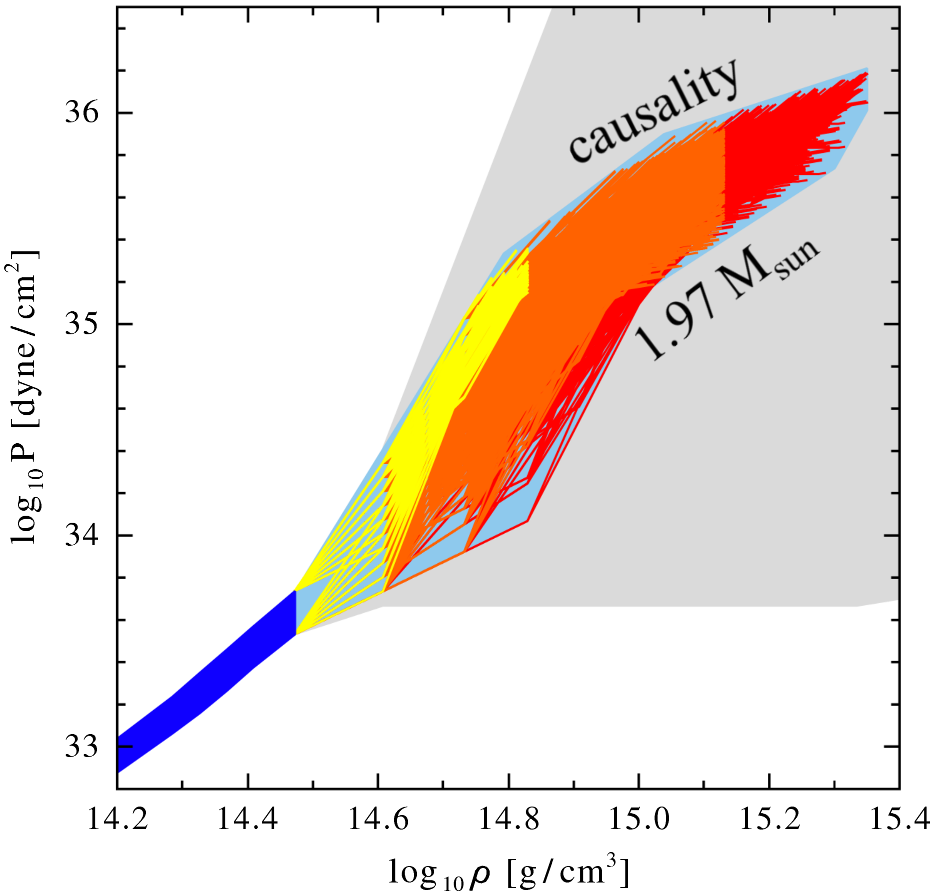
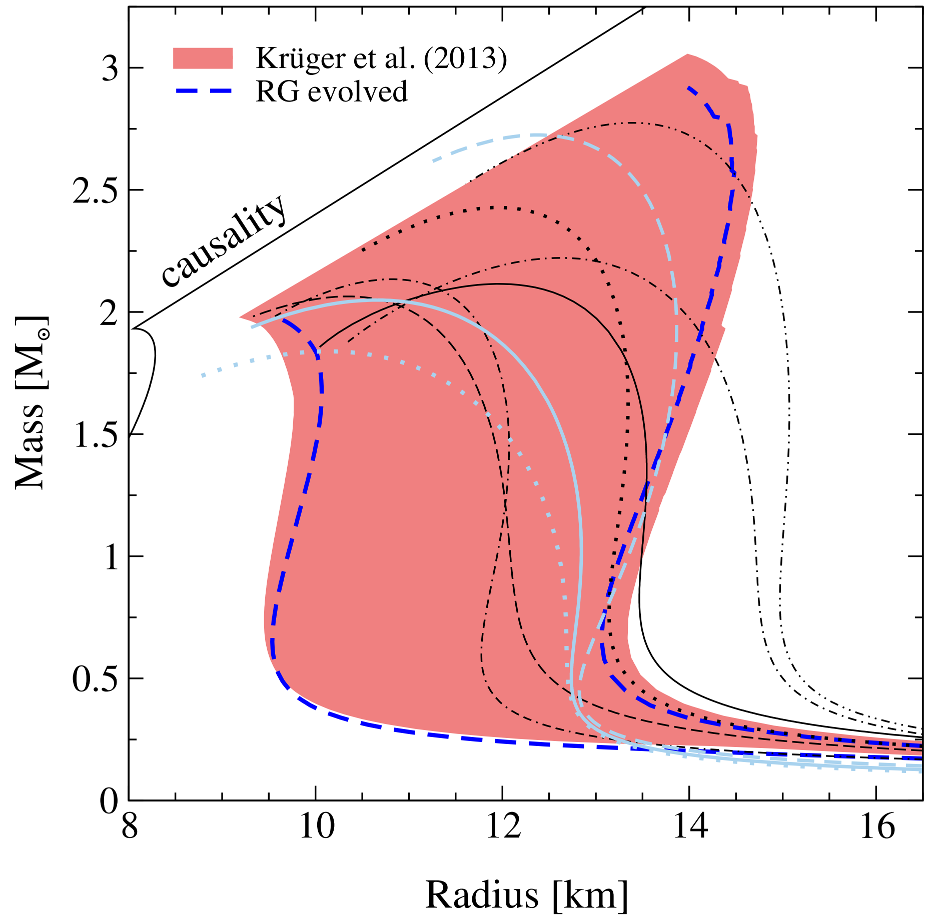


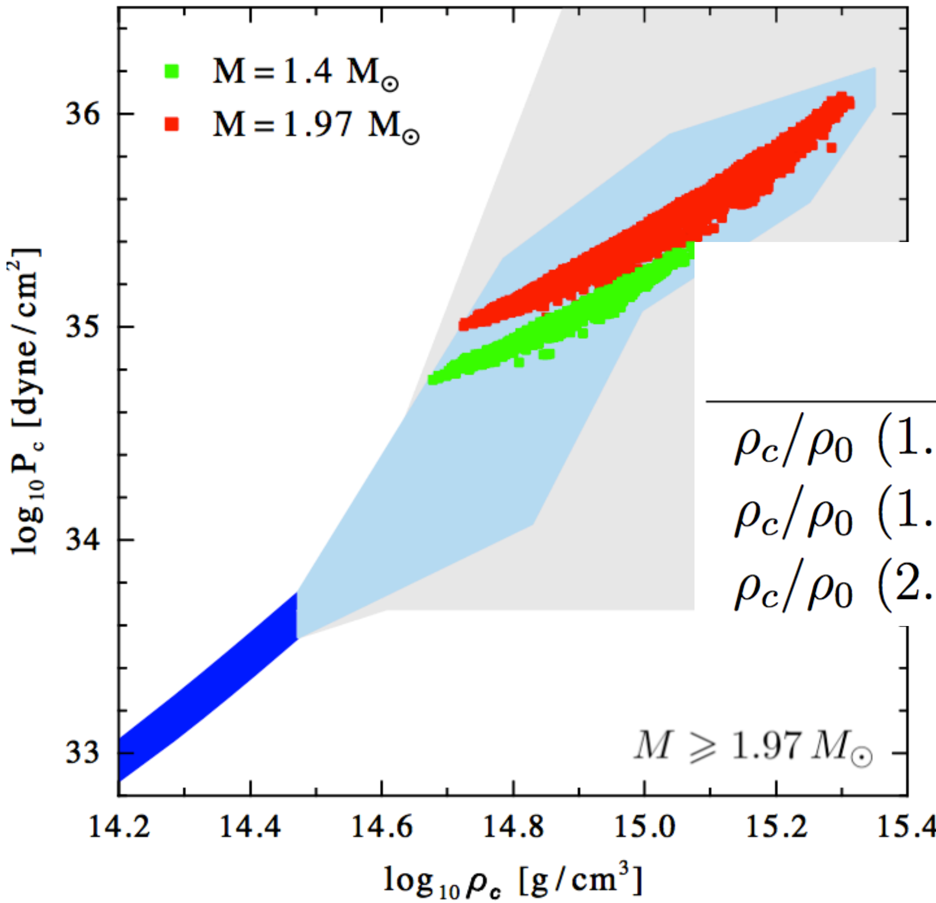


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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



	$\widehat{M} = 1.97\,M_\odot$		$\widehat{M} = 2.4\,M_\odot$	
	min	max	min	max
$\rho_c/\rho_0\ (1.4\,M_\odot)$	1.8	4.4	1.8	2.7
$\rho_c/\rho_0\ (1.97\,M_\odot)$	2.0	7.6	2.0	3.4
$\rho_c/\rho_0\ (2.4\,M_\odot)$			2.2	5.4

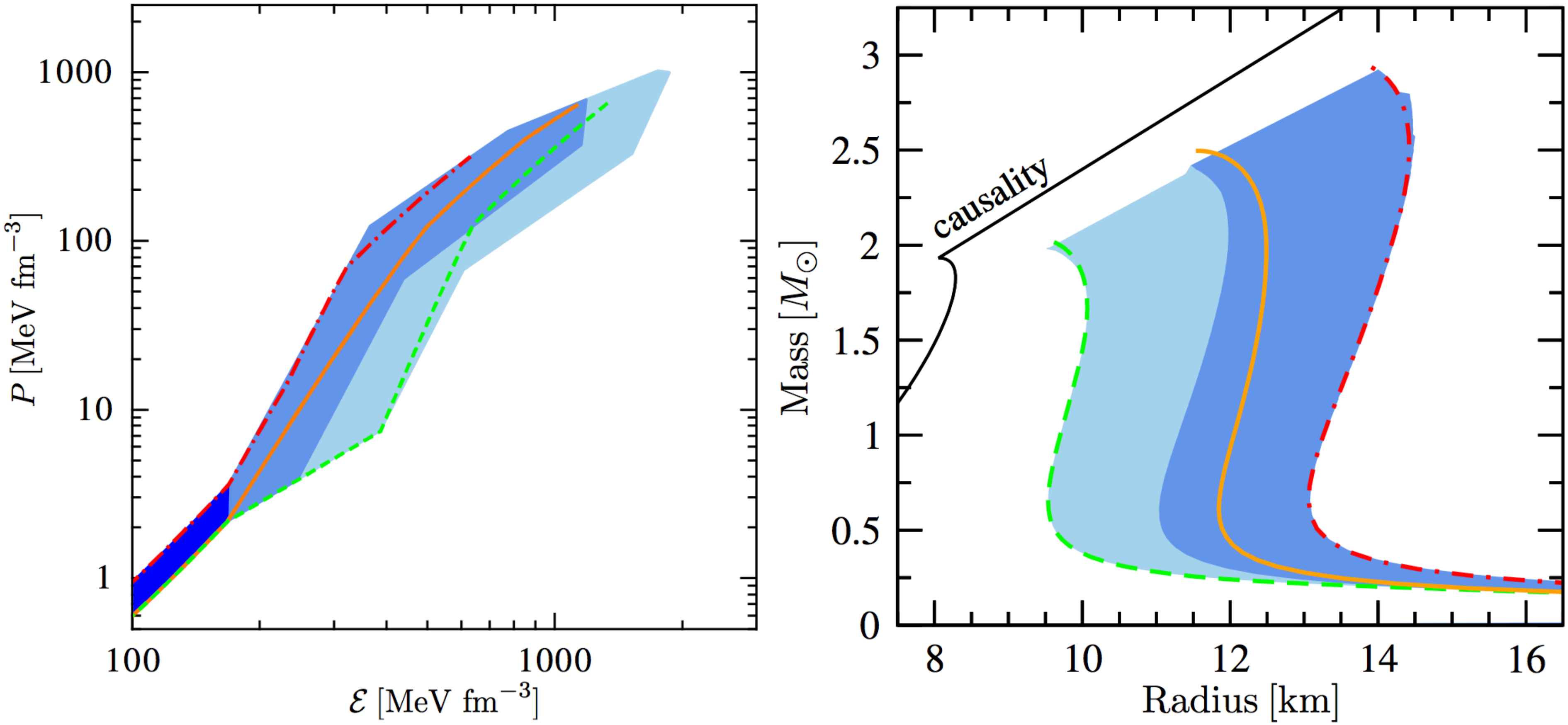
central densities
for 1.4 M_{sun} star: 1.8-4.4 ρ_0

not very high momenta!

Representative equations of state

all EOS for cold matter in beta equilibrium should go through our band

constructed 3 representative EOS for users: soft, intermediate, stiff



used to predict gravitational wave signal from neutron star mergers

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

Main message

3N forces and neutron-rich nuclei

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

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]

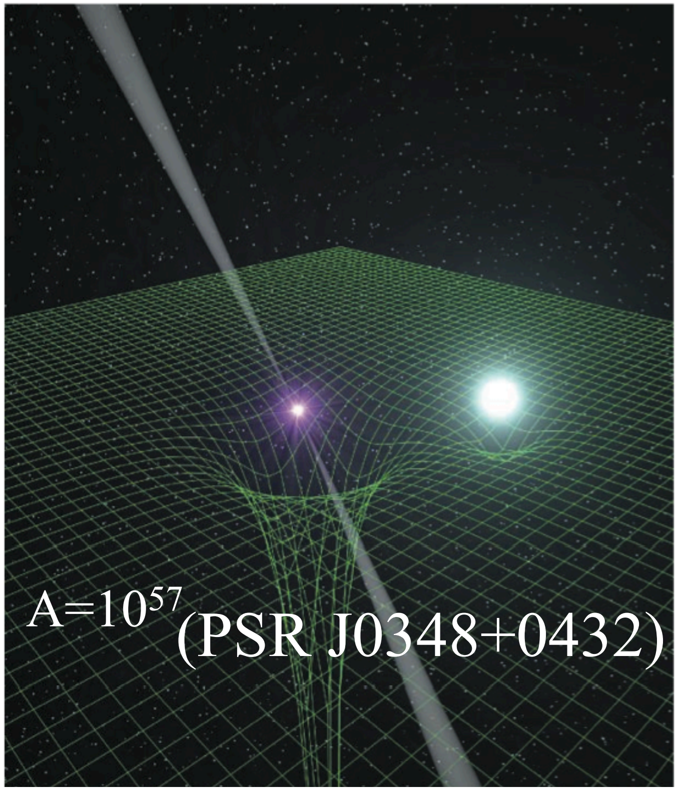
Evidence for a new nuclear ‘magic number’ from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

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!



Dark matter direct detection

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

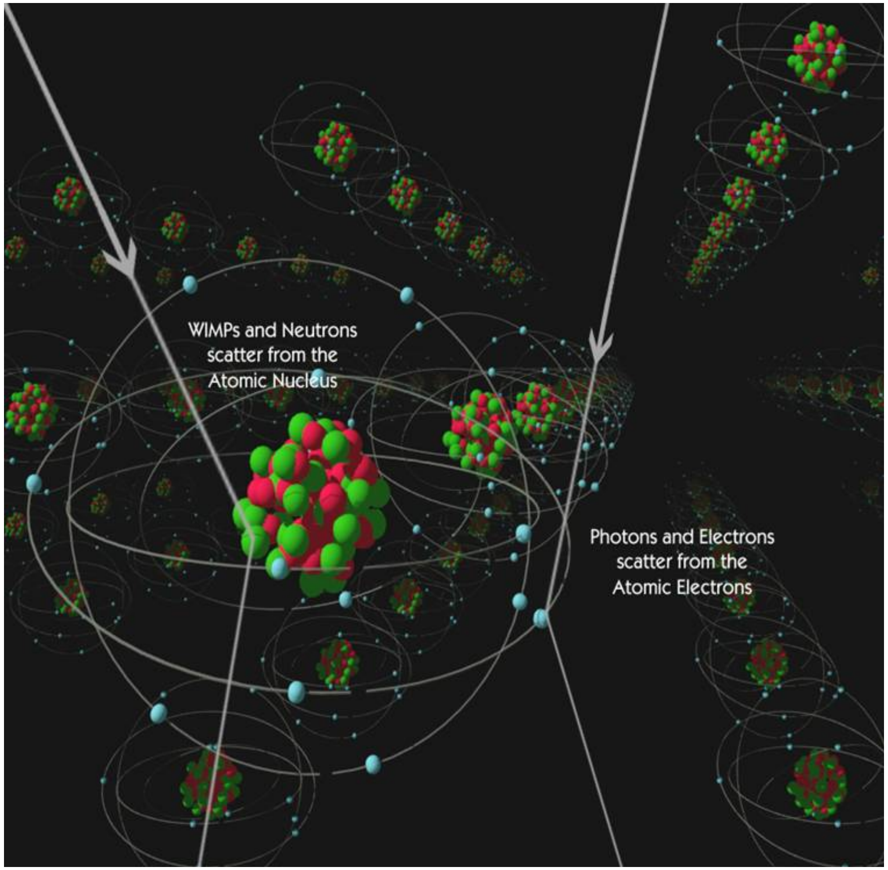
particularly sensitive to nuclear physics for **spin-dependent** couplings

relevant momentum transfers ~ m_π

calculate systematically
with chiral effective field theory

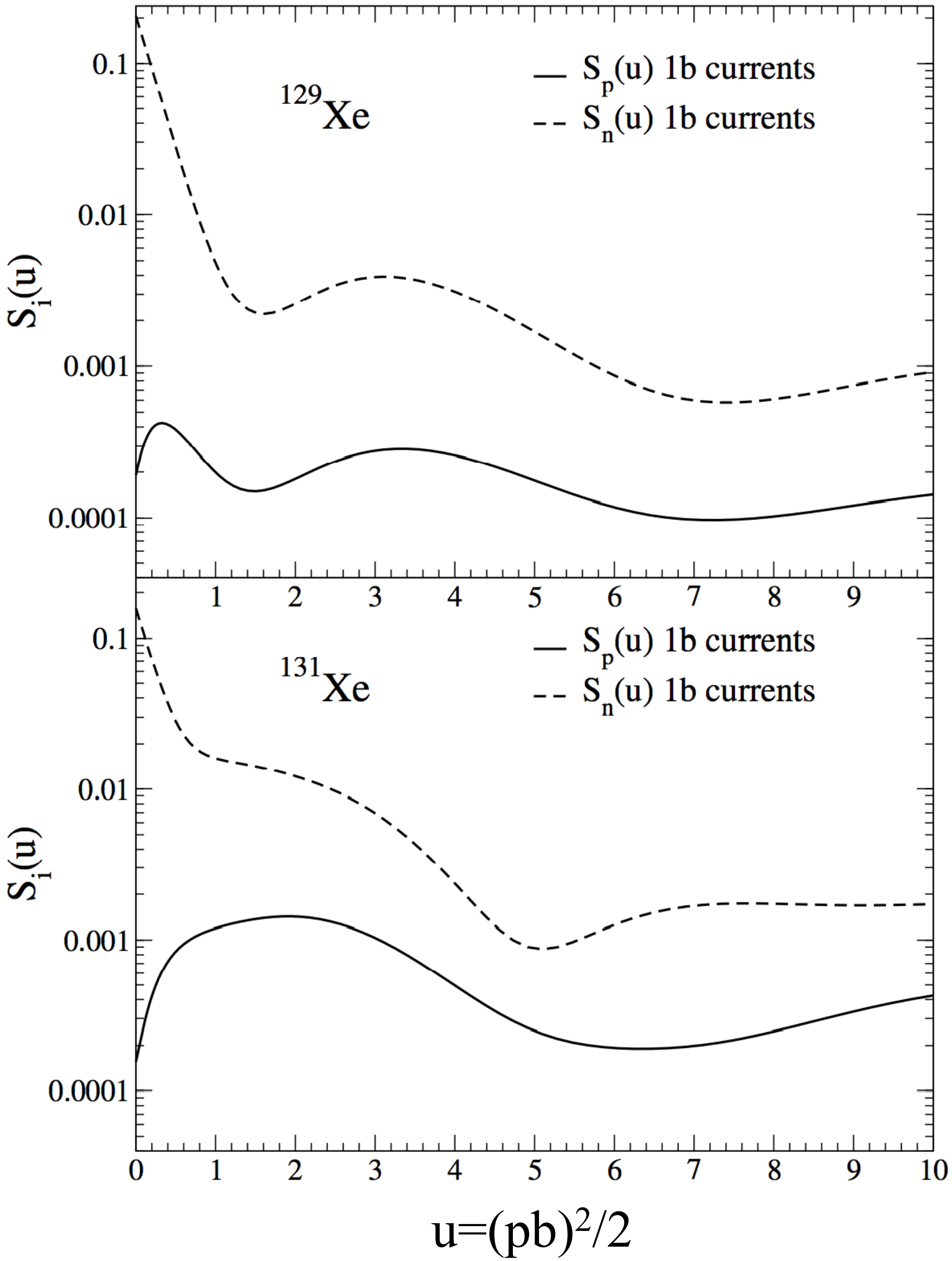
Menéndez, Gazit, AS, PRD (2012),
Klos, Menéndez, Gazit, AS, PRD (2013),
Baudis et al., PRD (2013)
Vietze et al., PRD in press.

incorporate what we know
about QCD/nuclear physics



from CDMS collaboration

Spin structure factors for xenon

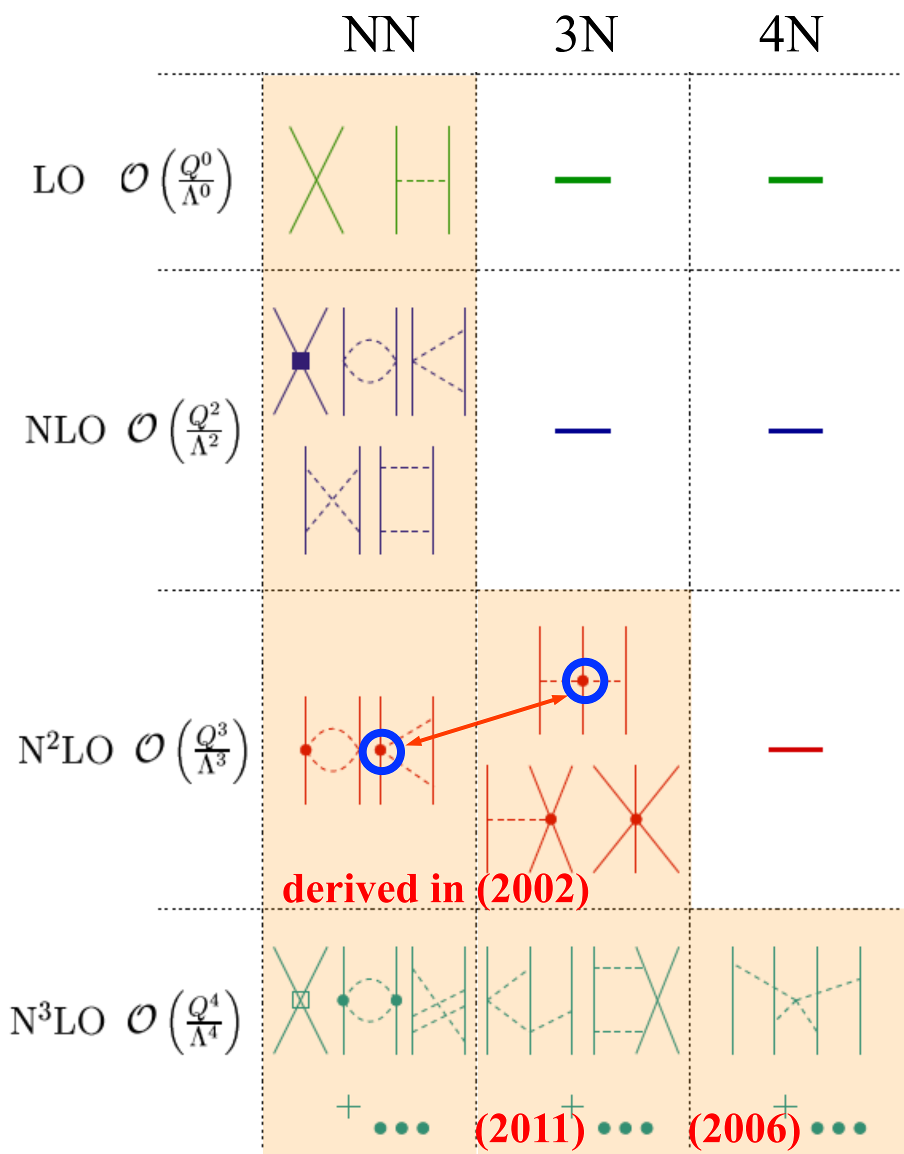


^{129,131}Xe are even Z, odd N, spin is carried mainly by neutrons

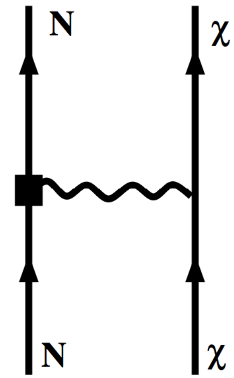
at p=0 structure factors at the level of one-body currents dominated by "neutron"-only

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

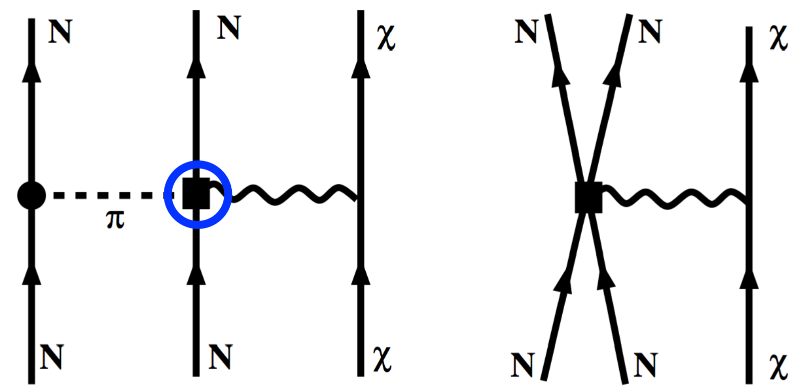
Chiral EFT for spin-dependent WIMP currents in nuclei



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

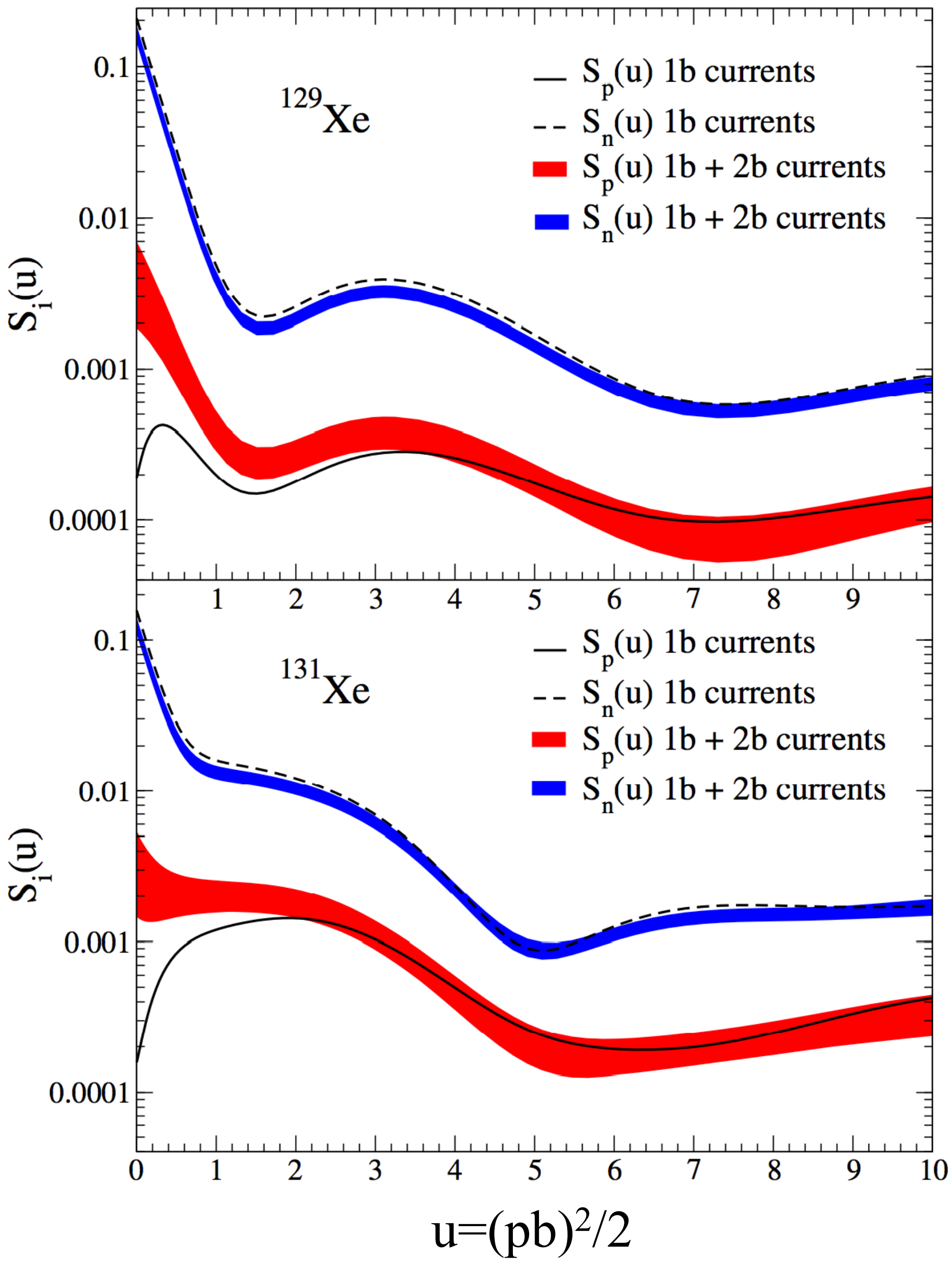


+ two-body currents at Q^3

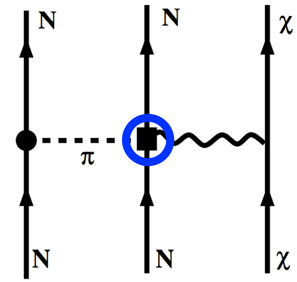


same couplings in forces and currents!

Xenon response with 1+2-body currents



two-body currents due to strong interactions among nucleons



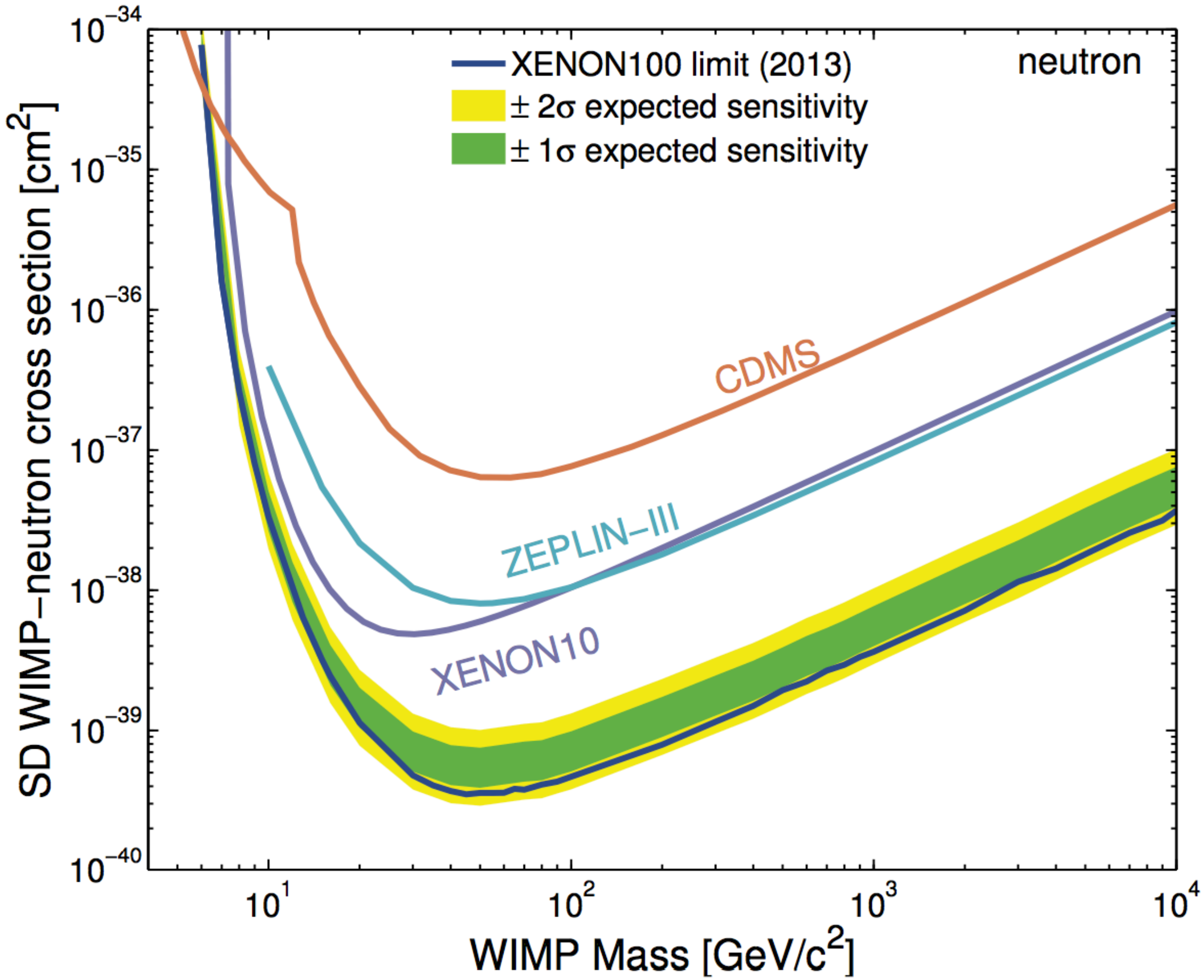
WIMPs couple to neutrons and protons at the same time

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

Limits on SD WIMP-neutron interactions

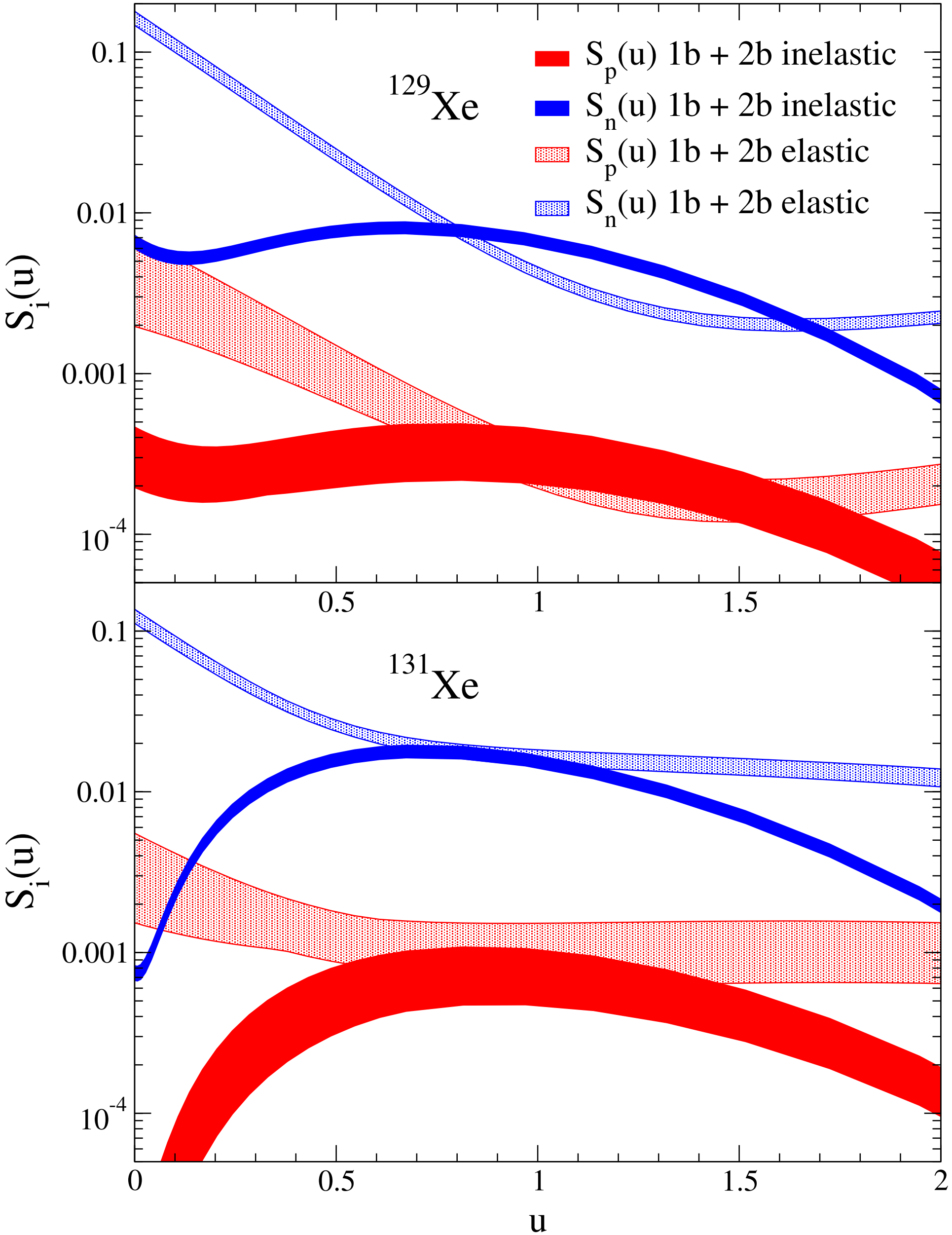
best limits from XENON100 Aprile et al., PRL (2013)

used our calculations with uncertainty bands for WIMP currents in nuclei

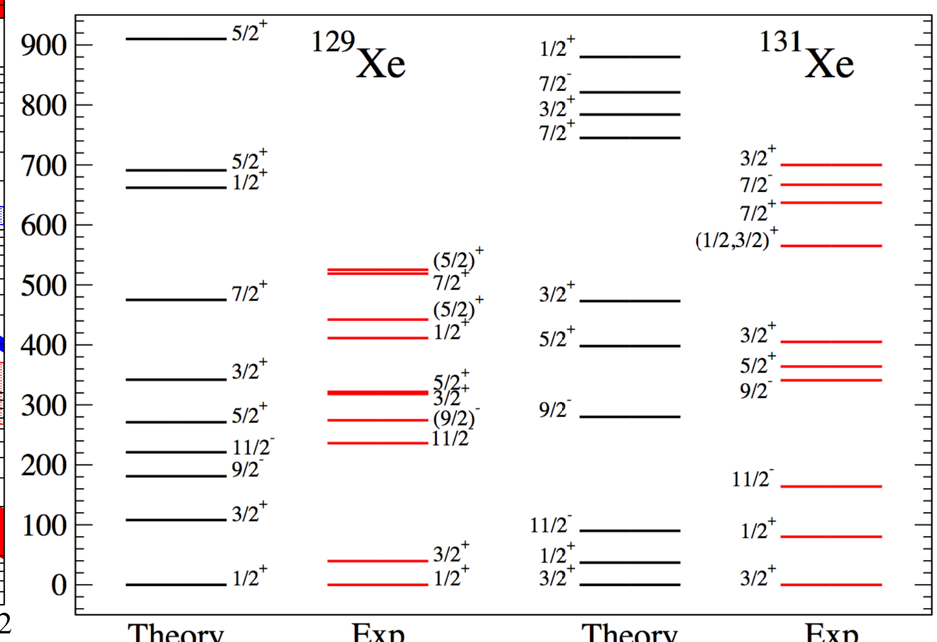


Inelastic WIMP scattering to 40 and 80 keV excited states

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



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

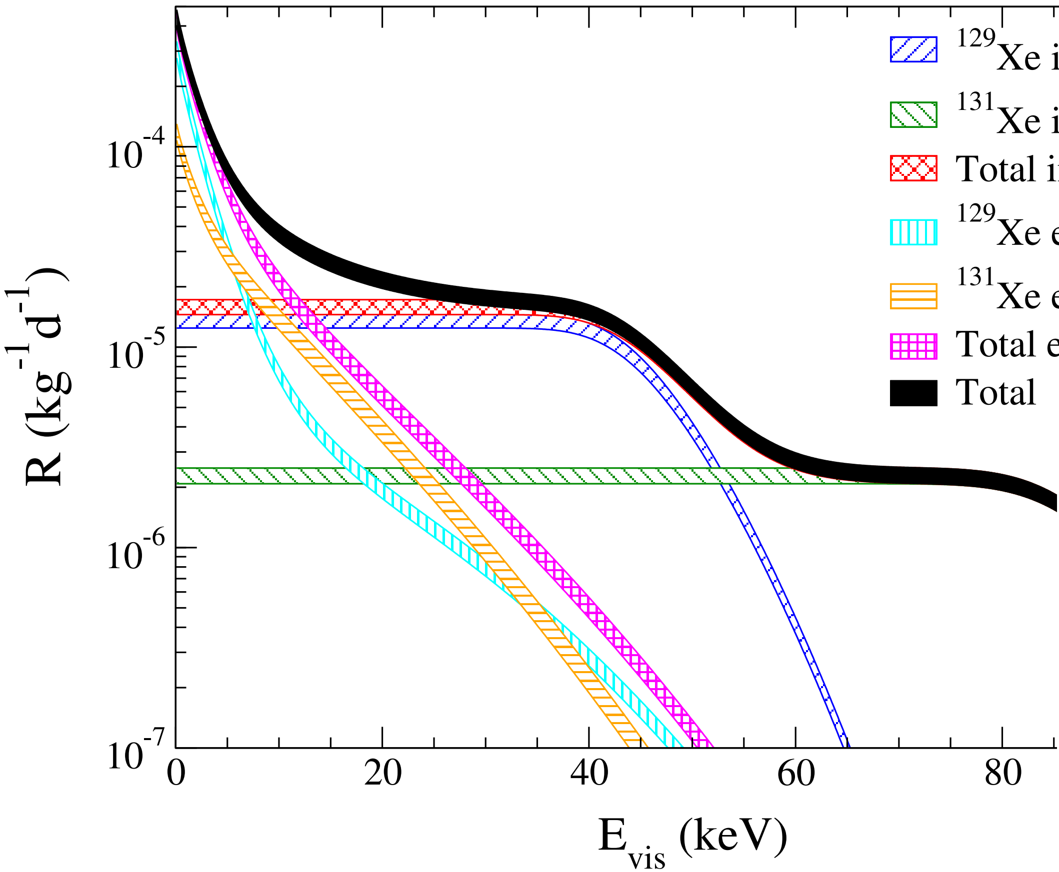


Signatures for **inelastic** WIMP scattering

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

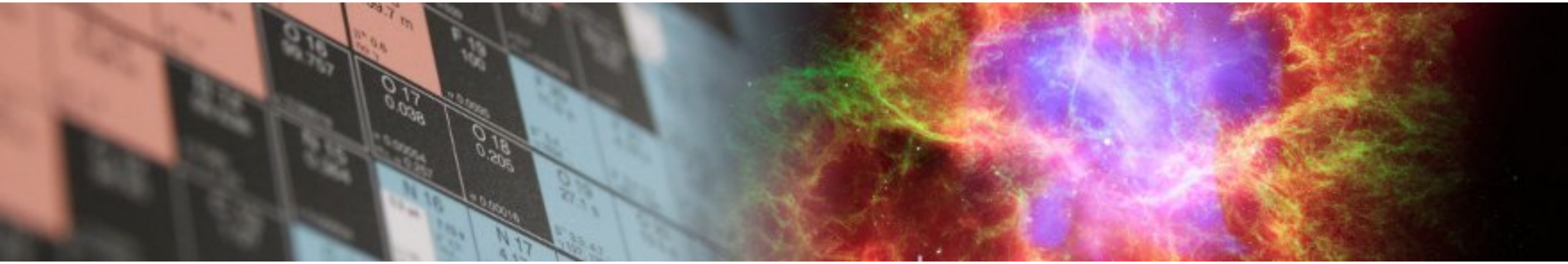


Mass [GeV]	^{129}Xe	^{131}Xe	Total
10	–	–	–
25	5	–	5
50	7	17	9
100	7	24	12
250	9	32	19
500	11	35	24

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.

Summary

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



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

3N forces key for neutron-rich nuclei

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

for neutron-rich matter and neutron stars

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

future: lattice QCD to connect chiral EFT to QCD and
to further constrain low-energy couplings