Three-nucleon forces:
From neutron-rich nuclei to matter in astrophysics

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TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

EGAN Workshop, GSI

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Main message

3N forces and neutron-rich nuclei

with Jason Holt, Javier Menendez, Taka Otsuka, Johannes Simonis, Toshio 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]

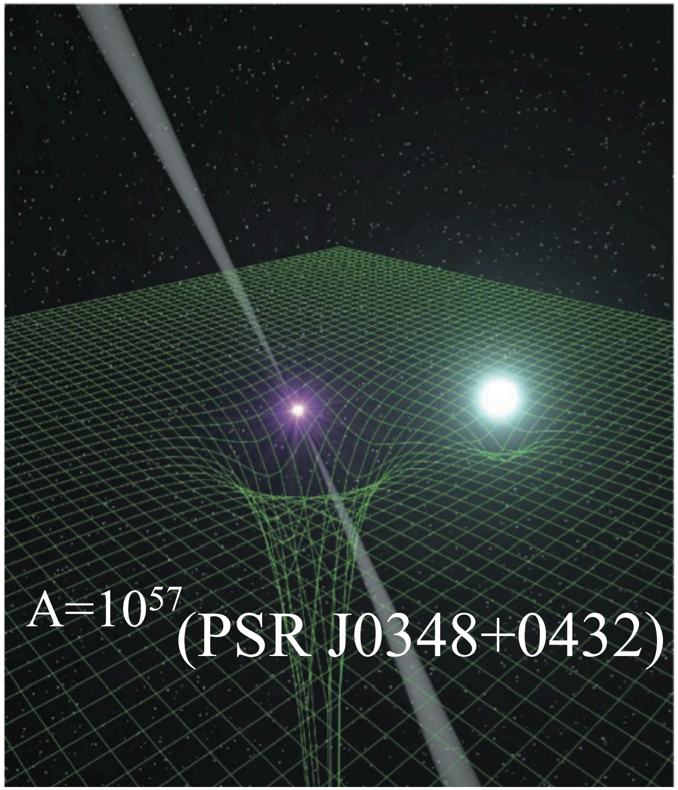
Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

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

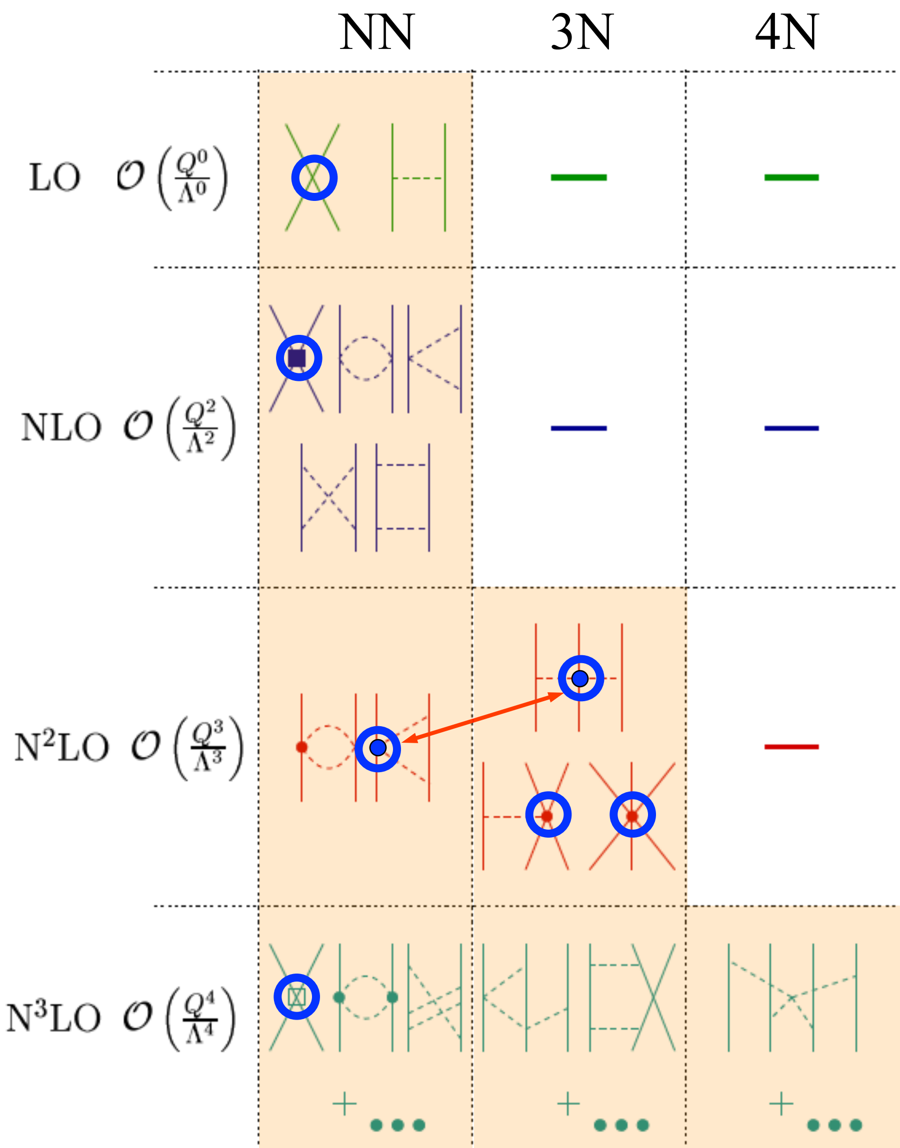
with Kai Hebeler, Thomas Krüger, Ingo Tews

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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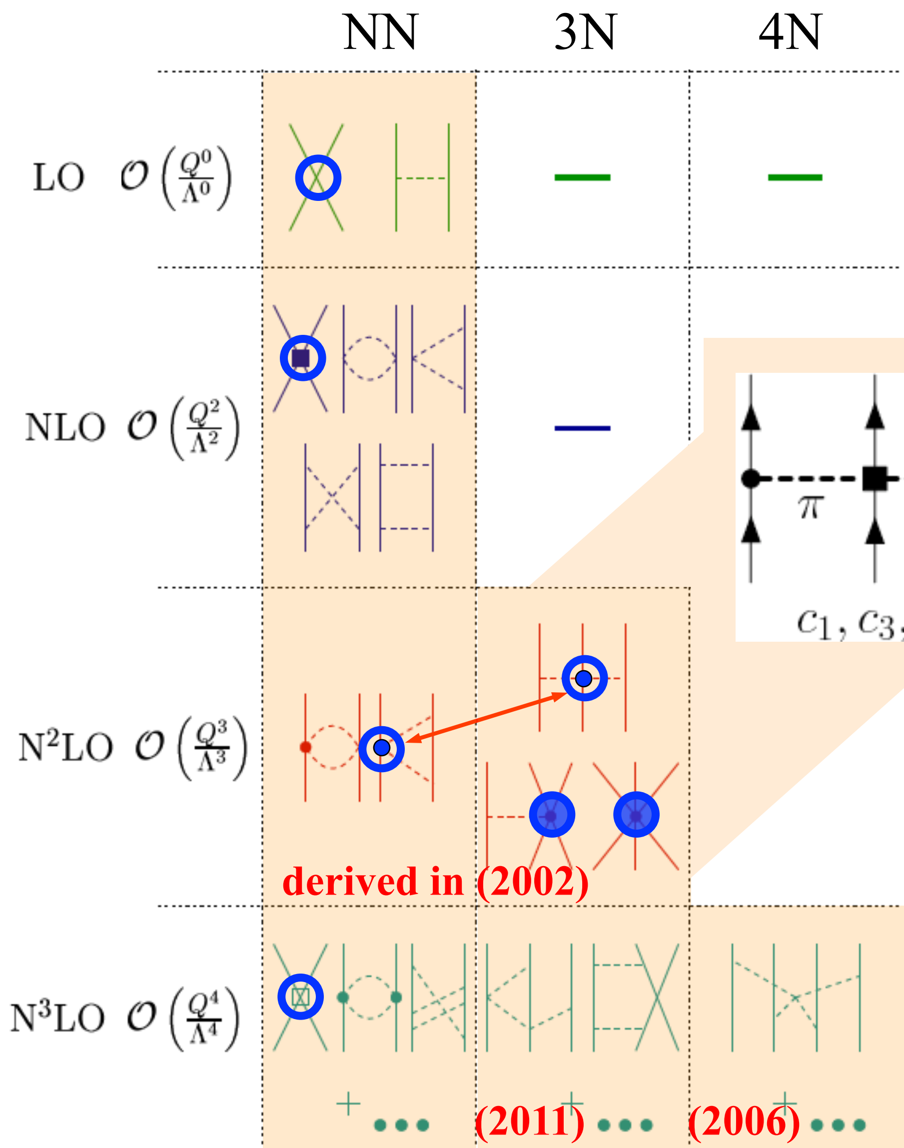
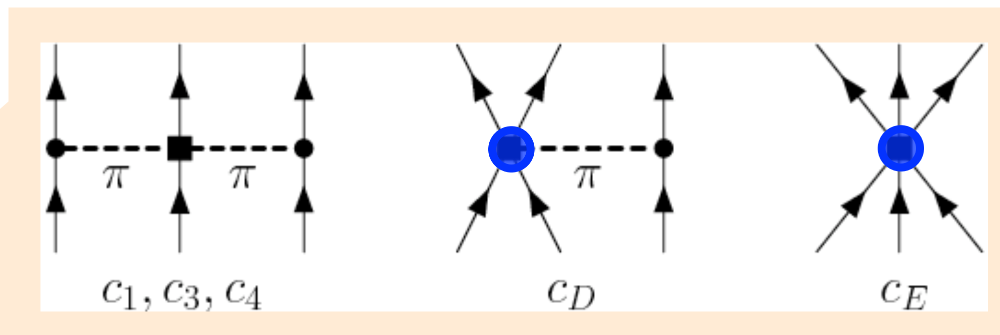


consistent NN-3N-4N interactions

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

+ no new couplings for neutrons



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

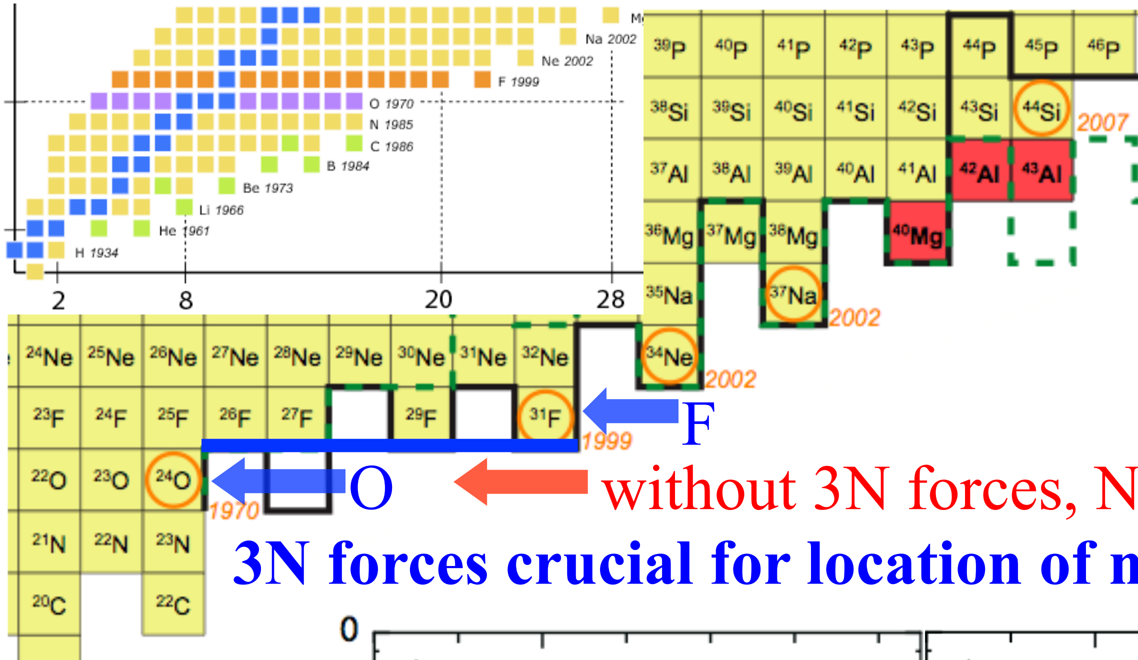
$$c_1 = -0.9^{+0.2}_{-0.5}\,, \quad c_3 = -4.7^{+1.2}_{-1.0}\,, \quad c_4 = 3.5^{+0.5}_{-0.2}$$

c_D, c_E fit to light nuclei only

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

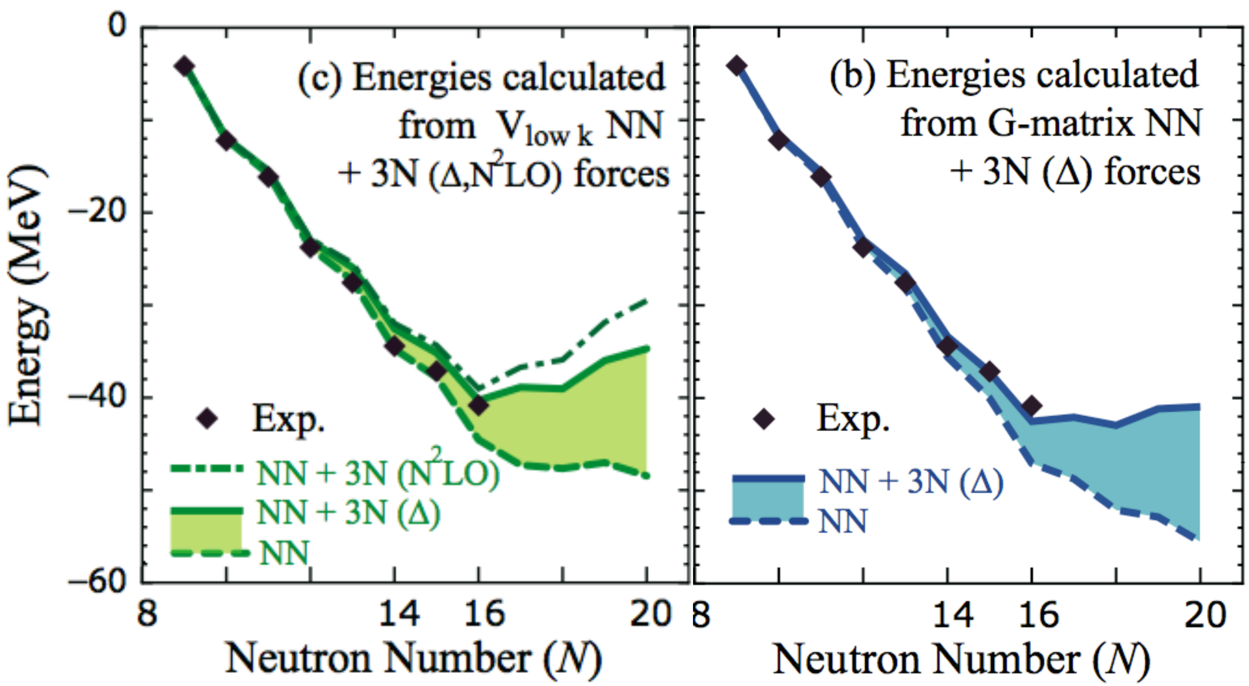
The oxygen anomaly

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



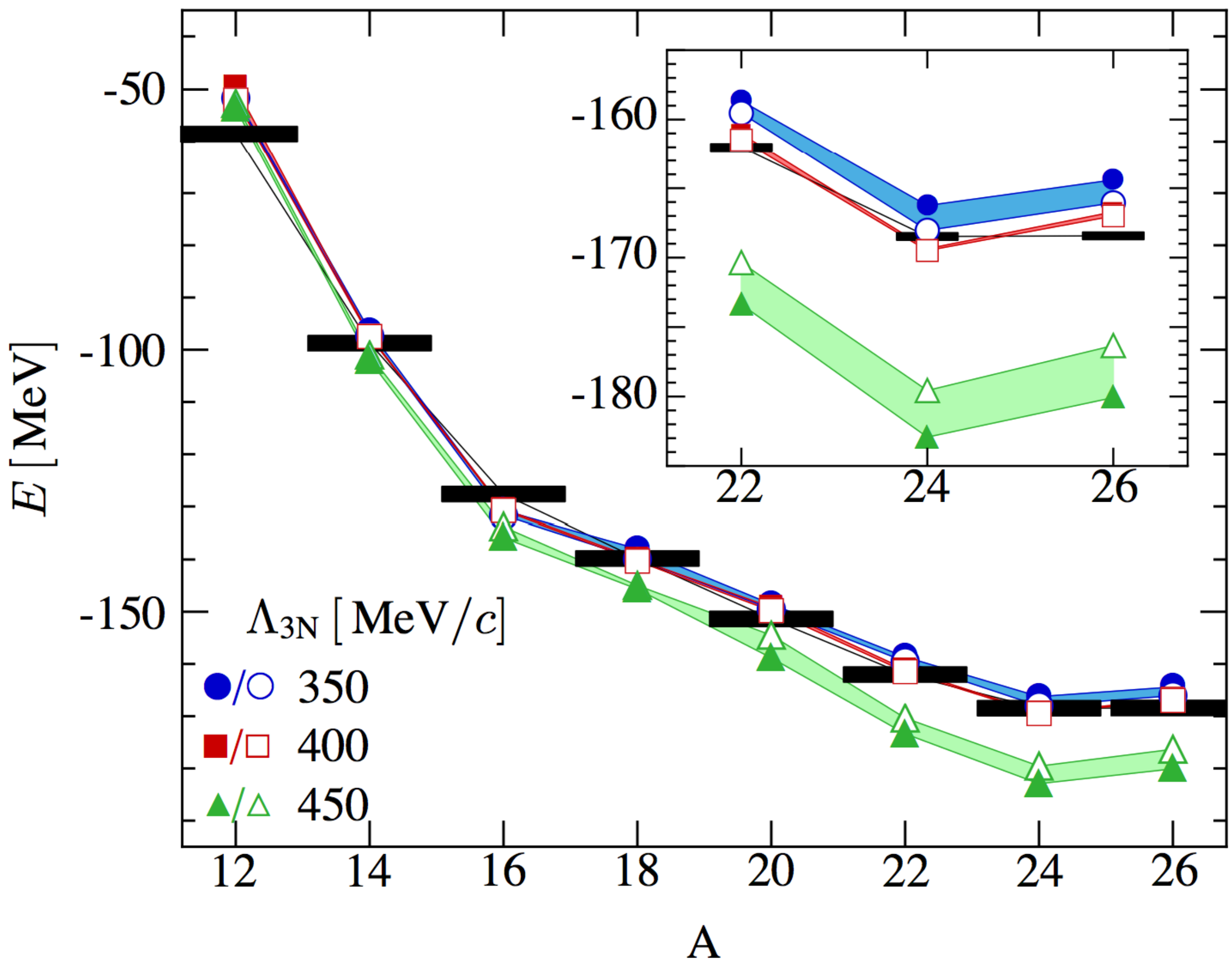
without 3N forces, NN interactions too attractive

3N forces crucial for location of neutron dripline



New ab initio methods extend reach

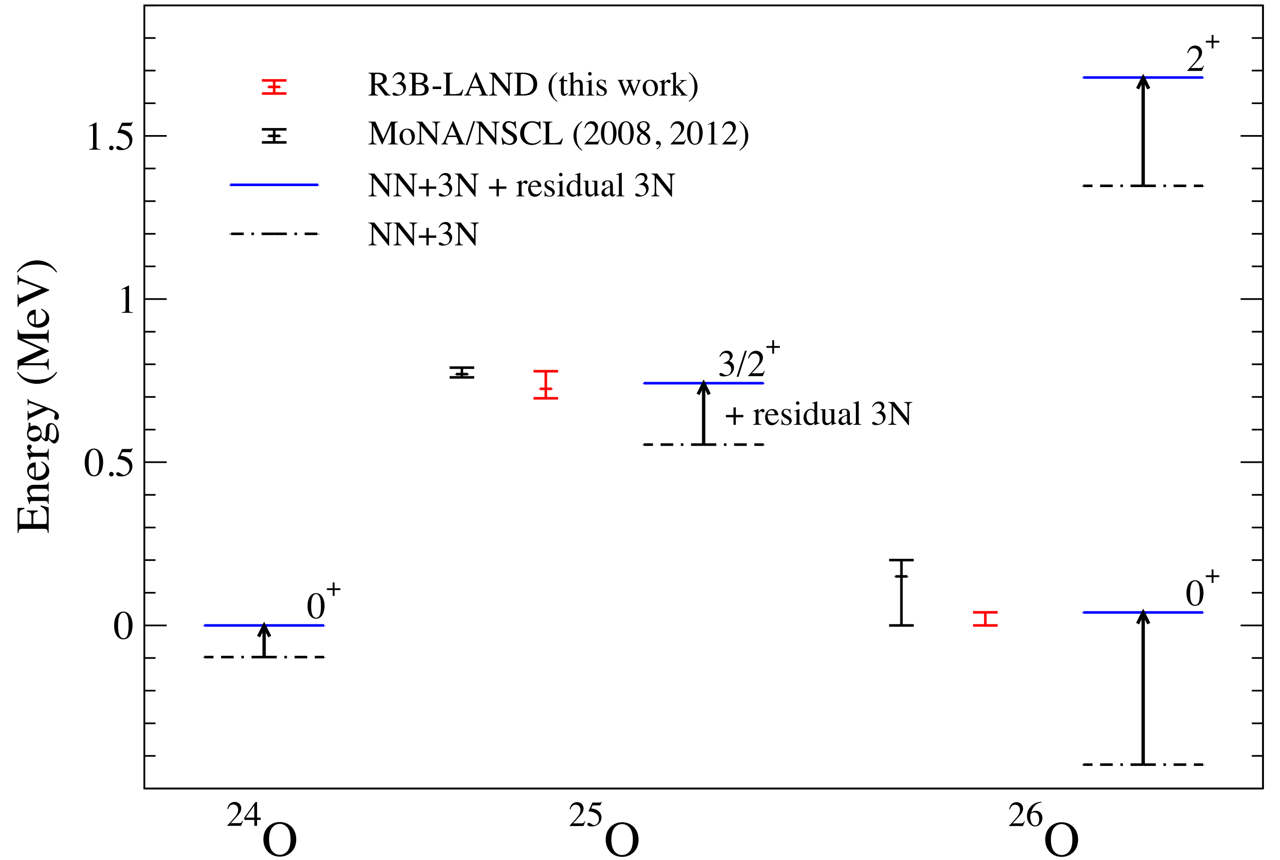
impact of 3N forces confirmed in large-space calculations:
Coupled Cluster theory with phenomenological 3N Hagen et al., PRL (2012)
In-Medium Similarity RG based on chiral NN+3N Hergert et al., PRL (2013)
Green's function methods based on chiral NN+3N Cipollone et al., PRL (2013)

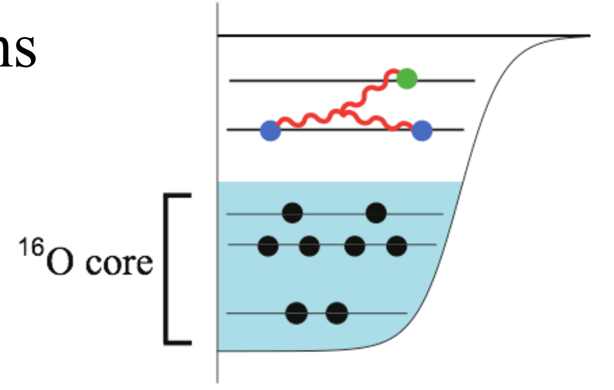


Residual 3N forces and extreme neutron-rich nuclei

amplified in the shell model with valence nucleons

R3B collaboration, **Simonis**, Holt, Menendez, AS, PRC (2013)



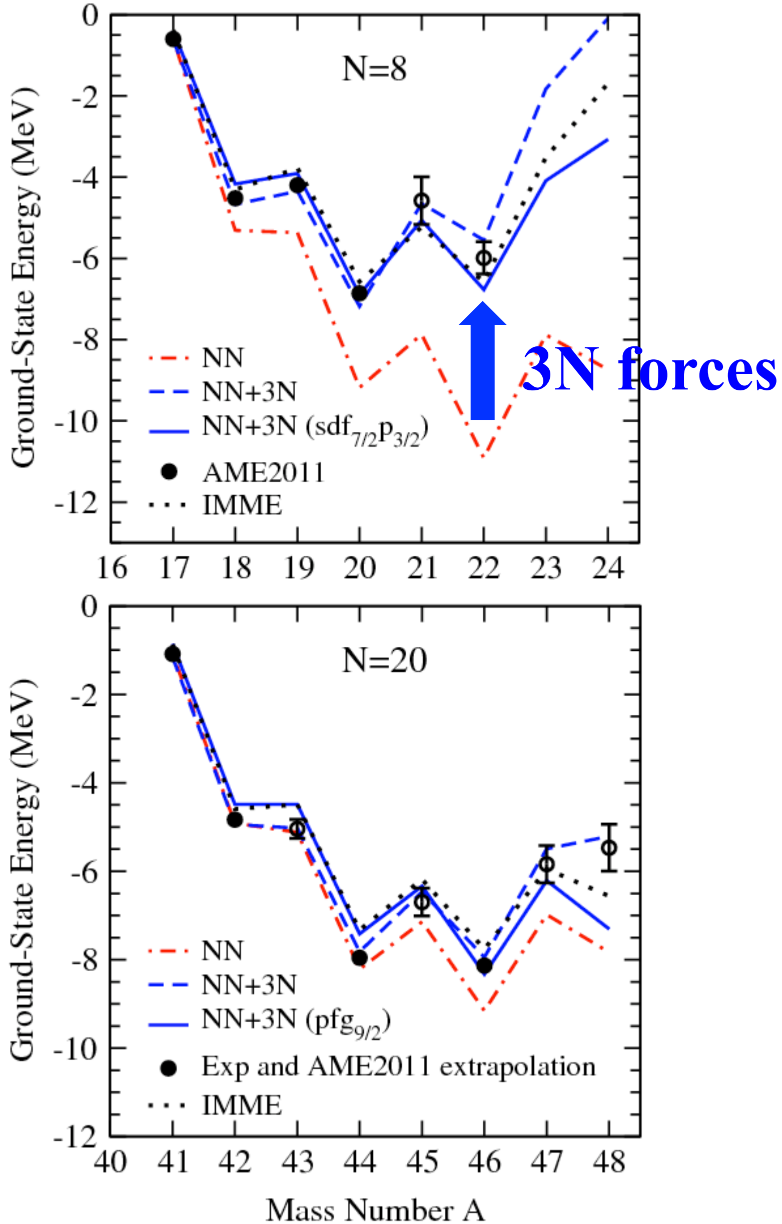


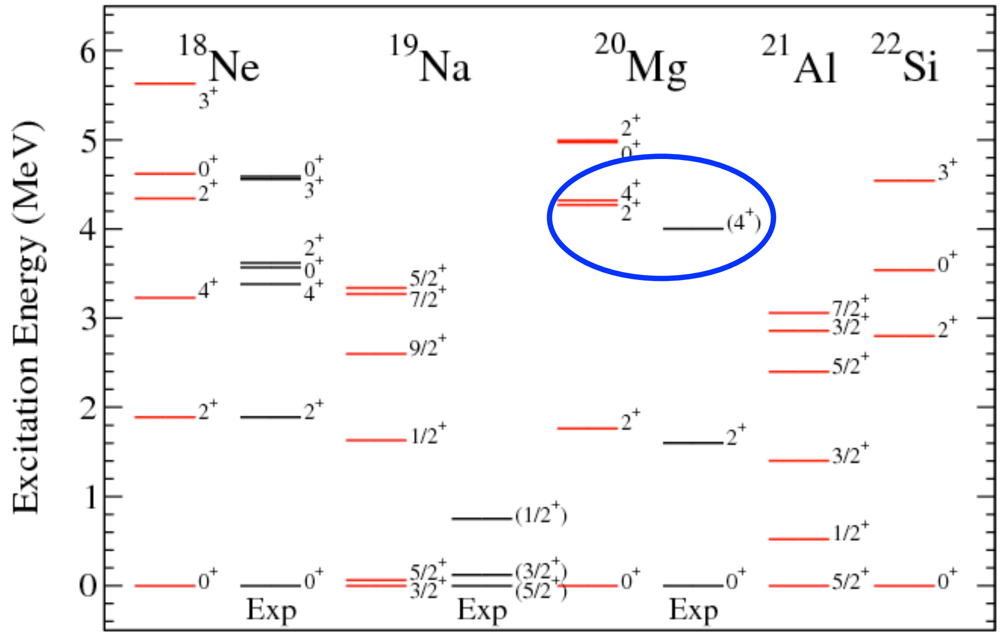
residual 3N small compared to normal-ordered contributions

increases with N, important for neutron-rich $^{25,26}O$
studied at MoNA/NSCL, R3B-LAND, RIBF

3N forces and proton-rich nuclei Holt, Menendez, AS, PRL (2013)

first results with 3N forces for ground and excited states of N=8, 20



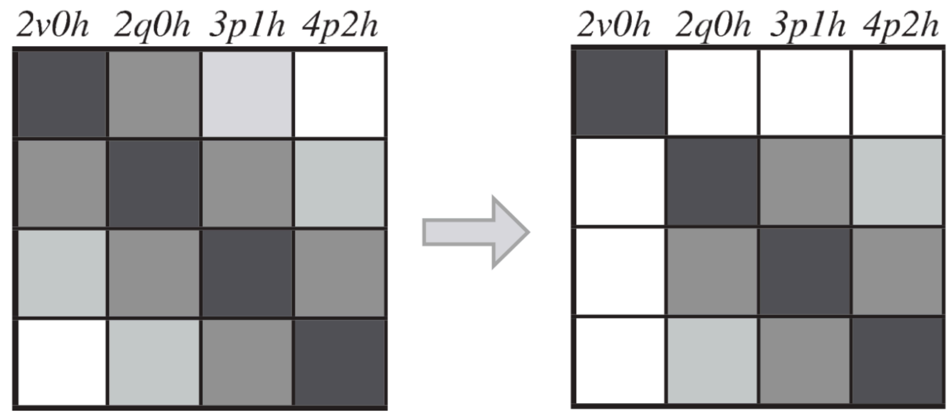


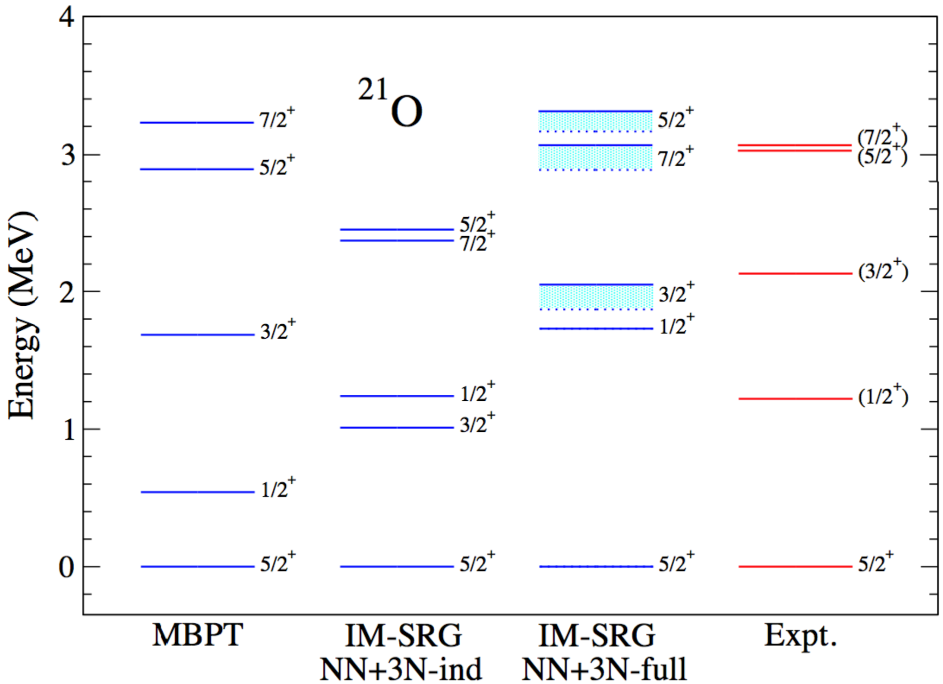
prediction for ^{20}Mg agrees with new state observed at GSI Mukha, private comm.

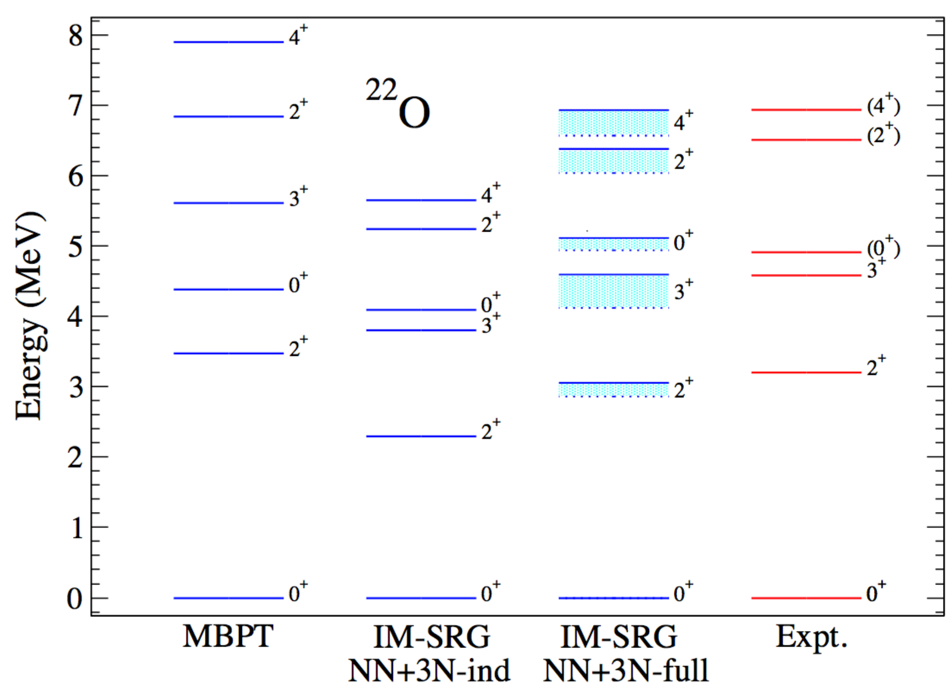
Ab initio calculations going open shell: SM interactions

In-Medium Similarity RG
to derive valence-shell interactions

Tsukiyama, Bogner, AS, PRL (2011), PRC (2012)
Bogner, **Hergert, Holt**, AS et al., 1402.1407







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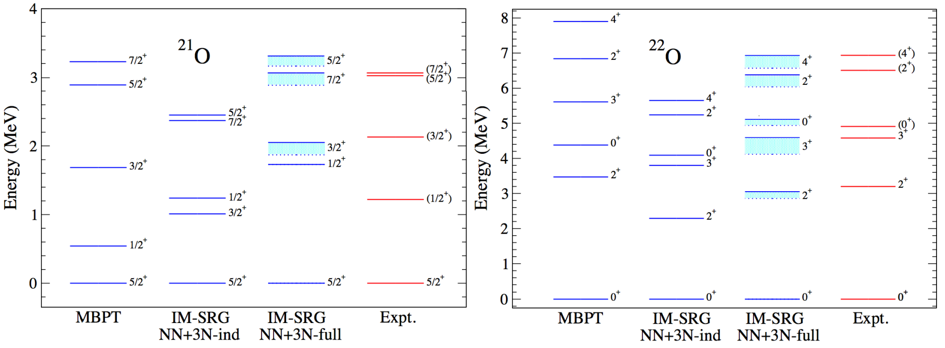
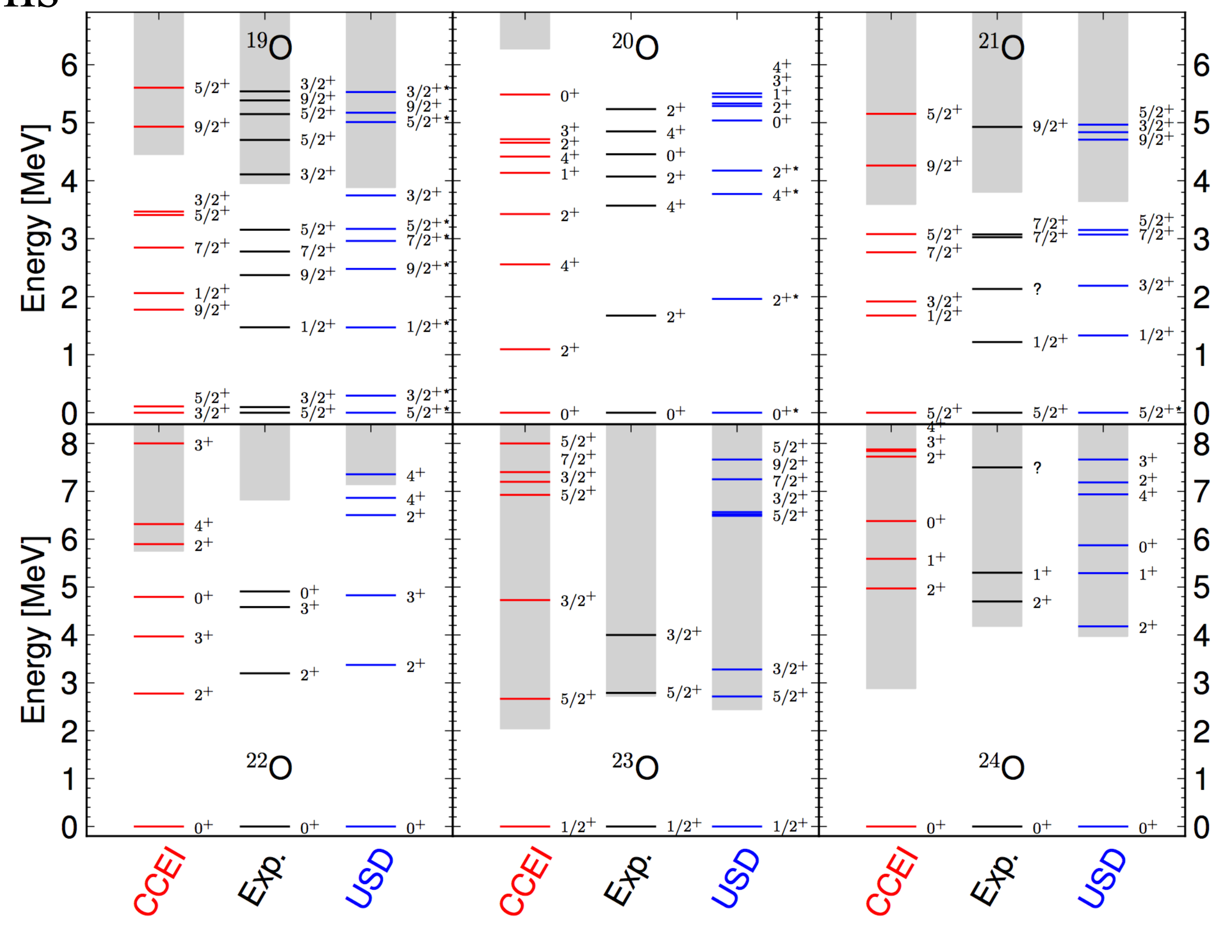


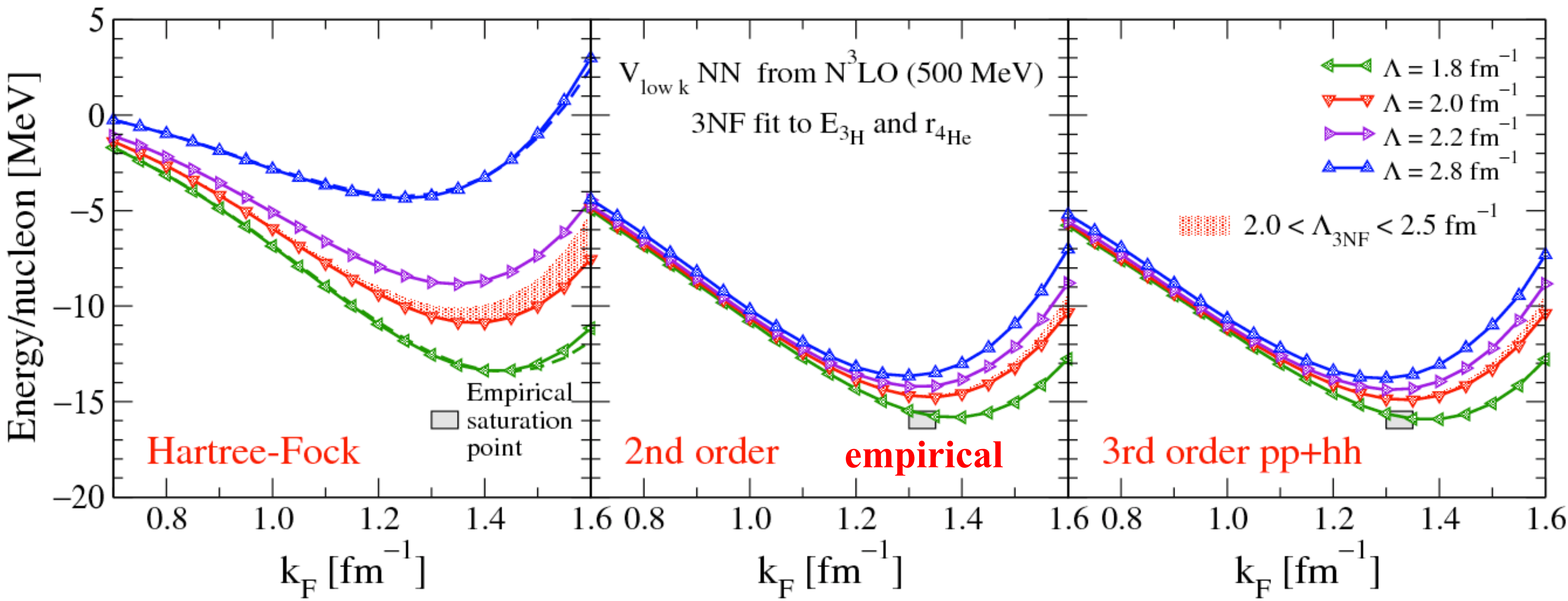
Coupled Cluster calculations for effective interactions

Jansen et al., arXiv:1402.2563



Impact of 3N forces on nuclear matter

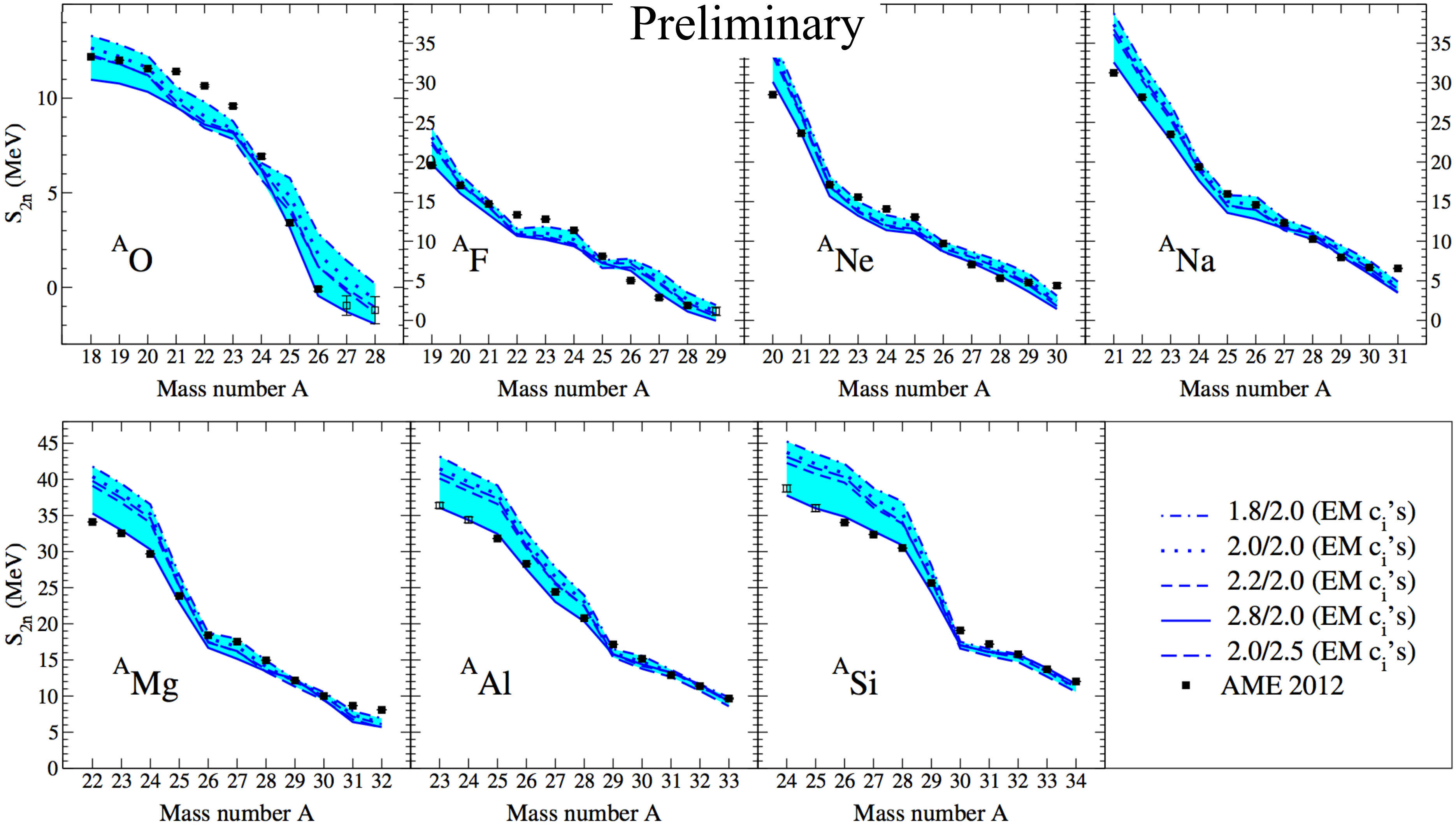
chiral 3N forces fit to light nuclei predict nuclear matter saturation with theoretical uncertainties Hebeler et al. (2011), Bogner et al. (2005)



Towards theoretical uncertainties

Simonis, Holt, Hebeler, Menendez, AS, in prep.

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



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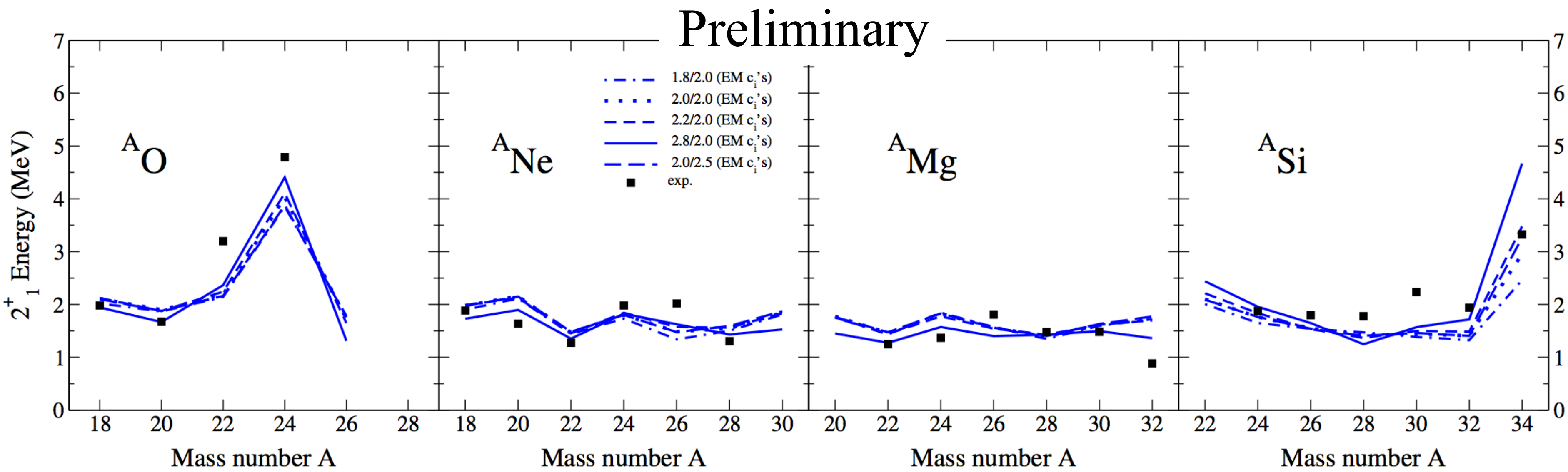
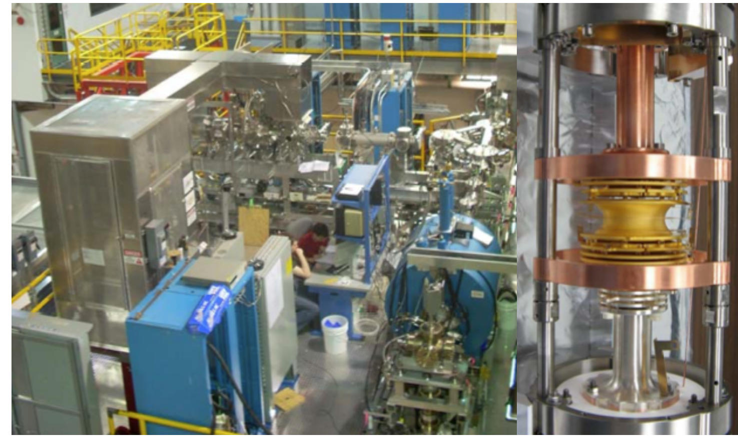


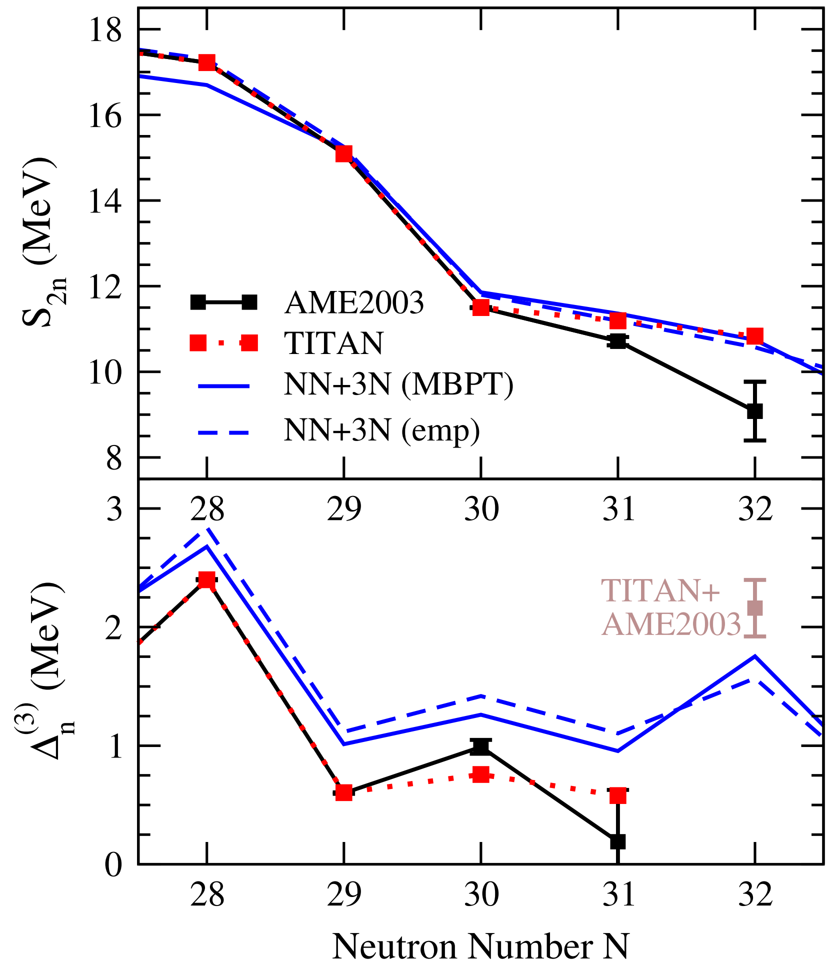
new ^{51,52}Ca TITAN measurements

^{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

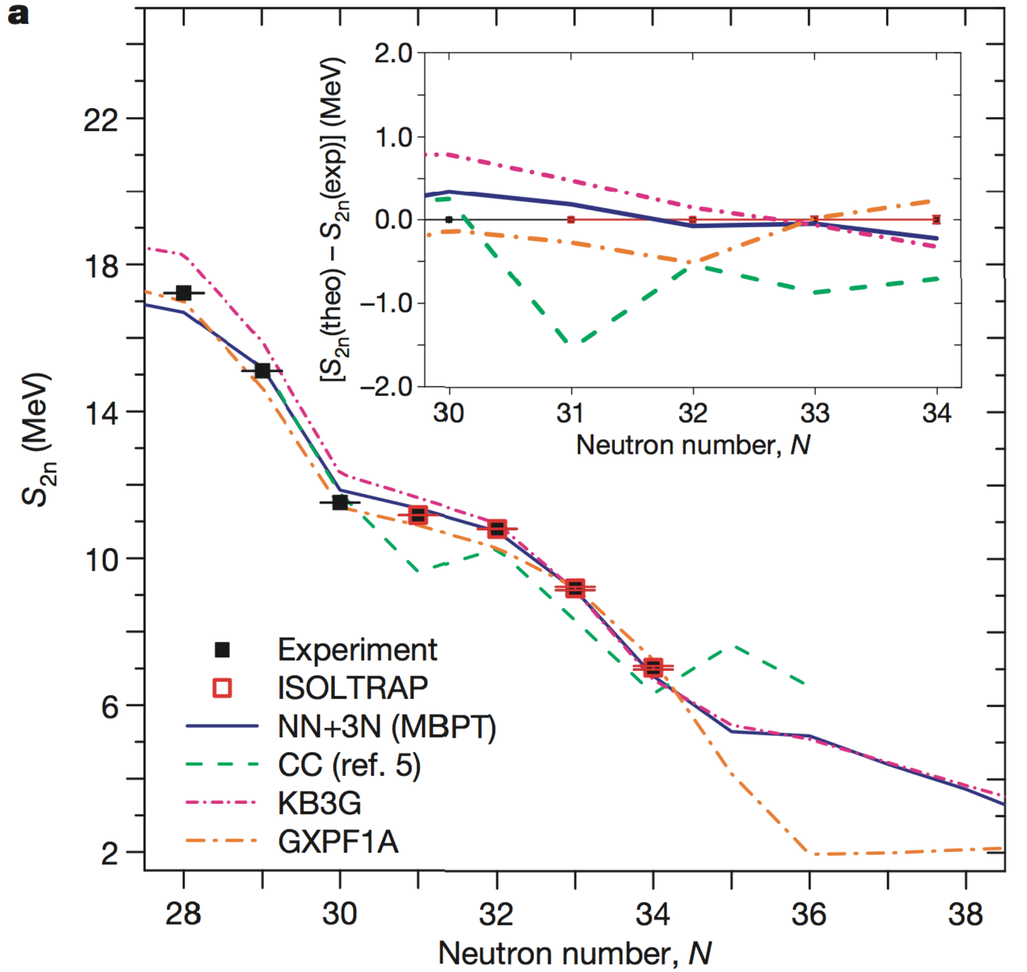
Masses of exotic calcium isotopes pin down nuclear forces

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



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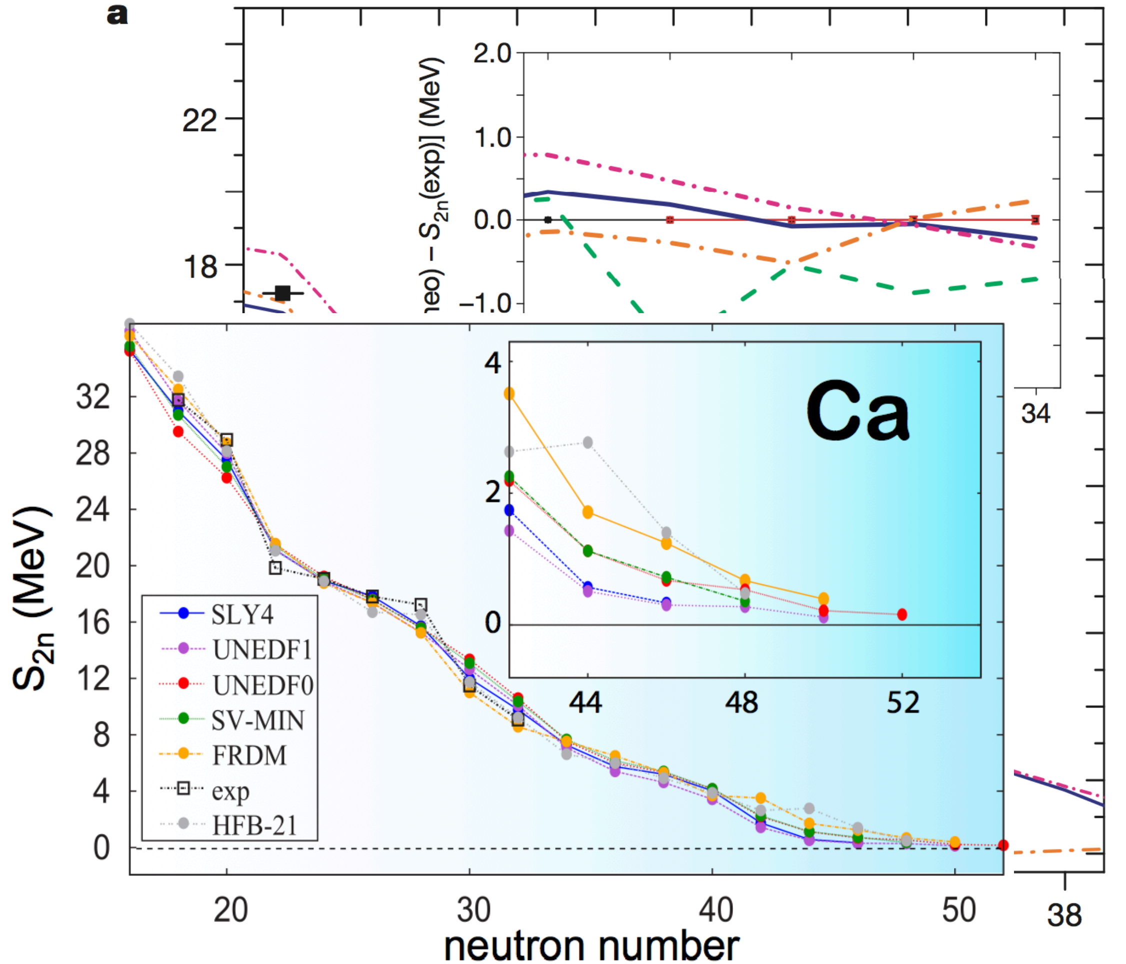
^{53,54}Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

interesting continuum effects for very neutron-rich Ca

see Forssen et al., Physica Scripta (2013)



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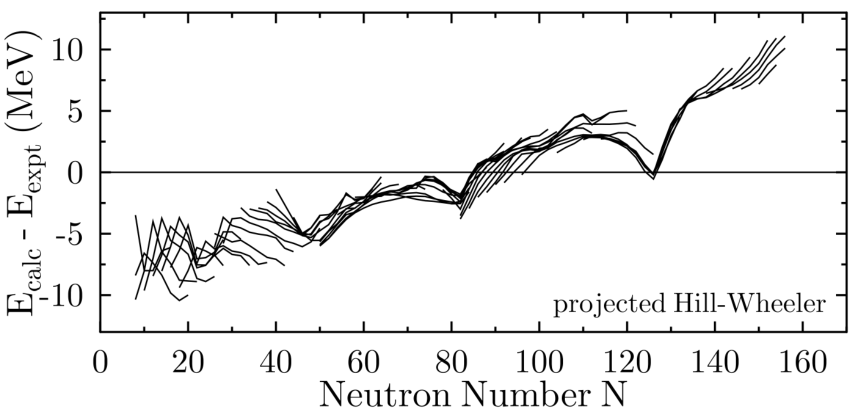
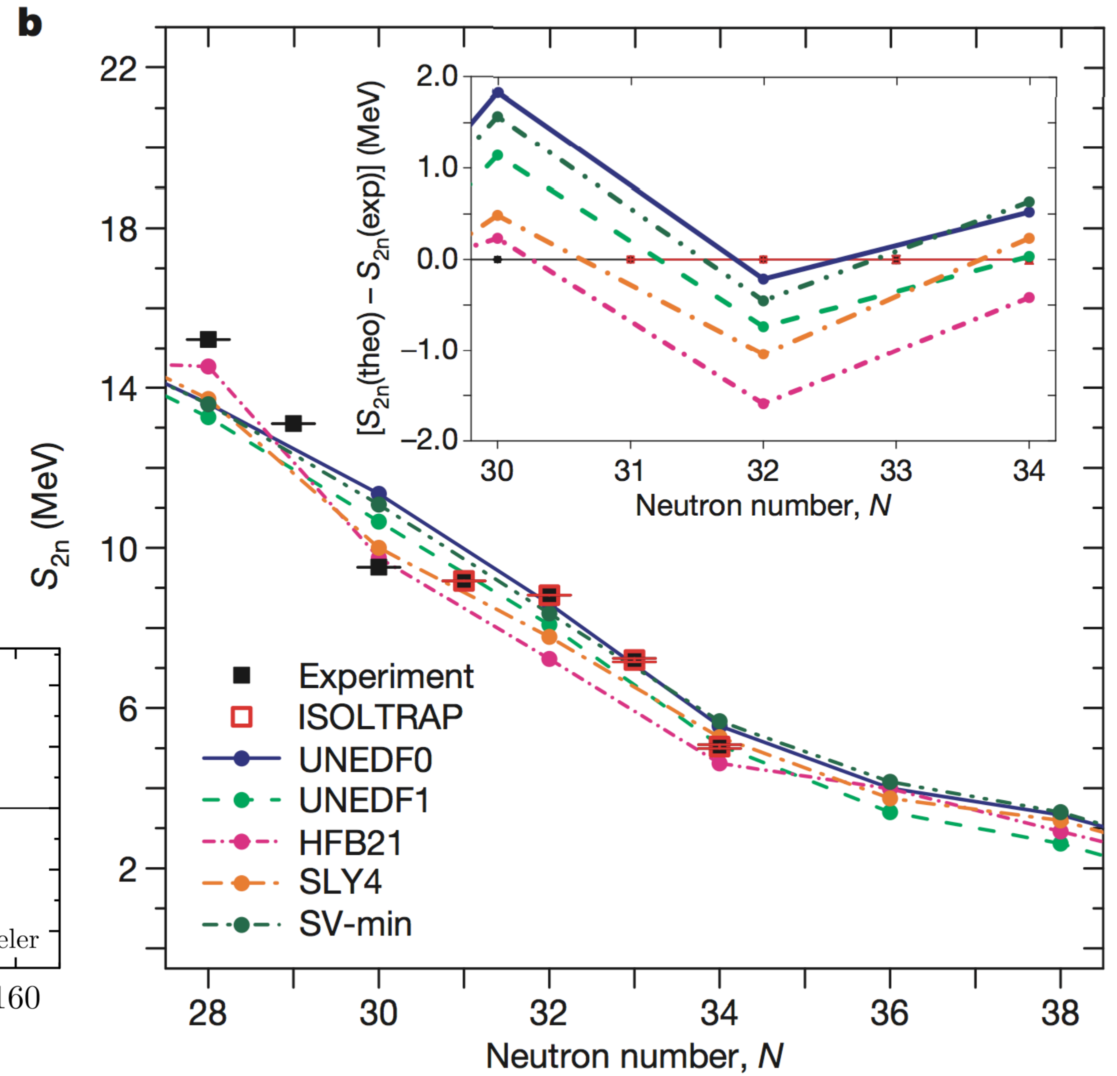
overall good agreement with density functional predictions

but DF's do not reproduce shell closures

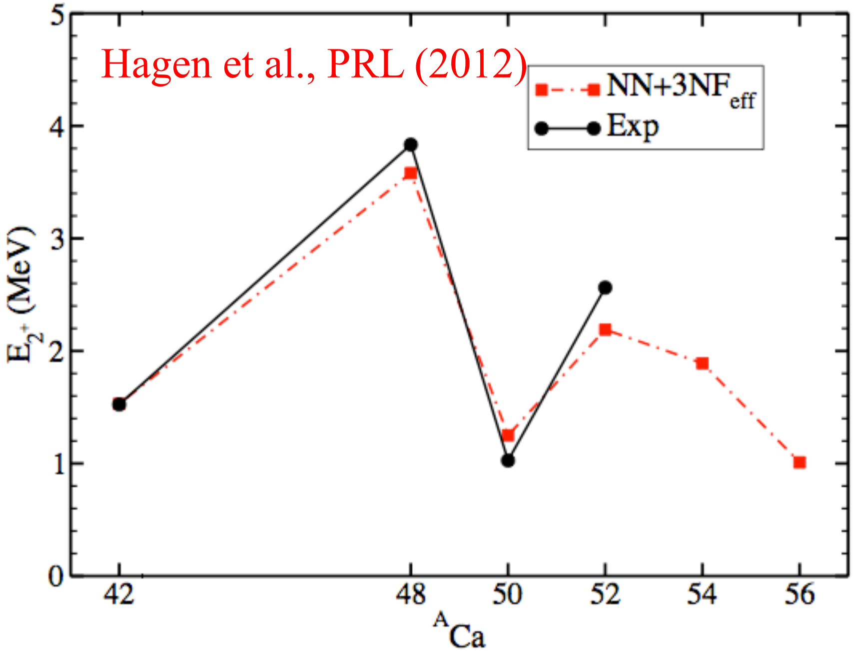
cf. N=50, 82, 126 "arches"

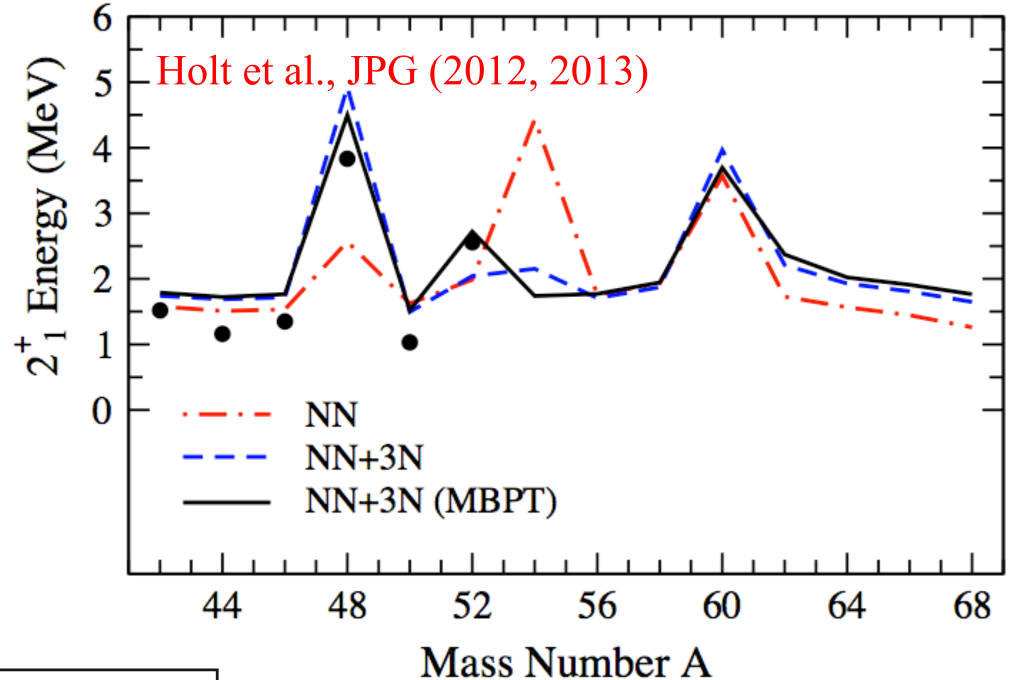
Bender et al. (2005)

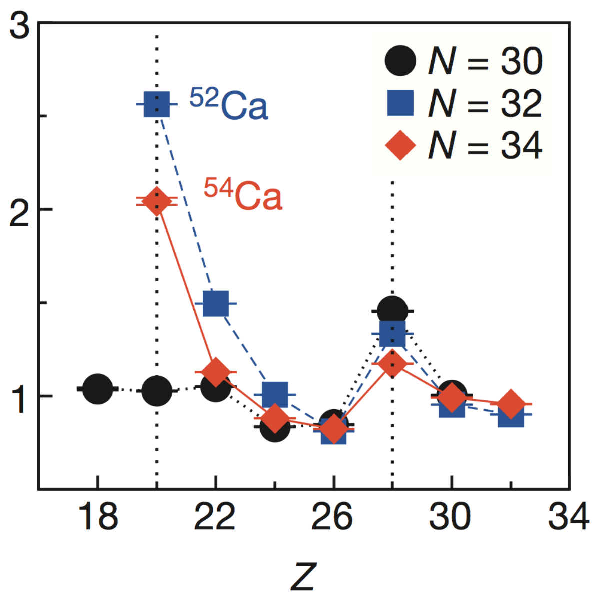




3N forces and magic numbers







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

Steppenbeck et al., Nature (2013)

Ab initio calculations going open shell: around Ca

Gorkov Green's function methods based on chiral NN+3N

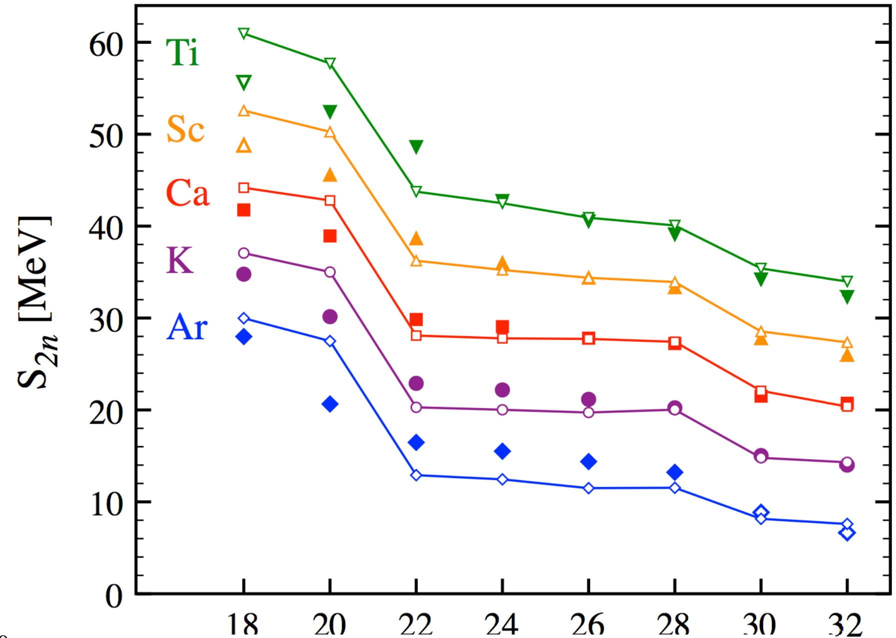
Somà, Cipollone, Barbieri, Navratil, Duguet, PRC (2014)

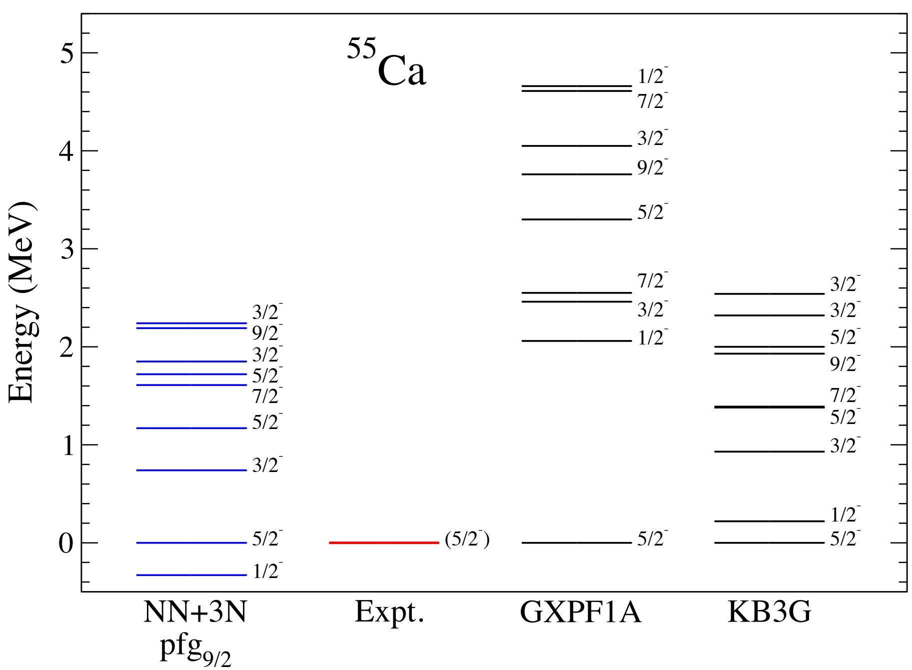
multi-reference IM-SRG

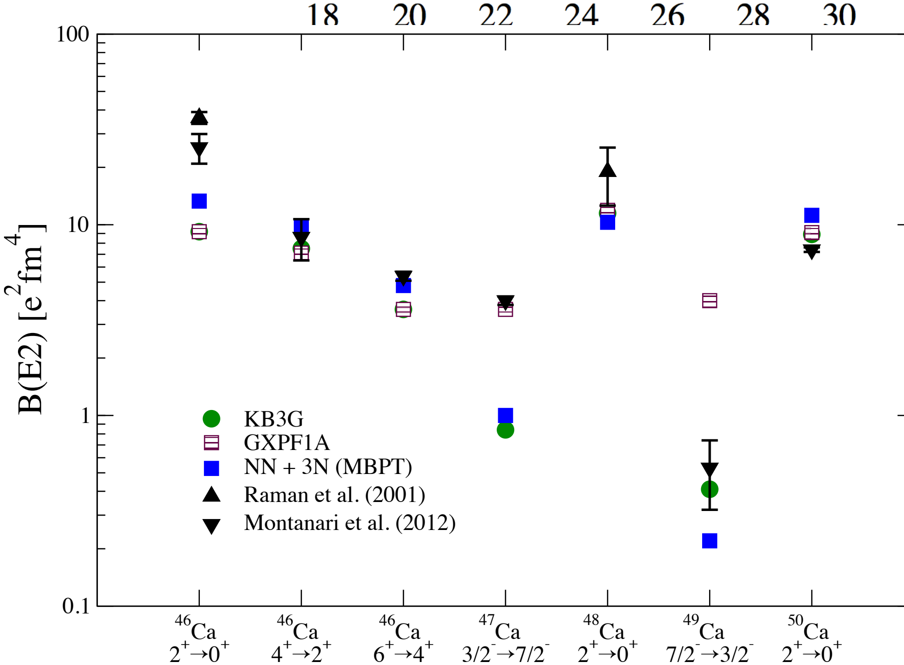
Hergert et al., PRL (2013)

shell model based on NN+3N

Holt, Menéndez, Simonis, AS, arXiv:1405.7602







Main message

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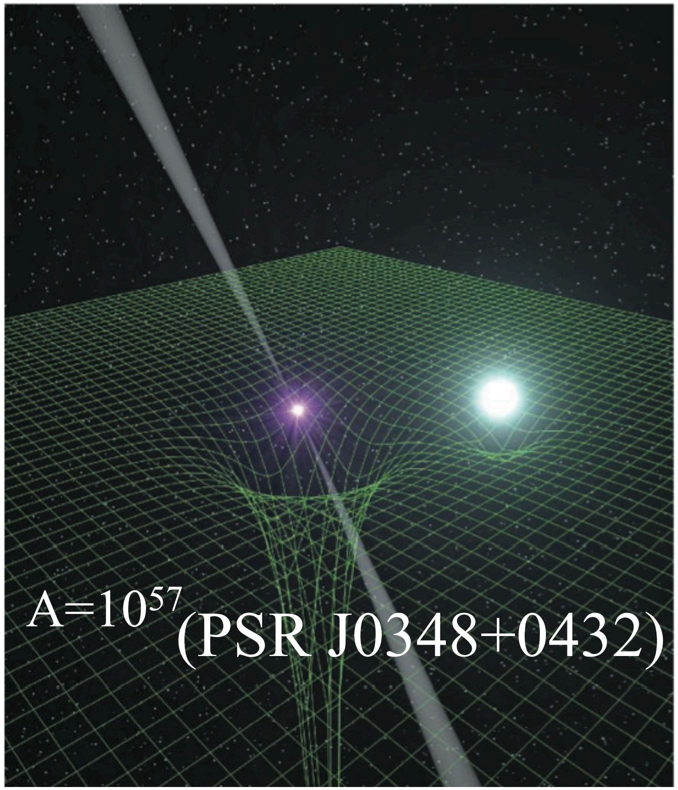

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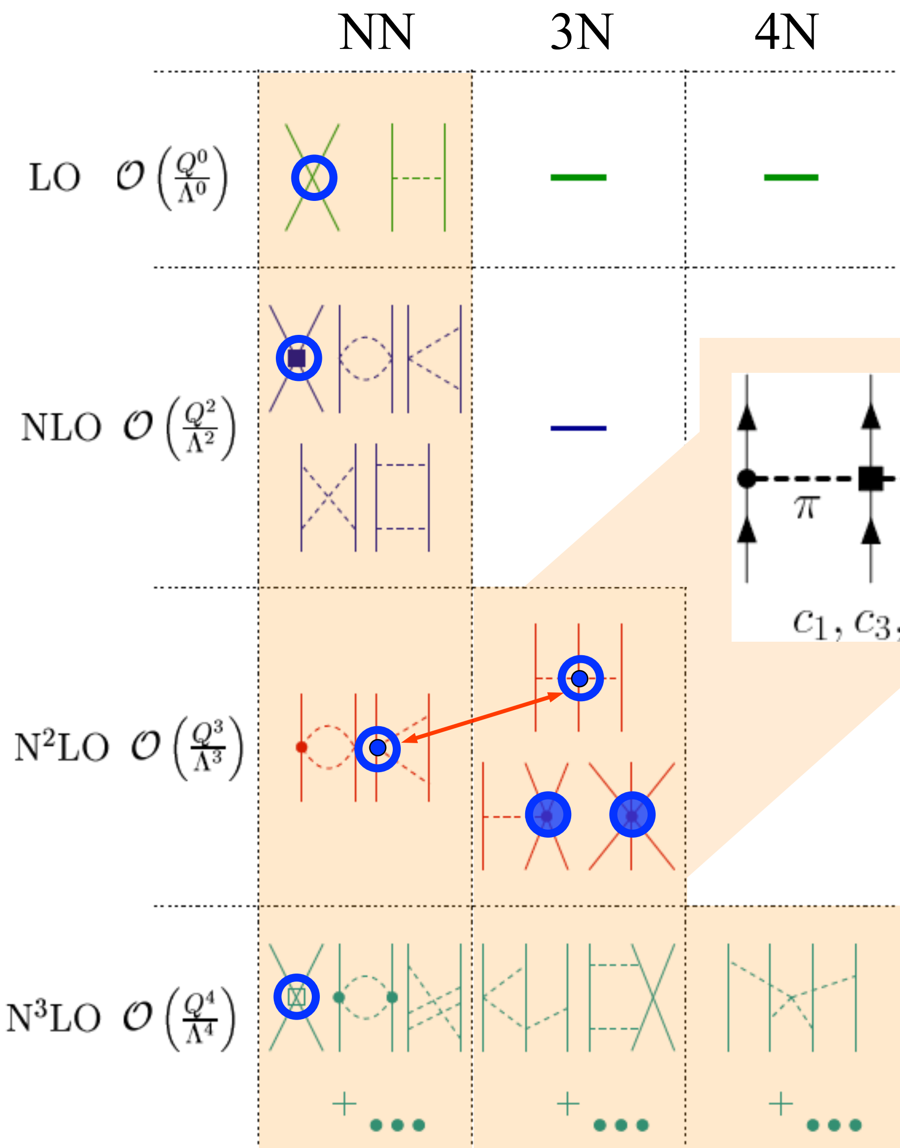

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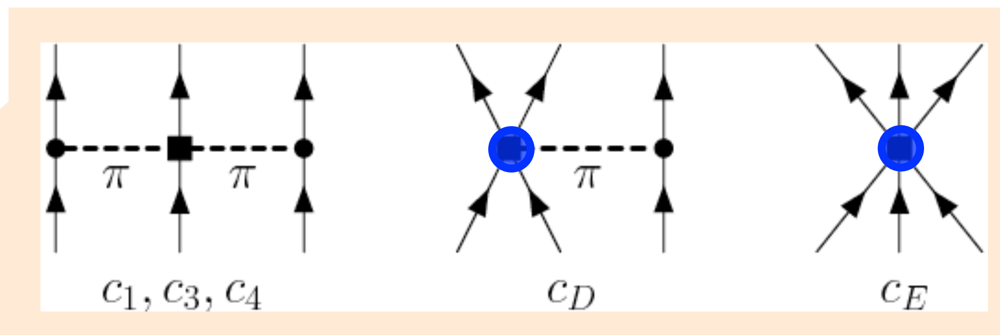

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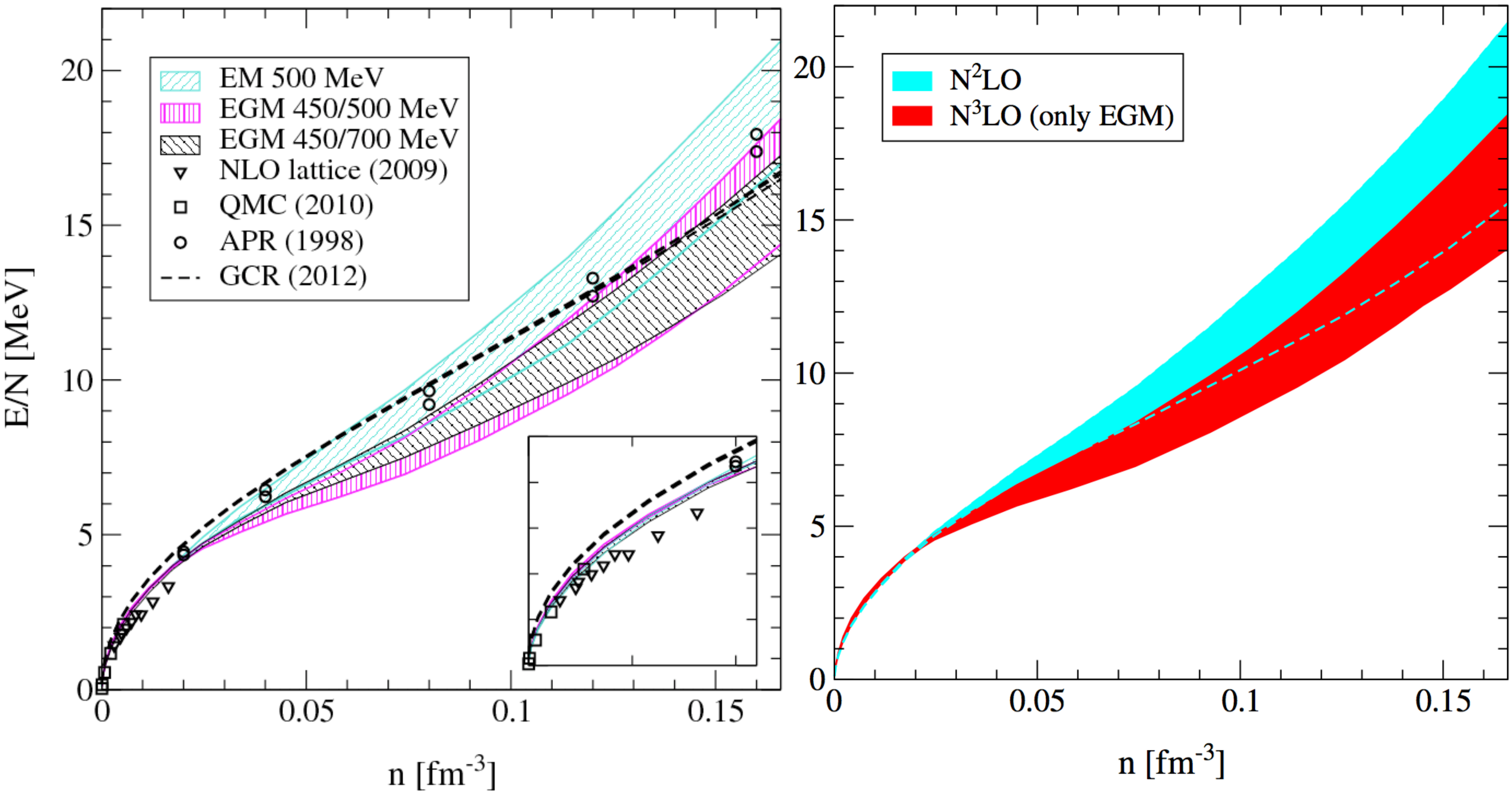
c_D, c_E fit to light nuclei only

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

Complete N^{3}LO calculation of neutron matter

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

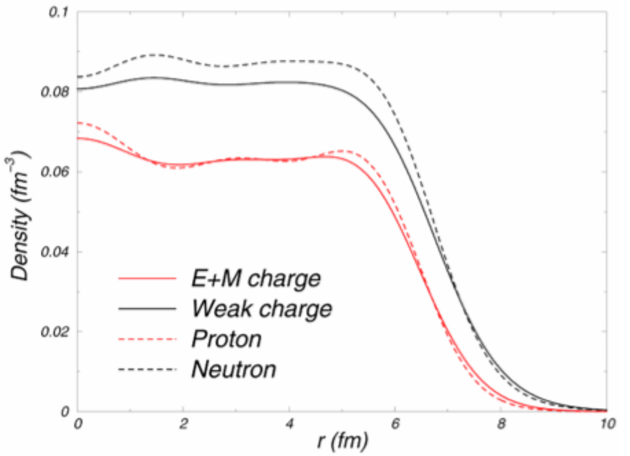
includes uncertainties from NN, 3N (dominates), 4N



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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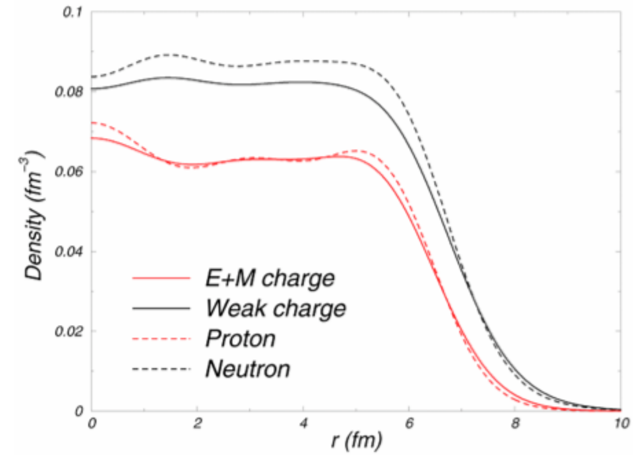


in excellent agreement with extraction from complete E1 response
0.156+0.025-0.021 fm

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

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

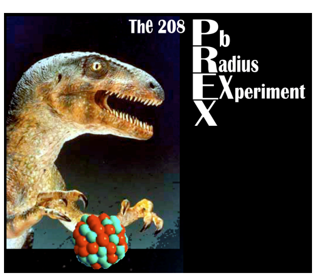
A benchmark experiment on ^{208}Pb shows that polarized proton inelastic scattering at very forward angles including 0° is a powerful tool for high-resolution studies of electric dipole ($E1$) and spin magnetic dipole ($M1$) modes in nuclei over a broad excitation energy range to test up-to-date nuclear 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 $A_{\rm PV} = 0.656 \pm 0.060$(stat) ± 0.014(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.



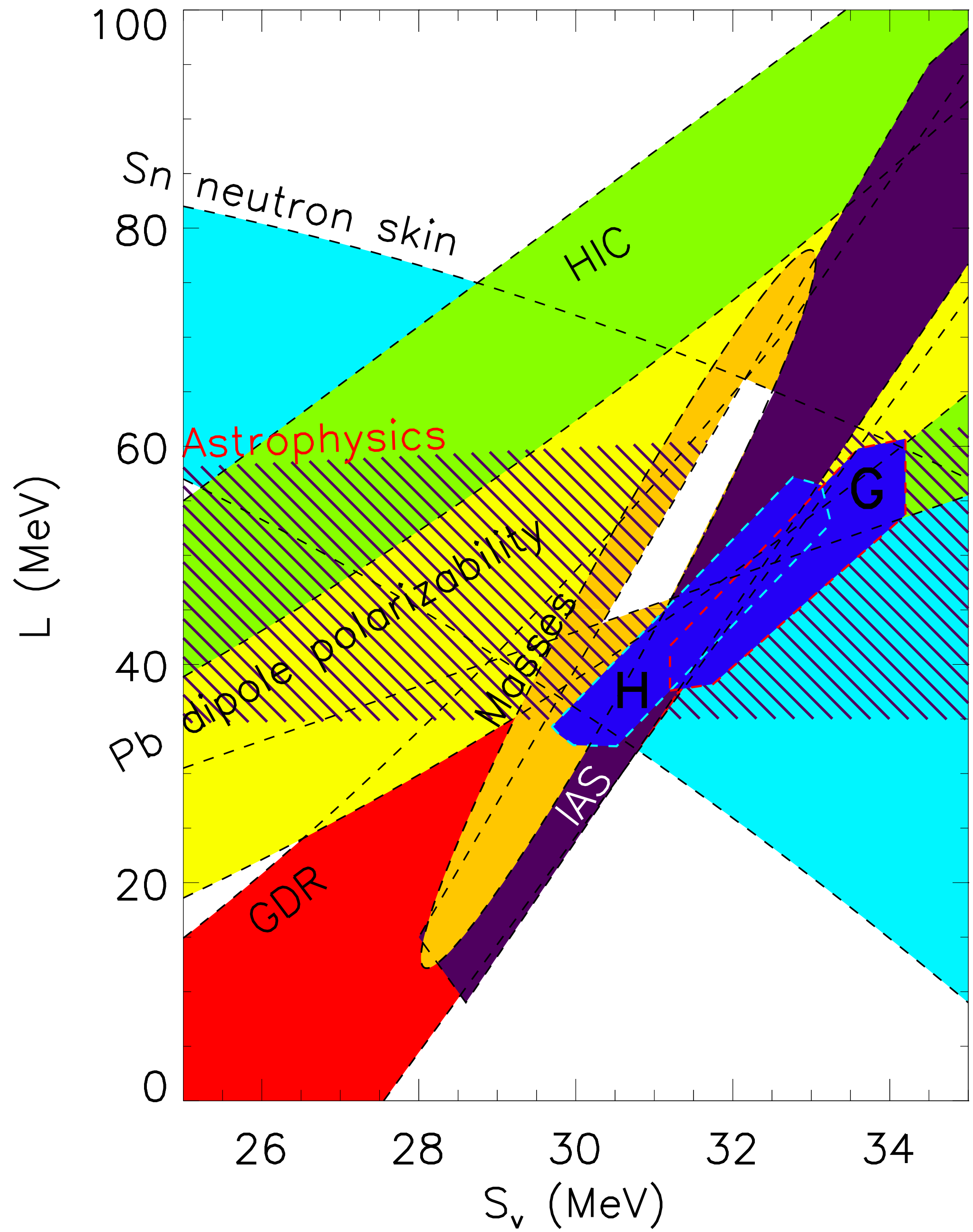
Symmetry energy and pressure of neutron matter

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

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

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

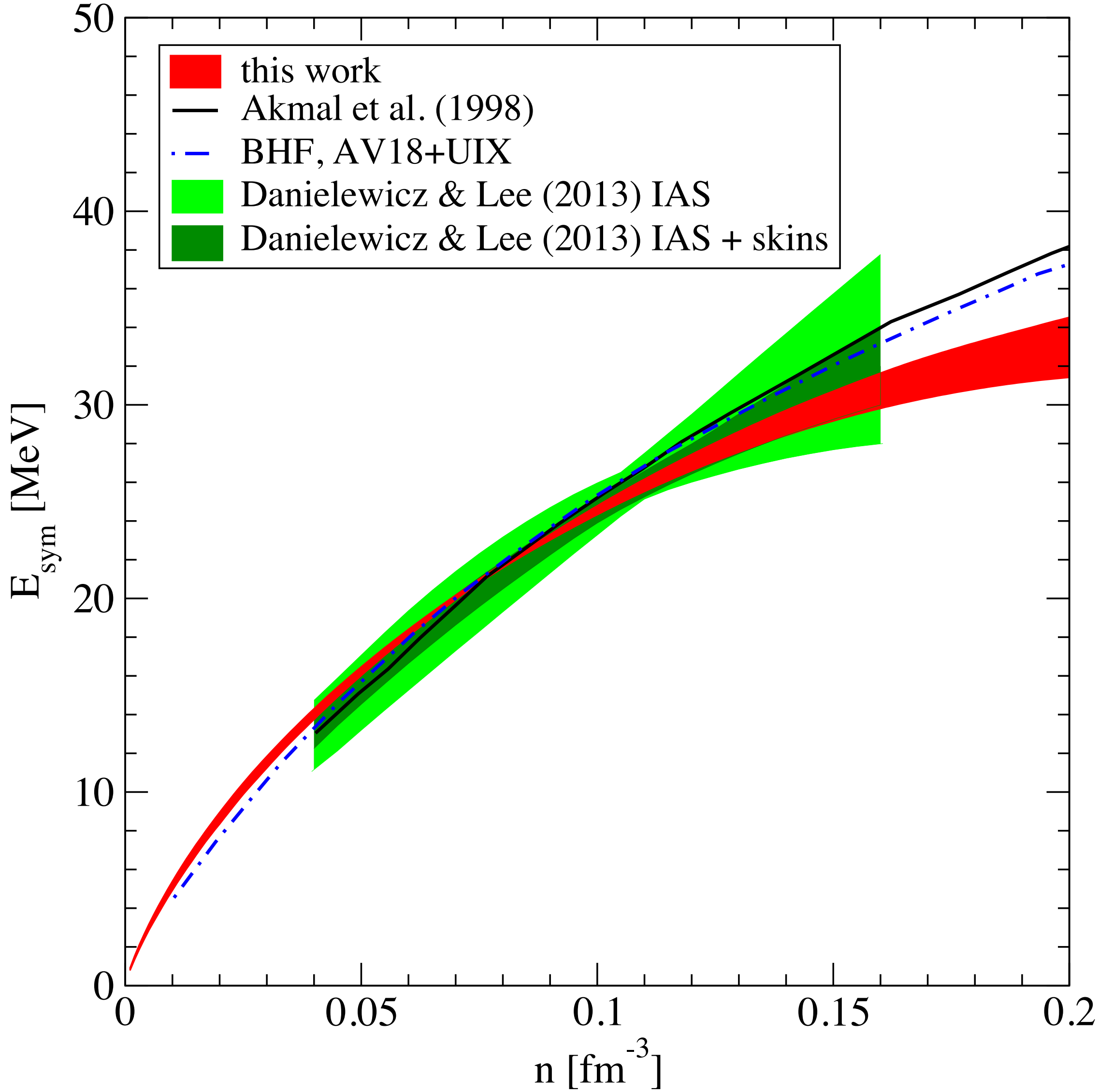
combined with Skyrme EDFs predicts neutron skin
^{208}Pb: 0.182(10) fm
^{48}Ca: 0.173(5) fm
Brown, AS, PRC (2014)



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

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

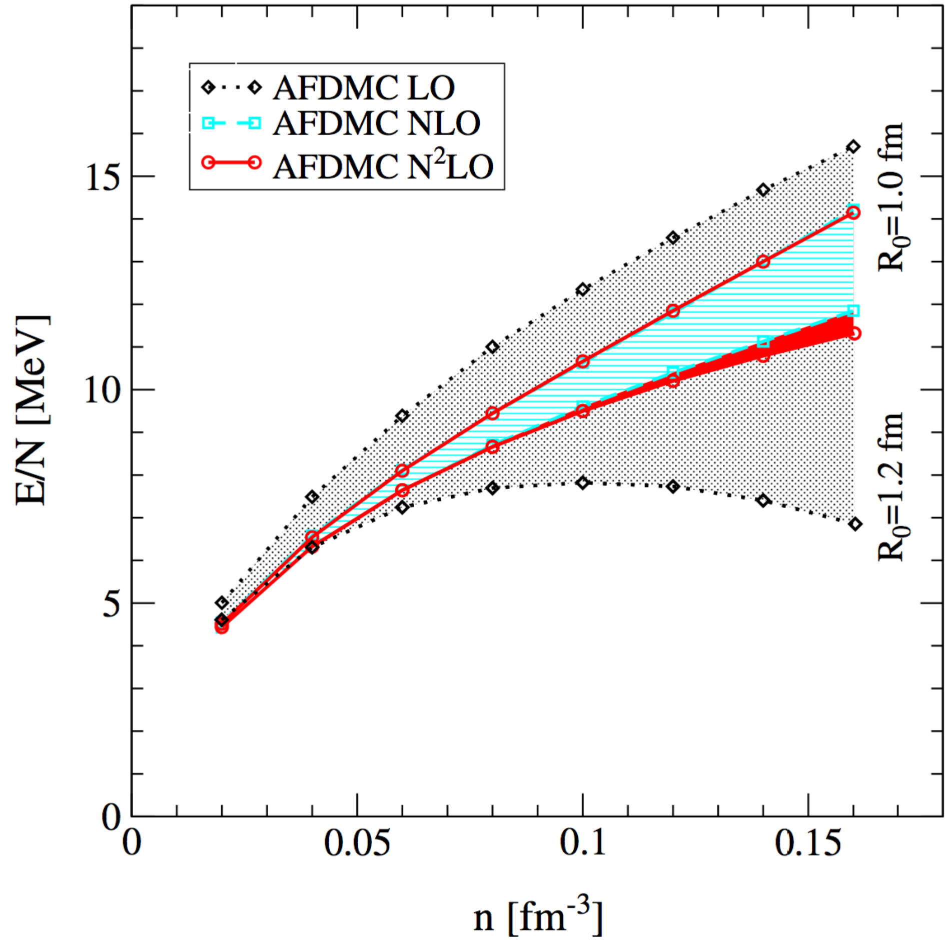
3N forces fit to ^3H, ^4He properties only



Quantum Monte Carlo for neutron matter

Gezerlis, Tews, et al., PRL (2013) and arXiv:1406.0454

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



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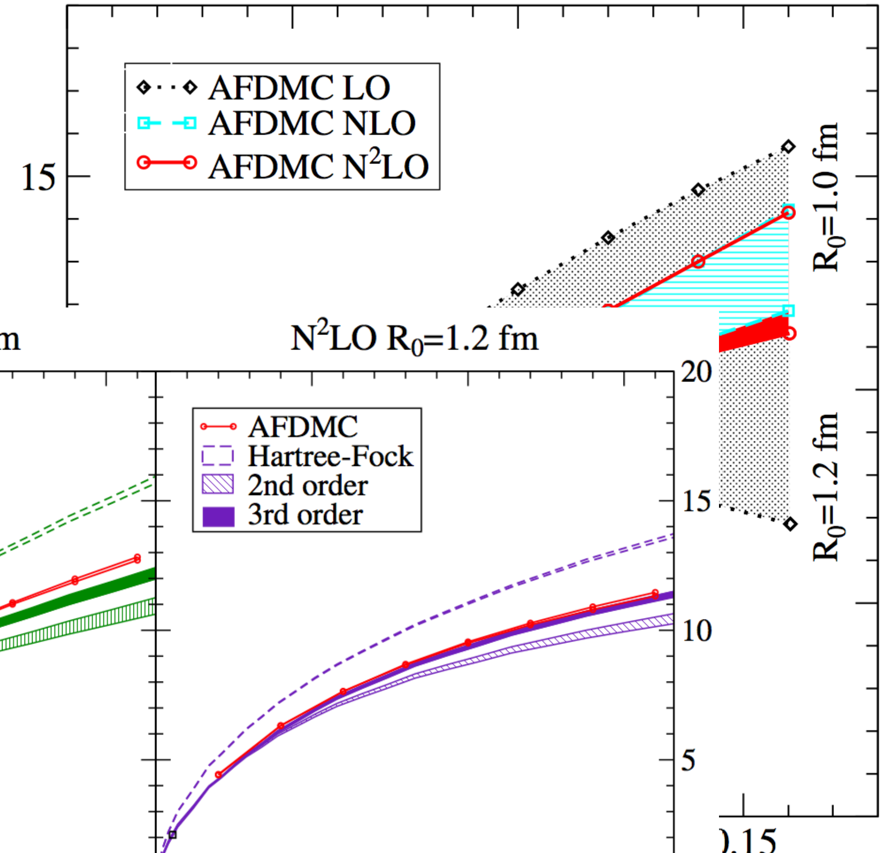

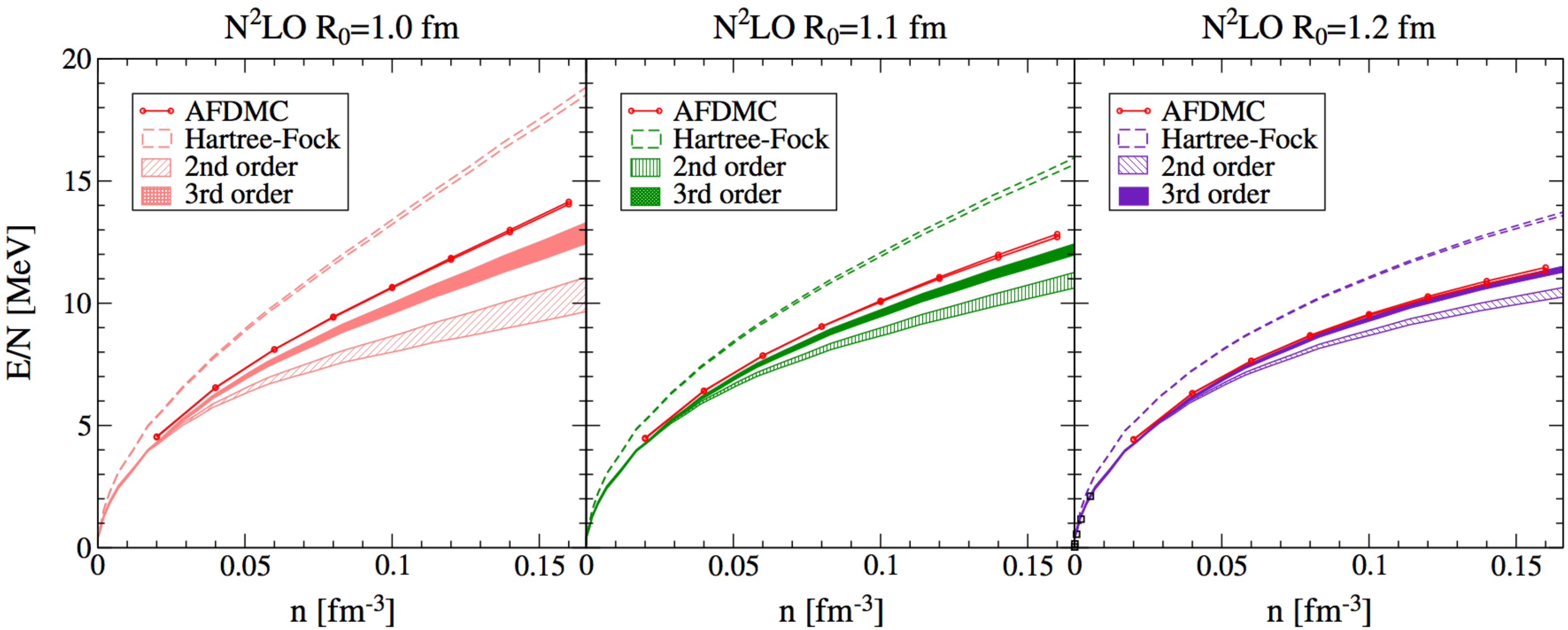

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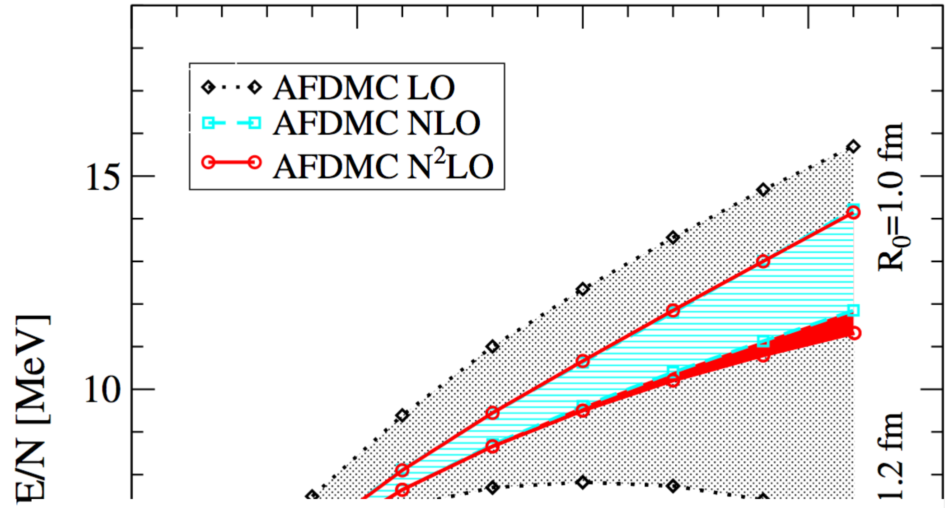
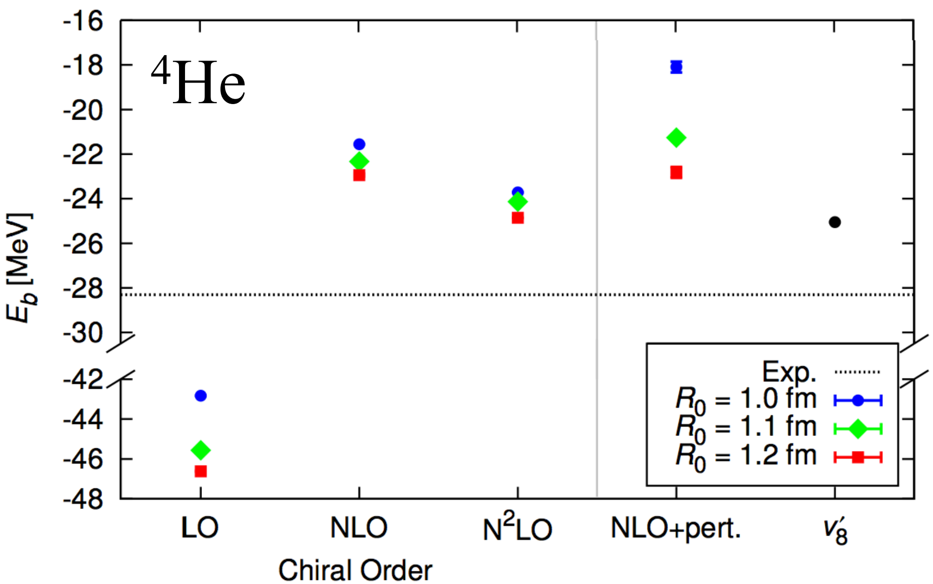
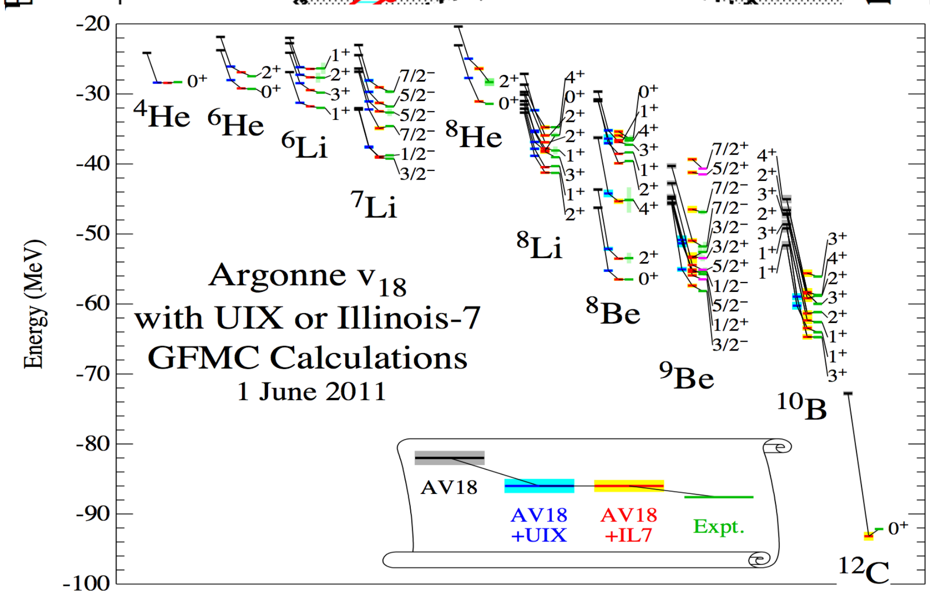


light nuclei based on GFMC

Lynn et al., arXiv:1406.2718





Discovery of the heaviest neutron star

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

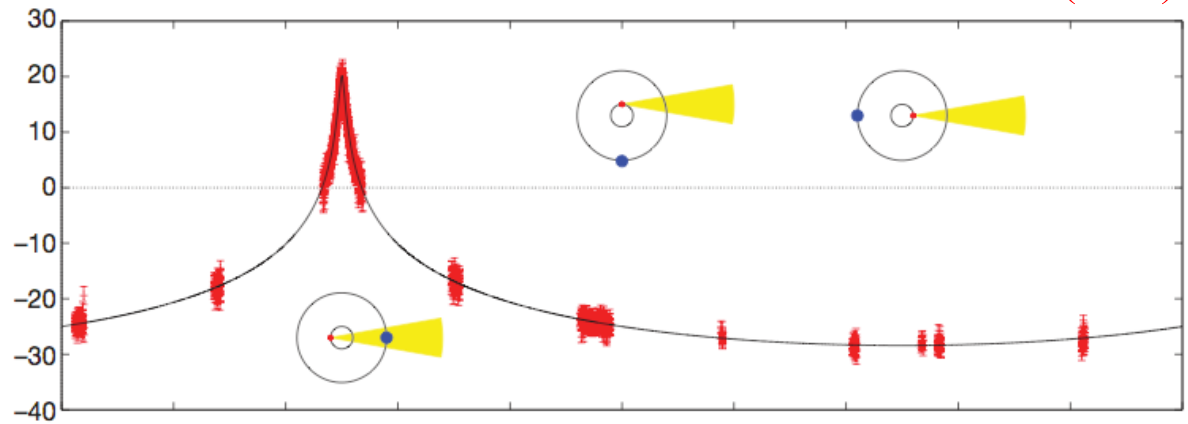
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

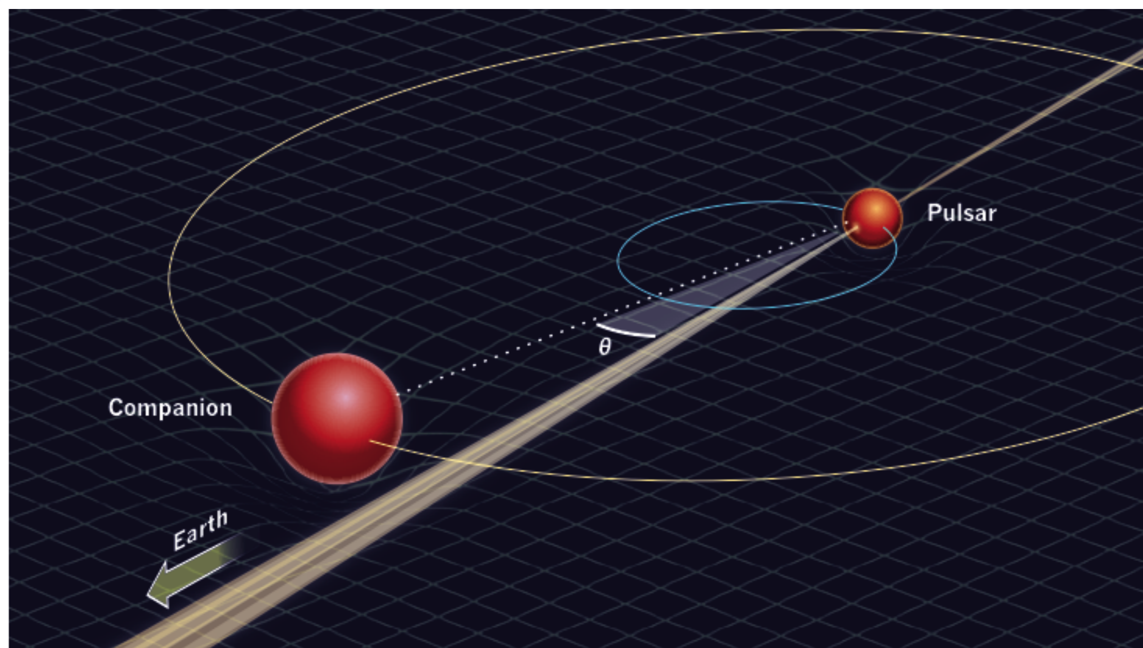
Nature (2010)

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

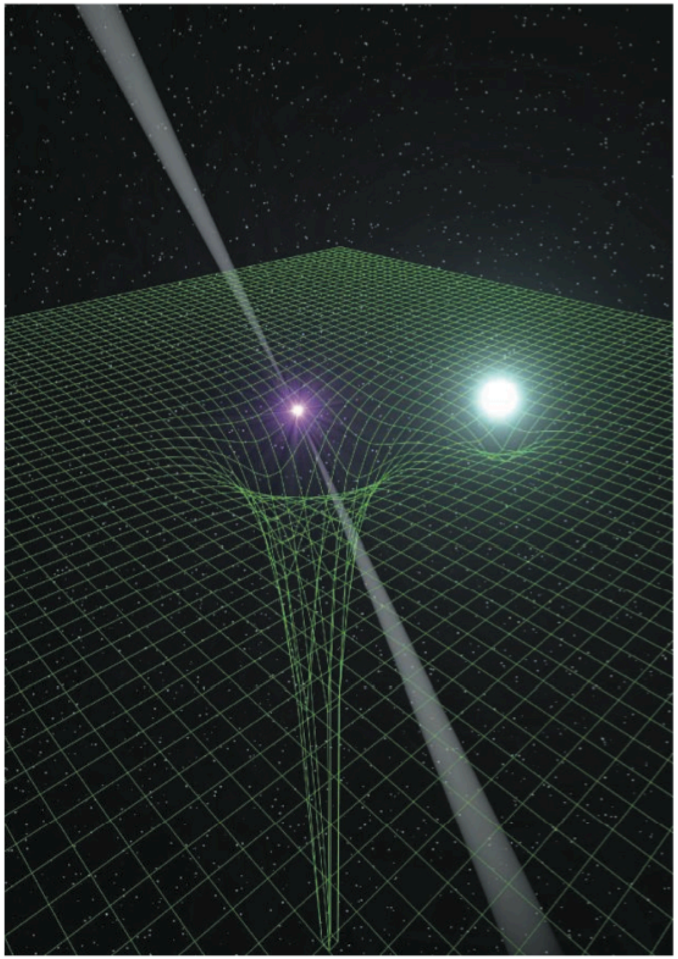
A Massive Pulsar in a Compact Relativistic Binary

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.

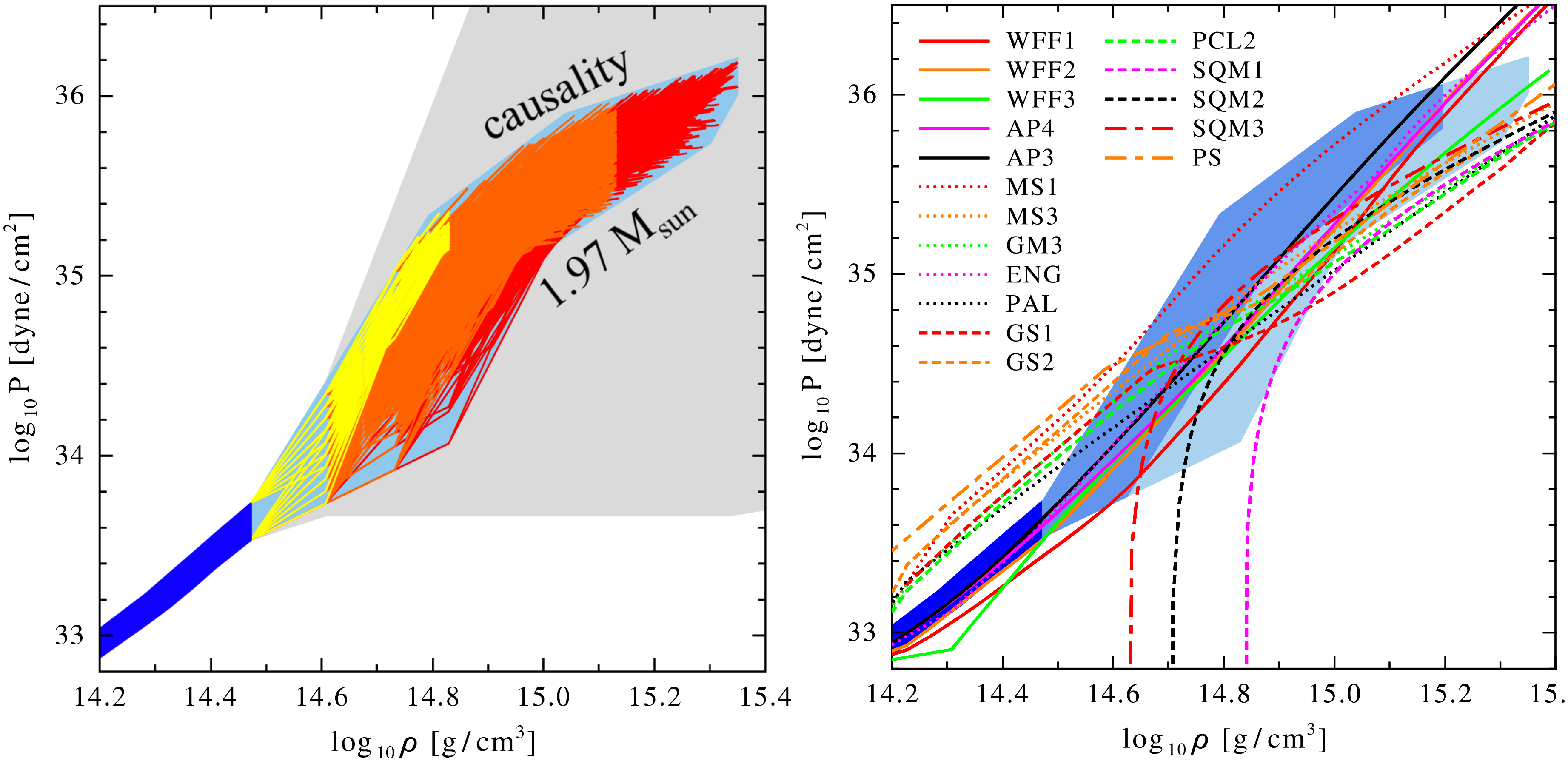
Results: We find that the white dwarf has a mass of 0.172 ± 0.003 $M_{\odot}$, which, combined with orbital velocity measurements, yields a pulsar mass of 2.01 ± 0.04 $M_{\odot}$. Additionally, over a span of 2 years, we observed a significant decrease in the orbital period, $\dot{P}_b^{obs} = -8.6 \pm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

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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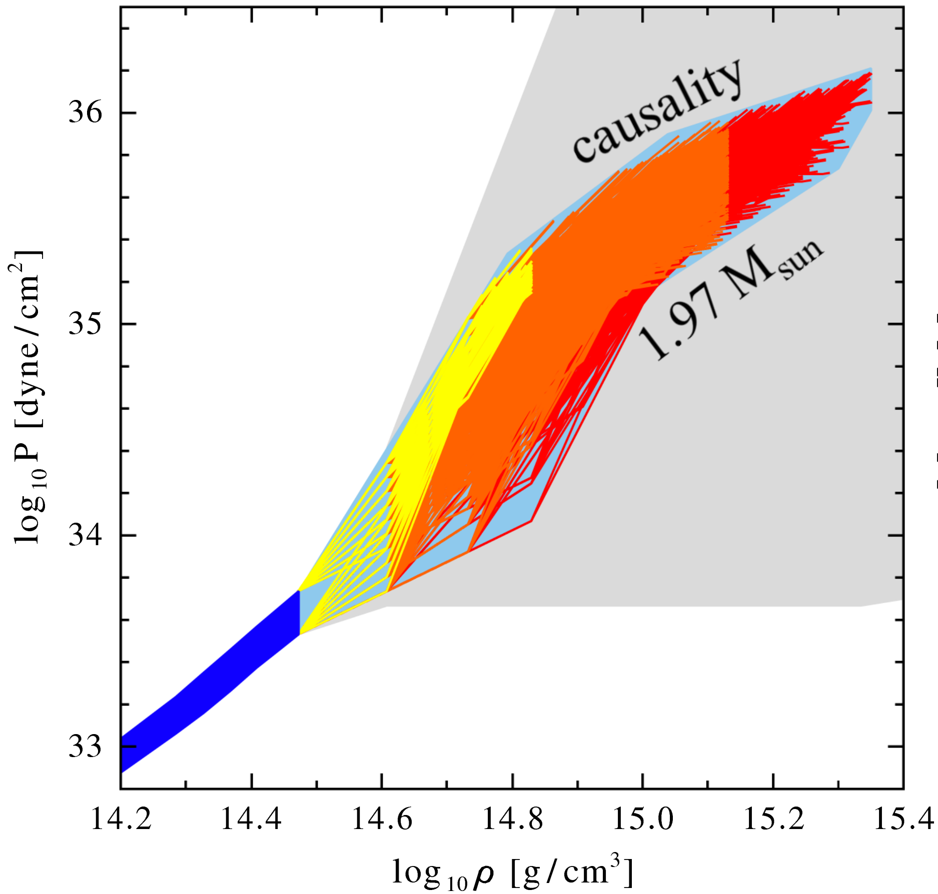
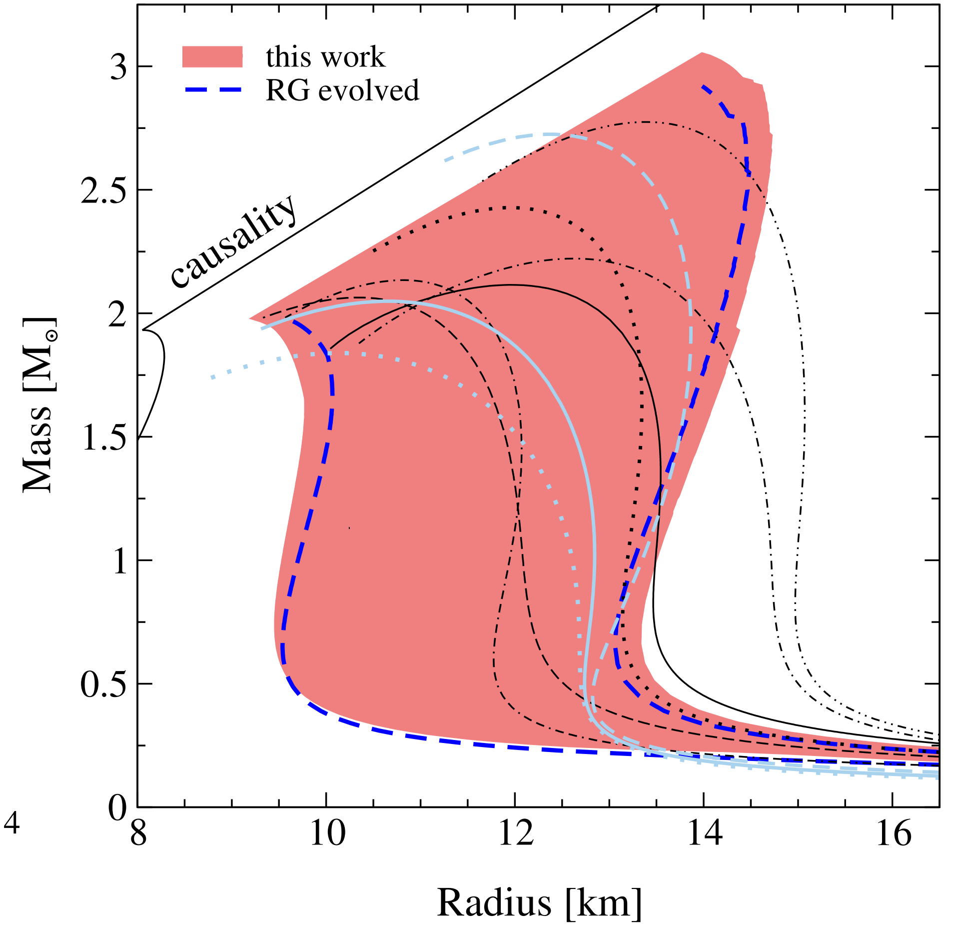


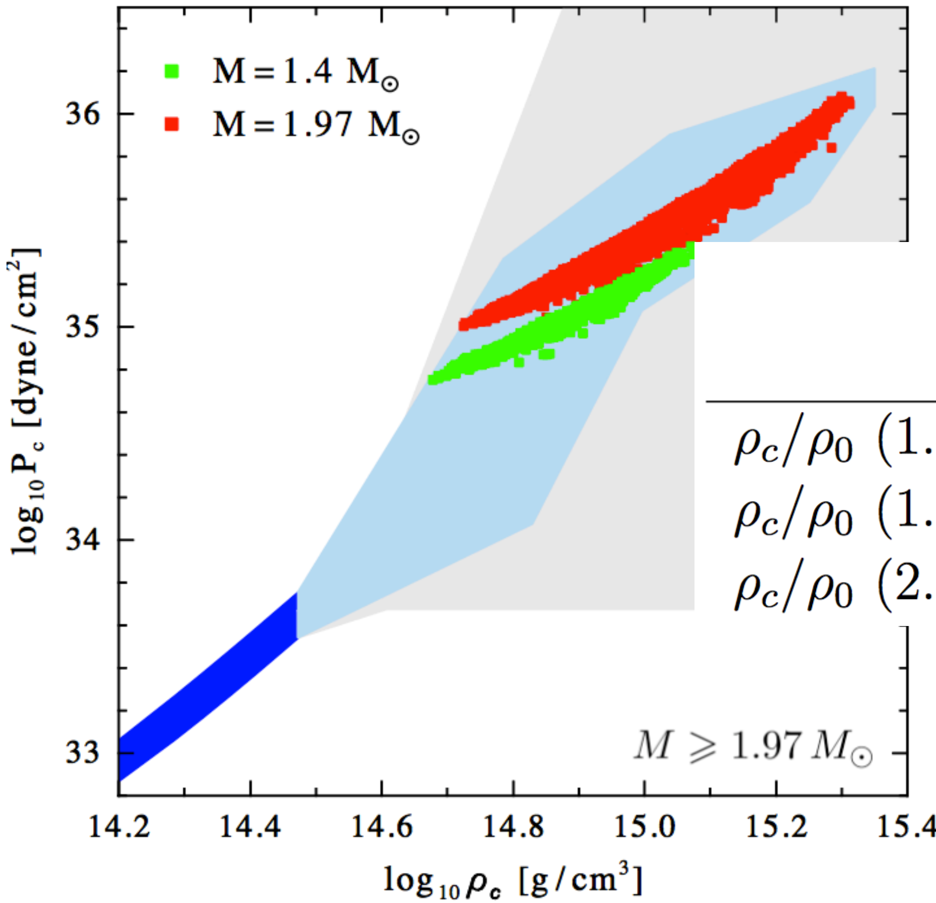


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

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



	$\widehat{M} = 1.97\,M_\odot$ 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

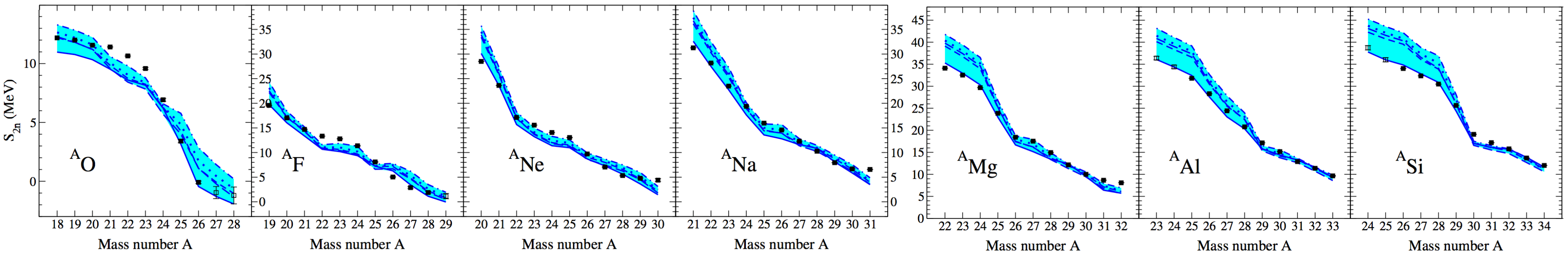
not very high momenta!

Summary and perspectives

3N forces are an exciting frontier for nuclei and astrophysics

ab initio calculations are going open shell: O to Ca/Ni/Sn region

need to quantify uncertainties, dominated by uncertainties in 3N forces



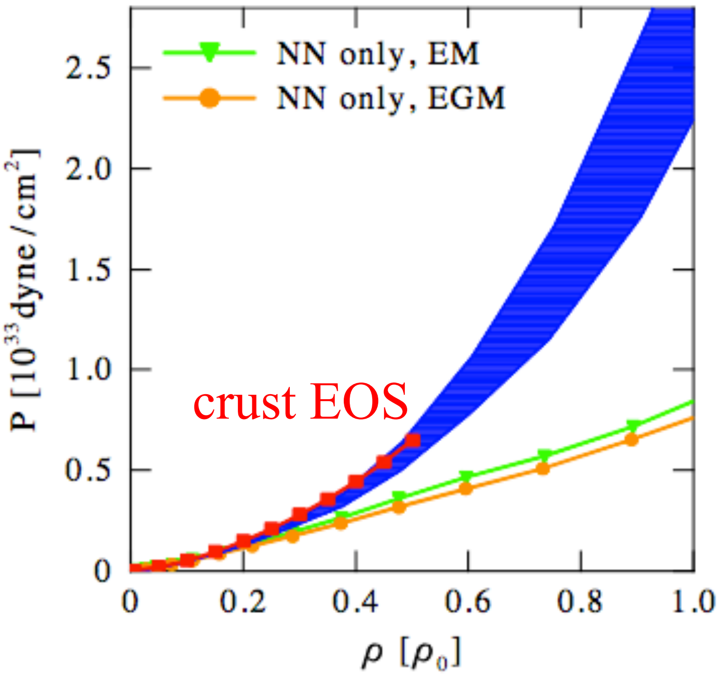
nuclear structure with N^3LO 3N forces breakthrough: 3N matrix elements by Kai Hebeler

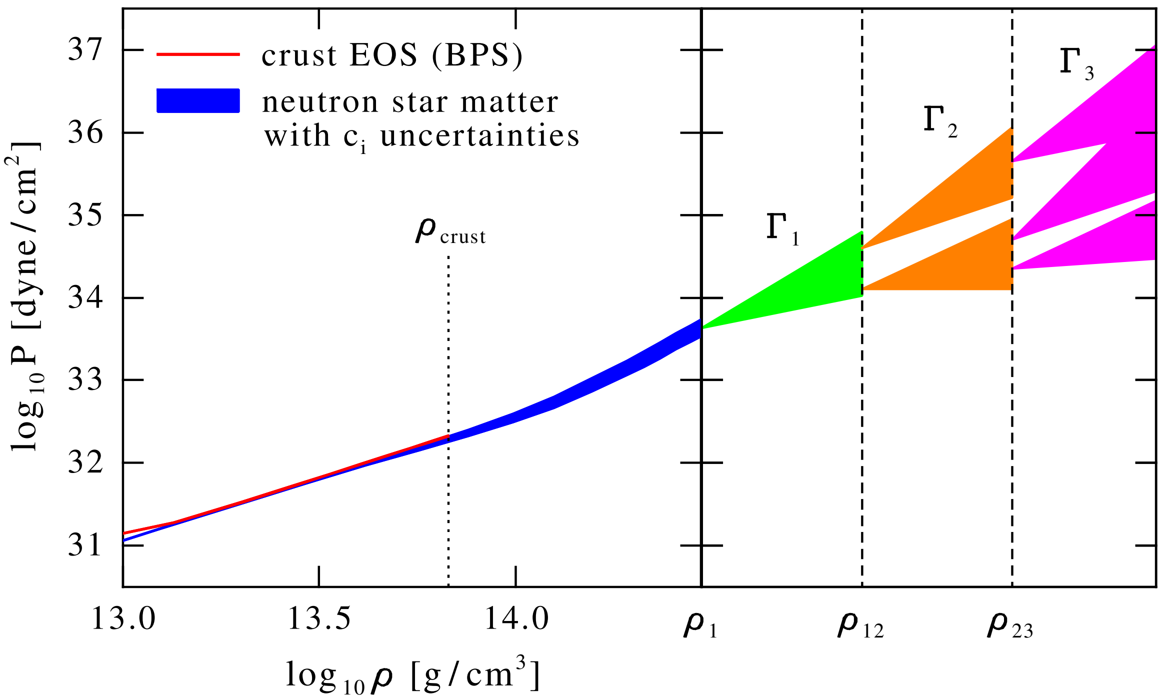
impact of chiral EFT two-body currents (meson-exchange currents) on electroweak transitions, provide new tests

provide ab initio constraints to powerful density functional theory

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

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)

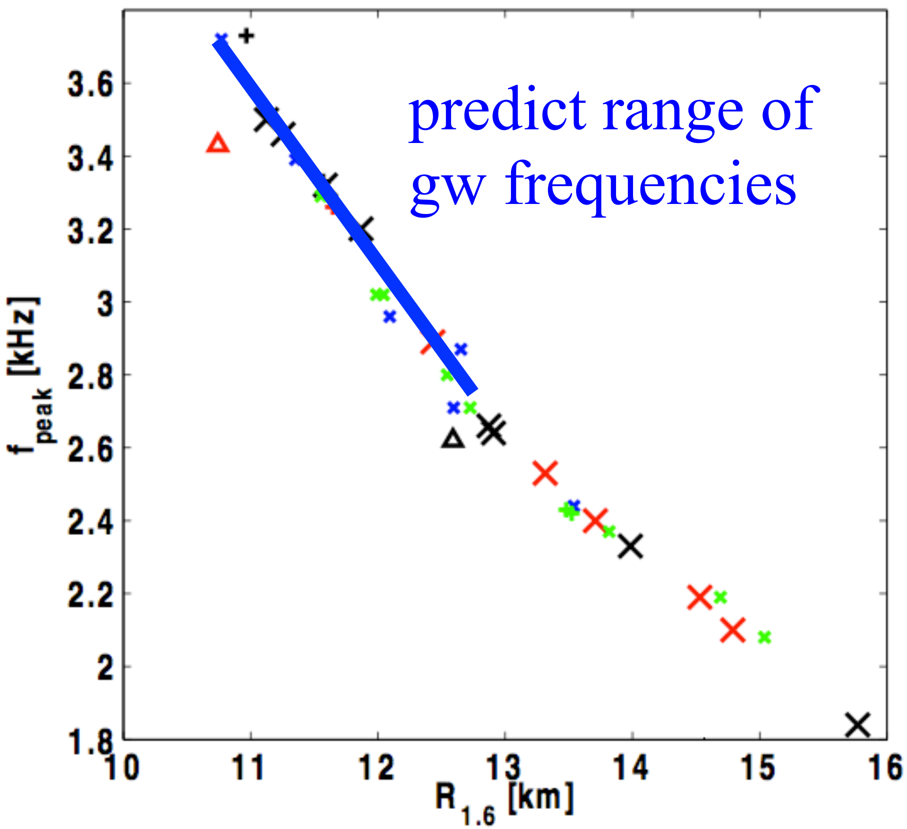


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.