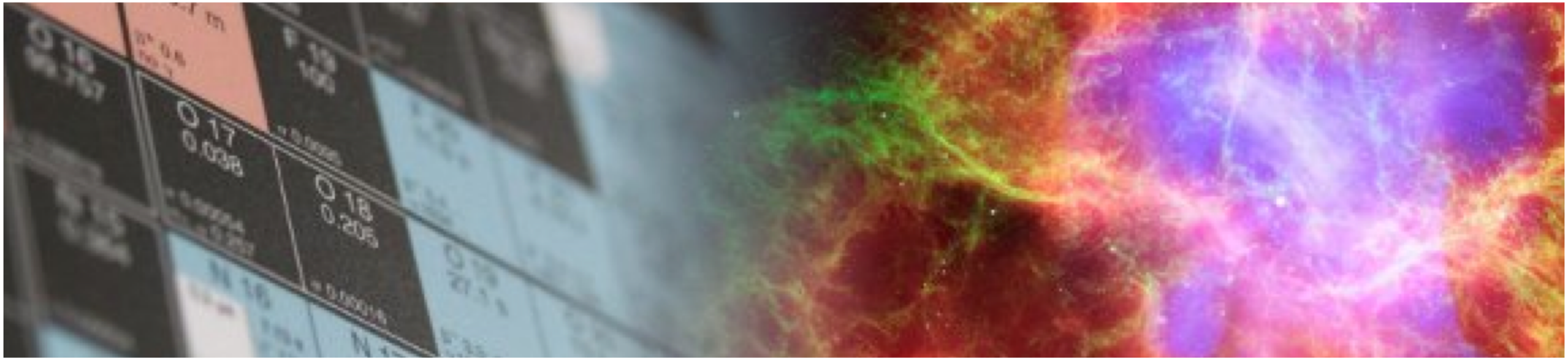
Always at the forefront – from NN experiments to ab initio theory

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT



TRIUMF 50th Anniversary Symposium, July 17, 2018

DFG SFB 1245 erc

Bundesministerium für Bildung und Forschung

HELMHOLTZ ASSOCIATION

Congratulations TRIUMF!!

Dear Director Bagger, Dear President Ono,

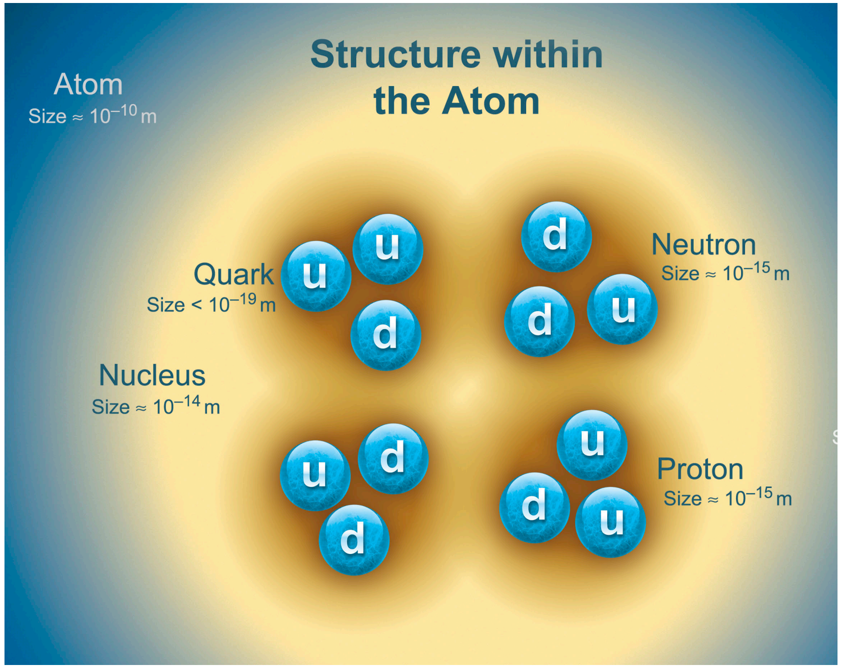
Warm greetings from TU Darmstadt! It has almost been two years since we met each other when I visited TRIUMF and UBC. During these two years your university has continued to prosper and I would like to take this opportunity to first congratulate you, President Ono, on all your great accomplishments.

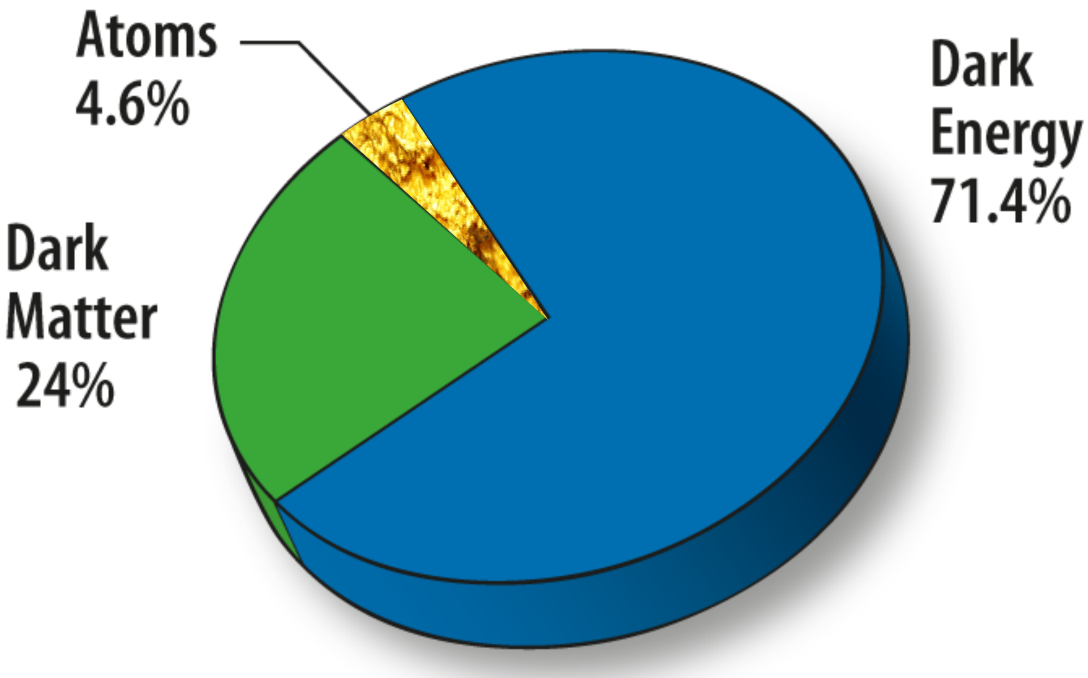
Similarly, I am very happy that our universities have flourishing collaborations in both research and student exchange which also is true for TU Darmstadt's cooperation with TRIUMF. TRIUMF is a remarkable research facility that has significantly contributed to advancing knowledge and research not only in Physics, but also in the Life Sciences and Materials Science both within Canada and internationally over the past 50 years. I would like to congratulate you, Director Bagger, and all TRIUMF constituents on this great success story!

For the coming (50) years I wish you all, dear colleagues at TRIUMF and UBC, the best of success for your future research endeavors. We at TU Darmstadt look forward to working with you. Thank you very much!

Hans-Jürgen Prömel, President, TU Darmstadt

Strong interactions in the Universe





Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at { 10^{-18} m	10^{-41}	0.8	1	25
Strength at { 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Nuclei bound by strong interactions

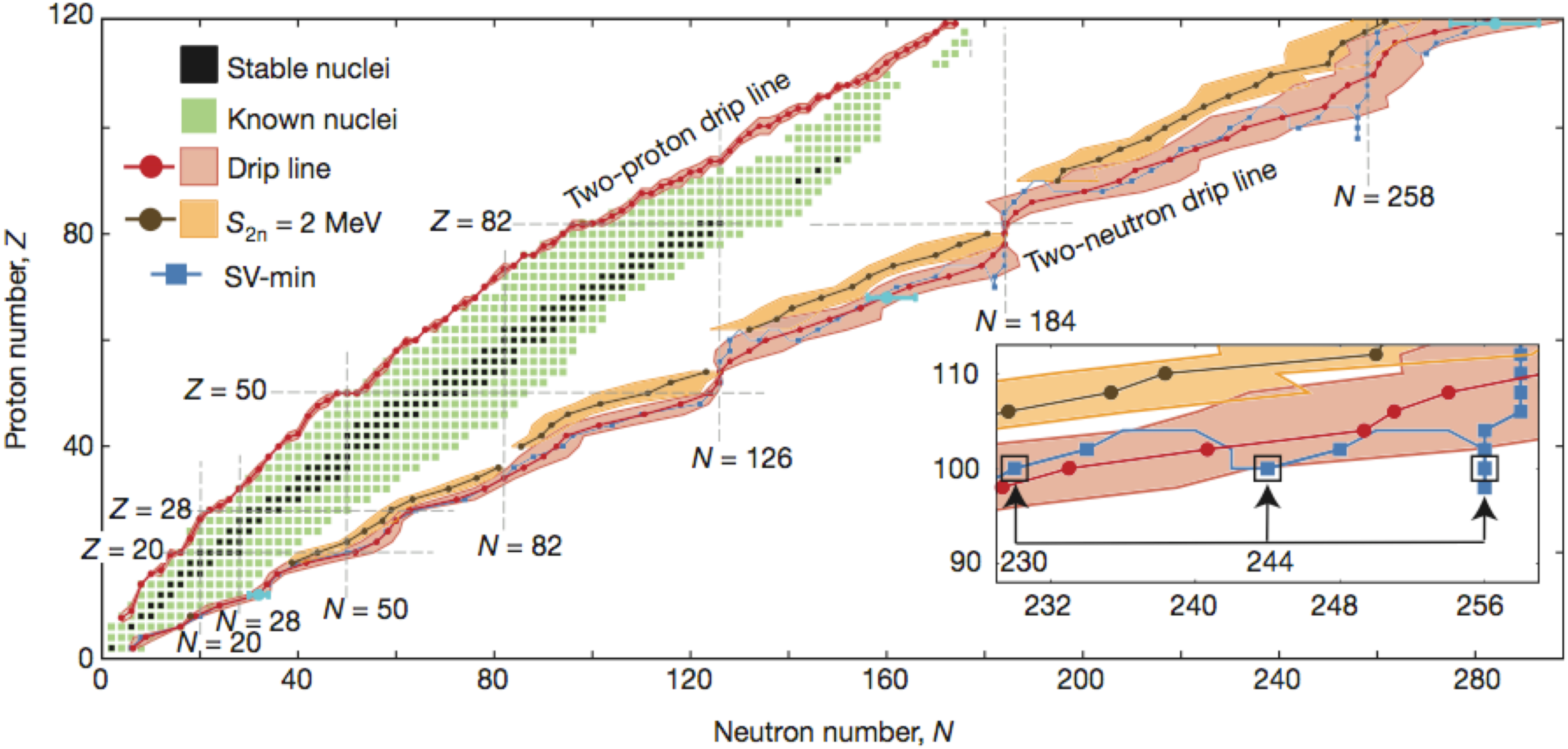
doi:10.1038/nature11188

The limits of the nuclear landscape

Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡

~ 3000 nuclei discovered (288 stable), 118 elements

~ 4000 nuclei unknown, extreme neutron-rich



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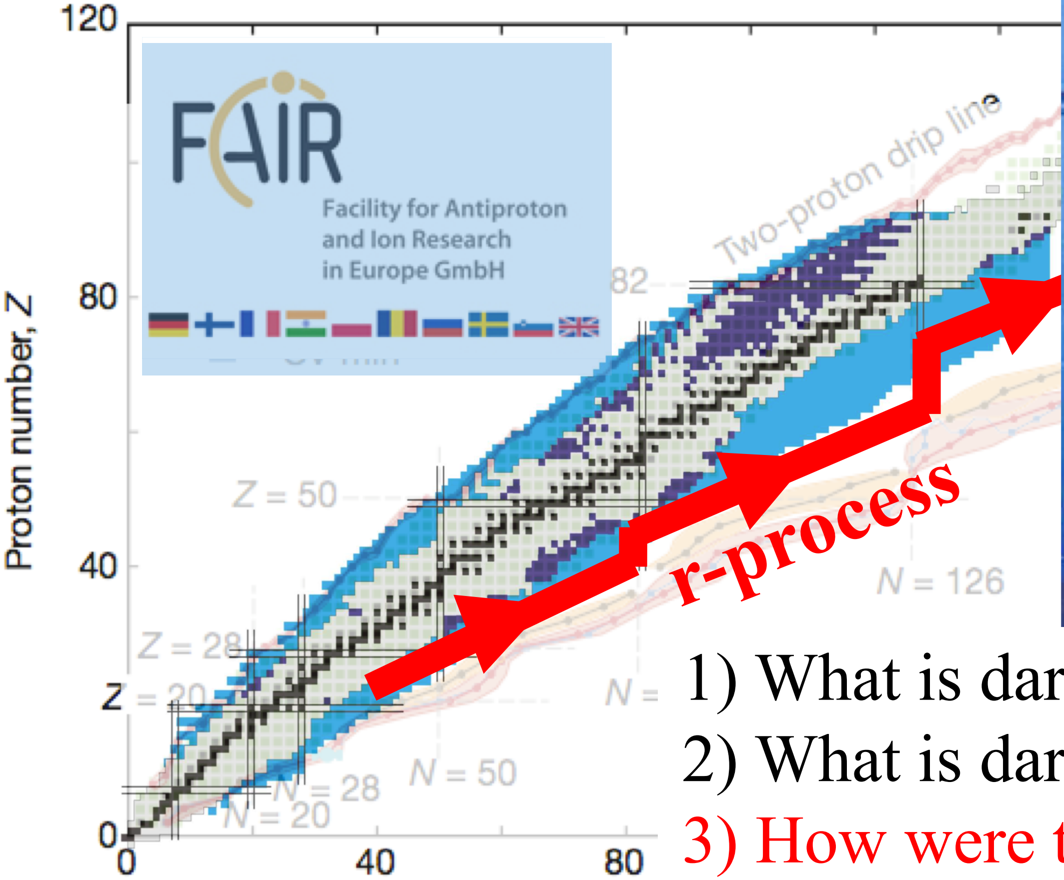
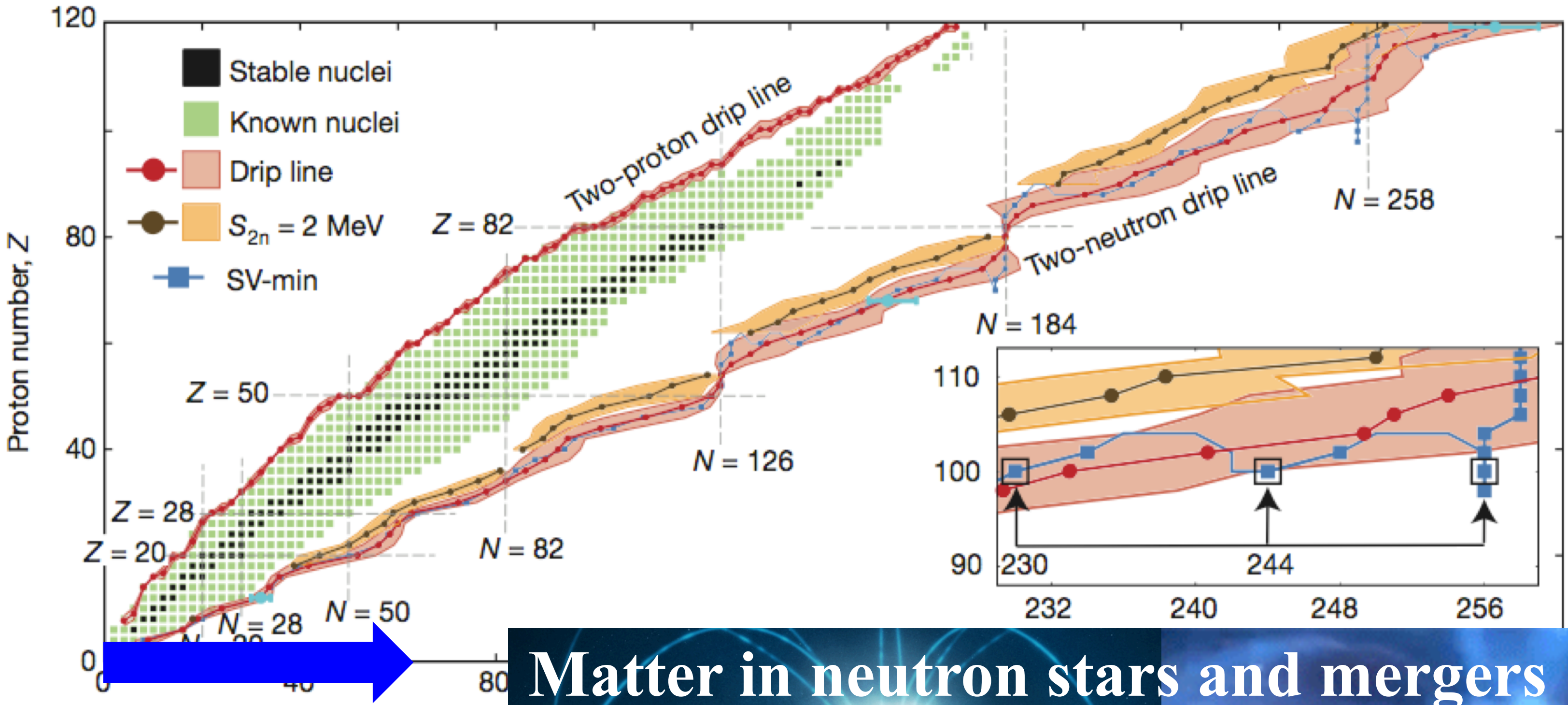


1) What is dark matter?

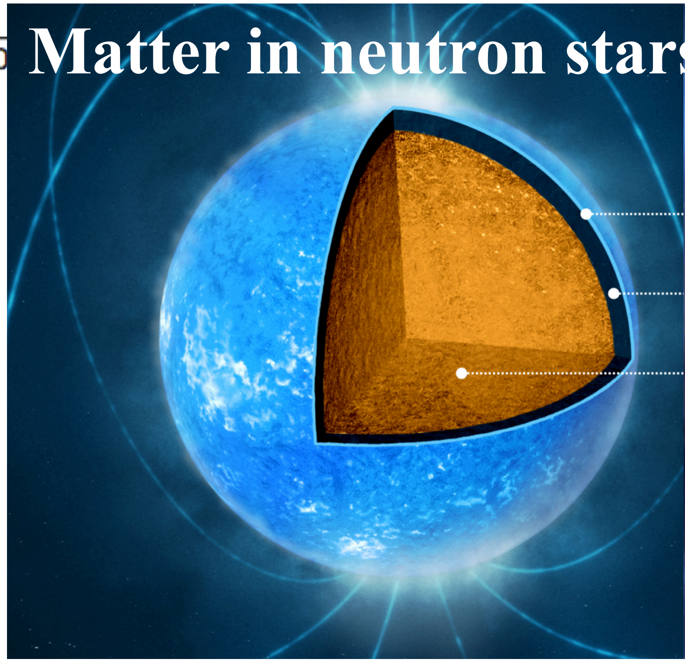
2) What is dark energy?

3) How were the elements from iron to uranium made?

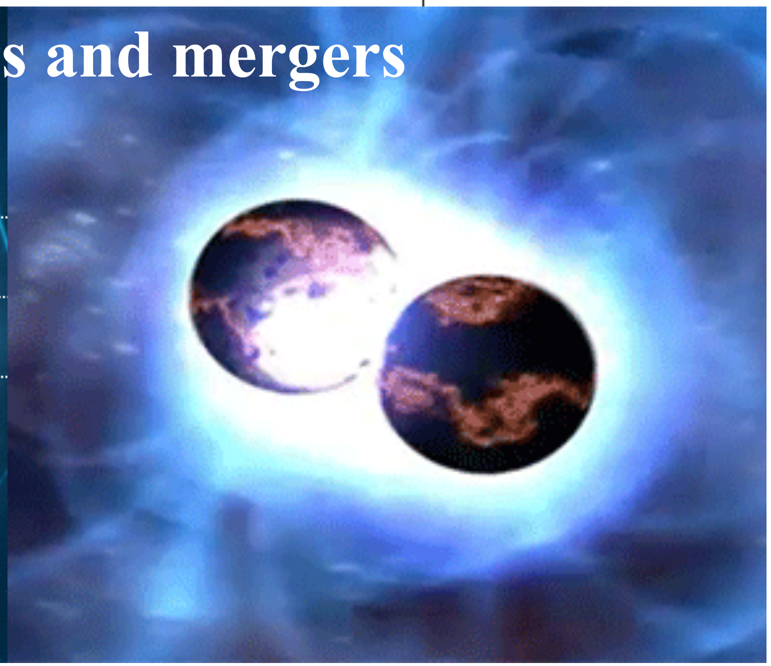


Neutrons

Matter in neutron stars and mergers



from Watts et al., RMP (2016)



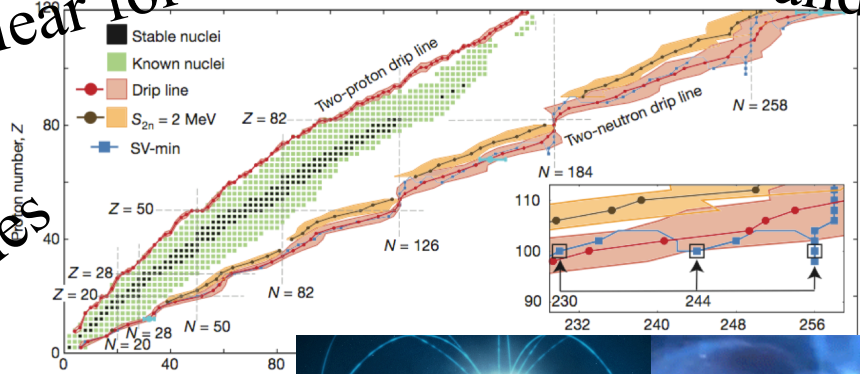
from NASA/Goddard/LIGO/Virgo

Physics of nuclei

Halos and skins

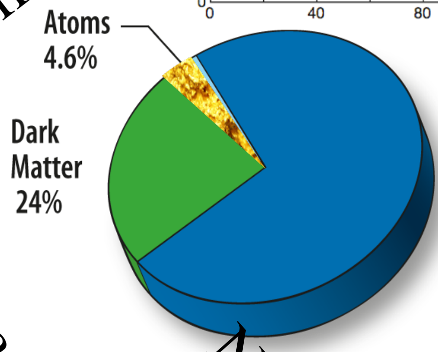
Emergence of structure from nuclear forces

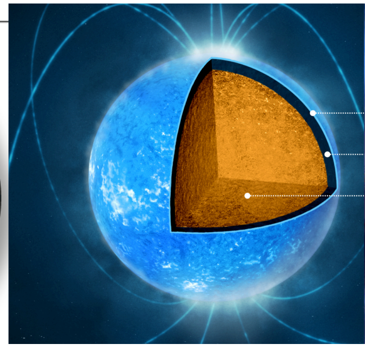
Nuclear reactions for structure and stars



Nuclei at the limits

Nuclei and neutrons for fundamental symmetries





Strong interaction in dense matter

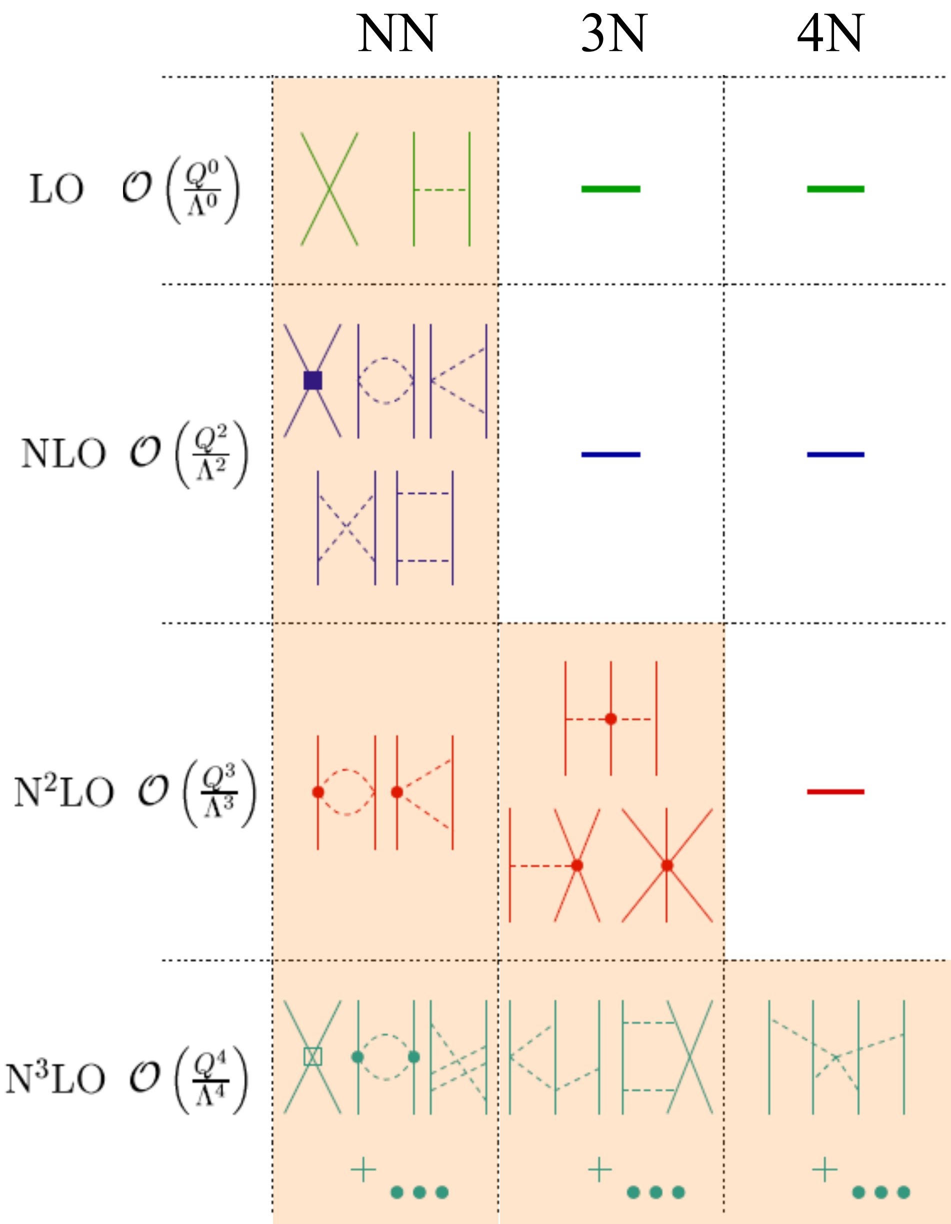
Nuclear physics of dark matter

Nuclear physics for neutrino physics

Synthesis of heavy elements in the Universe

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 $(Q/\Lambda_b)^n$

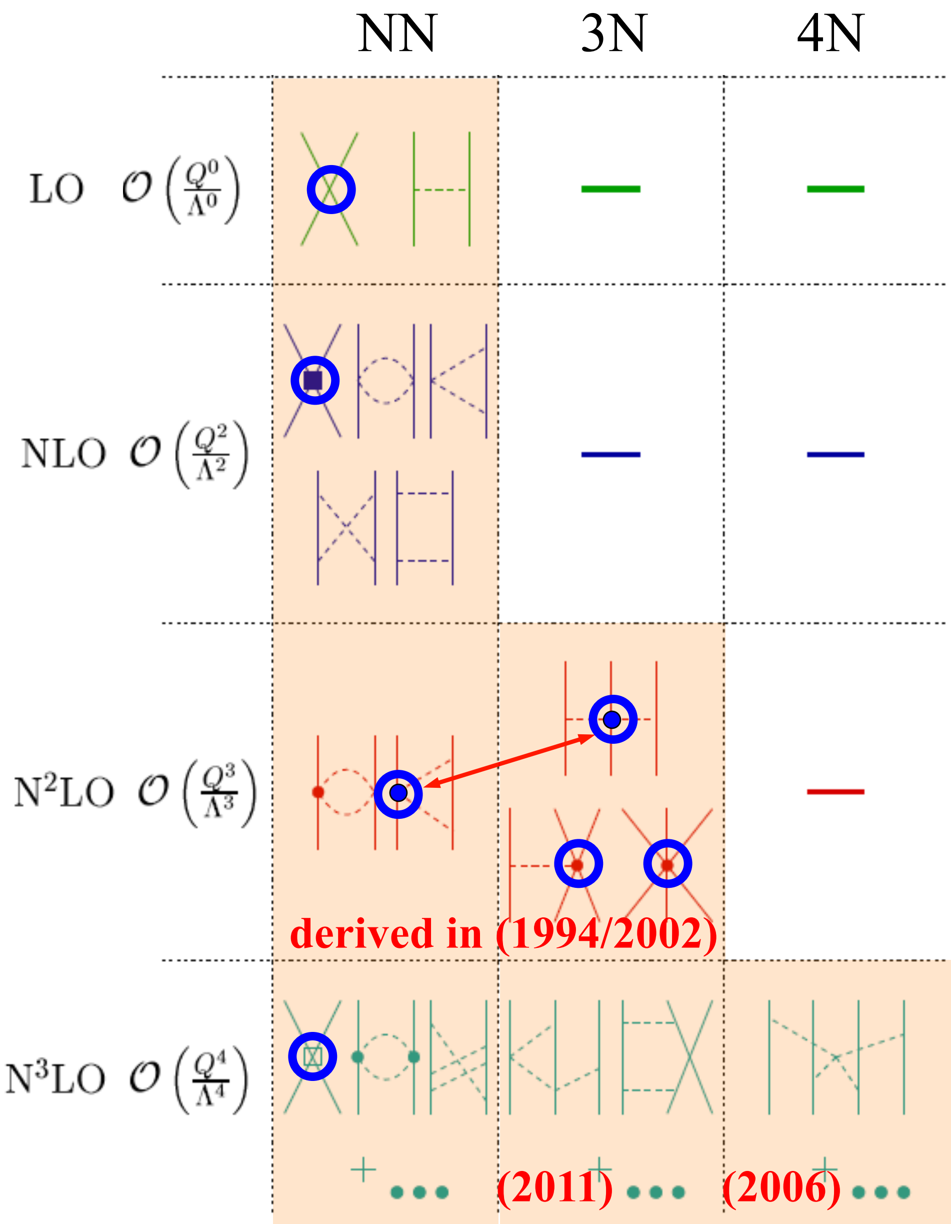
LO, n=0 - leading order,
NLO, n=2 - next-to-leading order,…

expansion parameter ~ 1/3

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

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,
NN scattering at TRIUMF

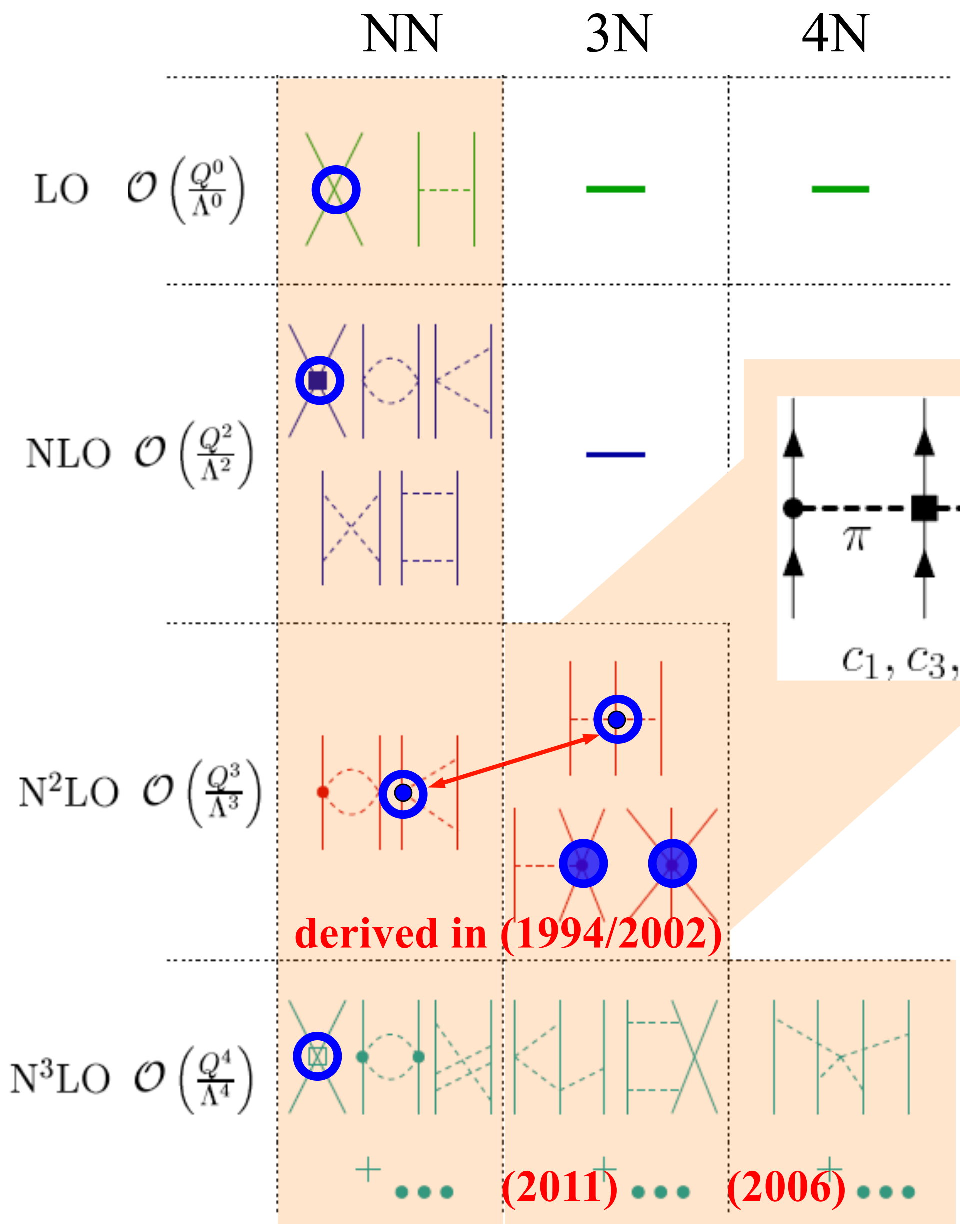
systematic with **error estimates**

consistent **electroweak interactions**,
matching to lattice QCD,
coupling to beyond SM particles,…

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

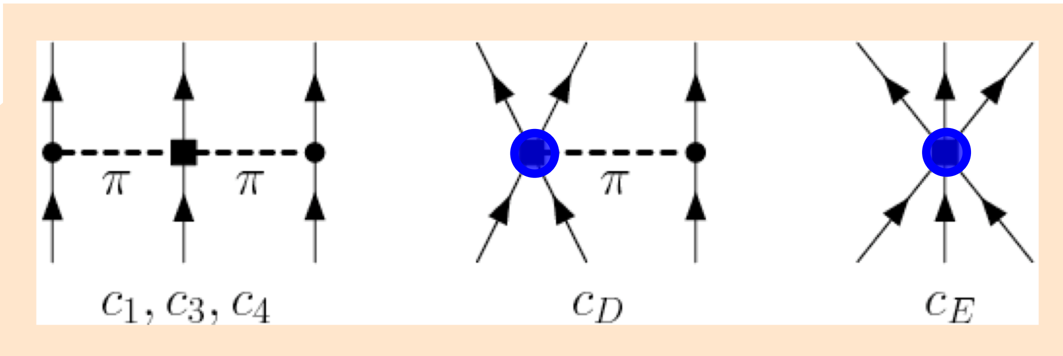
Chiral effective field theory and **many-body forces**

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



consistent NN-3N-4N interactions

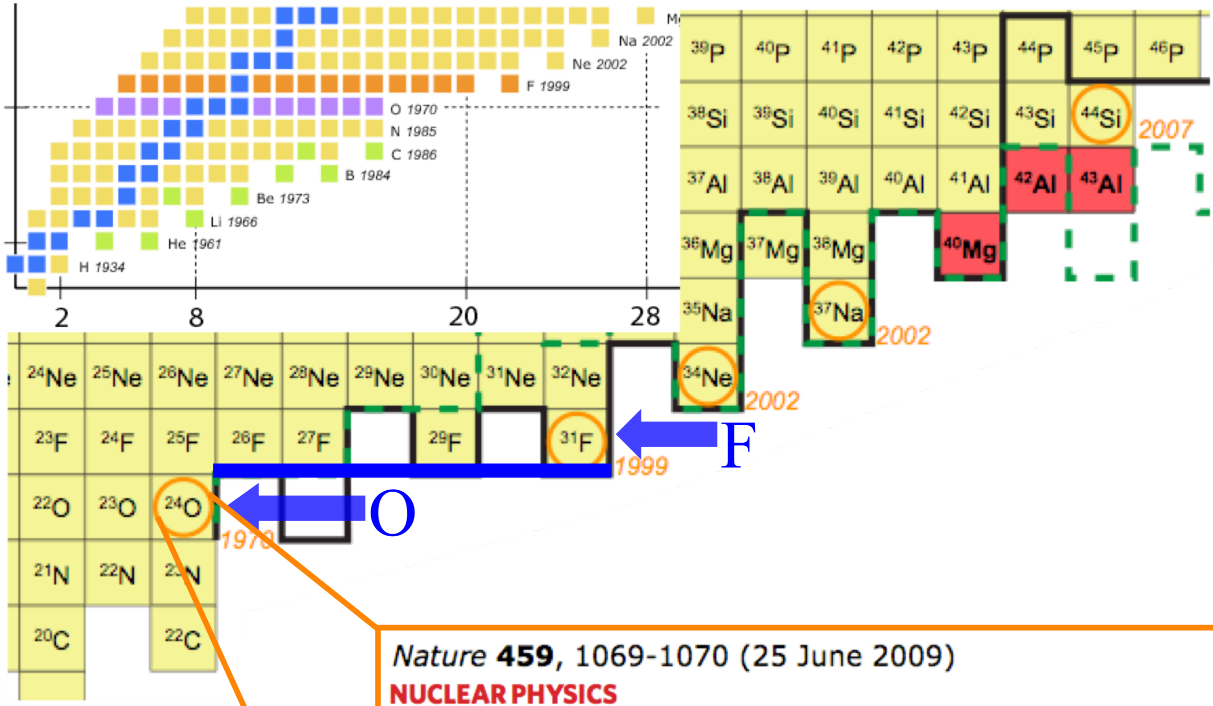
only **2 new couplings to N^{3}LO**



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

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

The oxygen anomaly



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

NUCLEAR PHYSICS

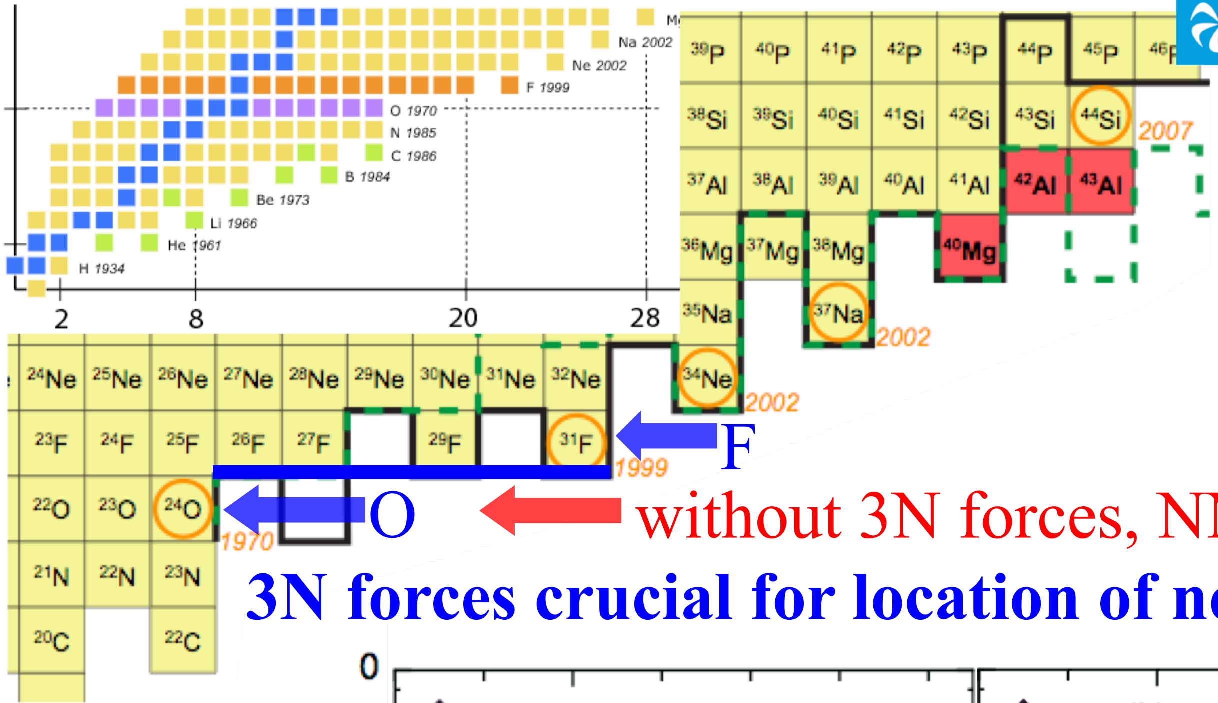
Unexpected doubly magic nucleus

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.

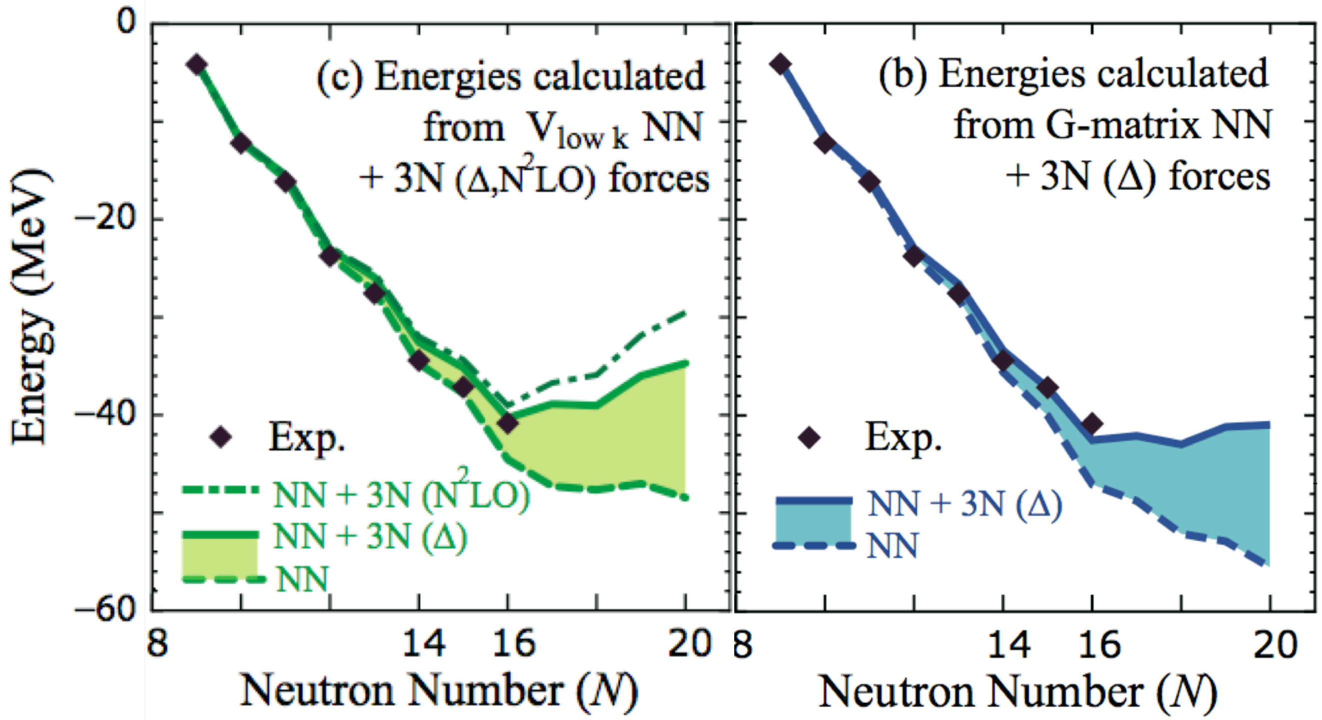
The oxygen anomaly

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 neutron-rich oxygen isotopes

based on same NN+3N interactions with different many-body methods

CC theory/CCEI

Hagen et al., PRL (2012),
Jansen et al., PRL (2014)

TRIUMF

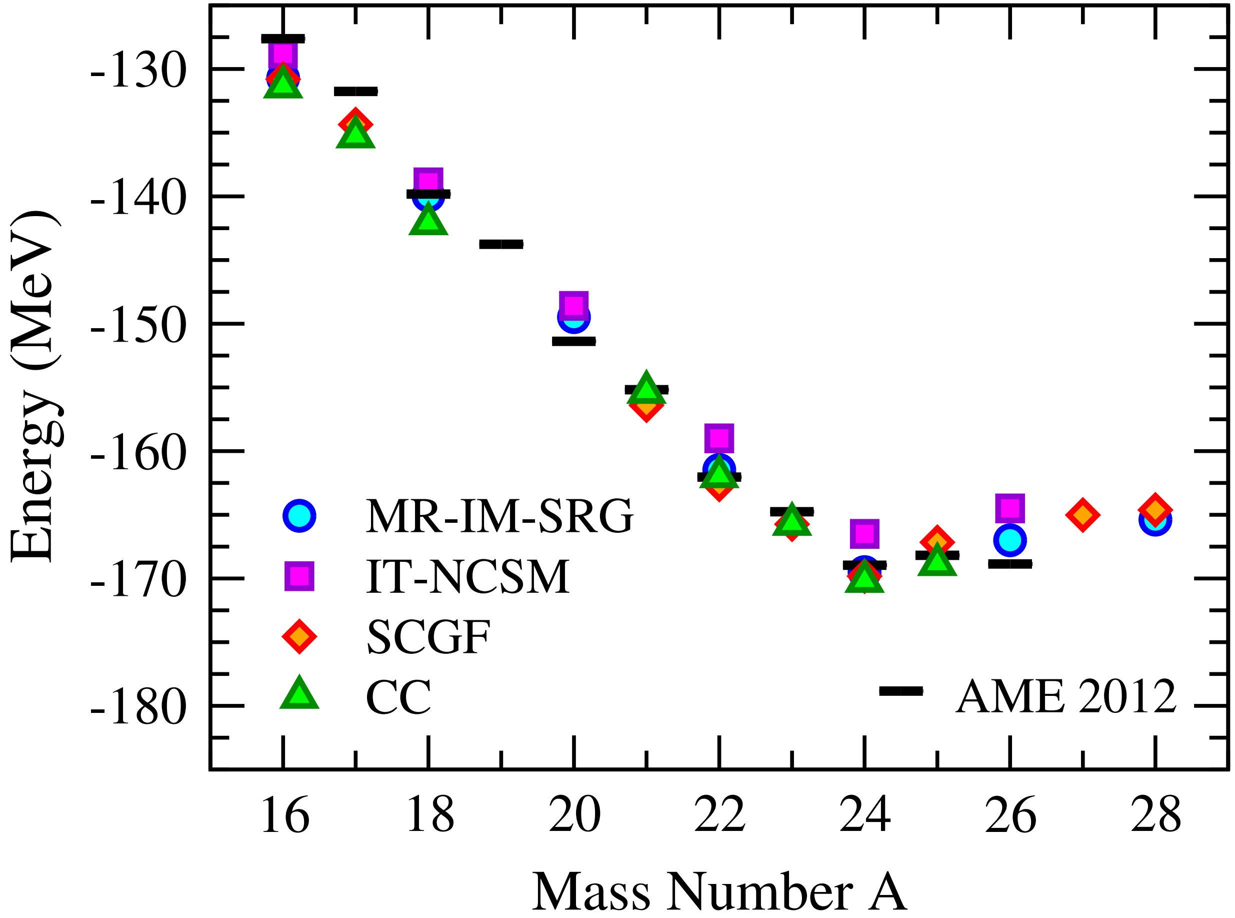
Multi-Reference
In-Medium SRG
and IT-NCSM

Hergert et al., PRL (2013)

Self-Consistent
Green's Functions

Cipollone et al., PRL (2013)

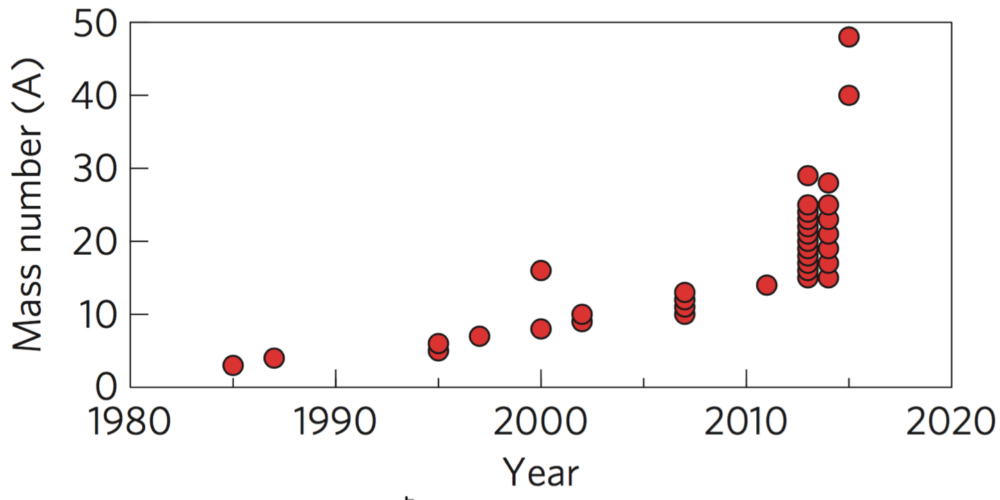
TRIUMF



Many-body calculations of medium-mass nuclei have smaller uncertainty compared to uncertainties in nuclear forces

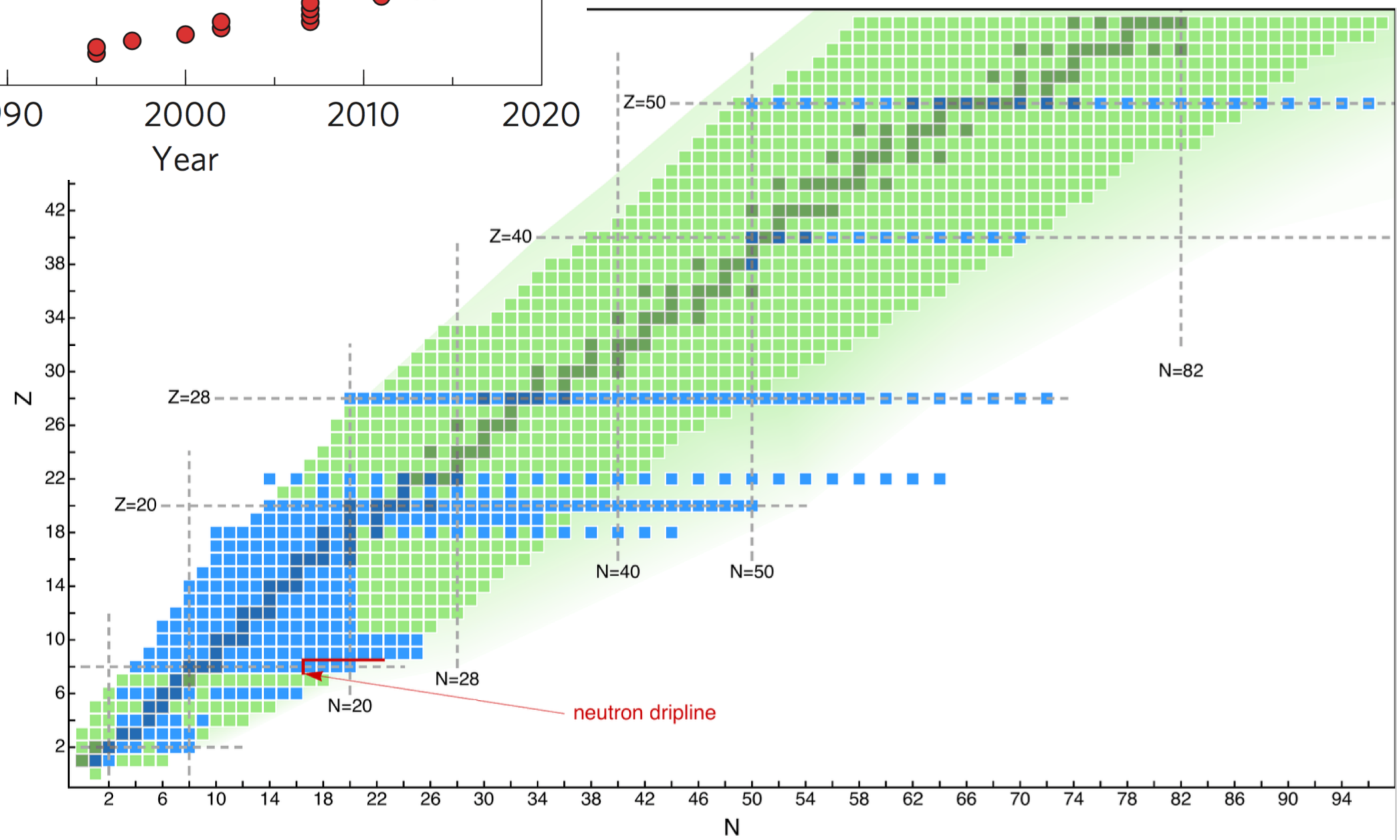
Progress in ab initio calculations of nuclei

dramatic progress in last 5 years to access nuclei up to A ~ 50



from Hagen et al., Nature Phys. (2016)

from Hergert et al., Phys. Rep. (2016)



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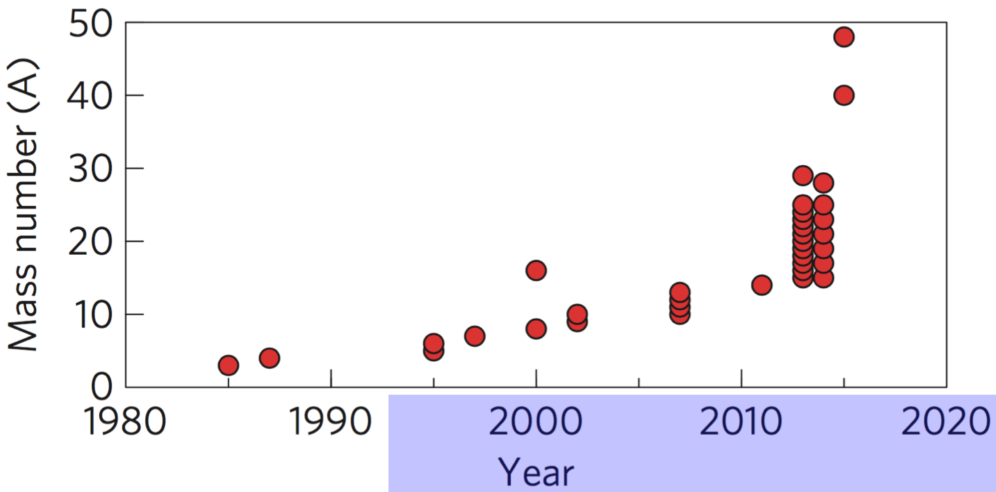

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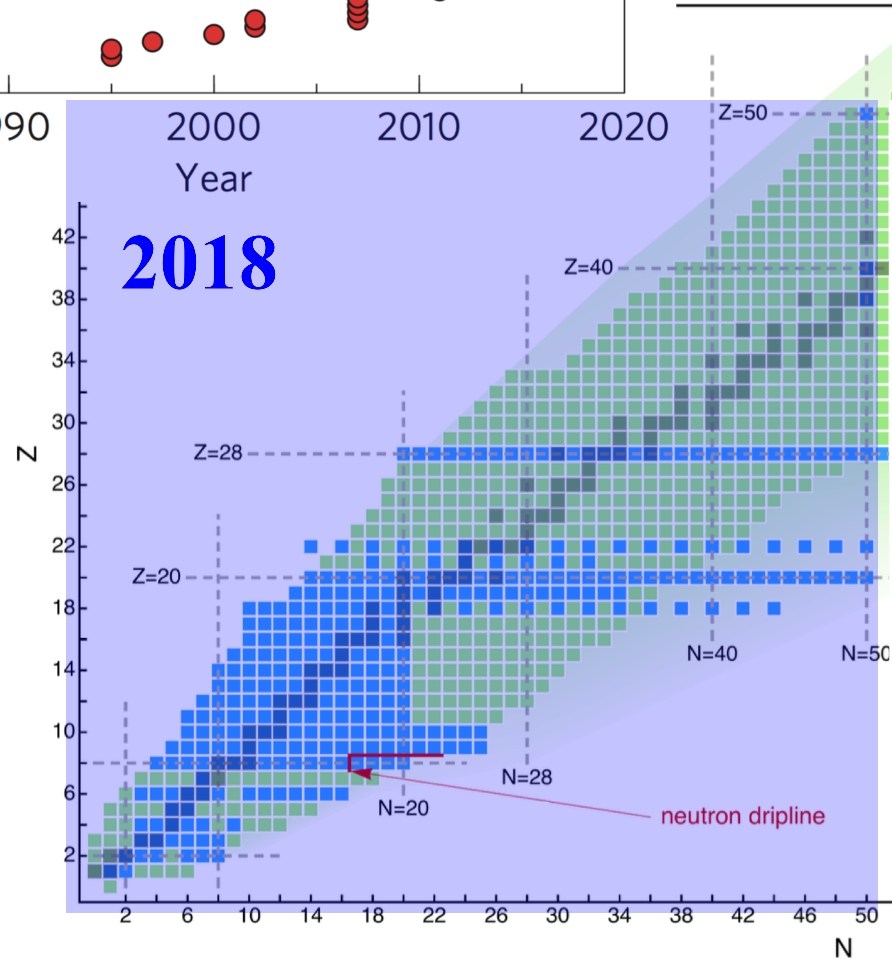

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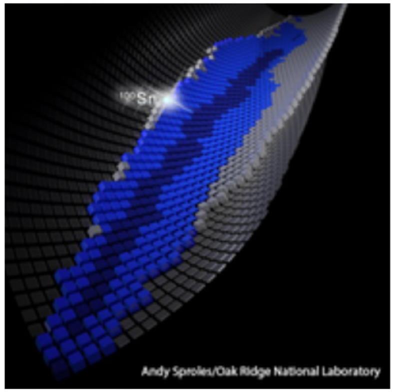
Editors' Suggestion

Structure of the Lightest Tin Isotopes

T. D. Morris, J. Simonis, S. R. Stroberg, C. Stumpf, G. Hagen, J. D. Holt, G. R. Jansen, T. Papenbrock, R. Roth, and A. Schwenk

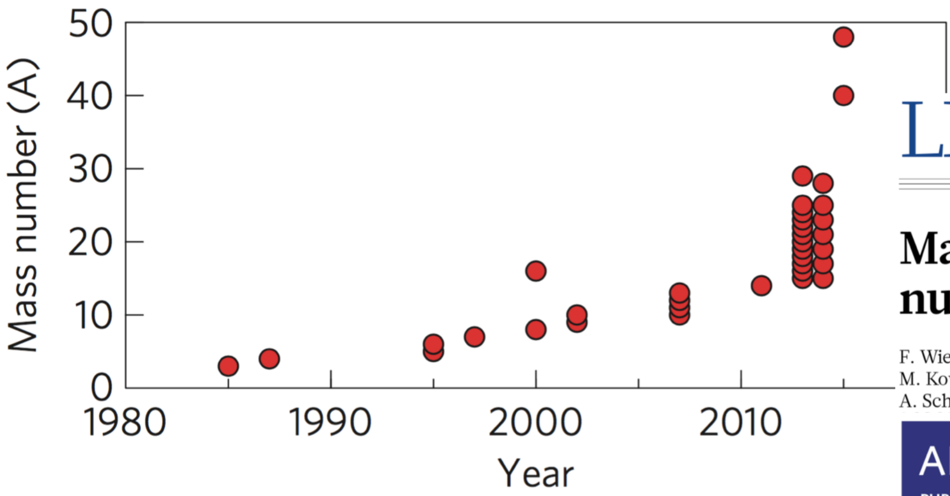
Phys. Rev. Lett. **120**, 152503 (2018) – Published 12 April 2018

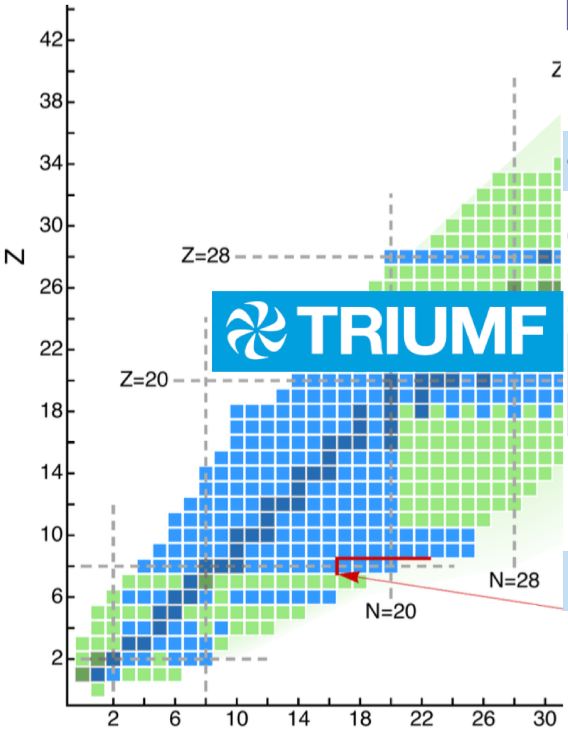


Ab-inito calculations of ^{100}Sn with $N = Z = 50$ predict it to be doubly magic.

Progress in ab initio calculations of nuclei

dramatic progress in last 5 years to access nuclei up to A ~ 50





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LETTER

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]

ARTICLES
PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3529
nature physics

Neutron and weak-charge distributions of the ^{48}Ca nucleus

G. Hagen[1,2★], A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J. Simonis[9,10]

nature physics
ARTICLES
PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3645

Unexpectedly large charge radii of neutron-rich calcium isotopes

R. F. Garcia Ruiz[1★], M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1], A. Schwenk[3,7,8], J. Simonis[7,8], K. A. Wendt[4,5] and D. T. Yordanov[3,13]

Start of a new era: ^{51,52}Ca TITAN measurements

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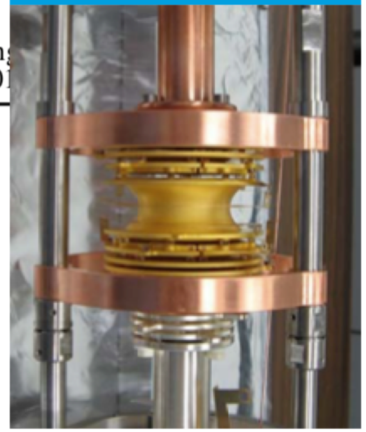


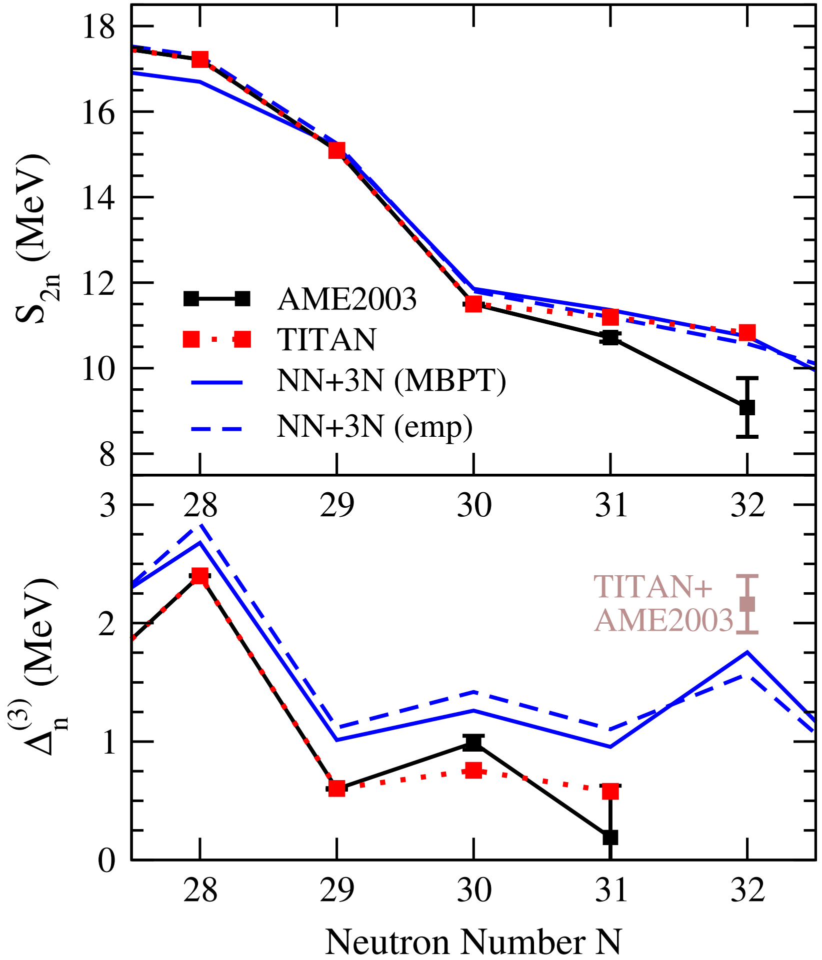
PRL **109,** 032506 (2012) PHYSICAL REVIEW LETTERS week ending 20 JULY 20

New Precision Mass Measurements of Neutron-Rich Calcium and Potassium Isotopes and Three-Nucleon Forces

A. T. Gallant,[1,2,*] J. C. Bale,[1,3] T. Brunner,[1] U. Chowdhury,[1,4] S. Ettenauer,[1,2] A. Lennarz,[1,5] D. Robertson,[1] V. V. Simon,[1,6,7] A. Chaudhuri,[1] J. D. Holt,[8,9] A. A. Kwiatkowski,[1] E. Mané,[1] J. Menéndez,[10,11] B. E. Schultz,[1] M. C. Simon,[1] C. Andreoiu,[3] P. Delheij,[1] M. R. Pearson,[1] H. Savajols,[12] A. Schwenk,[11,10] and J. Dilling[1,2]

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

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



Ab initio calculations at neutron-rich extremes

doi:10.1038/nature12226

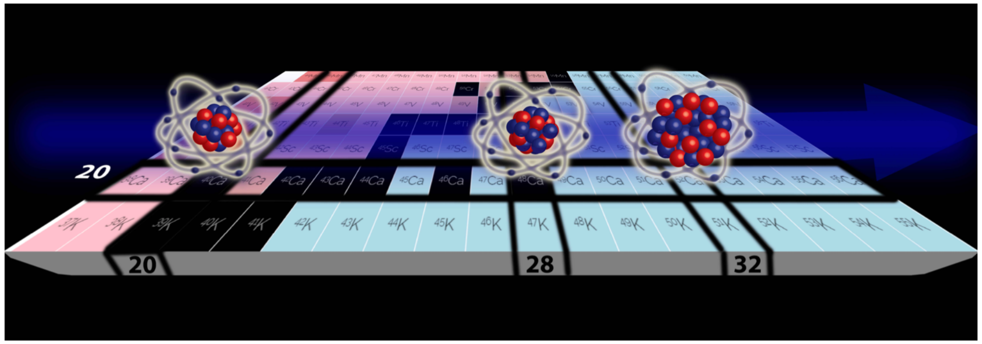
Masses of exotic calcium isotopes pin down nuclear forces

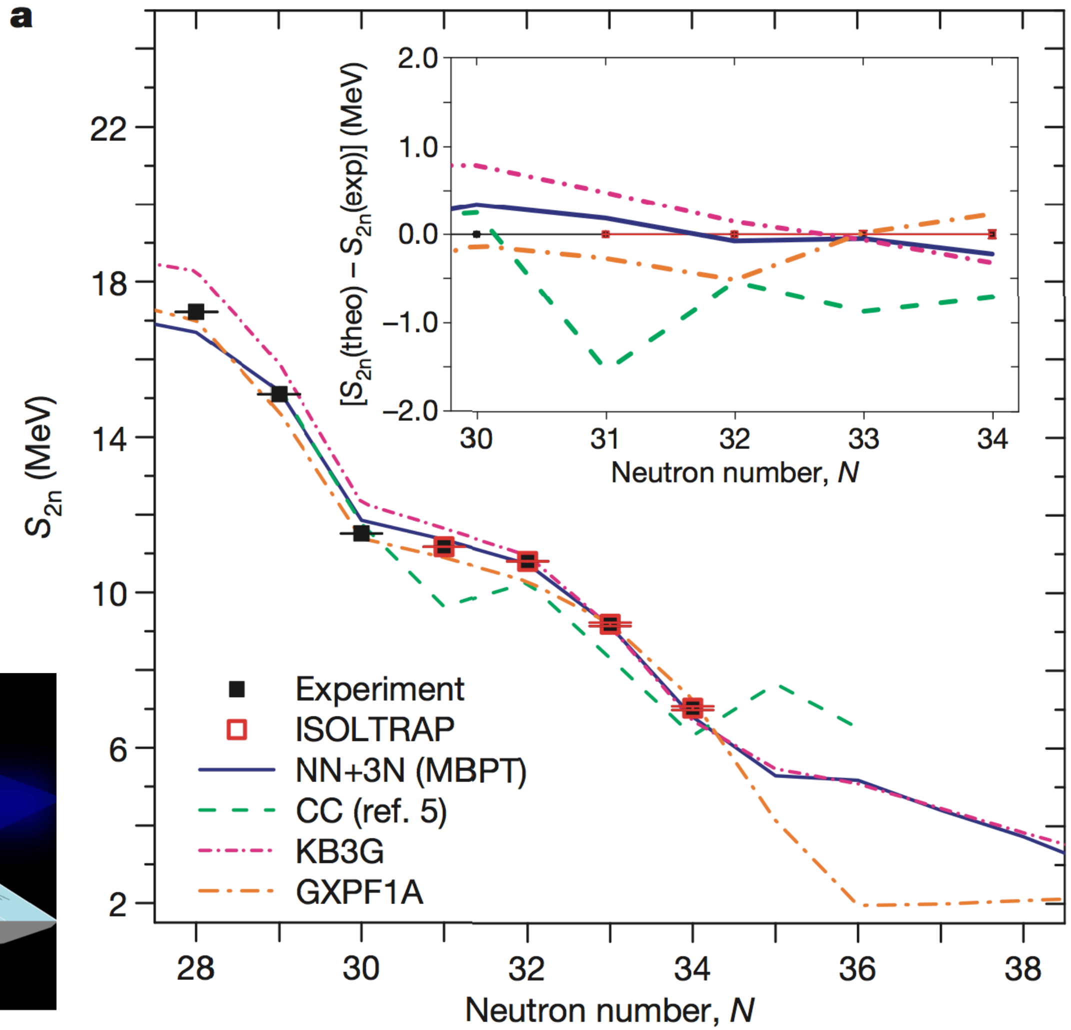
F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7],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

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

excellent agreement with theoretical NN+3N prediction

suggests N=32 shell closure



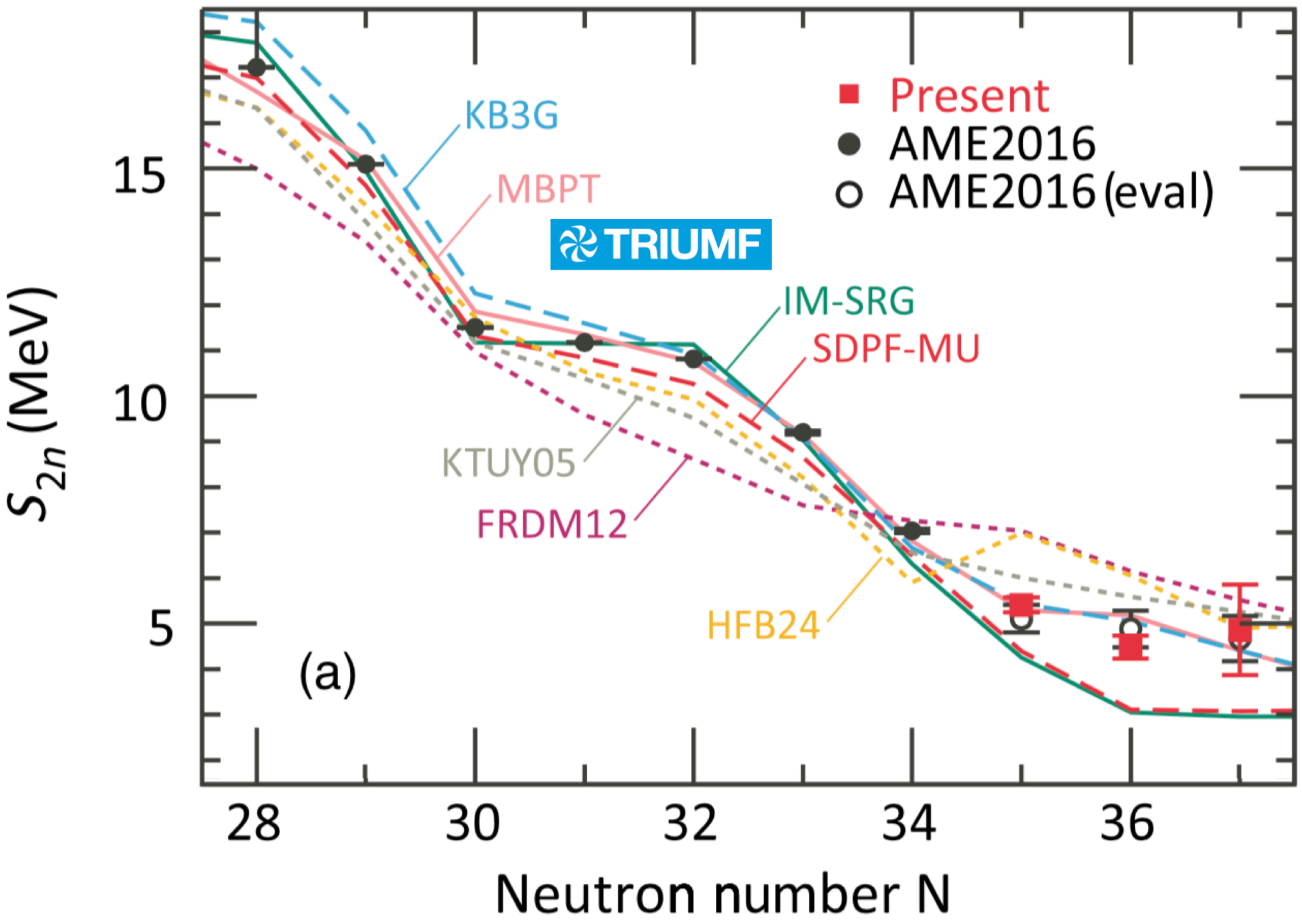


New results from RIBF at RIKEN

PHYSICAL REVIEW LETTERS **121,** 022506 (2018)

Magic Nature of Neutrons in ^{54}Ca: First Mass Measurements of $^{55-57}$Ca

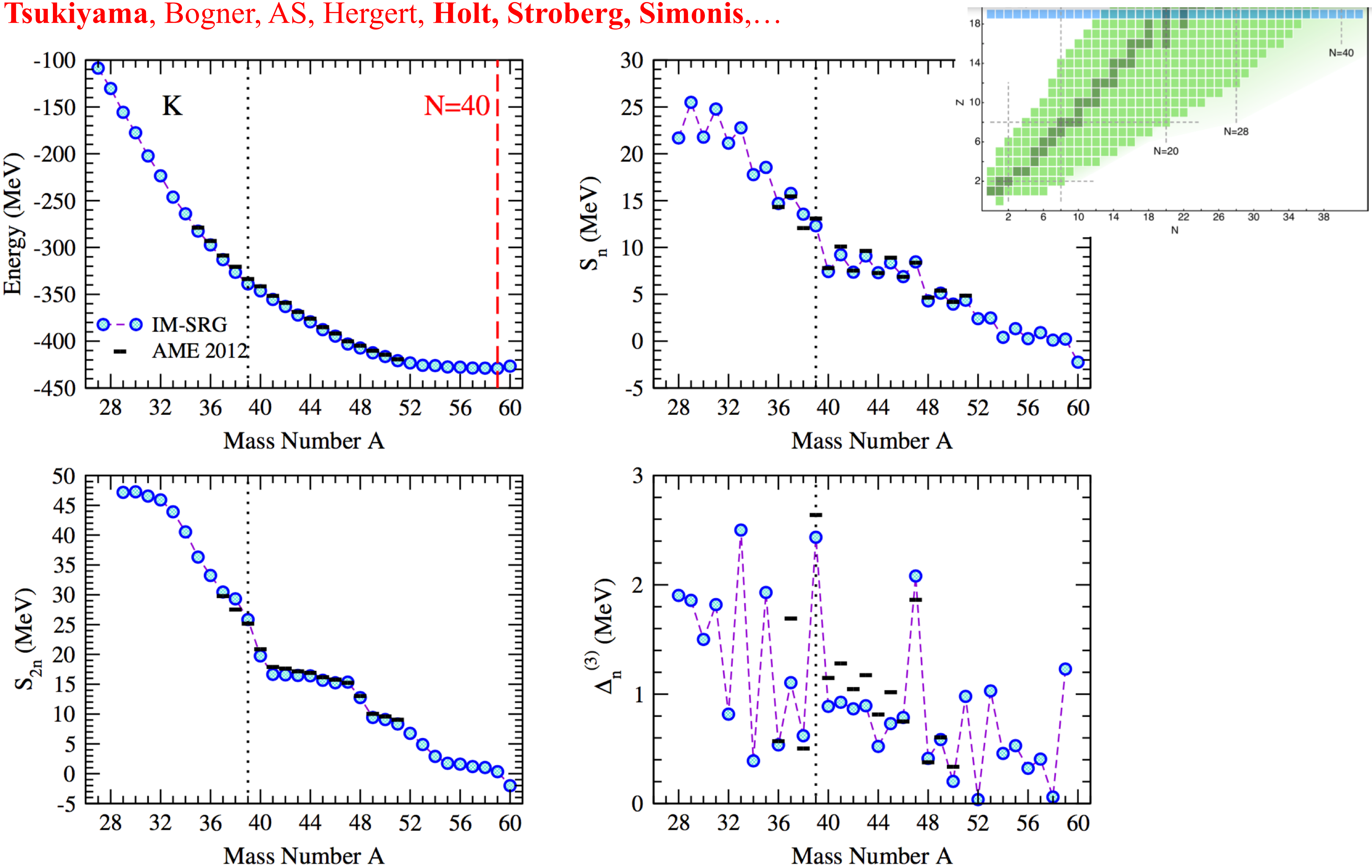
S. Michimasa,[1,*] M. Kobayashi,[1] Y. Kiyokawa,[1] S. Ota,[1] D. S. Ahn,[2] H. Baba,[2] G. P. A. Berg,[3] M. Dozono,[1] N. Fukuda,[2] T. Furuno,[4] E. Ideguchi,[5] N. Inabe,[2] T. Kawabata,[4] S. Kawase,[6] K. Kisamori,[1] K. Kobayashi,[7] T. Kubo,[8,9] Y. Kubota,[2] C. S. Lee,[1,2] M. Matsushita,[1] H. Miya,[1] A. Mizukami,[10] H. Nagakura,[7] D. Nishimura,[11] H. Oikawa,[10] H. Sakai,[2] Y. Shimizu,[2] A. Stolz,[9] H. Suzuki,[2] M. Takaki,[1] H. Takeda,[2] S. Takeuchi,[12] H. Tokieda,[1] T. Uesaka,[2] K. Yako,[1] Y. Yamaguchi,[1] Y. Yanagisawa,[2] R. Yokoyama,[13] K. Yoshida,[2] and S. Shimoura[1]



Great progress from medium to heavy nuclei

In-medium similarity renormalization group (IM-SRG) for open shell

Tsukiyama, Bogner, AS, Hergert, **Holt, Stroberg, Simonis**,…



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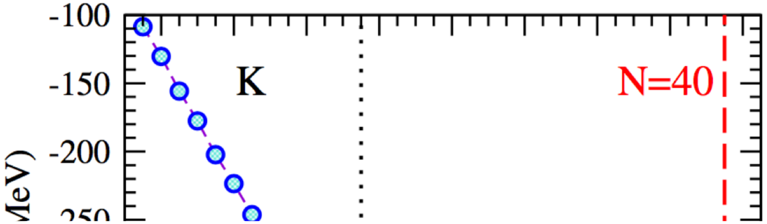

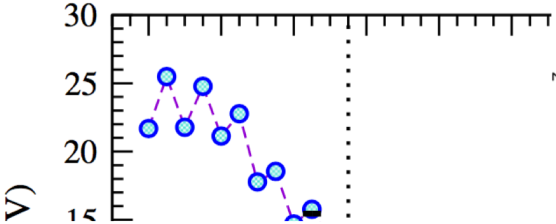

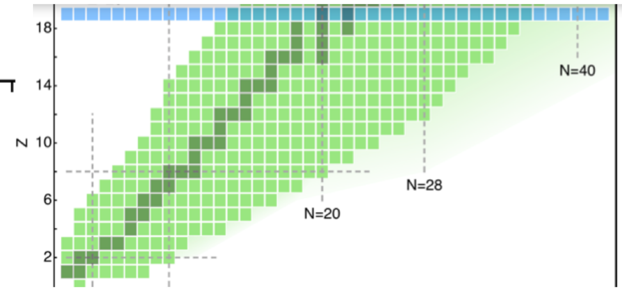

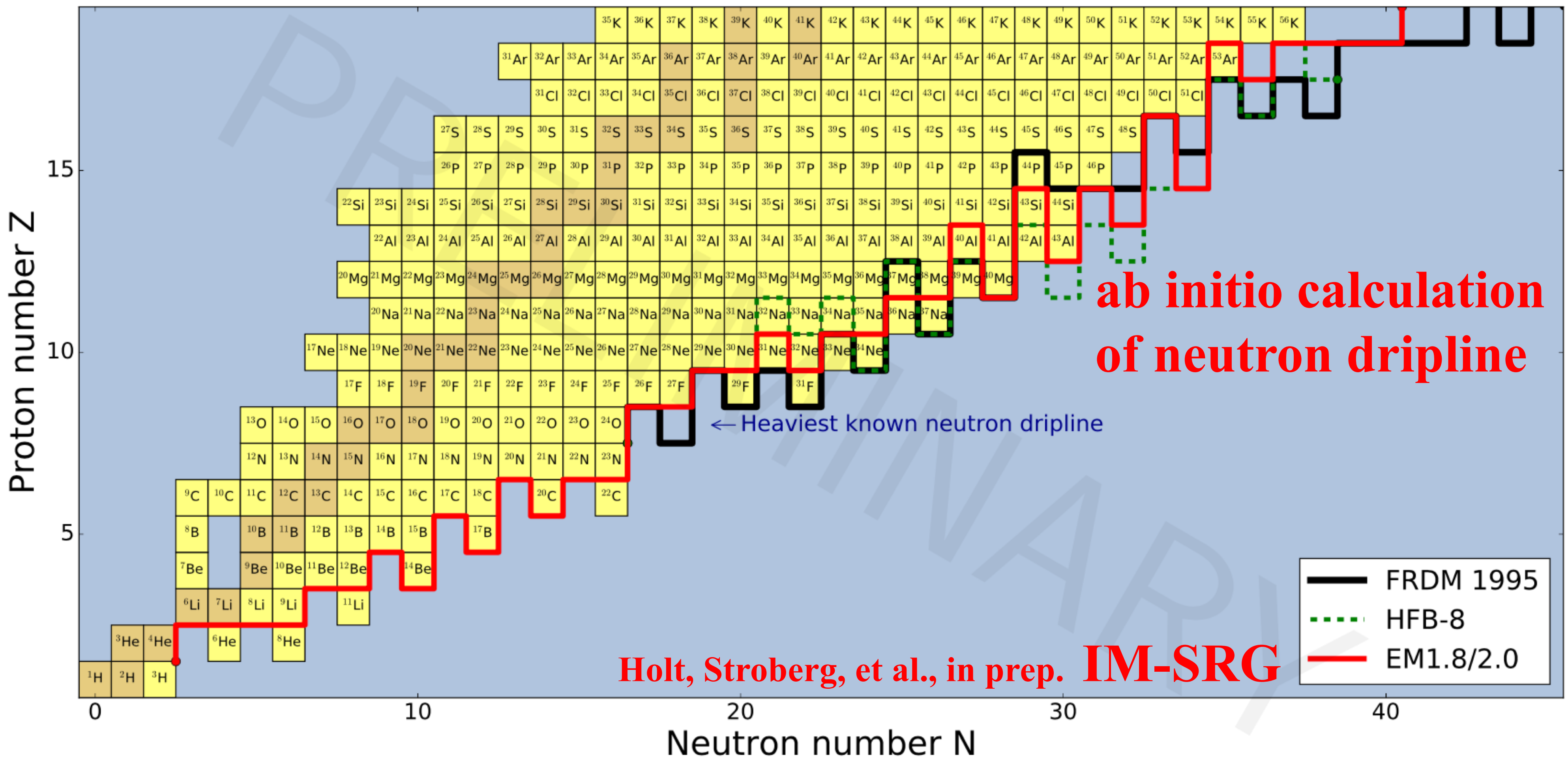

Neutron skin of ^{48}Ca

nature physics

ARTICLES

PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3529

Neutron and weak-charge distributions of the ^{48}Ca nucleus

G. Hagen[1,2★], A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J. Simonis[9,10]

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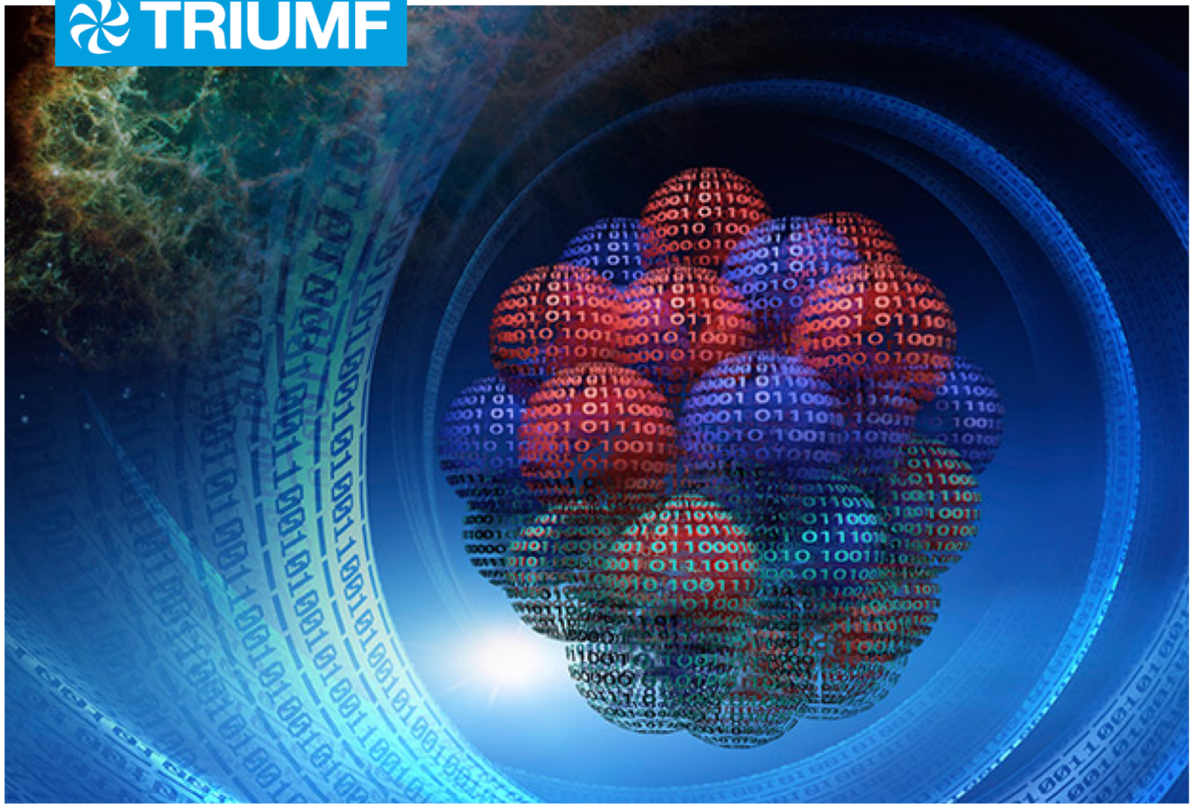
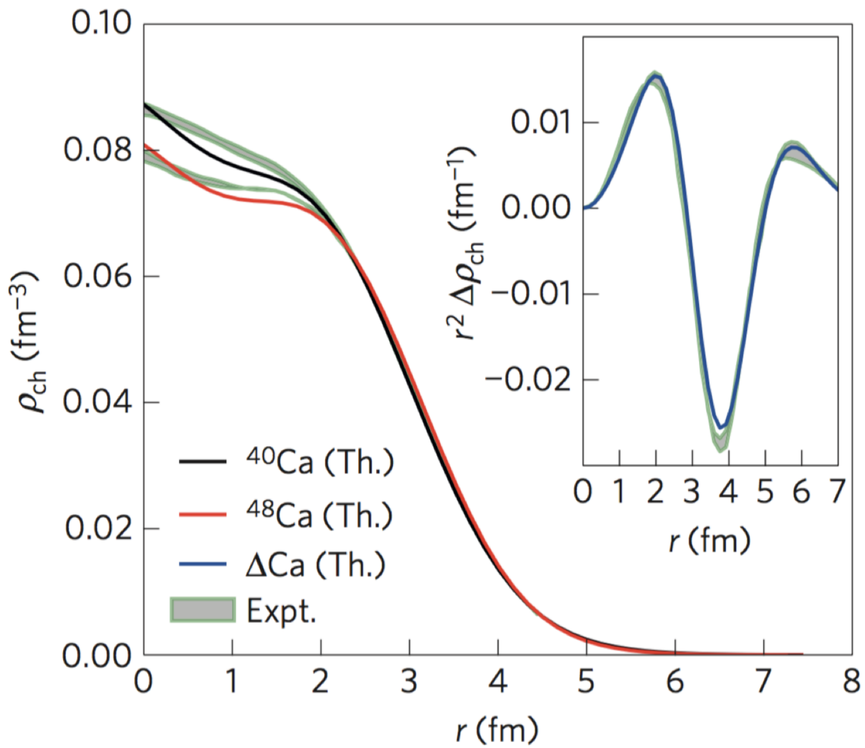


Neutron and weak-charge distributions of ^{48}Ca

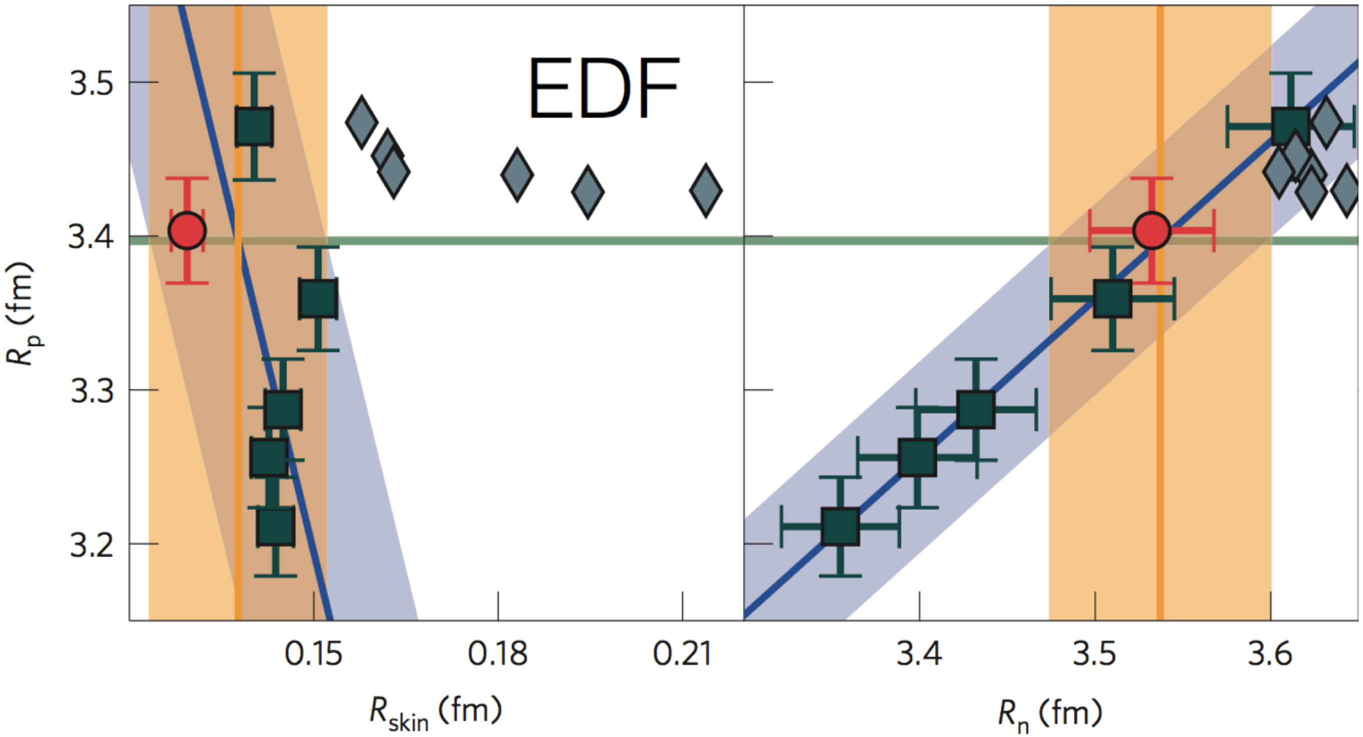
ab initio calculations lead to charge distributions consistent with experiment



Neutron and weak-charge distributions of ^{48}Ca

ab initio calculations lead to charge distributions consistent with experiment

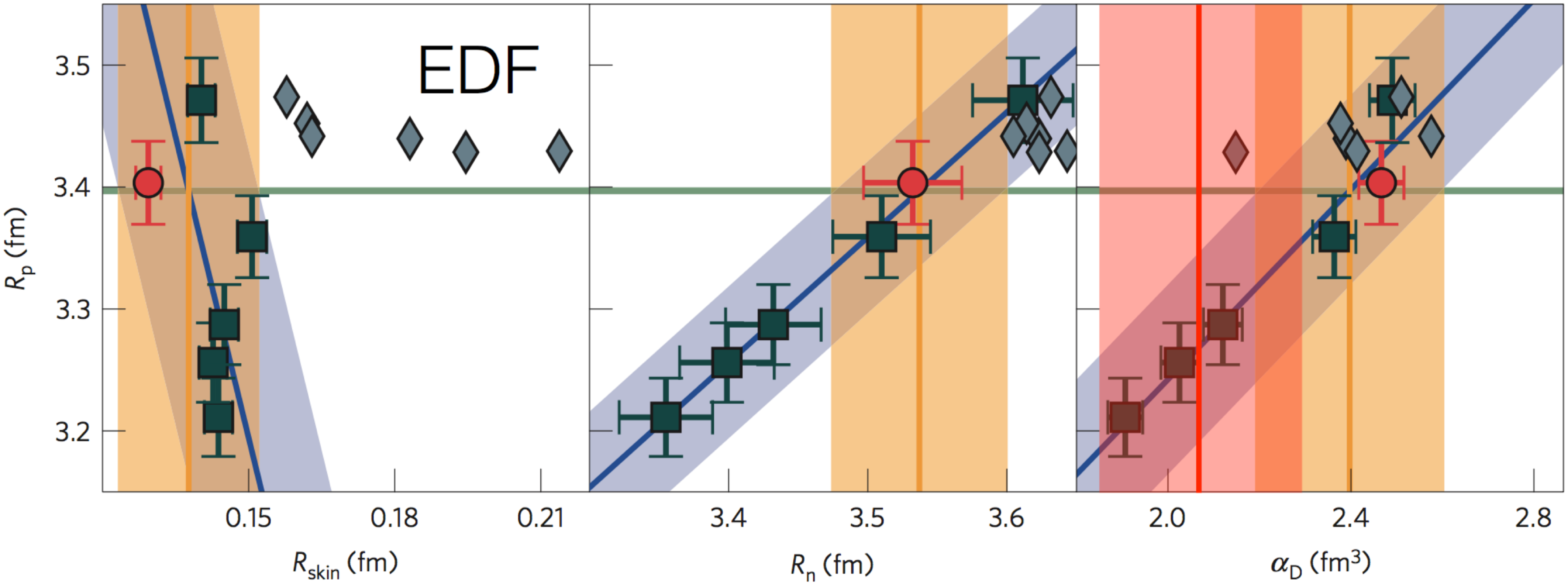
predict **small neutron skin**



Neutron and weak-charge distributions of ^{48}Ca

ab initio calculations lead to charge distributions consistent with experiment

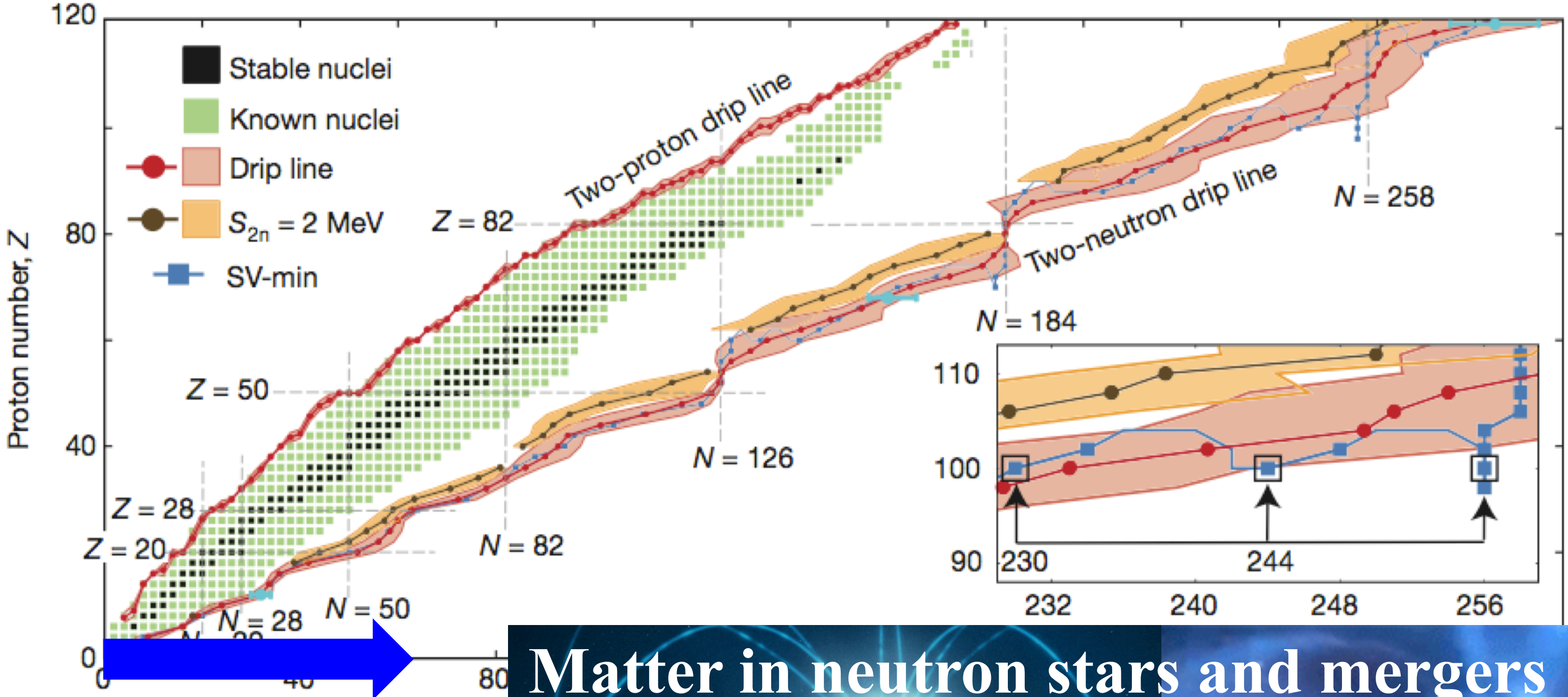
predict **small neutron skin**, dipole polarizability, and weak formfactor



dipole polarizability in good agreement with recent DA-Osaka expt.

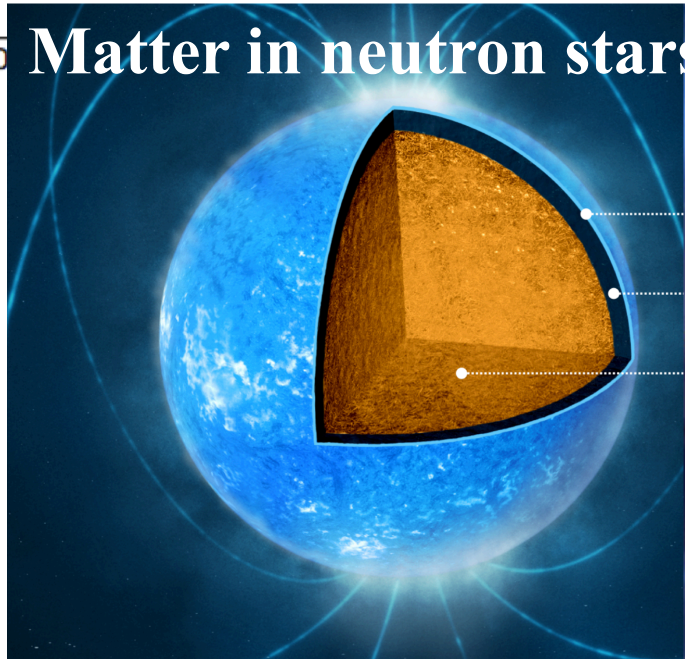
Birkhan, Miorelli, et al., PRL (2017)

TRIUMF

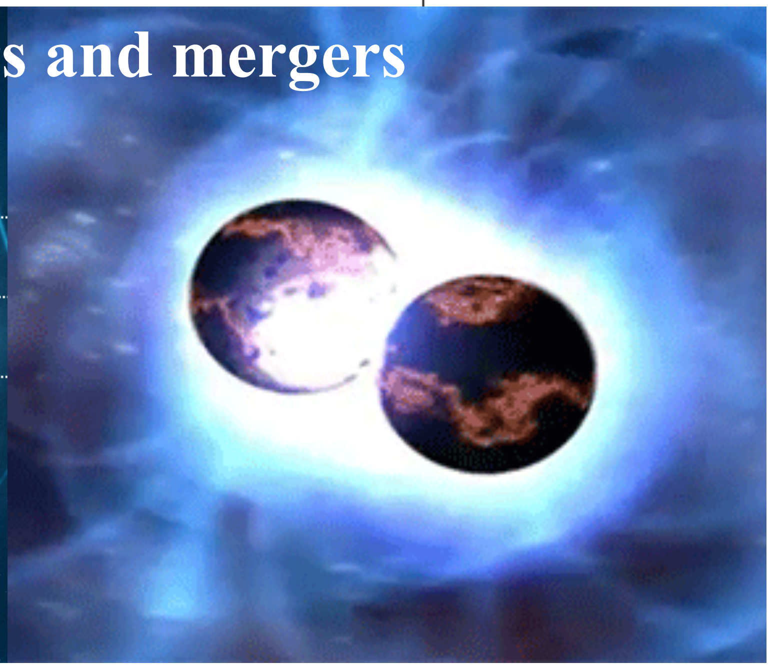


Neutrons

Matter in neutron stars and mergers



from Watts et al., RMP (2016)

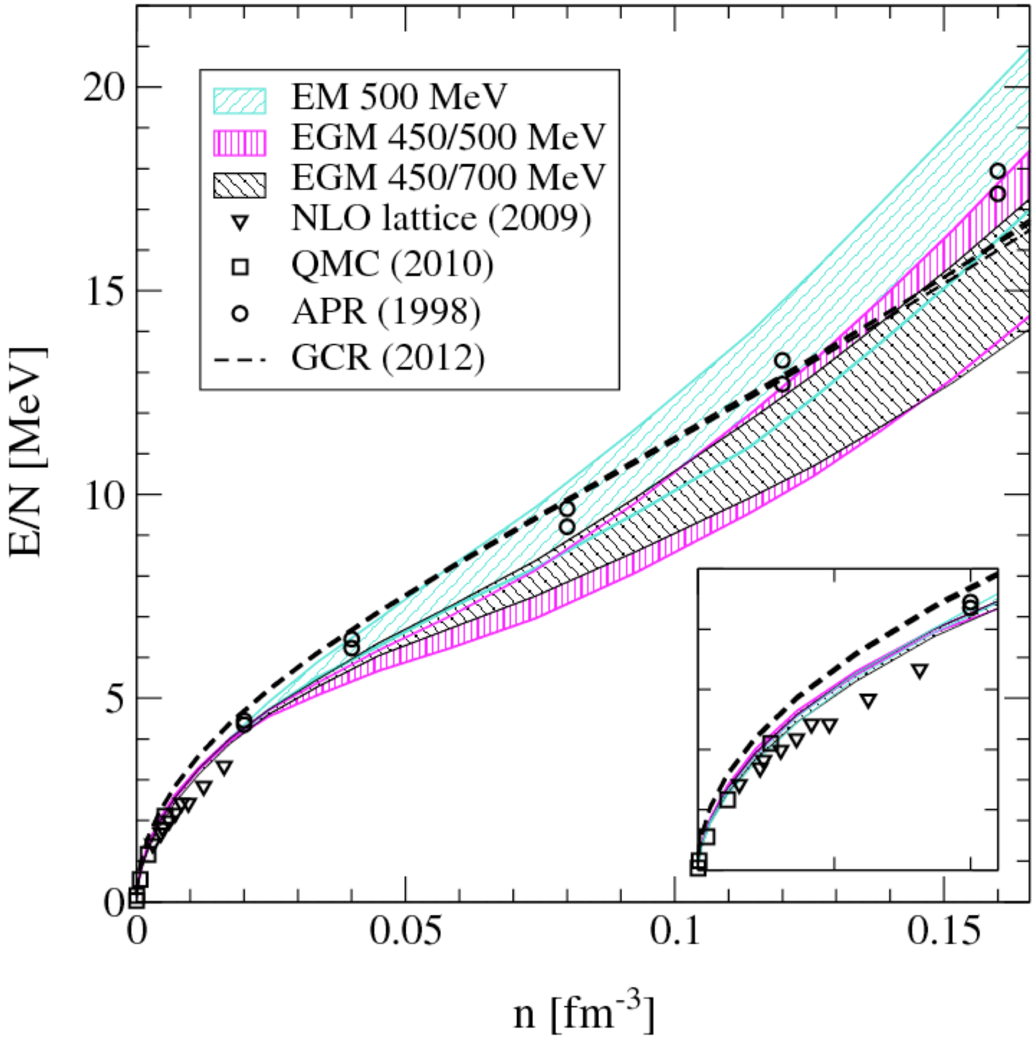


from NASA/Goddard/LIGO/Virgo

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



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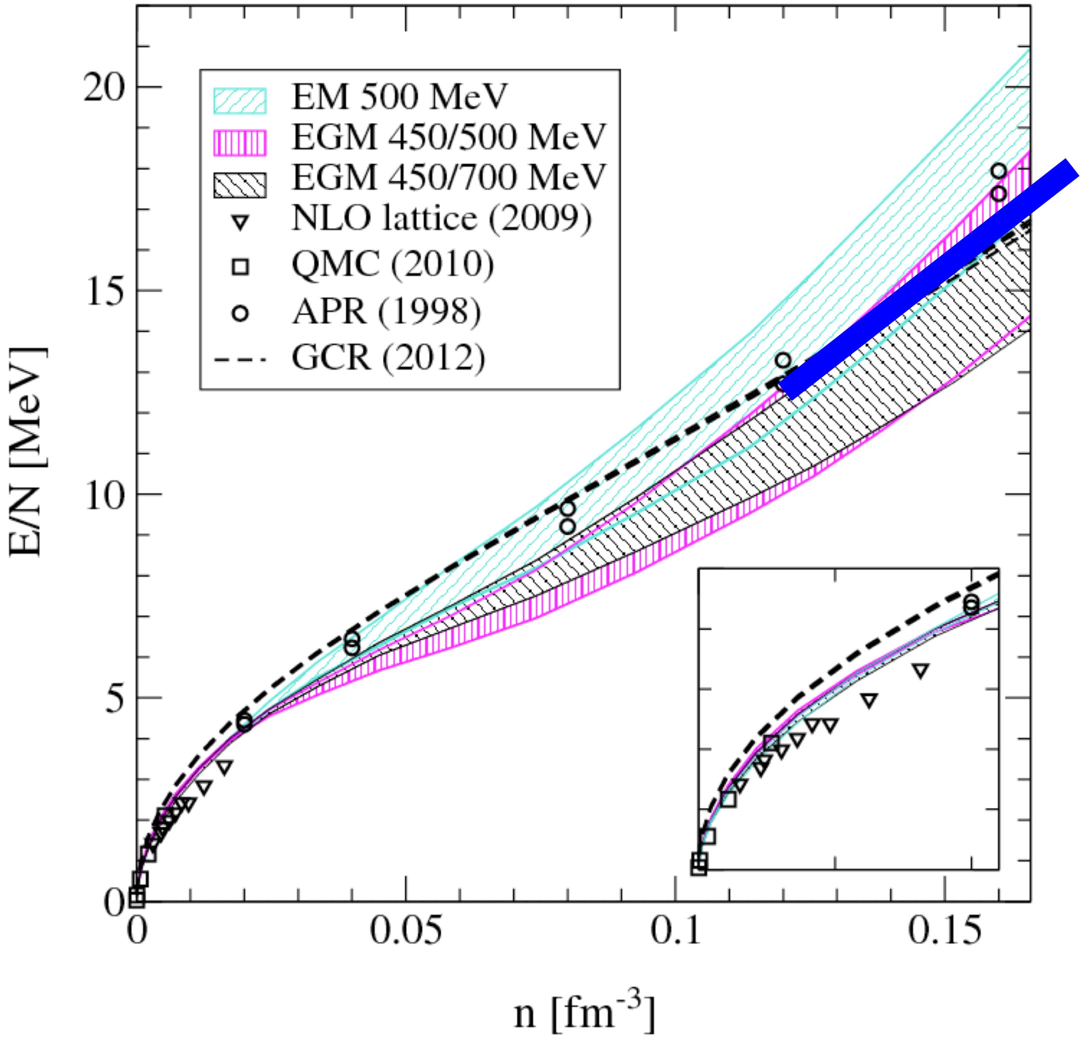
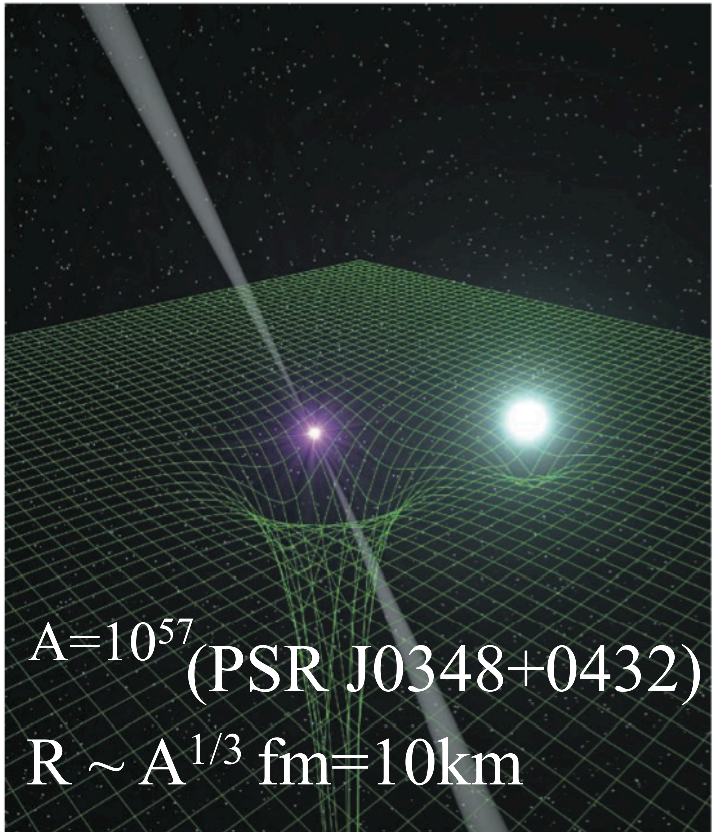


slope determines pressure of neutron matter

Chart of neutron star masses

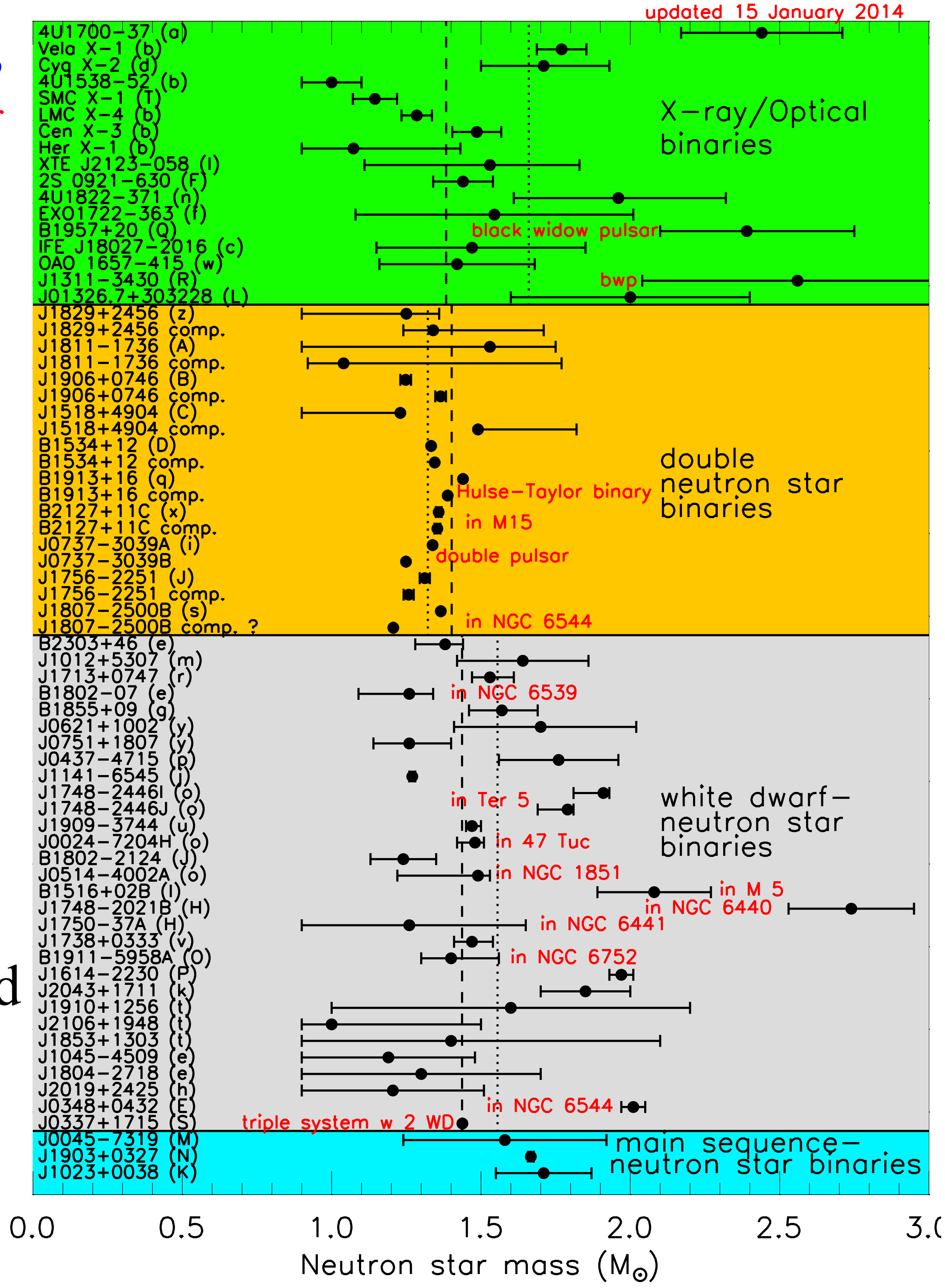
from Jim Lattimer



two 2 M_{sun} neutron stars observed

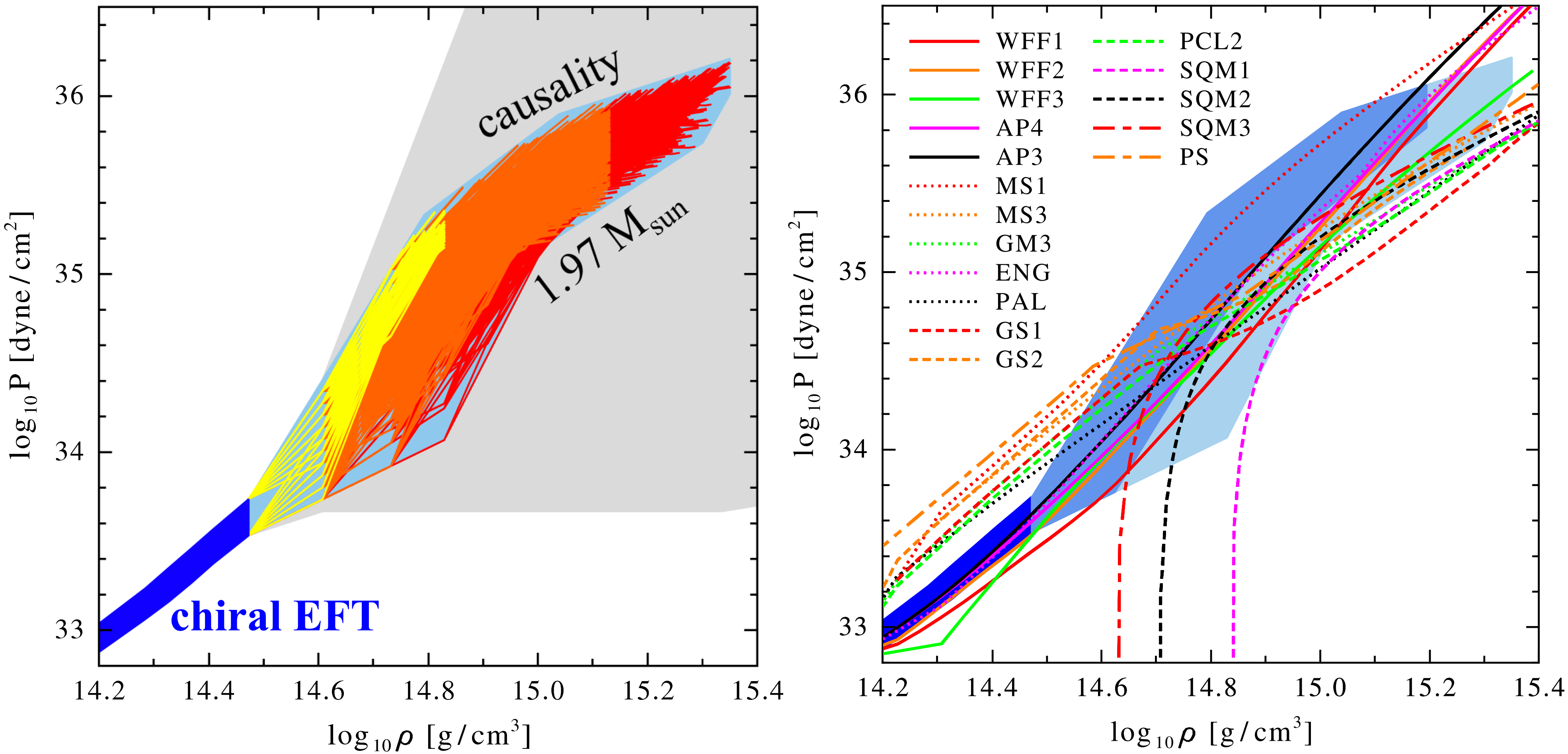
Demorest et al, Nature (2010),

Antoniadis et al., Science (2013)



Impact on neutron stars Hebeler et al., PRL (2010), ApJ (2013)

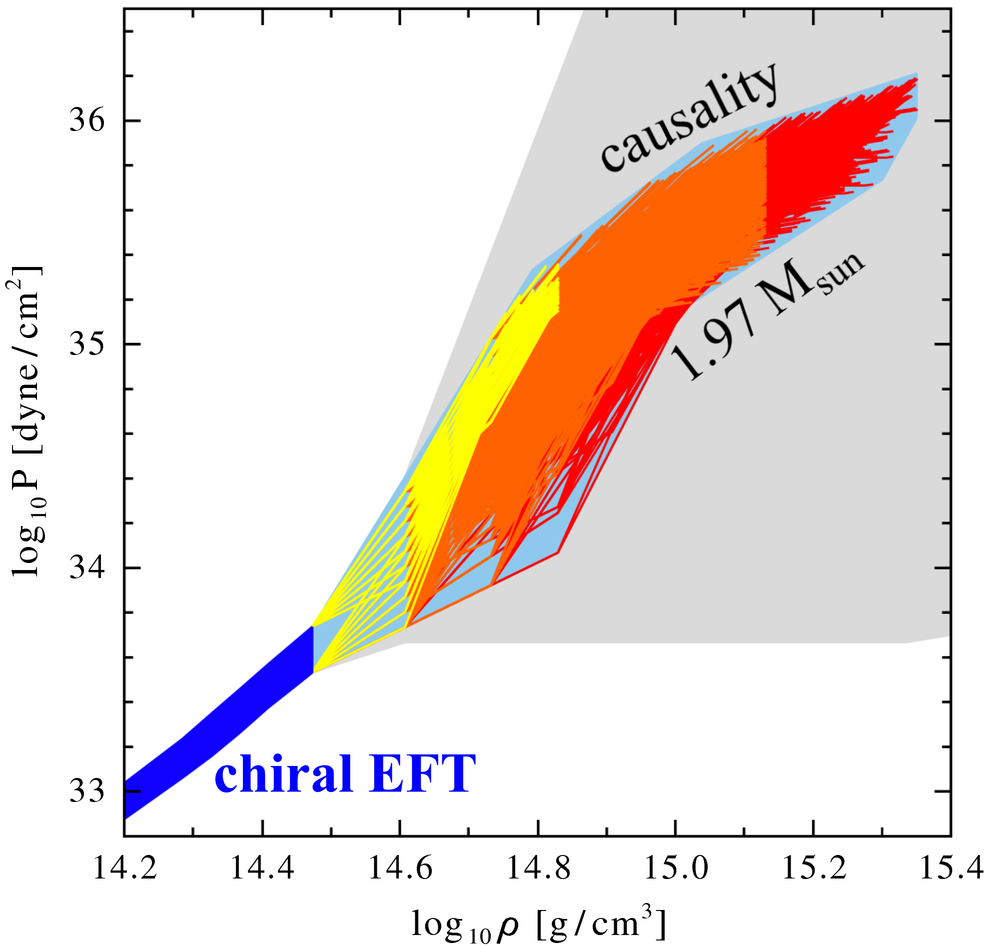
constrain high-density EOS by causality, require to support 2 M_{sun} star

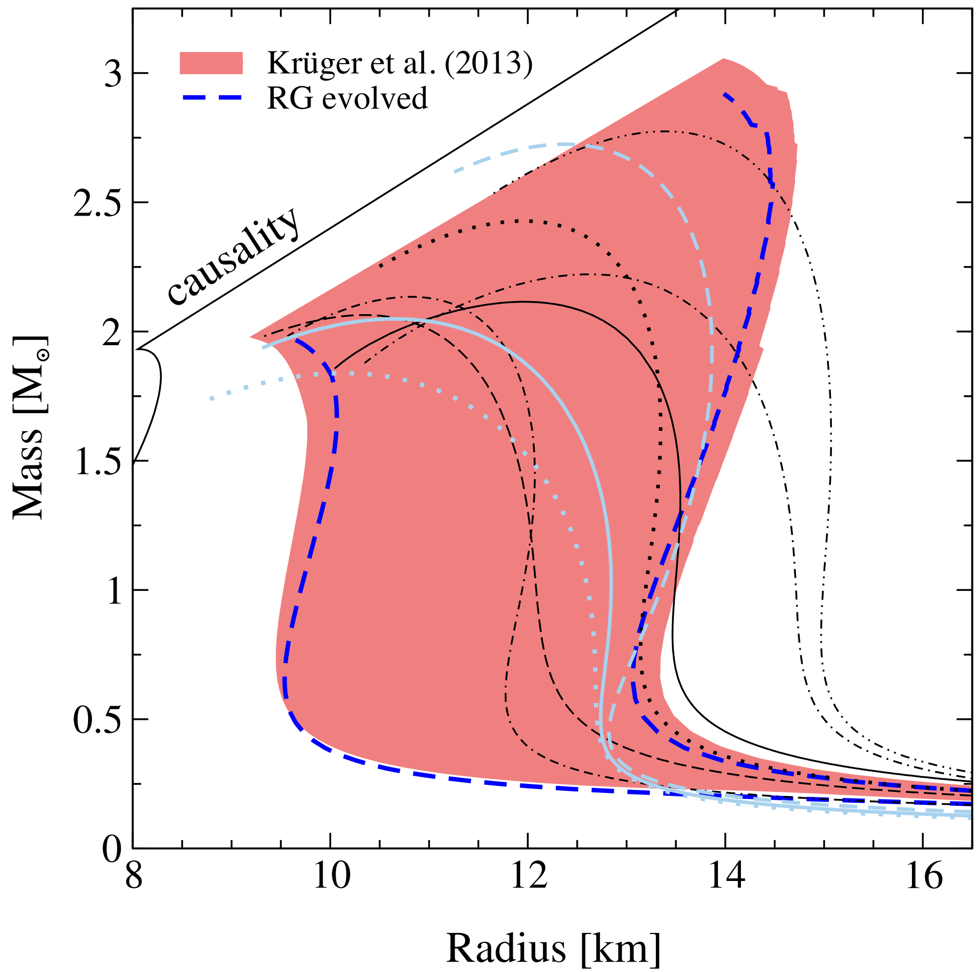


low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

Impact on neutron stars Hebeler et al., PRL (2010), ApJ (2013)

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





predicts neutron star radius: 9.7-13.9 km for M=1.4 M_{sun}

1.8-4.4 ρ_0 modest central densities

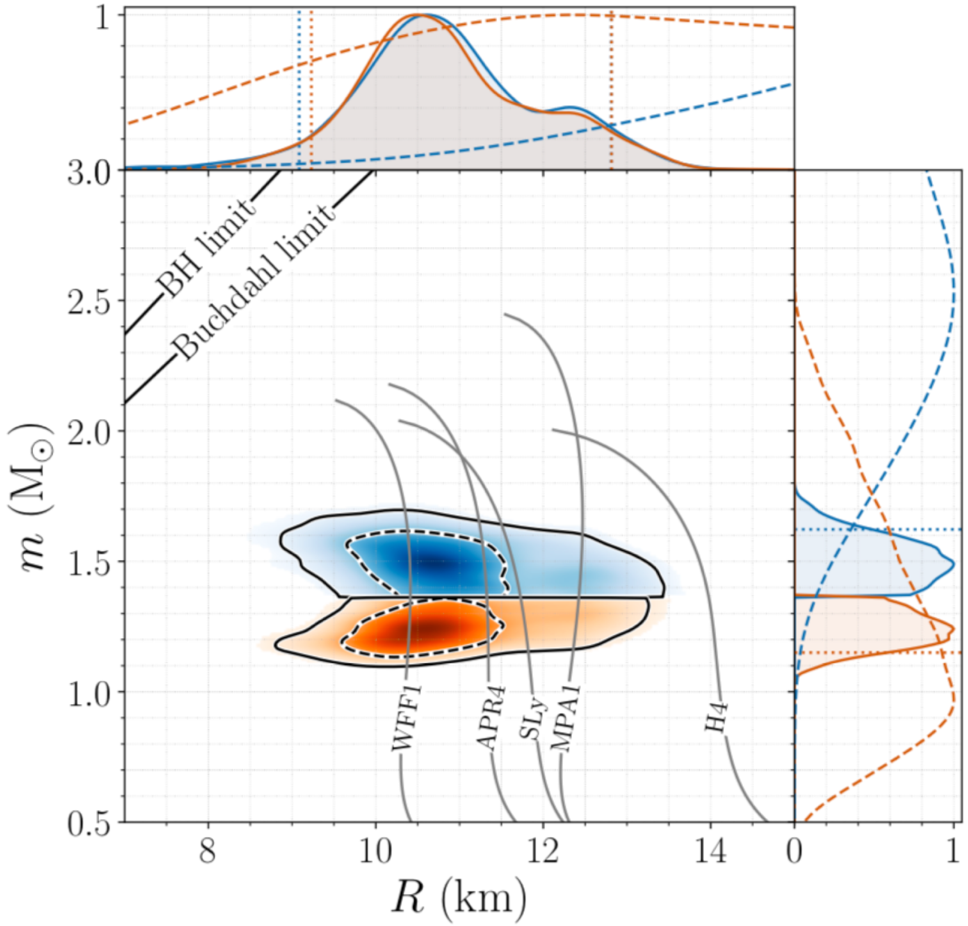
speed of sound needs to exceed ~0.65c to get 2 M_{sun} stars Greif et al.

Neutron star radius from GW170817

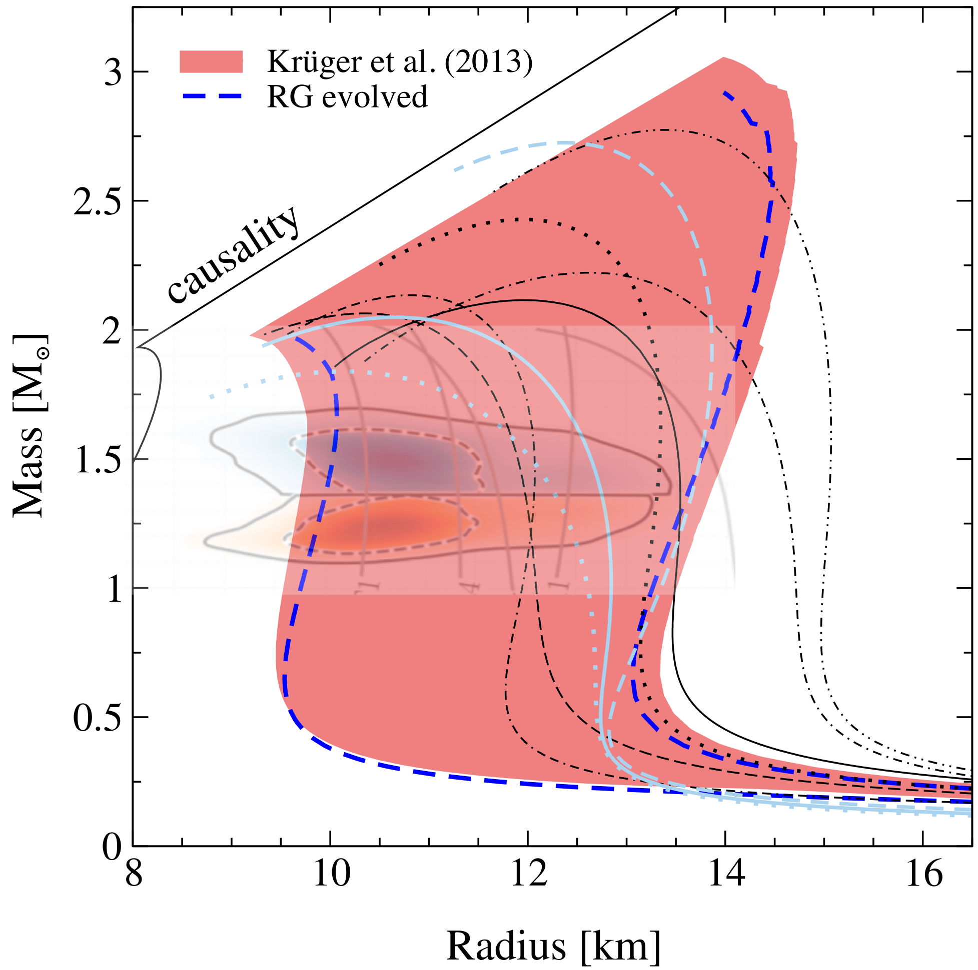
chiral EFT + general EOS extrapolation: 9.7-13.9 km for $M=1.4\ M_{sun}$

GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration
(compiled 30 May 2018)



excellent agreement with GW170817 from LIGO/Virgo



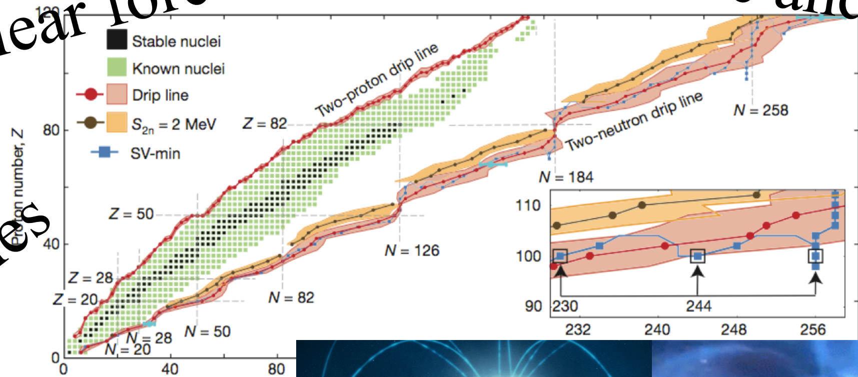
Physics of nuclei

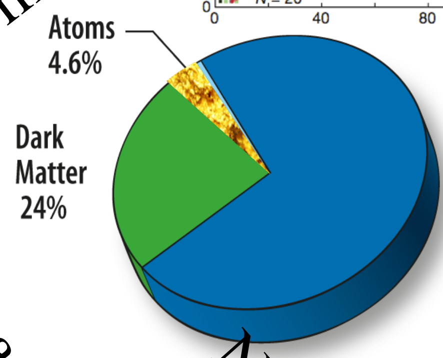
Emergence of structure
from nuclear forces

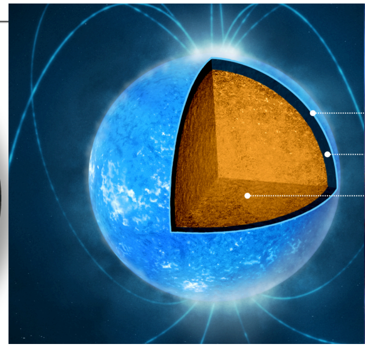
Nuclear reactions
for structure and stars

Halos
and skins

Nuclei and neutrons for
fundamental symmetries







Nuclei at
the limits

Strong interaction
in dense matter

Synthesis of heavy elements
in the Universe

Nuclear physics
of dark matter

Nuclear physics for
neutrino physics

Congratulations TRIUMF!!
Always at the forefront – On to the next 50 years!

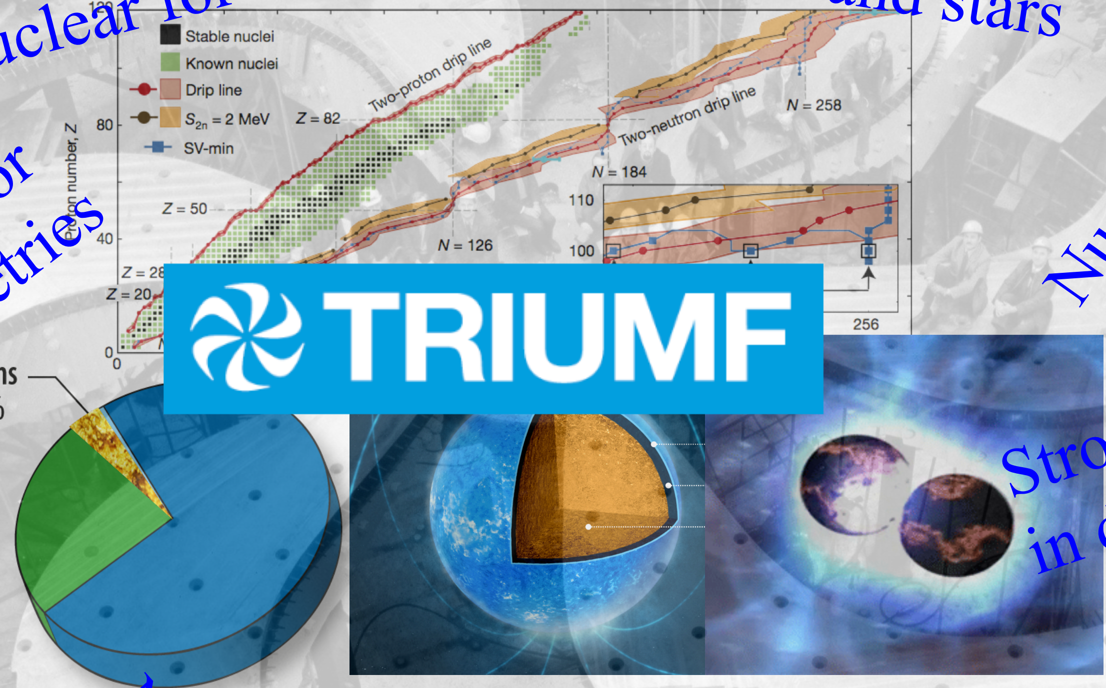
Emergence of structure from nuclear forces

Nuclear reactions for structure and stars

Halos and skins

Nuclei and neutrons for fundamental symmetries

Nuclei at the limits



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