From FRIB to Lattice QCD

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Facility for Rare Isotope Beams &
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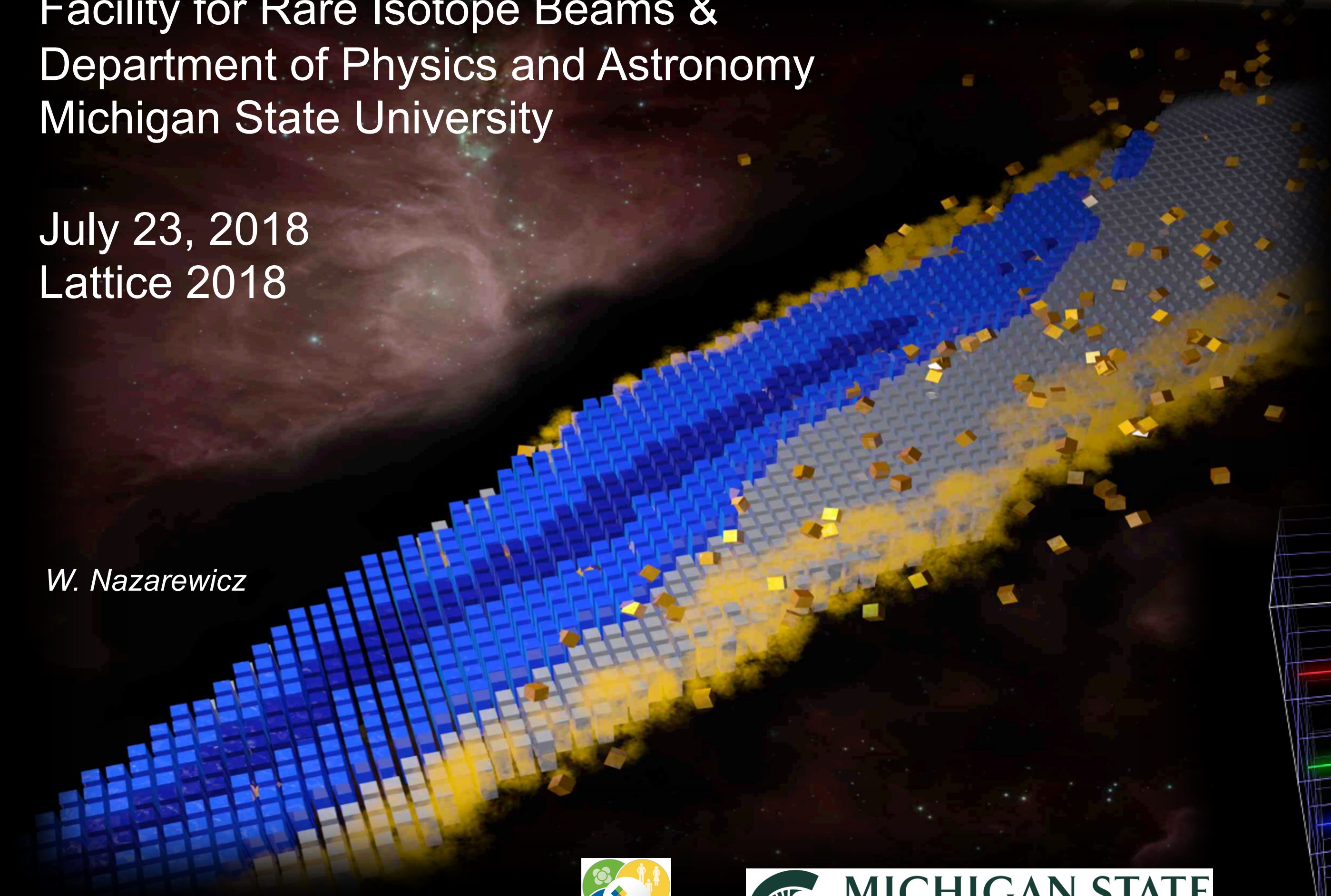
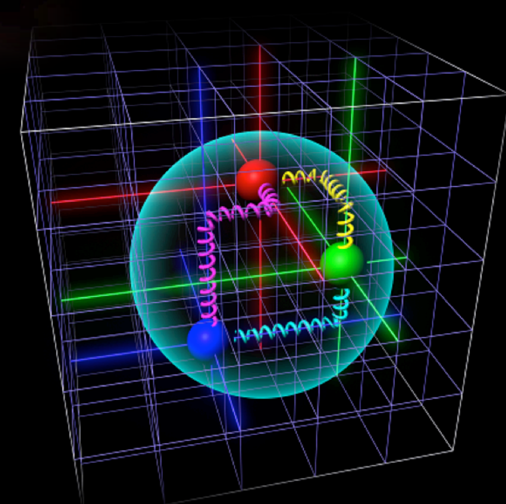
Michigan State University

July 23, 2018
Lattice 2018



W. Nazarewicz



FRIB

MICHIGAN STATE UNIVERSITY

Outline

Facility for Rare Isotope Beams

Nuclear Landscape

Astrophysical Processes

Nuclear Forces

Chiral Effective Field Theory

Microscopic *A*-body Methods

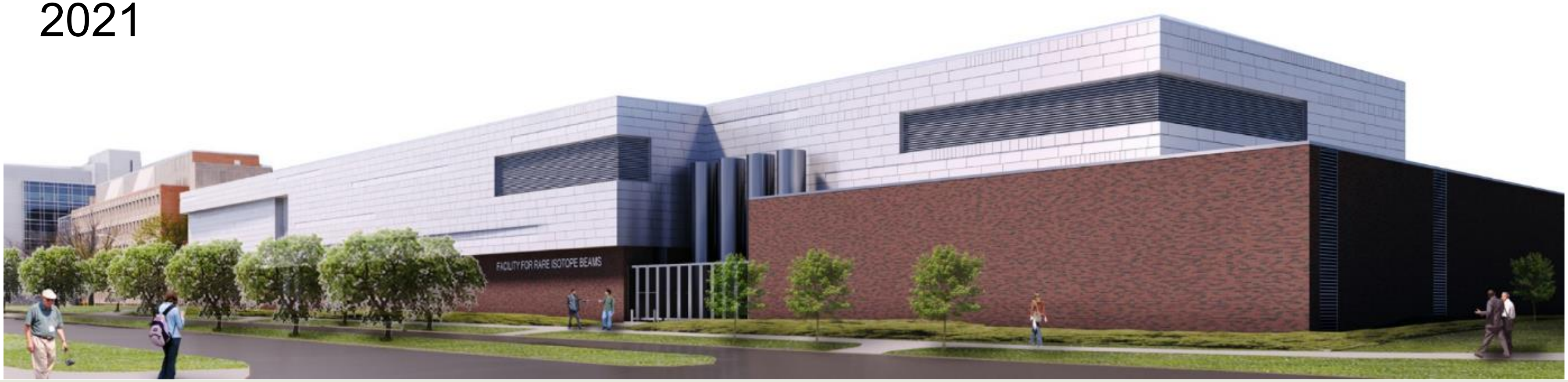
FRIB Opportunities for Lattice QCD

Isotope Harvesting and Fundamental Symmetries

Summary and Outlook

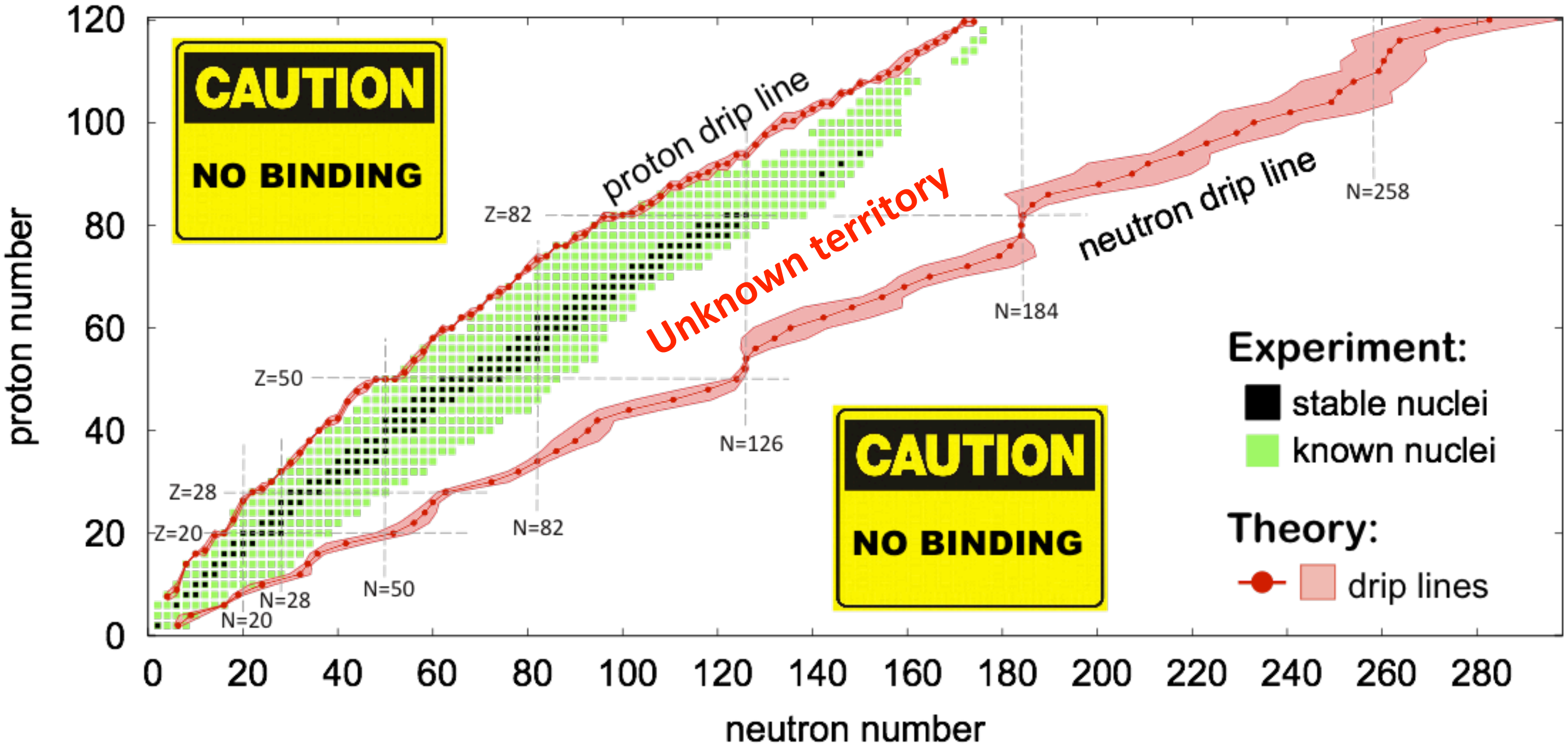
Facility for Rare Isotope Beams (FRIB)

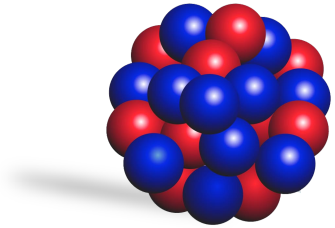
- A rare isotope facility has been a priority of the nuclear science community since the 1990's
- FRIB started in 2008 and will be a U.S. Department of Energy Office of Science scientific user facility for rare isotope research supporting the mission of the Nuclear Physics Program at the Office of Science
- FRIB Project constructs a $730 million national user facility funded by the U.S. Department of Energy Office of Science, Michigan State University, and the State of Michigan
- Planned completion date is June 2022, managing to early completion in 2021



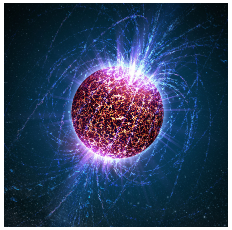
[FRIB Animation]

Nuclear Landscape

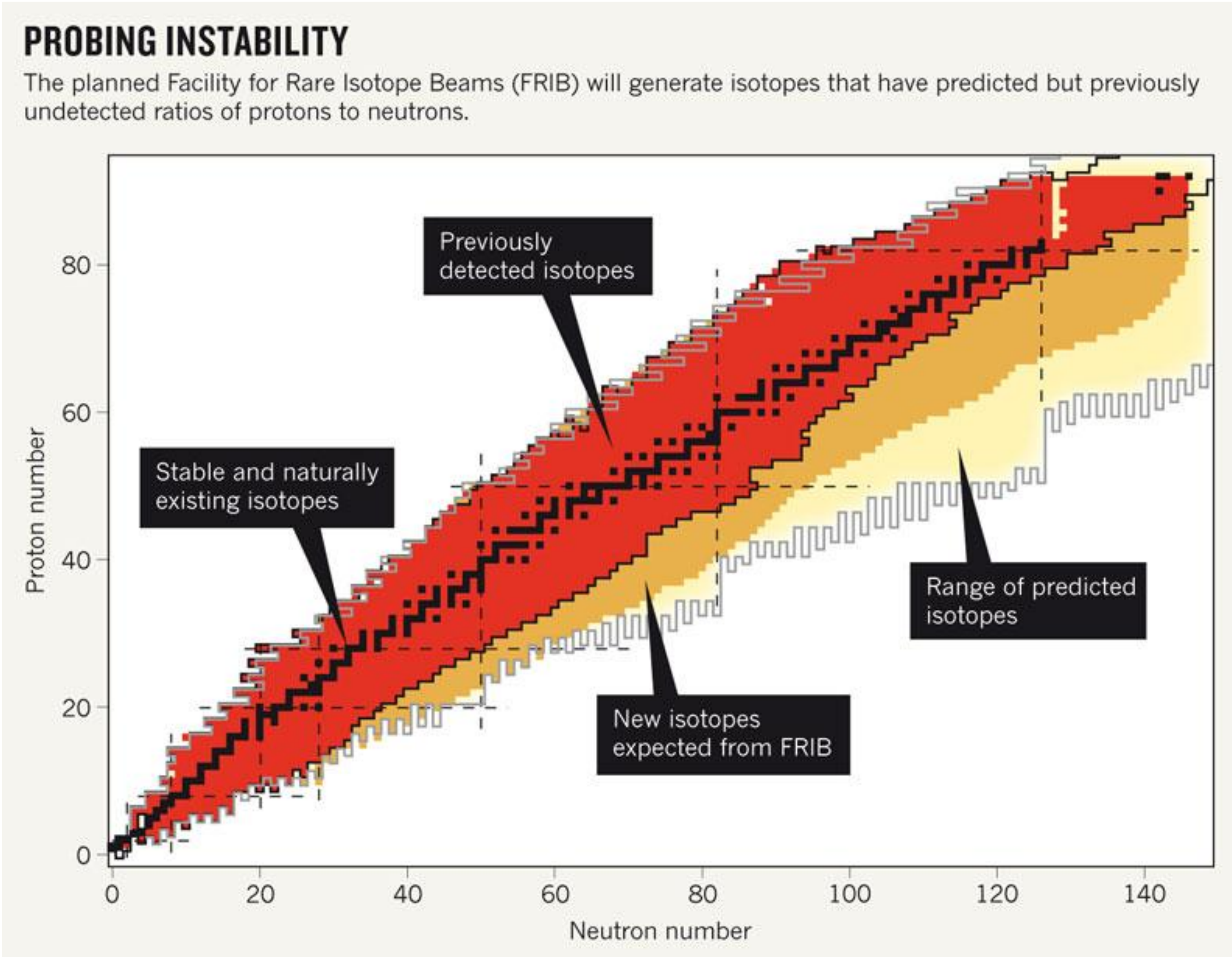




N ~ 10^{57}

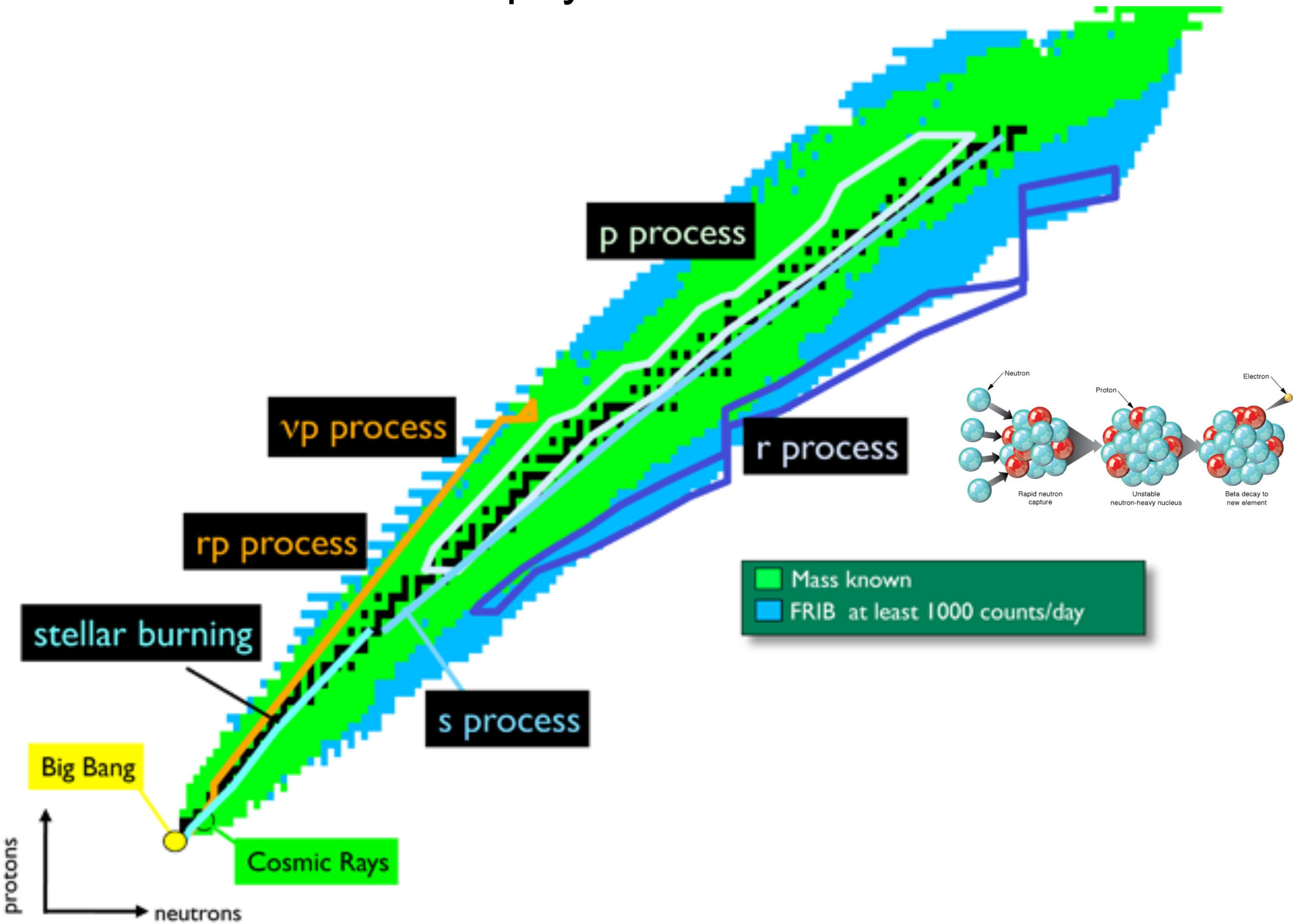


W. Nazarewicz

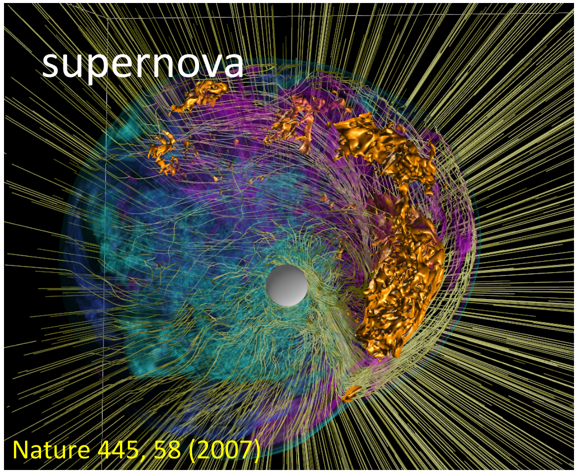


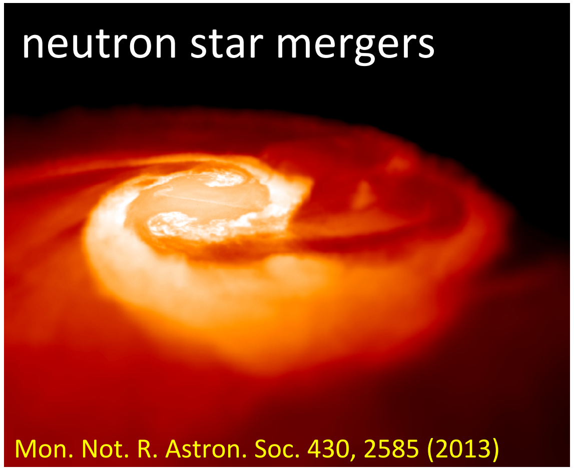
Nature 477, 15 (2011)

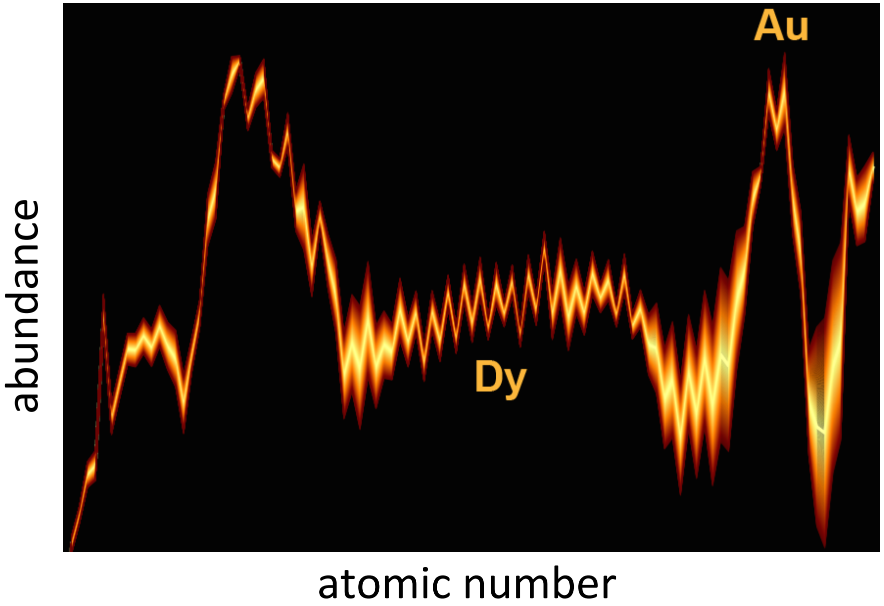
Astrophysical Processes



Half of the neutron-rich atomic nuclei heavier than iron are formed by the neutron-driven r-process.







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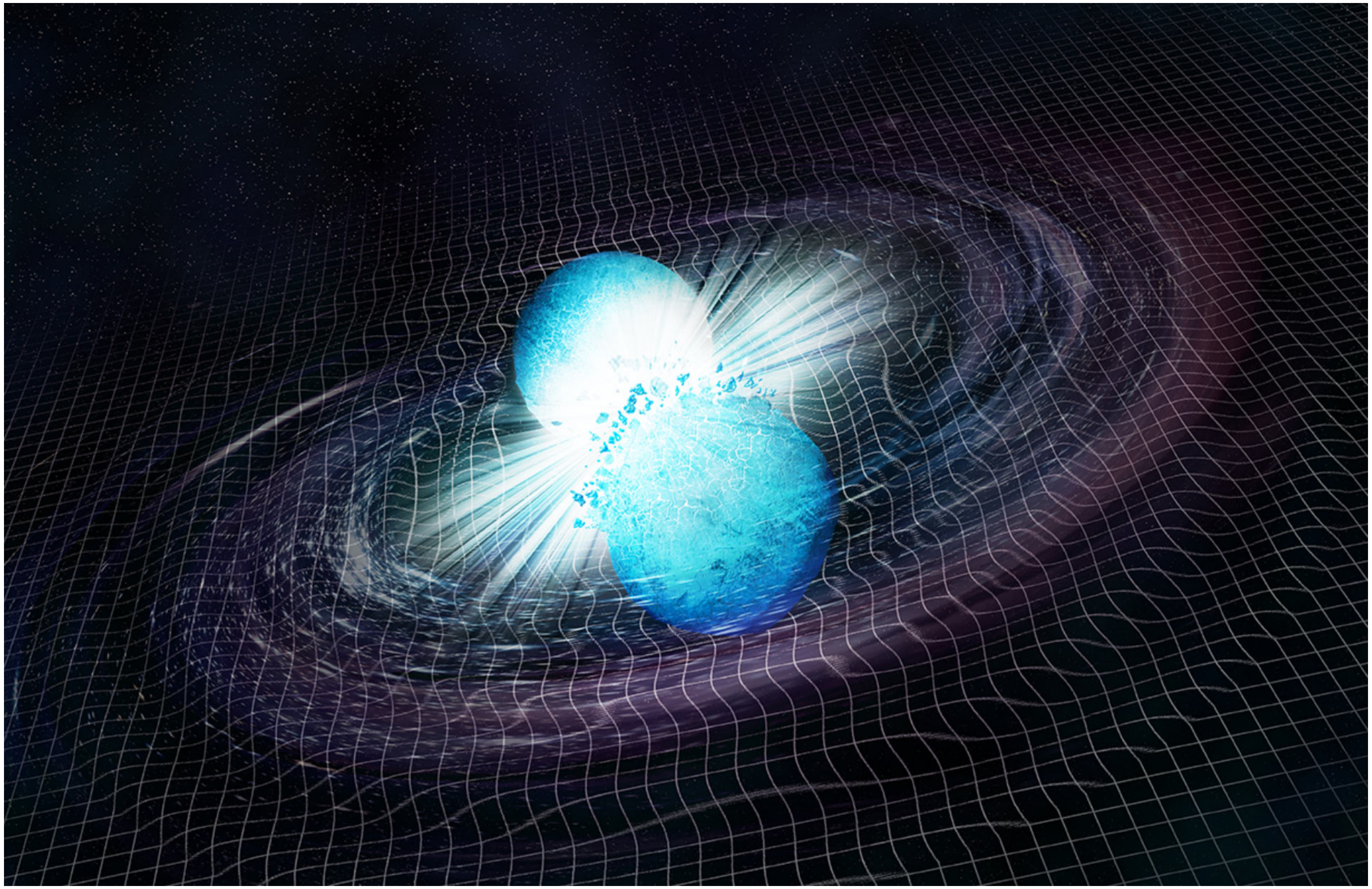
GW170817

Gravitational wave signal observed by LIGO and Virgo detectors on 17 August 2017.
Collision of two inspiraling neutron stars with a total mass of 2.82 solar masses.



NASA / CXC / M.Weiss

The neutron star merger event is thought to result in a kilonova, characterized by a short gamma ray burst followed by a longer optical "afterglow" powered by the radioactive decay of heavy r-process nuclei.

A total of 16,000 times the mass of the Earth in heavy elements is believed to have formed, including approximately ten Earth masses in the elements gold and platinum.

FRIB will give access to the extremely neutron-rich isotopes that have now been identified to play a key role in explaining the observed kilonova.

W. Nazarewicz

How were the elements made in the cosmos?

How do the fundamental forces produce atomic nuclei?

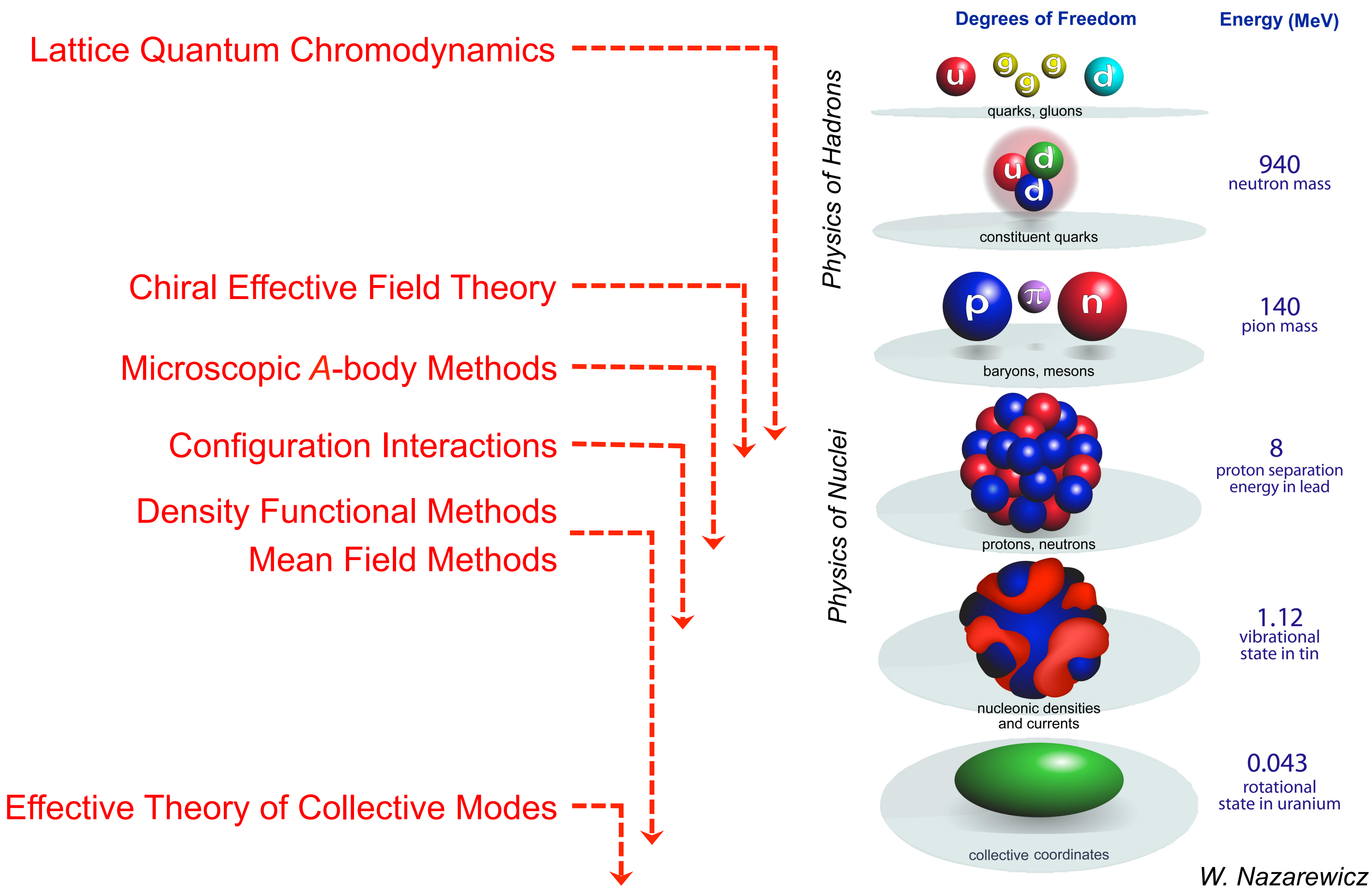
What is the nature of strongly-interacting matter?

Can we find new physics beyond the Standard Model?

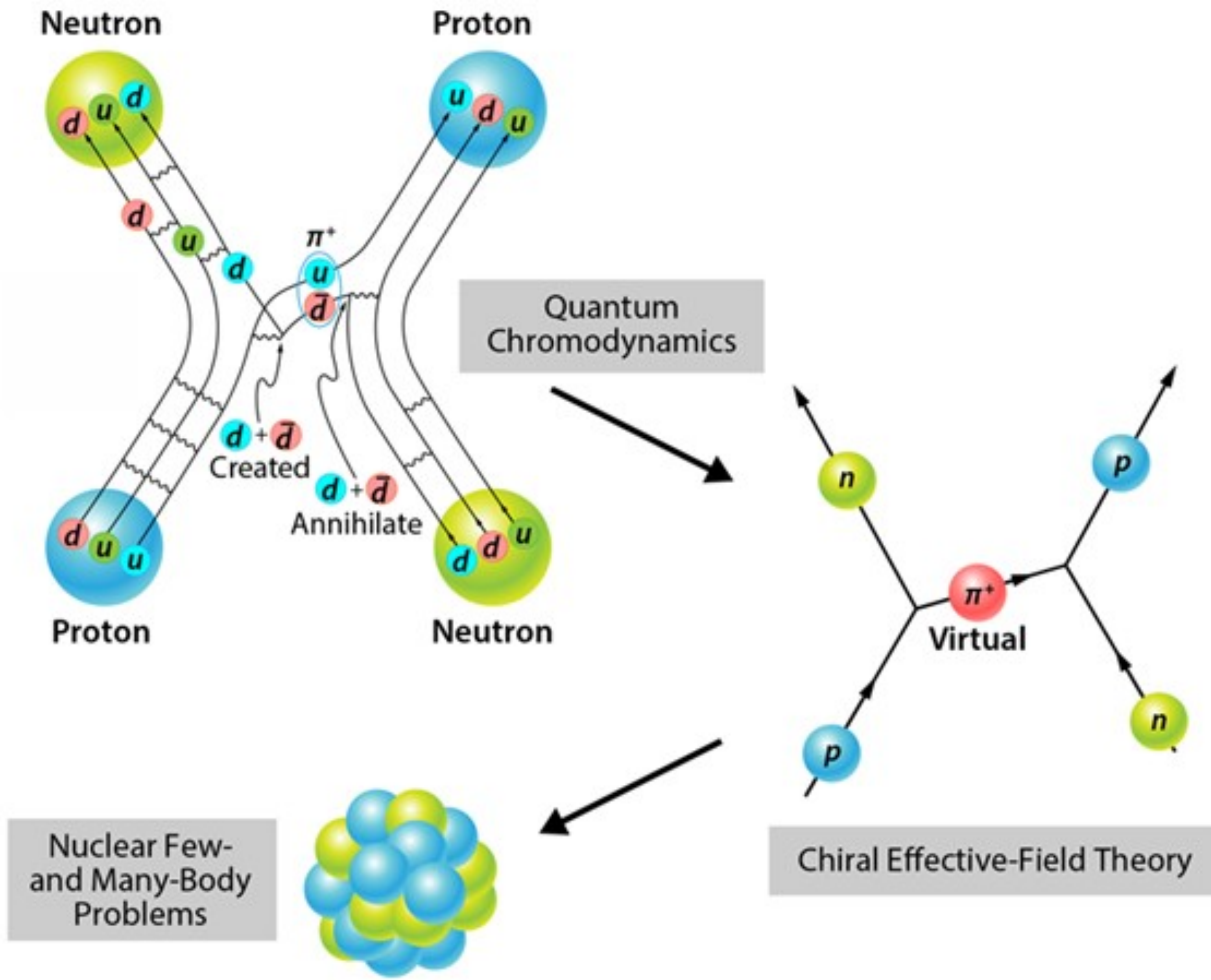
With new science waiting to be discovered at the Facility for Rare Isotope Beams and the dawning of the era of exascale supercomputing, these questions present profound challenges and opportunities for nuclear theory.

A good place to start is an overview of relevant energy scales and the principles of effective field theory.

Effective Field Theories and Energy Scales



Nuclear Forces



Nuclear Forces from Lattice QCD

NPLQCD

Hadron to Atomic Nuclei
HAL
from Lattice QCD

CalLat

PACS Collaboration

… and others

Scalar, Axial, and Tensor Interactions of Light Nuclei from Lattice QCD

Emmanuel Chang, Zohreh Davoudi, William Detmold, Arjun S. Gambhir, Kostas Orginos, Martin J. Savage, Phiala E. Shanahan, Michael L. Wagman, and Frank Winter (NPLQCD Collaboration)
Phys. Rev. Lett. **120**, 152002 – Published 13 April 2018

Most Strange Dibaryon from Lattice QCD

Shinya Gongyo, Kenji Sasaki, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda, Takashi Inoue, Takumi Iritani, Noriyoshi Ishii, Takaya Miyamoto, and Hidekatsu Nemura (HAL QCD Collaboration)
Phys. Rev. Lett. **120**, 212001 – Published 23 May 2018

Proton-Proton Fusion and Tritium β Decay from Lattice Quantum Chromodynamics

Martin J. Savage, Phiala E. Shanahan, Brian C. Tiburzi, Michael L. Wagman, Frank Winter, Silas R. Beane, Emmanuel Chang, Zohreh Davoudi, William Detmold, and Kostas Orginos (NPLQCD Collaboration)
Phys. Rev. Lett. **119**, 062002 – Published 10 August 2017

ELSEVIER

Physics Letters B

Volume 765, 10 February 2017, Pages 285-292

open access

Two-nucleon higher partial-wave scattering from lattice QCD

Evan Berkowitz [a], Thorsten Kurth [b, c], Amy Nicholson [c], Bálint Joó [d], Enrico Rinaldi [a], Mark Strother [c], Pavlos M. Vranas [a], André Walker-Loud [b, d, e]

Helium nuclei, deuteron, and dineutron in $2+1$ flavor lattice QCD

Takeshi Yamazaki, Ken-ichi Ishikawa, Yoshinobu Kuramashi, and Akira Ukawa
Phys. Rev. D **86**, 074514 – Published 19 October 2012

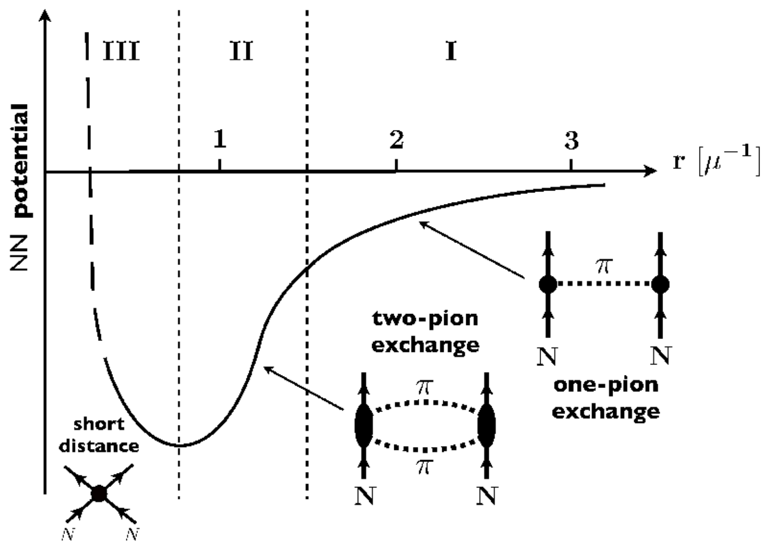
arXiv.org > hep-lat > arXiv:1805.03966

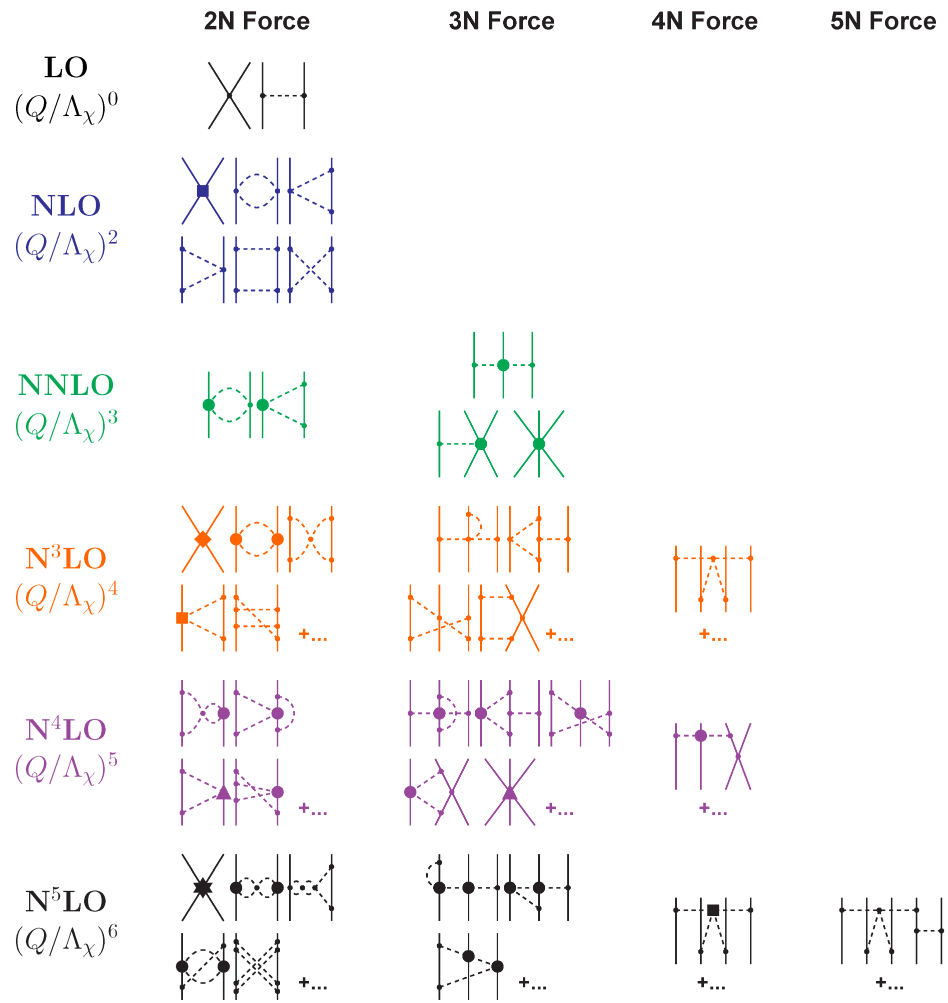
High Energy Physics – Lattice

Lattice QCD study of the H dibaryon using hexaquark and two-baryon interpolators

A. Francis, J.R. Green, P.M. Junnarkar, Ch. Miao, T.D. Rae, H. Wittig

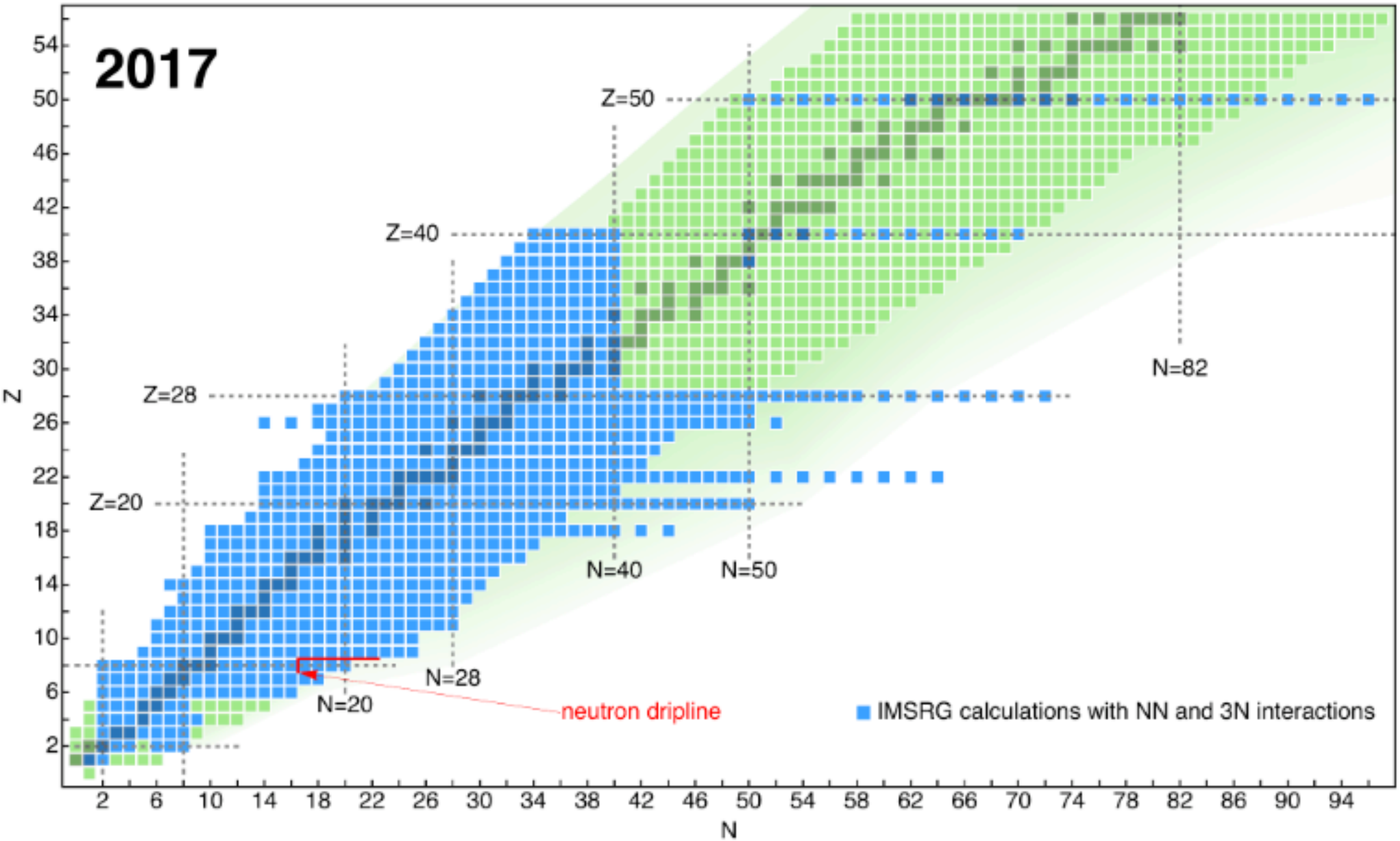
Chiral Effective Field Theory



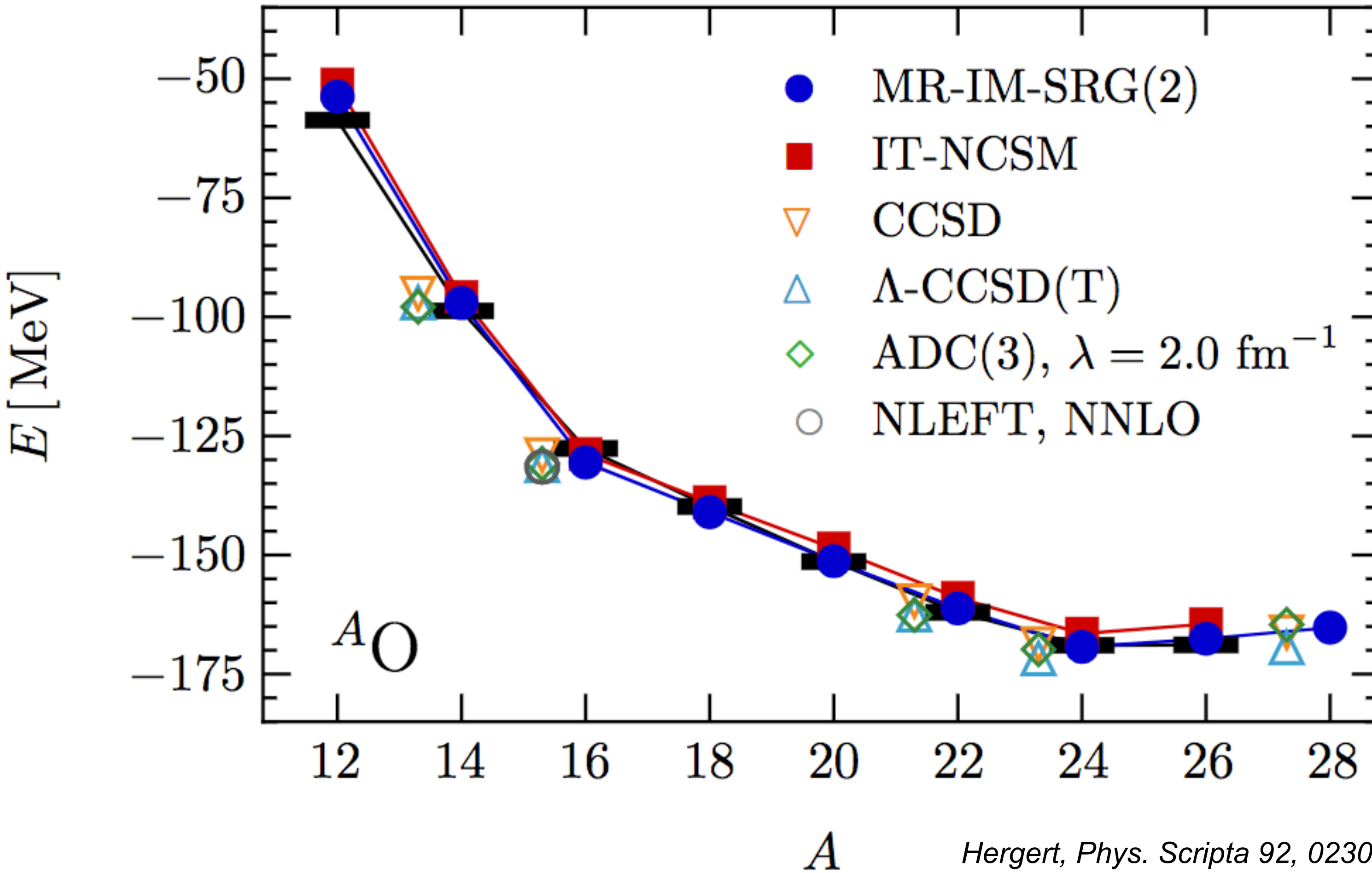


Weinberg, van Kolck, Epelbaum, Glöckle, Meißner, Krebs, Entem, Machleidt, ...

Microscopic *A*-body Methods

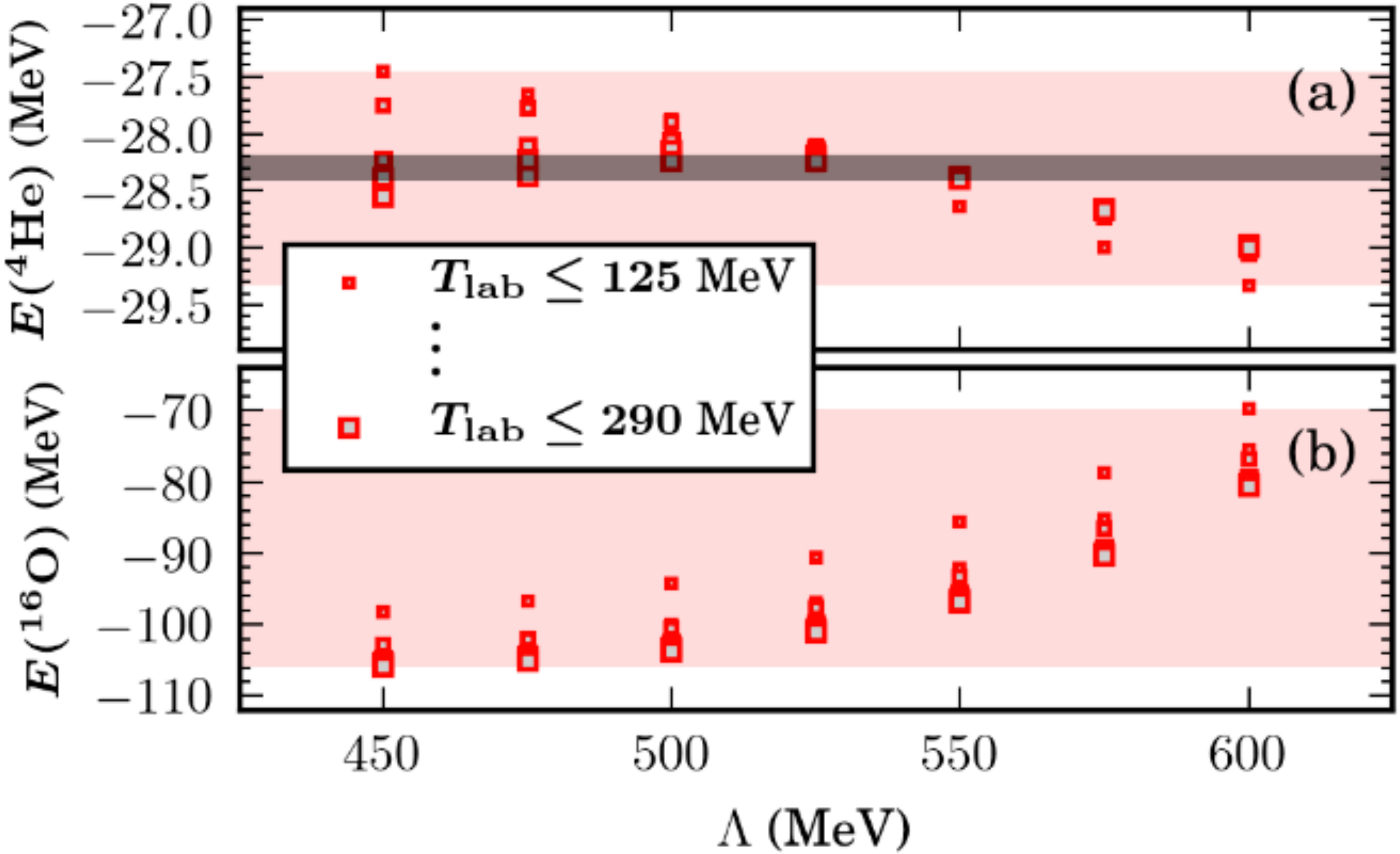


Hergert, Yao, Morris, Parzuchowski, Bogner, Engel,
Recent Progress in Many-Body Theories, June 25-30, 2017, APCTP, Pohang, Korea



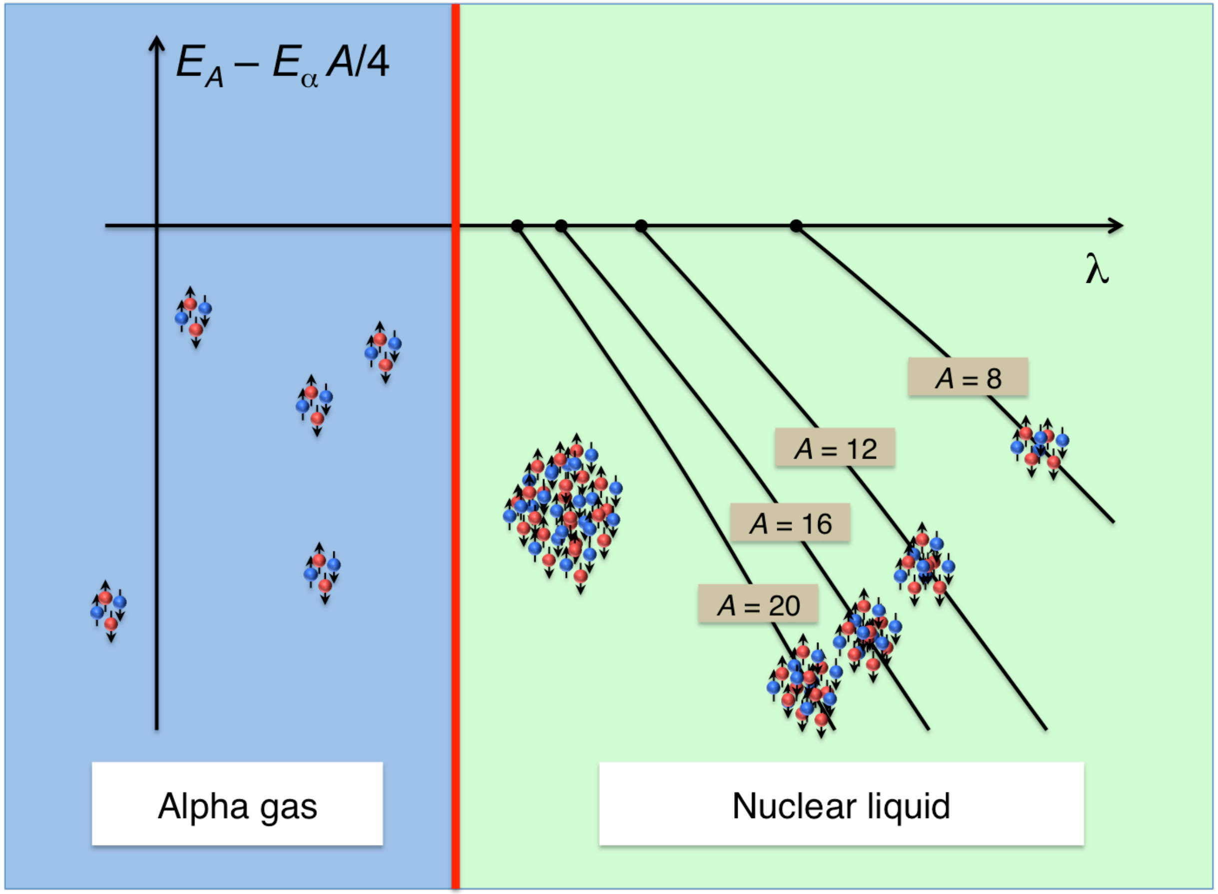
Hergert, Phys. Scripta 92, 023002 (2017)

Need to reduce systematic errors

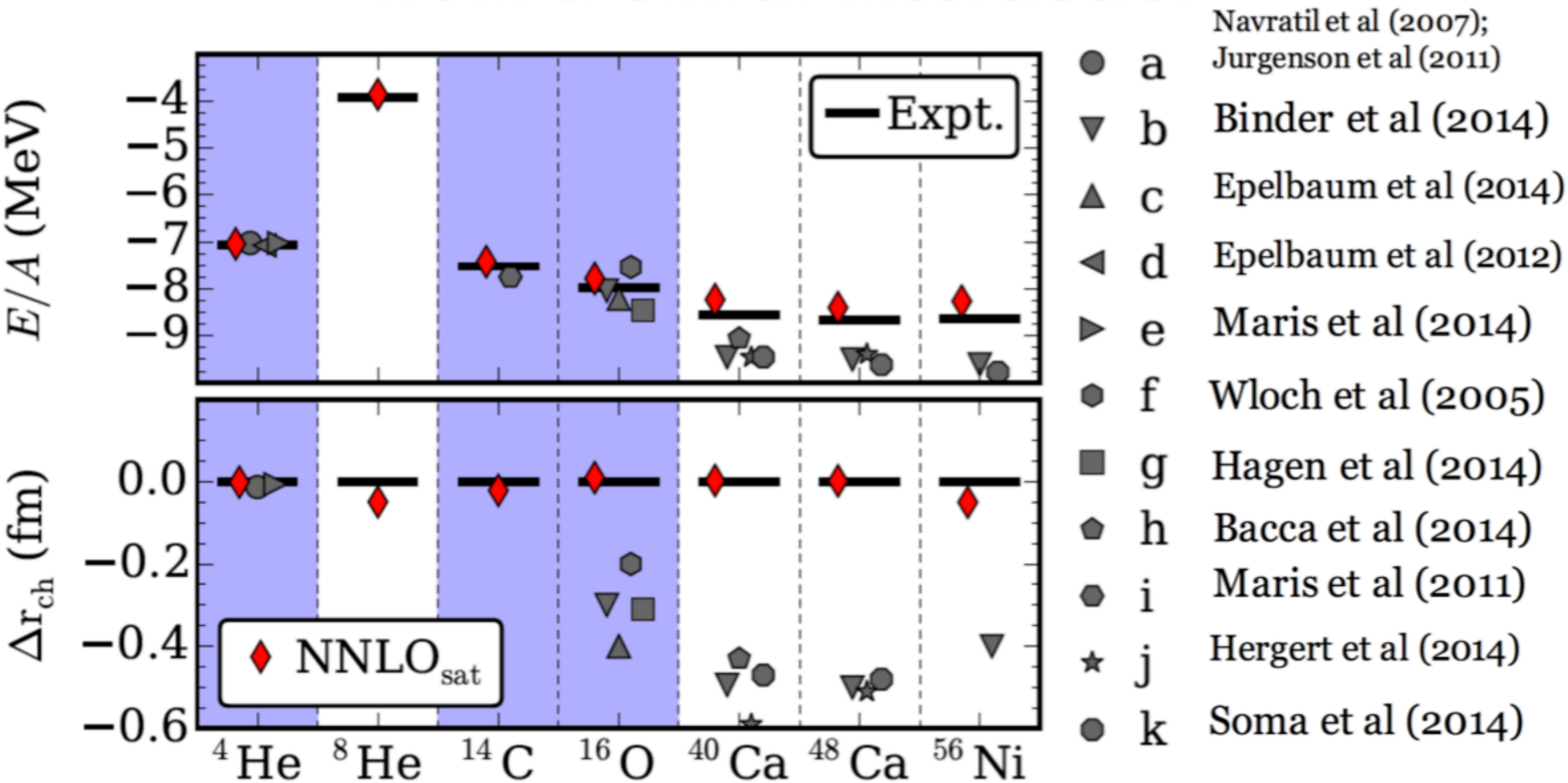


Carlsson, et al., Phys. Rev. X 6, 011019 (2016)

Nuclear interactions are close to a quantum phase transition

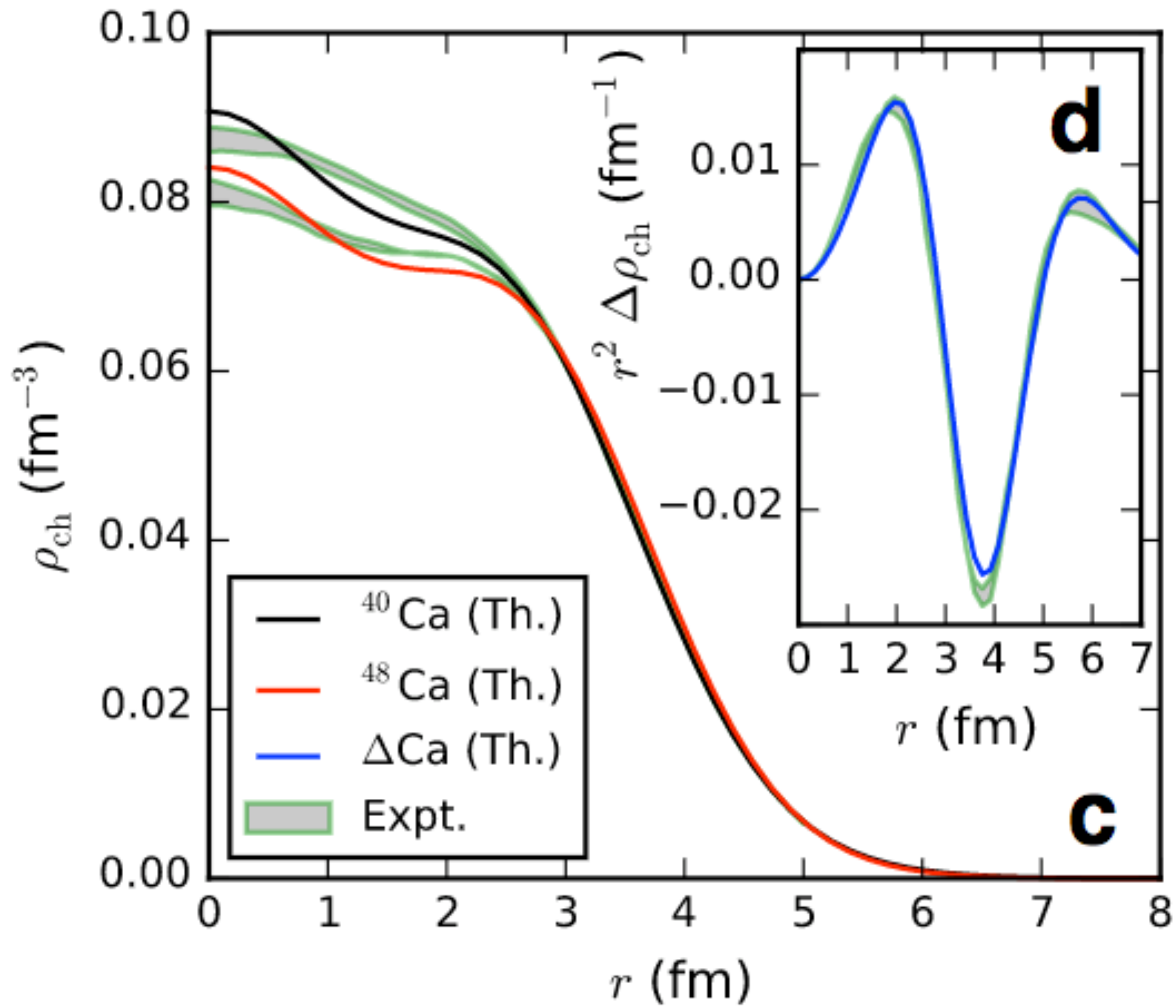


Elhatisari, et al., PRL 117, 132501 (2016)



Ekström, et al., PRC 91, 051301(R) (2015)

Using the $NNLO_{sat}$ interaction:

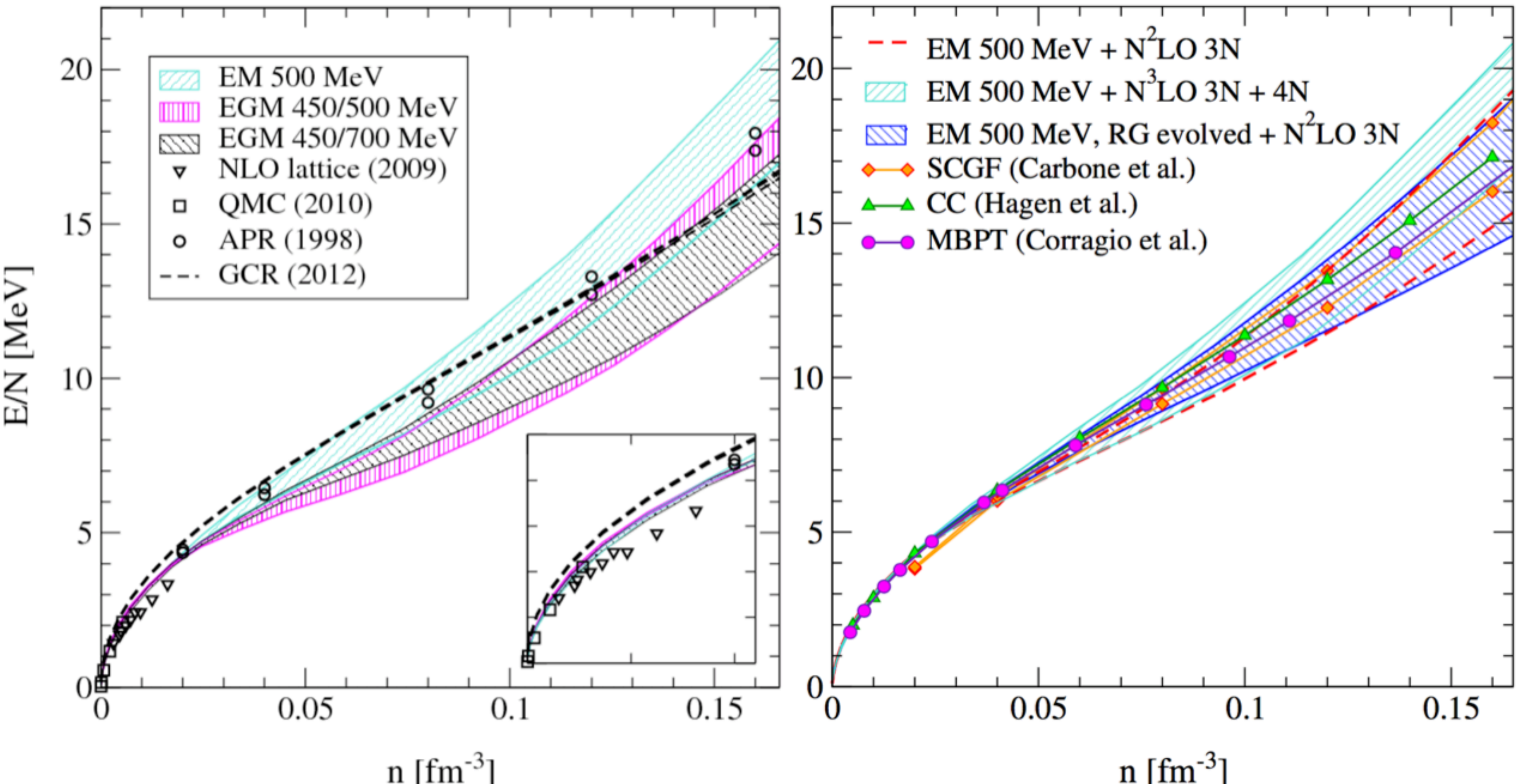


Hagen et al., Nature Physics 12, 186-190 (2016)

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

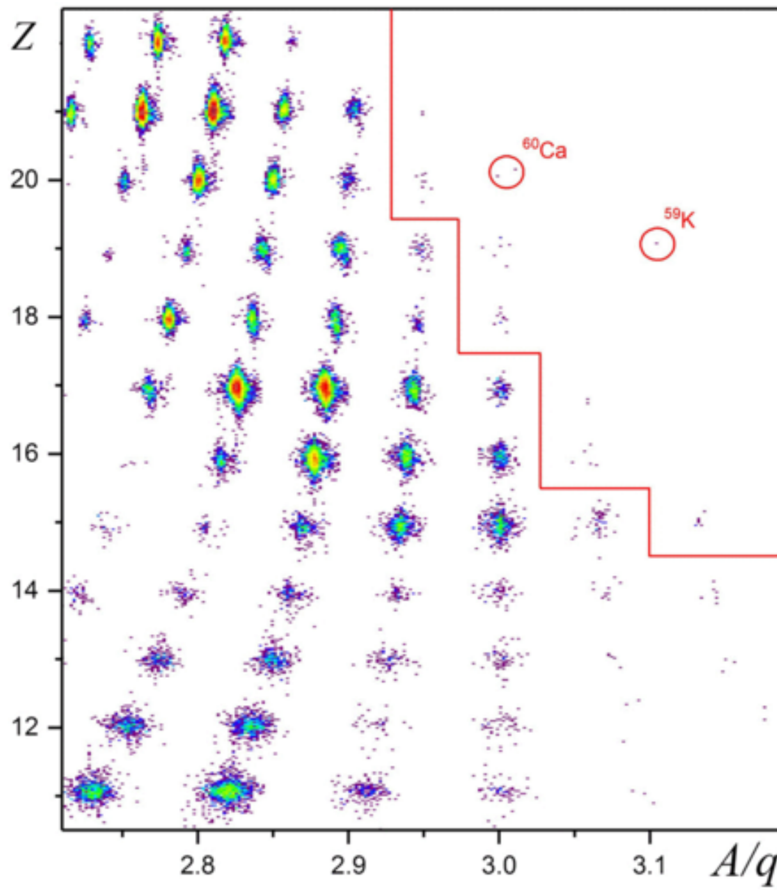


A. Schwenk

Editors' Suggestion

Discovery of ^{60}Ca and Implications For the Stability of ^{70}Ca

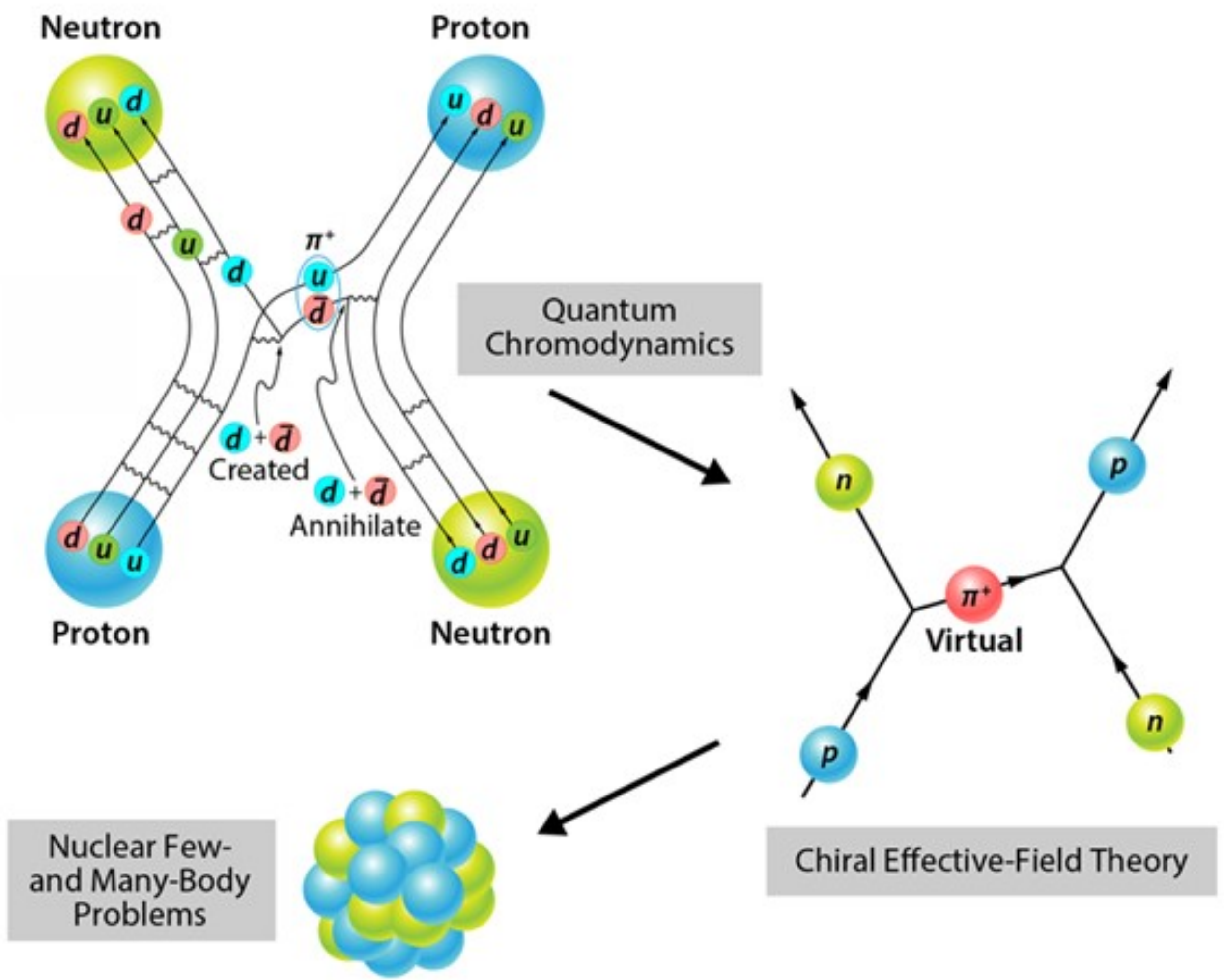
O. B. Tarasov *et al.*
Phys. Rev. Lett. **121**, 022501 – Published 11 July 2018



How is it that pure neutron matter is not bound, but twenty protons are enough to bind as many as forty or fifty neutrons?

Is this a universal property of attractive fermionic systems or is there something special about the nuclear interactions?

FRIB Opportunities for Lattice QCD



For few-body systems, chiral effective field theory converges quickly for low-energy observables. Any reasonable choice of ultraviolet regulator is successful. Fit the two-nucleon forces to scattering phase shifts and three-nucleon forces to three-body properties.

For many-body systems, chiral effective field theory sometimes converges quickly, but sometimes not. There is some fine-tuning. Need more information about how nucleons interact with each other in the many-body environment and systematic errors produced by the ultraviolet regulator.

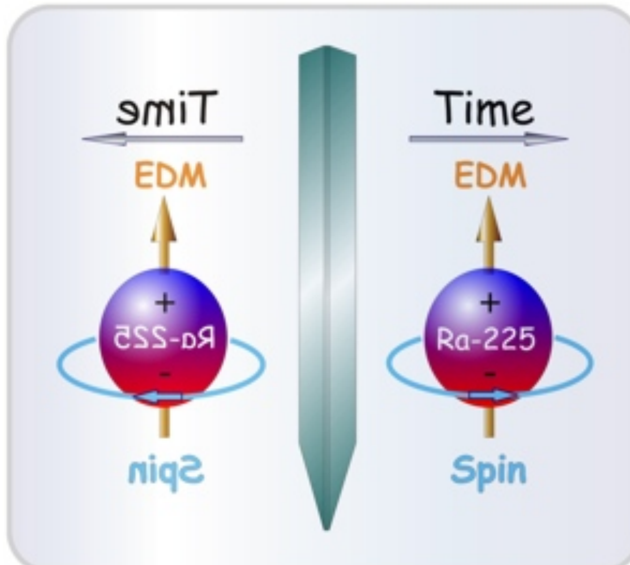
Lattice QCD can address these unresolved questions.

Lattice calculations of few-nucleon systems at several different small volumes would be extremely useful. The volumes should be small enough to see non-universal effects [*] that depend on the range of the interaction. The periodic copies will mimic the effect of the many-body system, but with only a few particles.

The calculations can be done at nonzero temperature and matched to lattice effective field theory calculations to extract three-nucleon forces and remove systematic errors in chiral effective field theory due to ultraviolet regulator effects.

**For universal asymptotic finite-volume properties see König, D.L., PLB 779, 9 (2018)*

Isotope Harvesting and Fundamental Symmetries



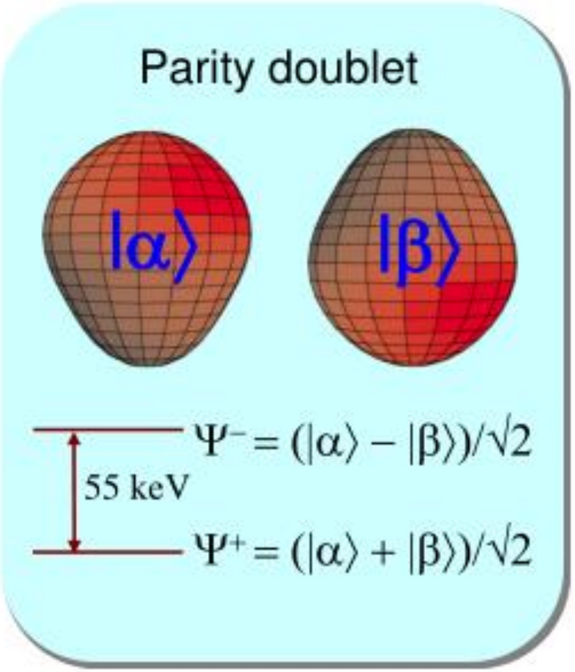
Argonne National Laboratory

^{225}Ra is a good candidate electric dipole moment (EDM) searches as it has a relatively long half-life of 15 days, and has spin 1/2, which eliminates systematic effects due to electric quadrupole coupling. Also its nuclear octupole deformation enhances the atomic EDM by increasing the Schiff moment collectively and by the parity doubling of the energy levels.

Z.-T. Lu

EDM of ^{225}Ra enhanced and more reliably calculated

- Closely spaced parity doublet – Haxton & Henley, PRL (1983)
- Large Schiff moment due to octupole deformation – Auerbach, Flambaum & Spevak, PRL (1996)
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3) – Dzuba, Flambaum, Ginges, Kozlov, PRA (2002)



$$Schiff\_moment = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

	Isoscalar	Isovector
Skyrme SIII	300	4000
Skyrme SkM*	300	2000
Skyrme SLy4	700	8000

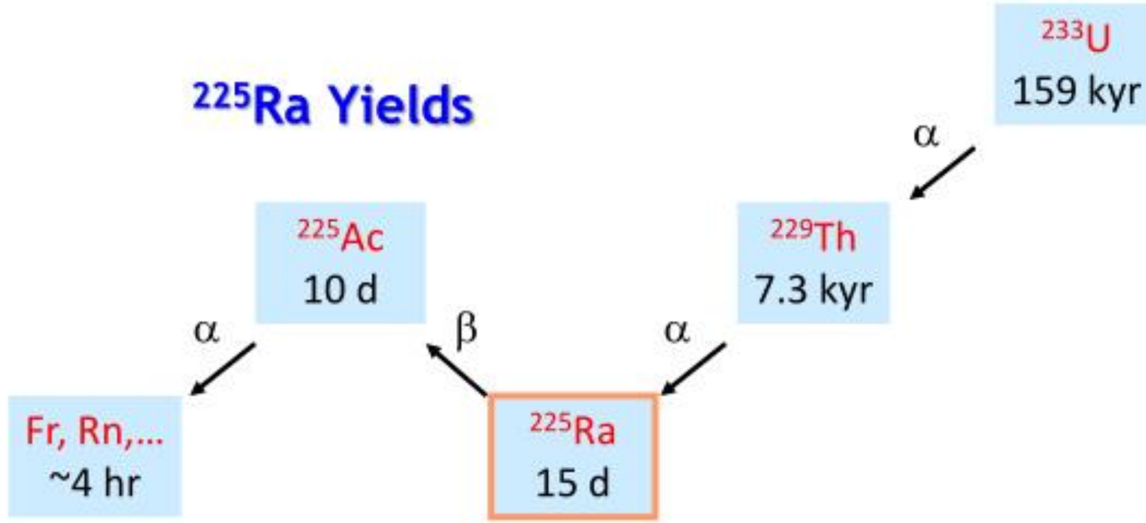
Schiff moment of ^{225}Ra, Dobaczewski, Engel, PRL (2005)
Schiff moment of ^{199}Hg, Dobaczewski, Engel *et al.*, PRC (2010)

"[Nuclear structure] calculations in Ra are almost certainly more reliable than those in Hg."
– Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. (2013)

Constraining parameters in a global EDM analysis.
– Chupp, Ramsey-Musolf, arXiv1407.1064 (2014)

Z.-T. Lu

^{225}Ra Yields



Presently available

- National Isotope Development Center, ORNL
  - Decay daughters of ^{229}Th ---------------------------------- ^{225}Ra: 10^8 /s

Projected

- FRIB (B. Sherrill, MSU)
  - Beam dump recovery with a ^{238}U beam -------------------- 6×10^9 /s
  - Dedicated running with a ^{232}Th beam --------------------- 5×10^{10} /s

- ISOL@FRIB (I.C. Gomes and J. Nolen, Argonne)
  - Deuterons on thorium target, 1 mA x 400 MeV = 400 kW 10^{13} /s

- MSU K1200 (R. Ronningen and J. Nolen, Argonne)
  - Deuterons on thorium target, 10 uA x 400 MeV = 4 kW 10^{11} /s

Z.-T. Lu

Summary and Outlook

These are exciting times for nuclear physics. With new science waiting to be discovered at the Facility for Rare Isotope Beams and the era of exascale supercomputing, we have an opportunity to address big science questions.

There are great opportunities for Lattice QCD to impact FRIB experiments through matching to chiral effective field theory and microscopic *A*-body methods.

While there has been great progress in nuclear structure and reaction theory, there are open questions about first principles calculations of larger nuclei. Lattice QCD simulations can play a breakthrough role in solving these problems.

fribtheoryalliance.org