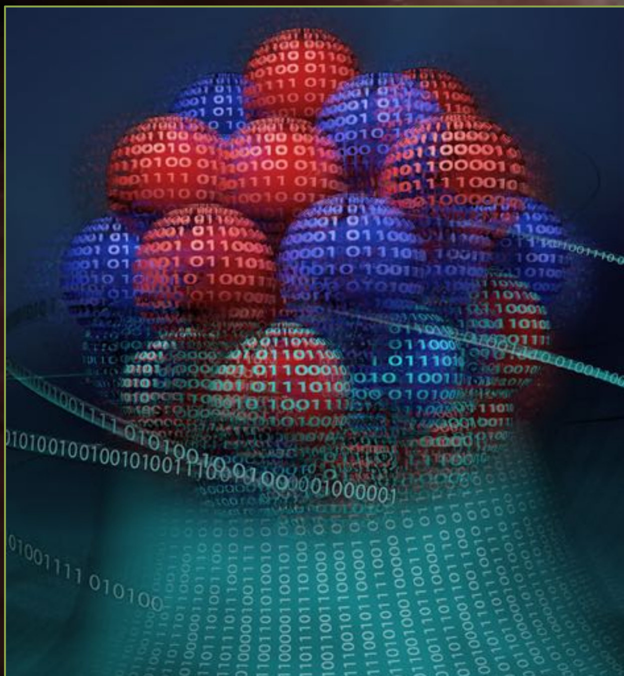
Prospects for Breakthroughs in Low-Energy Nuclear Theory

Witold Nazarewicz (FRIB/MSU)

First Tsukuba-CCS-RIKEN joint workshop on microscopic theories of nuclear structure and dynamics, December 12-16, 2016



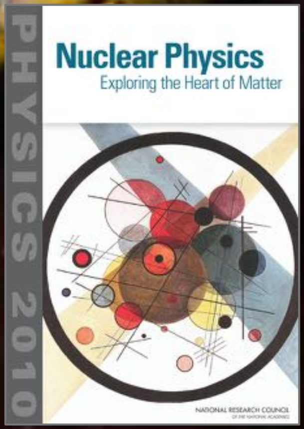
Menu

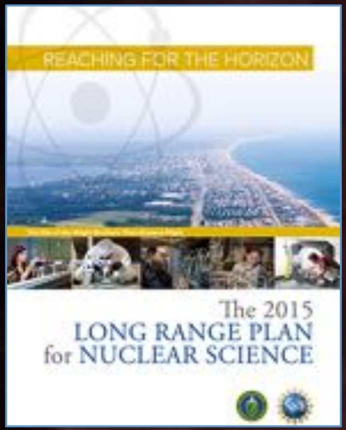
- Prospects
- Creating unfair advantage

a personal view…

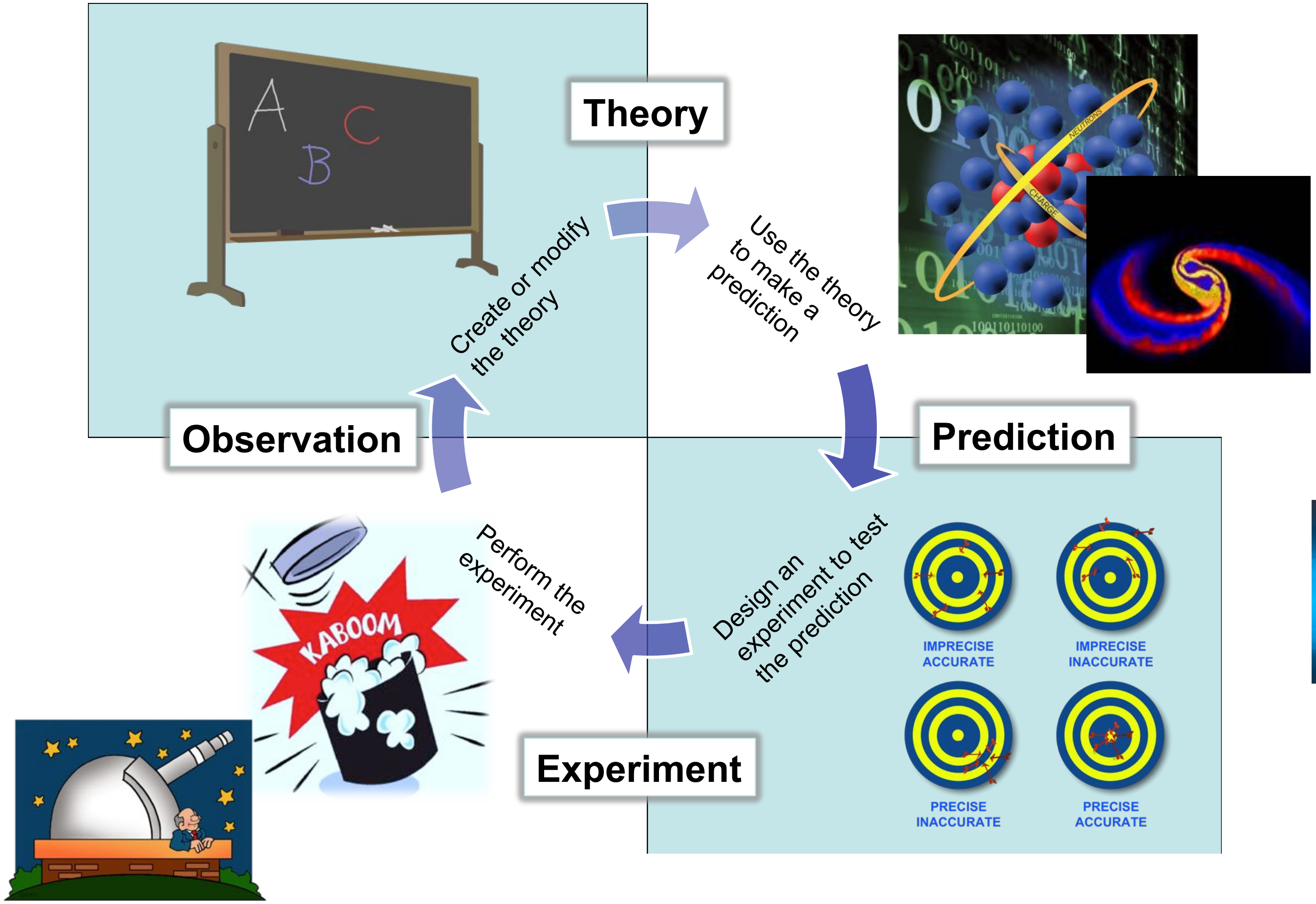
The Nuclear Landscape and the Big Questions

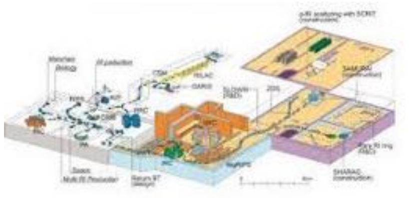
- Where did the atoms and atomic nuclei come from?
- How are the nuclei of atoms made and organized?
- What are the fundamental particles and forces at work inside atomic nuclei?
- What are practical and scientific uses of nuclei?

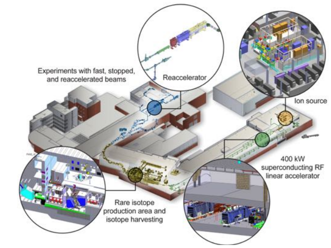


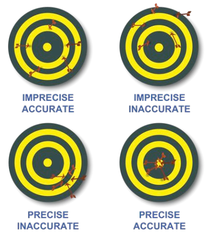


Guiding principle: the scientific method…





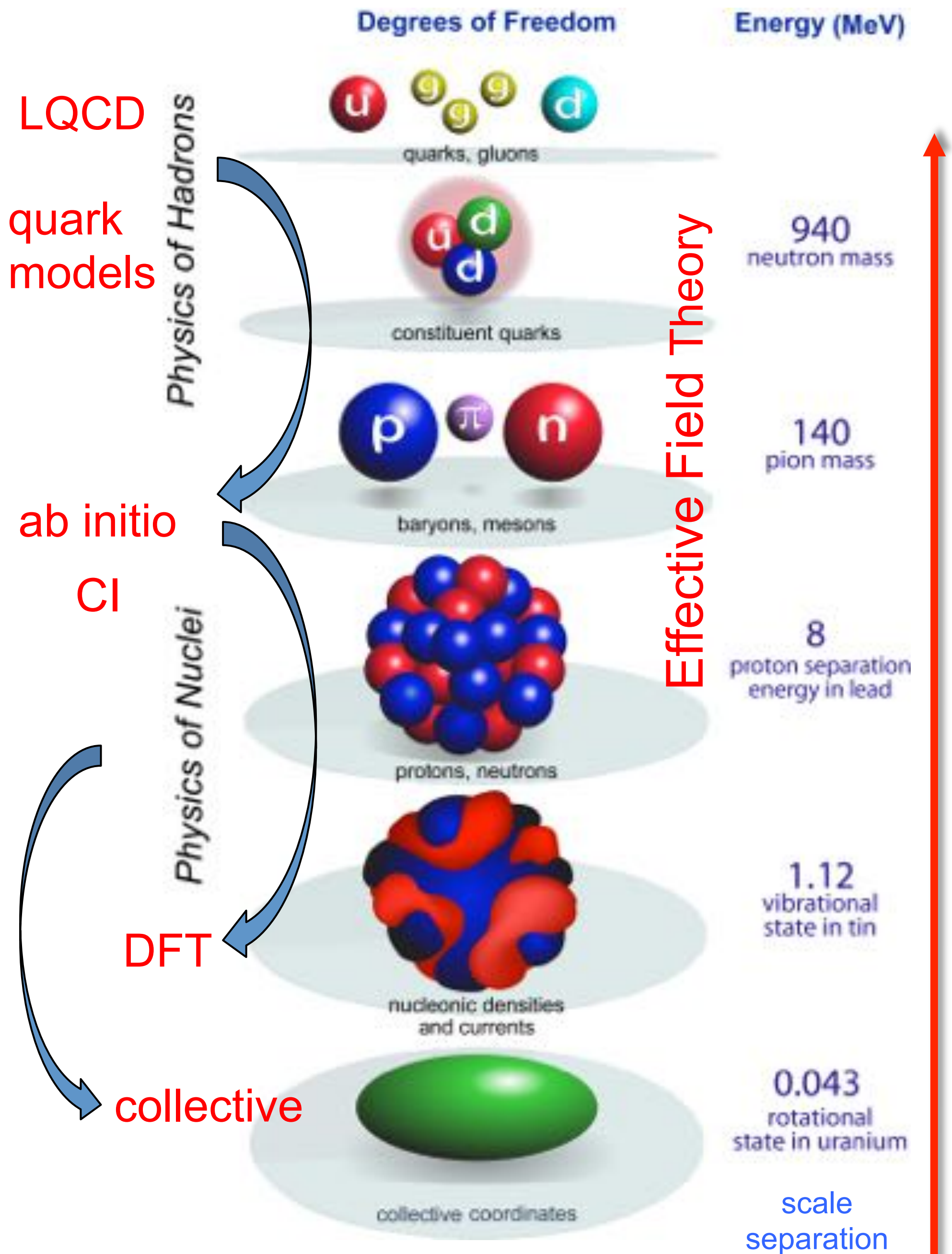




J. Phys. G 43, 044002 (2016)

PROSPECT Optimizing the cycle

How are nuclei made?



Hot and dense quark-gluon matter

Hadron structure

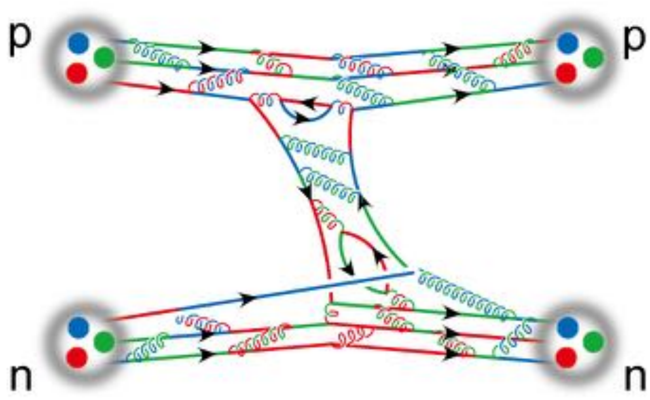
Nuclear-Particle Physics **PROSPECT**

Nuclear structure
Nuclear reactions
New standard model

Weinberg's Third Law of Progress in Theoretical Physics:

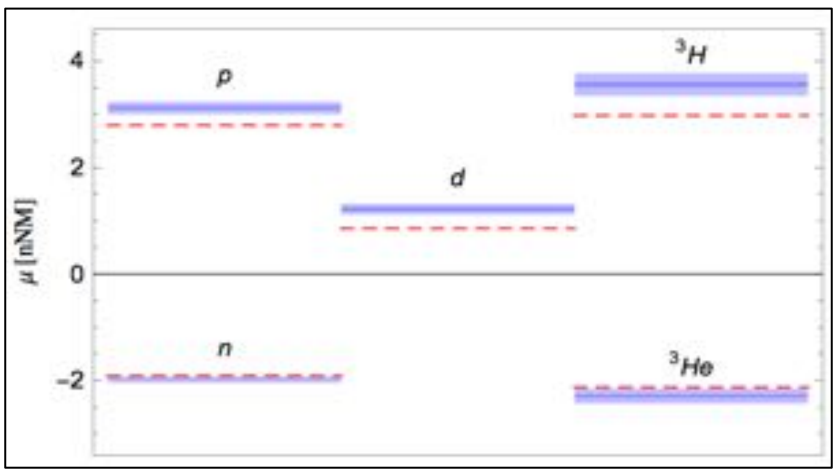
The resolving power of a theoretical model should always be as low as reasonably possible for the question at hand

Rooting nuclei in QCD



Nuclear Force from lattice QCD

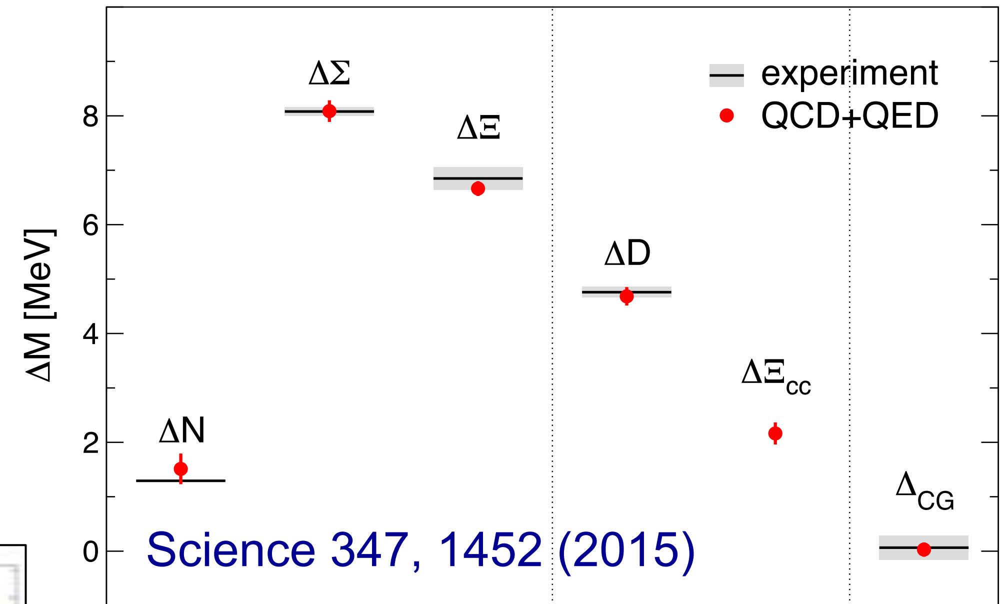
PRL 111, 112503 (2013)



LQCD predictions for magnetic moments A<4

PRL113, 252001 (2014)

n-p mass difference from LQCD



Science 347, 1452 (2015)

$$pp \rightarrow de^+\nu$$

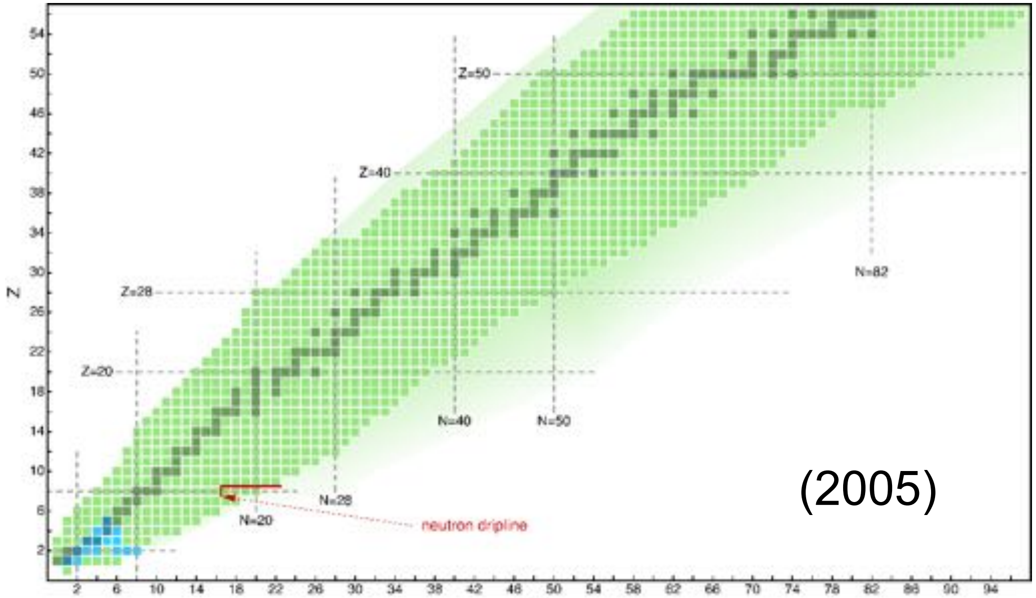
and tritium beta decay

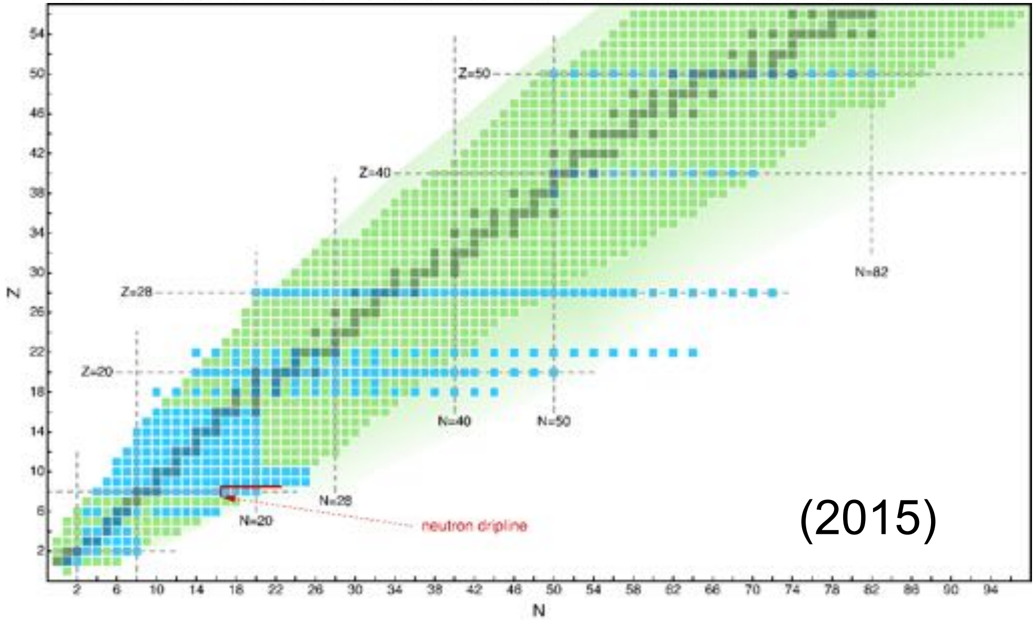
arXiv:1610.04545

PROSPECT

Calculating the lightest nuclei and operators in LQCD

Nuclei from the first principles





Recent news:

^{78}Ni in ab-initio, coupled-cluster

Phys. Rev. Lett. 117, 172501 (2016)

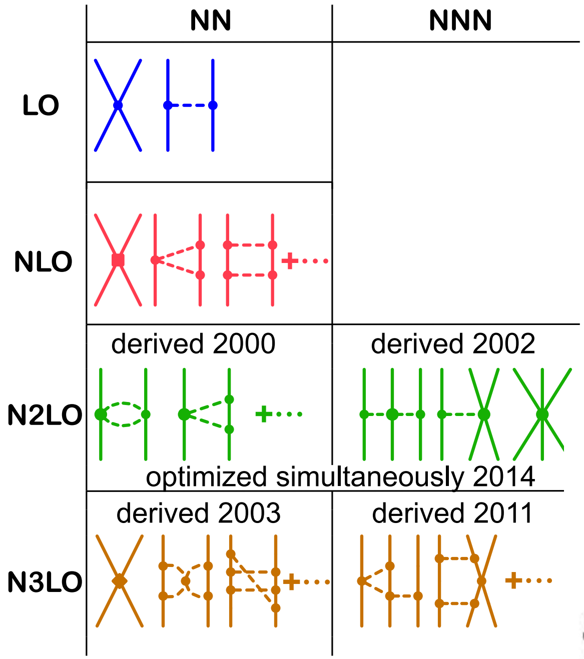
^{100}Sn and ^{208}Pb are on the way

Phys. Rept. 621, 1765 (2016)

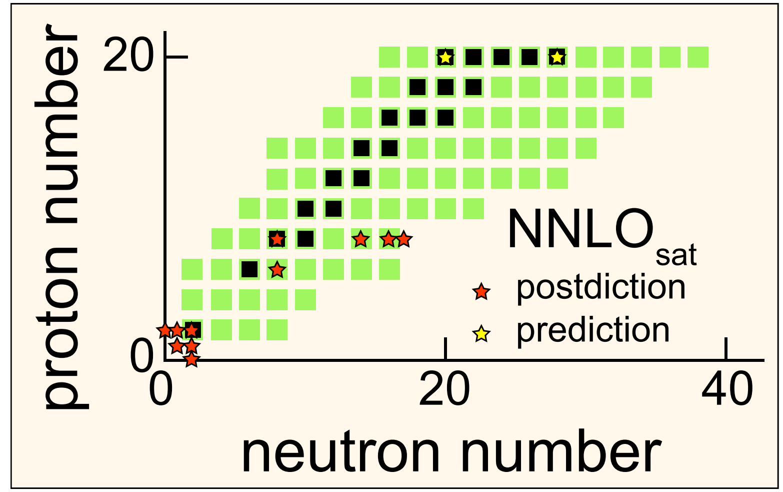
Linking few-body with many-body

Quantified input

Nuclear Forces from χEFT

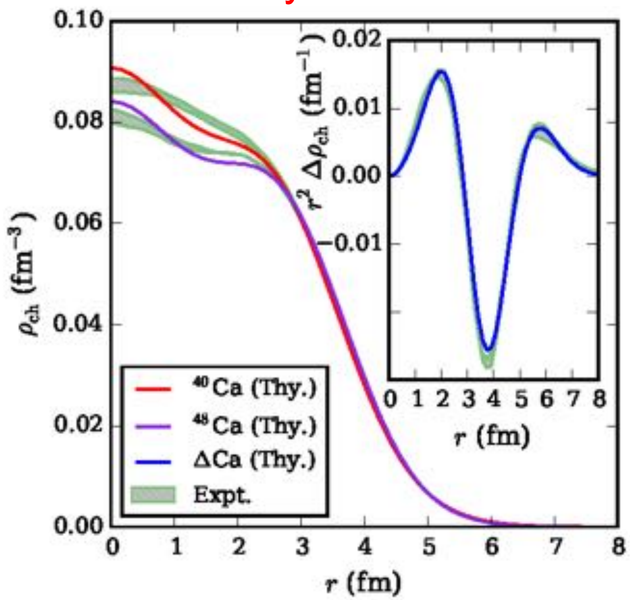


Comprehensive model of light and heavy nuclei

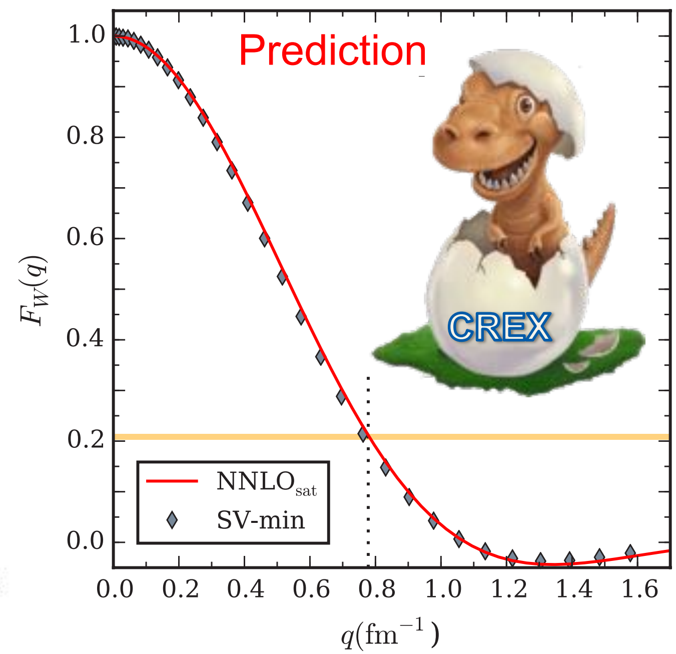


Nature Physics **12**, 186 (2016)

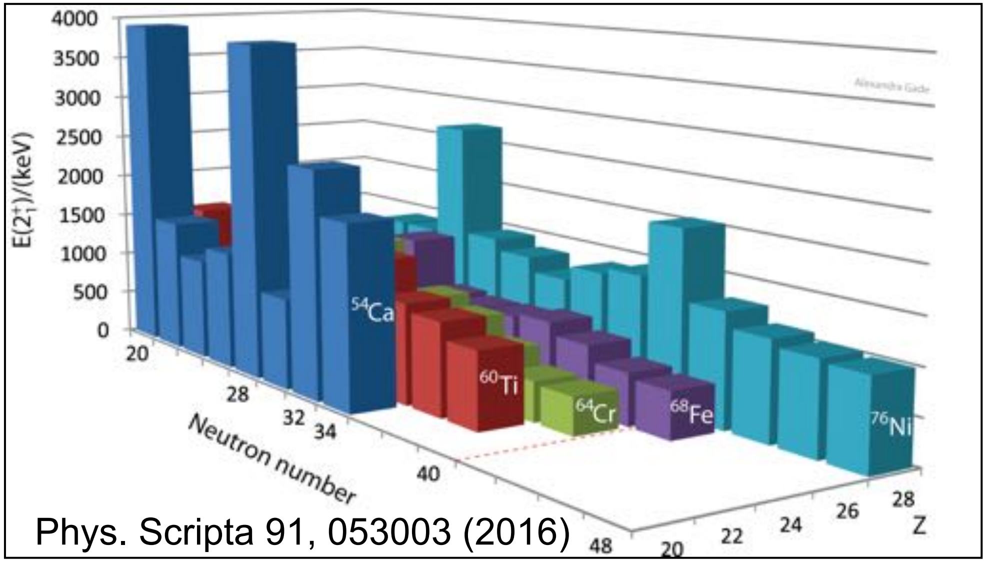
Consistency with known data



Prediction

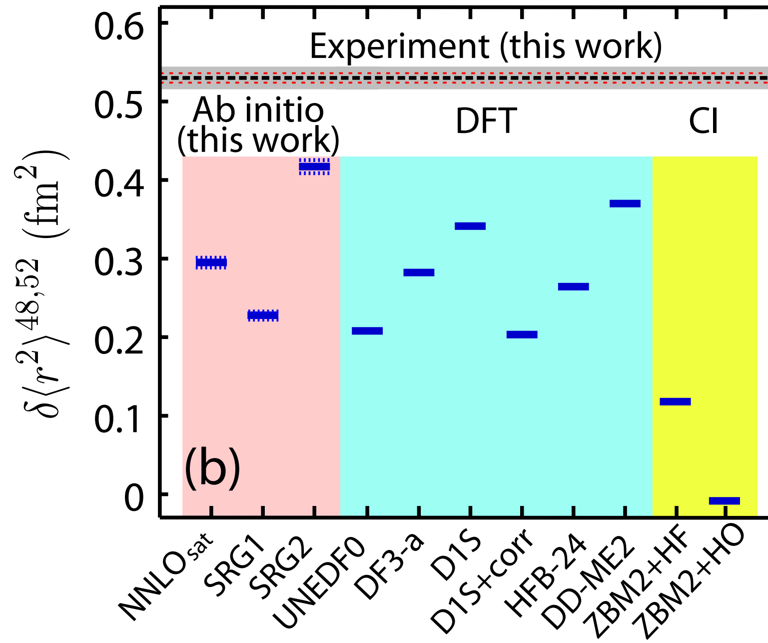


The frontier: calcium isotopes (where *ab-initio* and DFT meet)



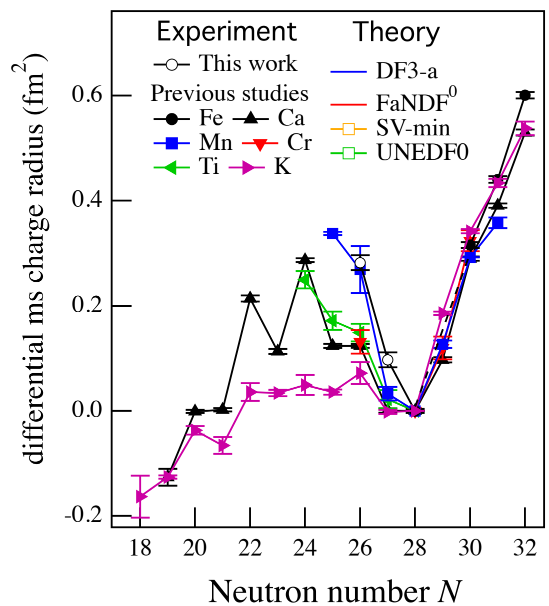
Phys. Scripta 91, 053003 (2016)

Nature Physics 12, 594 (2016)

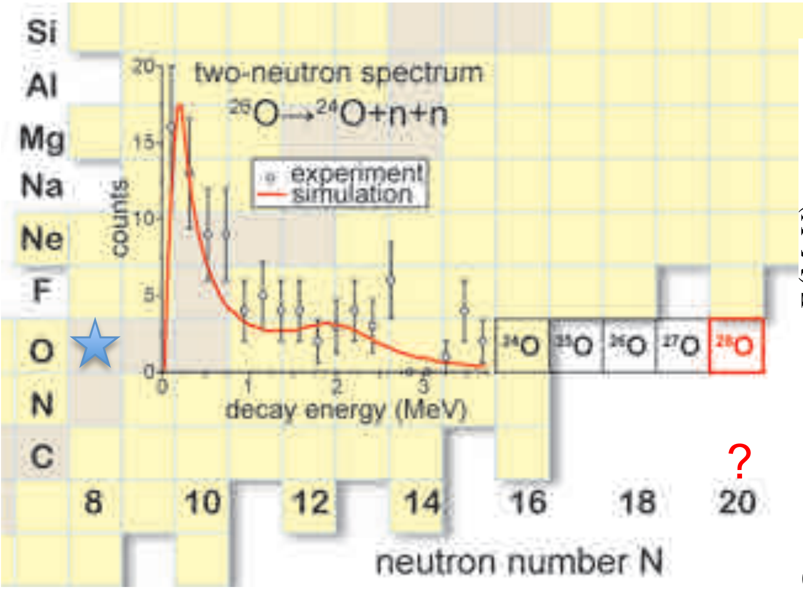


New shell closures at N = 32 & 34?

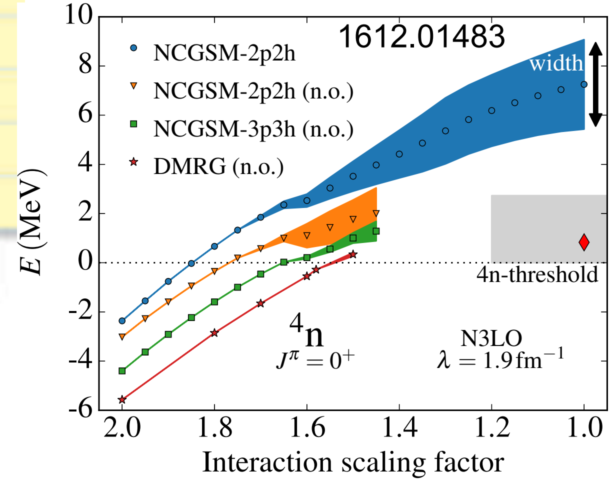
K. Minamisono et al., PRL, in press



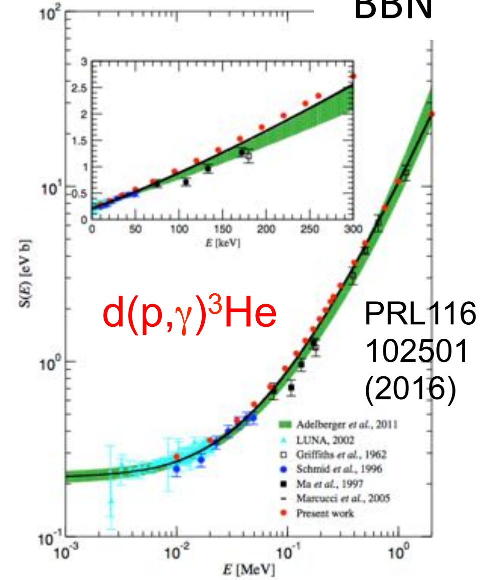
Revision of nuclear structure textbook knowledge



tetraneutron resonance?

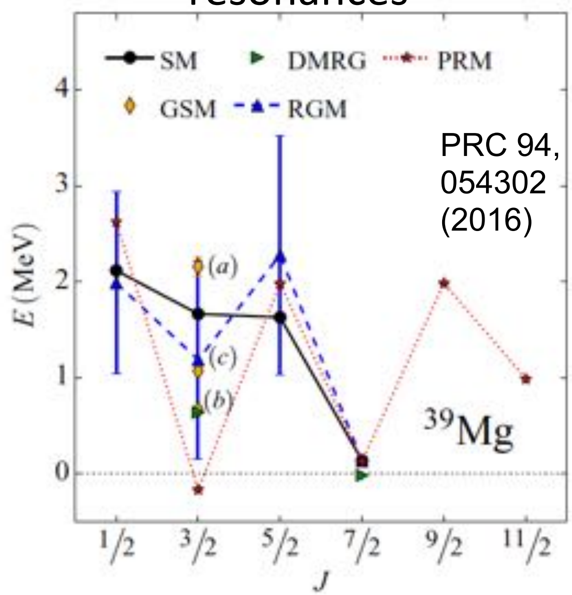


BBN



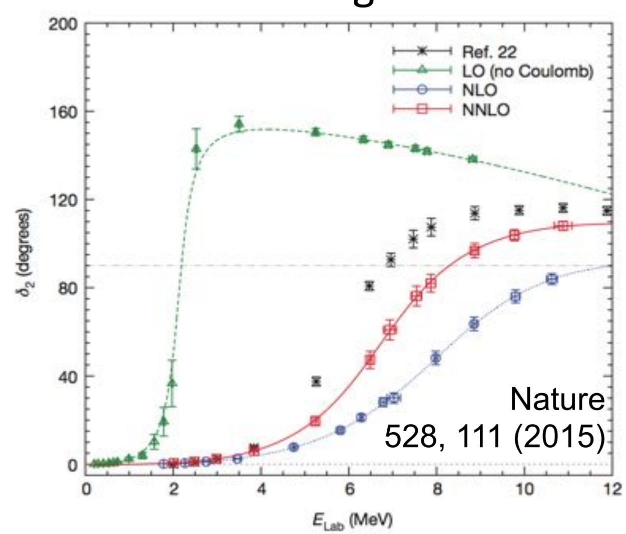
PRL116, 102501 (2016)

deformed neutron resonances



PRC 94, 054302 (2016)

alpha-alpha scattering in LEFT



Nature 528, 111 (2015)

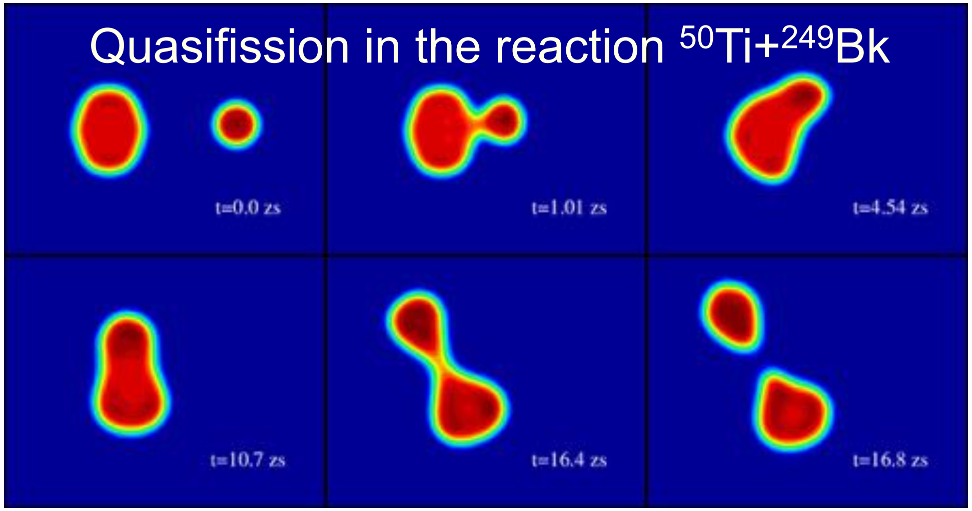
- ^{24,25,26}O: open quantum systems
- A dineutron in ^{26}O? The lifetime could be as large as 10^{-12} s.
- Is (doubly-magic) ^{28}O unbound? If so, how much?

Unification of structure and reactions

PROSPECT

Large Amplitude Collective Motion

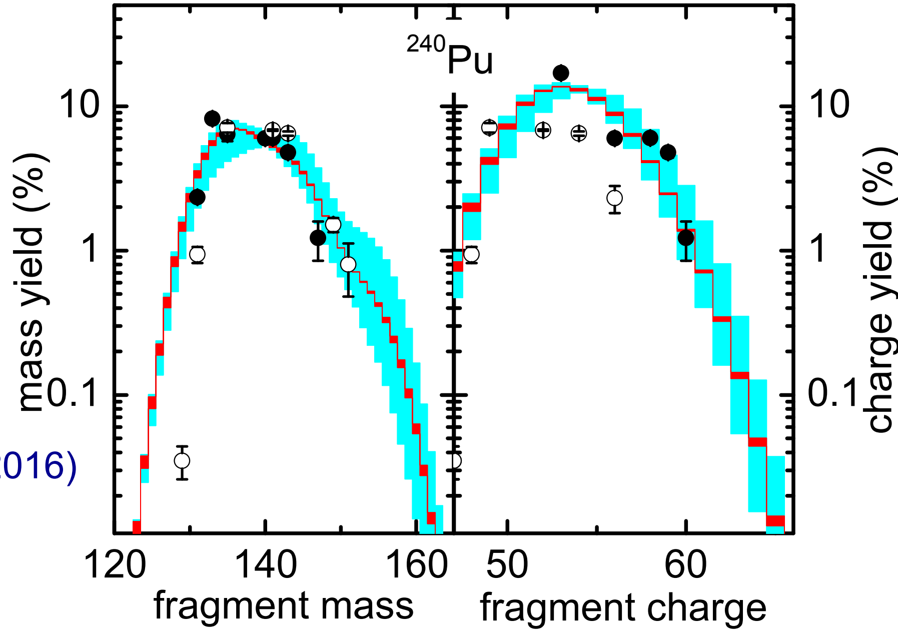
exceedingly difficult, many fundamental questions remain unsettled



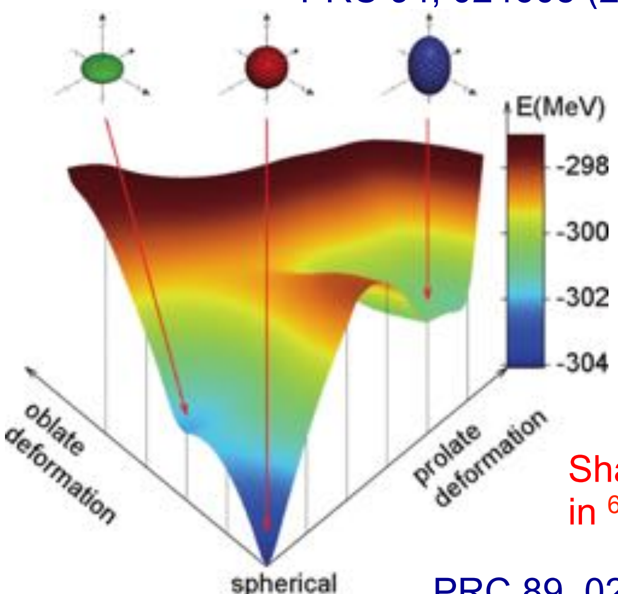
PRC 94, 024605 (2016)

- Fusion
- Fission
- Coexistence phenomena

Spontaneous fission yields



PRC 93 011304(R) (2016)



Shape coexistence in ^{68}Ni

PRC 89, 021301(R) (2014)

High performance computing

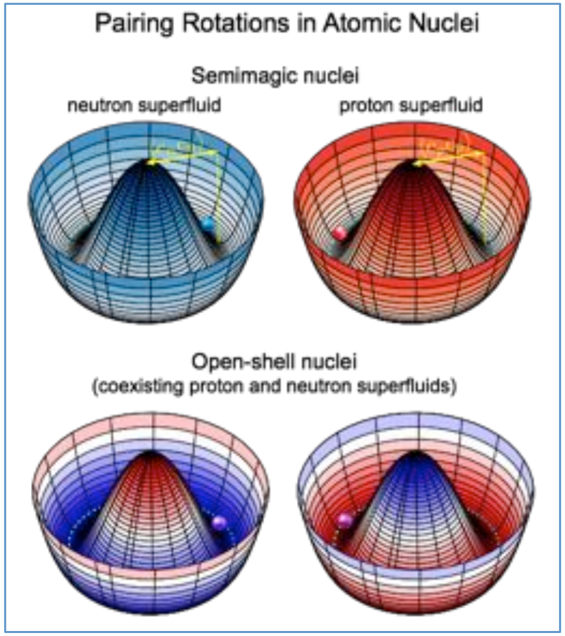
PROSPECT

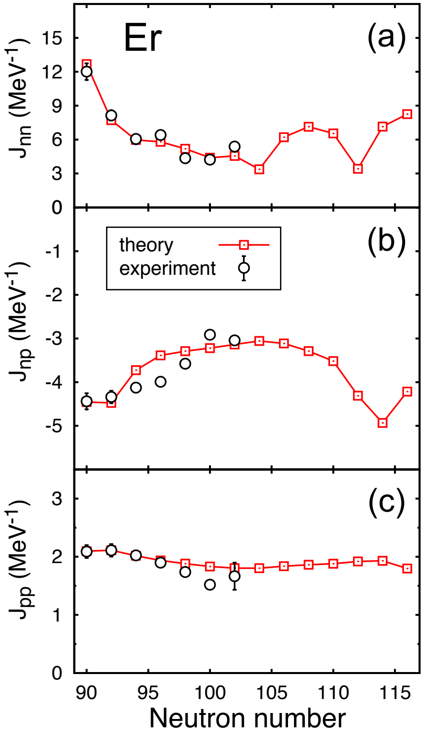
Time-dependent density-functional description of nuclear dynamics

Takashi Nakatsukasa, Kenichi Matsuyanagi, Masayuki Matsuo, and Kazuhiro Yabana

Rev. Mod. Phys. **88**, 045004 (2016) – Published 9 November 2016

“Many excitation modes of atomic nuclei and their reactions can be described as time-dependent processes, in which nuclei oscillate, rotate, collide, and split. A theoretical framework to describe nuclear dynamics at low energy is the time-dependent density functional theory. This reviews the foundations and extensions of this theory and its applications to nuclear collective motion, including giant resonances, heavy-ion collisions, and shape coexistence. Conceptual differences between nuclear and electronic applications are also discussed.”



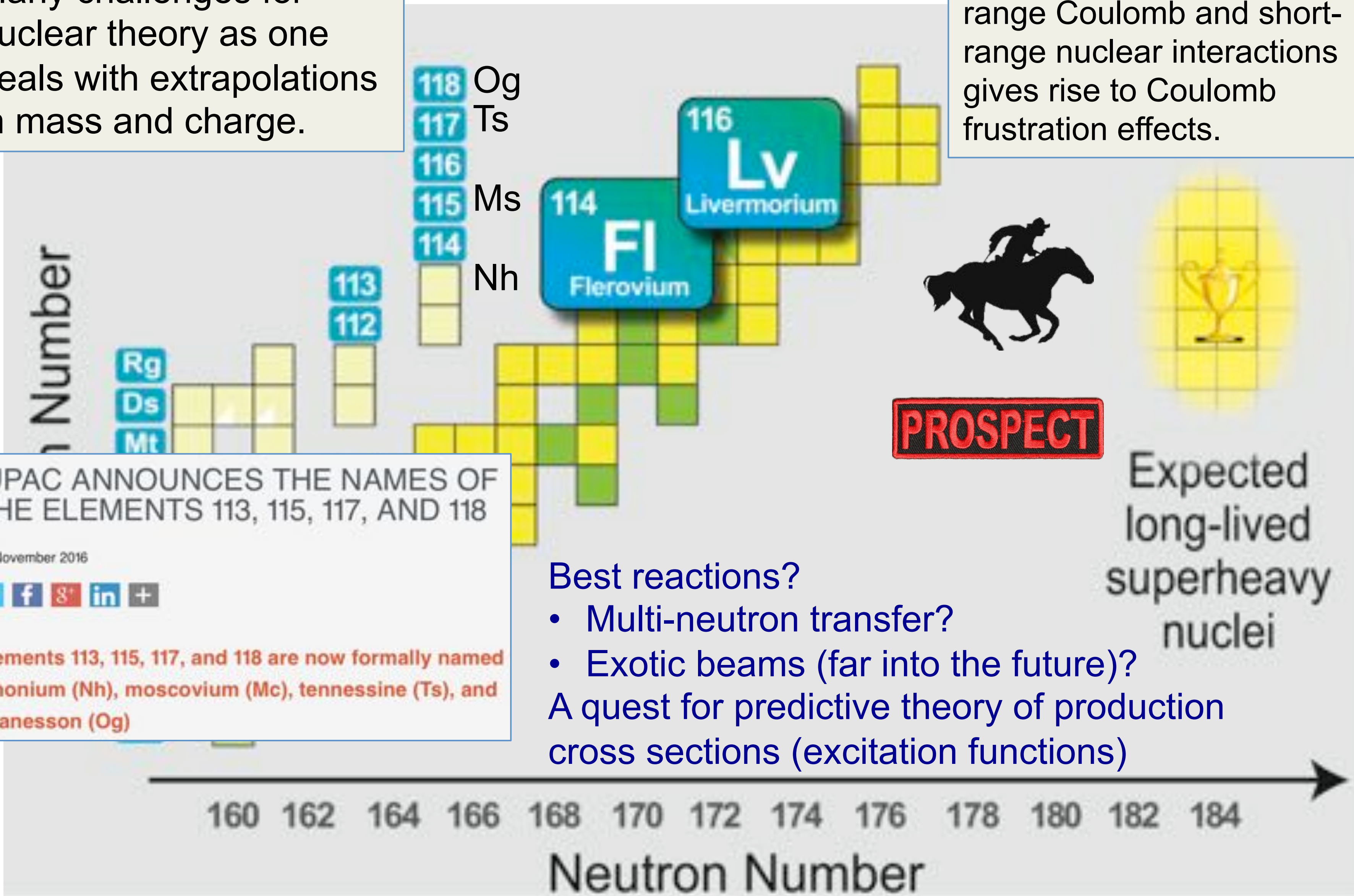


N. Hinohara et al, Phys. Rev. Lett. 116, 152502 (2016).

What are the limits of atoms and nuclei?

Many challenges for nuclear theory as one deals with extrapolations in mass and charge.

A competition between long-range Coulomb and short-range nuclear interactions gives rise to Coulomb frustration effects.



IUPAC ANNOUNCES THE NAMES OF THE ELEMENTS 113, 115, 117, AND 118

30 November 2016

Elements 113, 115, 117, and 118 are now formally named nihonium (Nh), moscovium (Mc), tennessine (Ts), and oganesson (Og)

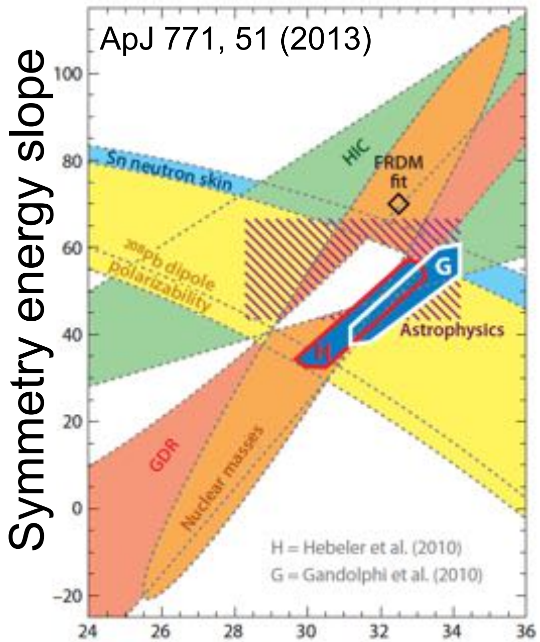
Best reactions?

- Multi-neutron transfer?
- Exotic beams (far into the future)?

A quest for predictive theory of production cross sections (excitation functions)

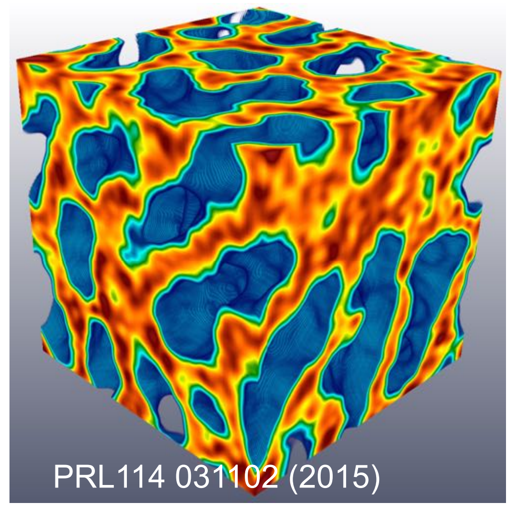
Quest for understanding the neutron-rich matter on Earth and in the Cosmos

Bounds on EOS

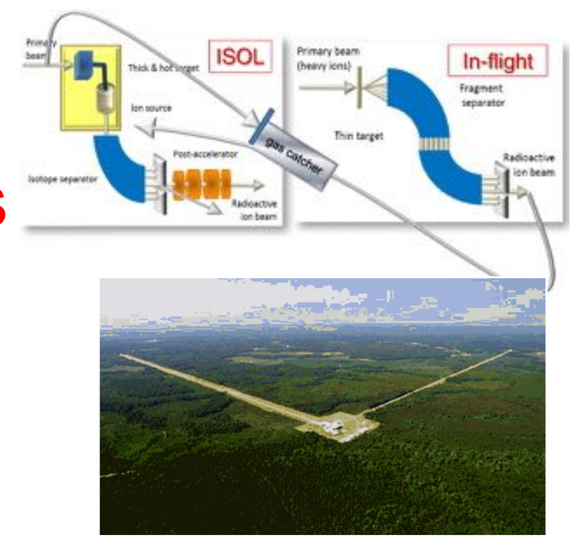


Symmetry energy

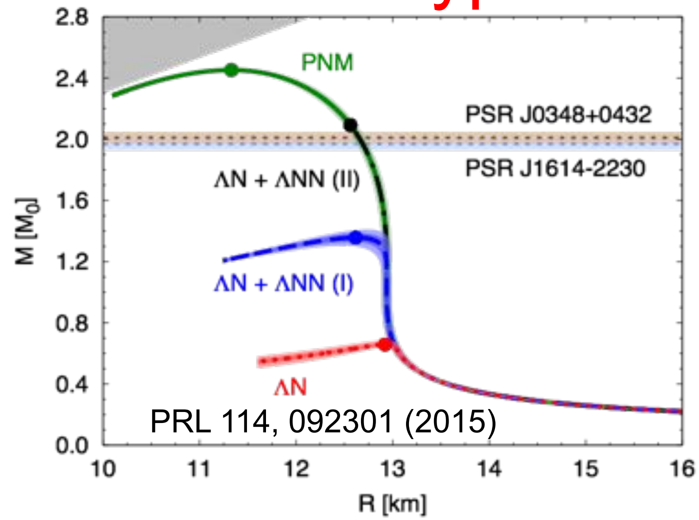
Crustal structures



Data



EOS with hyperons

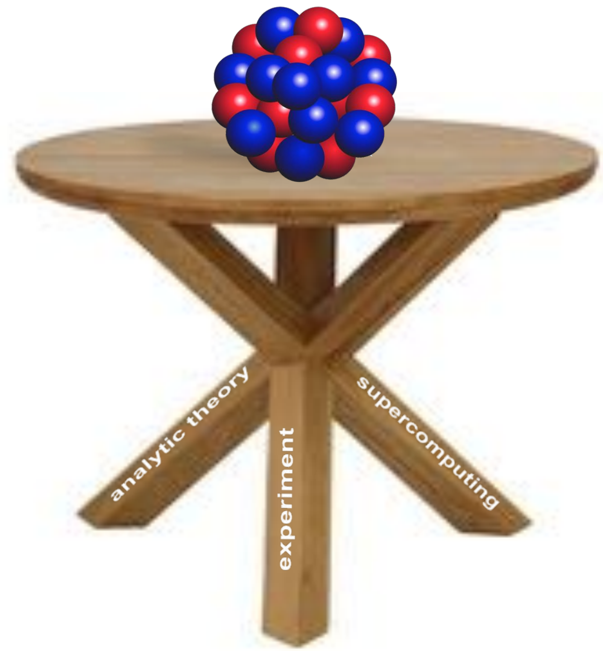


Exciting multi-disciplinary science

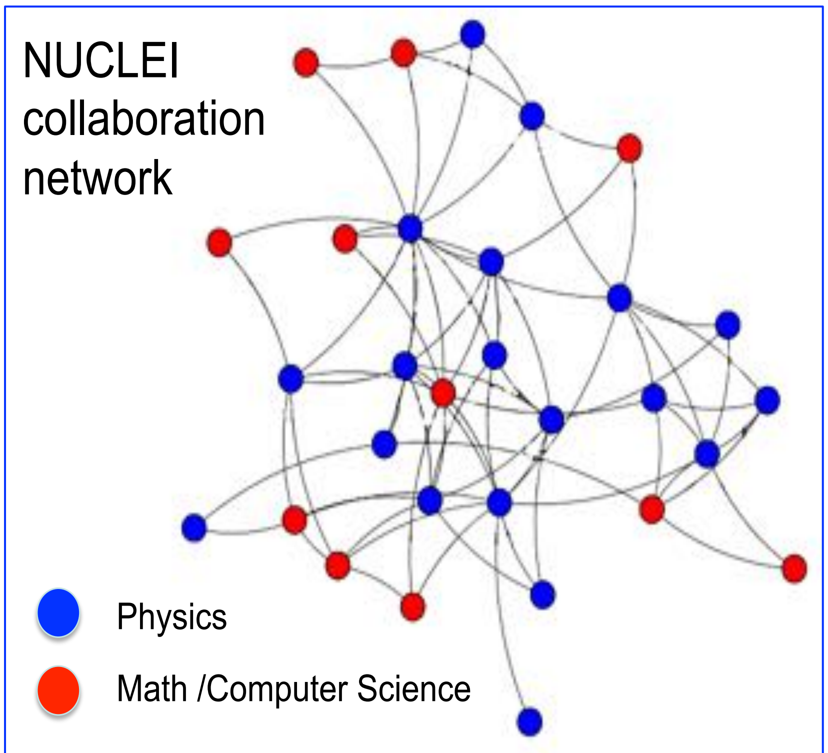
PROSPECT

PROSPECT

Creating unfair advantage:
the whole is greater than
the sum of its parts



Sociology of the field is changing: large multi-institutional efforts involving strong coupling between physics, computer science, and applied math



… and let us not forget about education and training!

TALENT: Training in Advanced Low Energy Nuclear Theory

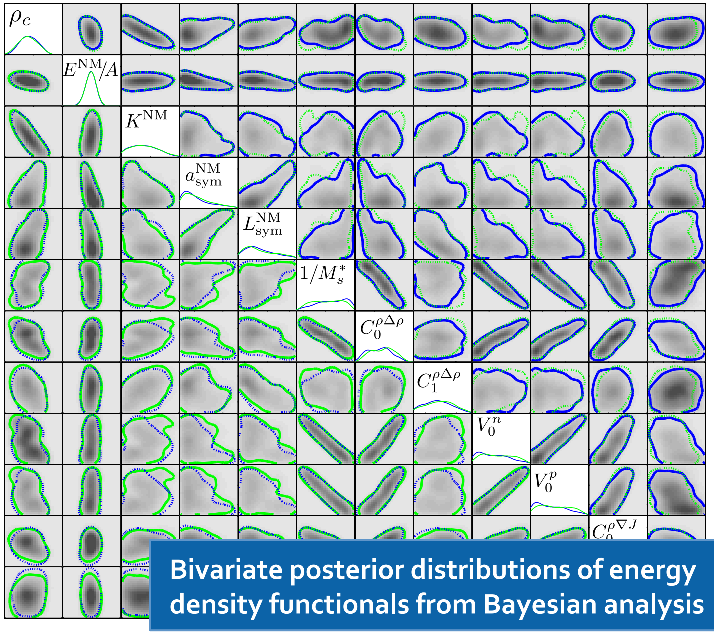
http://nucleartalent.org

Uncertainty quantification

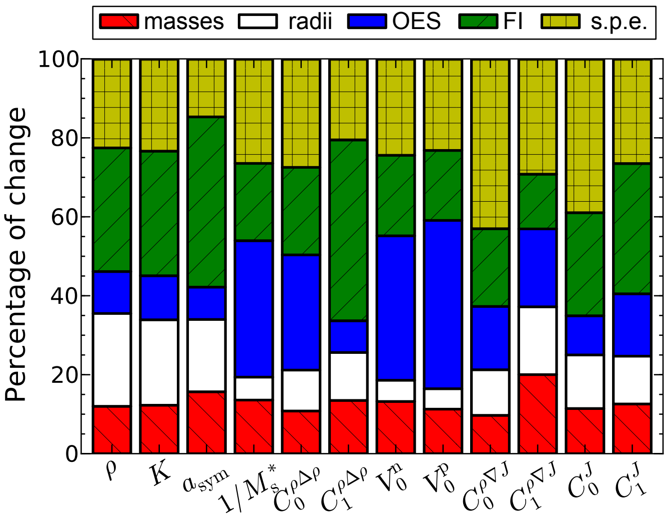
http://iopscience.iop.org/journal/0954-3899/page/ISNET

- Regression analysis
- Bayesian inference
- Extrapolations
- Model mixing
- Information content of new measurements

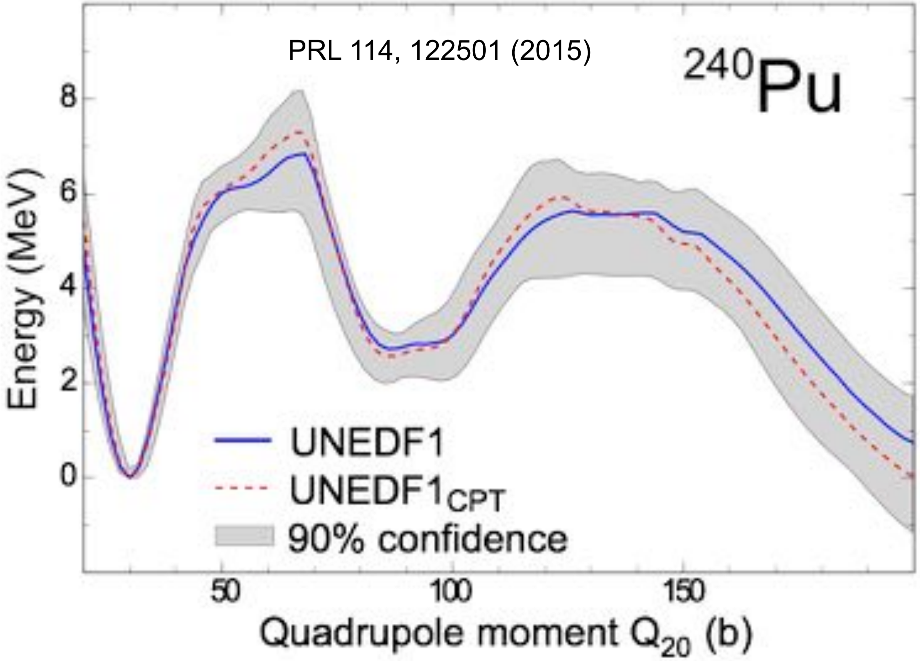
HUGE



Bivariate posterior distributions of energy density functionals from Bayesian analysis



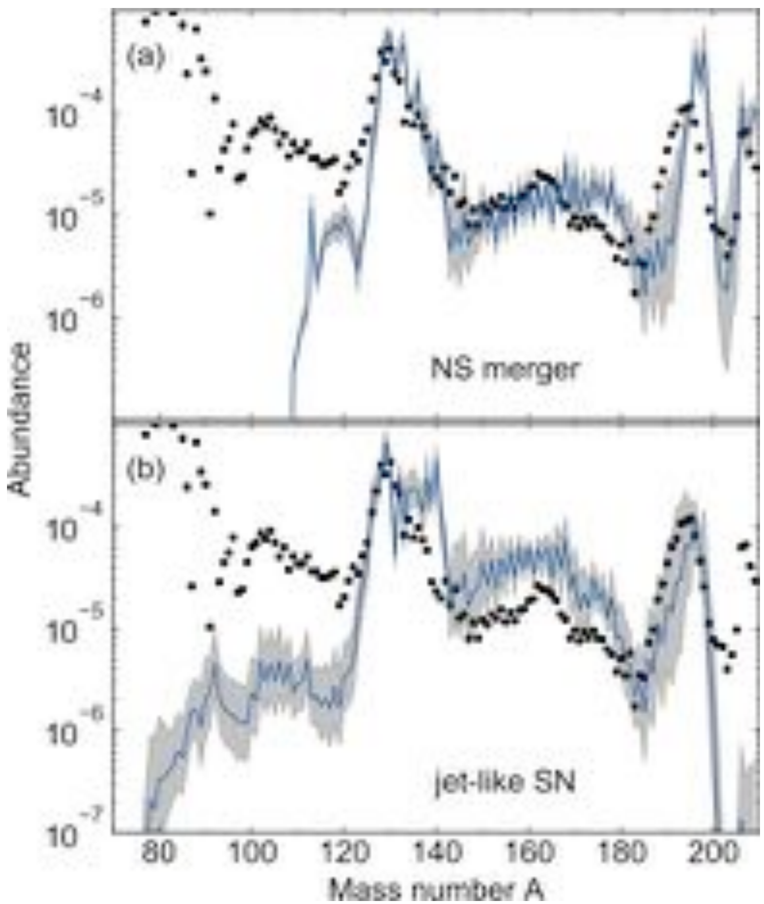
PRC 89, 054314 (2014)

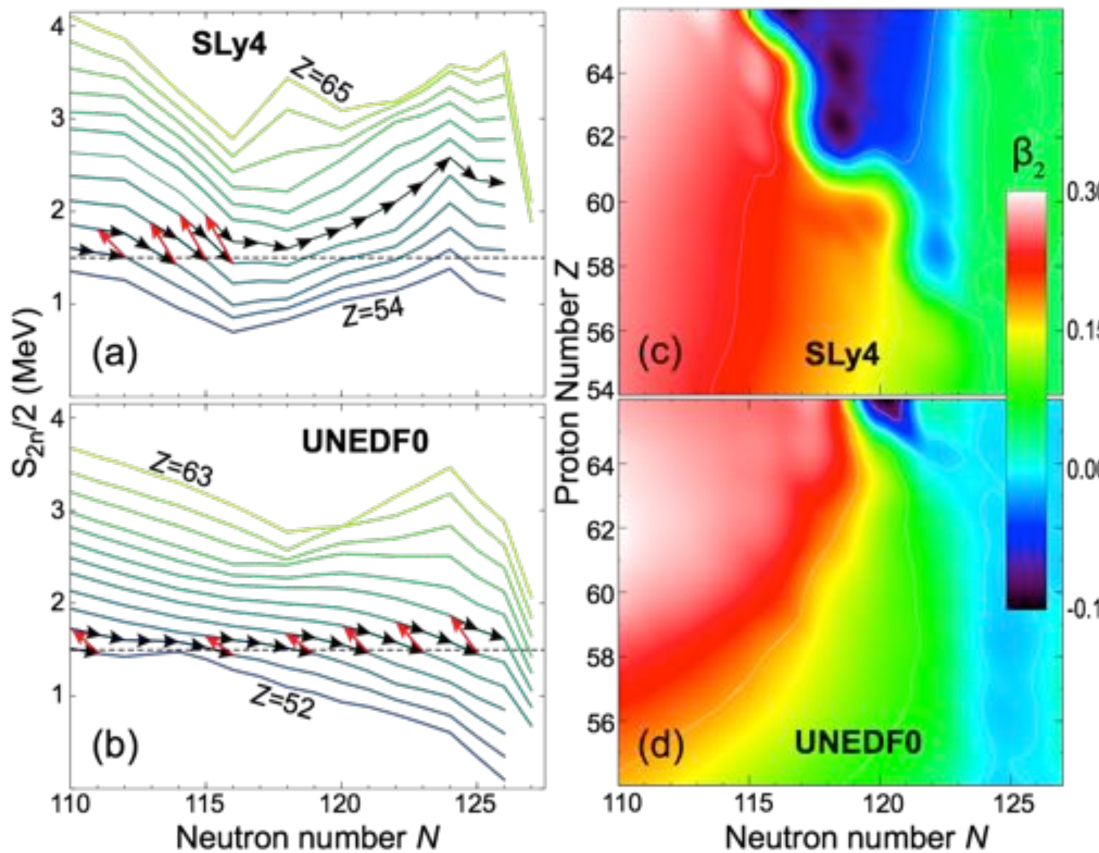


In many cases, nuclear modeling MUST involve massive extrapolations...

Impact of Nuclear Mass Uncertainties on the r Process

Phys. Rev. Lett., **116,** 121101 (2016)





PROSPECT

Uncertainty quantification
Getting critical measurements

"It is exceedingly difficult to make predictions, particularly about the future" (Niels Bohr)

Looking into the crystal ball: year 2030 and beyond

- We will understand the QCD origin of nuclear forces. We will develop the predictive ab-initio description of light and medium-mass nuclei and their reactions, including electroweak probes. We will construct the spectroscopic-quality energy density functional that will extrapolate in mass, isospin, and angular momentum. We will develop the comprehensive reaction theory consistent with nuclear structure. We will have a comprehensive description of weak transitions in nuclei and utilize them in multi-dimensional stellar evolution simulations.

Where do nuclei come from?

- We will know if very long-lived superheavy elements exist in nature. We will understand the mechanism of clustering and other aspects of open many-body systems. We will know whether proton-neutron superfluidity exists in finite nuclei. We will know the nuclear equation of state for normal and neutron matter from 0.1 to twice the saturation density.

How are nuclei organized?

- We will have a quantitative microscopic model of fission that will provide the missing data for nuclear security, astrophysics, and energy research. We will predict important fusion reaction rates important for fusion research and nuclear forensics. We will improve the sensitivity of EDM searches in atoms by one to two orders of magnitude over current limits.

What are nuclei good for?

MATERIALS SCIENCE

Making the most of materials computations

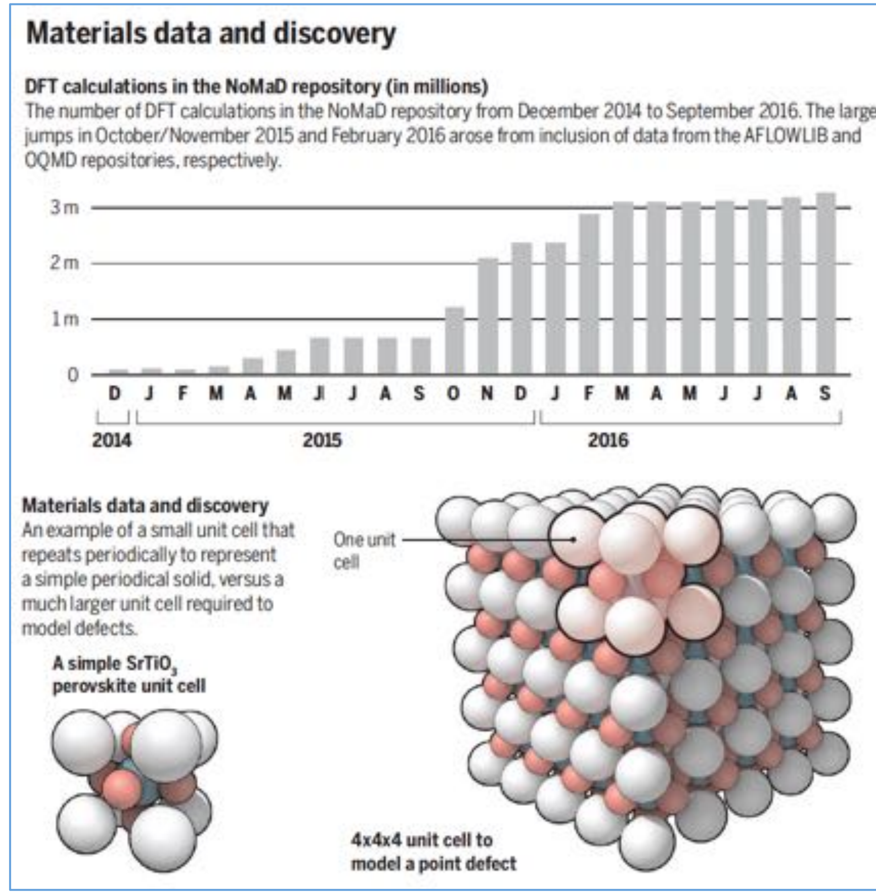
Databases of theoretical structures and properties of materials can speed real-world discovery

By **Kristian S. Thygesen** *and* **Karsten W. Jacobsen**

Science 354, 180 (2016)

For more than a century, materials scientists have accumulated experimental data on the structures of chemical compounds and the thermal, electronic, and mechanical properties that they exhibit. These data have been a cornerstone in the development, selection, and design of materials. In the past decade, experimental data have been augmented by an explosion of computational data from quantum-mechanical calculations, which can be obtained more quickly and in some cases with comparable accuracy.

The computational databases supplement the experimental ones mainly by providing additional systematic information about materials, but they also provide information about the properties of materials that do not occur naturally or that have never been synthesized in a laboratory.

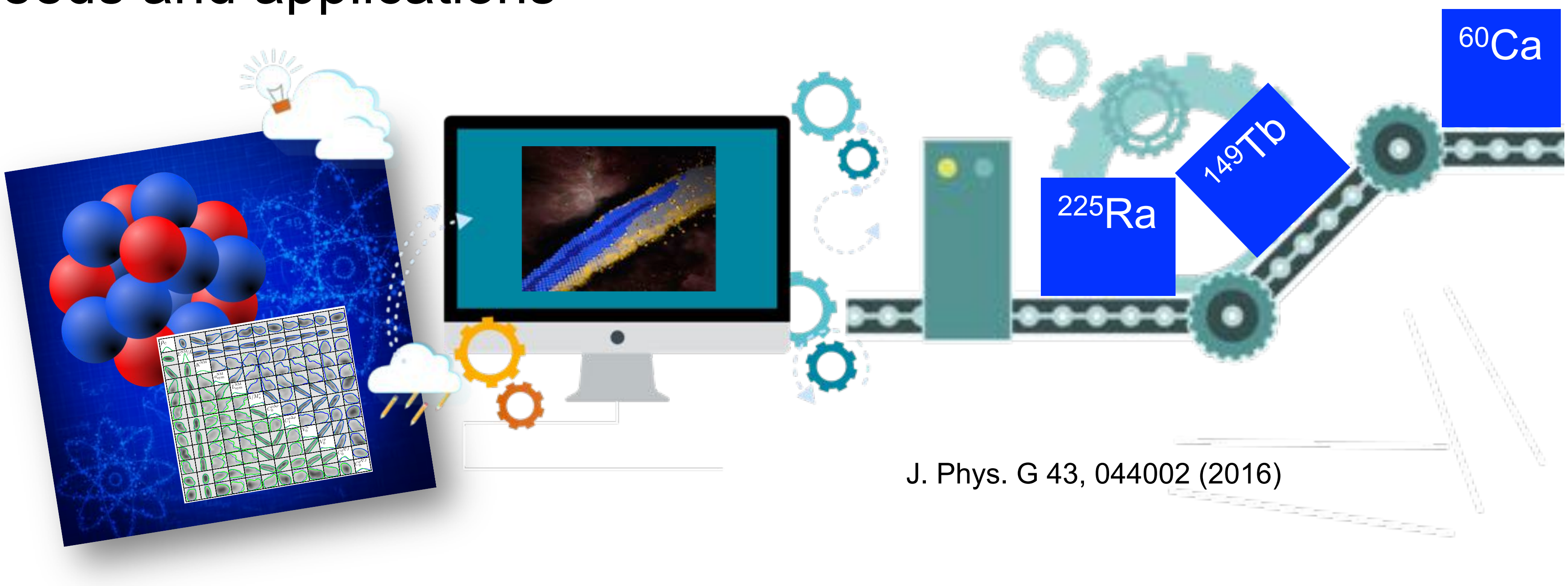


Computational materials scientists apply a range of different codes that all solve the same fundamental equations of DFT but apply diverse numerical approaches. In a large community effort, it was recently shown that in simple situations, like the calculation of the equation of state of elemental crystals, agreement between different codes can be established.

Computational databases mainly contain entries for bulk solids in simple crystal structures, primarily because calculation times grow quickly with the number of atoms N in the unit cell (typically as N to a power between 2 and 3). However, many materials properties are determined by defects, such as vacancies, atoms in interstitial sites, or impurities, or by grain boundaries or surfaces. For many applications, the simple materials described in the databases are not directly relevant, and more complex structures and materials must be included.

Some nuclei are more important than others

Over the last decade, tremendous progress has been made in techniques to produce and describe *designer nuclei*, rare atomic nuclei with characteristics adjusted to specific research needs and applications



J. Phys. G 43, 044002 (2016)

CONCEPT PREDICTION FABRICATION

Nuclei Matter

Our current understanding of nuclei has benefited from technological improvements in experimental equipment and accelerators that have expanded the range of available isotopes and allowed individual experiments to be performed with only a small number of atoms. Concurrent advances in theoretical approaches and computational science have led to a more detailed understanding and pointed toward which nuclei and what phenomena to study, creating conditions for major advances.

Profound intersections

- Astrophysics
- Fundamental Symmetries
- Complex systems
- Computing

How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

- Energy (fission, reactions, decays…)
- Security (stewardship, forensics, detection…)
- Isotopes (medicine, industry, defense, applied research…)
- Industry (radiation, ion implantation…)