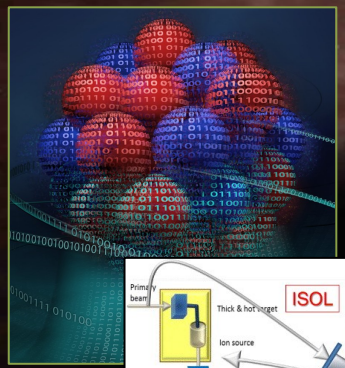
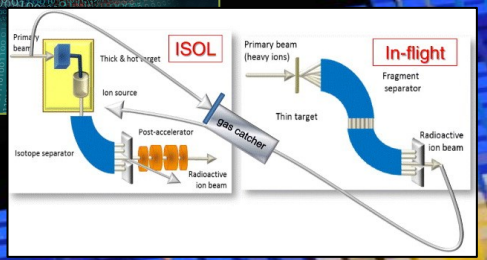
Prospects for breakthroughs in understanding nuclei

Witold Nazarewicz (FRIB/MSU)

26th International Nuclear Physics Conference, Adelaide, Australia 2016





Menu

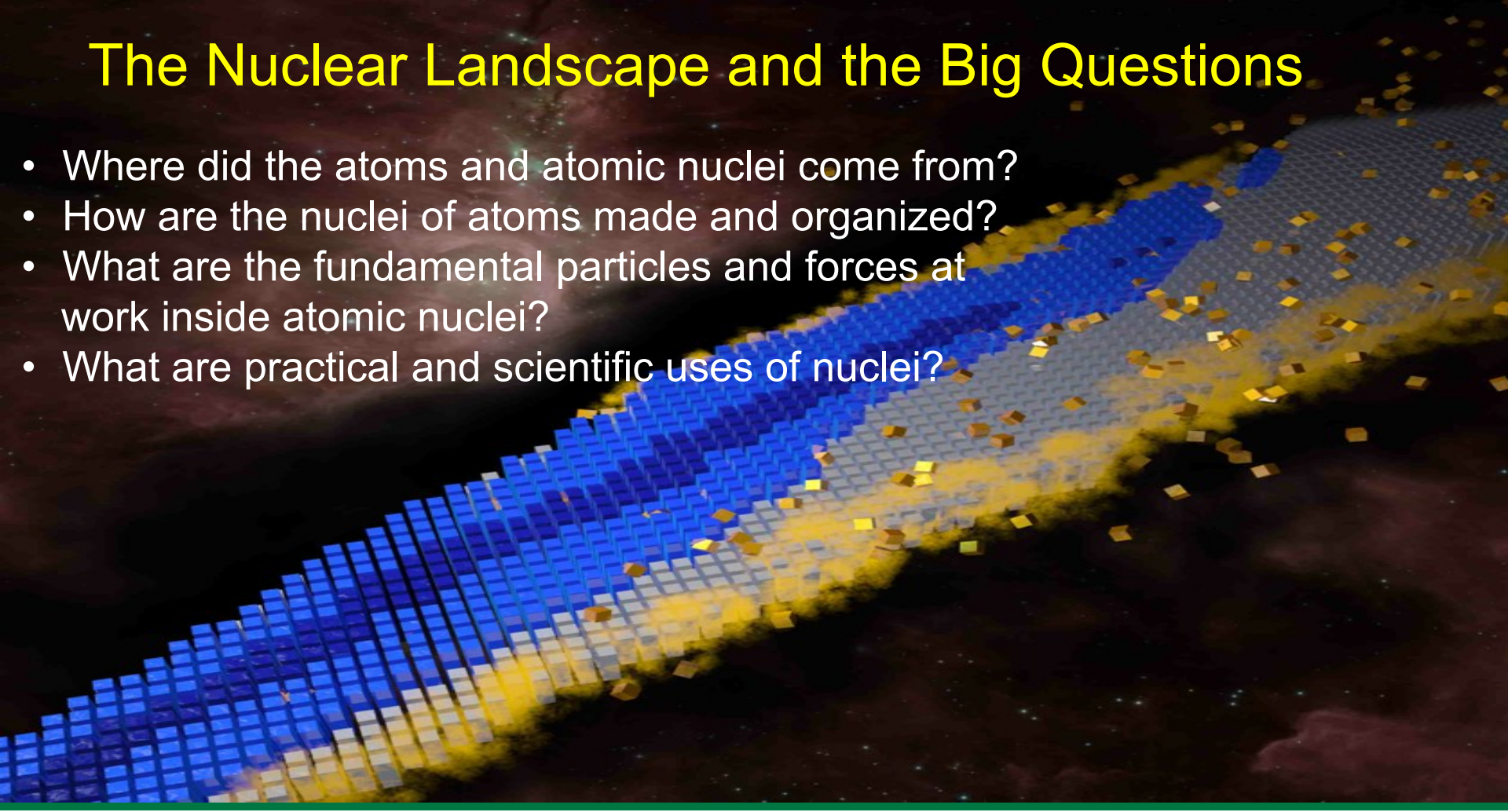
- Prospects
- Creating unfair advantage

PROSPECT

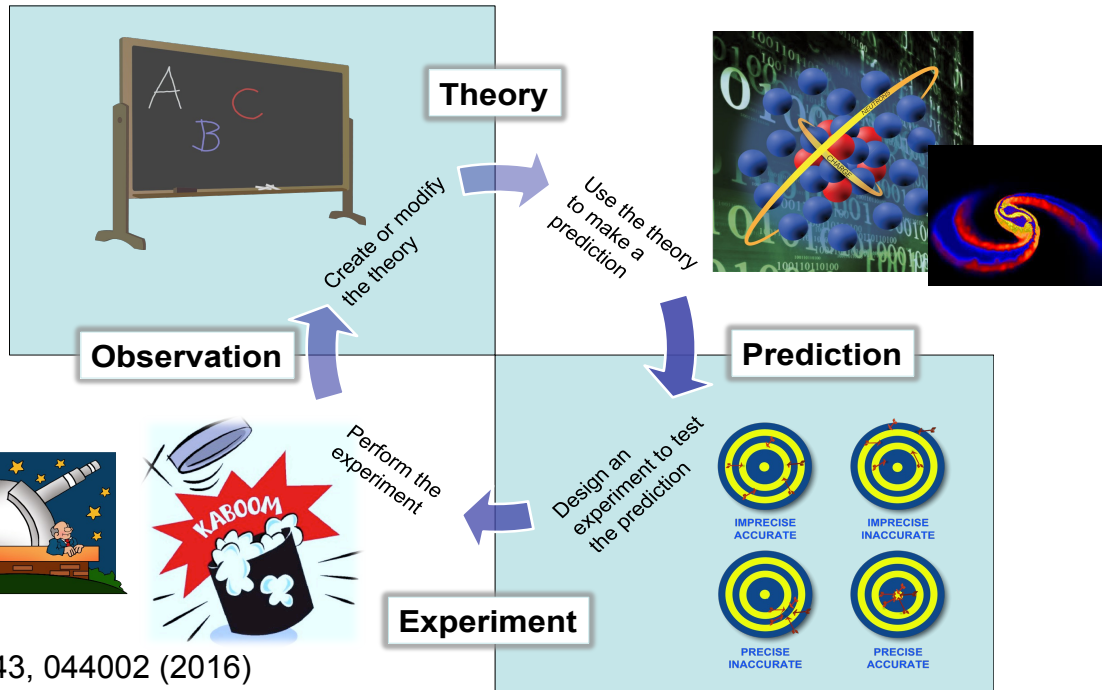
a personal view…

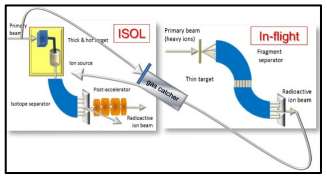
The Nuclear Landscape and the Big Questions

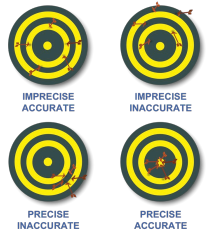
- Where did the atoms and atomic nuclei come from?
- How are the nuclei of atoms made and organized?
- What are the fundamental particles and forces at work inside atomic nuclei?
- What are practical and scientific uses of nuclei?



Guiding principle: the scientific method…







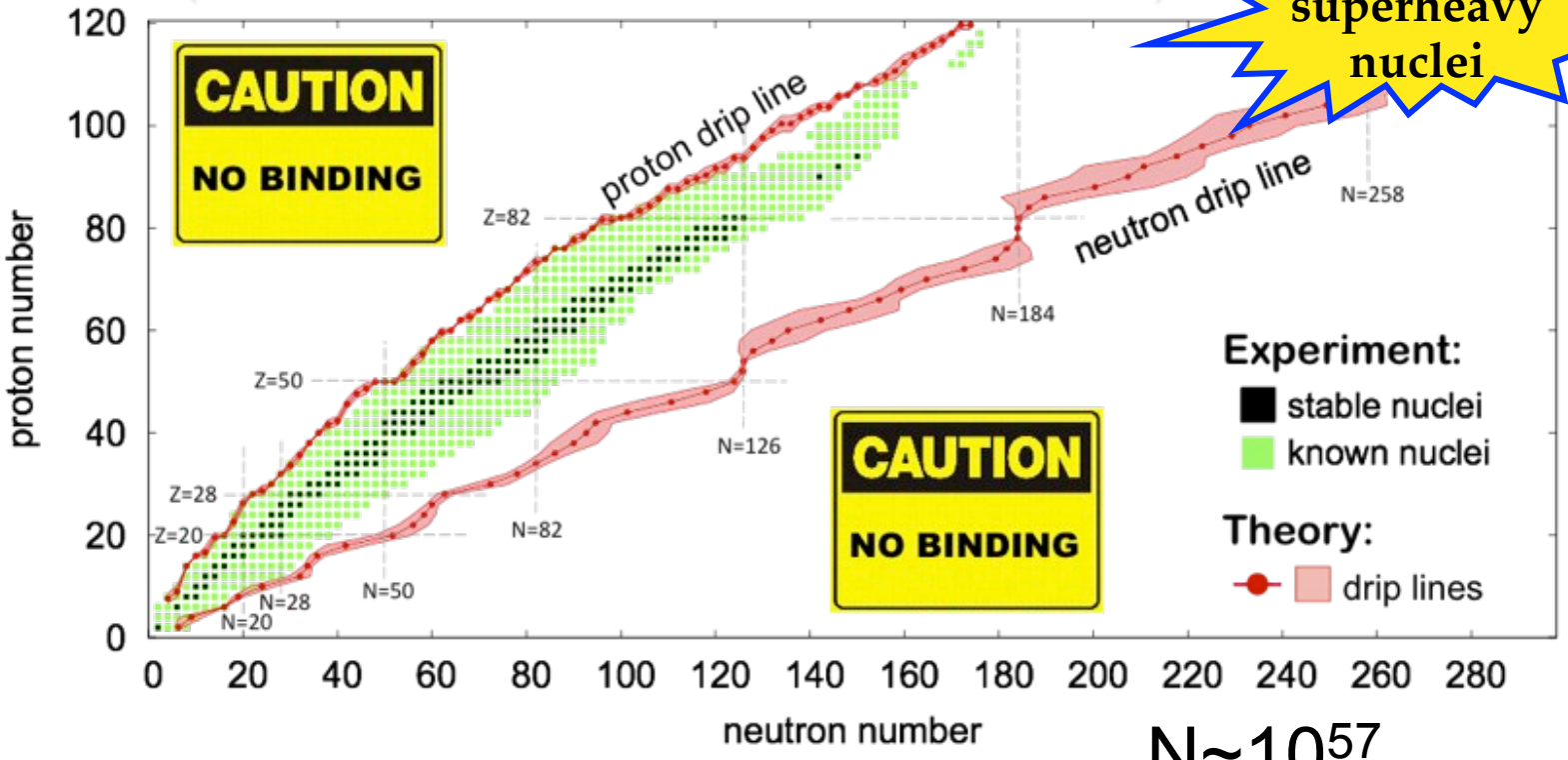
J. Phys. G 43, 044002 (2016)

PROSPECT

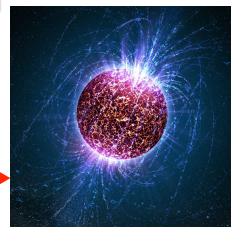
Optimizing the cycle

The Grand Nuclear Landscape

(finite nuclei + extended nucleonic matter)

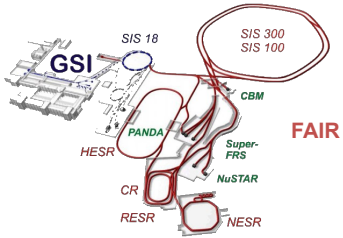


$N \sim 10^{57}$

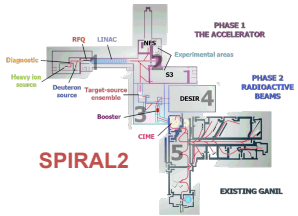


Experiment

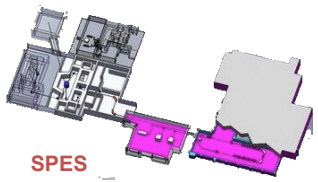
facilities, instrumentation, techniques



FAIR

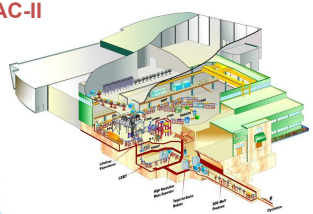


SPIRAL2

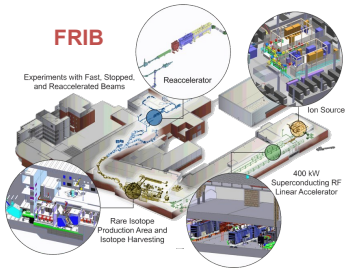


SPES

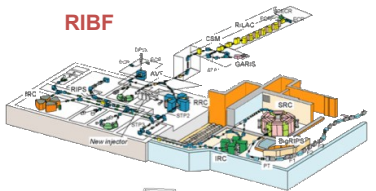
ISAC-II



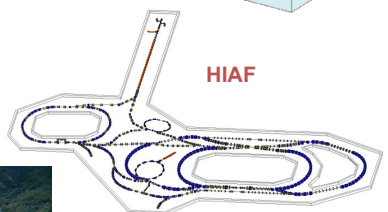
FRIB



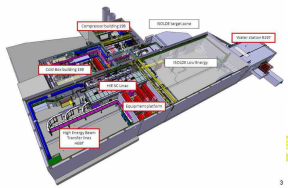
RIBF



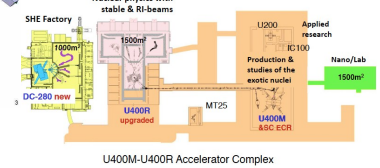
HIAF



HIE ISOLDE



FLNR



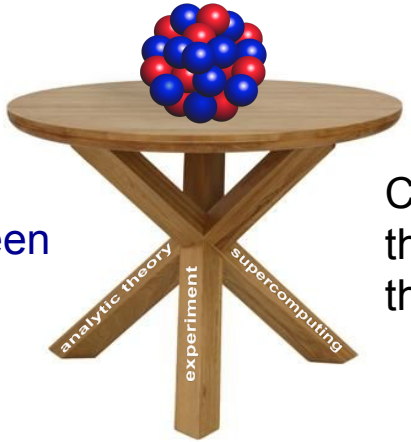
U400M-U400R Accelerator Complex

PROSPECT

RISP

Discovery breakthroughs

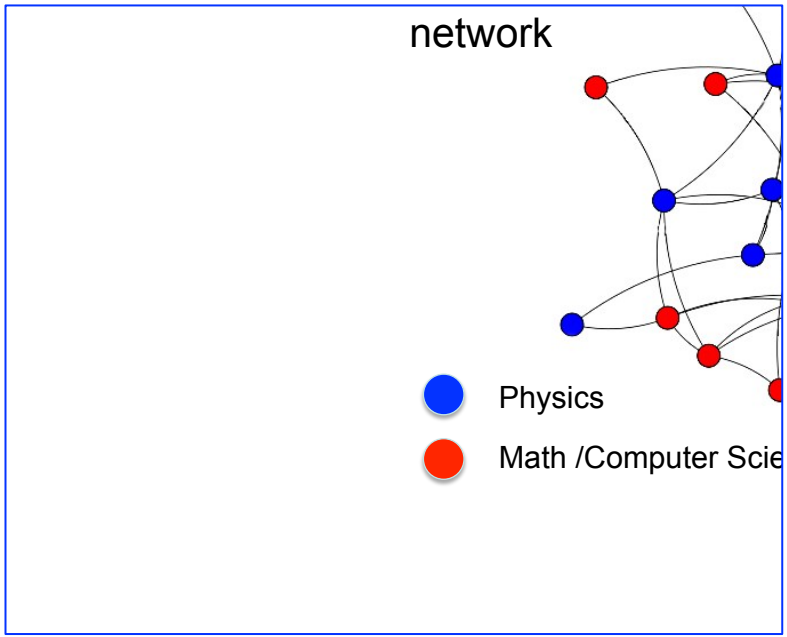
Theory



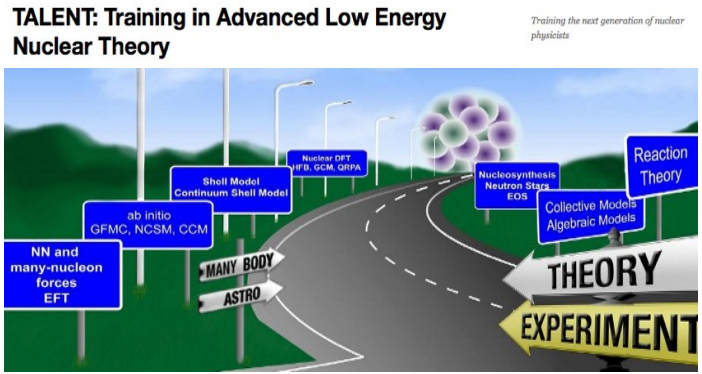
PROSPECT

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

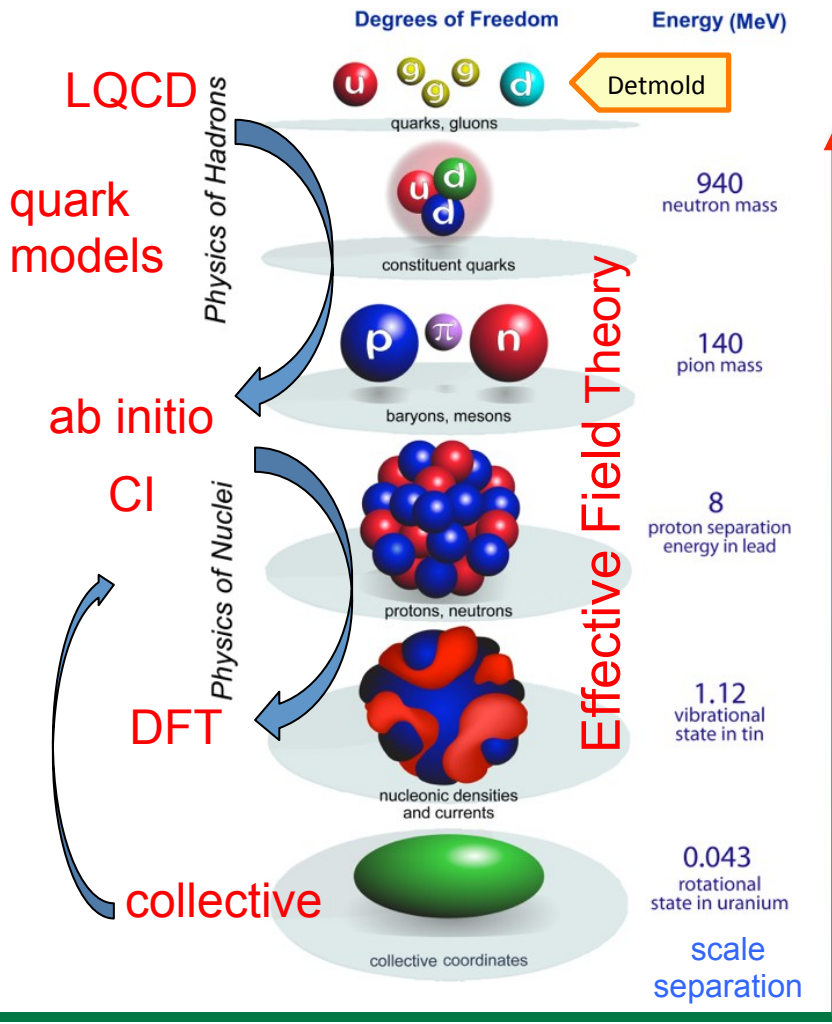


… and let us not forget about education and training!



http://nucleartalent.org

How are nuclei made?



Resolution

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:

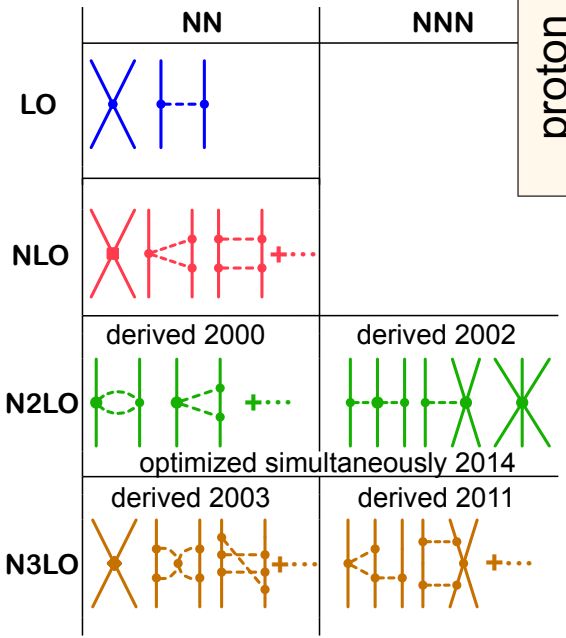
The resolving power of a theoretical model should always be as low as reasonably possible for the question at hand

Linking few-body with many-body

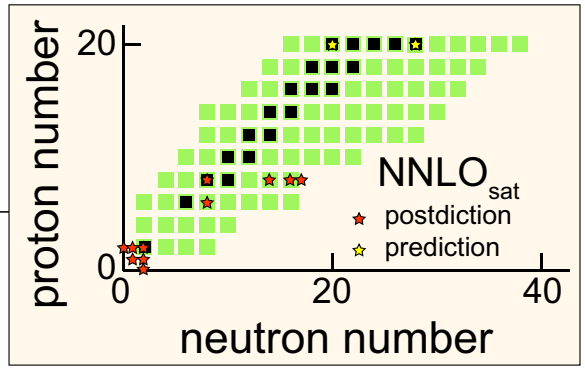
Quantified input

Bacca

Nuclear Forces from chiral-EFT



PRC 91, 051301(R) (2015)

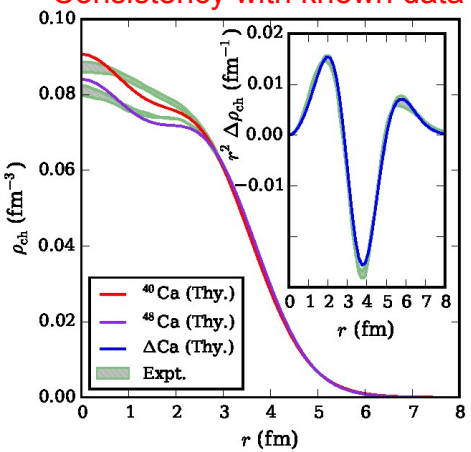


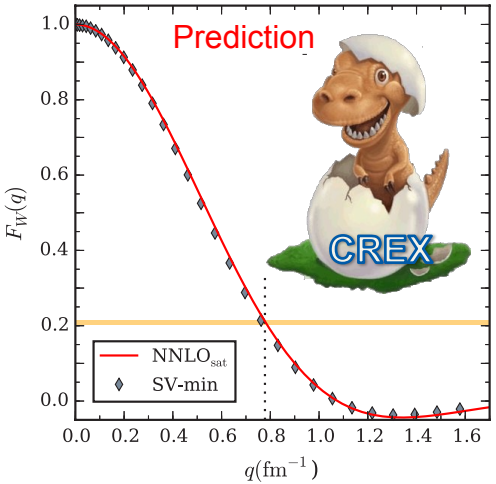
PROSPECT

Comprehensive model of light and heavy nuclei

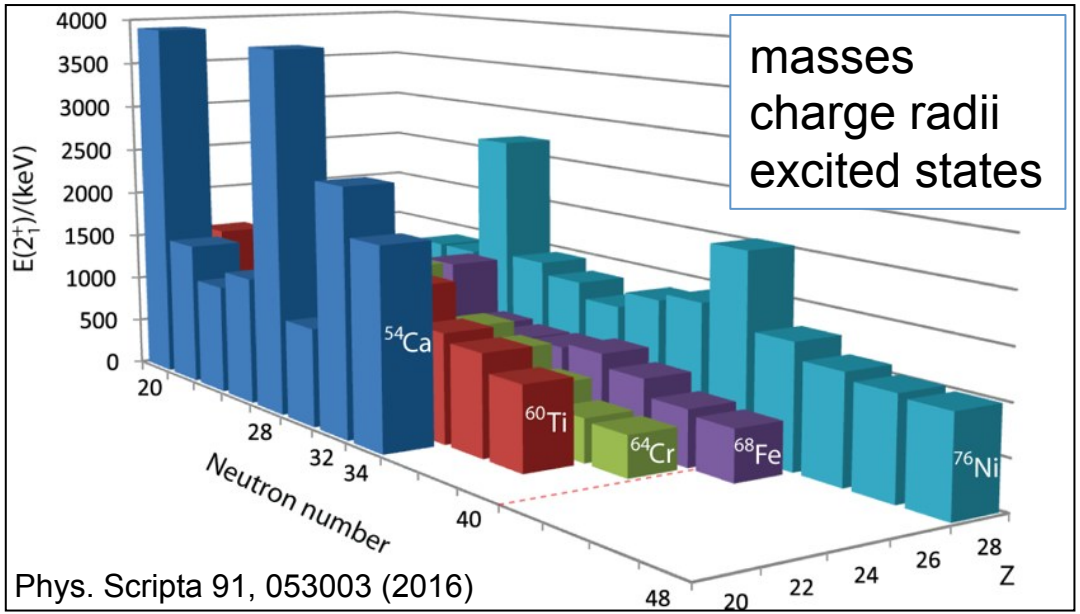
Nature Physics **12**, 186 (2016)

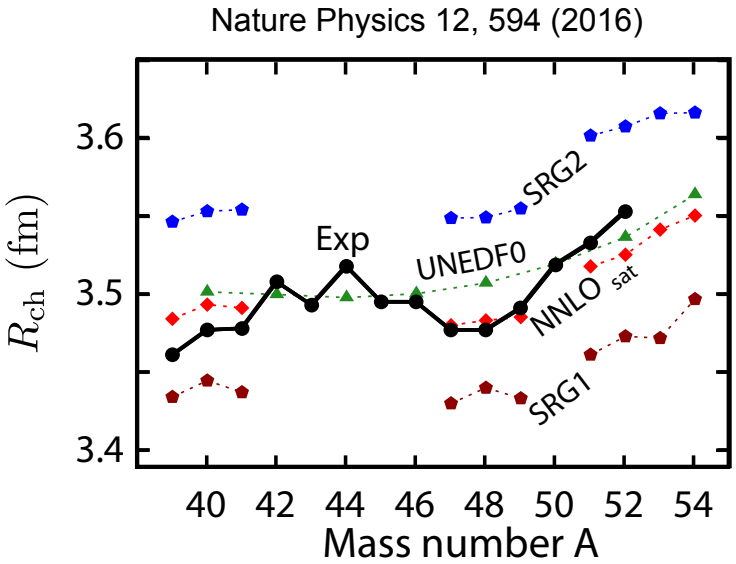
Consistency with known data





Revision of nuclear structure textbook knowledge





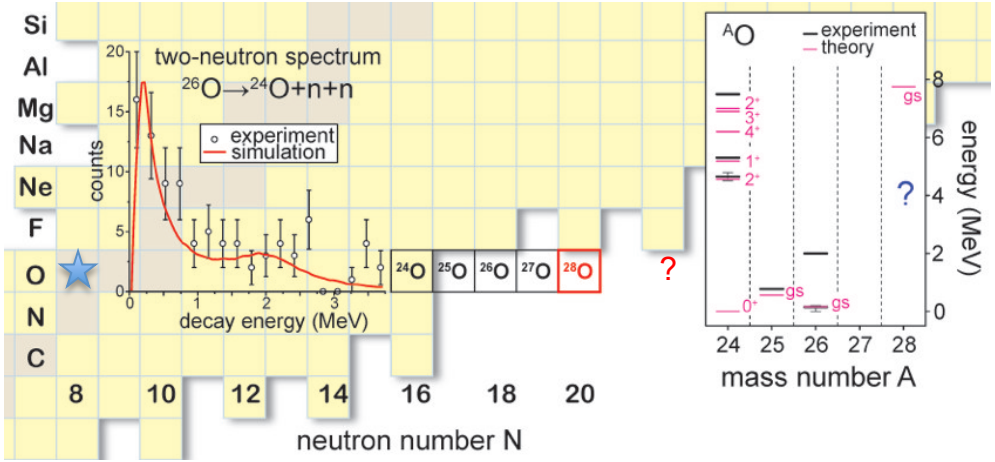
PROSPECT

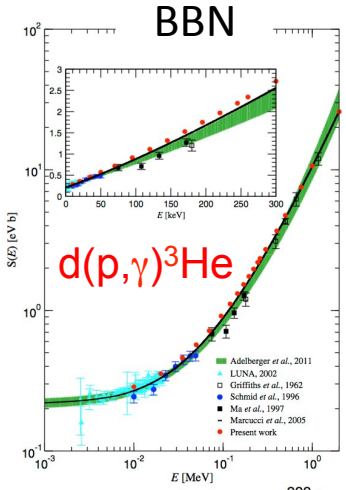
Developing new nuclear paradigms

New shell closures at N = 32 & 34?

Zhou

Revision of nuclear structure textbook knowledge

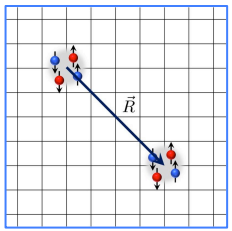


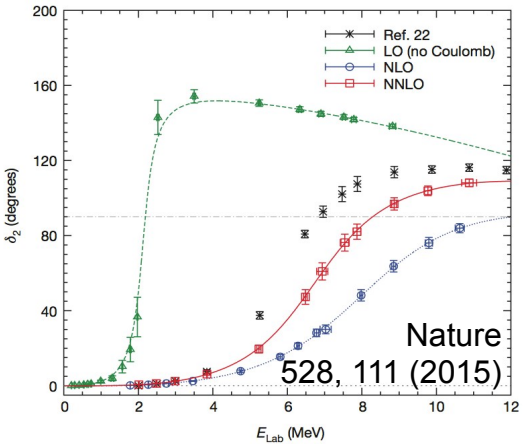


Bonaccorso

PRL116,102501 (2016)

alpha-alpha scattering in LEFT





- ^{16}O is a textbook doubly-magic nucleus
- $^{24,25,26}O$: 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?

PROSPECT

Unification of structure and reactions

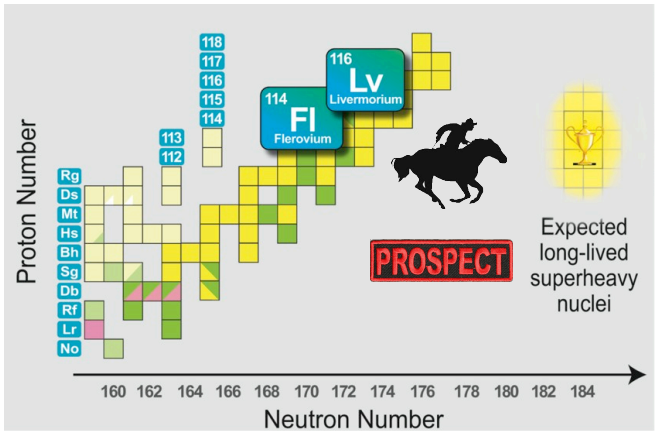
What are the limits of atoms and nuclei? Do very long-lived superheavy nuclei exist in nature?

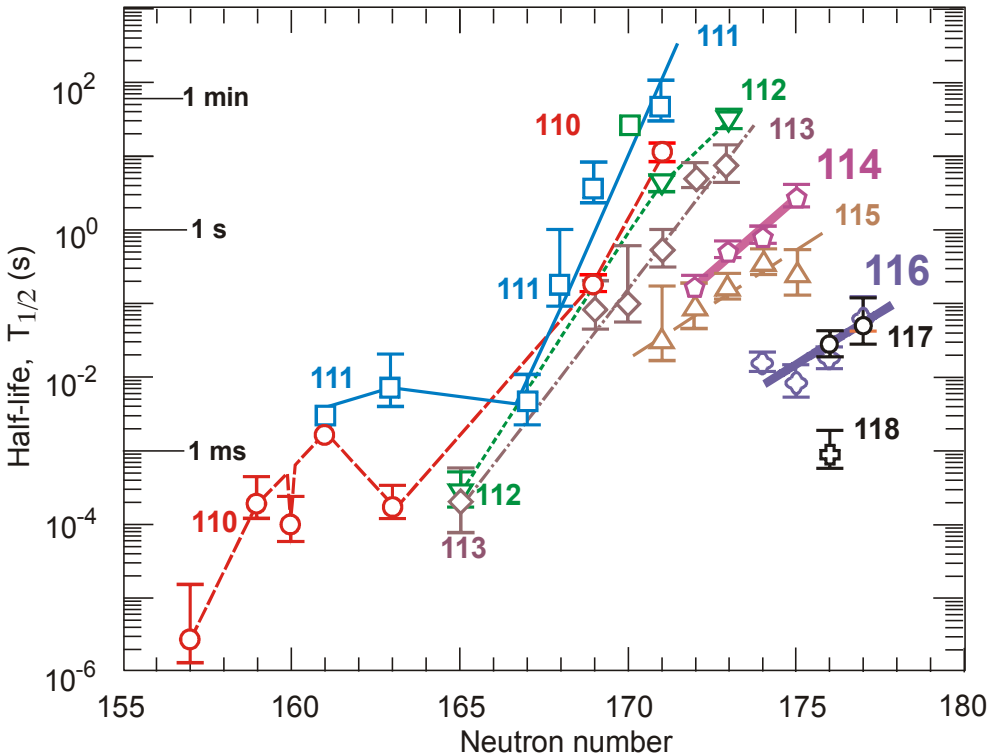
Morimoto

Hinde

Structure of nuclei at the limit of mass and charge
Very relativistic atoms with $Z\alpha \rightarrow 1$

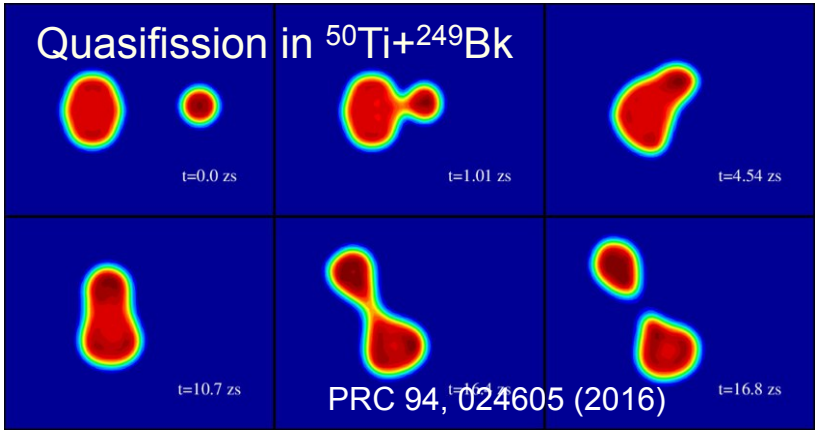
- Many new superheavy isotopes found
- Z=113, 115, 117 confirmed; names proposed
- Unique spectroscopic data above Z>102 collected
- Chemistry of Z=106, 112, 114

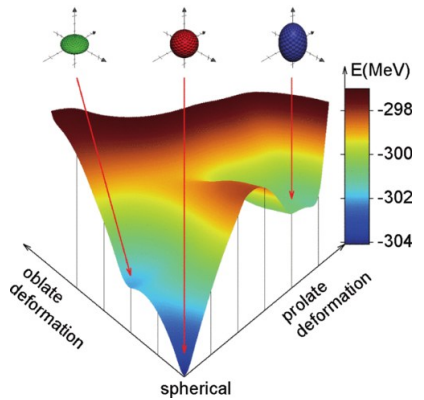




Large Amplitude Collective Motion

exceedingly difficult, many fundamental questions remain unsettled





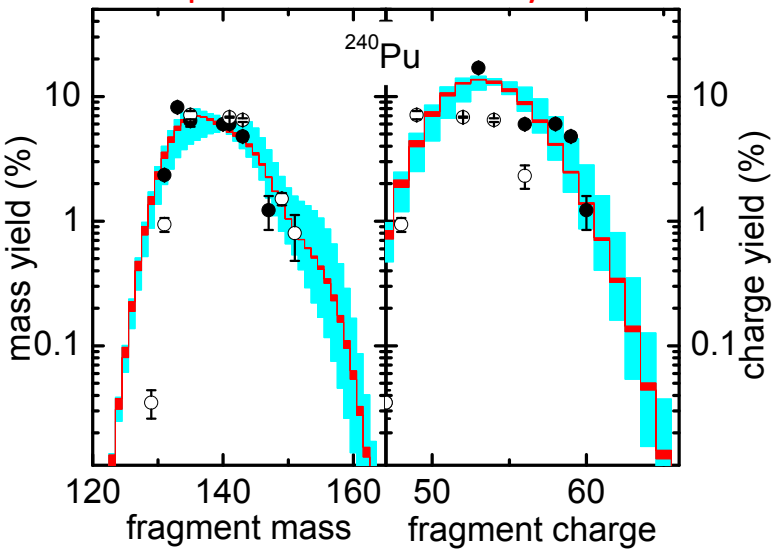
Shape coexistence in ^{68}Ni

PRC 89, 021301(R) (2014)

- Fusion
- Fission
- Coexistence phenomena

PROSPECT

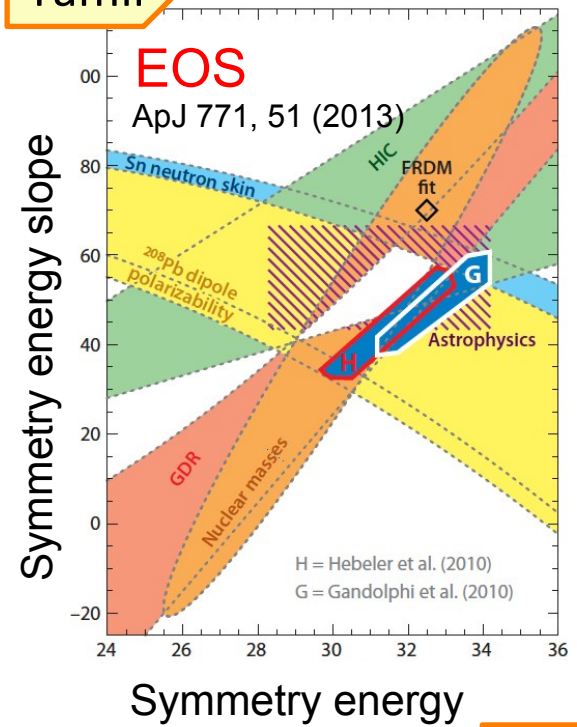
Spontaneous fission yields



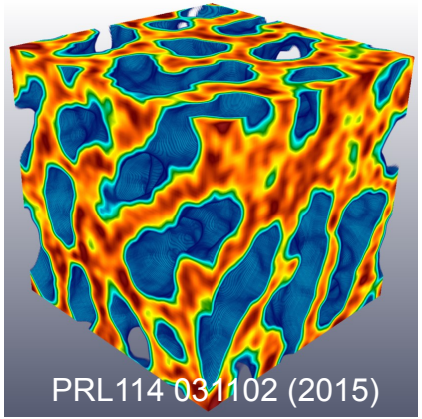
PRC 93, 011304(R) (2016)

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

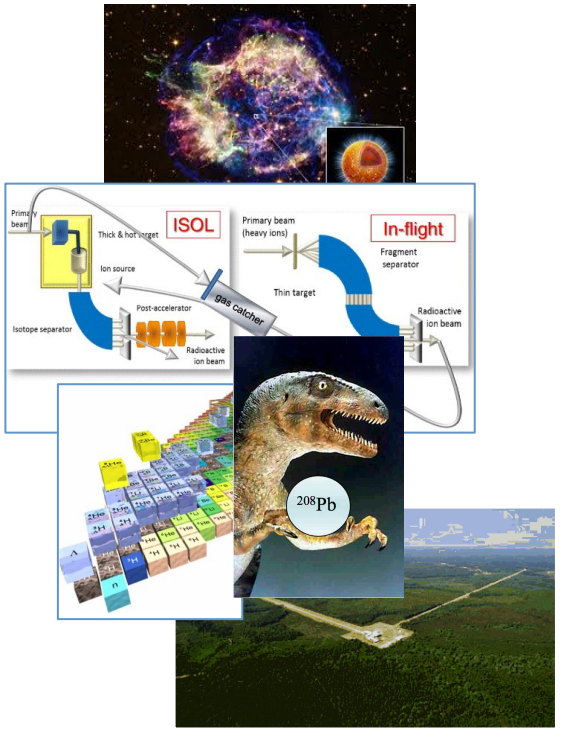
Tamii

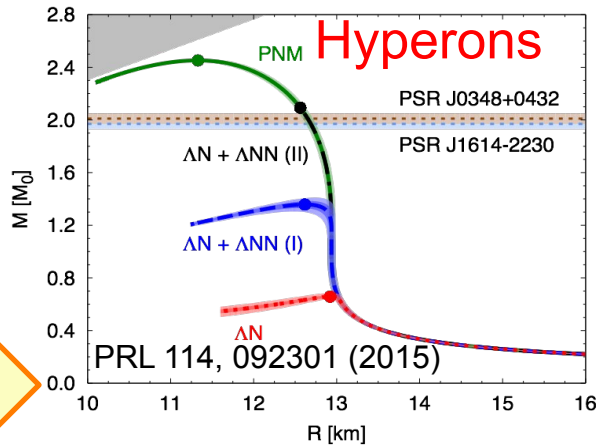


Crustal structures



Data





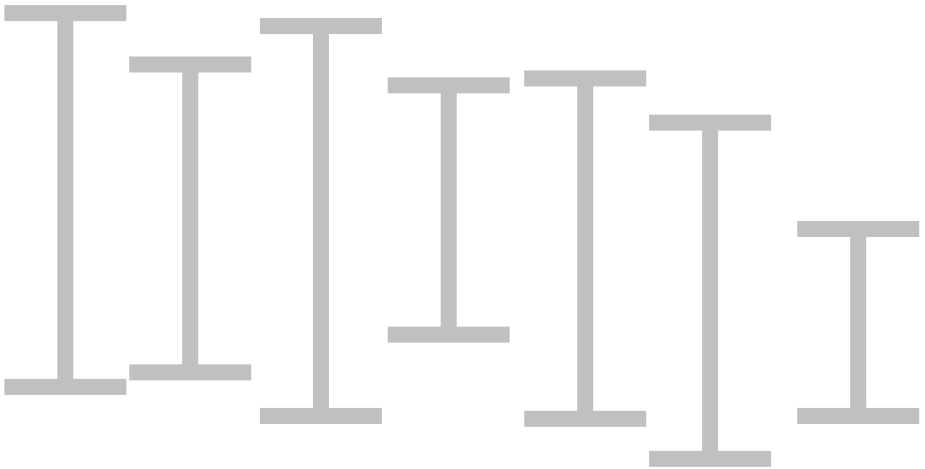
Tamura

PROSPECT

How can nuclei be exploited to reveal the fundamental symmetries of nature?

Current 0νββ predictions

in the equations of motion, resulting in states
configurations and their iterations. Usually, th



"There is generally significant variation among different calculations of the nuclear matrix elements for a given isotope. For consideration of future experiments and their projected sensitivity it would be very desirable to reduce the uncertainty in these nuclear matrix elements." (Neutrinoless Double Beta Decay NSAC Report 2014)

PROSPECT

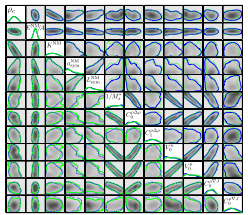
Precision calculations of nuclear matrix elements based on accurate models of nuclear interactions and currents (0νββ, EDM, anapole…)

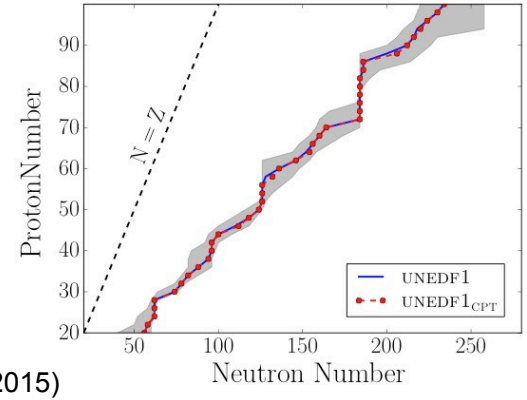
Uncertainty quantification

"Remember that all models are wrong; the practical question is *how wrong do they have to be to not be useful*" (E.P. Box)

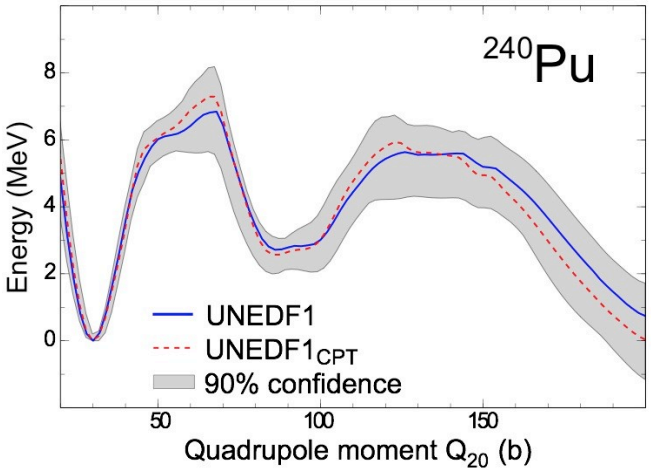
PROSPECT

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





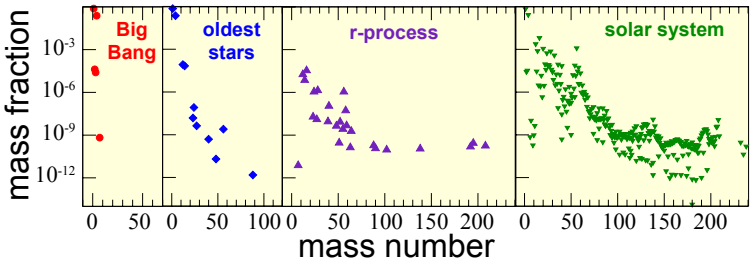
PRL 114, 122501 (2015)

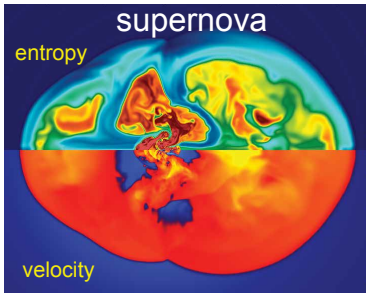


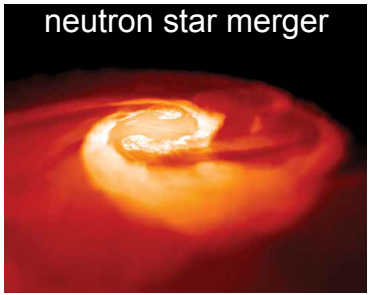
In many cases, nuclear modeling MUST involve massive extrapolations...

Surman

Larsen



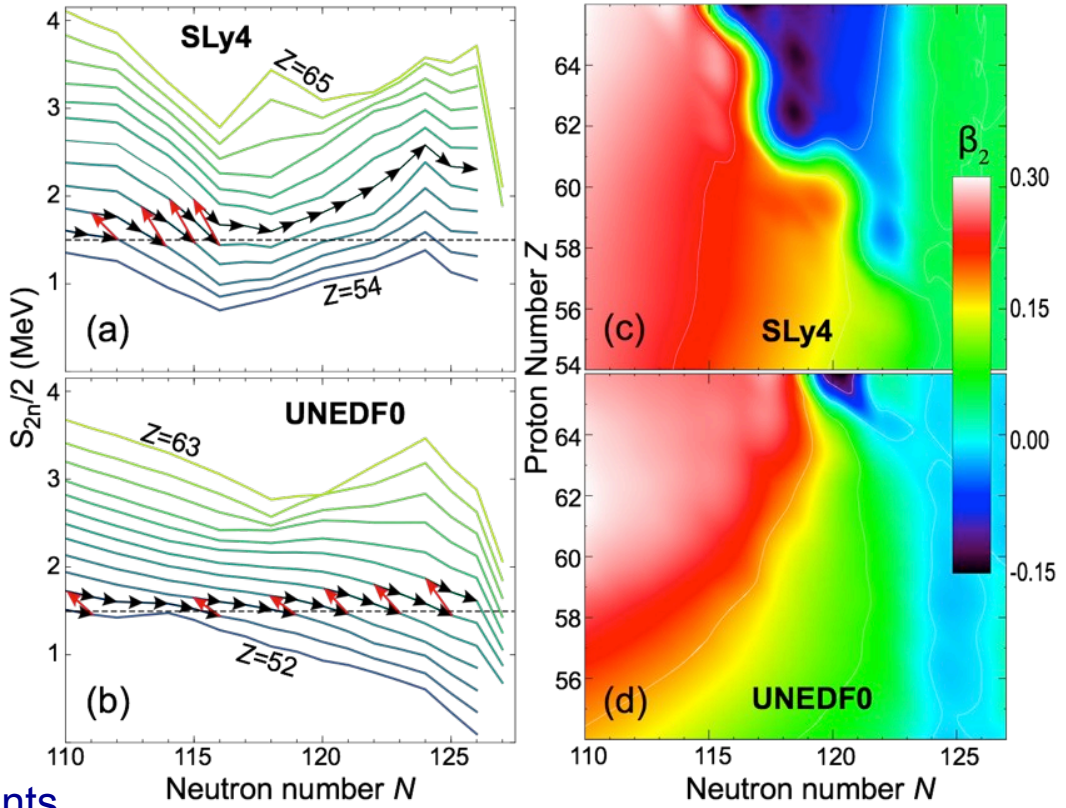




ApJ 767, L6 (2012)

MNRAS 430, 2585 (2013)

PRL **116,** 121101 (2016)



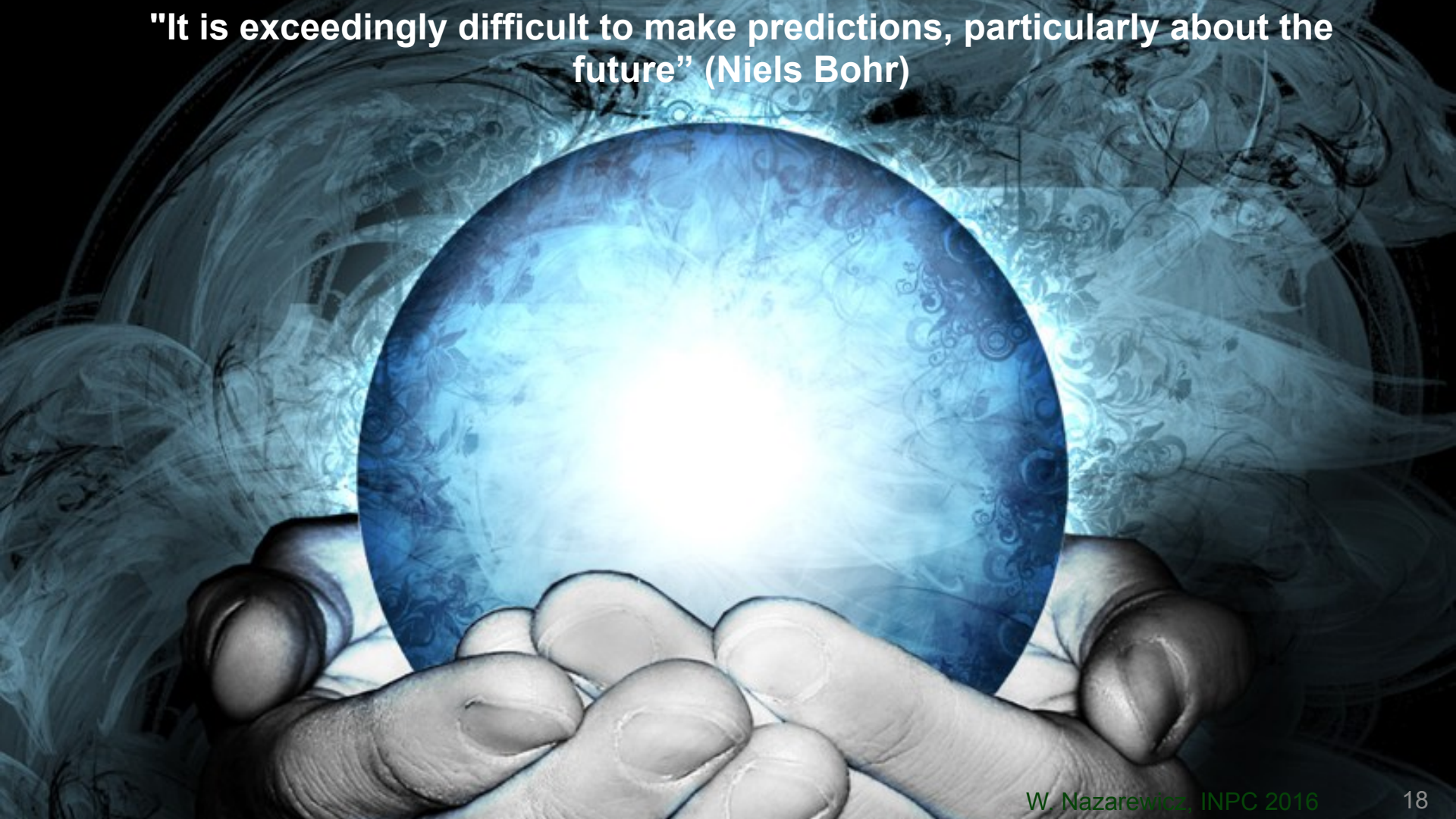
PROSPECT

Uncertainty quantification

Getting critical measurements

The Future

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



Some Anticipated NS&R Greatest Science Hits: by the 28th INPC

- Accessing the neutron drip line up to Mg to test models of nuclear binding with a strong focus on long isotopic chains, in particular Z=8 [illegible]. The existence (non-existence) of ^{28}O will be confirmed. Data on very neutr[illegible]test ab-initio, DFT, and reaction models, and help quantifying u[illegible].

- We will make first direct ch[illegible]mical characterization of superheavy elements with[illegible] will be discovered.

- Significant regions of the[illegible] first time for mass and decay-property measure[illegible]n to test many critical aspects of r-process mod[illegible].

- We will improve limits on [illegible]nd three-nucleon forces from measurement of the size of [illegible] and electric dipole polarizability in neutron-rich n[illegible].

- We will compute nuclear matrix elem[illegible]cay in complex nuclei and quantify theoretical uncertainties.

Some Anticipated NS&R Greatest Science Hits: by the 30th INPC

- Delineation of the neutron drip line up to Zr (A=120) to test models of nuclear binding. Key isotopic chains will be measured from pr[illegible]line to neutron drip-line
- Neutron pairing will be explored [illegible] nuclei with extreme neutron skins.
- We will know whether there [illegible] g-lived superheavy nuclei.
- Key regions of the r-proce[illegible] r mass and decay-property measurements. In particu[illegible] nd ^{78}Ni, ^{132}Sn, and in the region of N=126.
- A new region of nuclear t[illegible] on drip-line, will become accessible up to ^{100}Sn. Ne[illegible] perallowed Gamow-Teller decays, the role of proton-[illegible] t the nuclear surface.
- Key light-ion fusion reactions, [illegible] will be computed ab-initio. Spectroscopic-quality nuclear ef[illegible] oted in inter-nucleon interactions and optimized to data on nuclei with [illegible] os, ab-initio theories, and neutron star observations − will be developed.

Looking into the crystal ball: the 32nd INPC 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?

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?

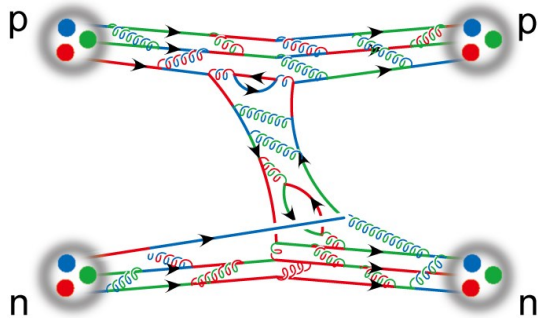
- Energy (fission, reactions, decays…)
- Security (stewardship, forensics, detection…)
- Isotopes (medicine, industry, defense, applied research…)
- Industry (radiation, ion implantation…)

THE FUTURE IS EXCITING

Backup

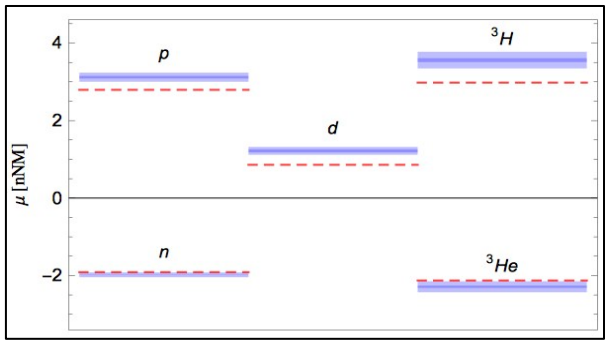
Rooting nuclei in QCD

Detmold



Nuclear force/phase shifts from lattice QCD

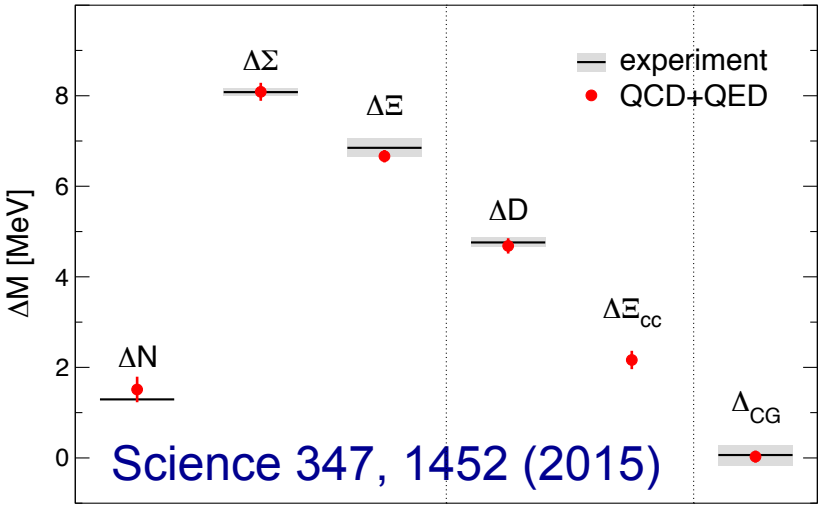
PRL 111, 112503 (2013); PRD 93, 114511 (2016)



LQCD predictions for magnetic moments A<4

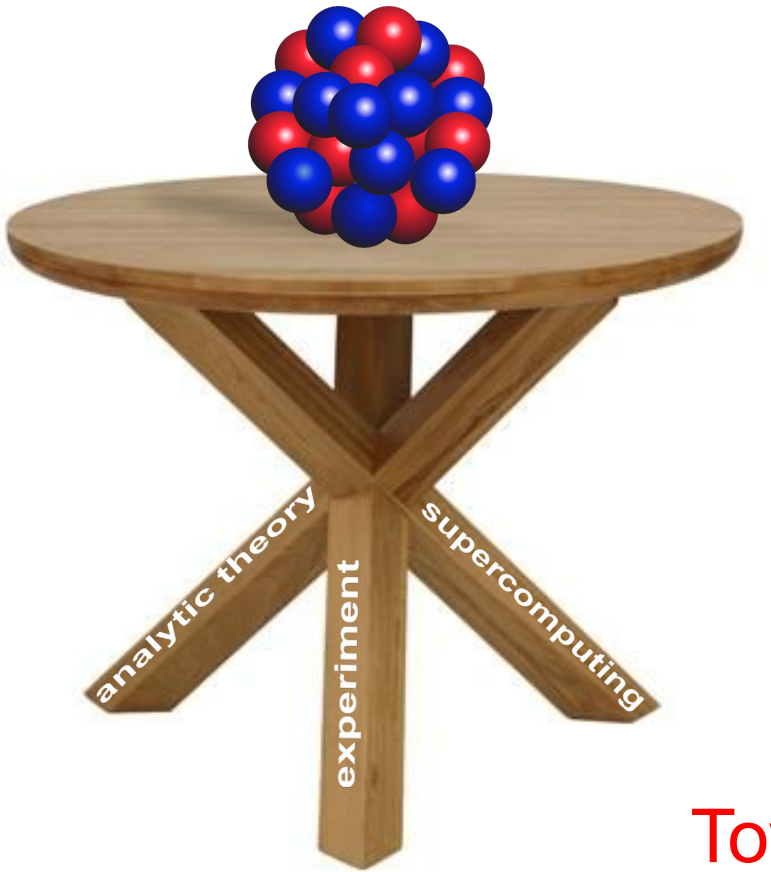
PRL113, 252001 (2014)

n-p mass difference from LQCD



"The neutron–proton mass difference, one of the most consequential parameters of physics, has now been calculated from fundamental theories. This landmark calculation portends revolutionary progress in nuclear physics." Wilczek, Nature 520, 303 (2015)

High Performance Computing and Nuclear Theory: Towards the Exascale

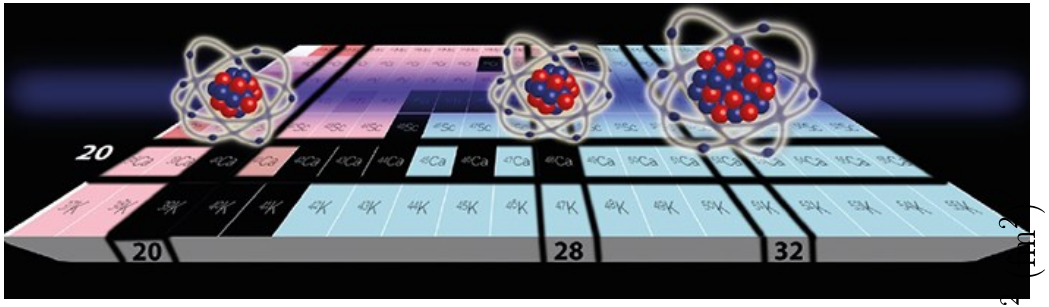


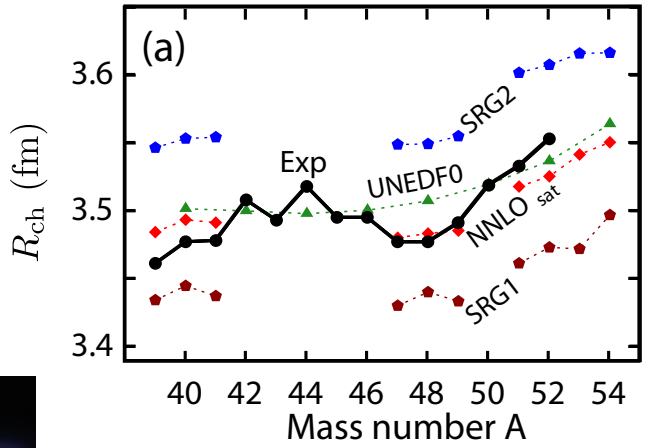
"High performance computing provides answers to questions that neither experiment nor analytic theory can address; hence, *it becomes a third leg supporting the field of nuclear physics*." (NAS Decadal Study Report)

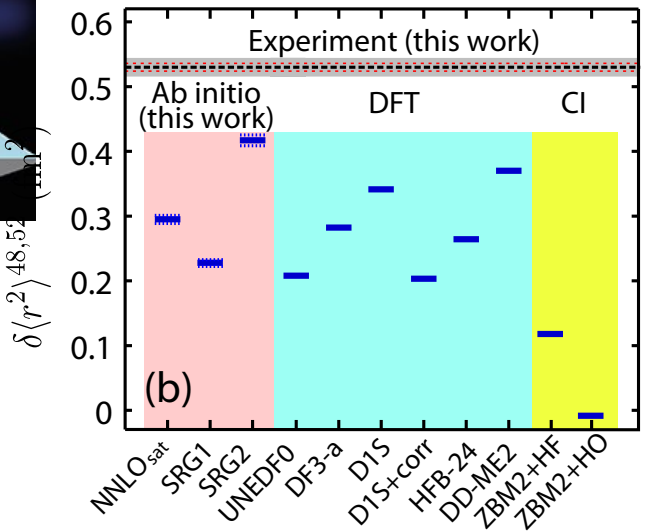
Towards predictive capability...

The frontier: calcium isotopes

Unexpectedly large charge radii of neutron-rich calcium isotopes
Nature Physics **12**, 594 (2016)

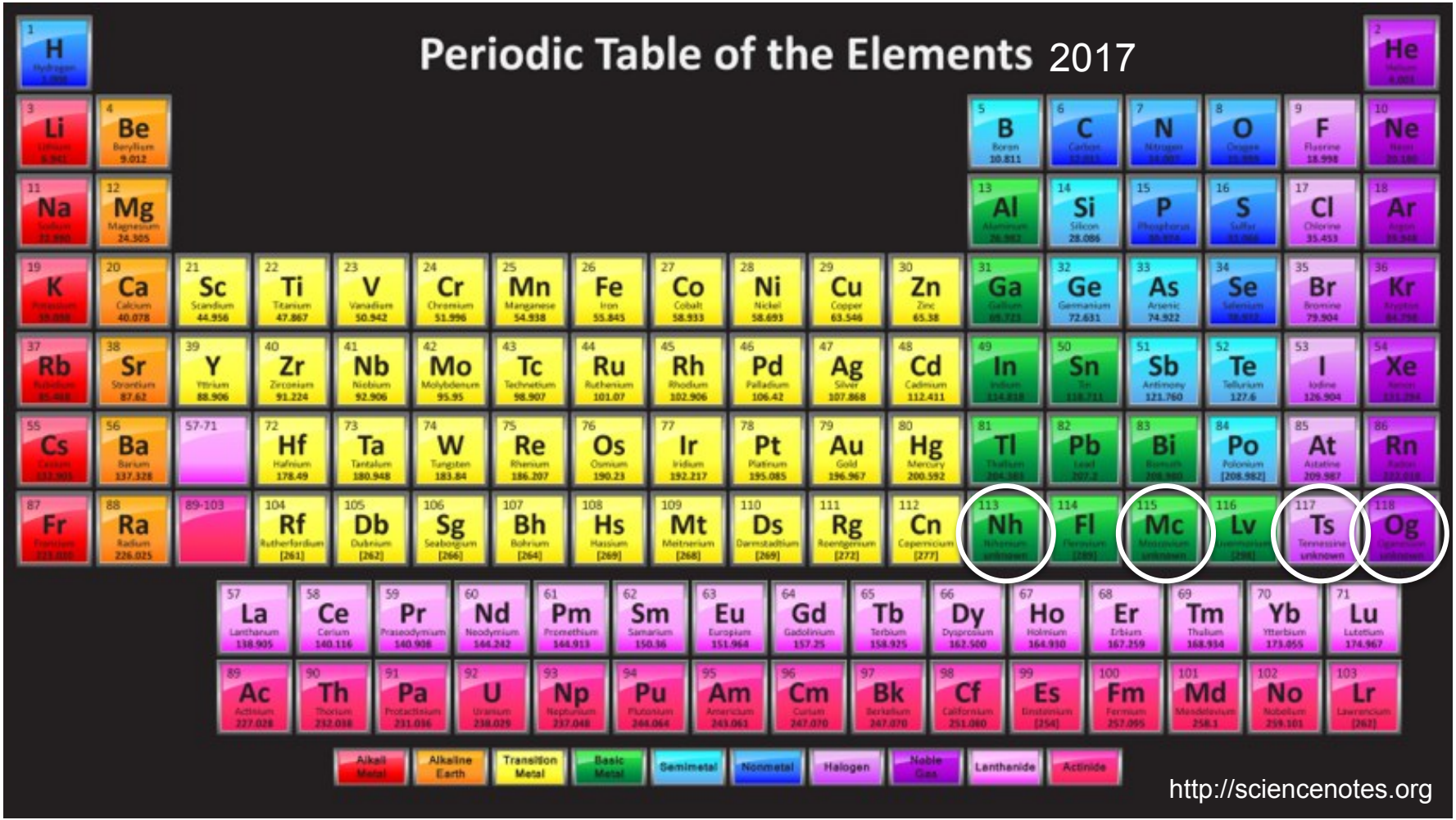






PROSPECT

Linking *ab-initio* with DFT

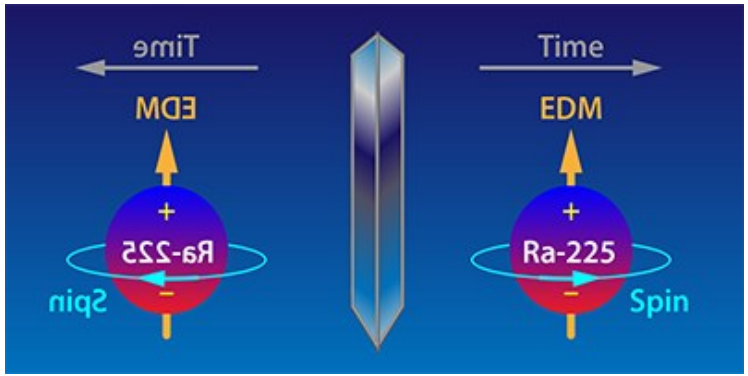

Periodic Table of the Elements 2017
http://sciencenotes.org

How can nuclei be exploited to reveal the fundamental symmetries of nature?

Atomic electric dipole moment: the violation of CP-symmetry is responsible for the fact that the Universe is dominated by matter over anti-matter

- Closely spaced parity doublet gives rise to enhanced electric dipole moment
- Large intrinsic Schiff moment
  - ^{199}Hg (Seattle, 1980's – present)
  - ^{225}Ra (ANL, KVI)
    PRL 114, 233002 (2015) d<5x10^{-22} e cm
  - ^{223}Rn at TRIUMF (E929)
  - FRIB
    - ^{238}U beam, beam dump recovery: ^{225}Ra: 6x10^{9}/s, ^{223}Rn: 8x10^{7}/s
    - ^{232}Th beam: ^{225}Ra: 5x10^{10}/s, ^{223}Rn: 1x10^{9}/s
    - 10^{12}/s w ISOL target FRIB upgrade

PROSPECT



PROSPECT

Precision calculations of nuclear matrix elements based on accurate models of nuclear interactions and currents (EDM, $0\nu\beta\beta$)

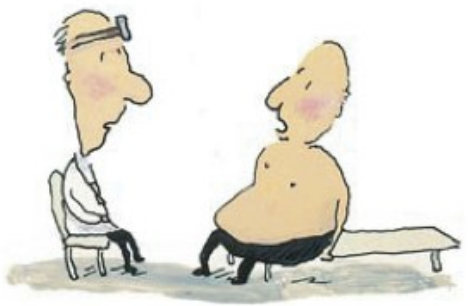
Weinberg's Laws of Progress in Theoretical Physics

From: "Asymptotic Realms of Physics" (ed. by Guth, Huang, Jaffe, MIT Press, 1983)

First Law: "The conservation of Information" (*You will get nowhere by churning equations*)

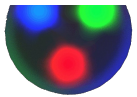
Second Law: "Do not trust arguments based on the lowest order of perturbation theory"

Third Law: "You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you'll be sorry!"



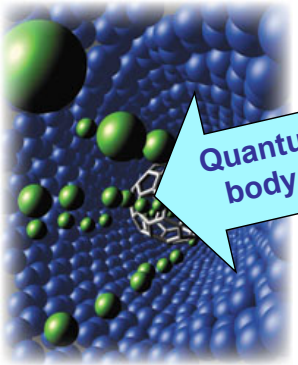
Patient: Doctor, doctor, it hurts when I do this!
Doctor: Then don't do that.

Profound intersections



QCD

Complex Systems



Quantum many-body physics

Physics of Nuclei

Nuclei in the Universe

Cosmos

Fundamental interactions

- Atomic and Molecular Physics
- Condensed Matter Physics
- Materials Science
- Quantum Chemistry

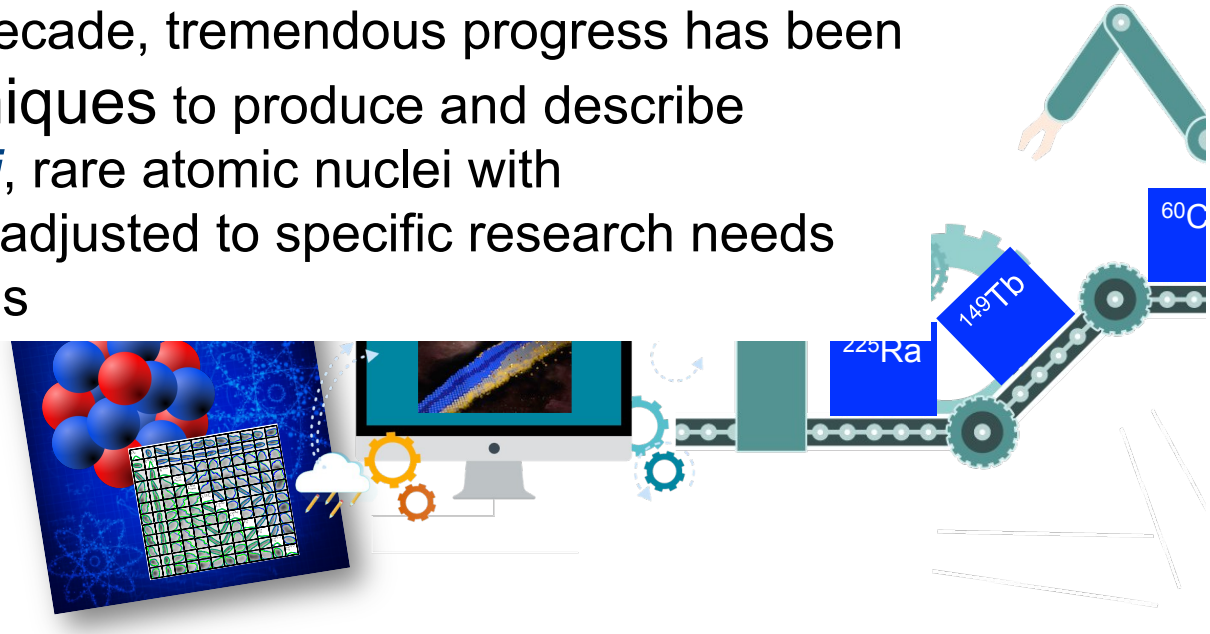
- Particle Physics
- Cosmology

- Astrophysics
- Cosmology
- Astronomy
- Gravitation

J. Phys. G 43, 044002 (2016)

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



CONCEPT PREDICTION FABRICATION

J. Phys. G 43, 044002 (2016)