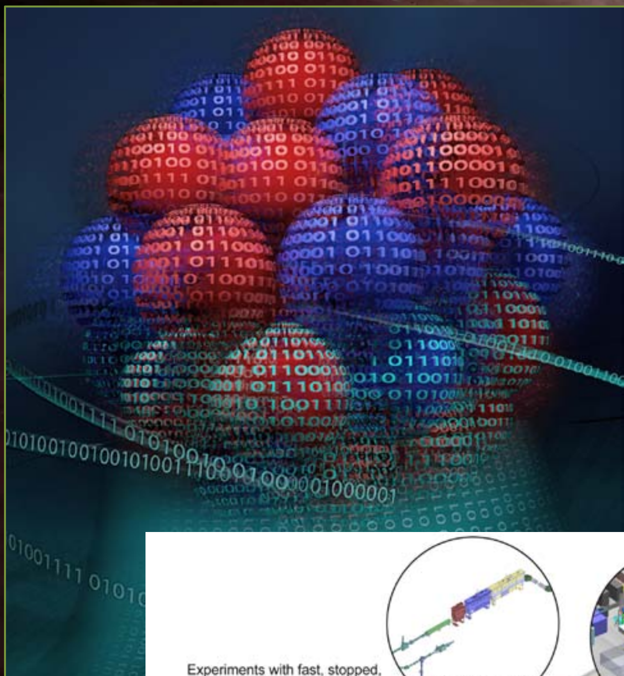
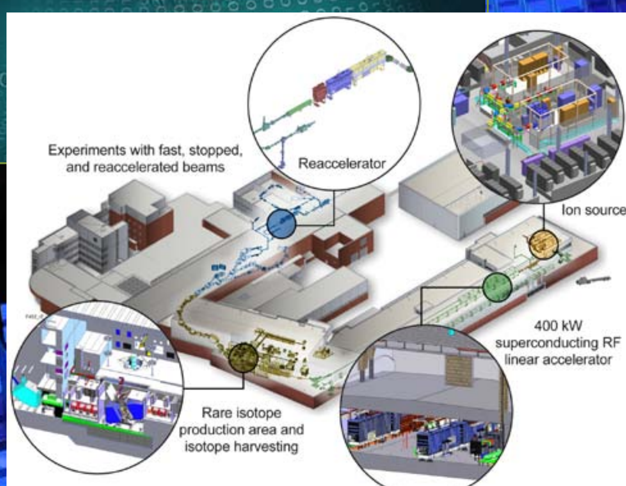
Science of Facility for Rare Isotope Beams (FRIB): Overarching Questions (a theoretical perspective)

Witold Nazarewicz (FRIB/MSU)

KITP program - "Frontiers in Nuclear Physics” 2016





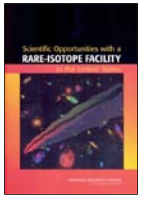
Menu

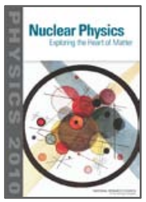
- Questions
- Generalities
- Prospects

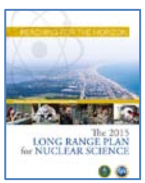
PROSPECT

a personal view…

FRIB Science Drivers







Science drivers (thrusts) from NRC RISAC 2007

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes

Intellectual challenges from NRC Decadal Study 2013

How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interac-tions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

Overarching questions from NSAC Long Range Plan 2015

How are nuclei made and organized? What is the nature of dense nuclear matter?	Where do nuclei and elements come from? What combinations of neutrons and protons can form a bound atomic nucleus? How do neutrinos affect element synthesis?	Are neutrinos their own antiparticles? Why is there more matter than antimatter in the present universe?	What are practical and scientific uses of nuclei?

Overarching questions are answered by rare isotope research

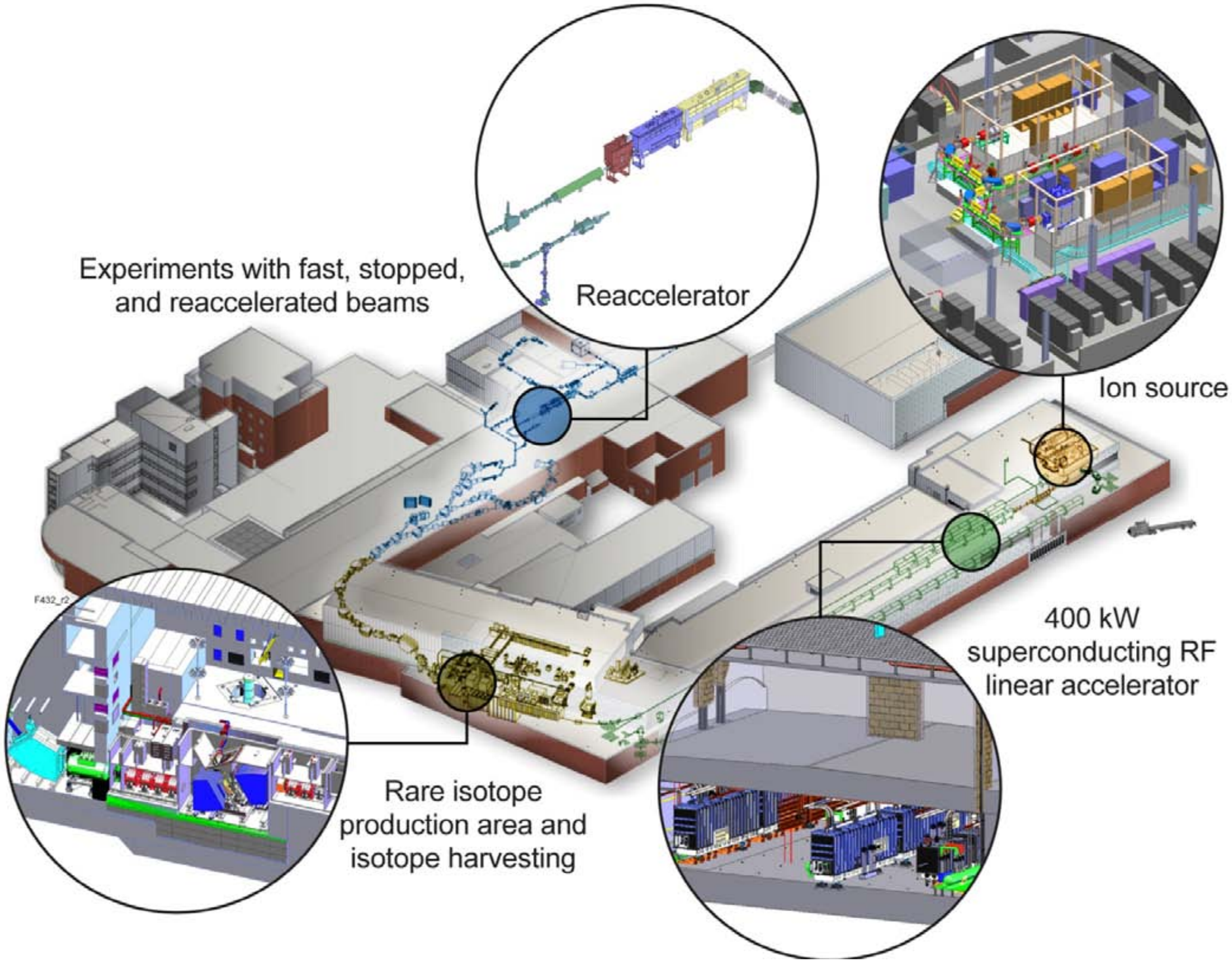
FRIB Project Summary

- FRIB will be a $730 million national user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project completion date is June 2022, managing to an early completion in fiscal year 2021

NEWS: October 21, 2016

- FRIB construction continues to move ten weeks ahead of schedule
- The Advanced Room-TEMperature Ion Source (ARTEMIS) platform is complete, which enabled ARTEMIS to make its first beam on 14 October.
- On 29 September, the first of 48 cryomodules was installed in FRIB's linear accelerator tunnel.
- The radio frequency quadrupole has been delivered and will take approximately two weeks to assemble.

World's Most Powerful Rare Isotope Research Facility



The Science is in the FRIB Logo

Properties of atomic nuclei

- Develop a predictive model of nuclei and their interactions

Astrophysics: Nuclear processes in the cosmos

- Origin of the elements, chemical history

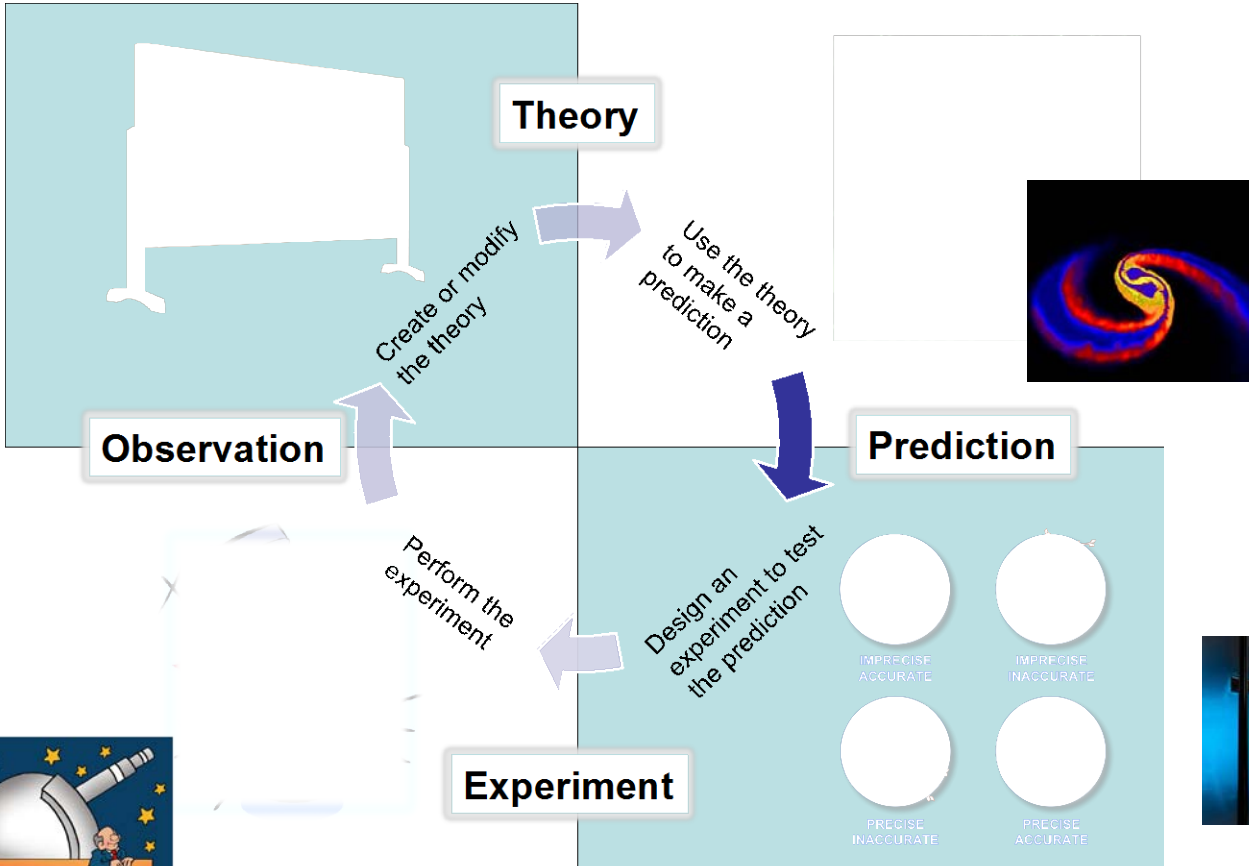
Societal applications and benefits

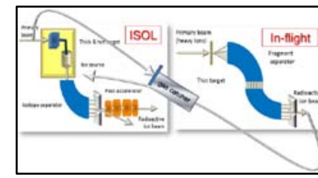
- Medicine, energy, material sciences, national security

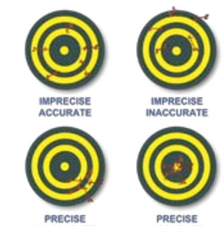
Tests of laws of nature

- Tiny effects amplified in certain nuclei; complementary information to LHC

Guiding principle: the scientific method…





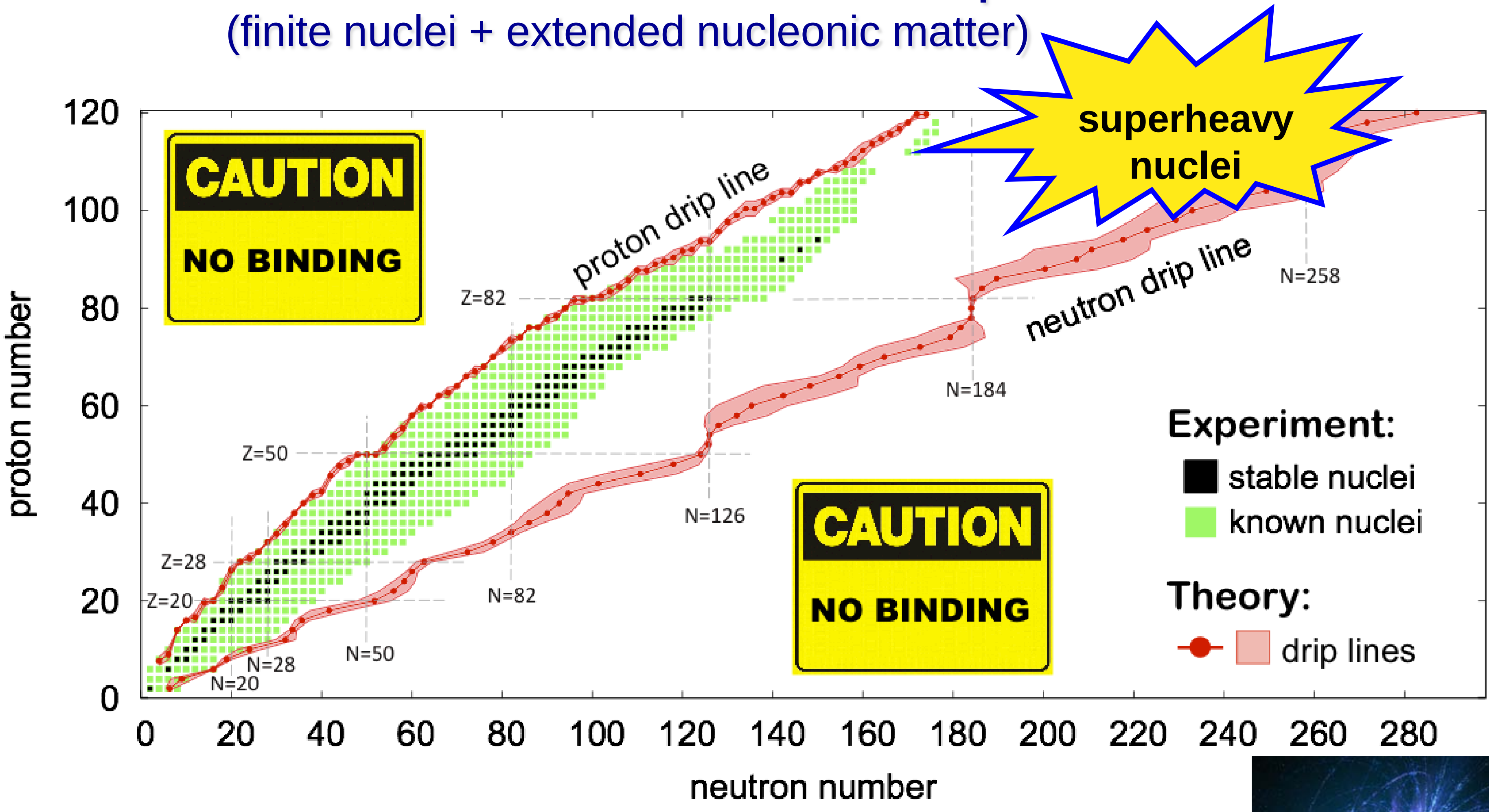


J. Phys. G 43, 044002 (2016)

Optimizing the cycle

The Grand Nuclear Landscape

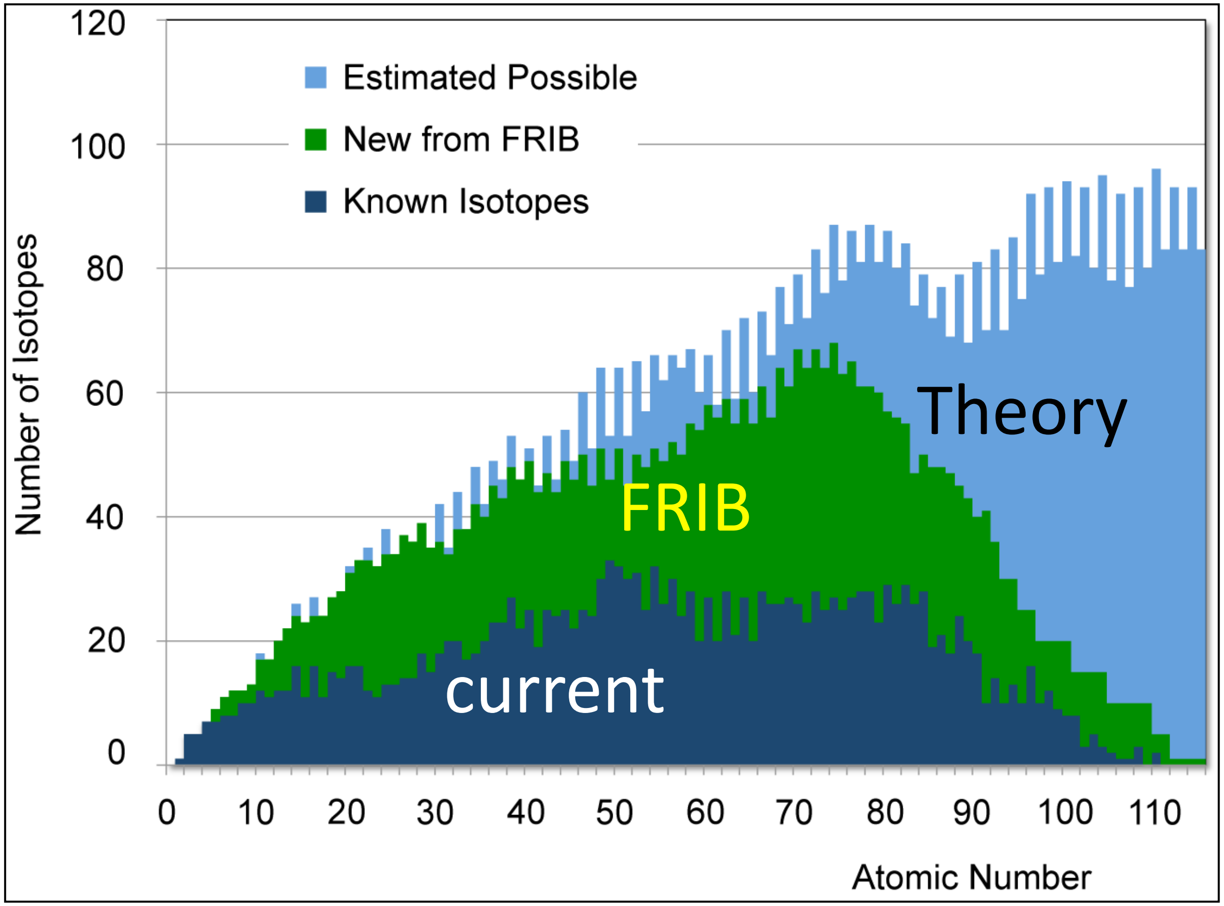
(finite nuclei + extended nucleonic matter)



Nature **486**, 509 (2012)

$N \sim 10^{57}$

What FRIB's power buys you

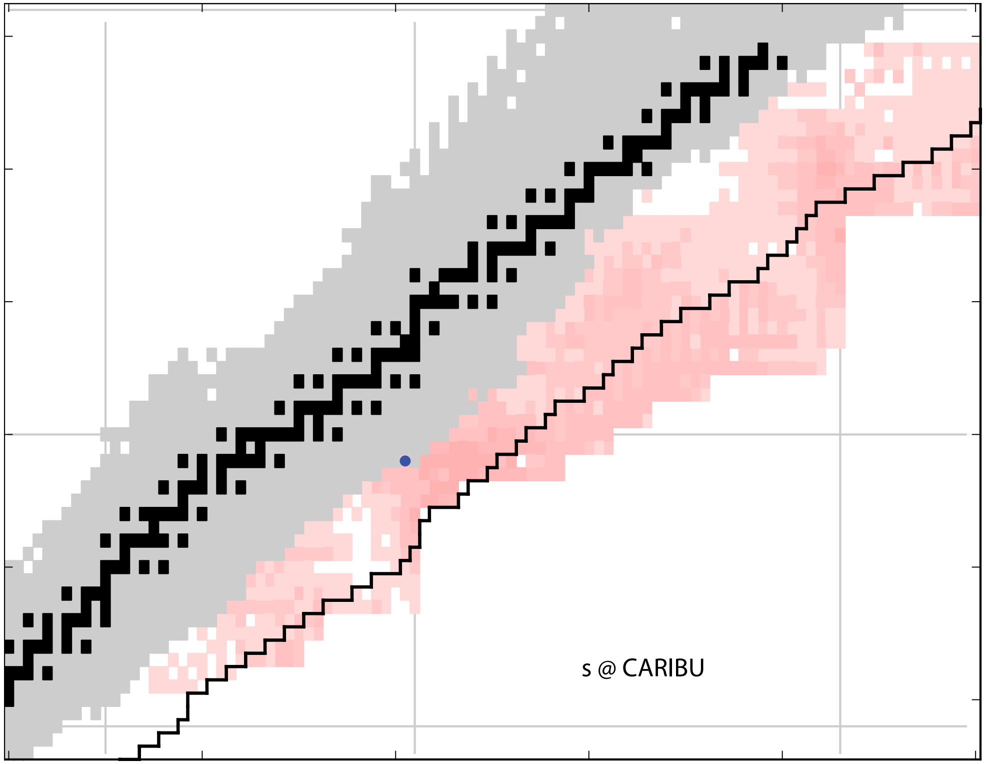


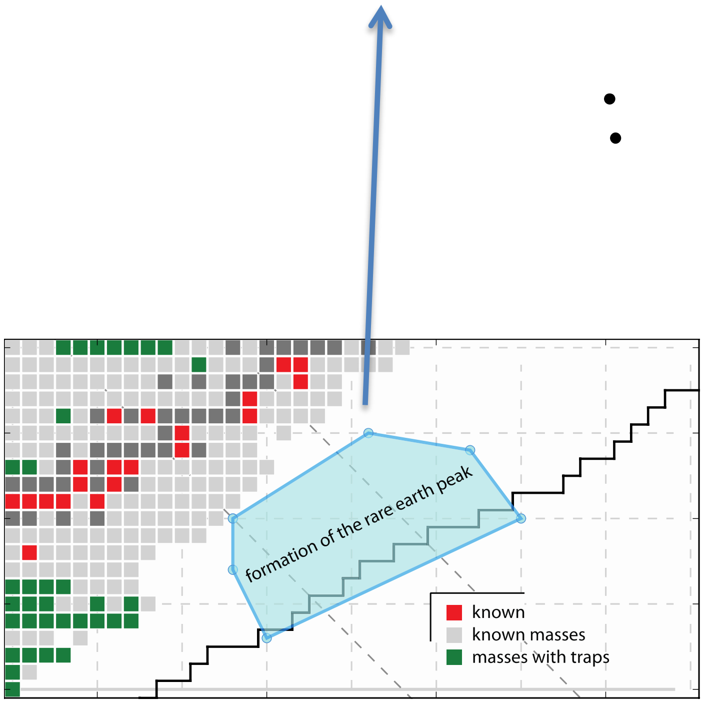
Cross section corresponding to the production of 1 atom/week at FRIB

- FRIB will double the knowledge of known nuclei; it will access 80% of all isotopes predicted to exist for elements below uranium
- FRIB will extend the neutron drip line from *Z=8* (now) to approximately *Z=40*

Reach into the r-process nuclei

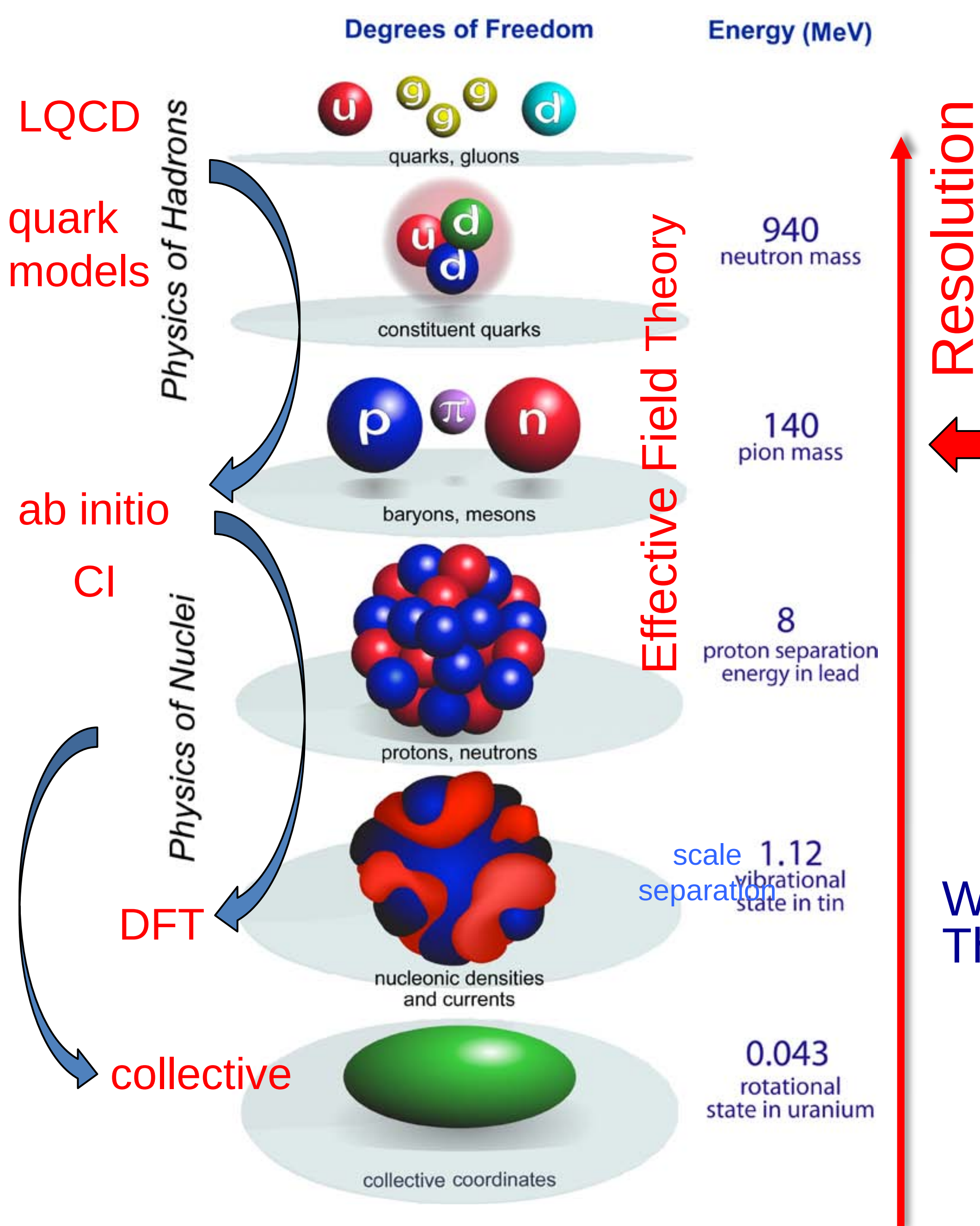
Constraints on the largest number of key observables





Prog. Part. Nucl. Phys. 86, 86 (2016)

How are nuclei made?



Hot and dense quark-gluon matter

Hadron structure

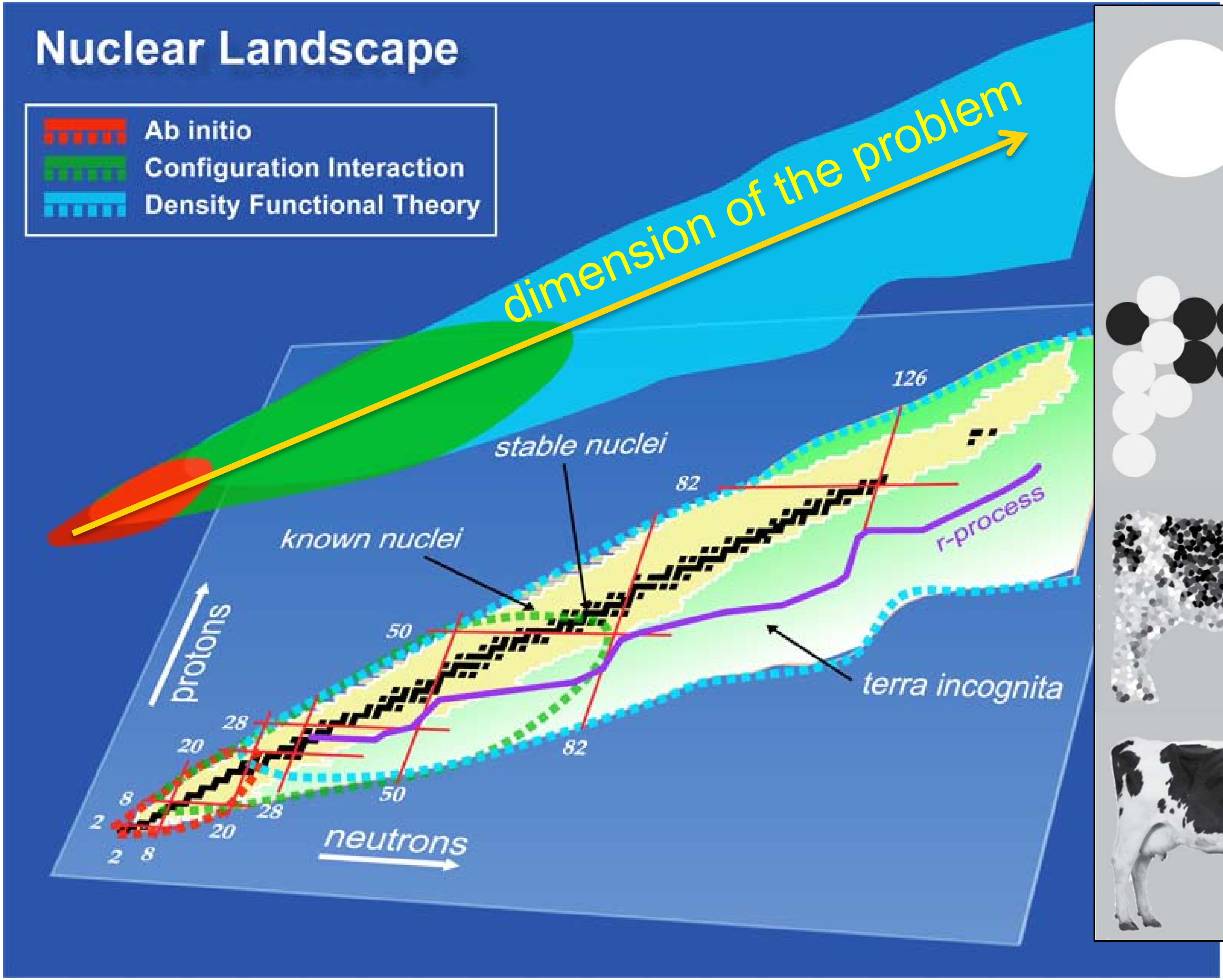
Nuclear-Particle Physics PROSPECT

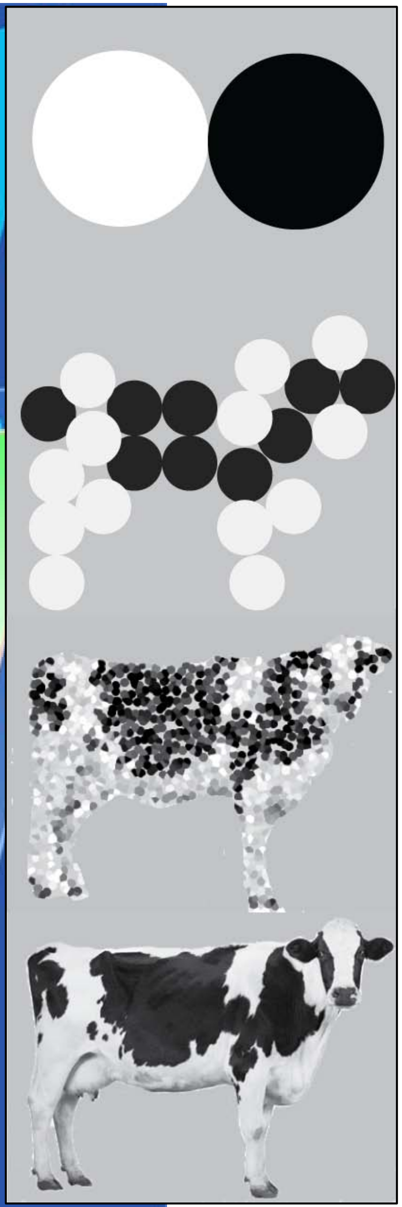
Nuclear structure
Nuclear reactions
New standard model

Weinberg's Third Law of Progress in Theoretical Physics:

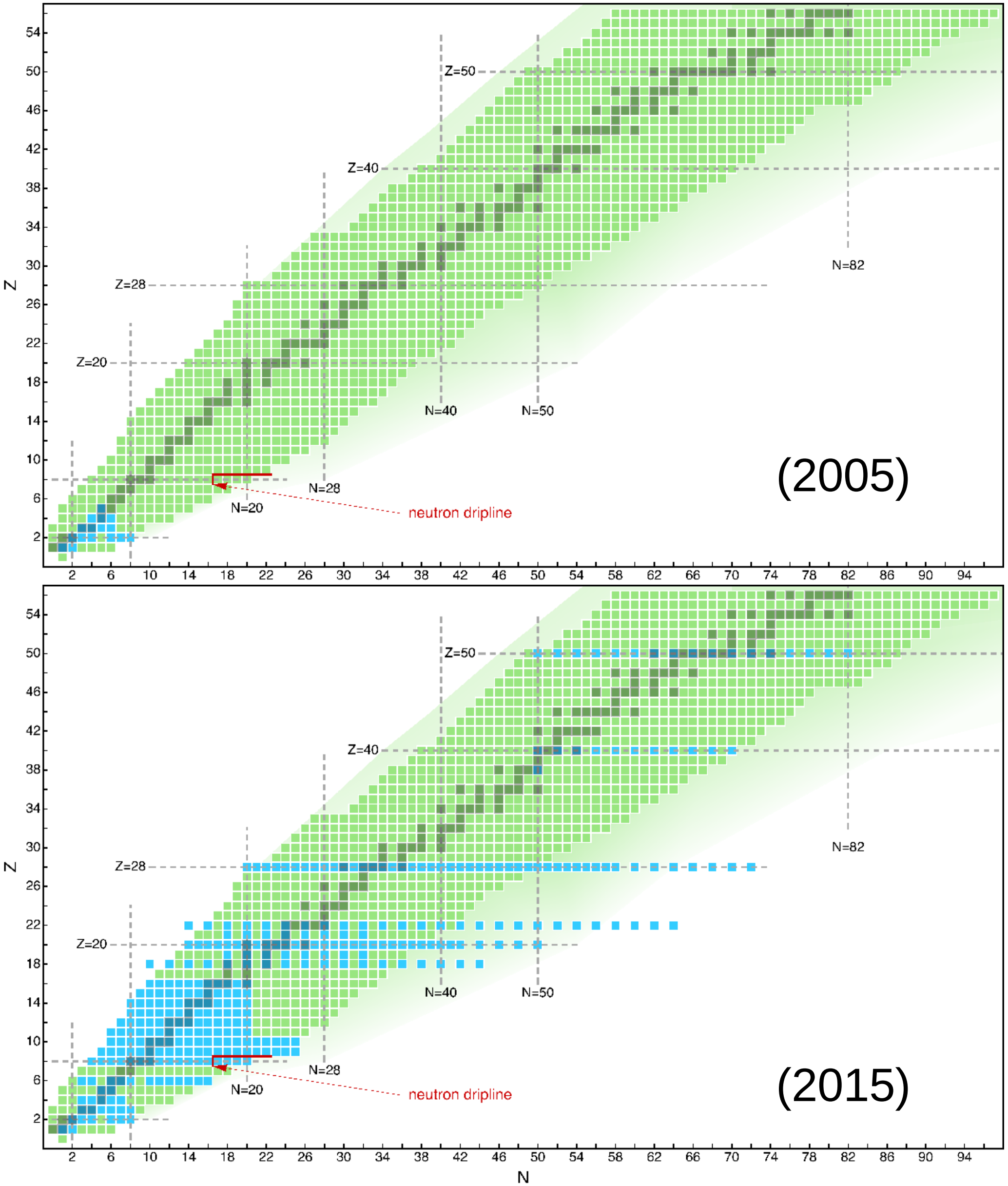
The resolving power of a theoretical model should always be as low as reasonably possible for the question at hand

How to explain the nuclear landscape from the bottom up? **Theory roadmap**





Nuclei from the first principles



Recent news:

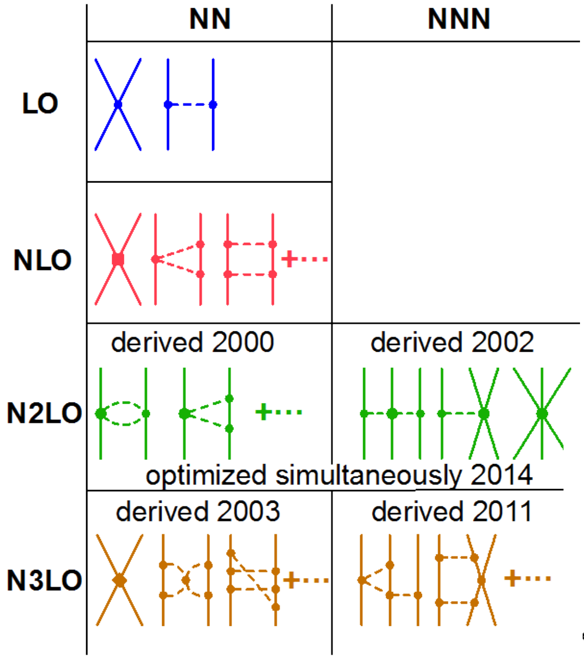
^{100}Sn and ^{208}Pb in ab-initio coupled-cluster

Phys. Rept. 621, 1765 (2016)

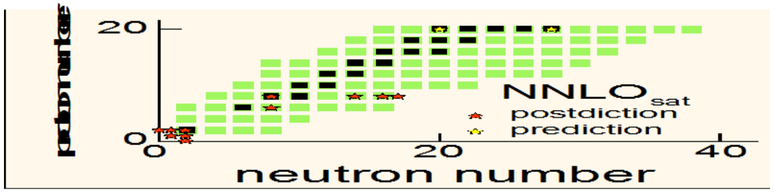
Linking few-body with many-body

Quantified input

Nuclear Forces
from χEFT

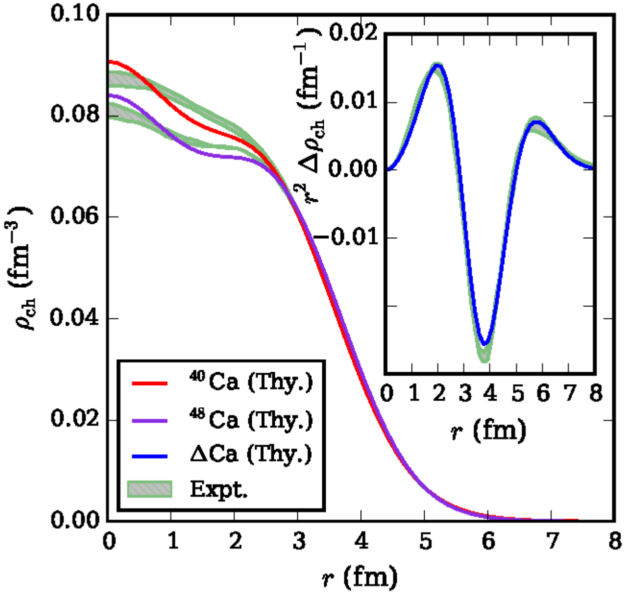


Comprehensive model of light and heavy nuclei



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

Consistency with known data

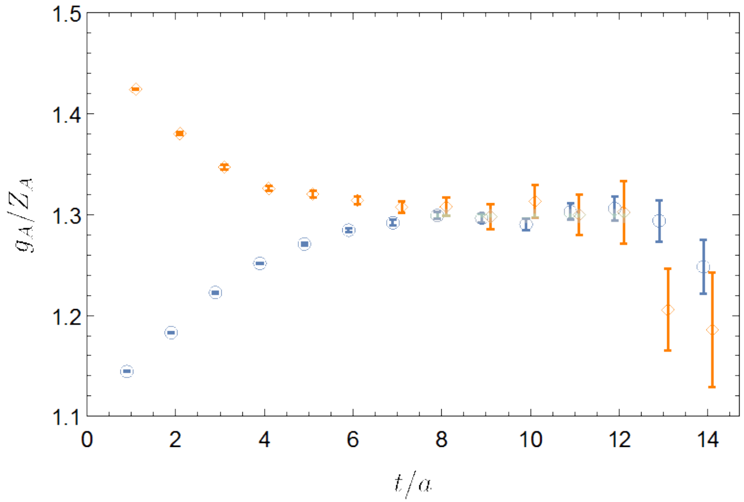


Prediction

NNLO$_{sat}$
SV-min

Two-Nucleon Currents: Moments and Transitions

Axial-current matrix elements in NN and NNN systems from LQCD

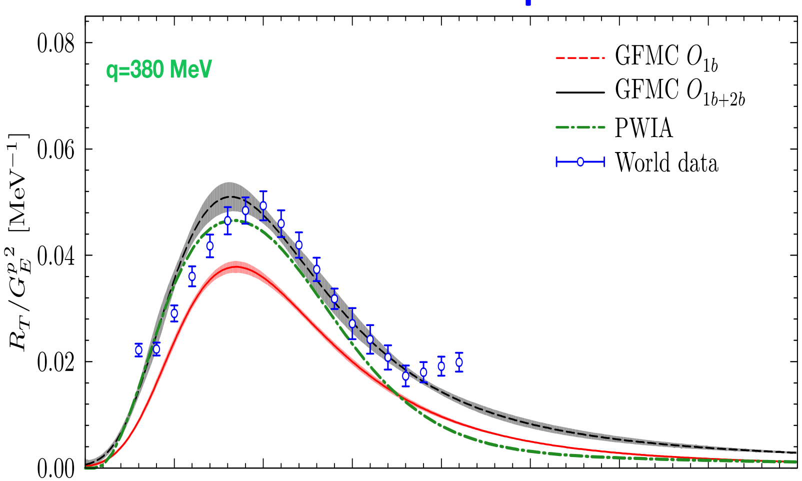


$$pp \rightarrow de^{+}\nu$$

and tritium beta decay

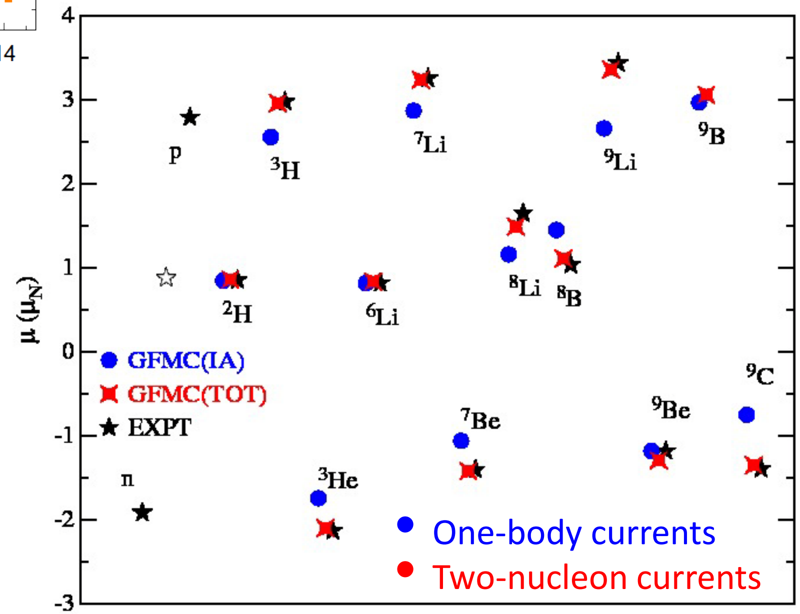
arXiv:1610.04545

Neutrino Response



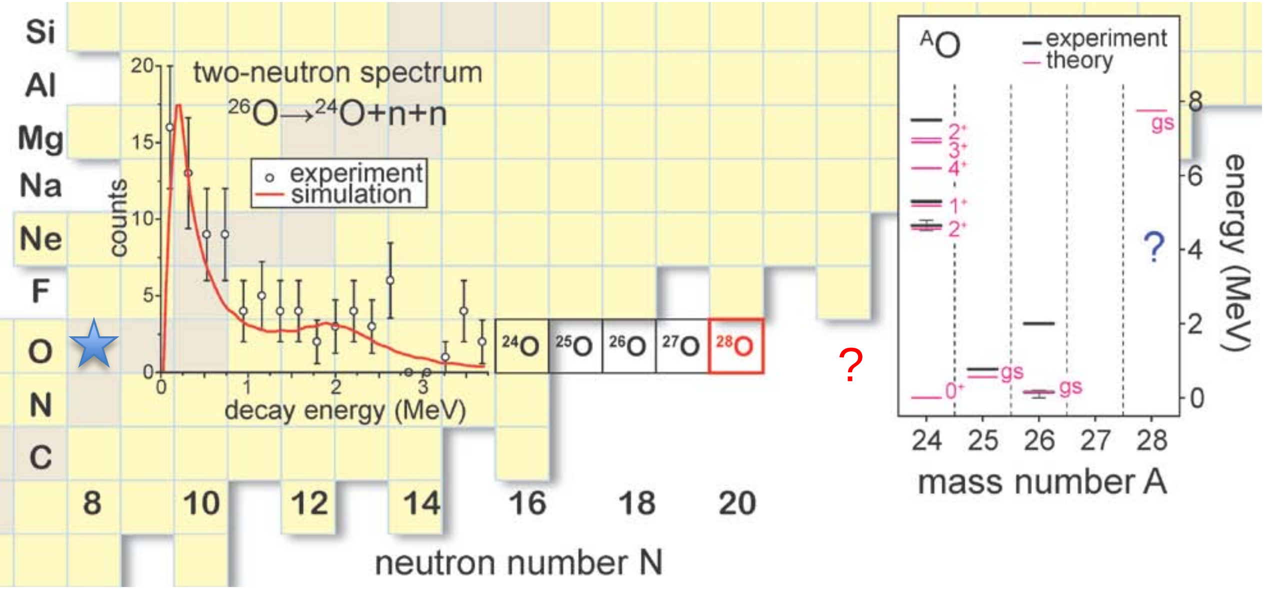
Phys. Rev. Lett. **117**, 082501 (2016)

Magnetic Moments

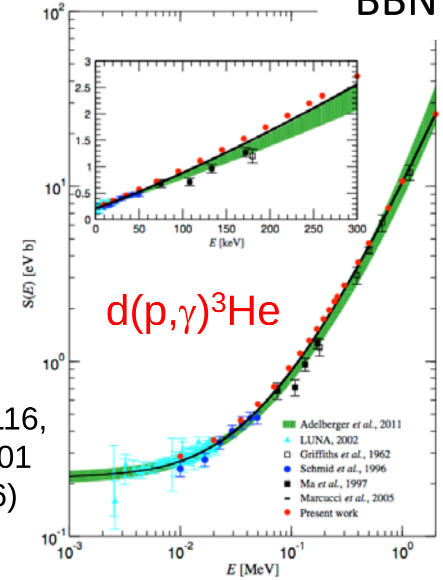


Phys. Rev. C 87, 035503 (2013)

Revision of nuclear structure textbook knowledge



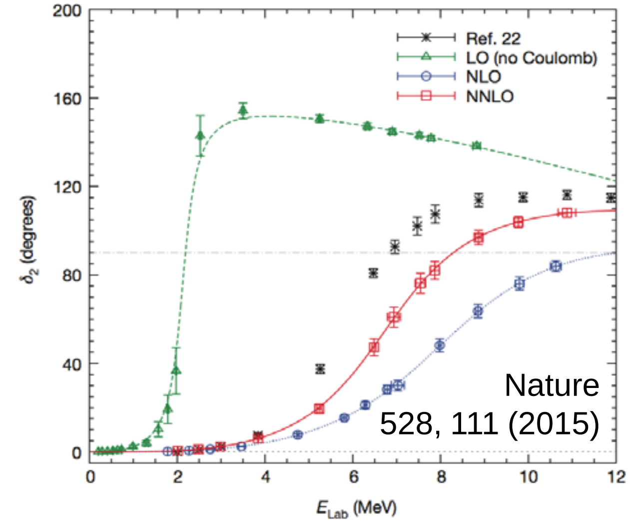
BBN



PRL116, 102501 (2016)

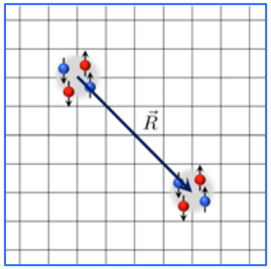
- $^{24,25,26}O$: open quantum systems
- A dineutron in ^{26}O? The lifetime could be as large as 10^{-12} s.
- Is (doubly-magic) ^{28}O unbound? If so, how much?

alpha-alpha scattering in LEFT

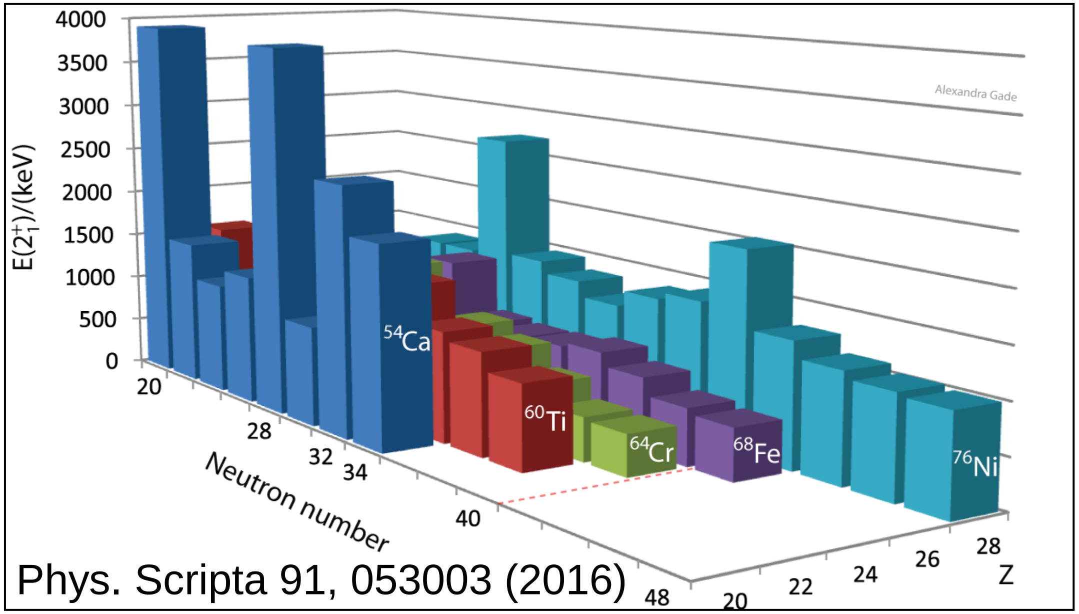


PROSPECT

Unification of structure and reactions

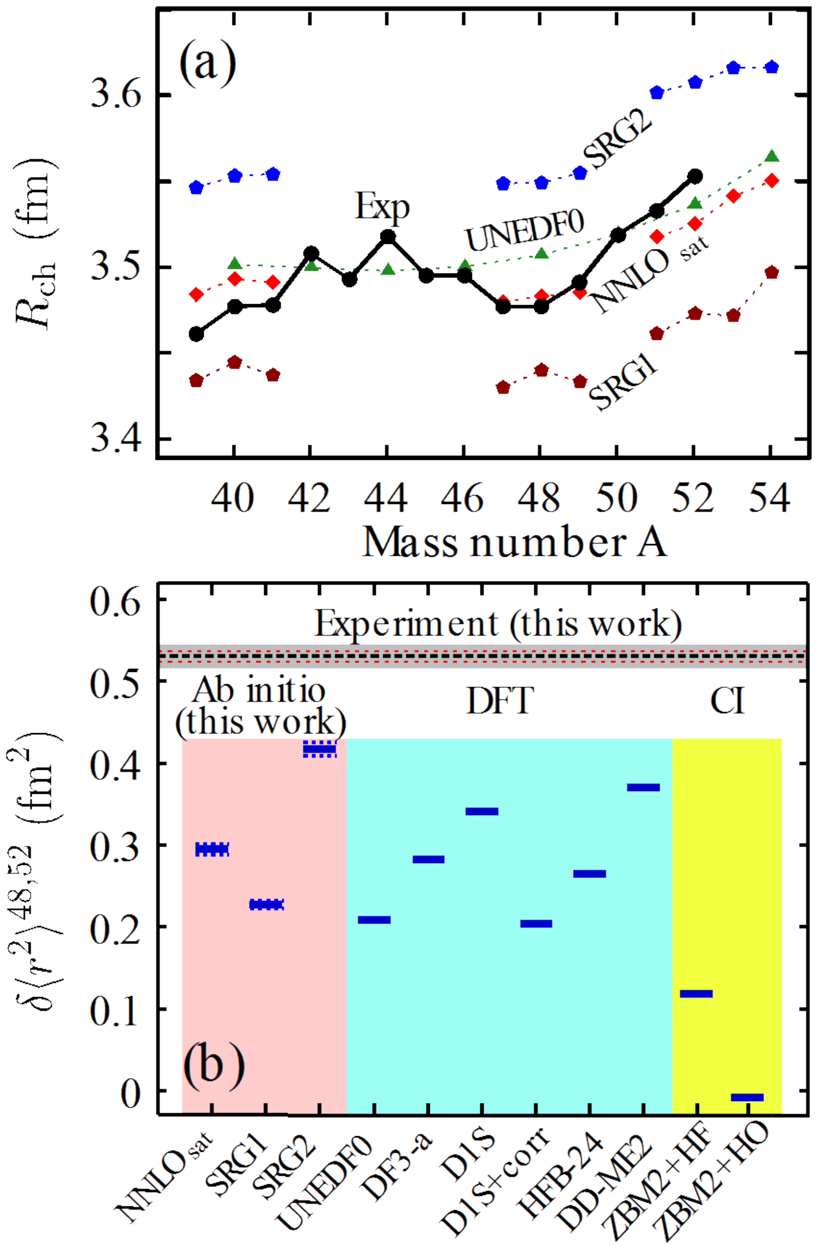


The frontier: calcium isotopes (where *ab-initio* and DFT meet)



Phys. Scripta 91, 053003 (2016)

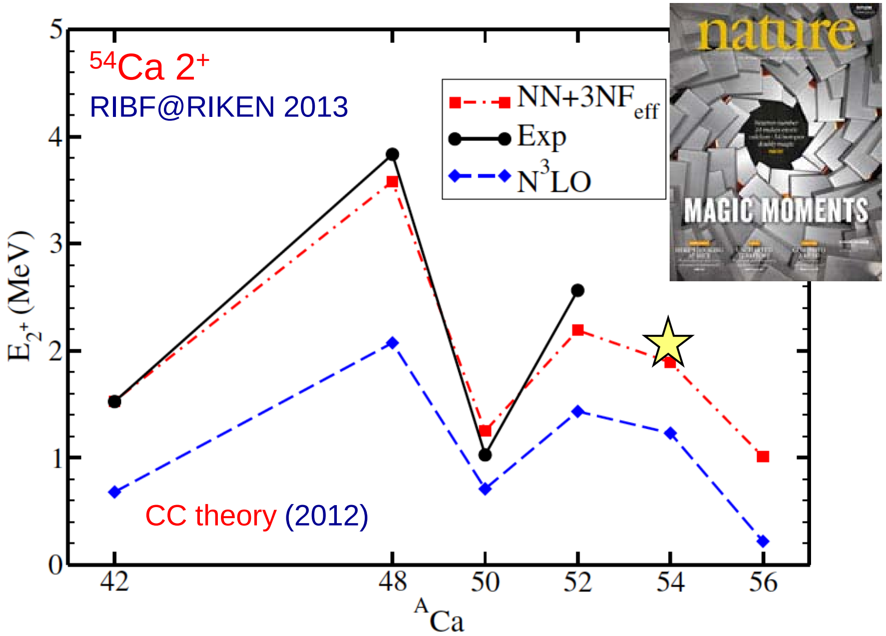
Nature Physics 12, 594 (2016)

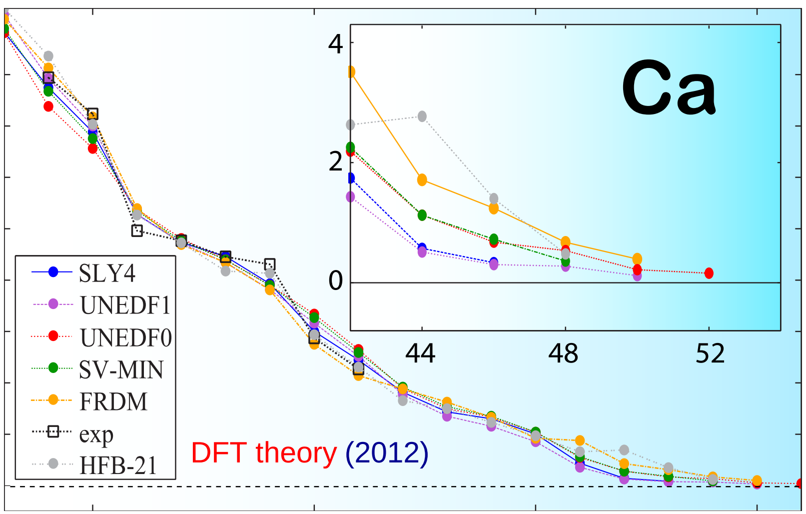


New shell closures at N = 32 & 34?

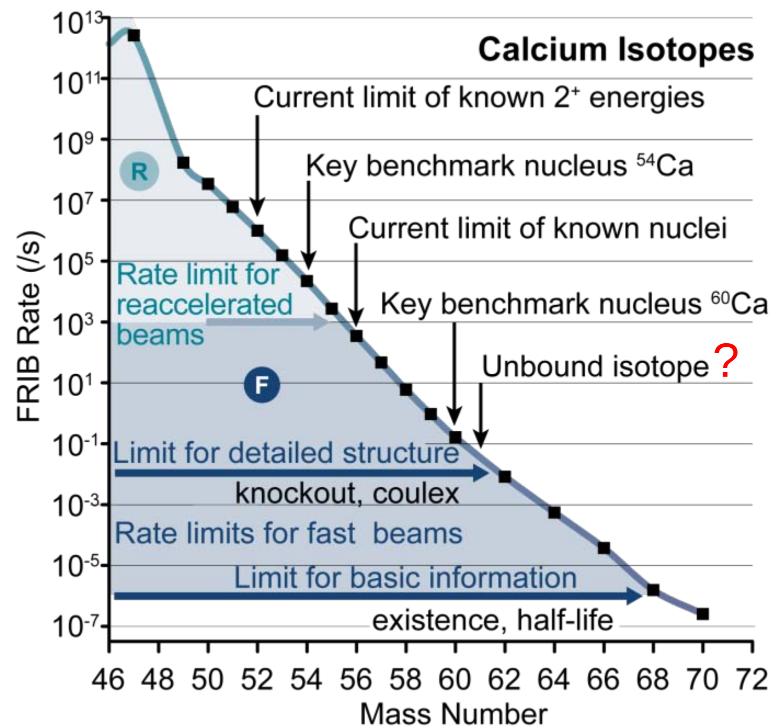
PROSPECT

Developing new nuclear paradigms





FRIB provides access to key neutron-rich Ca isotopes with intensities sufficient to measure crucial observables (masses, half-lives, decay properties, excitations…). It will be the only facility with ^{60}Ca yields above 0.01/s. FRIB will reach ^{64}Ca.

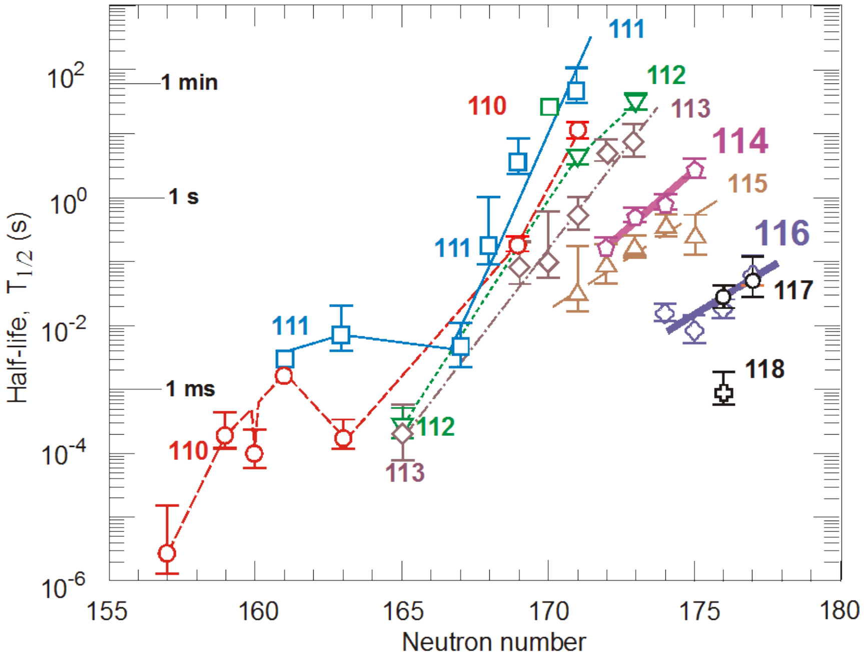


What are the limits of atoms and nuclei?

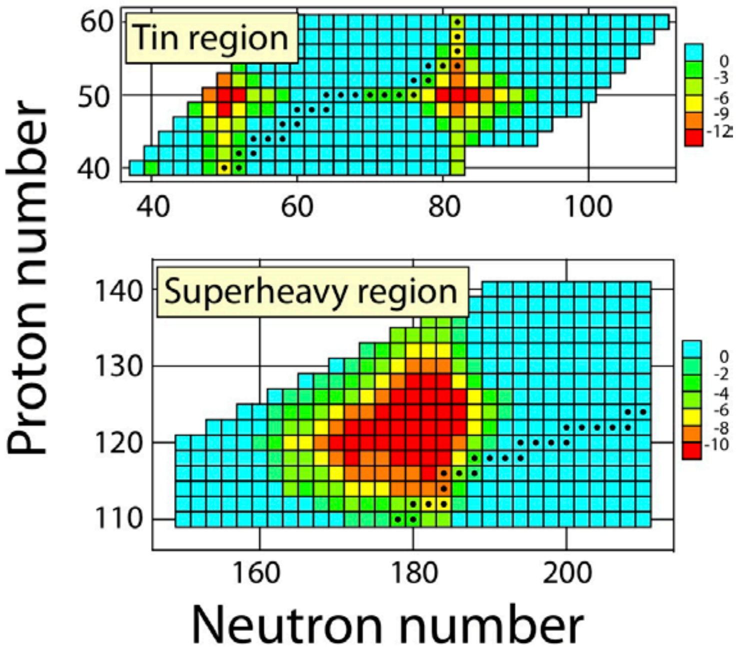
Structure of nuclei at the limit of mass and charge (Coulomb frustration)
Cosmic origin of superheavy nuclei?
Very relativistic atoms with $Z\alpha \rightarrow 1$

- Around 30 new superheavy isotopes found since 2007
- Z=114 (Fl) and 116 (Lv) named in 2012
- Z=117, 115, 113 confirmed; new names proposed
  Nh (113), Mc (115), Ts (117), Og (118)
- Unique spectroscopic data above Z>102
- Chemistry of Z=106, 112, 114

IUPAC: Discovery of a chemical element is the experimental demonstration, beyond reasonable doubt, of the existence of a nuclide with an atomic number *Z* not identified before, existing for at least 10^{-14} s

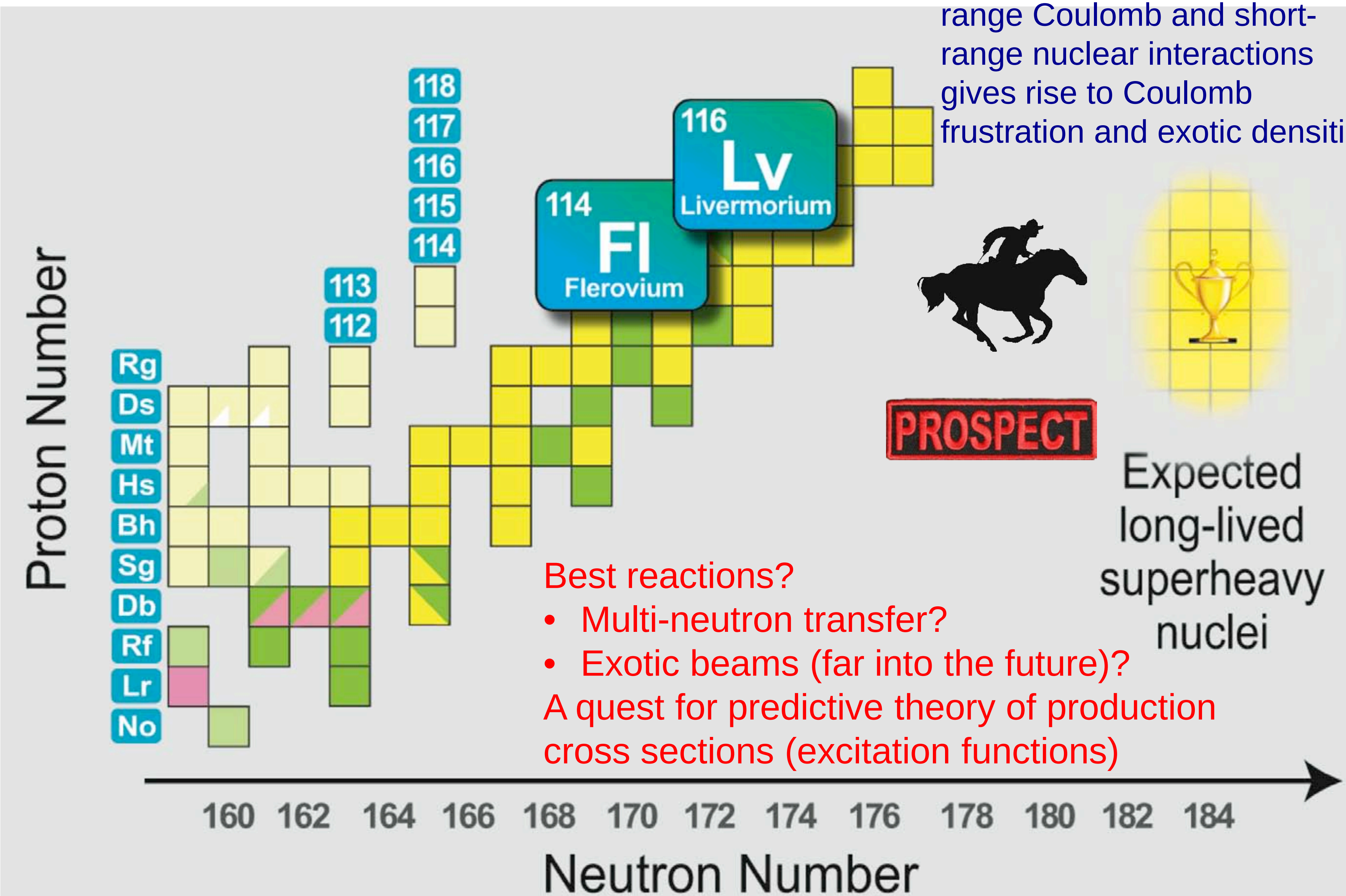


Shell energy



What are the limits of atoms and nuclei?

A competition between long-range Coulomb and short-range nuclear interactions gives rise to Coulomb frustration and exotic densities



Best reactions?

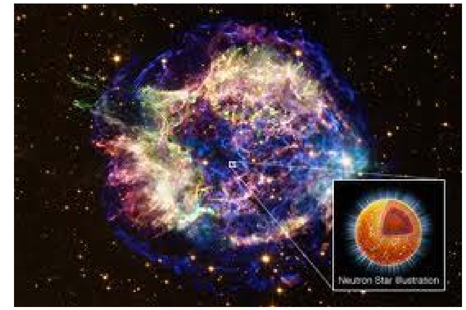
- Multi-neutron transfer?
- Exotic beams (far into the future)?

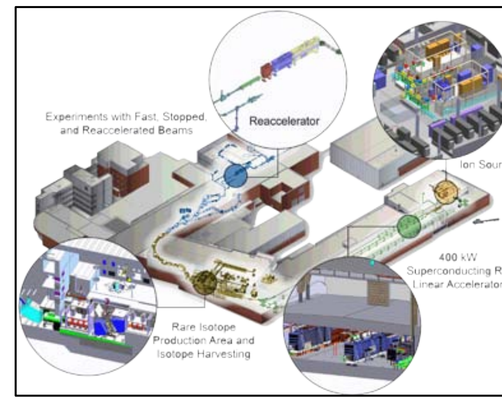
A quest for predictive theory of production cross sections (excitation functions)

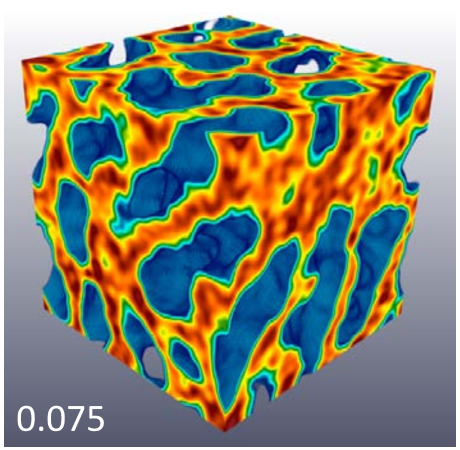
On Earth and in the Cosmos

Crustal structures in neutron stars

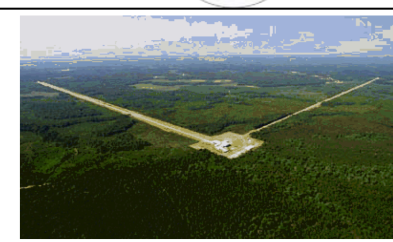
Data





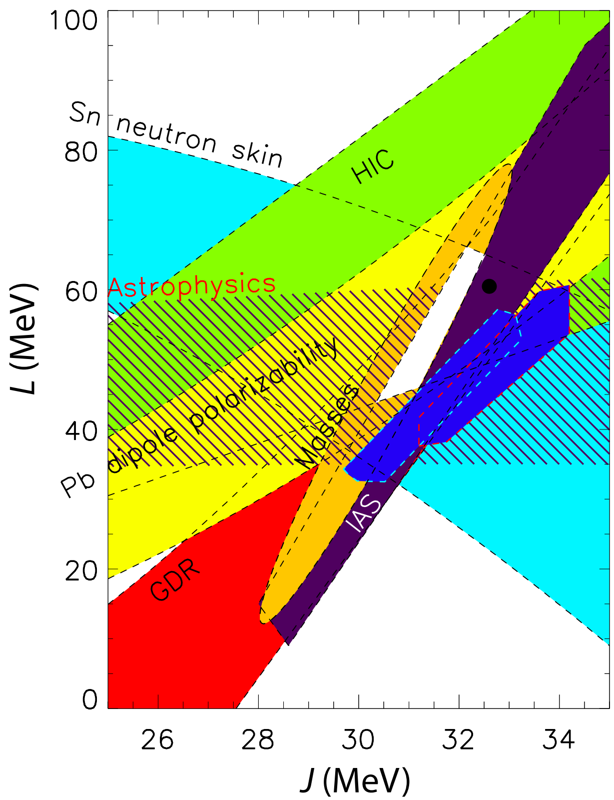


10^{-17} km

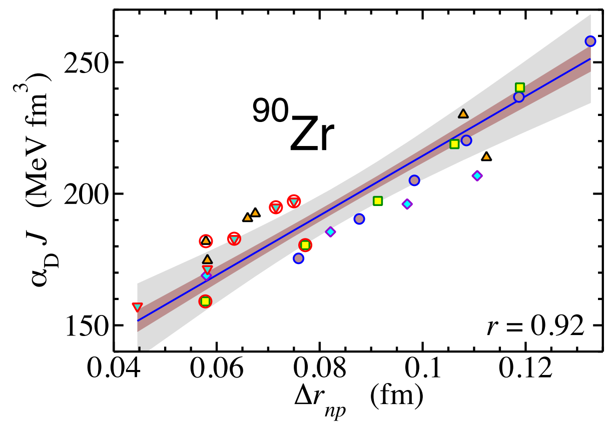


12 km

Only facility to allow study of extreme >0.5fm neutron skins
Will probe EOS with fast beams at the extremes of isospin



Lattimer & Lim 2013



Roca-Maza *et al*. 2015

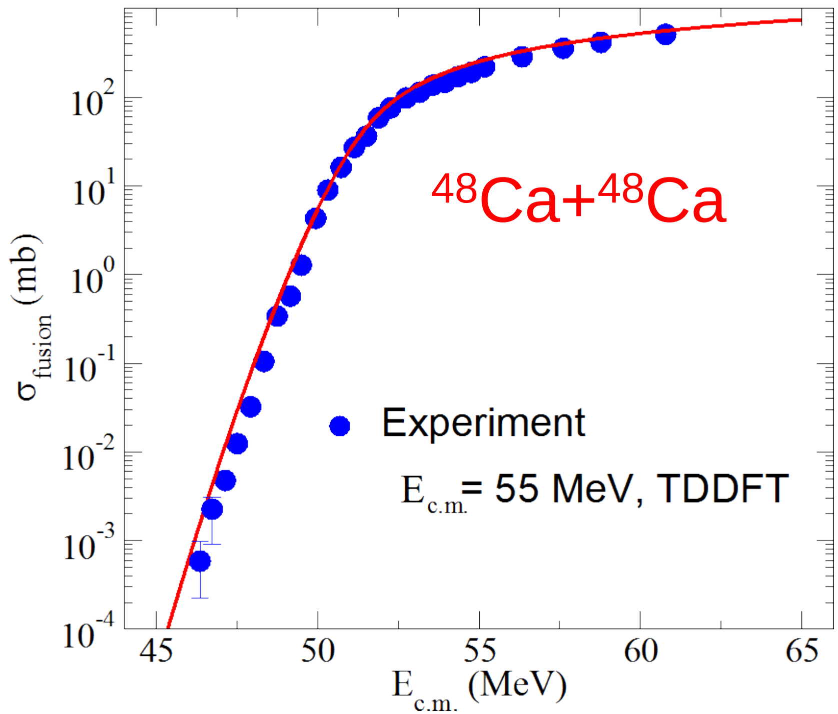
Large Amplitude Collective Motion

exceedingly difficult, many fundamental questions remain unsettled

PRC 94, 024605 (2016)

- Fusion
- Fission
- Coexistence phenomena

Fusion cross sections



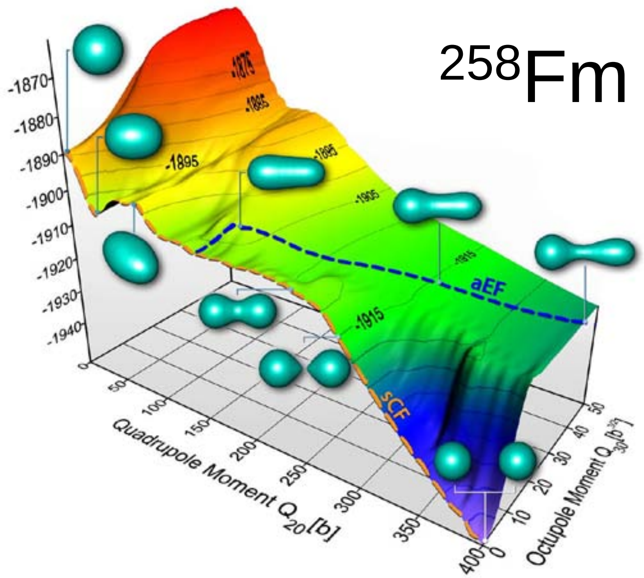
PRC 85, 044606 (2012)

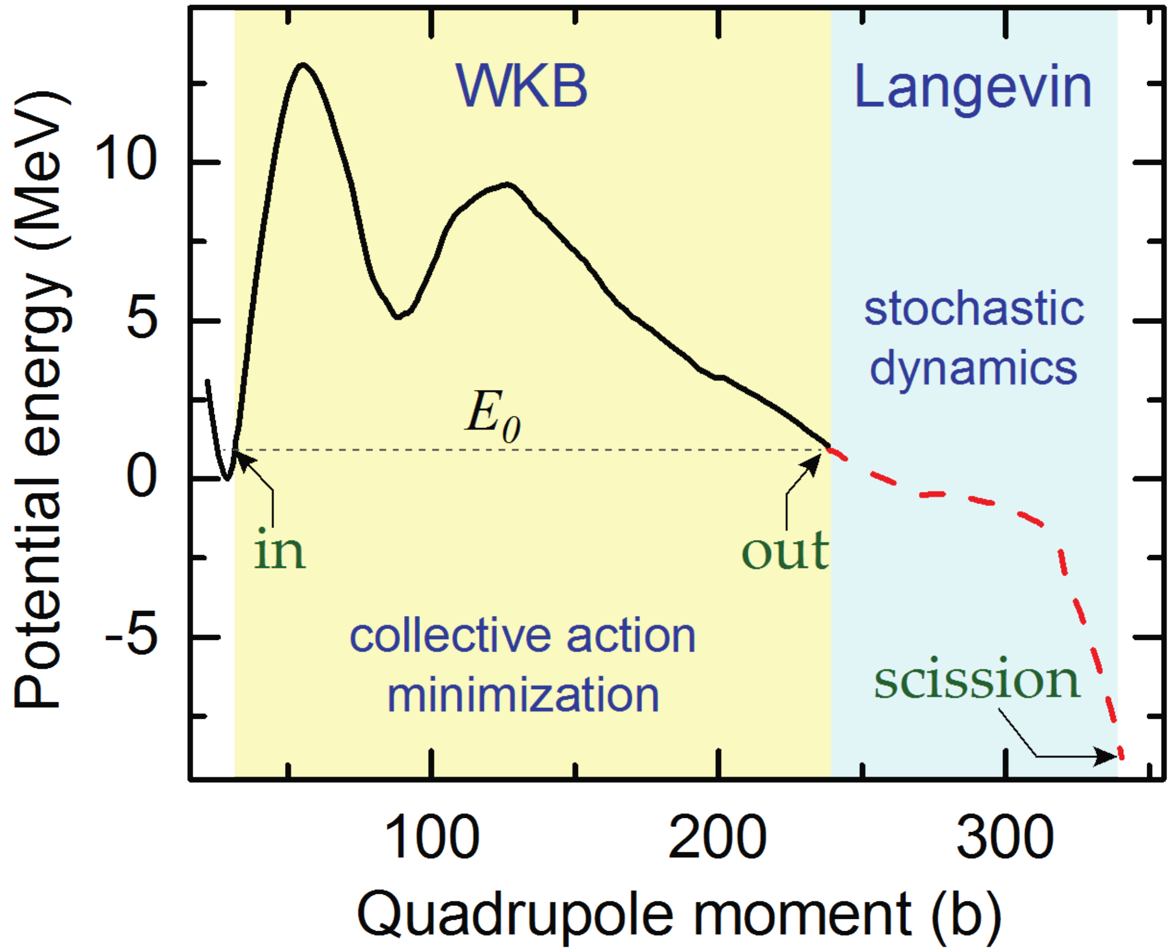
Microscopic description of SF yields

Phys. Rev. C 93, 011304(R) (2016)

$$S(L) = \int_{s_{\rm in}}^{s_{\rm out}} \frac{1}{\hbar}\sqrt{2\mathcal{M}_{\rm eff}(s)\left(V(s)-E_0\right)}\,ds$$

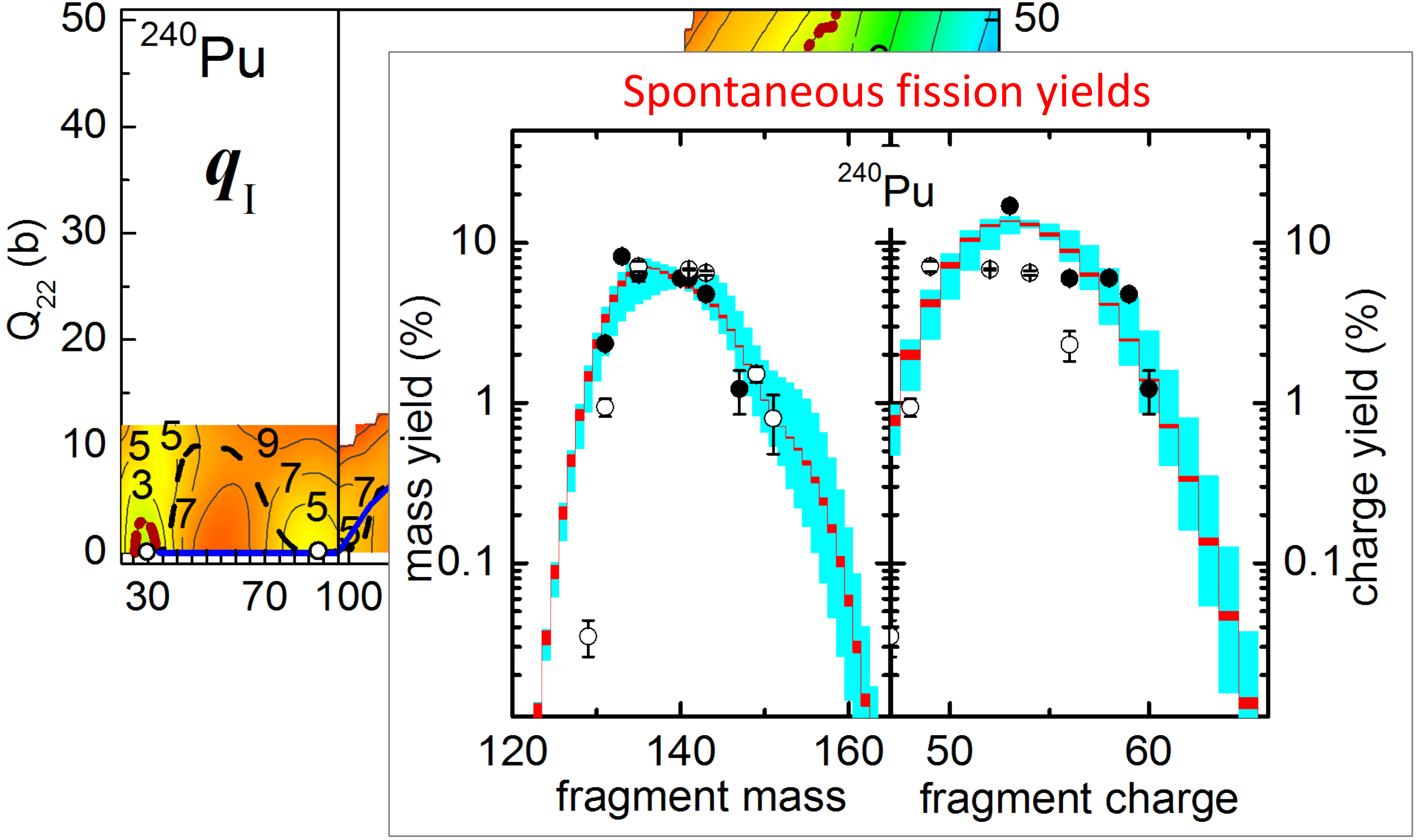
^{258}Fm



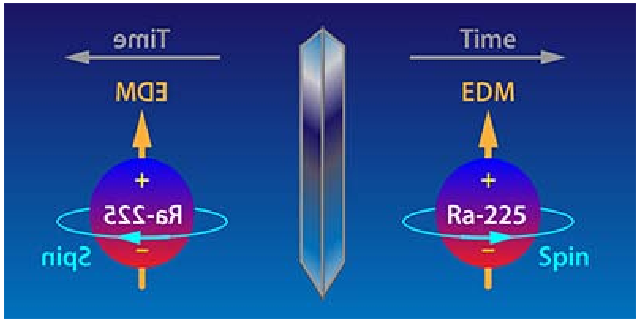


Spontaneous fission yields of ^{240}Pu

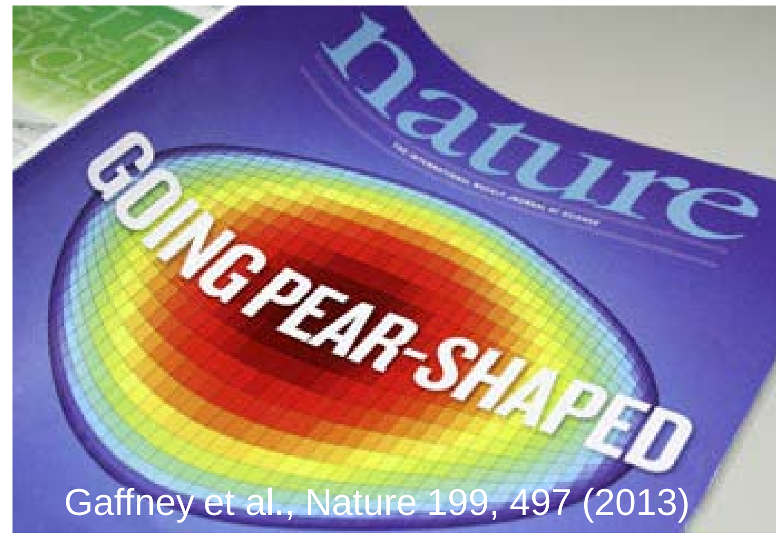
Phys. Rev. C 93, 011304(R) (2016)



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



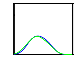
Atomic electric dipole moment: The violation of CP-symmetry is responsible for the fact that the Universe is dominated by matter over anti-matter



Gaffney et al., Nature 199, 497 (2013)

- Closely spaced parity doublet gives rise to enhanced electric dipole moment
- Large intrinsic Schiff moment
  - o ^{199}Hg (Seattle, 1980's – present)
  - o ^{225}Ra (ANL, KVI)
    Bishof et al. 2016, d<1.4×10^{-23} e cm
  - o ^{223}Rn at TRIUMF (E929)
  - o FRIB
    - Widest search for octupole deformations
    - ^{238}U beam, beam dump recovery: ^{225}Ra: 6×10^{9}/s, ^{223}Rn: 8×10^{7}/s
    - ^{232}Th beam: ^{225}Ra: 5×10^{10}/s, ^{223}Rn: 1×10^{9}/s
    - 10^{12}/s w ISOL target; FRIB upgrade

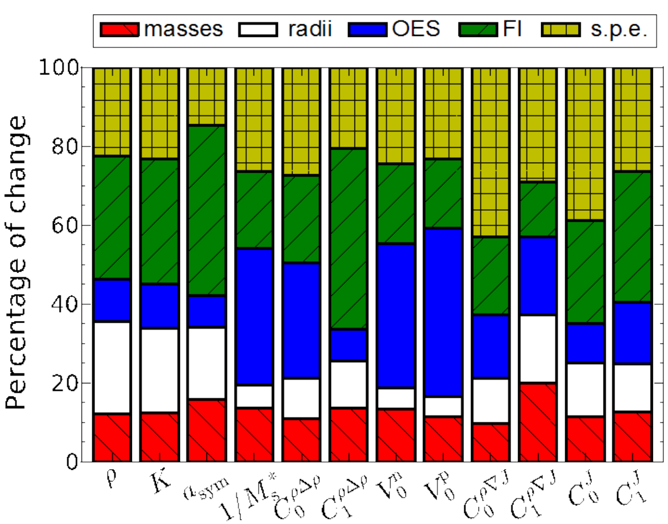
Uncertainty quantification



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

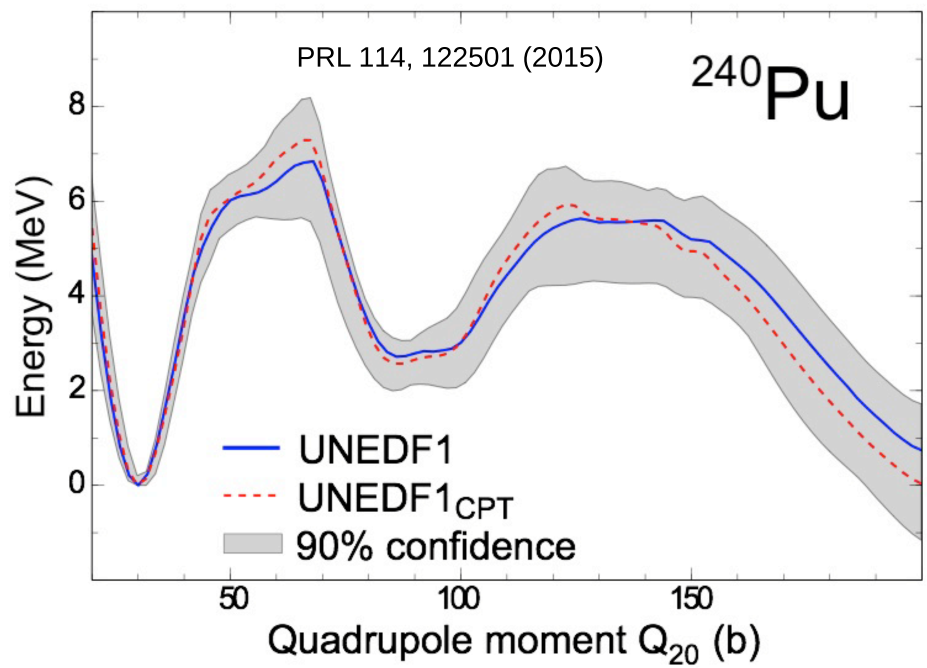
- Regression analysis
- Bayesian inference
- Extrapolations
- Model mixing
- Information content of new measurements

PROSPECT



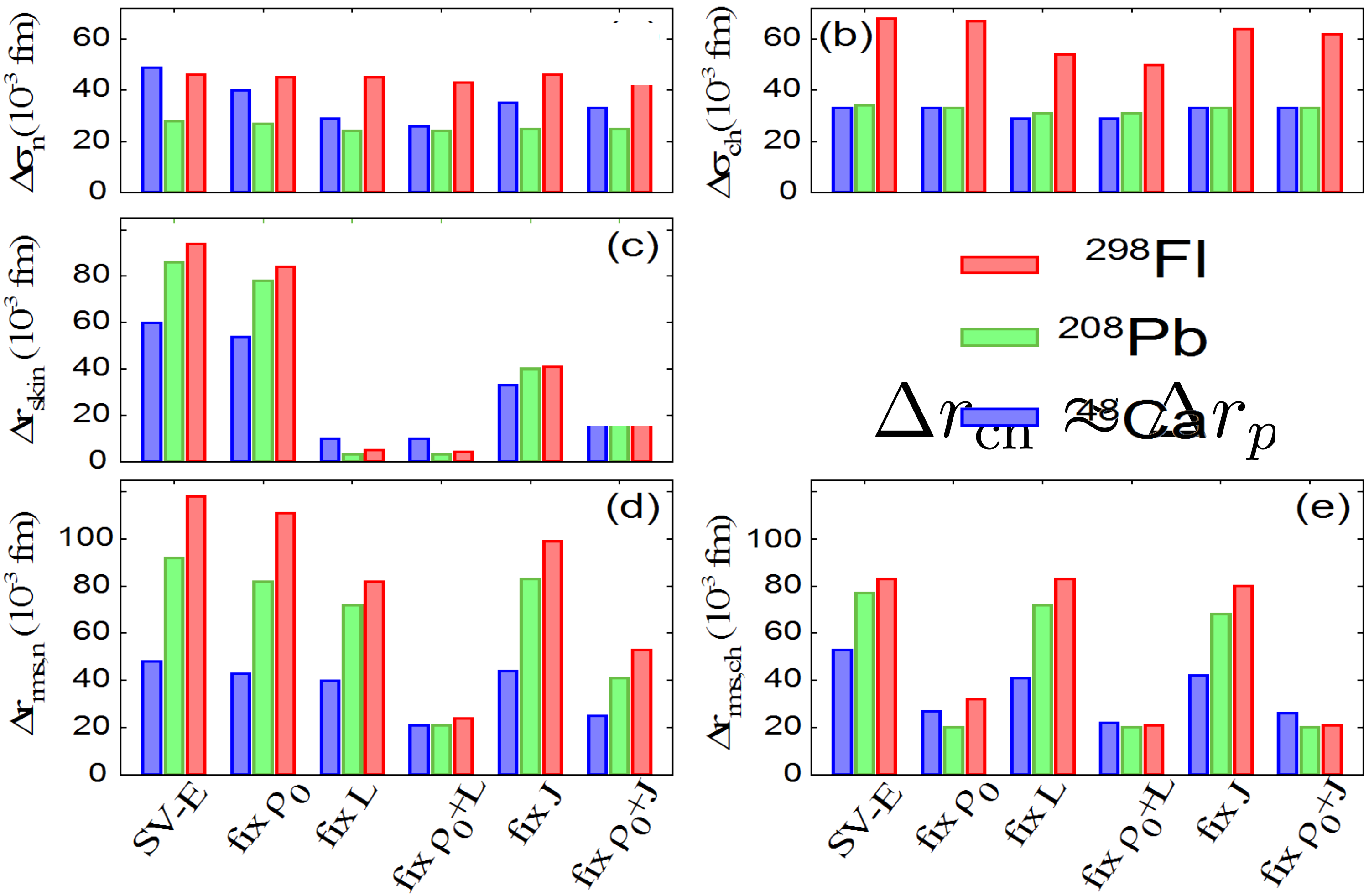
PRC 89, 054314 (2014)

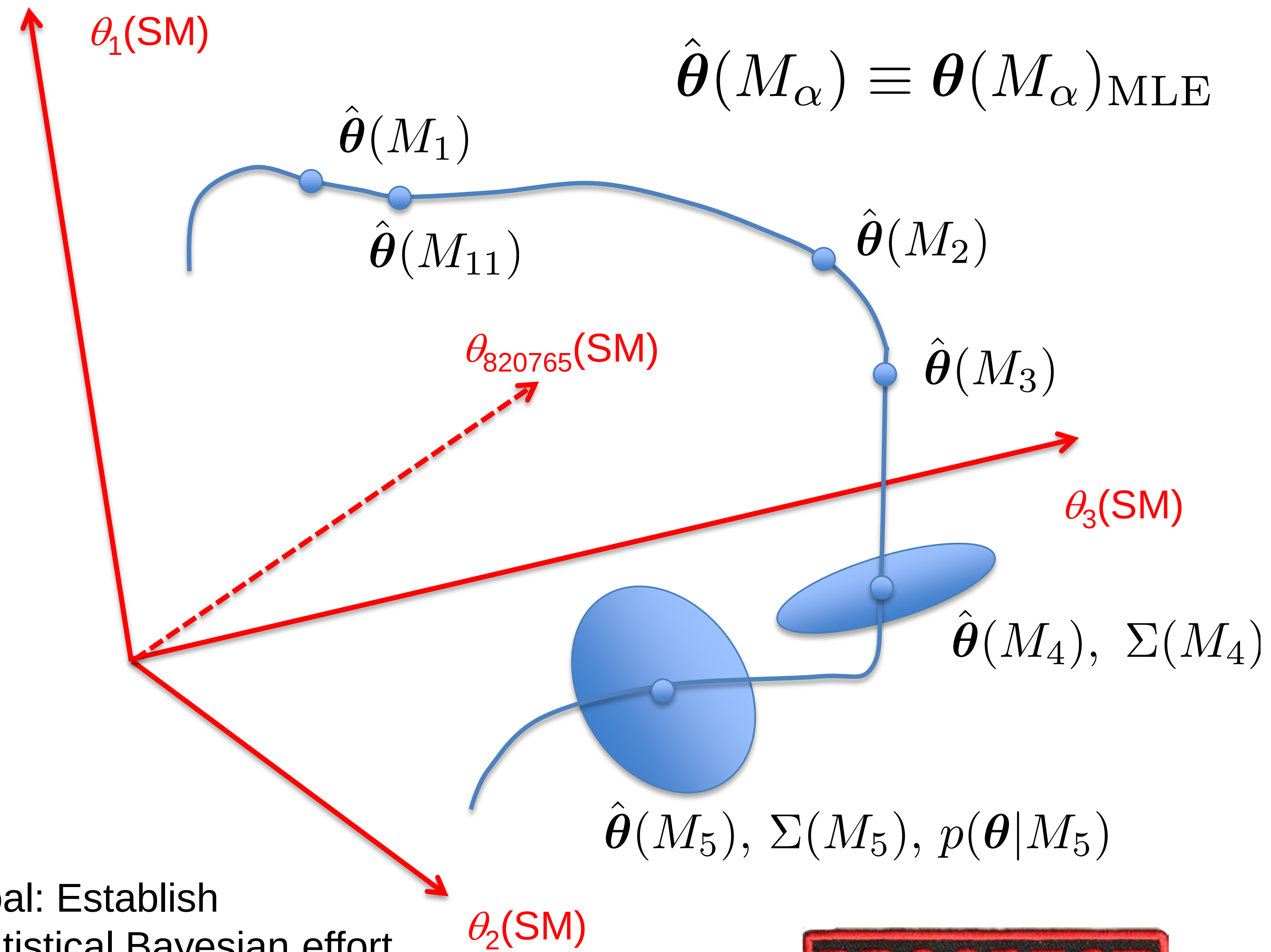
Bivariate posterior distributions of energy density functionals from Bayesian analysis



Nuclear charge and neutron radii, and nuclear matter: trend analysis

P.-G. Reinhard and WN, Phys. Rev. C 93, 051303(R) (2016)





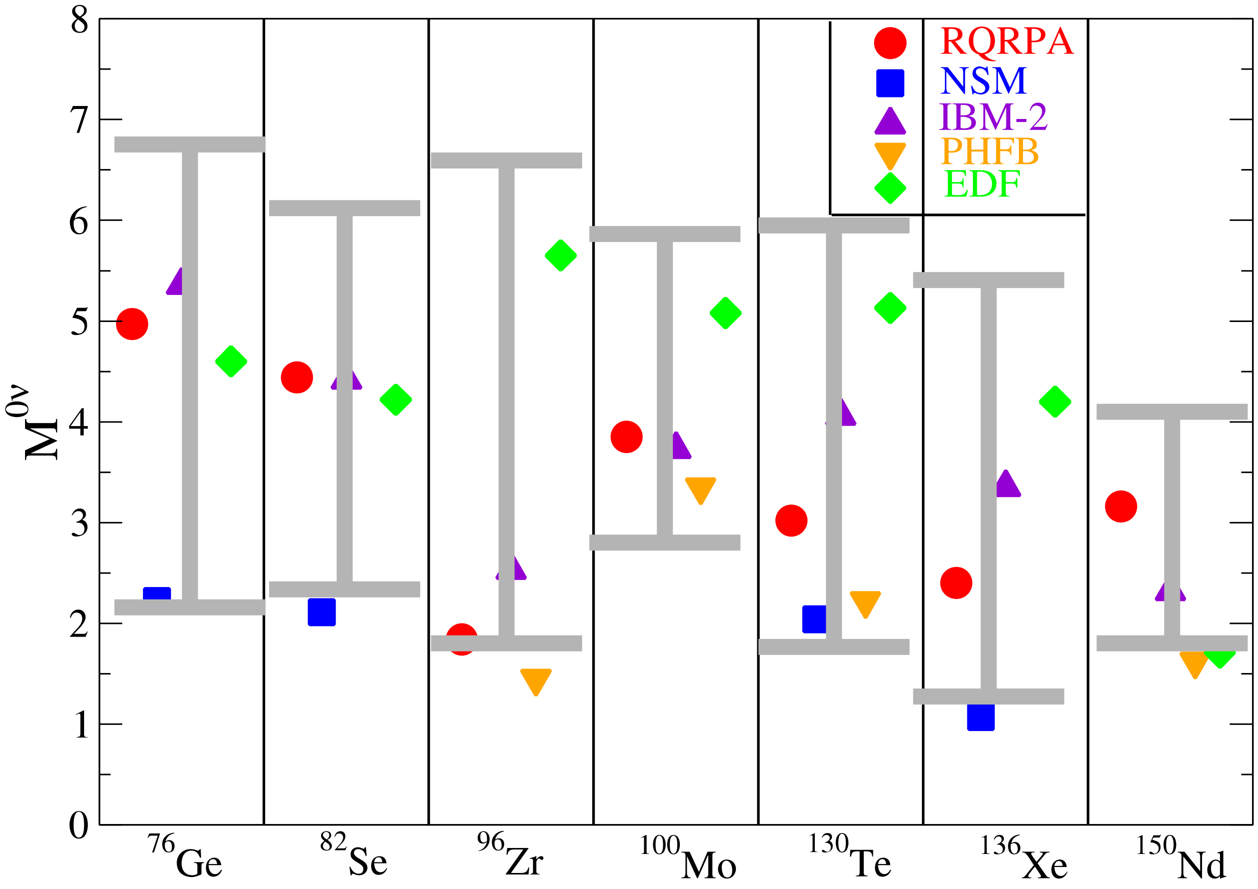
Goal: Establish statistical Bayesian effort around FRIB

PROSPECT

Model mixing

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

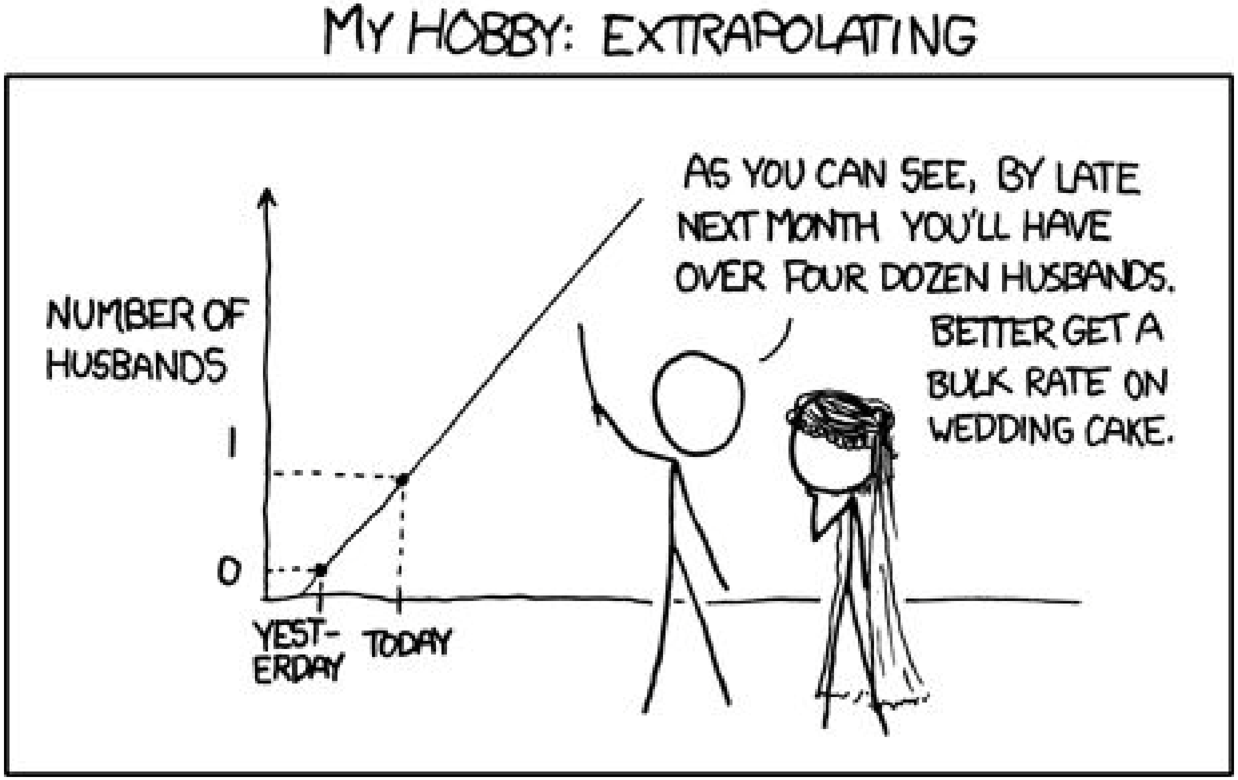
Current 0νββ predictions



"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)

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

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

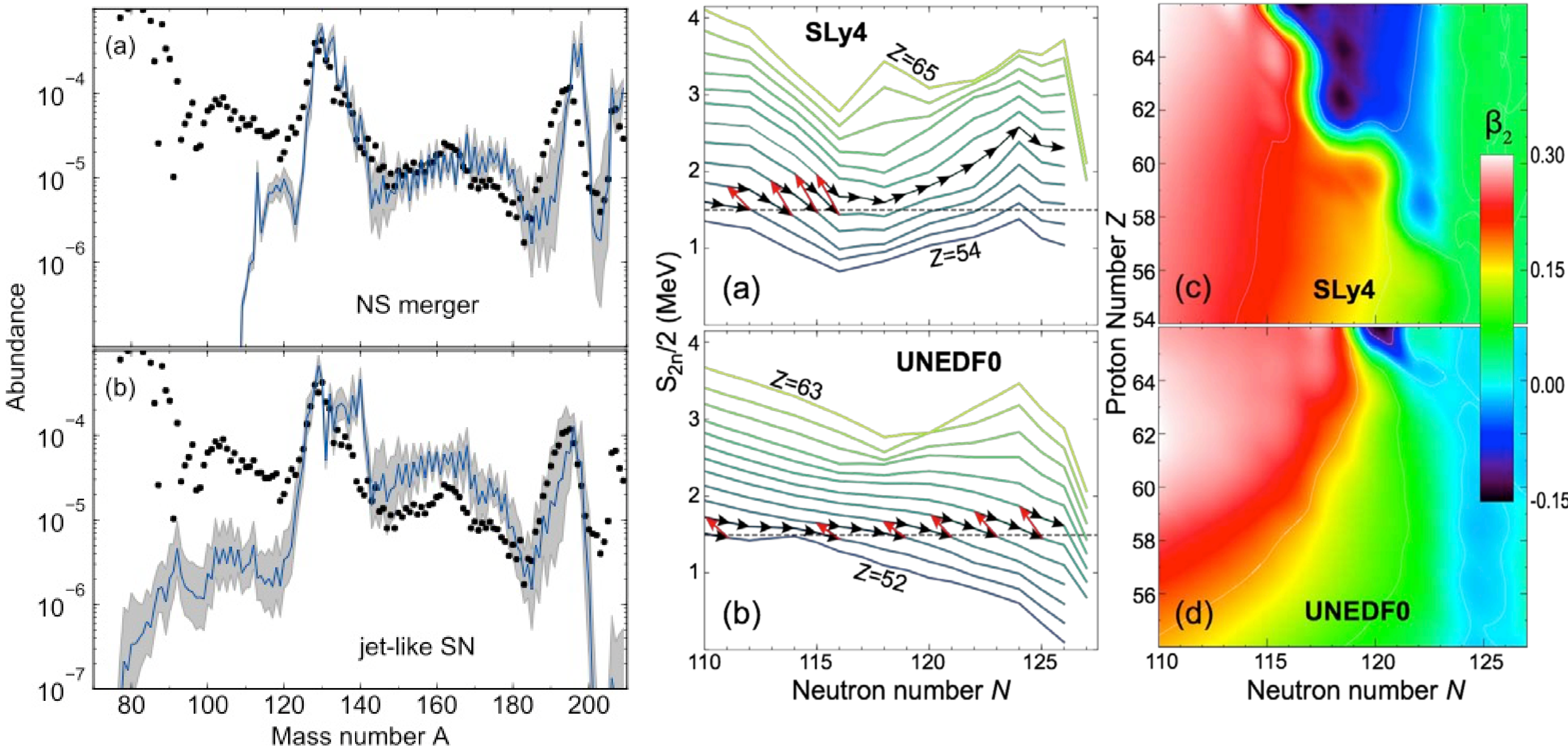


Unfortunately, in many cases, nuclear input MUST involve massive extrapolations...

Indeed, in many cases, nuclear modeling MUST involve massive extrapolations...

Impact of Nuclear Mass Uncertainties on the r Process

D. Martin, A. Arcones, WN, and E.Olsen, *Phys. Rev. Lett.,* **116,** 121101 (2016)

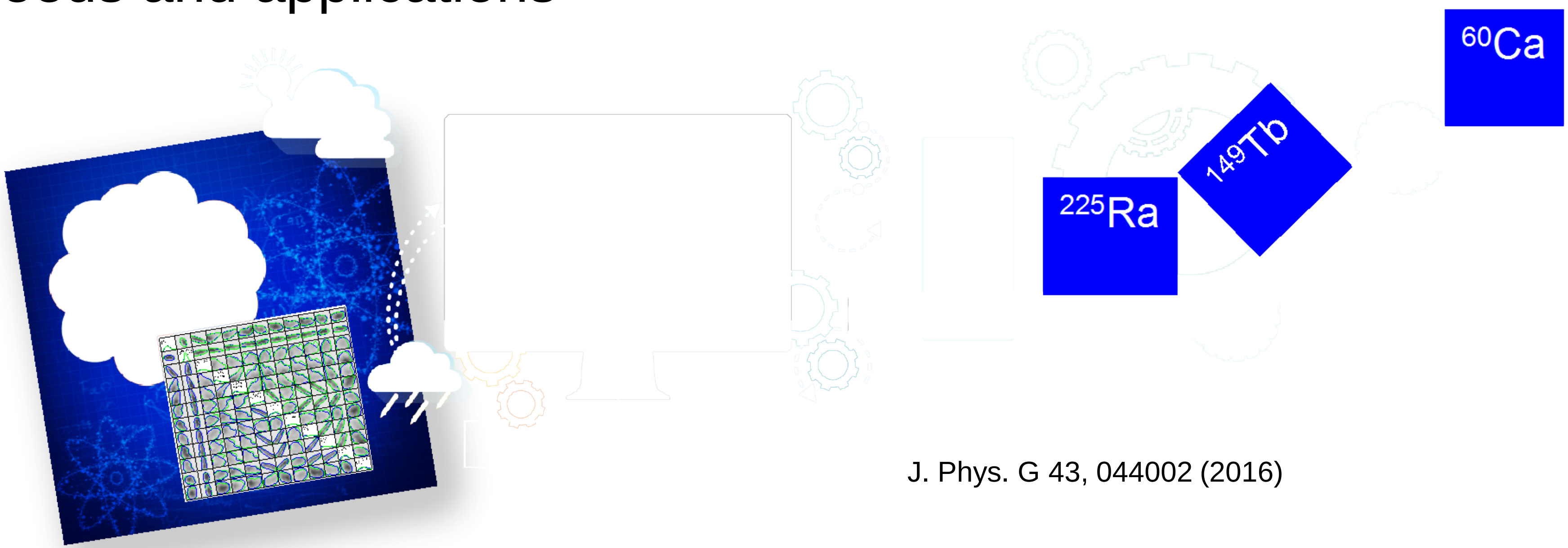


PROSPECT

Uncertainty quantification
Getting critical measurements

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

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)

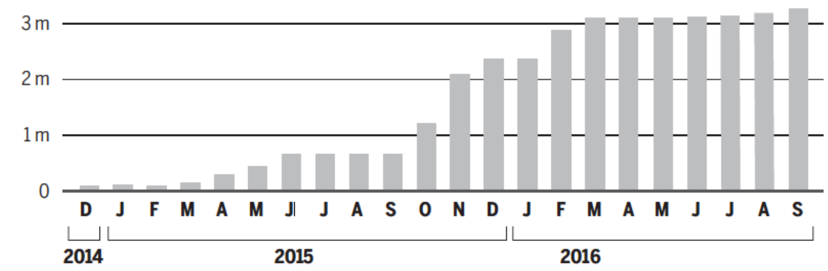
For more than a century, materials scientists have accumulated experimental data on the structures of chemical compounds and the thermal, electronic, and mechanical properties that they exhibit. These data have been a cornerstone in the development, selection, and design of materials. In the past decade, 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.

Materials data and discovery

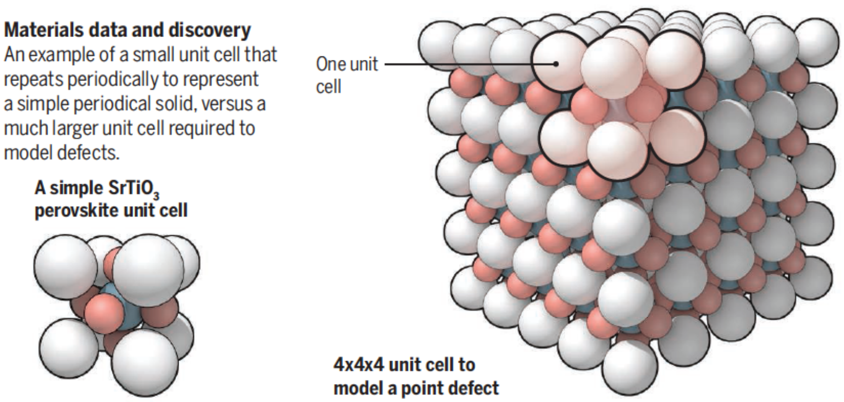
DFT calculations in the NoMaD repository (in millions)

The number of DFT calculations in the NoMaD repository from December 2014 to September 2016. The large jumps in October/November 2015 and February 2016 arose from inclusion of data from the AFLOWLIB and OQMD repositories, respectively.



Materials data and discovery

An example of a small unit cell that repeats periodically to represent a simple periodical solid, versus a much larger unit cell required to model defects.

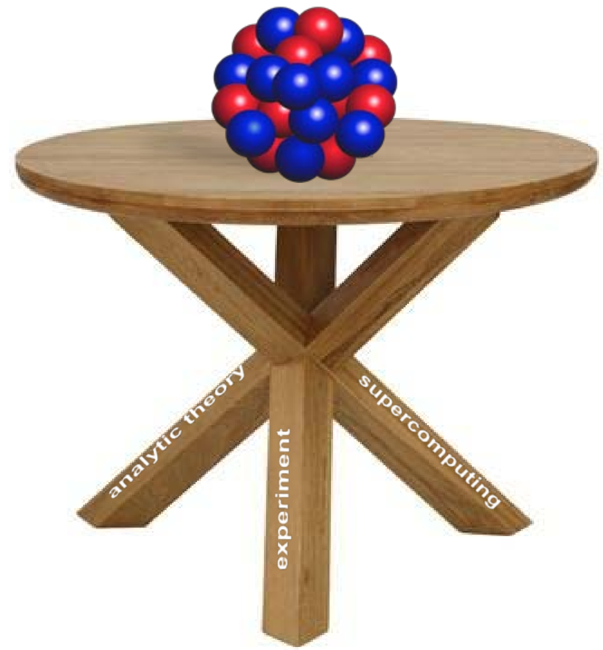


Computational materials scientists apply a range of different codes that all solve the same fundamental equations of DFT but apply diverse numerical approaches. In a large community effort, it was recently shown that in simple situations, like the calculation of the equation of state of elemental crystals,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

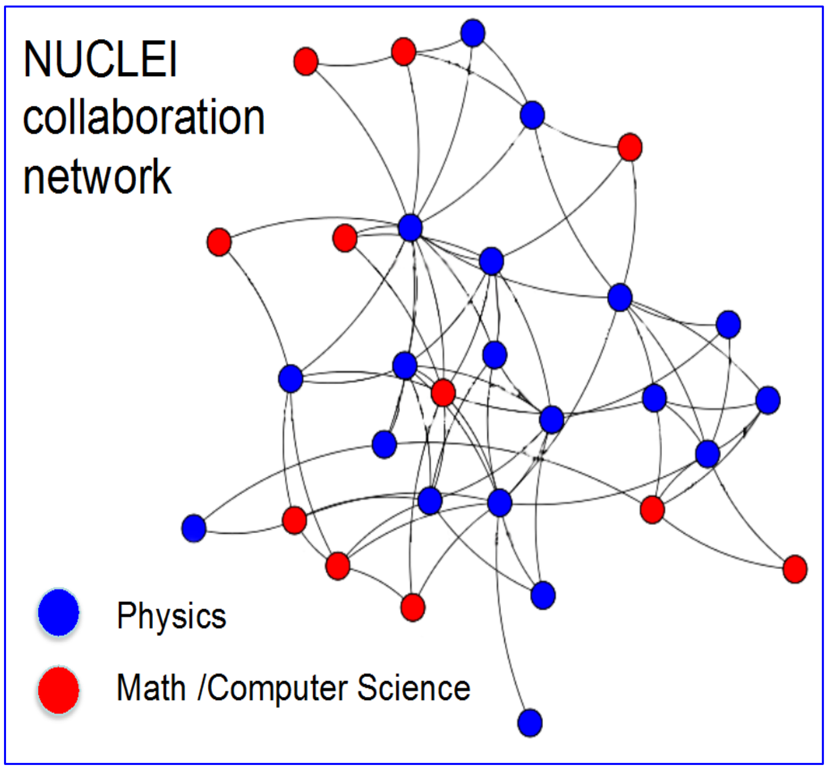
Computational databases mainly contain entries for bulk solids in simple crystal structures, primarily because calculation times grow quickly with the number of atoms N in the unit cell (typically as N to a power between 2 and 3). However, many materials properties are determined by defects, such as 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.

PROSPECT

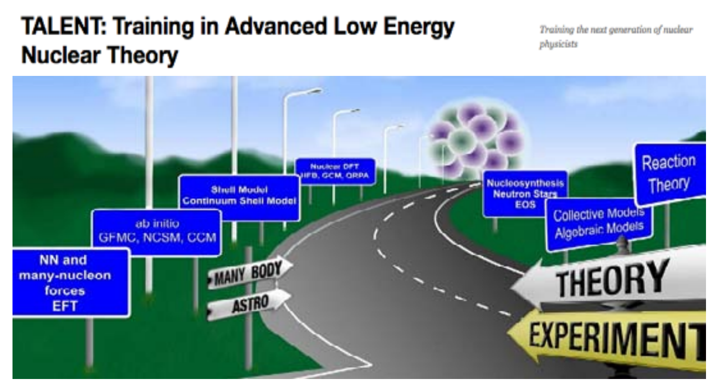
Creating unfair advantage:
the whole is greater than the sum of its parts



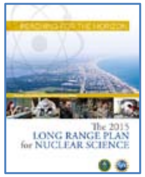
Sociology of the field is changing: large multi-institutional efforts involving strong coupling between physics, computer science, and applied math



… and let us not forget about education and training!



http://nucleartalent.org

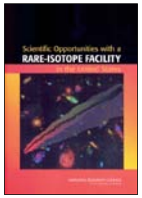


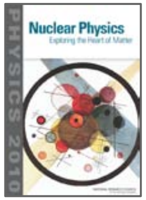
Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

http://fribtheoryalliance.org

The Long Range Plan 2015: “We recommend the establishment of a national FRIB theory alliance. This alliance will enhance the field through the national FRIB theory fellow program and tenure-track bridge positions at universities and national laboratories across the U.S.”

“FRIB will provide unprecedented access to key regions of the nuclear chart where the new measurements will challenge established concepts, highlight shortcomings, and, inevitably, guide the development of a new theoretical picture of atomic nuclei.” The proposed FRIB Theory Alliance, a modest-scale national effort comprising a broad theory community, will, therefore, be important for the success of FRIB. Finally, to reach the scientific goals, a strong interface with high-performance computing, the third leg of this field, will be crucial.”





More reading:

- Nuclear Theory and Science of the Facility for Rare Isotope Beams: arXiv:1401.6435
- Challenges in nuclear structure theory: J. Phys. G 43, 044002 (2016)

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

Looking into the crystal ball: KITP 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.
- 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.
- 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.

Where do nuclei come from?

How are nuclei organized?

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

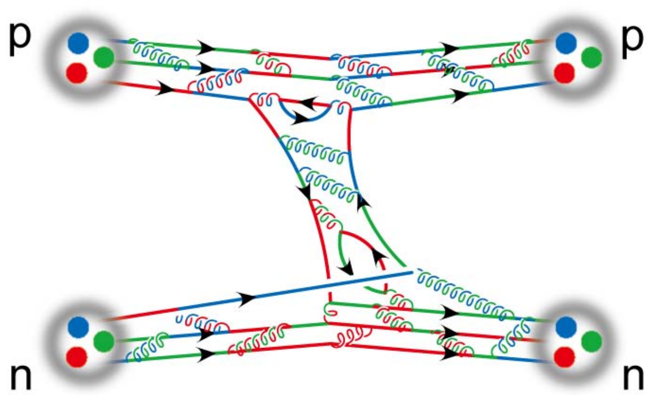
THE FUTURE
IS EXCITING

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

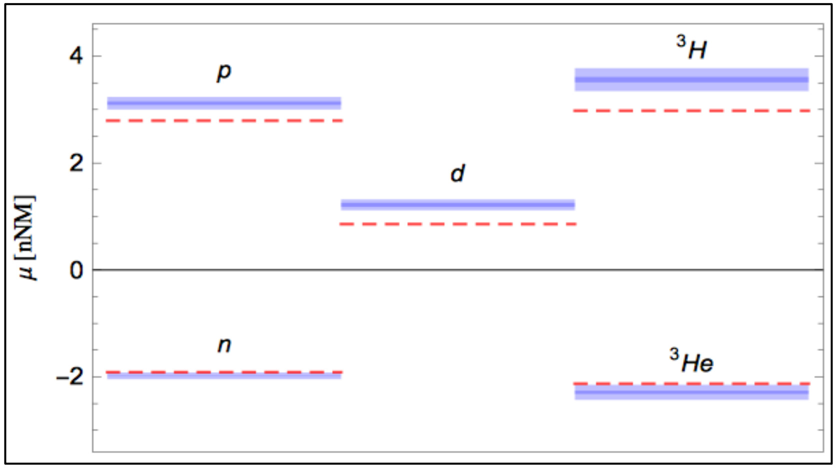
- Energy (fission, reactions, decays…)
- Security (stewardship, forensics, detection…)
- Isotopes (medicine, industry, defense, applied research…)
- Industry (radiation, ion implantation…)

Backup

Rooting nuclei in QCD

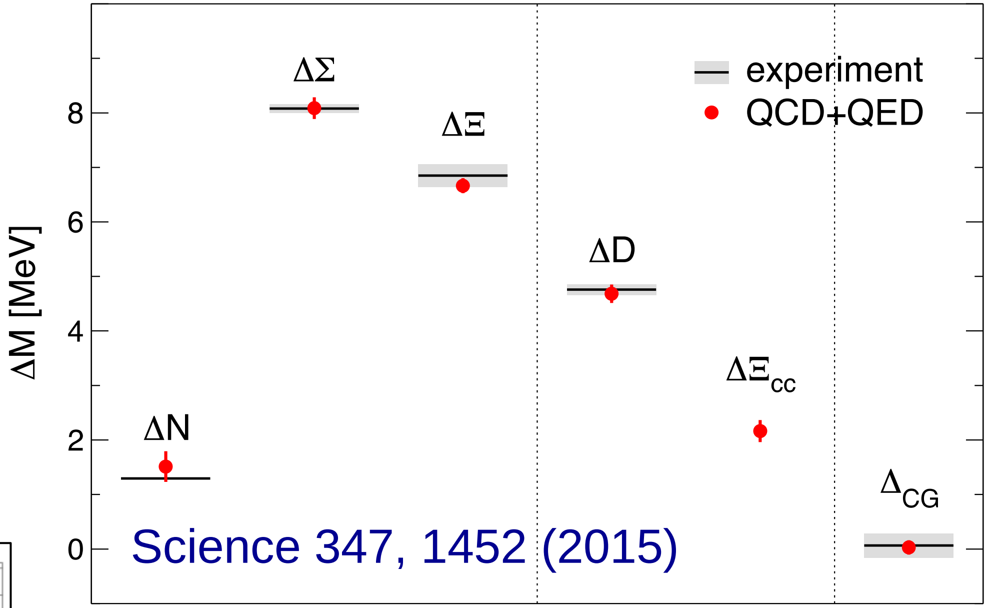


Nuclear Force from lattice QCD
PRL 111, 112503 (2013)



LQCD predictions for magnetic moments A<4
PRL113, 252001 (2014)

n-p mass difference from LQCD



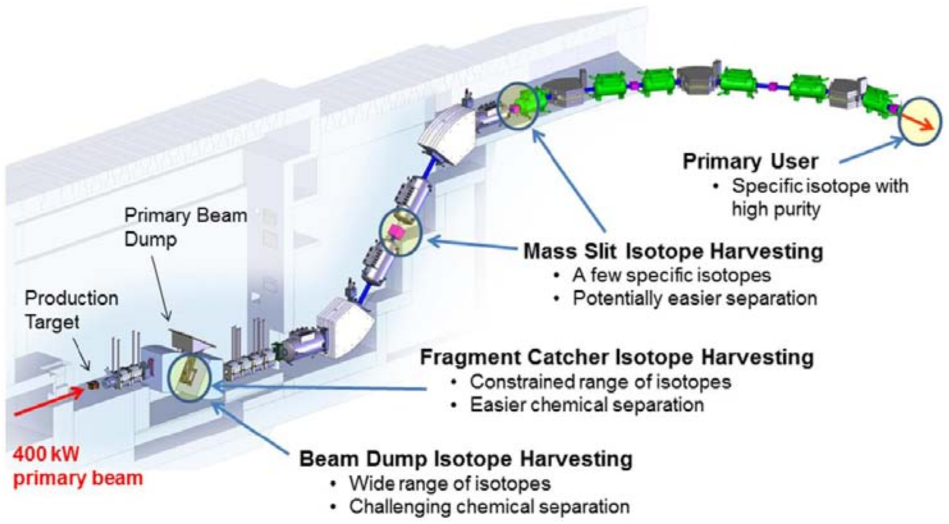
"The neutron–proton mass difference, one of the most consequential parameters of physics, has now been calculated from fundamental theories. This landmark calculation portends revolutionary progress in nuclear physics."
Wilczek, Nature 520, 303 (2015)

FRIB Early Program: Applications

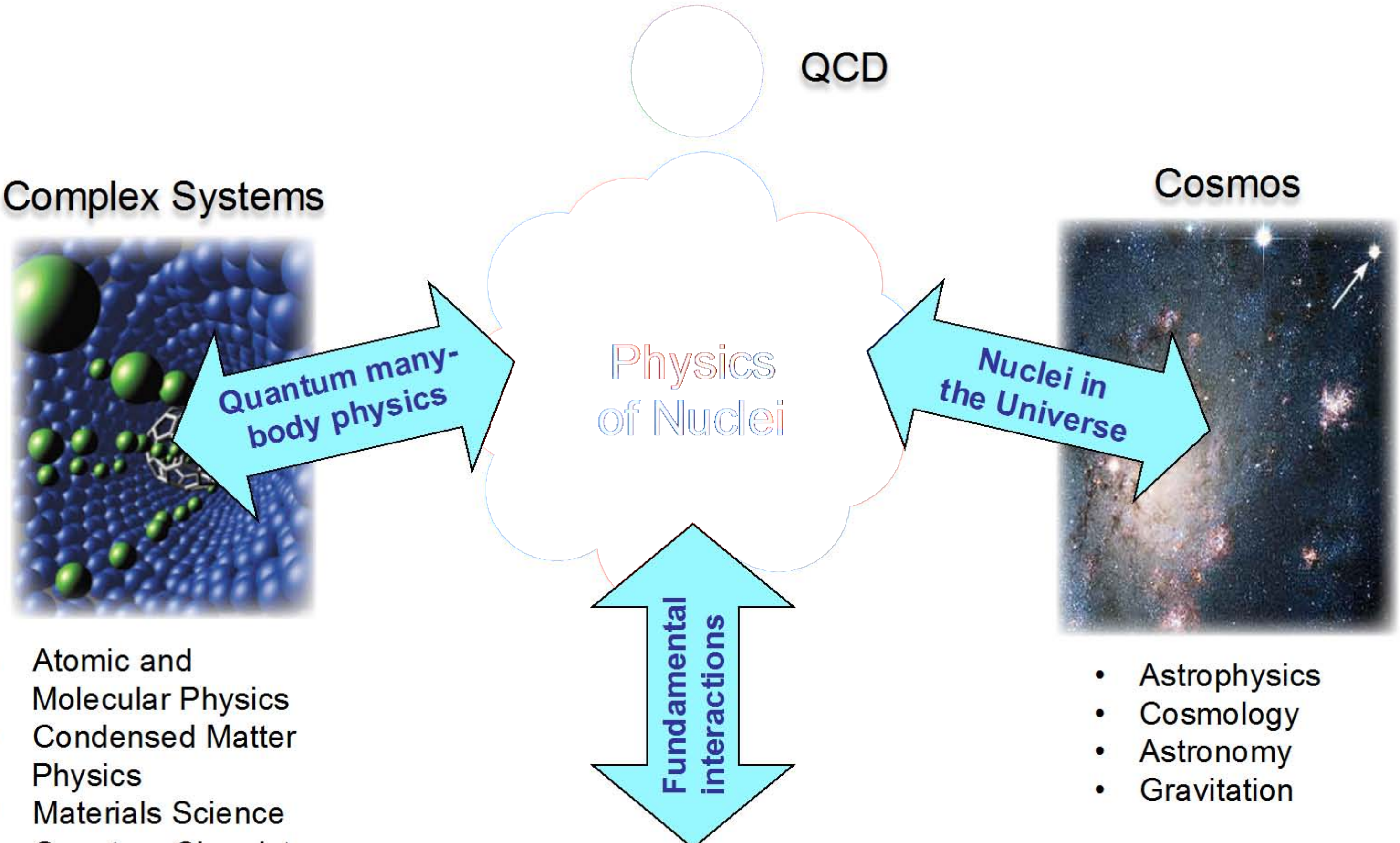
FRIB offers opportunities to harvest isotopes for applications

No	Programs	Example RI	Objective	Instrumentation
10	Medical isotopes	^{149}Tb and ^{211}At	Commensal isotope harvesting. Research quantities of these isotopes and others will advance the development of targeted cancer therapy	Harvesting at FRIB fragment separator
11	Stewardship	R: ^{88,89}Zr Stopped beams	Inverse kinematic reactions to determine (n,γ) and (n,2n) rates. Neutron capture rates. Enable a more reliable modeling of nuclear weapons tests for stockpile stewardship.	GRETINA/GRETA, Si array, Helios, SuN, Decay station

- FRIB's on-line isotope harvesting capability is ideally suited to support a broad program in applied isotope research
- Equipment for isotope harvesting not included in FRIB baseline, but provisions to incorporate are
  - Harvesting can be in place on day-one
  - R&D for developing necessary techniques underway at NSCL



Profound intersections

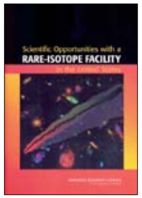


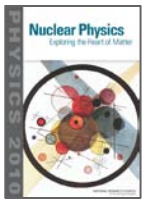
- Atomic and Molecular Physics
- Condensed Matter Physics
- Materials Science
- Quantum Chemistry

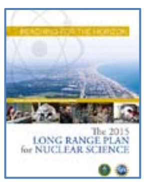
- Particle Physics
- Cosmology

- Astrophysics
- Cosmology
- Astronomy
- Gravitation

National Research Council's (NRC) RISAC Benchmarks for FRIB Science







Science drivers (thrusts) from NRC RISAC 2007

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
Intellectual challenges from NRC Decadal Study 2013			
How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interac-tions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?
Overarching questions from NSAC Long Range Plan 2015			
How are nuclei made and organized? What is the nature of dense nuclear matter?	Where do nuclei and elements come from? What combinations of neutrons and protons can form a bound atomic nucleus? How do neutrinos affect element synthesis?	Are neutrinos their own antiparticles? Why is there more matter than antimatter in the present universe?	What are practical and scientific uses of nuclei?
Overarching questions are answered by rare isotope research			
17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research 2007			
1. Shell structure 2. Superheavies 3. Skins 4. Pairing 5. Symmetries 6. Equation of state 13. Limits of stability 14. Weakly bound nuclei 15. Mass surface	1. Shell structure 6. Equation of state 7. r-Process 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe s-process 13. Limits of stability 15. Mass surface 16. rp-Process 17. Weak interactions	12. Atomic electric dipole moment 15. Mass surface 17. Weak interactions	10. Medical 11. Stewardship

NRC benchmarks are used by FRIB to check facility capabilities and develop beam priorities

FRIB Science Program: Nuclear Structure

No	Programs	Example RI	Objective	Instrumentation
1	Study of Shell Structure	$^{54-60}$Ca, ^{48}Ni, ^{100}Sn; R:^{54}Ca	Study of structure of exotic doubly magic nuclei to find missing physics in nuclear models	GRETINA/GRETA, MoNA/LISA HRS, Si arrays, Decay station, TPC
2	Towards superheavies	^{16}C, ^{22,24}O	Use fusion reactions with light RIBs on actinide targets to explore a path to superheavy nuclei	CFFD (coincident fission fragment detector), Si arrays, GRETINA/GRETA, ISLA
3	Neutron Skins	^{48}Ni, ^{84}Ni	Fast beam studies to estimate the skin thickness and constrain the EOS of nuclear matter	HRS, GRETINA/GRETA, LENDA, TPC
4	Pairing	R: heavy Ni and Sn isotopes	By means of (p,t) and (t,p) reactions explore how pairing changes in asymmetric nuclear matter	Si array, GRETINA/GRETA, ISLA or Helios, TPC
5	Nuclear Symmetries	^{96}Kr, ^{134}Sm, ^{156}Ba, also R	Study of nuclei with transitional structure between dynamical symmetry phases	GRETINA/GRETA, Si, HRS, Decay station
6	Equation of State	Heavy Ni isotopes	Verify the density dependence of the EOS	HRS, TPC, Si array, neutron wall
13	Limits of Stability	^{62,64,66}Ca	Search for the dripline in calcium isotopes	FRIB fragment separator
14	Weakly Bound Nuclei	beyond ^{40}Mg, ^{44}Si, ^{43}Al	Explore the effects of open channels on nuclear structure	HRS+MoNA/LISA
15	Mass Surface	^{79}Ni, ^{195}Ta	Provide key constraints for nuclear models	Penning traps, HRS

R - reaccelerated

04-Thoennessen

05- Crawford

FRIB will facilitate a high-impact science program in nuclear structure from day-one

FRIB Science Program: Nuclear Astrophysics

No	Programs	Example RI	Objective	Instrumentation
7	r-process	^{124}Mo,^{,200}W ^{162}Ce	With the lightest N=82, 126 nuclei, test assumptions used in r-process nucleosynthesis models. Measure half-lives and masses around A=162 to understand the rare earth peak	Decay station, Penning trap, HRS, SuN
8	^{15}O(α,γ)	R: ^{30}P, ^{45}V	Studies of key reaction rates for explosive nucleosynthesis. Solve the puzzle of the transition to stable burning in X-ray bursts as a function of accretion rate. Enabling the use of ^{44}Ti observations as supernova diagnostics	SECAR
9	^{59}Fe s-process	^{59}Fe	Use analysis of stardust samples to infer temperature and density conditions inside stars during the synthesis of the elements	Harvesting at FRIB fragment separator
16	rp-process	^{61}Ga, ^{74}Sr; R: ^{22}Mg, ^{65}As	Generate reliable burst light curve templates for X-ray burst observations	SECAR, JENSA, AT-TPC, GRETINA/GRETA, HRS
17	Weak interactions	^{82}Ge, ^{100}Zr, ^{100}Sn	Use charge exchange reactions to determine electron capture rates for modeling of pre-supernovae core evolution and neutron star crusts	HRS, GRETA/GRETINA, LENDA, MoNA/LISA

- Benchmark programs 1, 6, 13, 15 (previous slide) also address nuclear astrophysics objectives

04-Thoennessen 05- Crawford

FRIB will facilitate a high-impact science program in nuclear astrophysics from day-one

FRIB Early Program: Fundamental Symmetries

No	Programs	Example RI	Objective	Instrumentation
12	Atomic EDM	^{225}Ra, ^{223}Rn	Preliminary studies on systematic errors with samples harvested from the beam dump. Benchmark the nuclear structure, in particular octupole collectivity, in this region which is required nuclear structure input for EDM searches	GRETINA/GRETA, Si array, Decay station, HRS, laser spectroscopy, harvesting at FRIB fragment separator

- Benchmark programs 15 and 17 carried out jointly with Nuclear Structure/Astrophysics

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FRIB will facilitate a high-impact science program in fundamental symmetries from day-one

FRIB Early Program: Applications

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Benchmark program 11 carried out jointly with Nuclear Astrophysics

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