Physics with Rare Isotope beams, an overview

Witold Nazarewicz (Tennessee/ORNL)

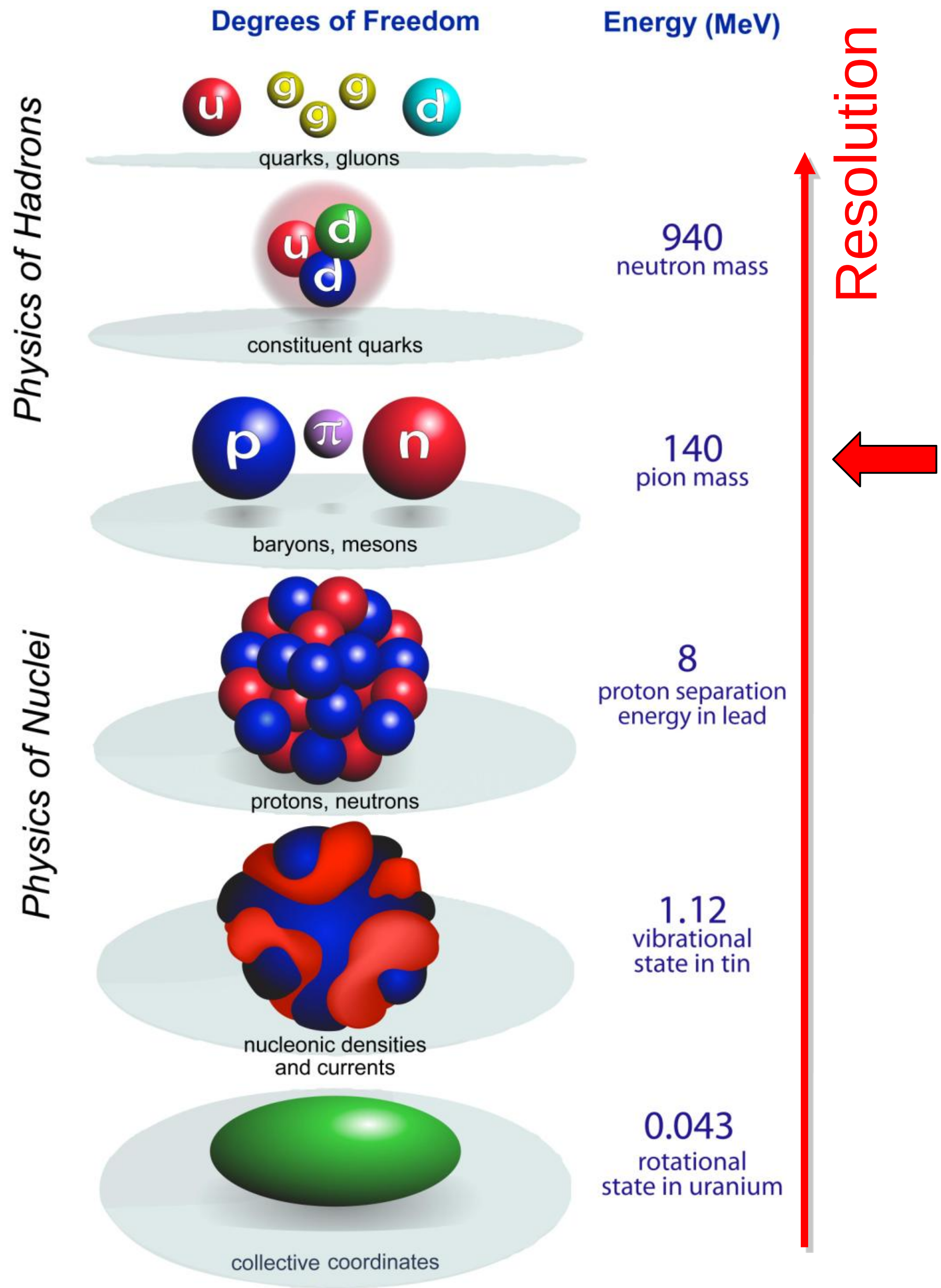
Tenth Exotic Beam Summer School, July 25, 2011

Take-away messages:

- Rare isotopes offer a broad and exciting scientific agenda, closely coupled to key intellectual drivers in many areas of science
- Nuclear scientists, experimentalists and theorists, are getting better and better at controlling short-lived nuclei, in particular those which are useful
- Rare isotopes provide society with numerous opportunities*

The intellectual drivers of nuclear physics today (overarching questions)

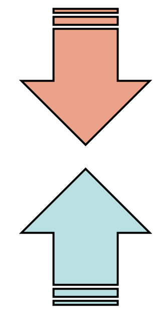
- How did the matter that makes up the visible universe come into being and how does it evolve?
  - Nature of building blocks (quarks+gluons, hadrons, nuclei, atoms,…)
  - Cosmic evolution of the visible matter
- How do the building blocks of subatomic matter organize themselves and what phenomena emerge as they do so?
  - Nature of composite structures and phases
  - Origin of simple patterns in complex systems
- How have forces hidden from view shaped the properties of matter?
  - In search of the New Standard Model
  - The nucleus as a laboratory for testing fundamental symmetries
- How can we best use the unique properties of nuclei and technologies developed in nuclear physics to benefit society?
  - Unique opportunities for applications
  - Public must be properly compensated for supporting what is fundamentally an intellectual enterprise.



Hot and dense quark-gluon matter

Hadron structure

Hadron-Nuclear interface

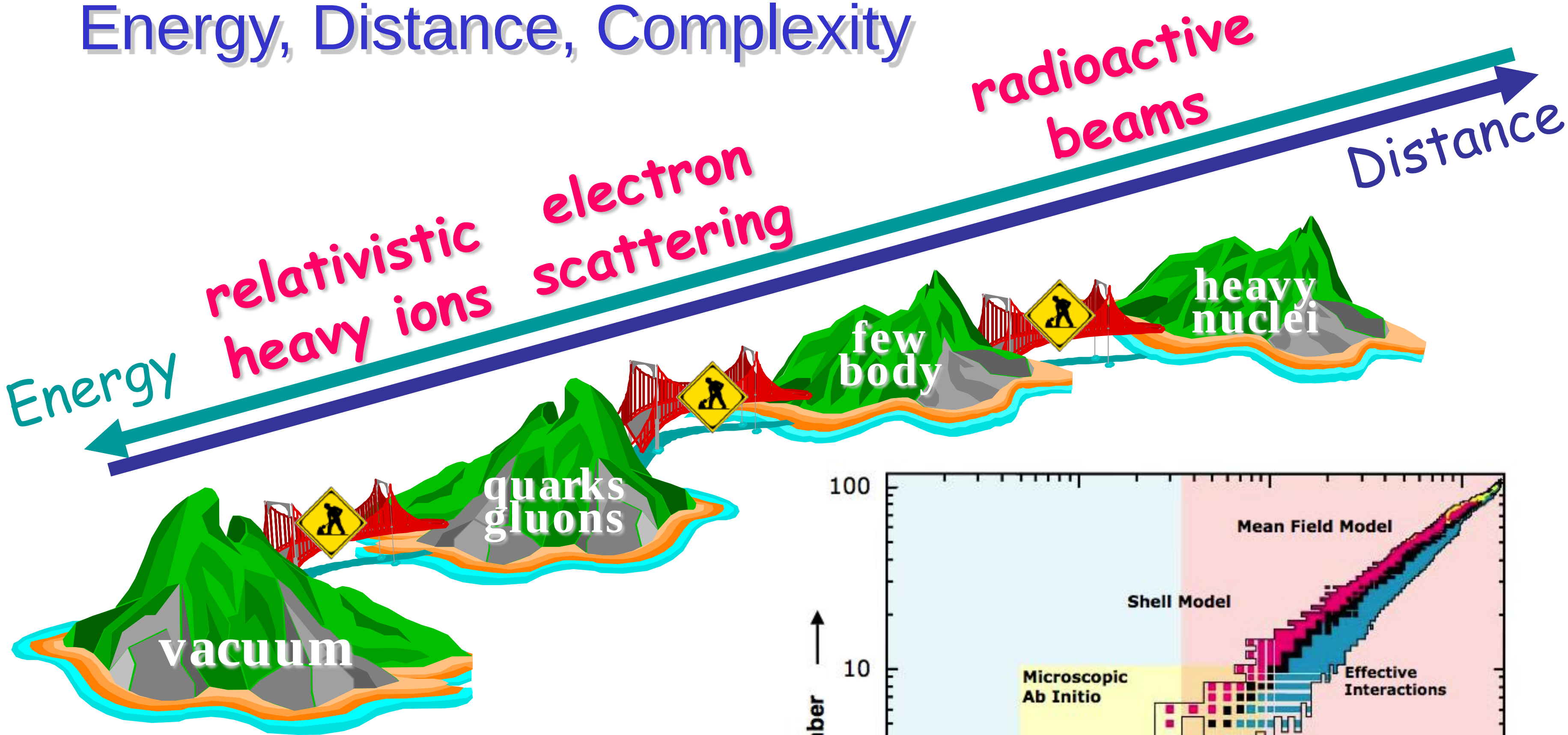


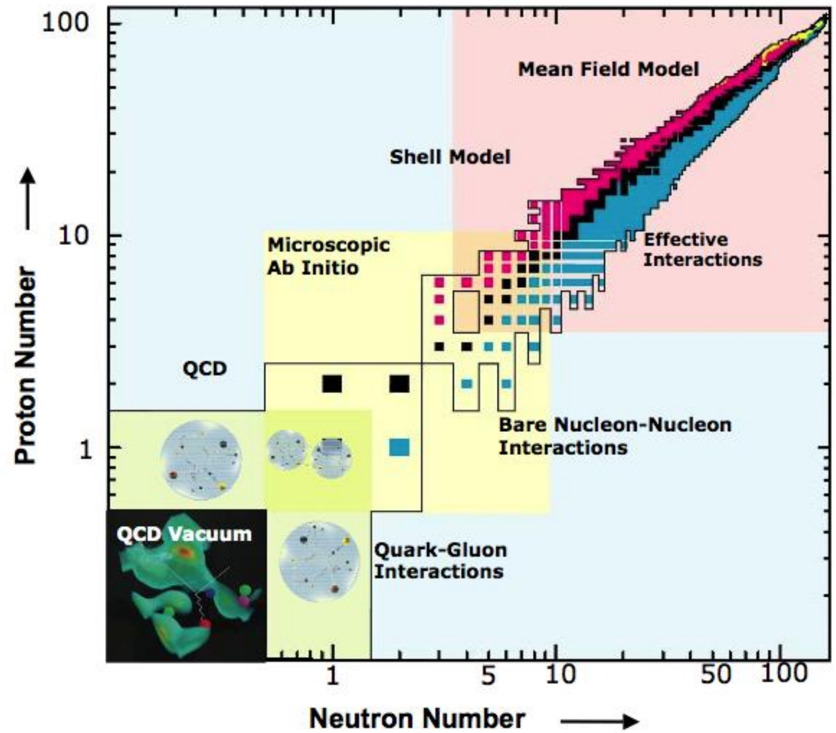
Nuclear structure
Nuclear reactions

Nuclear astrophysics
New standard model

Applications of nuclear science

The Nuclear Many-Body Problem
Energy, Distance, Complexity





A lot of progress is taking place at interfaces

Radioactive Ion Science Timeline

Europe
Japan
Canada
United States

Becquerel discovers radioactivity

The Curies discover polonium

Isotopic tracer technique by von Hevesy

6-He produced in Copenhagen

Neutron-induced fission

First therapeutic application of artificial radionuclide

Fermi builds controlled fission reactor

First ISOL experiment in Copenhagen

Explanation of magnetic numbers

Explanation of magic numbers

Parity violation in beta decay

iochemistry d to monitor ear weapons s

Z=100 (Fm) discovered

Mössbauer effect

Theory of nucleosynthesis

BBHF theory of nucleosynthesis

First in-flight separator at Oak Ridge

beta-NMR demonstrated at ANL

Z=105 (Db) discovered in Dubna

n emission vered at ell

radioactivity discovered at Dubna and McGill

Nobel Prize for magic numbers

Nobel Prize for magic numbers

ISOLDE

First mass measurement of short-lived nuclei at PS in CERN

Island of inversion at N=20 and shape coexistence in proton-rich Hg at ISOLDE

Nobel Prize for unified model

Nobel Prize for unified model

Invention of PET scanner

Nobel Prize for nucleosynthesis

First in-flight fragmentation experiments at Berkeley

First application of radiochemistry to inertial fusion target diagnosis

Measurement of half-life of r-process nucleus at Studsvik

Acceleration of RIBs at LLN

ISOLTRAP

IGISOL at Jyväskylä

Laser ion source at ISOLDE

RIKEN

GANIL

GSI

NSCL

Neutron halos discovered

Measurement of half-life of r-process nucleus at TRISTAN

Momentum distribution of halo at RIKEN

First accelerated beam experiment (13-N) at LLN

100-Sn discovered at GSI and GANIL

Relativistic Coulomb excitation of 32-Mg at RIKEN

Shell structure of exotic nuclei with knockout reactions at NSCL

Direct radiative capture with 21-Na at ISAC-I

38m-K β-ν correlations at TRINAT

Two-proton emitters discovered at GSI and GANIL

Element Z=112 discovered

Z=108 chemistry at GSI

Targeted alpha therapy at ISOLDE

SPIRAL1

ISAC-I

REX-ISOLDE

Collapse of magic numbers in exotic nuclei

6-He enhanced reaction cross sections at TwinSol

Studies with accelerated 132-Sn and 82-Ge at HRIBF

21-Na β-ν correlations at Berkeley

Charge radius of 6-He at ATLAS

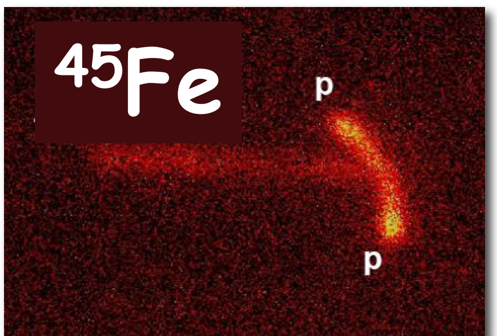
78-Ni lifetime at NSCL

1900 — 1930 — 1960 — 2000

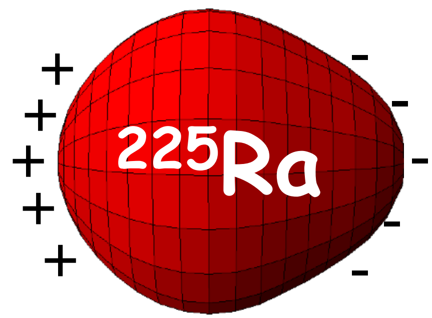
Some nuclei are more important than others

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

nuclear structure

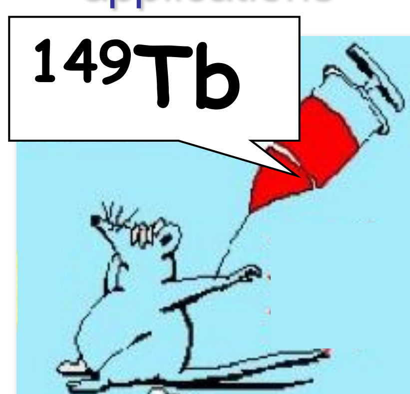


tests of
fundamental laws
of nature



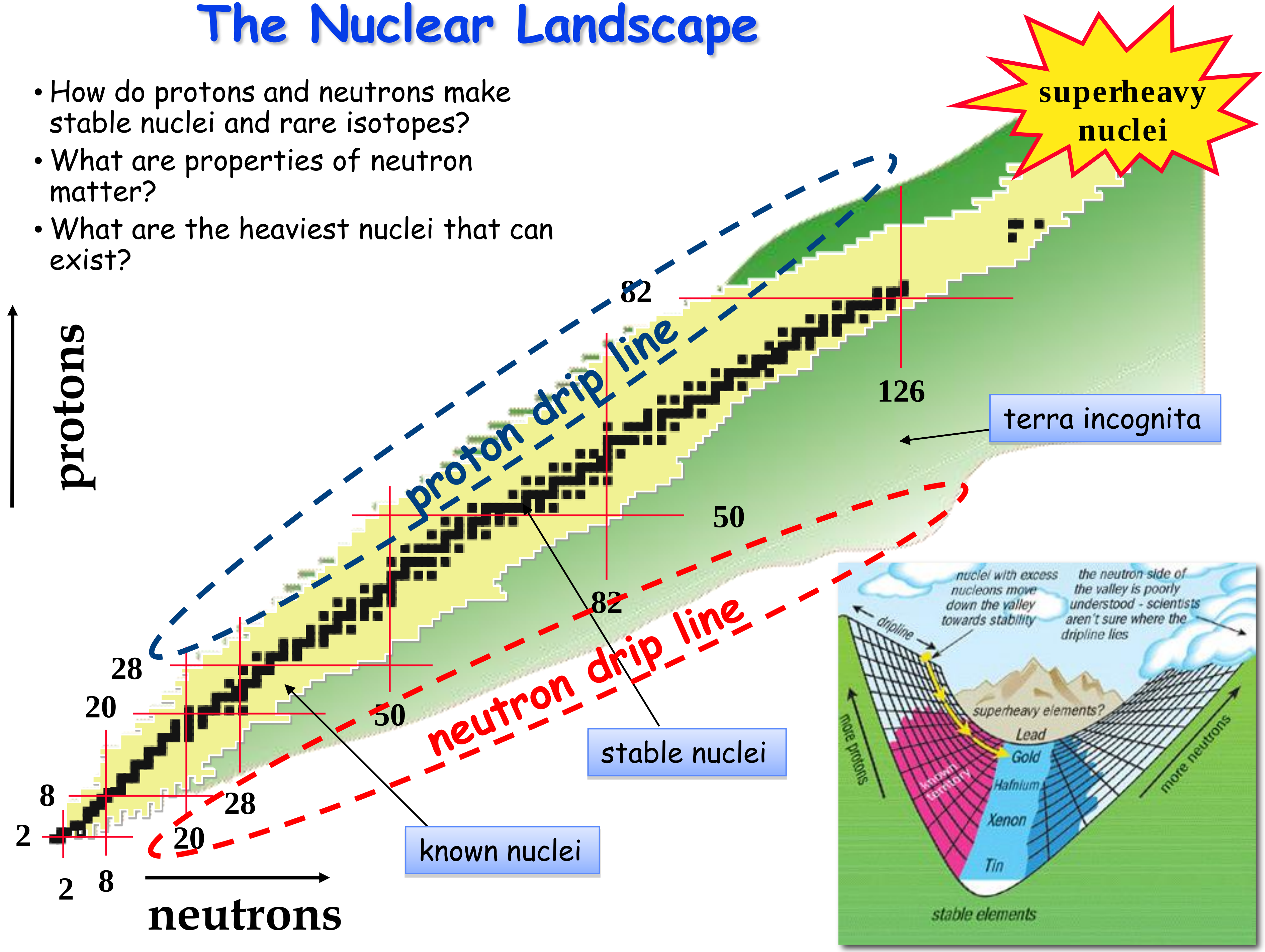
astrophysics

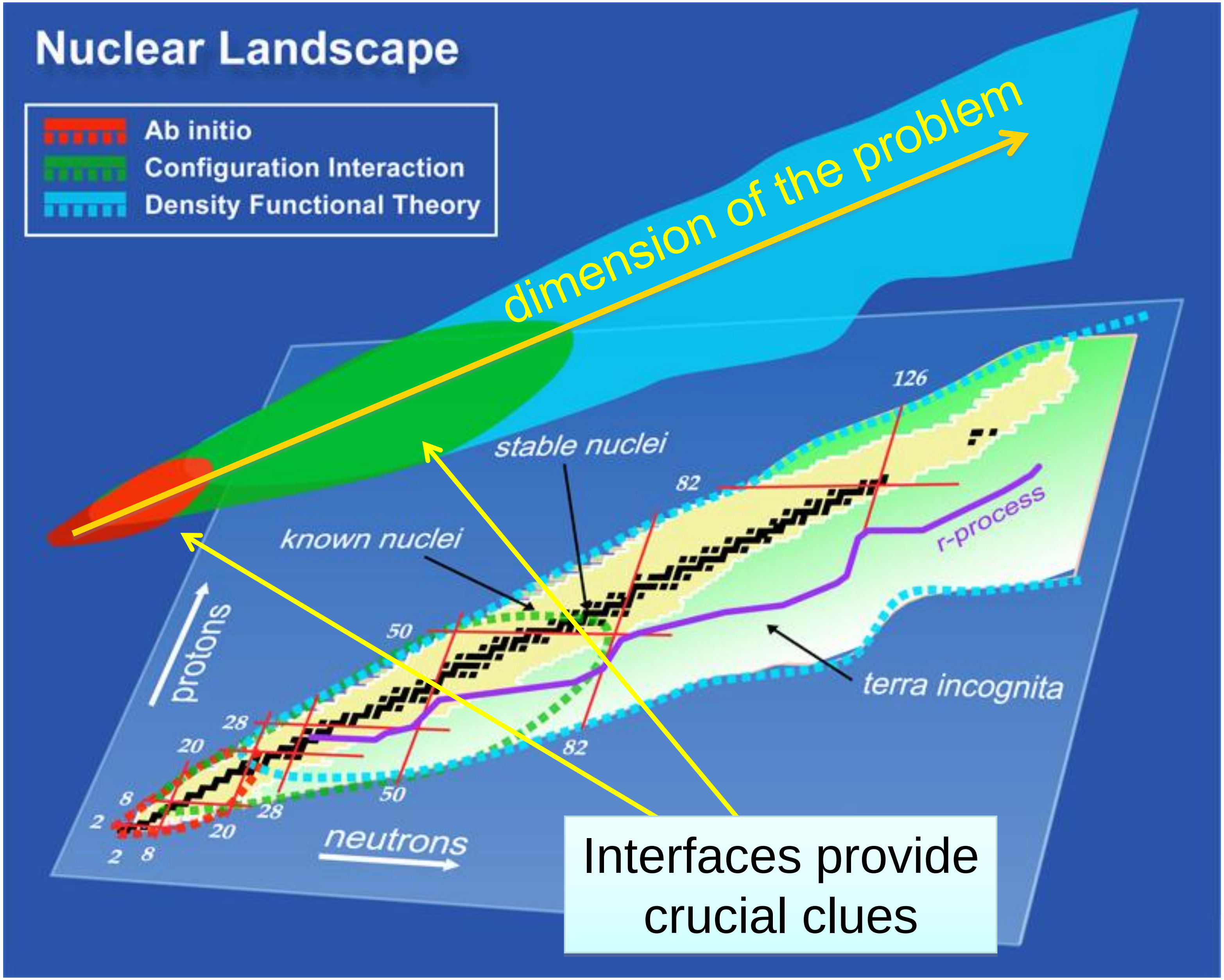
applications



The Nuclear Landscape

- How do protons and neutrons make stable nuclei and rare isotopes?
- What are properties of neutron matter?
- What are the heaviest nuclei that can exist?

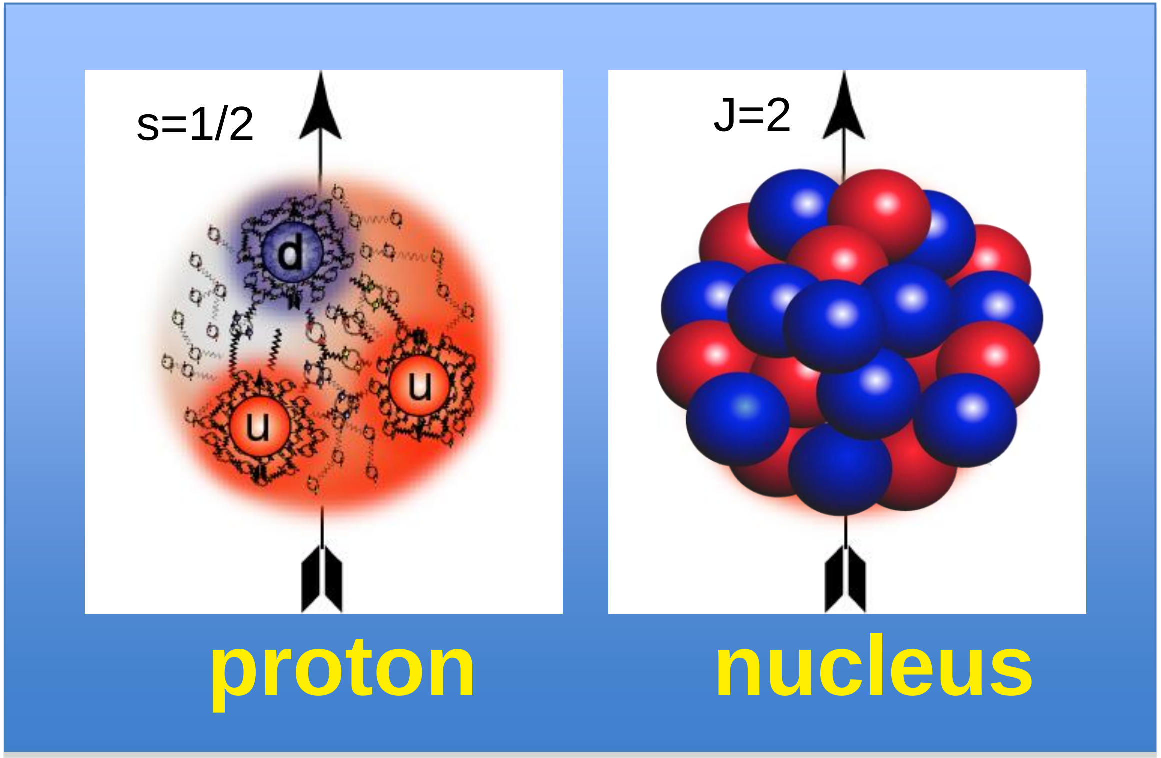




number of nuclei < number of processors!

Science: Overarching Themes

The Structure



hadron spectroscopy

•"missing" resonances (N*)
•glueballs, hybrids, exotic hadrons…
•collective excitations

The origin of confinement
The origin of mass, spin
Quantum numbers and symmetries

nuclear spectroscopy

•weakly bound nuclei and resonances
•exotic nuclear states
•collective excitations

The origin of binding,
The origin of binding, spin
Quantum numbers and symmetries

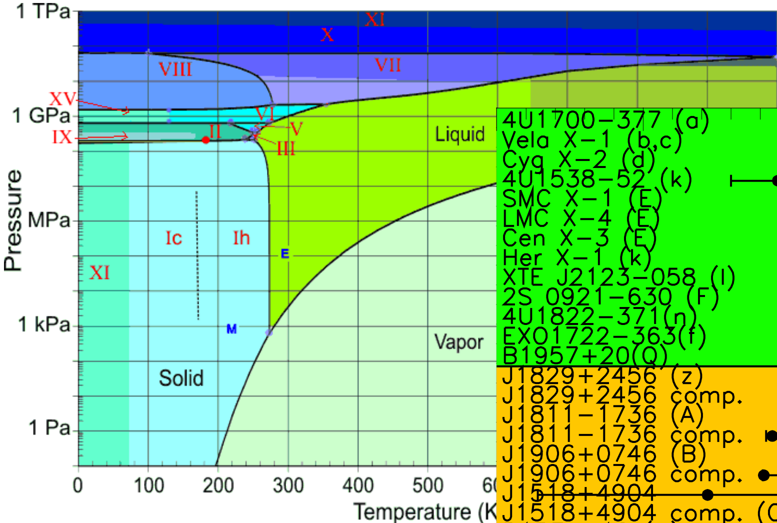
Phases, Phase Transitions, Emergent Behavior

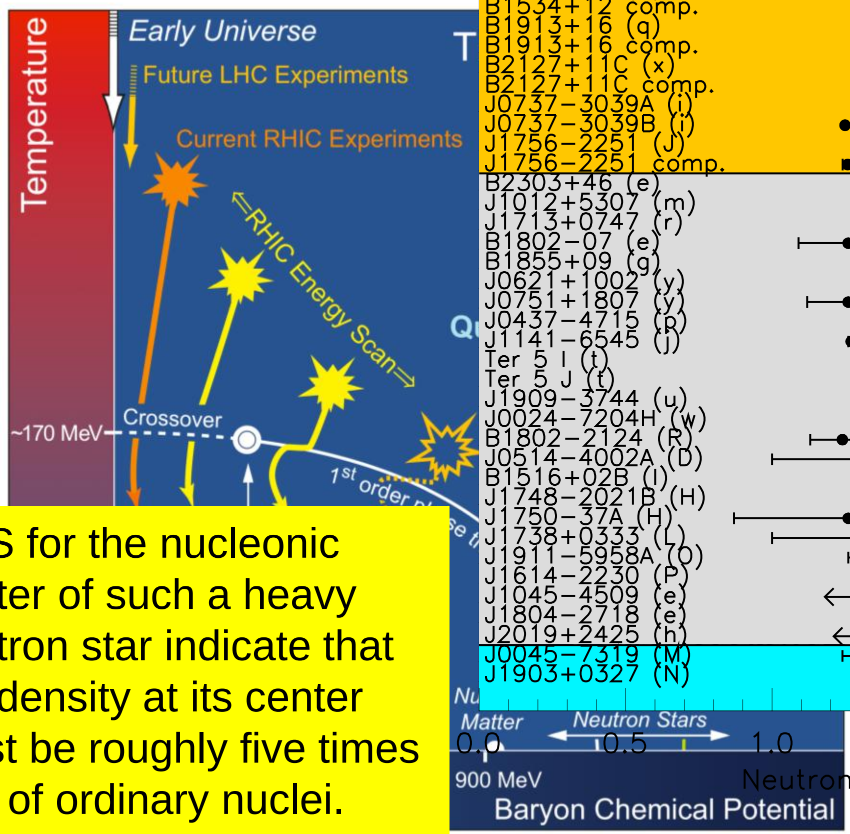
How do complex systems and patterns arise out of a multiplicity of elementary interactions?

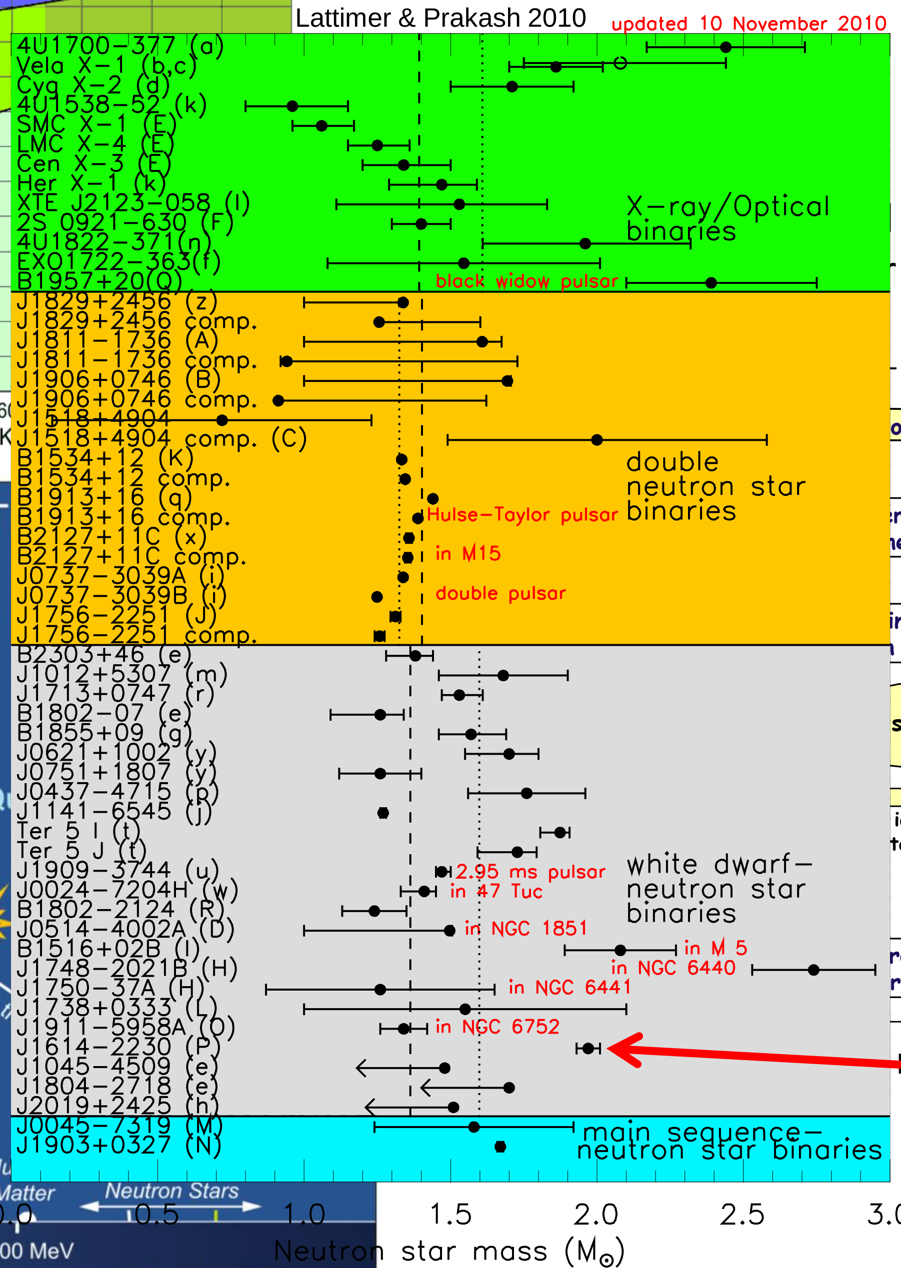
What symmetries are broken spontaneously and what are the corresponding collective modes/Goldstone bosons?

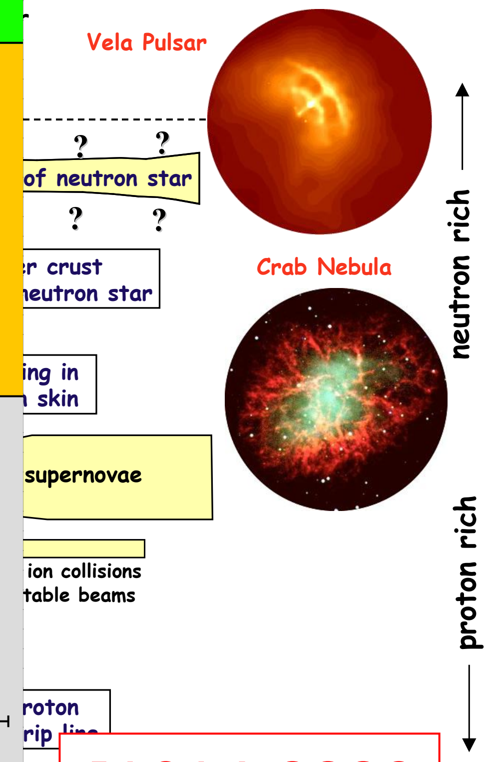
How can we best characterize emergent behavior of strongly interacting matter?

- Quark masses
- Collective states of hadrons (Roper resonance)
- Variety of nuclear shape and spin deformations
- Quark-gluon fluid created in heavy ion collisions
- Nucleonic and quark superconductivity
- …







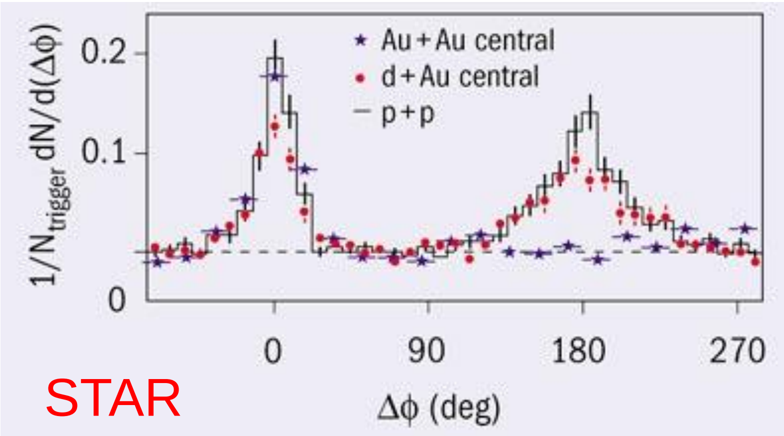


J1614-2230
1.97 ± 0.04

EOS for the nucleonic matter of such a heavy neutron star indicate that the density at its center must be roughly five times that of ordinary nuclei.

Particle Correlations/distributions

Detailed, high quality measurements enabled by technical advances

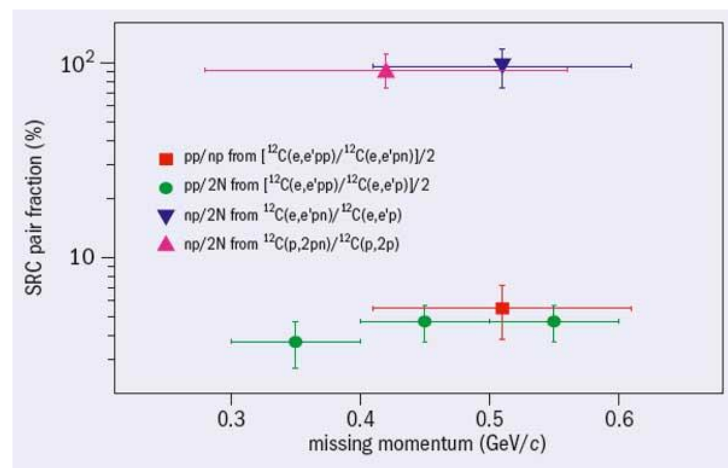


jet quenching

the observed deficit of high-energy jets in Au+Au collisions is the result of quenching the most energetic quarks as they propagate through a newly formed medium (a dense quark-gluon plasma).

two-nucleon knockout

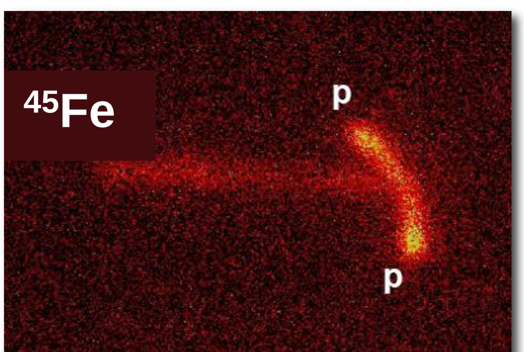
Dominance of proton–neutron pairs at intermediate range (c.o.m. momenta around 400 MeV/c). Explained by the tensor force.

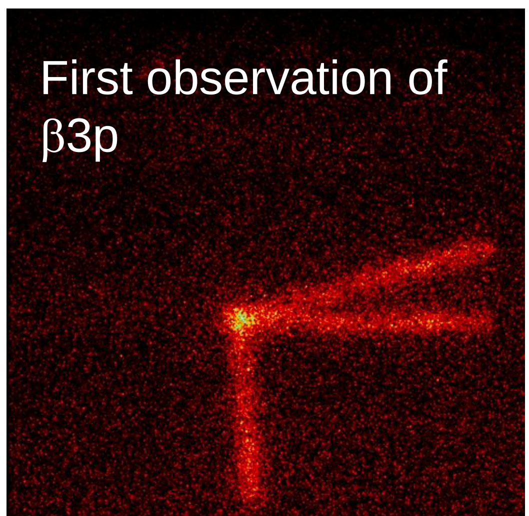


R Subedi et al. Science 320, 1475 (2008)

two-proton decay

Digital photography of the ground-state 2-proton emitter ^{45}Fe

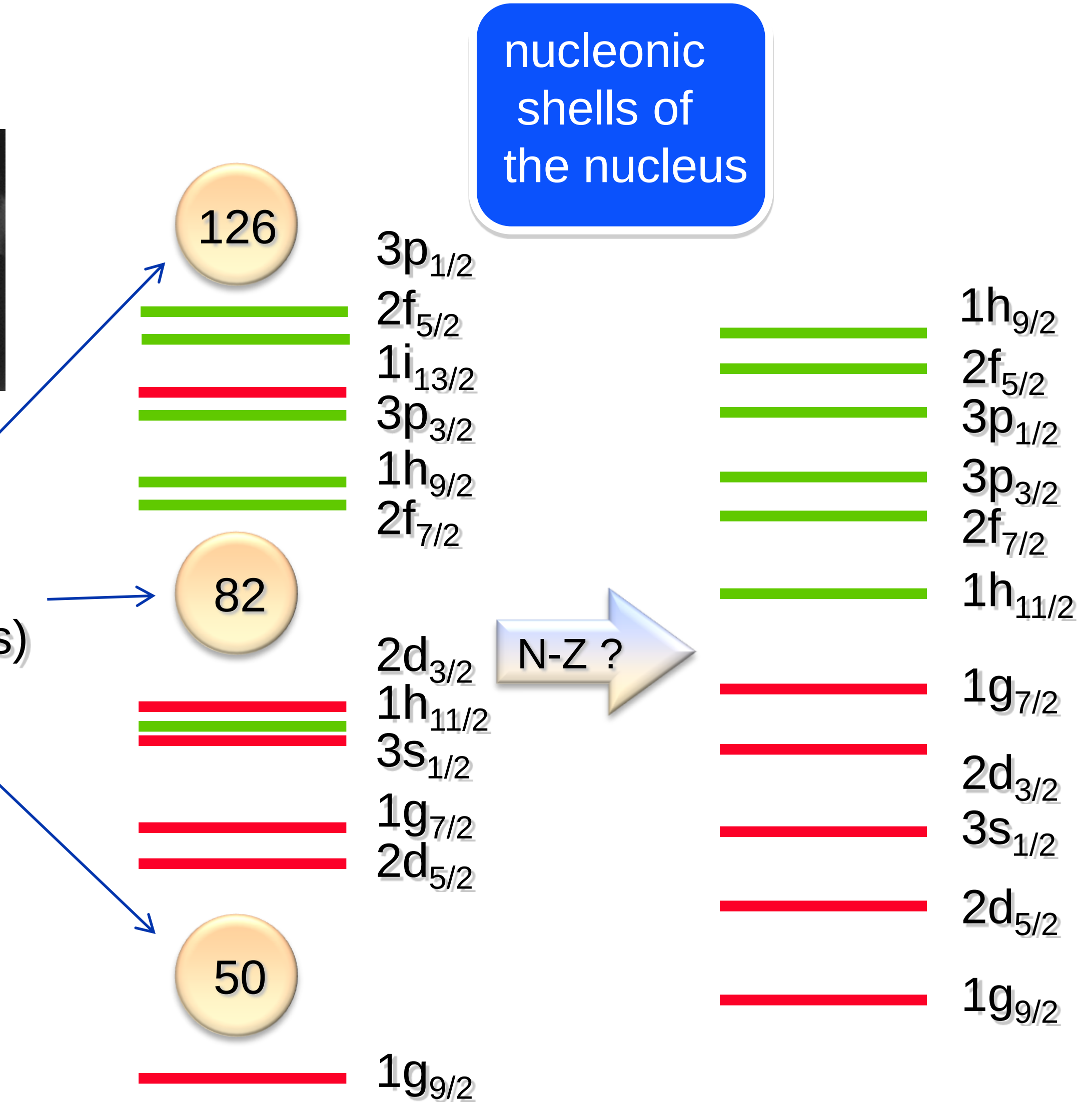




Miernik et al. PRL 99, 192501 (2007) and PRC 76, 041304 (2007)

Science: Rare Isotopes

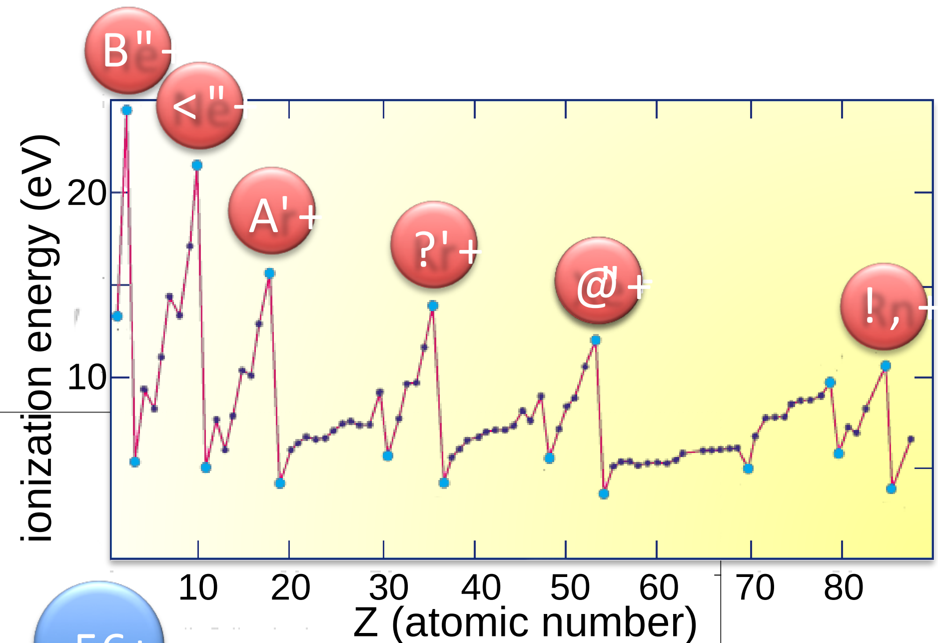
1949

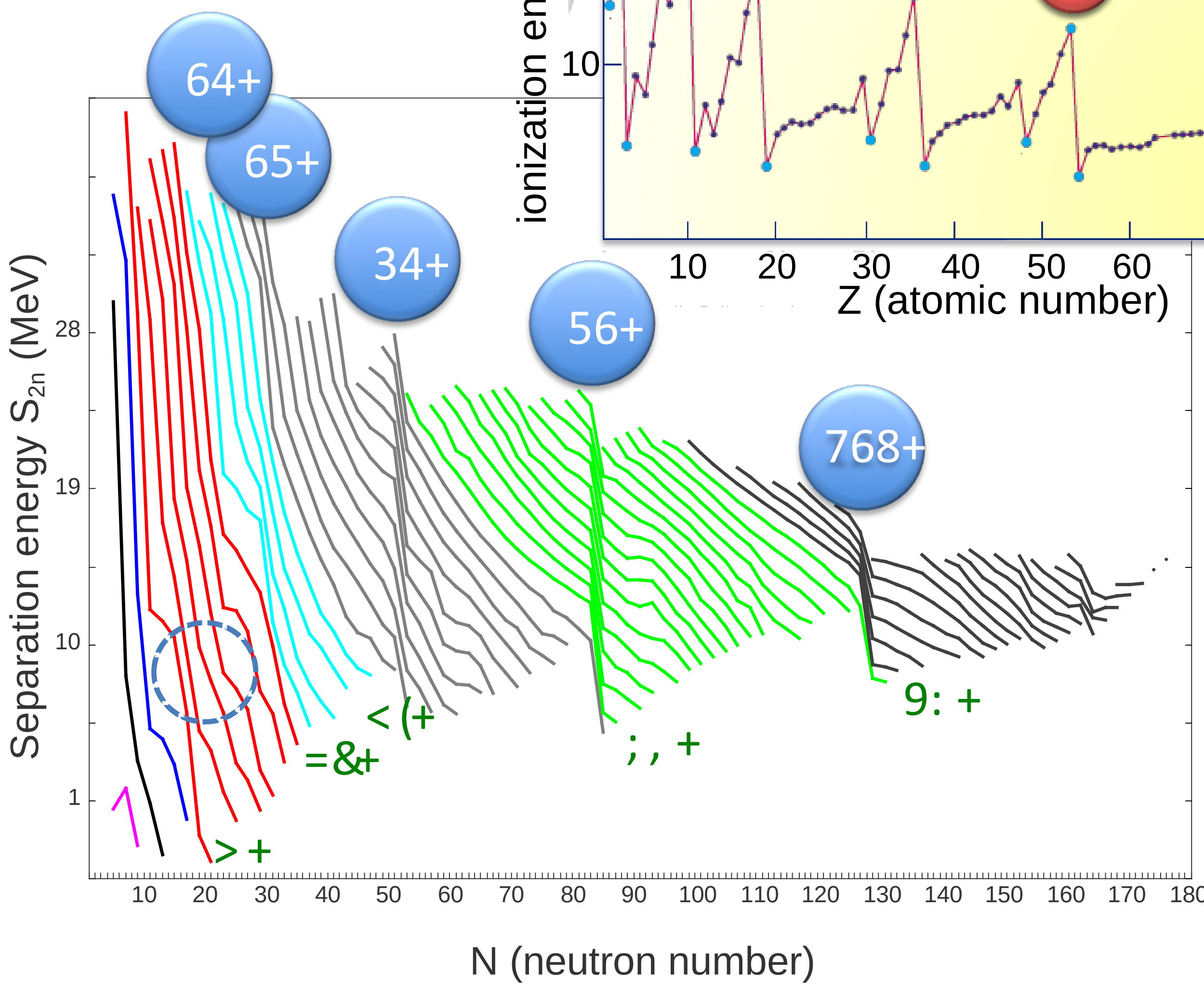


Magicity is a fragile concept

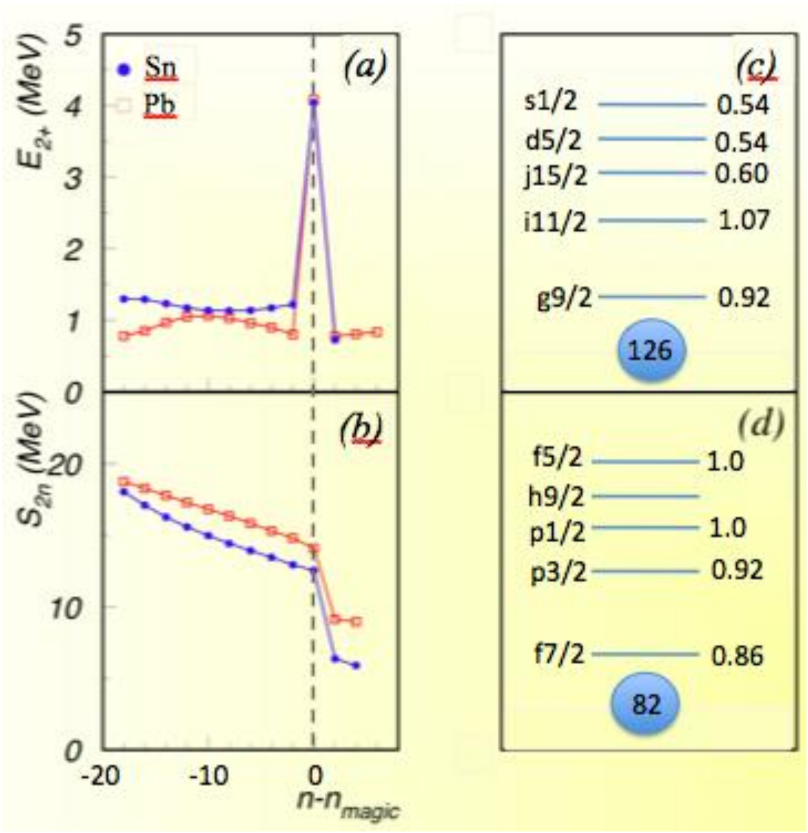
Near the drip lines nuclear structure may be dramatically different.

! " #$%&' () " *+&, - +
. " ' (/ - (0() " *+(, +
&1/ 2 *+&, - +, $0%(+

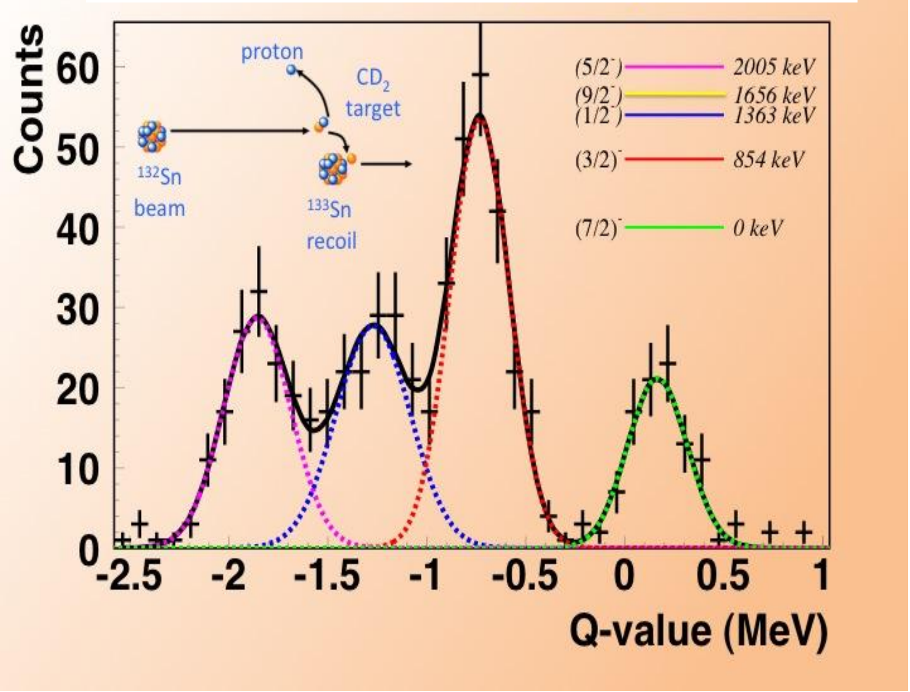

B" -
<" -
A' +
?' +
@' +
! , +
ionization energy (eV)
20
10
10
20
30
40
50
60
70
80
Z (atomic number)


64+
65+
34+
56+
768+
Separation energy S_{2n} (MeV)
28
19
10
1
> +
=&+
< (+
; , +
9: +
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
N (neutron number)

^{132} Sn region



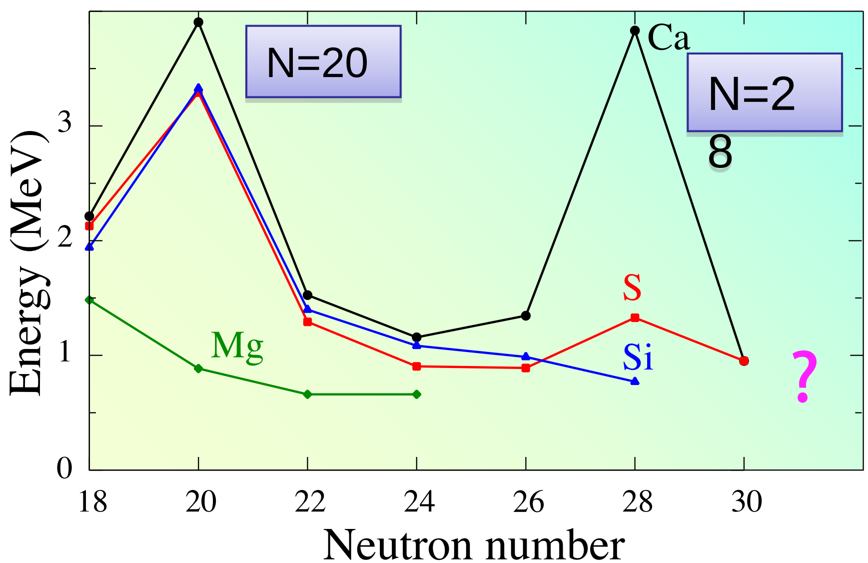
K. Jones et al., Nature 465, 454 (2010)



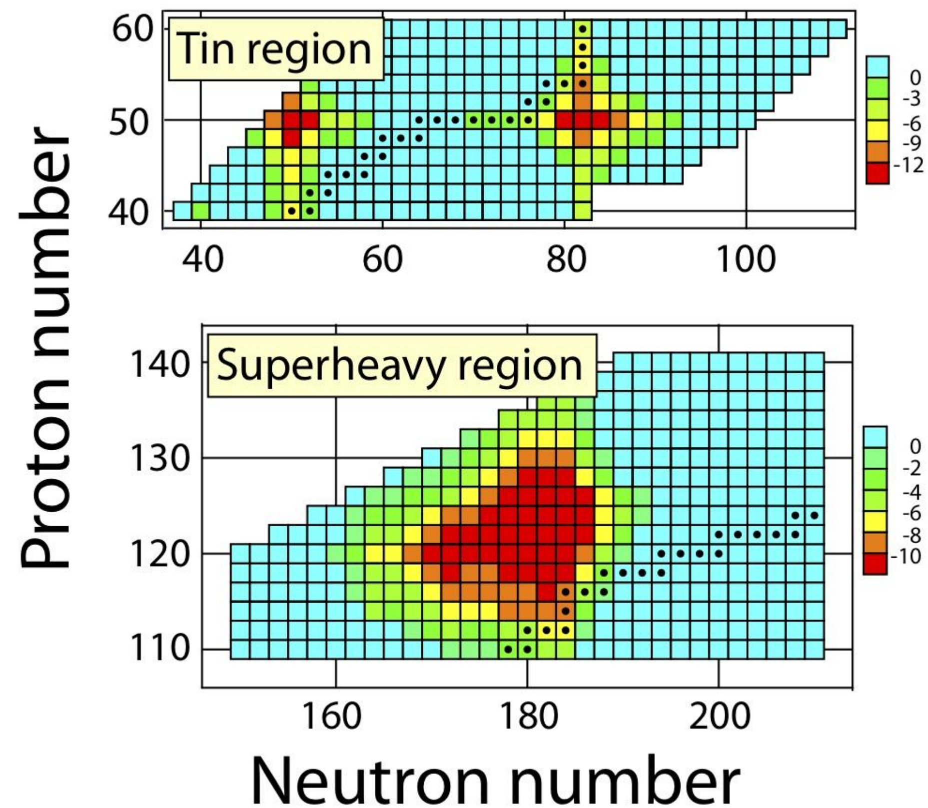
Old paradigms revisited. Crucial input for theory

Shell structure: a moving target

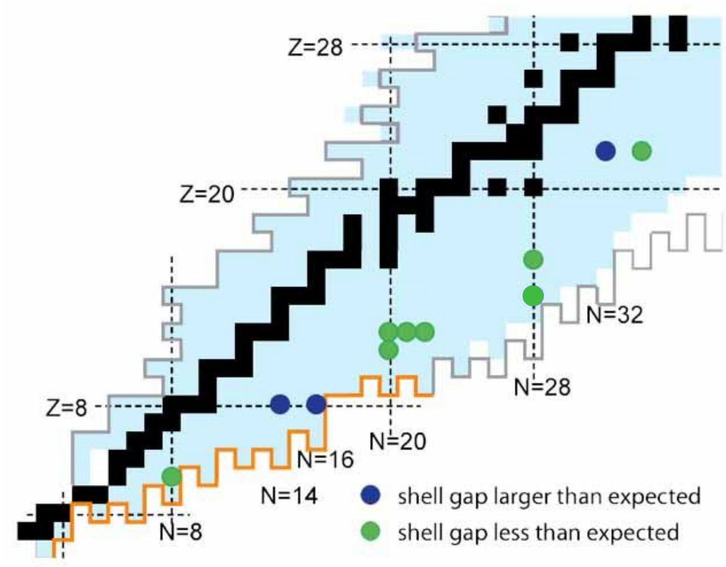
2^+ levels in neutron-rich nuclei



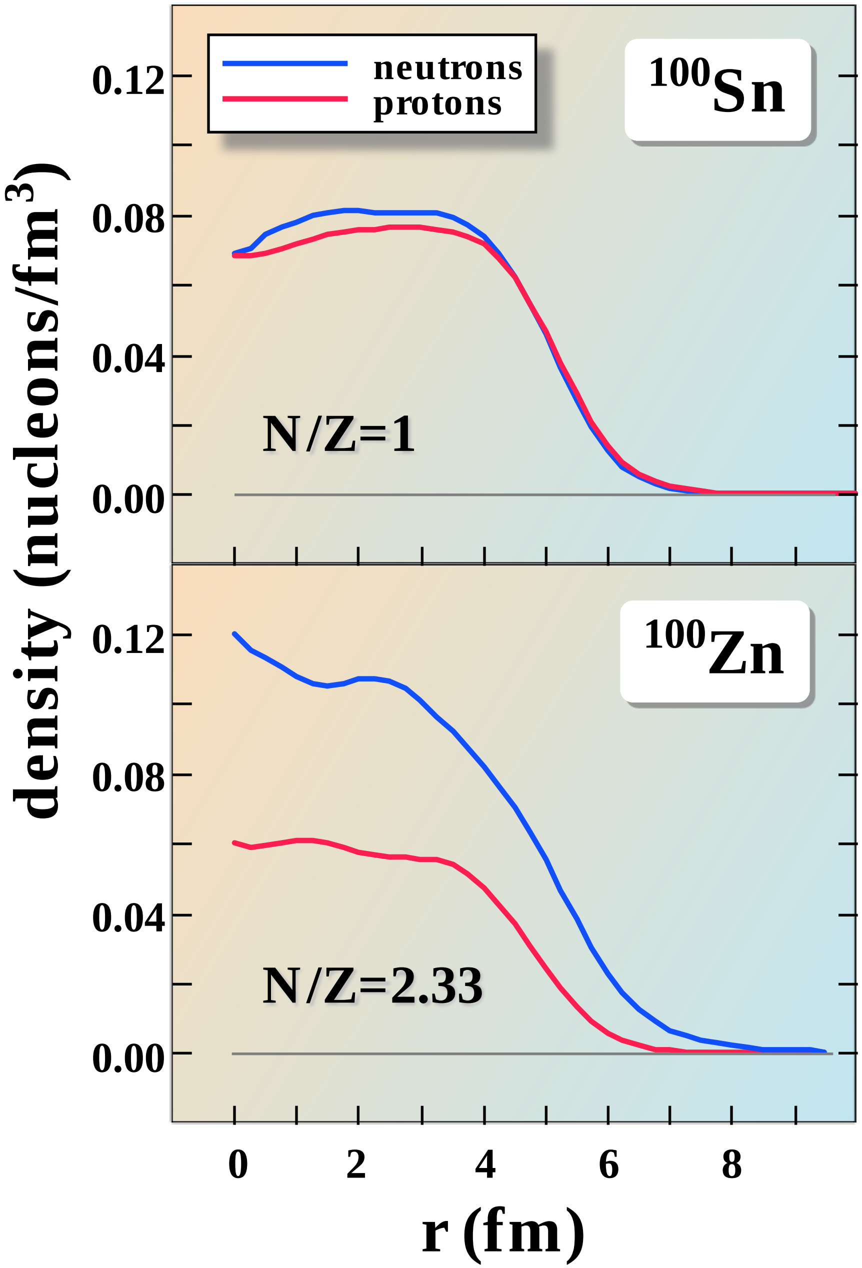
Shell energy



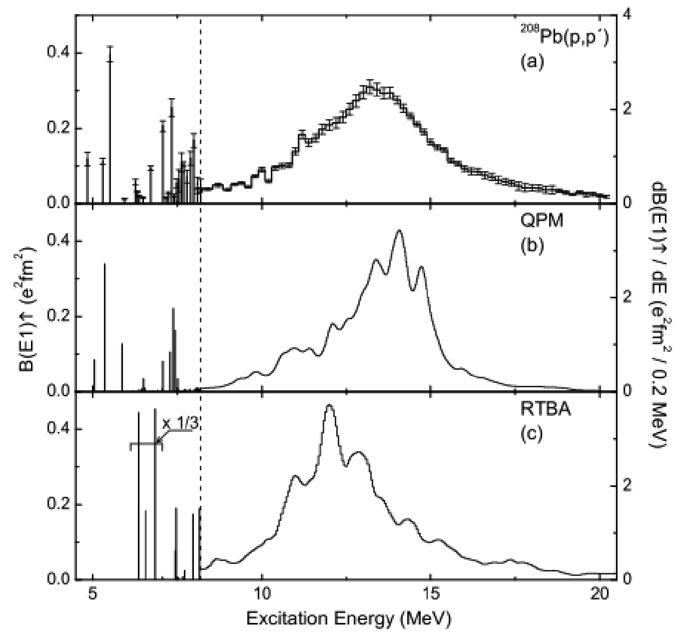
M. Bender et al.
Phys. Lett. B 515, 42–48 (2001)

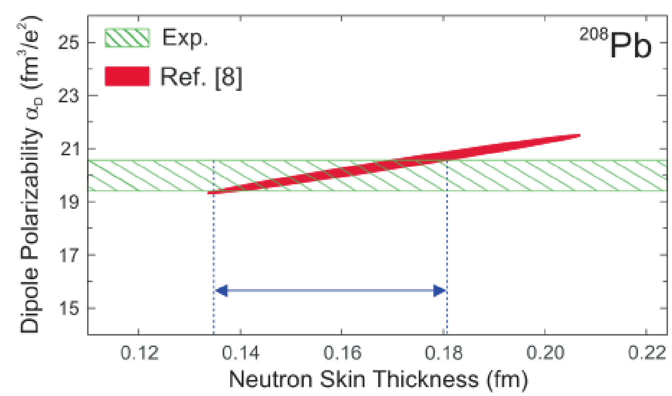


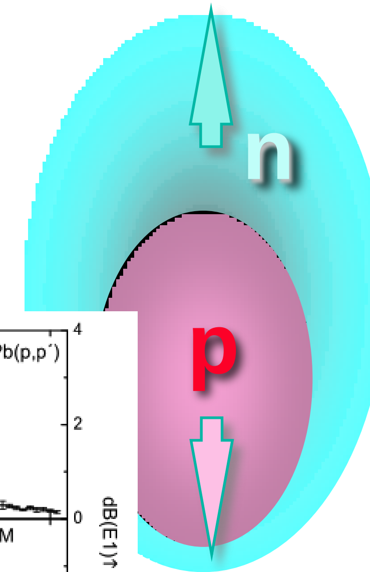
Neutron skins



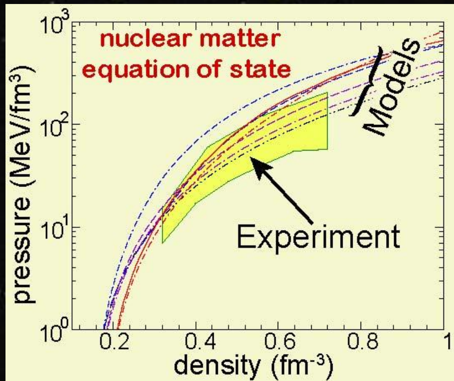
Tamii et al., Complete electric dipole response and the neutron skin in 208Pb, PRL in press

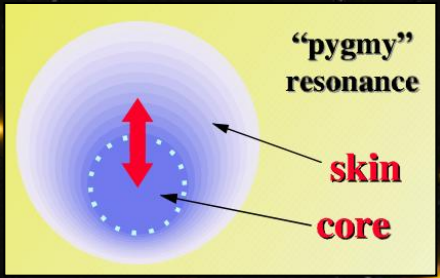




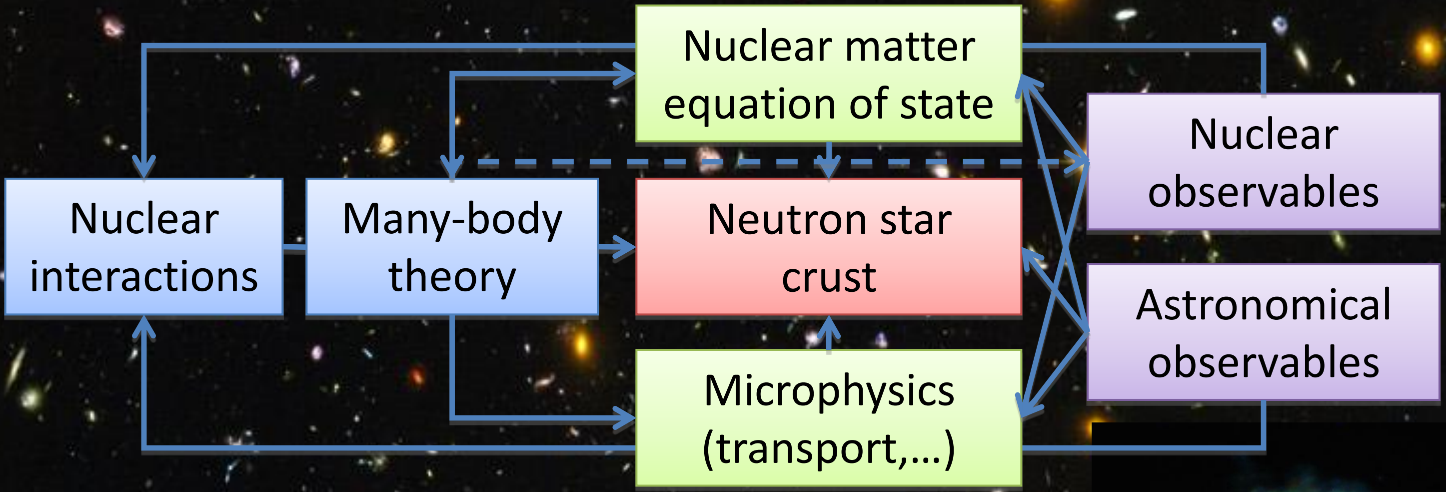


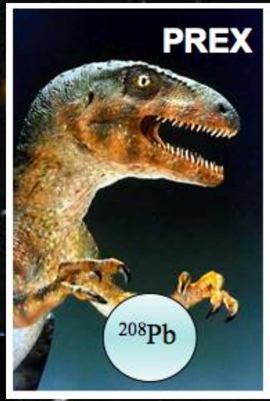
Quest for understanding the neutron-rich matter on Earth and in the Cosmos

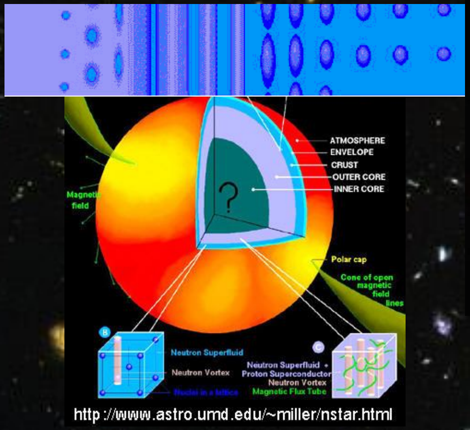


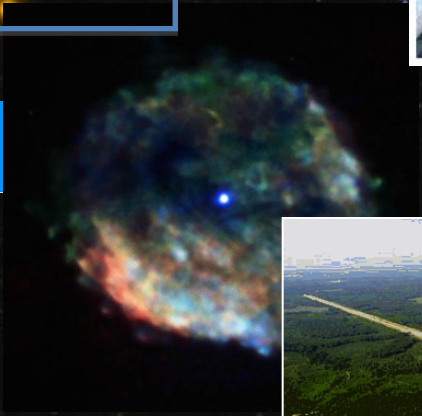


RNB facilities

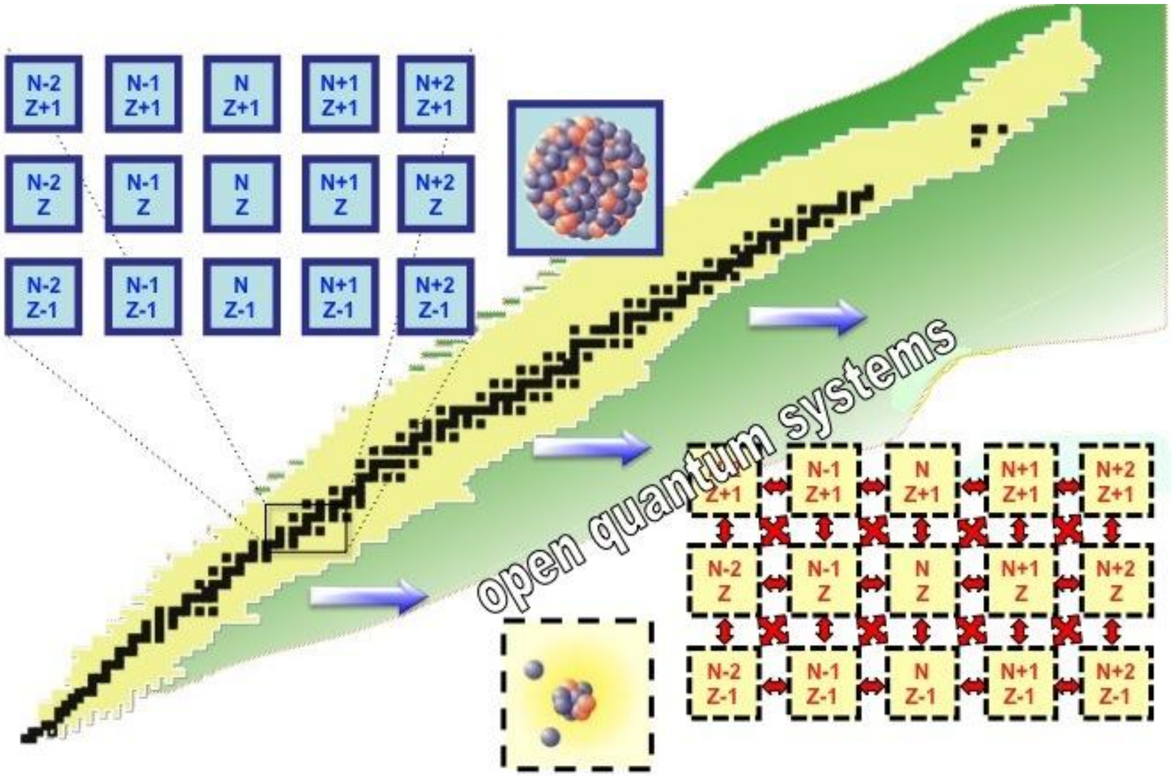


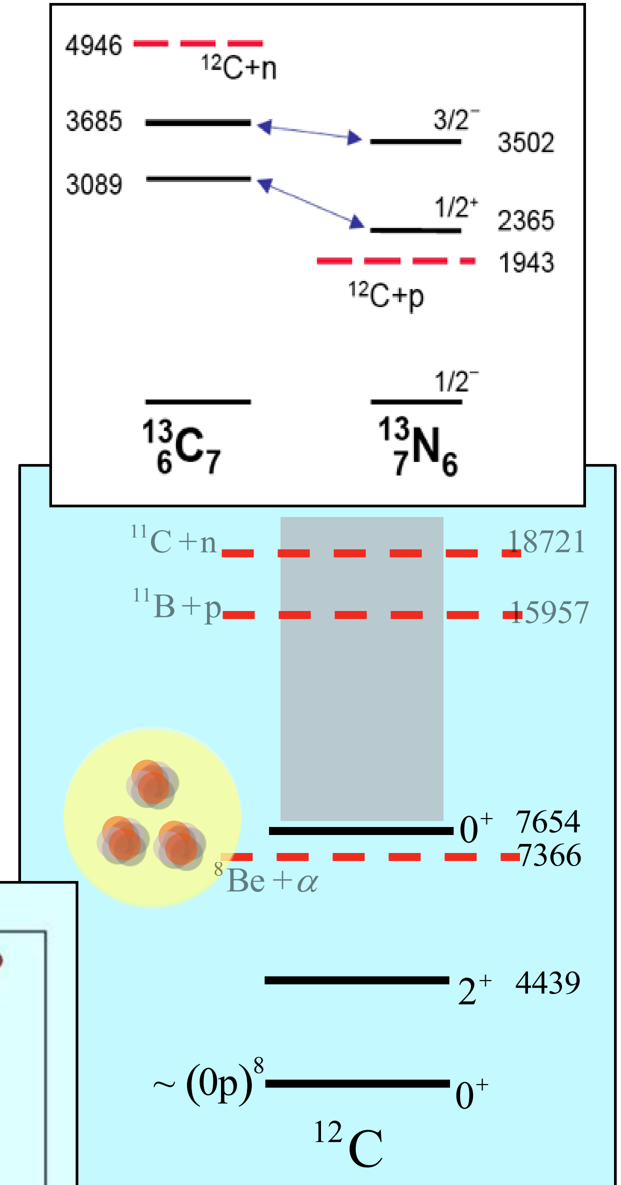


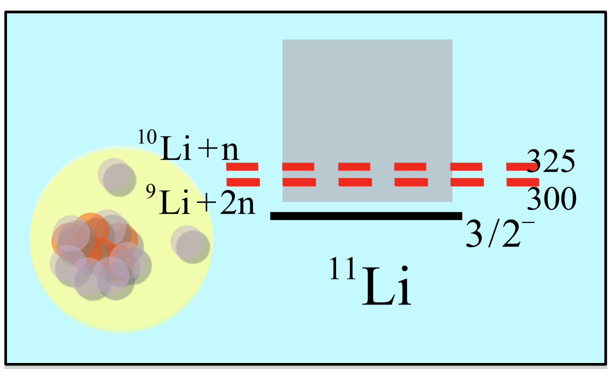


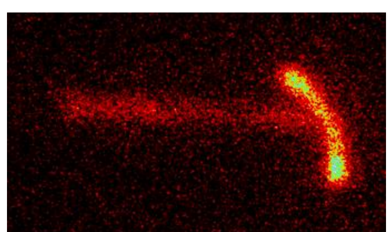


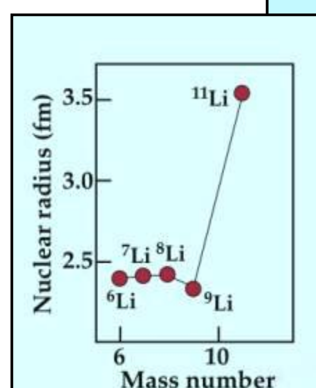
Nucleus as an open quantum system



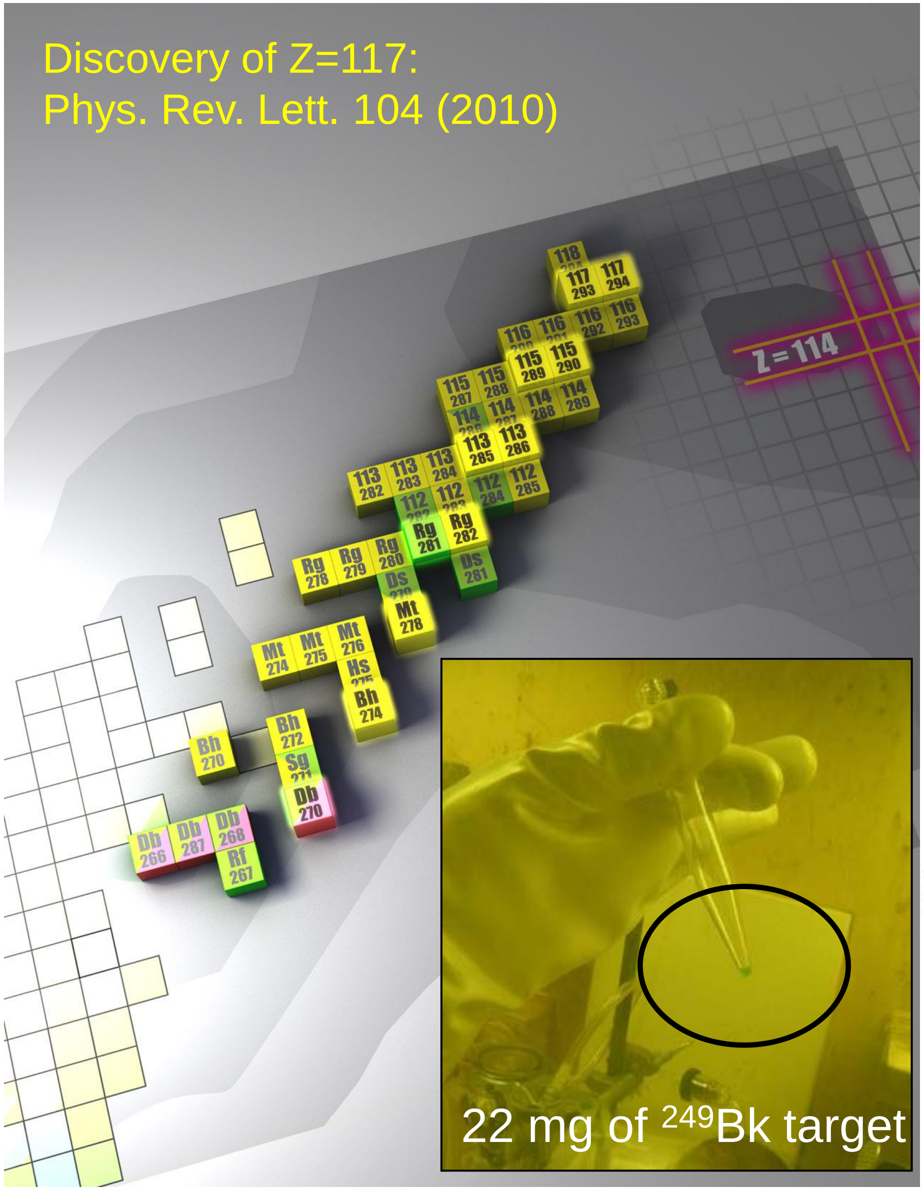


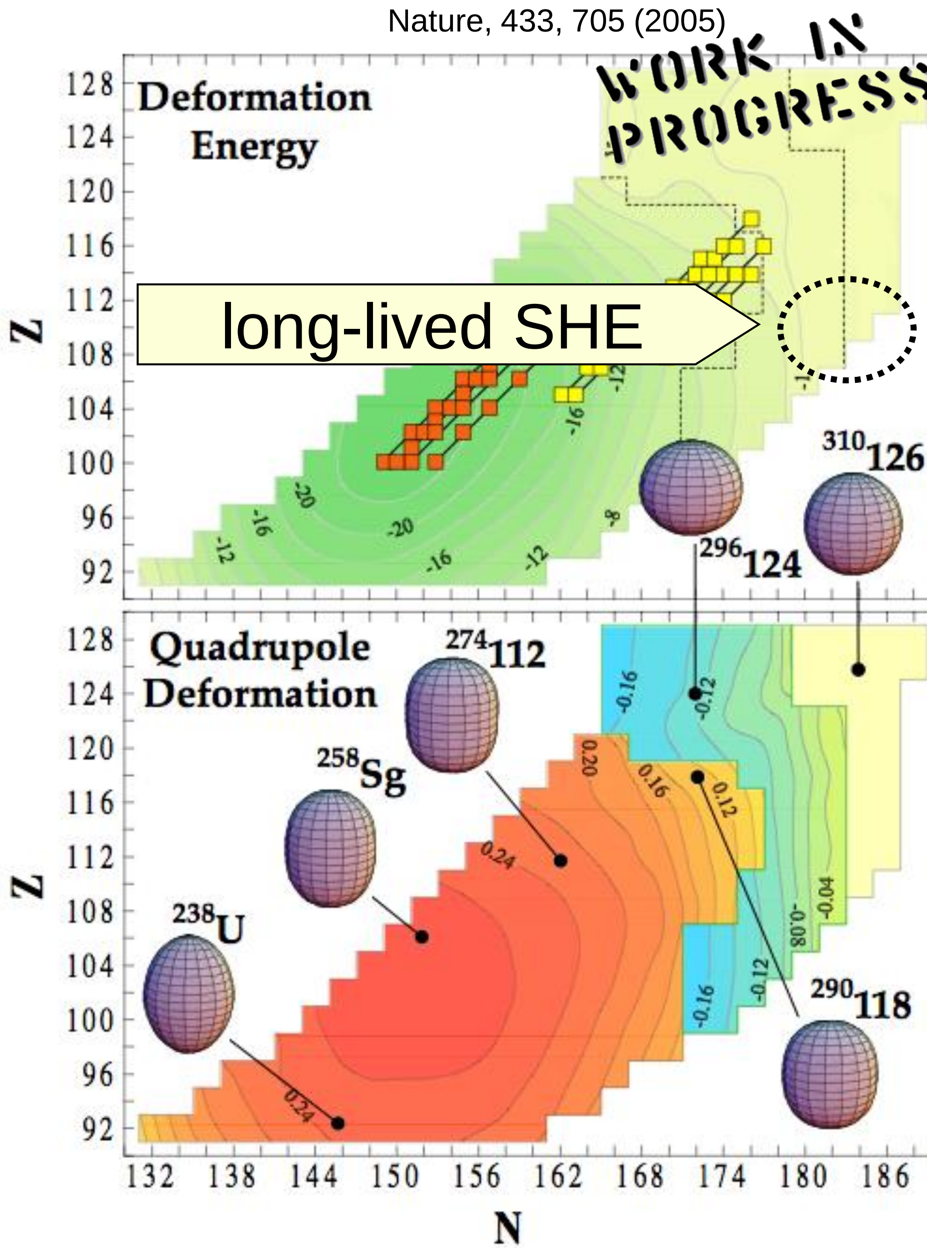




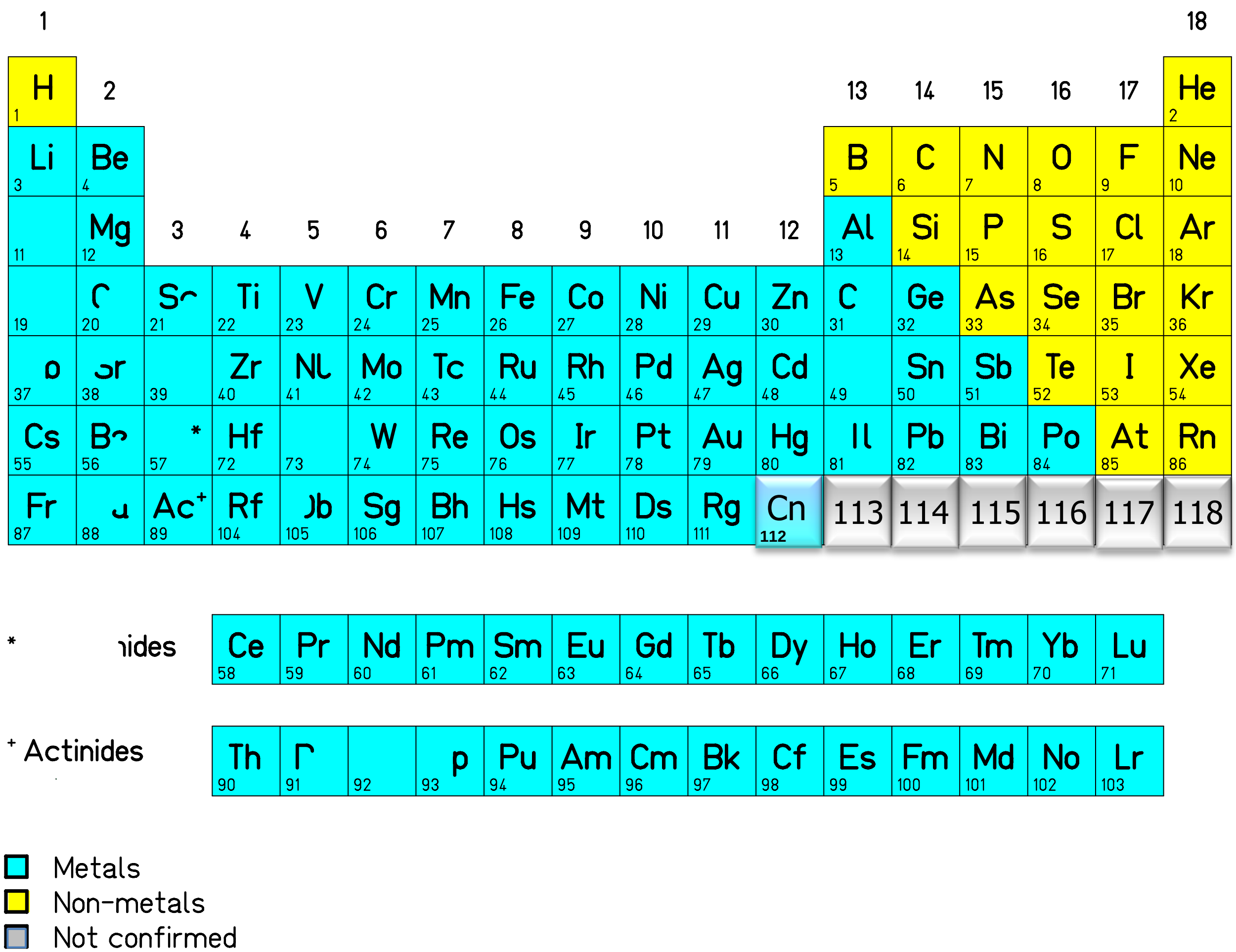


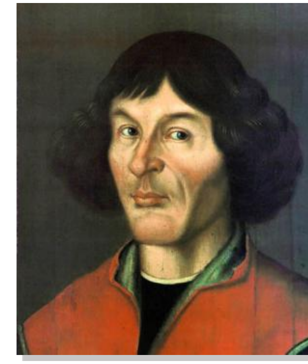
Limits of Mass and Charge: Superheavies

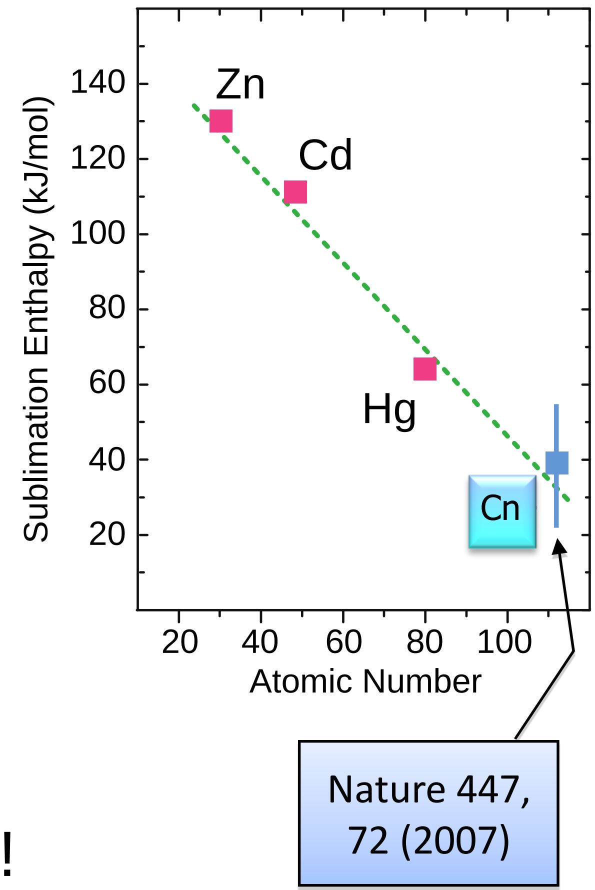




Periodic Table of Elements 2011





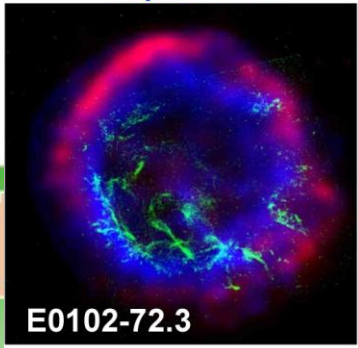


Z=112: Copernicium
very volatile noble metal!

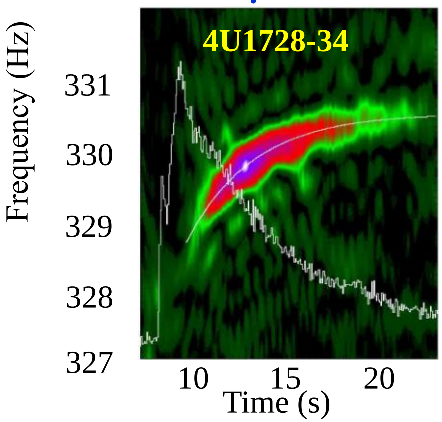
How does the physics of nuclei impact the physical universe?

- What is the origin of elements heavier than iron?
- How do stars burn and explode?
- What is the nucleonic structure of neutron stars?

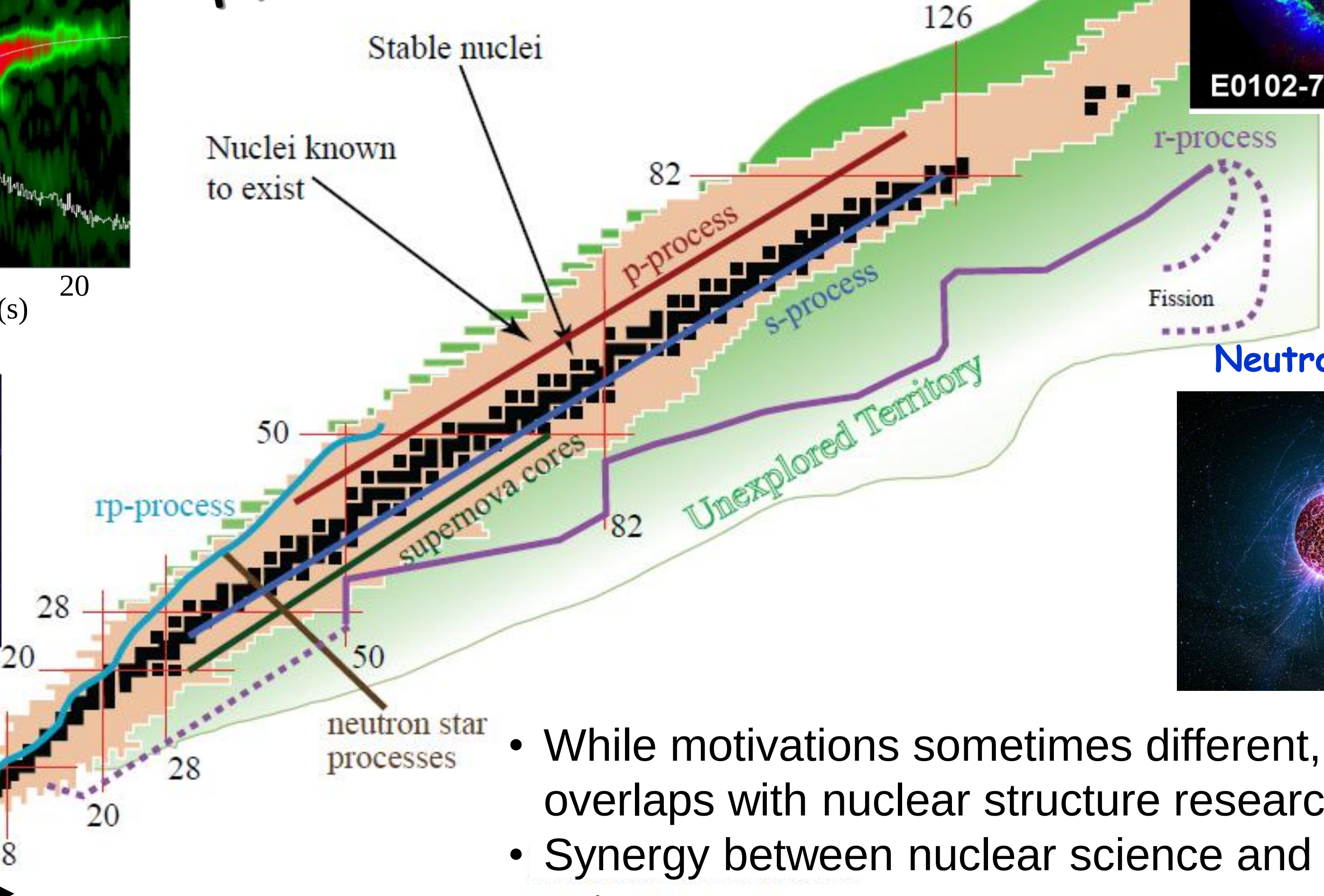
Supernova



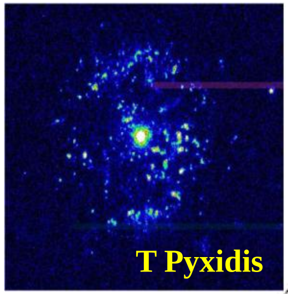
X-ray burst



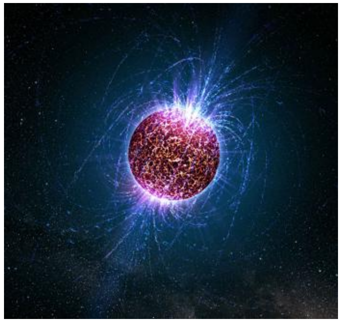
WORK IN PROGRESS



Nova



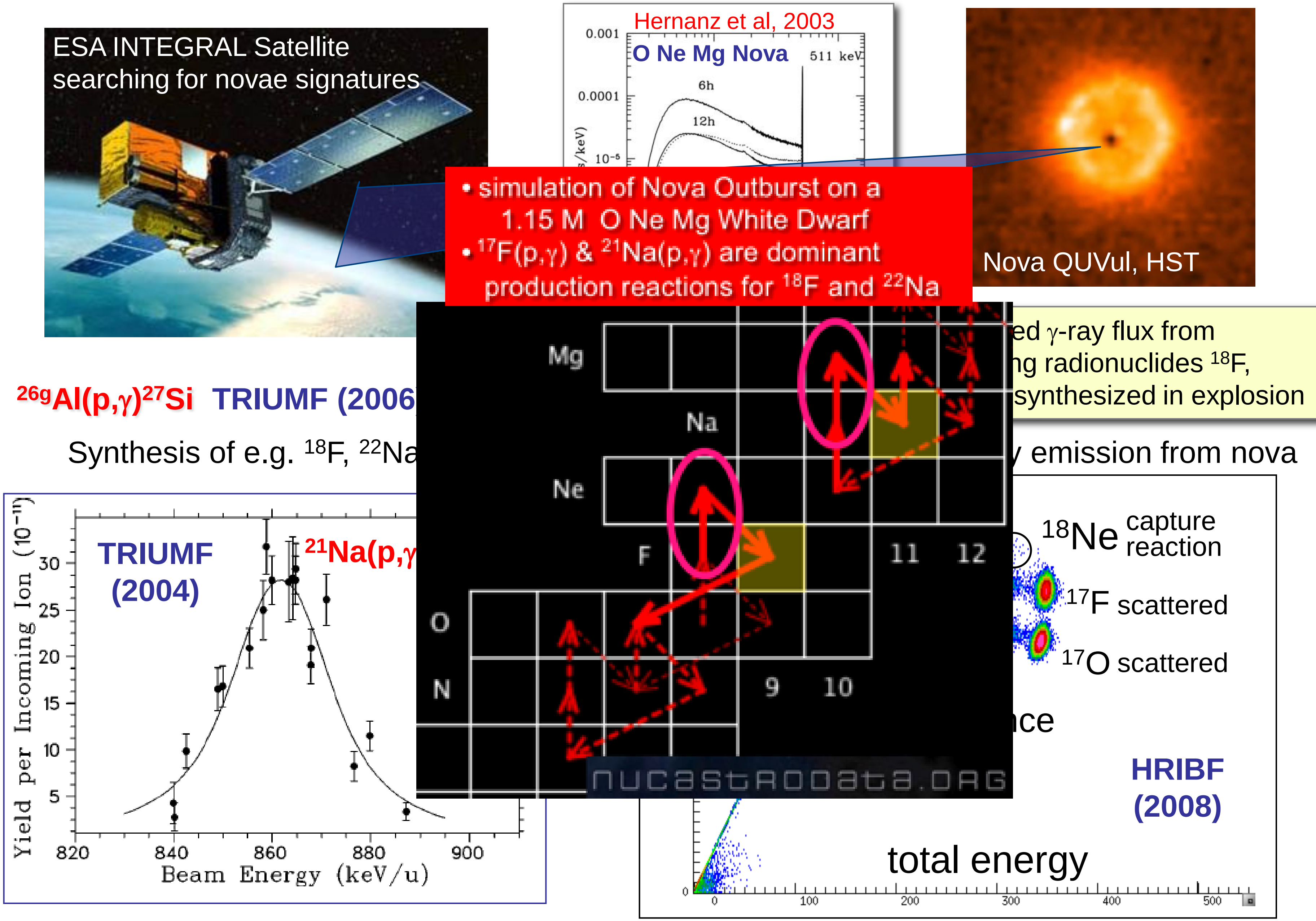
Neutron star



- While motivations sometimes different, huge overlaps with nuclear structure research
- Synergy between nuclear science and astronomy

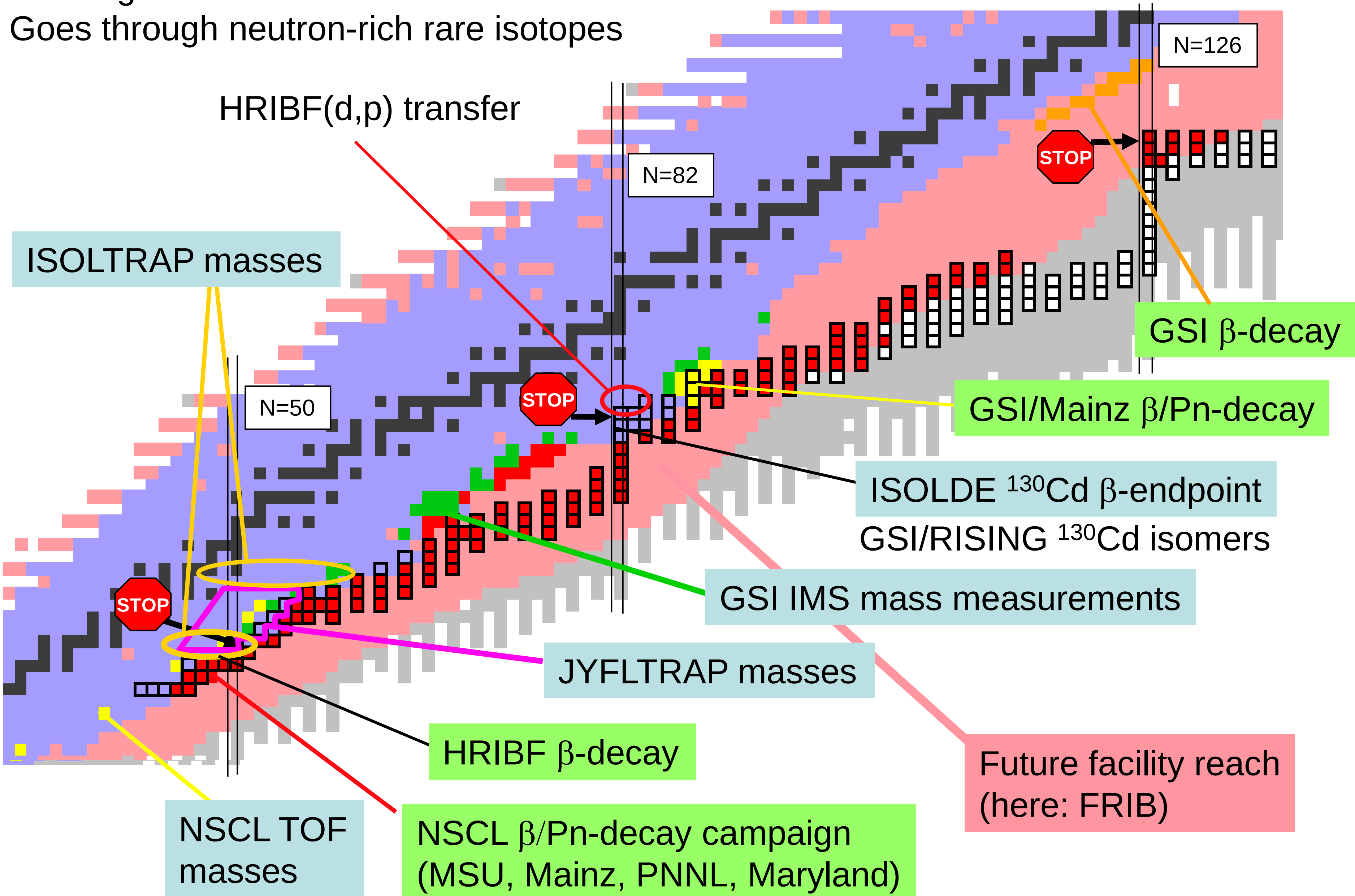
Rare isotope measurements for novae

Example of synergy between nuclear science and astronomy

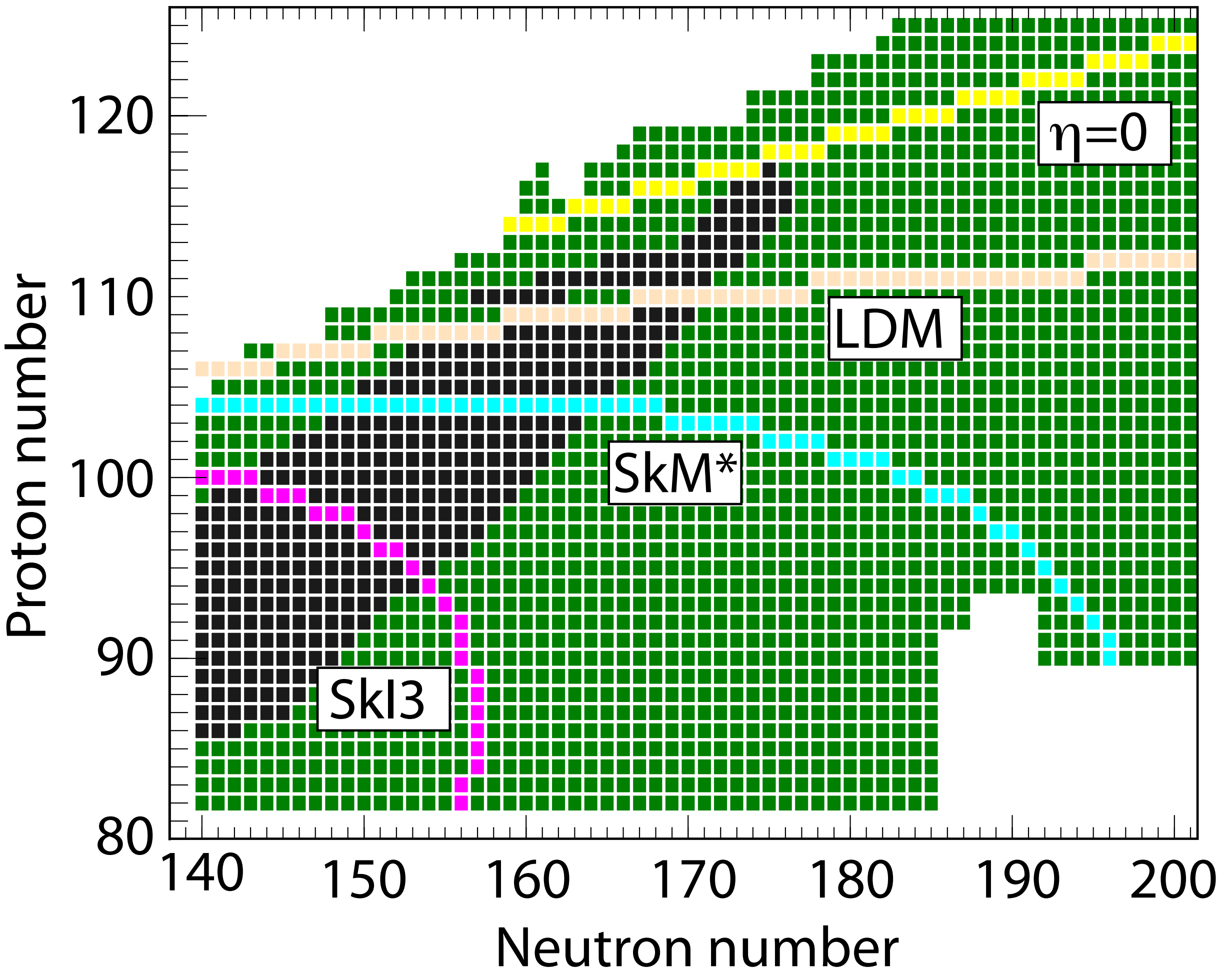


Example: r (apid neutron capture) process

- The origin of about half of elements heavier than iron
- Goes through neutron-rich rare isotopes



Surface symmetry energy and fission



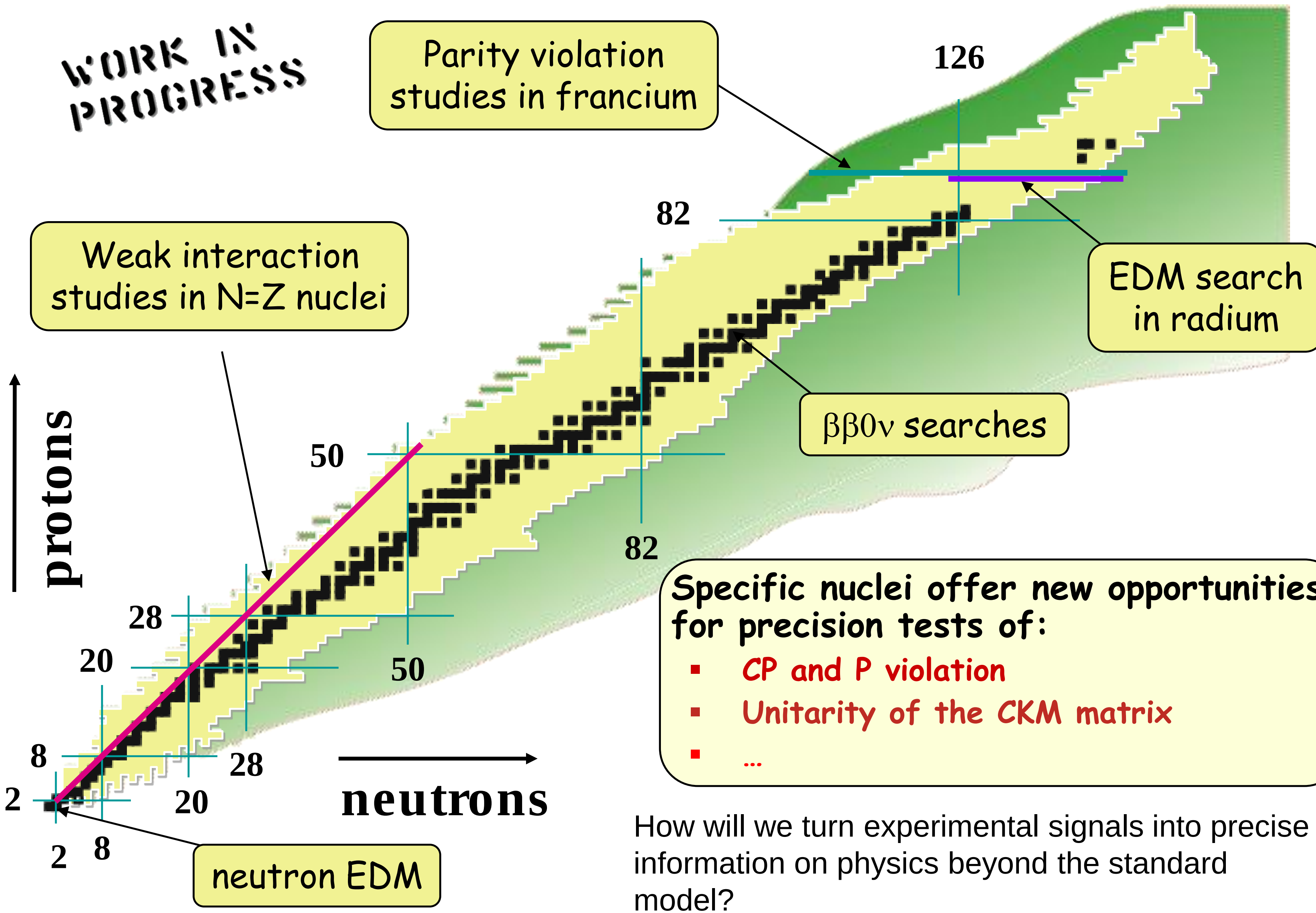
fissility parameter

$$x = \frac{E_{\mathrm{Coul}}(\mathrm{sph})}{2E_{\mathrm{surf}}(\mathrm{sph})} \approx \frac{Z^2}{47A\,(1-\eta I^2)}$$

$$\eta \equiv -\frac{a_{\mathrm{ssym}}}{a_{\mathrm{surf}}}$$

N. Nikolov et al., Phys. Rev. C 83, 034305 (2011)

Testing the fundamental symmetries of nature



Specific nuclei offer new opportunities for precision tests of:

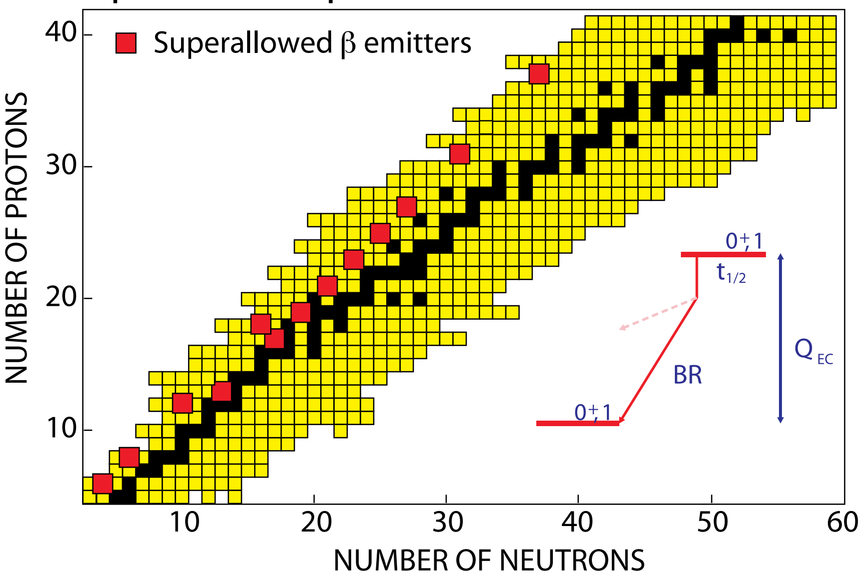
- CP and P violation
- Unitarity of the CKM matrix
- …

How will we turn experimental signals into precise information on physics beyond the standard model?

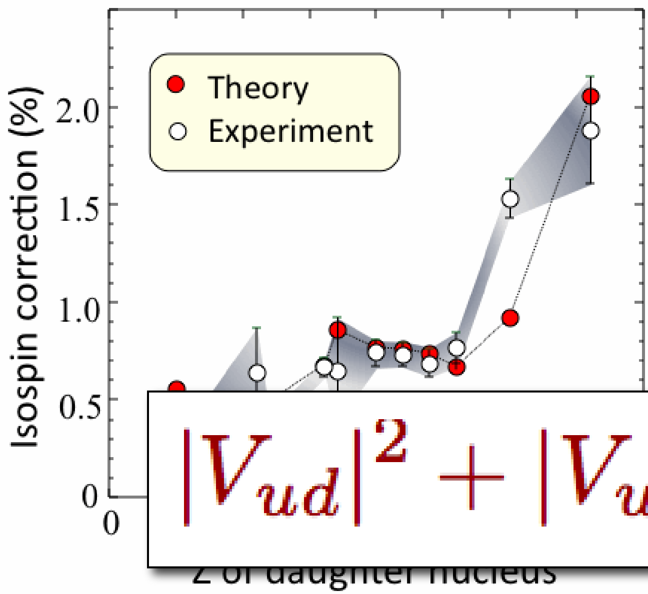
Rare Isotopes, Weak Force, and the 2008 Nobel Prize in Physics

Superallowed Fermi $0^+ \rightarrow 0^+$ β-decay studies

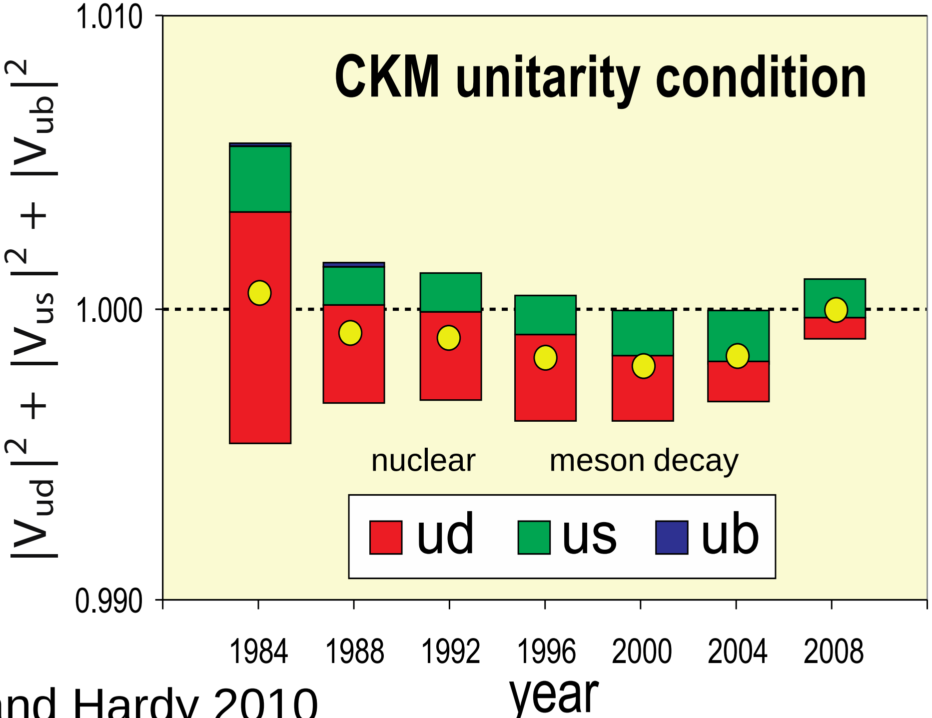
Impressive experimental effort worldwide



W. Satuła et al., PRL 106, 132502 (2011)



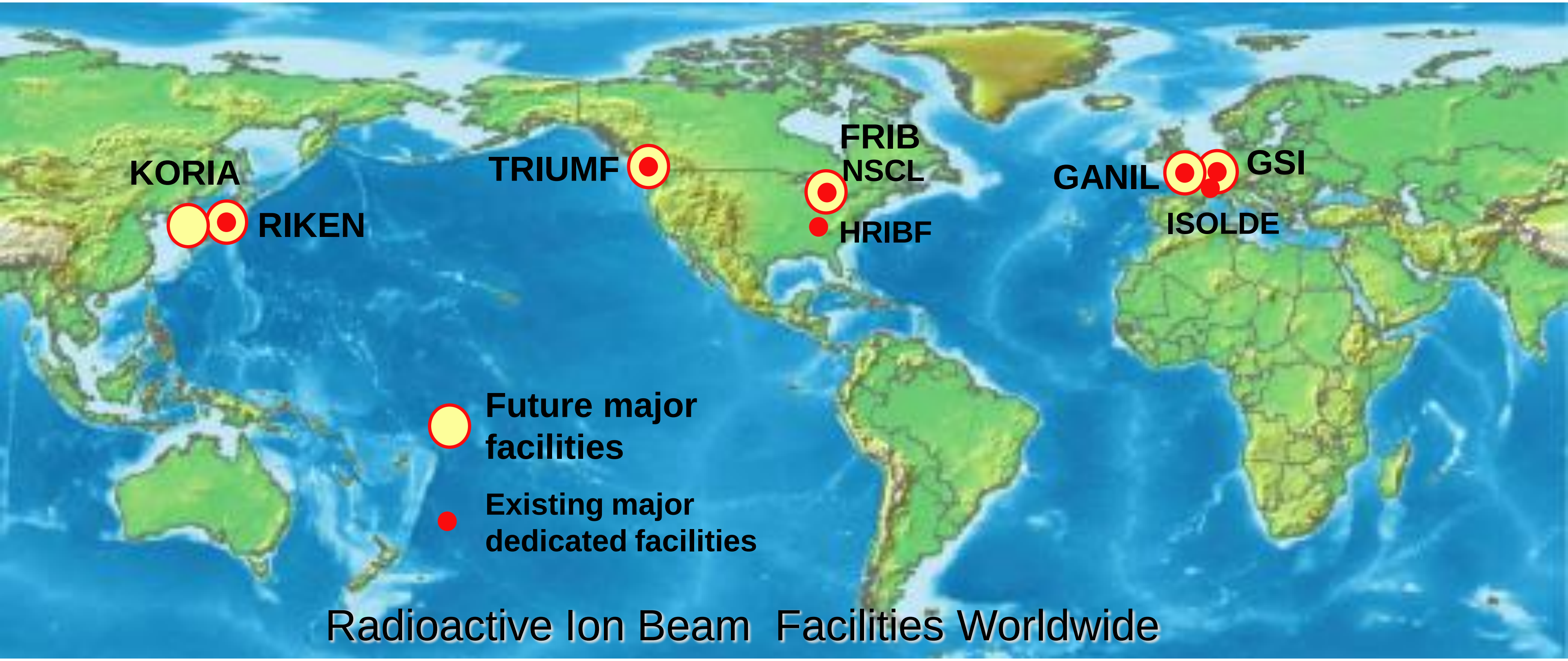
Kobayashi and Maskawa: … for "the discovery of the origin of broken symmetry, which predicts the existence of at least three families of quarks in nature."



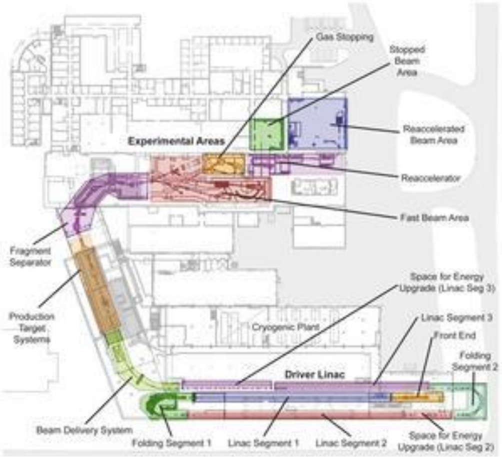
Towner and Hardy 2010

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999(6)$$

Experiment


KORIA
RIKEN
TRIUMF
FRIB
NSCL
HRIBF
GANIL
GSI
ISOLDE
Future major facilities
Existing major dedicated facilities
Radioactive Ion Beam Facilities Worldwide

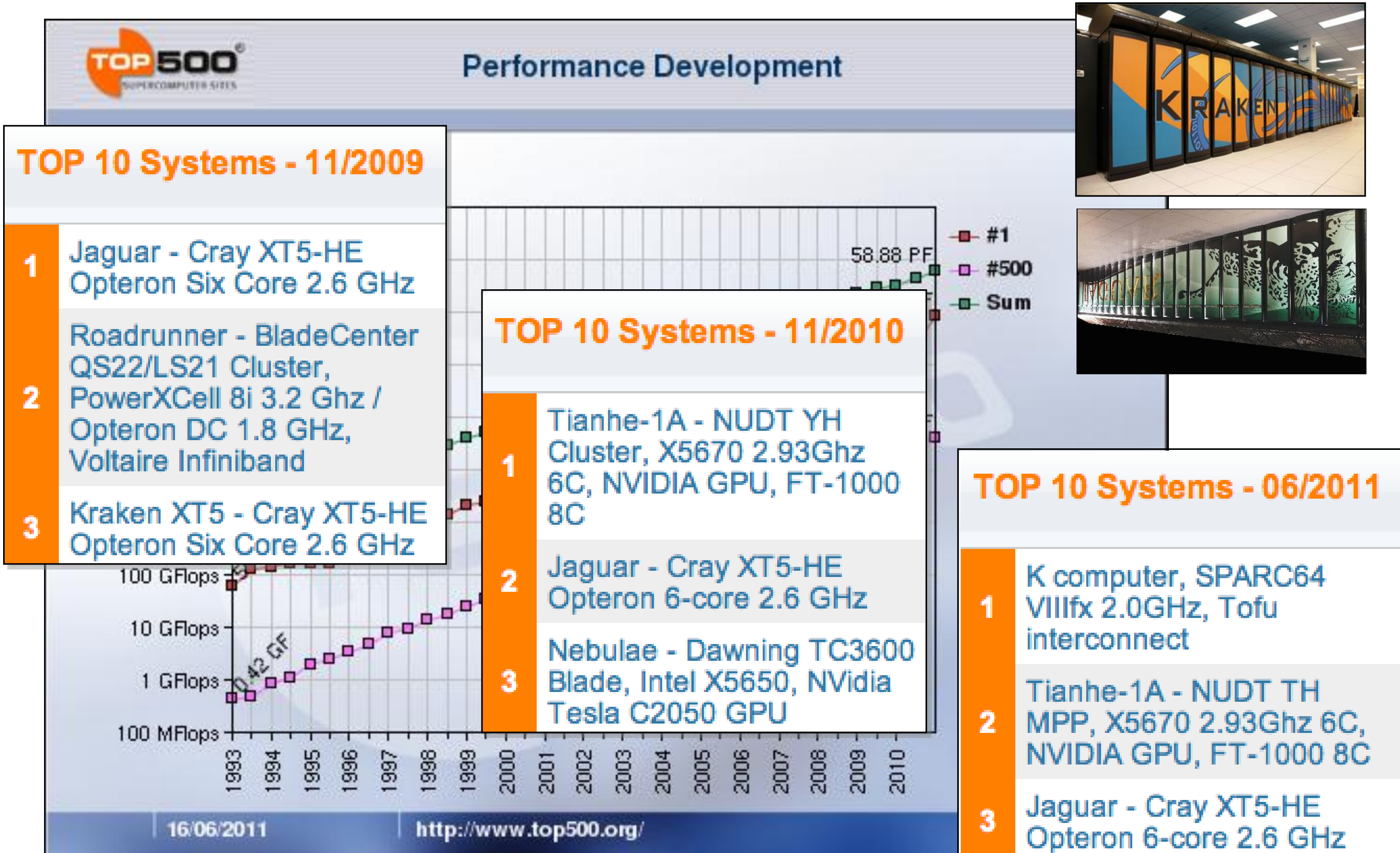

SOUTH SHAW LANE
EXISTING NSCL
BOGUE STREET
EXISTING SOUTH HIGHBAY
CRYOPLANT BUILDING
LINAC SUPPORT BUILDING
WILSON ROAD


Gas Stopping
Stopped Beam Area
Experimental Areas
Reaccelerated Beam Area
Reaccelerator
Fast Beam Area
Fragment Separator
Production Target Systems
Cryogenic Plant
Driver Linac
Beam Delivery System
Folding Segment 1
Linac Segment 1
Linac Segment 2

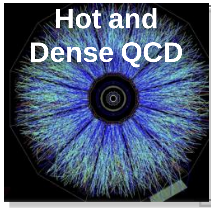
Theoretical Tools and Connections to Computational Science

1Teraflop=10^{12} flops
1peta=10^{15} flops (today)
1exa=10^{18} flops (next 10 years)

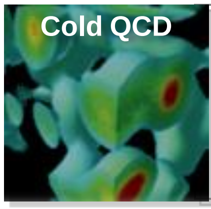
Tremendous opportunities for nuclear theory!



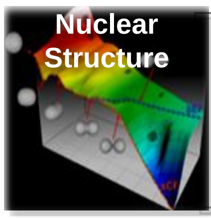
Nuclear Physics Requires Exascale Computing



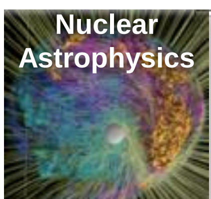
Transport in QCD (quenched)
QCD critical point
Quarkonium spectroscopy
QCD at T>0
High-T limit of QCD EOS
Continuum extrapolated QCD EOS



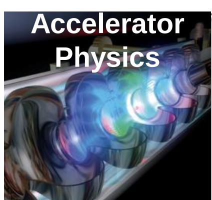
Nucleon Spin
Alpha particle
Nuclear force
Gluon distributions
Deuteron
Neutron EDM
Excited hadron spectrum



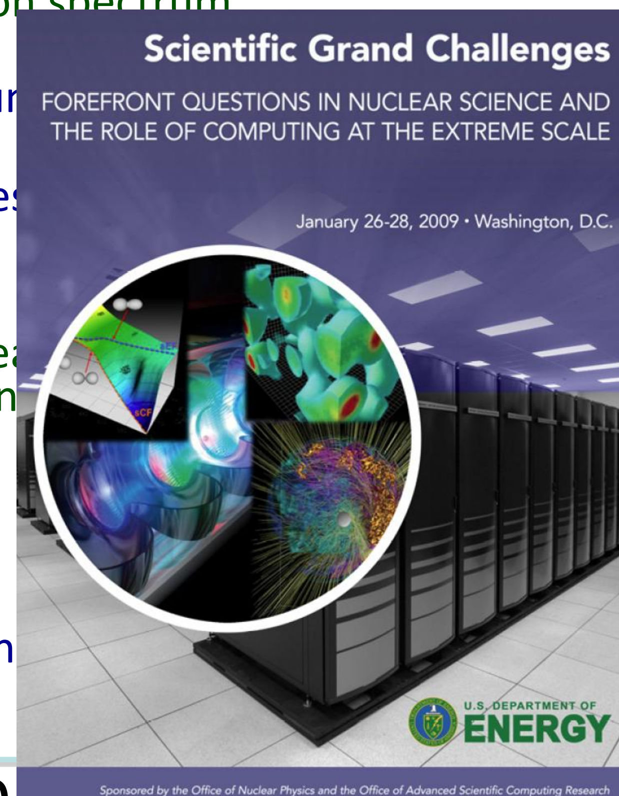
Light nuclei
Weakly bour
Light ion reactions
on
Triple α proces
ust



Global solar model
Precision nucle
Multienergy neutrino tran



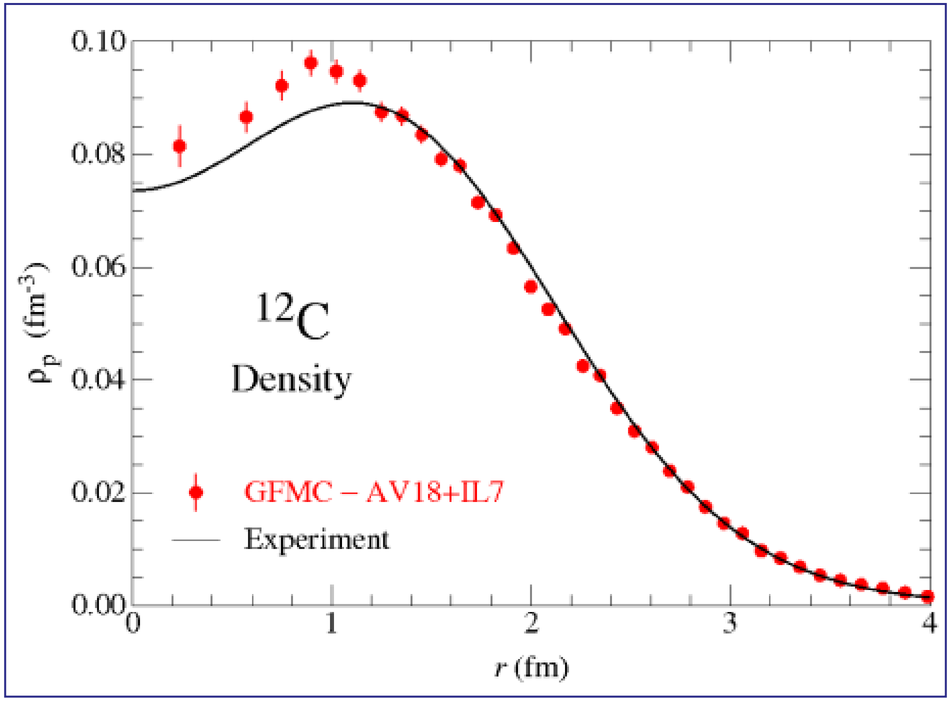
Isotope separator optimization
Electron-coolin

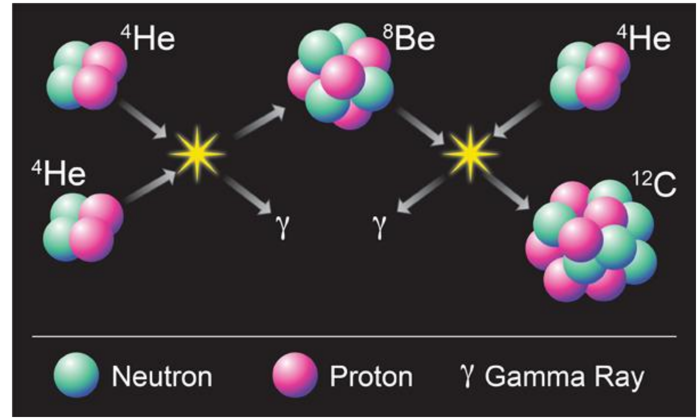


10^{-1} 1 10

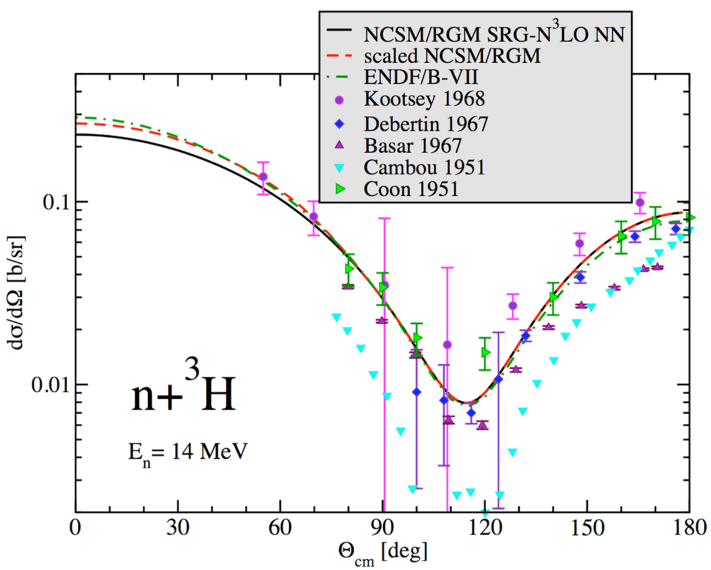
Petaflop-Yrs on Task

Lusk and Pieper, SciDAC Review 2010





The ADLB (Asynchronous Dynamic Load-Balancing) version of GFMC was used to make calculations of ^{12}C with a complete Hamiltonian (two- and three-nucleon potential AV18+IL7) on 32,000 processors of the Argonne BGP. These are believed to be the best converged ab initio calculations of ^{12}C ever made. The computed binding energy is 93.5(6) MeV compared to the experimental value of 92.16 MeV and the point rms radius is 2.35 fm vs 2.33 from experiment.



- The n-^{3}H elastic cross section for 14 MeV neutrons, important for understanding how the fuel is assembled in an implosion at NIF, was not known precisely enough. Nuclear theory was asked to help.
- Delivered evaluated data with required 5% uncertainty and successfully compared to measurements using an Inertial Confinement Facility

Navratil et al.,e-reports-ext.llnl.gov/pdf/386718.pdf

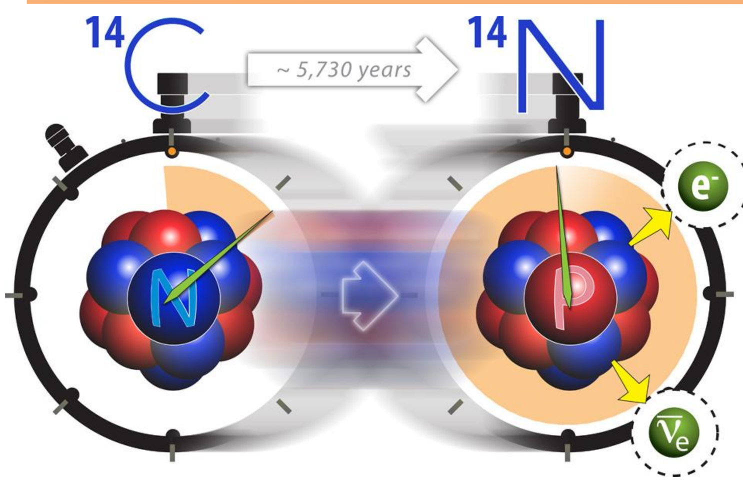
"Anomalous Long Lifetime of Carbon-14"

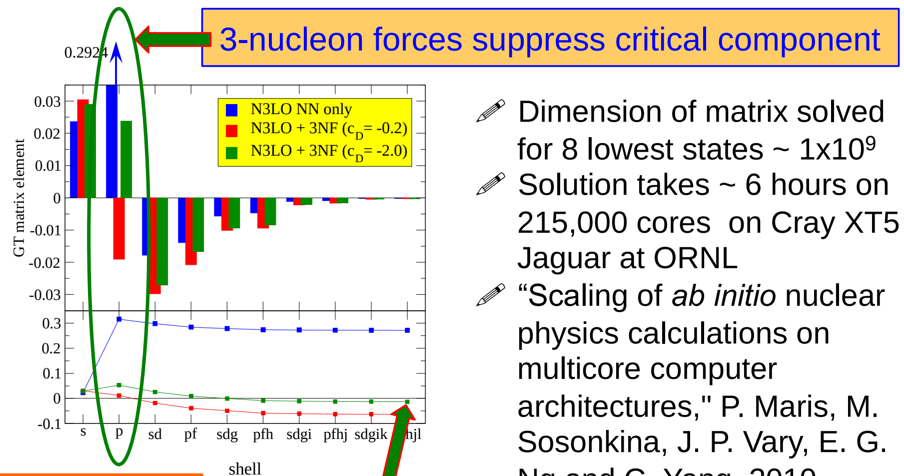
Objectives

- Solve the puzzle of the long but useful lifetime of ^{14}C
- Determine the microscopic origin of the suppressed ! -decay rate

Impact

- Establishes a major role for strong 3-nucleon forces in nuclei
- Verifies accuracy of *ab initio* microscopic nuclear theory
- Provides foundation for guiding DOE-supported experiments





PRL 106, 202502 (2011) PHYSICAL REVIEW LETTERS week ending 20 MAY 2011

Origin of the Anomalous Long Lifetime of ^{14}C

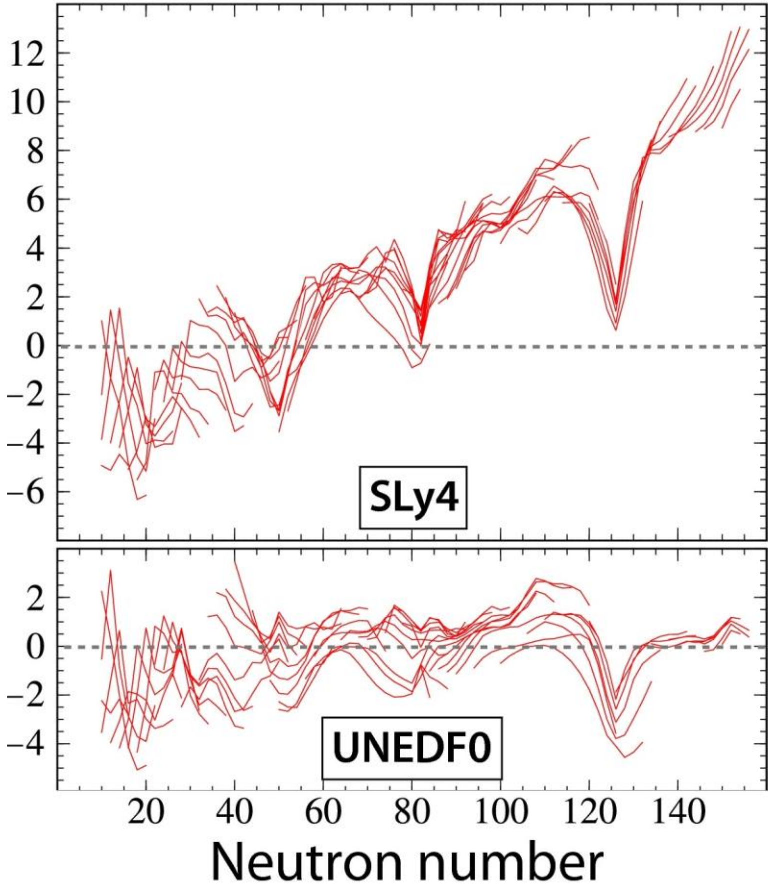
P. Maris,[1] J.P. Vary,[1] P. Navrátil,[2,3] W.E. Ormand,[3,4] H. Nam,[5] and D.J. Dean[5]

- Dimension of matrix solved for 8 lowest states ~ $1x10^9$
- Solution takes ~ 6 hours on 215,000 cores on Cray XT5 Jaguar at ORNL
- "Scaling of *ab initio* nuclear physics calculations on multicore computer architectures," P. Maris, M. Sosonkina, J. P. Vary, E. G. Ng and C. Yang, 2010 Intern. Conf. on Computer Science, Procedia Computer Science 1, 97 (2010)

U.S. DEPARTMENT OF ENERGY Office of Science | INCITE Advancing America's Science and Industrial Competitiveness | IOWA STATE UNIVERSITY | TRIUMF

UNEDF SciDAC Collaboration Universal Nuclear Energy Density Functional | NNSA | LAWRENCE LIVERMORE NATIONAL SECURITY | OAK RIDGE NATIONAL LABORATORY Managed by UT-Battelle for the Department of Energy

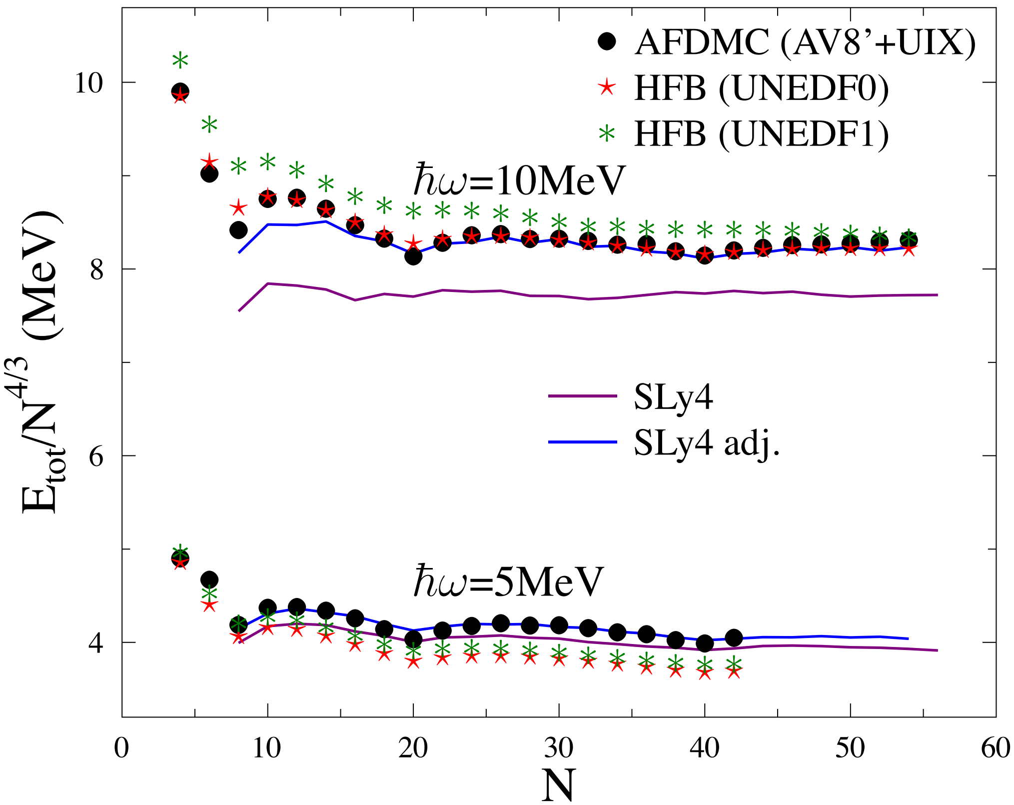
UNEDF functionals and neutron drops

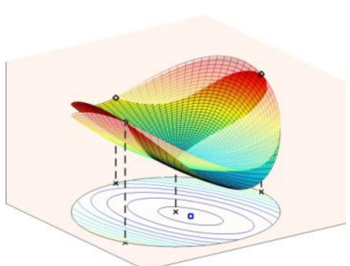


PHYSICAL REVIEW C **82**, 024313 (2010)

Nuclear energy density optimization

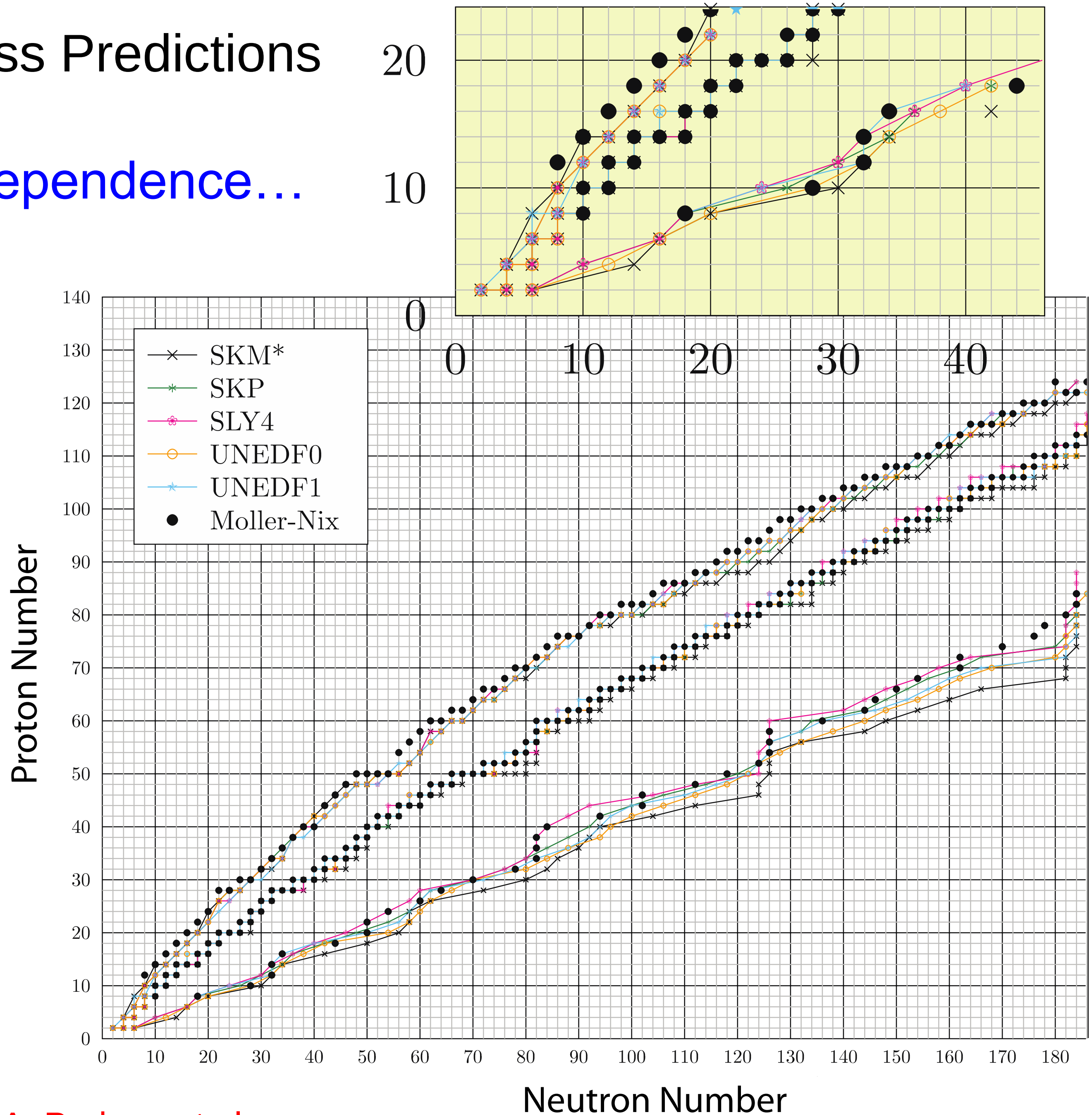
M. Kortelainen,[1,2] T. Lesinski,[1,2] J. Moré,[3] W. Nazarewicz,[1,2,4] J. Sarich,[3] N. Schunck,[1,2] M. V. Stoitsov,[1,2,5] and S. Wild[3]
[1] *Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[2] *Physics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831, USA*
[3] *Mathematics and Computer Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4] *Institute of Theoretical Physics, Warsaw University, ul. Hoża 69, PL-00681 Warsaw, Poland*
[5] *Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
(Received 27 May 2010; published 13 August 2010)





DFT Mass Predictions

Model dependence…

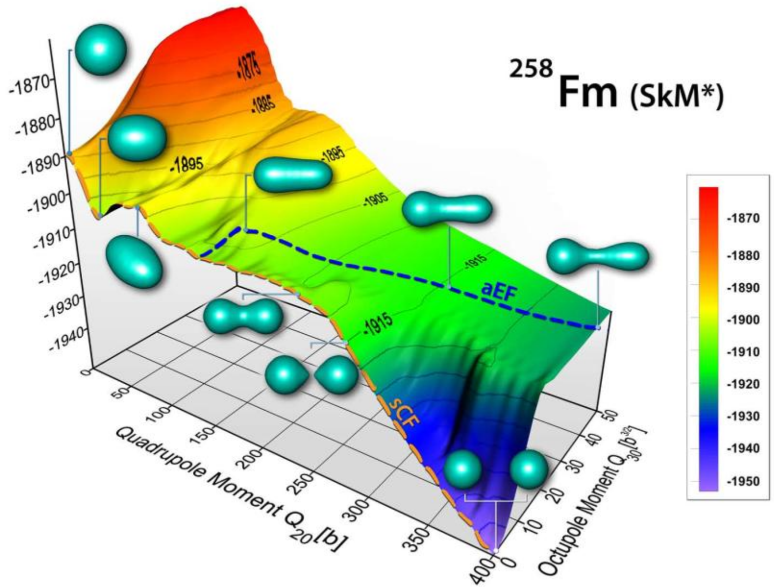


N. Birge, A. Perhac, et al.

A. Staszczak et al.,
B.Phys. Rev. C 80, 014309 (2009)

1939 - Meitner & Frisch
1939 - Bohr & Wheeler

70 years ago!



UNEDF1 functional: focus on heavy nuclei and fission

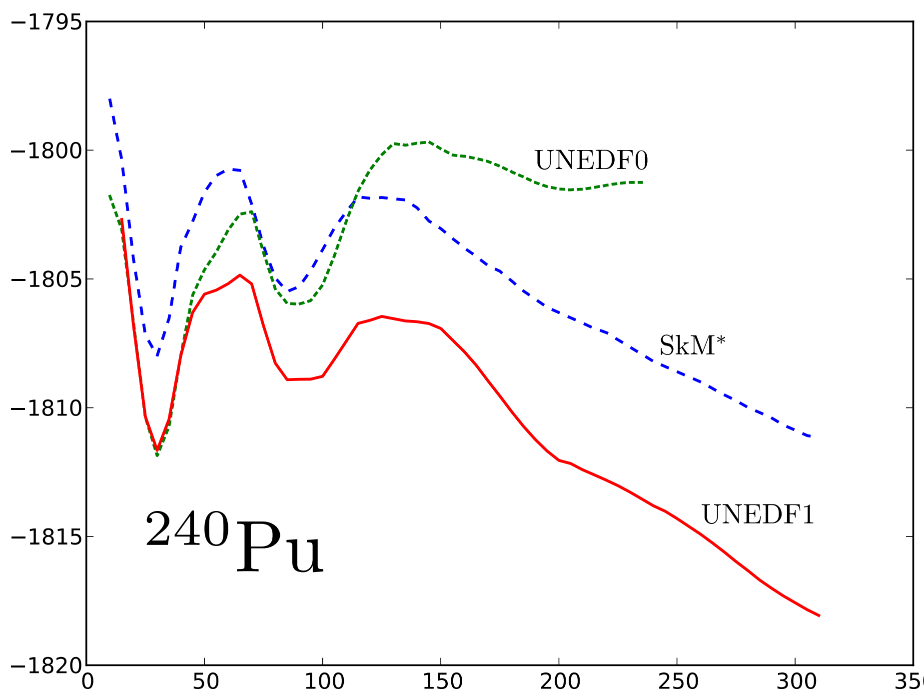


TABLE VIII: Binding energy and fission first barrier height for ^{240}Pu in units of MeV for SLy4, SkM*, UNEDF0, and UNEDF1. These are compared to the experimental value of [48].

Functional	Binding Energy	First Barrier Height
SLy4	1801.5	11.9
SkM*	1804.3	9.4
UNEDF0	1811.8	9.6
UNEDF1	1811.8	6.8
Exp	1813.5	6.1

Quality Control

Integral to this project is the verification of methods and codes, the estimation of uncertainties, and assessment.

Verification and Validation

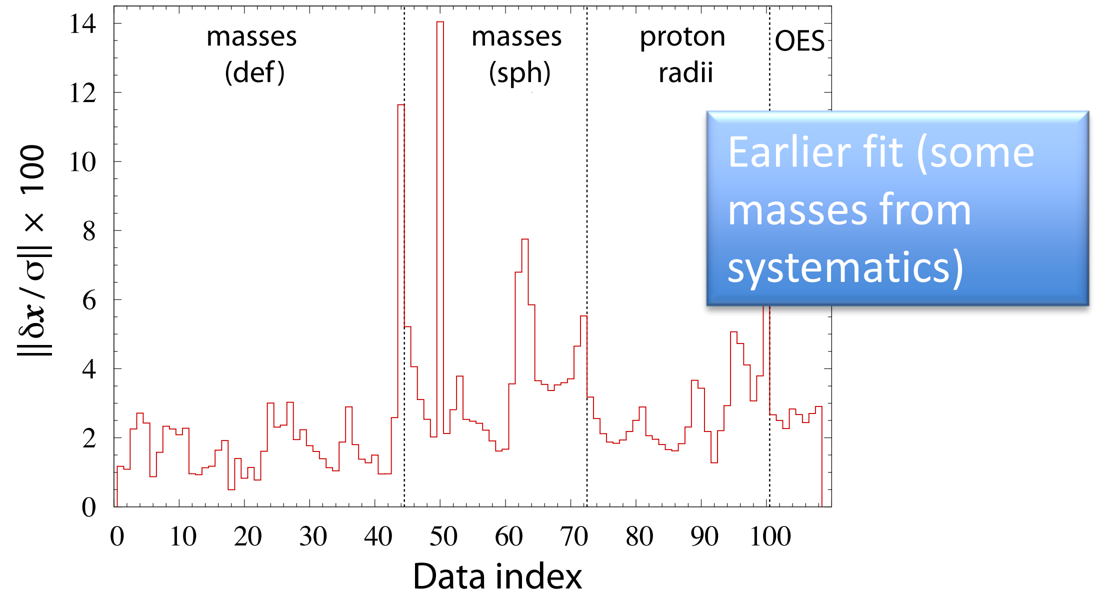
- Cross-check of different methods and codes
- Benchmarking

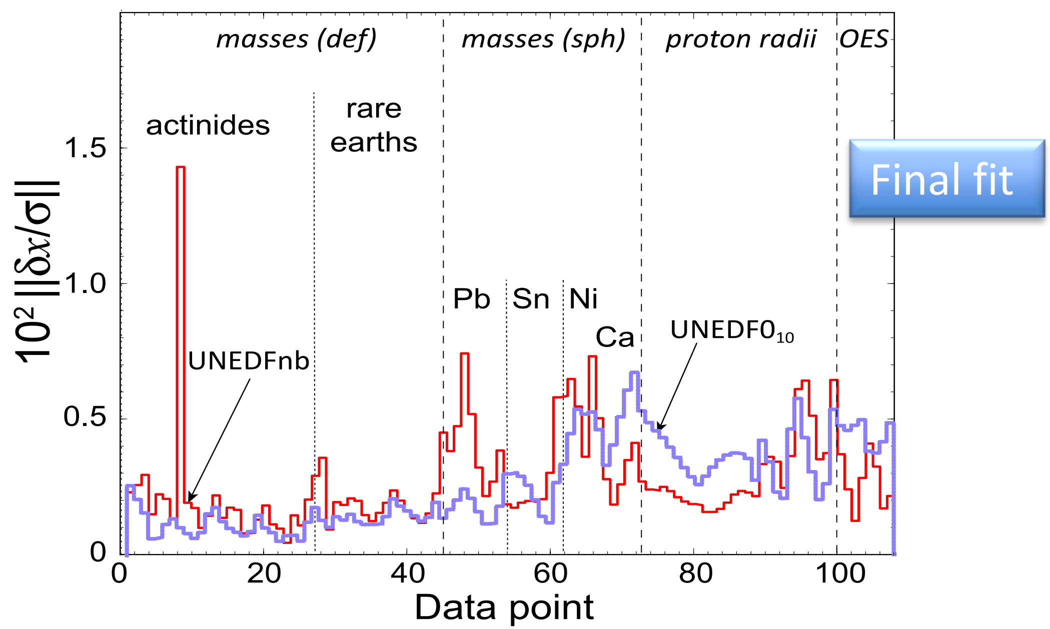
Uncertainty Quantification and Error Analysis

- Tools for correlation analysis to estimate errors and significance
- Uncertainty analysis

Assessment

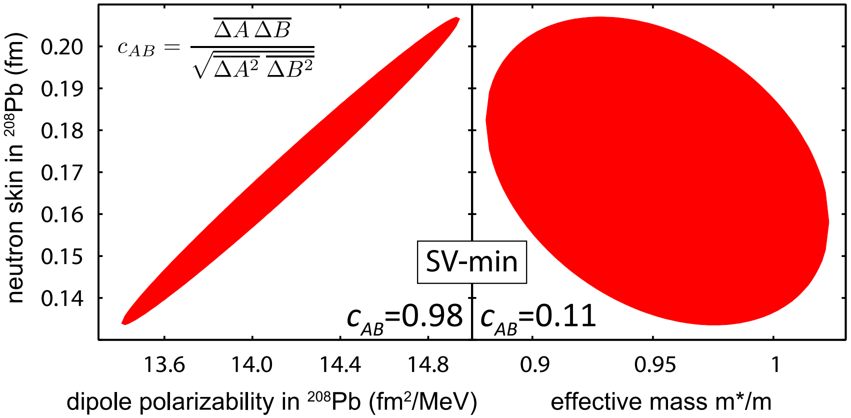
- Development and application of statistical tools
- Analysis of experimental data significance

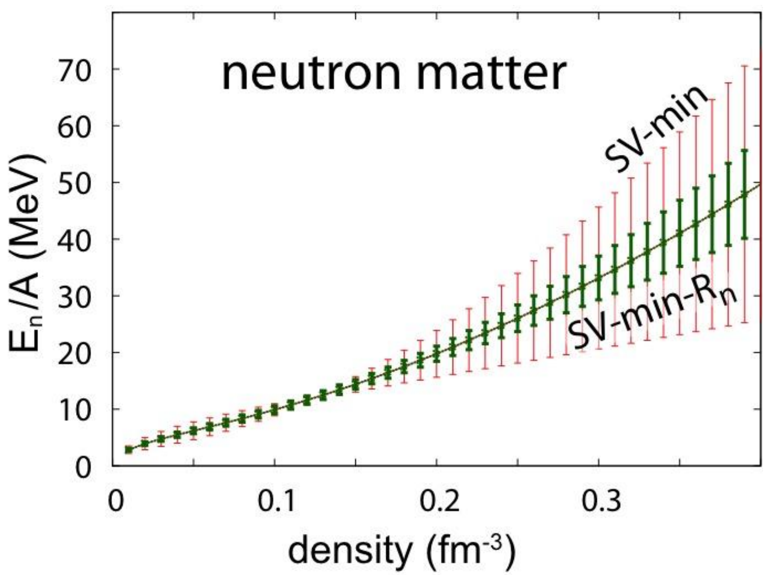


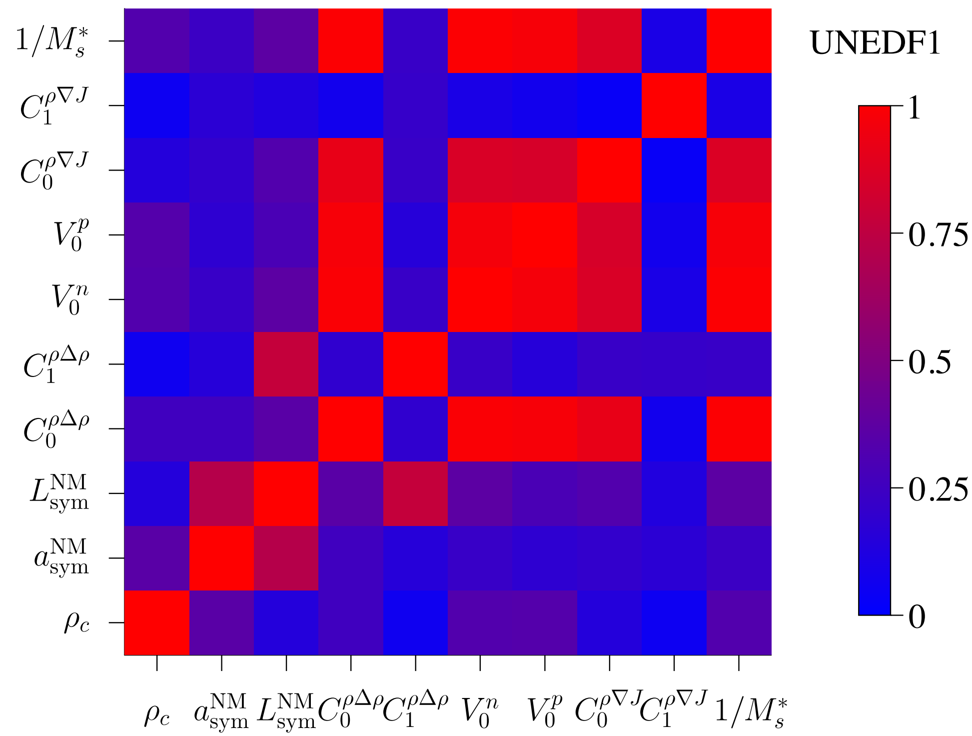


Quality Control (2)

Integral to this project is the verification of methods and codes, the estimation of uncertainties, and assessment.



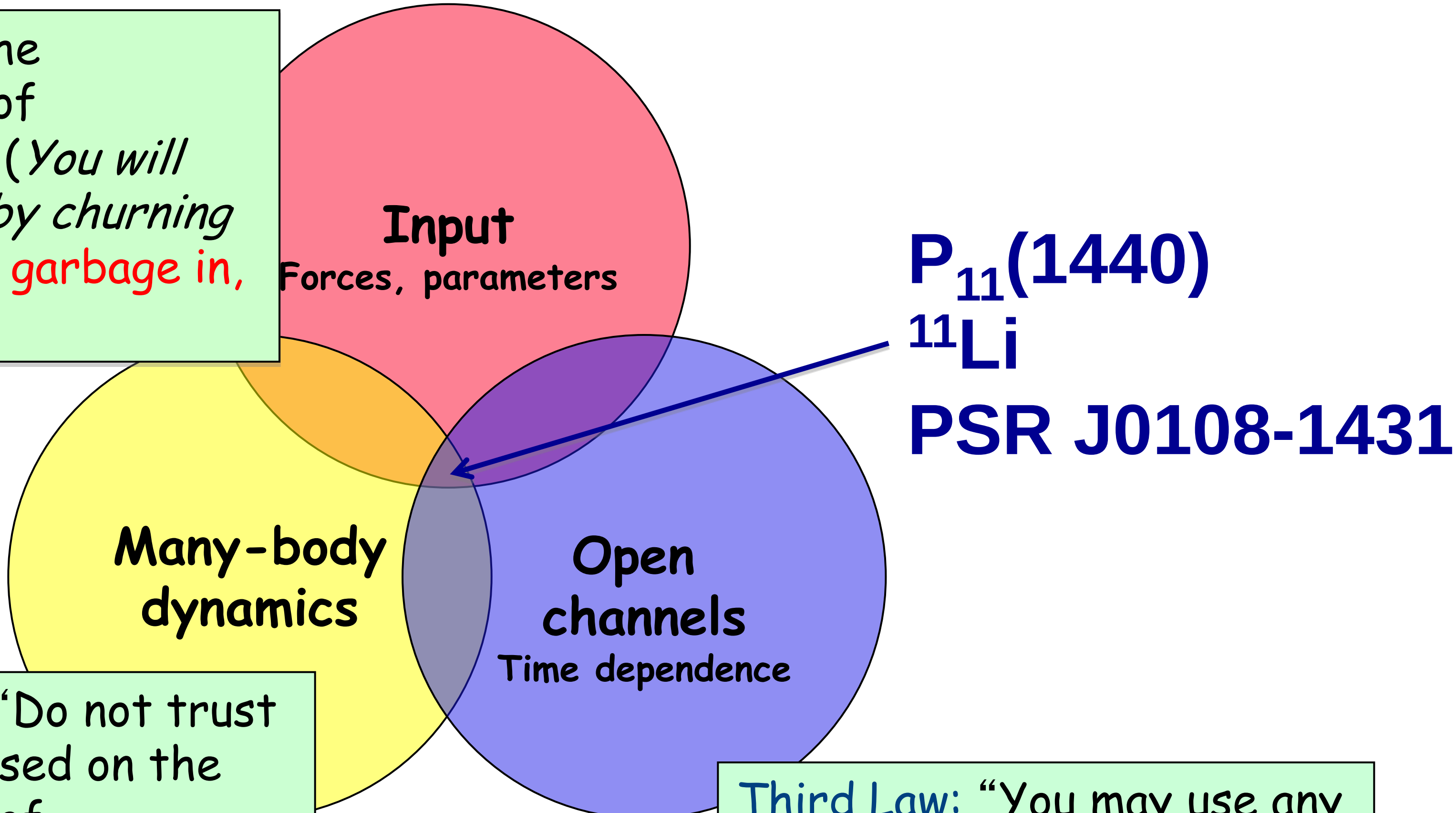




P.G. Reinhard and WN, Phys. Rev. C 81, 051303 (R) (2010)

Nuclear theory is demanding…

First Law: "The conservation of Information" (*You will get nowhere by churning equations*) … garbage in, garbage out…



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!"

Weinberg's Laws of Progress in Theoretical Physics

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

Outlook

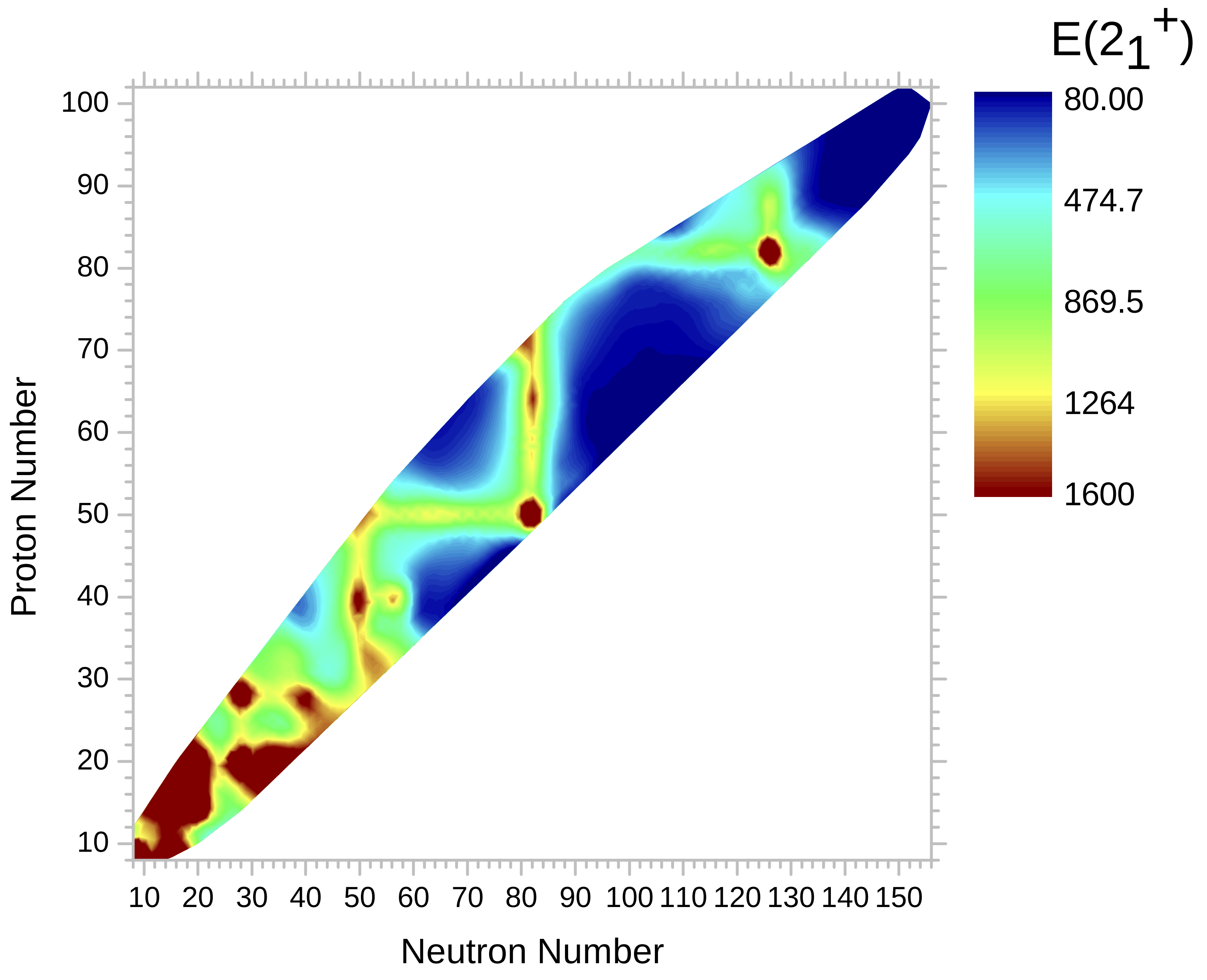
The study of rare isotopes makes the connection between the fundamental building block of matter, complex systems, and the cosmos

- Exciting and transformational science; old paradigms revisited
- Interdisciplinary science
- Science relevant to society

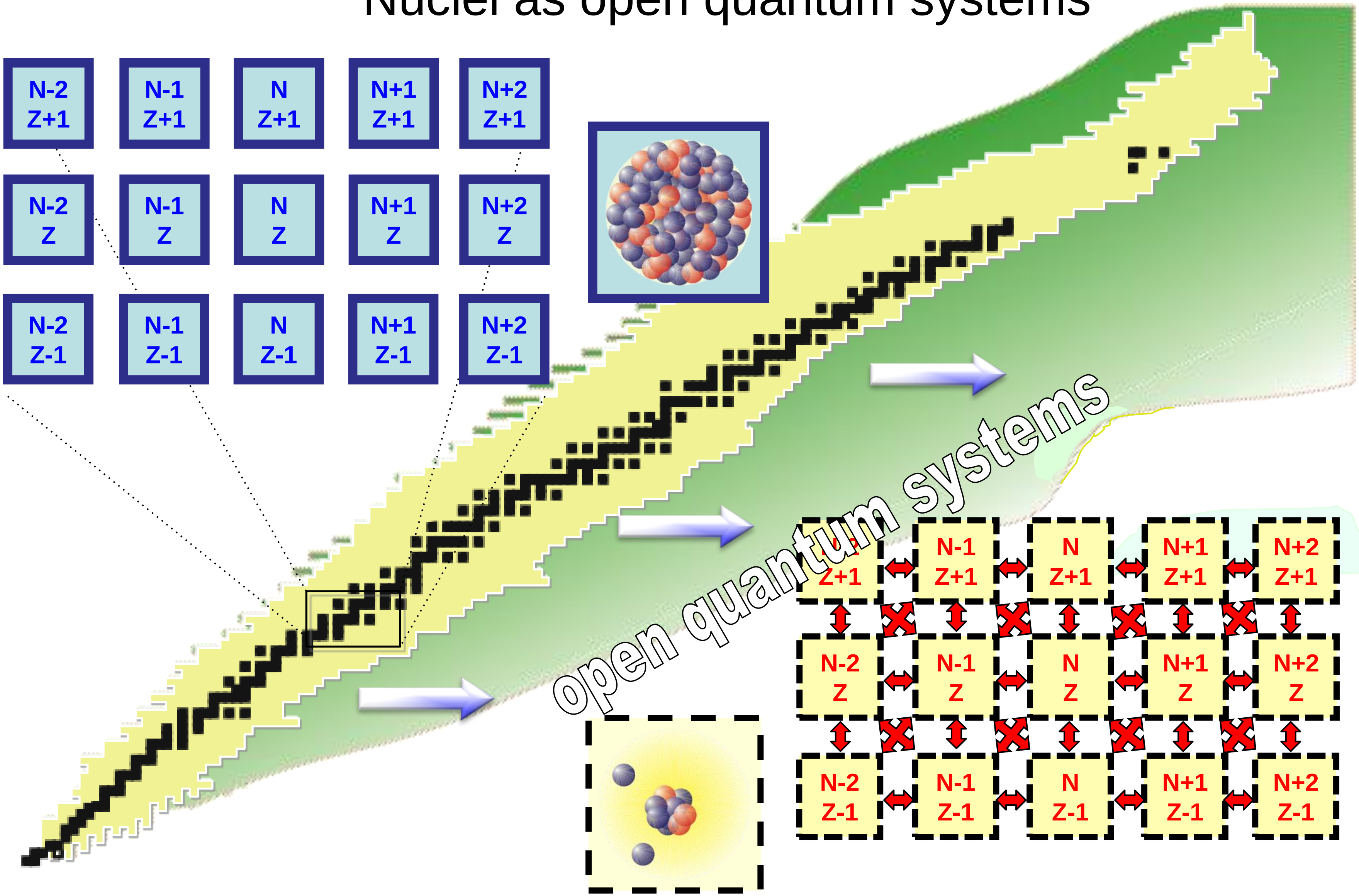
Over the last decade, tremendous progress has been made in techniques to produce *designer nuclei*, rare atomic nuclei with characteristics adjusted to specific research needs. Guided by unique data on short-lived nuclei, we are embarking on a comprehensive study of all nuclei based on the most accurate knowledge of nuclear interactions, the most reliable theoretical approaches, and the massive use of the computer power available at this moment in time. **The prospects are excellent.**

Thank You

Backup


E(2_1^+)
80.00
474.7
869.5
1264
1600
Proton Number
100
90
80
70
60
50
40
30
20
10
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Neutron Number

Nuclei as open quantum systems

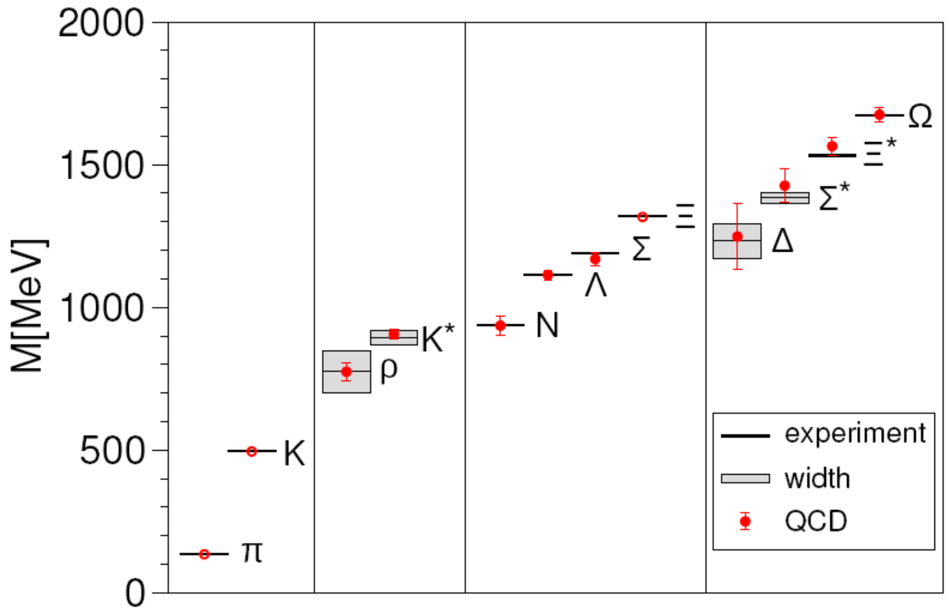


- A unification of structure and reaction aspects of nuclei
- Many phenomena (threshold effects, exceptional points, channel coupling…) are generic (atoms, molecules, nanotubes, quantum dots, microwave cavities,…)

Hadronic many-body problem

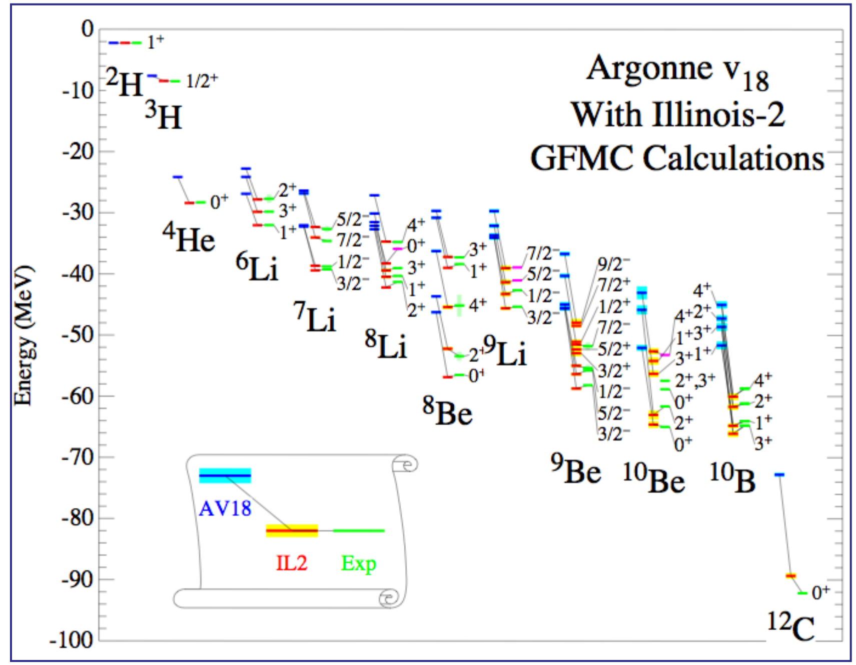
Low-lying Hadron Spectrum: LQCD

Dürr et al., Science 322, 1224 (2008)

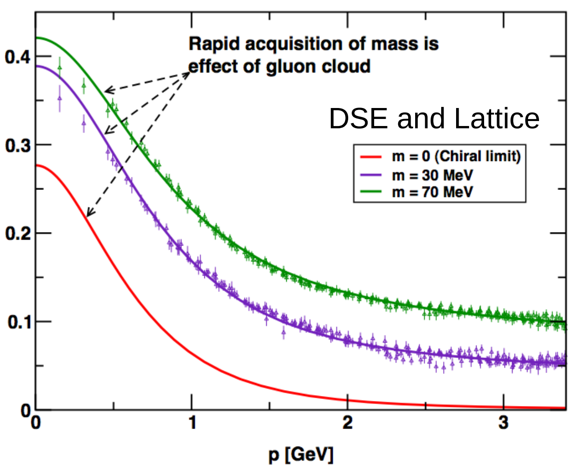


Low-lying Nuclear Spectrum: QMC

Pieper et al, (2008)

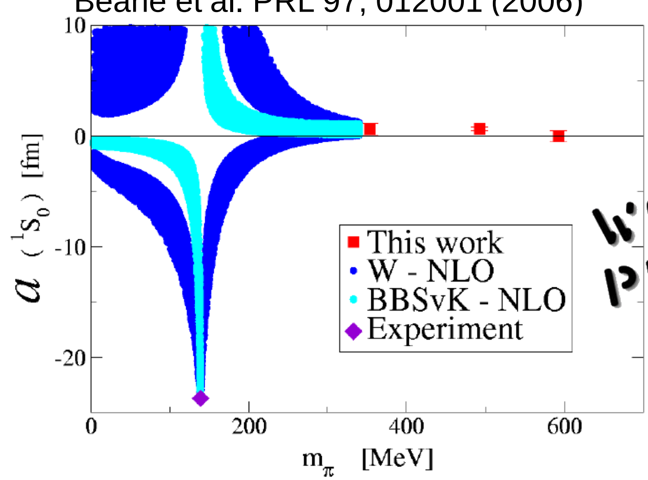


Mass from nothing: DCSB



NN scattering

Beane et al. PRL 97, 012001 (2006)

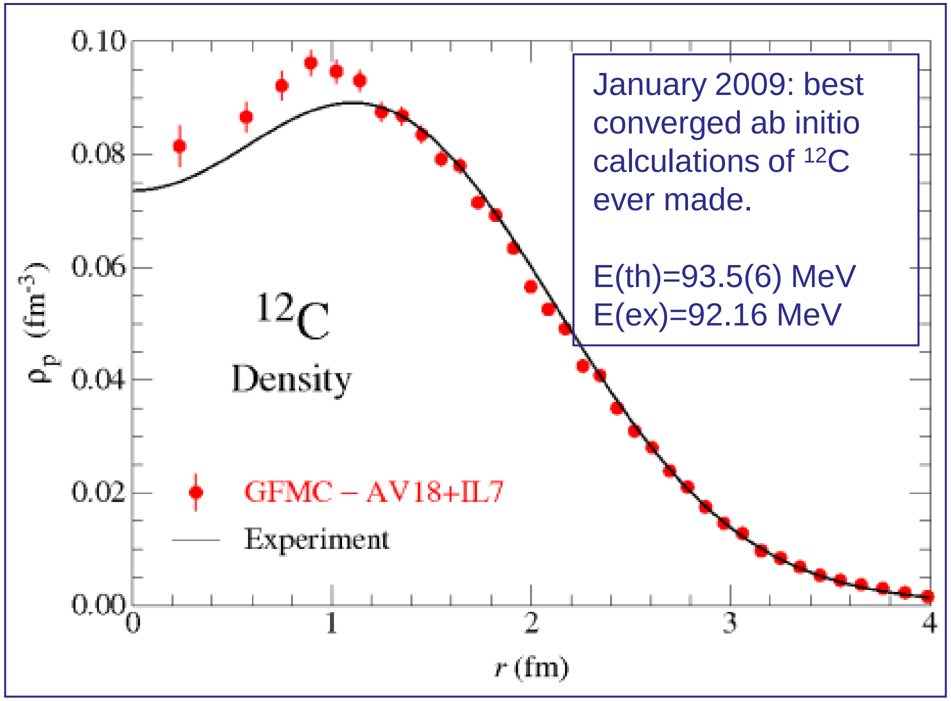


- Quantum Monte Carlo (GFMC) ^{12}C
- No-Core Shell Model ^{14}F, ^{14}C
- Coupled-Cluster Techniques ^{17}F, ^{56}Ni
- Lattice EFT ^{12}C (Hoyle)

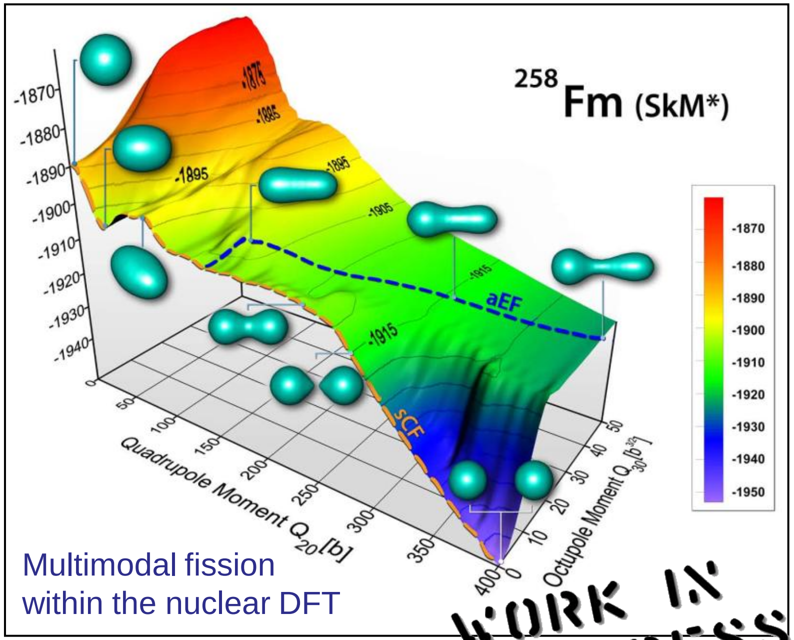
WORK IN PROGRESS

… Lattice explorations of the QCD phase diagram

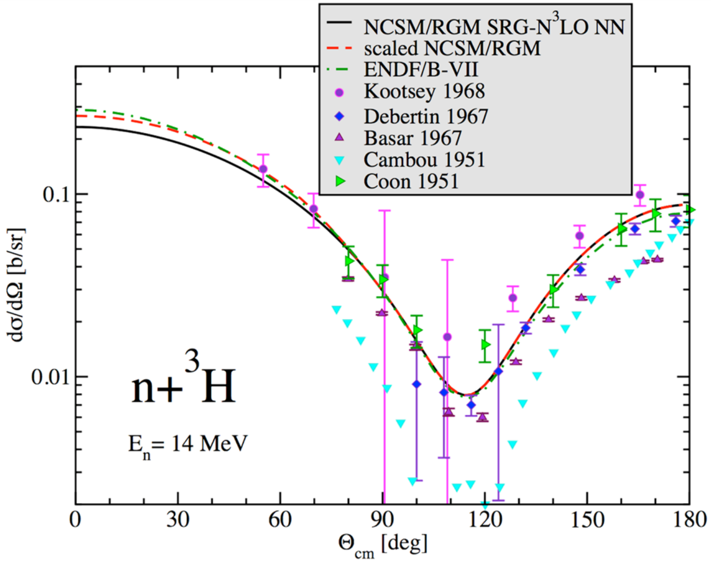
Lusk and Pieper, SciDAC Review 2010



Staszczak et al., Phys. Rev. C 80, 014309 (2009)



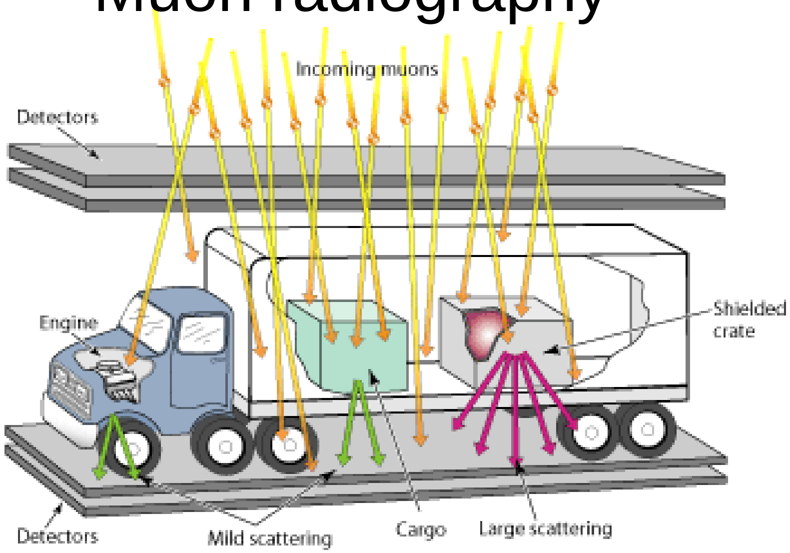
WORK IN PROGRESS



Navratil et al.,e-reports-ext.llnl.gov/pdf/386718.pdf

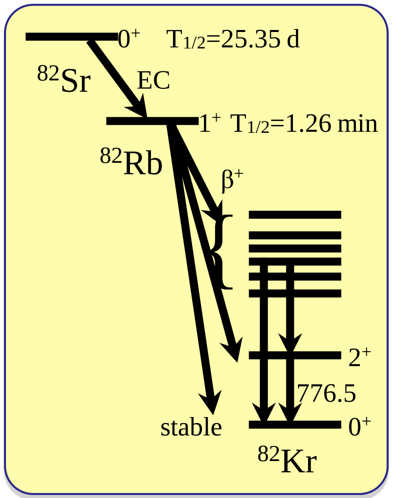
- The n-^{3}H elastic cross section for 14 MeV neutrons, important for understanding how the fuel is assembled in an implosion at NIF, was not known precisely enough. Nuclear theory was asked to help.
- Delivered evaluated data with required 5% uncertainty and successfully compared to measurements using an Inertial Confinement Facility

Muon radiography



Provides the capability to monitor large cargo containers for the presence of nuclear materials

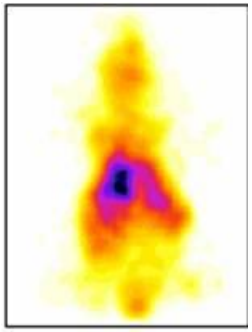
Medical isotopes

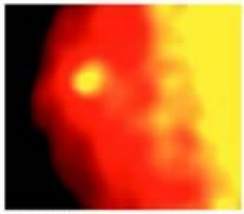


^{82}Sr-^{82}Rb Generator

The Sr/Rb generator is used by hospitals to provide a source of radioactive ^{82}Rb which is used to image the heart muscle by means of PET. Precise nuclear measurements helped to determine the amount of radioactive Sr needed.

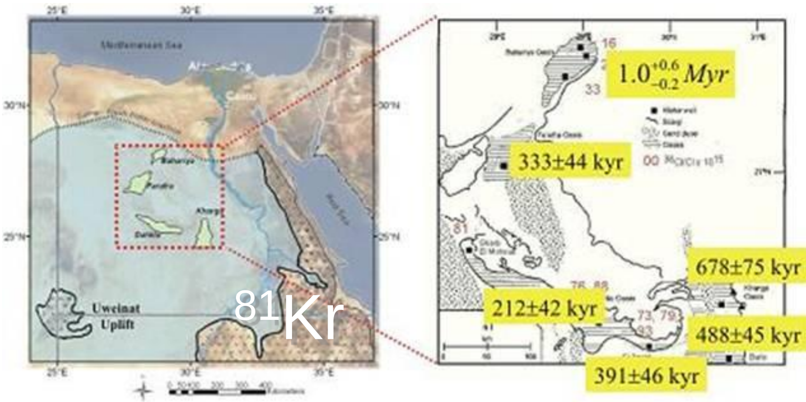
Medical imaging





gamma and positron imaging devices

Atom Trap Trace Analysis



Used to date old ground water by laser-trapping atoms of a particular isotope.

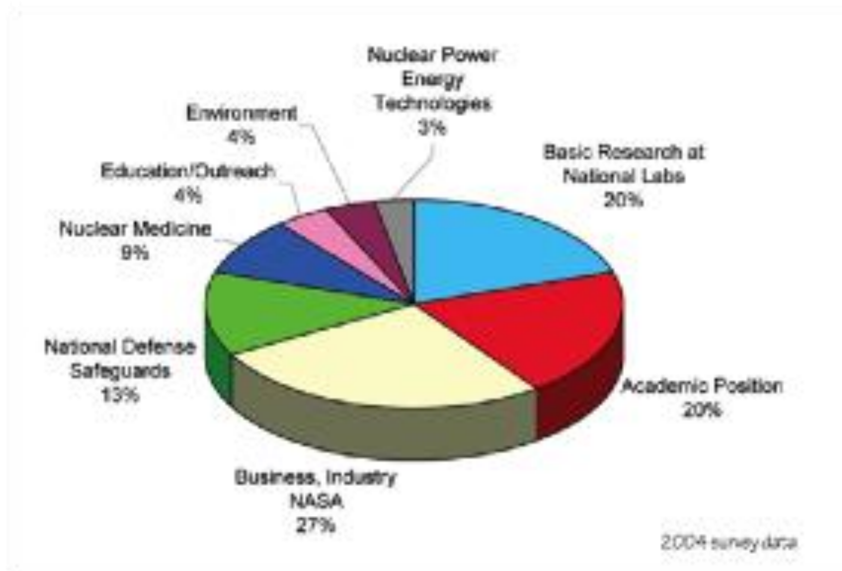
http://www.sc.doe.gov/np/brochure/index.shtml

Societal Benefits

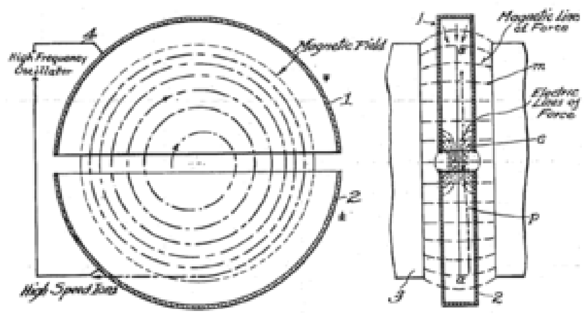
- Energy, transmutation of waste…
- Medical and biological research
- Materials science
- Environmental science
- Stockpile stewardship
- Security
- Computing

http://www.sc.doe.gov/np/brochure/index.shtml

Training the next generation of innovators



Ernest and John Lawrence



John Lawrence was a physicist and physician, a pioneer of nuclear medicine. He discovered treatments for leukemia and polycythemia by injecting infected mice with radioactive phosphorus derived from the cyclotron invented by his brother

In the summer of 1935, John came to Berkeley to conduct research on the medical applications of radiation. He injected some leukemic mice with radioactive phosphorus produced by the cyclotron and then went fishing; when he returned he found the mice improved. It was the beginning of medical physics at Berkeley. John was also more aware than were the physicists in the laboratory of the dangers of exposure to radiation, so he insisted that they undertake some experiments with the radiation produced by the cyclotron. He conducted an experiment that he described, years later, in this way:

One of the first animals that we exposed - I'm not sure that it wasn't the first one - we … placed within the cyclotron between the two poles of the magnet near the beryllium target which was being struck with alpha particles. So Paul and I told Ernest to turn off the cyclotron because we wanted to go back and see how the rat was. Well, the rat was dead. That scared everybody because it had only been exposed for about a minute and the dose was very low. We were very scared and we then recommended increasing the shielding around the cyclotron*. Later we found that the rat died of suffocation but not radiation.*

None of these achievements however was as important and satisfying as that which occurred in 1937. Within months of John's arrival in Berkeley, he and Ernest learned that their mother was diagnosed with uterine cancer; she went to the Mayo Clinic for treatment. John went to Mayo immediately. Mother Lawrence was told that she had only three months to live. John tells the story in his oral history, in the archives at Berkeley:

So then I got on the phone with Ernest. I said, "They don't want to treat her here with radiation. How about my bringing her out and we'll talk to Dr. Stone?" We did talk to Dr. Stone and he said, "Sure, I'll take her." So I took her on the train, wheeled her across the station in Omaha. (…) She was about 67 or 68 years old then…. They started treating her through four fields…. *To make a long story short, this massive tumor just started evaporating.* At the end of ten years my mother finally agreed that she must be cured. It took me about ten years to convince her and she died at 83 and had the best years of her life…. It was really, really a fantastic result.

What are the next medically viable radioisotopes required for enhanced and targeted treatment and functional diagnosis?

Example: Targeted Alpha Therapy in vivo

The radionuclide ^{149}Tb decays to alpha particles 17 percent of the time and has a half-life of 4.1 hours, which is conveniently longer than some other alpha-emitting radionuclides. Low-energy alpha particles, such as in ^{149}Tb decays, have been shown to be very efficient in killing cells, and their short range means that minimal damage is caused in the neighborhood of the target cells.

α-knife!

First in vivo experiment to demonstrate the efficiency of alpha targeted therapy using ^{149}Tb produced at ISOLDE, CERN

G.-J. Beyer et al. Eur. J. Nucl. Med. and Molecular Imaging **33**, 547 (2004)

Survival of mice…