Frontiers in Low-Energy Nuclear Physics – selected topics

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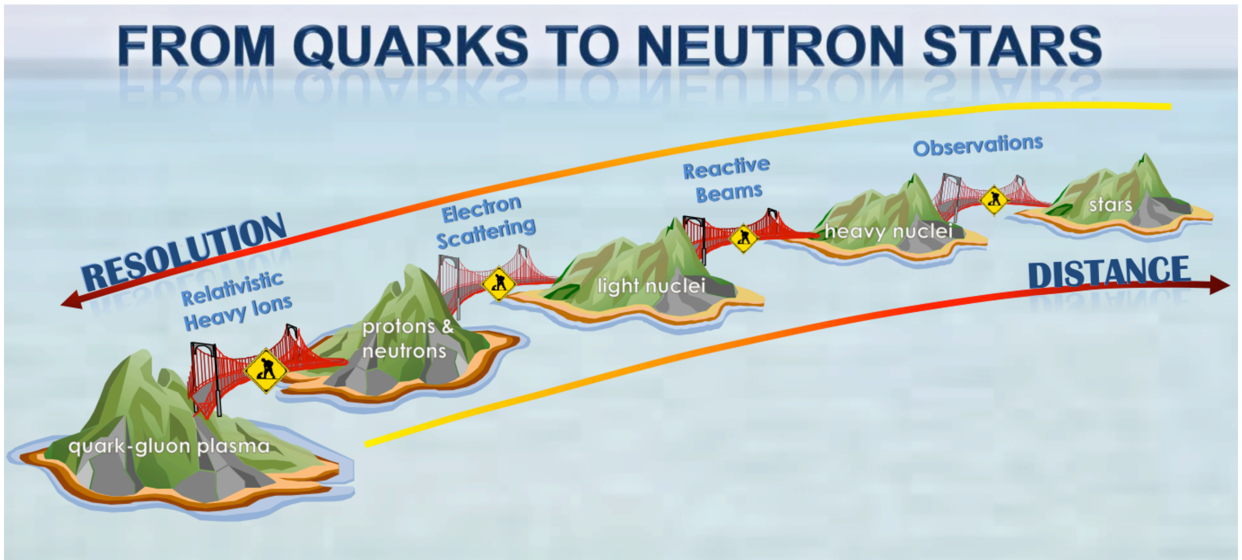
University of Tennessee/ORNL

EBSS2014: Exotic Beam Summer School

Oak Ridge, TN, July 28, 2014



- Introduction
  - Questions
  - Principles
- Science
- Perspectives

"All the matter that makes up all the living organisms and ecosystems, planets and stars, throughout every galaxy in the universe, is made of atoms, and 99.9% of the mass of all the atoms in the (visible) universe comes from the nuclei at their centers which are over 10,000 times smaller in diameter than the atoms themselves"

NRC Decadal Study Report

Philip Bredesen, Governor of Tennessee 2003-2011, PAC05 welcome address

(he earned a bachelor's degree in **physics** in 1967 from Harvard University in 1967)

We are doing an inadequate job of explaining why what we do is important

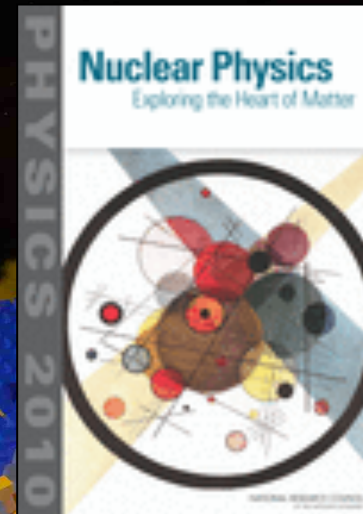
"People who truly understand something, who truly have command of a subject, can explain it at some level to anyone who asks and is willing to try to understand an answer. The point is that if you were asked about something and had to resort to that's all very complicated and until you take a course in differential equations and then give me a blackboard I can't possibly make you understand, that that was more often a signal of a failure of the physicist to have a real command of the issue than of the failure of the person asking the question.

I have adapted it to my own life is the **"Wal-Mart Test."** When I propose to take some course of action in the public sector, I do a thought experiment and imagine how I will explain it to the Wal-Mart checkout person. Let me clear that I don't mean in any way dumbing-down the idea, I mean taking the principle that if I understand well enough what I am doing, I can cogently explain it to another human being with a different reference point. If I can successfully do this thought experiment, I have the makings of a plan."

What about YOU?

The Nuclear Landscape and the Big Questions (NAS report)

- How did visible matter come into being and how does it evolve? (origin of nuclei and atoms)
- How does subatomic matter organize itself and what phenomena emerge? (self-organization)
- Are the fundamental interactions 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?



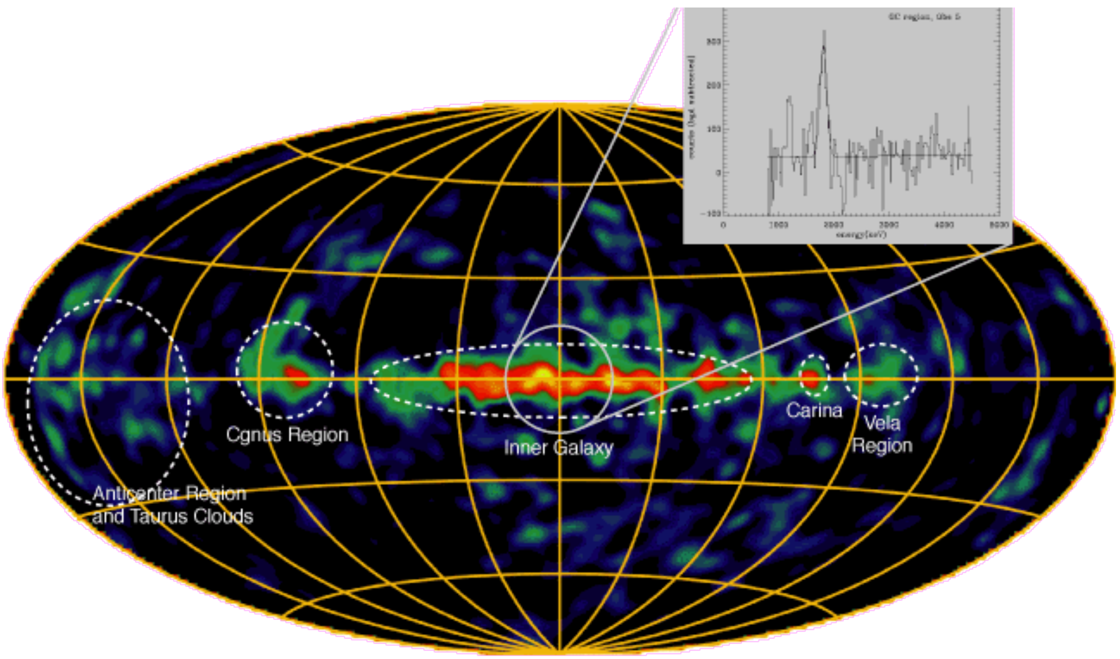
where the action is…

The Nuclear Landscape

- QCD transition (color singlets formed): 10 ms after Big Bang (13.8 billion years ago)
- D, ^{3,4}He, ^{7}Be/^{7}Li formed 3-50 min after Big Bang
- Other nuclei born later in heavy stars and supernovae

How did visible matter come into being and how does it evolve?

The radioactive galaxy demonstrates the continuing formation of new radioactive isotopes.

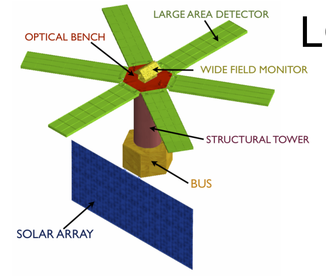


^{26}Al distribution along galactic plane

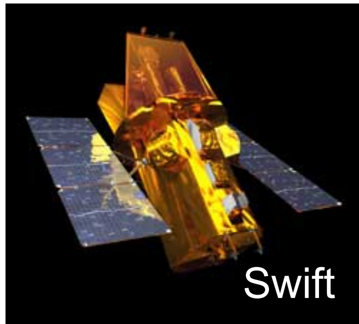
T=7.2·10^{5} yr
E_{γ}=1.809 MeV

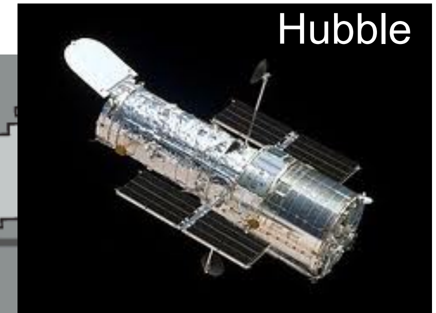
A 'snapshot' view of ongoing nucleosynthesis in the Galaxy by COMPTEL and INTEGRAL…

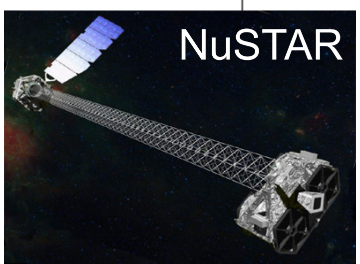
How are atoms cooked in the Cosmos?
Chemical evolution

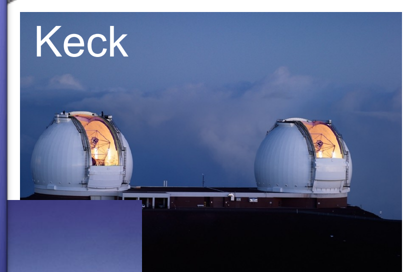


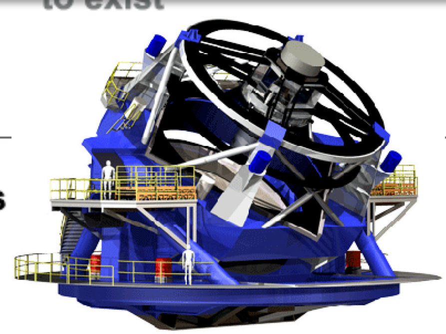
LOFT (early 2020s ?, ESA)









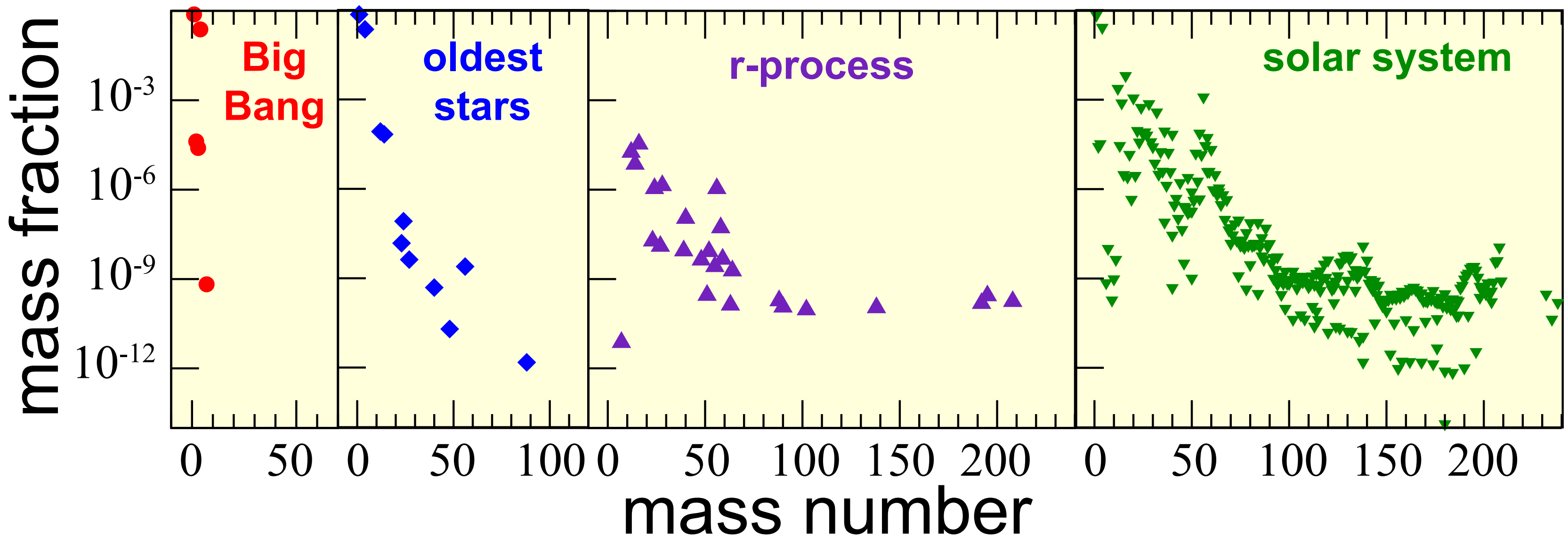


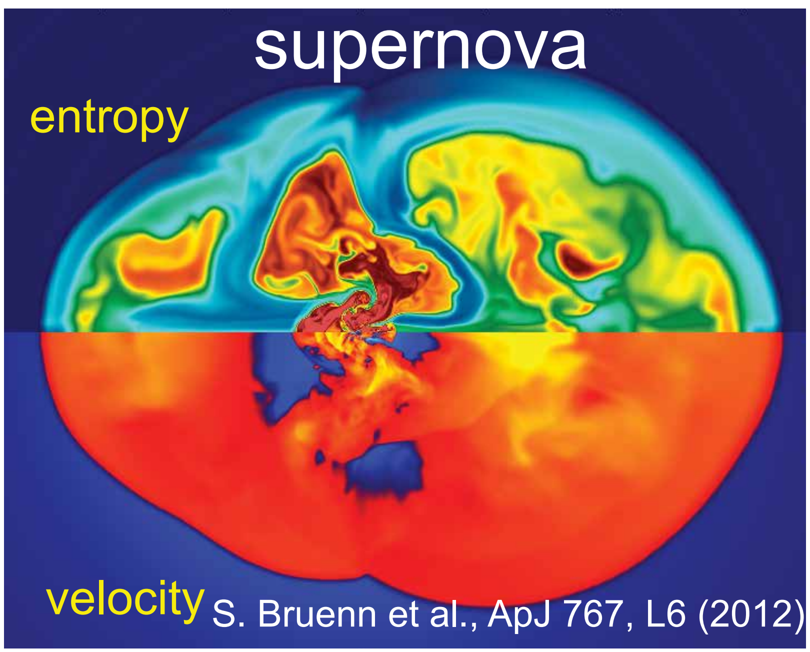
LSST
(High Priority ASTRO 2010)

Most elements are created in violent stellar explosions, and orbiting telescopes are capable of measuring these creation rates.

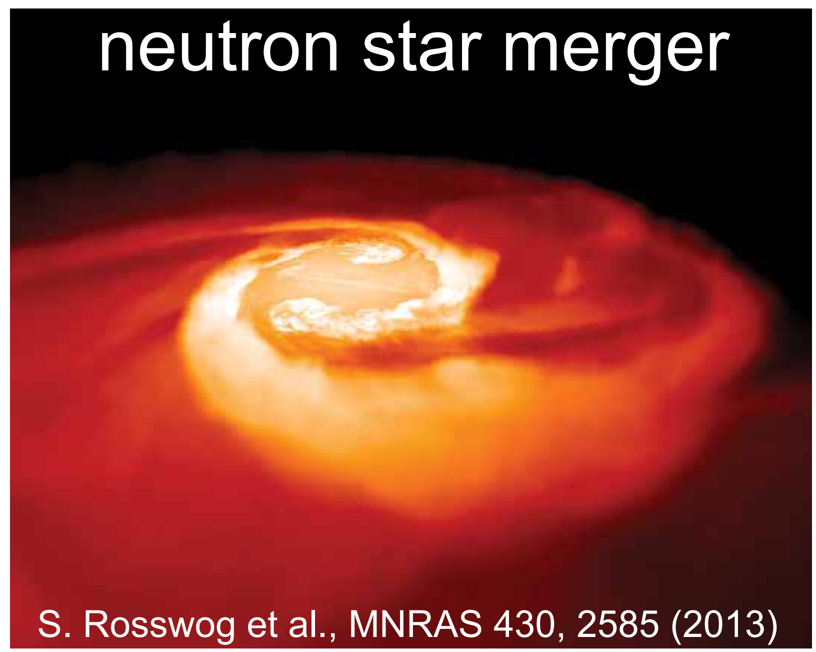
To interpret observations, however, we must understand reactions occurring in stellar explosions that create and destroy rare isotopes.

The radioactive galaxy demonstrates the continuing formation of new radioactive isotopes





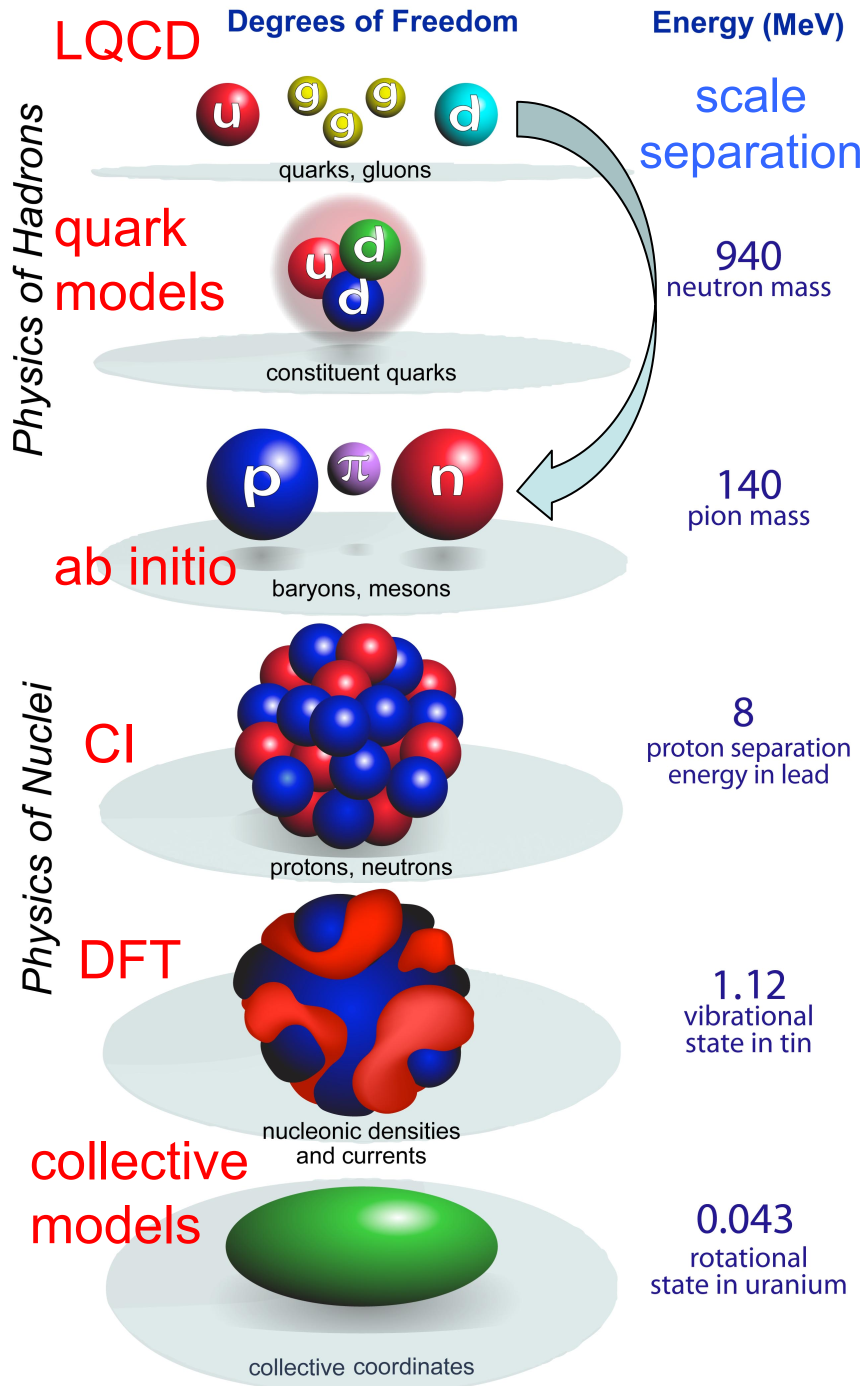
S. Bruenn et al., ApJ 767, L6 (2012)



S. Rosswog et al., MNRAS 430, 2585 (2013)

How are nuclei made?

Origin of elements, isotopes



Resolution

Hot and dense quark-gluon matter

Hadron structure

Hadron-Nuclear interface

Effective Field Theory

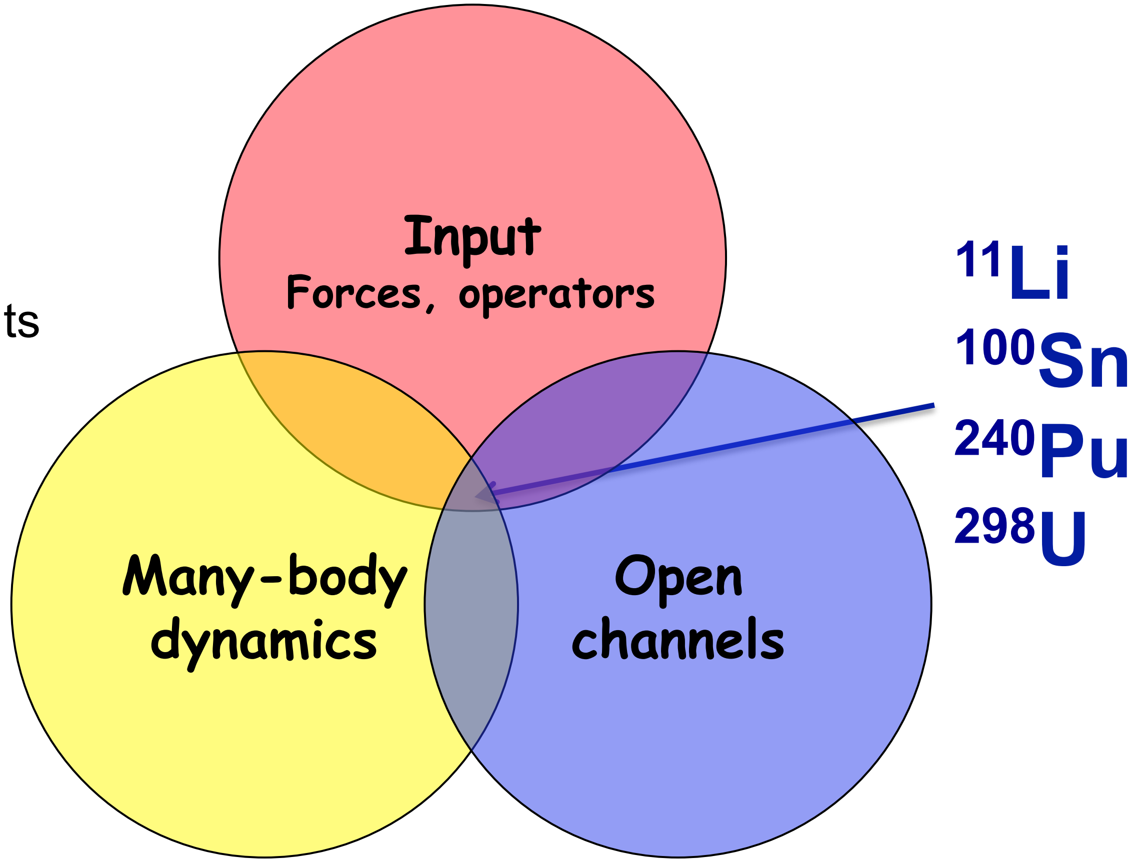
Nuclear structure
Nuclear reactions
New standard model

Applications of nuclear science

To explain, predict, use…

Theory of nuclei is demanding

- rooted in QCD
- insights from EFT
- many-body interactions
- in-medium renormalization
- microscopic functionals
- low-energy coupling constants optimized to data
- crucial insights from exotic nuclei

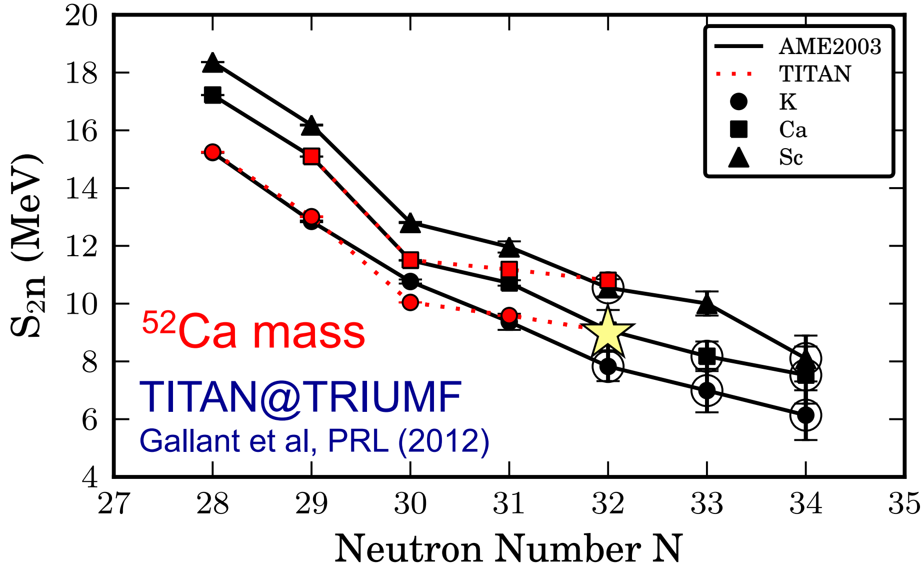


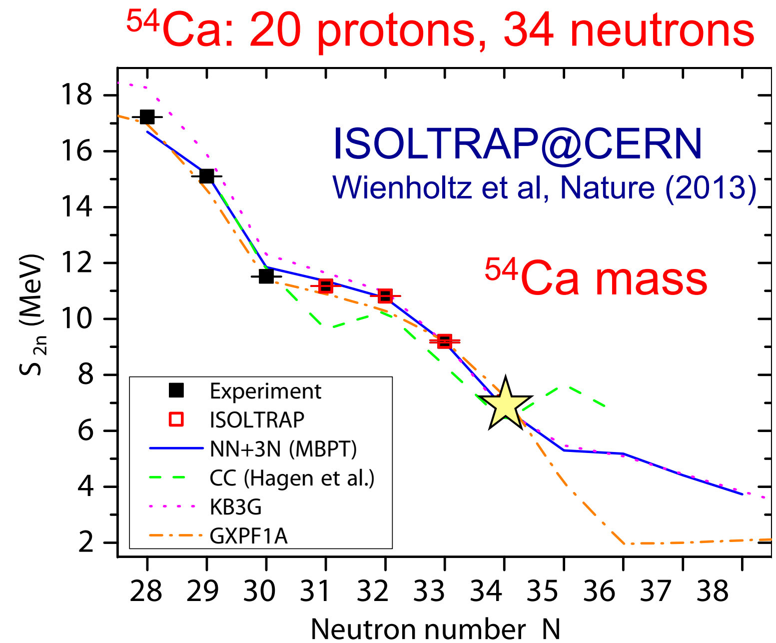
- many-body techniques
  - direct *ab initio* schemes
  - microscopic CI
  - nuclear DFT
- high-performance computing

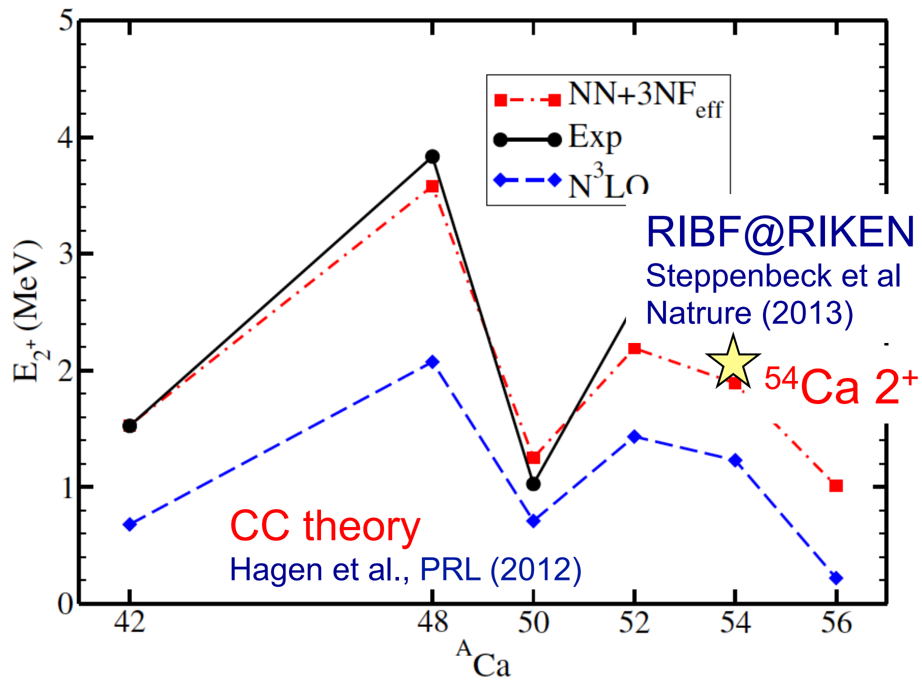
- nuclear structure impacted by couplings to reaction and decay channels
- clustering, alpha decay, and fission still remain major challenges for theory
- unified picture of structure and reactions

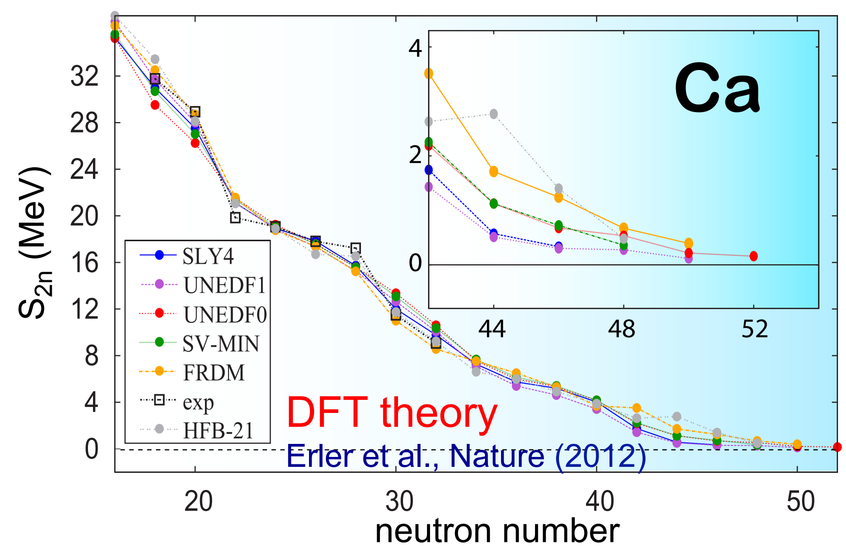
The frontier: neutron-rich calcium isotopes

probing nuclear forces and shell structure in a neutron-rich medium

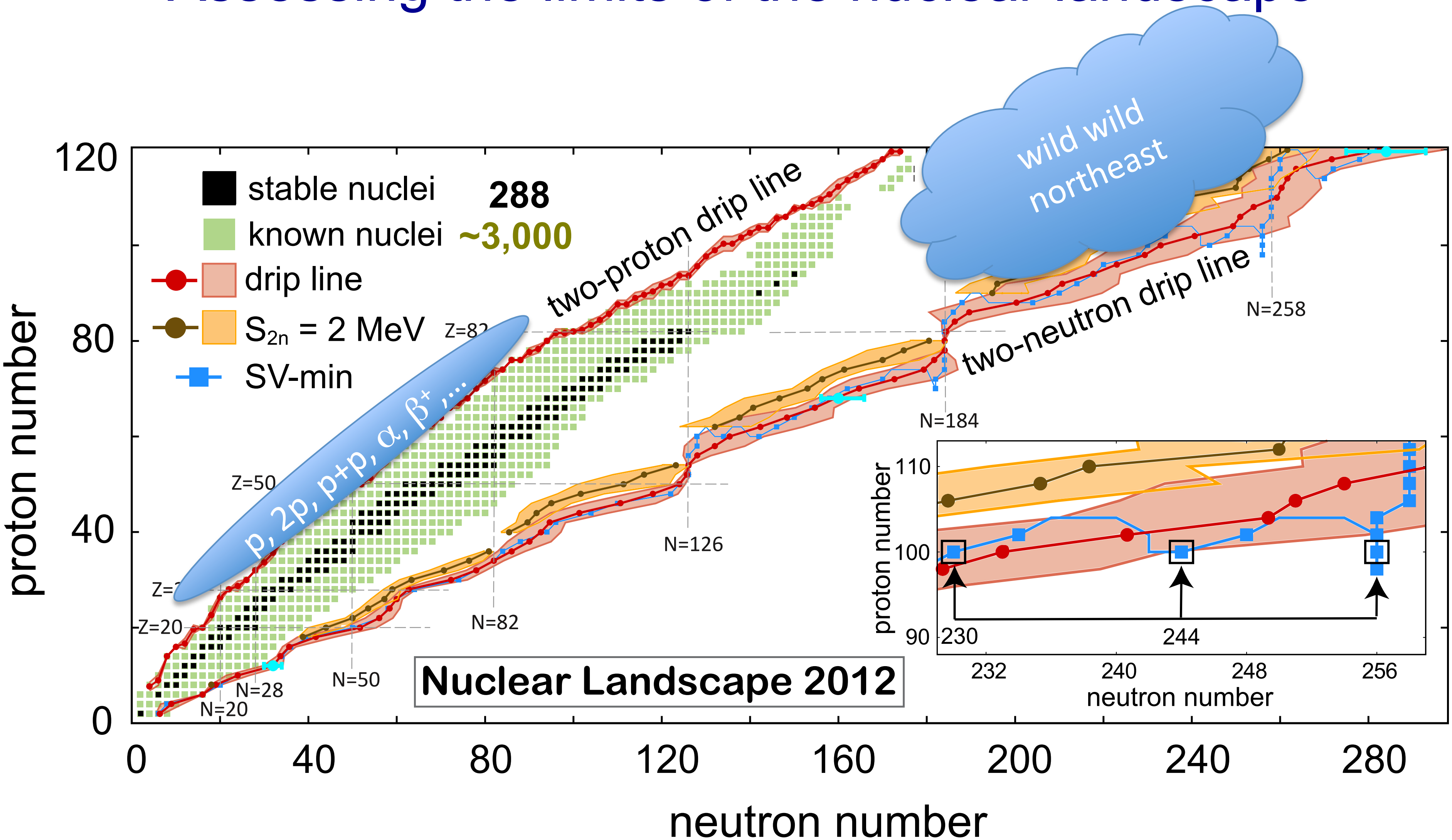






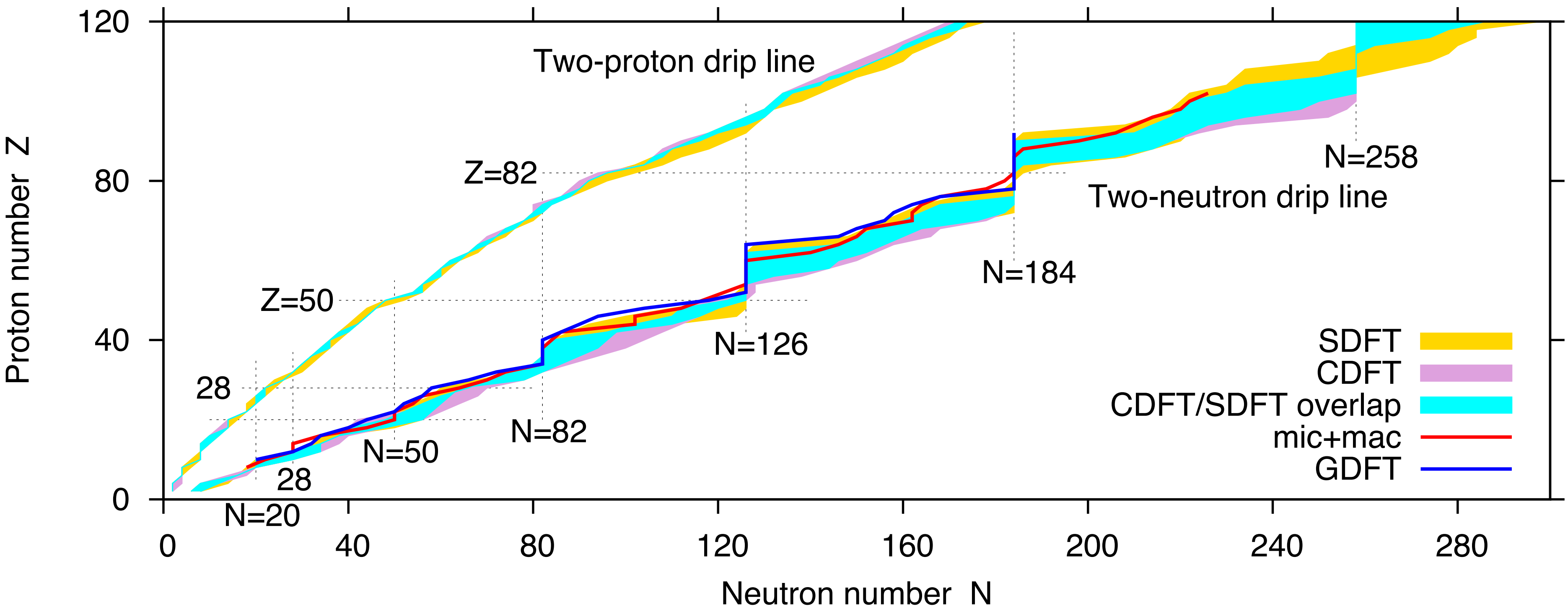


Assessing the limits of the nuclear landscape



Erler et al.
Nature 486, 509 (2012)

Quantified Nuclear Landscape (2)

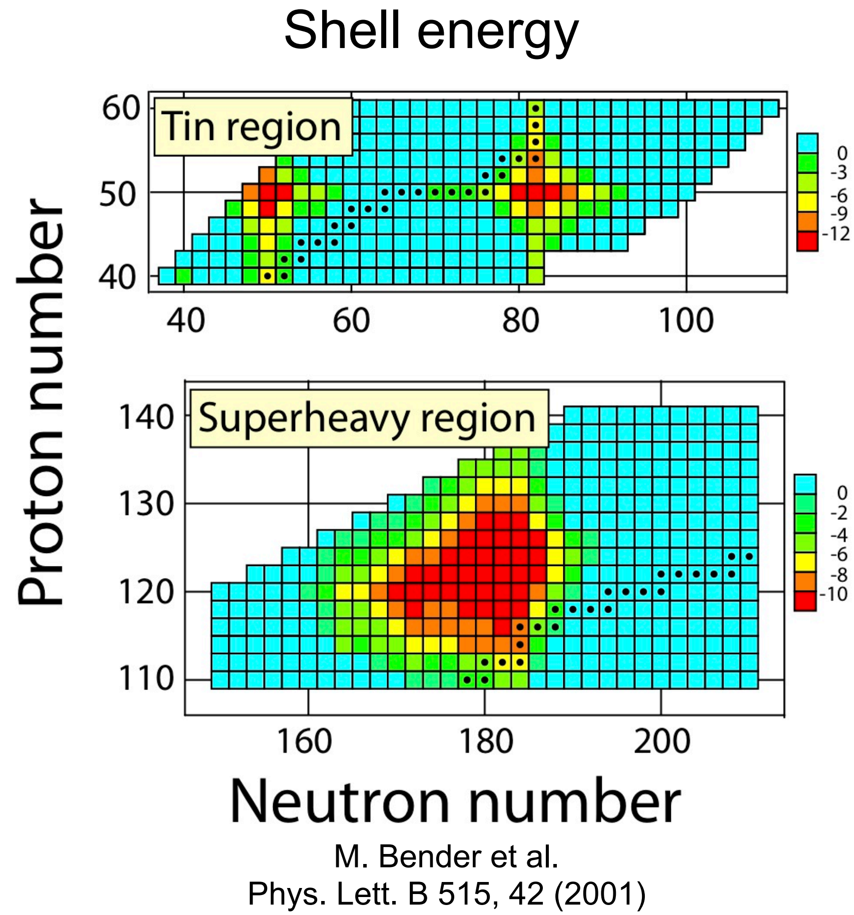


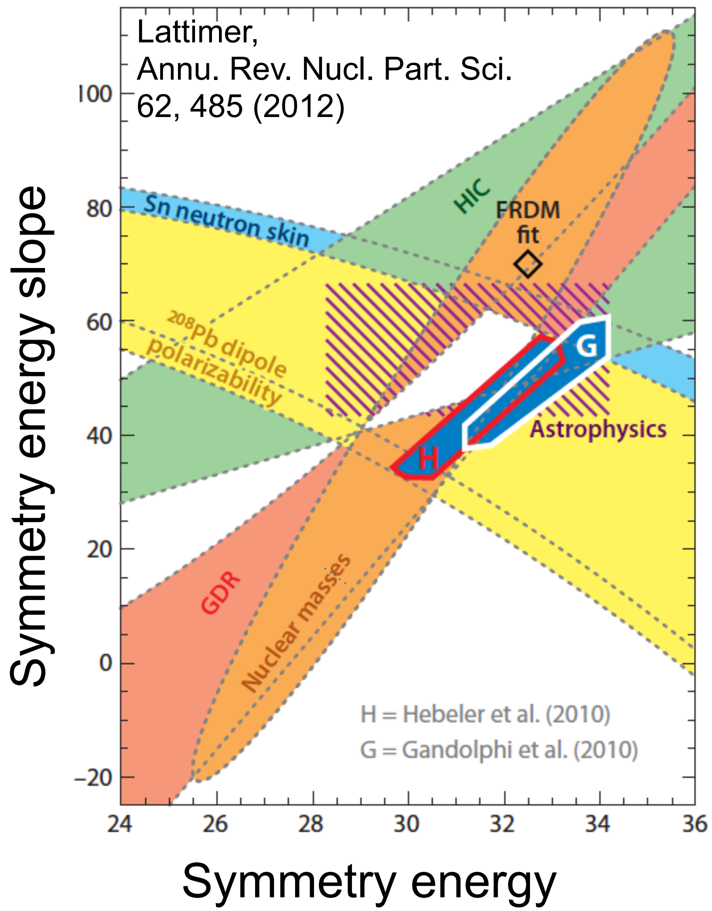
A.V. Afanasjev et al., Phys. Lett. B 726, 680 (2013)

How does subatomic matter organize itself and what phenomena emerge?

What do regular patterns in the behavior of nuclei tell us about the nature of nuclear forces?

Studies of regularities and periodicities of nuclear shells in neutron-rich and superheavy nuclei.



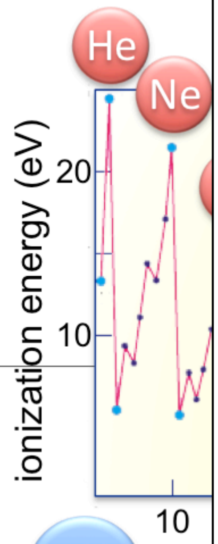


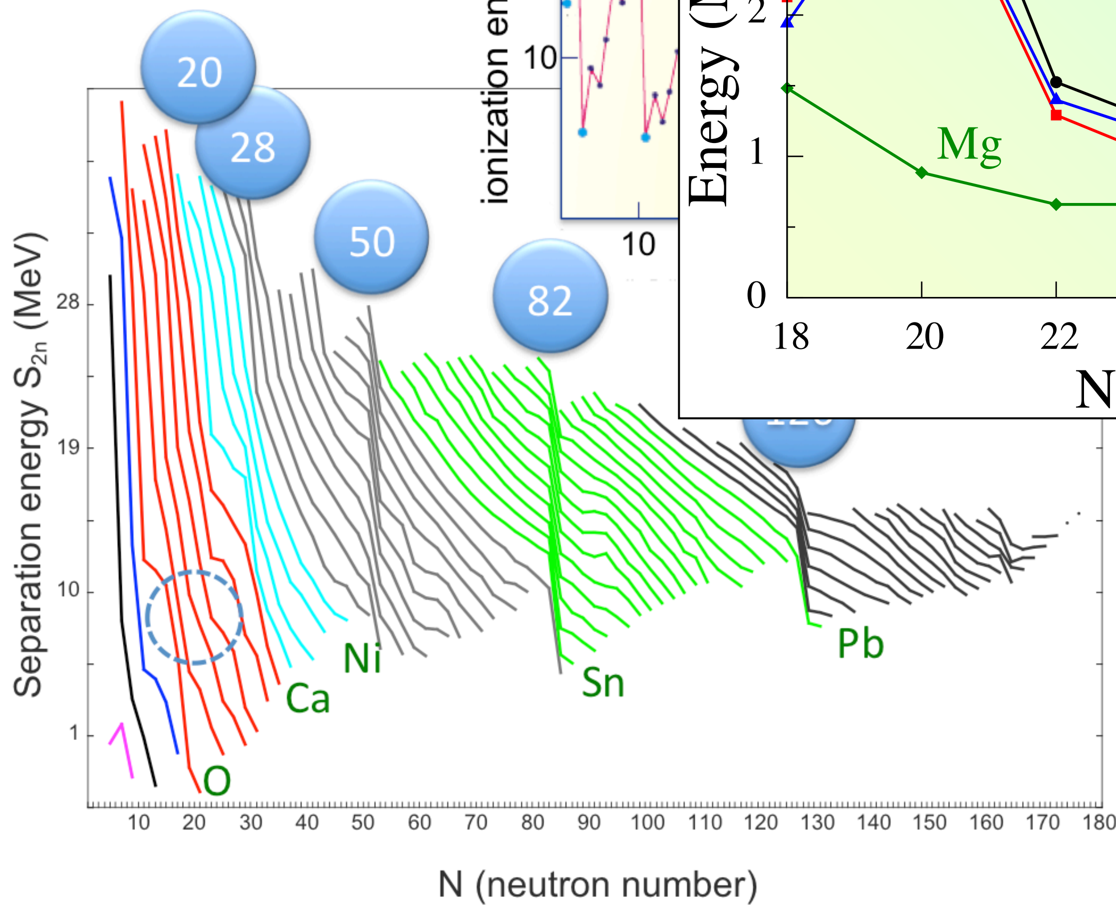
What is the nature of extended nucleonic matter?

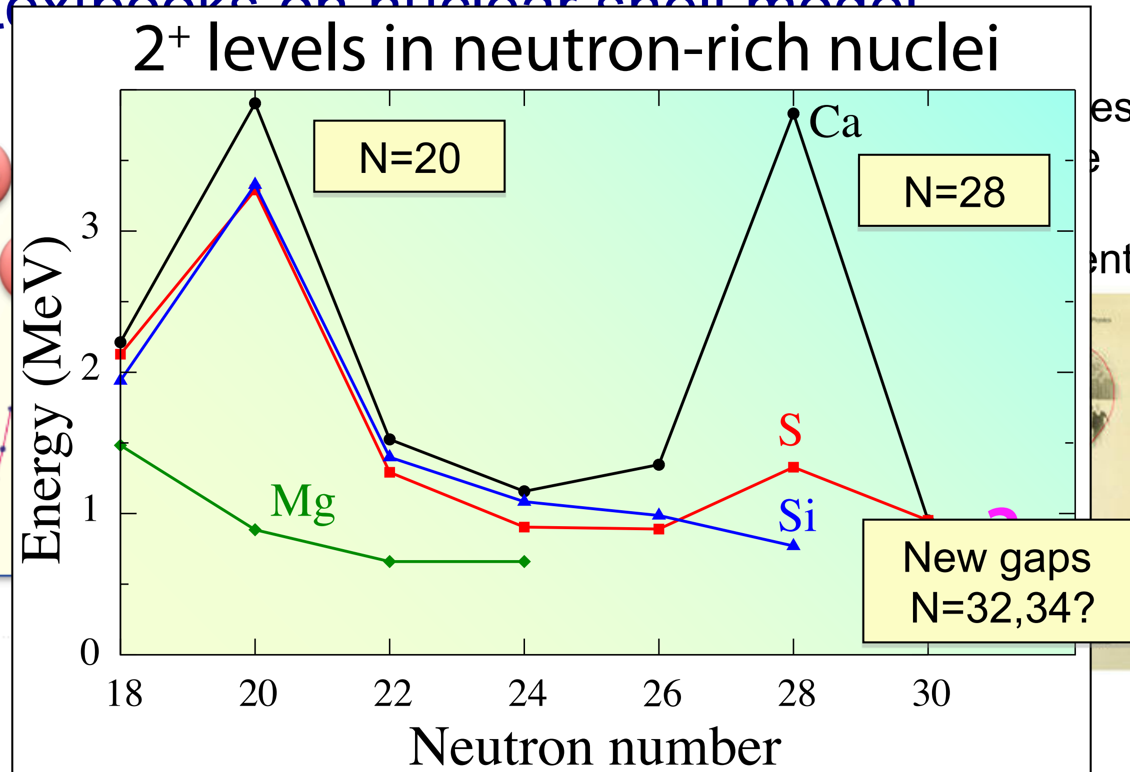
Exploring connection between neutron rich matter in the Cosmos and in the laboratory through isovector (N-Z) observables (skins, T=1 modes, electric dipole polarizability…).

Revising t

Regularities and periodicities in atoms and nuclei







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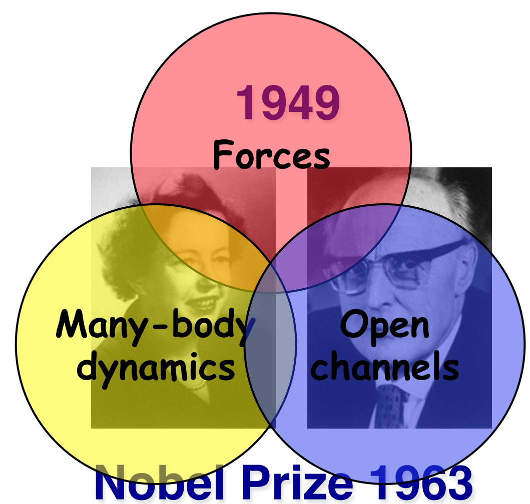
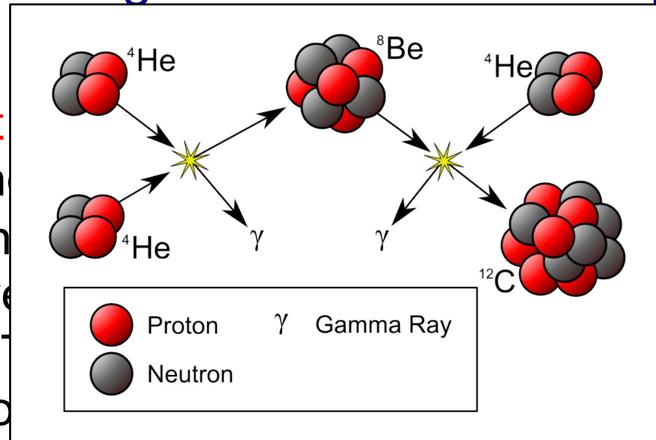
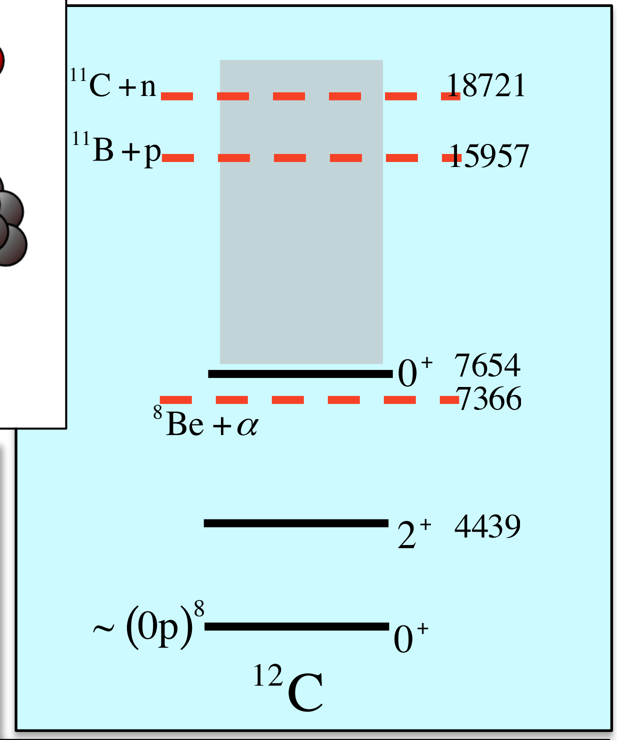


How does subatomic matter organize itself and what phenomena emerge?



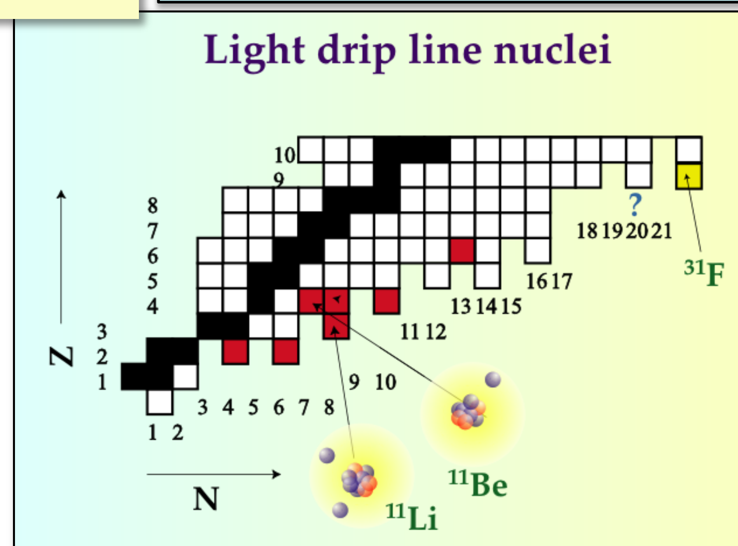


Proposed by Hoyle 1953…
Experiment:
ISOLDE, iThemba, HIγS, RCNP, ANU, ANL, Aarhus, JYFL, KVI, Birmingham…
THEORY:
JUGENE, ALCF

What is the nature of emergent atomic nuclei? Nucleonic pairin and isospin channels; in finite n nucleonic matter. New collective skins and angular momentum. collective motion, such as fissio coexistence.

How can finite nuclei exhibit phase behavior? Phase transitions betwe characterized by different many-bo Critical- and triple point searches as a function of particle number, spin, and temperature. Re-entrant phenomena.

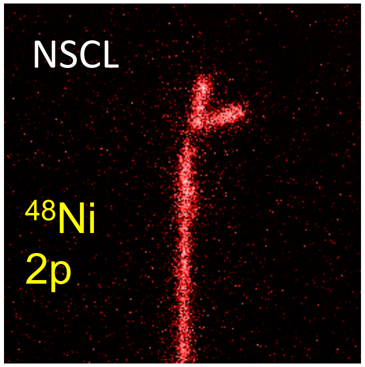
How can nuclear structure and reactions be described in a unified way? Understanding the role of the quantum openness in nuclei. Elucidating the role of reaction thresholds on appearance of collective cluster states.

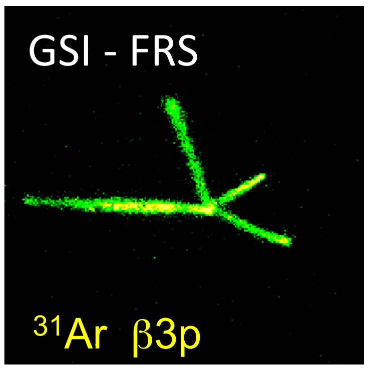


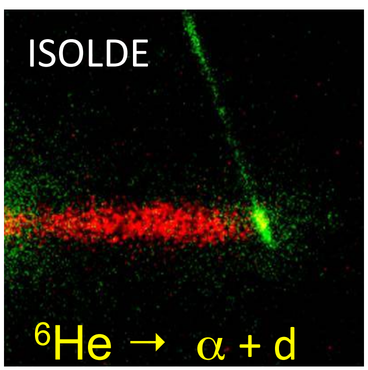
The landscape of two-proton radioactivity

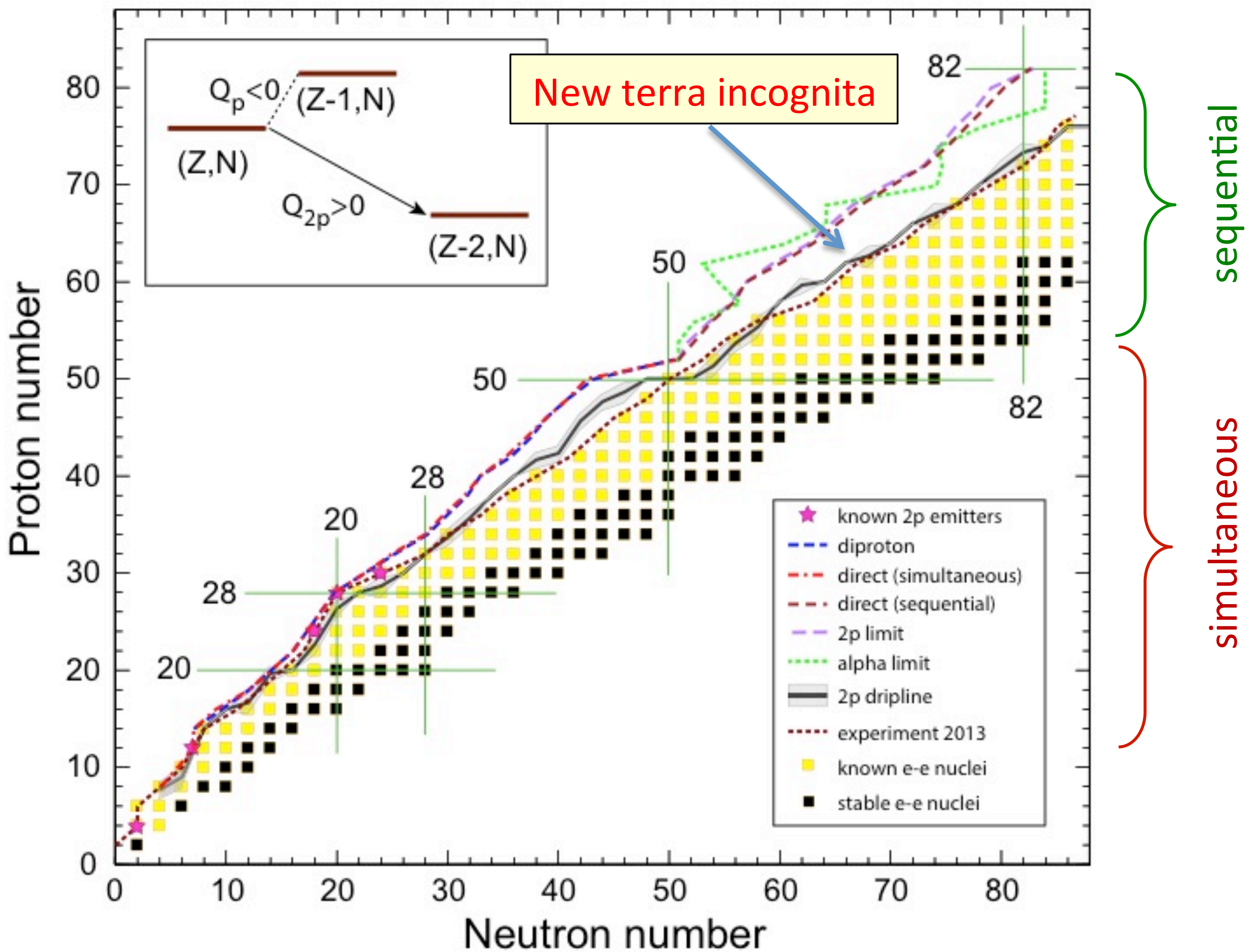
E. Olsen et al,

PRL 111, 139903 (2013); E: PRL 111, 139903 (2013)



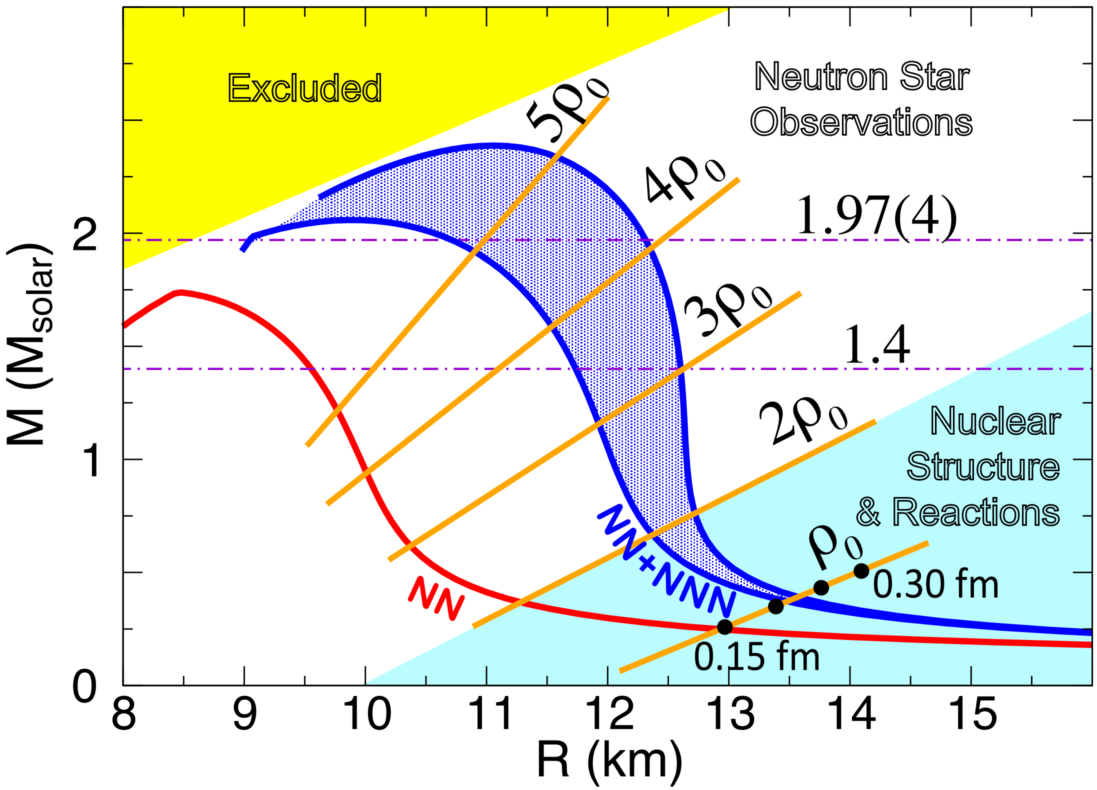




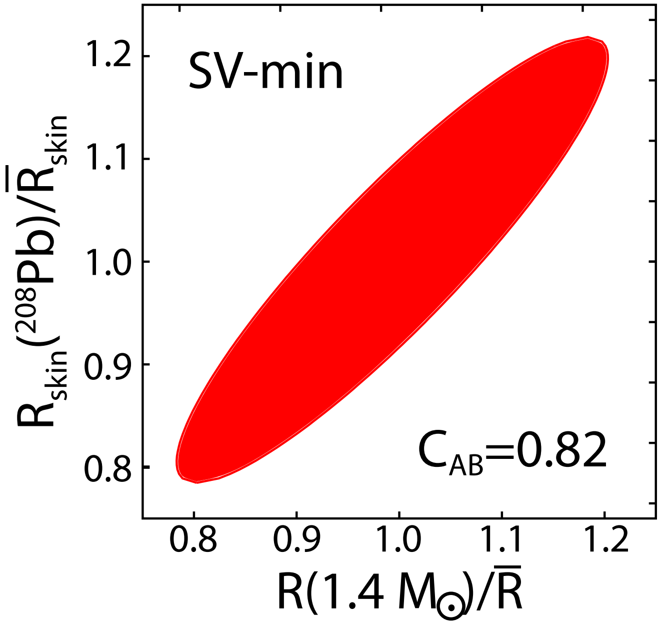


From nuclei to neutron stars (a multiscale problem)

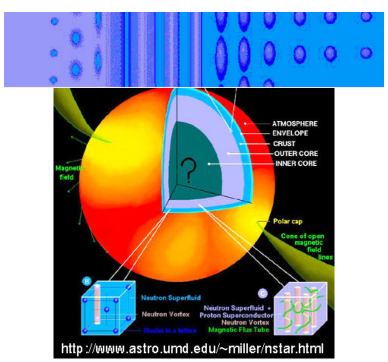
Gandolfi et al. PRC85, 032801 (2012)



J. Erler et al., PRC 87, 044320 (2013)

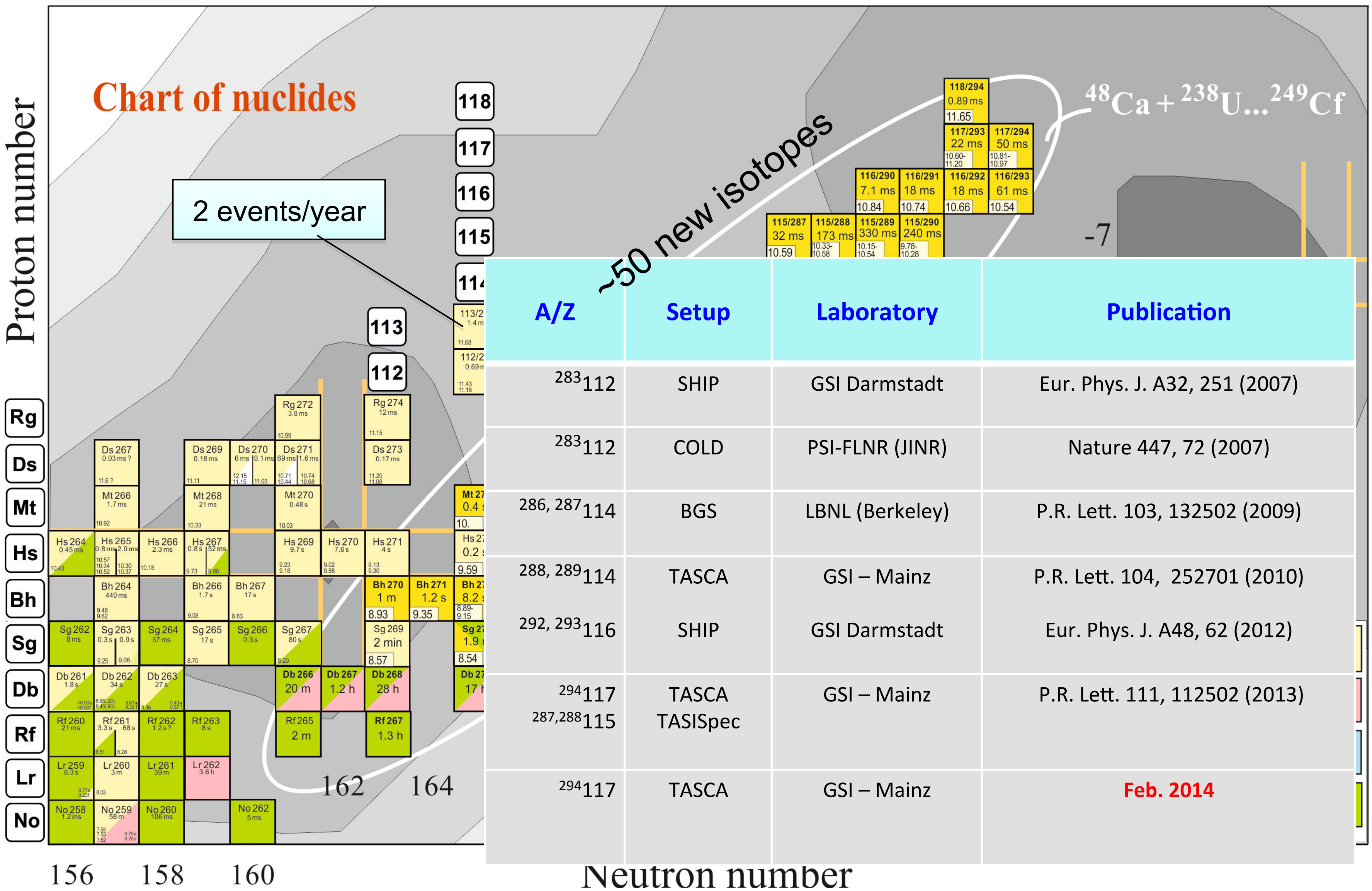


The covariance ellipsoid for the neutron skin R_{skin} in ^{208}Pb and the radius of a 1.4$M_\odot$ neutron star. The mean values are: R(1.4$M_\odot$)=10 km and R_{skin}= 0.17 fm.



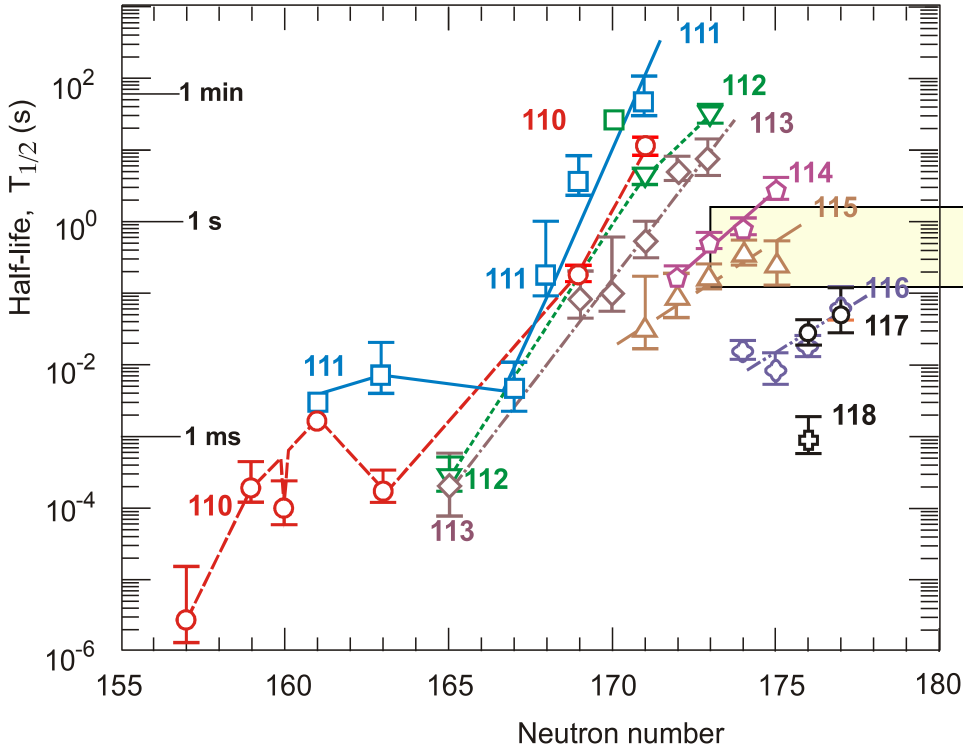
Major uncertainty: density dependence of the symmetry energy. Depends on T=3/2 3N forces

Limits of Mass and Charge: Superheavies

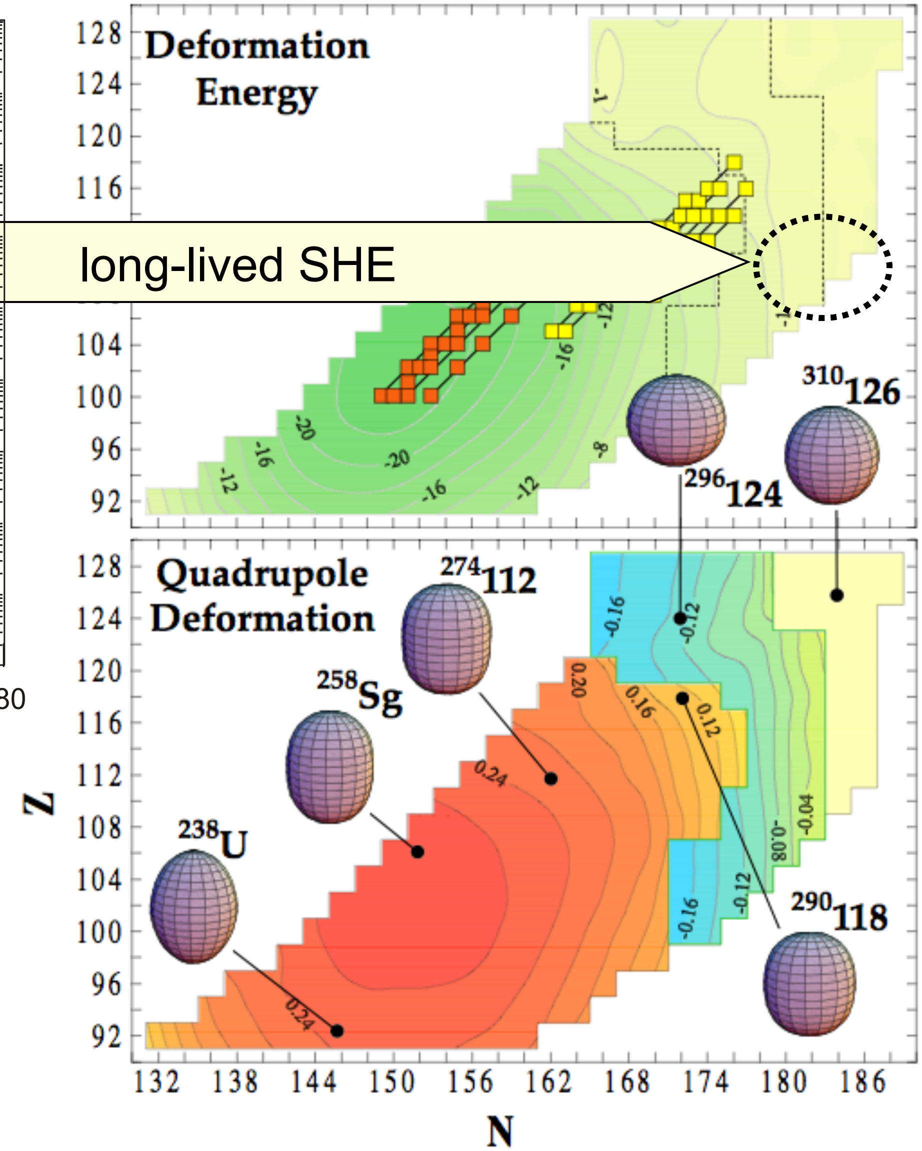


A/Z	Setup	Laboratory	Publication
^{283}112	SHIP	GSI Darmstadt	Eur. Phys. J. A32, 251 (2007)
^{283}112	COLD	PSI-FLNR (JINR)	Nature 447, 72 (2007)
$^{286, 287}$114	BGS	LBNL (Berkeley)	P.R. Lett. 103, 132502 (2009)
$^{288, 289}$114	TASCA	GSI – Mainz	P.R. Lett. 104, 252701 (2010)
$^{292, 293}$116	SHIP	GSI Darmstadt	Eur. Phys. J. A48, 62 (2012)
^{294}117 ^{287,288}115	TASCA TASISpec	GSI – Mainz	P.R. Lett. 111, 112502 (2013)
^{294}117	TASCA	GSI – Mainz	**Feb. 2014**

Towards long-lived Superheavy Nuclei



S. Cwiok, P.H. Heenen, W. Nazarewicz
Nature, 433, 705 (2005)



Are the fundamental interactions that are basic to the structure of matter fully understood?

Rare isotopes with enhanced sensitivity to fundamental symmetries provide opportunities for discovering new physics beyond the Standard Model

Experimental tests of the Standard Model

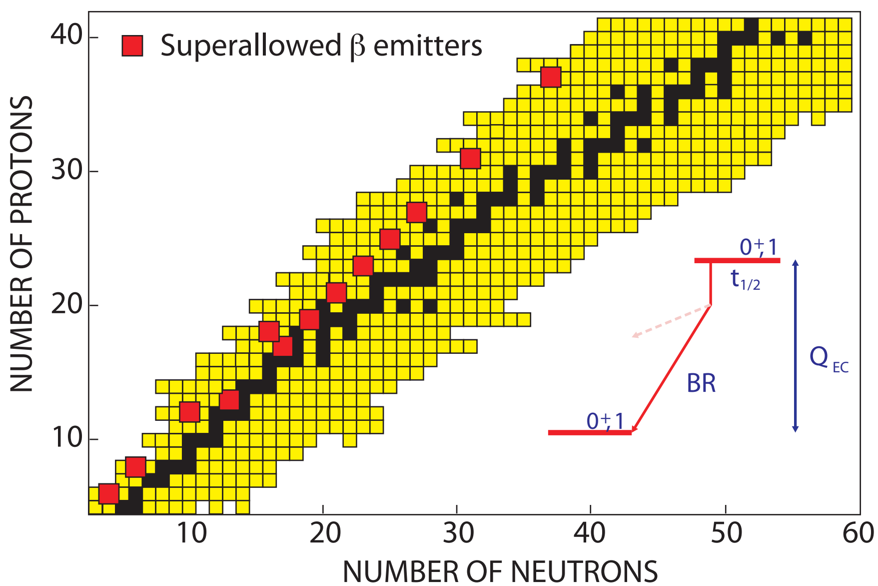
- Searches of atomic EDM in rare isotopes
- Tests of parity violation (anapole moment of Fr)
- Studies of superallowed β decays in N≃Z nuclei to test the CKM matrix unitarity
- β-ν angular correlation for the search of exotic scalar and tensor couplings
- Measurement of asymmetry-longitudinal polarization correlation in β decay to test deviations from maximal parity violation

Nuclear structure calculations relevant to SM tests

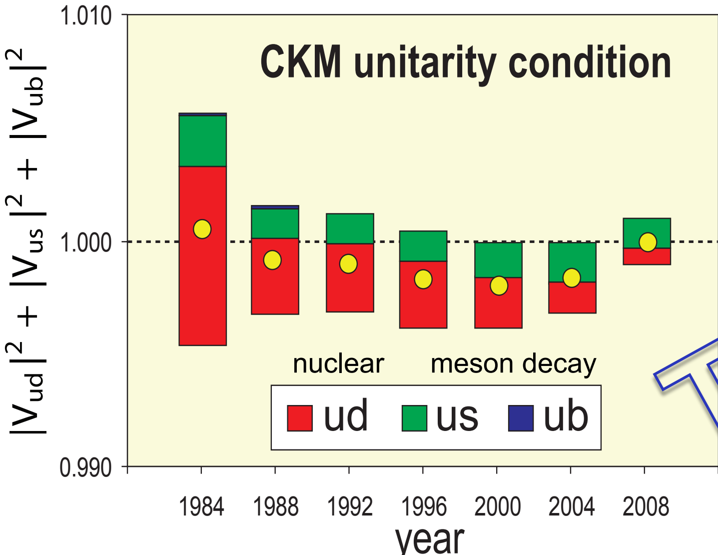
- Isospin mixing corrections for superallowed beta decays
- Calculations of nuclear anapole moments for parity violation tests
- Calculations of Schiff moments for atomic EDM searches
- Calculations of nuclear 2νββ and 0νββ matrix elements and comparison with observables

Rare Isotopes and fundamental symmetry tests

Superallowed Fermi $0^+ \rightarrow 0^+$ β-decays



ANL
ISOLDE
Jyväskylä
Munich
NSCL
TAMU
TRIUMF…
Warsaw, Tennessee..

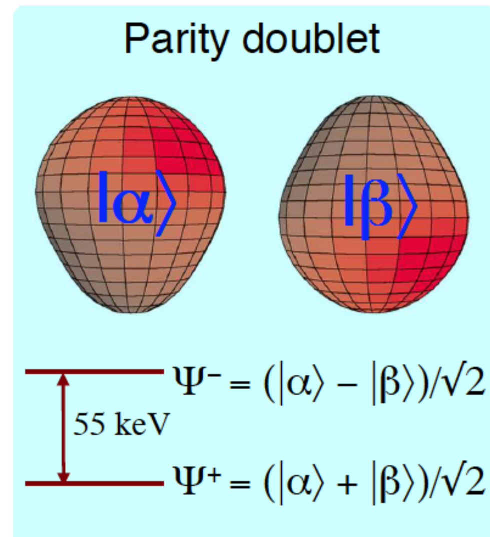


$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99935(67)$$

Theory!

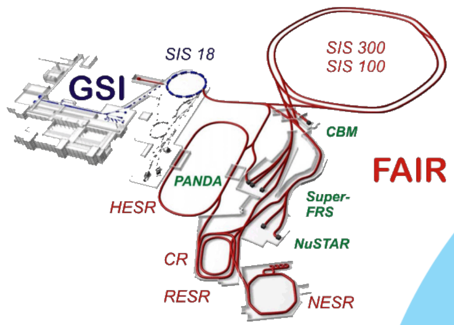
Atomic electric dipole moment

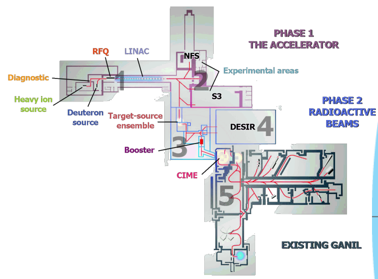
The violation of CP-symmetry is responsible for the fact that the Universe is dominated by matter over anti-matter

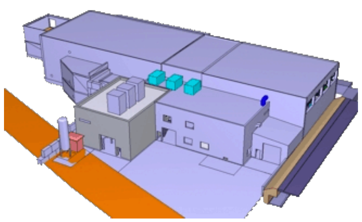


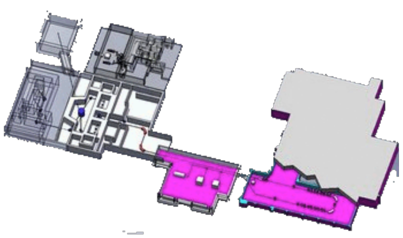
- Closely spaced parity doublet gives rise to enhanced electric dipole moment
- Large intrinsic Schiff moment
- ^{199}Hg (Seattle, 1980's – present)
- ^{225}Ra (Starting at ANL and KVI)
- ^{223}Rn at TRIUMF
- Potential at FRIB (10^{12}/s w ISOL target (far future); 10^{10} initially

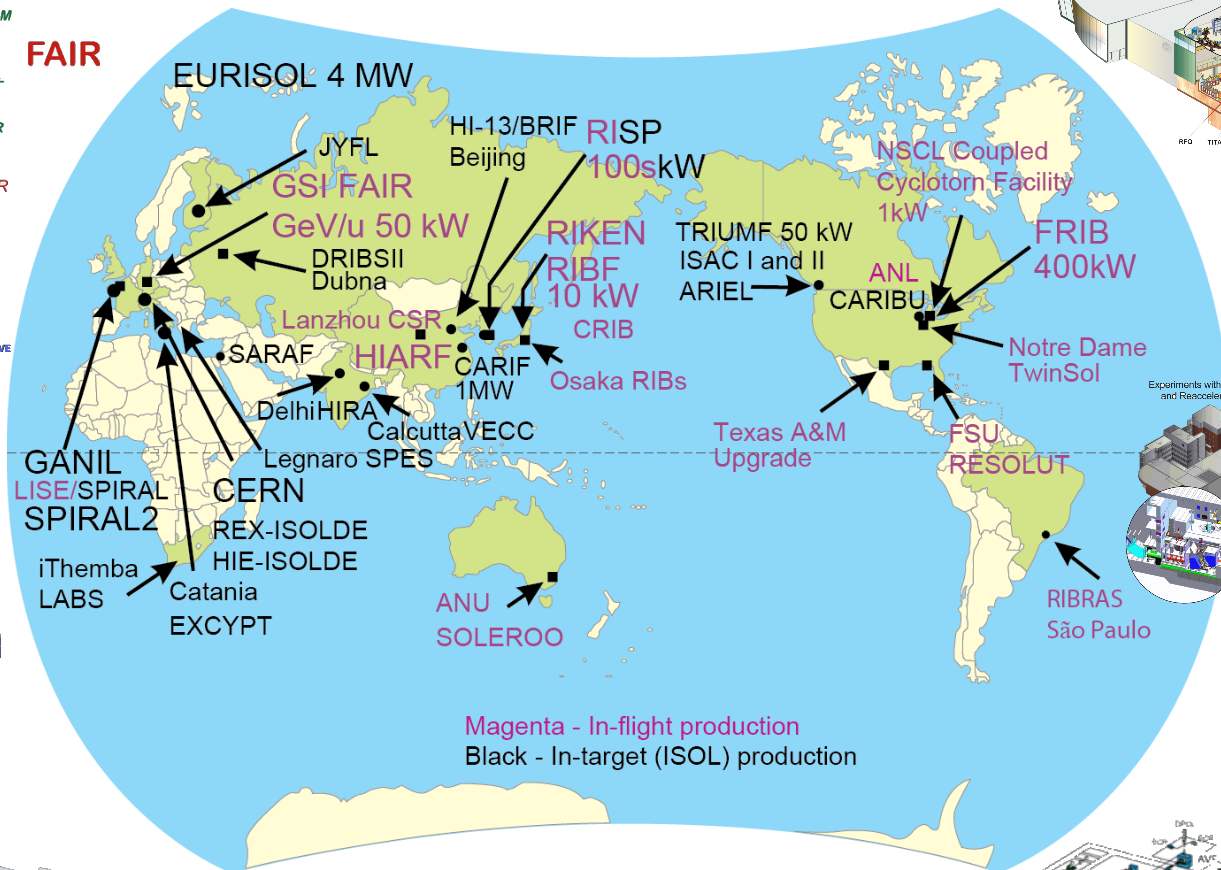
Experiment

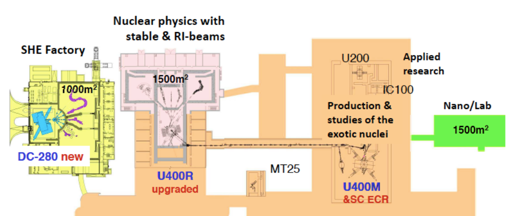






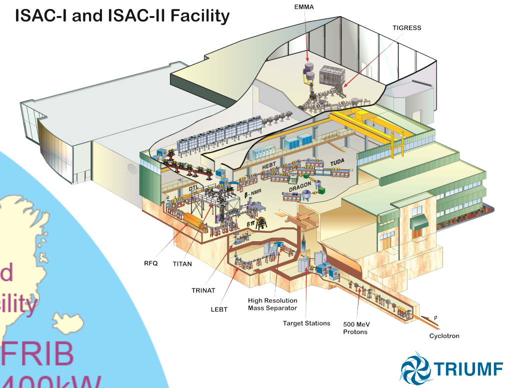


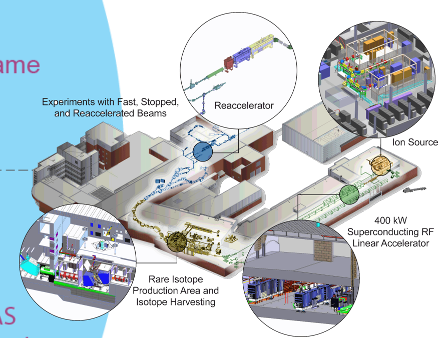


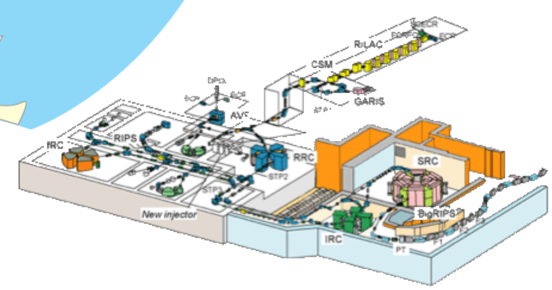


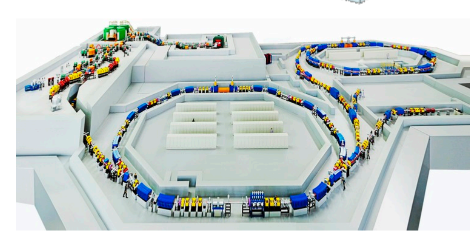
U400M-U400R Accelerator Complex

ISAC-I and ISAC-II Facility









Theoretical Tools and Connections to Computational Science

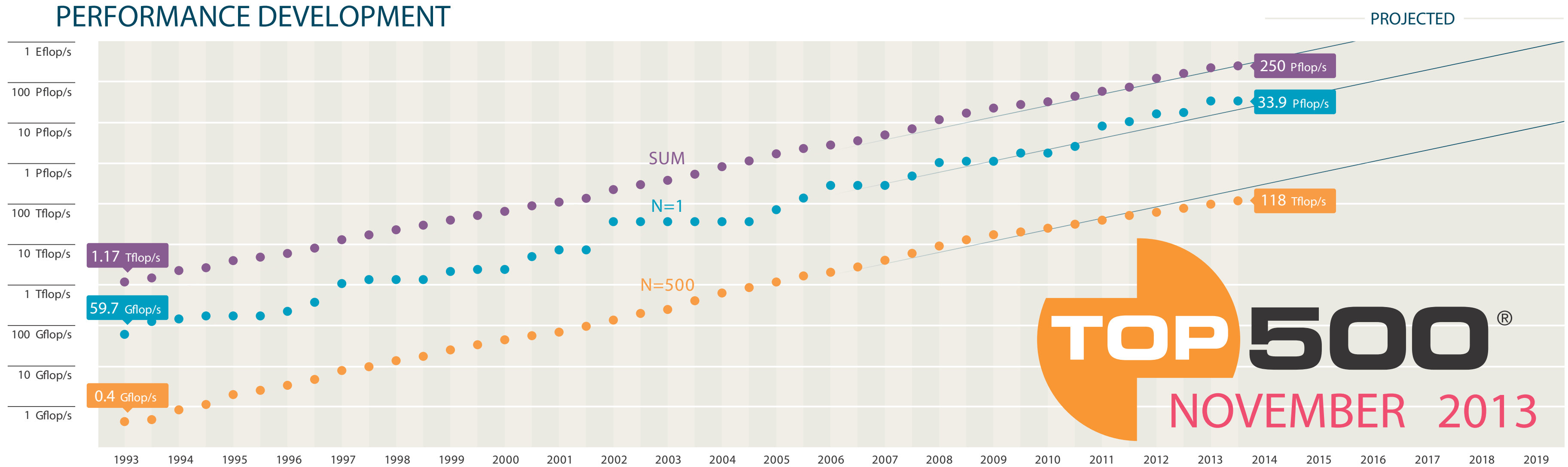
1teraflop=10^{12} flops
1peta=10^{15} flops (today)
1exa=10^{18} flops (next 10 years)

Tremendous opportunities for nuclear theory!

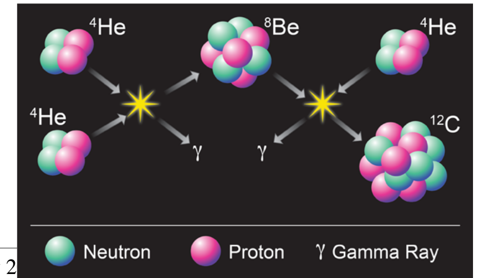
33.9 pflops

	NAME	SPECS	SITE	COUNTRY	CORES	R_{MAX} PFLOP/S	POWER MW
1	Tianhe-2 (Milkyway-2)	NUDT, Intel Ivy Bridge (12C, 2.2 GHz) & Xeon Phi (57C, 1.1 GHz), Custom interconnect	NSCC Guangzhou	China	3,120,000	33.9	17.8
2	Titan	Cray XK7, Operon 6274 (16C 2.2 GHz) + Nvidia Kepler GPU, Custom interconnect	DOE/SC/ORNL	USA	560,640	17.6	8.2
3	Sequoia	IBM BlueGene/Q, Power BQC (16C 1.60 GHz), Custom interconnect	DOE/NNSA/LLNL	USA	1,572,864	17.2	7.9
4	K computer	Fujitsu SPARC64 VIIIfx (8C, 2.0GHz), Custom interconnect	RIKEN AICS	Japan	705,024	10.5	12.7
5	Mira	IBM BlueGene/Q, Power BQC (16C, 1.60 GHz), Custom interconnect	DOE/SC/ANL	USA	786,432	8.59	3.95

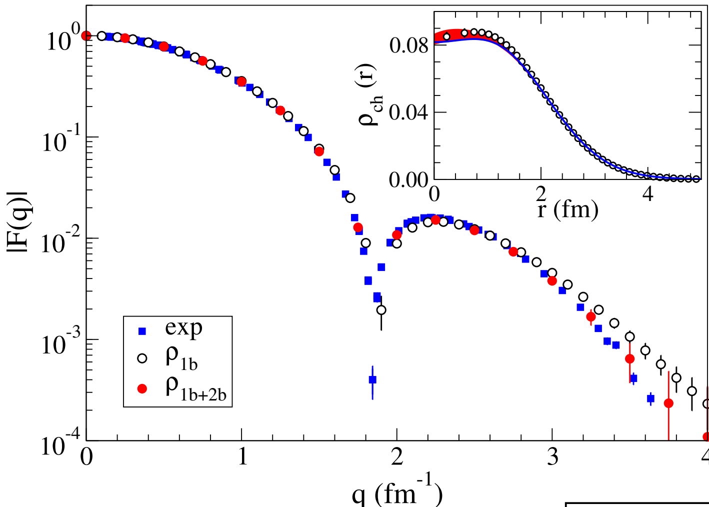
PERFORMANCE DEVELOPMENT

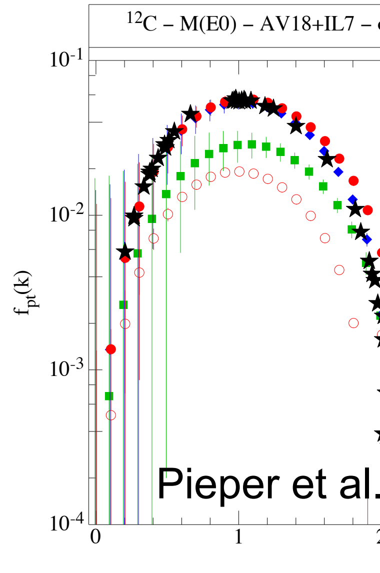


^{12}C: ground state and Hoyle state
state-of-the-art computing

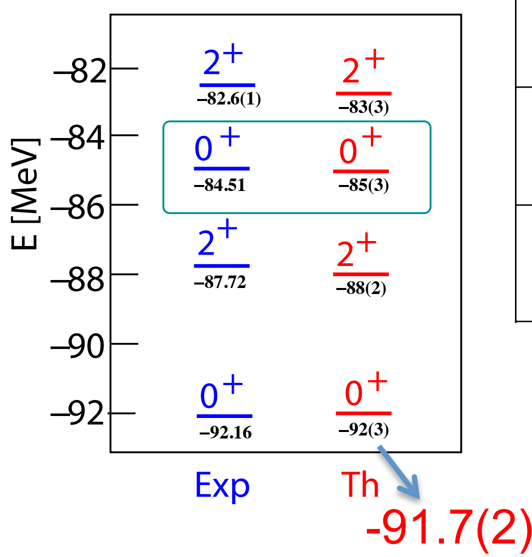


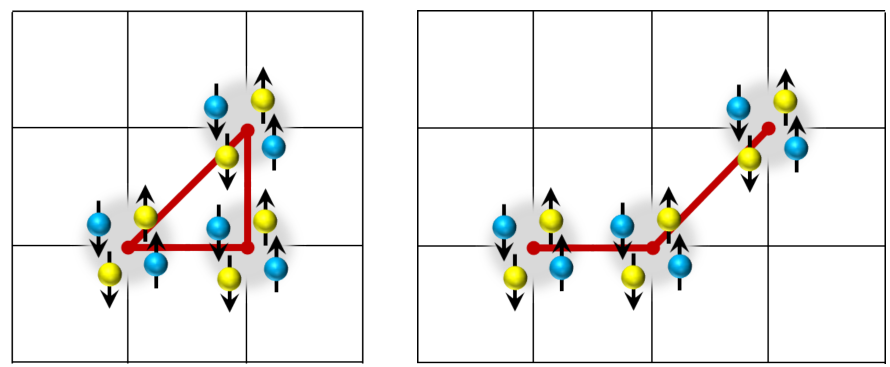
Wiringa et al. Phys. Rev. C 89, 024305 (2014); A. Lovato et al., Phys. Rev. Lett. 112, 182502 (2014)





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. 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.

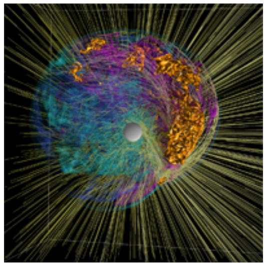
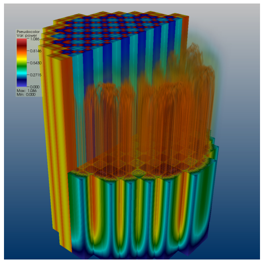


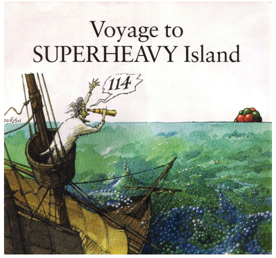


Epelbaum et al., Phys. Rev. Lett. 109, 252501 (2012). Lattice EFT
Lahde et al., Phys. Lett. B 732, 110 (2014).

Experimental context: some thoughts…

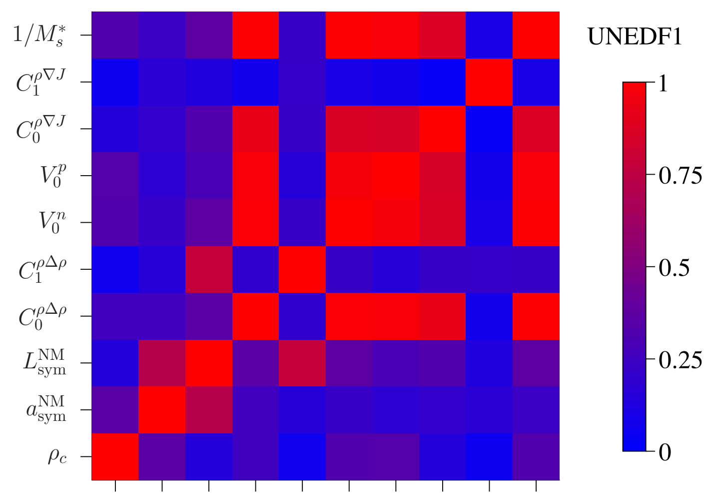
- **Beam time is difficult to get and expensive.** Theory should be more involved in assessing the impact of planned runs and projects.
  - Helping planning future experiments and experimental programs
  - Assessing the uniqueness and usefulness of an observable, i.e., its information content with respect to current theoretical models
  - Are estimated errors of measured observables meaningful?
  - What experimental data are crucial for better constraining current nuclear models?
- New technologies are essential for providing predictive capability, to estimate uncertainties, and to assess extrapolations
  - Theoretical models are often applied to entirely new nuclear systems and conditions that are not accessible to experiment

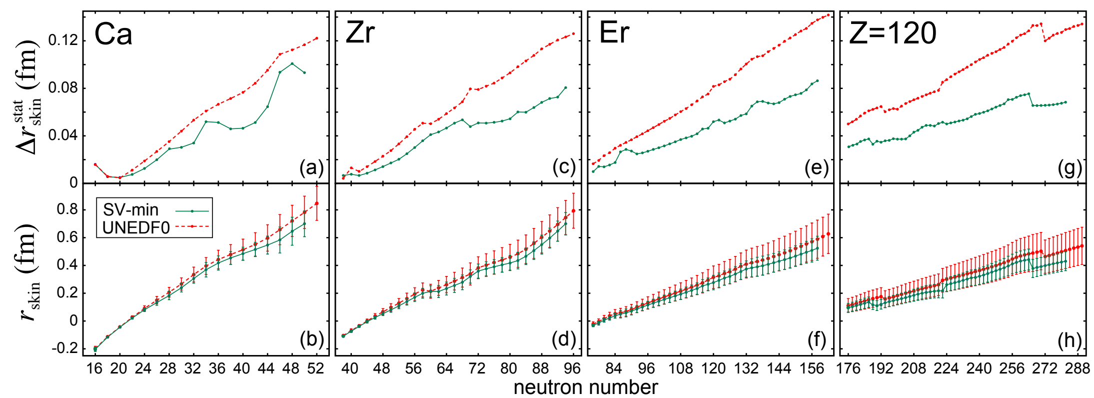





Information content of future measurements

Nuclear theory is developing tools to deliver uncertainty quantification and error analysis for the assessment of new experimental data. Theoretical tools can also be used to assess the information content of an observable with respect to current theoretical models, and evaluate the degree of correlation between different observables.





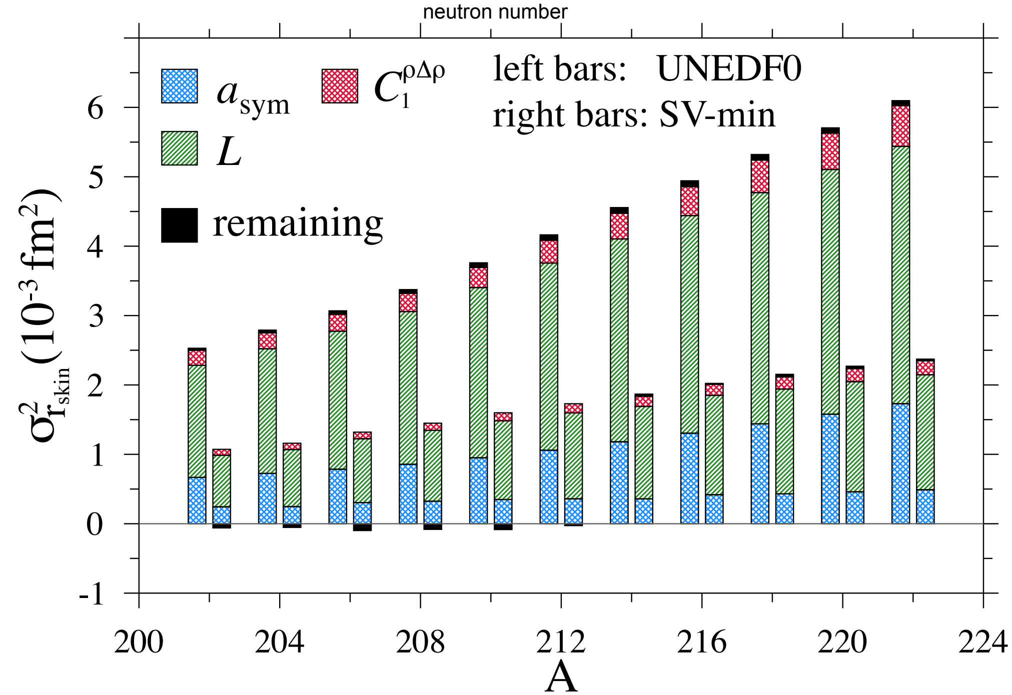


TABLE I. Theoretical uncertainties on r_{skin} in ^{208}Pb and ^{48}Ca (in fm). Shown are statistical errors of UNEDF0 and SV-min, systematic error Δr_{skin}^{syst}, the model-averaged deviation of Ref. [9], and errors of PREX [25] and planned PREX-II [29] and CREX [30] experiments.

nucleus	Δr_{skin}^{stat} UNEDF0	Δr_{skin}^{stat} SV-min	Δr_{skin}^{syst}	Ref. [9]	Experiment
^{208}Pb	0.058	0.037	0.013	0.022	0.18 [25], 0.06[29]
^{48}Ca	0.035	0.026	0.019	0.018	0.02 [30]

M. Kortelainen et al., Phys. Rev. C 88, 031305 (2013)


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

Some Anticipated NS/NA Greatest Hits: next 20 years

- We will know the site of the r-process
- We will understand the weak interaction rates that drive electron-capture supernovae
- We will understand the origin of the abundance patterns seen in the oldest observable stars
- We will know the nuclear equation of state for normal and neutron matter from 0.1 to twice the saturation density
- We will have predictive theory — based on forces firmly rooted in QCD — that will tell us the limits of isotopes and elements
- We will know if long-lived superheavy elements exist in nature
- We will understand the mechanism of clustering and other aspects of open many-body systems
- We will have a quantitative microscopic model of light-ion fusion and heavy-nuclei fission that will provide the missing data for nuclear security, astrophysics, and energy research
- We will improve the sensitivity of EDM searches in atoms by one to two orders of magnitude over current limits
- We will compute essential nuclear matric elements for fundamental symmetry tests in nuclei

Philip Bredesen, cont.

Big science has had a great run for the last 60 years: Manhattan project, Sputnik and space exploration, the explosion and excitement of particle physics and accelerator; the rationale was obvious and easy. But those rationales are getting long in the tooth now, and need to be reinvigorated.

(...) the reality is that resources are scarce, the reality is that big science needs resources that only the government can supply, and the reality is that those scarce resources will go to those things that ordinary citizens think are important to themselves and to their children and to our nation. That's our job, to remake that connection in the 21st century.

There's nothing wrong or demeaning in this; even Michelangelo had patrons who had a seat at the table and needed to be satisfied.

Outlook

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

- Cool
- Deals with fundamental and complex
- Interdisciplinary
- Relevant

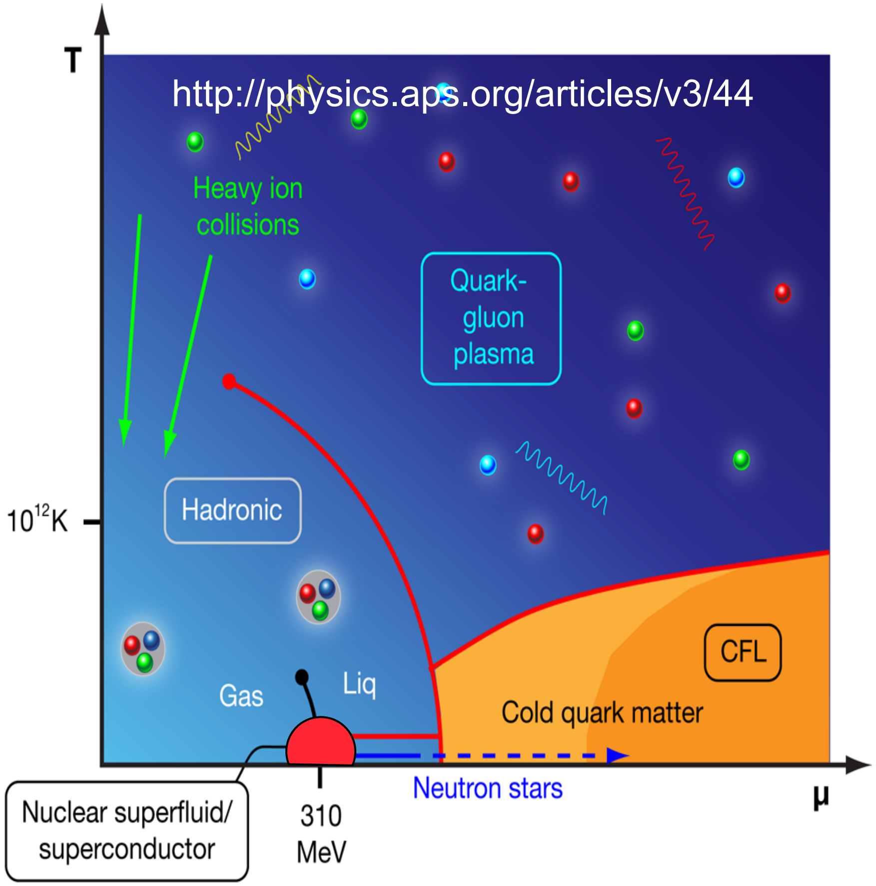
- Significant progress and discoveries worldwide in the physics of nuclei and nuclear astrophysics
- Comprehensive and validated theory of nuclei on the horizon
- World-class science program

Thank You

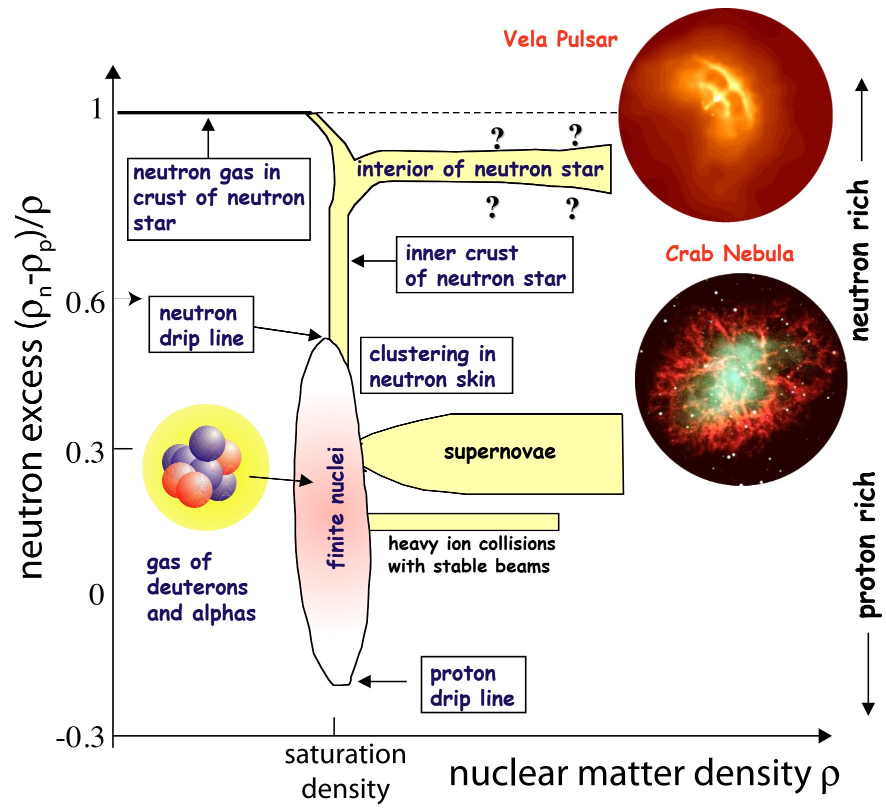
BACKUP

The Nuclear Landscape…

…as seen by the QCD phase diagram

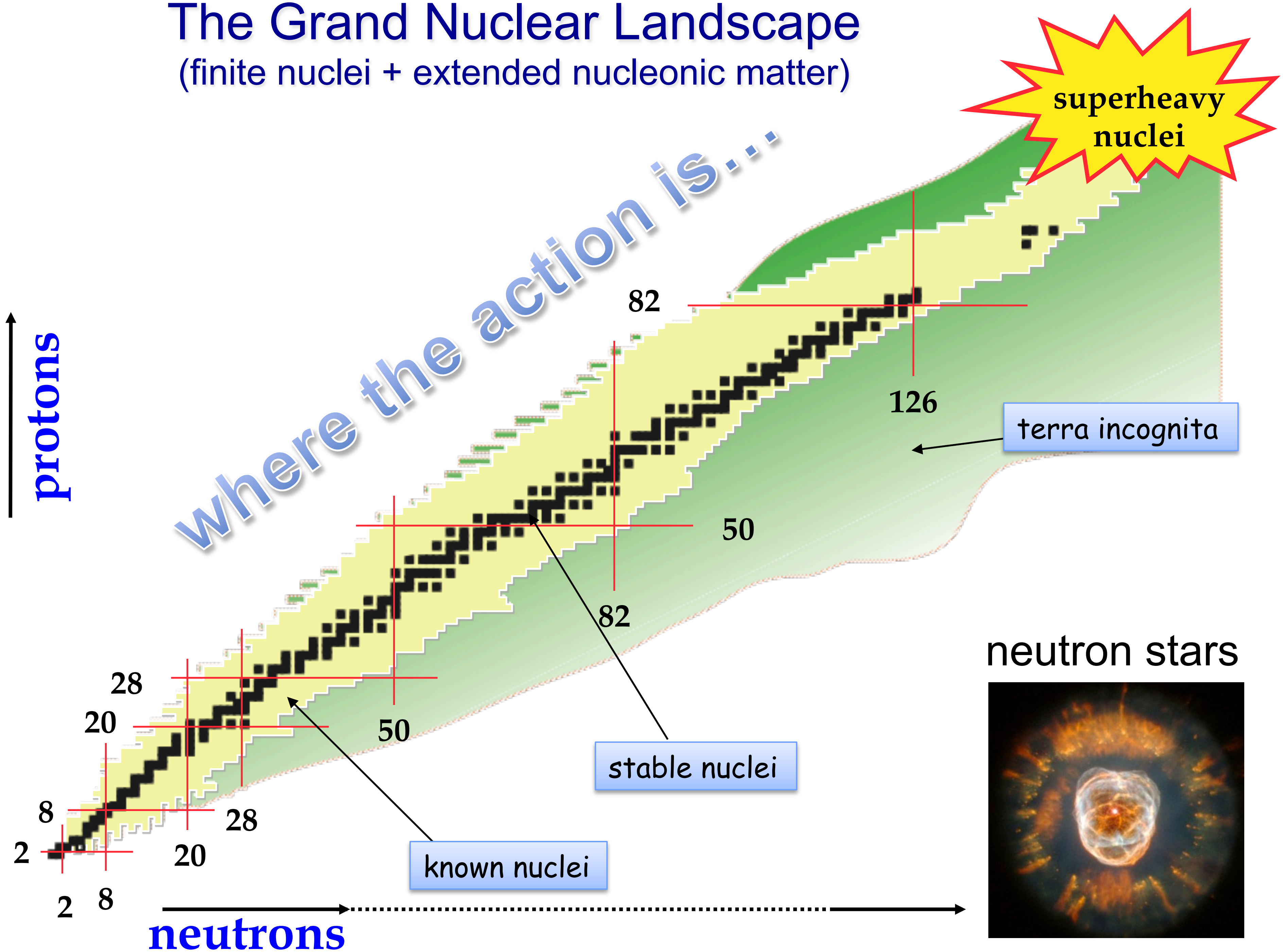


…as seen by astrophysicists

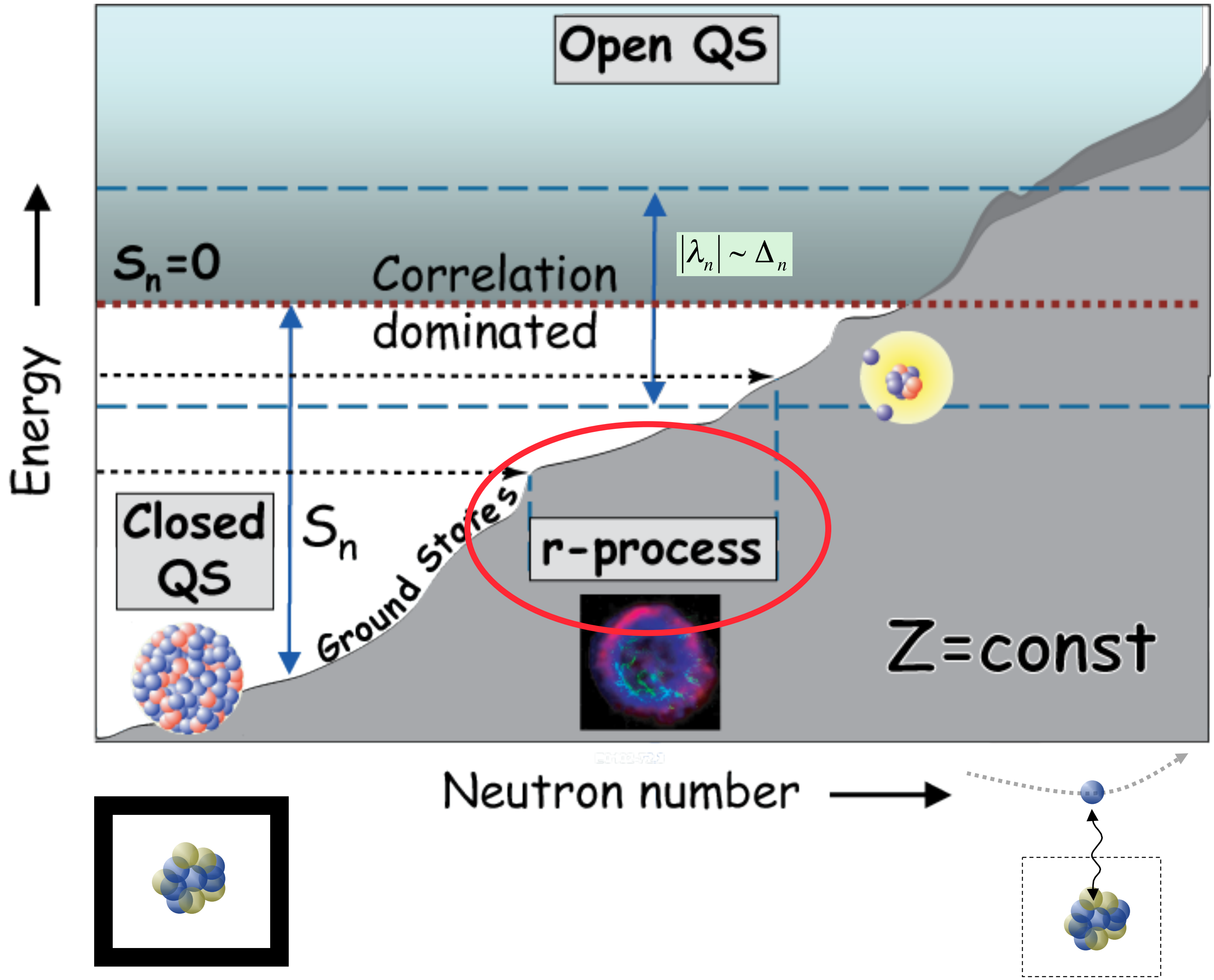


Pethick and Ravenhall, Annu. Rev. Nucl. Part. Sci. 45, 429 (1995)

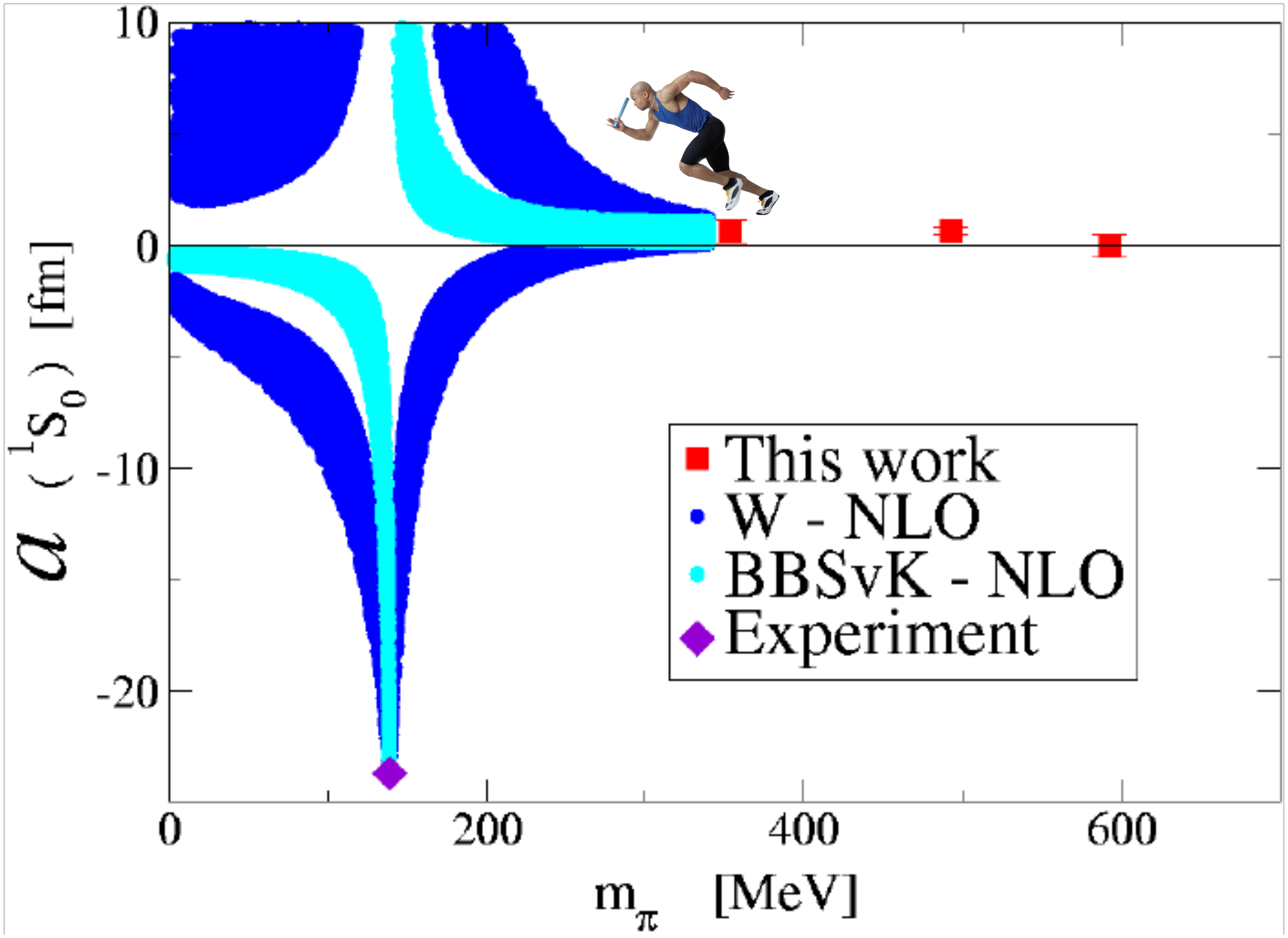
The Grand Nuclear Landscape
(finite nuclei + extended nucleonic matter)



Prog. Part. Nucl. Phys. 59, 432 (2007)



The challenge and the prospect:
NN scattering on Lattice



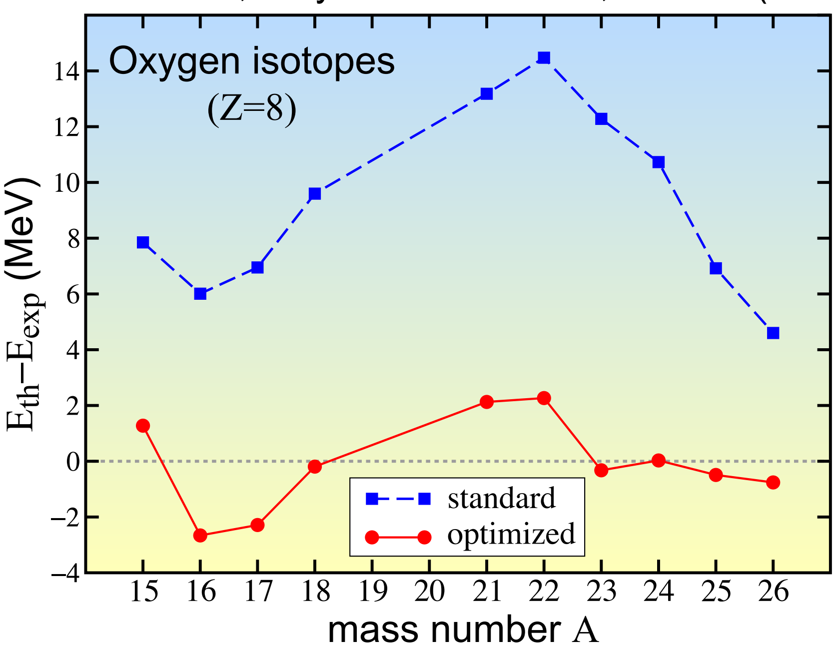
Beane et al. PRL 97, 012001 (2006)

Optimizing the nuclear force

input matters: garbage in, garbage out

- The derivative-free minimizer POUNDERS was used to systematically optimize NNLO chiral potentials
- The optimization of the new interaction NNLO_{opt} yields a χ^2/datum ≈ 1 for laboratory NN scattering energies below 125 MeV. The new interaction yields very good agreement with binding energies and radii for A=3,4 nuclei and oxygen isotopes
- Ongoing: Optimization of NN + 3NF

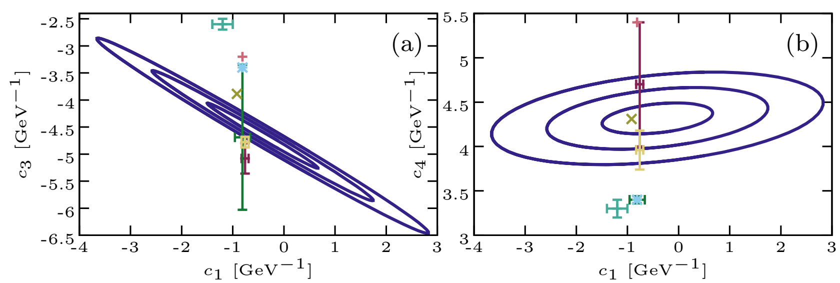
A. Ekström et al., Phys. Rev. Lett. 110, 192502 (2013)



http://science.energy.gov/np/highlights/2014/np-2014-05-e/

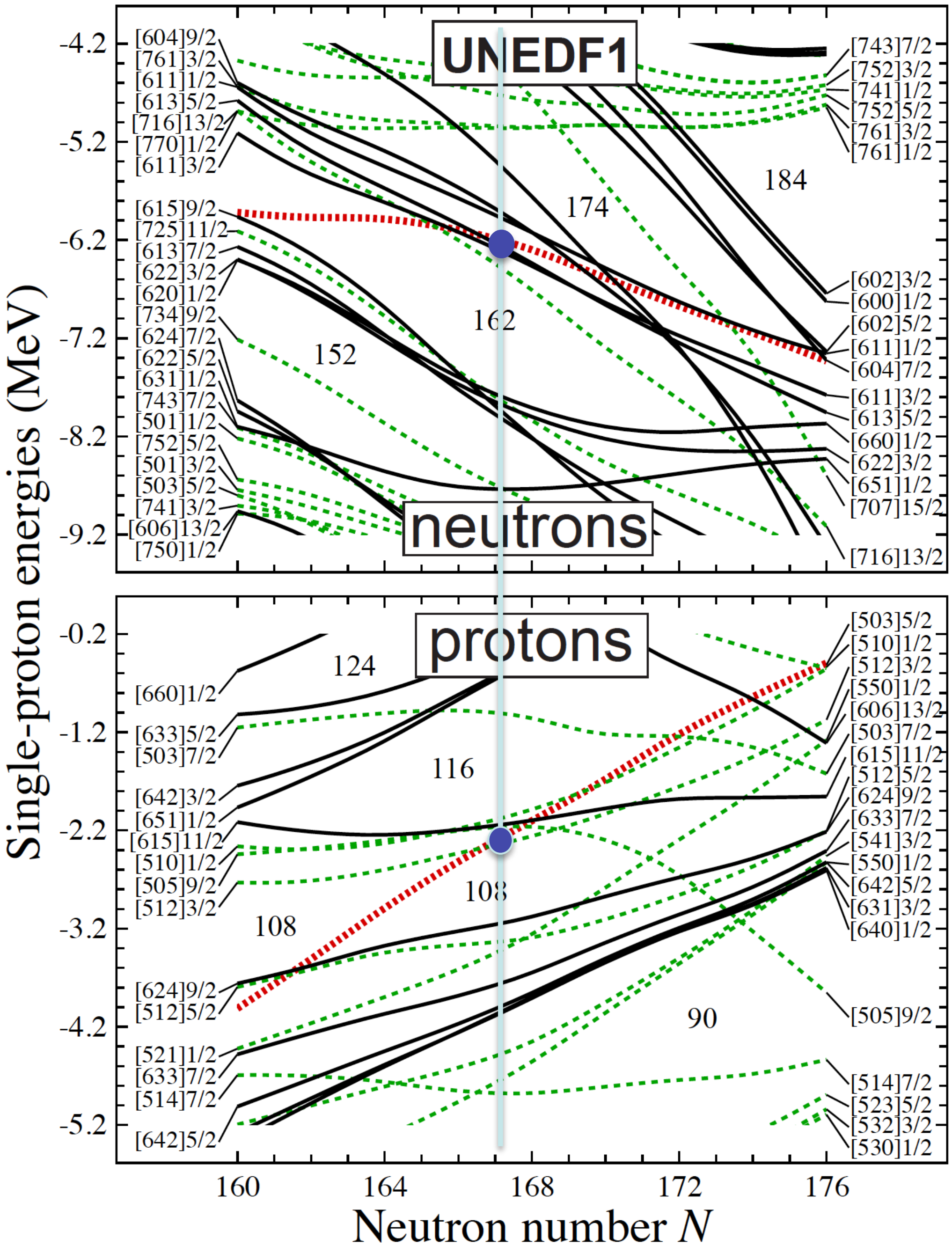
- Used a coarse-grained representation of the short-distance interactions with 30 parameters
- The optimization of a chiral interaction in NNLO yields a χ^2/datum ≈ 1 for a mutually consistent set of 6713 NN scattering data
- Covariance matrix yields correlation between LECCs and predictions with error bars.

Navarro Perez, Amaro, Arriola,
Phys. Rev. C 89, 024004 (2014) and
arXiv:1406.0625



	This work	Emp./Rec. [36–41]	δ she
E_d (MeV)	Input	2.224575(9)	Ir
η	0.02473(4)	0.0256(5)	0.02
A_S (fm$^{1/2}$)	0.8854(2)	0.8845(8)	0.88
r_m (fm)	1.9689(4)	1.971(6)	1.96
Q_D (fm^2)	0.2658(5)	0.2859(3)	0.26
P_D	5.30(3)	5.67(4)	5.62
$\langle r^{-1}\rangle$ (fm^{-1})	0.4542(2)		0.45

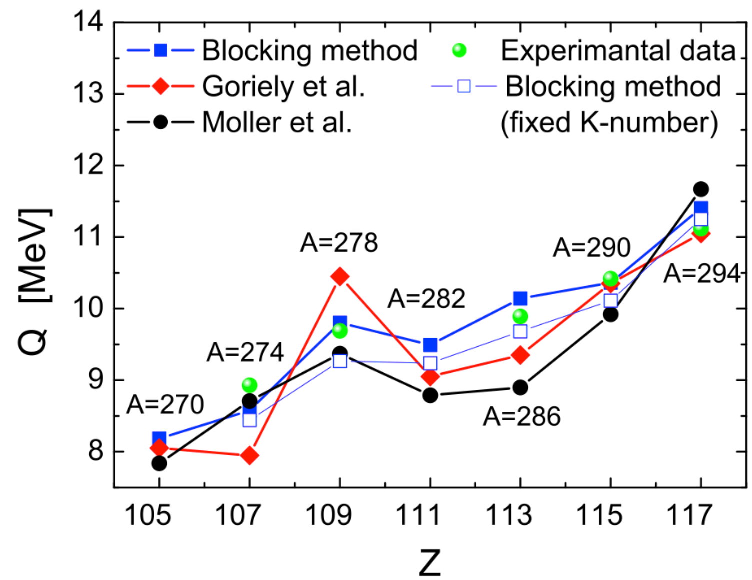
Yue Shi *et al.*, PRC 90, 014308 (2014)



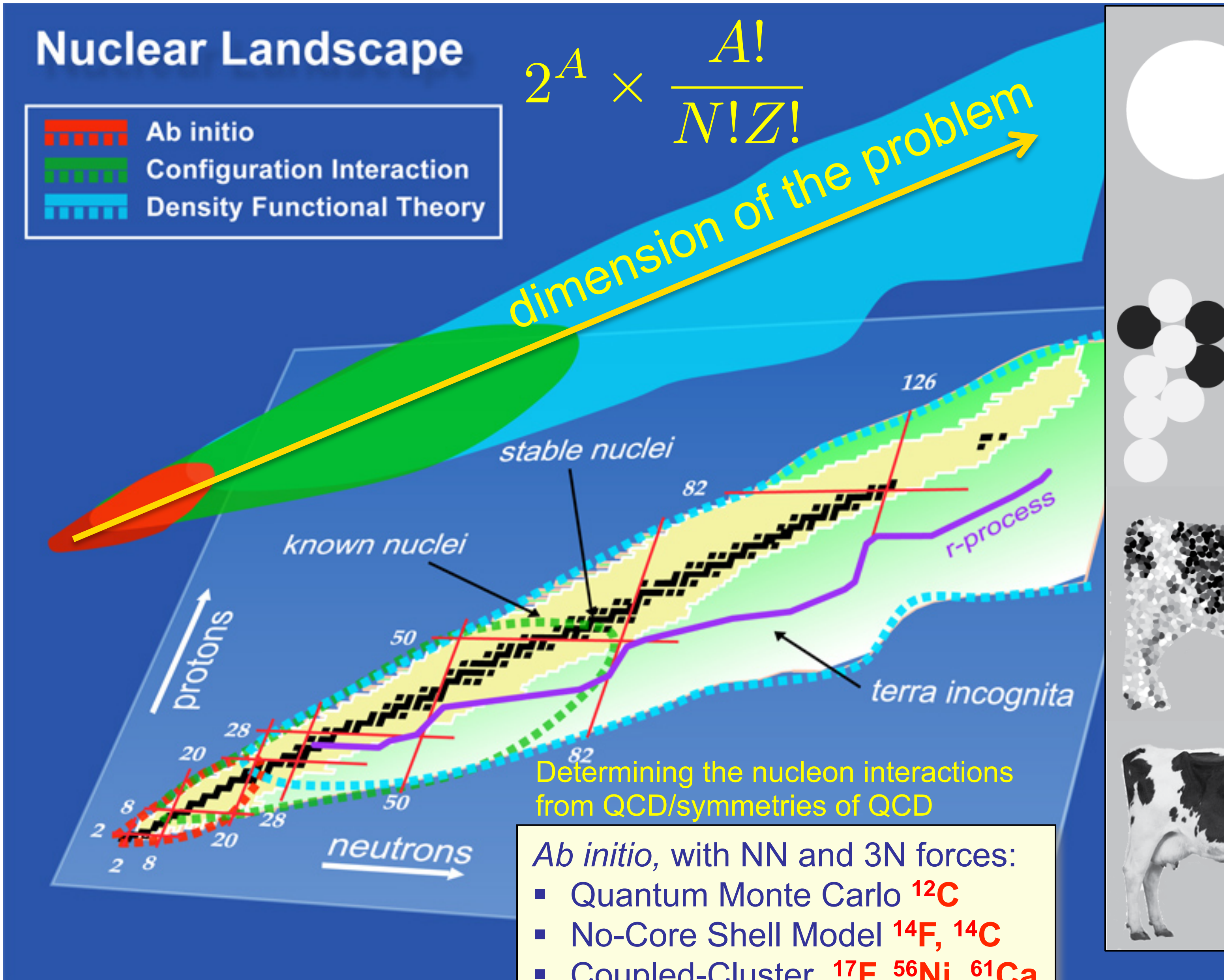
High-K states in SHE

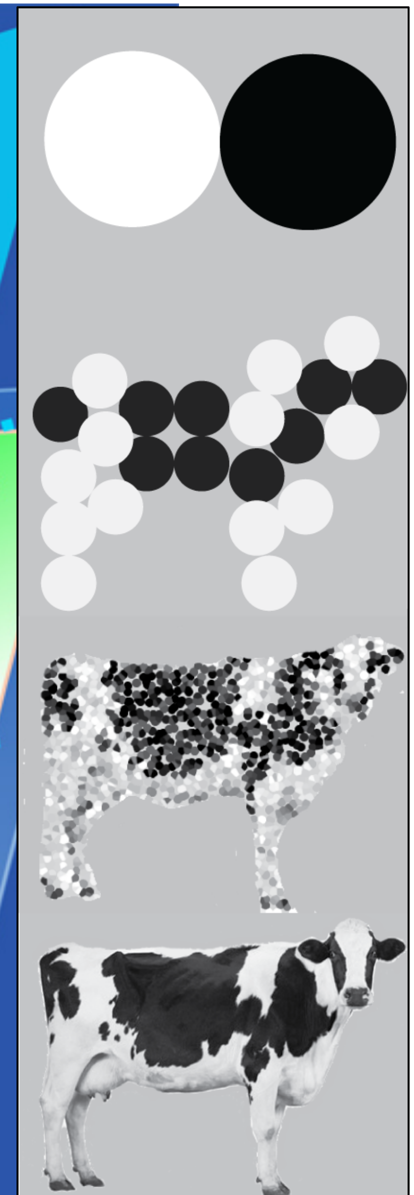
- unique structural indicators
- isomerism
- impact Q_α

see also Jachimowicz et al. arXiv:1401.3953, PRC in press



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



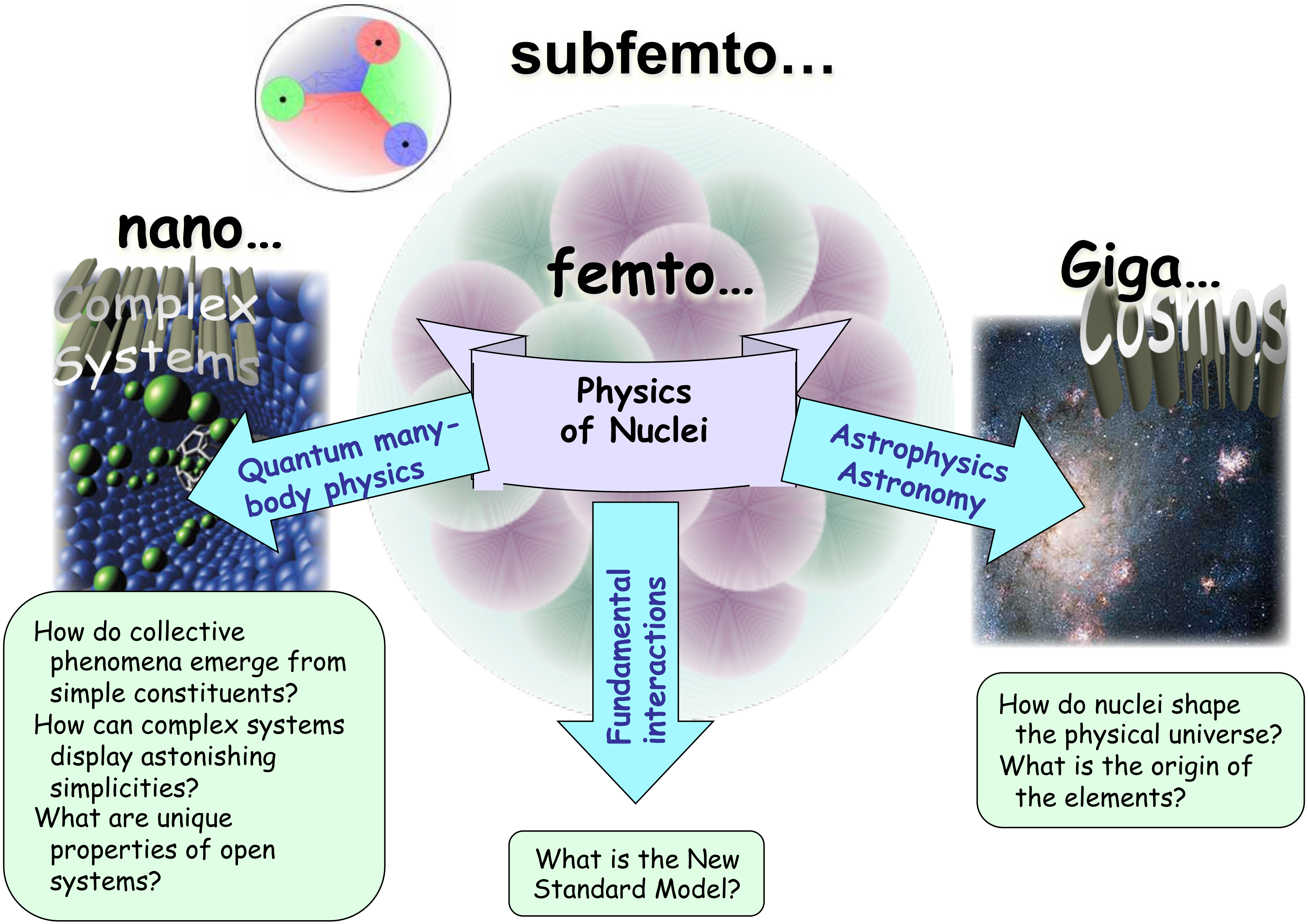


Determining the nucleon interactions from QCD/symmetries of QCD

Ab initio, with NN and 3N forces:

- Quantum Monte Carlo **^{12}C**
- No-Core Shell Model **^{14}F, ^{14}C**
- Coupled-Cluster **^{17}F, ^{56}Ni, ^{61}Ca**

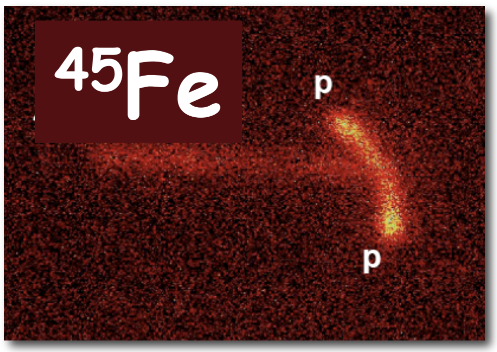
Profound intersections



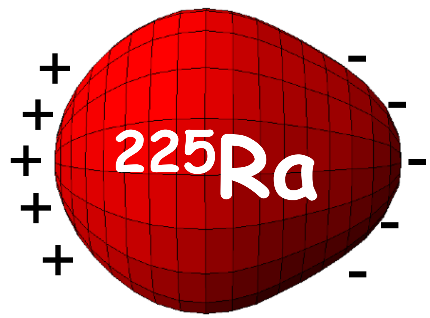
Some nuclei are more important than others

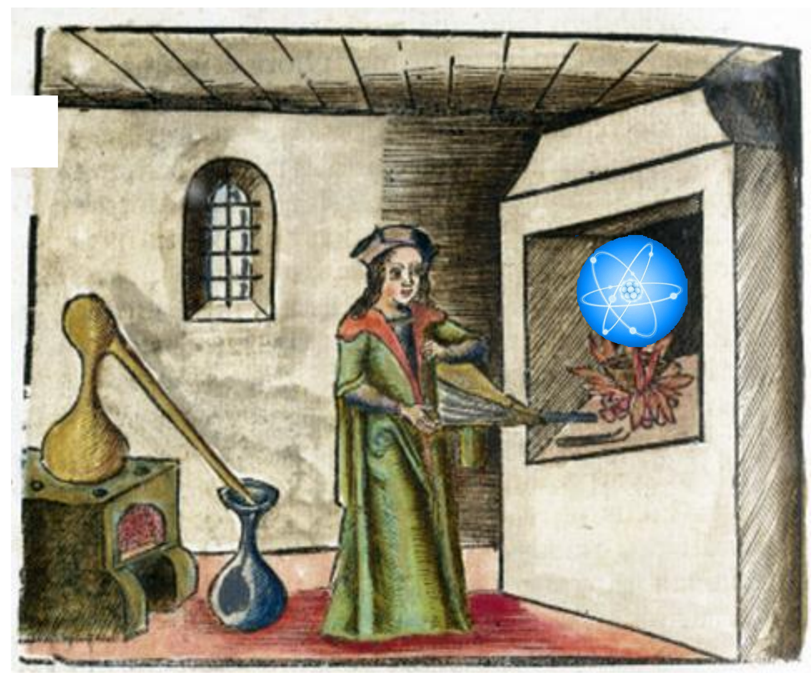
Over the last decade, tremendous progress has been made in techniques to produce and describe *designer nuclei*, rare atomic nuclei with characteristics adjusted to specific research needs and applications

nuclear structure



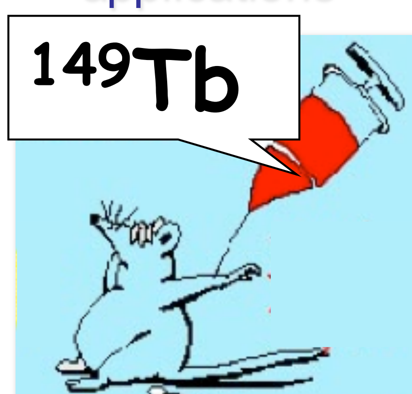
tests of fundamental laws of nature





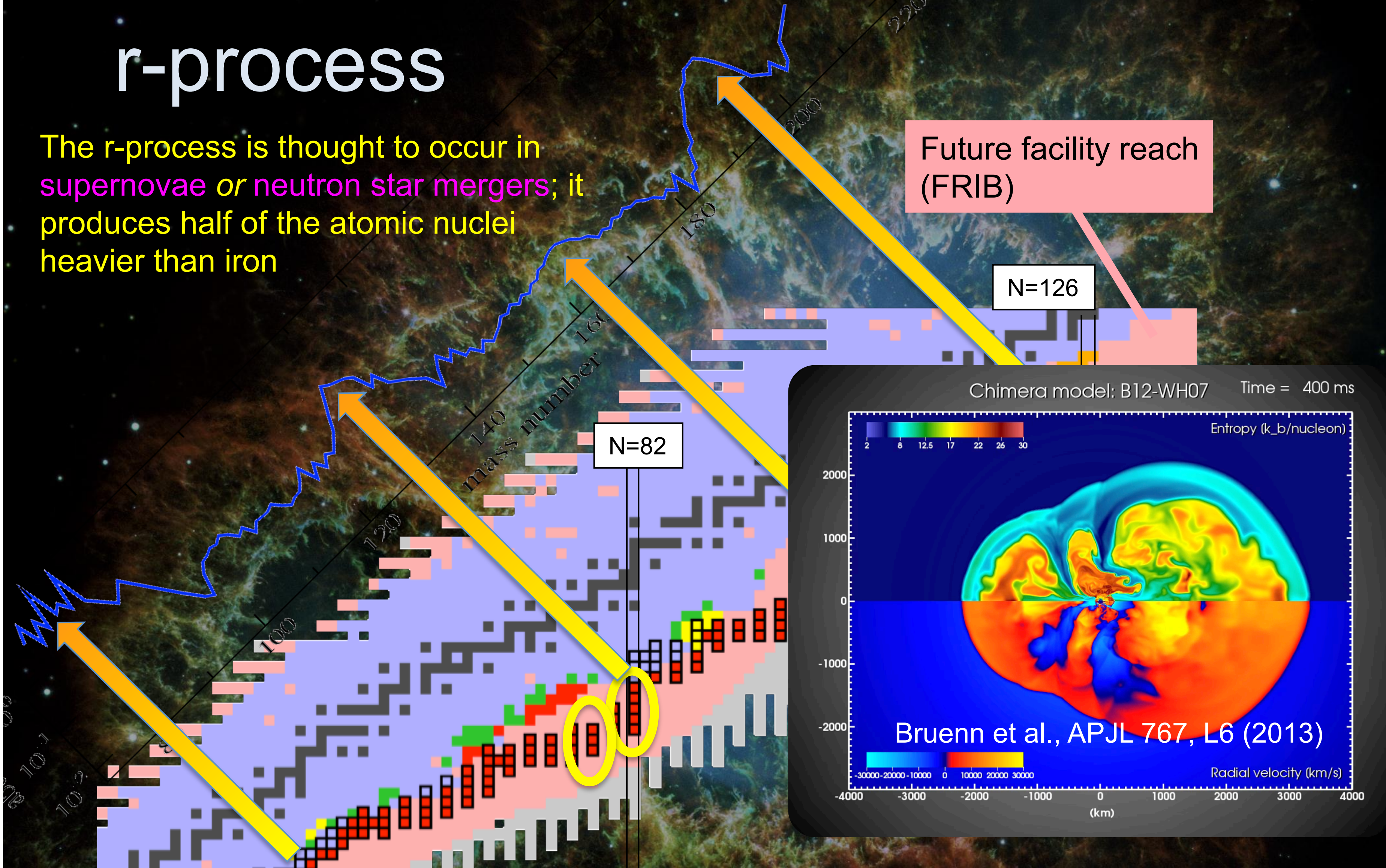
astrophysics

applications



r-process

The r-process is thought to occur in supernovae *or* neutron star mergers; it produces half of the atomic nuclei heavier than iron



⇒ Masses, $T_{1/2}$, P_n values

⇒ n-capture reactions through surrogate (d,p) transfer studies