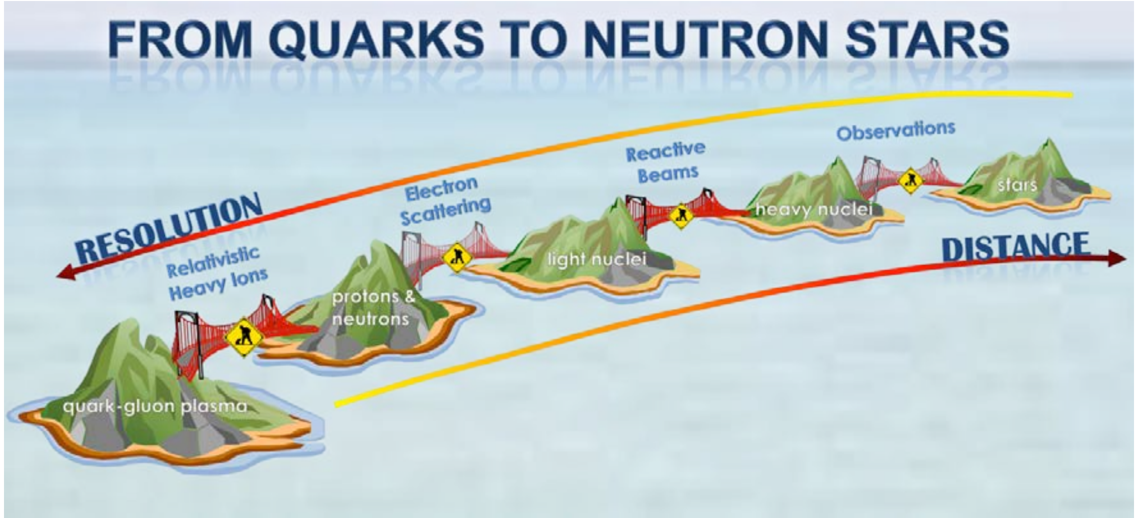
Challenges in Low-Energy Nuclear Physics

Witek Nazarewicz (MSU/Warsaw)

The 5th international conference on
"COLLECTIVE MOTION IN NUCLEI
UNDER EXTREME CONDITIONS"

"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



- Why?
  …should one care?
- What?
  …are the overarching questions?
- How?
  …to answer them?
- Where?
  …are we today?

The Nuclear Landscape and the Big Questions

- Where do nuclei and elements come from? Balantekin, Kistryn
- How are nuclei organized? Harakeh, Casten
- What are practical and scientific uses of nuclei? Olko

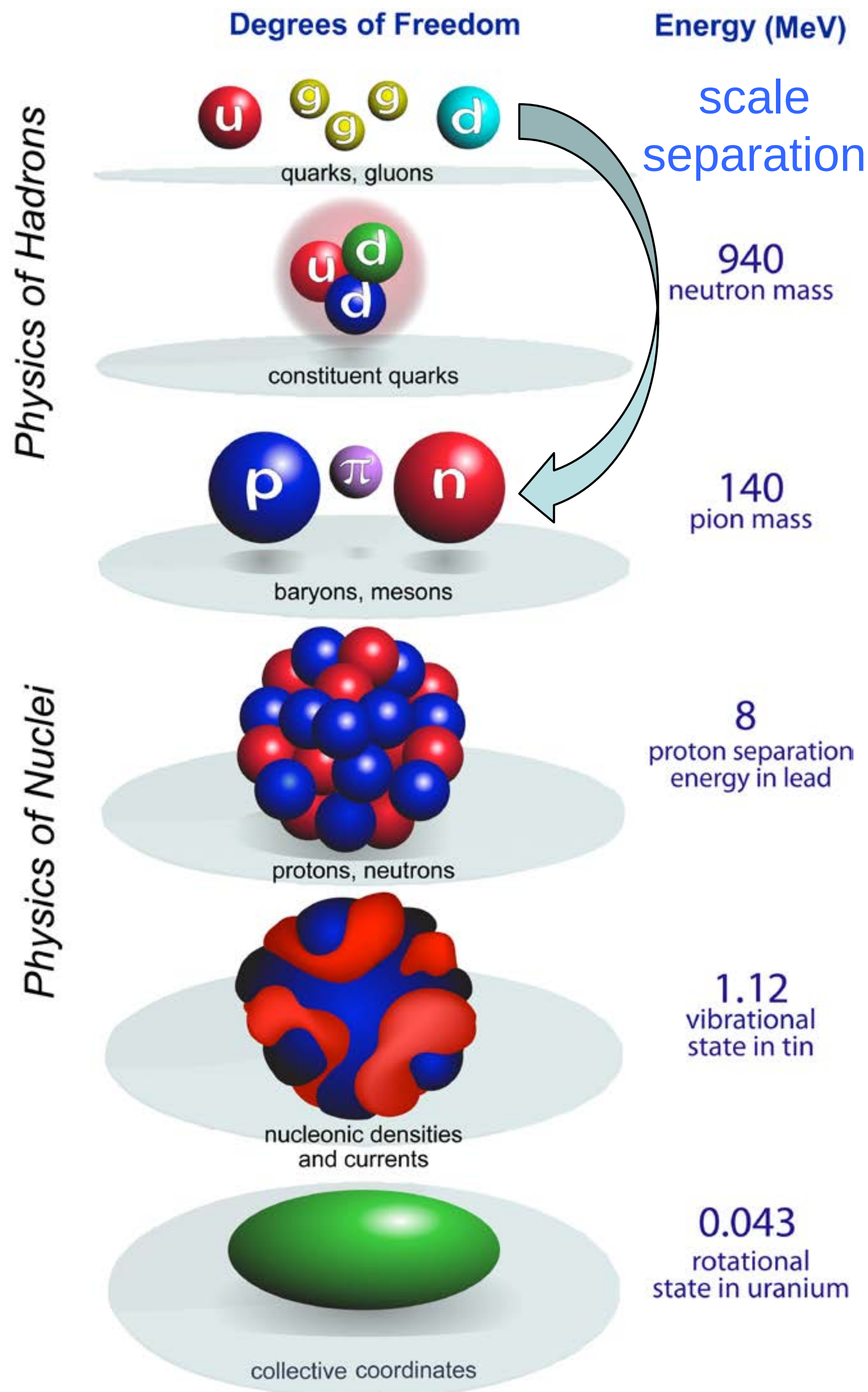
TIMESCALE

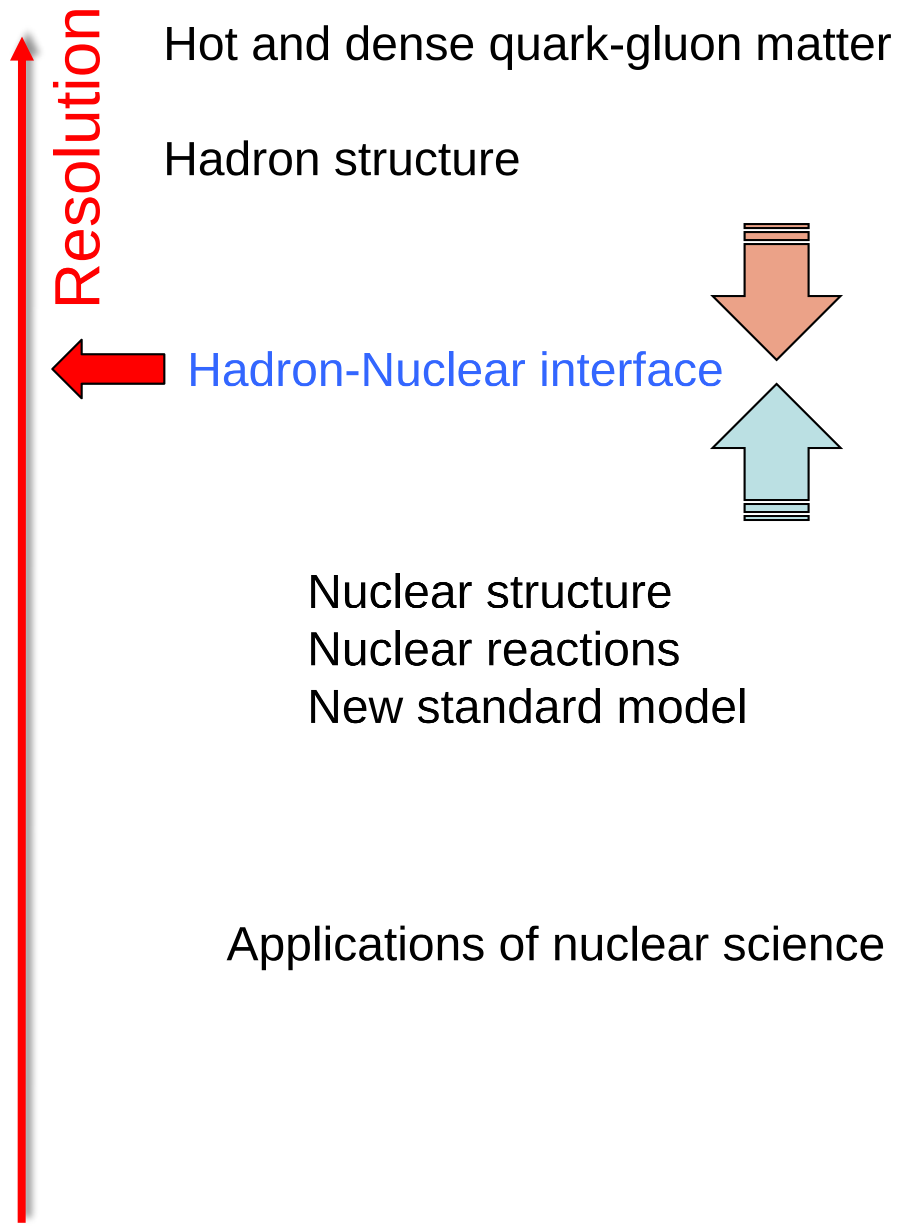
➥ from QCD transition (color singlets formed; 10 ms after Big Bang) till today (13.8 billion years later)

DISTANCE SCALE

➥ from 10^{-15} m (proton's radius) to ~12 km (neutron star radius)

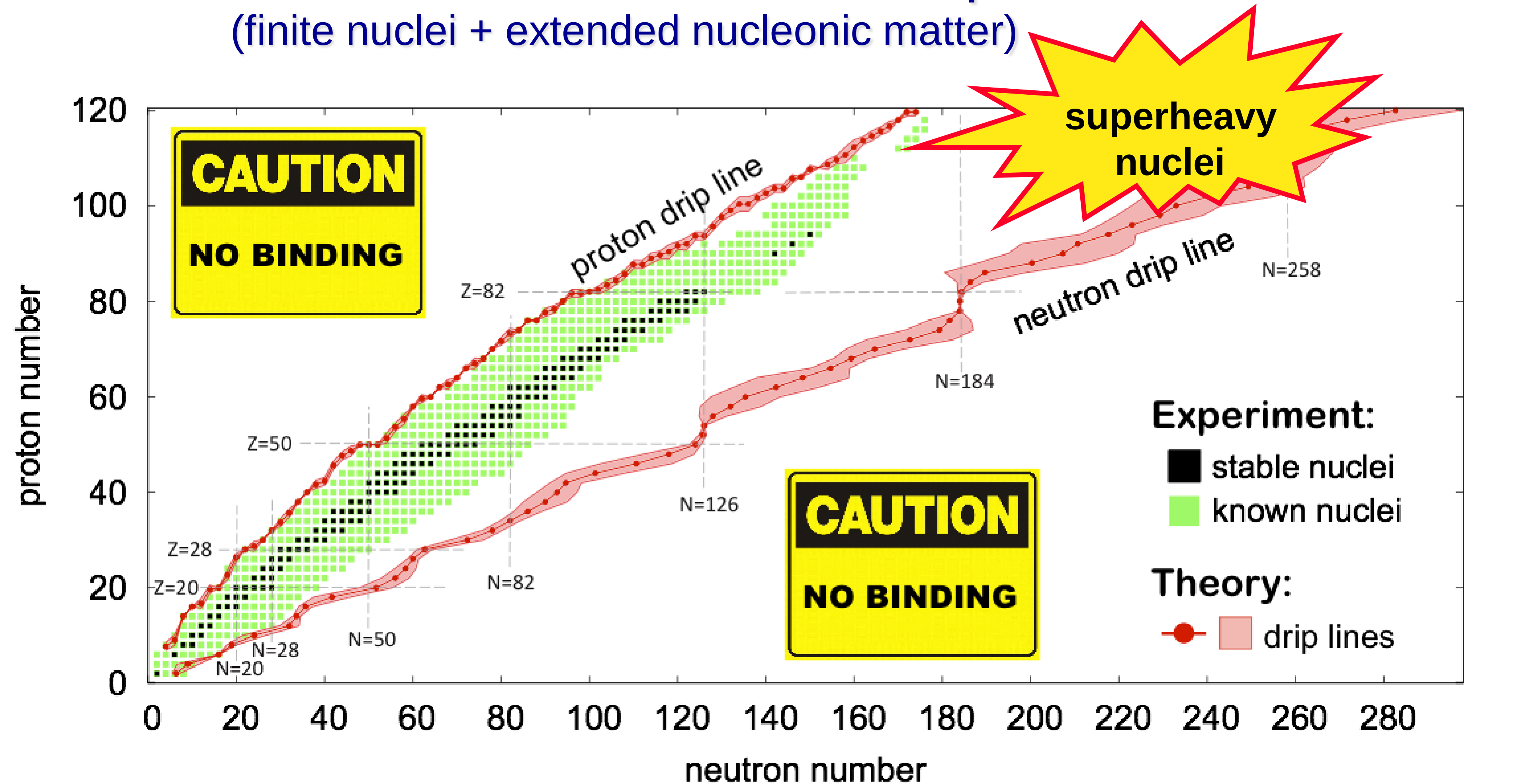
How are nuclei made?





The Grand Nuclear Landscape

(finite nuclei + extended nucleonic matter)



N~10^{57}

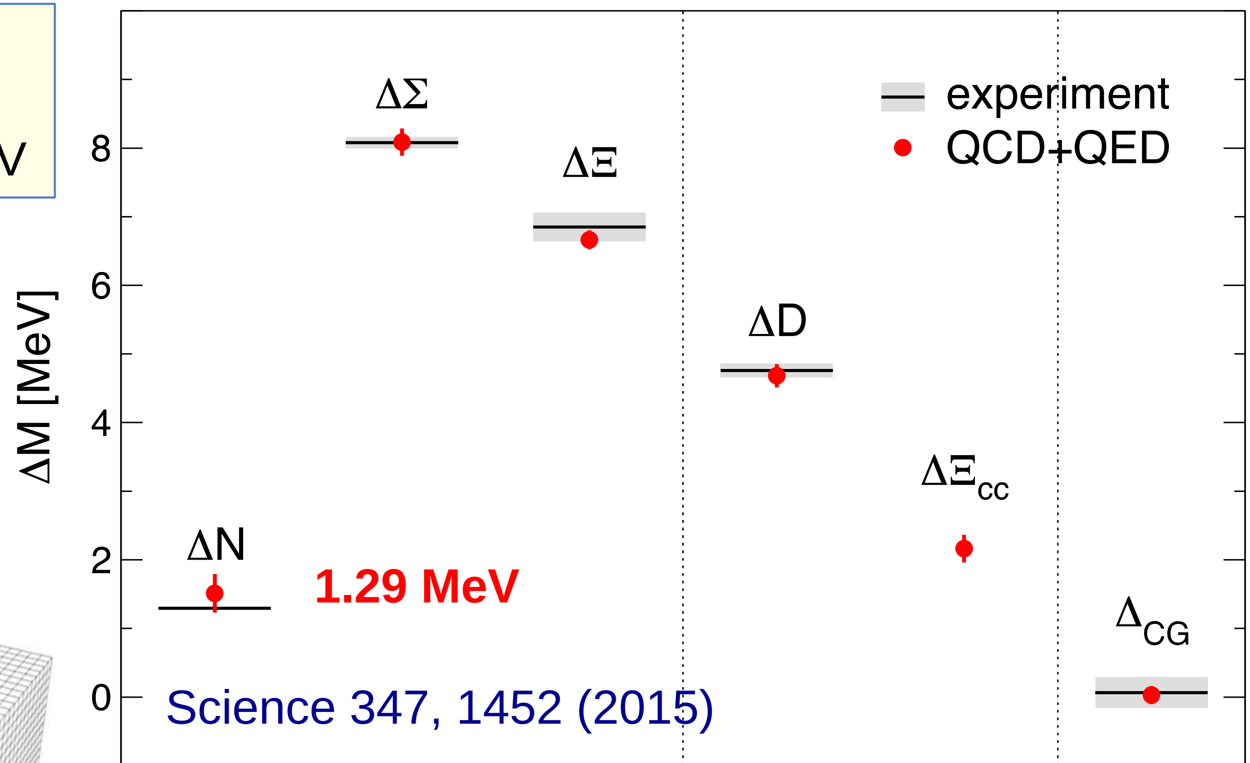
How many protons and neutrons can be bound in a nucleus with Z up to 120?

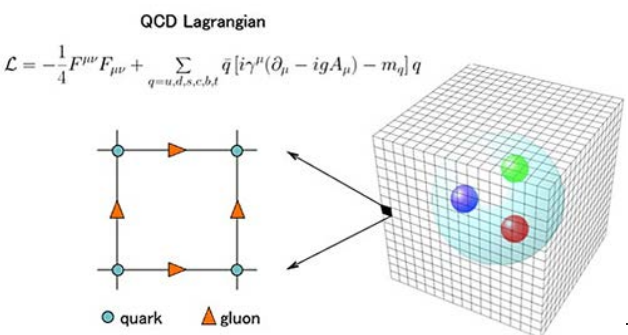
…current theory predicts around 7000

Isospin Splittings in the Light-Baryon Octet from Lattice QCD and QED
(ab initio calculation of the neutron-proton mass difference)

Neutron = 939.56563 MeV
Proton = 938.27231 MeV
Electron = 0.51099906 MeV

T_n=(887.7±1.2±1.9) s
… but bottle and in-beam experiments give a neutron lifetime that differs by 8 sec!



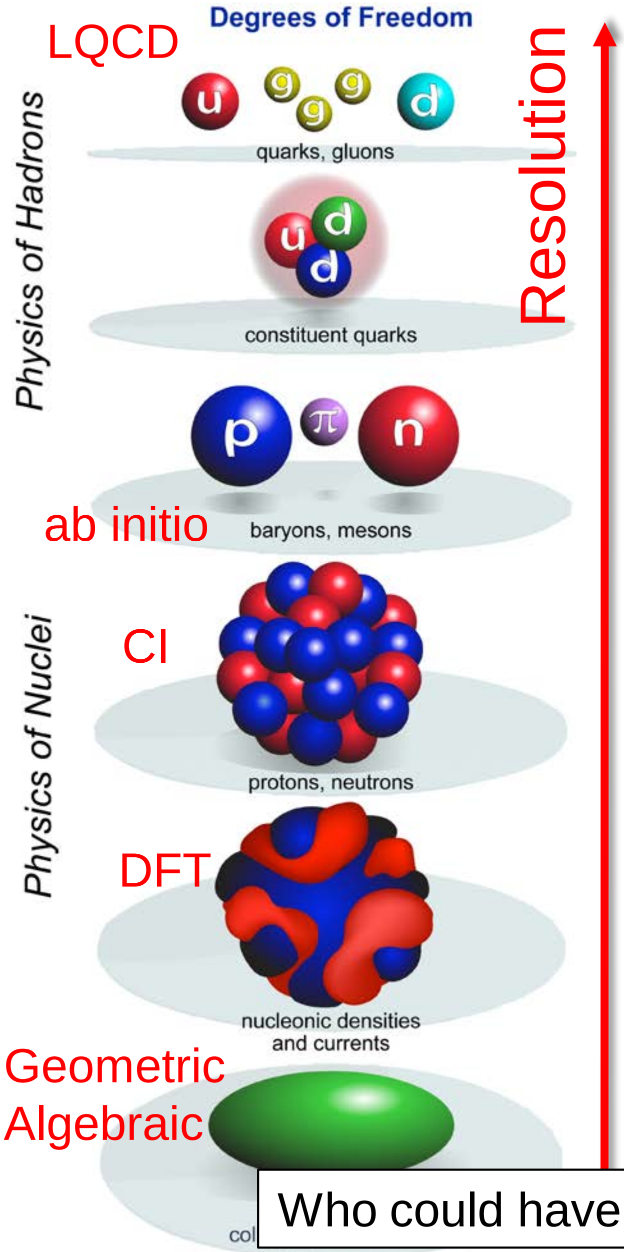


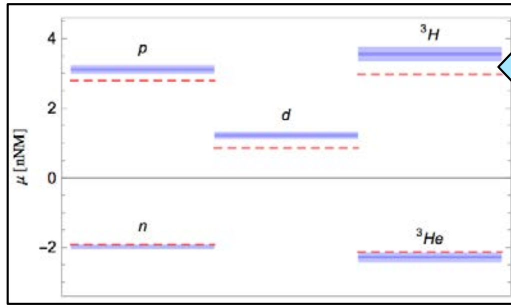
	mass splitting [MeV]	QCD [MeV]	QED [MeV]
$\Delta N = n - p$	1.51(16)(23)	2.52(17)(24)	-1.00(07)(14)
$\Delta\Sigma = \Sigma^- - \Sigma^+$	8.09(16)(11)	8.09(16)(11)	0
$\Delta\Xi = \Xi^- - \Xi^0$	6.66(11)(09)	5.53(17)(17)	1.14(16)(09)

"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)

How to explain the nuclear landscape from the bottom up?

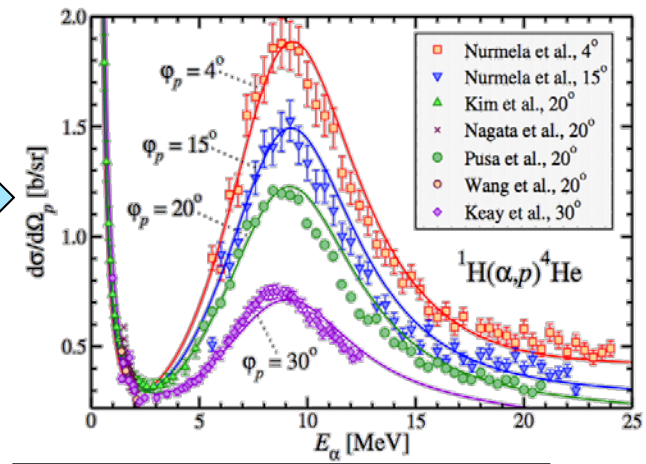
Theory revolution





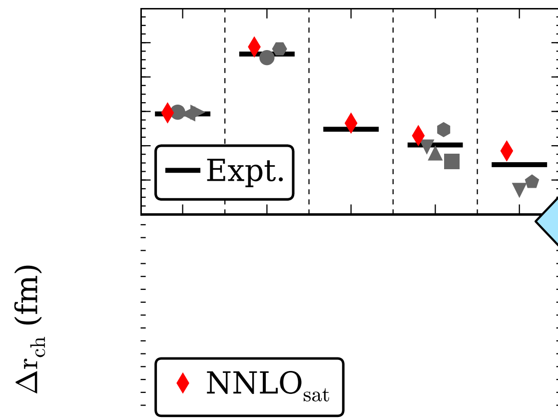
Nucleon and nuclear magnetic moments from Lattice QCD

S. Beane et al., PRL 113, 252001 (2014)



Ab-initio approach to reactions ($p+^4He$)

Hupin et al. PRC 90, 061601 (2014)

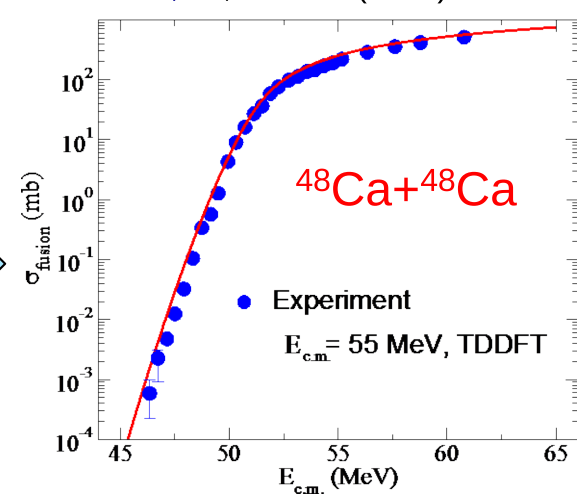


Coupled cluster description of binding energies and radii

A. Ekstrom et al., 91, 051301 (2015)

Fusion cross sections from TDDFT

R. Keser et al., PRC 85, 044606 (2012)

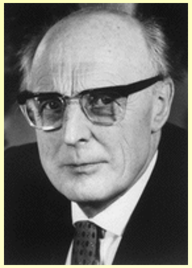


Who could have predicted this 20 years ago?

1912

electronic shells of the atom

1949

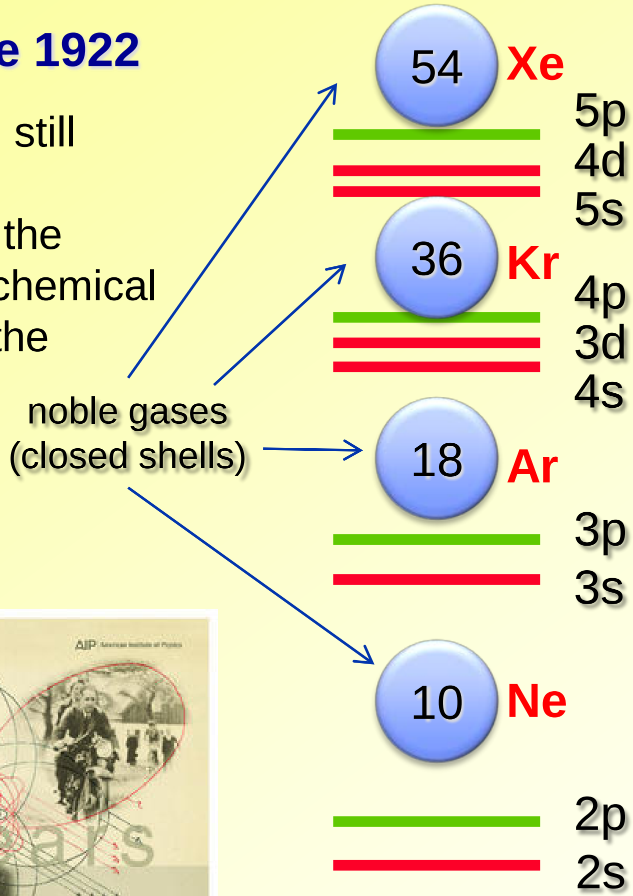


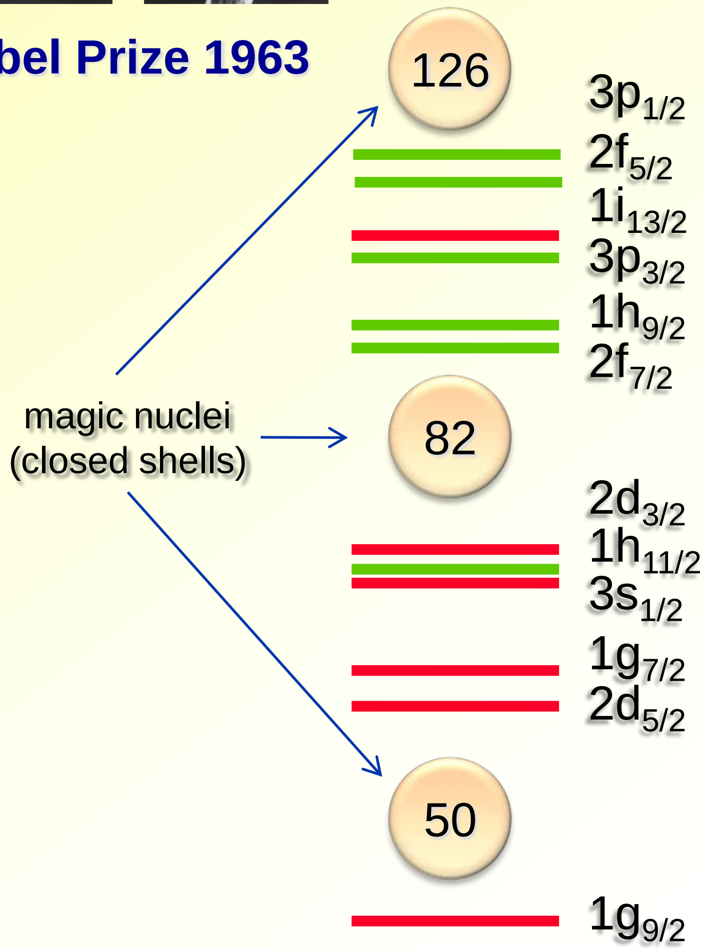
nucleonic shells of the nucleus

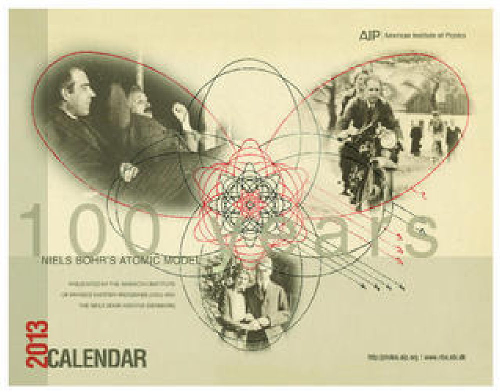
Nobel Prize 1922

Nobel Prize 1963

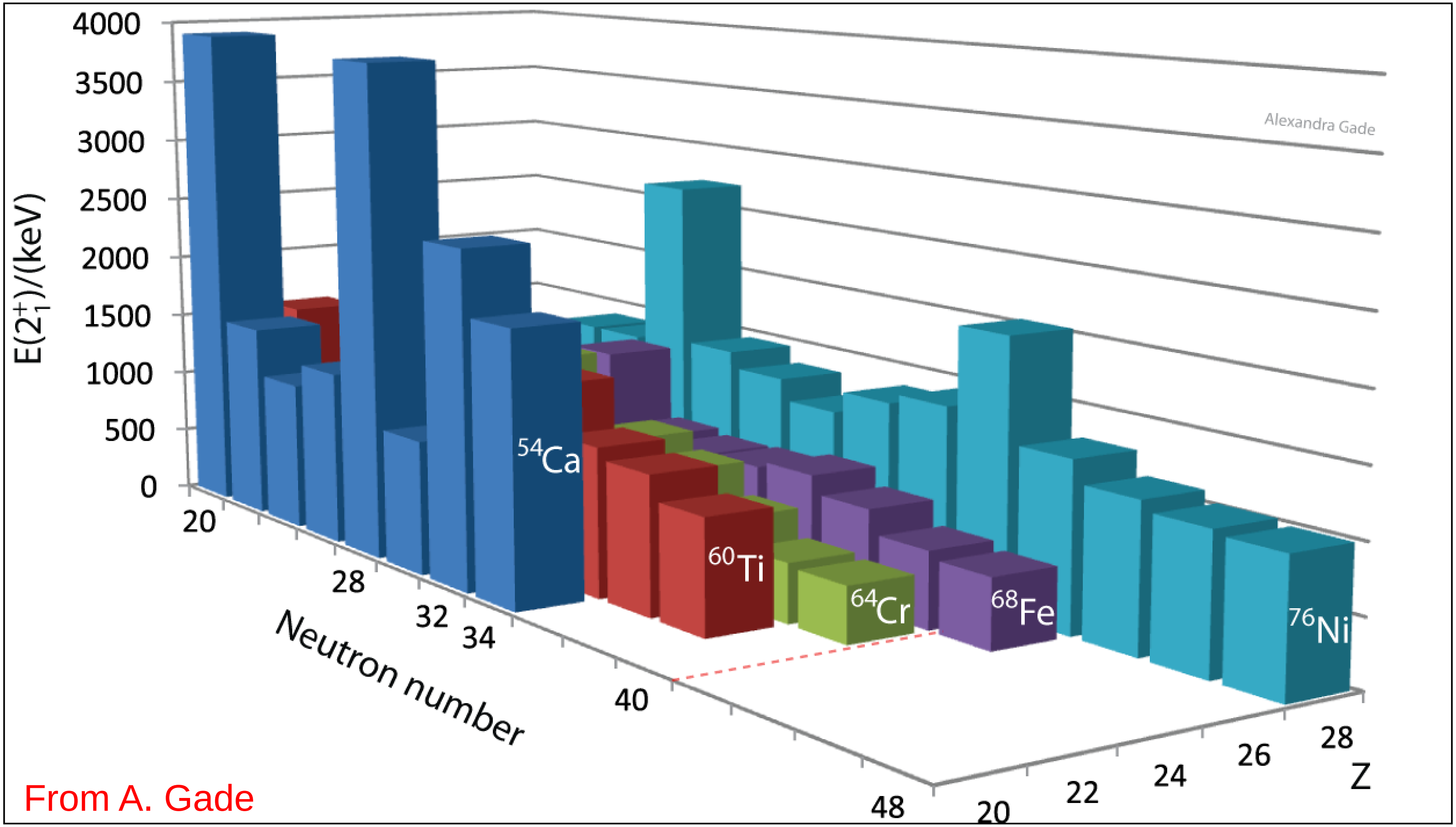
Bohr's picture still serves as an elucidation of the physical and chemical properties of the elements.





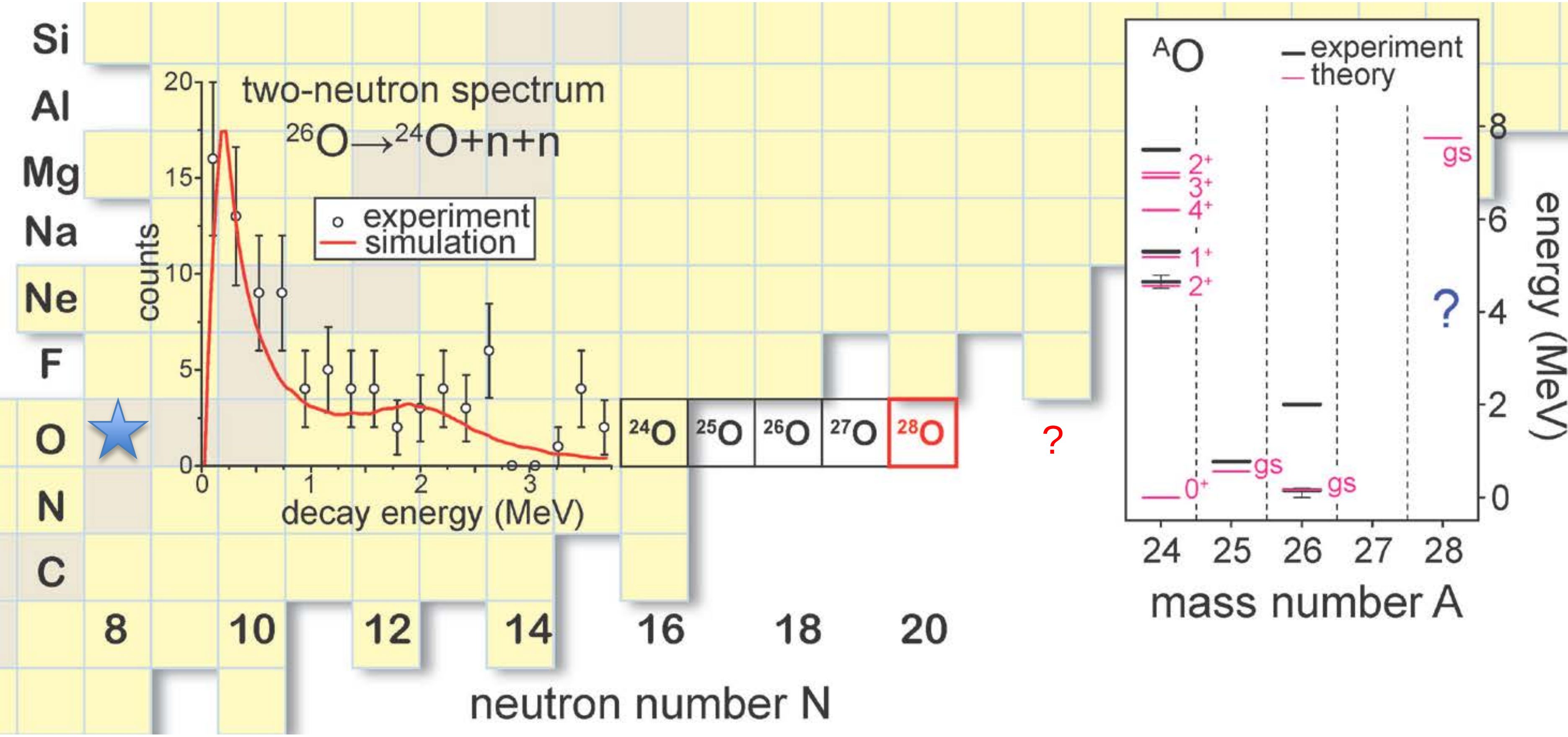


Revision of nuclear structure textbook knowledge



New shell closures at N = 32 & 34?

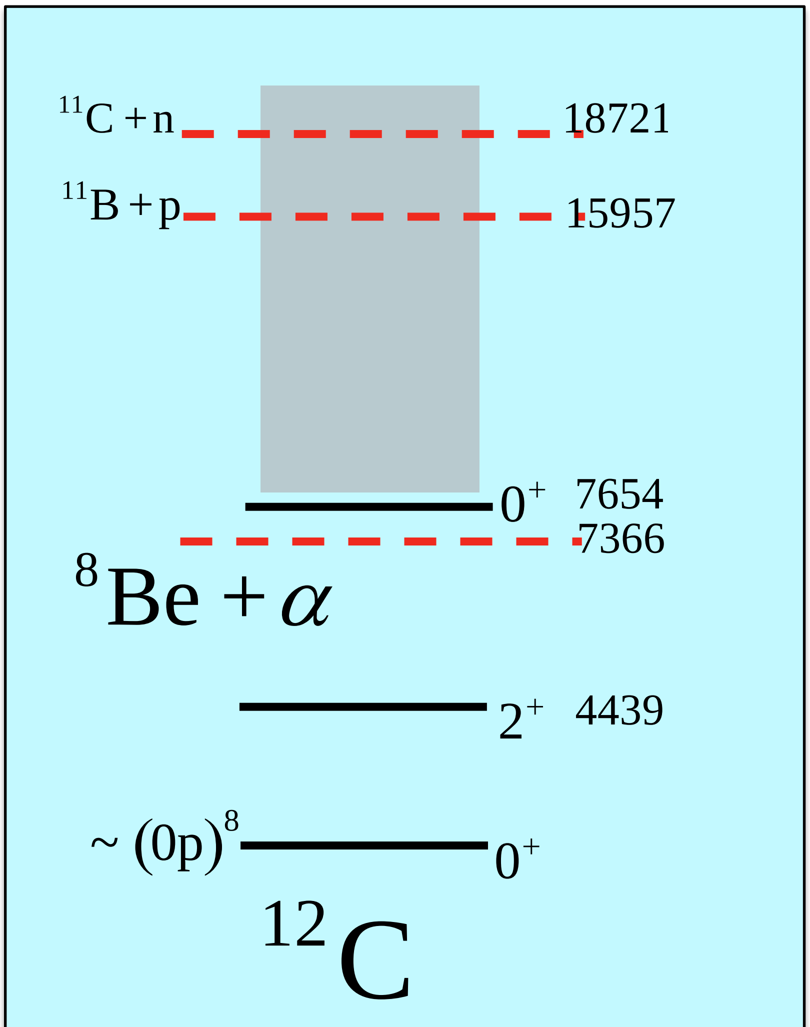
Revision of nuclear structure textbook knowledge

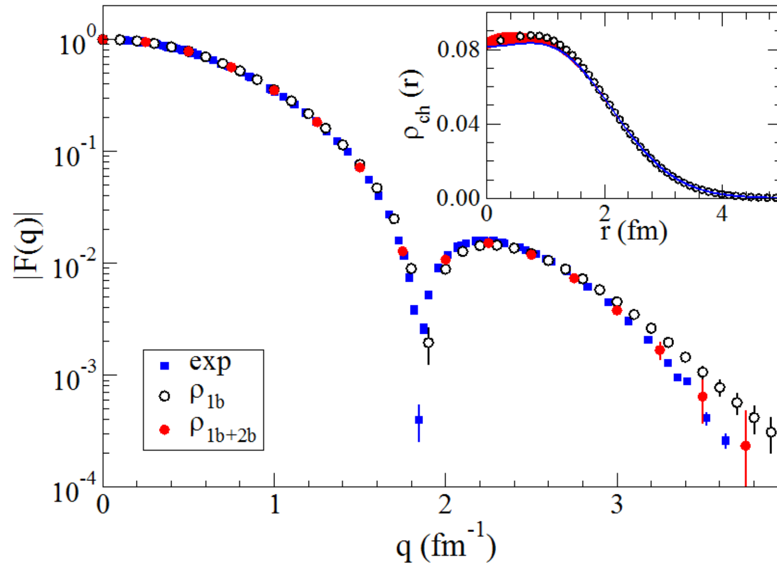


- ^{16}O is a textbook doubly-magic nucleus
- Measurements of the neutron-rich isotopes ^{22}O and ^{24}O suggest the presence of new magic numbers at N=14 and 16.
- A dineutron in ^{26}O? The lifetime could be as large as 10^{-12} s.
- Is (doubly-magic) ^{28}O unbound? If so, how much?

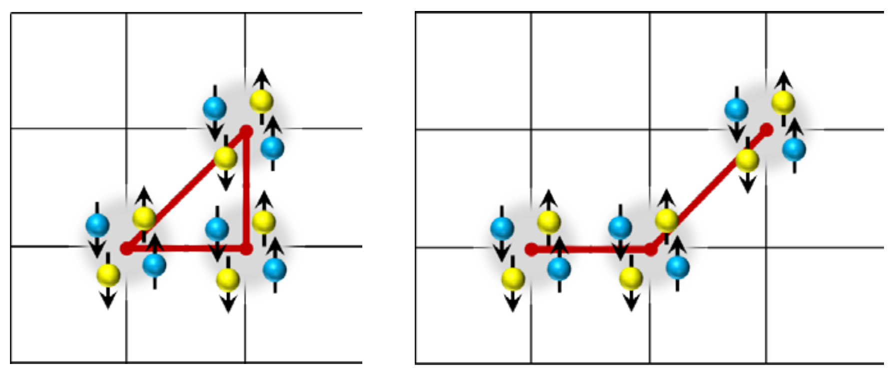
^{12}C structure: Ground-state and Hoyle-state

In 1954, Hoyle postulated that a7.65 MeV carbon state. This state plays a crucial role in the hydrogen burning of stars heavier than our sun and in the production of carbon and other elements necessary for life.



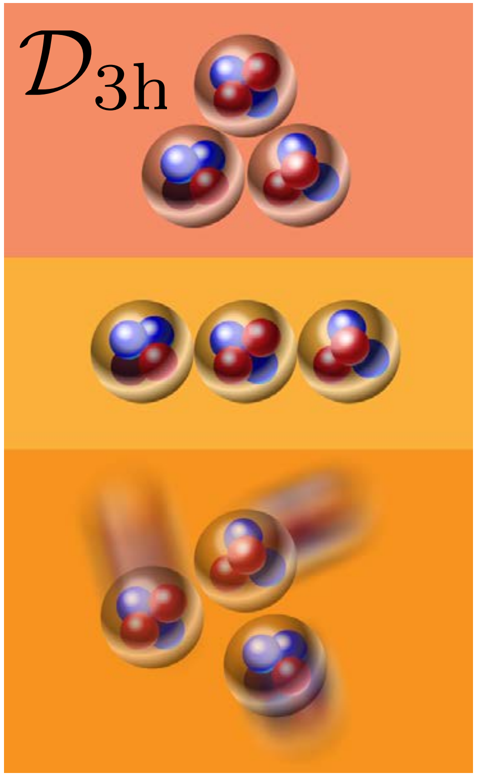


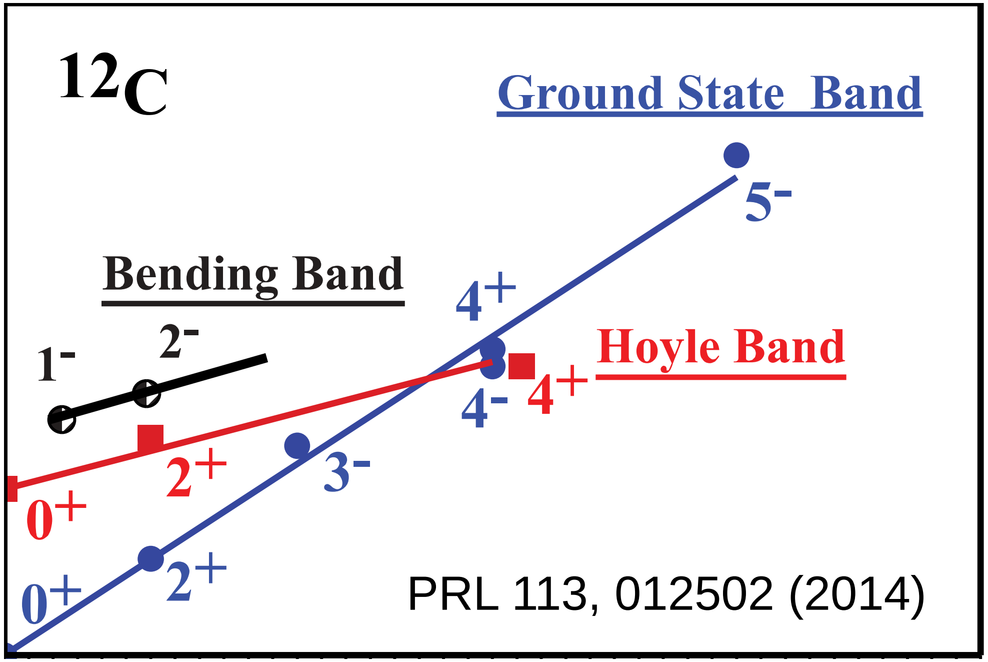
Lovato et al., Phys. Rev. Lett. 111, 092501 (2013). Quantum Monte Carlo



Epelbaum et al., Phys. Rev. Lett. 109, 252501 (2012). Lattice EFT

Carbon-12 Caught in a Triangle





$$T_{\mathrm{s.p.}} = 4R/v_{\mathrm{F}}$$
$$v_{\mathrm{F}} \approx 0.25c$$

$$T_{\mathrm{s.p.}} \approx 1.3 \cdot 10^{-22}\ \mathrm{sec}$$

10^{-22} sec = 1 babysec=0.1 zsec (z=zepto)=100 ysec (y=yocto)

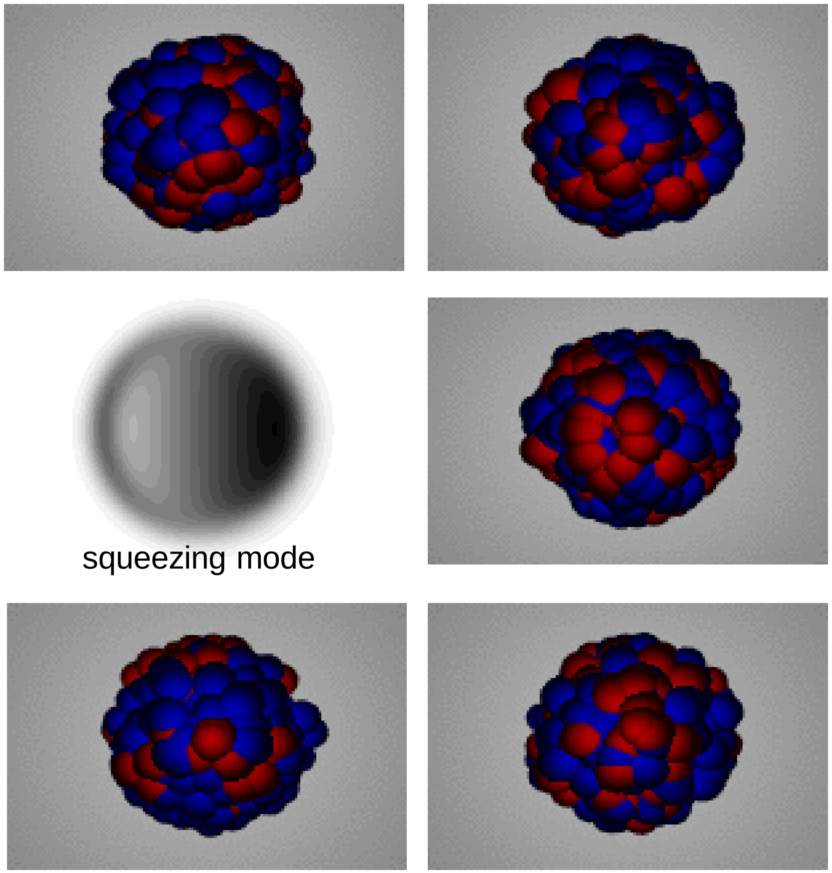
$$T_{1/2} = \ln 2\hbar/\Gamma$$

But what if $T_{1/2} \lesssim T_{\mathrm{s.p.}}$?

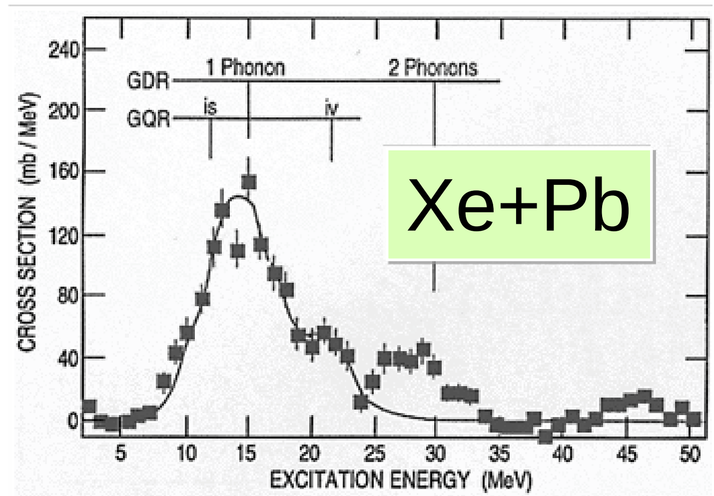
Nuclear collective motion

Giant nuclear vibrations

	Isoscalar p-n in phase	Isovector p-n out of phase
Monopole (GMR)		
Dipole (GDR)		
Quadrupole (GQR)		



by A. Krasznahorkay



- Dipole polarizability and skins
- Isoscalar dipole and EDM
- Monopole modes, radii and beta decay
- Multipole modes and fission
- Scissors (magnetic) modes

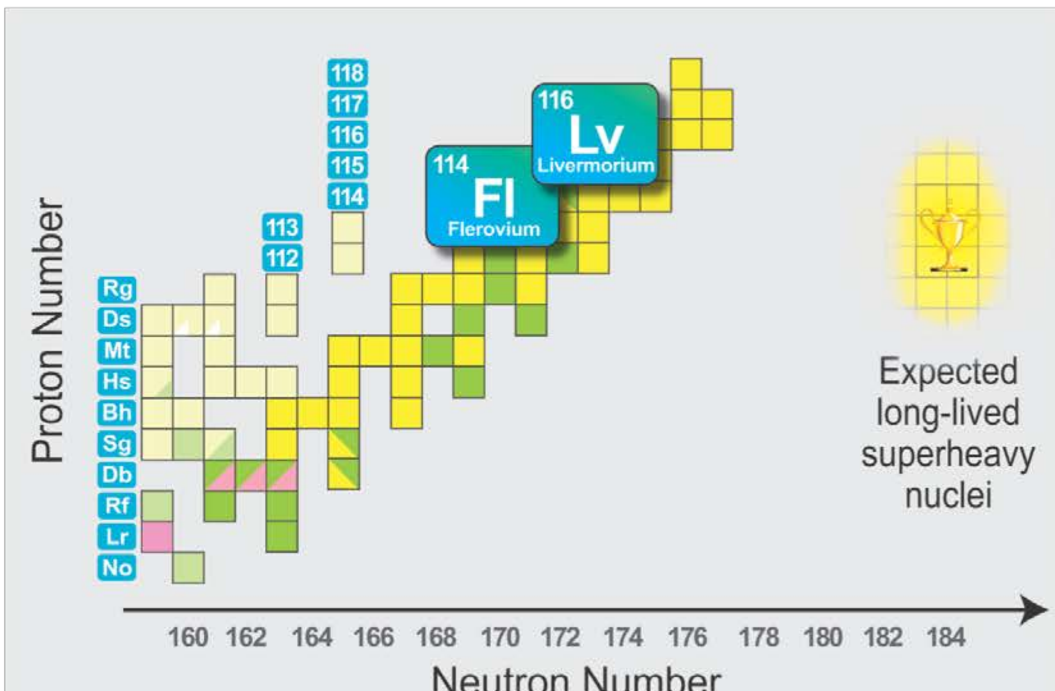
Nuclear response to external force

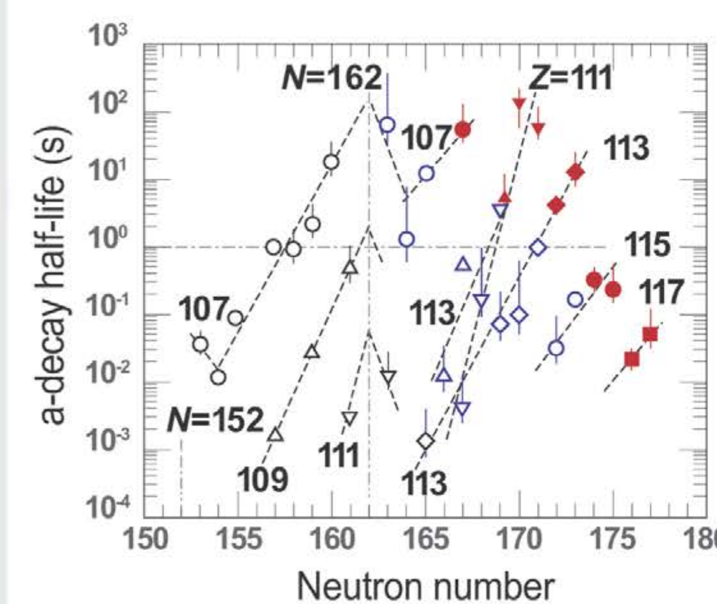
What are the limits of atoms and nuclei? Do very long-lived superheavy nuclei exist in nature?

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
- 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





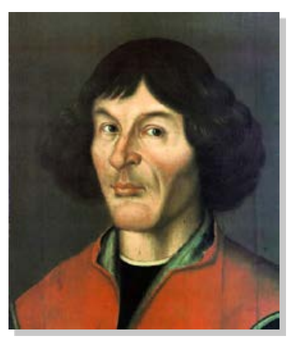
Periodic Table of Elements 2015

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La* 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac+ 89	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	113	Fl 114	115	Lv 116	117	118

* Lanthanides	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
+ Actinides	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

- Metals
- Non-metals
- Not confirmed

Generic IUPAC names:
113: Ununtrium, Uut
115: Ununpentium, Uup
117: Ununseptium, Uus
118: Ununoctium, Uuo

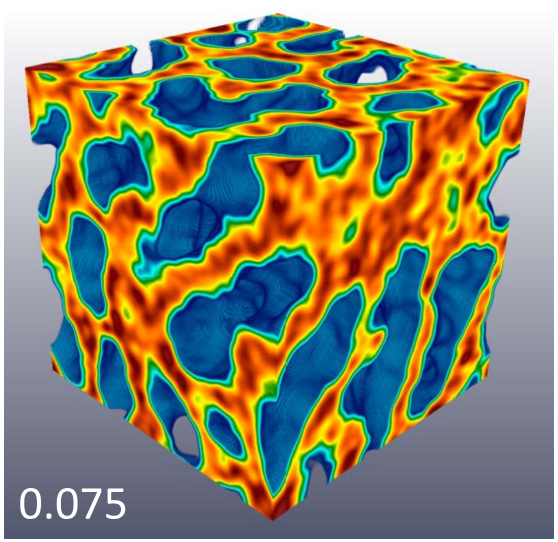


Z=112: Copernicium

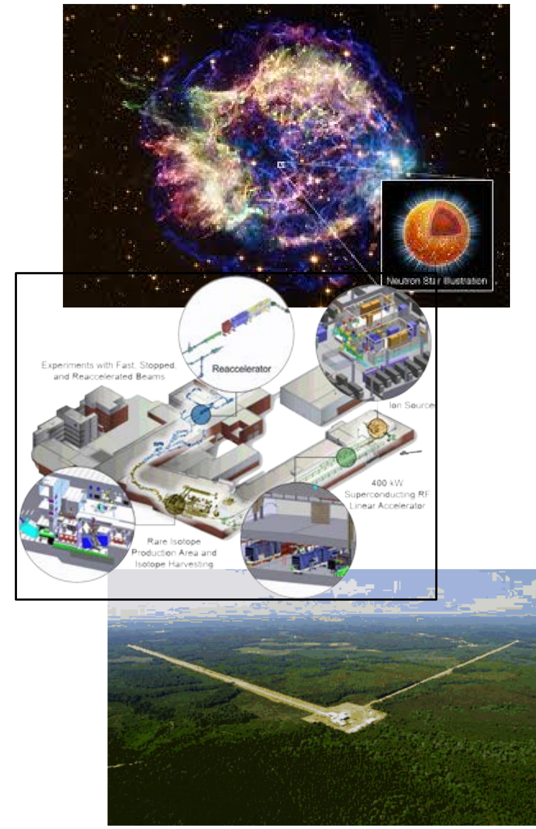
Z=114: Flerovium; Z=116: Livermorium

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

Crustal structures in neutron stars



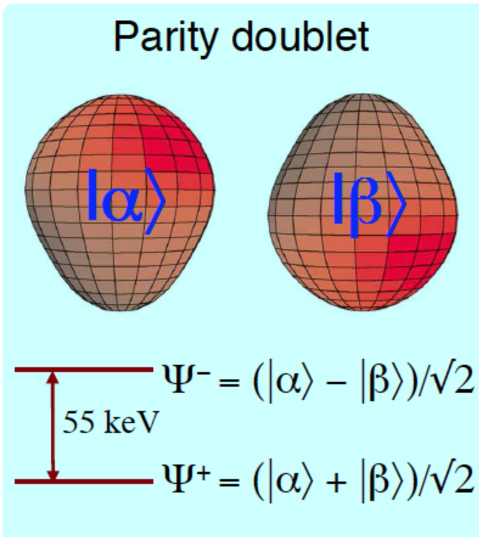
Data



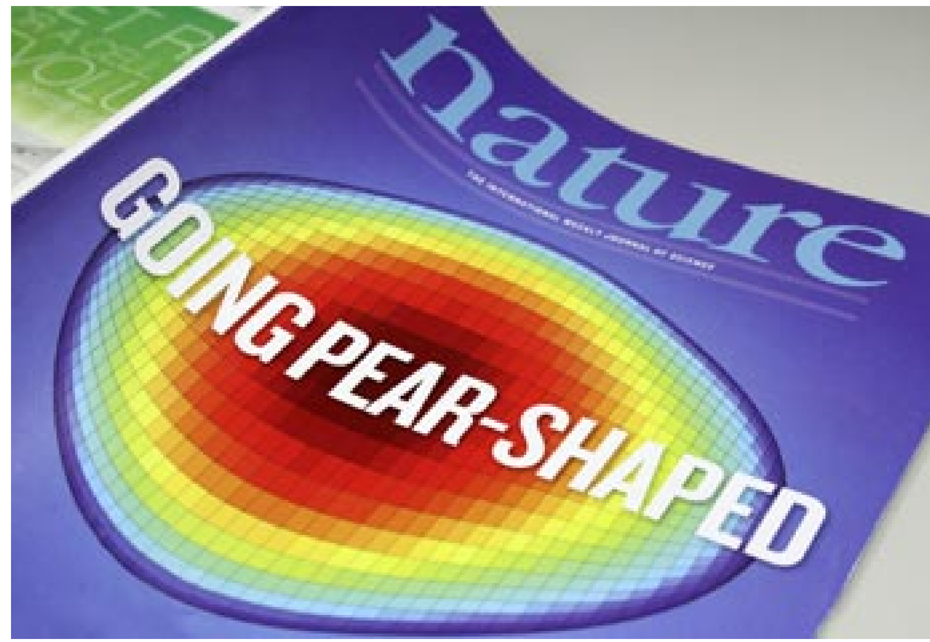
The covariance ellipsoid for the neutron skin R_{skin} in ^{208}Pb and the radius of a $1.4M_{\odot}$ neutron star. The mean values are: $R(1.4M_{\odot})$=10 km and R_{skin}= 0.17 fm.

Rare Isotopes and fundamental symmetry tests

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



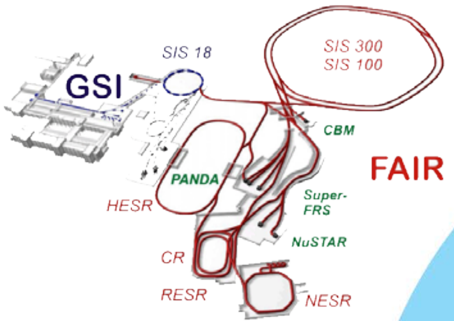
- Closely spaced parity doublet gives rise to enhanced electric dipole moment
- Large intrinsic Schiff moment
  - o ^{199}Hg (Seattle, 1980's – present)
  - o ^{225}Ra (Starting at ANL and KVI)
  - o ^{223}Rn at TRIUMF
  - o Potential at FRIB (10^{12}/s w ISOL target; far future)

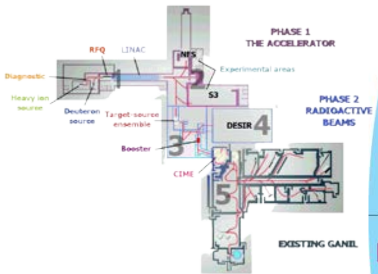


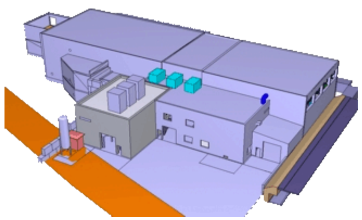
Gaffney et al., Nature 199, 497 (2013)

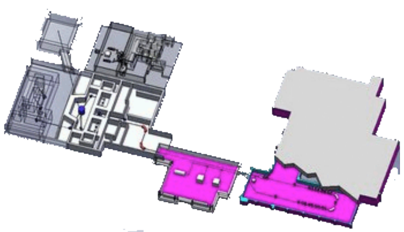
Prospects

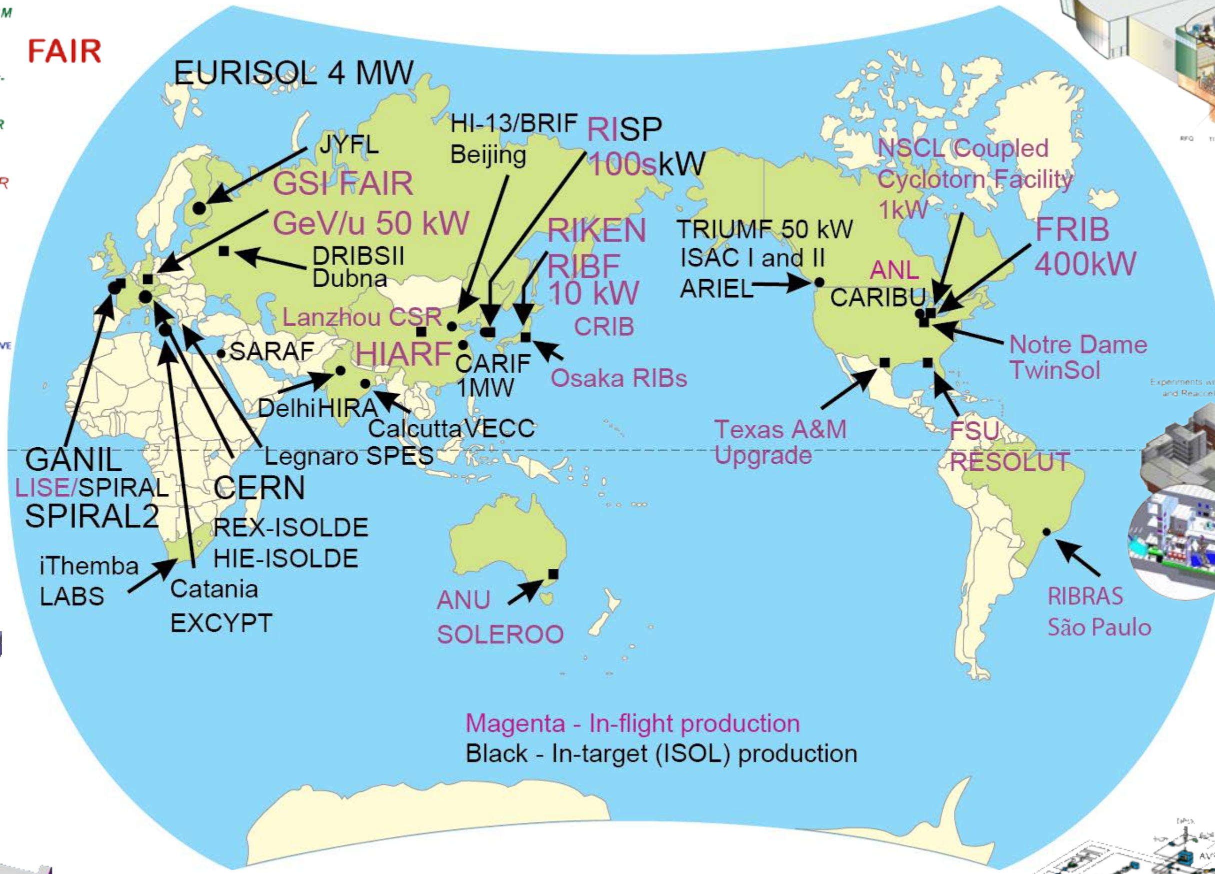
Experiment

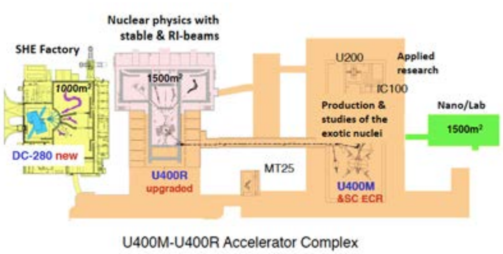

GSI
SIS 18
SIS 300
SIS 100
CBM
FAIR
PANDA
HESR
Super-FRS
NuSTAR
CR
RESR
NESR

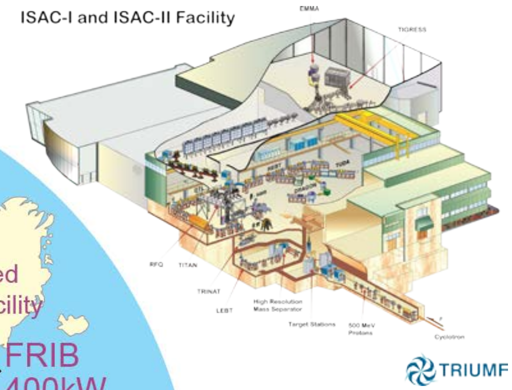

PHASE 1
THE ACCELERATOR
PHASE 2
RADIOACTIVE BEAMS
EXISTING GANIL

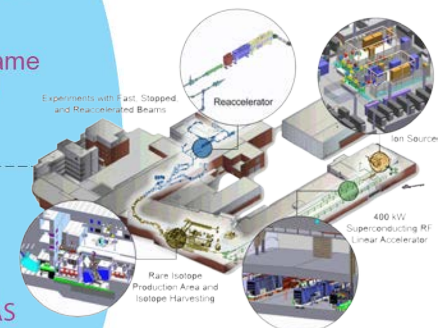


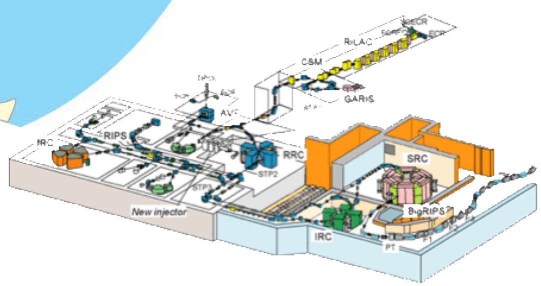


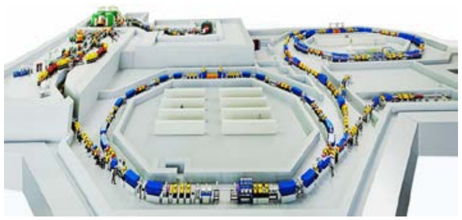

EURISOL 4 MW
JYFL
GSI FAIR
GeV/u 50 kW
DRIBSII
Dubna
HI-13/BRIF
Beijing
RISP
100skW
RIKEN
RIBF
10 kW
CRIB
Lanzhou CSR
HIARF
CARIF
1MW
Osaka RIBs
SARAF
Delhi HIRA
Calcutta VECC
Legnaro SPES
GANIL
LISE/SPIRAL
SPIRAL2
CERN
REX-ISOLDE
HIE-ISOLDE
iThemba
LABS
Catania
EXCYPT
ANU
SOLEROO
TRIUMF 50 kW
ISAC I and II
ARIEL
NSCL Coupled
Cyclotron Facility
1kW
ANL
CARIBU
FRIB
400kW
Notre Dame
TwinSol
Texas A&M
Upgrade
FSU
RESOLUT
RIBRAS
São Paulo
Magenta - In-flight production
Black - In-target (ISOL) production


Nuclear physics with stable & RI-beams
SHE Factory
Applied research
U200
IC100
Production & studies of the exotic nuclei
Nano/Lab
1500m²
1000m²
1500m²
DC-280 new
U400R upgraded
MT25
U400M &SC ECR
U400M-U400R Accelerator Complex

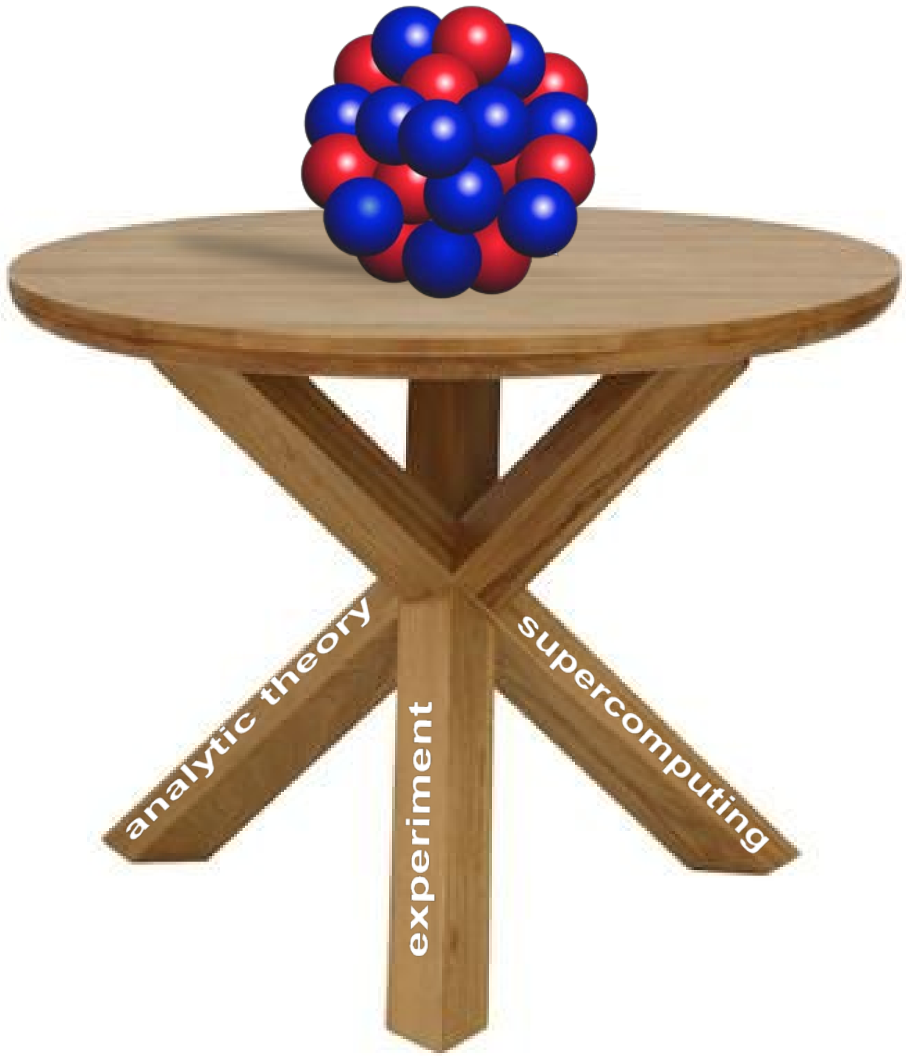

ISAC-I and ISAC-II Facility
TRIUMF


Experiments with Fast, Stopped and Reaccelerated Beams
Reaccelerator
Ion Source
400 kW Superconducting RF Linear Accelerator
Rare Isotope Production Area and Isotope Harvesting


CSM
RILAC
GARIS
AVF
RIPS
RRC
IRC
SRC
BigRIPS
New injector



High Performance Computing and Nuclear Theory



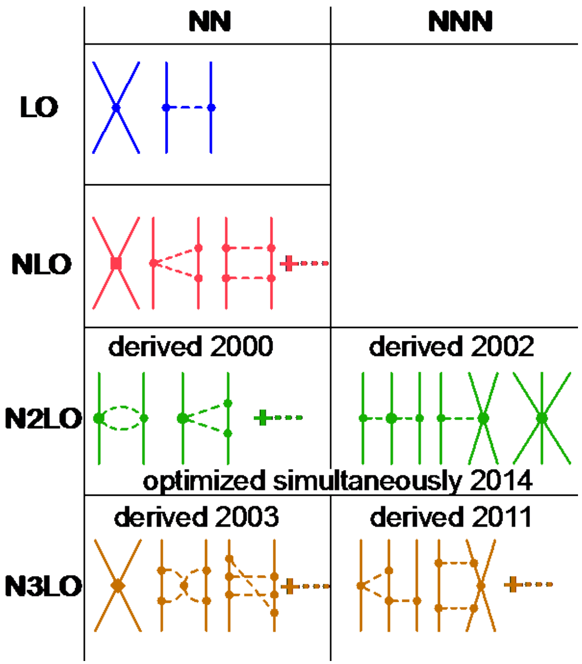
“High performance computing provides answers to questions that neither experiment nor analytic theory can address; hence, *it becomes a third leg supporting the field of nuclear physics*.” (NAC Decadal Study Report)

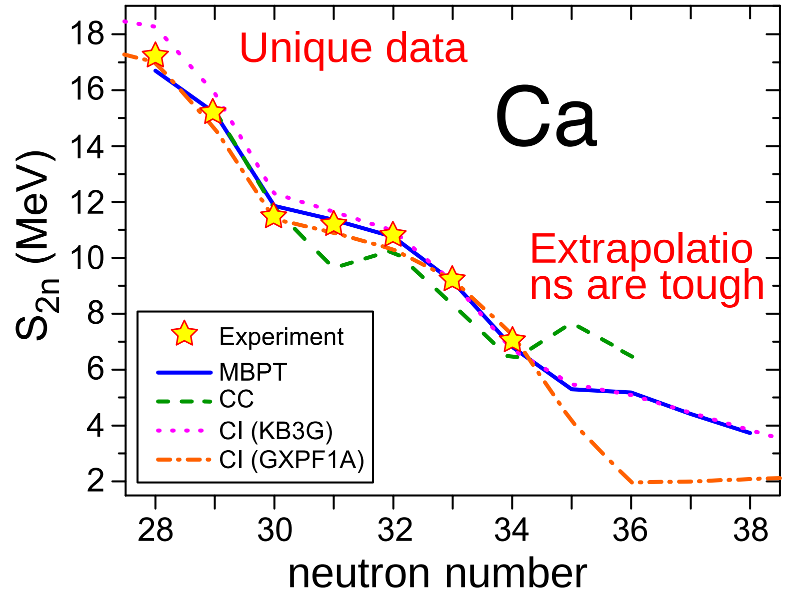
Future: large multi-institutional efforts involving strong coupling between physics, computer science, and applied math

The frontier in experiment and theory: neutron-rich calcium isotopes

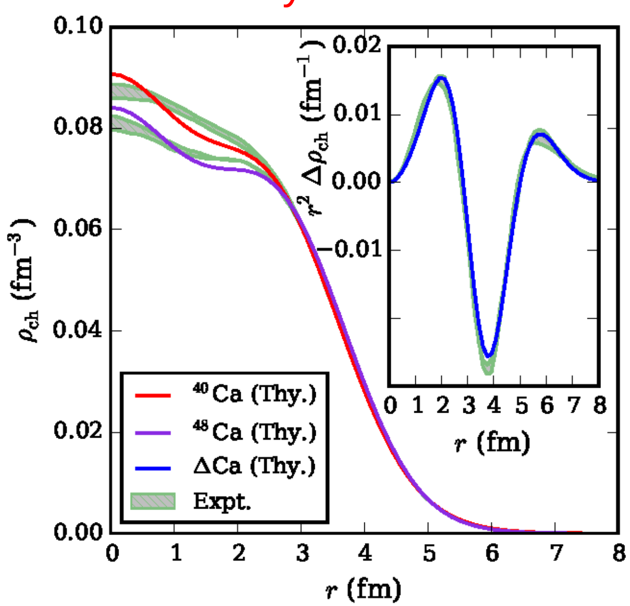
Quantified input

Nuclear Forces
from χEFT





Consistency with known data



Prediction

NNLO$_{sat}$

SV-min

Nuclei Matter

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

Profound intersections

- Astrophysics
- Fundamental Symmetries
- Complex systems
- Computing

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

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

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
- Future is exciting

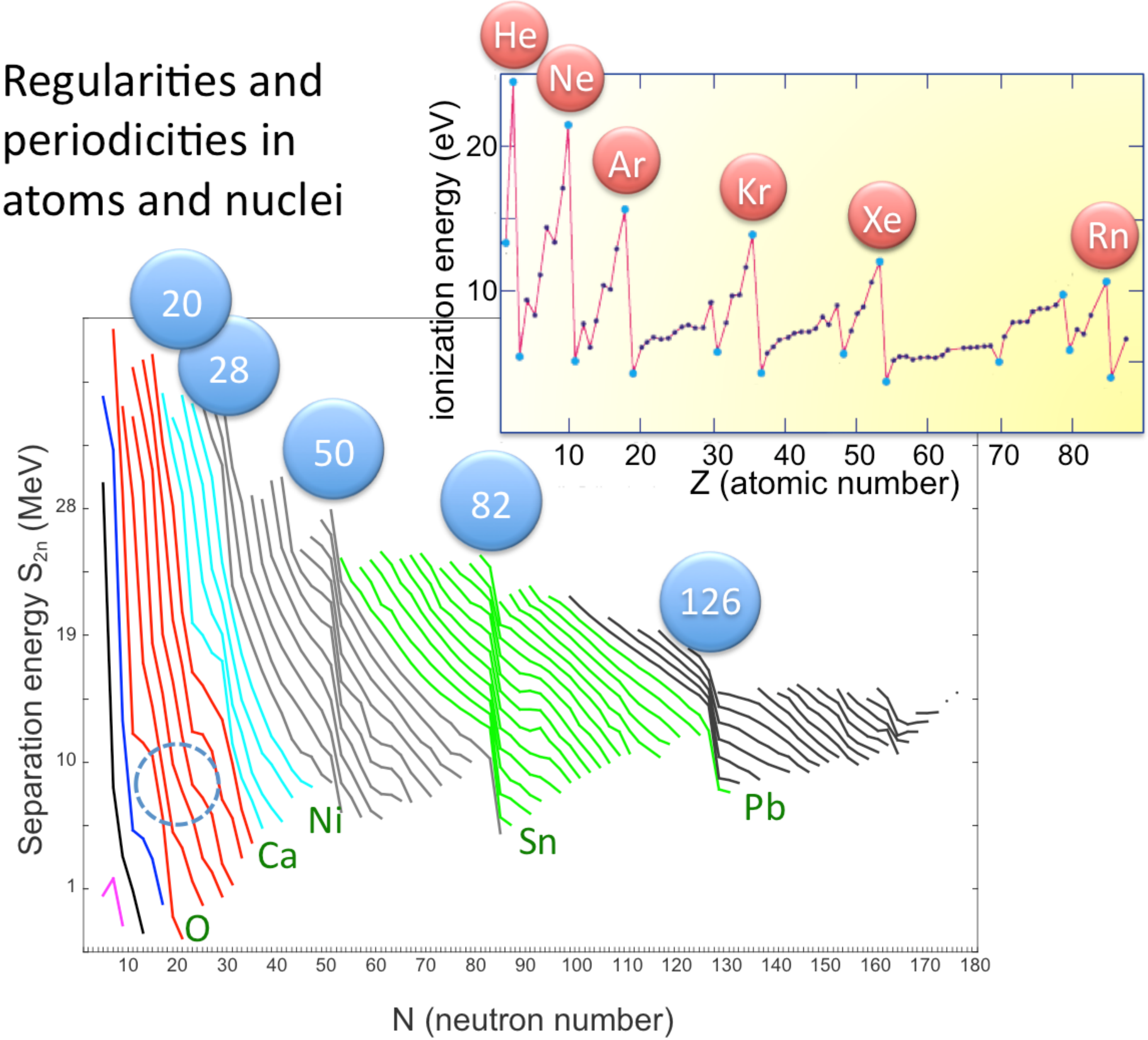
Thank You

Happy birthday, A^2!

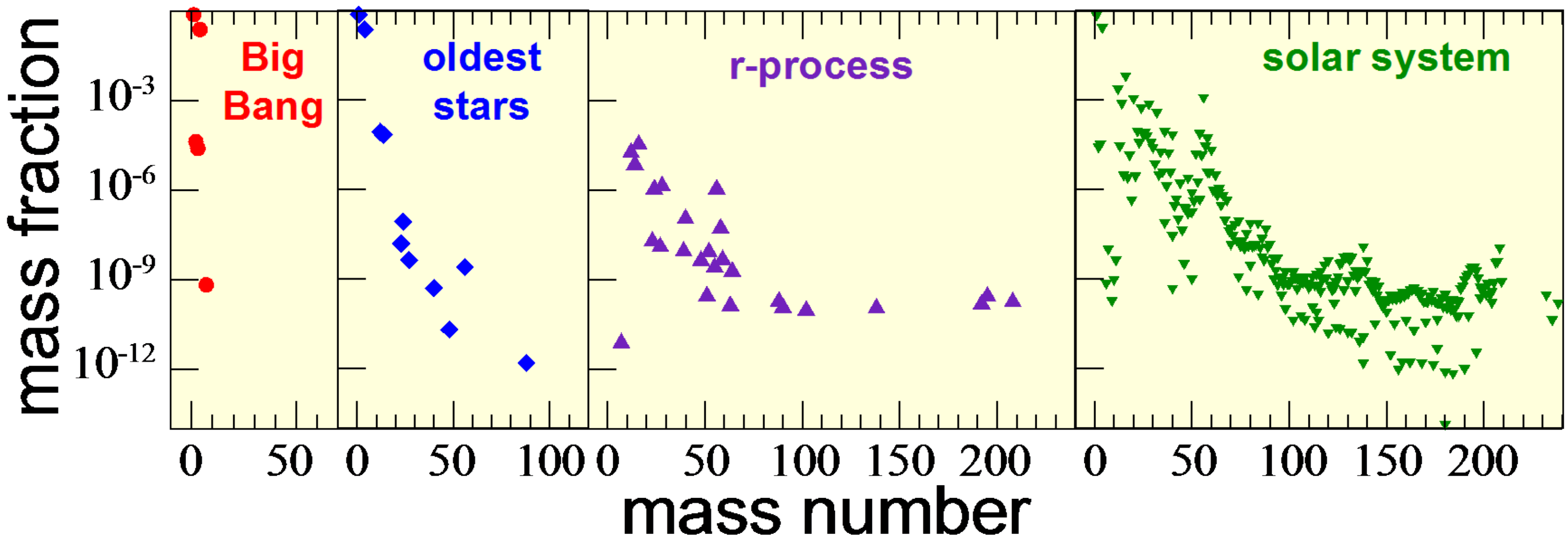
COMEX5

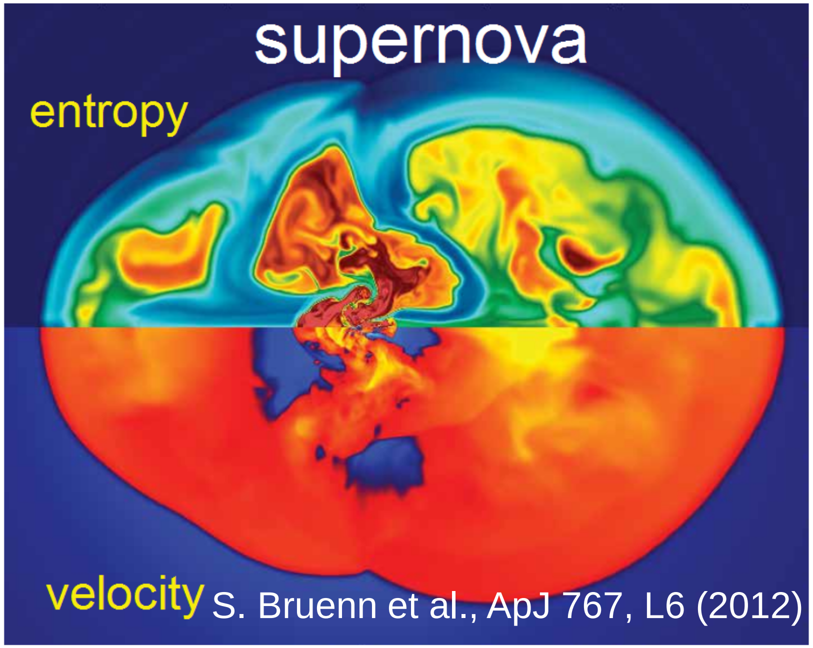
Backup

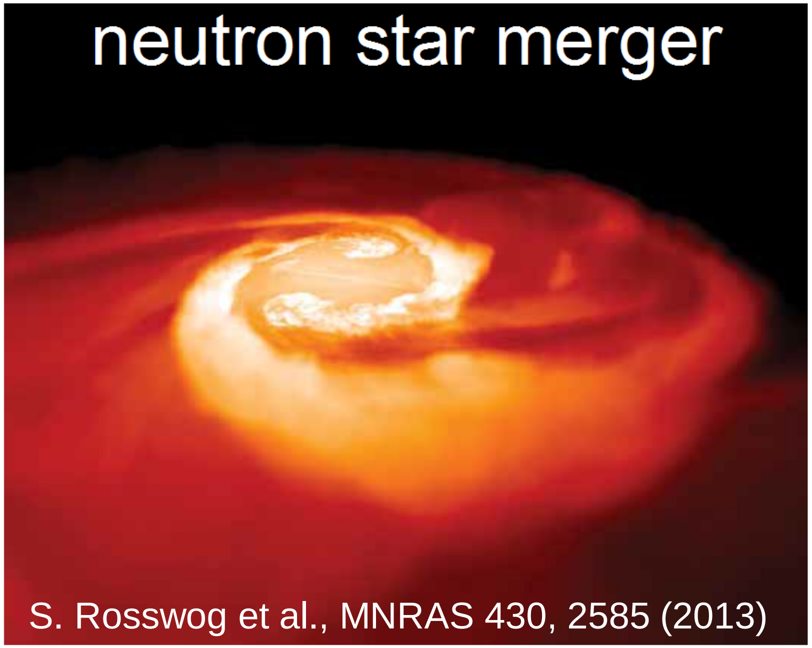
Regularities and periodicities in atoms and nuclei



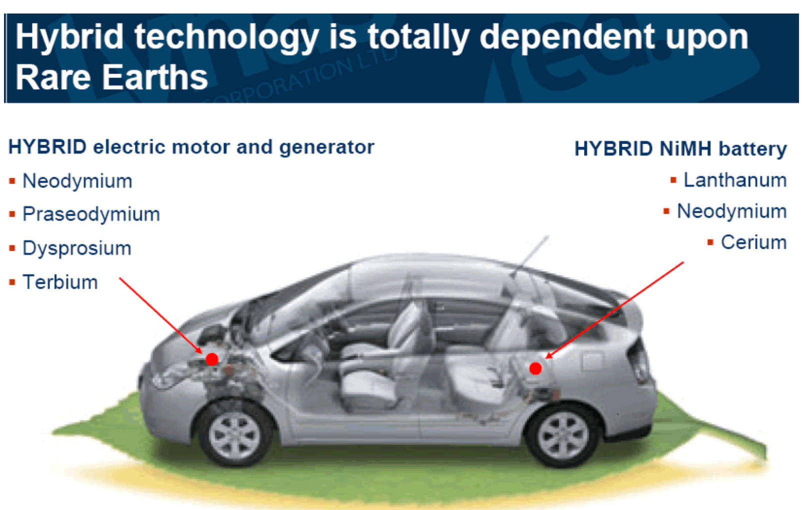
Chemical evolution







Half of the neutron-rich atomic nuclei heavier than iron are built by neutron driven r-process. The final abundances reflect the shell structure of nuclei, which determines the respective nucleosynthesis trajectories.



Curiosity Mars Rover – powered by ^{238}Pu

Theoretical Tools and Connections to Computational Science

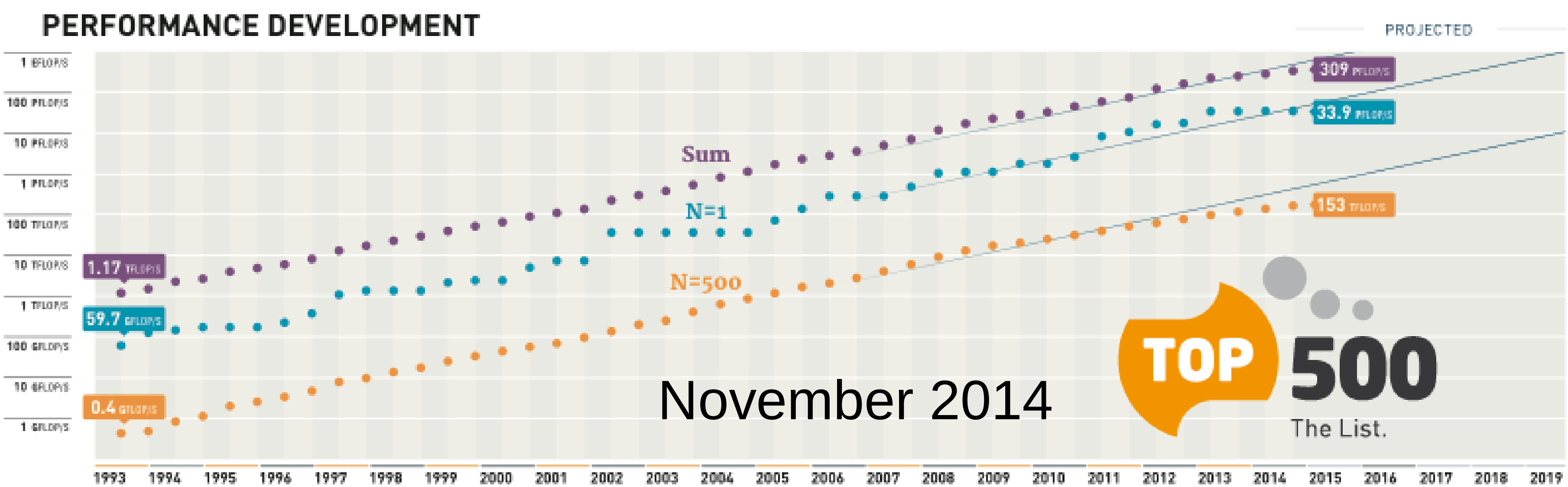
1teraflop=10^{12} flops
1peta=10^{15} flops (today)
1exa=10^{18} flops (next 10 years)

Tremendous opportunities for nuclear theory!

3,120,000 cores

33.9 pflops

	NAME	SPECS	SITE	COUNTRY	CORES	RMAX 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, Opteron 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

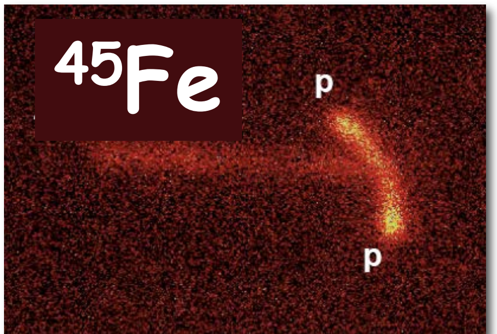


http://top500.org

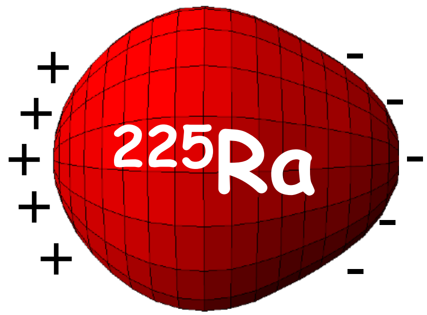
Some nuclei are more important than others

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