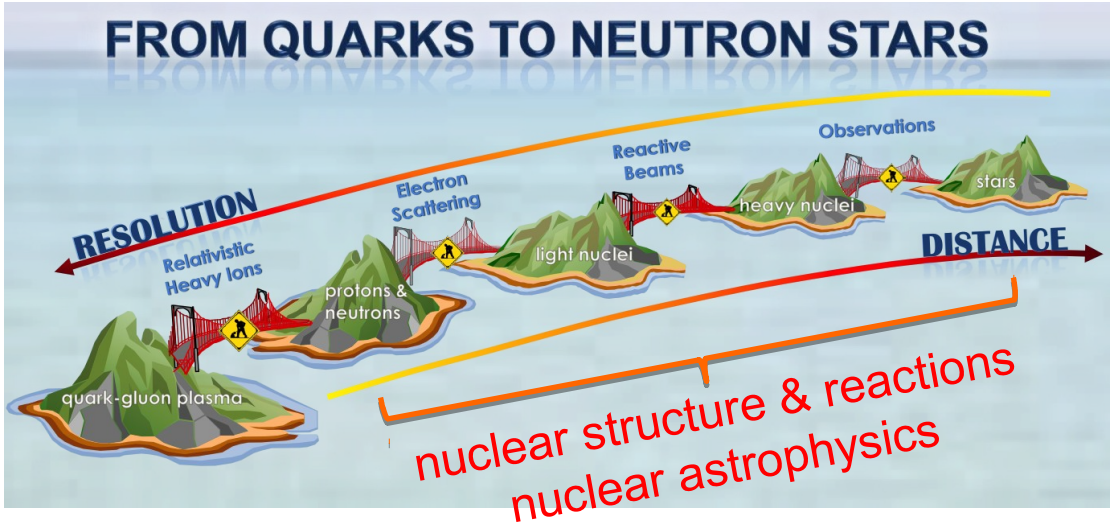
Nuclear structure I (preliminaries)

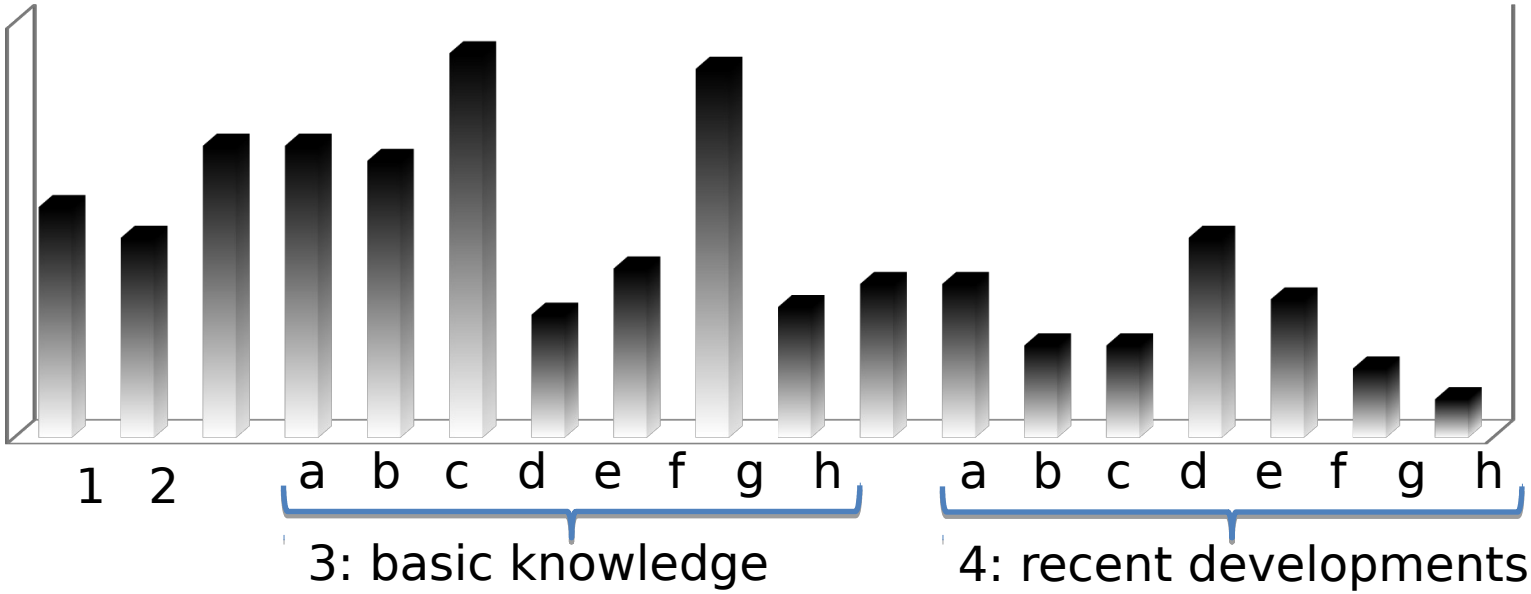
Witek Nazarewicz (UTK/ORNL)

National Nuclear Physics Summer School 2014
William & Mary, VA

- Introduction: questions
- Nuclear landscape
- General principles



TALENT: Training in Advanced Low Energy Nuclear Theory
nucleartalent.org



1. Have you ever taken a nuclear structure class or course?
2. Have you ever been offered a nuclear structure class or course?

3. Are you familiar with fundamental concepts of nuclear structure, such as:
   a) Liquid drop picture of the nucleus
   b) Nuclear shell effects
   c) Nuclear sizes and shapes
   d) Nuclear force
   e) Nucleonic pairing
   f) Particle drip lines
   g) Nuclear decays (alpha, beta, gamma,

4. Are you basically familiar with the recent developments in the following areas:
   a) Stellar nucleosynthesis
   b) Properties of rare isotopes
   c) Computational nuclear structure theory
   d) Search for superheavy nuclei
   e) Nuclear aspects of neutron stars
   f) Nuclei as laboratories of the new standard model
   g) Emergent behavior of many-body systems

Overarching Questions

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?

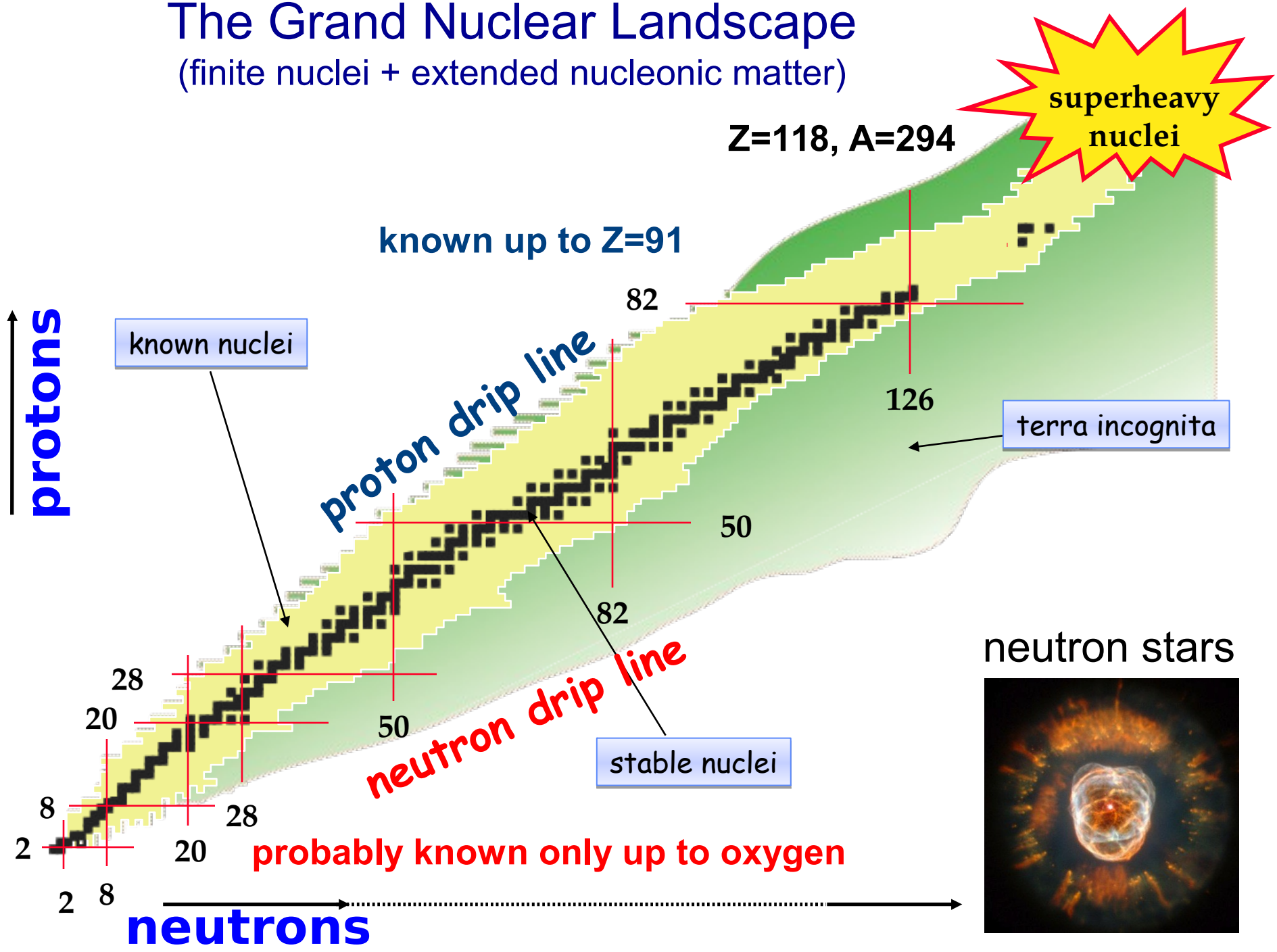
The Nuclear Landscape

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

The Nuclear Landscape

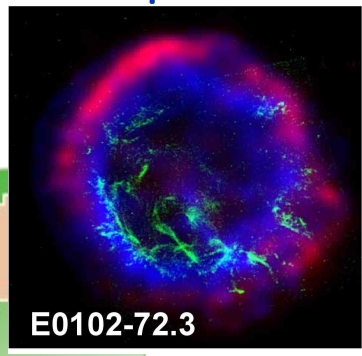
The Grand Nuclear Landscape

(finite nuclei + extended nucleonic matter)

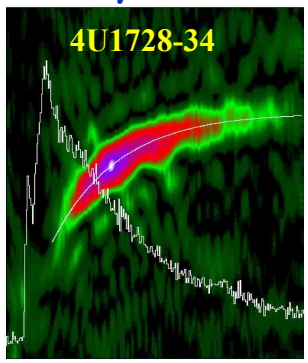


The Nuclear Landscape and the Cosmos

Supernova



X-ray burst

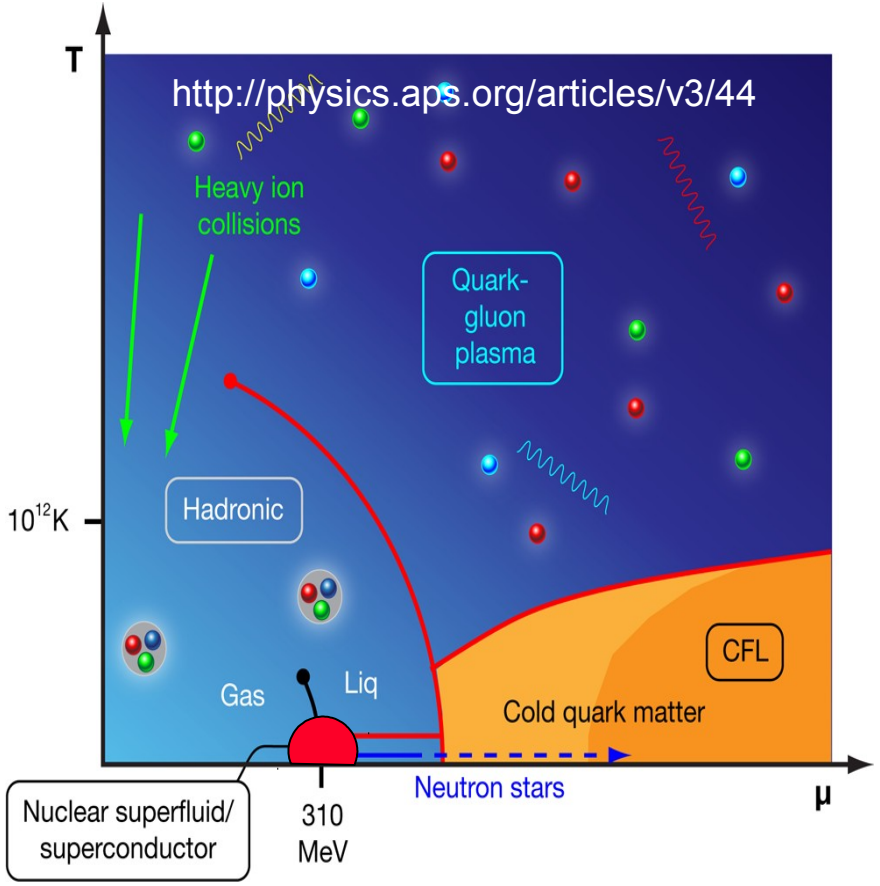


Nova

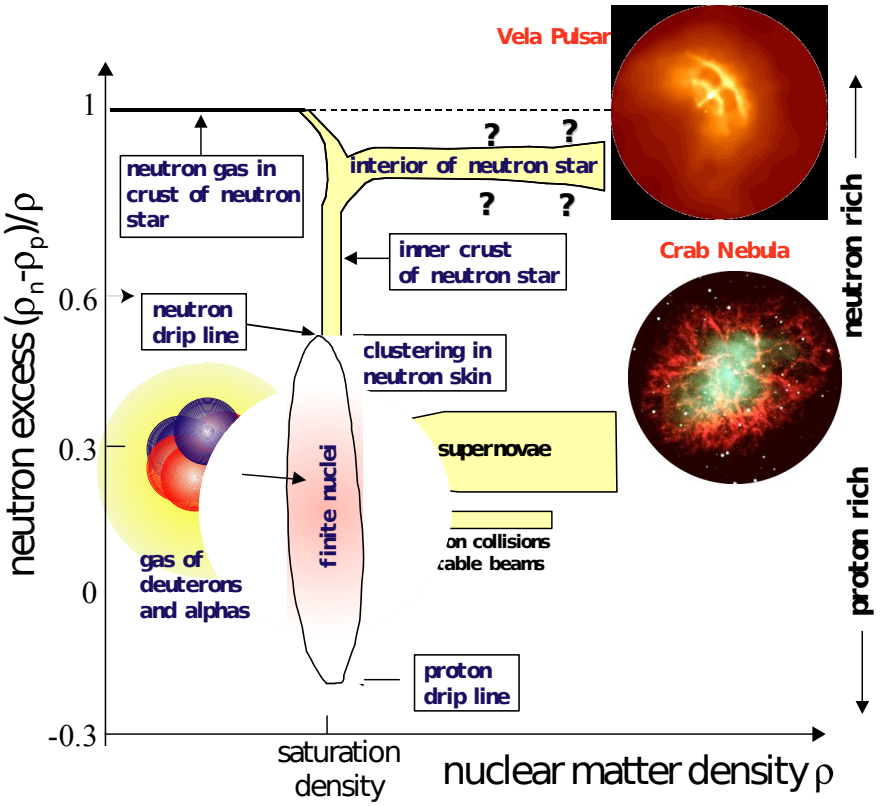
Neutron star

The Nuclear Landscape…

…as seen by the QCD phase diagram



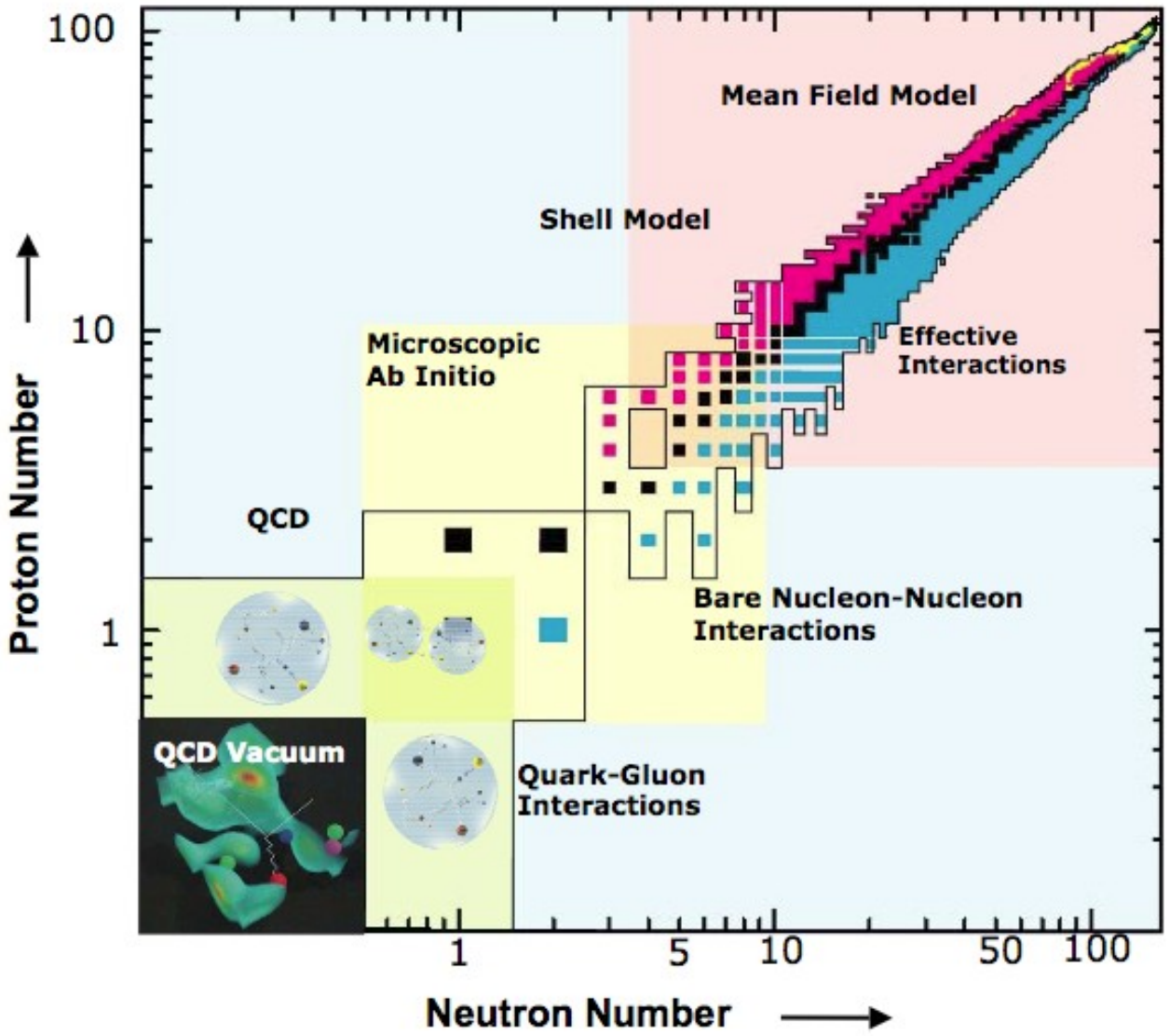
…as seen by nuclear astro theory



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

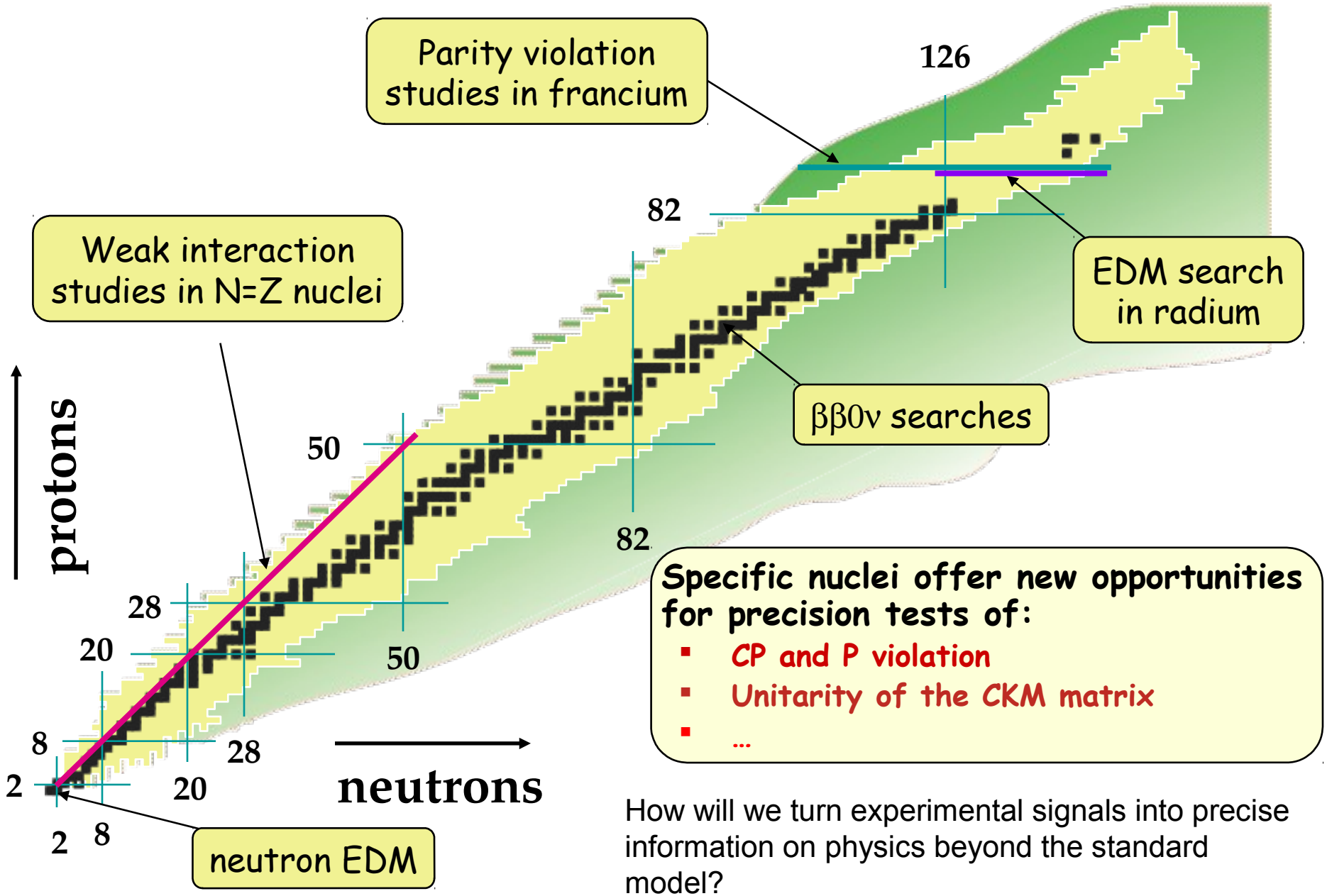
The Nuclear Landscape

…as seen by Jefferson Lab



A: 0, …, 1, 1, 2, 4, ^{208}Pb, ∞

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?

The Nuclear Landscape…

…as seen by chemists…

Periodic Table of Elements 2014

1												13	14	15	16	17	18
H 1	2																He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12	3	4	5	6	7	8	9	10	11	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

General Principles

How are nuclei made?

Origin of elements, isotopes

Hot and dense quark-gluon matter

Hadron structure

Hadron-Nuclear interface

Nuclear structure
Nuclear reactions
New standard model

Resolution

Effective Field Theory

Third Law of Progress in Theoretical Physics by Weinberg:

"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!"

Physics of Hadrons

Physics of Nuclei

LQCD

Degrees of Freedom

Energy (MeV)

scale separation

quarks, gluons

quark models

940
neutron mass

constituent quarks

140
pion mass

ab initio

baryons, mesons

CI

8
proton separation energy in lead

protons, neutrons

DFT

1.12
vibrational state in tin

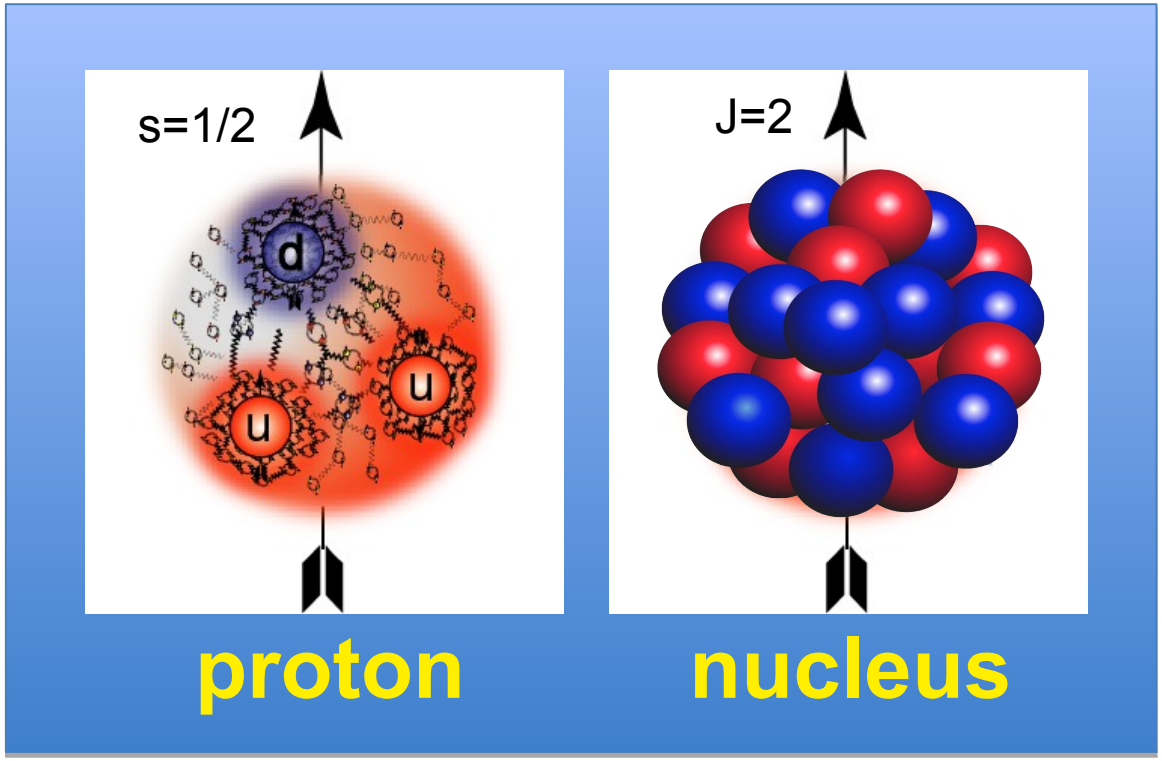
nucleonic densities and currents

collective models

0.043
rotational state in uranium

collective coordinates

The Hadronic Many-Body problem



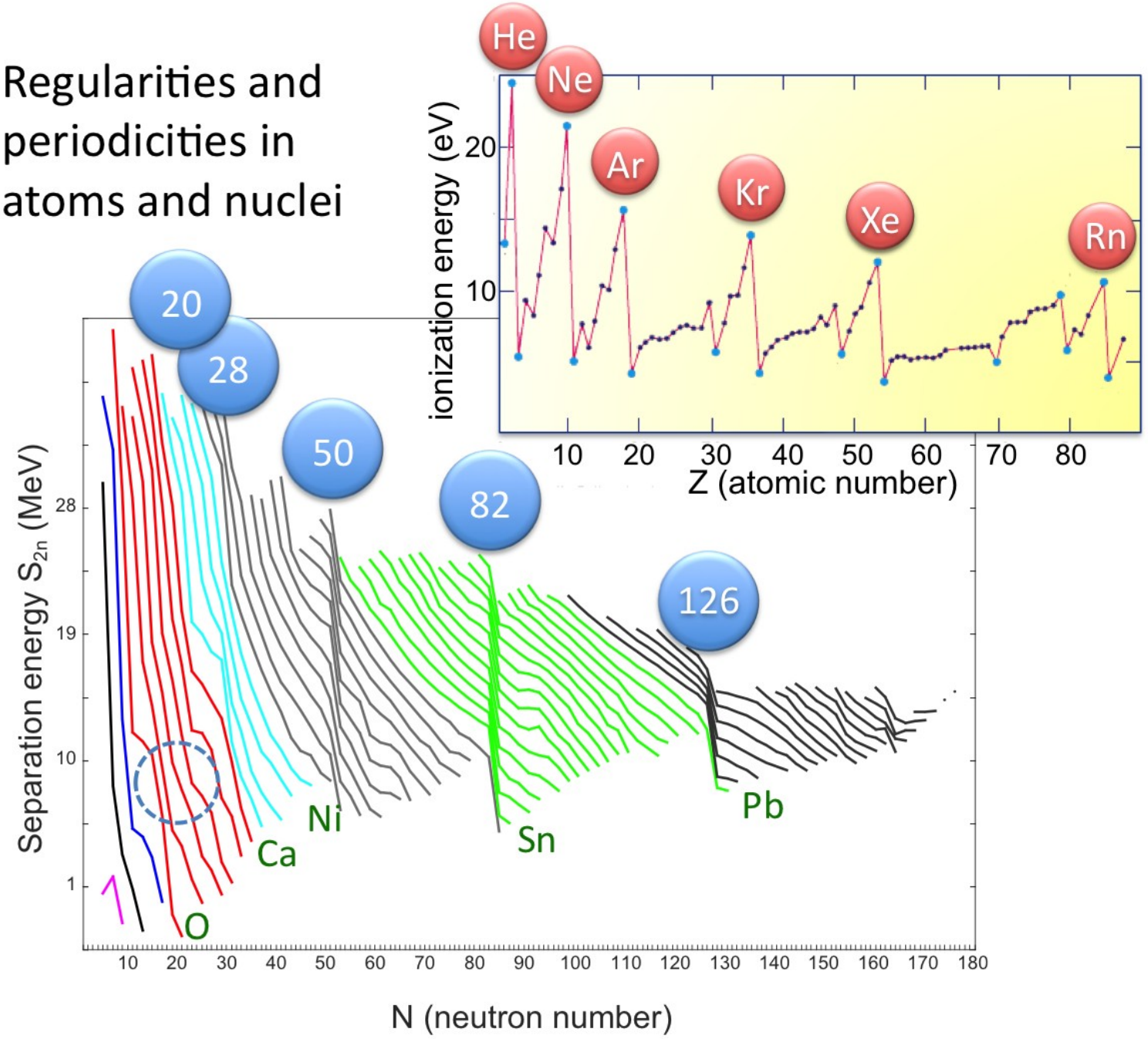
hadron spectroscopy

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

nuclear spectroscopy

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

Regularities and periodicities in atoms and nuclei



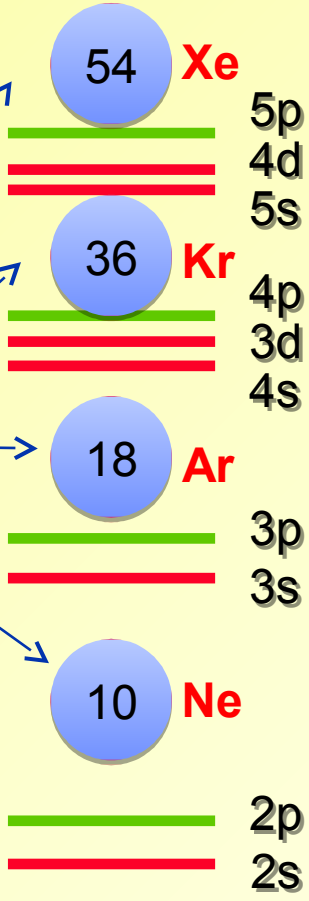
1912

electronic shells of the atom

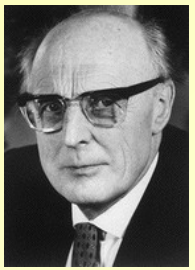
Nobel Prize 1922

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

noble gases (closed shells)



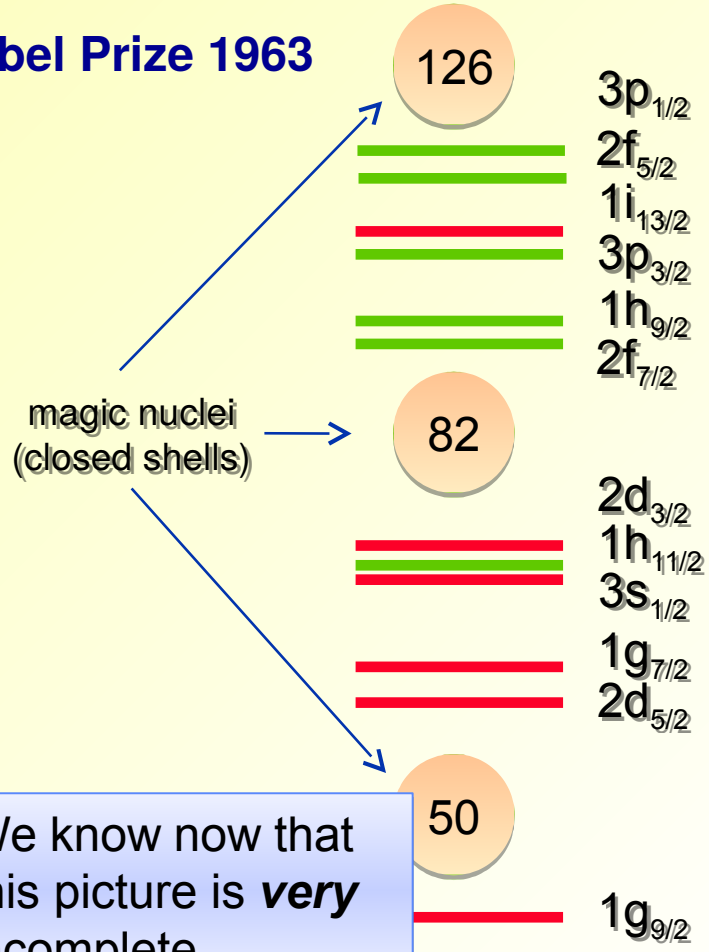
1949



nucleonic shells of the nucleus

Nobel Prize 1963

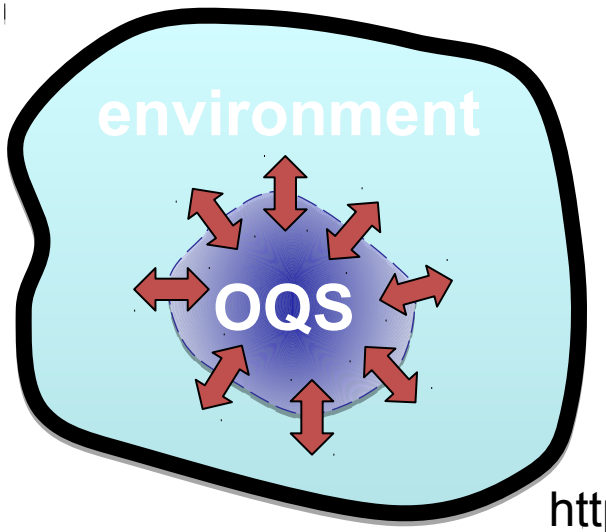
magic nuclei (closed shells)



We know now that this picture is ***very*** incomplete…

Wikipedia:

An open quantum system is a quantum system which is found to be in interaction with an external quantum system, the environment. The open quantum system can be viewed as a distinguished part of a larger closed quantum system, the other part being the environment.

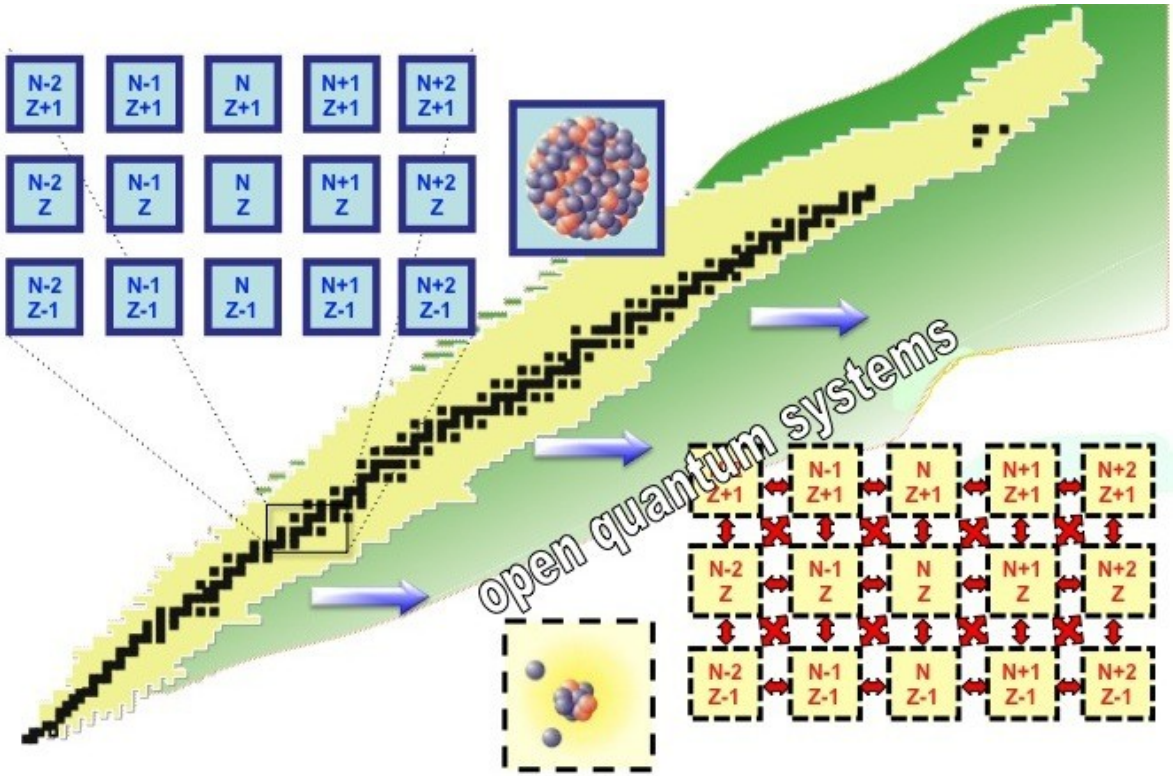


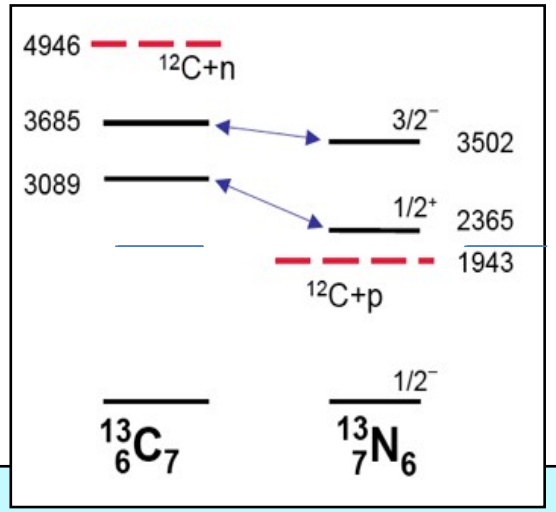
INTERDISCIPLINARY

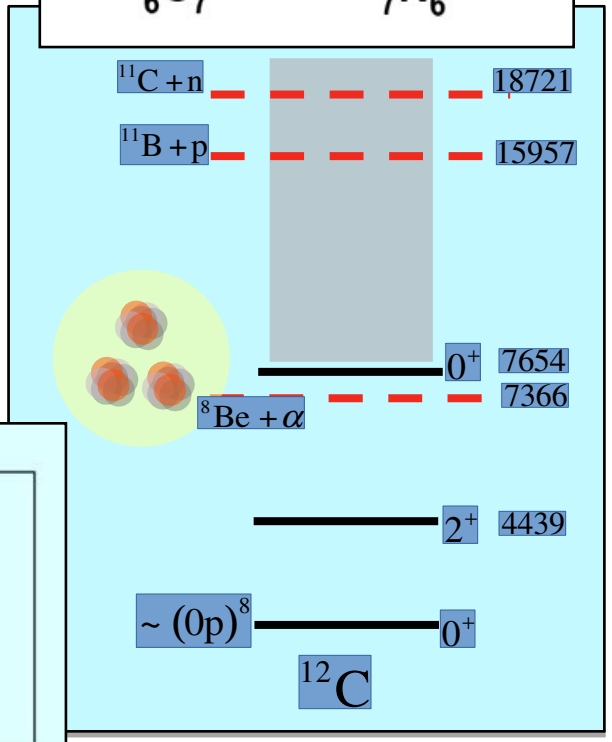
Small quantum systems, whose properties are profoundly affected by environment, i.e., continuum of scattering and decay channels, are intensely studied in various fields of physics: nuclear physics, atomic and molecular physics, nanoscience, quantum optics, etc.

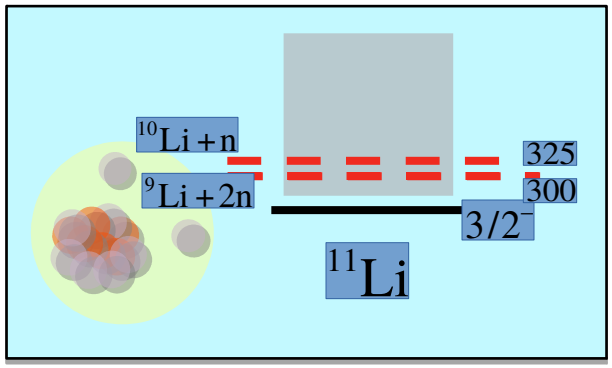
http://www.phy.ornl.gov/theory/MBOQS/Manifesto_09.html

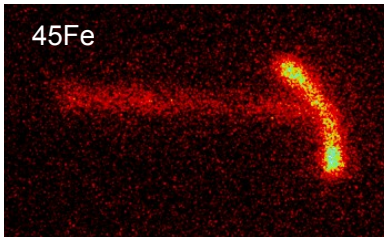
Nucleus as an open quantum system

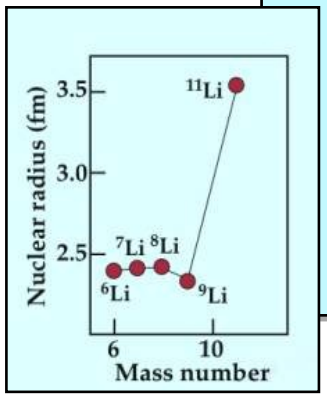












Nuclear theory: guiding principles

- NN interaction is short-ranged, spin- and isospin-dependent
- Nucleonic mean fields and single-particle motion provide zeroth-order picture
- Shell structure

- Mean fields can break symmetry of nuclear Hamiltonian
- Appearance of emergent behavior and collective modes
- Symmetry-driven many-body coupling schemes

- Correlations and quasiparticles
- Quantum corrections
- Openness

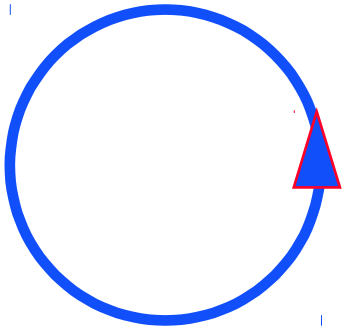
shell

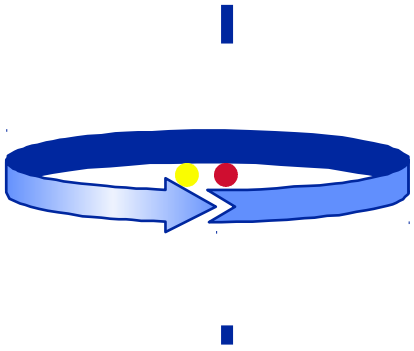
gap

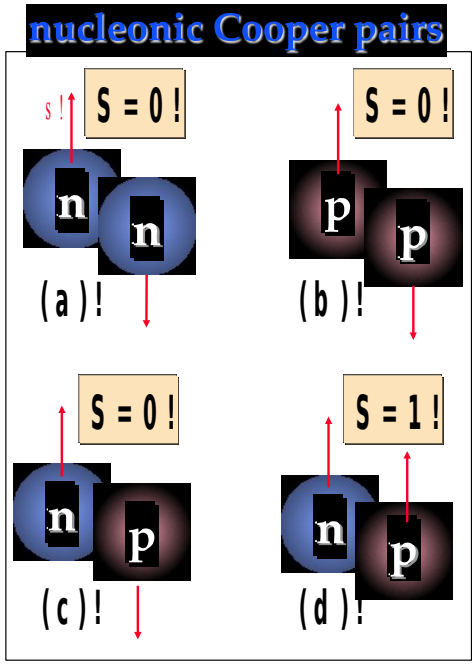
shell

gap

shell

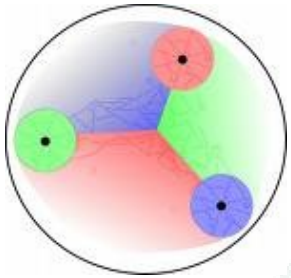






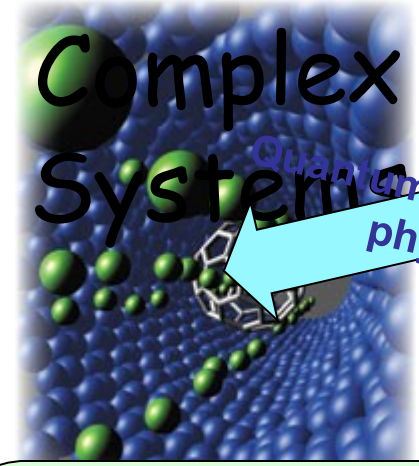
- (Band) structures labeled by quantum numbers of the internally broken symmetries
- Time scale of single-particle and collective motion not very different

Profound intersections



subfemto…

nano…



femto…

Giga…

Quantum many-body physics

Physics of Nuclei

Astrophysics Astronomy

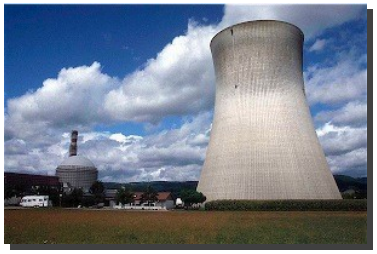
Fundamental interactions

How do collective phenomena emerge from simple constituents?
How can complex systems display astonishing simplicities?
What are unique properties of open systems?

What is the New Standard Model?

How do nuclei shape the physical universe?
What is the origin of the elements?

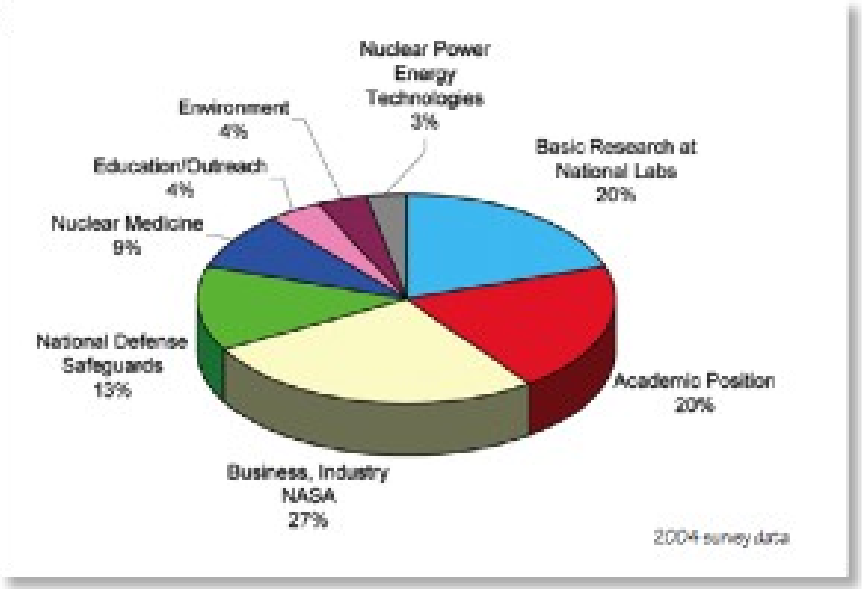
Societal Benefits



- 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



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

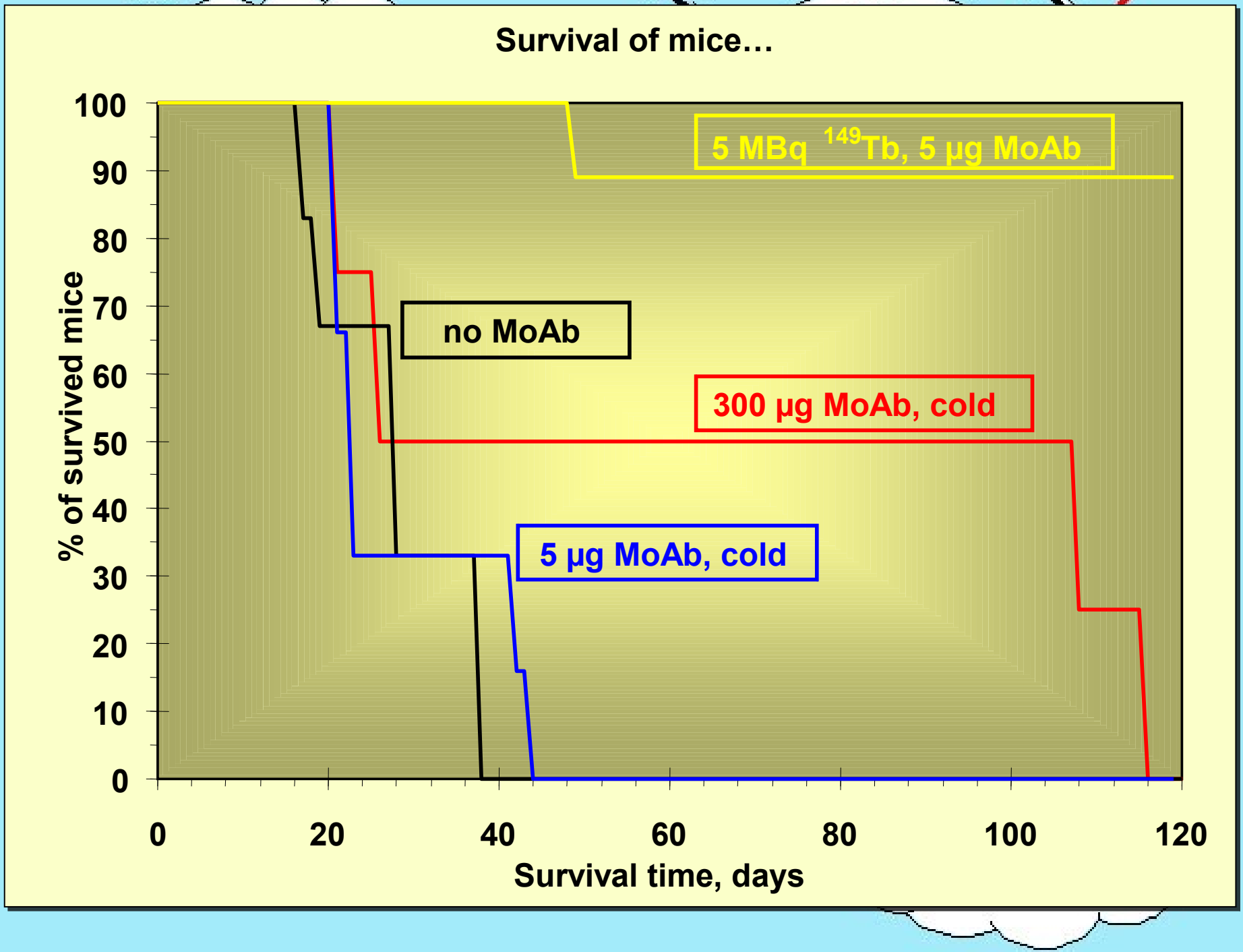
Example: Targeted Alpha Therapy in vivo

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…
100
90
80
70
60
50
40
30
20
10
0
% of survived mice
0
20
40
60
80
100
120
Survival time, days
5 MBq 149Tb, 5 µg MoAb
no MoAb
300 µg MoAb, cold
5 µg MoAb, cold