Nuclear physics: the ISOLDE facility

Lecture 1: Nuclear physics

Magdalena Kowalska
CERN, PH-Dept.
kowalska@cern.ch

on behalf of the CERN ISOLDE team
www.cern.ch/isolde

Outline

Aimed at both physics and non-physics students

- This lecture: Introduction to nuclear physics
  - Key dates and terms
  - Forces inside atomic nuclei
  - Nuclear landscape
  - Nuclear decay
  - General properties of nuclei
  - Nuclear models
  - Open questions in nuclear physics

- Lecture 2: CERN-ISOLDE facility
  - Elements of a Radioactive Ion Beam Facility

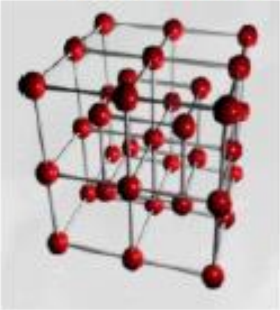
- Lecture 3: Physics of ISOLDE
  - Examples of experimental setups and results

Nuclear scale

Matter

Macroscopic

Crystal

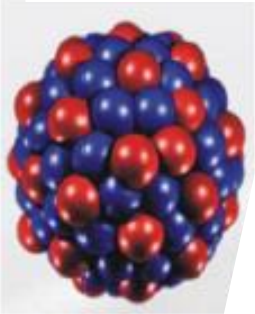


10^{-9} m

Atom

10^{-10} m

Atomic nucleus

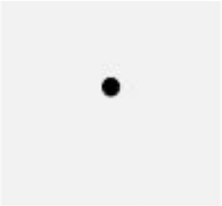


10^{-14} m

Nucleon

10^{-15} m

Quark

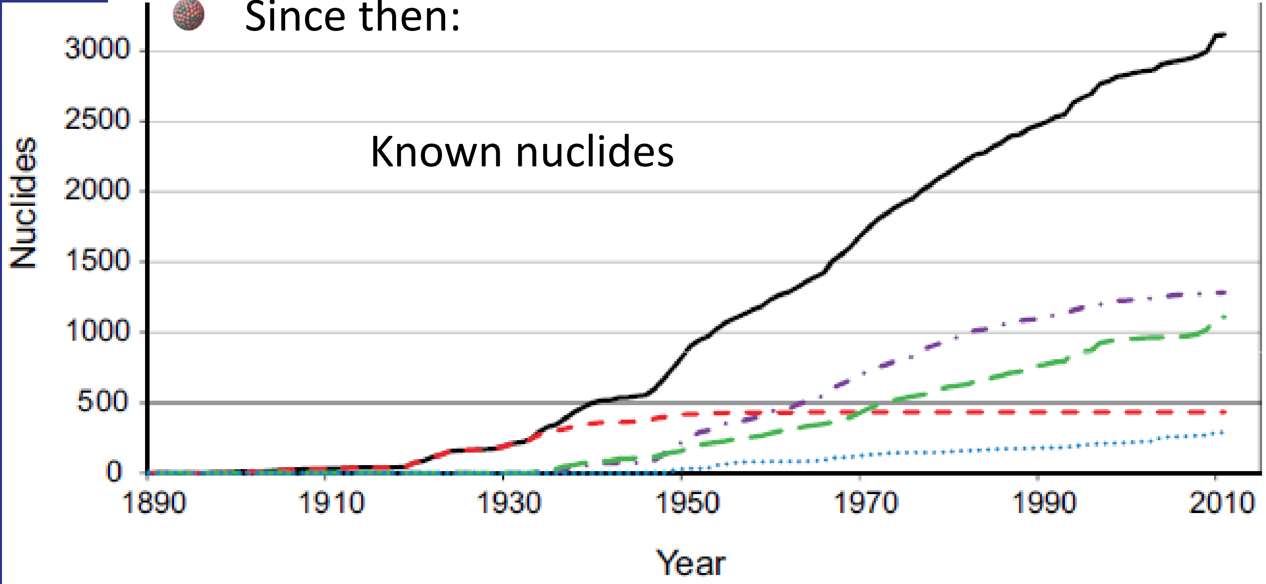


$< 10^{-18}$ m

Nuclear physics:
studies the properties of nuclei and
the interactions inside and between them

Key dates

- 1896: Becquerel, discovery of radioactivity
- 1898: Skłodowska-Curie and Curie, isolation of radium
- 1911: Rutherford, experiments with α particles, discovery of atomic nucleus
- 1932: Chadwick, neutron discovered
- 1934: Fermi, theory of β radioactivity
- 1935: Yukawa, nuclear force mediated via mesons
- 1949: Goeppert-Meyer, Jensen, Haxel, Suess, nuclear shell model
- 1964: Gell-Mann, Zweig, quark model of hadrons
- 1960’ties: first studies on short-lived nuclei
- Since then:



Today: the exact form of the nuclear interaction is still not known, but we are getting to know it better and better with many dedicated facilities

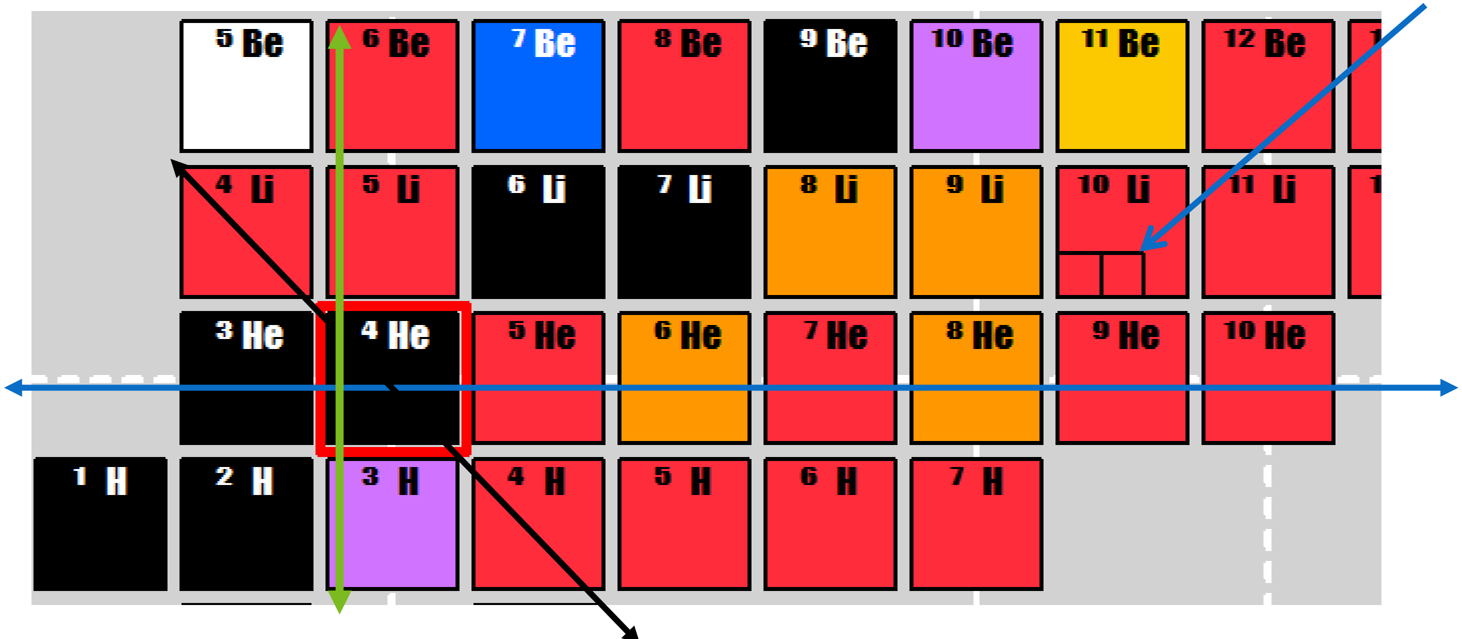
Terminology

- Nucleus/nuclide:

- atomic number A
- Z protons
- N= A-Z neutrons

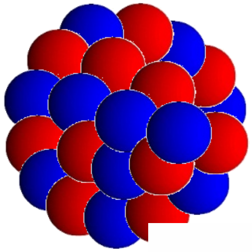
- Nucleons: protons and neutrons inside the nucleus
- **Isotopes**: nuclides with the same number of protons, but not neutrons
- **Isotones**: nuclides with the same number of neutrons, but not protons
- **Isobars**: nuclides with the same atomic number (but different Z and N)

Isomers = long-lived nuclear excited states

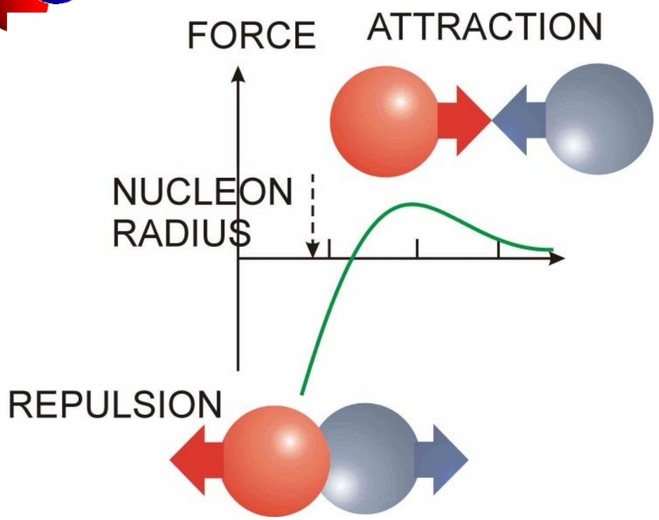


Forces acting in nuclei

- **Coulomb force** repels protons

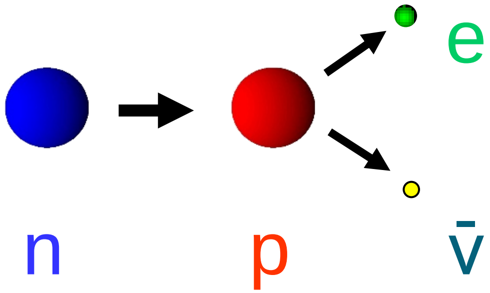


- **Strong interaction** ("nuclear force") causes binding which is stronger for proton-neutron (pn) systems than pp- or nn-systems



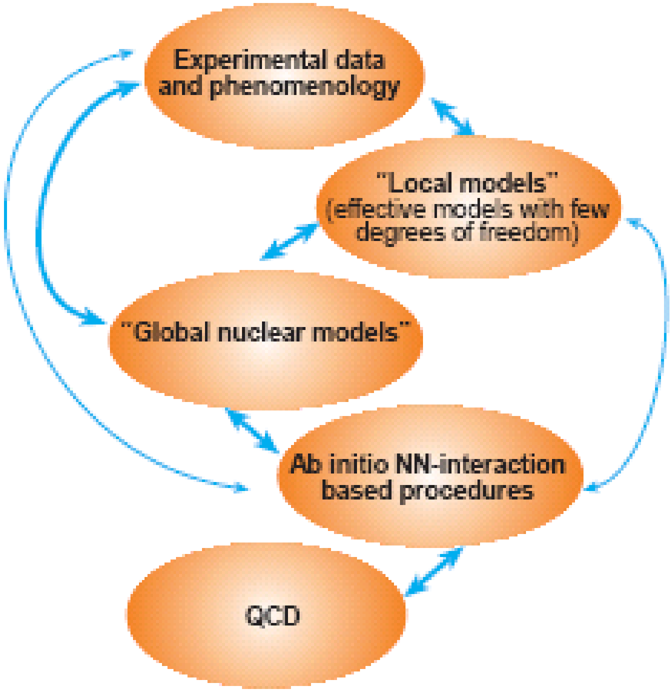
- Neutrons alone form no bound states (exception: neutron stars (**gravitation**!)

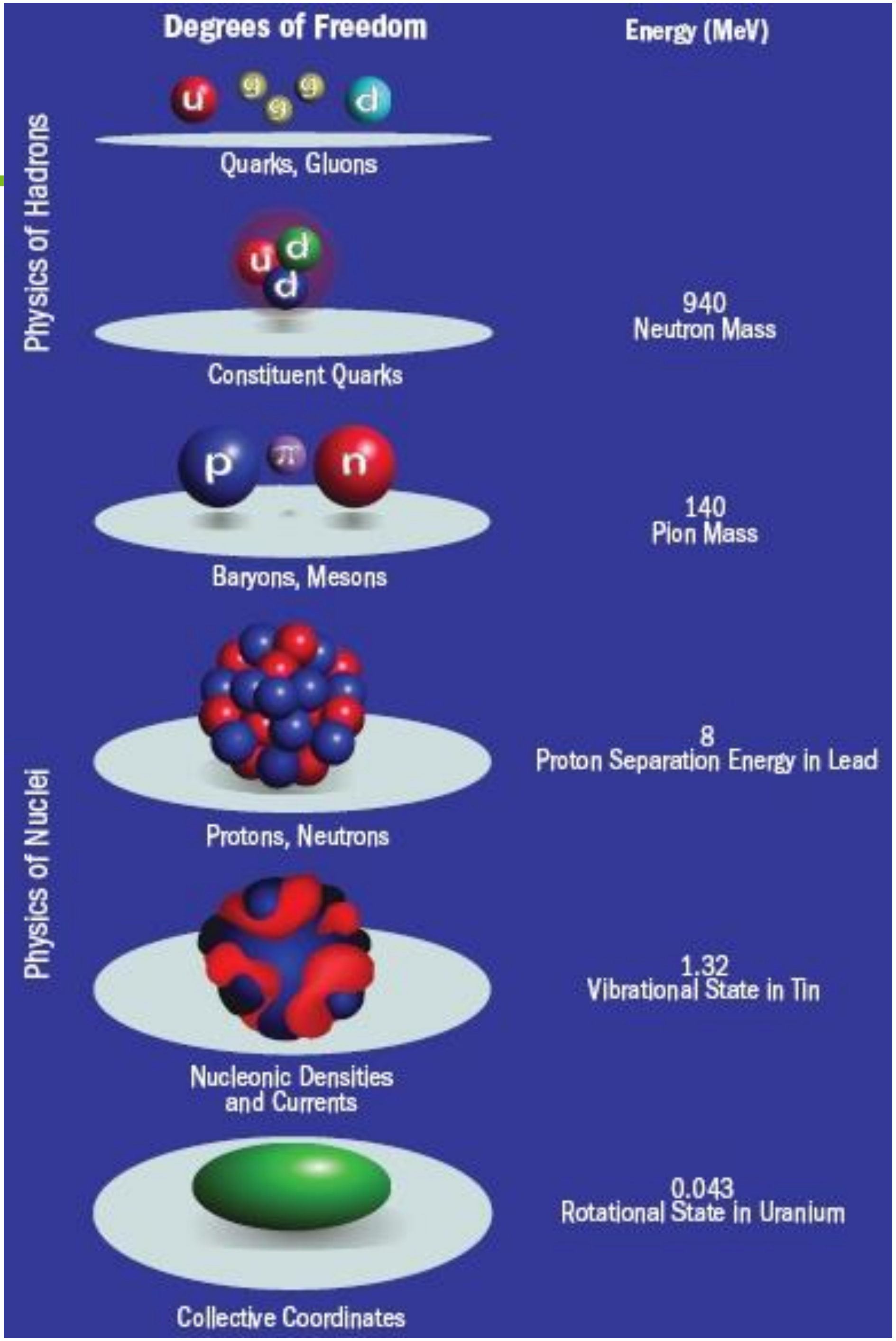
- **Weak interaction** causes β-decay



Nuclei and QCD

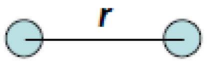
- Different energy scales
- In nuclei: non-perturbative QCD, so no easy way of calculating
- Have to rely on nuclear models (shell model, mean-field approaches)
- Recent progress: lattice QCD

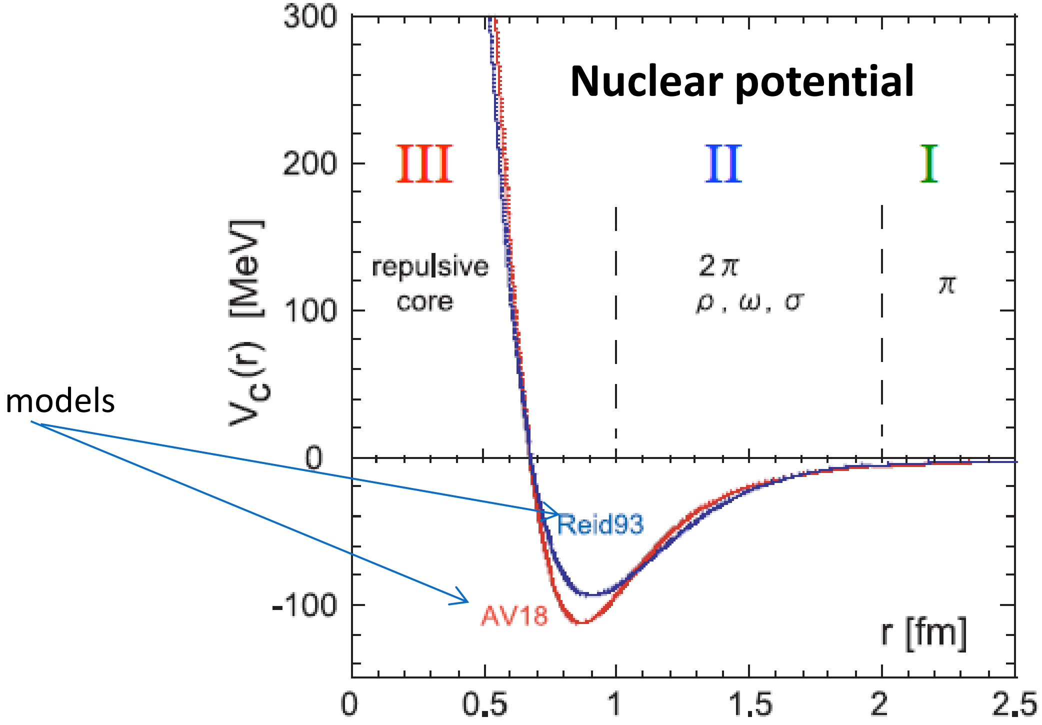




Properties of nuclear interaction

- Has a very short range
- Consists mostly of attractive central potential
- Is strongly spin-dependent
- Includes a non-central (tensor) term
- Is charge symmetric
- Is nearly charge independent
- Becomes repulsive at short distances





I Long range part

one pion exchange potential

II Medium range part

$\sigma,\ \rho,\ \omega$ exchange

2π exchange

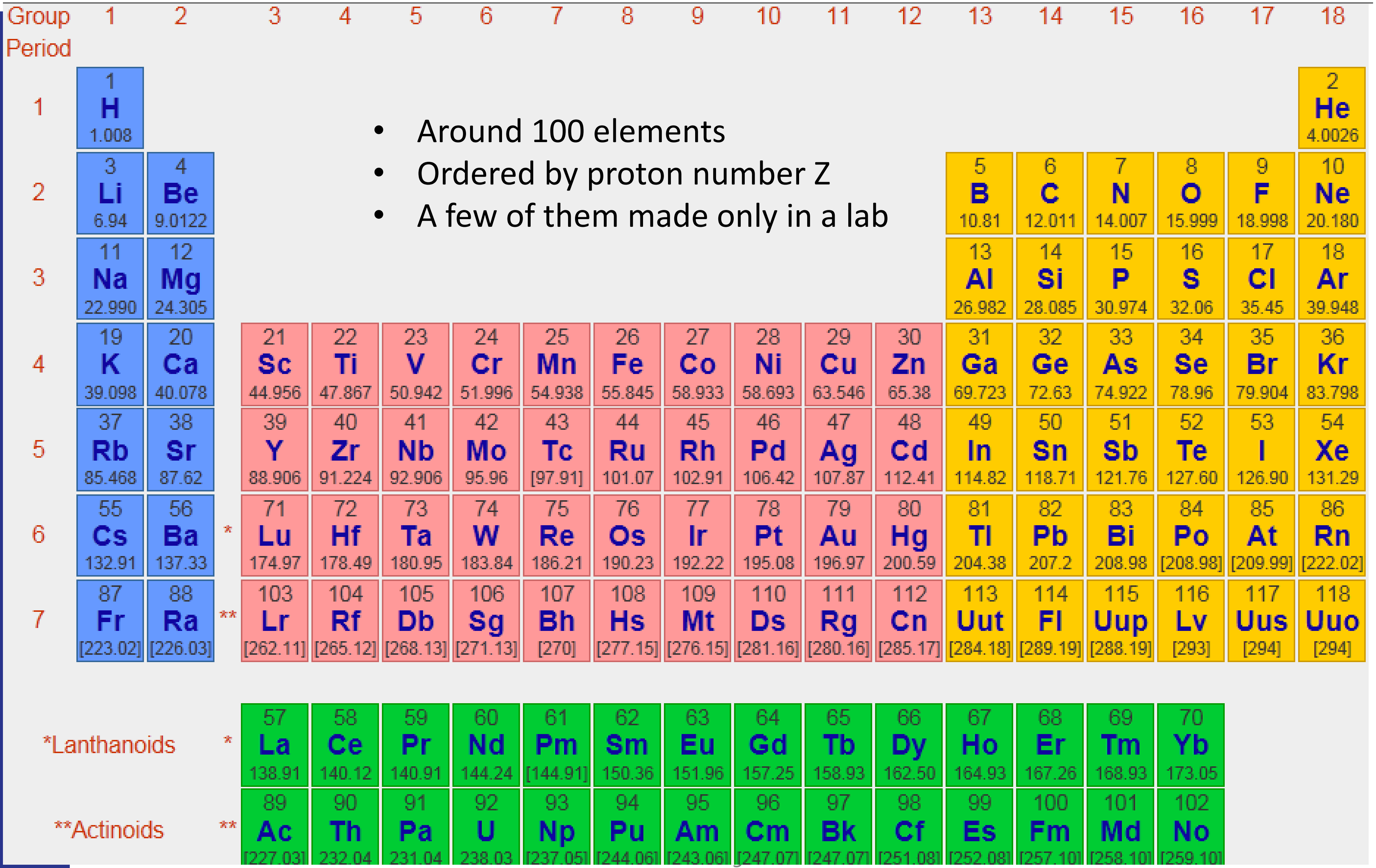
III Short range part

repulsive core (RC)

quark ?

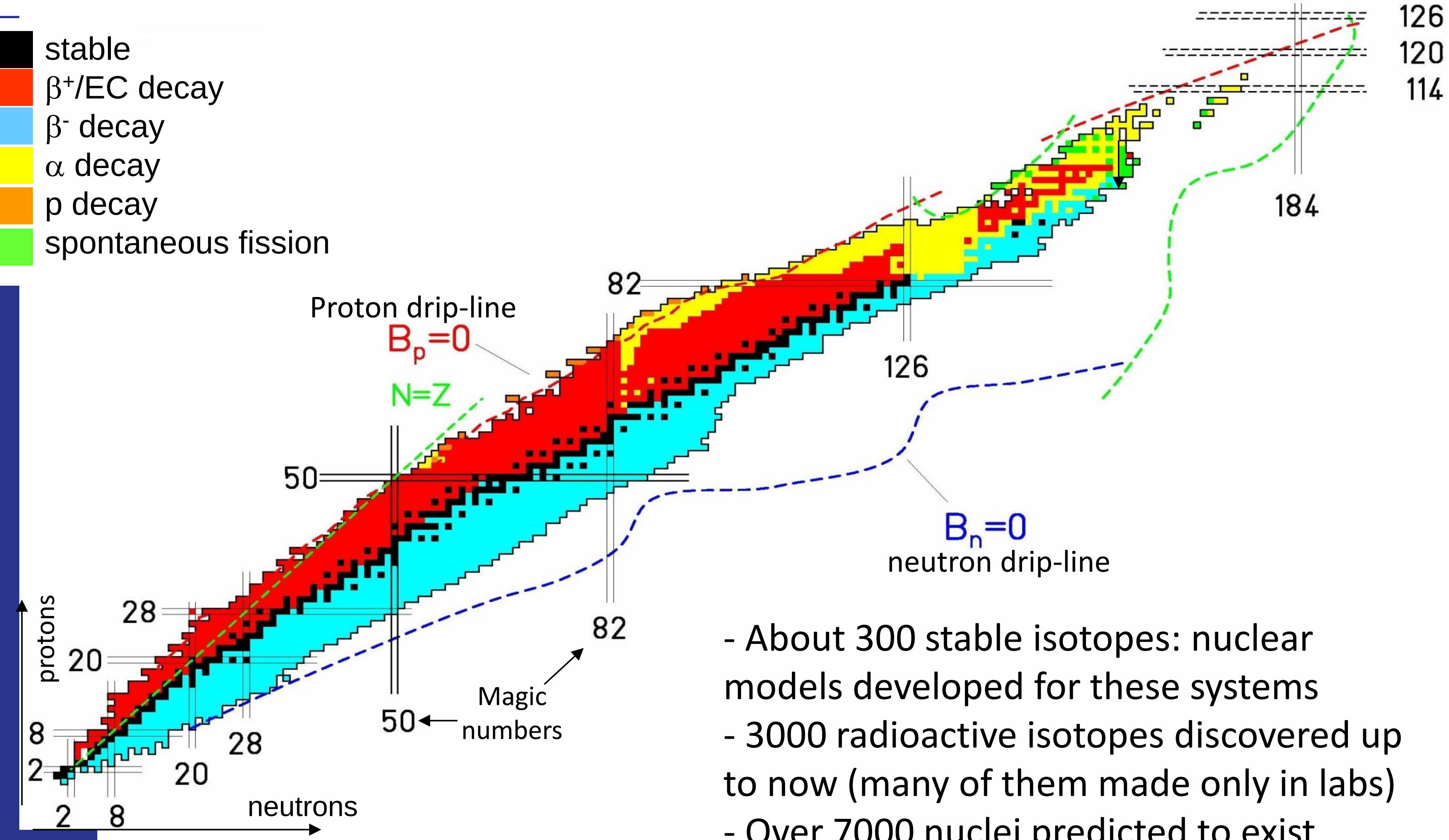
Chart of elements

- Around 100 elements
- Ordered by proton number Z
- A few of them made only in a lab



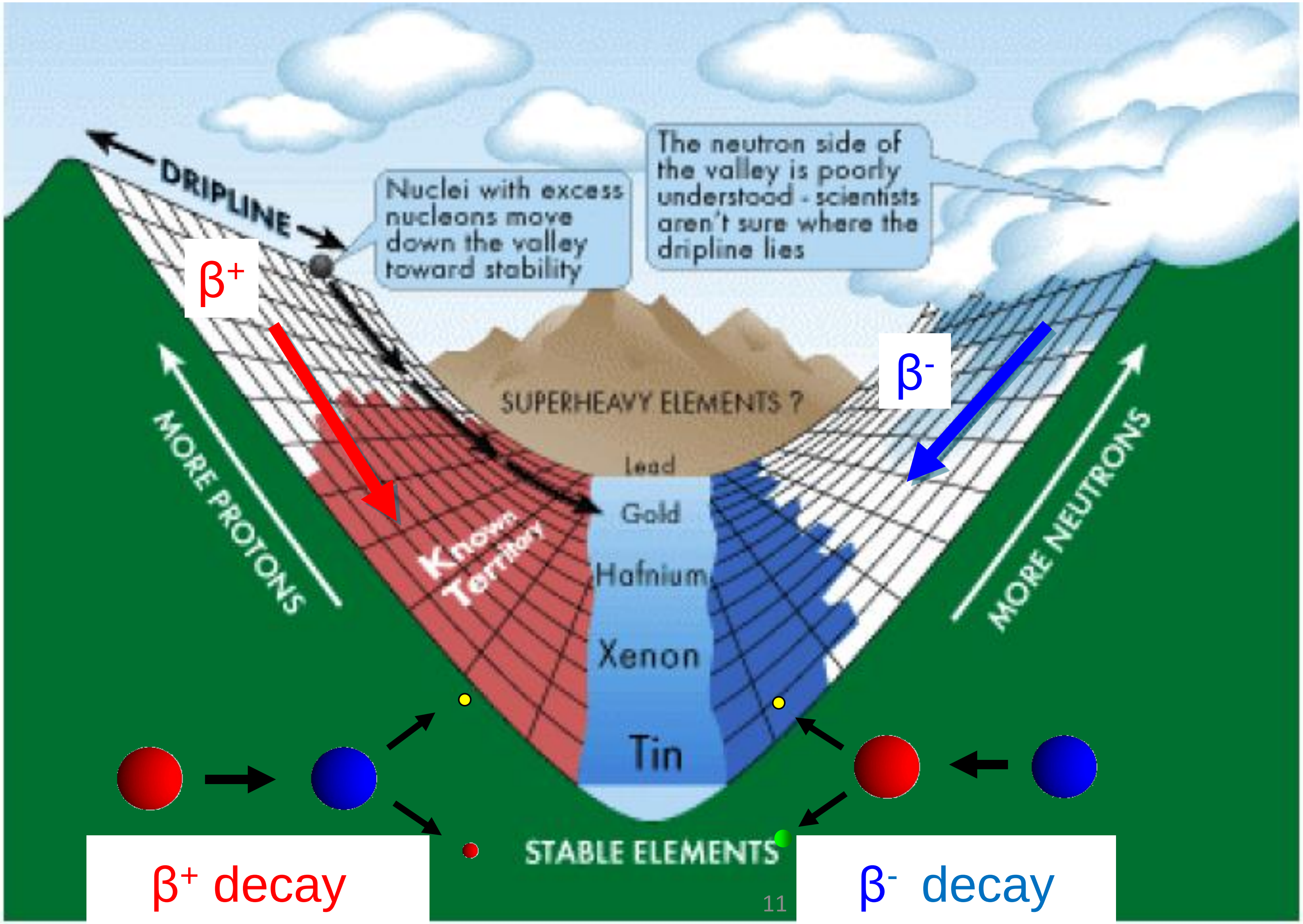
Group Period	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																		2 He 4.0026
2	3 Li 6.94	4 Be 9.0122												5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
3	11 Na 22.990	12 Mg 24.305												13 Al 26.982	14 Si 28.085	15 P 30.974	16 S 32.06	17 Cl 35.45	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078		21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.63	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.798
5	37 Rb 85.468	38 Sr 87.62		39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.96	43 Tc [97.91]	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	*	71 Lu 174.97	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po [208.98]	85 At [209.99]	86 Rn [222.02]
7	87 Fr [223.02]	88 Ra [226.03]	**	103 Lr [262.11]	104 Rf [265.12]	105 Db [268.13]	106 Sg [271.13]	107 Bh [270]	108 Hs [277.15]	109 Mt [276.15]	110 Ds [281.16]	111 Rg [280.16]	112 Cn [285.17]	113 Uut [284.18]	114 Fl [289.19]	115 Uup [288.19]	116 Lv [293]	117 Uus [294]	118 Uuo [294]
*Lanthanoids			*	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm [144.91]	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.05		
**Actinoids			**	89 Ac [227.03]	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np [237.05]	94 Pu [244.06]	95 Am [243.06]	96 Cm [247.07]	97 Bk [247.07]	98 Cf [251.08]	99 Es [252.08]	100 Fm [257.10]	101 Md [258.10]	102 No [259.10]		

Chart of nuclei



- About 300 stable isotopes: nuclear models developed for these systems
- 3000 radioactive isotopes discovered up to now (many of them made only in labs)
- Over 7000 nuclei predicted to exist

Valley of stability

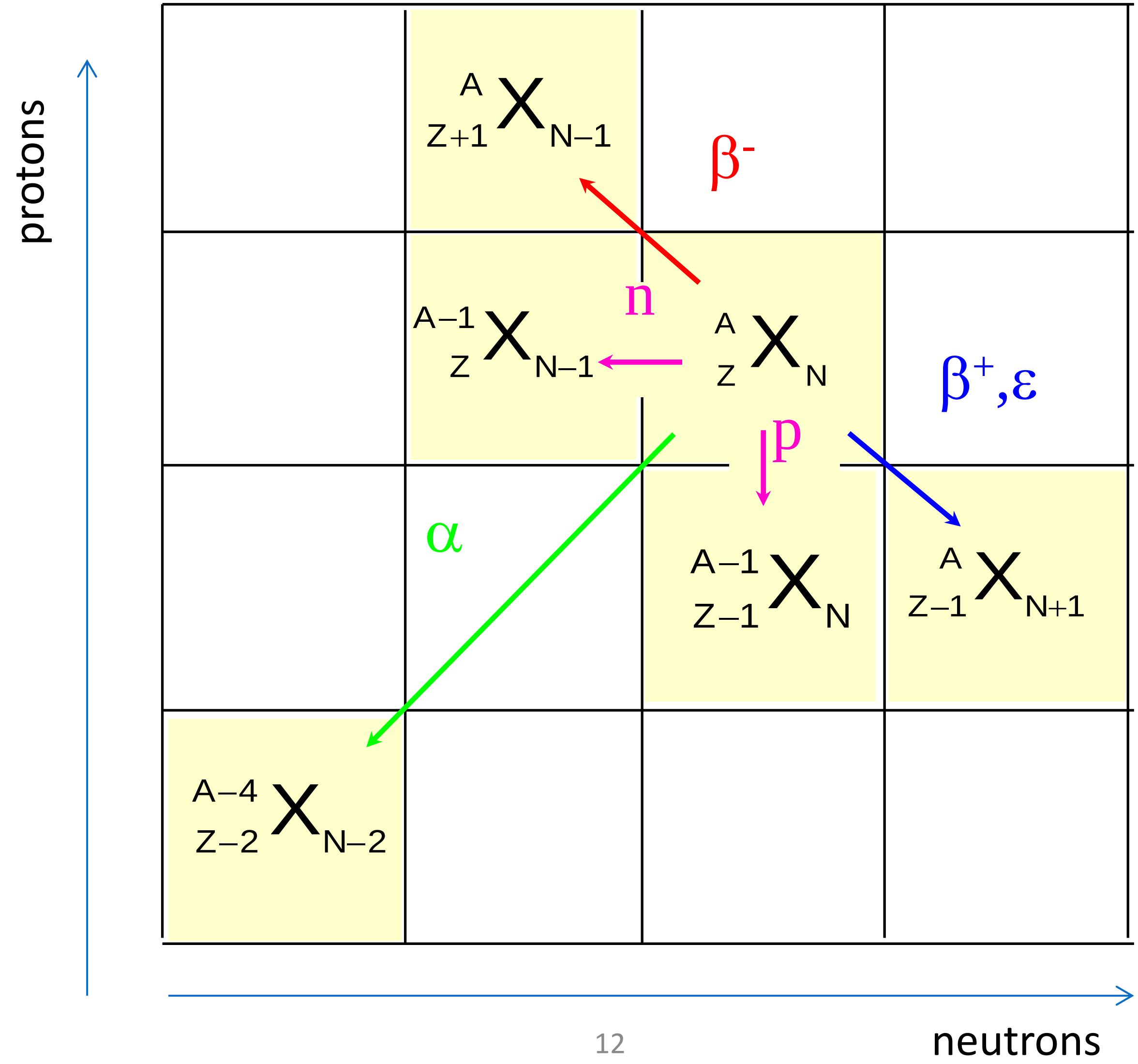


β^+ decay

β^- decay

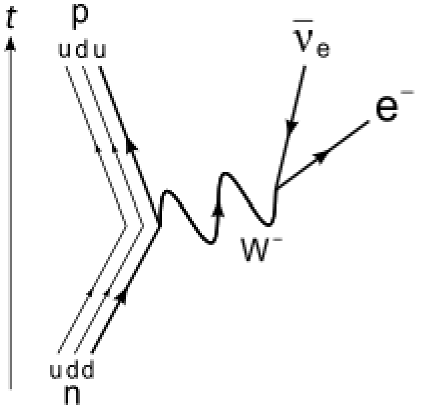
Nuclear decay

- Mass of mother nucleus = mass of decay products **+ energy**

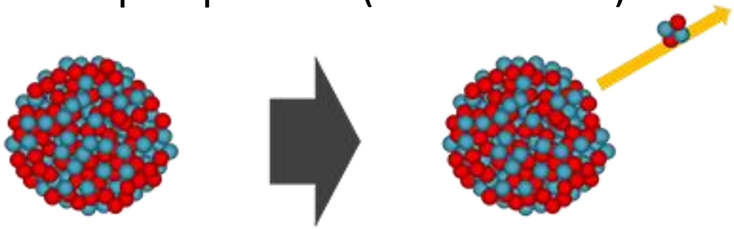


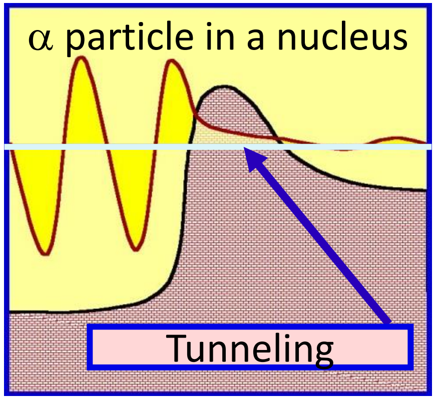
Nuclear decay

- β+ decay – emission of positron: $p \rightarrow n + e^+ + \nu_e$
- ε/EC – electron capture:
  - nucleus captures an atomic electron: $p + e^- \rightarrow n + \nu_e$
- β- decay – emission of electron

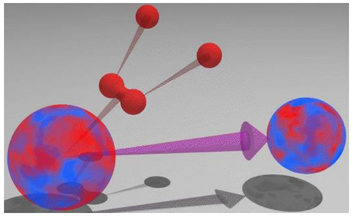


- α decay – emission of alpha particle (4He nucleus)

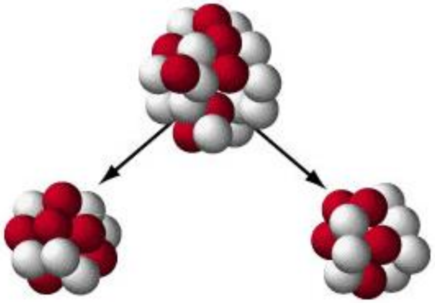




- p (or 2p) decay – emission of 1 or 2 protons
  - in very proton-rich nuclei

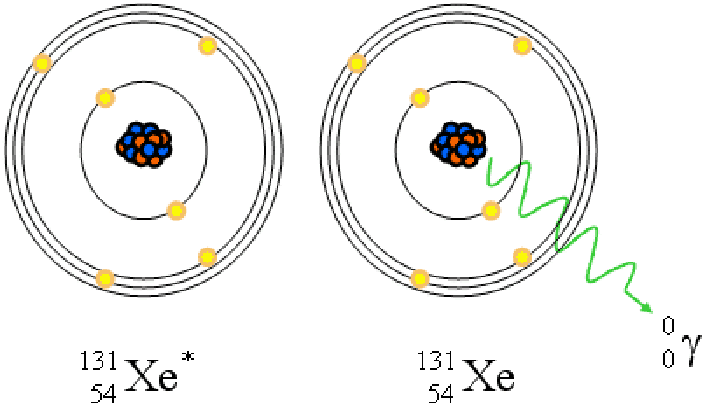


- spontaneous fission – spontaneous splitting into two smaller nuclei and some neutrons
  - Observed in heavy nuclei
  - Very long lifetimes



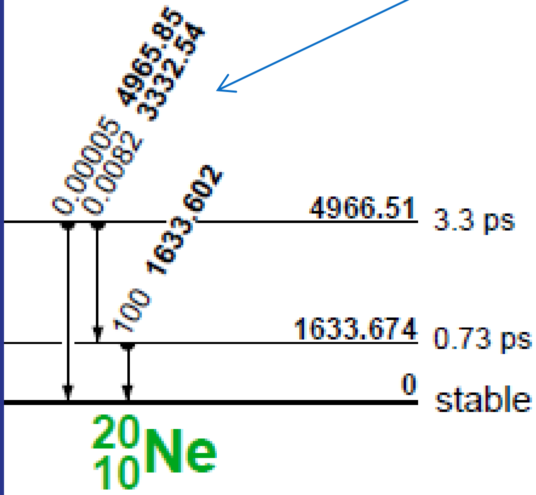
Nuclear deexcitation

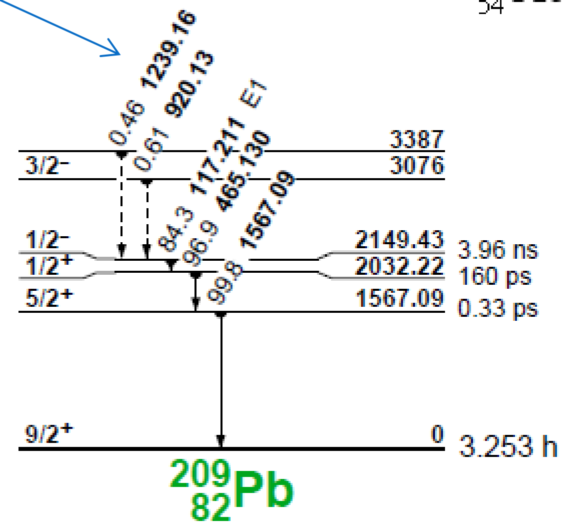
No change in Z or N, deexcitation of a nucleus:



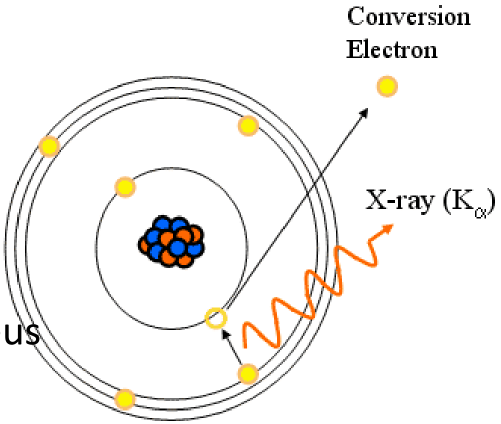
- Emission of gamma radiation:

Gamma ray relative intensities and energies (in keV)



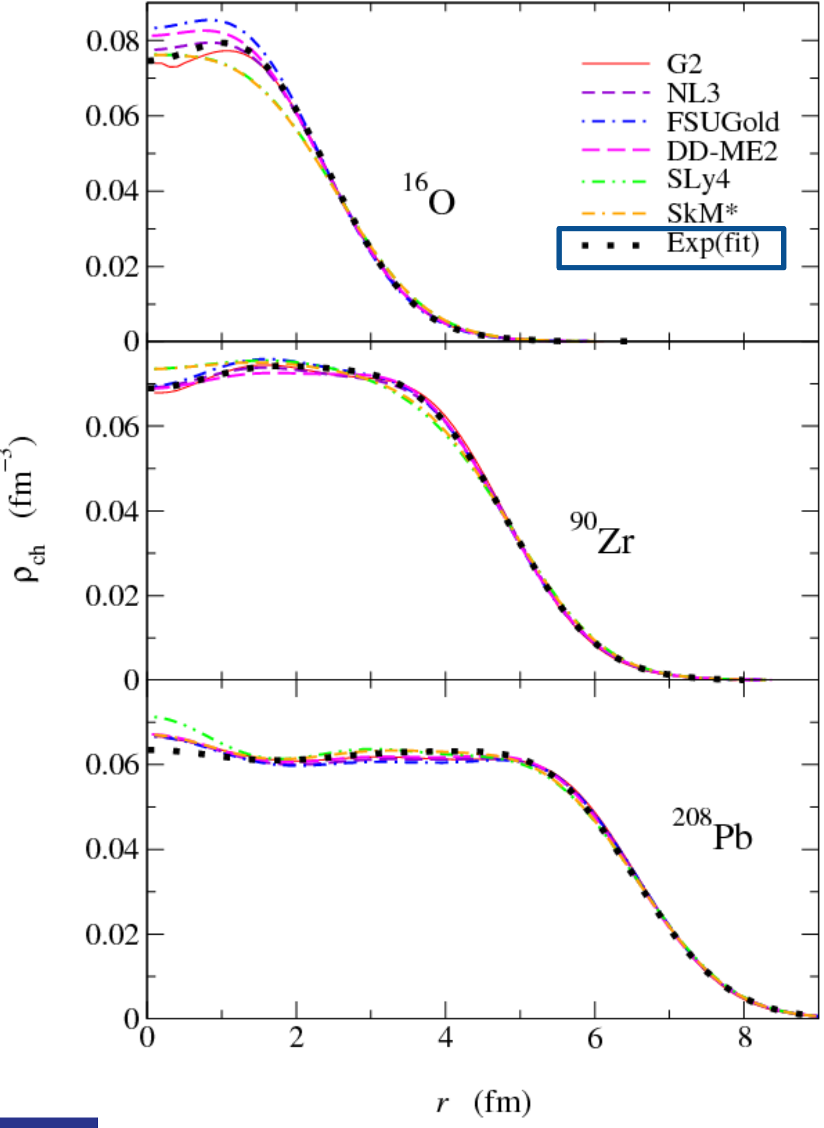


- Internal conversion:
  - Energy of deexciting nucleus causes emission of atomic nucleus

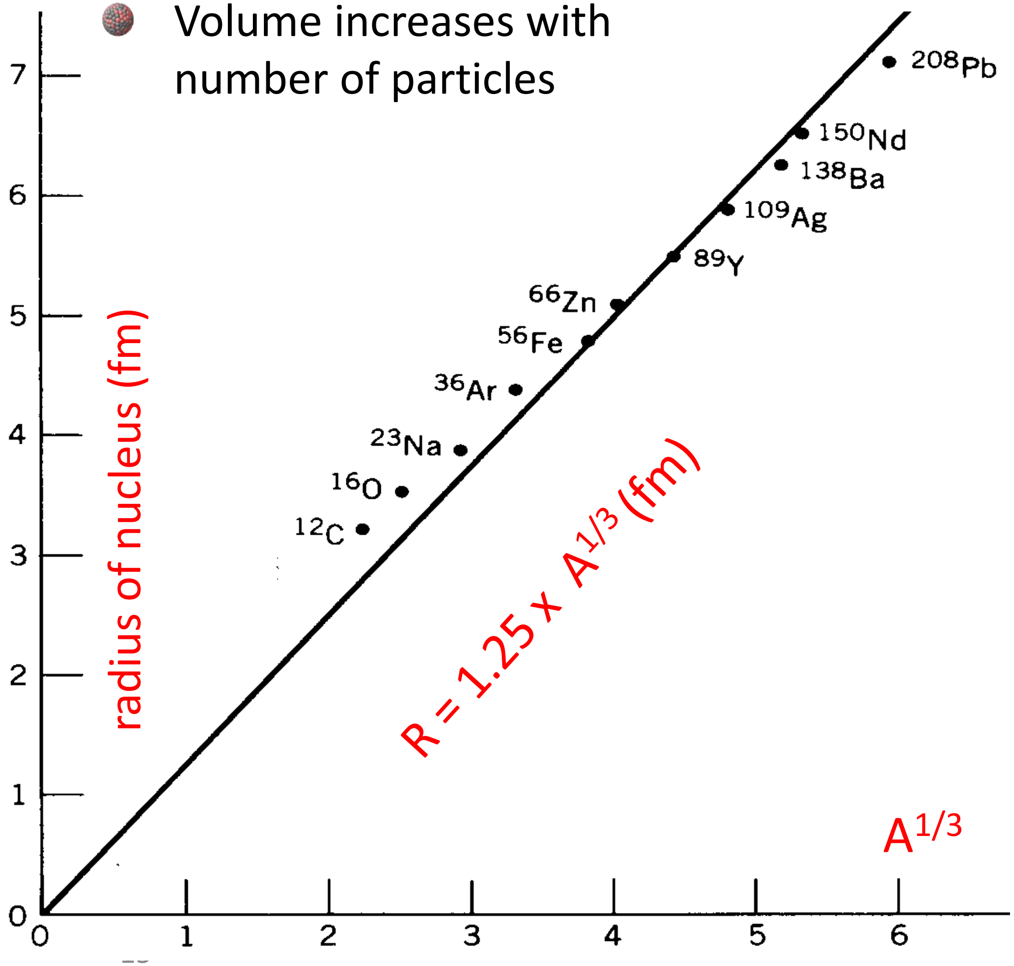


Radius

Charge distribution

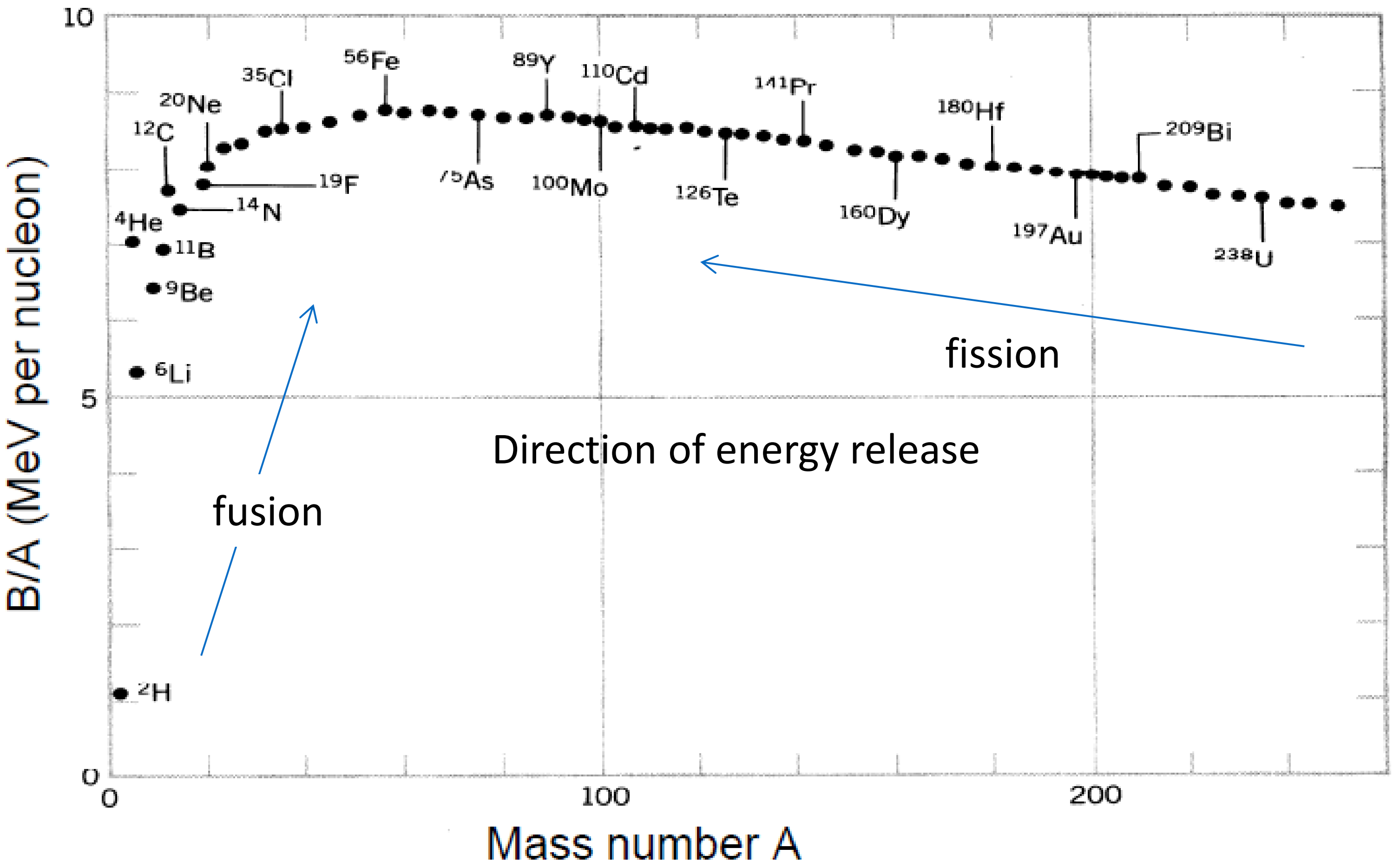


- Density of nucleons almost constant
- Radius increases with $A^{1/3}$
- Volume increases with number of particles

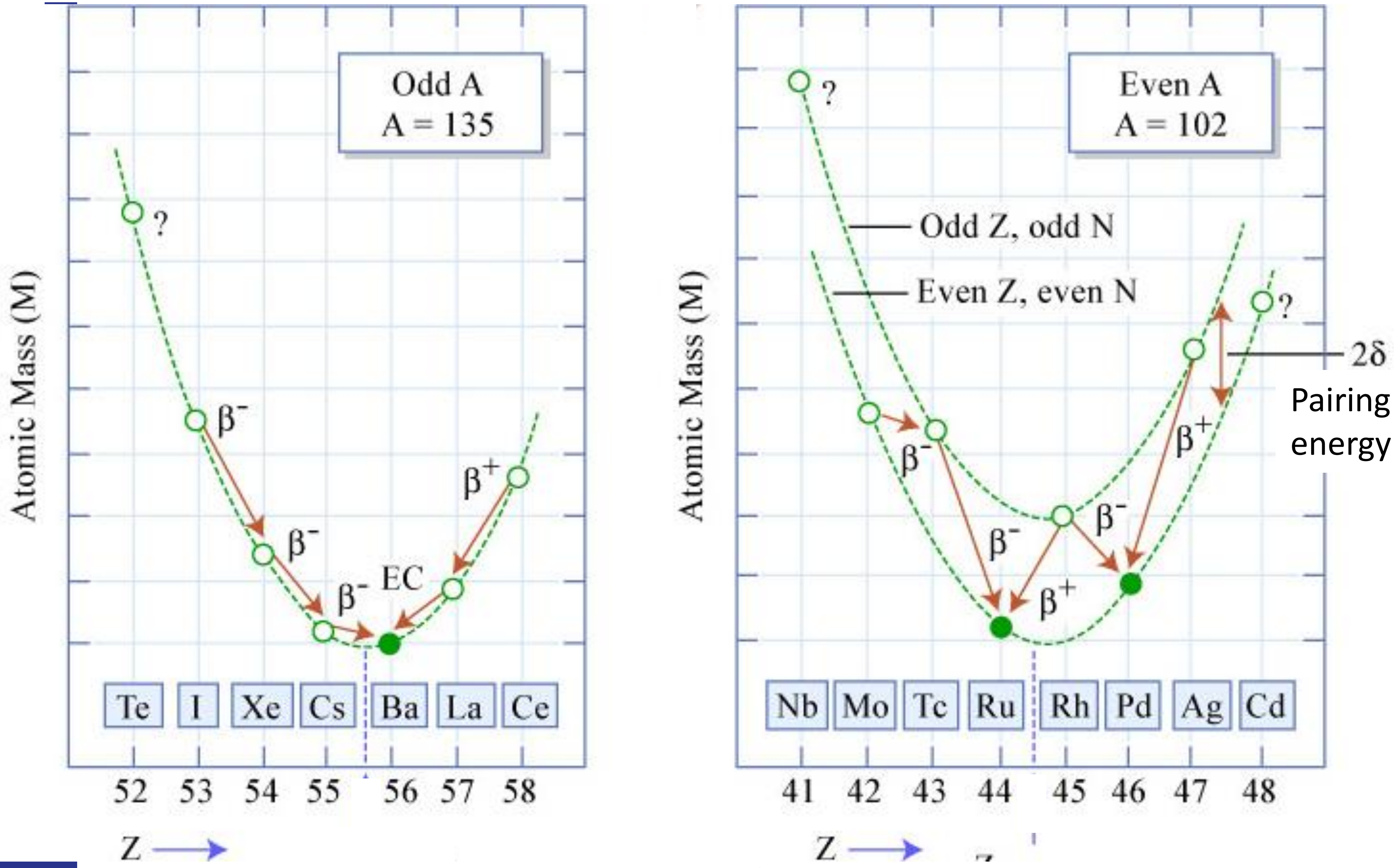


Mass and binding energy

- Nuclei are bound systems, i.e. mass of nucleus < mass of constituents
- Binding energy: $= N\,M_n + Z\,M_p - M(N,Z)$
- Binding energy/nucleon (B/A):



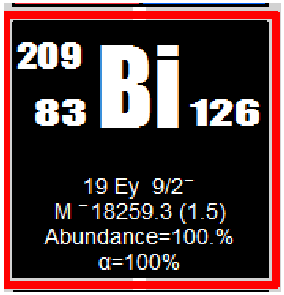
Mass parabola



Pairing energy

Lifetime

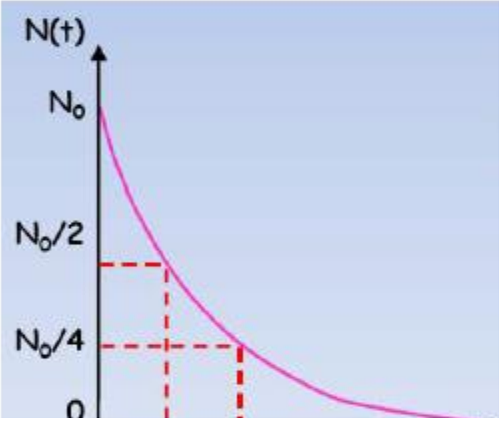
- Some nuclei are stable (i.e. their lifetimes are comparable to that of a proton and we have not seen their decay)
  - E.g. until recently 209Bi was thought to be stable
- Others are unstable – they transform into more stable nuclei
- Exponential decay: statistical process
  - Half-life = time after which half of the initial nuclei have decayed



Exa = 10^{18}

Exponential decay

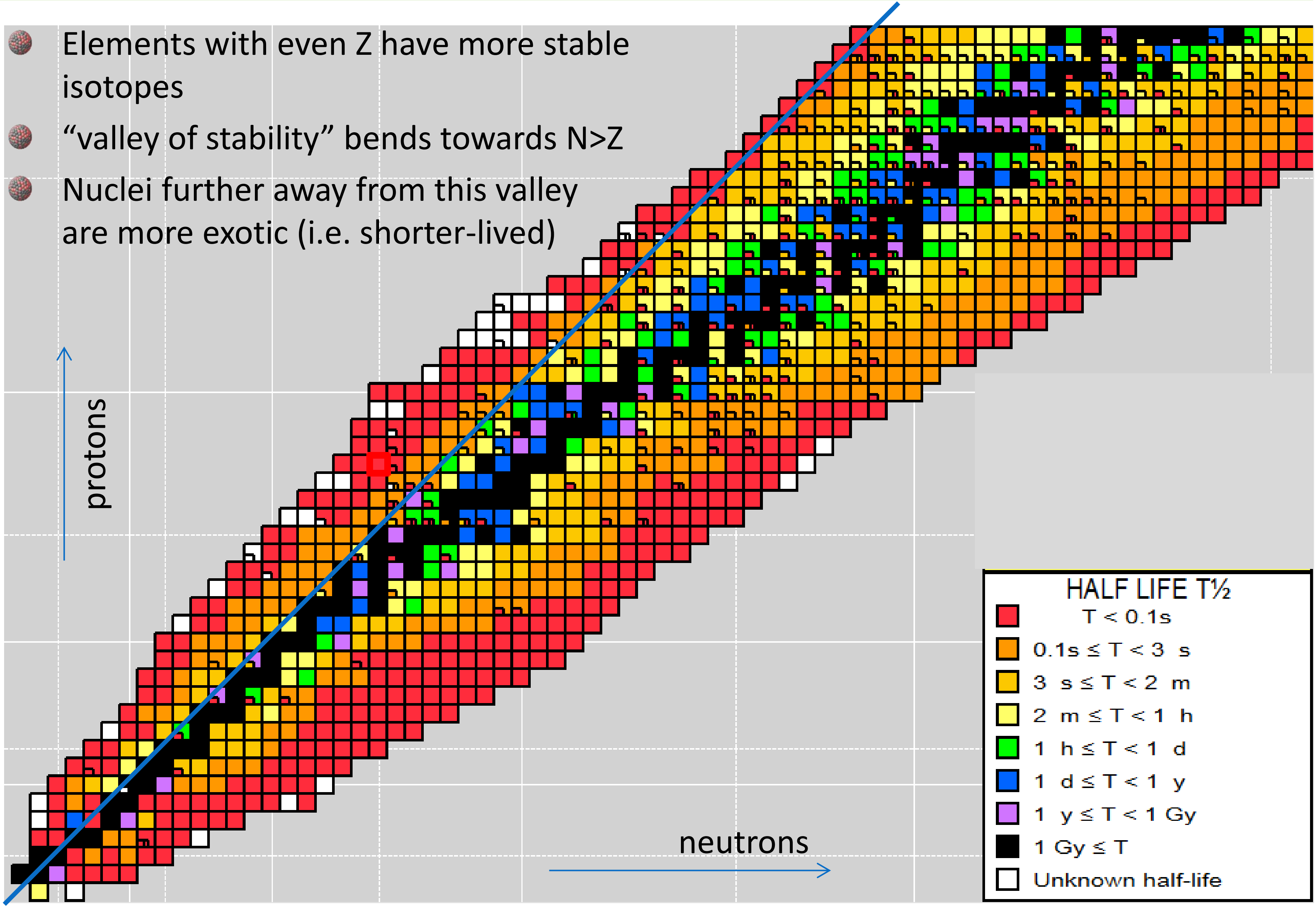
$$\frac{dN}{dt} = -\lambda N(t)$$



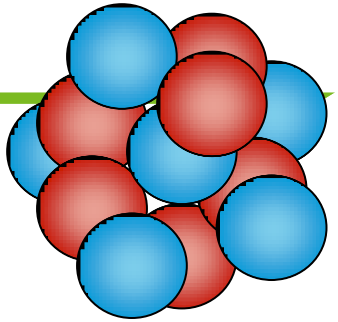
Examples of half-lives:
11Li: 9 ms
13Be: 0.5 ns
77Ge: 11h
173Lu: 74 us
208Pb: stable

Lifetime

- Elements with even Z have more stable isotopes
- “valley of stability” bends towards N>Z
- Nuclei further away from this valley are more exotic (i.e. shorter-lived)



Nuclear models



Nucleus = N nucleons in strong interaction

The many-body problem
(the behavior of each nucleon influences the others)

Can be solved exactly for N < 10

For N > 10 : approximations

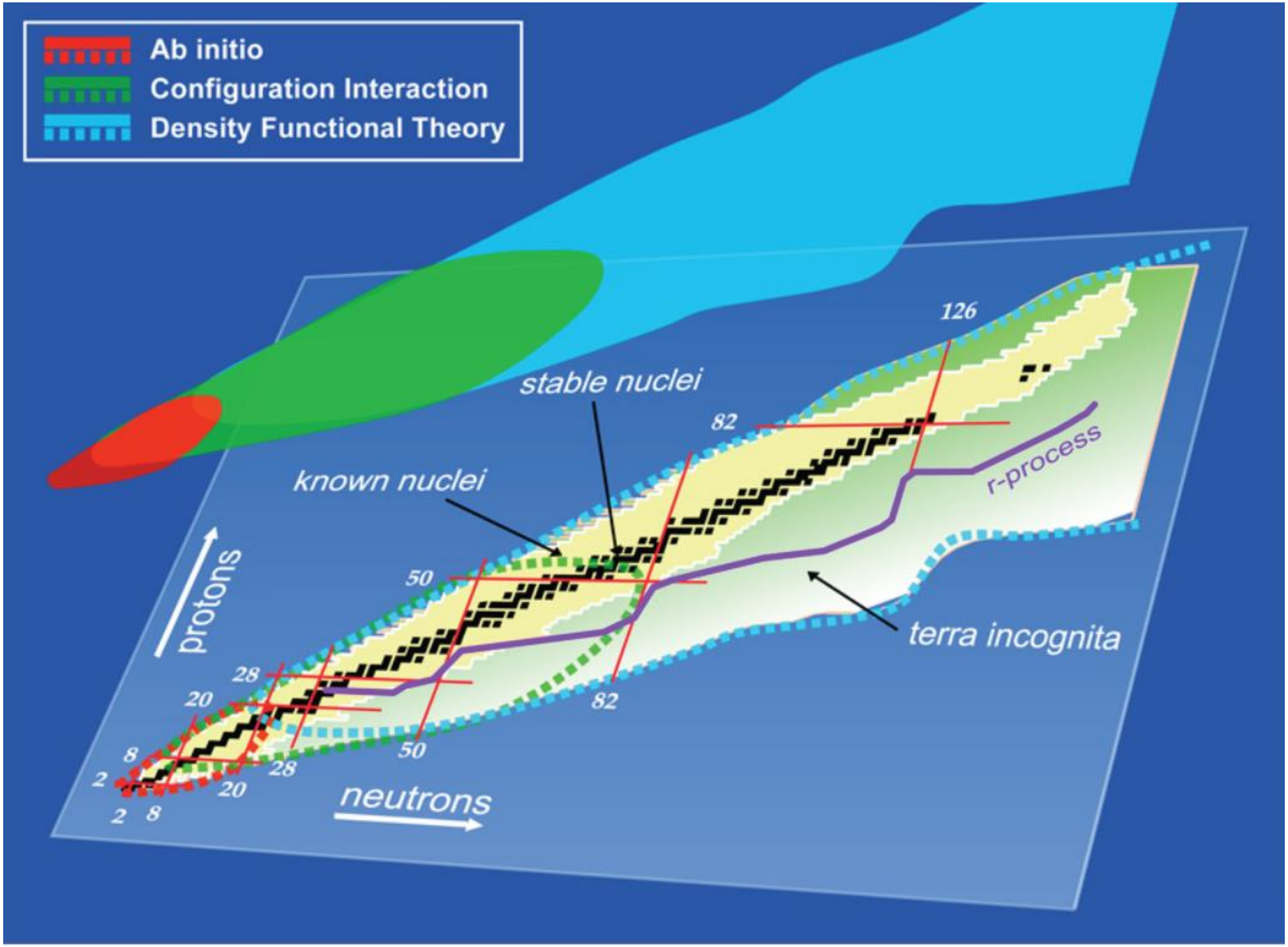
Shell model
- only a small number of particles are active

Approaches based on the mean field
- no inert core
- but not all the correlations between particles are taken into account

Nucleon-Nucleon force unknown
No complete derivation from the QCD

Different forces used depending on the method chosen to solve the many-body problem

Nuclear models

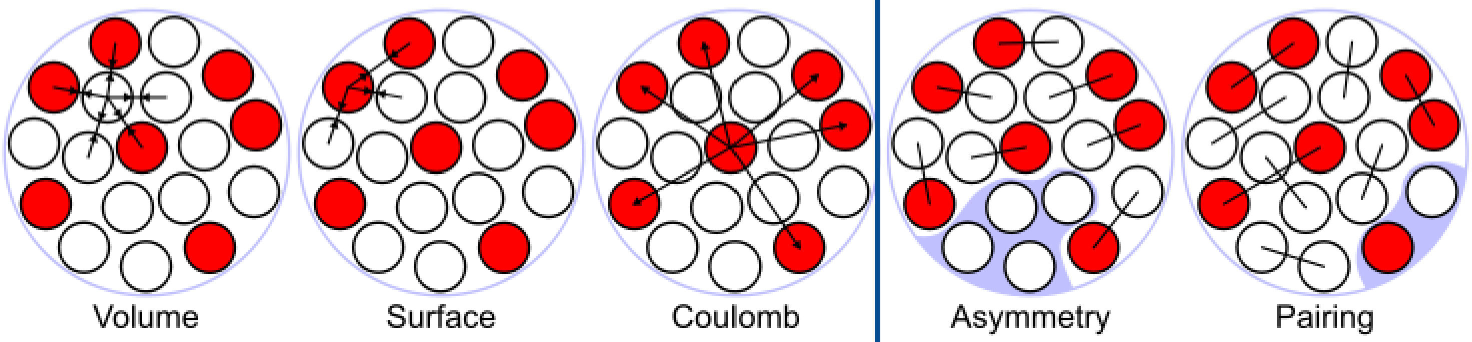


Liquid drop model

- Based on the experimental binding energy per nucleon
- Nuclei have nearly constant density => they behave like a drop of uniform (incompressible) liquid
- Forces on the nucleons on the surface are different from those inside
- Describes general features of nuclei, but not details
- .

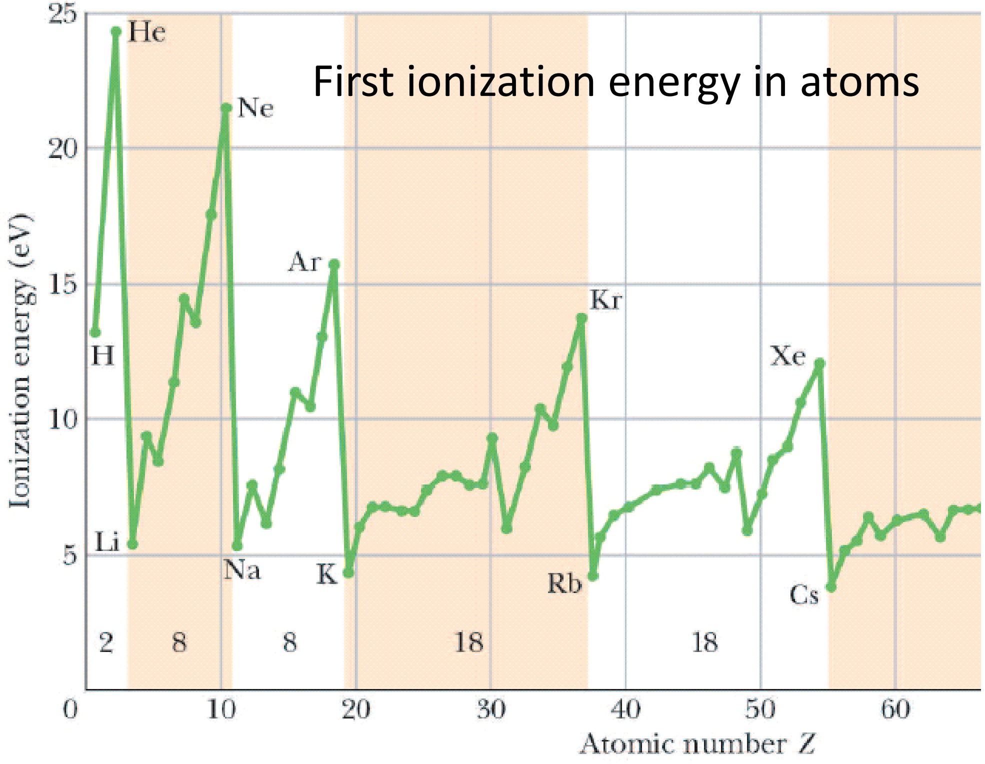
$$B(Z,A) = a_V A - a_S A^{\frac{2}{3}} - a_C \frac{Z^2}{A^{\frac{1}{3}}} - a_A \frac{(N-Z)^2}{A} + \delta(A,Z)$$

Additional terms -> shell model

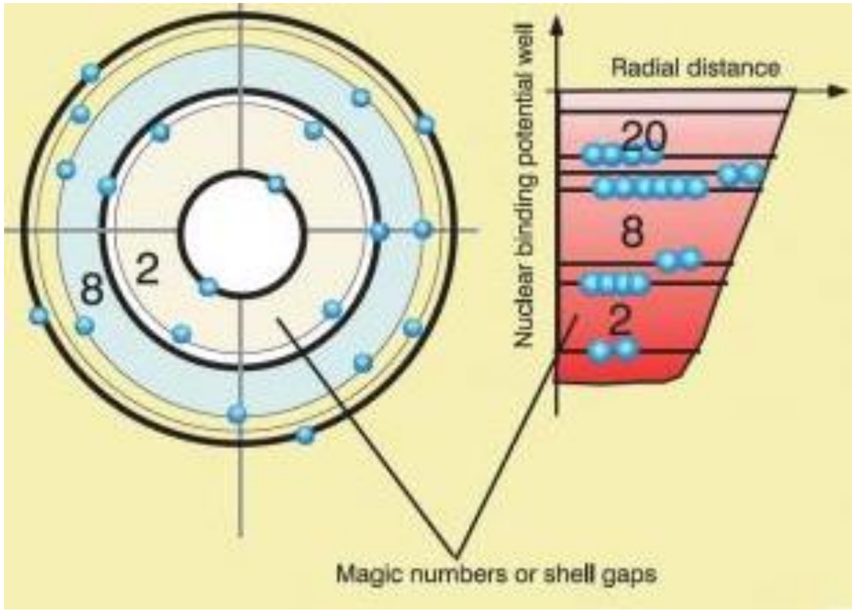


Nuclear shell model

- Created in analogy to the atomic shell model (electrons orbiting a nucleus)
- Based on the observation of higher stability of certain nuclei
  - filled shell of neutrons or protons results in greater stability
  - neutron and proton numbers corresponding to a closed shell are called ‘magic‘



First ionization energy in atoms

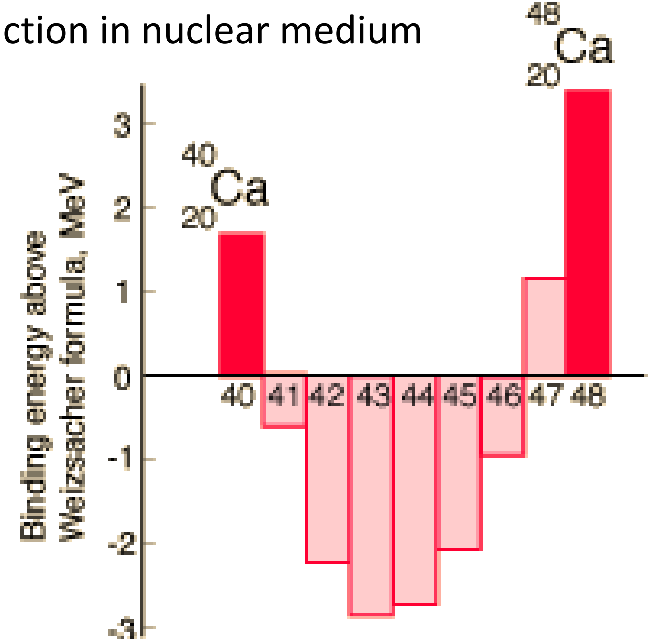


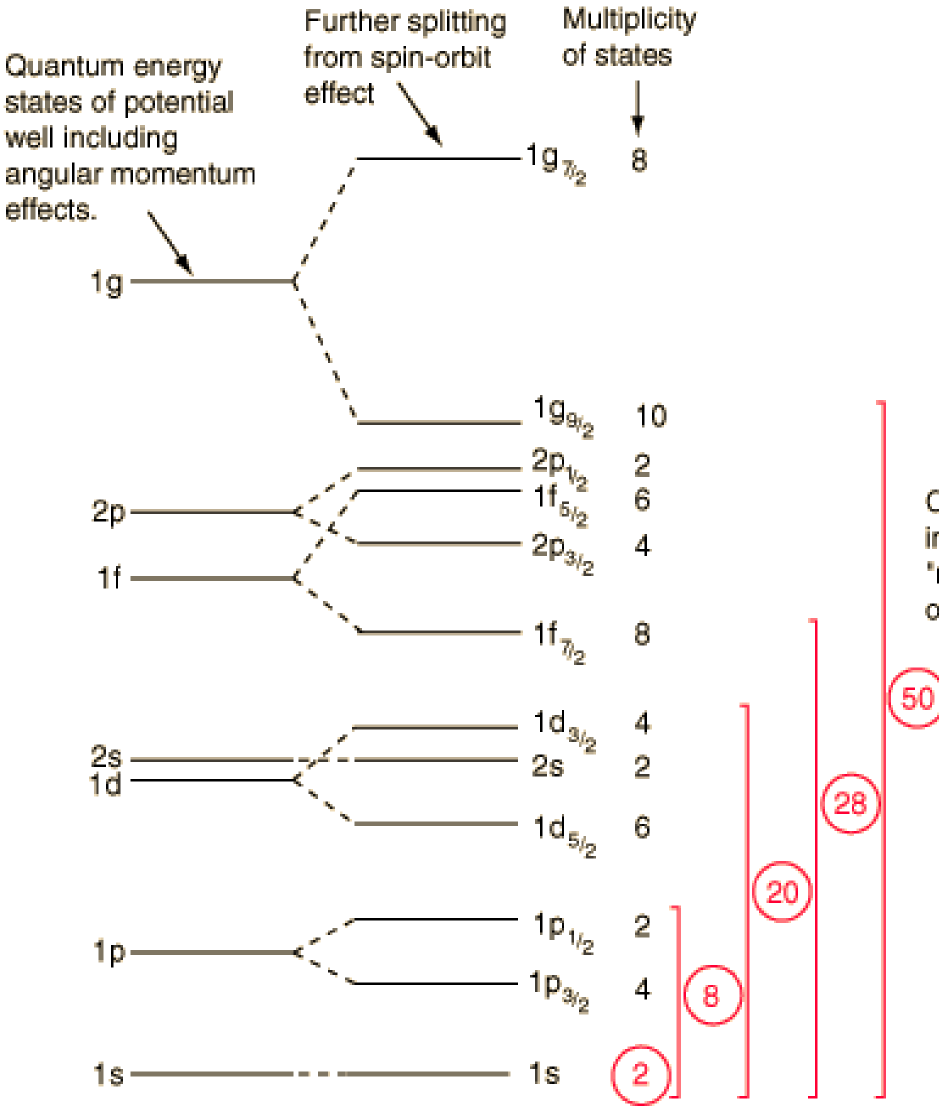
Challenge: created for stable nuclei, is it valid for radionuclides?

Nuclear shell model

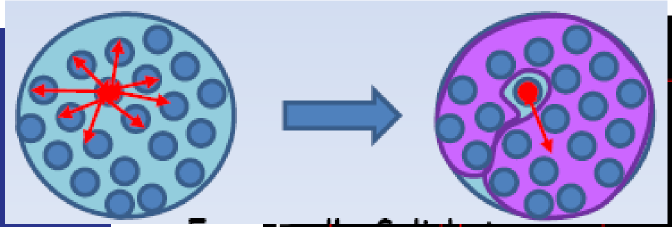
Differences to atomic shell model

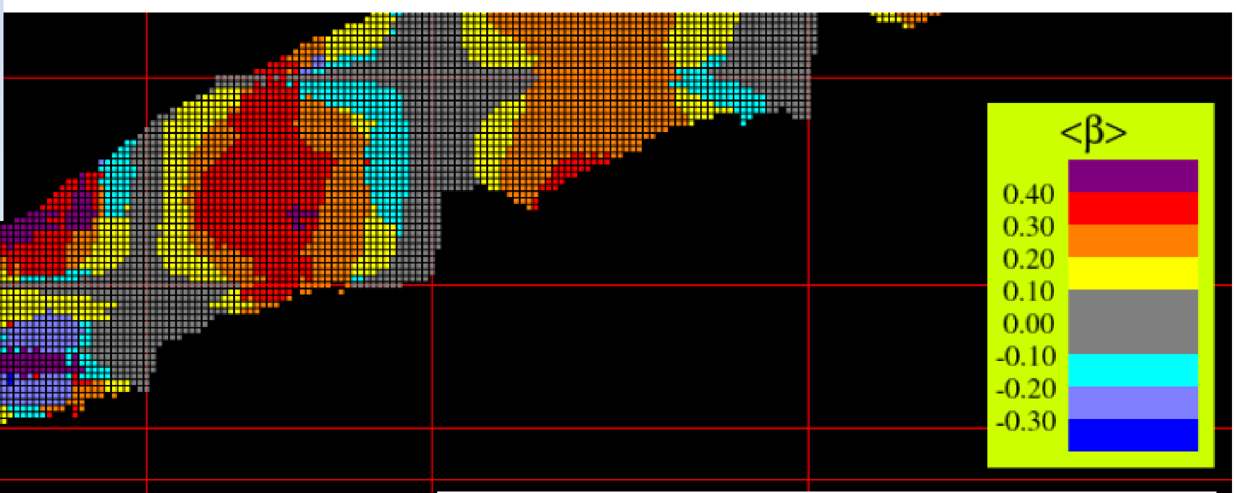
- No central potential but a self-created one
- Nucleon-nucleon interaction has tensor (non-central) components
- Two kinds of nucleons
- In ground state: all odd number of protons or neutrons couple to spin 0
- Strong spin-orbit coupling changes magic numbers: 8,20,28,50,…
- No analytic form of nucleon-nucleon interaction in nuclear medium

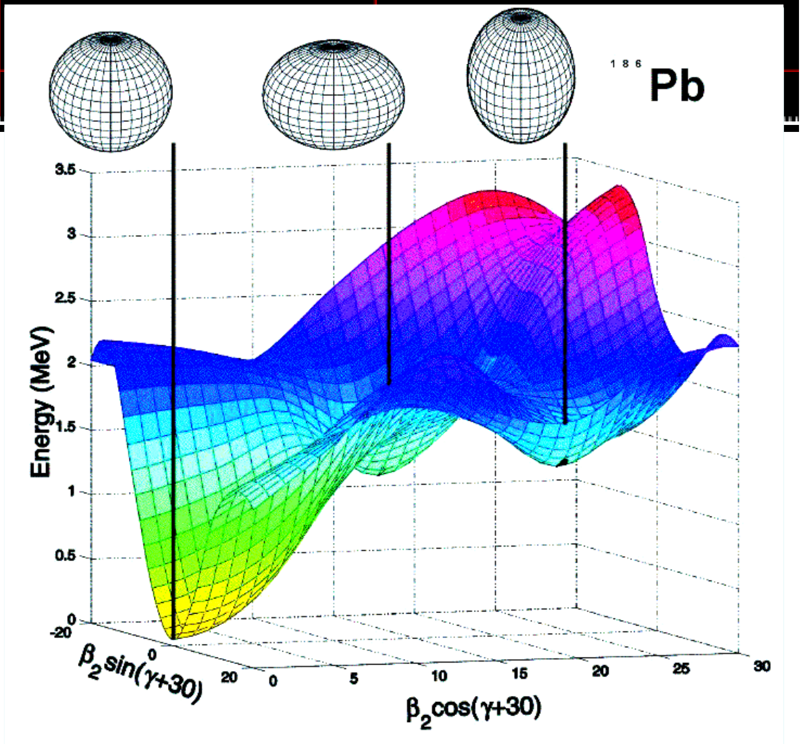




Mean-field models





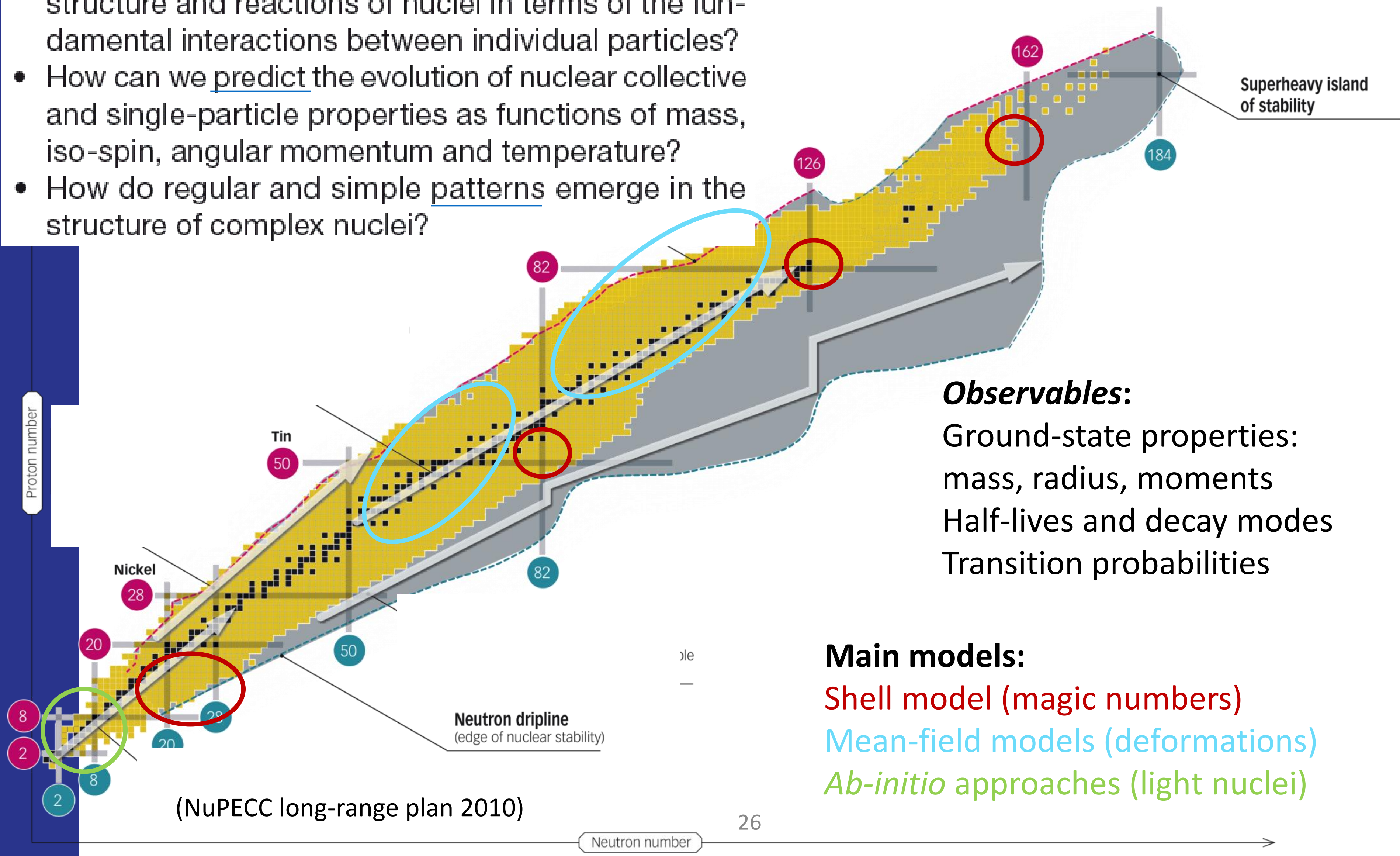


- Each particle interacts with an average field generated by all other particles: mean field
- Mean field is built from individual excitations between nucleons
- No inert core
- Very good at describing deformations
- Can predict properties of very exotic nuclei
- Not so good at closed shells

Open questions in nuclear physics

- How can we describe the rich variety of low-energy structure and reactions of nuclei in terms of the fundamental interactions between individual particles?
- How can we predict the evolution of nuclear collective and single-particle properties as functions of mass, iso-spin, angular momentum and temperature?
- How do regular and simple patterns emerge in the structure of complex nuclei?

2 kinds of interacting fermions



Observables:
Ground-state properties:
mass, radius, moments
Half-lives and decay modes
Transition probabilities

Main models:
Shell model (magic numbers)
Mean-field models (deformations)
Ab-initio approaches (light nuclei)

(NuPECC long-range plan 2010)

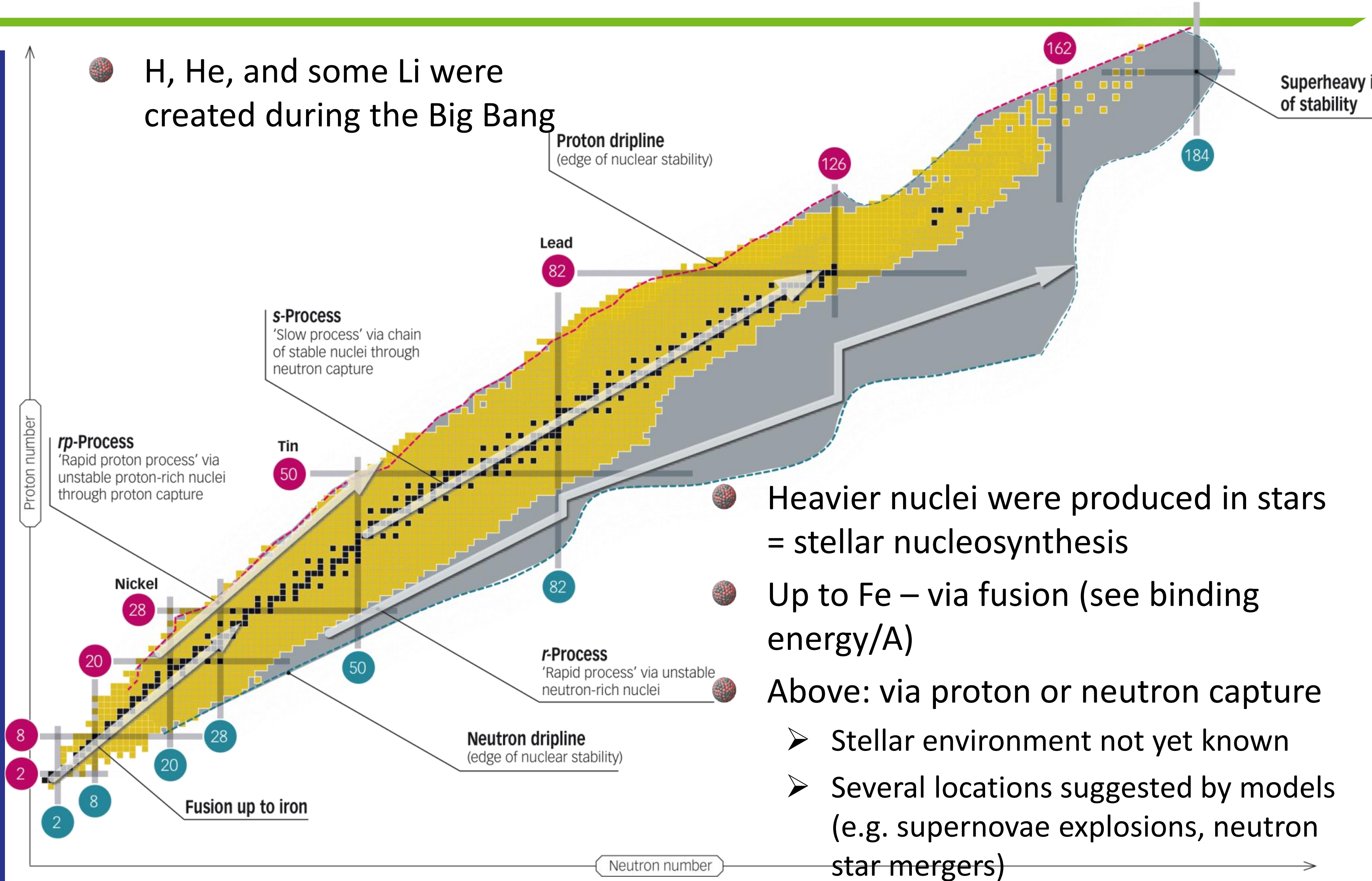
Summary

- Nuclear physics investigates the properties of nuclei and of the underlying nucleon-nucleon interaction
- Rich history and many nuclei discovered
- All 4 fundamental interactions at play
  - details of strong interaction are not known
- Nuclear landscape – over 3000 known nuclei and even more predicted
- Nuclear decays transform one nucleus into another
- Nuclear properties – reveal features of nuclear interaction
- Nuclear models
  - Each is better in one respect and worse in another
  - Aim: describe known properties and predict new ones
- Open questions in nuclear physics
  - How to describe various properties in with a fundamental interaction
  - How to make predictions
  - How do regular patterns emerge

- We are getting closer to the answers with radioactive ion beam facilities, such as ISOLDE -> Lecture 2 and 3

Creation of nuclides

- H, He, and some Li were created during the Big Bang

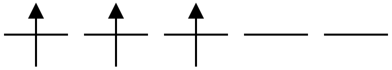
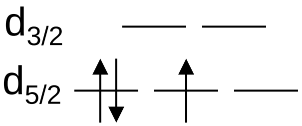


- Heavier nuclei were produced in stars = stellar nucleosynthesis
- Up to Fe – via fusion (see binding energy/A)
- Above: via proton or neutron capture
  - Stellar environment not yet known
  - Several locations suggested by models (e.g. supernovae explosions, neutron star mergers)
  - Need nuclear physics data to constrain models

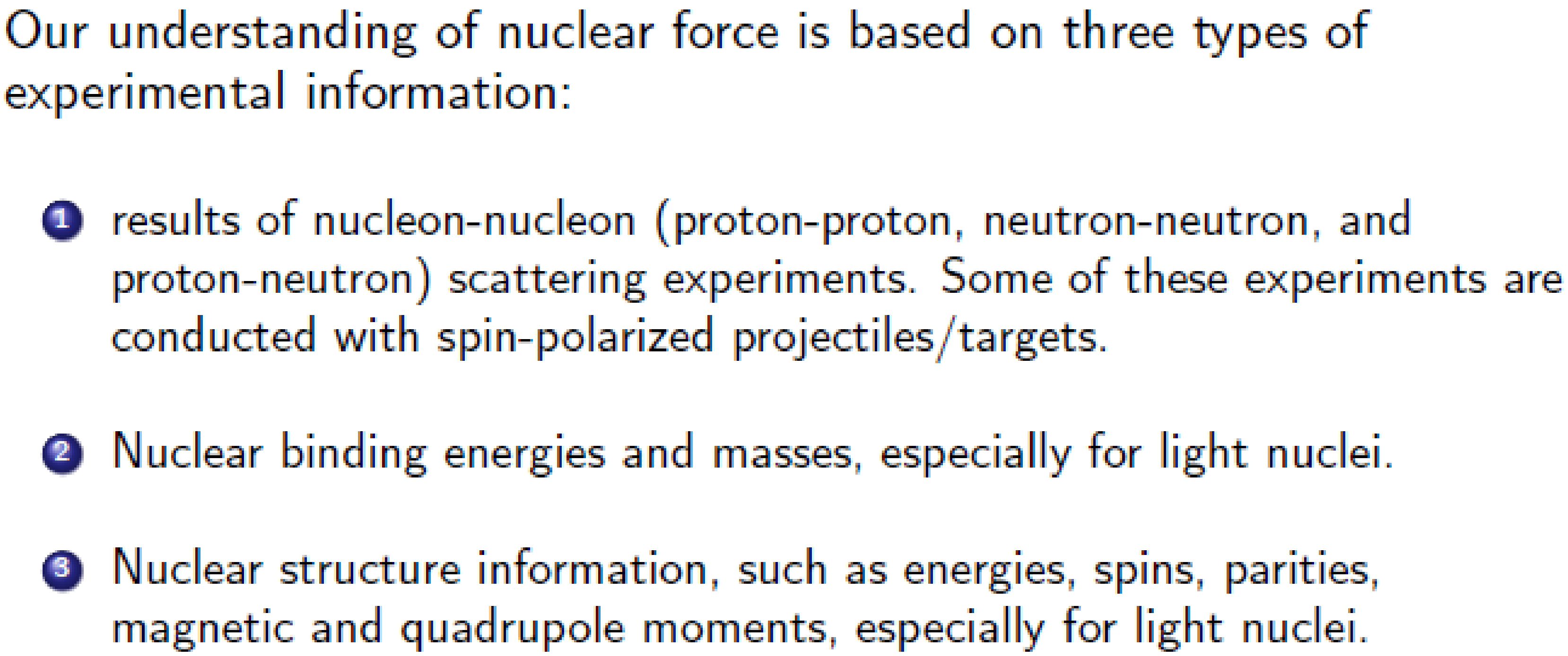
Binding energy

- Binding energy = mechanical energy required to disassemble a whole into separate parts
- Bound system = interaction energy is less than the total energy of each separate particle
    - Energy is needed to separate the constituents
    - Mass of constituents = mass of bound system + binding energy (positive)
- Atoms:
    - Mass of electrons + mass of nucleus > mass of the atom
- Nuclei:
    - Mass of protons + mass of neutrons > mass of the nucleus
    - E.g for 12C: 11.18 GeV > 11.27 GeV (difference of 90 MeV = binding energy)
- Nucleons:
    - It looks like mass of quarks < mass of nucleon (ca 10MeV < 1GeV)
    - But quarks don’t exist as separate particles, thus 10MeV is a rest mass of quarks inside a nucleon. It would take an enormous energy to isolate quarks, so as separate particles they would be much heavier, so:
    - mass of constituents > mass of nucleon

Atomic vs nuclear structure

Atoms		Nuclei
shell model: e^- fill quantized energy levels	**Description**	shell model (but not only): p and n separately fill quantized energy levels
n, l, m_ℓ, s, parity $(-1)^\ell$	**Quantum numbers**	n, l, m_ℓ, s, parity $(-1)^\ell$
max. S possible (due to Coulomb force): $J= L+S= \Sigma l_i + \Sigma s_i$ or $J= \Sigma j_i = \Sigma(l_i + s_i)$	**Lowest en. levels**	min. S possible (due to strong force pairing): $J = \Sigma j_i = \Sigma(l_i + s_i)$
weak	**Spin-orbit coupling**	strong
for 3 electrons in a d orbital 		for 3 nucleons in a d orbital 
calculated by solving Schrödinger equation with central potential dominated by nuclear Coulomb field	**Energy levels**	not easily calculated; nucleons move and interact within a self-created potential

Nuclear force and experiments



Our understanding of nuclear force is based on three types of experimental information:

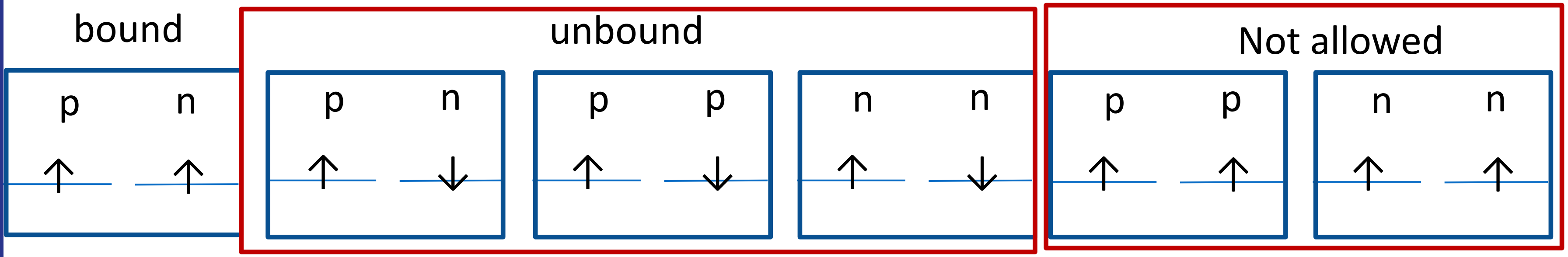
1. results of nucleon-nucleon (proton-proton, neutron-neutron, and proton-neutron) scattering experiments. Some of these experiments are conducted with spin-polarized projectiles/targets.
2. Nuclear binding energies and masses, especially for light nuclei.
3. Nuclear structure information, such as energies, spins, parities, magnetic and quadrupole moments, especially for light nuclei.

After http://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/LECTURE/Fraser/L5.pdf

Does di-neutron exist?

If nuclear force is charge independent, why does system with 1n and 1p exist (deuteron), but that with 2n and 2p, etc don't? And what binds neutrons in neutron stars?

- Nuclear force is charge independent, but it depends on the spin, i.e.
  - Spin-up to spin-up (↑ ↑) interaction of 2 protons is the same as for 2 neutrons
  - But ↑↓ interaction of 2p is different than ↑ ↑ for 2p or 2n
- And there is Pauli principle
- As a result => A system of n and p can form either a singlet or triplet state. The triplet state is bound, but not the singlet (we know it from deuteron). A system of 2n or 2p can only form a singlet (due to Pauli principle), so no bound state of 2p or 2n, etc, exists.



bound

p ↑ n ↑

unbound

p ↑ n ↓

p ↑ p ↓

n ↑ n ↓

Not allowed

p ↑ p ↑

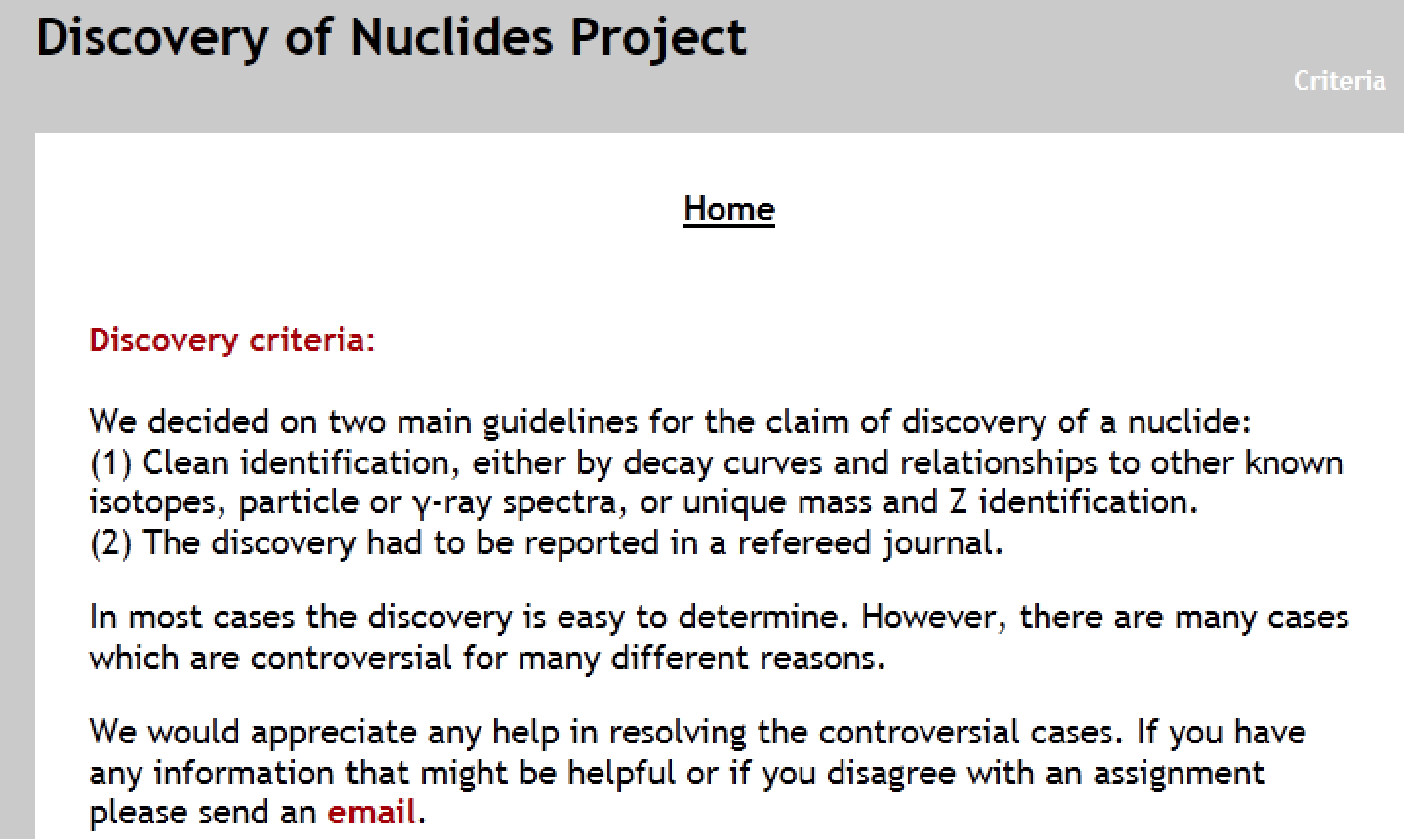
n ↑ n ↑

- Neutron stars exist thanks to gravity

See more details in http://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/LECTURE/Fraser/L5.pdf

Discovery of nuclei

- Discovery Project at MSU – documenting discoveries of nuclei



Discovery of Nuclides Project

Home

Discovery criteria:

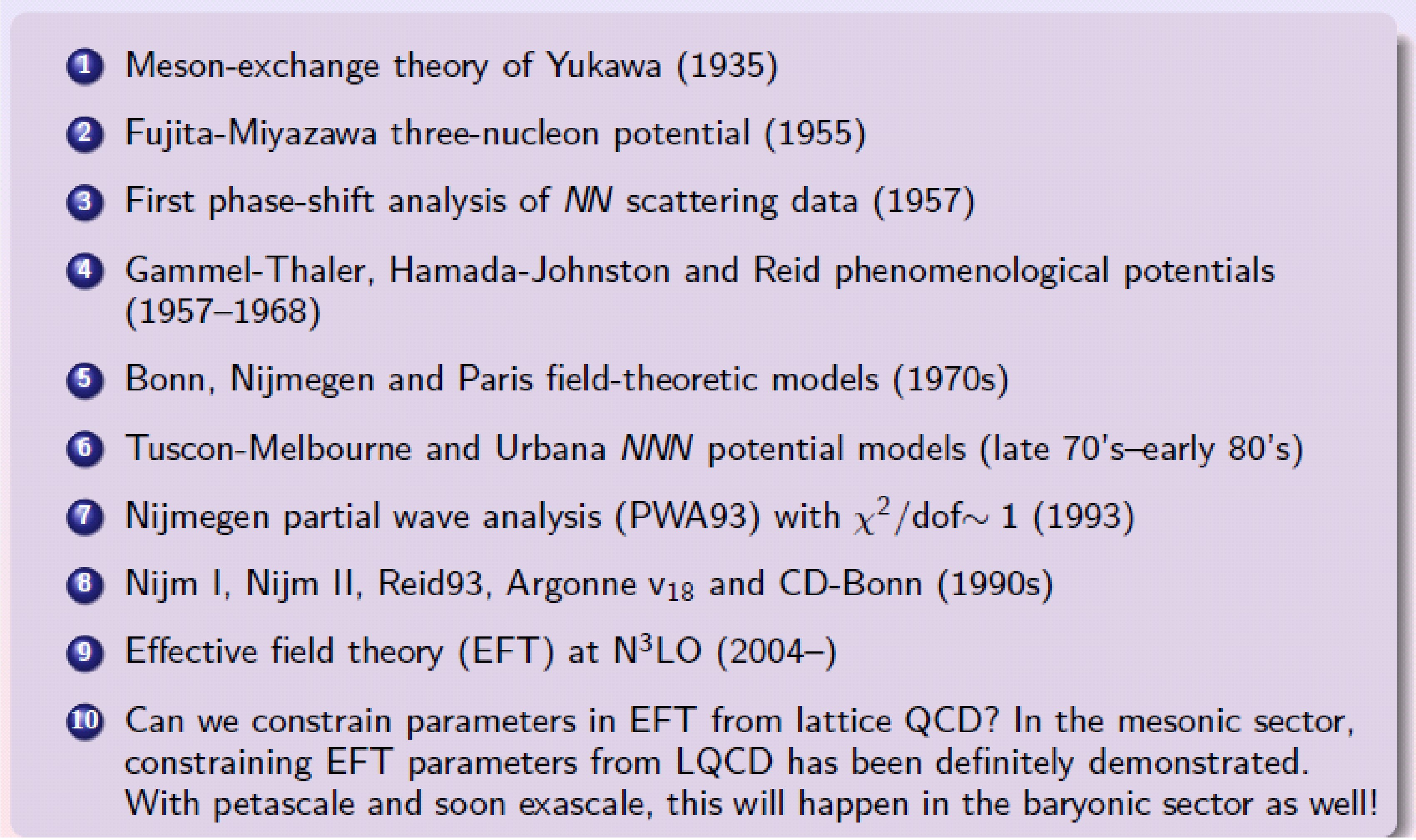
We decided on two main guidelines for the claim of discovery of a nuclide:
(1) Clean identification, either by decay curves and relationships to other known isotopes, particle or γ-ray spectra, or unique mass and Z identification.
(2) The discovery had to be reported in a refereed journal.

In most cases the discovery is easy to determine. However, there are many cases which are controversial for many different reasons.

We would appreciate any help in resolving the controversial cases. If you have any information that might be helpful or if you disagree with an assignment please send an email.

http://www.nscl.msu.edu/~thoennes/isotopes/criteria.html

Modelling nuclear interaction



① Meson-exchange theory of Yukawa (1935)

② Fujita-Miyazawa three-nucleon potential (1955)

③ First phase-shift analysis of *NN* scattering data (1957)

④ Gammel-Thaler, Hamada-Johnston and Reid phenomenological potentials (1957–1968)

⑤ Bonn, Nijmegen and Paris field-theoretic models (1970s)

⑥ Tuscon-Melbourne and Urbana *NNN* potential models (late 70's–early 80's)

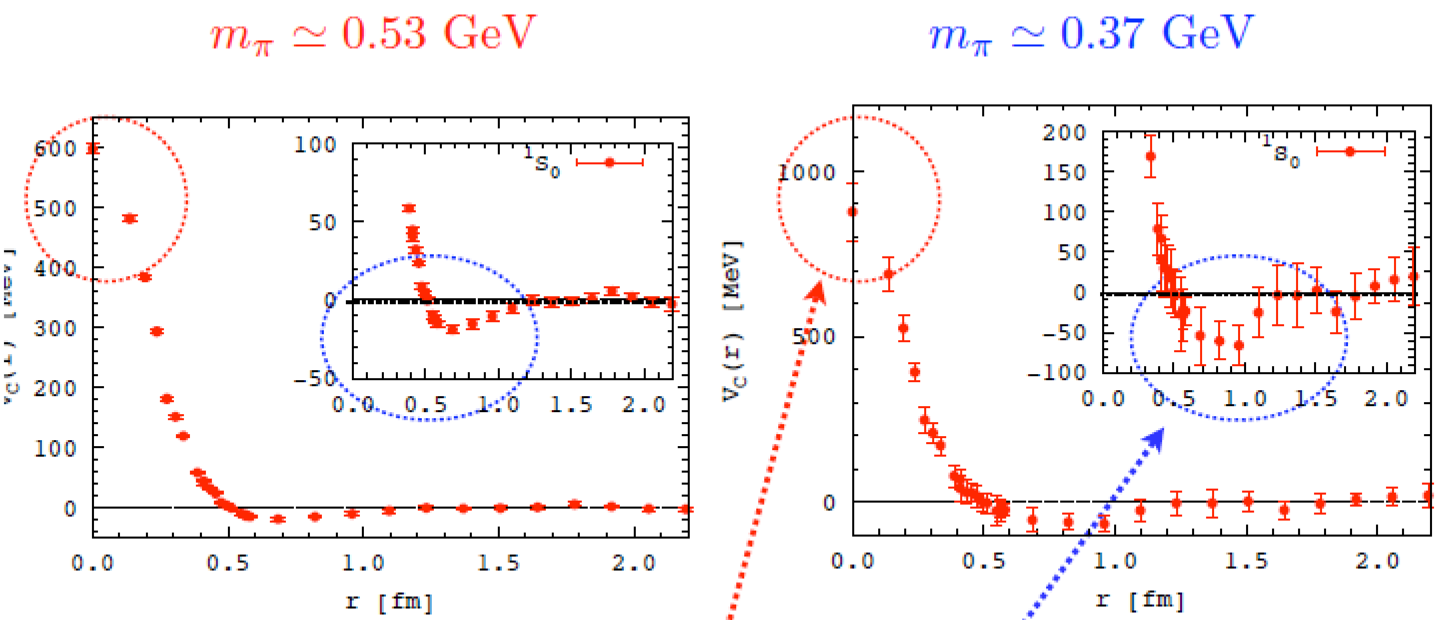
⑦ Nijmegen partial wave analysis (PWA93) with $\chi^2/\text{dof} \sim 1$ (1993)

⑧ Nijm I, Nijm II, Reid93, Argonne v_{18} and CD-Bonn (1990s)

⑨ Effective field theory (EFT) at N^3LO (2004–)

⑩ Can we constrain parameters in EFT from lattice QCD? In the mesonic sector, constraining EFT parameters from LQCD has been definitely demonstrated. With petascale and soon exascale, this will happen in the baryonic sector as well!

NN potential from QCD



$m_\pi \simeq 0.53$ GeV

$m_\pi \simeq 0.37$ GeV

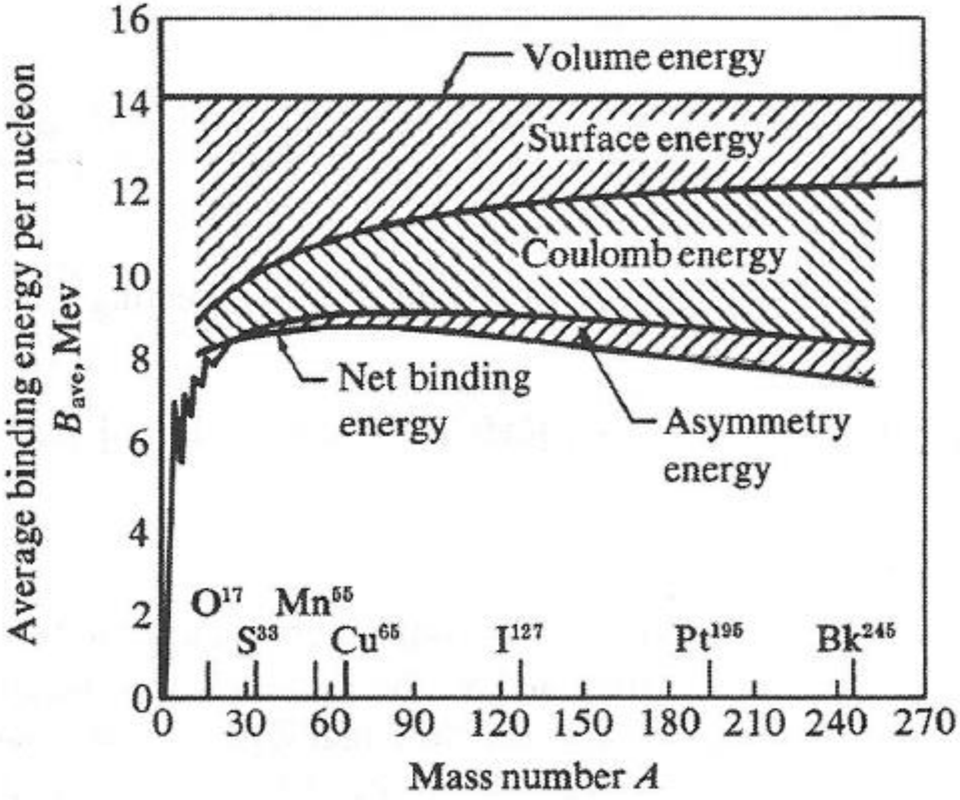
- stronger repulsive core at short distance.

- a little stronger attraction at intermediate distance.

$m_\pi \simeq 0.13$ GeV ?

Aoki, Ishii, Matsuda

Liquid drop model



- The volume term coefficient $a_V = 15.56$ MeV.
- The surface term coefficient $a_S = 17.23$ MeV.
- The Coulomb term coefficient $a_C = 0.7$ MeV.
- The asymmetry term coefficient $a_V = 23.285$ M
- The pairing term

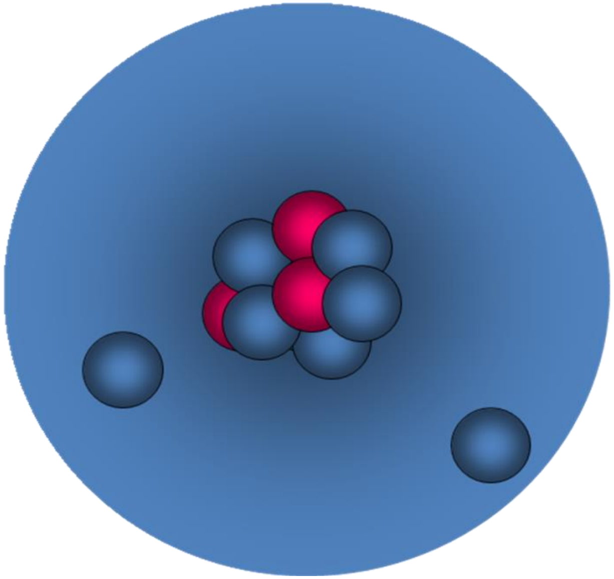
$$\delta = \begin{cases} -\frac{11}{\sqrt{A}}\ [\mathrm{MeV}] & \text{even-even nuclei} \\ 0\ [\mathrm{MeV}] & \text{odd-even nuclei} \\ +\frac{11}{\sqrt{A}}\ [\mathrm{MeV}] & \text{odd-odd nuclei} \end{cases}$$

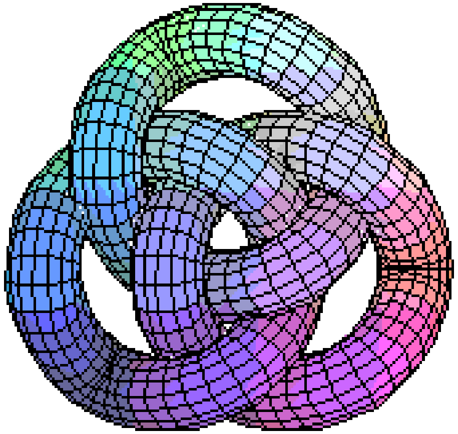
Properties of radio-nuclides

- Different neutron-to-proton ratio than stable nuclei leads to:
  - New structure properties
  - New decay modes

=> Nuclear models have problems predicting and even explaining the observations

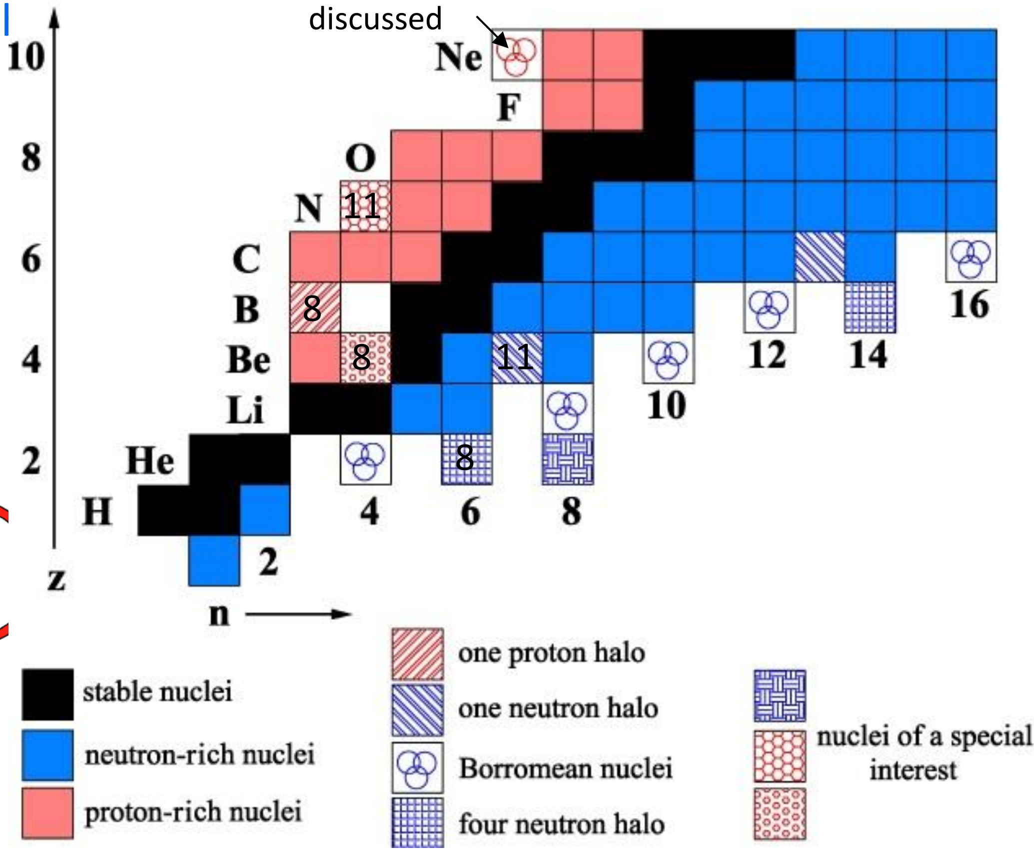
- Example - halo nucleus ^{11}Li:
  - Extended neutron wave functions make ^{11}Li the size of ^{208}Pb
  - When taking away 1 neutron, the other is not bound any more (10Li is not bound)





Halo nuclei

Halo: nucleus built from a core and at least one neutron/proton with spatial distribution much larger tl

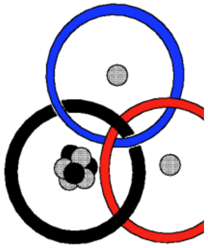


1985: first halo system identified: ^{11}Li
2013: half-dozen other halos known

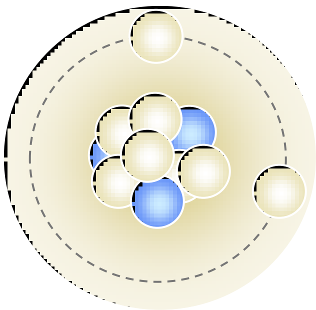
Nuclear structure and core-halo interaction still **not well understood**

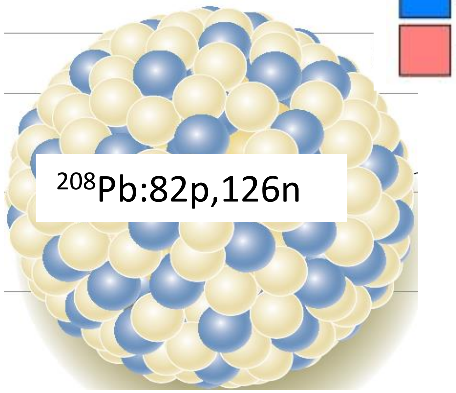
=> Crucial information:

Mass/binding energy
Spin-parity
Magnetic moment
Mass and charge radius
Quadrupole moment
Energy level scheme



^{11}Li:3p,8n





^{208}Pb:82p,126n

Recent achievements: charge radii of ^{11}Li (Uni Mainz/GSI), ^{6}He (Argonne)

Examples of nuclear decays