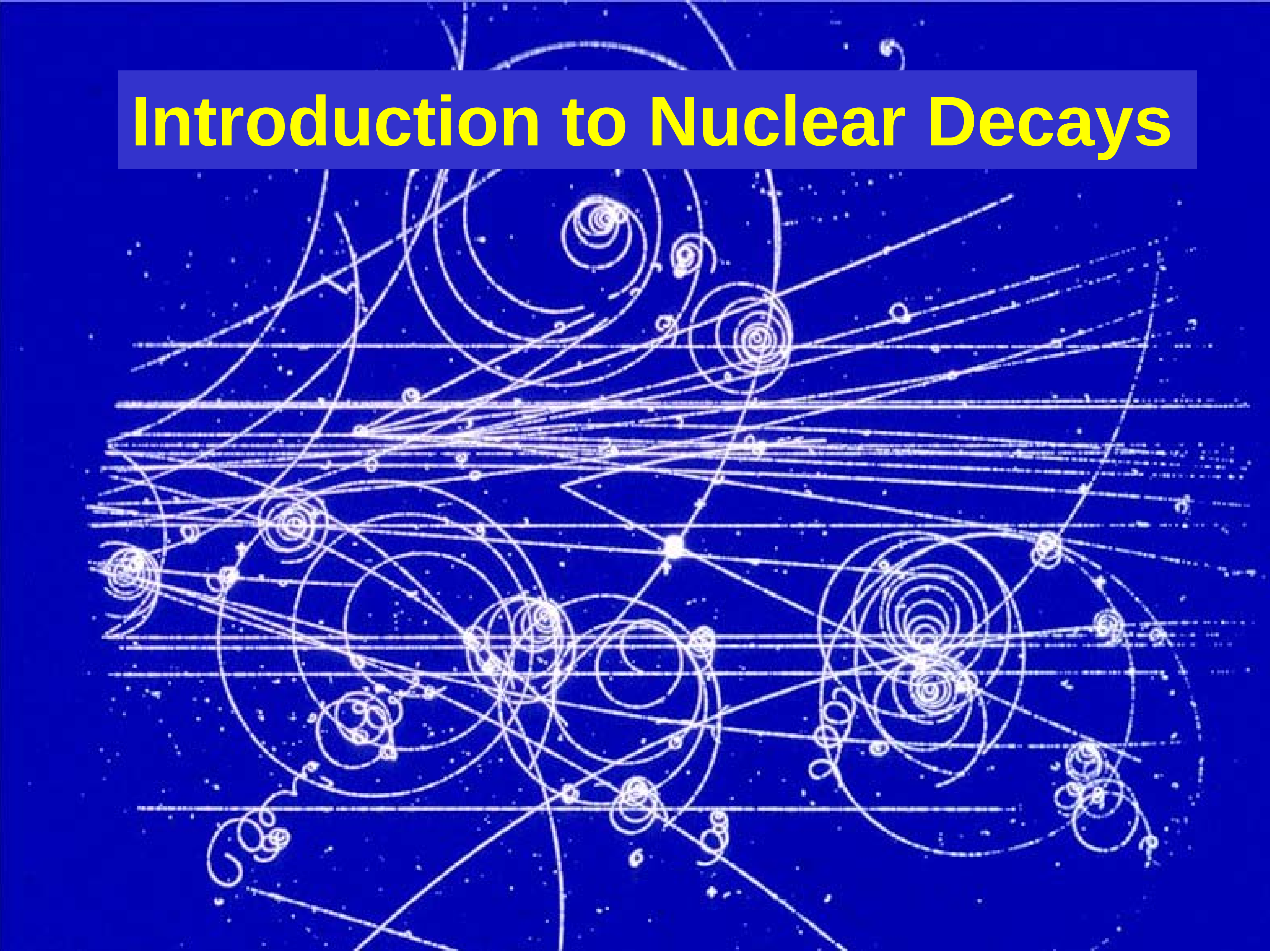
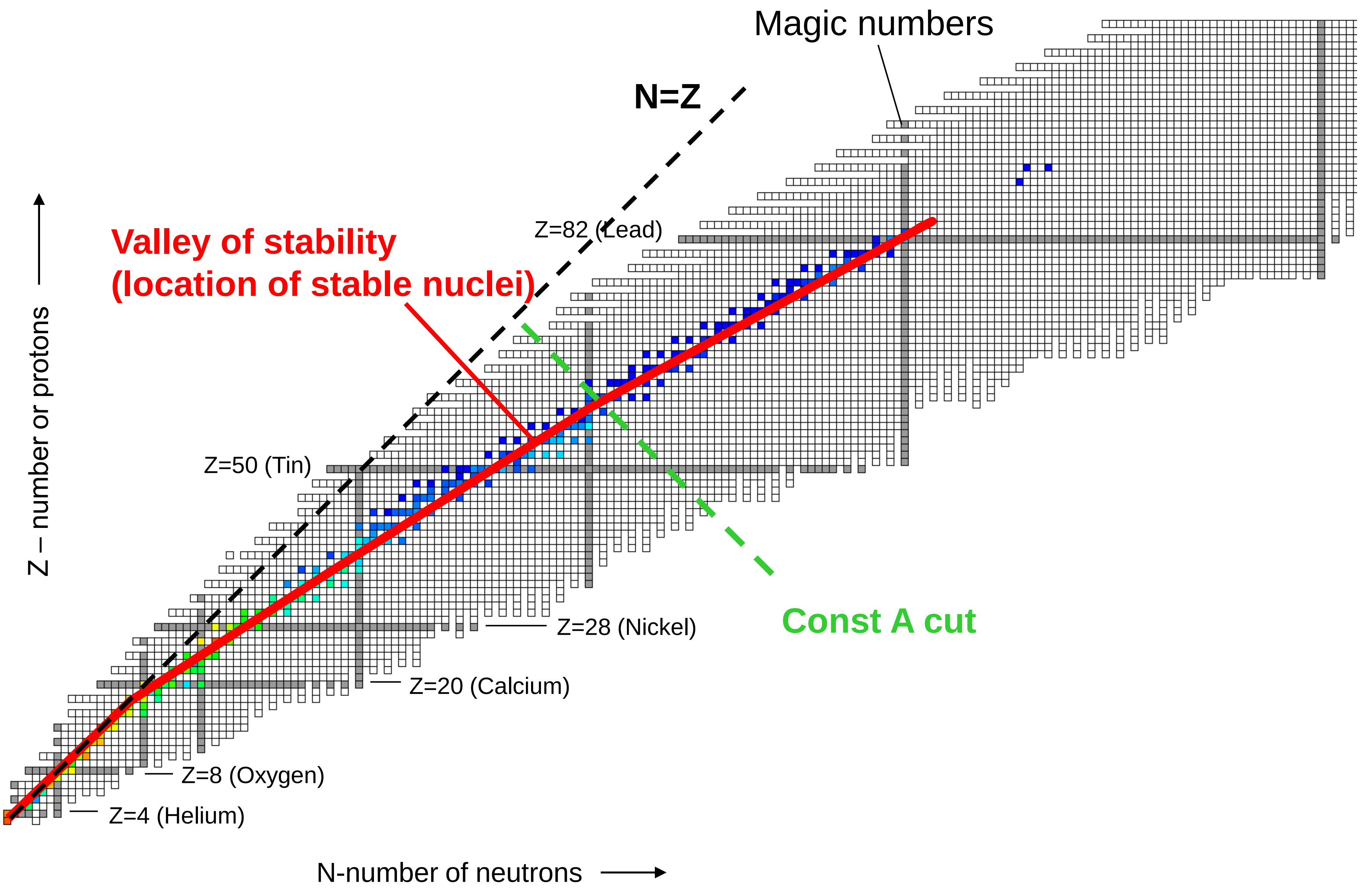
Introduction to Nuclear Decays



The valley of stability



Const. A cut:

Binding energy per nucleon along const A due to asymmetry term in mass formula

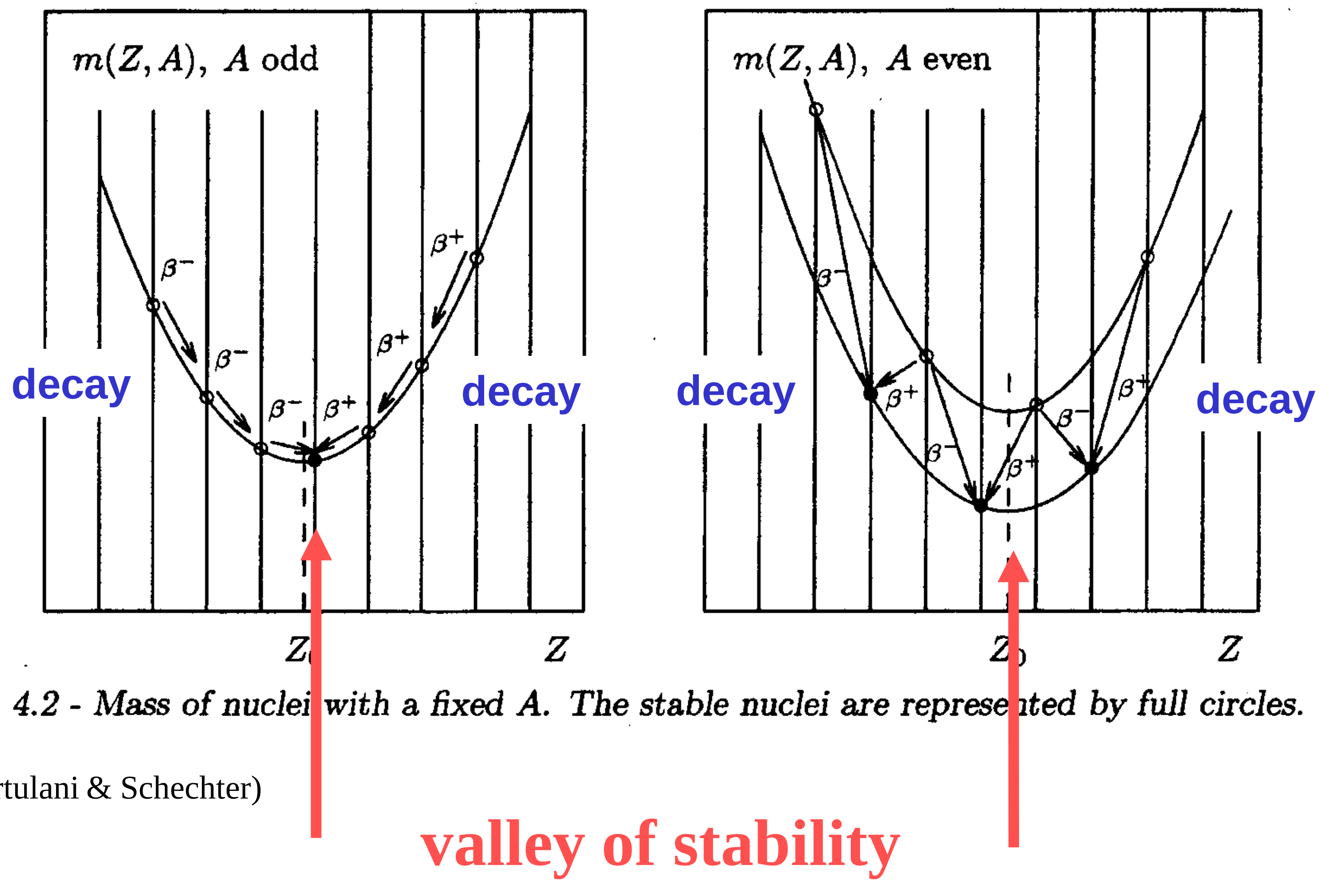


Fig. 4.2 - Mass of nuclei with a fixed A. The stable nuclei are represented by full circles.

(Bertulani & Schechter)

What happens when a nucleus outside the valley of stability is created ? (for example in a nuclear reaction inside a star ?)

Decay - energetics and decay law

Decay of A in B and C is possible if reaction A $\longrightarrow$ B+C has positive Q-value
(again – masses are critcical !)

BUT: there might be a barrier that prolongs the lifetime

Decay is described by quantum mechanics and is a pure random process, with a constant probability for the decay of a single nucleus to happen in a given time interval.

N: Number of nuclei A (Parent)
λ : decay rate (decays per second and parent nucleus)

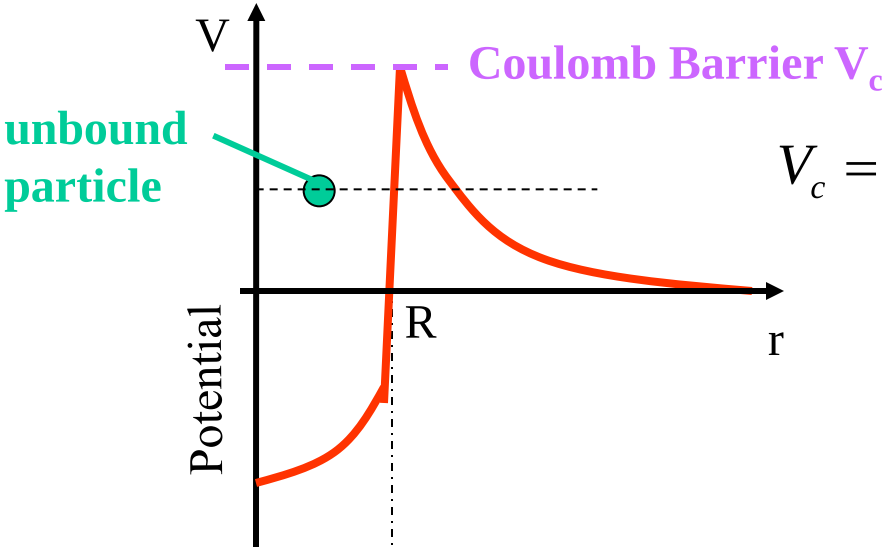
$$dN = -\lambda N dt \quad \text{therefore} \quad N(t) = N(t=0)\,\mathrm{e}^{-\lambda t}$$

lifetime $\tau = 1/\lambda$

half-life $T_{1/2} = \tau \ln 2 = \ln 2/\lambda$ is time for half of the nuclei present to decay

Decay modes

for anything other than a neutron (or a neutrino) emitted from the nucleus there is a Coulomb barrier



$$V_c = \frac{Z_1 Z_2 e^2}{R}$$

If that barrier delays the decay beyond the lifetime of the universe (~ 14 Gyr) we consider the nucleus as being stable.

Example: for ^{197}Au -> ^{58}Fe + ^{139}I has Q ~ 100 MeV !

yet, gold is stable.

→ **not all decays that are energetically possible happen**

most common:
- β decay
- n decay
- p decay
- α decay
- fission

β decay

p $\longleftrightarrow$ n conversion within a nucleus via weak interaction

Modes (for a proton/neutron in a nucleus):

β^+ decay	$p \longrightarrow n + e^+ + \nu_e$	Favourable for n-deficient nuclei
electron capture	$e^- + p \longrightarrow n + \nu_e$	Favourable for n-deficient nuclei
β^- decay	$n \longrightarrow p + e^- + \bar{\nu}_e$	Favourable for n-rich nuclei

Electron capture (or EC) of atomic electrons or, in astrophysics, of electrons in the surrounding plasma

Q-values for decay of nucleus (Z,N)

with nuclear masses — **with atomic masses**

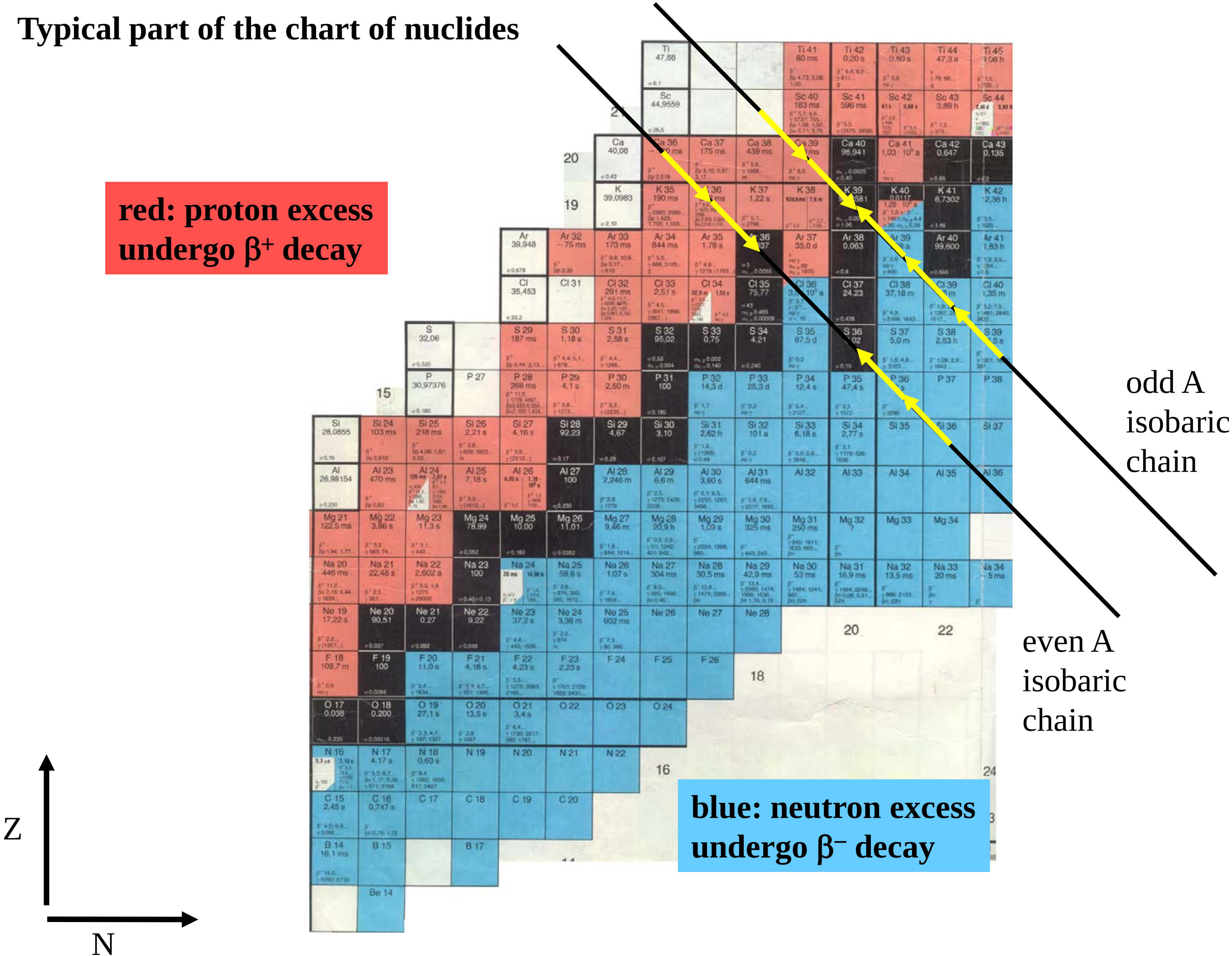
$$Q_{\beta+} / c^2 = m_{nuc}(Z,N) - m_{nuc}(Z-1,N+1) - m_e = m(Z,N) - m(Z-1,N+1) - 2m_e$$

$$Q_{EC} / c^2 = m_{nuc}(Z,N) - m_{nuc}(Z-1,N+1) + m_e = m(Z,N) - m(Z-1,N+1)$$

$$Q_{\beta-} / c^2 = m_{nuc}(Z,N) - m_{nuc}(Z+1,N-1) - m_e = m(Z,N) - m(Z+1,N-1)$$

Note: $Q_{EC} > Q_{\beta+}$ by 1.022 MeV

Typical part of the chart of nuclides



Typical β decay half-lives:

very near “stability” : occasionally Mio’s of years or longer

more common within a few nuclei of stability: minutes - days

most exotic nuclei that can be formed: ~ milliseconds

Proton or neutron decay:

Usually, the protons and neutrons in a nucleus are bound
→ Q-value for proton or neutron decay is negative

For extreme asymmetries in proton and neutron number nuclei become proton or neutron unbound

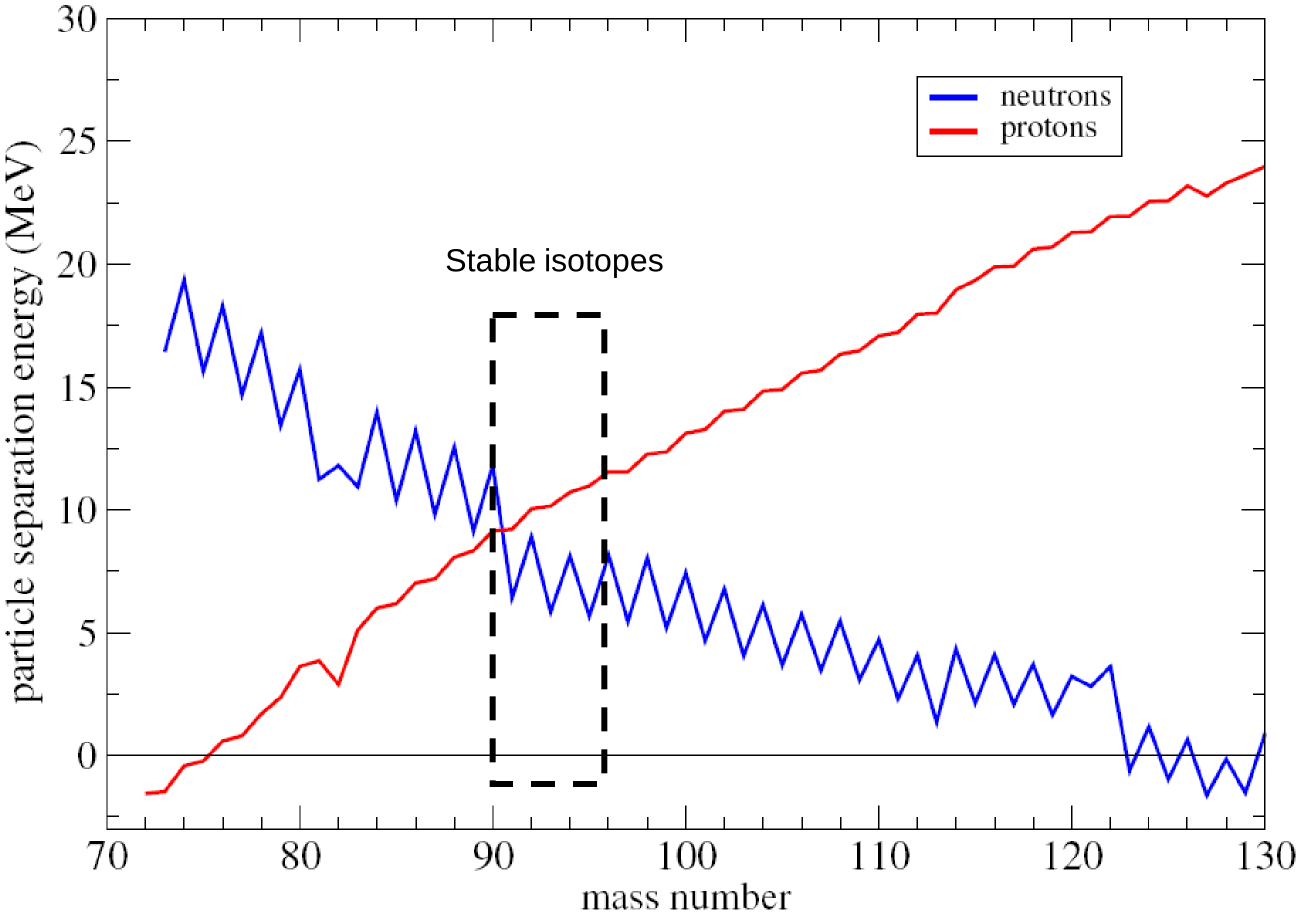
→ Proton or neutron decay is then possible

A nucleus that is proton unbound (Q-value for p-decay > 0) is beyond the "**proton drip line**"

A nucleus that is neutron unbound (Q-value for n-decay >0) is beyond the "**neutron drip line**"

NOTE: nuclei can exist beyond the proton and neutron drip line:
- for very short time
- for a "long" time beyond p-drip if Q-value for p-decay is small (Coulomb barrier !)
- for a long time beyond n-drip at extreme densities inside neutron stars

Zr isotopes (Z=40, N varies)



6.4. α decay

emission of an α particle (= ^{4}He nucleus)

Coulomb barrier twice as high as for p emission, but exceptionally strong bound, so larger Q-value

emission of other nuclei does not play a role (but see fission !) because of

- increased Coulomb barrier
- reduced cluster probability

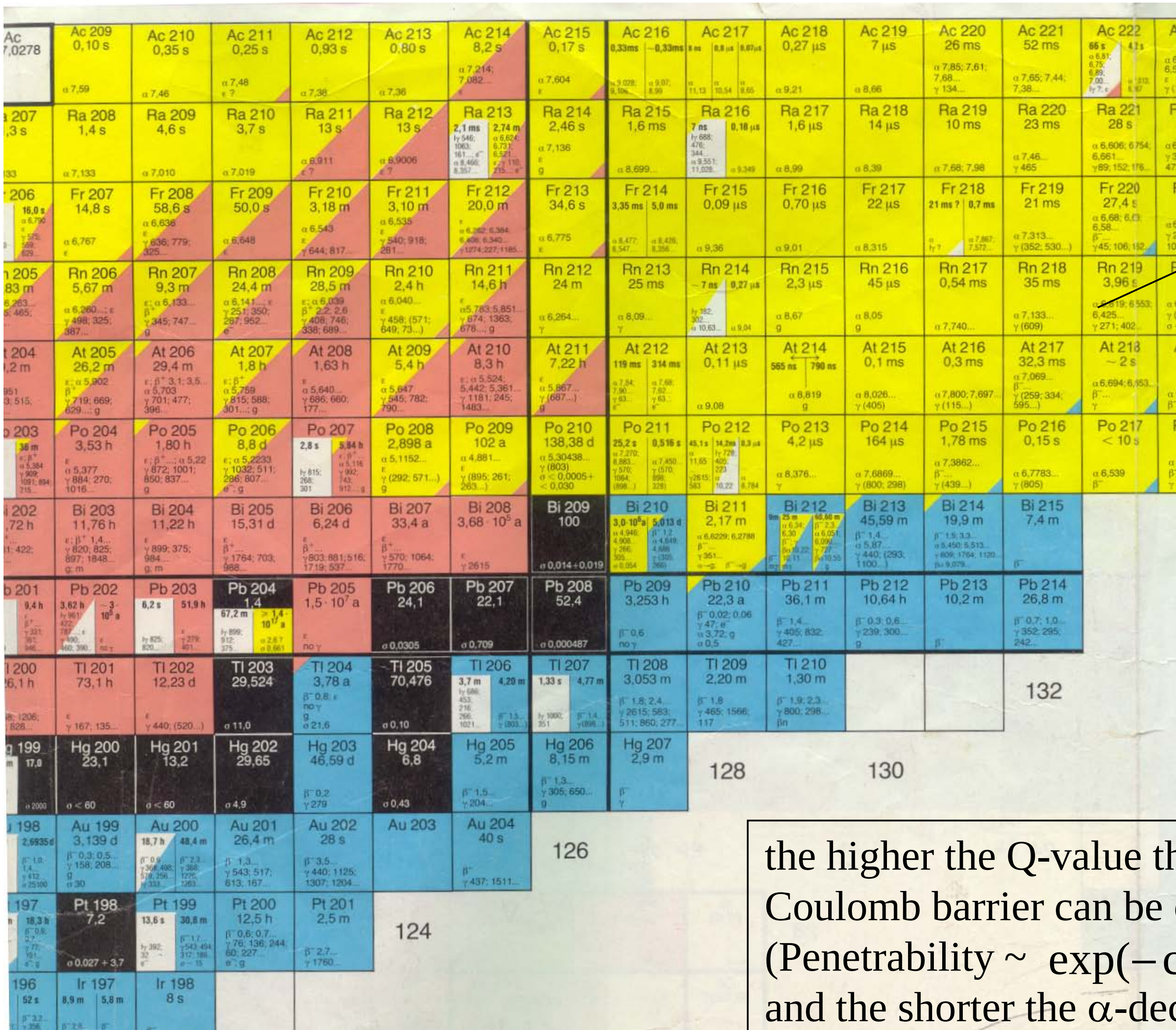
Q-value for α decay:

$$\begin{aligned} Q_\alpha &= m(Z,A) - m(Z-2,A-4) - m_\alpha \\ &= \underbrace{-B(Z,A) + B(Z-2,A-4)} + m_\alpha \end{aligned}$$

<0, but closer to 0 with larger A,Z

$\longrightarrow$ large A therefore favored lightest α emitter: ^{144}Nd (Z=60) (Qα=1.9 MeV but still $T_{1/2}$=2.3 x 10^{15} yr)

beyond Bi α emission ends the valley of stability !



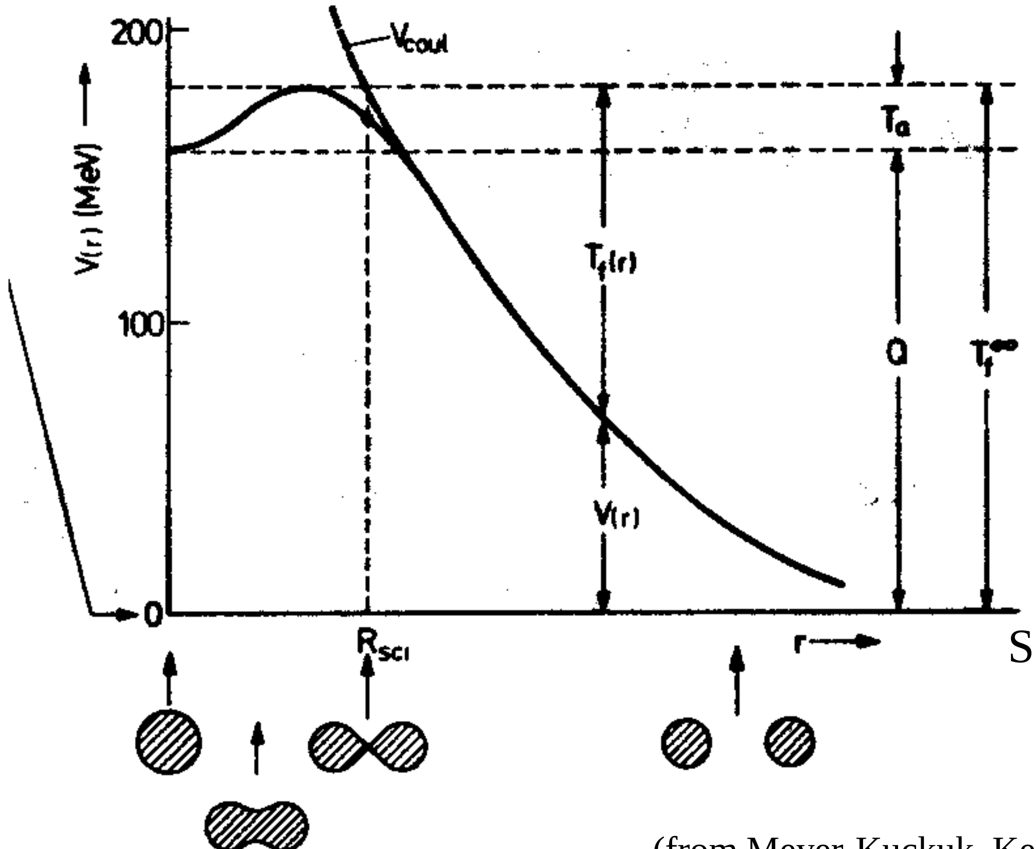
yellow are α emitter

the higher the Q-value the easier the Coulomb barrier can be overcome (Penetrability ~ $\exp(-\mathrm{const}\cdot E^{-1/2})$) and the shorter the α-decay half-lives

6.5. Fission

Very heavy nuclei can fission into two parts (Q>0 if heavier than ~iron already)

For large nuclei surface energy less important - large deformations less prohibitive. Then, with a small amount of additional energy (Fission barrier) nucleus can be deformed sufficiently so that coulomb repulsion wins over nucleon-nucleon attraction and nucleus fissions.



Separation

(from Meyer-Kuckuk, Kernphysik)

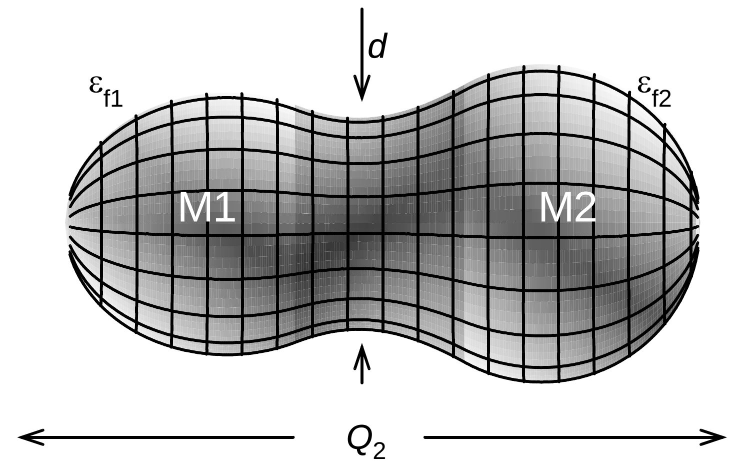
Real fission barriers:

Fission barrier depends on how shape is changed (obviously, for example. it is favourable to form a neck).

Real theories have many more shape parameters - the fission barrier is then a landscape with mountains and valleys in this parameter space. The minimum energy needed for fission along the optimum valley is “the fission barrier”

Example for parametrization in Moller et al. Nature 409 (2001) 485

Five Essential Fission Shape Coordinates



41 $\otimes$ 20 $\otimes$ 15 $\otimes$ 15 $\otimes$ 15

41	Q_2 ~	Elongation (fission direction)
$\otimes$ 20	α_g ~	(M1-M2)/(M1+ M2) Mass asymmetry
$\otimes$ 15	ε_{f1} ~	Left fragment deformation
$\otimes$ 15	ε_{f2} ~	Right fragment deformation
$\otimes$ 15	d ~	Neck

$\Rightarrow$ 2 767 500 grid points – 156 615 unphysical points

$\Rightarrow$ 2 610 885 physical grid points

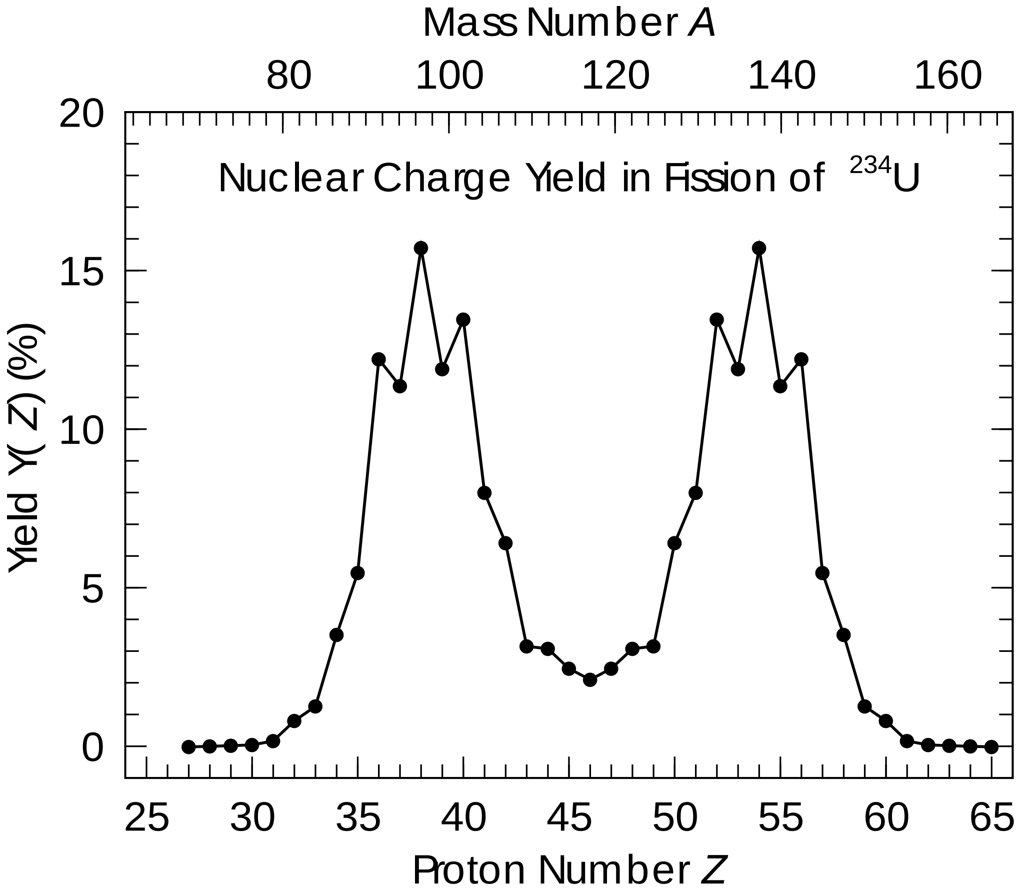
Fission fragments:

Naively splitting in half favourable (symmetric fission)

There is a asymmetric fission mode due to shell effects

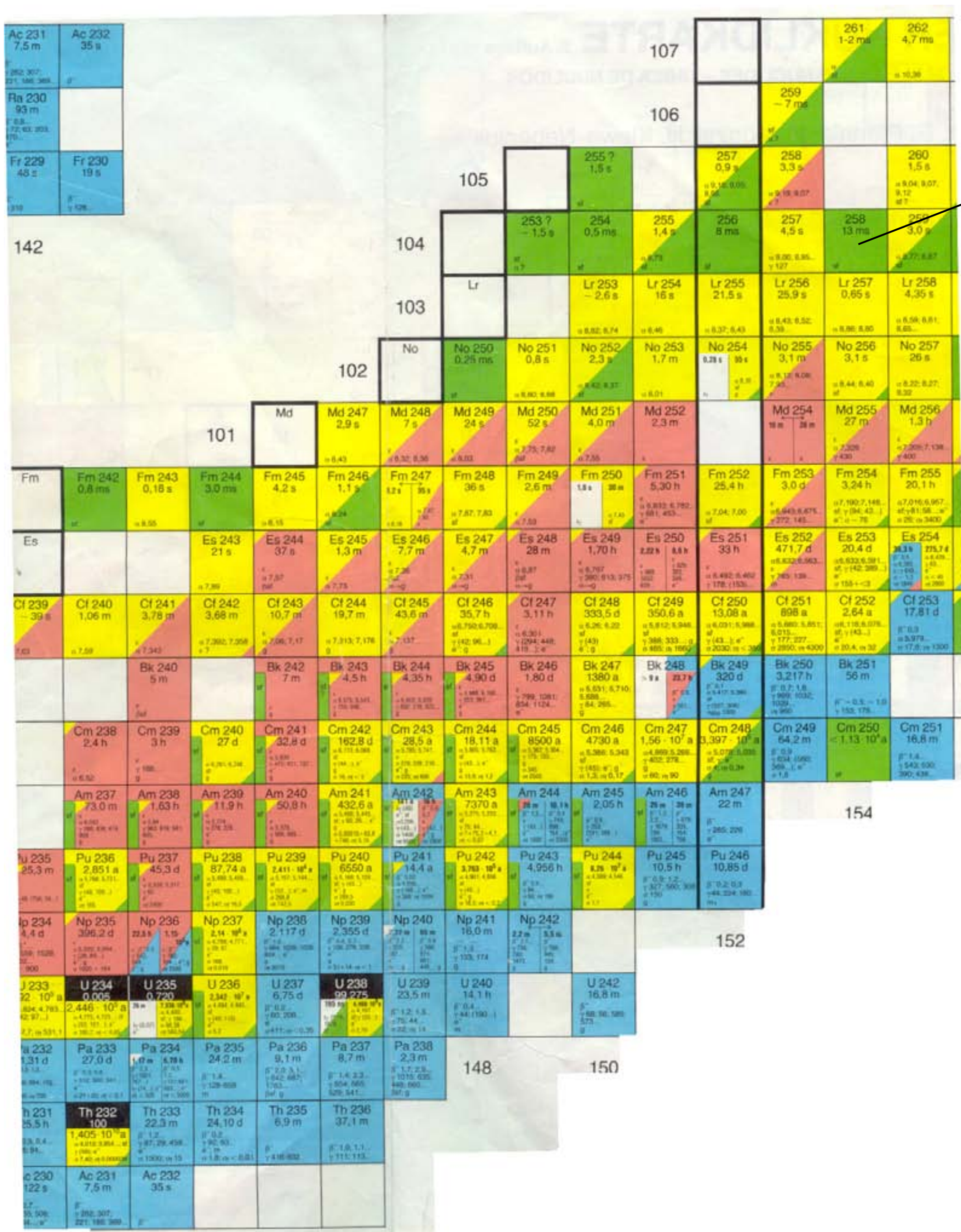
(somewhat larger or smaller fragment than exact half might be favoured if more bound due to magic neutron or proton number)

Both modes occur



Example from
Moller et al. Nature 409 (2001) 485

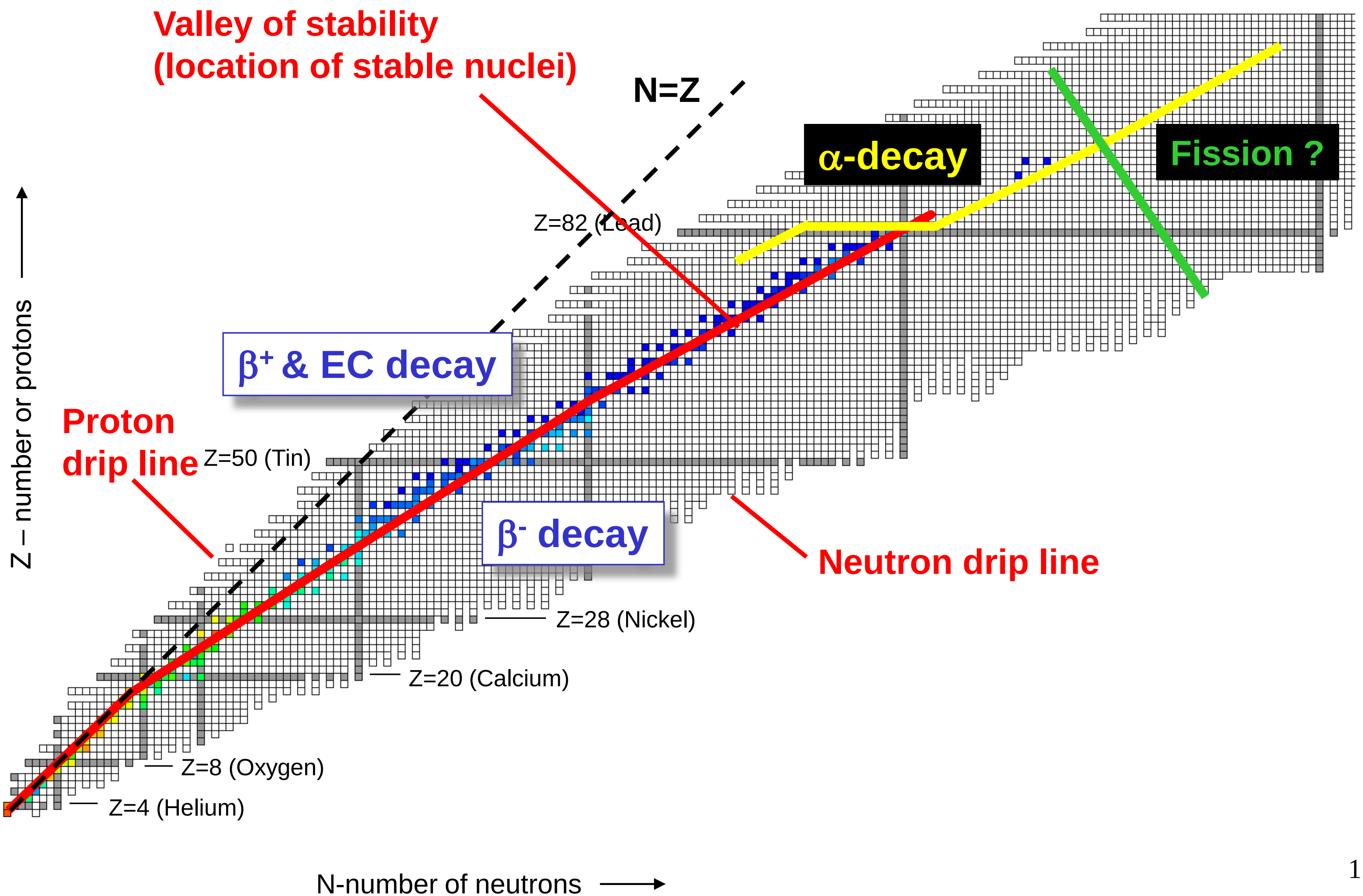
If fission barrier is low enough spontaneous fission can occur as a decay mode



green = spontaneous fission

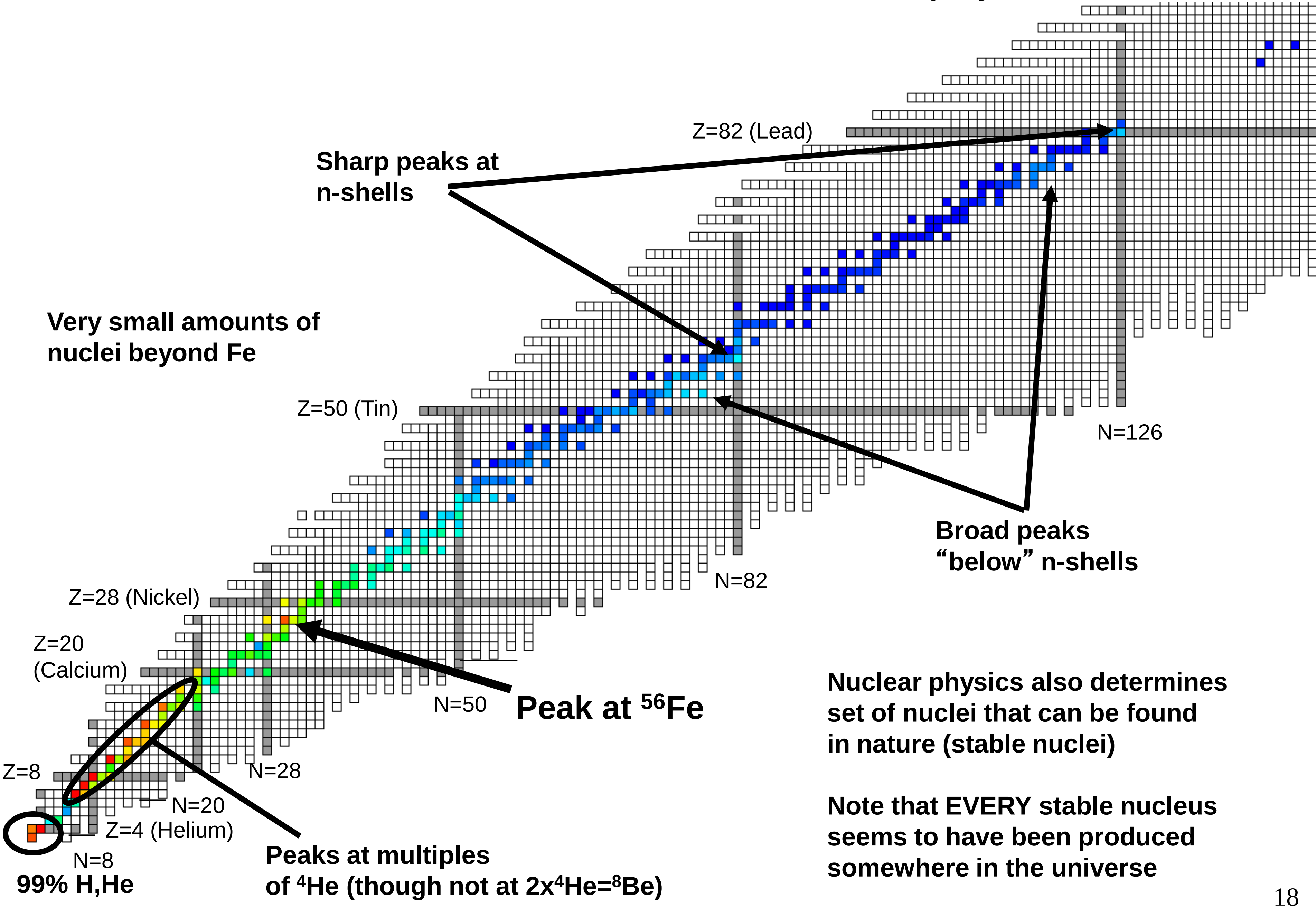
spontaneous fission is the limit of existence for heavy nuclei

Summary



Valley of stability
(location of stable nuclei)
N=Z
α-decay
Fission ?
Z=82 (Lead)
β+ & EC decay
Proton
drip line
Z=50 (Tin)
β- decay
Neutron drip line
Z=28 (Nickel)
Z=20 (Calcium)
Z=8 (Oxygen)
Z=4 (Helium)
Z – number or protons
N-number of neutrons

Solar abundances and nuclear physics



Nuclear physics also determines set of nuclei that can be found in nature (stable nuclei)

Note that EVERY stable nucleus seems to have been produced somewhere in the universe