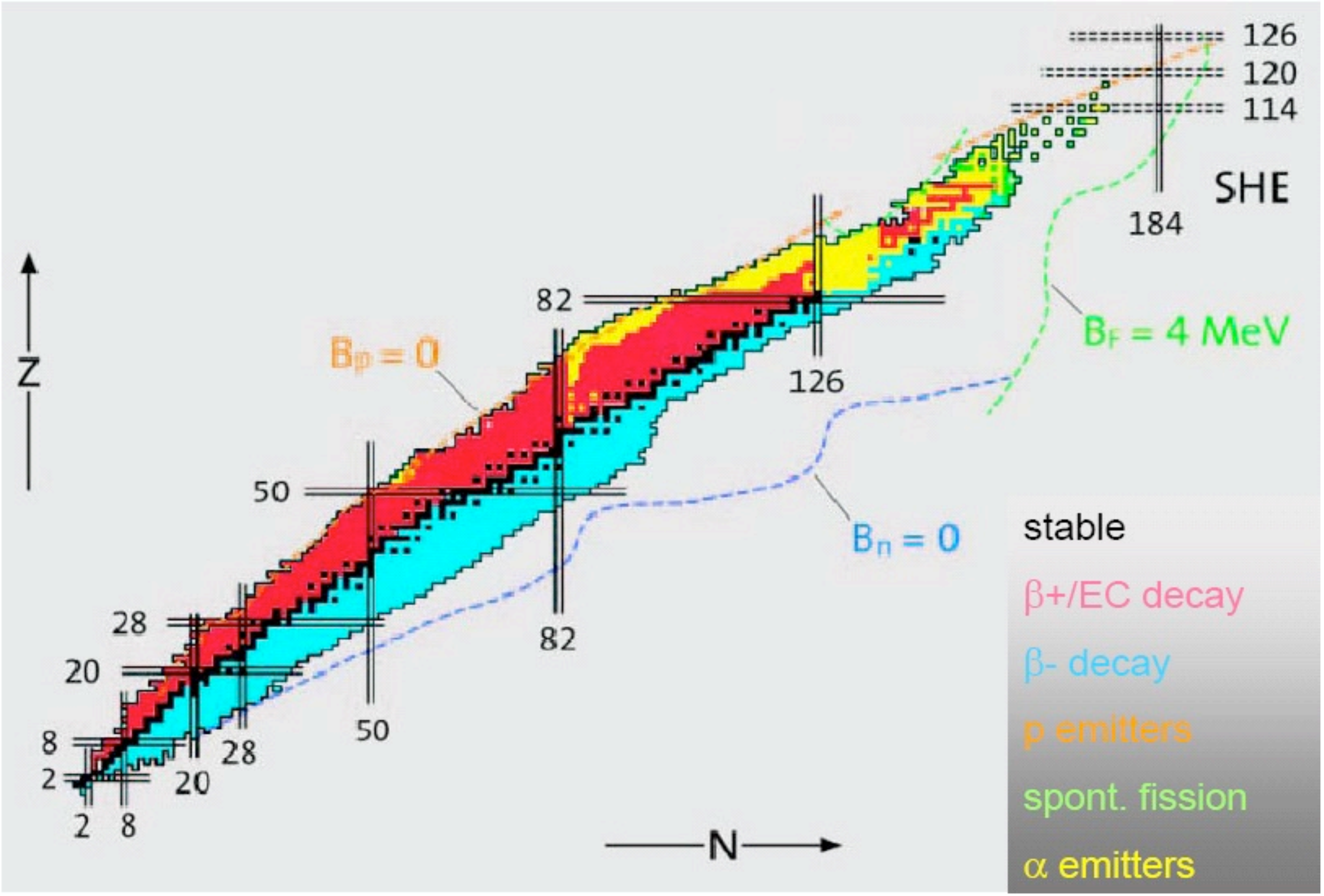
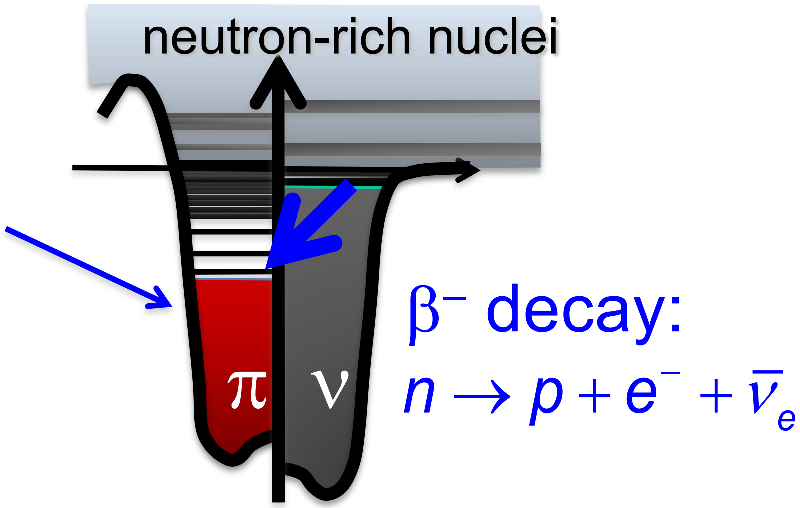
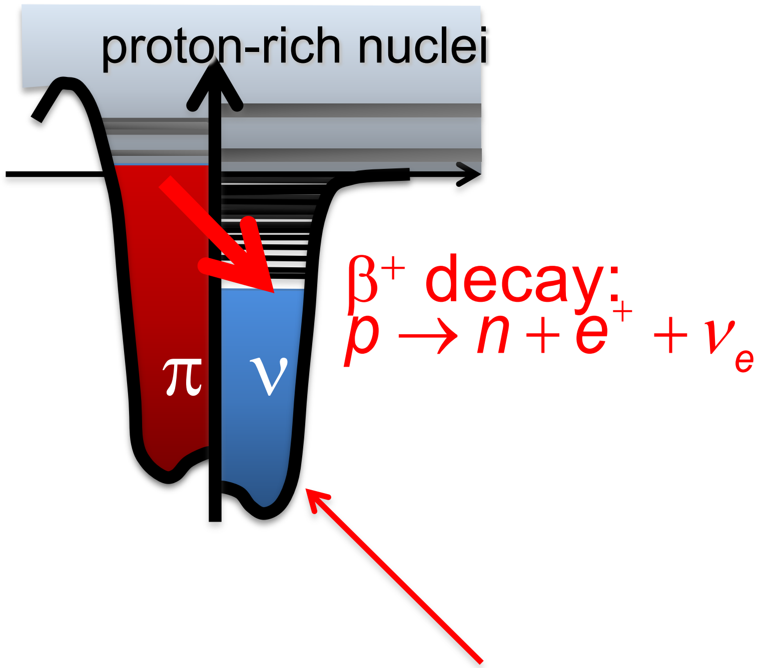
Exotic nuclei and drip lines
Part I

- Unstable vs. stable nuclei: neutron-rich and proton-rich systems
- Limit of nuclear stability and definition of drip lines



From: Exotic Nuclei, J. Enders, TU Darmstadt, Summer 2003





- Nuclei that are neutron- or proton-rich undergo β-decay.

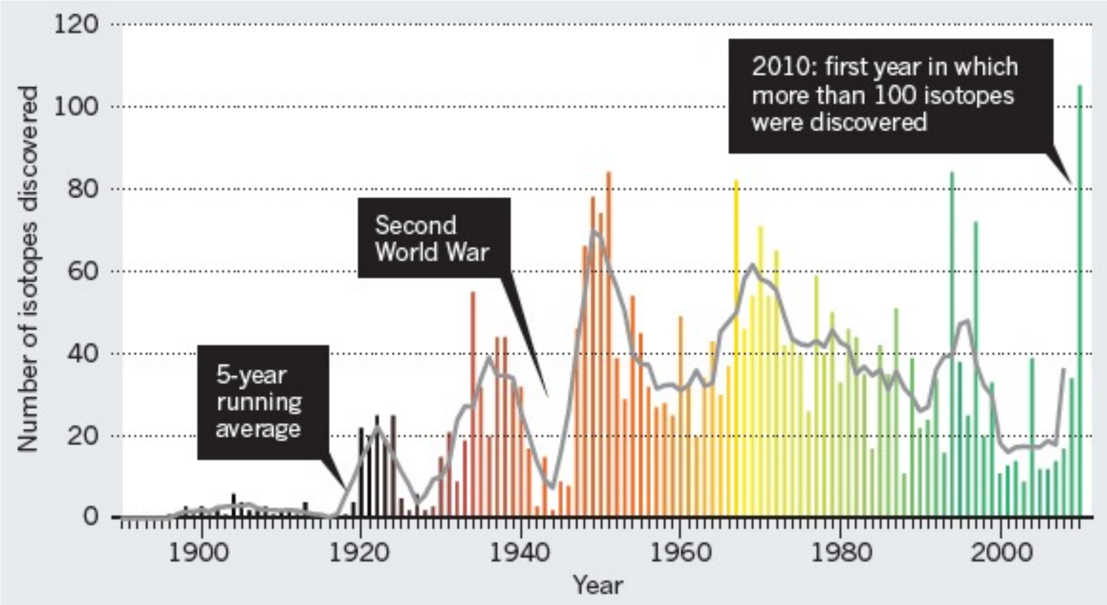
- Although unstable, these nuclei exist as bound systems. The limit of nuclear stability with respect to the strong interaction is the **drip line**. Neutron and proton **drip lines** are sketched in the previous slide but they are only partially known.

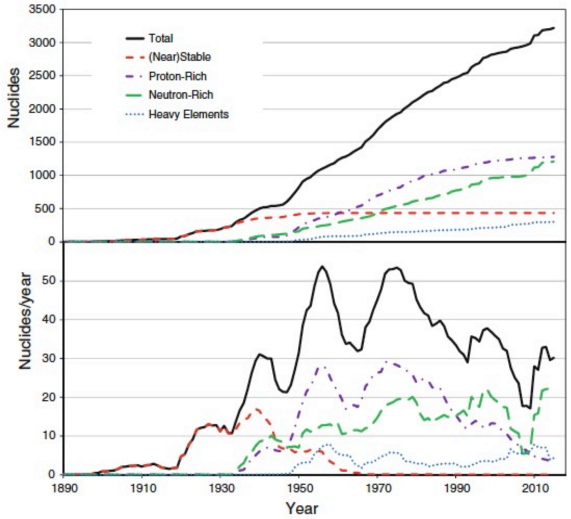
Lifetimes for beta-decay can be quite long and unstable nuclei can nonetheless be studied nowadays using RIB (Radioactive Isotope Beam) facilities.

We meet, by further increasing (or decreasing) N-Z the neutron (proton) drip line. These are defined as the limits beyond which the systems are unstable against particle emission. In the case of neutrons, the one-neutron or two-neutron separation energies (S_n = BE(N)-BE(N-1) or S_{2n}) become zero.

In certain cases, systems beyond the drip lines can be studied: for instance, if the lifetime is relatively long due to the fact that the extra neutron (or proton) has a resonant state available. But this is not the rule !

Discovering new exotic isotopes



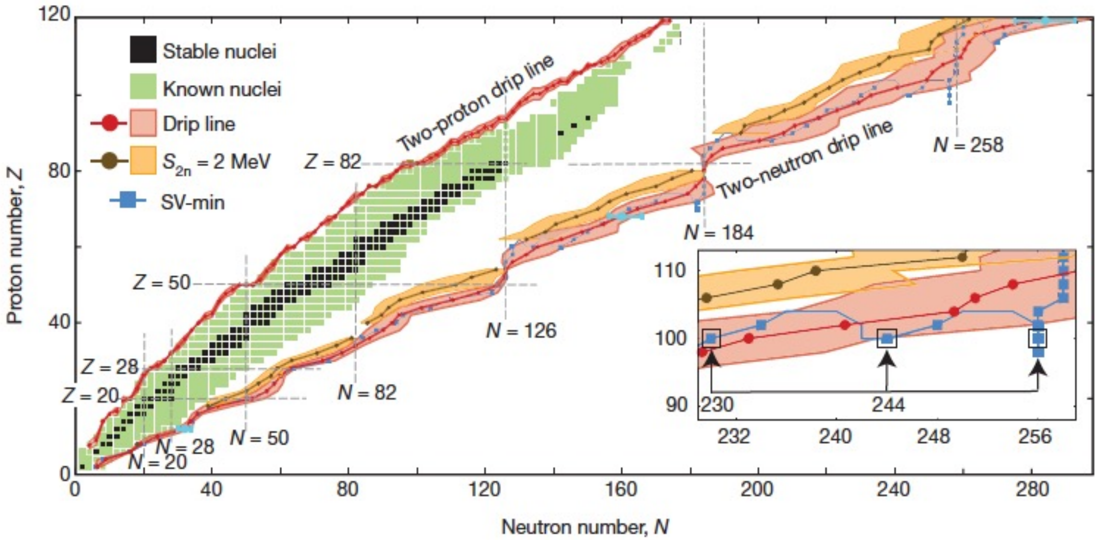


M. Thoennessen, B. Sherrill, Nature 473, 25 (2011).

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

In this web page new discovered isotopes are reported.
Updated to 2020.

Model extrapolations to the drip line



J. Erler *et al.*, Nature 486, 509 (2012) - SEDF

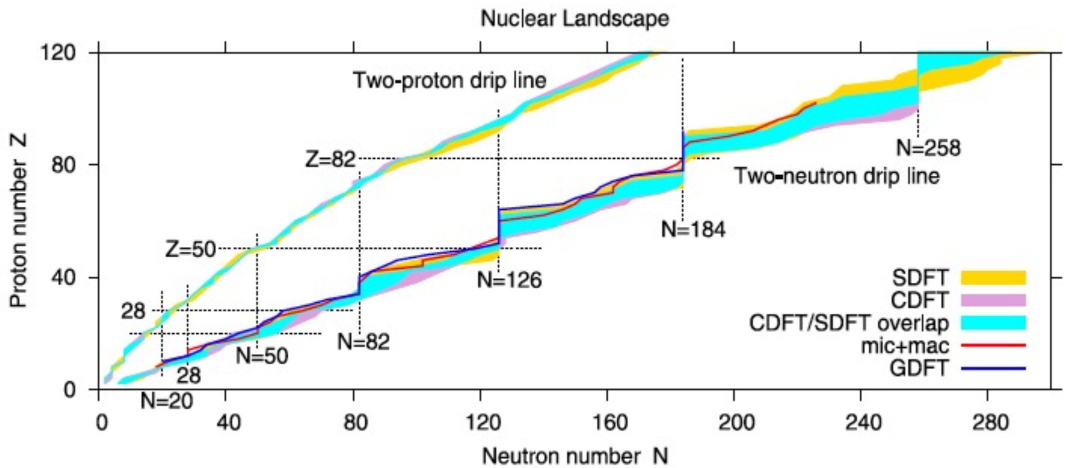


Fig. 4. The comparison of the uncertainties in the definition of two-proton and two-neutron drip lines obtained in CDFT and SDFT. The shaded areas are defined by the extremes of the predictions of the corresponding drip lines obtained with different parametrizations. The blue shaded area shows the area where the CDFT and SDFT results overlap. Non-overlapping regions are shown by dark yellow and plum colors for SDFT and CDFT, respectively. The results of the SDFT calculations are taken from the supplement to Ref. [2]. The two-neutron drip lines obtained by microscopic + macroscopic (FRDM [3]) and Gogny D1S DFT [5] calculations are shown by red and blue lines, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

A.V. Afanasjev *et al.*, Phys. Lett. B726, 680 (2013) - CEDF

In the previous figures:

black dots correspond to stable nuclei: i.e., infinite lifetime.

Stable nuclei can be found around the so-called stability line.

First problems: for each A (that is, for each isobaric chain), which is the nucleus with largest binding energy ? And how does this evolve if we move towards right (left) in the previous figure, that is, if we move increasing (decreasing) (N-Z) ?

The solution of the first problem can be attempted by using the well-known Bethe-Weiszäcker mass formula. We take this problem from [Hey94].

$$M(A,Z)c^2 = Zm_pc^2 + (A-Z)m_nc^2$$
$$-a_VA + a_SA^{2/3} + a_A(A-2Z)^2A^{-1}$$
$$+a_CZ(Z-1)A^{-1/3} +$$
$$\text{pairing term} : 0, \pm\delta. \qquad (1)$$

If we wish, for each A, the nucleus with the lowest mass, or largest binding energy, we must re-write the above equation (neglecting the pairing term) as

$$M(A,Z)c^2 = f(A) + pZ + qZ^2, \qquad (2)$$

where the constants p and q can be easily obtained, and then

$$\frac{\partial}{\partial Z}Mc^2 = 0 \qquad (3)$$

is solved for

$$Z_0 = \frac{-p}{2q}. \qquad (4)$$

We can obtain Z_0 (value of Z corresponding to the lowest mass) by replacing the values of p and q and then multiplying the numerator and denominator by $A/8a_A$:

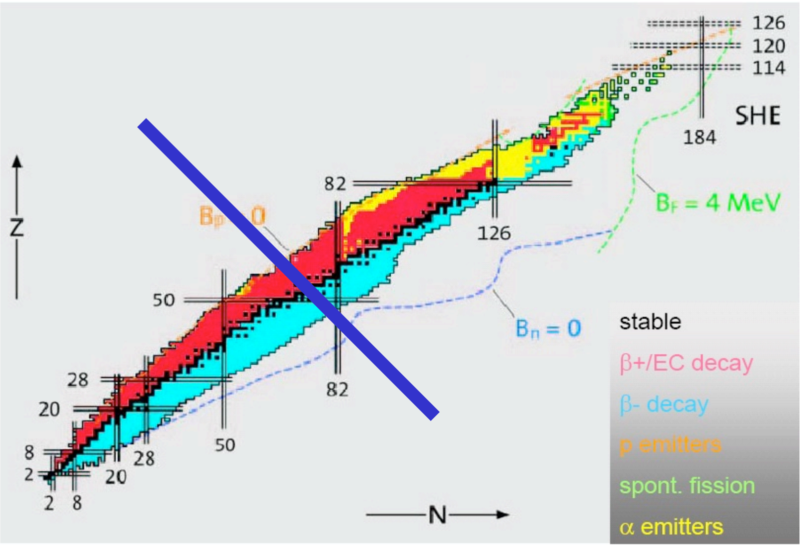
$$Z_0 = \frac{\frac{A}{2} + (m_n - m_p)c^2 \frac{A}{8a_A} + \frac{a_C A^{2/3}}{8a_A}}{1 + \frac{1}{4}\frac{a_C}{a_A} A^{2/3}}. \qquad (1)$$

In the numerator, the second and third terms are negligible with respect to the first one. This leads to

$$Z_0 = \frac{\frac{A}{2}}{1 + 0.0077 A^{2/3}}. \qquad (2)$$

Values:

a_V=15.85 MeV
a_S=18.34 MeV
a_C=0.71 MeV
a_A=23.21 MeV



The blue line represents constant A: for A=120 we meet Z_0 close to 50 (i.e., Sn).