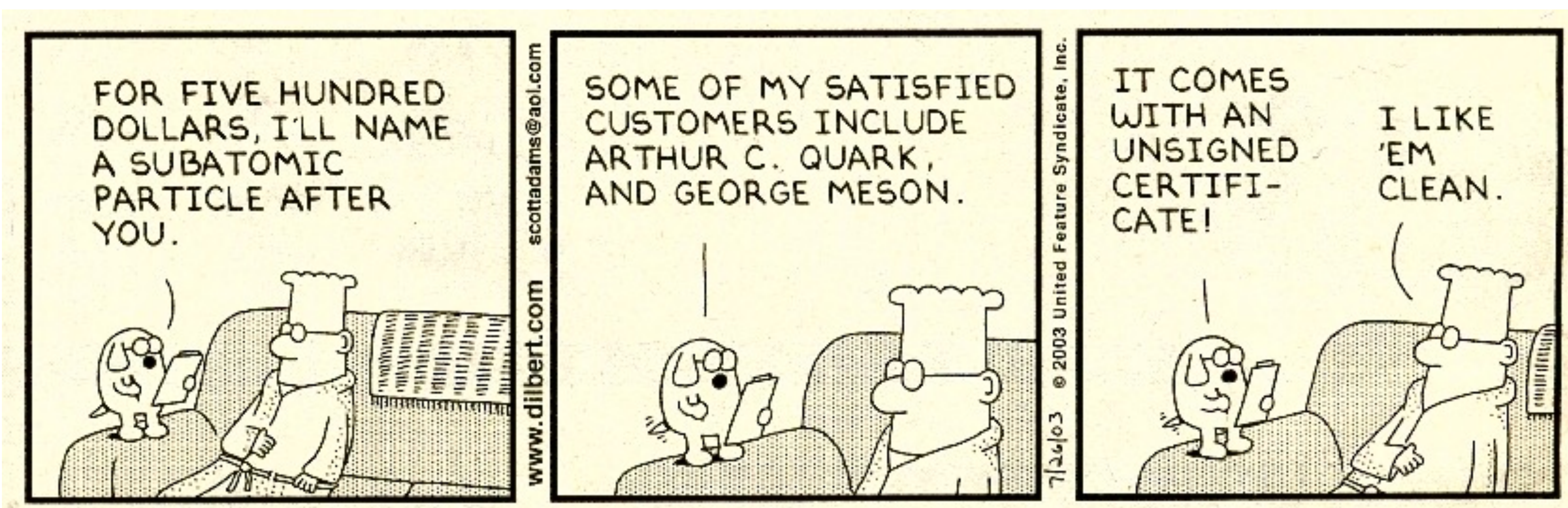
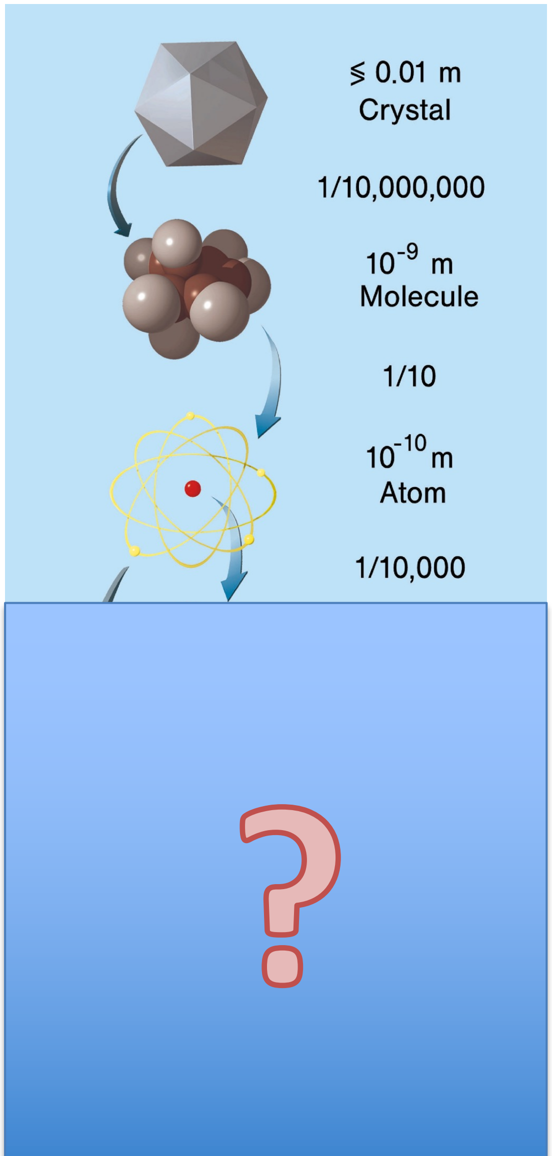
PHYS415/515:

Particle and Nuclear Physics

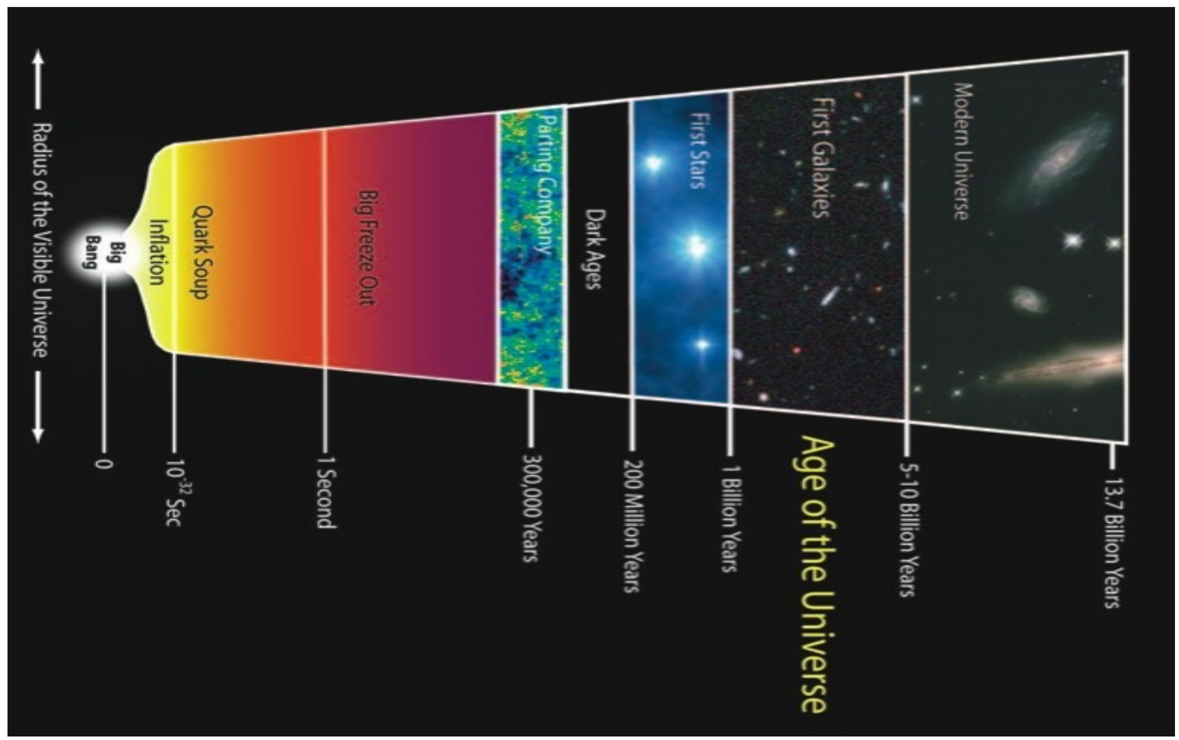
Sebastian Kuhn



The Structure of Matter



- What is the Universe made off?
- What are the most fundamental objects in Nature?
- What particles where there in the beginning (right after the big bang)?
- How do they interact? How do they form larger objects?
- Where does all matter in the present Universe come from?



Hydrogen Atom Wave functions

Remember Modern Physics / QM?

When n=1, l=0, m=0 : 1s $\Psi_{1,0,0} = \sqrt{\frac{1}{a_0^3\pi}} e^{-r/a_0}$

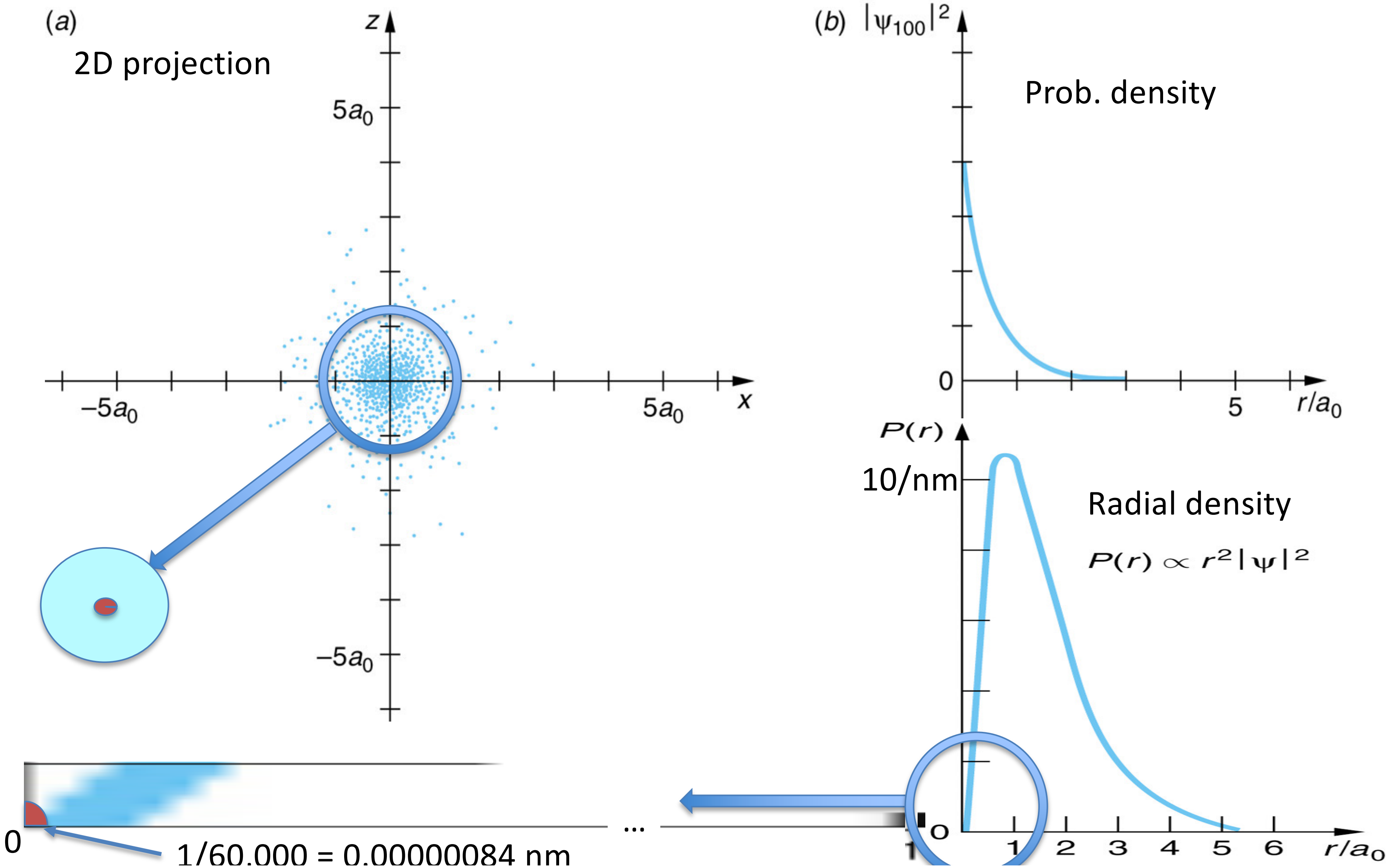
n=2, l=0, m=0 : 2s $\Psi_{2,0,0} = \sqrt{\frac{1}{32a_0^3\pi}} \left(2 - \frac{r}{a_0}\right) e^{-r/2a_0}$

l=1 m=0, ±1 : 2p $\Psi_{2,1,0} = \sqrt{\frac{1}{32a_0^3\pi}} \frac{r}{a_0} \cos\theta \, e^{-r/2a_0}$, $\Psi_{2,1,\pm1} = \mp\sqrt{\frac{1}{64a_0^3\pi}} \frac{r}{a_0} \sin\theta \, e^{\pm i\varphi} e^{-r/2a_0}$

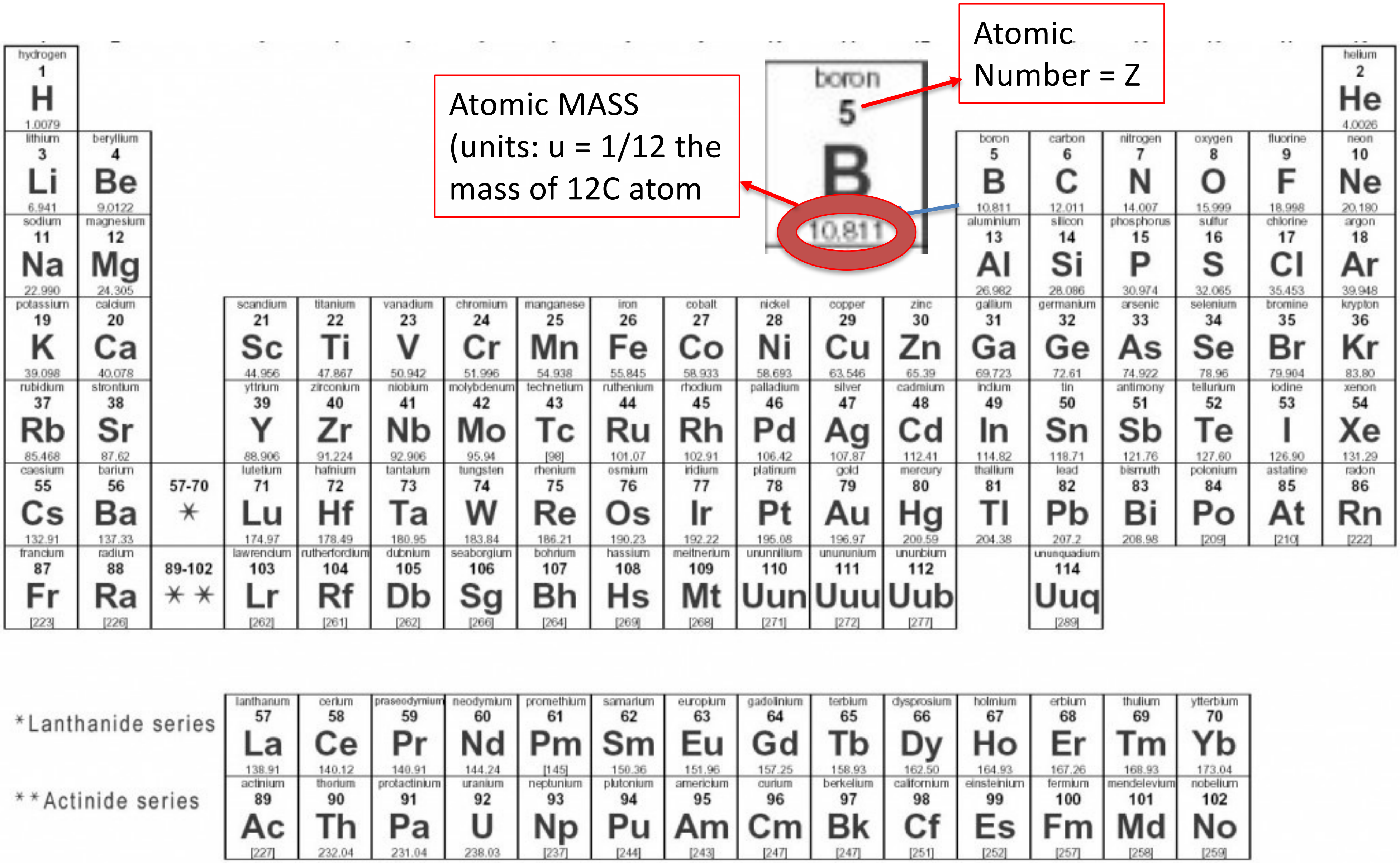
$$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{e^2 m_e} = \frac{\hbar}{m_e c\alpha}$$ = 0.0529 nm ≈ 0.53Å

- $\hbar$ is the reduced Planck constant, ≈ 197.33 $\frac{\text{nm eV}}{c}$
- m_e is the mass of an electron, ≈ 511 keV/c^2
- e is the elementary charge,
- c is the speed of light in vacuum, and
- α is the fine-structure constant. ≈ 1/137.036

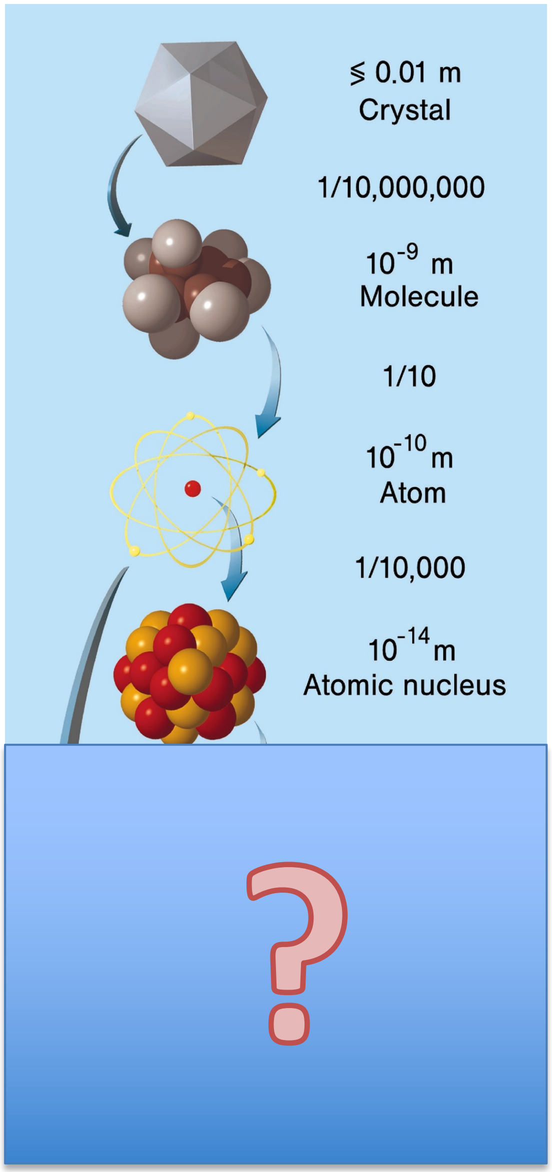
H ground state



Periodic Table

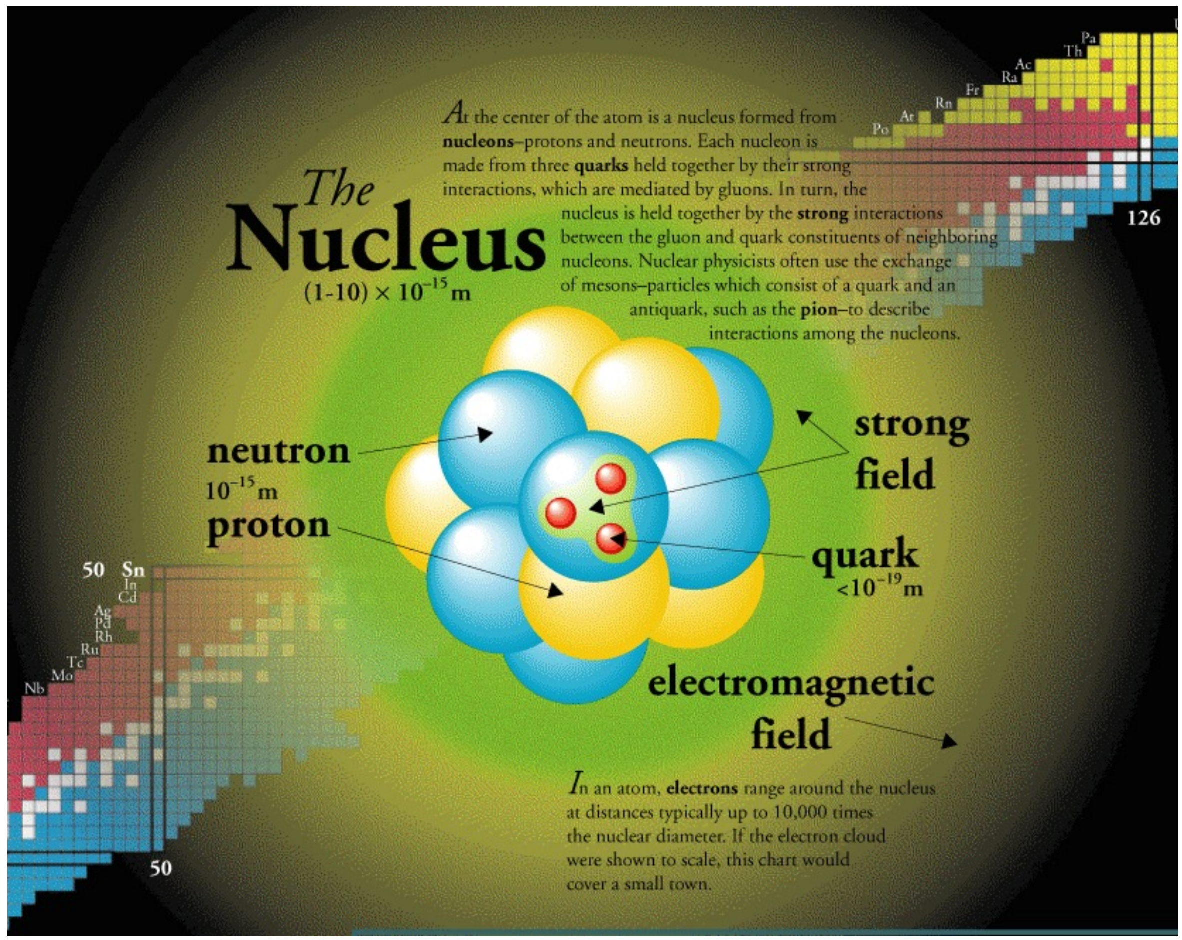


The Structure of Matter



99.97% of the mass of an atom (and hence of all visible matter) is concentrated in the nucleus.

0.000,000,000,024% of the atomic volume is occupied by the nucleus .



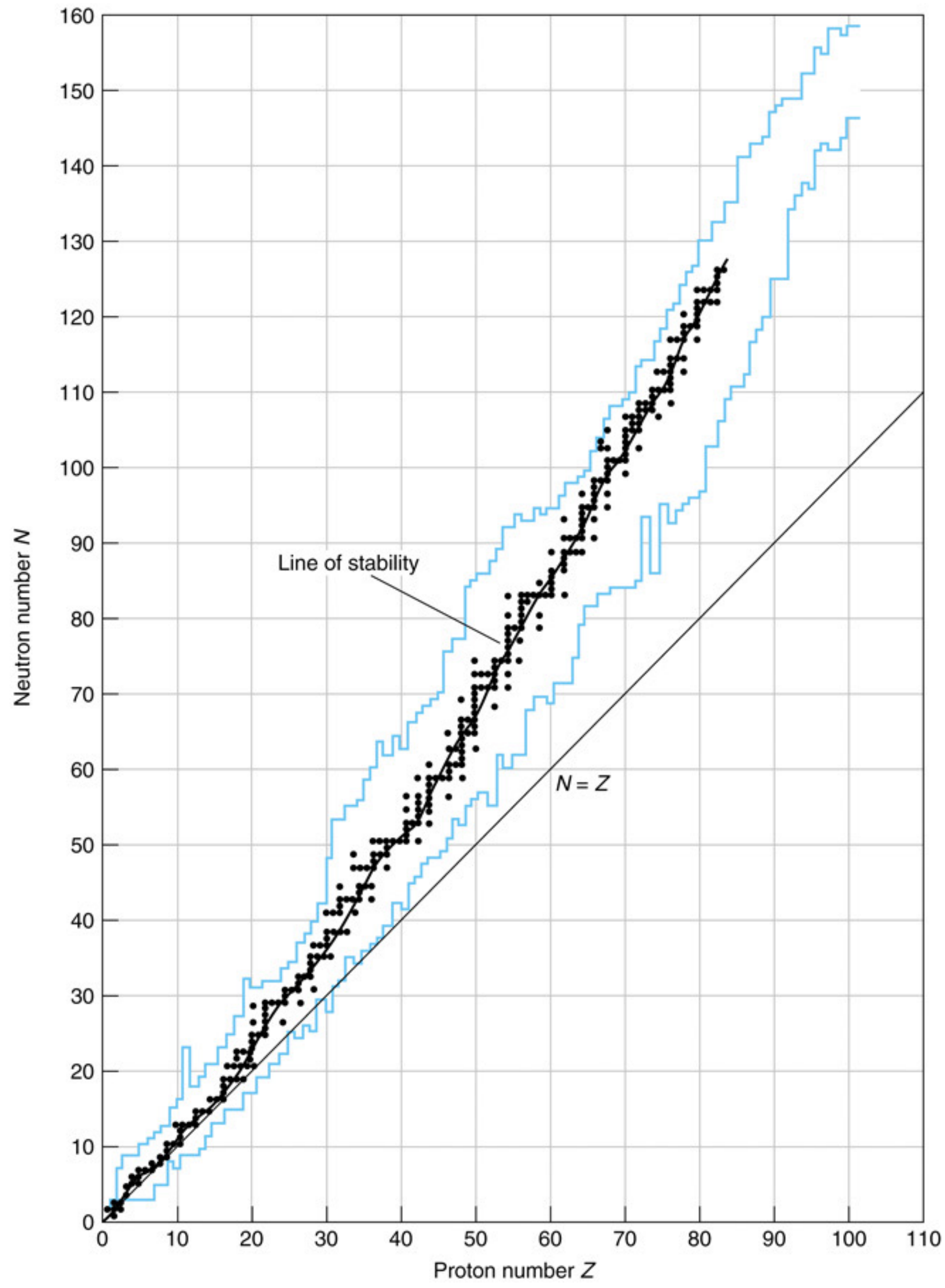
Stable nuclei

A = N + Z (all integers)

Isotopes: SAME Z
Isobars: SAME Z

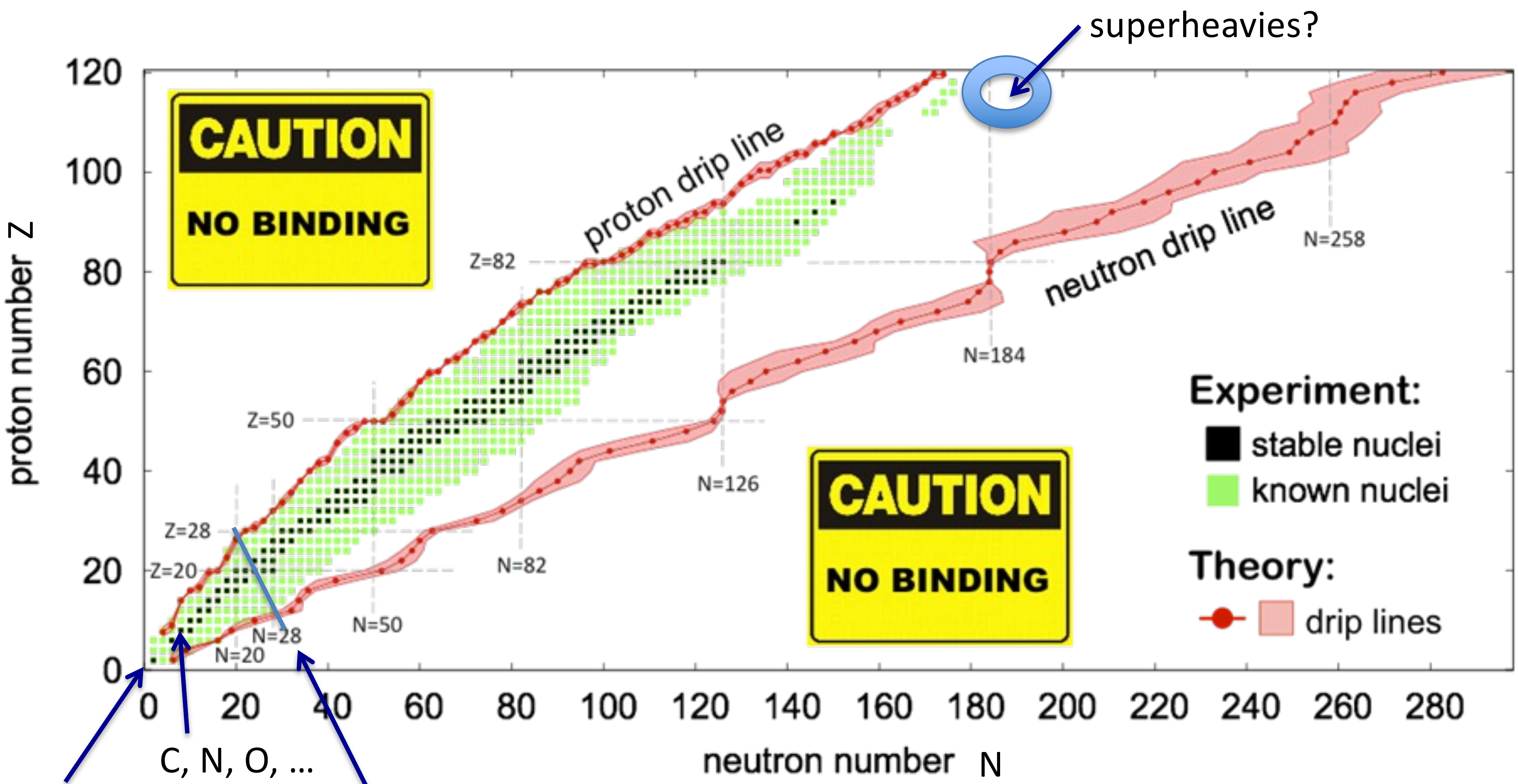
Nuclear mass is ROUGHLY proportional to A (see later)

ATOMIC mass can be fractional if the natural abundance of a given element has several stable isotopes



All the nuclei in the universe

n stars



H, ^{4}He, Li,...

Fe, Ni,...

Challenge: Most nuclear reactions in the Universe are at low energies or involve the weak interaction (tiny cross sections) => Experiments and Theory are HARD! (subtle effects play big role!)

Atomic Binding energy

$B_{atomic=}\ M_{At}c^2 - M_{Nuc}c^2 - Z \cdot m_e\ c^2$

M_{Nuc} = Mass of Nucleus
M_{At} = Atomic mass (single isotope)
Z = Element Number

Typical values: few eV's ... keV's

Nuclear Binding energy

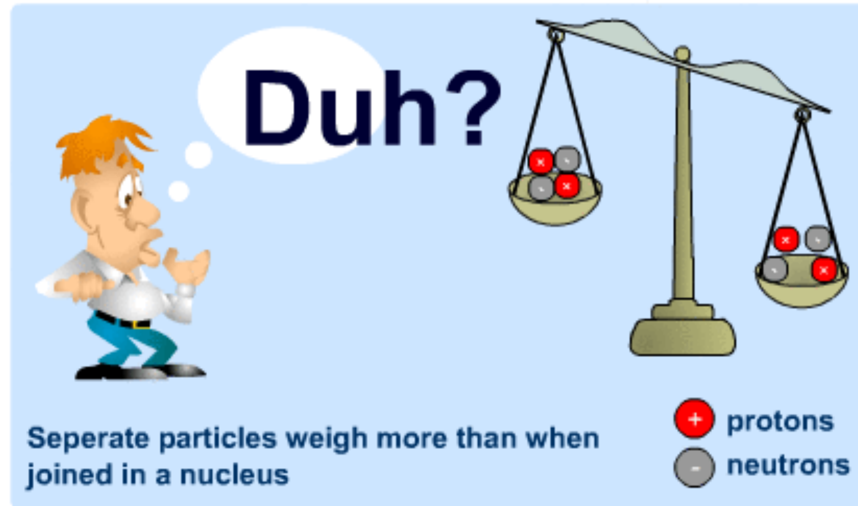
$B_{nuclear} = M_{\mathrm{N}}c^2 - Z \cdot m_p c^2 - N \cdot m_n c^2$

m_p = Mass of Proton
m_n = Mass of neutron

A= N + Z
A= Atomic Mass Number
N=Neutron Number
Z=Proton Number

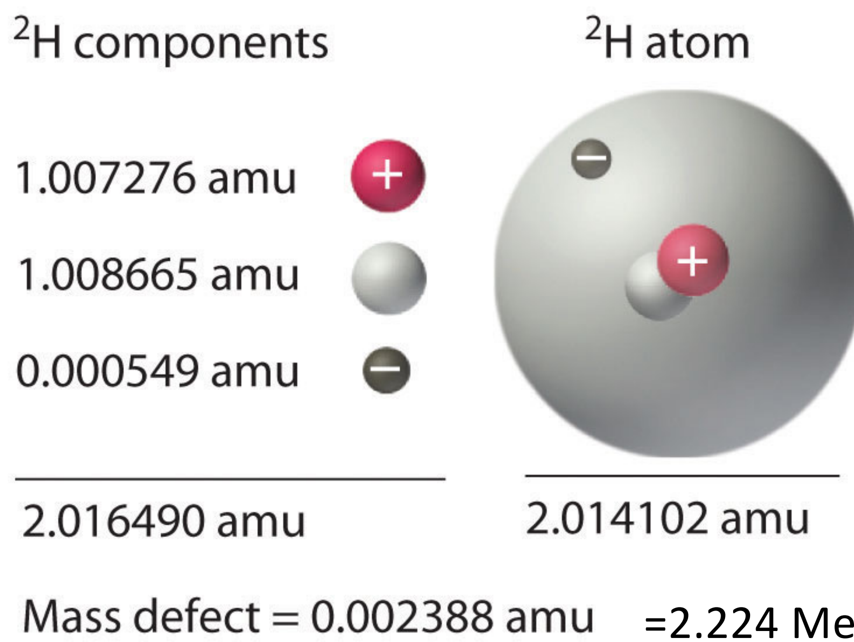
Typical values: keV's to 100's of MeV's

$$E = mc^2$$



In atomic and nuclear physics, masses are typically given in atomic mass units (u) 1 *u* = 1.66054 * 10^{-27} kg = 931.494 MeV/c^2

Proton = 938.27 MeV
Neutron = 939.51 Mev

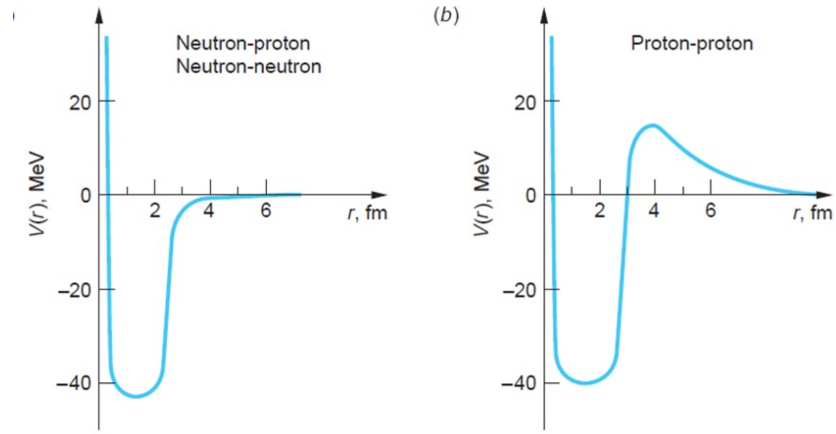


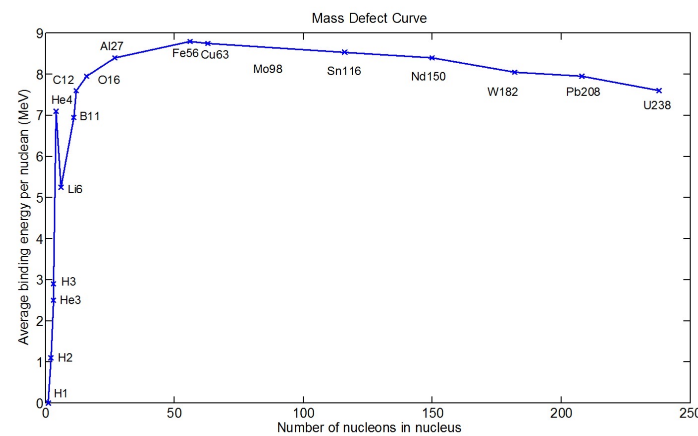
=2.224 MeV

Note: *amu* = *u* (depending on who is talking)

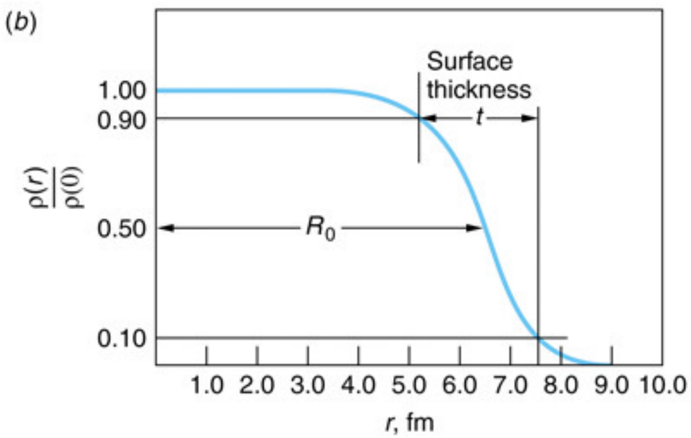
Nuclear Force

- Charge independent.
- Highly dependent on distance
- Saturated force
- Coulomb Repulsion will overcome the Nuclear Force as atoms become larger.

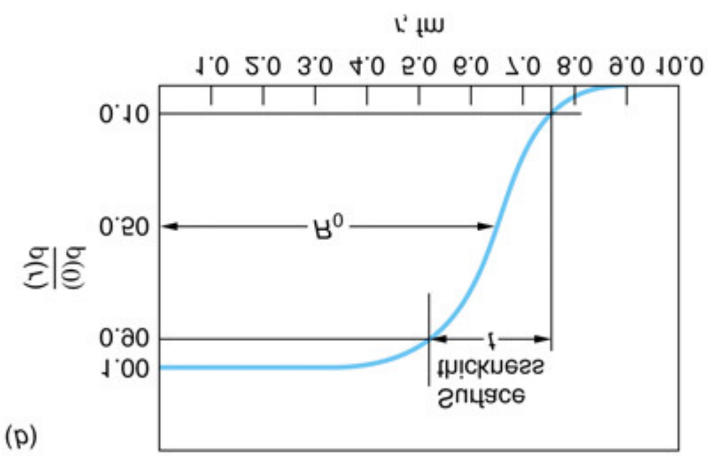




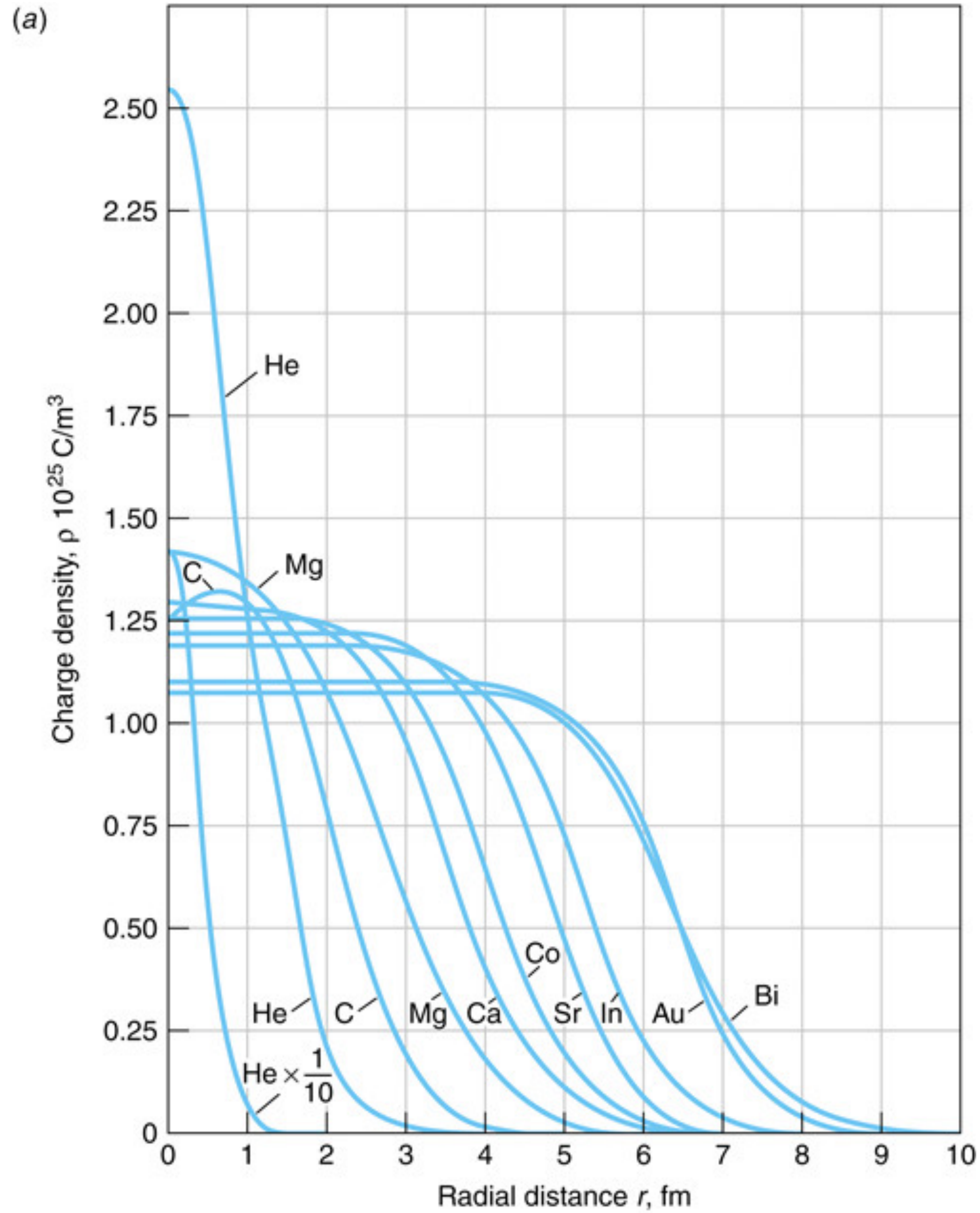
Nuclear Density



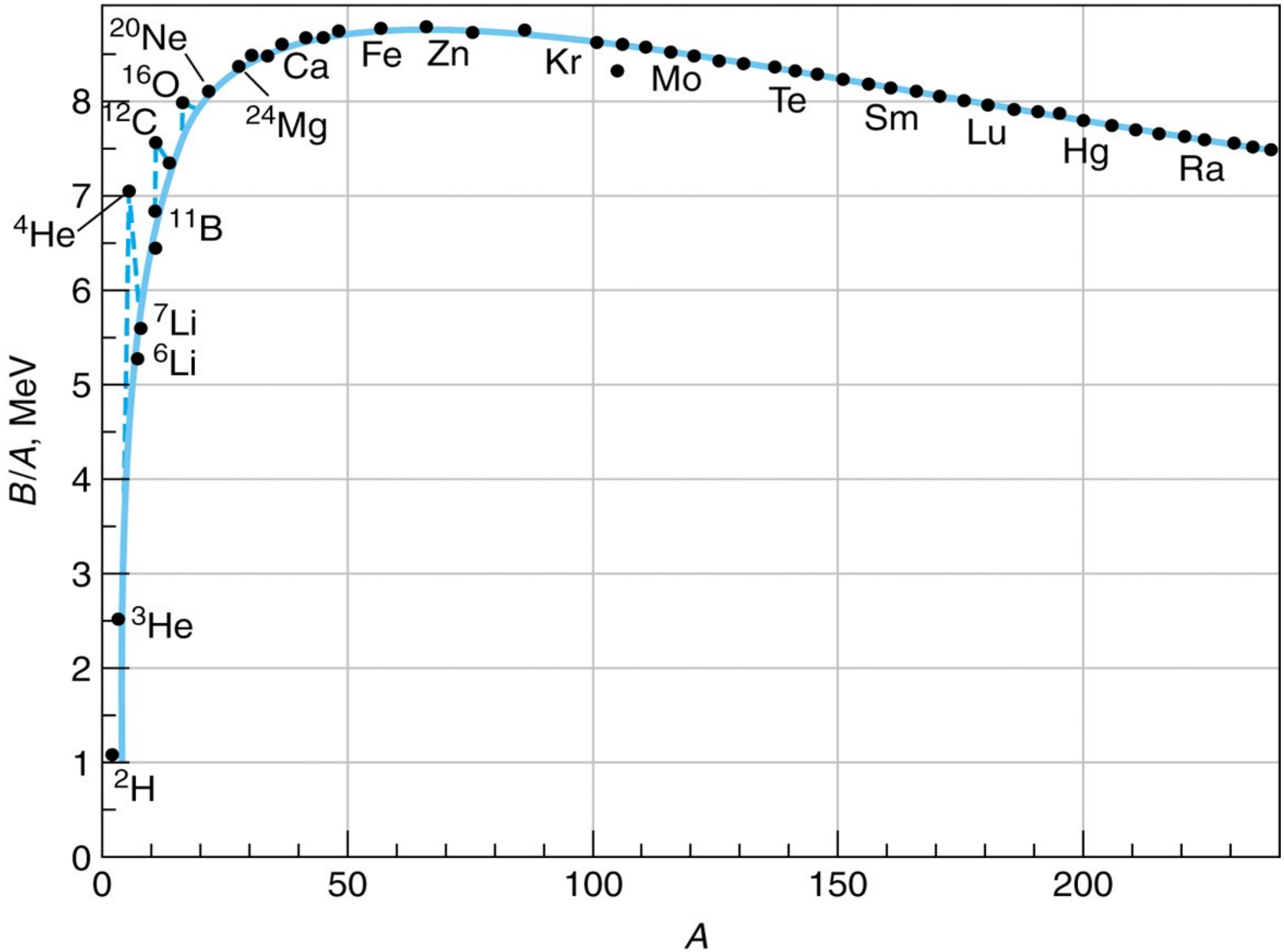
Typical Nuclear Density Profile
(Cesium?)



=> Due to short range nuclear force, each nucleon ”sees” THIS potential



Nuclear Binding energies



Liquid Drop Model

From previous slides, we find that nuclear density is roughly constant, and hence the nuclear radius goes like $A^{1/3}$

$R = 1.22\ \text{fm} \cdot A^{1/3}$
Surface = $19\ \text{fm}^2 \cdot A^{2/3}$

$$M(A,Z) = NM_\text{n} + ZM_\text{p} + Zm_\text{e} - a_\text{v}A + a_\text{s}A^{2/3} + a_\text{c}\frac{Z^2}{A^{1/3}} + a_\text{a}\frac{(N-Z)^2}{4A} + \frac{\delta}{A^{1/2}}$$

$$a_\text{v} = 15.67\ \text{MeV}/c^2$$

$$a_\text{s} = 17.23\ \text{MeV}/c^2$$

$$a_\text{c} = 0.714\ \text{MeV}/c^2$$

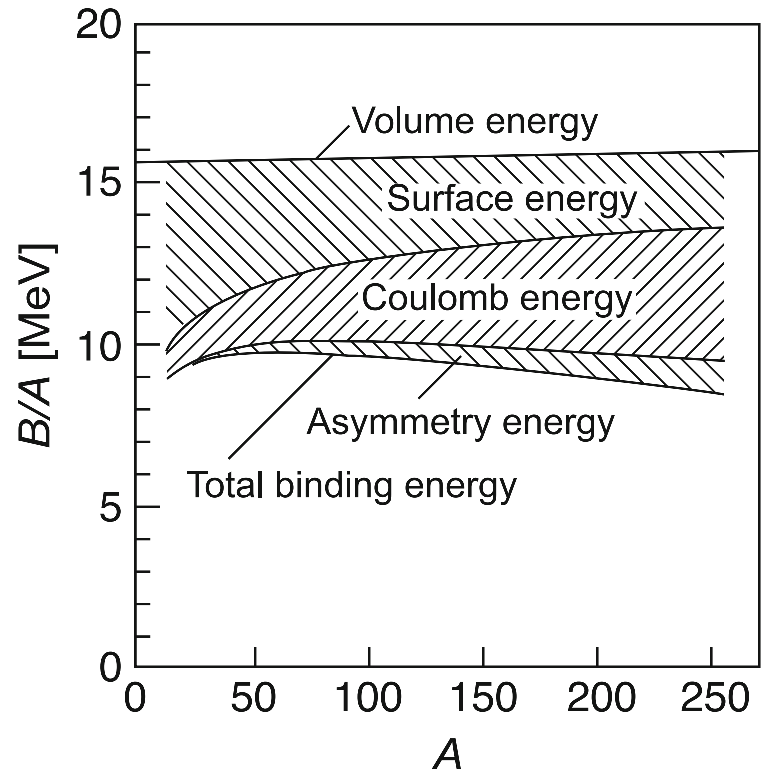
$$a_\text{a} = 93.15\ \text{MeV}/c^2$$

$$\delta = \begin{cases} -11.2\ \text{MeV}/c^2 & \text{for even } Z \text{ and } N \text{ (even-even nuclei)} \\ 0\ \text{MeV}/c^2 & \text{for odd } A \text{ (odd-even nuclei)} \\ +11.2\ \text{MeV}/c^2 & \text{for odd } Z \text{ and } N \text{ (odd-odd nuclei).} \end{cases}$$

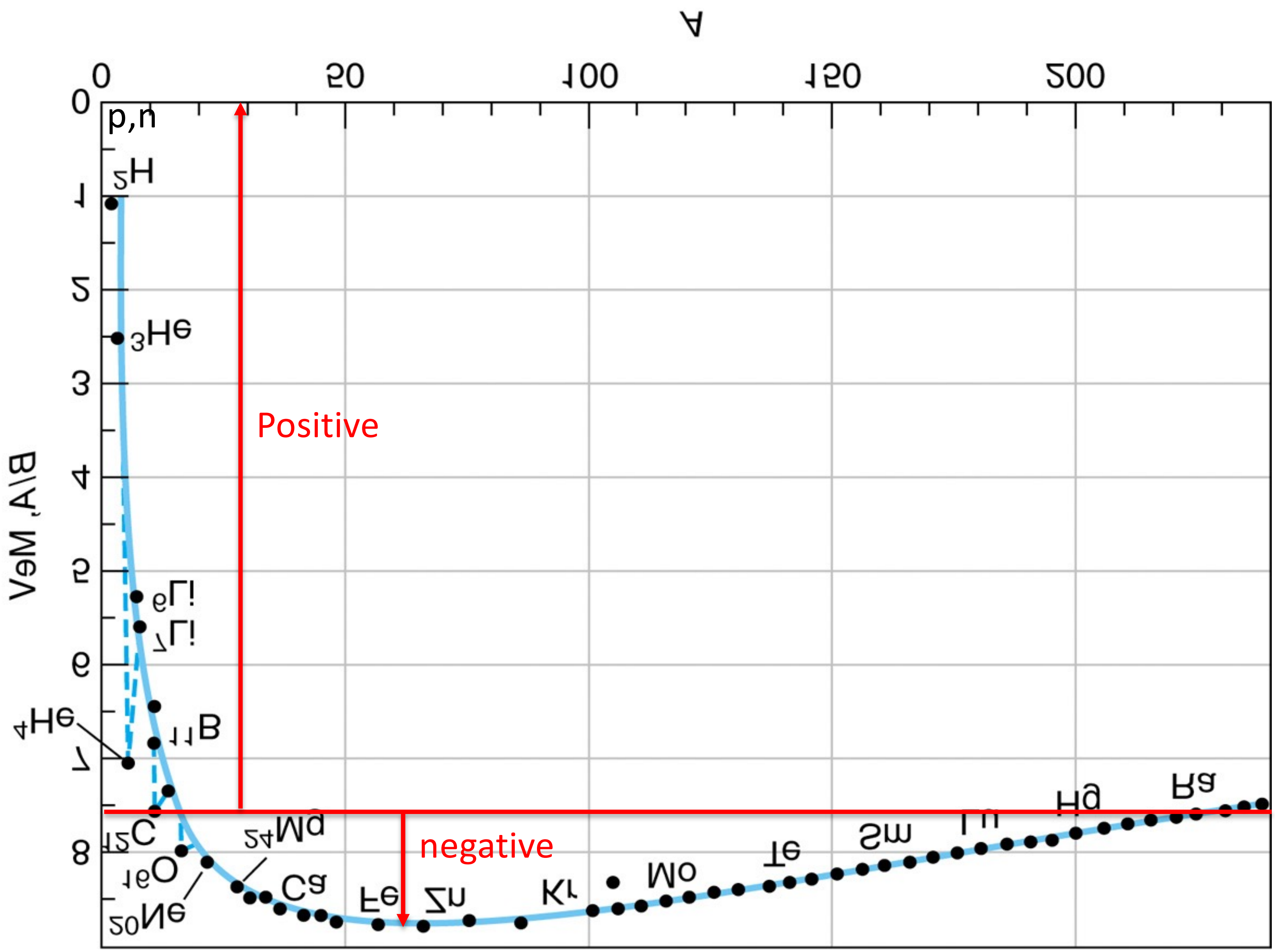
Central (saturation) density:

$$\varrho_0 \approx 0.17\ \text{nucleons/fm}^3 = 3 \cdot 10^{17}\ \text{kg/m}^3$$

Average density: $0.13\ \text{nucleons/fm}^3$

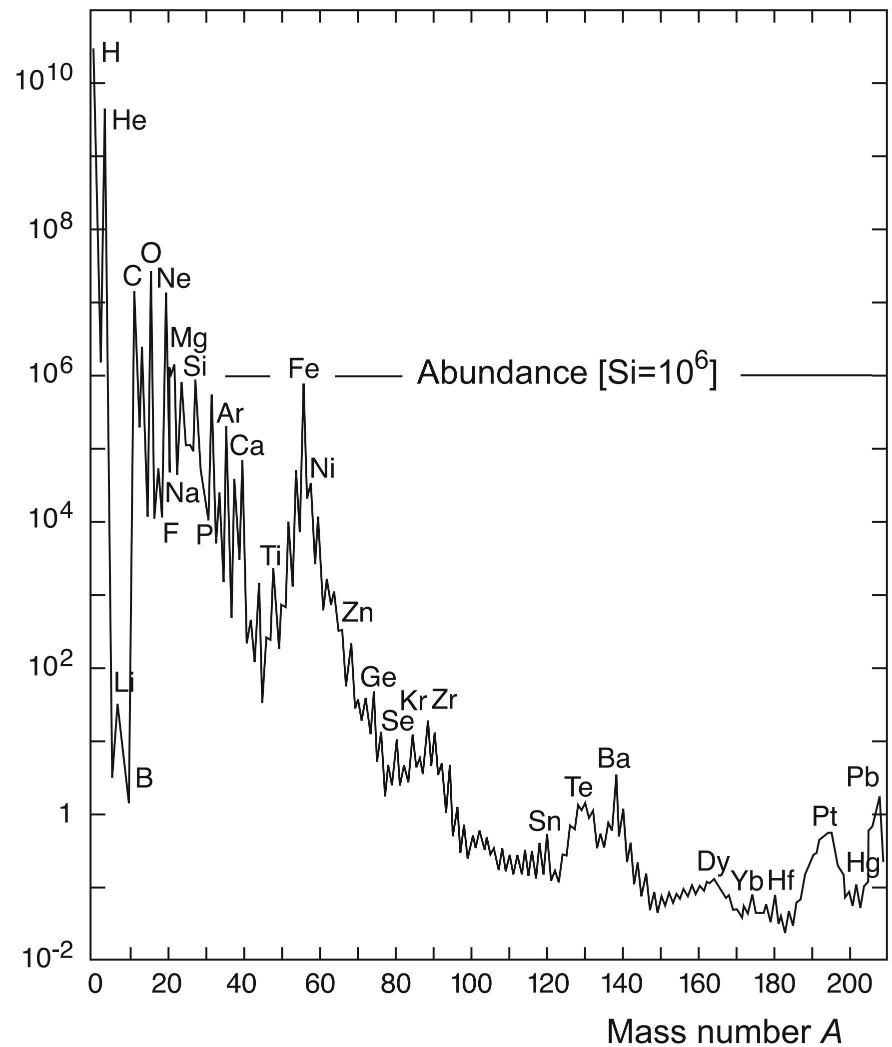


Nuclear Mass excess per nucleon



Partially explains abundance of elements

Fig. 2.2 Abundance of the elements in the solar system as a function of their mass number *A*, normalised to the abundance of silicon (=10^6)



Full explanation requires:

1) INITIAL ("primordial") abundance (nearly all ^1H and ^4He)
2) Reaction path from these to heavier elements (stars and their collapse, supernovae, neutron star mergers,…)