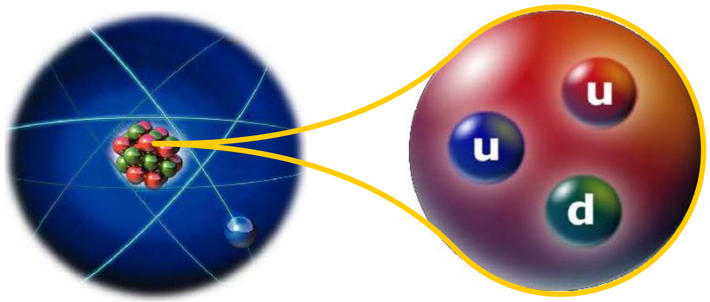
Lectures: Hans-Jürgen Wollersheim

office: 360 phone: 0188 1242294
e-mail: h.j.wollersheim@gsi.de

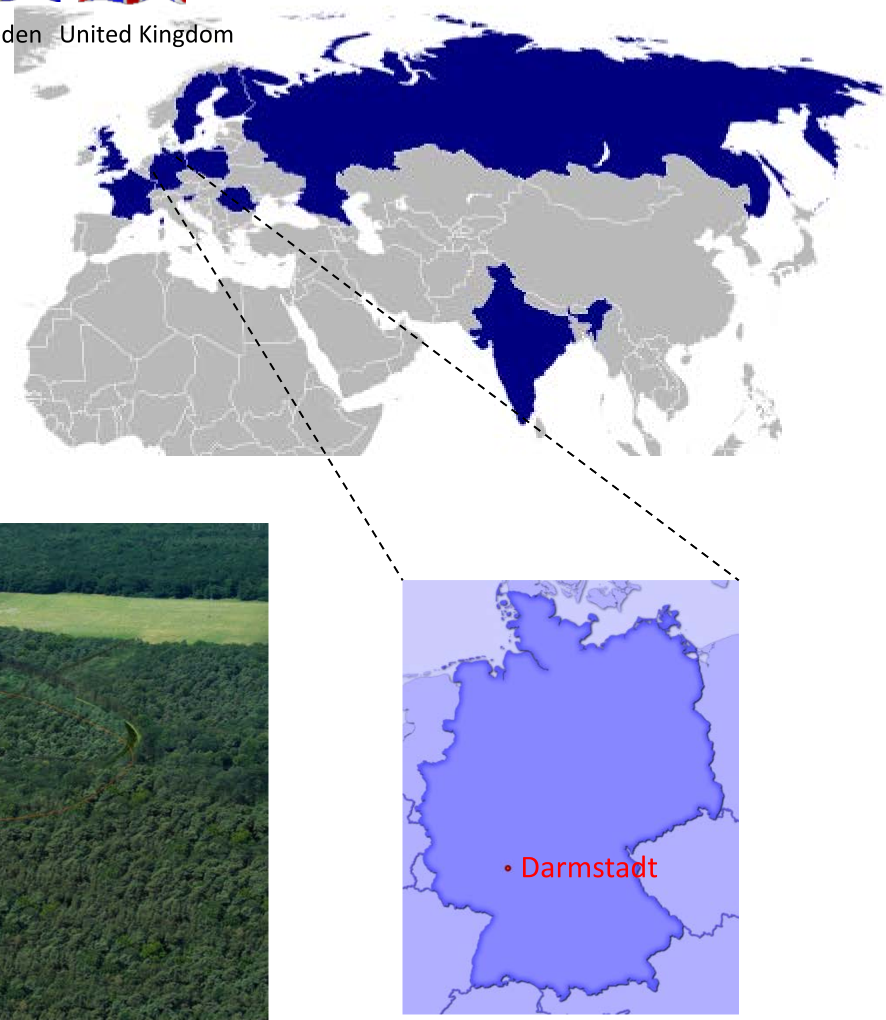
Wednesday	9:55 – 10:45
Thursday	10:50 – 11:40
Friday	11:45 – 12:35
Friday(T)	8:00 – 8:50

Tutor: Kanhaiya Jha (kanhaiya.jha@iitrpr.ac.in)

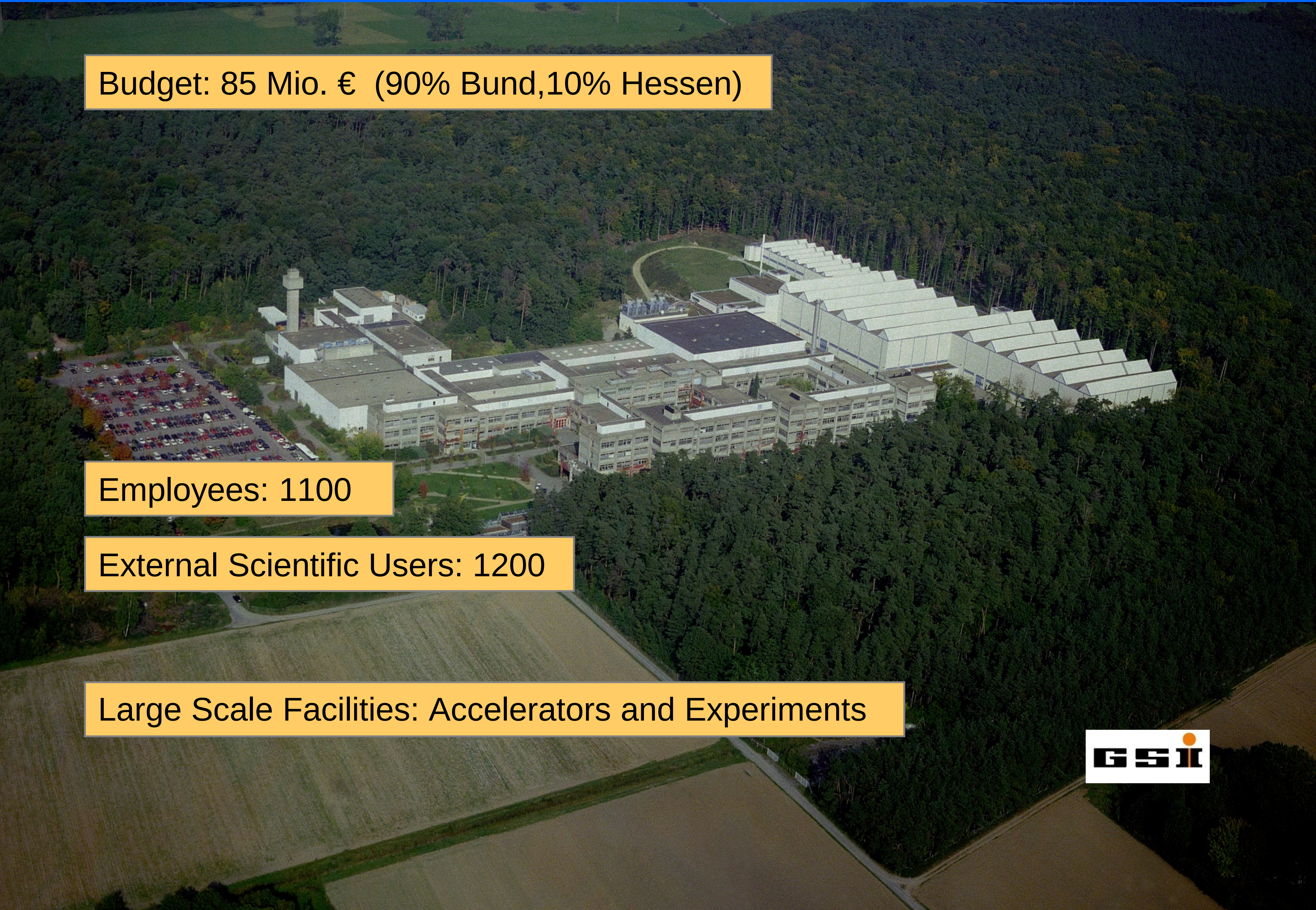


Facility for Antiproton and Ion Research

Finland France Germany India Poland Romania Russia Slovenia Sweden United Kingdom



GSI – Helmholtzzentrum für Schwerionenforschung



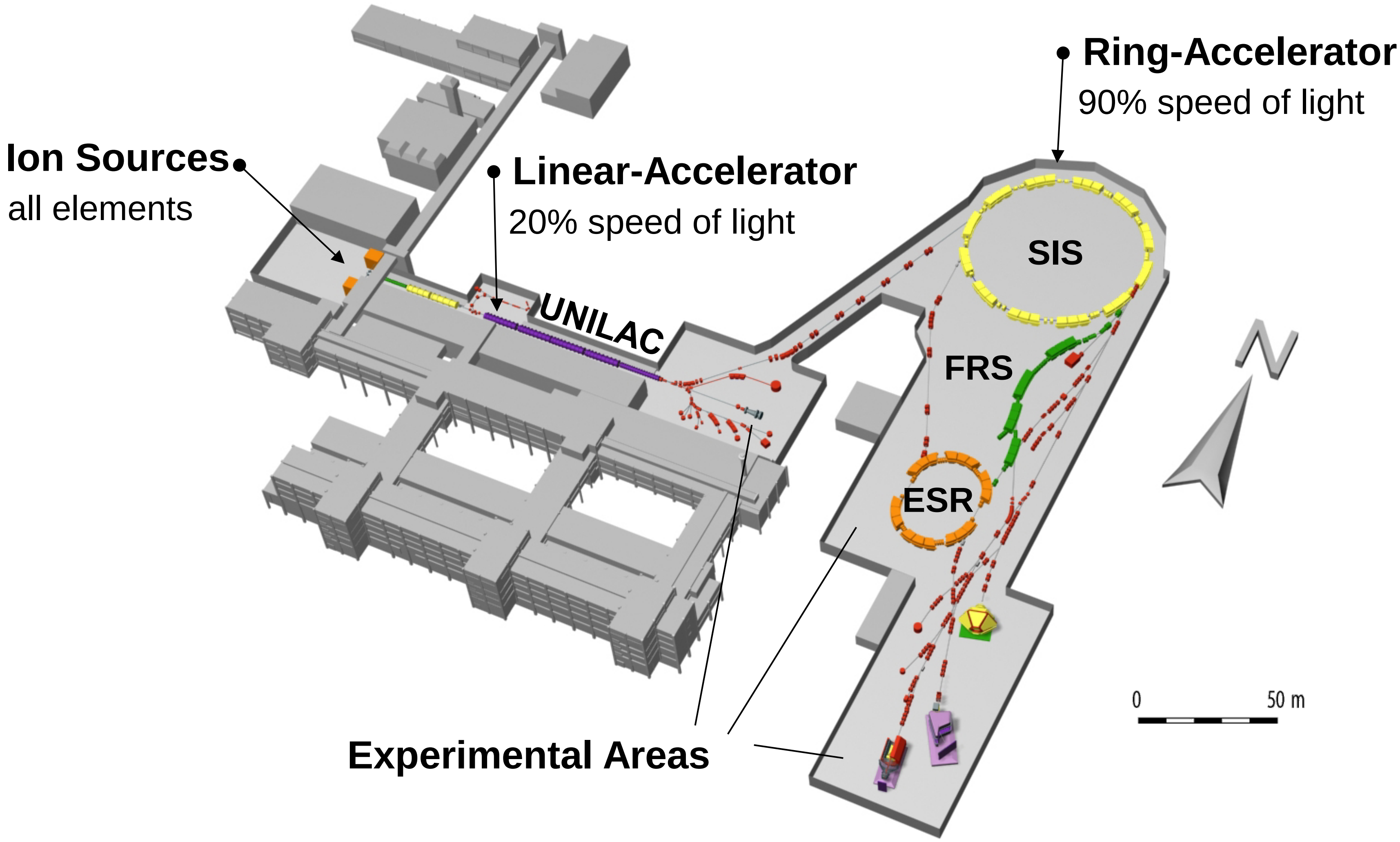
Budget: 85 Mio. € (90% Bund,10% Hessen)

Employees: 1100

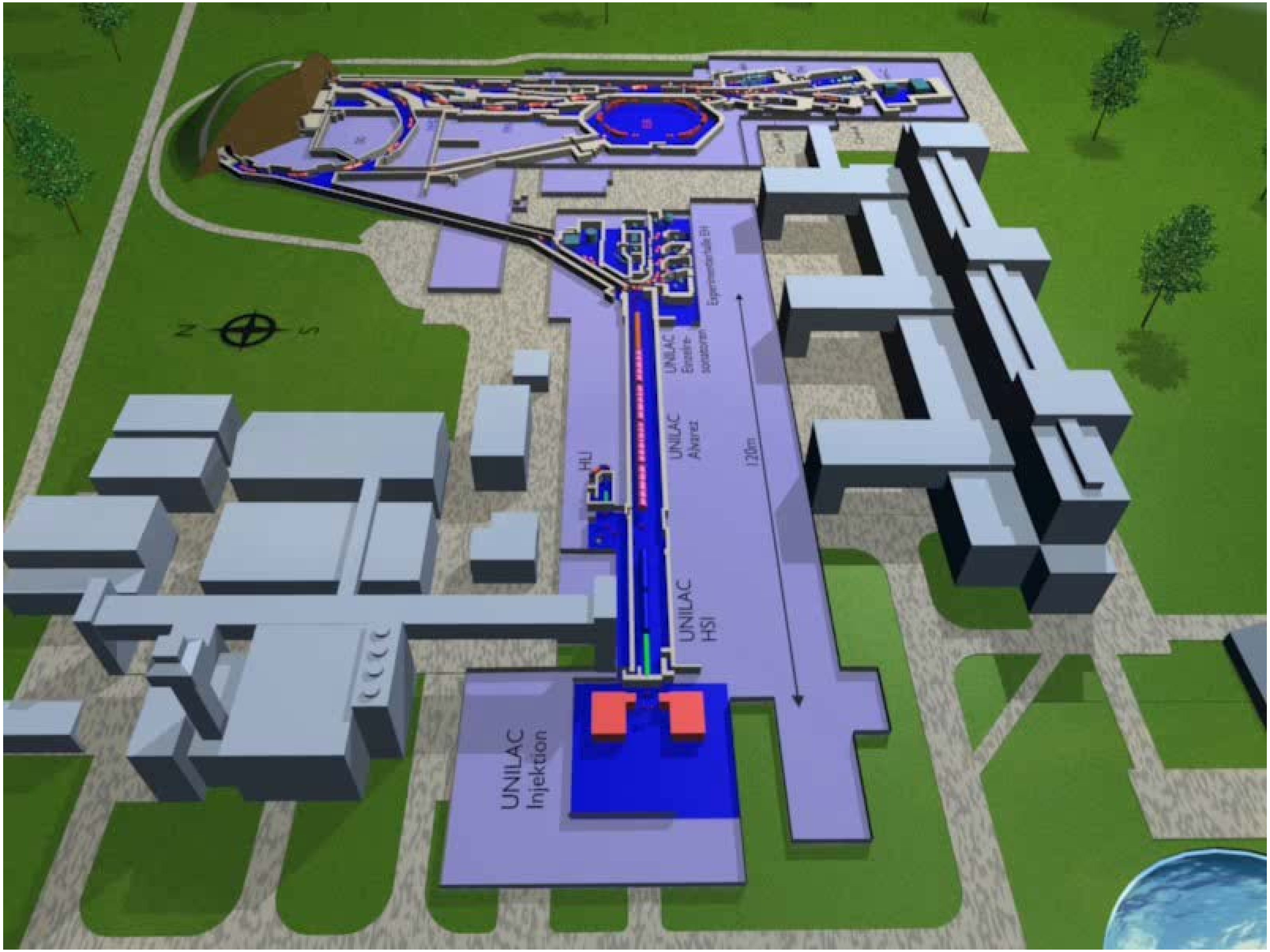
External Scientific Users: 1200

Large Scale Facilities: Accelerators and Experiments

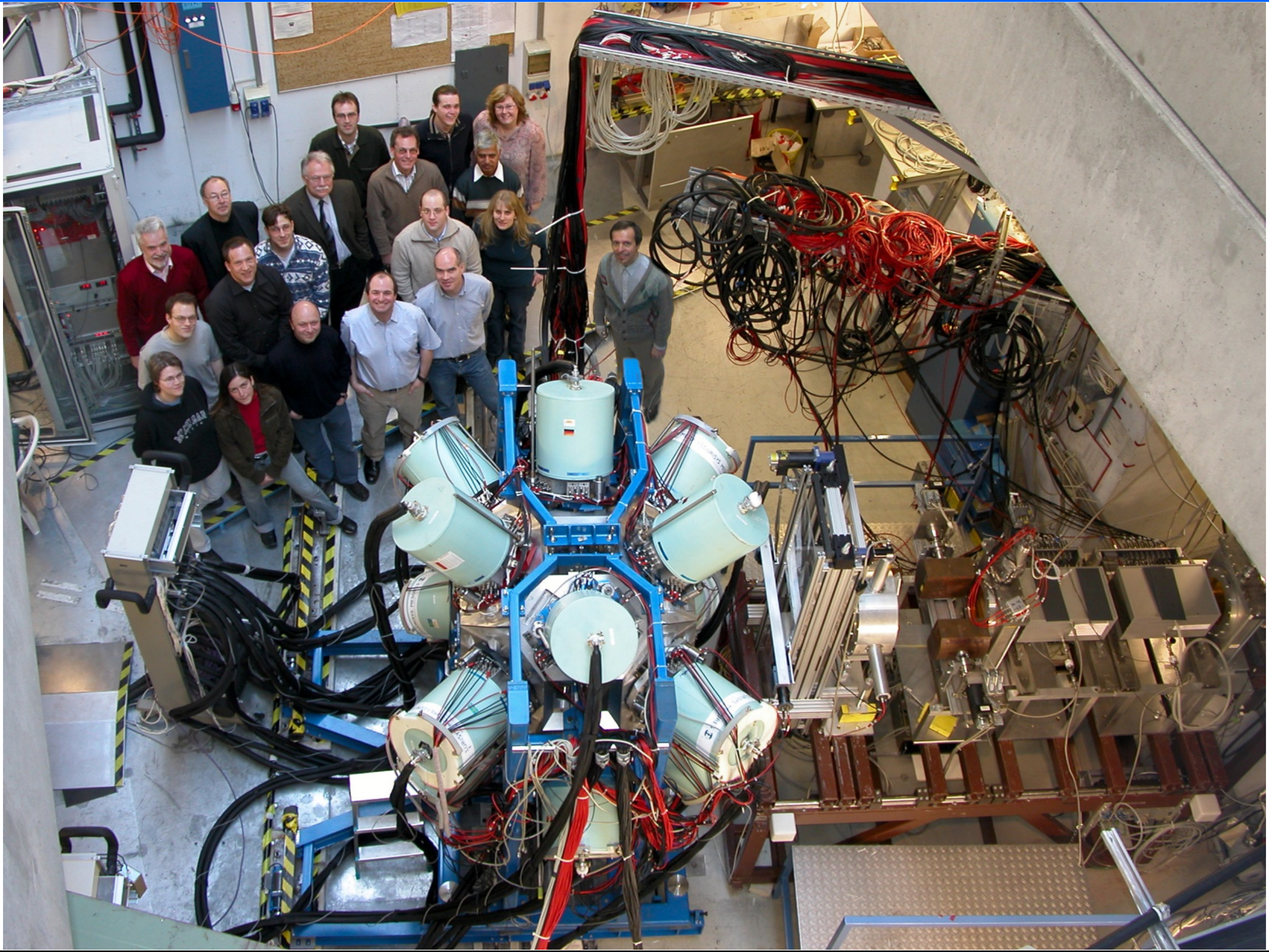
Accelerator Facility



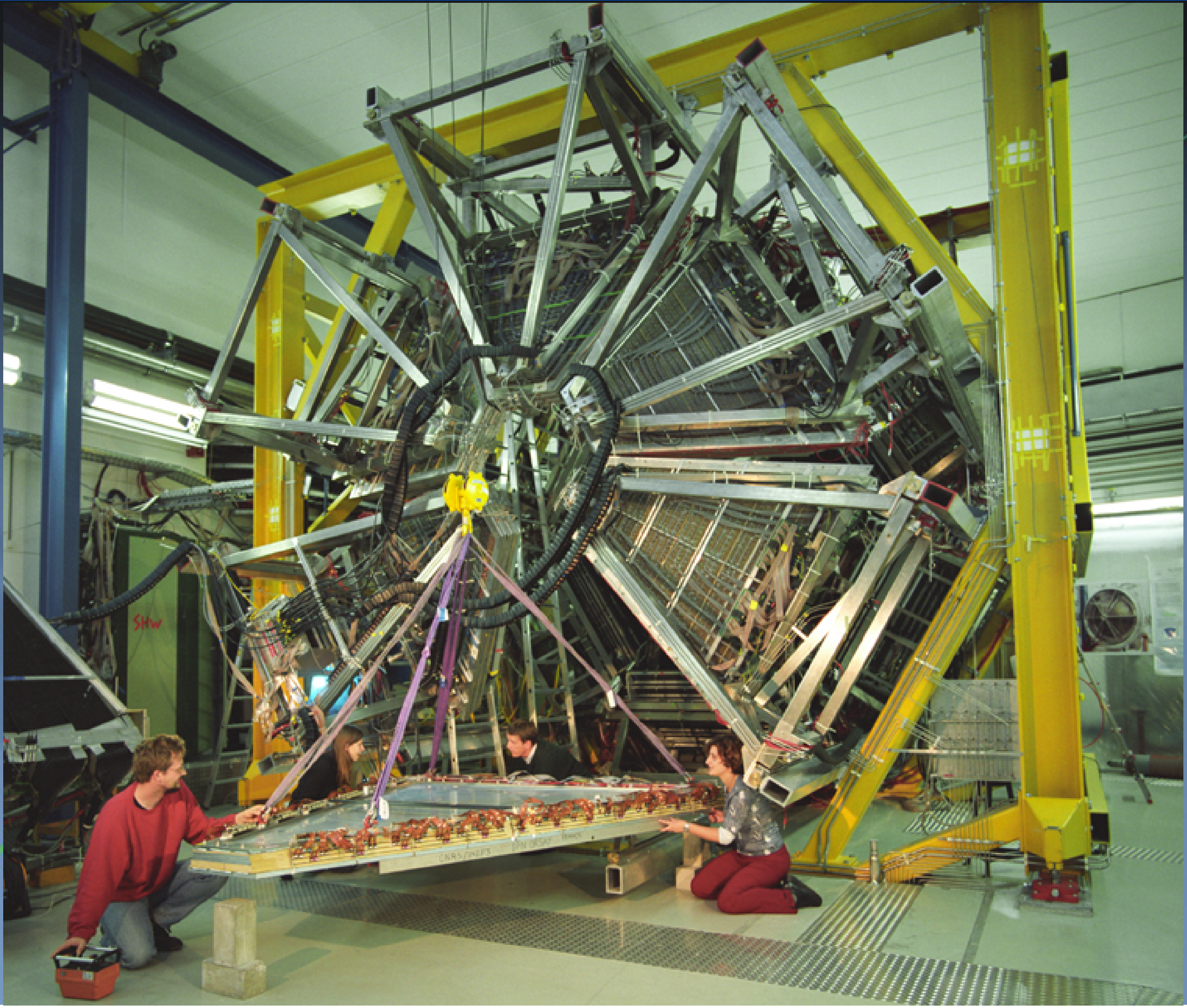
Accelerator Facility



Rare ISotope INvestigation at GSI



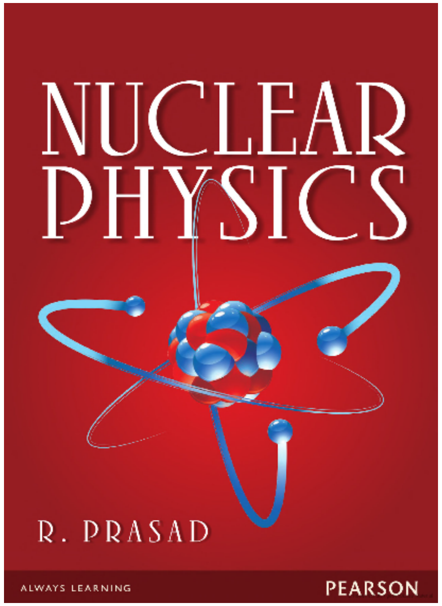
The HADES experiment @ GSI



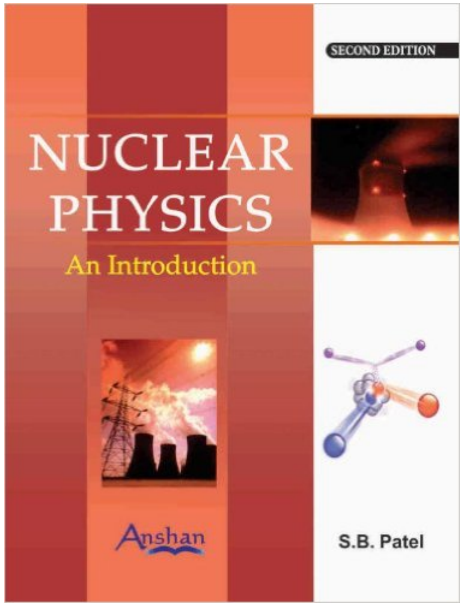
Tentative outline of Nuclear Physics

- **Gross properties of nuclei**
  - Rutherford scattering
  - nuclear radii, masses, and binding energies
  - Bethe-Weizäcker mass formula
  - angular momentum, magnetic moment
- **Radioactivity**
  - α - decay
  - β - decay
  - γ – decay
- **Fundamental forces**
  - nuclear force between nucleons
  - nuclear shell model
  - spherical and deformed nuclei
- **Nuclear reactions**
  - direct reactions
  - fusion reaction

Literature

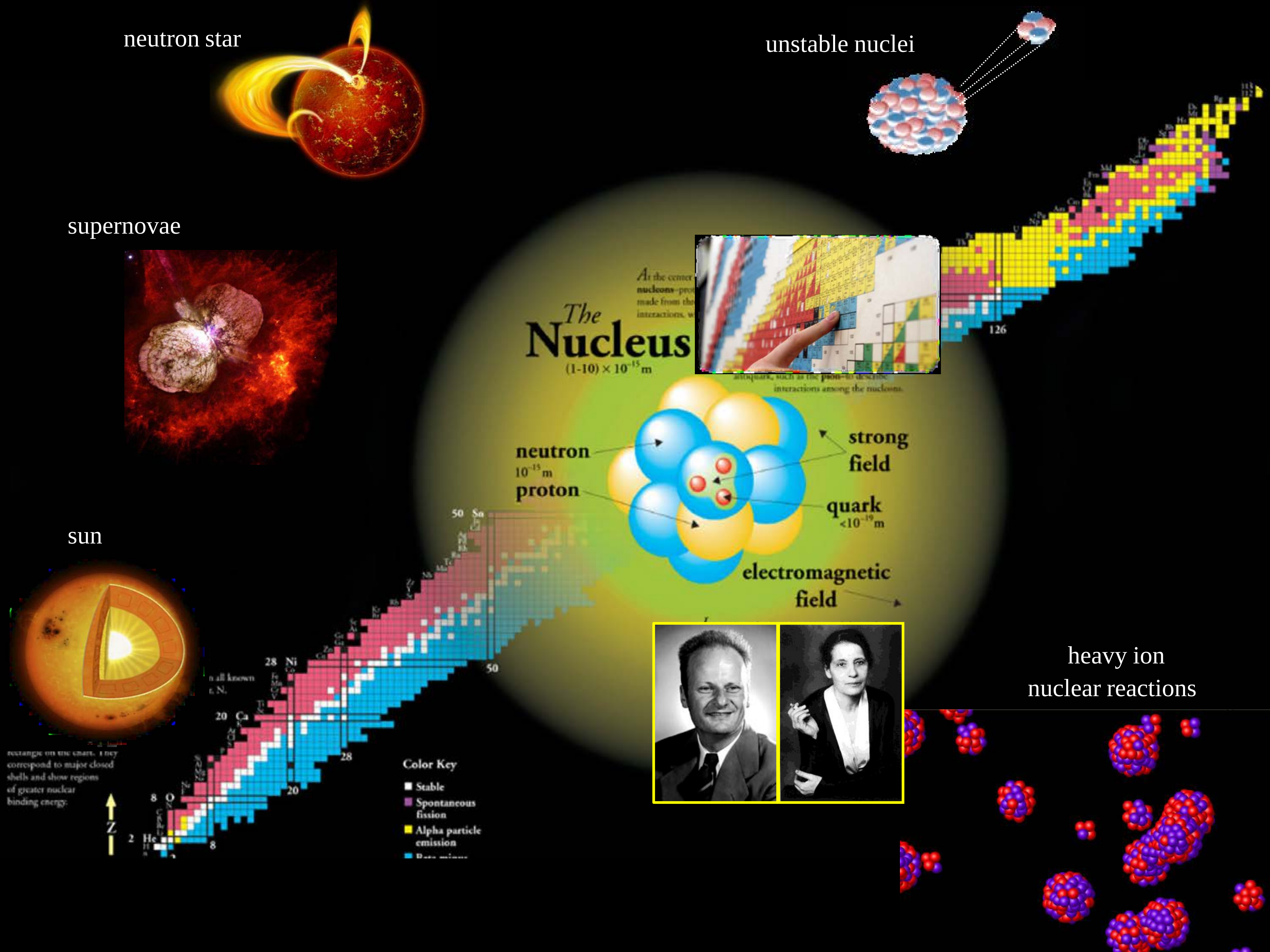


❖ Recommended Textbook



❖ Supplemental Textbook

www.bookzz.org


neutron star
unstable nuclei
supernovae
The Nucleus
(1-10) × 10^-15 m
neutron
10^-15 m
proton
strong
field
quark
<10^-19 m
electromagnetic
field
sun
heavy ion
nuclear reactions
126
50 Sn
50
28 Ni
28
20 Ca
20
8 O
8
2 He
Z
Color Key
Stable
Spontaneous fission
Alpha particle emission

Brief historical overview

in search of the building blocks of the universe ...

Greek philosophers

4 building blocks

earth

air

water

fire

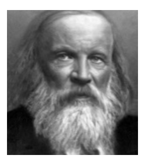
5th BC - Democritus

atomic hypothesis

18th – 19th century Lavoisier, Dalton, ...

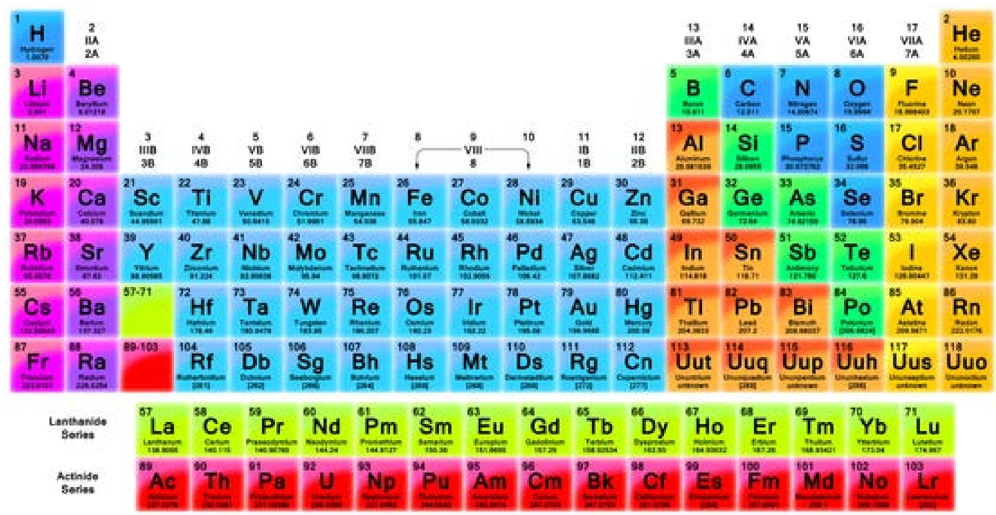
put atomic hypothesis on firm basis
distinction between compounds and pure elements

1896 Dmitri Mendeleev



92 building blocks
(chemical elements)

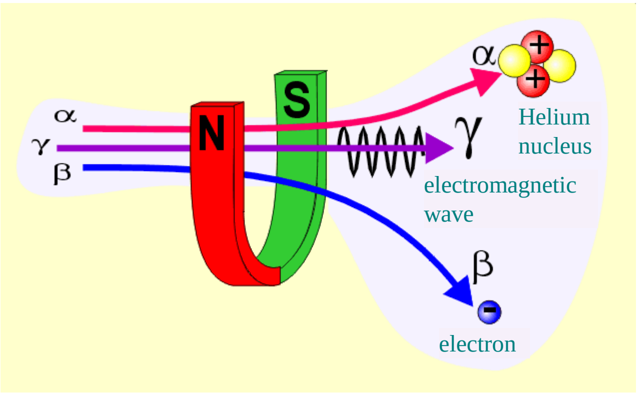
$_1H$, $_2He$, ... $_{92}U$



1896 Henri Becquerel

discovers radioactivity

⇨ emission of radiation from atoms
3 types observed: α, β and γ



α and β deflected in opposite direction ⇨ opposite charges
α deflected less than β ⇨ α must have larger mass
γ not deflected ⇨ uncharged

~1900 Ernest Rutherford

investigates new radiation

"... it was as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you"

α and β emissions change nature of element
α's charge = +2e   α's mass ~ 4H
β radiation = electrons
γ = electromagnetic radiation (photons)

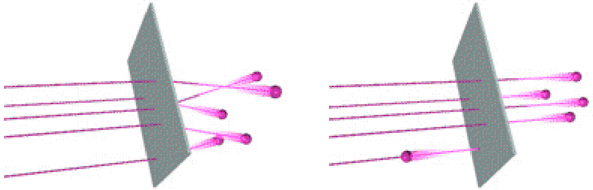
1911 Ernest Rutherford tests Thomson's model of the atom

N electrons (-e·N) embedded in (+e·N) charge uniformly distributed over atomic volume

"plum pudding model"

expected: α's ($_2$He) pushed a little to the side by charges of atom ($_{79}$Au)

observed: some α's deflected backwards to 180^0!!

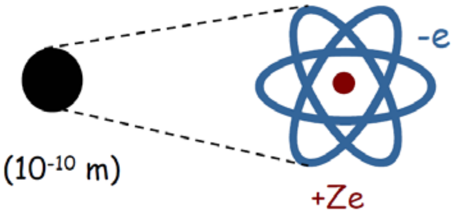


1913 Niels Bohr

planetary model of atom

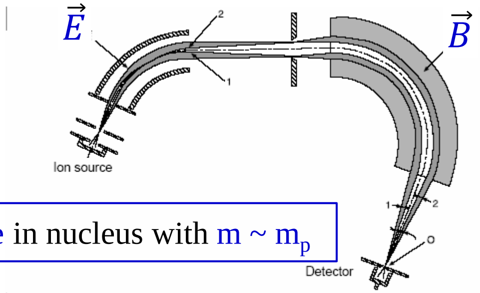
all positive charges (and ~ all mass) concentrated in tiny region at the center

Atom = nucleus + electron



1920 Francis William Aston mass spectrograph ⇨ measures masses of atoms

mass	charge
He ~ 4 H	He = 2 H
C ~ 12 H	C = 6 H
O ~ 16 H	O = 8 H



hypothesis of neutral particle in nucleus with $m \sim m_p$

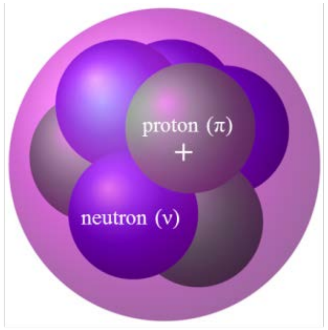
1925 Werner Heisenberg

quantum mechanic
simplest atom = H
its nucleus = proton

1932 James Chadwick

discovers the neutron

3 building blocks
electron + proton + neutron

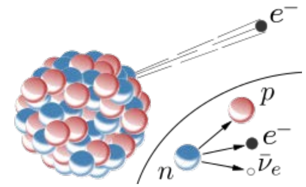


~ 10^{-15} m = fm

⇨ NUCLEAR PHYSICS

<u>1932</u> Enrico Fermi

developed the theory of β-decay

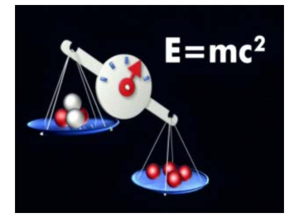


<u>1934</u> Irene Joliot-Curie & Frederic Joliot

artificial radioactivity $^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P^{*} + 1n$

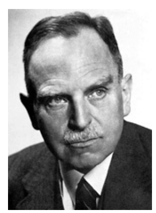
<u>1934</u> Hans Bethe

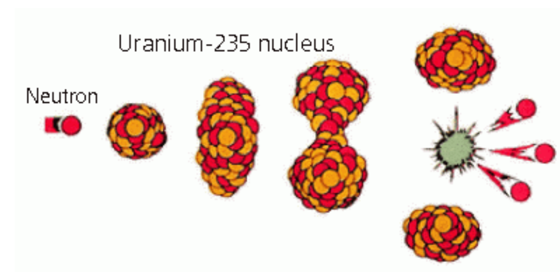
liquid drop model and mass formula



<u>1938</u> Otto Hahn, Lise Meitner & Fritz Strassmann

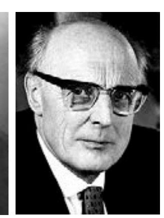
discover nuclear fission

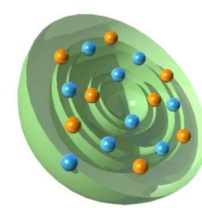




<u>1948</u> Maria Goeppert-Mayer & J. Hans D. Jensen

develop the nuclear shell model



Brief historical overview

in search of the building blocks of the universe

1953 Aage Niels Bohr, Ben Roy Mottelson, Leo James Rainwater

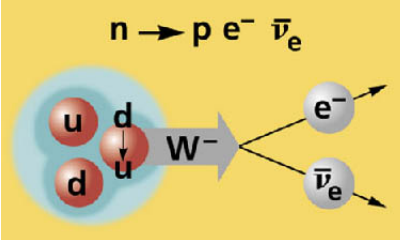
developed the collective nuclear model

1956 Frederick Reines & Clyde L. Cowan

discovery of the neutrino

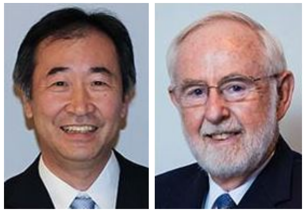
1983 Carlo Rubbia

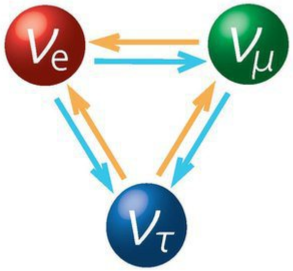
discovery of the W and Z Boson



1998 Takaaki Kajita & Arthur B. McDonald

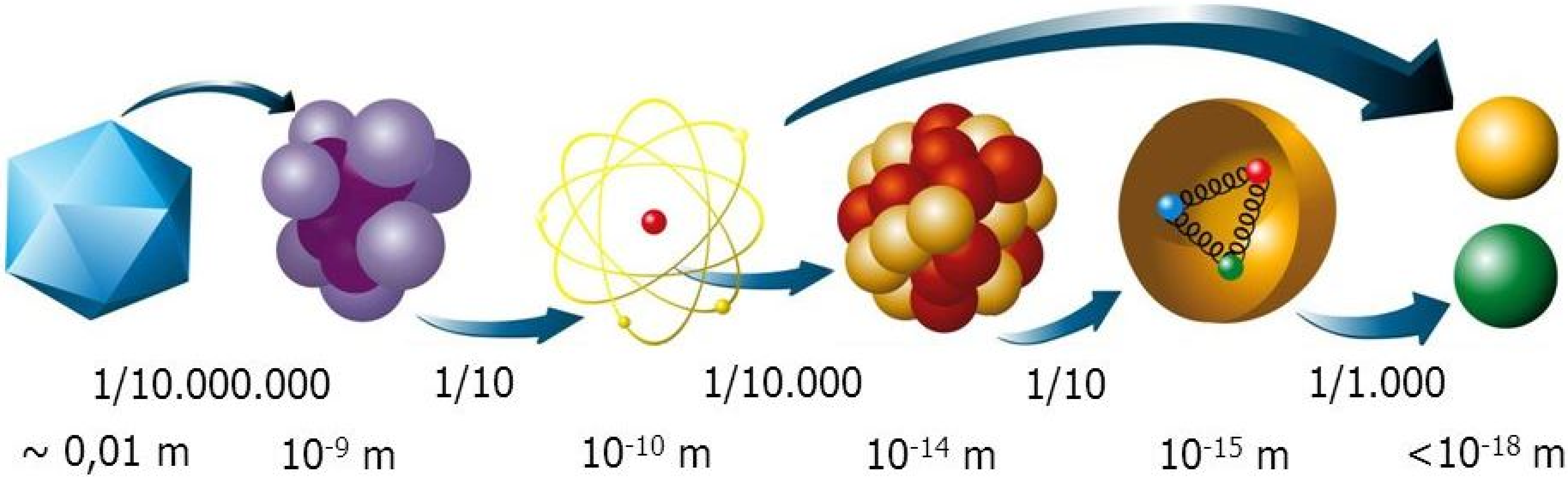
discovery of neutrino oscillations ⇨ neutrinos must have some mass





So ... Where Do We Start?

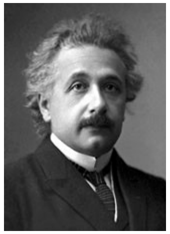
We need a point of reference to start discussing nuclear physics.



crystal molecule atom **nucleus** proton quark

Nuclear units

- length unit:
  Fermi = femtometer = fm = 10^{-15} [m]
- energy unit:
  MeV = 10^6 eV = $10^6 \cdot 1.602 \cdot 10^{-19}$ CV = $1.602 \cdot 10^{-13}$ [J]
- mass unit:
  1 u = $1/12 \cdot m[^{12}C]$ = 931.49432 MeV/c^2 = $1.66054 \cdot 10^{-27}$ [kg]
- time unit:
  [s] or [fm/c] ≈ $3 \cdot 10^{-24}$ [s]



Albert Einstein
1879-1955
Nobel price 1921

$$E = m \cdot c^2$$

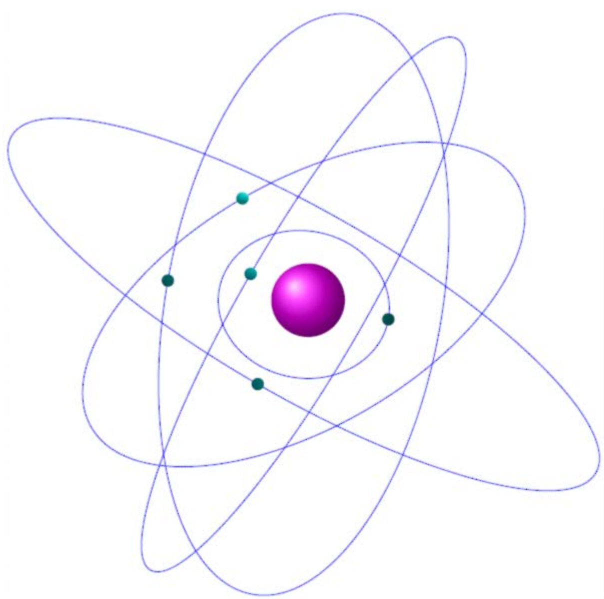
Constant of nature relevant to nuclear physics

- speed of light in vacuum, c = $2.99792458 \cdot 10^8$ [m/s]
- Planck's constant / 2π = ħ = $6.58211889 \cdot 10^{-22}$ [MeV s] = 1.054·10-34 [J s]
- ħc = 197.3269602 [MeV fm]
- fine structure constant (dimensionless), $\alpha = e^2/(\hbar c)$ = 1/137.0359976
  → $e^2 = \alpha \cdot \hbar c$ = 1.4399643929 [MeV fm]
- elementary charge, e = $1.602 \cdot 10^{-19}$ [C] or e = 1.1999851636 $\left[\sqrt{MeV\ fm}\right]$
- rest energy of proton, $m_p c^2$ = 938.27231 [MeV]
- rest energy of neutron, $m_n c^2$ = 939.56563 [MeV]
- rest energy of electron, $m_e c^2$ = 0.51099906 [MeV]
- Avogadro's number, $N_A = 6.0221367 \cdot 10^{23}$ /mol

- E – p relationship: $E^2 = p^2c^2 + {m_0}^2c^4$
- Kinetic energy: $T = E - m_0c^2 = m_0c^2(\gamma - 1)$

The atom

❖ atom is a neutral system

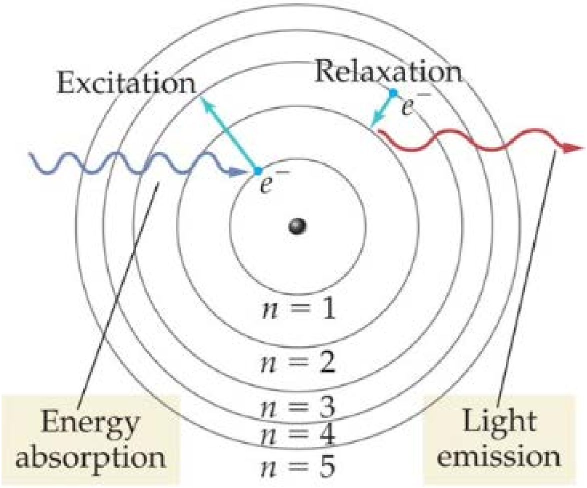


~ 10^{-10} m

atomic excitations

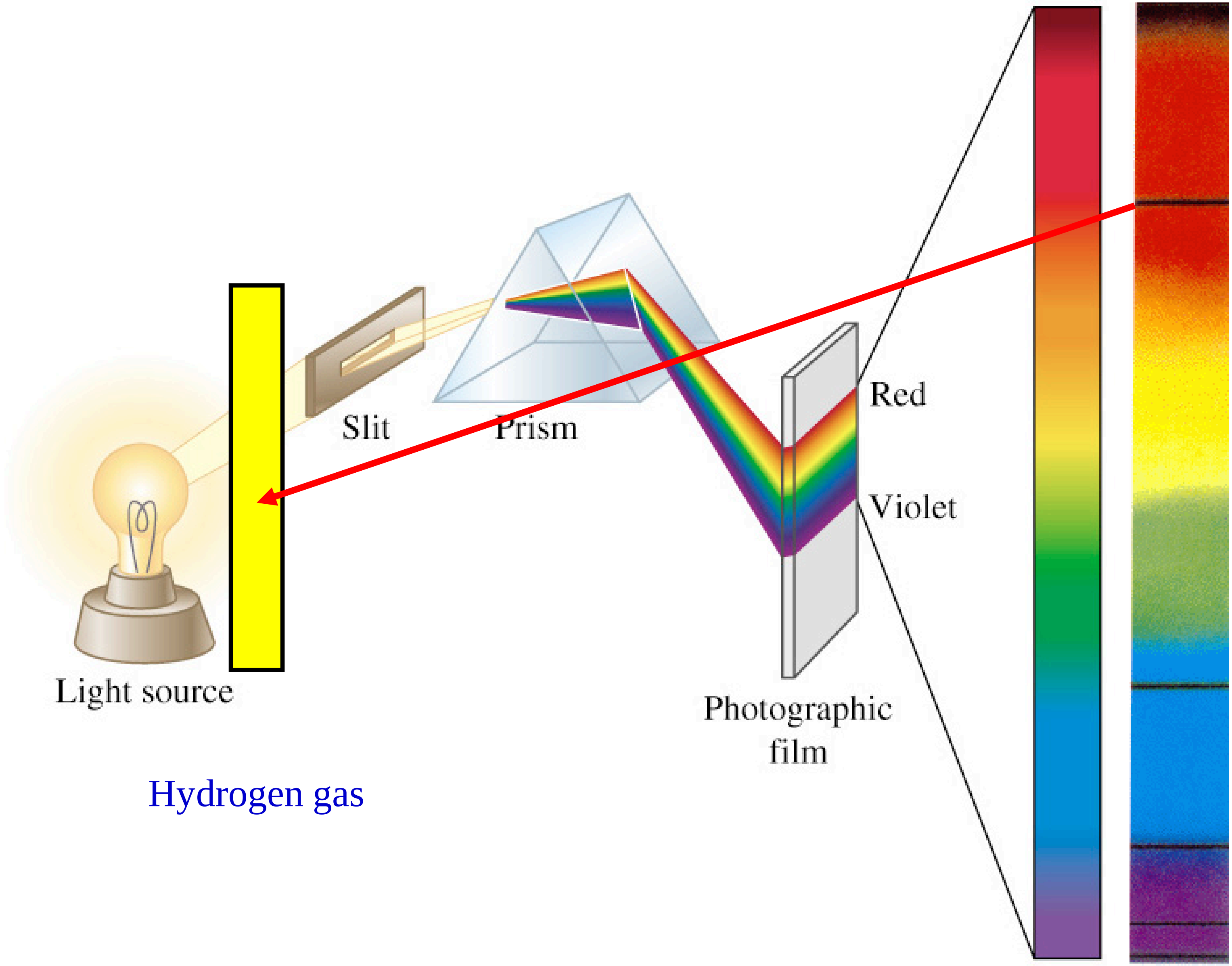
~ 1-10^5 eV

caused by transitions between electronic states



Bohr atomic model

absorption spectrum



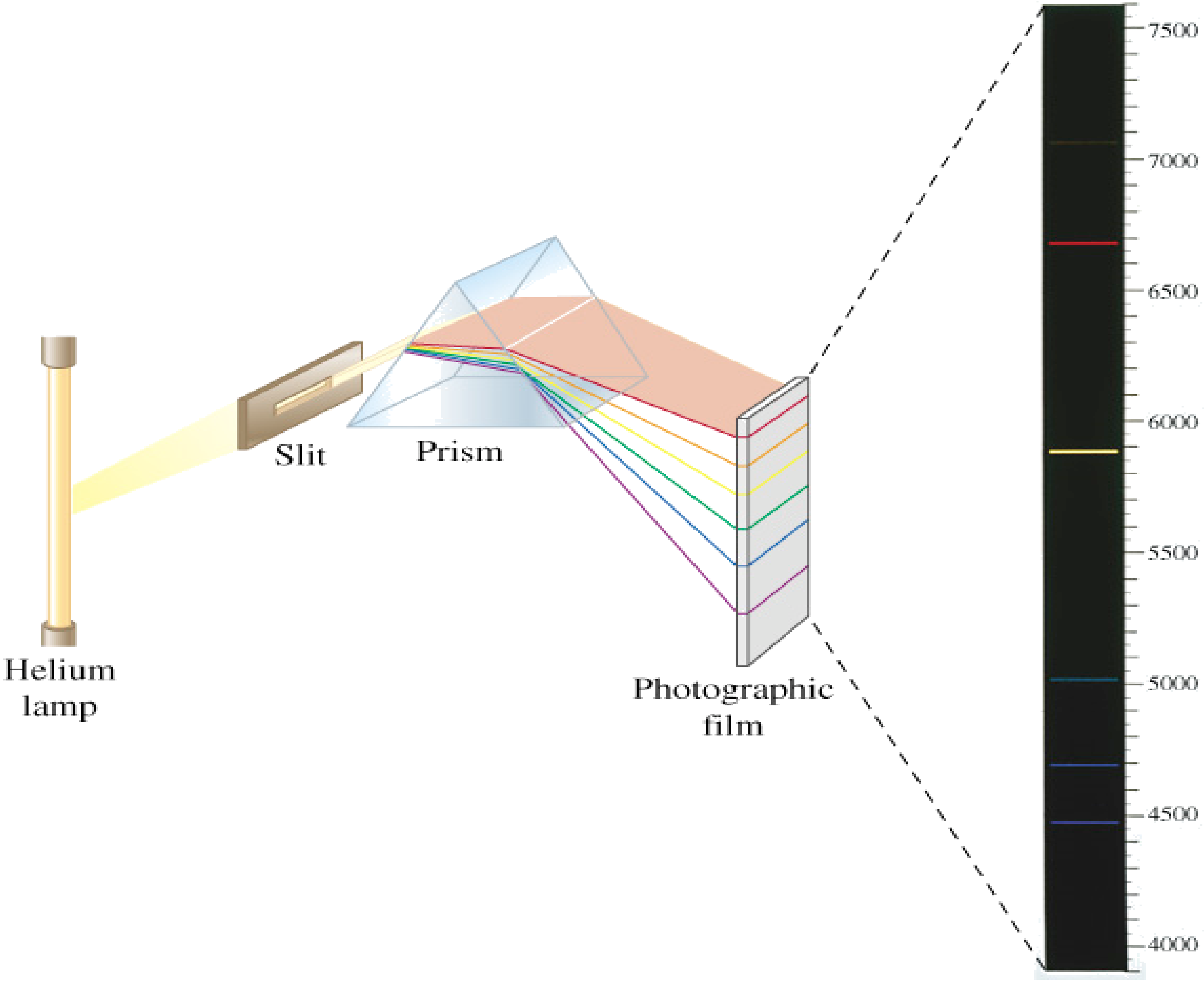
Hydrogen gas

Hydrogen

absorption spectrum

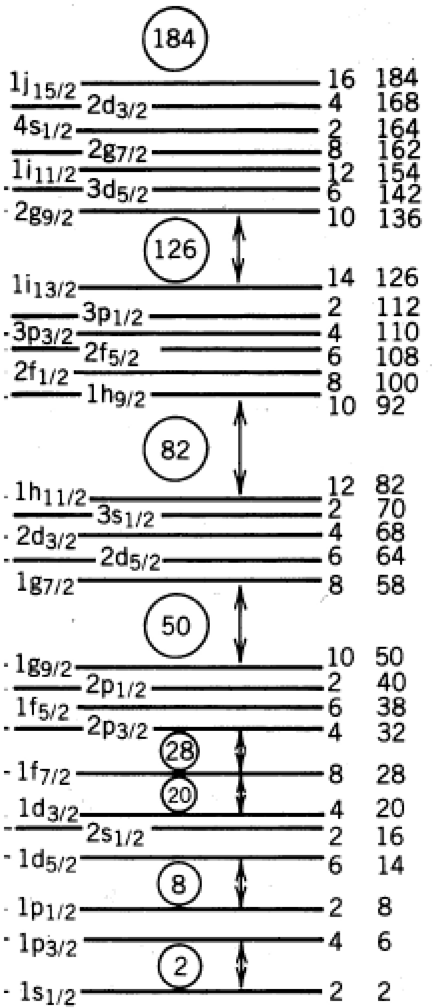
Bohr atomic model

emission spectrum

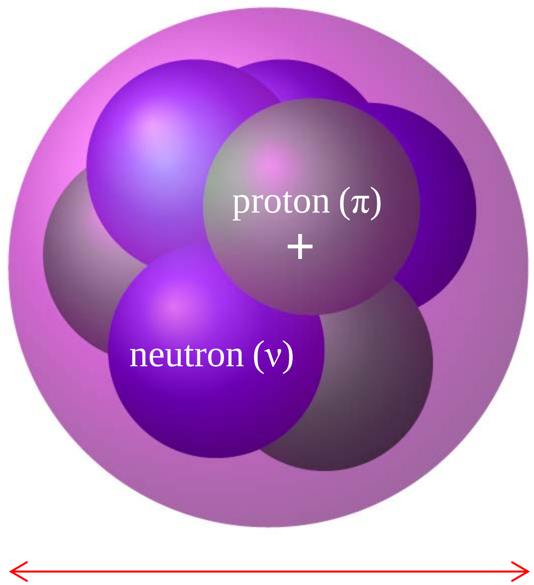


Helium

emission spectrum



nuclear shell model



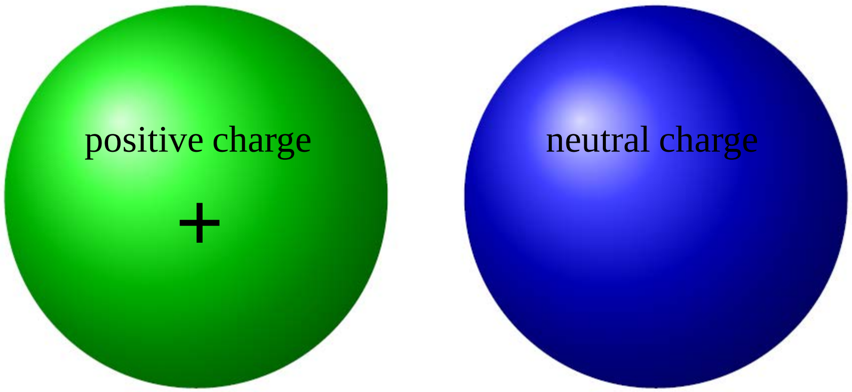
~ 10^{-15} m = fm

nuclear excitations
~ 10^5-10^8 eV

caused by transitions between nuclear states

excitations can be caused by individual nucleons or as a collective motion of the nucleus

Inside the atomic nucleus

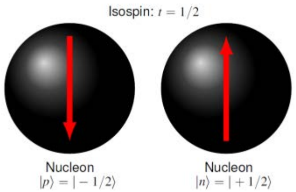


proton neutron

protons and neutrons are very similar, they can be classified as the same object: **the nucleon**

Nucleons are quantum mechanical objects:

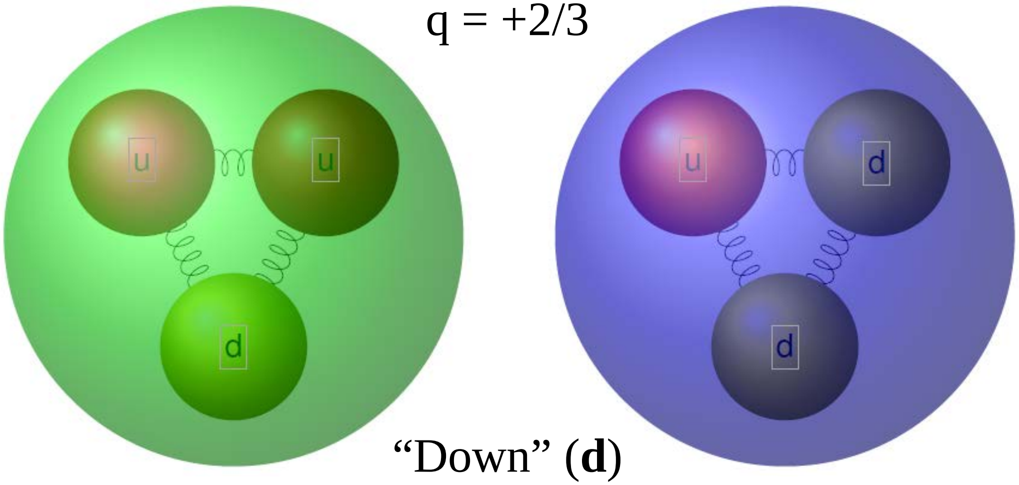
- They are spin ½ Fermions
- Radius: $r \sim 1 \cdot 10^{-15}$ m, or 1 fm (fermi)
- Charge: p → + e
  n → 0
- Mass: p → 938.27 MeV/c^2
  n → 939.56 MeV/c^2
- Isospin: |p > = | -1/2 >
  |n > = | +1/2 >



Structure of nucleons

particle excitations
> 10^9 eV

“Up” (**u**)
m = 2.4 MeV/c^2
q = +2/3



“Down” (**d**)
m = 4.8 MeV/c^2
q = -1/3

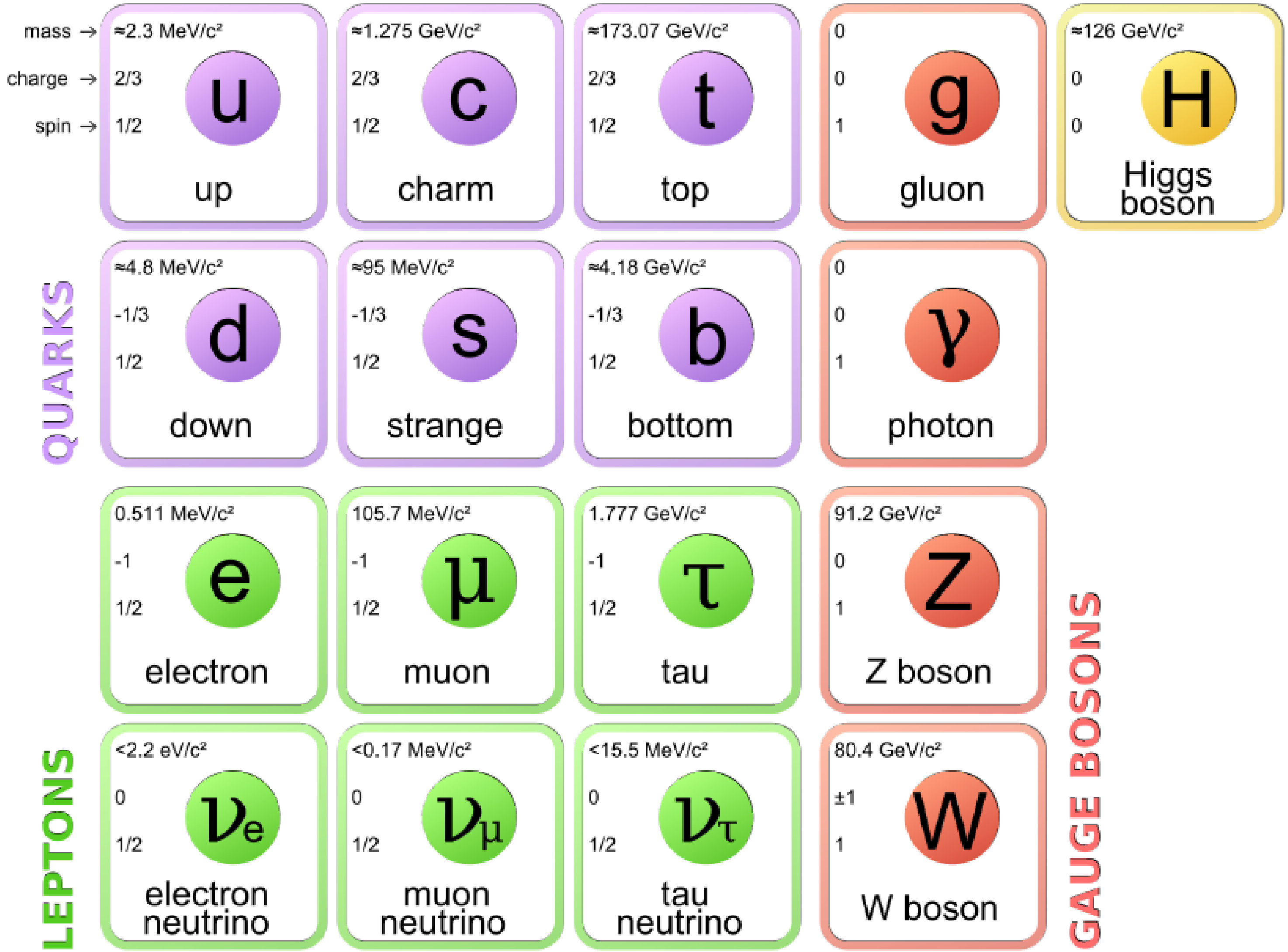
proton

u, u, d

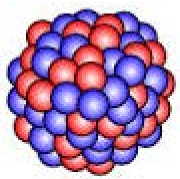
neutron

u, d, d

Elementary particles of the standard model



Terminology



A – mass number gives the number of nucleons in the nucleus
Z – number of protons in the nucleus (atomic number)
N – number of neutrons in the nucleus

A = **Z** + **N**

In nuclear physics, nucleus is denoted as $^{A}_{Z}X$, where X is the chemical element
e.g. $^{1}_{1}H$ - hydrogen, $^{12}_{6}C$ - carbon, $^{197}_{79}Au$ - gold.

Different combinations of Z and N (or Z and A) are called nuclides

- nuclides with the same mass number **A** are called *isobars* — $^{17}_{7}N, ^{17}_{8}O, ^{17}_{9}F$
- nuclides with the same atomic number **Z** are called *isotopes* — $^{12}_{6}C, ^{13}_{6}C, ^{14}_{6}C$
- nuclides with the same neutron number **N** are called *isotones* — $^{13}_{6}C, ^{14}_{7}N$
- nuclides with equal proton number and equal mass number, but different excited states are called *nuclear isomers* — $^{180}_{73}Ta, ^{180m}_{73}Ta$

The most long-lived non-ground state nuclear isomer is tantalum-180m, which has a half-life in excess of 1000 trillion years

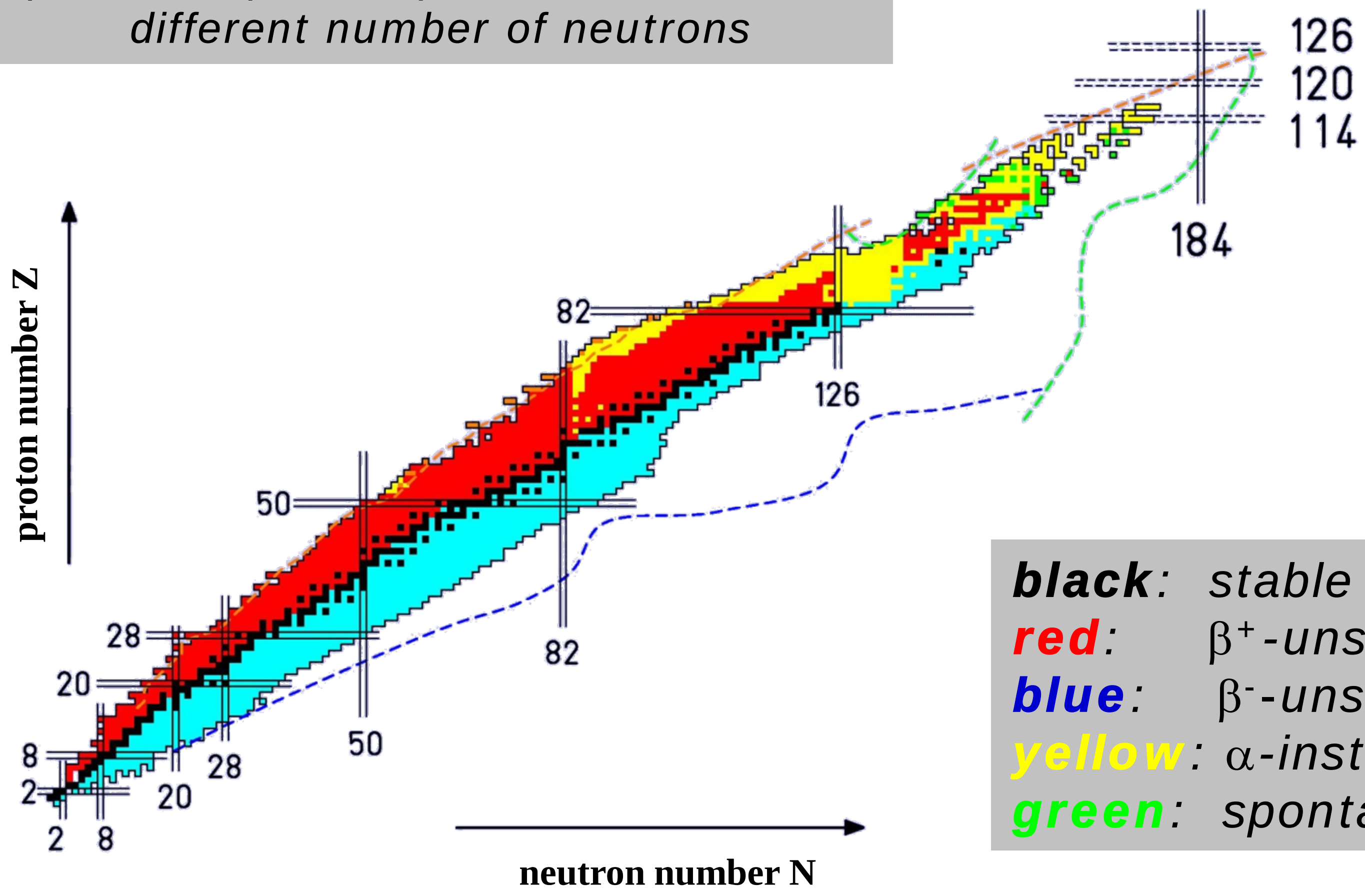
The Chart of Nuclides

- the "Playground" for Nuclear Physics

chart of nuclides:

-representation of isotopes in the Z-N plane

-isotope: atom (nucleus) of an element with different number of neutrons



black*: stable isotope*

red*: β^+-unstable isotope*

blue*: β^--unstable isotope*

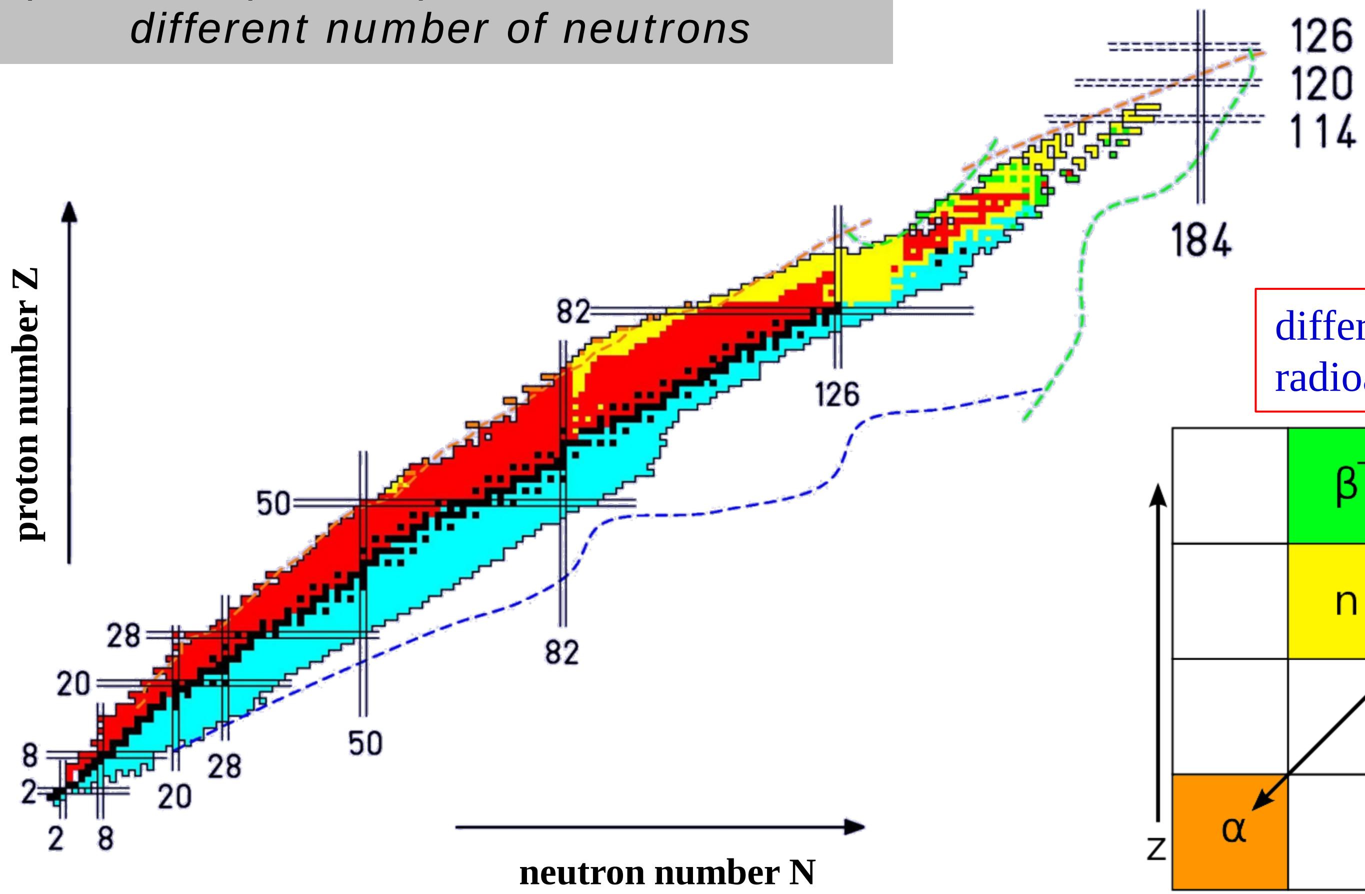
yellow*: α-instable isotope*

green*: spontaneous fission*

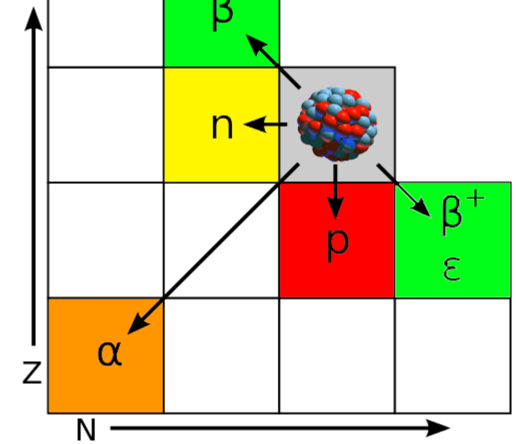
chart of nuclides:

-representation of isotopes in the Z-N plane

-isotope: atom (nucleus) of an element with different number of neutrons



different modes of radioactive decay



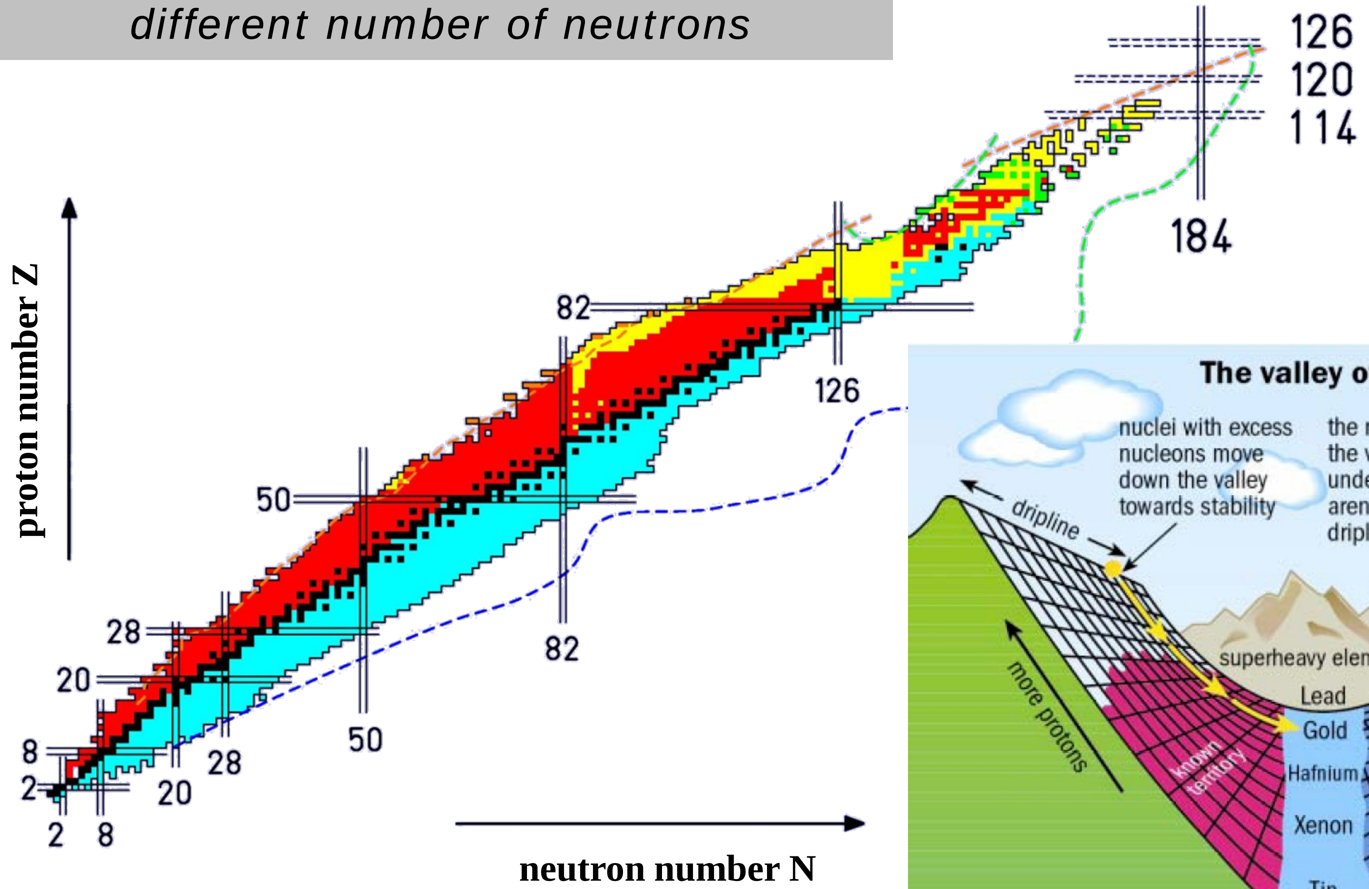
The Chart of Nuclides

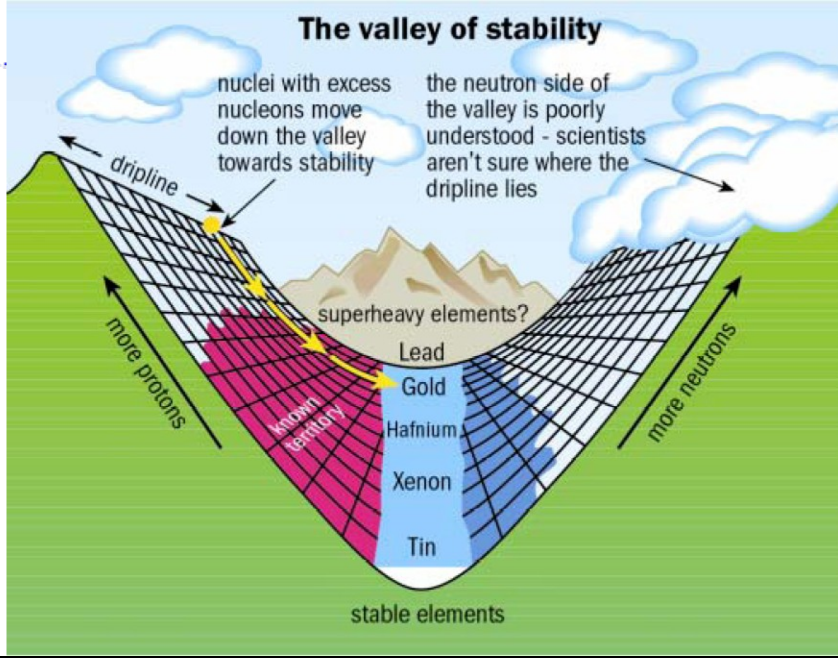
- the “Playground” for Nuclear Physics

chart of nuclides:

-representation of isotopes in the Z-N plane

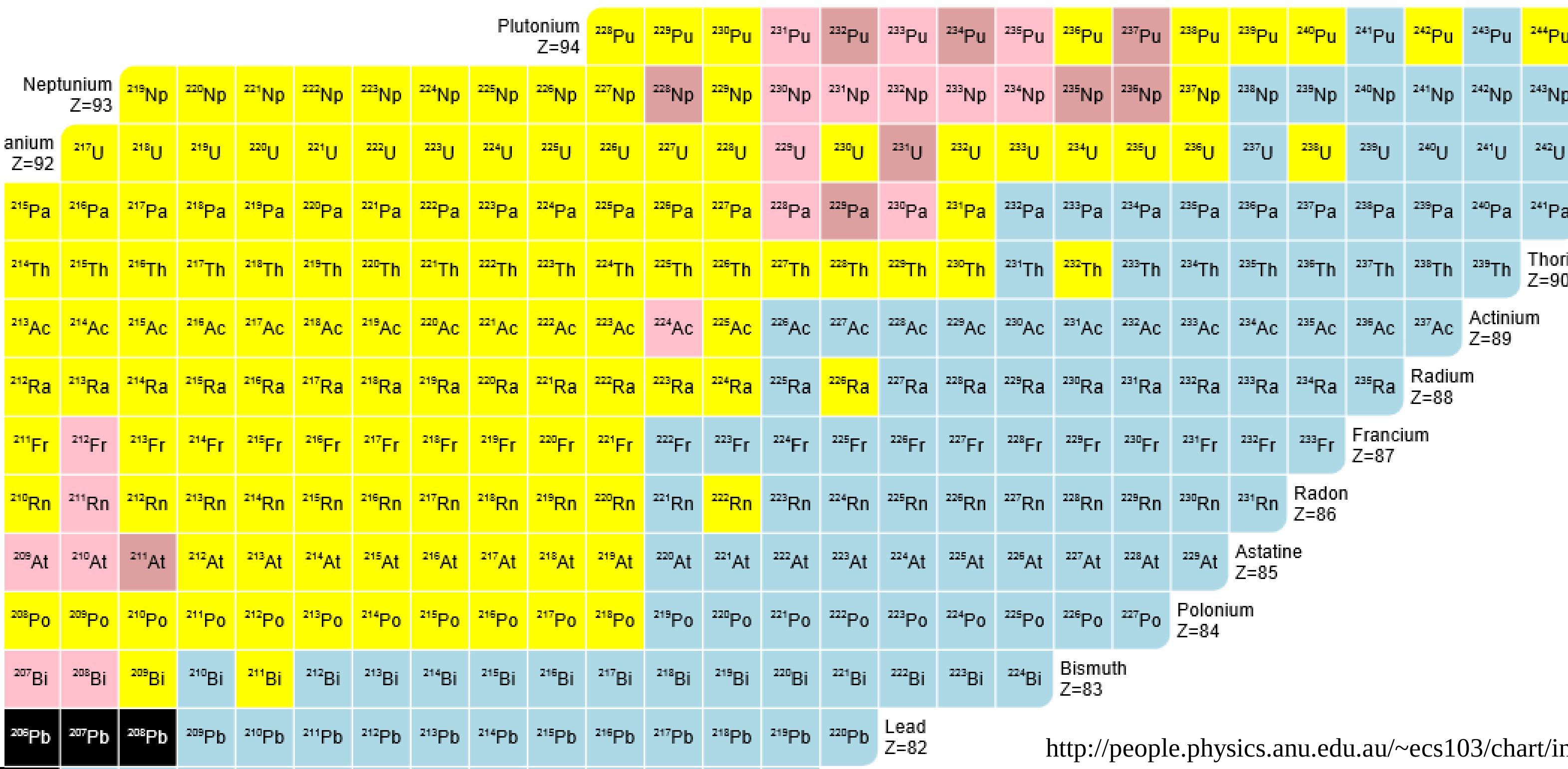
-isotope: atom (nucleus) of an element with different number of neutrons





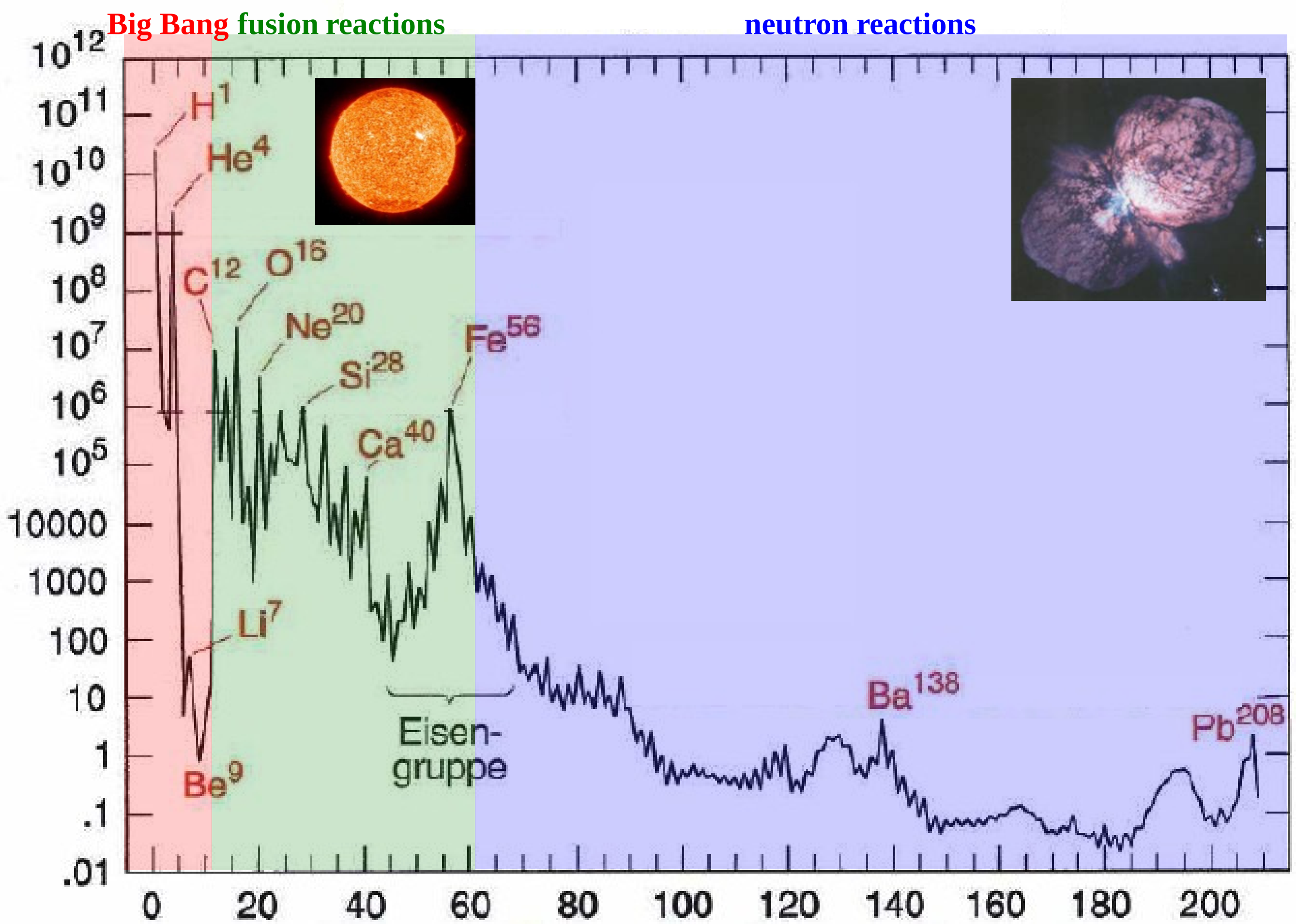
Questions: Chart of Nuclides

1. How are the *isotopes* of an element arranged on the chart?
2. Nuclides with the same number of neutrons are called *isotones*. How are they arranged on the chart?
3. Nuclides with the same mass number are called *isobars*. What would be the orientation of a line connecting an *isobaric* series?
4. Begin with the following radioactive parent nuclei, ^{235}U, ^{238}U, ^{244}Pu, trace their decay processes and depict the mode and direction of each decay process on the chart. What are the final stable nuclei?



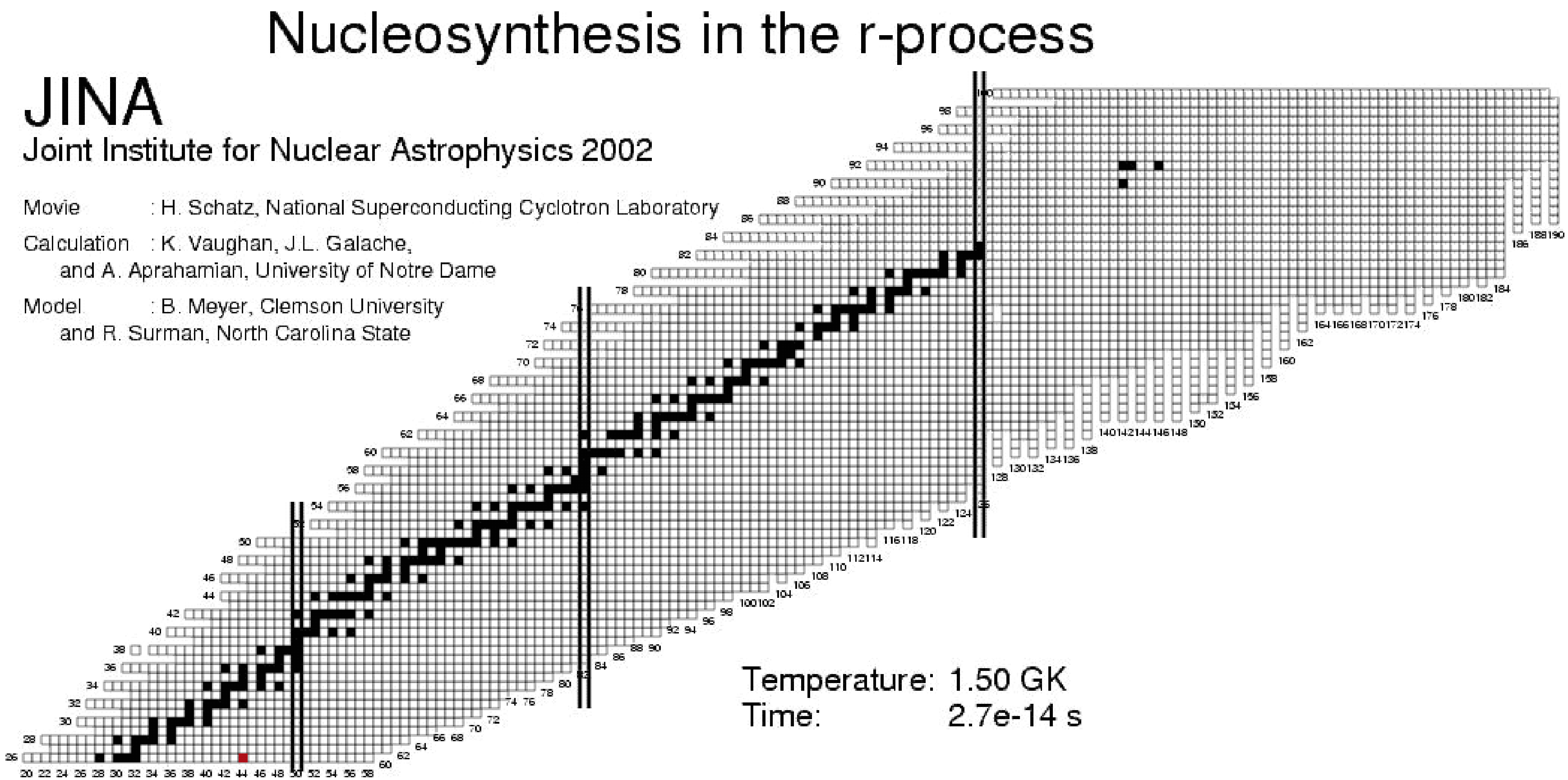
http://people.physics.anu.edu.au/~ecs103/chart/index.php

Solar abundance ($Si^{28} = 10^6$)

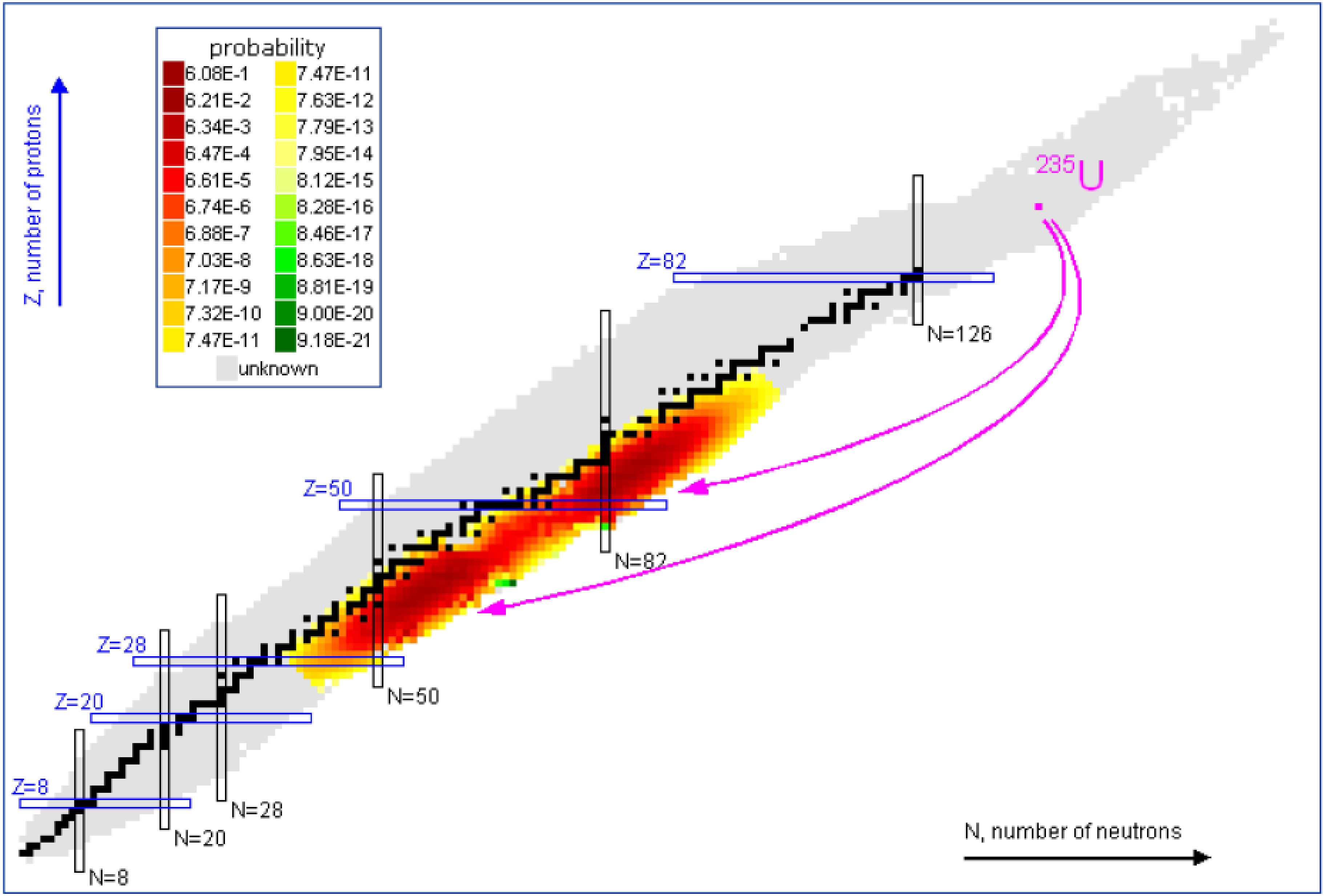


open questions:

- Why is Fe more common than Au ?
- Why do the heavy elements exist and how are they produced?
- Can we explain the solar abundances of the elements?


Nucleosynthesis in the r-process
JINA
Joint Institute for Nuclear Astrophysics 2002
Movie : H. Schatz, National Superconducting Cyclotron Laboratory
Calculation : K. Vaughan, J.L. Galache, and A. Aprahamian, University of Notre Dame
Model : B. Meyer, Clemson University and R. Surman, North Carolina State
Temperature: 1.50 GK
Time: 2.7e-14 s

Nuclear Fission: Energy and Engineering



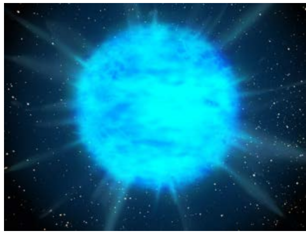
Nuclear matter has exotic properties

- Nuclear matter is extremely heavy $2.3 \cdot 10^{17}$ kg/m^3

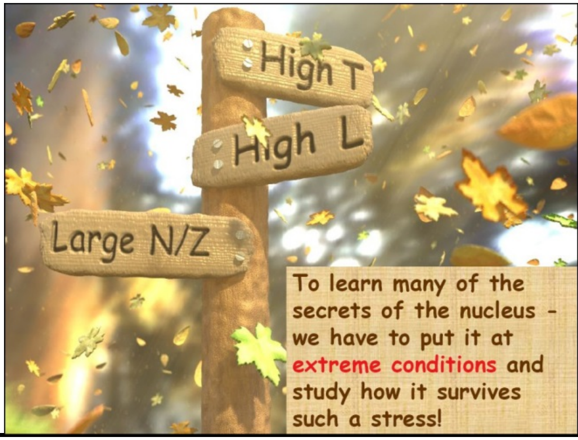
for comparison:

- sea water: $1.0 \cdot 10^3$ kg/m^3
- tin oxide: $1.6 \cdot 10^3$ kg/m^3
- steel: $1.1 \cdot 10^4$ kg/m^3
- lead: $2.5 \cdot 10^4$ kg/m^3
- core of the sun: $1.5 \cdot 10^5$ kg/m^3

- Although we know nuclear matter only in small portions inside atoms, it exists in nature also in big portions:
  - Neutron Stars have a diameter of typically 10 km



- Nuclear structure physics investigates the response of the nucleus as a function of:

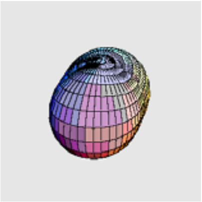


$$\rho = \frac{Am_p}{4/3\,\pi \cdot R^3} = \frac{m_p}{4/3\,\pi \cdot r_0^3} = \frac{1.66 \cdot 10^{-27} kg}{4/3\,\pi \cdot (1.2 \cdot 10^{-15} m)^3}$$

Properties of stable nuclei

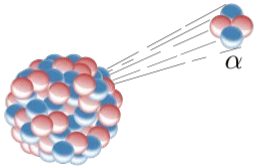
Radius & shape

– size: nuclear radius ($R = 1.2 \cdot A^{1/3}$ fm)
– shape: spherical / deformed (prolate / oblate)



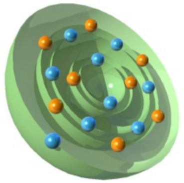
Density & mass

– constant nuclear density ($\rho = 10^{17}$ kg/m^3)
– nuclear mass & valley of stability



Nuclear states

– quantum numbers spin S, parity P, magnetic moments
– shell structure: valence-nucleons, collective excitations



Nuclear reactions

– binding energy: fusion & fission, nuclear astrophysics
– special reactions: exchange / transfer