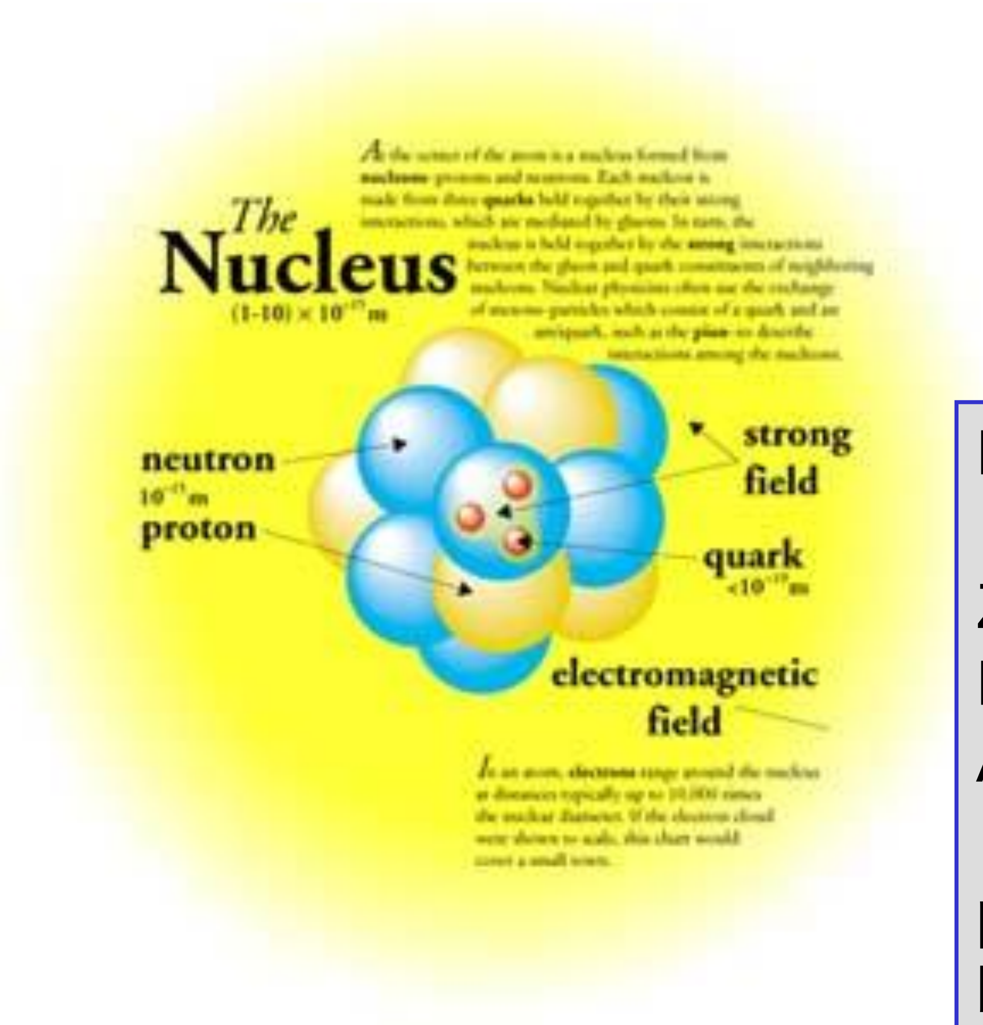
1.3. Basic Principles of Nuclear Physics



A_{number}^{mass} $\;{}^{14}_{6}C$

Z_{number}^{atomic}

$N_{number}^{neutron} = A - Z$

Nucleus consists of:

Z protons with e^+ charge
N neutrons with no charge.
A Mass number A=Z+N

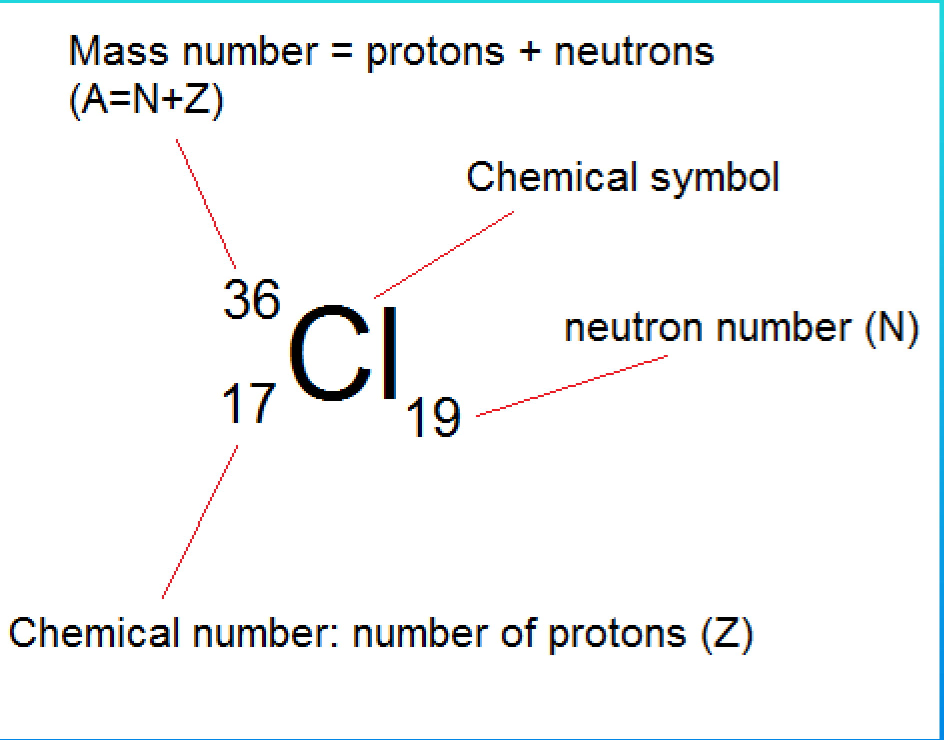
protons & neutrons are bound by strong force: $R \cong 10^{-13}$ m

Nomenclature and common units

Power	Prefix	Abbrev.
10^{-15}	femto	f
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P

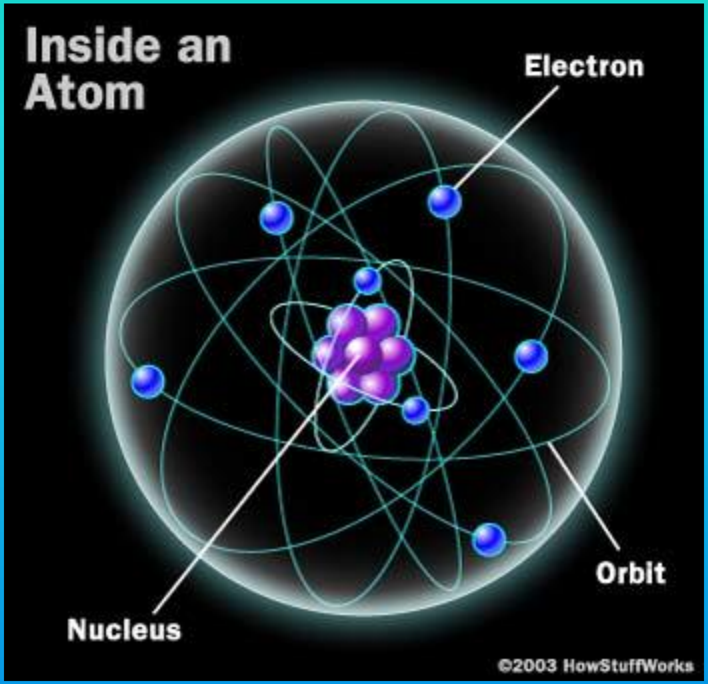
Units: MKSA

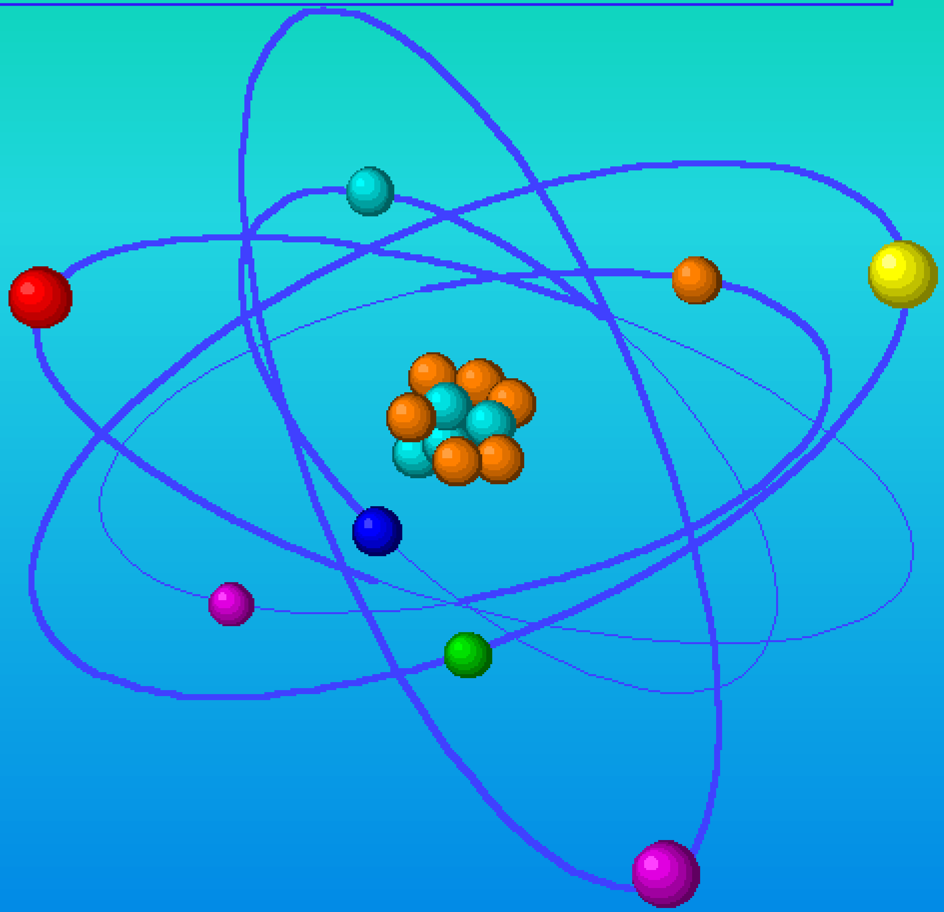
Distance	m	
Mass	Kg	
Time	seconds	
Current	Ampere	
Charge	Coulomb	A.s
Velocity		m/s
Acceleration		m/s^2
Force $\vec{F} = m\vec{a}$		$N \equiv Kg.m/s^2$
Energy		$J \equiv Kg.m^2/s^2$
	$1eV = 1.6022 \times 10^{-19}$ J	



Speed of light c = 2.998×10^{8} m/s ≈ 3×10^{8} m/s

The realm of atomic and nuclear physics

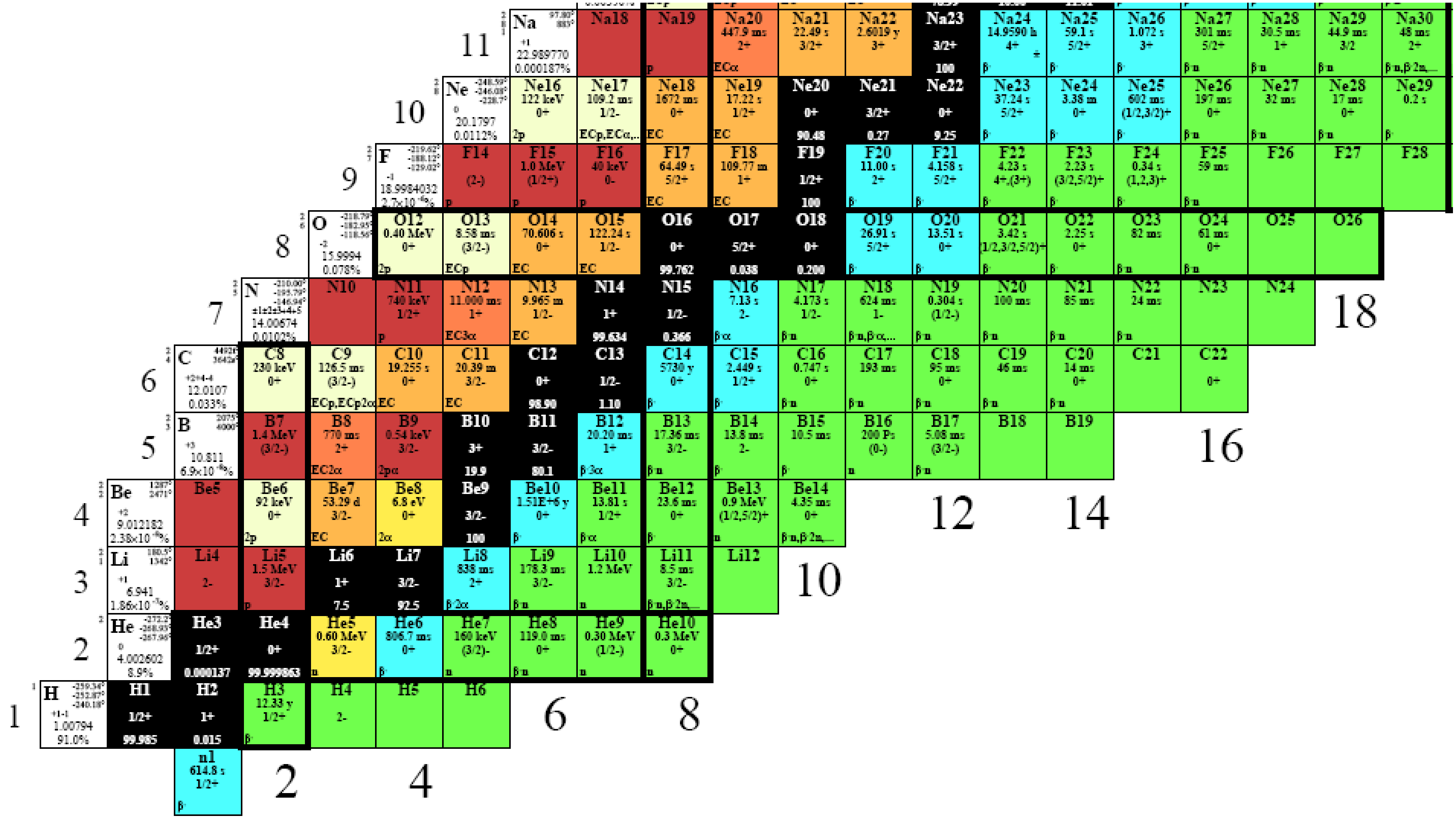




Nuclear physics is the field of physics that studies the building blocks and interactions of atomic nuclei.

Atomic physics (or **atom physics**) is the field of physics that studies atoms as an isolated system of electrons and an atomic nucleus. It is primarily concerned with the arrangement of electrons around the nucleus and the processes by which these arrangements change.

The chart of the nuclides or Segre Chart

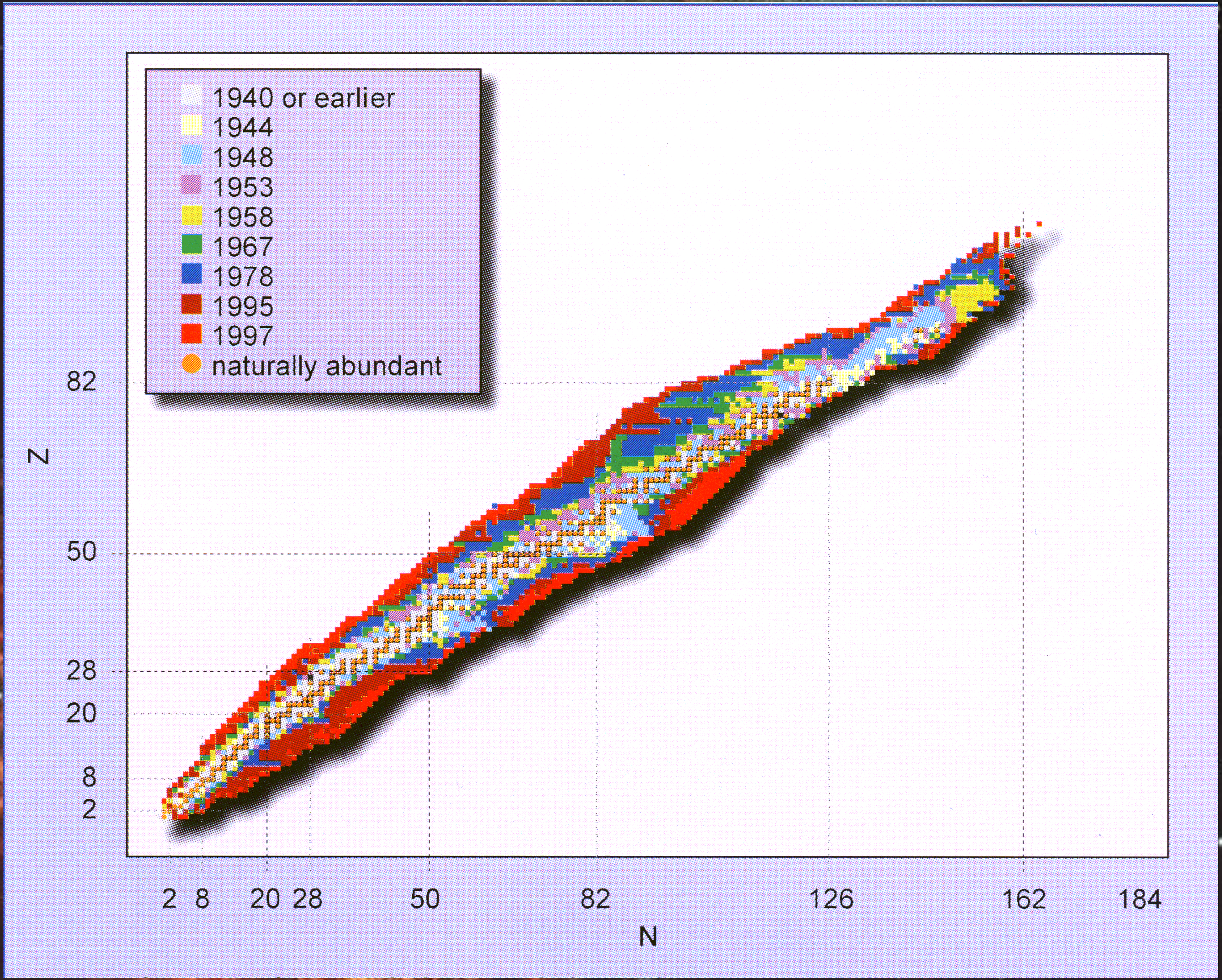


1
H
1.00794
91.0%
H1 1/2+ 99.985
H2 1+ 0.015
H3 12.33 y 1/2+ β-
H4 2-
H5
H6
n1 614.8 s 1/2+ β-
2
He
4.002602
8.9%
He3 1/2+ 0.000137
He4 0+ 99.999863
He5 0.60 MeV 3/2- n
He6 806.7 ms 0+ β-
He7 160 keV (3/2)- n
He8 119.0 ms 0+ β-n
He9 0.30 MeV (1/2-) n
He10 0.3 MeV 0+ n
3
Li
6.941
Li4 2- p
Li5 1.5 MeV 3/2- p
Li6 1+ 7.5
Li7 3/2- 92.5
Li8 838 ms 2+ β-2α
Li9 178.3 ms 3/2- β-n
Li10 1.2 MeV n
Li11 8.5 ms 3/2- β-n,β-2n,...
Li12
4
Be
9.012182
Be5
Be6 92 keV 0+ 2p
Be7 53.29 d 3/2- EC
Be8 6.8 eV 0+ 2α
Be9 3/2- 100
Be10 1.51E+6 y 0+ β-
Be11 13.81 s 1/2+ β-α
Be12 23.6 ms 0+ β-
Be13 0.9 MeV (1/2,5/2)+ n
Be14 4.35 ms 0+ β-n,β-2n,...
5
B
10.811
B7 1.4 MeV (3/2-) p
B8 770 ms 2+ EC2α
B9 0.54 keV 3/2- 2pα
B10 3+ 19.9
B11 3/2- 80.1
B12 20.20 ms 1+ β-3α
B13 17.36 ms 3/2- β-n
B14 13.8 ms 2- β-
B15 10.5 ms β-
B16 200 Ps (0-) n
B17 5.08 ms (3/2-) β-n
B18
B19
6
C
12.0107
0.033%
C8 230 keV 0+
C9 126.5 ms (3/2-) ECp,ECp2α
C10 19.255 s 0+ EC
C11 20.39 m 3/2- EC
C12 0+ 98.90
C13 1/2- 1.10
C14 5730 y 0+ β-
C15 2.449 s 1/2+ β-
C16 0.747 s 0+ β-n
C17 193 ms β-n
C18 95 ms 0+ β-n
C19 46 ms β-n
C20 14 ms 0+ β-n
C21
C22 0+
7
N
14.00674
0.0102%
N10
N11 740 keV 1/2+ p
N12 11.000 ms 1+ EC3α
N13 9.965 m 1/2- EC
N14 1+ 99.634
N15 1/2- 0.366
N16 7.13 s 2- β-α
N17 4.173 s 1/2- β-n
N18 624 ms 1- β-n,β-α,...
N19 0.304 s (1/2-) β-n
N20 100 ms β-n
N21 85 ms β-n
N22 24 ms β-n
N23
N24
8
O
15.9994
0.078%
O12 0.40 MeV 0+ 2p
O13 8.58 ms (3/2-) ECp
O14 70.606 s 0+ EC
O15 122.24 s 1/2- EC
O16 0+ 99.762
O17 5/2+ 0.038
O18 0+ 0.200
O19 26.91 s 5/2+ β-
O20 13.51 s 0+ β-
O21 3.42 s (1/2,3/2,5/2)+ β-
O22 2.25 s 0+ β-
O23 82 ms β-n
O24 61 ms 0+ β-n
O25
O26
9
F
18.9984032
F14 (2-) p
F15 1.0 MeV (1/2+) p
F16 40 keV 0- p
F17 64.49 s 5/2+ EC
F18 109.77 m 1+ EC
F19 1/2+ 100
F20 11.00 s 2+ β-
F21 4.158 s 5/2+ β-
F22 4.23 s 4+,(3+) β-
F23 2.23 s (3/2,5/2)+ β-
F24 0.34 s (1,2,3)+ β-
F25 59 ms β-n
F26
F27
F28
10
Ne
20.1797
0.0112%
Ne16 122 keV 0+ 2p
Ne17 109.2 ms 1/2- ECp,ECα,...
Ne18 1672 ms 0+ EC
Ne19 17.22 s 1/2+ EC
Ne20 0+ 90.48
Ne21 3/2+ 0.27
Ne22 0+ 9.25
Ne23 37.24 s 5/2+ β-
Ne24 3.38 m 0+ β-
Ne25 602 ms (1/2,3/2)+ β-
Ne26 197 ms 0+ β-n
Ne27 32 ms β-n
Ne28 17 ms 0+ β-n
Ne29 0.2 s β-
11
Na
22.989770
0.000187%
Na18
Na19 p
Na20 447.9 ms 2+ ECα
Na21 22.49 s 3/2+
Na22 2.6019 y 3+
Na23 3/2+ 100
Na24 14.9590 h 4+ β-
Na25 59.1 s 5/2+ β-
Na26 1.072 s 3+ β-
Na27 301 ms 5/2+ β-n
Na28 30.5 ms 1+ β-n
Na29 44.9 ms 3/2 β-n
Na30 48 ms 2+ β-n,β-2n,...
2
4
6
8
10
12
14
16
18

Stable vs. unstable nuclides

Known nuclides:~3760
Stable nuclides: 269
Radionuclides: ~3481
$t_{1/2}$ > 1year : 144
primordial :26

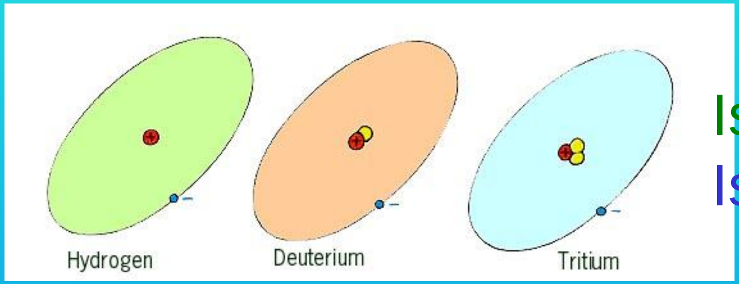
A radionuclide is a atom that has an unstable nucleus (i.e. an excess of energy, characterized by an excess of protons or neutrons). It will decay (i.e. lose its excess energy) by emitting particles (alpha and beta decay) or photons (gamma rays or x-rays) to reach a stable configuration.



1940 or earlier
1944
1948
1953
1958
1967
1978
1995
1997
naturally abundant
Z
82
50
28
20
8
2
2
8
20
28
50
82
126
162
184
N

Isotope, Isobar, Isotone

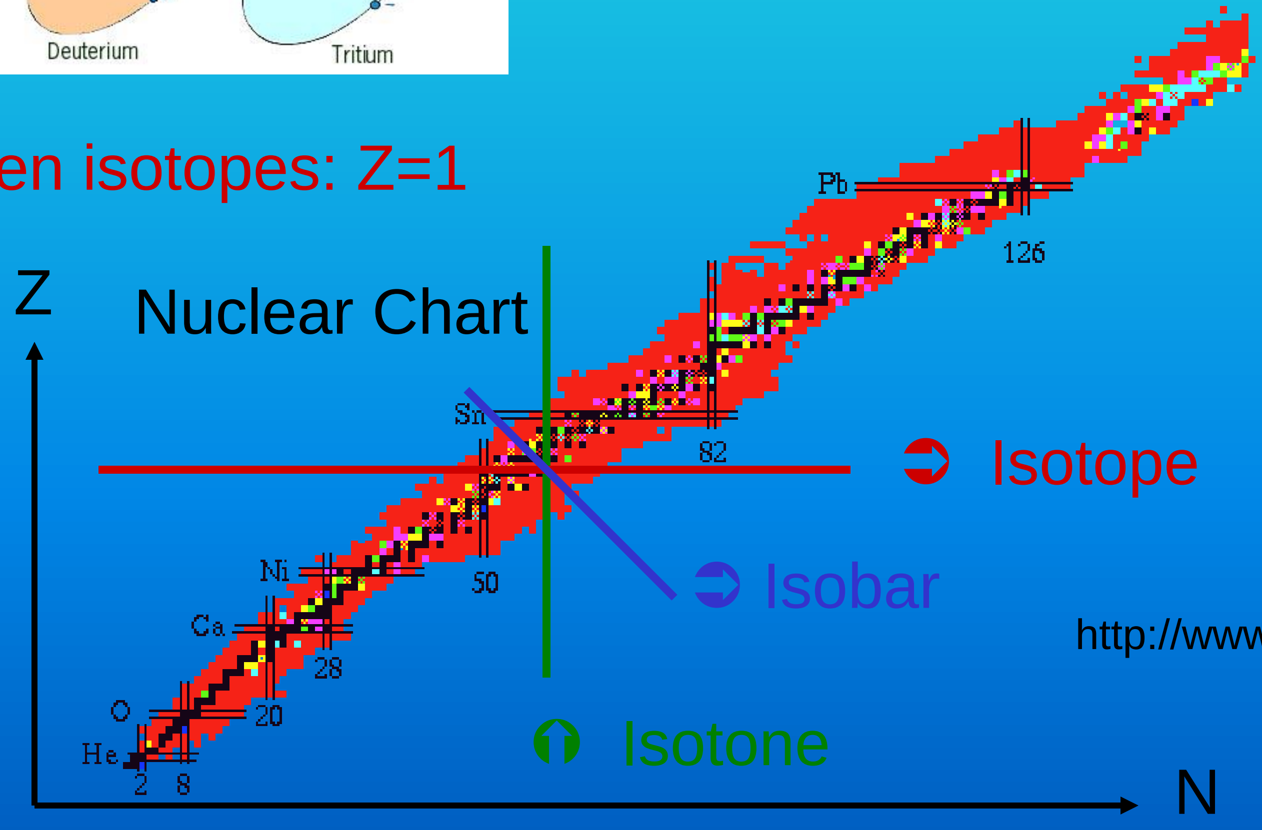
Isotopes: nuclei with Z=constant, N varies!



Isotones: nuclei with N=constant, Z varies!

Isobars: nuclei with A=constant, Z,N varies!

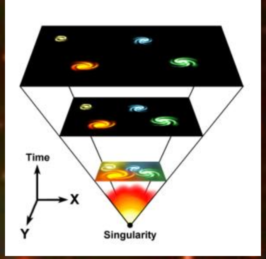
hydrogen isotopes: Z=1



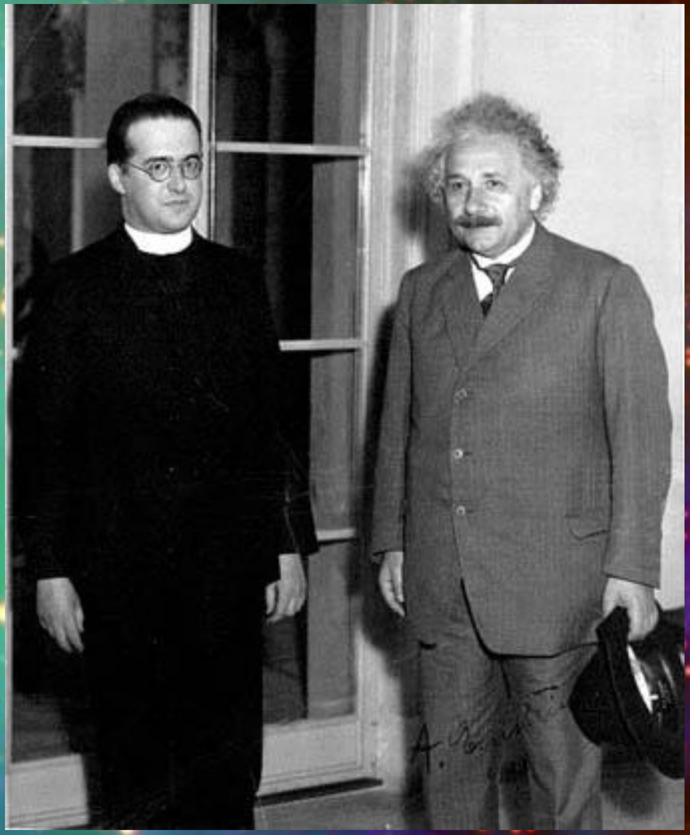
http://www.nndc.bnl.gov/chart/

From the Big-Bang to nowt of the nuclides or Segre Chart

Georges Lemaitre



Monsignor Georges Henri Joseph Édouard Lemaître (lemaitre.ogg (help·info) July 17, 1894 – June 20, 1966) was a Belgian Roman Catholic priest, honorary prelate, professor of physics and astronomer at the Catholic University of Leuven. He sometimes used the title *Abbé* or *Monseigneur*.

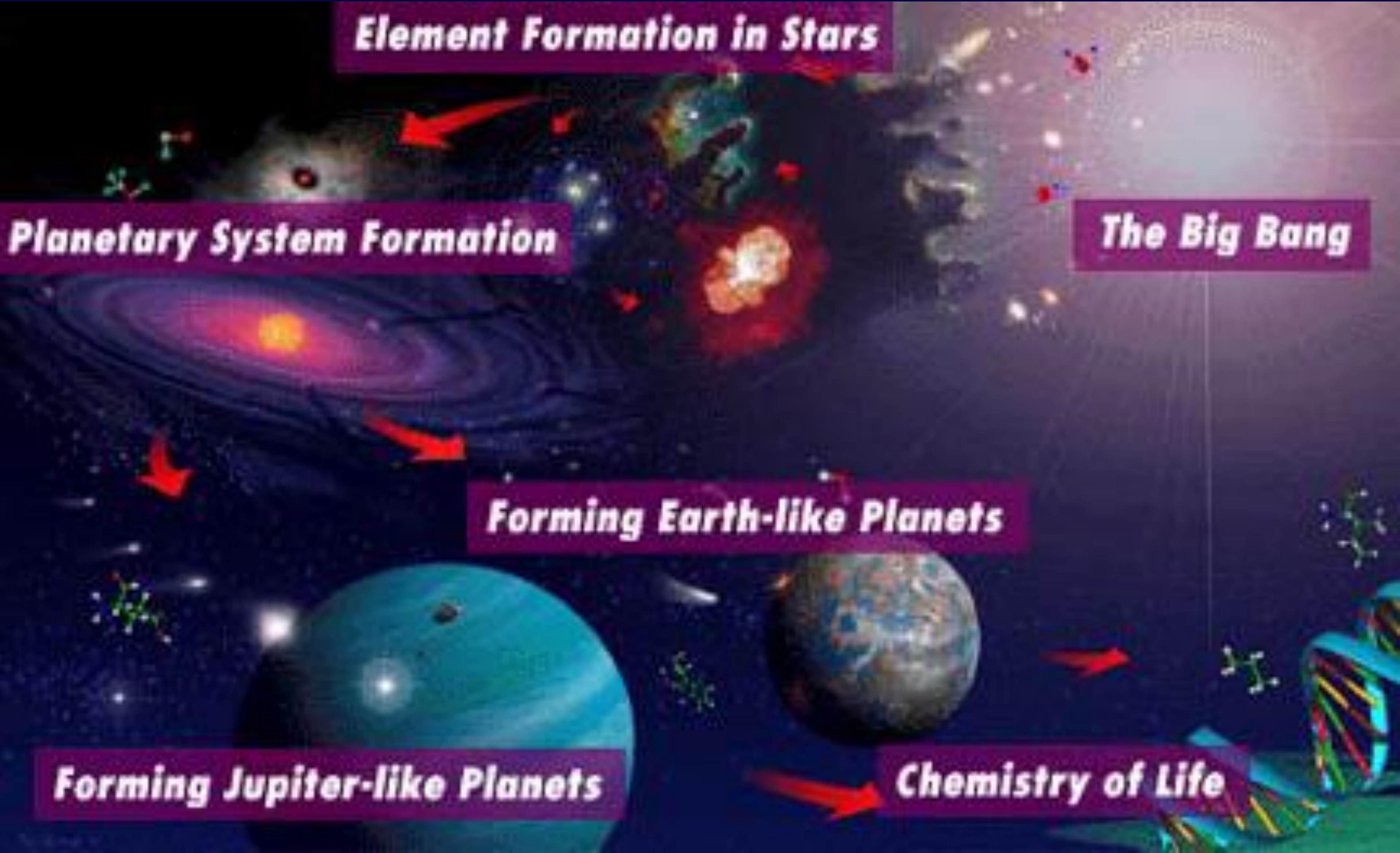


Georges Lemaitre – Short bio

- After a classical education at a Jesuit secondary school (Collège du Sacré-Coeur, Charleroi), Lemaître began studying civil engineering at the Catholic University of Leuven at the age of 17. In 1914, he interrupted his studies to serve as an artillery officer in the Belgian army for the duration of World War I. At the end of hostilities, he received the Military Cross with palms.
- After the war, he studied physics and mathematics, and began to prepare for priesthood. He obtained his doctorate in 1920 with a thesis entitled *l'Approximation des fonctions de plusieurs variables réelles* (*Approximation of functions of several real variables*), written under the direction of Charles de la Vallée-Poussin. He was ordained a priest in 1923.
- In 1923, he became a graduate student in astronomy at the University of Cambridge, spending a year at St Edmund's House (now St Edmund's College, Cambridge). He worked with Arthur Eddington who initiated him into modern cosmology, stellar astronomy, and numerical analysis. He spent the following year at Harvard College Observatory in Cambridge, Massachusetts with Harlow Shapley, who had just gained a name for his work on nebulae, and at the Massachusetts Institute of Technology, where he registered for the doctorate in sciences.

From Wikipedia

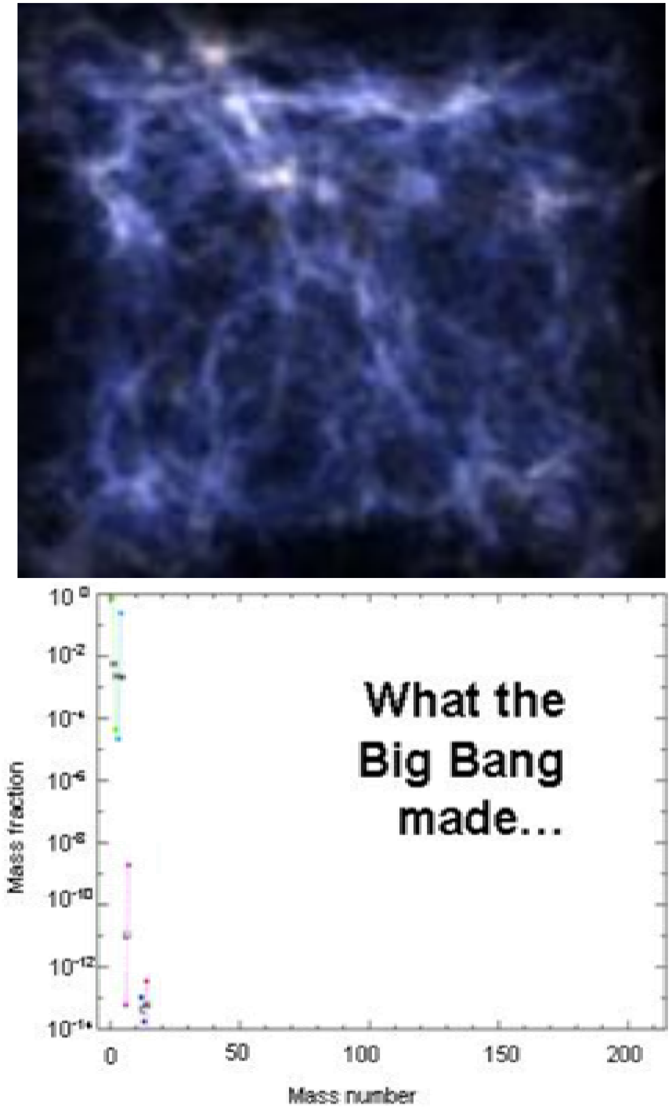
From the Big-Bang to now



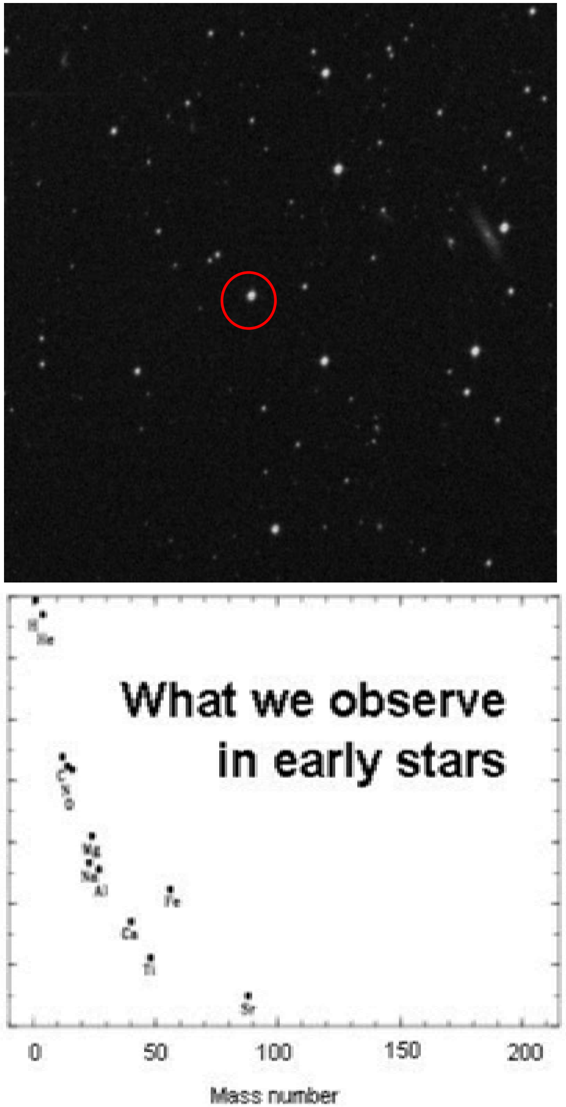
Timeline

THE COSMOS, START TO FINISH
Astrophysicists now have a pretty clear idea how the universe got from the Big Bang to where it is today - and how it will evolve in the unimaginably distant future
NOW
Dark energy causes expansion of the universe to accelerate
1 second after Big Bang
1 day
1 year
1 billion years
1 trillion years
Time in seconds*
Time in years*
BIG BANG
About 15 billion years ago, the universe bursts into existence in the Big Bang, which gives birth to space, time and all the matter and energy the universe will ever hold
INFLATION ERA
The universe undergoes a brief, explosive period of inflation, growing from smaller than an atom to the size of a grapefruit. The inflationary expansion stops when the force driving it is transformed into matter and energy as we know them
RADIATION-DOMINATED ERA
Most of the energy is in the form of electromagnetic radiation—visible light, X rays, radio waves and ultraviolet rays. Quarks clump into protons and neutrons, which later combine to make the nuclei of all atoms. The lightest nuclei—helium, deuterium and lithium—are forged in the first three minutes of cosmic history
STELLIFEROUS ERA
Electrons combine with existing nuclei to form atoms, mostly hydrogen and helium. This raw material condenses into the first generation of stars during the first billion years. The galaxies also take shape during this window of time. Our sun and solar system were formed 4.6 billion years ago, and the first life-forms appeared on Earth a surprisingly short time afterward. Modern humans show up only 100,000 years before the present. Earth should remain habitable for another few billion years
DEGENERATE ERA
This era extends to 10 trillion trillion trillion years after the Big Bang. Planets detach from stars; stars and planets evaporate from galaxies. Most of the ordinary matter in the universe is locked up in degenerate stellar remnants—dead stars that have withered into white dwarfs or blown up and collapsed into neutron stars and black holes. Eventually, over spans of time greatly exceeding the current age of the universe, the protons themselves decay
BLACK-HOLE ERA
This era extends to 10,000 trillion trillion trillion trillion trillion trillion trillion years after the Big Bang. After the epoch of proton decay, the only large objects remaining are black holes, which eventually evaporate into photons and other types of radiation
*This time line is plotted on a logarithmic scale, which allows it to show both infinitesimal and immense periods of time on the same line. Each tick mark represents a tenfold greater span of time than the one before it. For example, the tick at 10¹⁰ marks 10 billion years after the Big Bang; the next one, at 10¹¹, marks 100 billion years after the Big Bang. Negative powers of 10 represent fractions of a second, with 10⁻¹ marking one-tenth of a second, 10⁻² one-hundredth and so on
TIME Graphic by Joe Lertola

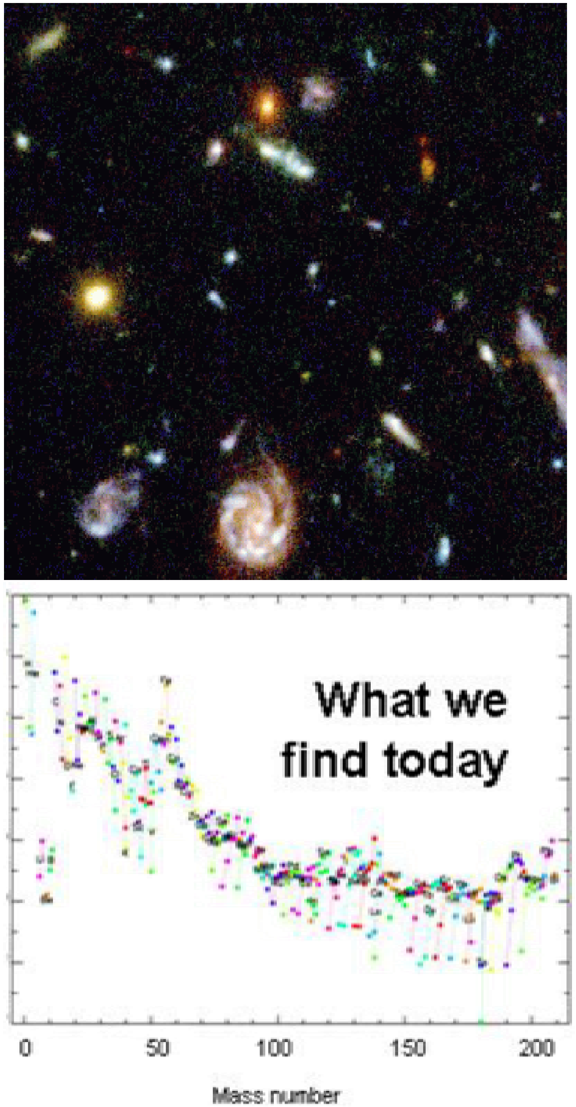
Nuclei are made in Stars



(The primordial abundance pattern)
Brian Fields (2002)

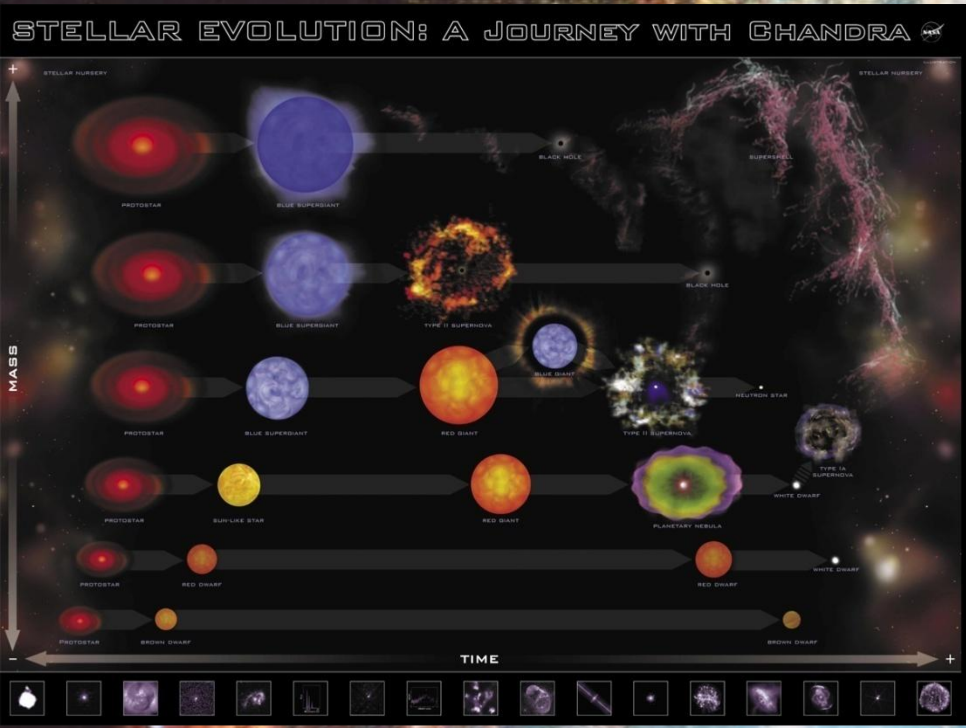


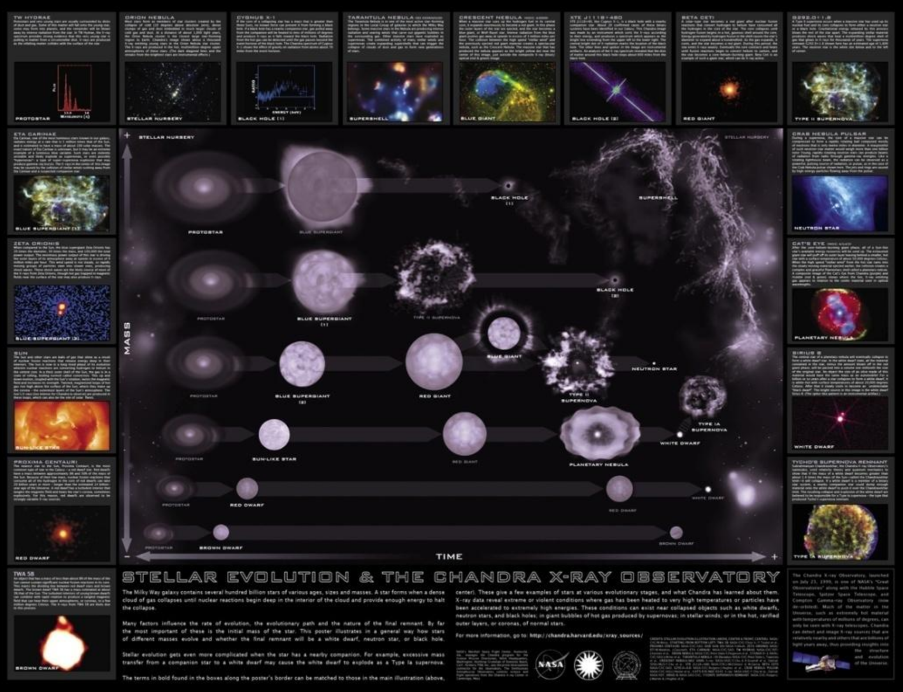
(The abundance pattern in the oldest observed stars He1017 & HH1327)
Anna Frebel (2006)



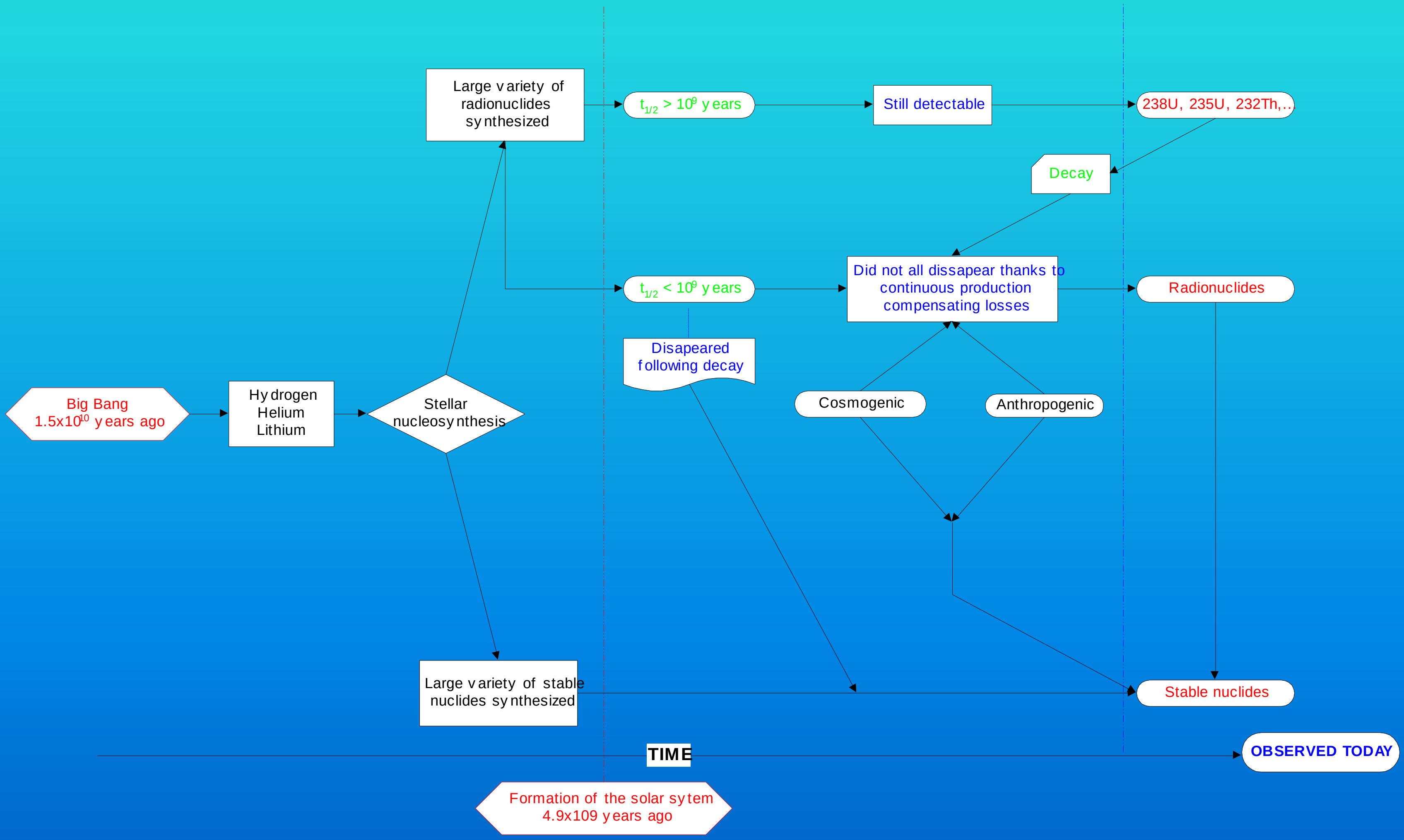
(The solar abundance pattern)
Grevesse & Noels (1995)

Stellar Evolution





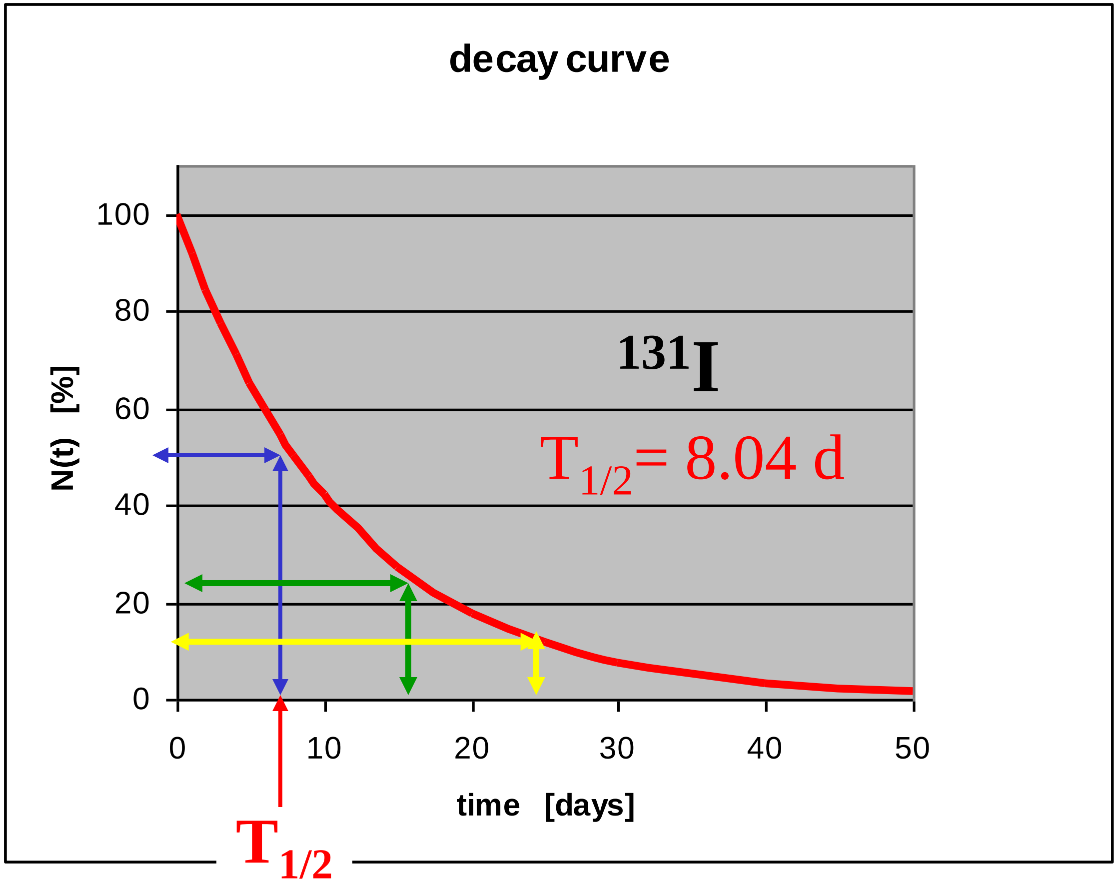
Origin of the radionuclides



Half-Life of Radio-Isotope

time (days)	^{131}I (%)
0	100.0000
1	91.7411
2	84.1642
3	77.2132
4	70.8362
5	64.9859
6	59.6188
7	54.6949
8	50.1777
9	46.0335
10	42.2317
15	27.4446
20	17.8351
25	11.5903
30	7.5321
40	3.1809
50	1.3434
60	0.5673
70	0.2396
80	0.1012
90	0.0427
100	0.0180

$$N(t) = N_0 \cdot e^{-\lambda \cdot t}$$



Math and Units – units of mass ($E=Mc^2$)

$$1\,J = 1\,\frac{kg \cdot m^2}{s^2}$$

$$1\,eV = 1.6022 \cdot 10^{-19}\ J$$

$$A\,g \equiv 6.022 \cdot 10^{23}\ particles$$

$$c = 300000\ m/s$$

$$1\,amu = 1.66 \cdot 10^{-27} kg = 931.49\ MeV/c^2$$

http://en.wikipedia.org/wiki/Electronvolt

The concept of energy and binding energy

Energy

Instead of looking at a physical system in terms of its kinematics and the forces acting on its components we can look at a physical system in terms of its energy

In the concept of this course we will consider 2 forms of energy:

Kinetic energy (is the energy of motion): $k=(mv^2)/2$ always positive

Potential energy (is the energy of position) can be positive or negative

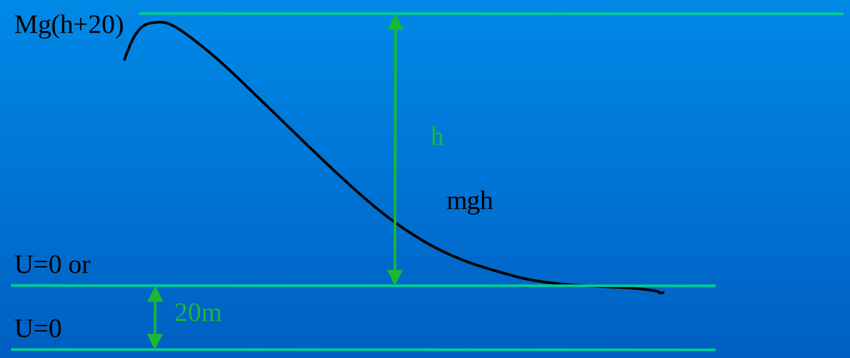
Gravitational potential energy: $U_g = m.g.y$ (y:height)

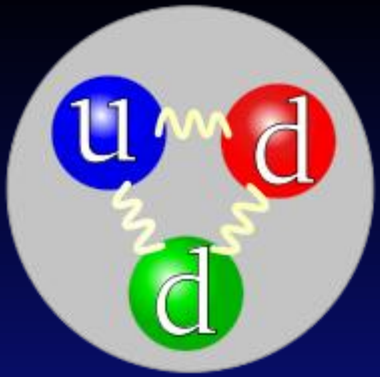
U_g = zero is generally taken at ground level

Electric potential energy (of 2 point charges): $U(r) = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r}$

U(r) = 0 for 2 point charges separated by an infinite distance

Energy is a relative term and only differences are important!!!!

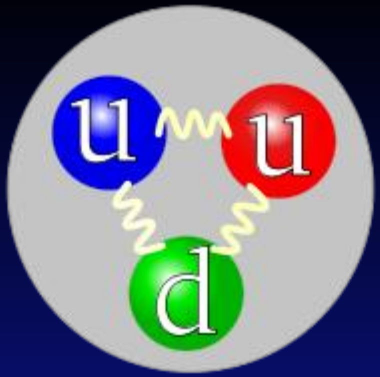




Neutron

The quark structure of the neutron.

Classification:	Baryon
Composition:	1 up quark, 2 down quarks
Statistical behavior:	Fermion
Group:	Hadron
Interaction:	Gravity, Weak, Strong
Symbol(s):	n, n^0, N^0
Antiparticle:	Antineutron
Theorized:	Ernest Rutherford[1] (1920)
Discovered:	James Chadwick[1] (1932)
Mass:	$1.67492729(28)\times10^{-27}$ kg 939.565560(81) MeV/c^2 1.0086649156(6) u [2]
Mean lifetime:	885.7(8) s (free)
Electric charge:	0 e 0 C
Electric dipole moment:	$<2.9\times10^{-26}$ e cm
Electric polarizability:	$1.16(15)\times10^{-3}$ fm^3
Magnetic moment:	−1.9130427(5) μ_N
Magnetic polarizability:	$3.7(20)\times10^{-4}$ fm^3
Spin:	$\frac{1}{2}$
Isospin:	$-\frac{1}{2}$
Parity:	+1
Condensed:	$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$



Proton

The quark structure of the proton.

Classification:	Baryon
Composition:	2 up, 1 down
Statistical behavior:	Fermion
Group:	Hadron
Interaction:	Gravity, Electromagnetic, Weak, Strong
Symbol(s):	p, p^+, N^+
Antiparticle:	Antiproton
Theorized:	William Prout (1815)
Discovered:	Ernest Rutherford (1919)
Mass:	$1.672621637(83)\times10^{-27}$ kg 938.272013(23) MeV/c^2 1.00727646677(10) u [1]
Mean lifetime:	$>2.1\times10^{29}$ years (stable)
Electric charge:	+1 e $1.602176487(40)\times10^{-19}$ C[1]
Charge radius:	0.875(7) fm[2]
Electric dipole moment:	$<5.4\times10^{-24}$ e cm
Electric polarizability:	$1.20(6)\times10^{-3}$ fm^3
Magnetic moment:	2.792847351(28) μ_N
Magnetic polarizability:	$1.9(5)\times10^{-4}$ fm^3
Spin:	$\frac{1}{2}$
Isospin:	$\frac{1}{2}$
Parity:	+1
Condensed:	$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

From Wikipedia

Nuclear Masses & Energetics

The mass M of the nucleus is smaller than the mass of its proton and neutron constituents!

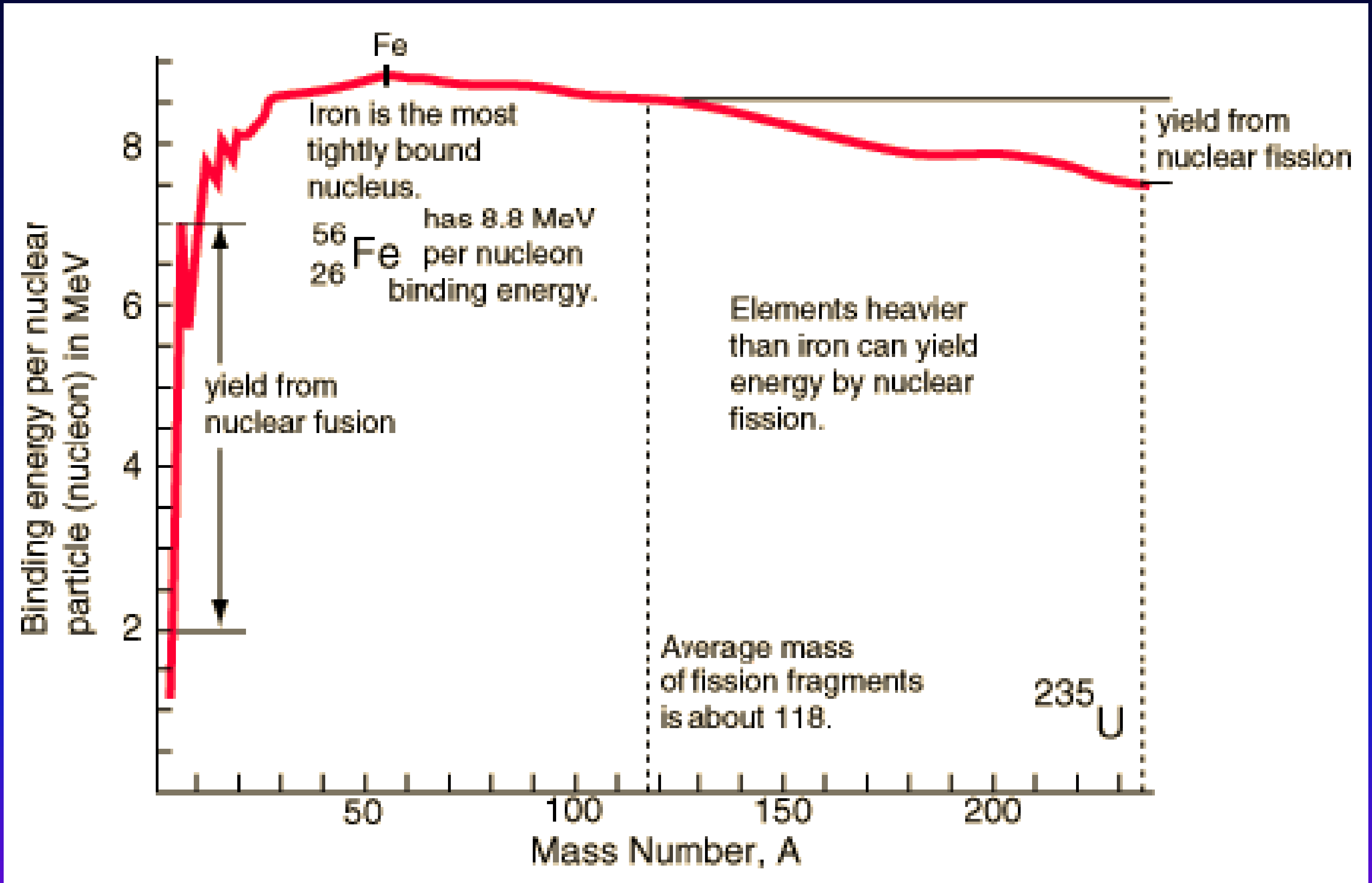
$$M \cdot c^2 < Z\, m_p \cdot c^2 + N\, m_n \cdot c^2$$

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

The mass difference is the binding energy B

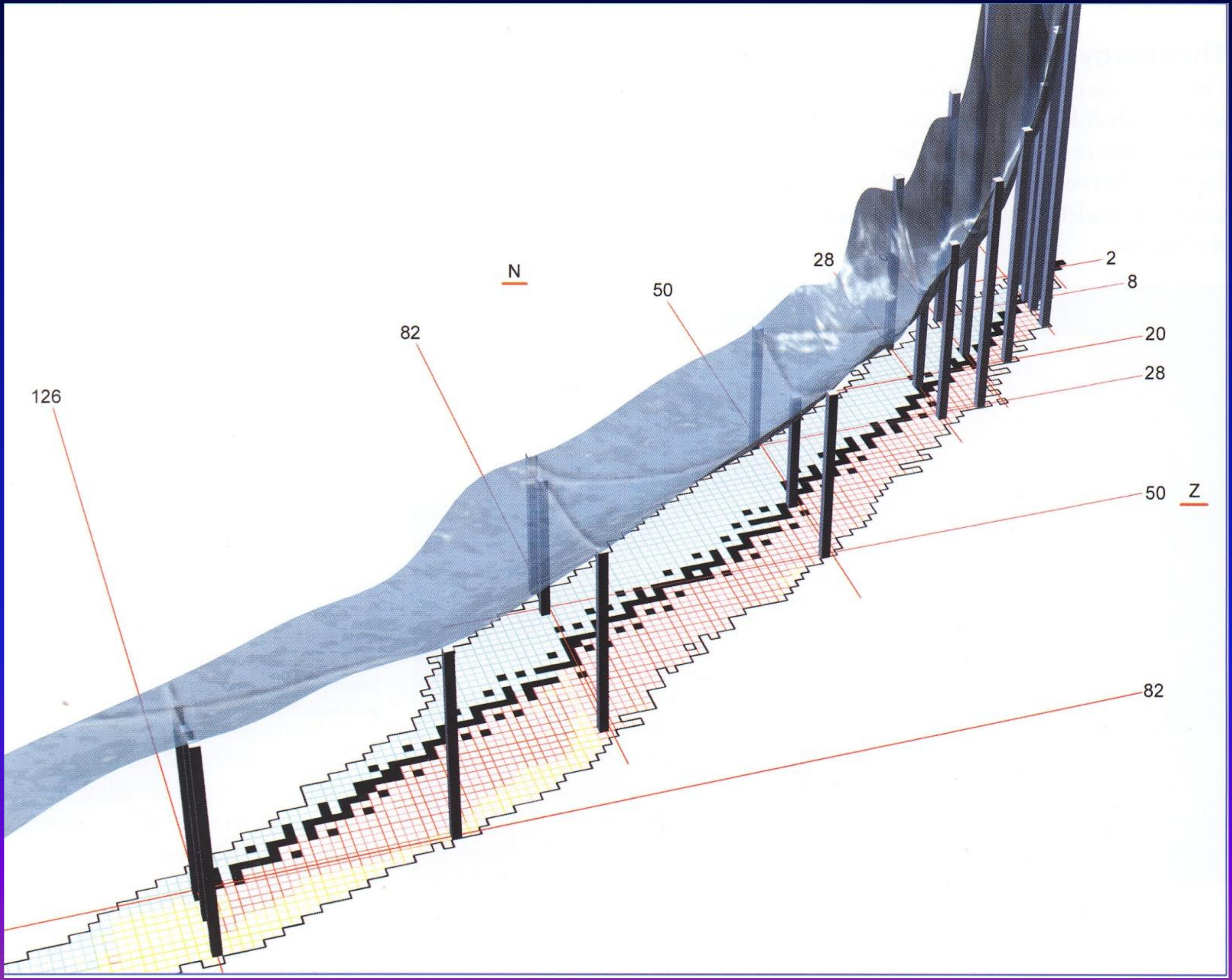
The binding energy is the energy that is needed to dissociate a nucleus into its single constituents. It is released when N neutrons and Z protons fuse together to form a nucleus with the mass number A!

Binding energy per nucleon B/A

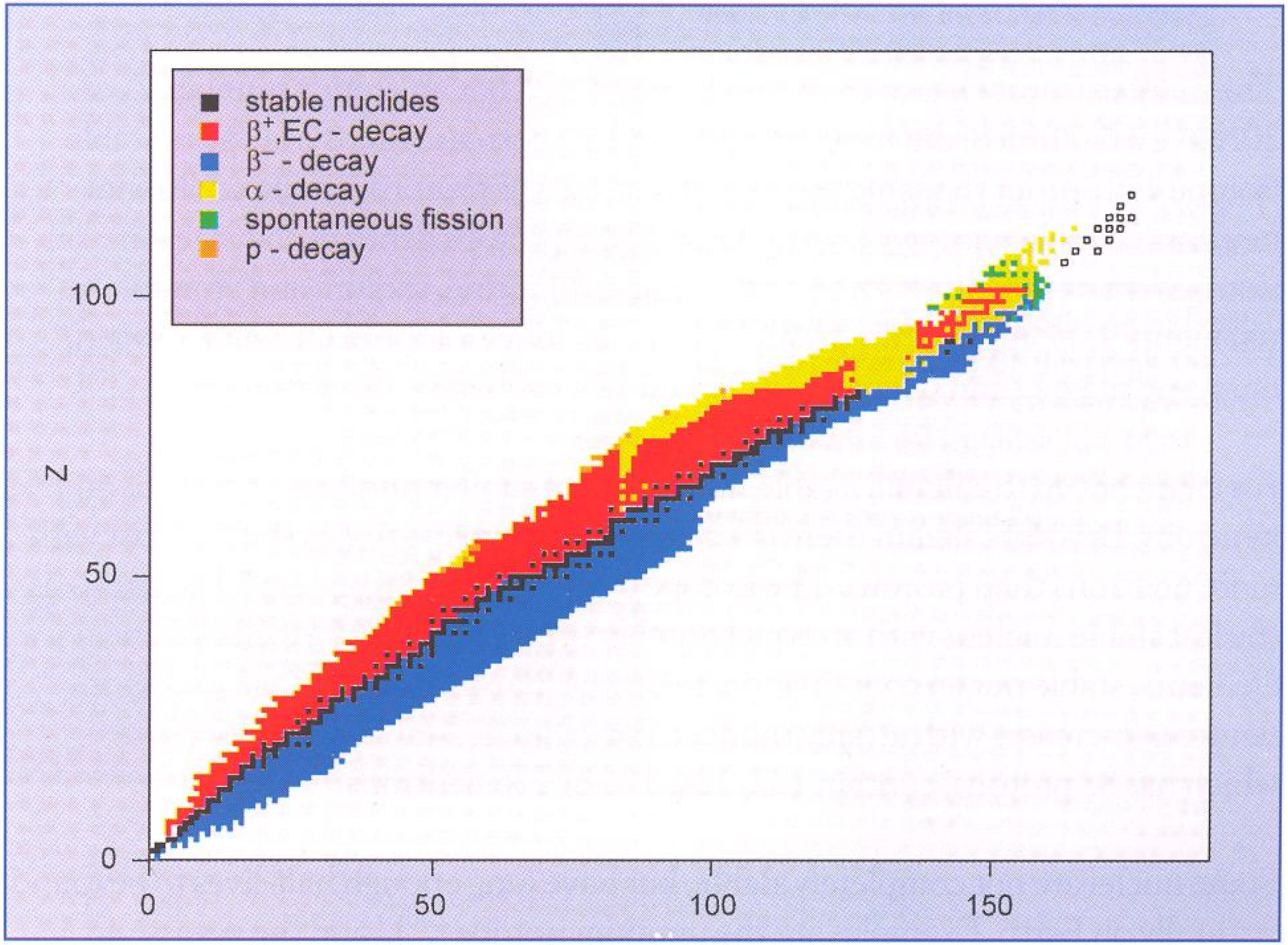


Picture taken from world mysteries.com

Excess mass and half-life



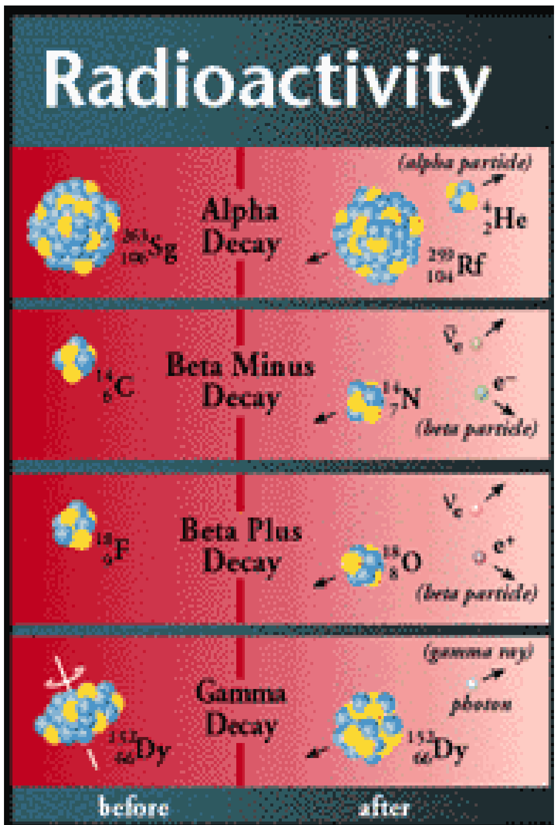
Types of nuclear decay



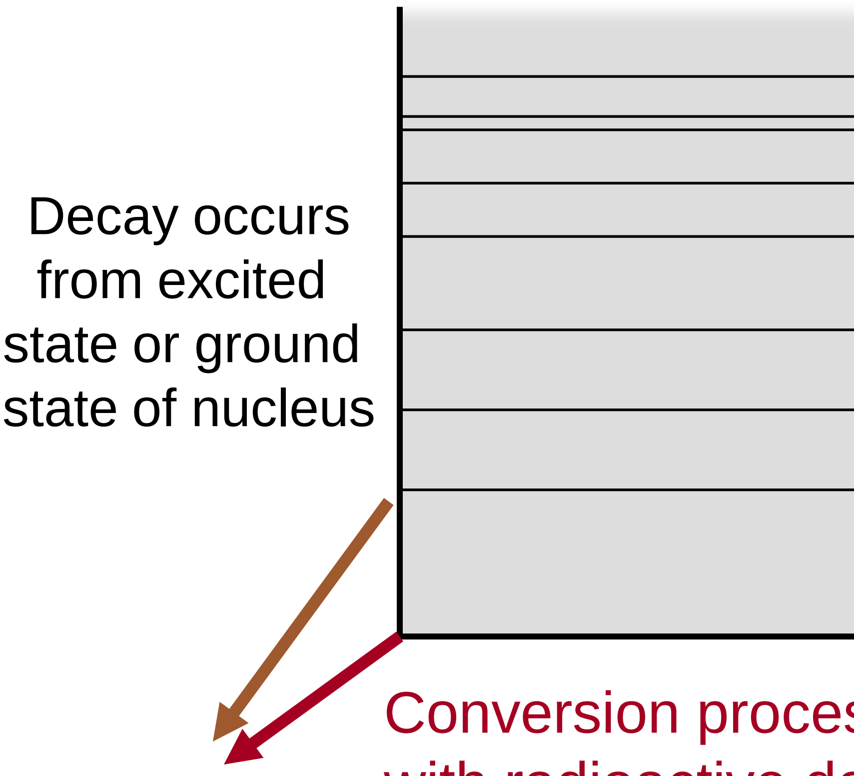
stable nuclides
β+,EC - decay
β− - decay
α - decay
spontaneous fission
p - decay
Z
100
50
0
0
50
100
150

Nuclear Decay & Radioactivity

Nuclei are only in certain Z,N configuration stable (minimum of energy $E=mc^2$)
Otherwise nucleus 'decays' by particle or radiation emission to energetically more favorable configuration!



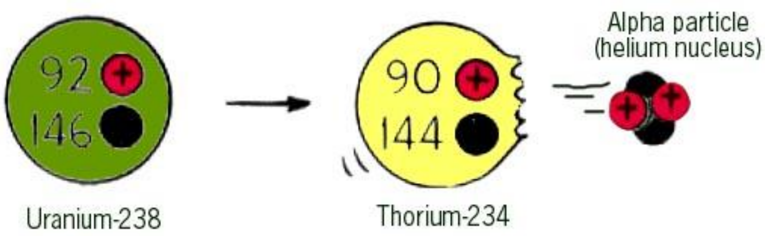
Decay occurs from excited state or ground state of nucleus



Nucleus can be displayed in terms of a level scheme like atom (nuclear shell model)

Conversion process associated with radioactive decay

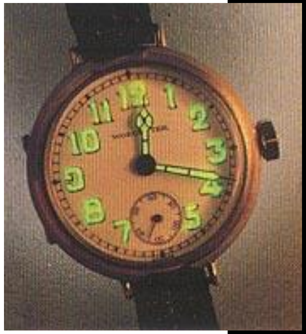
Alpha Decay of the Nucleus

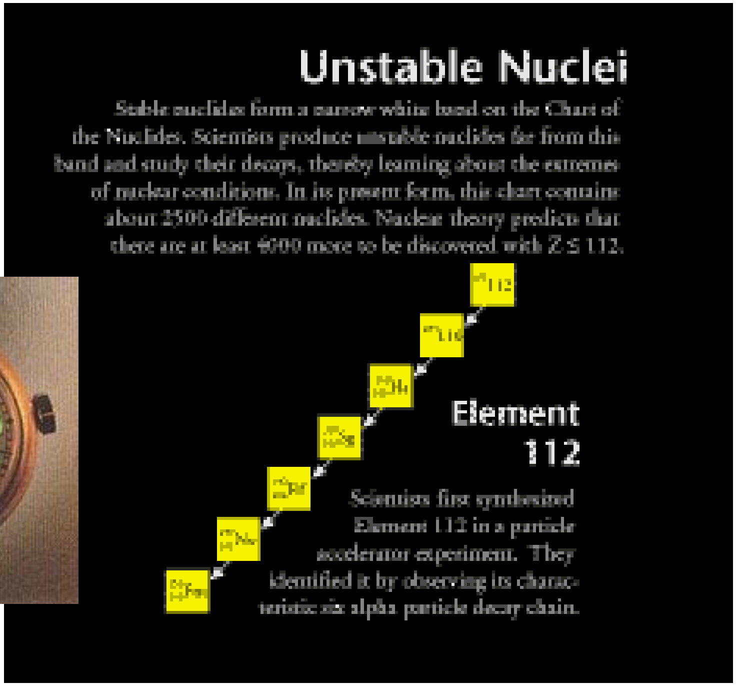


Occurs mainly for very heavy nuclei which are not stable against alpha emission

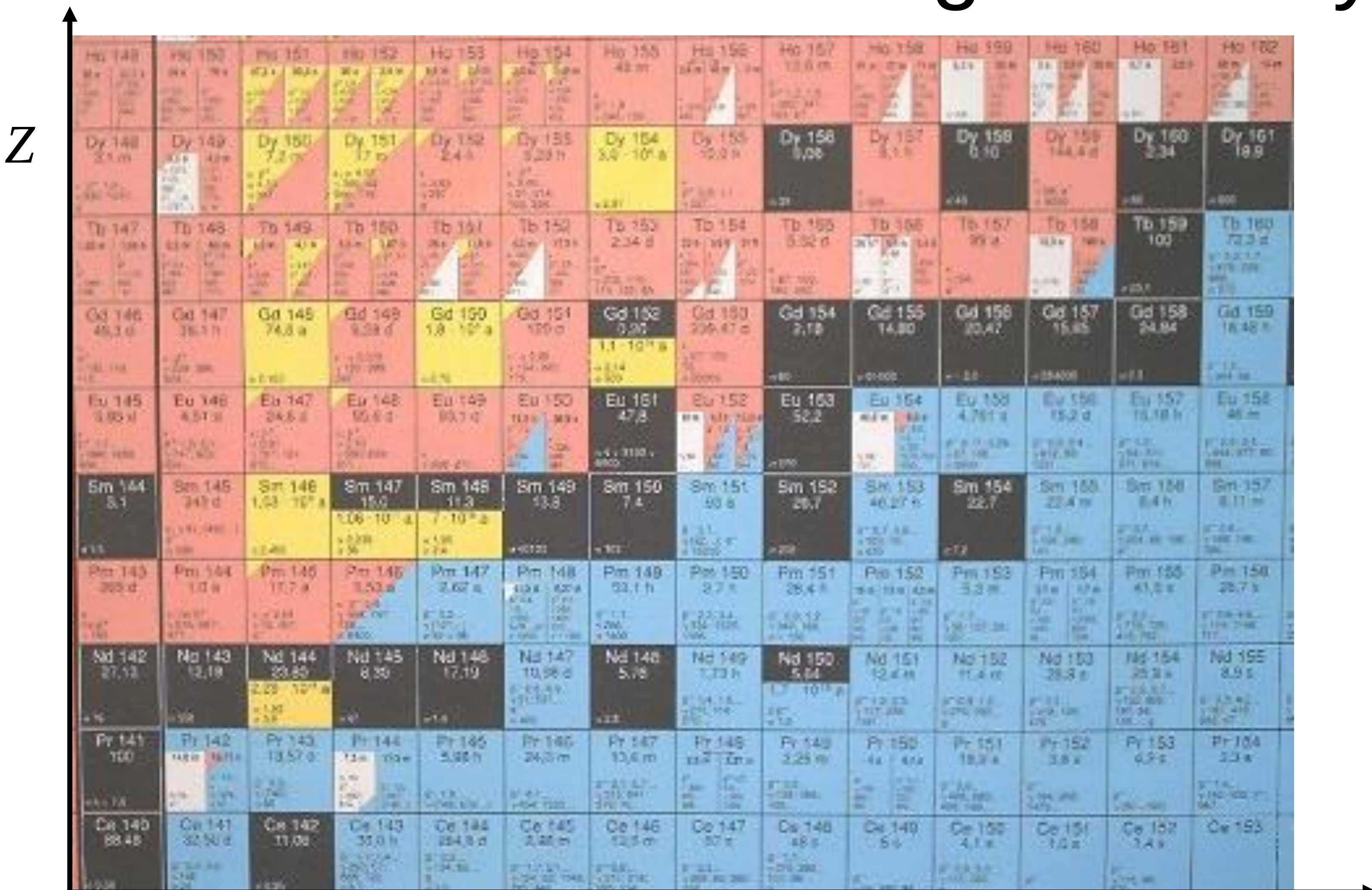
Alpha particle $\alpha = {}^{4}He$

$$^{226}_{88}Ra \Rightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$$



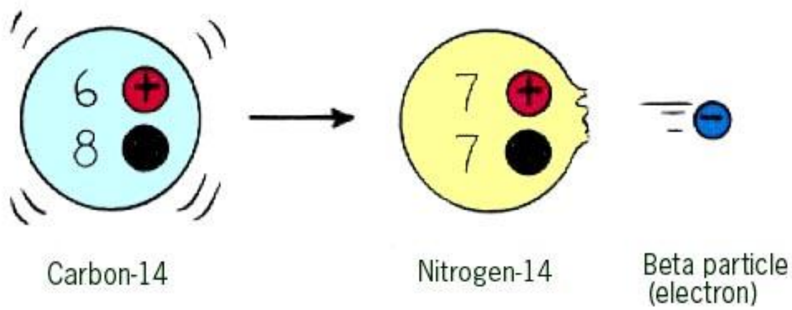


Nucleus conversion through α-decay



Determine the end-product of the 'yellow' α-emitter: $^{A}_{Z}X_{N} \Rightarrow {}^{A-4}_{Z-2}X_{N-2} + \alpha$

Beta Decay of the Nucleus



β decay is the emission of an electron e^- or positron e^+ to convert neutron to proton or proton to neutron inside nucleus

$$6 \cdot e^+ \Rightarrow 7 \cdot e^+ + 1 \cdot e^-$$

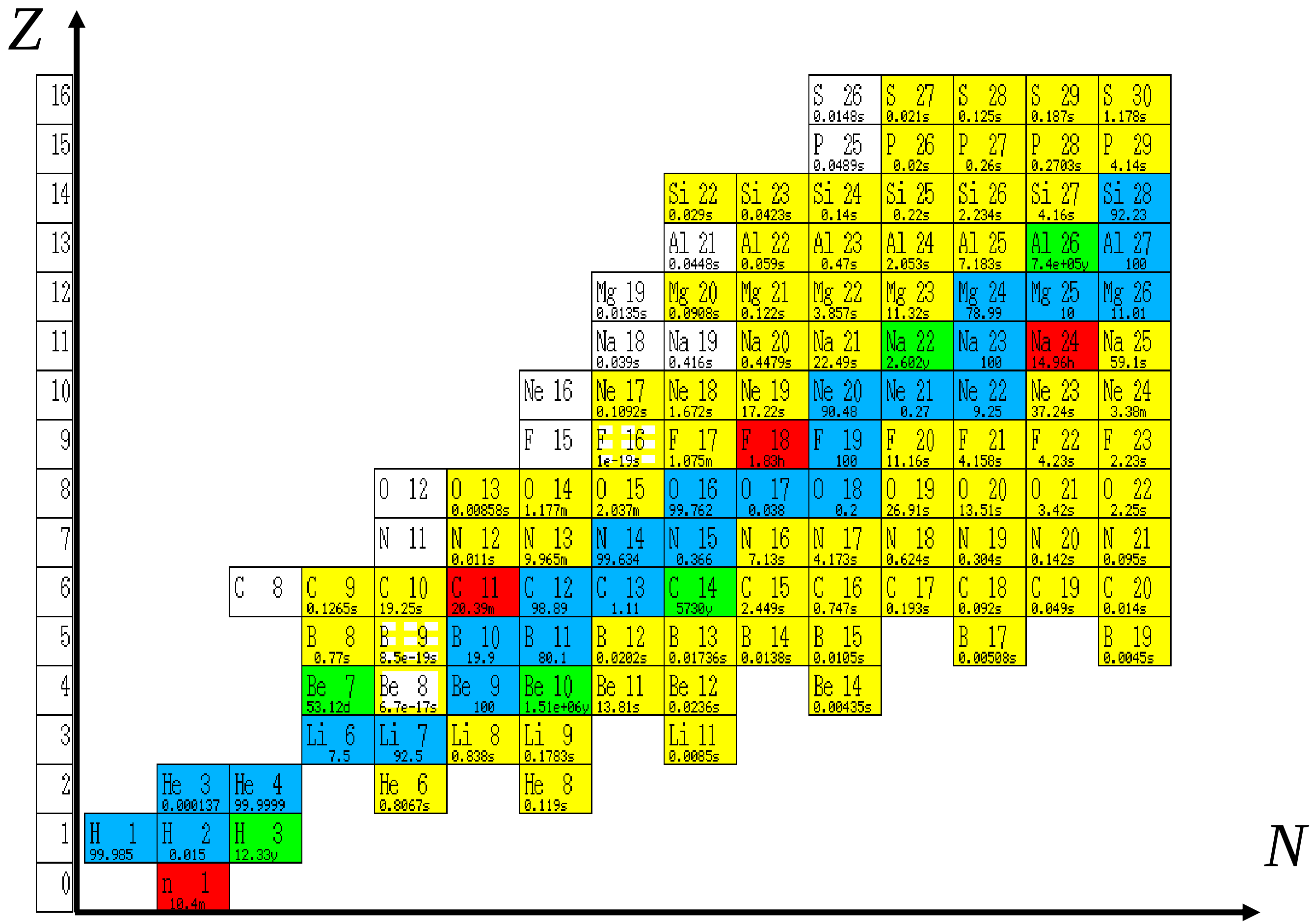
Too many protons

The β decay always converts along isobars

11			Na 18 0.039s	Na 19 0.416s	Na 20 0.4479s	Na 21 22.49s	Na 22 2.602y	Na 23 100
10		Ne 16	Ne 17 0.1092s	Ne 18 1.672s	Ne 19 17.22s	Ne 20 90.48	Ne 21 0.27	Ne 22 9.25
9		F 15	F 16 1e-19s	F 17 1.075m	F 18 1.83h	F 19 100	F 20 11.16s	F 21 4.158s
8	O 13 0.00858s	O 14 1.177m	O 15 2.037m	O 16 99.762	O 17 0.038	O 18 0.2	O 19 26.91s	O 20 13.51s
7	N 12 0.011s	N 13 9.965m	N 14 99.634	N 15 0.366	N 16 7.13s	N 17 4.173s	N 18 0.624s	N 19 0.304s
6	C 11 20.39m	C 12 98.89	C 13 1.11	C 14 5730y	C 15 2.449s	C 16 0.747s	C 17 0.193s	C 18 0.092s
5	B 10 19.9	B 11 80.1	B 12 0.0202s	B 13 0.01736s	B 14 0.0138s	B 15 0.0105s		B 17 0.00508s

Too many neutrons

Nucleus conversion through $\beta^{+,-}$-decay



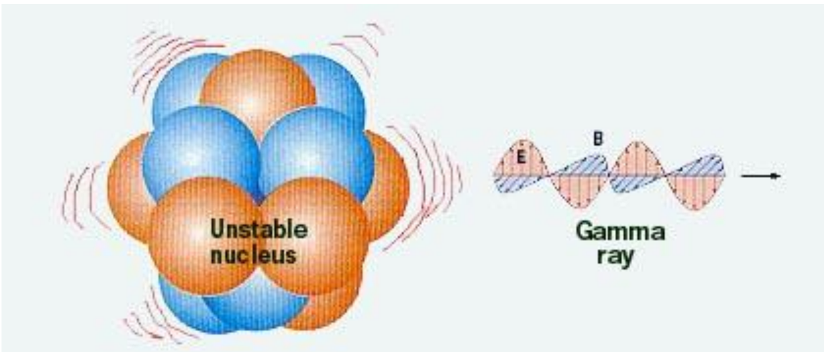
Determine the end-product of the β^+-emitter:

$$ {}^{A}_{Z}X_{N} \Rightarrow {}^{A}_{Z-1}X_{N+1} + \beta^{+} $$

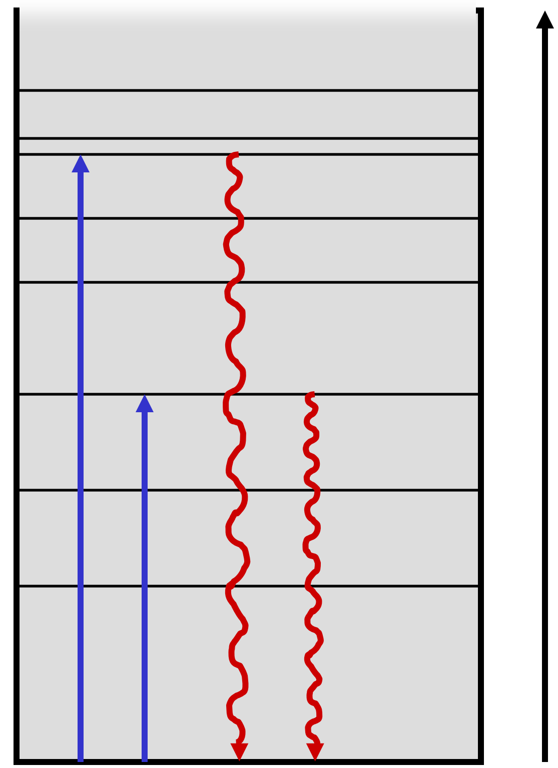
Determine the end-product of the β^--emitter:

$$ {}^{A}_{Z}X_{N} \Rightarrow {}^{A}_{Z+1}X_{N-1} + \beta^{-} $$

Gamma Decay of Nucleus



excited states
in nucleus



γ emission
$\lambda < 10^{-15}$ m

E_x

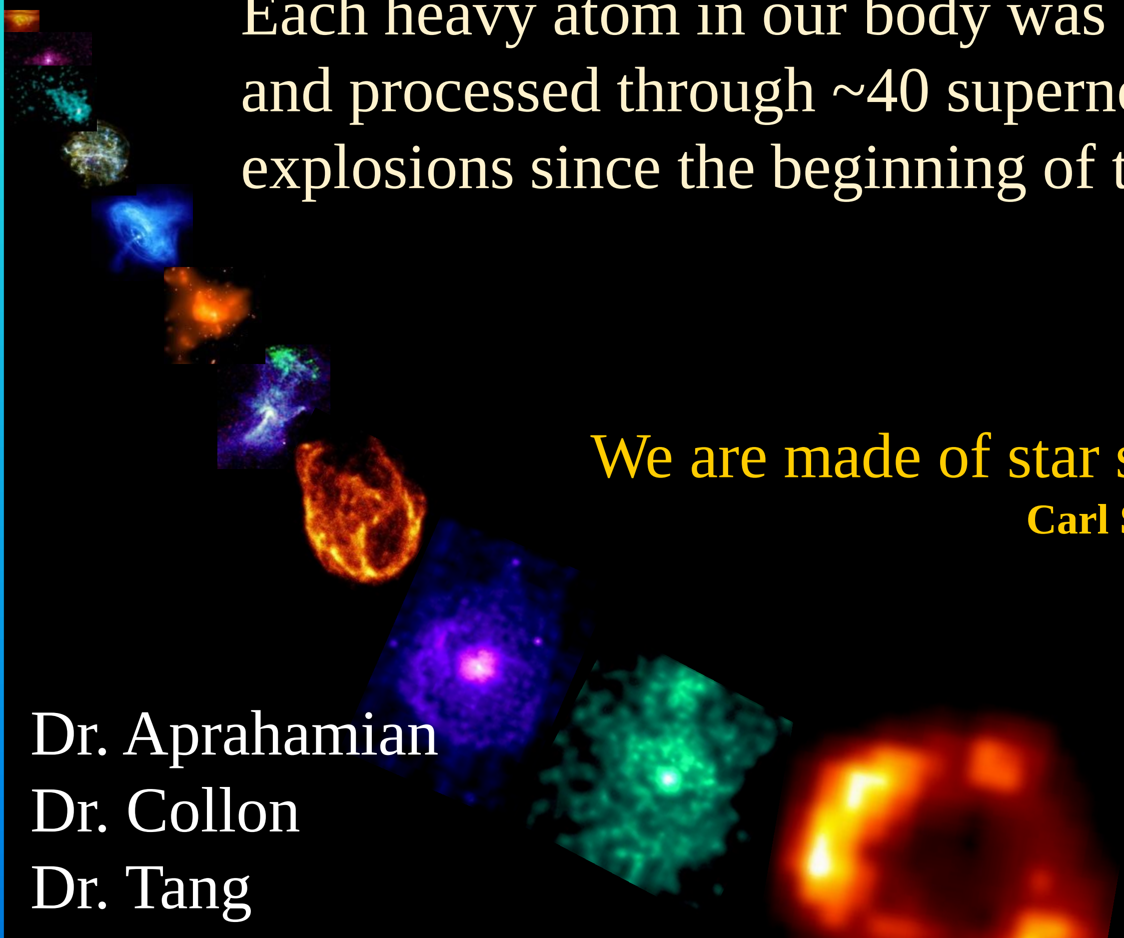
Excitation of nucleus
with subsequent
characteristic γ emission

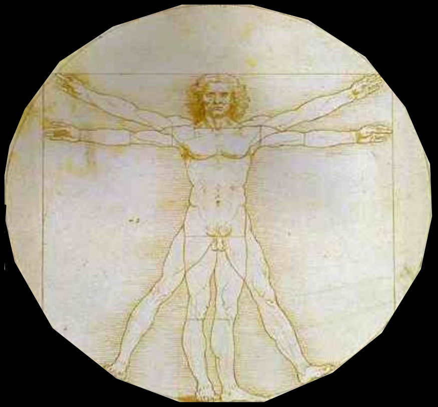
Excited states correspond
to vibration, rotation or
quantum state excitation

The Origin of the Elements

Without going to the stars how can we test our theory? The nuclear physics laboratory

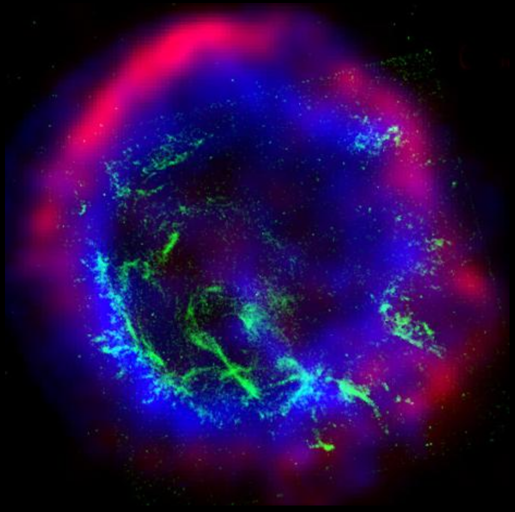
Each heavy atom in our body was built and processed through ~40 supernova explosions since the beginning of time!





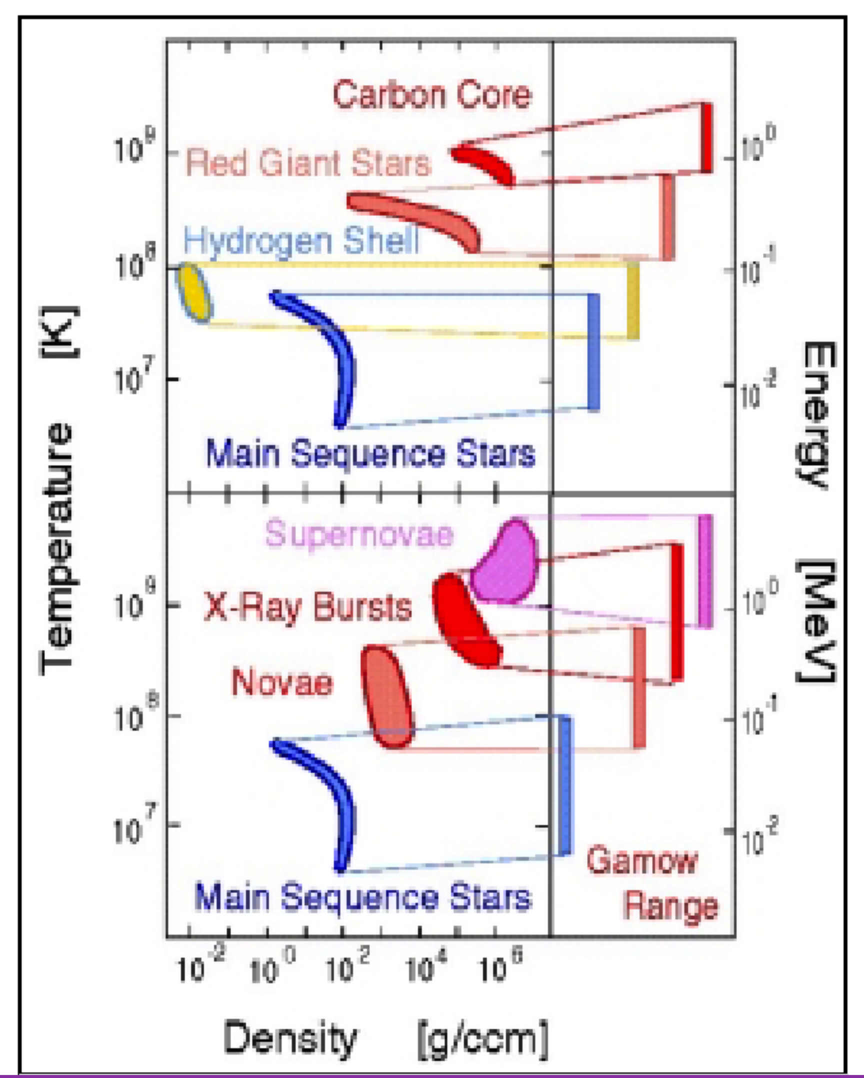
We are made of star stuff

Carl Sagan



Dr. Aprahamian
Dr. Collon
Dr. Tang
Dr. Wiescher

Energy ranges of stellar nucleosynthesis



$E = kT$

$k = 8.617\,343(15) \times 10^{-5}$

Energy range:

Steady state burning:

$[10^{-2} – 1 \text{ MeV}]$

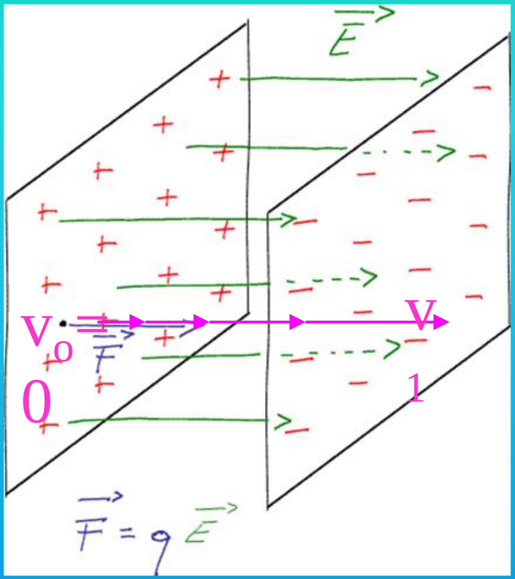
Explosive nucleosynthesis:

$[10^{-2} – 10 \text{ MeV}]$

The concept of reaction cross sections

Electrical and magnetic fields

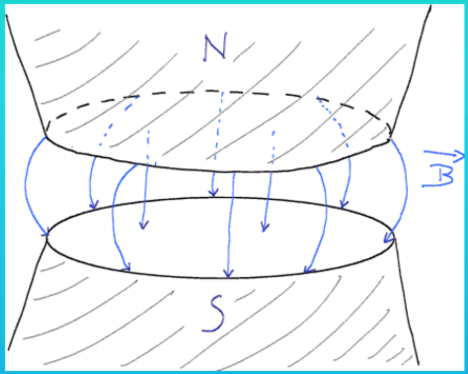
Charged particle in an electric field

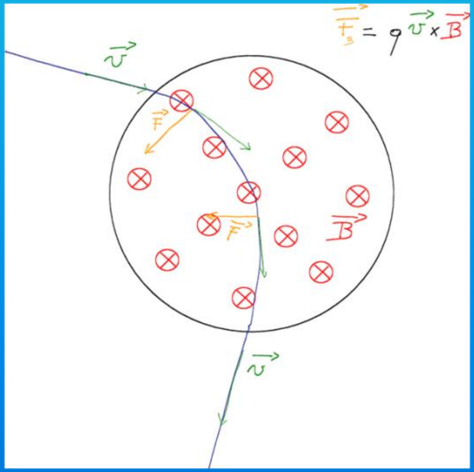


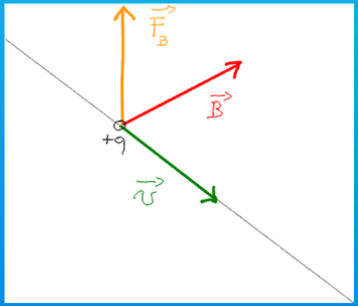
The velocity of a charged particle in an electric field increases or decreases. A positive charge, initially at rest on the positive plate, is submitted to a force F=qE. It will be accelerated between the two plates

The energy of the particle increases: $k=(mv^2)/2$

Charged particle in an magnetic field



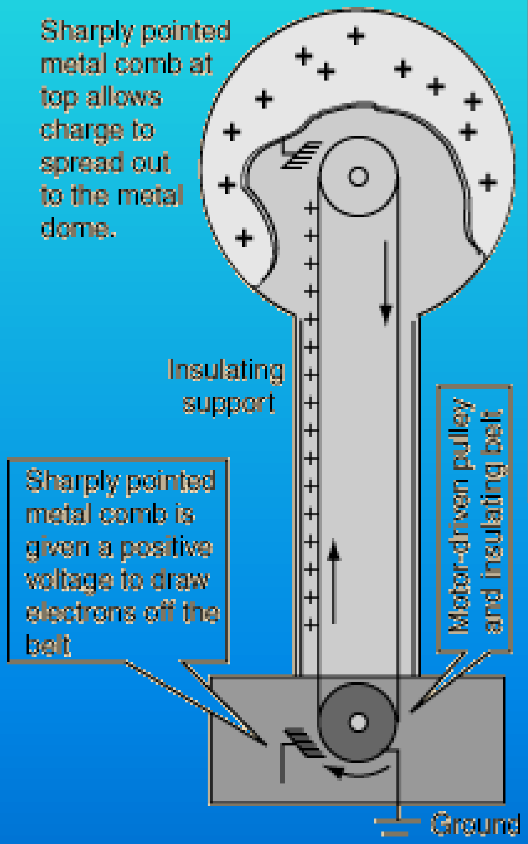




The energy of the particle stays unchanged. The magnetic force does no work on the particle (the force is at 90˚ to the velocity)

Charged particle in an electric and magnetic field: Lorentz force $\vec{F} = q\vec{E} + q\vec{v}\times\vec{B}$ or $|\vec{F}| = qE + q.v.B.\sin\theta$

Technical Principle of the Van de Graaff



potential: $U = \dfrac{Q}{C}$ with Q = charge and C = capacity

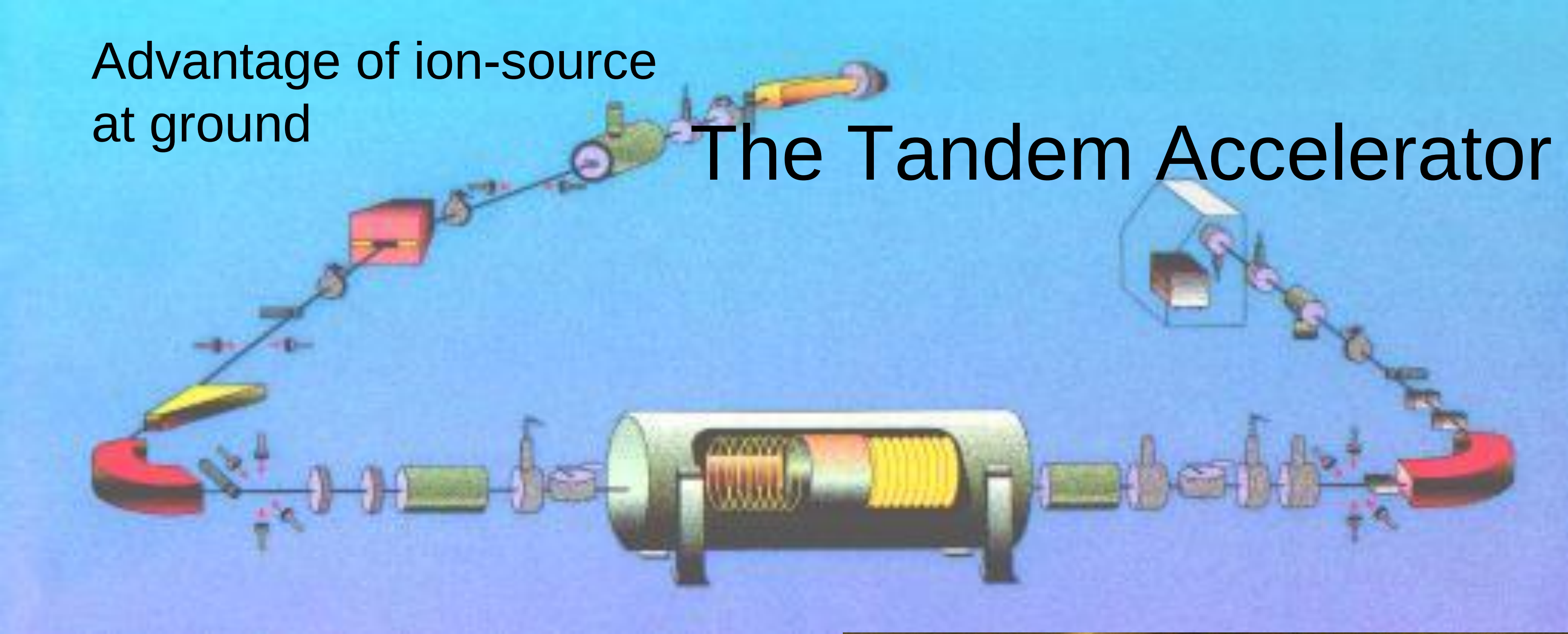
Energy: $E = \dfrac{1}{2} m \cdot v^2 = q \cdot U$;

with U up to 10000000 V: $E \leq q \cdot 10^7 eV = 10 \cdot q\ MeV$

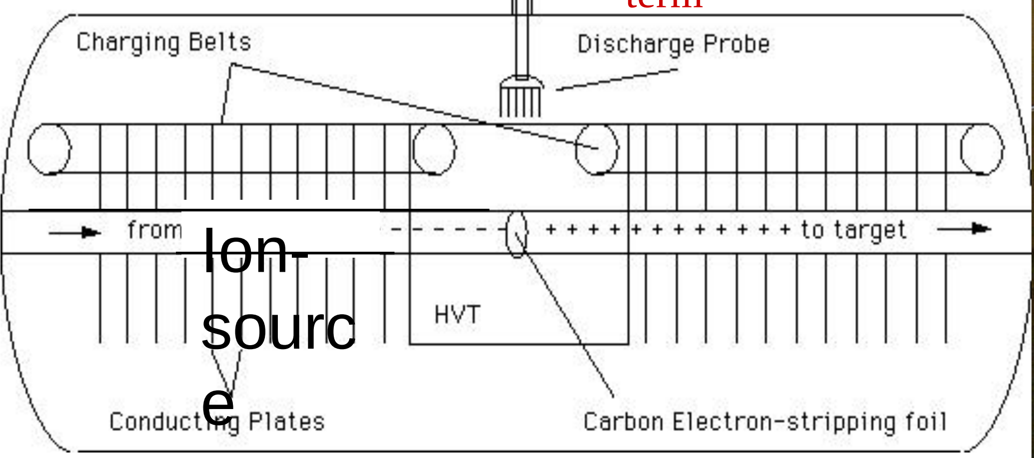
Sufficient energy for necessary excitation mechanisms!

The Tandem Accelerator

Advantage of ion-source at ground



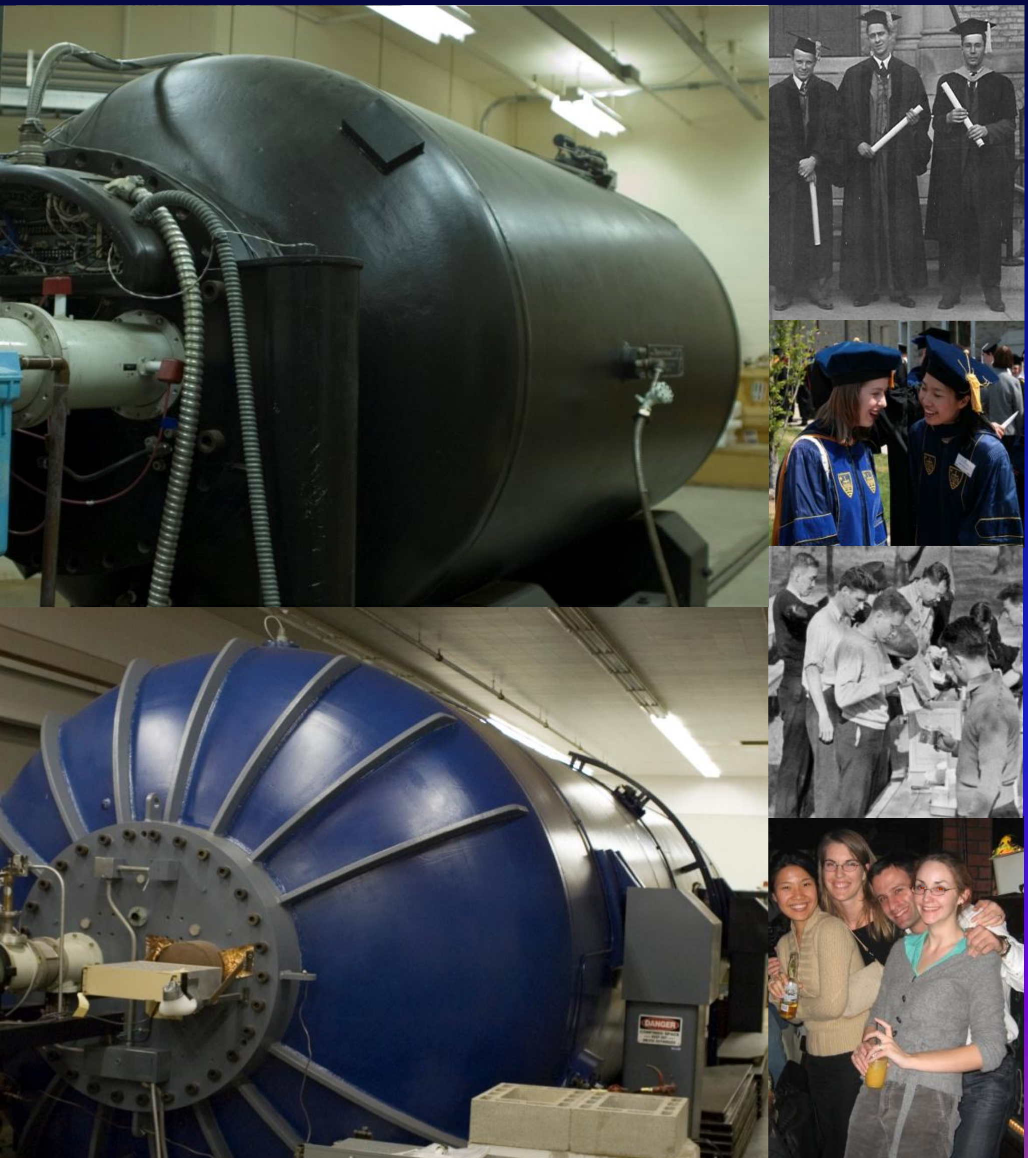
Terminal potential V_{term}



Ion-source

Total energy: $E=(1+q)V_{term}$

70 Years of Science History and Continuing Education

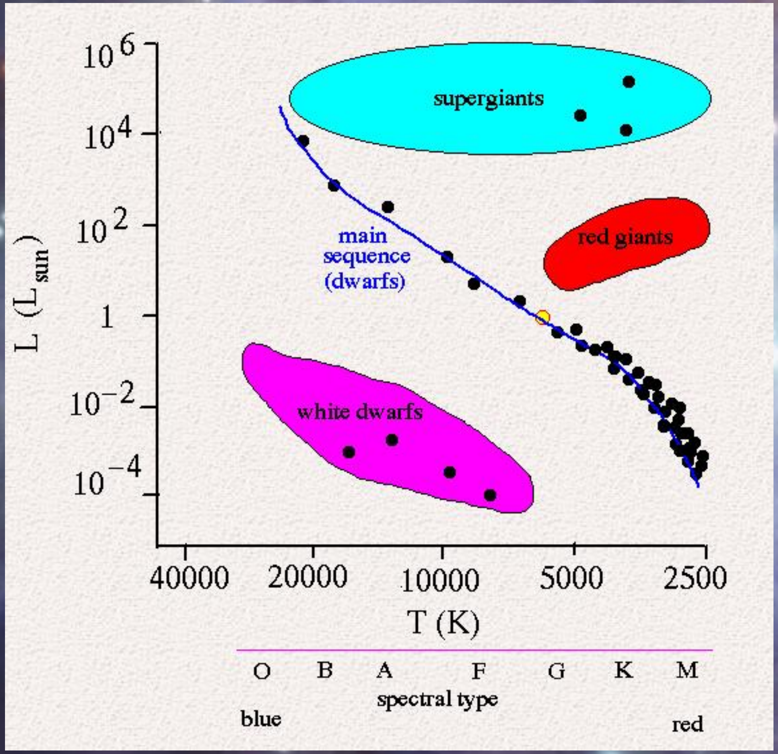


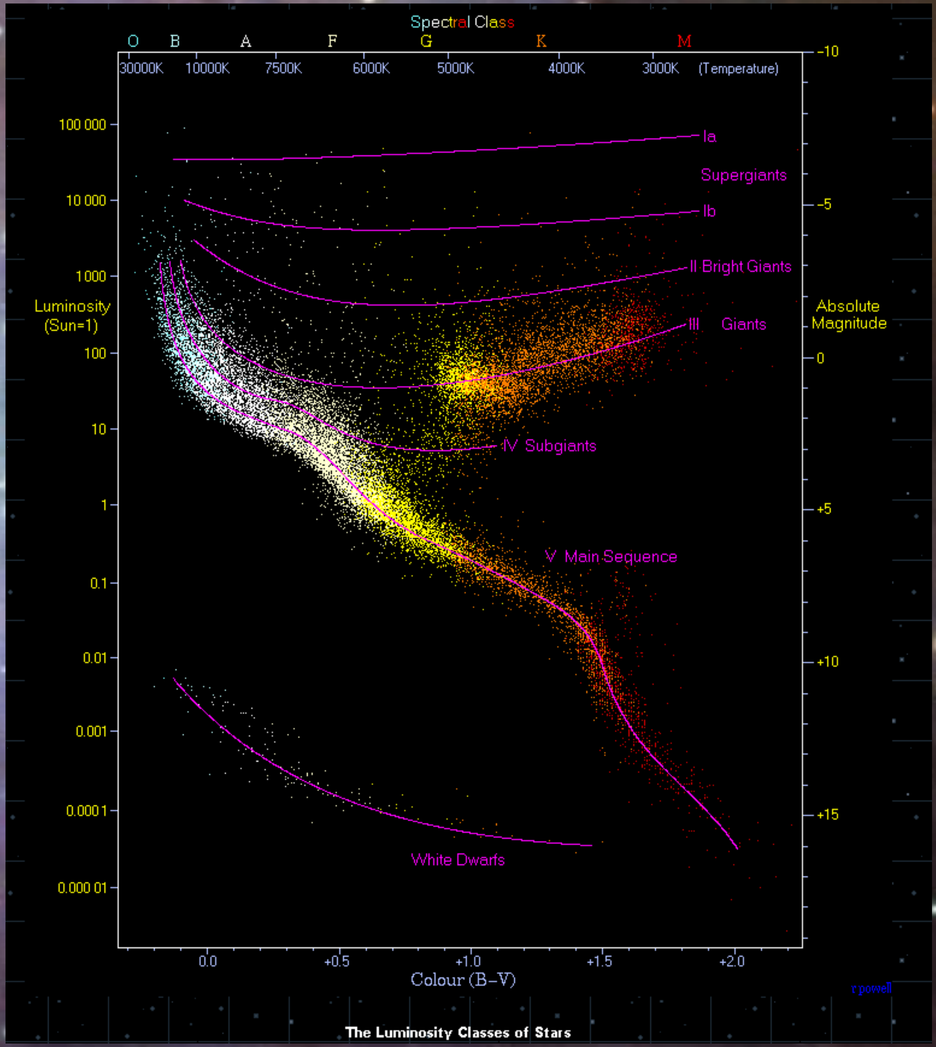
Today:

4 accelerators
6 T&R faculty
10 research staff
25 +3 grad students
15 undergrad students

More than 30 national & international user groups: Australia, Austria, Belgium, Brazil, Canada, China, Germany, Hungary, India, Israel, Italy, Japan, Mexico, Portugal, Romania, Turkey, UK, Ukraine

The Herzsprung-Russell diagram





Stellar nucleosynthesis, A≤60

Contraction of a protostar

contraction → T° and ρ increase

Hydrogen burning

-pp-chain

-CNO cycle

→ Formation of ^{4}He

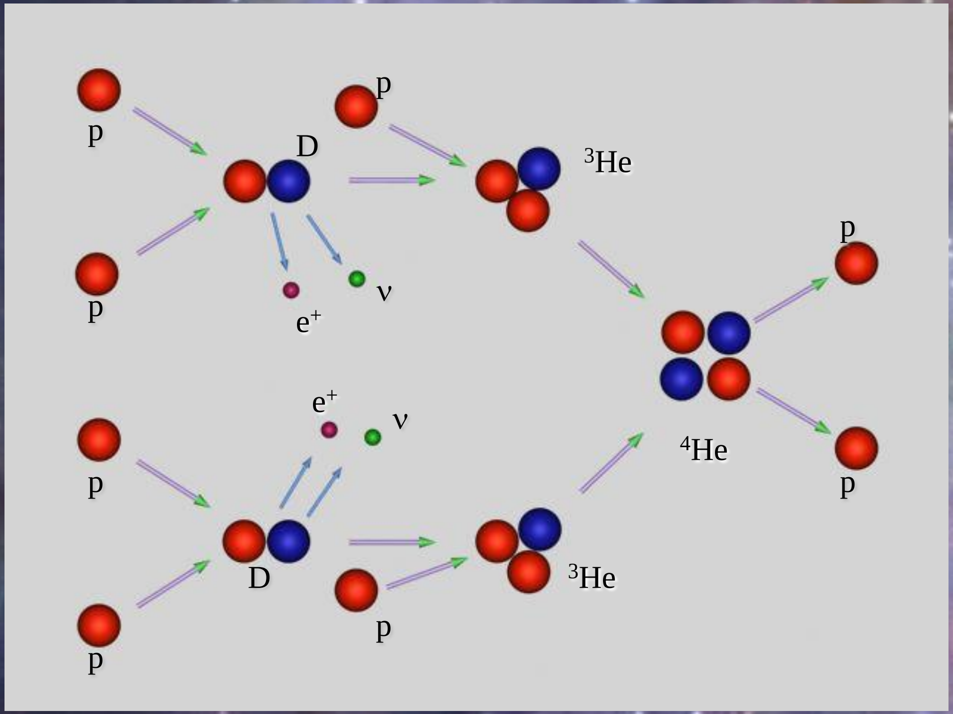
Fuel exhaustion → contraction → T° and ρ increase → new reactions

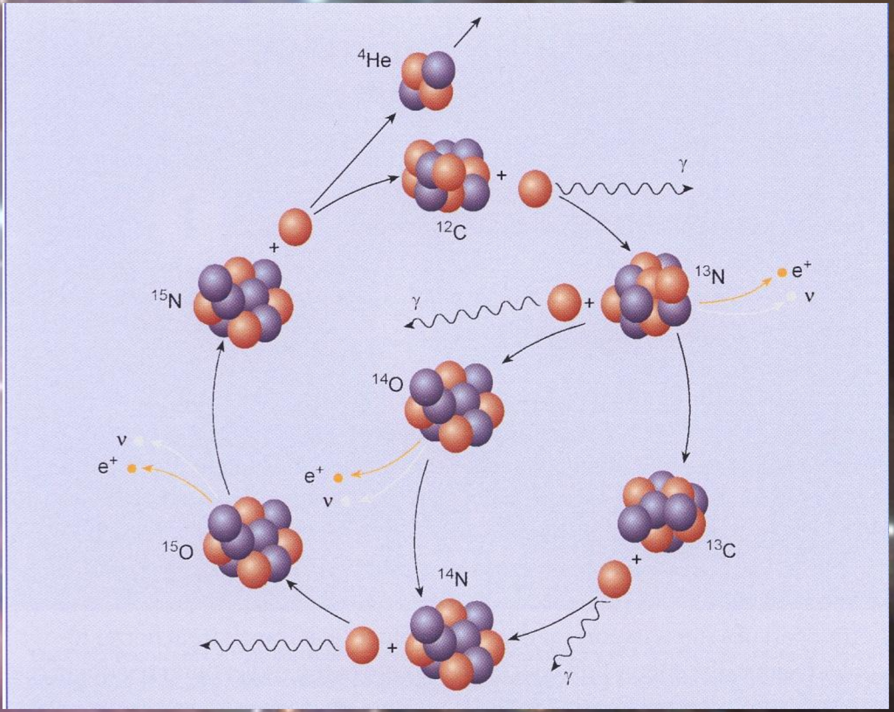
Helium burning (core) → red giant

$3\alpha \rightarrow {}^{12}C$ and $^{12}C(\alpha, \gamma)\,{}^{16}O$ up to ^{20}Ne

Hydrogen burning in the outer shell (CNO cycle)

Hydrogen burning





Sun: 85% 15%

Massive stars

Carbon burning

$^{12}C + {}^{12}C$ produces mainly ^{20}N $^{12}C(^{12}C, \alpha)^{20}Ne$

also: $^{12}C(^{12}C, p)^{23}Na$ & $^{12}C(^{12}C, n)^{23}Mg$

Photodisintegration $^{20}Ne(\gamma, \alpha)^{16}O$

Oxygen burning

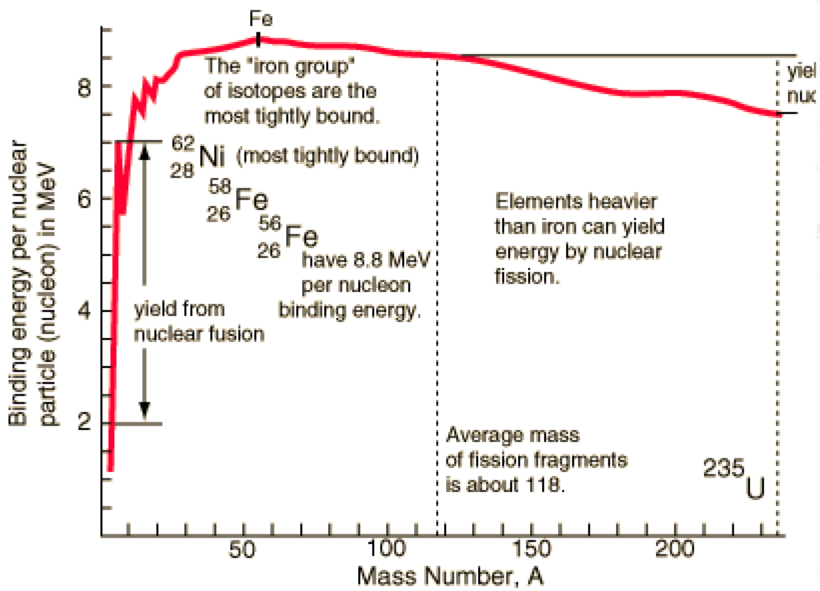
$^{16}O + {}^{16}O$ produces mainly ^{28}Si $^{16}O(^{16}O, \alpha)^{28}Si$

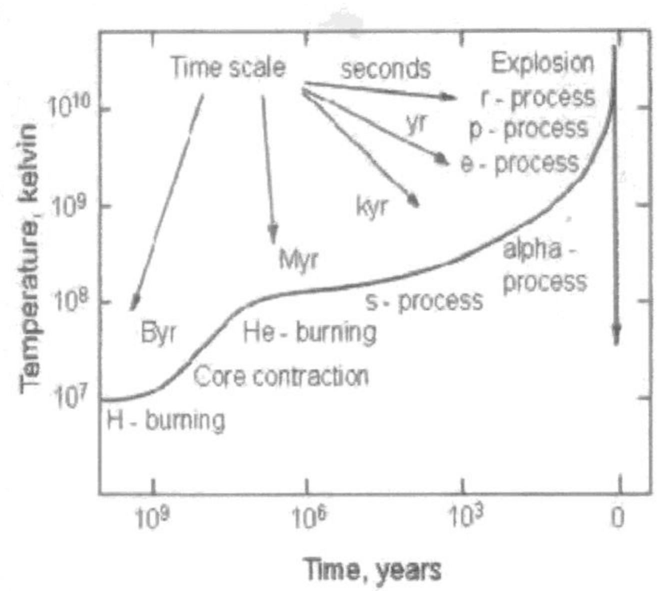
Silicon burning

(α, γ) produces ^{32}S, ^{36}Ar, ^{44}Ca, ……

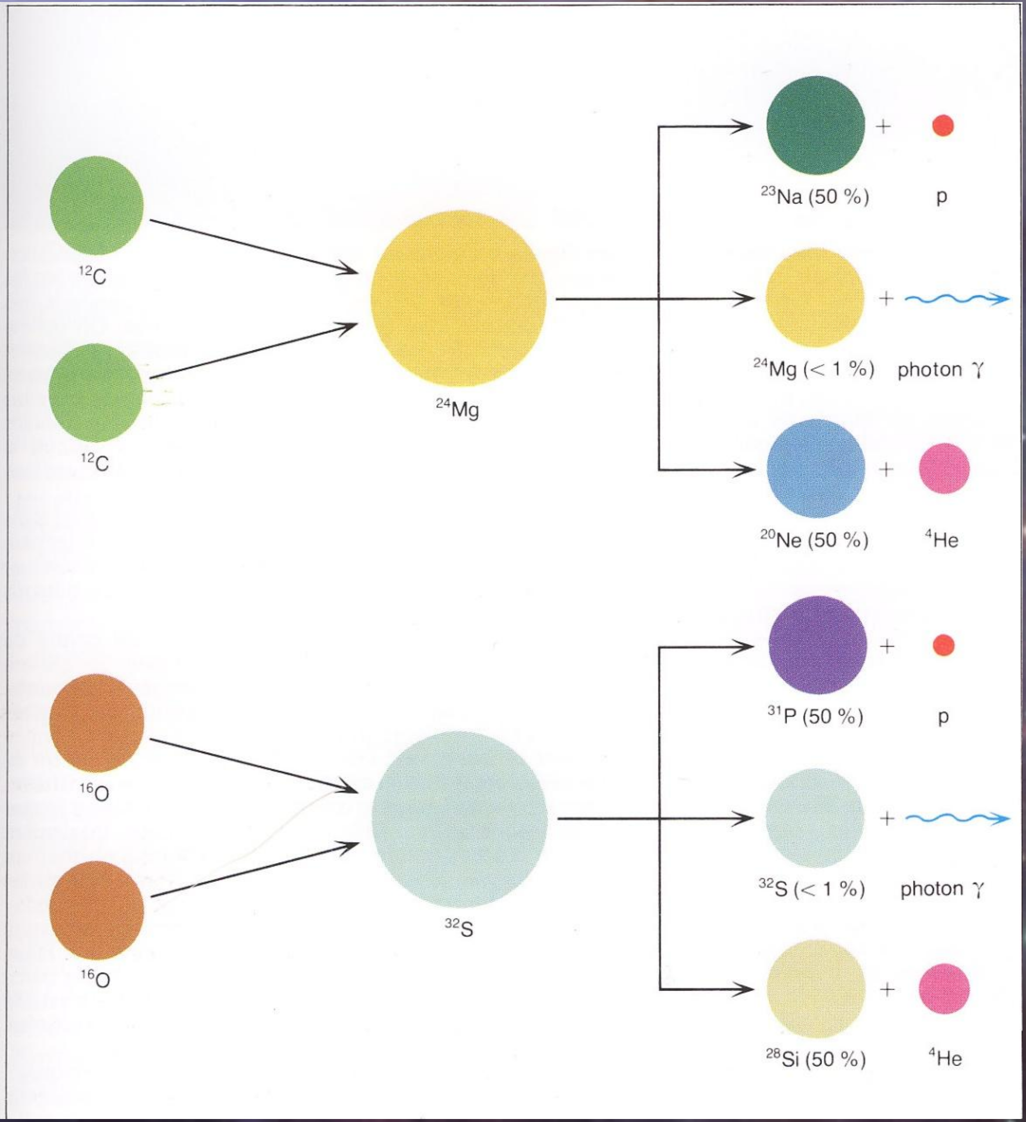
Fusion reactions are not energetically favored above A>60

Binding energy per nucleon

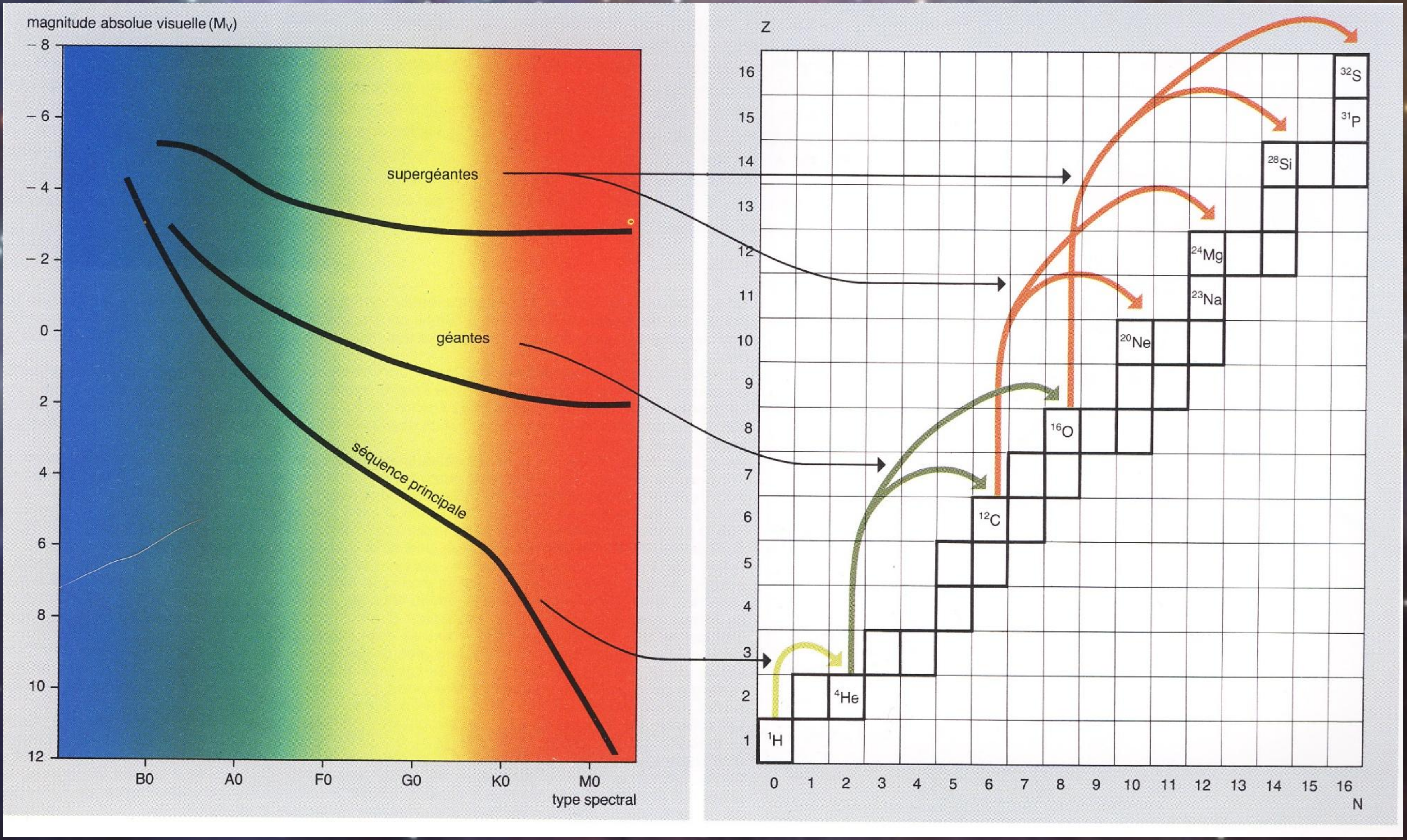




Carbon and oxygen burning



Stellar mass and nucleosynthesis (A<60)



Stellar nucleosynthesis, A≥60

Nuclei with masses A>60 are formed by neutron or proton capture which takes place in 2 different astrophysical environments:

- "steady state" burning nucleosynthesis
  - s-process
- explosive nucleosynthesis
  - r-process
  - rp-process

s-process: neutron capture is on a slow rate compared to β-decay

Located near the valley of stability, takes place in red giants and the neutrons are provided by: $^{13}C(\alpha, n)^{16}O$

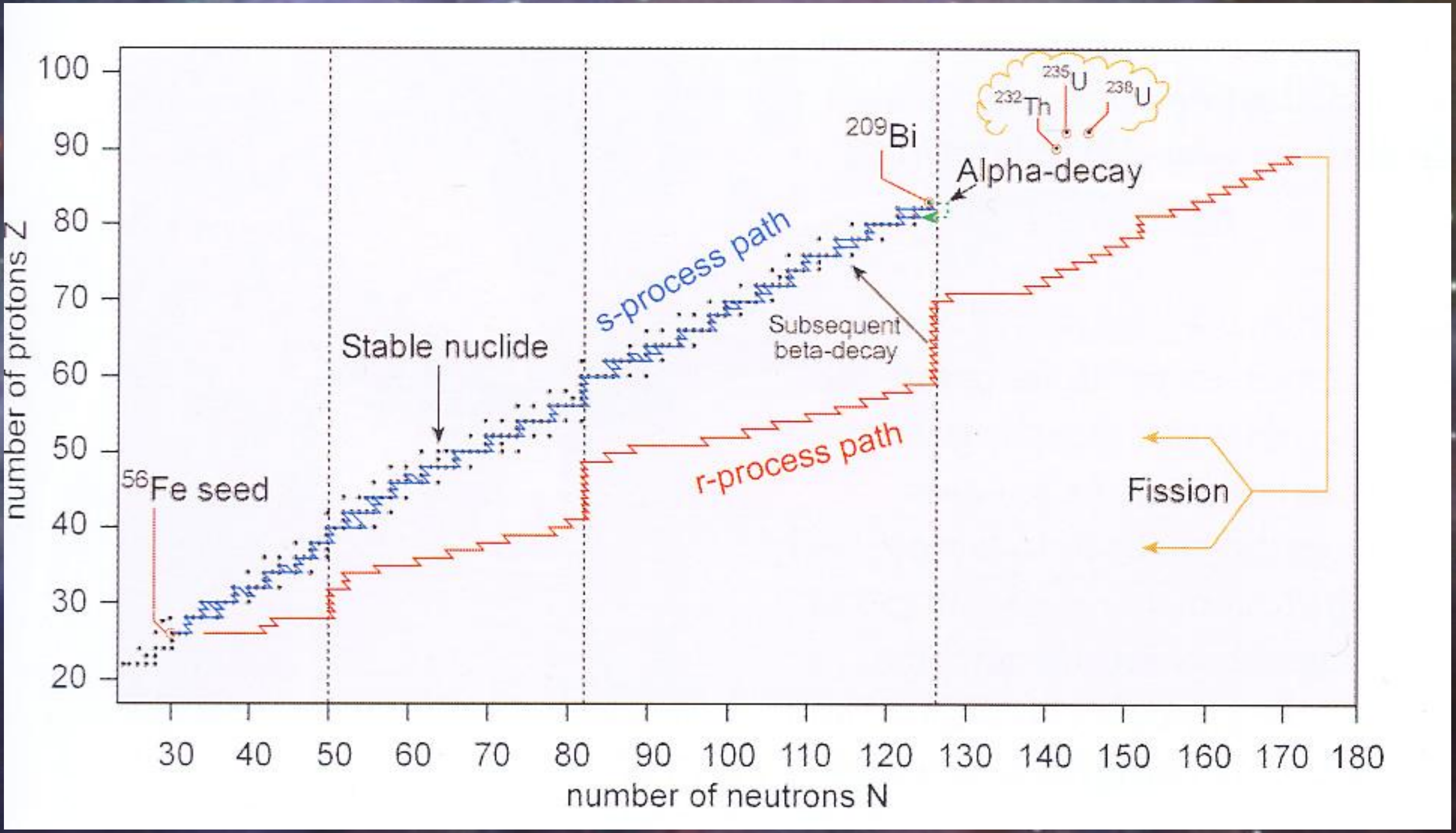
$^{22}Ne(\alpha, n)^{25}Mg$

r-process: neutron capture is on a fast rate compared to β-decay

Needs high neutron fluxes $>10^{20}$ /cm^3

Probably takes place in supernovae

r and s process



rp-process

The seat of this process lies in explosive binary stars.

Accretion of the atmosphere (mostly H, He) of expanding star on the compact object

↓

Ignition of the unburnt H → Energy generation is from the hot CNO cycle

↓

Break out

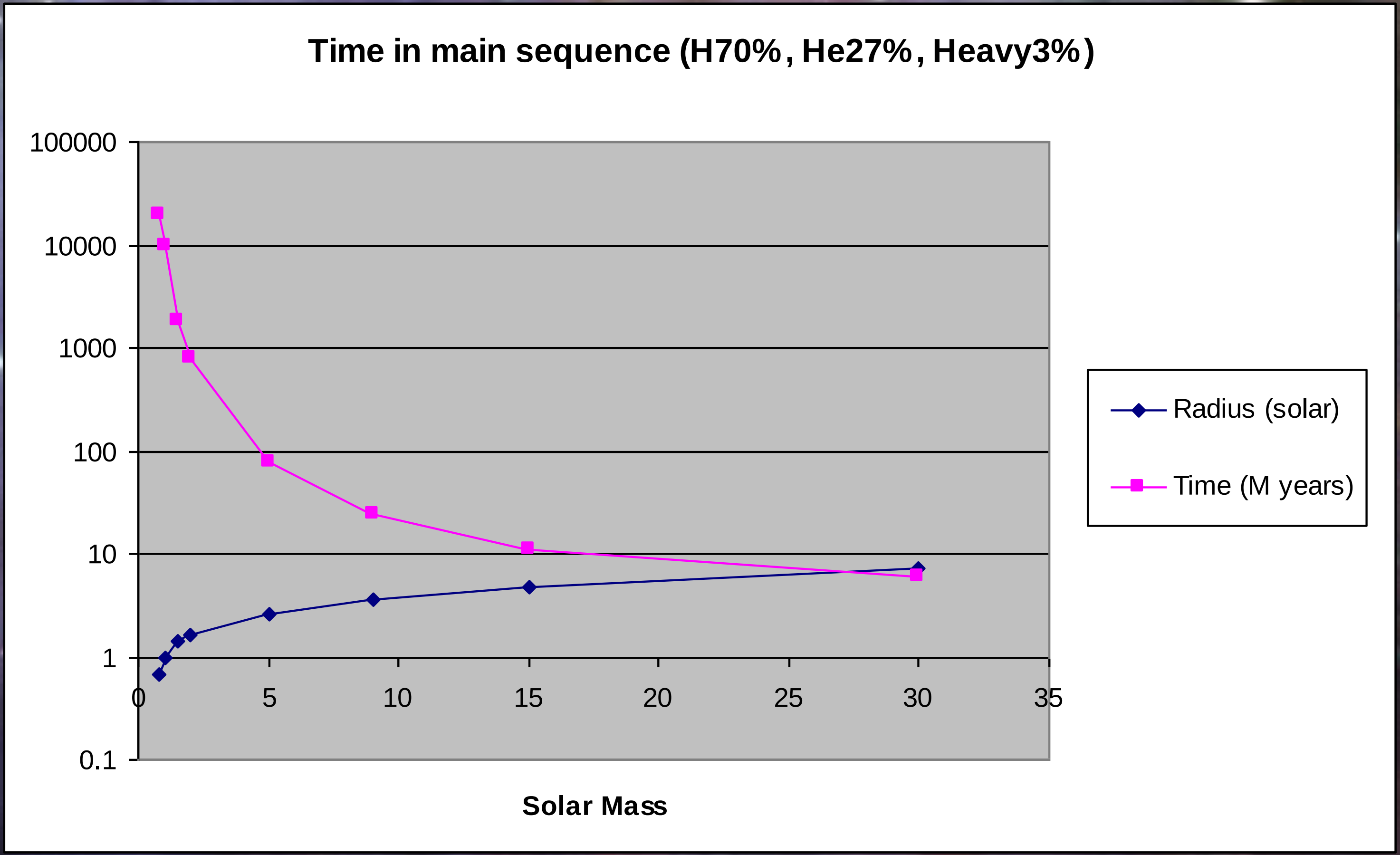
↓

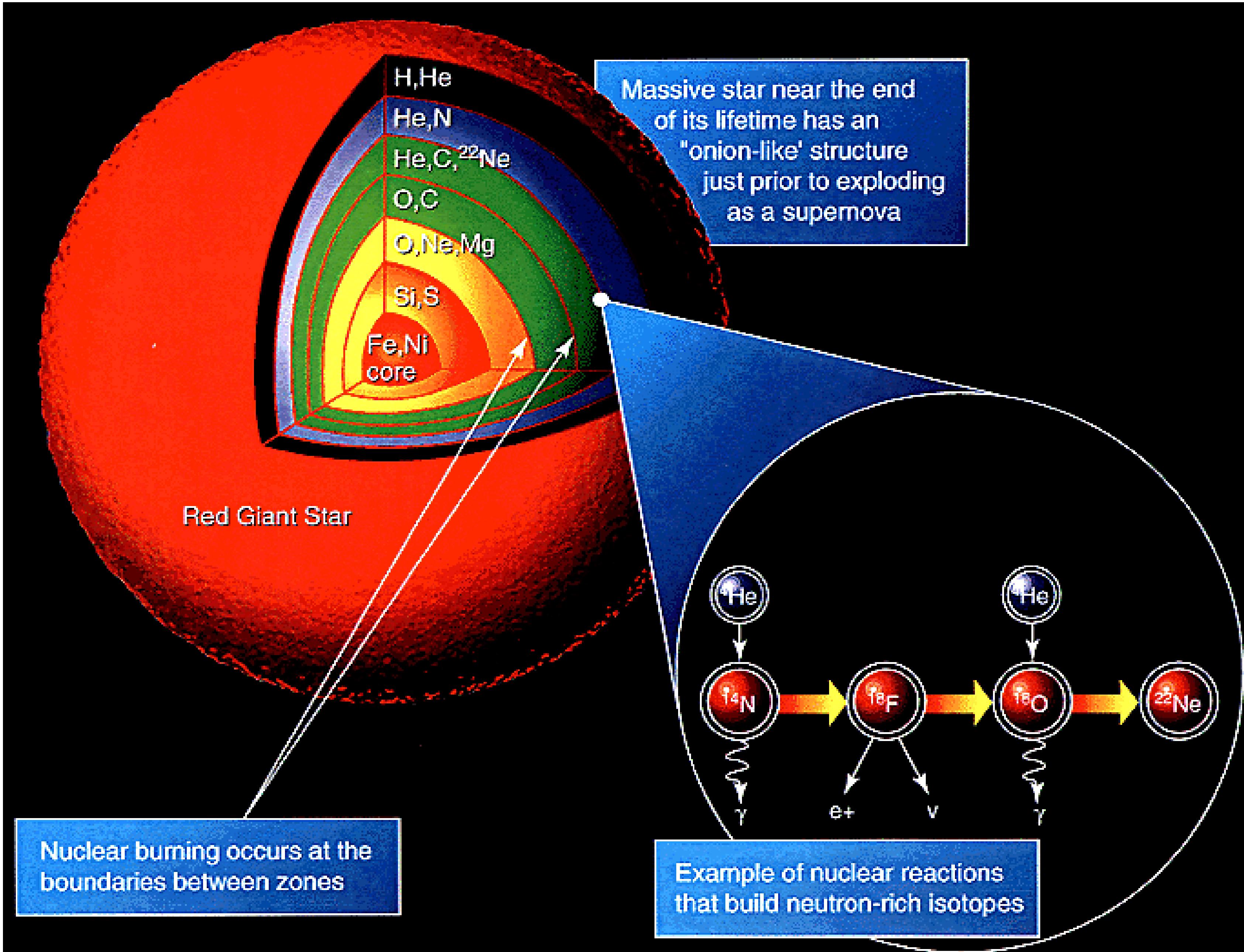
Explosive H burning: series of fast p capture processes produce nuclei faster than they decay: rp-process

→ Leads to proton rich nuclei → Sn, Sb, Te region

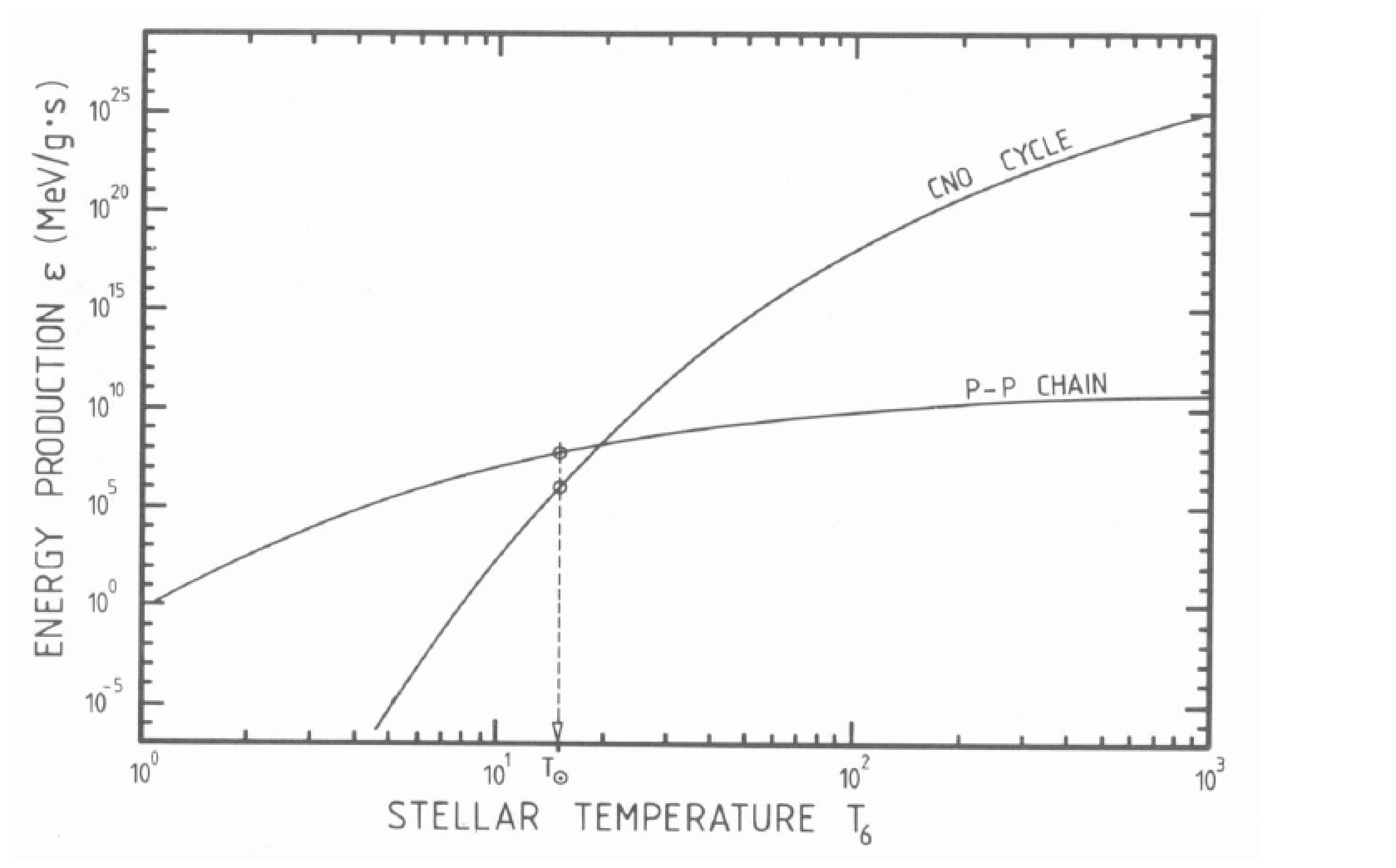
Explosions in such accreting systems are classified as:
- Novae
- X-ray bursts
- Type Ia supernovae

Lifetime of a star



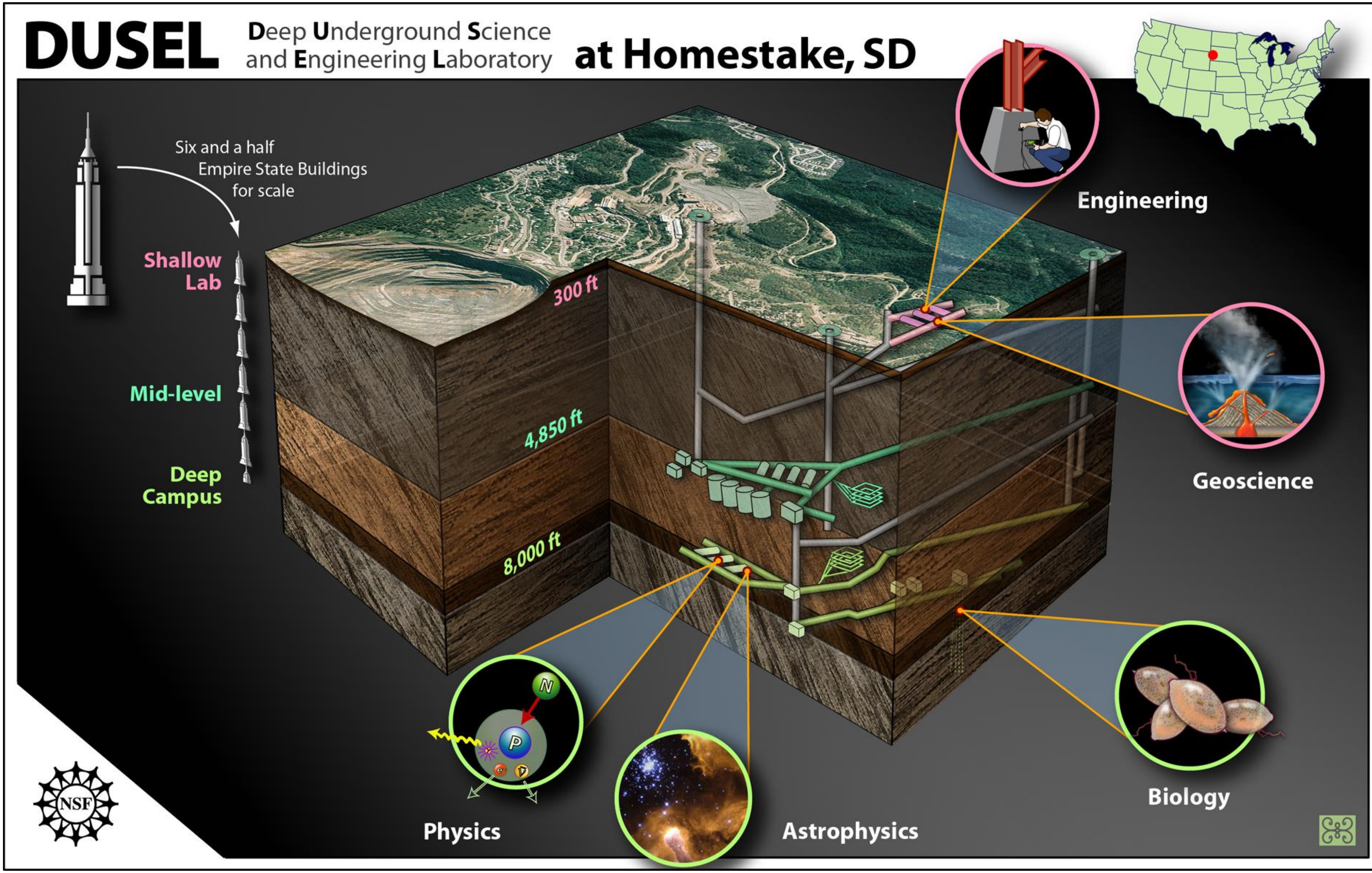


H,He
He,N
He,C,22Ne
O,C
O,Ne,Mg
Si,S
Fe,Ni core
Massive star near the end of its lifetime has an "onion-like' structure just prior to exploding as a supernova
Red Giant Star
4He
4He
14N
18F
18O
22Ne
γ
e+
ν
γ
Nuclear burning occurs at the boundaries between zones
Example of nuclear reactions that build neutron-rich isotopes

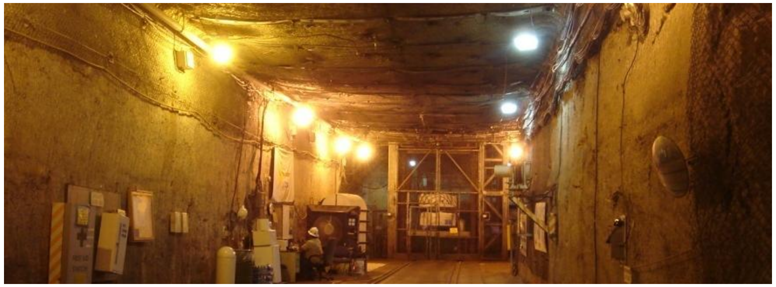


ENERGY PRODUCTION ε (MeV/g·s)
10^25
10^20
10^15
10^10
10^5
10^0
10^-5
CNO CYCLE
P-P CHAIN
10^0
10^1
T⊙
10^2
10^3
STELLAR TEMPERATURE T6

The underground laboratory


DUSEL
Deep Underground Science and Engineering Laboratory
at Homestake, SD
Six and a half Empire State Buildings for scale
Shallow Lab
Mid-level
Deep Campus
300 ft
4,850 ft
8,000 ft
Engineering
Geoscience
Biology
Physics
Astrophysics
NSF

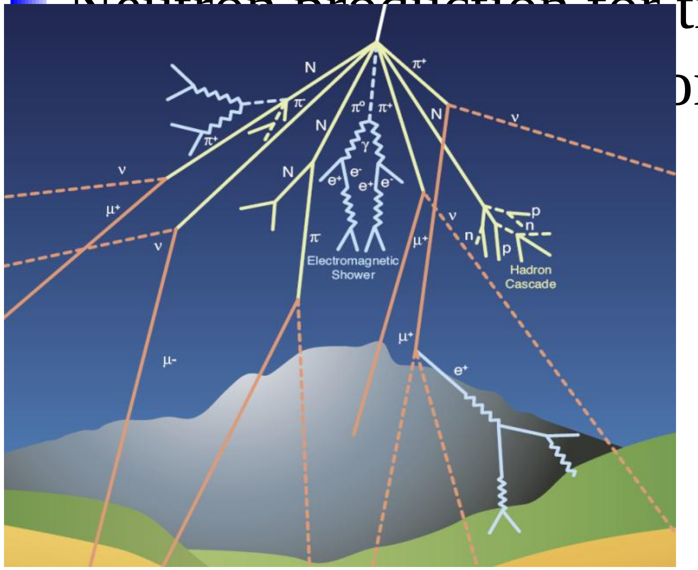
Astrophysics underground

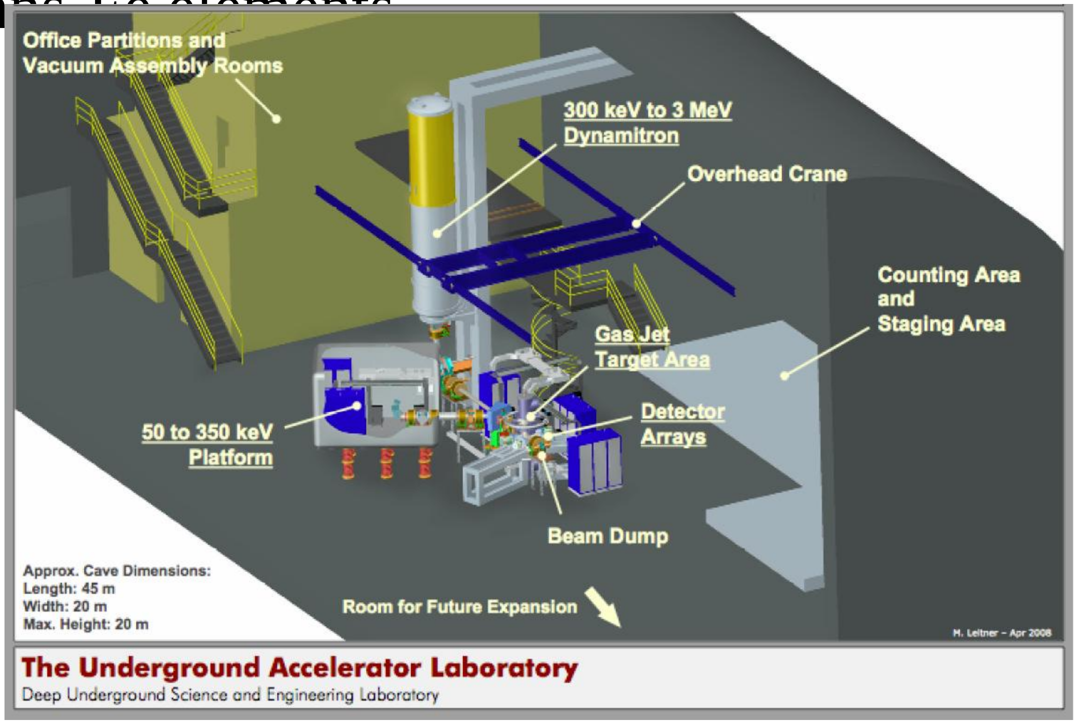


Nuclear Reactions at stellar temperatures

- Timescale of stellar evolution
- Stellar energy production
- Nucleosynthesis from He to Fe
- Seed production for explosive nucleosynthesis
- Neutron production for trans-Fe elements

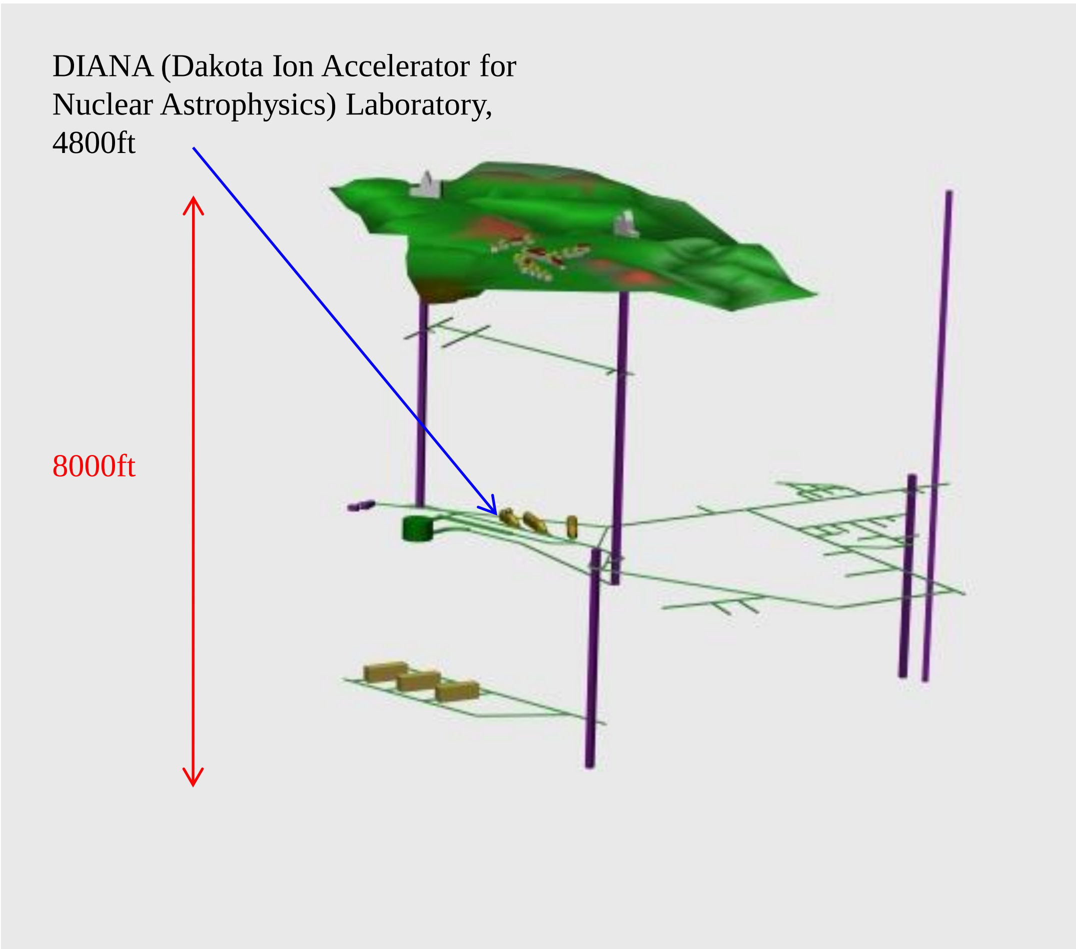
Two-Accelerator Laboratory at DUSEL





Measurements handicapped by Cosmic Ray background

DIANA at DUSEL



A view of Homestake in South Dakota

A conceptual view of the DIANA lab.