INFN LNS

Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali del Sud

PID
Programma Infn per Docenti

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Astrofisica Nucleare

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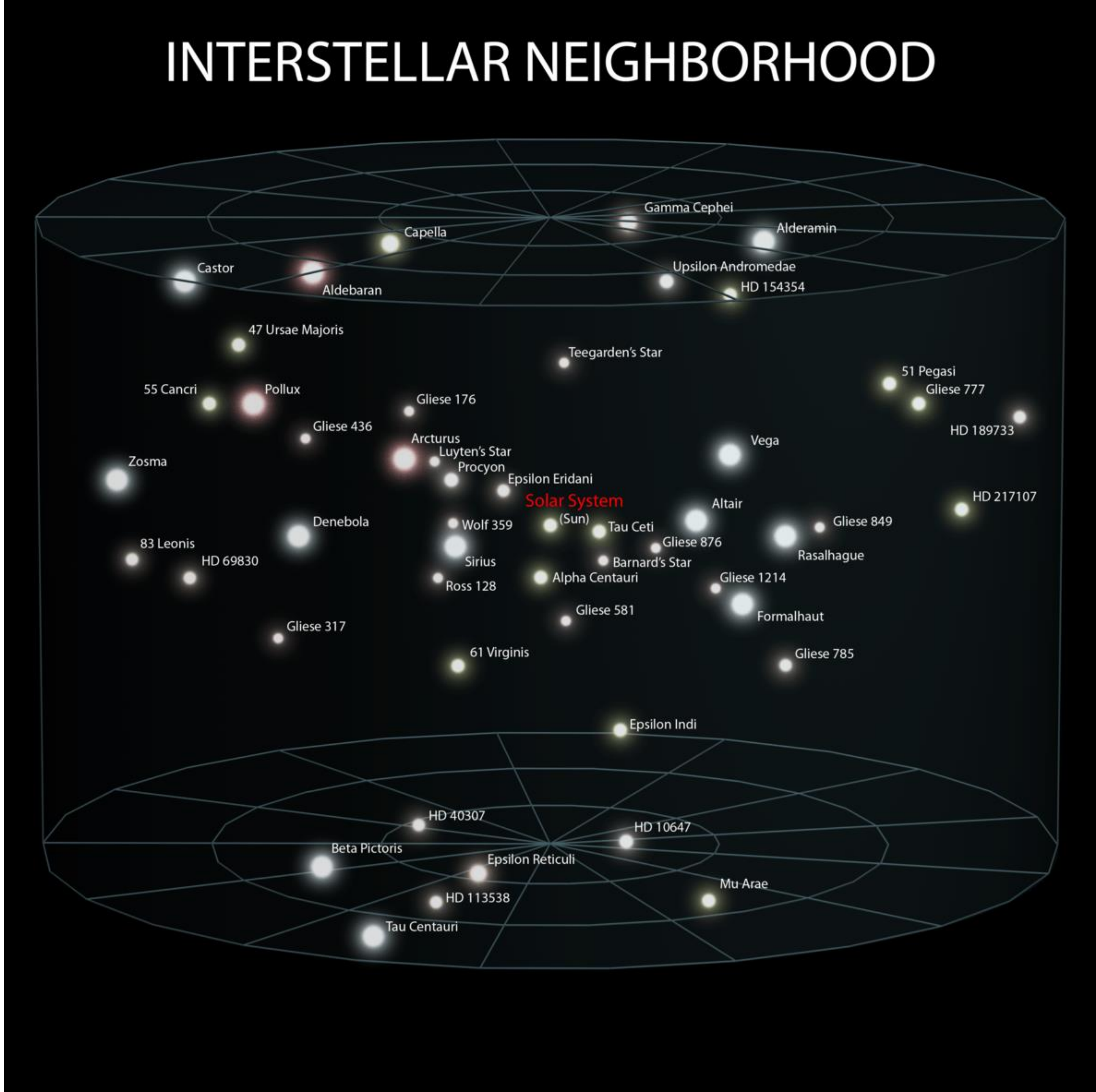


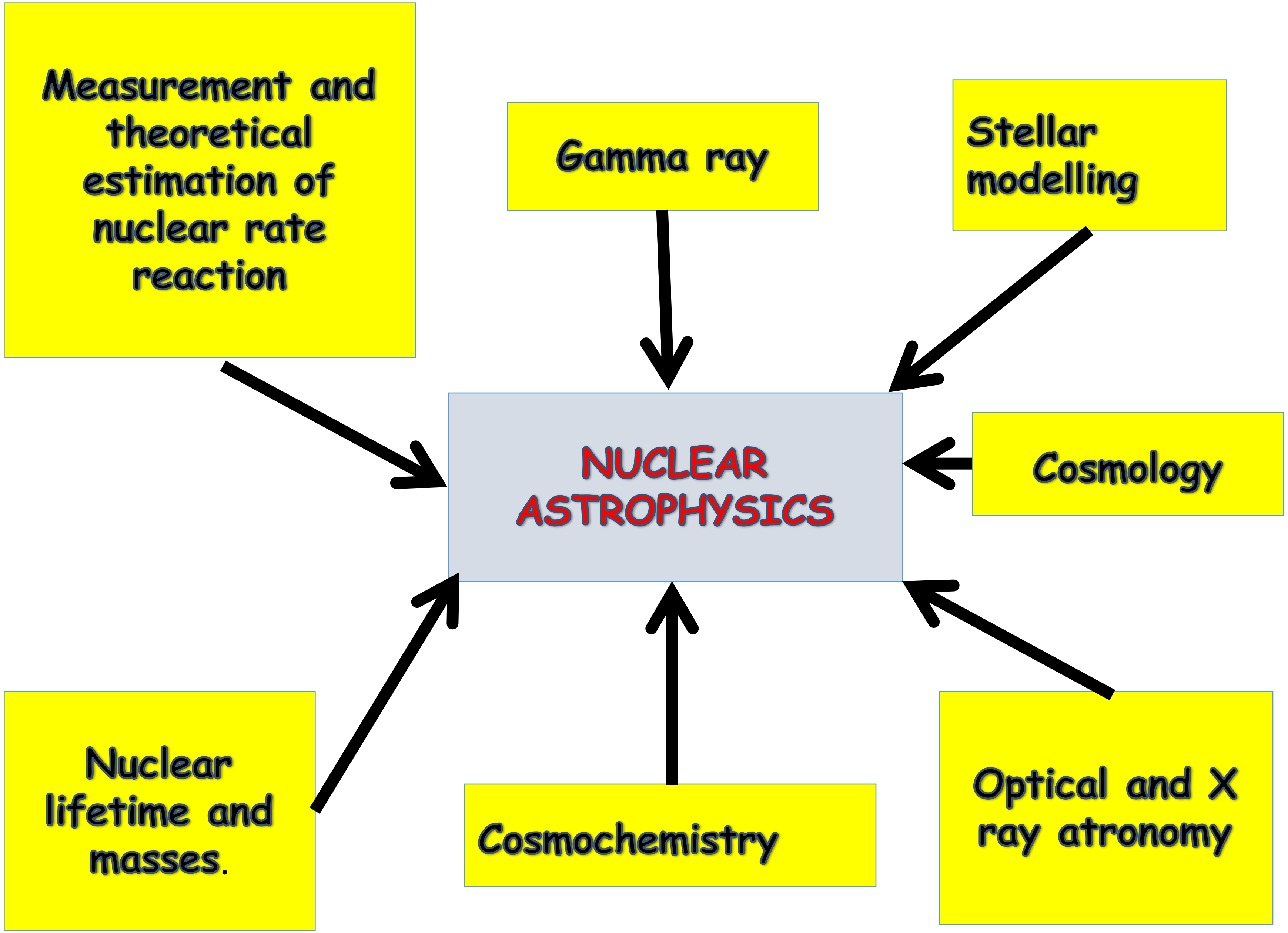
What is Nuclear Astrophysics?

Starts from the marriage between

ASTROPHYSICS **NUCLEAR PHYSICS**

William A. Fowler
Nobel Price Physics
(1983)

Premio Nobel per la Fisica nel 1983 per i suoi studi teorici e sperimentali sulle reazioni nucleari che danno origine agli elementi chimici nell'universo.


Measurement and theoretical estimation of nuclear rate reaction
Gamma ray
Stellar modelling
NUCLEAR ASTROPHYSICS
Cosmology
Nuclear lifetime and masses.
Cosmochemistry
Optical and X ray atronomy

Argomenti

- Introduzione all’Astrofisica Nucleare

    osservazioni astronomiche e aspetti astrofisici

    aspetti nucleari

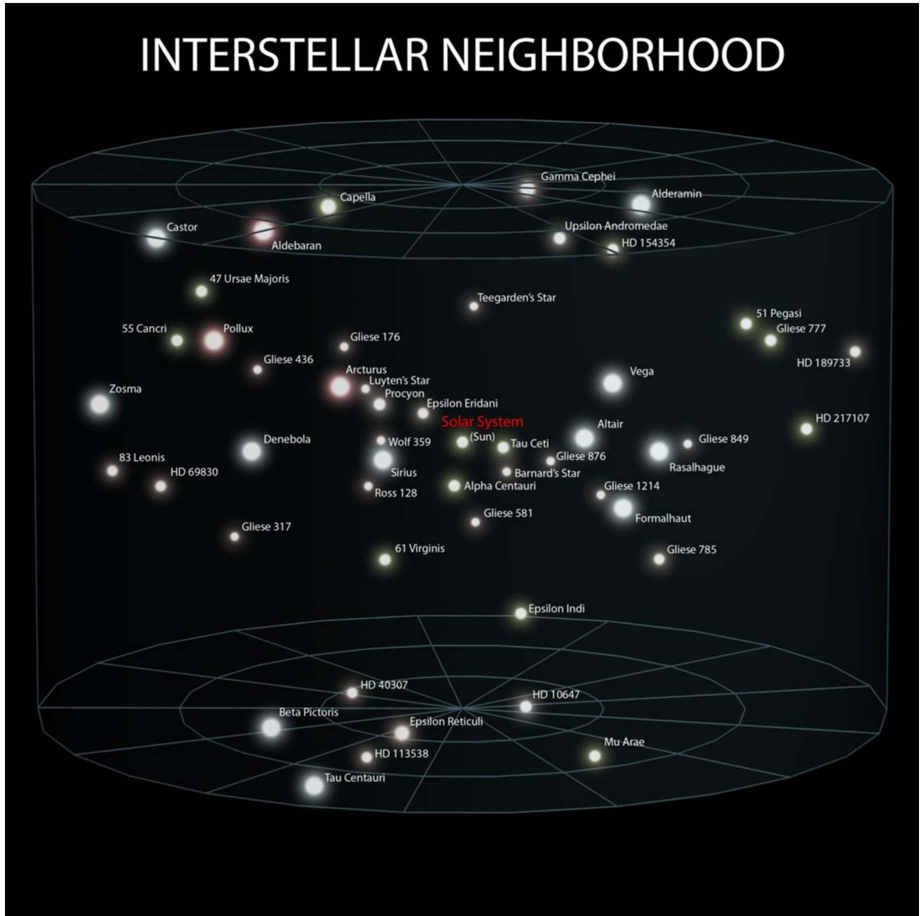
- reazioni termonucleari
- Parametri nucleari di interesse astrofisico: rate di reazione
- misure di sezione d’urto di interesse astrofisico
- Astrofisica nucleare ai LNS: tecniche e apparati sperimentali in Astrofisica Nucleare

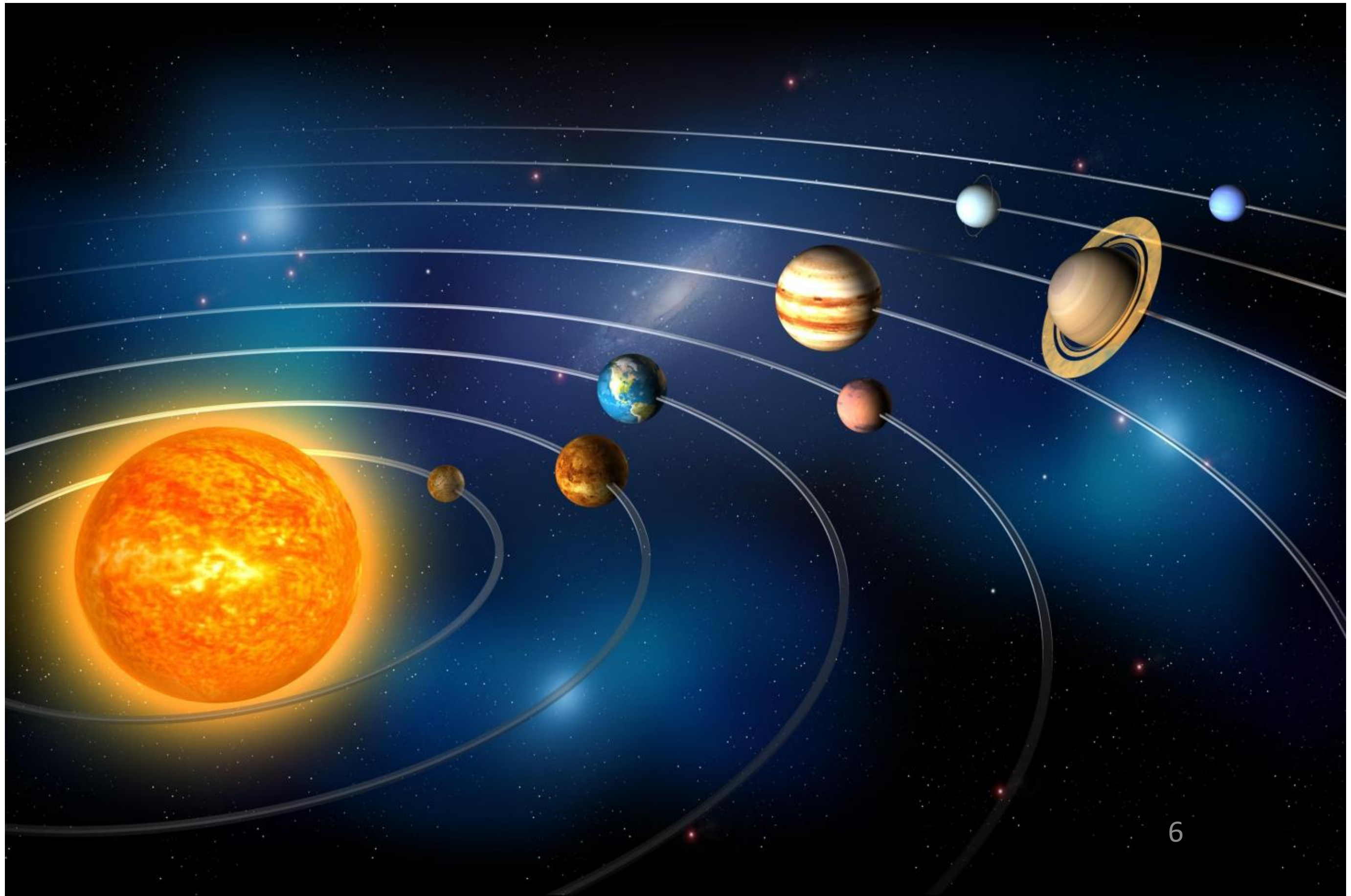
Osservazioni astronomiche

- Oggetti di «lunga vita» nel cielo

Astro… aspects

The study of stars is central to astronomy and astrophysics since stars are long-lived objects that are responsible for most of the visible light we observe from normal galaxies.





Osservazioni astronomiche

- Oggetti di «lunga vita» nel cielo

- luminosità

Stellar Magnitude --- Luminosity

- Greek astronomer Hipparchus was one of the first skywatchers to systematically catalogue the ~850 stars he observed
- He assigned a magnitude index to each star ranging from m=1, for the brightest stars, to m=6 for the dimmest (opposite ordering of what one would expect)
- Human eye has a nearly logarithmic subjective response to radiant energy flux
- Modern astronomy defines: a 5 magnitude difference corresponds to a factor 100 in brightness (flux)
- Apparent magnitude, the brightness of an object as it appears in the night sky.
- Absolute magnitude, which measures the luminosity of an object (or reflected light for non-luminous objects like asteroids); it is the object's apparent magnitude as seen from a specific distance, conventionally 10 parsecs (32.6 light years).

Osservazioni astrofisiche

- Oggetti di «lunga vita» nel cielo

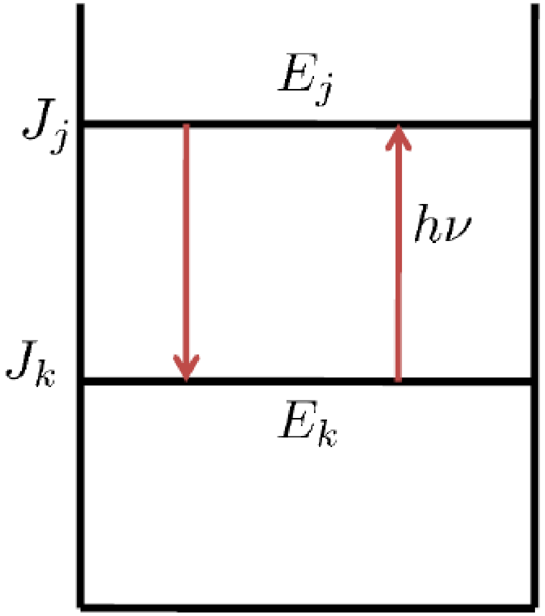
- Luminosità

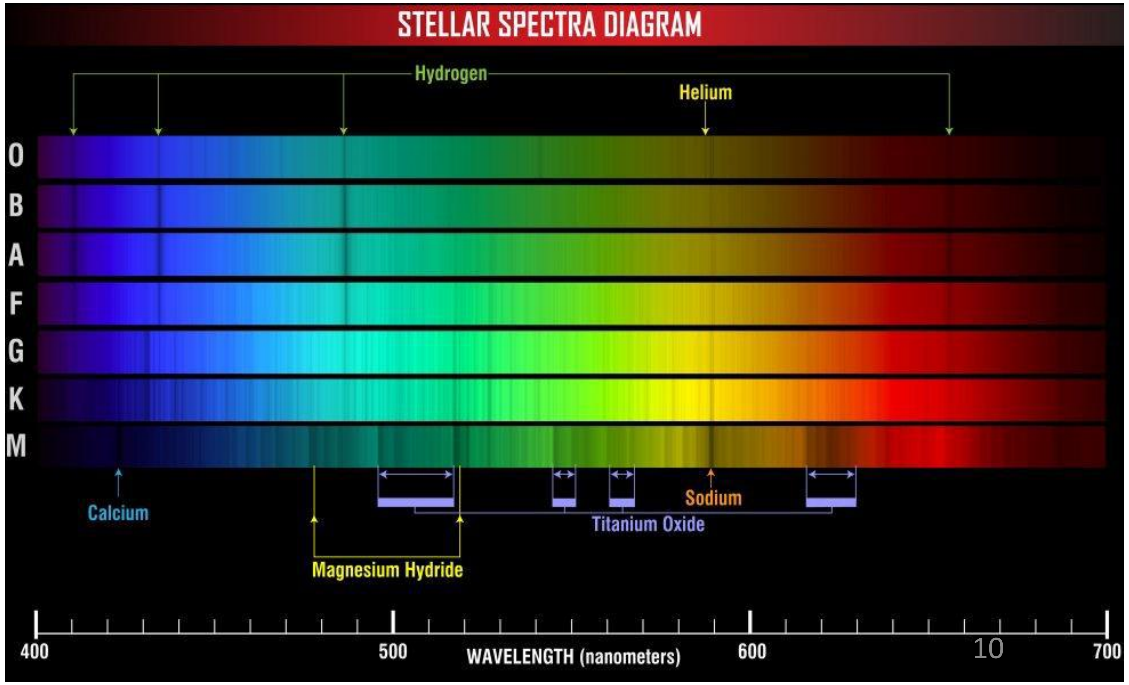
- temperatura

Stellar Temperatures

- Astronomers measure the spectra of atomic transitions
- The spectral source is line absorption of continuum light in the stellar atmosphere
- Photo-absorption and scattering can cause atomic transitions
- Population ratio between two atomic states in thermal equilibrium given by Boltzmann's formula:

$$\frac{n_j}{n_k} = \frac{g_i}{g_k} \exp\left(-\frac{E_j - E_k}{kT}\right)$$

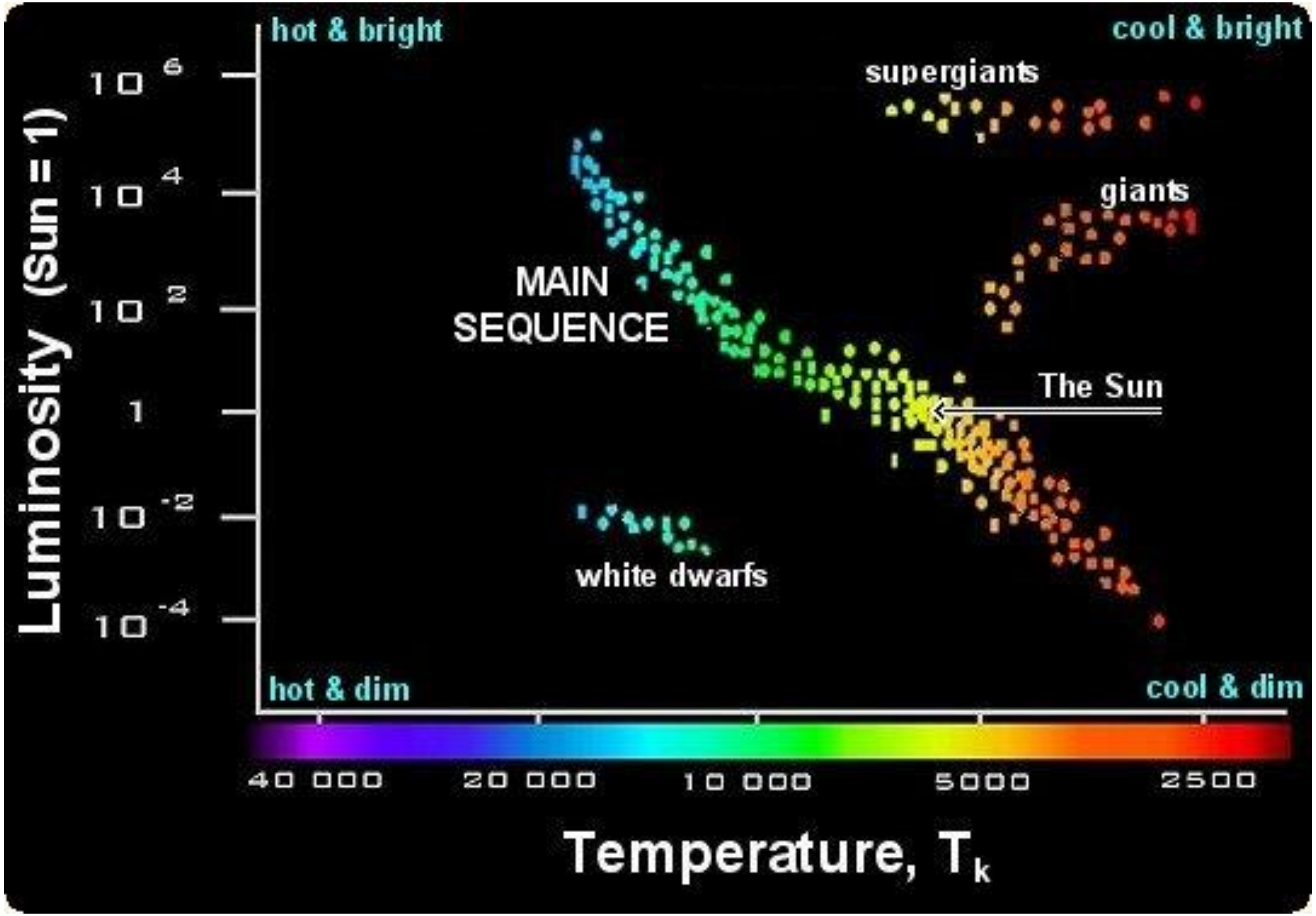




Osservazioni astrofisiche

- Oggetti di «lunga vita» nel cielo
- Luminosità
- Temperatura
- Evoluzione delle stelle e dell’universo

Hertzsprung-Russel Diagram – stellar evolution



Stellar birth

1. Stars are born of "seed" gas undergoing localized gravitational collapse

2. 1st generation stars: primordial gas: H and He

3. Later generations formed of processed gas

4. Points 2 & 3 suggest possibility of 2 populations of stars: very old and young

5. Point 4 suggests populations should have different abundance distributions

Virial Theorem $2T + \Omega = \frac{d^2 I}{dt^2}$

T = total kinetic energy Ω = gravitational energy
I = momentum of inertia

Static configuration $2T + \Omega = 0$ → $dT = - d\Omega/2$

Stellar Populations

- Population I (Pop I): Stars that are "metal-rich" (the Sun is included).
  They are young stars, having formed within the past few billion years, and can be found in the disk of the Galaxy.

- Population II (Pop II): Stars that are "metal-poor". *Ancient* relics of the initial star formation periods of Galaxies and first generation of primordial stars.
  Their metal abundance, relative to hydrogen, is smaller by a factor of 100 or more compared to population I stars.

- Metals: any element $A > 4$; that is, any element with $Z > 2$

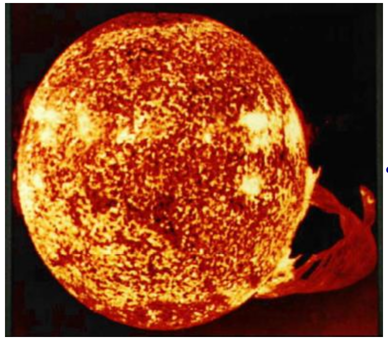
STELLAR LIFE CYCLE

BIRTH
gravitational contraction

Stars

mixing of interstellar gas

INCREASE THE mixing of interstellar gas



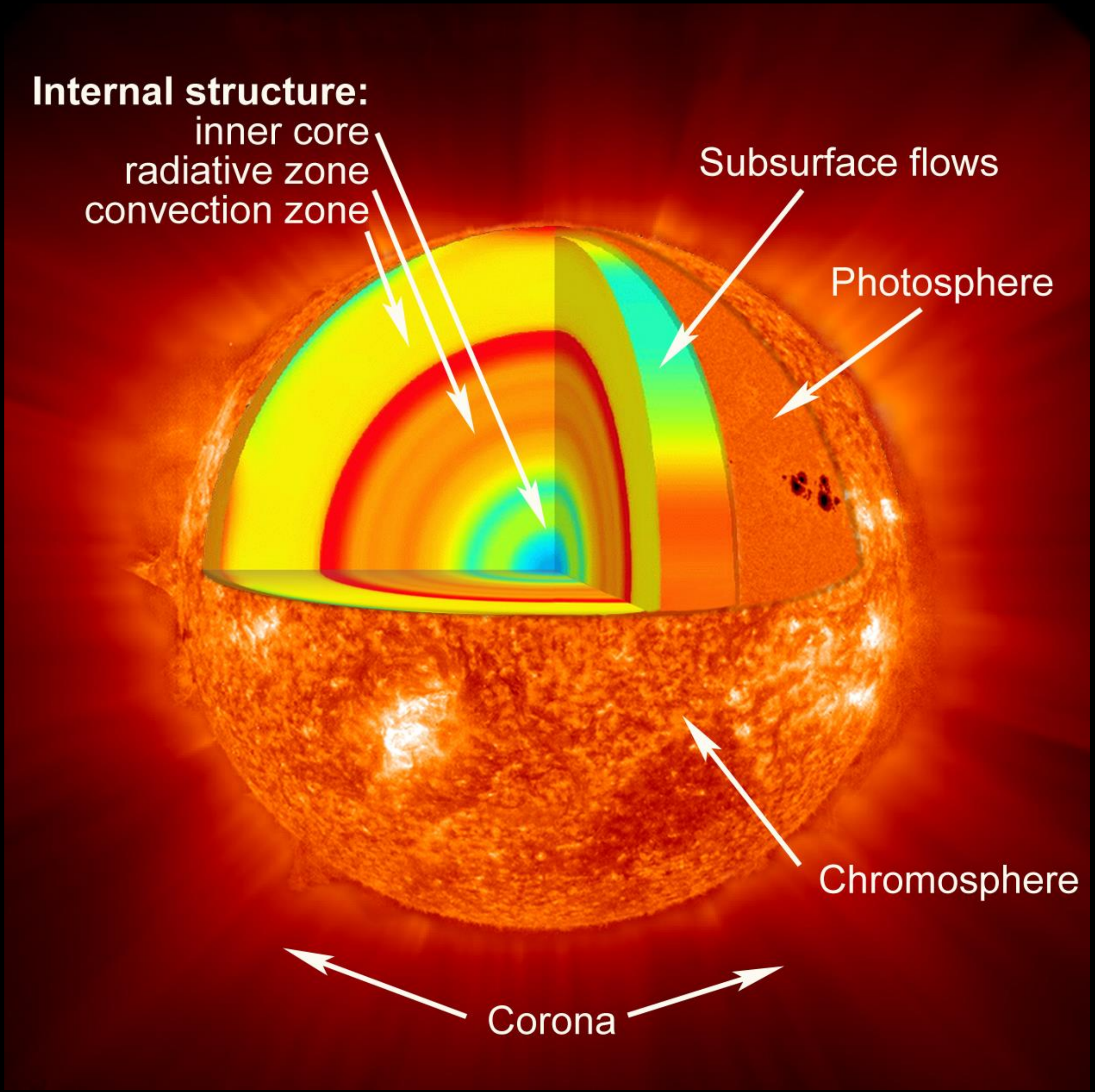
thermonuclear reactions

- energy production
- stability against collapse
- synthesis of "metals"

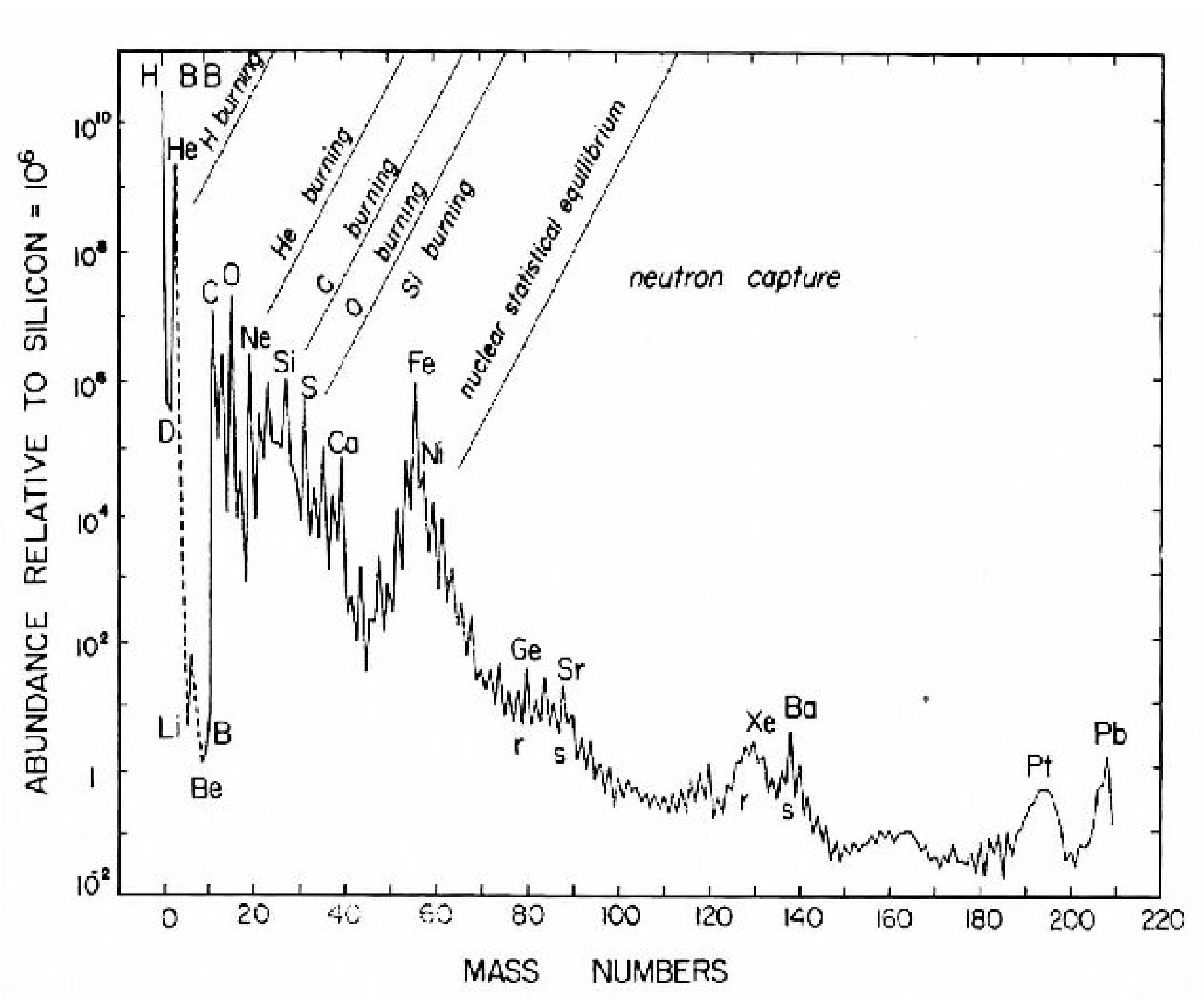
explosion
DEATH

Our star: the most known

- $M_\odot$ = (1.98855±0.00025)×10^{30} kg
  about 332946 times the mass of Earth ($M_\oplus$)
- mean density = 1.408 × 10^3 kg/m³
- radius = 695.700 km
  about 110 times the radius of the Earth)
- volume = 1.4122 × 10^{27} m³
  about 1.3 × 10^6 the volume of the Earth
- age = 4.6 Gyr
- luminosity = 3.827 × 10^{26} W
- surface temperatore = 6000 K
- core temperature = 16 MK
- distance from Earth = 15 × 10^7 km = 1 AU



Solar system abundances



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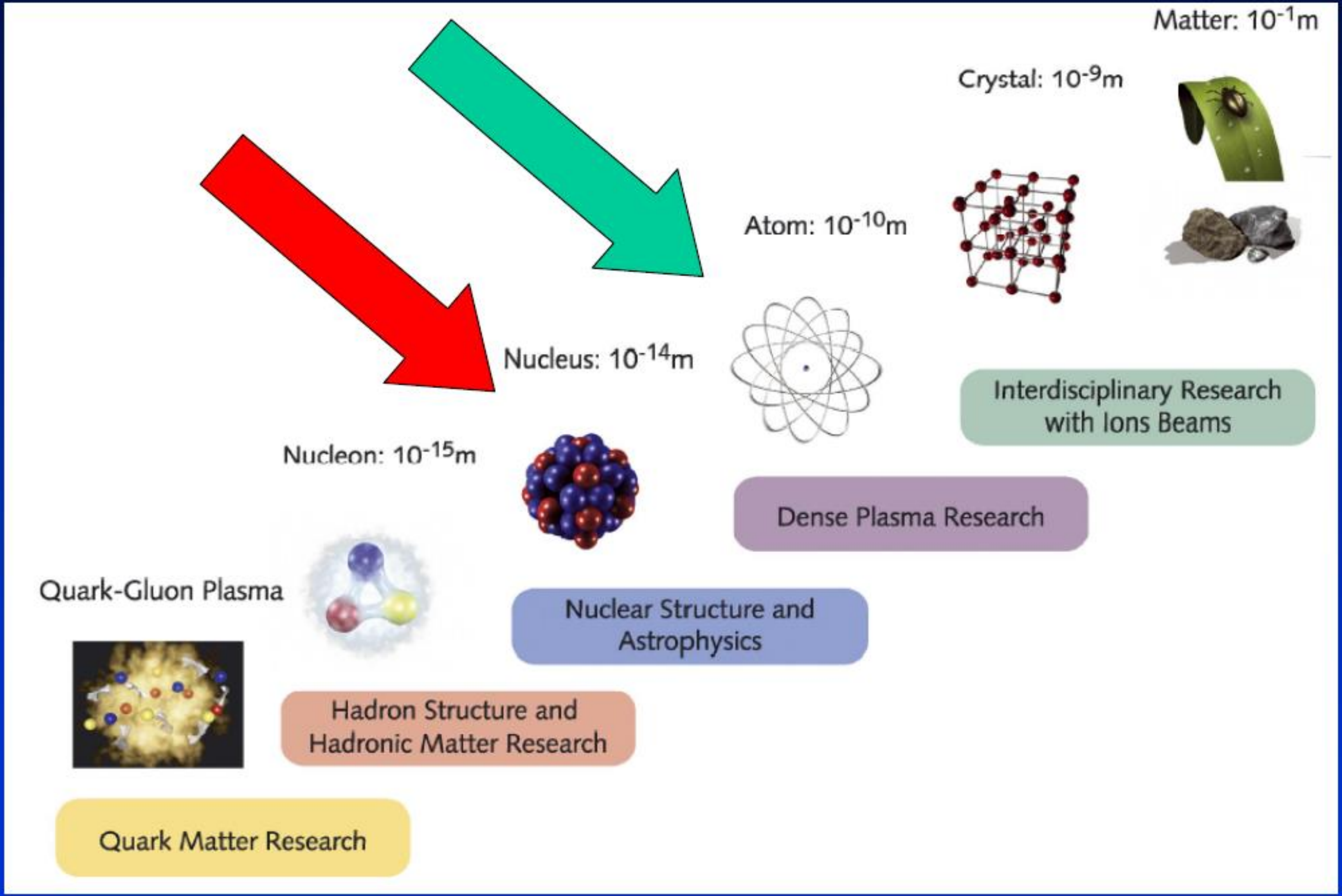
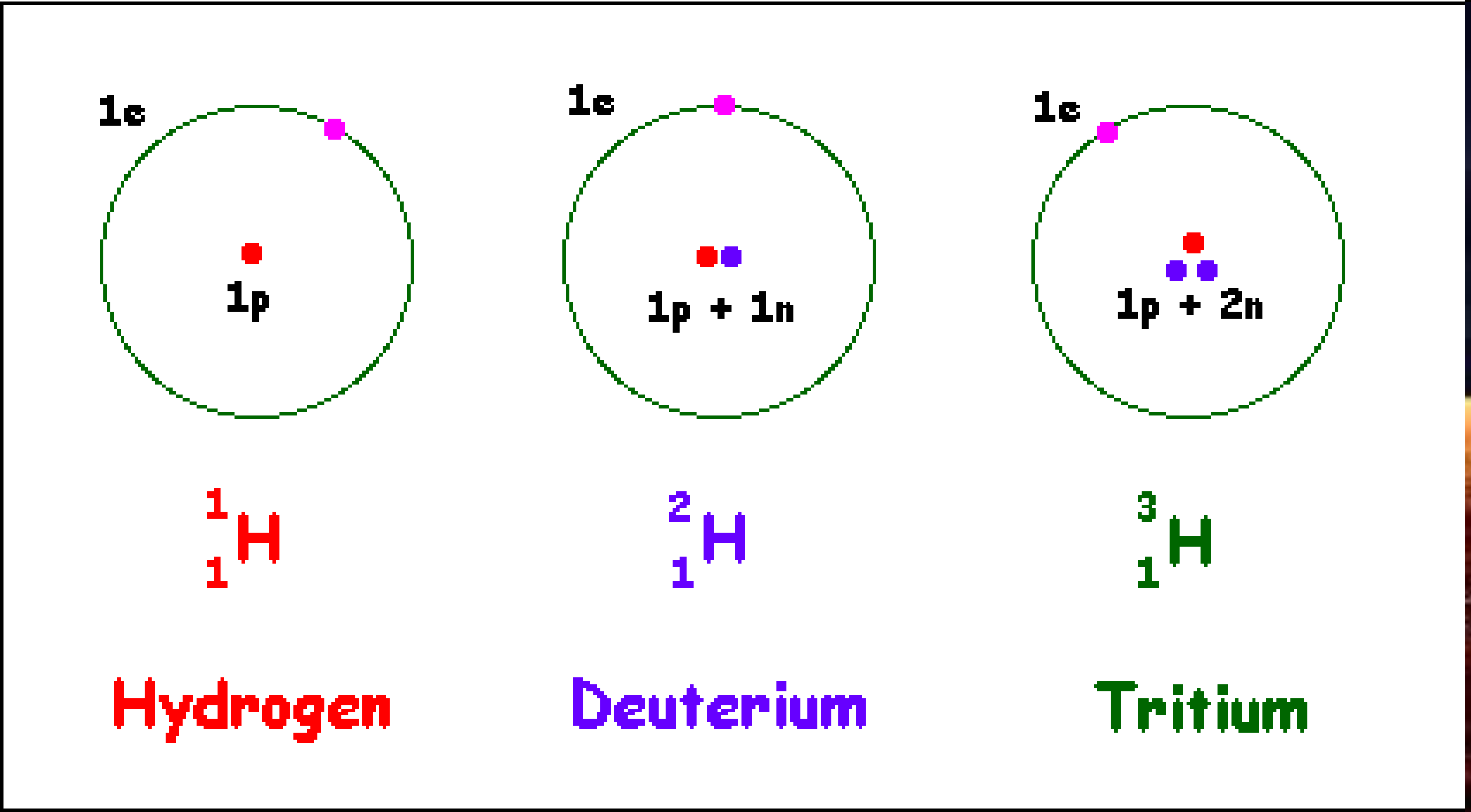
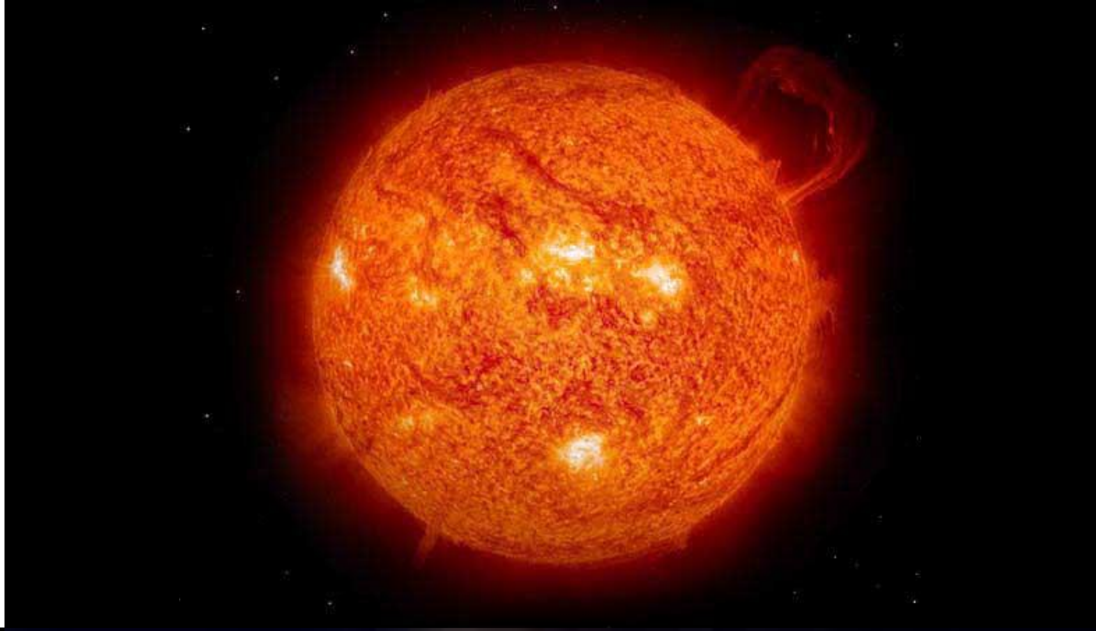
Di cosa ci occupiamo....



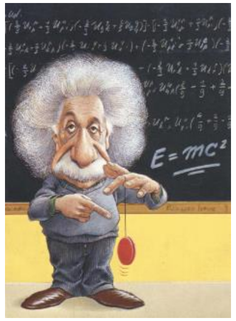
Nuclear aspects

- Nuclear mass = the most fundamental property of the atomic nucleus
- According to the Einstein relationship the mass *m* is equivalent to an energy of $E = m \cdot c^2$



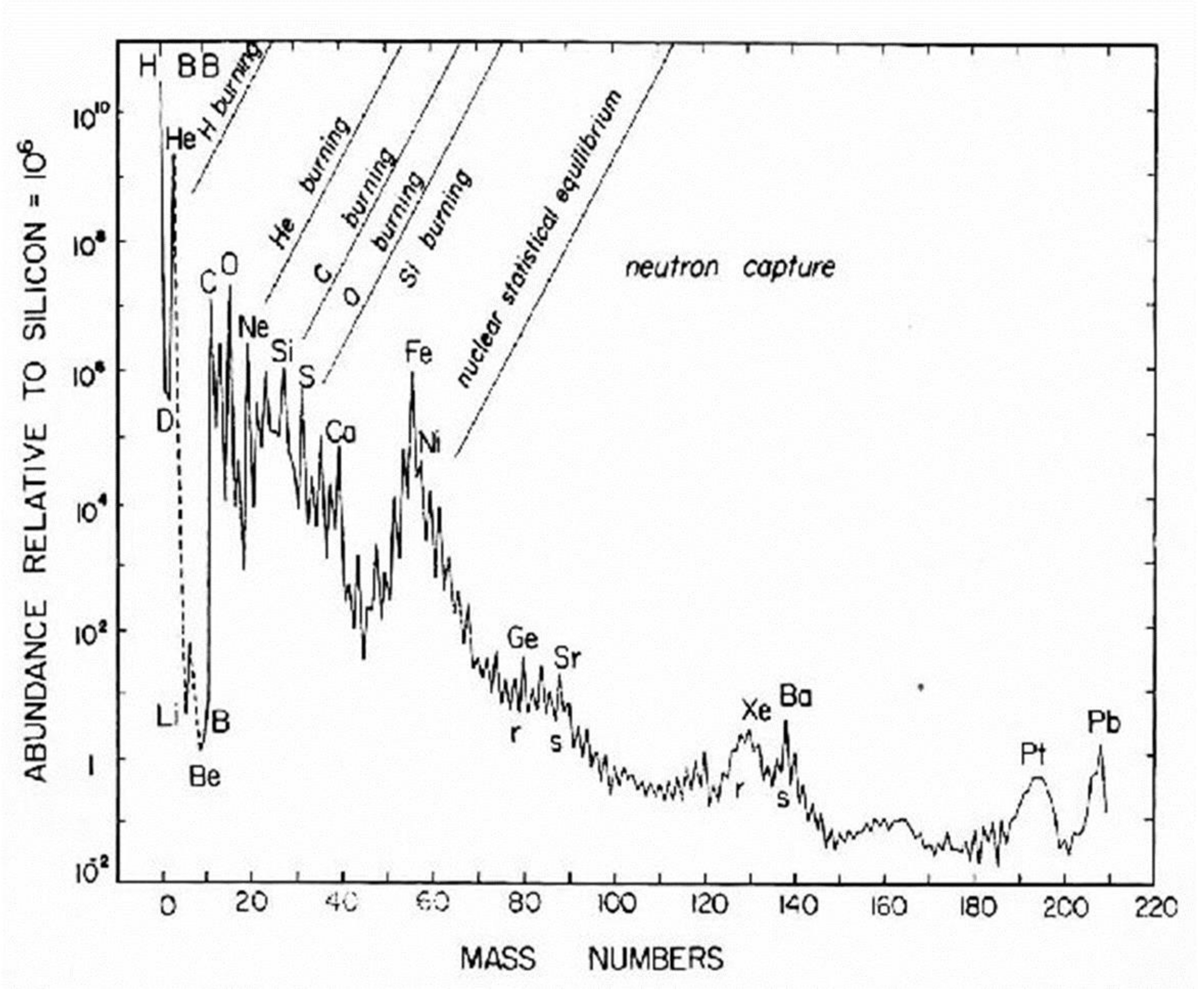


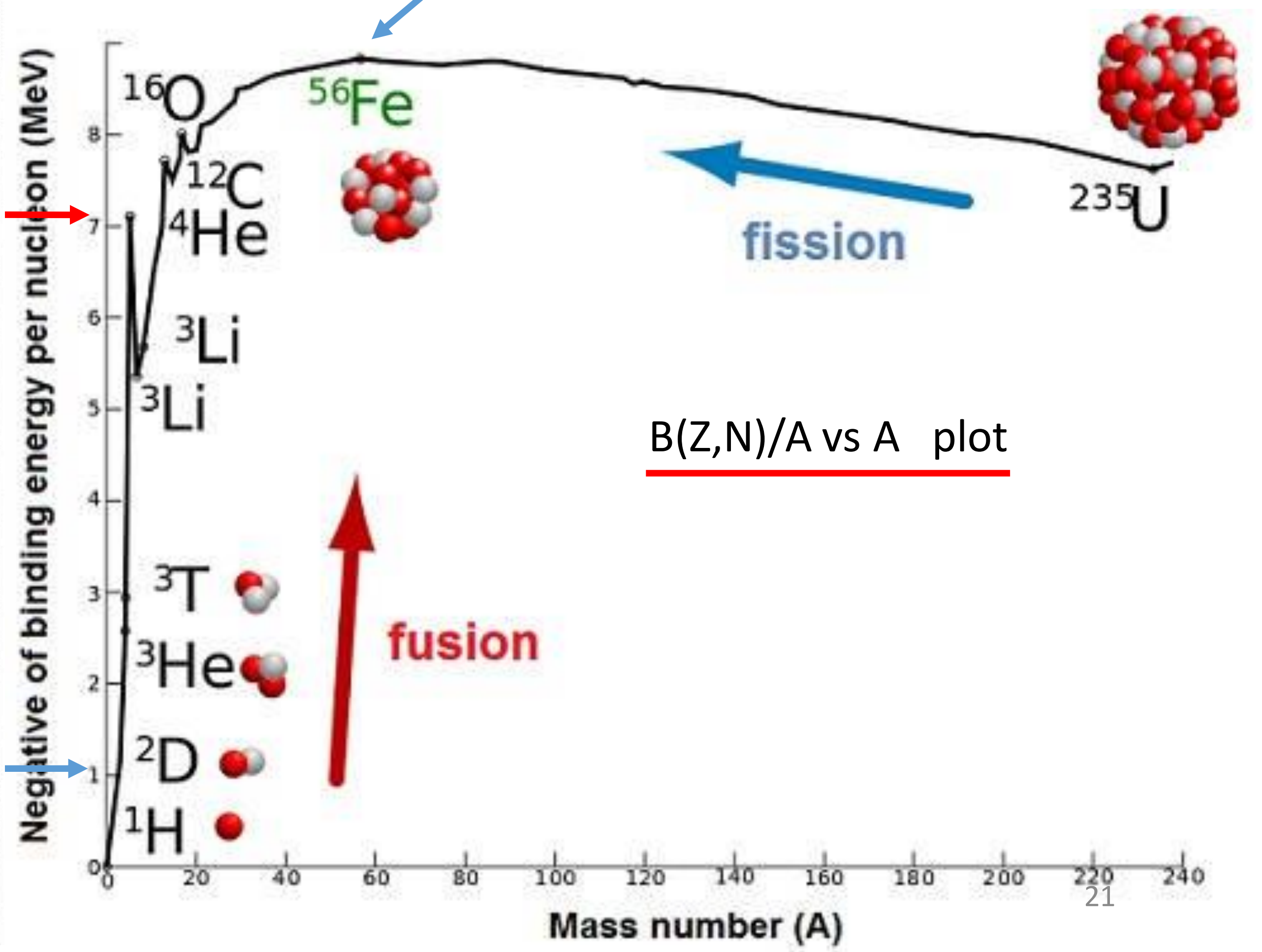
Nuclear aspects



- measurements showed that the total nuclear mass, m_{nuc}, is less than the sum of masses of the constituent nucleons.

Iron peak in the solar system abundances

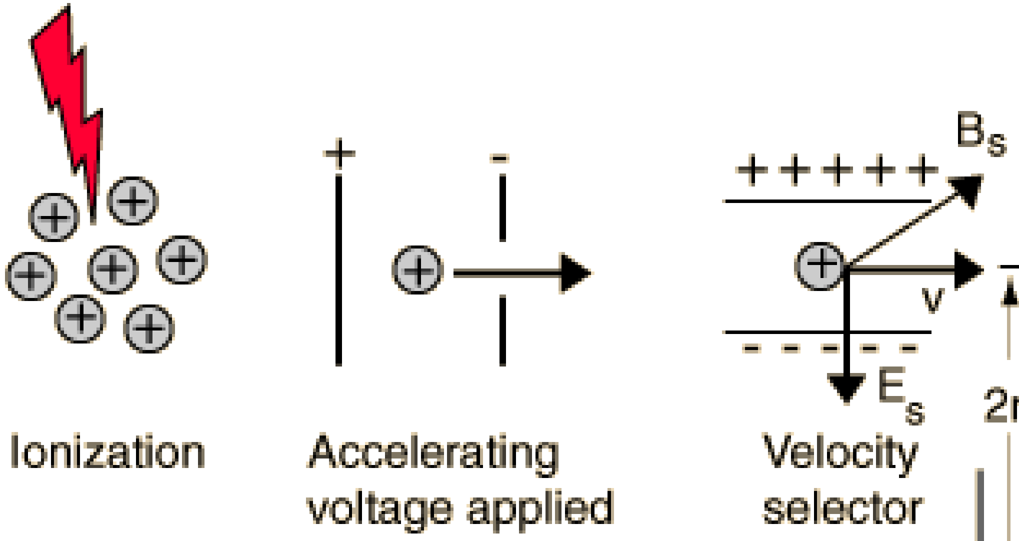


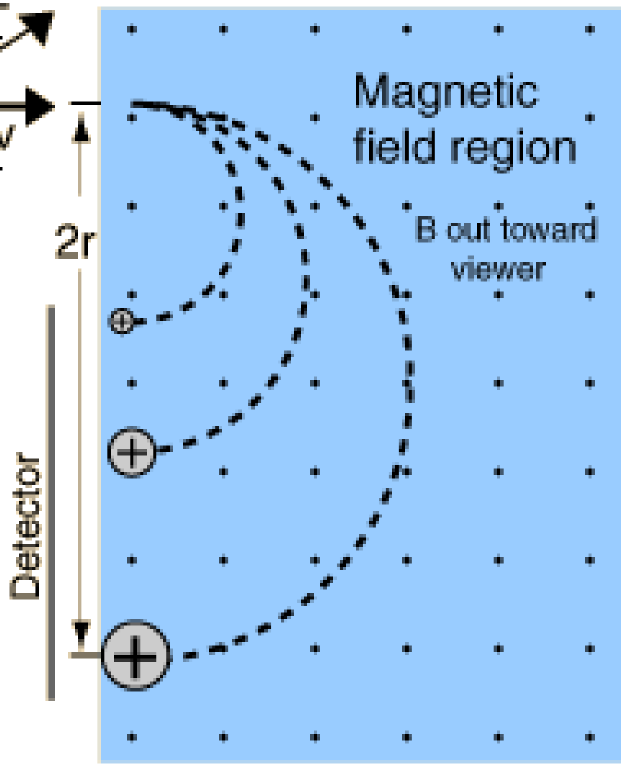


B(Z,N)/A vs A plot

Cosa conosciamo dei nuclei?

Nuclear mass measurement





After ionization, acceleration, and selection of single velocity particles, the ions move into a mass spectrometer region where the radius of the path and thus the postion on the detector is a function of the mass.

$$r = \frac{mv}{qB} = \frac{mE_s}{qBB_s}$$

Quantum behaviour

It is known (experimentally) that the kinetic energies of nucleons in a nucleus is of the order of 10 MeV.

10 MeV << nucleon rest energy (about 1000 MeV) → nonrelativistic quantum mechanics.

Quantum mechanic fundamental concepts:

- The size of a classical particle is the same in every experiment we may do; the "size" of a quantum particle varies with the experiment we perform.

Dimension Δx of an electron:

- electrical conduction in solids → Δx = dimension of the material block
- atomic physics → Δx = dimension of a single atom
- β decay → Δx = nucleus

Heisenberg uncertainty relationships:

$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}; \quad \Delta E \cdot \Delta t \geq \frac{\hbar}{2}; \quad \Delta l_z \cdot \Delta\emptyset \geq \frac{\hbar}{2}$$

Matematical aspects → Schrödinger equation: $-\frac{\hbar^2}{2m}\frac{d^2\Psi}{dt^2} + V(x)\,\Psi(x) = E\,\Psi(x)$ Ψ(x) = Schr. wave function

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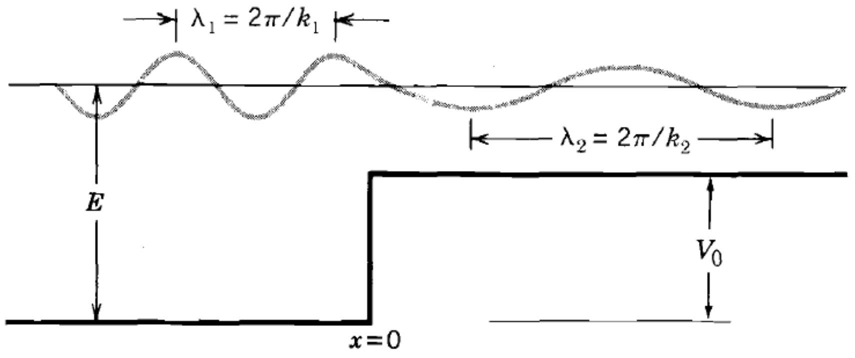
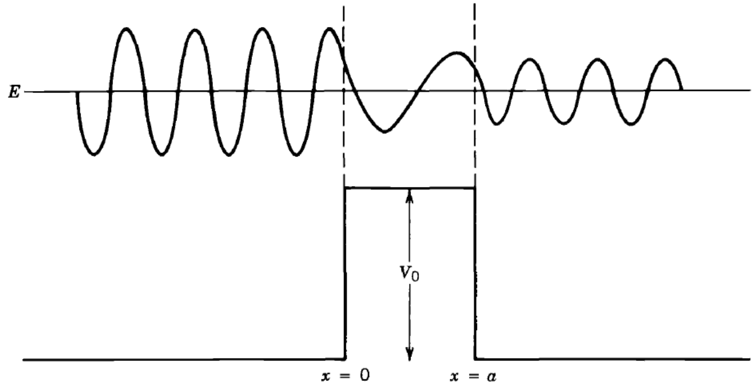
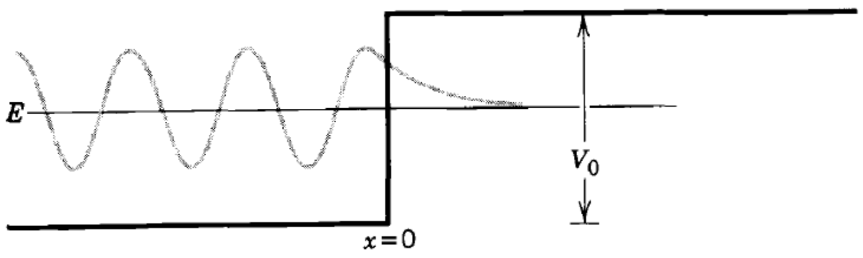
Problem in one dimension – free particle



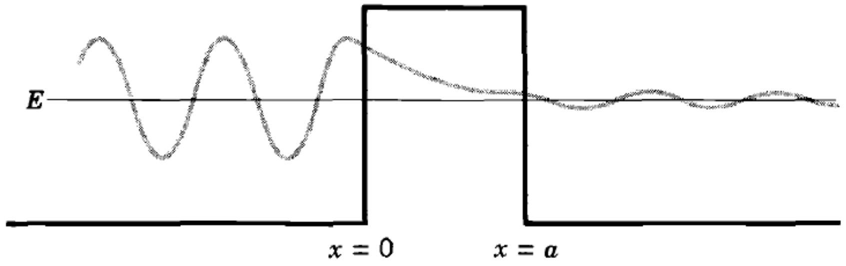
Step potential E > V_0



Barrier potential E > V_0



Step potential E < V_0

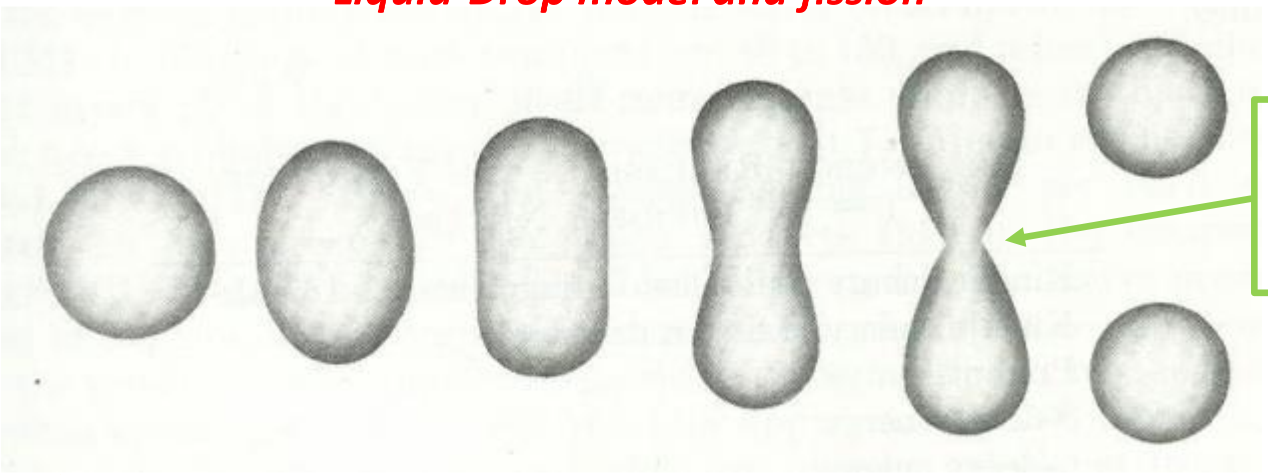


Barrier potential E < V_0 (tunneling)

Liquid-Drop model

- is based on: short range of nuclear forces, additivity of volumes and binding energies
- The nearest nucleons interact so strongly as the molecules in a drop of water
- The nuclear properties can be described (as an approximation) with the analog quantities, i. e., radius, density, surface tension, volume energy

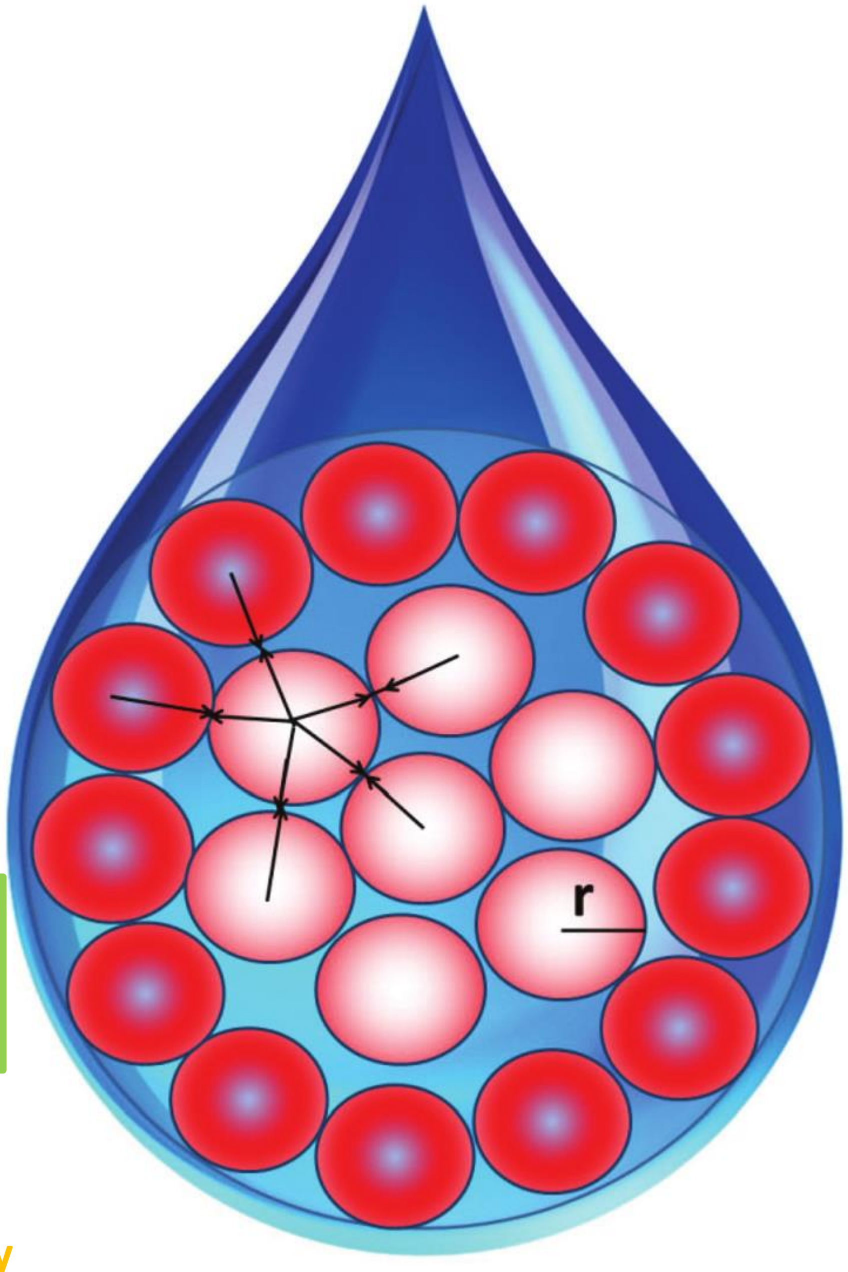
Liquid-Drop model and fission



Coulomb energy wins over surface energy

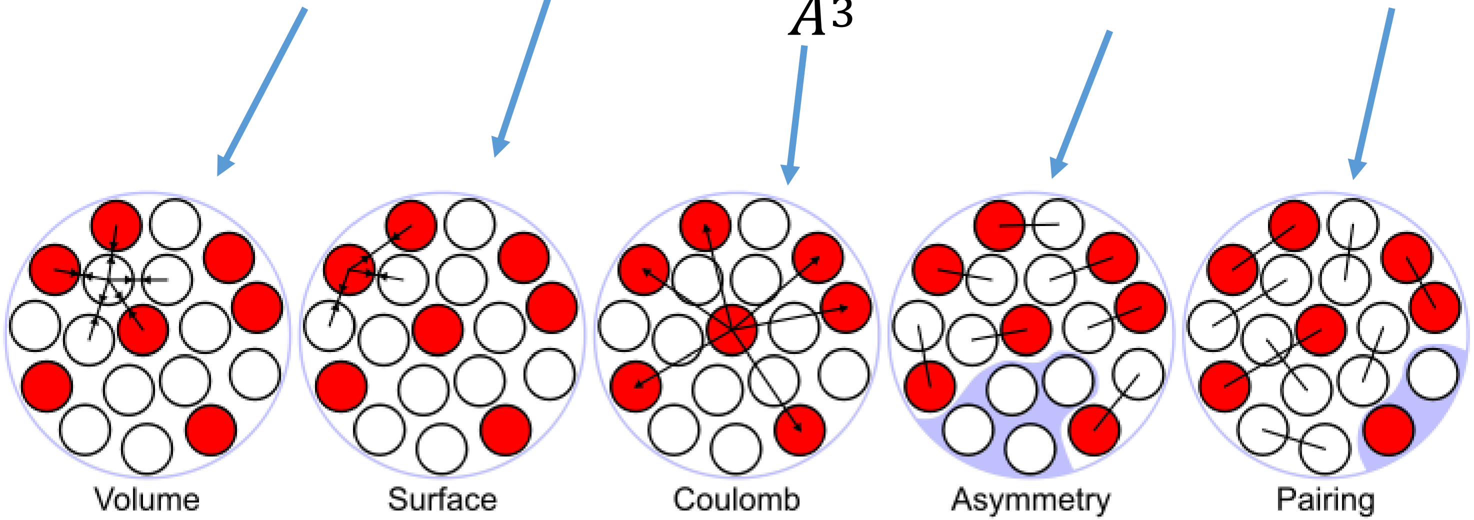
Coulomb energy

Surface energy



Bethe–Weizsäcker mass formula

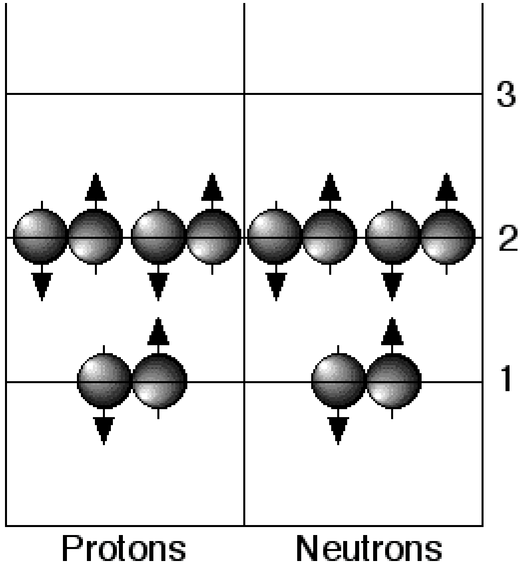
$$B(A,Z) = a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - a_a \frac{(N-Z)^2}{A} + \delta(A)$$



$$a_v = 15.7\ MeV$$
$$a_s = 17.8\ MeV$$
$$a_c = 0.7\ \ MeV$$
$$a_a = 23.7\ MeV$$

$$\delta(A) = \begin{cases} 33.6\, A^{-\frac{3}{4}} & (even - even) \\ -36.6\, A^{-\frac{3}{4}} & (odd - odd) \\ 0 & (eo, oe) \end{cases}$$

Shell model



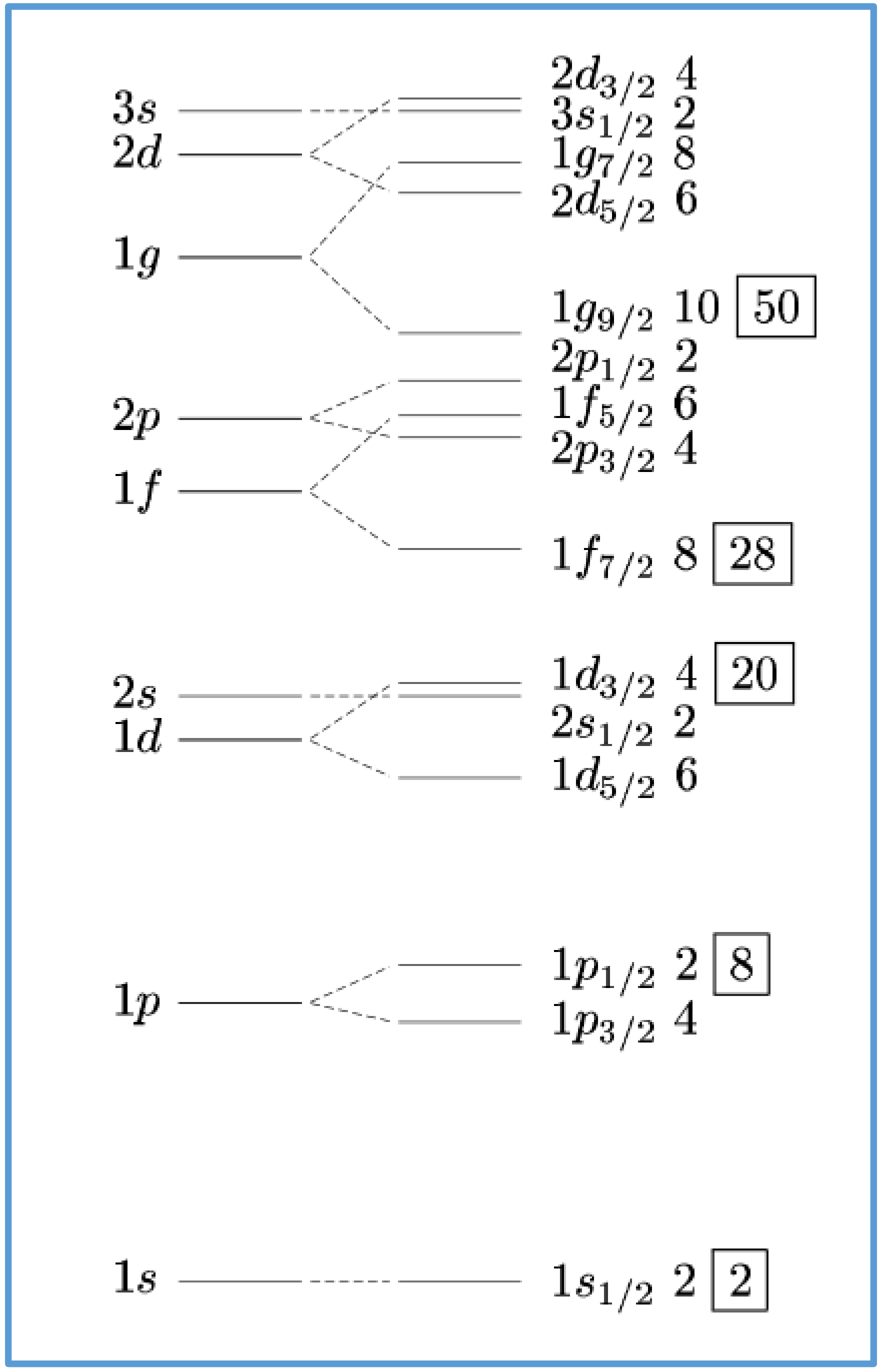
- Analogy with atomic case: the atomic electron configuration follow the Pauli exclusion principle and the shells are filled in order of increasing energy → configuration with filled shells and some valence electrons

- Nuclear case: different kind of interaction (even not well know); two different particles (proton and neutrons); there is not a clear centre of the interaction field → BUT high performance in the description of many nuclear proprierties

- everage potential $V(r)$ plus strong spin-orbit coupling → three quantum numbers n, l, j in the S.E. solutions

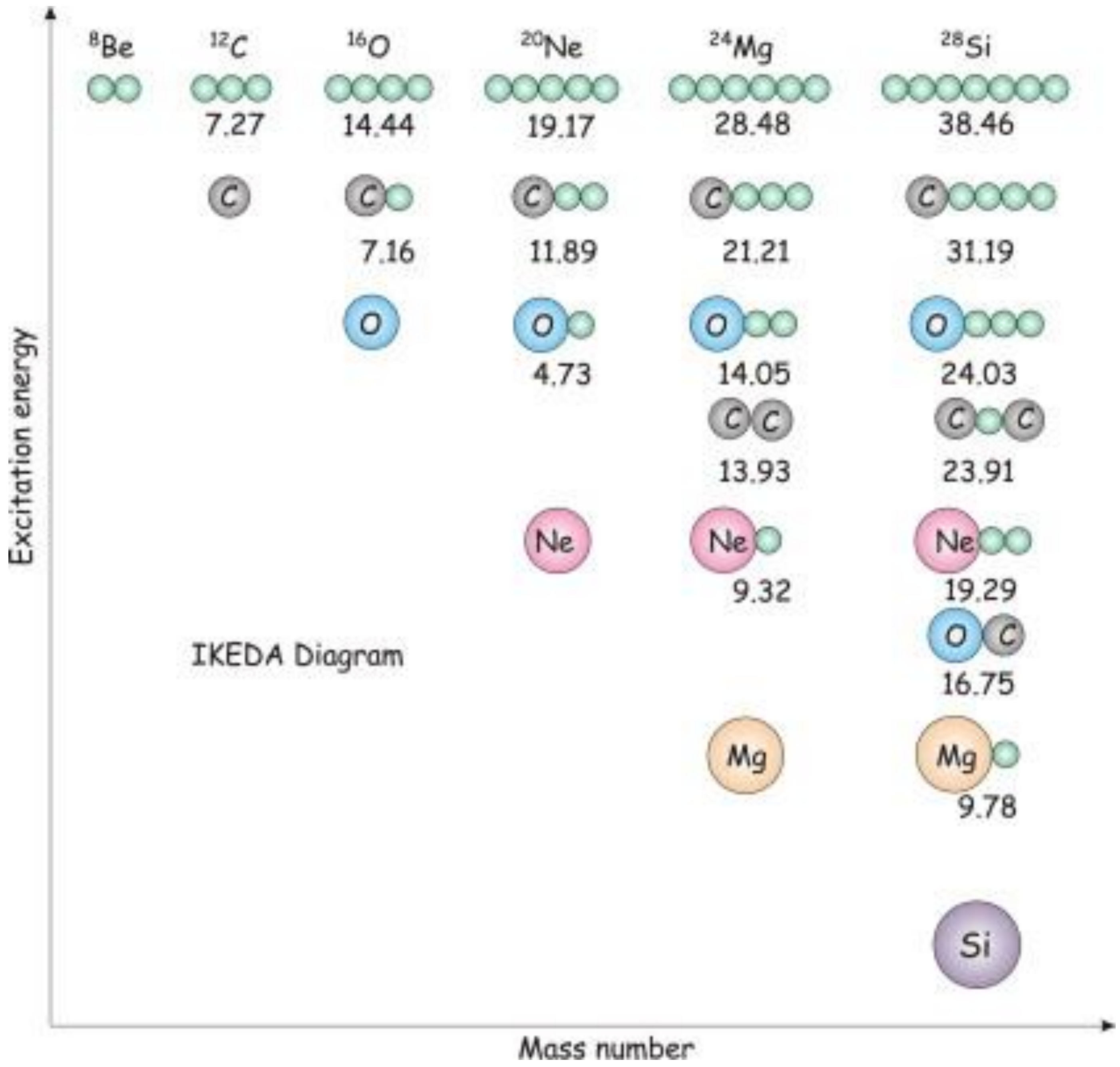
Magic numbers

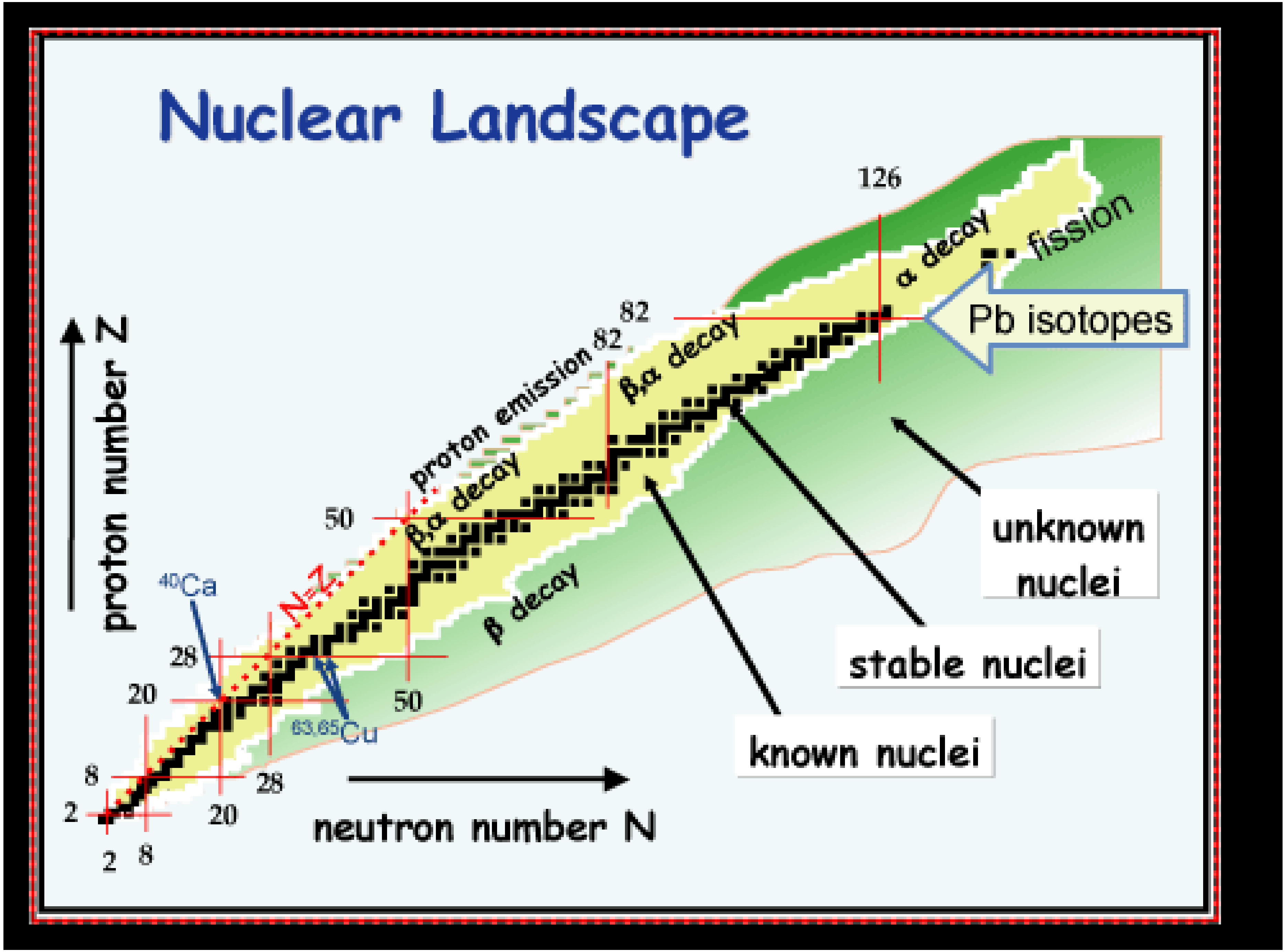
- 2
- 8 = 2 + 6
- 20 = 2 + 6 + 12
- 28 = 2 + 6 + 12 + 8
- 50 = 2 + 6 + 12 + 8 + 22
- 82 = 2 + 6 + 12 + 8 + 22 + 32
- 126 = 2 + 6 + 12 + 8 + 22 + 32 + 44
- 184 = 2 + 6 + 12 + 8 + 22 + 32 + 44 + 58



Cluster α configurations

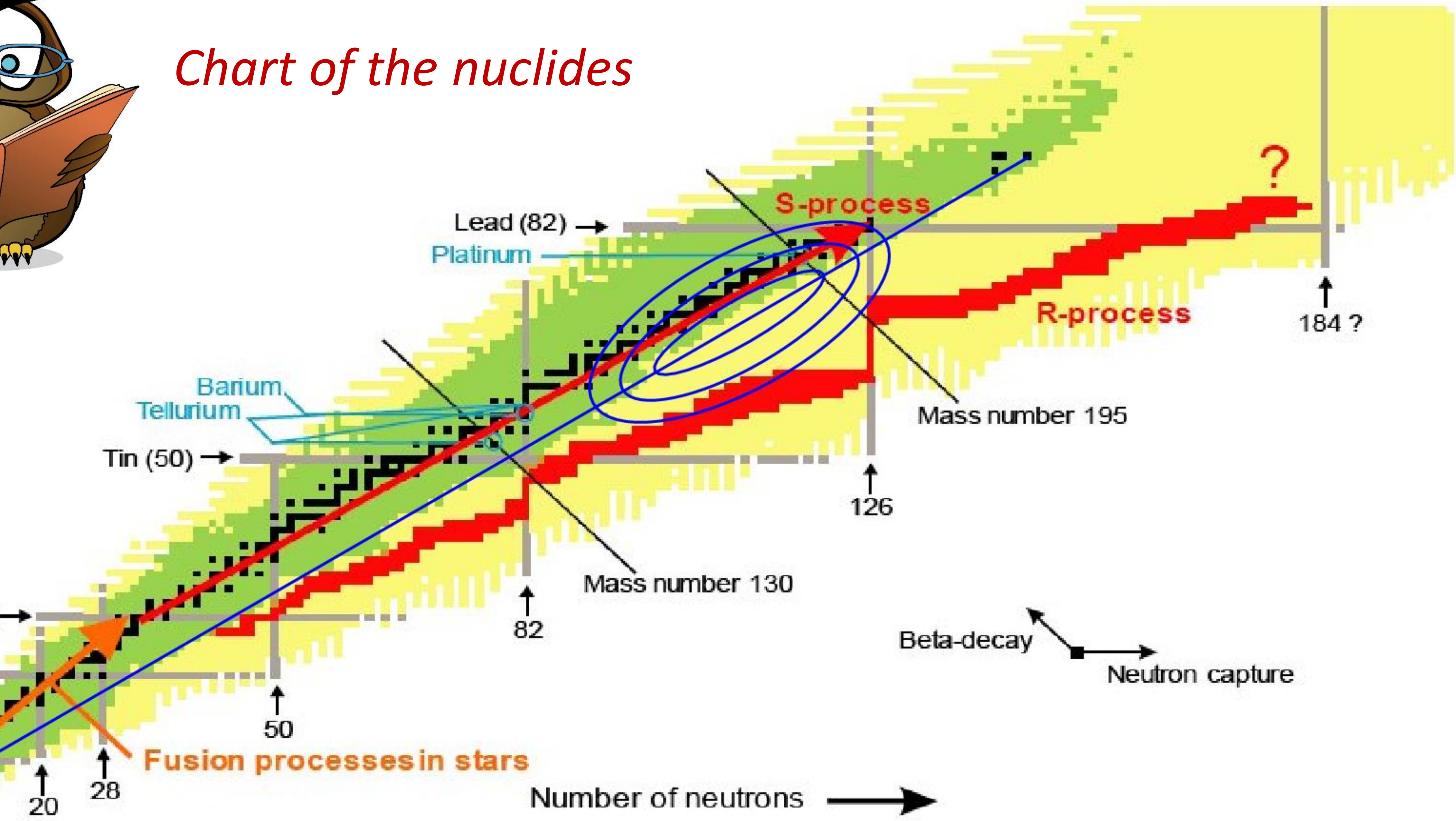
Ikeda diagram





Nuclear Landscape
126
α decay
fission
Pb isotopes
82
82
β,α decay
proton emission
β,α decay
50
β,α
N=Z
40Ca
28
20
8
2
2
8
20
28
50
63,65Cu
β decay
proton number Z
neutron number N
unknown nuclei
stable nuclei
known nuclei

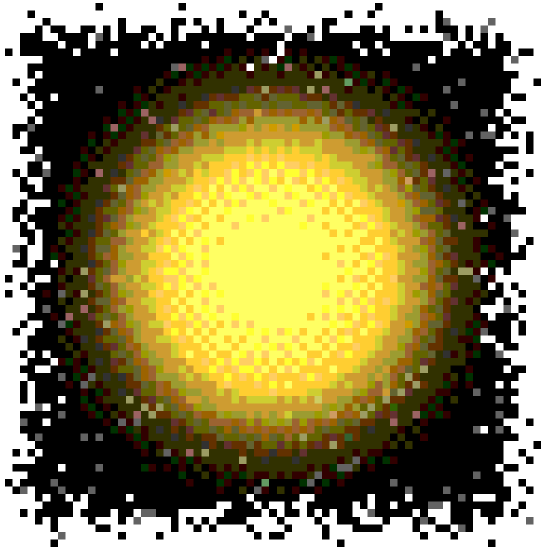
Chart of the nuclides



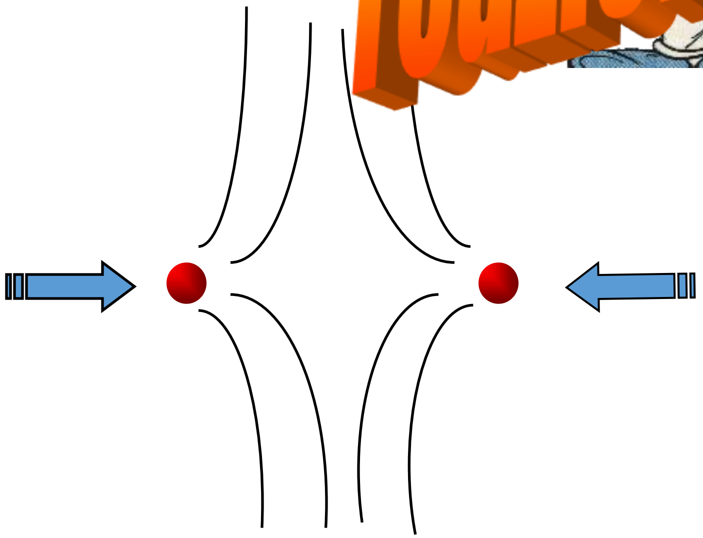
… qual è la provenienza degli elementi?

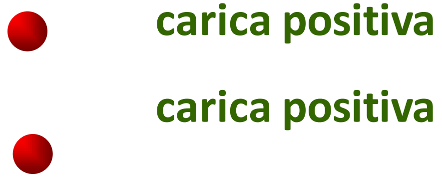
Per scoprirlo …

… ritorniamo nelle stelle.

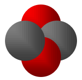



reazioni nucleari

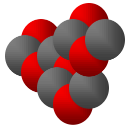



carica positiva
carica positiva

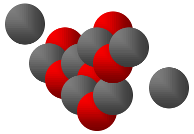
Esempi



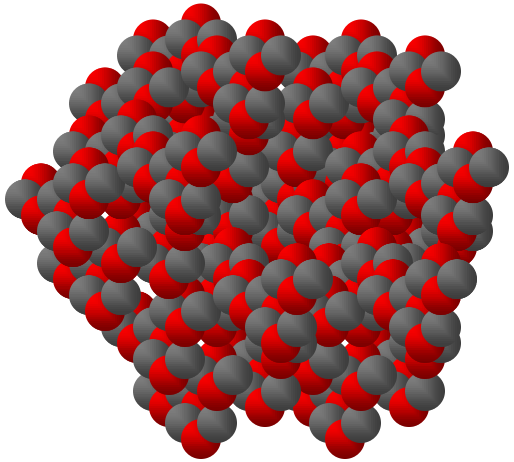
nucleo di He – particella α – 2p + 2n



nucleo di ^{12}C – 6p + 6n

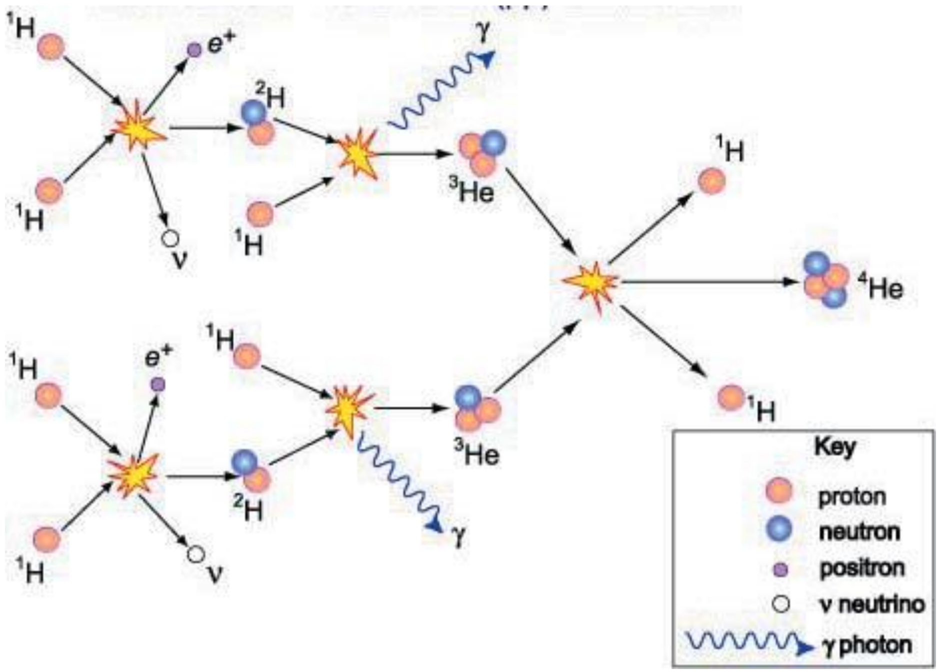


nucleo di ^{14}C – 6p + 8n (isotopo del ^{12}C)



$${}^{p+n}_{p}X$$

Catena p-p



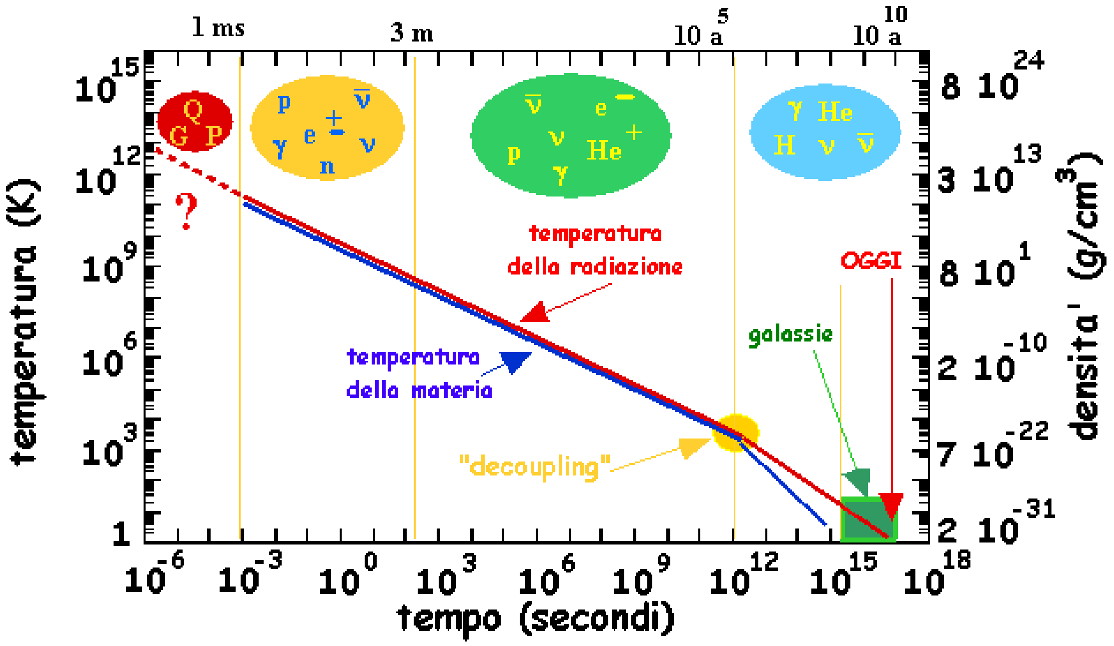
1H
e+
γ
2H
1H
3He
1H
ν
1H
1H
4He
1H
e+
1H
1H
3He
2H
γ
1H
ν
Key
proton
neutron
positron
ν neutrino
γ photon

Tavola Periodica degli Elementi

Fin dai primi istanti dopo il big bang, le reazioni nucleari hanno governato l'evoluzione e la morte delle stelle, hanno determinato l'evoluzione chimica delle galassie e la produzione di tutti gli elementi dai quali dipende la nostra stessa composizione.

Astrofisica ↔ fisica nucleare

La fisica nucleare e l'origine dell'Universo



nei …."primi tre minuti"
creazione p, n, d, He

$m_p > kT$ per
$T < 10^{12}$K

negli …. ultimi 10 miliardi di anni formazione di stelle e galassie
nascita, vita e morte delle stele nucleosintesi degli elementi

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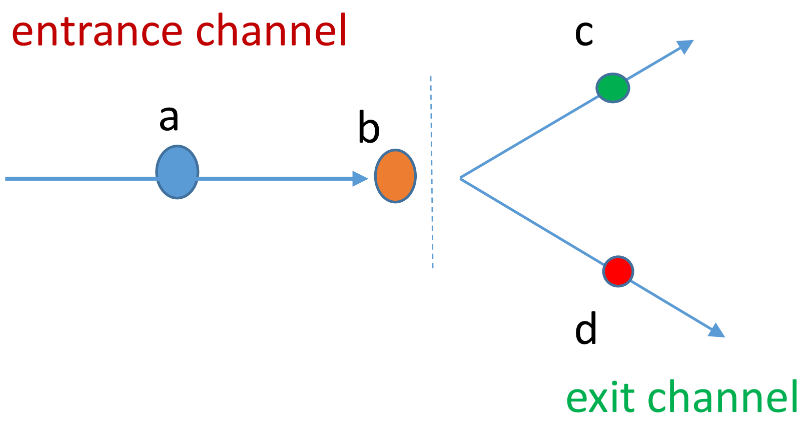
Nuclear reactions



A nuclear reaction may be indicated by the following symbolic relationship

$$a + b \rightarrow c + d$$

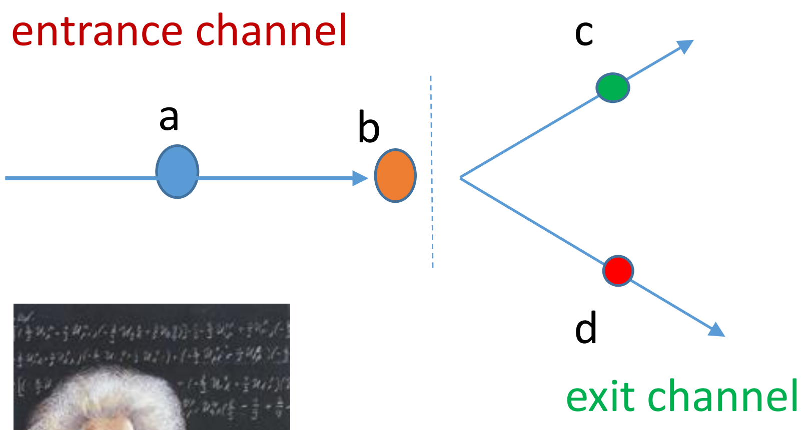
Where a and b are the colliding nuclei before the interaction, while c and d denote the products after the interaction.

Different types of reactions:

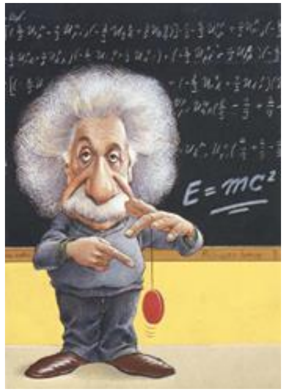
1) $a + b \rightarrow a + b$ *elastic* or *inelastic* scattering (identical species in the two channels)
2) $a + b \rightarrow c + d$ two body transfer reaction
3) $a + b \rightarrow c + d + e$ three body transfer reaction
4) $a + b \rightarrow c + \gamma$ radiative capture reaction
5) $a + \gamma \rightarrow b + c$ photodisintegration reaction
6) $(a + b) + c \rightarrow a + b + c$ breakup reaction

Most nuclear interactions of astrophysical interest involve just two species before and after the interaction.

Energetics of Nuclear reactions



The total relativistic energy in a nuclear reaction must be conserved:



Bilancio energetico

$a + b \rightarrow c + d$

$$m_a c^2 + m_b c^2 + E_a + E_b = m_c c^2 + m_d c^2 + E_c + E_d$$

or

in — out — out — in

$$Q_{(a+b \rightarrow c+d)} = \underbrace{m_a c^2 + m_b c^2}_{\text{in}} \underbrace{- m_c c^2 - m_d c^2}_{\text{out}} = \underbrace{E_c + E_d}_{\text{out}} \underbrace{- E_a - E_b}_{\text{in}}$$

where E_i are kinetic energies, m_i are rest masses and $Q_{(a+b \rightarrow c+d)}$ is the *reaction Q-value*

The *reaction Q-value* is the difference in masses before and after the reaction, or the difference in kinetic energies after and before the reaction.
It is equal to the reaction energy release.

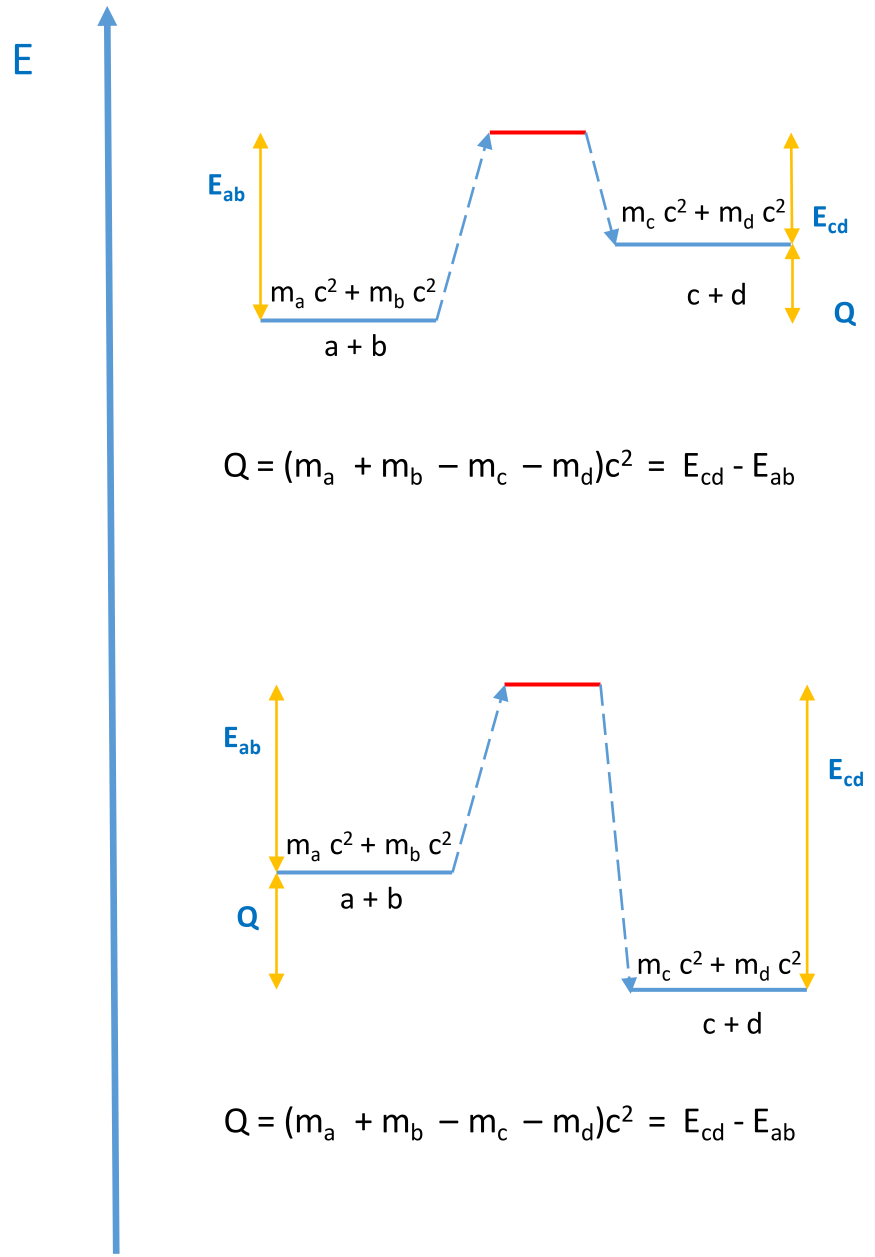
Energetics of Nuclear reactions

- If ***Q* is positive**, the reaction releases energy and is called ***exothermic***.

- Otherwise the reaction consumes energy and is called ***endothermic***.

- **Apart from a few exceptions, the most important nuclear reactions in stars are exothermic ($Q > 0$).**

- The quantities E_{ab} and E_{cd} represent the total kinetic energies in the center-of-mass system before and after the reaction, respectively.



Esempio: energia scambiata nella formazione di un nucleo di elio

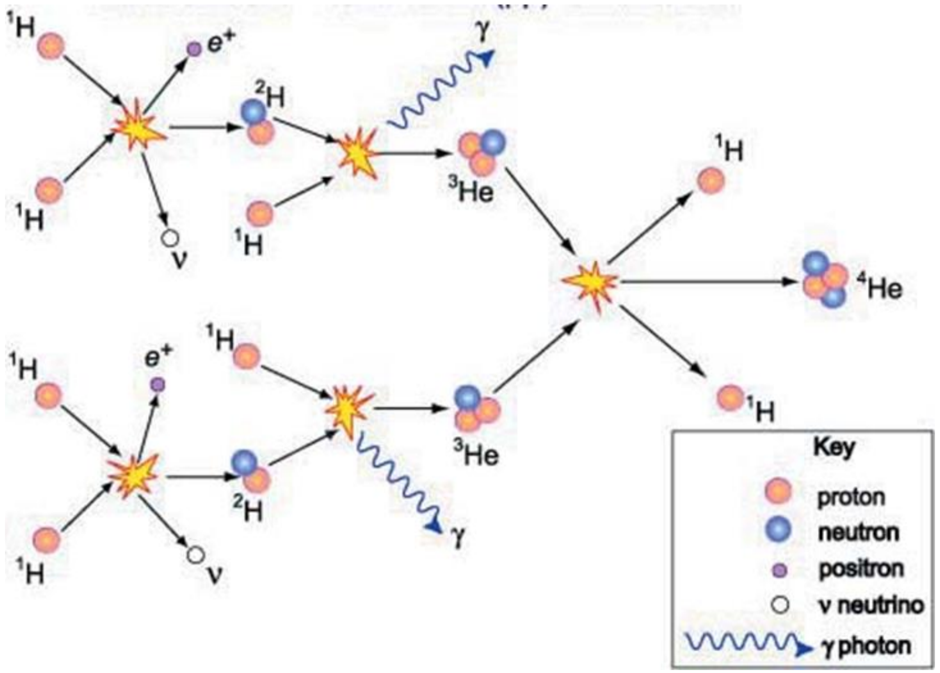
α = 2p + 2n

2p + 2n → 2 * 938 + 2 * 939.5 = 3755 MeV

α → 3727 MeV

$(m_i - m_f)c^2 = Q_{value}$ = 3755 – 3727 = 28 MeV

2p + 2n → α + 28 MeV !!!

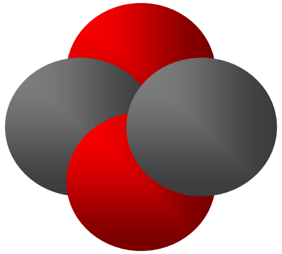


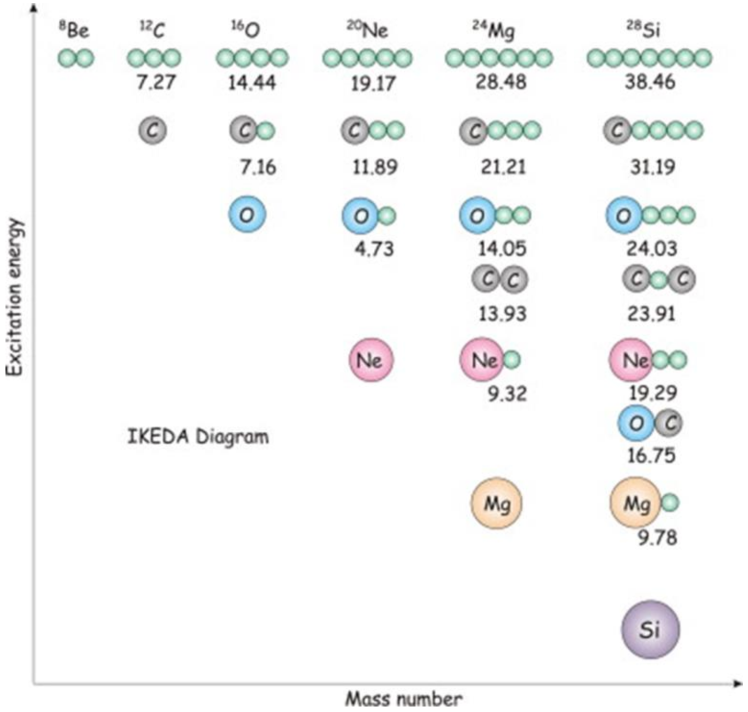
nuclei stabili

reazioni nucleari

energia corrispondente a

10 milioni di gradi → ~ keV (1 eV = 1.6 10^{-19} J)





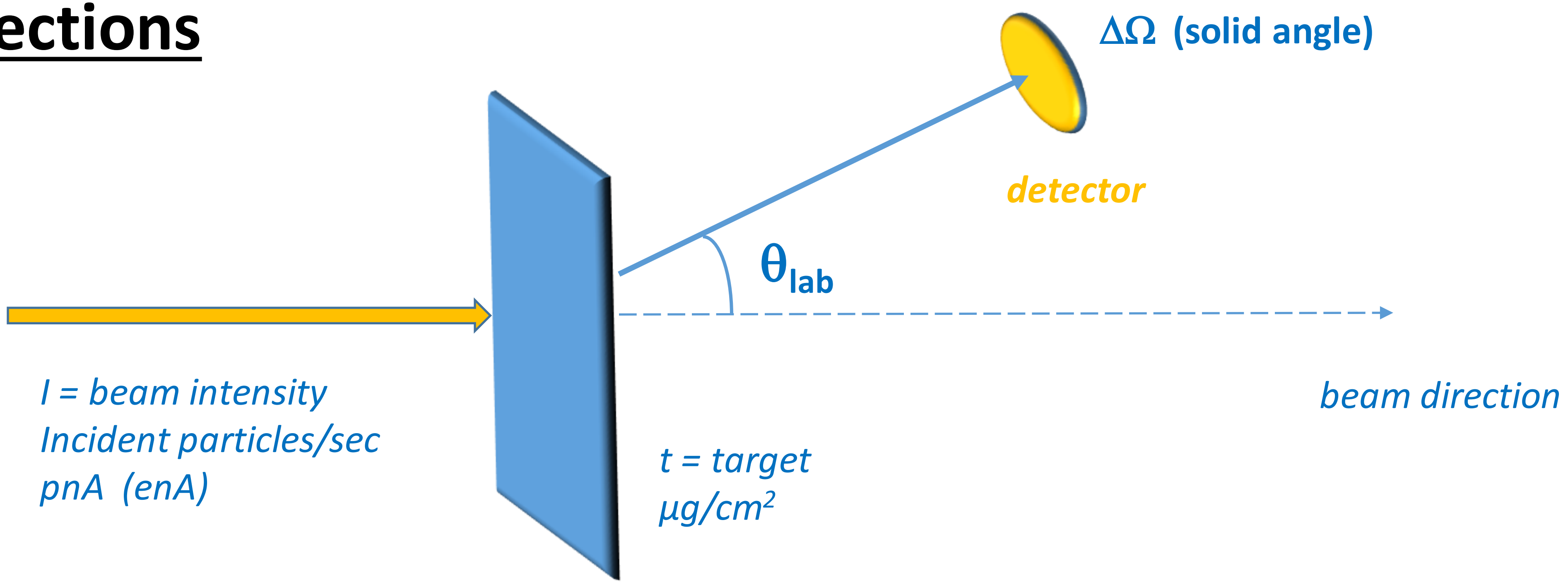
particella α

energia di legame 28 MeV →

100 miliardi di gradi !!!

Come posso descrivere la probabilità che una reazione nucleare avvenga? … **sezione d’urto** (cross section)

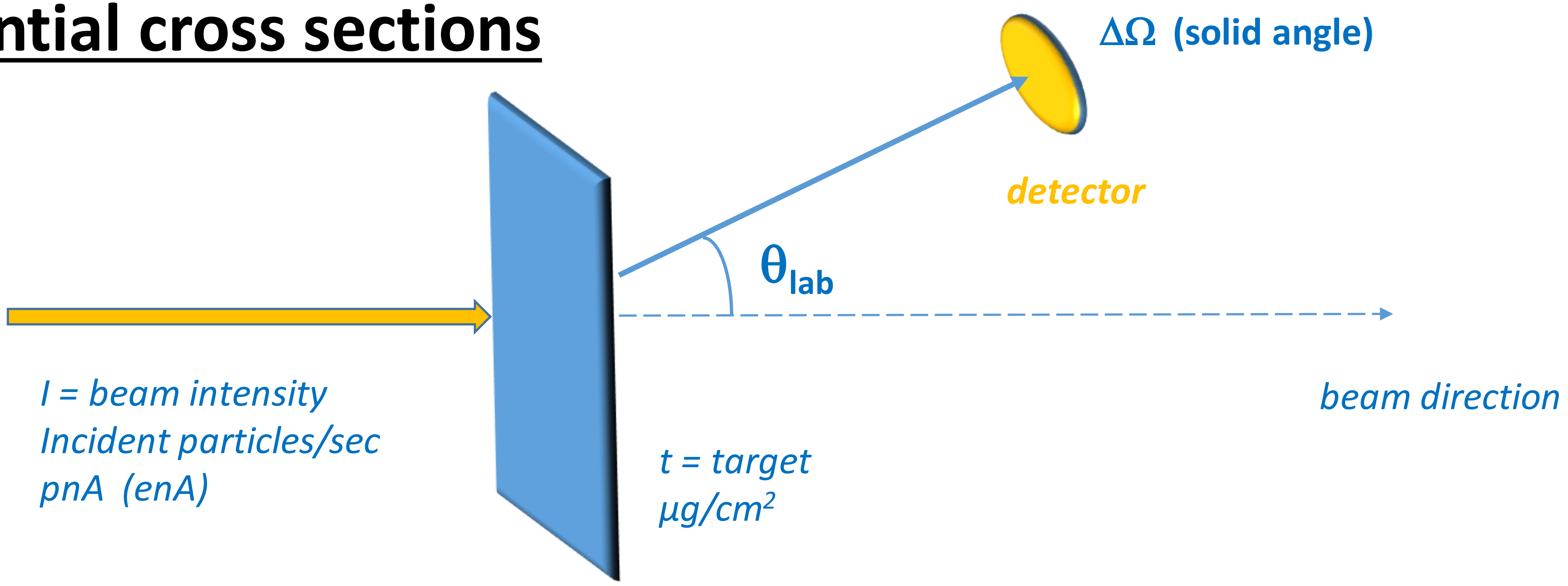
Cross sections



$$\sigma \equiv \frac{(number\ of\ interactions\ per\ time)}{(number\ of\ incident\ particles\ per\ area\ per\ time)(number\ of\ target\ nuclei\ within\ the\ beam)} = \frac{N_R/t}{(N_b/tA)N_t}$$

The *cross section* is a quantitative measure of an interaction probability → **1 barn = 10^{-24} cm^2**

Differential cross sections



$$\frac{d\sigma}{d\Omega} = \frac{N_d/t}{(N_b/t)(N_t/A)} \frac{1}{d\Omega}$$

$$N_d = number\ of\ products\ detected$$

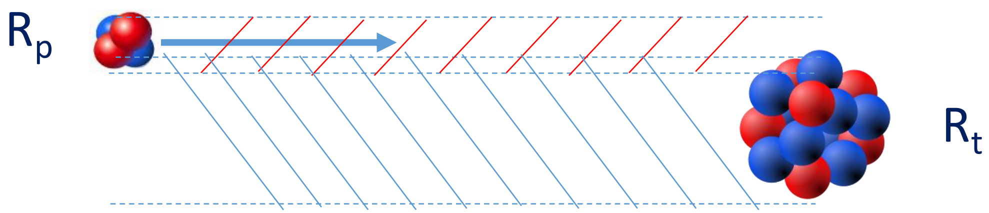
$$\frac{d\sigma}{d\Omega} \rightarrow mbarn/sr$$

(***geometrical efficiency***)

$1\ b = 10^{-24}\ cm^2 = 10^{-28}\ m^2$

$1\ fm^2 = (10^{-15})^2\ m^2 = 10^{-2}\ b$

Classically

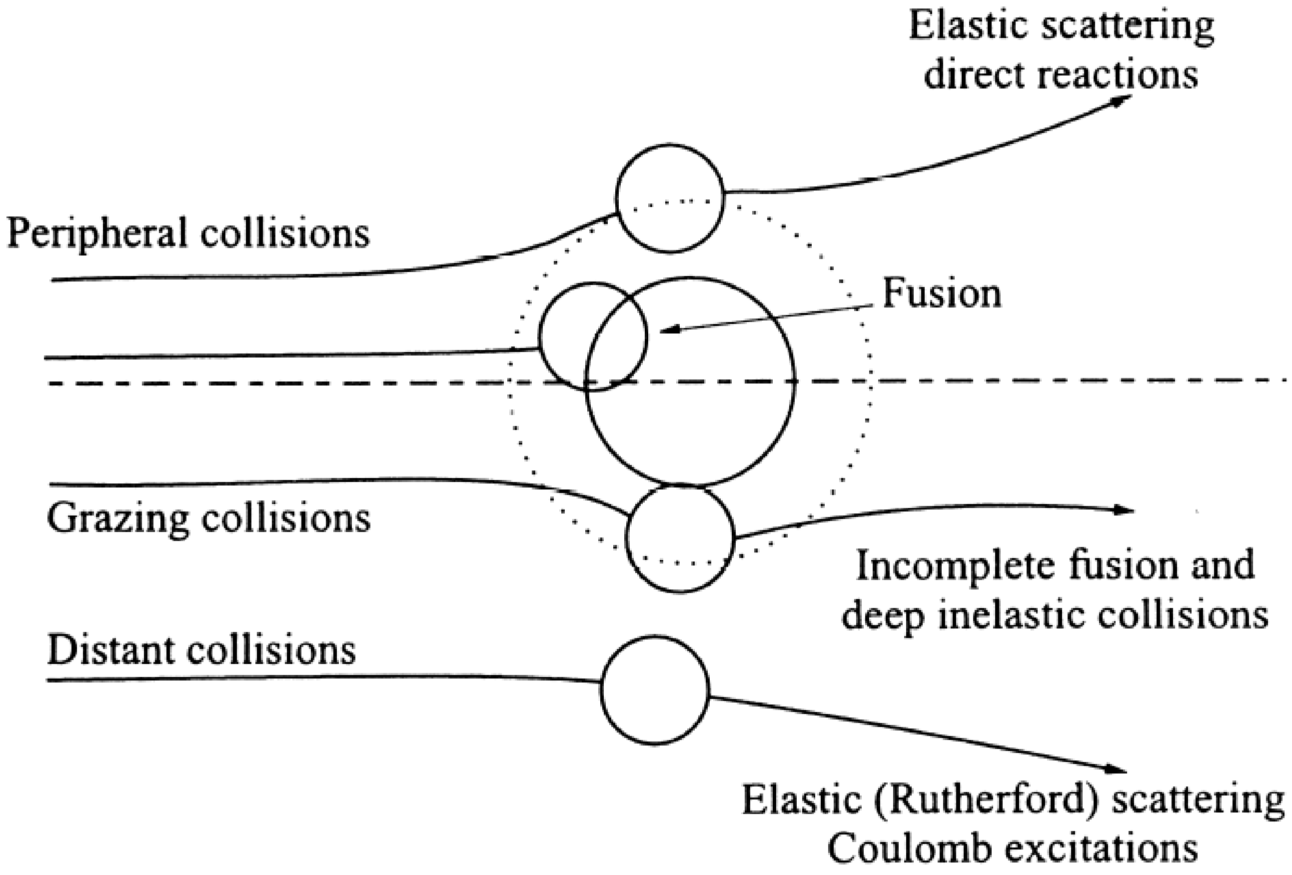


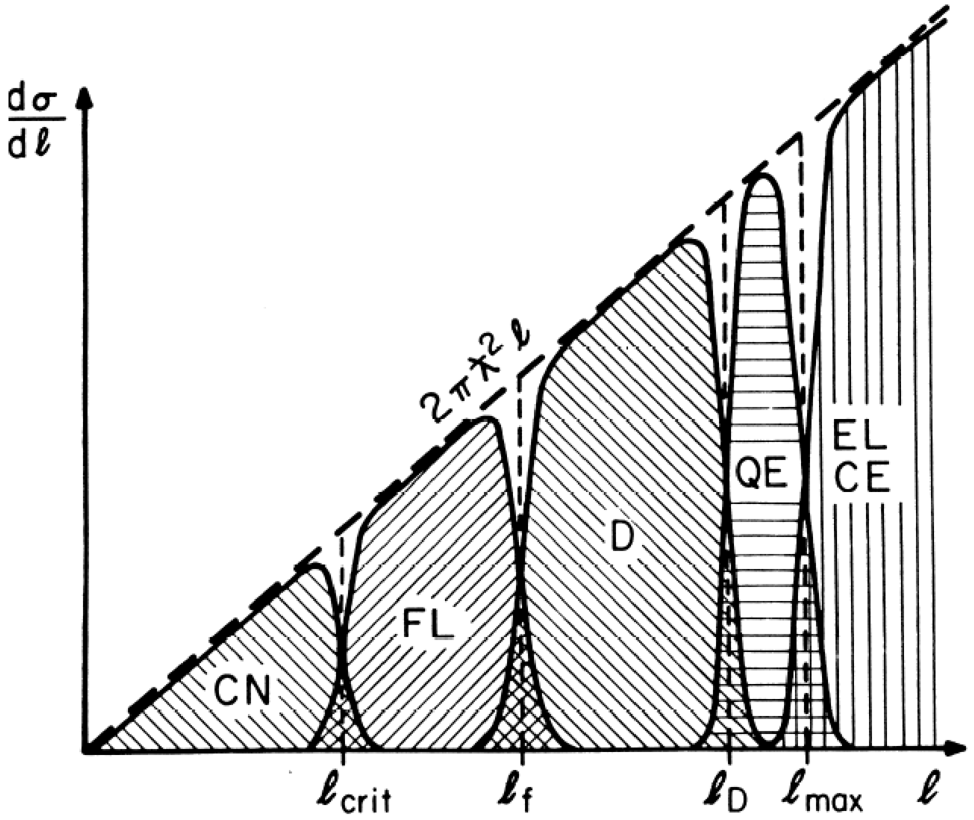
$$\sigma = \pi\,(R_p + R_t)^{\,2} \qquad R = R_0\,A^{\frac{1}{3}} \qquad R_0 \cong 1.2\ fm = 1.2^{-13}\ cm$$

collision	σ (cm^2)
$^{1}H + {}^{1}H$	0.2×10^{-24}
$^{1}H + {}^{238}U$	2.8×10^{-24}
$^{238}U + {}^{238}U$	4.8×10^{-24}

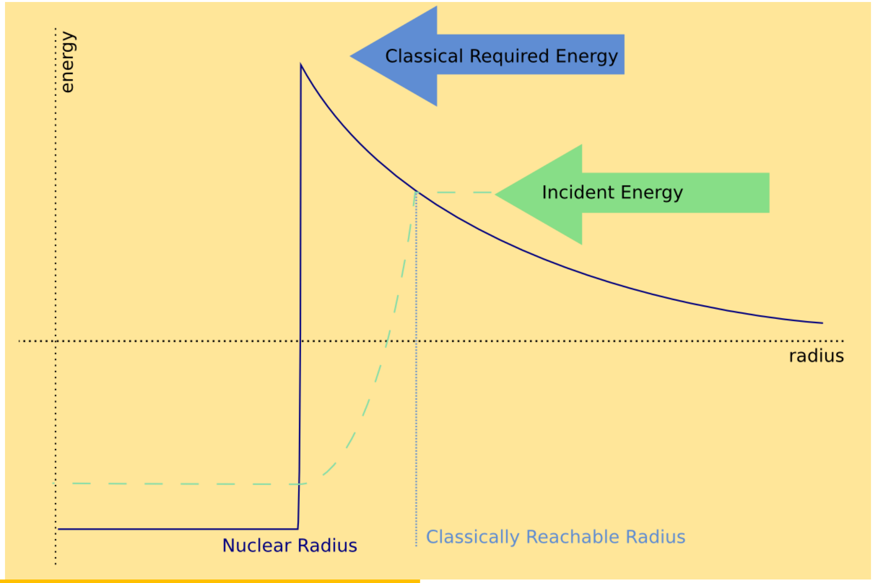
Strong force $^{15}N(p,\alpha)^{12}C$	$\sigma = 0.5$ b	Ep = 2.0 MeV
Eletromagnetic force $^{3}He(\alpha,\gamma)^{7}Be$	$\sigma = 10^{-6}$ b	Ep = 2.0 MeV
Weak force $p(p,e{+}\nu)d$	$\sigma = 10^{-20}$ b	Ep = 2.0 MeV

Heavy ion reactions



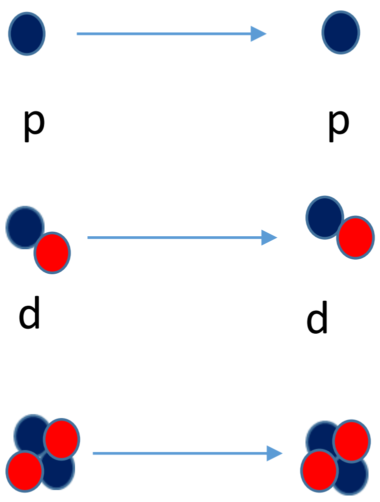


Cross section and coulomb barrier



$$E_c = \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{(R_1+R_2)} \approx 1.2\frac{Z_1 Z_2}{\left(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}}\right)}\ MeV$$

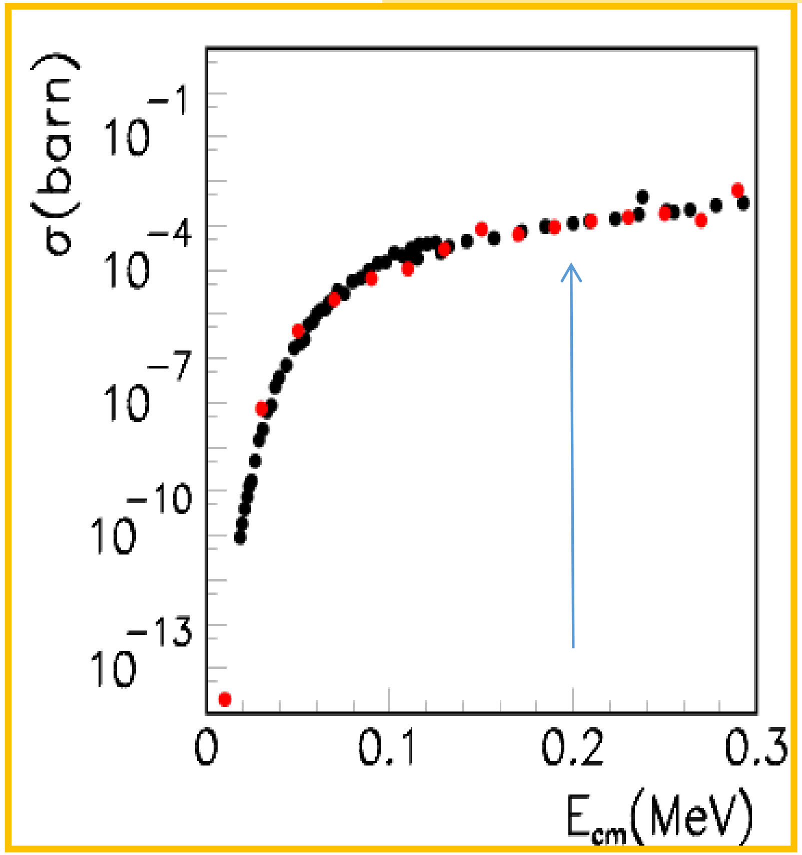
Examples:



$E_c = 0.60\ MeV$

$E_c = 0.48\ MeV$

$E_c = 1.51\ MeV$

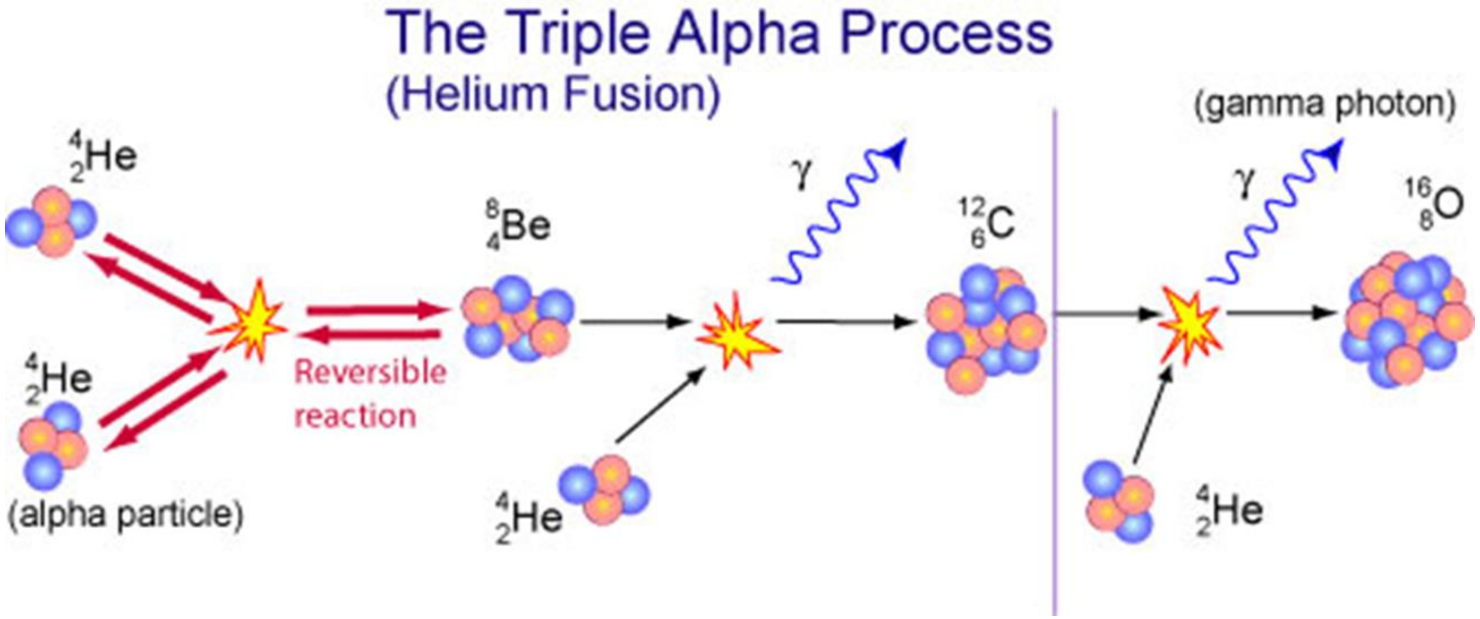


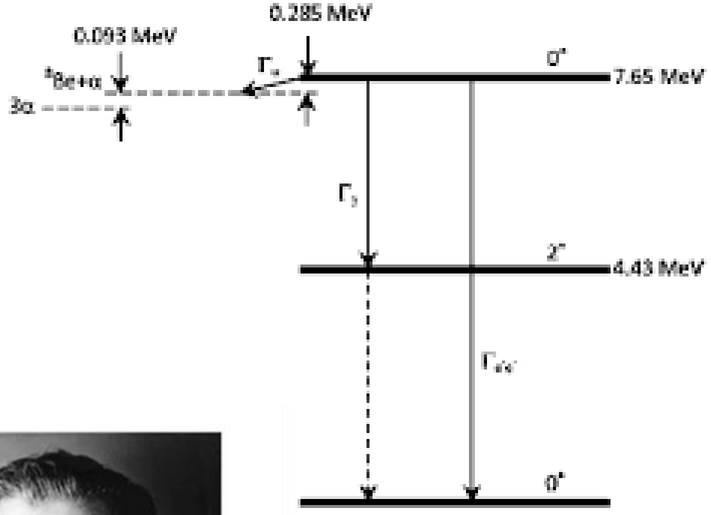
$^{10}B + p$

$E_c = 1.9$ MeV

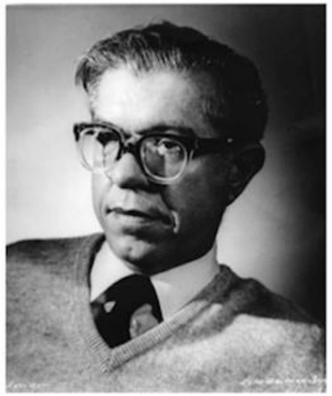
$E_{cm} = 0.2$ MeV

Esempio





^{12}C



Fred Hoyle

1915-2001

T = 100 MK !!!

Alto numero di reazioni (rate) fortemente improbabili

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Energy production in stars: Thermonuclear Reactions

The *reaction Q-value* is the difference in masses before and after the reaction, or the difference in kinetic energies after and before the reaction.
It is equal to the reaction energy release.

$$\sigma \equiv \frac{(number\ of\ interactions\ per\ time)}{(number\ of\ incident\ particles\ per\ area\ per\ time)(number\ of\ target\ nuclei\ within\ the\ beam)} = \frac{N_R/t}{(N_b/tA)N_t}$$

Reaction rate: number of reactions per time t and unit volume V

Nuclear reaction rate – particle-induced reactions

Consider the reaction

$$1 + 2 \rightarrow 3 + 4$$

Where both the projectile 1 and the target 2 are particles with rest mass.
This means that neither 1 nor 2 represents a photon.

$$\mathbf{r_{12} = N_1 N_2}\, v\, \sigma(v)$$

Where $N_1 = N_b/V \quad N_2 = N_t/V$

Nuclear reaction rate – particle-induced reactions

In a stellar plasma the relative velocity of the interacting 1 – 2 nuclei is not constant, but it is described by a distribution of relative velocities with a probability function P($\boldsymbol{v}$).

P($\boldsymbol{v}$)$d\,\boldsymbol{v}$ represents the probability that $\boldsymbol{v}$ is within the $\boldsymbol{v} - \boldsymbol{v} + d\,\boldsymbol{v}$ range

with $\int_0^\infty P(v)dv = 1$

Therefore

$$r_{12} = N_1 N_2 \int_0^\infty v P(v) \sigma(v) dv = N_1 N_2 \langle \sigma v \rangle_{12}$$

Where $\langle \sigma v \rangle_{12} = \int_0^\infty v P(v) \sigma(v) dv$ is the reaction rate per particle pair

$N_1 N_2$ represents pair density of nonidentical 1 and 2 nuclei

Nuclear reaction rate – particle-induced reactions

In stellar plasma the relative velocity is generated by the termal motion and the nuclear reactions are called *thermonuclear reactions*.

In most cases the velocities of nuclei can be described by a *Maxwell-Boltzmann* distribution

$$P(v)dv = \left(\frac{m_{12}}{2\pi kT}\right)^{3/2} e^{-m_{12}v^2/(2kT)} 4\pi v^2 dv$$

Where $m_{12} = \frac{m_1 m_2}{(m_1+m_2)}$ is the reduced mass

$k = 8.6173 \times 10^{-5}$ eV/K is the Boltzmann constant

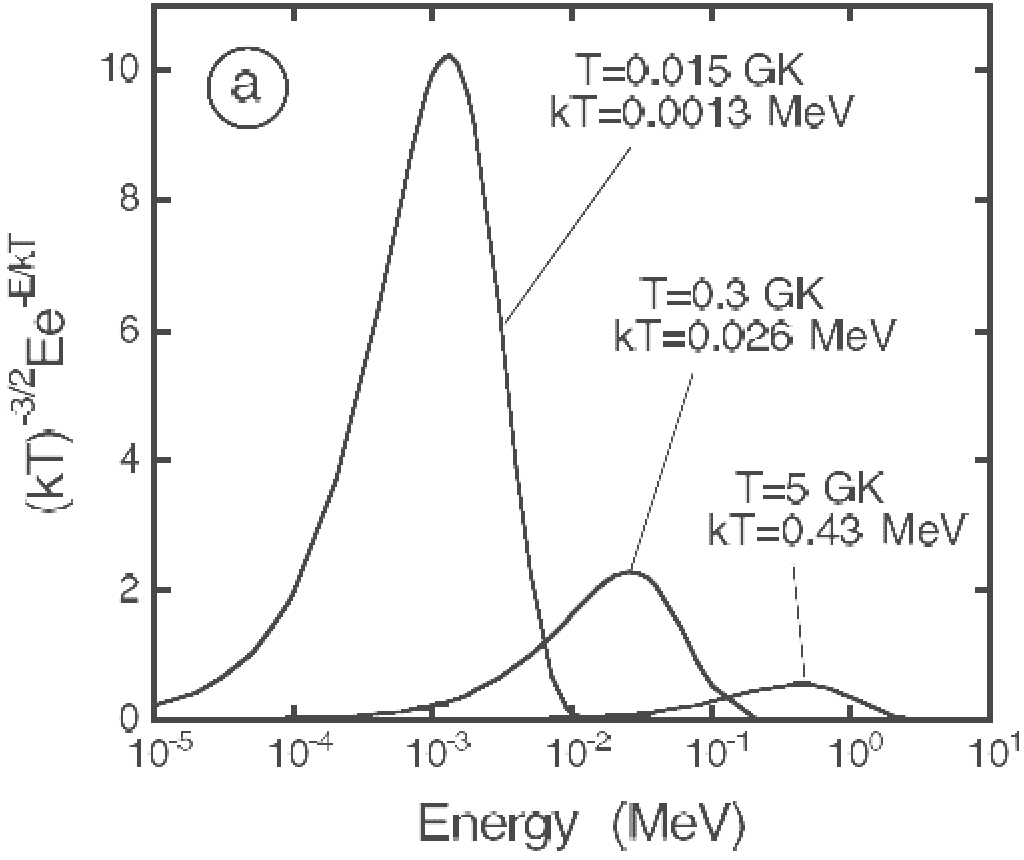
Nuclear reaction rate – particle-induced reactions

Maximum at E = kT

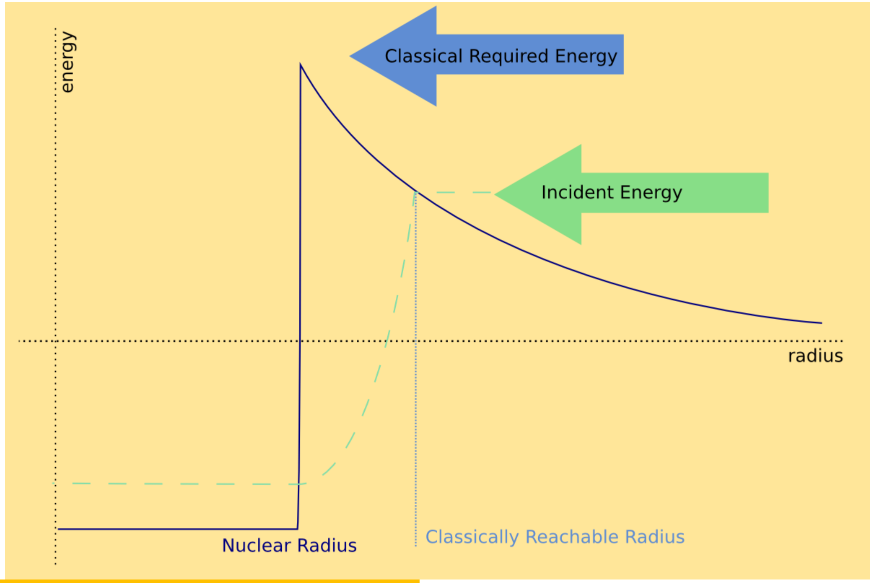
T = 15 MK → Sun core

T = 300 MK → nova

T = 5 GK → supernova



Cross section and coulomb barrier



$$E_c = \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{(R_1+R_2)} \approx 1.2\frac{Z_1 Z_2}{\left(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}}\right)}\ MeV$$

Examples:

p p

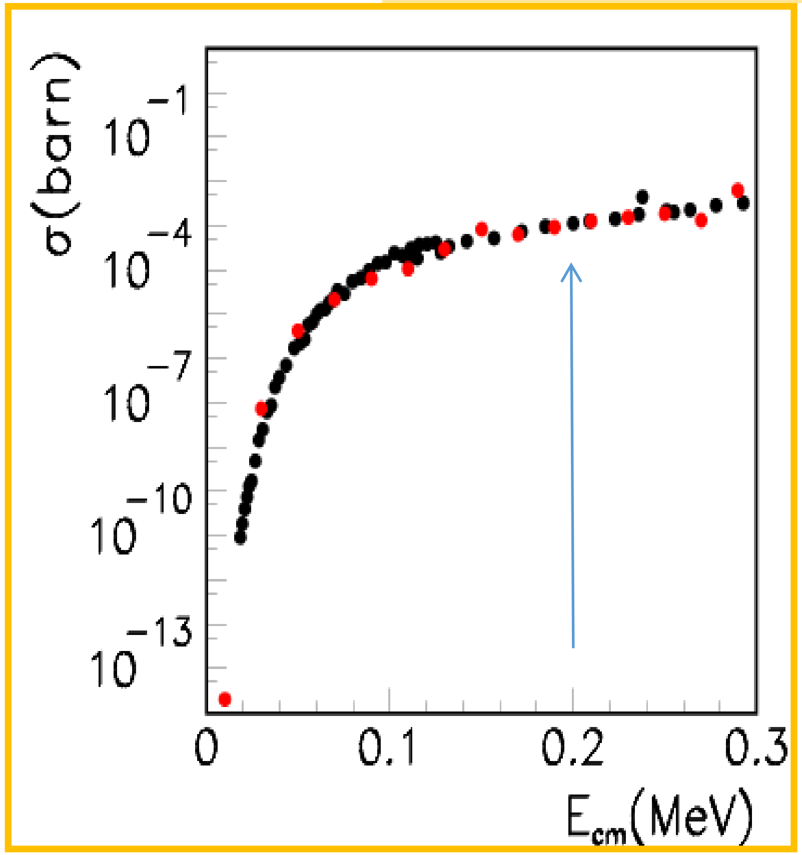
$$E_c = 0.60\ MeV$$

d d

$$E_c = 0.48\ MeV$$

He He

$$E_c = 1.51\ MeV$$



$^{10}B + p$

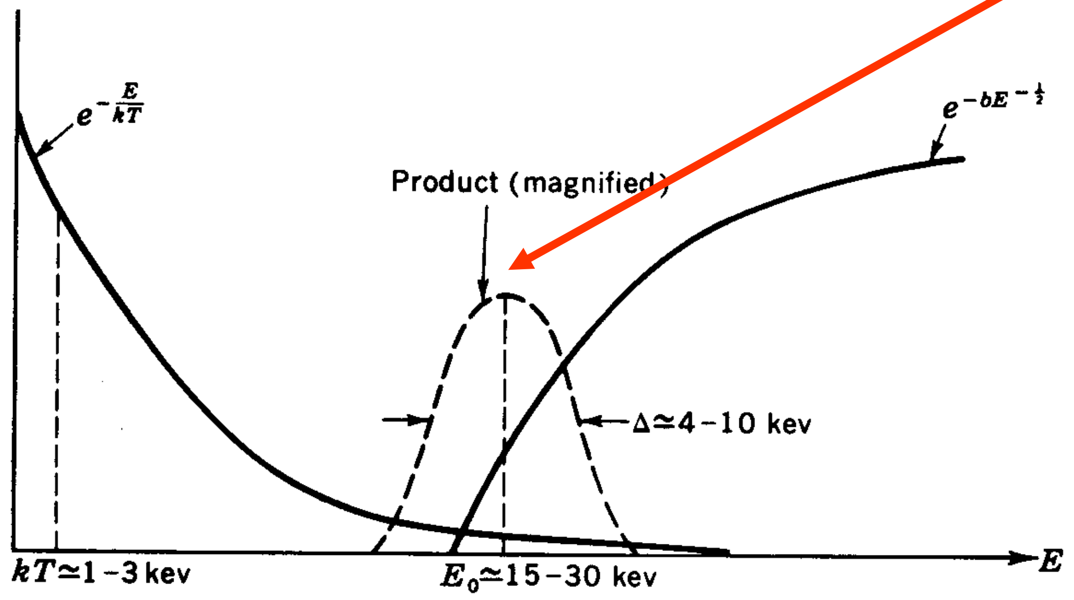
$E_c = 1.9$ MeV

$E_{cm} = 0.2$ MeV

Charged particle-induced reactions (non-resonant)

$$\langle \sigma v \rangle = \left(\frac{8}{\pi m_{ab}}\right)^{\frac{1}{2}} \frac{1}{(kT)^{\frac{3}{2}}} \int_0^\infty S(E)\, e^{-\left(\frac{b}{\sqrt{E}}+\frac{E}{kT}\right)} dE$$

Gamov Peak



Note: relevant cross section in tail of M.B. distribution, much larger than kT (very different from n-capture !)

For astrophysical purposes the reaction rates are needed.

The nuclear physicist have been asked to measure the nuclear reaction cross sections in the astrophysical relevant energy region.

If the nuclear reactions are induced by charged particles, two coulomb effects represent a limitation in direct measurements:

1) Coulomb barrier
2) Electron screening

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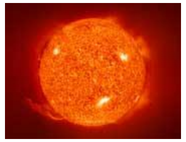
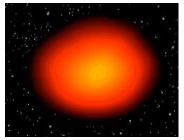
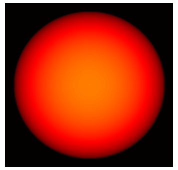
Nuclear Astrophysics :

Stellar environments

nuclear processes

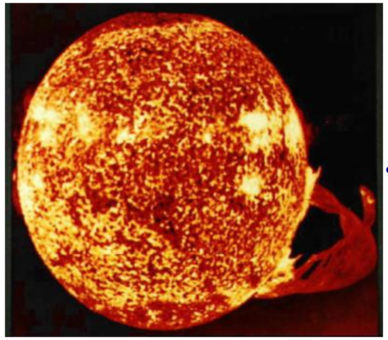
	Stellar environments	nuclear processes
	Big Bang (primordial nucleosyntesis)	Reaction light elements p, d, He, Be, Li, B
	Main sequenza (es. Sun)	H burning proton – proton chain , cicle CNO, cicle Ne-Na, cicle Mg-Al
	Red Gigant, asymptotic branch	'He burning 3α-process, $^{12}C(a,\gamma)^{16}O$ (a,γ) and (α,n) reazioni
	Super gigant Wolf-Rayet e Pre-supernovae	advanced stages of burning Reaction C, O, N, Ne, Si…
	Novae, supernovae, X-ray bursts	explosive burning Cicle HCNO Process rp
	AGB stars, supernovae II, Neutrons stars	nucleosynthesis beyond iron s-process r-process Photodisintegration and p-process

STELLAR LIFE CYCLE

BIRTH
gravitational contraction

Stars

mixing of interstellar gas

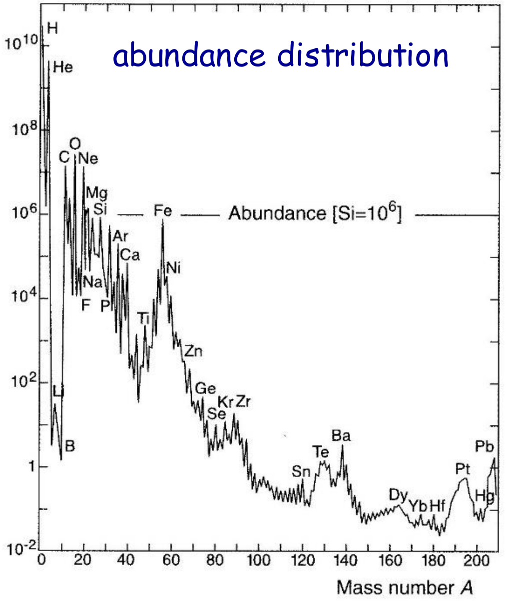


thermonuclear reactions

INCREASE THE mixing of interstellar gas

- energy production
- stability against collapse
- synthesis of "metals"

explosion
DEATH



Proton-Proton-Chain

$p + p \rightarrow d + e^+ + \nu$

$p + d \rightarrow {}^3He + \gamma$

86%

$^3He + {}^3He \rightarrow {}^4He + 2p$

PP-I

$Q_{eff} = 26.20$ MeV

14%

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.7%

$^7Be + e^- \rightarrow {}^7Li + \nu$

$^7Li + p \rightarrow 2\,{}^4He$

PP-II

$Q_{eff} = 25.66$ MeV

0.3%

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+ + \nu$

$\downarrow$

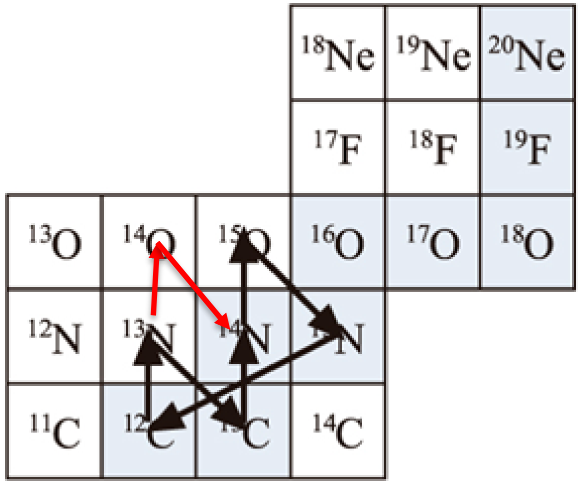
$2\,{}^4He$

PP-III

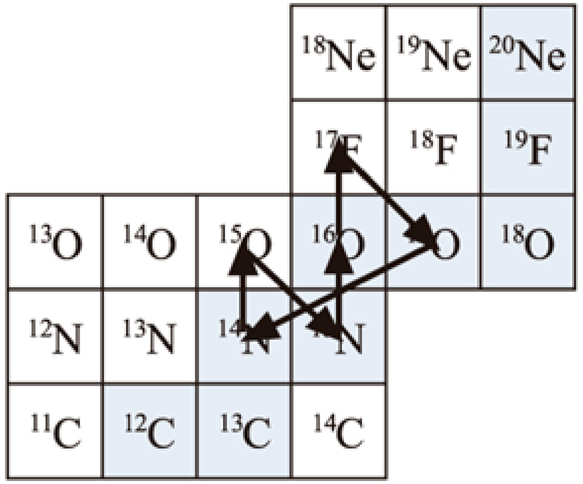
$Q_{eff} = 19.17$ MeV

$4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{eff}$

Hydrogen burning: CNO cycles

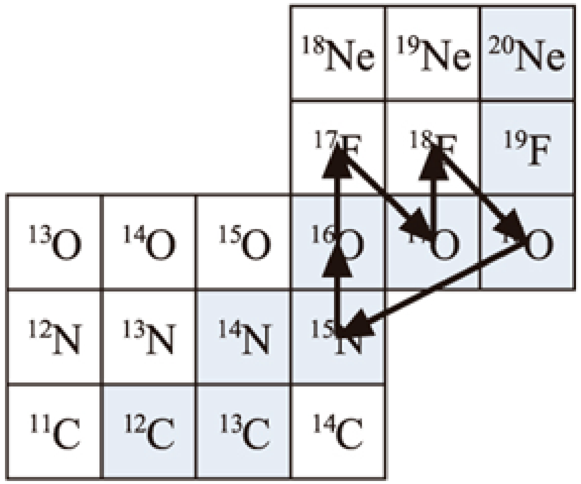


CNO1

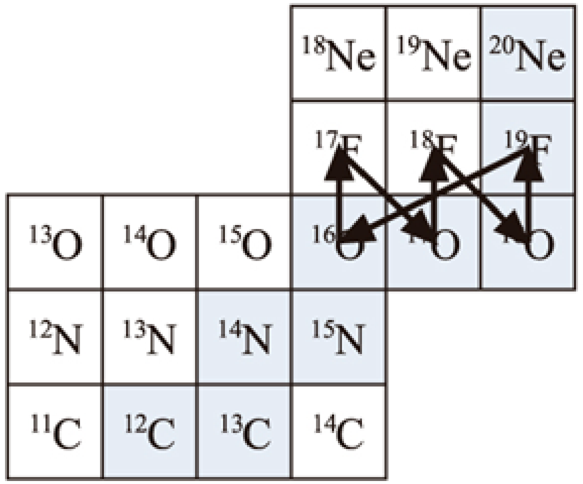


CNO2

^{13}N: $T_{1/2}$ = 9.965 min

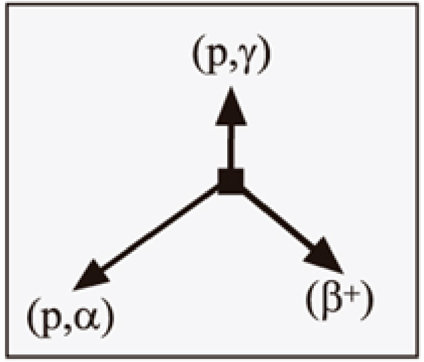


CNO3



CNO4

CNO1	CNO2	CNO3	CNO4
$^{12}C(p,\gamma)^{13}N$	$^{14}N(p,\gamma)^{15}O$	$^{15}N(p,\gamma)^{16}O$	$^{16}O(p,\gamma)^{17}F$
$^{13}N(\beta^+\nu)^{13}C$	$^{15}O(\beta^+\nu)^{15}N$	$^{16}O(p,\gamma)^{17}F$	$^{17}F(\beta^+\nu)^{17}O$
$^{13}C(p,\gamma)^{14}N$	$^{15}N(p,\gamma)^{16}O$	$^{17}F(\beta^+\nu)^{17}O$	$^{17}O(p,\gamma)^{18}F$
$^{14}N(p,\gamma)^{15}O$	$^{16}O(p,\gamma)^{17}F$	$^{17}O(p,\gamma)^{18}F$	$^{18}F(\beta^+\nu)^{18}O$
$^{15}O(\beta^+\nu)^{15}N$	$^{17}F(\beta^+\nu)^{17}O$	$^{18}F(\beta^+\nu)^{18}O$	$^{18}O(p,\gamma)^{19}F$
$^{15}N(p,\alpha)^{12}C$	$^{17}O(p,\alpha)^{14}N$	$^{18}O(p,\alpha)^{15}N$	$^{19}F(p,\alpha)^{16}O$



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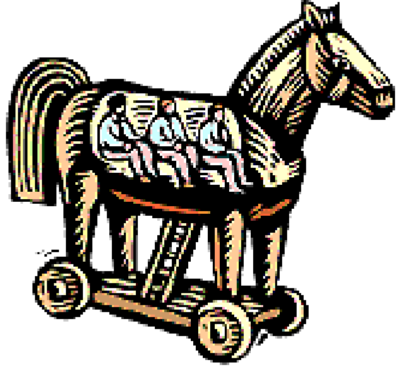
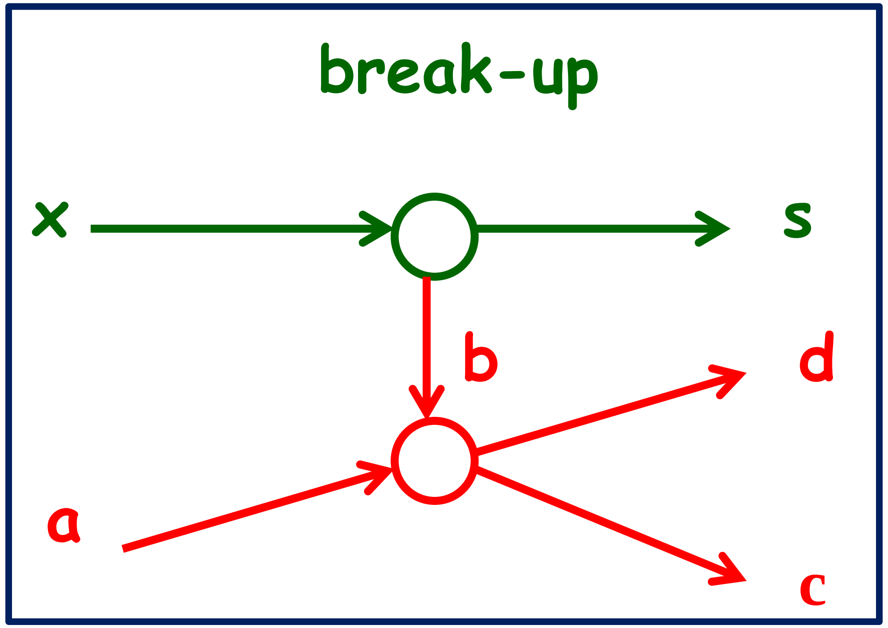


Trojan Horse Method

If the incoming energy of the incident particle is larger than the Coulomb barrier energy ………

the TH nucleus x can be brought into nuclear field of nucleus a and the cluster b induces the virtual reaction



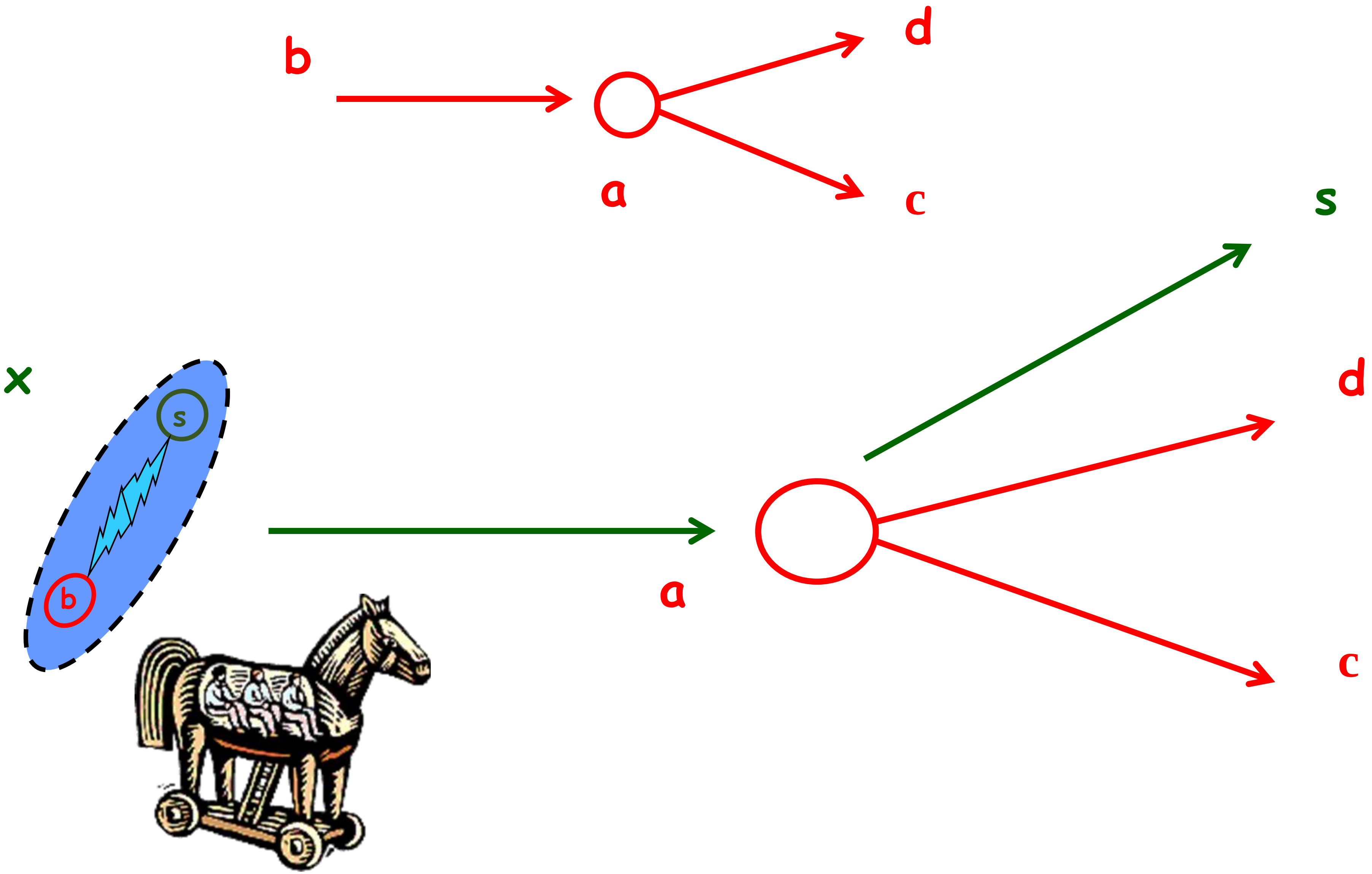
NO Coulomb-suppression

NO Screening effects

virtual two body reaction

a + b → c + d

C. Spitaleri et al., PRC 64(2001)068801
C. Spitaleri et al., PRC 69(2004)055806


b
d
a
c
s
x
s
b
d
a
c

... on NATURE (May – 2018)

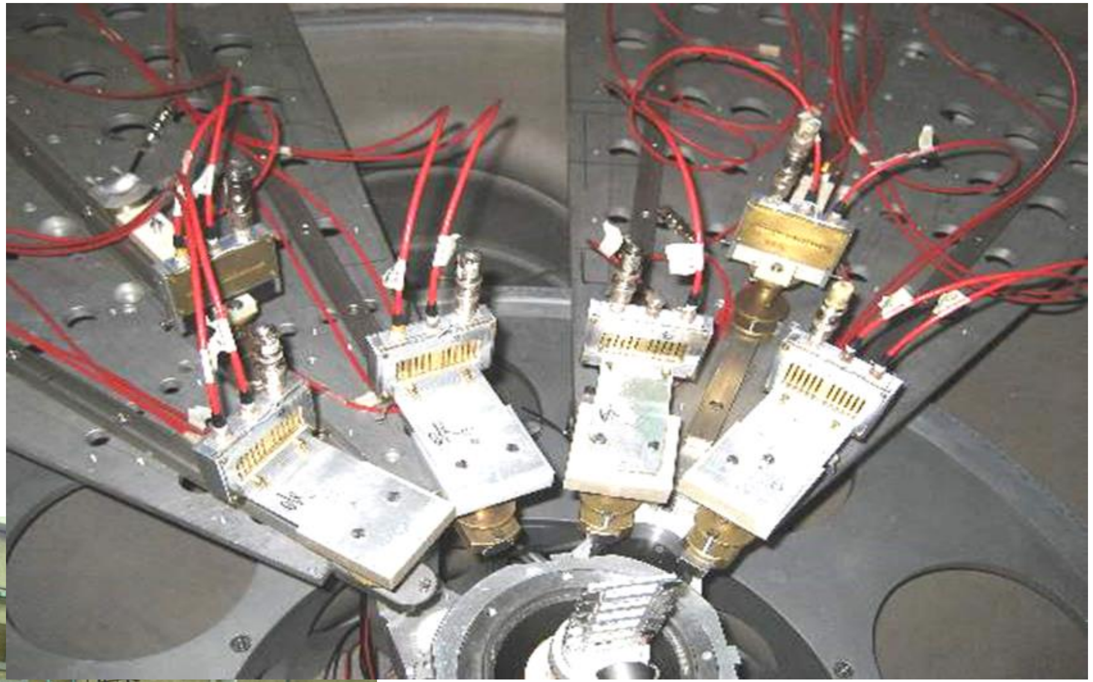
LETTER

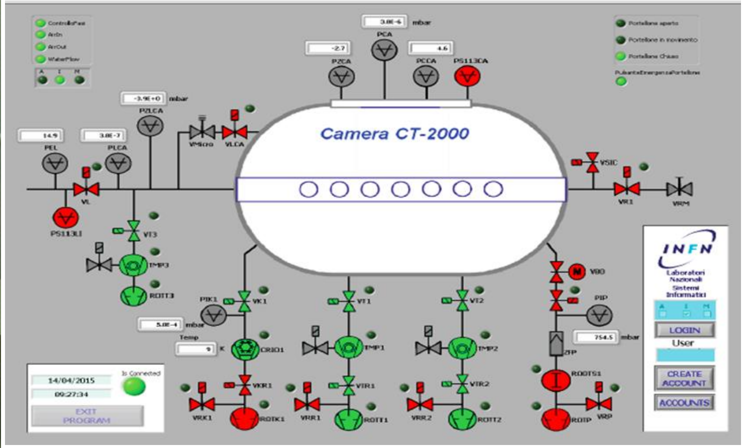
https://doi.org/10.1038/s41586-018-0149-4

An increase in the $^{12}C + ^{12}C$ fusion rate from resonances at astrophysical energies

A. Tumino[1,2*], C. Spitaleri[2,3], M. La Cognata[2], S. Cherubini[2,3], G. L. Guardo[2,4], M. Gulino[1,2], S. Hayakawa[2,5], I. Indelicato[2], L. Lamia[2,3], H. Petrascu[4], R. G. Pizzone[2], S. M. R. Puglia[2], G. G. Rapisarda[2], S. Romano[2,3], M. L. Sergi[2], R. Spartá[2] & L. Trache[4]

experimental facilities





Astrophysical Application

Light nuclei depletion:
Li, B, Be: Li reactions

DIRECT REACTIONS

$^{7}Li + p \rightarrow \alpha + \alpha$

$^{6}Li + d \rightarrow \alpha + \alpha$

$^{6}Li + p \rightarrow \alpha + {}^{3}He$

INDIRECT REACTIONS

$^{7}Li + d \rightarrow \alpha + \alpha + n_{spett.}$

$^{7}Li + {}^{3}He \rightarrow \alpha + \alpha + d_{spett}$

$^{6}Li + {}^{6}Li \rightarrow \alpha + \alpha + a_{spett.}$

$^{6}Li + {}^{3}He \rightarrow \alpha + \alpha + d_{spett}$

$^{6}Li + d \rightarrow \alpha + {}^{3}He + n_{spett}$

$^{6}Li + {}^{3}He \rightarrow \alpha + {}^{3}He + d_{spett}$

Astrophysical Application

Light nuclei depletion:
Li, B, Be

Be reactions

INDIRECT REACTION

$^{9}Be + p \rightarrow \alpha + {}^{6}Li$

$^{9}Be + p \rightarrow \alpha + {}^{6}Li + n_{spett}$

Astrophysical Application

Depletion lights nuclei:
Li, B, Be

B reactions

INDIRECT REACTIONS

$^{11}B + p \rightarrow \alpha_0 + {}^{8}Be$
$^{11}B + p \rightarrow \alpha_1 + {}^{8}Be$
$^{10}B + p \rightarrow \alpha_0 + {}^{7}Be$

$^{11}B + d \rightarrow \alpha_0 + {}^{8}Be + n_{spect}$
$^{11}B + d \rightarrow \alpha_1 + {}^{8}Be + n_{spect}$
$^{10}B + d \rightarrow \alpha_0 + {}^{7}Be + n_{spect}$

Astrophysical Application

The Fluorine problem in the AGB

INDIRECT REACTIONS

$^{15}N + p \rightarrow \alpha_o + {}^{12}C$

$^{17}O + p \rightarrow a + {}^{14}N$

$^{18}O + p \rightarrow \alpha + {}^{15}N$

$^{19}F + \alpha \rightarrow {}^{22}Ne + p$

$^{15}N + d \rightarrow \alpha_o + {}^{12}C + n_{spect}$

$^{17}O + d \rightarrow a + {}^{14}N + n_{spect}$

$^{18}O + d \rightarrow \alpha + {}^{15}N + n_{spect}$

$^{19}F + {}^{6}Li \rightarrow {}^{22}Ne + p + a_{spect}$

Summary

What is Nuclear Astrophysics?

Starts from the marriage between

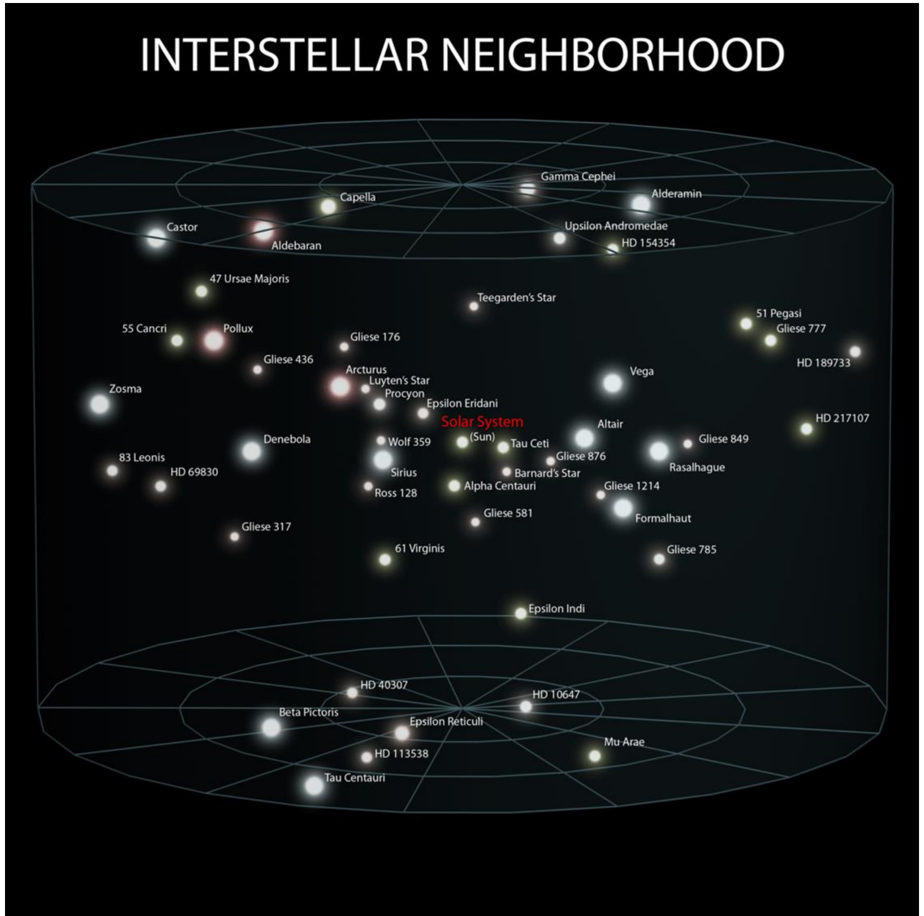
ASTROPHYSICS **NUCLEAR PHYSICS**

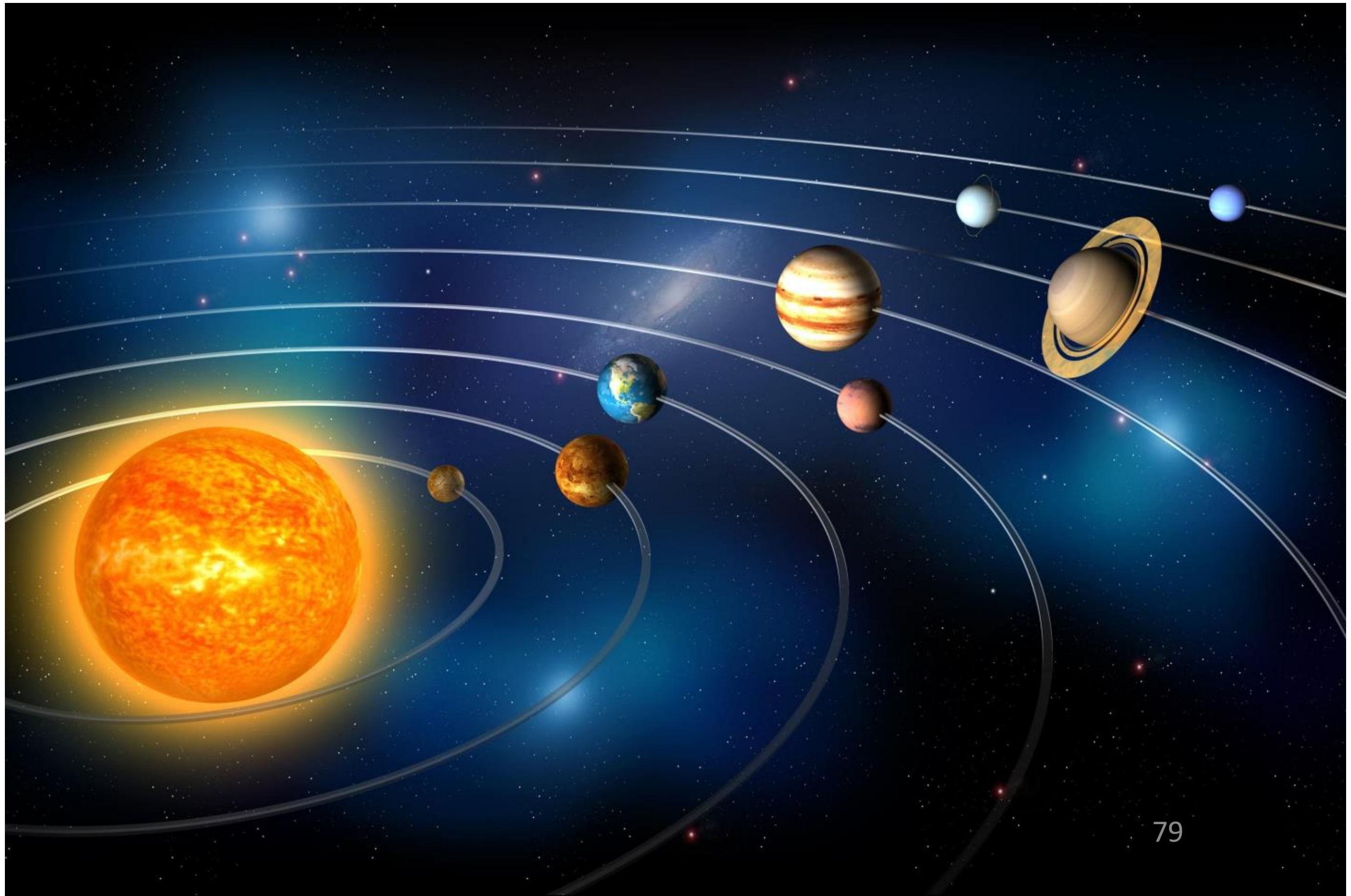
William A. Fowler
Nobel Price Physics
(1983)

Astrophysical aspects

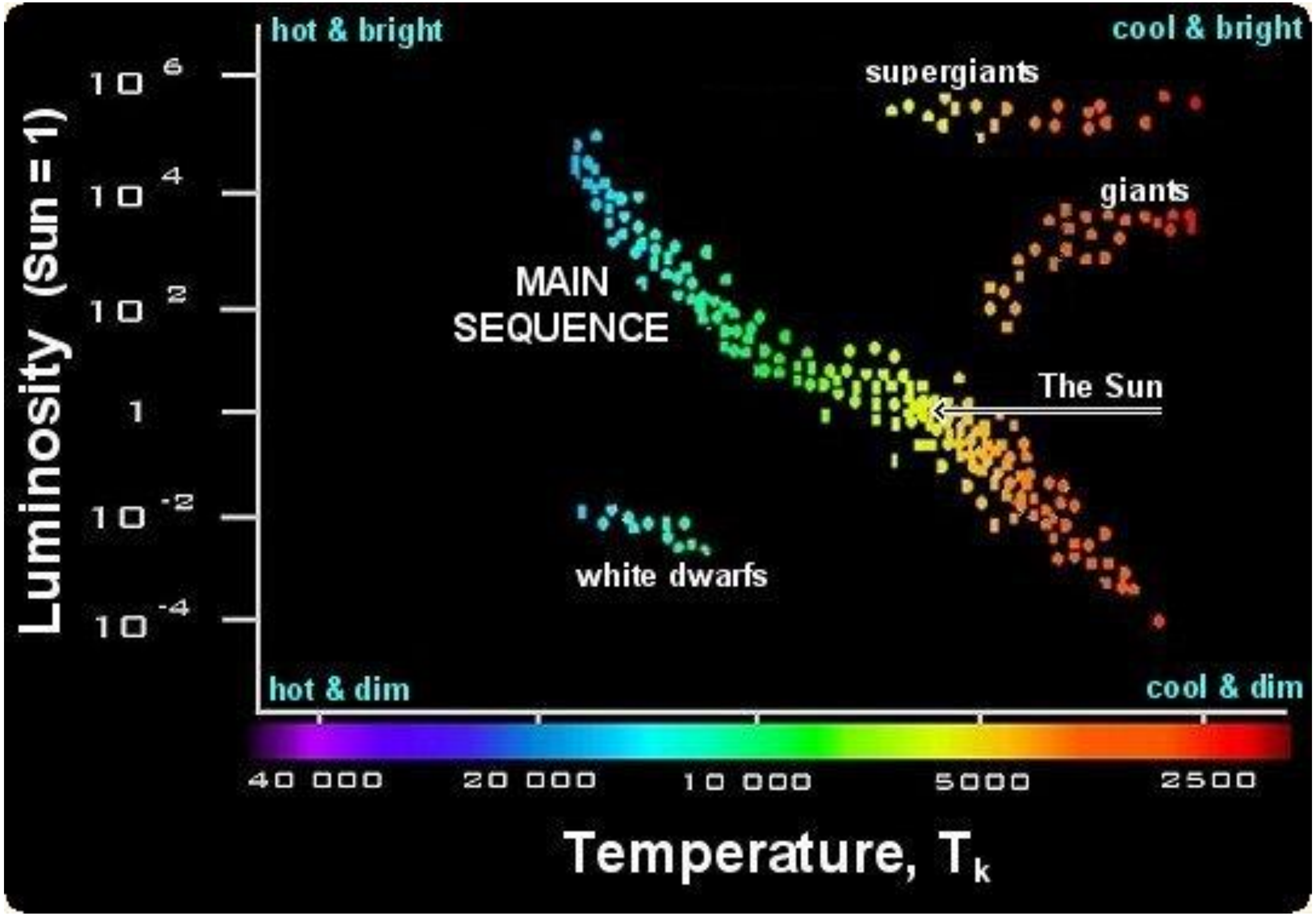
FROM

The study of stars is central to astronomy and astrophysics since stars are long-lived objects that are responsible for most of the visible light we observe from normal galaxies.





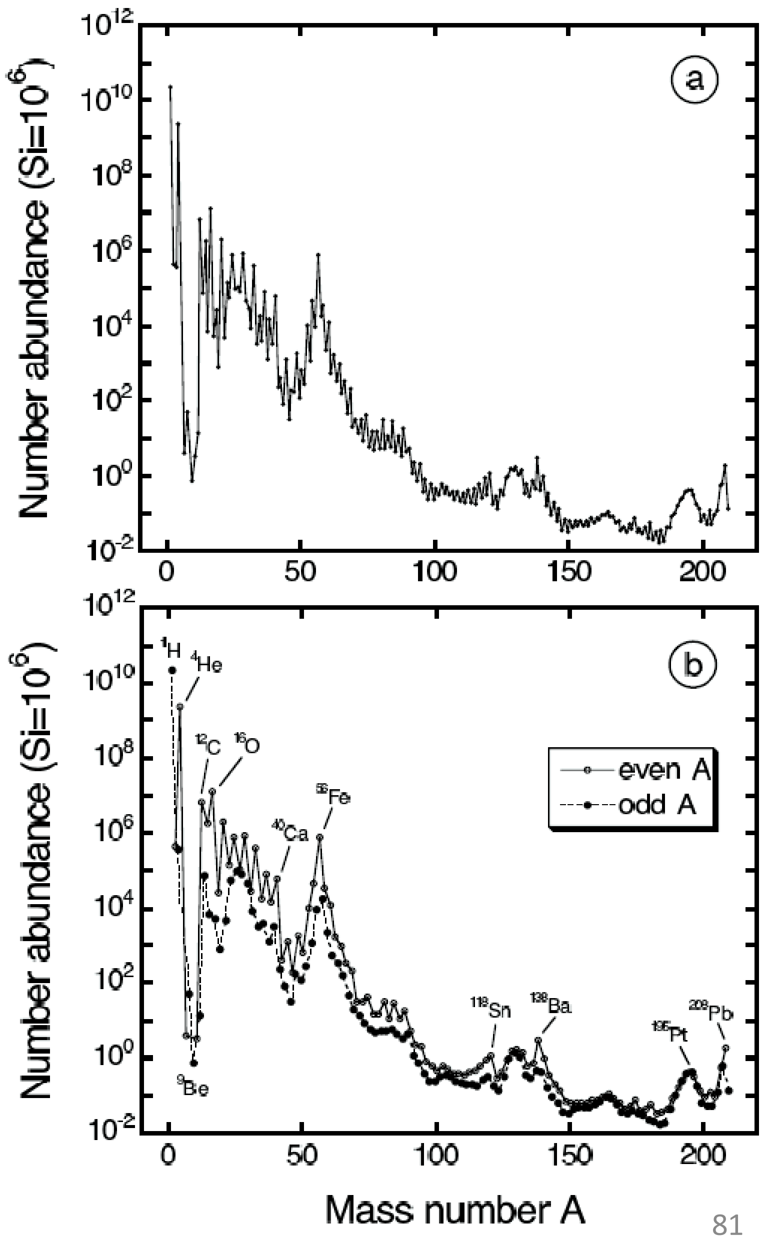
Hertzsprung-Russel Diagram – stellar evolution



Solar system abundances

Data from Lodders (2003)

- Solar system abundances of the nuclides versus mass number A
- The abundances are normalized to the number of silicon atoms
- Figure (a): sum of nuclide abundances at a given A
- Figure (b): abundances separately for even-A and odd-A nuclides
- Almost all the mass is contained in 1H(71.1%) and 4He (27.4%)
- There is an abundance minimum in the A = 5–11 region, corresponding to the elements Li, Be, and B
- More than half of the remaining mass (1.5%) is in the form of 12C and 16O
- The abundances drop slowly with increasing mass number (charge!)
- Another minimum occurs in the A = 41–49 region, around the element Sc
- The abundance curve exhibits a maximum in the A = 50–65 region, near the element Fe (iron peak)



Nuclear aspects

TO ....

- measurements showed that the total nuclear mass, m_{nuc}, is less than the sum of masses of the constituent nucleons.
- We may write

$$m_{nuc} = Zm_p + Nm_n - \Delta m$$

The quantity

$$B(Z,N) = \Delta m \cdot c^2 = (Zm_p + Nm_n - m_{nuc}) \cdot c^2$$

represents the *nuclear binding energy*

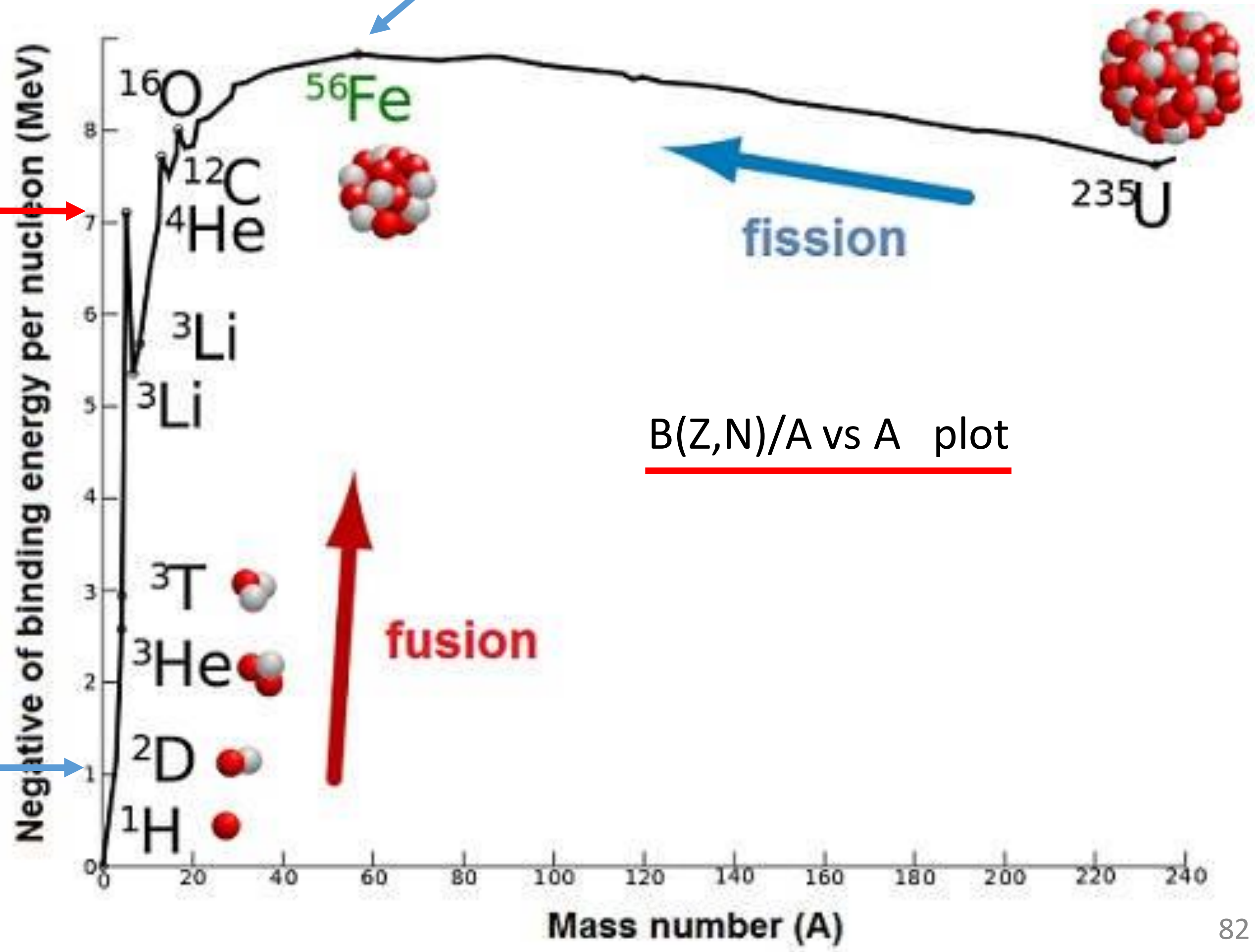
Example

binding energies of deuterium and ^{4}He:

B(d) = B(d)/A · A = (1.112 MeV) · 2 = 2.224 MeV

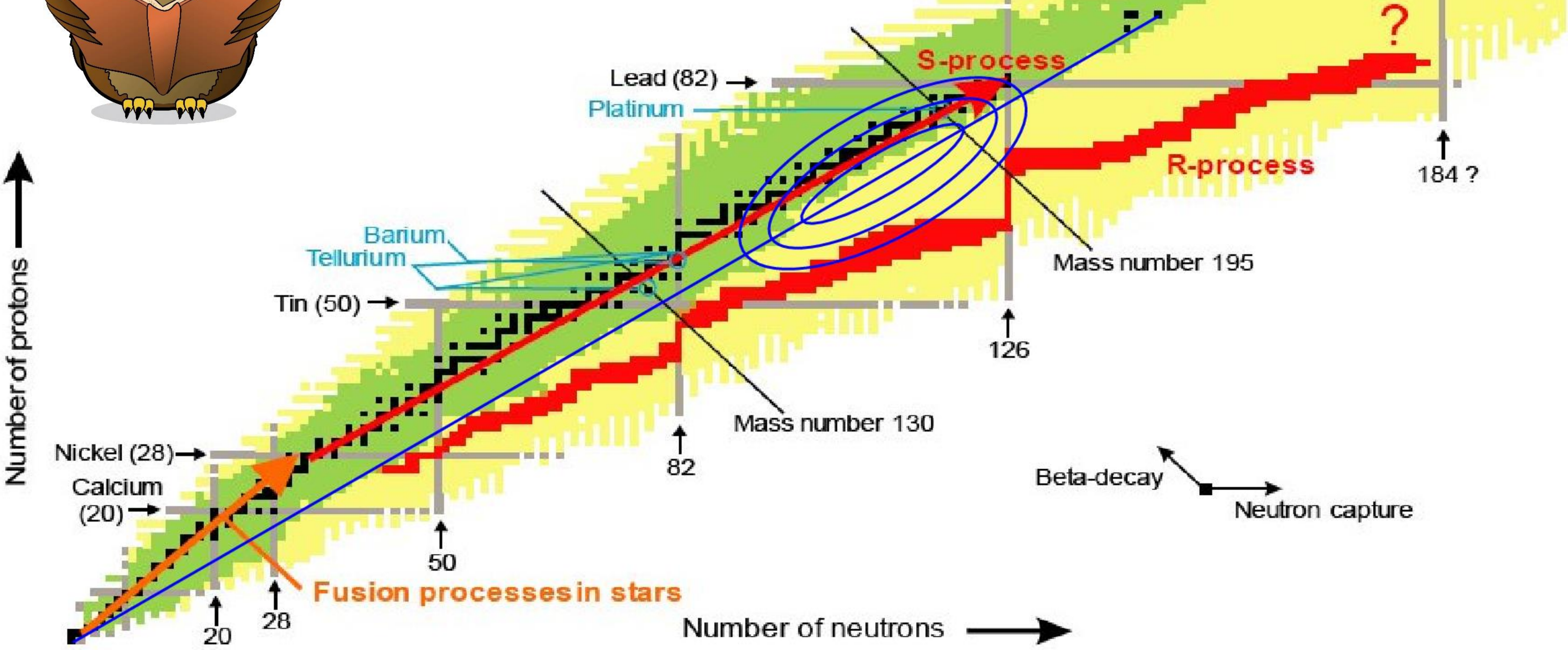
$B(\alpha)$ = $B(\alpha)/A$ · A = (7.074 MeV) · 4 = 28.296 MeV

Iron peak in the solar system abundances

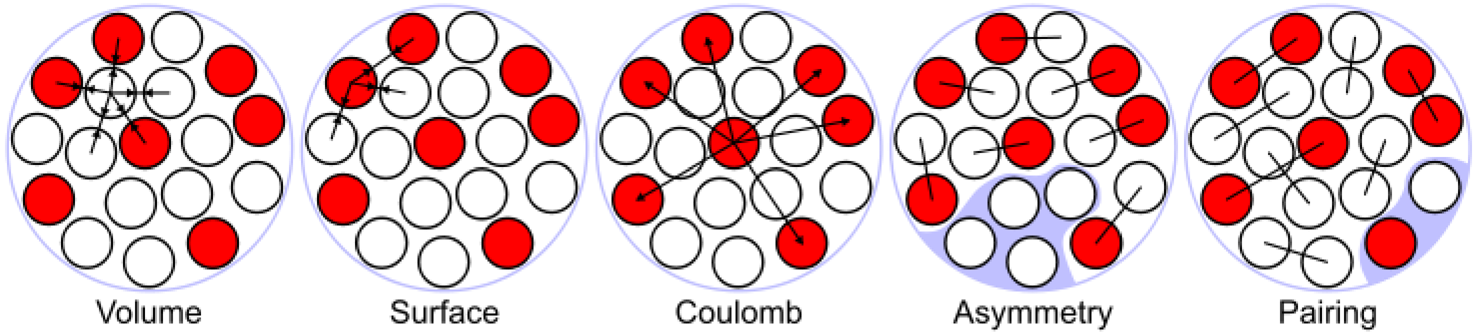


B(Z,N)/A vs A plot

Chart of the nuclides



$$B(A,Z) = a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - a_a \frac{(N-Z)^2}{A} + \delta(A)$$

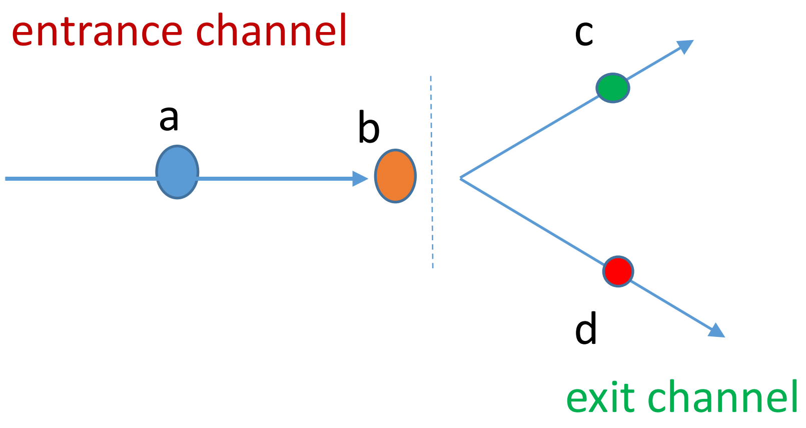


$$a_v = 15.7 \ MeV$$
$$a_s = 17.8 \ MeV$$
$$a_c = 0.7 \ MeV$$
$$a_a = 23.7 \ MeV$$

$$\delta(A) = \begin{cases} 33.6 \, A^{-\frac{3}{4}} & (even - even) \\ -36.6 \, A^{-\frac{3}{4}} & (odd - odd) \\ 0 & (eo, oe) \end{cases}$$

… FROM

Nuclear reactions



A nuclear reaction may be indicated by the following symbolic relationship

a + b → c + d

Where a and b are the colliding nuclei before the interaction, while c and d denote the products after the interaction.

Different types of reactions:

1) a + b → a + b *elastic* or *inelastic* scattering (identical species in the two channels)

2) a + b → c + d two body transfer reaction

3) a + b → c + d + e three body transfer reaction

4) a + b → c + γ radiative capture reaction

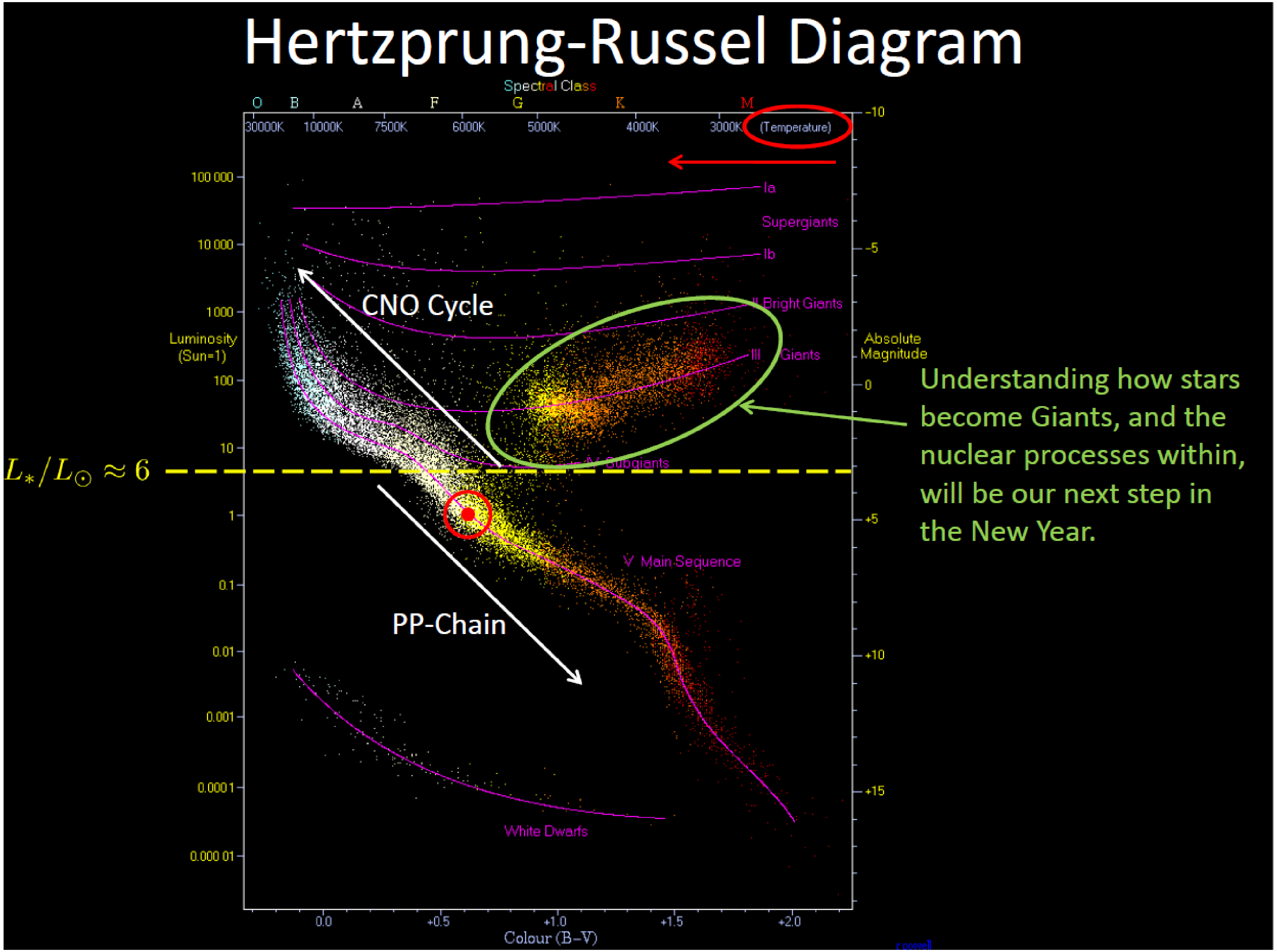
5) a + γ → b + c photodisintegration reaction

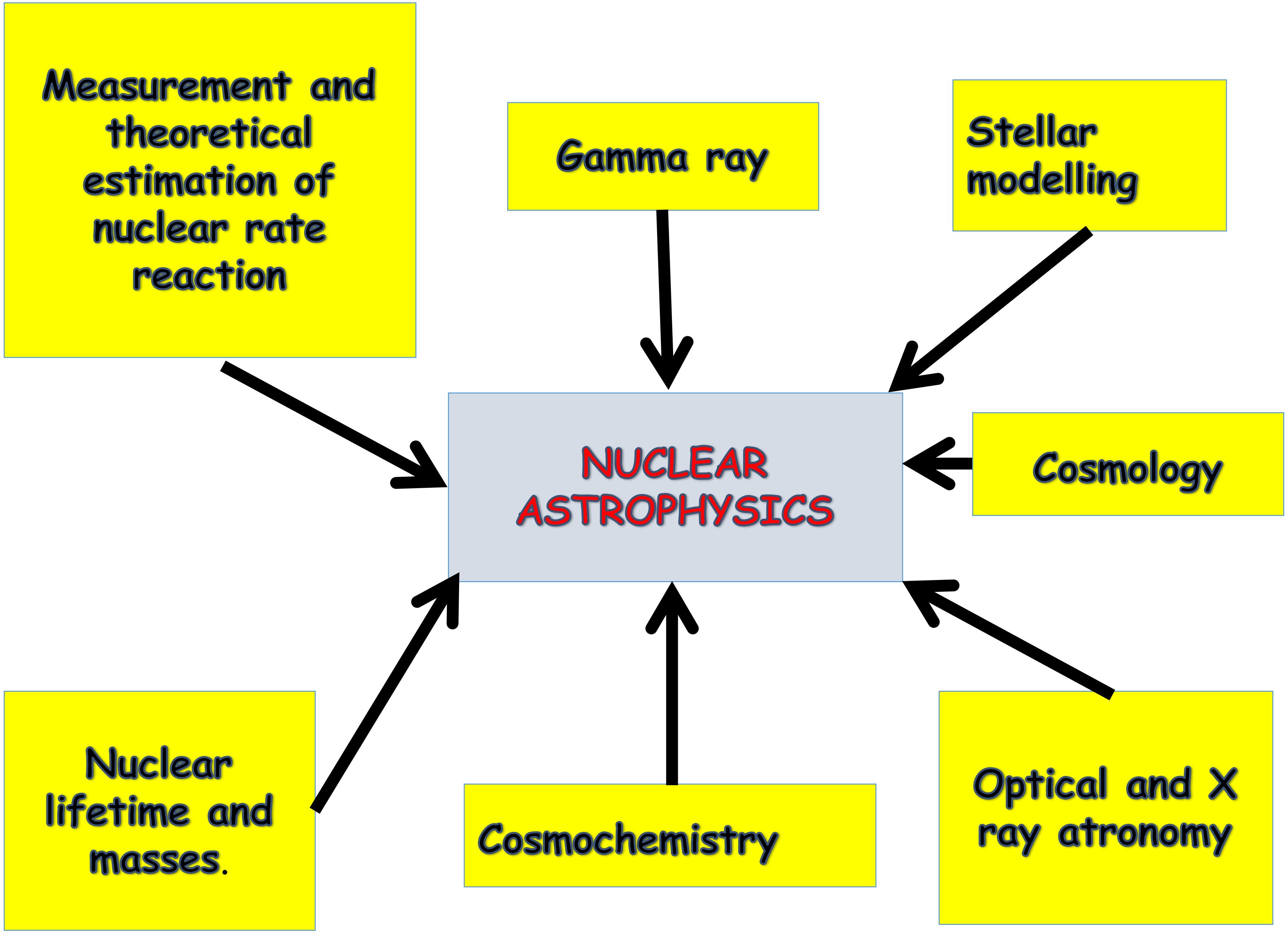
6) (a + b) + c → a + b + c breakup reaction

Most nuclear interactions of astrophysical interest involve just two species before and after the interaction.

...FROM

- Theory
- Observations
- Models
- ...




Measurement and theoretical estimation of nuclear rate reaction
Gamma ray
Stellar modelling
NUCLEAR ASTROPHYSICS
Cosmology
Nuclear lifetime and masses.
Cosmochemistry
Optical and X ray atronomy

A che serve la ricerca fondamentale?

Questa domanda è stata posta diverse volte nella storia…

Caro Sir Faraday, ma a cosa servirà mai questa elettricità che lei sta studiando?

Caro Primo Ministro, ancora non lo so, ma sono sicuro che il governò ci metterà una tassa sopra

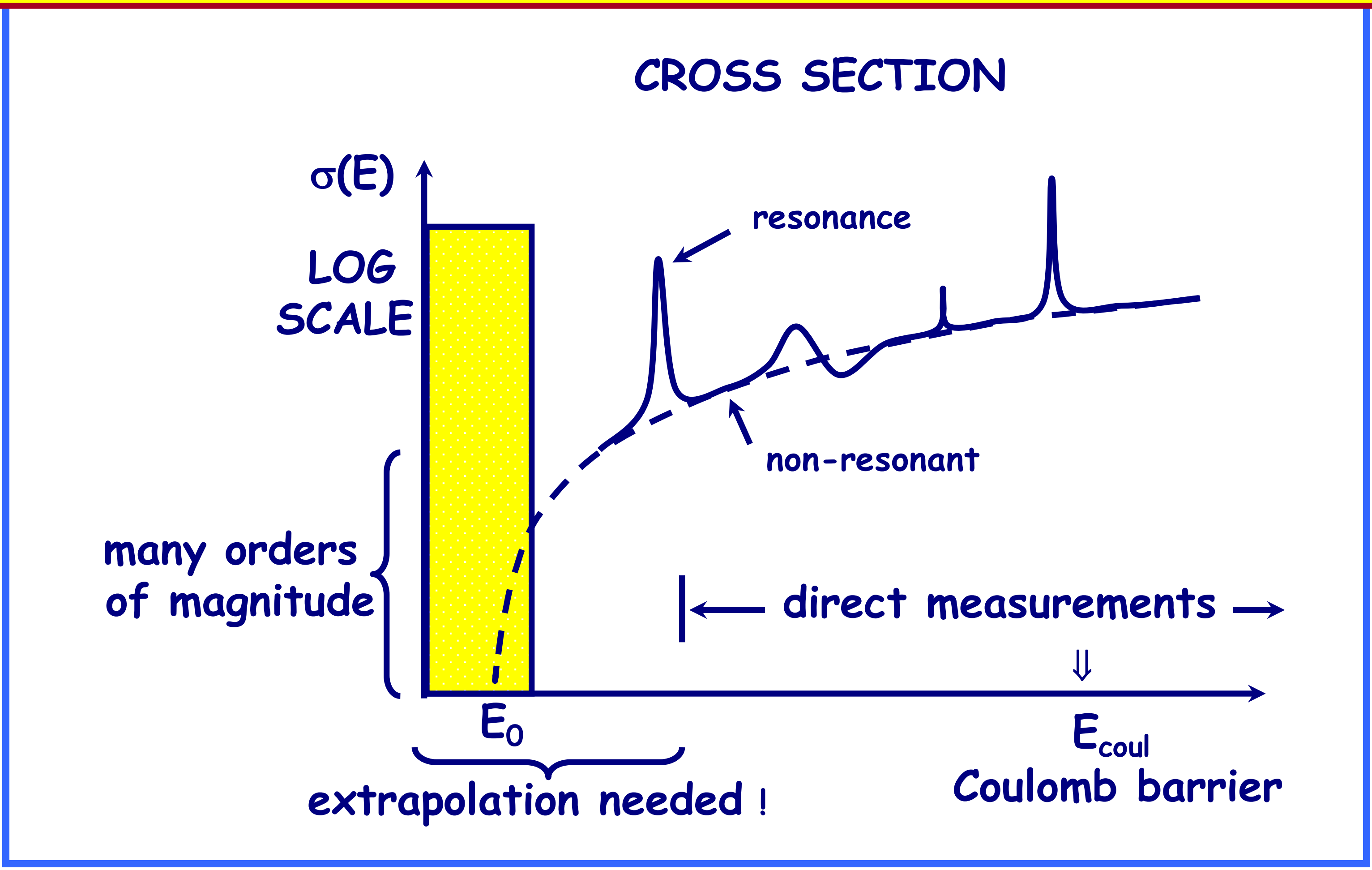
Sir Michael Faraday (1791-1867)

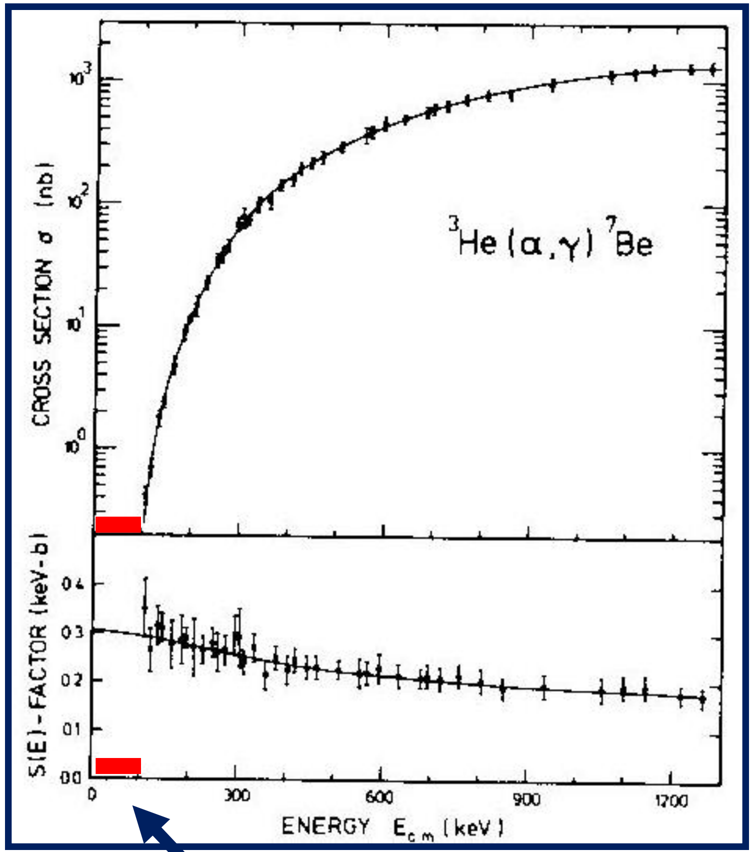
Sir Robert Peel (1788-1850)

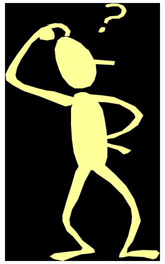
THE END

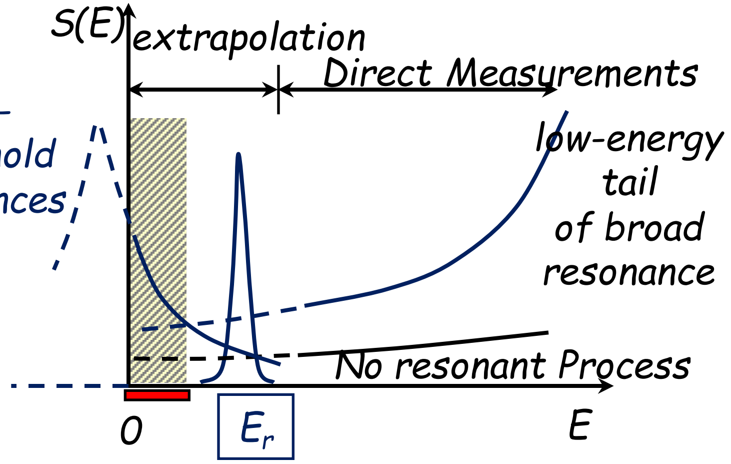
Since the cross-section varies of several orders of magnitude, the extrapolation procedure can be quite complicate

Astrophysical S(E)-factor is introduced.









Astrophysical energies

(Gamow region)

$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

Possible solutions to improve the signal/noise ratio:

Increase the number of detected particle

4 π detectors

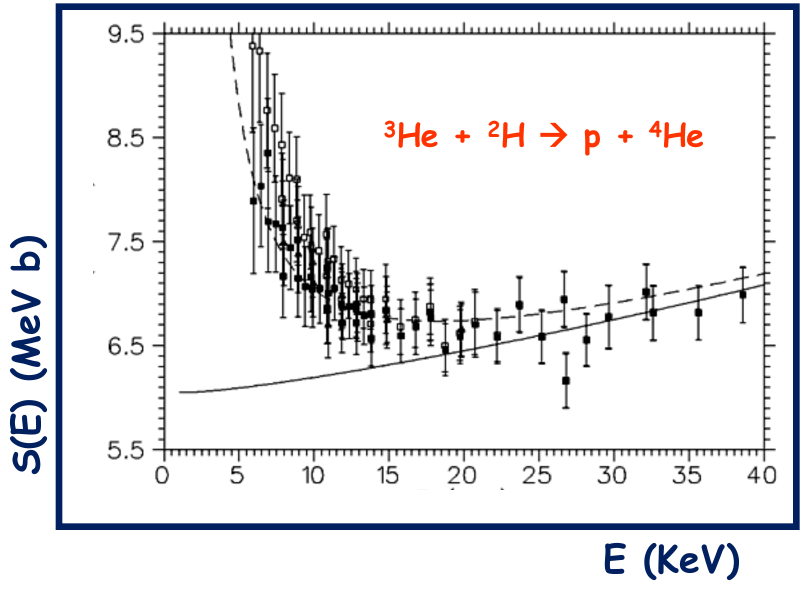
High beam intensity

Reduce the background

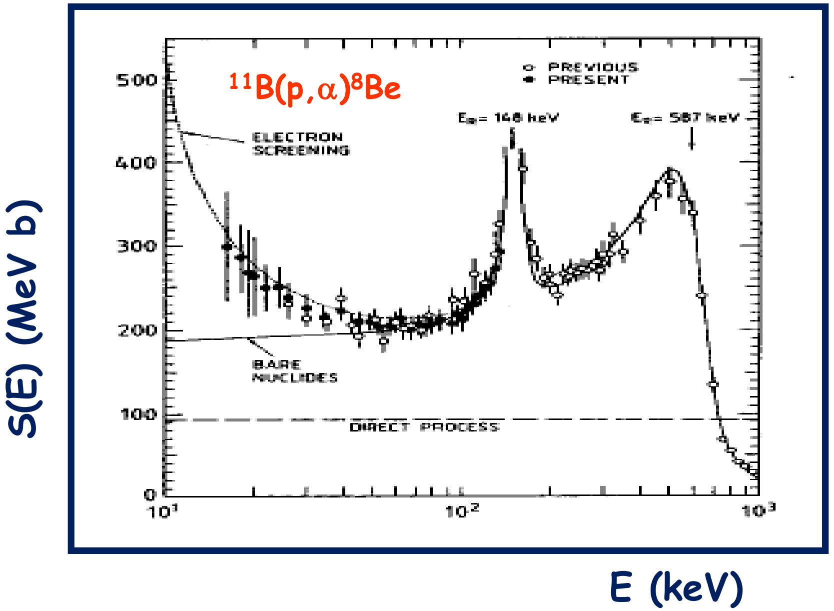
Underground laboratories

Evidences of electron screening

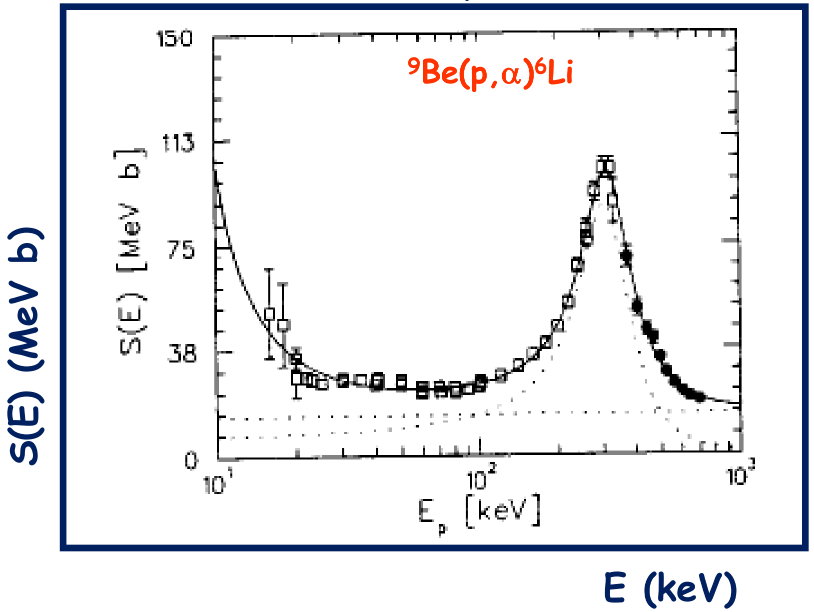
R.Bonetti et al: Phys. Rev. Lett.82,(1999),5205

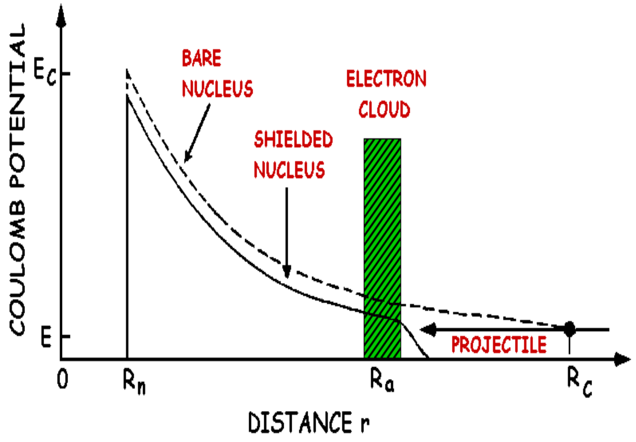


H.W. Becker et al., Z. Phys. A 327 (1987)341



D. Zahnow et al., Z. Phys. A 359(1997)211





electron screening

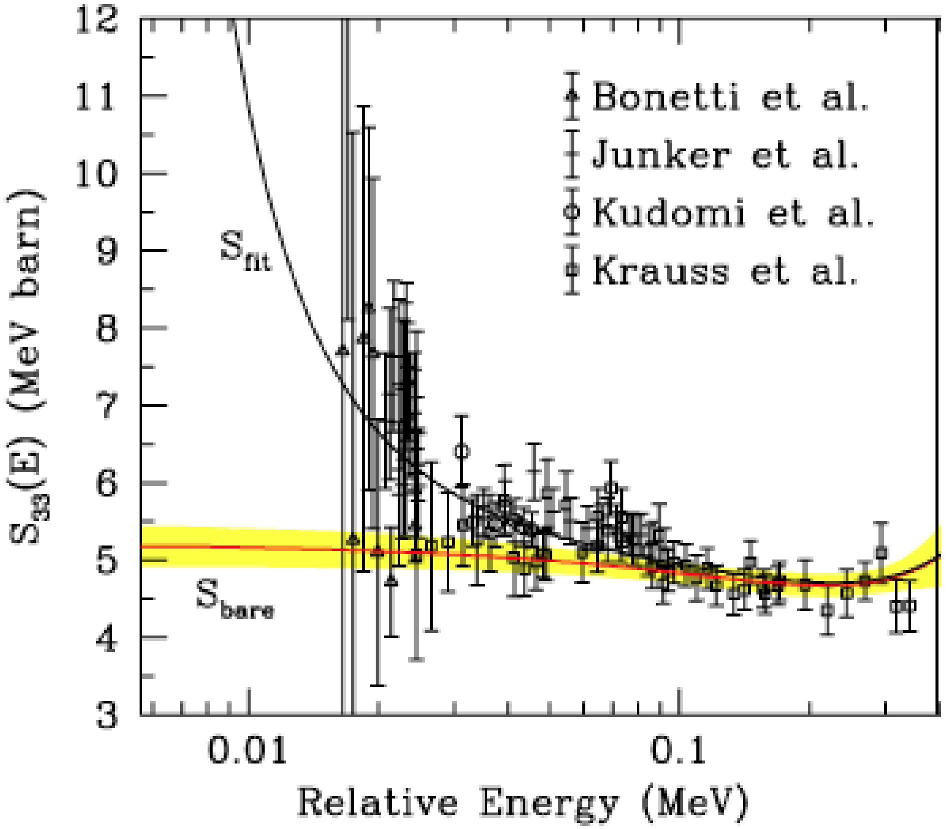
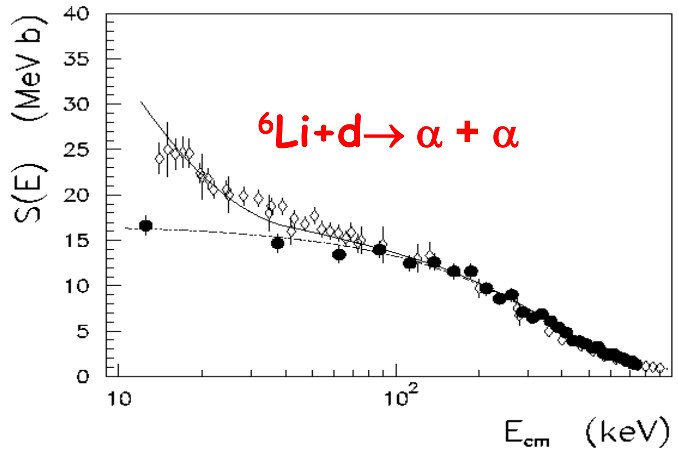


FIG. 4 (color online). The data, the best quadratic + screening result for $S_{33}(E)$, and the deduced best quadratic fit (line) and allowed range (band) for $S_{33}^{\rm bare}$. See text for references.

E.G.Adelberger , C.S. et al.. Review of Modern Physics 83, 195 (2011)

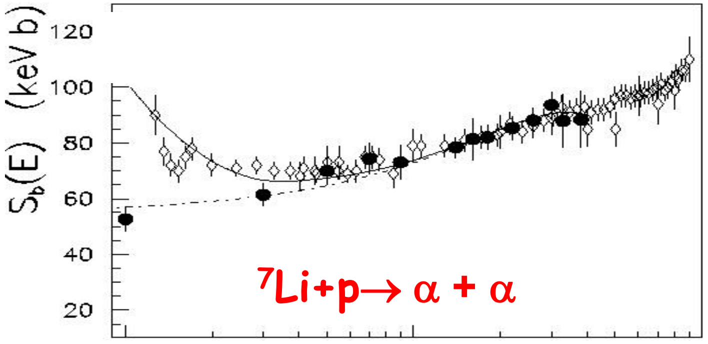
$^6Li + d \rightarrow \alpha + \alpha$ $S_0 = 16.9$ MeV b

U_e (ad)		U_e (Dir) ^6Li+d
186 eV		330 ± 120 eV



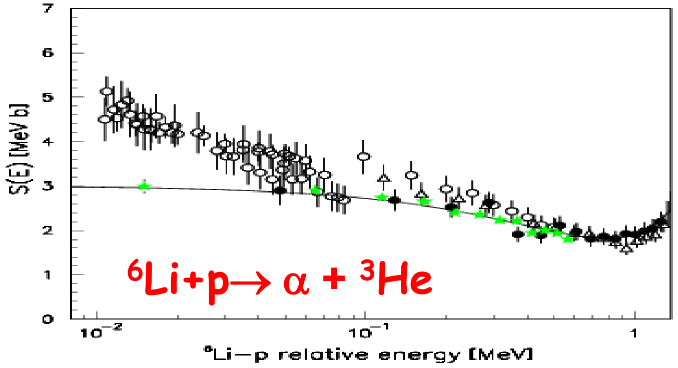
$^7Li + p \rightarrow \alpha + \alpha$ $S_0 = 55 \pm 3$ keV b

U_e (ad)		U_e (Dir) ^7Li+p
186 eV		300 ± 160 eV

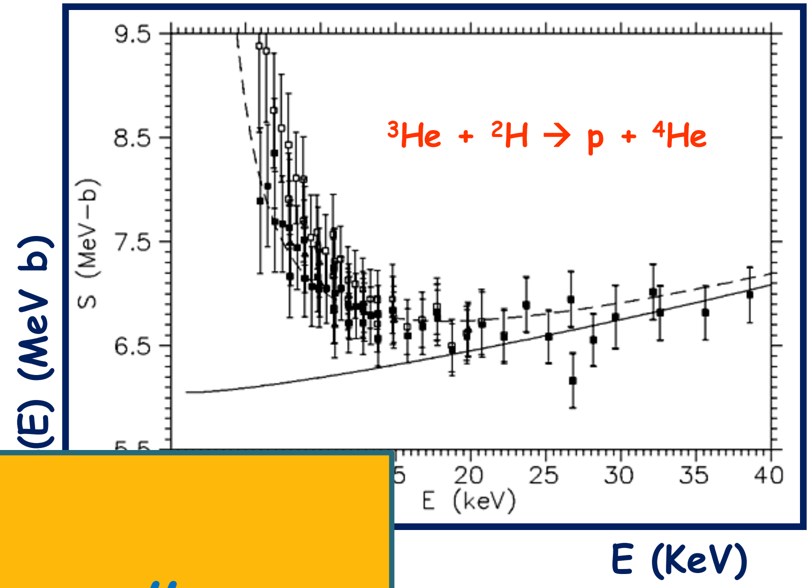


^6Li+p $\alpha + ^3He$ So = 3 ± 0.9 MeVb

U_e (ad)		U_e(Dir) ^6Li+p
186 eV		440 ± 80 eV



$$f_{lab}(E) = \frac{S_s(E)}{S_b(E)} \approx \exp\left(\pi\eta \frac{U_e}{E}\right) \geq 1$$

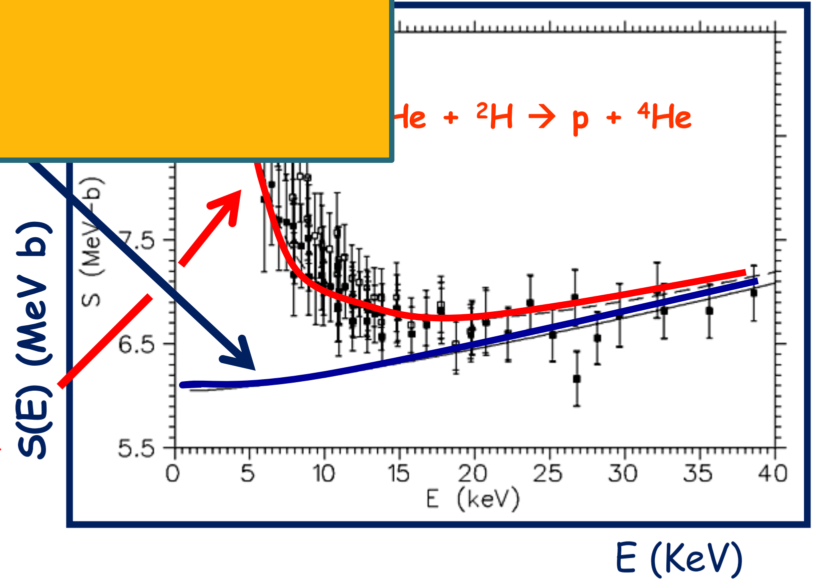


The extrapolation is still needed!

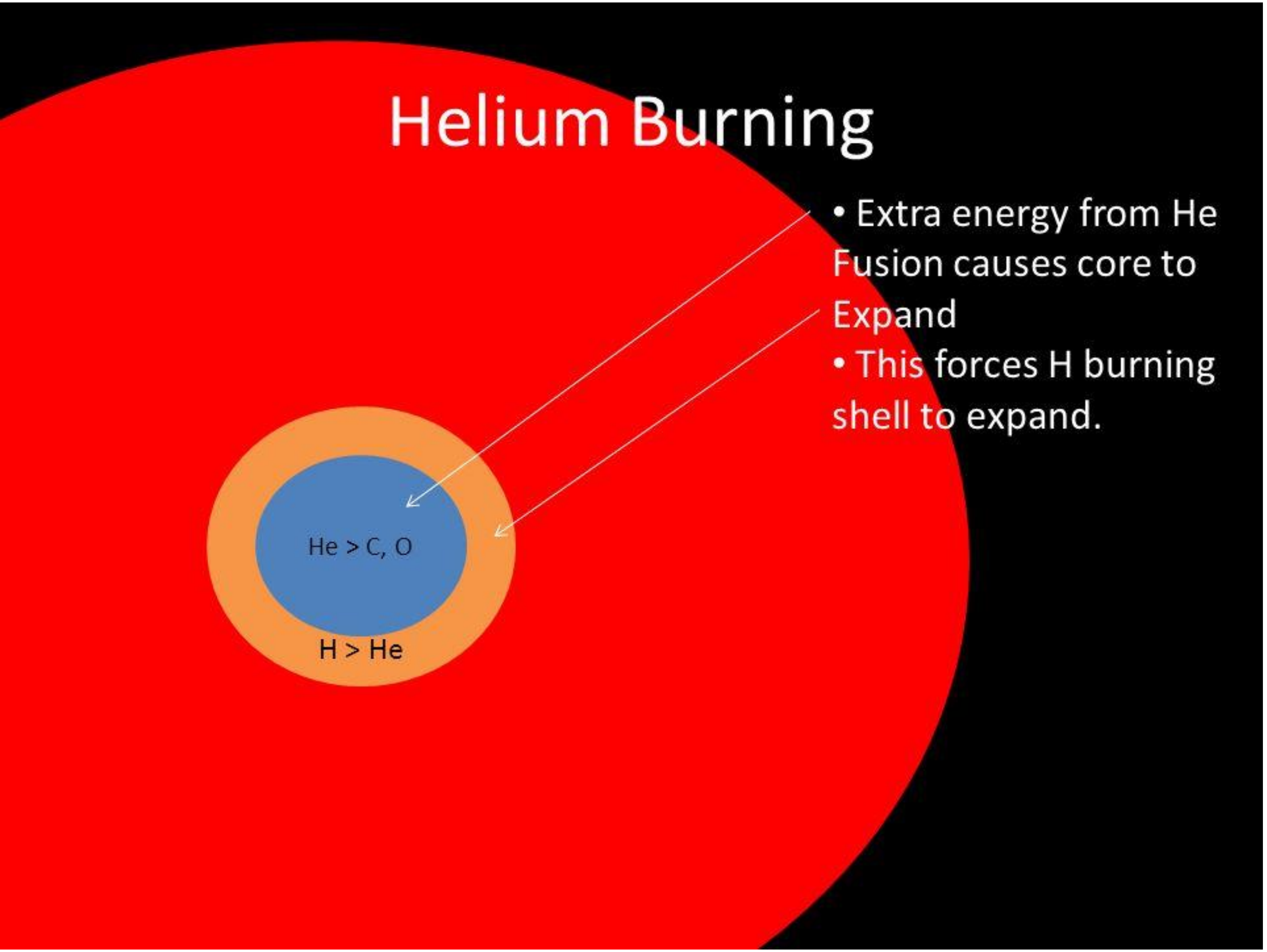
b

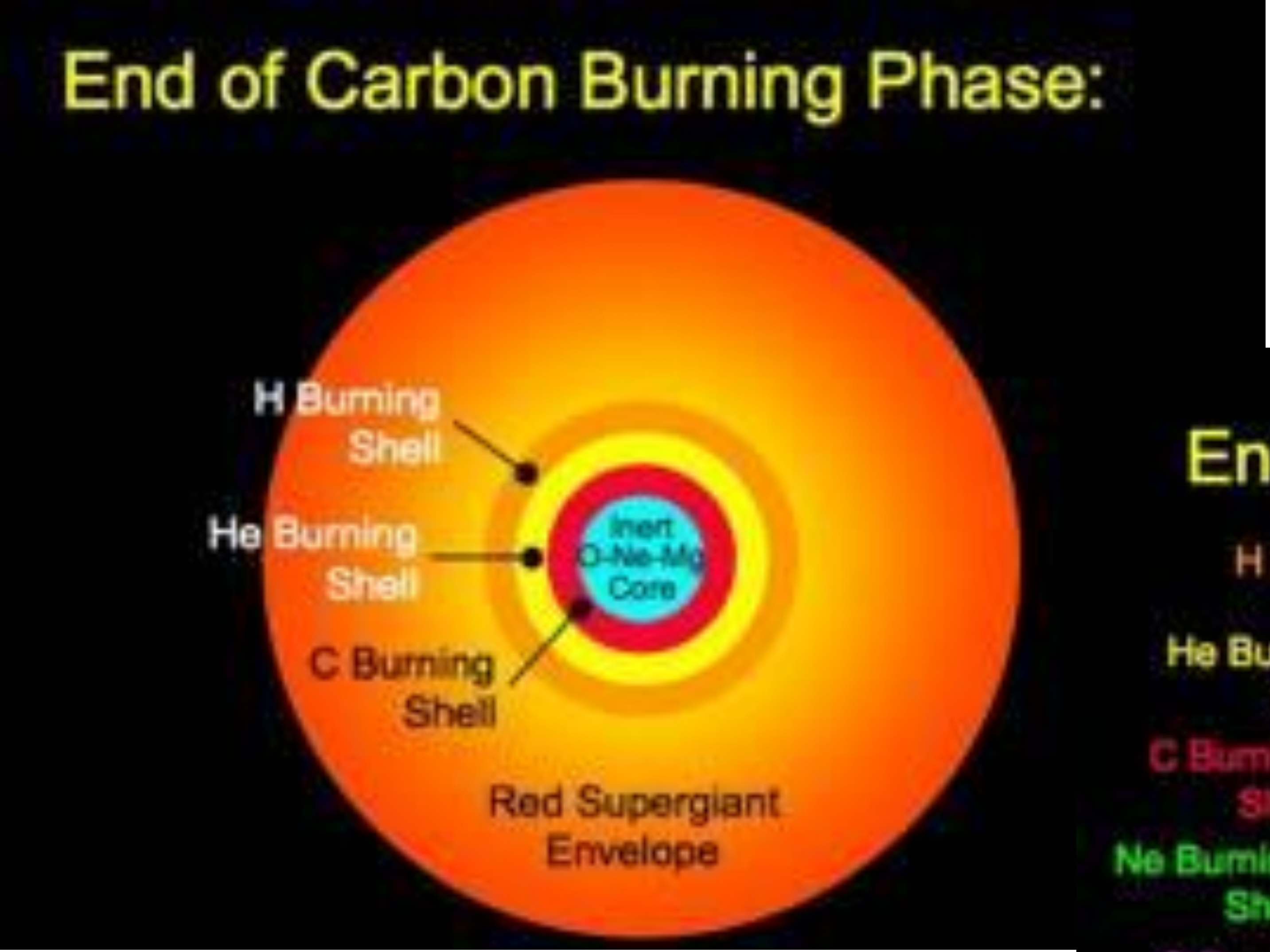
$$U_e = \frac{E}{\pi\eta} \ln \frac{S_b(E)}{S_S(E)}$$

Directly measured



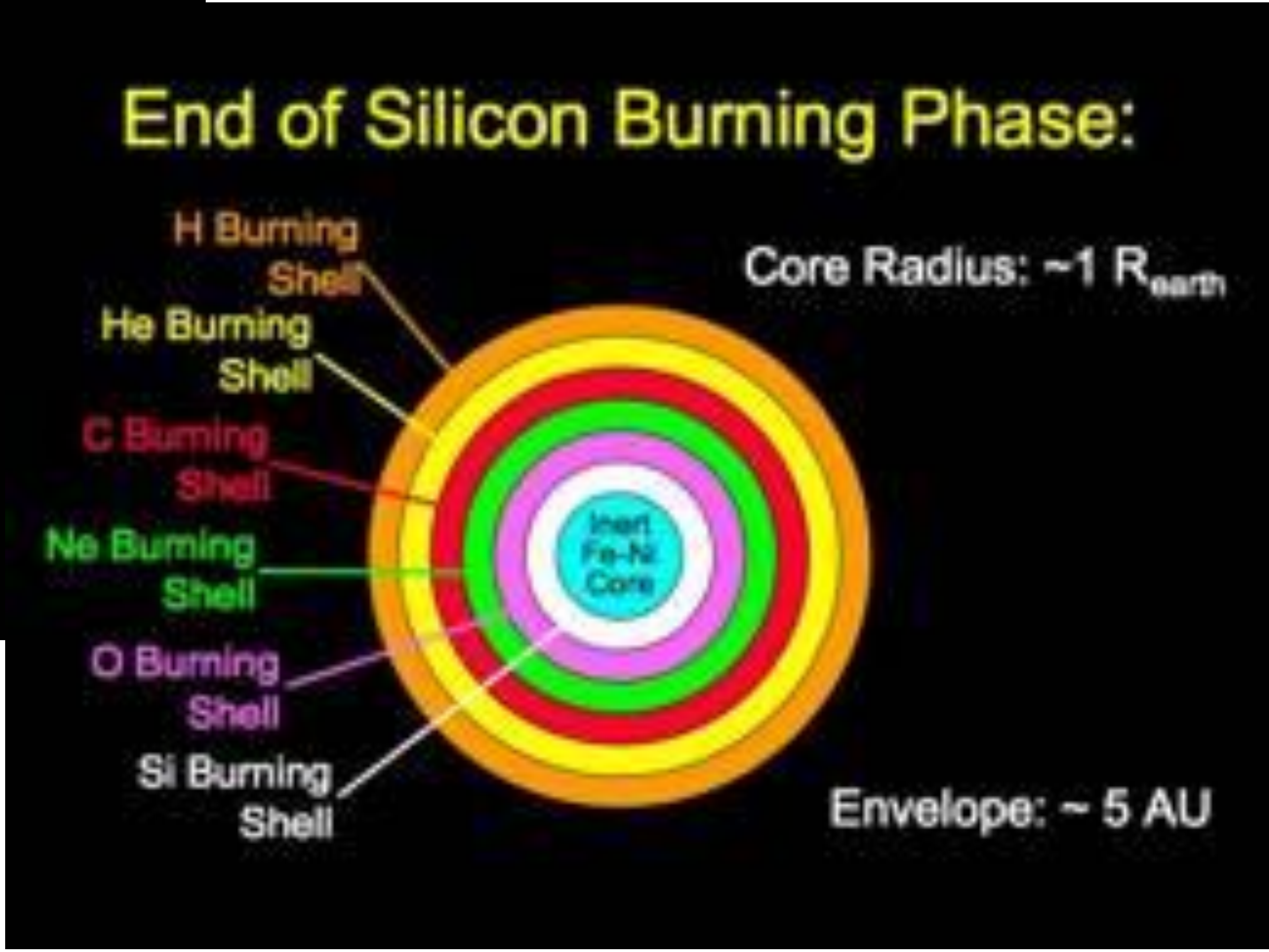
End of He-burning

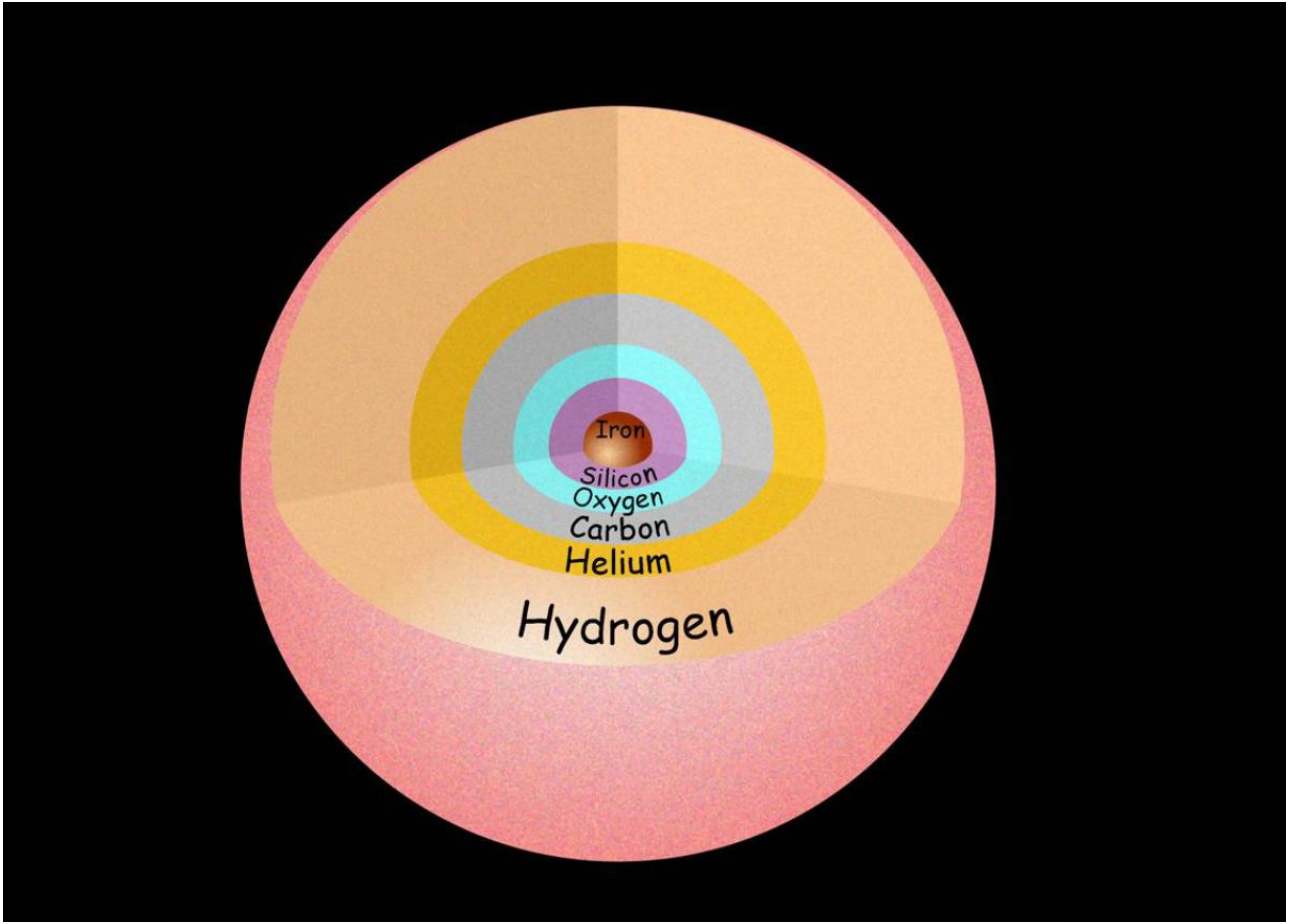


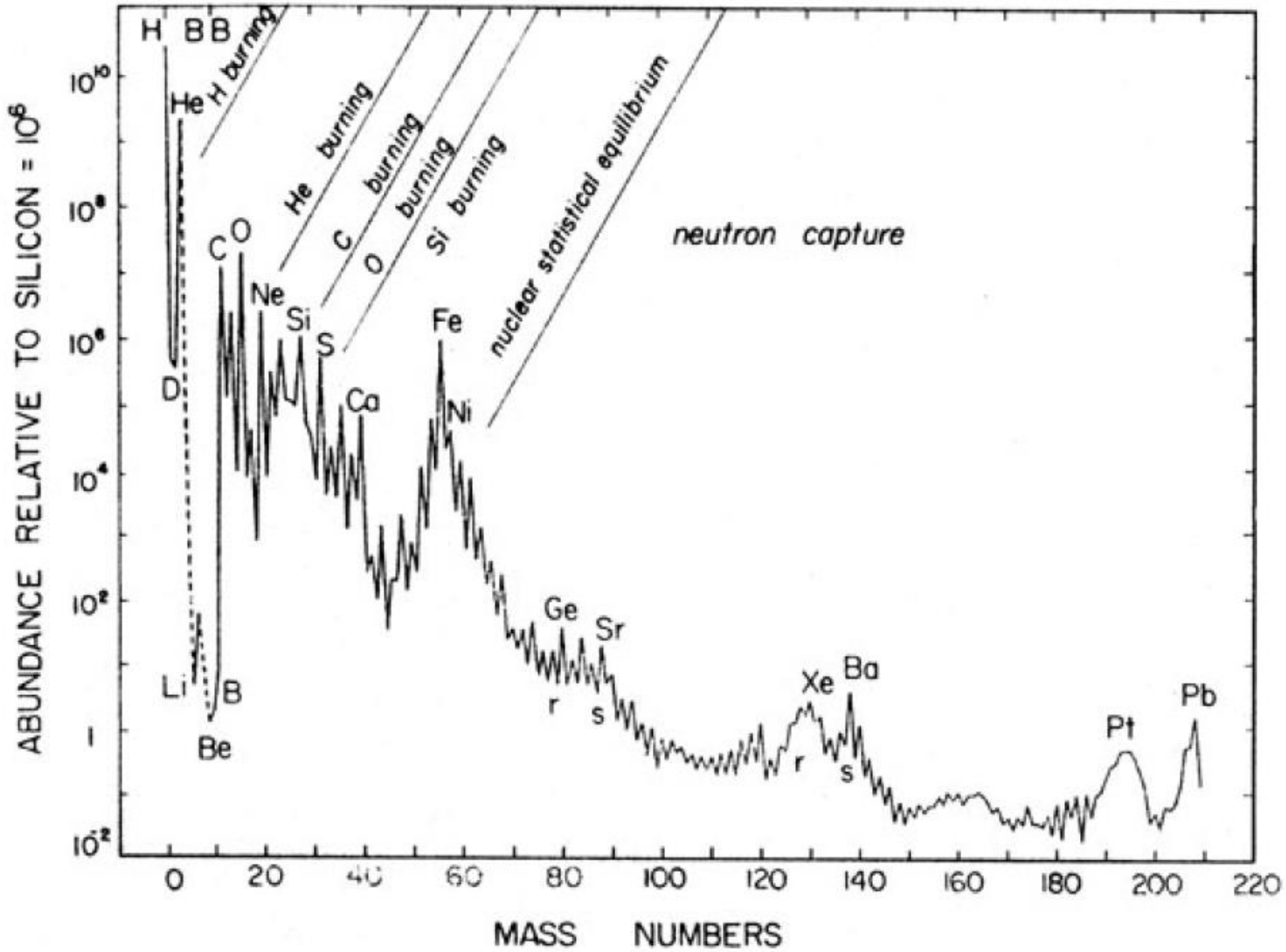


Start: $M > 8\ M_{\odot}$

Start: 2.7-3.5 billion Kelvin (GK)




Iron
Silicon
Oxygen
Carbon
Helium
Hydrogen



Going beyond the Iron Peak

BUILDING THE HEAVY ELEMENTS