ASTROFÍSICA EN EL LABORATORIO

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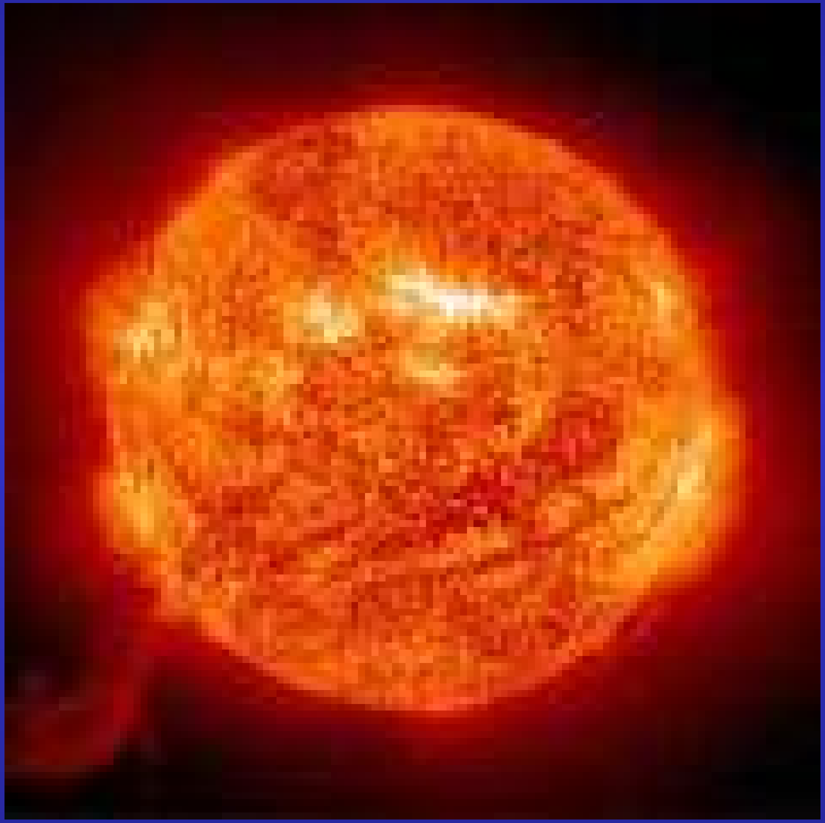
Noviembre 2008

Energía del Sol y las estrellas



El Sol.

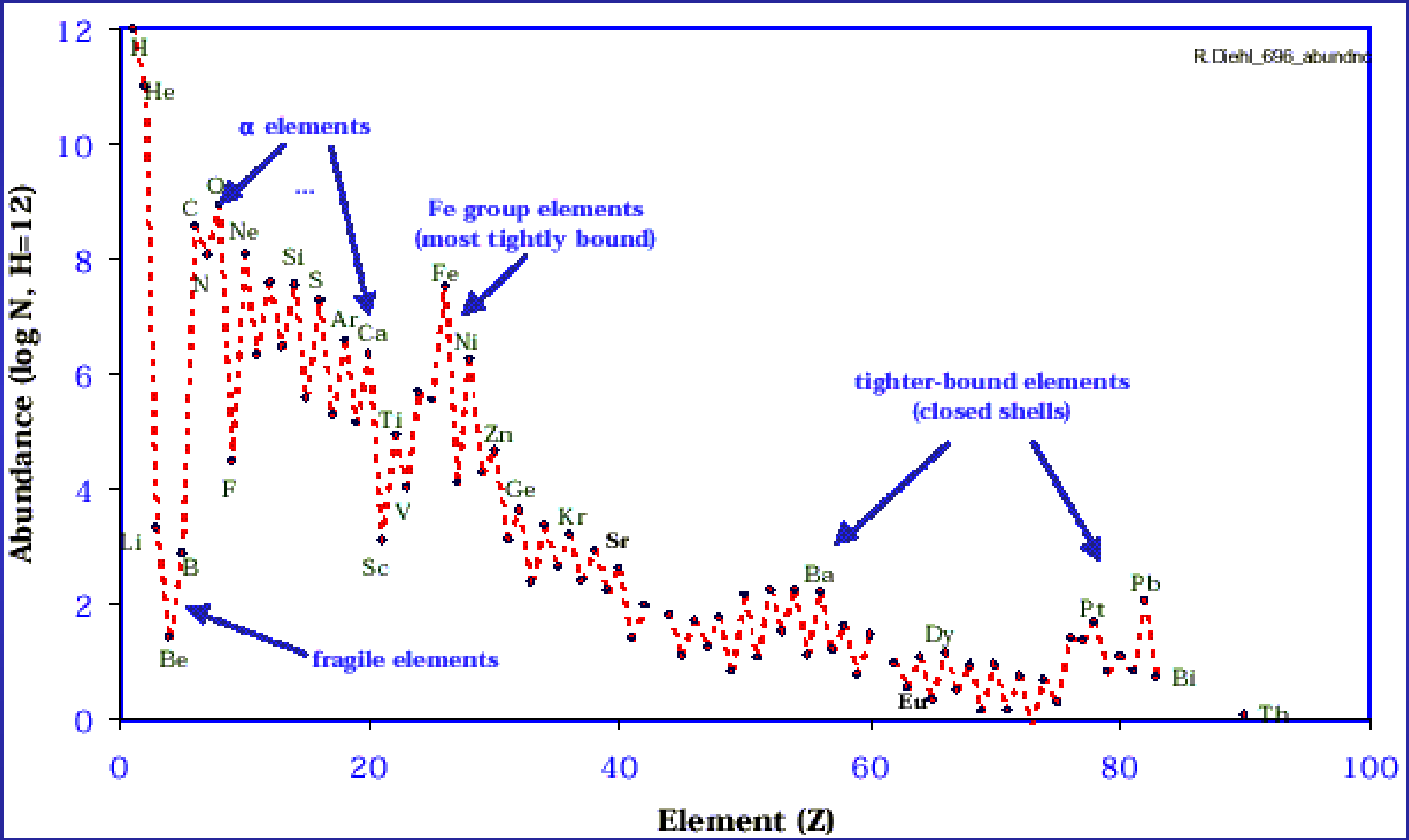
$M_{\odot} = 2 \times 10^{33}$ g $= 10^{57}$ átomos H

$P_{\odot} = 4 \times 10^{26}$ W $= 2 \times 10^{39}$ MeVs^{-1}

¿Energía química? ⟹ $T^{\odot}_{1/2} \sim 10^{5}$ años

¿Energía gravitatoria? ⟹ $T^{\odot}_{1/2} \sim 10^{7}$ años

Abundancia de elementos en el Sistema Solar



Abundancia $\propto$ energía de ligadura (defecto de masa) nuclear

Energía nuclear

- **Rutherford (Cavendish, 1919):**

primera reacción nuclear observada $\alpha + {}^{14}\mathrm{N} \rightarrow \mathrm{p} + \mathrm{X}$

reacciones nucleares →

- **generación de energía**
- **transmutación de elementos**

- **Eddington (Gales, 1920):**

> ***"What is possible in the Cavendish Laboratory may not be too difficult in the sun"***

<u>1948:</u> 1ra conexión entre la física nuclear y la astronomía

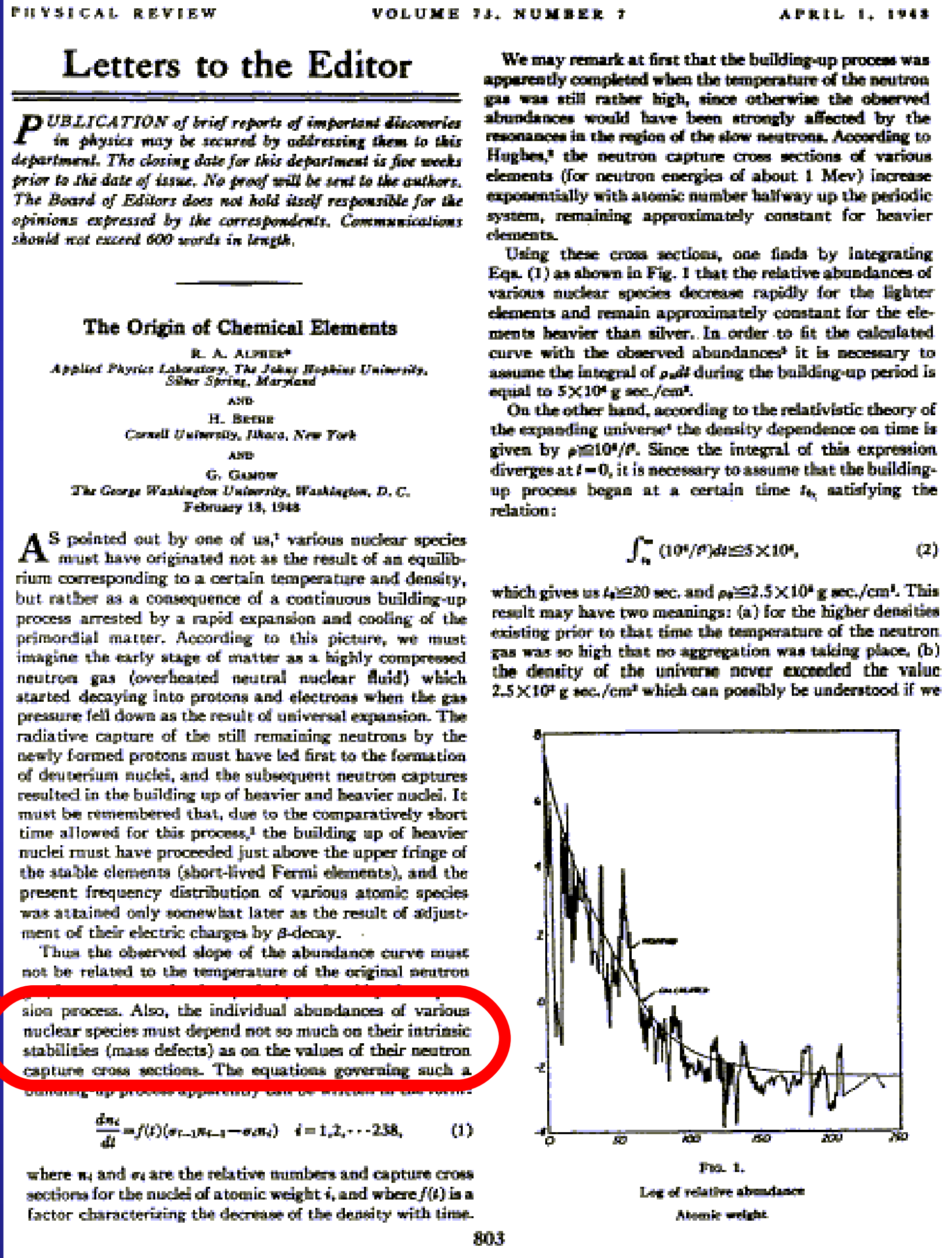
R.A. Alpher,

H. Bethe &

G. Gamow:

"The individual abundances of various nuclear species must depend not so much on the values of their intrinsic stabilities (mass defects) as on the values of their ***neutron capture cross sections****."*

$$n + {}^{A}X \rightarrow {}^{A+1}X \rightarrow {}^{A+1}Y$$



PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

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AND
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Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.

February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[2] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron

sion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt} = f(t)(\sigma_{i-1}n_{i-1} - \sigma_i n_i) \qquad i = 1, 2, \cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[3] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[4] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[5] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression diverges at $t = 0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty} (10^6/t^2)\,dt \cong 5\times10^4, \qquad (2)$$

which gives us $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5\times10^3$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^3 g sec./cm^3 which can possibly be understood if we

FIG. 1.

Log of relative abundance

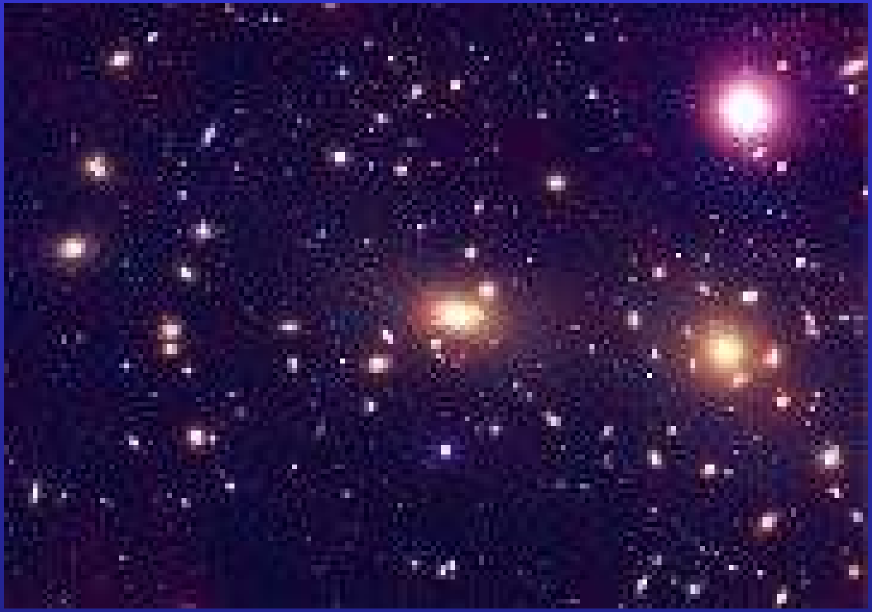
Atomic weight

803

ASTROFÍSICA NUCLEAR

Astronomía:

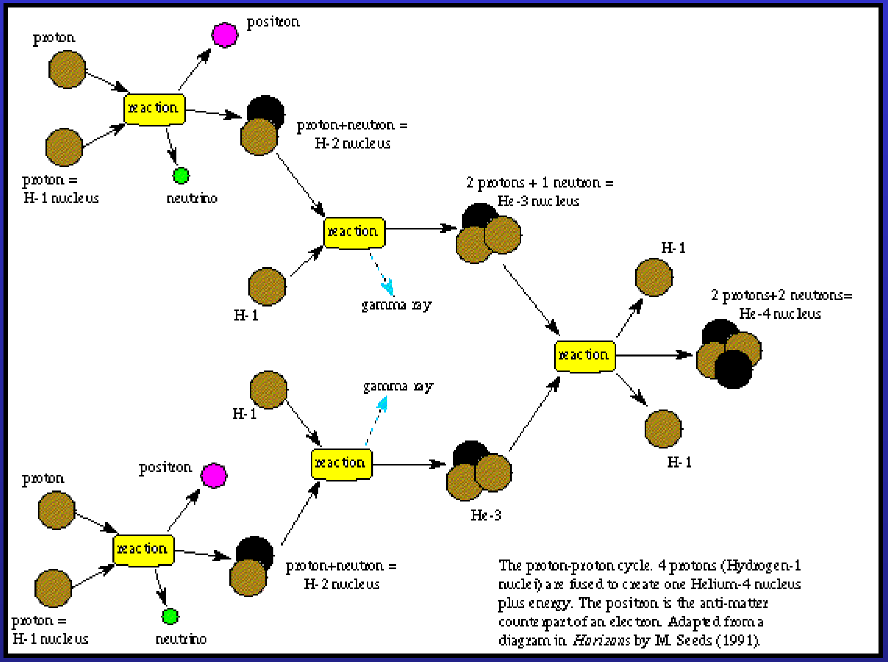
- más antigua de las ciencias:
  primeras observaciones en Egipto
  y América central ~ **4000 a.C.**
- mayor de las escalas:
  cúmulo de galaxias ~ **10^{24} m**



Cúmulo de galaxias Coma. Cada punto es una galaxia.

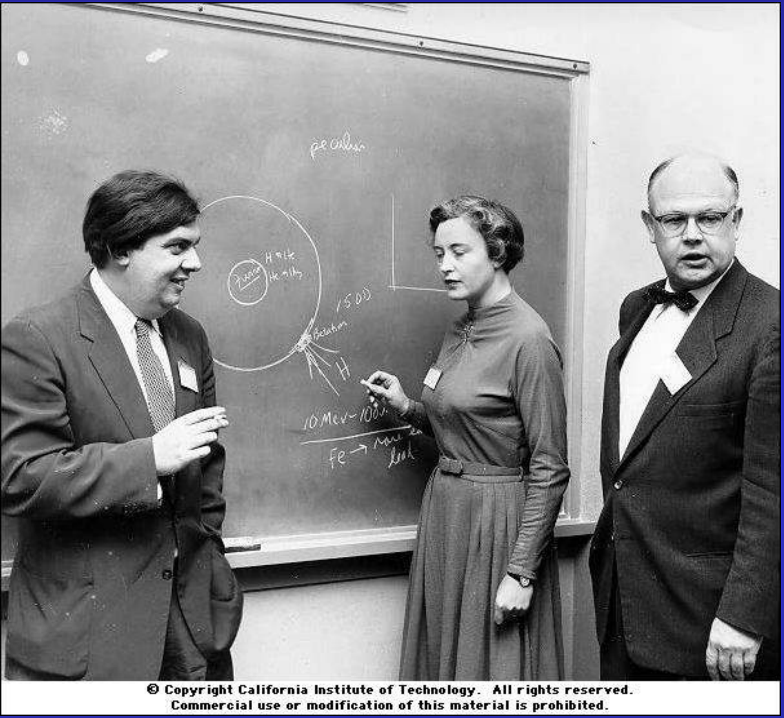
Física nuclear:

- más reciente de las ciencias:
  secciones eficaces de reacción
  siglo XX
- menor de las escalas:
  partículas ~ **10^{-15} m**



The proton-proton cycle. 4 protons (Hydrogen-1 nuclei) are fused to create one Helium-4 nucleus plus energy. The positron is the anti-matter counterpart of an electron. Adapted from a diagram in *Horizons* by M. Seeds (1991).

Primer modelo de la nucleosíntesis estelar



Geoffrey R. Burbidge, E. Margaret Burbidge y William A. Fowler

**E.M. Burbidge, G.R. Burbidge,
W.A. Fowler, F. Hoyle**

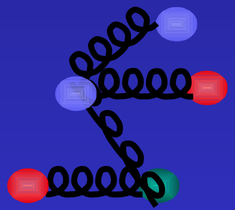
“Synthesis of the Elements in Stars”

Review of Modern Physics
Volume 29, Number 4, October (1957) p. 547-650.

Nucleosíntesis primordial

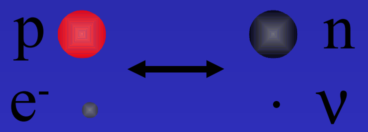
$t = 0$

$0 < t < 10^{-6}$ s
Plasma q-g



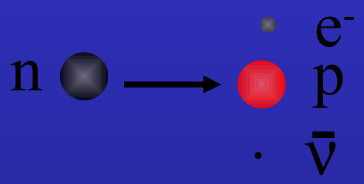
$T > 10^{12}$ K
$E > 100$ MeV
$\rho \sim 10^{15}$ g/cm^3

$t \sim 10^{-2}$ s
equilibrio p-n



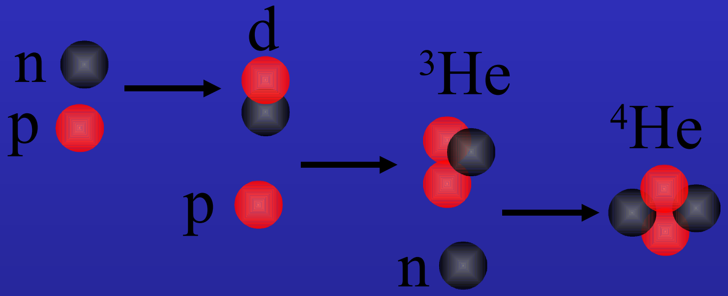
$T \sim 10^{11}$ K
$E \sim 10$ MeV
$\rho \sim 10^{11}$ g/cm^3

$t \sim 1$ s
decaimiento n



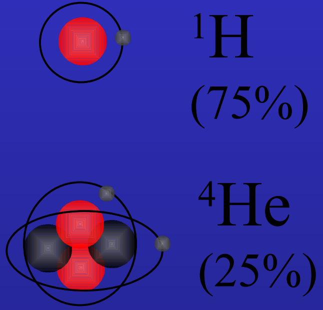
$T \sim 10^{10}$ K
$E \sim 1$ MeV
$\rho \sim 10^{5}$ g/cm^3

$t \sim 10^{2}$ s
nucleosíntesis



$T \sim 10^{9}$ K
$E \sim 0{,}1$ MeV
$\rho \sim 10^{5}$ g/cm^3

$t \sim 10^{10}$ años
actualidad



$T \sim 3$ K
$E \sim 0{,}25$ meV
$\rho \sim 10^{-29}$ g/cm^3 ?

Resultado de la nucleosíntesis primordial

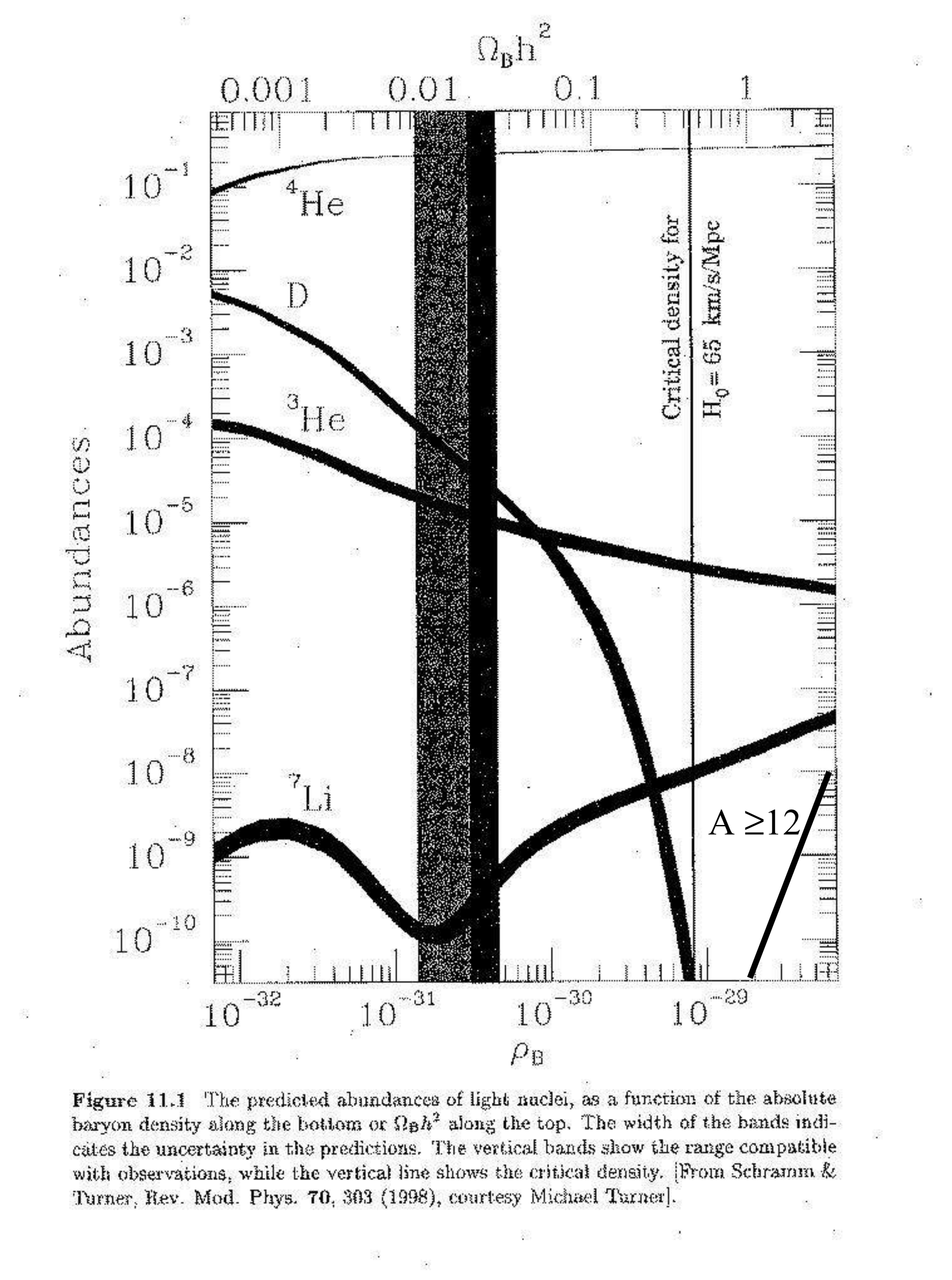


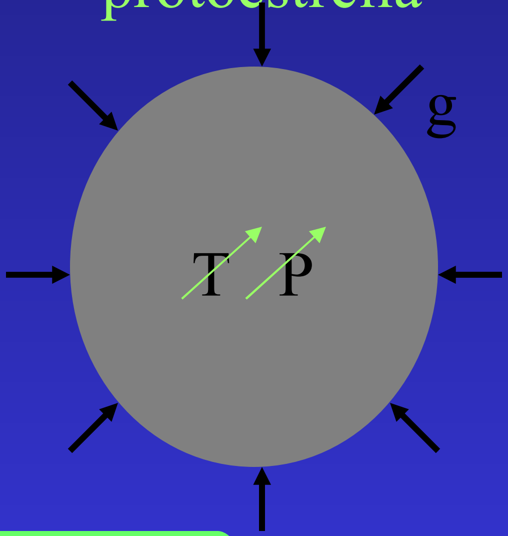
Figure 11.1 The predicted abundances of light nuclei, as a function of the absolute baryon density along the bottom or $\Omega_B h^2$ along the top. The width of the bands indicates the uncertainty in the predictions. The vertical bands show the range compatible with observations, while the vertical line shows the critical density. [From Schramm & Turner, Rev. Mod. Phys. **70**, 303 (1998), courtesy Michael Turner].

Nucleosíntesis estelar

nubes moleculares

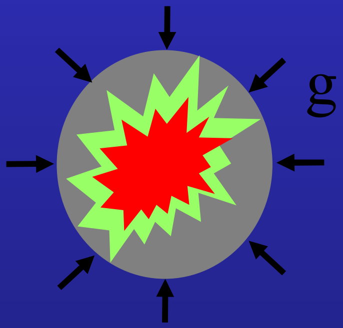
colapso gravitatorio ➡

protoestrella



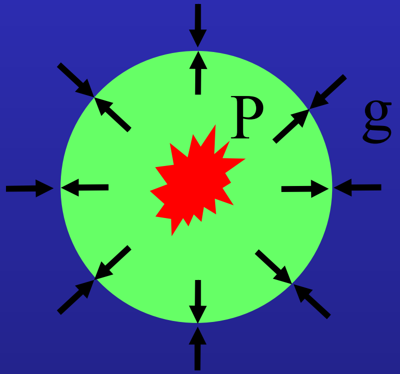
Si $M > 0{,}08\ M_\odot$ ➡ fusión de H

encendido de la combustión de hidrógeno



presión térmica ➡

combustión de hidrógeno en equilibrio hidrostático ($T \sim 10^7$ K)



Energías de la nucleosíntesis estelar

$$T \sim 10^7\ \mathrm{K} \quad \rightarrow \quad kT \sim 0{,}86\ \mathrm{keV}$$

pero

$V_{BC}(p\text{-}p) = 468\ \mathrm{keV}$!

a $T \sim 10^7$ K

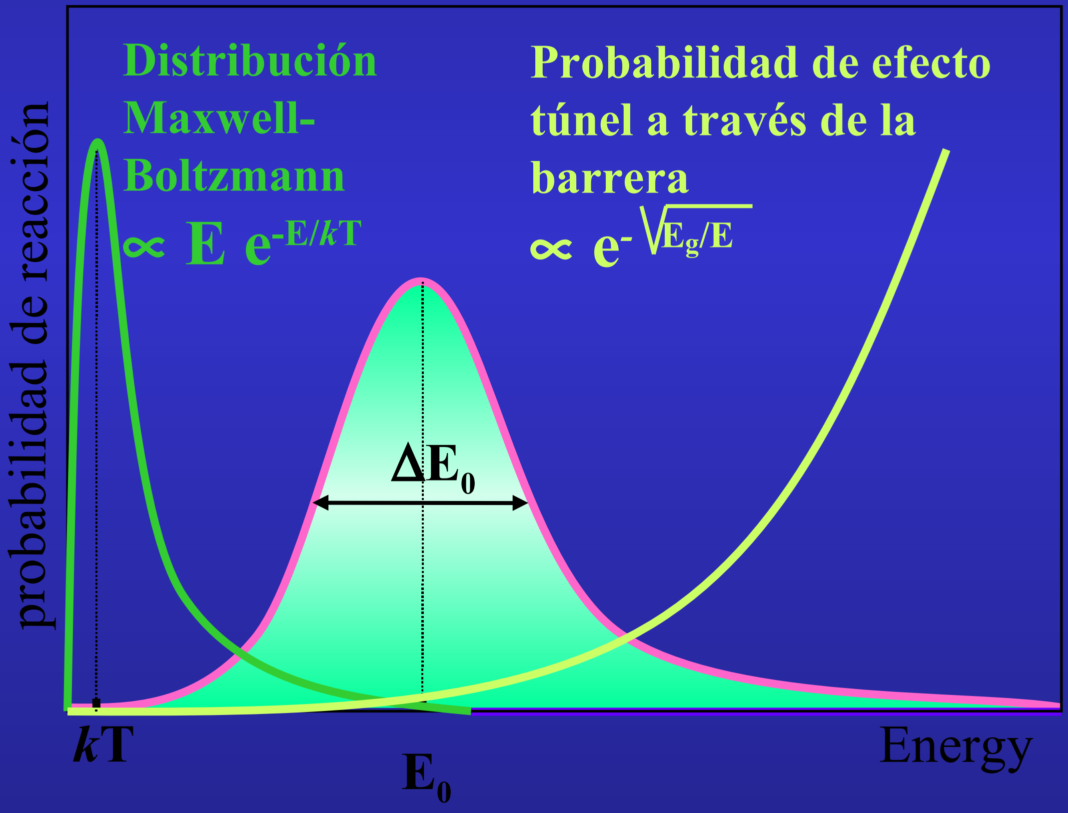
$$\frac{\phi_{MB}(468\ \mathrm{keV})}{\phi_{MB}(0{,}86\ \mathrm{keV})} \sim 10^{-233}$$

La probabilidad de hallar un protón en el sol con energía > $V_{BC}(p\text{-}p)$ es menor a 10^{-177} !!!

Fusión de H por debajo de la barrera coulombiana por efecto túnel.

Pico de Gamow

$$\text{Reaction rate}: \ N_A\langle \sigma v\rangle = N_A\sqrt{\frac{8}{\pi M_{12}(kT)^3}}\int_0^\infty \sigma(E)\, E\, e^{-E/kT}\, dE$$



$$E_0 \propto T^{2/3} \qquad \Delta$$

$$E_0 \propto T^{5/6}$$

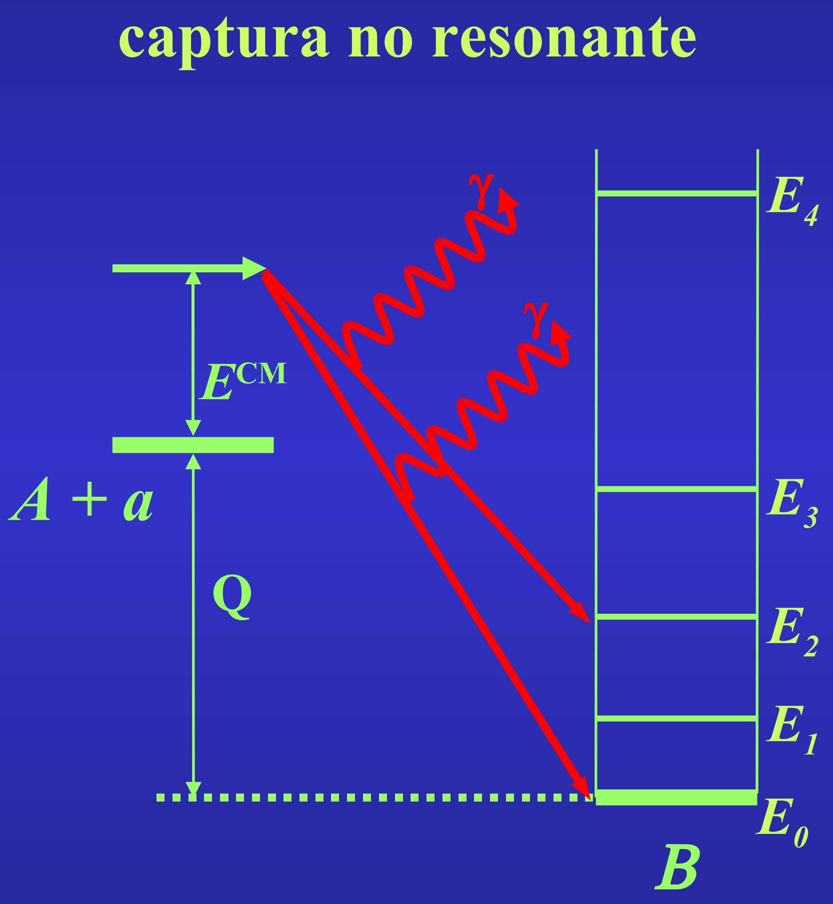
a $T_\odot$ =15 MK

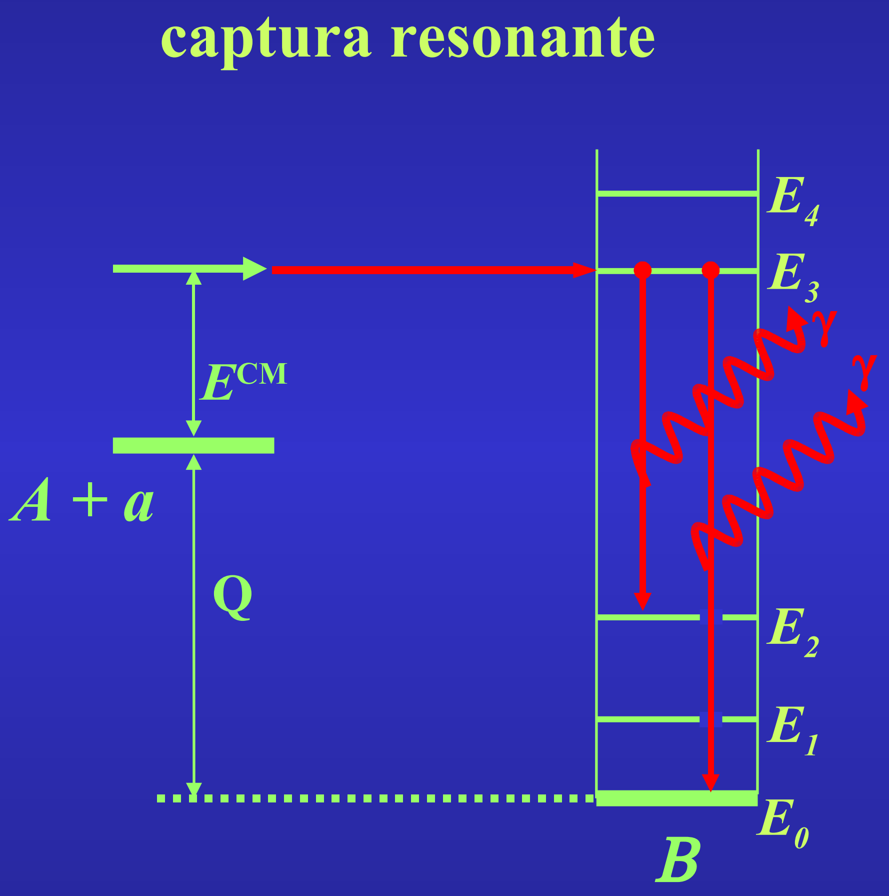
p + p E_0= 6 keV

P + ^{12}C E_0= 24 keV

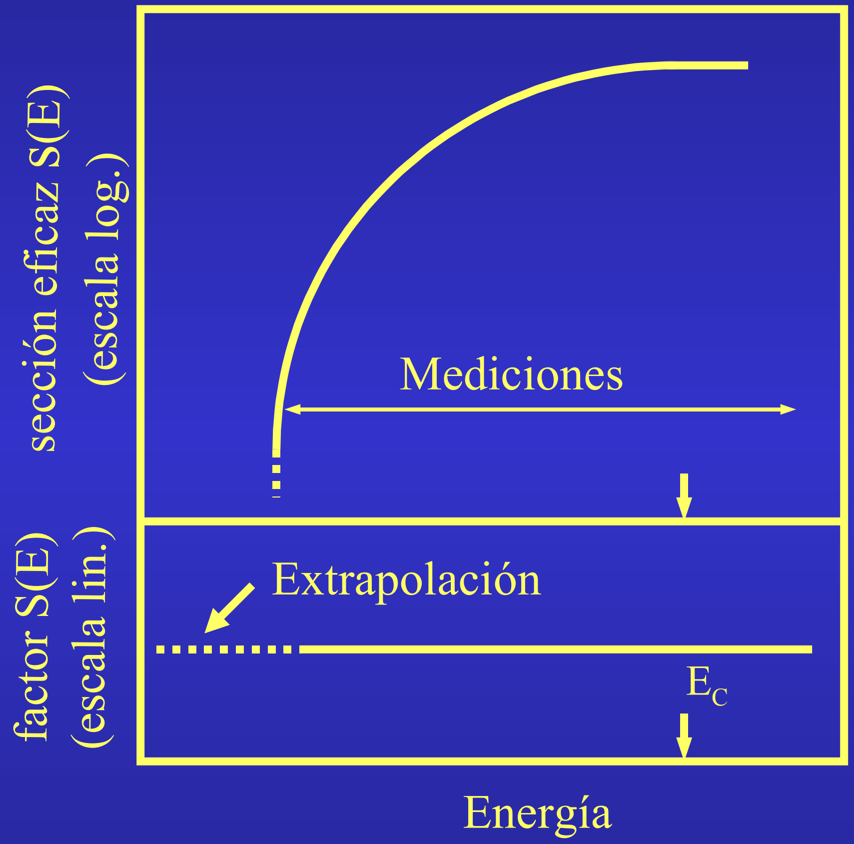
$$\sqrt{E_g/E} = 2\pi Z_1 Z_2\, e^2/\hbar v$$

Reacciones de captura


captura no resonante


captura resonante

Captura no resonante



a $E \ll E_C$

$$\sigma(E) = \pi\lambda^2 e^{-2\pi\eta} S(E)$$

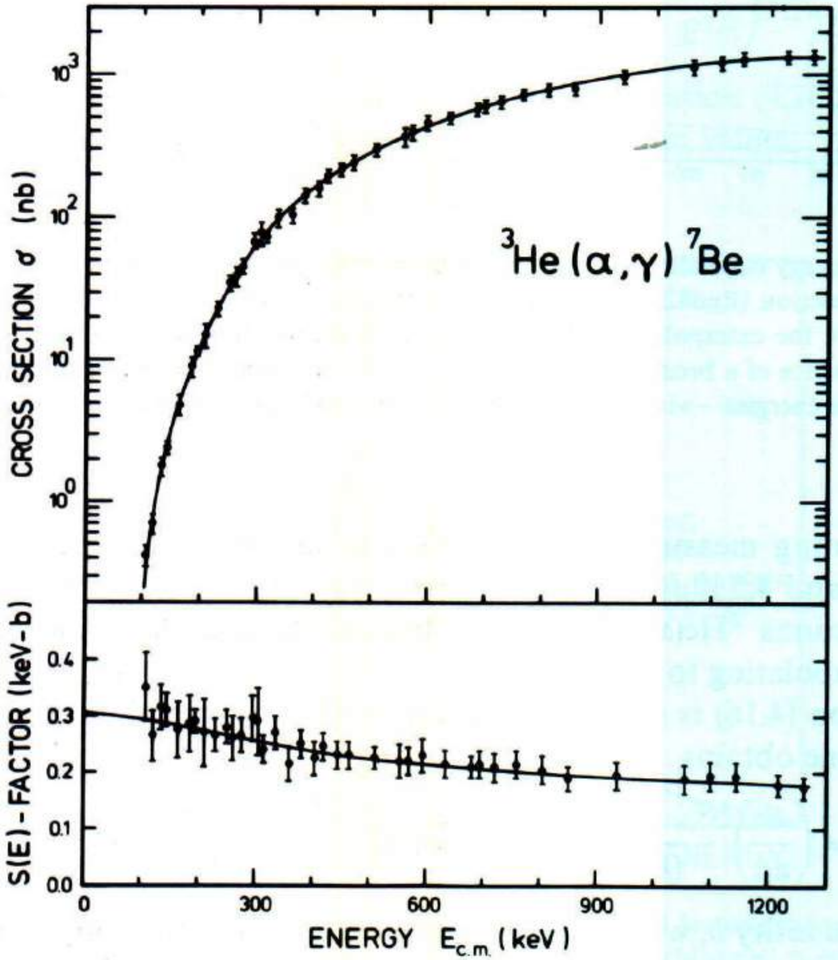
$\eta = Z_1 Z_2 e^2/(h\nu)$ es el parámetro de Sommerfeld.

S(E) es el factor astrofísico

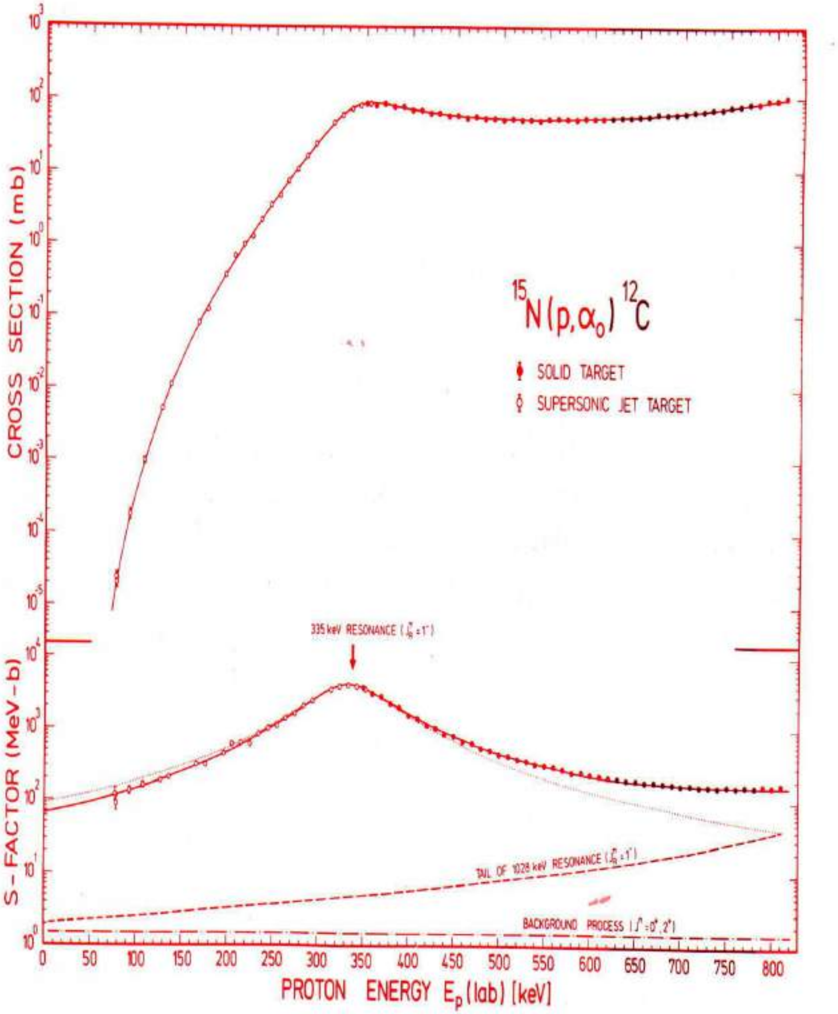
(contiene todos los factores estrictamente nucleares).

$$<\sigma v> \propto T^{(Eo/kT-2/3)}$$

Ejemplos

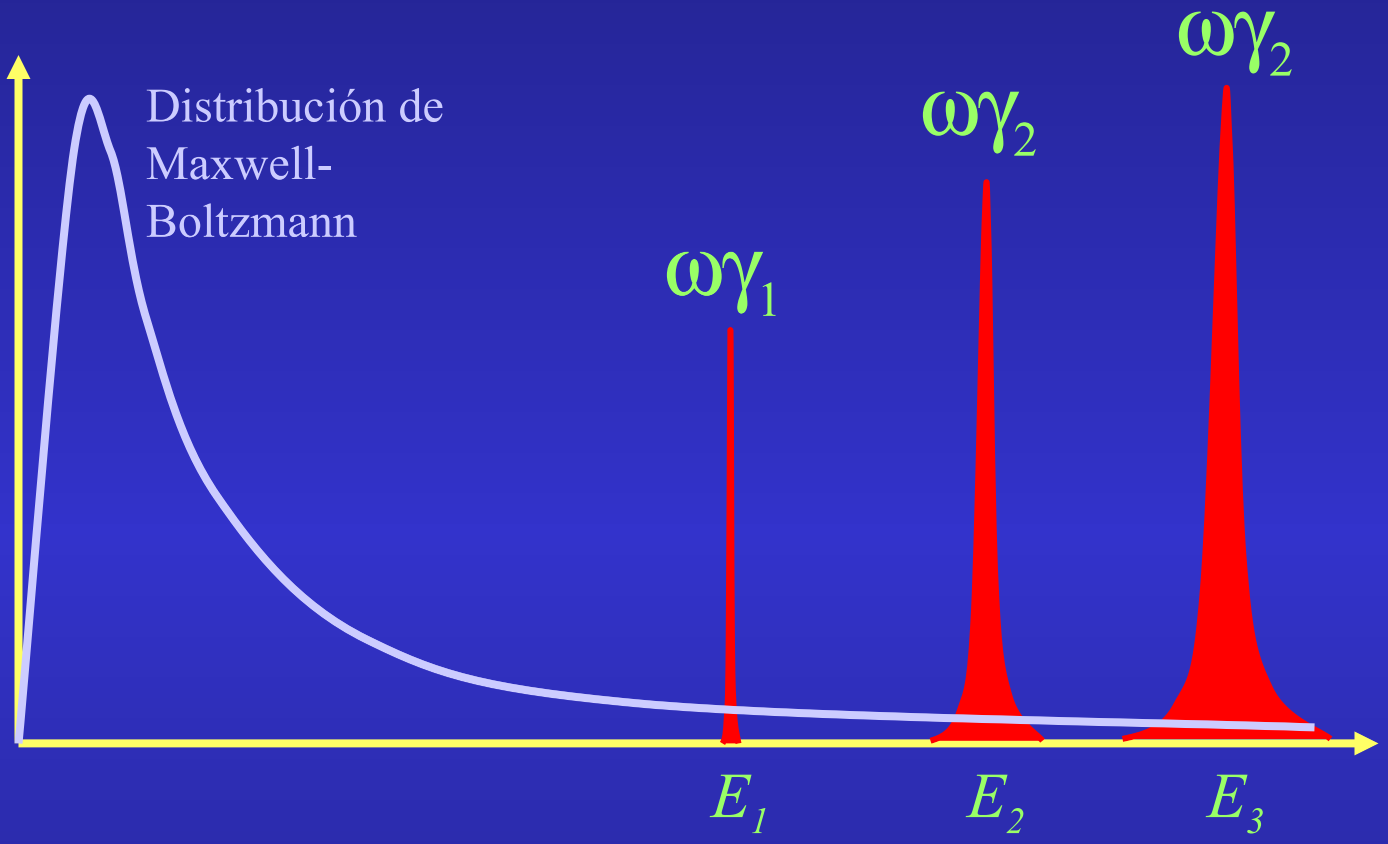


CROSS SECTION σ (nb)
10³
10²
10¹
10⁰
³He (α,γ) ⁷Be
S(E) - FACTOR (keV-b)
0.4
0.3
0.2
0.1
0.0
0
300
600
900
1200
ENERGY E c.m. (keV)



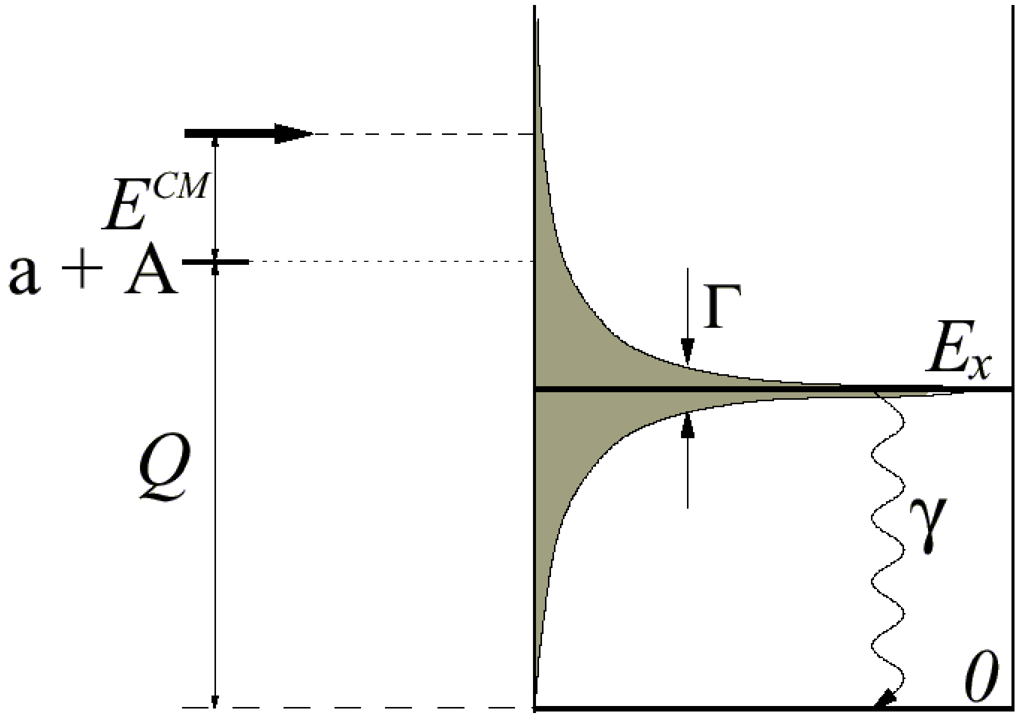
CROSS SECTION (mb)
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
¹⁵N (p,α₀) ¹²C
SOLID TARGET
SUPERSONIC JET TARGET
S - FACTOR (MeV-b)
10⁴
10³
10²
10¹
10⁰
335 keV RESONANCE (J^π = 1⁻)
TAIL OF 1028 keV RESONANCE (J^π = 1⁻)
BACKGROUND PROCESS (J^π = 0⁺, 2⁺)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
PROTON ENERGY Ep (lab) [keV]

Captura resonante



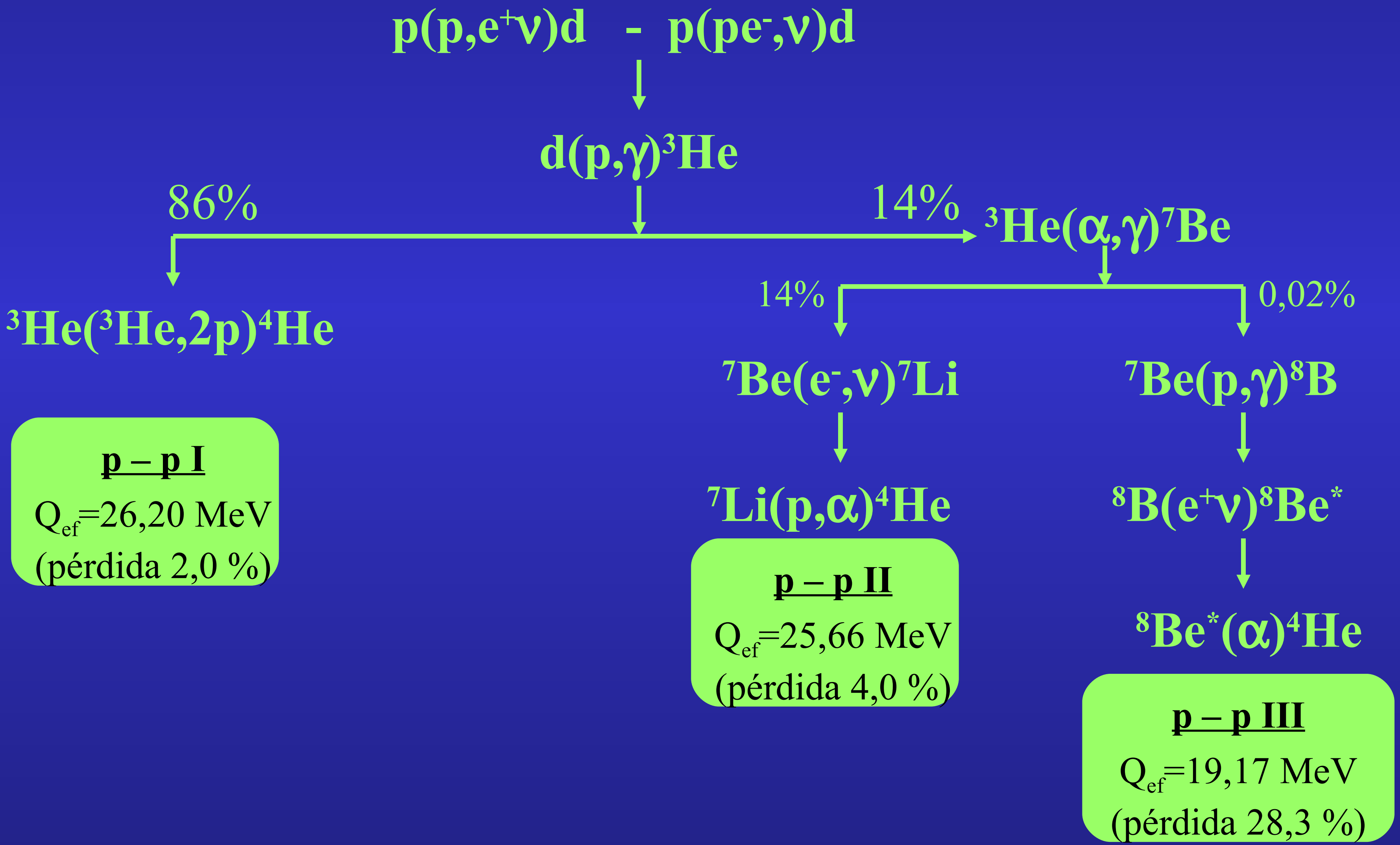
$$<\sigma v> \propto \sum \omega\gamma_i \, e^{-Ei/kT}$$

Captura resonante por debajo del umbral



Cadena protón – protón

$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu + 26{,}73\ MeV$$



$p(p,e^{+}\nu)d$ - $p(pe^{-},\nu)d$

$d(p,\gamma){}^{3}He$

86%

14%

${}^{3}He(\alpha,\gamma){}^{7}Be$

${}^{3}He({}^{3}He,2p){}^{4}He$

14%

0,02%

${}^{7}Be(e^{-},\nu){}^{7}Li$

${}^{7}Be(p,\gamma){}^{8}B$

${}^{7}Li(p,\alpha){}^{4}He$

${}^{8}B(e^{+}\nu){}^{8}Be^{*}$

${}^{8}Be^{*}(\alpha){}^{4}He$

p – p I

Q_{ef}=26,20 MeV

(pérdida 2,0 %)

p – p II

Q_{ef}=25,66 MeV

(pérdida 4,0 %)

p – p III

Q_{ef}=19,17 MeV

(pérdida 28,3 %)

Emisión de neutrinos

captura electrónica:

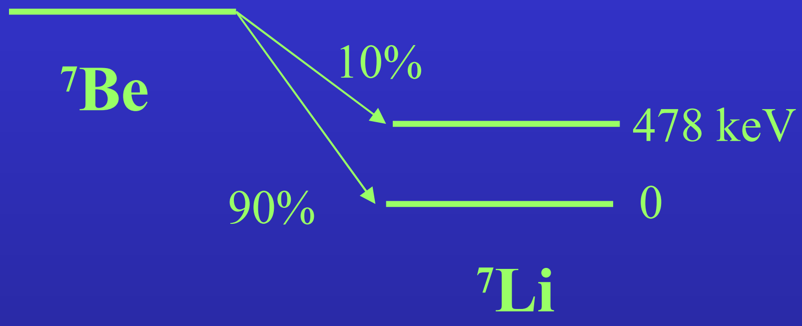
$p(pe^-,\nu)d$

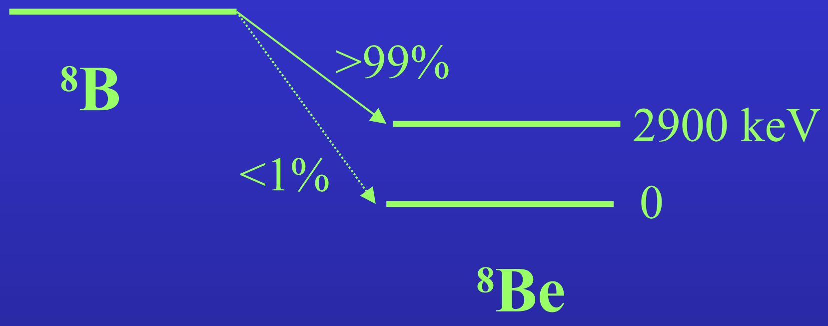
$^7Be(e^-,\nu)^7Li$

decaimiento β^+:

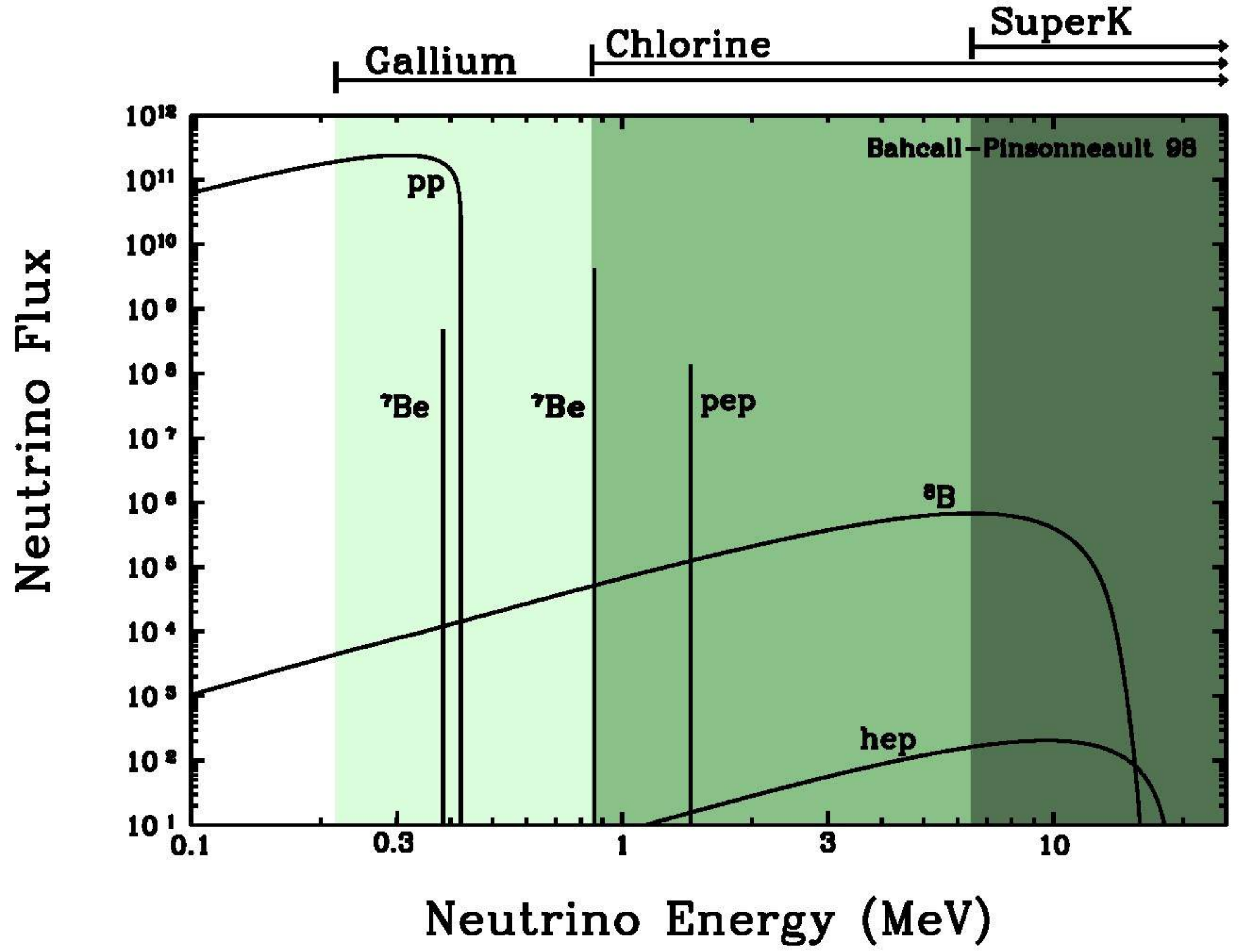
$p(p,e^+\nu)d$

$^8B(e^+\nu)^8Be^*$





Espectro de neutrinos solares



Ciclo C – N – O

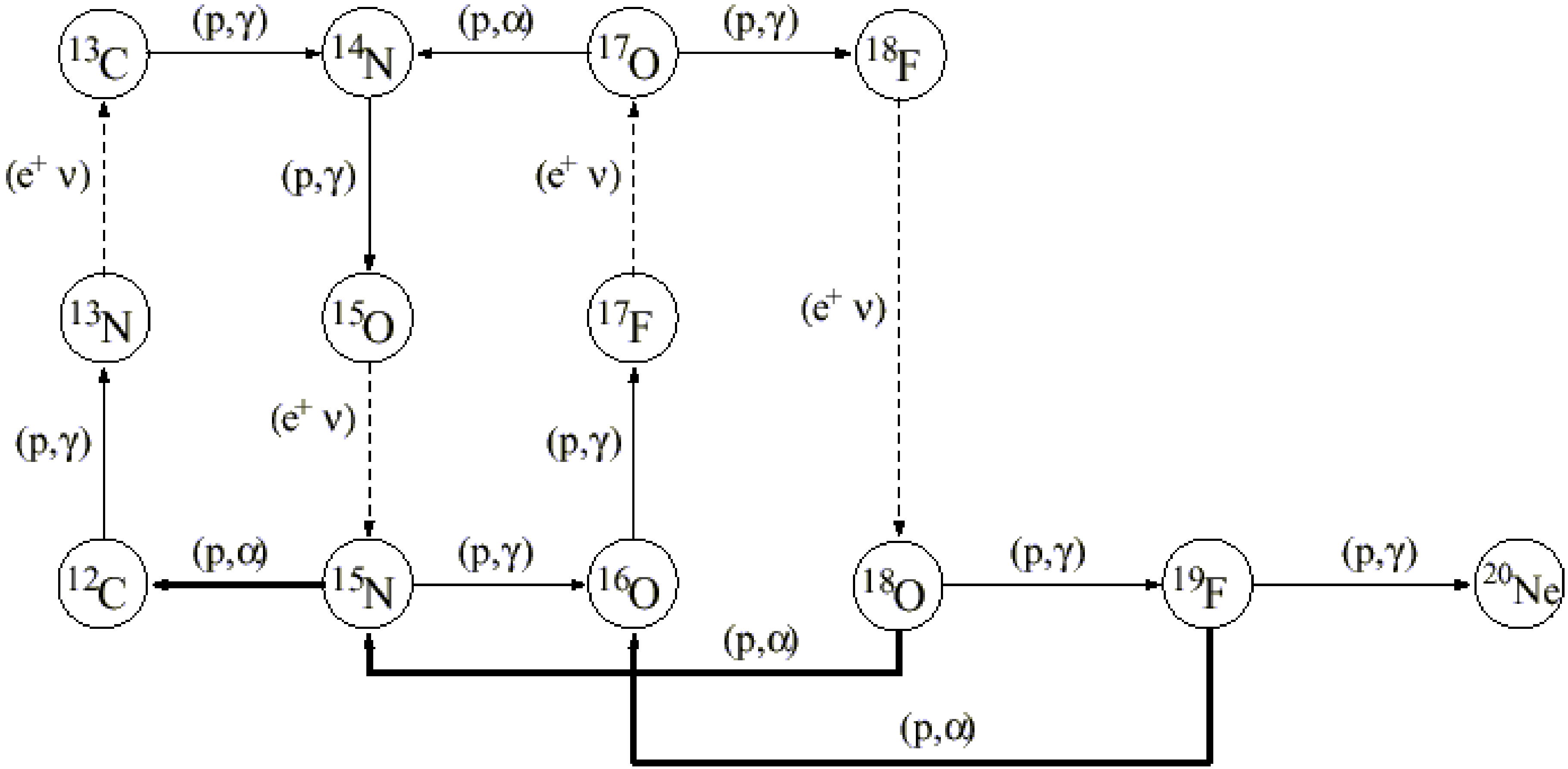

^{13}C
(p,γ)
^{14}N
(p,α)
^{17}O
(p,γ)
^{18}F
(e⁺ ν)
(p,γ)
(e⁺ ν)
^{13}N
^{15}O
^{17}F
(e⁺ ν)
(p,γ)
(e⁺ ν)
(p,γ)
^{12}C
(p,α)
^{15}N
(p,γ)
^{16}O
^{18}O
(p,γ)
^{19}F
(p,γ)
^{20}Ne
(p,α)
(p,α)

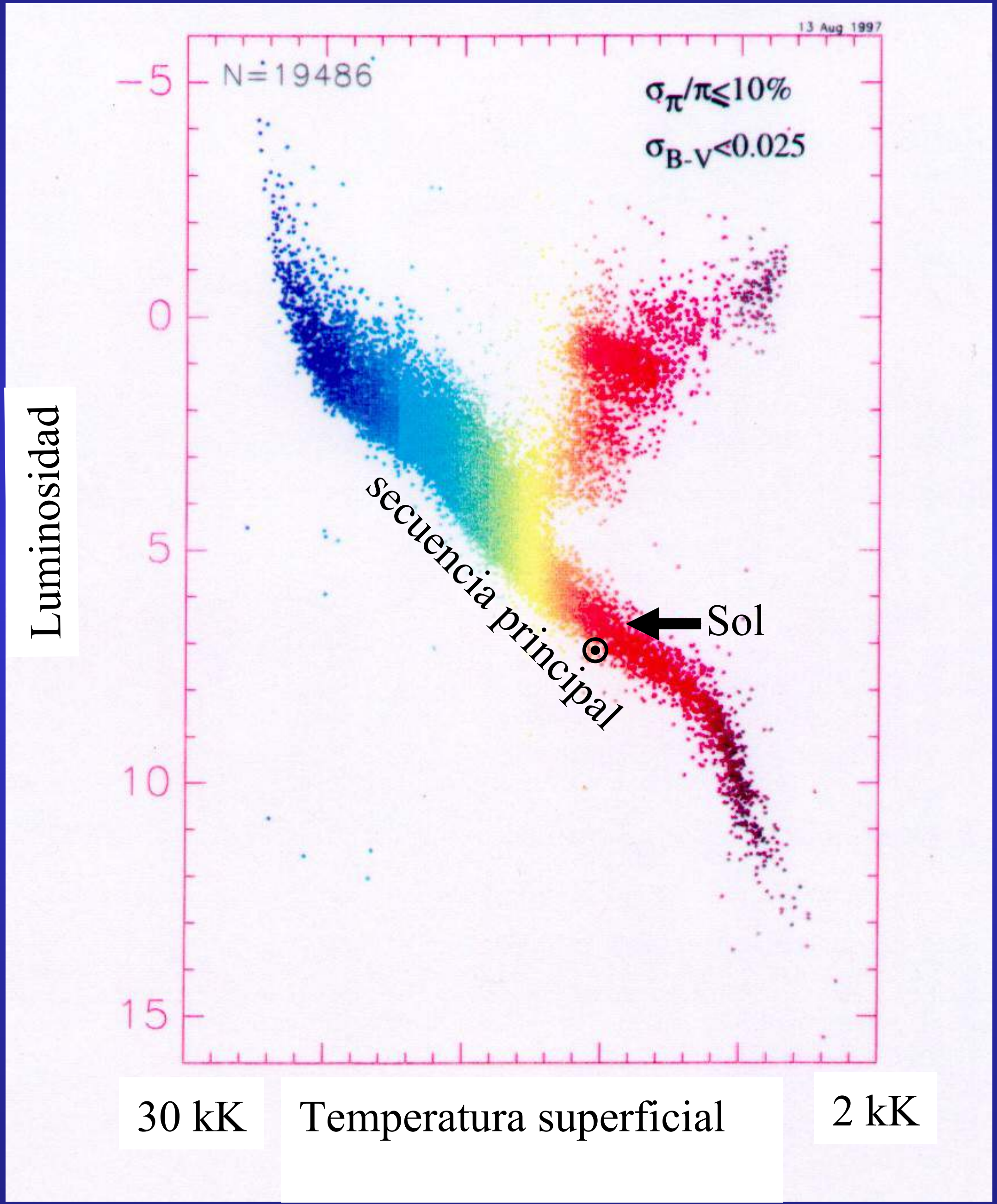
Diagrama de Hertzprung-Russell

Ley de Stefan:

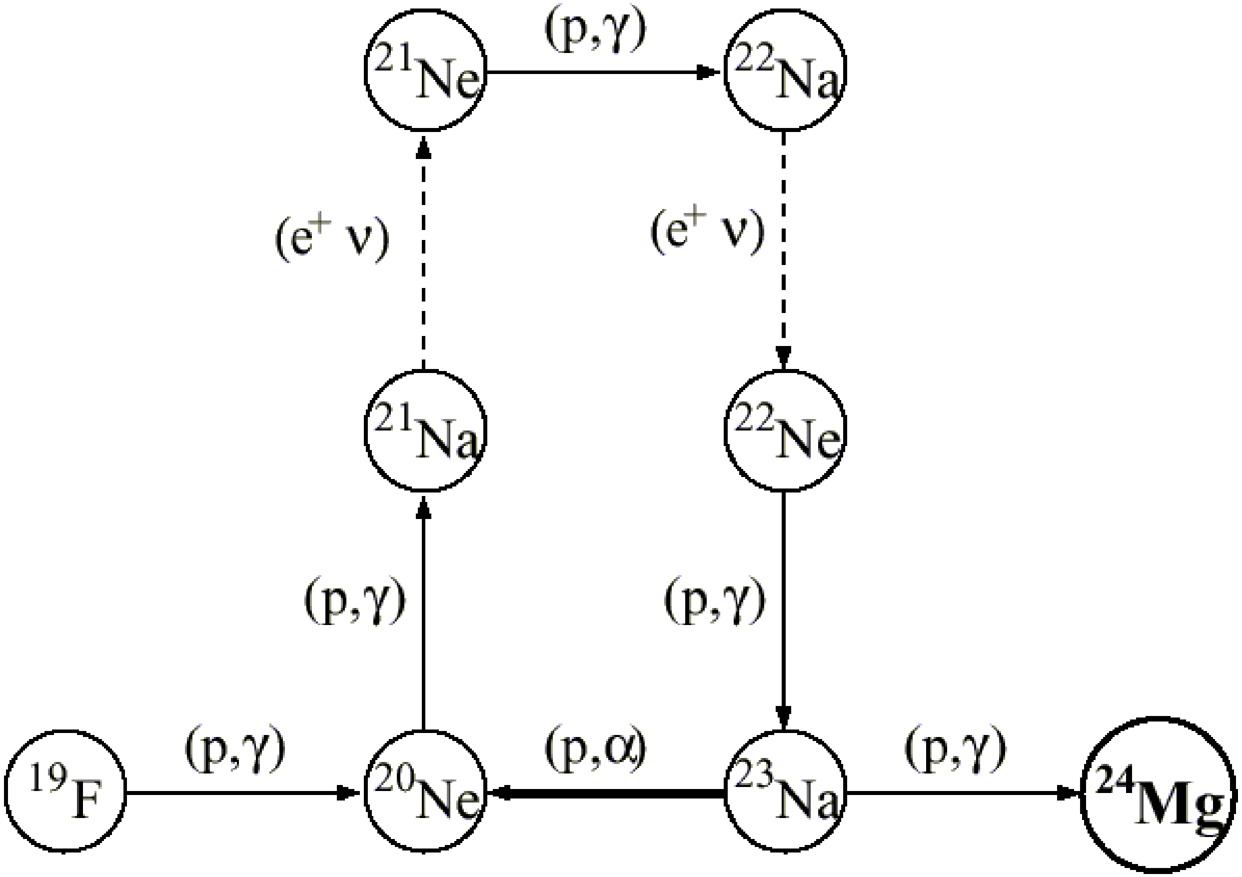
$$L=4\pi R^2\sigma T^4$$

➡

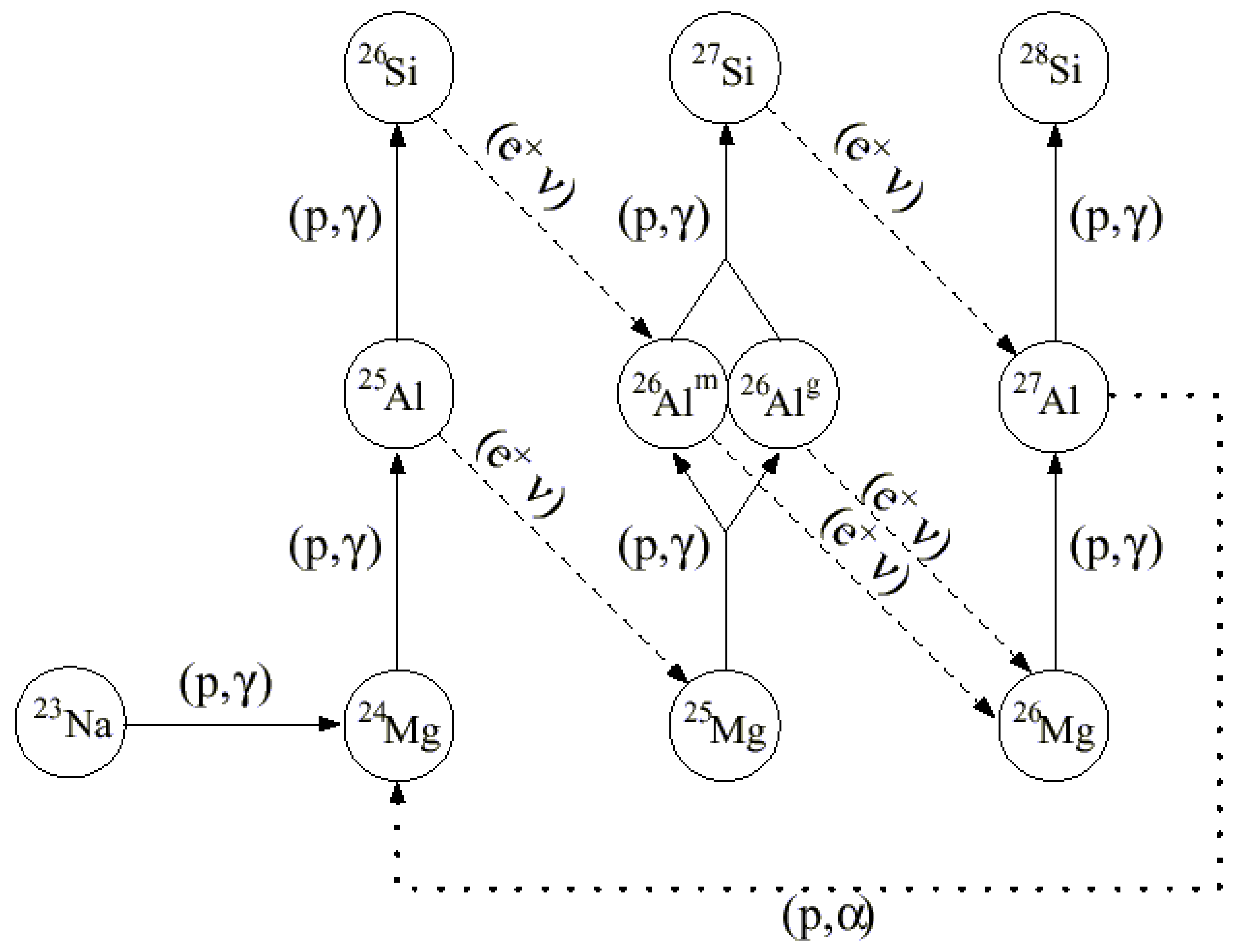
$$L/L_\odot =(R/R_\odot)^2(T/T_\odot)^4$$



Ciclo Ne – Na



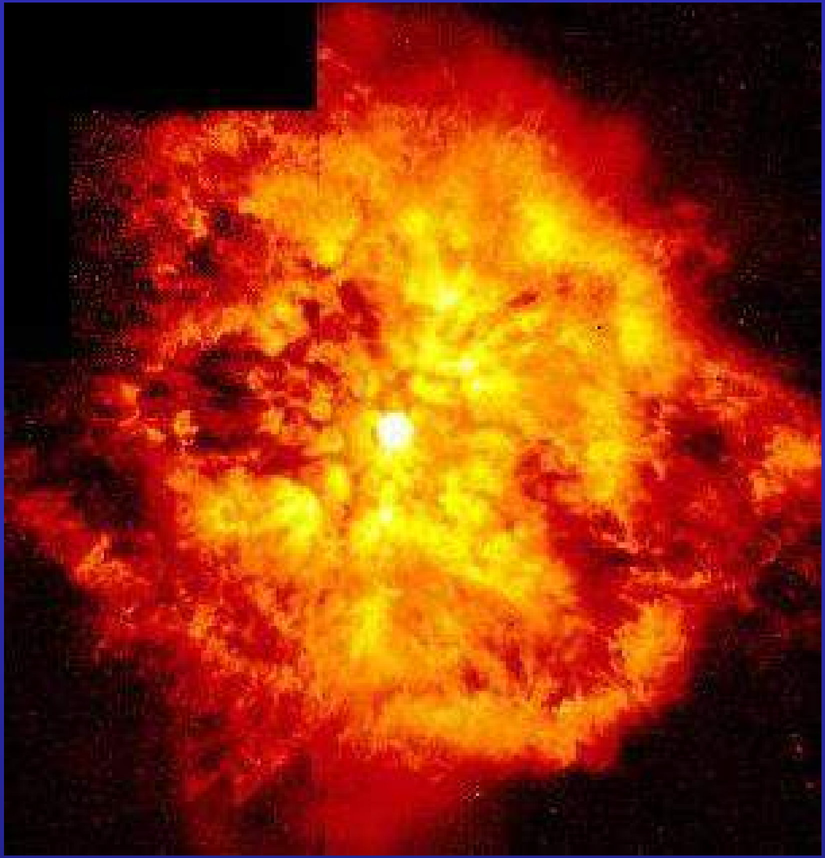
Cadena Mg – Al



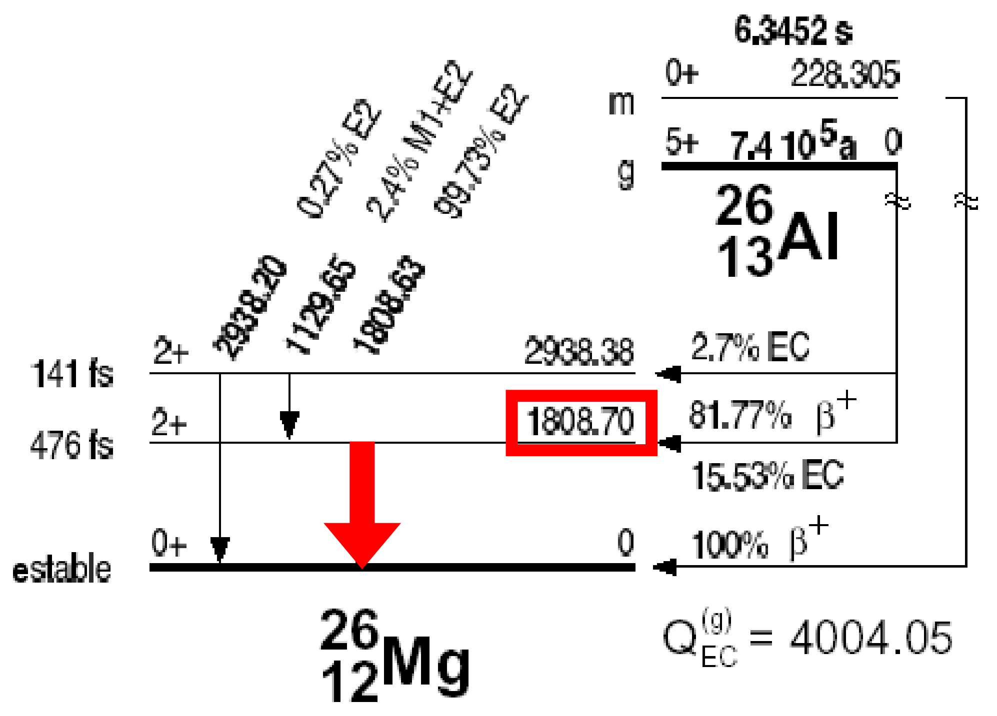
²⁶Si
²⁷Si
²⁸Si
(e⁺ ν)
(e⁺ ν)
(p,γ)
(p,γ)
(p,γ)
²⁵Al
²⁶Alᵐ
²⁶Alᵍ
²⁷Al
(e⁺ ν)
(e⁺ ν)
(e⁺ ν)
(p,γ)
(p,γ)
(p,γ)
²³Na
(p,γ)
²⁴Mg
²⁵Mg
²⁶Mg
(p,α)

Expulsión de ^{26}Al^{g} al medio interestelar y su decaimiento

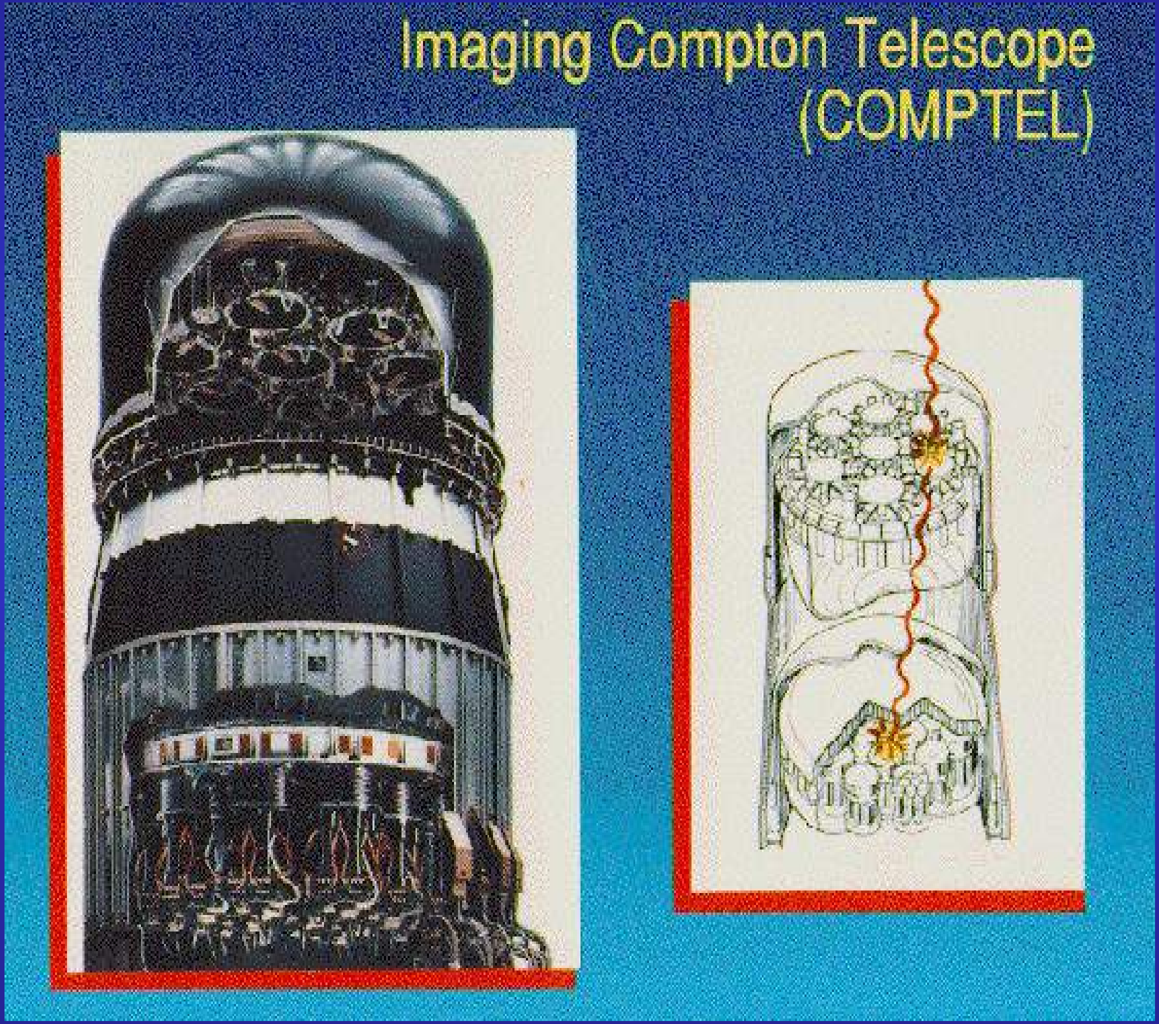
Estrellas masivas
(M ~ 40 – 100 M$_\odot$)
en etapa de Wolf-Rayet:
expulsan 10^{-4} M$_\odot$ de ^{26}Al



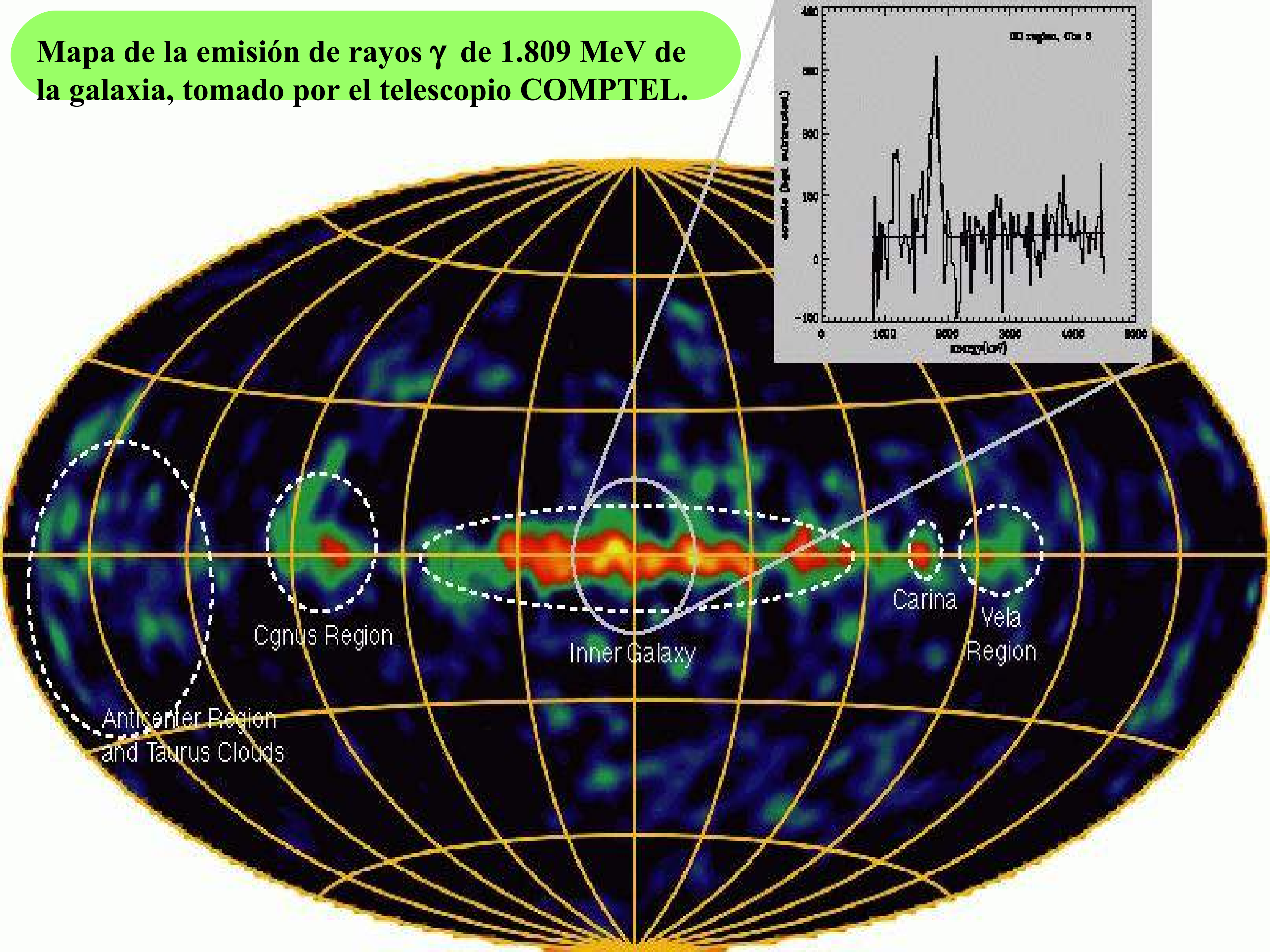
^{26}Al en el medio interestelar:
emite su rayo γ característico
de 1809 keV



Telescopio de rayos γ COMPTEL



Mapa de la emisión de rayos γ de 1.809 MeV de la galaxia, tomado por el telescopio COMPTEL.



Combustión de He

$$\alpha + \alpha + \alpha \leftrightarrow {}^{8}\mathrm{Be} + \alpha \leftrightarrow {}^{12}\mathrm{C}^{*} \rightarrow {}^{12}\mathrm{C} + \gamma$$

$$\uparrow$$

$$\tau \sim 10^{-16}\,\mathrm{s} \Rightarrow \varepsilon_{3\alpha} \propto T^{41}$$

$$ {}^{12}\mathrm{C}\,(\alpha,\gamma)\,{}^{16}\mathrm{O}\,(\alpha,\gamma)\,{}^{20}\mathrm{Ne}\,(\alpha,\gamma)\,{}^{24}\mathrm{Mg}$$

Proceso triple α: único puente para pasar el intervalo de instabilidad A=5 y A=8

^{12}C* (estado excitado en 7,68 MeV) :
predicho por Hoyle para poder explicar la abundancia de ^{12}C en el Universo

astronomía ➡ física nuclear

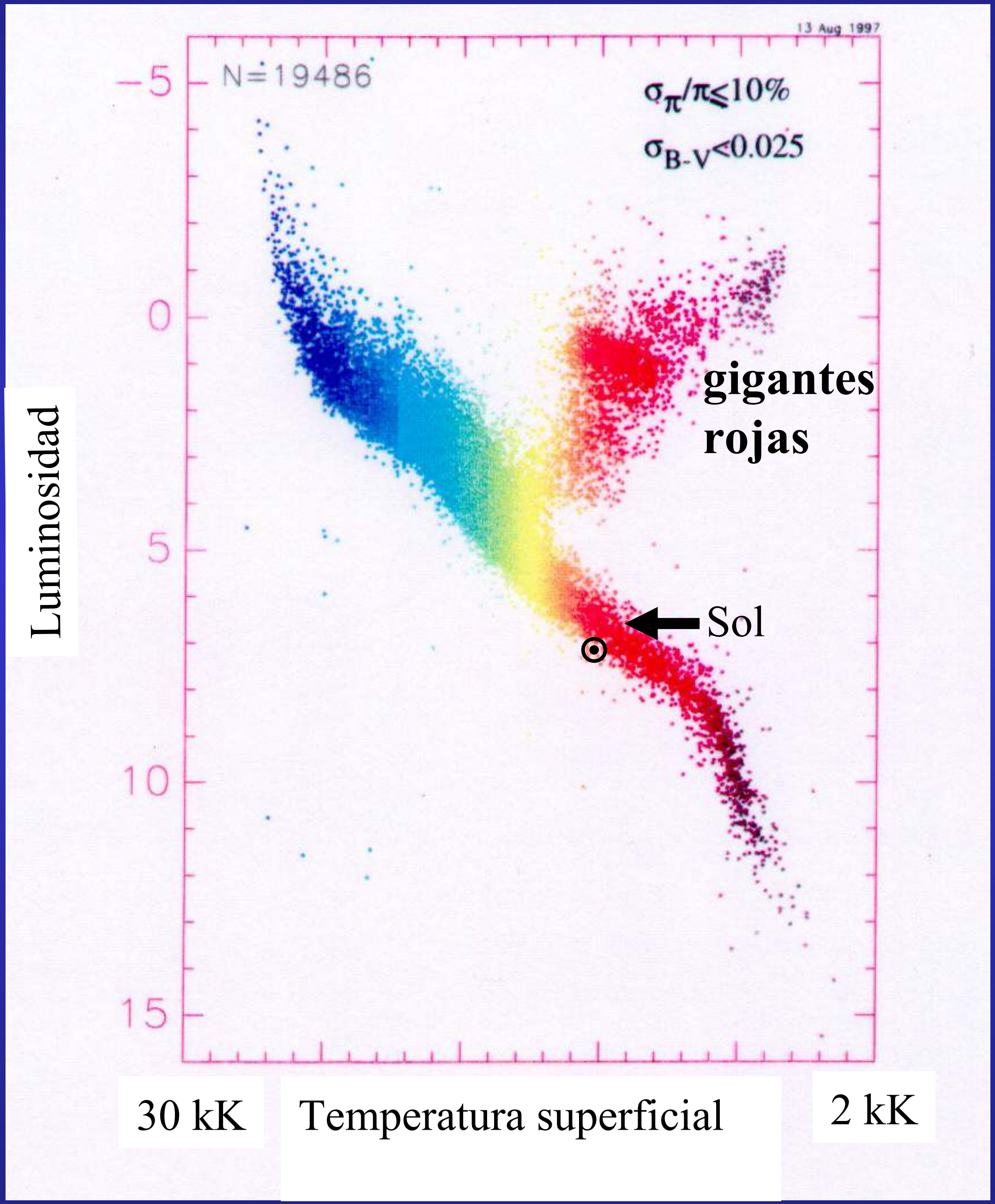
Diagrama de Hertzprung-Russell

Ley de Stefan:

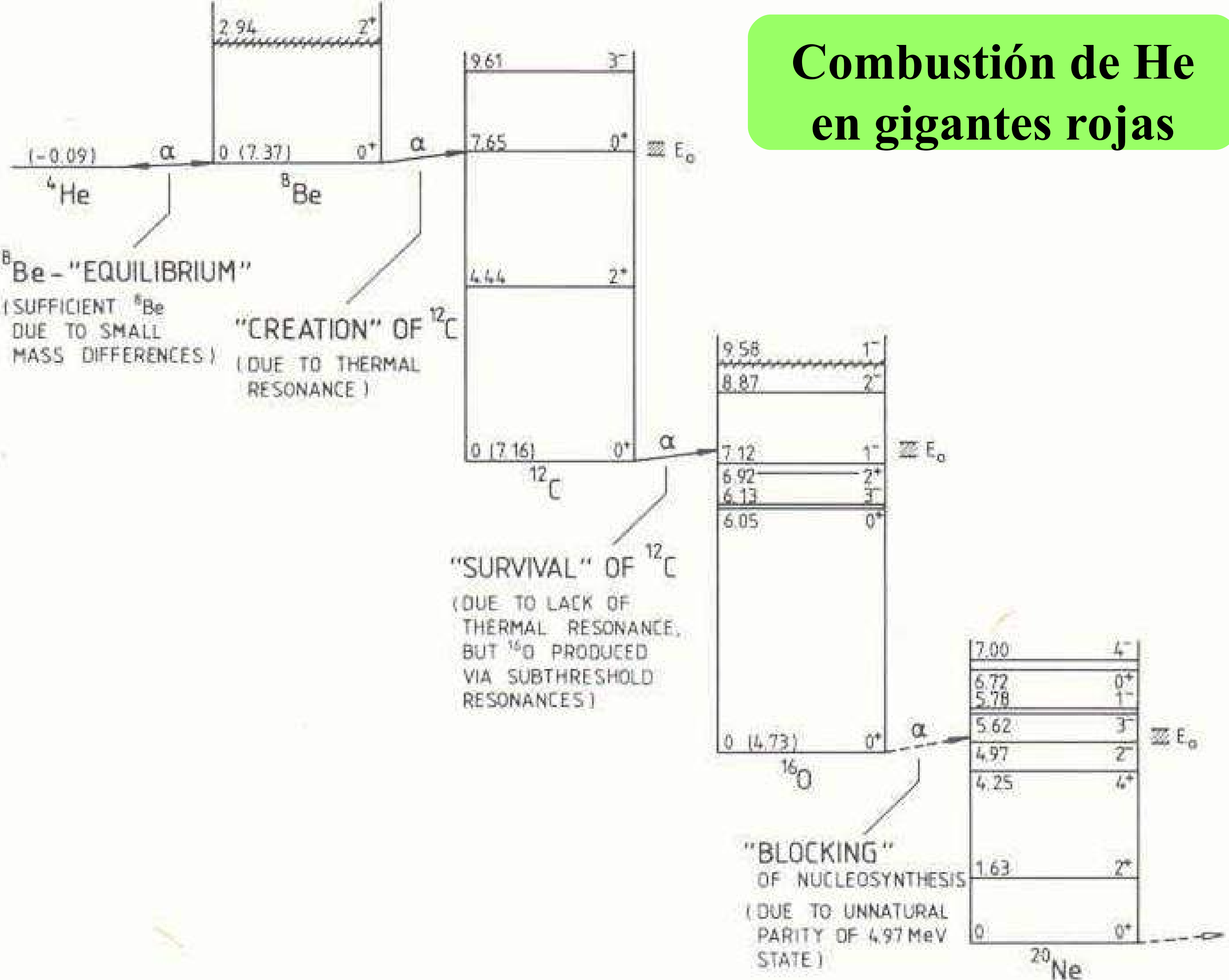
$$L=4\pi R^2\sigma T^4$$

→

$$L/L_\odot = (R/R_\odot)^2(T/T_\odot)^4$$



Combustión de He en gigantes rojas



Combustión de C

T ~ 0,5 GK:

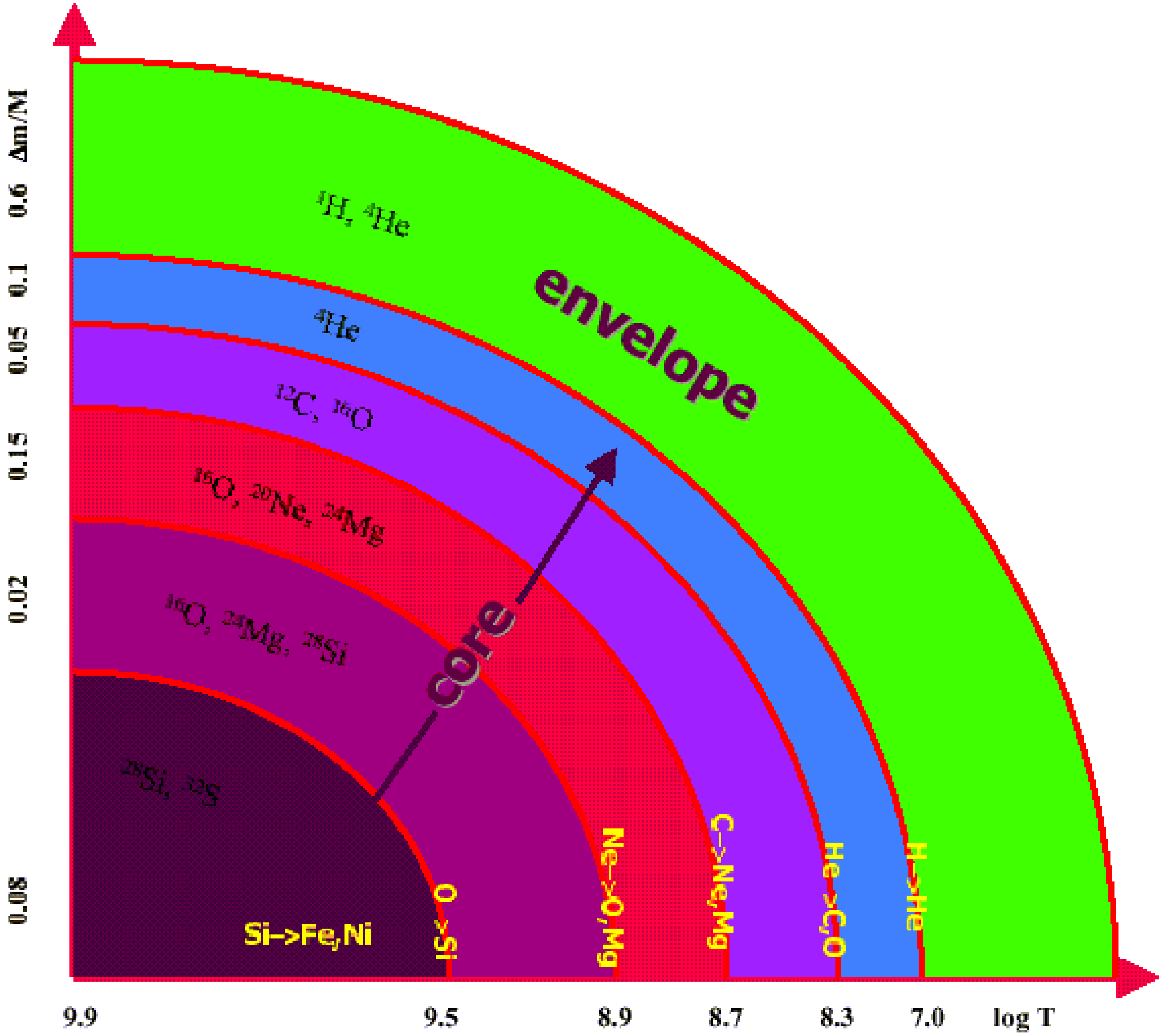
$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \longrightarrow \begin{cases} ^{20}\mathrm{Ne} + \alpha \\ ^{23}\mathrm{Na} + p \\ ^{23}\mathrm{Mg} + n \end{cases}$$

Combustión de Si

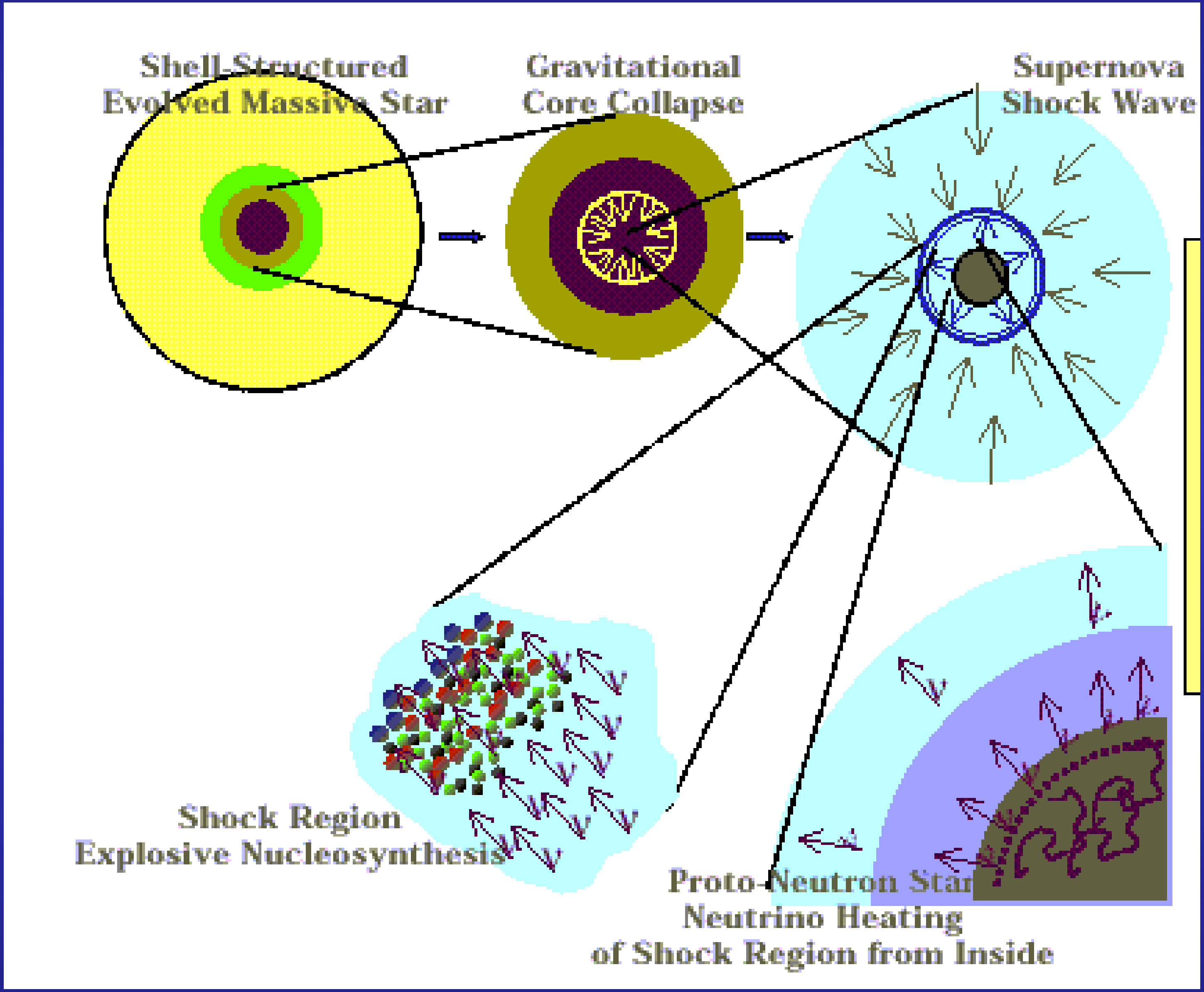
T ~ 3 GK:

$$^{28}\mathrm{Si}(\alpha,\gamma)^{32}\mathrm{S}\,(\alpha,\gamma)^{36}\mathrm{Ar}\,(\alpha,\gamma)\ldots{}^{52}\mathrm{Fe}\,(\alpha,\gamma)^{56}\mathrm{Ni}$$

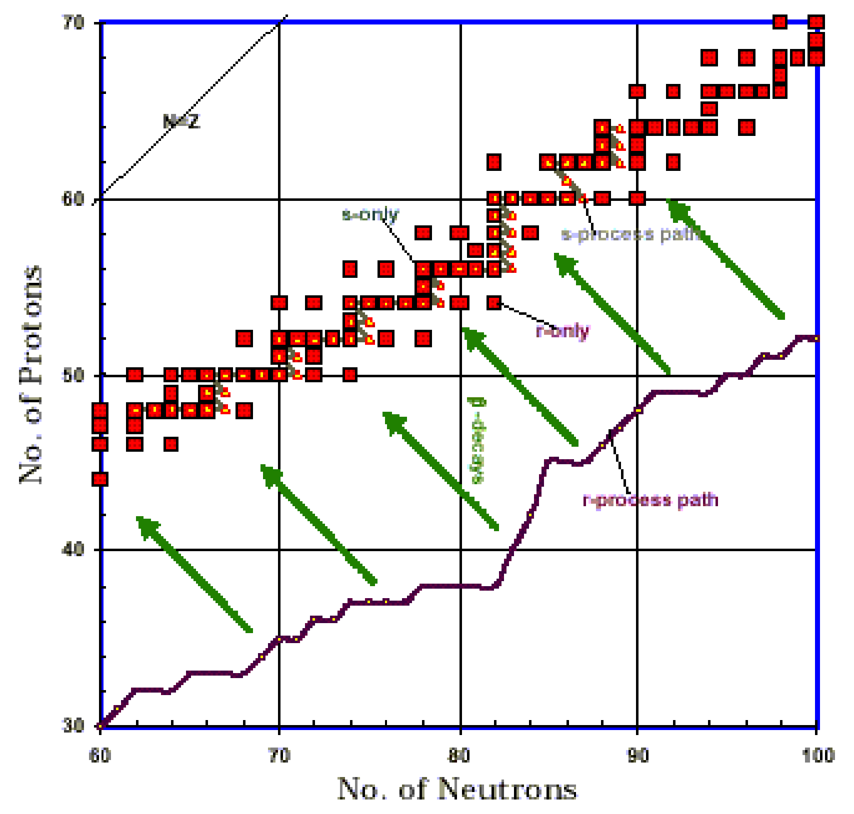
Estrella masiva en estado avanzado de combustión



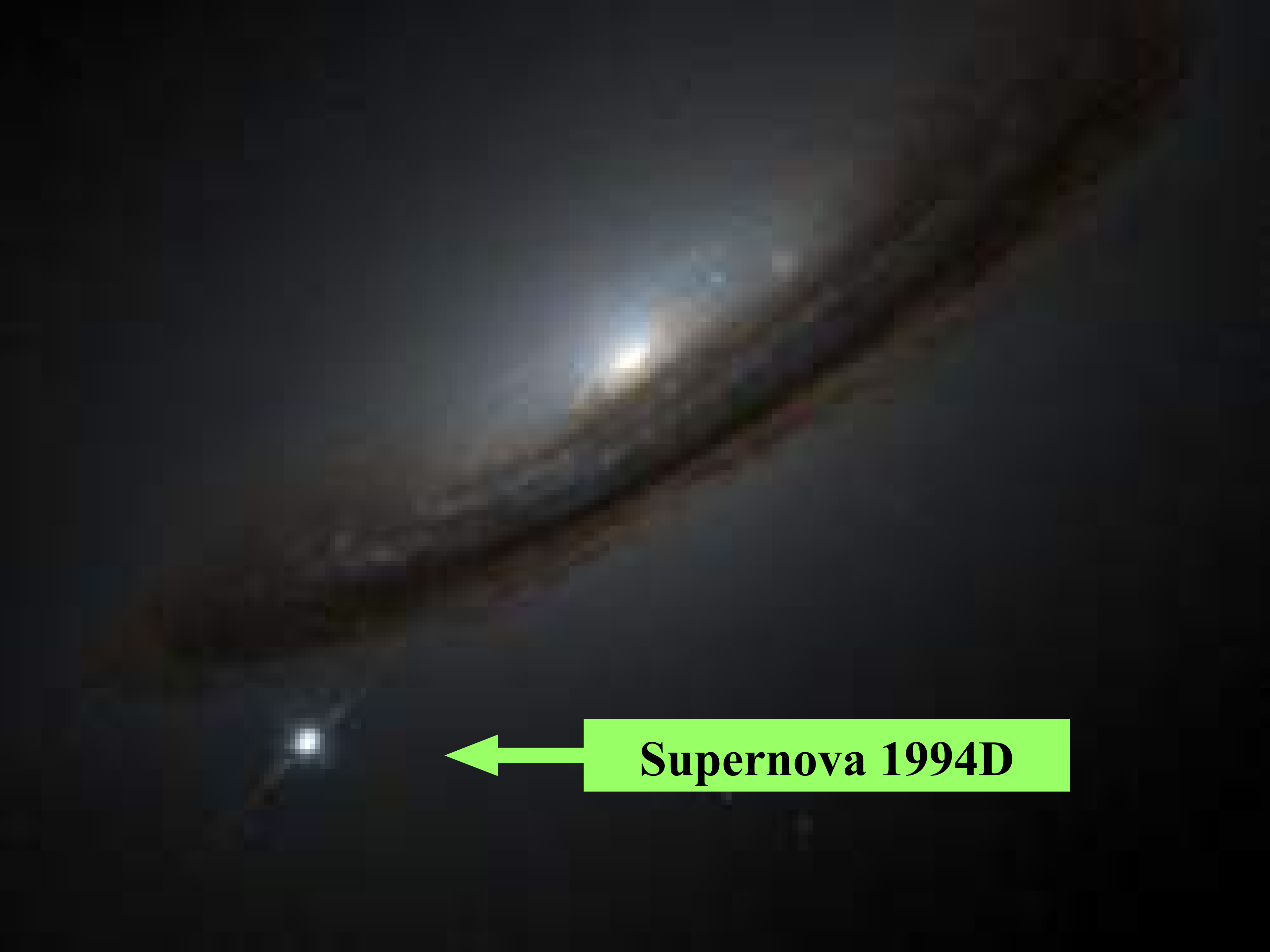
Supernova tipo II: núcleo colapsante



Producción de elementos más pesados que el hierro

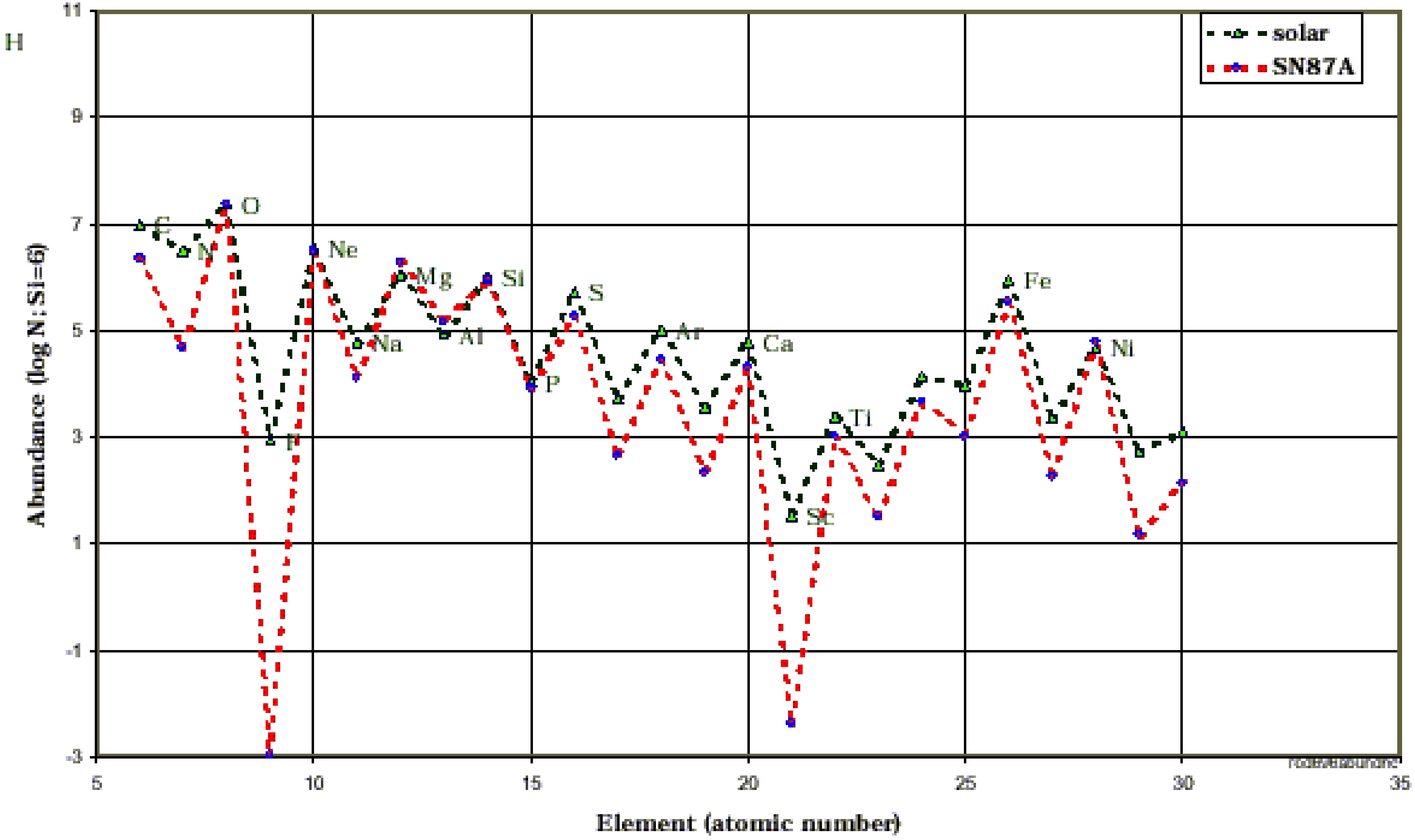


- <u>**Proceso *s*:**</u> **(n,γ) < β⁻**
- <u>**Proceso *r*:**</u> **(n,γ) > β⁻**

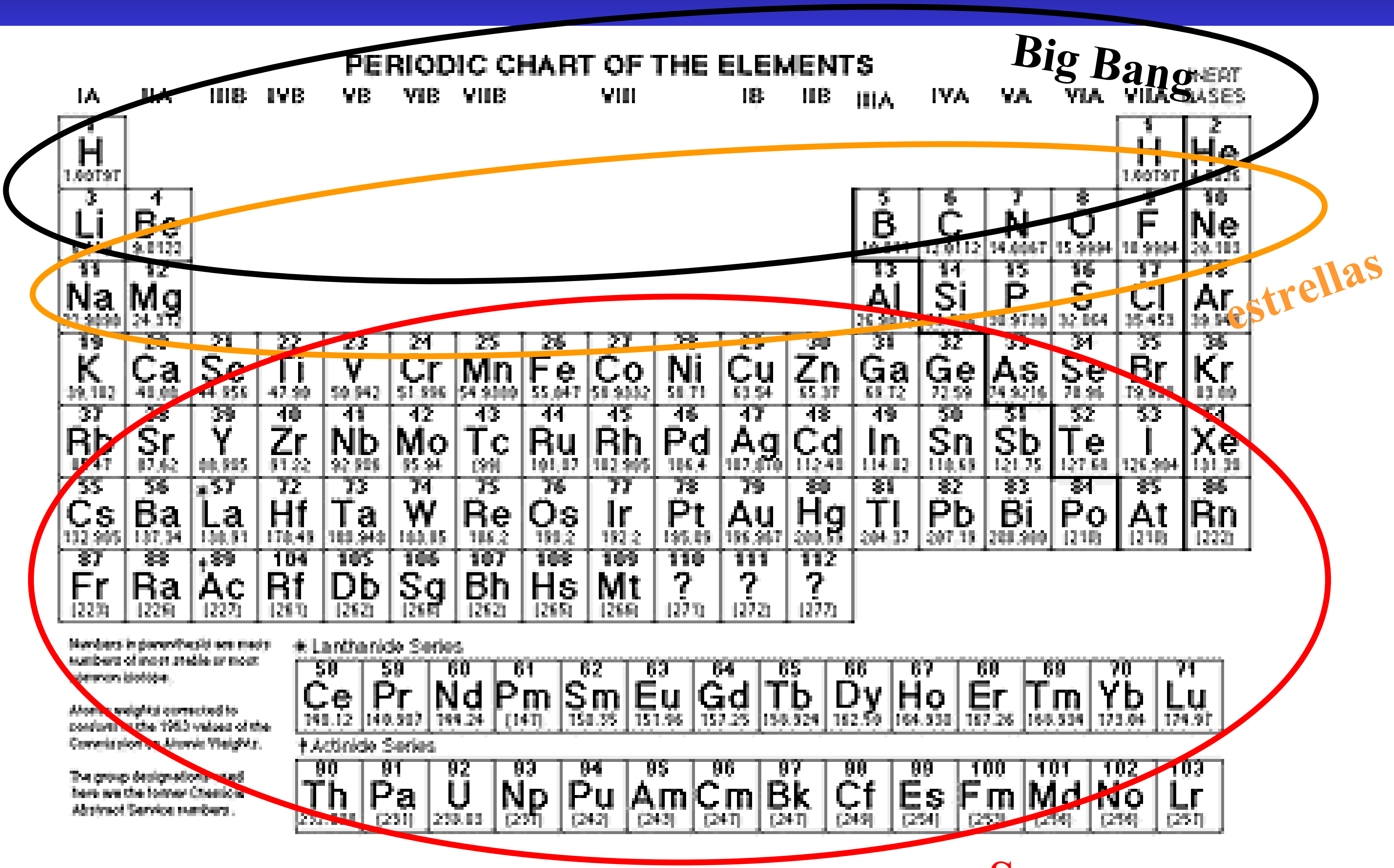


Supernova 1994D

Abundancia del sistema solar ~ eyección de supernova de 25 $M_{\odot}$



Síntesis de la nucleosíntesis



astrofísica nuclear experimental

↓

reacciones nucleares a muy bajas energías (centenas de keV)

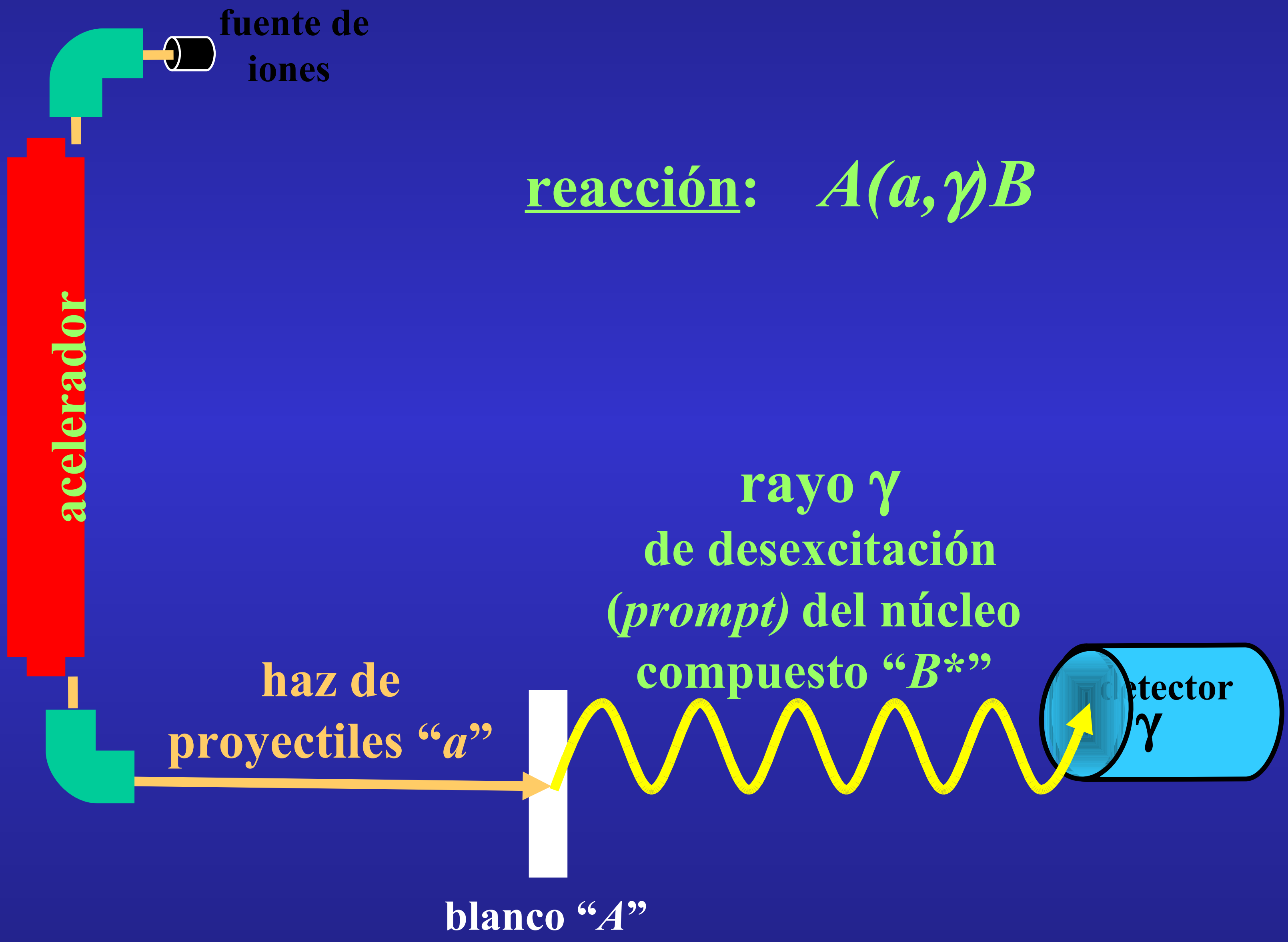
↓

medición de secciones eficaces en extremo pequeñas (decenas de pico-barn!)

Métodos de medición

- **Detección *on-line* de rayos γ**
- **Método integrado midiendo la actividad γ**
- **Método integrado contando átomos con AMS**
- **Análisis de las partículas de retroceso**
- **Reacciones con haces radioactivos**
- **Actividad de material terrestre**
- **Actividad de material extraterrestre**
- **Caballo de Troya**

Detección *on-line* de rayos γ



fuente de
iones

acelerador

reacción: $A(a,\gamma)B$

rayo γ
de desexcitación
(*prompt*) del núcleo
compuesto "*B**"

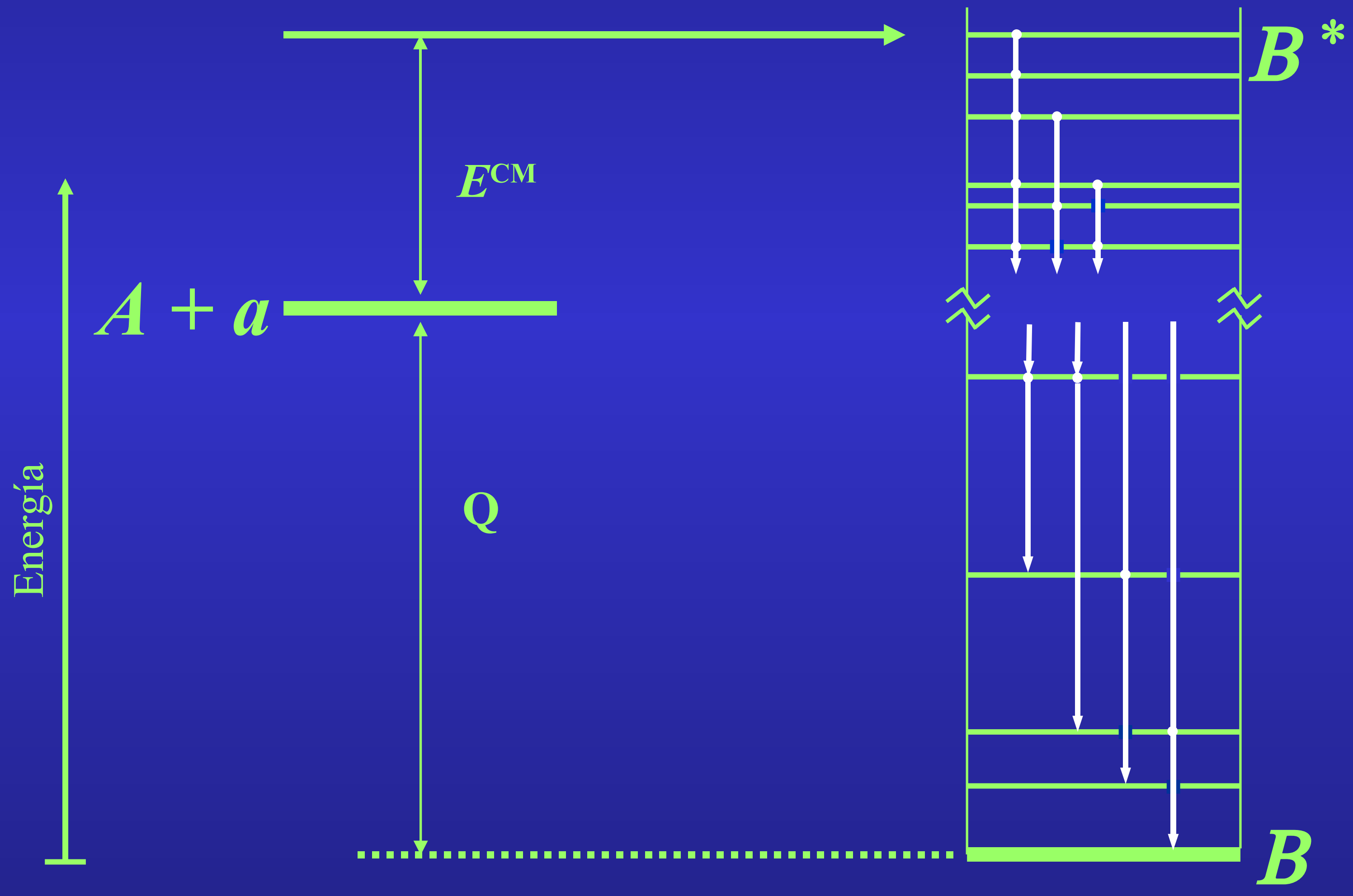
haz de
proyectiles "*a*"

detector
γ

blanco "*A*"

Detección *on-line* de rayos γ

reacción $A(a,\gamma)B$: $a + A \rightarrow B^* \rightarrow B + \gamma$



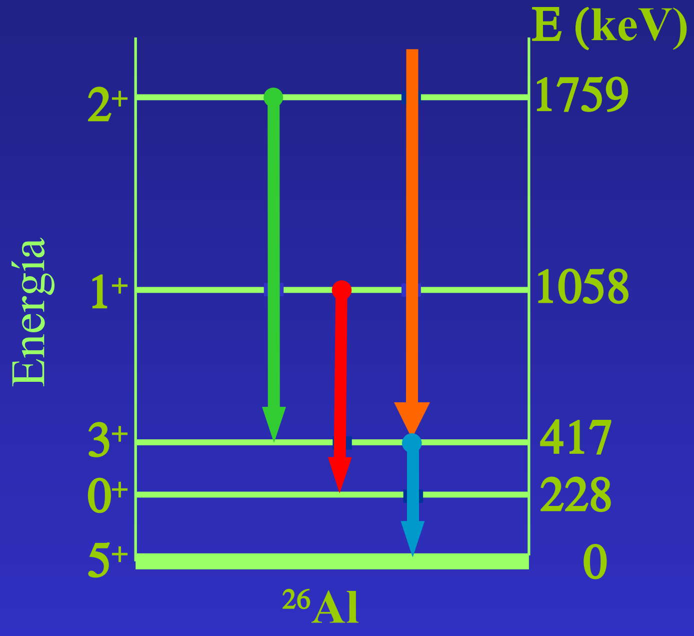
Detección *on-line* de rayos γ

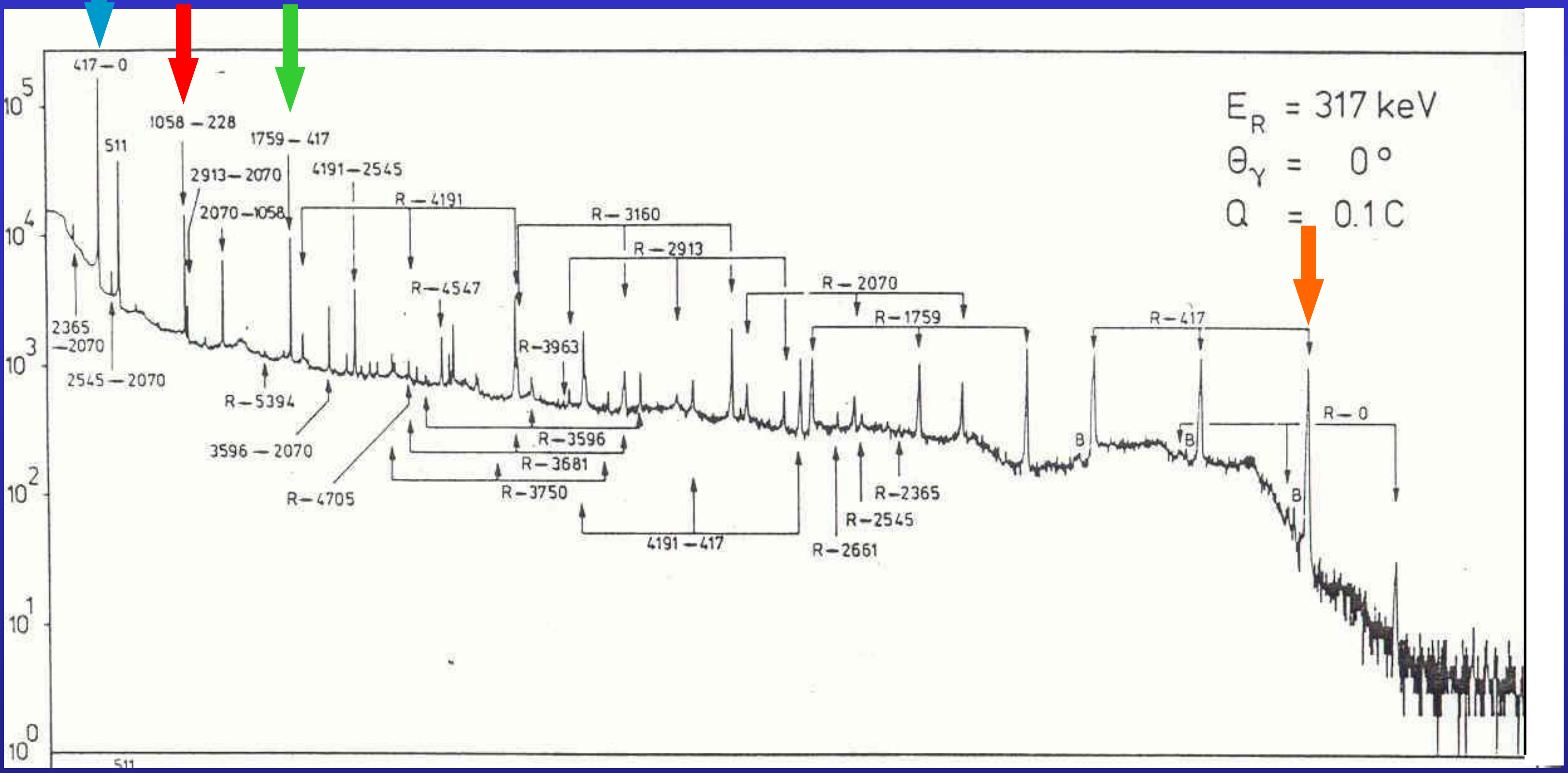
Ej:

^{25}Mg(p,γ)^{26}Al

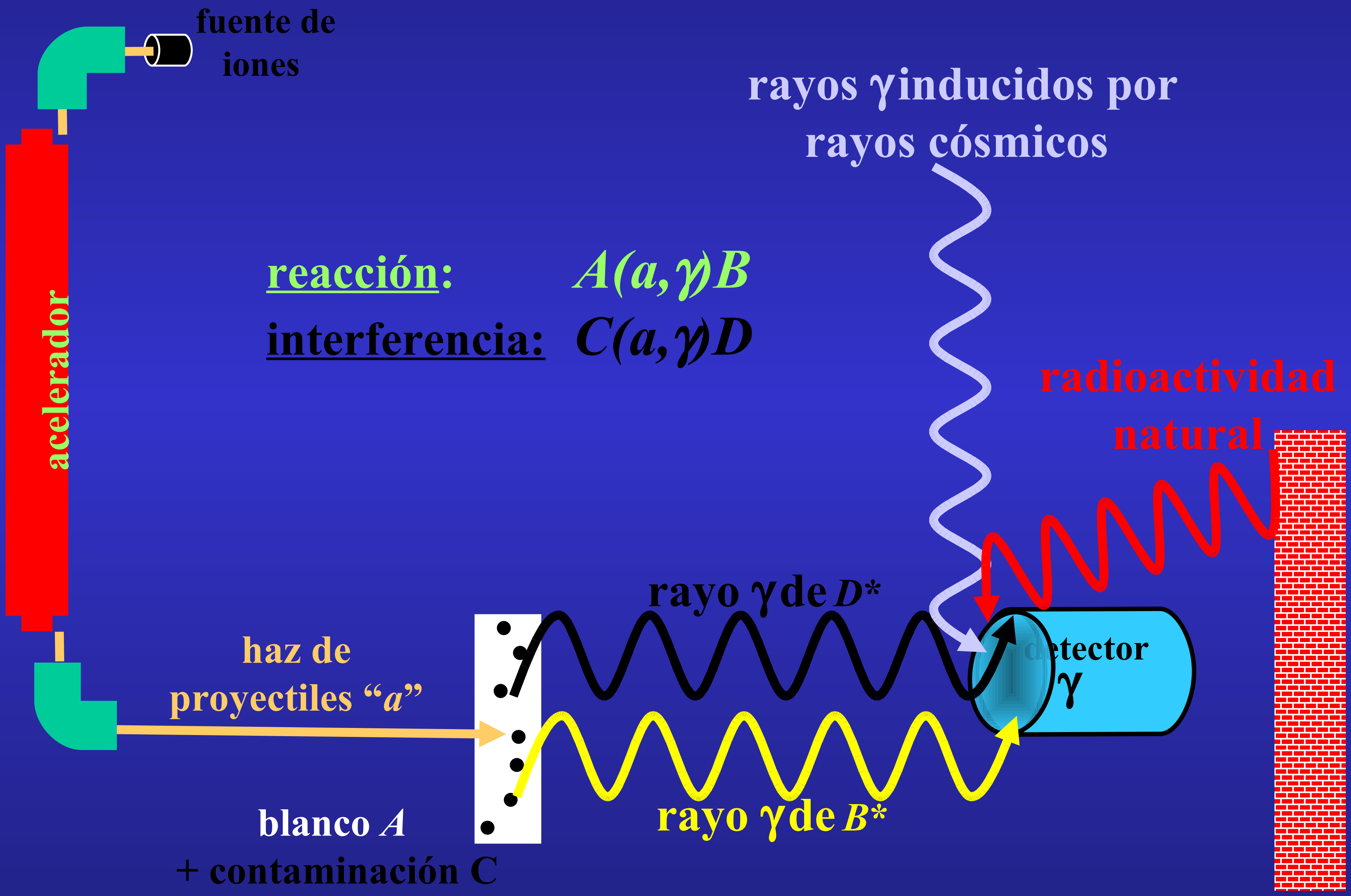
E_R^{lab}=317 keV

E_x=6610 keV





Detección *on-line* de rayos γ



fuente de iones

acelerador

rayos γ inducidos por rayos cósmicos

reacción: $A(a,\gamma)B$

interferencia: $C(a,\gamma)D$

radioactividad natural

rayo γ de D^*

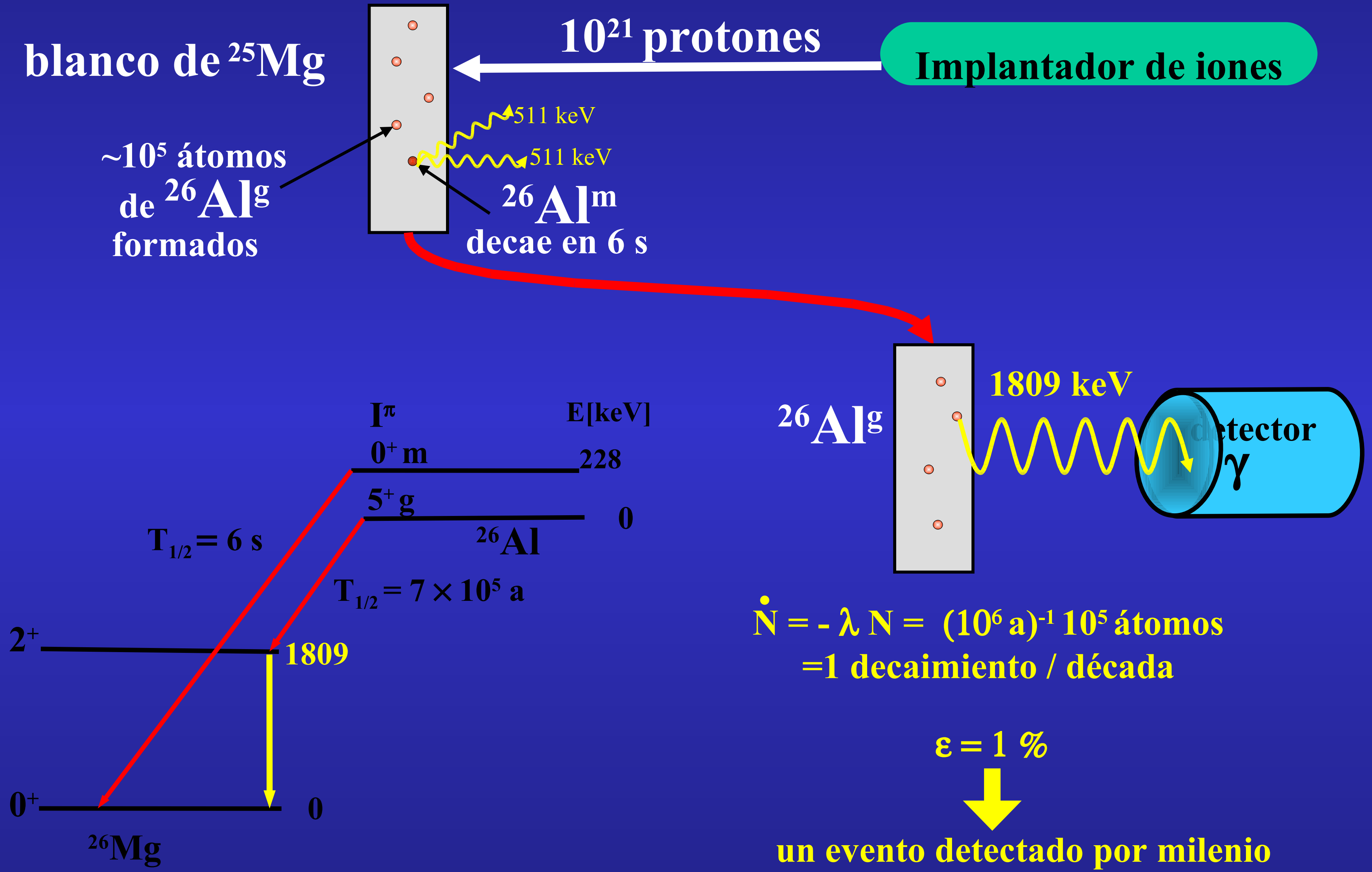
detector γ

haz de proyectiles "*a*"

rayo γ de B^*

blanco *A* + contaminación C

Método integrado midiendo la actividad γ



blanco de ^{25}Mg

10^{21} protones

Implantador de iones

~10^5 átomos de ^{26}Al^g formados

^{26}Al^m decae en 6 s

^{26}Al^g

1809 keV

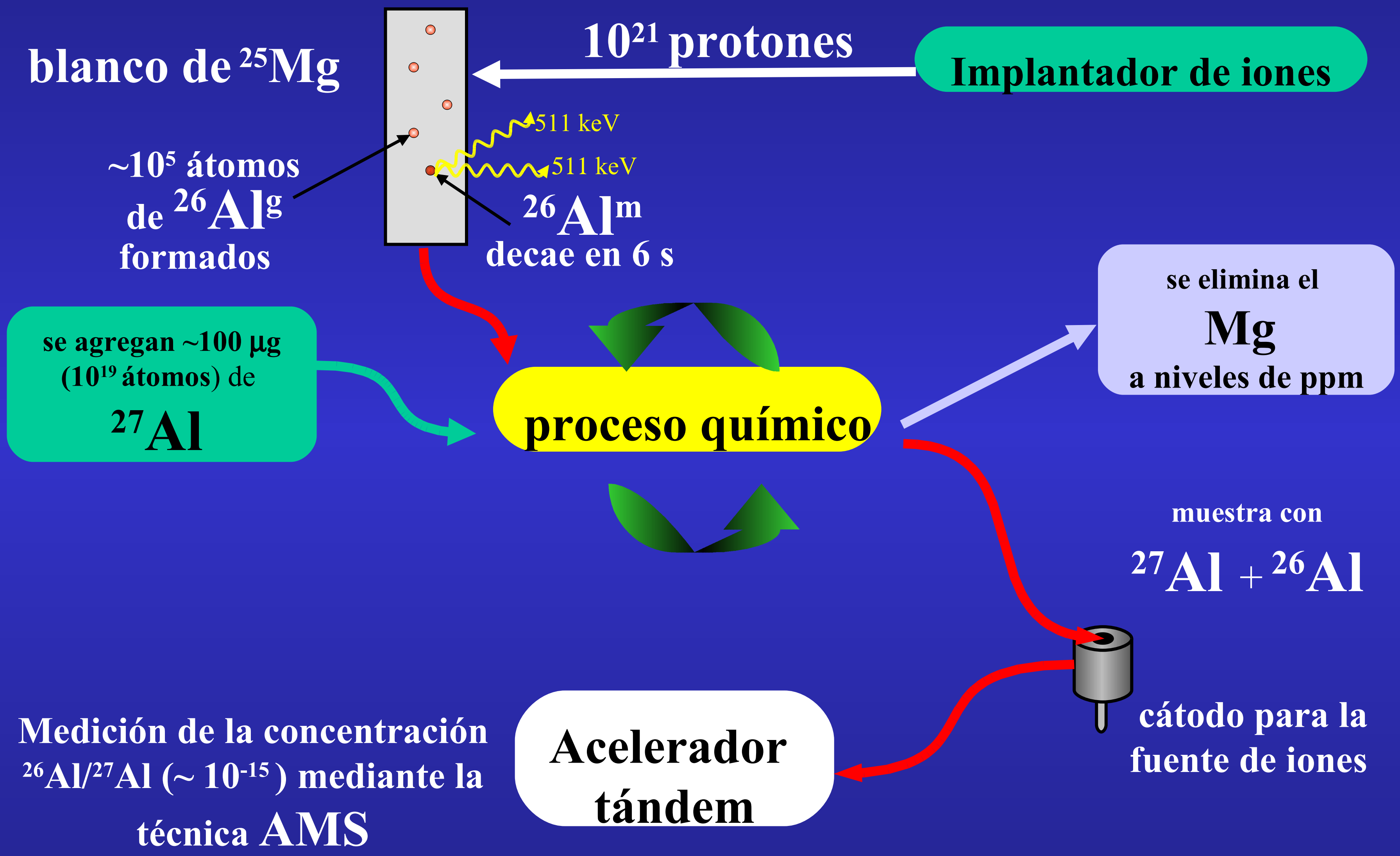
$$\dot{N} = -\lambda N = (10^6\,\mathrm{a})^{-1}\,10^5 \text{ átomos}$$

=1 decaimiento / década

$$\varepsilon = 1\ \%$$

un evento detectado por milenio

Método integrado contando átomos con AMS



blanco de ^{25}Mg

10^{21} protones

Implantador de iones

~10^5 átomos de ^{26}Al^g formados

^{26}Al^m decae en 6 s

se elimina el Mg a niveles de ppm

se agregan ~100 µg (10^{19} átomos) de ^{27}Al

proceso químico

muestra con ^{27}Al + ^{26}Al

cátodo para la fuente de iones

Acelerador tándem

Medición de la concentración ^{26}Al/^{27}Al (~ 10^{-15}) mediante la técnica AMS

Conteo de átomos mediante Espectrometría de Masas con Aceleradores (AMS)

imán inyector

selección de masa

fuente de iones

muestra

$^{26}\mathrm{AlO}^- / {}^{27}\mathrm{AlO}^-$

pre-aceleración

disociación molecular

folia de carbono (*stripper*)

terminal de alta tensión:

12,5 MV / 12,0 MV

eliminación de interferencias

filtro de Wien

selección de p/q

imán analizador

$^{26}\mathrm{Al}^{7+} / {}^{27}\mathrm{Al}^{7+}$

identificación y conteo

detector gaseoso múltiple-ΔE

separación de isobáros

$^{26}\mathrm{Mg}$

$^{26}\mathrm{Al}$

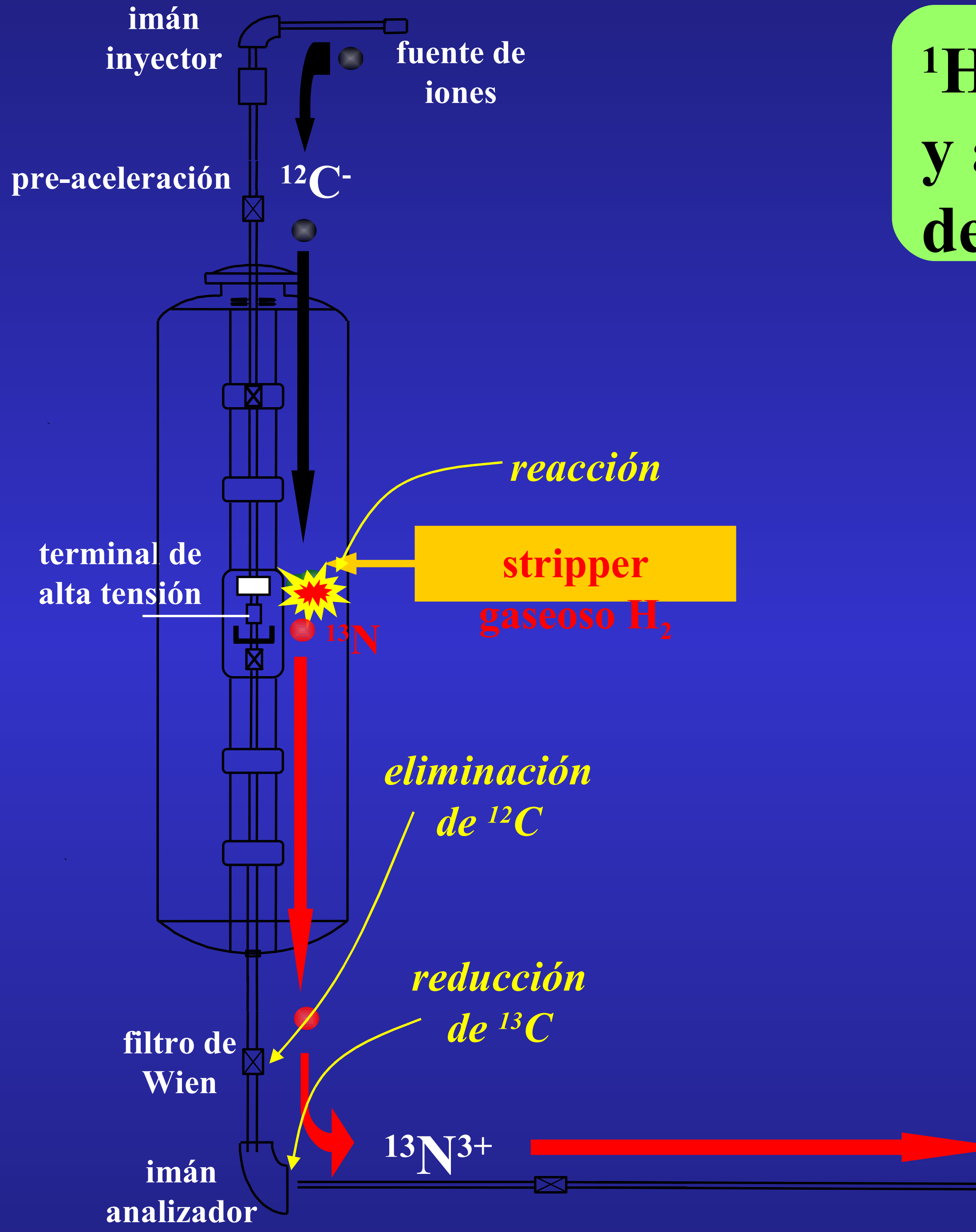
imán con gas

copa de Faraday

$$\text{Concentración} = \frac{\text{eventos de } {}^{26}\text{Al en el detector}}{{}^{27}\text{Al en FC } (\mu\text{A} \times 1 \text{ hora})}$$

$$\Rightarrow \quad C = {}^{26}\mathrm{Al}/{}^{27}\mathrm{Al} \sim 10^{-15}$$

$^{1}H(^{12}C,\gamma)^{13}N$ en stripper y análisis de la partícula de retroceso



imán inyector

fuente de iones

pre-aceleración

$^{12}C^{-}$

terminal de alta tensión

reacción

stripper gaseoso H_2

^{13}N

eliminación de ^{12}C

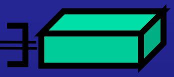
reducción de ^{13}C

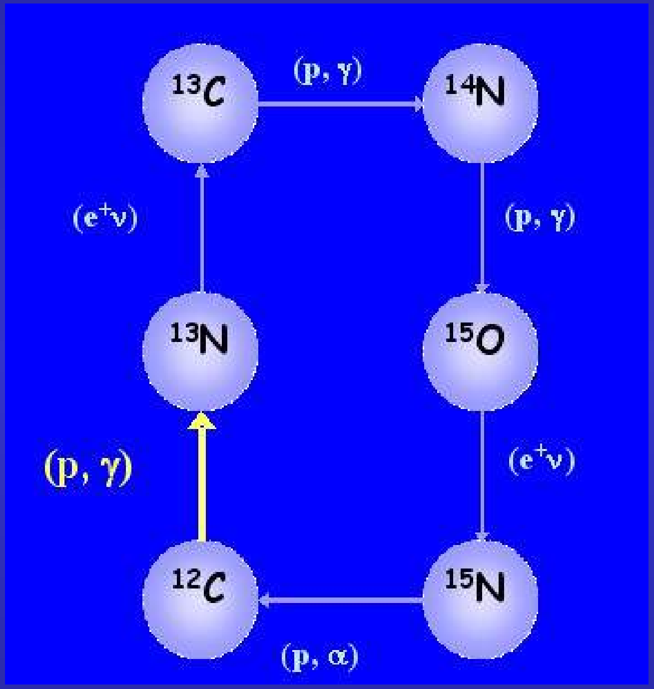
filtro de Wien

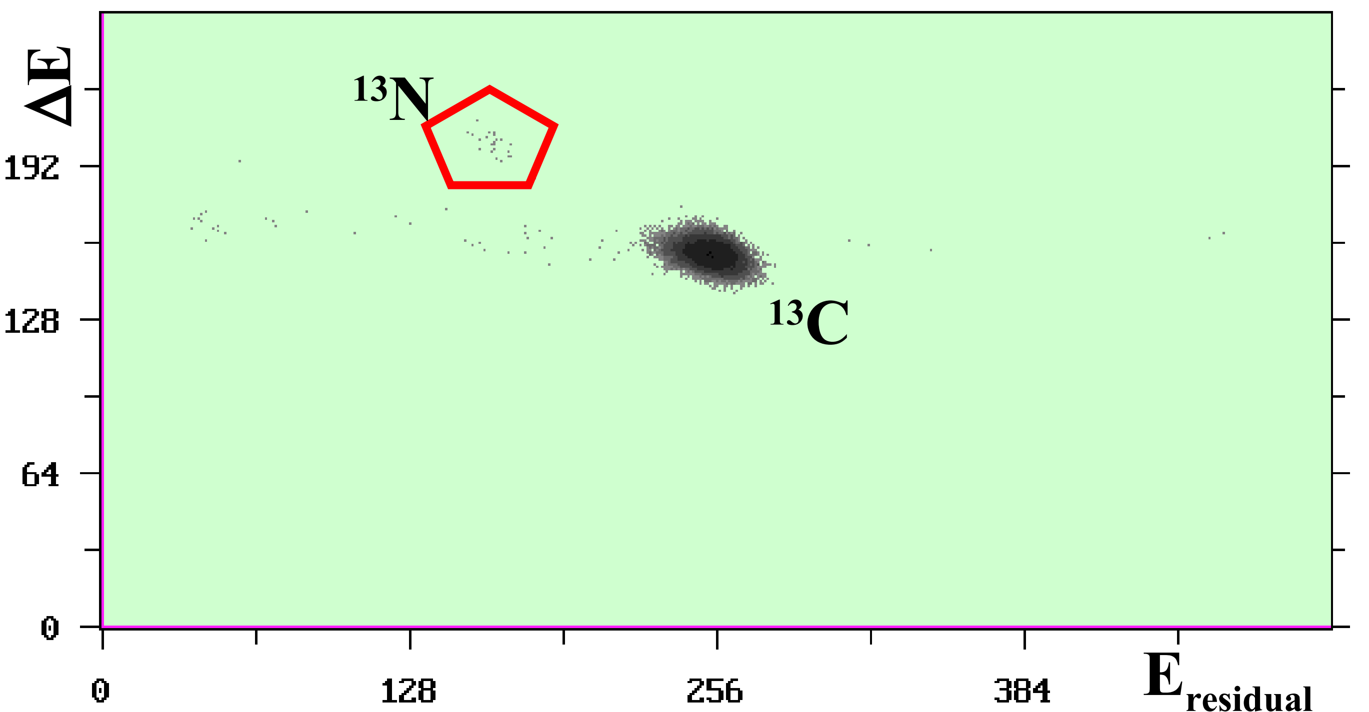
imán analizador

$^{13}N^{3+}$

detector gaseoso ΔE-E







reacción en cinemática inversa:

- reacción a baja energía

$$E(^{12}C) = 2{,}7\ \mathrm{MeV} \leftrightarrow E^{CM} = 206\ \mathrm{keV}$$

- alta energía para la discriminación

Origen de los núcleos $\geq {}^{12}C$ en el universo

- ~~Nucleosíntesis durante el Big Bang~~

  Densidad del universo insuficiente

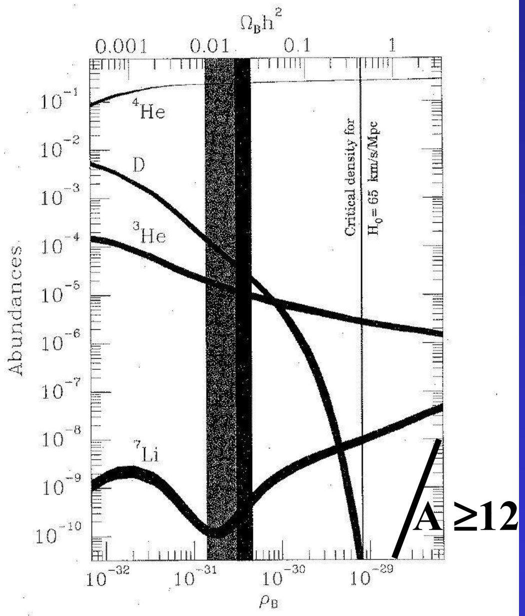


Figure 11.1 The predicted abundances of light nuclei, as a function of the absolute baryon density along the bottom or $\Omega_B h^2$ along the top. The width of the bands indicates the uncertainty in the predictions. The vertical bands show the range compatible with observations, while the vertical line shows the critical density. [From Schramm & Turner, Rev. Mod. Phys. **70**, 303 (1998), courtesy Michael Turner].

- Nucleosíntesis estelar

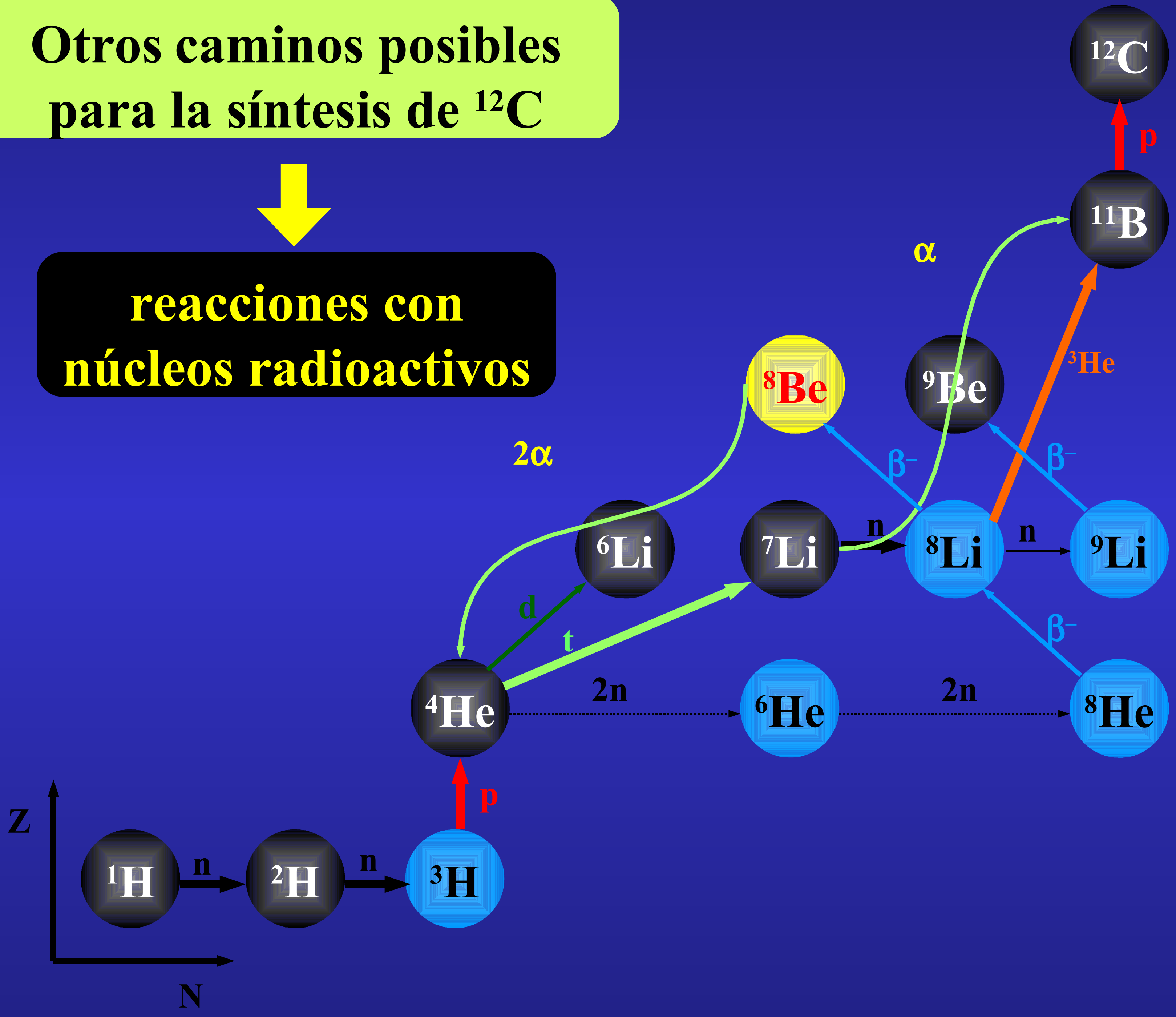
  Proceso triple α

$$\alpha + \alpha + \alpha \leftrightarrow {}^{8}Be + \alpha \leftrightarrow {}^{12}C^{*} \rightarrow {}^{12}C + \gamma$$

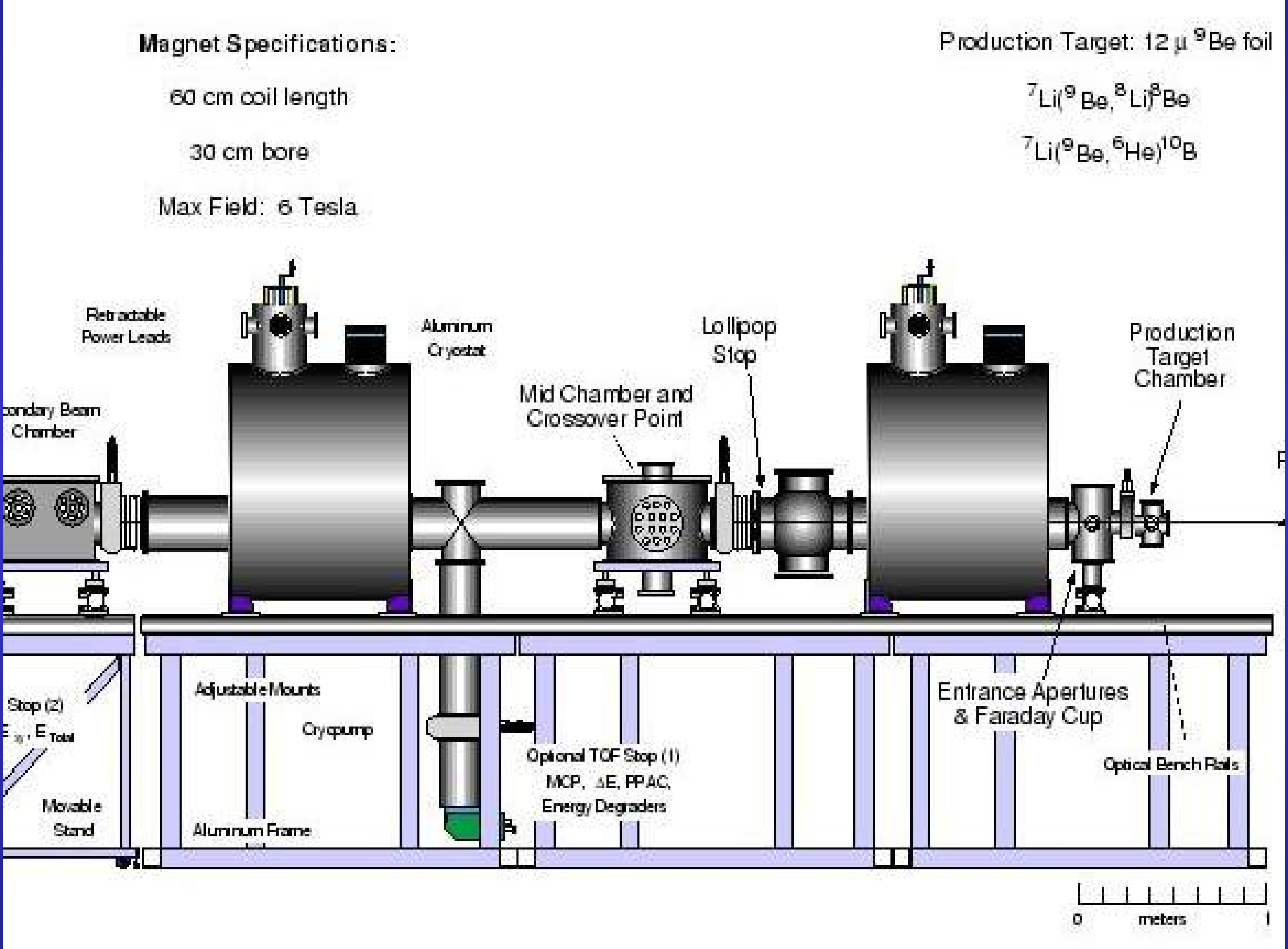
¿único proceso?

Otros caminos posibles para la síntesis de ^{12}C

reacciones con núcleos radioactivos



Proyecto **RIBRAS** (**R**adioactive **I**ons **Bras**il)



Magnet Specifications:

60 cm coil length

30 cm bore

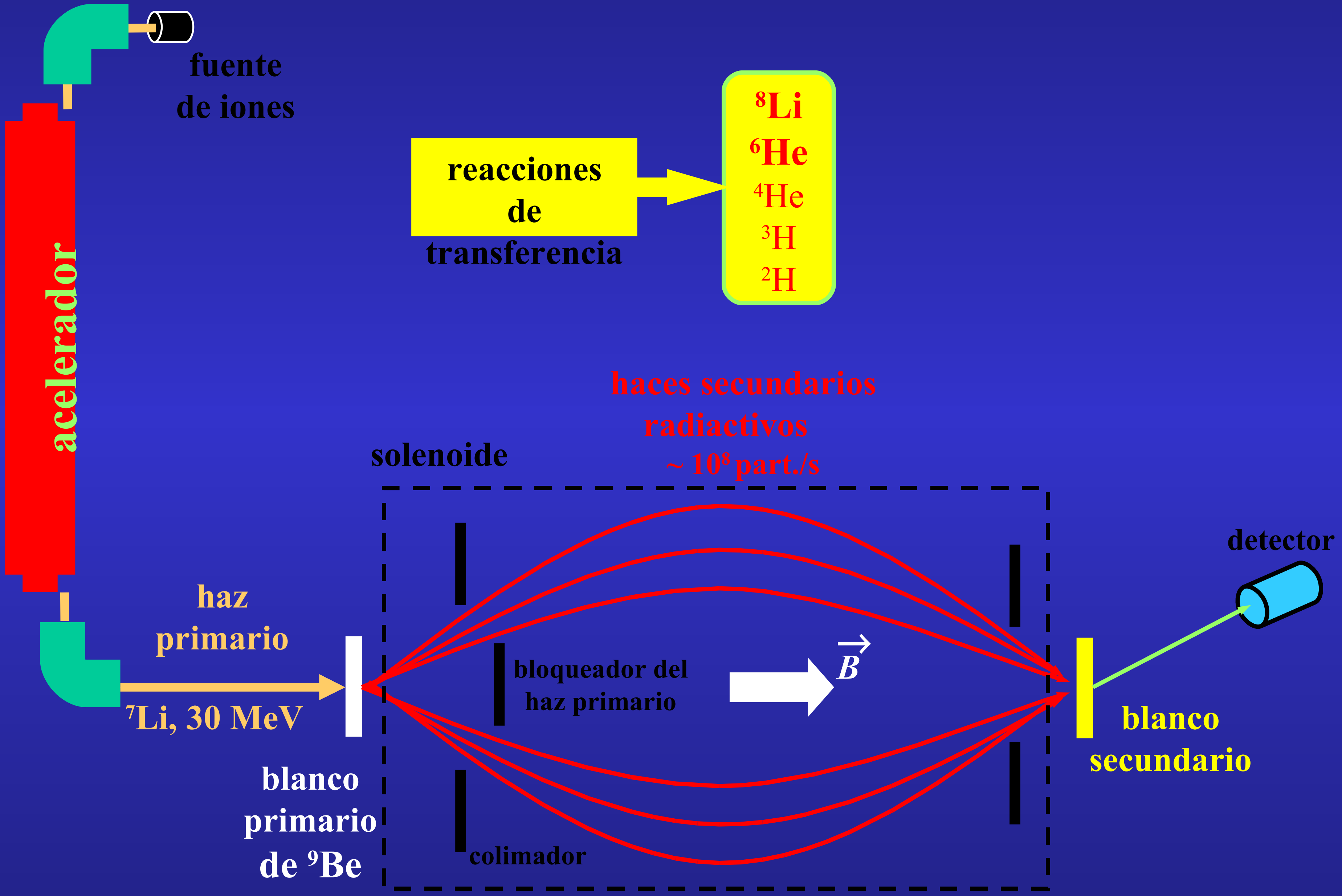
Max Field: 6 Tesla

Production Target: 12 µ ^{9}Be foil

$^{7}Li(^{9}Be,^{8}Li)^{8}Be$

$^{7}Li(^{9}Be,^{6}He)^{10}B$

Reacciones con haces radiactivos



fuente
de iones

acelerador

reacciones
de
transferencia

^{8}Li
^{6}He
^{4}He
^{3}H
^{2}H

haces secundarios
radiactivos
~ 10^{8} part./s

solenoide

haz
primario

^{7}Li, 30 MeV

blanco
primario
de ^{9}Be

bloqueador del
haz primario

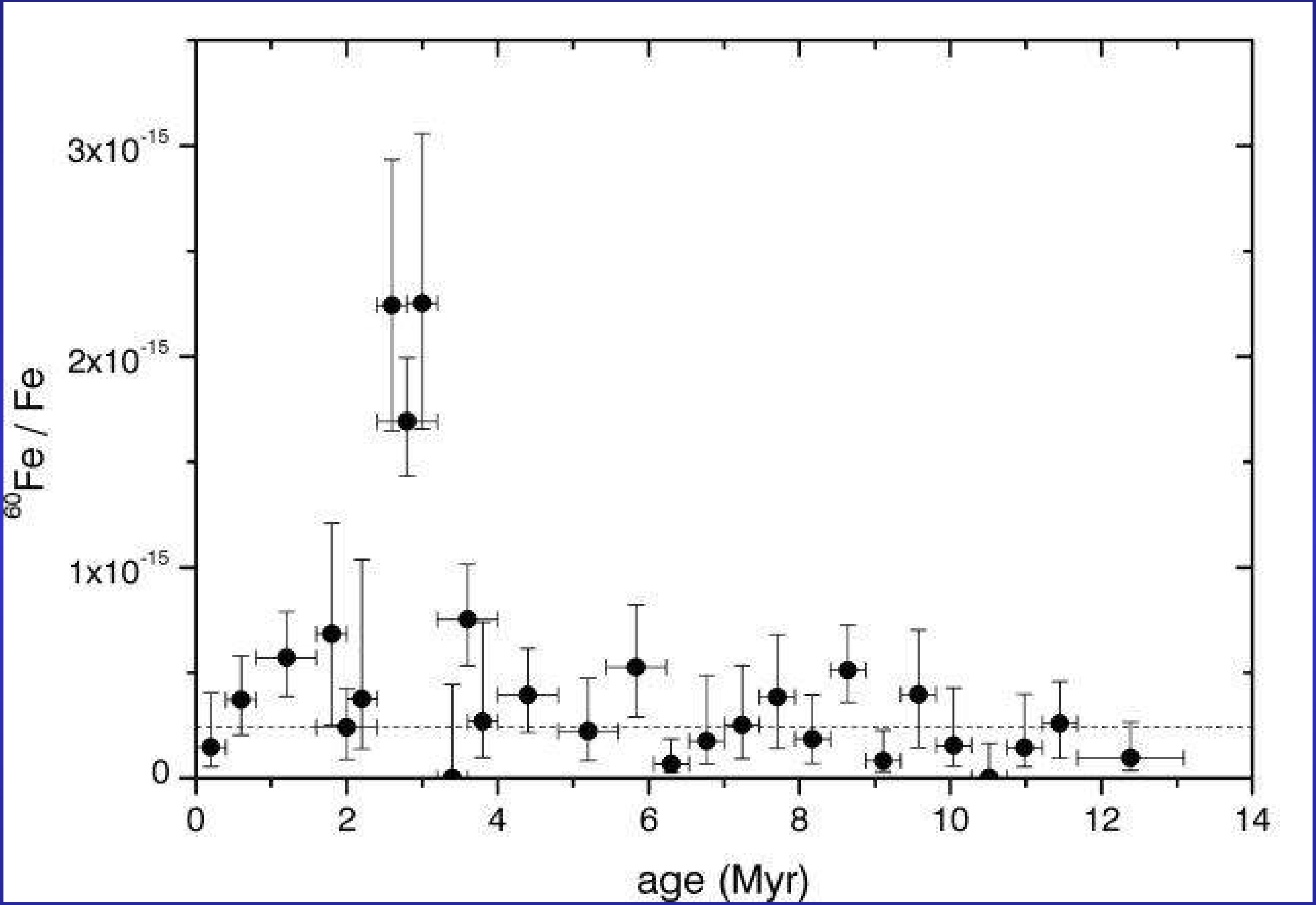
$\vec{B}$

colimador

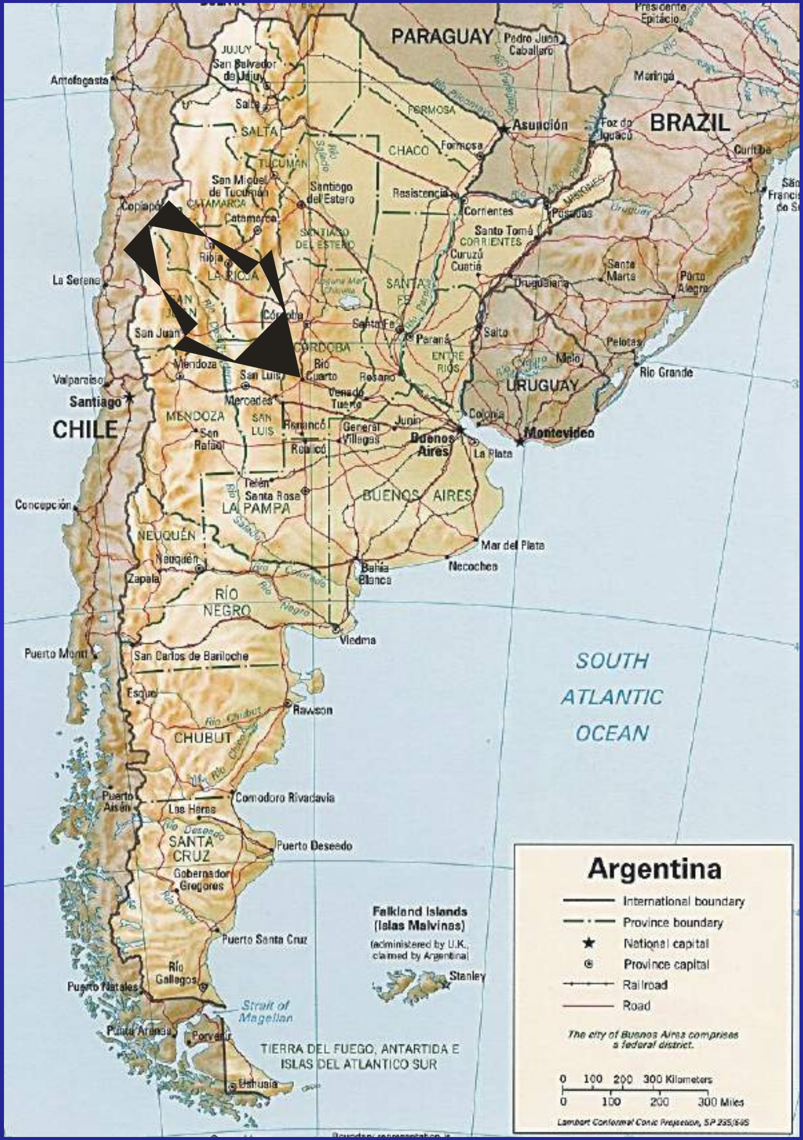
detector

blanco
secundario

Radioactividad en la Tierra: ^{60}Fe producido en una Supernova cercana


3x10^{-15}
2x10^{-15}
1x10^{-15}
0
^{60}Fe / Fe
0
2
4
6
8
10
12
14
age (Myr)

Radionucleidos en el Meteorito acondrito de Río IV

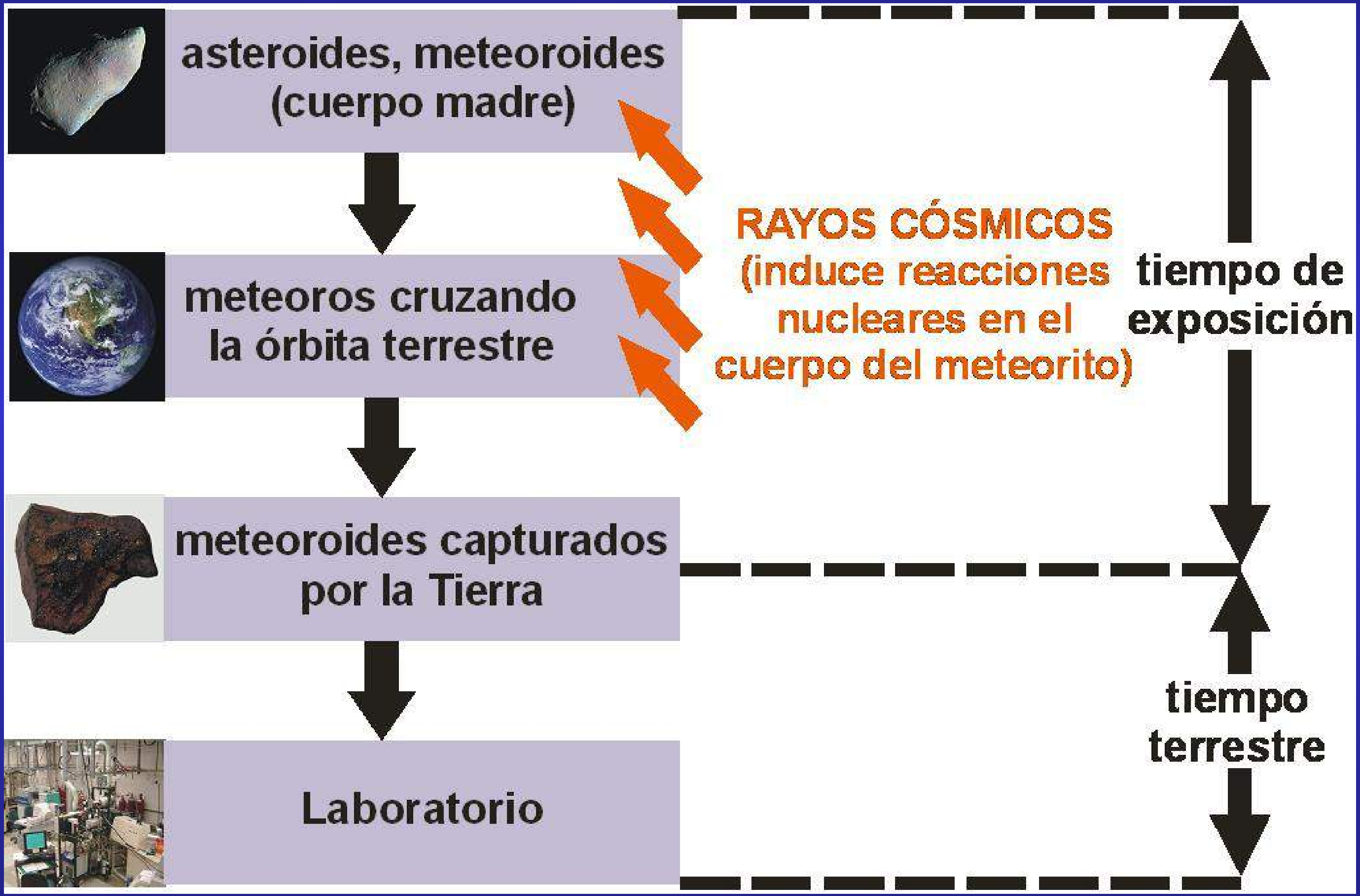


acondrito ferrorrocoso (nuestra muestra)

núcleo ferroso

capa rocosa

Viaje en el Espacio



asteroides, meteoroides (cuerpo madre)

meteoros cruzando la órbita terrestre

meteoroides capturados por la Tierra

Laboratorio

RAYOS CÓSMICOS (induce reacciones nucleares en el cuerpo del meteorito)

tiempo de exposición

tiempo terrestre

Producción de radionucleidos

$$P_j(R,d)=\sum_{i=1}^{T} c_i \frac{N_A}{A_i}\sum_{k=1}^{p}\int_0^\infty \sigma_{j,i,k}(E)\times J_k(E,R,d)\,dE$$

Decaimiento en la Tierra

$$A_j(t)=P_j(R,d)\,e^{-\lambda_j t}$$

Separación química de elementos

2 mg de muestra de meteorito acondrito ferrorrocoso

^{10}Be ^{26}Al ^{36}Cl ^{41}Ca ^{53}Mn ^{59}Ni ^{60}Fe

HNO_3 (distillation)

+$AgNO_3$ ^{36}Cl as AgCl↓

80°C

Ag^{36}Cl for AMS

+HCl

^{10}Be ^{26}Al ^{41}Ca ^{53}Mn ^{59}Ni ^{60}Fe

+dipropopyl ether

org. ^{60}Fe

aq.

^{10}Be ^{26}Al ^{41}Ca ^{59}Ni

+10N HCl

Anion exchange

7N HCl ^{53}Mn

10N HCl

^{10}Be ^{26}Al ^{36}Cl ^{41}Ca

+NH_3 aq.

^{41}Ca ^{59}Ni

+1N HCl

Cation exchange

7.1N HCl ^{41}Ca

^{59}Ni

+$(NH_4)_2C_2O_4$ at 900°C

$^{41}CaH_2$ for AMS

^{10}Be ^{26}Al

+1N HCl

Cation exchange

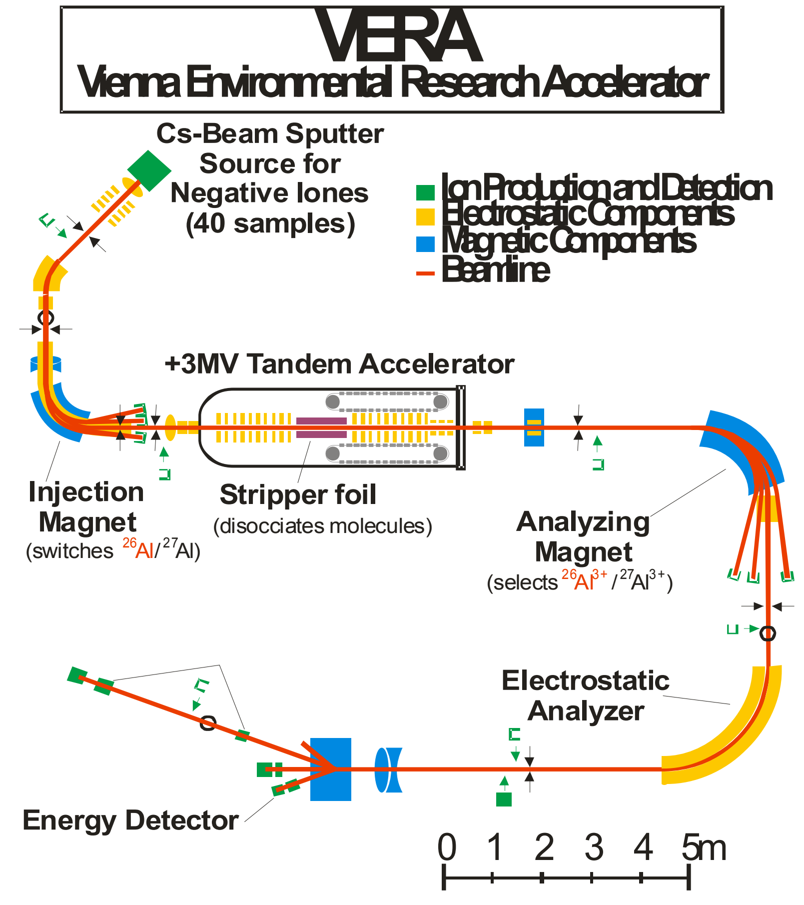
^{10}Be

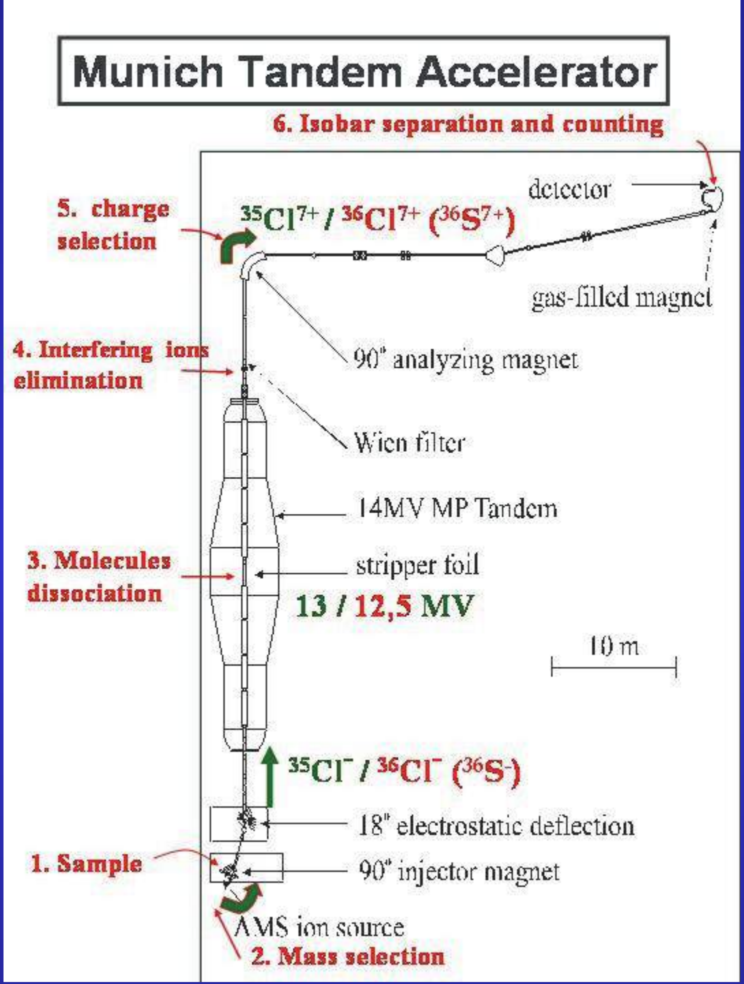
^{26}Al

+NH_3 aq. at 900°C

$^{26}Al_2O_3$ for AMS

Conteo de átomos con AMS





$^{26}\mathrm{Al}/^{27}\mathrm{Al} \sim 10^{-11}$

$^{36}\mathrm{Cl} / \mathrm{Cl} \sim 10^{-11}$

$^{41}\mathrm{Ca} / \mathrm{Ca} \sim 10^{-13}$

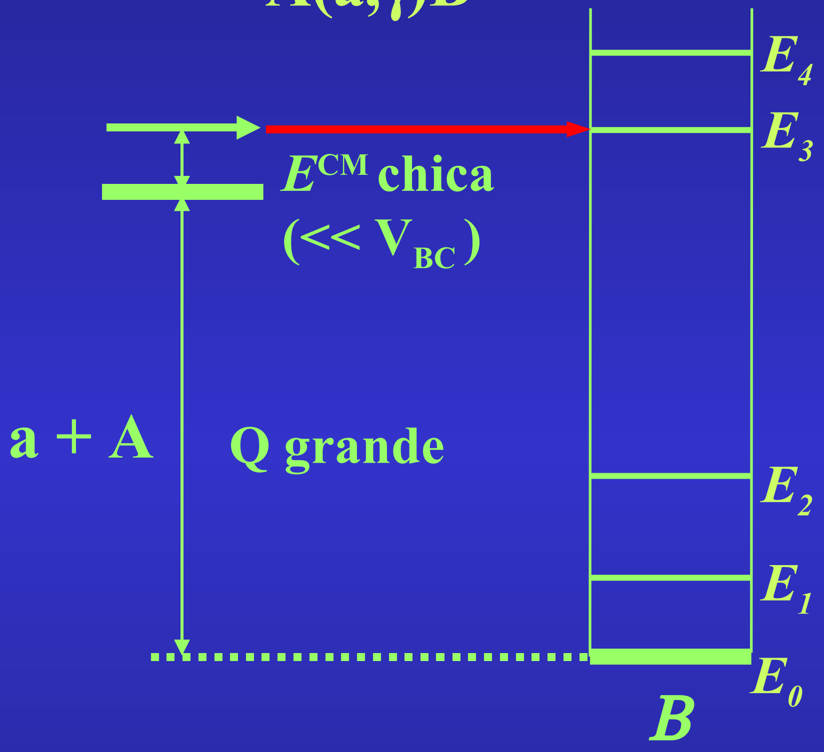
Resultados

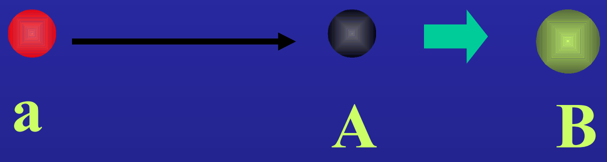
- Radio preatmosférico: 50 – 60 cm
- Posición de la muestra: 28 – 37 cm
- Edad terrestre 260 – 310 ka

Caballo de Troya

Reacción de interés

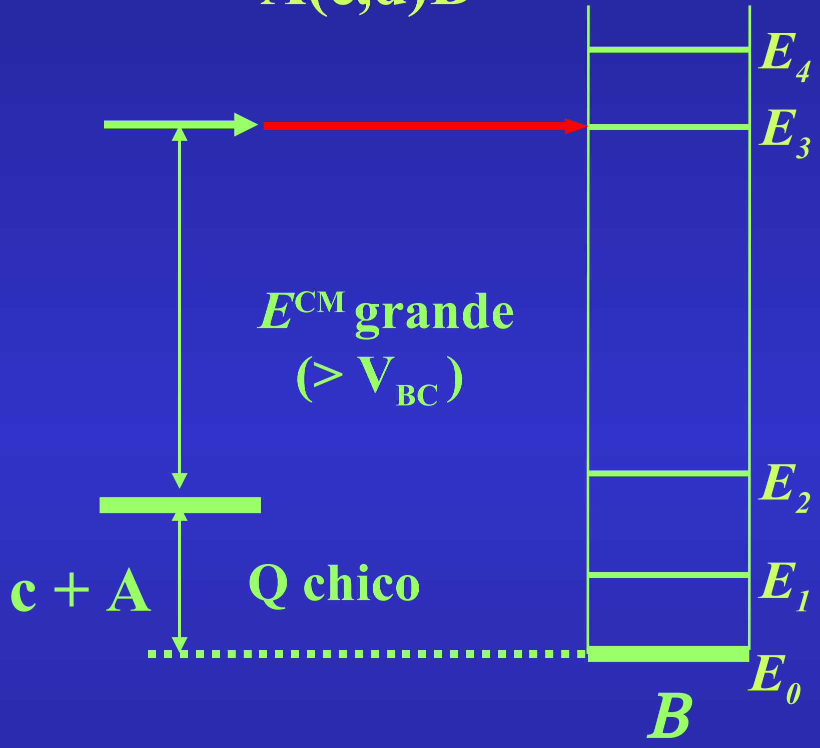
$A(a,\gamma)B$

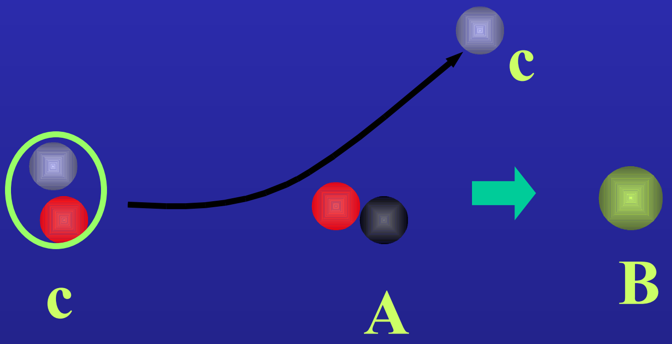




Reacción sustituta

$A(c,d)B$

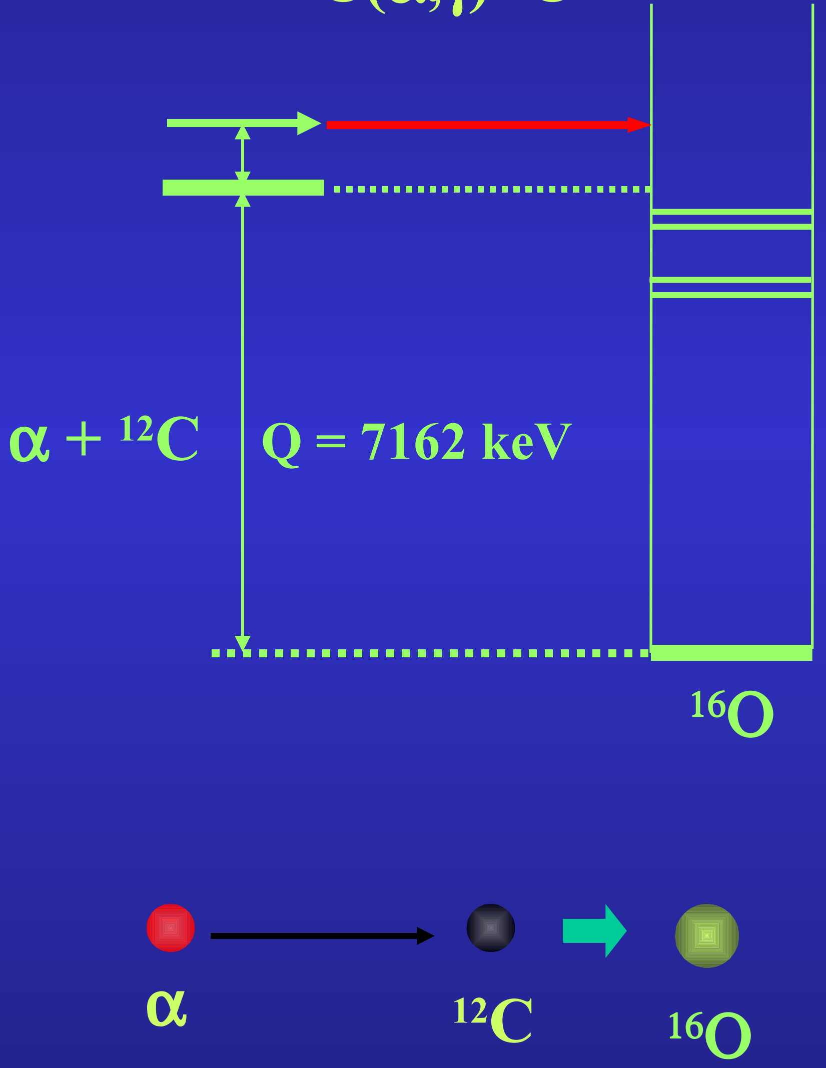




Reacción de α + ^{12}C en gigantes rojas

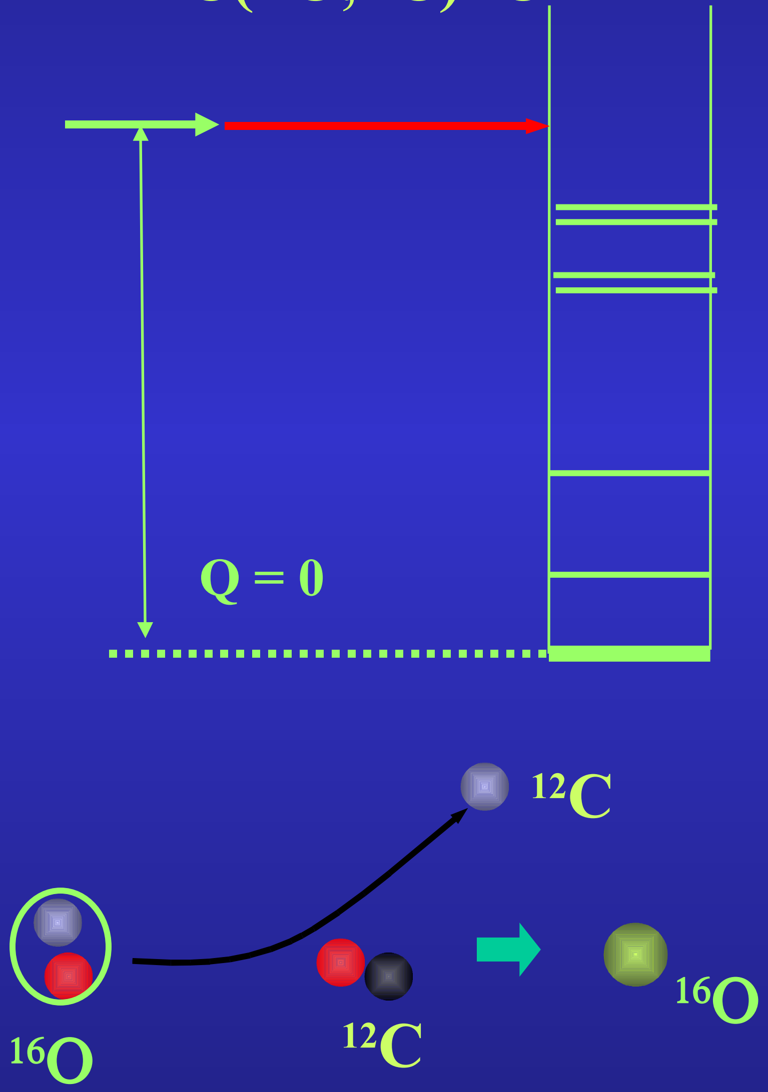
Reacción de interés

$^{12}C(\alpha,\gamma)^{16}O$

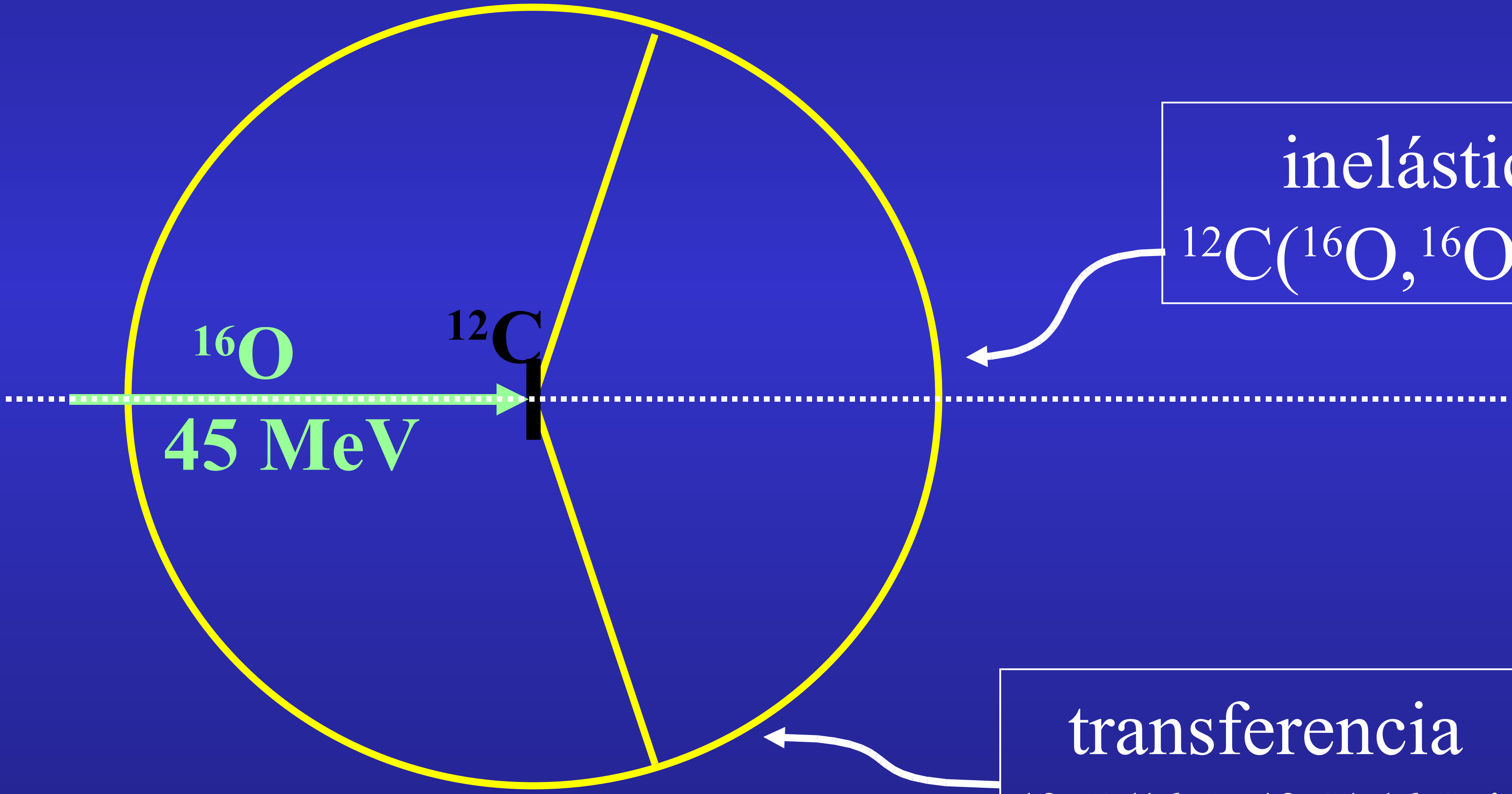


Reacción sustituta

$^{12}C(^{16}O,^{12}C)^{16}O$



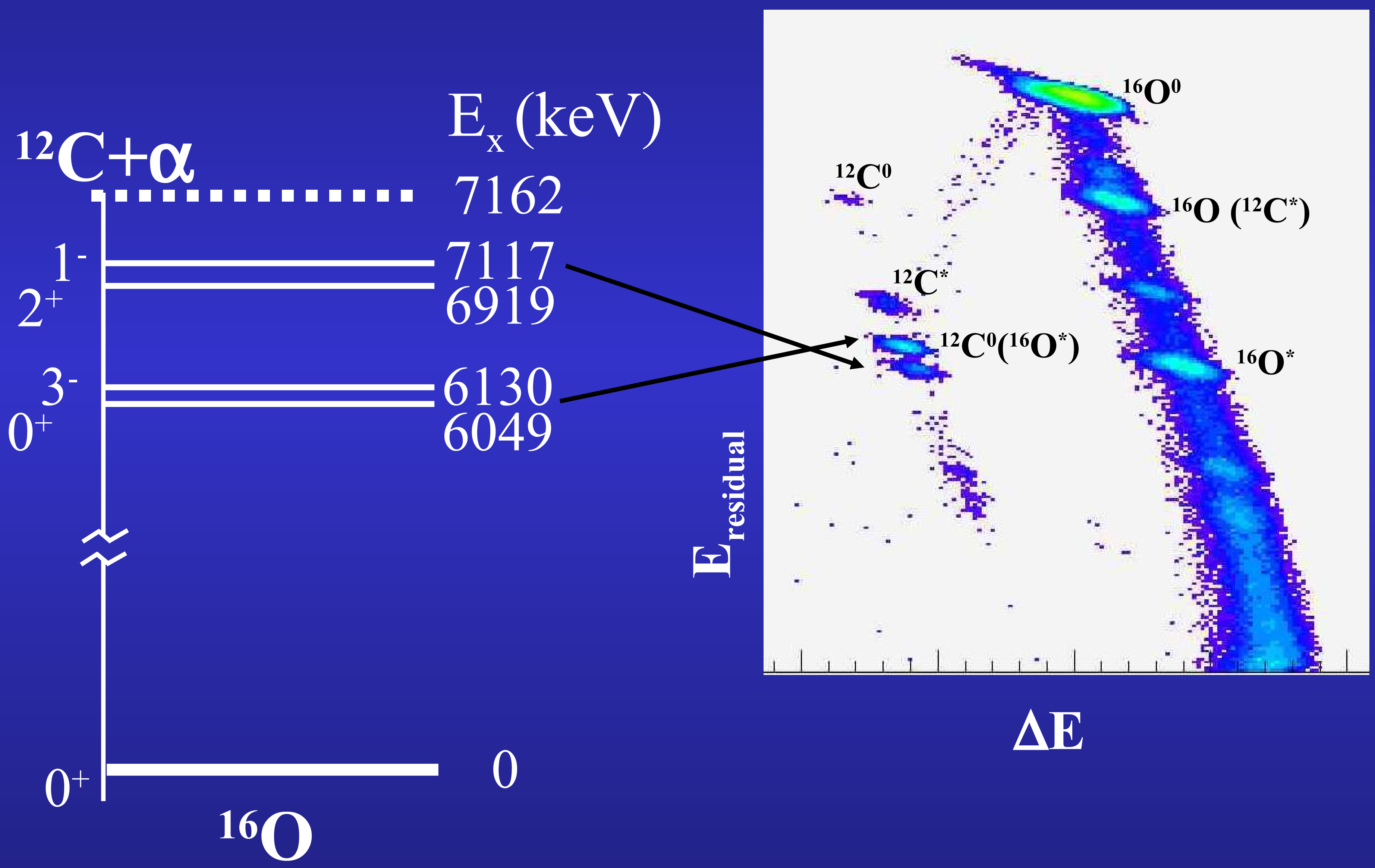
Transferencia de alfa y determinación de factores espectroscópicos subumbrales del proceso $\alpha + {}^{12}C$ de interés astrofísico



inelástico
$^{12}C(^{16}O,^{16}O^*)^{12}C$

transferencia
$^{12}C(^{16}O,^{12}C)^{16}O^*$

Factores espectroscópicos subumbrales del proceso $\alpha + {}^{12}C$



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