L'astrofisica nucleare: l'esperimento LUNA

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Breve storia dell'astrofisica-nucleare

- **1920: A.S. Eddington; Rep. Brit. Ass. Adv. Sci.; (Cardiff):**

"What is possible in the Cavendish Laboratory cannot be too difficult in the Sun".

- **1948*:* Gamow; Physical Review:** *tutti gli elementi prodotti durante la nucleosintesi primordiale.*
- **1957: E.M. Burbidge, G.R. Burbidge, W.A. Fowler and F. Hoyle;**

Review of Modern Physics: *"Synthesis of the Elements in Stars".*

- **1964: R. Davis Jr; Physical Review Letters:**

Rivelazione di neutrini solari nella minieara di Homestake.

- **oggi è noto che tutti gli eventi nell'Universo hanno lasciato dietro di loro una traccia nucleare.**

Lo scopo dell'Astrofisica-nucleare è la comprensione dei processi nucleari che avvengono in ambiente astrofisico:

- ✓ **Big Bang nucleosintesi;**
- ✓ **Nucleosintesi Galattica;**
- ✓ **Nuclesosintesi stellare e generazione di energia.**

Luminosità versus Temperature

Stelle come Corpo Nero

$$L = 4\pi R^2 \sigma T^4_{eff}$$

Principali proprità della sequenza principale

$M_\odot = 1.989 * 10^{33}$ g

$M \sim 0.5 - 40\ M_\odot$

$R_\odot = 6.9599 * 10^{10}$ cm

$R \sim 0.8 - 13\ R_\odot$

$L_\odot = 3.826 * 10^{33}$ ergs s

$L \sim 0.08 - 4 \times 10^5\ L_\odot$

$T_\odot = 5800$ K

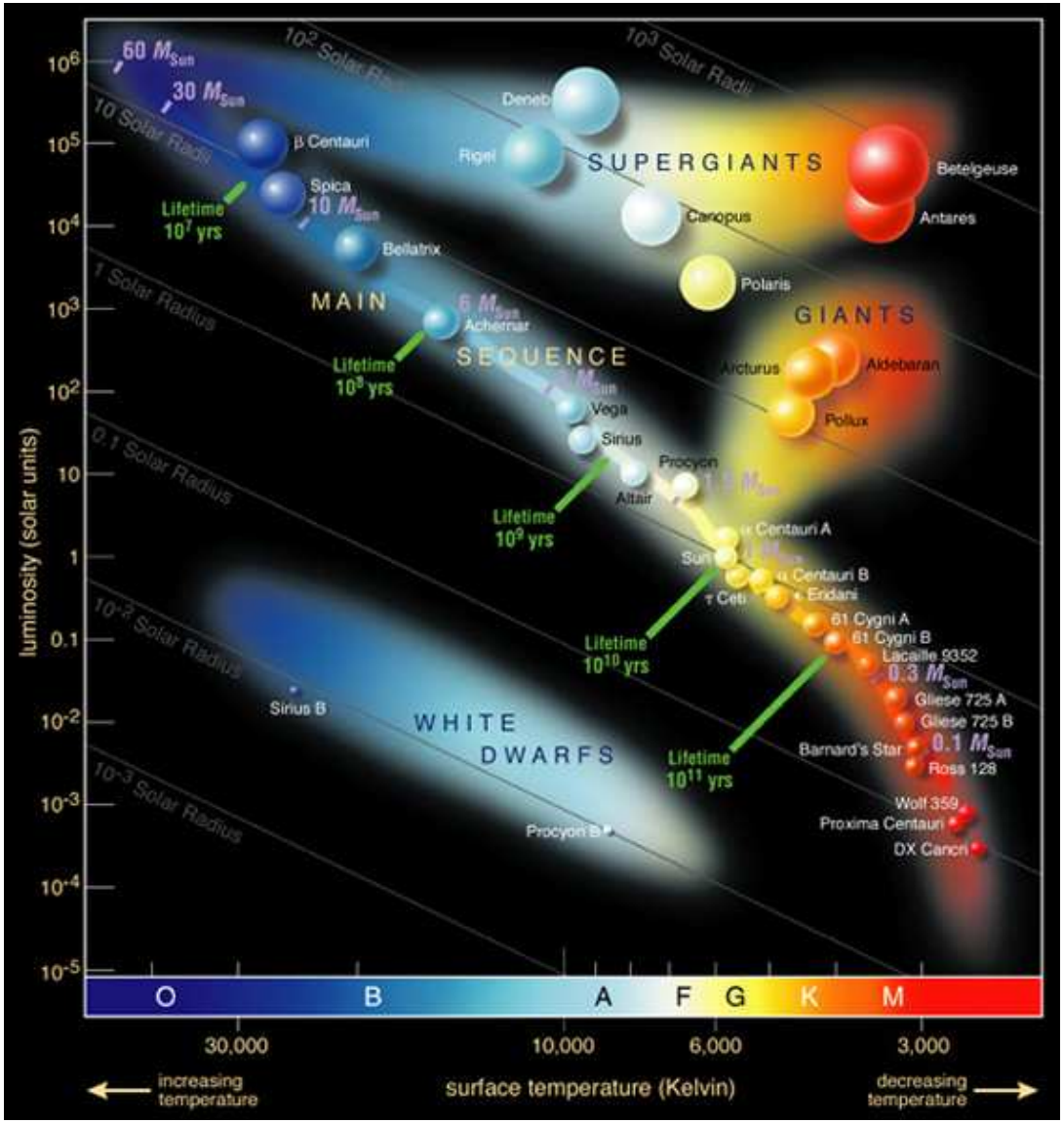
$T \sim 3500 - 40000\ T_\odot$

Luminosity

~ 95% delle stelle nella MAIN SEQUENCE

⇒ massima probilità di osservazione

Hertzsprung-Russel (HR) Diagram



Quanto tempo vivono le stelle

Possibili tempi scali per il Sole

1. tempo di caduta libera $t_{ff} = \left(\frac{R^3}{GM}\right)^{1/2} \sim 26$ min

2. tempo scala di Kelvin-Helmotz $t_K = \frac{E_T}{L_\odot} \sim 4.4 \cdot 10^7$ y

tempo scala biologico $>10^8$y

radioattività delle rocce ~ 10^9 y

$$E_G = -\frac{GM^2}{R} \approx 2E_T = \frac{3}{2}\frac{k}{m}TM \approx 4 \cdot 10^{48} erg$$

3. tempo scala di Einstein o nucleare $t_E = \frac{0.008 * Mc^2}{L} \sim 1.1 \cdot 10^{11}$ y

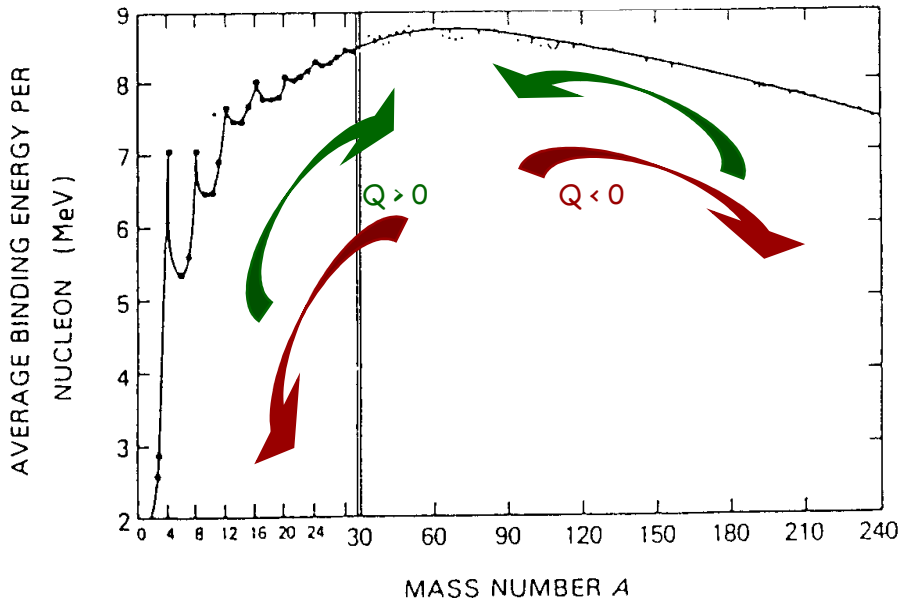
LA FISICA NUCLEARE È CRUCIALE PER COMPRENDERE L'EVOLUZIONE STELLARE

Q-valore di una reazione

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

$$Q=(M_a+M_b-M_c-M_d)c^2 \begin{cases} >0 \text{ esoenergetica} \\ <0 \text{ endoenergetica} \end{cases}$$

Energia di legame al variare di *A*

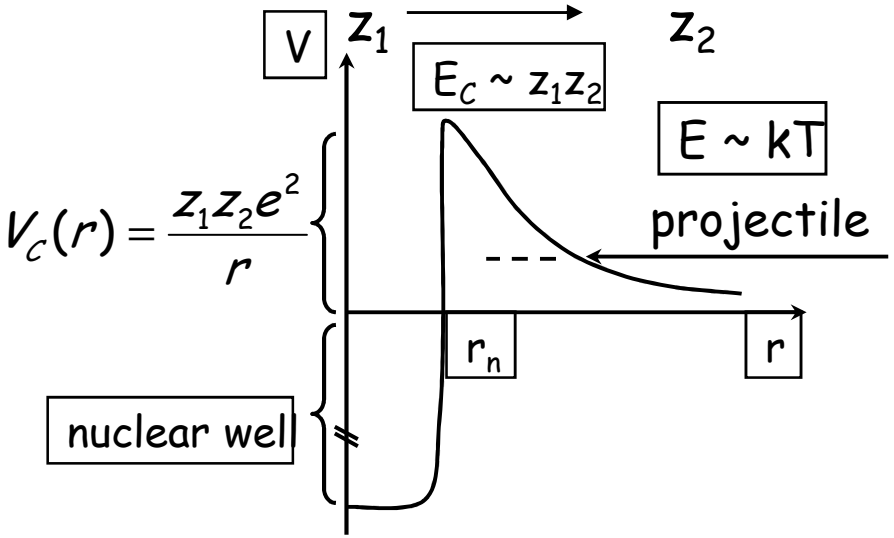


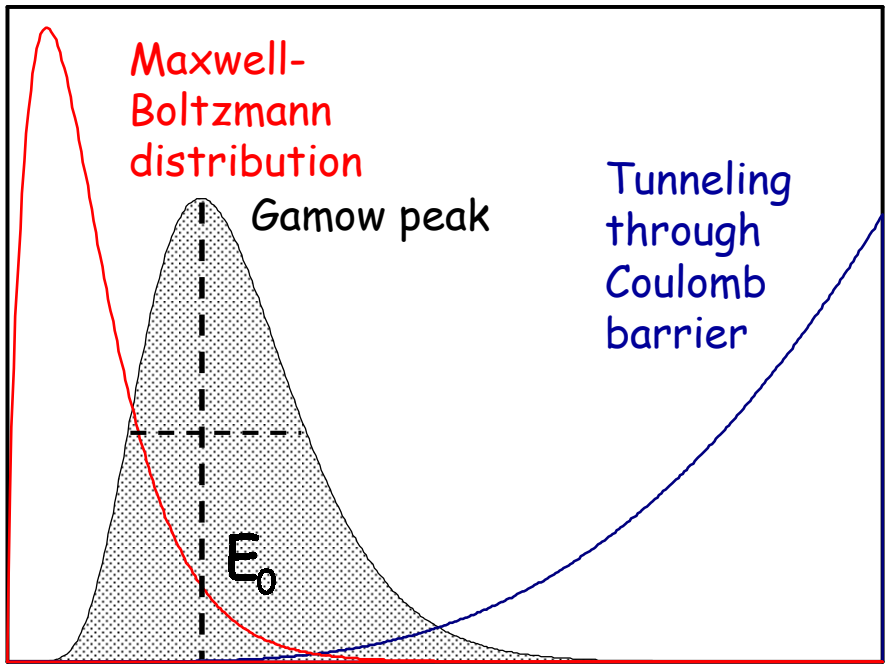
processi nucleari spontanei: **Q > 0**

fusione fino al Fe

fissione oltre il Fe

Le reazioni nucleari nelle stelle





Esempio z_1=p and z_2=p (nel Sole)

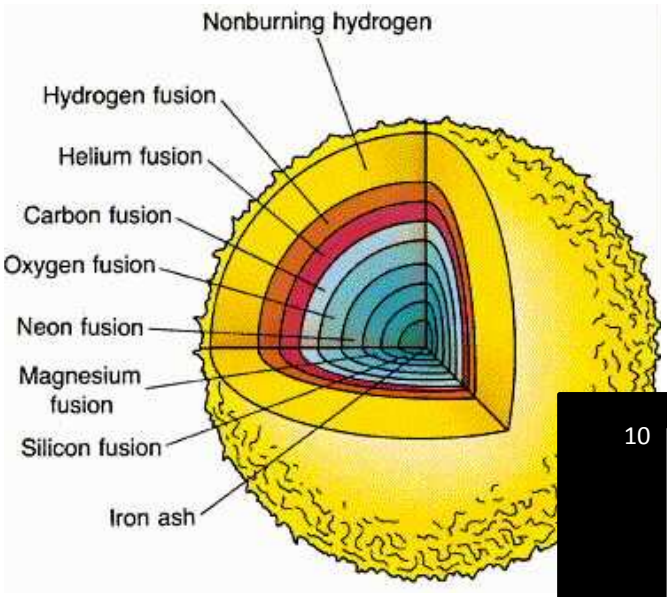
$T \sim 15 \times 10^6$ K $\Rightarrow$ $E = kT \sim 1$ keV

$E_C = 550$ keV

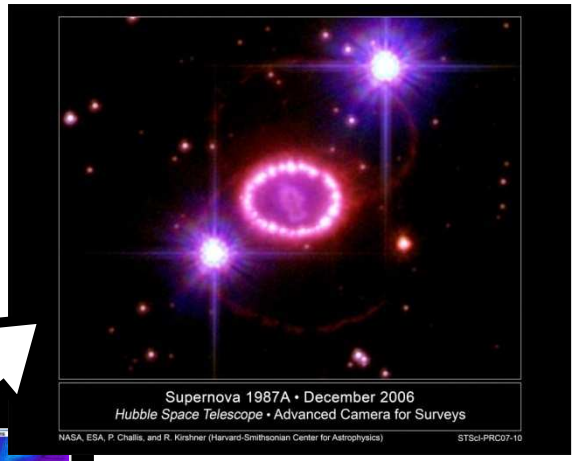
Durante le combustioni quiescenti:
$kT \ll E_c$
Le reazione avvengono per TUNNEL EFFECT

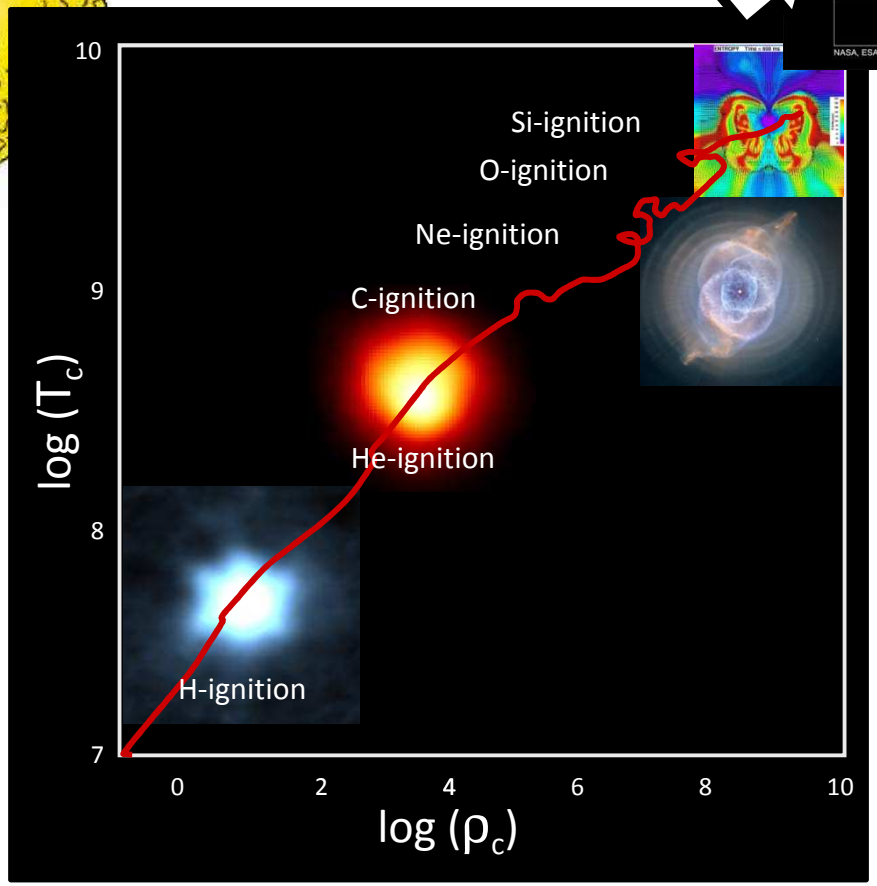
reaction	Coulomb barrier (MeV)	E_0 (keV)
p + p	0.55	5.9
$\alpha + {}^{12}C$	3.43	56
${}^{16}O + {}^{16}O$	14.07	237

Vita e "morte" di una stella

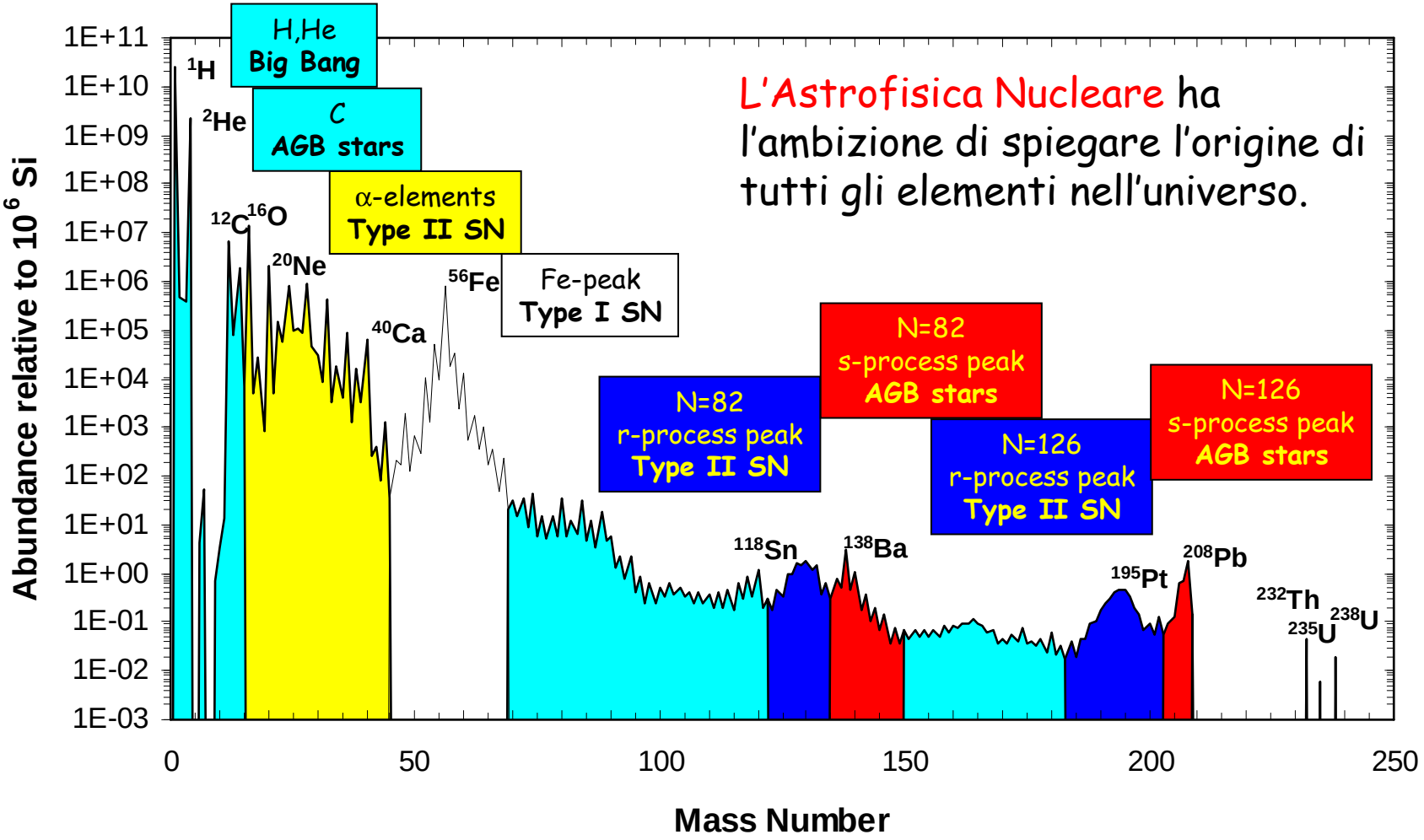


Supernova





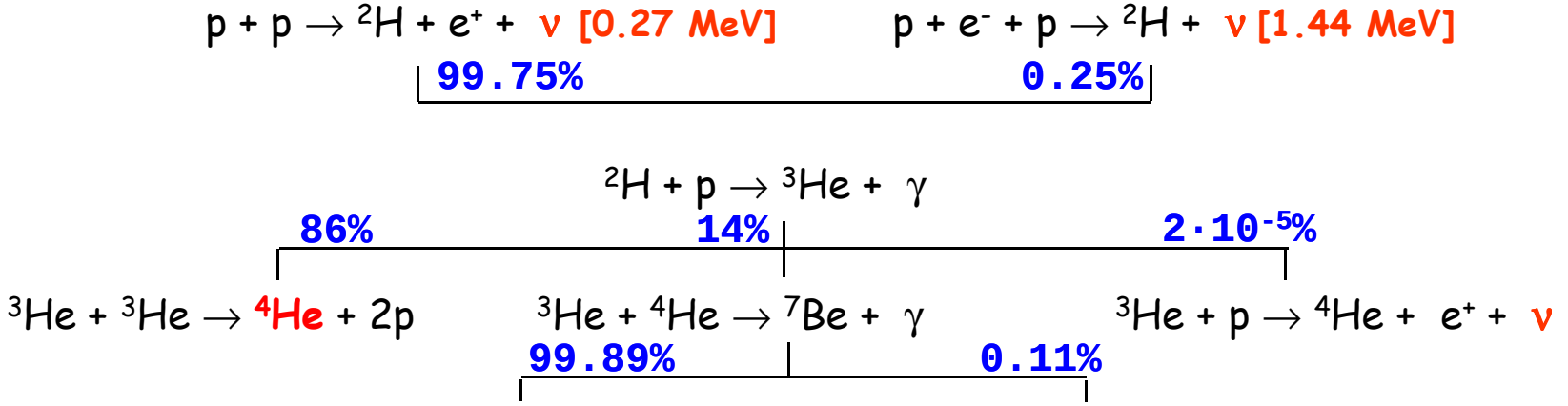
L'origine degli elementi



Ogni molecola del nostro corpo contiene materiale che è stato esposto alle enormi temperature e pressioni presenti nel centro di una stella; dove il **ferro** presente nel nostro sangue, l'**ossigeno** che noi respiriamo, il **carbonio** e l'azoto nei nostri tessuti e il **calcio** nelle nostra ossa si sono originati.

H burning

pp chain

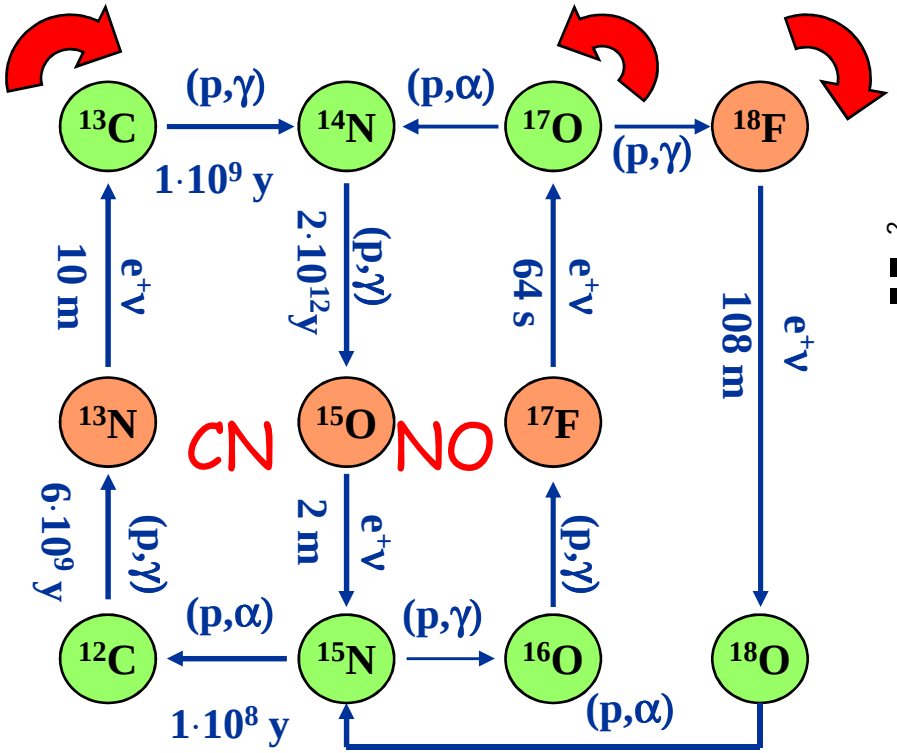


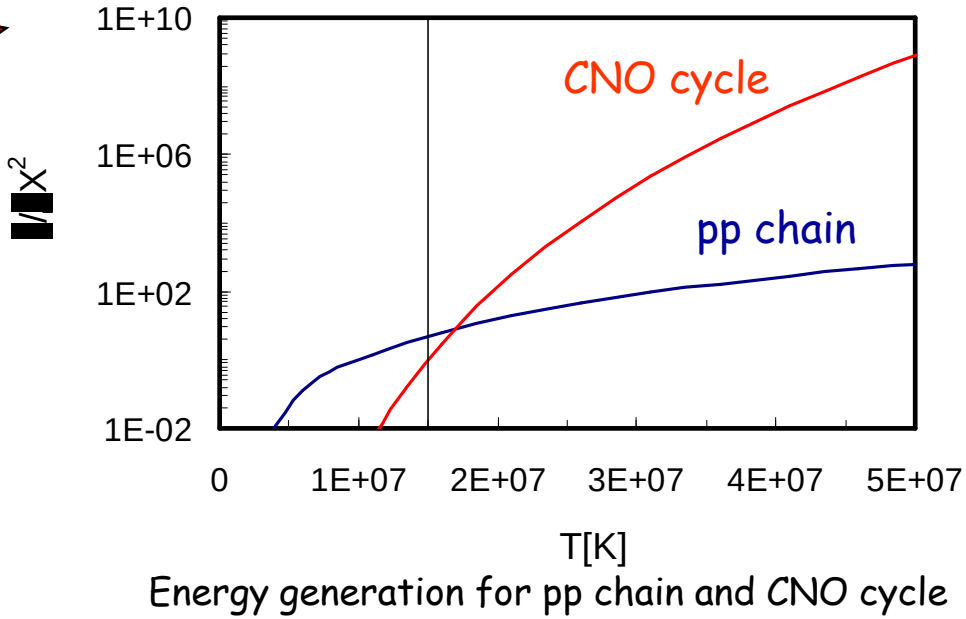
CHAIN I	CHAIN II	CHAIN III	CHAIN IV
Q_{eff} = 26.20 MeV	Q_{eff}= 25.66 MeV	Q_{eff}= 19.67 MeV	Q_{eff}= 16.84 MeV

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

H burning

CNO CYCLE





Energy generation for pp chain and CNO cycle

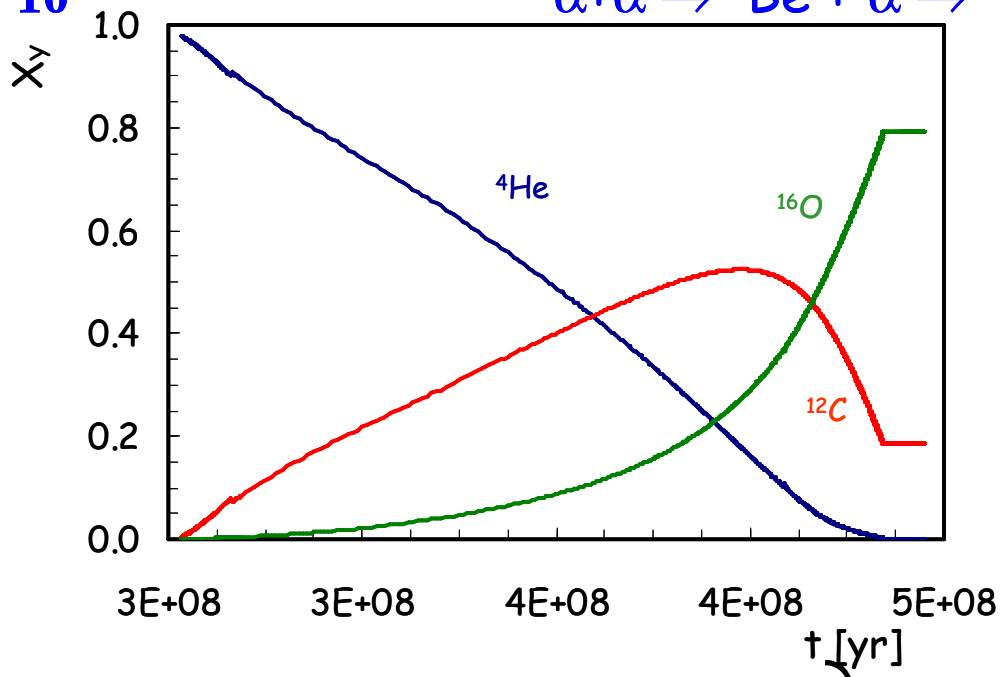
CN	NO
Q_{eff} = 26.02 MeV	Q_{eff} = 25.73 MeV

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

Le altre combustioni

$10^8 < T_C < 3.5*10^8$

$\alpha+\alpha \rightarrow {}^8Be + \alpha \rightarrow {}^{12}C + \alpha \rightarrow {}^{16}O$



$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{12}C,p)^{23}Na$ → $^{23}Na(p,\alpha)^{20}Ne$, $^{23}Na(p,\gamma)^{24}Mg$ } C-burning

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

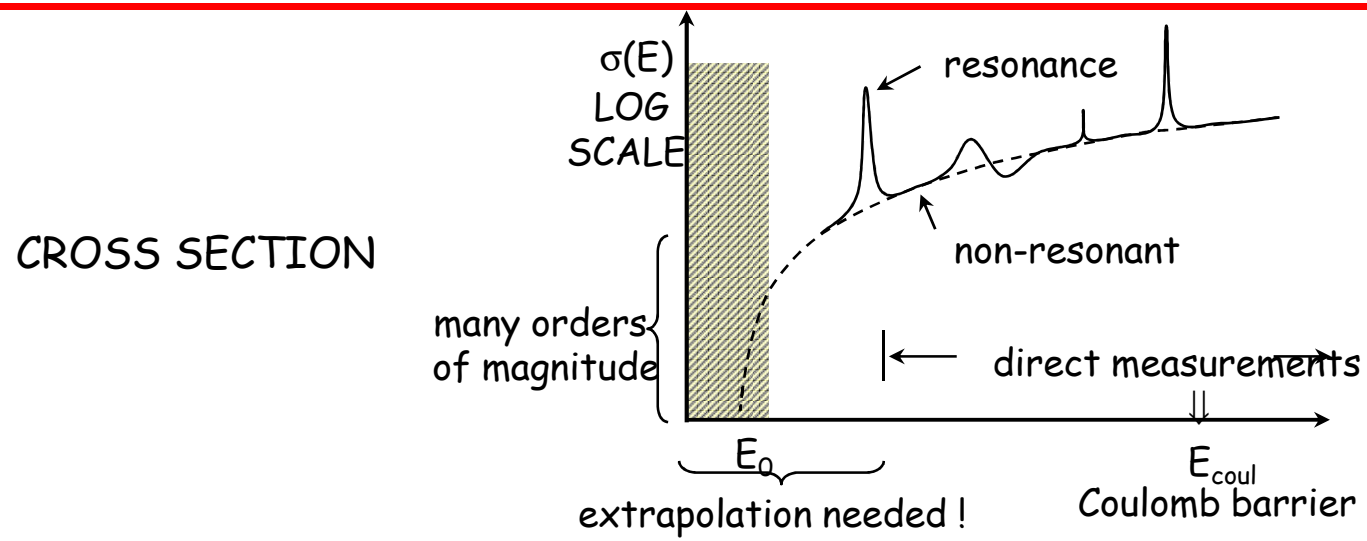
$^{20}Ne(\alpha,\gamma)$

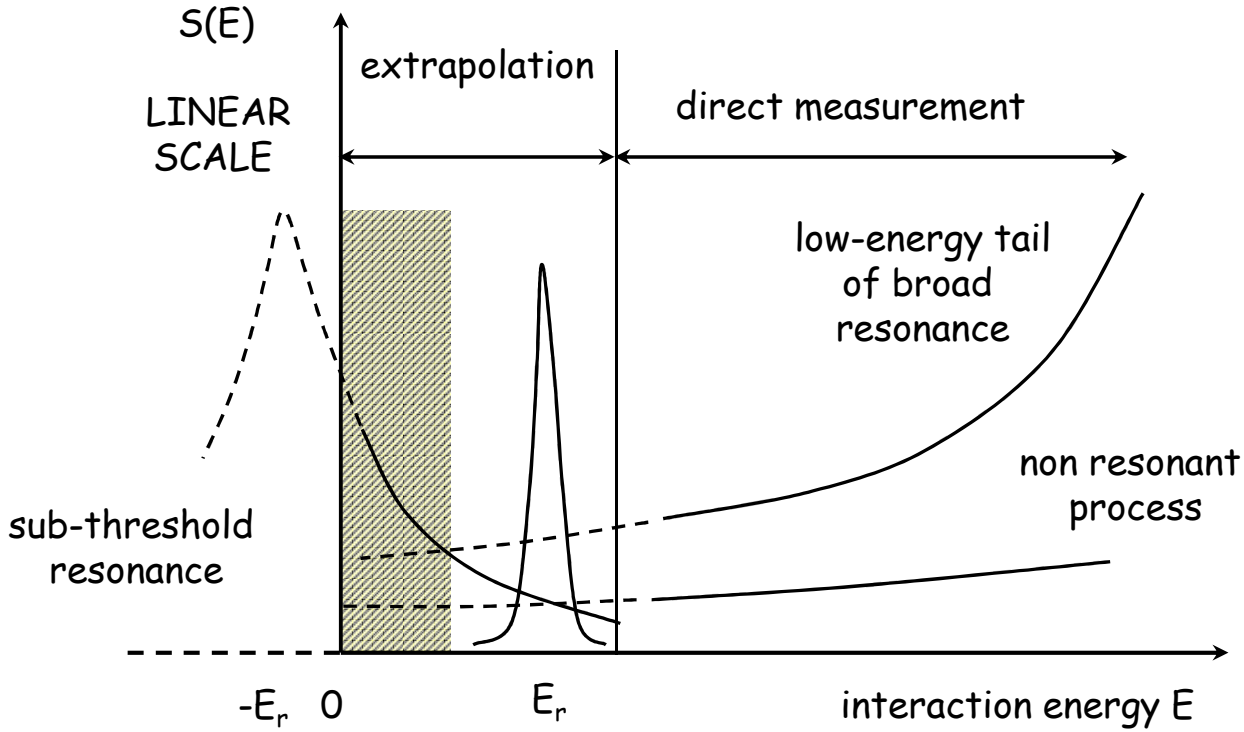
$^{23}Na(p,\gamma)$

→ ^{24}Mg → (α,γ), $(n,\gamma)^{24}Mg(\alpha,n)$ → ^{28}Si } Ne-burning

Problematiche sperimentali

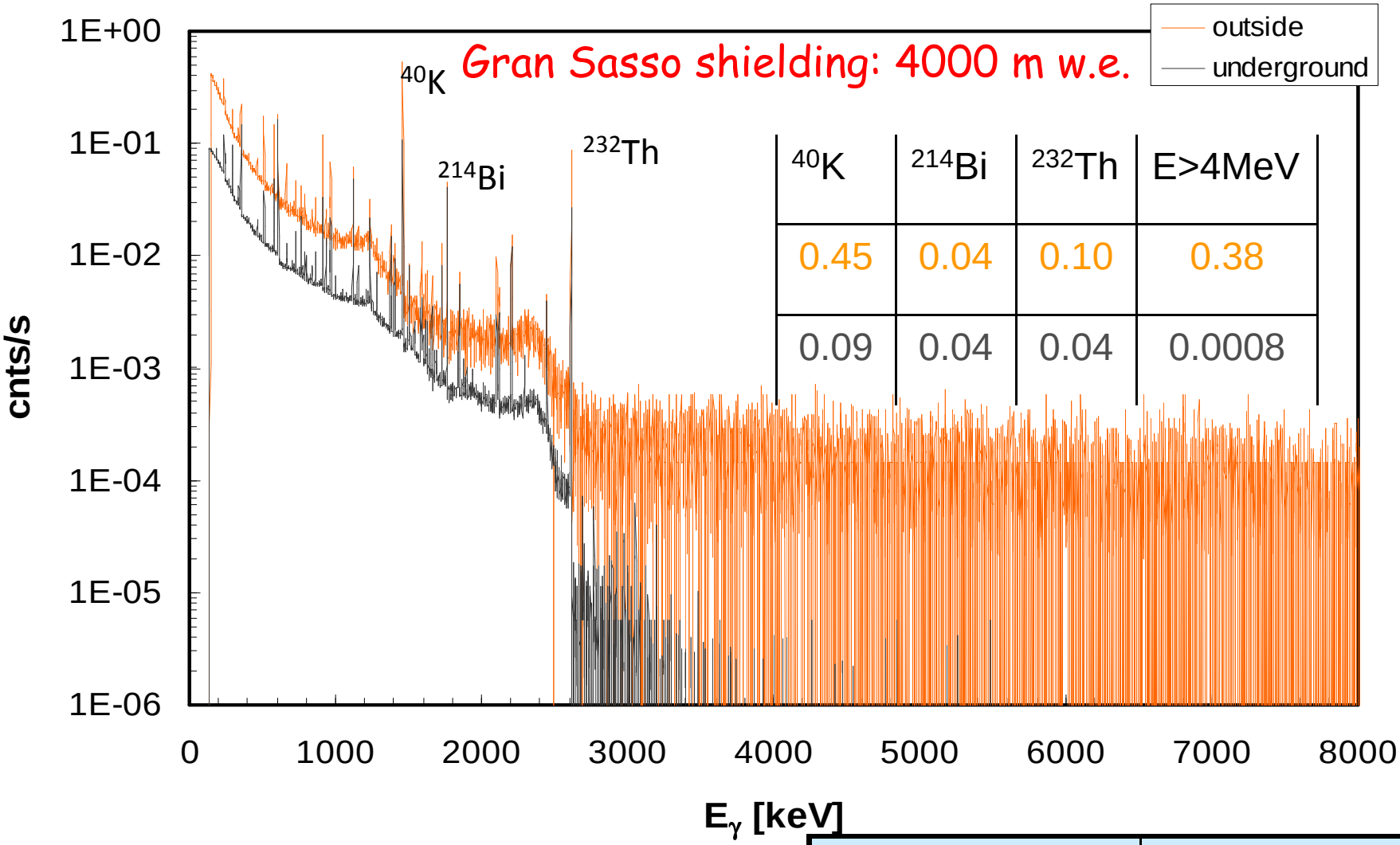
Il problema dell'estrapolazione alle basse energie





S(E)-FACTOR

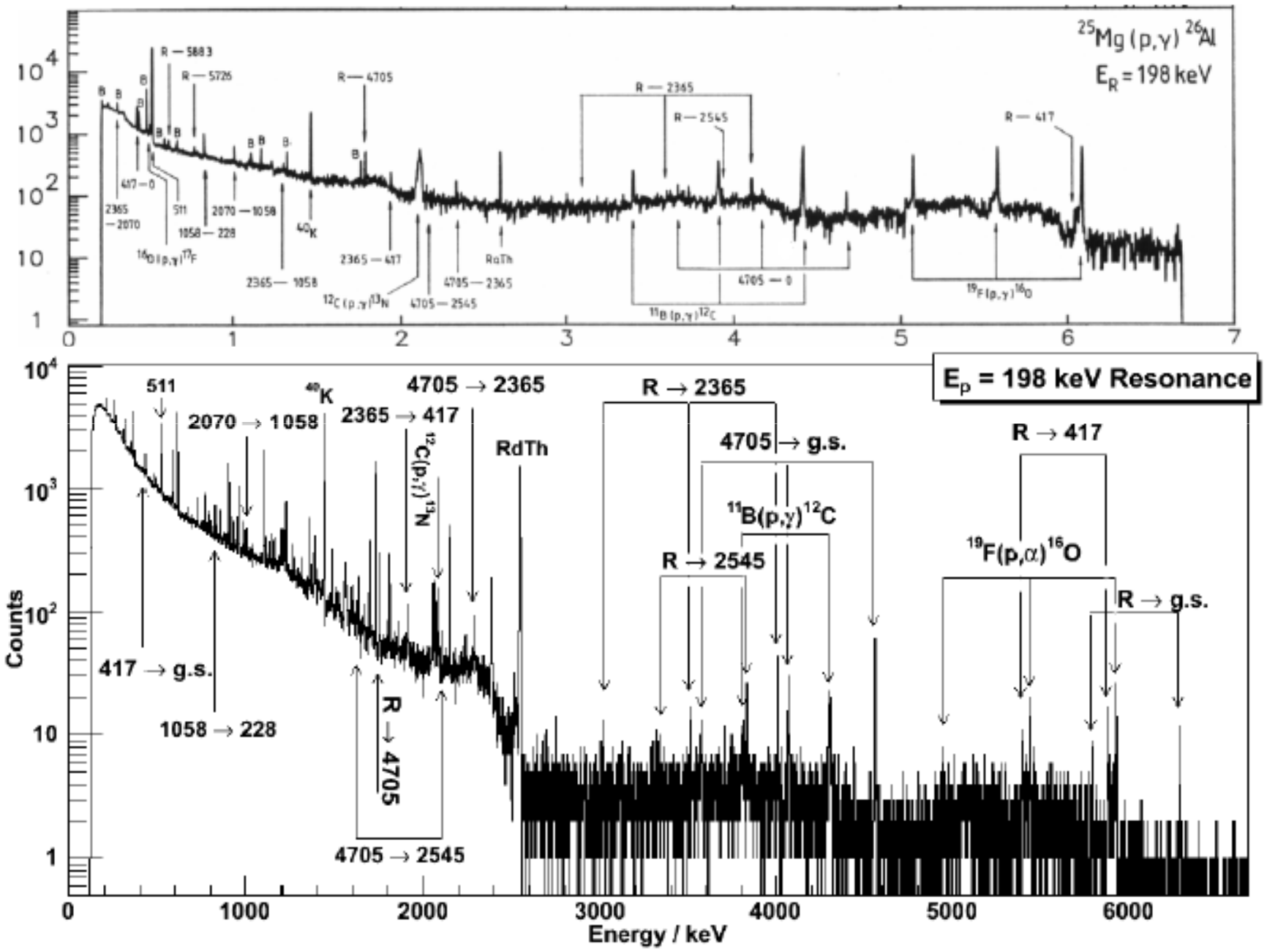
Perché andare sottoterra



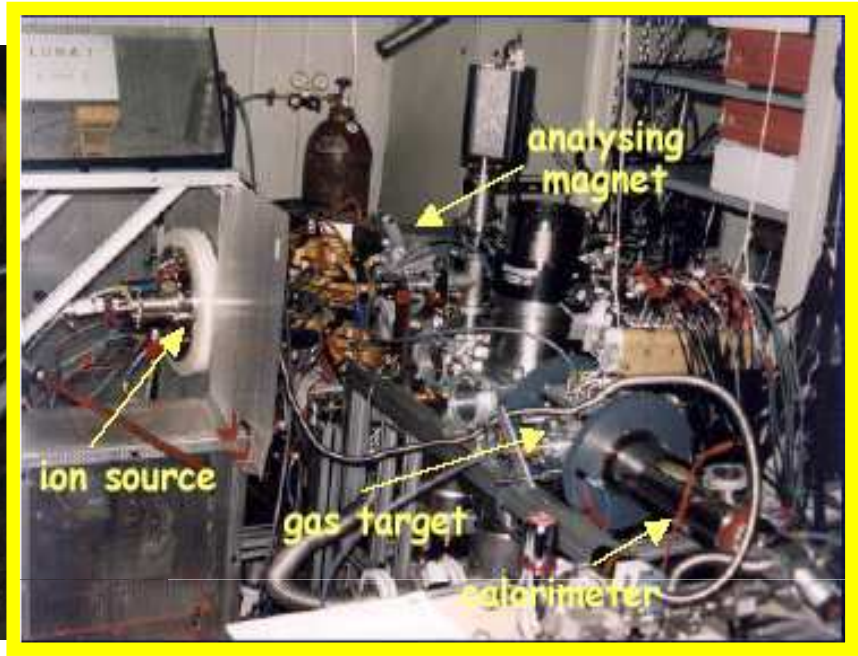
^{40}K	^{214}Bi	^{232}Th	E>4MeV
0.45	0.04	0.10	0.38
0.09	0.04	0.04	0.0008

Radiation	LNGS/out
muons	10^{-6}
neutrons	10^{-3}

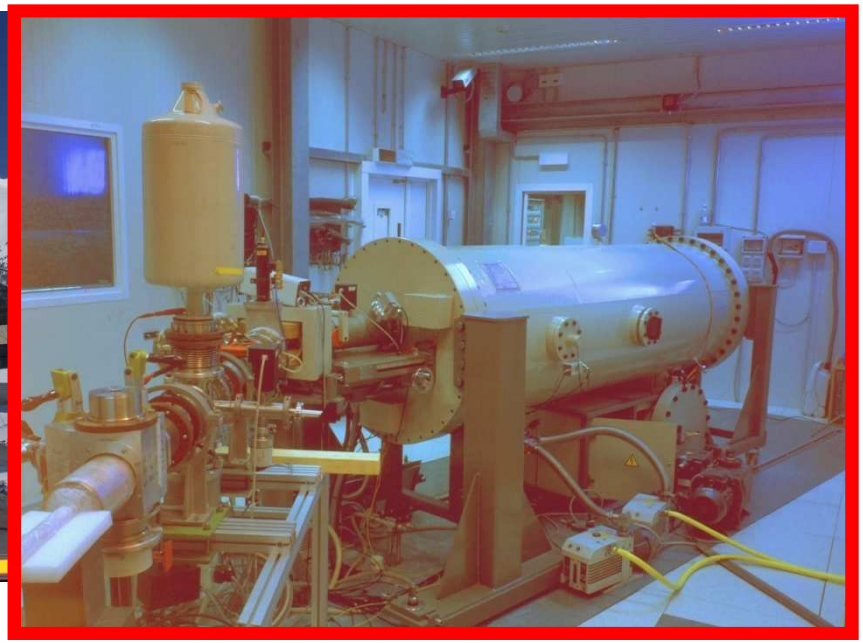
Un esempio.....


^{25}Mg (p,γ) ^{26}Al
E_R = 198 keV
R — 5883
R — 5725
R — 4705
R — 2365
R — 2545
R — 417
511
2365 — 2070
417 — 0
2070 — 1058
1058 — 228
^{40}K
RdTh
2365 — 1058
2365 — 417
4705 — 2365
4705 — 2545
4705 — 0
^{16}O (p,γ) ^{17}F
^{12}C (p,γ) ^{13}N
^{11}B (p,γ) ^{12}C
^{19}F (p,γ) ^{16}O
E_p = 198 keV Resonance
511
^{40}K
4705 → 2365
2365 → 417
2070 → 1058
RdTh
^{12}C(p,γ)^{13}N
R → 2365
4705 → g.s.
^{11}B(p,γ)^{12}C
R → 2545
R → 417
^{19}F(p,α)^{16}O
R → g.s.
417 → g.s.
1058 → 228
R → 4705
4705 → 2545
Counts
Energy / keV

LUNA 1997-2009 - experimental set-up

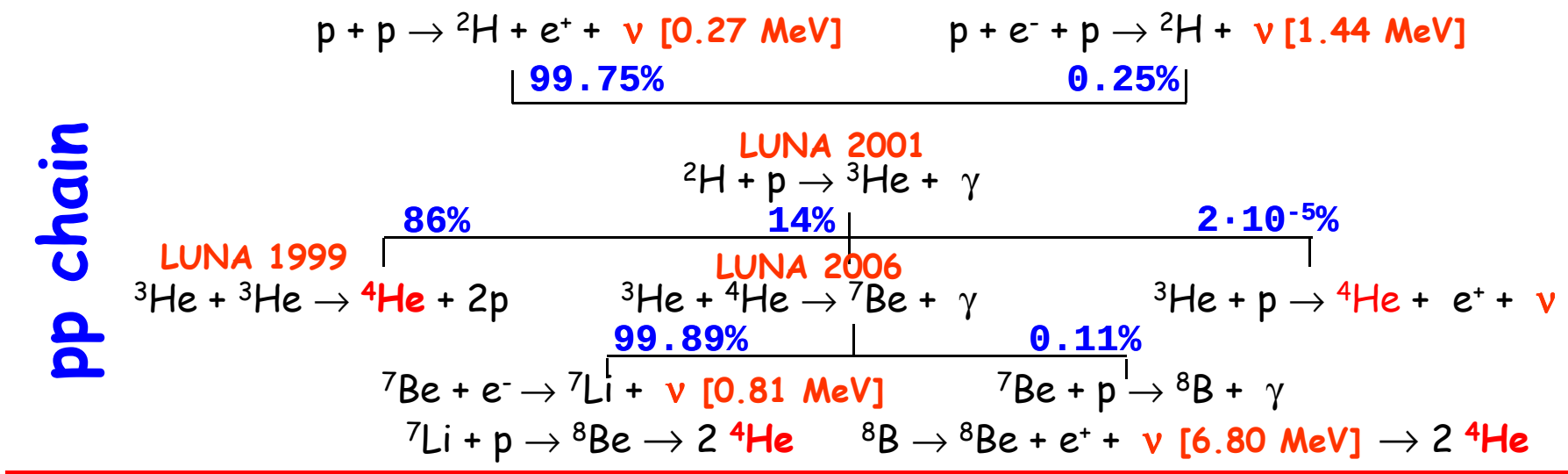


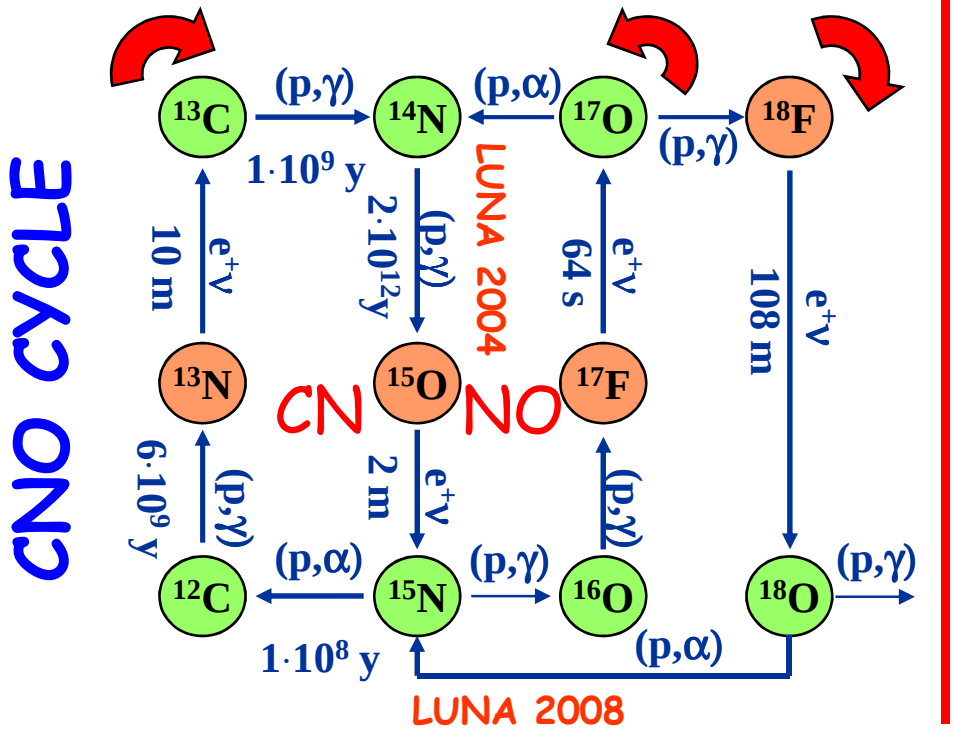
Voltage Range :
1 - 50 kV
Output Current:
1 mA
Beam energy spread:
20 eV

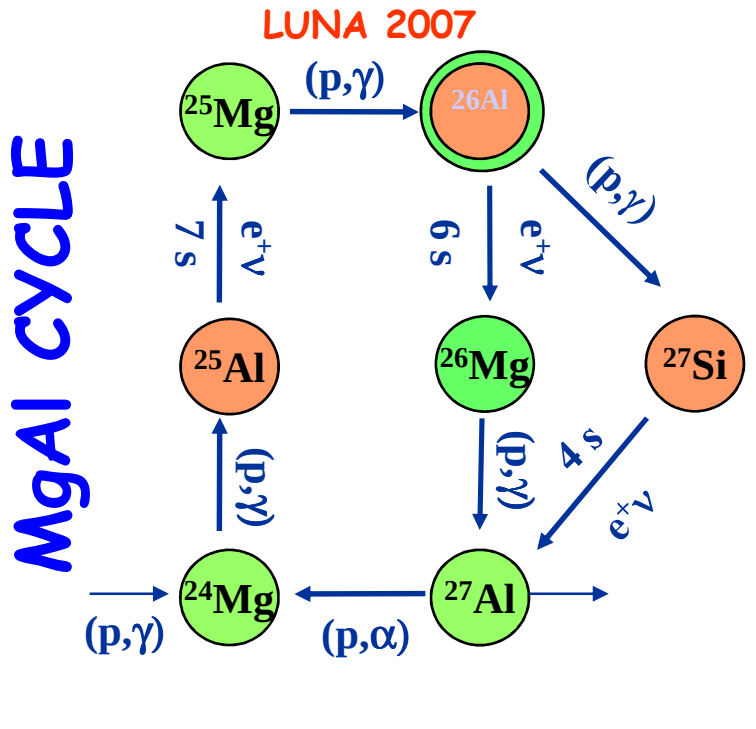


Voltage Range :
50 - 400 kV
Output Current:
500 μA
Beam energy spread:
70 eV

LUNA 1997-2009 - results







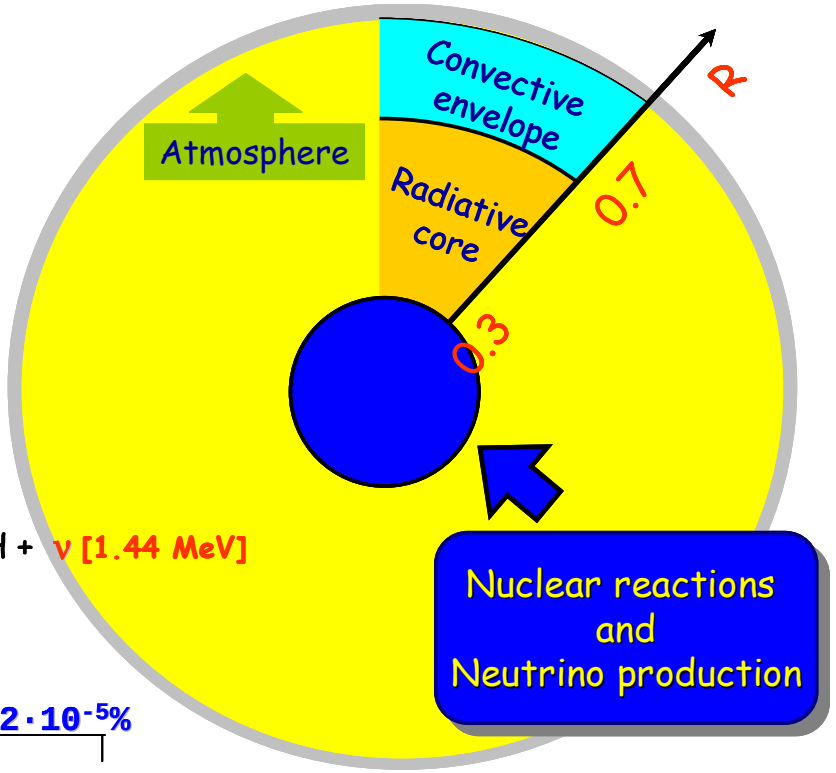
LUNA

Solar neutrino

Where Neutrinos are generated

$^{13}N \rightarrow {}^{13}C + e^+ + \nu$
$^{15}O \rightarrow {}^{15}N + e^+ + \nu$
$^{17}F \rightarrow {}^{17}O + e^+ + \nu$

} CNO cycle



pp-chain

$p + p \rightarrow {}^2H + e^+ + \nu$ [0.27 MeV] (99.75%)
$p + e^- + p \rightarrow {}^2H + \nu$ [1.44 MeV] (0.25%)

$^2H + p \rightarrow {}^3He + \gamma$

86% | 14% | $2 \cdot 10^{-5}$%

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

$^3He + {}^4He \rightarrow {}^7Be + \gamma$ (99.89% | 0.11%)

$^3He + p \rightarrow {}^4He + e^+ + \nu$

$^7Be + e^- \rightarrow {}^7Li + \nu$ [0.81 MeV]

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

$^7Li + p \rightarrow {}^8Be$

$^8B \rightarrow {}^8Be + e^+ + \nu$ [6.80 MeV]

$^8Be \rightarrow 2\ {}^4He$

$^8Be \rightarrow 2\ {}^4He$

CHAIN I	CHAIN II	CHAIN III	CHAIN IV
Q_{eff} = 26.20 MeV	Q_{eff}= 25.66 MeV	Q_{eff}= 19.67 MeV	Q_{eff}= 16.84 MeV

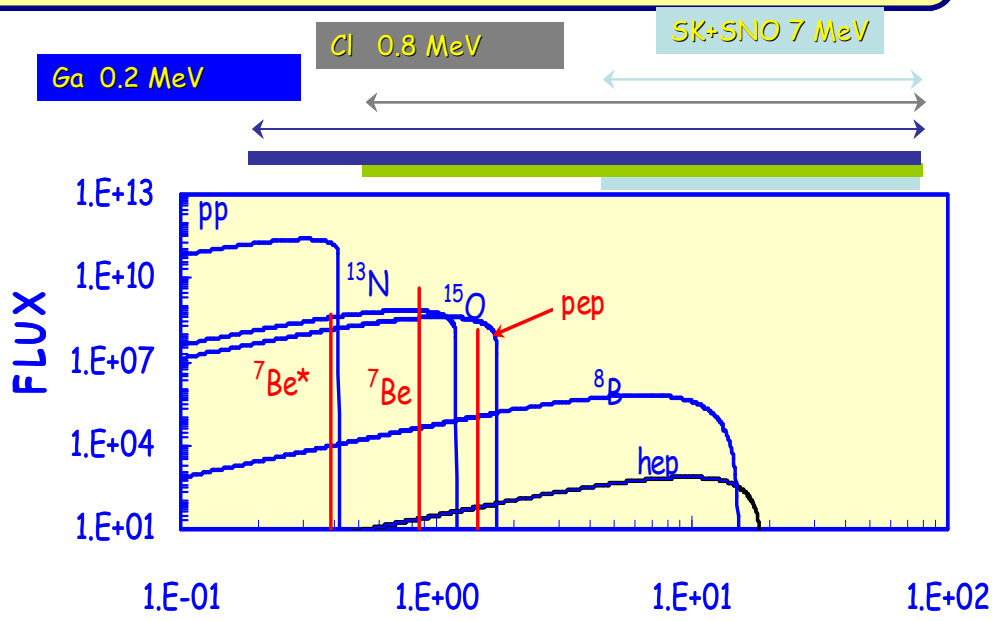
The solar neutrino problem

1. MISSING NEUTRINO: in Ga experiments (75 ± 8) SNU measured vs (129 ± 3) SNU expected

2. $^{7}Be/^{8}B$ anomaly: incompatibility Kamiokande/Homestake experiments

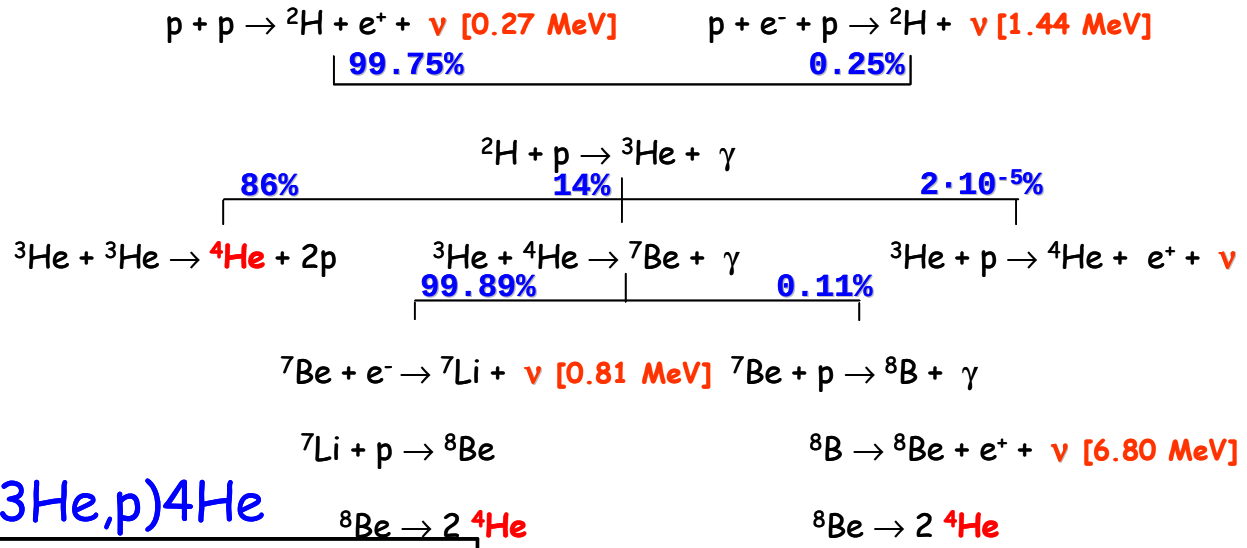
3. MISSING ^{7}Be NEUTRINO: Using data from Ga and SK experiments $73^{pp} + 5^{8B} > 75$

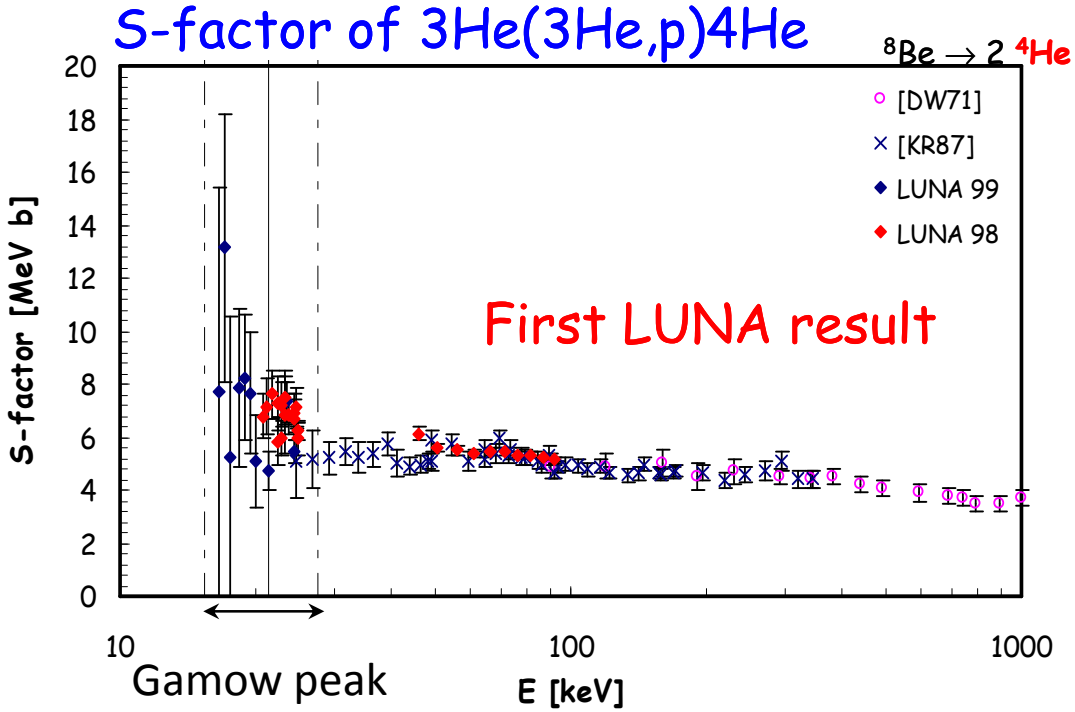
The solution of solar neutrino problem is not in the uncertainty of SSM



Situation before SNO results

Possible solution before SNO and Kamland





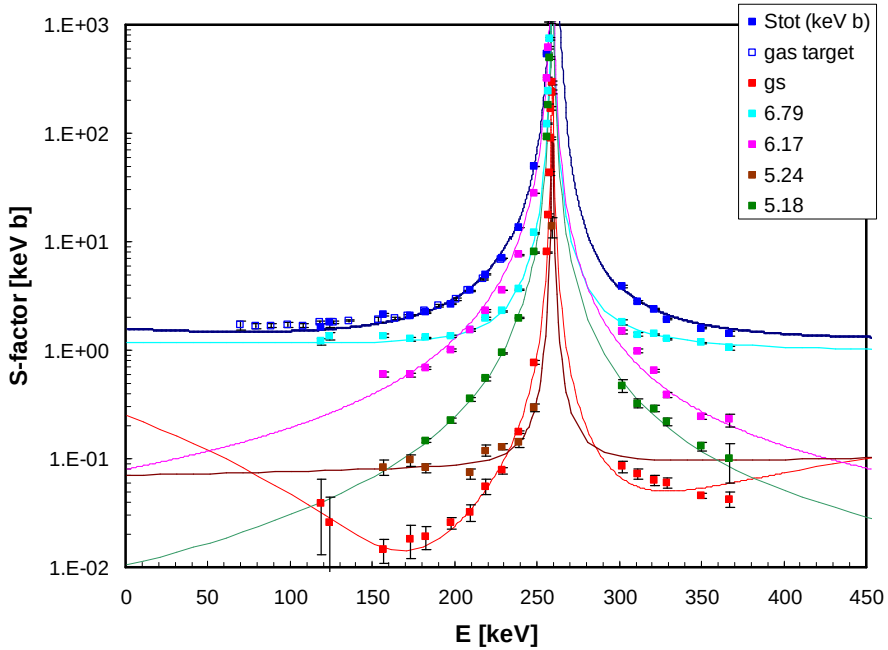
Cross section of ^{3}He(^{3}He,2p)^{4}He measured at solar energies
Phys. Rev. C 57(1998)2700

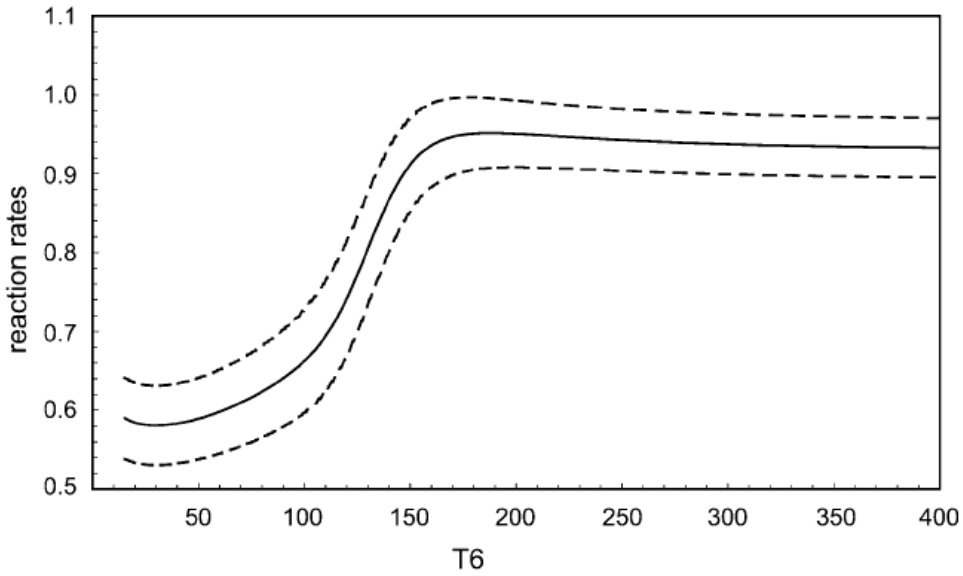
First measurement of the ^{3}He(^{3}He,2p)^{4}He cross section down to the lower edge of the solar Gamow peak Phys. Rev. Lett. 82(1999)5205

$^{14}N(p,\gamma)^{15}O$

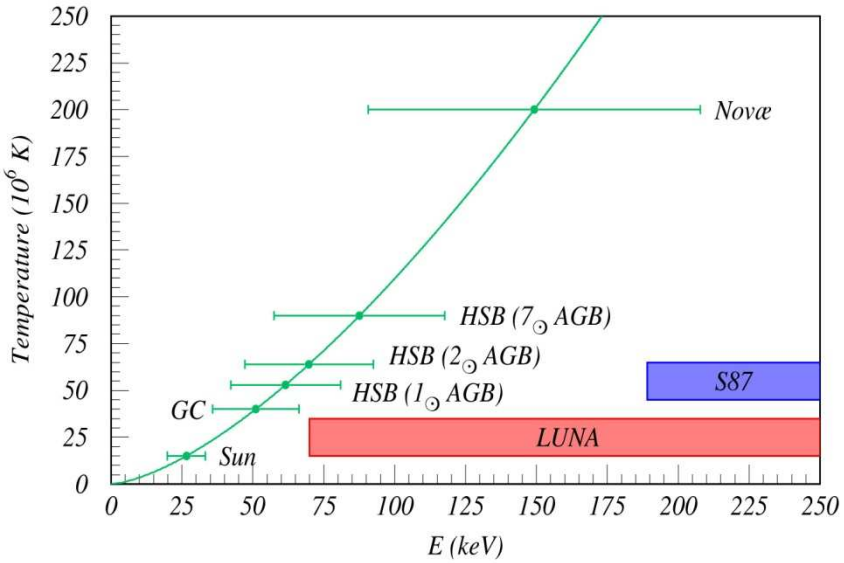
Age of Globular Clusters

Risultati della $^{14}N(p,\gamma)^{15}O$

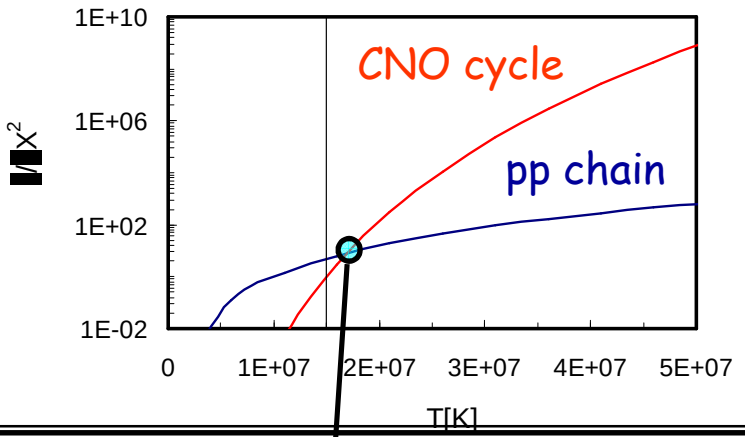




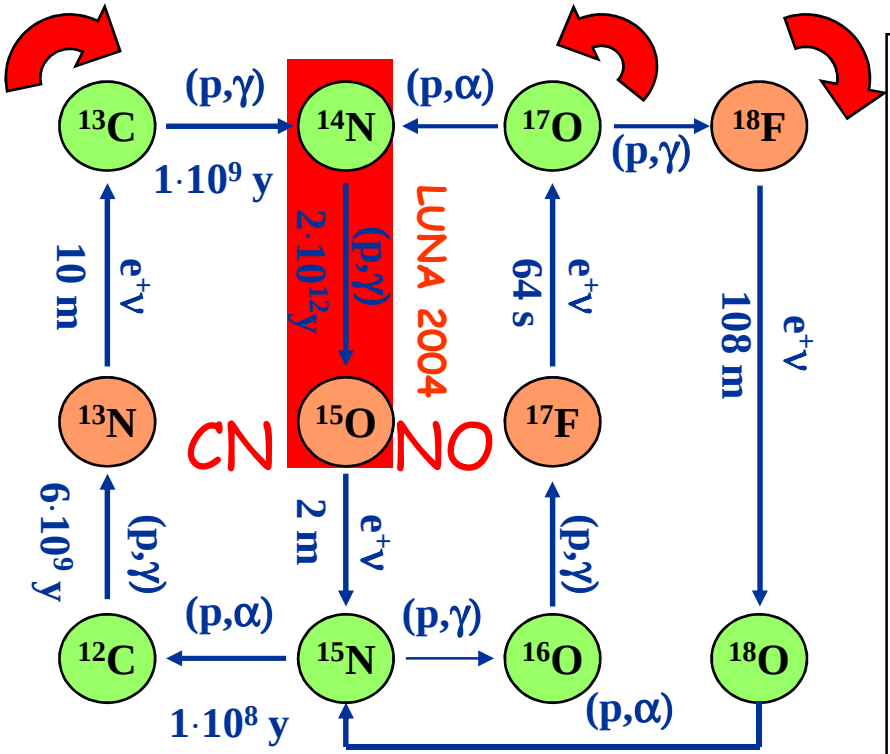
Astrophysical energy information reached directly by LUNA experiment



The Age of Globular Clusters



CNO CYCLE



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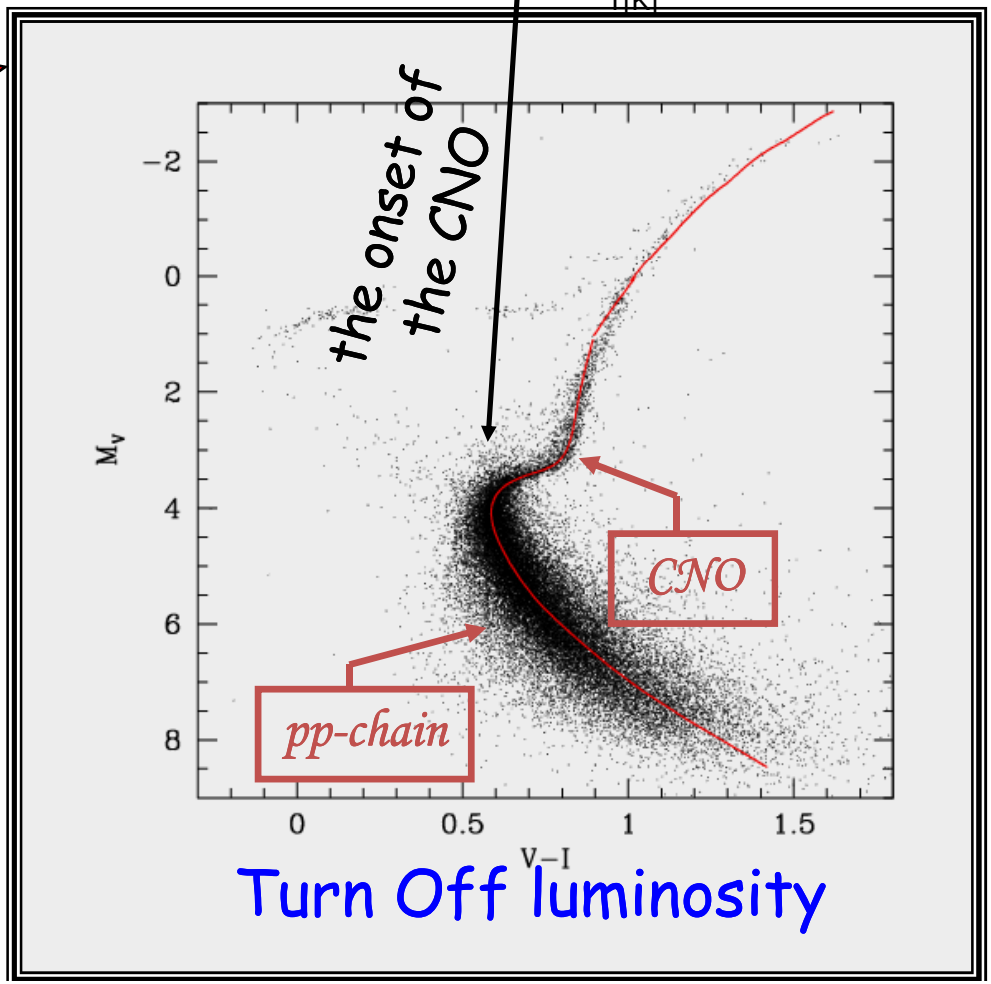
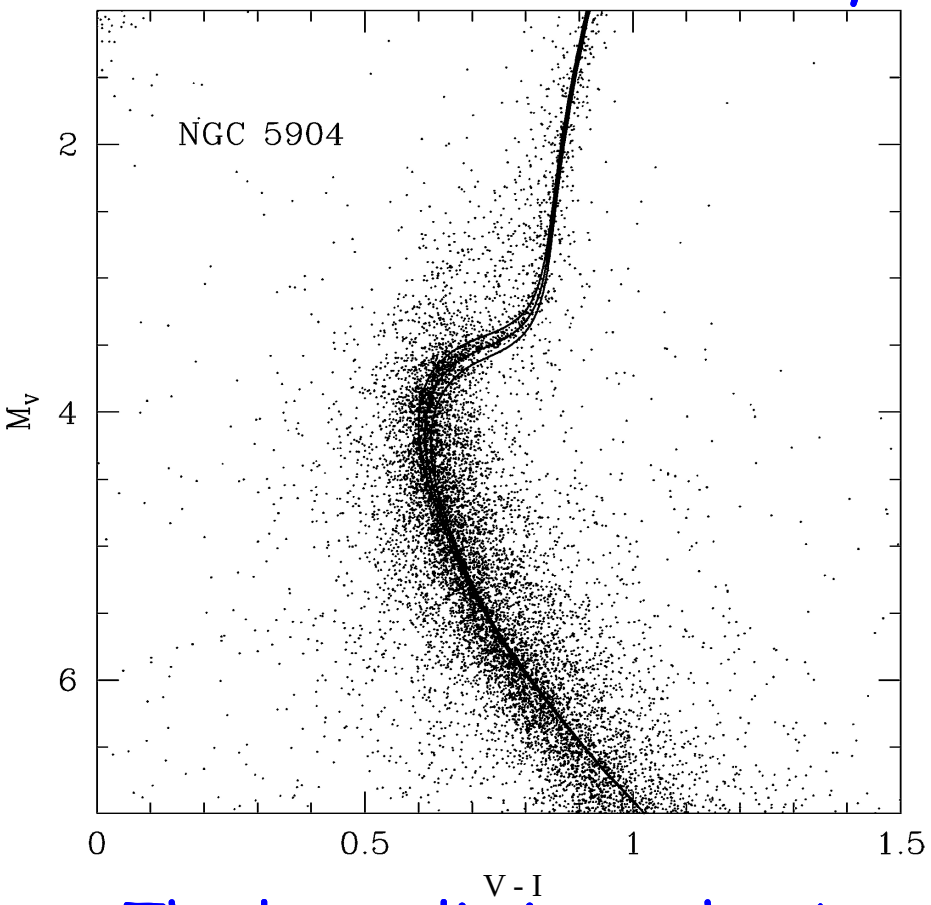
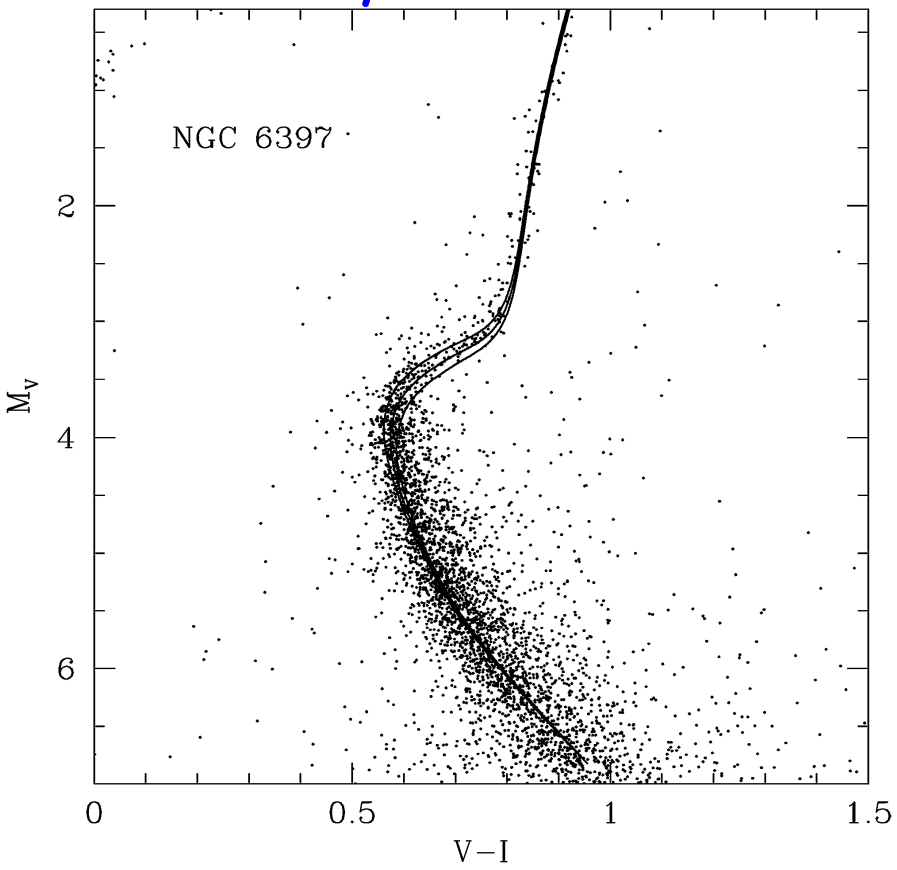


Isochrones for Globular Clusters after LUNA

The age of the oldest Globular Clusters should be increased by about 0.7-1 Gyr

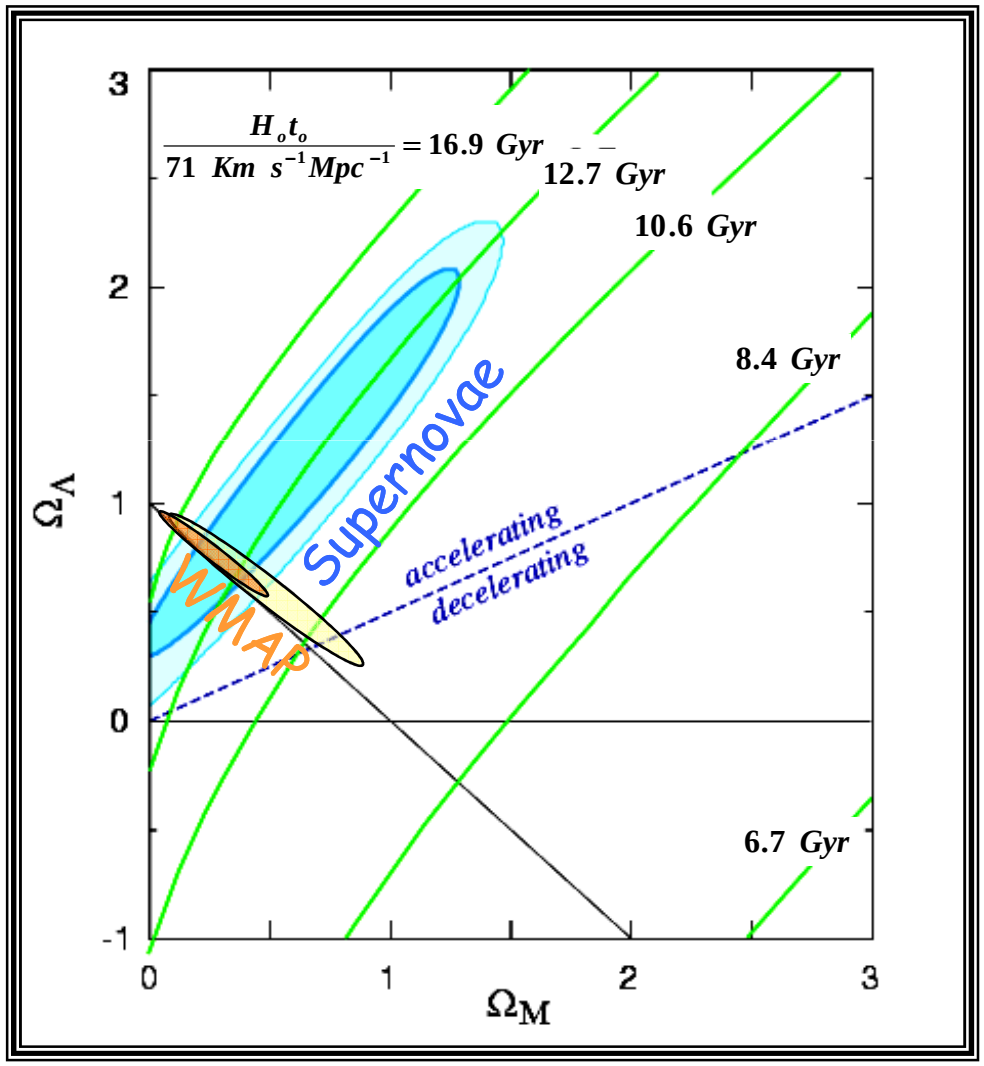




The lower limit to the Age of the Universe, using the Gratton et *al*, 2003 result, becomes 14 ± 1 Gyr.

Imbriani *et al.*, **Astronomy & Astrophysics, 420, 2004**

Experimental cosmology



Cosmic Concordance

$\Omega_m \sim 0.3$
$\Omega_\lambda \sim 0.7$

$H_o = 70$ km/s/Mpc

Age of the Universe

13.7 ± 0.2 Gyr
Spergel et al. 2003

WMAP + LCDM model + other measures (SNe Ia, Lyman-a forest……)