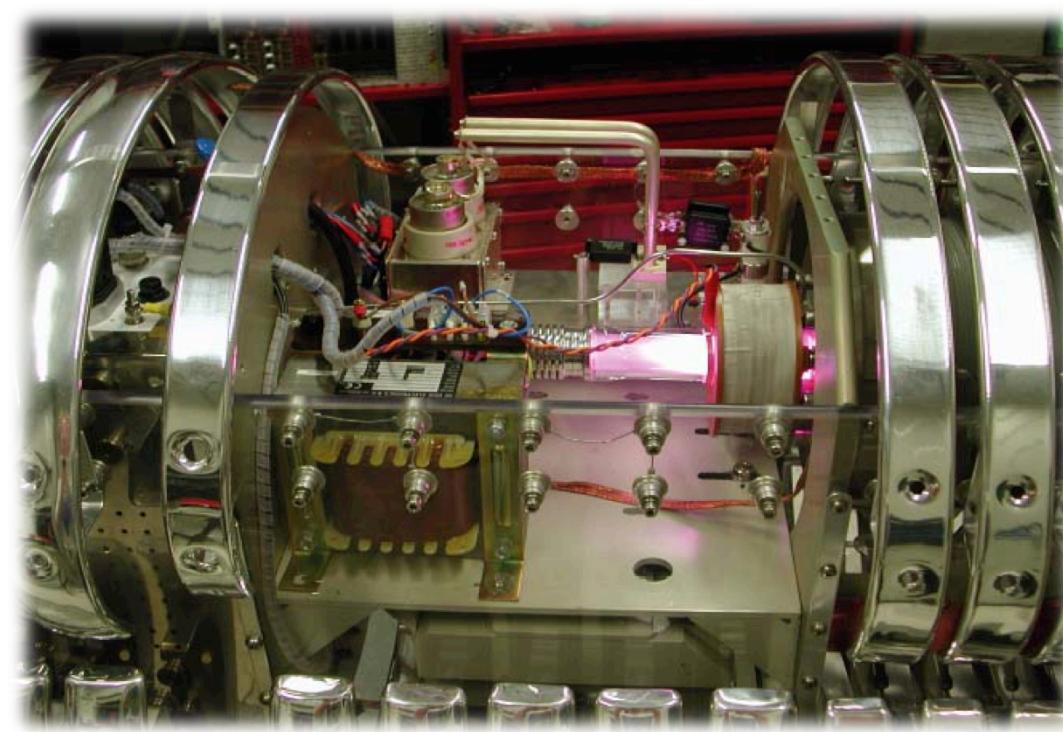


# LUNA400 e LUNA-MV: presente e futuro dell'Astrofisica Nucleare al Gran Sasso



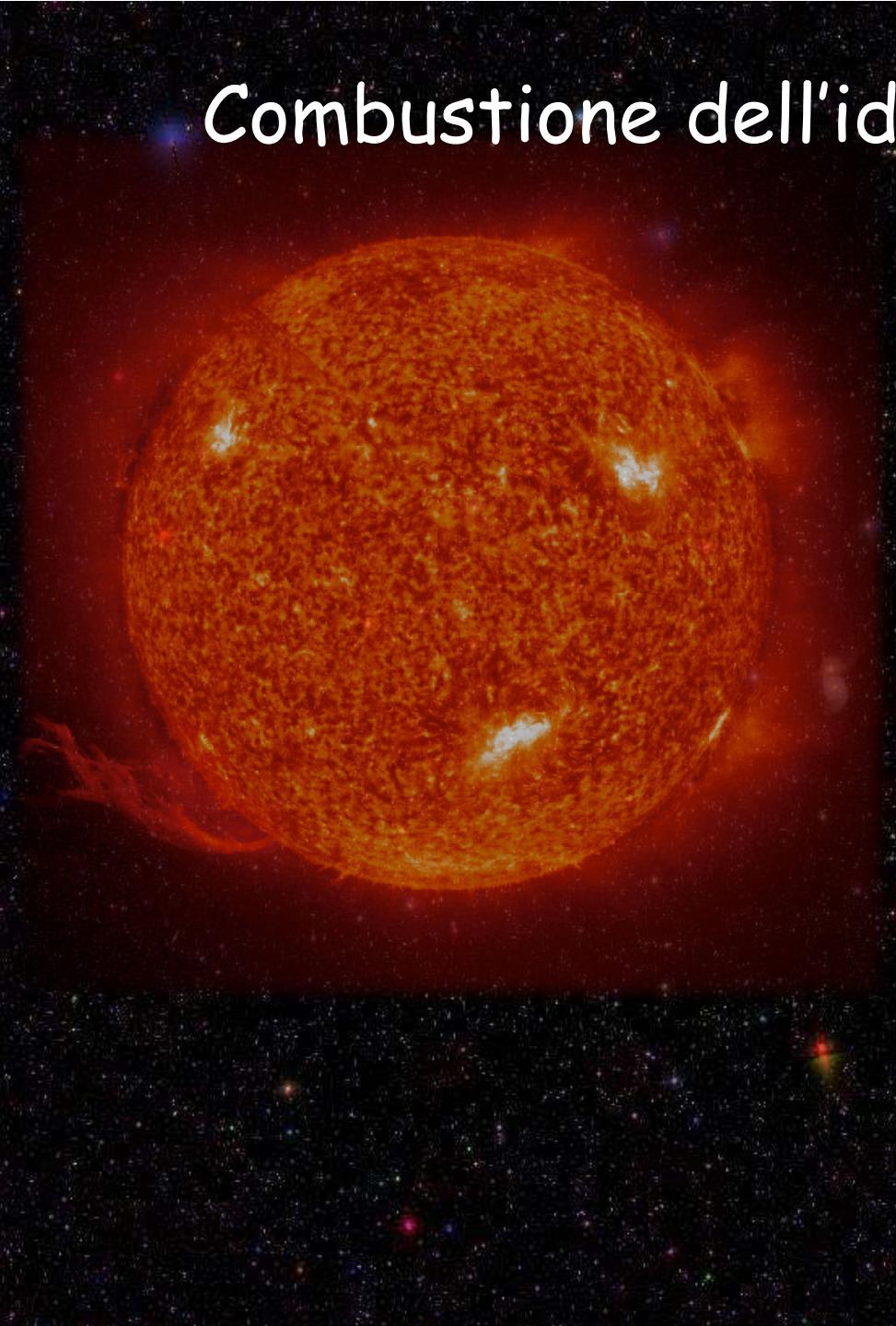
C. Gustavino  
INFN-Roma

- Il Sole
- La Nucleosintesi Primordiale
- L' Evoluzione delle stelle



- Fisica dei neutrini
- Cosmologia
- Astrofisica

# Combustione dell'idrogeno nelle stelle



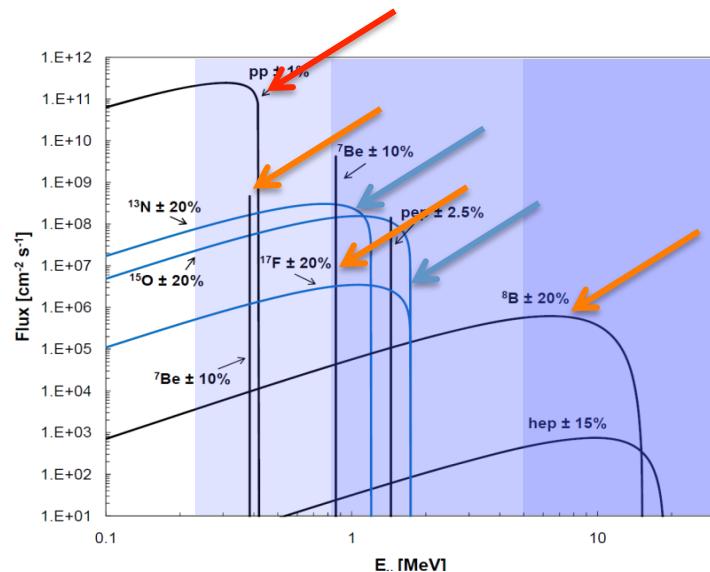
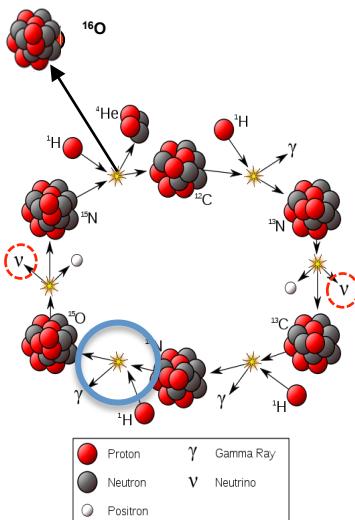
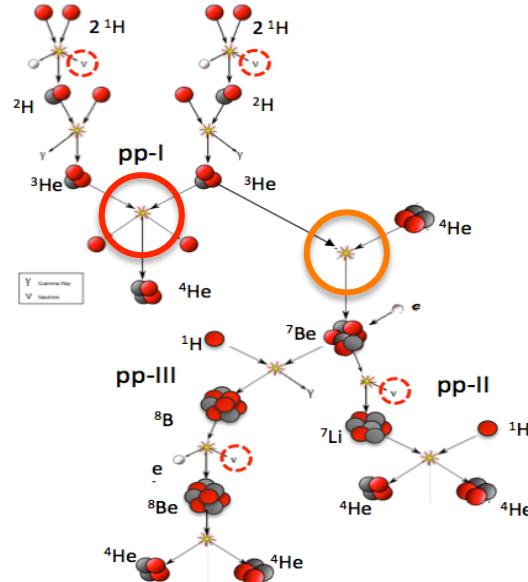
In quasi 20 anni di attività, L'esperimento LUNA ha studiato molte reazioni nucleari che regolano la combustione dell'idrogeno nel Sole e in altri corpi celesti:

- pp-chains,
- CNO cycle
- Ne-Na cycle
- Mg-Al cicle

..Con risultati di elevatissimo valore scientifico:

- Parametri di mixing del neutrino solare
- Temperatura e metallicità del sole
- Età dell'Universo
- Evoluzione delle stelle
- Abbondanze isotopiche

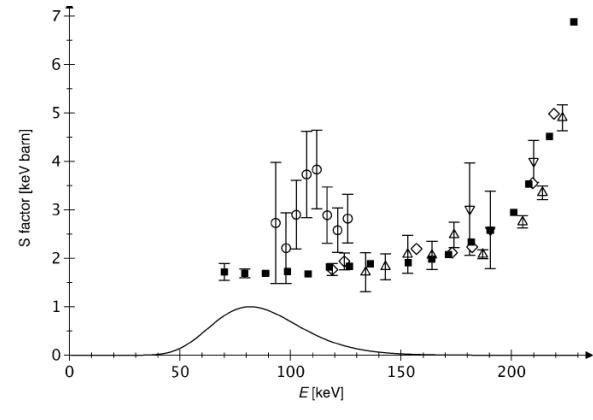
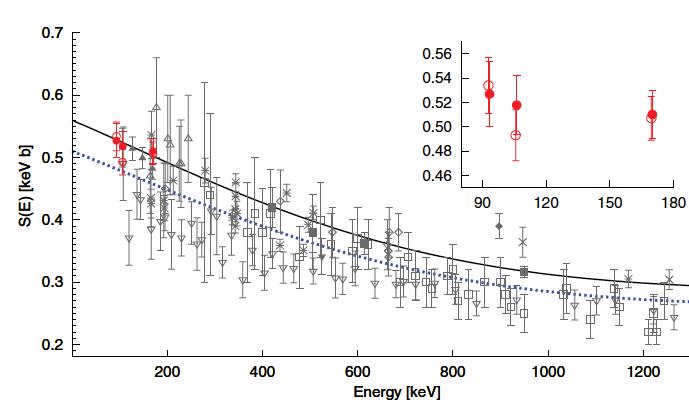
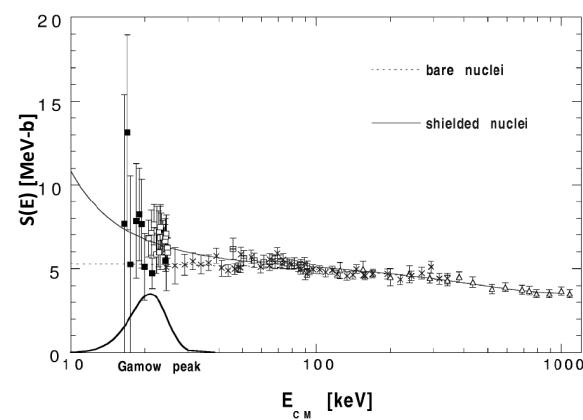
# Neutrini solari



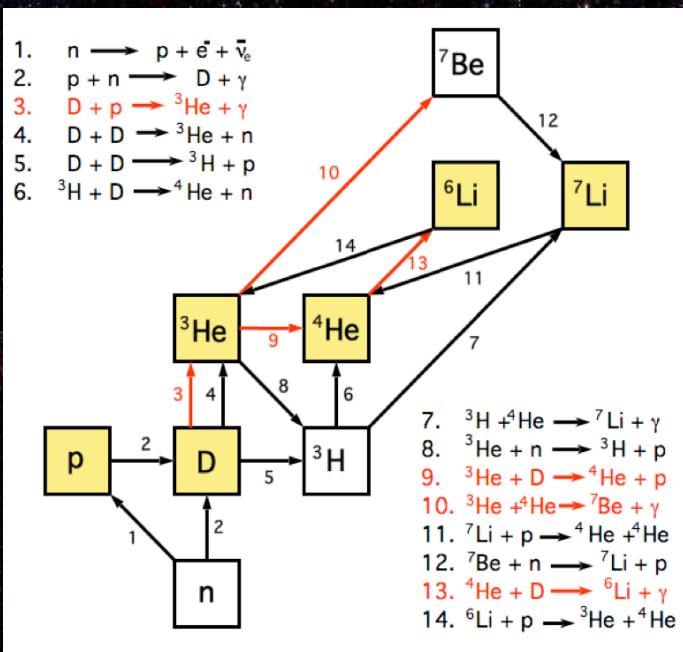
Dear Professors Corvisiero and Rolfs:

I am writing to you about a historic opportunity of which I first became aware at the recent meeting on Solar Fusion Reactions at the Institute of Nuclear Theory, Washington University. At this meeting, I had the opportunity to see for the first time the results of the LUNA measurements of the important  ${}^3\text{He} - {}^3\text{He}$  reaction in a region that covers a significant part of the Gamow energy peak for solar fusion. This was a thrill that I had never believed possible. These measurements signal the most important advance in nuclear astrophysics in three decades.

J. Bachall: "Historical breakthrough"



# La Nucleosintesi primordiale



Lo studio di queste reazioni serve a "calibrare" l'Universo dei primi 10 minuti, cioè la principale sorgente di elementi leggeri osservabili ( $D$ ,  ${}^3\text{He}$ ,  ${}^4\text{He}$ ,  ${}^6\text{Li}$ ,  ${}^7\text{Li}$ ).

$$H^2 = \frac{8\pi}{3} G \rho$$

$$\rho = \rho_\gamma \left( 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right)$$

L'abbondanza primordiale dipende esclusivamente da:

- Densità barionica
- Fisica delle particelle
- Sezioni d'urto Nucleari

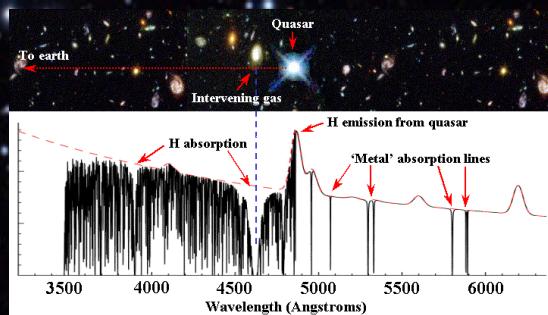
Stretta connessione con CMB (PLANCK, BICEP2).

BBN: "fotografa" l'Universo dopo 10 minuti

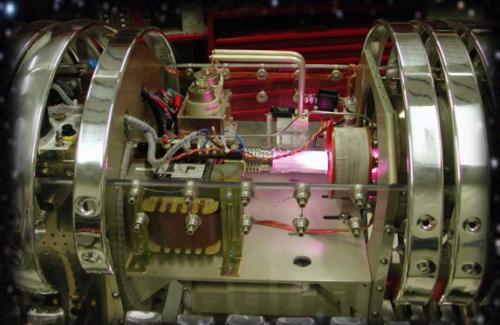
CMB: "fotografa" l'Universo dopo 380.000 anni.

- Cosmologia
- Susy
- $N_{\text{eff}}$
- Lepton degeneracy
- Gravità
- ...

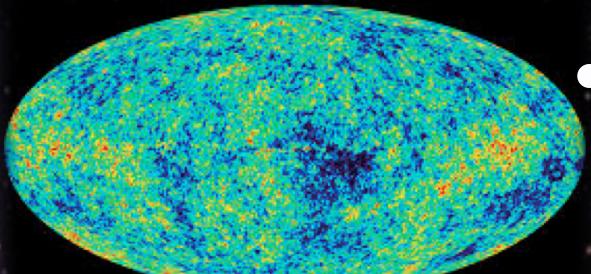
# BBN "Flowchart"



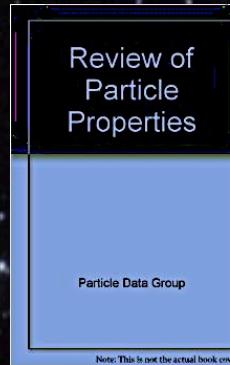
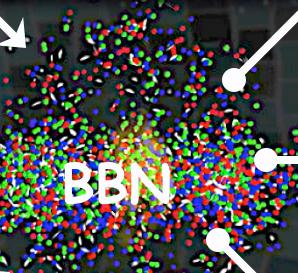
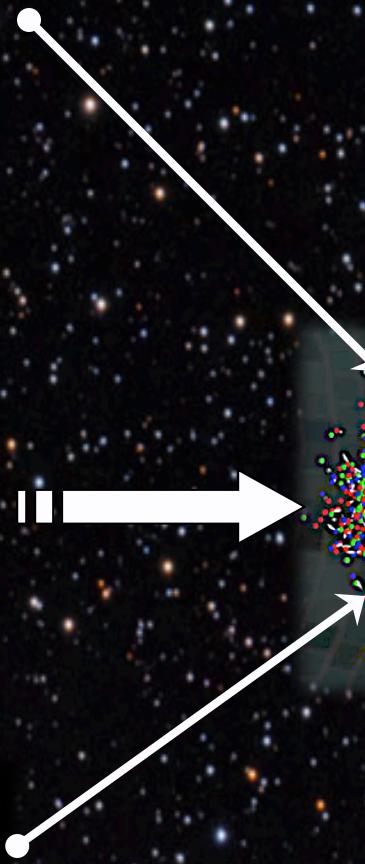
Osservazioni dirette  
Elementi leggeri



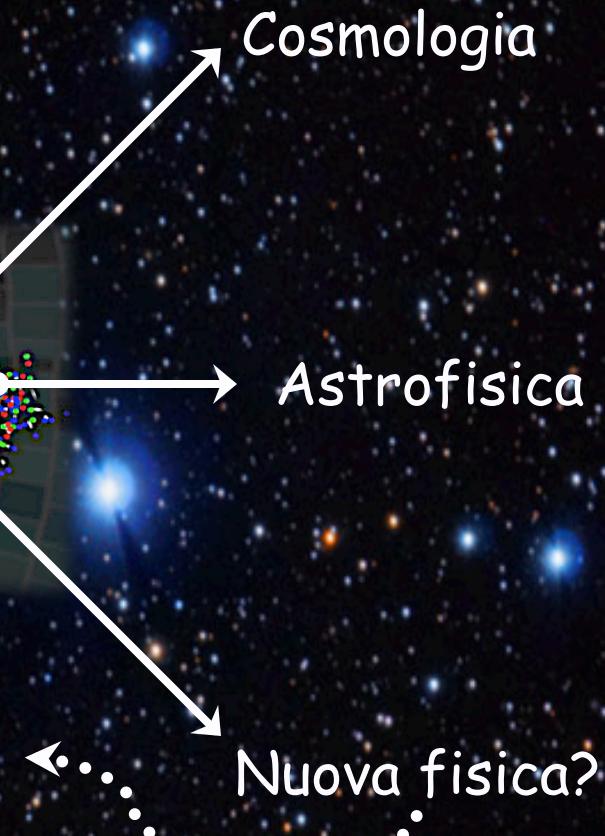
Astrofisica Nucleare



CMB



Parametri "PDG"  
 $\tau_h, G, N_{\text{eff}} \dots$

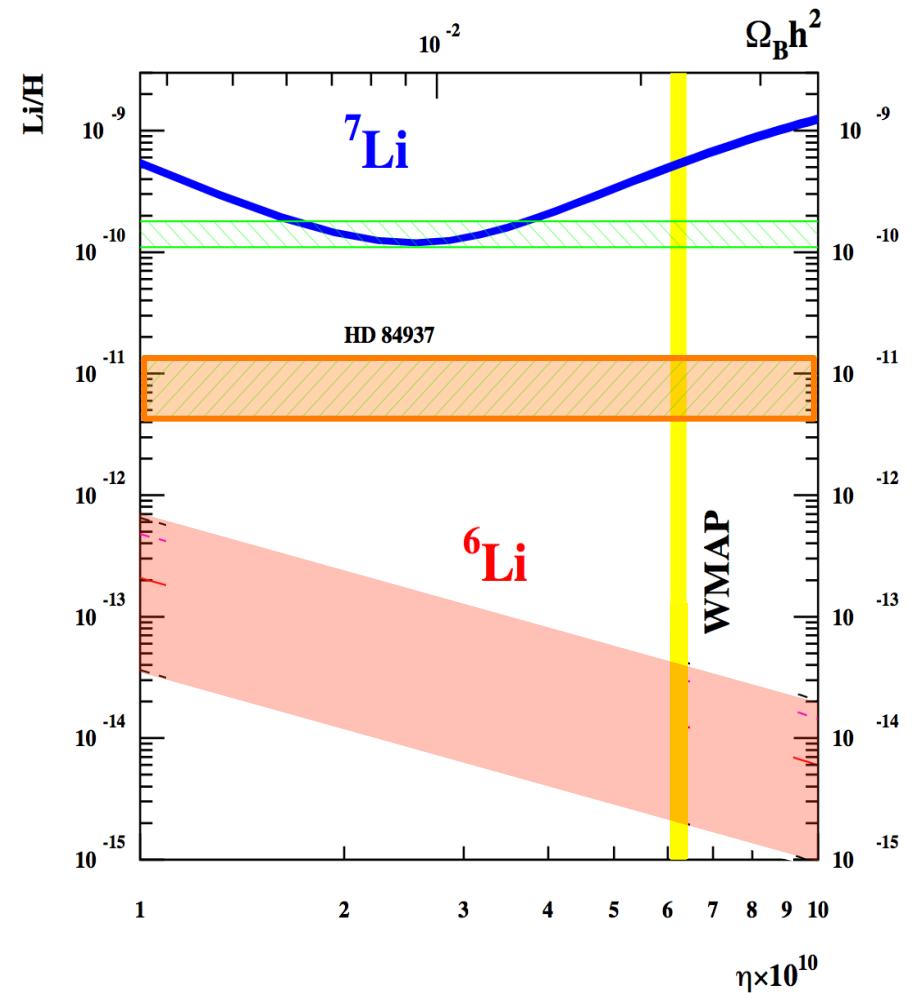


# Passato recente: La reazione $D(\alpha,\gamma)^6\text{Li}$ e il "lithium problem"

- L'abbondanza osservata di  $^7\text{Li}$  è circa 3-4 volte inferiore del previsto.
- L'abbondanza osservata di  $^6\text{Li}$  sembra molto superiore del previsto (fattore 1000!)

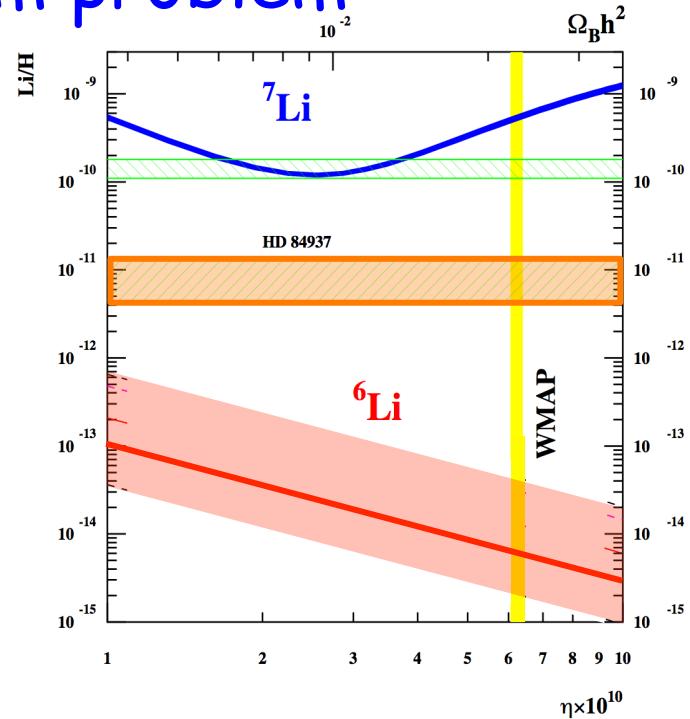
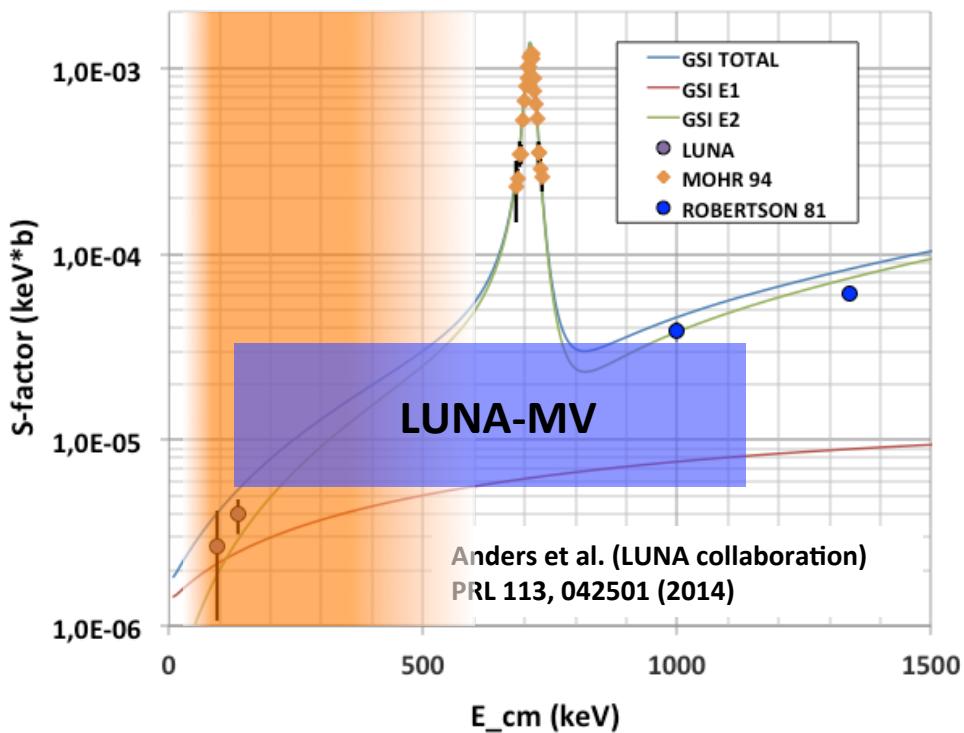
Possibili spiegazioni:

- Sistematiche nelle osservazioni
- Processi astrofisici sconosciuti
- Fisica oltre il modello standard
- Incertezza nelle sezioni d'urto nucleari



L'abbondanza di  $^6\text{Li}$ , dipende dalla reazione  $D(\alpha,\gamma)^6\text{Li}$ , che non era mai stata misurata prima di LUNA, alle energie BBN.

# La reazione $D(\alpha,\gamma)^6\text{Li}$ e il "lithium problem"



**Prima misura diretta ad energie BBN della sezione d'urto  $D(\alpha,\gamma)^6\text{Li}$**

Si esclude con certezza un errore nei calcoli BBN.

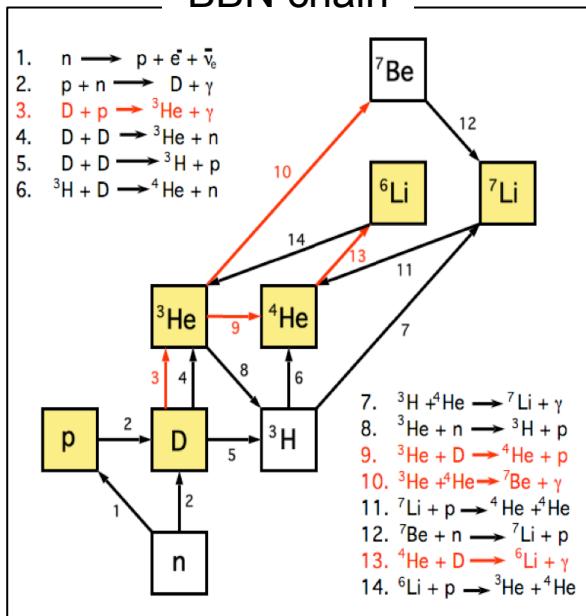
$$S_{24}(134 \text{ keV}) = (4.0 \pm 0.8^{(\text{stat})} \pm 0.5^{(\text{syst})}) \times 10^{-6} \text{ keV b}$$

$$S_{24}(94 \text{ keV}) = (2.7 \pm 1.5^{(\text{stat})} \pm 0.3^{(\text{syst})}) \times 10^{-6} \text{ keV b}$$

$$({}^6\text{Li}/\text{H})_{\text{BBN}} = 7.4 \pm 1.6 \times 10^{-15}$$

# Futuro Prossimo: la reazione $D(p,\gamma)^3\text{He}$

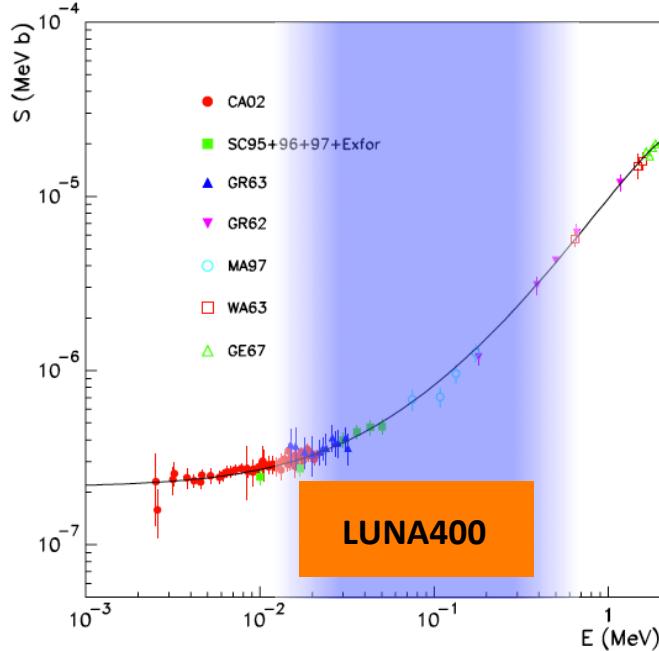
BBN chain



## Primordial deuterium error budget (Di Valentino et al. 2014)

Reaction	Rate Symbol	$\sigma_{D/H} / H \cdot 10^5$
$p(n, \gamma)^2\text{H}$	$R_1$	$\pm 0.002$
$d(p, \gamma)^3\text{He}$	$R_2$	$\pm 0.062$
$d(d, n)^3\text{He}$	$R_3$	$\pm 0.020$
$d(d, p)^3\text{H}$	$R_4$	$\pm 0.013$

The error of computed deuterium abundance  $(D/H)_{\text{BBN}}$  is mainly due to the  $D(p, \gamma)^3\text{He}$  reaction, because of the paucity of data in the BBN energy region



Physics:

- 1) **Cosmology**: measurement of  $\Omega_b h^2$ .
- 2) **Neutrino physics**: measurement of  $N_{\text{eff}}$ .
- 3) **Nuclear physics**: comparison of data with theoretical "ab initio" predictions.

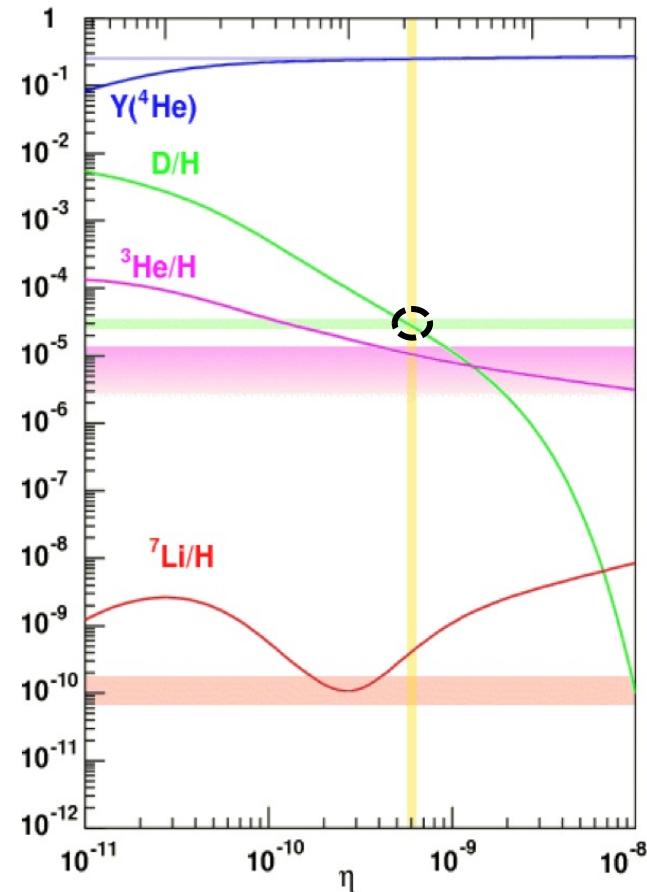
# Reazione $D(p,\gamma)^3He$ : Densità barionica

La densità barionica  $\Omega_b$  si determina in modo completamente indipendente con gli esperimenti CMB e con l'abbondanza di deuterio, che è l'isotopo più sensibile a questo parametro.

$$100\Omega_{b,0}h^2(\text{CMB}) = 2.20 \pm 0.03 \text{ (PLANCK2013)}$$

$$100\Omega_{b,0}h^2(\text{BBN}) = 2.20 \pm 0.02 \pm 0.04 \text{ (Cooke&Pettini 2013)}$$

Osservazioni D/H  $\uparrow$   
Reazione D $\gamma$   $\uparrow$



Nota Bene:

$\Omega_b$ (CMB) e  $\Omega_b$ (BBN) si riferiscono a tempi cosmici differenti.

$\Omega_b$ (CMB) e  $\Omega_b$ (BBN) hanno errore confrontabile.

$\Omega_b$ (BBN) può essere ridotto considerevolmente con una misura di precisione delle reazione D $\gamma$

# Reazione $D(p,\gamma)^3He$ : $N_{\text{eff}}$ (numero di neutrini)

**Fisica del neutrino:** L'abbondanza del deuterio è sensibile anche al numero di famiglie di neutrini. Con i dati in letteratura della reazione  $D(p,\gamma)^3He$  abbiamo:

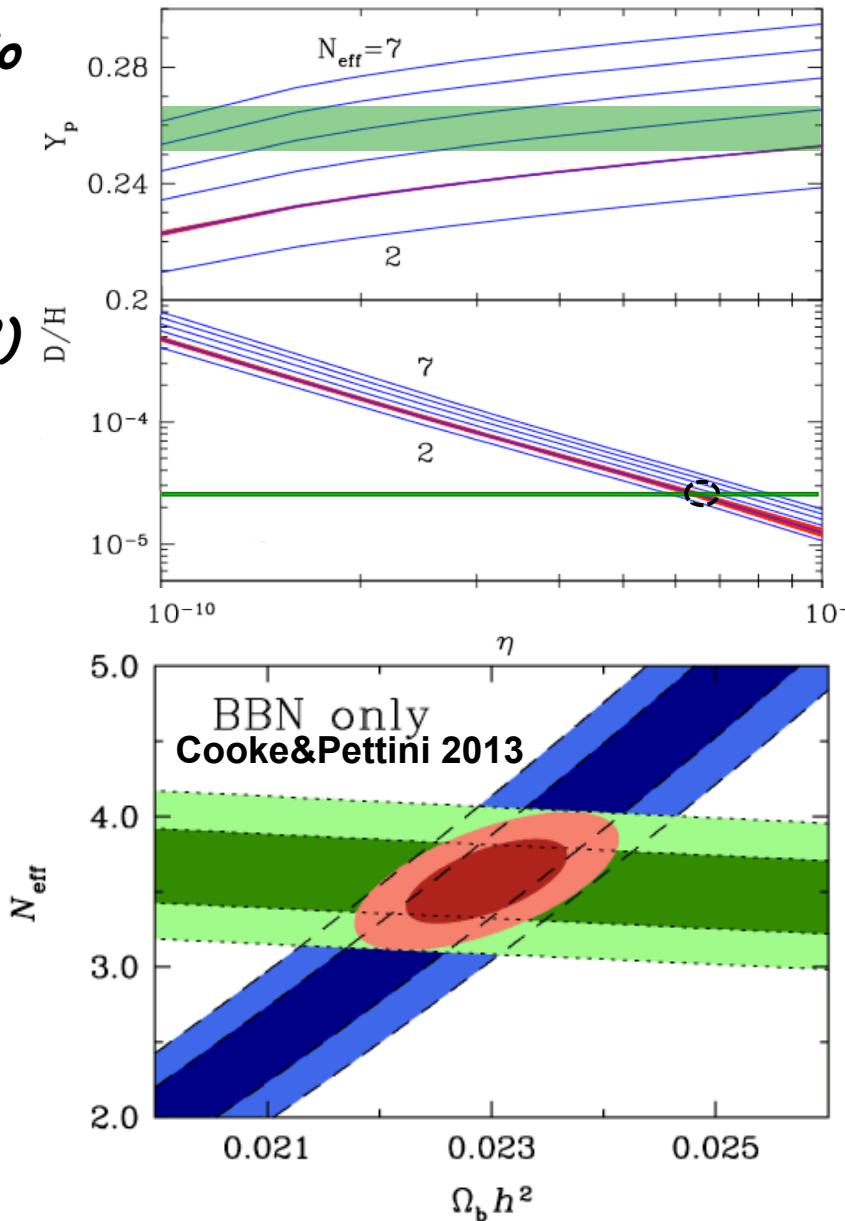
$$N_{\text{eff}} \text{ (CMB)} = 3.36 \pm 0.34 \text{ (PLANCK 2013)}$$

$$N_{\text{eff}} \text{ (BBN)} = 3.57 \pm 0.18 \text{ (Cooke&Pettini 2013)}$$

$$N_{\text{eff}} \text{ (SM)} = 3.046$$

Nota bene:

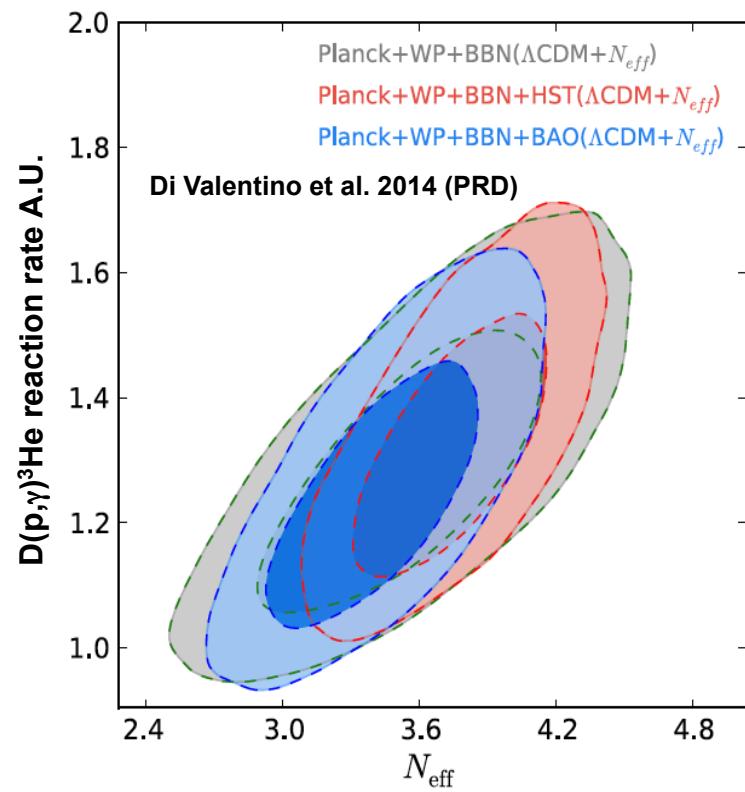
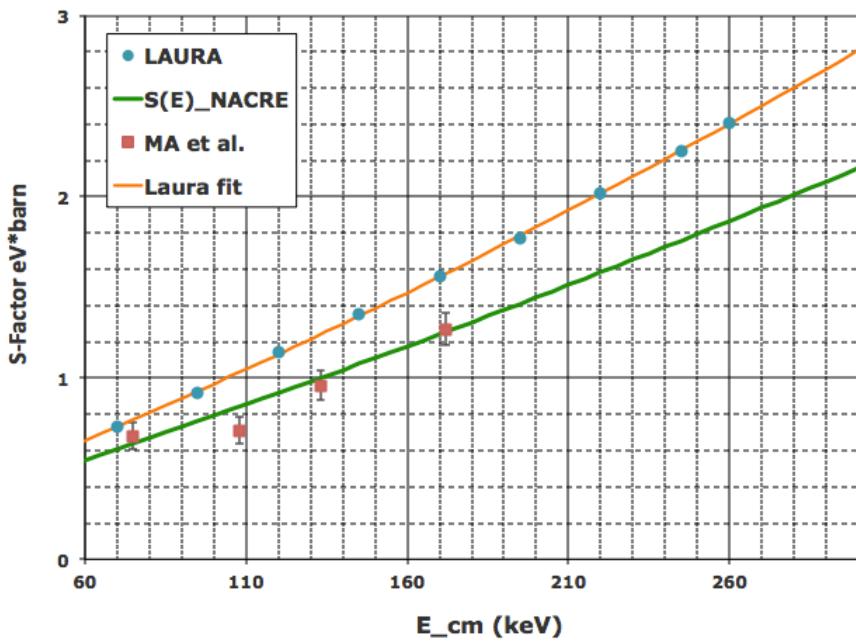
- Buon accordo fra i risultati ottenuti da CMB e BBN.
- Entrambi suggeriscono la presenza di "radiazione scura".
- L'incertezza sperimentale sui dati relativi alla reazione  $D(p,\gamma)^3He$  sono il principale ostacolo per migliorare questi limiti.



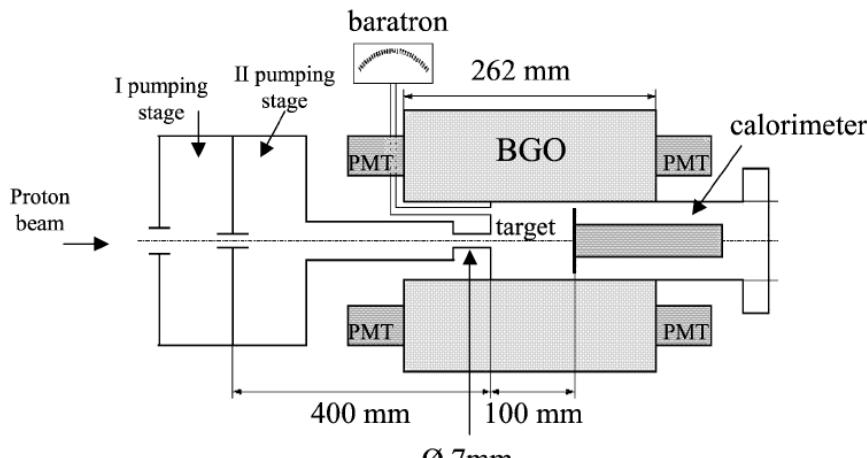
# Reazione $D(p,\gamma)^3\text{He}$ : Fisica Nucleare

Attualmente i dati su  $S_{12}$  differiscono del 20-30% rispetto alle calcoli "ab initio".

Una sezione d'urto in accordo con i calcoli teorici fornisce un accordo migliore fra CMB e BBN, nella direzione  $N_{\text{eff}} > 3$

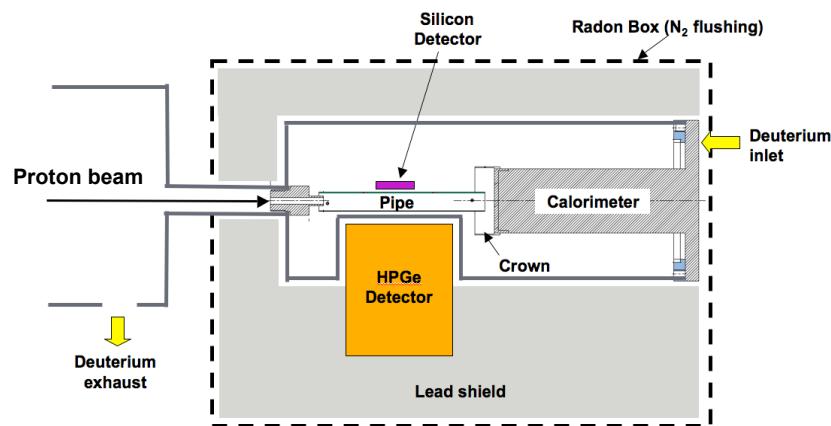


# Reazione $D(p,\gamma)^3He$ : Possibile setup @ LUNA



BGO detector

## Total cross section Vs Energy

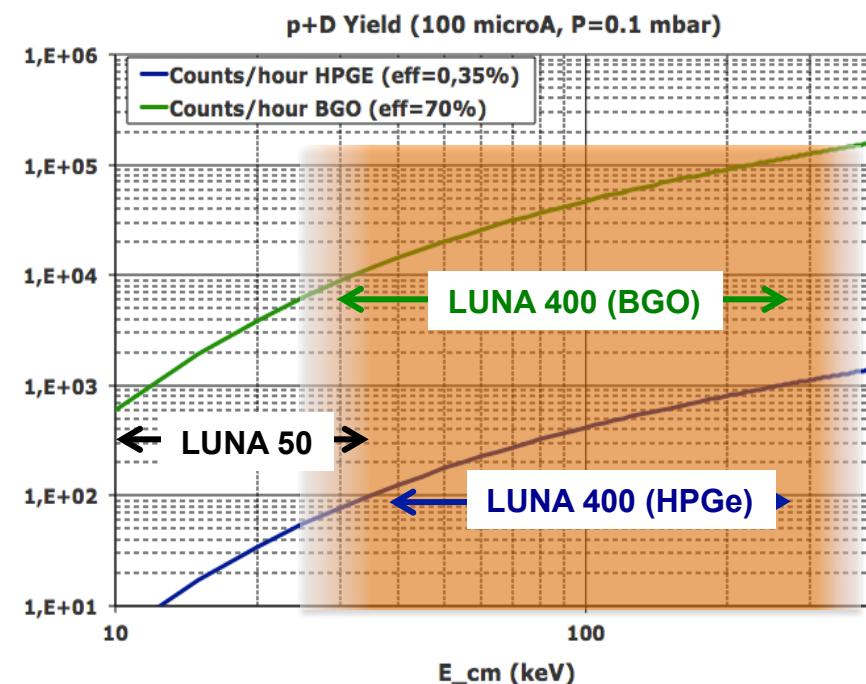


Ge(Li) detector

## Study of angular emission of photons

### Experimental goals:

- Misura della sezione d'urto totale in un ampio intervallo di energia:  $45 < E_{lab}(\text{keV}) < 400$
- Precisione a livello del 3%.
- Misura della sezione d'urto differenziale.



# Conclusioni (Cosmologia e BBN)

Da una decina di anni siamo entrati nell'era della cosmologia di precisione

Per esempio:

$\Omega_b$  error: 4.3% (WMAP2003) → 1.4% (PLANCK2013)

$(D/H)_{obs}$  error: 8% (Cyburt 2006) → 1.6% (Cooke&Pettini 2013)

CMB

Misure di polarizzazione (BICEP2 → LSPE)

BBN:

Osservazioni dirette →  $y_p$ , D/H,  $^3\text{He}/\text{H}$ ,  $^7\text{Li}/\text{H}$ ,  $^6\text{Li}/\text{H}$

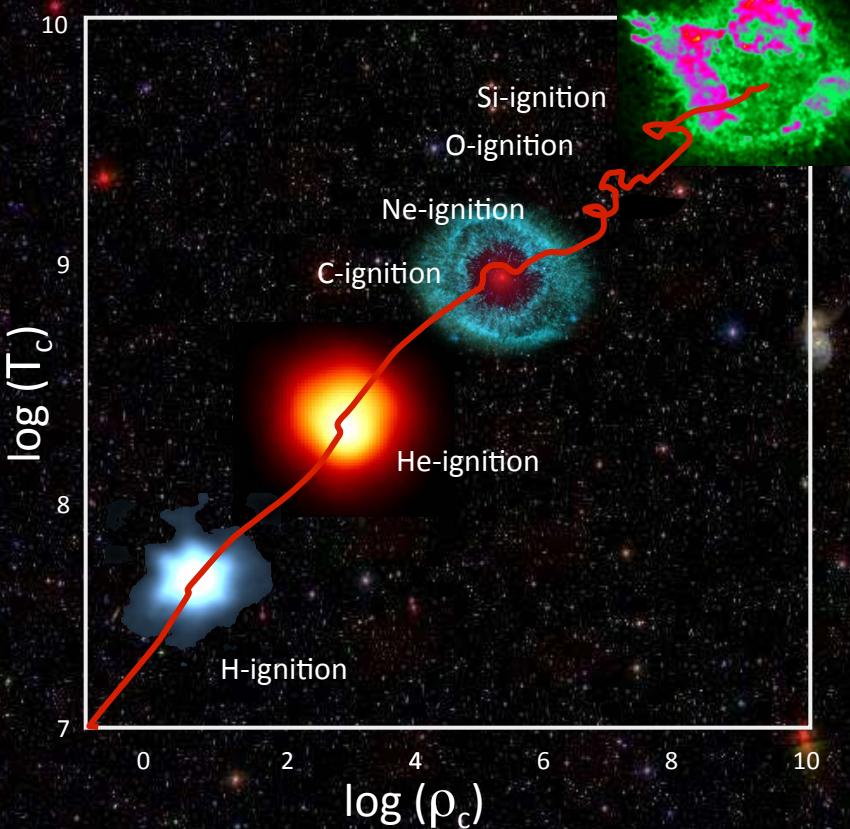
Astrofisica Nucleare →

$D(p,\gamma)^3\text{He}$  → abbondanza deuterio, LUNA400

$D(\alpha,\gamma)^6\text{Li}$  → abbondanza  $^6\text{Li}$ , LUNA-MV

$^3\text{He}(\alpha,\gamma)^7\text{Be}$  → abbondanza  $^7\text{Li}$ , LUNA-MV

# What next?



LUNA400 (2015-2018):

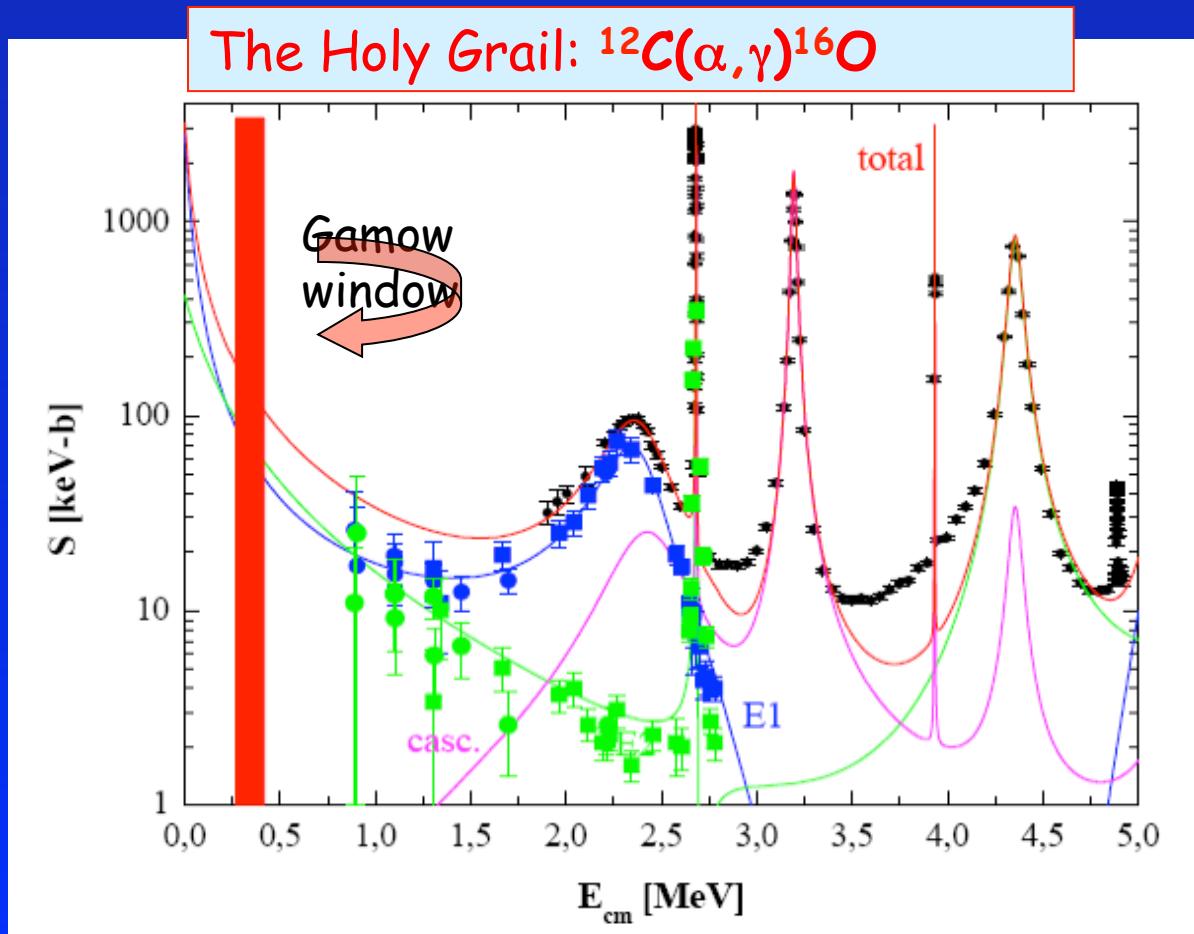
- $^{13}\text{C}(\alpha, n)^{16}\text{O}$
- $^{12}\text{C}(\text{p}, \gamma)^{13}\text{N}$  and  $^{13}\text{C}(\text{p}, \gamma)^{14}\text{N}$
- $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$
- $^2\text{H}(\text{p}, \gamma)^3\text{He}$
- $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$
- $^6\text{Li}(\text{p}, \gamma)^7\text{Be}$

LUNA-MV:

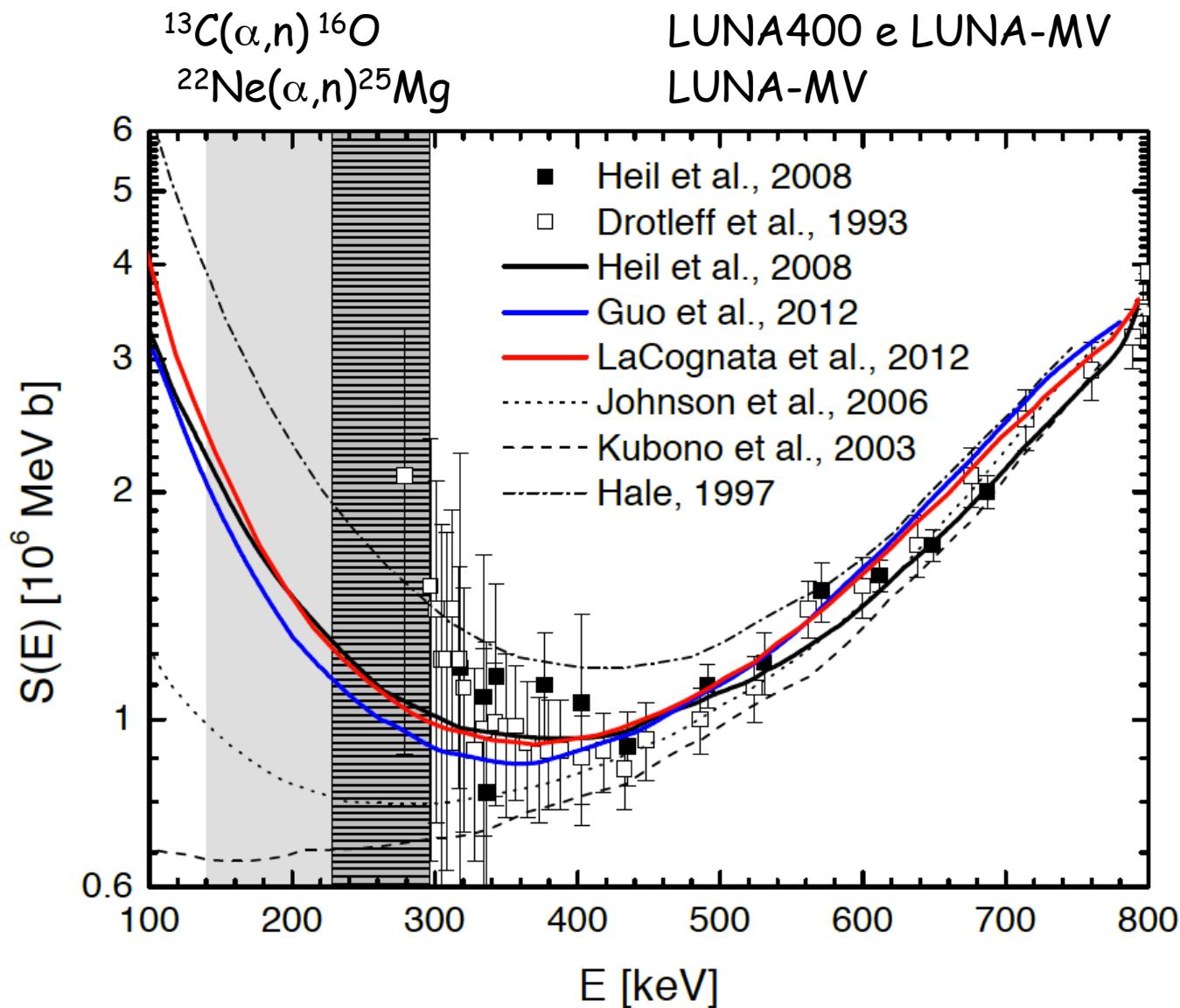
- $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$
- $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- $^{13}\text{C}(\alpha, n)^{16}\text{O}$
- $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$

- Combustione dell'idrogeno in stelle massive
- Evoluzione delle stelle nelle fasi successive alla combustione dell'idrogeno
- S-process
- Misure di precisione dei processi della BBN

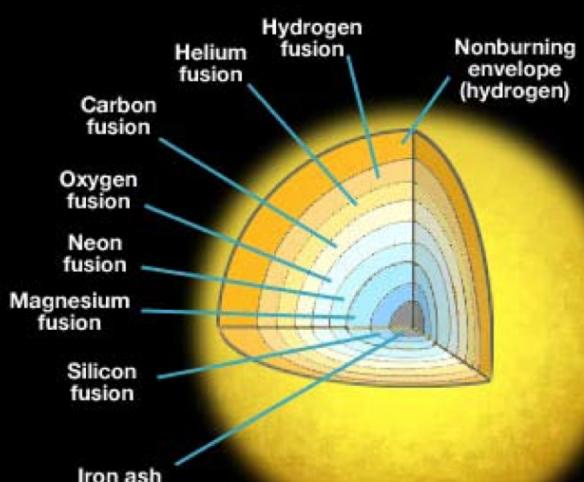
# What next: Helium Burning



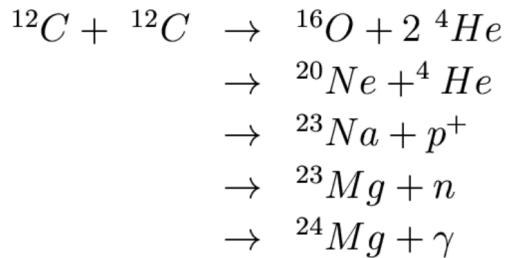
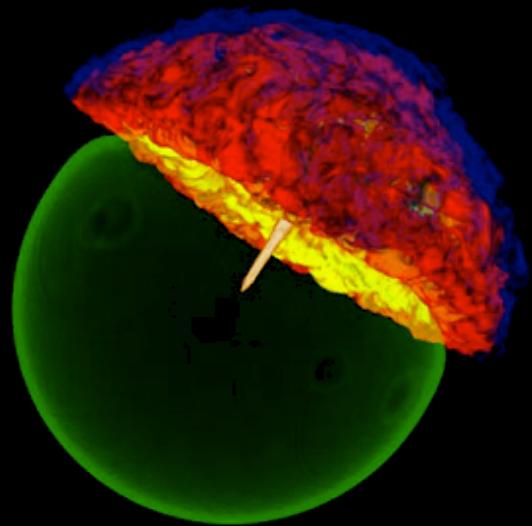
# What next: s-process



# Carbon burning & type Ia supernovae

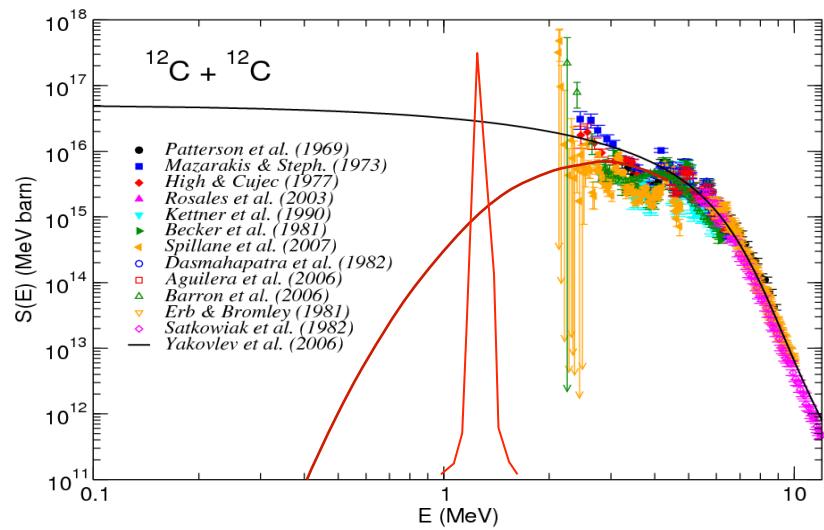


Massive star

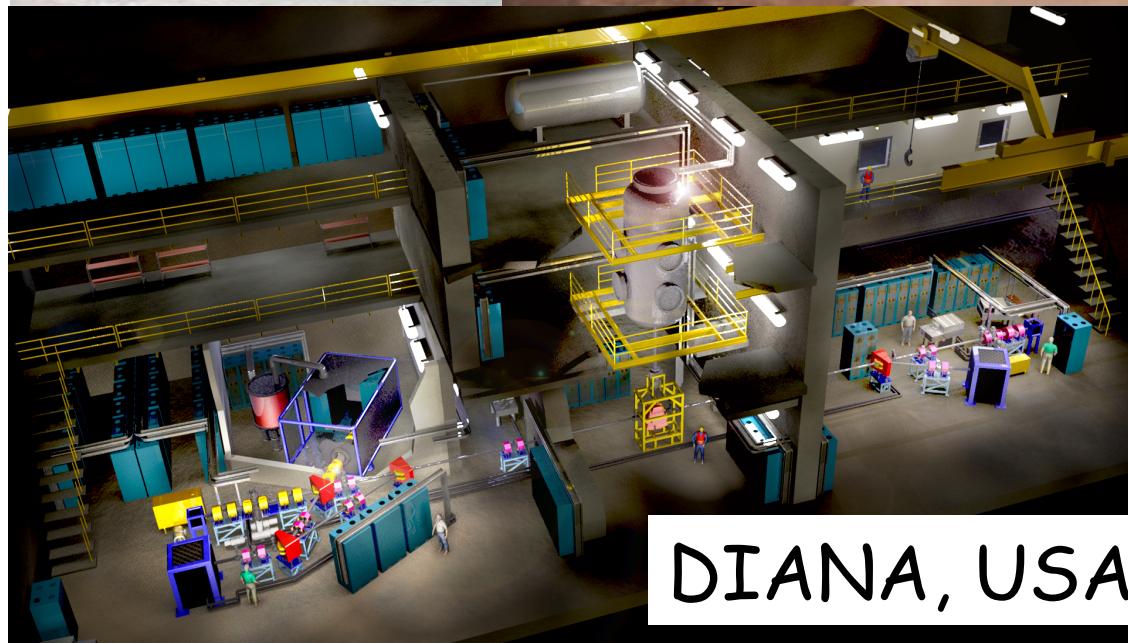
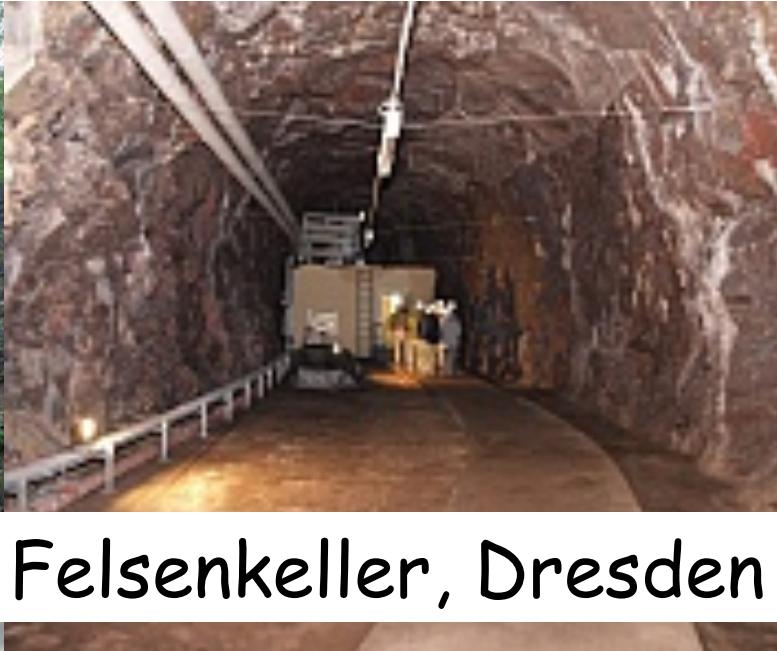
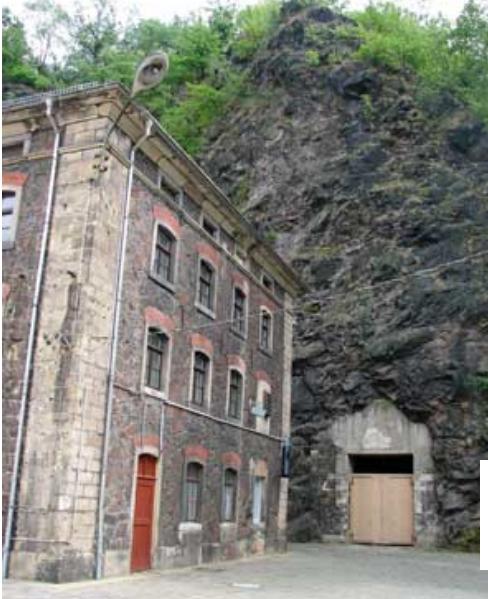


For a  $15 M_{\odot}$  star:

Reaction	Timescale
Hydrogen burning	10 million years
Helium burning	1 million years
Carbon burning	300 years
Oxygen burning	200 days
Silicon burning	2 days



# Altre iniziative



DIANA, USA

# Un ulteriore sguardo al futuro..

Realizzazione al Gran Sasso di una struttura di eccellenza per misure di Fisica Nucleare Applicata, aperta ad utenti esterni.

- È opportuno, già da ora, riservare un'area attrezzata sufficientemente grande, in vista di futuri sviluppi.
- Creazione di un ambiente dotato di opportuna schermatura verso e di sistema di monitoraggio. Di assoluta priorità è infatti il consolidamento della fama del LNGS come laboratorio di "certificata" eccellenza per misure in condizioni di bassa radioattività.

Principali attività:

Astrofisica Nucleare:

- Evoluzione stellare (combustione di elio, carbonio, neon, silicio +S-process)
- Processi BBN
- Electron Screening

Sinergia con ERNA (Caserta) e ASFIN (Catania)

Analisi dei materiali (Ion Beam Analysis, IBA)

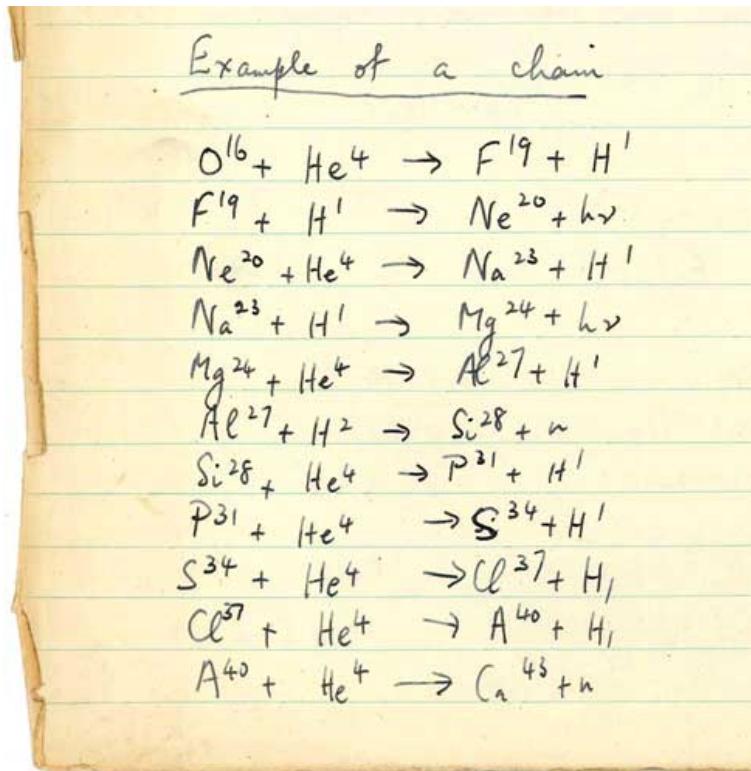
- Beni Culturali
- Monitoraggio ambientale
- biologia, cristalli, geologia...

Sinergia con STELLA (LNGS), LABEC (Firenze), CIRCE (Caserta)

*Grazie per l'attenzione*

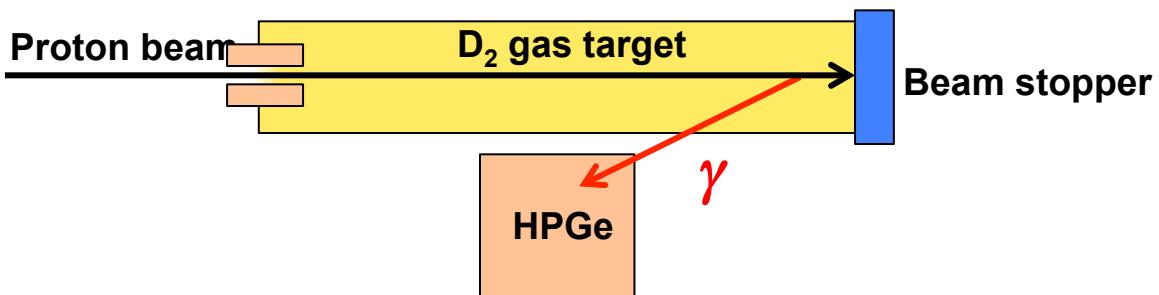
# SPARES

# Nuclear reactions in stars



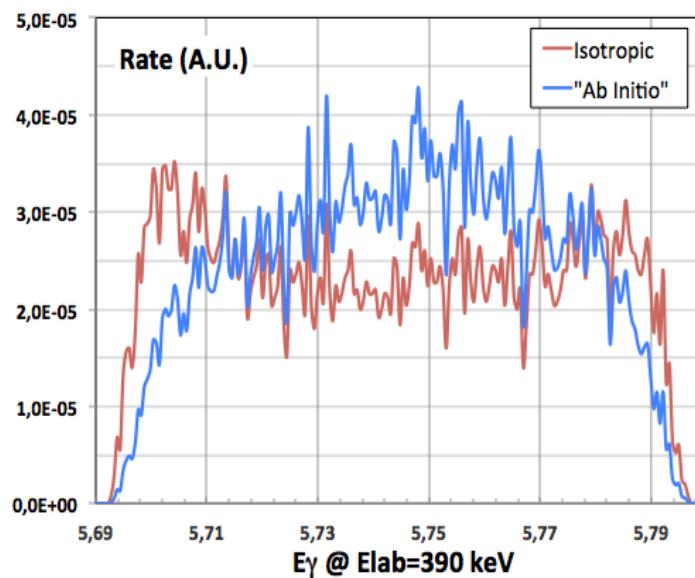
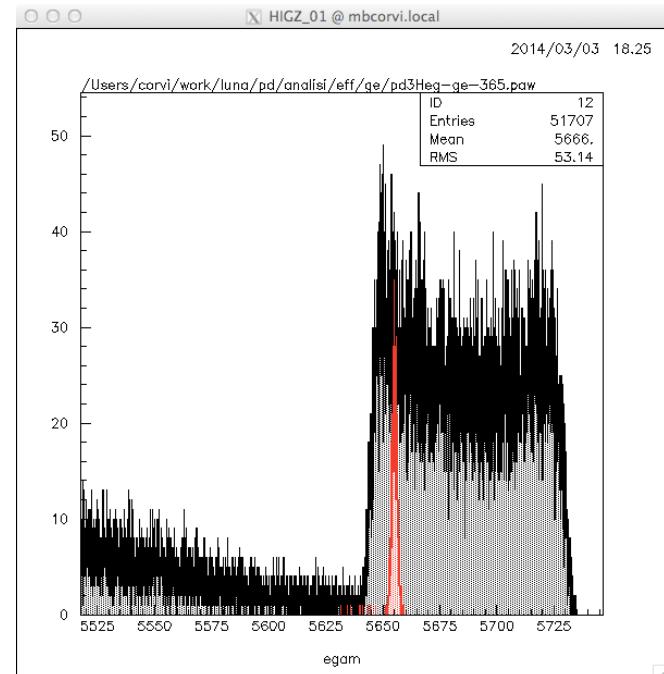
Molti cicli sono presenti nelle stelle. Di solito i più importanti sono i processi che determinano la velocità del ciclo e quelli che si trovano in una biforcazione

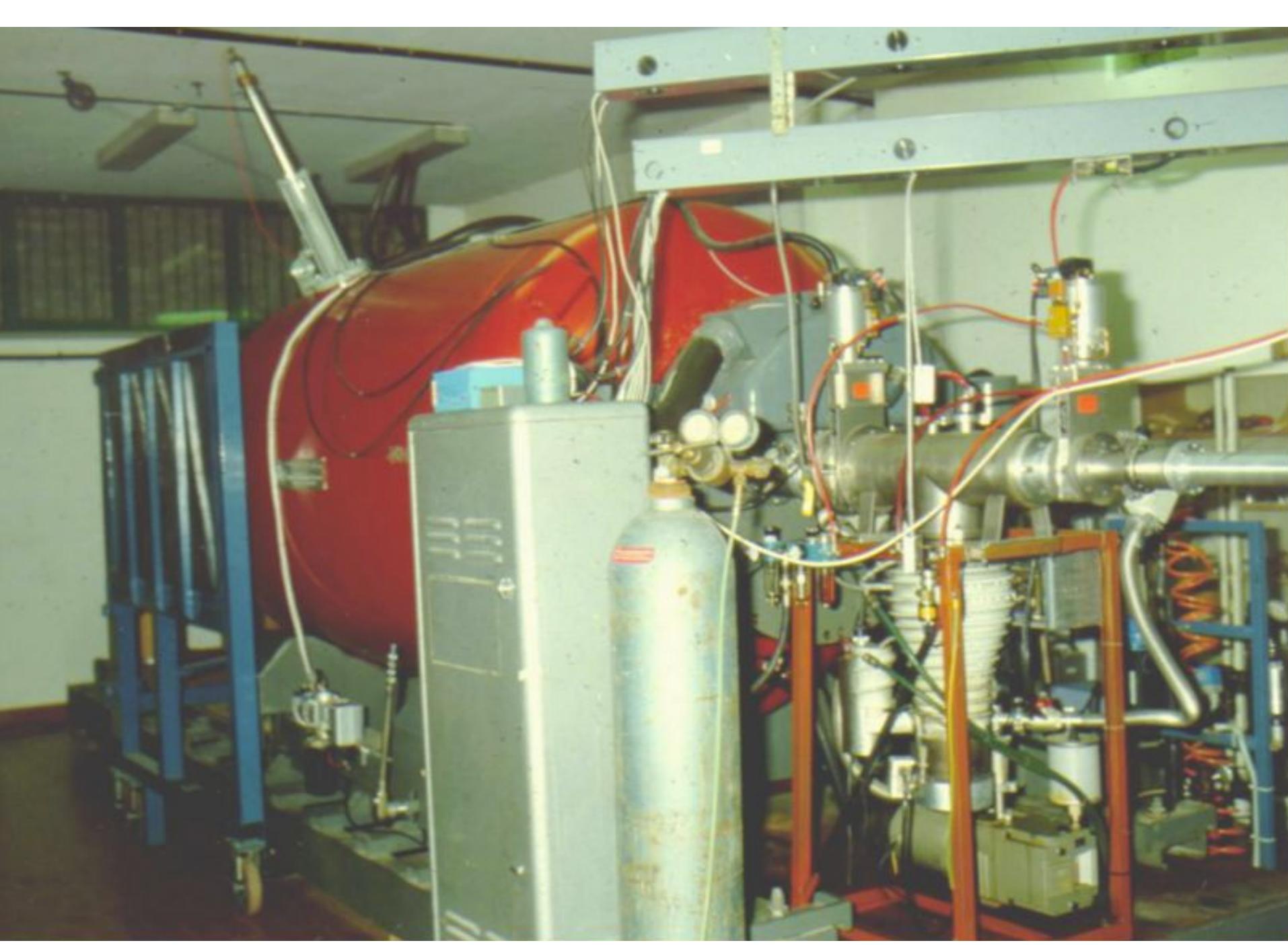
# $D(p, \gamma)^3\text{He}$ reaction: Angular distribution

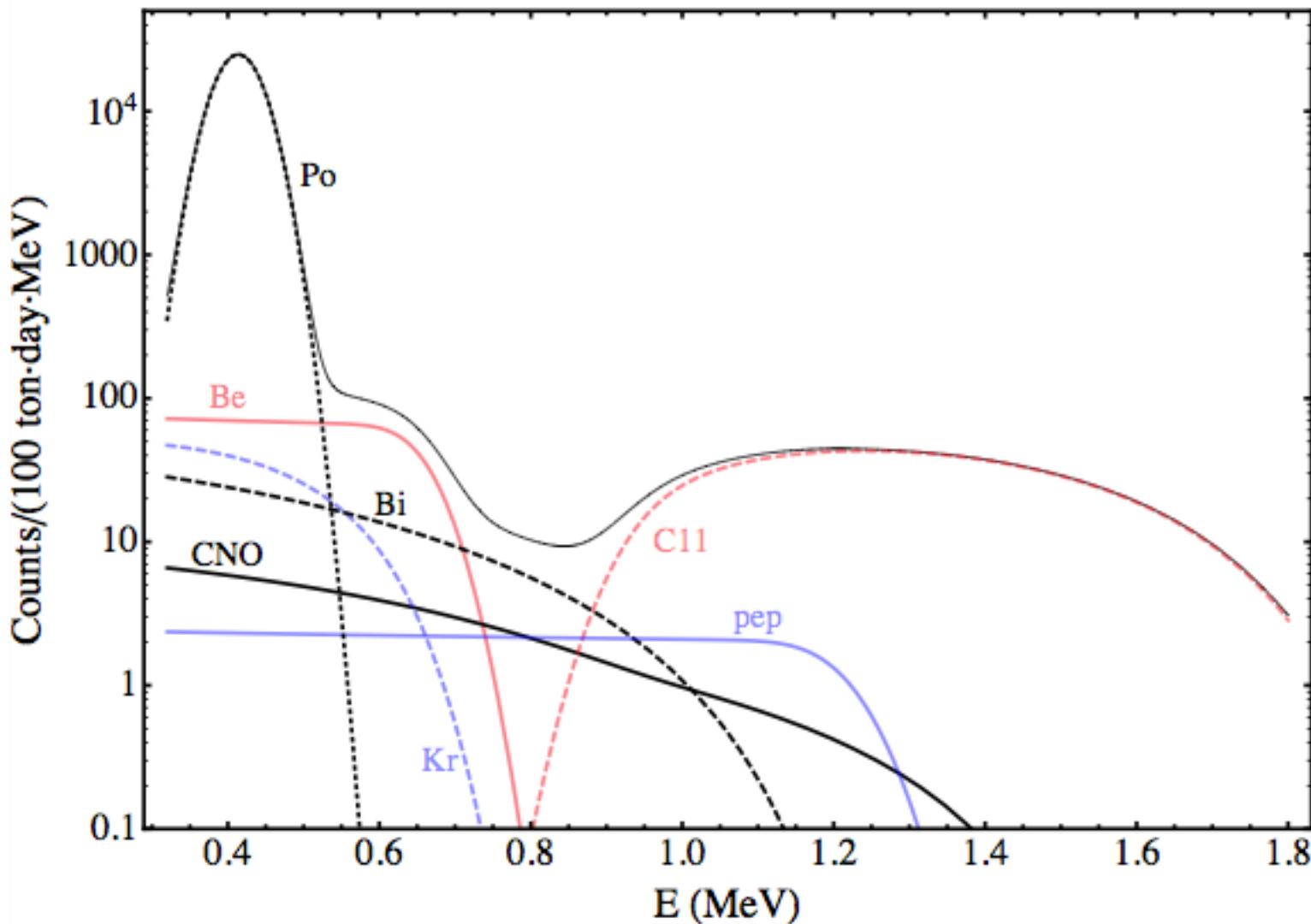


Doppler effect and high resolution  
Germanium detector to extract the angular  
distribution.

**Validation test: october 2014.**







# The Lithium Problem(s)

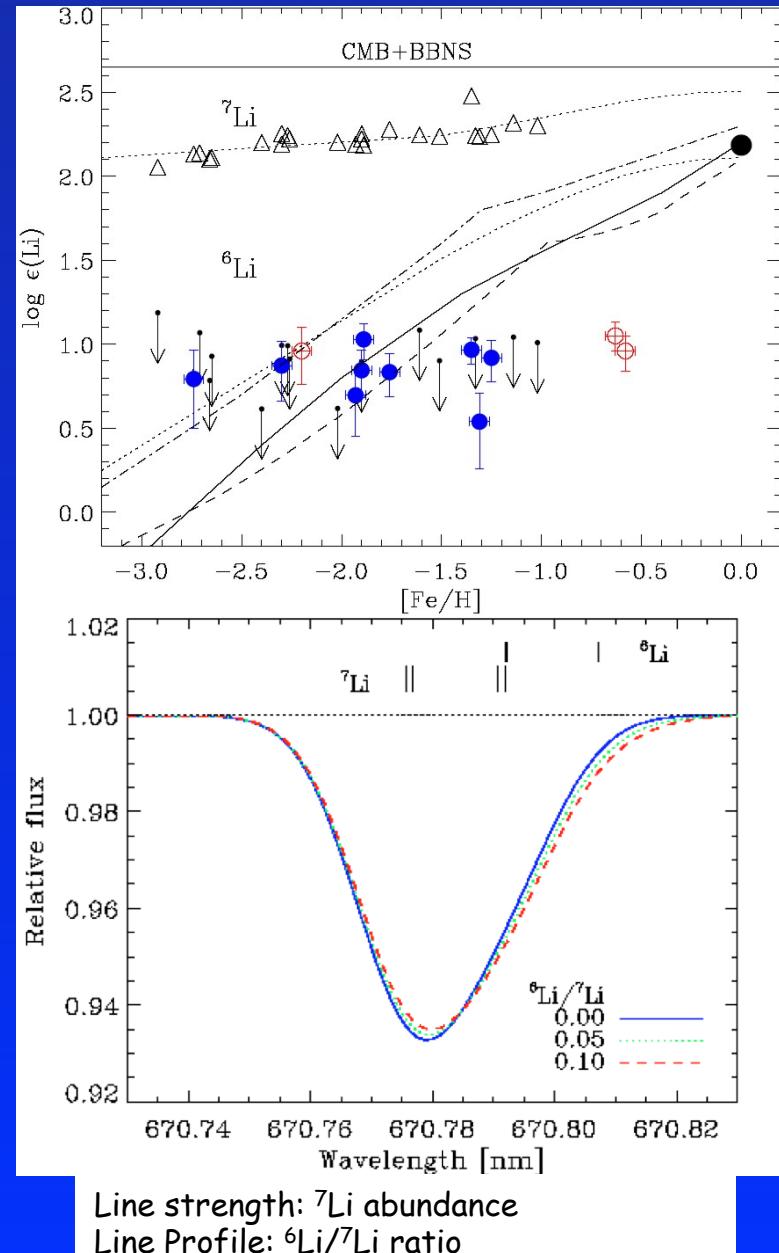
Basic Concepts to unfold primordial abundances

- Observation of a set of primitive objects (born when the Universe was young)
- Extrapolate to zero metallicity:

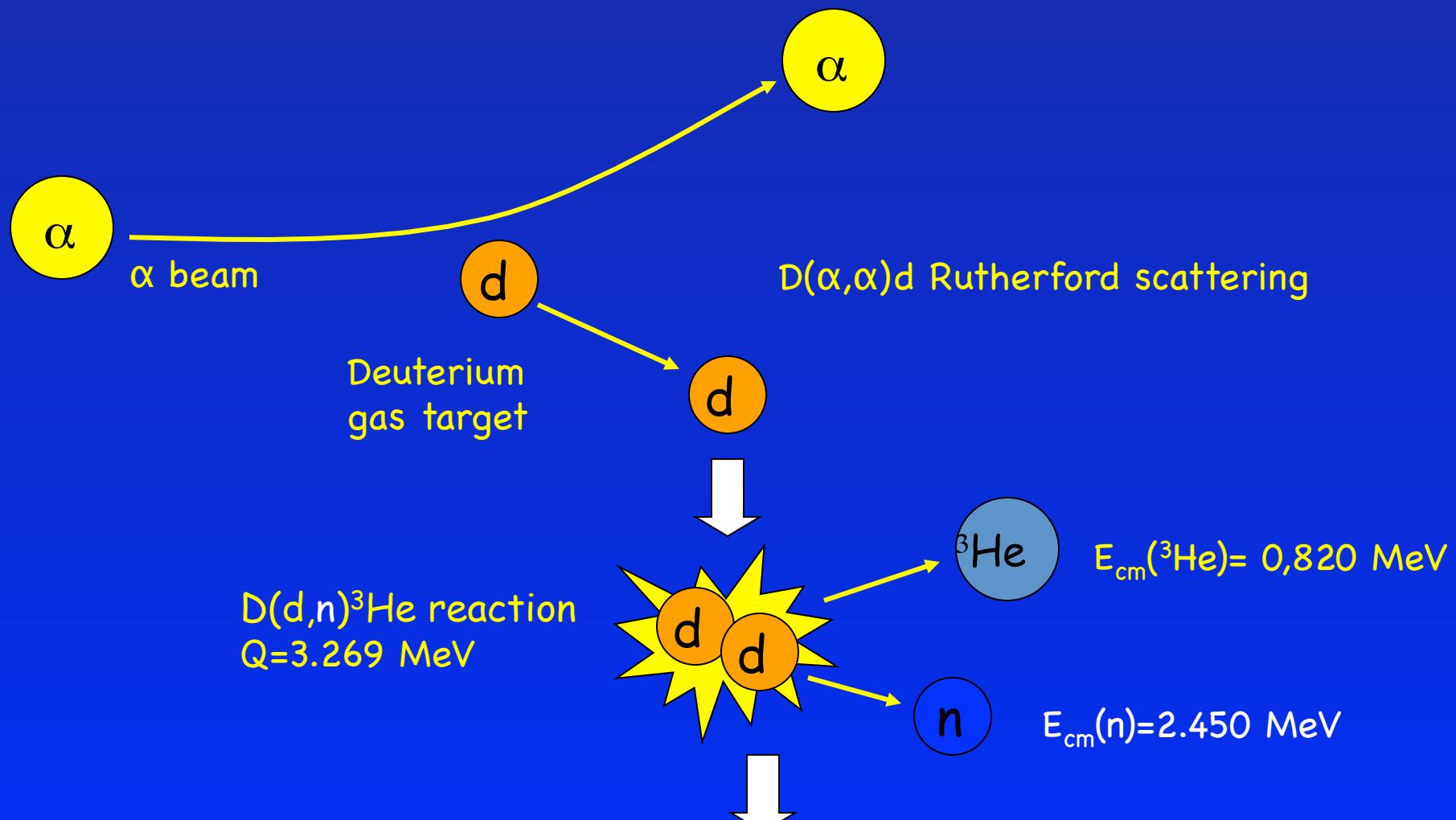
$\text{Fe/H}, \text{O/H}, \text{Si/H} \longrightarrow 0$

Lithium observations

- ${}^7\text{Li}$  primordial abundance: observation of the absorption line at the surface of metal-poor stars in the halo of our Galaxy
- ${}^6\text{Li}$  abundance : observation of the asymmetry of the  ${}^7\text{Li}$  absorption line.

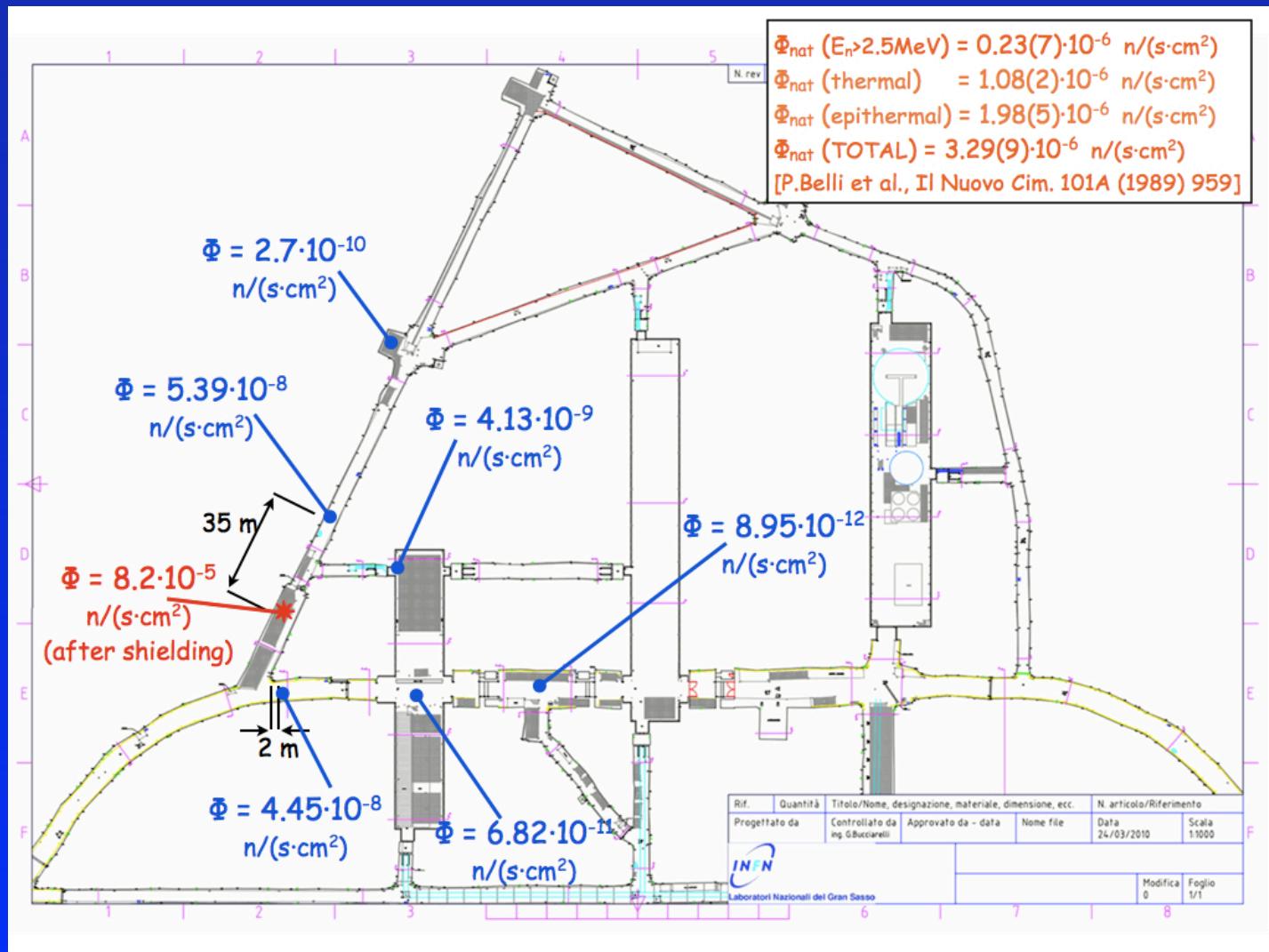


# Beam Induced Background in the $D(\alpha,\gamma)^6\text{Li}$ measurement

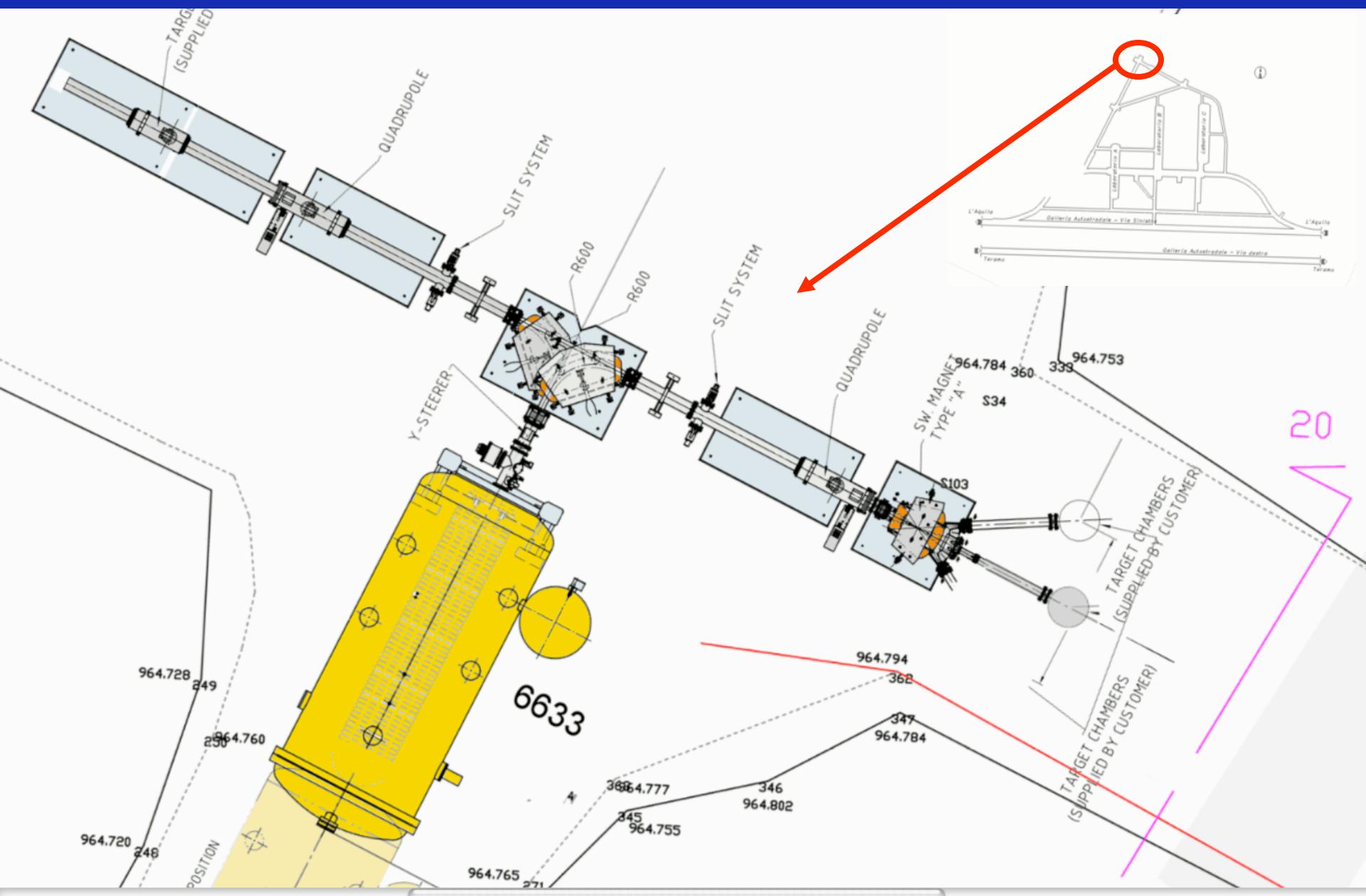


$(n,n'\gamma)$  reaction on the surrounding materials (lead, steel, copper and germanium)  
 $\gamma$ -ray background in the ROI for the  $D(\alpha,\gamma)^6\text{Li}$  DC transition (~1.6 MeV)

# Neutron flux inside LNGS (GEANT simulation)

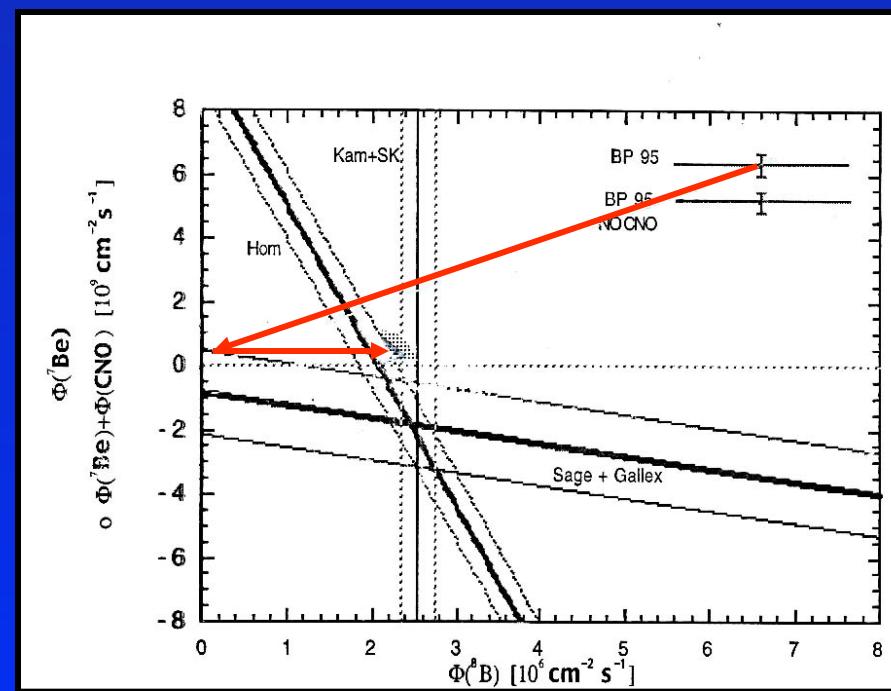
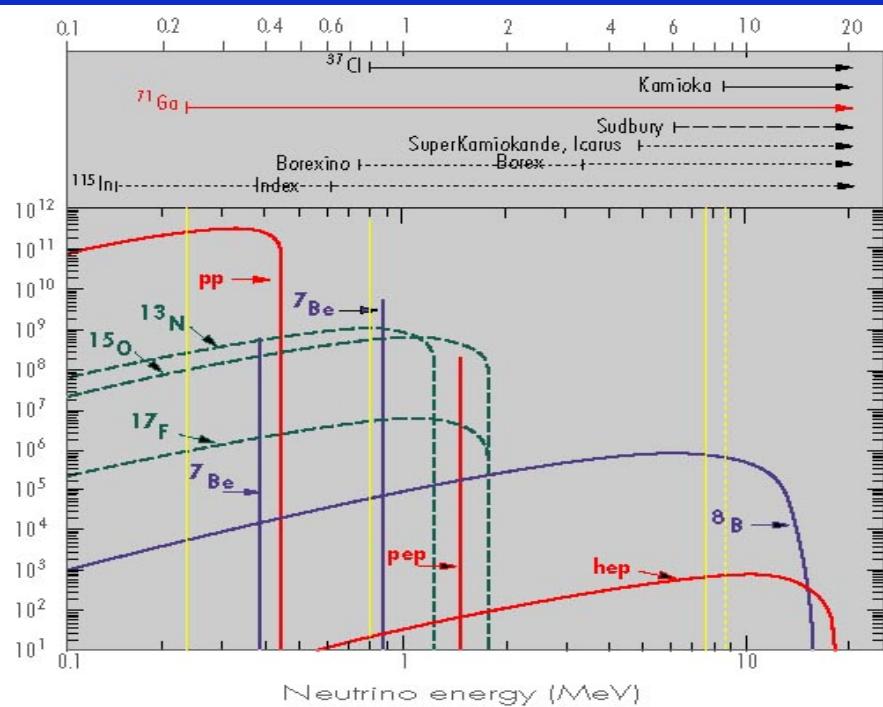


# Possible location of the 3.5 MV accelerator



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

Goal: Reject (or establish) a nuclear solution for the solar neutrino problem, by searching for a possible resonance inside the solar Gamow peak

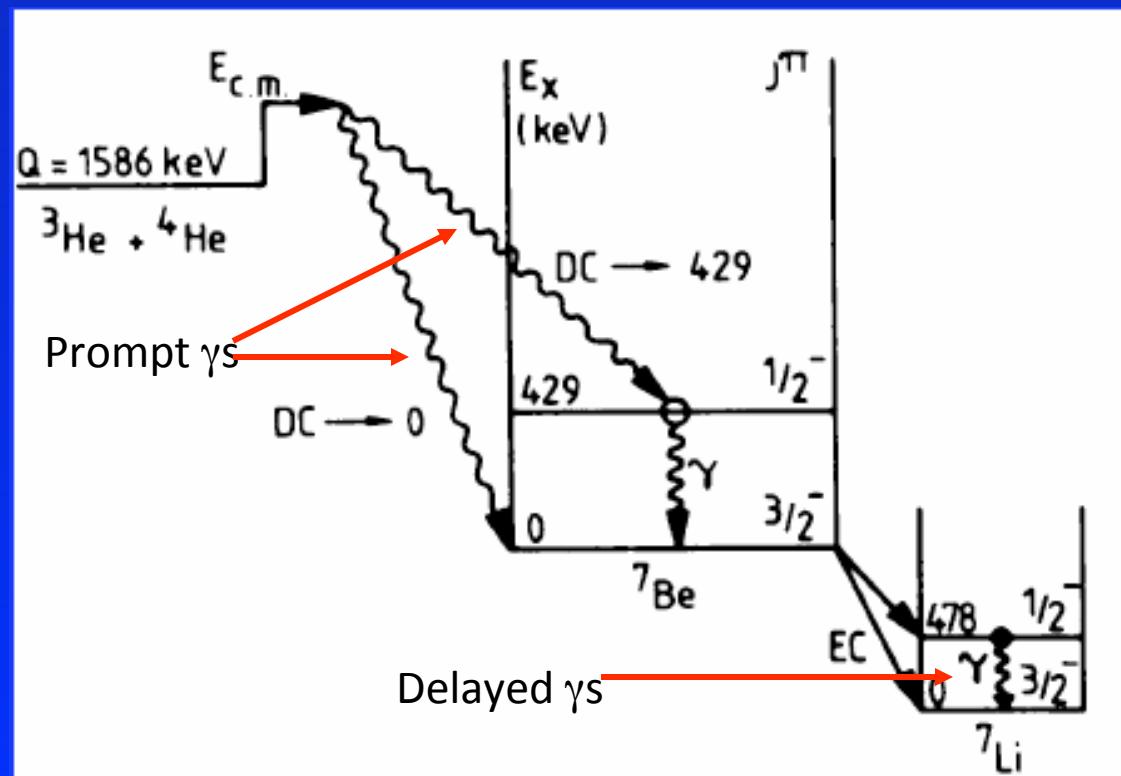
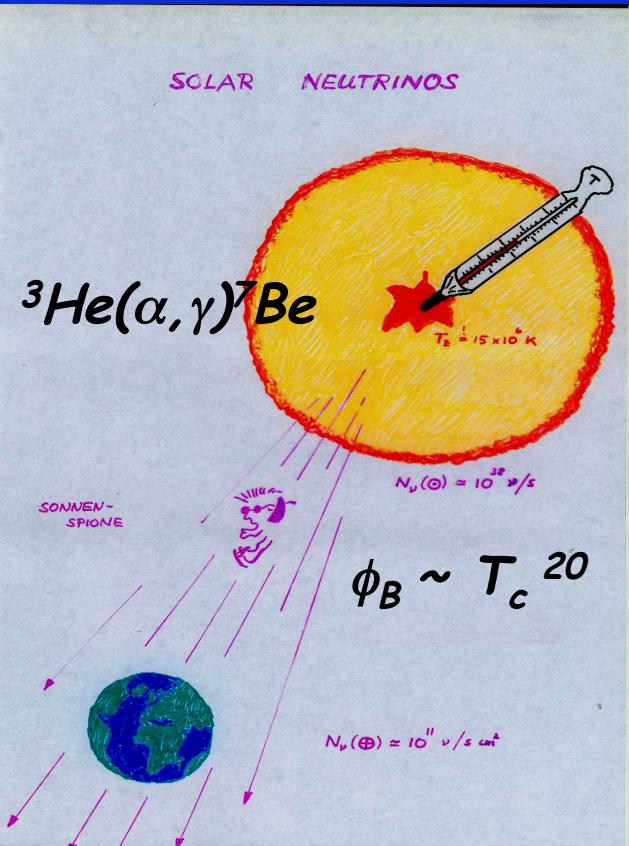


# $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$

Goal: After the discovery of neutrino oscillation, the solar neutrino are back to study the Solar interior.

Three objectives for the LUNA measurement:

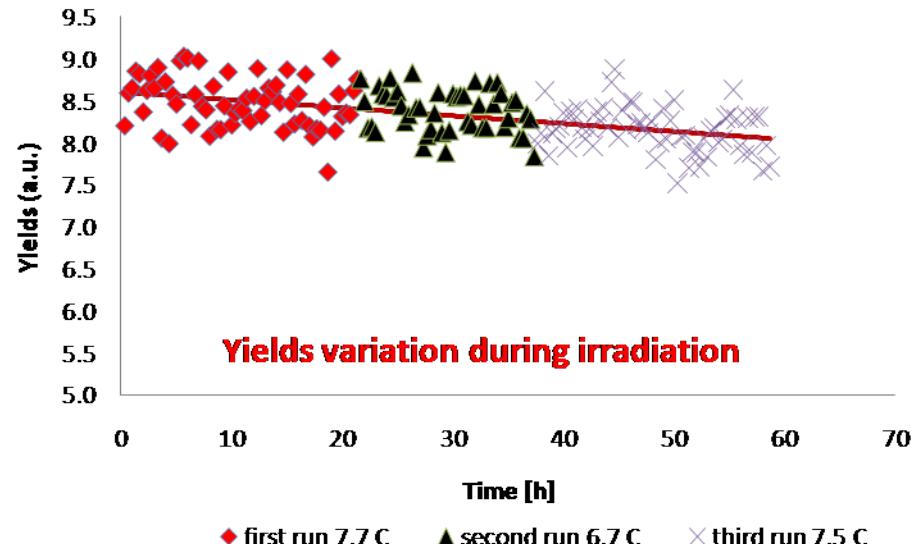
- Lowest energy ever reached (90 keV)
- Lowest uncertainty (4%)
- Simultaneous measurement of prompt and delayed  $\gamma$ s (systematic discrepancy od previous



# The AMS measurement



CIRCE lab. Caserta, Italy



## Results of the $^{26}\text{Al}/^{27}\text{Al}$ measurement

Sample	Total time (s)	Experimental ratio(a.u)	Error (%)
S1	11270	9.06e-12	0.8
S2	11270	8.90e-12	0.9
BLK 1	11270	3.5e-14	37
V1	11270	1.51e-11	0.6
M11	11270	8.78e-12	0.7

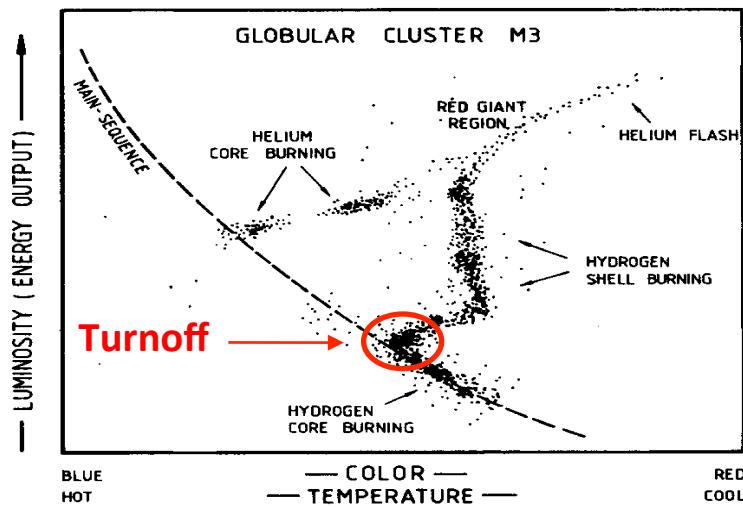
## $\omega\gamma$ results ( $\omega\gamma_{\text{gs}}/\omega\gamma=88.5\%$ )

	Iliadis ( $\gamma$ -meas.)	Arazi (AMS)	PD070701_7 (AMS-meas)
$\omega\gamma_{\text{gs}}$ (meV)	25+/-4	2.1+/-0.2	23.9+/-0.4
$\omega\gamma_{\text{tot}}$ (meV)	29+/-4	2.4+/-0.2	27.5+/-0.4

# $^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$ : L'età dell'Universo

Verso la fine della loro vita, le stelle escono dalla sequenza principale (turnoff) e brucano l' idrogeno residuo attraverso il ciclo CNO, la cui efficienza è regolata dalla reazione  $^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$ .

La misura di LUNA ha permesso di stabilire che l'età delle stelle degli ammassi globulari calcolata precedentemente, era sottostimata di quasi un miliardo di anni.



Età dell'universo (LUNA):  $14.5 \pm 1$  Gyears

Età dell'universo (PLANCK):  $13.81 \pm 0.06$  Gyears

