Direct measurements of cross sections of Astrophysical

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LUNA
Laboratory for Underground Nuclear Astrophysics

UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II

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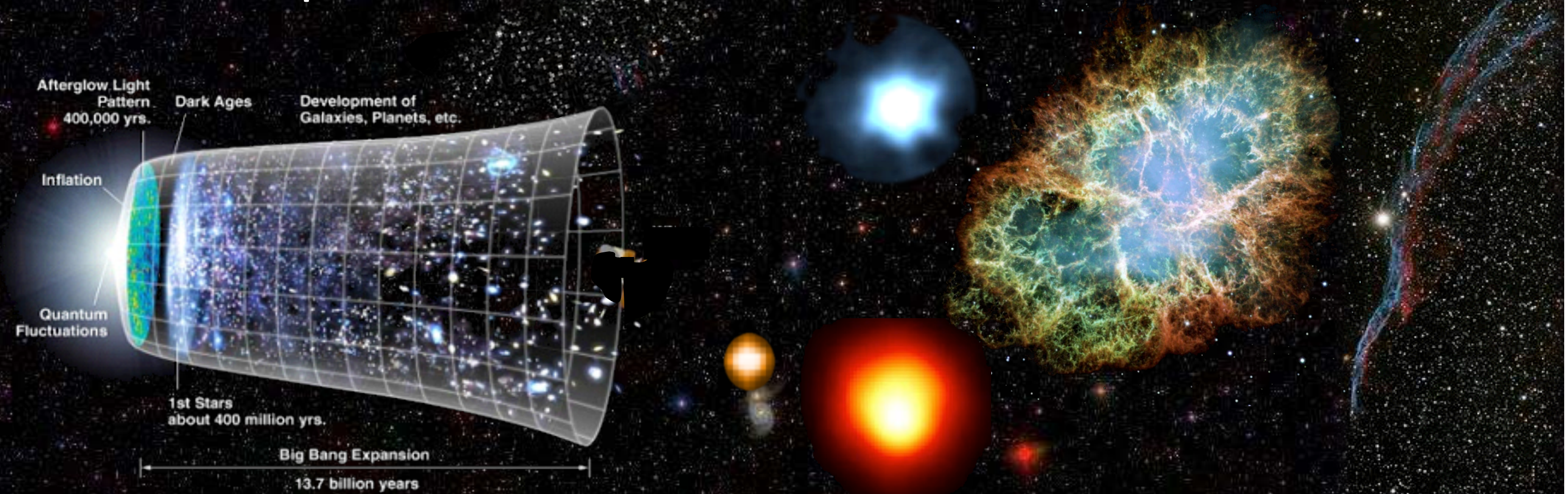
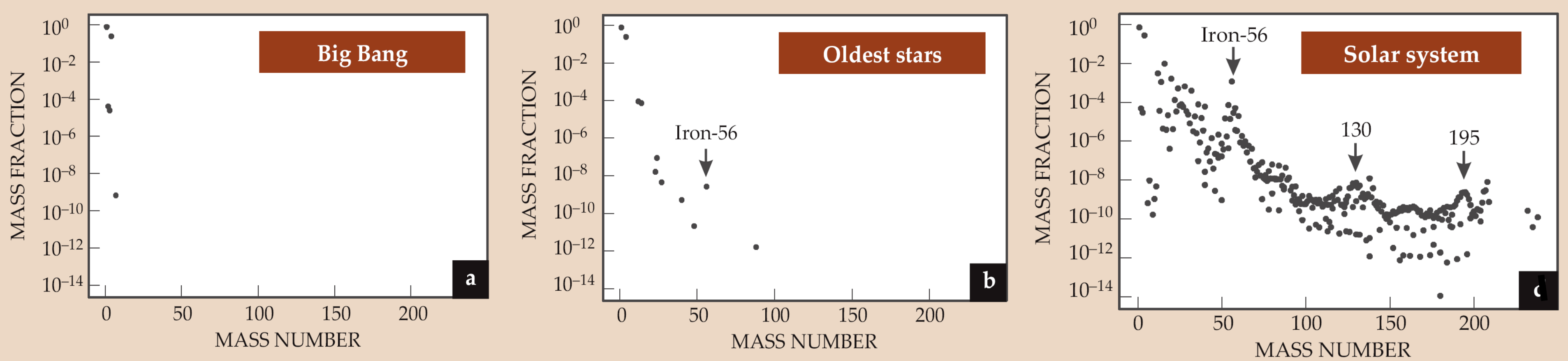
INFN
Sezione di Napoli

Galactic chemical evolution

Almost all important events in the Universe have left behind them nuclear clues

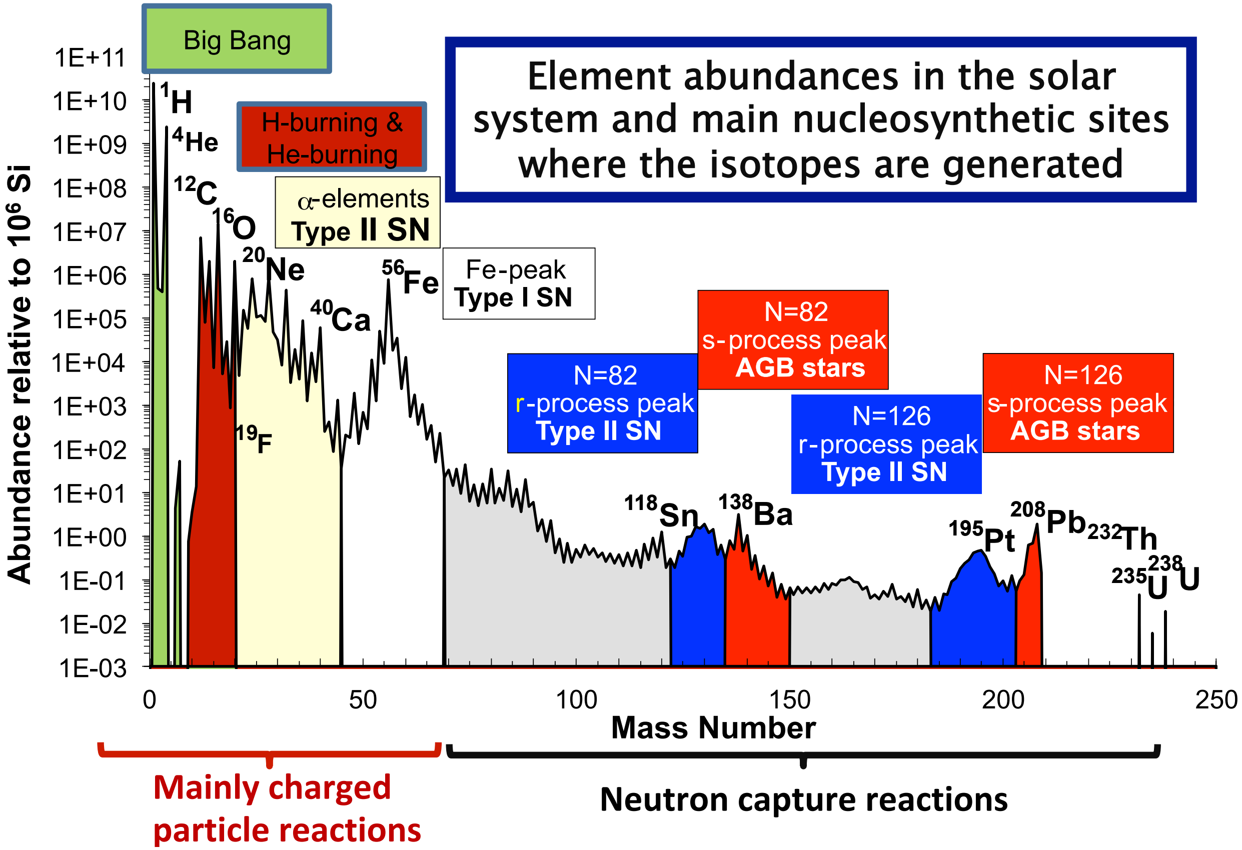


Subject of N.A. is the understanding of nuclear processes taking place in astrophysical environments



Le origini 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".*
- **1939: Hans Bethe; Physical Review,** *descrizione della combustione dell'idrogeno.*
- **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 miniera di Homestake.*



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

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

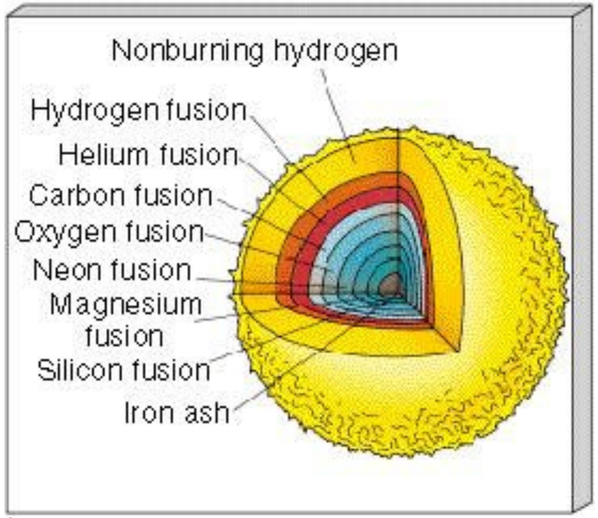
Stellar evolution during thermal equilibrium

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$ hydrostatic equilibrium

$$\frac{dT}{dM_r} = \nabla \frac{GM_r T}{4\pi r^2 P}$$ heat transport

$$\frac{dr}{dM_r} = -\frac{1}{4\pi r^2 \rho}$$ mass contuinity

$$\frac{dL_r}{dM_r} = \varepsilon_g + \varepsilon_\upsilon + \varepsilon_n$$ energy conservation



$$\varepsilon_n = \varepsilon_{12} + \varepsilon_{34} = (r_{12} - r_{34})\frac{Q}{\rho}$$

$$r_{12} = N_1 N_2 \langle \sigma v \rangle$$

$$\frac{dY_i}{dt} = \sum_j c_i(j)\lambda_j Y_j + \sum_{j,k} c_i(j,k)\rho N_A \langle \sigma v \rangle_{j,k} Y_j Y_k + \ldots\ldots$$

chemical evolution

Some examples

- **BBN and H-burning in the Sun and solar neutrinos**:

$p+p \to d+e^+ +\nu$, $p(d,\gamma)^3He$, $d(\alpha,\gamma)^6Li$, $^3He(^3He, 2p)^4He$, $^3He(\alpha,\gamma)^7Be$, $^7Be(p,\gamma)^8B$ and $^{14}N(p,\gamma)^{15}O$

- **Age of Globular Clusters and C production in AGB:**

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

- **AGB nucleosynthesis – light nuclei abundances:**

$^{14}N(p,\gamma)^{15}O$, $^{15}N(\alpha,\gamma)^{19}F$, $^{15}N(p,\gamma)^{16}O$, $^{15}N(p,\alpha)^{12}C$, $^{17}O(p,\gamma)^{18}F$, $^{17}O(p,\alpha)^{14}N$, $^{18}O(p,\gamma)^{19}F$, $^{18}O(p,\alpha)^{15}N$, $^{18}O(\alpha,\gamma)^{22}Ne$, $^{18}F(\alpha,p)^{21}Ne$, $^{19}F(\alpha,p)^{22}Ne$, $^{22}Ne(p,\gamma)^{23}Na$, $^{23}Na(p,\gamma)^{24}Mg$, $^{24}Mg(p,\gamma)^{25}Al$, $^{25}Mg(p,\gamma)^{26}Al(\beta^+)^{26}Mg$, $^{26}Mg(p,\gamma)^{27}Al$

- **Main neutron sources:**

$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$

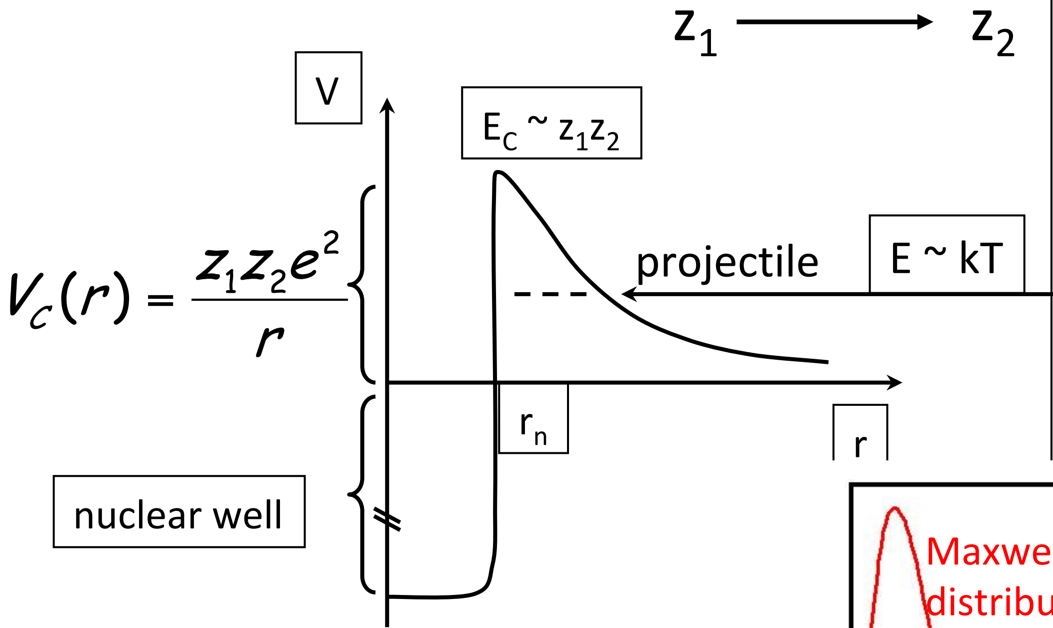
- **Explovive CNO burning:**

$^{15}O(\alpha,\gamma)^{19}Ne$, $^{14}O(\alpha,\gamma)^{18}Ne$, $^{18}Ne(\alpha,p)^{21}Na$

- **He and advanced burnings:**

$^{12}C(\alpha,\gamma)^{16}O$, $^{12}C(^{12}C, p)^{23}Na$, $^{12}C(^{12}C,\alpha)^{20}Ne$, $^{16}O(\alpha,\gamma)^{20}Ne$

Charged particle reactions in stars



Example z_1=p and z_2=p (e.g. Sun)

T ~ 15×10^6 K $\Rightarrow$ E = kT ~ 1 keV

E_C = 550 keV

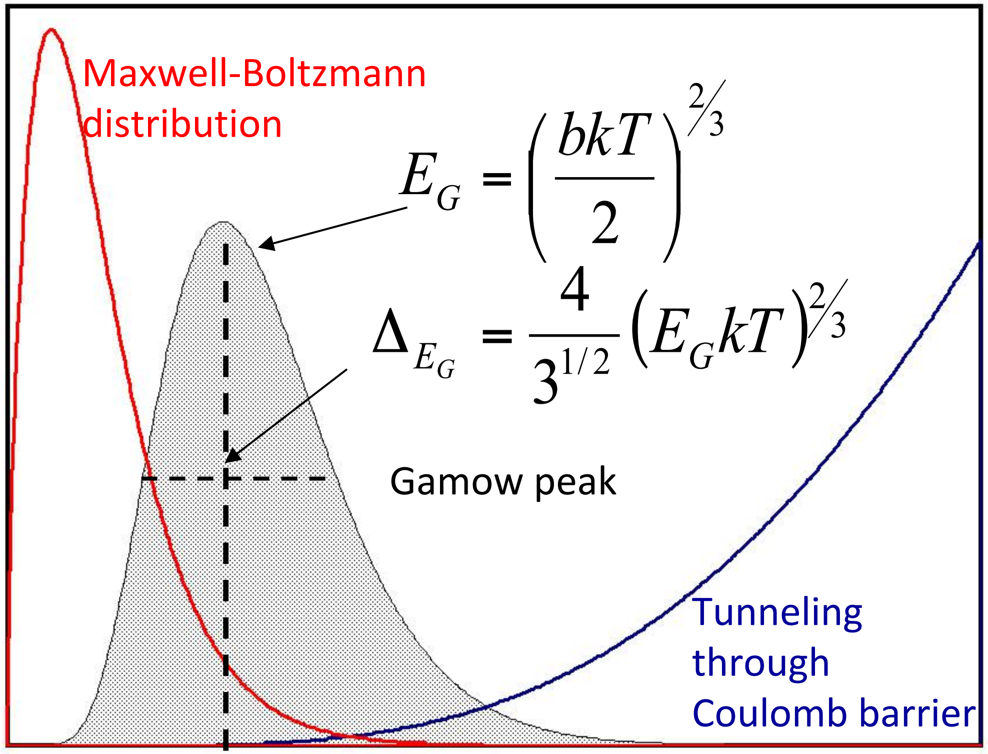
during quiescent burnings:

kT << E_c

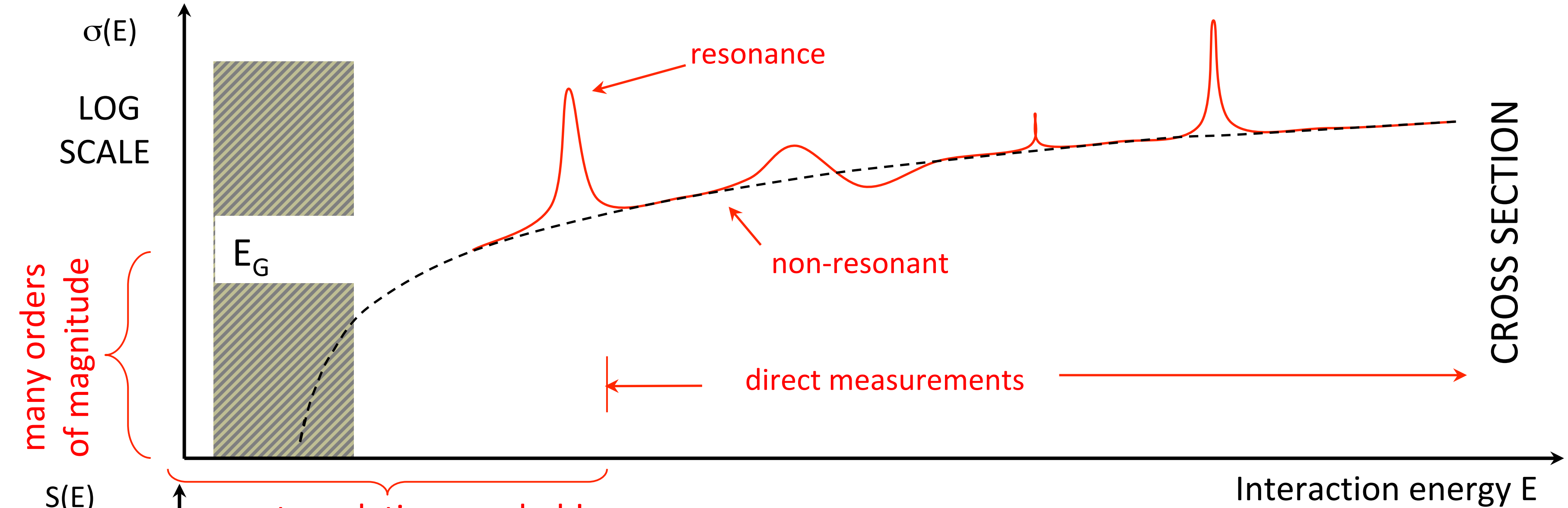
reactions occur through

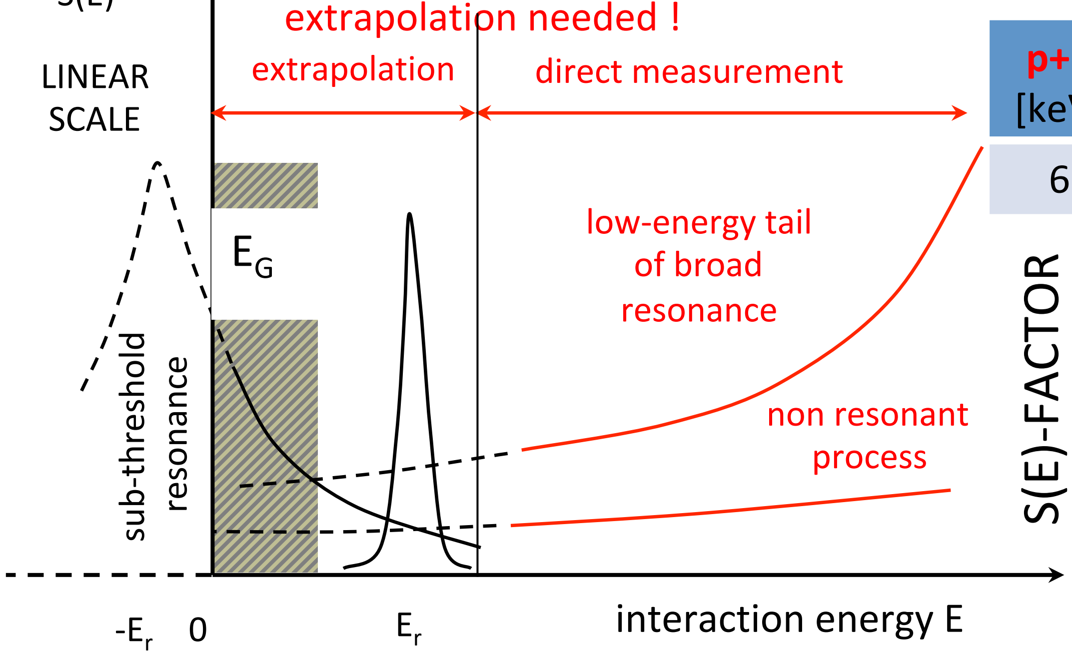
TUNNEL EFFECT

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left[-\frac{E}{kT}\right] dE$$



Problem of extrapolation



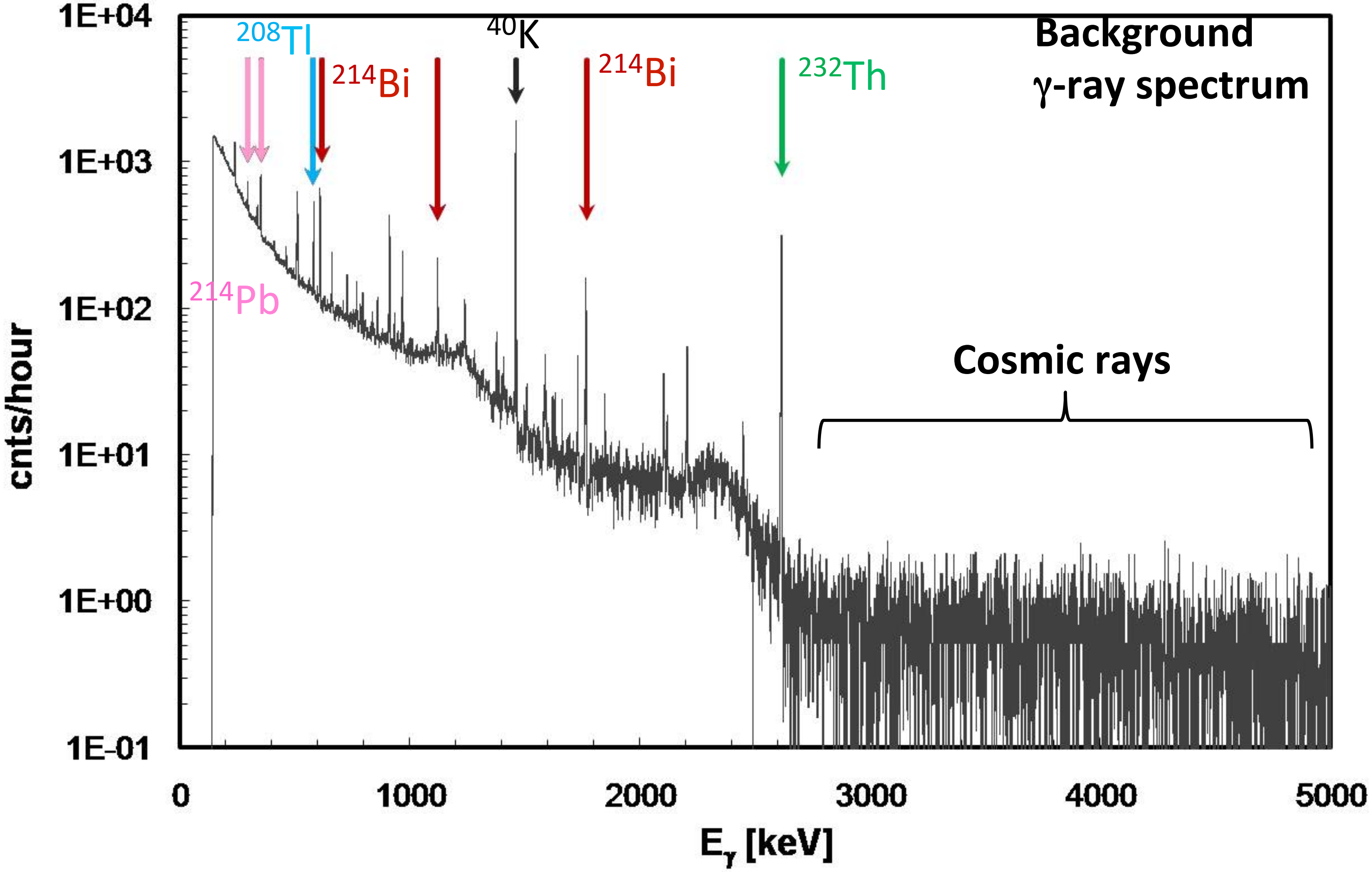


p+p [keV]	$^{3}He+^{3}He$ [keV]	$^{3}He+^{4}He$ [keV]	$^{7}Be+p$ [keV]	$^{14}N+p$ [keV]
6	22	23	18	27

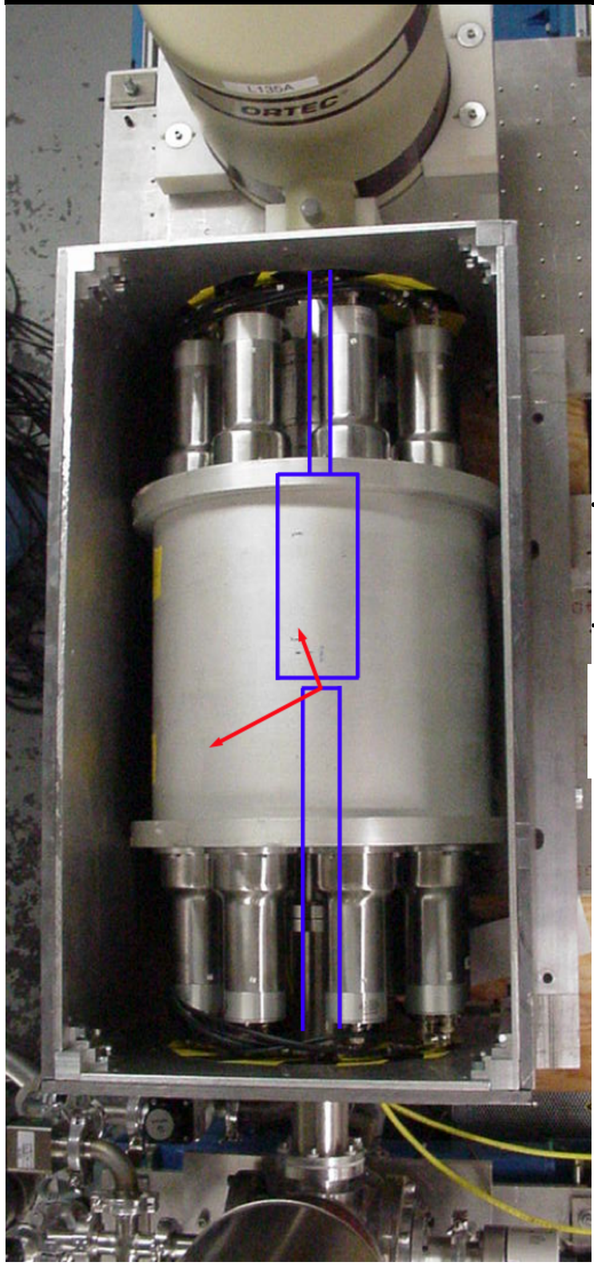
Most of the reactions of astrophysical interest happen via radiative capture.
$^{3}He(\alpha,\gamma)^{7}Be$, $^{14}N(p,\gamma)^{15}O$, $^{12}C(\alpha,\gamma)^{16}C$...

γ-ray natural background

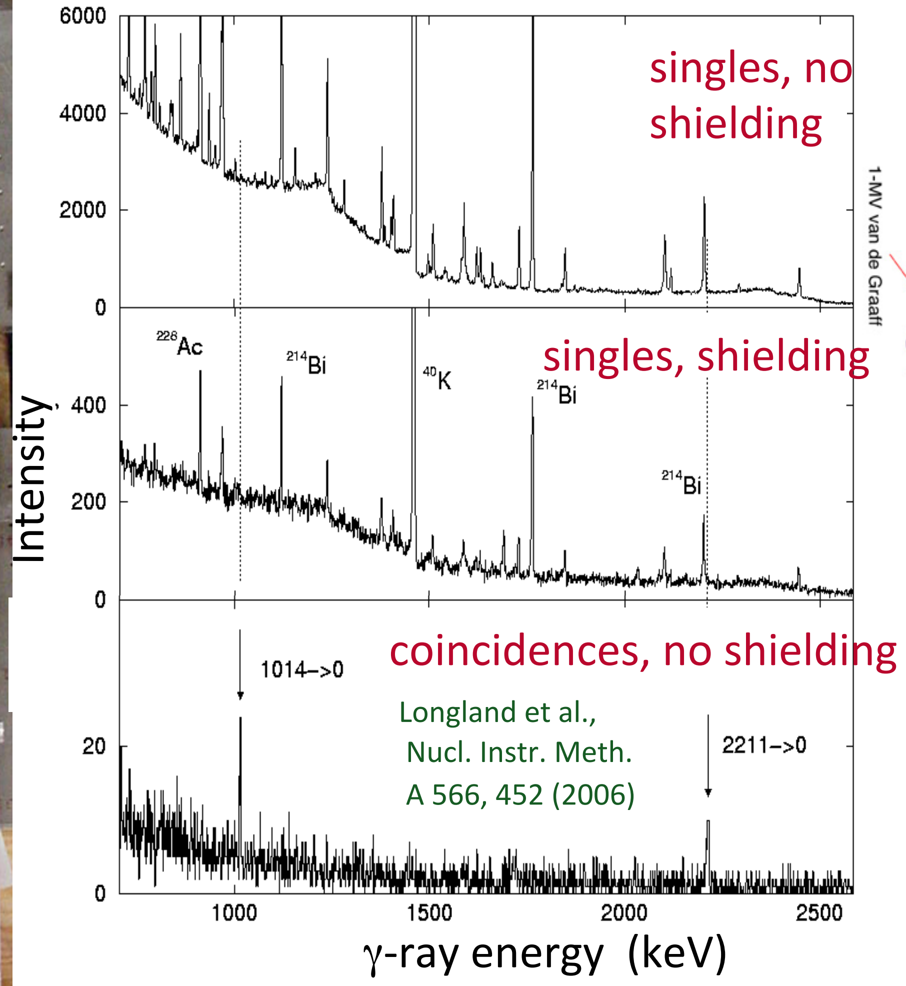
1. **Environmental radioactivity (γ-rays of low energy)**:
   a) natural radioactive series **^{226}Ra, ^{214}Bi, ^{214}Pb** (from **^{238}U**) and **^{224}Ra, ^{208}Tl, ^{212}Pb** (from **^{232}Th**);
   b) radon (**^{222}Rn - ^{220}Rn**) a short-lived radioactive gas (from **^{238}U** and **^{232}Th** respectively);
   c) long-lived natural radionuclides such as **^{40}K, ^{87}Rb, ^{115}In, ^{133}La, ^{142}Ce**, etc.
2. **Cosmic rays (γ-rays of high energy).**



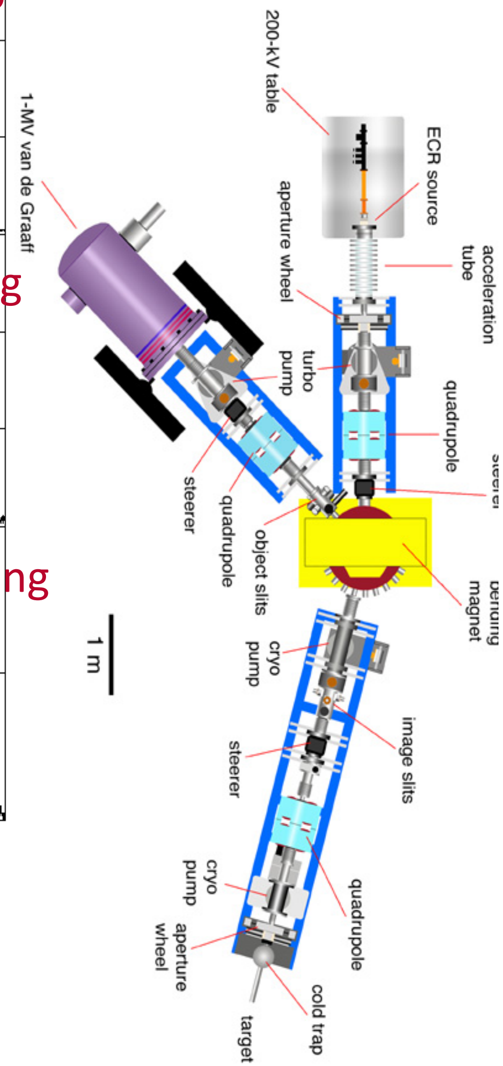
Coincidence γγ + passive shielding



resonance at 227 keV in $^{26}Mg(p,\gamma)^{27}Al$, 1μA



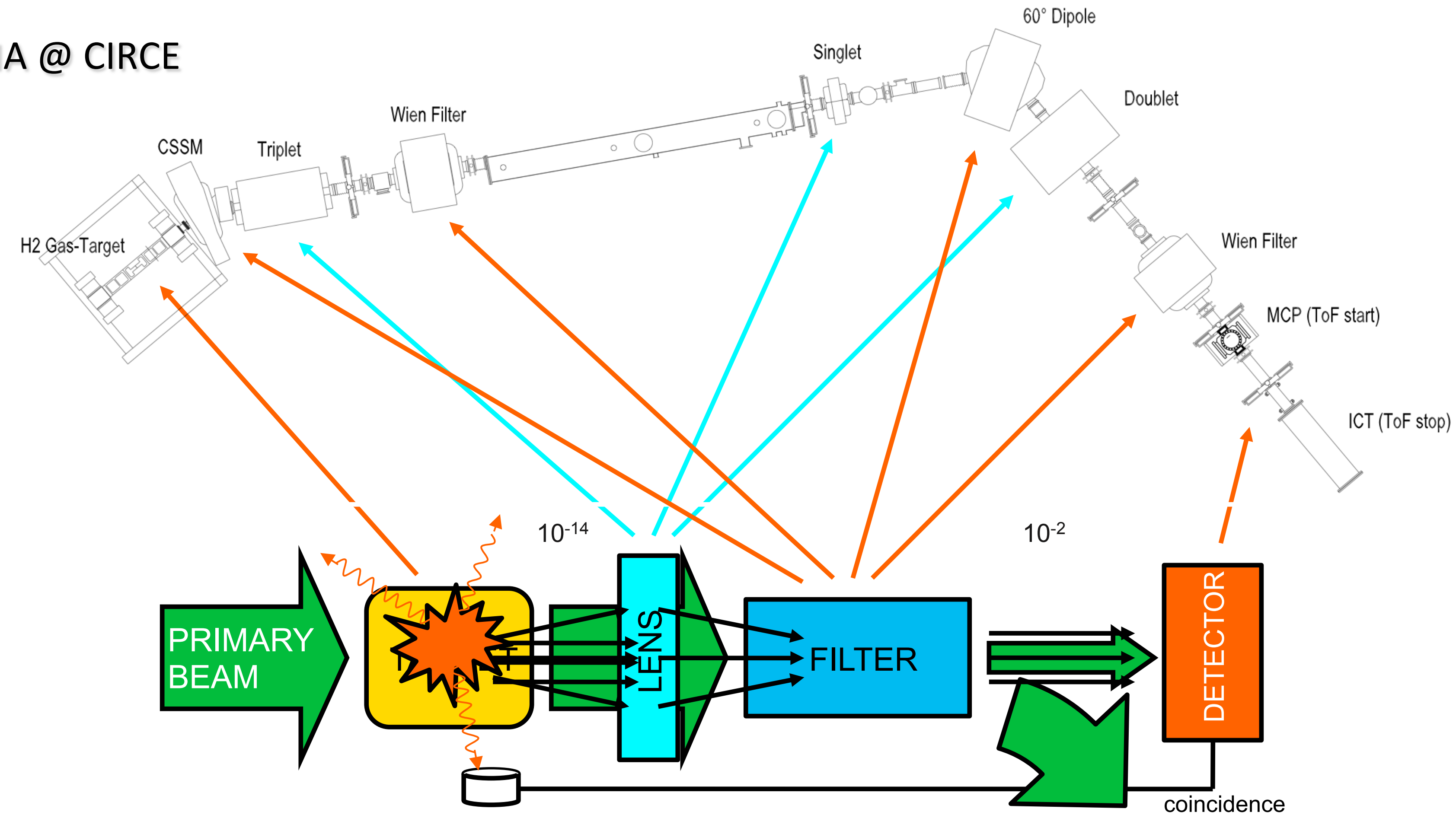
LENA - experiment



Background reduction:
up to 3000 for 0.6 < E_γ(MeV) < 3
20 for 3 < E_γ(MeV) < 9

An alternative approach: Recoil Mass Separator

ERNA @ CIRCE



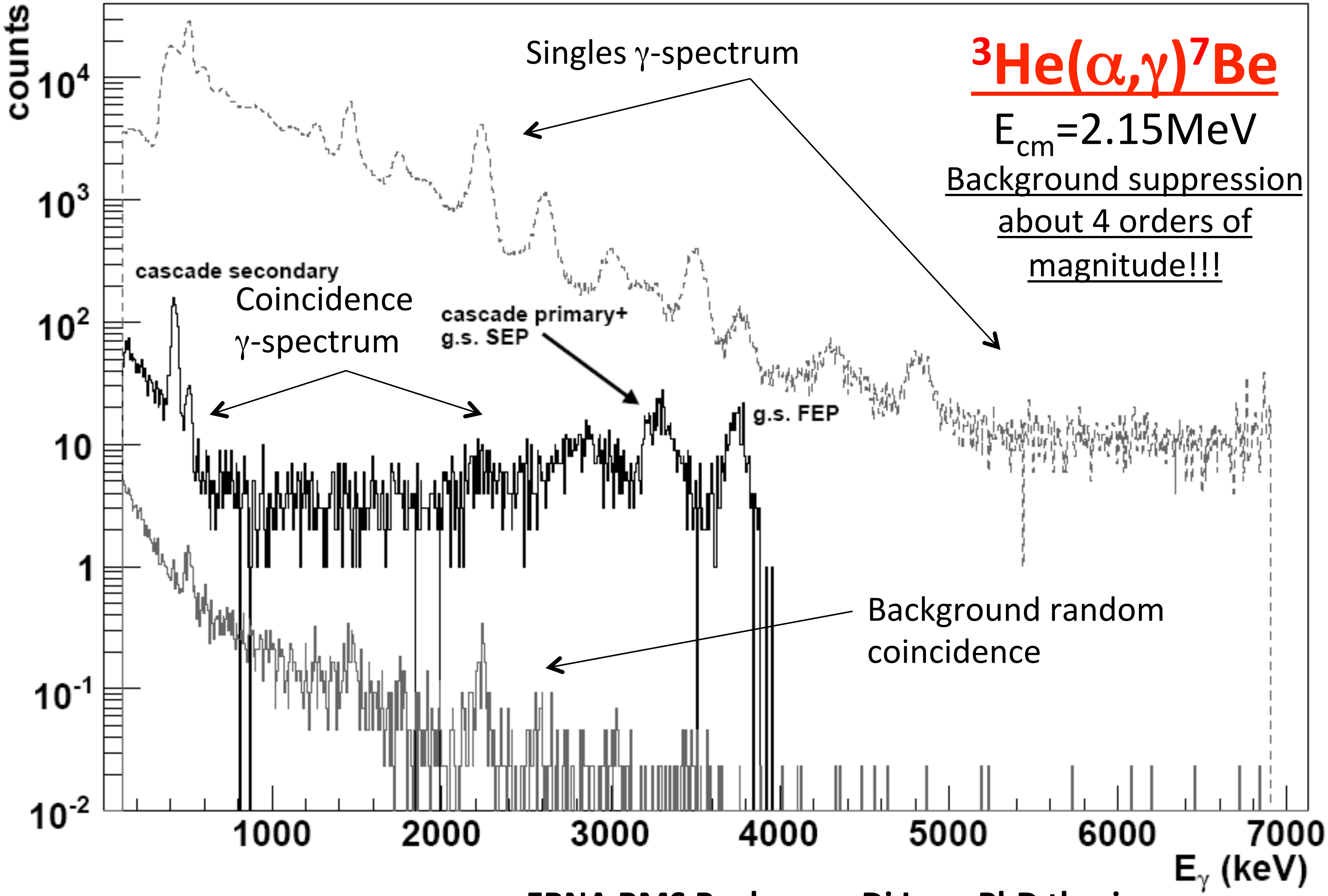
Why Recoil Separators?

- **High efficiency**
- **(mostly) background free**
- **Excellent background reduction for γ-spectroscopy**

Disadvantages

- **Very difficult to do!!**

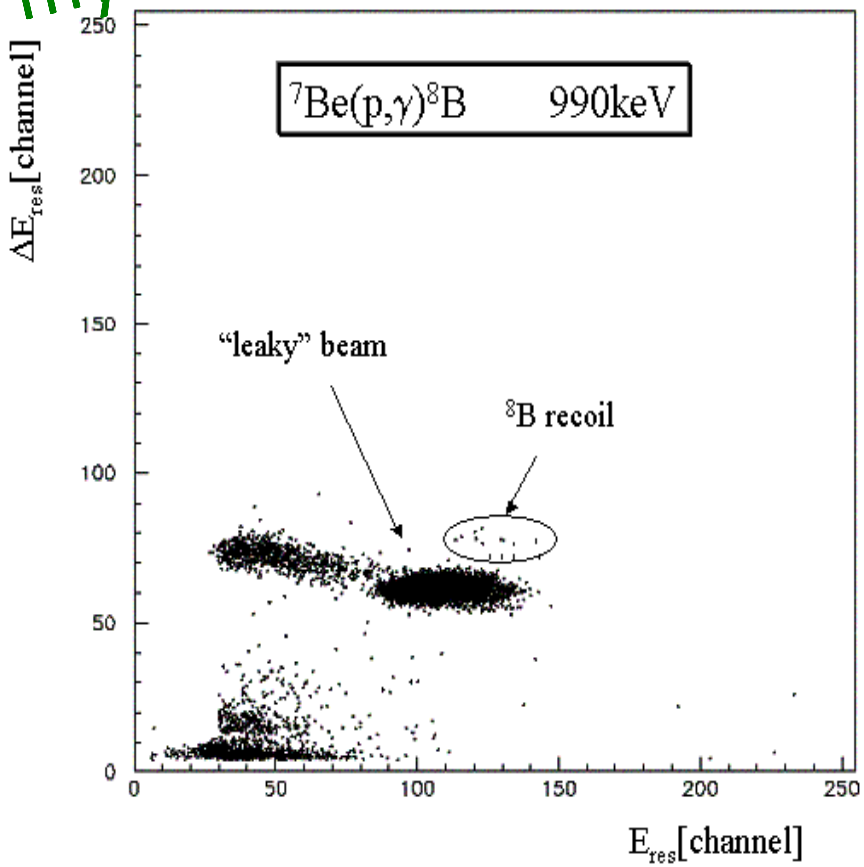
Coincidence γ-spectrum

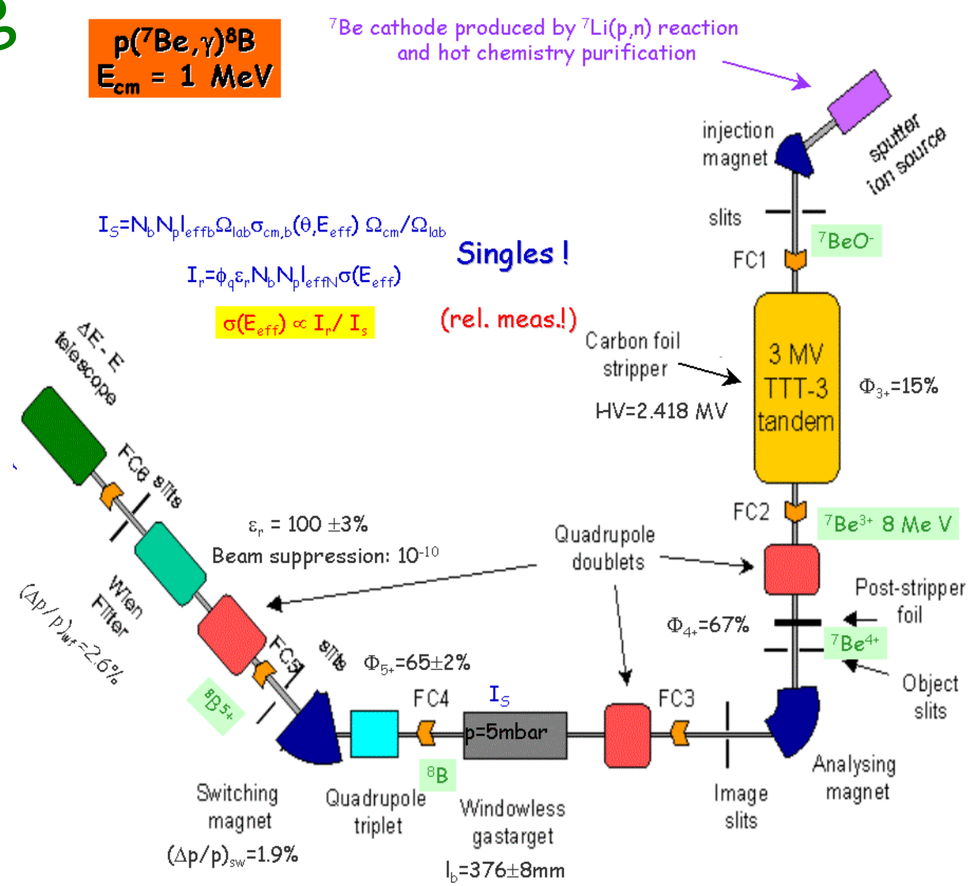


ERNA RMS Bochum - Di Leva PhD thesis

Direct measurement of the absolute cross section of $^{1}H(^{7}Be,\gamma)^{8}B$, using NABONA recoil mass separator

Almost 20 years ago during my PhD thesis





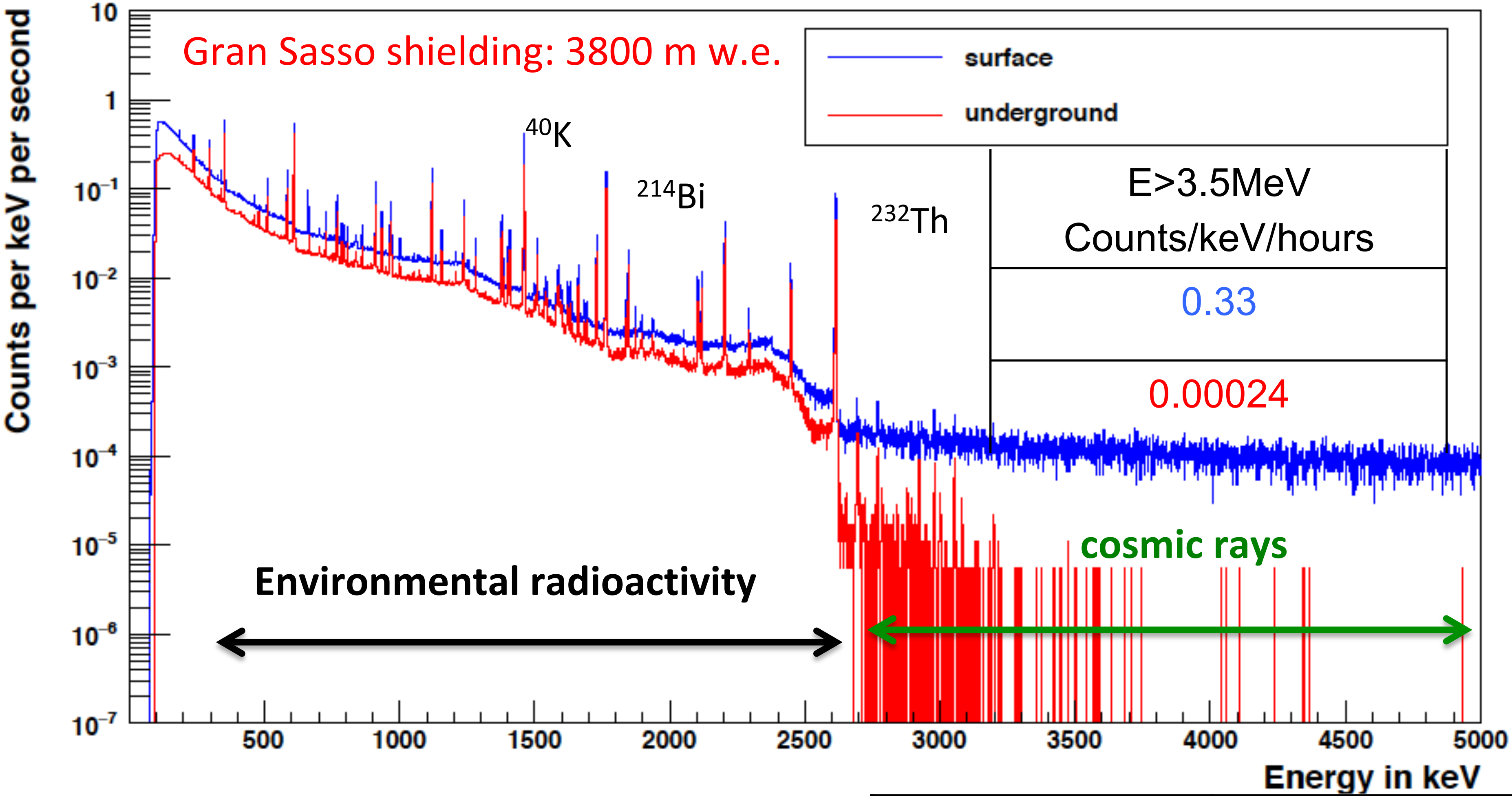
We quoted a cross section of $\sigma(990\ keV)$ = 0.40 ± 0.12 $\mu\ b$. Scaling the previous analysis the corresponding astrophysial factor is:

$S(0)$ = 15.3 ± 4.5 *eVb*.

Nucl.Phys.A688(2001)

Eur.Phys.J.A,7(2000).

Why going underground γ-background

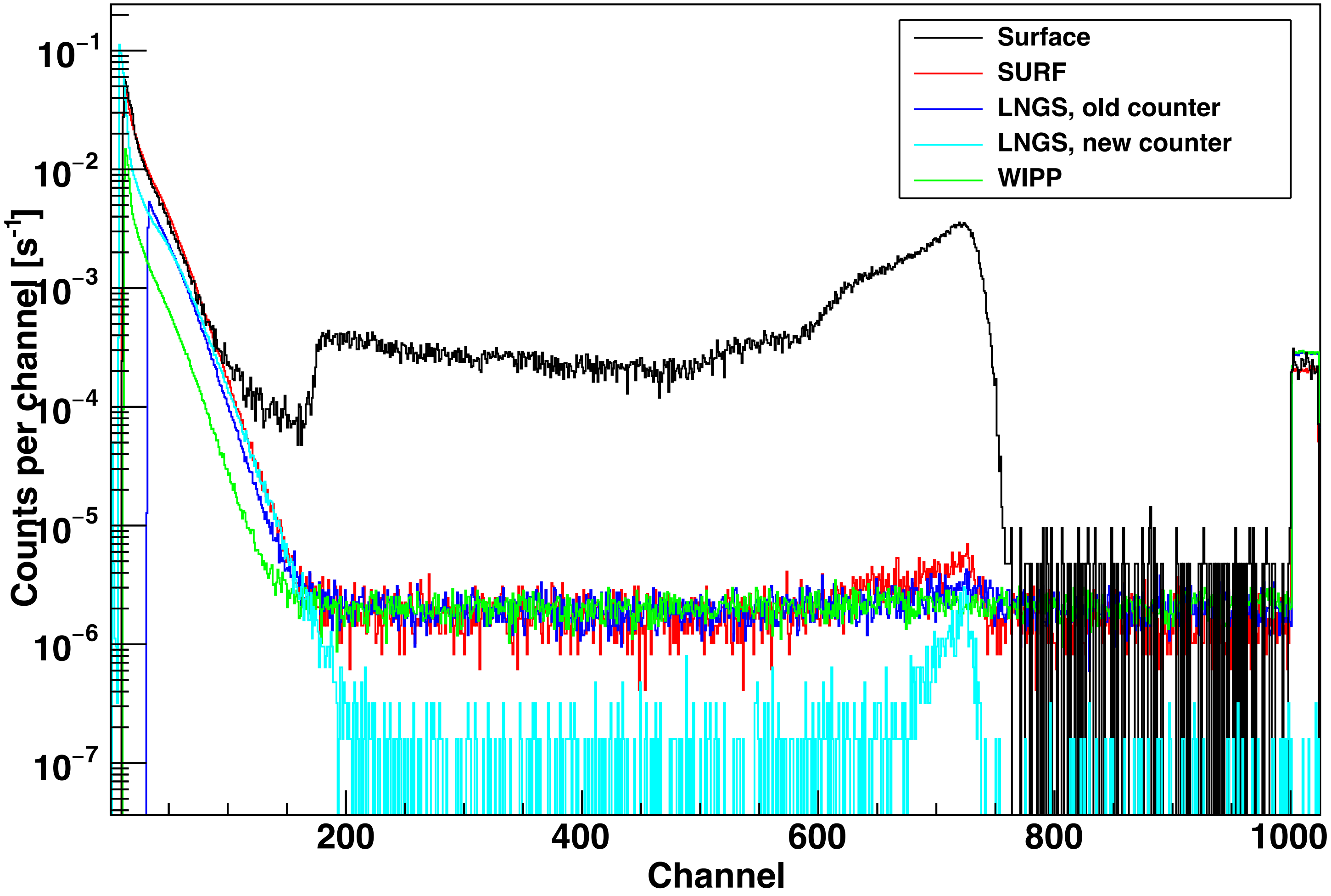


E>3.5MeV Counts/keV/hours
0.33
0.00024

Therefore, the advantage of an underground environment is evident for high Q-value reactions such as **$^{14}N(p,\gamma)^{15}O$, $^{15}N(p,\gamma)^{16}O$, $^{17}O(p,\gamma)^{18}F$, $^{25}Mg(p,\gamma)^{26}Al$**......

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

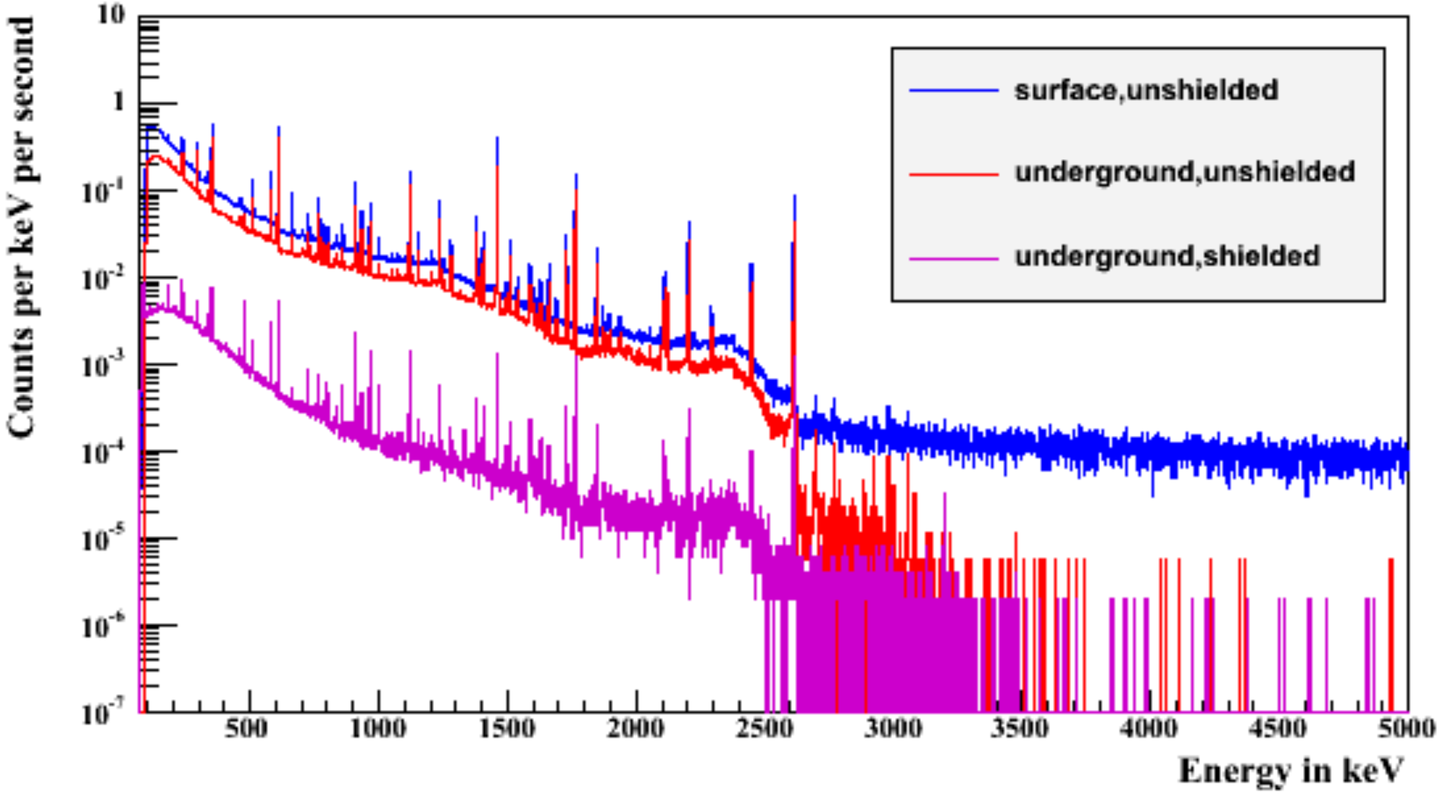
Why going underground n-background



Therefore, the advantage of an underground environment is evident for n-source reaction as **$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$**

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

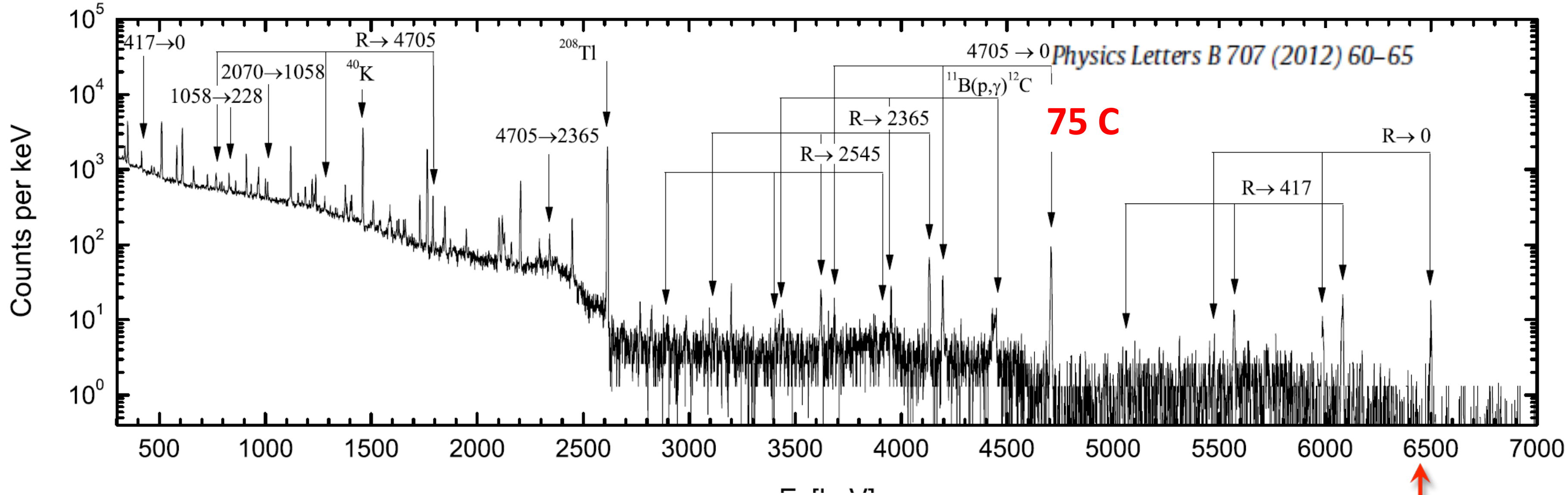
Underground Pb-shielding

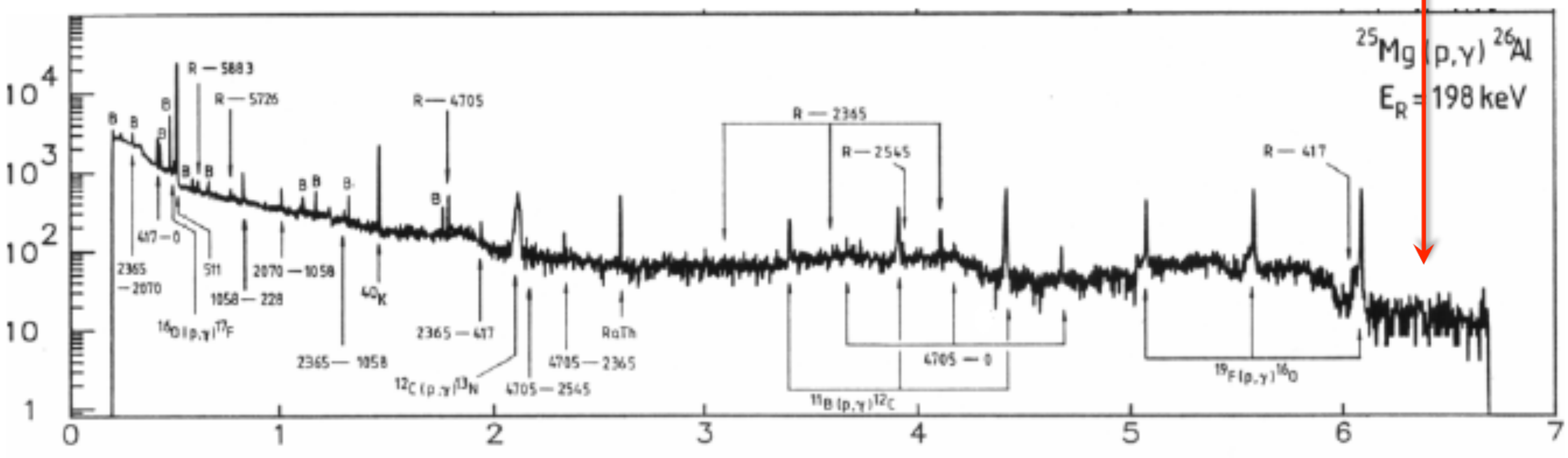


			Surface	Underground		
			unshielded	unshielded	shielded (this setup)	
^{40}K	primordial	1460 keV	*	2244	15	counts / hour
^{214}Bi	^{238}U chain	1764 keV	*	1271	13	counts / hour
^{208}Tl	^{232}Th chain	2614 keV	*	679	15	counts / hour
region 3300 – 6000 keV			$3.30(2) \cdot 10^{-1}$	$2.4(4) \cdot 10^{-4}$	$1.9(2) \cdot 10^{-4}$	counts / keV / hour

HPGe fully sorrounded (55°) with 15 cm of Pb

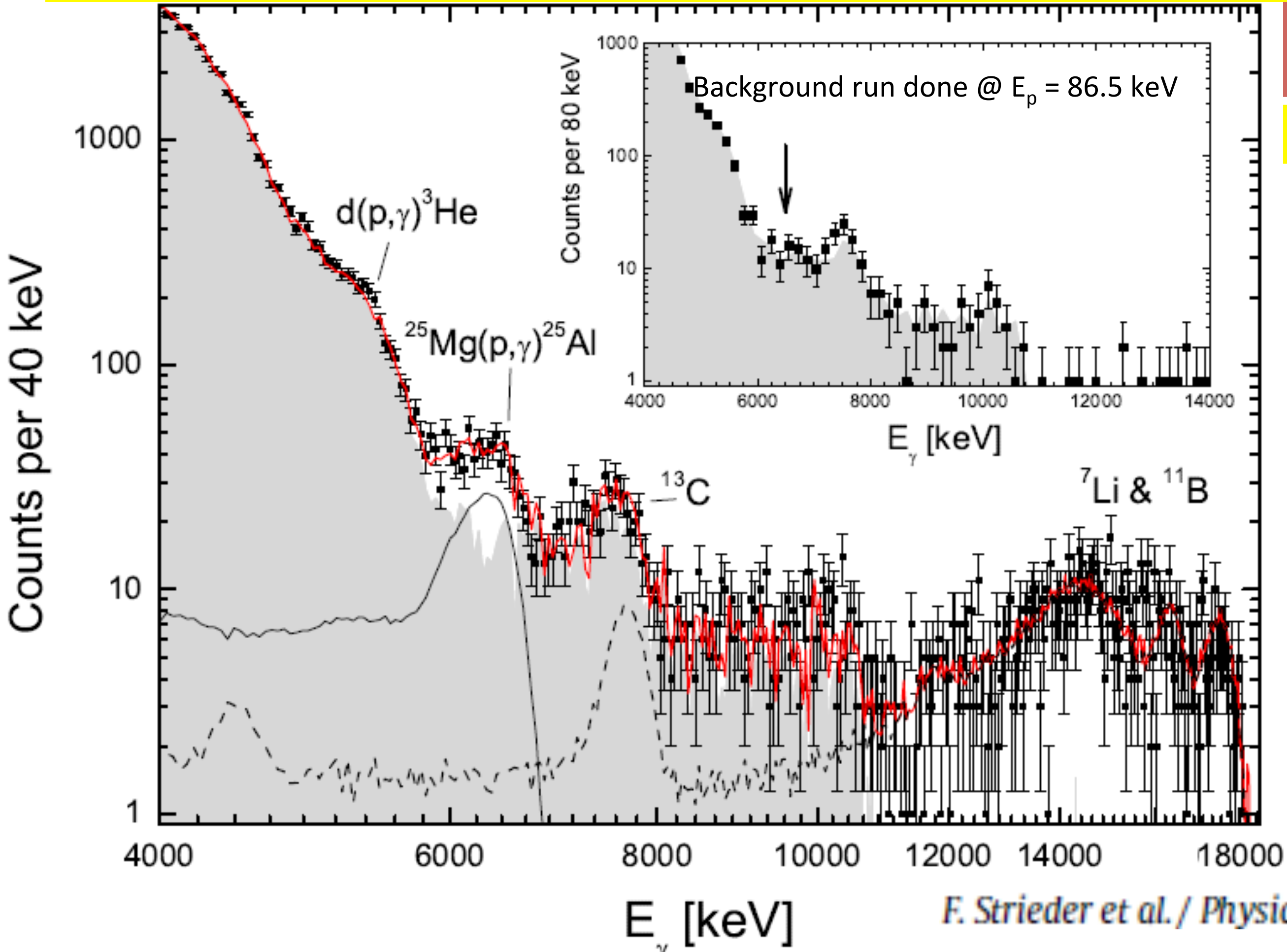
$^{25}Mg(p,\gamma)^{26}Al$ - HPGe spectra E_R = 190 keV





$^{25}Mg(p,\gamma)^{26}Al$ - BGO spectra E_R = 90 keV

the weakest ever directly measured resonance strength



F. Strieder et al. / Physics Letters B 707 (2012) 60–65

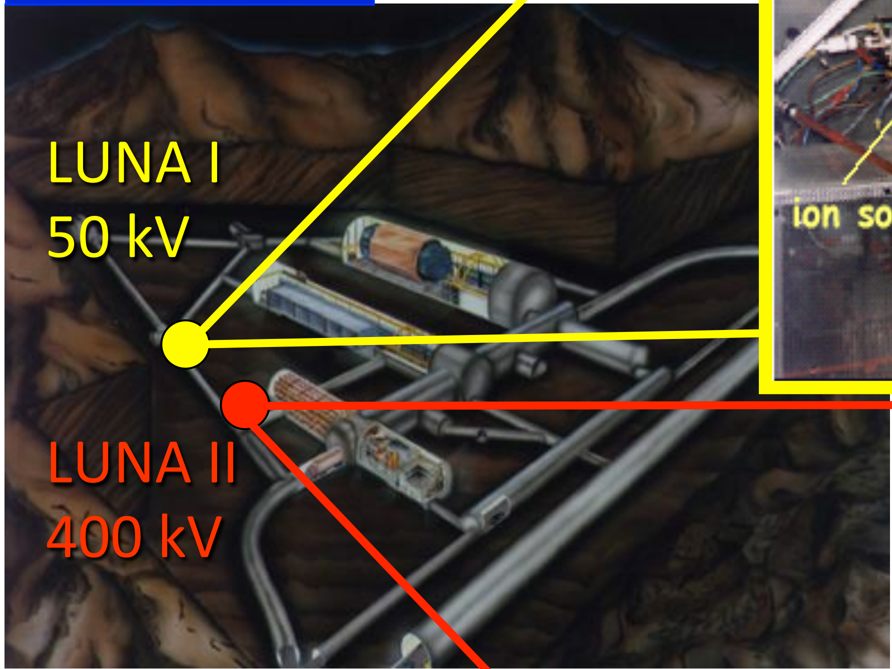
$\omega\gamma$ [10^{-10} eV] LUNA	$\omega\gamma$ [10^{-10} eV] NACRE ind.
2.9 ± 0.6	$1.16^{+1.16}_{-0.39}$

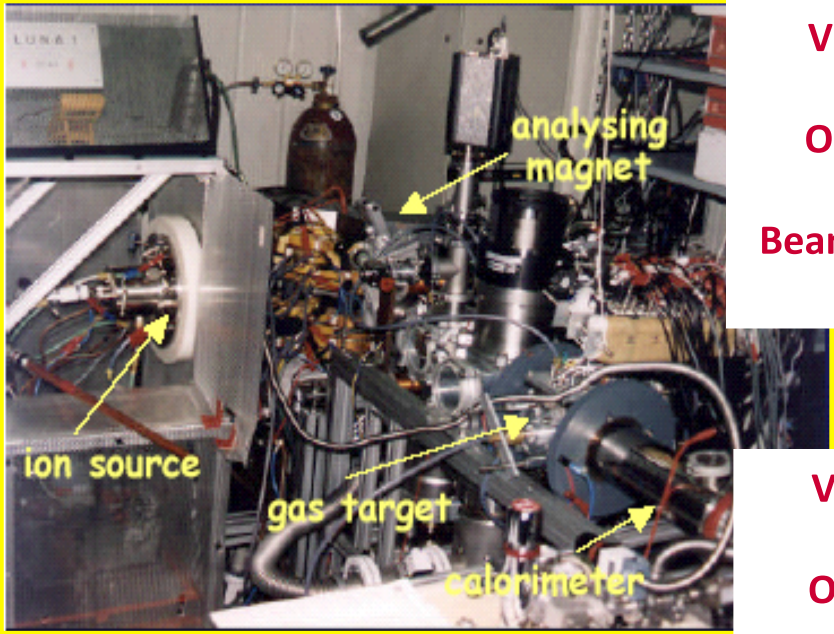
BR→0 = (60^{+20}_{-10}) %

The BGO γ-ray total sum spectrum on the 92 keV $^{25}Mg(p,\gamma)^{26}Al$ resonance (E_p = 100 keV).

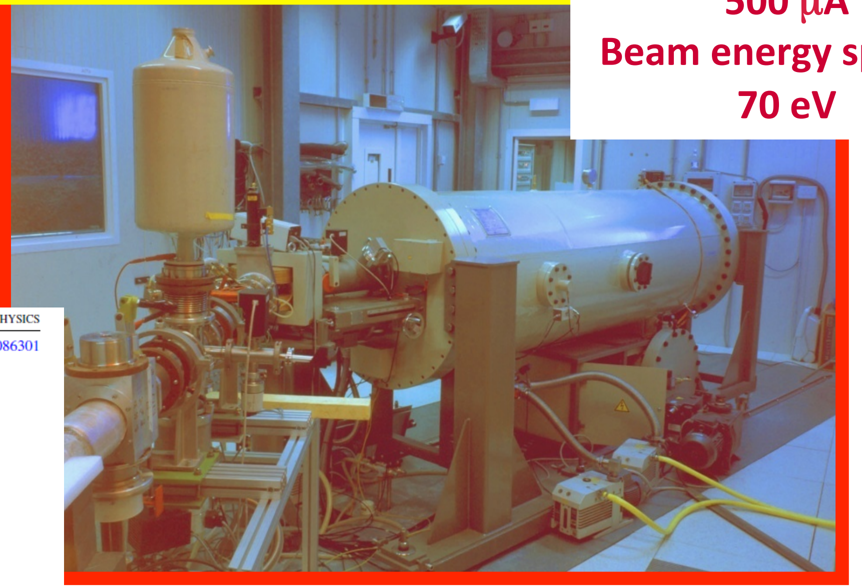
1. The shaded area → envinromental background
2. Thin solid line → $^{25}Mg(p,\gamma)^{26}Al$ simulation varying the primaries branchings .
3. Solid red line → total yield fit including background and simulation.

LUNA - experimental set-ups





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

IOP Publishing — Reports on Progress in Physics
Rep. Prog. Phys. 72 (2009) 086301 (25pp) — doi:10.1088/0034-4885/72/8/086301

LUNA: a laboratory for underground nuclear astrophysics

H Costantini[1], A Formicola[2], G Imbriani[3,4], M Junker[2], C Rolfs[5] and F Strieder[5]

H-burning @ LUNA – three important results

- **BBN and H-burning in the Sun and solar neutrinos**:

p+p->d+e^++ν, p(d,γ)^{3}He, d(α,γ)^{6}Li, ^{3}He(^{3}He, 2p)^{4}He, ^{3}He(α,γ)^{7}Be, ^{7}Be(p,γ)^{8}B and ^{14}N(p,γ)^{15}O

- **Age of Globular Clusters and C production in AGB:**

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^{14}N(p,γ)^{15}O, ^{15}N(α,γ)^{19}F, ^{15}N(p,γ)^{16}O, ^{15}N(p,α)^{12}C, ^{17}O(p,γ)^{18}F, ^{17}O(p,α)^{14}N, ^{18}O(p,γ)^{19}F, ^{18}O(p,α)^{15}N, ^{18}O(α,γ)^{22}Ne, ^{18}F(α,p)^{21}Ne, ^{19}F(α,p)^{22}Ne, ^{22}Ne(p,γ)^{23}Na, ^{23}Na(p,γ)^{24}Mg, ^{24}Mg(p,γ)^{25}Al, ^{25}Mg(p,γ)^{26}Al(β^+)^{26}Mg, ^{26}Mg(p,γ)^{27}Al

- **Main neutron sources:**

^{13}C(α,n)^{16}O, ^{22}Ne(α,n)^{25}Mg

- **Explovive CNO burning:**

^{15}O(α,γ)^{19}Ne, ^{14}O(α,γ)^{18}Ne, ^{18}Ne(α,p)^{21}Na

- **He and advaced burnings:**

^{12}C(α,γ)^{16}O, ^{12}C(^{12}C, p)^{23}Na, ^{12}C(^{12}C,α)^{20}Ne, ^{16}O(α,γ)^{20}Ne

Possible nuclear solution of the Solar neutrino problem (before SNO and Borexino)

$p + p \rightarrow {}^{2}H + e^{+} + \nu$ [0.27 MeV] $p + e^{-} + p \rightarrow {}^{2}H + \nu$ [1.44 MeV]

99.75% 0.25%

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

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

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$ $^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$ $^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu$

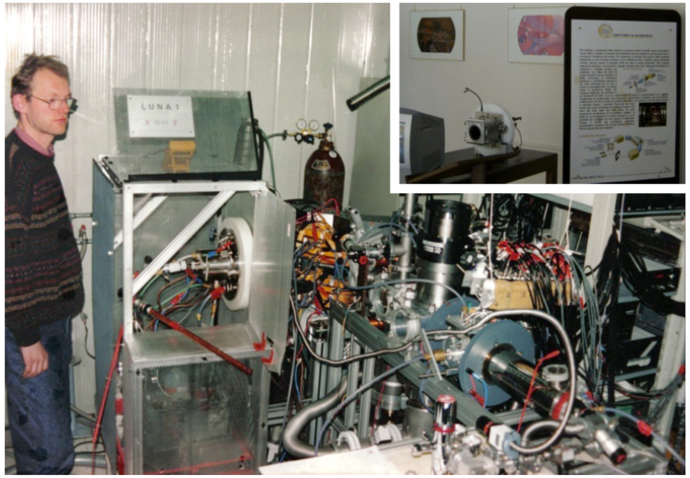
99.89% 0.11%

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$ [0.81 MeV] $^{7}Be + p \rightarrow {}^{8}B + \gamma$

$^{7}Li + p \rightarrow {}^{8}Be$ $^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$ [6.80 MeV]

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

$^{3}He(^{3}He,p)^{4}He$ measurement @ LUNA 50 kV 2001



The dream of W. Fowler

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

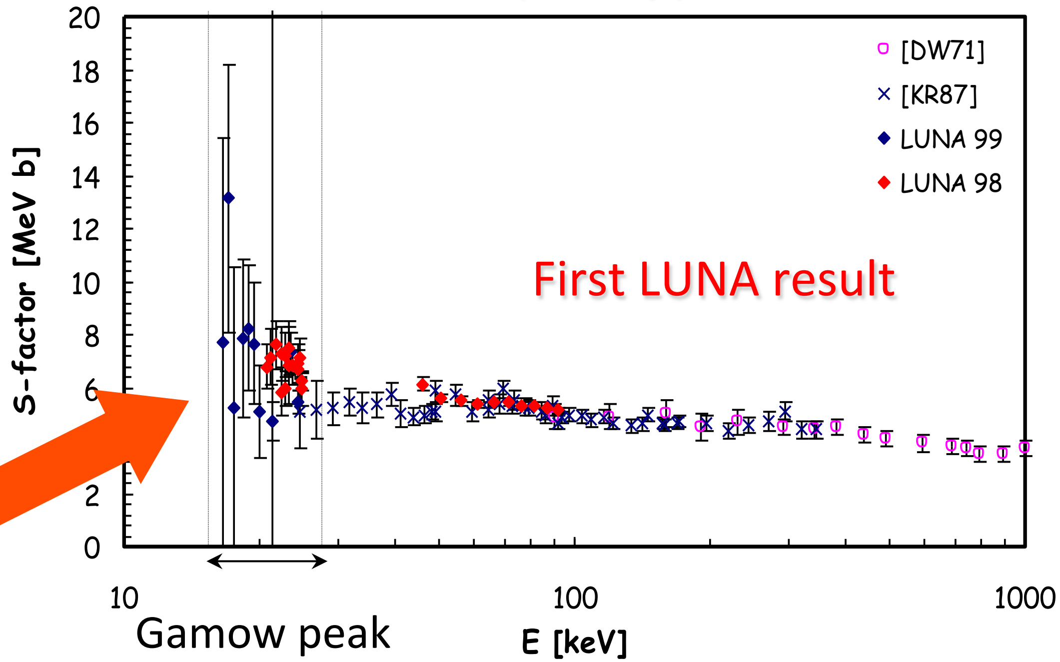
First measurement of the $^3He(^3He,2p)^4He$ cross section down to the lower edge of the solar Gamow peak `Phys. Rev. Lett. 82(1999)5205`

S(0)=5.3 ± 0.3 MeVb 6%

$\sigma_{min=}$ 0.02 pb

2 events/month !

S-factor of $^3He(^3He,2p)^4He$

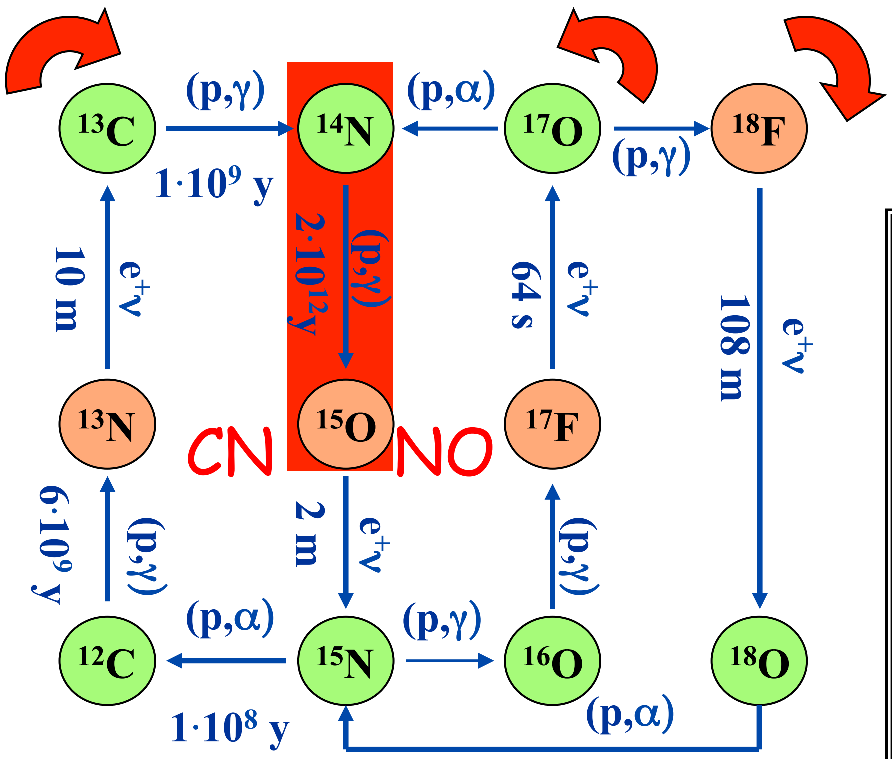


Dear Professors Corvisiero and Rolfs:

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 $3He - 3He$ 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.

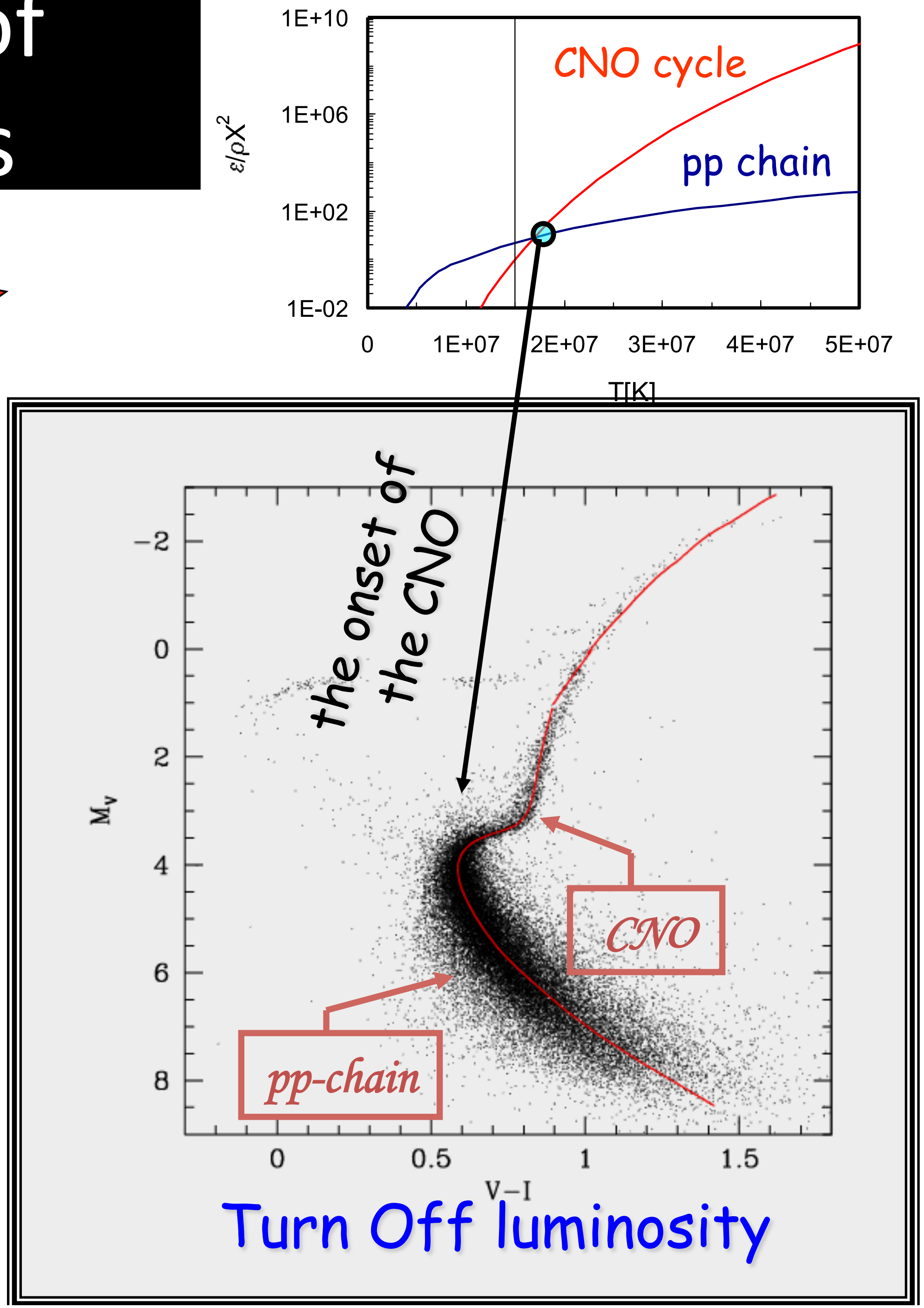
J. Bahcall

$^{14}N(p,\gamma)^{15}O$: Age of Globular Clusters

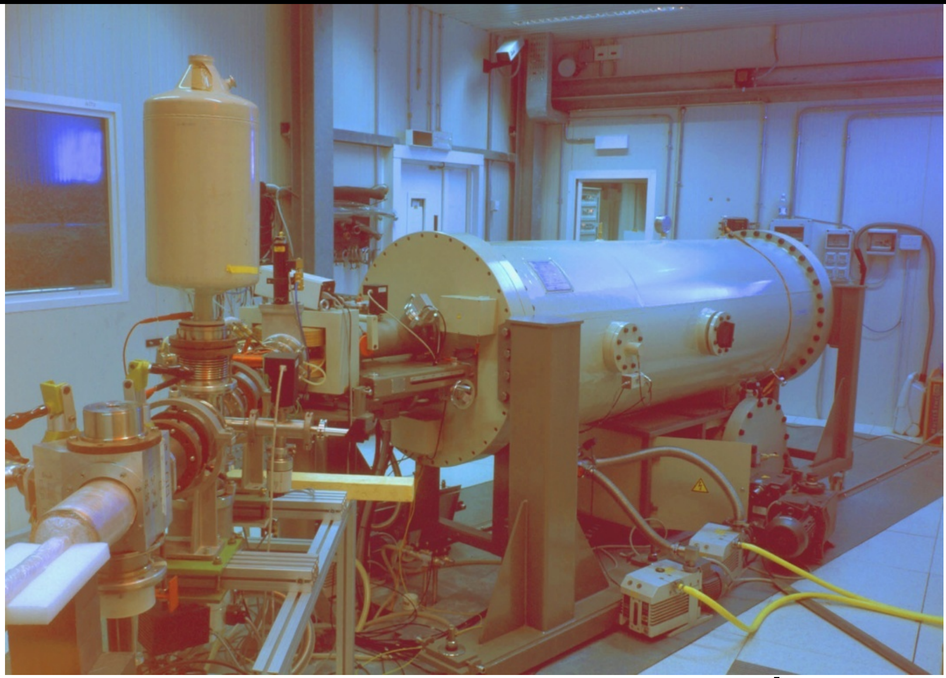


CN	NO
Q_{eff} = 26.02 MeV	Q_{eff} = 25.73 MeV

$^{14}N(p,\gamma)^{15}O$ is the bottleneck of the cycle, therefore the initial abundance of C, N, O is, mostly, converted in ^{14}N!!



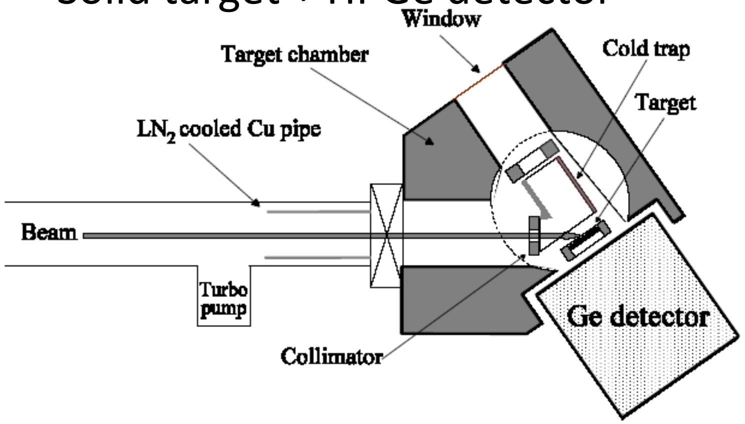
$^{14}N(p,\gamma)^{15}O$ @ LUNA400kV



Accelerator Specifications

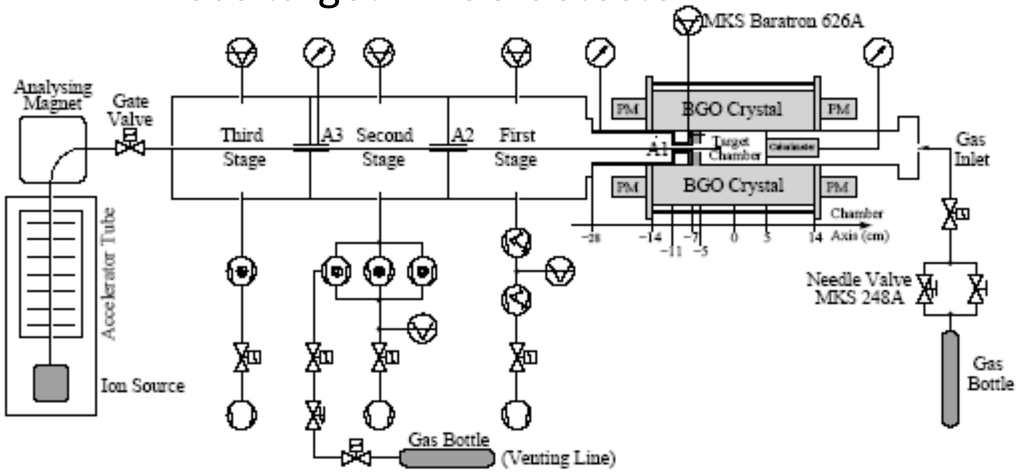
- ✓ U = 50 – 400 kV
- ✓ I ~ 300 μA *for proton*
- ✓ ΔE_{max}= 0.07 keV
- ✓ Energy spread : 72eV
- ✓ Total uncertainty is ± 300 eV for E_p=100 ÷ 400keV

Solid target + HPGe detector



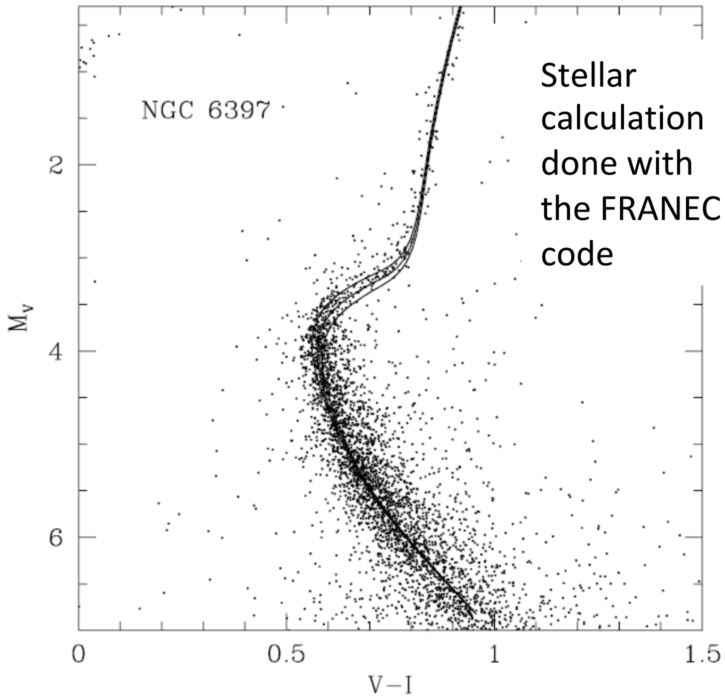
TiN (1/(1.08 ± 0.05)) targets

Gas target + BGO detector



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

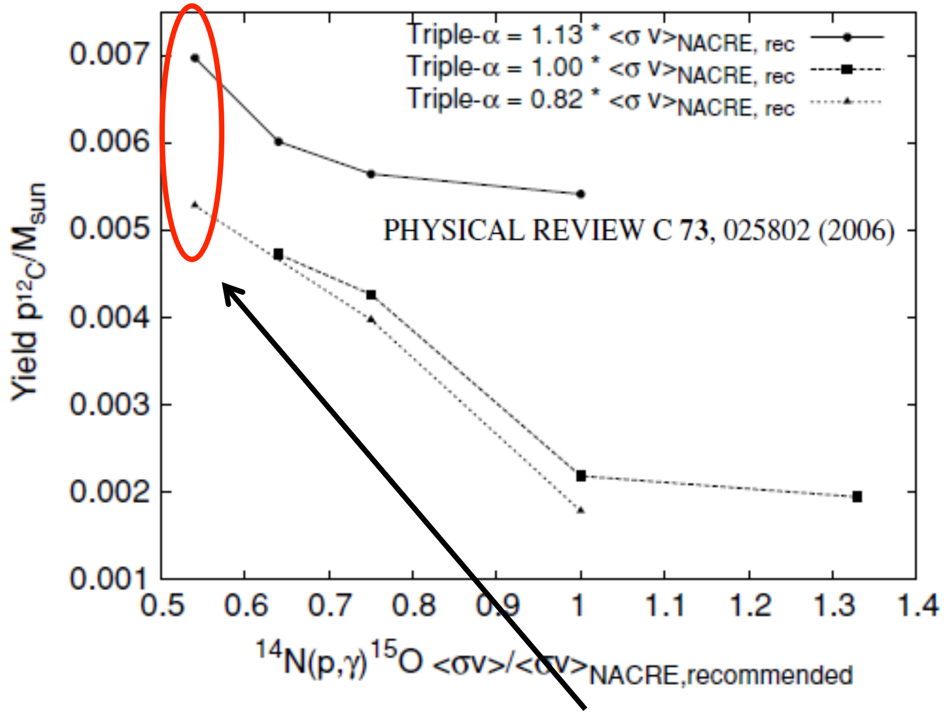
G. Imbriani, et al., A&A 420(2004)



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 is 14 ± 1 Gyr.

In good agreement with the precise determination of WMAP.

FALK HERWIG, SAM M. AUSTIN, AND JOHN C. LATTANZIO



With $^{14}N(p,\gamma)^{15}O$ rate = ½ of NACRE agreement between observation and calculation.

CNO ν-flux reduced by a factor 2

LUNA measurements 1991-2017

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

- **AGB nucleosynthesis – light nuclei abundances:**

$^{14}N(p,\gamma)^{15}O$, $^{15}N(\alpha,\gamma)^{19}F$, $^{15}N(p,\gamma)^{16}O$, $^{15}N(p,\alpha)^{12}C$, $^{17}O(p,\gamma)^{18}F$, $^{17}O(p,\alpha)^{14}N$, $^{18}O(p,\gamma)^{19}F$, $^{18}O(p,\alpha)^{15}N$, $^{18}O(\alpha,\gamma)^{22}Ne$, $^{18}F(\alpha,p)^{21}Ne$, $^{19}F(\alpha,p)^{22}Ne$, $^{22}Ne(p,\gamma)^{23}Na$, $^{23}Na(p,\gamma)^{24}Mg$, $^{24}Mg(p,\gamma)^{25}Al$, $^{25}Mg(p,\gamma)^{26}Al$, $^{26}Mg(p,\gamma)^{27}Al$

- **Main neutron sources:**

$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$

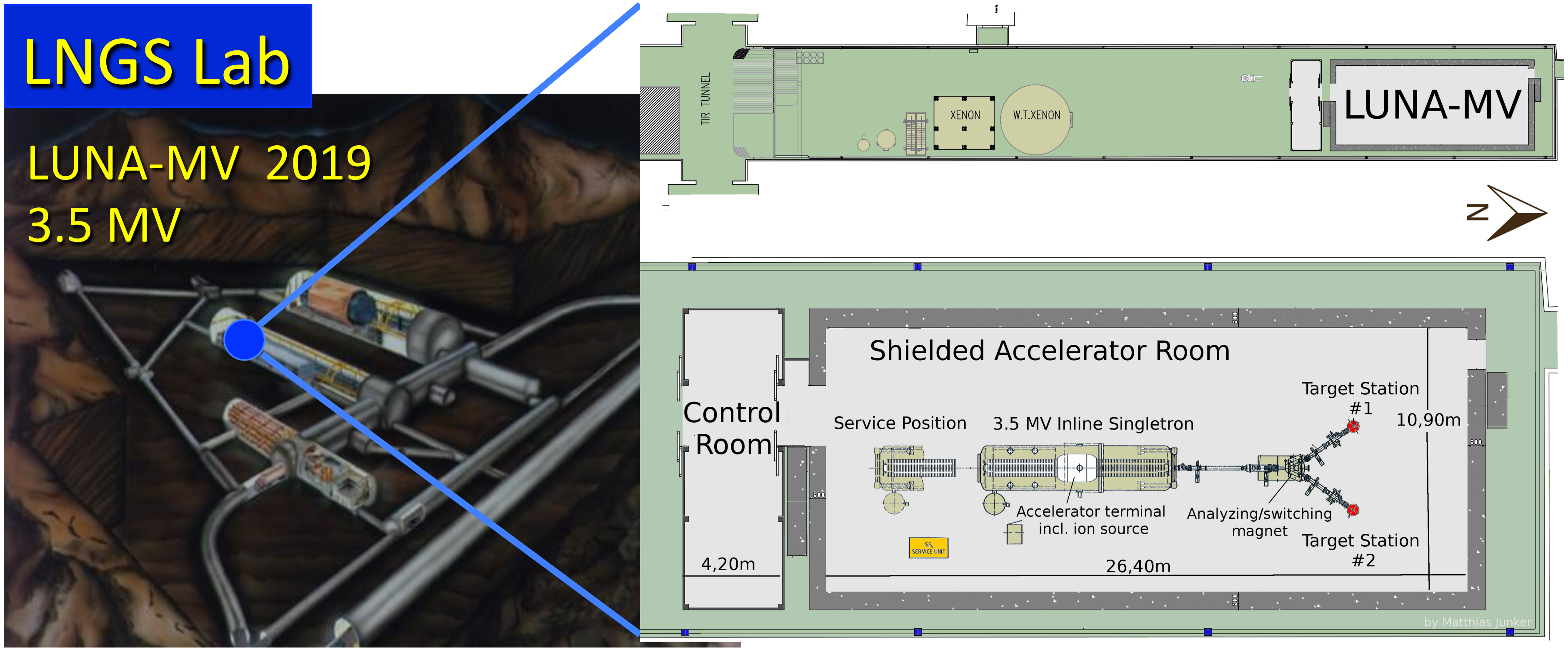
- **Explovive CNO burning:**

$^{15}O(\alpha,\gamma)^{19}Ne$, $^{14}O(\alpha,\gamma)^{18}Ne$, $^{18}Ne(\alpha,p)^{21}Na$

- **He and advaced burnings:**

$^{12}C(\alpha,\gamma)^{16}O$, $^{12}C(^{12}C, p)^{23}Na$, $^{12}C(^{12}C,\alpha)^{20}Ne$, $^{16}O(\alpha,\gamma)^{20}Ne$

LUNA MV – future setup



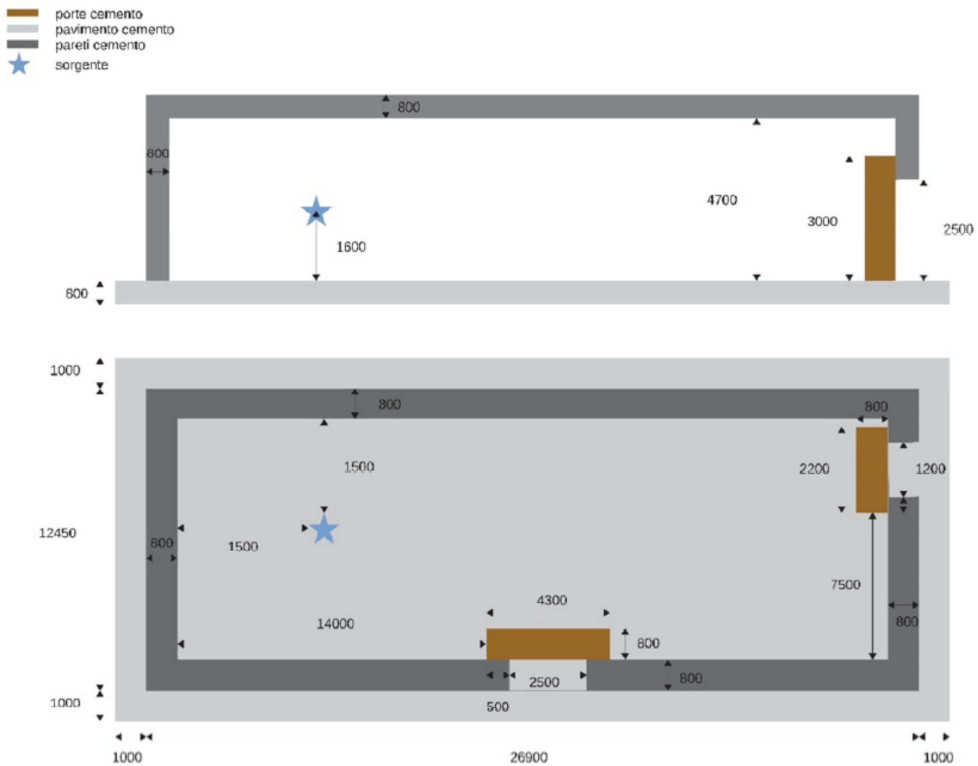
The accelerator and the neutron shielding

$^{1}H^{+}$ (TV: 0.3 – 0.5 MV): 500 μA
$^{1}H^{+}$ (TV: 0.5 – 3.5 MV): 1000 μA

$^{4}He^{+}$ (TV: 0.3 – 0.5 MV): 300 μA
$^{4}He^{+}$ (TV: 0.5 – 3.5 MV): 500 μA

$^{12}C^{+}$ (TV: 0.3 – 0.5 MV): 100 μA
$^{12}C^{+}$ (TV: 0.5 – 3.5 MV): 150 μA
$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 μA

- inline Cockcroft Walton accelerator
- **TERMINAL VOLTAGE: 0.2 – 3.5 MV**
- Precision of terminal voltage reading: 350 V
- Beam energy reproducibility: 0.01% TV
- Beam energy stability: 0.001% TV / h
- Beam current stability: < 5% / h



- 80 cm thick concrete shielding calculated by GEANT4 & MCNP
- E_n = 5.6 MeV, 2 10^3 n/s, isotropic

MCNP: $\Phi_n = 1.38\ 10^{-7}$ n/(cm^2 s)
GEANT4: $\Phi_n = 3.40\ 10^{-7}$ n/(cm^2 s)

Φ_n(LNGS) = 3 10^{-6} n/(cm^2 s)

LUNA-MV basic schedule

Action	Date
Approval of the first HVEE technical design	October 2016
Opening of the tendering procedure for LUNA-MV plants	November 2016
Submission of the Authorization request to «Prefettura dell'Aquila»	December 2016
Beginning of the clearing works in Hall B	February 2017
End of the tendering procedure for the new LUNA-MV building	June 2017
Beginning of the construction works in Hall B	September 2017
End of the tendering procedure for LUNA-MV plants	October 2017
Beginning of the construction of the plants in the LUNA-MV building	December 2017
In-house acceptance test for the new LUNA-MV accelerator	June 2018
Completion of the new LUNA-MV building and plants	September 2018
LUNA-MV accelerator delivering at LNGS	January 2019
Conclusion of the commissioning phase	July 2019
Beginning First Experiment	September 2019

LUNA future measurements

- **BBN and H-burning in the Sun and solar neutrinos**:

p+p->d+e^++ν, p(d,γ)^{3}He, d(α,γ)^{6}Li, ^{3}He(^{3}He, 2p)^{4}He, ^{3}He(α,γ)^{7}Be, ^{7}Be(p,γ)^{8}B and ^{14}N(p,γ)^{15}O

- **Age of Globular Clusters and C production in AGB:**

^{14}N(p,γ)^{15}O

- **AGB nucleosynthesis − light nuclei abundances:**

^{14}N(p,γ)^{15}O, ^{15}N(α,γ)^{19}F, ^{15}N(p,γ)^{16}O, ^{15}N(p,α)^{12}C, ^{17}O(p,γ)^{18}F, ^{17}O(p,α)^{14}N, ^{18}O(p,γ)^{19}F, ^{18}O(p,α)^{15}N, ^{18}O(α,γ)^{22}Ne, ^{18}F(α,p)^{21}Ne, ^{19}F(α,p)^{22}Ne, ^{22}Ne(p,γ)^{23}Na, ^{23}Na(p,γ)^{24}Mg, ^{24}Mg(p,γ)^{25}Al, ^{25}Mg(p,γ)^{26}Al, ^{26}Mg(p,γ)^{27}Al

- **Main neutron sources:**

^{13}C(α,n)^{16}O, ^{22}Ne(α,n)^{25}Mg

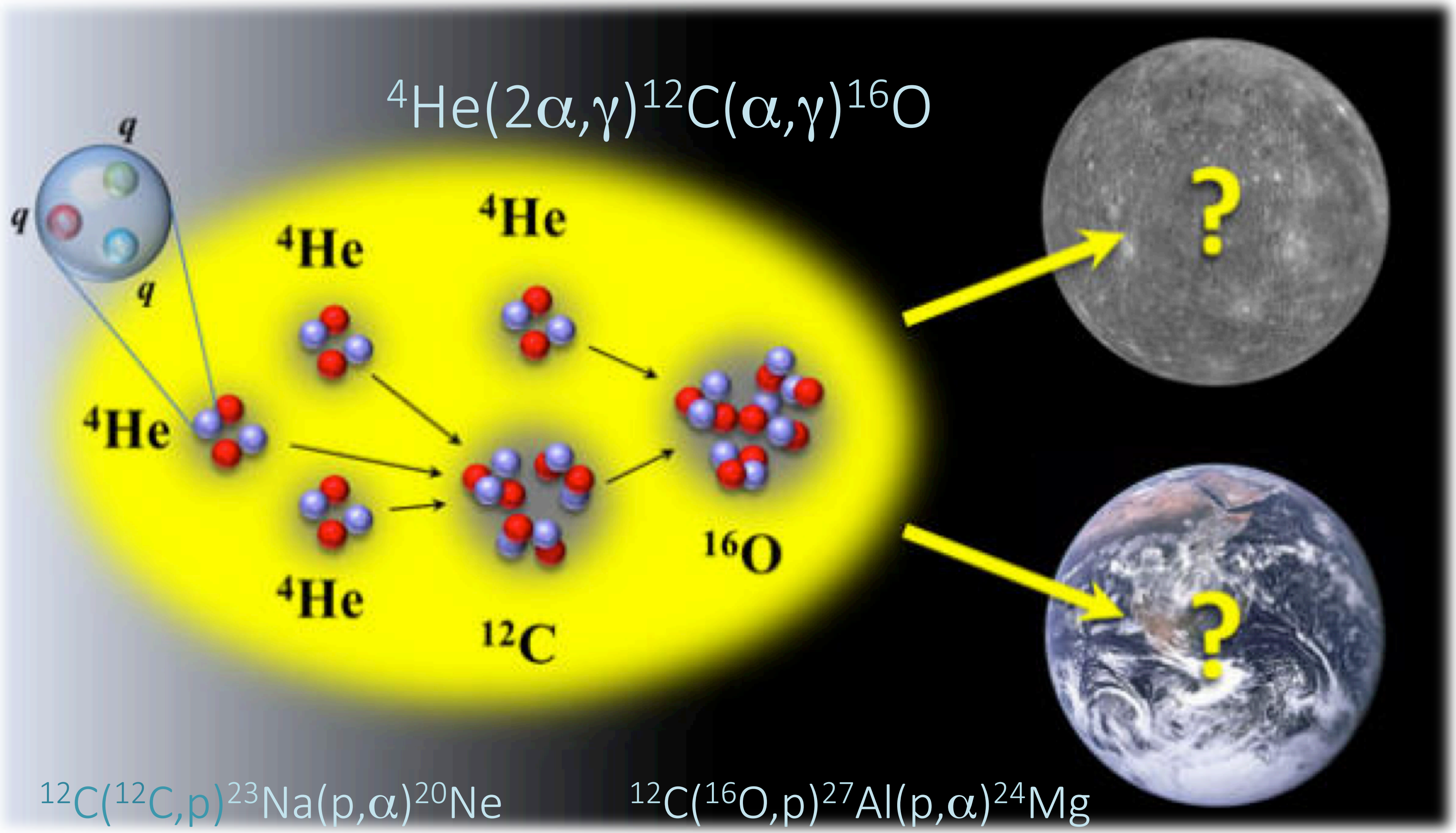
- **Explovive CNO burning:**

^{15}O(α,γ)^{19}Ne, ^{14}O(α,γ)^{18}Ne, ^{18}Ne(α,p)^{21}Na

- **He and advaced burnings:**

^{12}C(α,γ)^{16}O, ^{12}C(^{12}C, p)^{23}Na, ^{12}C(^{12}C,α)^{20}Ne, ^{16}O(α,γ)^{20}Ne

Helium Burning: The Cosmo-Chemistry of Carbon and Oxygen



$^{12}C(^{12}C,p)^{23}Na(p,\alpha)^{20}Ne$

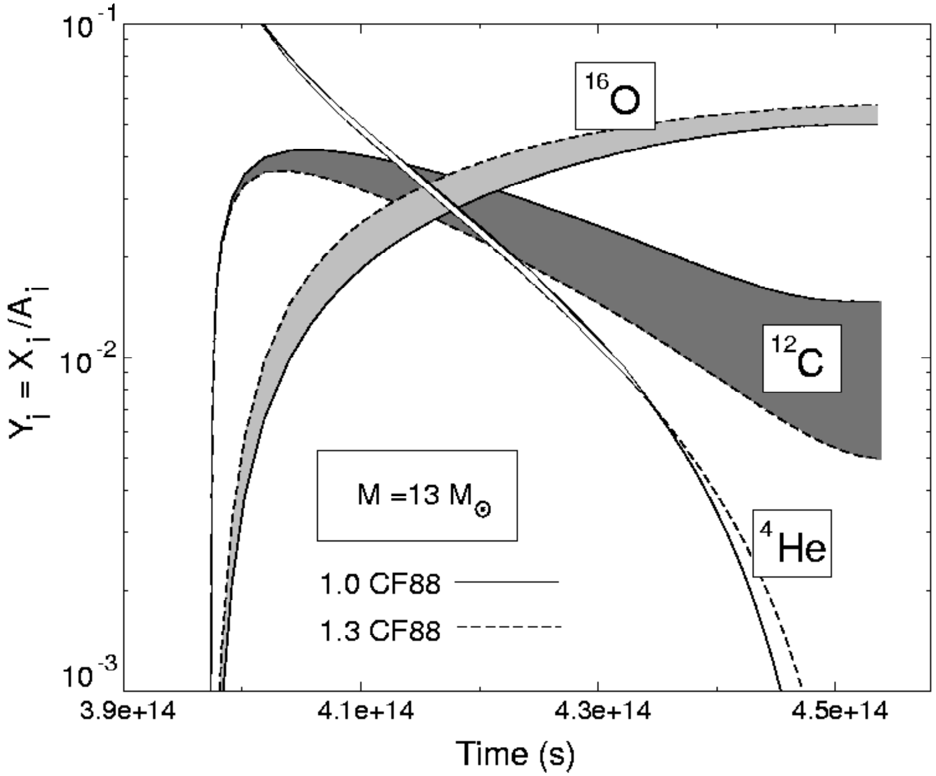
$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{16}O,p)^{27}Al(p,\alpha)^{24}Mg$

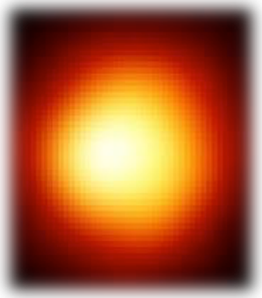
$^{12}C(^{16}O,\alpha)^{24}Mg$

The “holy Grail”

The step after carbon is being formed in a high temperature density environment:
$^{12}C(\alpha,\gamma)^{16}O$ determining the early $^{12}C/^{16}O$ ratio

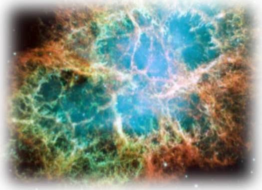


- Late Stellar Evolution
  determines Carbon and/or Oxygen phase

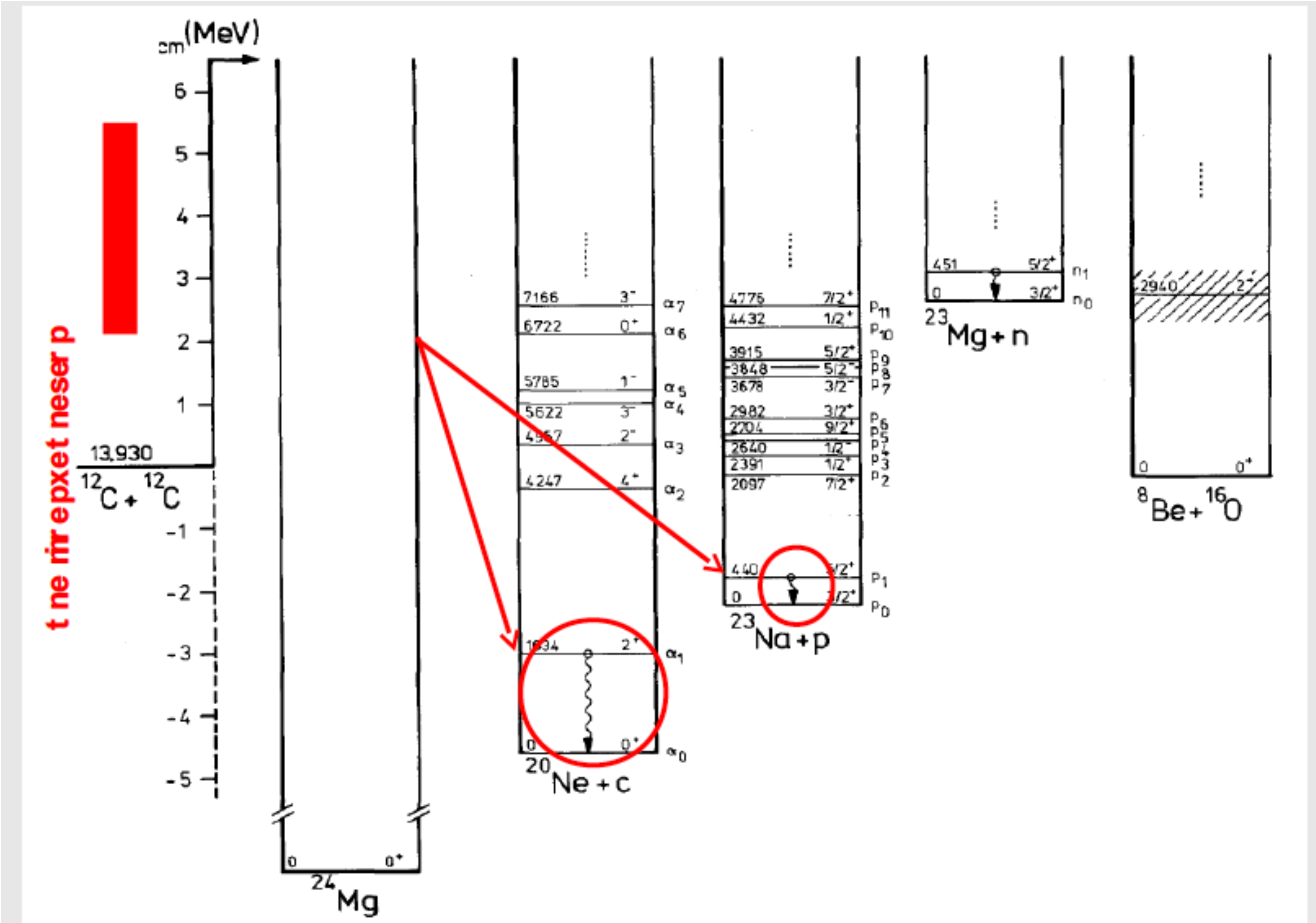


- Type Ia Supernova
  central carbon burning of C/O white dwarf

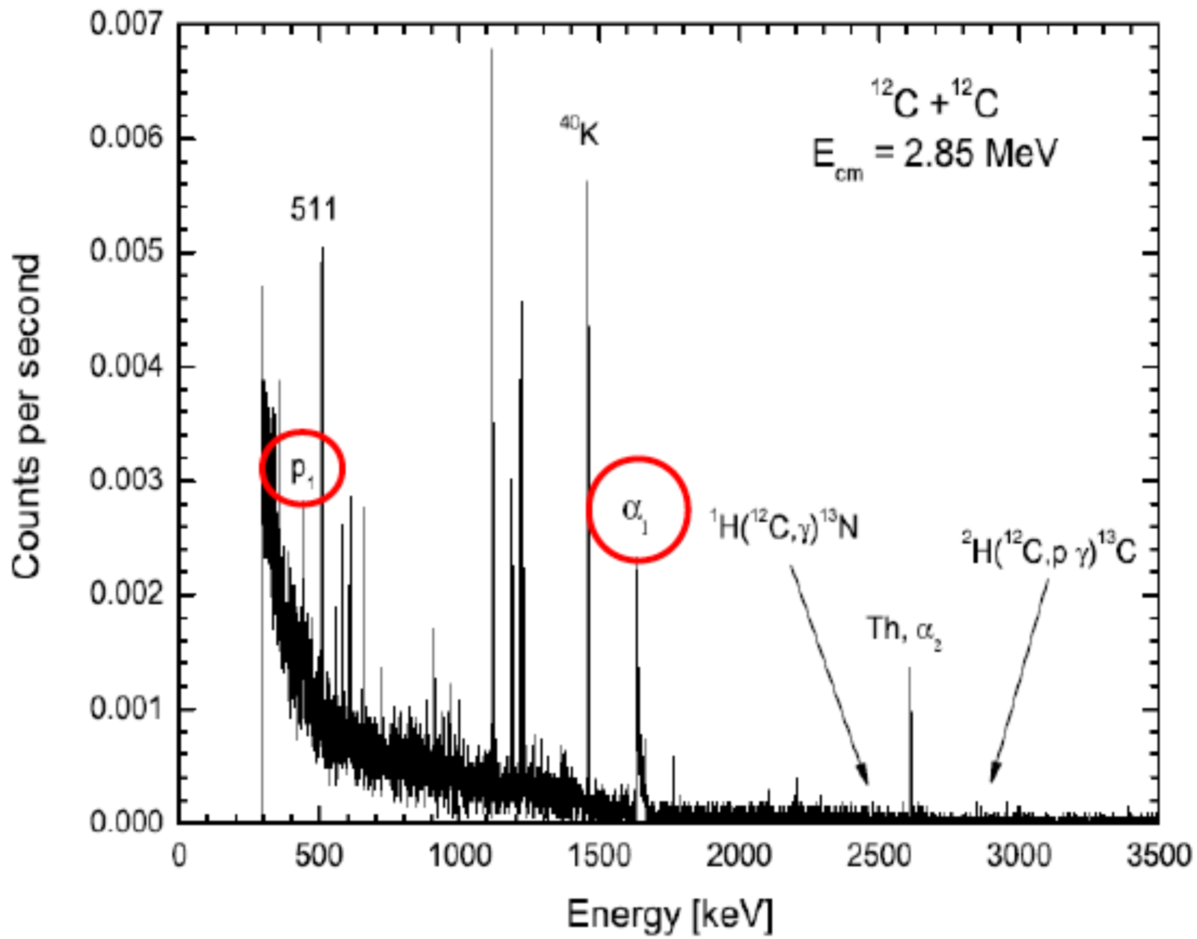
- Type II Supernova
  shock-front nucleosynthesis in C and He shells of pre-supernova star

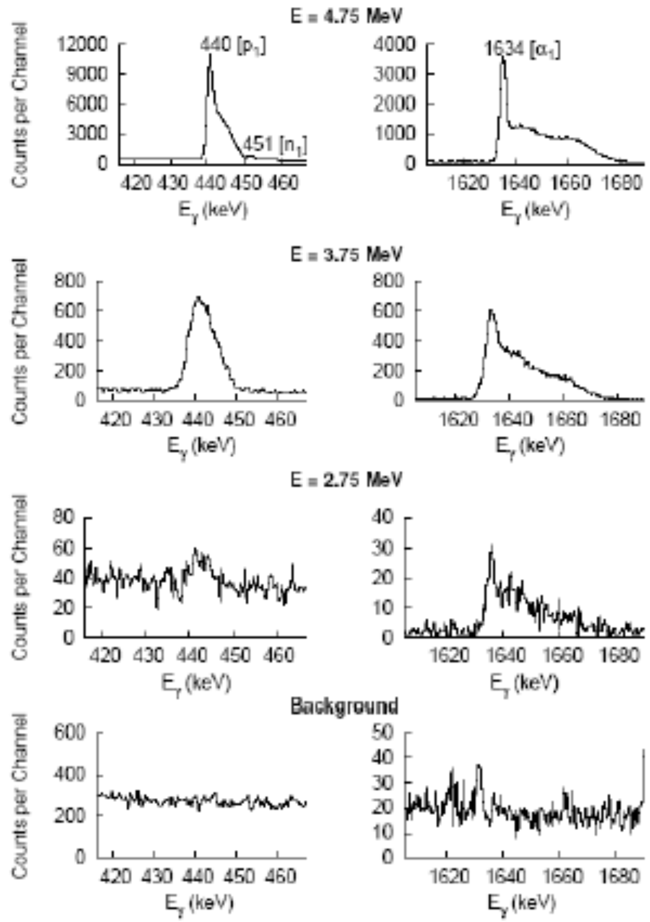


Carbon burning in stars



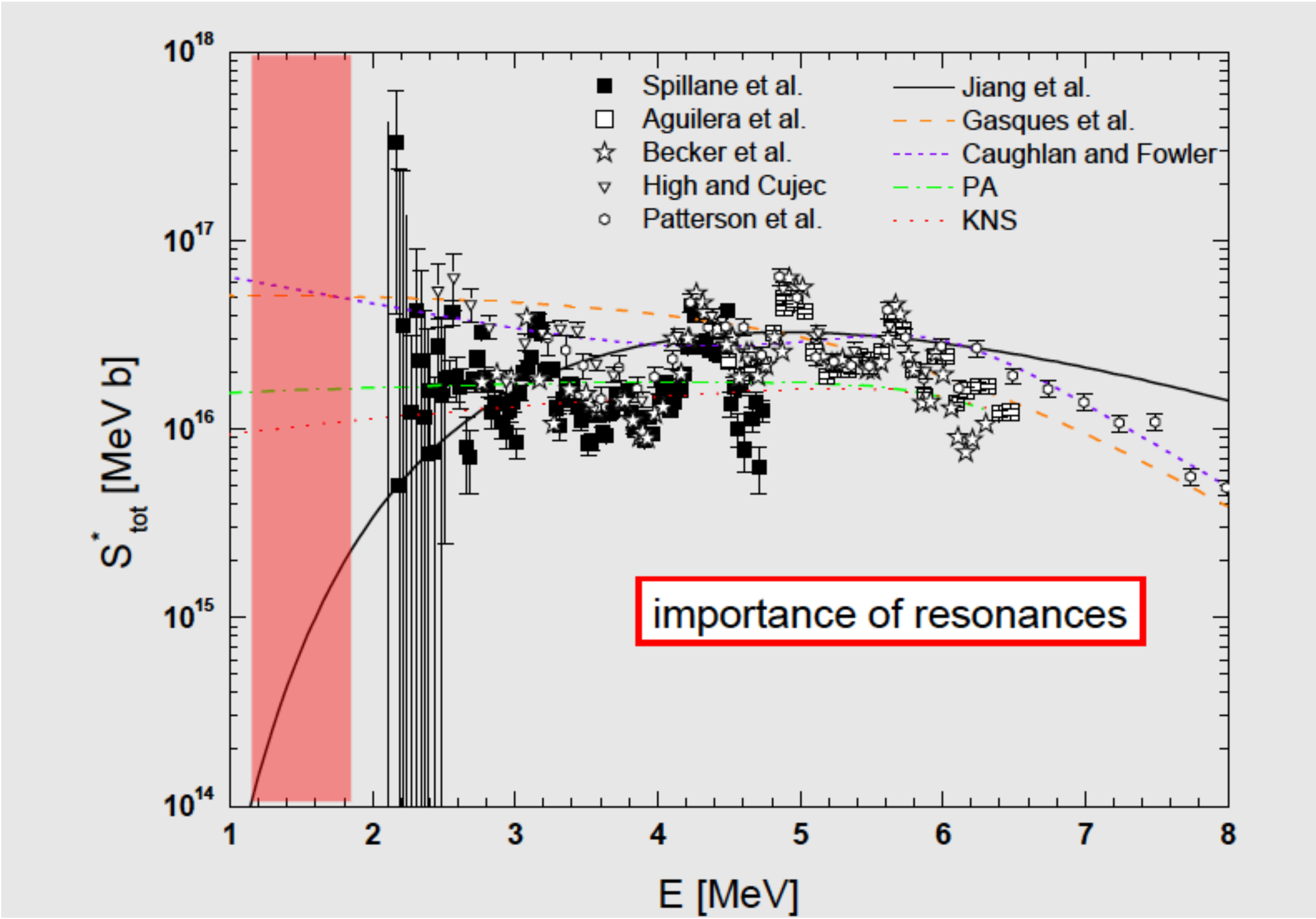
Experimental results in γ-ray spectrometry





Spillane et al., PRL 98, 122501 (2007)

Total S-factor



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