# LUNA: the experimental status of the art

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Laboratory
Underground
Nuclear
Astrophysics

Outline:

- Why going underground to measure nuclear fusion reactions in a laboratory

-The Luna Experiment: most important results

- On-going measurements and future perspectives

# Sun

Luminosity = $2 \cdot 10^{39}$ MeV/s

Q-value ( H burning) = 26.73 MeV

Reaction rate = $10^{38}$ $s^{-1}$

# Laboratory

$R_{lab} = N_p \, N_t \, \sigma \, \varepsilon$

$N_p$ = number of projectile ions ≈ $10^{14}$ pps (100 $\mu$A $q=1^+$)

$N_t$ = number of target atoms ≈ $10^{19}$ at/cm$^2$

$\sigma$ = cross section = $10^{-15}$ barn

$\varepsilon$= efficiency ≈ 100% for charged particles
1% for gamma rays

$R_{lab}$ ≈ 0.3-30 counts/year

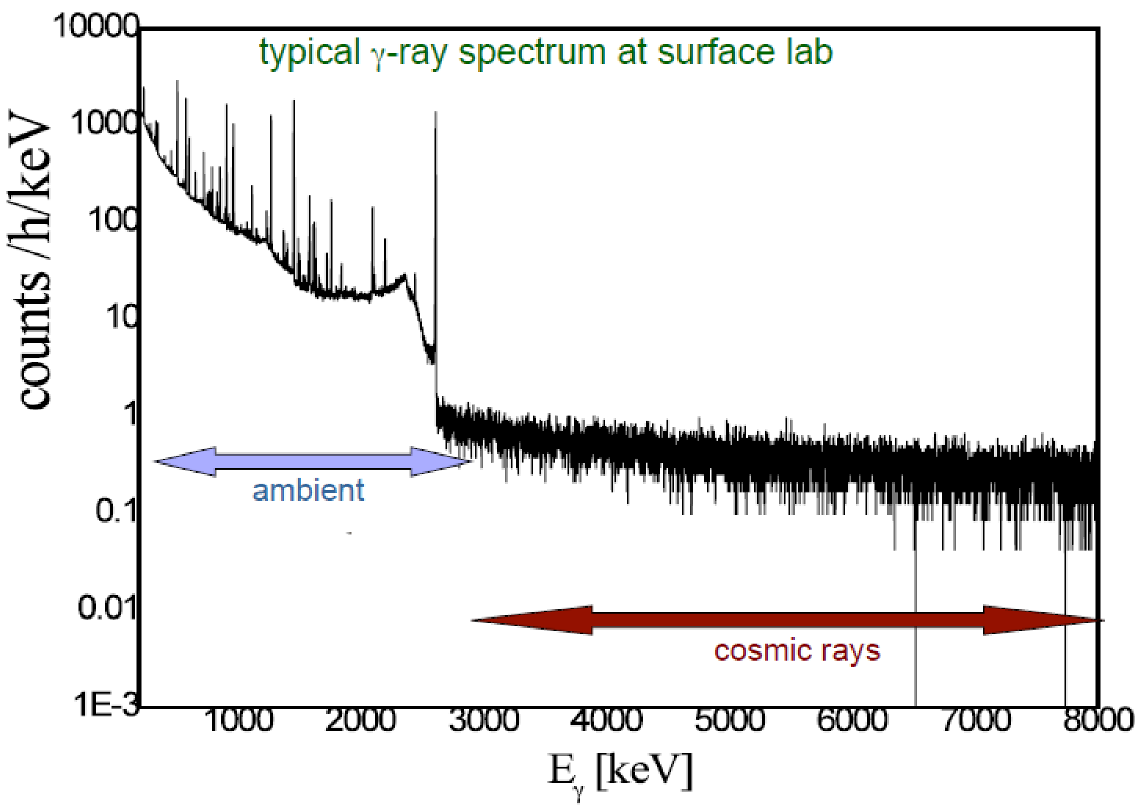
$R_{lab} > B_{beam\ induced} + B_{env} + B_{cosmic}$

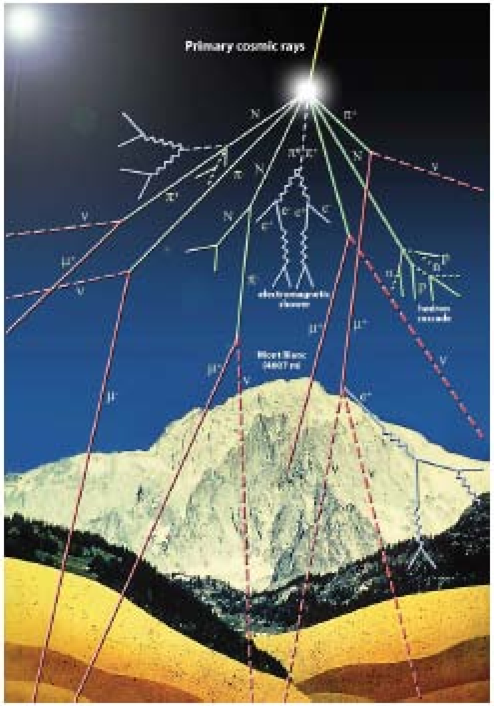
$B_{beam\ induced}$ : reactions with impurities in the target

reactions on beam collimators/apertures

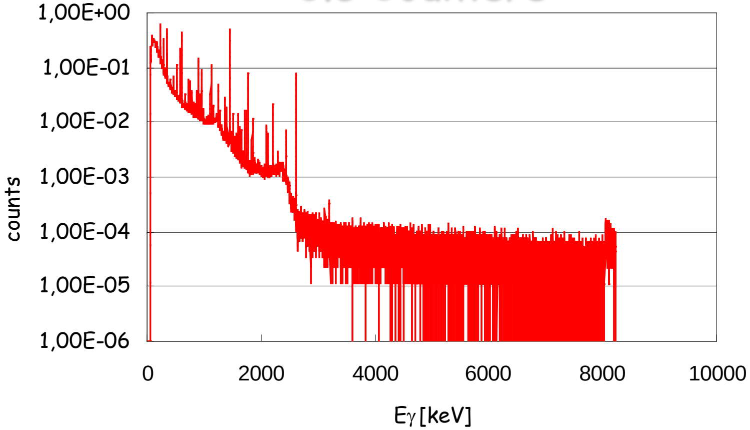
$B_{env}$ : natural radioactivity mainly from U and Th chains

$B_{cosmic}$ : mainly muons



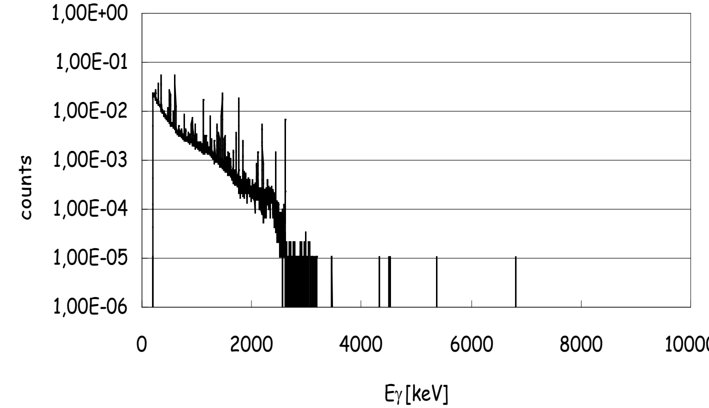
$3\,\mathrm{MeV} < E_\gamma < 8\,\mathrm{MeV}$:
0.5 Counts/s




HpGe

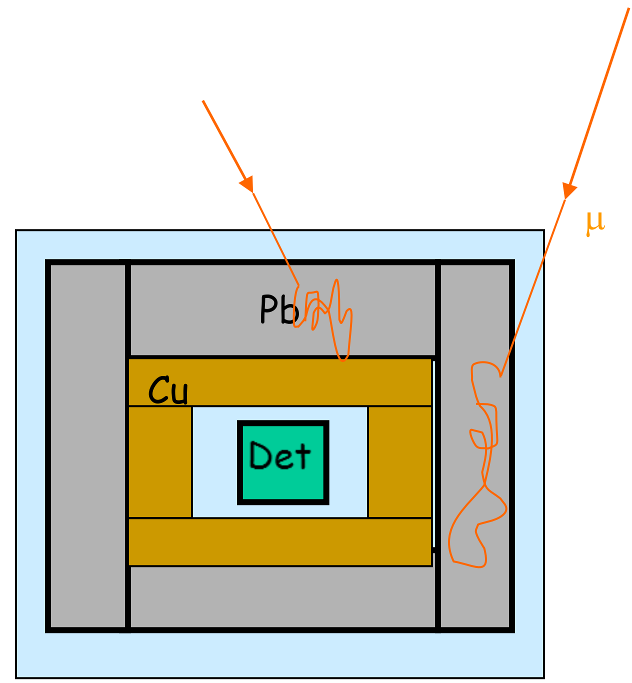
GOING UNDERGROUND

$3\,\mathrm{MeV} < E_\gamma < 8\,\mathrm{MeV}$
**0.0002 Counts/s**




$E_\gamma < 3\,\mathrm{MeV} \rightarrow$ passive shielding for environmental background radiation

underground passive shielding is more effective since μ flux,that create secondary γ's in the shield, is suppressed

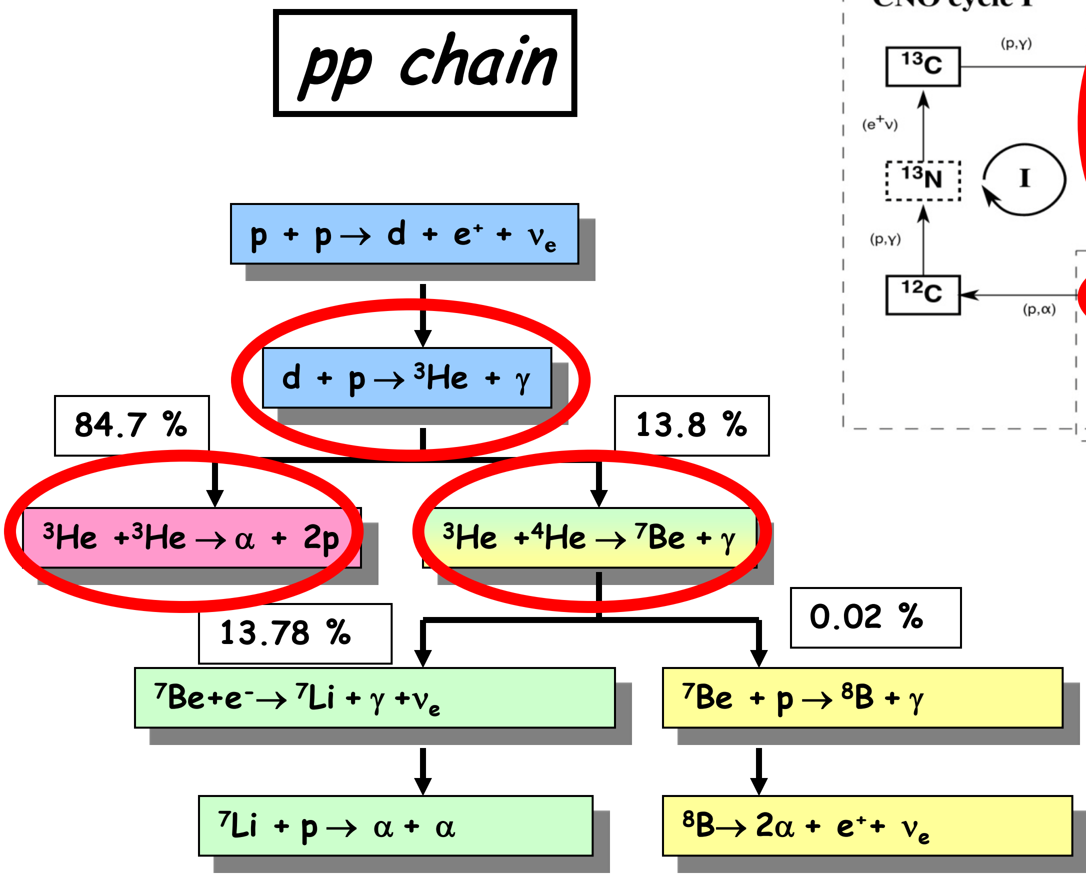


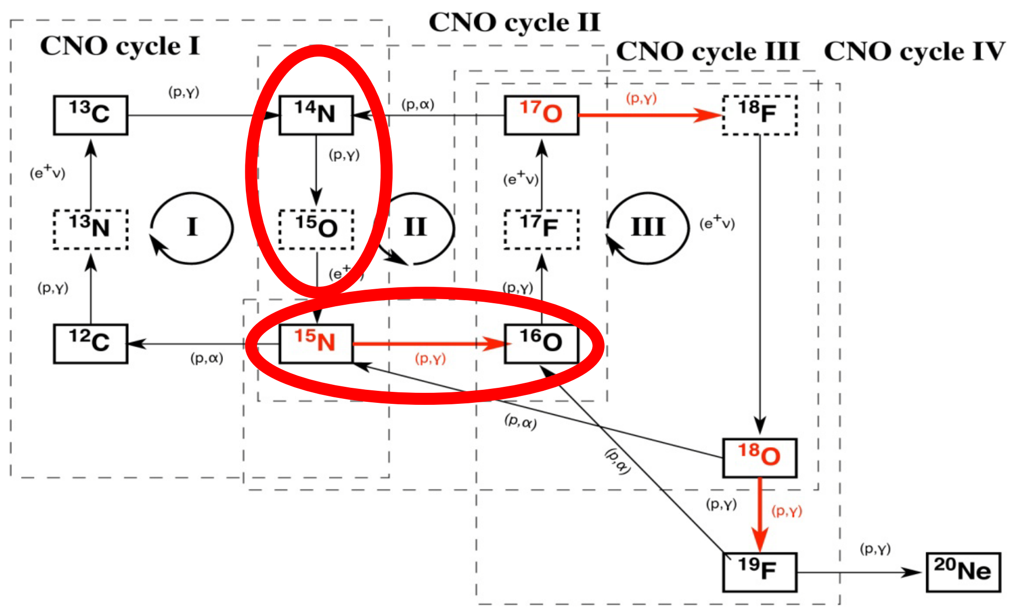
# Laboratory for Underground Nuclear Astrophysics



| Radiation | LNGS/surface |
|---|---|
| Muons | $10^{-6}$ |
| Neutrons | $10^{-3}$ |

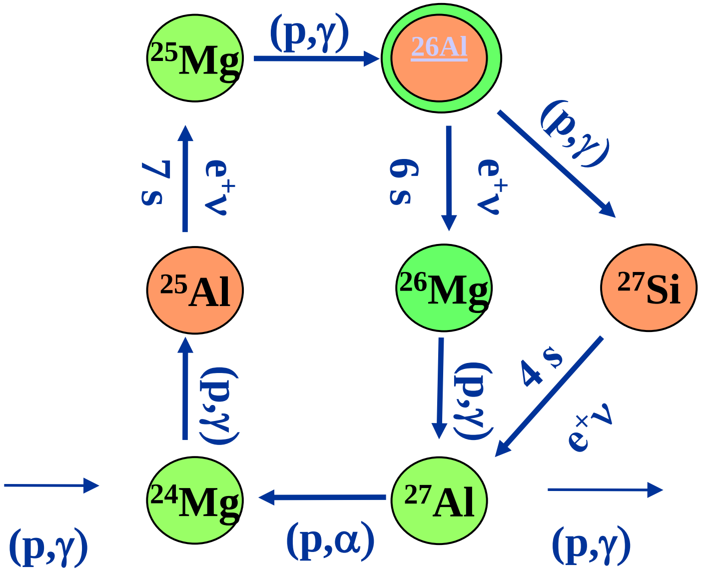
# LUNA results

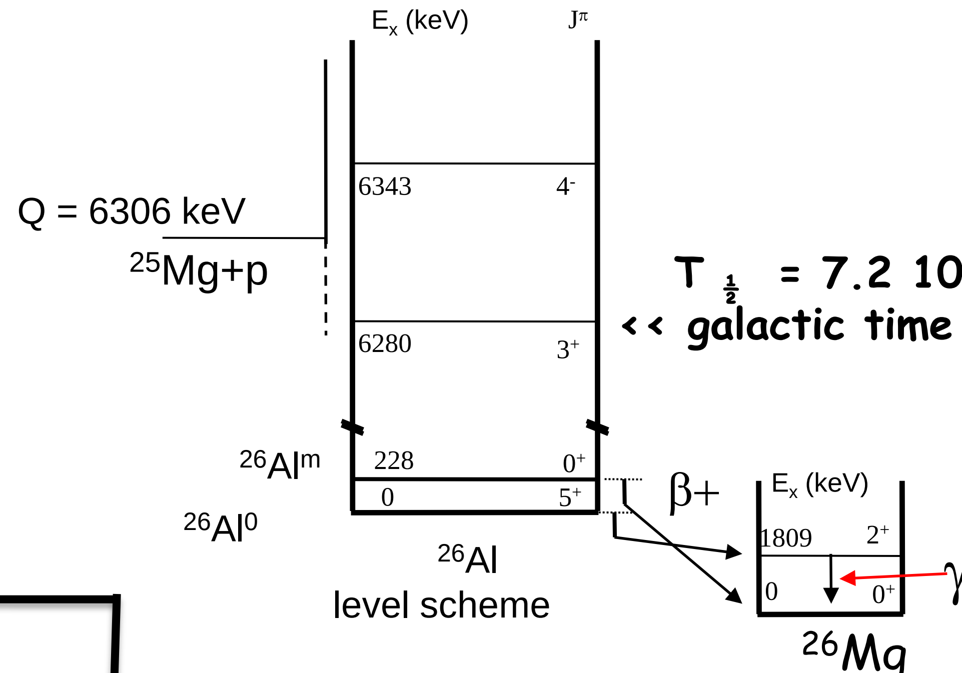



$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73\ MeV$$

# $^{25}Mg(p,\gamma)^{26}Al$

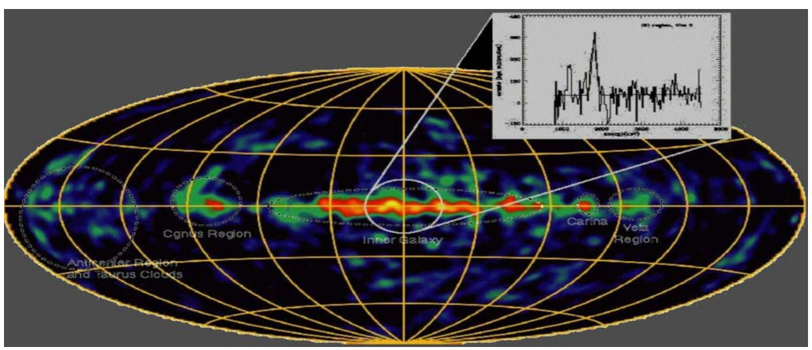



$T_{\frac{1}{2}} = 7.2\ 10^5$ y

<< galactic time scale

1.8 MeV $^{26}$Al decay γ-ray line

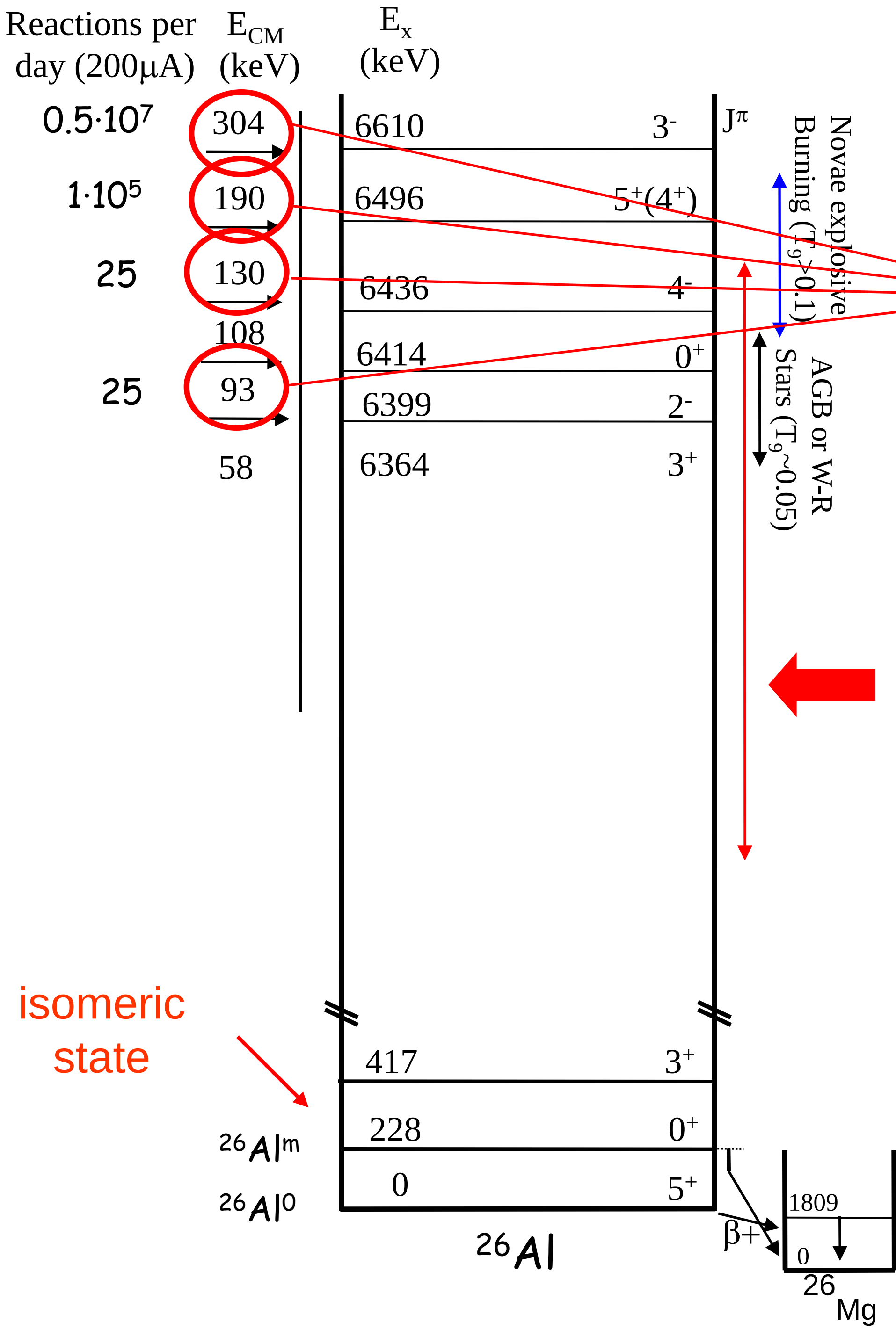



$^{26}$Mg excess in meteorite

Evidence that $^{26}$Al nucleosynthesis is still active (SN and NOVAE)

$^{26}$Al produced before the formation of the solar system

# $^{25}Mg(p,\gamma)^{26}Al$

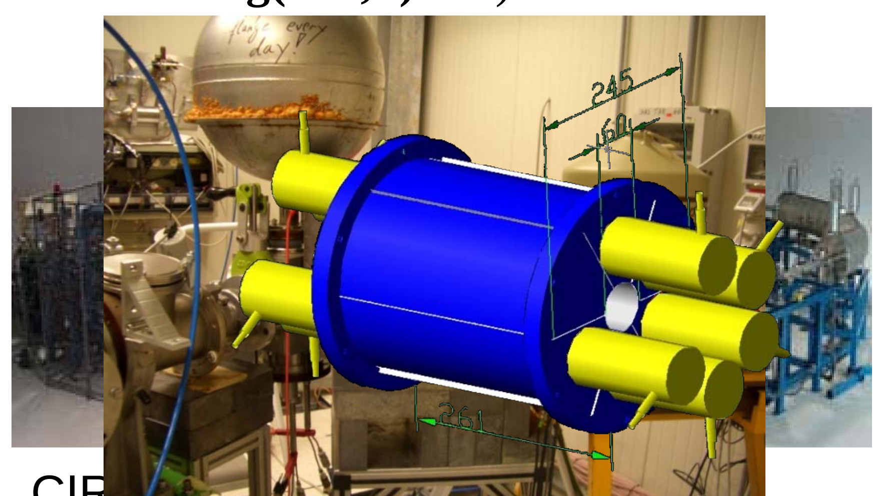



γ-ray Spectroscopy with 4πBGO + solid target

High efficiency (> 60%) – Low resolution set-up

**No direct strength resonance data**

(level structure derived from the single particle transfer reaction: $^{25}$**Mg(**$^{3}$**He,d)**$^{26}$**Al**)



Precise measurement of a resonance → accurate evaluation of the target stoichiometry

Enriched targets may contain oxygen

Study of "high" energy resonances with natural and enriched Mg targets of :

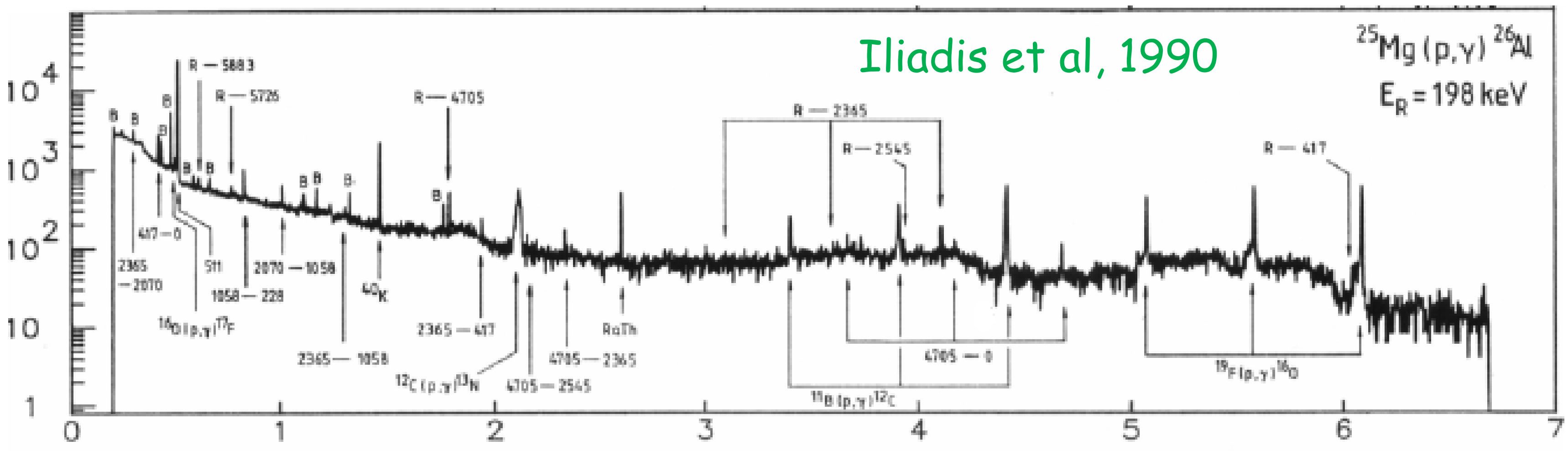
$^{25}$Mg(p,$\gamma$)$^{26}$Al ($E_r$=304 keV): Confirmed NACRE result but reduced uncertainty to 4%. This resonance will serve as normalization standard for lower-energy resonances

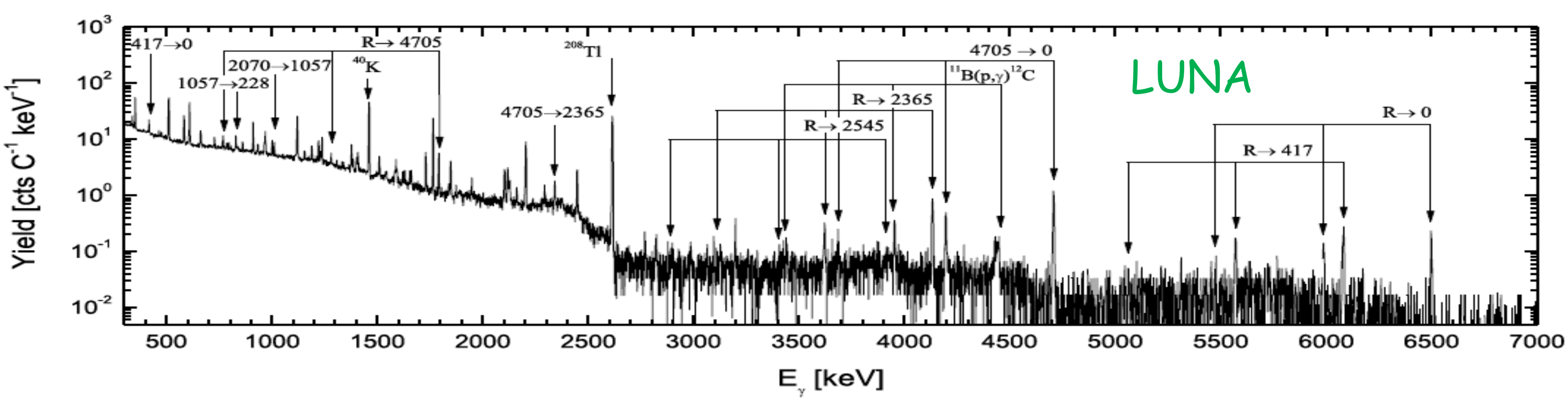
$^{24}$Mg(p,$\gamma$)$^{25}$Al ($E_r$=214 keV): lower resonance strength with respect to previous literature data. Strong direct capture component. Need of a re-analysis with R-matrix

$^{26}$Mg(p,$\gamma$)$^{27}$Al ($E_r$=326 keV): apparent discrepancy in literature data solved. Resonance strength measured with higher accuracy

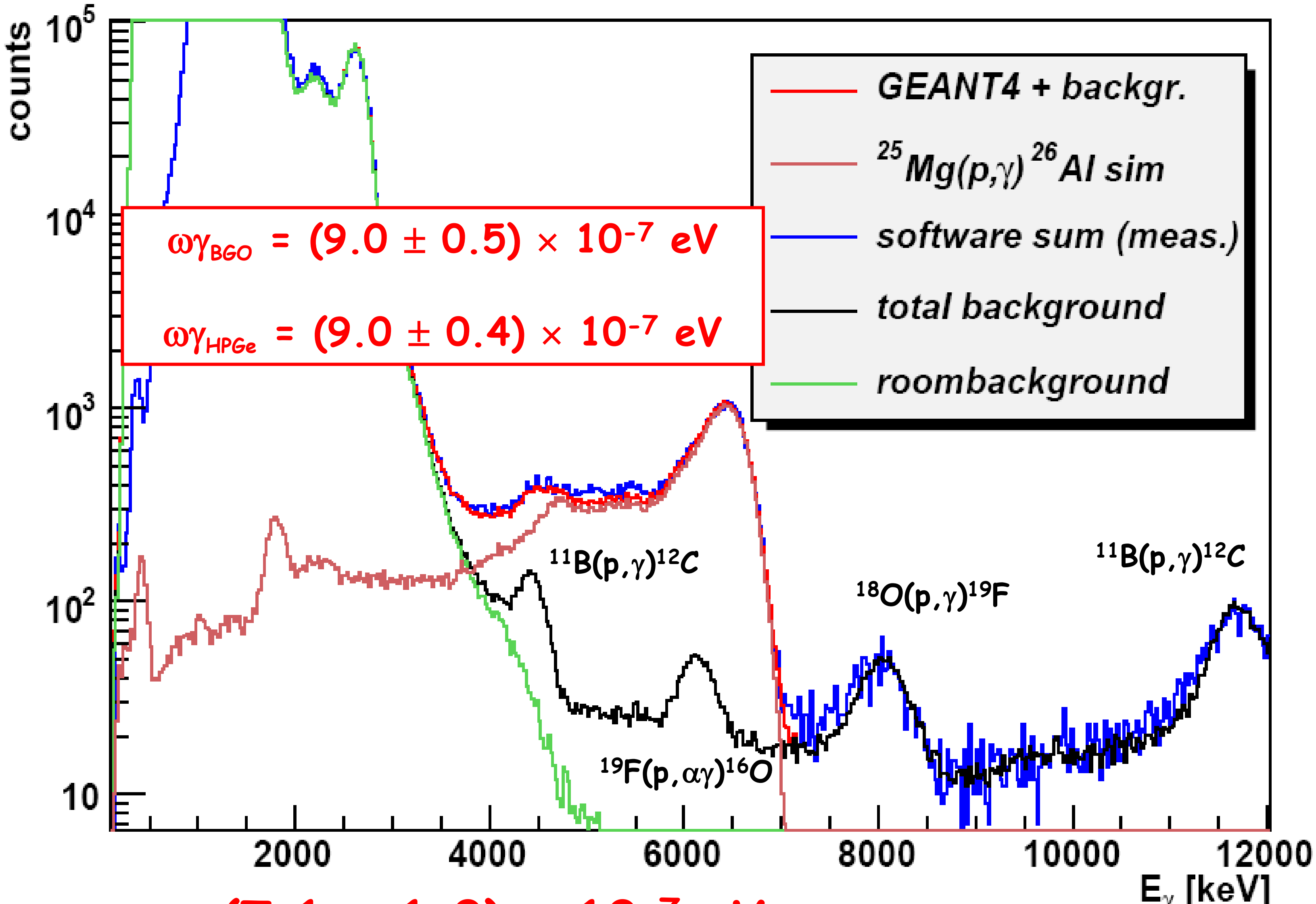
# $^{25}Mg(p,\gamma)^{26}Al$

# 198 keV resonance HPGe $\gamma$-ray spectra: single transitions



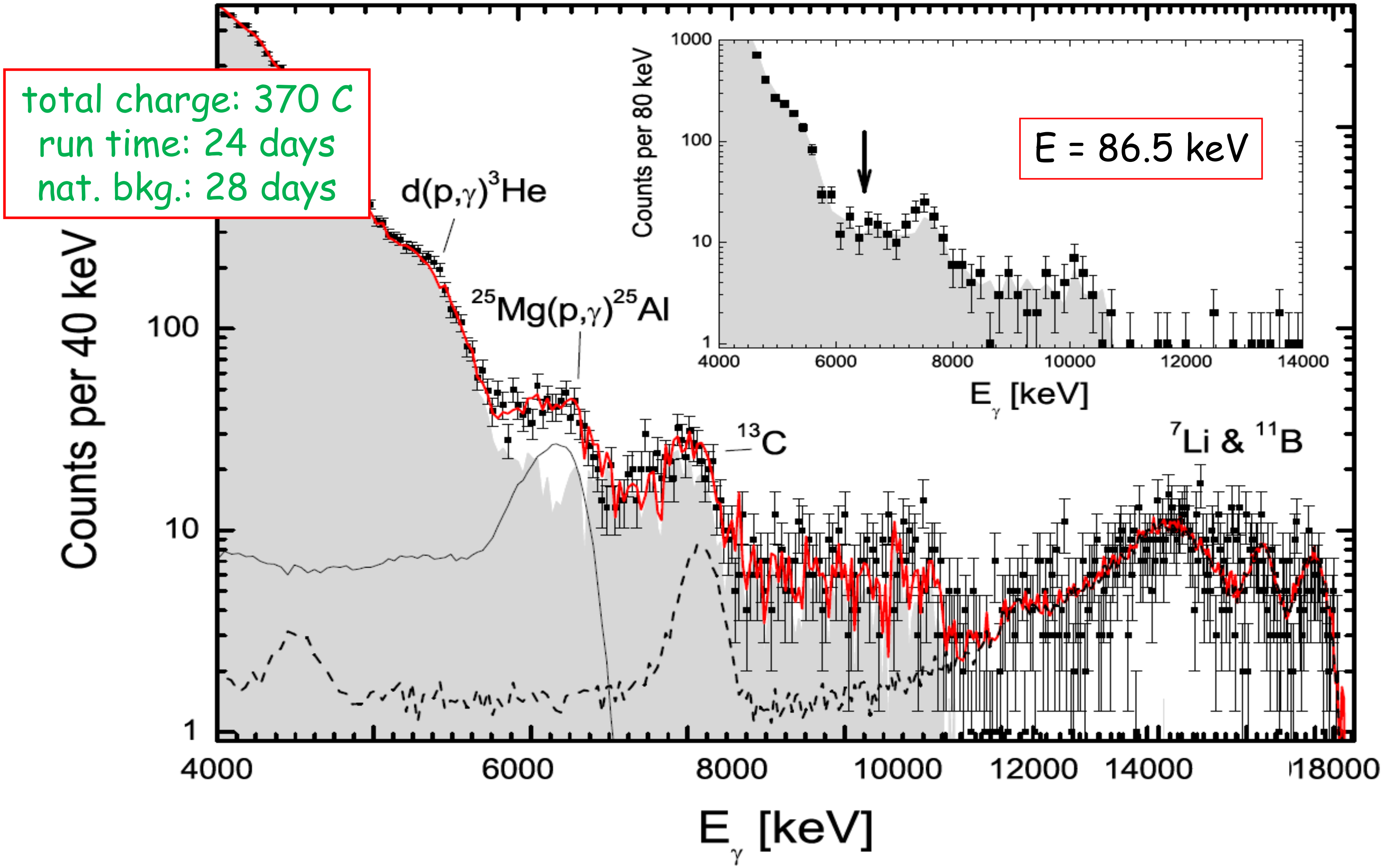



# 198 keV resonance BGO $\gamma$-ray spectra




$\omega\gamma_{NACRE}$ = $(7.1 \pm 1.0) \times 10^{-7}$ eV

# 92 keV resonance BGO γ-ray spectra




$$\omega\gamma_{92} = (2.9 \pm 0.6) \times 10^{-10} \text{ eV}$$

$$\omega\gamma_{92}^{\text{NACRE}} = (1.16^{+1.16}_{-0.39}) \times 10^{-10} \text{ eV}$$ (indirect)

# LUNA present program

CNO cycle

In progress

Ne-Na cycle

BBN

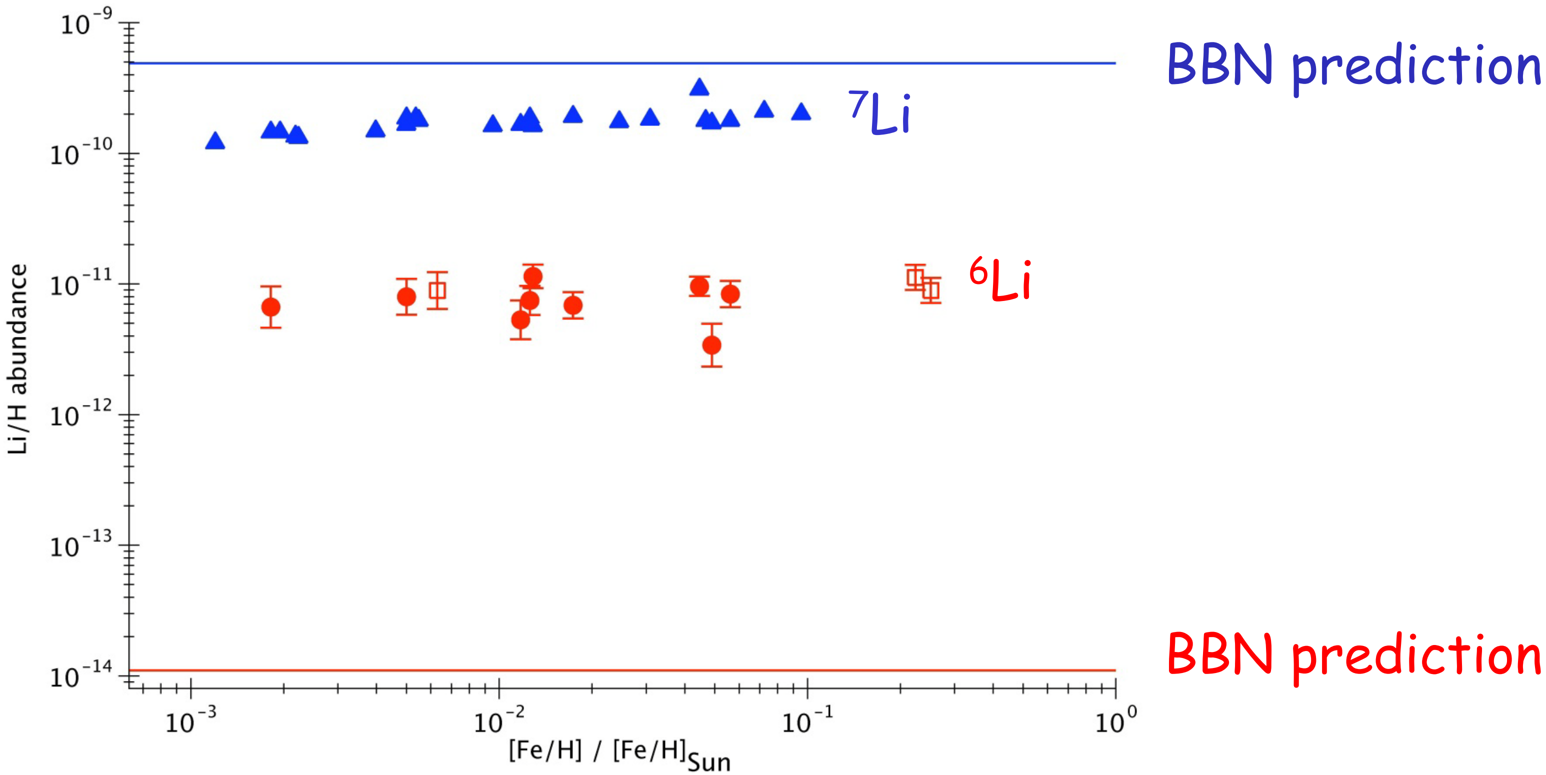
In progress

| reaction | Q-value (MeV) | Gamow energy (keV) | Lowest meas. Energy (keV) | LUNA limit |
|---|---|---|---|---|
| $^{17}O(p,\gamma)^{18}F$ | 5.6 | 35-260 | 300 | 65 |
| $^{18}O(p,\gamma)^{19}F$ | 8.0 | 50-200 | 143 | 89 |
| $^{23}Na(p,\gamma)^{24}Mg$ | 11.7 | 100-200 | 240 | 138 |
| $^{22}Ne(p,\gamma)^{23}Na$ | 8.8 | 50-300 | 250 | 68 |
| $D(\alpha,\gamma)^{6}Li$ | 1.47 | 50-300 | 700(direct)<br>50(indirect) | 50 |

to be completed presumably by 2014

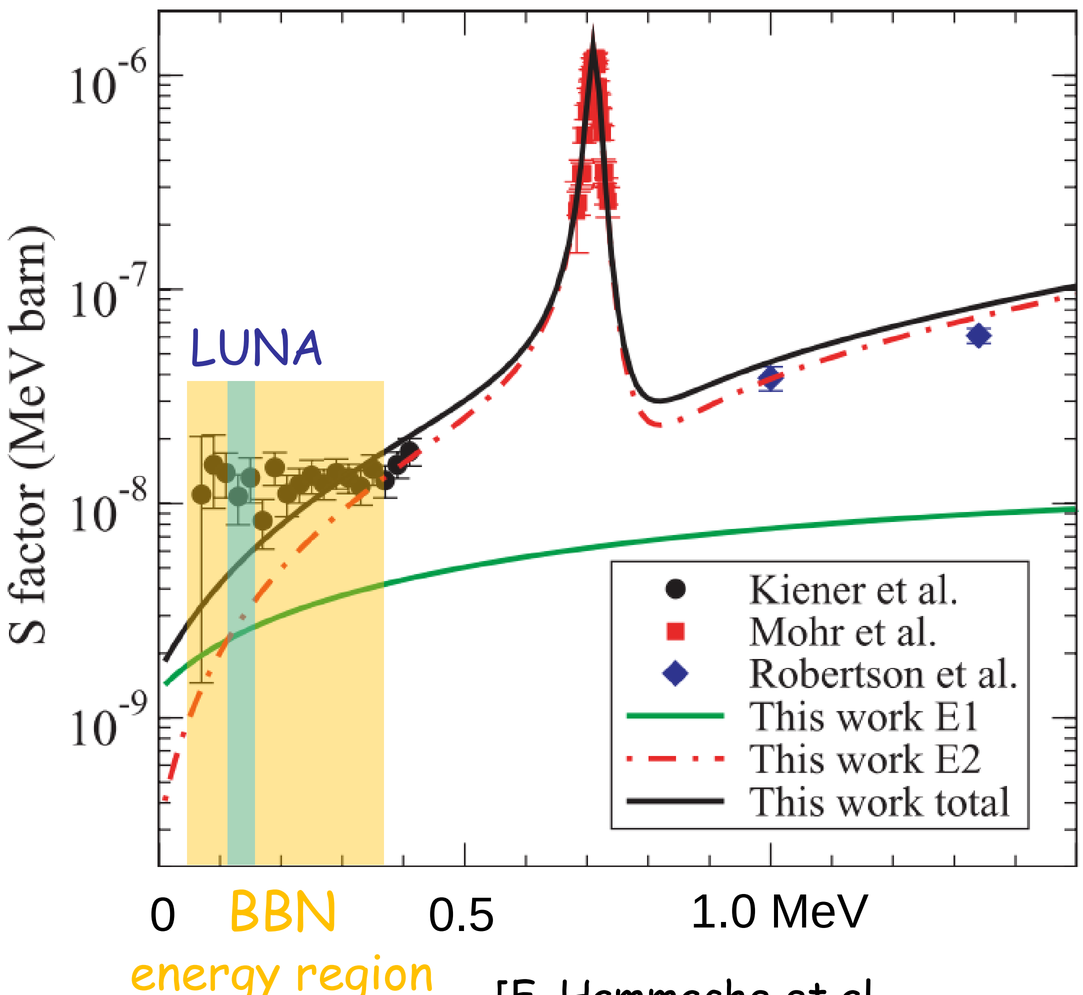
# The $^6$Li case

Constant amount in stars of different metallicity (→age)
2-3 orders of magnitude higher than predicted with the BBN network (NACRE)




The primordial abundance is determined by:
$^2H(\alpha,\gamma)^6Li$ producing almost all the $^6$Li
$^6Li(p,\alpha)^3He$ destroying $^6$Li → well known

# Available data




[F. Hammache et al.,
Phys. Rev. C 82, 065803 (2010)]

Direct measurements:

- Robertson et al.
E > 1 MeV
- Mohr et al.
around the 0.7 MeV resonance

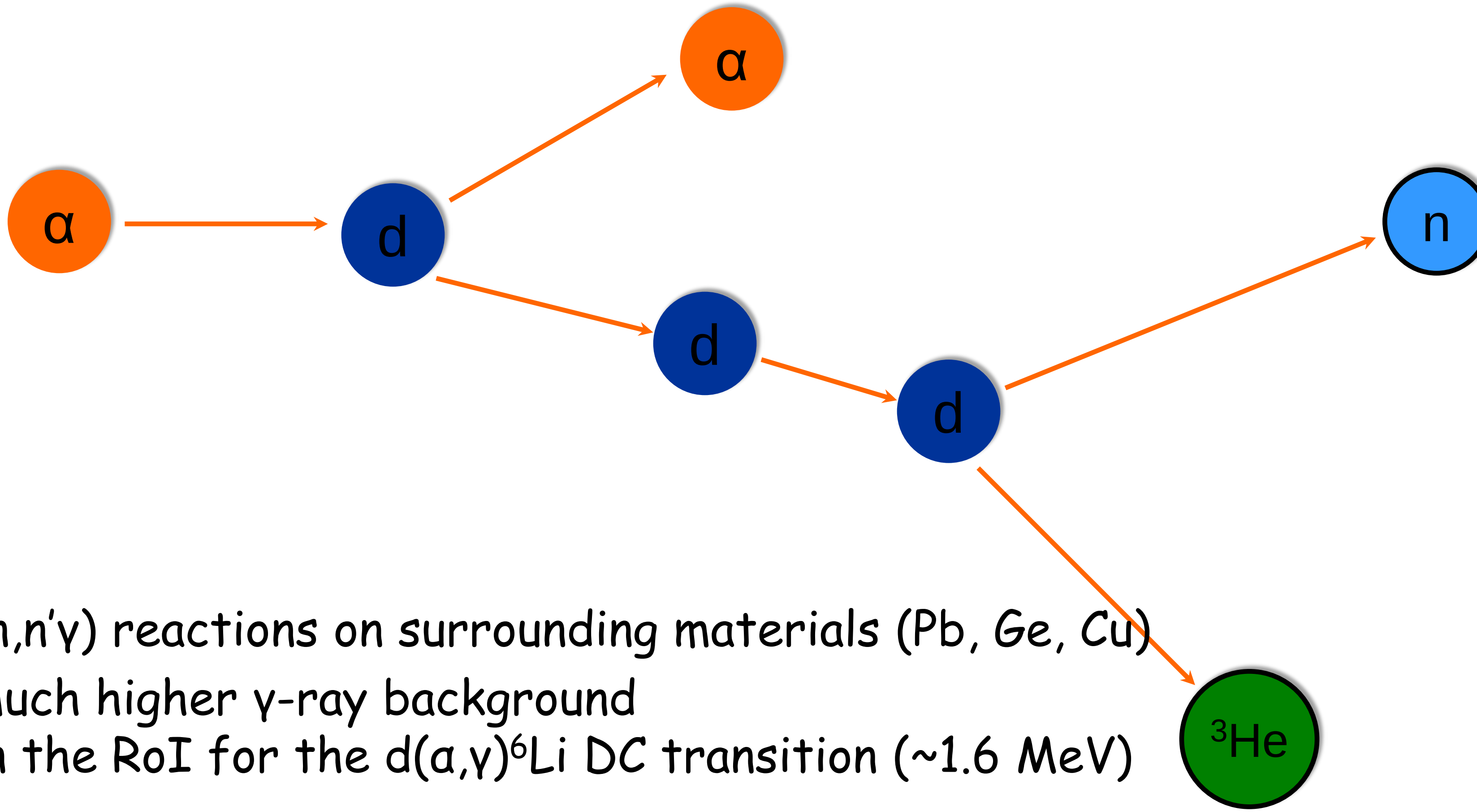
Indirect measurements:

- Hammache et al.
upper limits with high energy Coulomb break-up

**At LUNA direct measurements at the energies of astrophysical interest**

# The beam-induced background

- neutron background generated by $d(\alpha,\alpha)d$ Rutherford scattering followed by $d(d,n)^3He$ reactions




-> (n,n′γ) reactions on surrounding materials (Pb, Ge, Cu)

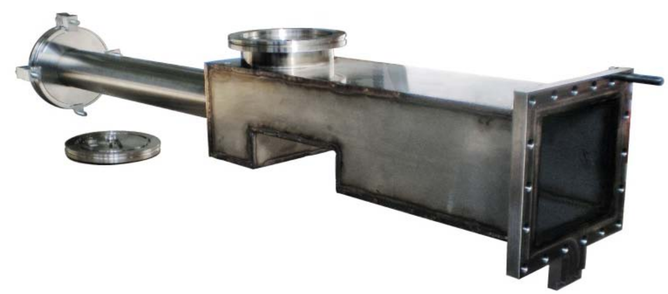
-> much higher γ-ray background in the RoI for the $d(\alpha,\gamma)^6Li$ DC transition (~1.6 MeV)

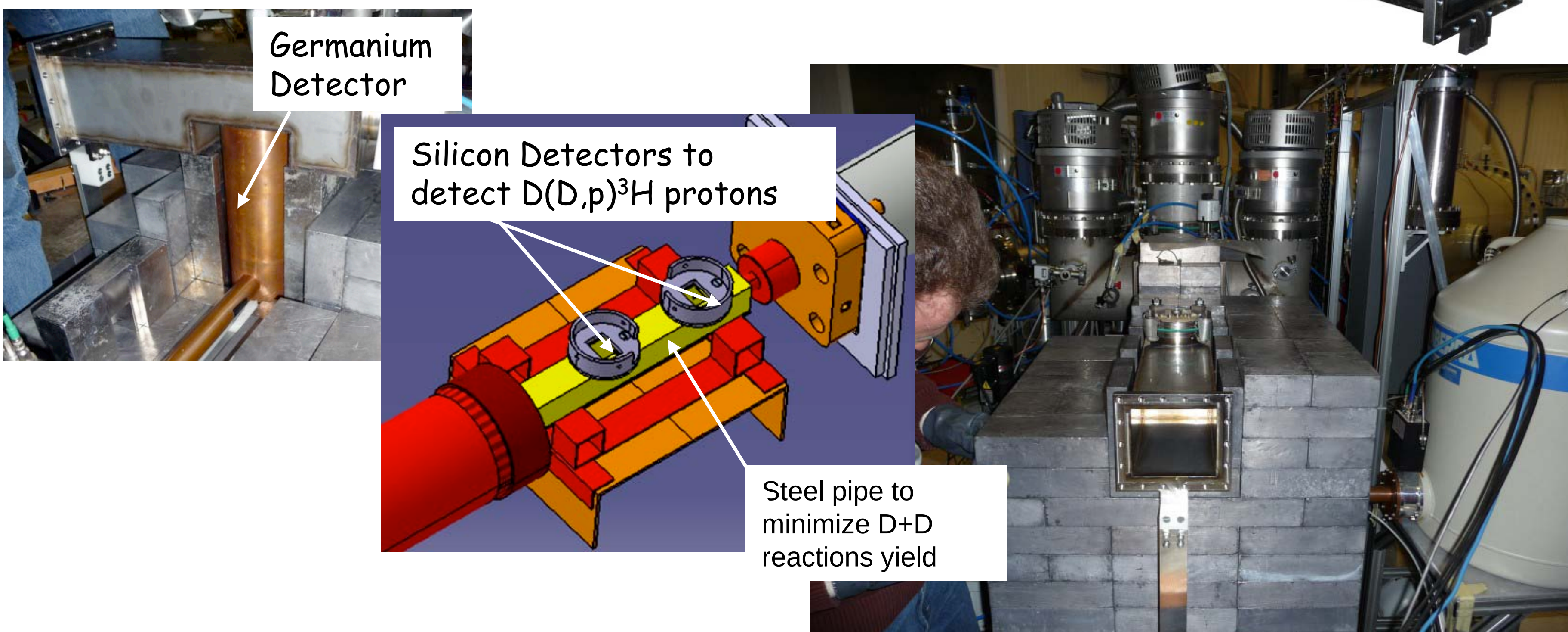
# Experimental set-up

Reduced gas volume: pipe to minimize the path of scattered $^{2}H$ and hence to minimize the d(d,n)$^{3}$He reaction yield

- HPGe detector in close geometry: larger detection efficiency and improved sygnal-to-noise ratio

- Silicon detectors to measure $^{2}H(^{2}H,p)^{3}H$





# Measurement strategy

Expected Noise/Signal ratio is 16 at 400 keV (Signal from GSI data, Noise from LUNA data)

Experimental strategy:

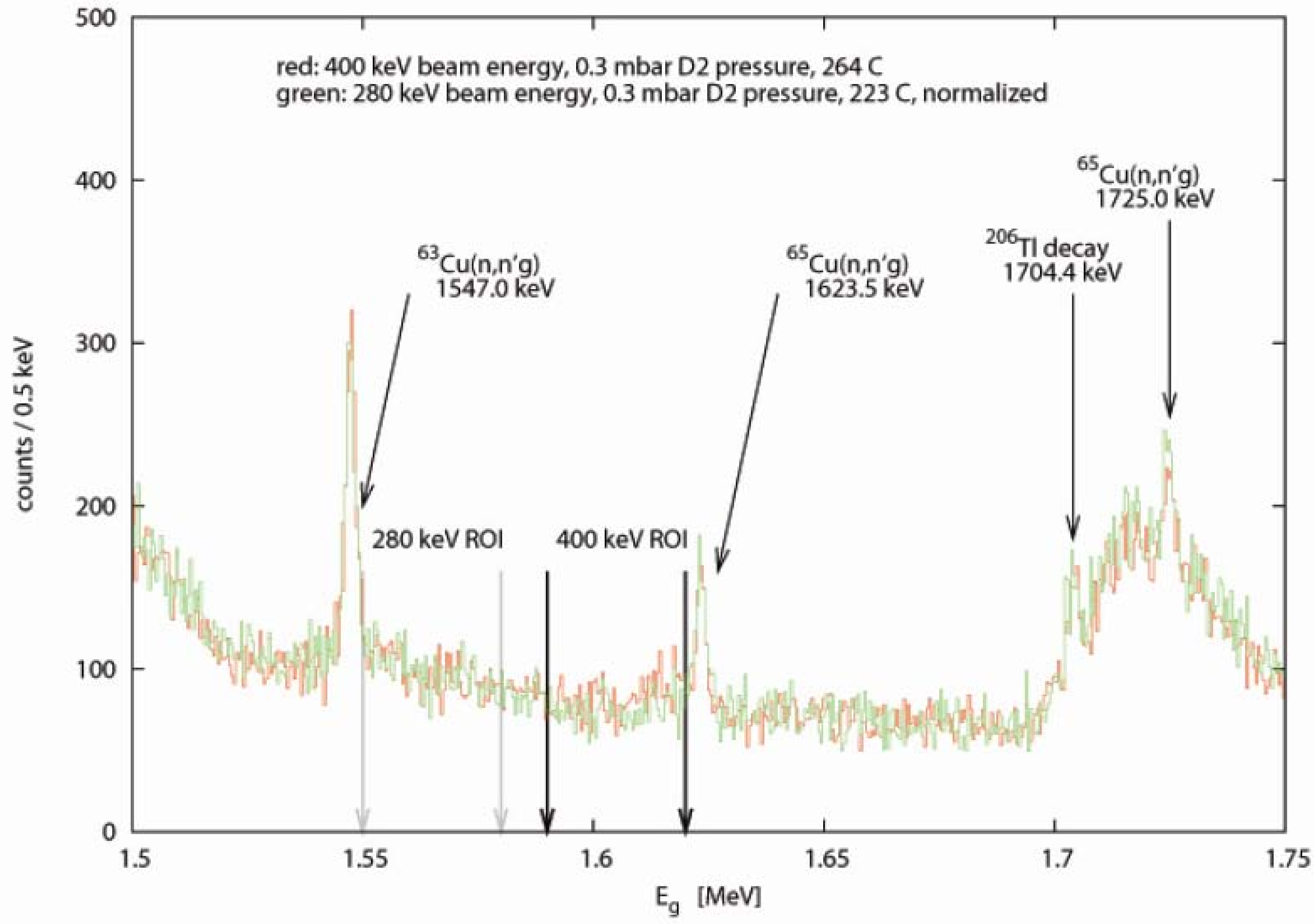
$E_\gamma = Q + E_{CM} - \Delta E_{rec} - \Delta E_{Doppler}$

Measurement with $\alpha$ beam on $^2H$ gas target at 400 keV
(ROI: 1585-1620 keV)

Measurement with $\alpha$ beam on $^2H$ gas target at 280 keV
(ROI: 1545-1580 keV)

Subtraction of the two normalized spectra to obtain the 400 keV Signal

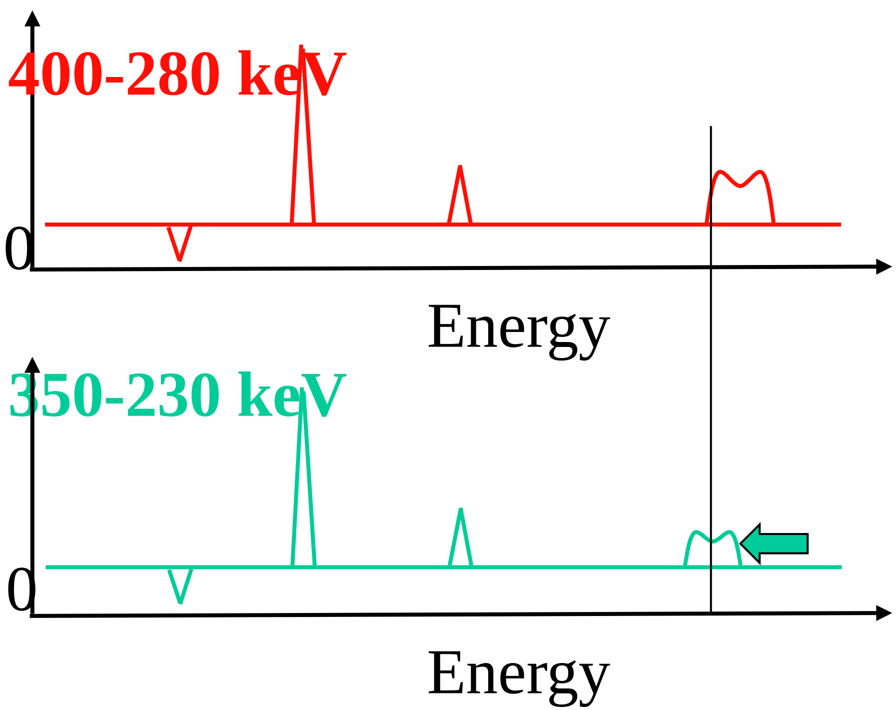
# Preliminary data

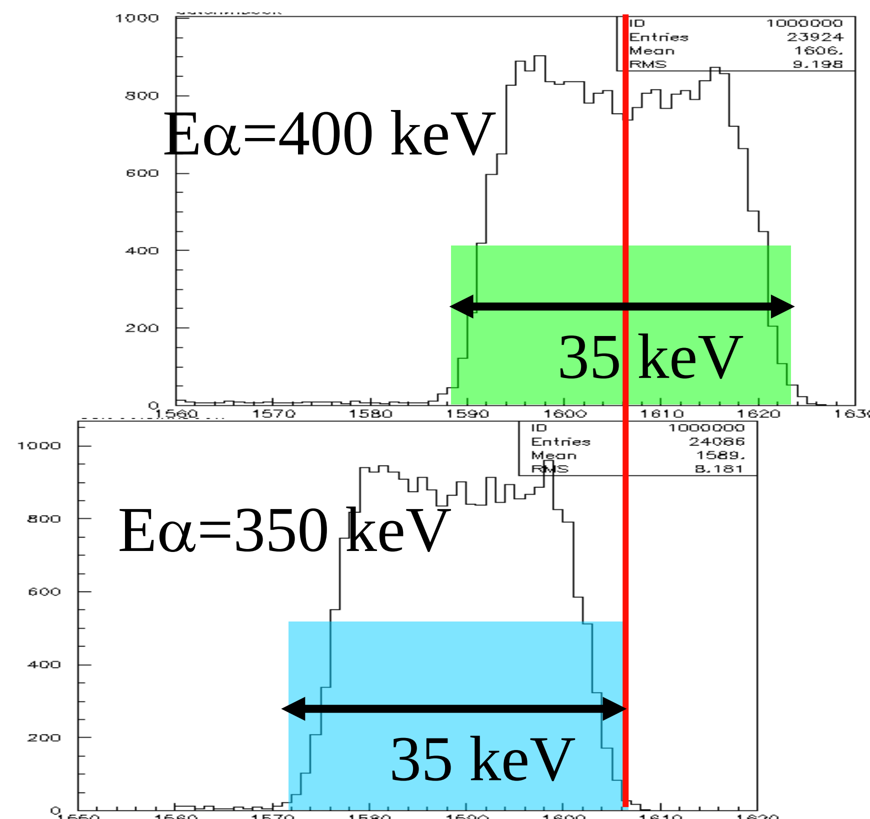


# Future measurements

A measurement with the pair 350-230 keV can confirm/discard the hypothesis that the excess seen around at 400 keV is a genuine $^{2}H(\alpha,\gamma)^{6}Li$ signal

At 350 keV the RoI centroid is shifted by approximately 17 keV (half of the total RoI). The expected N/S ratio is 19 (16 at 400 keV)

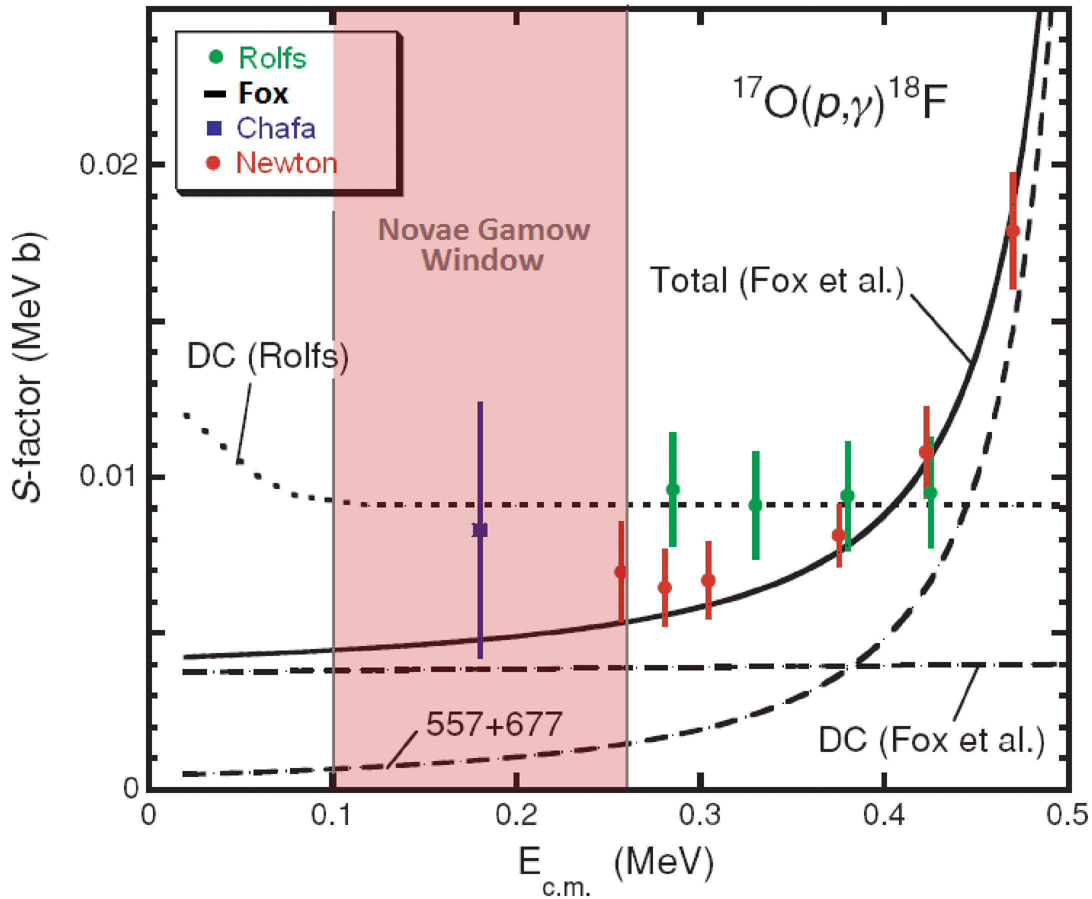


# $^{17}O(p,\gamma)^{18}F$

$^{17}O$+p is very important for hydrogen burning in different stellar environments:

- Red giants
- Massive stars
- AGB
- Novae

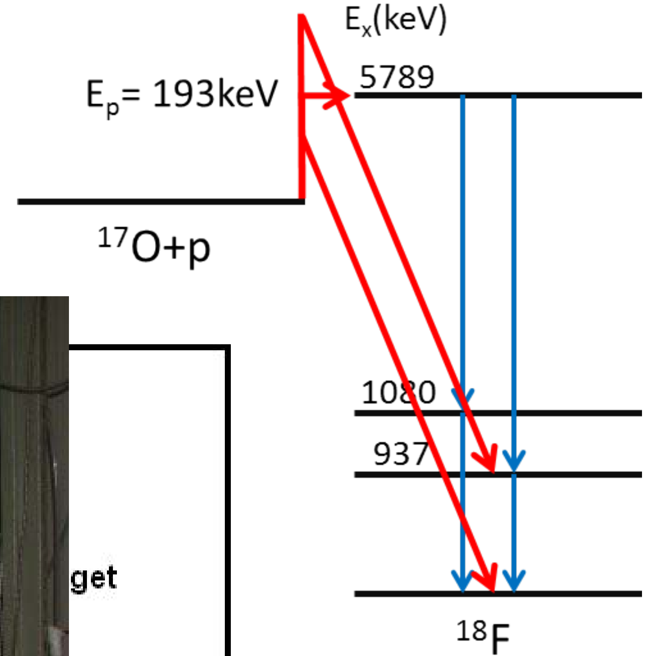


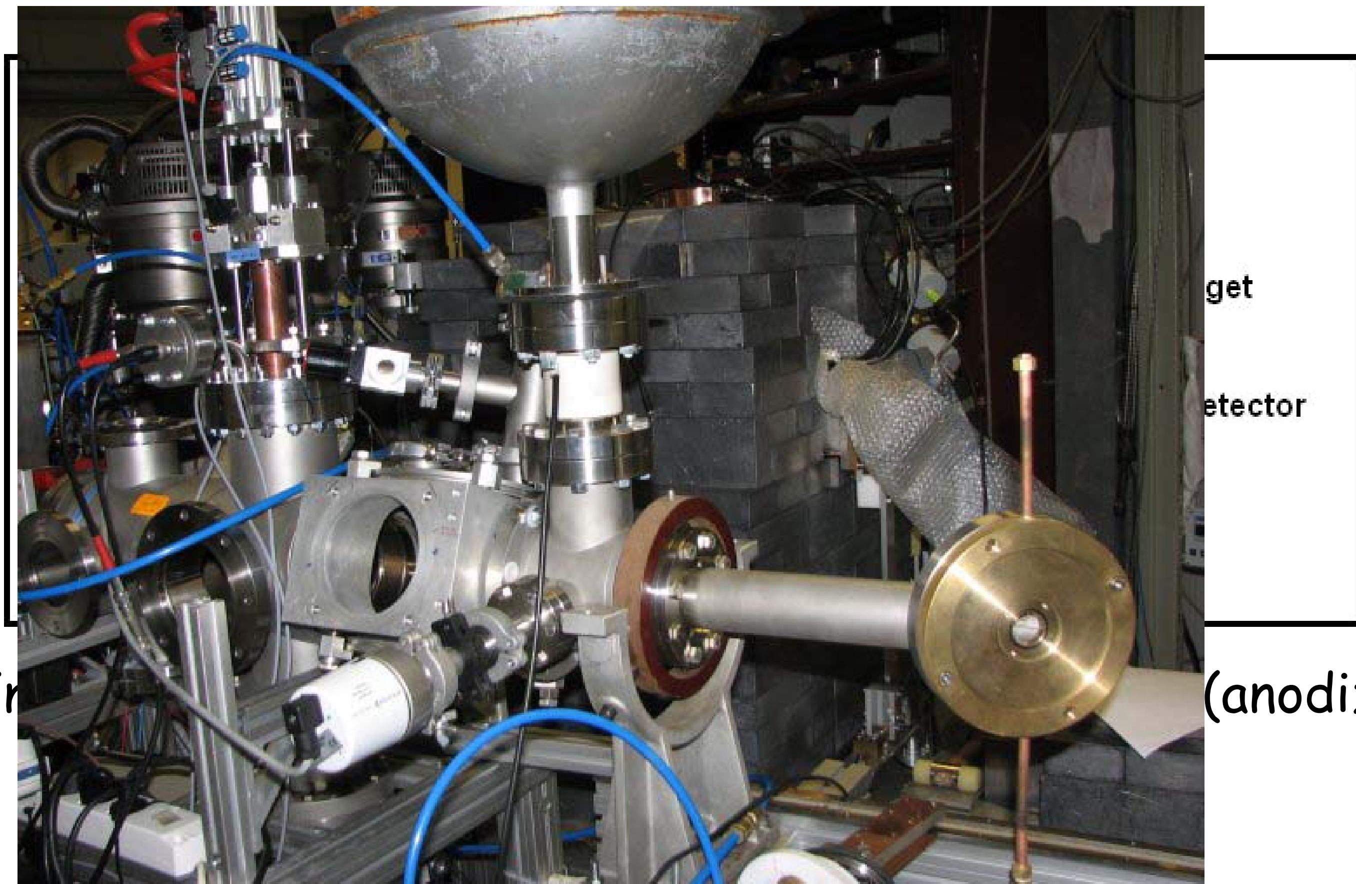

$\omega\gamma_{193}$= $(1.2\pm0.2)\times10^{-6}$ eV — Fox et al.

$\omega\gamma_{193}$= $(2.2\pm0.4)\times10^{-6}$ eV — Chafa et al. (activation)

# LUNA measurement

Resonant and direct capture study with prompt gammas and activation **(Ep=185-400 keV)**

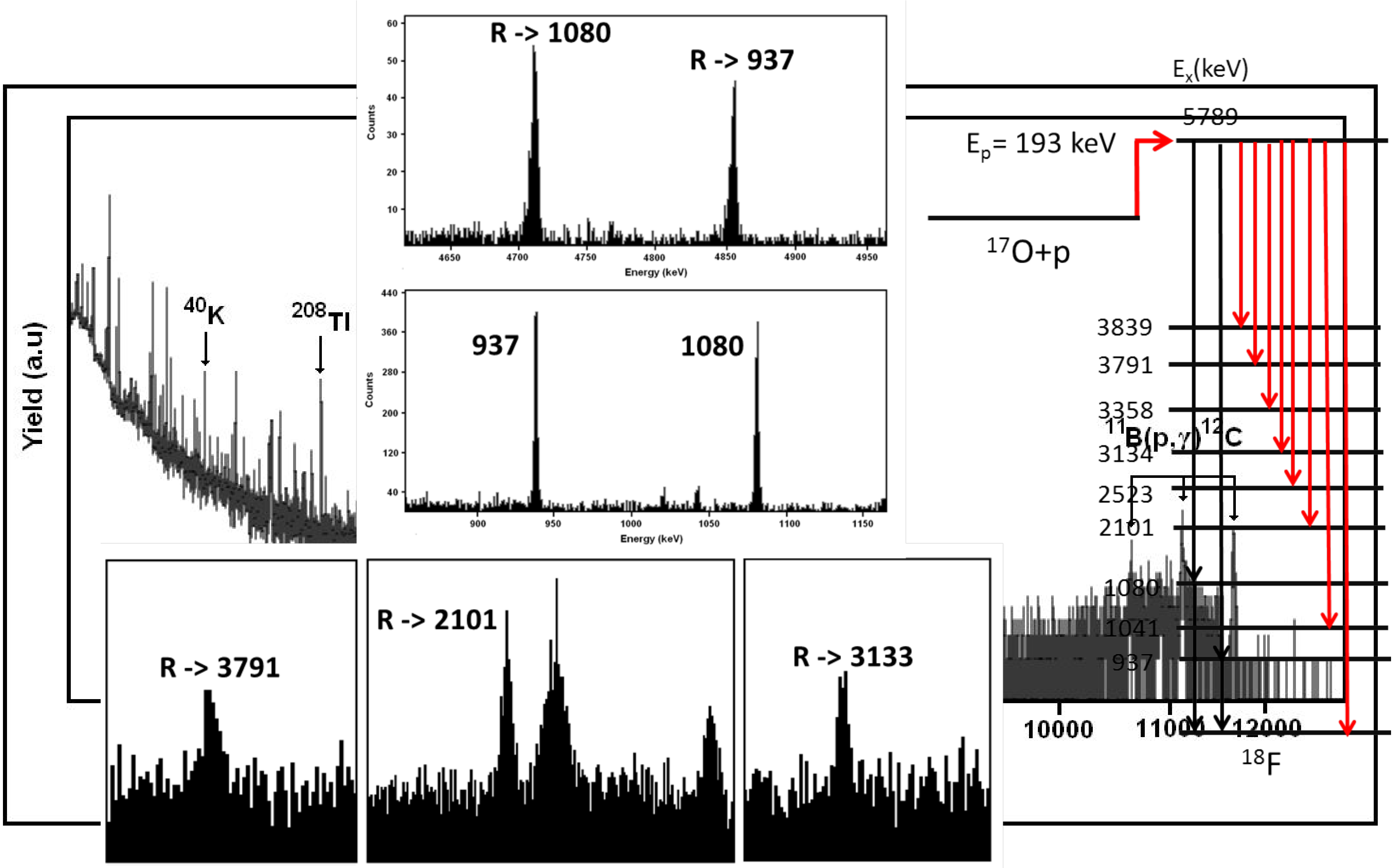



En (anodization process)

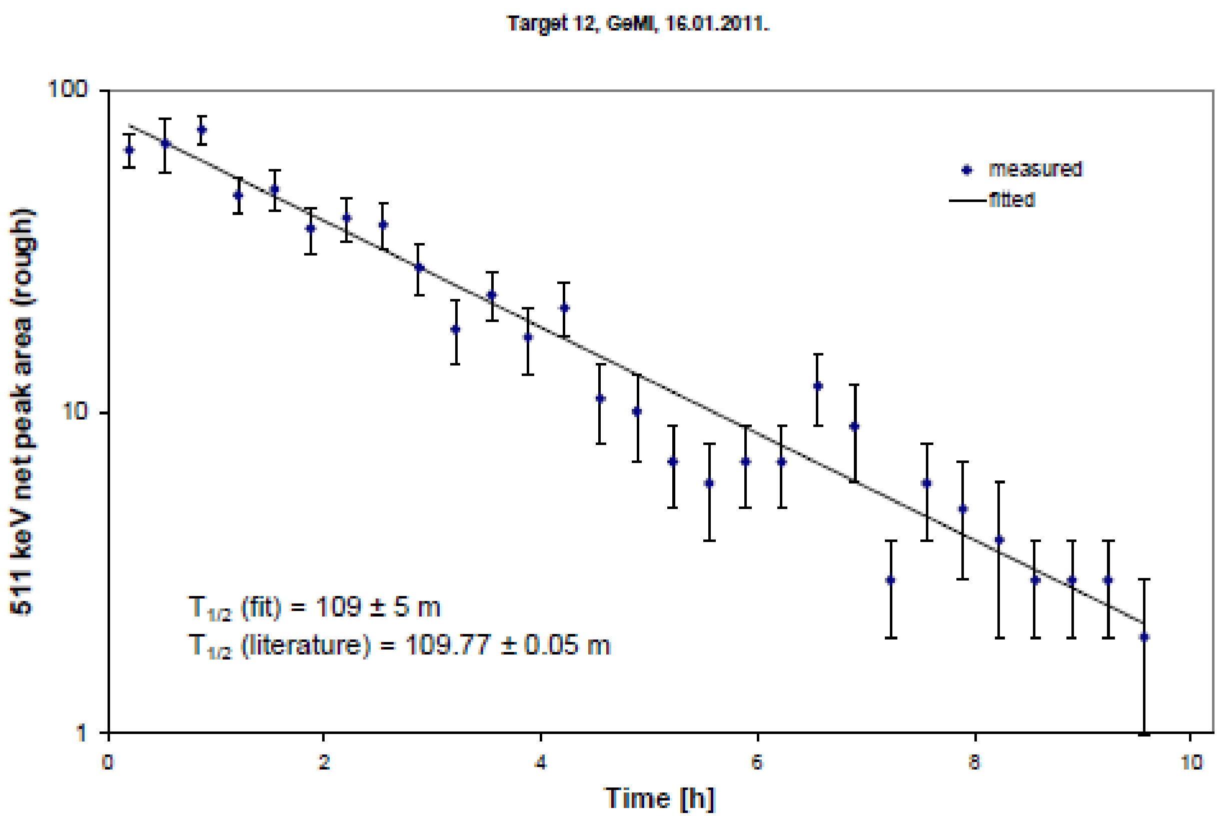
# LUNA measurement

193 keV resonance with prompt gammas



# LUNA measurement

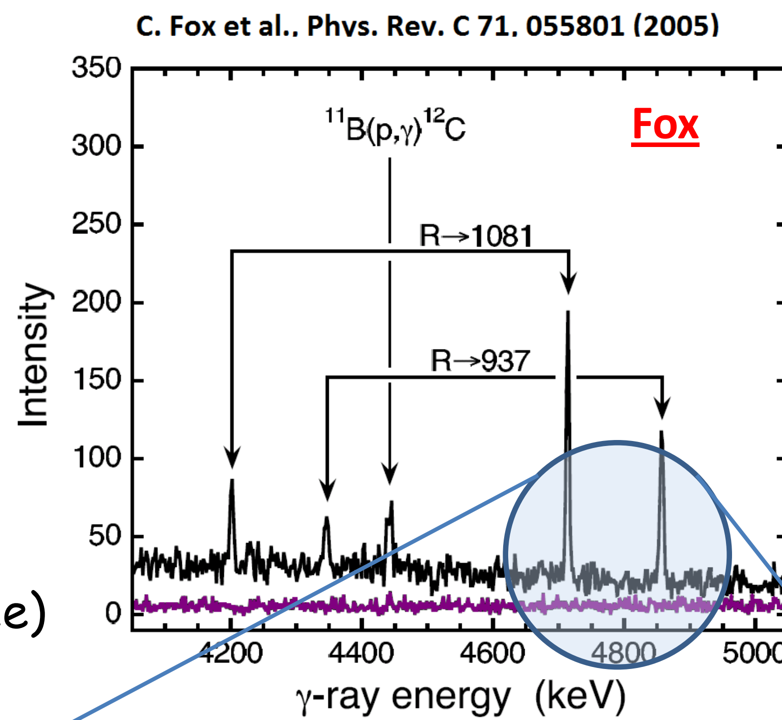
193 keV resonance with activation technique ($^{18}F \rightarrow ^{18}O$)



# LUNA measurement

Study of the DC component is possible at LUNA

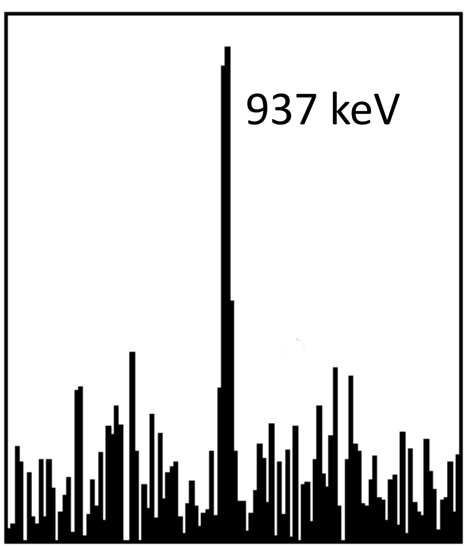
On-resonance (black)
off-resonance (purple)

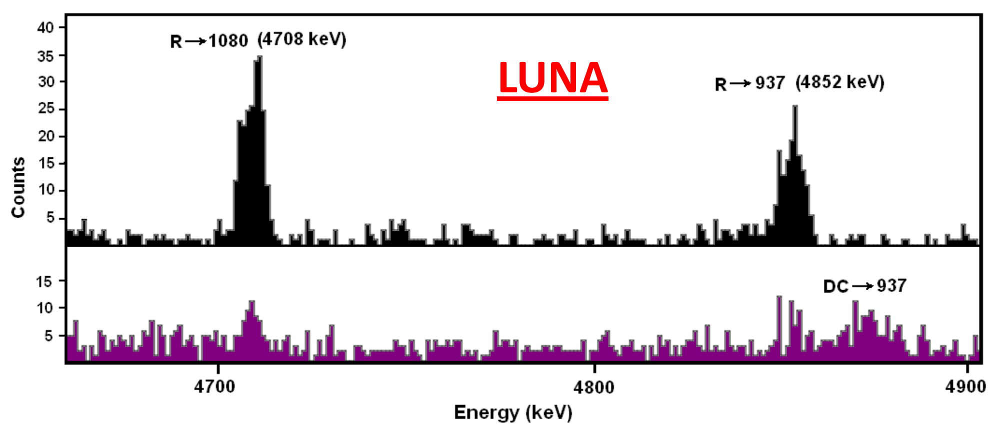



$E_p$ = 200 keV

$E_p$ = 228 keV

$E_p$ = 185 keV (below resonance)




$E_p$ = 197 keV

$E_p$ = 221 keV

# LUNA MV Project

April 2007: a Letter of Intent (LoI) was presented to the LNGS Scientific Committee (SC) containing key reactions of the He burning and neutron sources for the s-process:

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

$^{13}C(\alpha,n)^{16}O$

$^{22}Ne(\alpha,n)^{25}Mg$

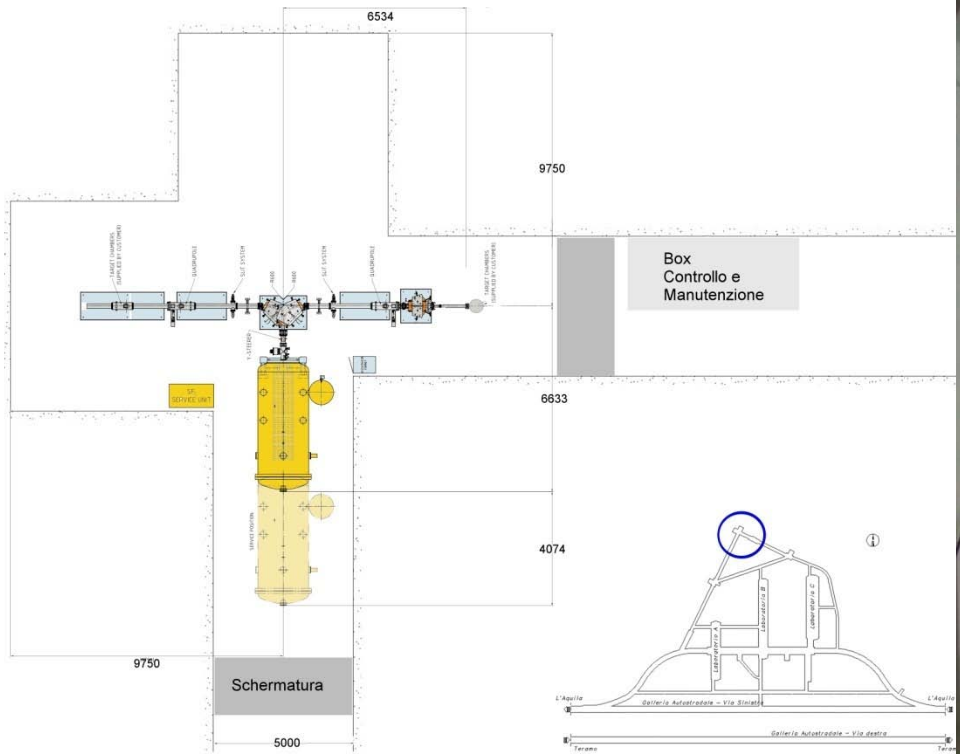
$(\alpha,\gamma)$ reactions on $^{14,15}N$ and $^{18}O$

These reactions are relevant at higher temperatures (larger energies) than reactions belonging to the hydrogen-burning studied so far at LUNA

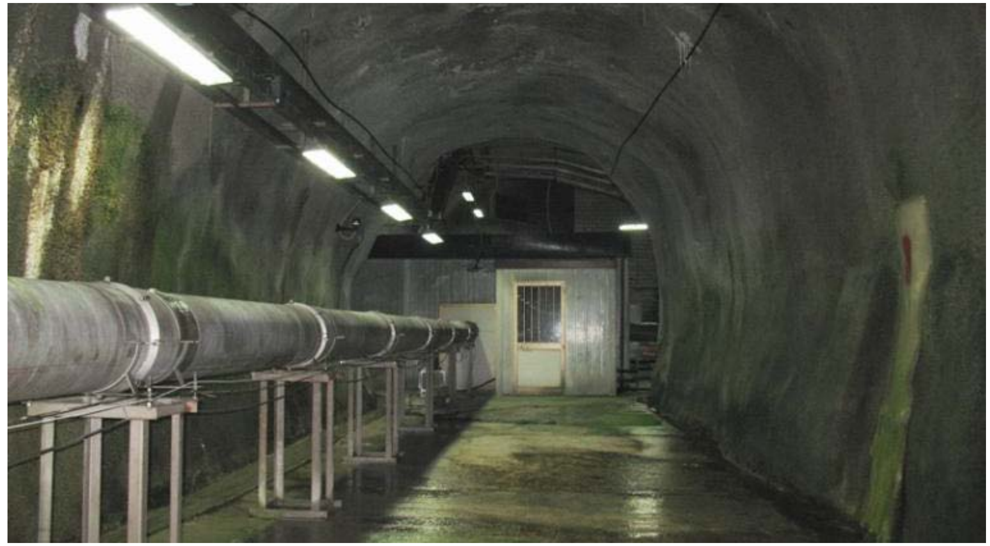
↓

Higher energy machine→ 3.5 MV single ended positive ion accelerator

# Possible location at the "B node" of a 3.5 MV single-ended positive ion accelerator




- In a very low background environment such as LNGS, it is mandatory not to increase the neutron flux above its average value



$^{13}C(\alpha,n)^{16}O$

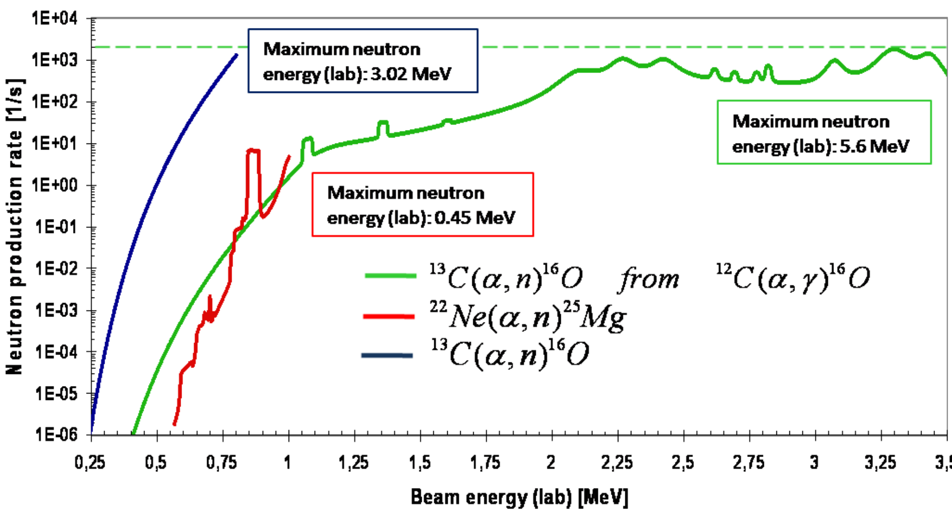
α beam intensity: 200 μA
Target: $^{13}C$, 2 $10^{17}$at/cm$^2$ (99% $^{13}C$ enriched)
Beam energy(lab) ≤ 0.8 MeV

$^{22}Ne(\alpha,n)^{25}Mg$

α beam intensity: 200 μA
Target: $^{22}Ne$, 1 $10^{18}$at/cm$^2$
Beam energy(lab) ≤ 1.0 MeV

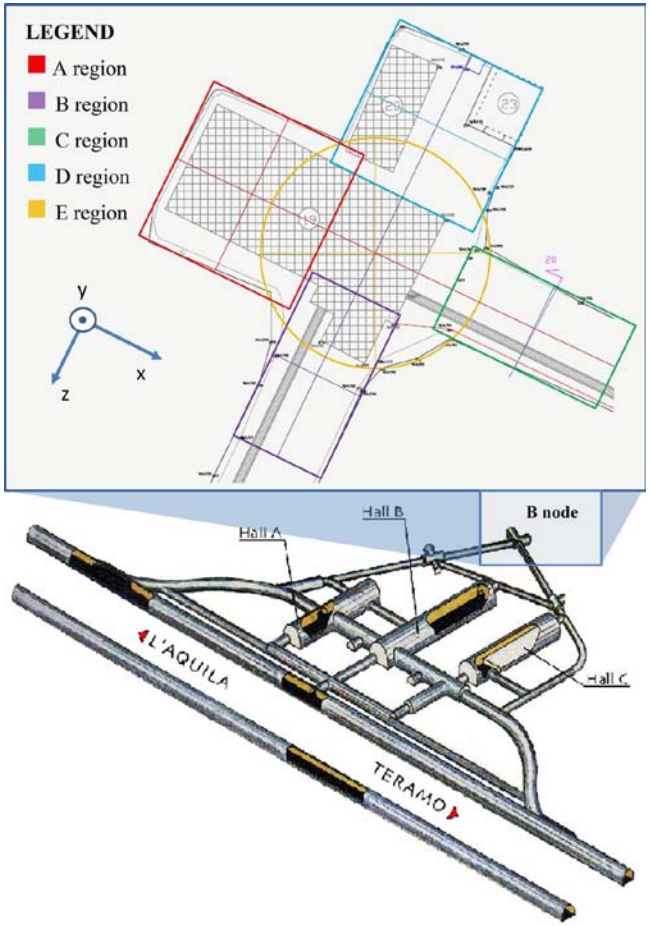
$^{13}C(\alpha,n)^{16}O$ from $^{12}C(\alpha,\gamma)^{16}O$

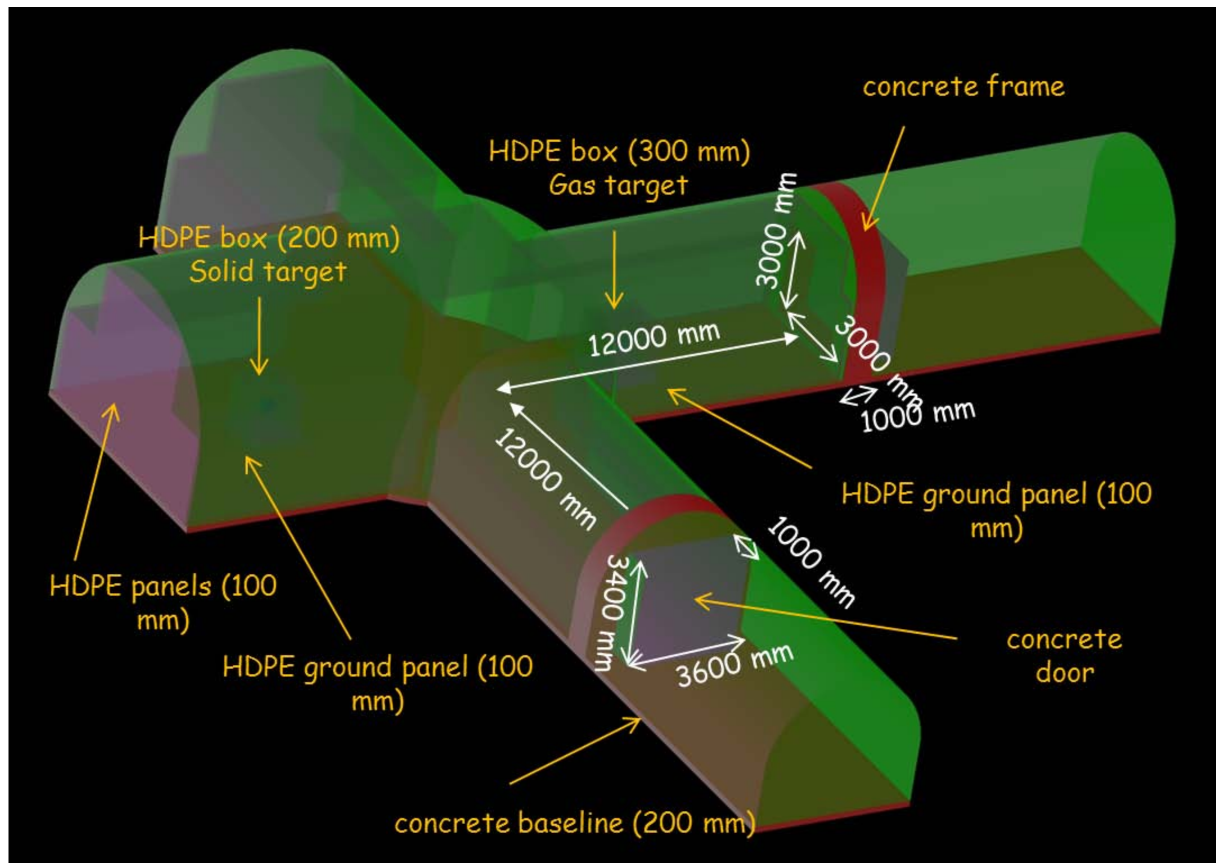
α beam intensity: 200 μA
Target: $^{13}C$, 1 $10^{18}$at/cm$^2$ ($^{13}C/^{12}C = 10^{-5}$)
Beam energy(lab) ≤ 3.5 MeV




- Maximum neutron production rate : 2000 n/s
- Maximum neutron energy (lab) : 5.6 MeV

# Geant4 simulations for neutron fluxes just outside the experimental hall and on the internal rock walls



# Laboratory for Underground Nuclear Astrophysics

LUNA MV

Round Table: "LUNA - MV at LNGS"

February 10-11, 2011

- **STATUS OF SIMILAR UNDERGROUND PROJECTS**
  - Status of the Canfranc project, Luis FRAILE
  - The Bulby mine: an opportunity for underground nuclear astrophysics, Maria Luisa ALIOTTA
  - The Dresden Felsenkeller: A shallow underground option for accelerator – based nuclear astrophysics, Daniel BEMMERER
  - Status of the DIANA project, Alberto LEMUT
- **GENERAL DESCRIPTION OF THE LUNA-MV PROJECT**
  - The LUNA-MV project: from 2007 to now, Alessandra GUGLIELMETTI
  - A Megavolt Accelerator for Underground Nuclear Astrophysics, Matthias JUNKER
  - The Site for LUNA-MV at LNGS, Paolo MARTELLA
  - The Shielding of the LUNA-MV site, Davide TREZZI
- **PHYSICS CASES FOR LUNA-MV**
  - The $^{12}C(\alpha,\gamma)^{16}O$ reaction from the astrophysical point of view, Oscar STRANIERO
  - The rates of neutron – realeasing reactions in He-burning phases and their astrophysical consequences, Maurizio BUSSO
  - The seeds of the S-process: experimental issues in the study of $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$, Paolo PRATI
  - Towards the Gamow peak of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, Roberto MENEGAZZO
  - Stellar helium burning studied at LUNA-MV. The $^{14}N(\alpha,\gamma)^{18}F$, $^{15}N(\alpha,\gamma)^{19}F$, $^{16}O(\alpha,\gamma)^{20}Ne$, and $^{18}O(\alpha,\gamma)^{22}Ne$, Daniel BEMMERER
- **DISCUSSION AND LAYOUT OF A POSSIBLE LOI EXTENDED TO OTHER GROUPS**
  - Workpackages towards European Underground Accelerator

## Next-generation underground laboratory for Nuclear Astrophysics

## Executive summary

This document originates from discussions held at the LUNA MV Roundtable Meeting that took place at Gran Sasso on 10-11 February 2011. It serves as a call to the European Nuclear Astrophysics community for a wider collaboration in support of the next-generation underground laboratory. To state your interest to contribute to any of the Work Packages, please add your name, contact details, and WP number under *International Collaboration*.

WP1: Accelerator + ion source

WP2: Gamma detectors

WP3: Neutron detectors

WP5: Solid targets

WP6: Gas target

WP7: Simulations

WP8: Stellar model calculations

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