Laboratory
Underground
Nuclear
Astrophysics

INFN

The LUNA experiment at the Gran Sasso Laboratory

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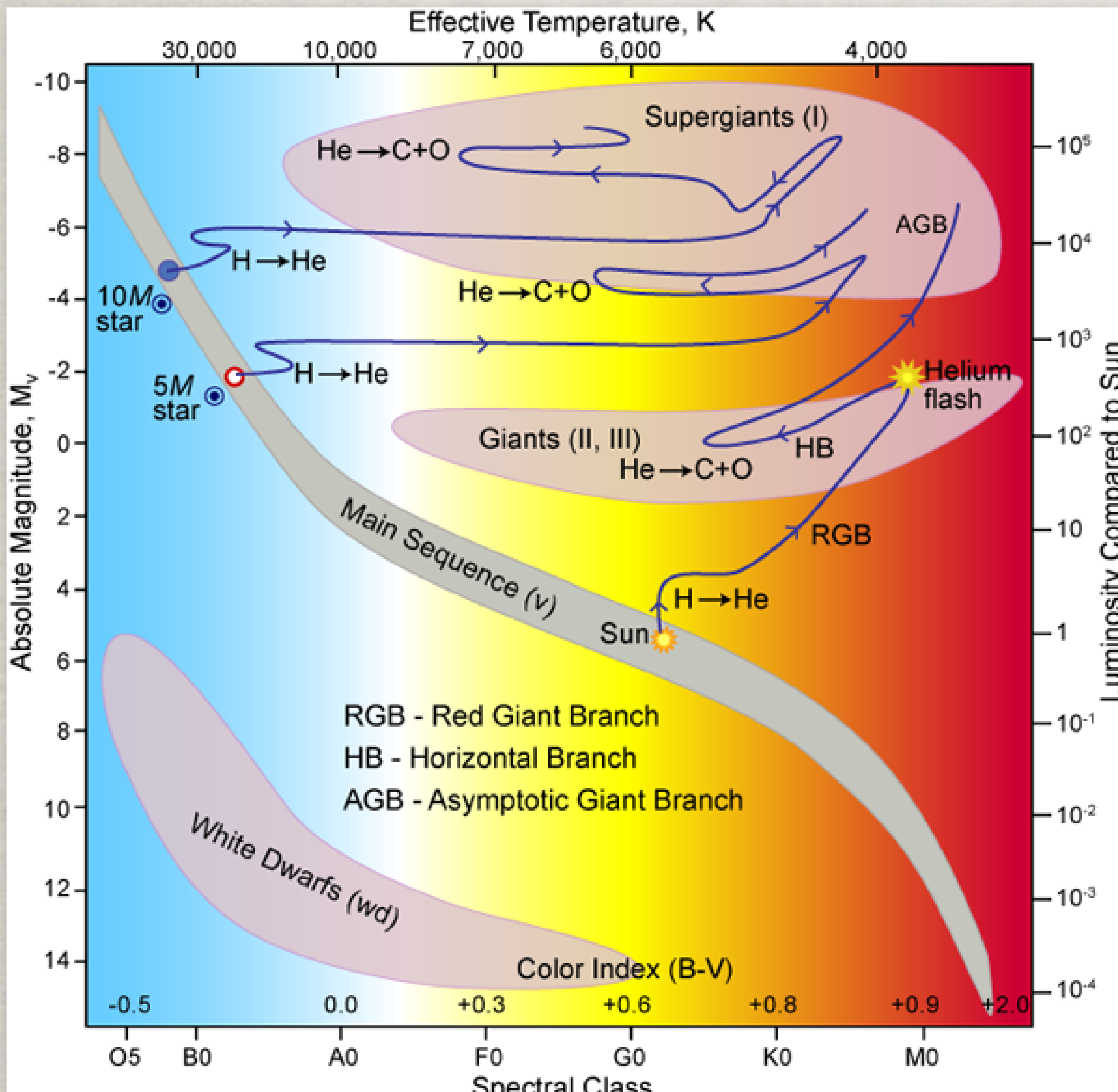
OUTLOOK

- LUNA: Why going underground to measure nuclear fusion reactions in a laboratory ?
  - The Sun: p-p chain, CNO cycle and solar neutrinos
  - Nucleosynthesis at work: ^{26}Al
  - Hot environment: BBN and Novae
- The LUNA-MV project: a big step forward

Nucleosynthesis



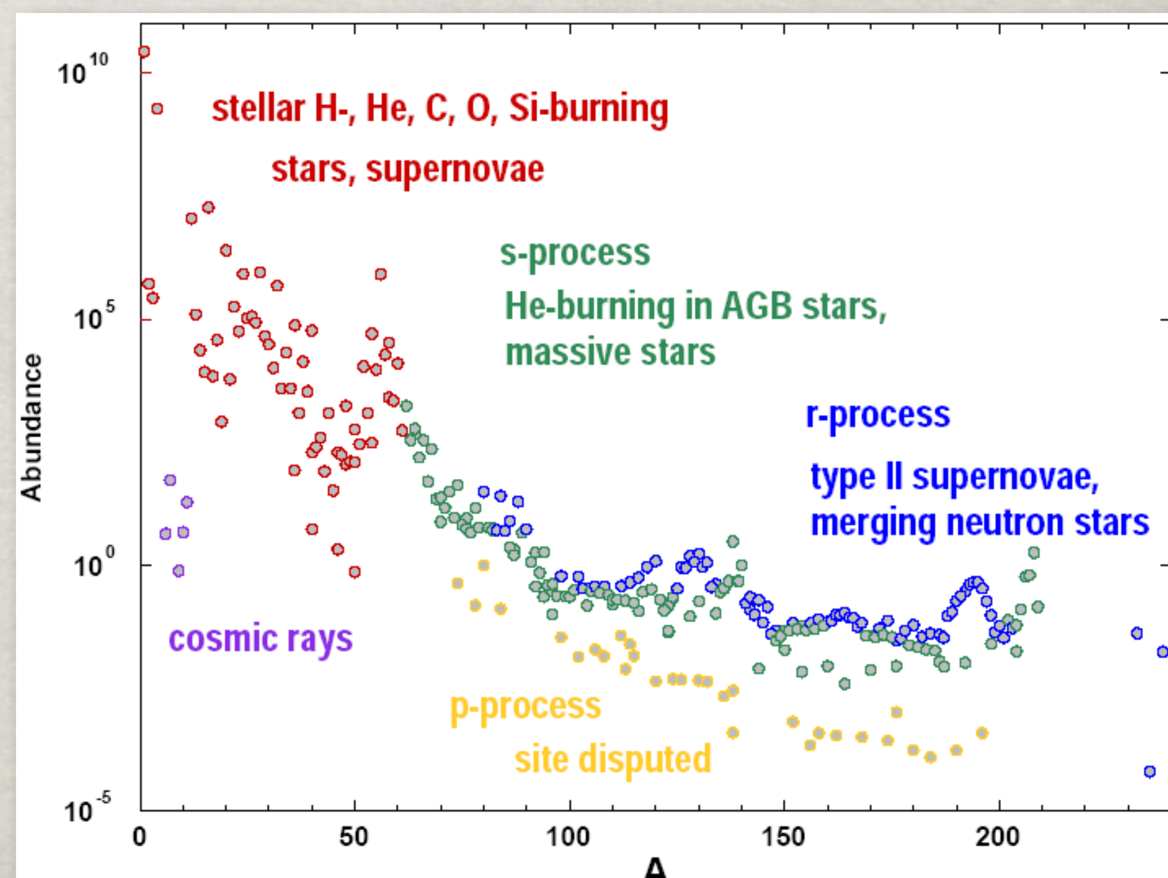
- H burning → He
- He burning → C, O, Ne
- C/O … Si burning → Fe
- explosive burning

Solar Neutrinos and element abundances in stars and BBN

T_{SUN} = 0.015 GK ~ 2 keV

T_{RGB} = 0.1 GK ~ 80 keV

T_{NOVAE} = 0.3 GK ~ 140 keV

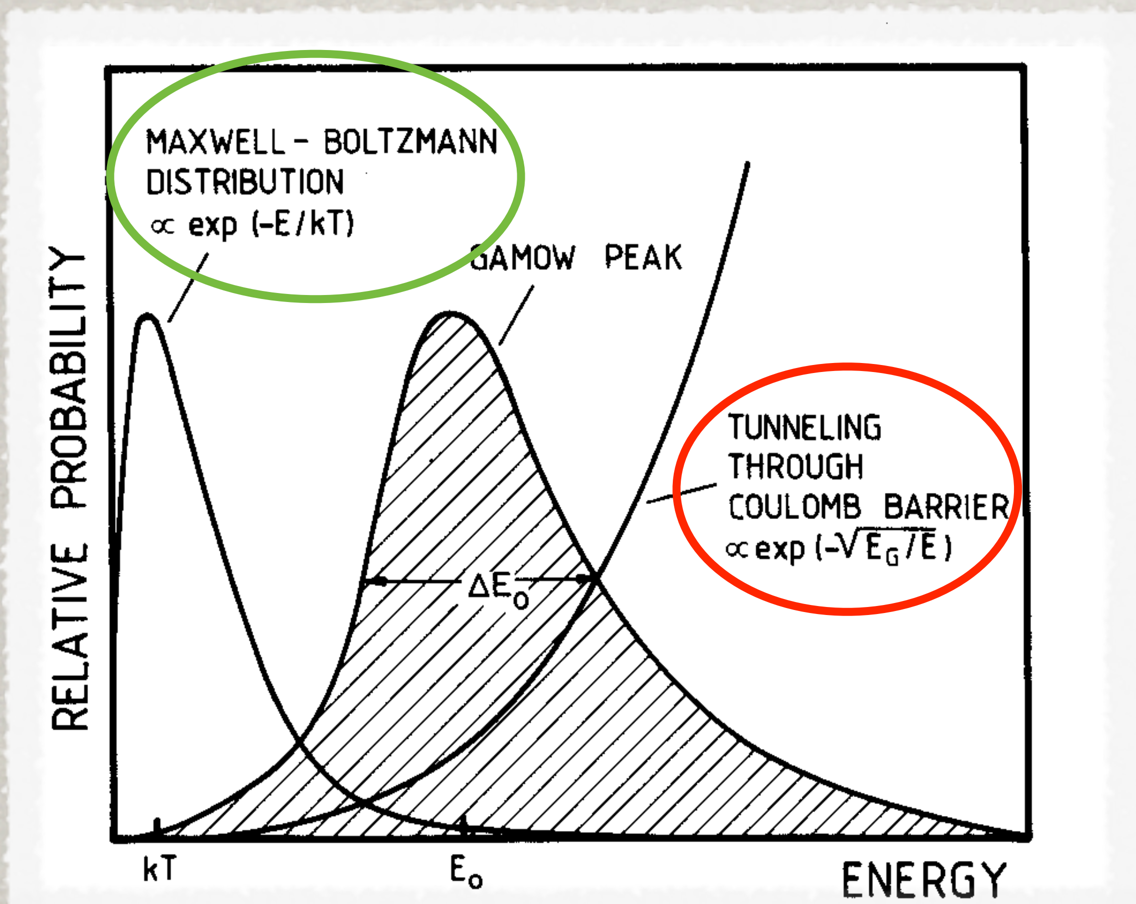


Reaction Rate for Charged Particles

$$\sigma(E) = \frac{S(E)}{E} \exp\left(-31.29 \cdot Z_1 \cdot Z_2 \cdot \sqrt{\frac{\mu}{E}}\right)$$

Astrophysical factor

Gamow factor



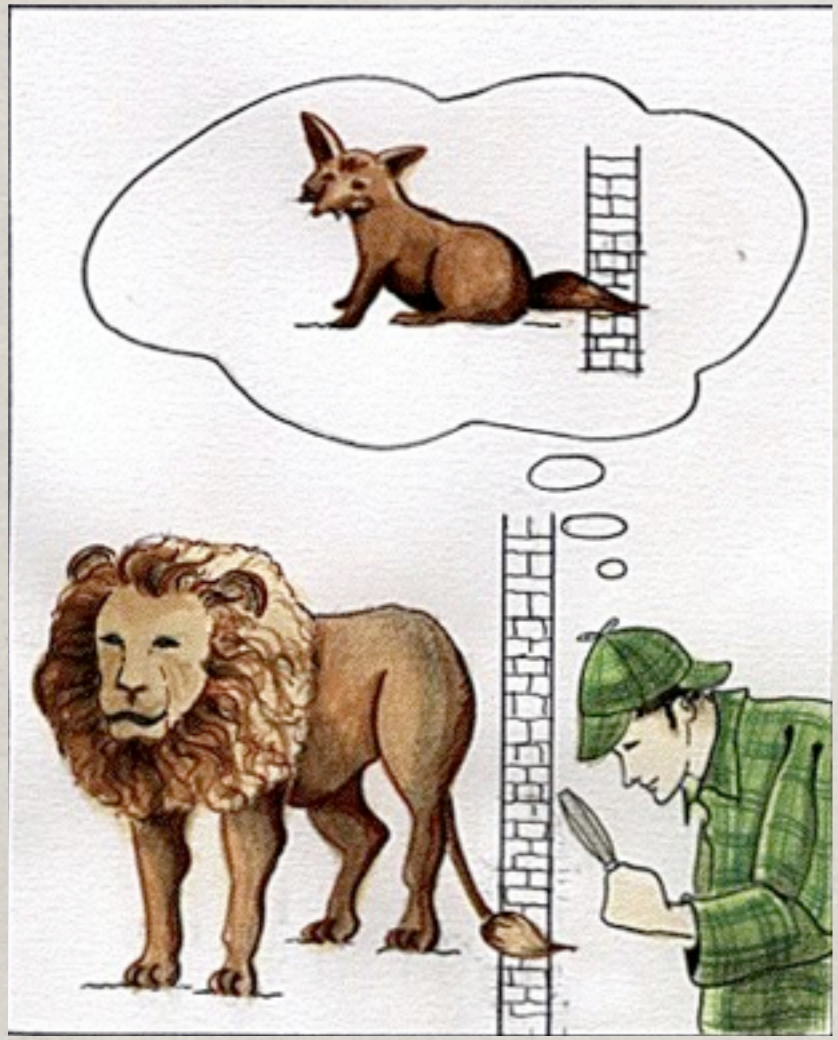
In the Sun: $T = 1.5\ 10^7$ K
$kT = 1$ keV $\ll E_{coul}$ (0.5-2MeV)

Nuclear reactions that generate energy and synthesize elements take place inside the stars in a relatively narrow energy window: the **Gamow peak**

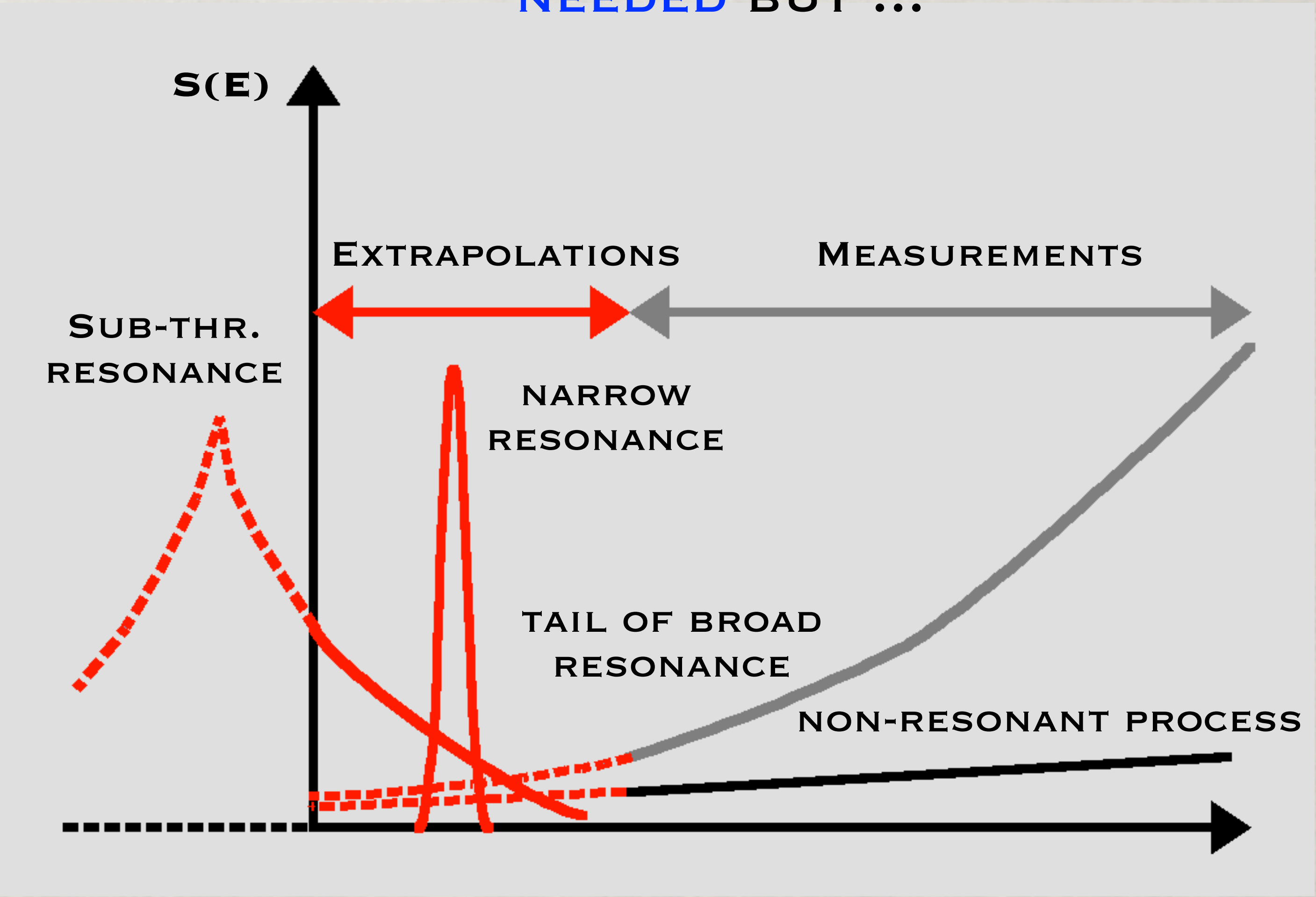
Gamow Energy for H-burning reactions: few to several tens keV

$$\text{pbarn} < \sigma < \text{nbarn}$$

Extrapolation risks



Extrapolation down to astrophysical energies is needed but ...



sometimes extrapolation fails!

Experimental requirements

The cross section varies strongly with energy

- ☑ precise beam energy resolution
- ☑ high purity and stable targets

and it's very small at low energies

How to improve signal to noise ratio

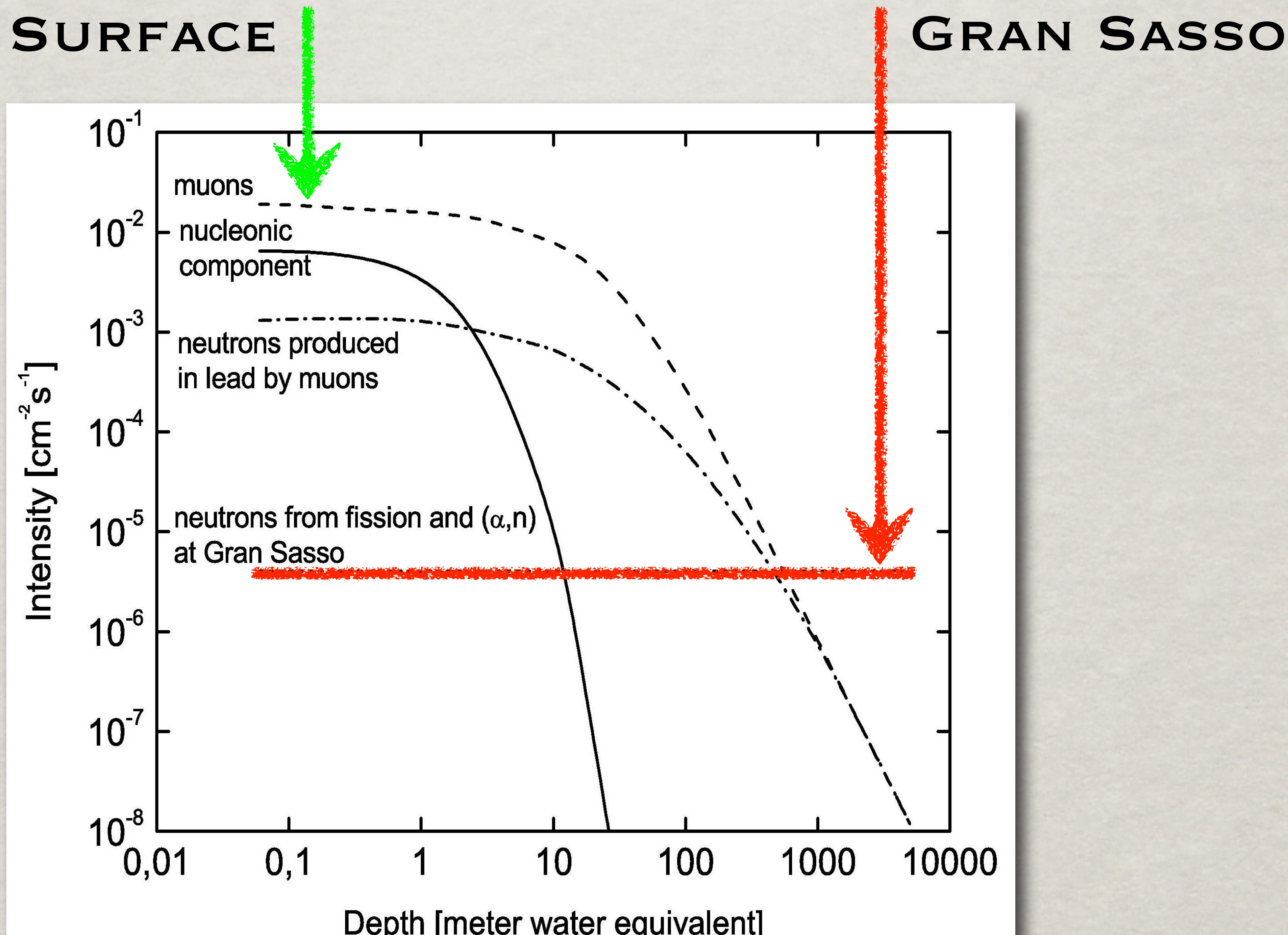
- setup efficiency ↑
- natural background (cosmic radiation, radioactive isotopes) ↓
- beam induced background ↓

Direct cross section measurements feasible with reduced cosmic-ray induced background

↓

Underground measurements

Why Going Underground ?

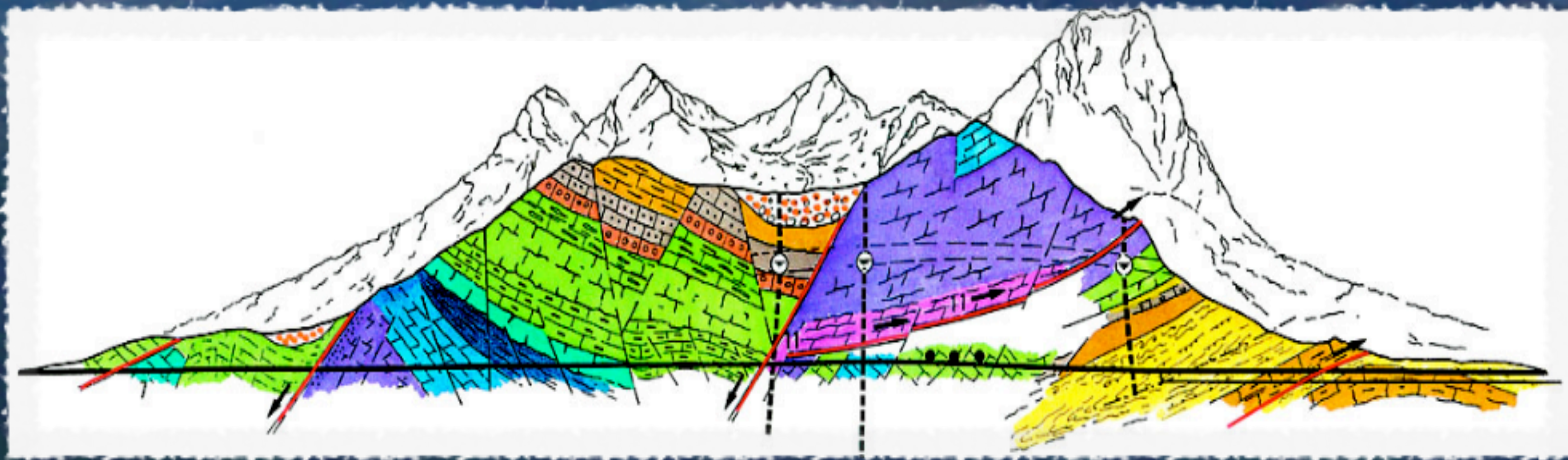


@ LNGS

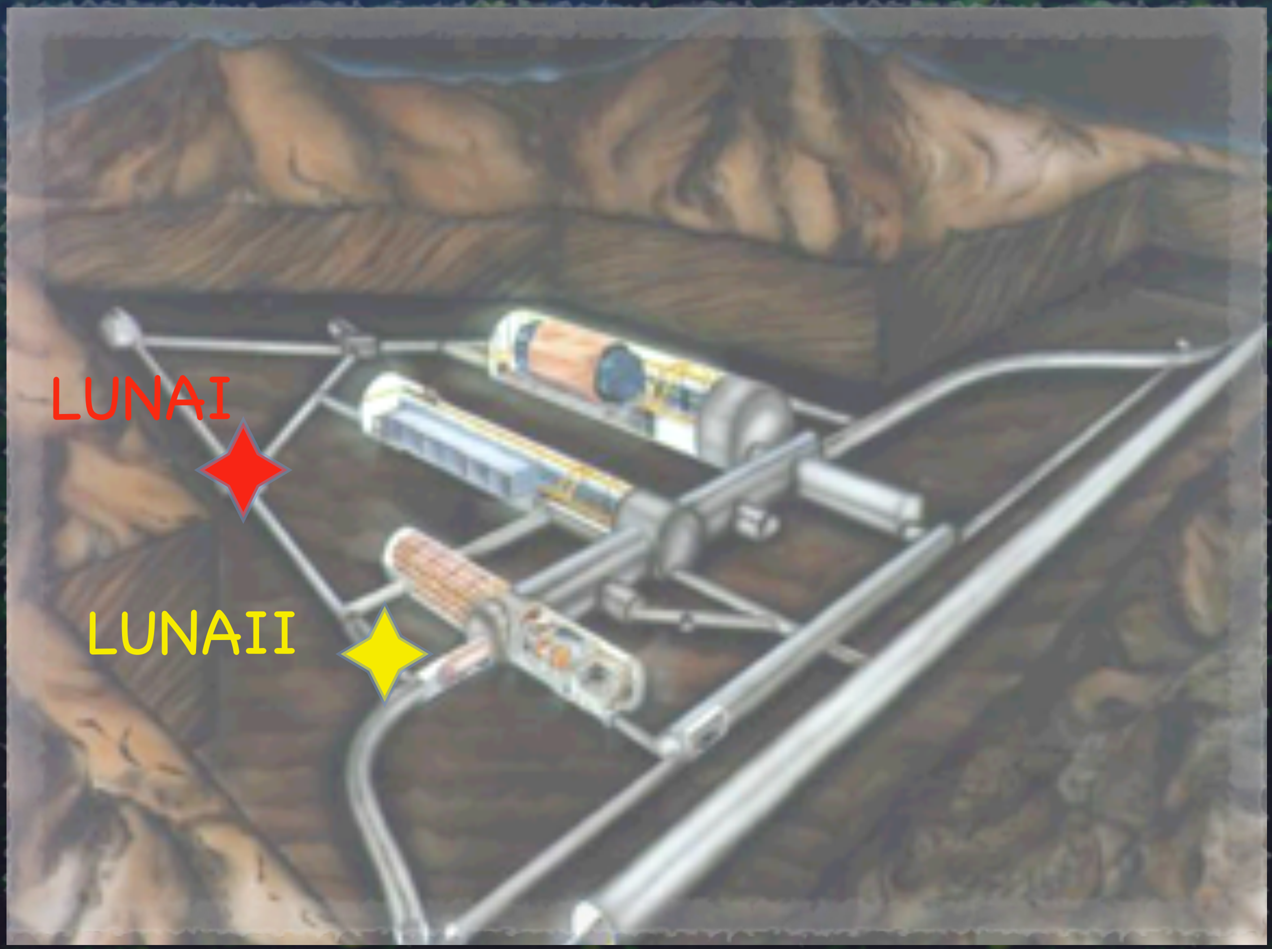
muons: 1 /($m^2 \cdot h$), E > 1 TeV

neutrons: 4 x 10^{-6} $cm^{-2}s^{-1}$ with fission and (α,n)

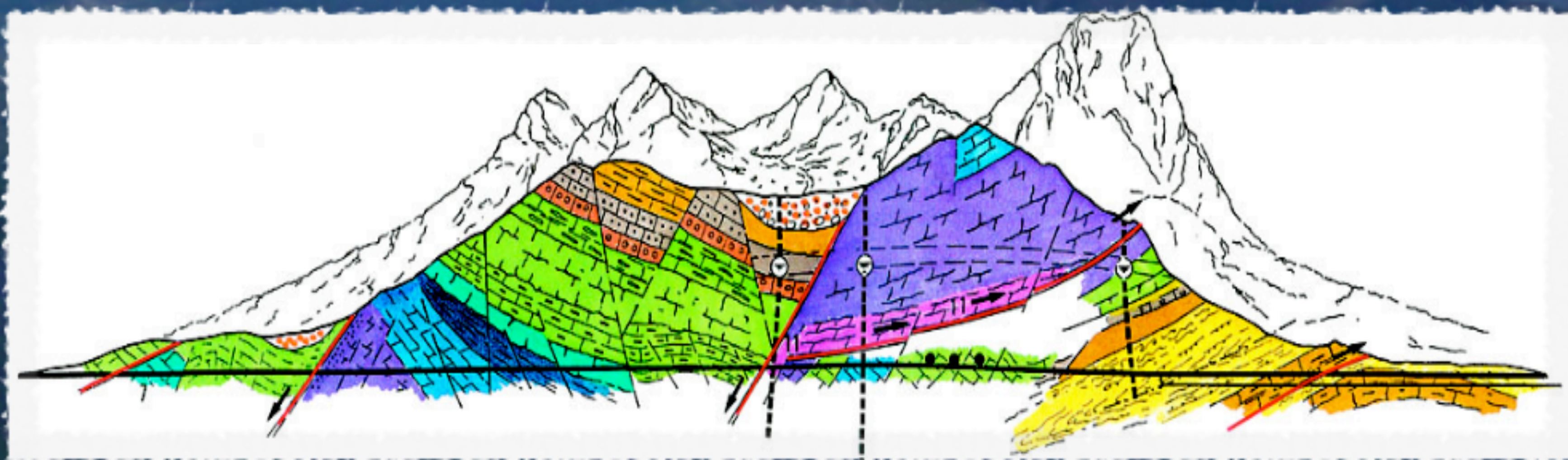
Laboratori Nazionali del Gran Sasso



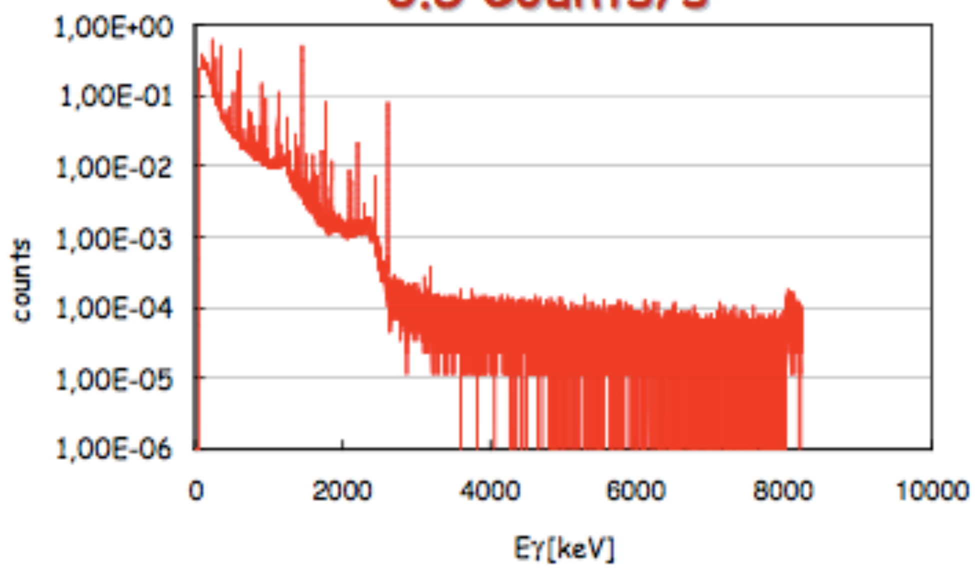
- 1400 m rock overburden
- Flux attenuation: n 10^{-3}
  μ 10^{-6}
- underground area 18000 m^2
- support facilities on the surface



Laboratori Nazionali del Gran Sasso



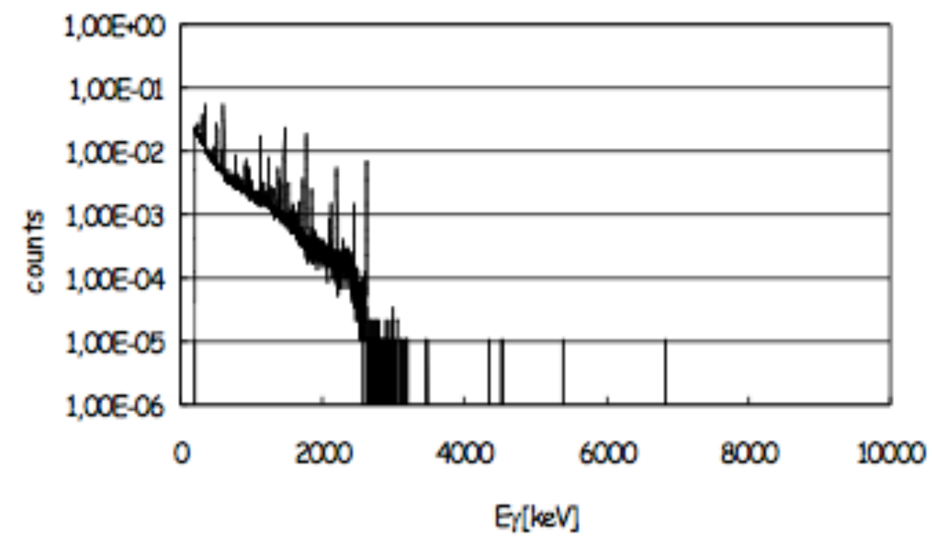
3MeV < Eγ < 8MeV:
0.5 Counts/s



HpGe

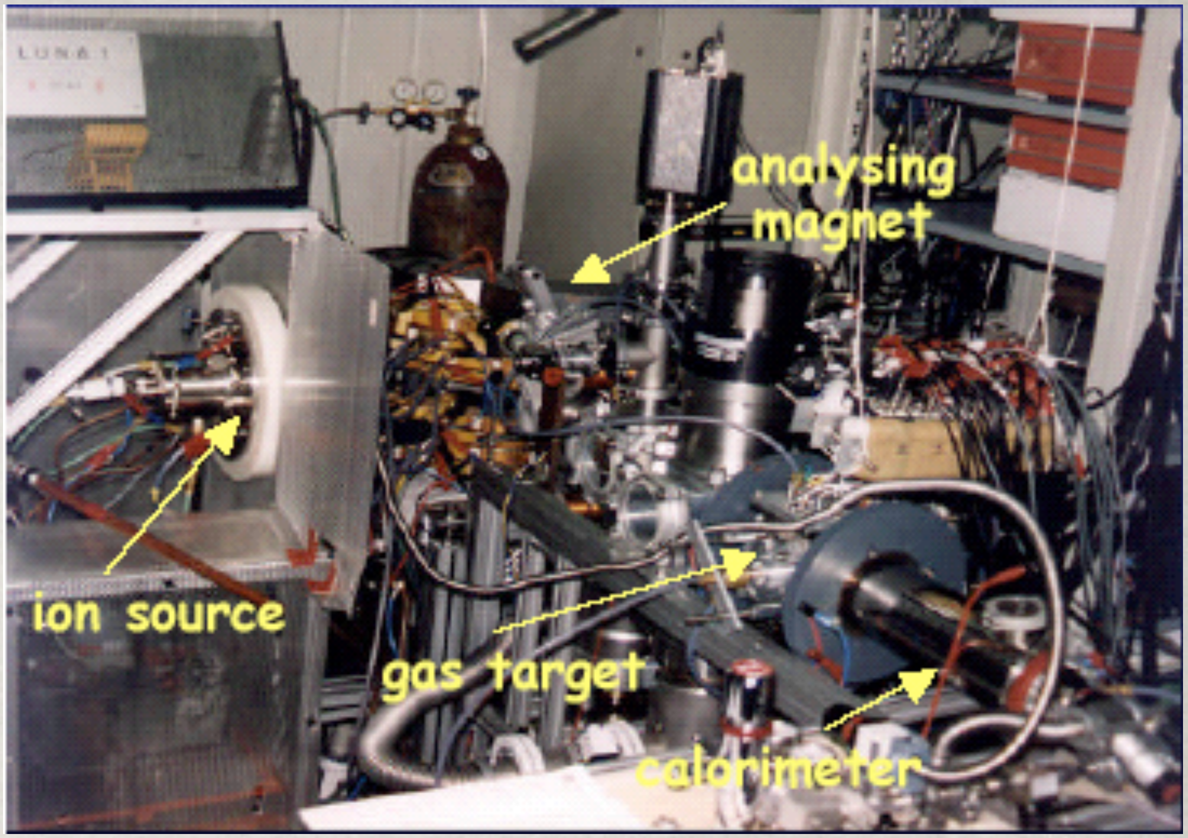
GOING UNDERGROUND →

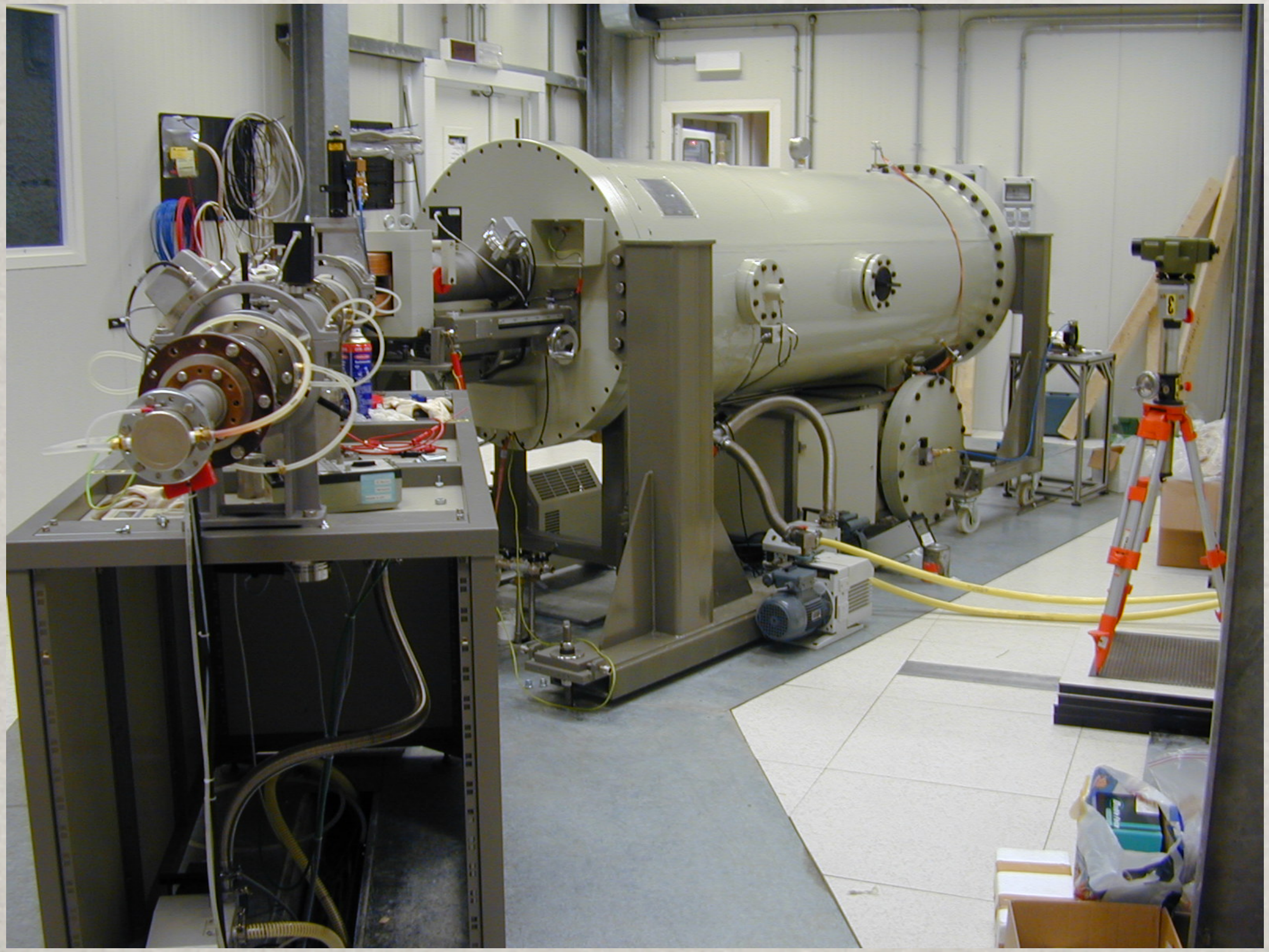
3MeV < Eγ < 8MeV
0.0002 Counts/s



LUNA I

beams = p, α
Current max = 1 mA
Voltage range = 1 - 50 kV
Beam energy spread: 20 eV
Long term stability (8 h): 10^{-4} eV





LUNA II

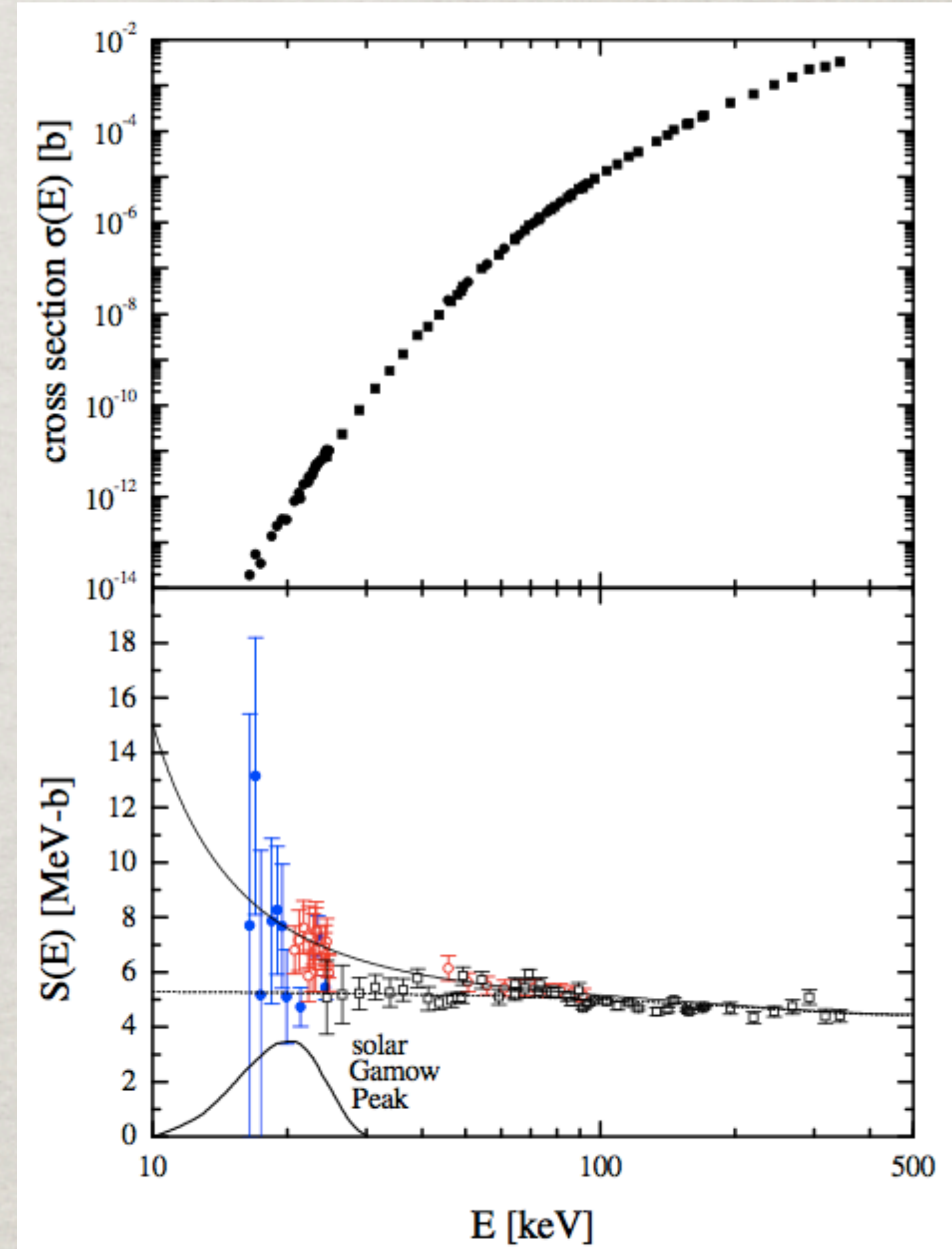
Cockcroft-Walton accelerator
beams = p, α
Current max = 500 μA (protons)
250 μA (alphas)
Voltage range = 50 - 400 kV
Absolute energy error: ±300 eV
Beam energy spread < 100 eV
Long term stability (1 h): 5 eV

Measurements at LUNA I

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

- possible solution of the Solar Neutrino Problem
- cross section measured directly at Gamow energies

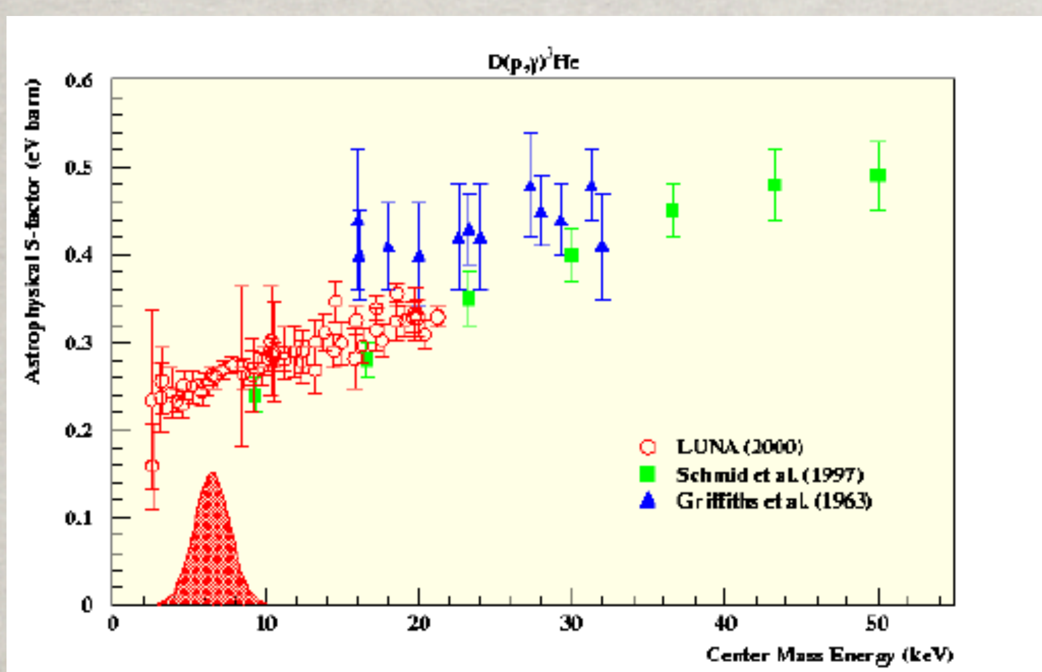
count rate @ lowest energy: 2 cts/month
lowest cross section: 0.02 pbarn
background < $4 \cdot 10^{-2}$ cts/d in ROI



S(0) = 5.32(8) MeVb

R. Bonetti et al., PRL 82 (1999) 26

$p + d \rightarrow {^3He} + \gamma$



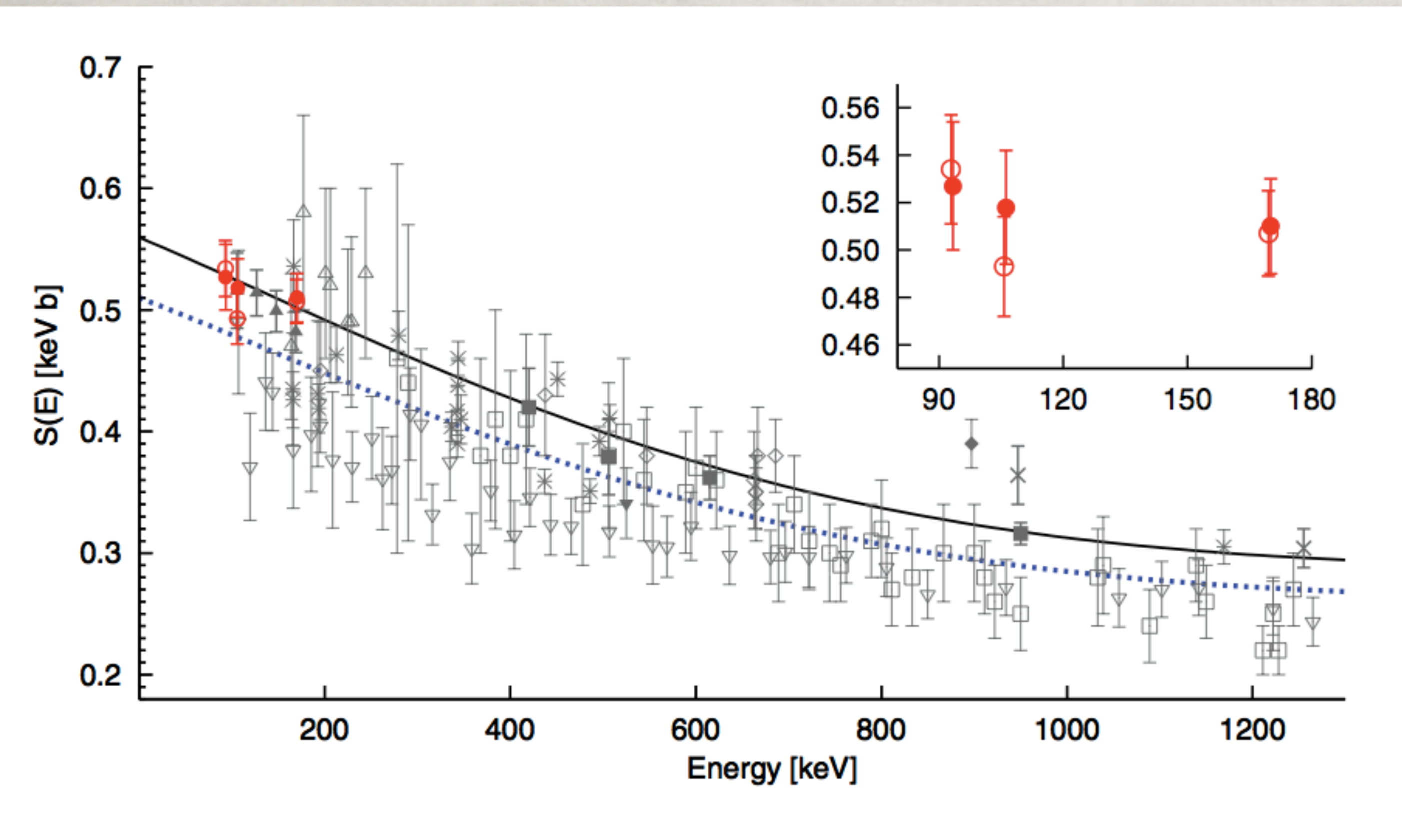
C. Casella et al., NPA 706 (2002) 203

NO EXTRAPOLATION NEEDED !

Measurements at LUNA II

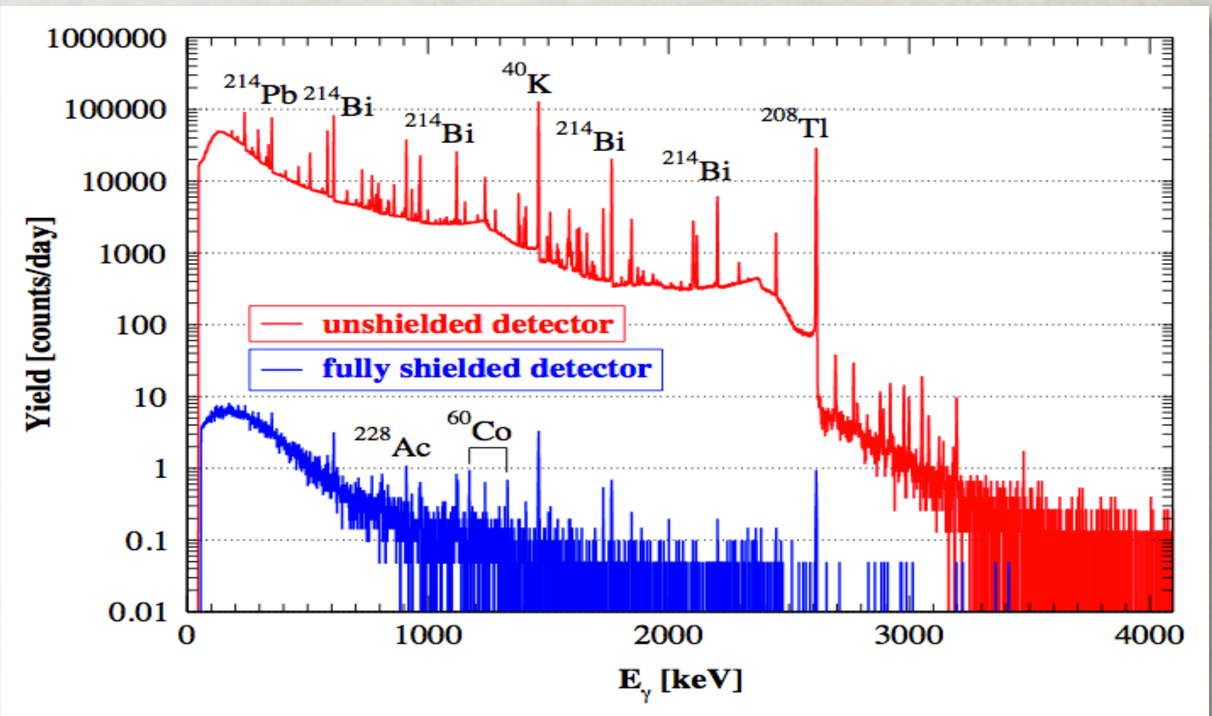
$^3He + ^4He \rightarrow ^7Be + \gamma$

* key reaction in the p-p chain for ^7Be e ^8B neutrinos in the Sun
* fundamental for ^7Li in BBN
* gamma-prompt and activation method



$S_{3,4}(0)$ = 0.560(17) keVb

F. Confortola et al., PRC 75 (2007) 065803



A. Caciolli et al., EPJA 39 (2009) 179

Measured background attenuation factor for the $^3He(\alpha,\gamma)^7Be$ setup is ~ **10^{-5}** !!!
(i.e. **1.9** and **0.8 counts/day** with ΔE = 20 keV)

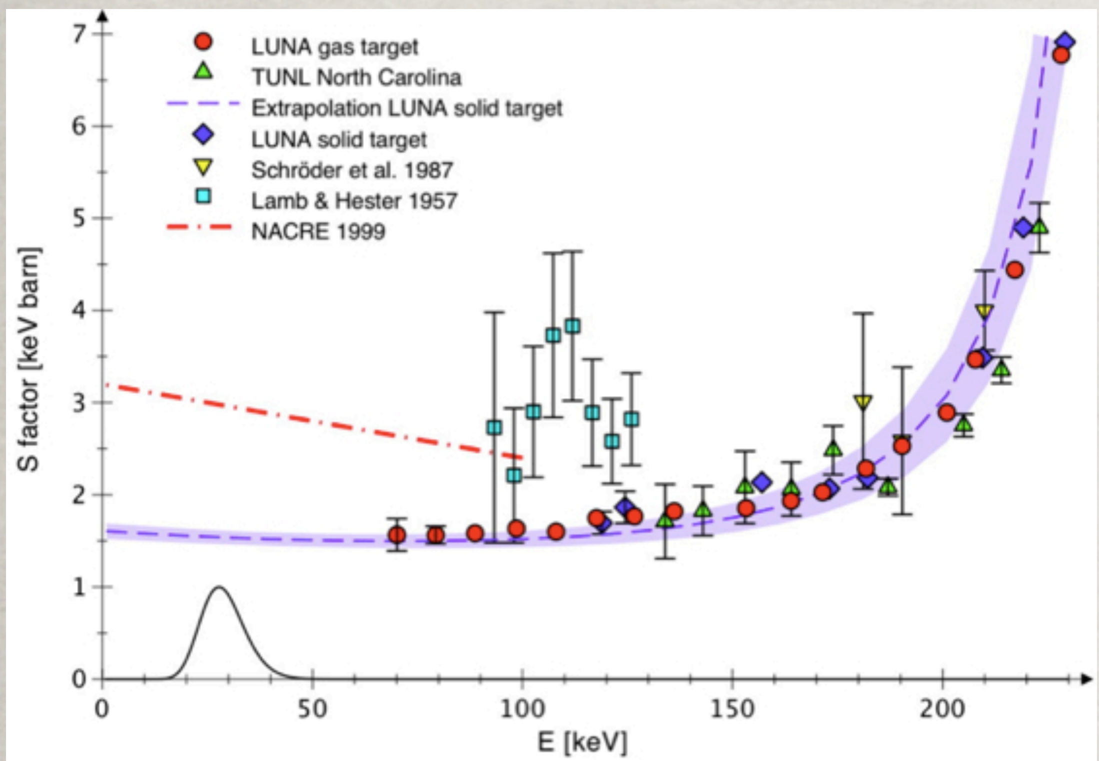
Uncertainties on the neutrino fluxes

^8B -> from 12% to 10%

^7Be -> from 9.4% to 5.5%

CNO cycle

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

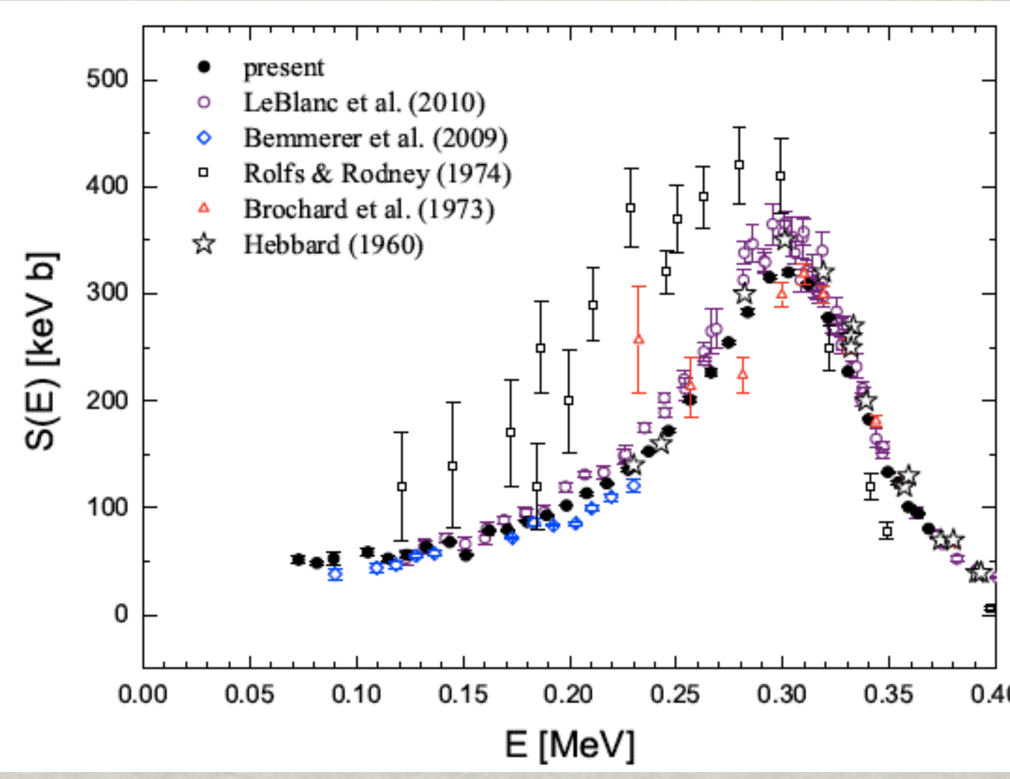


M. Marta et al., PRC 83(2011)045804

Bottleneck of the CN cycle studied both with solid and gas target

- CNO neutrino fluxes reduced by a factor of 2
- Globular Cluster Age increased by 0.7 - 1.0 Gy
- reduced uncertainties below 8%

$^{15}N(p,\gamma)^{16}O$



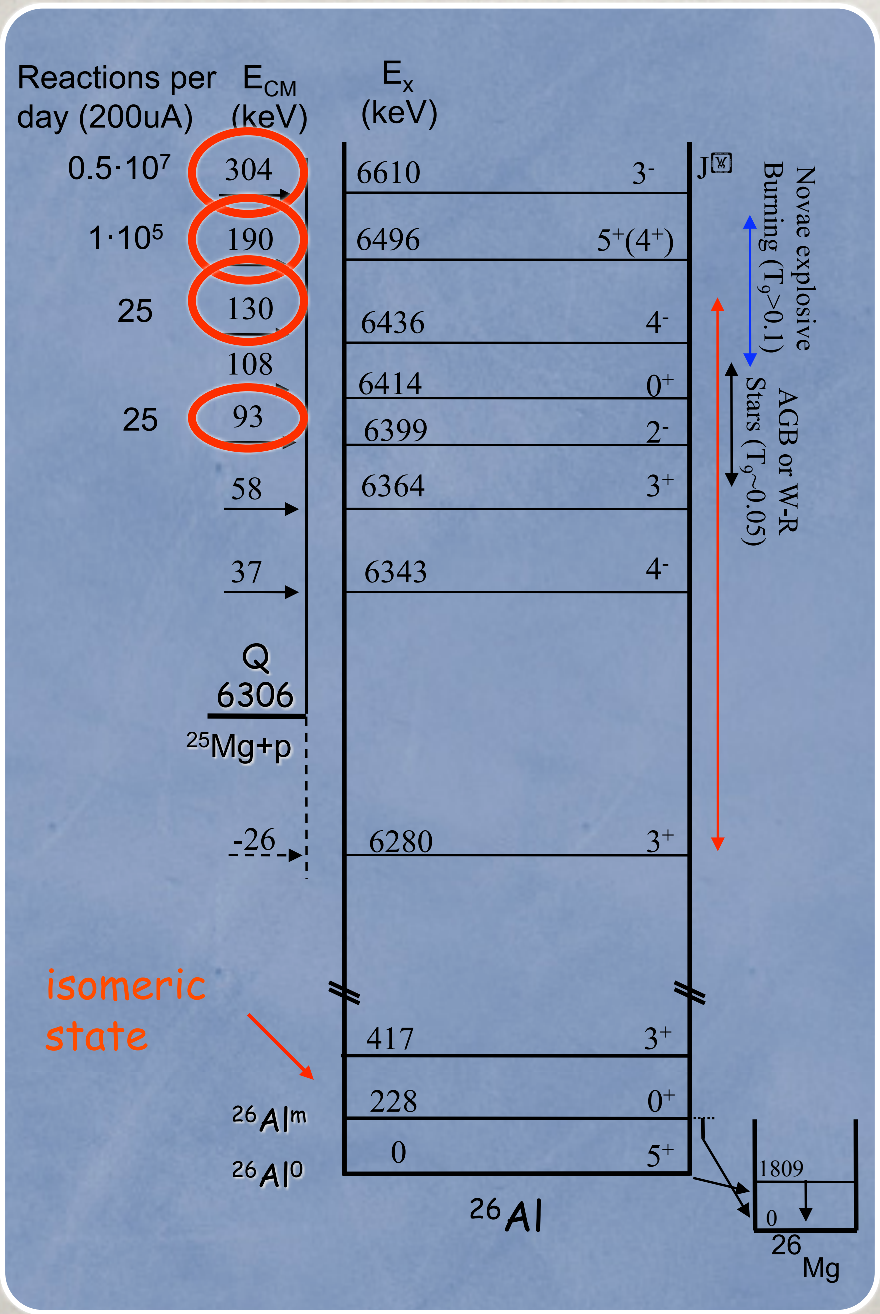
A. Caciolli et al., A&A 533(2011)A66

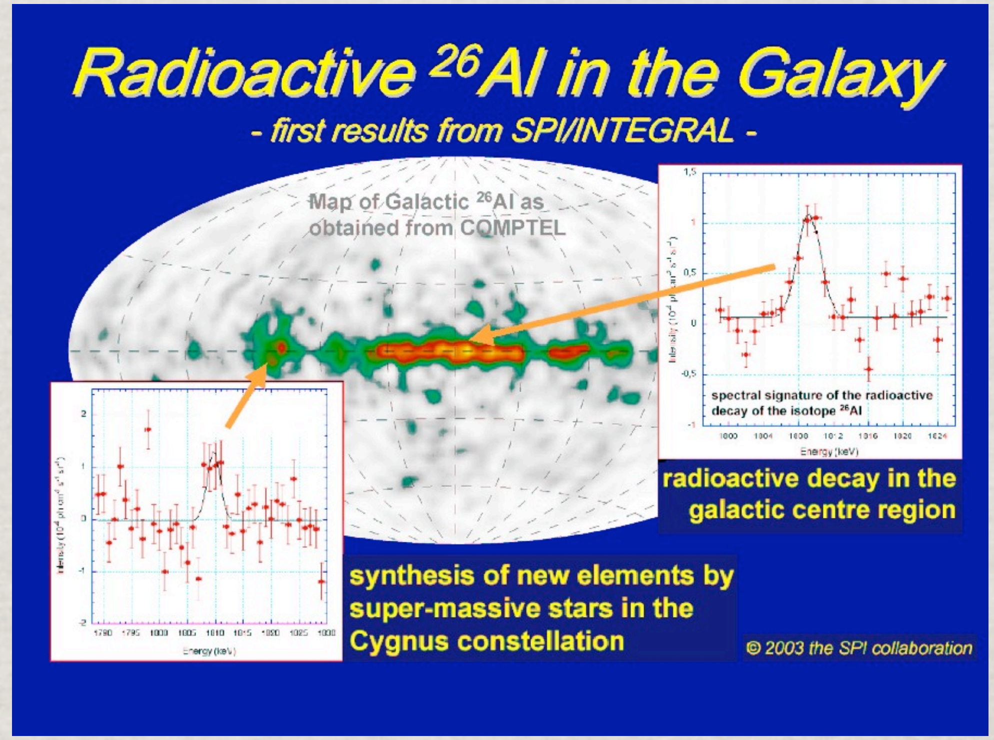
Link the first and second CNO cycles

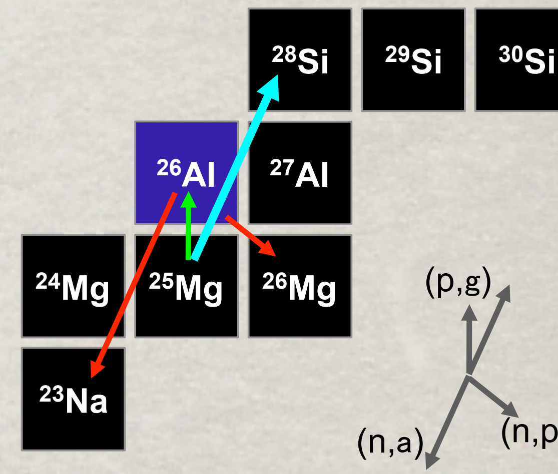
- totally covered the Nova Gamow peak
- reduced the S-factor by a factor of 2
- reduction ^{16}O produced by novae explosions

Mg - Al cycle

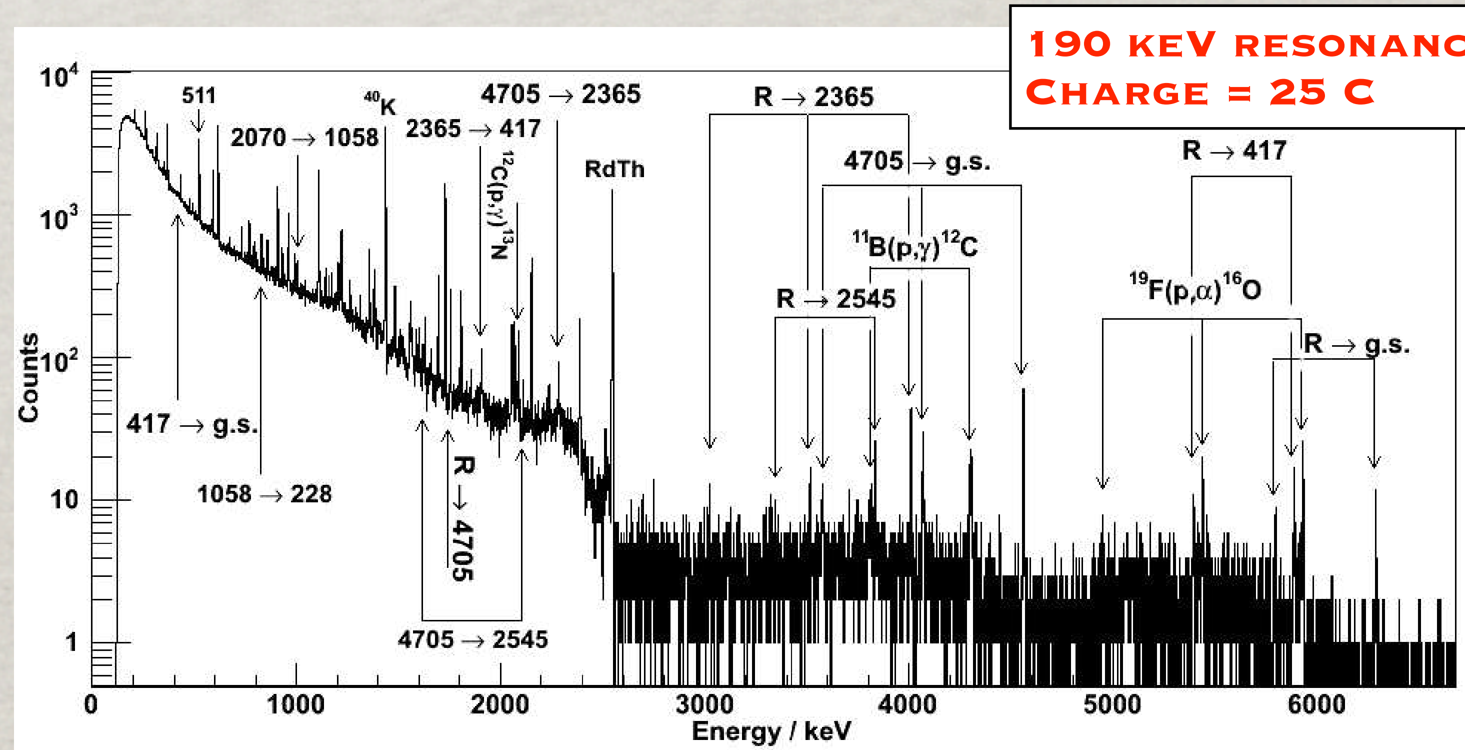
$^{25}Mg(p,\gamma)^{26}Al$







190 keV resonance
Charge = 25 C

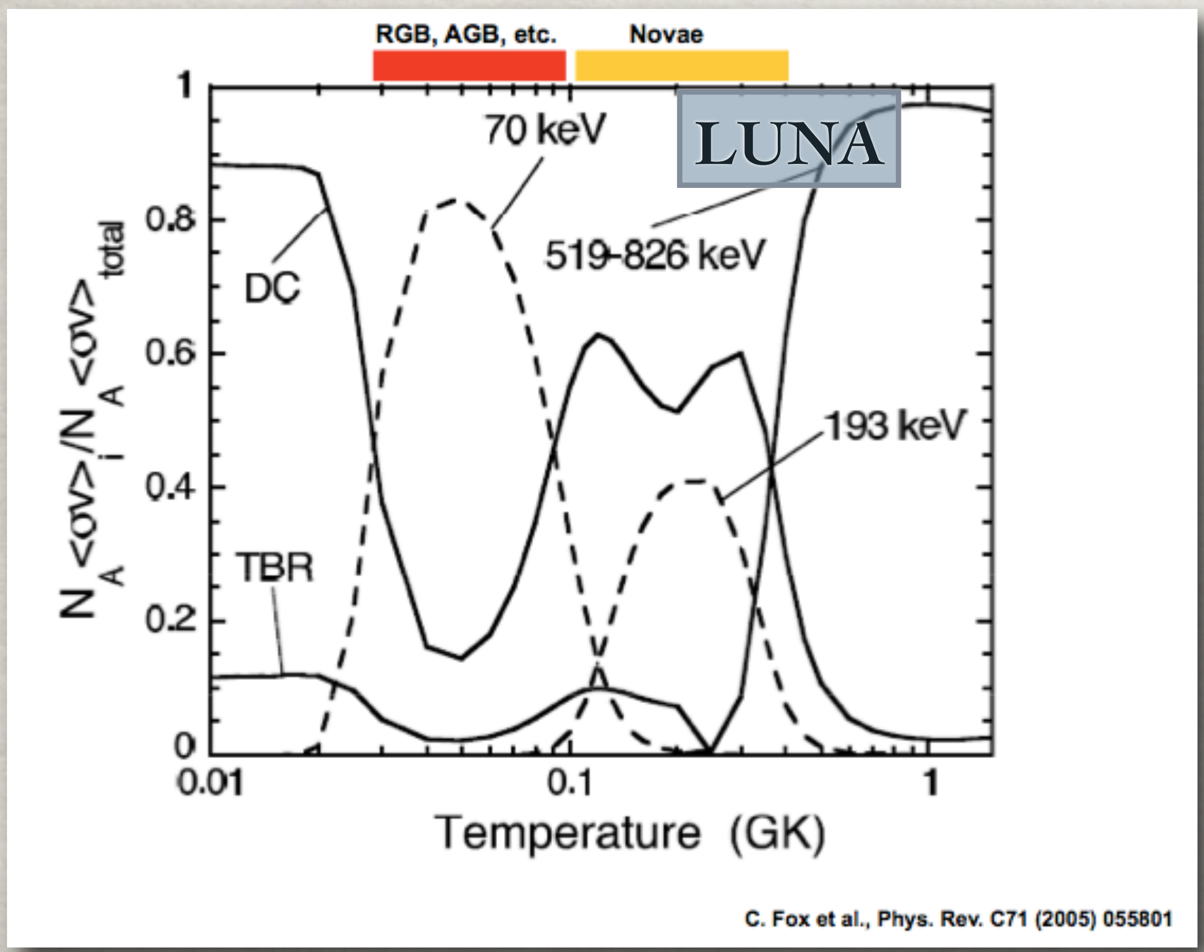


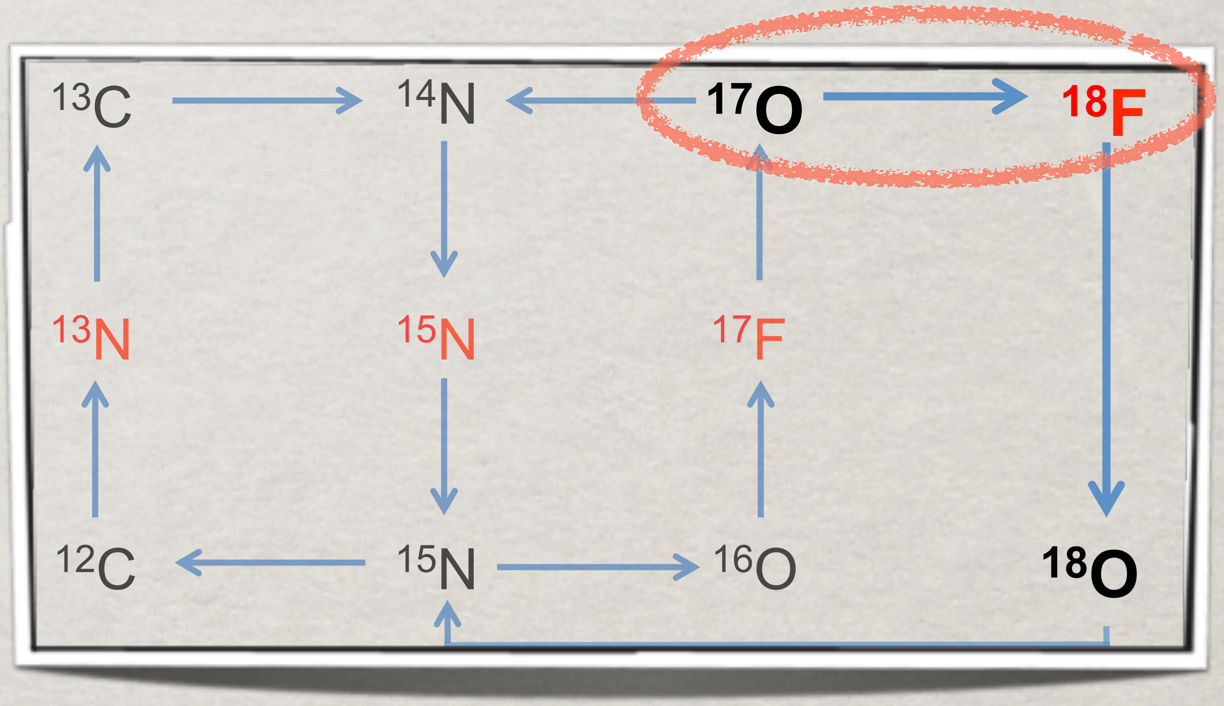
B. Limata et al., PRC 82 (2010) 015801

Recent activity: $^{17}O(p,\gamma)^{18}F$

$^{17}O+p$ is of paramount importance for understanding hydrogen-burning in different stellar environments:

- AGB and RGB stars
- massive stars
- classical novae

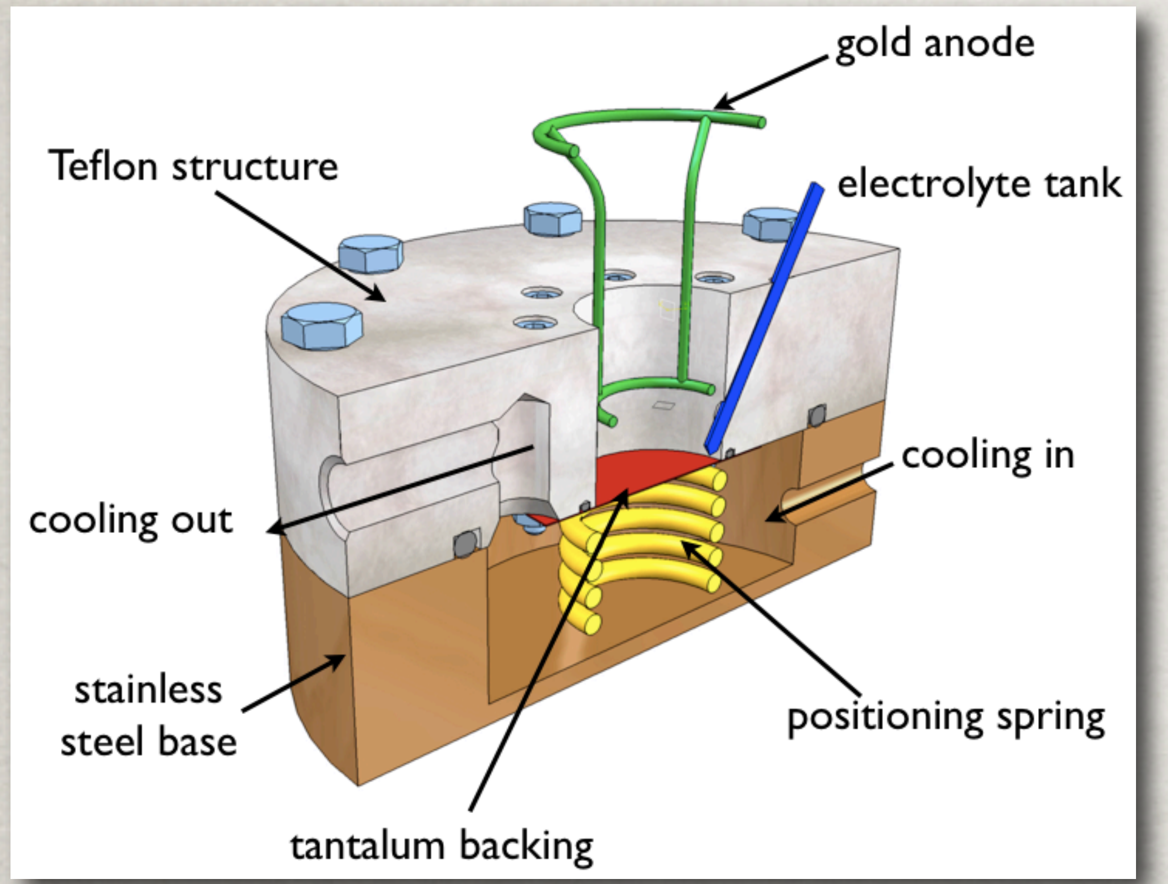




It is important for galactic synthesis of ^{17}O, ^{18}F, and predicted O isotopic ratios in presolar grains.

It affects directly the production of ^{17}O, ^{18}O, ^{18}F, and ^{19}F in Classical Novae

TARGET PREPARATION



Ta_2O_5 targets

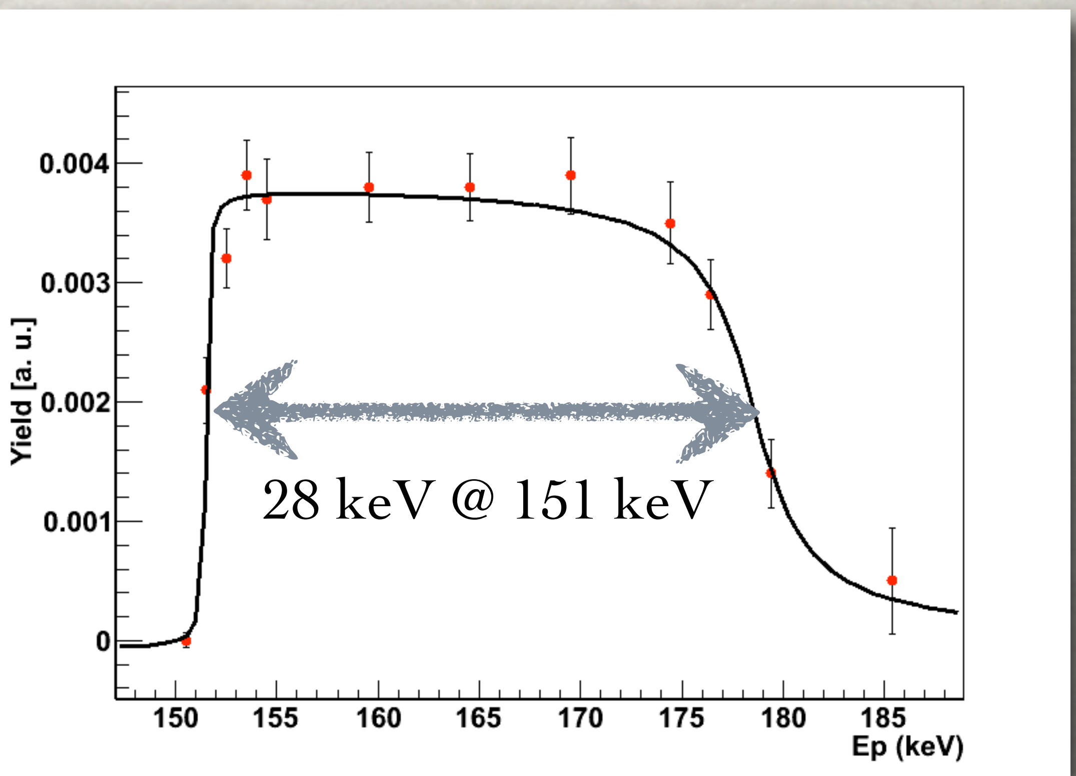
^{17}O enrichment up to 69% (with 5% ^{18}O)

Backing treated with citric acid and cooled to 25 °C during the anodization process

Stoichiometry and isotopic ratio from 151 keV $^{18}O(p,\gamma)^{19}F$ resonance scans, RBS and SIMS measurements

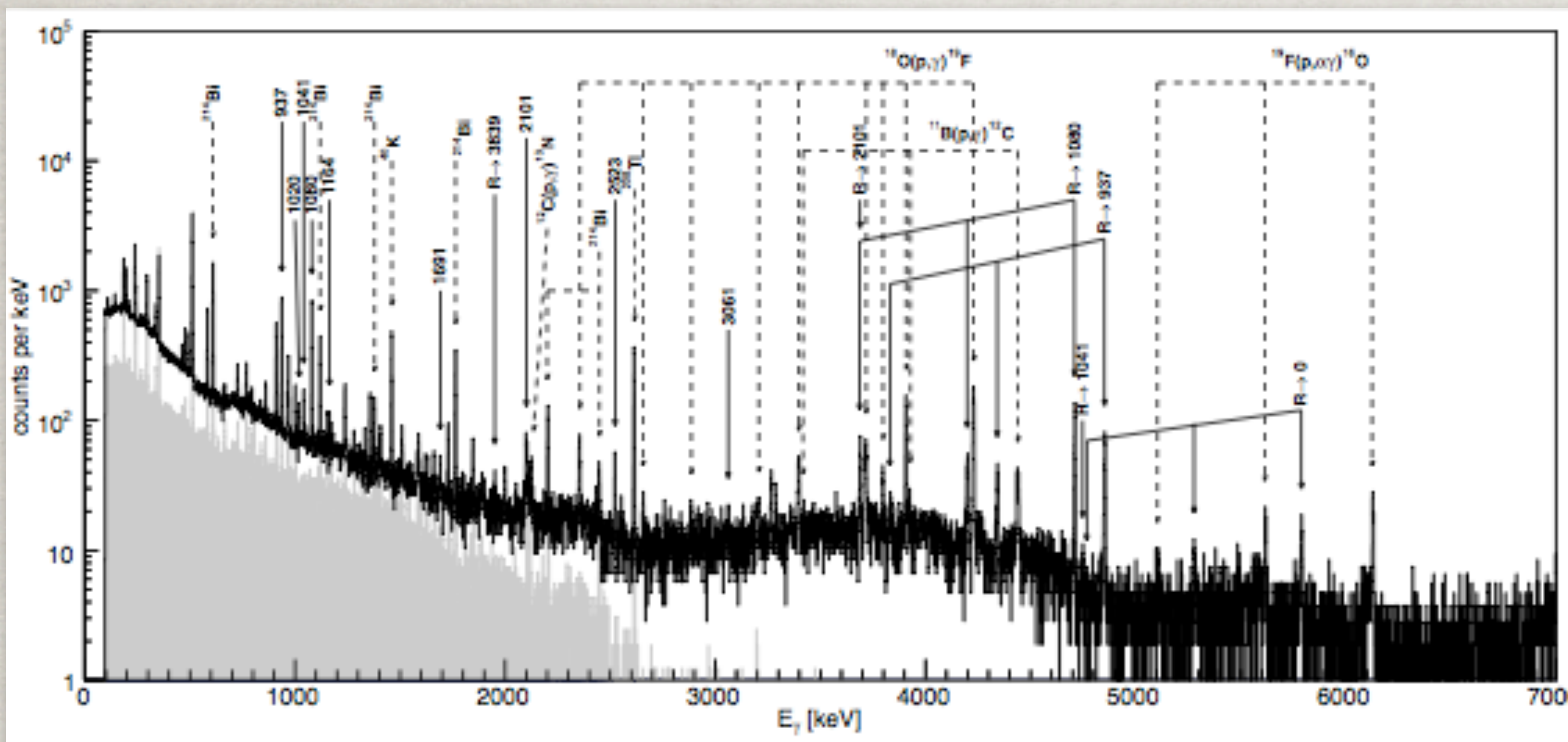
Targets stable up to ~ 20 C

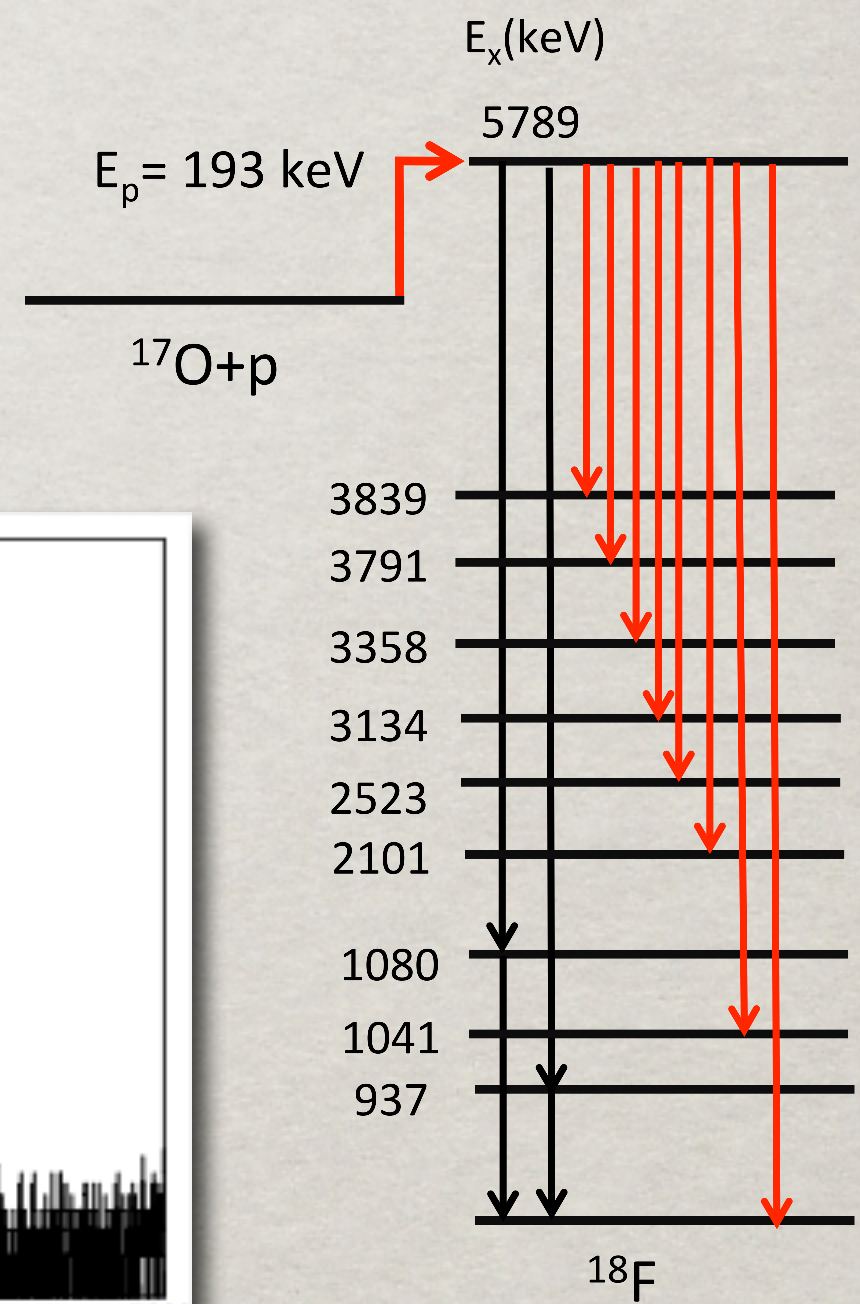
Caciolli et al. EPJA48(2012)144



$^{17}O(p,\gamma)^{18}F$: Prompt Gamma Spectroscopy

- Efficiency measured at three different distances to correct for summing effect
- Lead shielding to reduce the natural background at low γ energies by a factor of 2
- New branchings observed

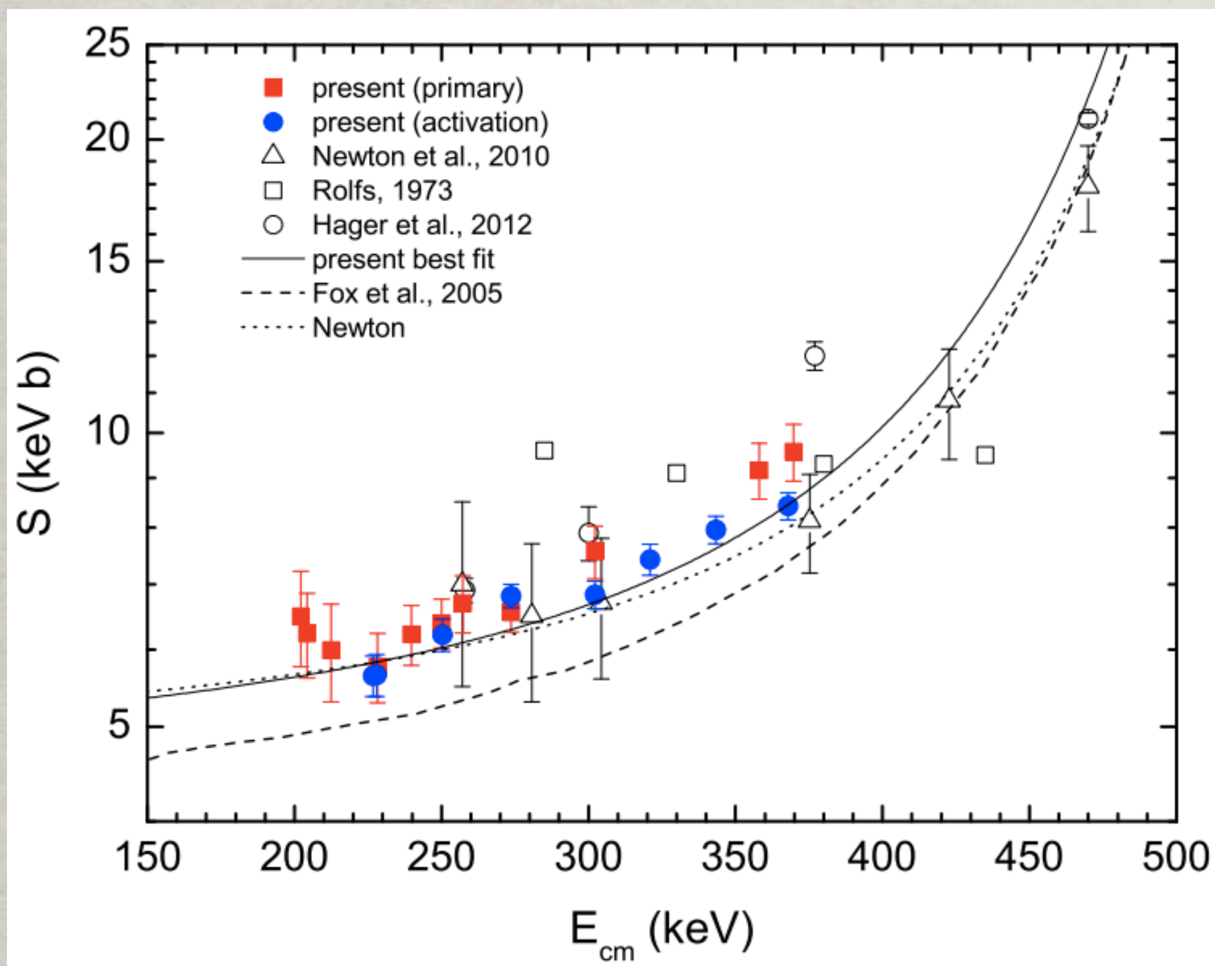


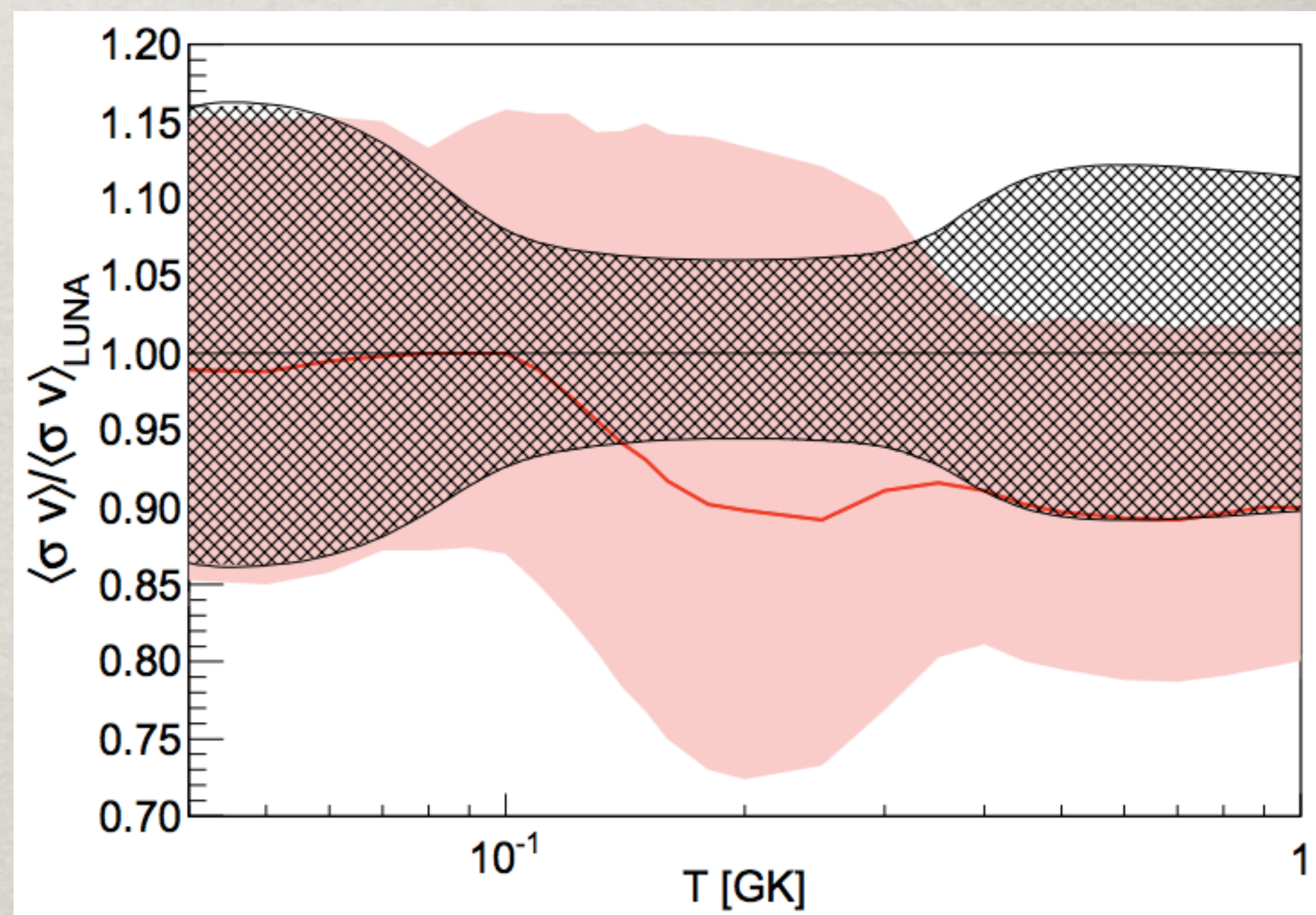


Also measured with activation technique

S-Factor

- S-factor measured for the First time down to 200 keV
- Uncertainty reduced by a factor of 4 with respect to previous works
- Novae Gamow Peak covered totally for the first time with experimental data

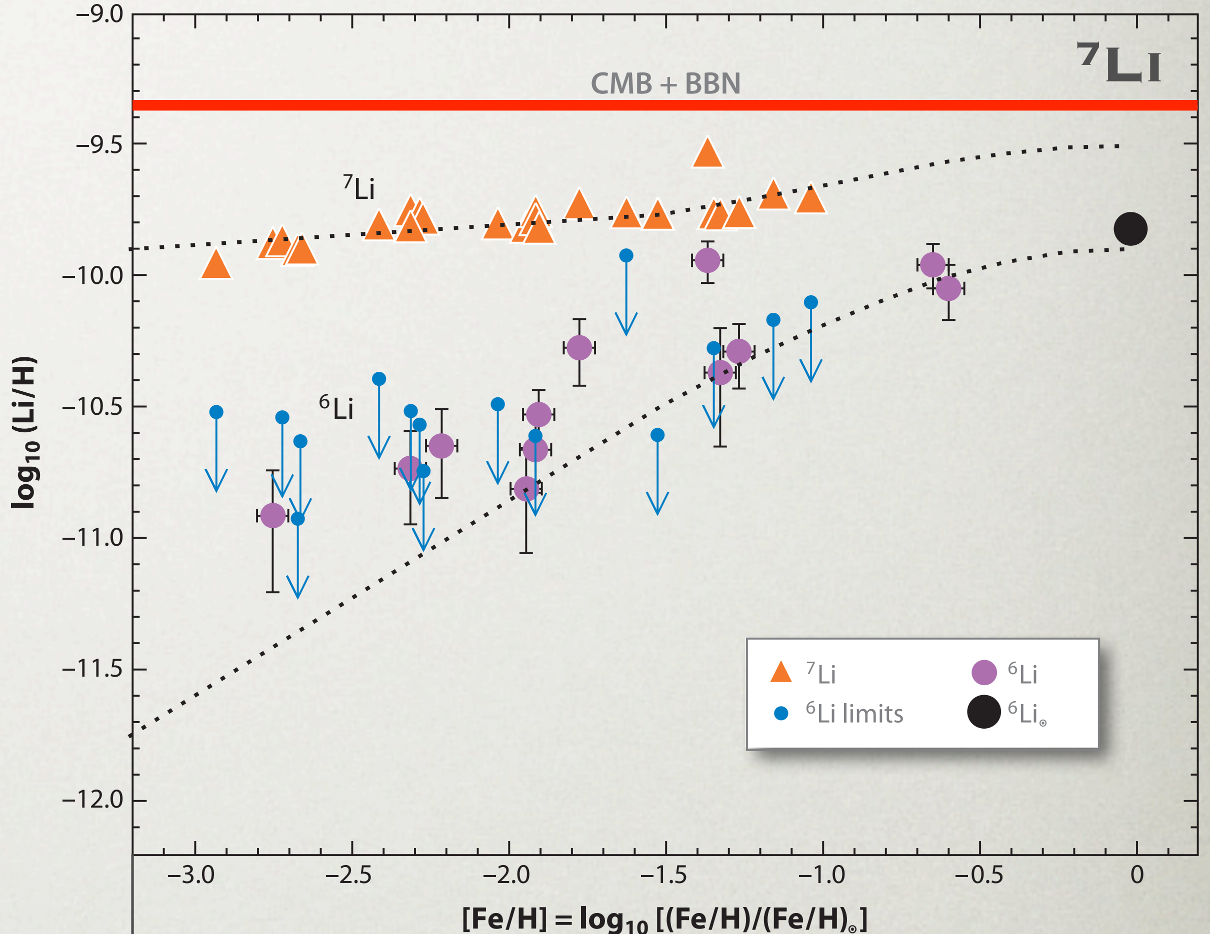




D. Scott et al. PRL 109 (2012) 208001 Editors' Suggestion

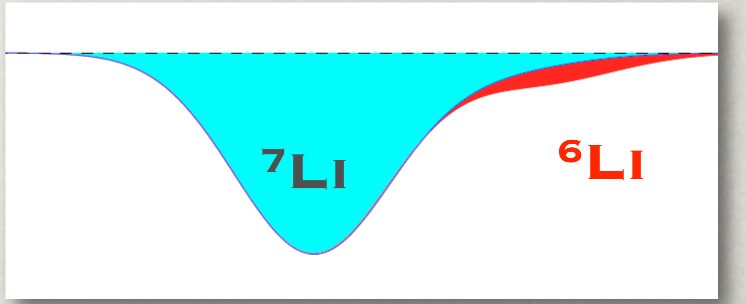
^{6}Li and ^{7}Li nucleosynthesis

Unfolding primordial abundances
Observation of a set of primitive objects, born when the Universe was young, and **extrapolate** to zero metallicity: Fe/H, O/H, Si/H → 0



^{7}Li abundance: observation of the **absorption line** at the surface of metal-poor stars in the halo of our Galaxy

^{6}Li abundance: no direct observation. From the **asymmetry** of the ^{7}Li absorption line



^{7}Li abundance from line intensity
^{6}Li/^{7}Li from line shape

M.Asplund et al. Astrophys. J. 644 (2006)

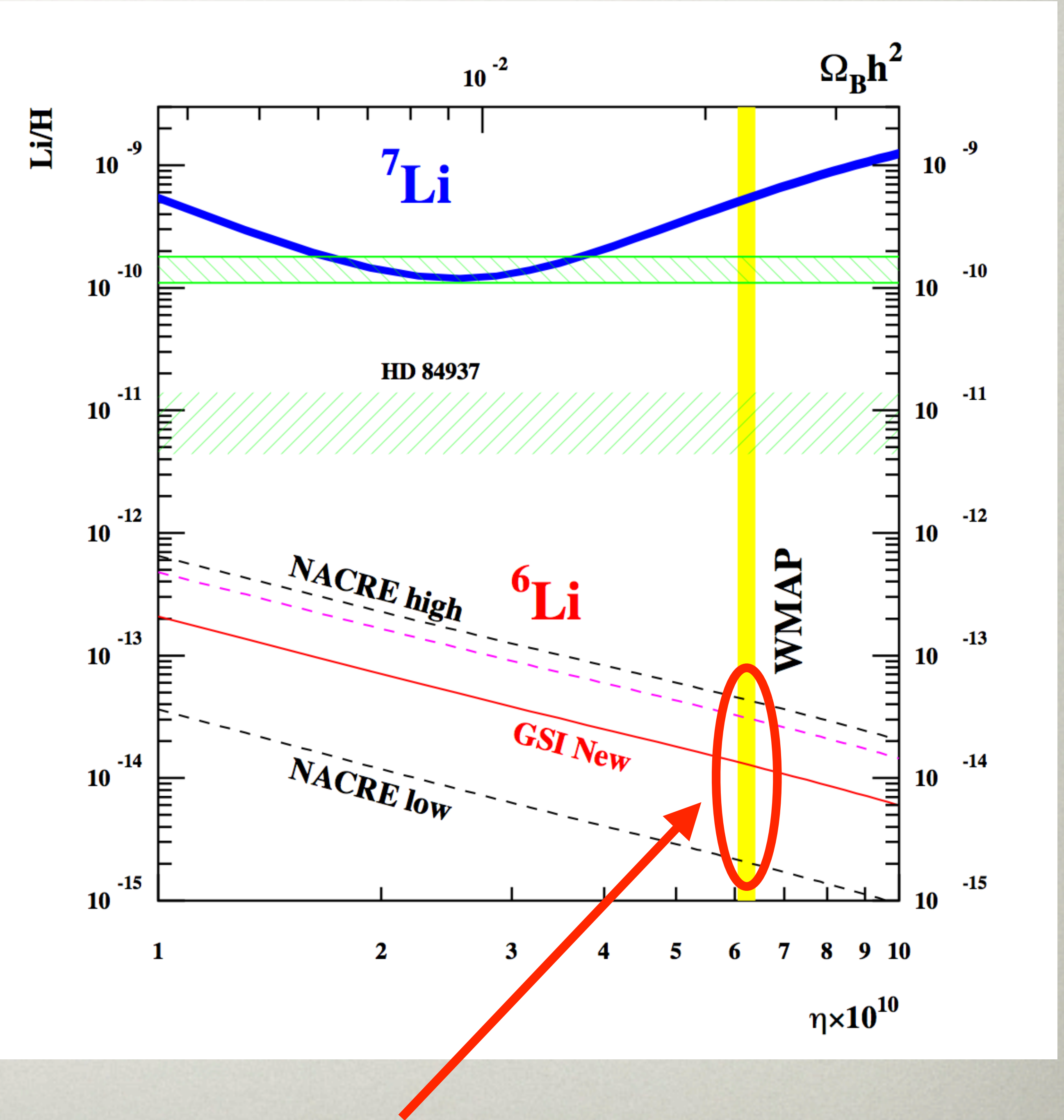
The Li problems

Observational Results:

^{7}Li abundance is 3-4 times lower than foreseen (Spite Plateau): well established ^{7}Li problem

^{6}Li abundance is orders of magnitude higher than expected (Asplund 2006)

However the Second Lithium problem is debated, because convective motions on the stellar surface can give an asymmetry of the absorption line, mimicking the presence of ^{6}Li



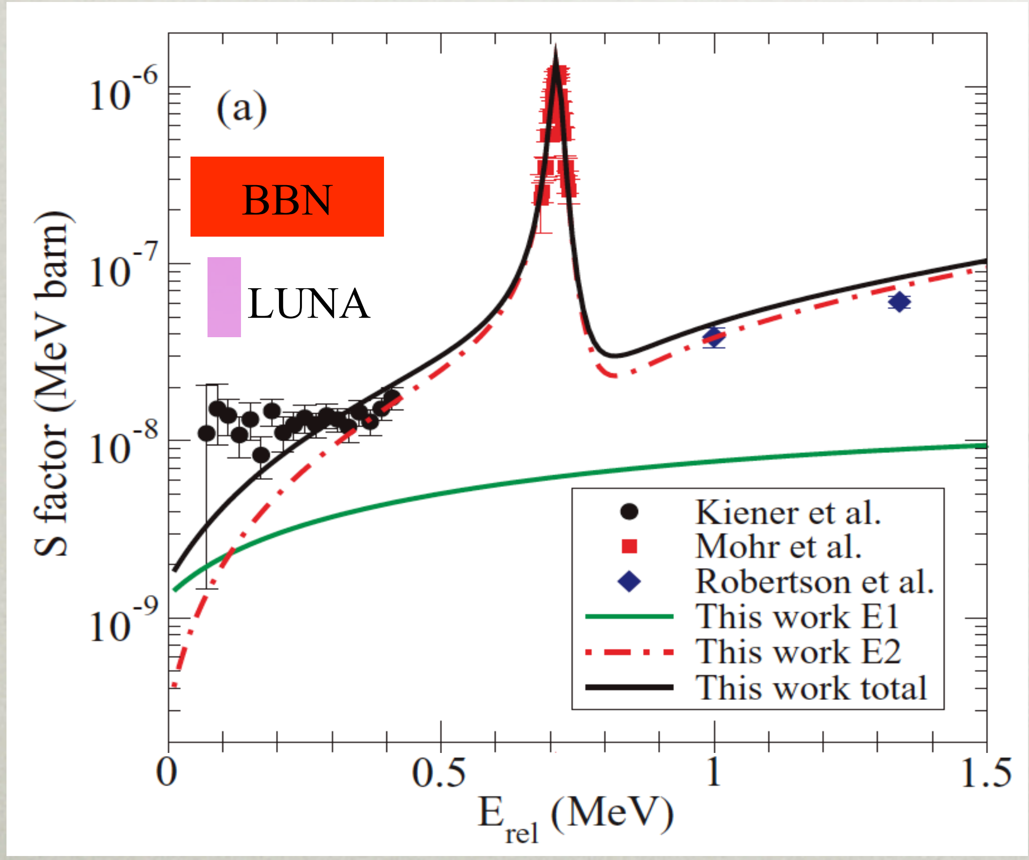
Uncertainty from $^2H(\alpha,\gamma)^6Li$

d(α,γ)^{6}Li reaction

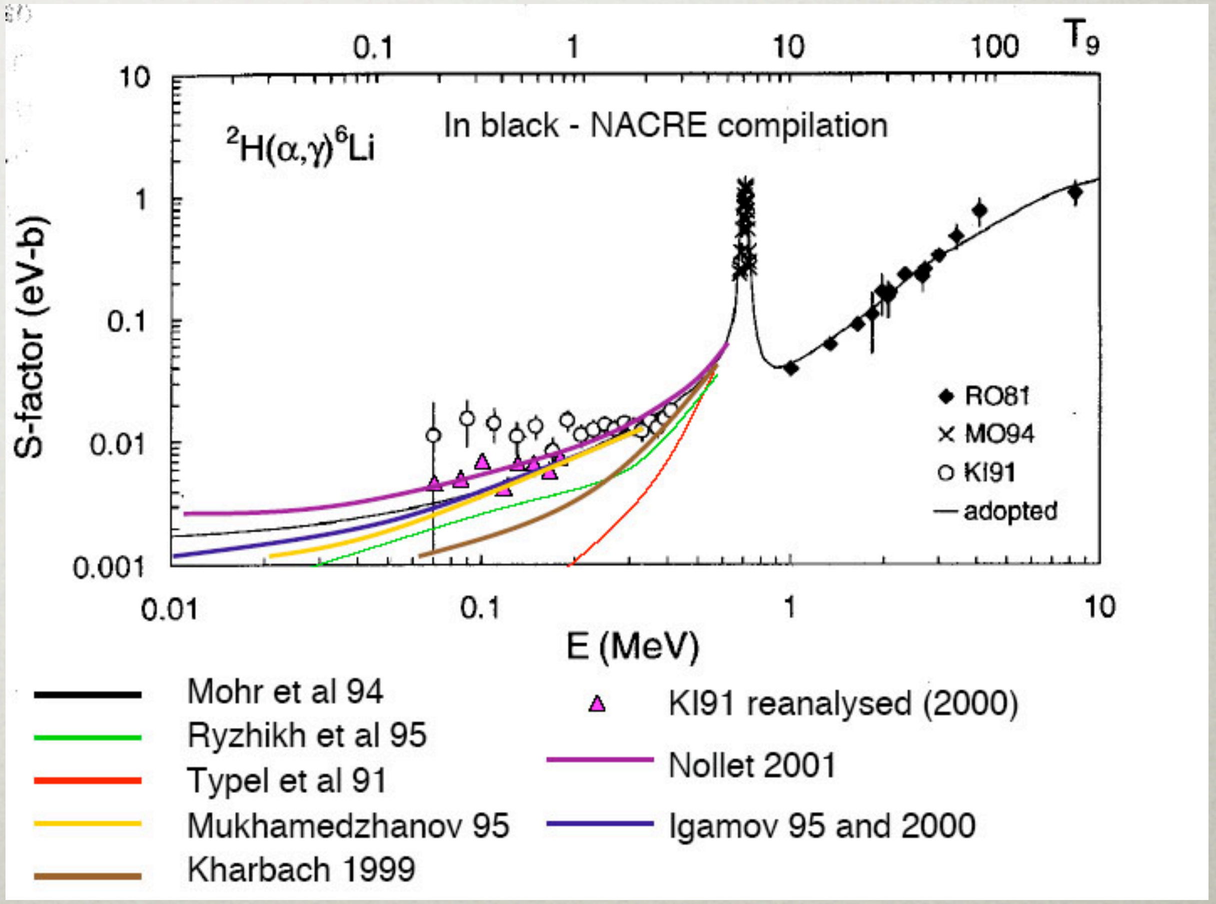
Why is it important ? How much do we know about it ?

- d(α,γ)^{6}Li is the **main reaction** for ^{6}Li production
- In BBN, this reaction occurs at energies in the range **50 < E_{CM} < 400 keV**
- **No direct measurement** exists at **E_{CM} < 650** keV (E_{LAB} < 1950 keV)
- **Theoretical calculations** for the astrophysical S-factor differ by more than one order of magnitude

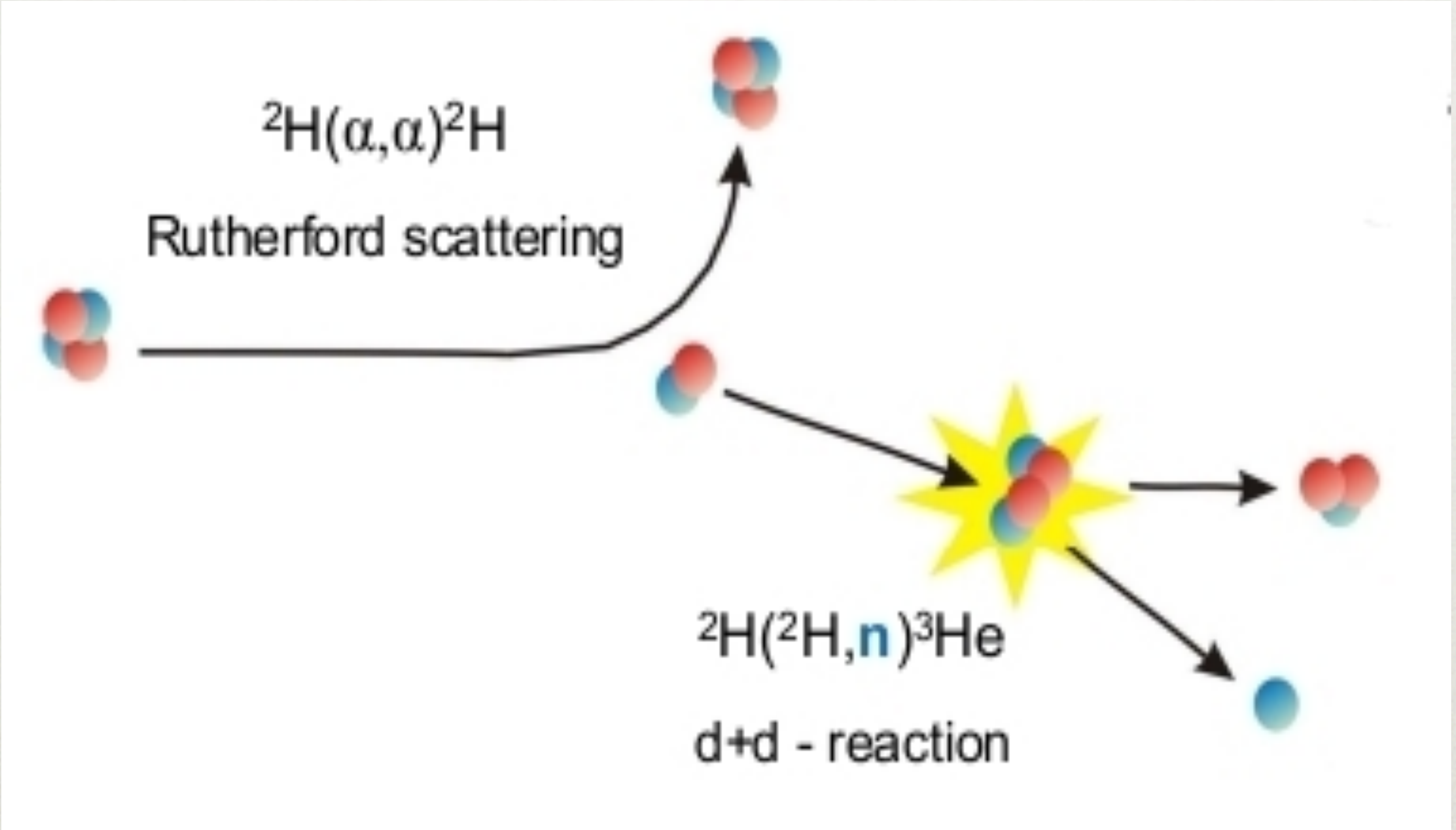
LUNA direct measurement at $E_{CM} \lesssim$ 133 keV



F.Hammache et al. Phys. Rev. C 82 (2010)



Beam Induced Background

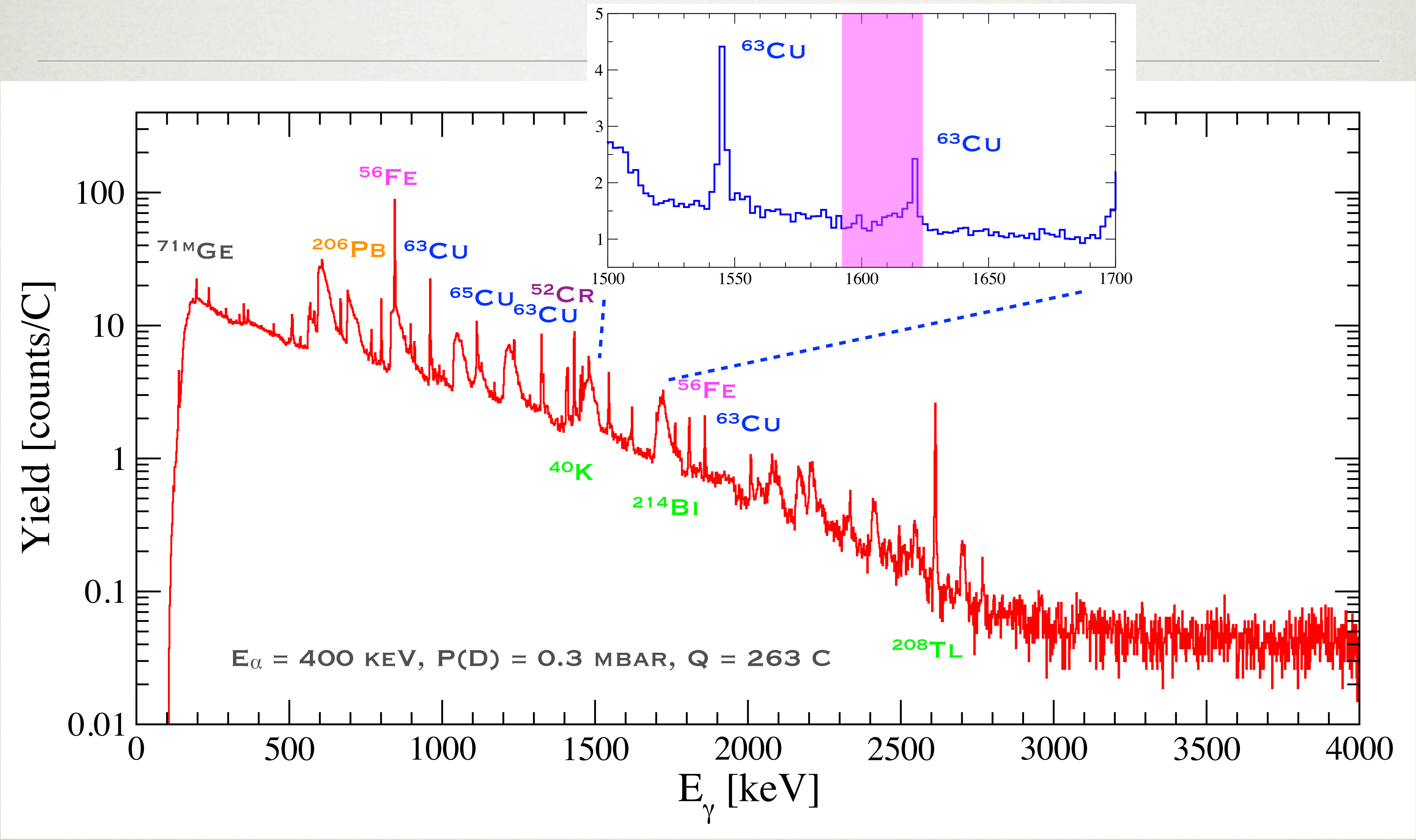


(n,n'γ) reactions on the surrounding materials (Pb, Ge, Cu)

γ-ray background in the ROI for the $D(\alpha,\gamma)^6Li$ DC transition (~1.6 MeV)

LNGS constraints on available beam time and neutron production

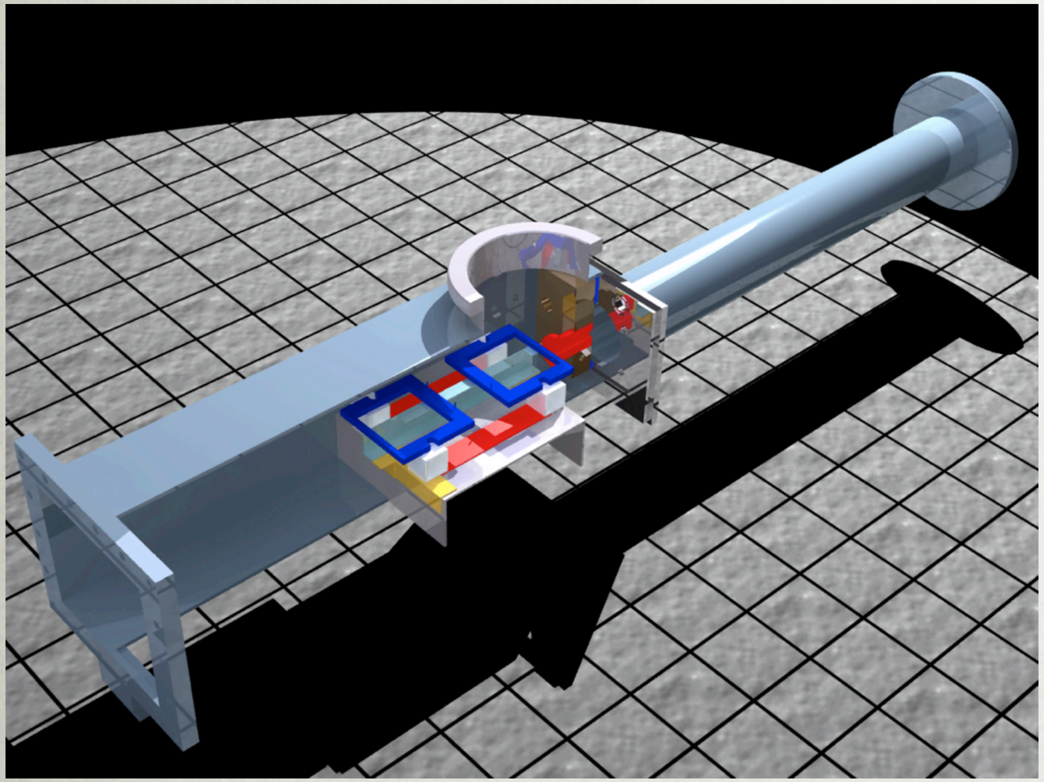
Spectrum from D(α,γ)^{6}Li

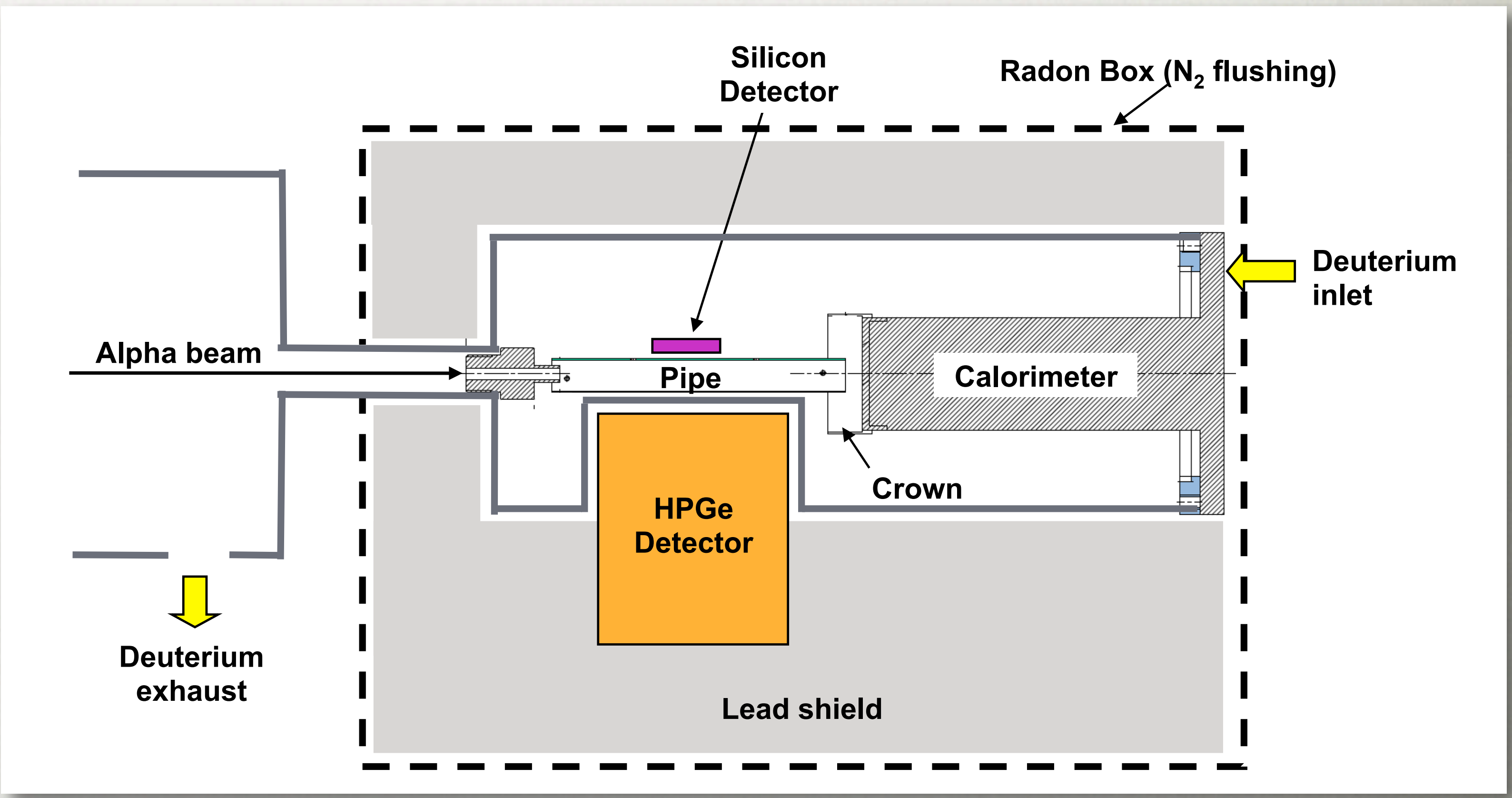


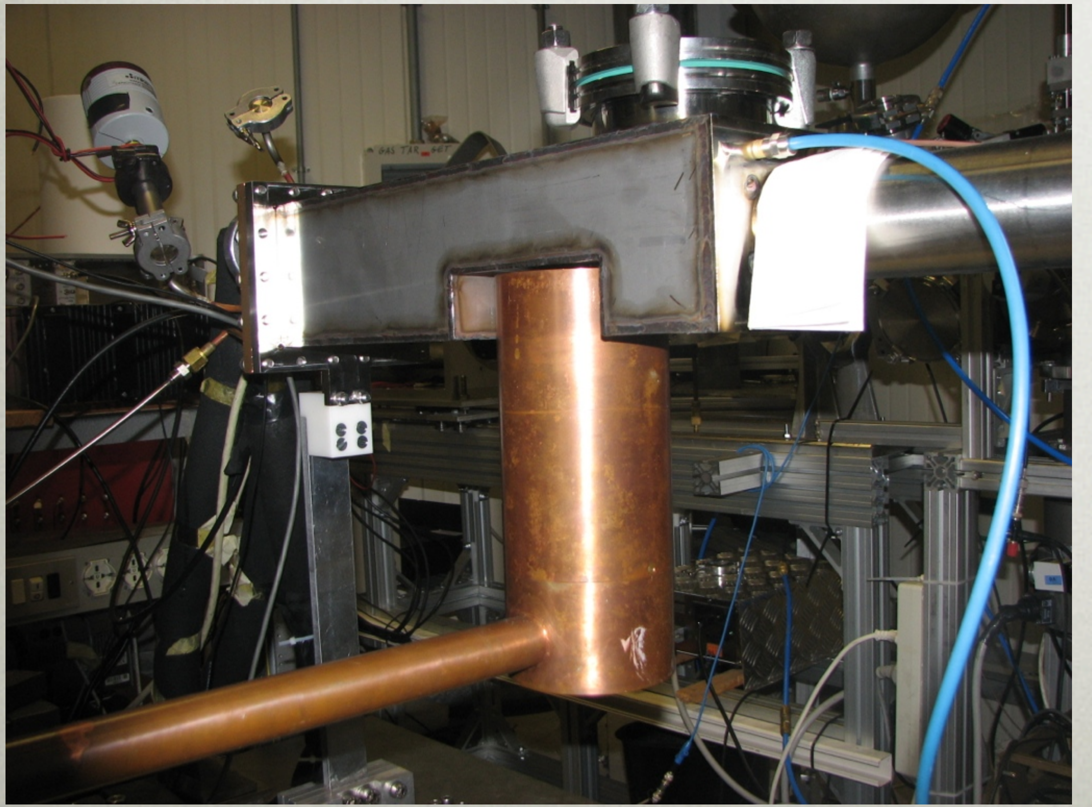
Well understood beam induced background

M. Anders et al., EPJA 49 (2013) 28

Experimental setup





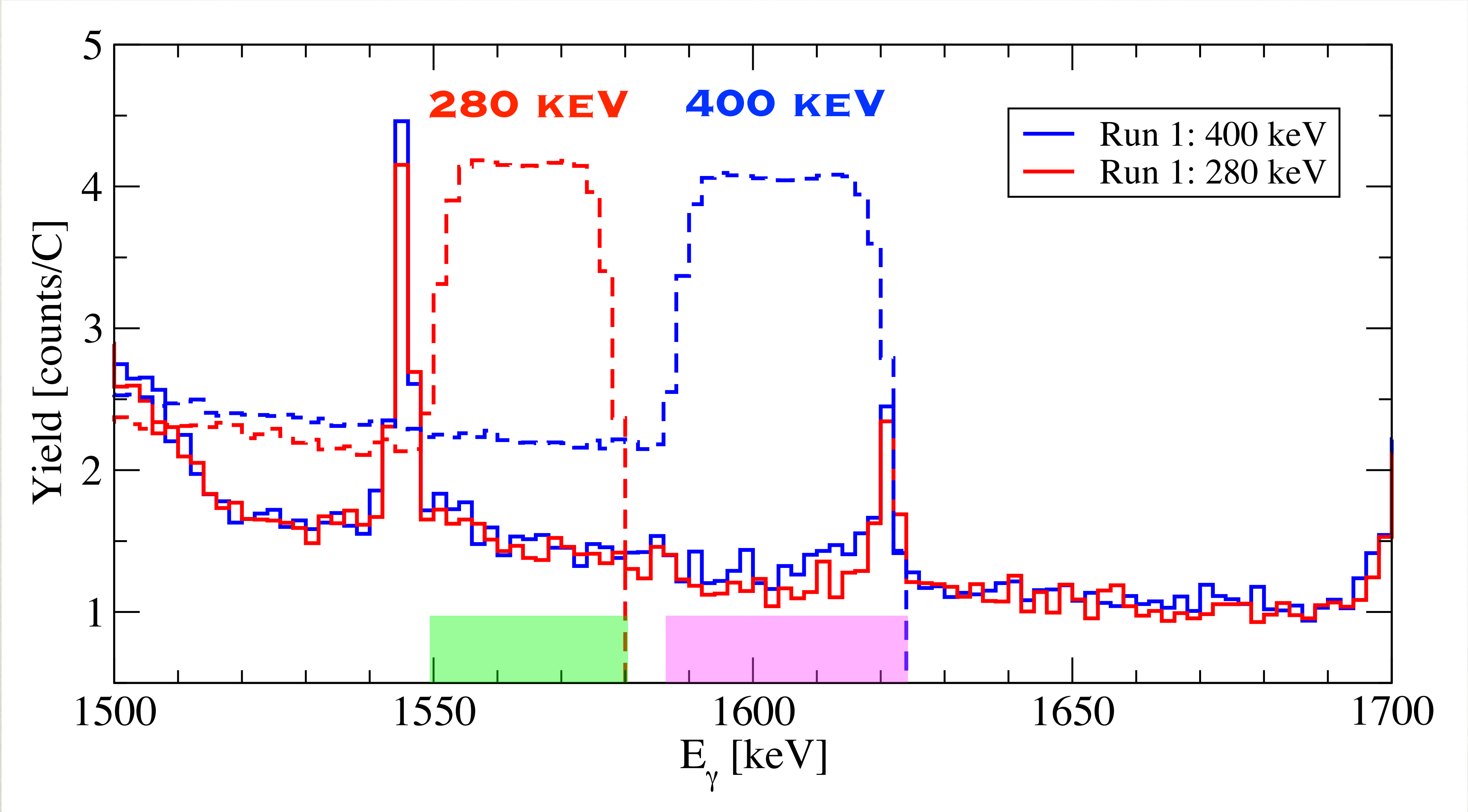


- Germanium detector close to the beam line to increase the **detection efficiency**
- Pipe to reduce the path of scattered deuterium, to **minimize** the **$d(d,n)^3He$ reaction** yield
- Target length optimized
- Copper removal
- **Silicon detector** to monitor the neutron production through the $d(d,p)^3H$ reaction
- Lead, Radon Box to reduce and stabilize Natural Background
- **Borated polyethylene** envelope to reduce neutron contamination

Some results

What should we observe ? A single γ-ray with

E_γ = 1473.48 + E_{CM} ± $E_{DOPPLER}$

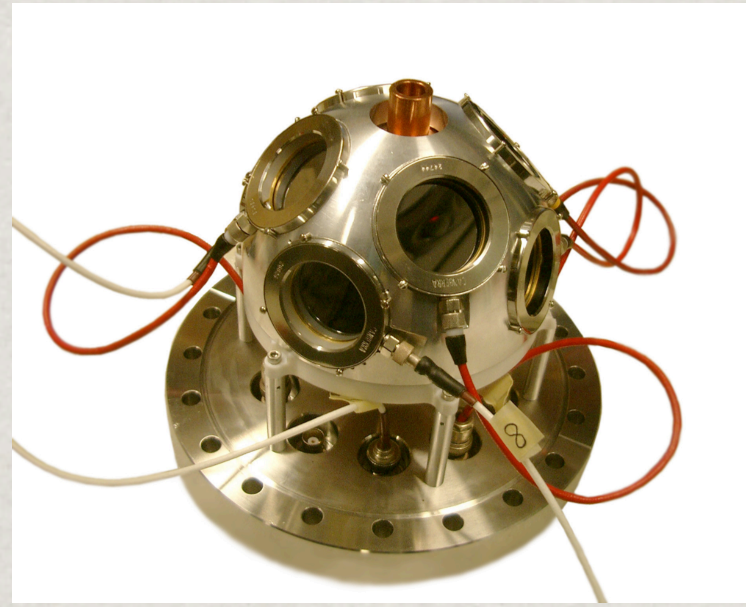


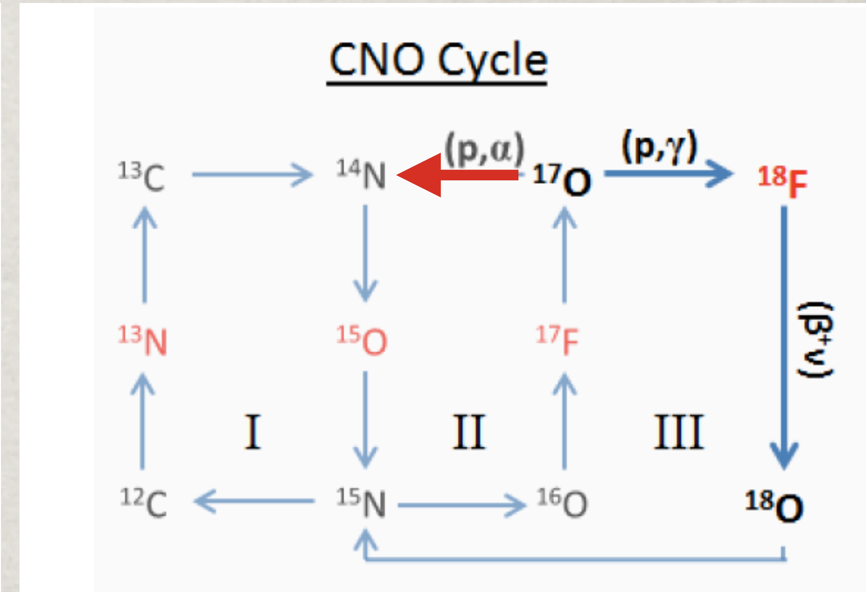
P(D_2) = 0.3 mbar, Q(400) = 263 C, Q(280) = 278 C

The shape of Beam Induced Background spectra weakly depends on the α-beam energy

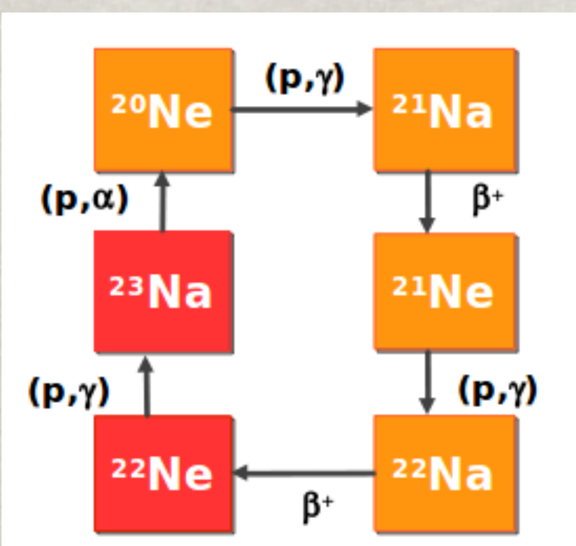
Next measurements

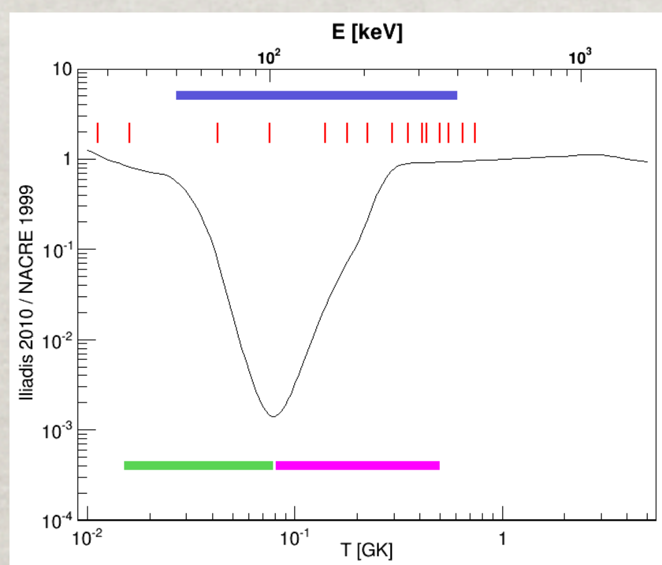
- $^{17}O(p,\alpha)^{14}N$ data taking for 65 keV and 183 keV resonances (end 2013)

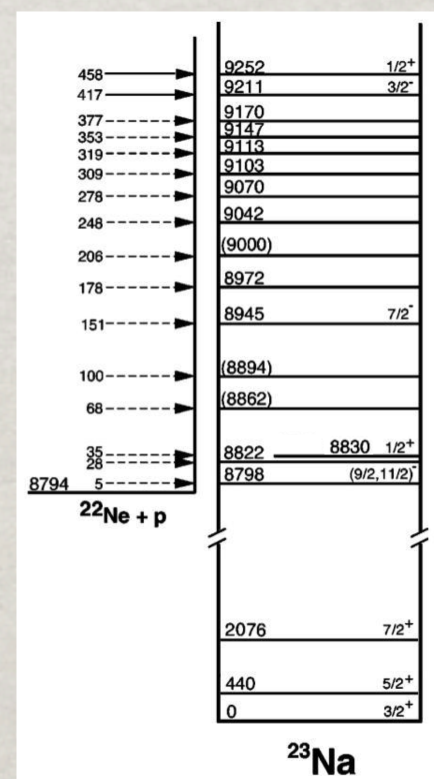


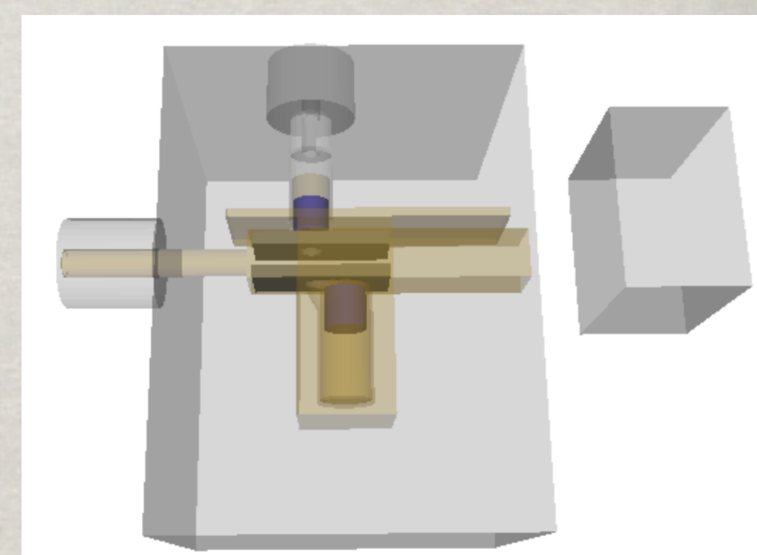


- $^{22}Ne(p,\gamma)^{23}Na$ setup under construction and calibration (2014)









- $^{18}O(p,\alpha)^{15}N$, $^{18}O(p,\gamma)^{19}F$, and $^{23}Na(p,\gamma)^{24}Mg$ under study

A new accelerator underground

Limits of a 400 kV accelerator

- Solar fusion reactions
- Stellar Helium and Carbon burning
- Neutron sources for astrophysical s-processes

A new, higher energy underground accelerator is needed !

proposed solutions:

- LUNA-MV at Gran Sasso National Laboratory (Italy)
- CANFRANC (Spain)
- Felsenkeller (Germany) <-- shallow underground
- DIANA (formerly part of DUSEL) (United States)
- China
- South America

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:

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

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

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

(α,γ) reactions on $^{14,15}N$ and ^{18}O

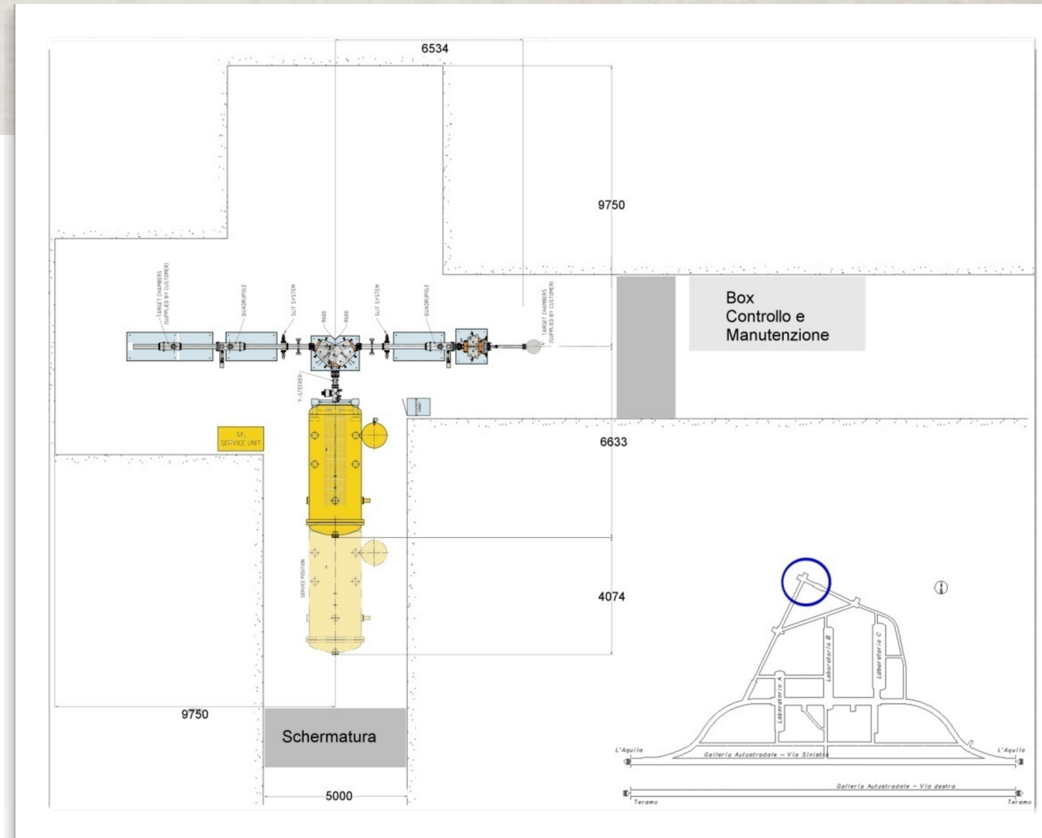
These reactions are relevant at higher temperatures (larger energies) than reactions belonging to the hydrogen-burning studied so far at LUNA

↓

Single ended 3.5 MV positive ion accelerator

LUNA - MV PROJECT

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



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

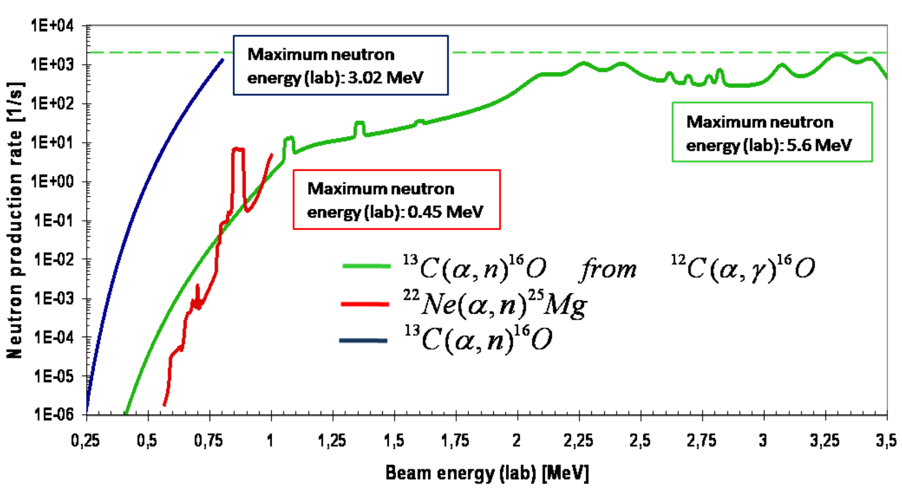
α beam intensity: 200 μA
Target: ^{13}C, 2 10^{17}at/cm^2 (99% ^{13}C enriched)
Beam energy(lab) ≤ 0.8 MeV

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

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

THE ESTIMATED N-FLUX (FLUKA & GEANT 4 SIMULATIONS) WILL INCREASE LESS THAN 1% OF THE LNGS NATURAL FLUX !

"Progetto Premiale" LUNA - MV

Italian Research Ministry financed the LUNA-MV special project with 2.8 MEuro in 2012

Time schedule:

2012 - 2013 Hall preparation, Tender for the accelerator and Shielding

2014 Beam lines R&D, Infrastructures

2015 Accelerator installation, Beam lines construction, Detectors installation

2016 Calibration of the apparatus and first tests of beam on target

Location at LNGS underground laboratory still **uncertain** !

New funding from 2nd "Progetto Premiale" **under discussion** !

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New collaborators are welcome!