LUNA latest results

and

lessons learned from running underground accelerators

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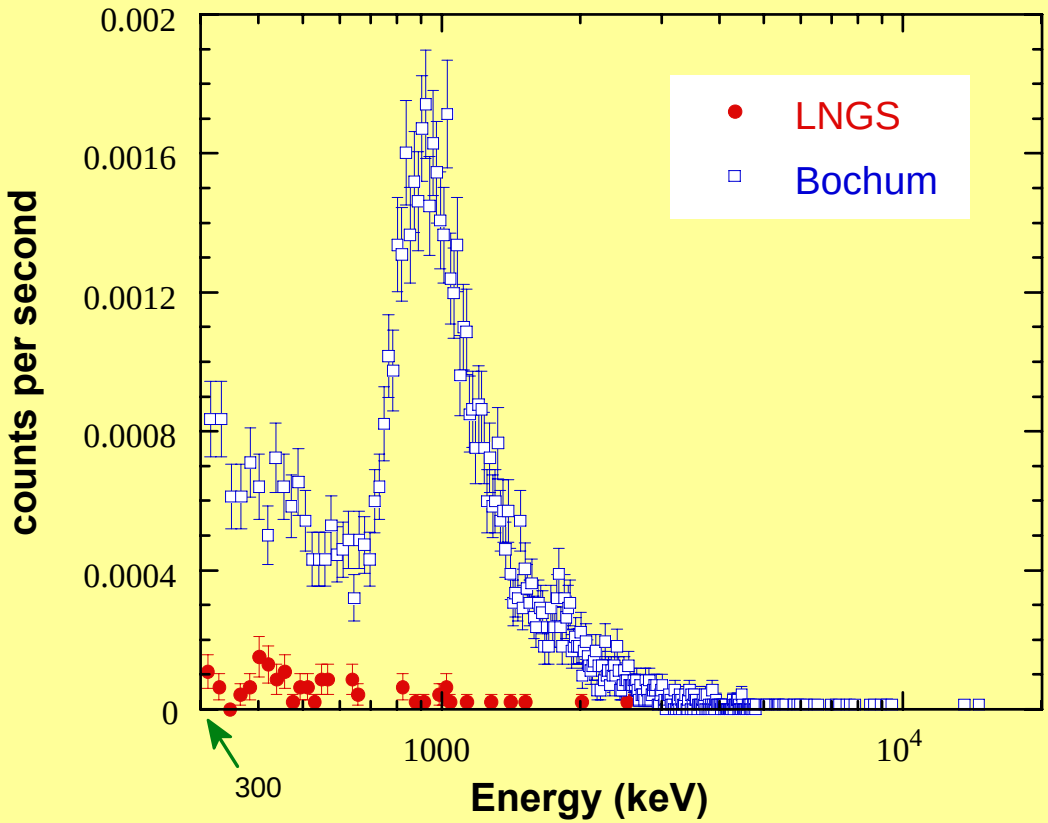
1991: First Background Test in LNGS

surface-barrier silicon Detector

thickness = 2 mm

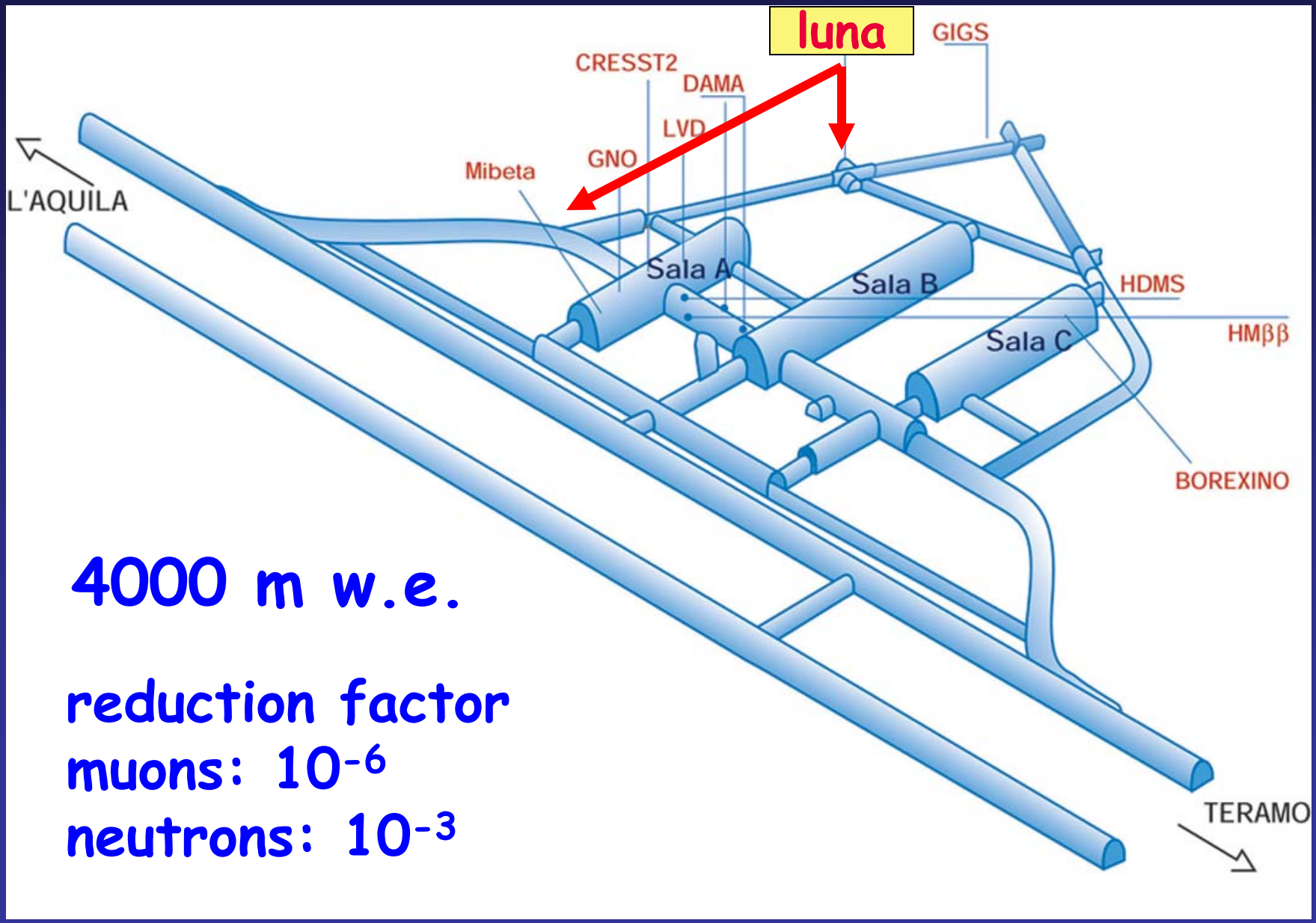


Laboratory
Underground
Nuclear
Astrophysics

" Some people are so crazy that they actually venture into deep mines to observe the stars in the sky ".

(Naturalis Historia - Plinio, 23-79 B.C.)

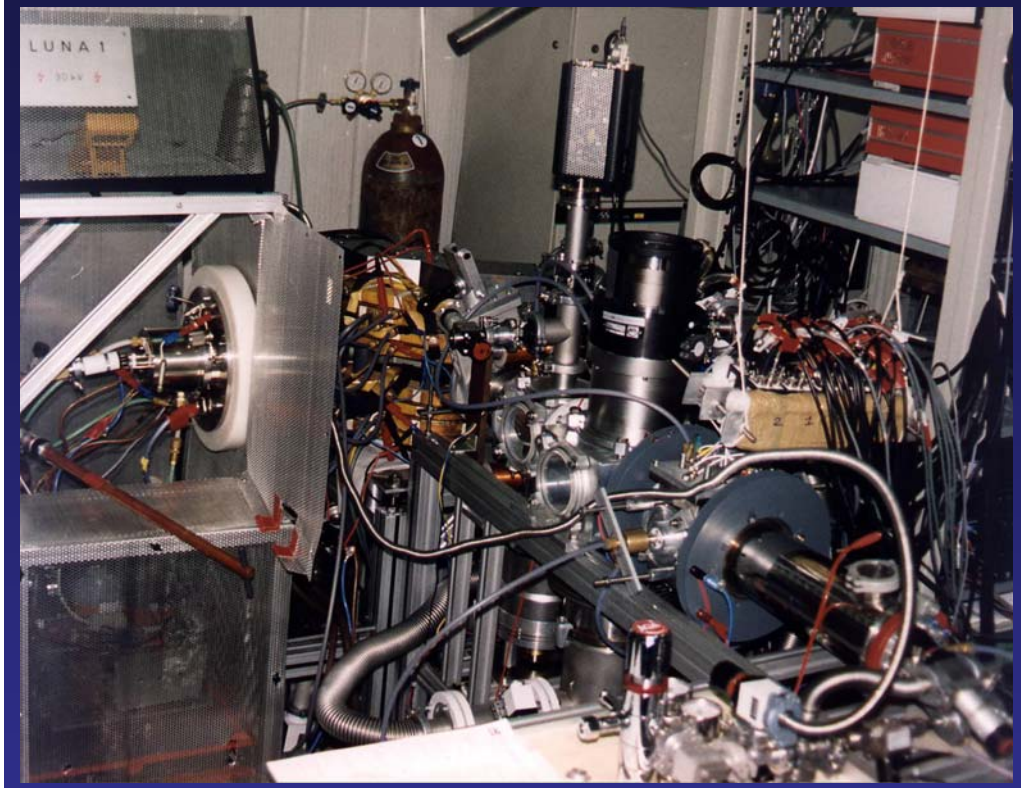
$\Phi_{\mu} = 0.7\ m^{-2}\ h^{-1}$ $\Phi_{n} \approx 3*10^{-6}\ cm^{-2}\ s^{-1}$



4000 m w.e.

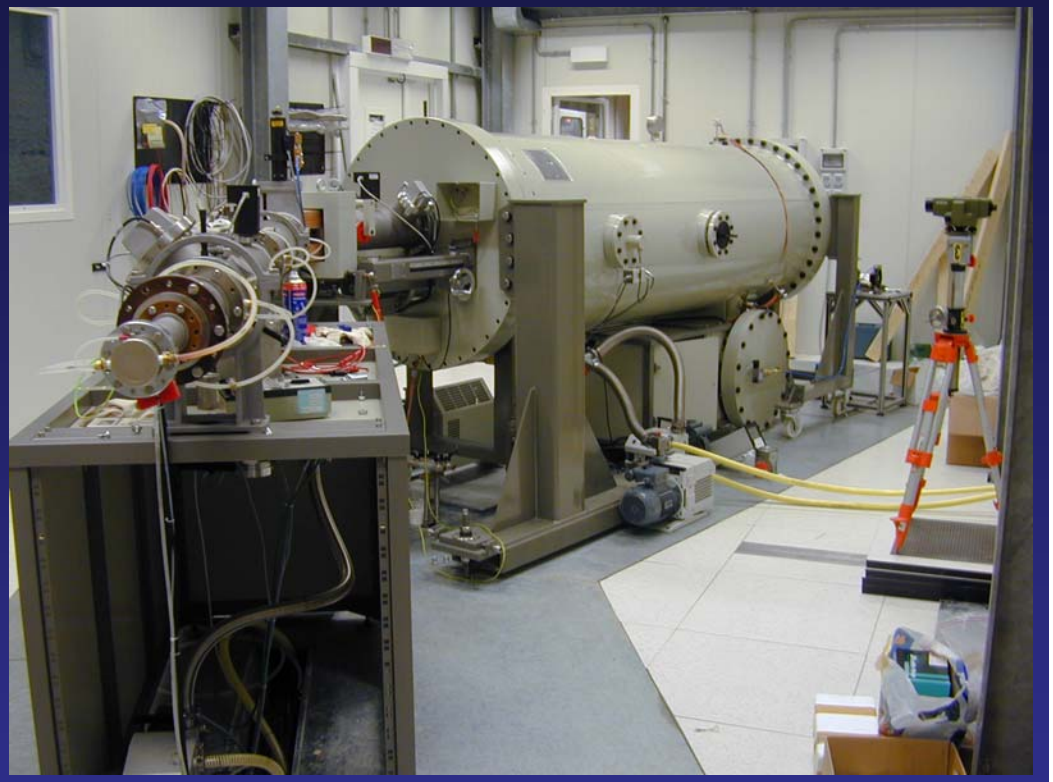
reduction factor
muons: 10^{-6}
neutrons: 10^{-3}

LUNA1 (50 kV)



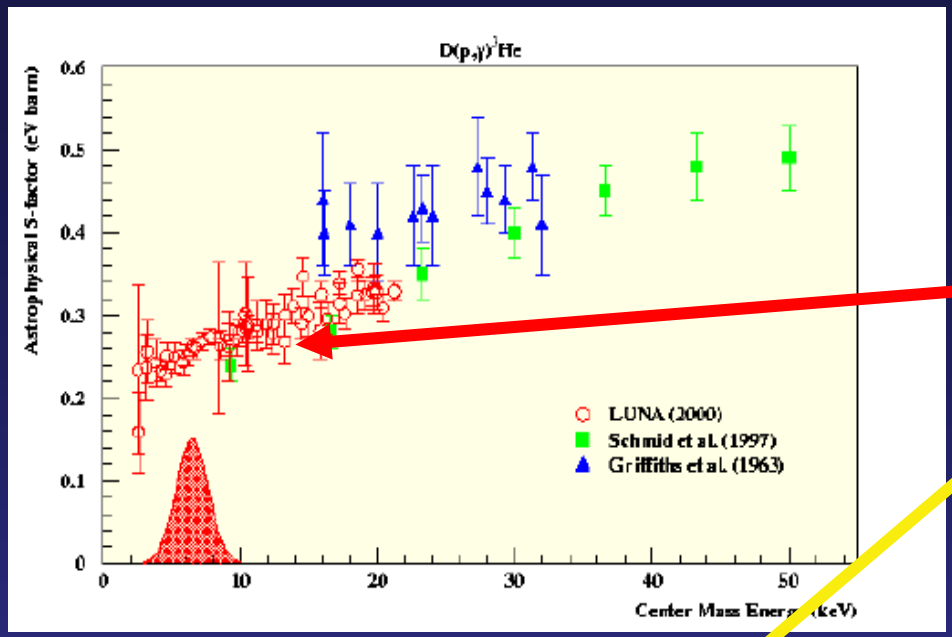
Voltage Range :1 - 50 kV
Output Current:1 mA
Beam energy spread:20 eV
Long term stability (8 h):10^{-4}
Terminal Voltage ripple:5 10^{-5}

LUNA2 (400 kV)



Voltage Range :50-400 kV
Output Current: 1 mA (@ 400 kV)
Absolute Energy error: ±300 eV
Beam energy spread: <100 eV
Long term stability (1 h): 5 eV
Terminal Voltage ripple:5 Vpp Ge det

pp chain



$p + p \rightarrow d + e^{+} + \nu_e$

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

84.7 %

13.8 %

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

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

13.78 %

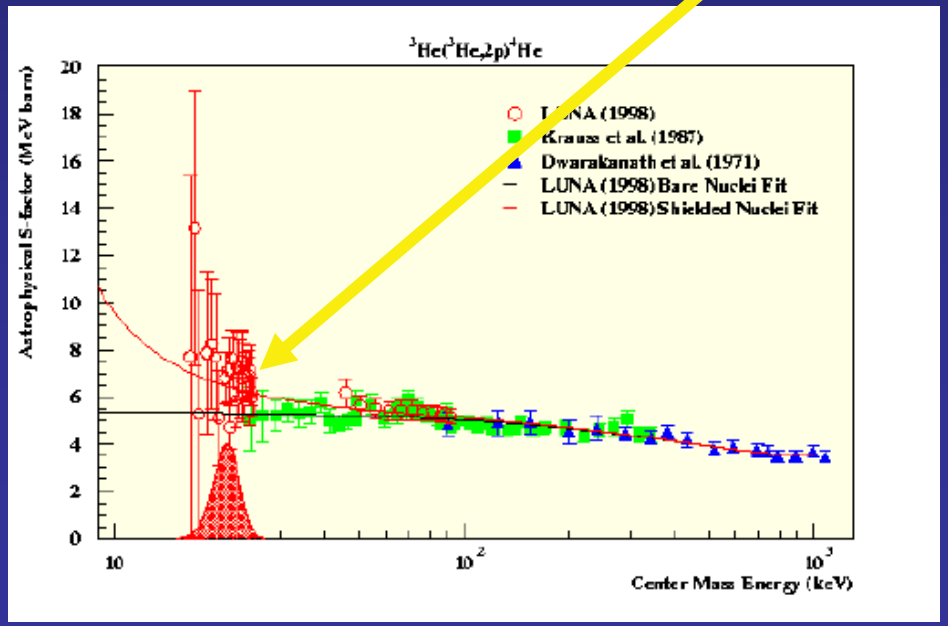
0.02%

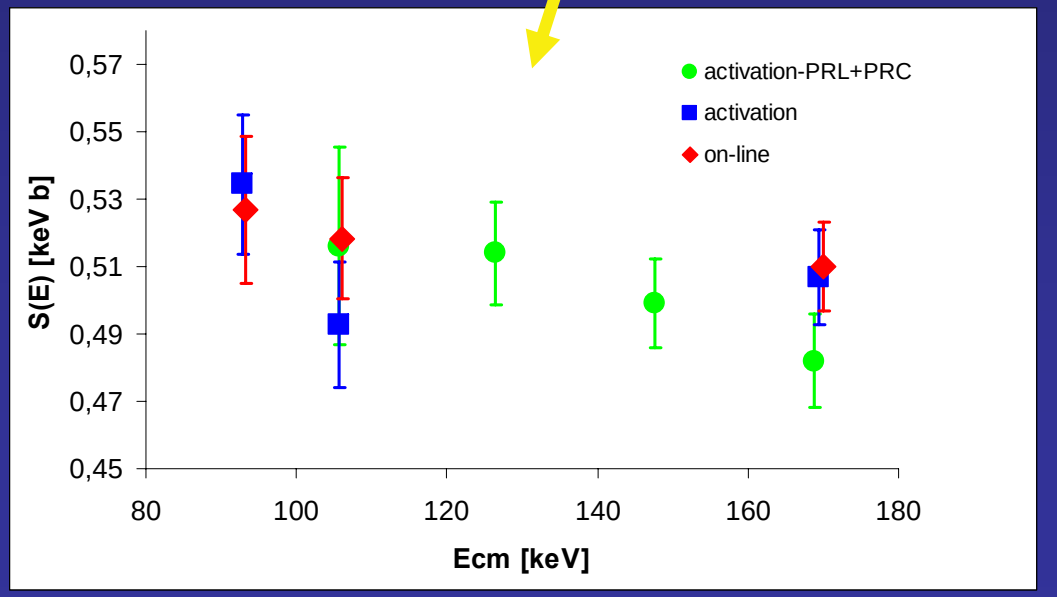
$^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$

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

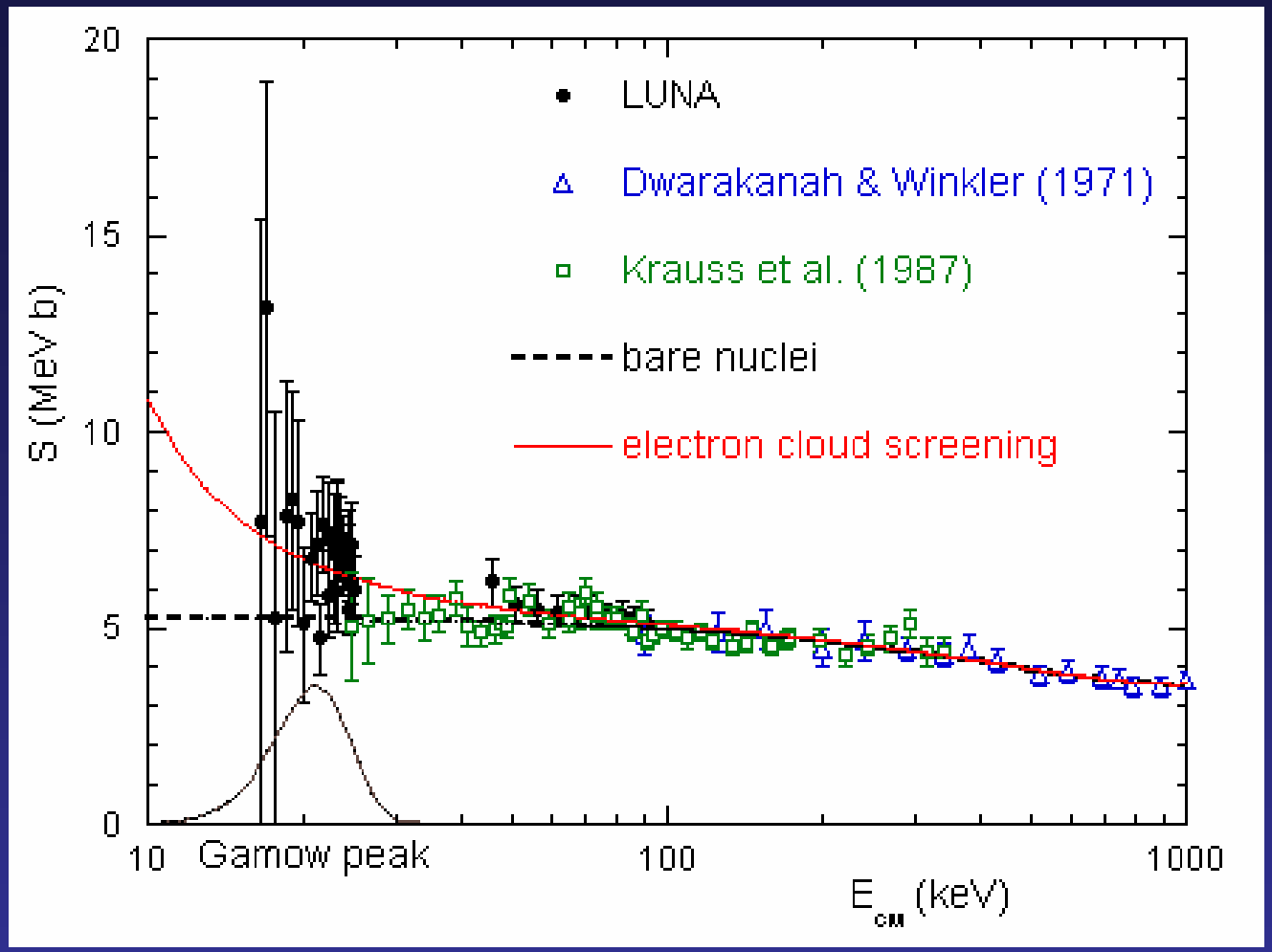
$^{7}Li + p \rightarrow \alpha + \alpha$

$^{8}B \rightarrow 2\alpha + e^{+} + \nu_e$





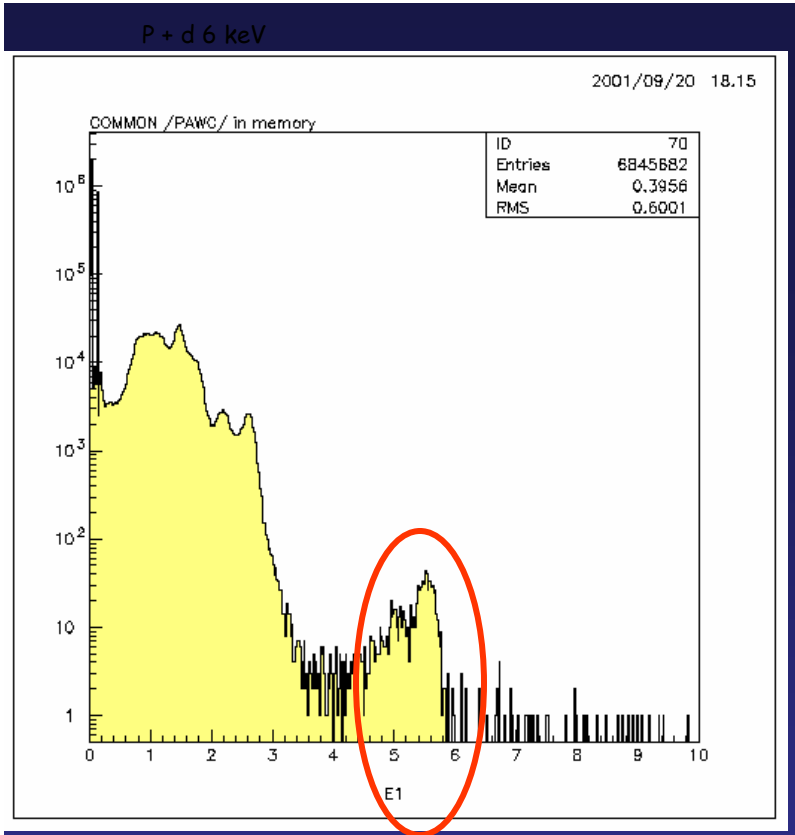
He3 + He3



count rate @ lowest energy: 2cts/month

lowest cross section: 0.02 pbarn

background < $4*10^{-2}$ cts/d in ROI

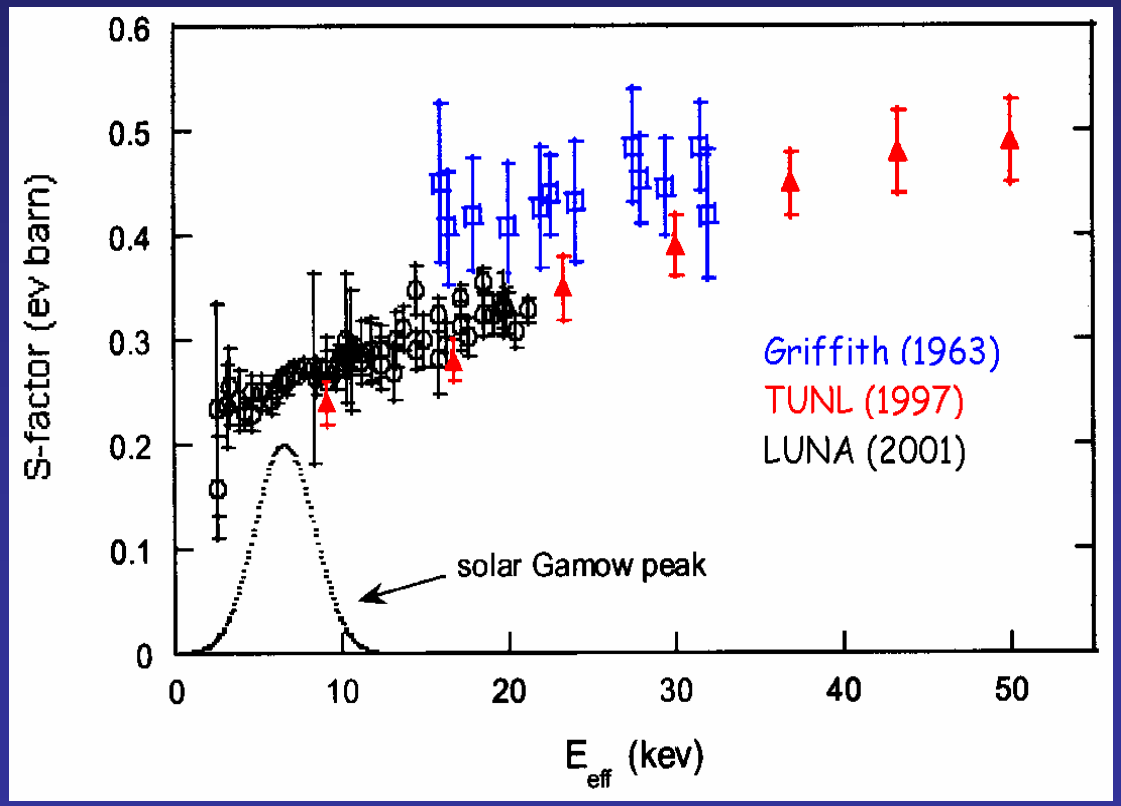


$D(p,\gamma)^3He$

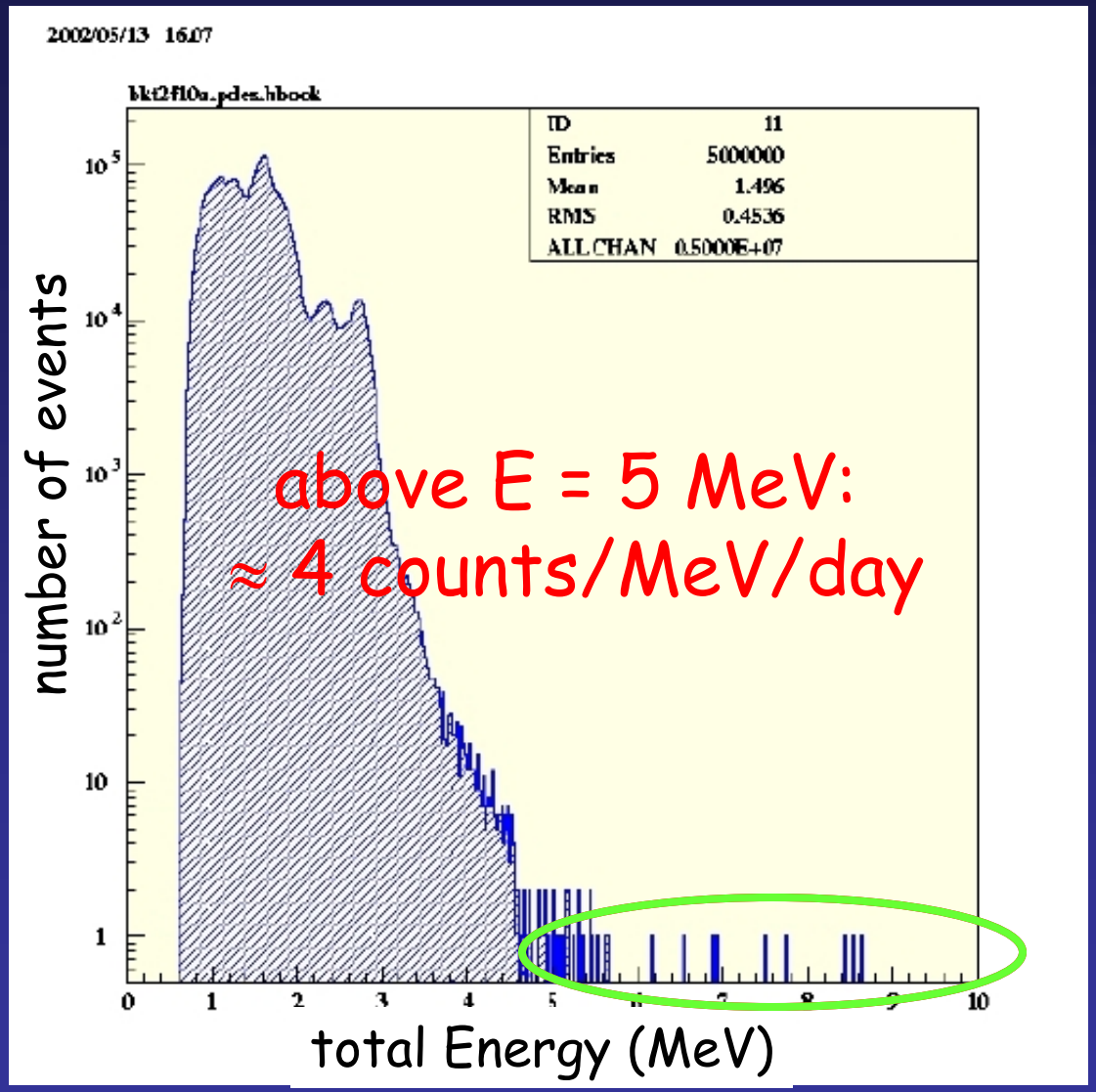
below the Gamow peak

E_{cm}= 6 keV

σ = 0.01 pbarn



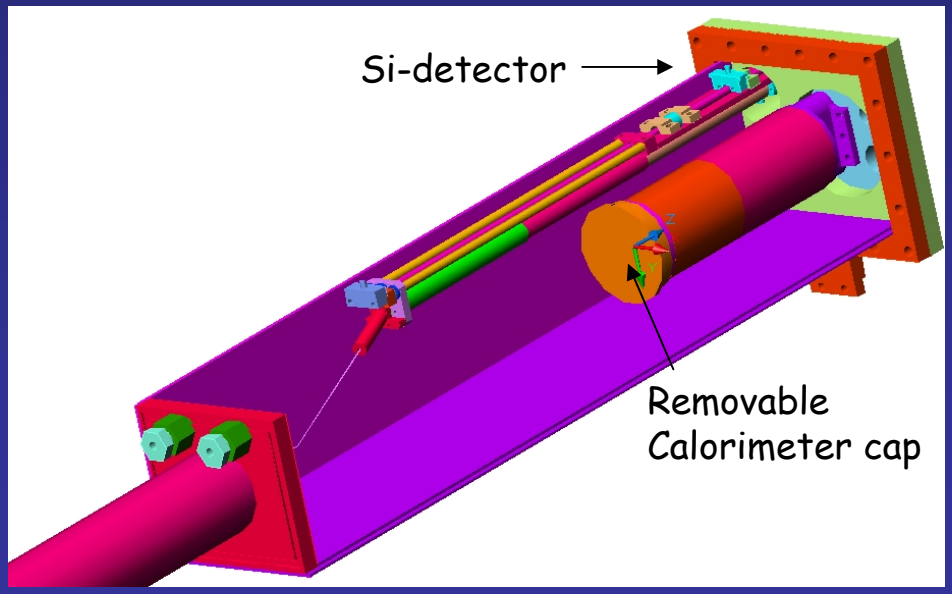
Background for BGO detector

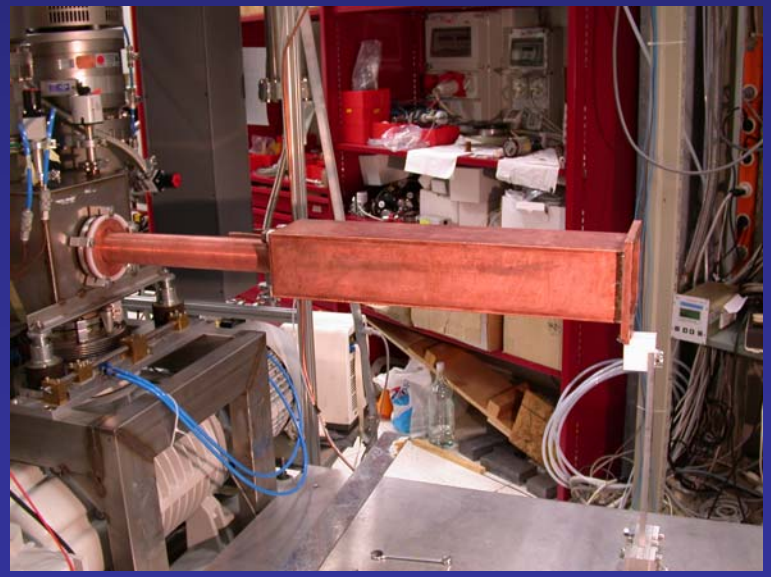


excellent for reactions with a Q-value > 5 MeV

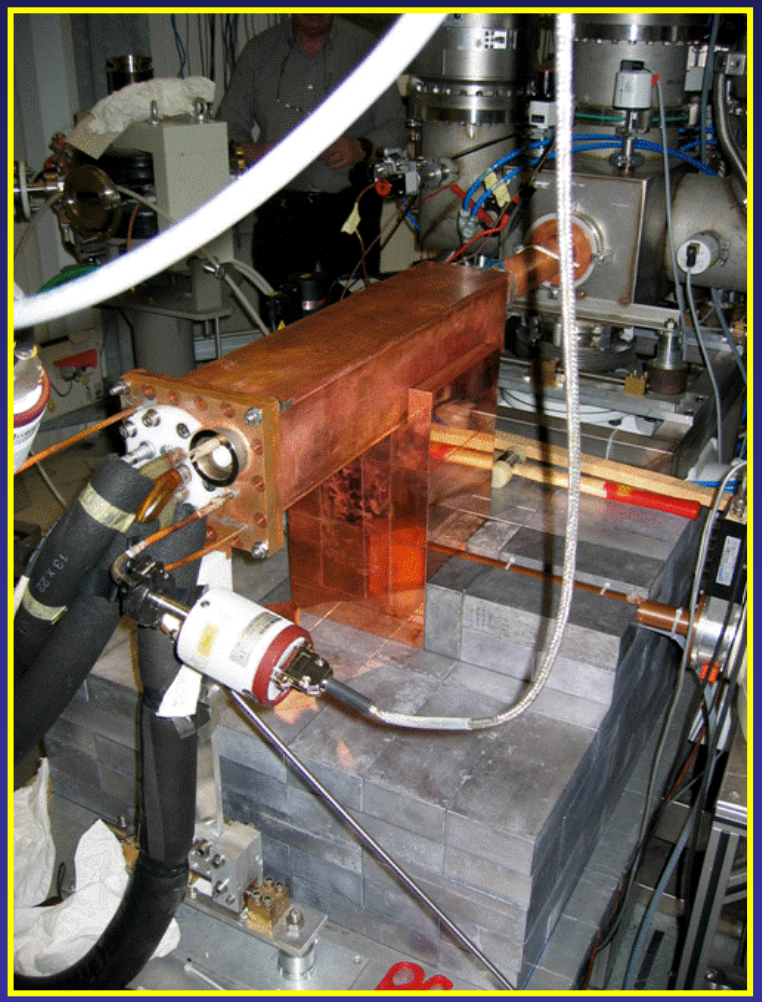
$^3He(\alpha,\gamma)^7Be$ – experimental setup

- ^3He recirculating gas target
- HpGe detector in close geometry for online γ detection
- Removable calorimeter cap for offline ^7Be counting
- Si-monitor for target density measurements (beam heating effect)
- 0.4 m^3 Pb-Cu shield around detector
- chamber in OFC to reduce background on the detector



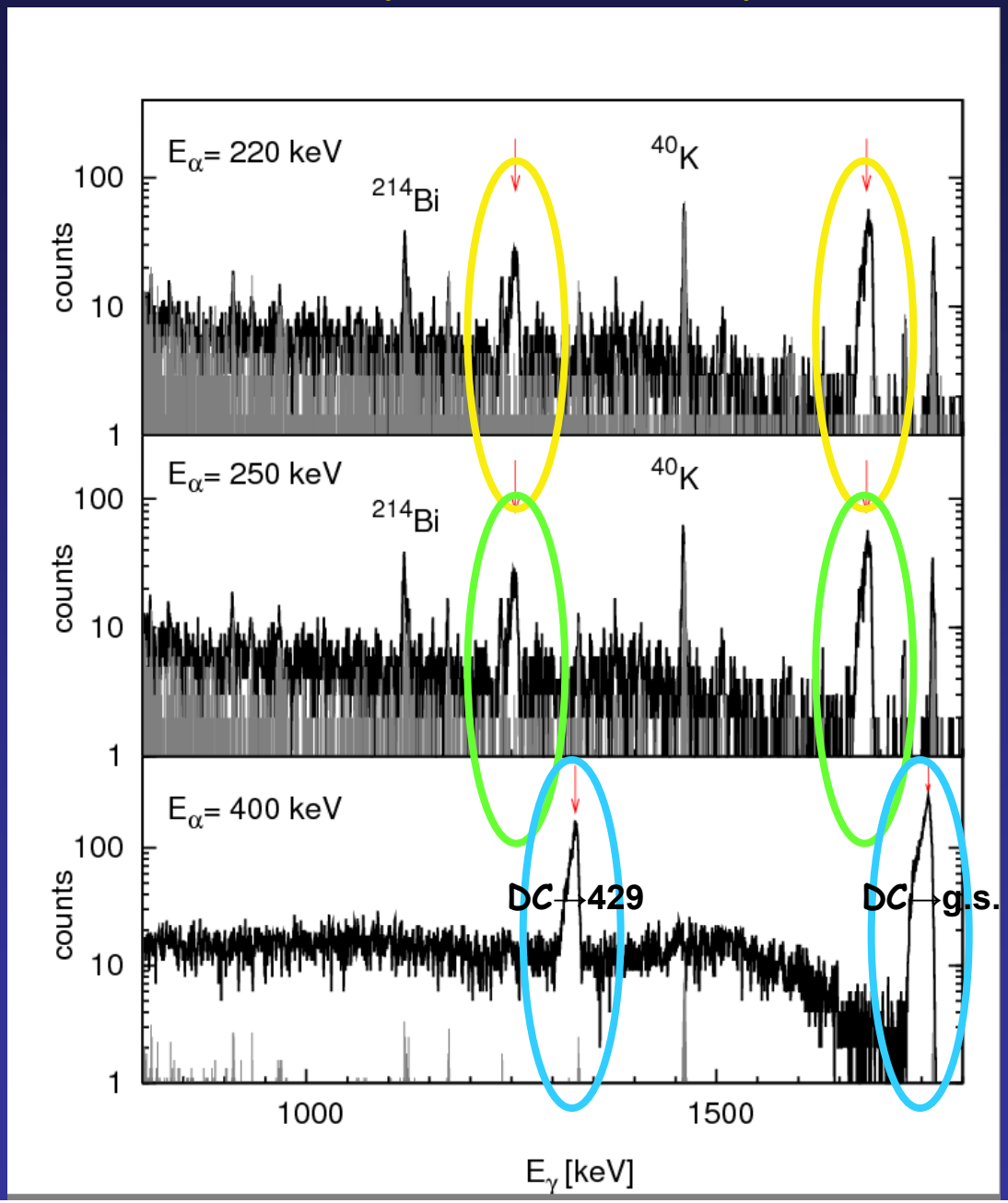


E_γ<3MeV ⟶ passive shielding for environmental background radiation



0.4 m^3 Pb and Cu shield
bck reduction: 10^5

Prompt-γ: experimental spectra



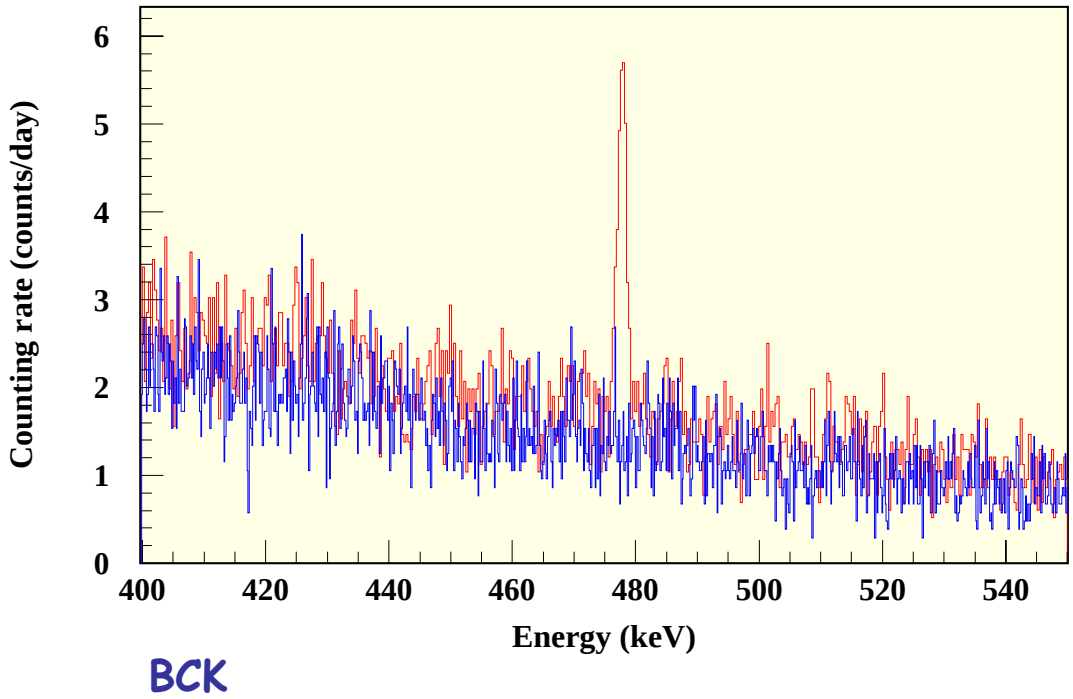
E_{cm} = 93.3 keV
T = 30.1 d
C = 637 C

E_{cm} = 106.1 keV
T = 20.8 d
C = 407 C

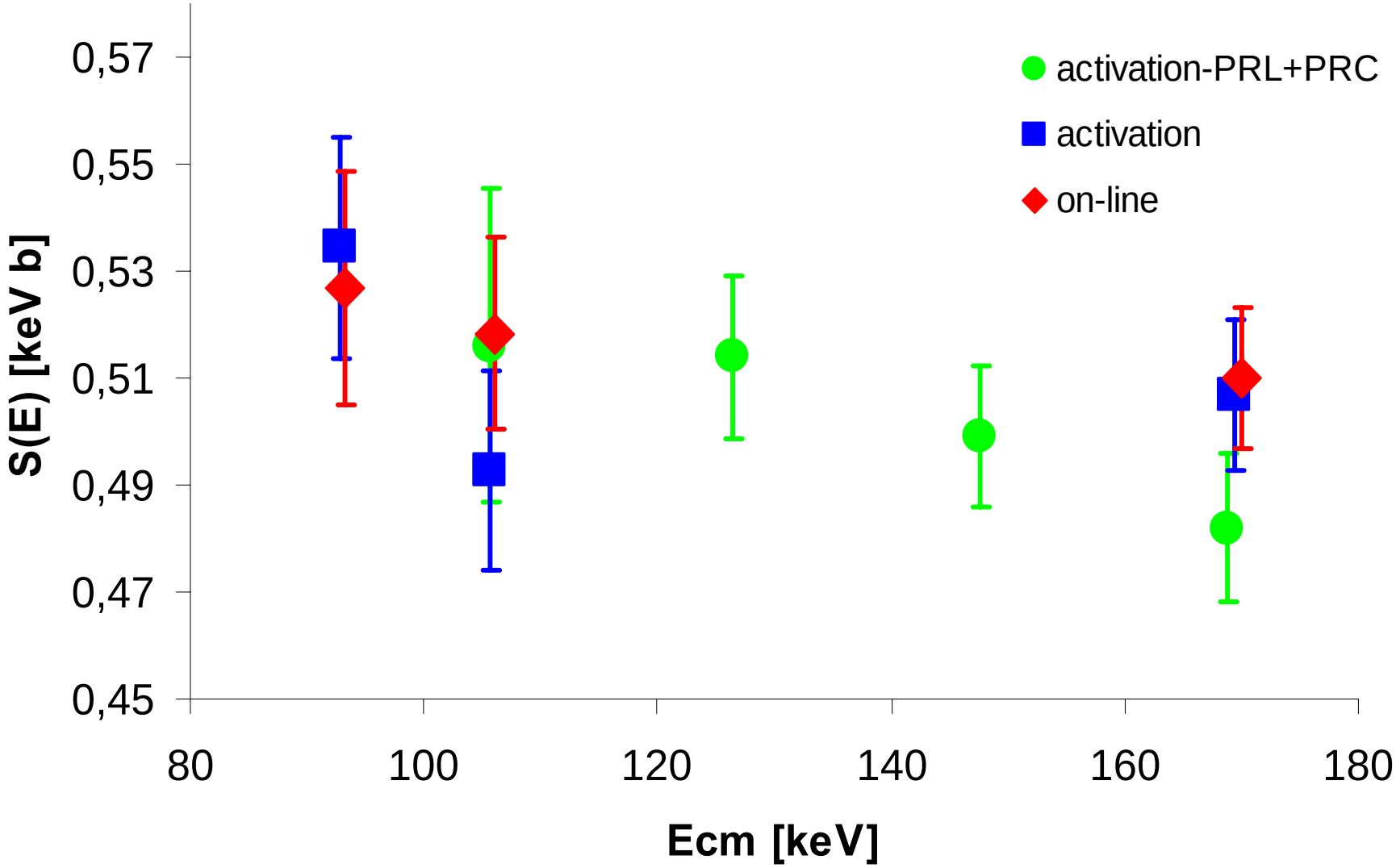
E_{cm} = 170.1 keV
T = 4.35 d
C = 112.7 C

Activation measurement

E_{lab}=220 keV Q= 637 C T = 11.58 d

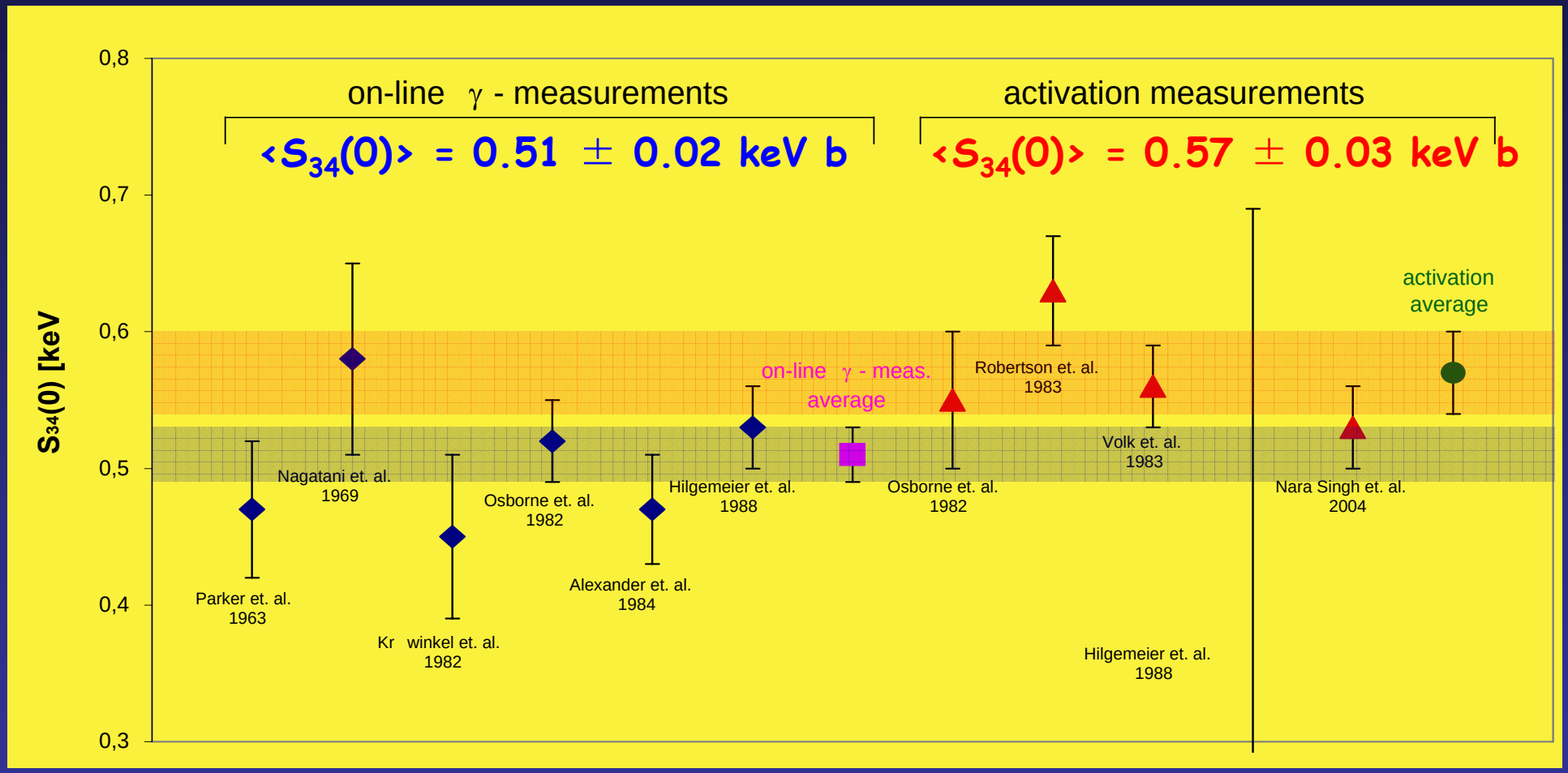


(D. Bemmerer et al, Phys. Rev. Lett. 97, 122502 (2006))


activation-PRL+PRC
activation
on-line
S(E) [keV b]
0,57
0,55
0,53
0,51
0,49
0,47
0,45
80
100
120
140
160
180
Ecm [keV]

ΔS = -1.4 ± 4.2 %

Summary of previous measurements

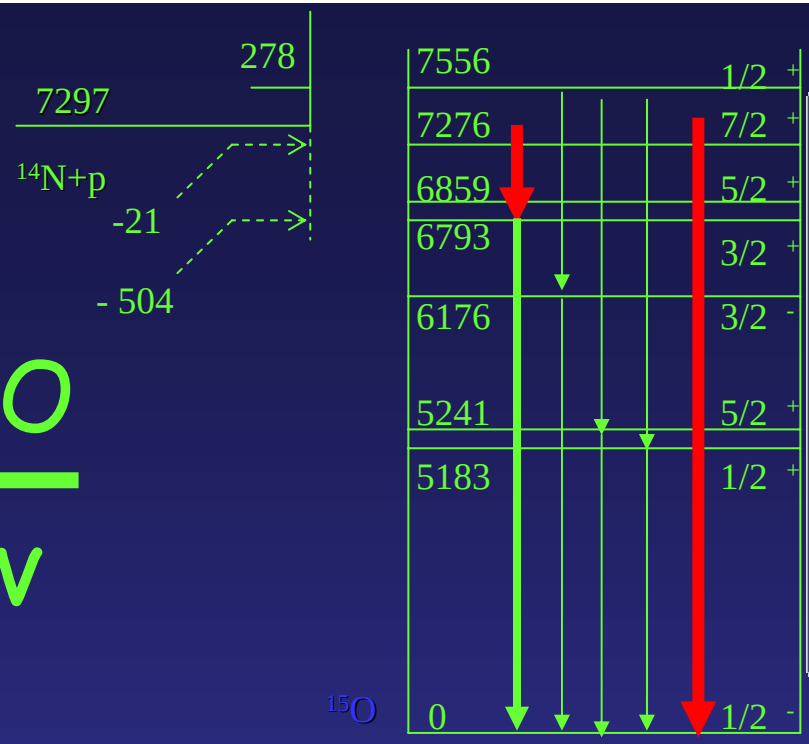


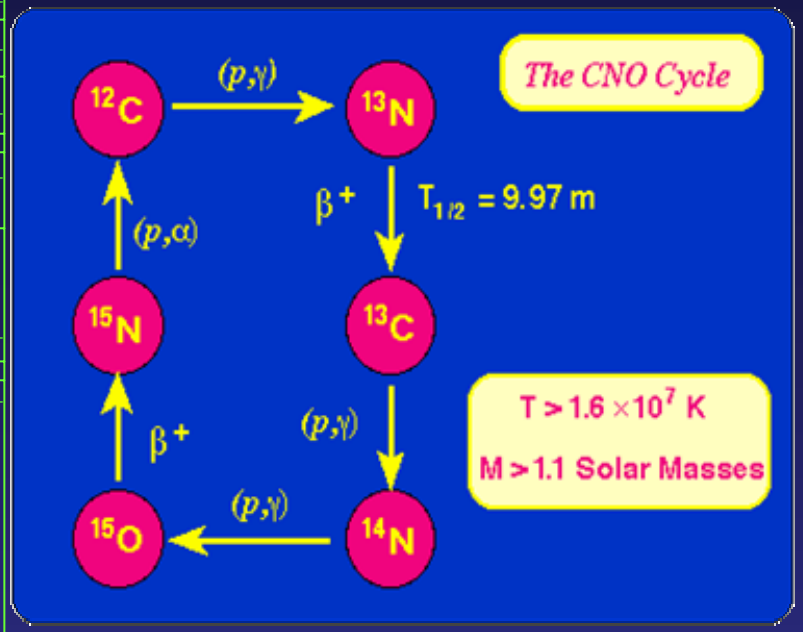
Recommended $S_{34}(0)$ values: 0.53 ± 0.05 keV b (9%) [Adelberger 98]
0.54 ± 0.09 keV b (16%) [NACRE 99]

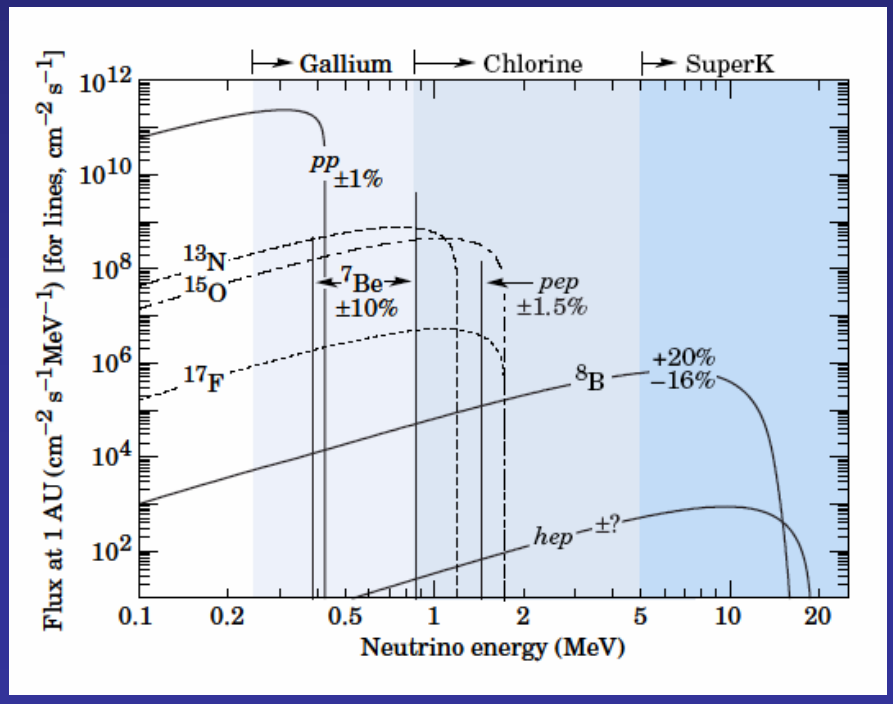
R-matrix analysis: **0.51 ± 0.04 keV b (8%) [Descouvemont 2004]**

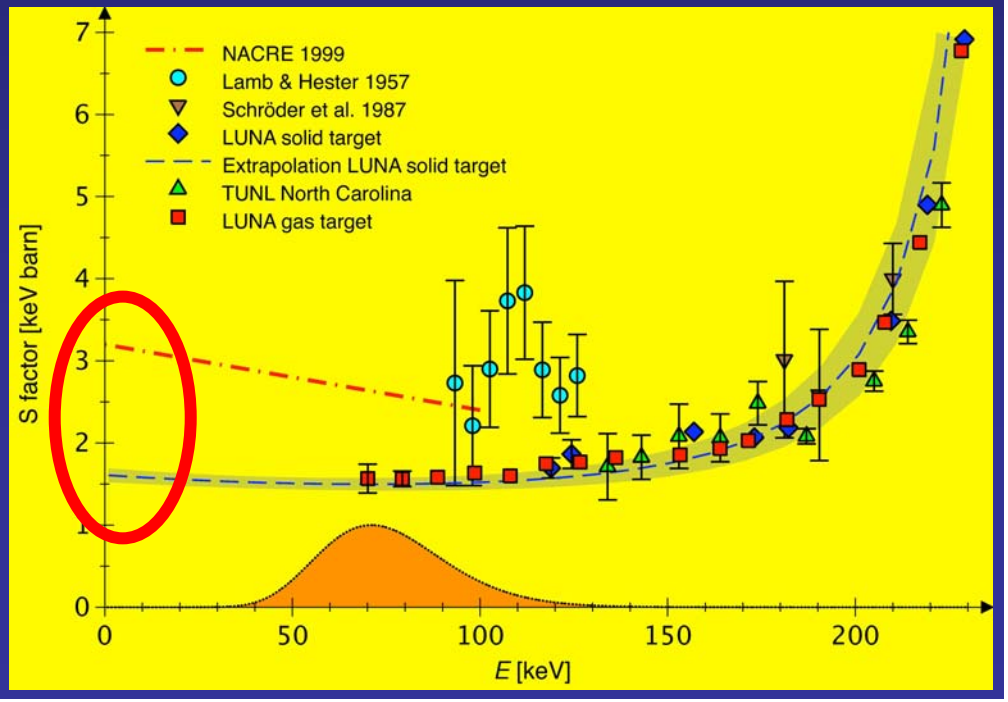
$^{14}N(p,\gamma)^{15}O$

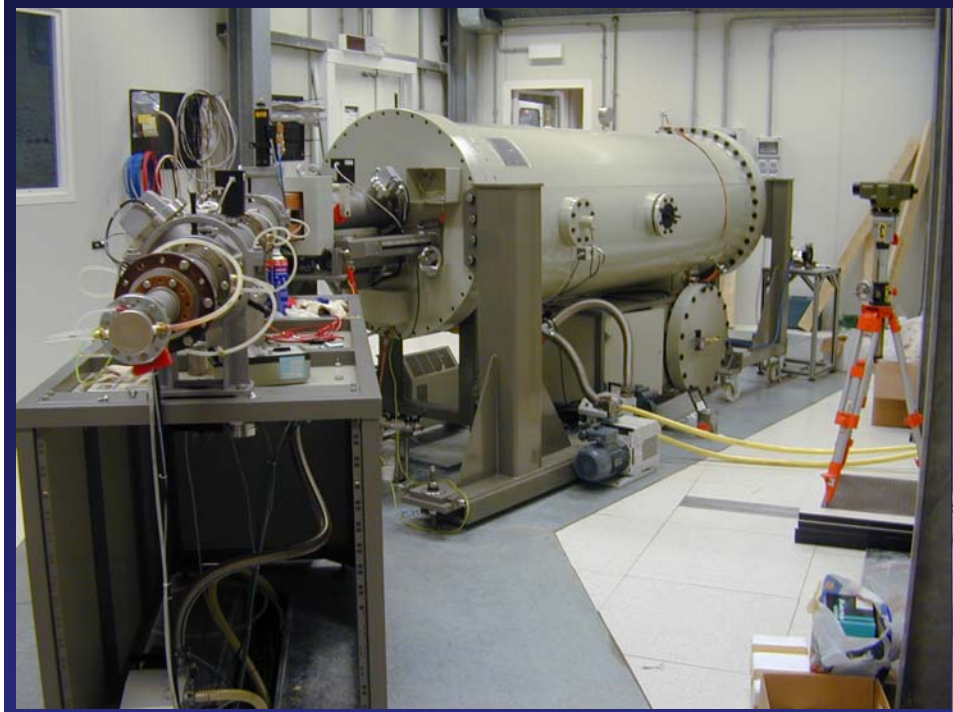
Q=7.3 MeV

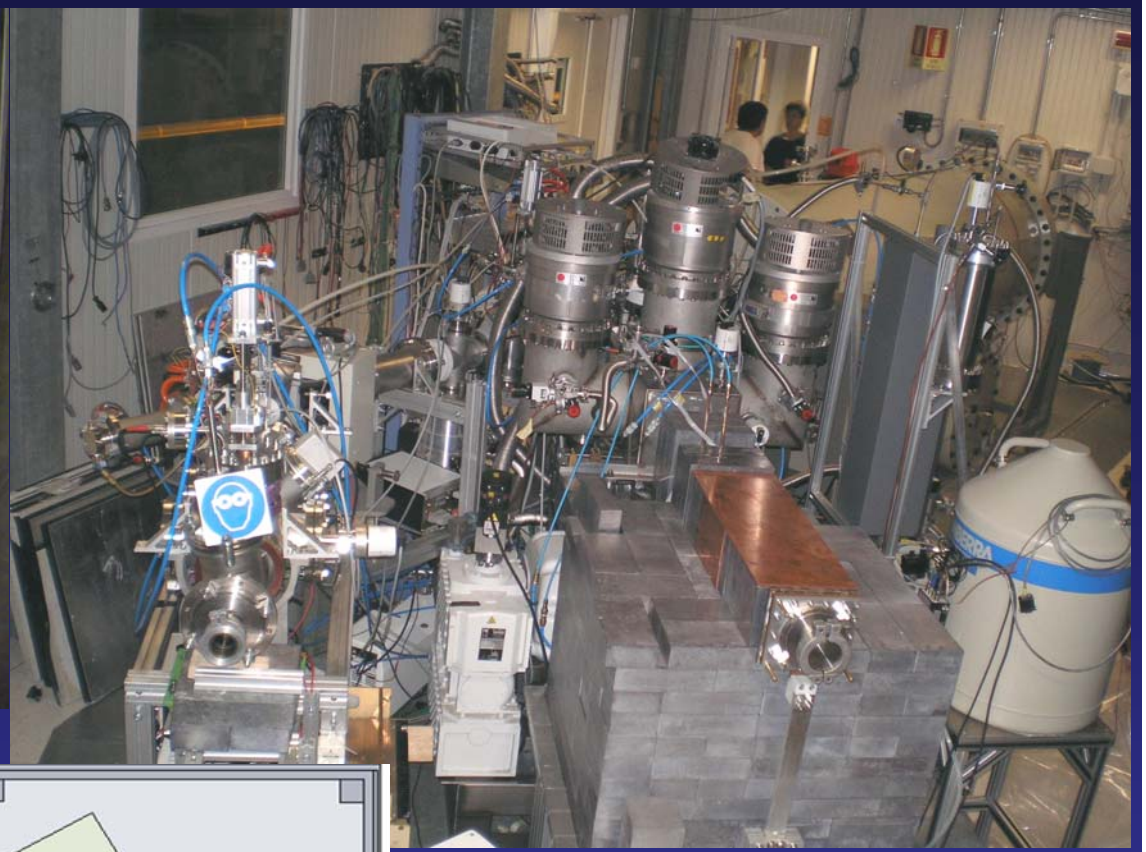


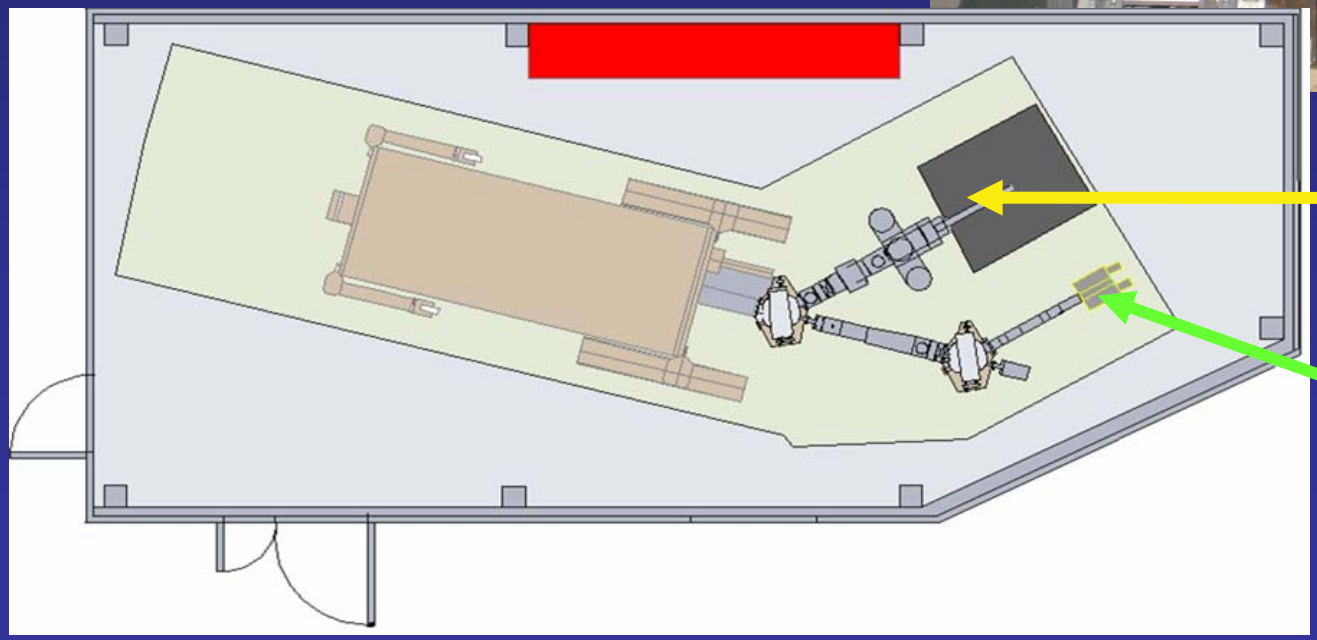










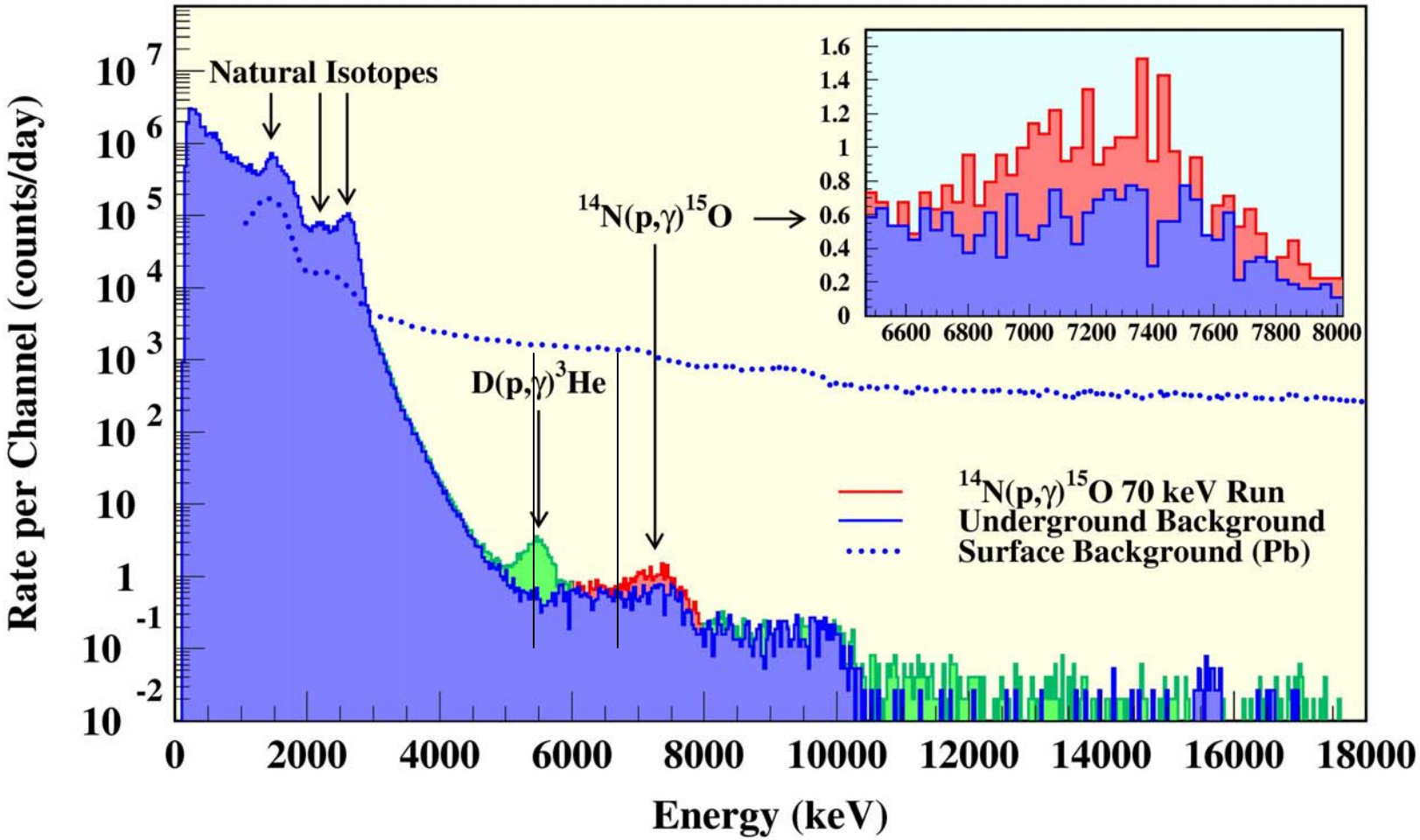


gas target
BGO
high efficiency

solid target
HPGe
high resolution

$^{14}N(p,\gamma)^{15}O$ spectrum at 70 keV

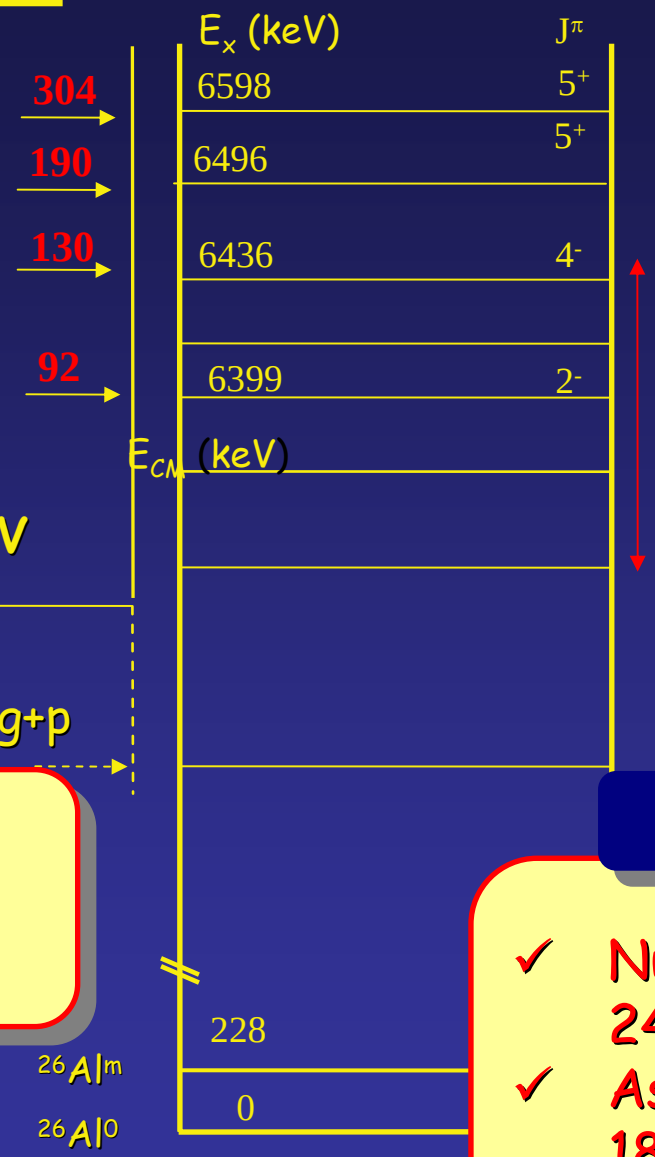
reaction rate = 10.95 ± 0.83 counts/day
background rate = 21.14 ± 0.75 counts/day



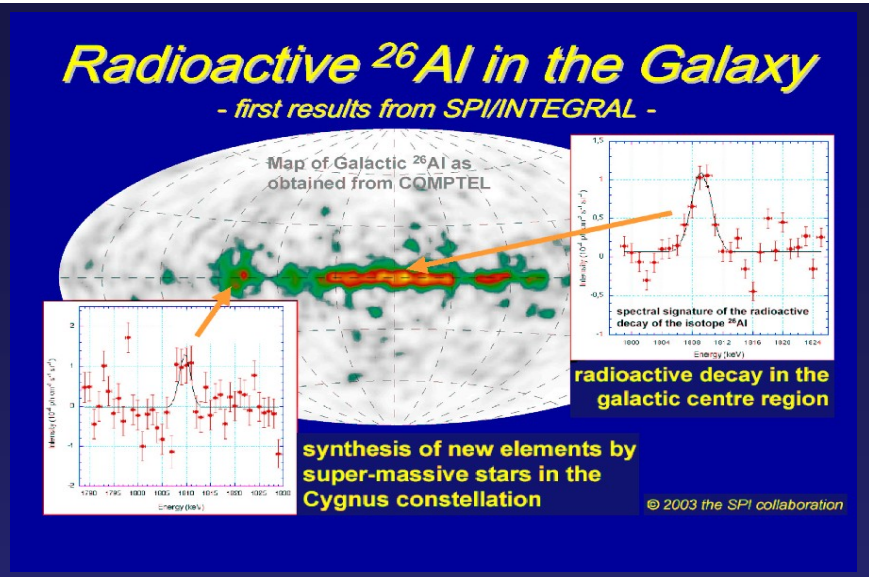
$^{25}Mg(p,\gamma)^{26}Al$

Novae explosive Burning (T_9>0.1)

AGB or W-R Stars (T_9~0.05)



Q = 6306 keV



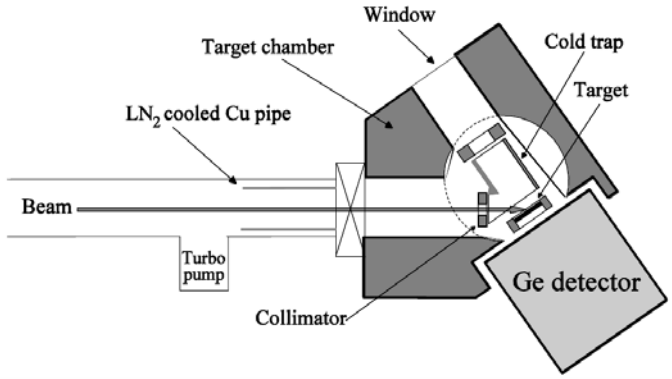
No direct strength resonance data
(level structure derived from the singe particle transfer reaction: **$^{25}Mg(^3He,d)^{26}Al$**)

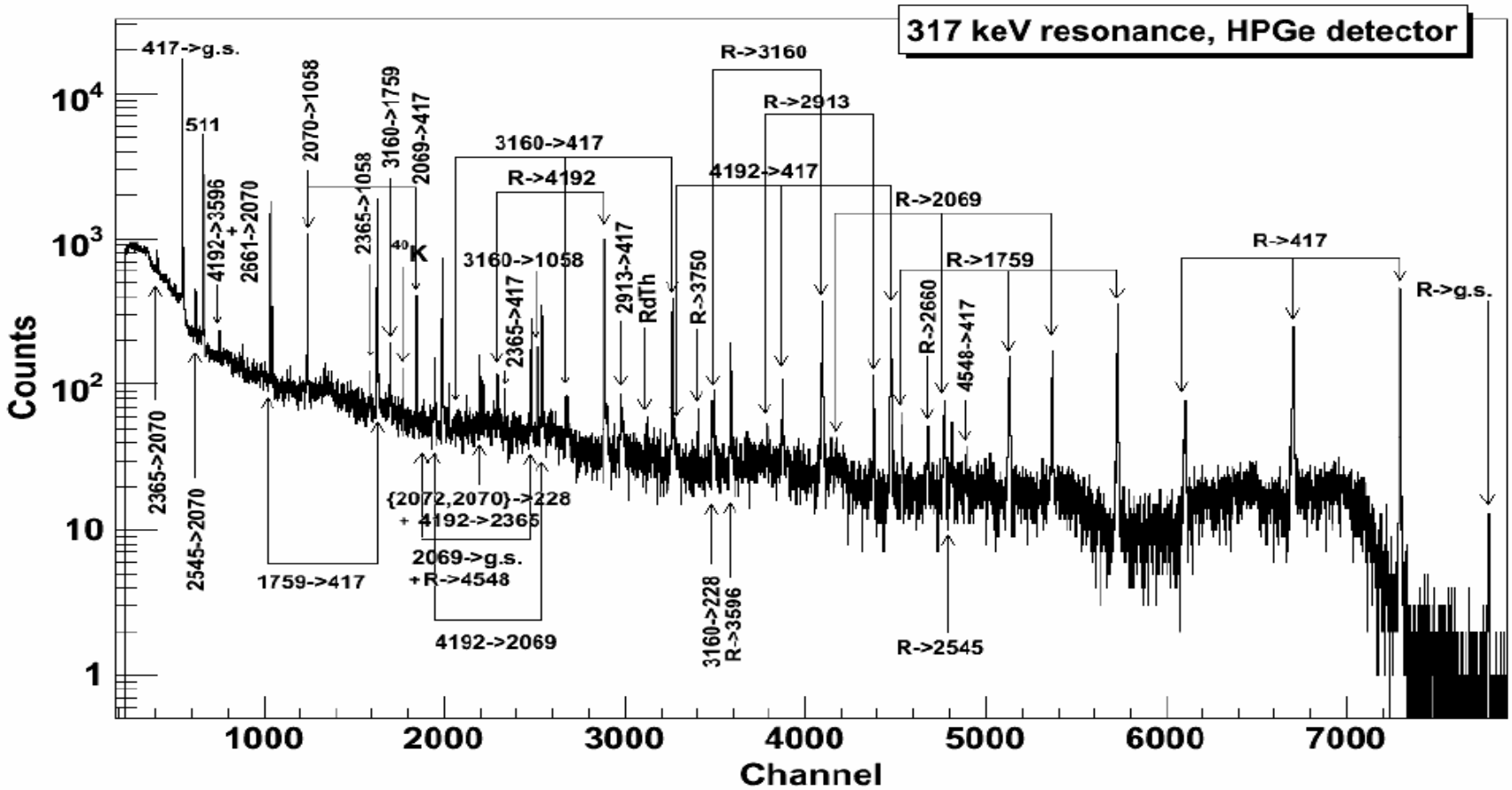
Astrophysical sites
- ✓ AGB stars;
- ✓ Novae;
- ✓ Massive stars.

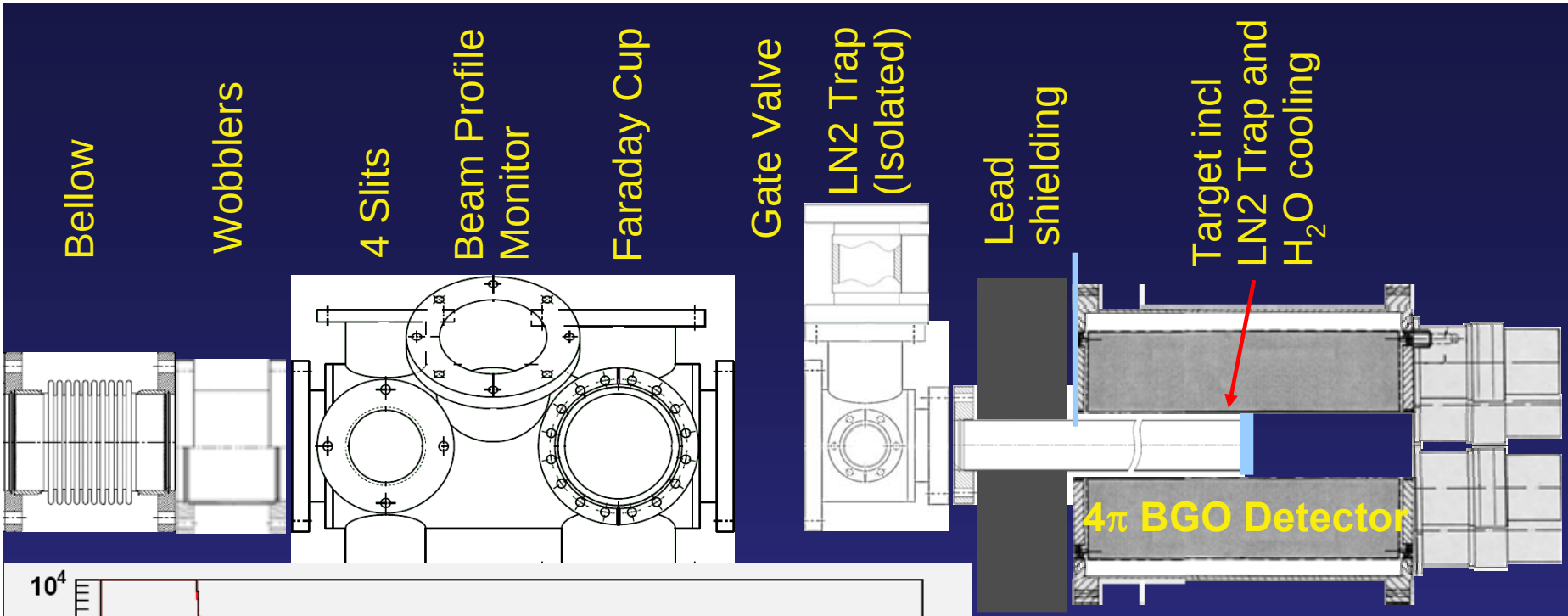
Motivation

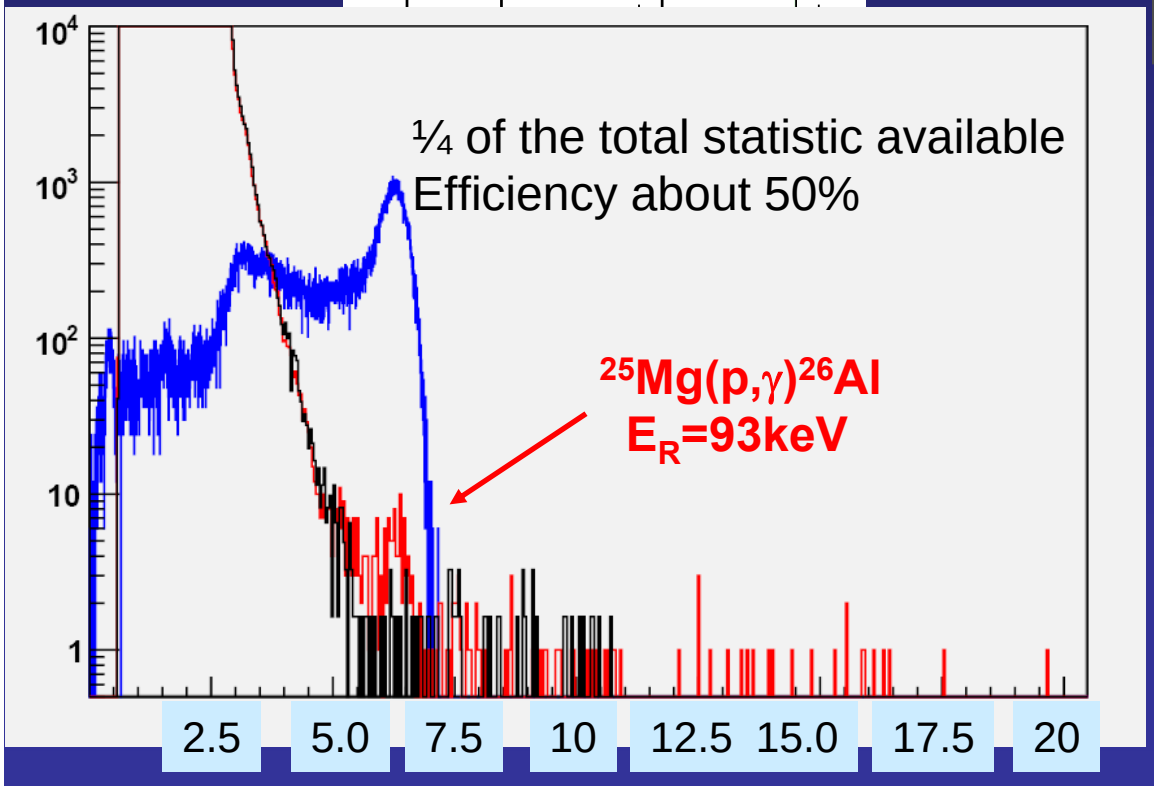
- ✓ Nucleosintesis of the elements 24<A<27
- ✓ Astronomical interest of 1809 keV ^{26}Mg γ line

High resolution set-up









Conclusions:

- we are finishing to collect data using the high efficiency set up;
- by the end of the year we will improve the study of the high resolution set-up to decrease the total efficiency uncertainty.

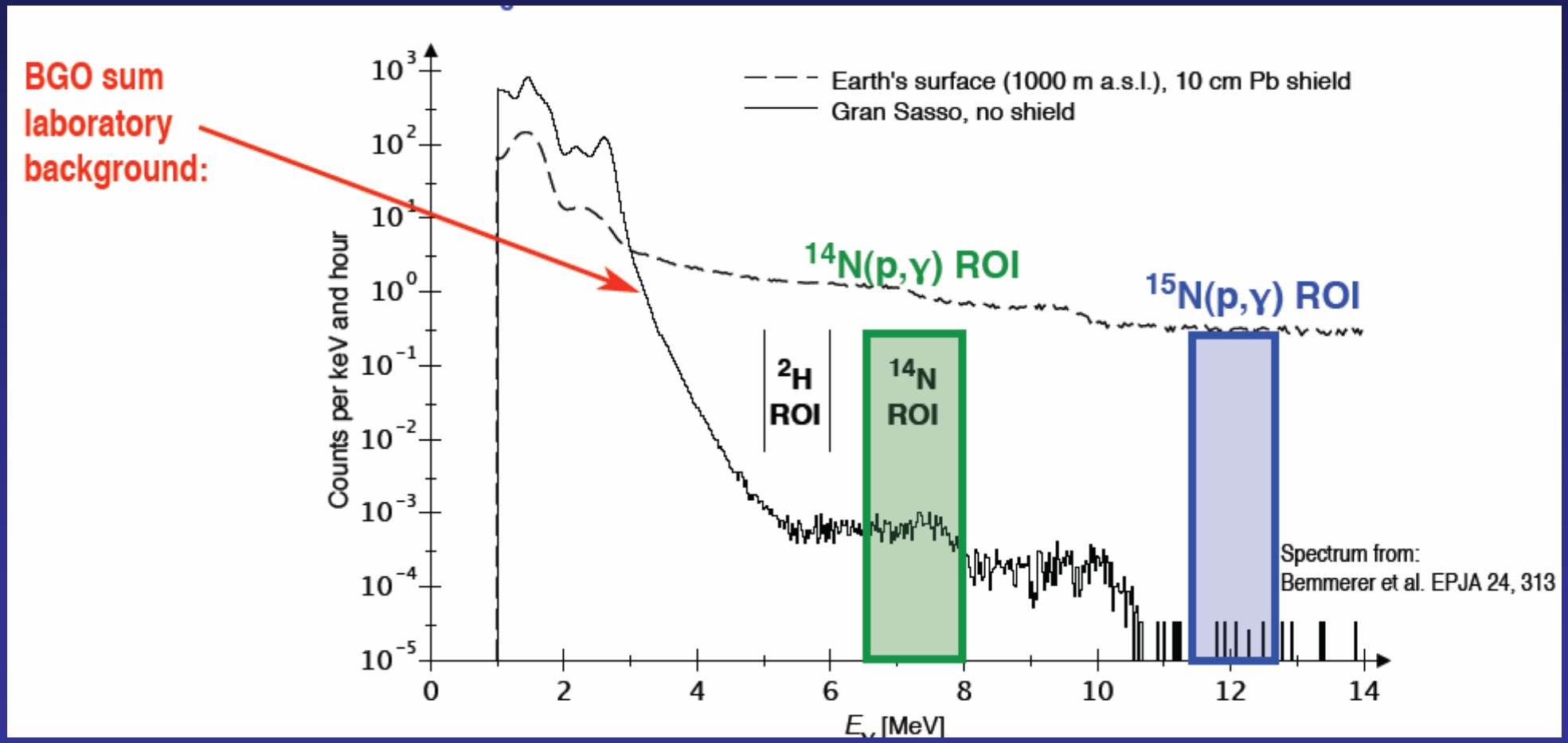
What else can be done with LUNA II (400kV) ?

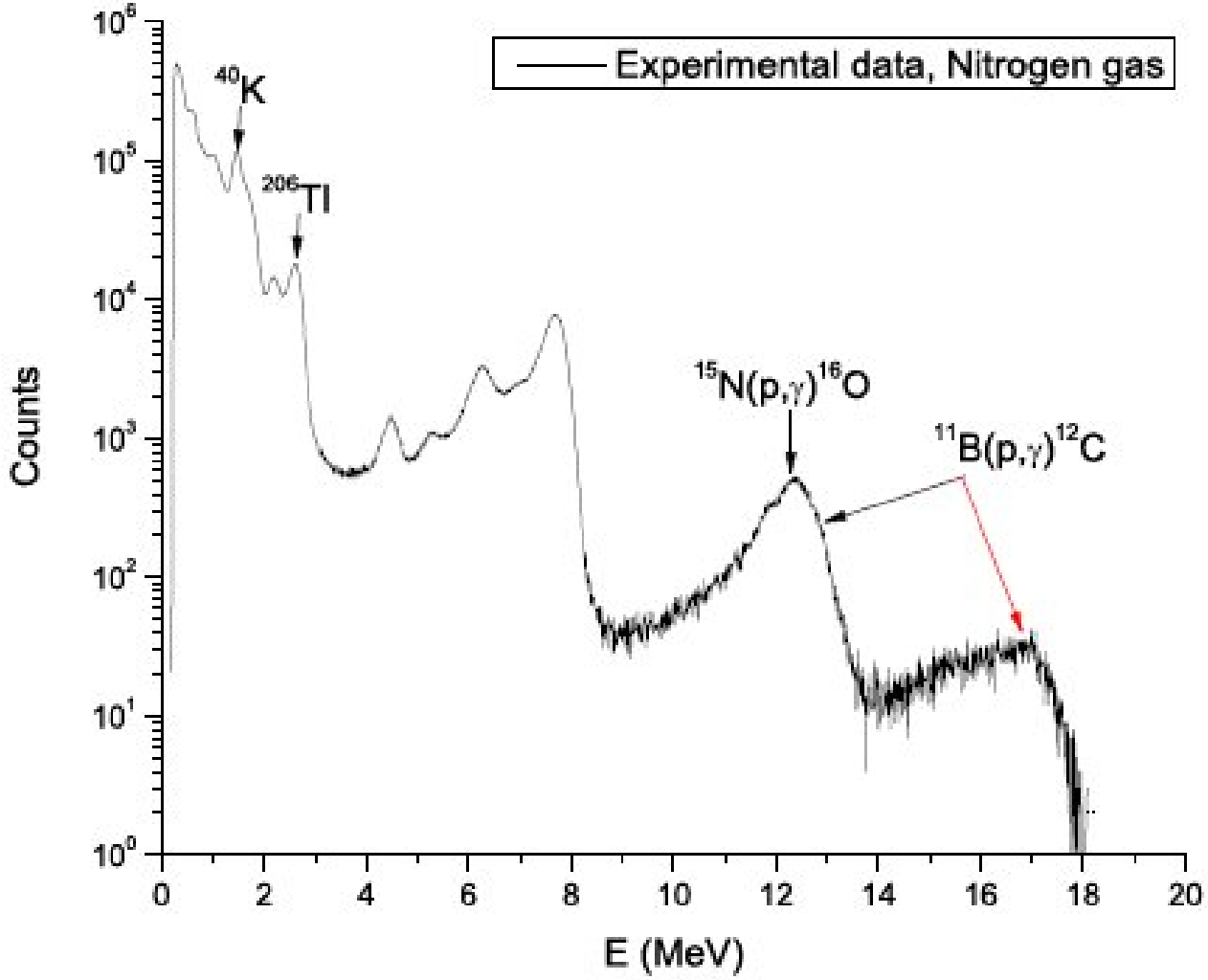
	reaction	Q-value (MeV)	Gamow energy (keV)	Lowest meas. Energy (keV)	LUNA limit
CNO	$^{15}N(p,\gamma)^{16}O$	12.13	10-300	130	50
CNO	$^{17}O(p,\gamma)^{18}F$	5.6	35-260	300	65
CNO	$^{18}O(p,\gamma)^{19}F$	8.0	50-200	143	89
Ne-Na	$^{23}Na(p,\gamma)^{24}Mg$	11.7	100-200	240	138
Ne-Na	$^{22}Ne(p,\gamma)^{23}Na$	8.8	50-300	250	68
BBN	$D(\alpha,\gamma)^{6}Li$	1.47	50-300	700(direct) 50(indirect)	50

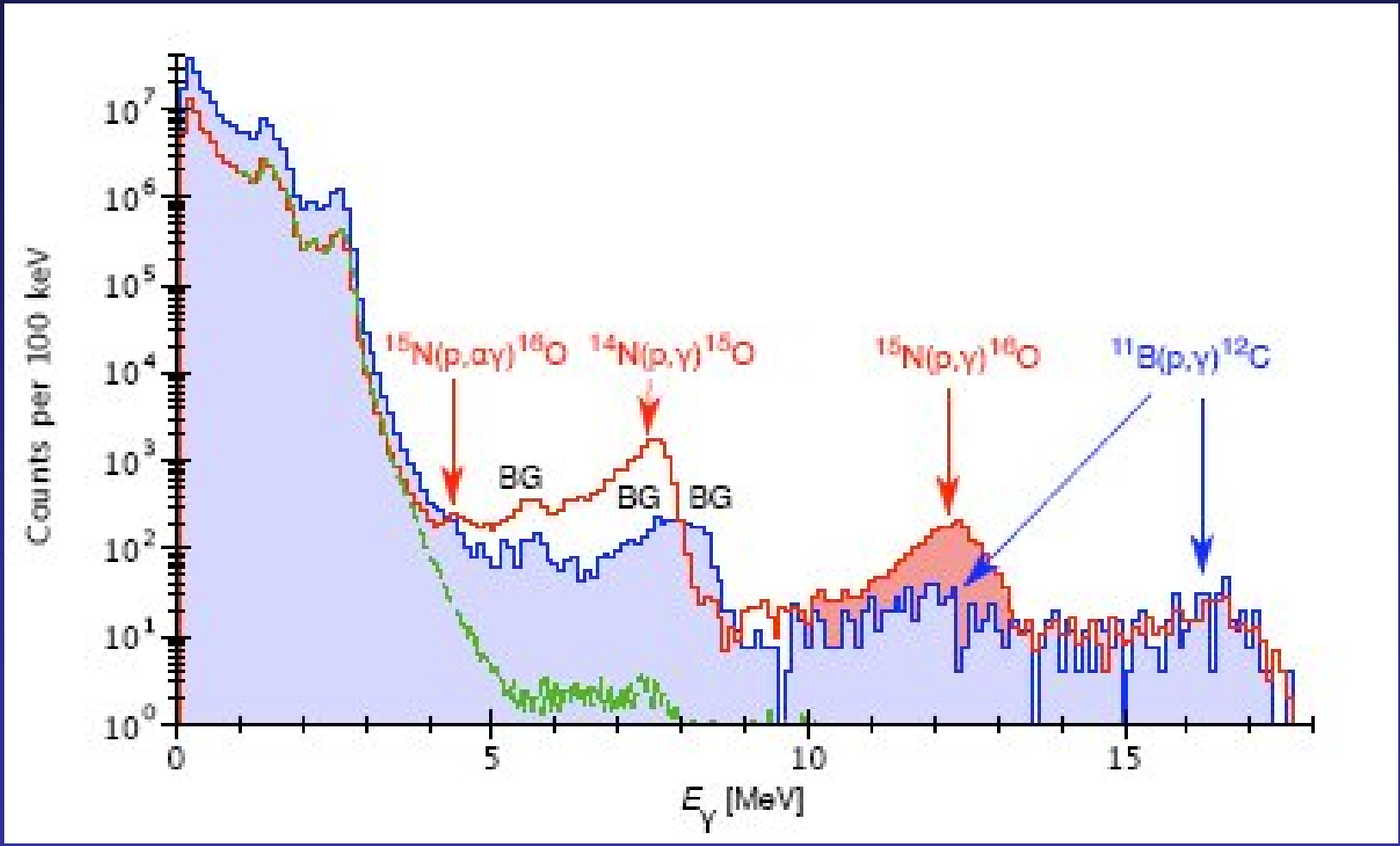
proposal submitted to INFN (2008-2012)

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

(from $^{14}N(p,\gamma)^{15}O$ experiment; $^{15}N/N_{nat}$ = 0.366%)

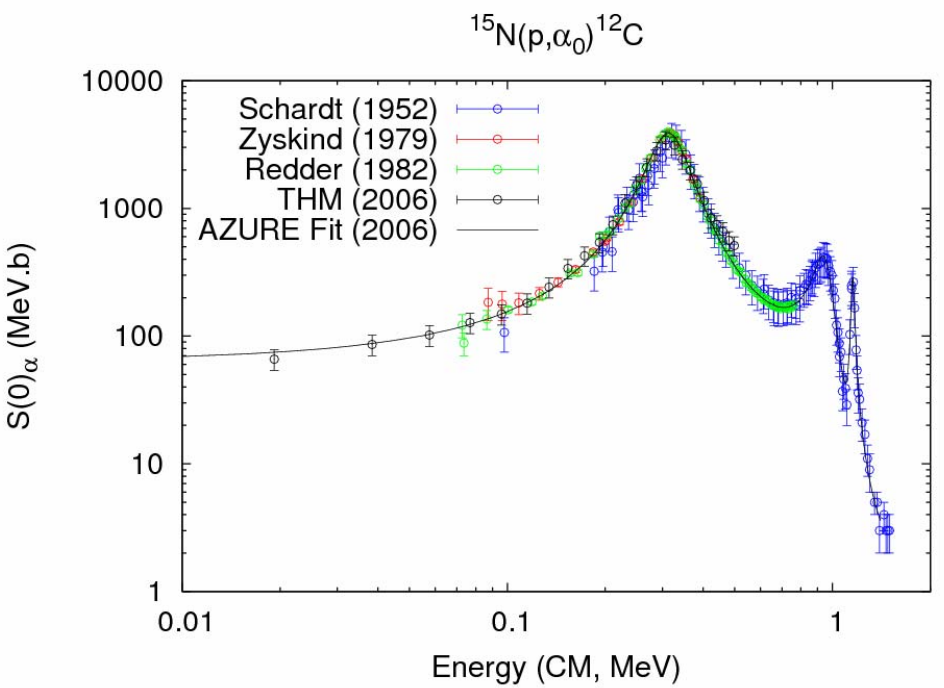


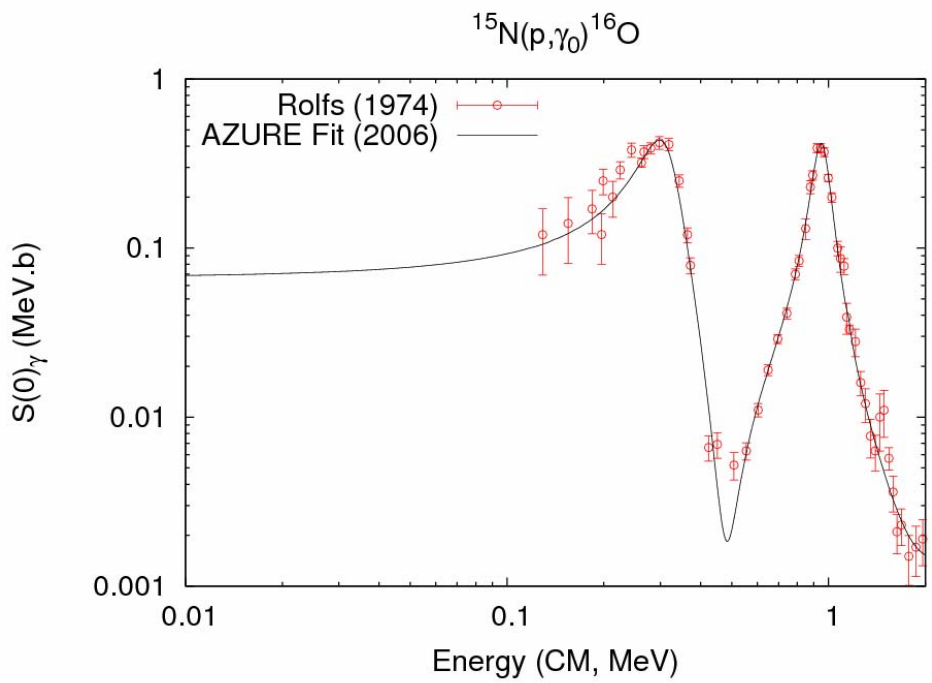

Experimental data, Nitrogen gas
^{40}K
^{206}Tl
^{15}N(p,γ)^{16}O
^{11}B(p,γ)^{12}C
Counts
E (MeV)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
0
2
4
6
8
10
12
14
16
18
20


Counts per 100 keV
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
0
5
10
15
E_γ [MeV]
$^{15}N(p,\alpha\gamma)^{16}O$
$^{14}N(p,\gamma)^{15}O$
$^{15}N(p,\gamma)^{16}O$
$^{11}B(p,\gamma)^{12}C$
BG
BG
BG

The first branch $^{15}N(p,\alpha)/(p,\gamma)$

New results with multi-level, multi-channel R-matrix code AZURE





New R-matrix fit leads to different predictions about the 1st CNO branching ratio, new experiments are presently underway, Notre Dame & LUNA, to reduce the experimental uncertainties in the $^{15}N(p,\gamma)$ capture & the $^{15}N(p,p)$ scattering channel.

ND detection set-up

Institute for Structure and Nuclear Astrophysics

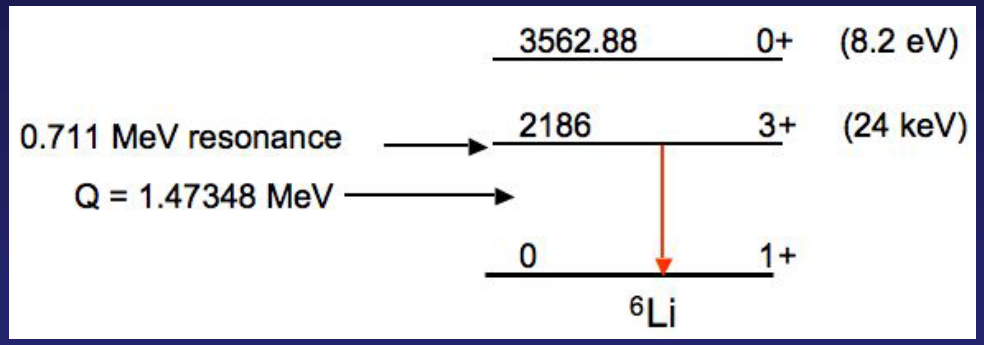
$^{15}N(p,\gamma)^{16}O$ @ LUNA

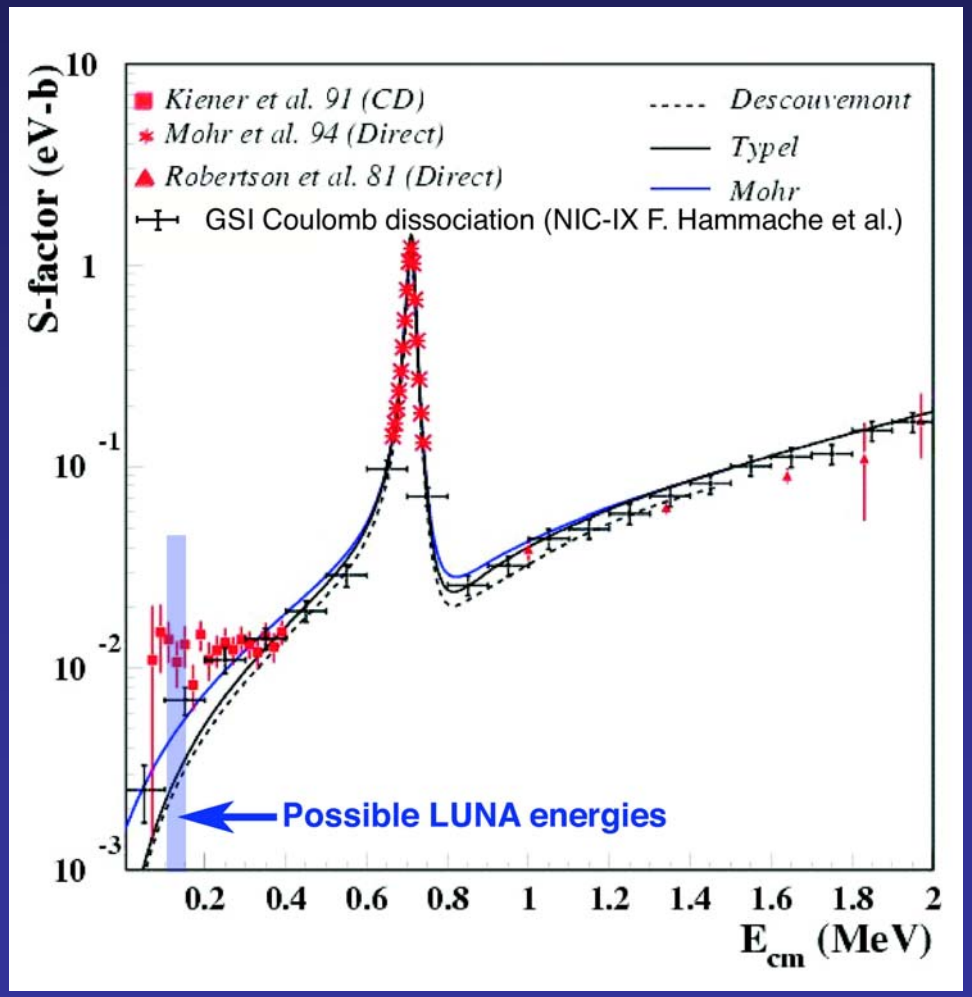
- High resolution set-up starting from january 2008;
- High efficiency set-up 2009, to directly reach 50 keV (AGB Gamow peak).

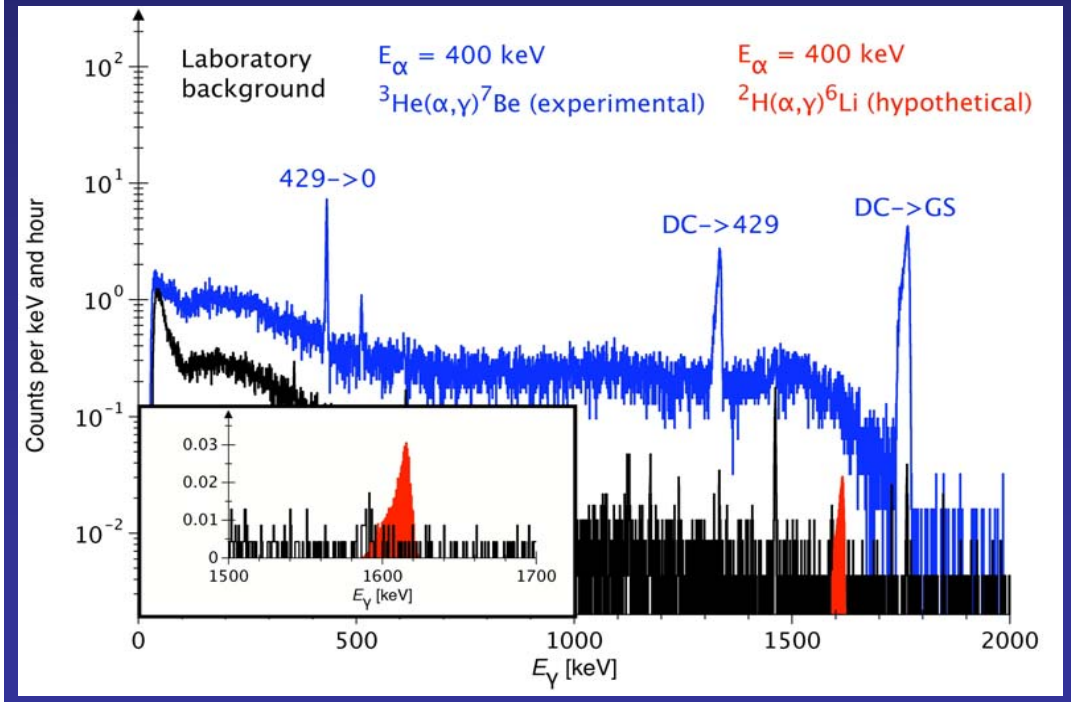
$^2H(\alpha,\gamma)^6Li$

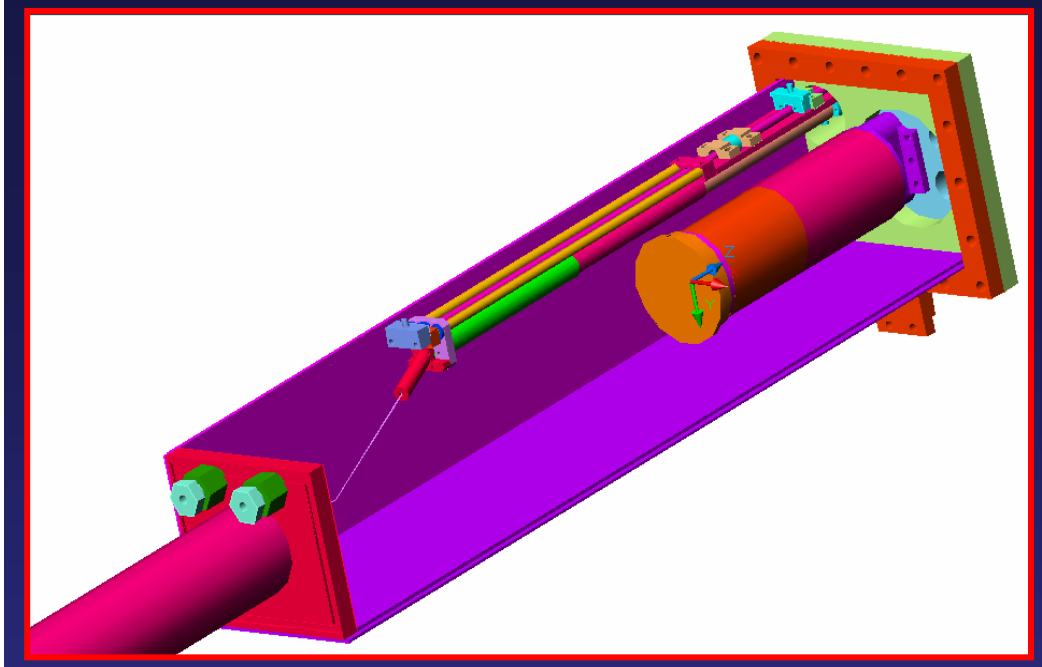
Q=1.47 MeV

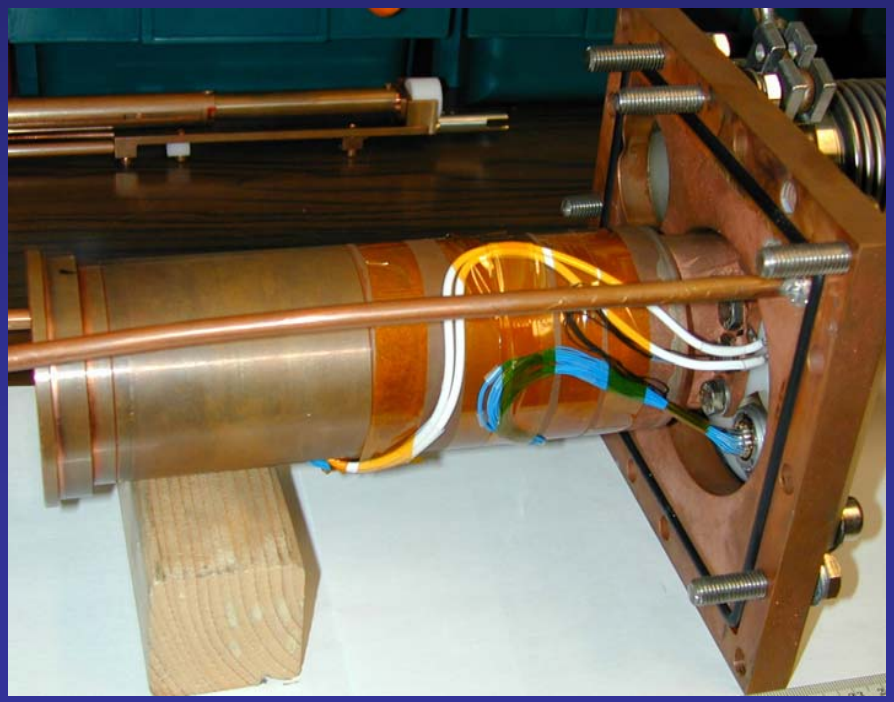
Burning energy: 50-300 keV

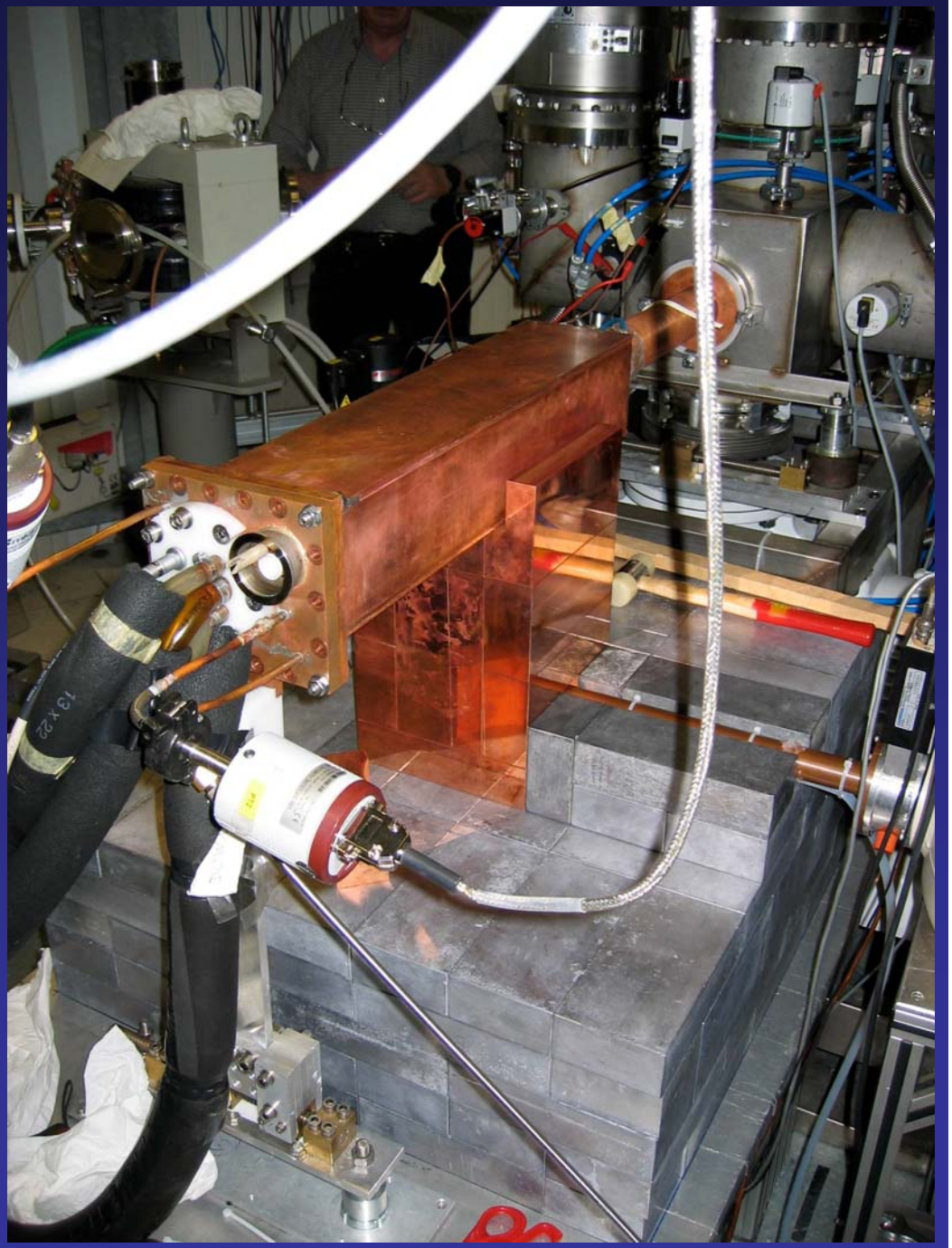


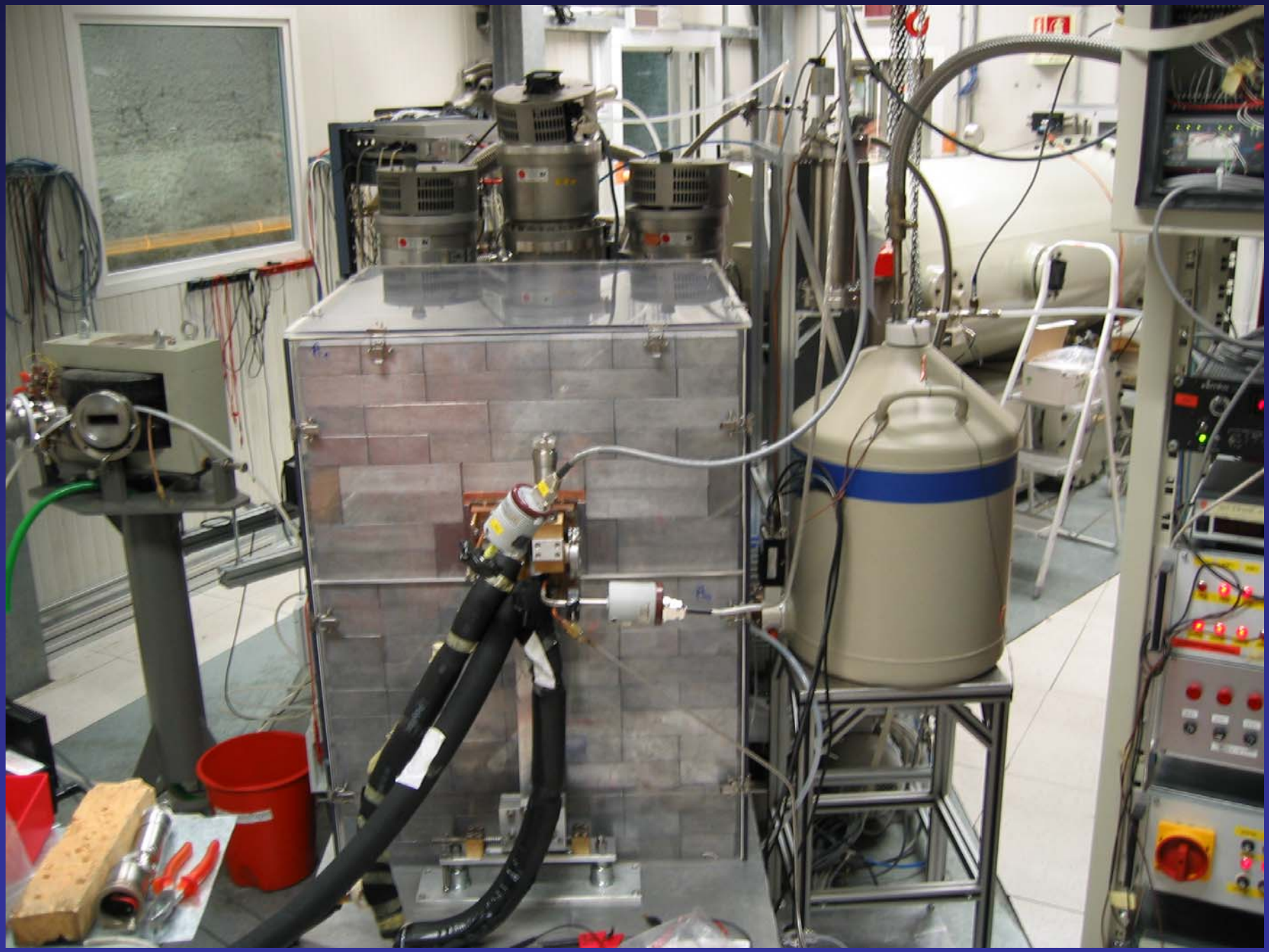












LUNA-MV
LETTER OF INTENT

Submitted to LNGS scientific board

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

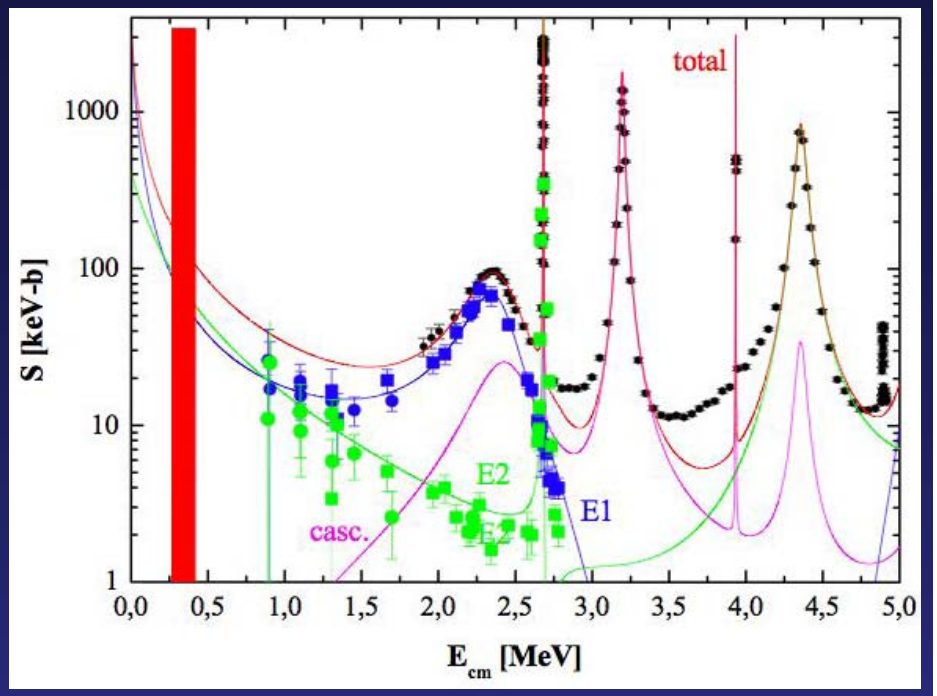
the "Holy Grail" reaction..

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

reactions powering the astrophysical s-process

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

- MV-accelerator
- ^{12}C-enriched targets
- Beam intensity: 500μA
- Detection efficiency: 50% total
  2.5% single segment (angular distributions)
- Detection set-up: scintillator-crystal ball



- We would have the possibility to measure angular distributions down to 600 keV and total S-factor down to 500 keV with 10% accuracy
- Theoreticians ask for 10% uncertainty on $S_{tot}(300)$

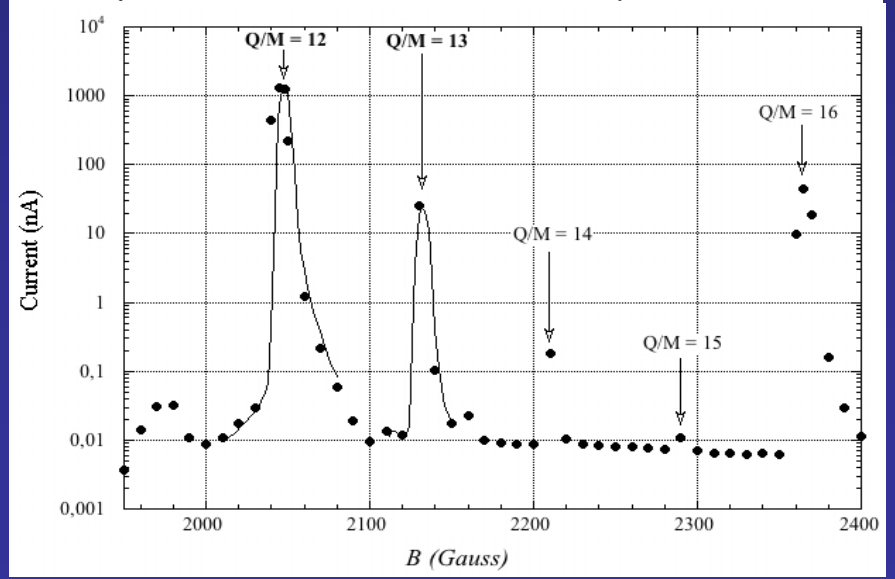
Great step forward: so far, 10% accuracy only over 1.5 MeV

Target preparation

$$\frac{^{13}C}{^{12}C} \approx 10^{-2} \qquad \frac{\sigma\left(^{13}C(\alpha,n)^{16}O\right)}{\sigma\left(^{12}C(\alpha,\gamma)^{16}O\right)} \approx 10^{7}$$

goal: reduce ^{13}C content to $10^{-7} \div 10^{-6}$

Implantation facility @ LNL



magnet resolving power seems ok

How to measure?

sharp resonance of $^{13}C(p,\gamma)^{14}N$ @ 1.75 MeV

Reactions powering the astrophysical s-process

Neutron source reactions: **$^{13}C(a,n)^{16}O$** and **$^{22}Ne(a,n)^{25}Mg$**

- Important for nucleosynthesis of elements heavier than iron

-Take place in helium- and carbon-burning reactions in massive and AGB stars

-For $^{13}C(a,n)^{16}O$ data above 270 keV are available
(Gamow peak ~170 keV, LUNA ~200 keV)

- For $^{22}Ne(a,n)^{25}Mg$ data above 850 keV are available
(Gamow peak ~470-700 keV, LUNA ~630 keV)

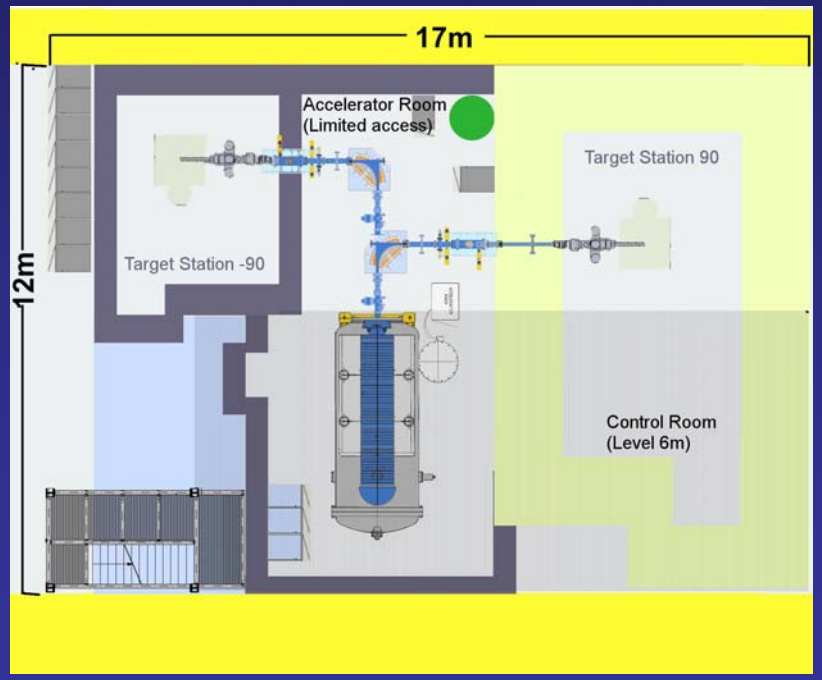
→ MV-accelerator

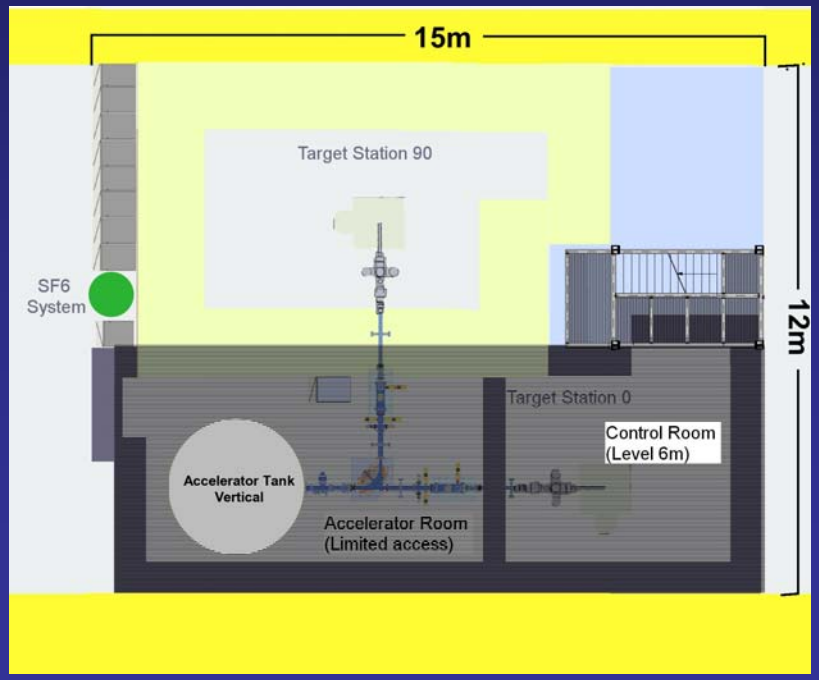
Accelerator

Accelerator requirements:

- MV electrostatic accelerator
- Option 1: HVEE + conventional RF ion source
- Option 2: NEC + ECR high charge state ion source

Two possible layouts:



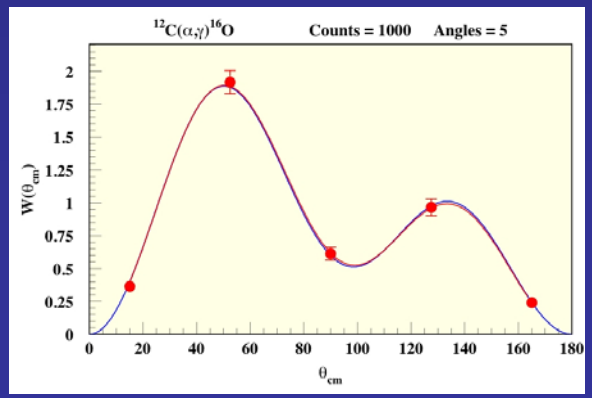


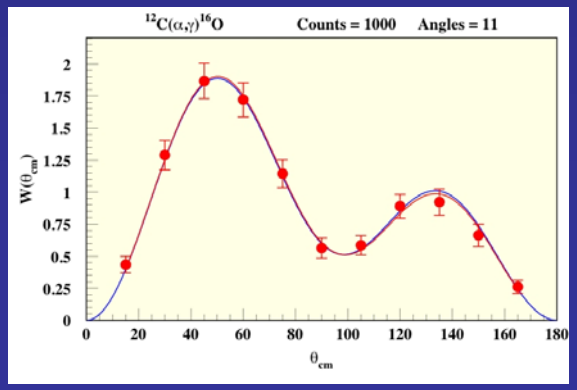
letter of intent submitted to LNGS

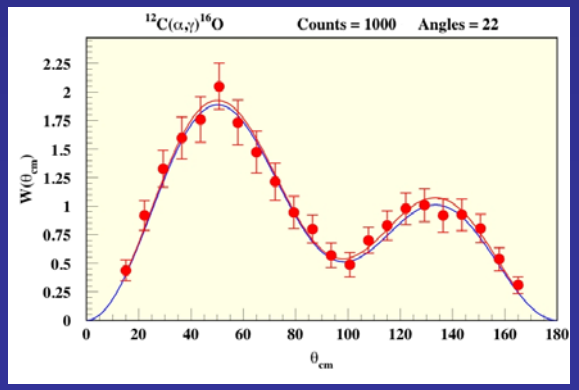
γ detector

	Density (g/cm^3)	l_g (cm) @7 MeV	Light yield (ph/keV)	ΔE/E (%) @1 MeV
NaI(Tl)	3.67	7.71	40	6
BGO	7.13	3.52	**8÷10**	11 ÷ **12**
CsI(Na)	4.51	5.9	45	6 ÷ **7**
$LaBr_3$(Ce)	5.29	5.5	63	2.3

segmented chrystal ball

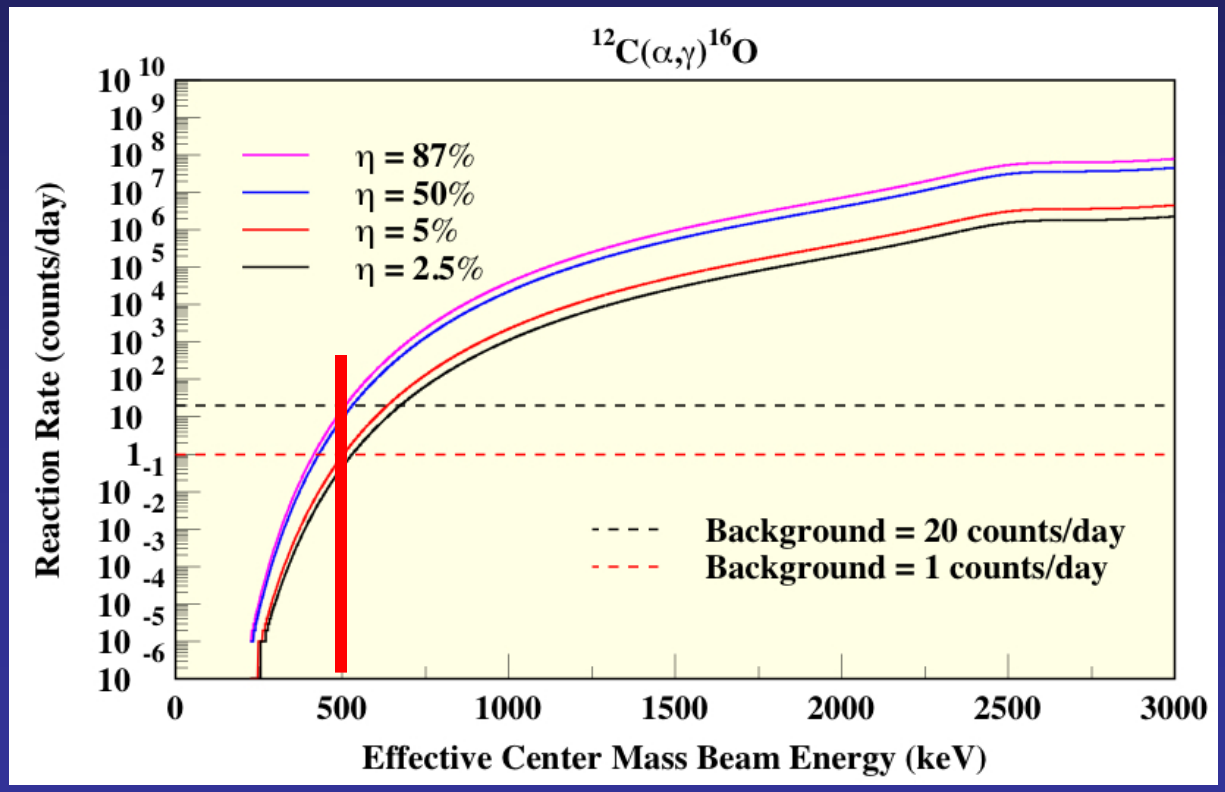






$^{12}C(\alpha,\gamma)^{16}O$

counting rate



50% effic.

400 μA

solid target
$2 \cdot 10^{18}$ atoms/cm2

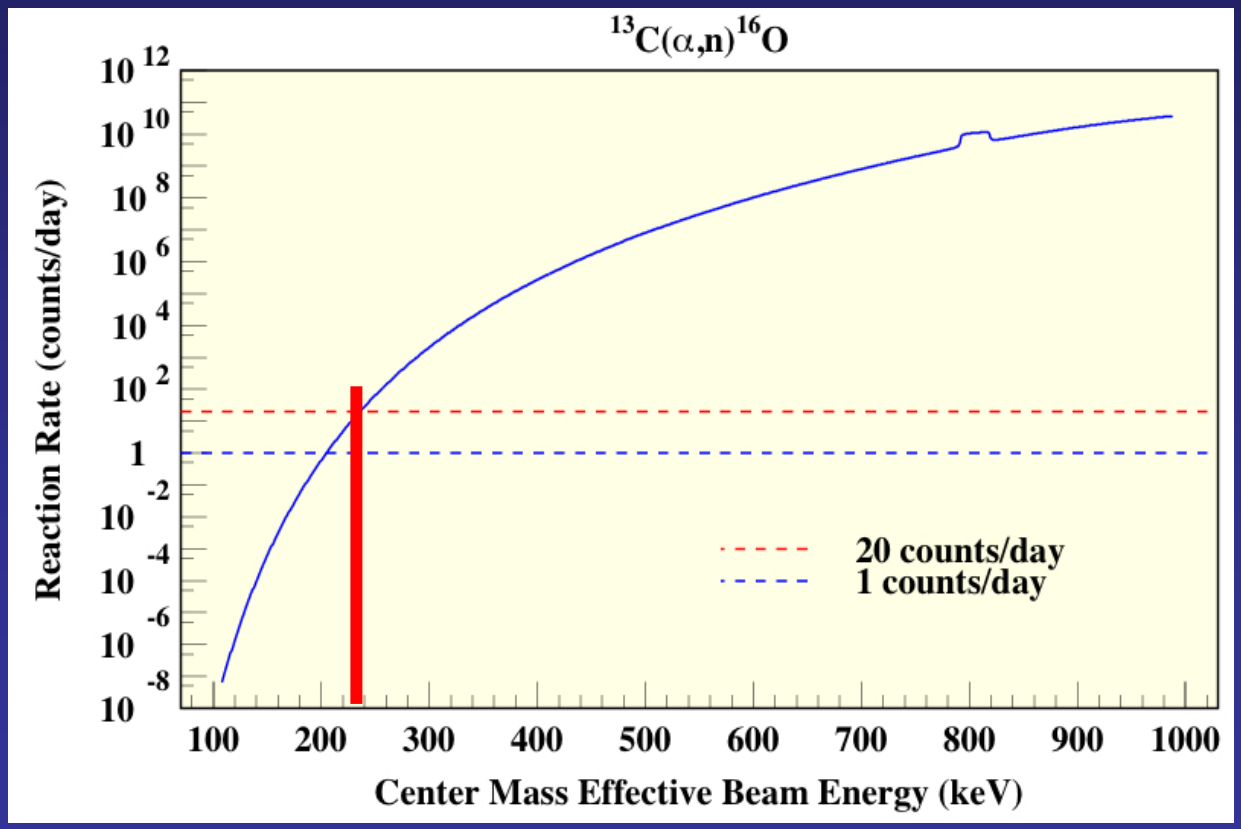
neutron detector

"Stuttgard" detector
existing

liquid scintillator detector
new – to be developed

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

counting rate



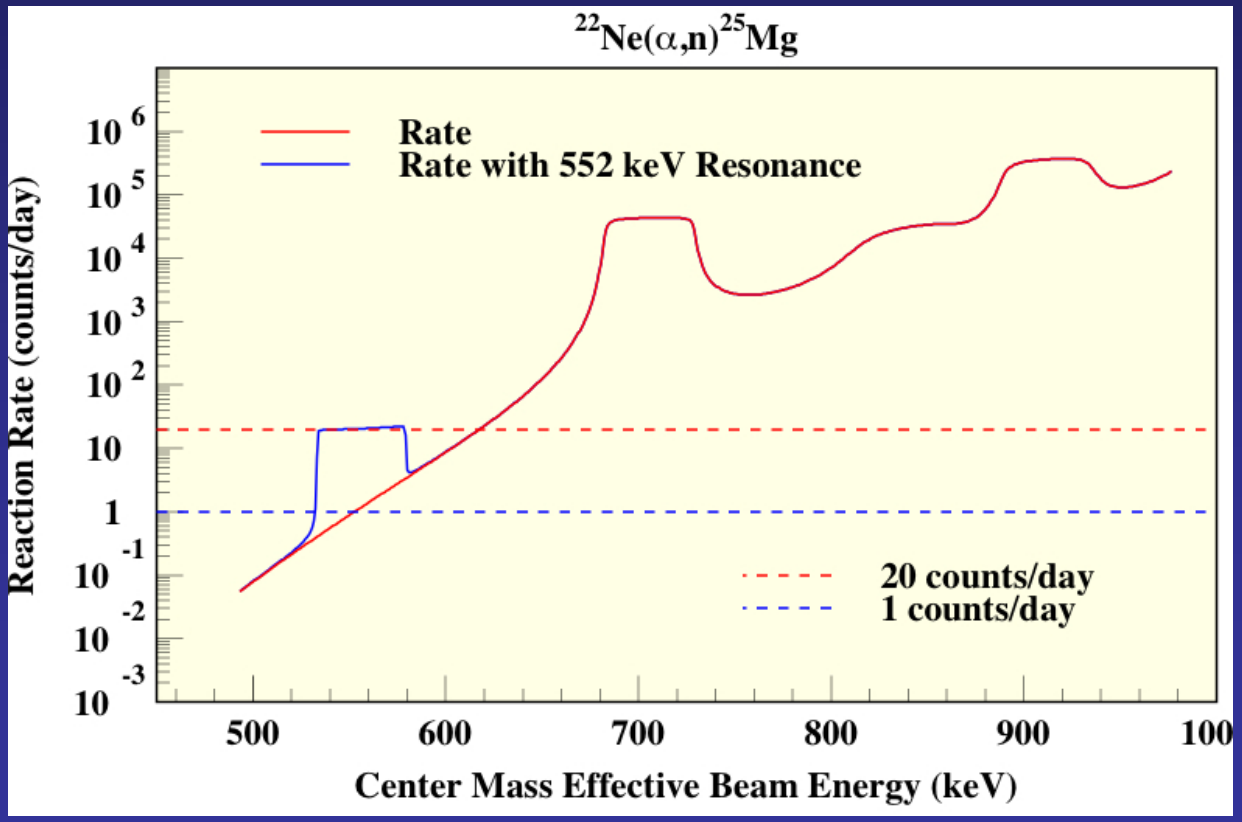
10% effic.

100 μA

solid target
$5 \cdot 10^{18}$ atoms/cm2

$^{22}Ne(\alpha,n)^{24}Mg$

counting rate



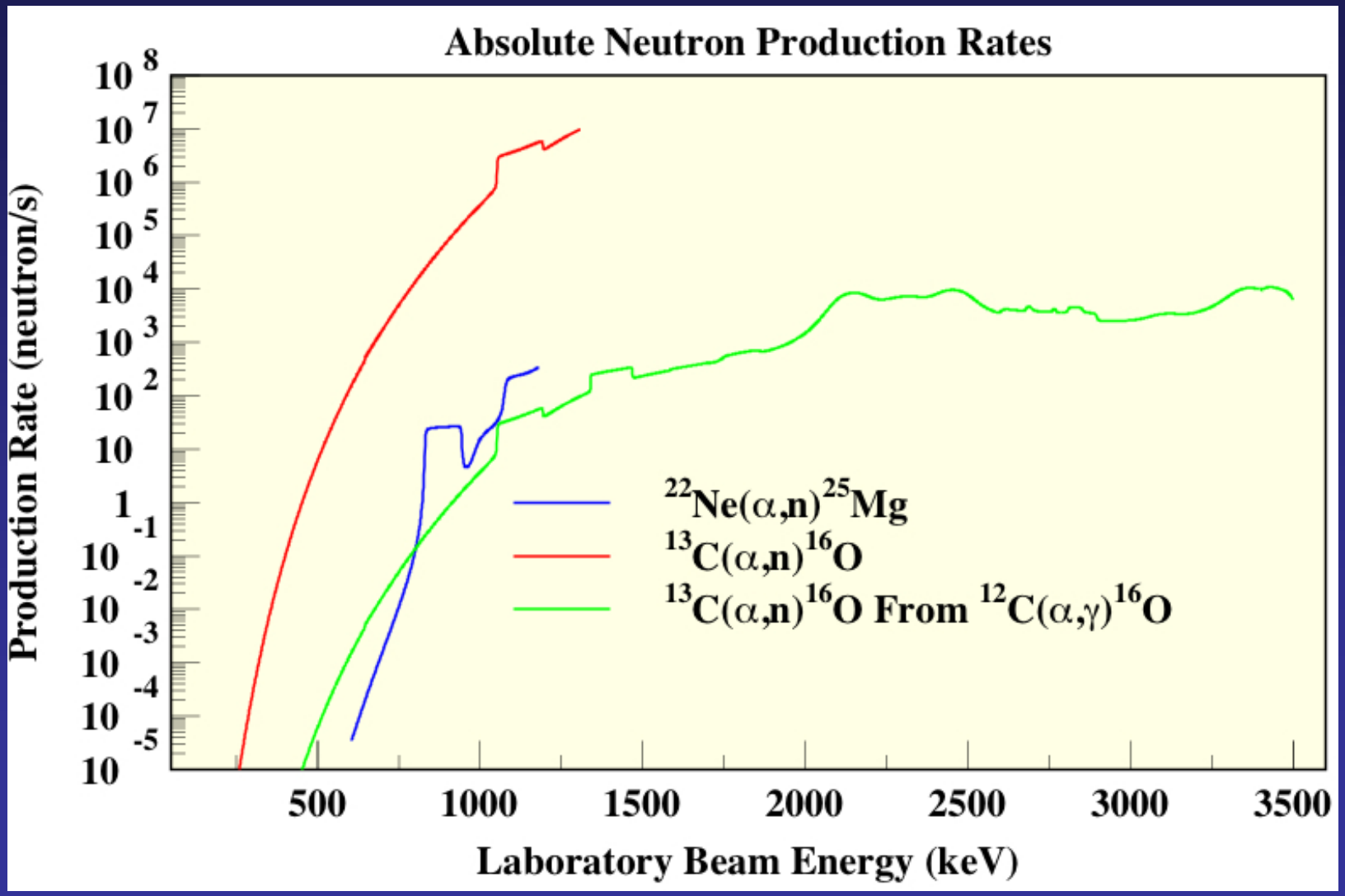
10% effic.

100 μA

5 mbar
10^{18} atoms/cm2

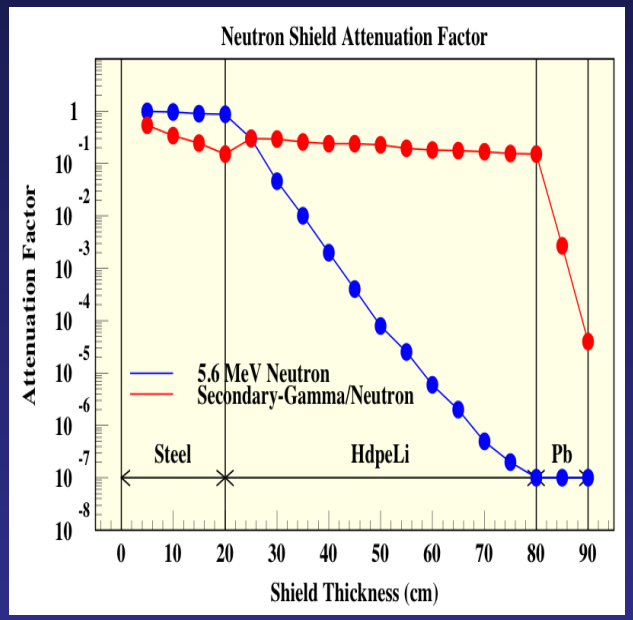
Neutron shielding

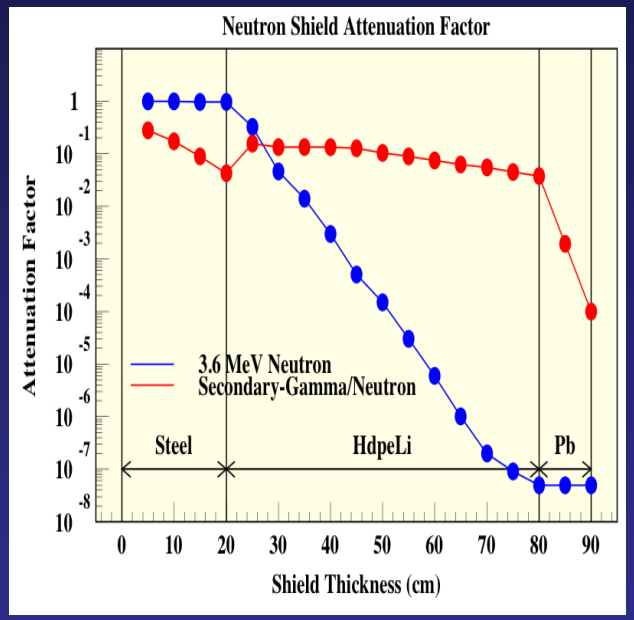
neutron production rate

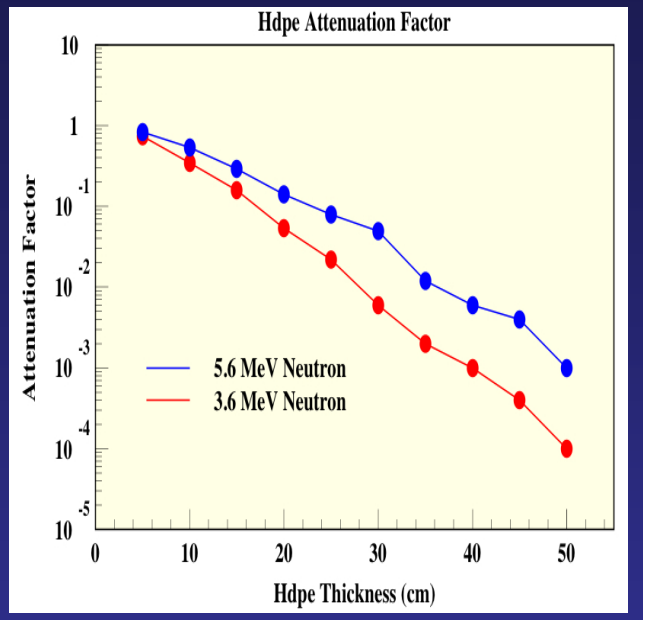


Neutron shielding

GEANT4 simulation – Fluka simulation







20 cm steel
60 cm HD poliethylene(Li)
10 cm lead

$\phi_{nat}=3.78\cdot10^{-6}$ neutrons/($m^2\cdot d$)

LUNA COLLABORATION

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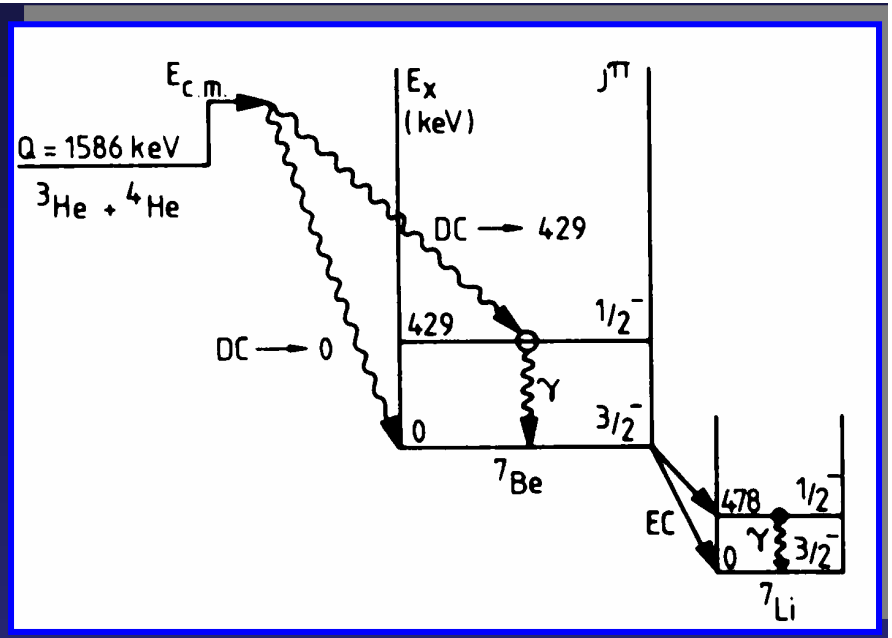
G. Gervino

$^3He(\alpha,\gamma)^7Be$

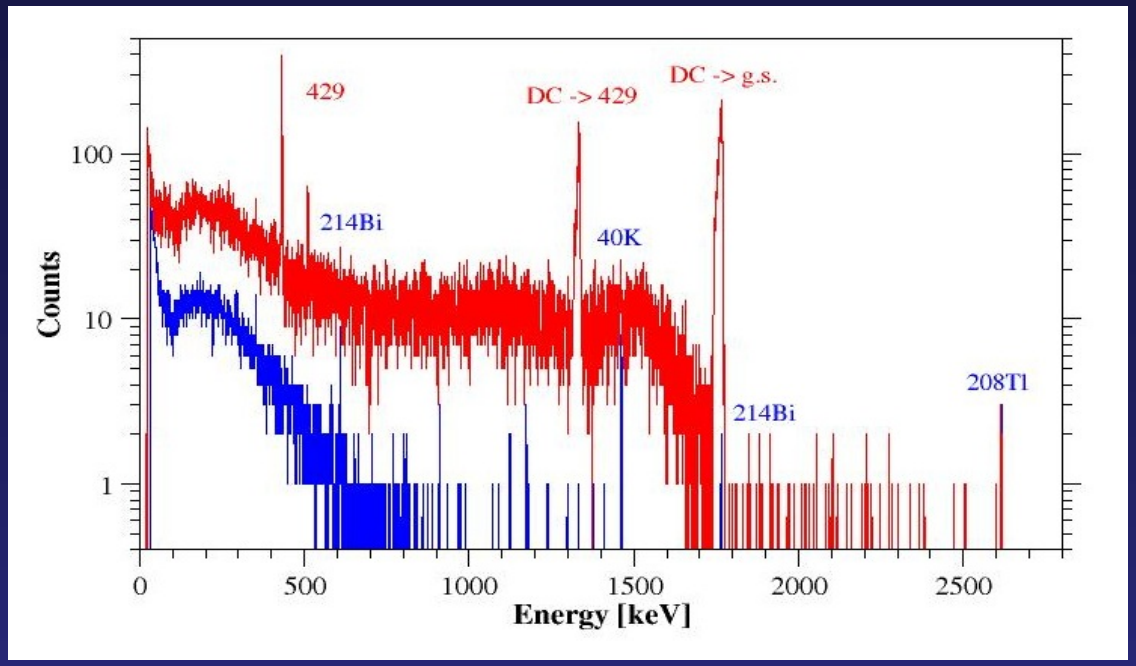
Q=1.6 MeV

- Solar Neutrinos: ^7Be, ^8B
- BBN ^7Li

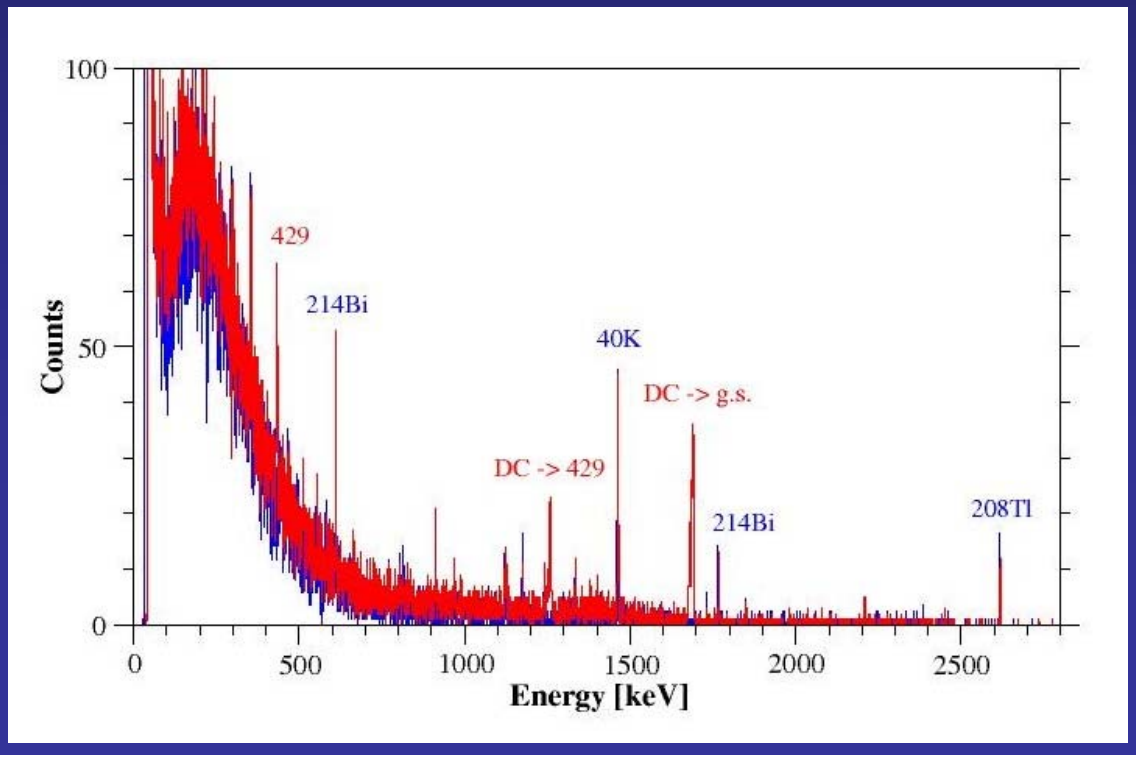


- Cross section from **prompt gamma** down to 90 keV (CM energy) using ^4He beam on ^3He target
- Activation via off-line **radioactive decay** measurements of the ^7Be atoms collected in the beam catcher
- All with a final error < 5 %

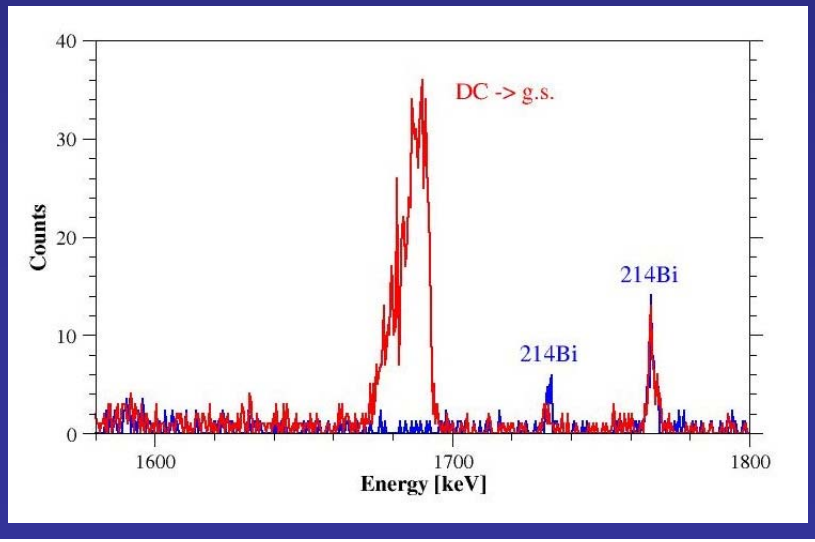
Prompt γ-spectra



- ^{4}He beam @ 400 keV
- <I> ~ 300 μA
- Irradiation time: 4.4d



- ^{4}He beam @ 220 keV
- <I> ~ 240 μA
- Irradiation time: 24.4d



- σ of $^3He(\alpha,\gamma)^7Be$ down to 93 keV
  $^7Be \approx$ prompt γ

- $S_{34}(0) = 0.560 \pm 0.016$ keV barn
  $\Delta\Phi(\nu_B)$ reduced from 12% to 10%
  $\Delta\Phi(\nu_{Be})$ reduced from 9.4% to 5.5%
  (C. Pena Garay)

LUNA

INFN - Laboratori Nazionali del Gran Sasso

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- INFN :

Genova, LNGS, Milano, Napoli, Padova, Torino

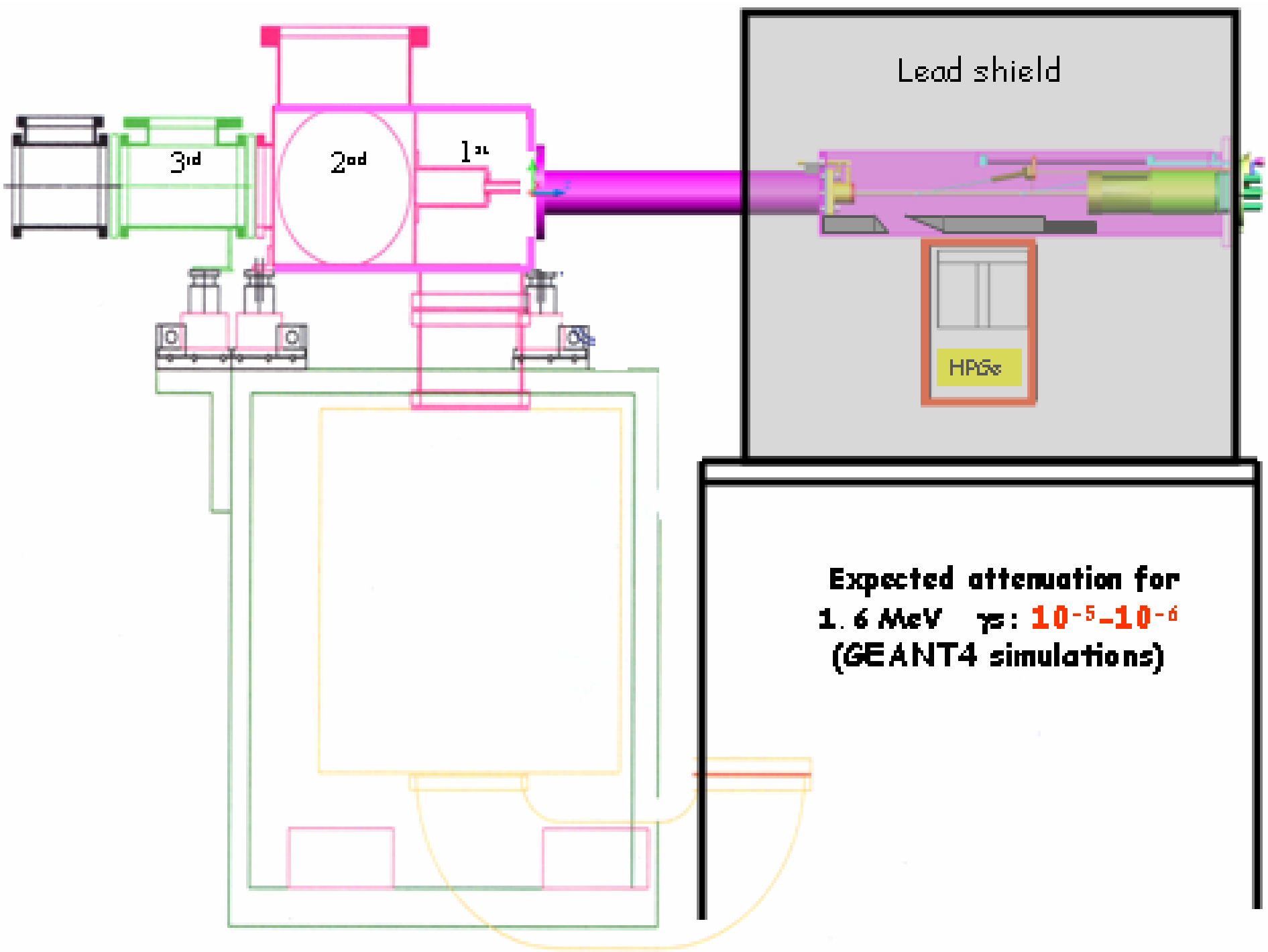
- Inst.Physik mit Ionenstrahlen, Ruhr-Universität Bochum (GE)
- Atomki Debrecen (Hungary)

ACTIVITY

^{7}Be counting efficiency	1.8%
Beam intensity	1.5%
Beam heating effect	1.3%
Target density without beam	0.6%
^{7}Be backscattering	0.5%
Incomplete ^{7}Be collection	0.4%
^{7}Be distribution in catcher	0.4%
478 keV branching	0.4%
^{7}Be half-life	0.1%
^{3}He purity in target	0.1%

PROMPT-γ

Beam intensity	1.5%
Target density	1.5%
^{3}He purity	0.1%
Efficiency	1.5%
Angular distribution	1.5%



Expected attenuation for 1.6 MeV γs: 10^{-5}–10^{-6} (GEANT4 simulations)