Status of the LUNA experiment

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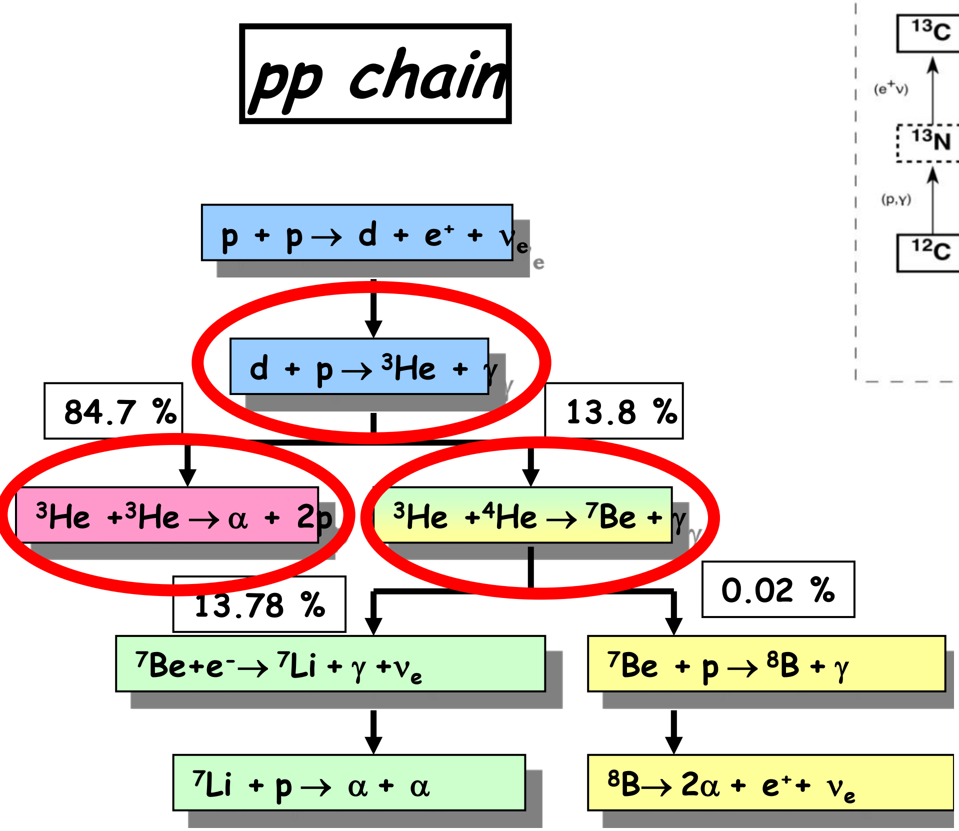
Laboratory
Underground
Nuclear
Astrophysics

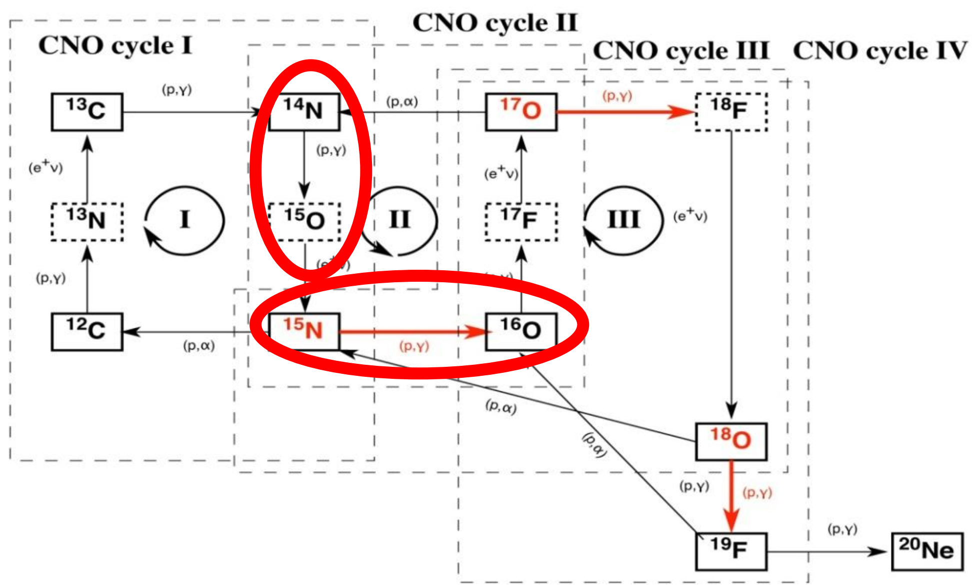
Outline:

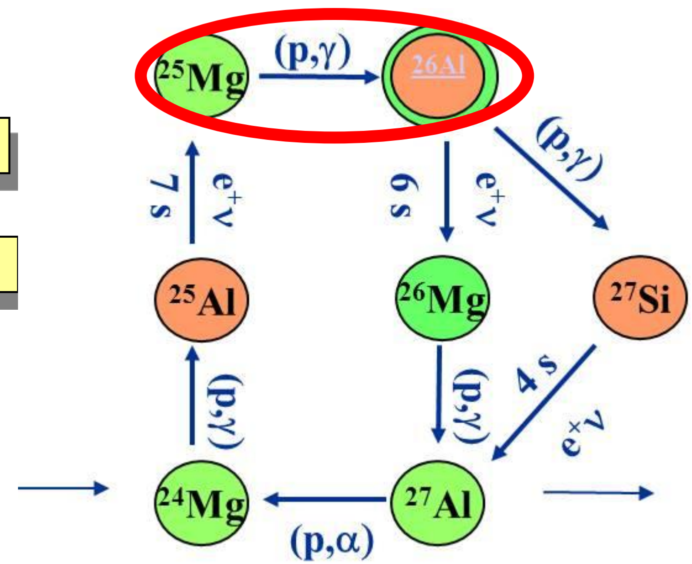
- Nuclear Fusion reactions in stars
- Why going underground
- The Luna Experiment: most important results
- On-going measurements and future perspective: the LUNA-MV project

Hydrogen burning

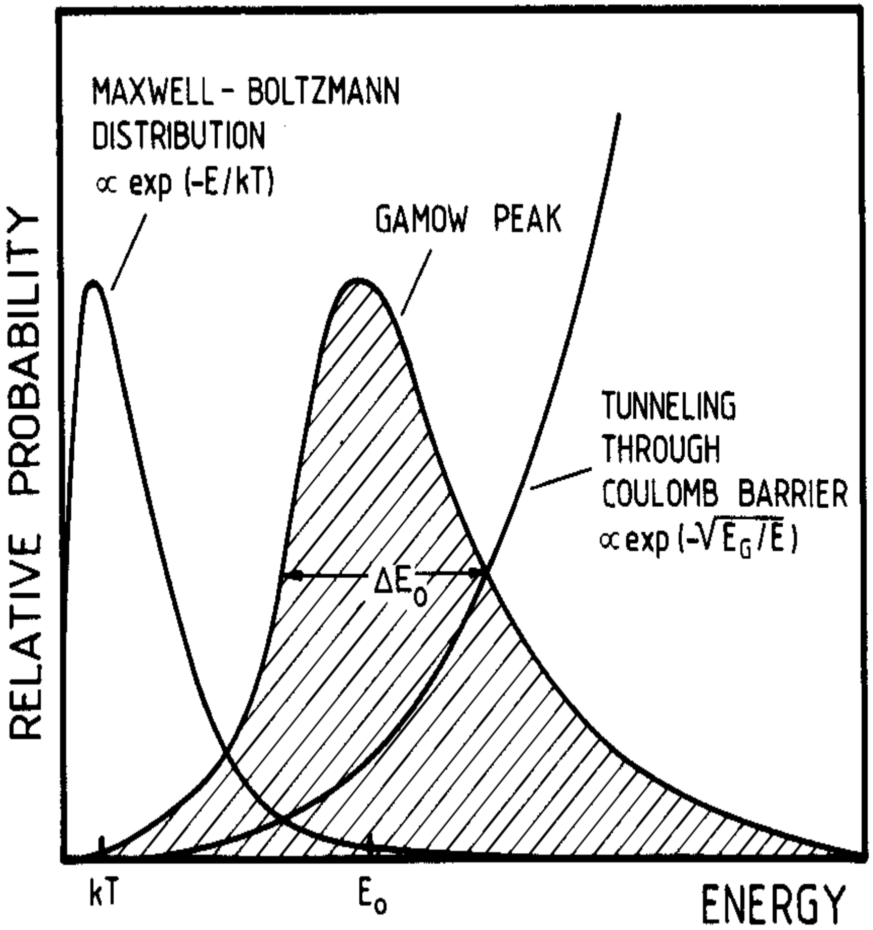
$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 26.73\ MeV$$







Nuclear reactions in stars



Sun:

T= 1.5 10^7 K

kT = 1 keV<< E_C (0.5-2 MeV)

Reaction	E_0
$^3He(^3He,2p)^4He$	21 keV
$d(p,\gamma)^3He$	6 keV
$^{14}N(p,\gamma)^{15}O$	27 keV
$^3He(^4He,\gamma)^7Be$	22 keV

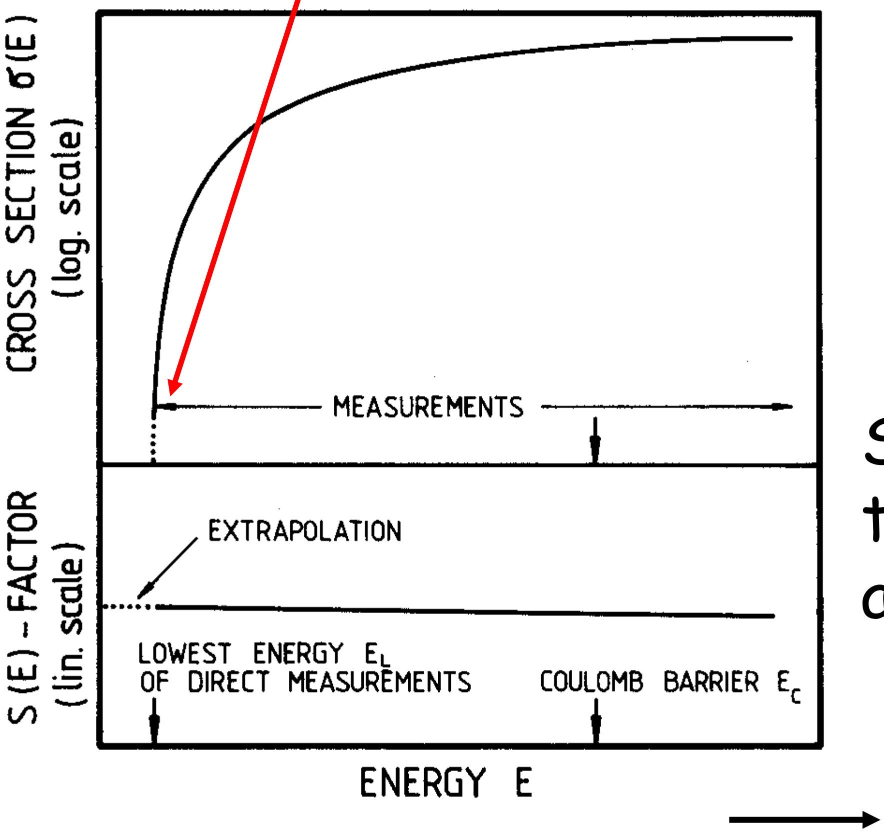
Cross section and astrophysical S factor

$$\sigma(E) = \frac{1}{E}\exp(-31.29 Z_1 Z_2 \sqrt{\mu/E})\, S(E)$$

Gamow factor E_G

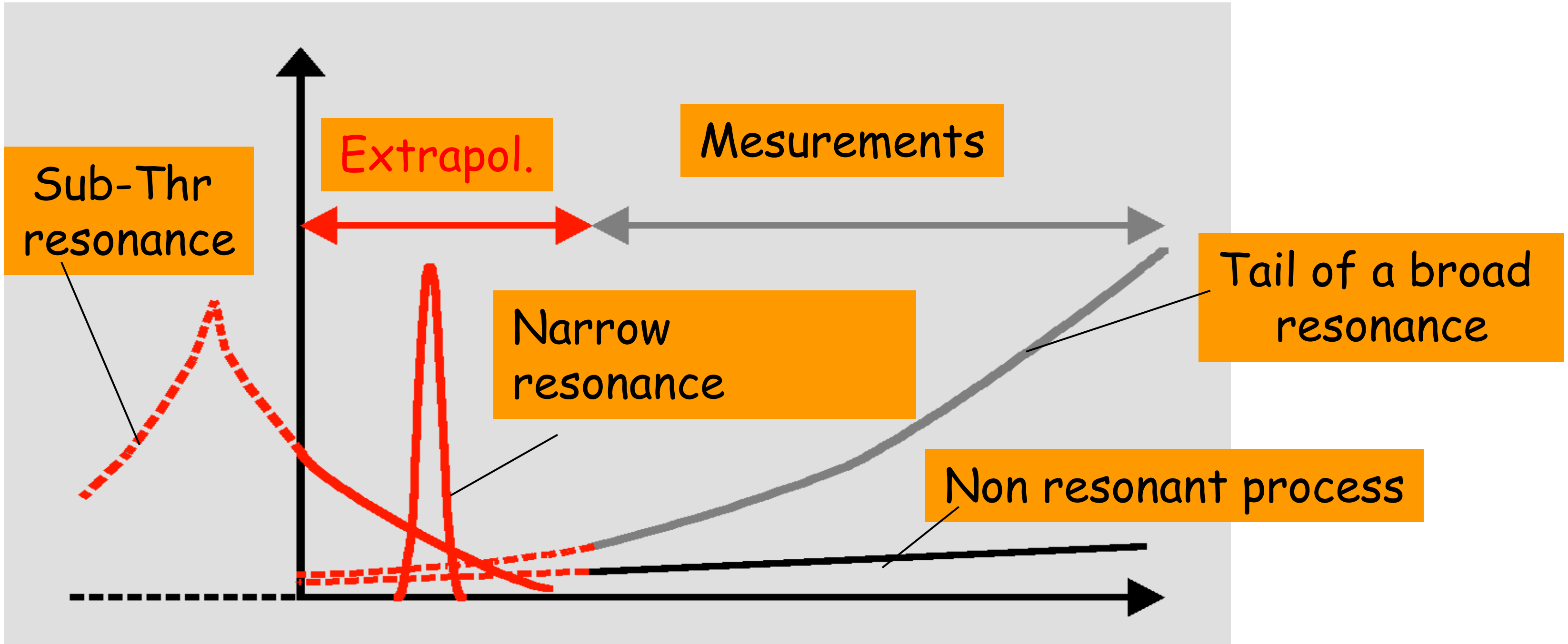
Astrophysical factor

Gamow energy region



Cross section of the order of pb!

S factor can be extrapolated to zero energy but if resonances are present?



Danger in extrapolations!

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 μA $q=1^+$)

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

σ = cross section = 10^{-15} barn

ε= efficiency ≈ 100% for charged particles
1% for gamma rays

R_{lab} ≈ 0.3-30 counts/year

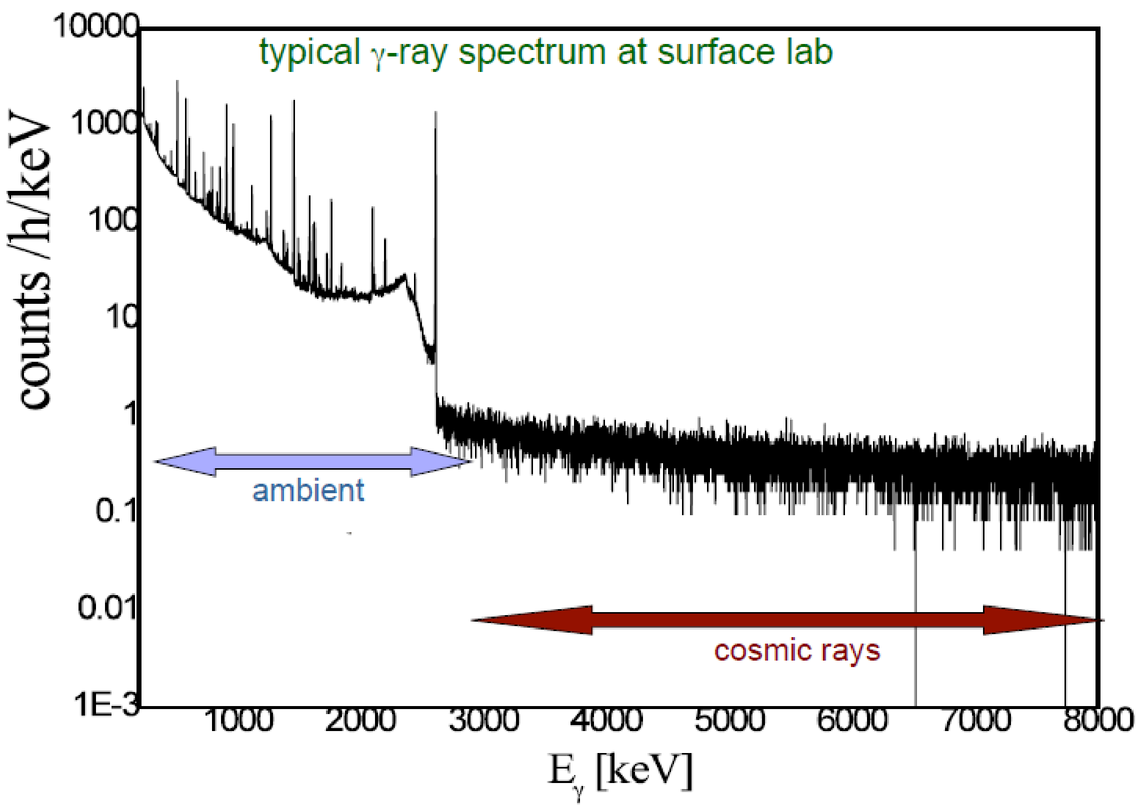
$R_{lab} > B_{beam\ induced} + B_{env} + B_{cosmic}$

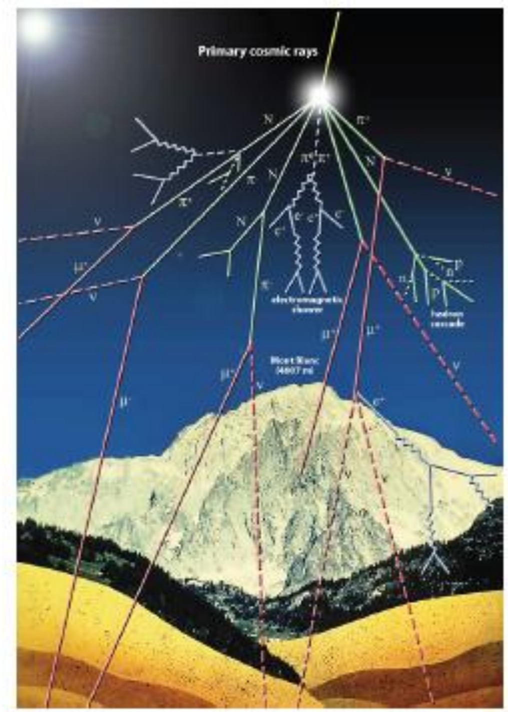
$B_{beam\ induced}$: reactions with impurities in the target

reactions on beam collimators/apertures

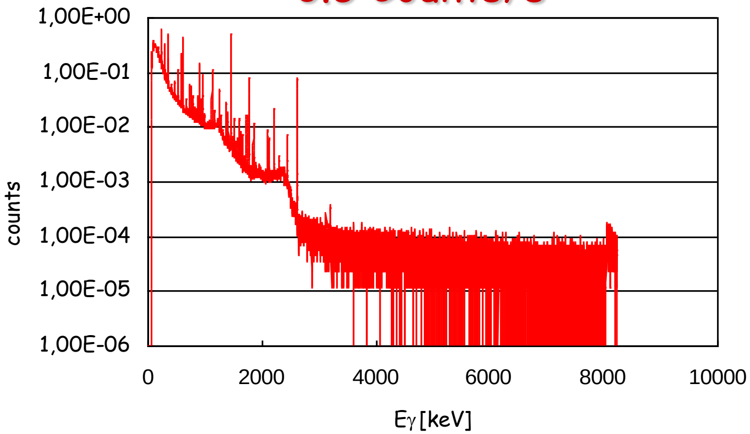
B_{env} : natural radioactivity mainly from U and Th chains

B_{cosmic} : mainly muons





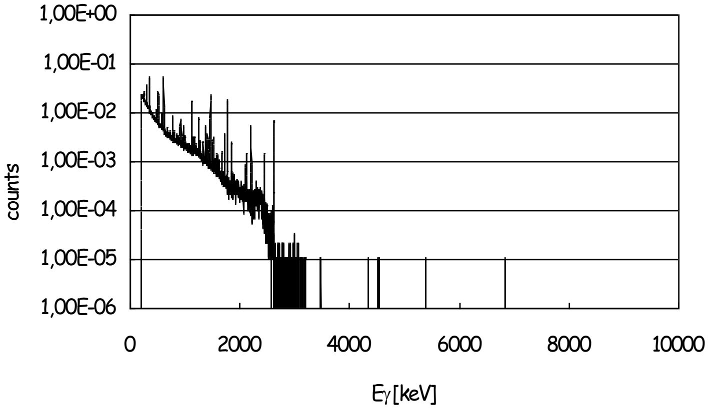
3MeV < Eγ < 8MeV:
0.5 Counts/s



HpGe

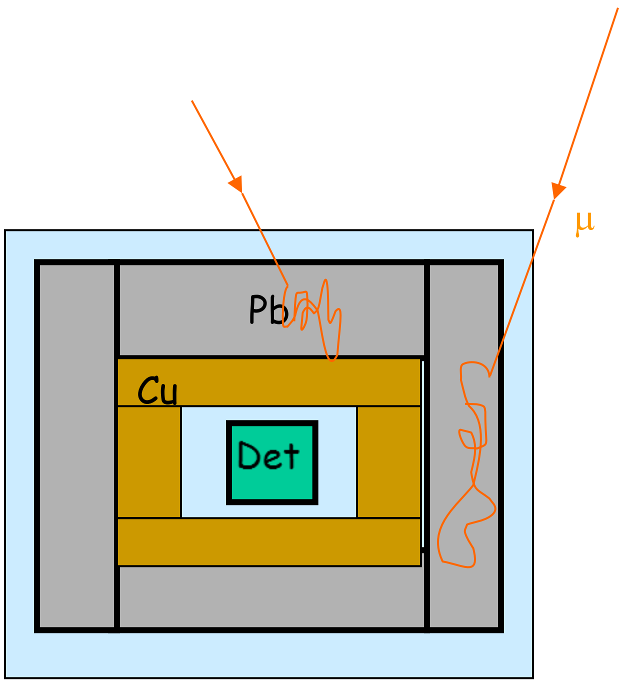
GOING UNDERGROUND →

3MeV < Eγ < 8MeV
0.0002 Counts/s

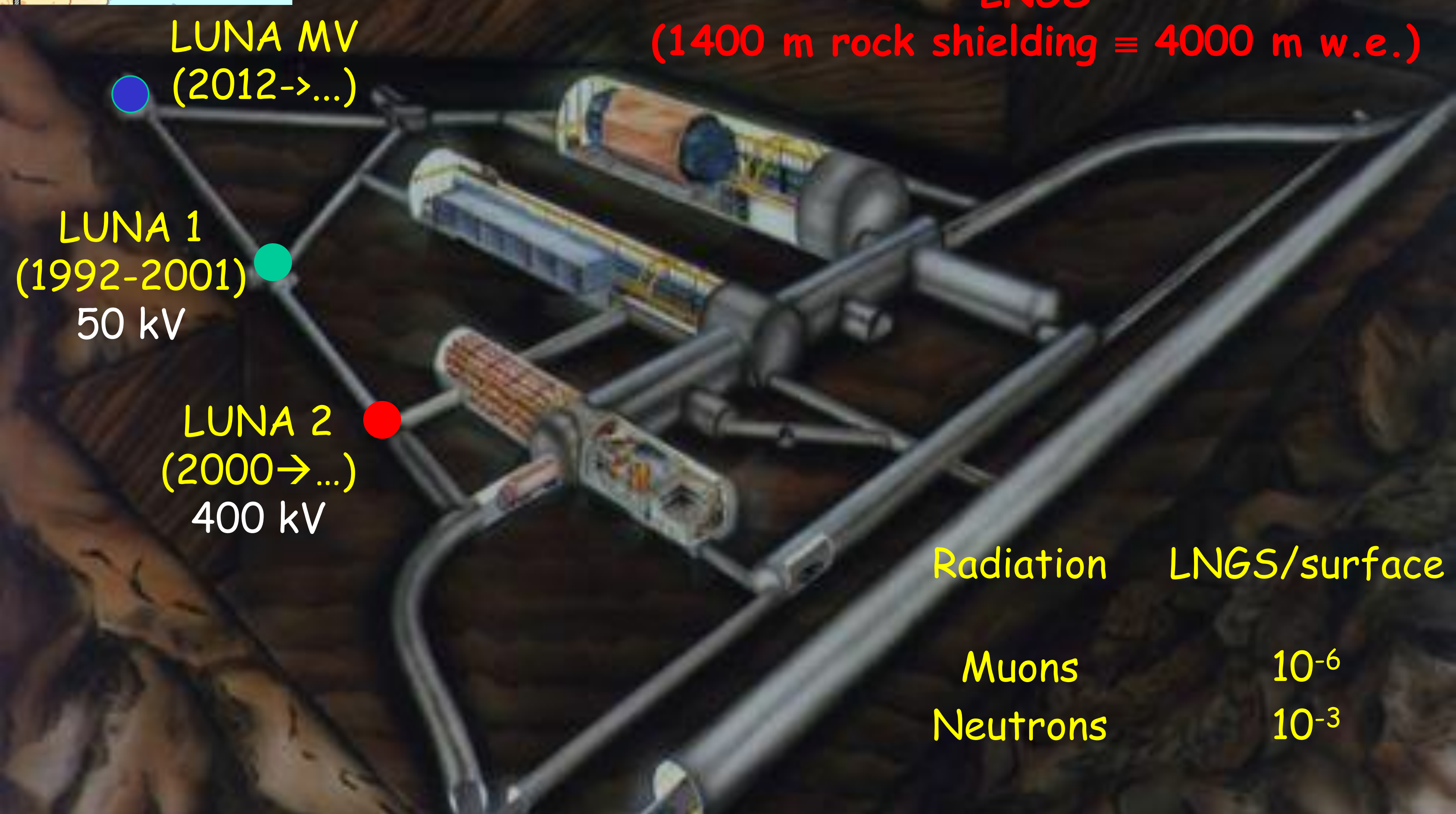


E_γ<3MeV→passive shielding for environmental background radiation

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 present program

completed!

CNO cycle

completed!

Ne-Na cycle

In progress

BBN

In progress

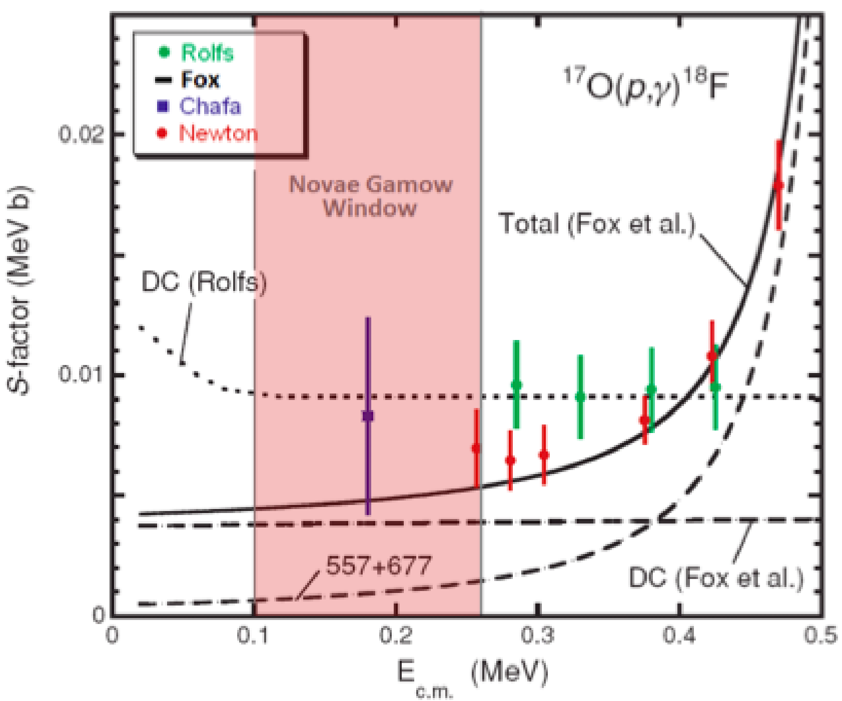
reaction	Q-value (MeV)	Gamow energy (keV)	Lowest meas. Energy (keV)	LUNA limit
$^{15}N(p,\gamma)^{16}O$	12.13	10-300	130	50
$^{17}O(p,\gamma)^{18}F$	5.6	35-260	300	65
$^{18}O(p,\gamma)^{19}F$	8.0	50-200	143	89
$^{23}Na(p,\gamma)^{24}Mg$	11.7	100-200	240	138
$^{22}Ne(p,\gamma)^{23}Na$	8.8	50-300	250	68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

to be completed presumably by 2014

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

17O+p is very important for hydrogen burning in different stellar environments:

- Red giants
- Massive stars
- AGB
- Novae



<u>Status of the art before the LUNA measurement:</u>

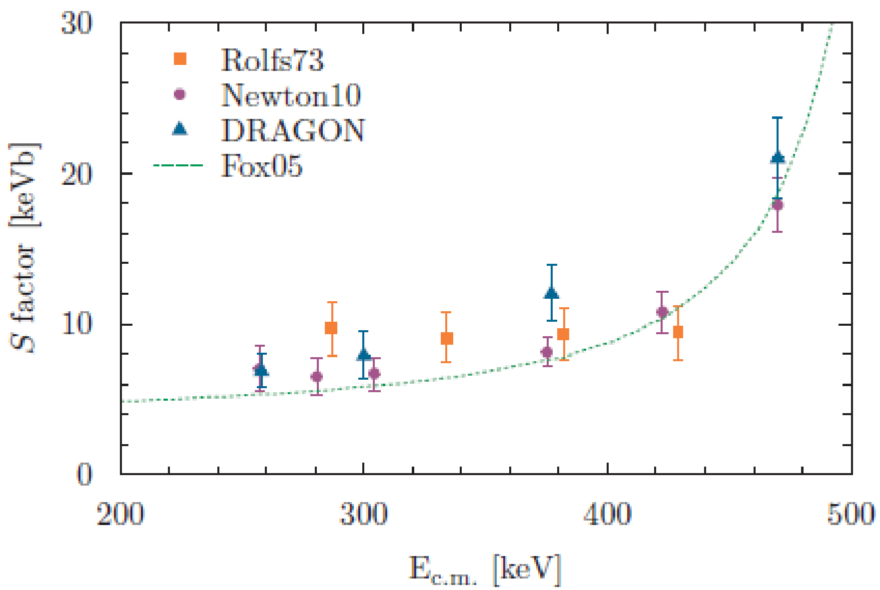
Rolfs et al., 1973, prompt γ
S_{DC} measured at 4 energies in the range E_{cm} = 290-430 keV
$S_{DC} \approx 9$ keV b for E_{cm}= 100-500 keV

Fox et al., 2005, prompt γ
discovered 183 keV resonance
$\omega\gamma = (1.2\pm0.2)\ 10^{-6}$ eV
calculation of DC
$S_{DC} = 3.74 + 0.676E - 0.249E^2$
determination of high energy resonance influence on S total

Chafa et al., 2007, activation
$\omega\gamma = (2.2\pm0.4)\ 10^{-6}$ eV
measured $S_{DC} = (8.3\pm4.0)$ keV b
$S_{DC} = 6.2 + 1.61E - 0.169E^2$
larger than Fox by more than 50%

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

Status of the art before the LUNA measurement:

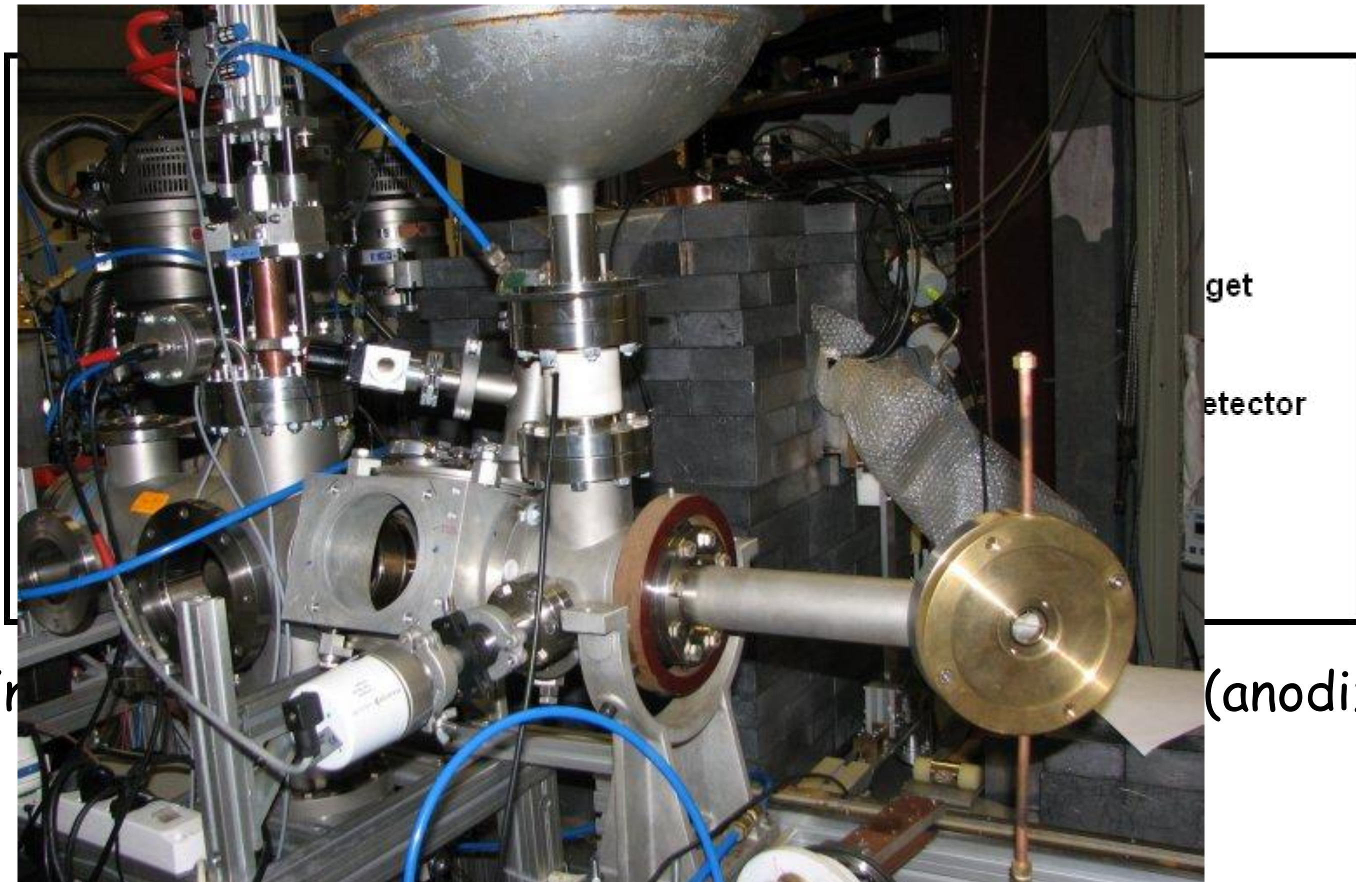


Newton et al., 2010, prompt γ
S_{DC} measured at 6 energies in the range E_{cm} = 260-470 keV
Calculated $S_{DC}(E)$ = 4.6 keV b (±23%)

Hager et al.(DRAGON), 2012, recoil separator
E_{cm} = 250-500 keV
S_{DC} higher than Newton and Fox. No flat dependence. Re-evaluate resonant contributions

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

183 keV resonance and direct capture component for E=200-370 keV measured with prompt gammas and activation →Gamow window for peak temperatures T=0.1-0.4 GK (Novae region) explored with the highest precision to-date

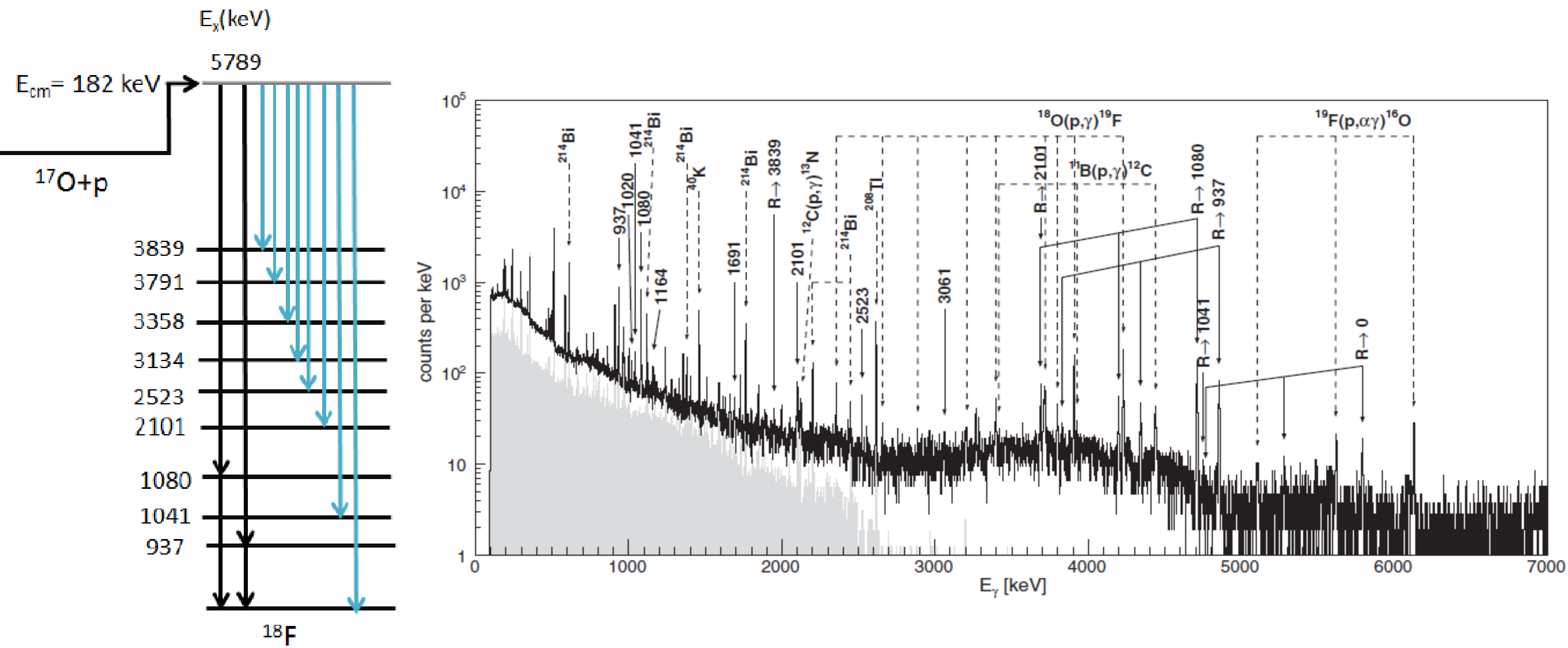


Er (anodization process)

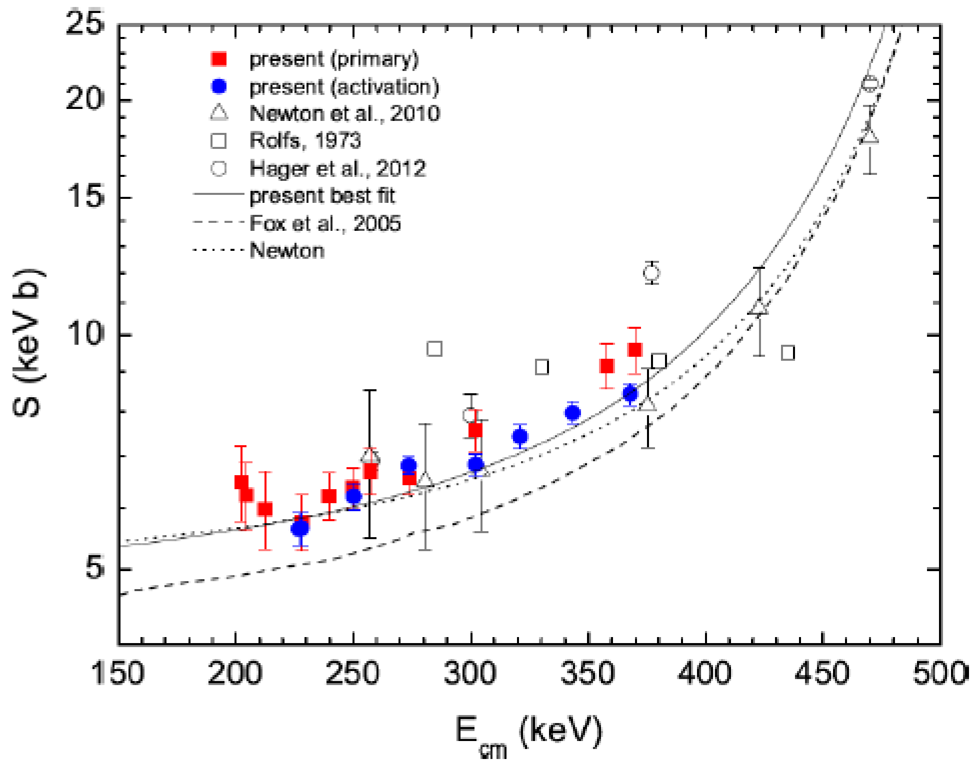
$^{17}O(p,\gamma)^{18}F$ measurement

183 keV resonance: $\omega\gamma$=1.67±0.12 μeV (weighted average of prompt and activation)

Several new transitions identified and branching ratios determined



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



The best fit includes the contribution from the E=557 and E=667 broad resonances from literature and a constant direct capture component

Improvement of a factor of 4 in the reaction rate uncertainty!

D. Scott et al., Phys Rev Lett 109 (2012) 202501

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:

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

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

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

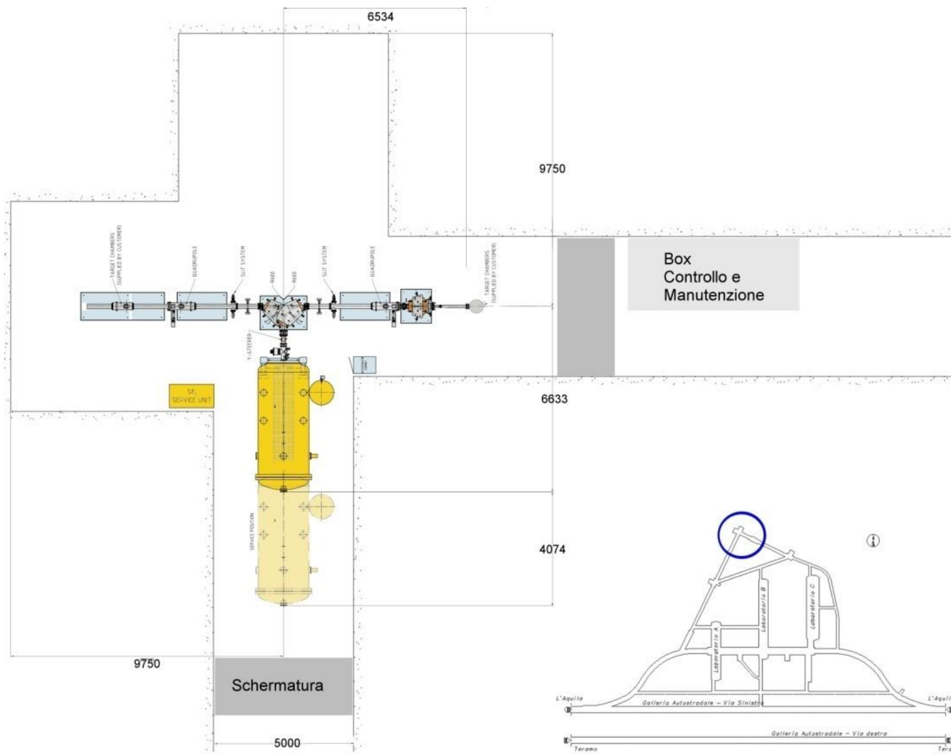
(α,γ) reactions on $^{14,15}N$ and ^{18}O

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

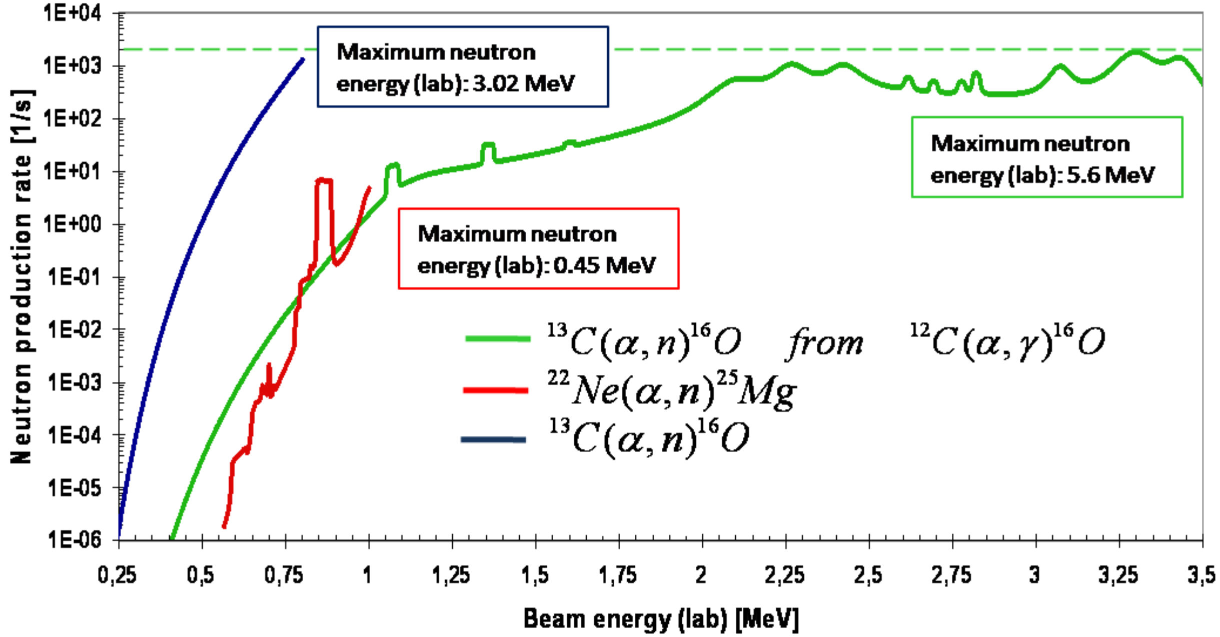
↓

Higher energy machine→ 3.5 MV single ended positive ion accelerator

Location at the "B node" of a 3.5 MV single-ended positive ion accelerator

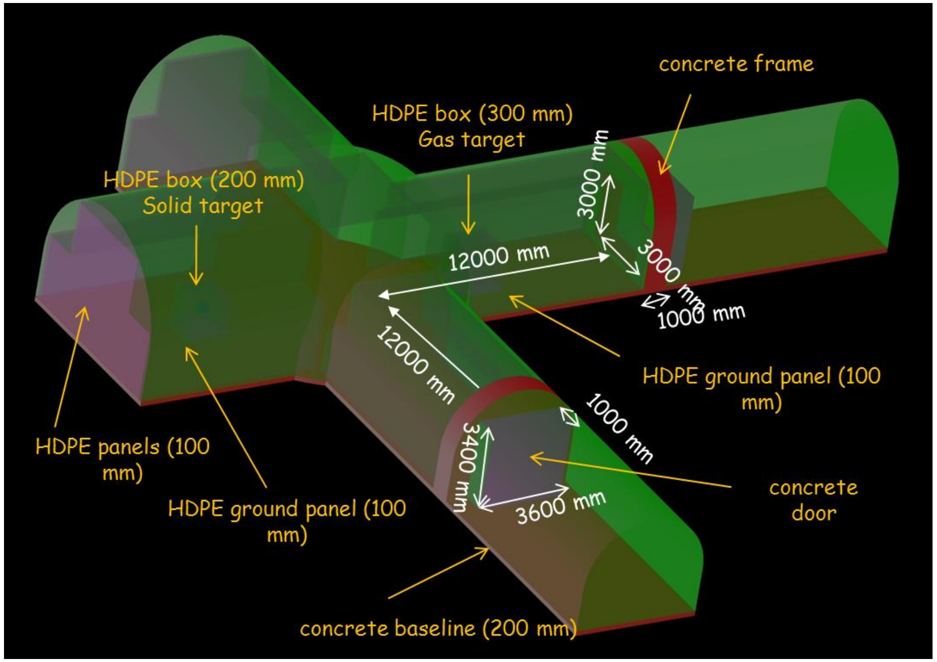


In a very low background environment such as LNGS, it is mandatory not to increase the neutron flux above its average value



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

Just-outside the wall the n-flux is less than 1% of the LNGS natural flux



"Progetto Premiale LUNA -MV"

Special Project financed from the Italian Research Ministry with 2.805 Millions of Euros in 2012

Schedule:
2012-2013 Hall preparation- Tender for the accelerator- Shielding
2014 Beam lines R&D- Infrastructures
2015 Accelerator installation - Beam lines construction- Detectors installation
2016 Calibration of the apparatus and first tests
2017 First beam on gas and solid targets

2.1 Millions of Euros still missing...

Workshop at LNGS 6-8 February 2013, LNGS

"Growing-up the LUNA MV collaboration"

luna-mv.lngs.infn.it

The LUNA-MV project aims at measuring the astrophysical key reactions

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

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

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

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

using a MV machine placed in the Gran Sasso underground laboratory.

Goal of the workshop is to define the scientific priorities as well as the structure and the task sharing of the new collaboration. A possible timeline of the project will also be discussed.

LOCAL ORGANIZING COMMITTEE

A. Guglielmetti (chair)
A. Formicola (scientific secretary)
M. Junker
P. Prati
F. Chiarizia (secretary)

INTERNATIONAL PROGRAMME COMMITTEE

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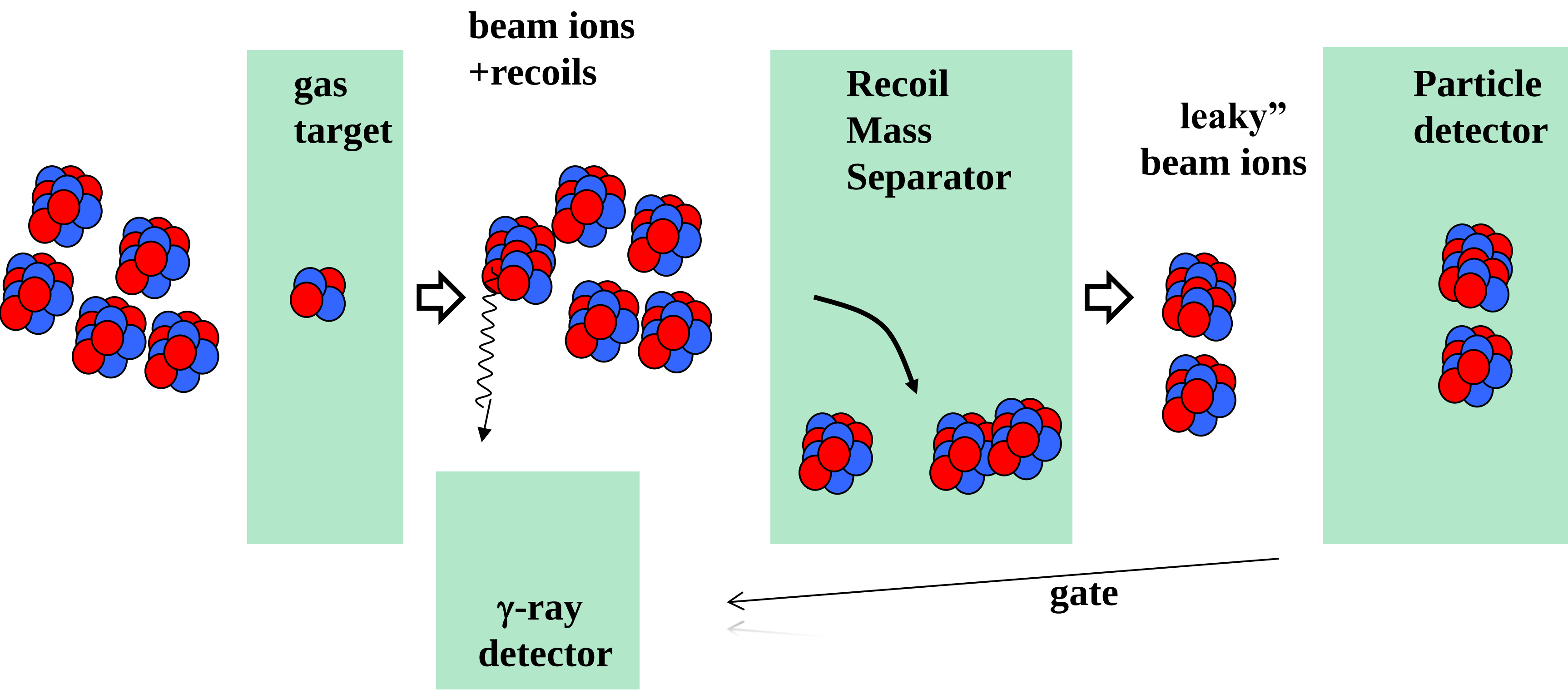
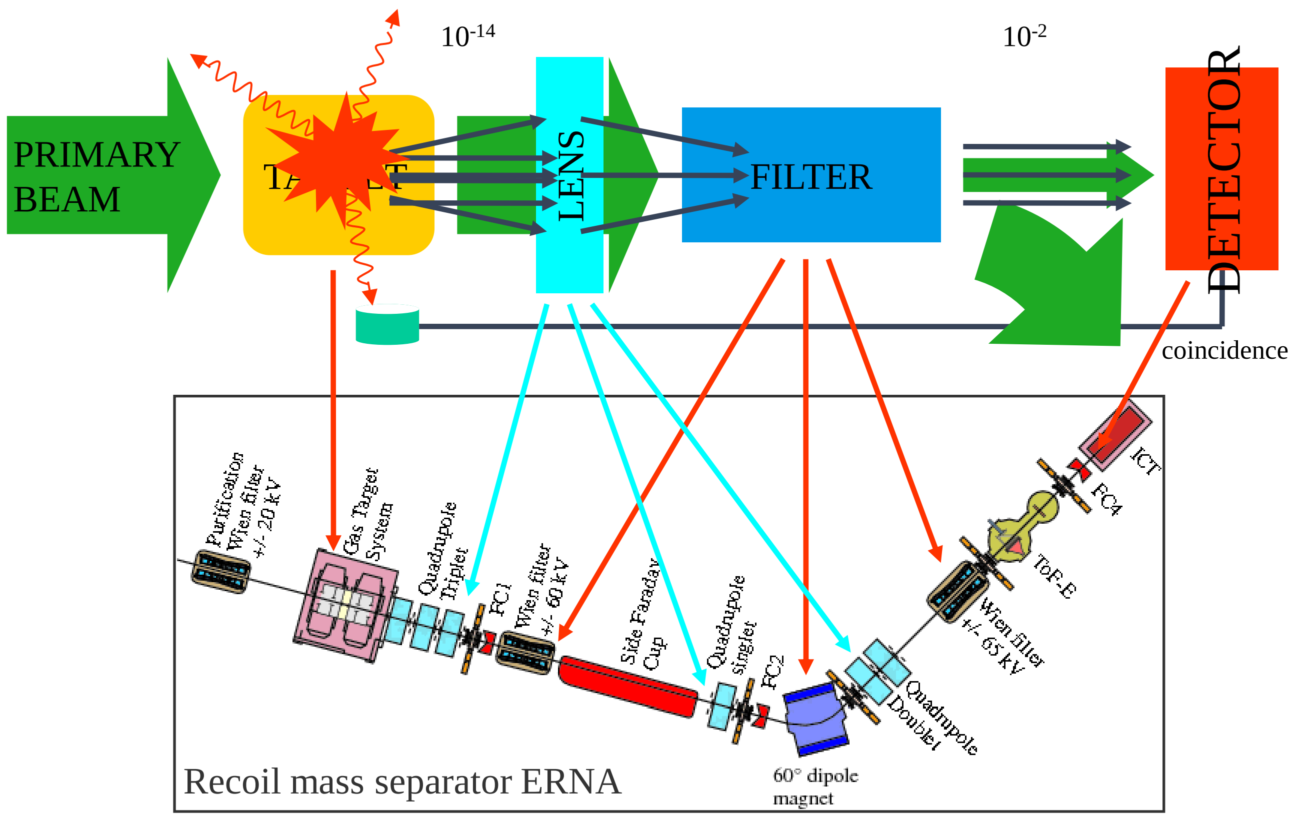
L. Gialanella - Seconda Università di Napoli, Italy
M. Hass - The Weizmann Institute, Israel
C. Iliadis - University of North Carolina, USA
A. Lefebvre - CSNSM CNRS/IN2P3, France

A complementary approach: the ERNA experiment



$$N_{recoils} = N_{projectiles} \times n_{target} \times \sigma \times T_{ERNA} \times \Phi_q \times \varepsilon_{part}$$
$$N_{gamma} = N_{recoils} \times \varepsilon_\gamma$$

Working principle



ERNA Measurements:

$^{7}Be(p,\gamma)^{8}B$ (2012-2013)
$^{12}C(\alpha,\gamma)^{16}O$ (2015-2018)
$^{16}O(\alpha,\gamma)^{20}Ne$ (2015-2018)
$^{33}S(p,\gamma)^{34}Cl$ (2013-2014)
$^{14,15}N(\alpha,\gamma)^{18,19}F$ (2013-2014)

A synergic working group to study the $^{12}C(\alpha,\gamma)\,^{16}O$ reaction has recently started between the ERNA and LUNA collaborations

THE LUNA COLLABORATION

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