The LUNA experiment: direct measurement of thermonuclear cross sections of astrophysical interest

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Laboratory
Underground
Nuclear
Astrophysics

Outline:

-Nuclear Fusion reactions in stars

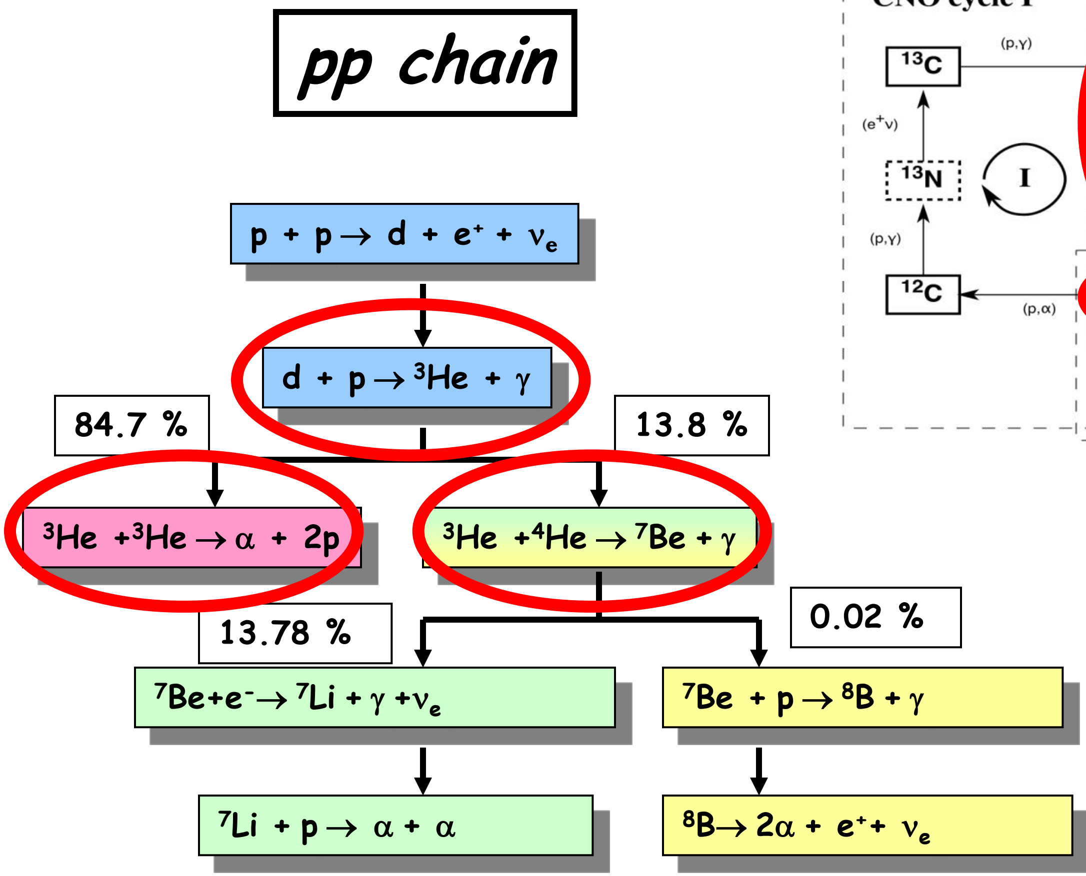
-Why going underground

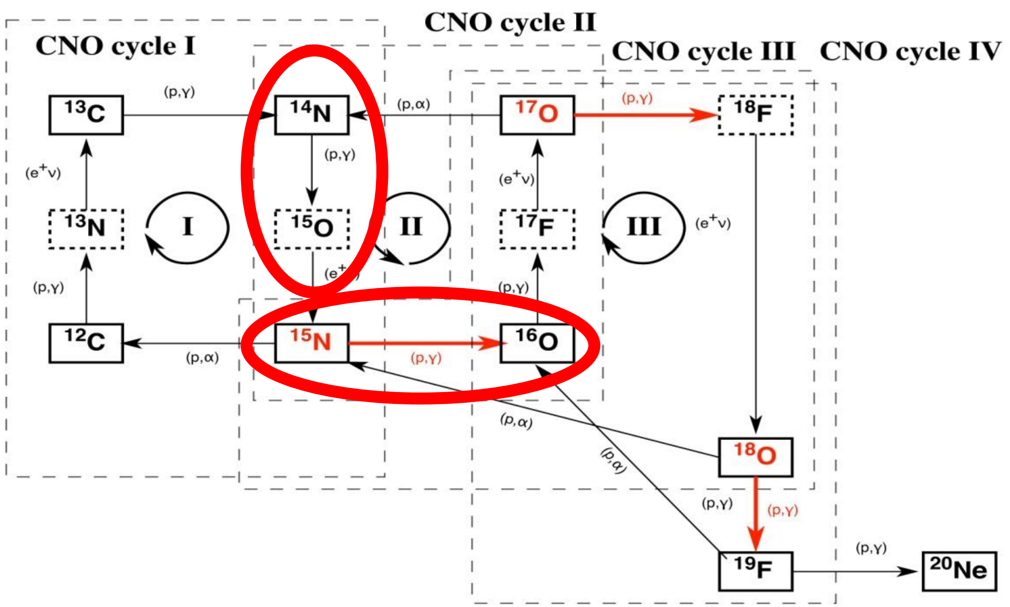
-The Luna Experiment: most important results

- On-going measurements and future perspective

Hydrogen burning

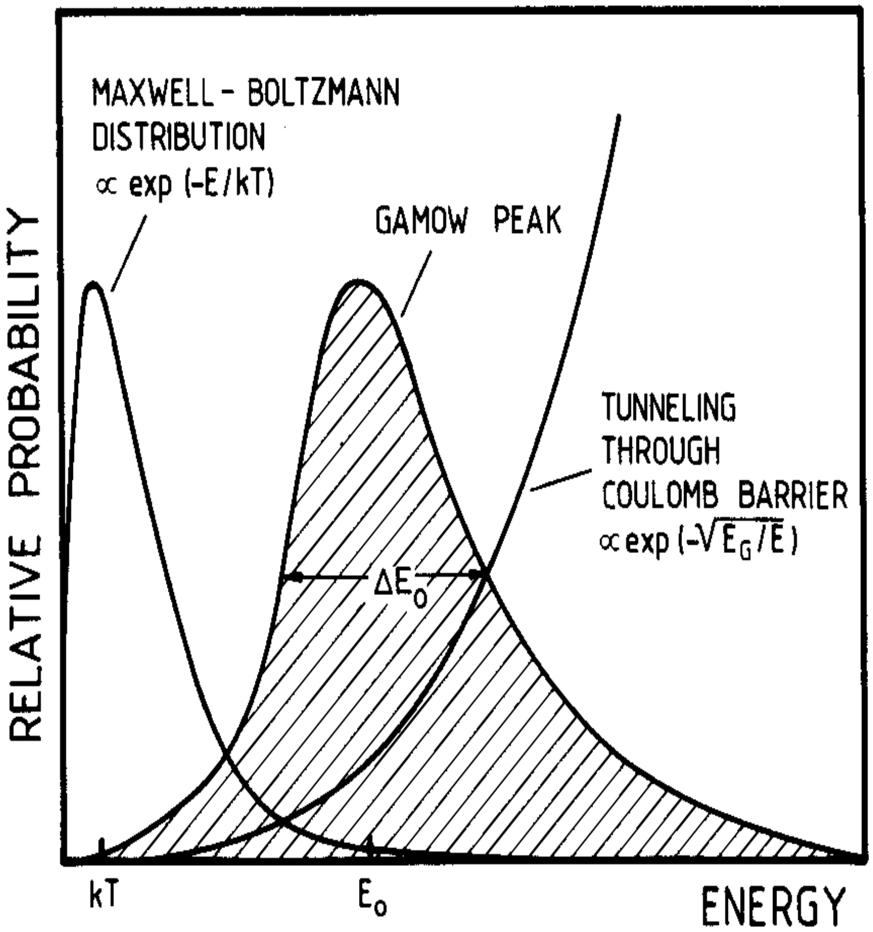
Produces energy for most of the life of the stars





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

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

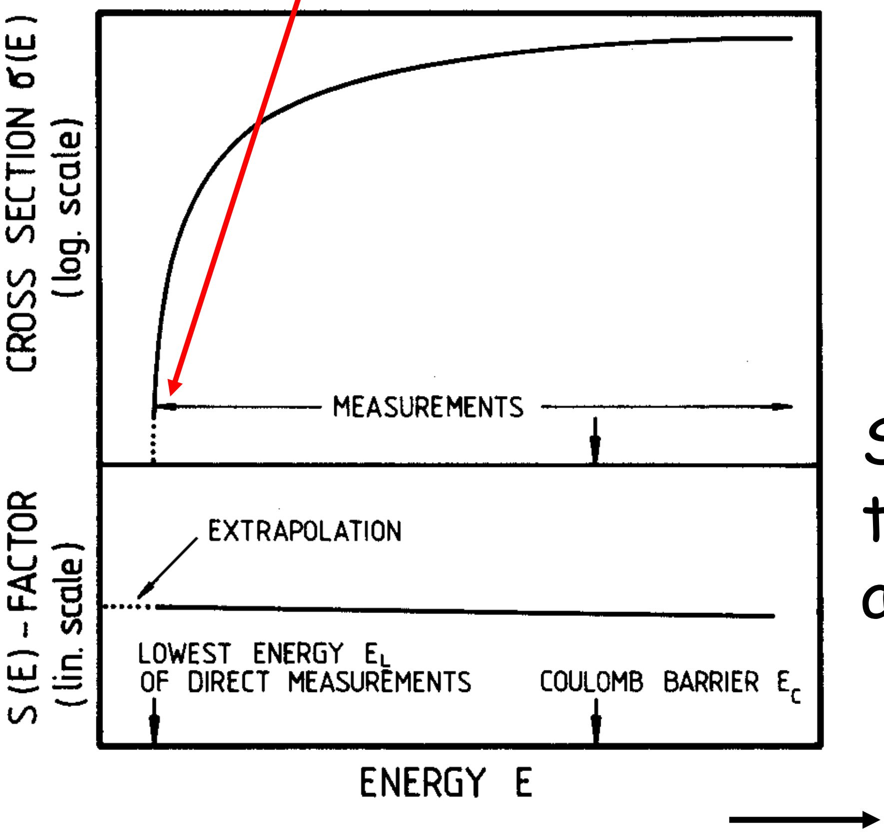
Cross section and astrophysical S factor

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

Gamow factor E_G

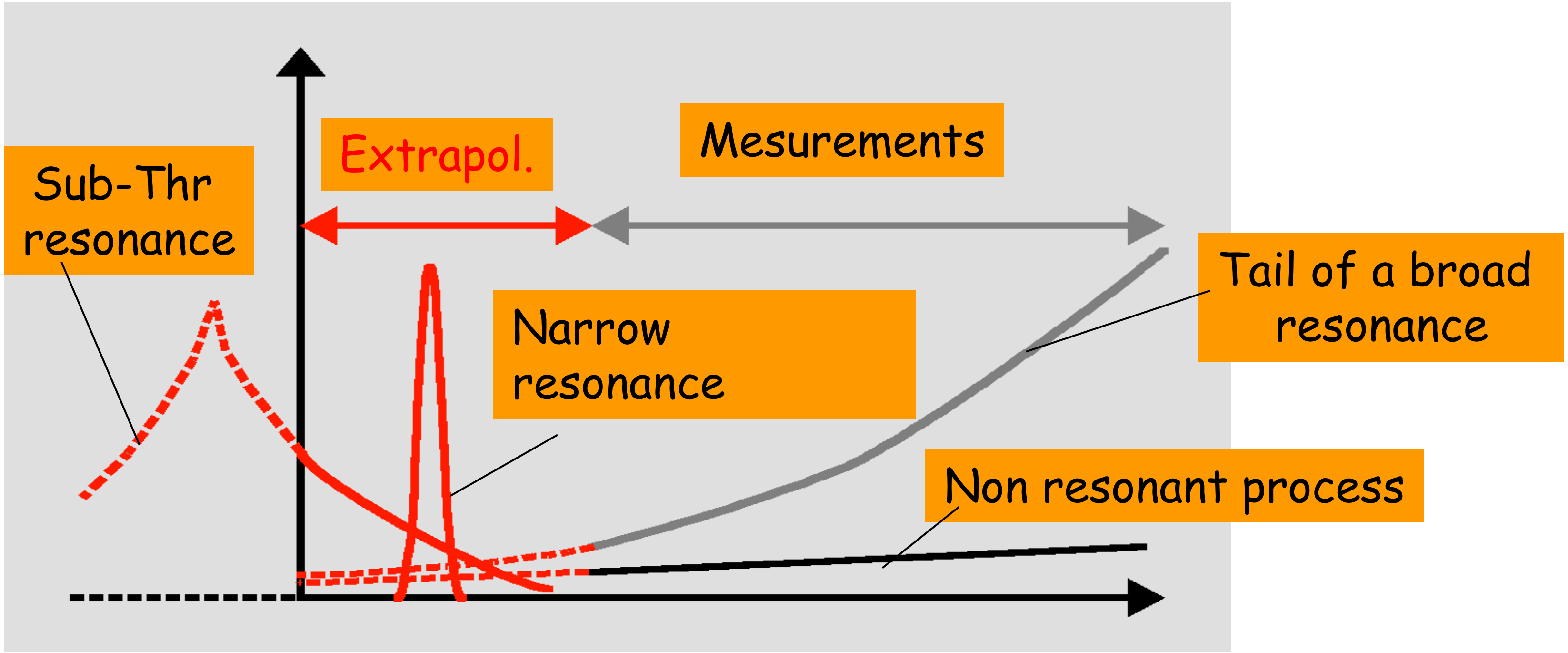
Astrophysical factor

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 (irradiated energy per time) = $2 \cdot 10^{39}$ MeV/s
Q-value (energy for each reaction) = 26.73 MeV
$\Downarrow$

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

Laboratory

$R_{lab} = \sigma \cdot \varepsilon \cdot I_p \cdot \rho \cdot N_{av} / A$

$\varepsilon \sim 10\ \%$
$I_p \sim$ mA
$\rho \sim \mu g/cm^2$

pb < σ < nb
event/month < R_{lab} < event/day

$\Downarrow$

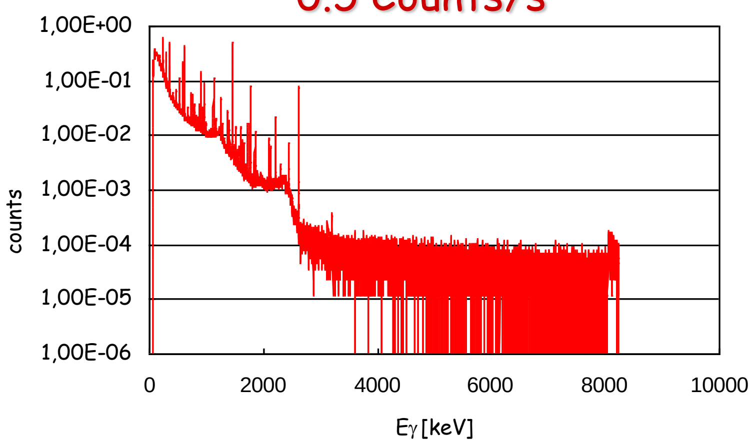
Underground Laboratory

Environmental radioactivity has to be considered underground → shielding

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

Beam induced bck from impurities in beam & targets → high purity

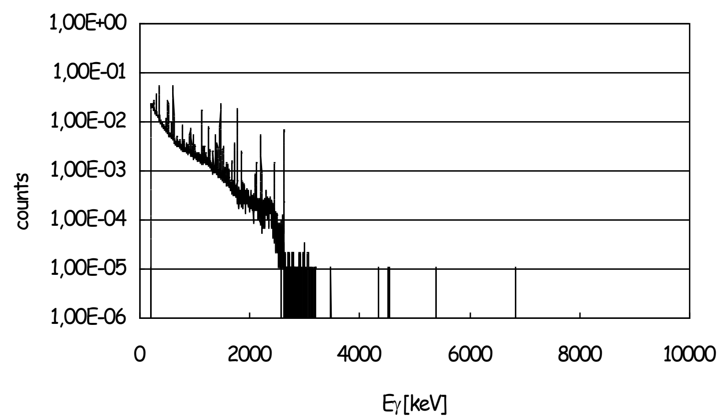
3MeV < Eγ < 8MeV:
0.5 Counts/s



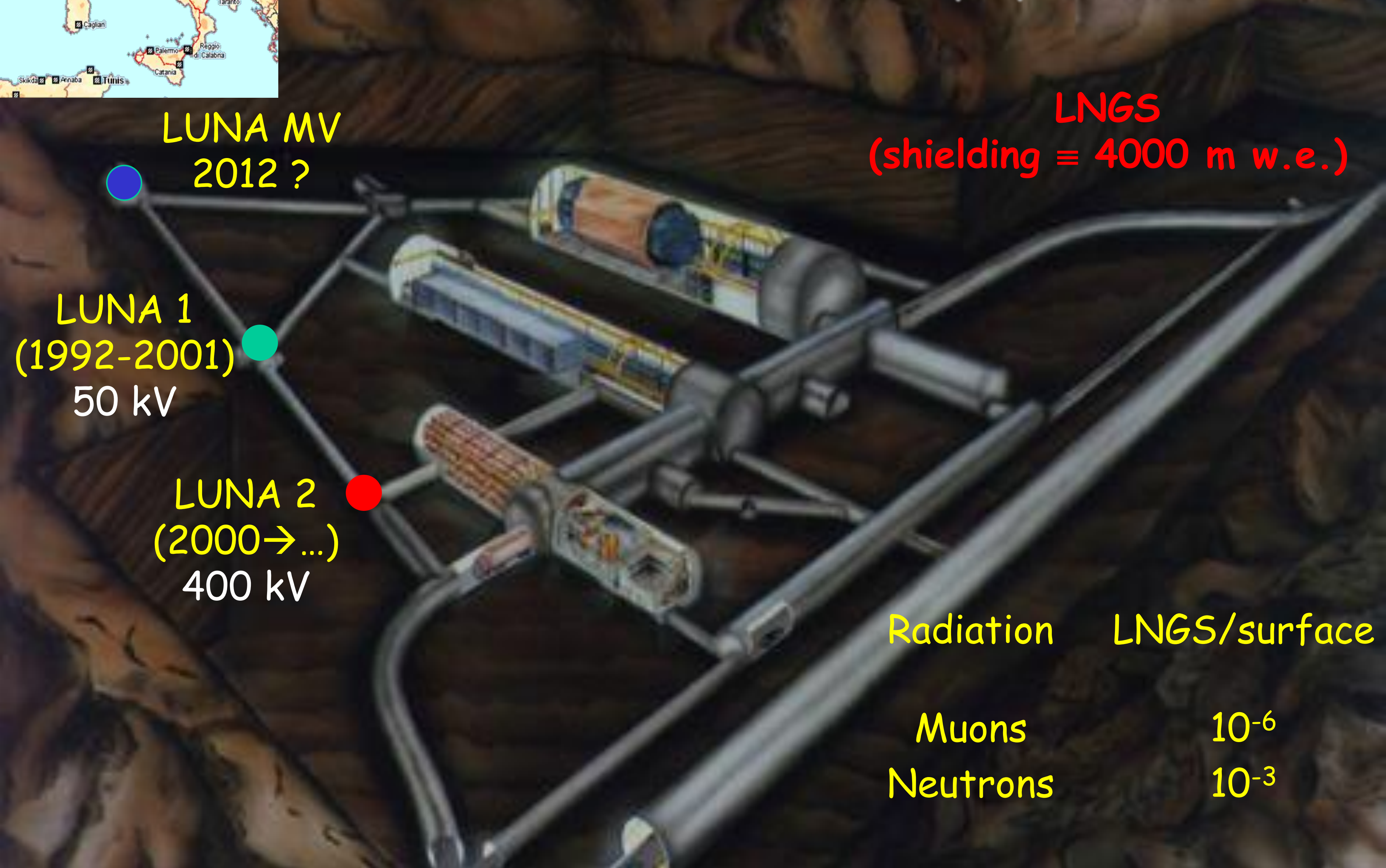
HpGe

GOING UNDERGROUND →

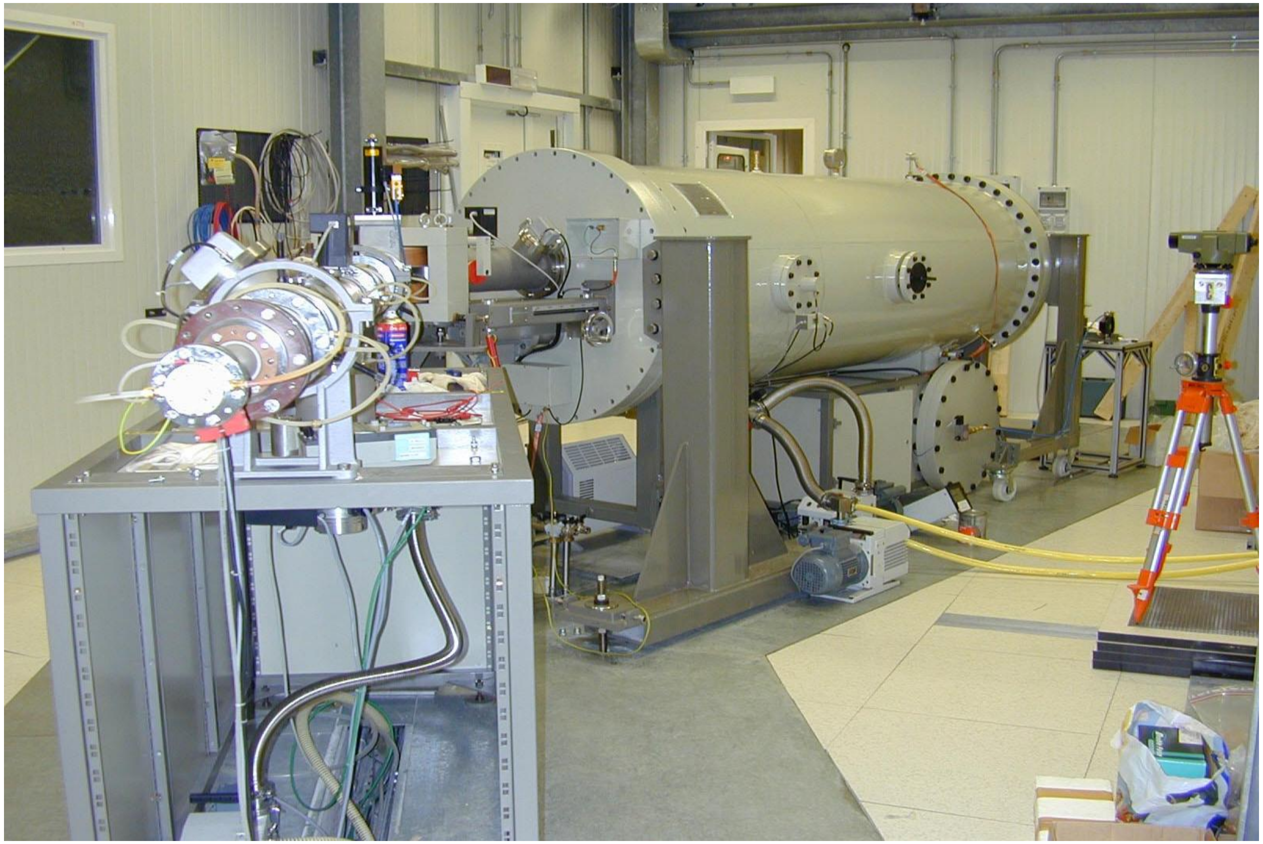
3MeV < Eγ < 8MeV
0.0002 Counts/s



Laboratory for Underground Nuclear Astrophysics



Laboratory for Underground Nuclear Astrophysics



400 kV Accelerator : $E_{beam} \approx 50 - 400$ keV

$I_{max} \approx 500\ \mu A$ protons $I_{max} \approx 250\ \mu A$ alphas

Energy spread ≈ 70 eV Long term stability ≈ 5eV/h

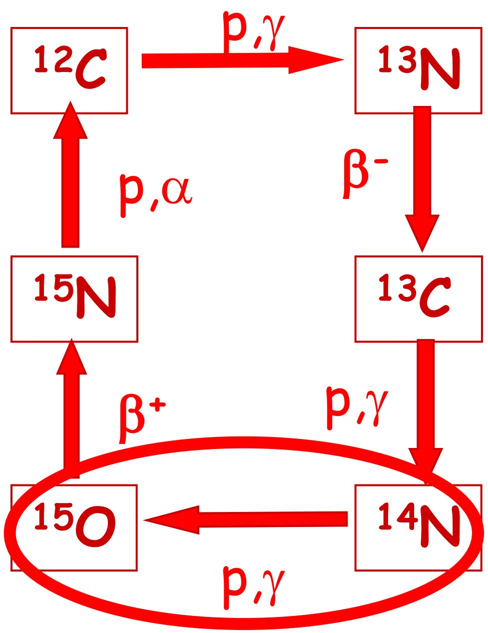
CNO Cycle

T>1.6 10^7 K   M>1.1 Solar masses

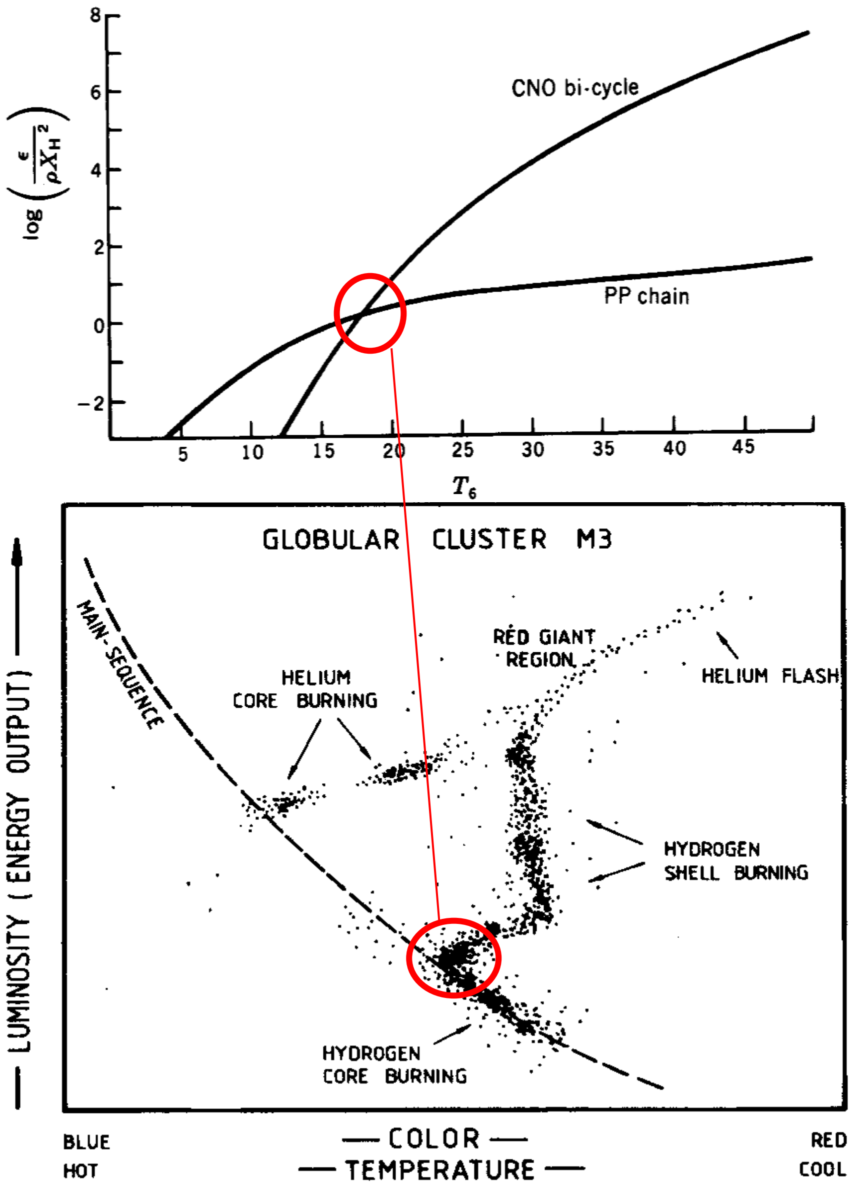
$^{14}N(p,\gamma)^{15}O$ is the slowest reaction and determines the rate of energy production

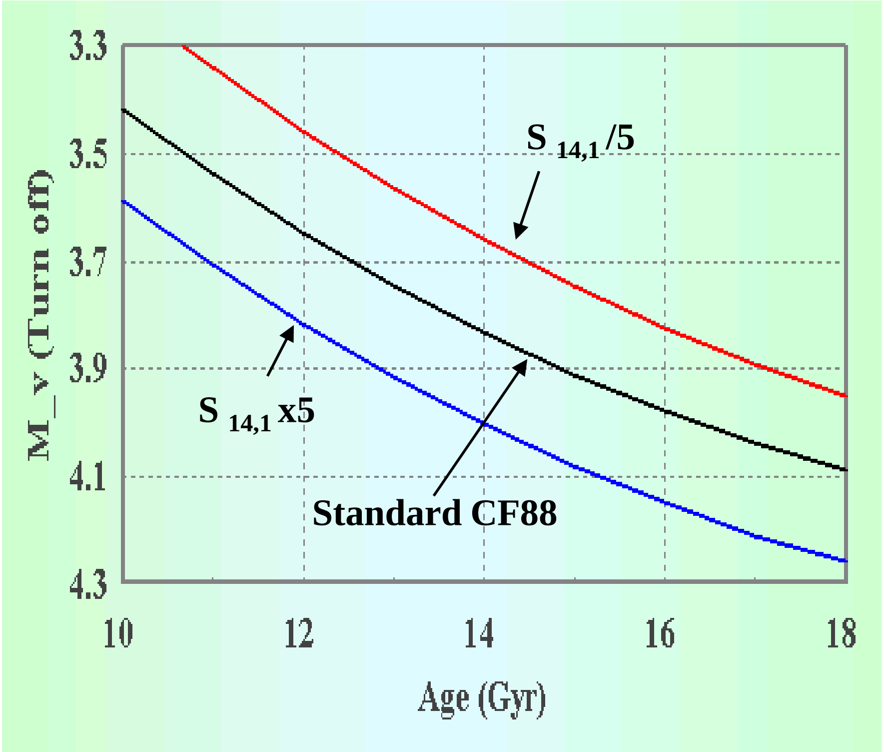
Its cross section influences:

- CNO neutrino flux→ solar metallicity
- Globular cluster age

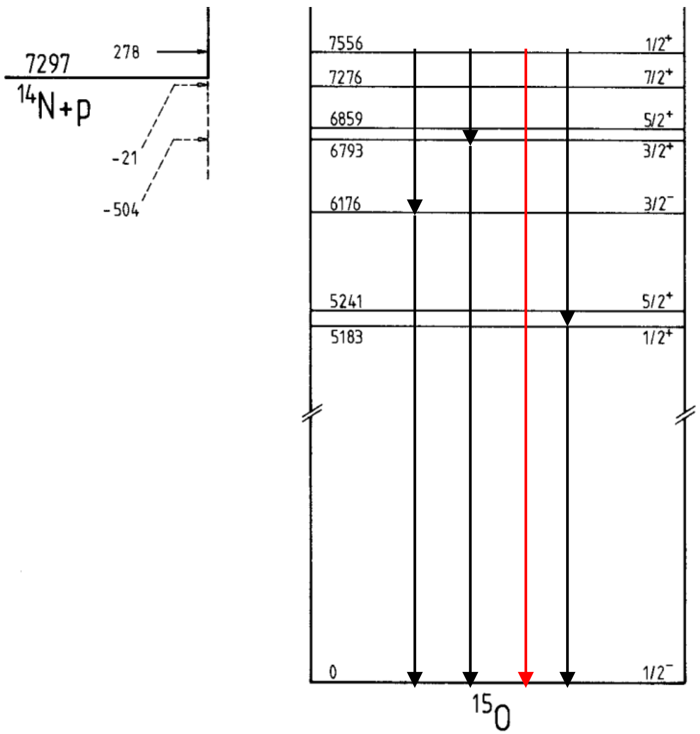


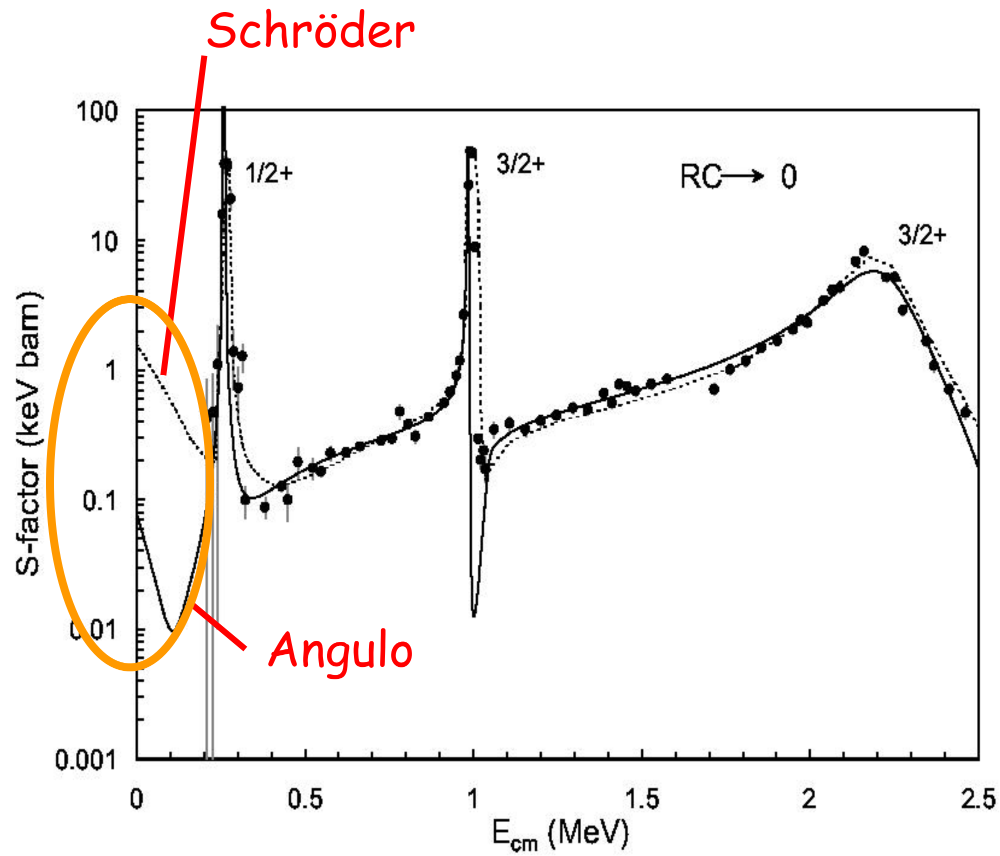
Globular cluster age





$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle

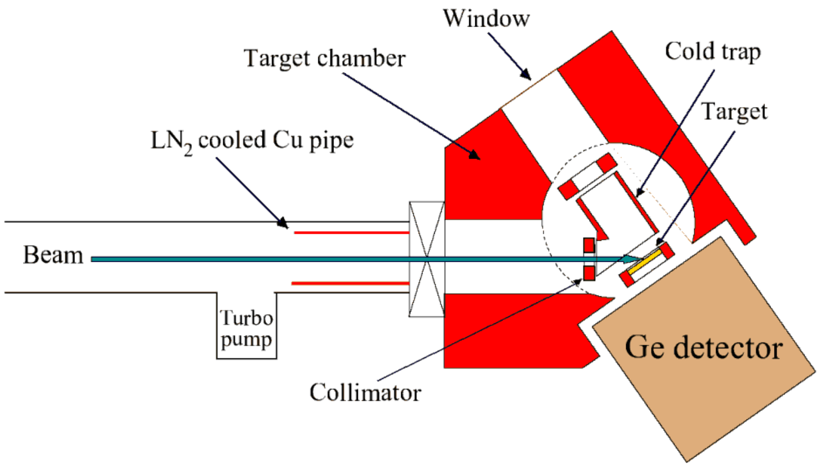




factor 20 !

Transition (MeV)	Schröder et al. (Nucl.Phys.A 1987)	Angulo et al. (Nucl.Phys.A 2001)
RC / 0	1.55 ± 0.34	0.08 ± 0.06
S(0) [kev-b]	3.20 ± 0.54	1.77 ± 0.20

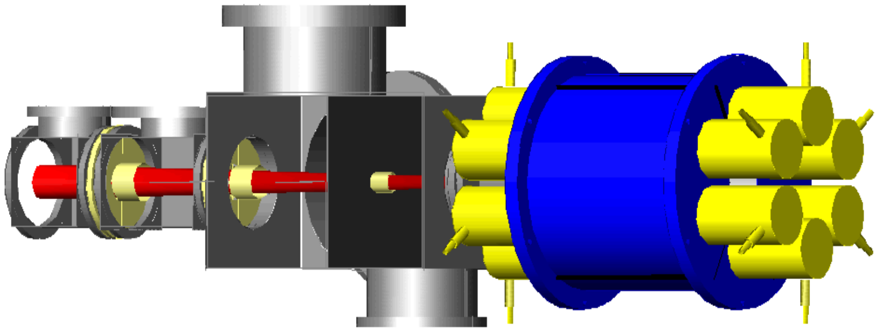
High resolution measurement (2004)



Solid target + HPGe detector

- single γ transitions
- Energy range 119-367 keV
- summing had to be considered

High efficiency measurement (2006)



Gas target+ BGO detector

- high efficiency
- total cross section
- Energy range 70-230 keV

S_0(LUNA) = 1.61 ± 0.08 keV b

CNO neutrino flux decreases of a factor ≈ 2

Globular Cluster age increases of 0.7 – 1 Gyr

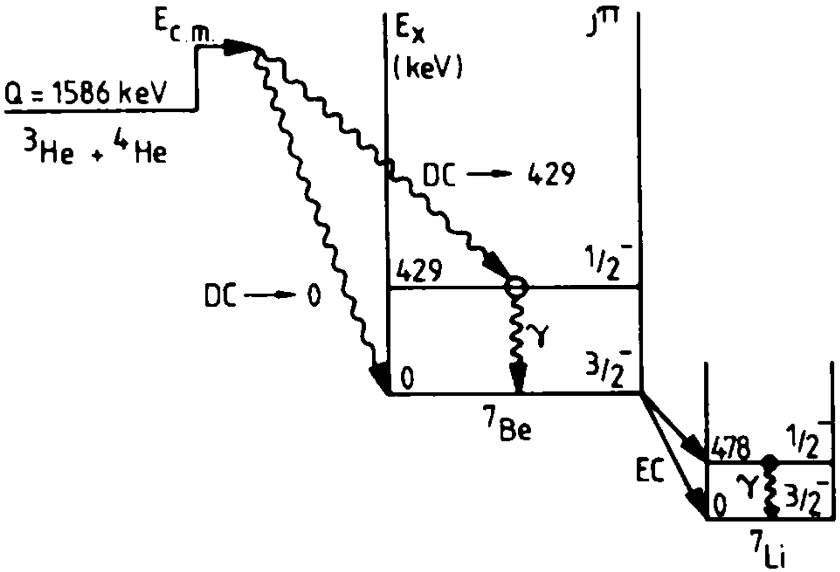
$^{3}He(^{4}He,\gamma)^{7}Be$

John Bahcall e M. H. Pinsonneault, astro-ph/0402114v1, 2004:

The rate of the reaction **$^{3}He(^{4}He,\gamma)^{7}Be$** is the largest nuclear physics contributor to the uncertainties in the solar model predictions of the neutrino fluxes in the p-p chain. In the past 15 years, no one has remeasured this rate; it should be the **highest priority for nuclear astrophysicists**."

$$\Phi(^{8}B) \sim (1+\delta S_{11})^{-2.73} (1+\delta S_{33})^{-0.43} (1+\delta S_{34})^{0.85} (1+\delta S_{17})^{1.0} (1+\delta S_{e7})^{-1.0} (1+\delta S_{1,14})^{-0.02}$$

where fractional uncertainty $\delta S_{11} \equiv \Delta S_{11}/S_{11}(0)$



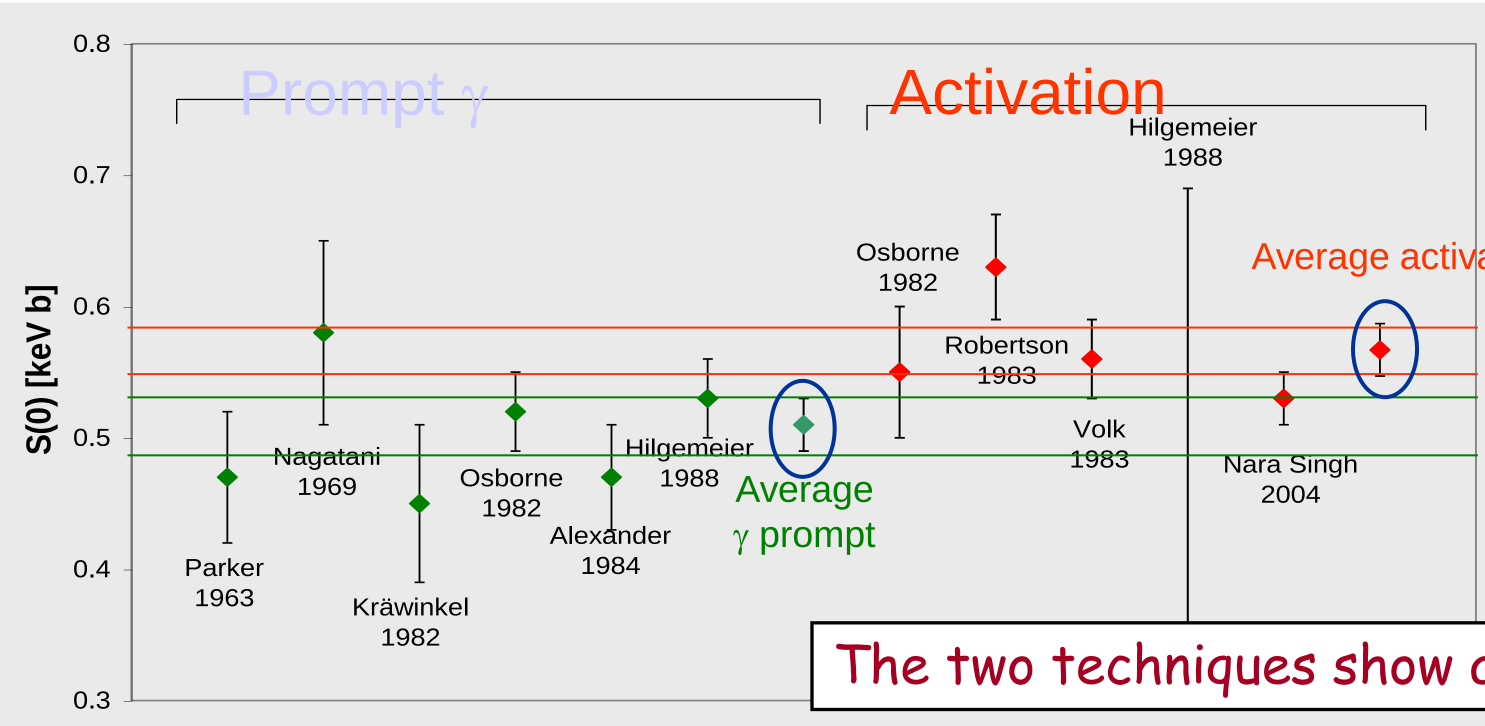
$^{3}He(\alpha,\gamma)^{7}Be(e,\nu)\ ^{7}Li^{*}(\gamma)^{7}Li$

$E\gamma$ = 478 keV

$E\gamma$ =1586 keV + E_{cm} (DC → 0);

$E\gamma$ = 1157 keV + E_{cm} (DC → 429)

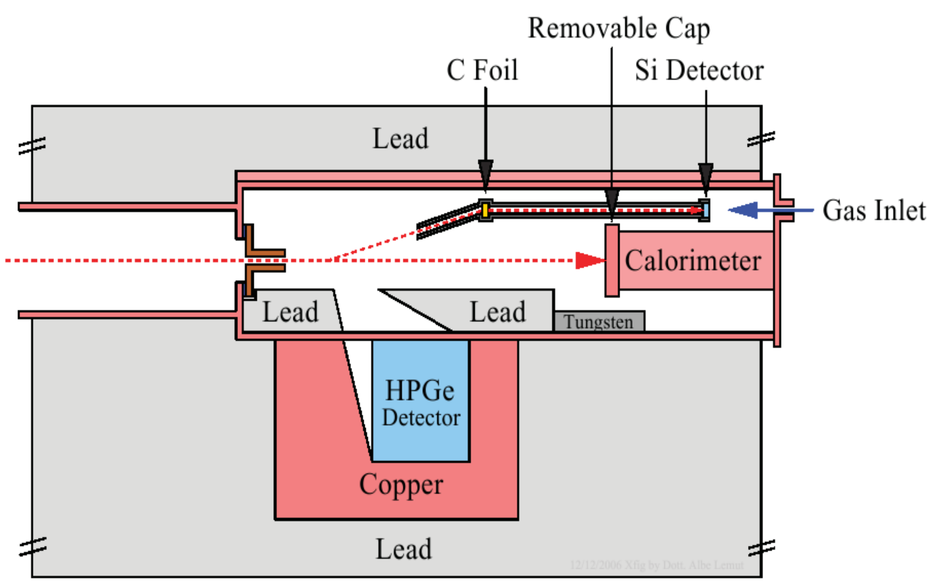
$E\gamma$ = 429 keV



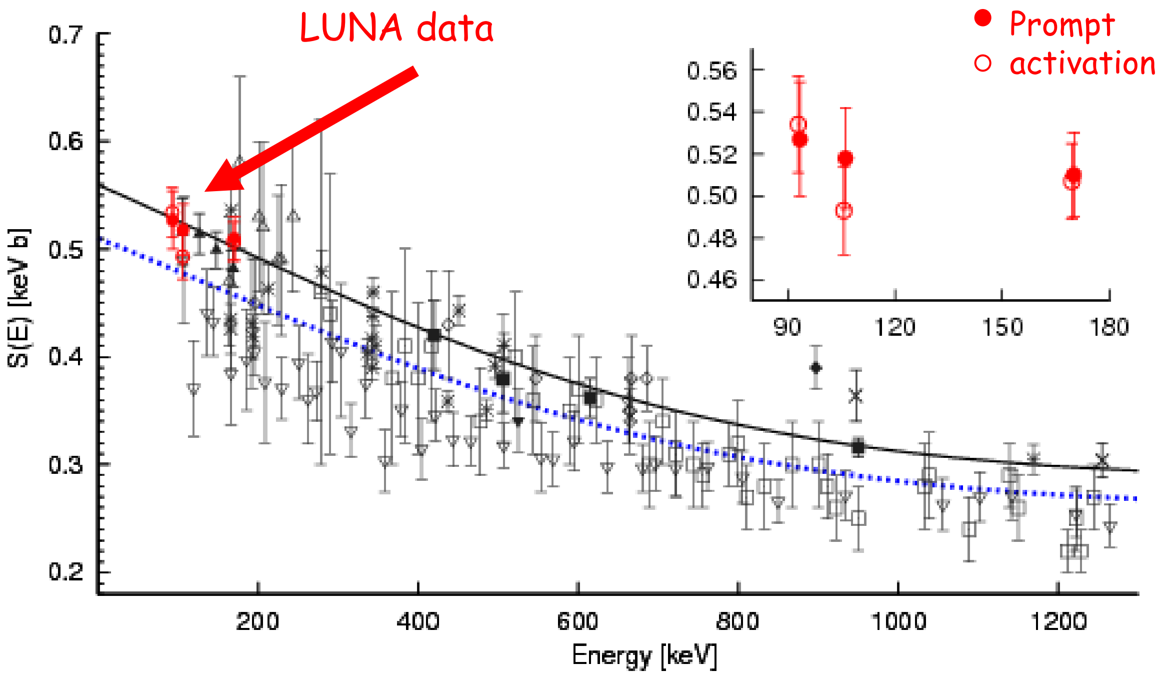
The two techniques show a 9% discrepancy

Luna measurement: both techniques and accuracy of 4-5%

- ^{3}He recirculating gas target p=0.7mbar
- Si-monitor for target density measurement (beam heating effect)
- Collimated HPGe detector to collect γ ray at 55°
- 0.3 m^3 Pb-Cu shield suppression five orders of magnitude below 2MeV
- Removable calorimeter cap for offline ^{7}Be counting



Results



S_{34} (LUNA) =0.567±0.018±0.004 keV b

in Solar fusion cross sections II: arXiv:1004.2318v3
based on LUNA and successive measurements:
S_{34}= 0.56 0.02 (exp) 0.02 (model) keV b

Uncertainty due to S_{34} on neutrinos flux:
$\Phi(^8B)$ 7.5% → 4.3%
$\Phi(^7Be)$ 8% → 4.5%

LUNA present program

completed!

CNO cycle

In progress

Ne-Na cycle

BBN

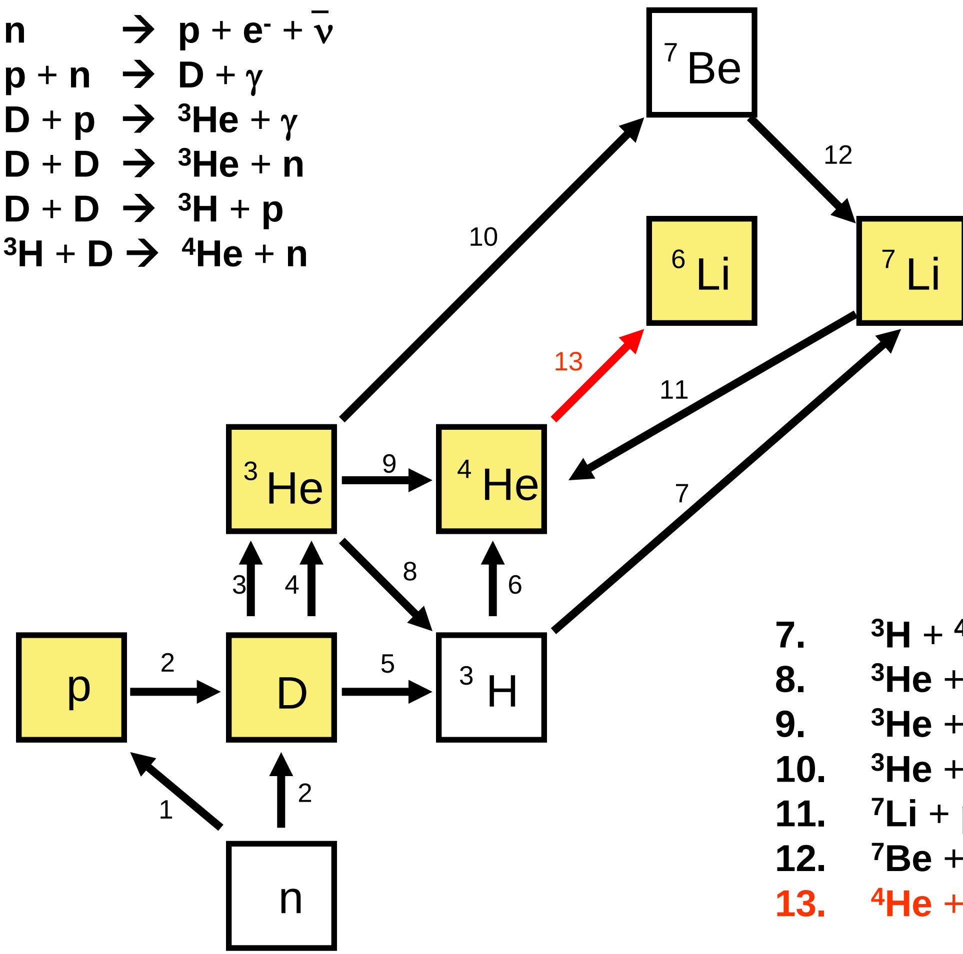
In progress

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

BBN: production of the lightest elements (D, ^{3}He, ^{4}He, ^{7}Li, ^{6}Li) in the first minutes after the Big Bang

1. n → p + e^- + $\bar{\nu}$
2. p + n → D + γ
3. D + p → ^{3}He + γ
4. D + D → ^{3}He + n
5. D + D → ^{3}H + p
6. ^{3}H + D → ^{4}He + n

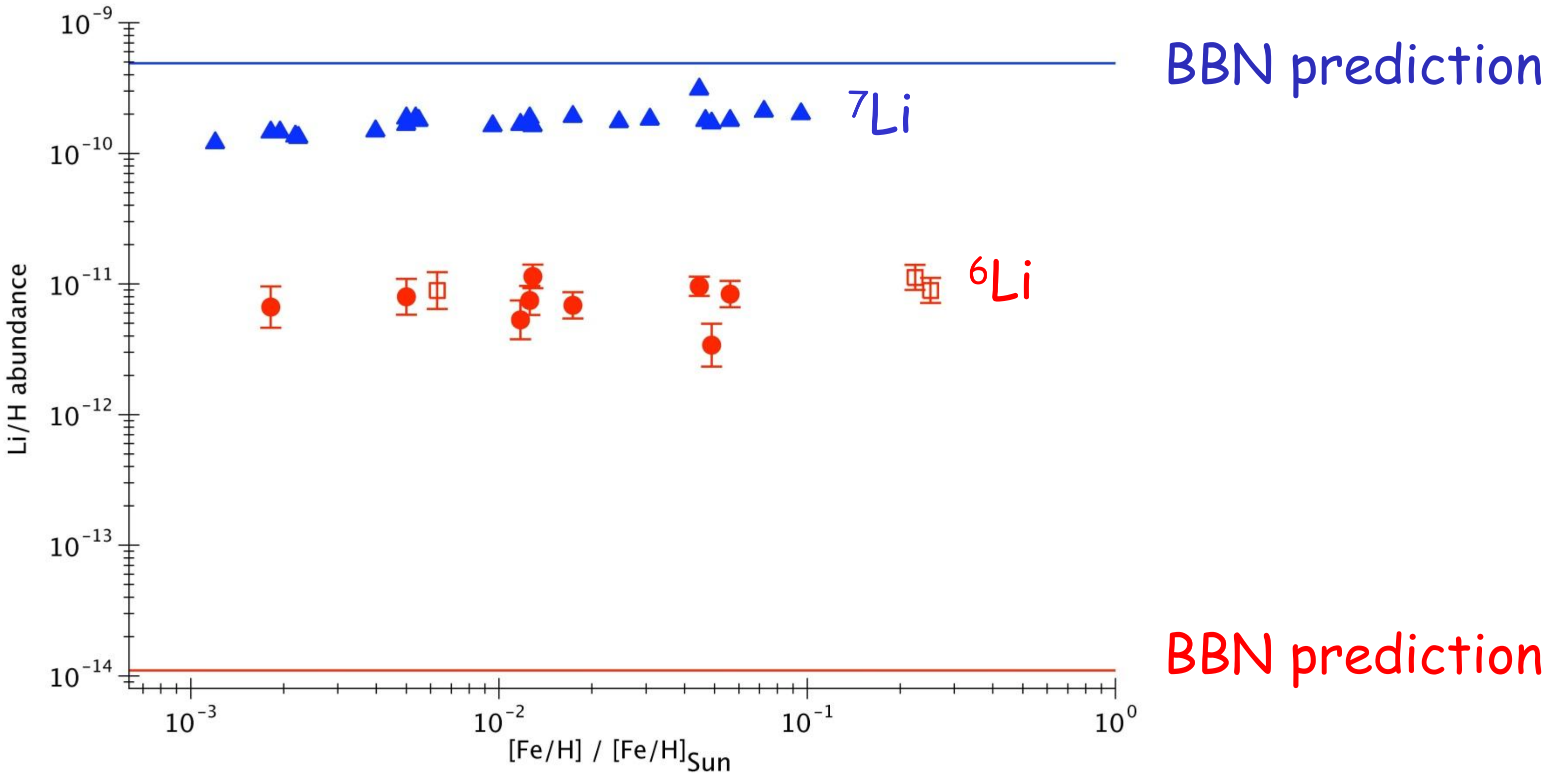


7. ^{3}H + ^{4}H → ^{7}Li + γ
8. ^{3}He + n → ^{3}H + p
9. ^{3}He + D → ^{4}He + p
10. ^{3}He + ^{4}He → ^{7}Be + γ
11. ^{7}Li + p → ^{4}He + ^{4}He
12. ^{7}Be + n → ^{7}Li + p
13. ^{4}He + D → ^{6}Li + γ

Apart from ^{4}He, uncertainties are dominated by systematic errors in the nuclear cross sections

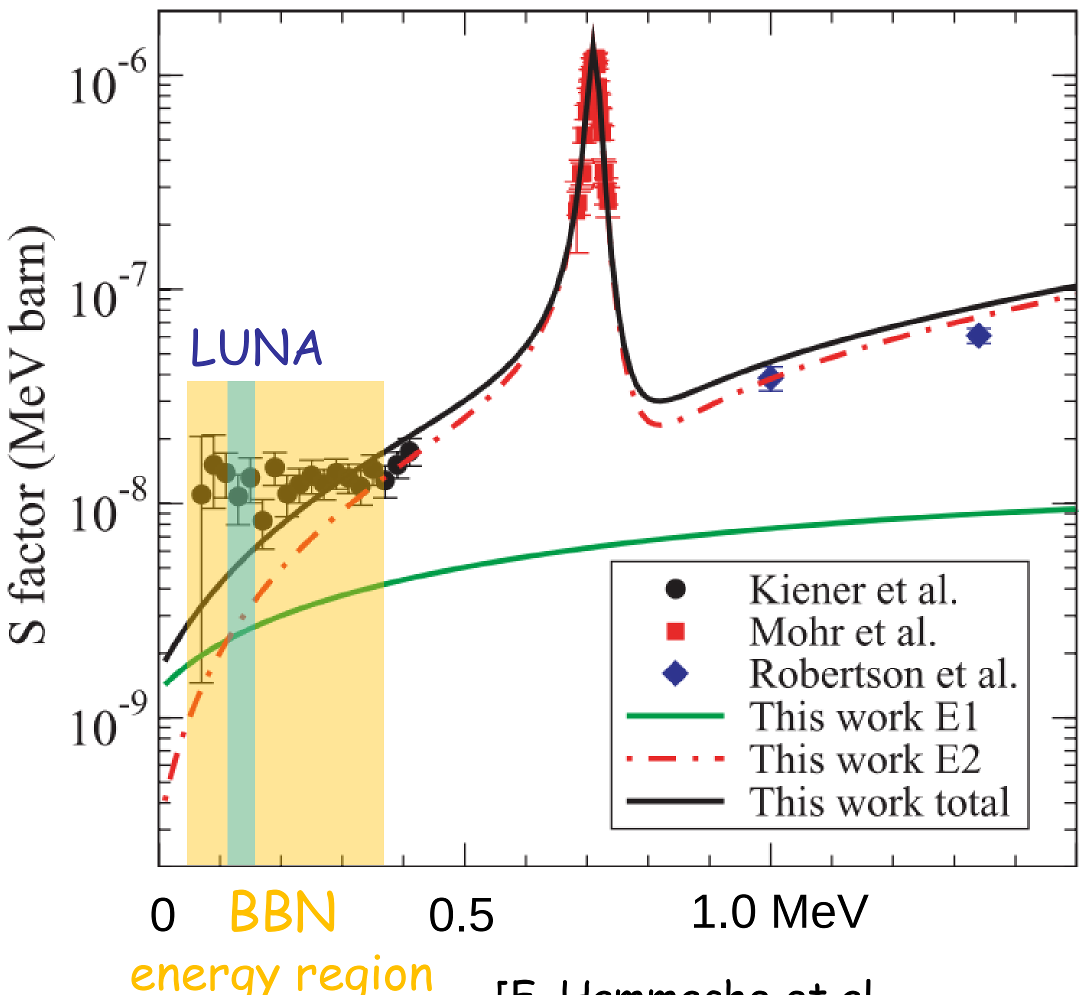
The ^{6}Li case

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:
^{2}H(α,γ)^{6}Li producing almost all the ^{6}Li
^{6}Li(p,α)^{3}He destroying ^{6}Li → well known

Available data



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

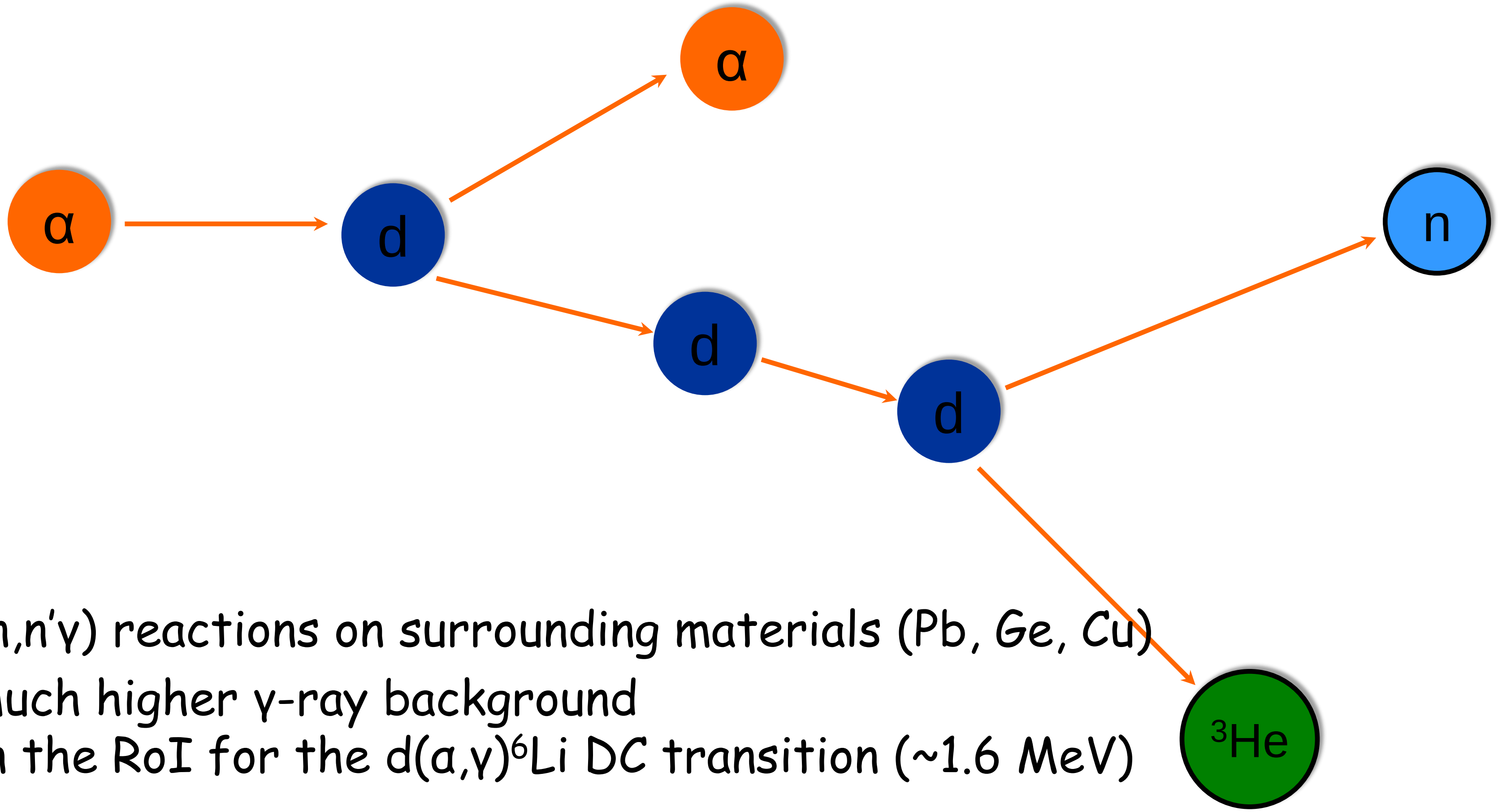
Direct measurements:
- Robertson et al.
E > 1 MeV
- Mohr et al.
around the 0.7 MeV resonance

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(α,α)d Rutherford scattering followed by $d(d,n)^3He$ reactions



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

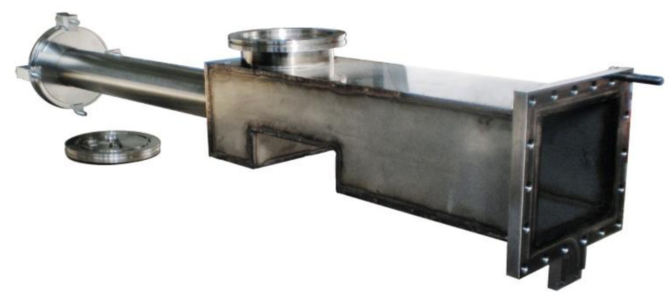
-> much higher γ-ray background in the RoI for the $d(\alpha,\gamma)^6Li$ DC transition (~1.6 MeV)

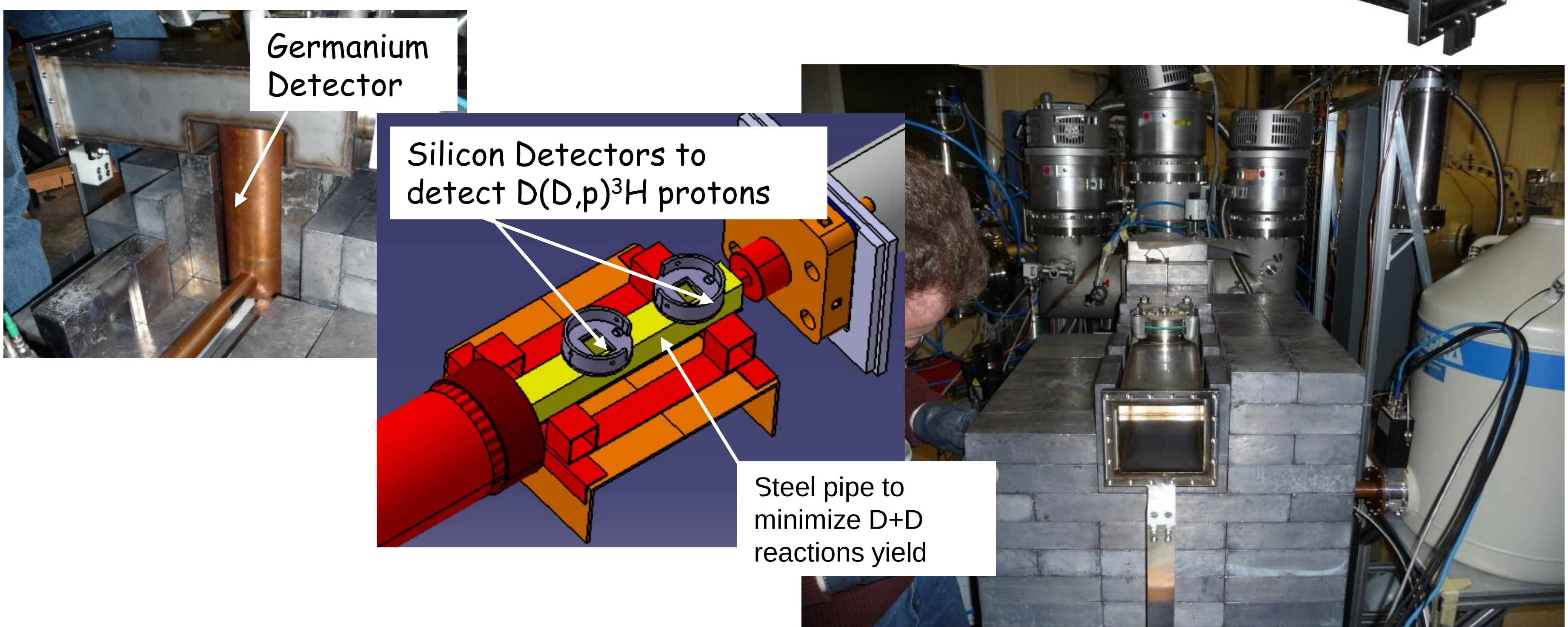
Experimental set-up

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

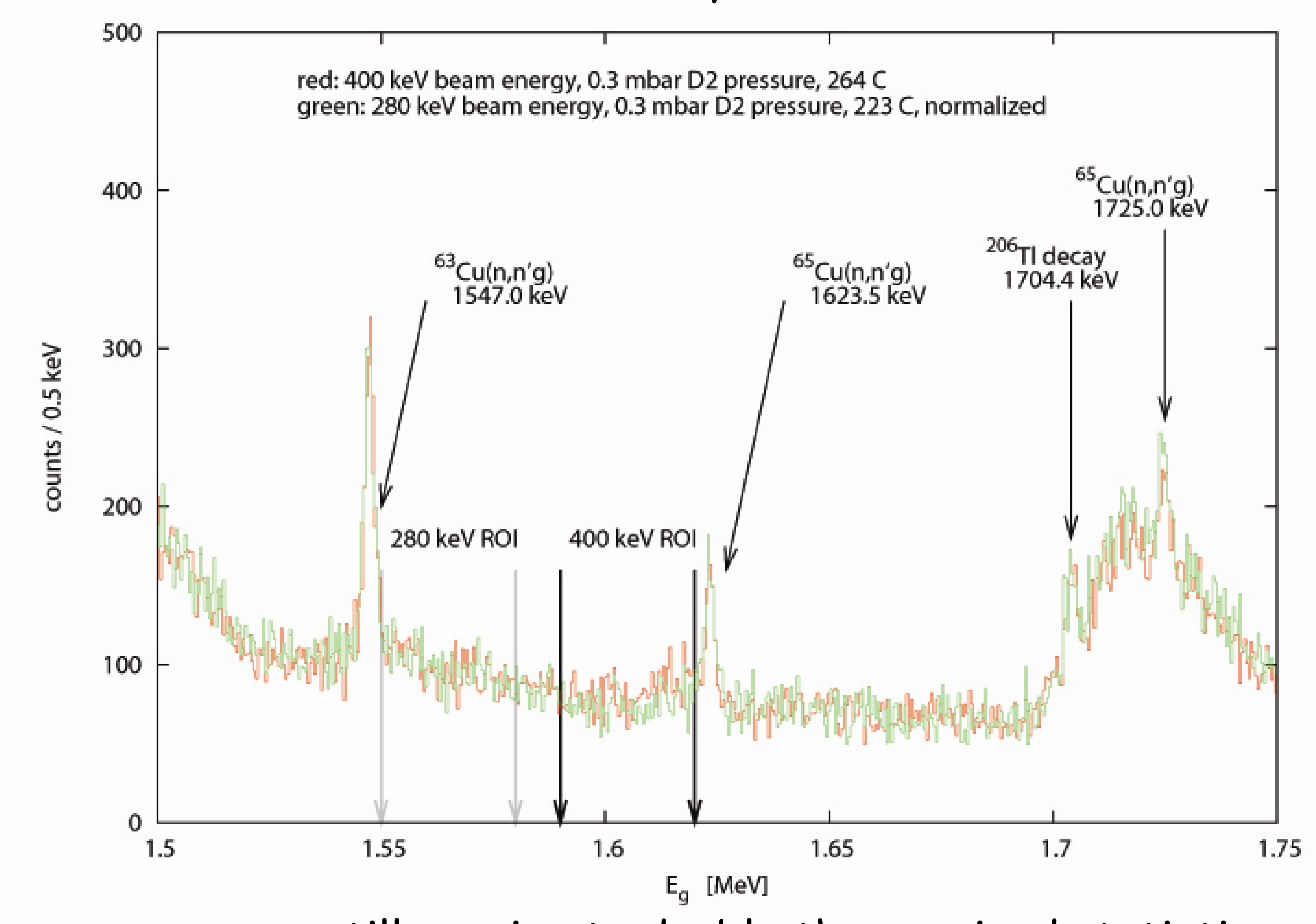
- Silicon detectors to measure ^{2}H(^{2}H,p)^{3}H





LUNA measurement (preliminary)

230 h at 400 keV, 285 h at 280 keV



still running to double the acquired statistics

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:

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

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

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

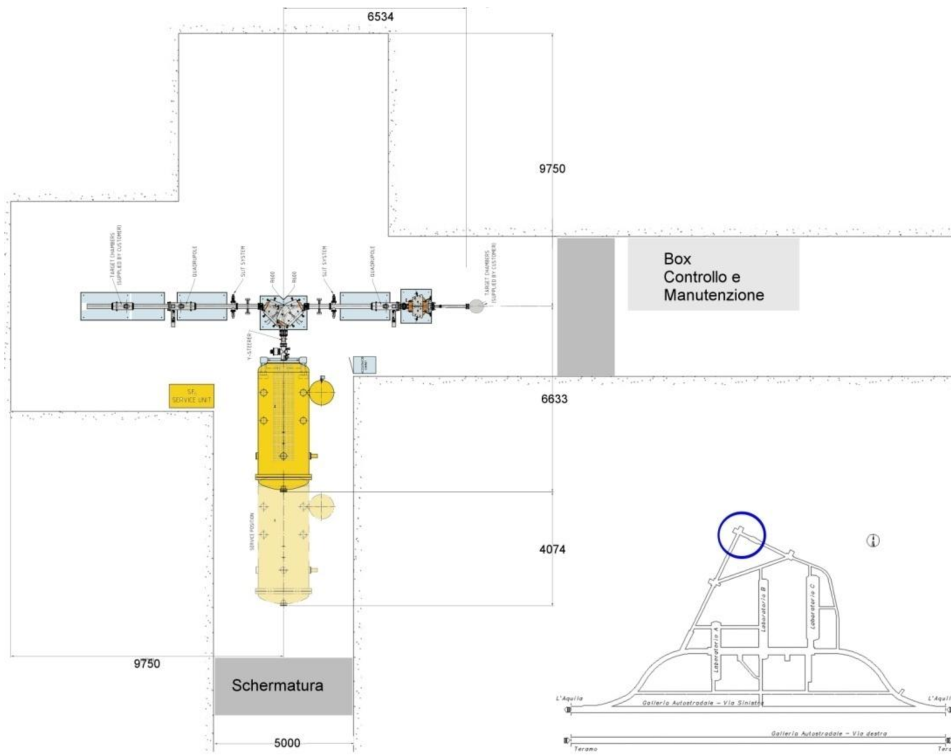
(α,γ) reactions on $^{14,15}N$ and ^{18}O

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

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

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

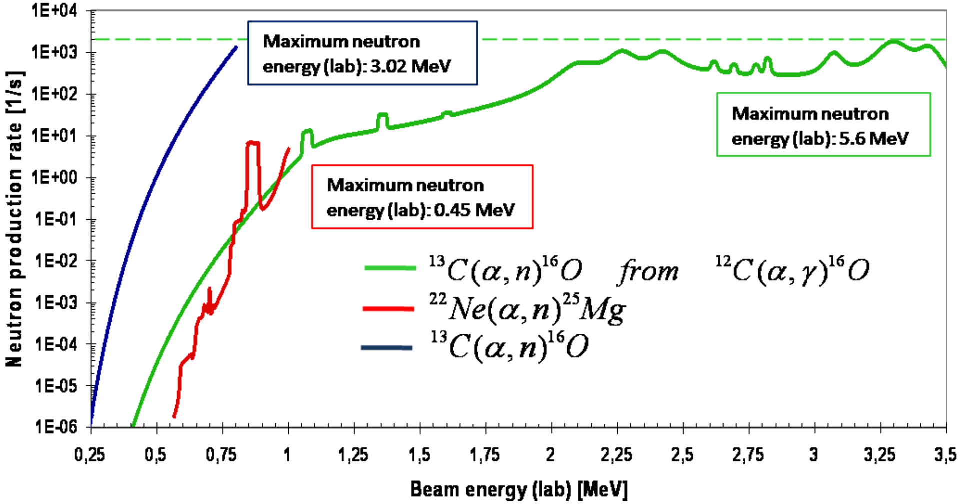
α beam intensity: 200 μA
Target: ^{13}C, 2 10^{17}at/cm^2 (99% ^{13}C enriched)
Beam energy(lab) ≤ 0.8 MeV

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

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

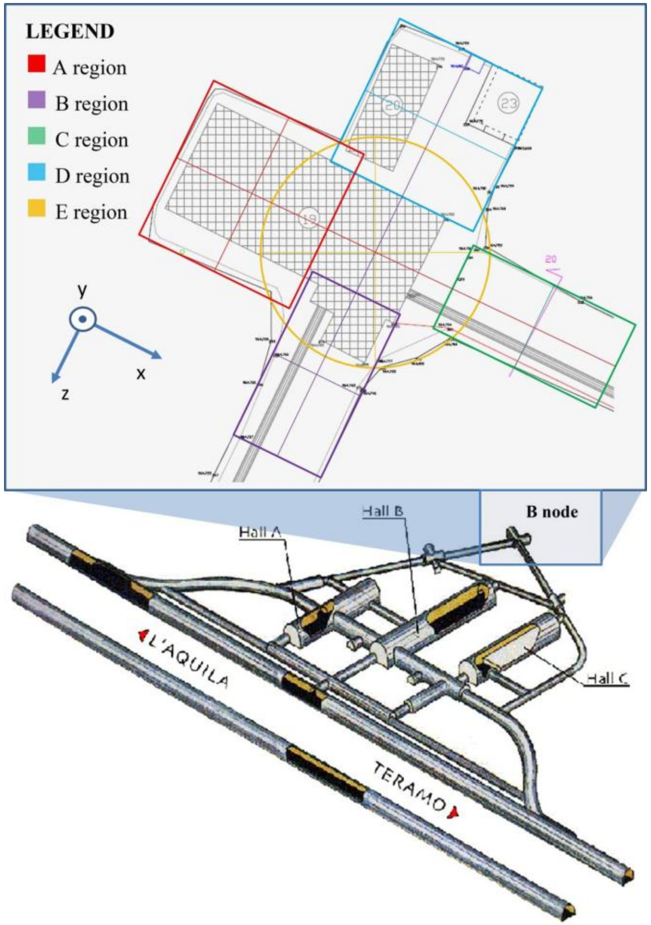
$^{13}C(\alpha,n)^{16}O$ from $^{12}C(\alpha,\gamma)^{16}O$

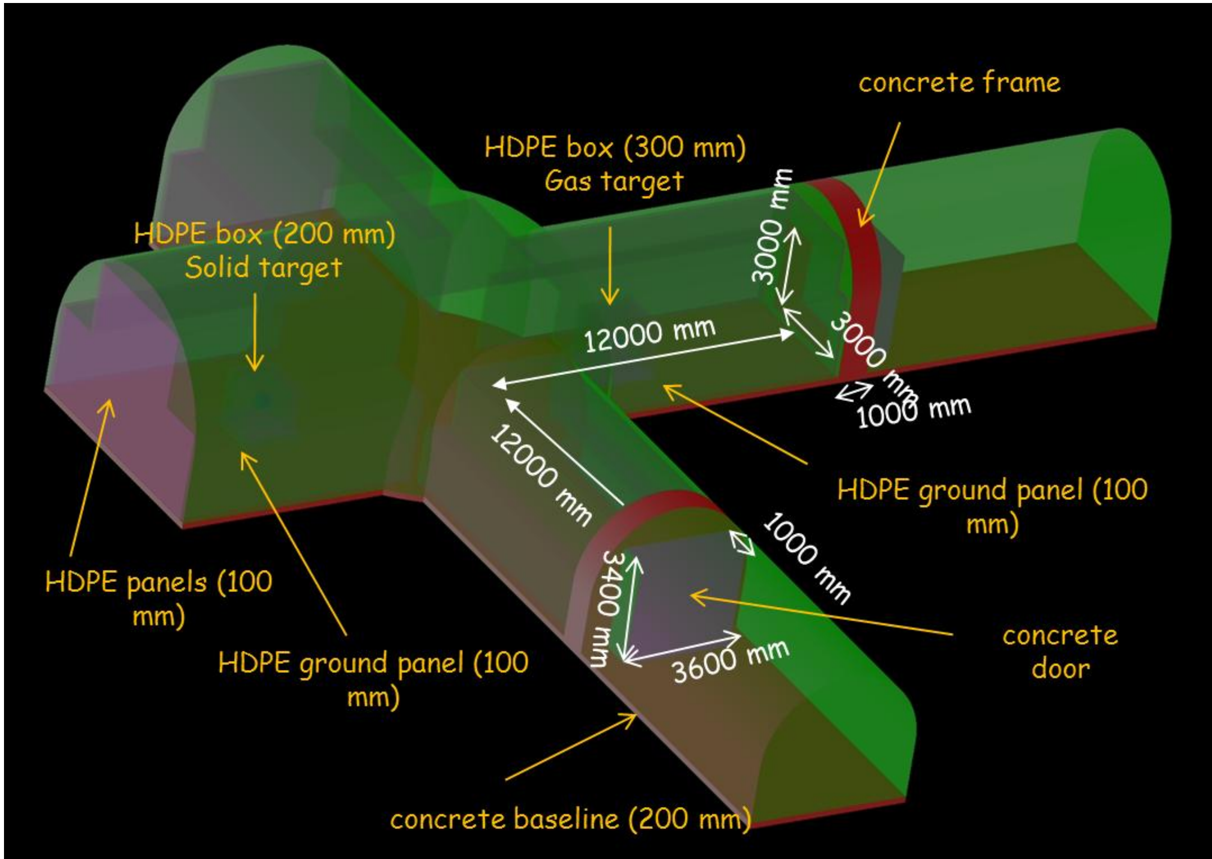
α beam intensity: 200 μA
Target: ^{13}C, 1 10^{18}at/cm^2 ($^{13}C/^{12}C = 10^{-5}$)
Beam energy(lab) ≤ 3.5 MeV

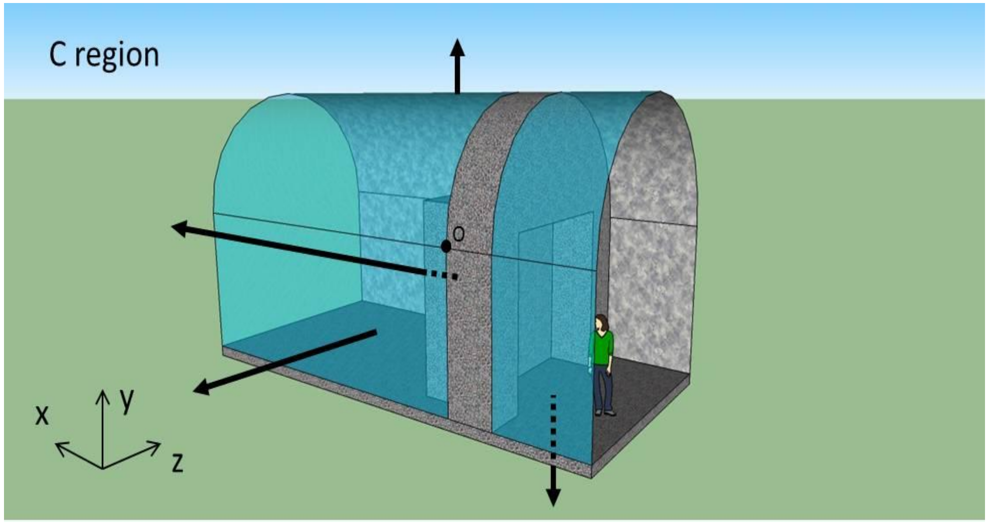


- Maximum neutron production rate : 2000 n/s
- Maximum neutron energy (lab) : 5.6 MeV

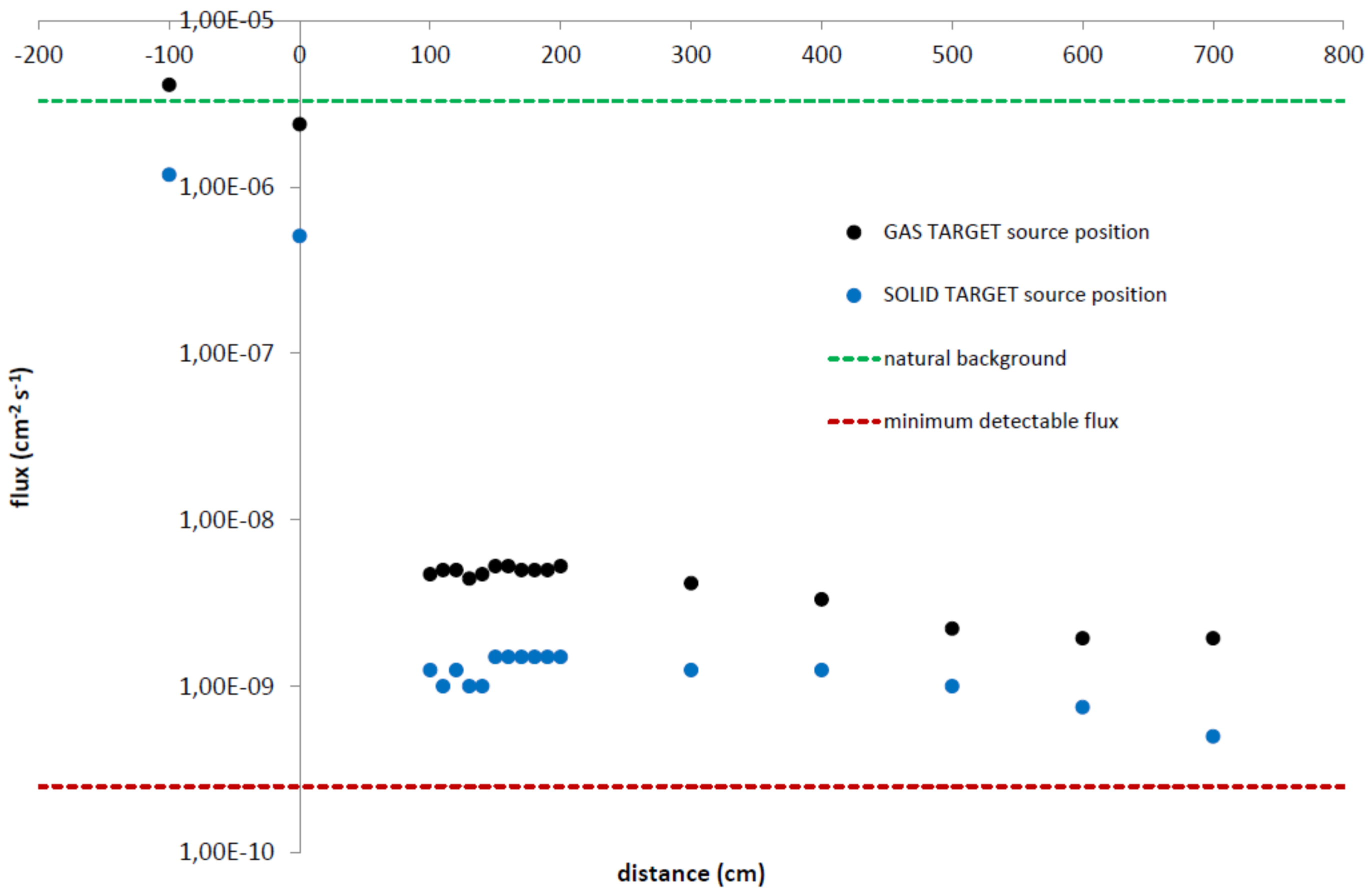
Geant4 simulations for neutron fluxes just outside the experimental hall and on the internal rock walls







First results



Round Table "LUNA-MV at LNGS"
10th-11th February 2011

http://luna.lngs.infn.it/luna-mv

35 scientists from Europe, USA and Asia:

- Status of similar projects in Europe and USA
- Description of the LUNA MV project (site, machine, shielding,...)
- Astrophysical importance of the envisaged reactions
- Experimental open problems
- Discussion

↓

Two documents:
A) Proceedings
B) Brief description of the project and list of "Working packages" to be distributed for adhesions (Aliotta, Fraile, Fulop , Guglielmetti)

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*.

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