The LUNA - MV project at the Gran Sasso Laboratory

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for the LUNA Collaboration

2nd CUNA Workshop, Canfranc, February 29, 2014

OUTLOOK

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

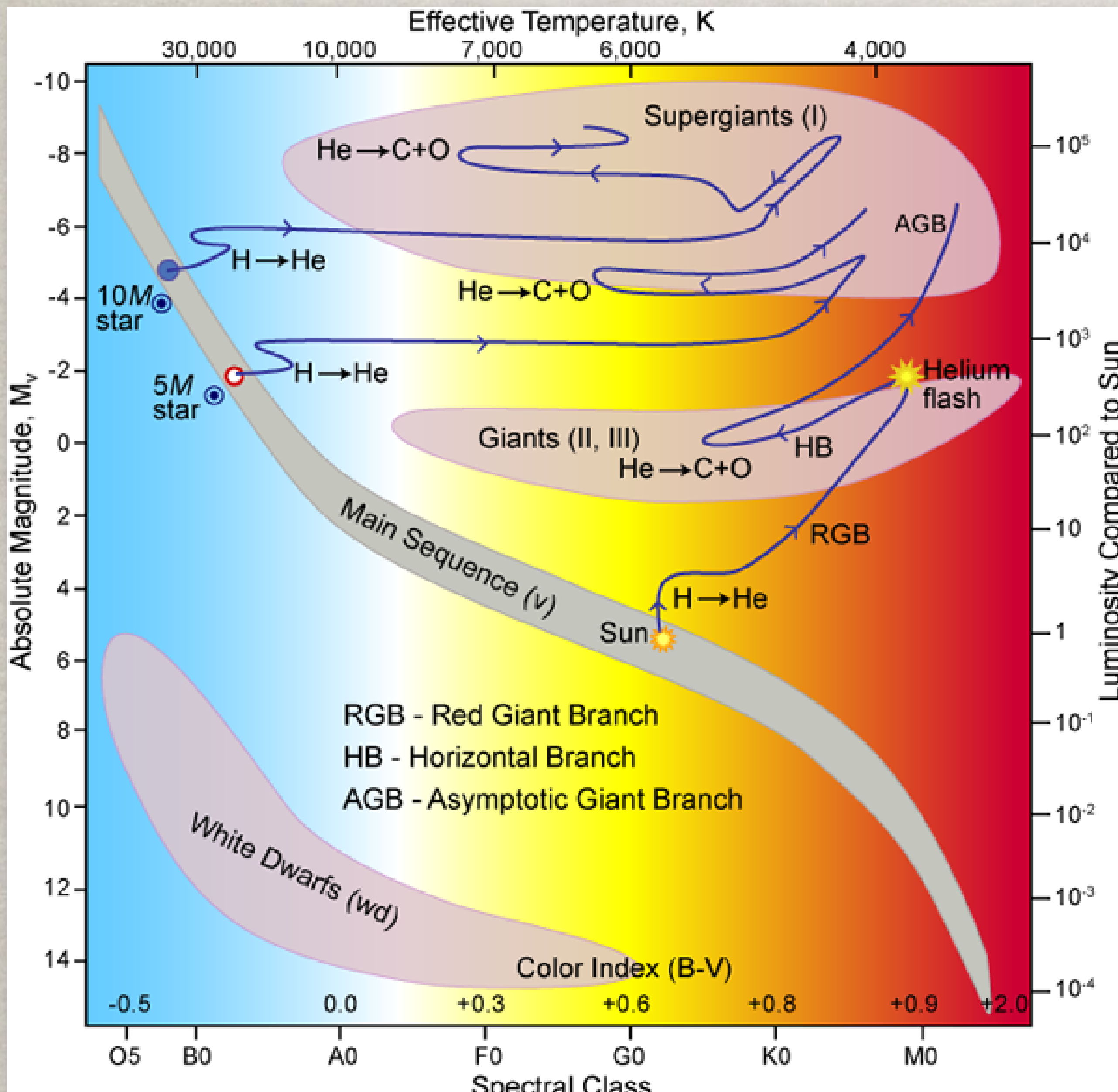
- The LUNA 400 kV Accelerator

  - The Sun: p-p chain, CNO cycle and solar neutrinos
  - Nucleosynthesis at work: ^{26}Al
  - Hot environment: BBN and Novae

- Target preparation and analysis: a tough job

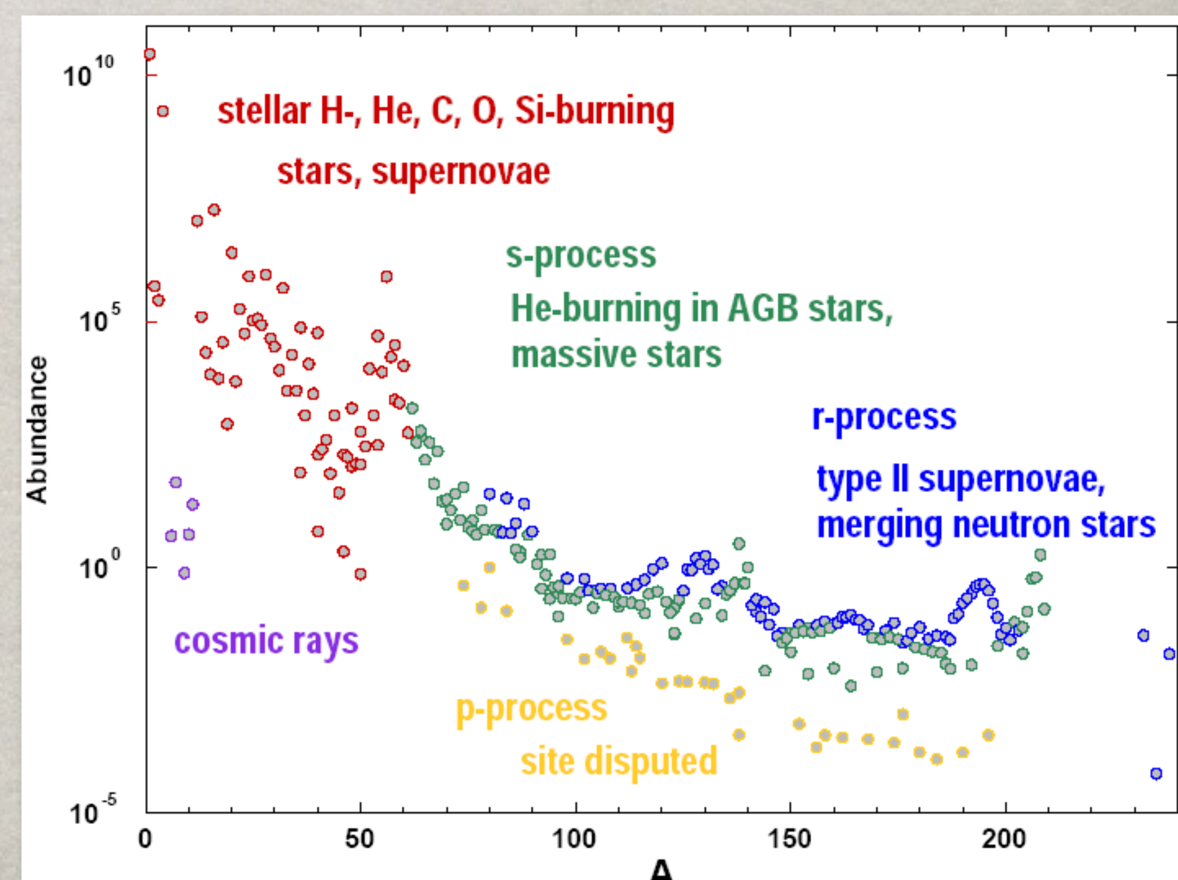
- The LUNA-MV project: a big step forward

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

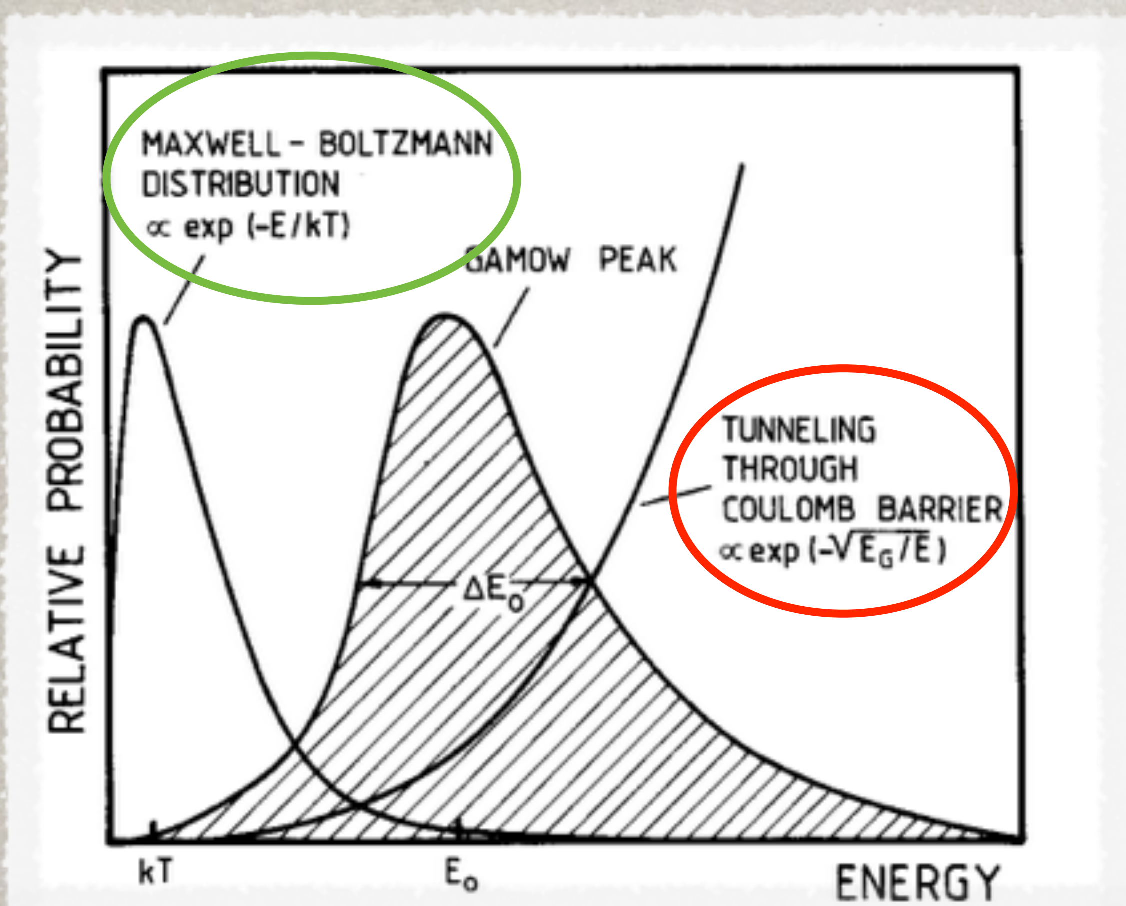
T_{NOVAE} = 0.3 GK ~ 140 keV

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: $T = 1.5 \cdot 10^7$ K

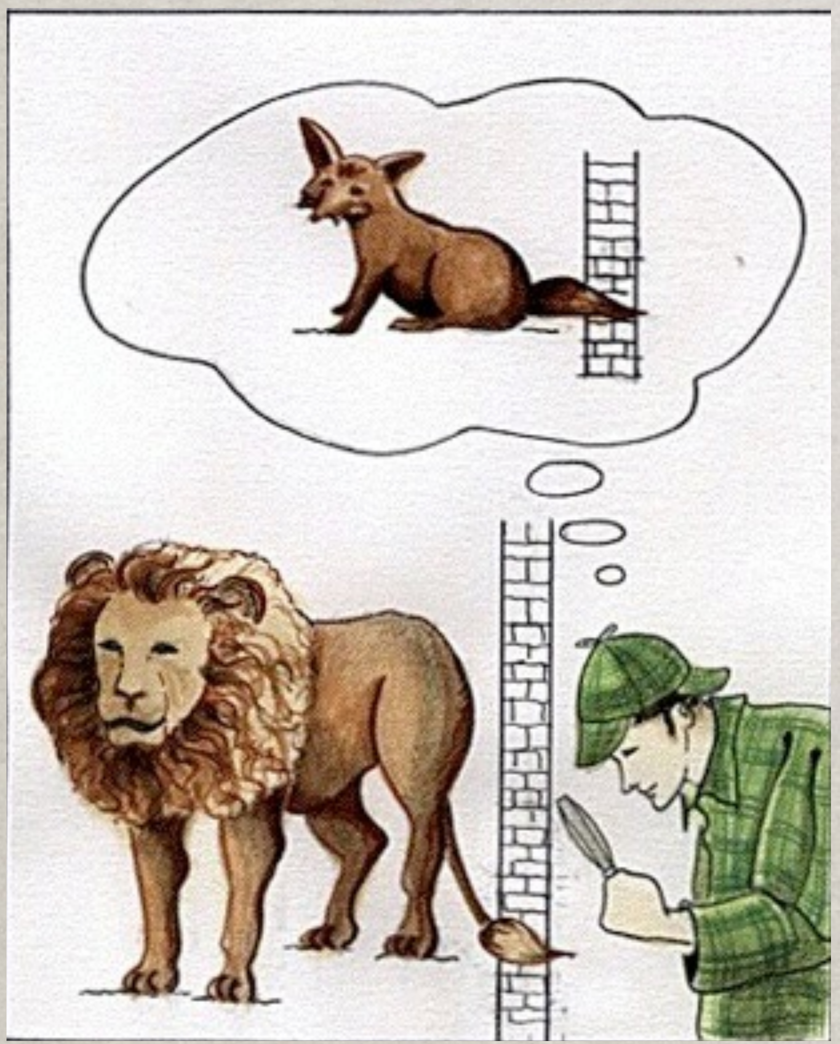
kT = 1 keV << E_{coul} (0.5-2MeV)

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

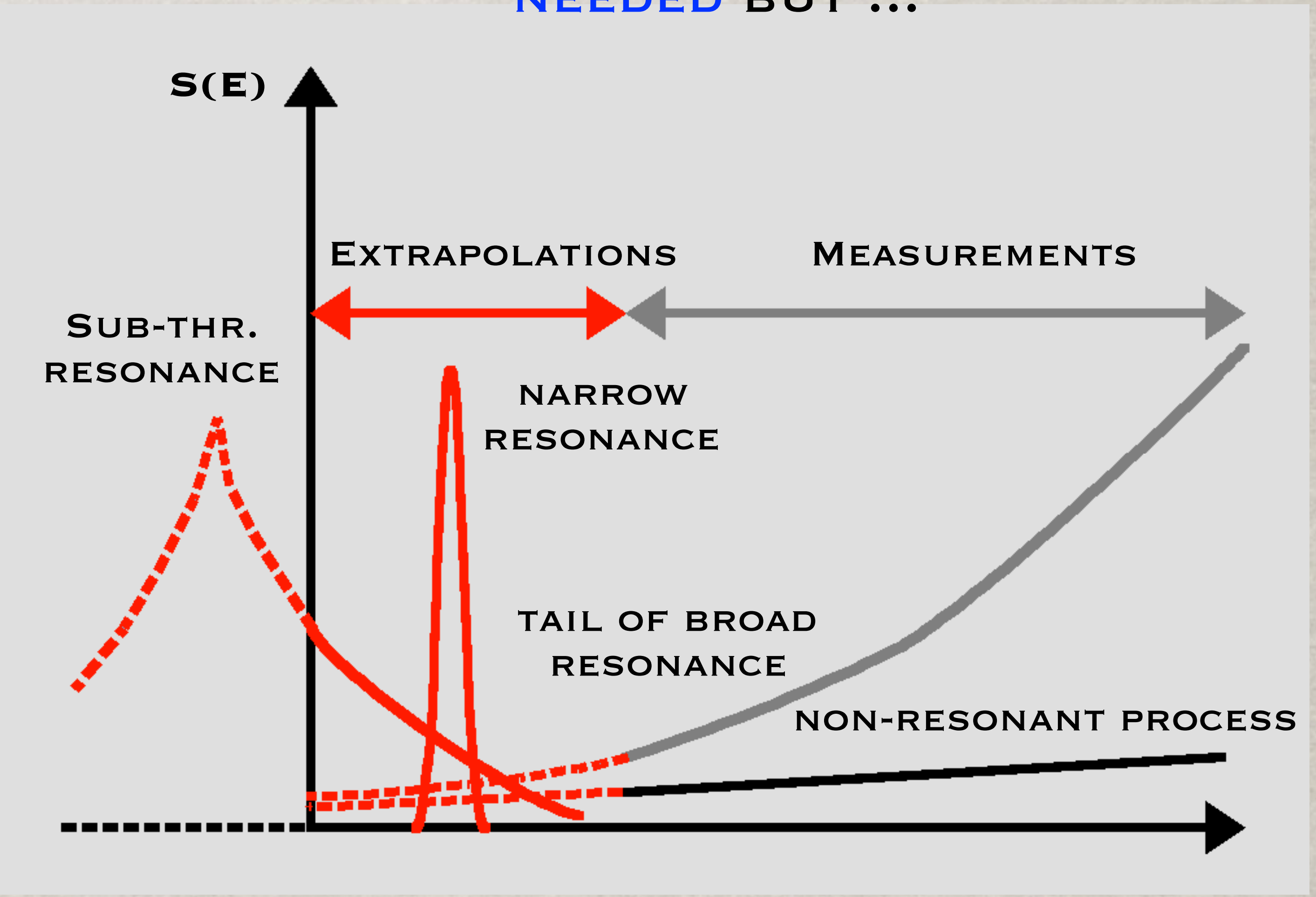
Gamow Energy for H-burning reactions: few to several tens keV

pbarn < σ < 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
- ☑ high purity and stable targets

and it's very small at low energies

How to improve signal to noise ratio

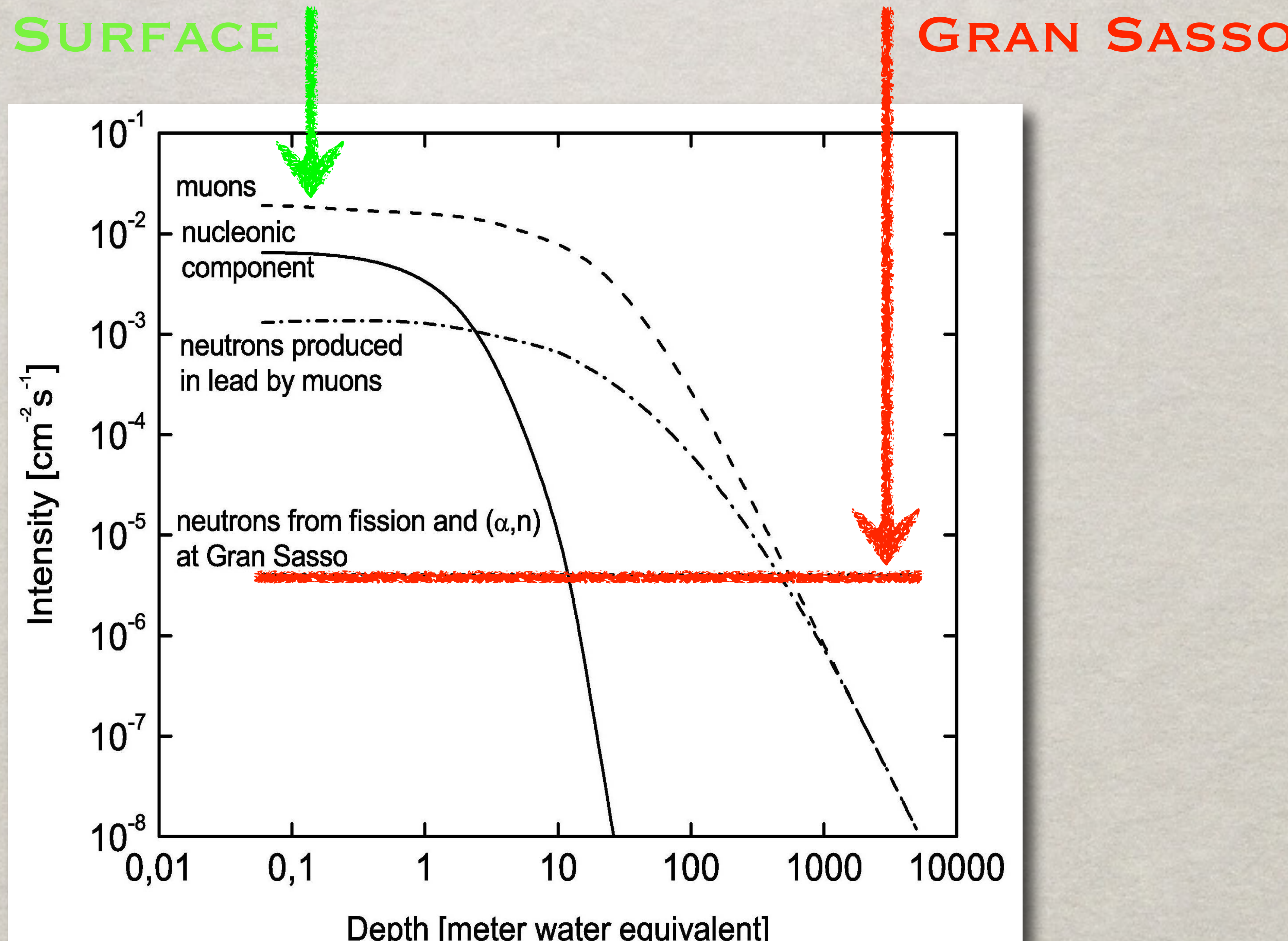
- setup efficiency ↑
- natural background (cosmic radiation, radioactive isotopes) ↓
- beam induced background ↓

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

⬇

Underground measurements

Why Going Underground ?

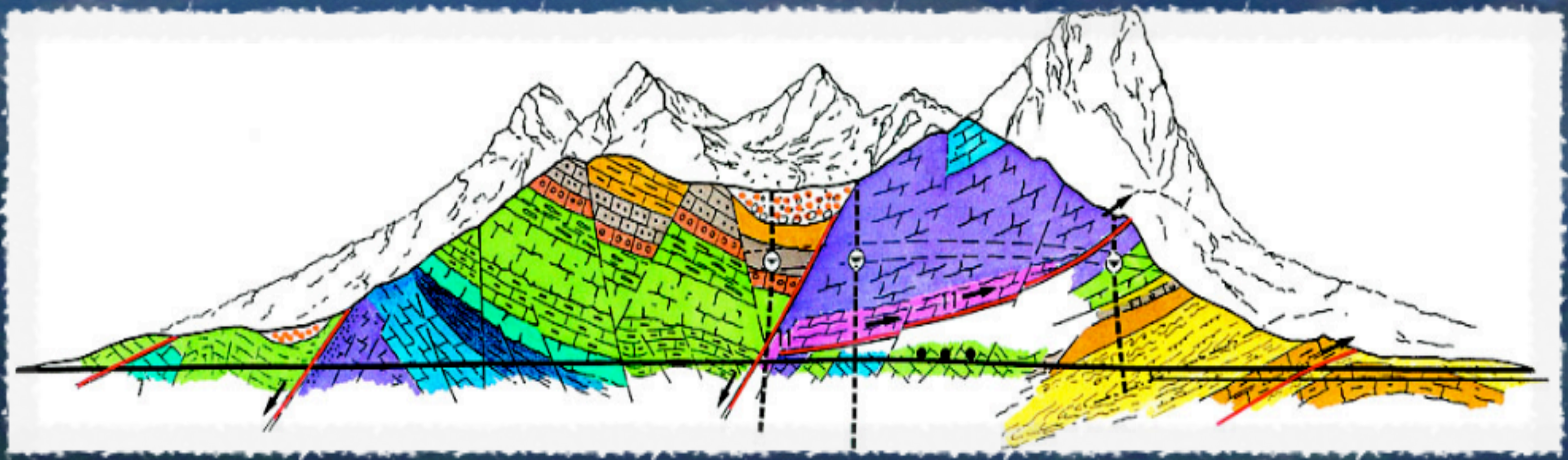


@ LNGS

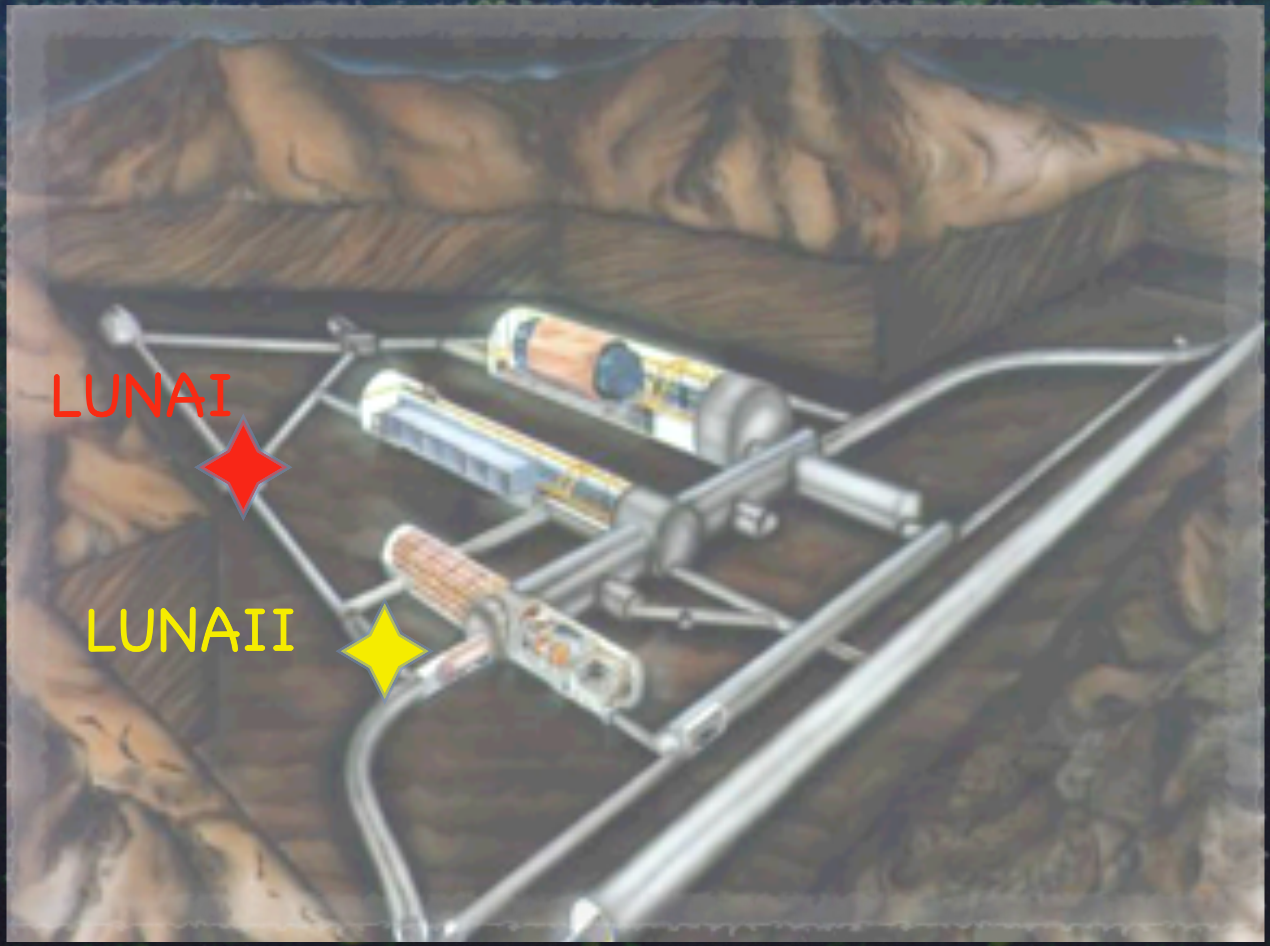
muons: 1 /($m^2 \cdot h$), E > 1 TeV

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}
  m 10^{-6}
- underground area 18000 m^2
- support facilities on the surface



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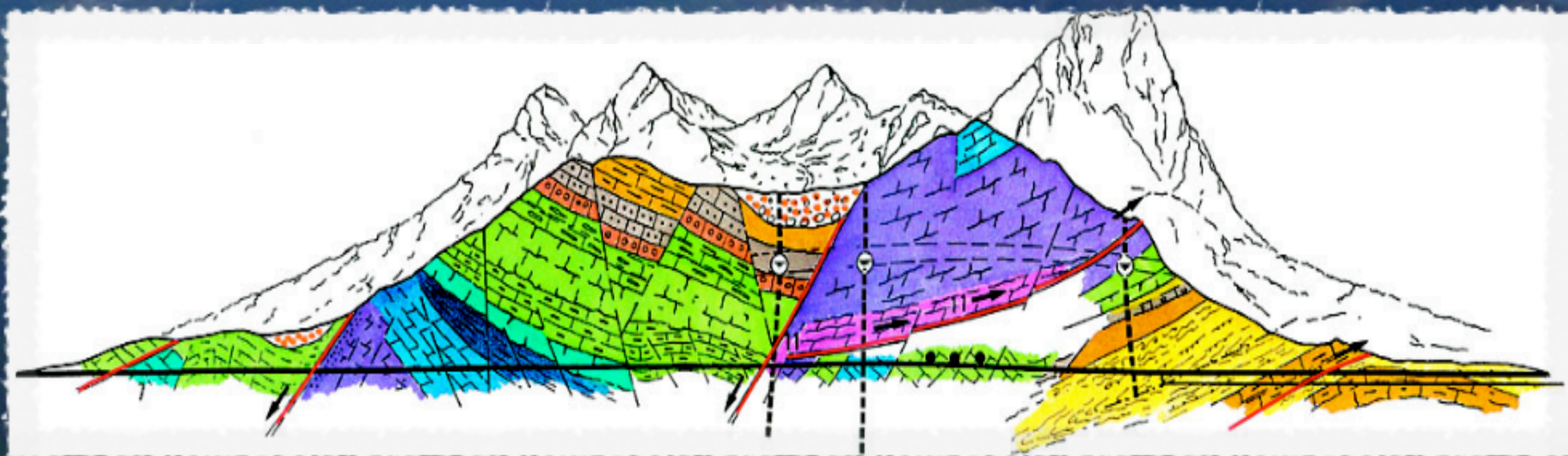
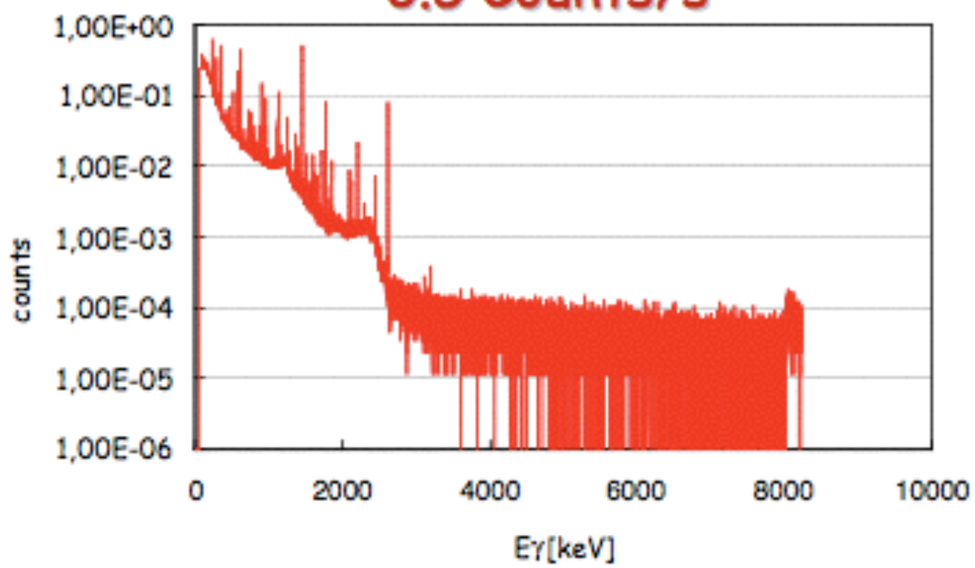


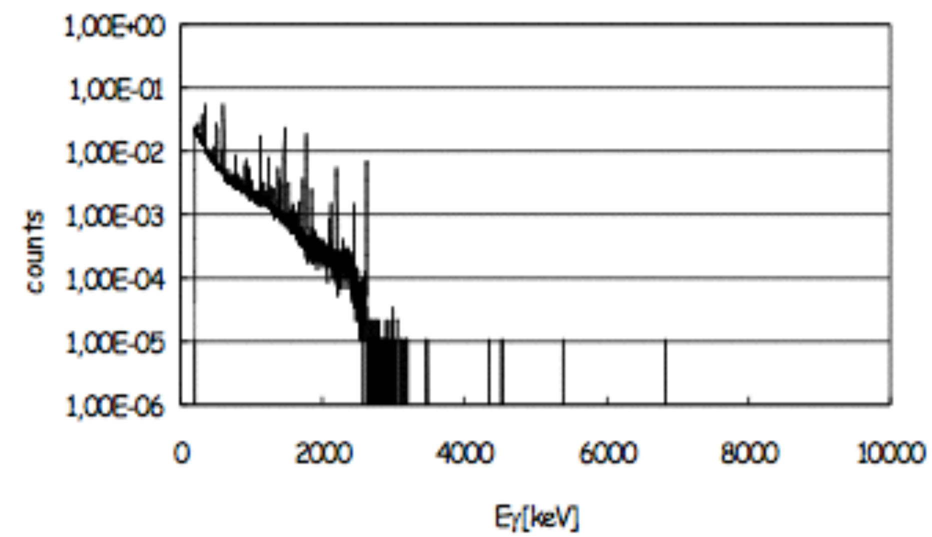
$3MeV < E_\gamma < 8MeV$:
0.5 Counts/s



HpGe

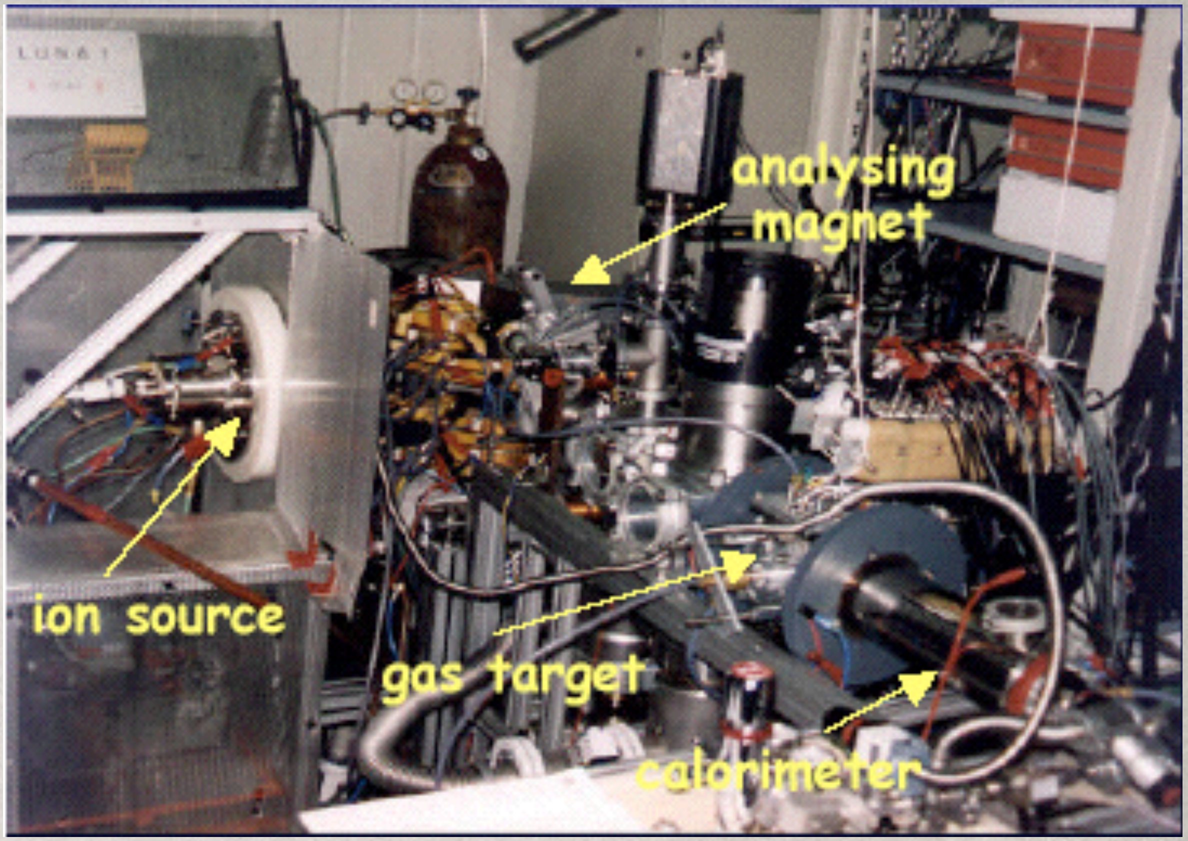
GOING UNDERGROUND →

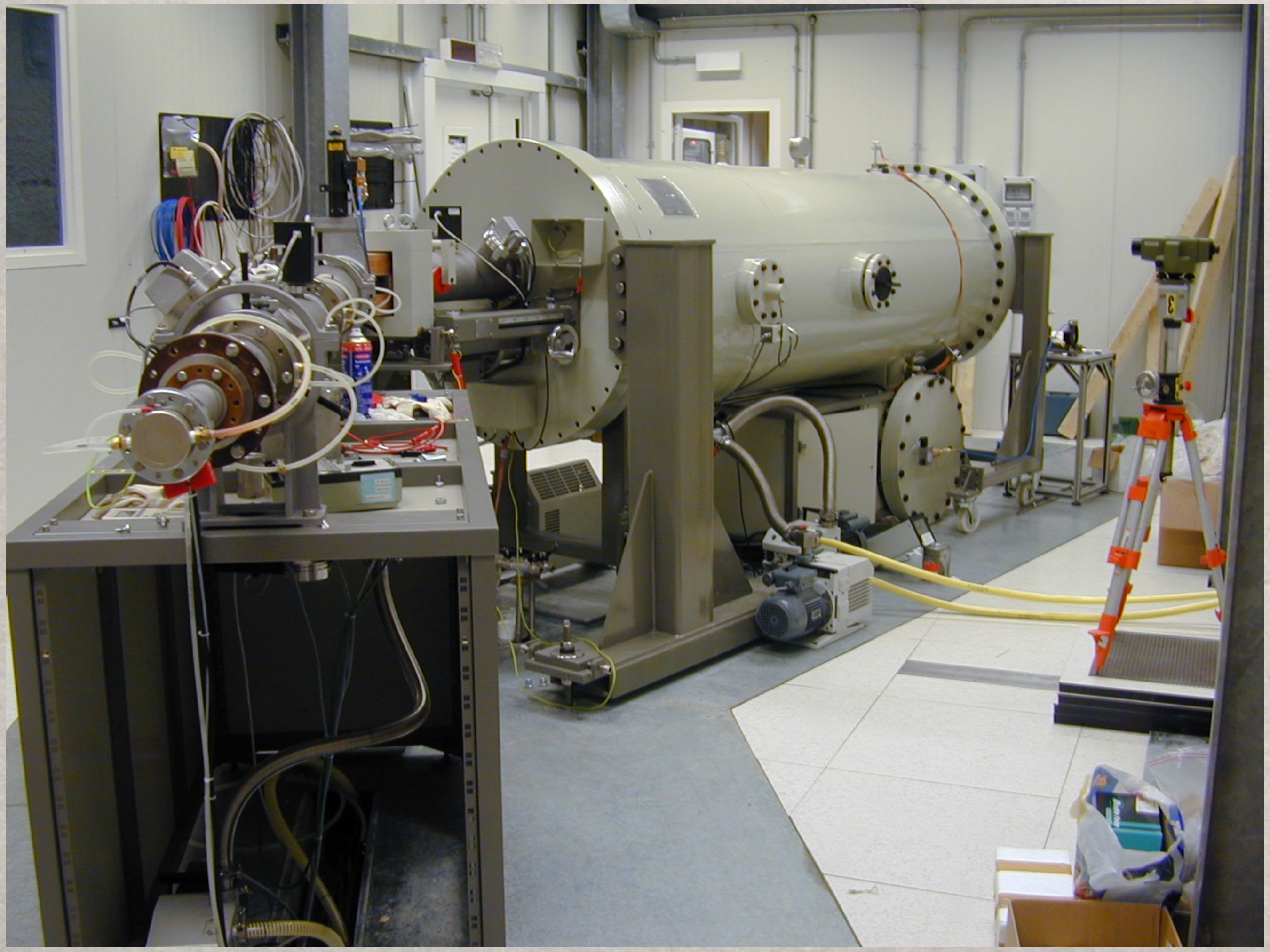
$3MeV < E_\gamma < 8MeV$
0.0002 Counts/s



LUNA I

beams = p, a
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, a
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

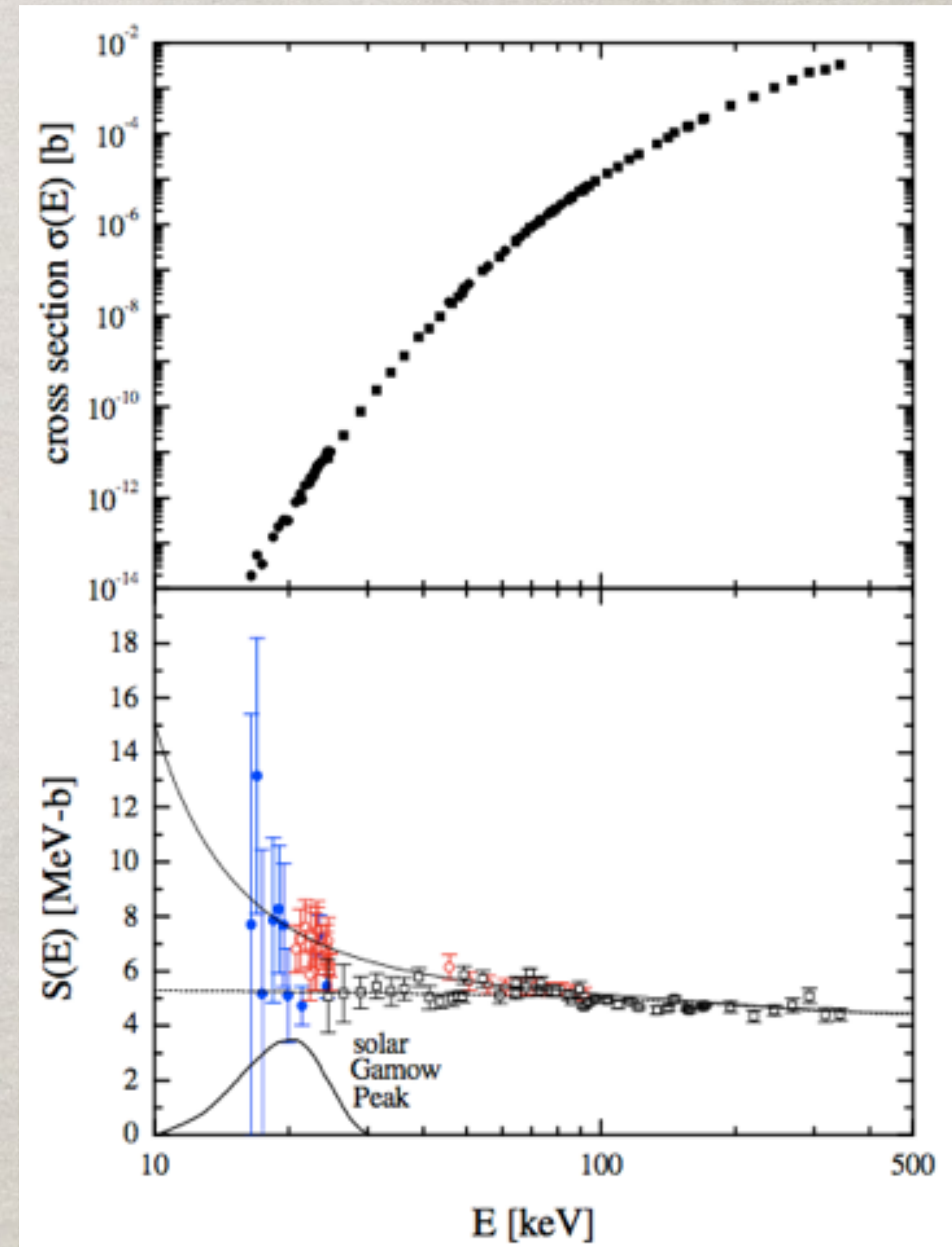
$^3He + ^3He \rightarrow ^4He + 2p$

- 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

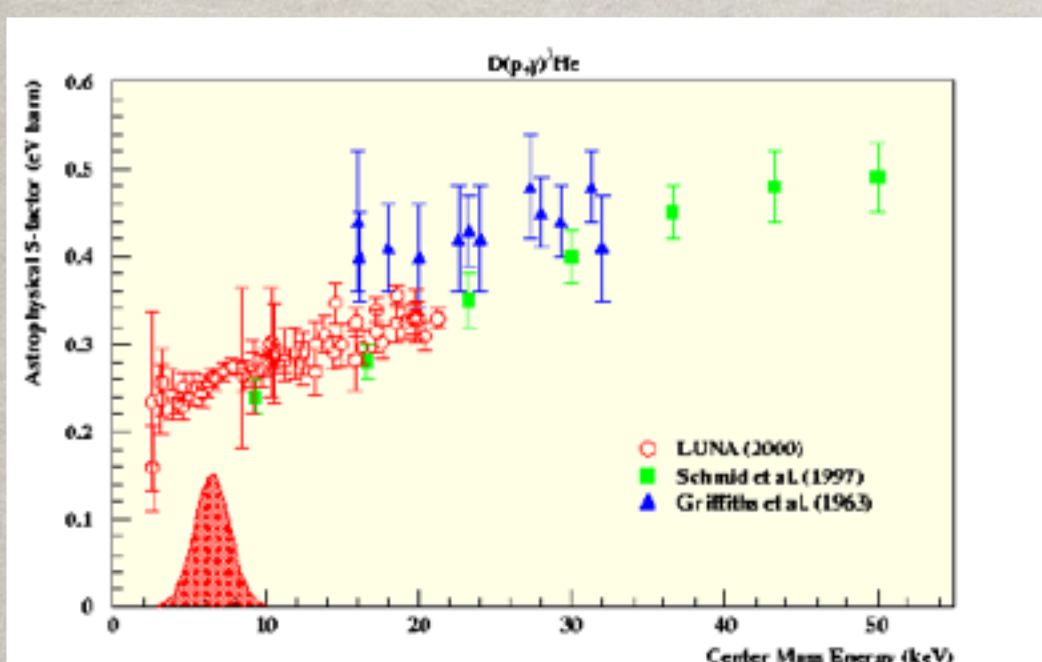
background < $4*10^{-2}$ cts/day in ROI



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

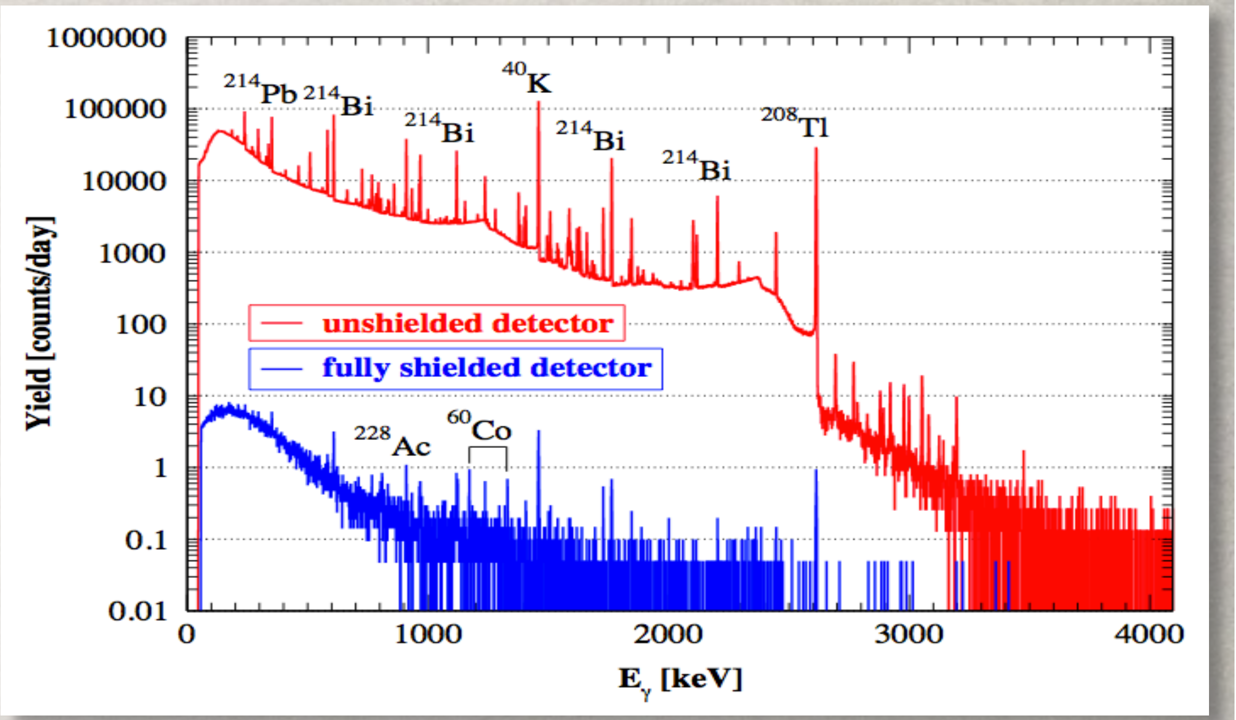
no extrapolation needed !

Measurements at LUNA II

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

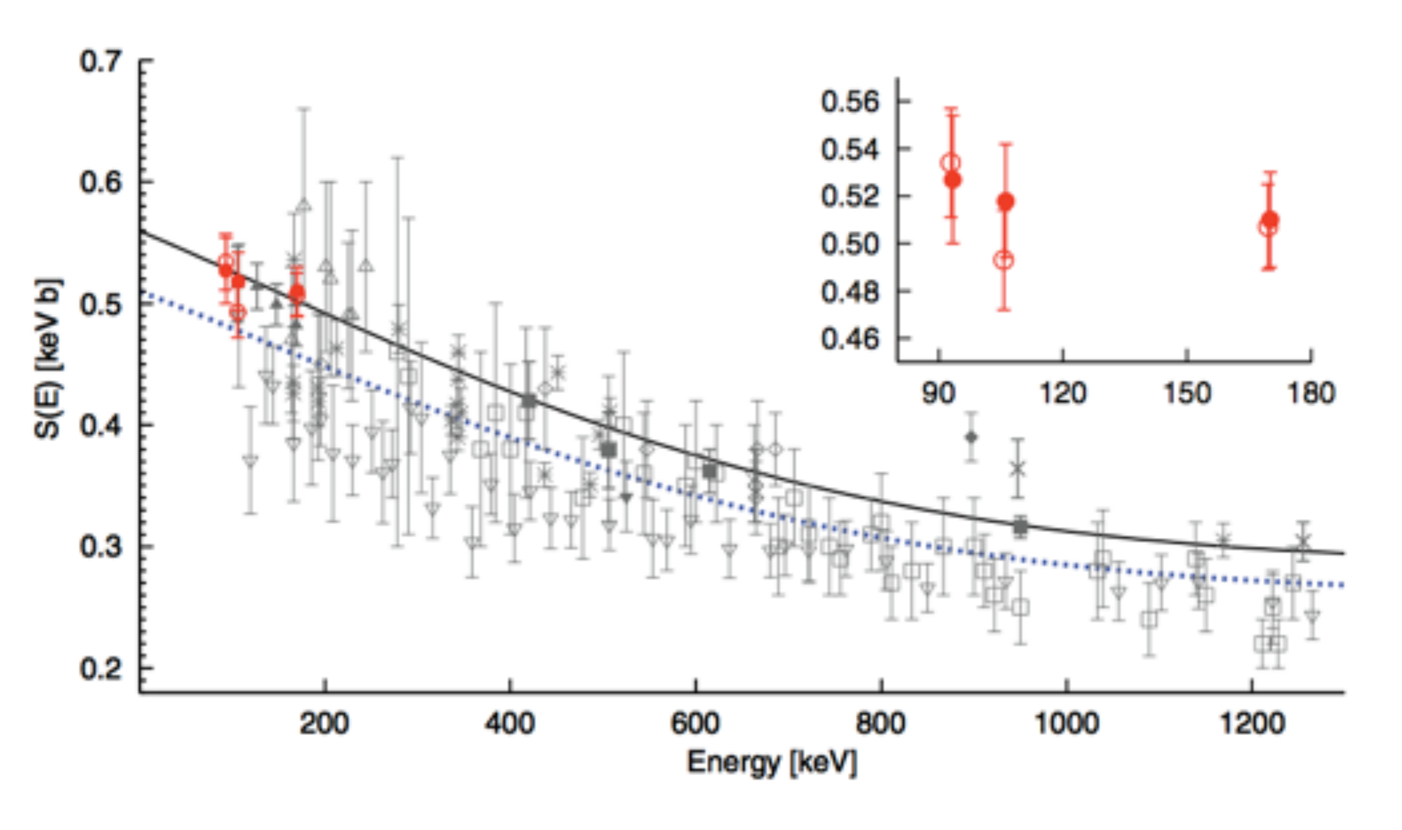
- key reaction in the p-p chain for ^7Be e ^8B neutrinos in the Sun
- fundamental for ^7Li in BBN

- gamma-prompt and activation method



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)



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

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

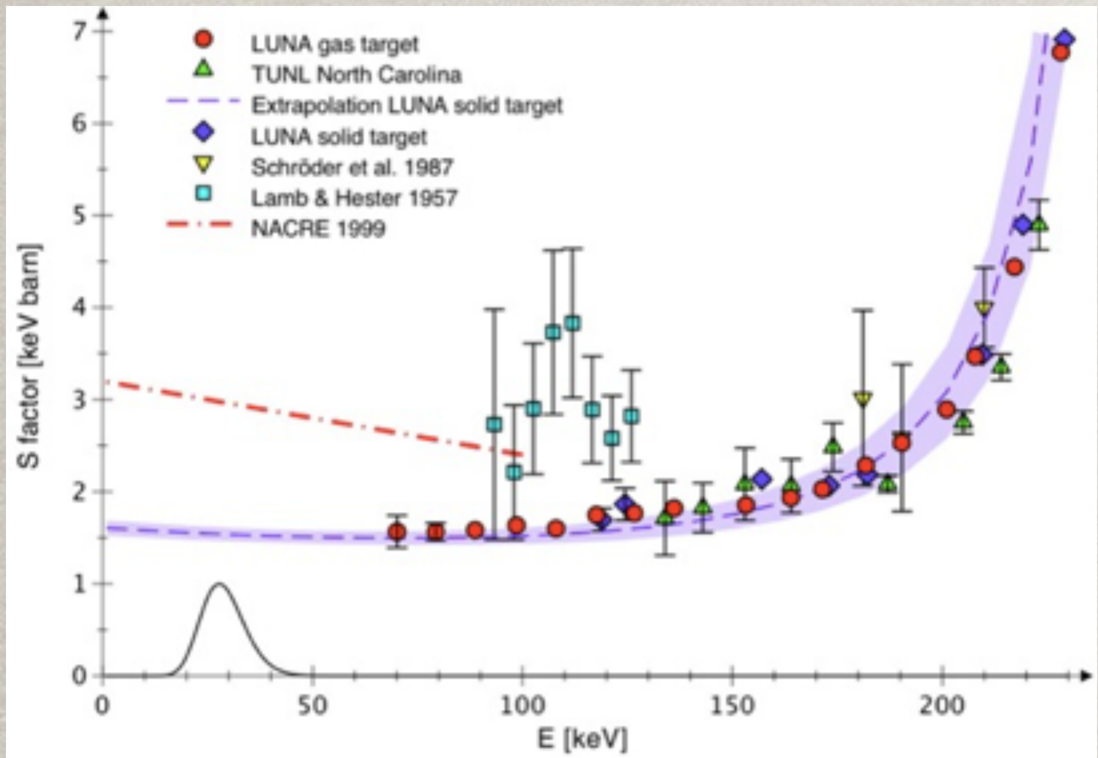
uncertainties on the neutrino fluxes

$\Phi_\nu(^8B)$ -> from 12% to 10%

$\Phi_\nu(^7Be)$ -> from 9.4% to 5.5%

CNO cycle

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

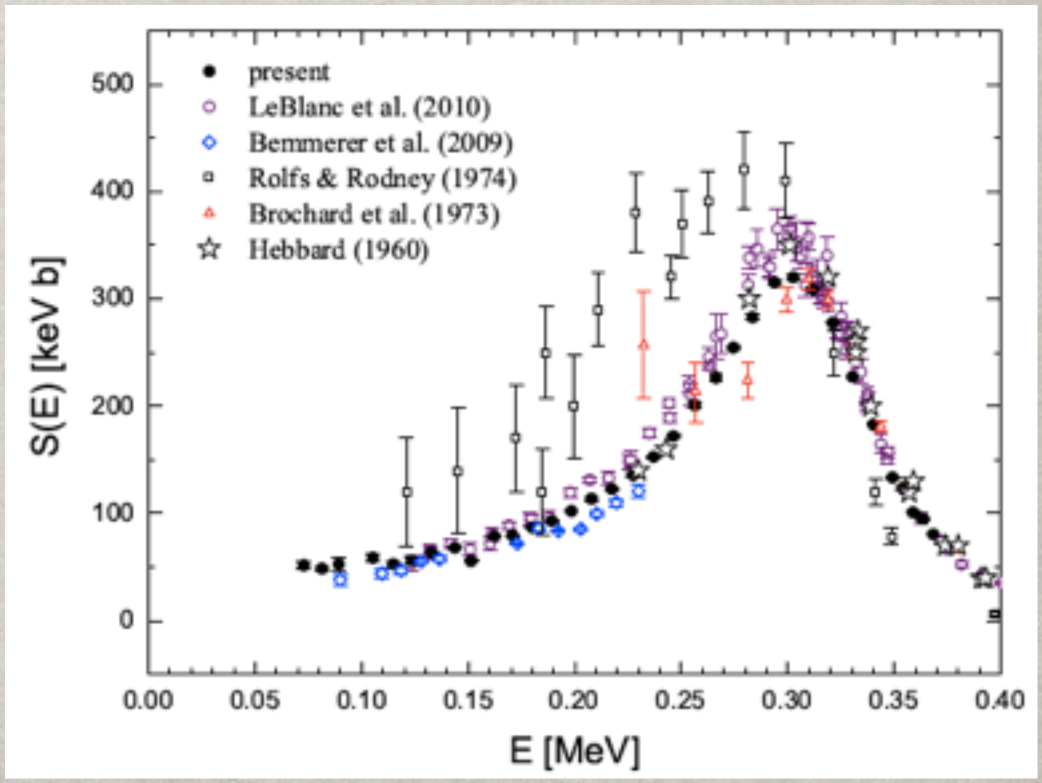


M. Marta et al., PRC 83 (2011) 045804

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

Target Analysis

^{15}N enriched TiN target:

reactive sputtering

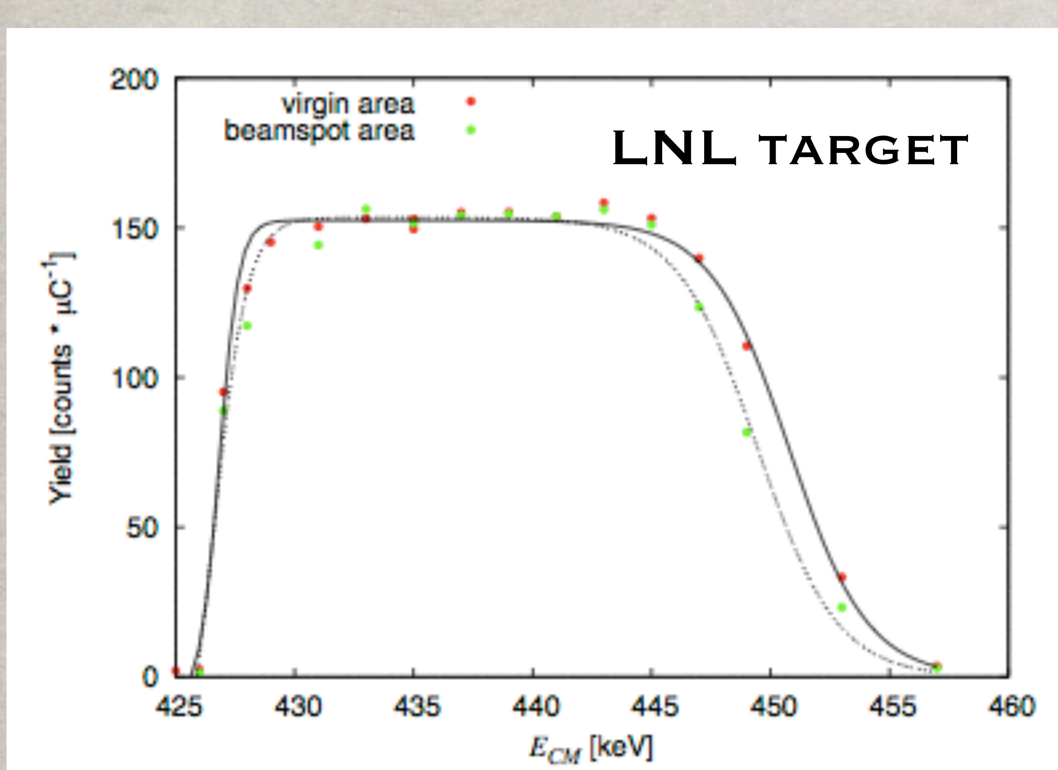
Resonance profile scans:

- depth profile
- nitrogen concentration

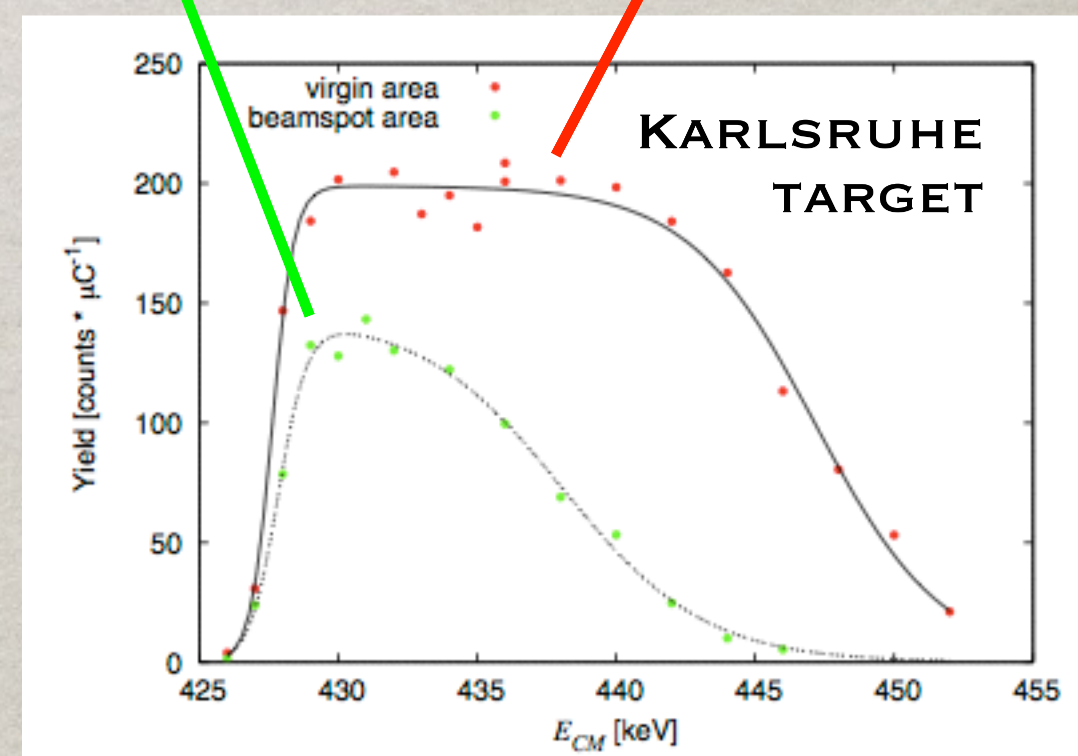
Narrow resonance required

Beam Current: 1-5 μA

E_p = 426 – 460 keV



No significant deterioration after 10 C



Highly deteriorated, up to ~ 30%

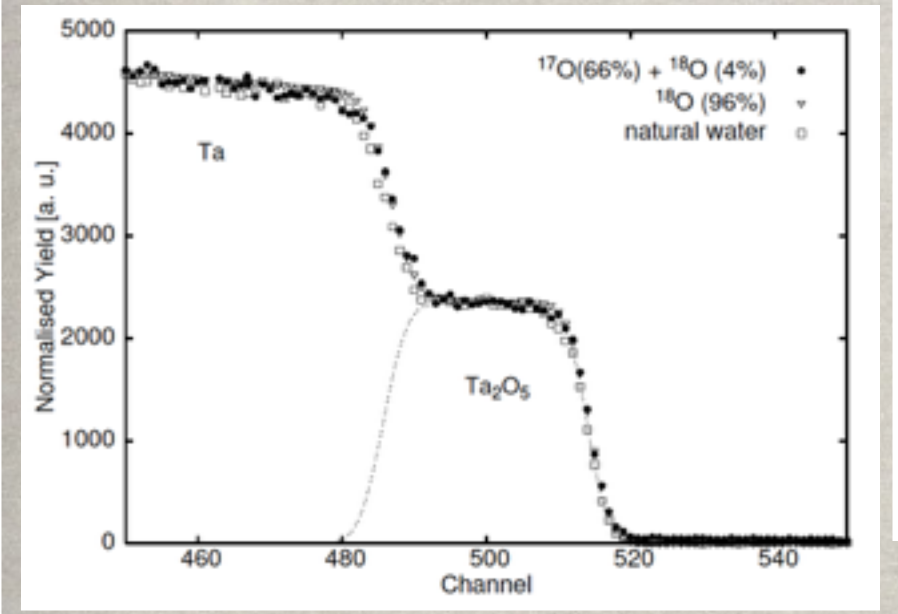
Total integrated charge from 6 to 36 C

Target Analysis

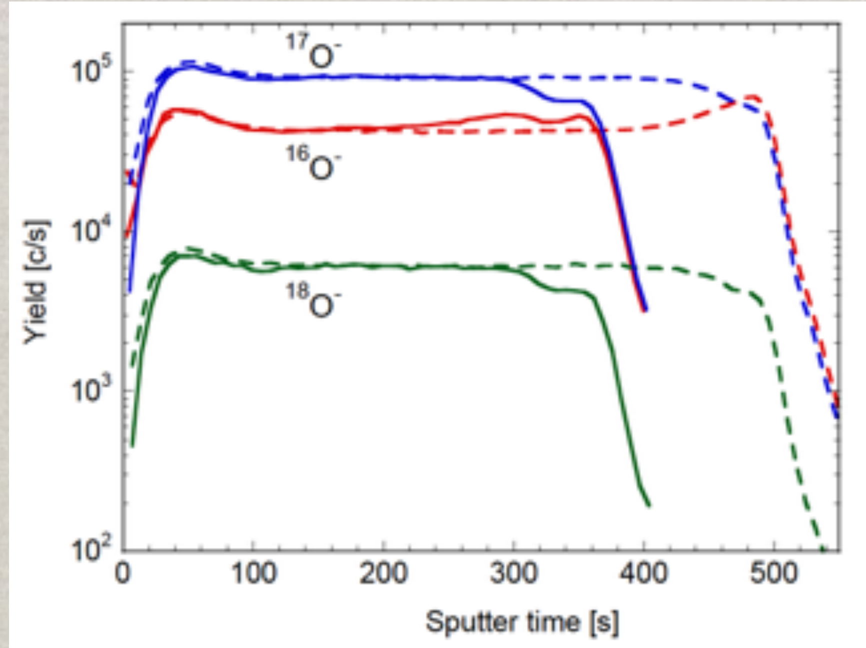
Targets are made oxidising the tantalum backing. Ta_2O_5 enriched in ^{17}O up to 70% are made directly in the chemistry lab of the National Laboratories of Gran Sasso.

A small percentage of ^{18}O is included in the solution (5%) in order to check the target conditions by using the well known 151 keV resonance of the $^{18}O(p,\gamma)^{19}F$ reaction.

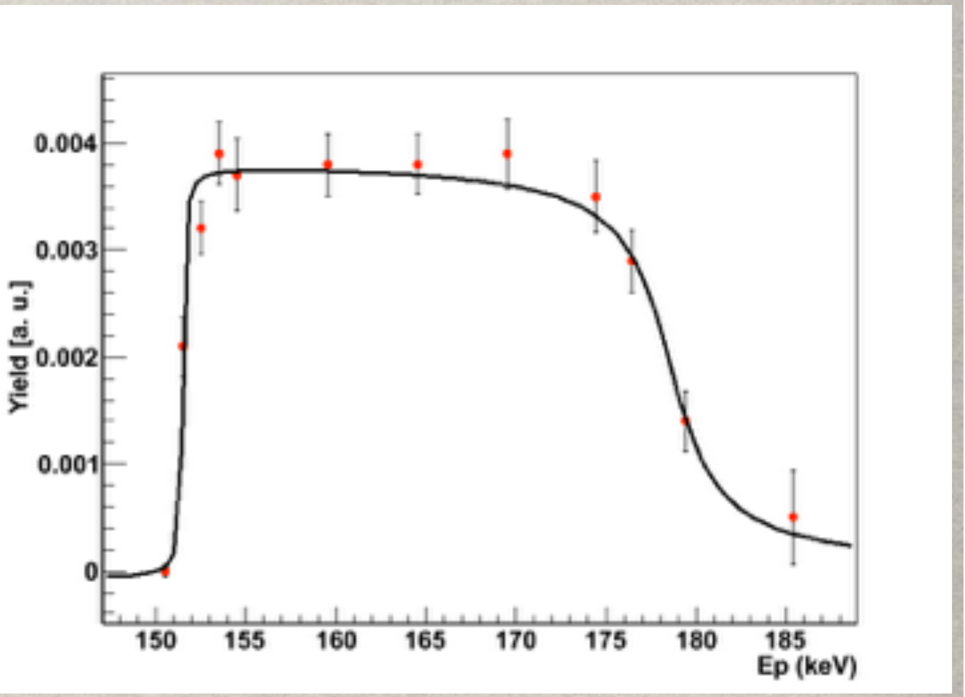
The target has been analysed by using Rutherford backscattering and SIMS in order to characterise the stoichiometry and isotopic ratio.



Rutherford Back Scattering (RBS)



SIMS Technique



Resonance Scan on contaminant

No significant target deterioration observed before 20C irradiated charge

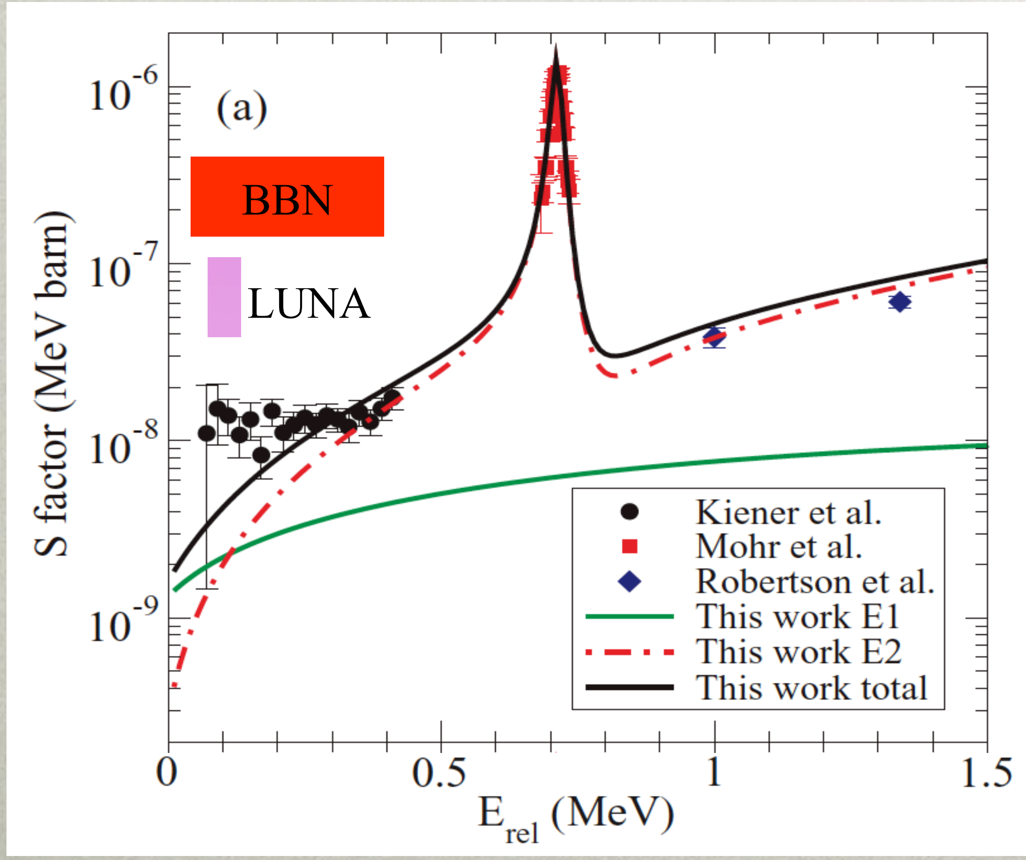
D(α,γ)^{6}Li reaction

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

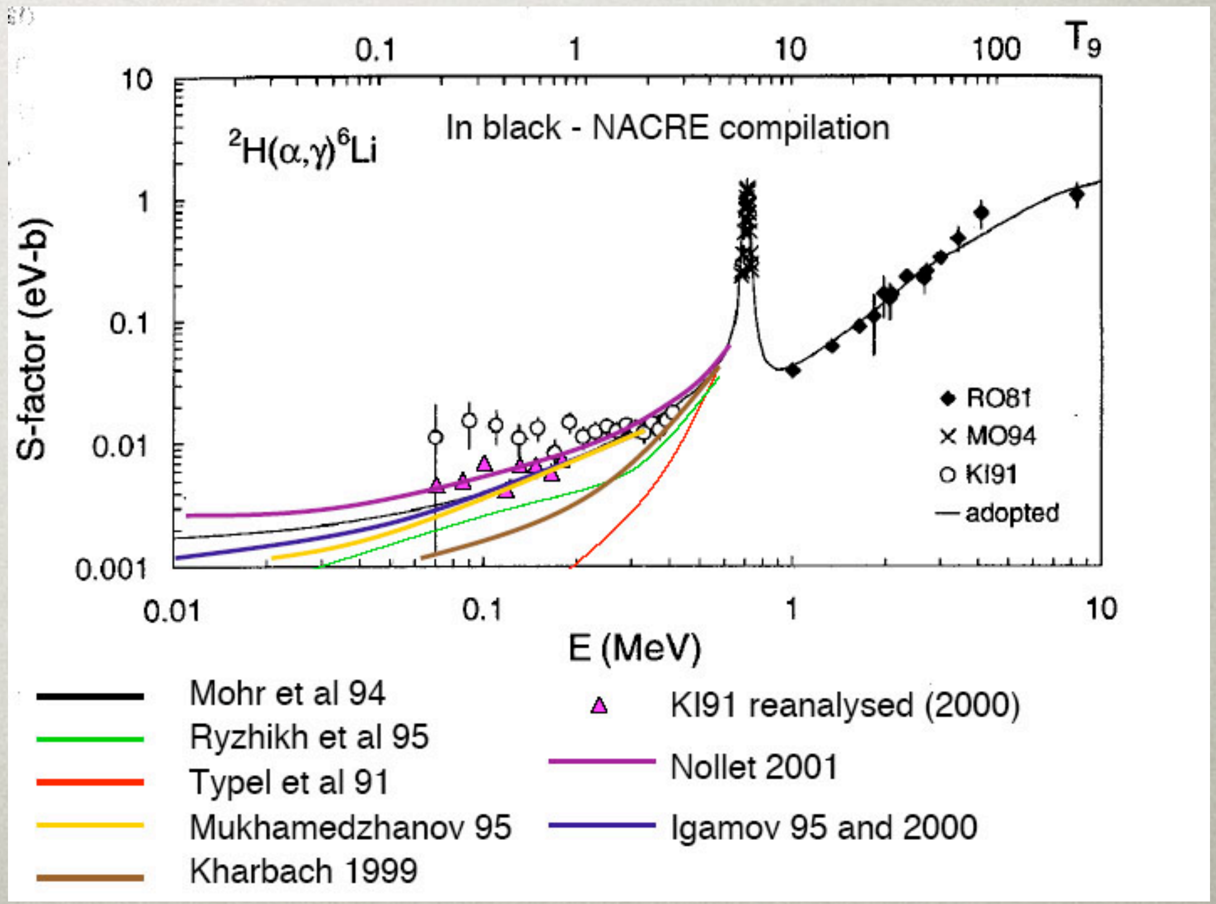
- D(α,γ)^{6}Li is the **main reaction** for ^{6}Li production
- In BBN, this reaction occurs at energies in the range **50 < E_{CM} < 400 keV**
- **No direct measurement** exists at E_{CM} < 650 keV (E_{LAB} < 1950 keV)
- **Theoretical calculations** for the astrophysical S-factor differ by more than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

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

✱ see talk by Davide Trezzi

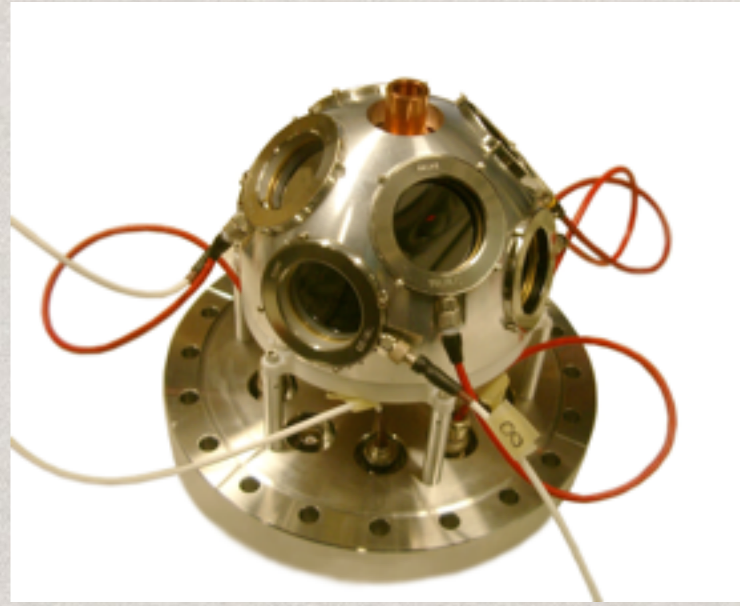


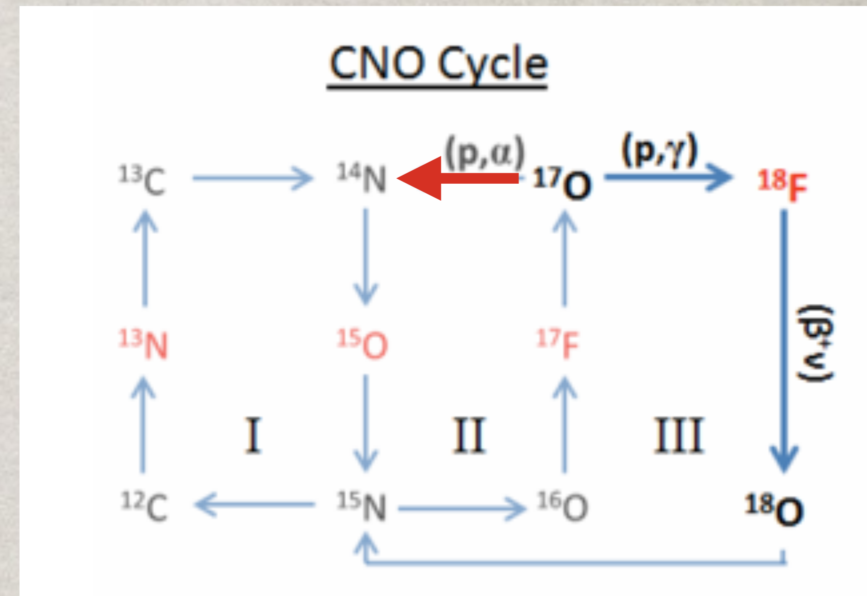
F. Hammache et al. Phys. Rev. C 82 (2010)



Other measurements

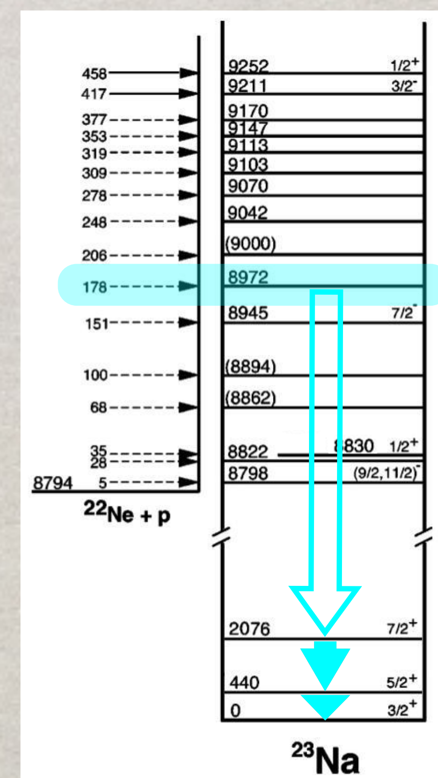
- $^{17}O(p,\alpha)^{14}N$ CNO cycle of Hydrogen burning stars
- Never measured for AGB stars (T = 0.03 ÷ 0.1 GK)
- data taking for 71 keV and 193 keV resonances completed



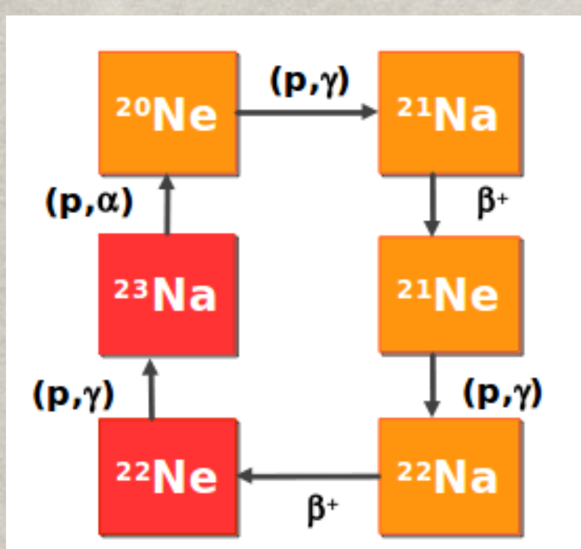


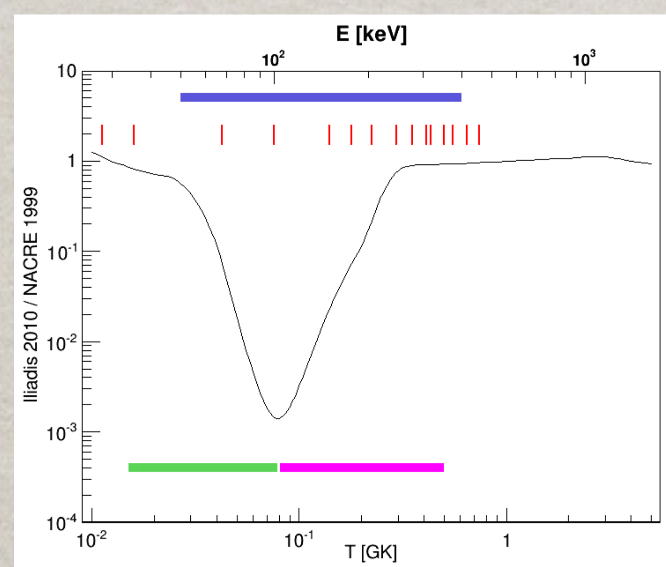
C.G. Bruno et al., Eur. Phys. J A 51 (2015) 94

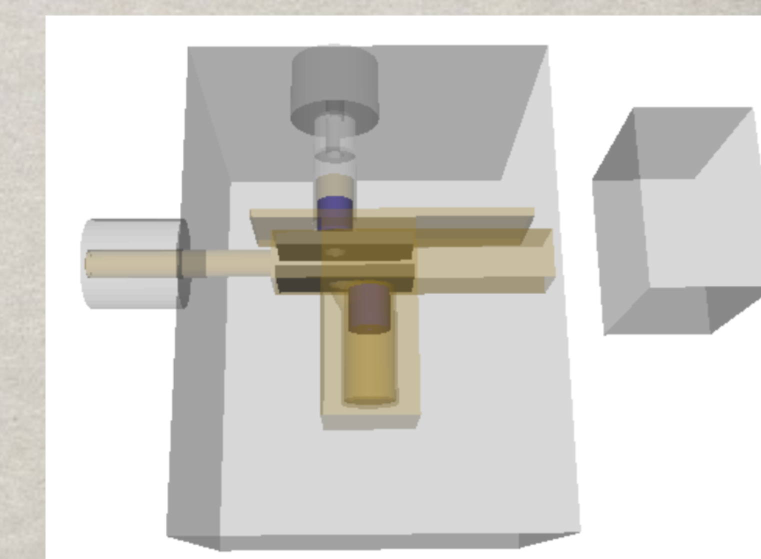
- $^{22}Ne(p,\gamma)^{23}Na$ NeNa cycle of Hydrogen burning stars
- New resonances detected
- BGO measurement in progress



see talk by Federico Ferraro







F. Cavanna et al., Eur. Phys. J. A 50 (2014) 179 and F. Cavanna et al., submitted to PRL

- $^{18}O(p,\alpha)^{15}N$ completed, $^{18}O(p,\gamma)^{19}F$ and $^{23}Na(p,\gamma)^{24}Mg$ measurement in progress

LUNA 400 kV - Future program

$^{13}C(\alpha,n)^{16}O$ – neutron source (LUNA MV)

$^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$ – relative abundance of ^{12}C-^{13}C in the deepest layers of H-rich envelopes of any star

$^{2}H(p,\gamma)^{3}He$ – ^{2}H production in BBN

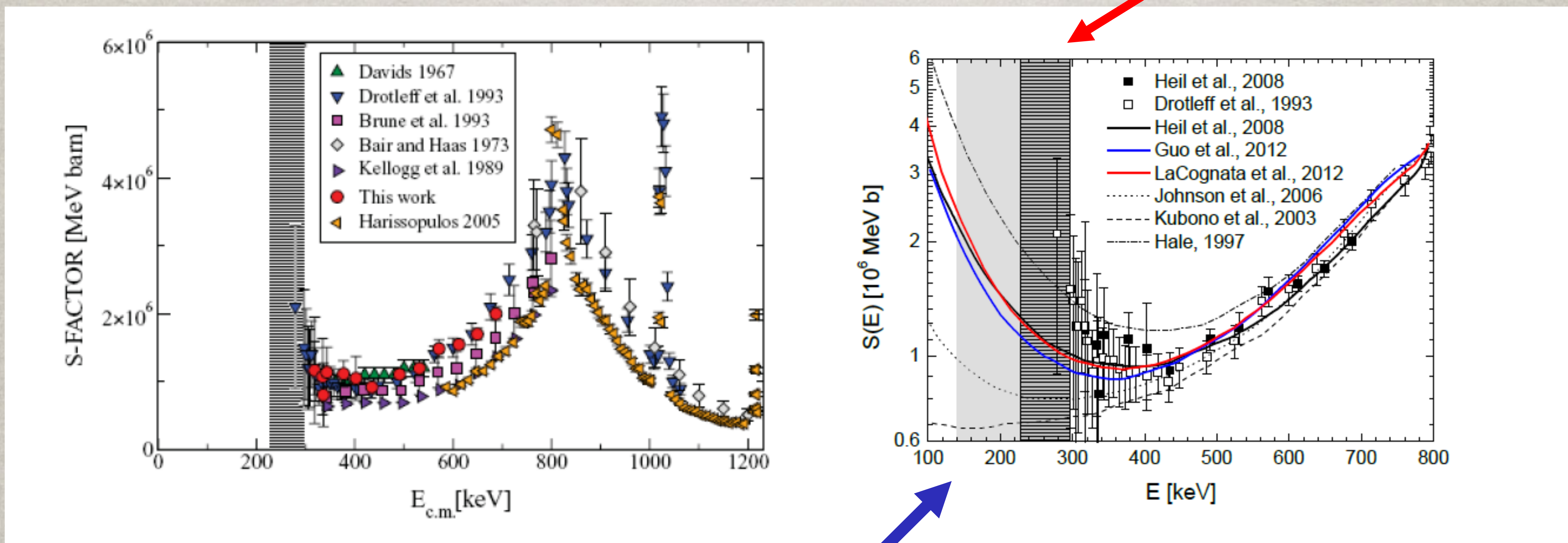
$^{22}Ne(\alpha,\gamma)^{26}Mg$ – competes with $^{22}Ne(\alpha,n)^{25}Mg$ neutron source (LUNA MV)

$^{6}Li(p,\gamma)^{7}Be$ – improves the knowledge of $^{3}He(\alpha,\gamma)^{7}Be$ key reaction of p-p chain (LUNA MV)

A bridge toward the LUNA - MV accelerator

^{13}C(a,n)^{16}C @LUNA400

LUNA400 range



Gamow peak in AGB stars (T≈ 90 -100 MK): 180 – 200 keV

Big uncertainties in the R-matrix extrapolations due to subthreshold resonances

On beam @LUNA400 at mid 2017, expected ≈ 9 month beam time

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
- CASPAR (United States)
- JUNA - Jinping Underground laboratory for Nuclear Astrophysics (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

- $^{12}C(\alpha,\gamma)^{16}O$
- $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$
- (α,γ) reactions on $^{14,15}N$ and ^{18}O
- $^{3}He(\alpha,\gamma)^{7}Be$ on a wide energy range
- $^{12}C + ^{12}C$ (added recently)

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

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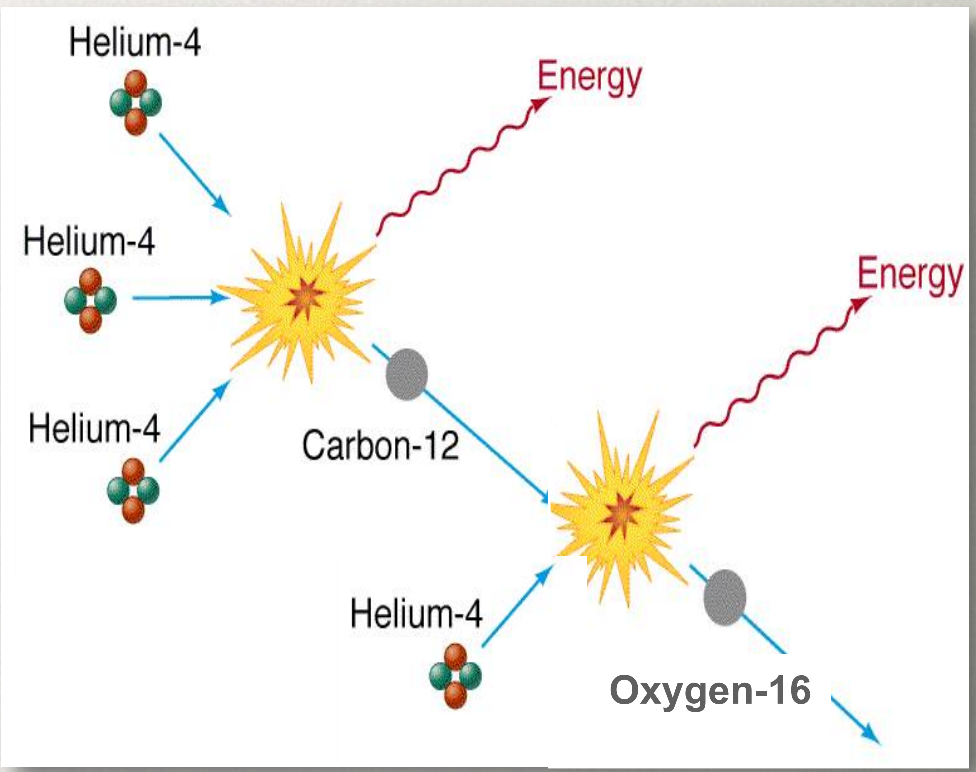
Single ended 3.5 MV positive ion accelerator

Stellar Helium burning: $^{12}C(\alpha,\gamma)^{16}O$

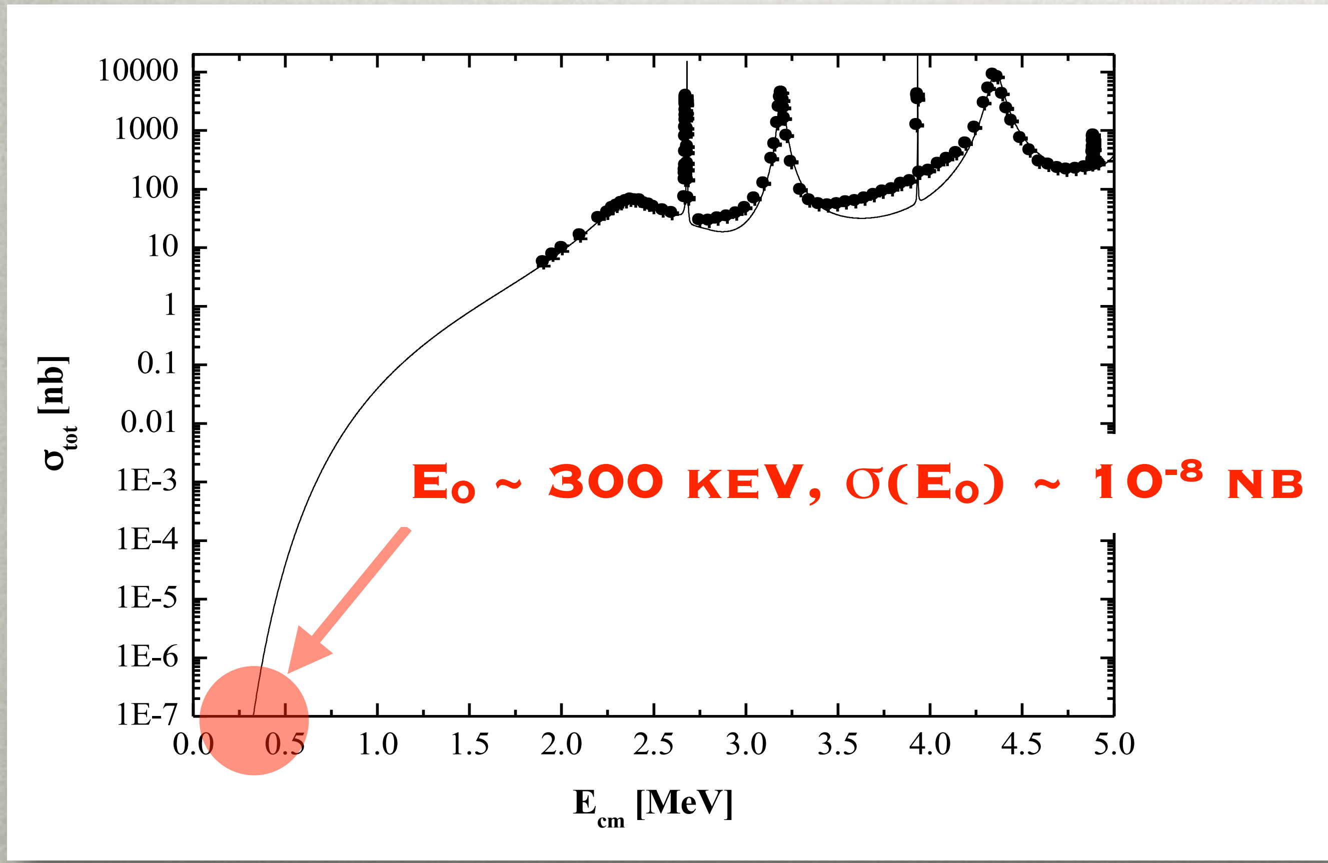


$^{12}C/^{16}O$ abundance ratio

Subsequent stellar evolution and nucleosynthesis

Composition of White Dwarfs

Mechanism of Supernovae



E_0 ~ 300 keV, $\sigma(E_0)$ ~ 10^{-8} nb

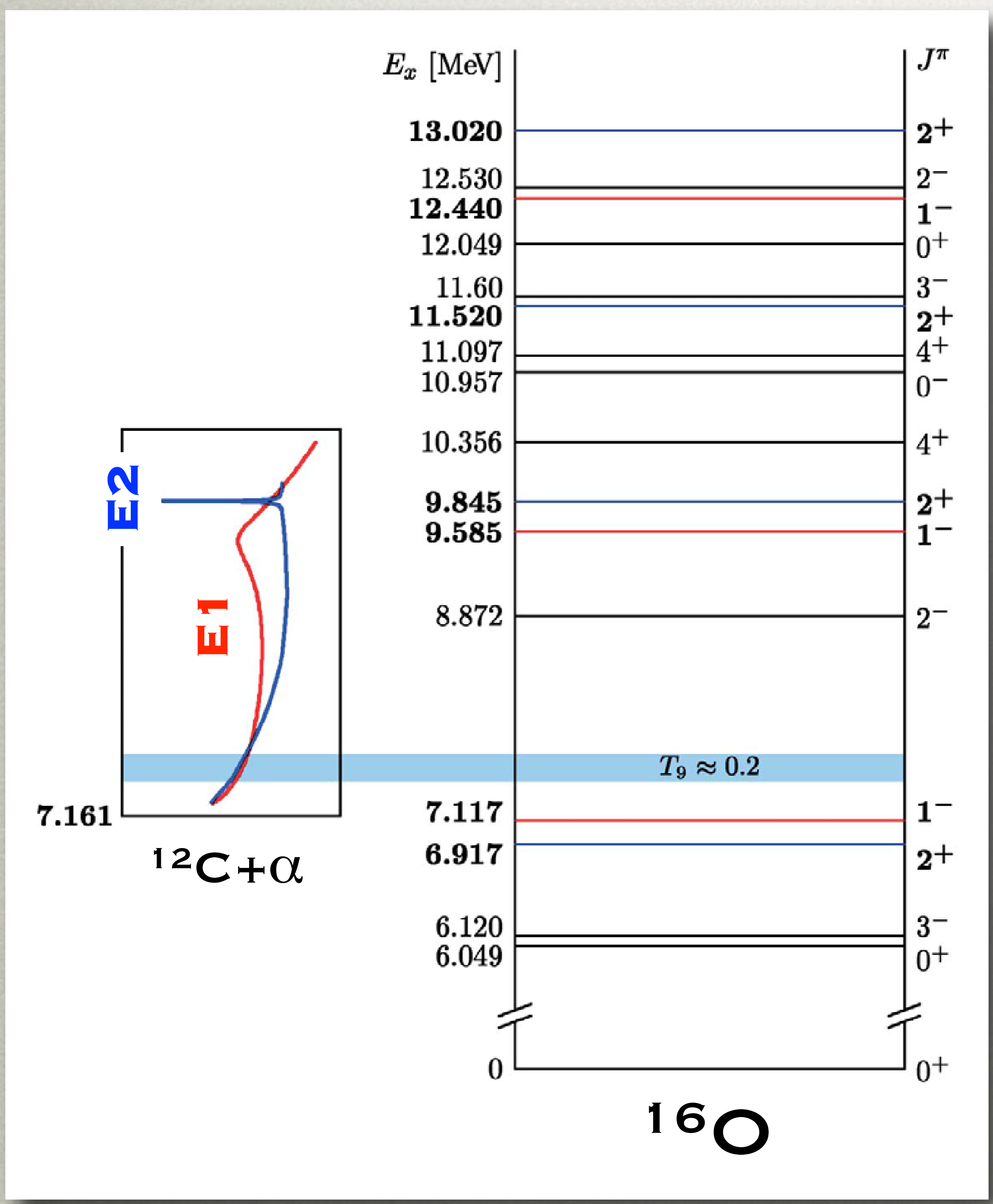
3α → ^{12}C and $^{12}C(\alpha,\gamma)^{16}O$

Creation and Destruction of ^{12}C

Even with
Accurate measurements at low and high energy

extrapolation to E_0 are needed

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



Complex level scheme

- Several 1^- and 2^+ Resonances
- Sub-threshold resonances dominate the S-factor at low energy
- Cascade transitions
- Direct capture

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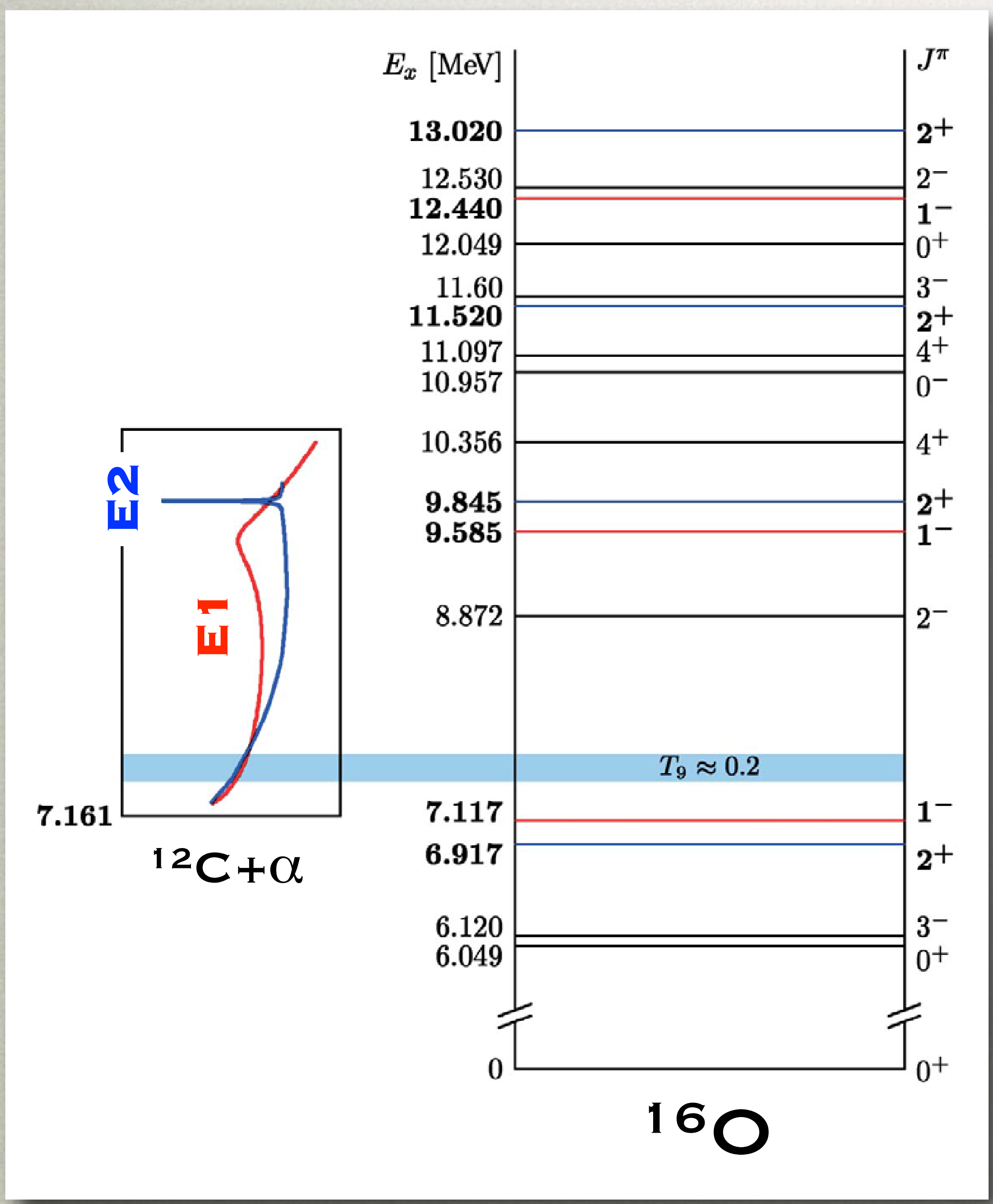

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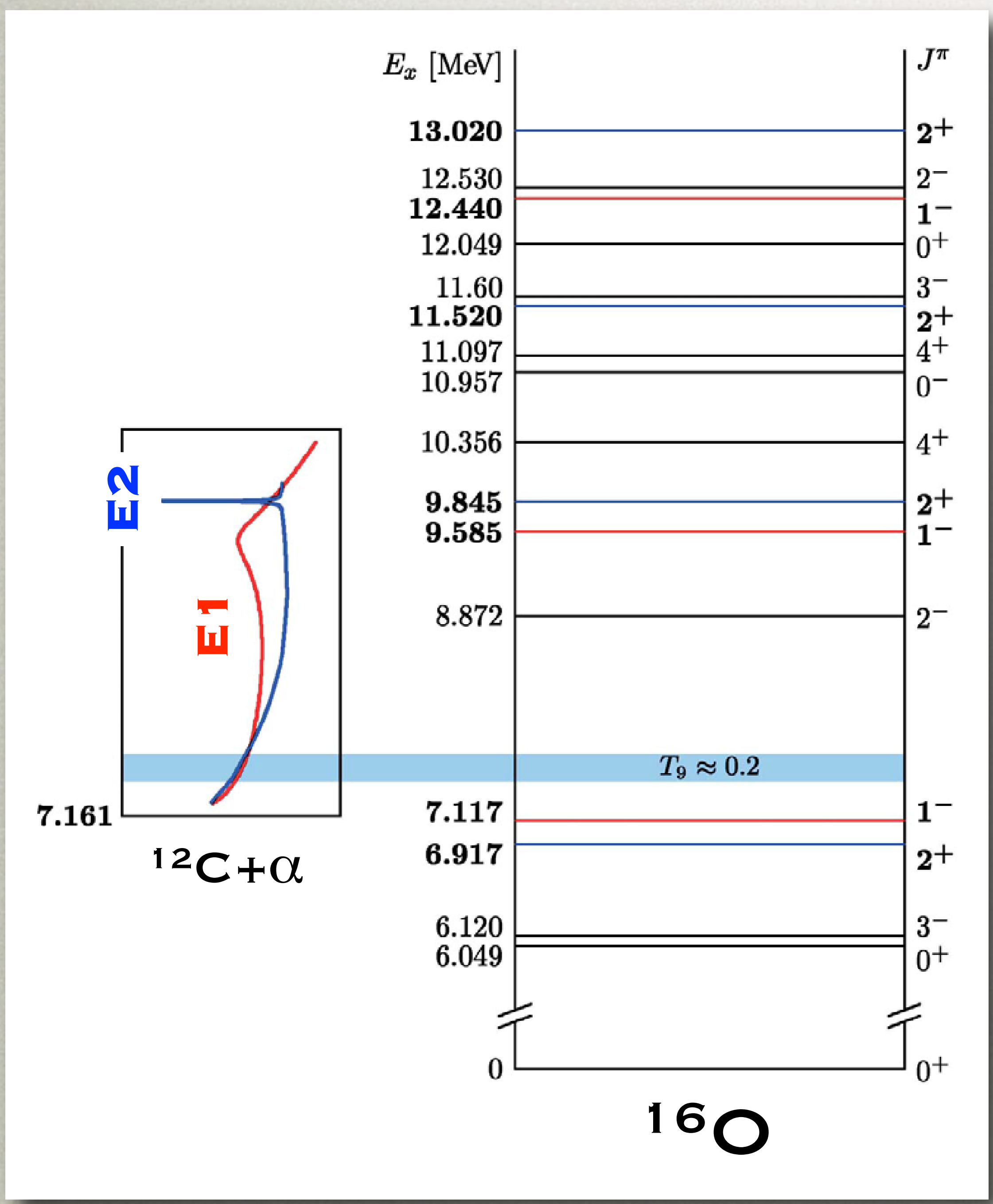

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Experimental data needed

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

- ground and excited states of ^{16}O
- wide range of energies

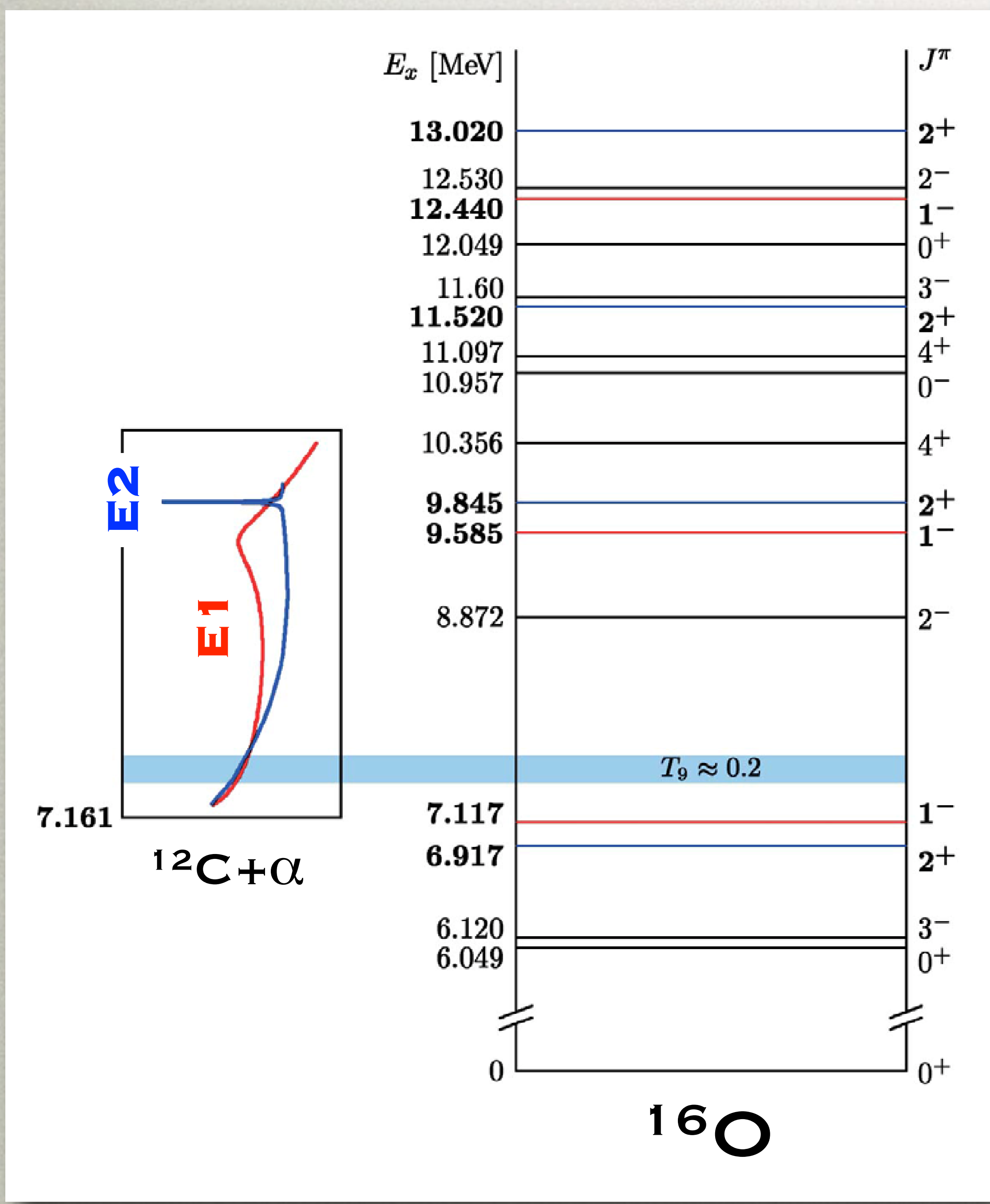
$^{12}C(\alpha,\alpha)^{12}C$ elastic scattering data

^{16}N b-delayed a spectrum

Bound-state spectroscopy (E_x, Γ_x, ...)

Transfer reactions

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



Complex level scheme

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^{16}N b-delayed a spectrum

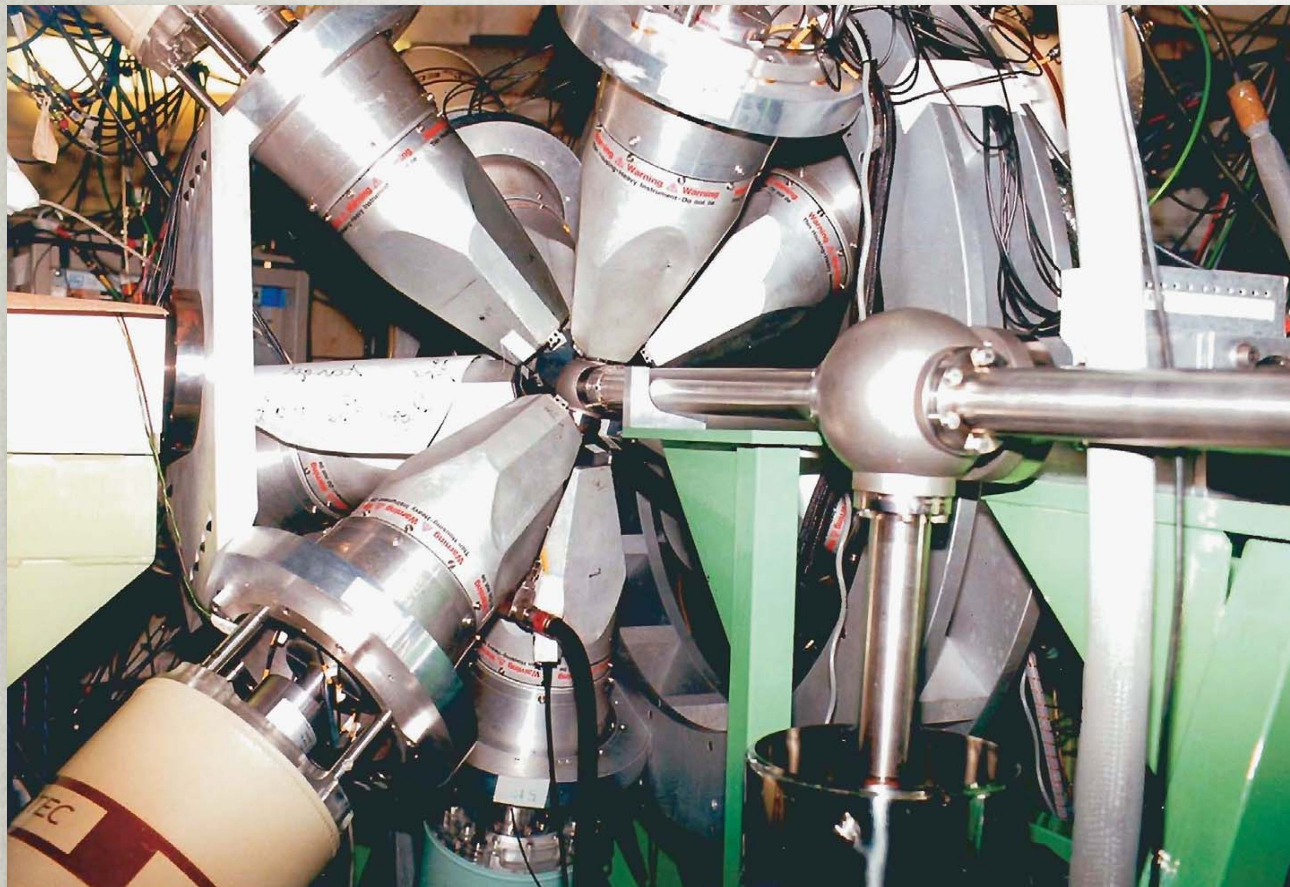
Bound-state spectroscopy (E_x, Γ_x, …)

Transfer reactions

To obtain the S-factor with an uncertainty < 10%

A modern experiment
(Stuttgart Group)

R.Kunz and M.Fey PhD Thesis



EUROGAM Detectors

Efficiency
Background suppression
Granularity

GANDI

Angular distribution

Ion Beam

Intensity 500 μA He^{+}
Stability
Beam Induced Background

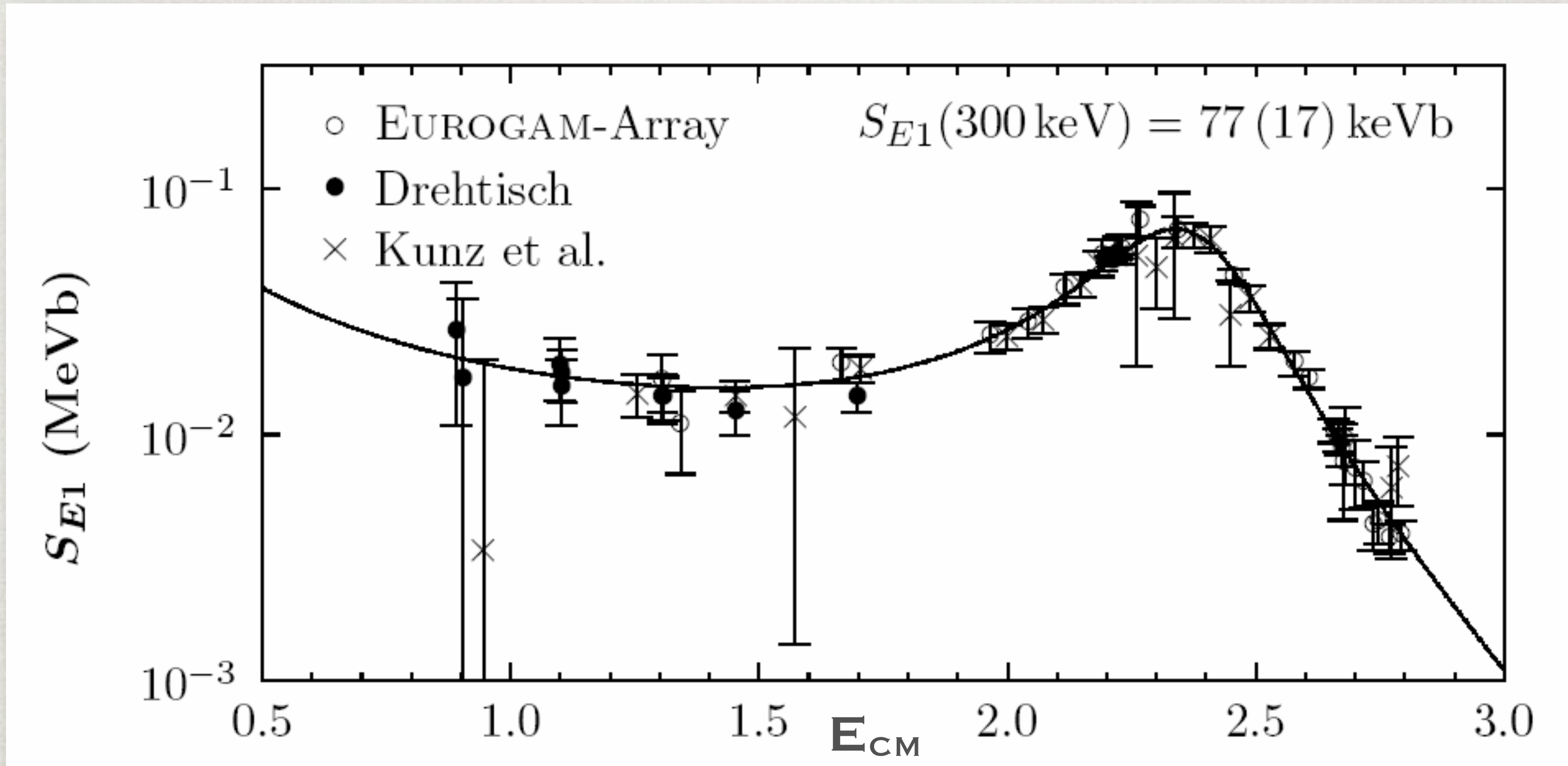
Targets

Isotope separation
Density ~ $2 \cdot 10^{18}$ atoms/cm^{2}
Purity ($^{12}C/^{13}C \sim 10^{5}$)
Omogeneity
Standing Time

but also: CalTech, Queens Univ., RUB Bochum, FZ Karlsruhe, and others → **~ 12 data sets**

A modern experiment

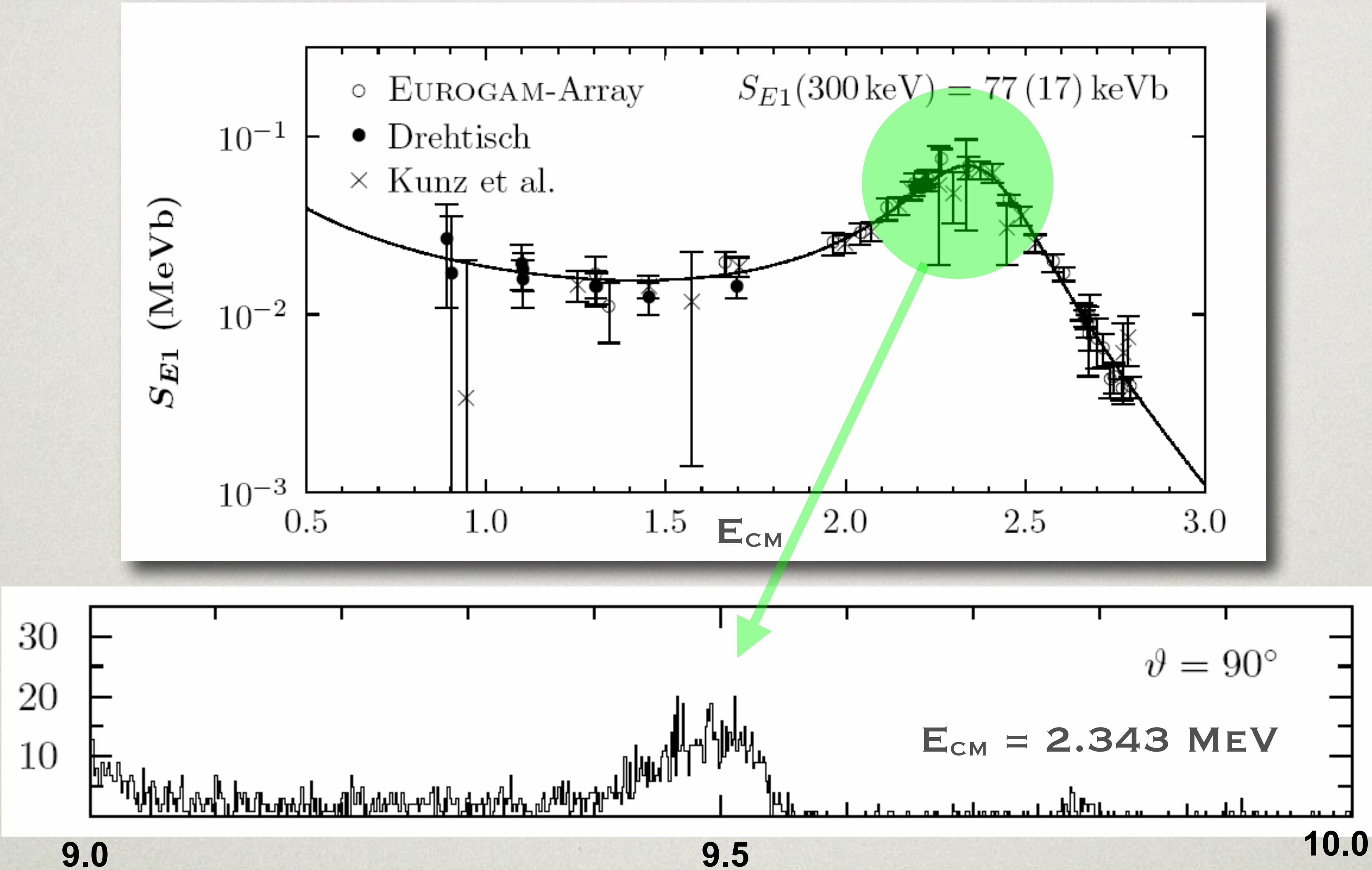
(some results)



M.Fey PhD Thesis 2004

A modern experiment

(some results)



M.Fey PhD Thesis 2004

A modern experiment

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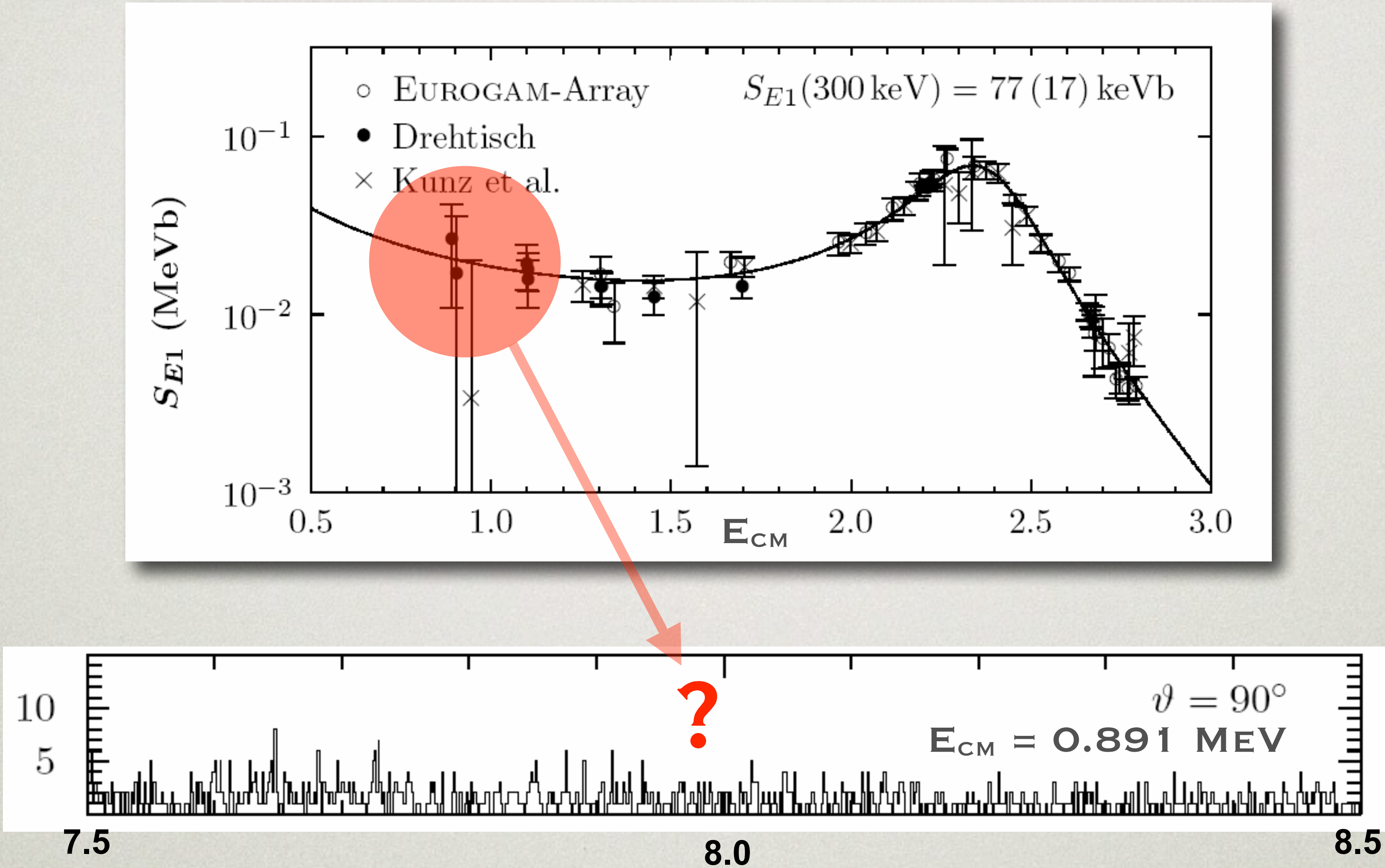


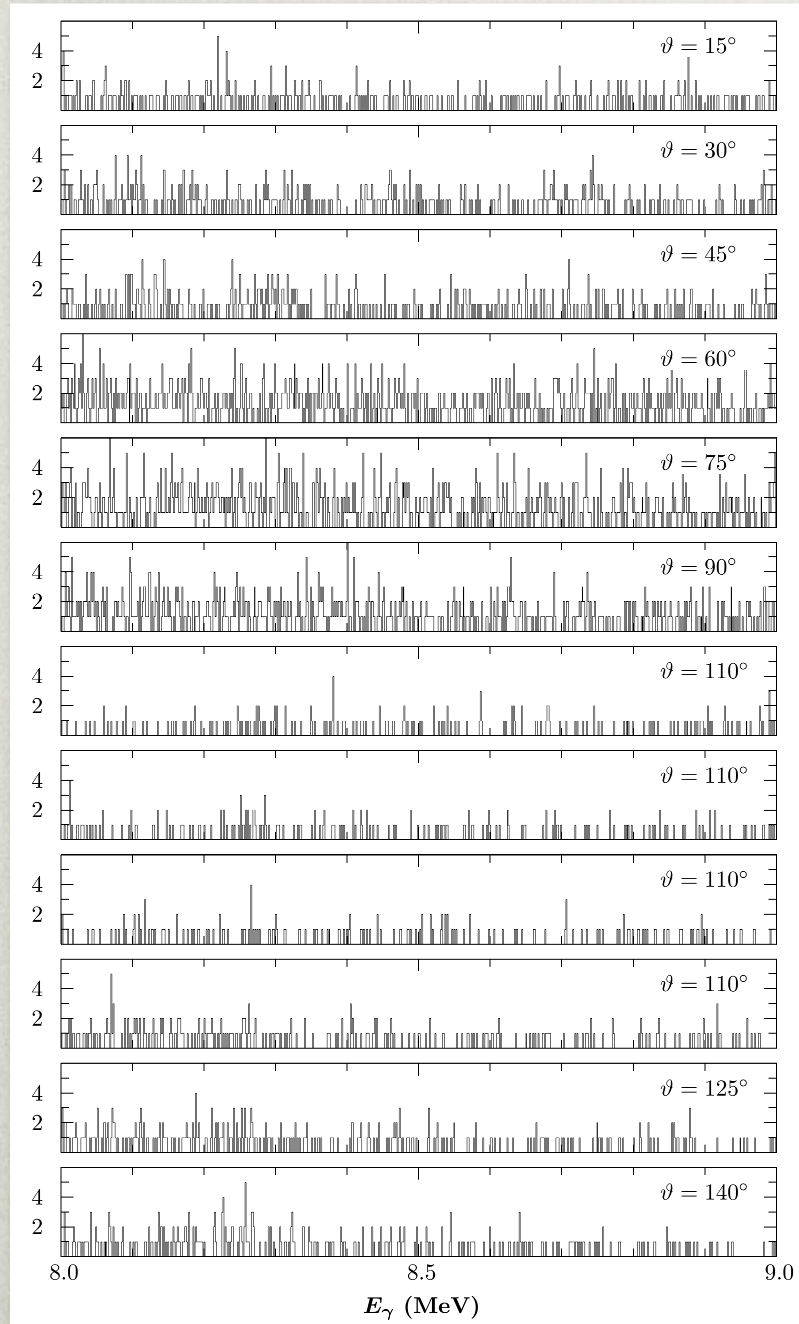
Limitation from
Beam Induced or Natural
Background ?

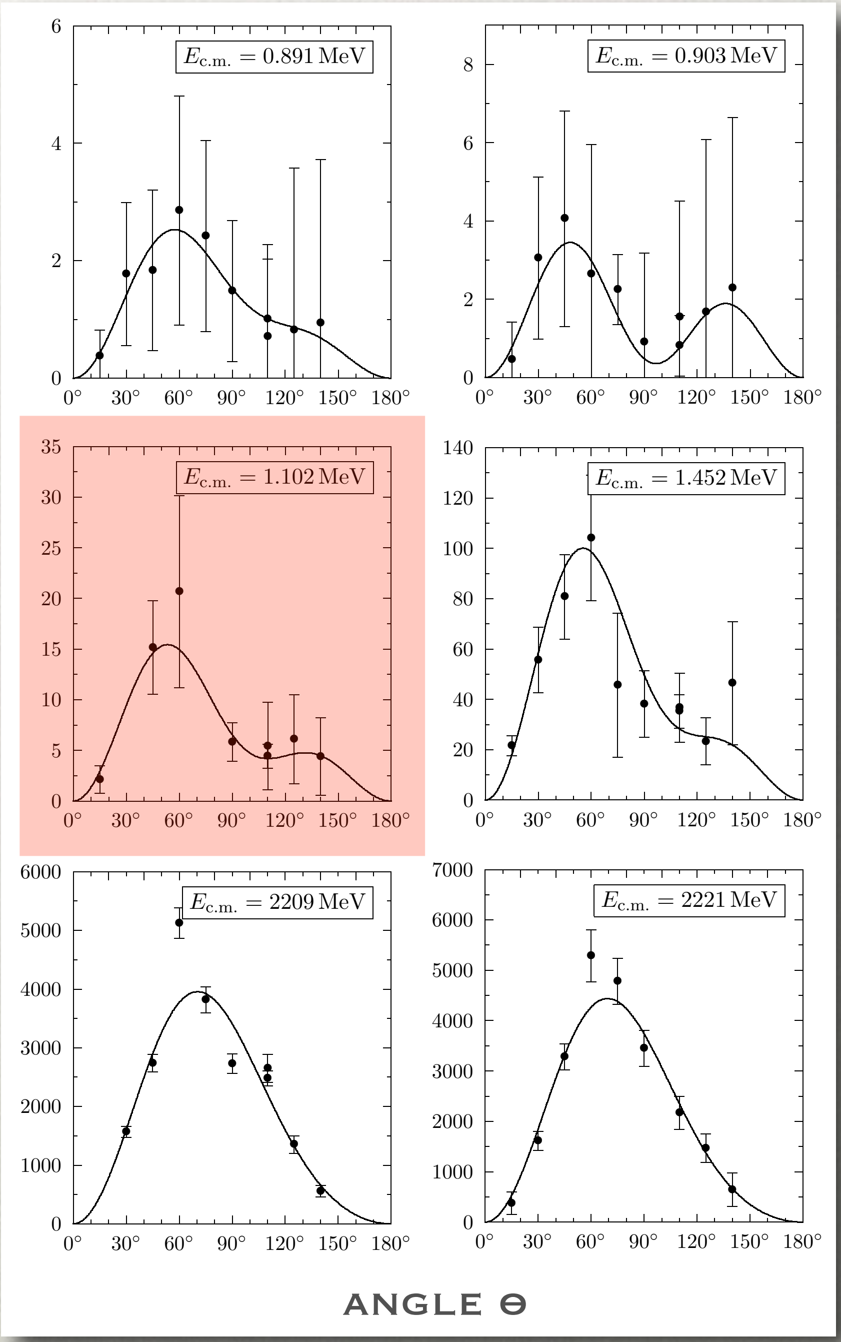
M.Fey PhD Thesis 2004

A modern experiment

(some results)

E_{CM} = 1.202 MeV

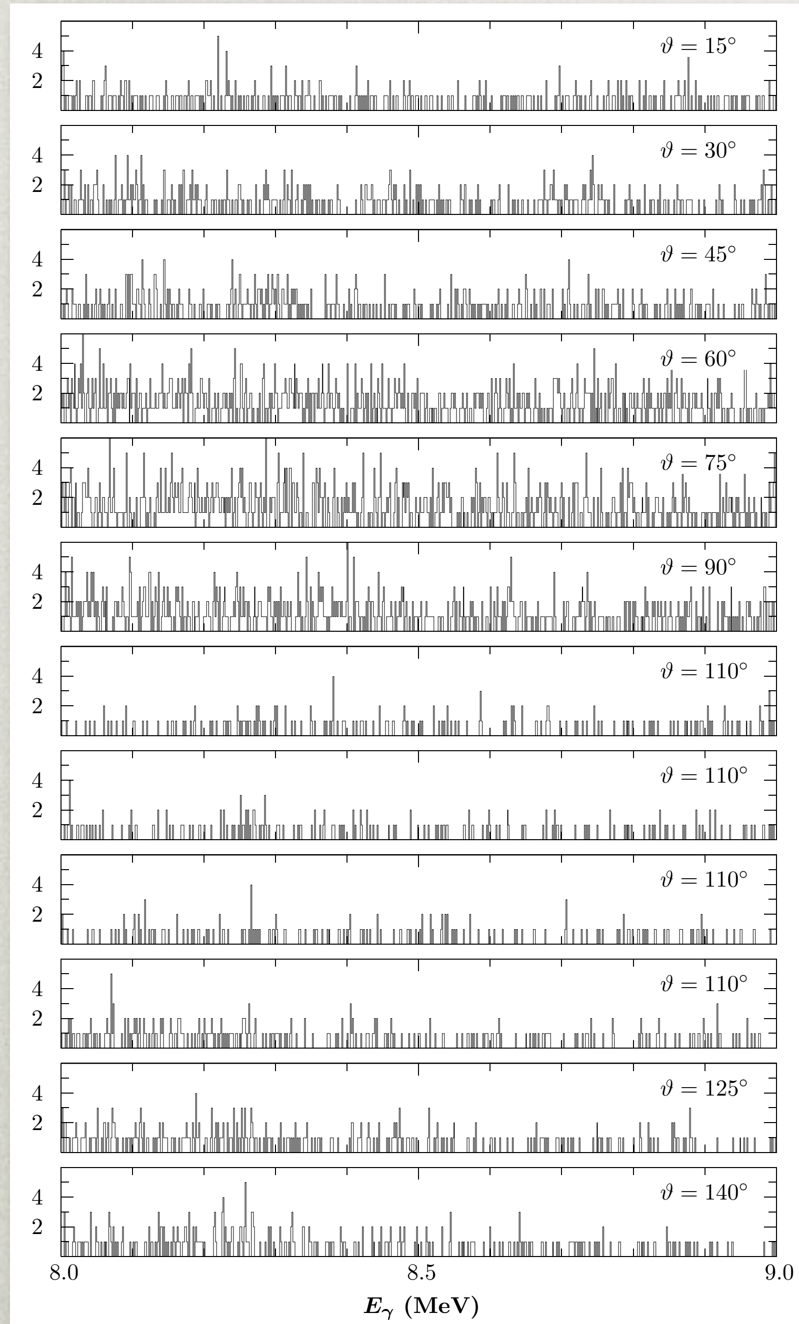


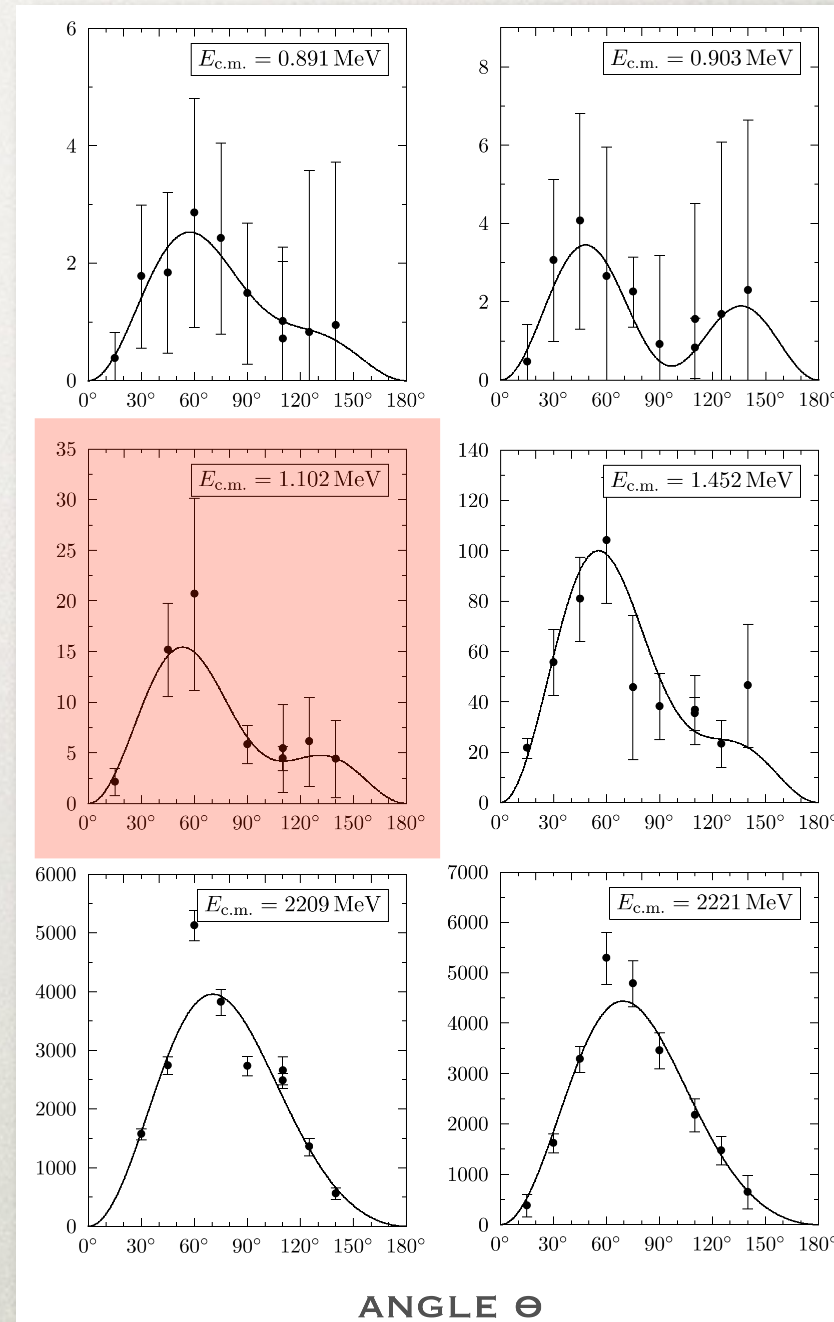


A modern experiment

(some results)

E_{CM} = 1.202 MeV





Measurements at low energies are very difficult !!

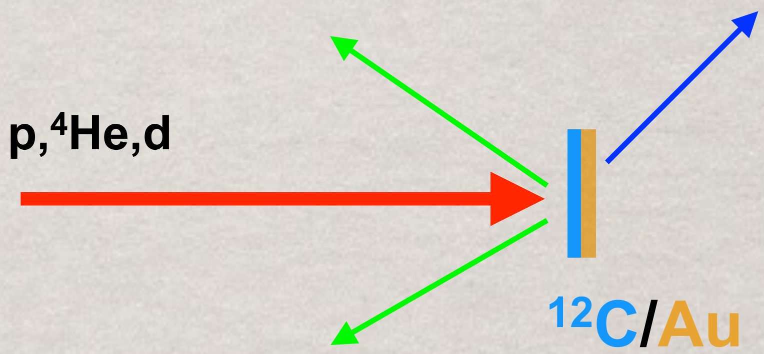
A new measurement

(wish list)

- Beam current $I_{beam} \sim 1$ mA (pulsed ?)
- Ultraclean Vacuum $< 10^{-8}$ mbar
- BIB monitors (neutron and high resolution γ)
- Detection Efficiency 100 times higher (HPGe or Scintillator ball + GE monitor)
- Improved targets $^{13}C/^{12}C < 10^{-6}$
- Better R-matrix and/or fitting codes

CARTA: CARbon TArget

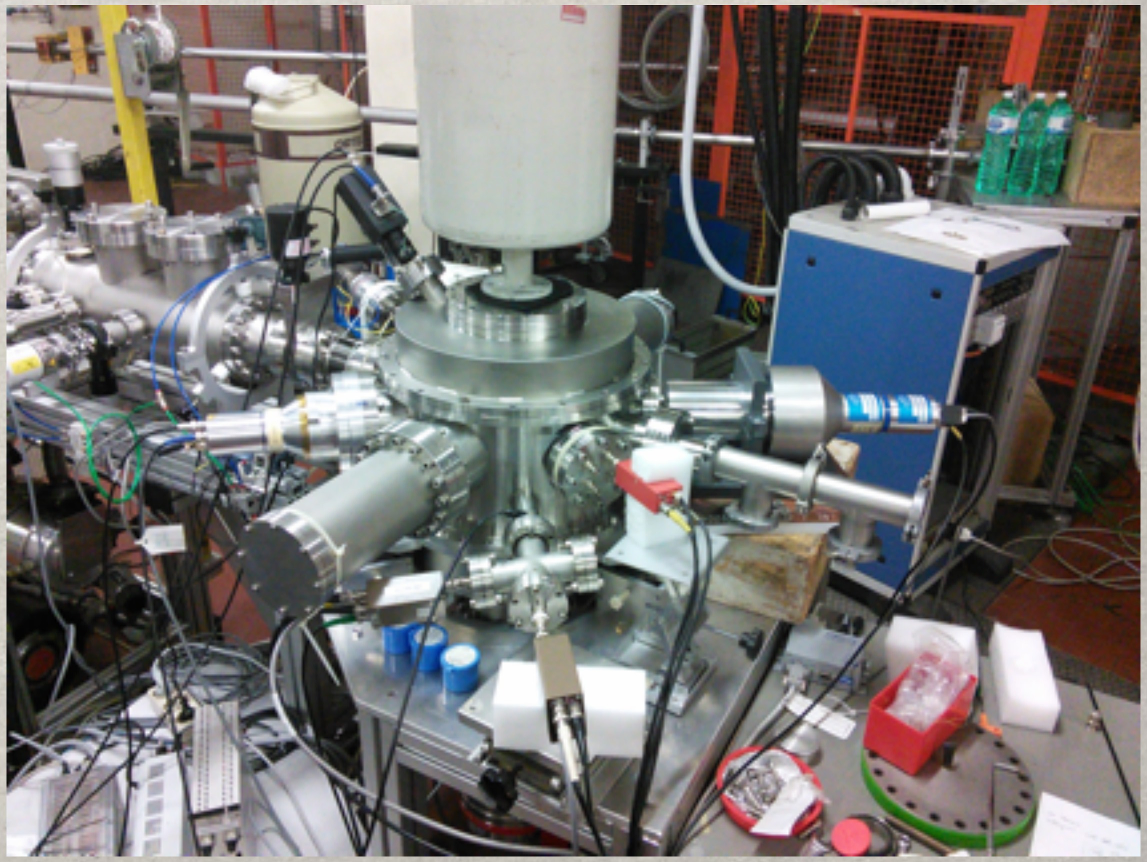
a dedicated experiment to study ^{12}C target with a isotopic ratio $^{12}C/^{13}C$ above 10^5 to be used at LUNA-MV to study the $^{12}C(\alpha,\gamma)^{16}O$ reaction



CN Van de Graaf Accelerator
Terminal ~ 7 MV
Beams: H,^{2}H,^{3,4}He
Continuous and pulsed beam

7 channels for:
IBA, Nuclear Astrophysics, ...

Large volume $LaBr_3$ detectors: 3”x3” + 3.5”x6”

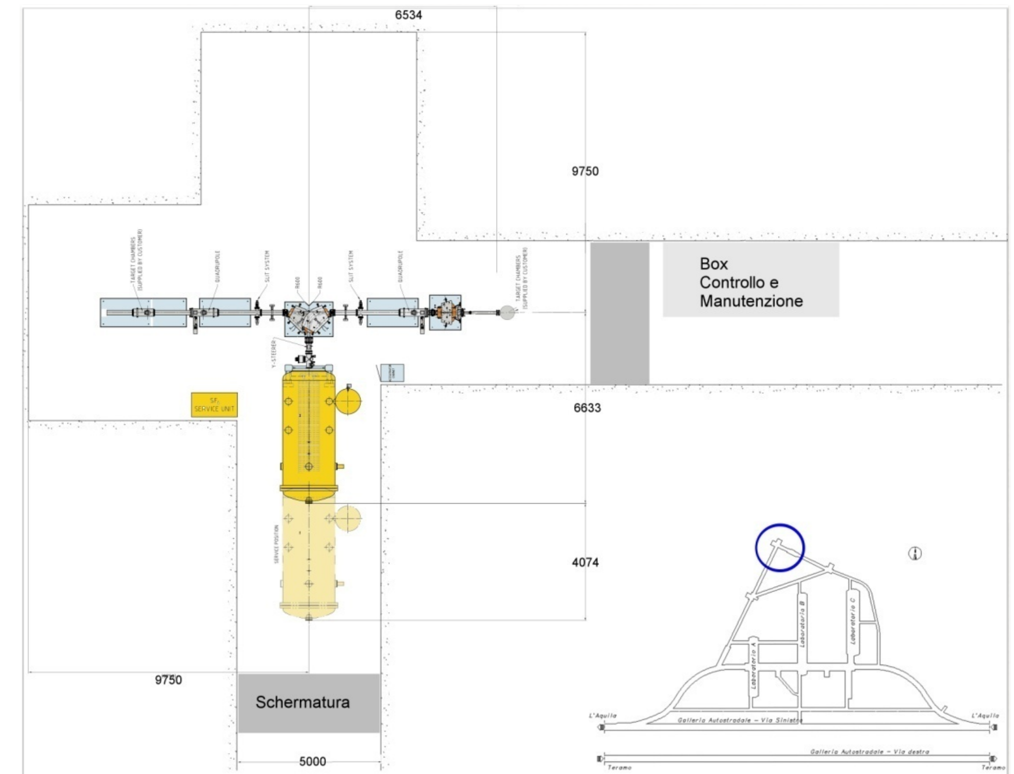


Ion Beam Analysis with charged particle and gamma detectors is used to characterise the target produced at Sidonie. Preliminary tests reach a sensitivity of 10^5 for the $^{12}C/^{13}C$ isotopic ratio

a samples analysis is planned for late 2014

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



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

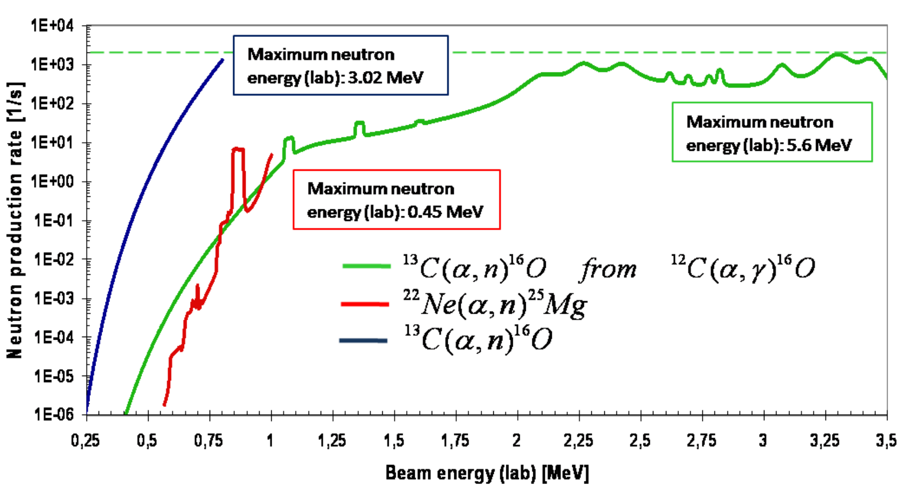
α beam intensity: 200 μA
Target: ^{13}C, 2 10^{17}at/cm^2 (99% ^{13}C enriched)
Beam energy(lab) ≤ 0.8 MeV

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

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

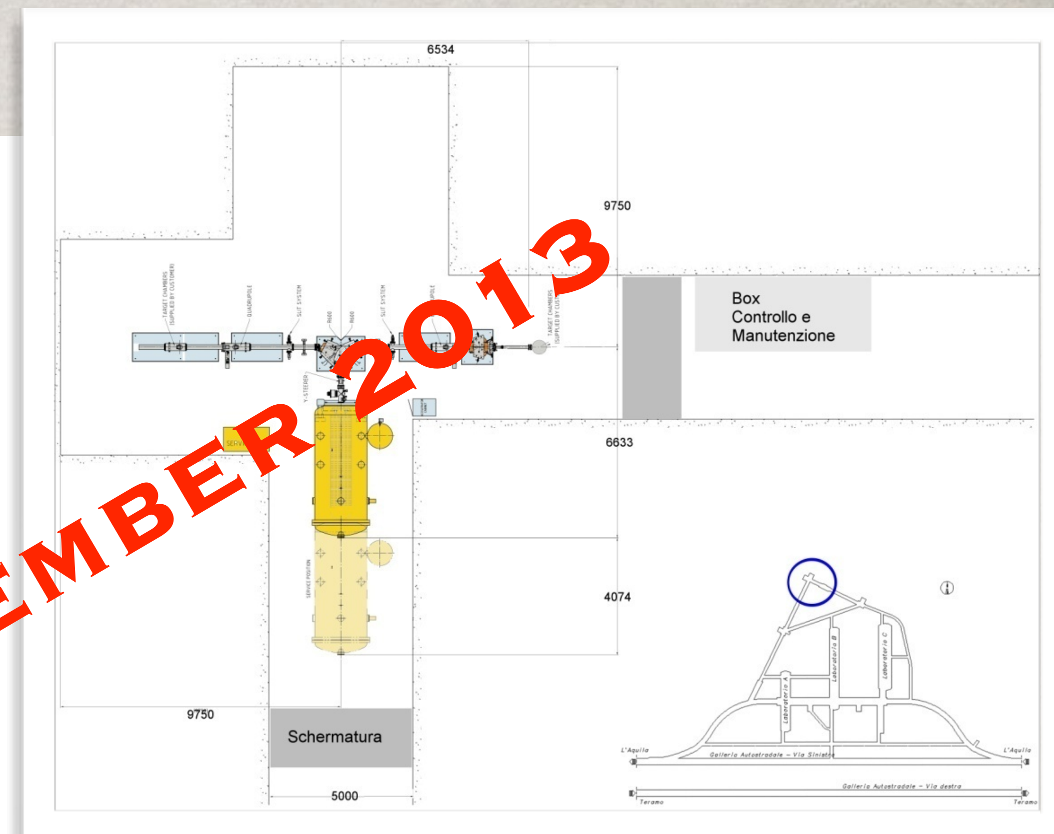


- Maximum neutron production rate : 2000 n/s
- Maximum neutron energy (lab) : 5.6 MeV

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

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



B-NODE HYPOTHESIS: RULED OUT IN SEPTEMBER 2013

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

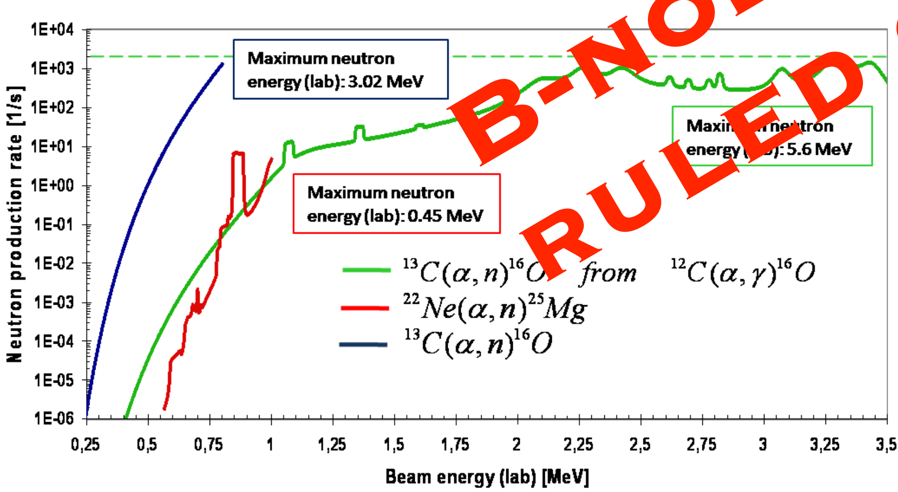
α beam intensity: 200 μA
Target: ^{13}C, 2 10^{17}at/cm^2 (99% ^{13}C enriched)
Beam energy(lab) ≤ 0.8 MeV

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

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

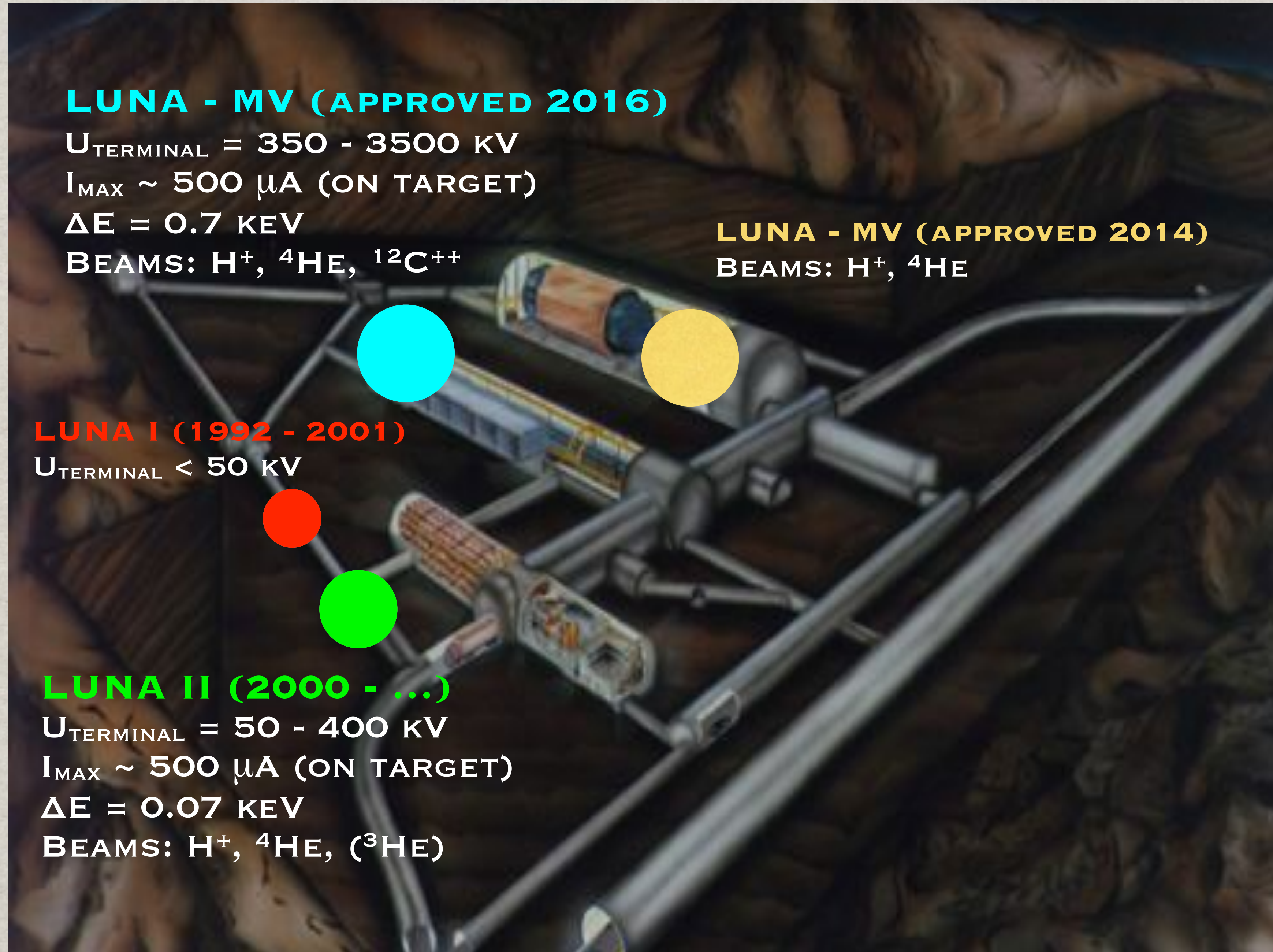
α beam intensity: 200 μA
Target: ^{13}C 1 10^{18}at/cm^2 ($^{13}C/^{12}C = 10^{-5}$)
Beam energy(lab) ≤ 3.5 MeV



- 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 !

LUNA - MV project

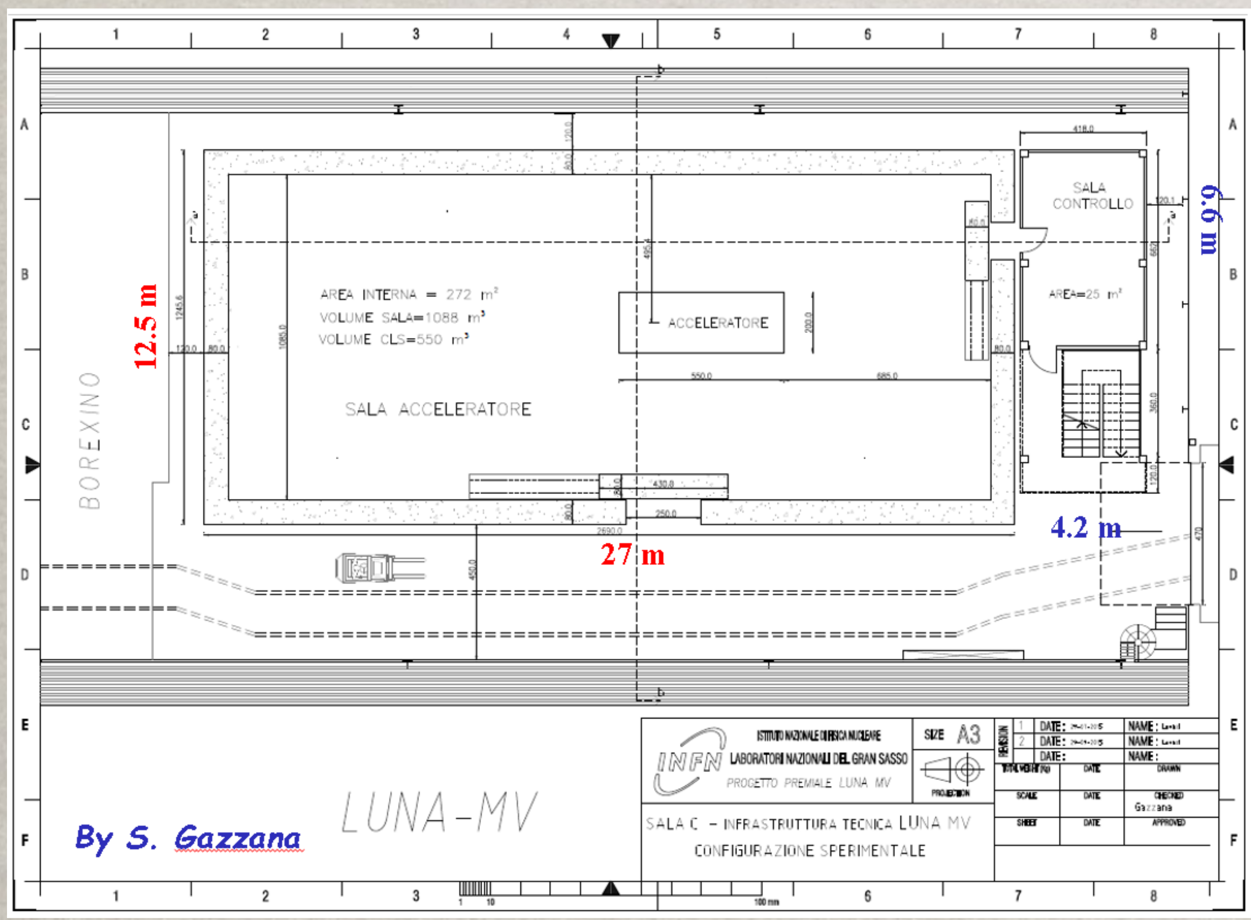


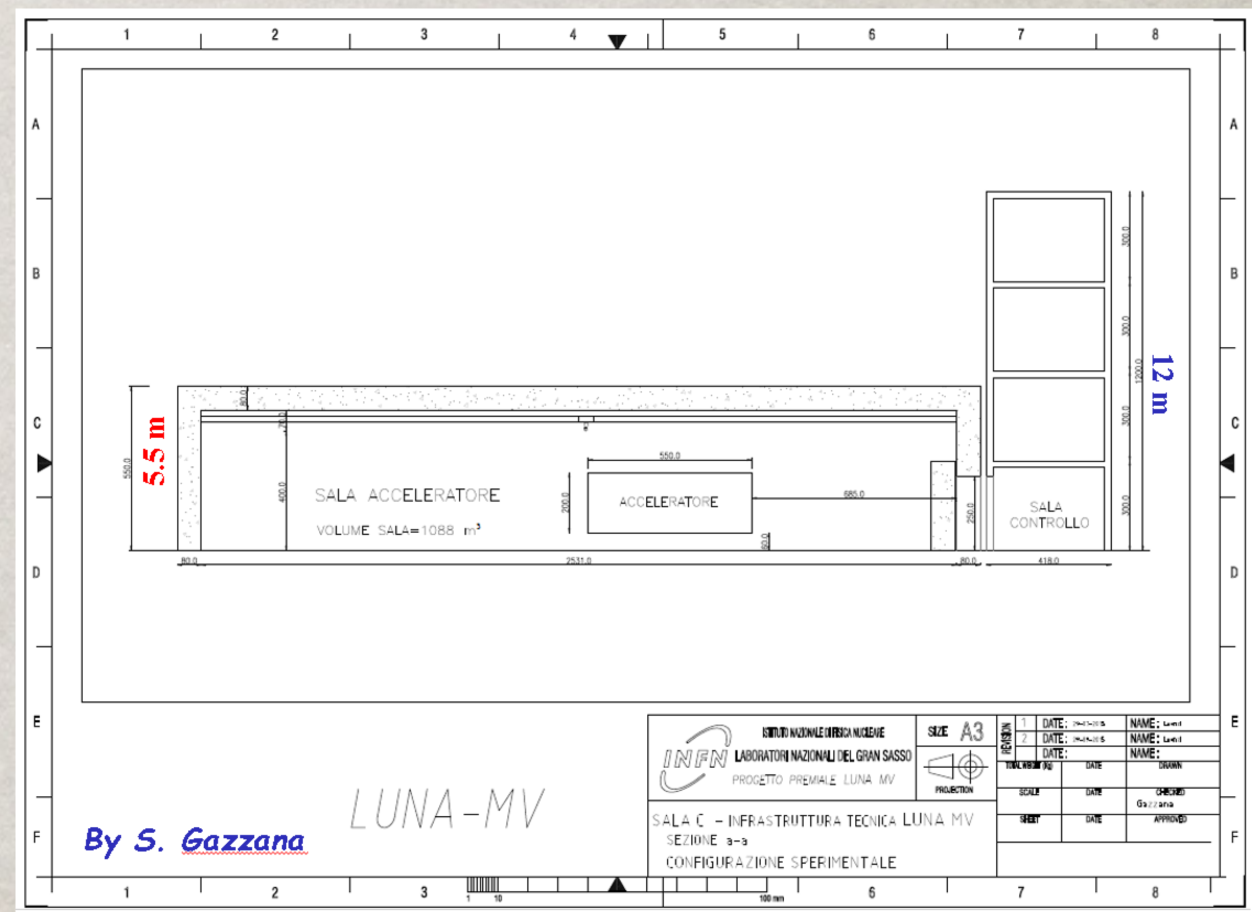
~~Hall C (south side) definitely assessed in early 2014~~

Hall B (north side)

more definitely assessed in early 2016

LUNA-MV: new building in Hall C

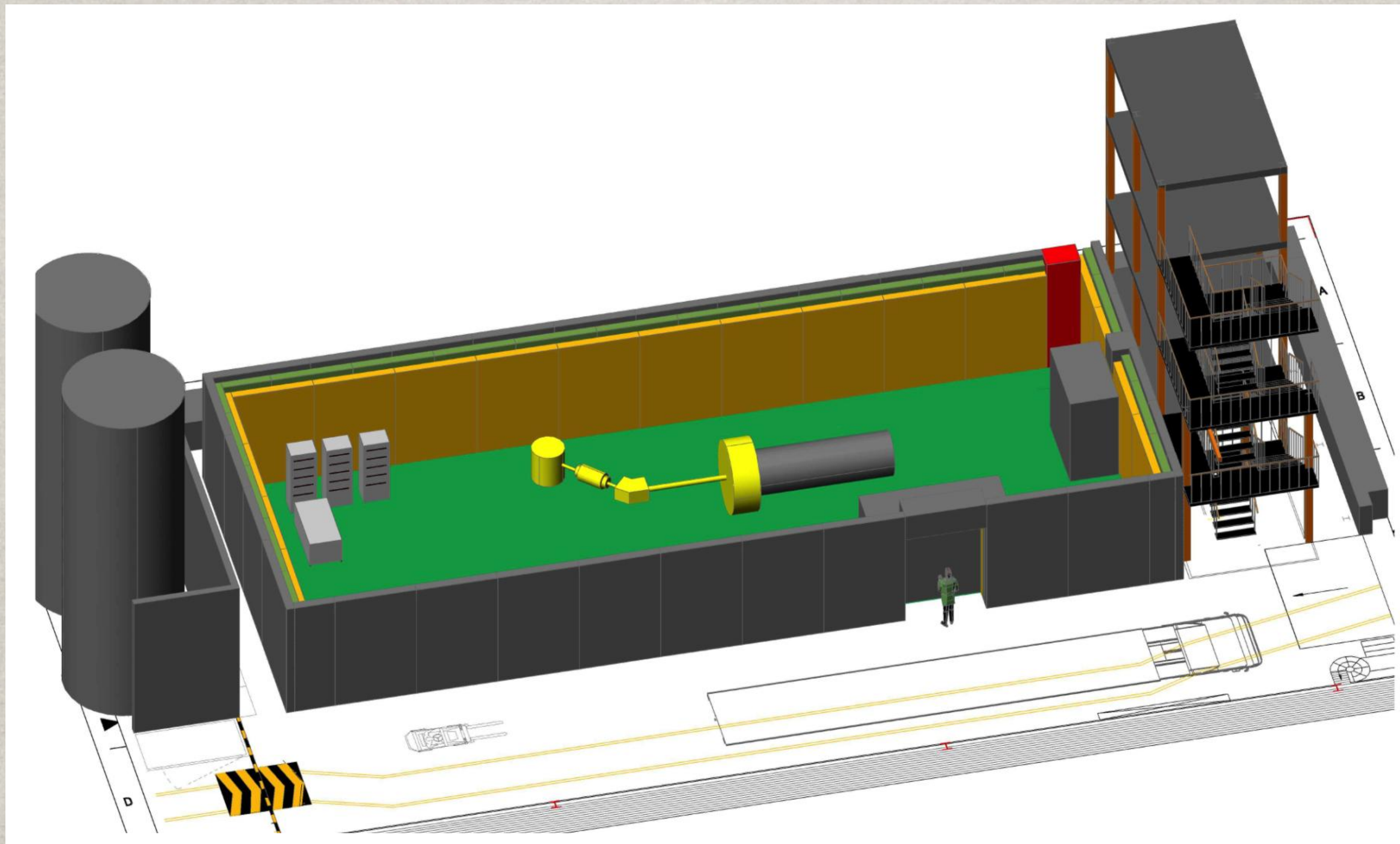




The construction design of the LUNA-MV building will start in January 2016 once fixed the shielding

A working group coordinated by M. Junker started the analysis of the technical requirements related to the use of the accelerator and the scientific equipment (power, cooling, conditioning, ...)

LUNA-MV: new building in Hall C



S. Gazzana, LUNA General Meeting, July 2015

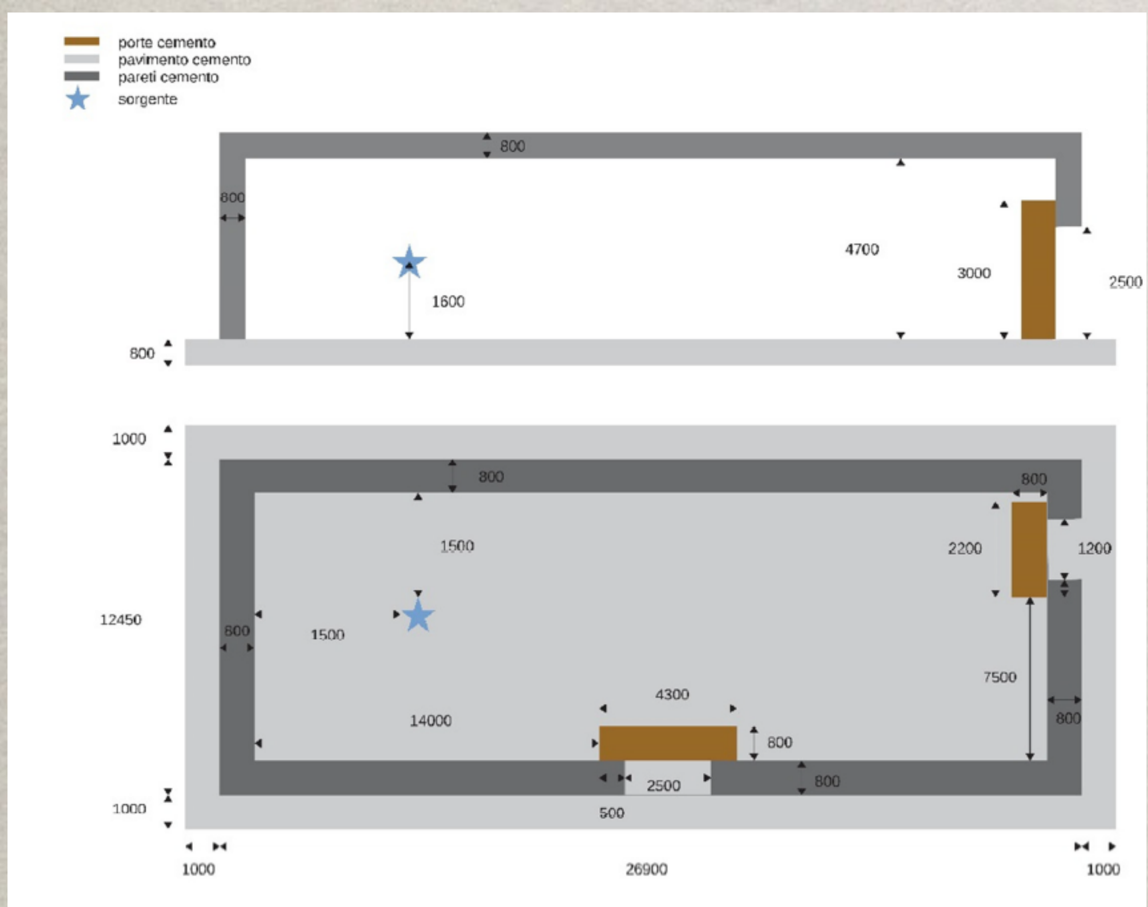
In Hall B, the control room will be widened to 50 m^2. Concrete shielding 80 cm are enough to have a neutron flow outside the LUNA-MV building $\lesssim 10^{-6}$ n /(cm^2 s)

LUNA-MV: neutron shielding

First design of a 80 cm thick concrete shielding has been performed by GEANT4

E_N = 5.6 MeV, 2 10^3 n/s, isotropic

D. Trezzi



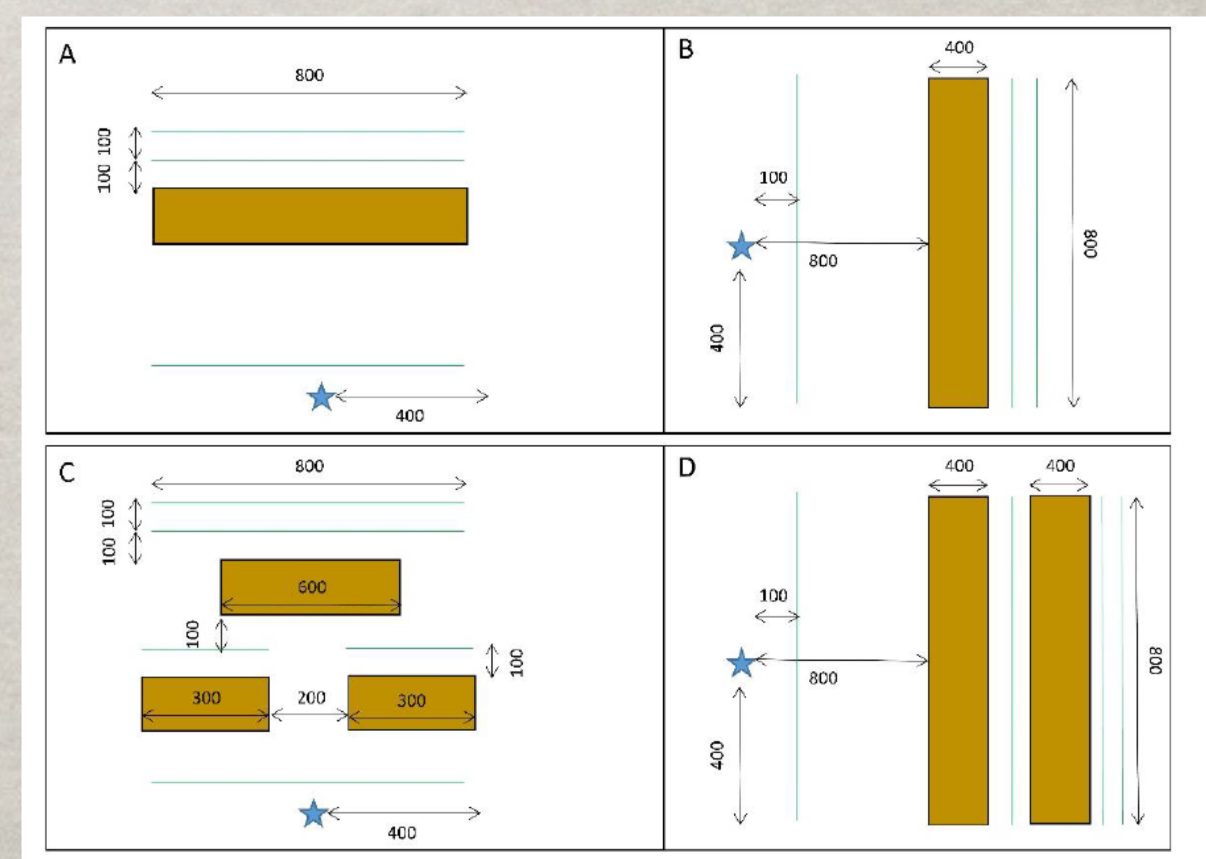
$(\Phi_n)_{av}$ = 1.422 10^{-6} n cm^{-2} s^{-1}

3.22 10^8 neutron stories

Several weeks CPU time

Validation through independent MCNP calculation presently underway at the INFN central radioprotection service (LNF-ISMEL, Dr. A. Esposito)

The validation will lead to the final (possibly refined) design of the shielding concept



"Progetto Premiale" LUNA - MV

Italian Research Ministry financed the LUNA-MV project with
2.8 M€ in 2012 + 2.5 M€ in 2013

Time schedule (recently updated):

April 2014 requested 3.5 M€ to start Tender for the accelerator and Infrastructure. ok from LNGS director

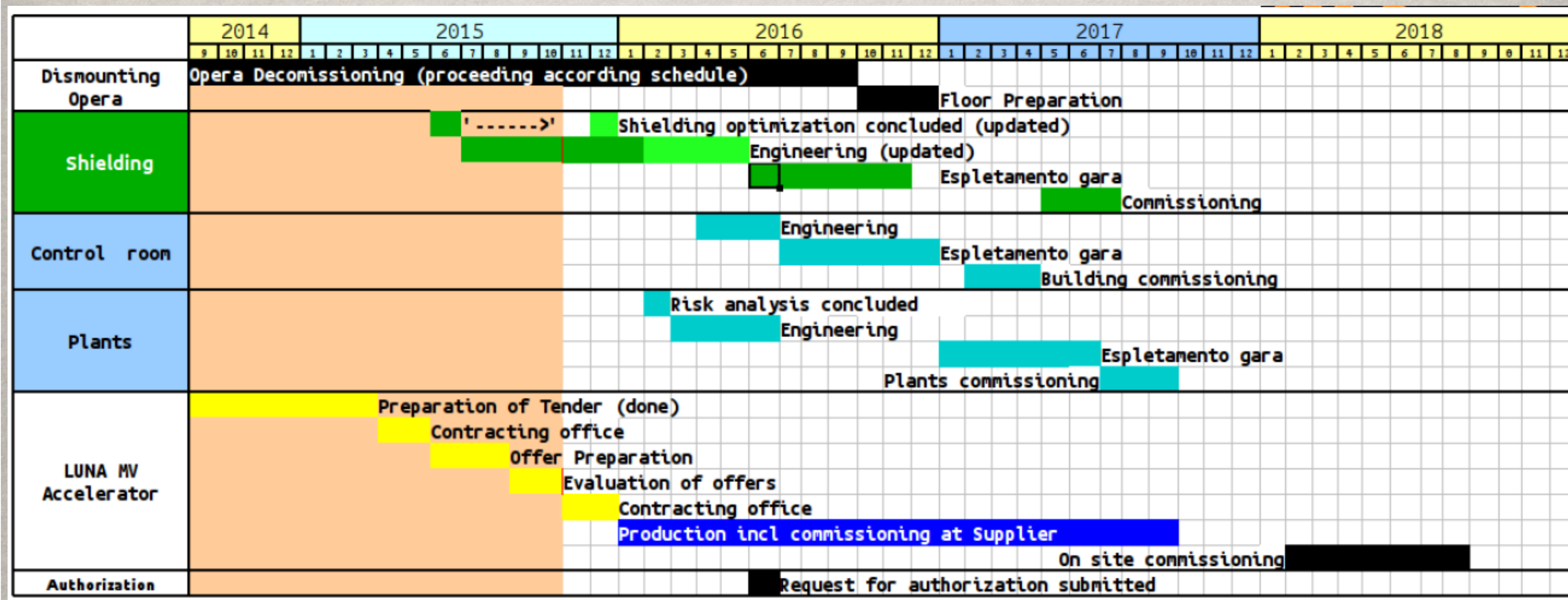
May 2014 Accelerator specifications presented to INFN - MAC. Positive reaction from referees

site preparation: 12 months from December 2016 required for OPERA decommissioning

Legal permission to operate: 12-18 months

Accelerator working in Hall C after 39 months from tender begin

LUNA - MV PROJECT TIMELINE



LUNA and the others

	Background	Accelerator	Beam intensity	Program	Expected start	Note
LUNA	We know it	LUNA 400	~300 μA	$^{13}C(\alpha,n)$ et al.,	2017	Solid target
JUNA	~ 2 OoM better	400 kV – ECR	10 mA	$^{25}Mg(p,\gamma)$ $^{13}C(\alpha,n)$ $^{12}C(\alpha,\gamma)$	Mid 2016 2019	Gas target + ^{3}He tubes in liq. Scint.
CASPAR	~ LUNA	Old 1 MV	150 μA	$^{14}N(p,\gamma)$? $^{13}C(\alpha,n)$ $^{22}Ne(\alpha,n)$	Mid 2016 ? ?	Gas target + ^{3}He tubes
LUNA MV	We know it	3.5 MV + ECR	1 mA	$^{14}N(p,\gamma)$ $^{13}C(\alpha,n)$ $^{22}Ne(\alpha,n)$ $^{12}C(\alpha,\gamma)$ $^{12}C + ^{12}C$	2019 ? ? ? ?	

With the next year LUNA will be no more alone !

The LUNA collaboration

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New collaborators are welcome!

LUNA & LUNA - MV news

Between end of November - Beginning of December 2016 we'll organize a 2-day workshop both to celebrate the silver-moon (part likely open to the public and to the media) and to announce the starting of the LUNA-MV scientific program (mainly reserved to scientists). The exact date will be fixed soon with the INFN management.

More details will come soon ...


Laboratori Nazionali del Gran Sasso