L’esperimento LUNA-MV ai Laboratori Nazionali del Gran Sasso

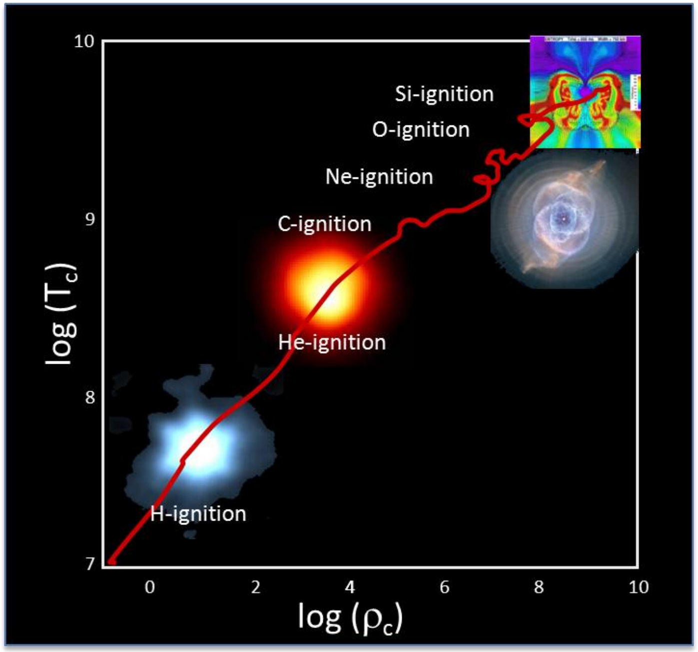
Francesca Cavanna
for the LUNA collaboration

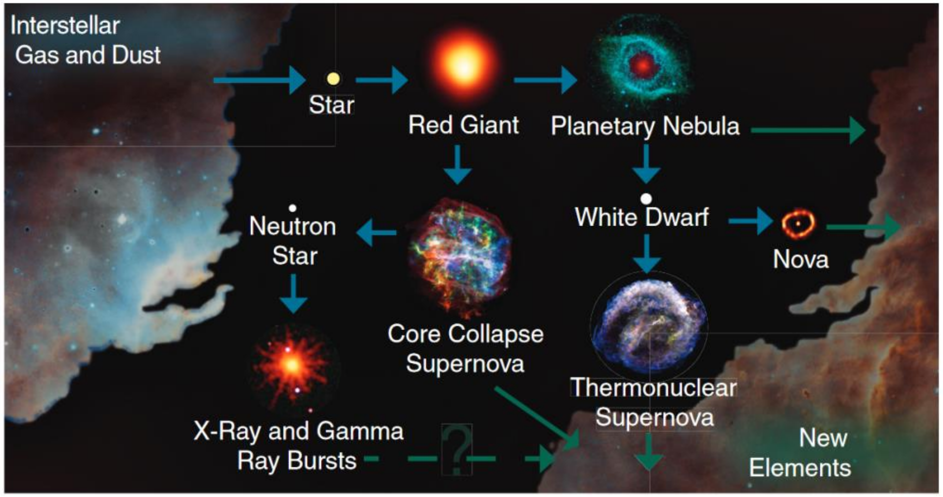
Outlook

- ✓ Why measuring the cross section of nuclear fusion reactions powering stars
- ✓ Importance of going underground
- ✓ From LUNA to LUNA-MV: from Hydrogen burning to Helium and Carbon burning
- ✓ Scientific program of LUNA-MV
- ✓ Celebrating 25 years of LUNA: Silver Moon

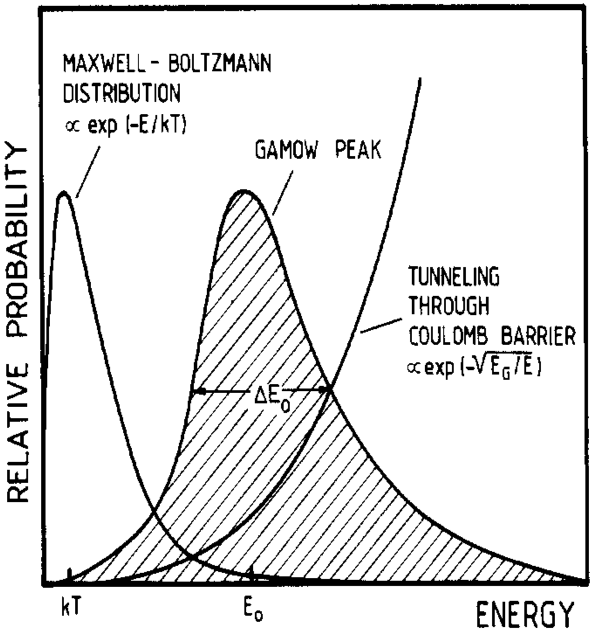
Nuclear astrophysics

- Aim of nuclear astrophysics: understand nuclear reactions that shape much of the visible universe
- Nuclear fusion is the engine of stars: it produces the energy that stabilizes them against gravitational collapse and makes them shine
- Among the key parameters (chemical composition, opacity, etc.) to model stars, reactions cross sections play an important role
- The evolution of the stars is determined by fusion reactions
- They determine the origin of elements in the cosmos, stellar evolution and dynamic
- Many reactions ask for high precision data





The importance of going underground…



Sun:
kT = 1 keV
$E_C \approx$ 0.5-2 MeV
$E_0 \approx$ 5-30 keV
for reactions of H burning

kT but also $E_0 << E_C$!!

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

Cross sections in the range of pb-fb at stellar energies

with typical laboratory conditions reaction rate R can be as low as few events per month

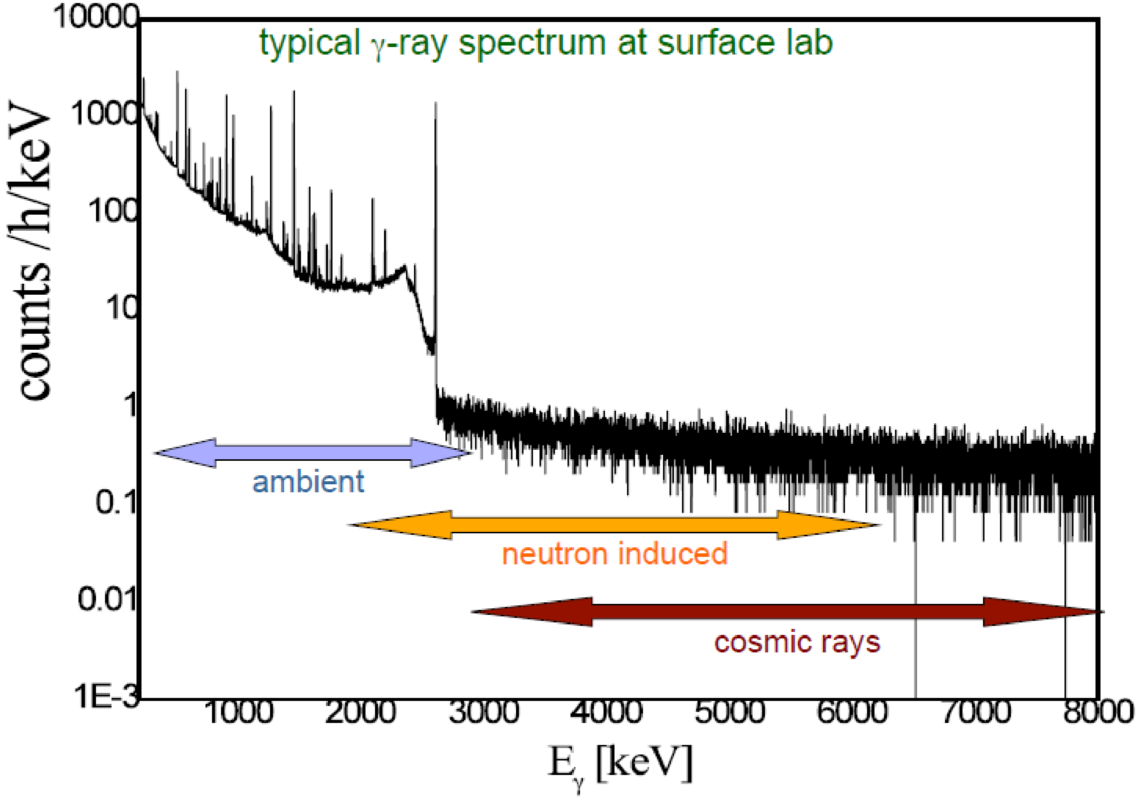
Rate and background

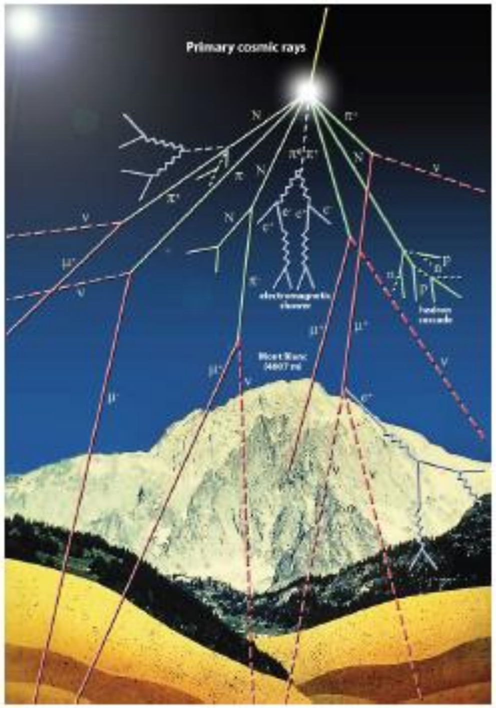
The rate R has to be compared with background B

$B_{beam\ induced}$: reactions with impurities in the target, collimators,… secondary processes

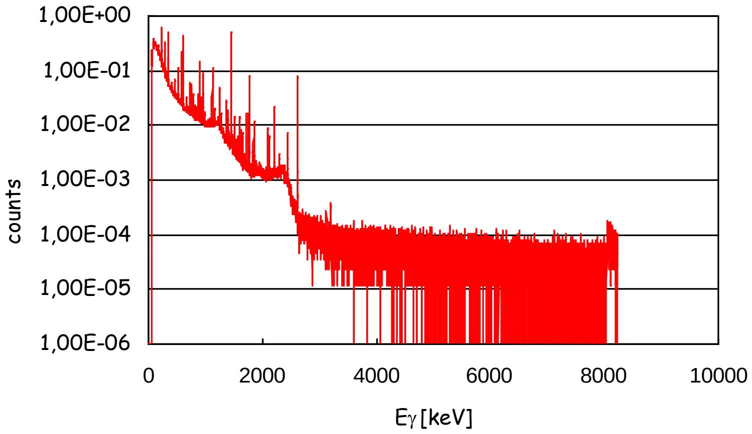
B_{env} : natural radioactivity mainly from U and Th chains

B_{cosmic} : mainly muons



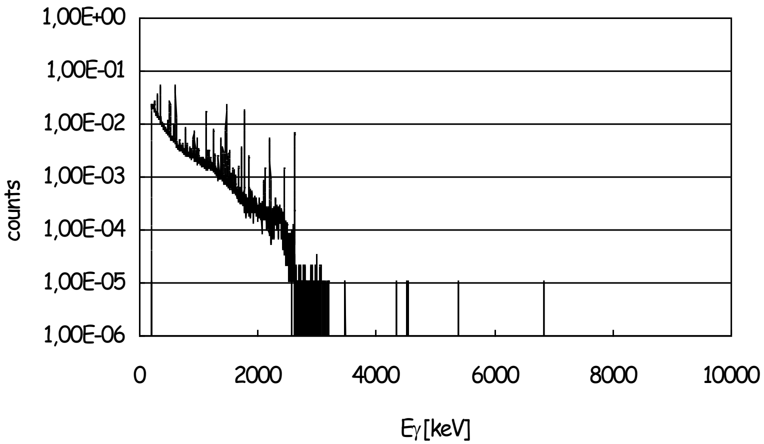


Background reduction – HpGe detectors - gamma



3 MeV < E_γ < 8 MeV

0.5 Counts/s



3 MeV < E_γ < 8 MeV

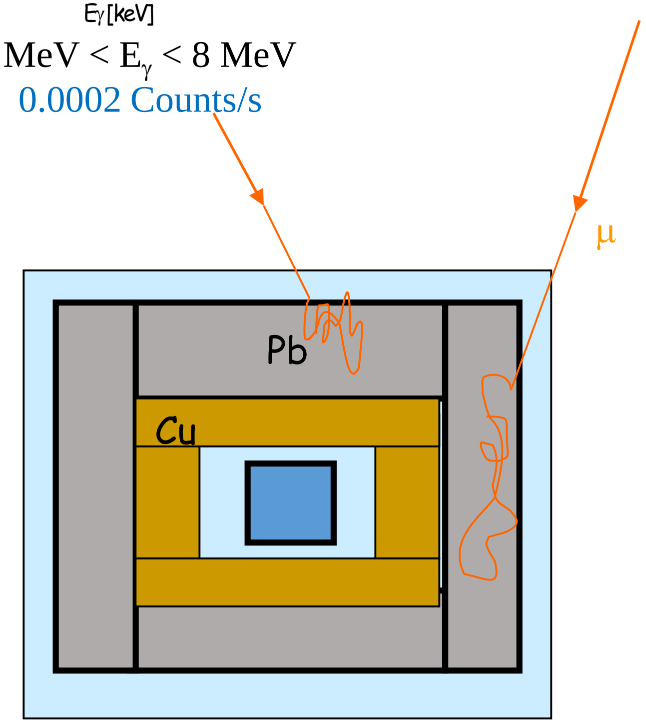
0.0002 Counts/s

E_γ< 3 MeV→passive shielding for environmental bck

Secondary gammas created by μ interactions are reduced

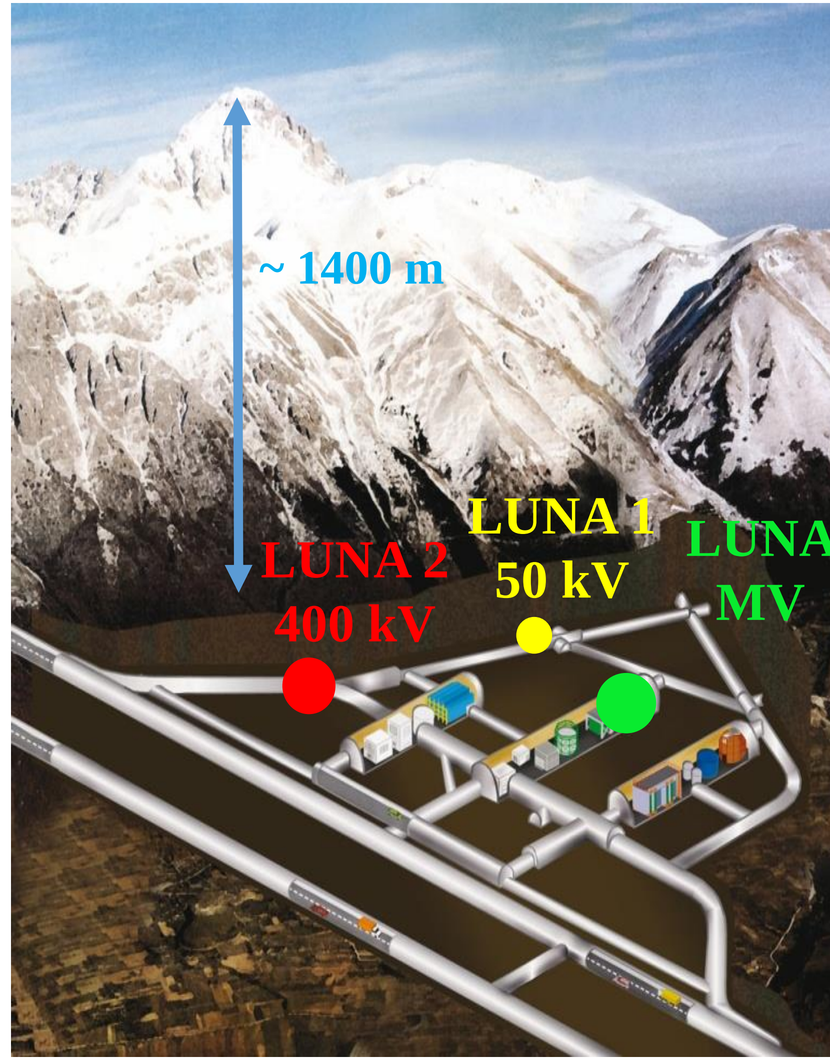
↓

underground passive shielding is more effective!



Laboratory for Underground Nuclear Astrophysics

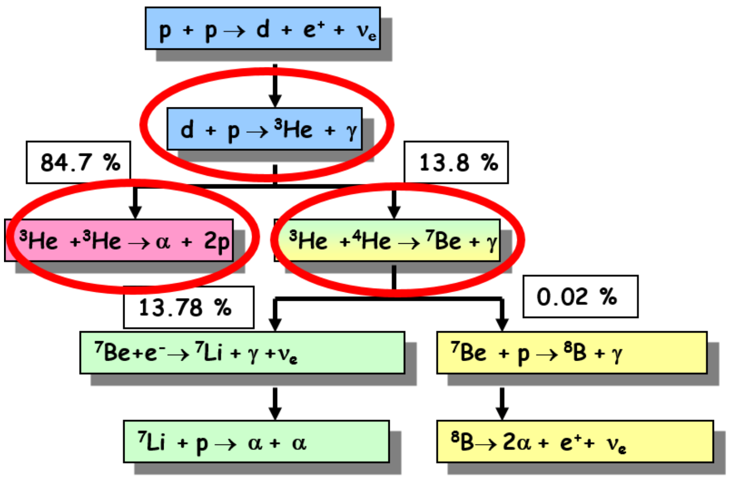
Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}



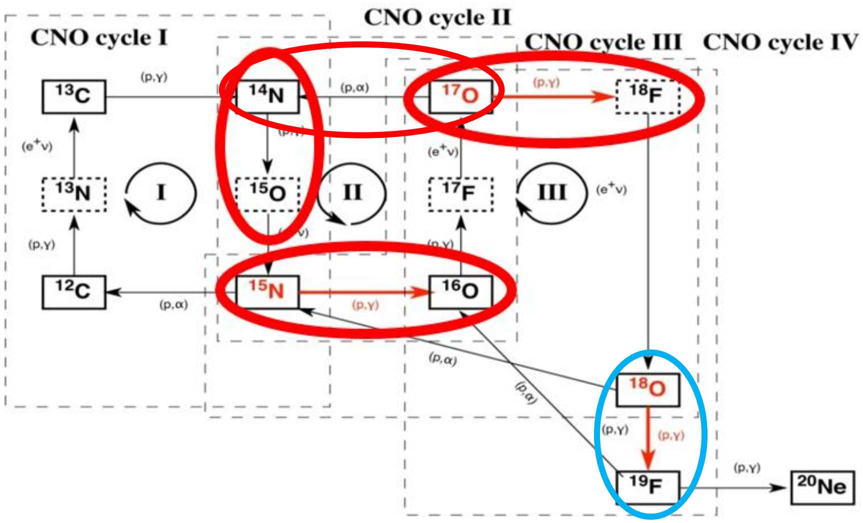
LNGS (1400 m rock shielding ≡ 4000 m w.e.)

Hydrogen burning reactions

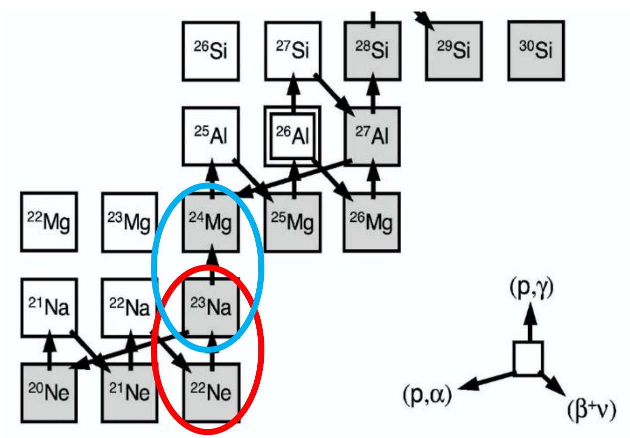
pp chain



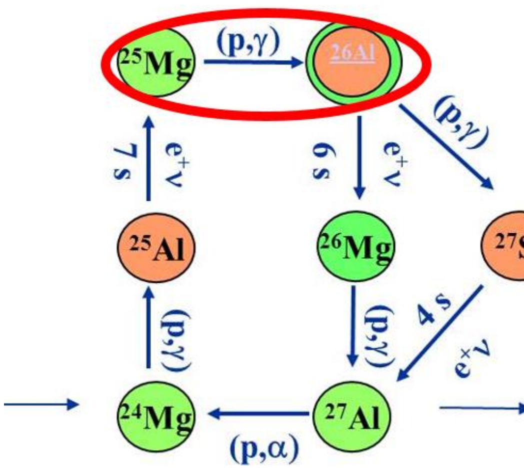
CNO cycle



Ne-Na cycle



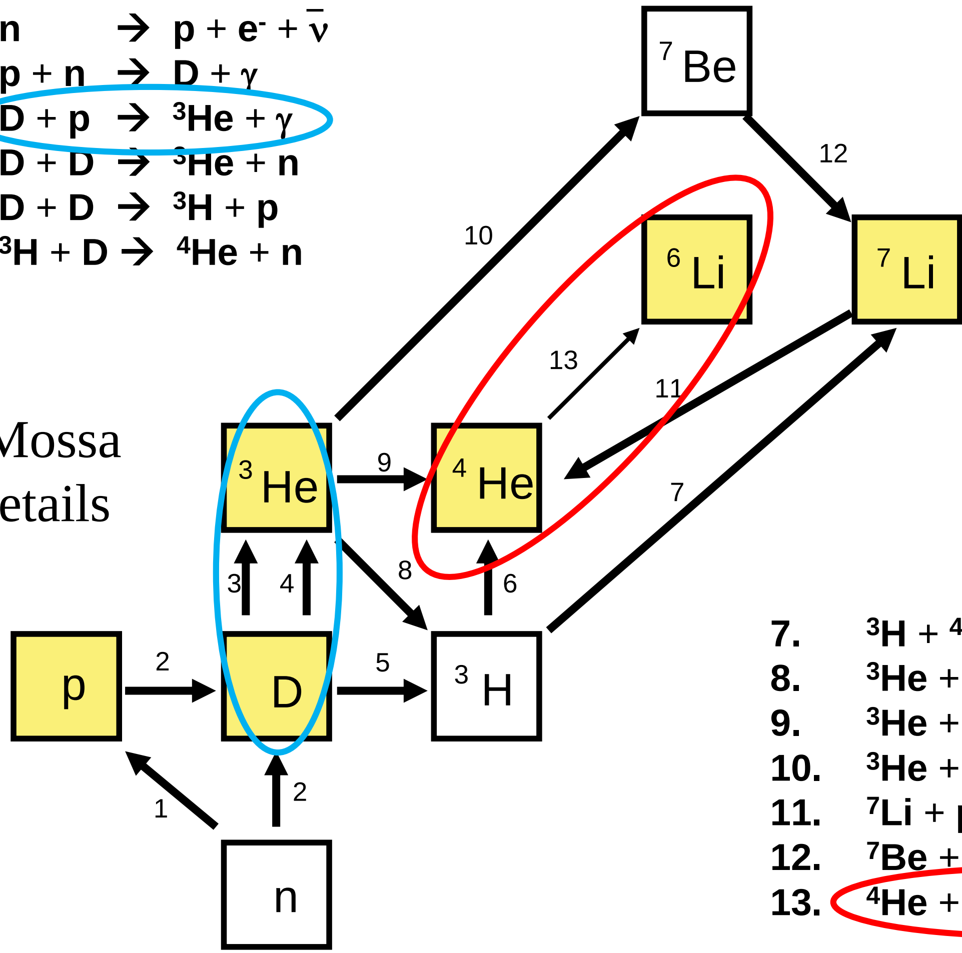
Mg-Al cycle



Big bang nucleosynthesis

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

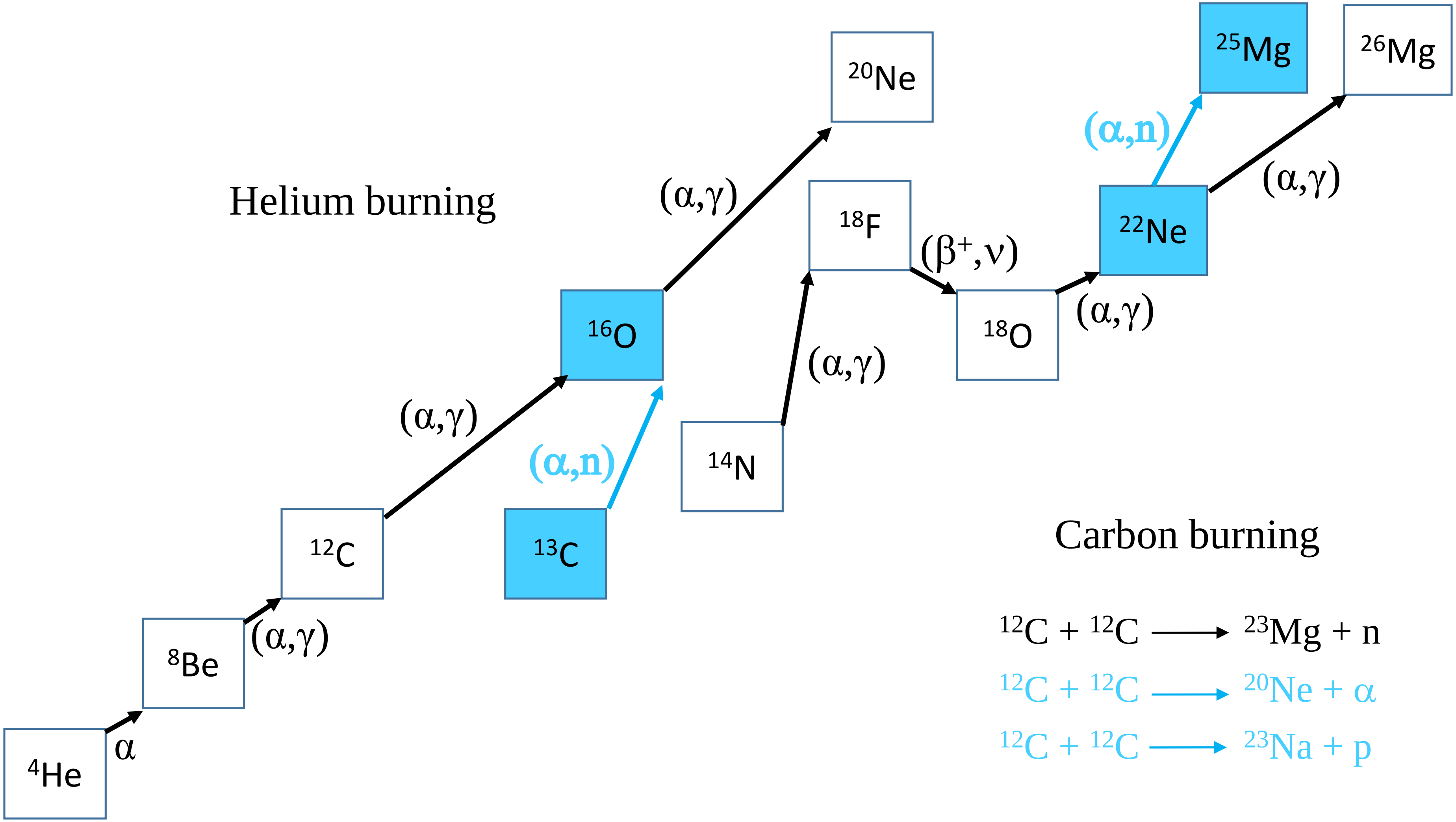
Viviana Mossa talk for details



7. ${}^{3}H + {}^{4}H \rightarrow {}^{7}Li + \gamma$
8. ${}^{3}He + n \rightarrow {}^{3}H + p$
9. ${}^{3}He + D \rightarrow {}^{4}He + p$
10. ${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
11. ${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$
12. ${}^{7}Be + n \rightarrow {}^{7}Li + p$
13. ${}^{4}He + D \rightarrow {}^{6}Li + \gamma$

Helium and carbon burning

In order to study reactions occurring at higher temperature than those belonging to hydrogen burning or BBN an higher energy machine is needed



s-process nucleosynthesis

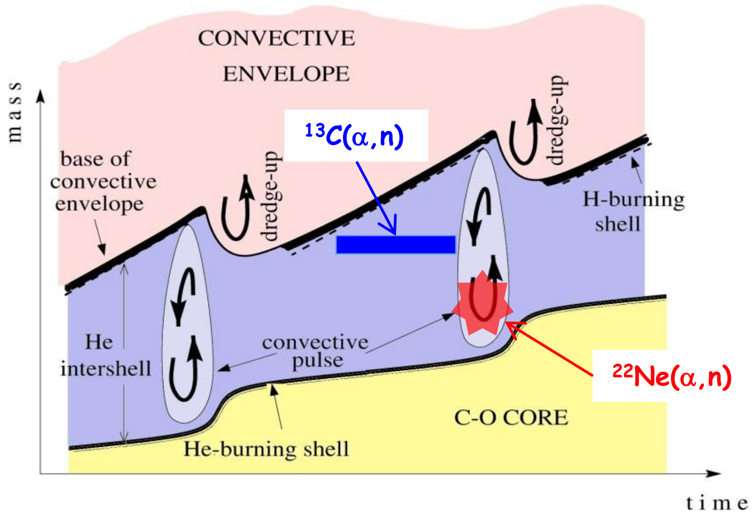
Two components were identified and connected to stellar sites:

Main s-process 90≲A<210

TP-AGB stars 1-3 $M_\odot$

shell H-burning
$T_9 \sim 0.1$ K
10^7-10^8 cm^{-3}
$^{13}C(\alpha,n)^{16}O$

He-flash
$0.25 \leq T_9 \lesssim 0.4$ K
10^{10}-10^{11} cm^{-3}
$^{22}Ne(\alpha,n)^{25}Mg$



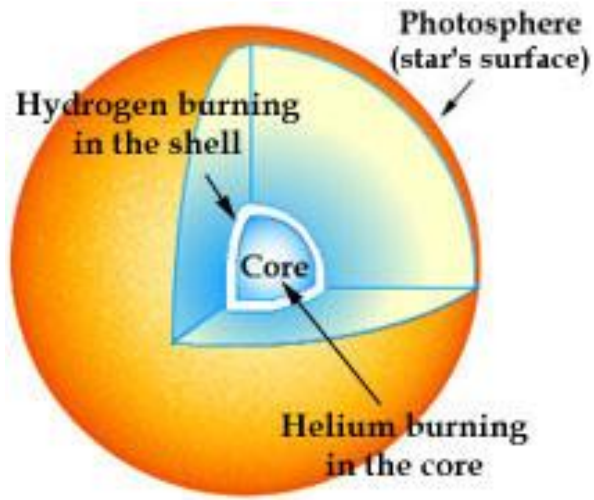
Weak s-process A≲90

massive stars > 8 $M_\odot$

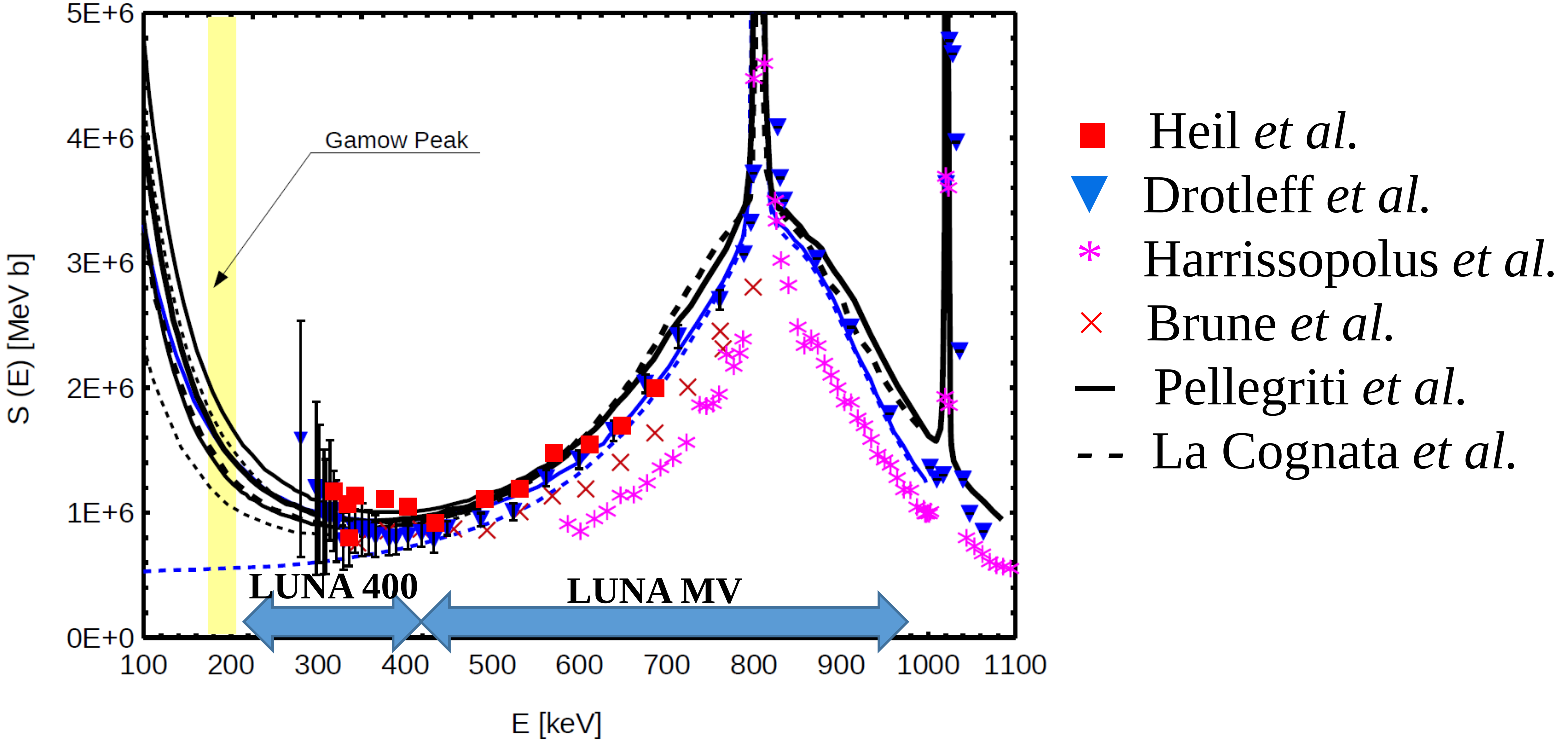
core He-burning
3-3.5·10^8 K
10^6 cm^{-3}

C-burning
~ 10^9 K
10^{11}-10^{12} cm^{-3}

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



$^{13}C(\alpha,n)^{16}O$: state of the art



- large statistical uncertainties at low energies
- large scatter in absolute values (normalization problem)
- systematic uncertainties (unknown, inconsistently treated)
- uncertainties in detection efficiencies (experimental vs simulated)

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

Direct Kinematics

- energy range E_{cm} = 210 – 300 keV (E_{beam} ~ 275 – 400 keV) at LUNA-400
- energy range E_{cm} = 240 – 1060 keV (E_{beam} ~ 0.3 – 1.4 MeV) at LUNA-MV
- ^{4}He beam
- $^{13}CH_4$ gas target:
  - ✓ P = 1 mbar → $2.5\ 10^{17}$ atoms/cm^2
  - ✓ L = 10 cm
- ^{13}C-enriched solid target:
  - ✓ density $2\ 10^{17}$-10^{18} at/cm^2 (evaporation / implantation on Au, Ta, sapphire)

Inverse Kinematics

- ^{13}C beam (only possible at LUNA-MV)
- ^{4}He gas target:
  - ✓ P = 1 mbar → $2.5\ 10^{17}$ atoms/cm^2
  - ✓ L = 10 cm
- neutron energy range: E_n = 2 – 3.5 MeV (E_{beam} = 0.3 – 1.4 MeV)

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

Enriched target ^{13}C: 99% I_α = 200 μA (direct kinematics)

E_{lab} [keV]	E_{cm} [keV]	Rate [neutr/h] $N_t = 10^{18}$ at/cm^2
1200	918	$2\ 10^5$
1000	764	$4\ 10^6$
800	612	$2\ 10^7$
400	306	339
375	287	103
350	268	28
300	229	1.3
275	210	**0.2**
250	191	**0.02**

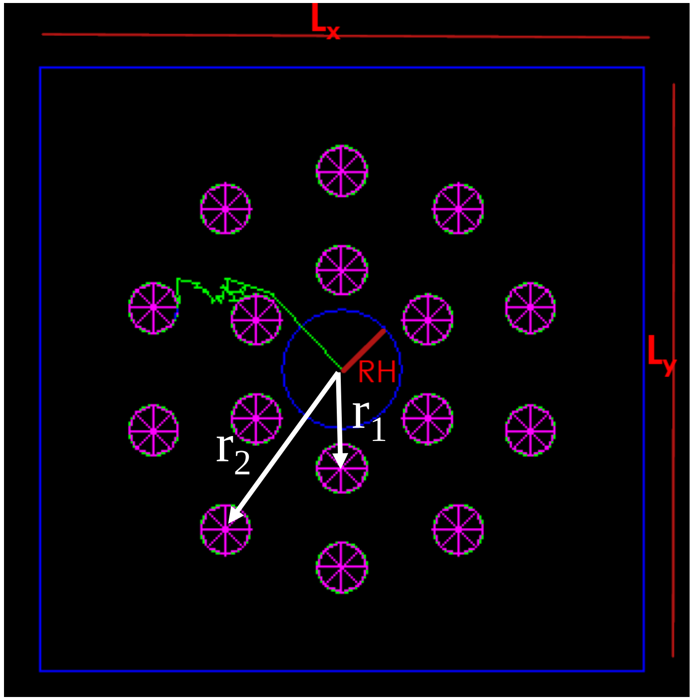
I_α = 1 μA

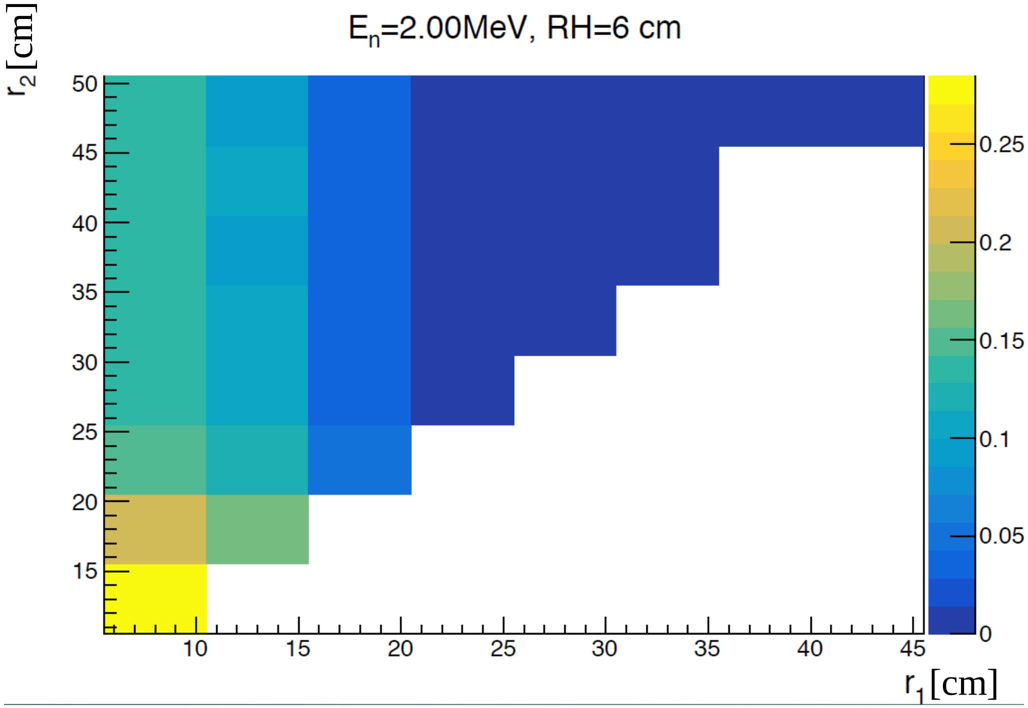
Lower beam current at high energy to reduce the neutron production

≈ 1-2 months
Beam time with
bck = 0

A neutron detector with high efficiency and low intrinsic background is required!

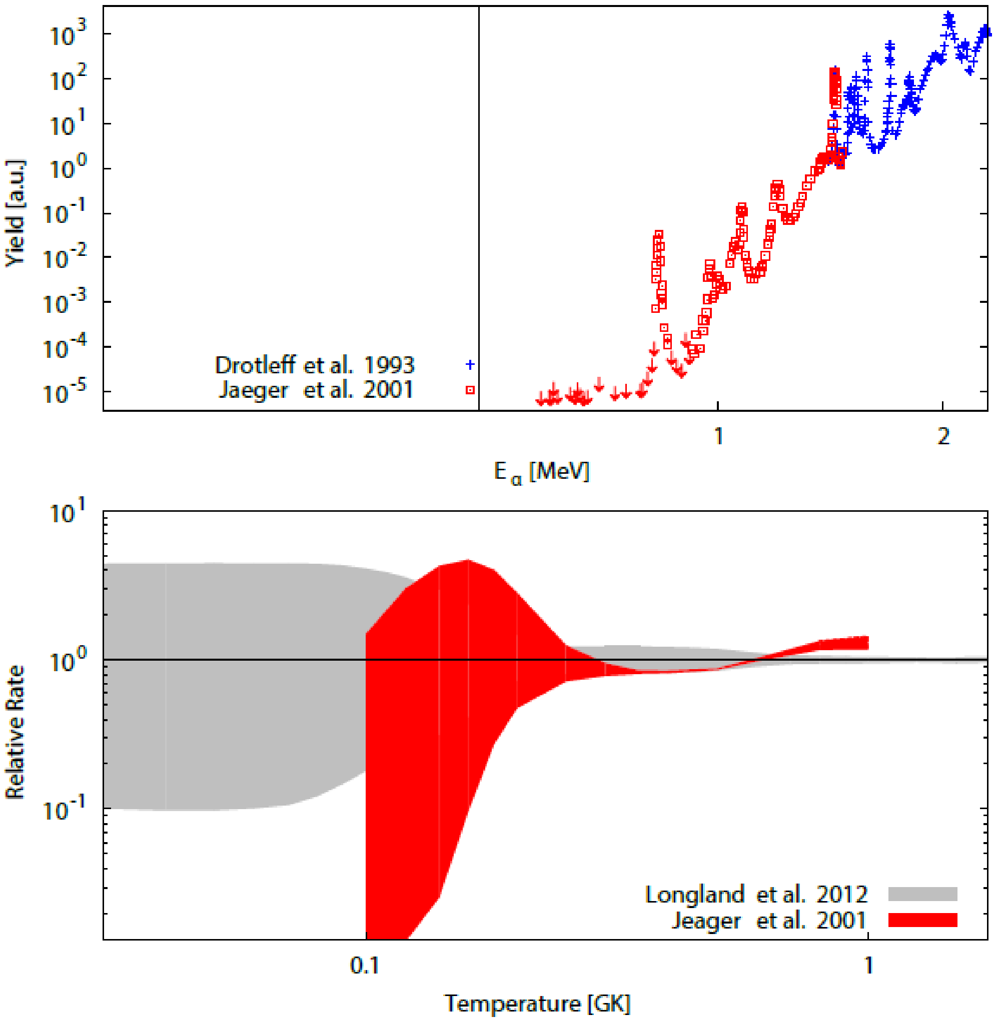
$^{13}C(\alpha,n)^{16}O$: neutron detector





- RH radius of the target chamber
- ^{3}He tubes positioned in two concentric ring: r_1 inner radius, r_2 outer radius
- Polyethylene matrix
- Simulation optimized for E_n = 2 MeV
- 16 stainless tubes (1 inch diameter, 40 cm long, P = 10 atm)
- Efficiency @ 2 MeV about 25%
- Low intrinsic background about 0.5 counts/h/counter in the region of interest

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



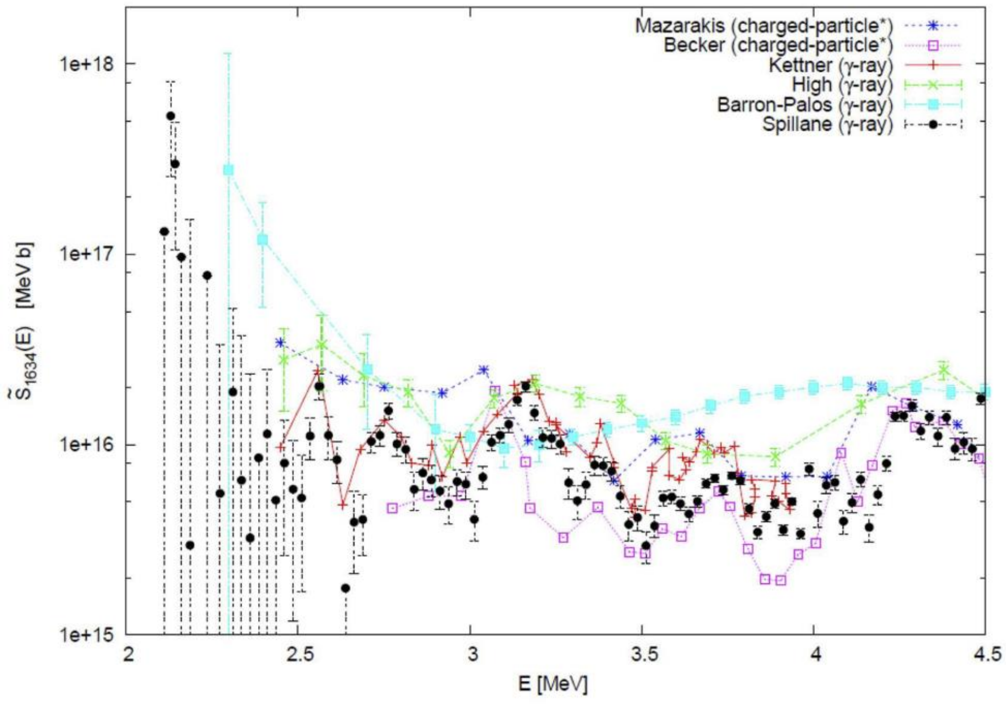
- The lowest well studied resonance at 832 keV dominates the rate (Drotleff et al. 1993)
- The influence of a possible resonance at 635 keV was ruled out based on parity (Longland et al. 2009)
- Theoretical extrapolations may be affected by other unknown low-energy resonances
- Same neutron detector as for $^{13}C(\alpha,n)^{16}O$
- Gas target with enriched ^{22}Ne gas
- The $^{22}Ne(\alpha,\gamma)^{26}Mg$ has been measured at LUNA 400, currently under analysis

The $^{12}C+^{12}C$: reaction channels and state of the art

- $^{12}C + ^{12}C \rightarrow ^{24}Mg + \gamma$ Q = 13.93 MeV negligible
- $^{12}C + ^{12}C \rightarrow ^{23}Mg + n$ Q = -2.62 MeV endothermic for low energies (relevant E_{CM} > 3 MeV)

- $^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ Q = 4.62 MeV
- $^{12}C + ^{12}C \rightarrow ^{23}Na + p$ Q = 2.24 MeV

- $^{12}C + ^{12}C \rightarrow ^{16}O + 2\alpha$ Q = -0.12 MeV three particles → reduced probability
- $^{12}C + ^{12}C \rightarrow ^{16}O + ^{8}Be$ Q = -0.21 MeV higher Coulomb barrier



Coulomb barrier: E_C= 6.7 MeV

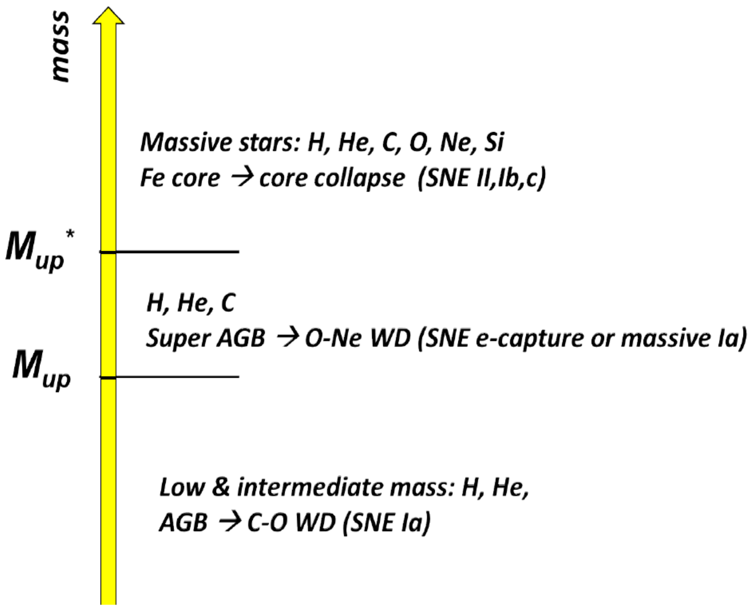
Quiescent carbon burning: 0.9 MeV<E_{CM}<3.4 MeV

Gamow energy 1.7-2.1 MeV for quiescent carbon burning

For explosive carbon burning ignition may occur for E_{CM} as low as 0.7 MeV

$^{12}C+^{12}C$: astrophysical motivations

- M_{up} minimum stellar mass for the occurrence of hydrostatic carbon burning
  - M_{up} depends on $^{12}C+^{12}C$ cross section
- Influence on the ignition of type Ia supernovae
  - The existence of the resonance at 1.5 MeV would have profound consequences for the physical conditions in the SNIa explosion (central density, degree of neutronization …)
- Impact on nuclesynthesis in massive stars:
  - The amount of neutrons available for the s-process decreases with increasing p channel strength compared to α channel
    - ➡ $^{22}Ne(\alpha,n)^{25}Mg$ suppressed compared to $^{22}Ne(p,\gamma)^{23}Na$



$^{12}C + ^{12}C \rightarrow ^{23}Na + p$

$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$

$^{12}C + ^{12}C$: measurement strategy

^{12}C target: thick (1 mm) or thin (40 μg/cm^2 which corresponds to 0.18 μm):

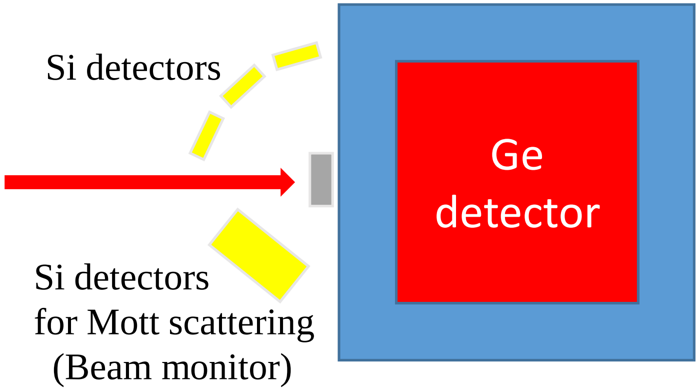
- Thick targets enhance counting rates and are more resistant
- Thin targets: Carbon build-up issues. Less auto-absorption for particles

$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha_i + \gamma_i$ In particular E_γ = 1634 keV first excited state

$^{12}C + ^{12}C \rightarrow ^{23}Na + p_i + \gamma_i$ In particular E_γ = 440 keV first excited state

Particle yield Gamma yield

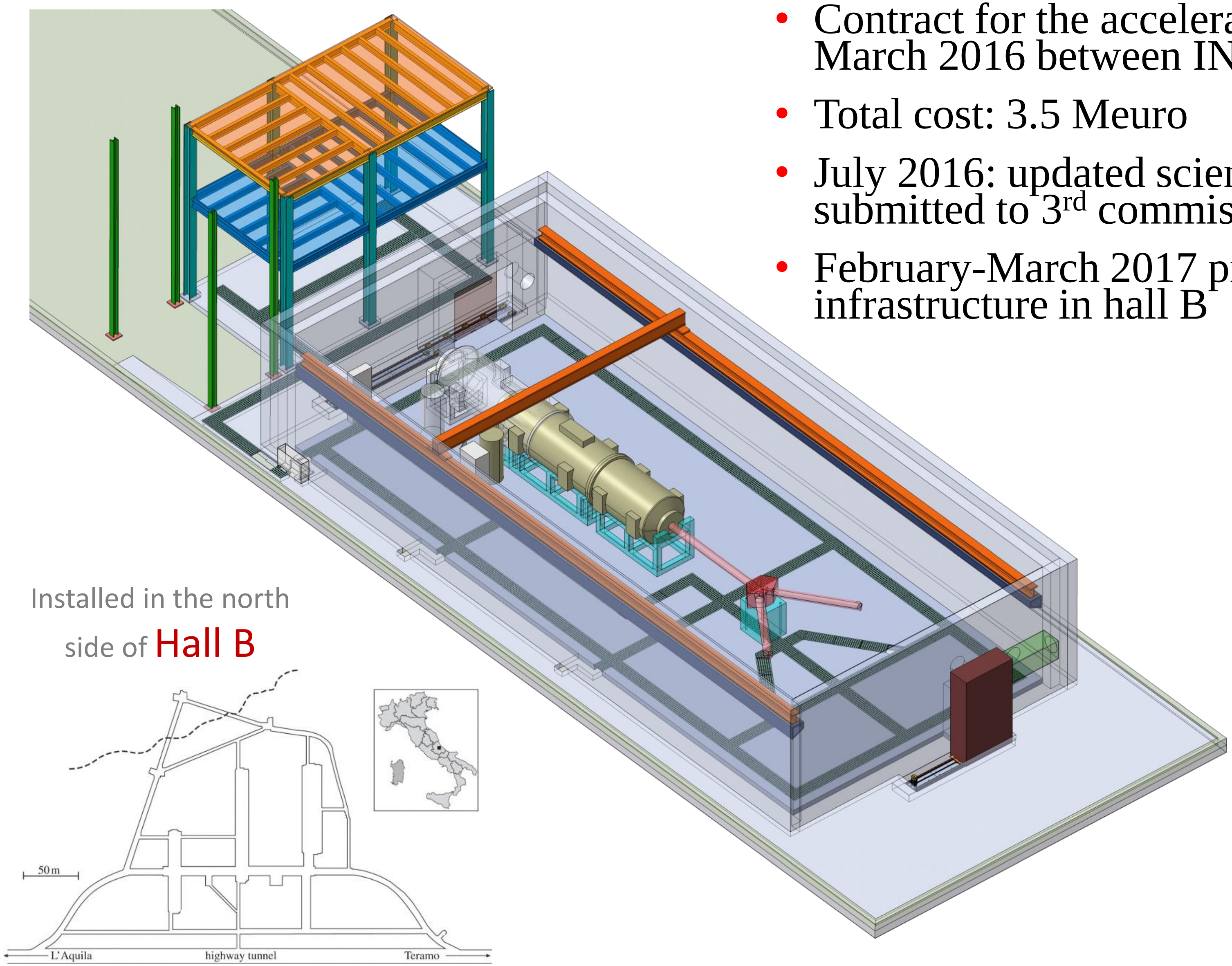
- High efficiency HPGe detector at 0° for gammas
- 4 Si detectors (100 mm^2, 500 μm thick) for α and p at E_{CM} > 2.5 MeV
- 2ΔE-E telescopes for p at E_{CM} < 2.5 MeV
- Data taking: 2 years to reach 30% uncertainty on the cross section



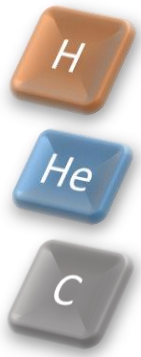
Current status of LUNA-MV

- Contract for the accelerator signed in March 2016 between INFN and HVEE
- Total cost: 3.5 Meuro
- July 2016: updated scientific program submitted to 3rd commission
- February-March 2017 preparation of the infrastructure in hall B

Installed in the north side of Hall B



The accelerator and neutron shielding

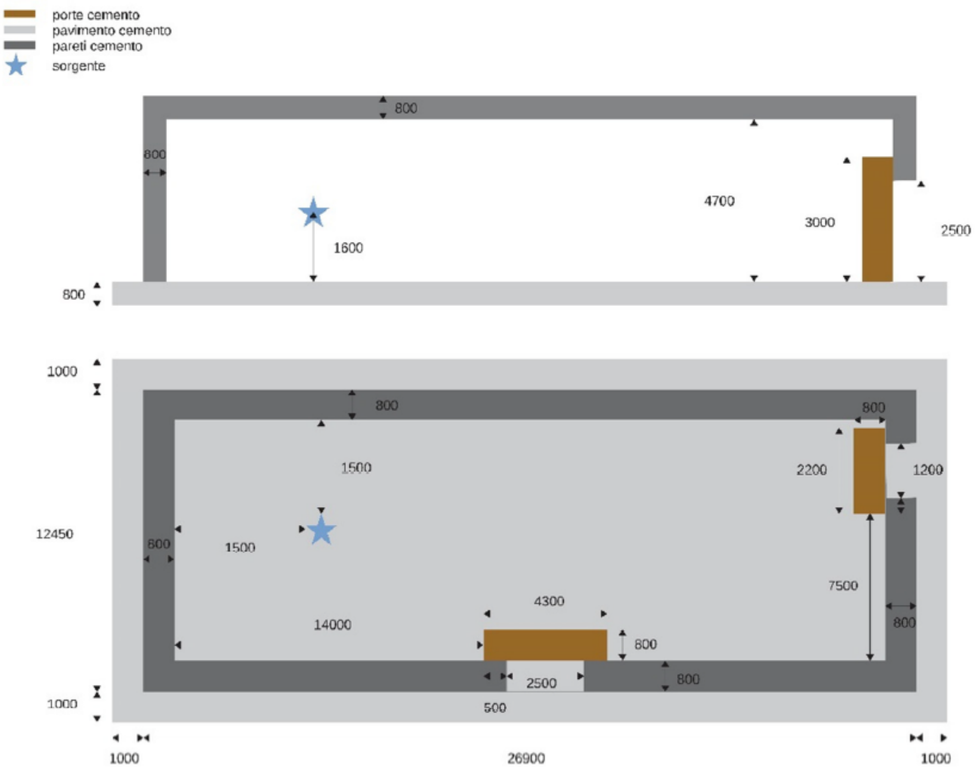


$^{1}H^{+}$ (TV: 0.3 – 0.5 MV): 500 µA
$^{1}H^{+}$ (TV: 0.5 – 3.5 MV): 1000 µA

$^{4}He^{+}$ (TV: 0.3 – 0.5 MV): 300 µA
$^{4}He^{+}$ (TV: 0.5 – 3.5 MV): 500 µA

$^{12}C^{+}$ (TV: 0.3 – 0.5 MV): 100 µA
$^{12}C^{+}$ (TV: 0.5 – 3.5 MV): 150 µA
$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 µA

- inline Cockcroft Walton accelerator
- **TERMINAL VOLTAGE: 0.2 – 3.5 MV**
- Precision of terminal voltage reading: 350 V
- Beam energy reproducibility: 0.01% TV
- Beam energy stability: 0.001% TV / h
- Beam current stability: < 5% / h



- 80 cm thick concrete shielding
- Monte Carlo simulations have been performed to predict the neutron flux outside the shielding
- Two different codes: GEANT4 & MCNP
- E_n = 5.6 MeV, 2 10^3 n/s, isotropic

MCNP: $\Phi_n = 1.38\ 10^{-7}$ n/(cm^2 s)
GEANT4: $\Phi_n = 3.40\ 10^{-7}$ n/(cm^2 s)

Φ_n(LNGS) = 3 10^{-6} n/(cm^2 s)

LUNA-MV schedule

Action	Date
Beginning of the clearing works in Hall B	**February 2017**
Beginning of the construction works in Hall B	**September 2017**
Beginning of the construction of the plants in the LUNA-MV building	**December 2017**
Completion of the new LUNA-MV building and plants	**April 2018**
LUNA-MV accelerator delivering at LNGS	**May 2018**
Conclusion of the commissioning phase	**December 2018**
Beginning First Experiment	**January 2019**

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

- Day 0 reaction at LUNA-MV
- Already very well study at LUNA-400
  - ✓ Formicola et al. (PLB 591, 61, 2004), Imbriani et al. (EPJA 25, 455, 2005), Bemmerer et al. (NPA 779, 297, 2006), Lemut et al. (PLB 634, 483, 2006), Marta et al. (PRC 78, 022802(R), 2008)
- Solid target + HPGe detector
- At high energies (above E_p = 270 keV): high counting rate = short and easy measurement

SCIENTIFIC INTEREST

- Recently re-measured by Li et al. (PRC 93, 055806, 2016) and by Daigle et al. (PRC 94, 025803, 2016)
- Two ingredients needed to address the ‘solar abundance problem’ [Serenelli09-16]
  1. CNO neutrino flux
  2. $^{14}N(p,\gamma)^{15}O$ cross section
- Globular Clusters age estimation

Silver Moon: The first and the next 25 years of LUNA at Gran Sasso

- Underground nuclear astrophysics was born twenty five years ago in Gran Sasso, when LUNA started its activity with a 50kV accelerator, implementing the visionary idea of Enrico Bellotti, Gianni Fiorentini and Claus Rolfs
- The extremely low laboratory background has allowed for the first time the realization of nuclear physics experiments with very small count rates, down to a couple of events per month
- Today, after the first 25 years of LUNA, a new phase has started with the ambitious LUNA-MV project
- Program available at: silvermoon.lngs.infn.it

December 1st – 2nd 2016: **SAVE THE DATE**

LUNA collaboration

- A. Best, A. Boeltzig*, A. Formicola, G.F. Ciani*, M. Junker, I. Kochanek | INFN LNGS /*GSSI, Italy
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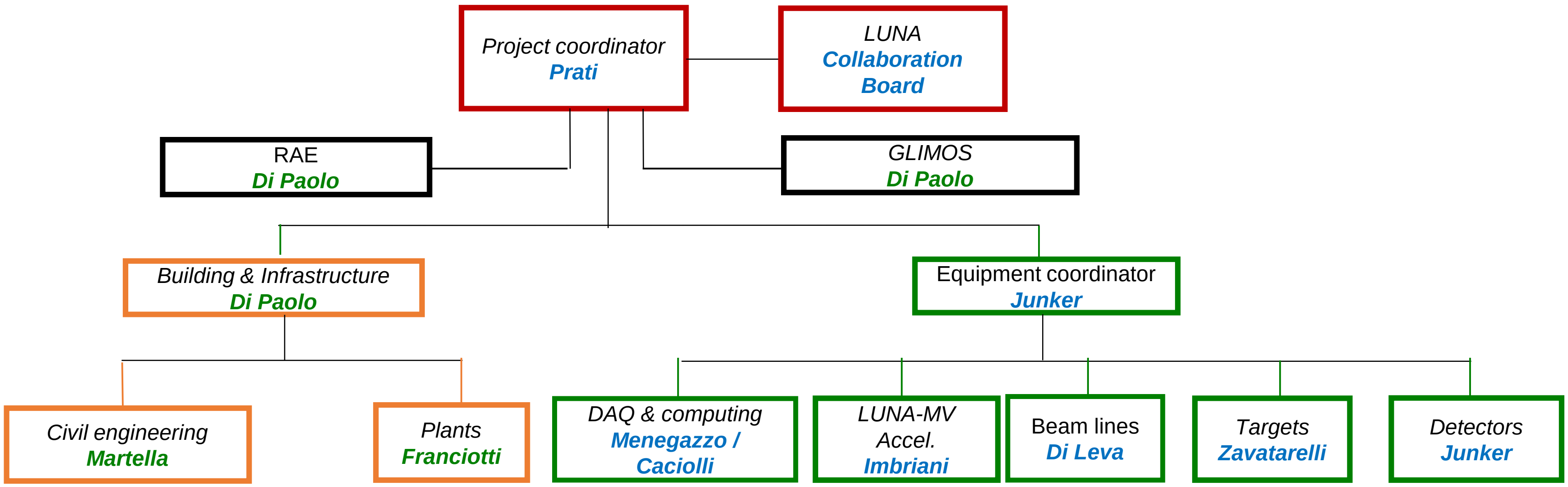
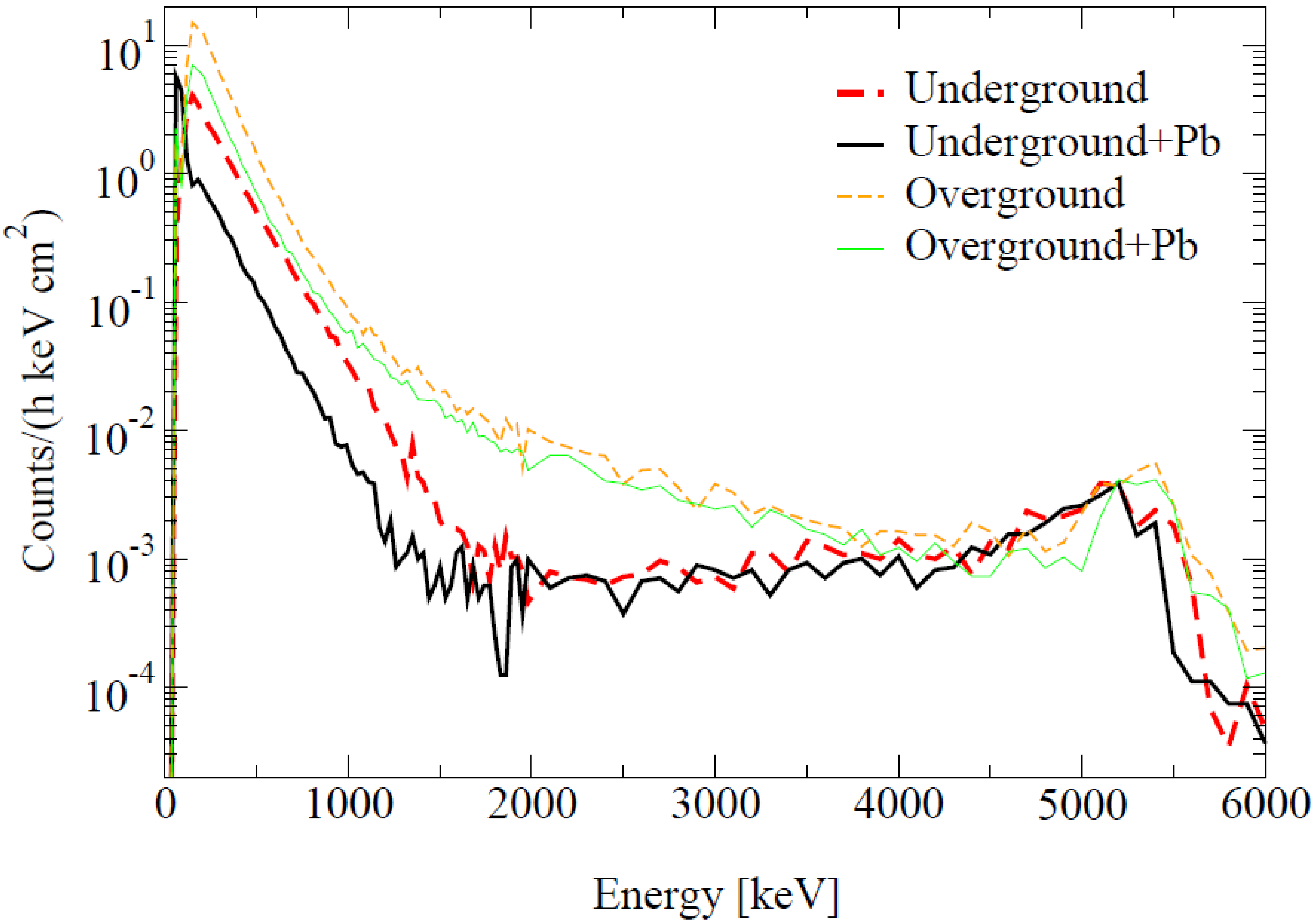


Extra slides

Competitor

	Bck.	Acceler.	Beam intensity	Program	Expected start	Notes
LUNA	LNGS	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	~ LNGS	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	LNGS	3.5 MV + ECR	1 mA	$^{14}N(p,\gamma)$? $^{13}C(\alpha,n)$ $^{22}Ne(\alpha,n)$ $^{12}C + {}^{12}C$	2019 ? ? ?	

Background



Underground
Underground+Pb
Overground
Overground+Pb
Counts/(h keV cm^2)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1000
2000
3000
4000
5000
6000
Energy [keV]