Latest results from LUNA experiment

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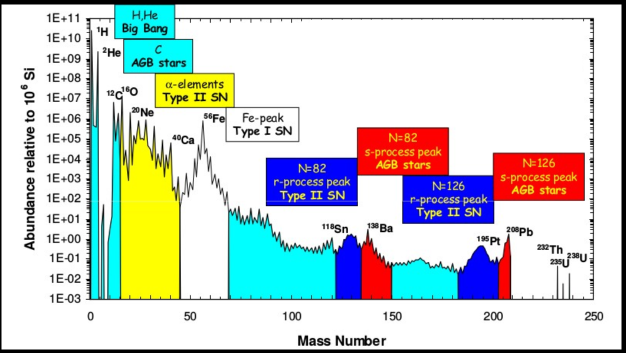
Laboratory for Underground Nuclear Astrophysics

Introduction

- Nuclear Astrophysics
  - Importance of going underground
- LUNA experiment: Laboratory for Underground Nuclear Astrophysics
- Recent results:
  - Emphasis will be given to:
    - Setup commissioning for an improved measurement of the $D(p,\gamma)^3He$ cross section at Big Bang Nucleosynthesis energies
  - The future of LUNA
    - LUNA 400 (bridge proposal)
    - LUNA MV and the scientific plan

Nuclear Astrophysics



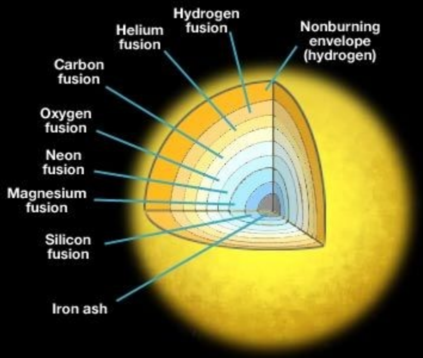
Nuclear reactions determine the abundances of the elements in the cosmos, stellar evolution and dynamic

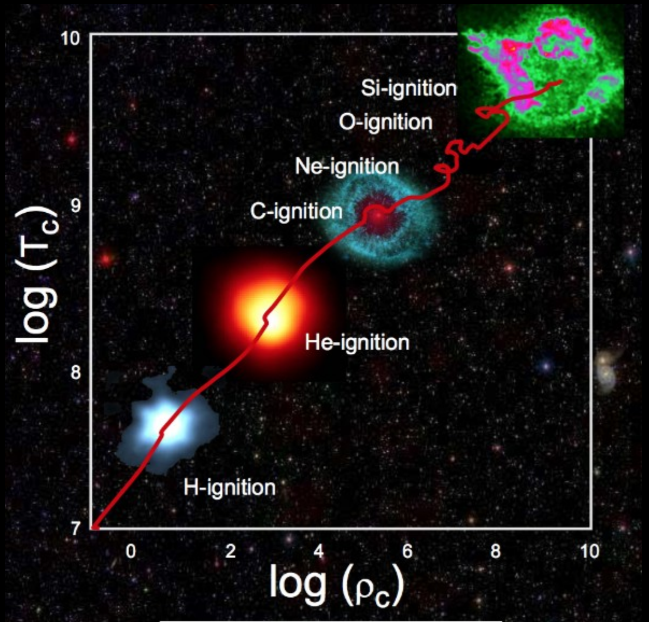
Nuclear fusion is the engine of stars: it produces the energy that stabilizes them against gravitational collapse and makes them shine

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





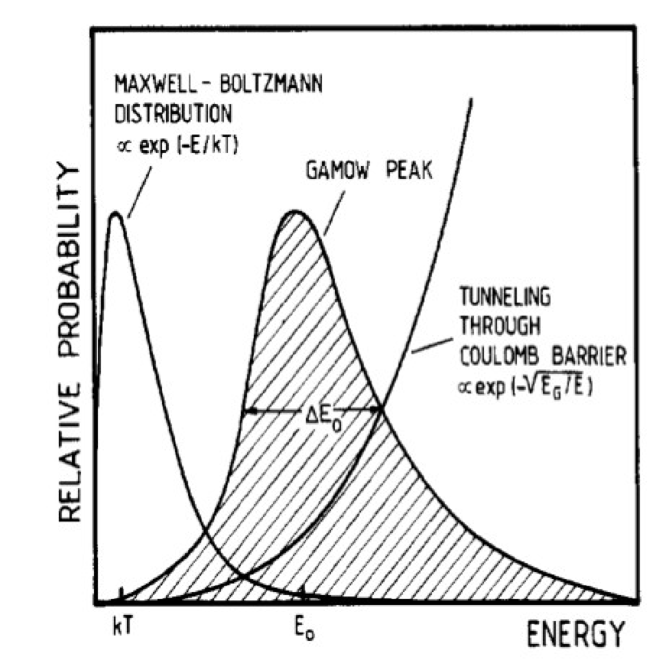
For a 15 M_{sun} star:

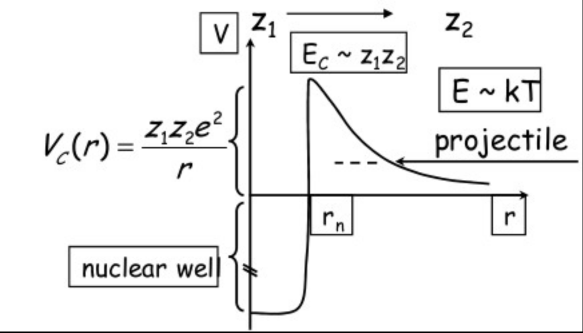
Reaction	Timescale
Hydrogen burning	10 million years
Helium burning	1 million years
Carbon burning	300 years
Oxygen burning	200 days
Silicon burning	2 days

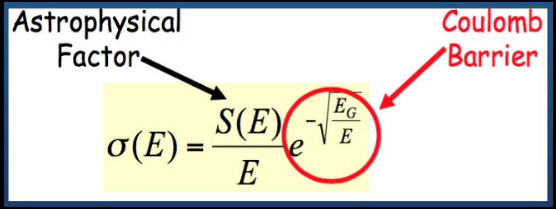
The importance of going underground

- For nuclear reactions in stars, the convolution of the thermal energy distribution and the tunneling probability through the Coulomb barrier defines the effective energy window, centered around the so-called Gamow peak (E_0), where fusion reactions take place

- Sun:
  - kT ~ 1 keV (T ~ 1.5 x 10^7 K)
  - E_C ~ 0.5 - 2 MeV (Coulomb barrier)
  - E_0 ~ 5 - 30 keV (Gamow peak) for reactions of H burning
  - kT << E_C → Tunnel effect
  - 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..







Precise direct measurement at stellar energies... Not an easy task!

low cross sections → low yields → poor signal-to-noise ratio

10^{19} atoms/cm^2 typical solid state targets

~100% for charged particles

~1-10% for gamma rays (HPGe)

Yield = N_p x N_t x cross section x detection efficiency

10^{-15} barns (often even smaller)

10^{14} pps (~100 µA q= 1+) typical stable beam intensities

Yield ~ 0.3-30 counts/year

but..

~ 1.2 - 220 counts/day (background)

Rate and background

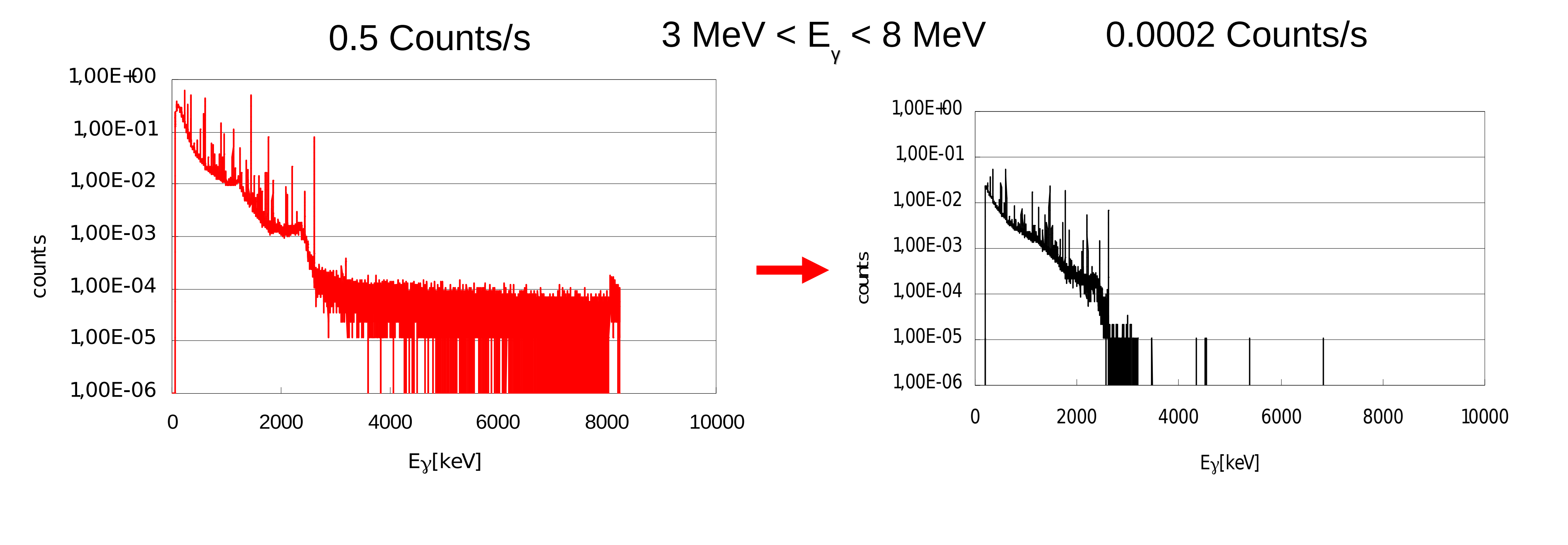
- The rate R has to be compared with background B:

$$R > B_{\text{beam induced}} + B_{\text{env}} + B_{\text{cosmic}}$$

  - $B_{\text{beam induced}}$: 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

- Gamma spectra with High Purity Germanium detector (survace vs underground)



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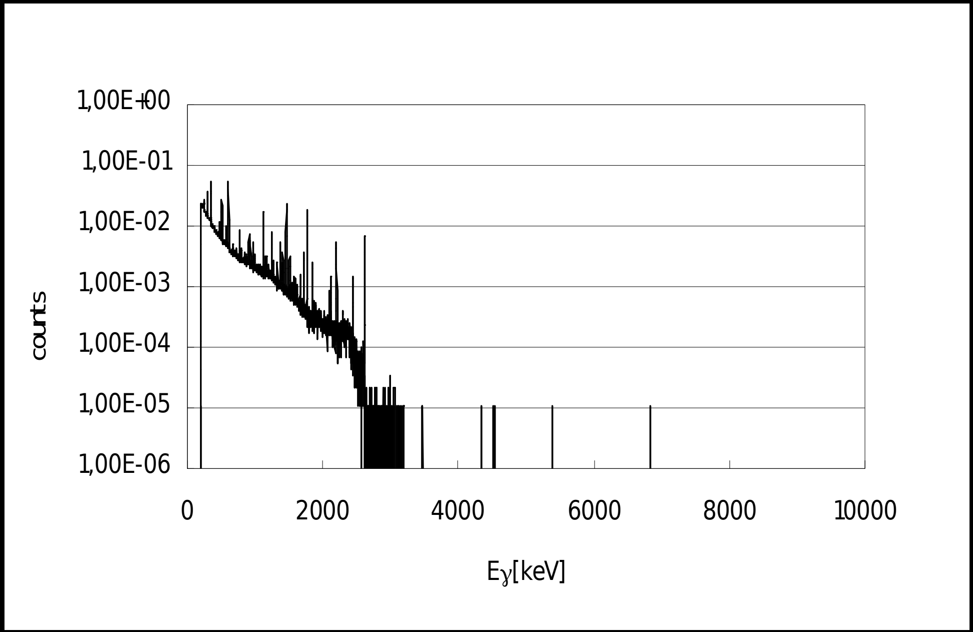
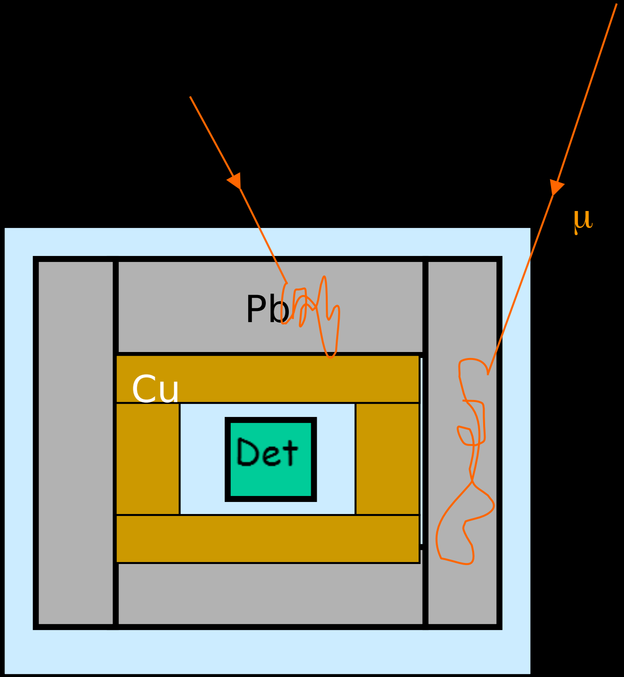
Rate and background

- $E_\gamma < 3$ MeV → passive shielding for environmental background radiation

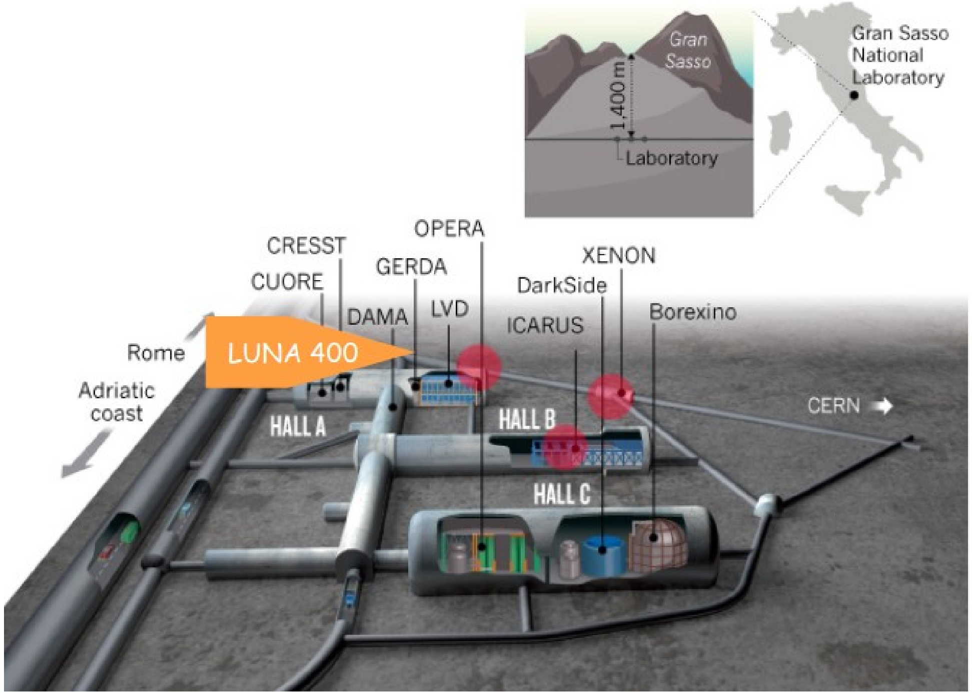




Laboratory for Underground Nuclear Astrophysics

The LUNA facility inside the Laboratori Nazionali del Gran Sasso in central Italy. The site is shielded against cosmic rays by a rock cover - 1400 m thick equivalent to ~ 4000 m water - suppressing the muon and neutron fluxes by six and three orders of magnitude, respectively

Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}
Gammas	10^{-2}-10^{-5}



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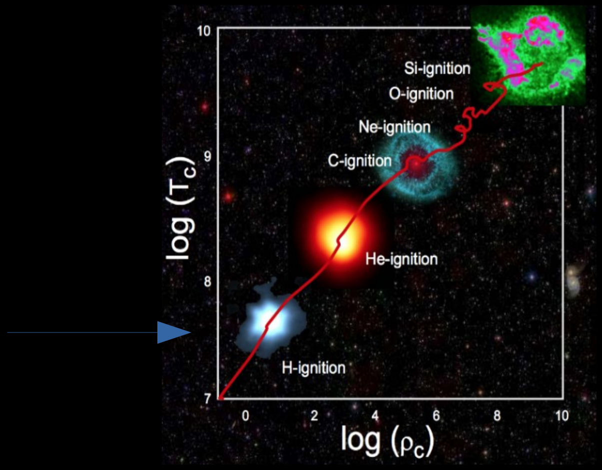
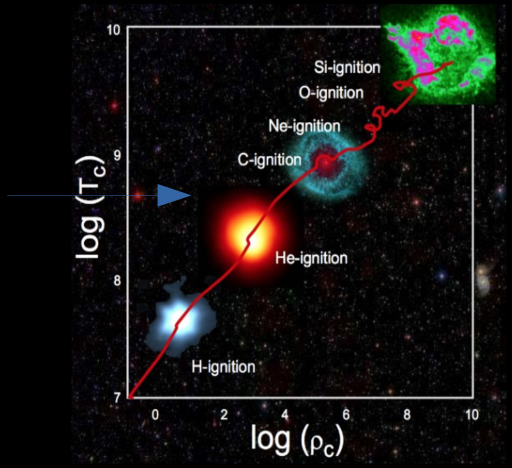
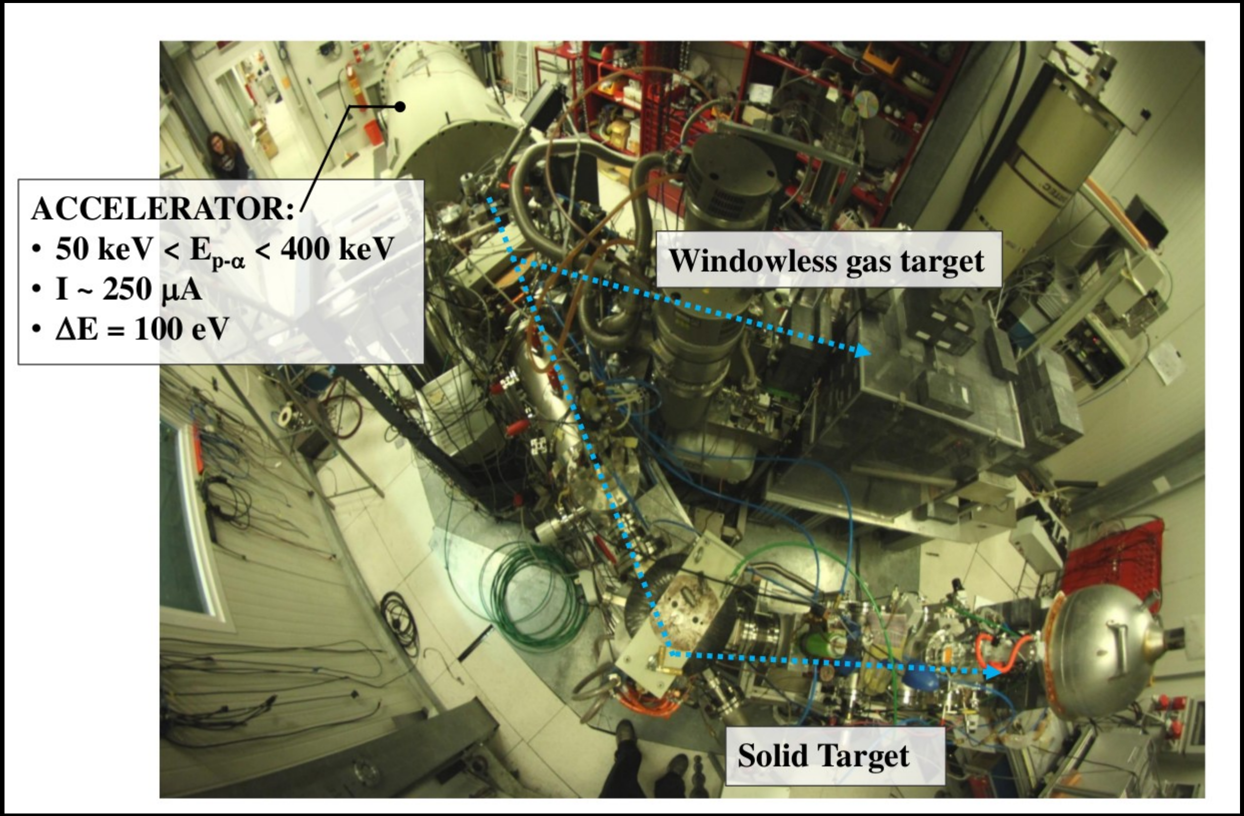
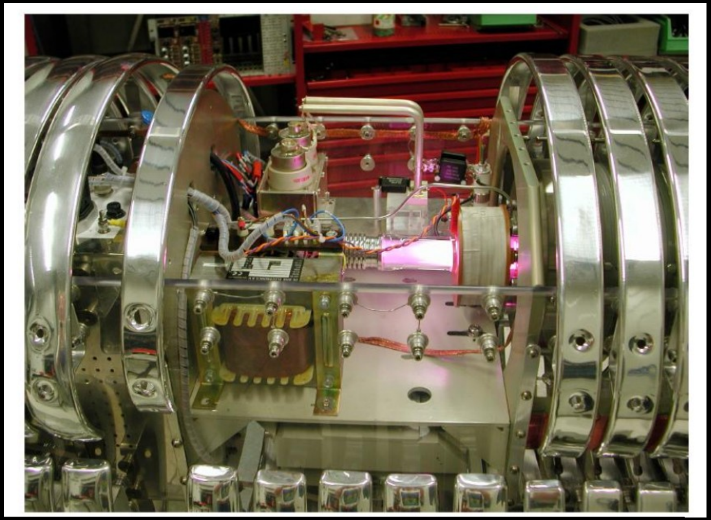




LUNA experimental setup





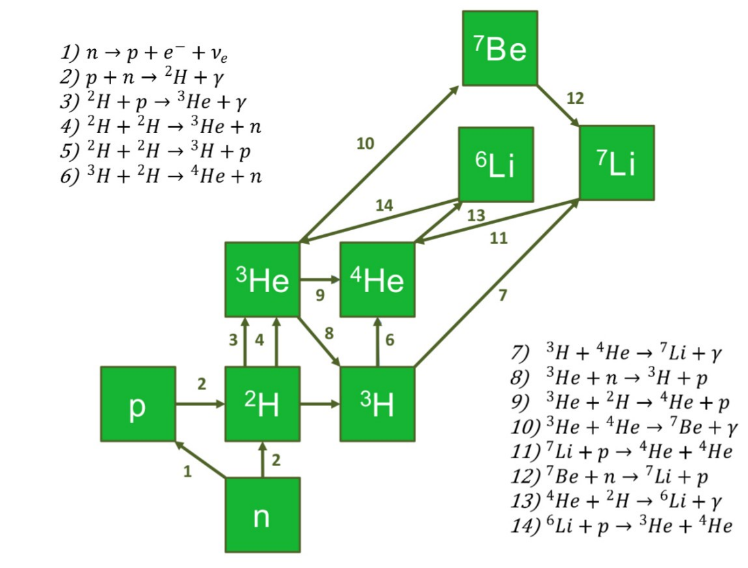
Radio frequency ion source of the LUNA 400 kV accelerator. The characteristic pink light of the hydrogen plasma is visible.

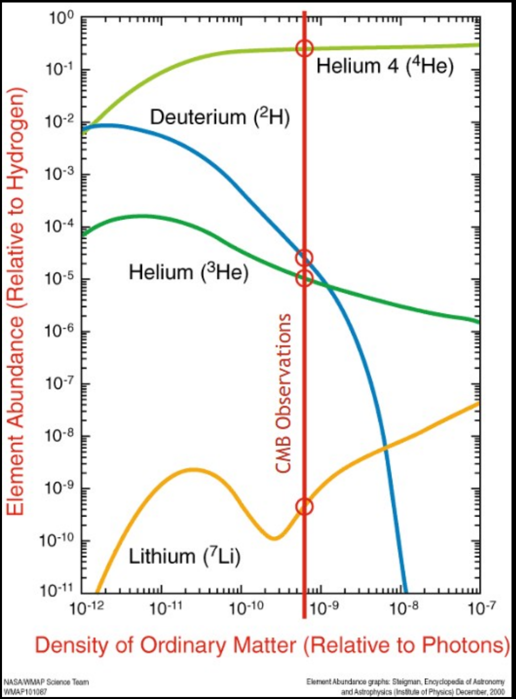
Possibility of different detection setup by combining: HpGe (high resolution), BGO (high efficiency) ^{3}He counters..

Big Bang Nucleosynthesis

Big Bang Nucleosynthesis

- Big Bang Nucleosynthesis (BBN) occurs during the first minutes of cosmological time in a rapidly expanding hot and dense Universe
- Fraction of protons and nearly all free neutrons end up bound in ^{4}He, while D, ^{3}H, ^{3}He, ^{6}Li, ^{7}Li and ^{7}Be nuclei form in trace quantities
- The **primordial abundance of deuterium** can provide stringent constraints on the baryon density and the number of relativistic particles in the early Universe
- Observations of D, ^{3}He, ^{4}He, and ^{7}Li in very old (metal poor) stars provide stringent tests of BBN..





Big Bang Nucleosynthesis

- <u>Observed abundance:</u>

  [D/H] = (2.527 ± 0.030) x 10^{-5}

  Cooke et al, APJ 855 (2018) 102

- <u>Predicted abundance (BBN theory):</u>

  [D/H] = (2.65 ± 0.07) x 10^{-5}

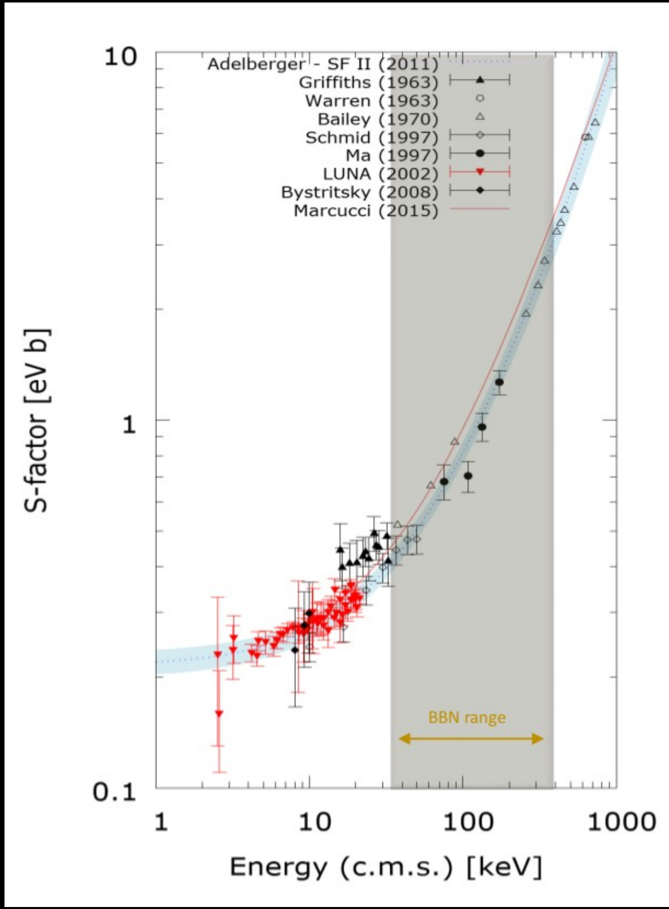
  Di Valentino et al, PRD 90 (2014) 023543

- Observed abundance up to 5% lower than predicted abundance
- To interpret → more precise BBN D/H abundance
- <u>main uncertainty in BBN prediction due to $D(p,\gamma)^3He$ cross section</u>

Reaction	$\sigma_{^2H/H} \times 10^5$
$p(n,\gamma)^2H$	± 0.002
$d(p,\gamma)^3He$	± 0.062
$d(d,n)^3He$	± 0.020
$d(d,p)^3H$	± 0.013

*E. Di Valentino et al., Phys. Rev. D 90 (2014) 023543

BBN: A new $D(p,\gamma)^3He$ cross section measurement



- Several data sets of this reaction cross section, or equivalently its S(E)-factor, are available in the literature
- In the E_{cm} ~ 2 – 20 keV, mostly relevant to hydrogen burning in the Sun and in protostars, cross sections were obtained with a systematic error of at most 5.3% (LUNA 50 kV)
- At higher energies (E_{cm} ~ 30−700 keV), available data sets are affected by systematic errors of 9% or higher
- The situation is further compounded by the fact that a recent “ab initio” calculation [1] disagrees at the 20–30% level with both the S-factor of Ma et al. [2] and a best fit [3] to selected data, widely used in BBN calculations
- **LUNA 400kV measurement goal: Cross section in 30 keV < E_{cm} < 300 keV**

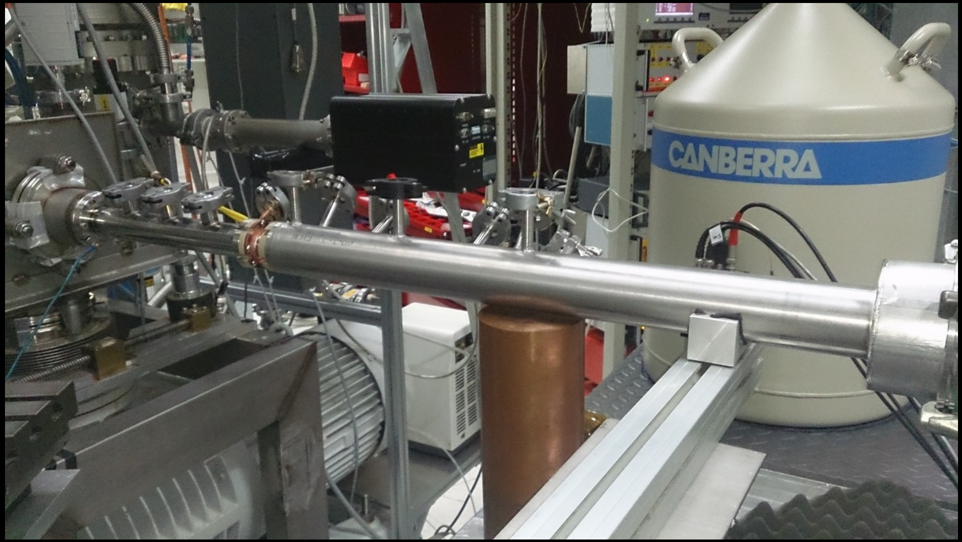
[1] L. Marcucci, Ab initio angular distribution for D(p,γ)3He reaction, Private communication (2018)
[2] L. Ma et al., Phys. Rev. C 55, 588 (1997)
[3] E. Adelberger et al., Rev. Mod. Phys. 83, 195 (2011)

Big Bang Nucleosynthesis

Approach and setup @ LUNA 400

D(p,γ)^{3}He: experimental approach and setup

- The reaction (Q-value = 5.5 MeV) is studied in direct kinematics using a windowless and extended D_2 gas target and detecting the emitted γ rays with a high purity germanium detector.
- At LUNA, the γ-ray background is reduced by more than four orders of magnitude in the region of interest for the D(p,γ)^{3}He reaction (E_γ = 5−5.8 MeV);



D(p,γ)^{3}He: experimental approach and setup

- The cross section - for an extended gas target of length L:

Number of detected gamma rays at a given interaction energy E

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_{-L/2}^{L/2} \rho(z)\epsilon(z, E_\gamma) W(z) dz}$$

term accounting for the angular distribution of the emitted gamma rays

the number of incident protons

the number density of target atoms as a function of interaction position z along the target

the gamma ray photo-peak detection efficiency

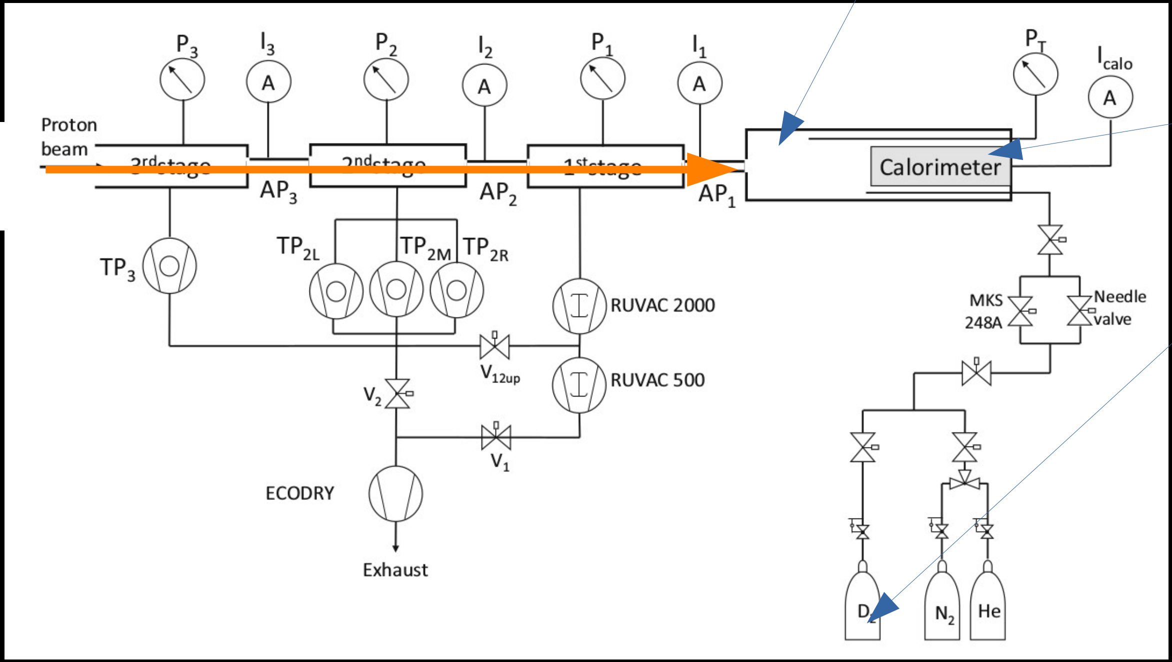
D(p,γ)^{3}He: experimental approach and setup

- Scheme of the LUNA windowless gas target: 3 pumping stages and the target chamber (L:330mm, diameter: 56 mm) with the calorimeter

windowless gas target

calorimeter

Proton beam



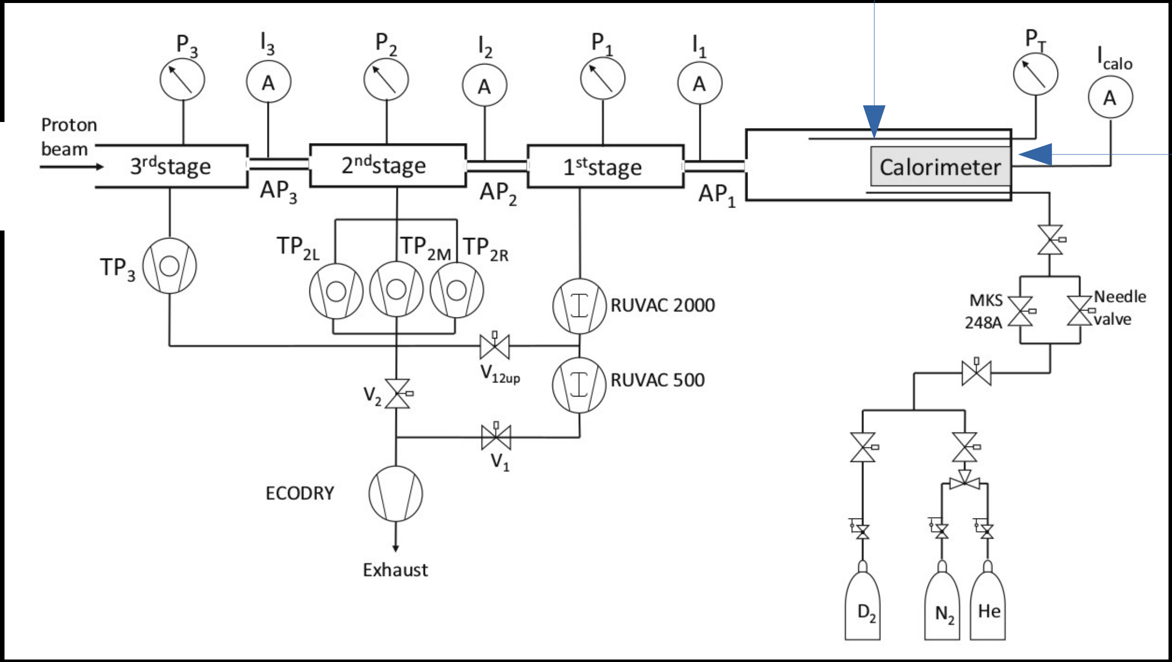
Deuterium gas of 99.999% isotopic purity (as certified by
the vendor, Rivoira).
0.3 mbar in reaction chamber

D(p,γ)^{3}He: experimental approach and setup

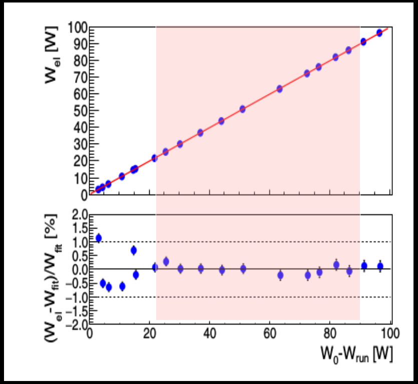
- Calorimiter: Hot side (beam stop + 8 heating resistors + cold side).
- The beam current has been measured with calorimiter, with uncert. ~ 1%

Hot side (70°C) – beam stop

Proton beam



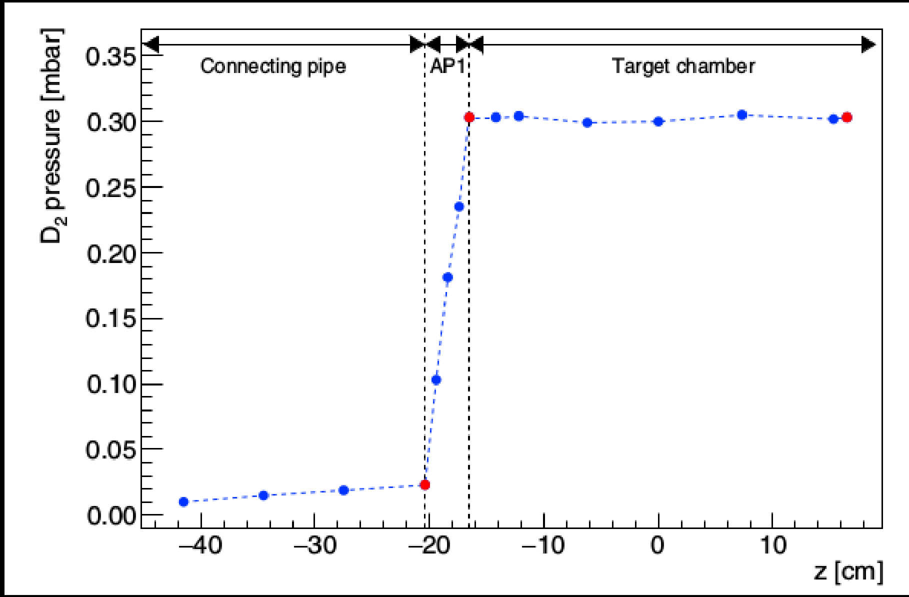
Cold side (0°C)



Calorimeter electrical calibration. Electrical reading vs Power calorimetric power

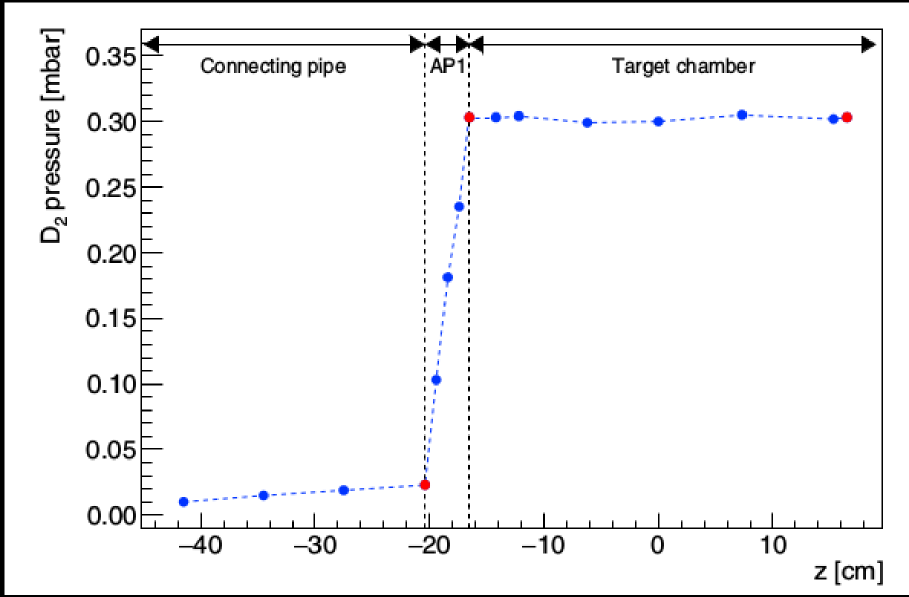
D(p,γ)^{3}He

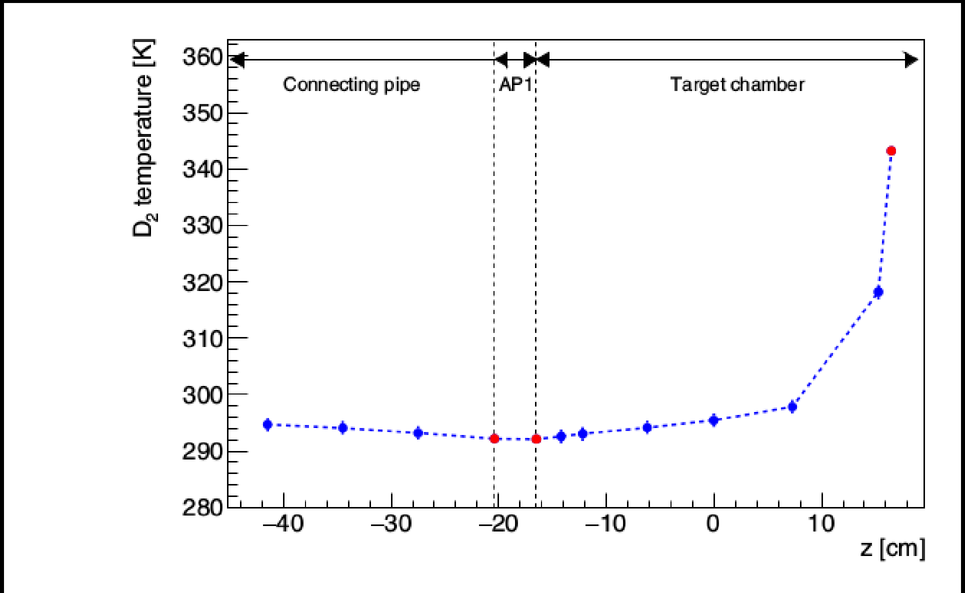
- Effective target density measurements: the pressure is measured at 12 different positions
  - the gas pressure remains constant within ±0.9% inside the chamber, decreases along the collimator, and vanishes within the connecting pipe.
  - Calibration + instrumental accuracy: a total uncertainty ~ ±0.9% (inside target ch.)



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

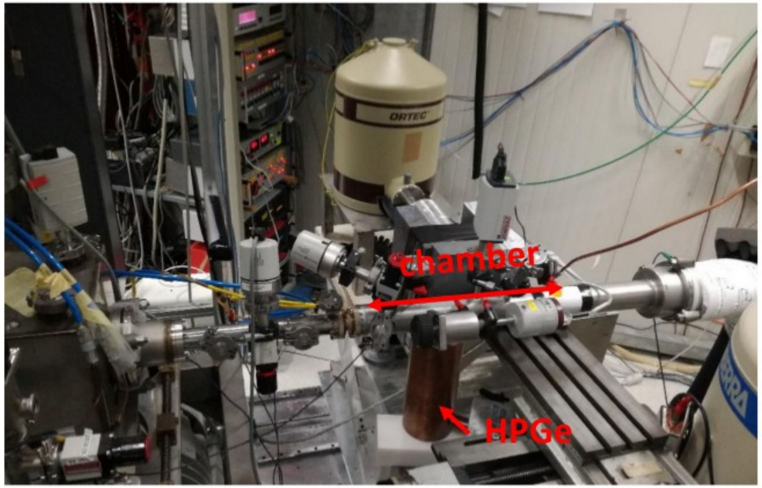
- Effective target density measurements: the temperature is measured at 12 different positions
  - the temperature drops between the calorimeter beam stop heated to 343 K and the collimator, constant to within ±0.2% inside the connecting pipe at about 294 K (21°C)
  - The overall temperature error ~ 1K → relative error ± 0.3%

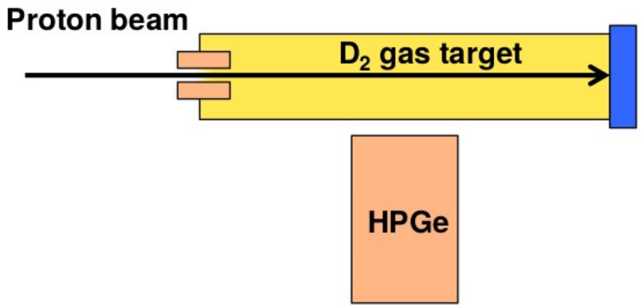


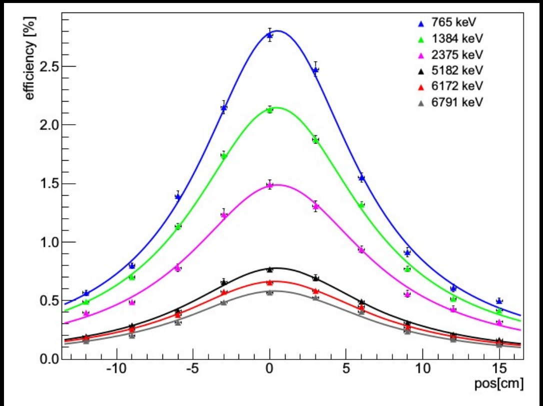


Detection efficiency - HPGe

- Gamma rays from the D(p,γ)^{3}He reaction were detected with a high purity germanium detector (relative efficiency ~ 135%) located under the target chamber and facing its centre.
- Energy resolution: ~10 keV @ 6 MeV
- Efficiency for gamma of 5.5 MeV ~ 2%
- Possibility of performing angular distribution measurements with extended gas target (33 cm)
- Approach: Monte-Carlo simulation + data driven approach + radioactive sources [see. Eur. Phys. J. A (2020) 56 :144]







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

- An overall systematic uncertainty below 3% achieved → Interesting consequences for BBN and cosmology!

Table 1 Contributions to the overall systematic uncertainty in the $D(p,\gamma)^3He$ S factor arising from different sources. Values shown refer to a representative energy $E_p = 200$ keV ($E_{cm} = 133$ keV)

Source	Method	$\Delta S/S$ (%)
Beam energy	Direct measurement	0.2
Energy loss	Low gas pressure	0.04
T and P profiles	Direct measurement	1.0
Beam heating	Direct measurement	0.5
Gas purity	Data sheet	0.1
Beam current	Calorimeter calibration	1.0
Efficiency	Direct measurement	2.0
Instrumental effects	Pulser method	0.2
Angular distribution	Simulations	0.5
Total		2.6

Eur. Phys. J. A (2020) 56:144
https://doi.org/10.1140/epja/s10050-020-00149-1
THE EUROPEAN PHYSICAL JOURNAL A
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Special Article - Tools for Experiment and Theory

Setup commissioning for an improved measurement of the $D(p,\gamma)^3He$ cross section at Big Bang Nucleosynthesis energies

LUNA collaboration

V. Mossa[1], K. Stöckel[2,3], F. Cavanna[4], F. Ferraro[4,5], M. Aliotta[6], F. Barile[1], D. Bemmerer[2], A. Best[7], A. Boeltzig[8,9], C. Broggini[10], C. G. Bruno[6], A. Caciolli[10,11], L. Csedreki[8,9], T. Chillery[6], G. F. Ciani[8], P. Corvisiero[4,5], T. Davinson[6], R. Depalo[10], A. Di Leva[7], Z. Elekes[12], E. M. Fiore[1,13], A. Formicola[9], Zs. Fülöp[12], G. Gervino[14], A. Guglielmetti[15], C. Gustavino[16,a], G. Gyürky[12], G. Imbriani[7], M. Junker[9], I. Kochanek[9], M. Lugaro[17], L. E. Marcucci[18], P. Marigo[10,11], E. Masha[15], R. Menegazzo[10], F. R. Pantaleo[1,19], V. Paticchio[1], R. Perrino[1,21], D. Piatti[10], P. Prati[4,5], L. Schiavulli[1,13], O. Straniero[20], T. Szücs [2], M. P. Takács[2,3], D. Trezzi[15], S. Zavatarelli[4,b], G. Zorzi[15]

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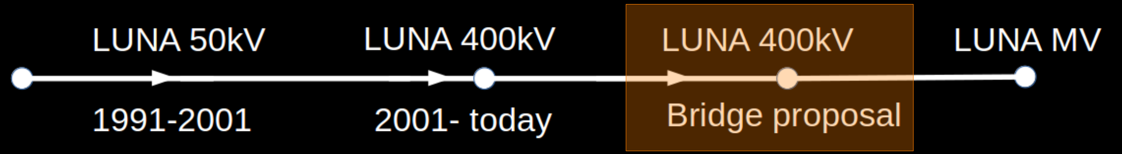
Paper close to be published..

LUNA 400 Bridge proposal

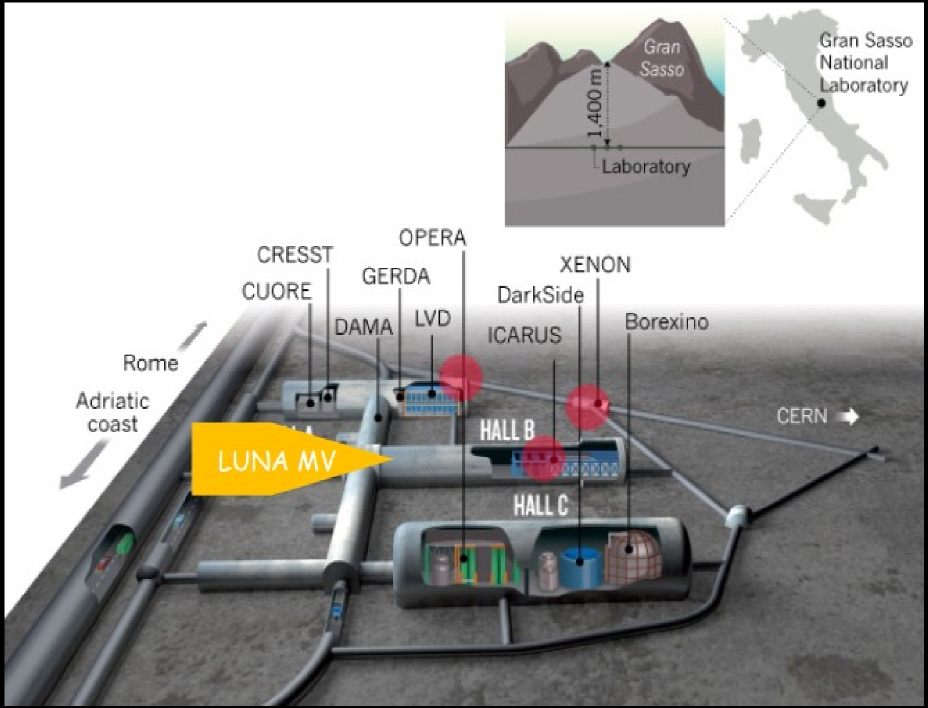


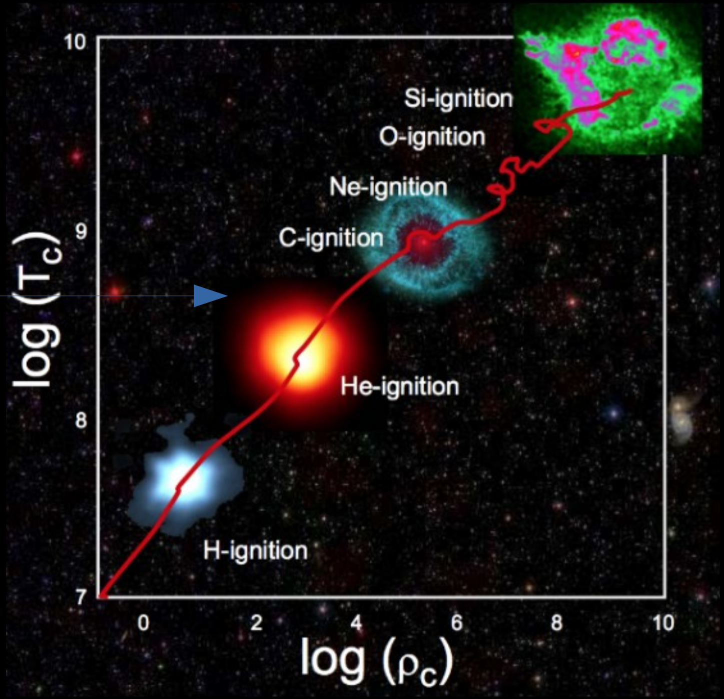
Bridge proposal:

- $^{17}O(p,\gamma)^{18}F$ → Abundance ratio of the oxygen isotopes in the stellar environment (^{18}O, ^{17}O, ^{16}O) where hydrogen burning is active (in AGB nucleosynthesis, in explosive hydrogen burning occurring in type Ia novae...)
- $^{20}Ne(p,\gamma)^{21}Na$ → Speed of NeNa. It is the first reaction of the NeNa cycle and having the slowest reaction rate, it controls the speed at which the entire cycle proceeds. It occurs in different stellar scenarios such as red giants stars (during II shell-burning), asymptotic giant branch stars, novae, and massive stars..
- $^{12,13}C(p,\gamma)^{13,14}N$ → $^{12}C/^{13}C$ abundance ratio

From hydrogen to helium and carbon burning: from LUNA to LUNA-MV

- A new 3.5 MV accelerator will be installed in the north part of Hall B at Gran Sasso





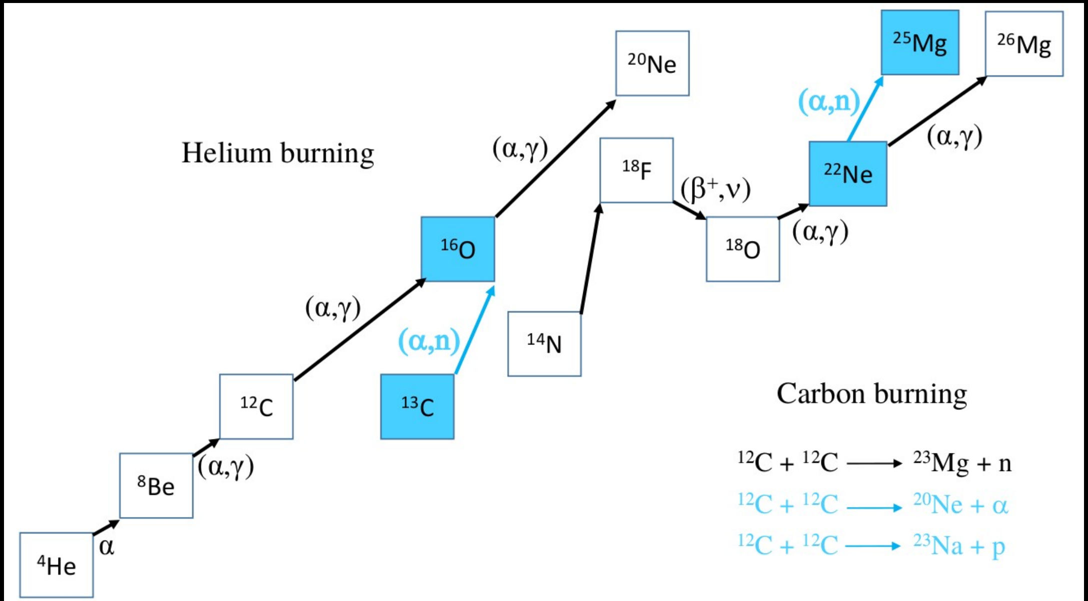
Luna MV

- 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

LUNA MV Helium/Carbon Burning

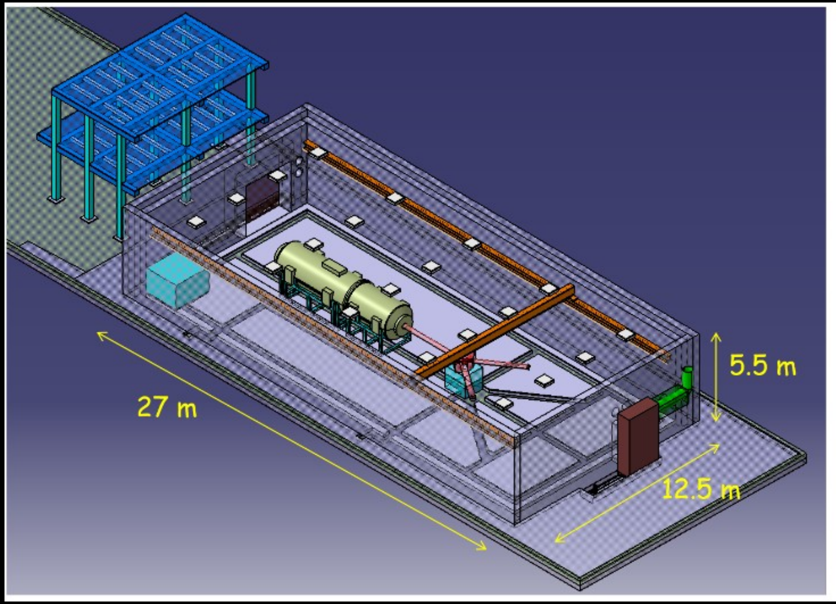
First 5 years proposal

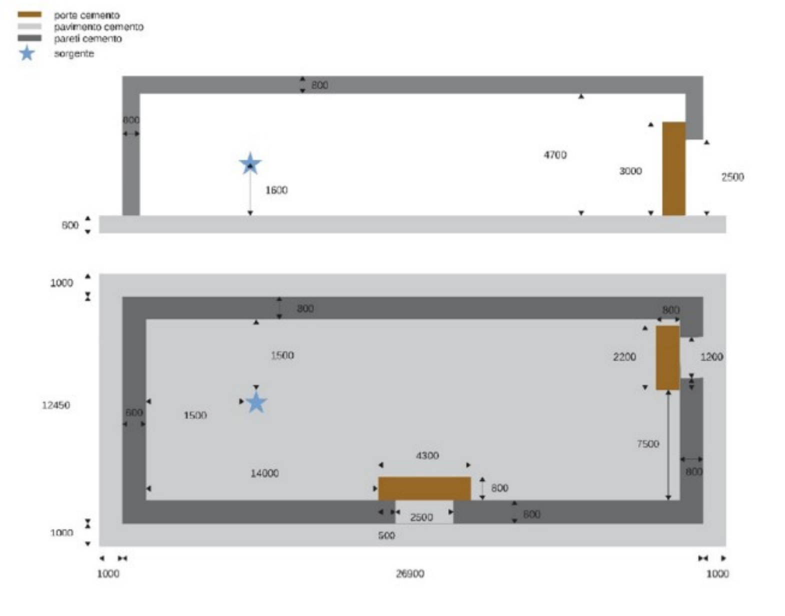
- $^{14}N(p,\gamma)^{15}O$ → test and calibration
- $^{12}C(^{12}C,p)^{23}Na$ → C burning
- $^{12}C(^{12}C,a)^{20}Ne$ → C burning
- $^{13}C(a, n)^{16}O$ → n for s-process in AGB star
- $^{22}Ne(a, n)^{25}Mg$ → n for s-process in AGB star

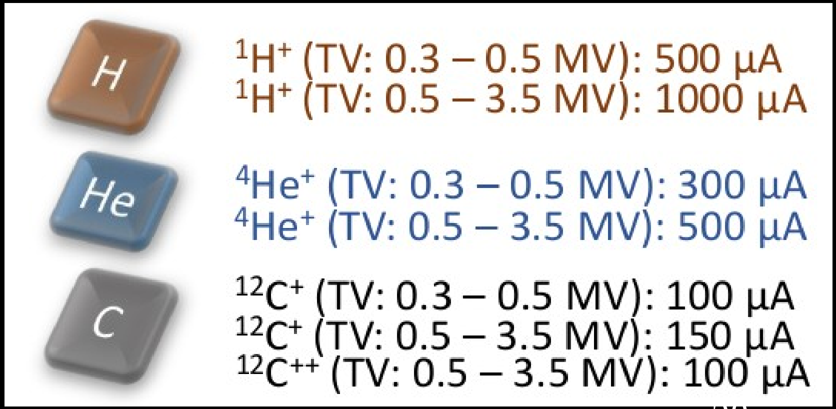


LUNA MV

- For the LUNA-MV project, High Voltage Engineering has developed a 3.5 MV linear single-ended DC accelerator
- The in-line Singletron will provide intense beams of H^+, $^4He^+$, $^{12}C^+$ and $^{12}C^{2+}$
- The accelerator tube with voltage gradient design to allow high current beam transport with minimal transmission losses over the entire terminal voltage range of 300 kV–3.5 MV
- 80 cm thick concrete shielding



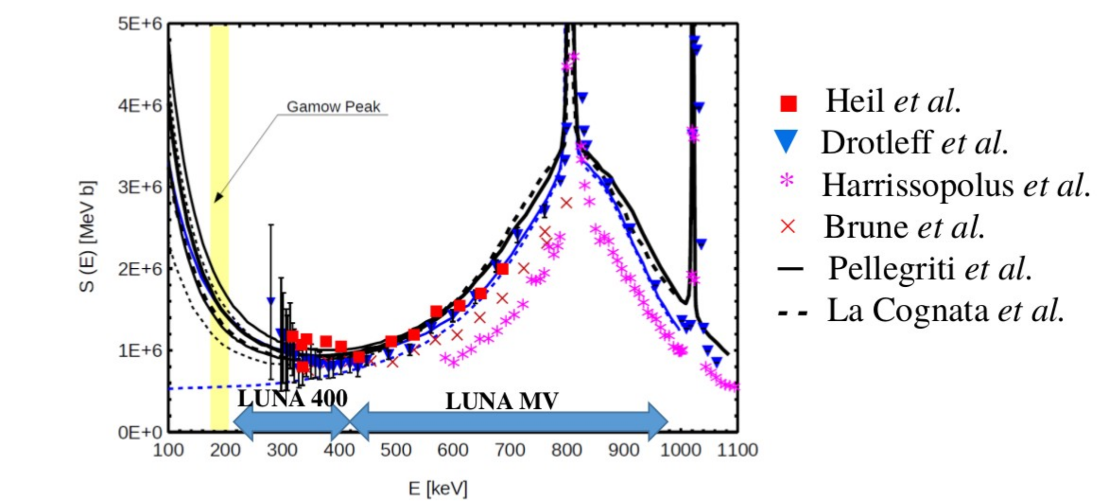


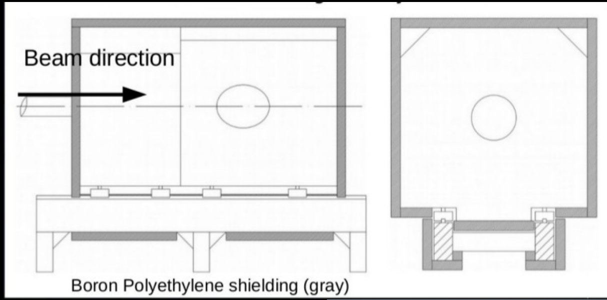


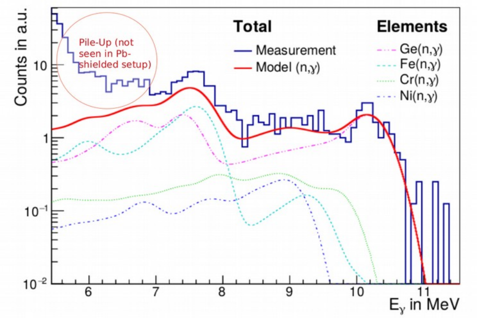
The $^{13}C(\alpha,n)\,^{16}O$ reaction

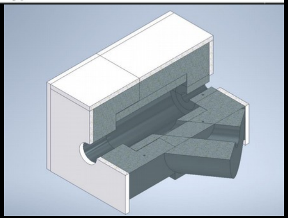
- The $^{13}C(\alpha,n)^{16}O$ reaction (Q = 2.216 MeV)
  - Several direct measurements → the astrophysical S factor as a function of centre of mass energy
  - No data at the energy of astrophysical interest (dark area) severe limitations imposed by the high neutron background in surface laboratories
  - The lowest energy data with uncertainties large to constrain extrapolations of higher energy data to astrophysical energies. Extrapolations differ by a factor ~4 (10% accuracy would be required)
  - Discrepancies exist between different data sets both in energy dependence and absolute values (normalization?)
  - main obstacle: high neutron background

neutrons from cosmic-rays / from (α,n) reactions following the α-decay of long-lived radionuclides (e.g., U and Th) in the material (Al or steel) / from beam-induced reactions on target impurities or along the beam line (e.g., on slits, collimators, etc.)

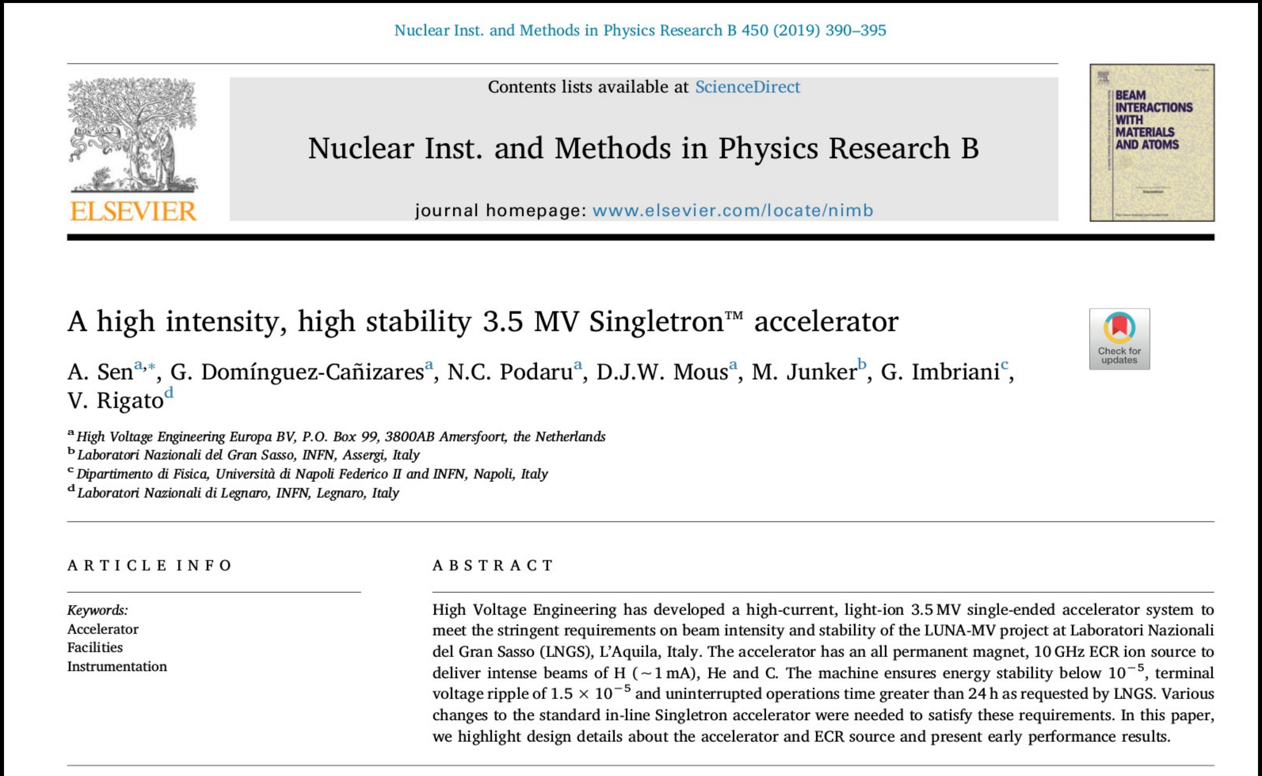








LUNA MV



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BEAM INTERACTIONS WITH MATERIALS AND ATOMS

A high intensity, high stability 3.5 MV Singletron™ accelerator

Check for updates

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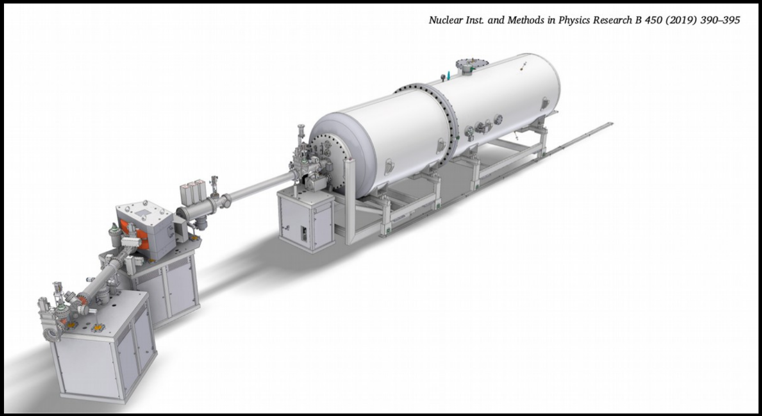
ABSTRACT

High Voltage Engineering has developed a high-current, light-ion 3.5 MV single-ended accelerator system to meet the stringent requirements on beam intensity and stability of the LUNA-MV project at Laboratori Nazionali del Gran Sasso (LNGS), L'Aquila, Italy. The accelerator has an all permanent magnet, 10 GHz ECR ion source to deliver intense beams of H ($\sim$1 mA), He and C. The machine ensures energy stability below 10^{-5}, terminal voltage ripple of 1.5×10^{-5} and uninterrupted operations time greater than 24 h as requested by LNGS. Various changes to the standard in-line Singletron accelerator were needed to satisfy these requirements. In this paper, we highlight design details about the accelerator and ECR source and present early performance results.



The $^{13}C(\alpha,n)\,^{16}O$ reaction at LUNA 400

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THE EUROPEAN PHYSICAL JOURNAL A

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Special Article - New Tools and Techniques

A new approach to monitor ^{13}C-targets degradation in situ for $^{13}C(\alpha, n)^{16}O$ cross-section measurements at LUNA

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Conclusions

- The extremely low laboratory background of LNGS has allowed the realization of nuclear physics experiments with very small count rates, down to a couple of events per month

- Several hydrogen burning and BBN fusion reactions have been studied in the last 25 years

- Recent results have been presented

- A new phase devoted to hydrogen burning @ LUNA 400 is starting and helium and carbon burning will start @ LUNA-MV

Conclusions

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Physics Letters B

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Direct measurements of low-energy resonance strengths of the ^{23}Na(p,γ)^{24}Mg reaction for astrophysics

A. Boeltzig[a,b,c,d,*], A. Best[e,f], F.R. Pantaleo[g,h], G. Imbriani[e,f], M. Junker[d,a], M. Aliotta[i], J. Balibrea-Correa[e,f], D. Bemmerer[j], C. Broggini[l], C.G. Bruno[i], R. Buompane[f,k], A. Caciolli[m,l], F. Cavanna[n], T. Chillery[i], G.F. Ciani[a,d], P. Corvisiero[o,n], L. Csedreki[d,a], T. Davinson[i], R.J. deBoer[b,c], R. Depalo[m,l], A. Di Leva[e,f], Z. Elekes[p], F. Ferraro[o,n], E.M. Fiore[g,h], A. Formicola[d], Zs. Fülöp[p], G. Gervino[q,r], A. Guglielmetti[s,t], C. Gustavino[u], Gy. Gyürky[p], I. Kochanek[d], M. Lugaro[v], P. Marigo[l,m], R. Menegazzo[l], V. Mossa[g,h], F. Munnik[j], V. Paticchio[h], R. Perrino[h,1], D. Piatti[m,l], P. Prati[o,n], L. Schiavulli[g,h], K. Stöckel[j,w], O. Straniero[x,d], F. Strieder[y], T. Szücs[j], M.P. Takács[j,w,2], D. Trezzi[s,t], M. Wiescher[b,c], S. Zavatarelli[n]

Physics Letters B 790 (2019) 237–242

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Physics Letters B

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Improved astrophysical rate for the ^{18}O(p,α)^{15}N reaction by underground measurements

C.G. Bruno[a,*], M. Aliotta[a,*], P. Descouvemont[b], A. Best[c], T. Davinson[a], D. Bemmerer[d], A. Boeltzig[e,f,1], C. Broggini[g], A. Caciolli[h], F. Cavanna[i], T. Chillery[a], G.F. Ciani[e], P. Corvisiero[i,j], R. Depalo[h], A. Di Leva[c], Z. Elekes[k], F. Ferraro[i,j], A. Formicola[f], Zs. Fülöp[k], G. Gervino[l], A. Guglielmetti[m], C. Gustavino[n], Gy. Gyürky[k], G. Imbriani[c], M. Junker[f], M. Lugaro[o], P. Marigo[g,h], R. Menegazzo[h], V. Mossa[p], F.R. Pantaleo[p], D. Piatti[h], P. Prati[i,j], K. Stöckel[d,q], O. Straniero[f,r], F. Strieder[s], T. Szücs[d,k], M.P. Takács[d,q], D. Trezzi[m]

Physics Letters B 797 (2019) 134900

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Physics Letters B

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Cross section of the reaction ^{18}O(p, γ)^{19}F at astrophysical energies: The 90 keV resonance and the direct capture component

A. Best[d,e,*], F.R. Pantaleo[f,g], A. Boeltzig[a,b,c,1], G. Imbriani[d,e], M. Aliotta[h], J. Balibrea-Correa[d,e], D. Bemmerer[i], C. Broggini[k], C.G. Bruno[h], R. Buompane[e,j], A. Caciolli[l,k], F. Cavanna[m], T. Chillery[h], G.F. Ciani[a,c], P. Corvisiero[n,m], L. Csedreki[c,a], T. Davinson[h], R.J. deBoer[b], R. Depalo[l,k], A. Di Leva[d,e], Z. Elekes[o], F. Ferraro[n,m], E.M. Fiore[f,g], A. Formicola[c], Zs. Fülöp[o], G. Gervino[p,q], A. Guglielmetti[r,s], C. Gustavino[t], Gy. Gyürky[o], M. Junker[c,a], I. Kochanek[c], M. Lugaro[u], P. Marigo[k,l], R. Menegazzo[k], V. Mossa[f,g], V. Paticchio[g], R. Perrino[g,1], D. Piatti[l,k], P. Prati[n,m], L. Schiavulli[f,g], K. Stöckel[i,v], O. Straniero[w,c], F. Strieder[x], T. Szücs[i], M.P. Takács[i,v,2], D. Trezzi[r,s], M. Wiescher[b], S. Zavatarelli[m]

THE LUNA COLLABORATION

LUNA

http://luna.lngs.infn.it

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- D. Bemmerer, K. Stoeckel, M. Takacs | HZDR, Germany
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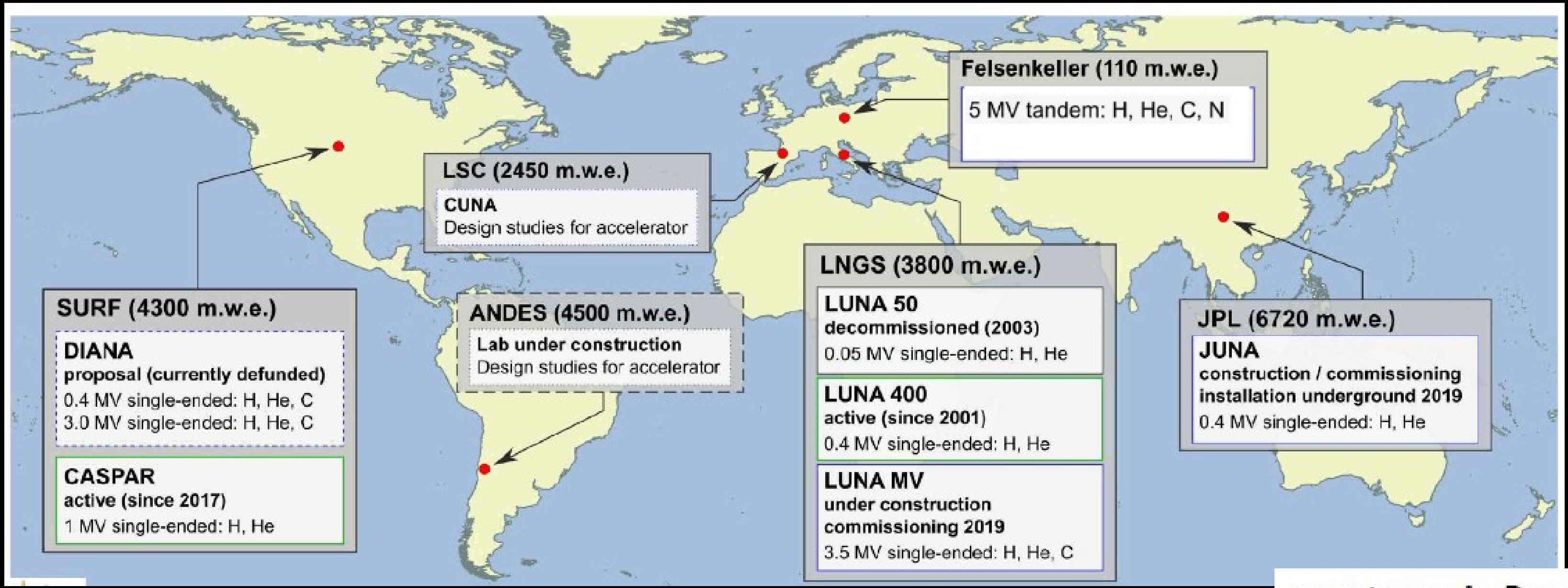
- G. Gervino | Università di Torino and INFN Torino, Italy
- C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy

Several facilities and experimental projects in the incoming years



courtesy: A. Boeltzig

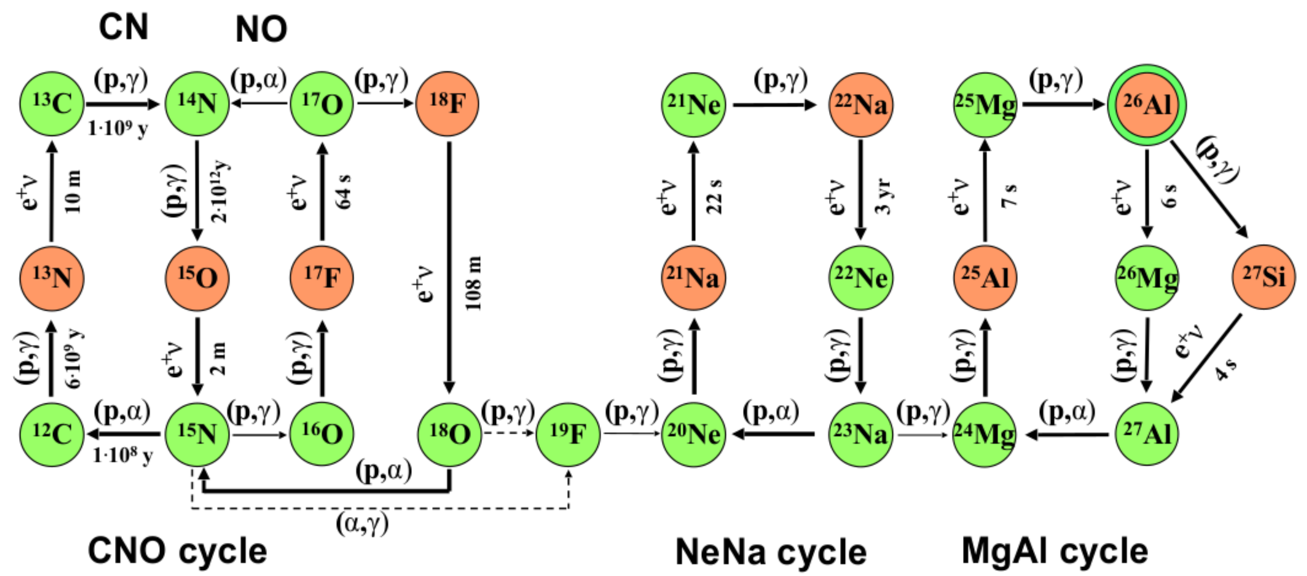
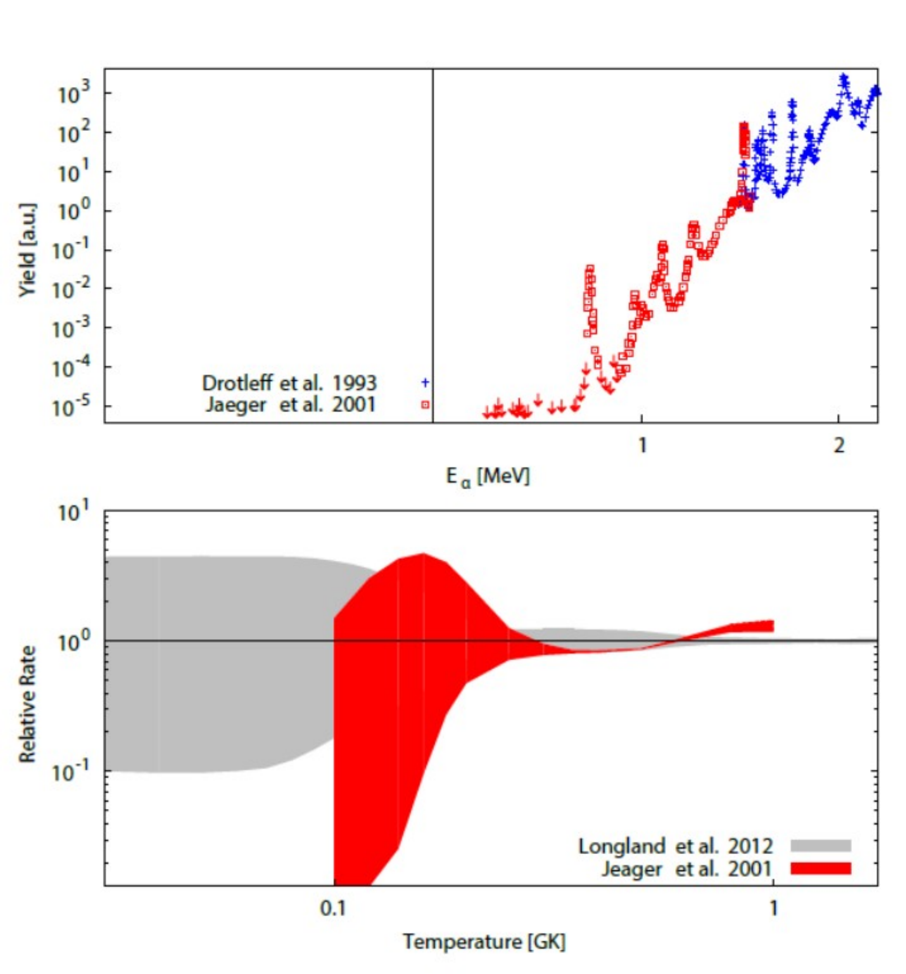


Figure 1: Reaction network of CNO, NeNa, and MgAl cycles. Stable and long lived radioactive nuclei are shown in green, while short lived are shown in orange. The ground state of ^{26}Al is long lived, while its metastable state decays directly to ^{26}Mg with a short half life, see text for details. Characteristic time scales and lifetimes are indicated for some of the processes.

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

- The lowest well studied resonance at 832 keV dominates the rate (Drotleff et al. 1993)
- Only upper limits (~10 pb) at: 570 keV < E a < 800 keV (energy region of interest for AGB stars). Extrapolations may be affected by unknown resonances
- Proposed measurement LUNA MV: 470 keV < E_{cm}(KeV) < 800 keV
- How: use of an intense $^{4}He^{+}$ beam impinging on a windowless gas target of 99.9% enriched ^{22}Ne (p ~ 0.1 to 5 mbar) surrounded by a 4π neutron detector + recirculation system – Same neutron detector as for $^{13}C(\alpha,n)^{16}O$



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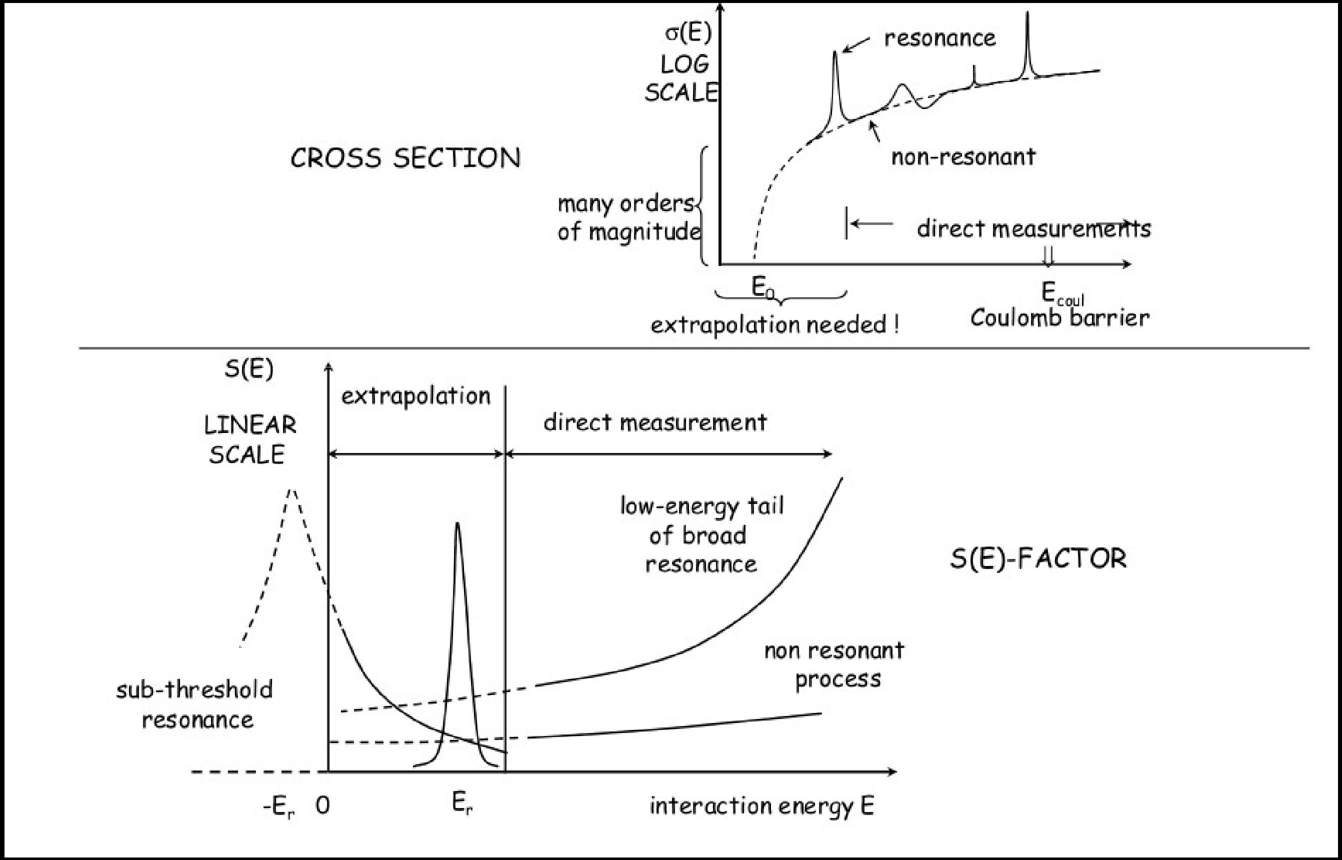
σ(E)
LOG
SCALE
resonance
CROSS SECTION
non-resonant
many orders
of magnitude
direct measurements
E0
Ecoul
extrapolation needed !
Coulomb barrier
S(E)
LINEAR
SCALE
extrapolation
direct measurement
low-energy tail
of broad
resonance
S(E)-FACTOR
non resonant
process
sub-threshold
resonance
-Er
0
Er
interaction energy E

Table 1 Contributions to the overall systematic uncertainty in the in the $D(p,\gamma)^3He$ S factor arising from different sources. Values shown refer to a representative energy $E_p = 200$ keV ($E_{cm} = 133$ keV)

Source	Method	ΔS/S (%)
Beam energy	Direct measurement	0.2
Energy loss	Low gas pressure	0.04
T and P profiles	Direct measurement	1.0
Beam heating	Direct measurement	0.5
Gas purity	Data sheet	0.1
Beam current	Calorimeter calibration	1.0
Efficiency	Direct measurement	2.0
Instrumental effects	Pulser method	0.2
Angular distribution	Simulations	0.5
Total		2.6

Eur. Phys. J. A (2020) 56:144

[1] The astrophysical $S(E)$ factor is defined as [6]: $S(E) = E\sigma(E)\exp(2\pi\eta)$, where E is the energy of interaction in the centre of mass system, $\sigma(E)$ is the energy dependent cross-section, and η is the Sommerfeld parameter $\eta(E) = Z_1 Z_2 \alpha(\mu c^2/2E)^{1/2}$ (with Z_i atomic numbers of the interacting particles, α fine structure constant, μ reduced mass, and c speed of light).

6. C. Rolfs, W. Rodney, *Cauldrons in the Cosmos* (University of Chicago Press, Chicago, 1988)