Nuclear astrophysics at Gran Sasso Laboratory: the LUNA experiment

15th Varenna Conference on Nuclear Reaction Mechanisms

11-15 June, Villa Monastero Varenna

LUNA
Laboratory for Underground Nuclear Astrophysics

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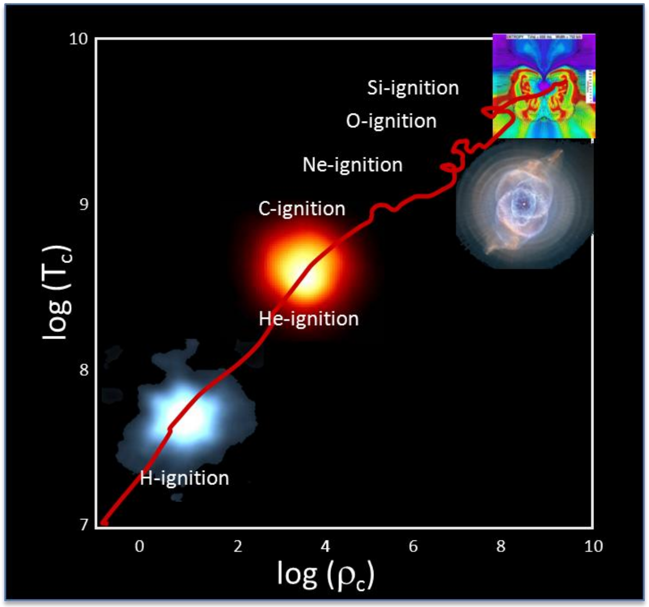
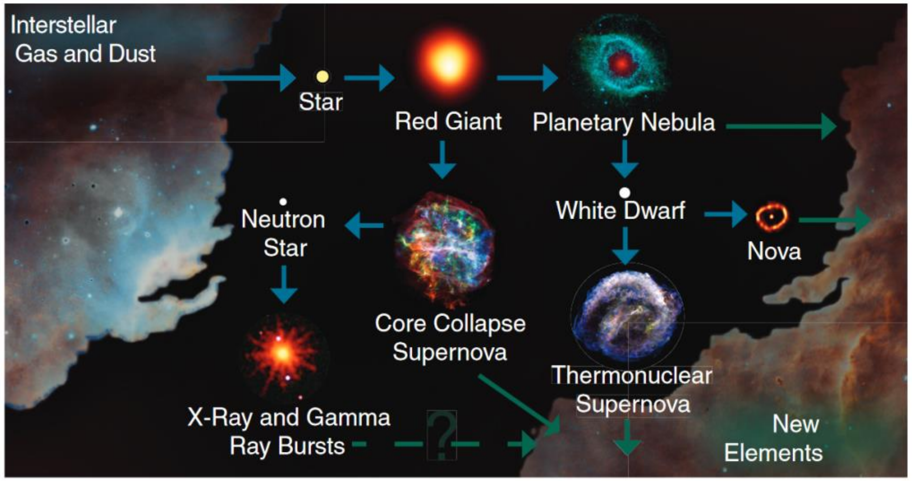
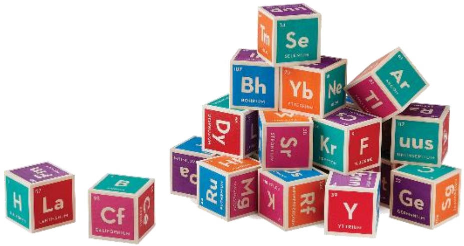
Nuclear astrophysics

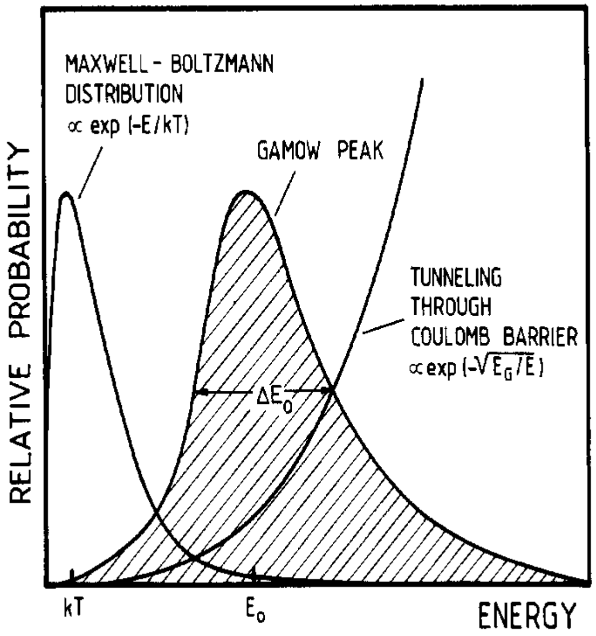
- ✓ Aim of nuclear astrophysics: understand nuclear reactions that shape much of the visible universe
- ✓ Nuclear fusion is the engine of stars: it produces the energy that stabilizes them against gravitational collapse and makes them shine
- ✓ Among the key parameters (chemical composition, opacity, 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

$E_C \approx 0.5\text{-}2$ MeV

$E_0 \approx 5\text{-}30$ keV

for reactions of H burning

kT but also $E_0 \ll E_C$!!

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

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

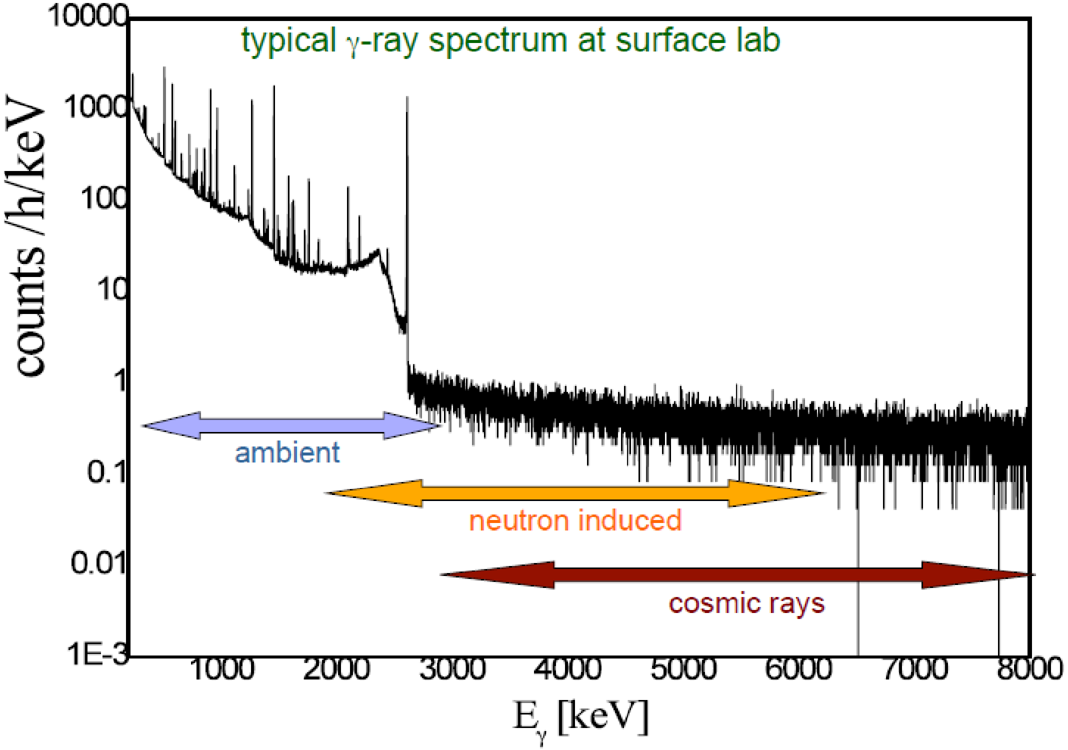
Rate and background

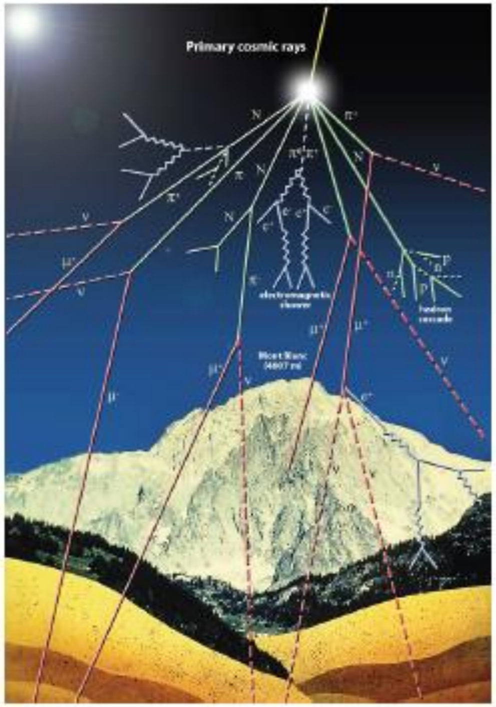
The rate R has to be compared with background B

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

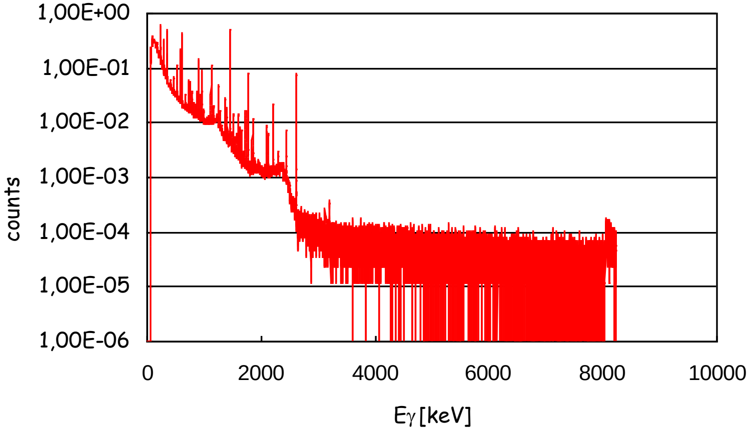
B_{env} : natural radioactivity mainly from U and Th chains

B_{cosmic} : mainly muons

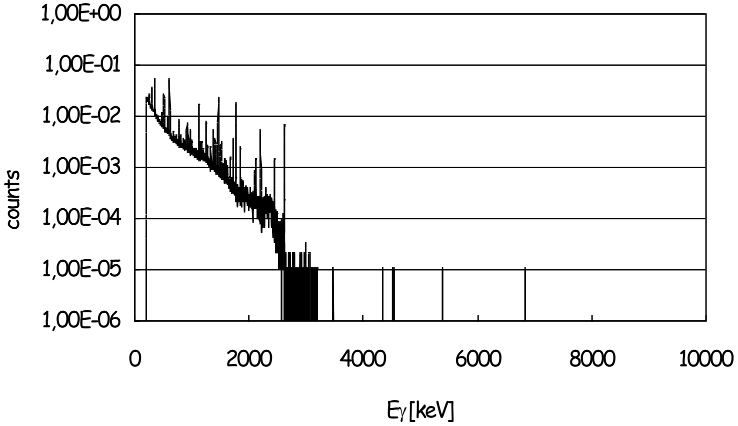




Background reduction – HpGe detectors - gamma



3 MeV < E_γ < 8 MeV
0.5 Counts/s



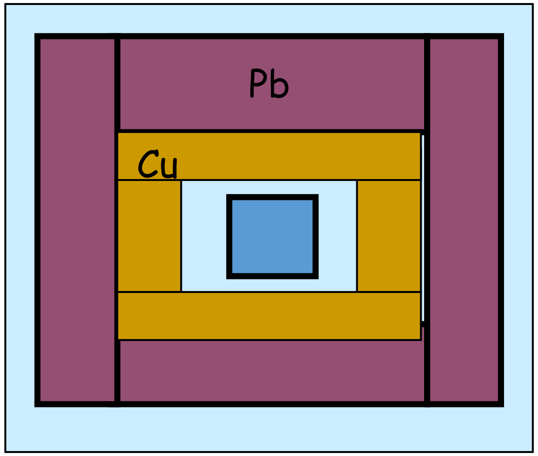
3 MeV < E_γ < 8 MeV
0.0002 Counts/s

E_γ< 3 MeV→passive shielding for environmental bck

Secondary gammas created by μ interactions are reduced

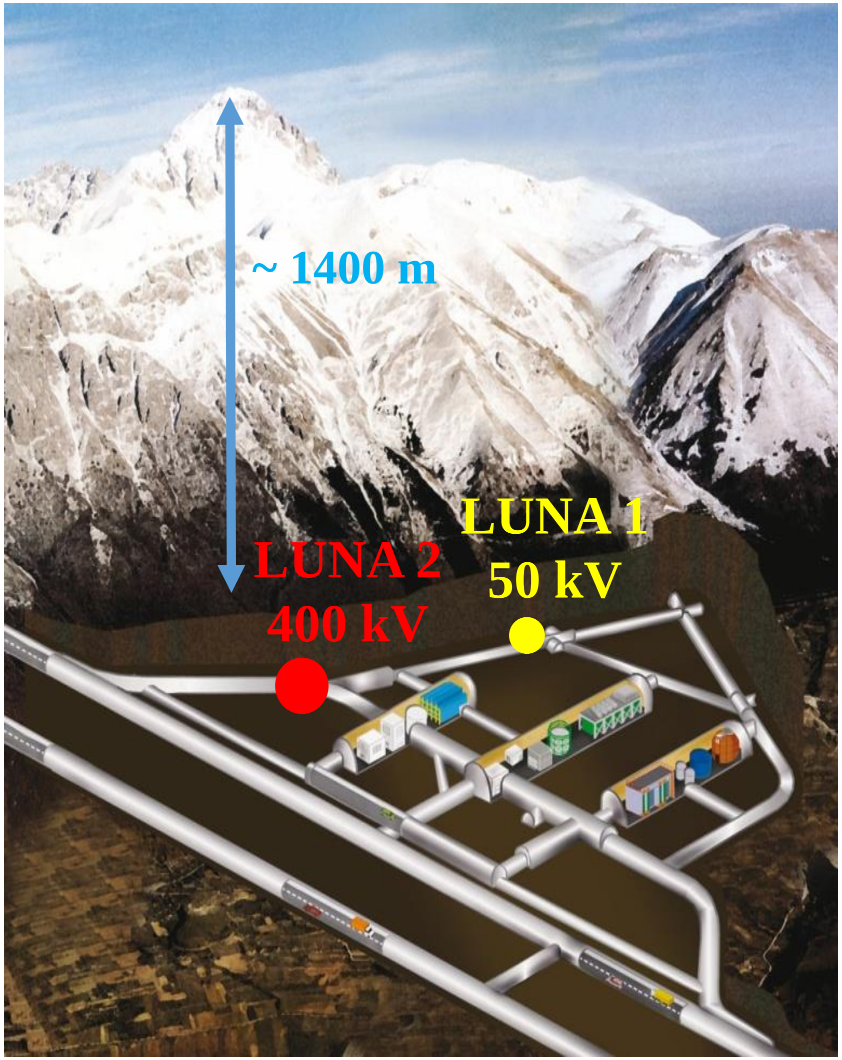
↓

underground passive shielding is more effective!



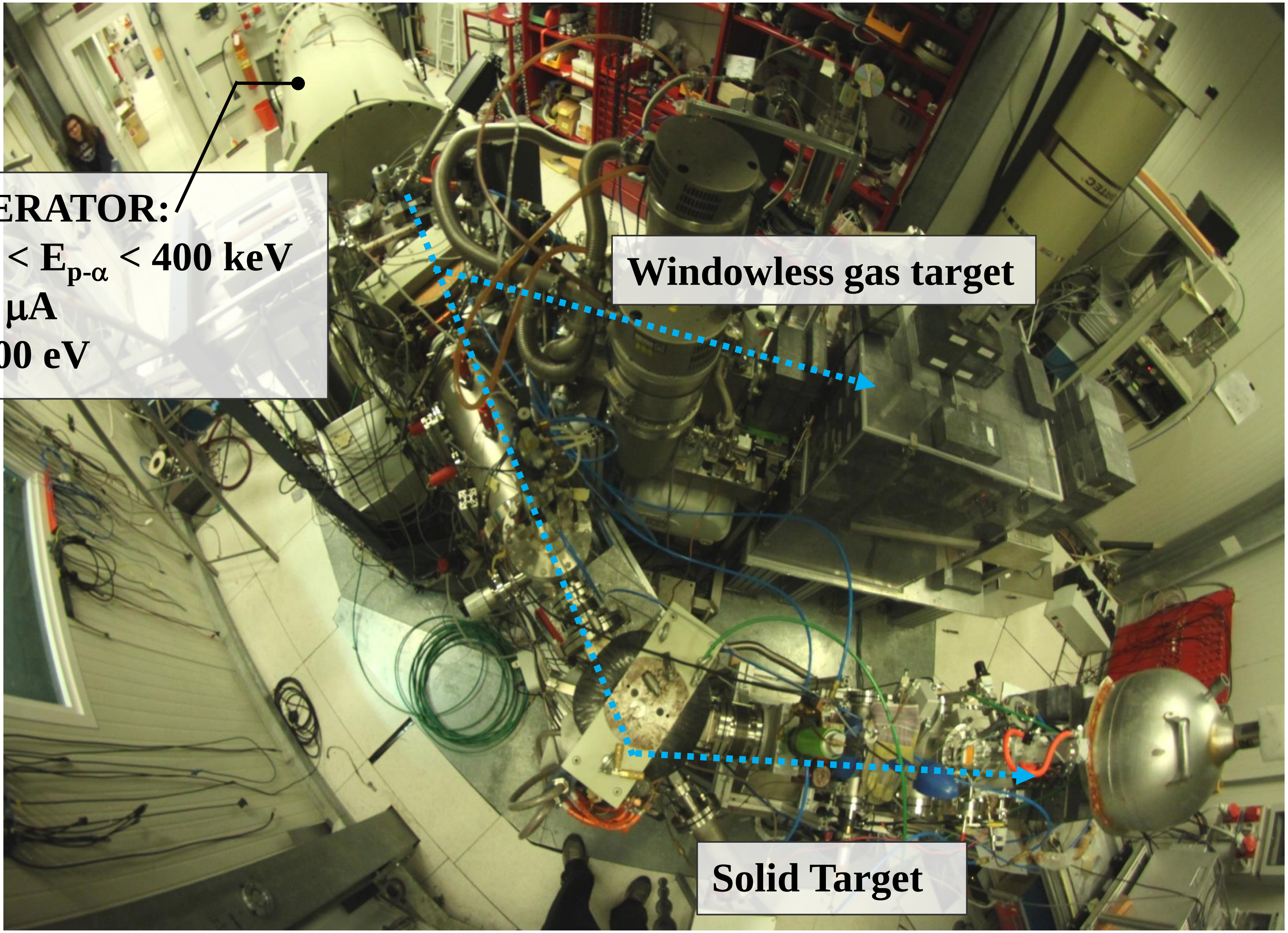
Laboratory for Underground Nuclear Astrophysics

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



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

LUNA experimental setup



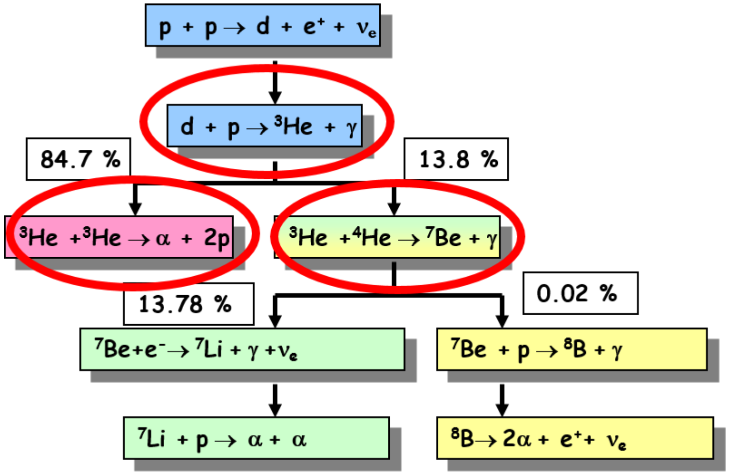
ACCELERATOR:
- **50 keV < $E_{p\text{-}\alpha}$ < 400 keV**
- **I ~ 250 μA**
- **ΔE = 100 eV**

Windowless gas target

Solid Target

Hydrogen burning reactions

pp chain



$p + p \rightarrow d + e^{+} + \nu_e$

$d + p \rightarrow {}^{3}He + \gamma$

84.7 %

13.8 %

${}^{3}He + {}^{3}He \rightarrow \alpha + 2p$

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

13.78 %

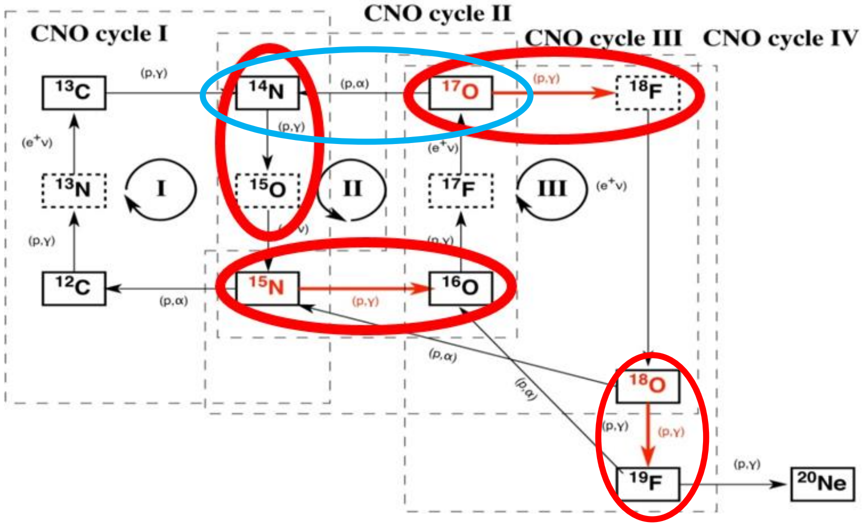
0.02 %

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$

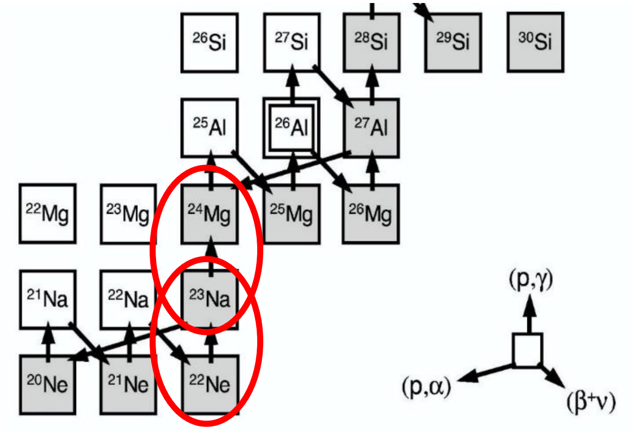
${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Li + p \rightarrow \alpha + \alpha$

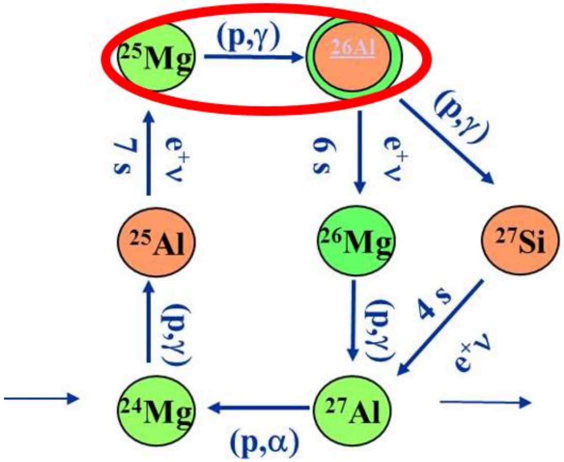
${}^{8}B \rightarrow 2\alpha + e^{+} + \nu_e$



Ne-Na cycle

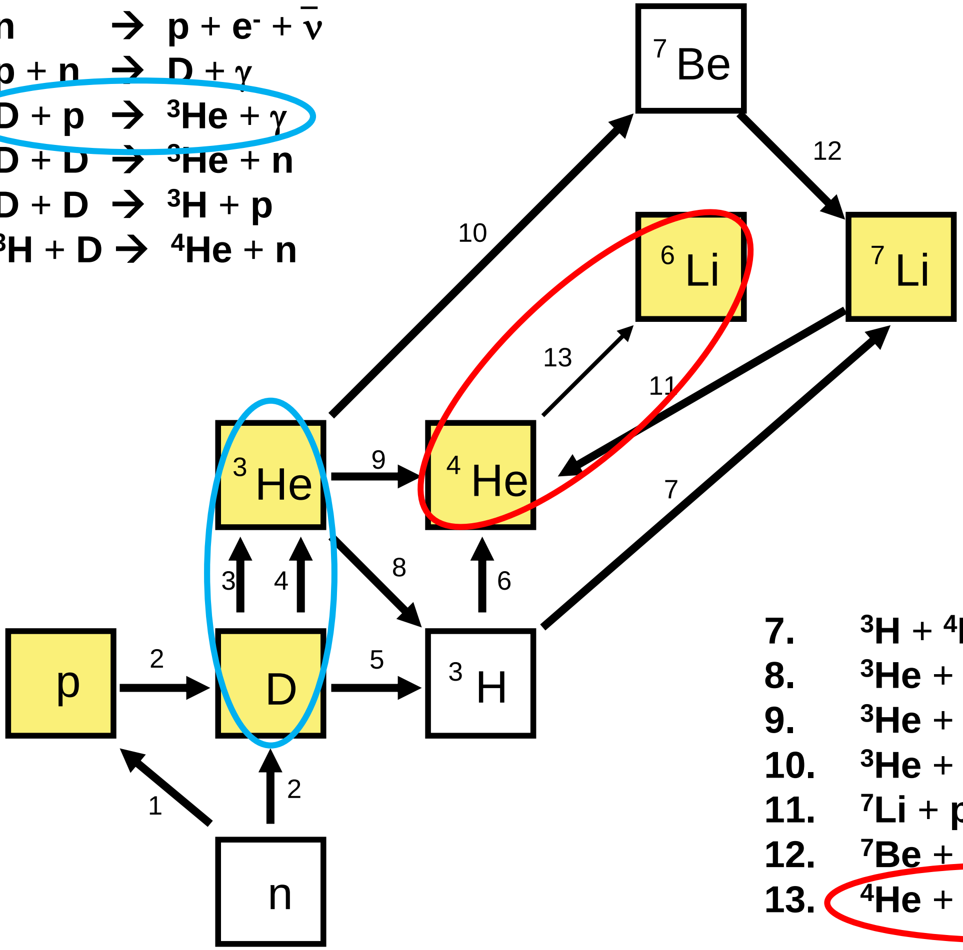


Mg-Al cycle



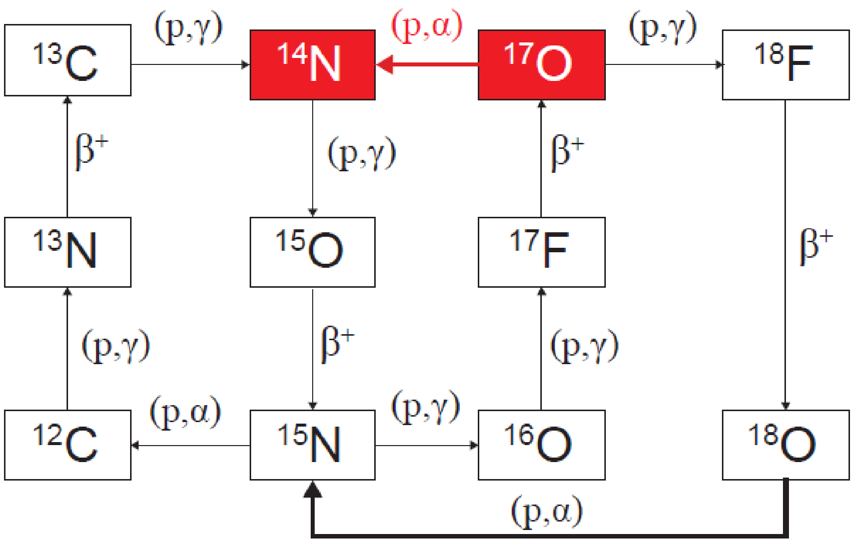
Big bang nucleosynthesis

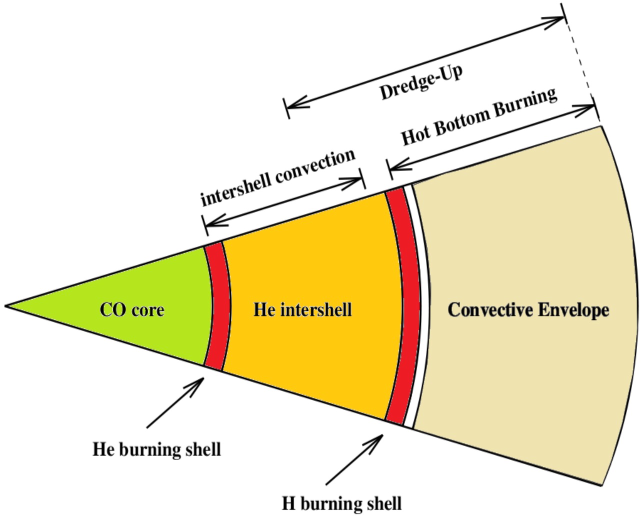
1. n → $p + e^- + \bar{\nu}$
2. p + n → $D + \gamma$
3. D + p → $^3He + \gamma$
4. D + D → $^3He + n$
5. D + D → $^3H + p$
6. $^3H + D$ → $^4He + n$



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

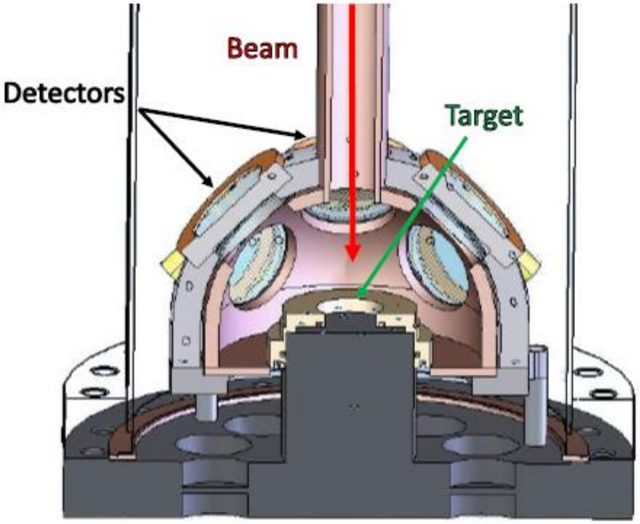
Origin of meteoritic stardust: the ^{17}O(p,α)^{14}N reaction





- ✓ ^{17}O(p,α)^{14}N reaction affects ^{17}O/^{16}O ratio and ^{18}F abundance in several stellar scenarios (AGB, Classical Novae..)
- ✓ Resonance studied at LUNA: E_R = 64.5 keV
- ✓ Intense proton beam on ^{17}O enriched solid target
- ✓ Alpha particles detected with an array of 8 silicon detectors
- ✓ Detected alpha particle energy ~ 250 keV

Origin of meteoritic stardust: the $^{17}O(p,\alpha)^{14}N$ reaction



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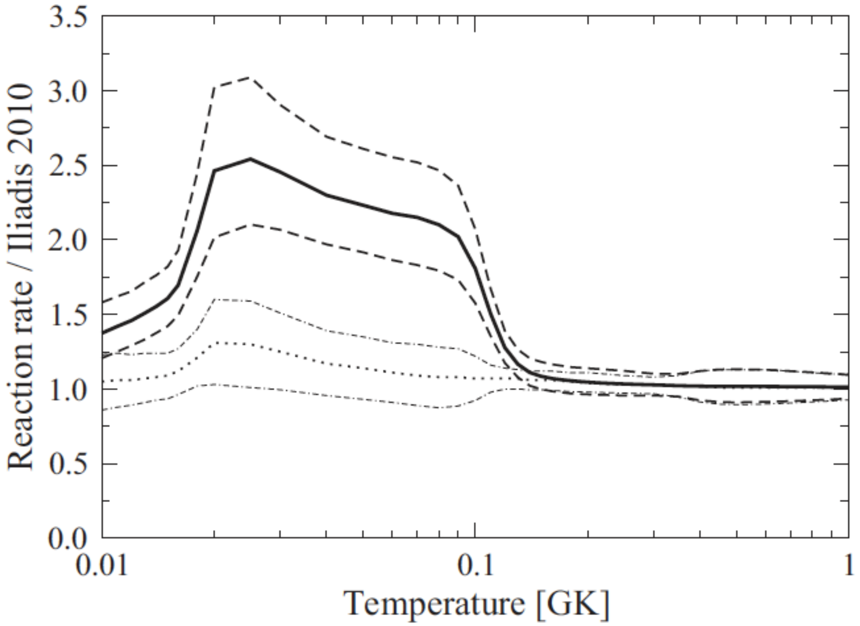
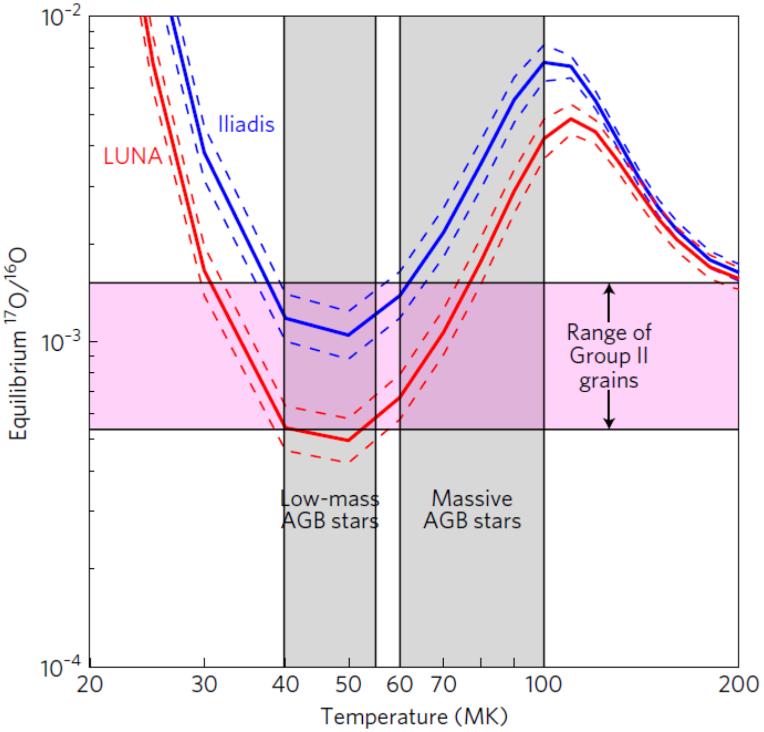


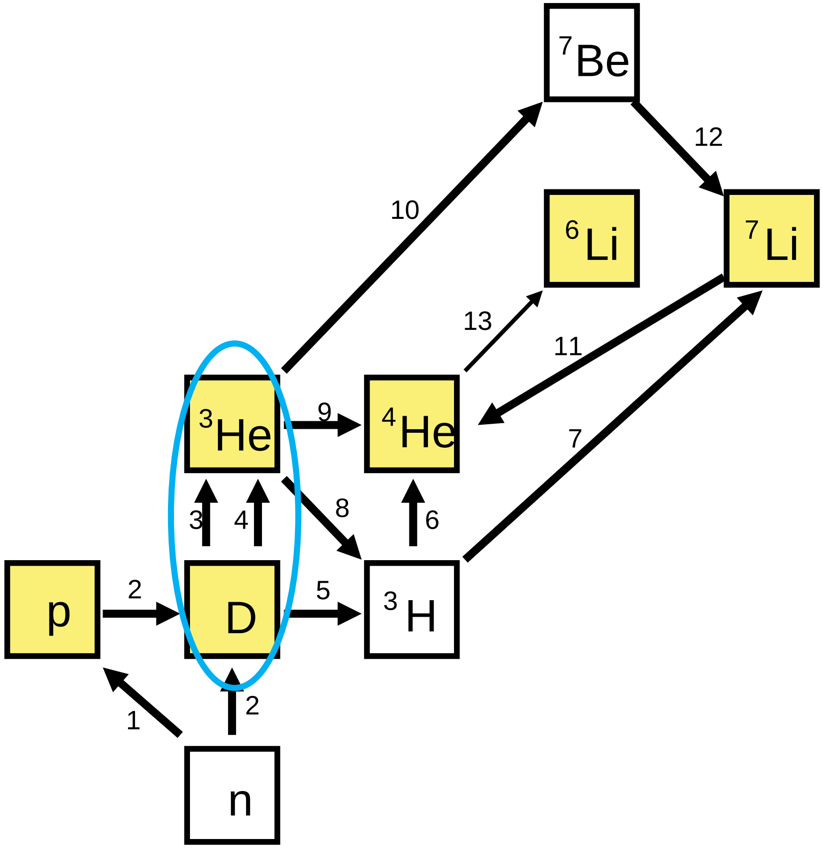


C.G. Bruno et al., **PRL 2016**

M. Lugaro et al., **Nature Astronomy 2017**

- ✓ The reaction rate is a factor 2-2.5 higher than previously thought→ stardust grains recovered from meteorites can now be attributed to massive AGB stars (4-8 M_{Sun}).
- ✓ These stars contributed to the dust inventory from which the Solar System formed!

BBN: A new ^{2}H(p,γ)^{3}He cross section measurement



- ✓ Direct measurements: observation of absorption lines

$$\left[\frac{D}{H}\right]_{OBS} = (2.547 \pm 0.033) \cdot 10^{-5}$$

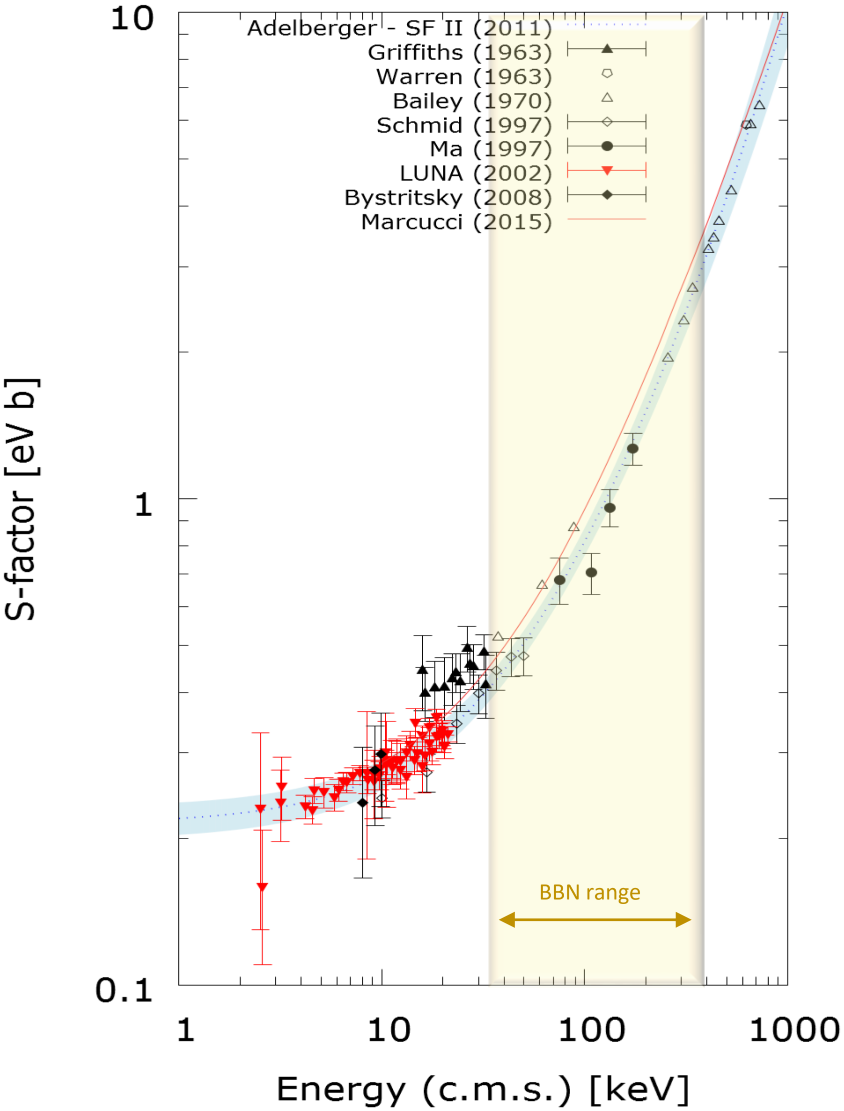
*R. Cooke at al., ApJ. 781 (2016) 31

- ✓ BBN theory: from the cosmological parameters and the cross sections of the processes involved in ^{2}H creation and destruction

$$\left[\frac{D}{H}\right]_{BBN} = (2.65 \pm 0.07) \cdot 10^{-5}$$

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

BBN: A new $^{2}H(p,\gamma)^{3}He$ cross section measurement



✓ The error budget of computed abundance of deuterium is mainly due to the $d(p,\gamma)^{3}He$ reaction

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

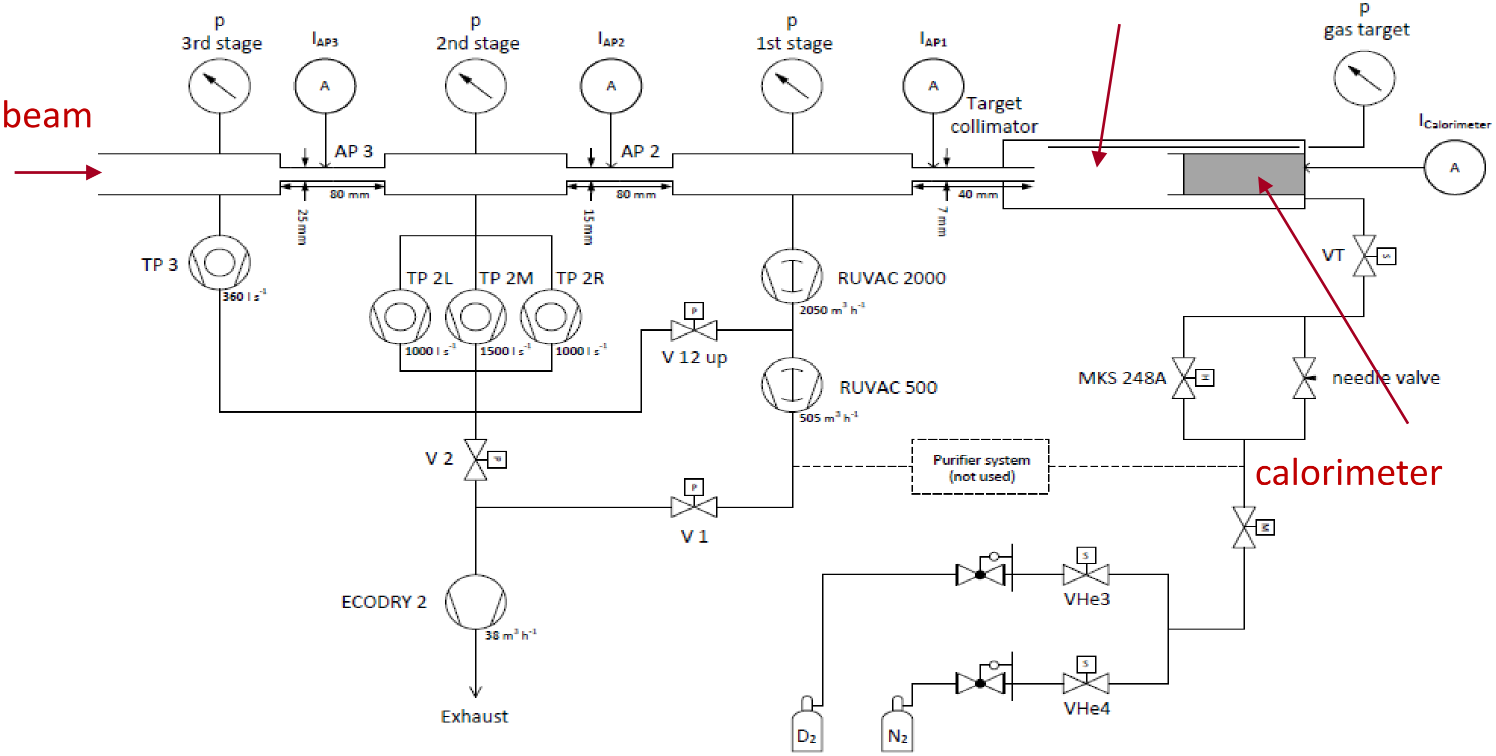
✓ Only a single dataset is currently available at the BBN energy range with a systematic error of 9%

✓ No perfect agreement with recent «Ab-initio» calculations (Marcucci et al. 2016)

Measurement goal:

✓ Cross section measurement at $30keV<E_{cm}<300keV$ with ~5% accuracy

LUNA gas target setup



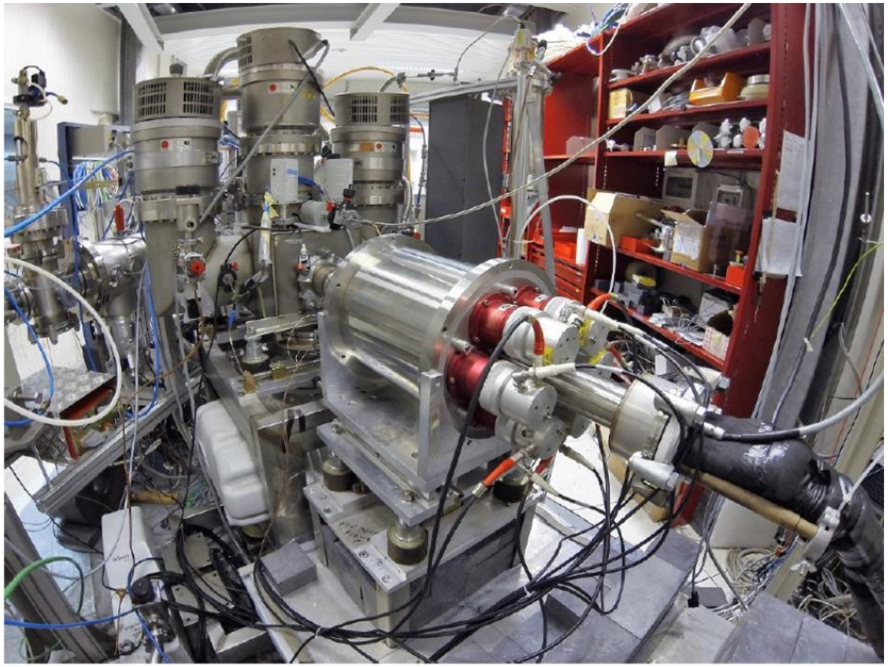
windowless gas target

Proton beam

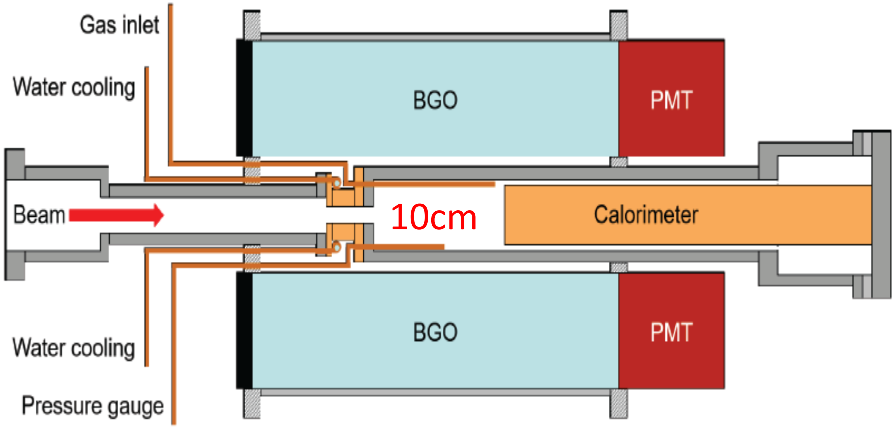
calorimeter

BBN: A new $^{2}H(p,\gamma)^{3}He$ cross section measurement

I phase: the BGO setup

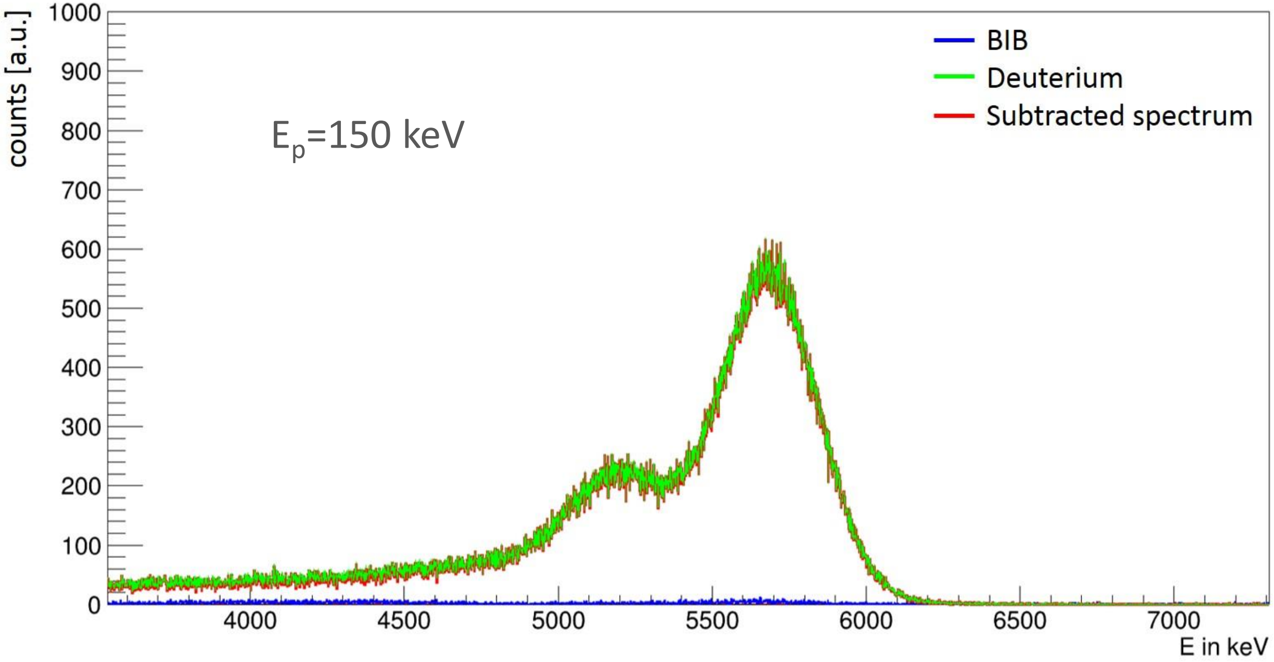


- ✓ $E_{beam} \sim 50 - 300\ keV$
- ✓ Energy resolution in the total absorption peak ~ 8%
- ✓ $\sim 4\pi$ geometry
- ✓ High detection efficiency for 5.5 MeV γ-rays ~ 62%



BGO spectra analysis

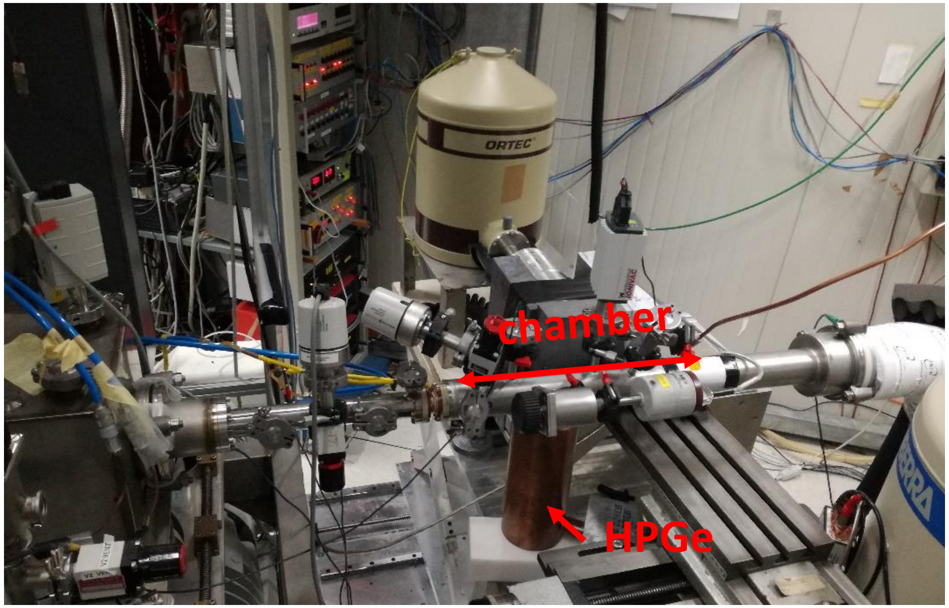
- $^2H(p,\gamma)^3He$ run (50 < E_{beam} < 300 keV)
- Beam induced background run in vacuum at the same proton energy
- Selection of the energy ROI (4000-6500 keV)
- N_γ obtained by integrating each BGO spectrum within the ROI

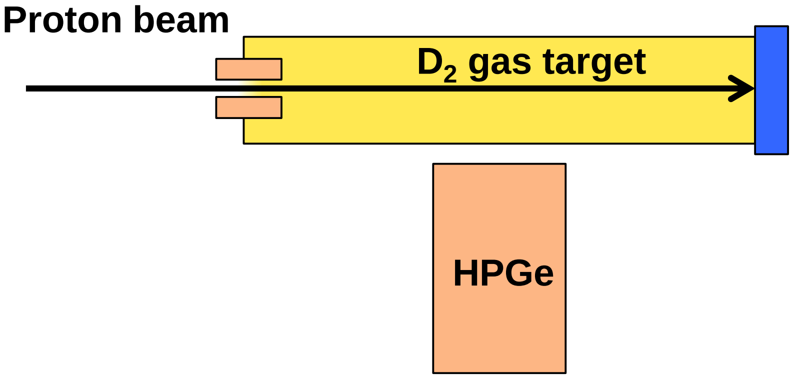


$^{2}H(p,\gamma)^{3}He$: HPGe phase

II phase: the HPGe setup

- ✓ High energy resolution in the total absorption peak < 0.10%
- ✓ Efficiency in the total absorption peak ~ 0.6%
- ✓ Possibility of performing angular distribution measurements with extended gas target (33 cm)

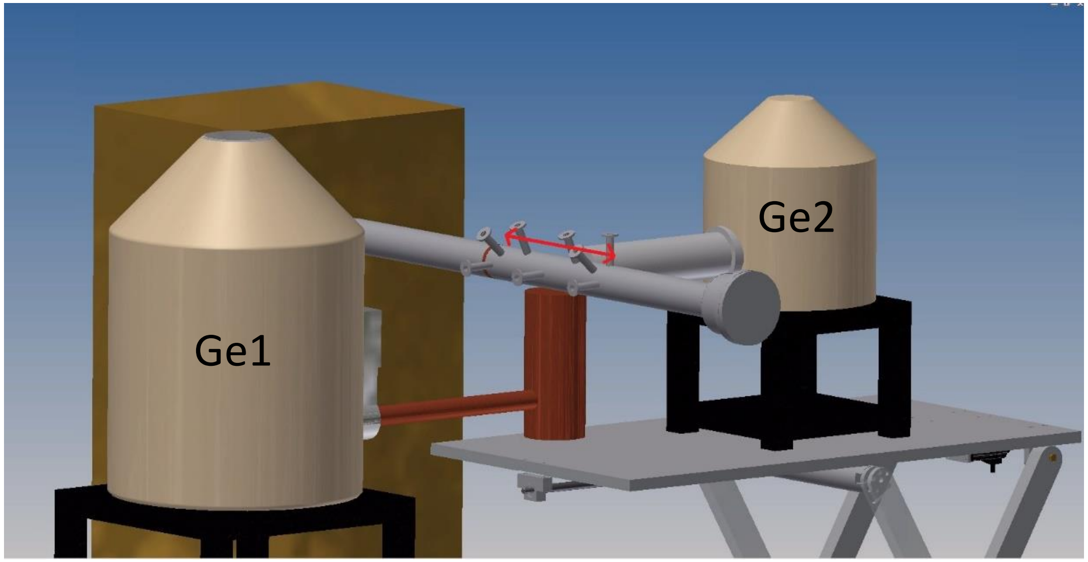




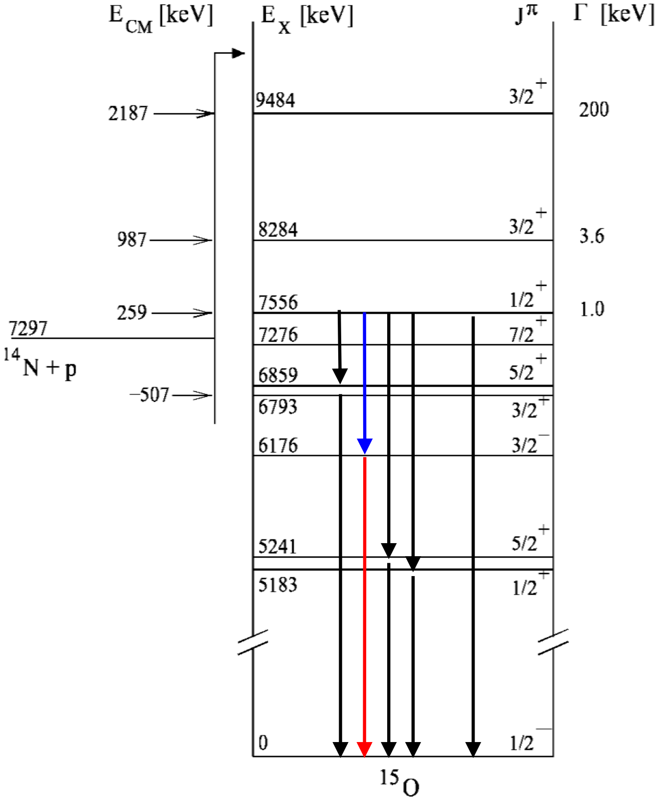
Efficiency calibration

Efficiency calibration → coincidence between two γ rays emitted in cascade (decay γ–γ angular correlation is well known) :

- ✓ Low energies (1172-1333keV): ^{60}Co radioactive source
- ✓ High energies (1384-6172) keV : ^{14}N(p,γ)^{15}O on the E_R=259 keV resonance



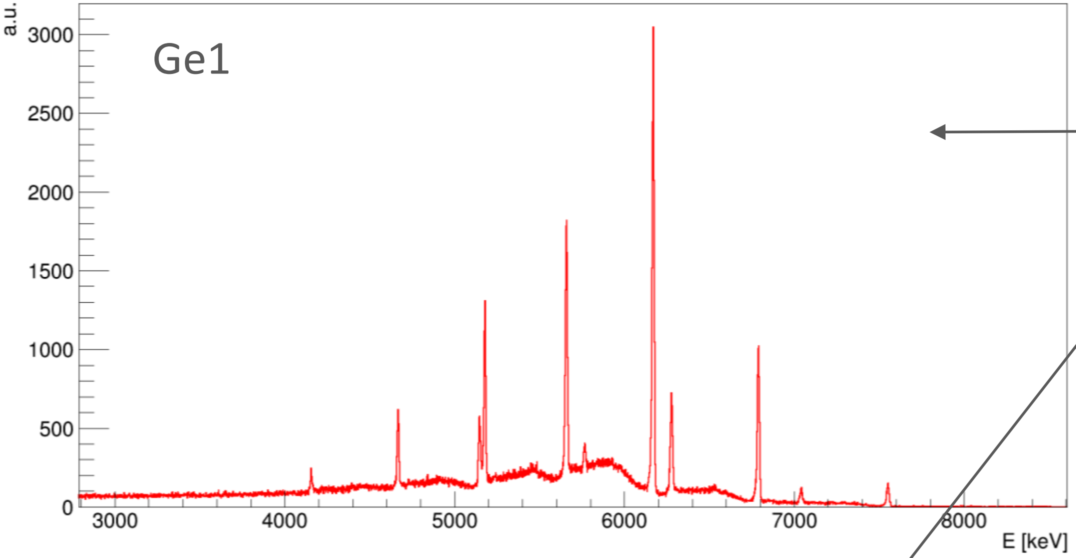
$$\varepsilon(6{,}1\ MeV) = \frac{N_{Ge1}}{N_{Ge2}}$$

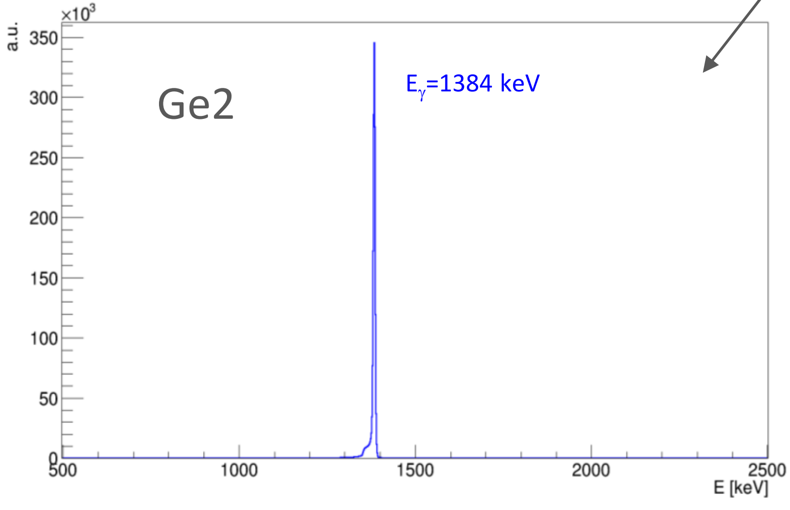


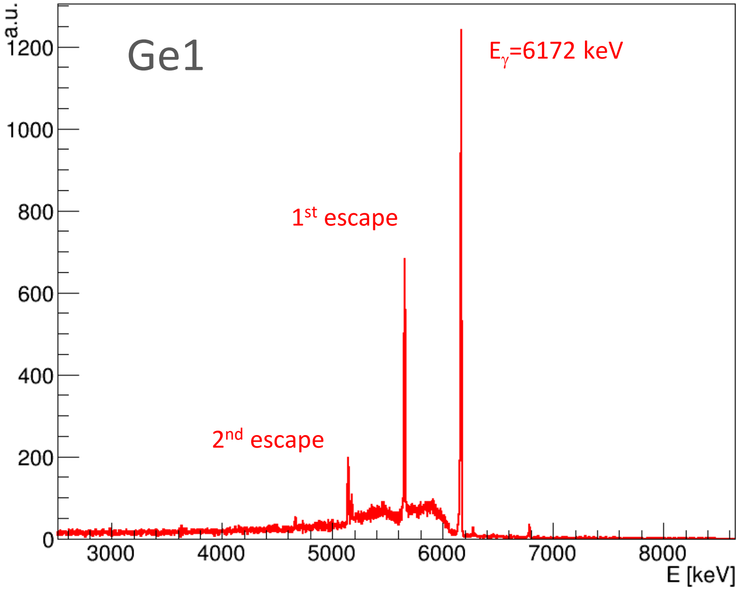
E_γ (keV)	Branching (%)
5181 + 2375	16.9 ± 0.4
5240 + 2315	0.22 ± 0.07
6172 + 1384	58.3 ± 0.3
6791 + 764	23.0 ± 0.3
7556 + 0	1.50 ± 0.03

Efficiency evaluation above 1333 keV

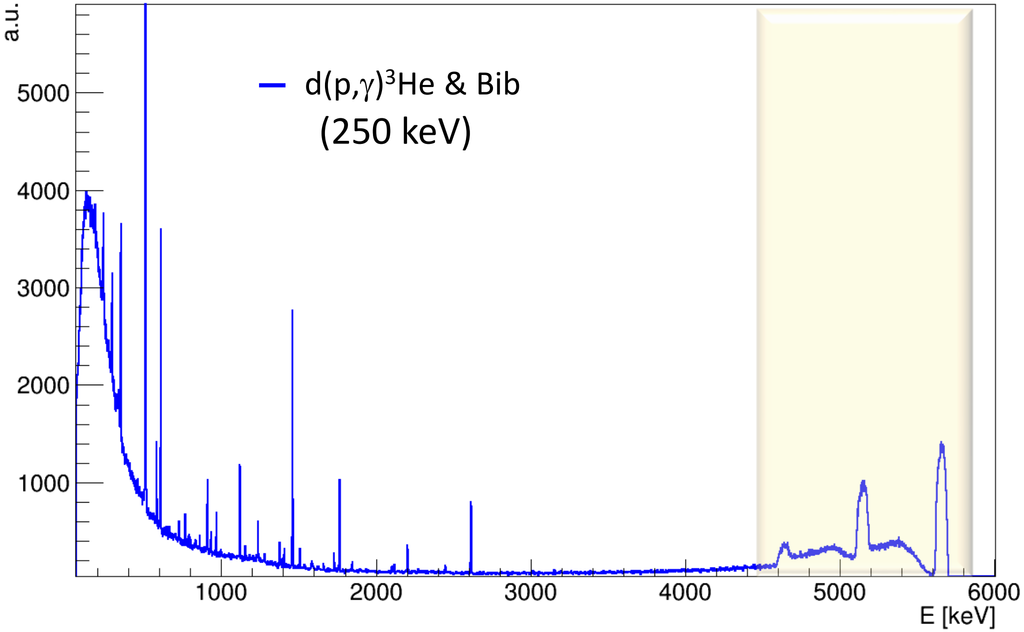
- Ge1 $^{14}N(p,\gamma)^{15}O$ inclusive spectrum
- Ge1 and Ge2 coincidence spectra



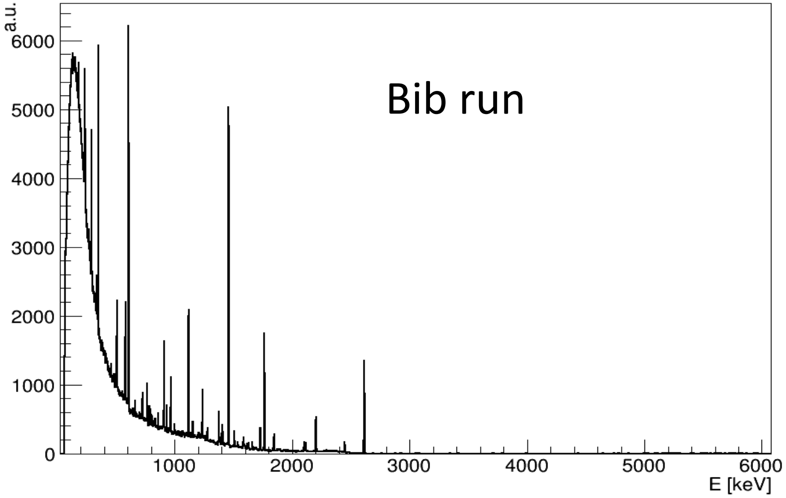




BBN: A new $^{2}H(p,\gamma)^{3}He$ cross section measurement

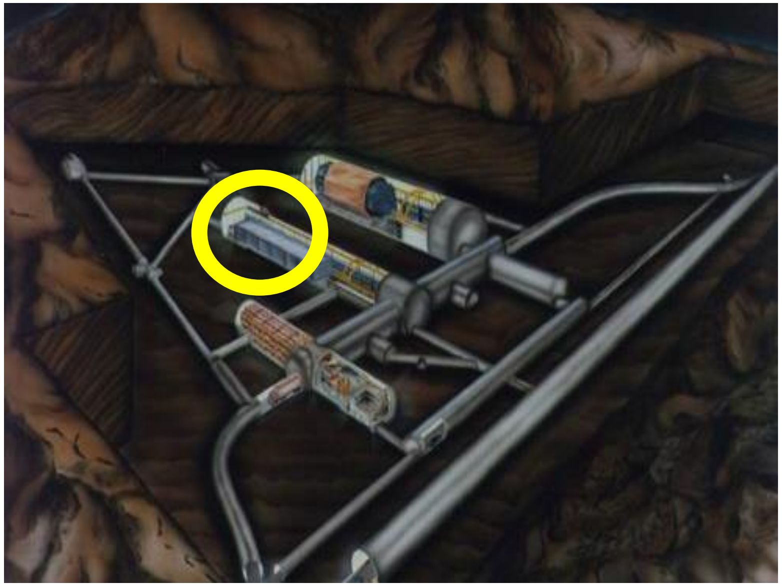


- ✓ $d(p,\gamma)^{3}He$ run at 0.3 mbar of pressure inside the chamber
- ✓ Beam induced background run in ^{4}He

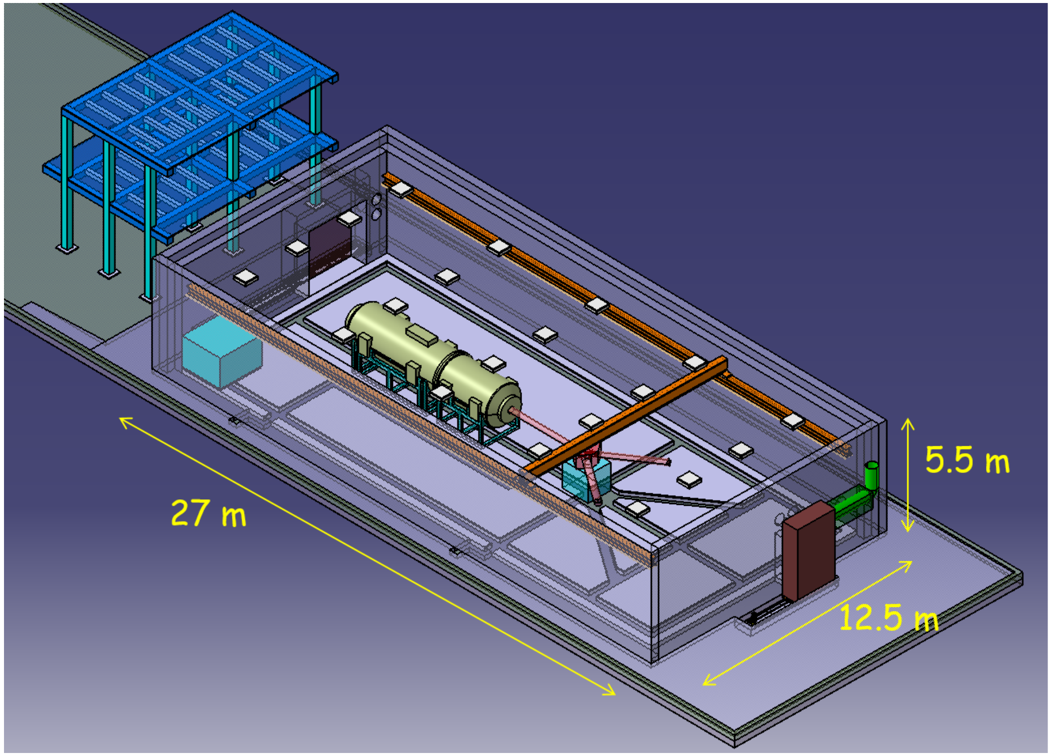


From hydrogen to helium and carbon burning or … from LUNA to LUNA-MV

A new 3.5 MV accelerator will be installed soon in the north part of Hall B at Gran Sasso which is now being cleared



The LUNA-MV accellerator



- 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
- No perturbation of the LNGS natural neutron flux

H

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

He

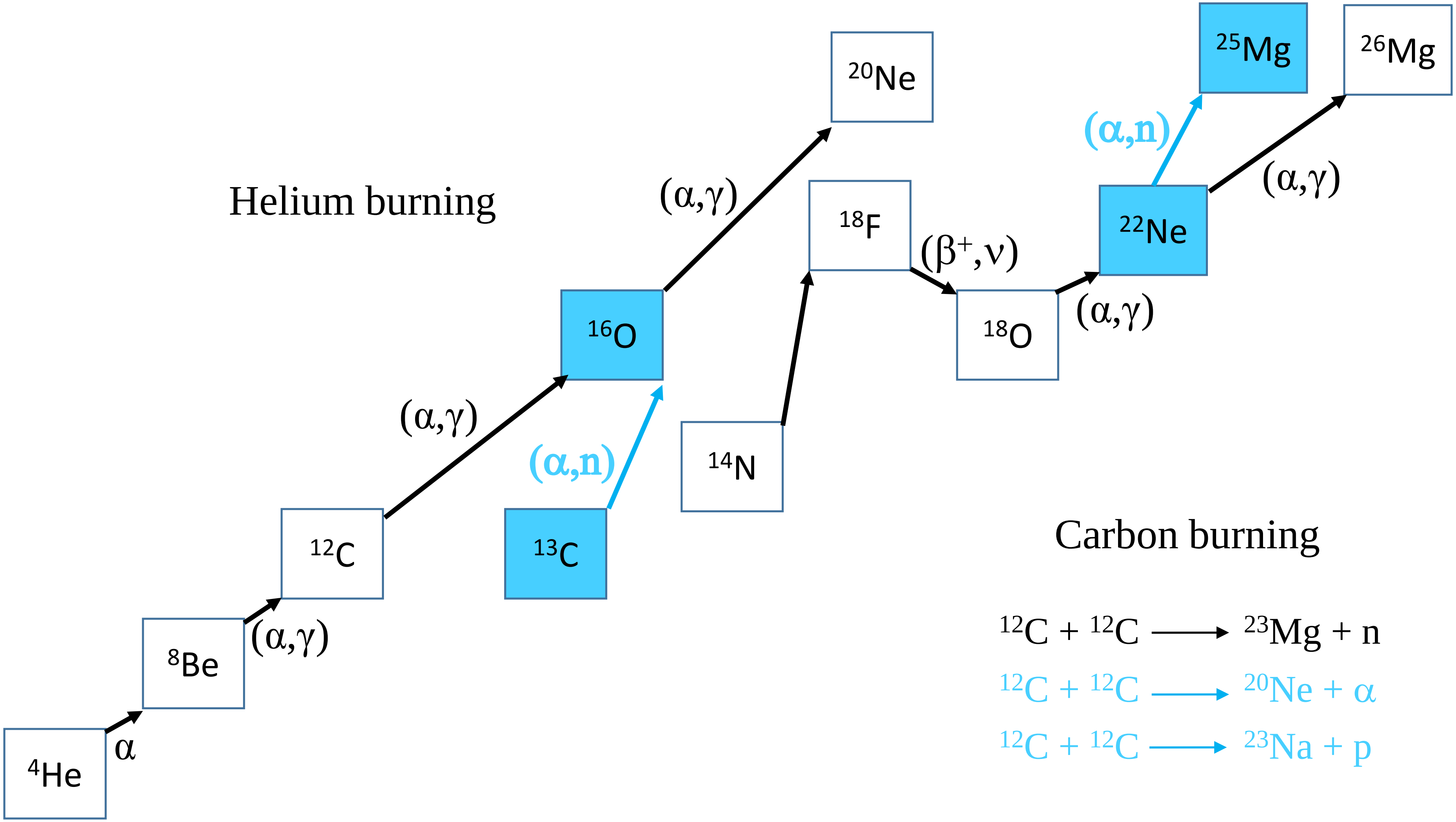
$^{4}\mathrm{He}^{+}$ (TV: 0.3 – 0.5 MV): 300 μA
$^{4}\mathrm{He}^{+}$ (TV: 0.5 – 3.5 MV): 500 μA

C

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

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



Carbon burning

$^{12}C + ^{12}C \longrightarrow ^{23}Mg + n$

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

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

Helium and Carbon burning

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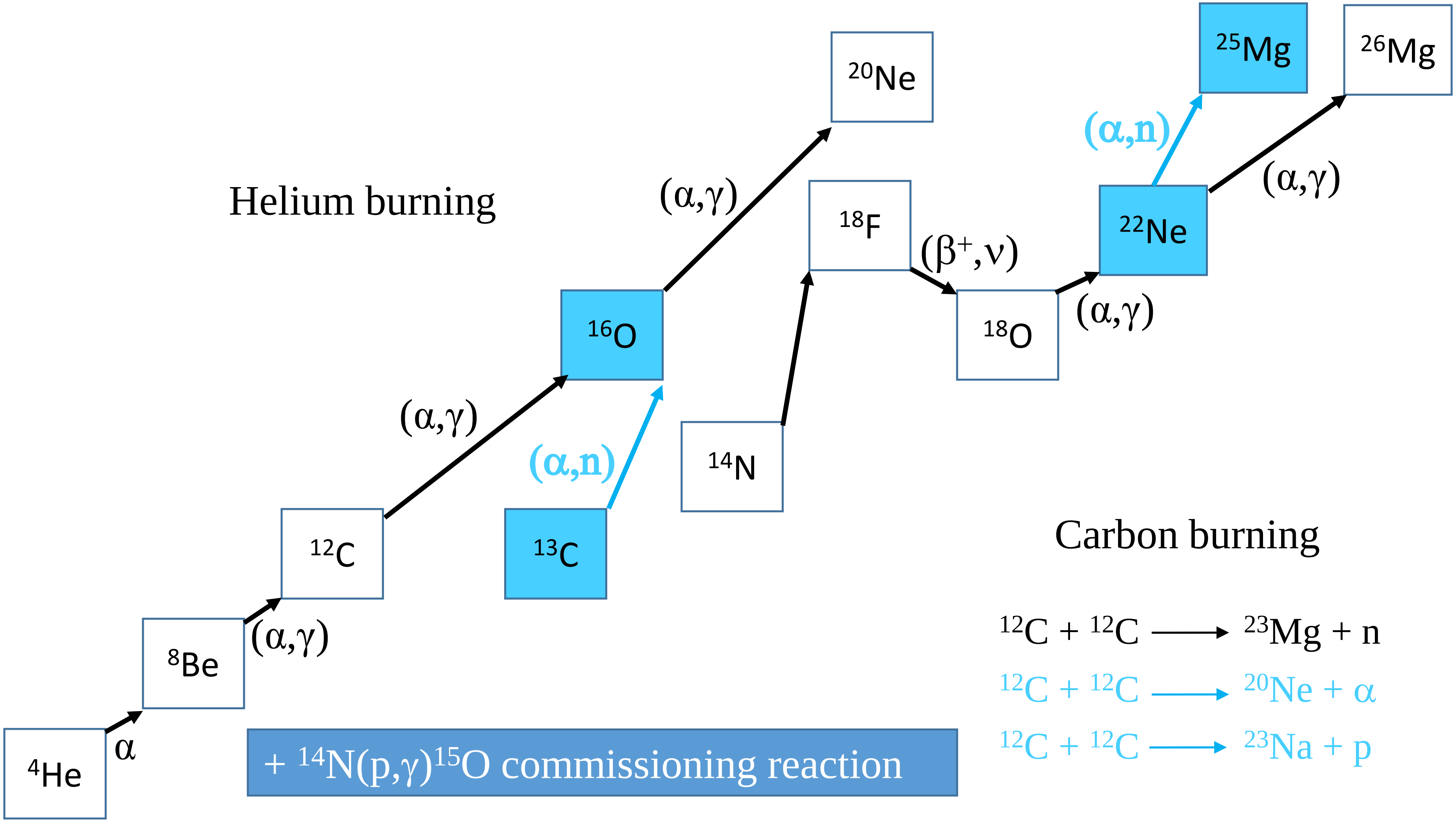


+ ^{14}N(p,γ)^{15}O commissioning reaction

Carbon burning

$^{12}C + ^{12}C \longrightarrow ^{23}Mg + n$

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

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

The neutron source reactions for the s-process: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$

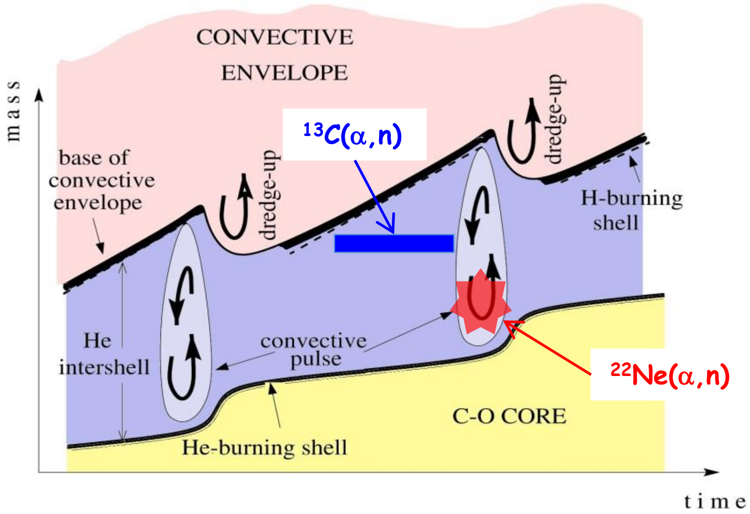
Nucleosynthesis of half of the elements heavier than Fe

Main s-process $90 \lesssim A < 210$

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



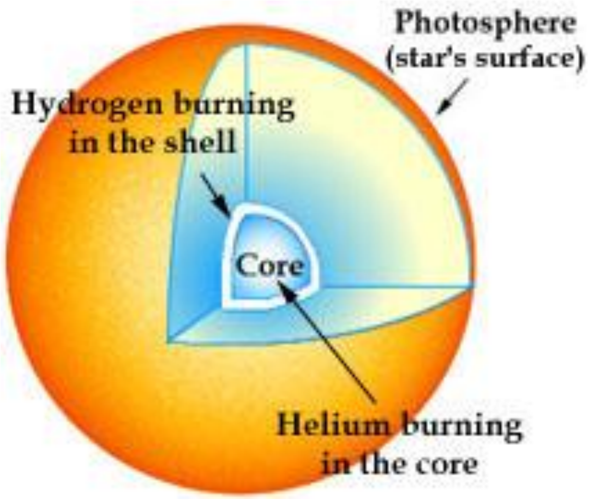
Weak s-process $A \lesssim 90$

massive stars > 8 $M_\odot$

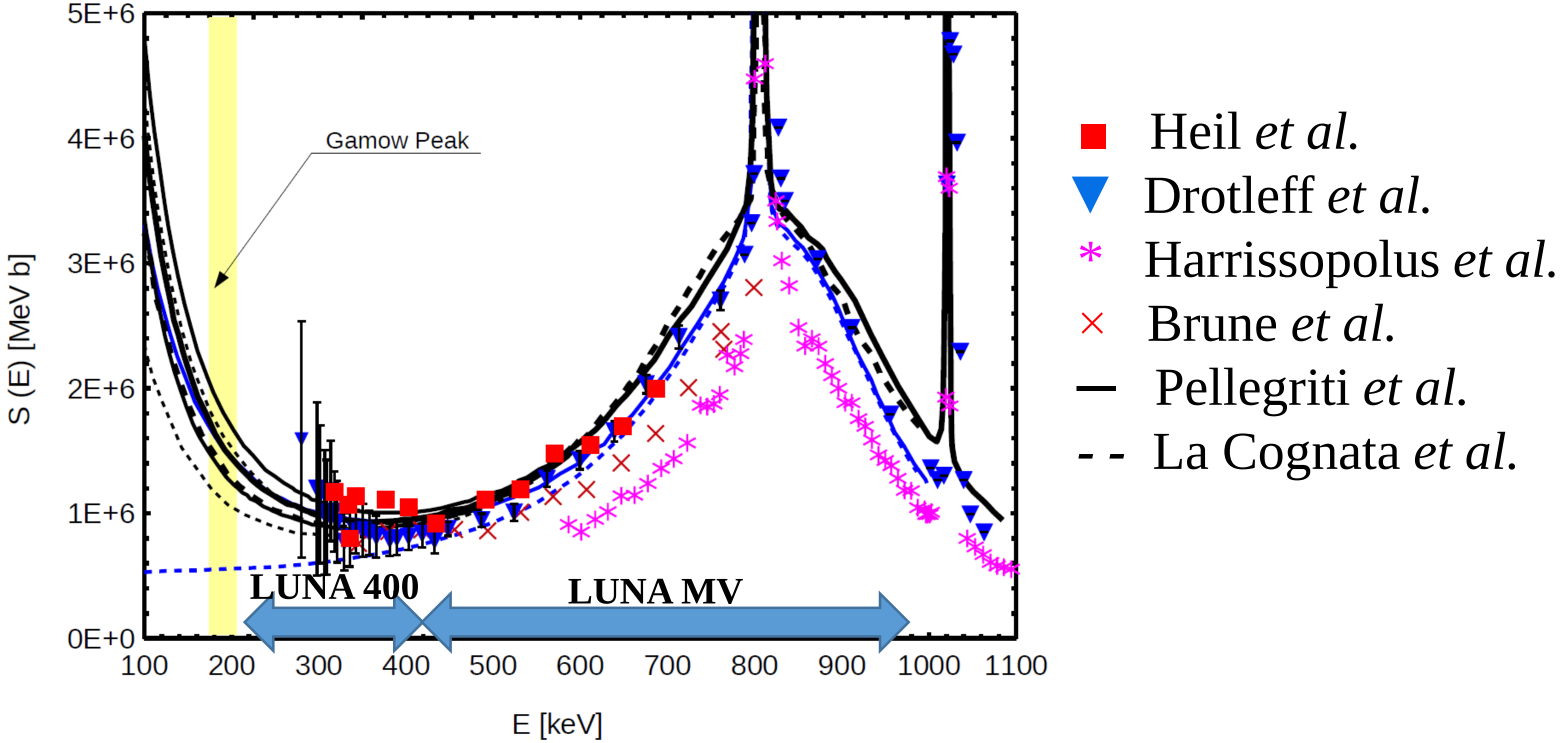
core He-burning
3-$3.5 \cdot 10^8$ K
10^6 cm^{-3}

C-burning
$\sim 10^9$ K
10^{11}-10^{12} cm^{-3}

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



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



- ✓ 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)
- ✓ No data at low energy because of high neutron background in surface laboratories.
- ✓ Extrapolations differ by a factor ~4 (10% accuracy would be required).

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

Direct Kinematics (^{4}He beam on ^{13}C target)

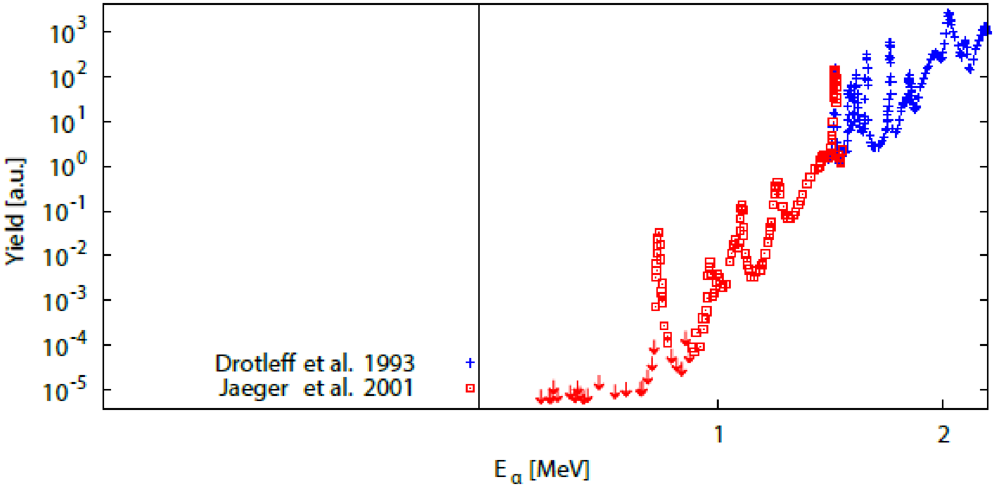
- ✓ energy range E_{cm} = 210 – 300 keV (E_{beam} ~ 275 – 400 keV) at LUNA-400
- ✓ energy range E_{cm} = 240 – 1060 keV (E_{beam} ~ 0.3 – 1.4 MeV) at LUNA-MV
- ✓ ^{13}C-enriched solid target (drawbacks: degradation, possible carbon deposition)
  - Tipical density 2 10^{17}-10^{18} at/cm^2
- ✓ Beam induced background: (α,n) reaction on impurities (^{10}B, 11B, 17O, 18O) in the target and beam line
- ✓ neutron energy range: E_n = 2 – 3.5 MeV (E_{beam} = 0.3 – 1.4 MeV)
- ✓ 18 ^{3}He counters embedded in a polyethylene matrix (10 atm, 1 inch dimeter, 40 cm long)

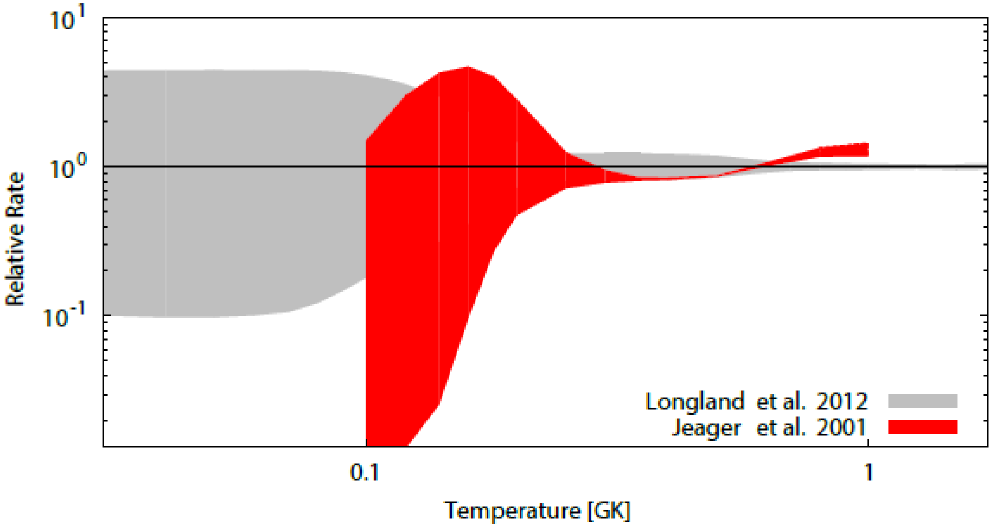
Inverse Kinematics (^{13}C beam on ^{4}He target)

- ✓ Only possible at LUNA-MV
- ✓ ^{4}He gas target:
  - P = 1 mbar
  - L = 10 cm

→ 2.5 10^{17} atoms/cm^2 at STP

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_{α} < 800 keV (energy region of interest for AGB stars). Extrapolations may be affected by unknown resonances
- ✓ At $T_9 < 0.18$ the competing reaction $^{22}Ne(\alpha,\gamma)^{26}Mg$ (Q=10.6 MeV) should become dominant (now measured at LUNA 400 kV) (Denise Piatti talk for details)
- ✓ Same neutron detector as for $^{13}C(\alpha,n)^{16}O$
- ✓ Gas target with enriched ^{22}Ne gas

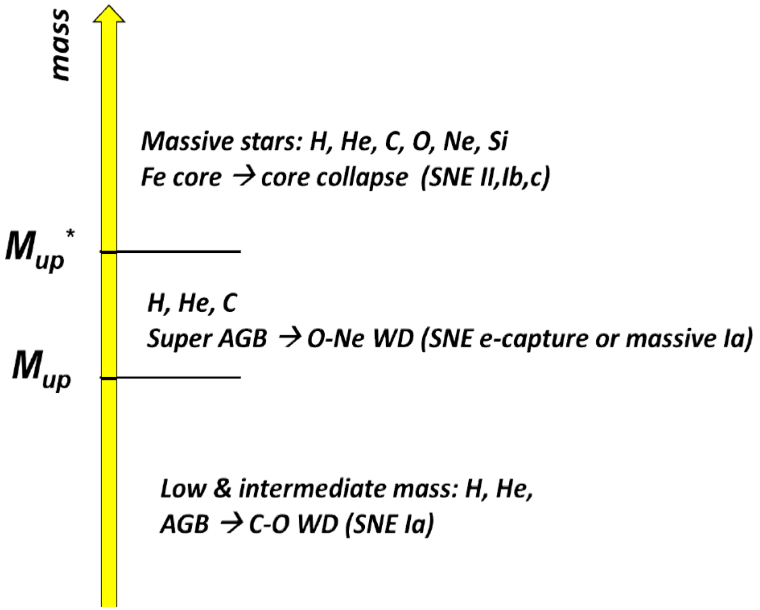
^{12}C+^{12}C: measurement strategy

$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha_i + \gamma_i$ $E_\gamma = 1634$ keV

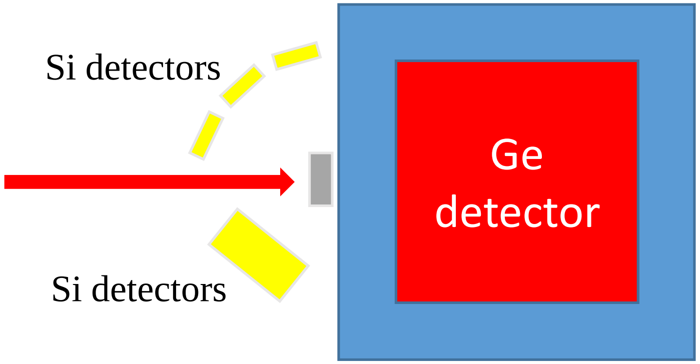
$^{12}C + ^{12}C \rightarrow ^{23}Na + p_i + \gamma_i$ $E_\gamma = 440$ keV

Particle yield

Gamma yield



- ✓ ^{12}C target: thick (1 mm) or thin (40 μg/cm^2 which corresponds to 0.18 μm)
- ✓ 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
- ✓ 2 ΔE-E telescopes for p at $E_{CM} < 2.5$ MeV



Conclusions

- ✓ The extremely low laboratory background of LNGS 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
- ✓ Several hydrogen burning and BBN fusion reactions have been studied in the last 25 years
- ✓ A new phase devoted to helium and carbon burning is starting with LUNA-MV
- ✓ The new accelerator will arrive at the beginning of 2019; the first experiment will start in summer 2019
- ✓ LUNA will be not anymore alone: JUNA (China), Felsenkeller (Germany), Caspar (United States)

Thanks for your attention

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