Nuclear astrophysics and LUNA MV

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LUNA
Laboratory for Underground
Nuclear Astrophysics

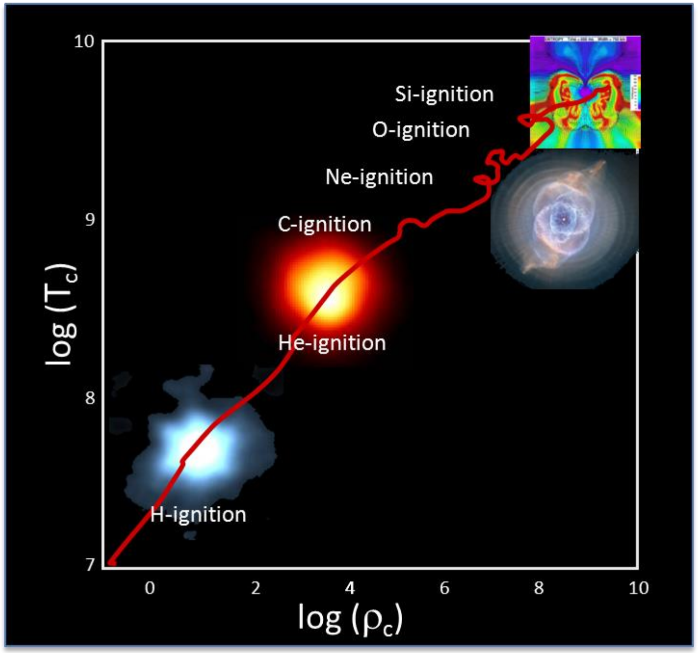
Outline:

-Nuclear astrophysics: why and how

-Underground nuclear astrophysics at Gran Sasso laboratory: the LUNA experiment

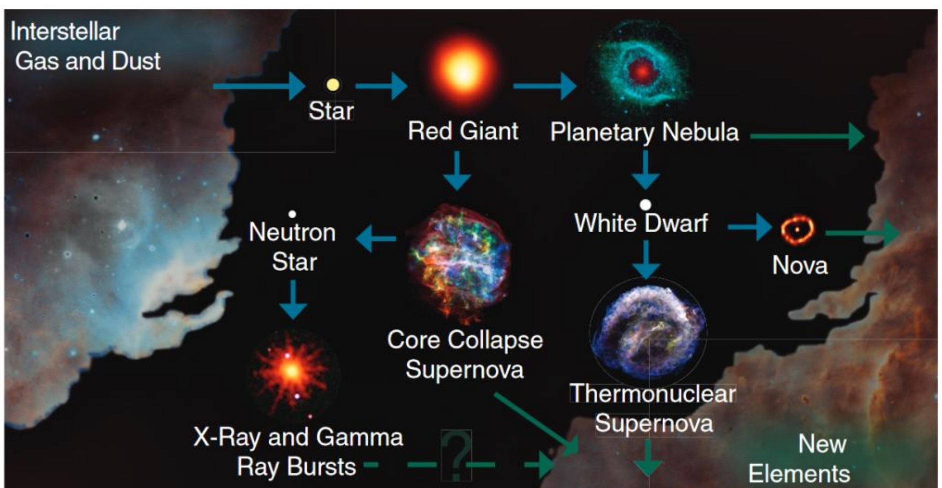
-Future perspective: the LUNA-MV project

Nuclear cross sections and stellar models



-Stars are powered by nuclear reactions

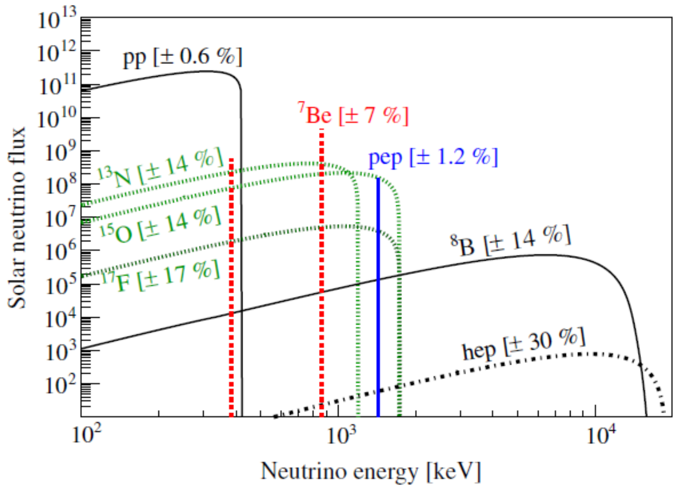
-Among the key parameters (chemical composition, opacity, ...) to model stars, reaction cross sections play an important role



- They determine the origin of elements in the cosmos, stellar evolution and dynamic

- Many reactions ask for high precision data

Neutrino production in the Sun



G. Bellini et al. PRD 2014

p-p chain

$p + p \rightarrow {}^{2}H + e^{+} + \nu$

$p + e^{-} + p \rightarrow {}^{2}H + e^{+} + \nu$

${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu$

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

${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$

CNO cycle

${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu$

${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu$

${}^{17}F \rightarrow {}^{17}O + e^{+} + \nu$

Neutrino flux from the Sun can be used to study:

- Solar interior composition
- Neutrino properties

only if the cross sections of the involved reactions are known with enough accuracy

Big Bang nucleosynthesis

Production of the lightest elements (D, ^3He, ^4He, ^7Li, ^6Li) in the first minutes after the Big Bang

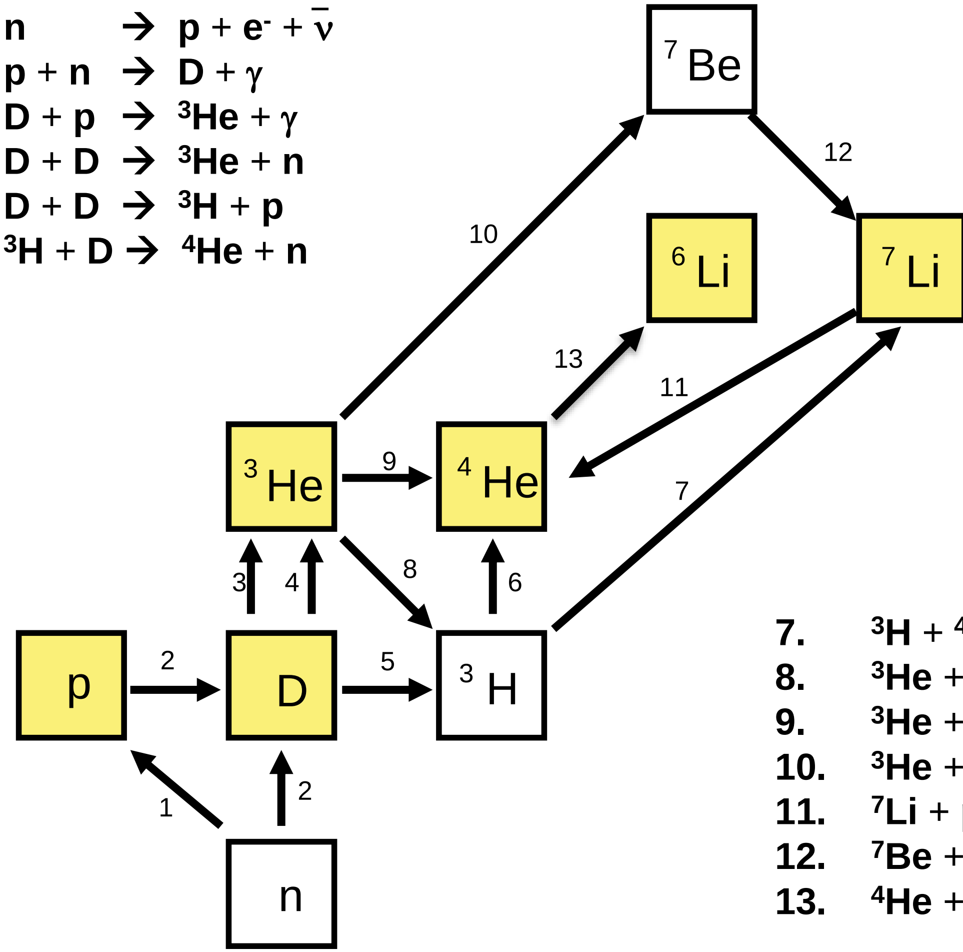
The general concordance between predicted (BBN theory) and observed (stellar spectra) abundances gives a direct probe of the Universal baryon density

CMB anisotropy measurement (e.g. Planck satellite) gives an independent measurement of the Universal baryon density

The agreement of the two results has to be understood in terms of uncertainties in the BBN predictions

BBN reaction network

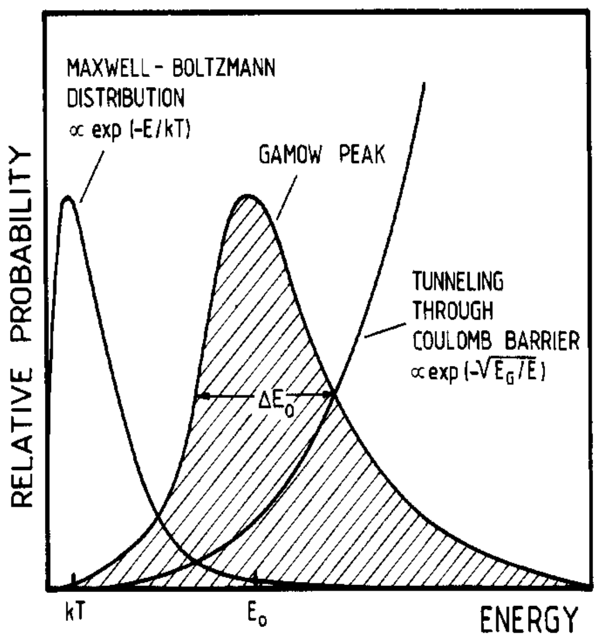
1. n → $p + e^- + \bar{\nu}$
2. p + n → D + γ
3. D + p → ^{3}He + γ
4. D + D → ^{3}He + n
5. D + D → ^{3}H + p
6. ^{3}H + D → ^{4}He + n



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

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

Underground nuclear astrophysics: why?



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 $E_0 \ll E_C$!!

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

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

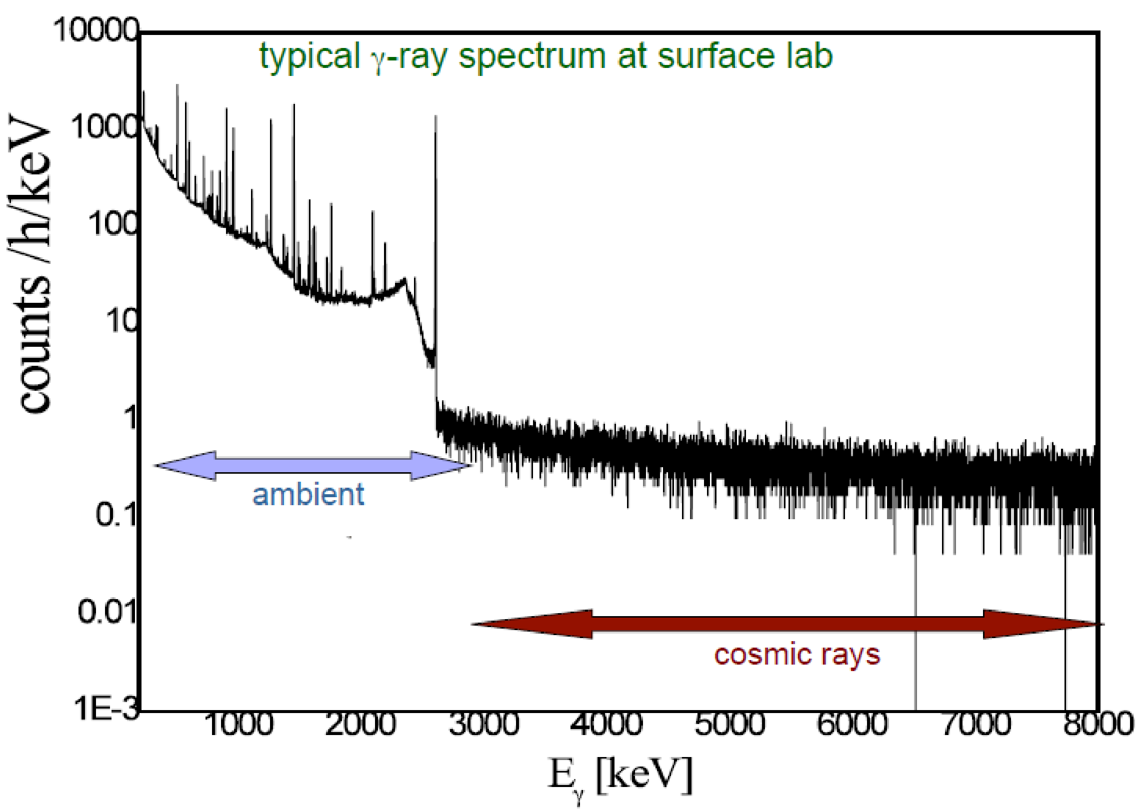
Rate and background

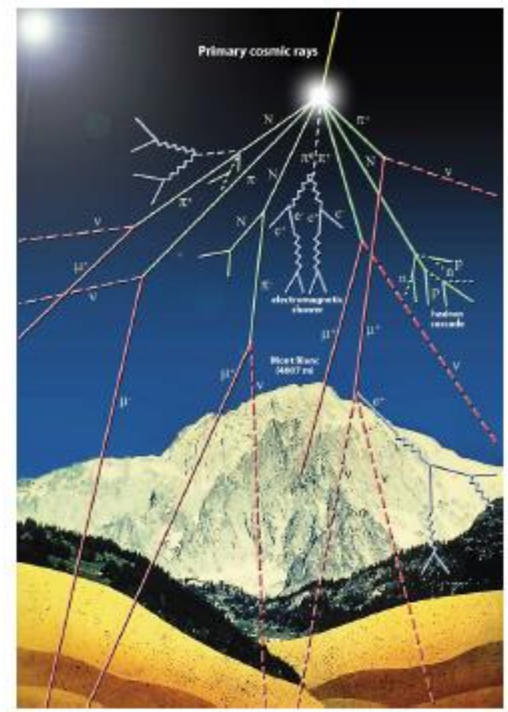
R has to be compared with background B

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

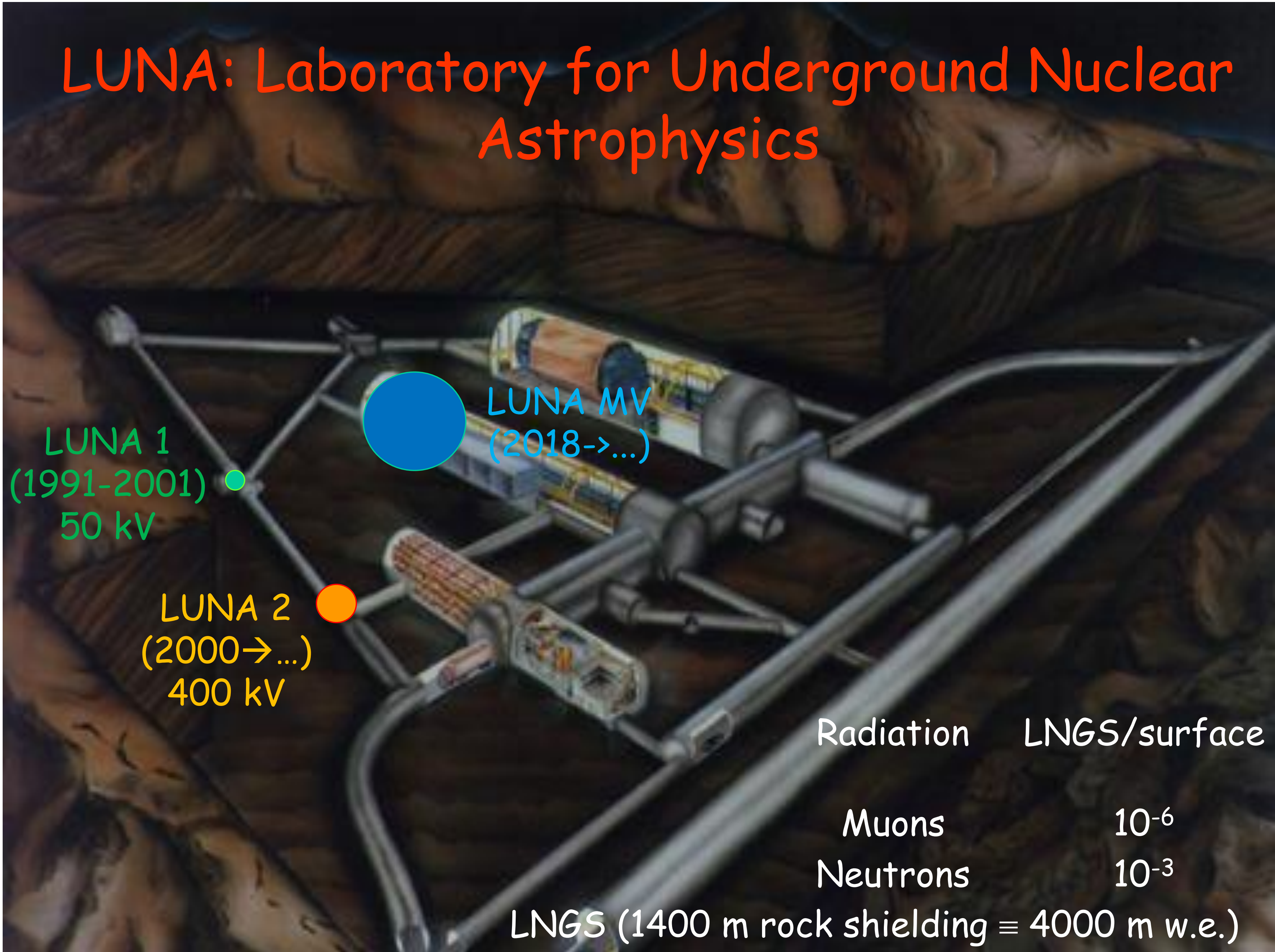
B_{env} : natural radioactivity mainly from U and Th chains

B_{cosmic} : mainly muons





LUNA: Laboratory for Underground Nuclear Astrophysics

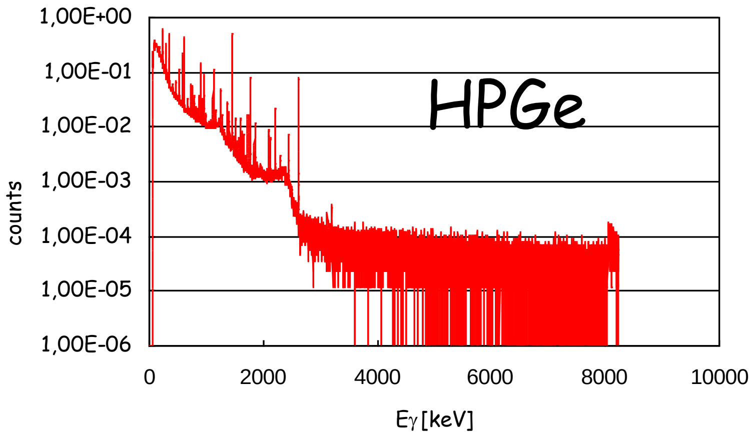


Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}

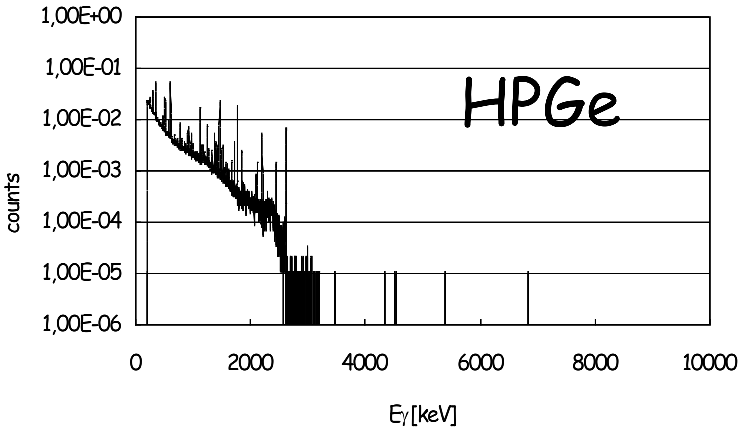
LNGS (1400 m rock shielding ≡ 4000 m w.e.)

LUNA: background reduction

E_γ>3MeV: reduction of a factor 2000 simply going underground



3MeV < Eγ < 8MeV: 0.5 Counts/s

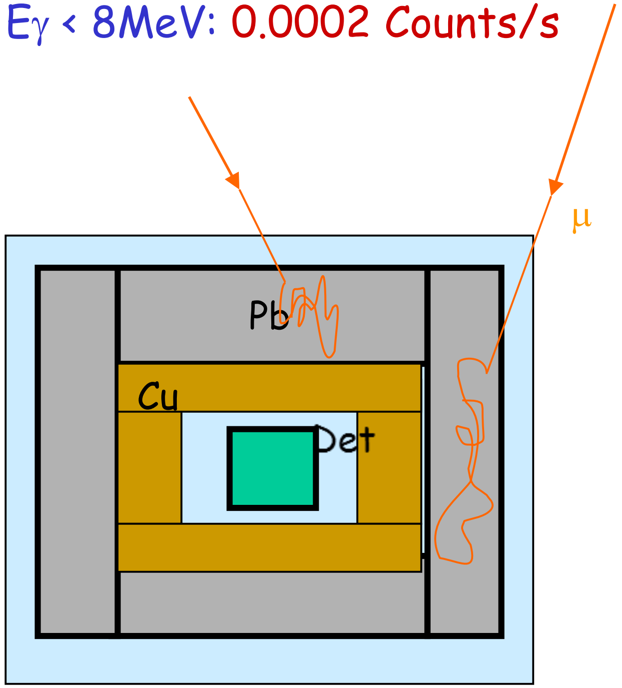


3MeV < Eγ < 8MeV: 0.0002 Counts/s

E_γ<3MeV→passive shielding

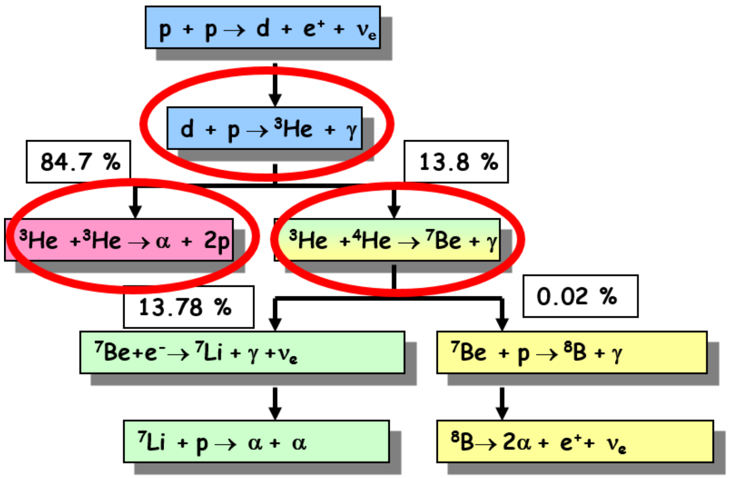
Underground passive shielding is more effective since μ flux, that create secondary γ's in the shield, is suppressed.

A reduction of 5 o.o.m. was obtained

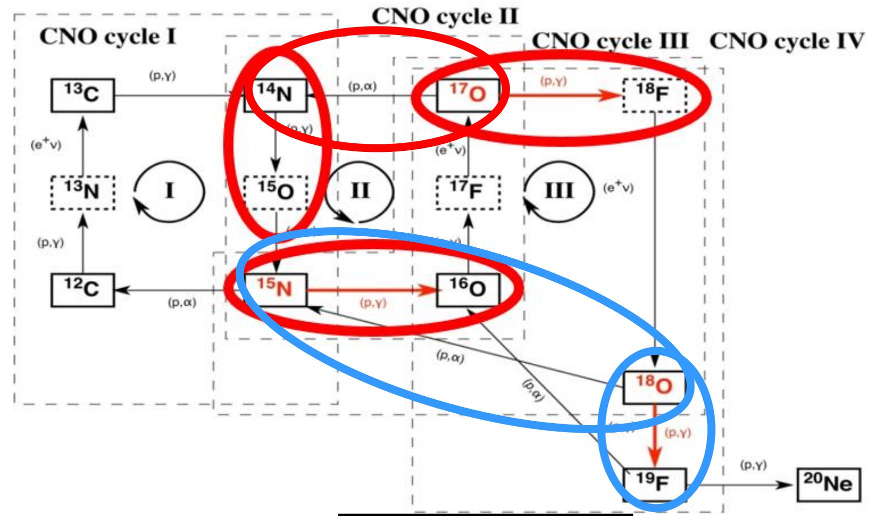


The last 25 years at LUNA: Hydrogen burning

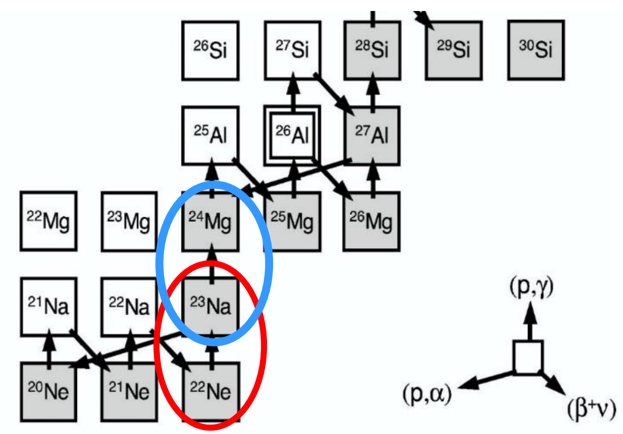
pp chain



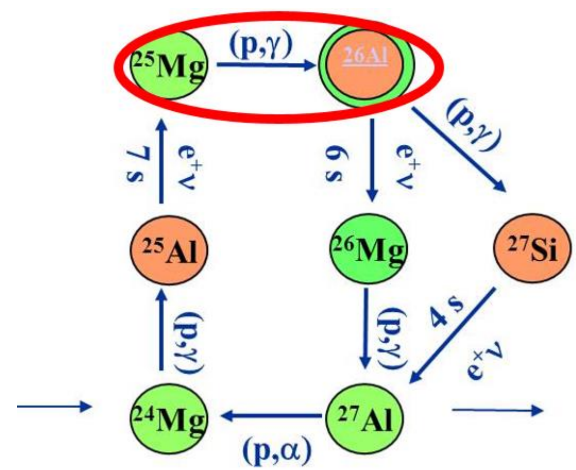
CNO cycle



Ne-Na cycle

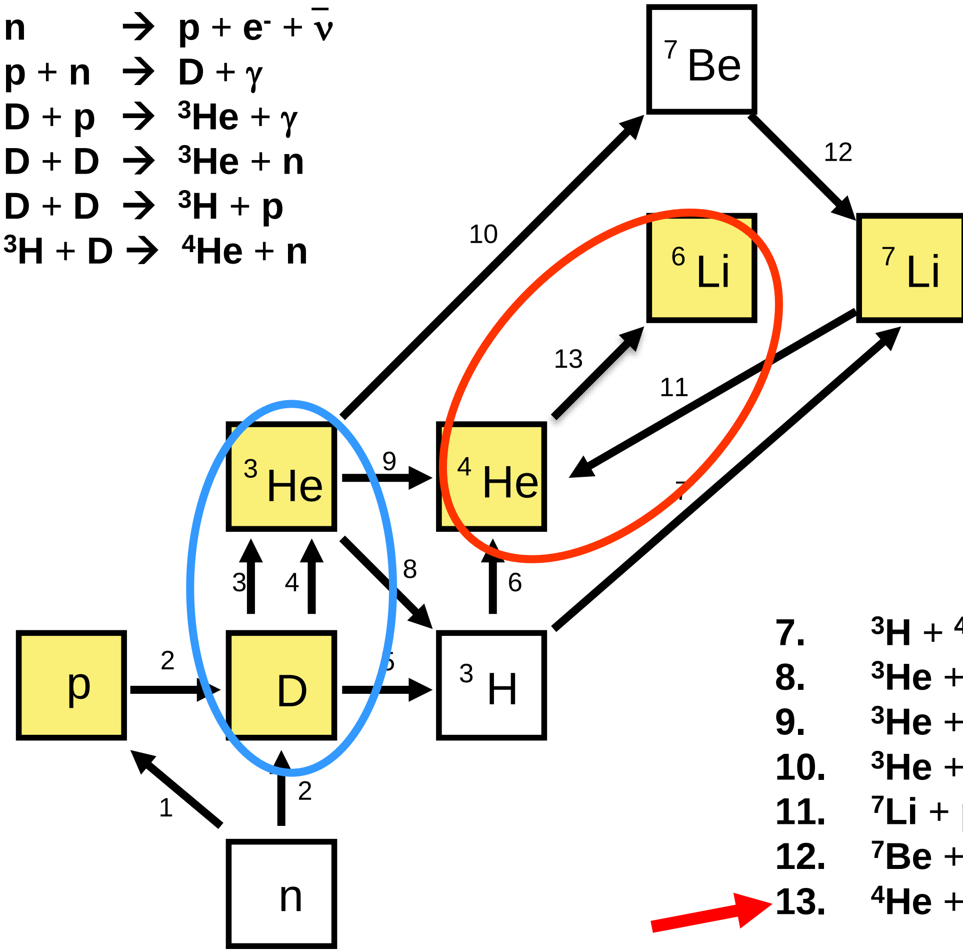


Mg-Al cycle



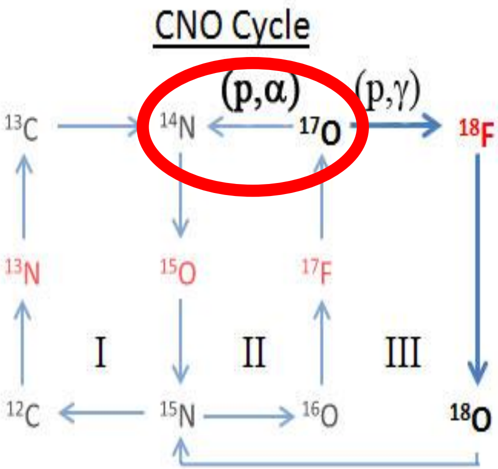
...and BBN

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

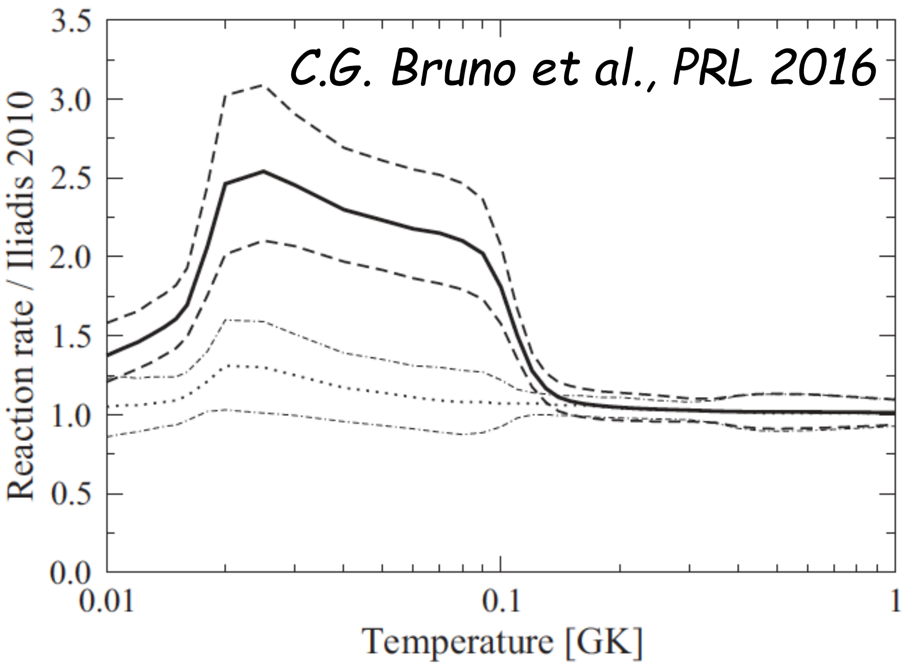


7. ${}^3H + {}^4H \rightarrow {}^7Li + \gamma$
8. ${}^3He + n \rightarrow {}^3H + p$
9. ${}^3He + D \rightarrow {}^4He + p$
10. ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11. ${}^7Li + p \rightarrow {}^4He + {}^4He$
12. ${}^7Be + n \rightarrow {}^7Li + p$
13. ${}^4He + D \rightarrow {}^6Li + \gamma$

LUNA and the origin of meteoritic sturdust



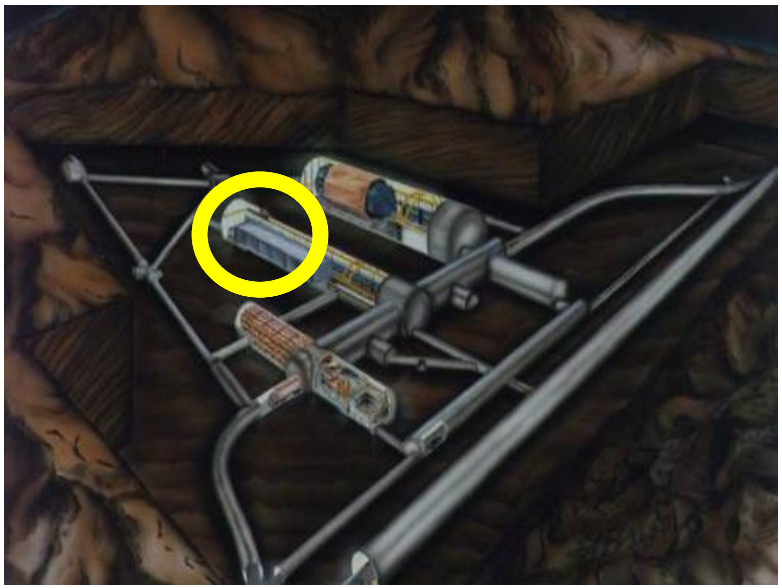
$^{17}O(p,\alpha)^{14}N$ reaction affects $^{17}O/^{16}O$ ratio and ^{18}F abundance in in several stellar scenarios.
At LUNA: intense proton beam on ^{17}O enriched solid target. Alpha particles detected with an array of silicon detectors



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!

M. Lugaro et al., Nature Astronomy 2017

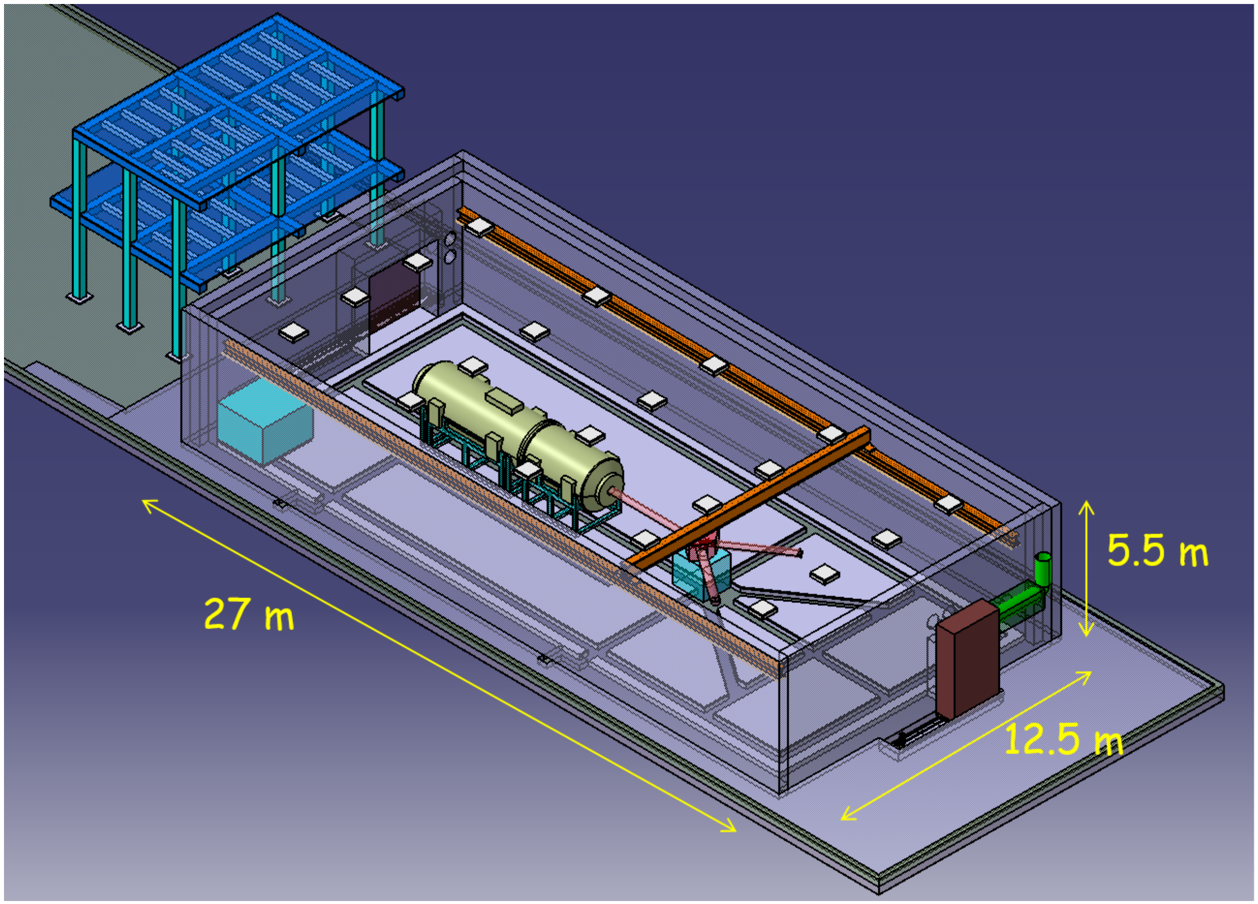
From Hydrogen burning to Helium and Carbon burning or… from LUNA to LUNA MV



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 accelerator

In-line Cockcroft Walton accelerator



In the energy range 0.3-3.5 MeV

H^+ beam:
500-1000 eμA

He^+ beam:
300-500 eμA

C^+ beam:
100-150 eμA

C^{++} beam:
100 eμA

Beam energy reproducibility : 10^{-4} * TV or 50 V
The accelerator hall will be shielded by 80 cm thick concrete walls: no perturbation of the LNGS natural neutron flux

The scientific program of LUNA MV for the first 5 years (2019-2023)

$^{14}N(p,\gamma)^{15}O$: the bottleneck reaction of the CNO cycle in connection with the solar abundance problem. Also commissioning measurement for the LUNA MV facility

$^{12}C+^{12}C$: energy production and nucleosynthesis in Carbon burning. Global chemical evolution of the Universe

$^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$: neutron sources for the s-process (nucleosynthesis beyond Fe)

Later on…

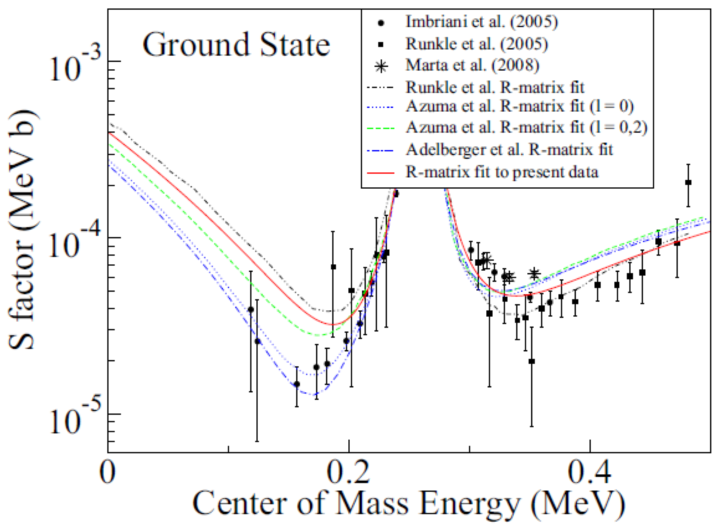
$^{12}C(\alpha,\gamma)^{16}O$: key reaction of Helium burning: determines C/O ratio and stellar evolution

…..

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

Three different measurements already performed at LUNA 400 kV in the energy range 70-370 keV.
In 2016 measured by Li et al. over a wide energy range

Still <u>a complete and clear picture is not available</u>:
A low background measurement over a wide energy range is highly desirable to reduce the present uncertainty of 7.5% on the S factor



Li et al. 2016

The cross section of the $^{14}N(p,\gamma)^{15}O$ reaction is one of the main contributor in the global uncertainty on the SSM model prediction for the solar composition

ν(CNO) depends on $S_{1,14}$ and (C+N) abundance in the core: a measurement with 10% uncertainty would allow a determination of the (C+N) abundance at 15%

The $^{12}C+^{12}C$ reaction: astrophysical impact

$^{12}C+^{12}C \rightarrow {}^{20}Ne + \alpha$ $Q = 4.62$ MeV

$^{12}C+^{12}C \rightarrow {}^{23}Na + p$ $Q = 2.24$ MeV

$^{12}C+^{12}C \rightarrow {}^{24}Mg + \gamma$ $Q = 13.93$ MeV negligible

$^{12}C+^{12}C \rightarrow {}^{23}Mg + n$ $Q = -2.62$ MeV endothermic for low energies

$^{12}C+^{12}C \rightarrow {}^{16}O + 2\alpha$ $Q = -0.12$ MeV three particles→ reduced prob.

$^{12}C+^{12}C \rightarrow {}^{16}O + {}^{8}Be$ $Q= -0.21$ MeV higher Coulomb barrier

Coulomb barrier: $E_C= 6.7$ MeV

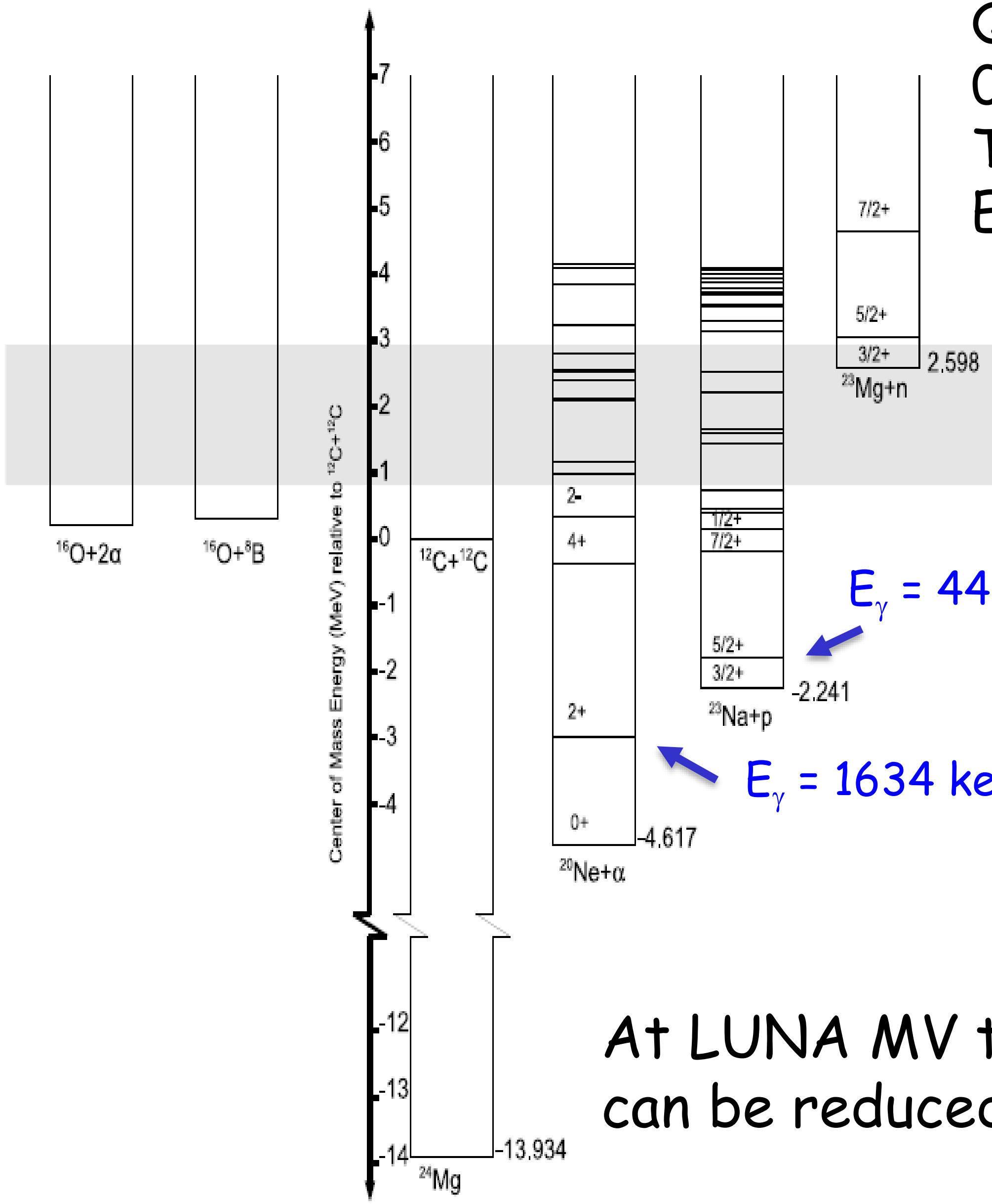
Its rate determines the value of "M_{up}":

If $M_{star}>M_{up}$: quiescent Carbon burning→ core-collapse supernovae, neutron stars, stellar mass black holes

If $M_{star}<M_{up}$: no Carbon burning→ white dwarfs, nova, type Ia supernovae

The reaction produces protons and alphas in a hot environment→ nucleosynthesis in massive stars

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



Quiescent carbon burning:
0.9 MeV<E_{CM}<3.4 MeV
Type Ia supernovae:
$E_{CM} \geq 0.7$ MeV

$^{12}C+^{12}C \rightarrow ^{20}Ne + \alpha_i + \gamma_i$

$^{12}C+^{12}C \rightarrow ^{23}Na + p_i + \gamma_i$

E_γ = 440 keV

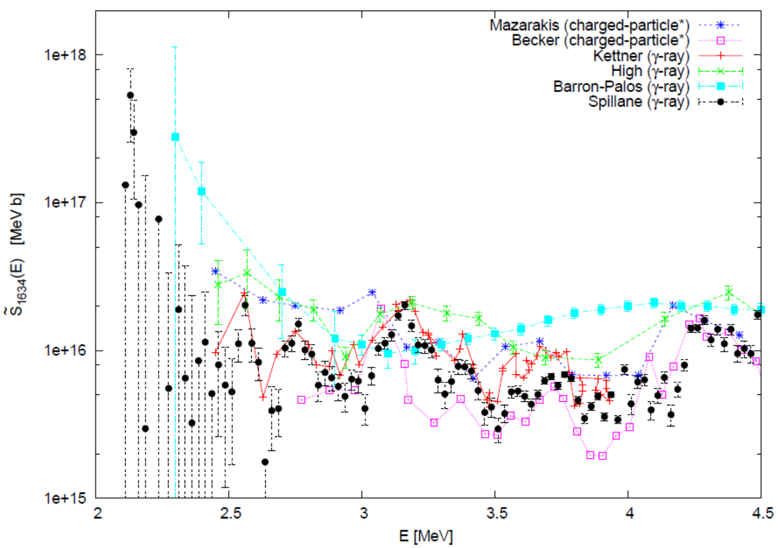
E_γ = 1634 keV

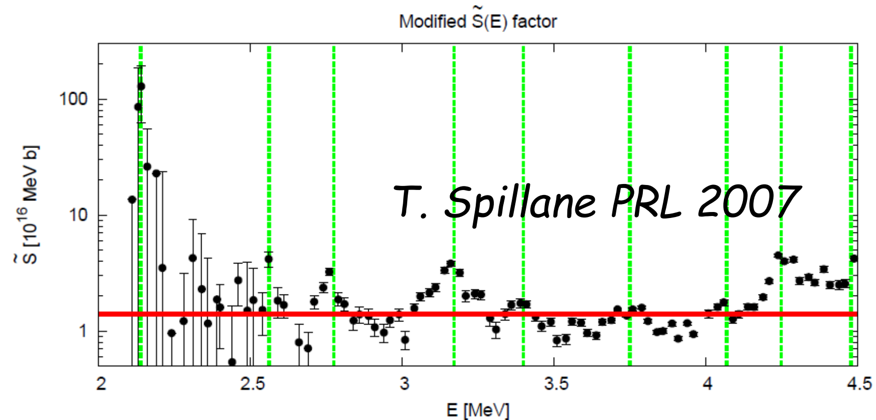
Particle detection:
Si or ΔE/E telescopes

Gamma detection: HpGe

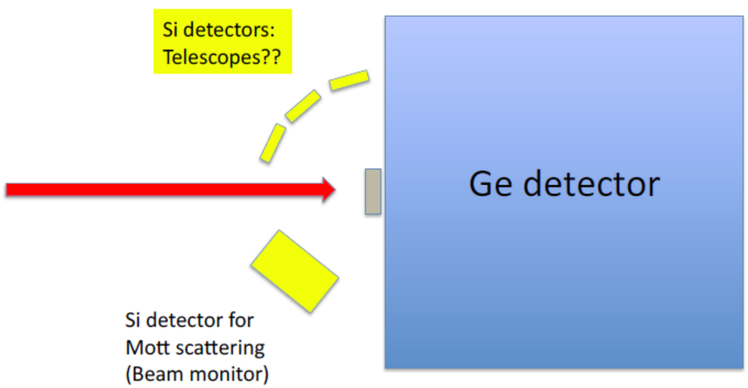
At LUNA MV the γ natural background can be reduced by 5 o.o.m.

The $^{12}C+^{12}C$ reaction at LUNA MV





Several resonances spaced by 300-500 keV Typical width $\Gamma \approx$ 10keV



1mm thick C target and well shielded HpGe detector: search for low energy resonances with 5 keV spacing and 30% statistical uncertainty:
Beam induced background from ^{1}H and ^{2}H contamination in the target to be investigated

E > 1955 for the proton channel (background limited)
E > 1605 keV for the alpha channel (time limited)
Total time needed 2.5 y

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<A<210

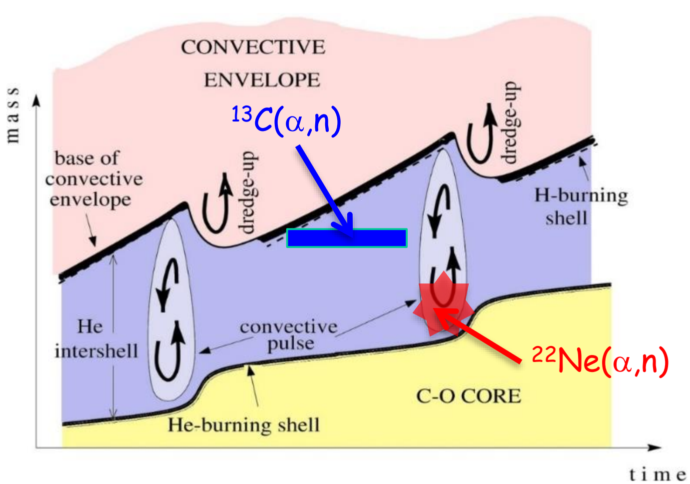
TP-AGB stars

shell H-burning
$T_9 \sim 0.1$ K
10^7-10^8 cm^{-3}

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

He-flash
$0.25 \leq T_9 \sim 0.4$ K
10^{10}-10^{11} cm^{-3}

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



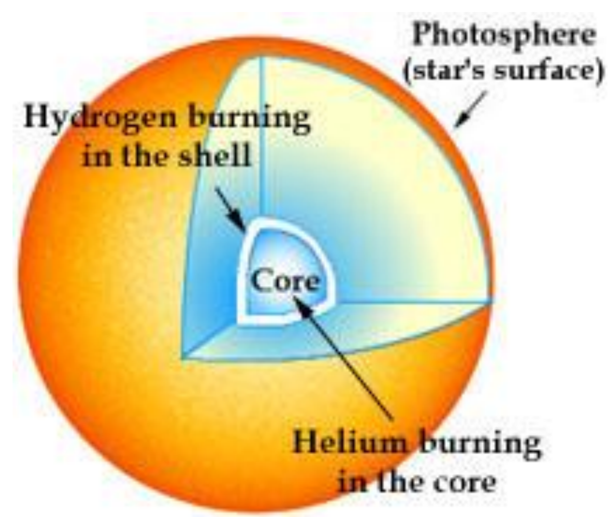
Weak s-process A<~90

massive stars > 10 M_{Sun}

core He-burning
3-$3.5\cdot10^8$ K
10^6 cm^{-3}

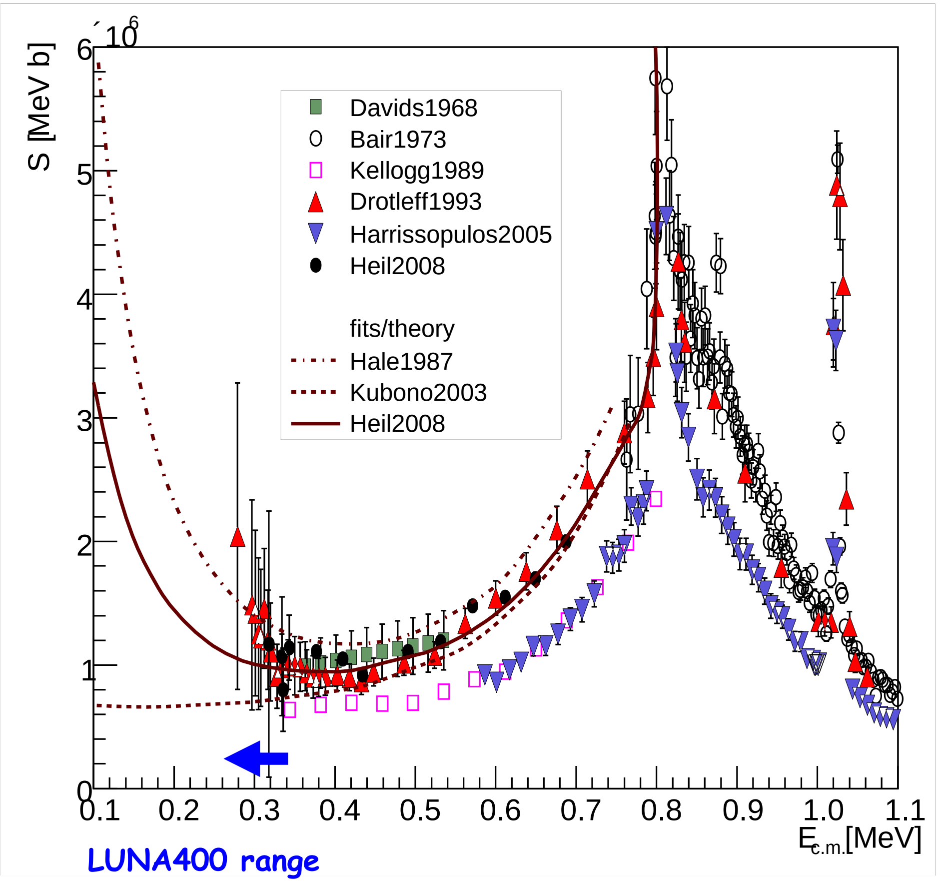
shell C-burning
$\sim10^9$ K
10^{11}-10^{12} cm^{-3}

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



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

E = 140-230 keV (T = 90 · 10^6 K)



large statistical uncertainties at low energies
large scatter in absolute values (normalization problem)
unknown systematic uncertainties
uncertainties in detection efficiencies
contribution from sub-threshold state (E=6.356 MeV in ^{17}O)
contribution from electron screening

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 400 and LUNA MV

Direct kinematics (^{4}He beam on ^{13}C target):
210 keV$<E_{cm}<$300 keV (275 keV$<E_{beam}<$400 keV) at LUNA 400 kV
240 keV$<E_{cm}<$1060 keV (300 keV$<E_{beam}<$1.4 MeV) at LUNA MV
$^{13}CH_4$ gas target (drawbacks: limit on the density, possible molecule cracking). With typical conditions: 2.5 10^{17} atoms/cm^2
^{13}C enriched solid target (drawbacks: degradation, possible carbon deposition). Typically 2 10^{17}-10^{18} atoms/cm^2
Beam induced background: (α,n) reaction on impurities (^{10}B, ^{11}B, ^{17}O, ^{18}O) in the target and beam line
E_n = 2-3.5 MeV ^{3}He counters embedded in a polyethylene matrix

Inverse kinematics (^{13}C beam on ^{4}He target): only possible at LUNA MV
^{4}He gas target 2.5 10^{17} atoms/cm^2
Beam induced background: ^{13}C induced reaction on ^{2}H, ^{6}Li, ^{7}Li, ^{10}B, ^{11}B, ^{16}O, ^{19}F
E_n = 2-5.5 MeV: same detector as above

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

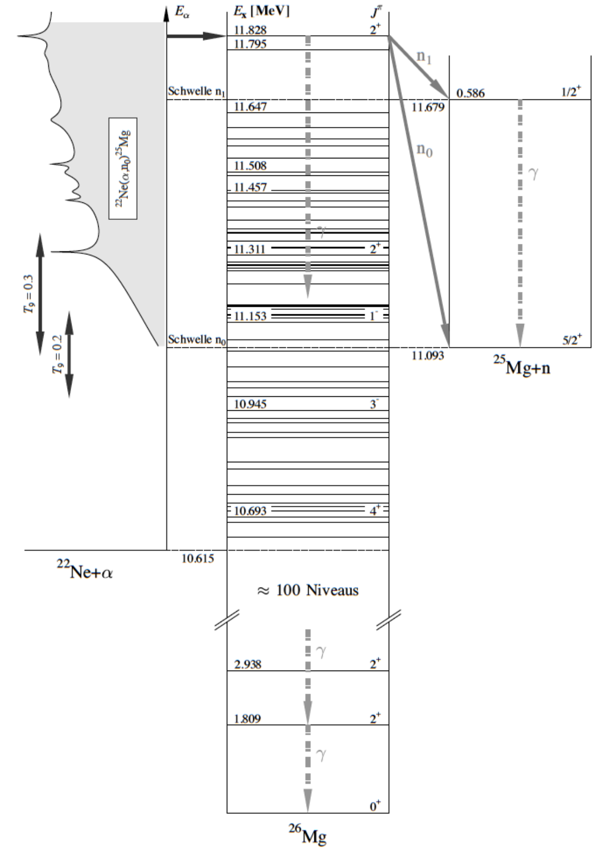
E_{th}= 0.57 MeV
Level scheme of ^{26}Mg is very complex

The lowest well studied resonance at E_α=832 keV dominates the rate

The influence of a possible resonance at 635 keV has been ruled out because of parity conservation

Only upper limits (~10 pb) at: $570<E_\alpha<800$ 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)



At LUNA MV: ^{22}Ne windowless gas target + ^{3}He counters inside moderator
To fully exploit LNGS low background: shielded detector, selected tubes, pulse shape discrimination, remove ^{11}B (because of $^{11}B(\alpha,n)^{14}N$) to reach the level of ~10 n/day.

The LUNA MV time 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

The LUNA collaboration

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