Underground Nuclear Astrophysics: Present and future of the LUNA experiment

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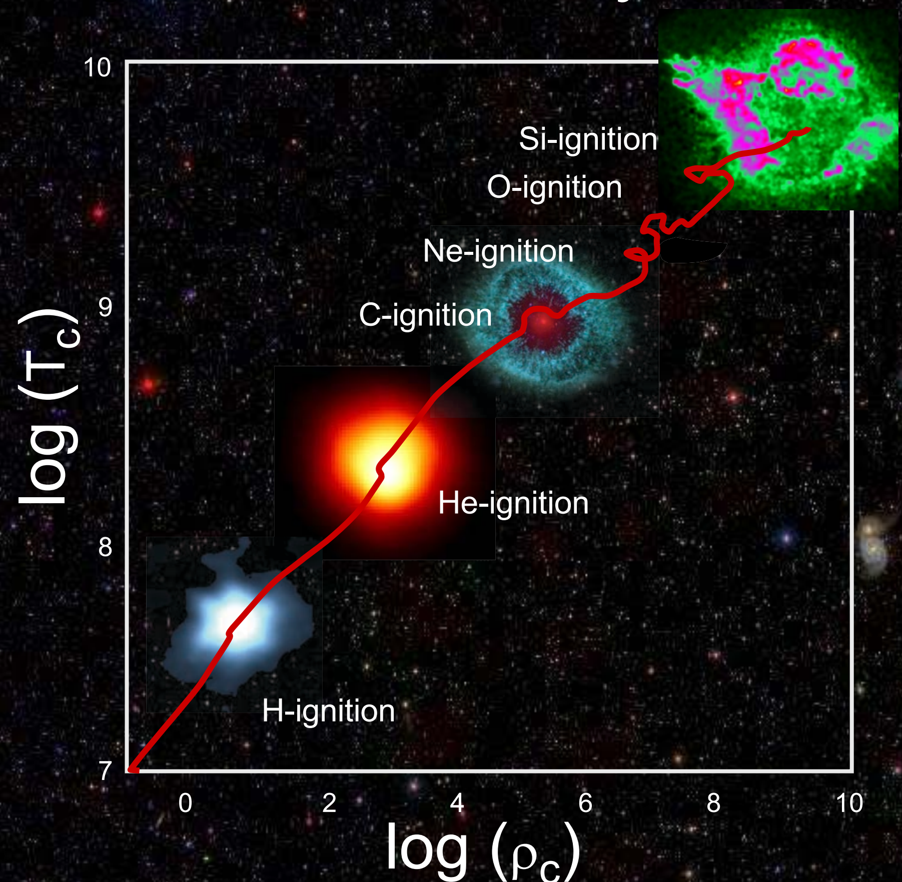
- Nuclear Astrophysics overview
- LUNA 50 kV: Solar Neutrinos
- LUNA 400 kV: The Sun, Hydrogen Burning, BBN
- Luna MV: Evolution and fate of stars

Why Nuclear astrophysics?

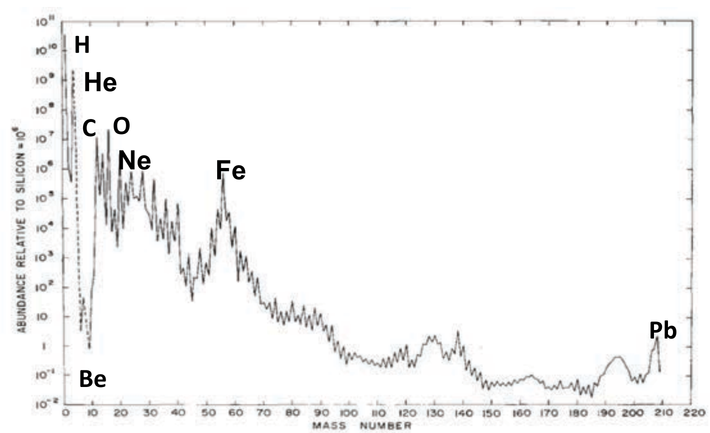


For a 15 M_{sun} star:

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

Nuclear reactions are responsible for the synthesis of the elements in the celestial bodies and BBN:
High precision data are required

- Understanding the Sun
- Stellar population
- Evolution and fate of stars
- Big Bang Nucleosynthesis
- Isotopic abundances in the cosmos
- Cosmology
- Particle Physics
- Theoretical nuclear physics

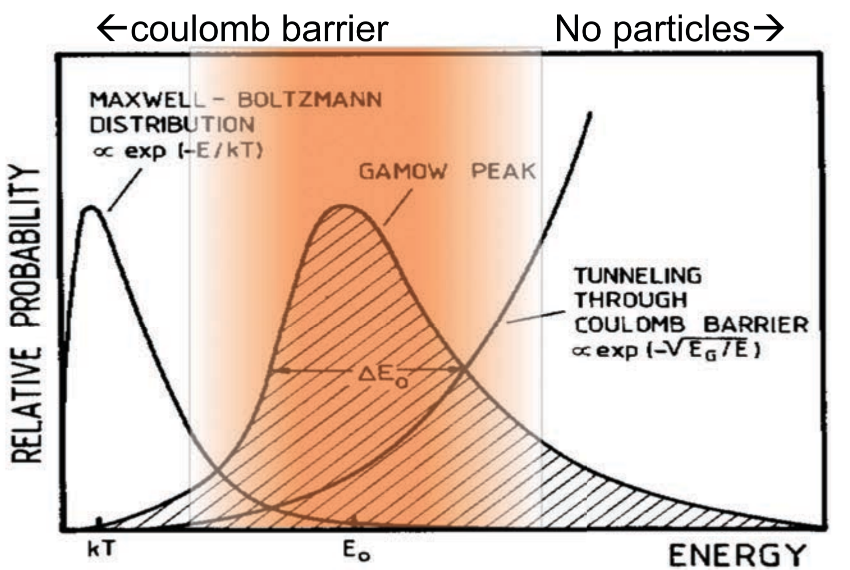


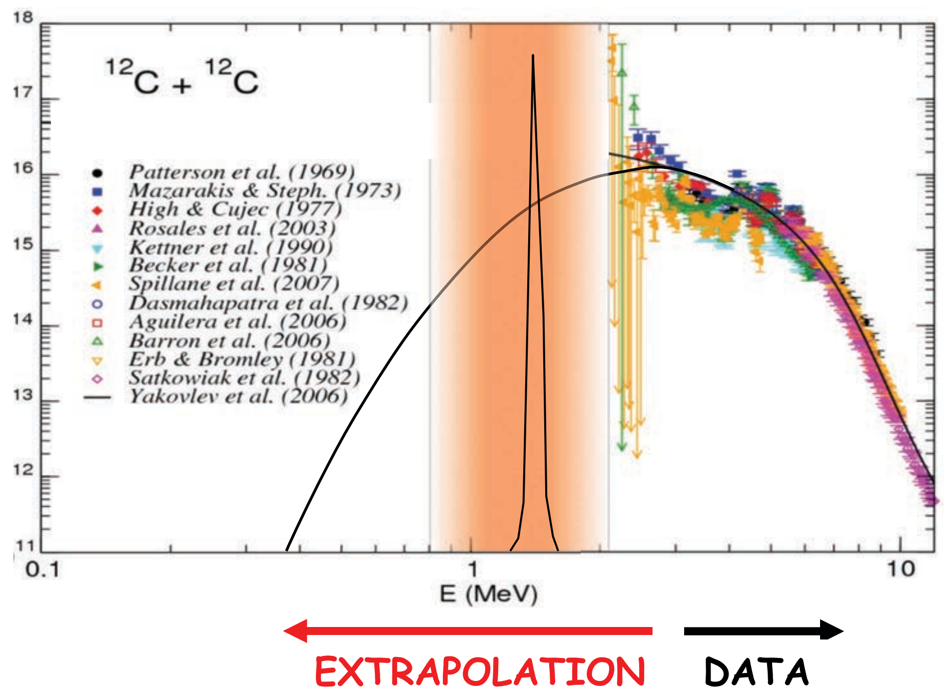
Why Underground Measurements?

Very low cross sections because of the Coulomb barrier

Underground accelerator to reduce the background induced by Cosmic Rays

→Direct measurements inside the energy region of interest





Astrophysical Factor

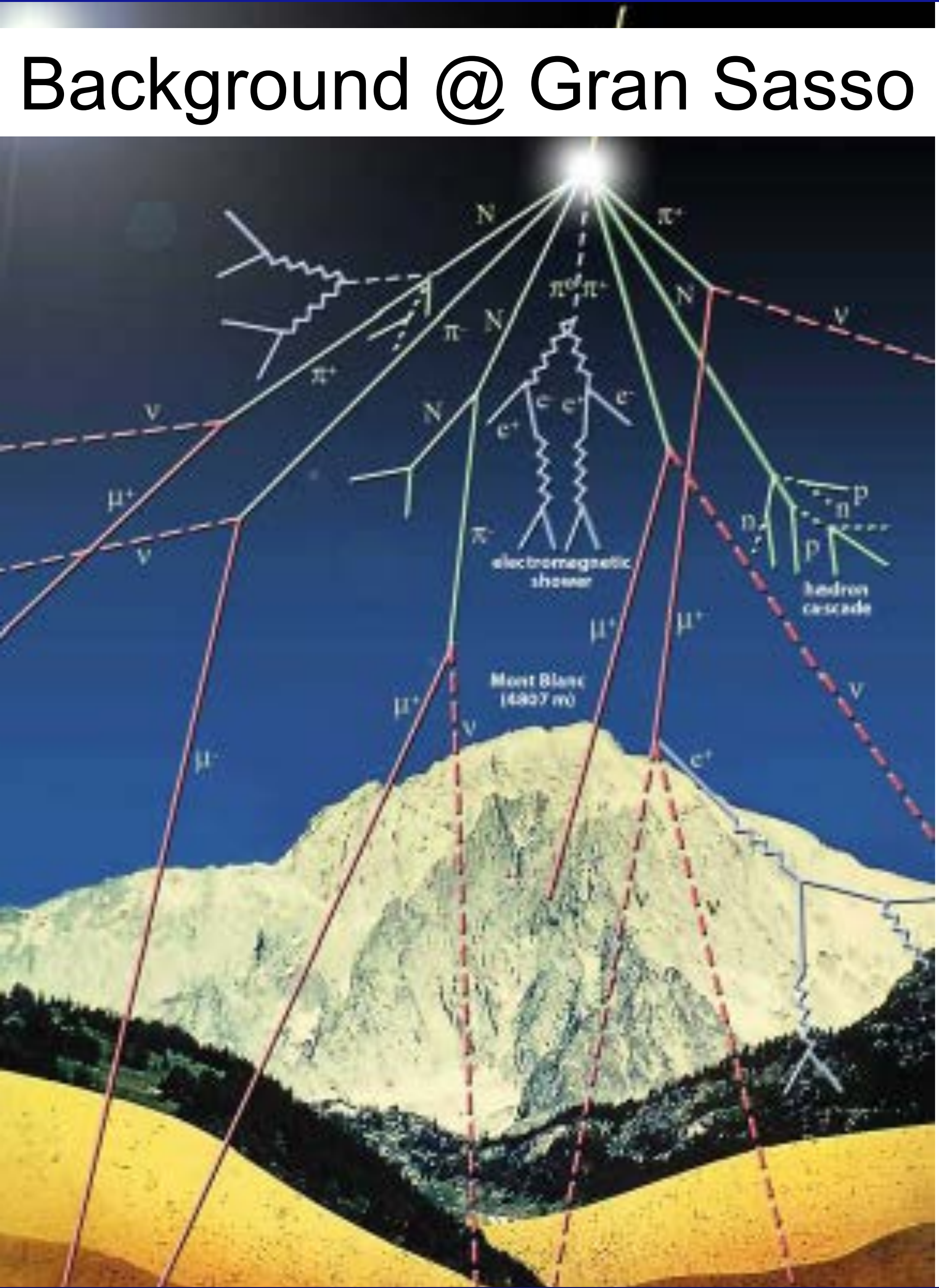
Coulomb Barrier

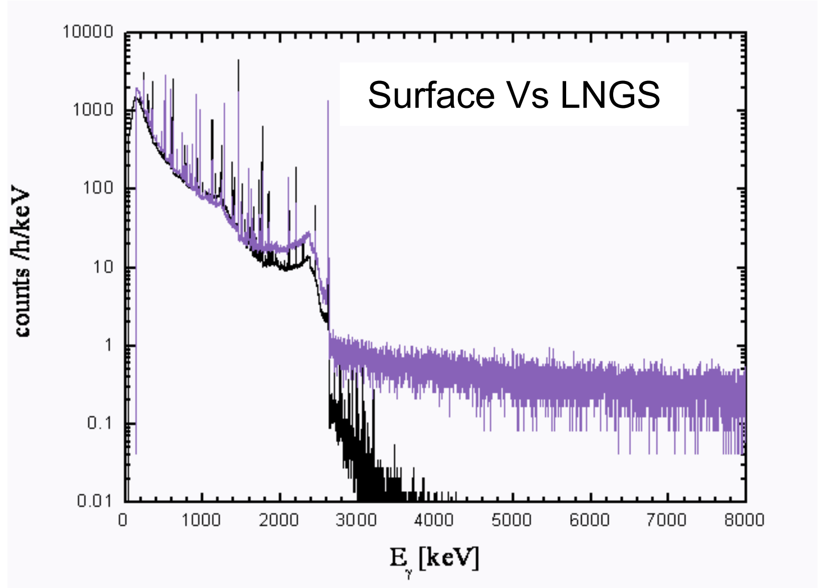
$$\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}$$

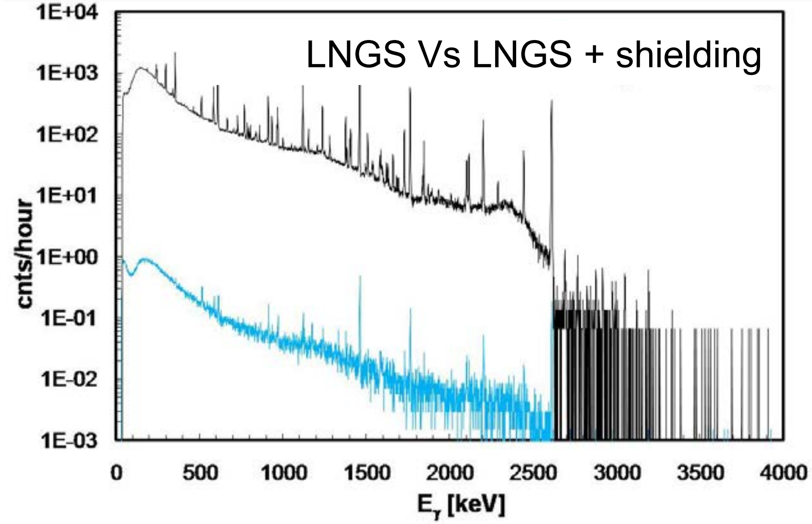
Gran Sasso National Laboratories

Background reduction with respect to Earth's surface: $\mu \sim 10^{-6}$
$\gamma \sim 10^{-2}$-10^{-5}
neutrons $\sim 10^{-3}$

Background @ Gran Sasso



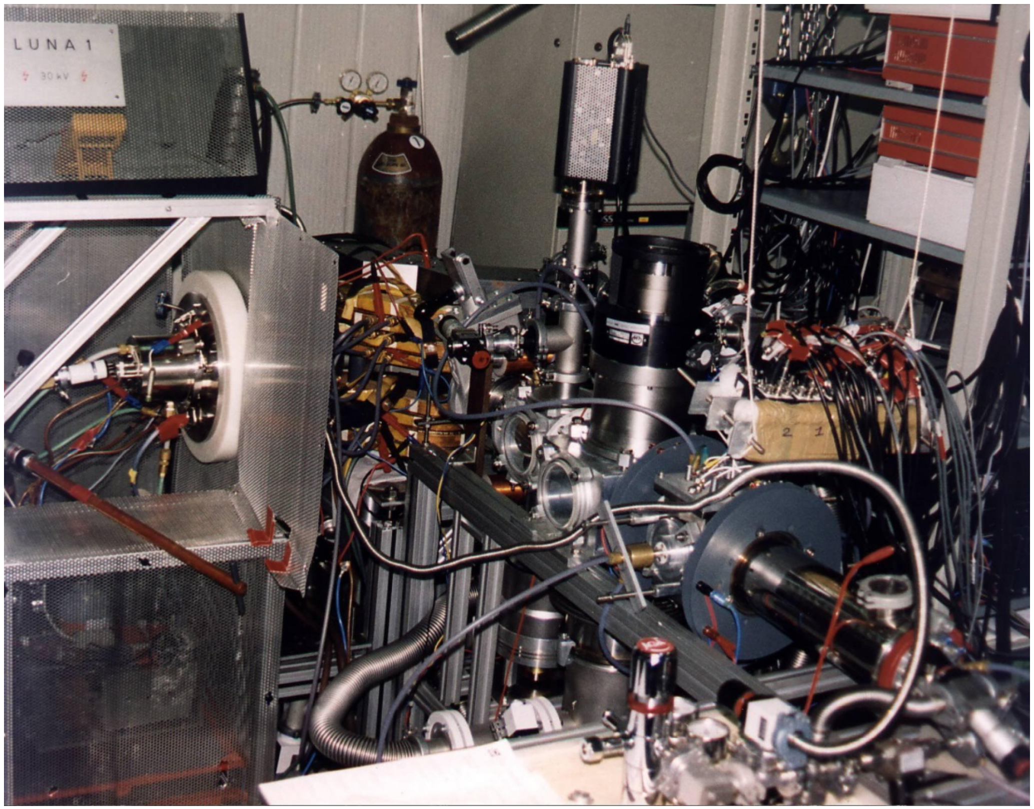




Passive shielding is more effective underground since the μ flux, that create secondary γs, is suppressed.

LUNA 50 kV

1991: Birth of underground Nuclear Astrophysics.
Thanks to E. Bellotti, C. Rolfs and G. Fiorentini

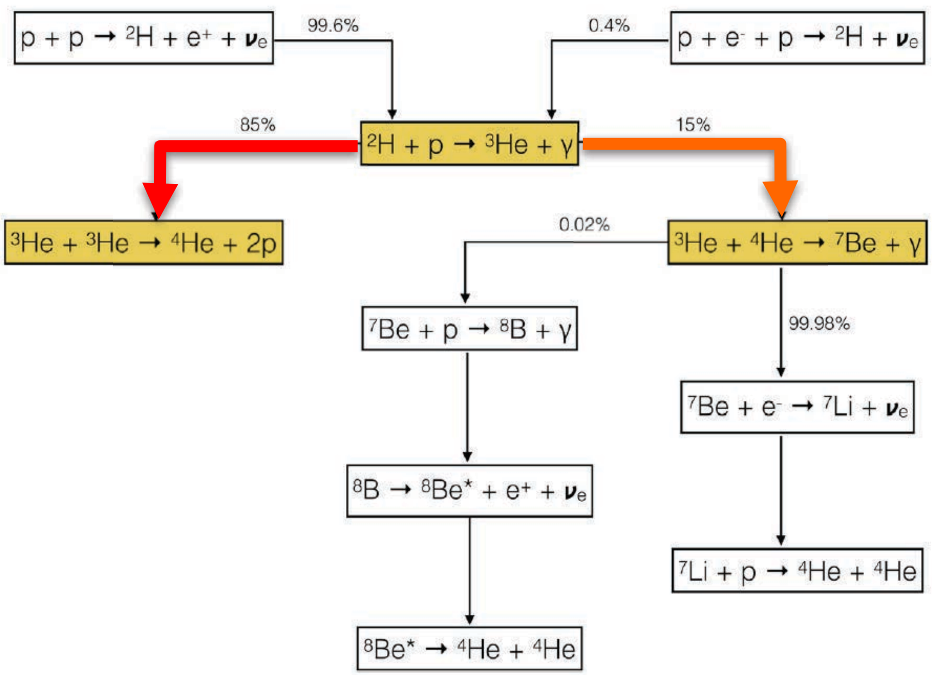


$^3He(^3He,2p)^4He$ (solar ν)
$^2H(p,\gamma)^3He$ (BBN)

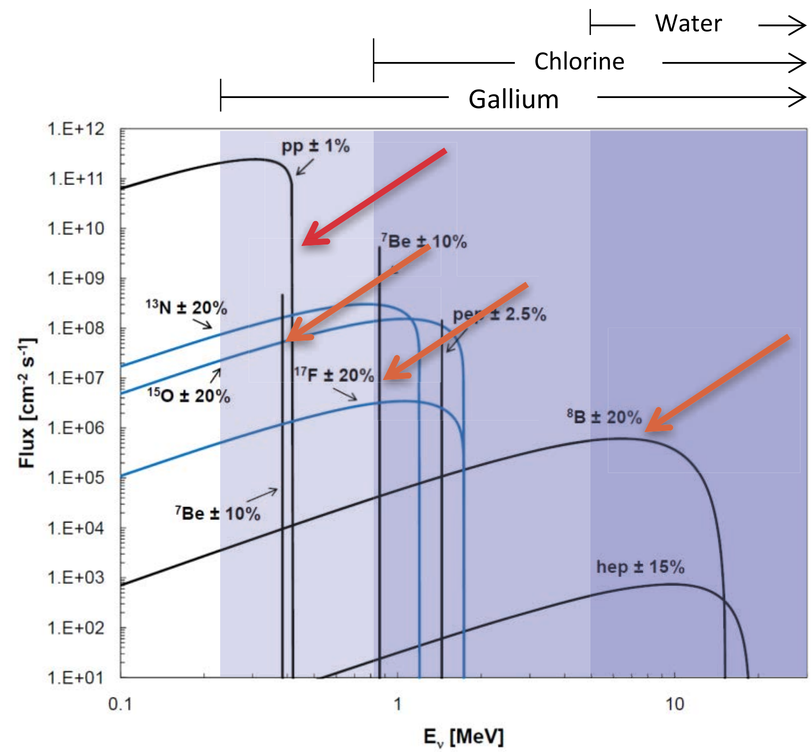
$E_{beam} \approx 1 - 50$ keV
$I_{max} \approx 500\ \mu A$ protons, ^3He
Energy spread ≈ 20 eV

Solar Neutrinos

In the Sun, 98% of neutrinos are produced by the p-p chain.

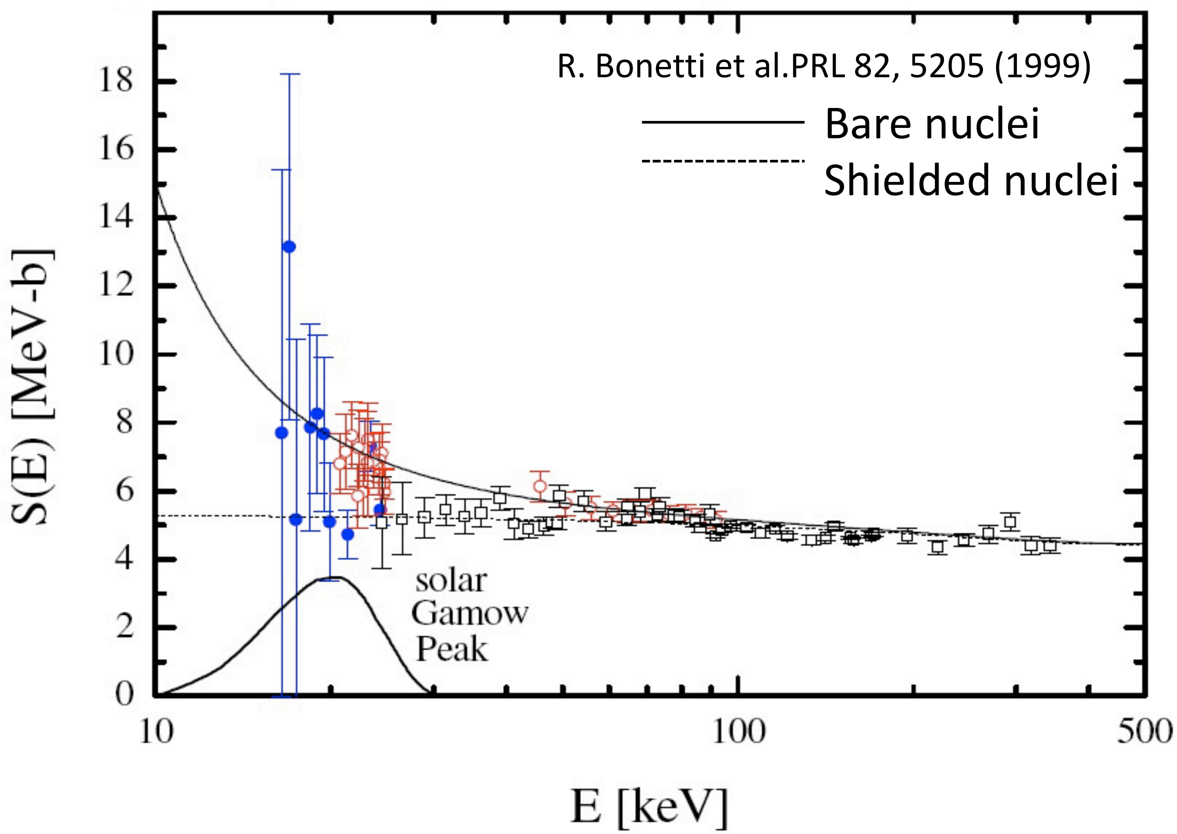


p-p chain



Following the Fowler idea, a natural way to explain the observed neutrino deficit was the existence of a narrow resonance inside the ${}^3He+{}^3He$ solar gamow peak

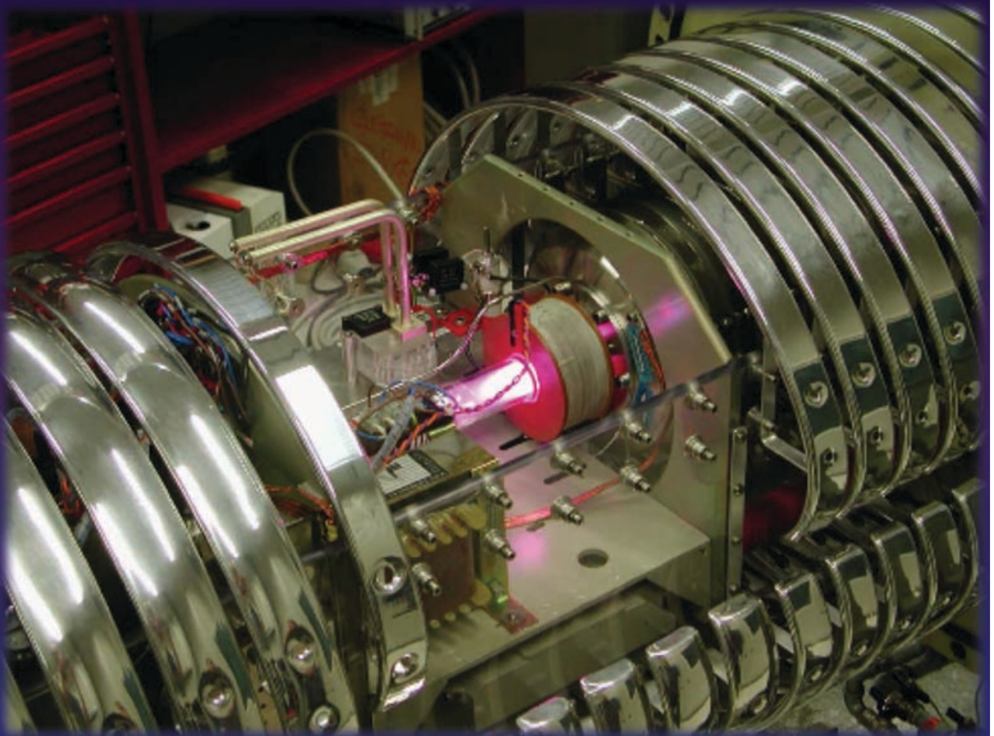
$^3He(^3He,2p)^4He$ reaction



-First measurement below the Gamow peak
-2 events/month @ E_{cm}=16,5 keV→s(16,5 keV)=20±10 fb
-No evidence for a narrow resonance → SSM validation
-LUNA measurement "triggered" the second generation of solar neutrino experiment (Borexino, Kamland, SNO), focused on the measurement of v's mixing parameters

LUNA 400 kV

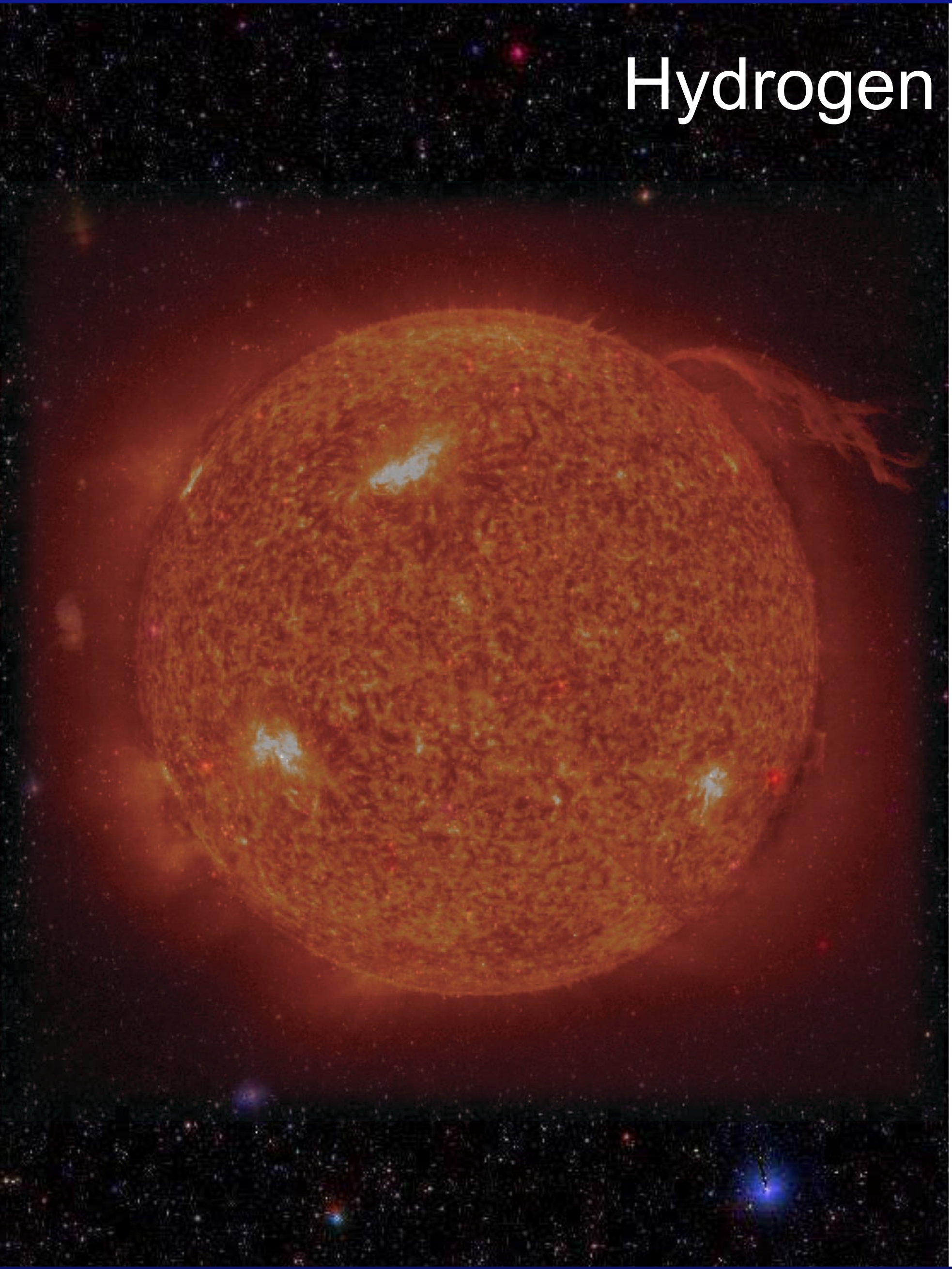
...Still the word's only operating underground accelerator



- $^{14}N(p,\gamma)^{15}O$ (Sun,CNO-I cycle)
- $^{3}He(^{4}He,\gamma)^{7}Be$ (Sun, BBN)
- $^{25}Mg(p,\gamma)^{26}Al$ (Mg-Al Cycle)
- $^{15}N(p,\gamma)^{16}O$ (CNO-II Cycle)
- $^{17}O(p,\gamma)^{18}F$ (CNO-III Cycle)
- $^{2}H(^{4}He,\gamma)^{6}Li$ (BBN)
- $^{22}Ne(p,\gamma)^{23}Na$ (Ne-Na Cycle)
- $^{2}H(p,\gamma)^{3}He$ (BBN)
- $^{13}C(\alpha,n)^{16}O$ (s-process)
- $^{12,13}C(p,\gamma)^{13,14}N$ ($^{12}C/^{13}C$ ratio)
- $^{22}Ne(\alpha,\gamma)^{23}Na$ (s-process)

$E_{beam} \approx 50 – 400$ keV
$I_{max} \approx 300\ \mu A$ protons, ^{4}He
Energy spread ≈ 70 eV

Hydrogen Burning



Many rections regulating the Hydrogen burning in stars have been studied by LUNA:

- pp-chain,
- CNO cycles
- Ne-Na cycle
- Mg-Al cicle

..With outstanding results related to:

-Mixing parameters of solar neutrinos
-Stellar evolution
-Age of Universe
-Isotopic abundances.
-Temperature and metallicity of Sun
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Hydrogen burning cycles

Sun: ~15 MK
AGB:~30-100 MK
Massive Stars: ~ 100 MK
Novae~100-400 MK
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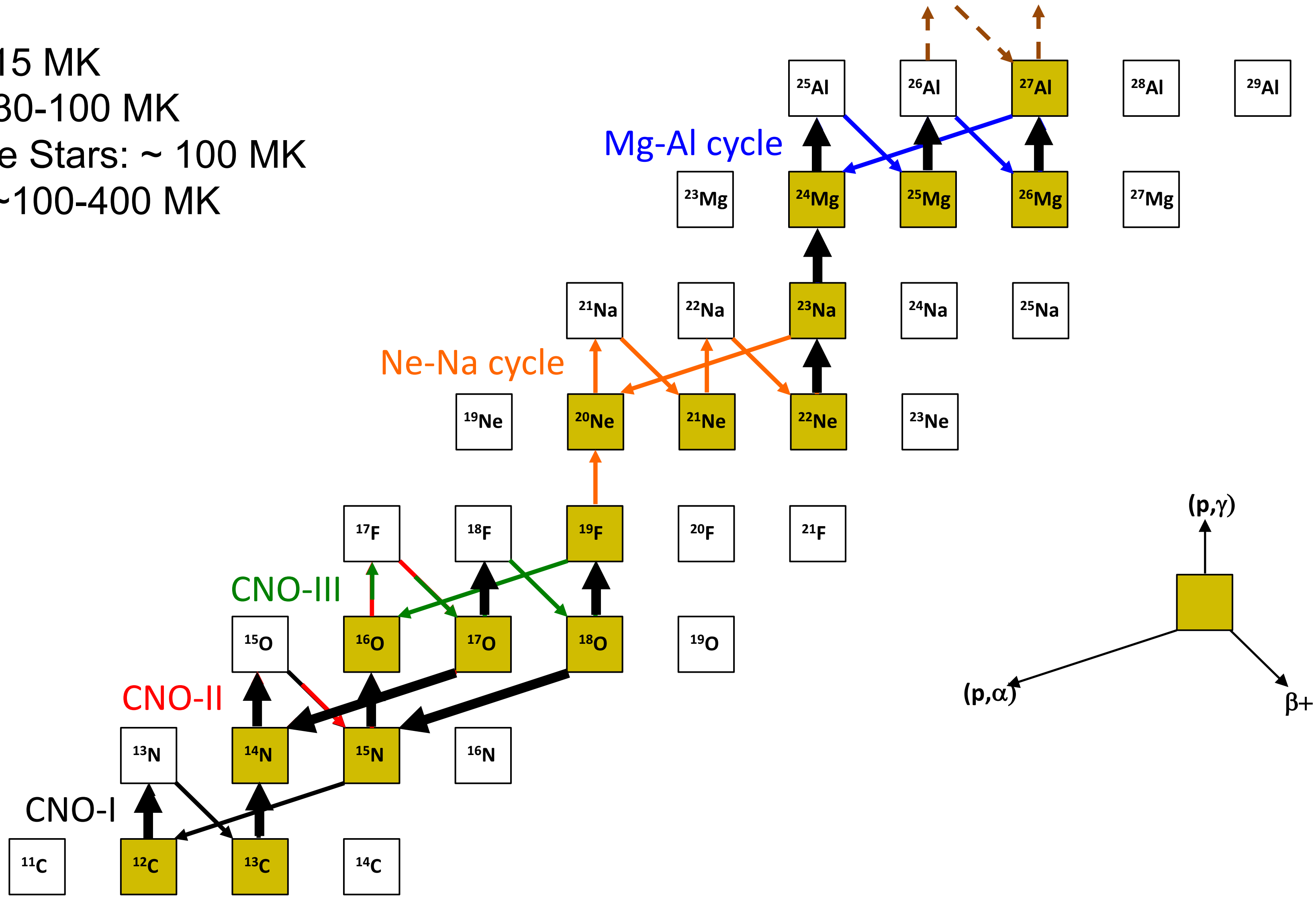
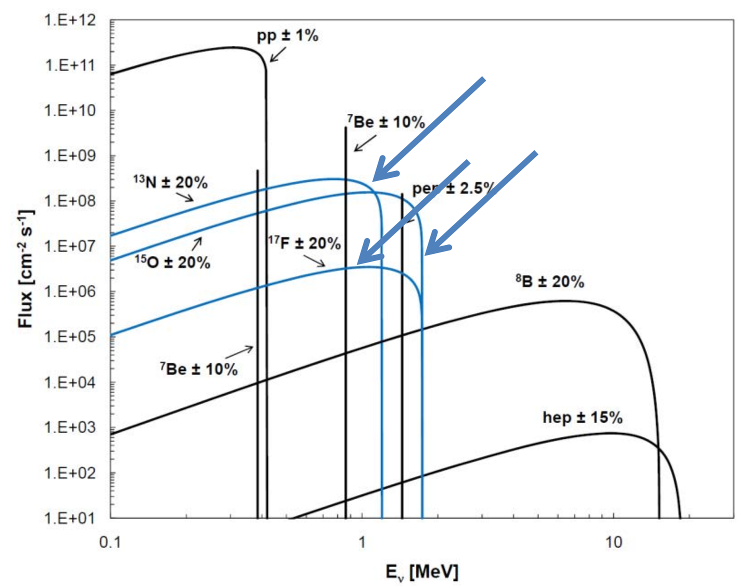


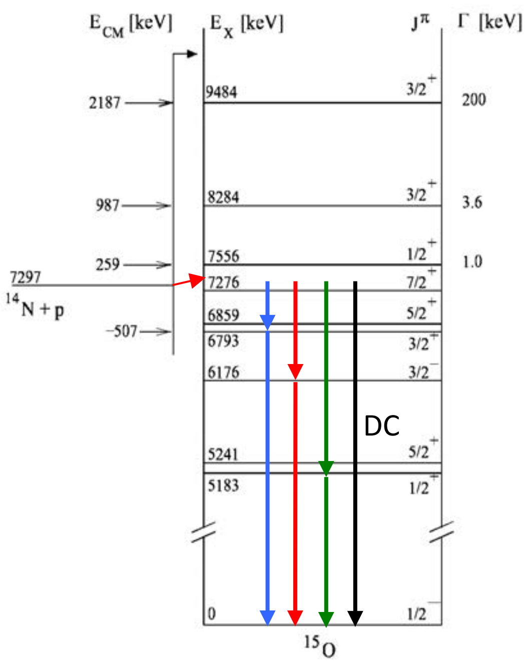
$^{14}N(p,\gamma)^{15}O$ reaction

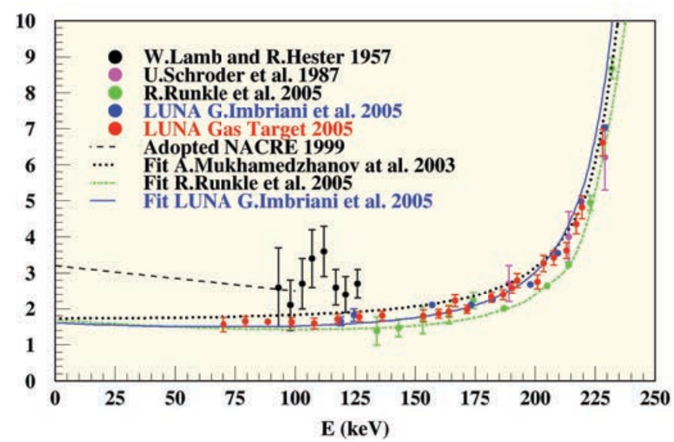
CNO neutrino flux (metallicity of Sun)
Age of Globular Clusters (→Age of Universe)

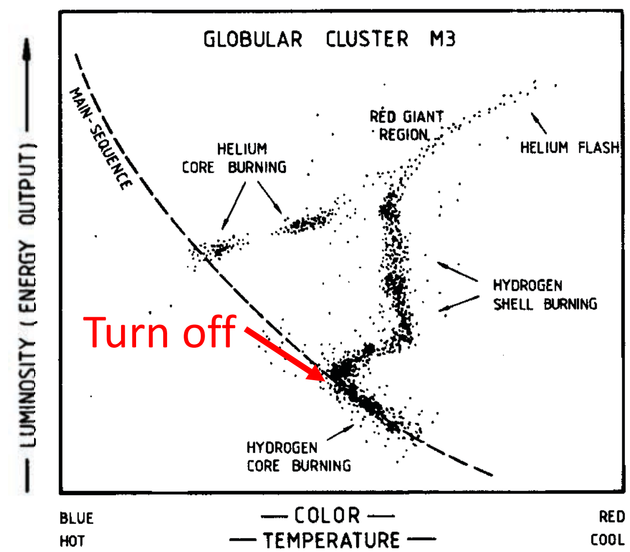
The astrophysical factor $S_{1,14}$ were found to be a factor two lower than previously extrapolated, halving the calculated CNO ν flux and increasing the GC age of about 1 Gy.

$S_{DC}(0) = 1.55 \pm 0.34$ keVb → $S_{DC}(0) = 0.25 \pm 0.06$ keVb
$S_{tot}(0) = 3.2$ keVb → $S_{tot}(0) = 1.61 \pm 0.08$ keVb









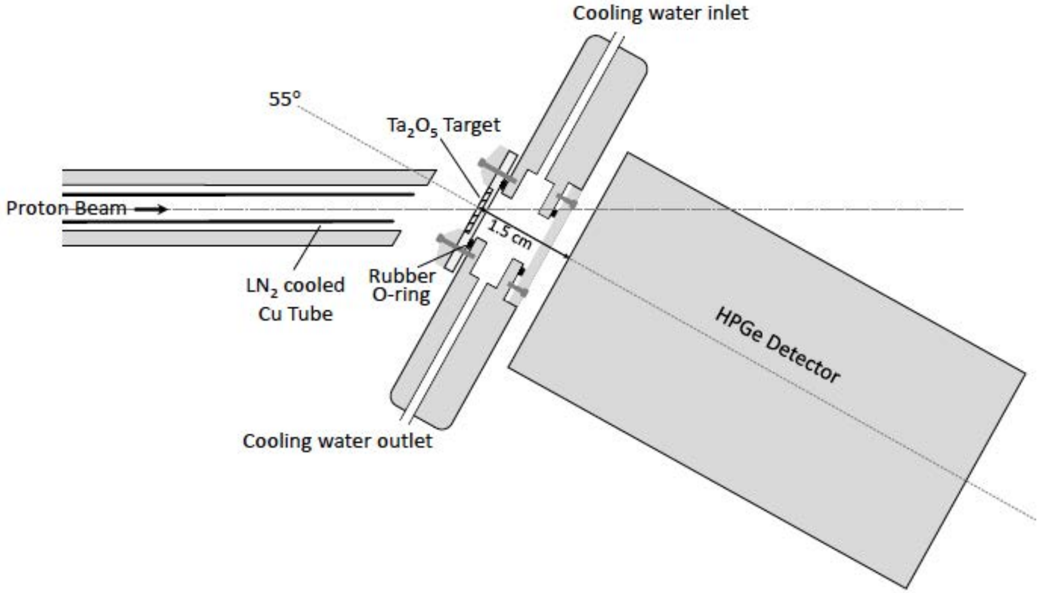
$^{17}O(p,\gamma)^{18}F$ and $^{17}O(p,\alpha)^{14}N$ reactions

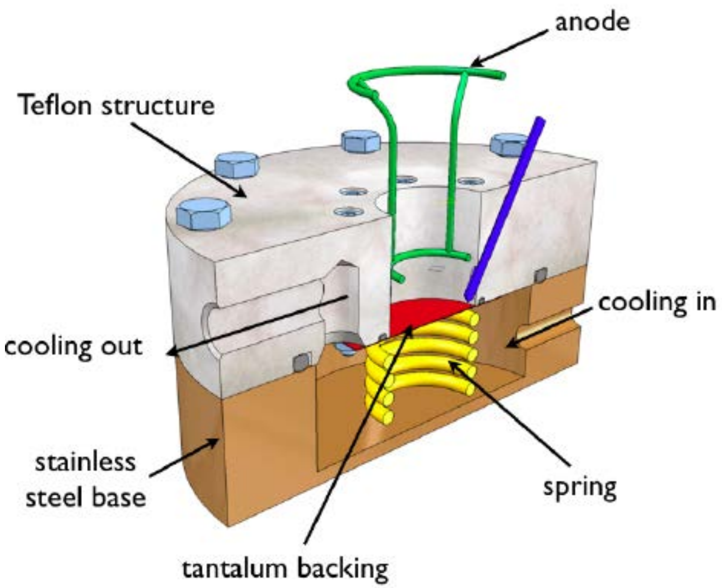
high-intensity proton beam onto Ta_2O_5 targets

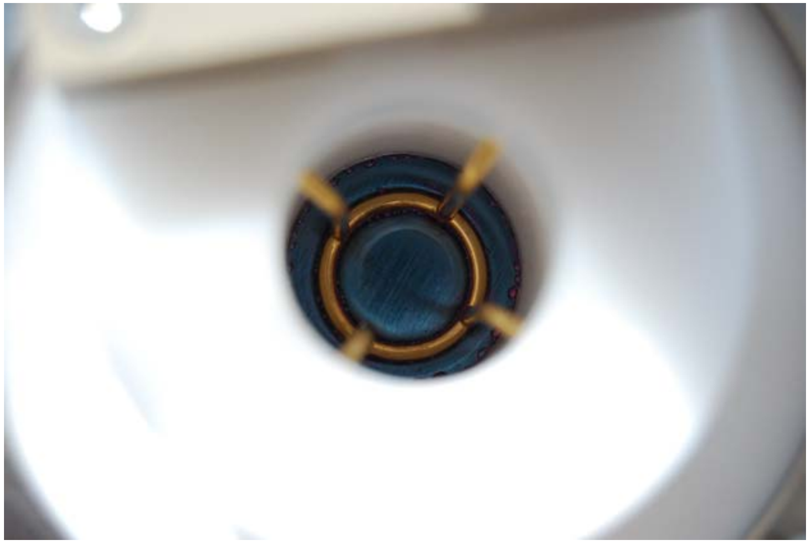
HPGe detector in close geometry for prompt γ-ray measurement

targets prepared by anodization of Ta backing in ^{17}O-enriched water

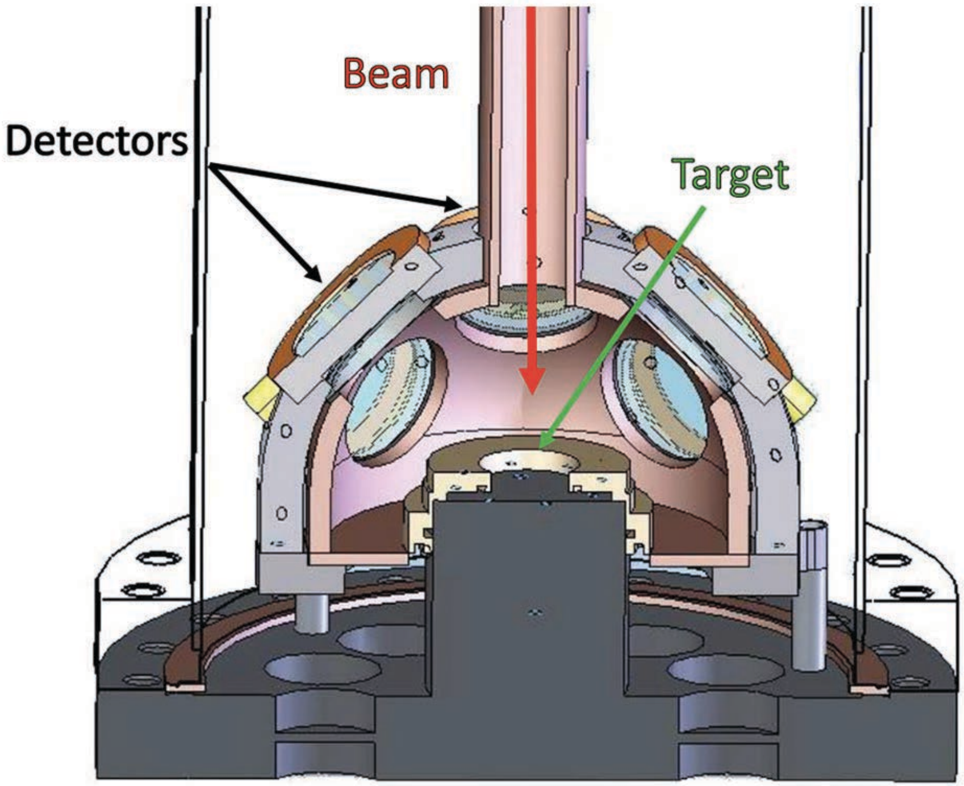
Caciolli et al. EPJA 48 (2012) 144

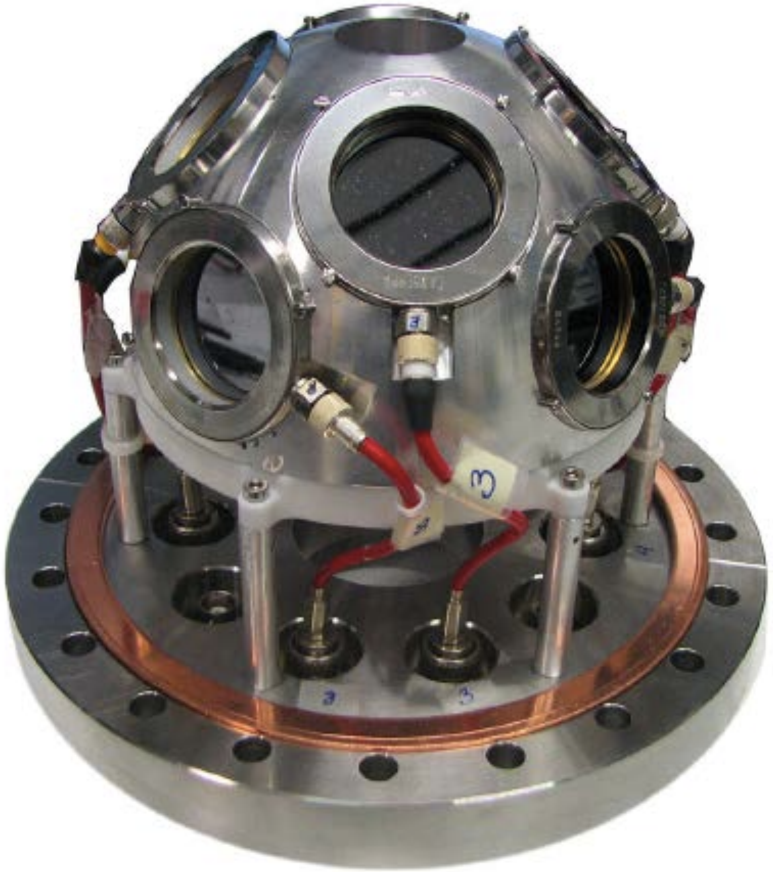






$^{17}O(p,\gamma)^{18}F$ and $^{17}O(p,\alpha)^{14}N$ reactions

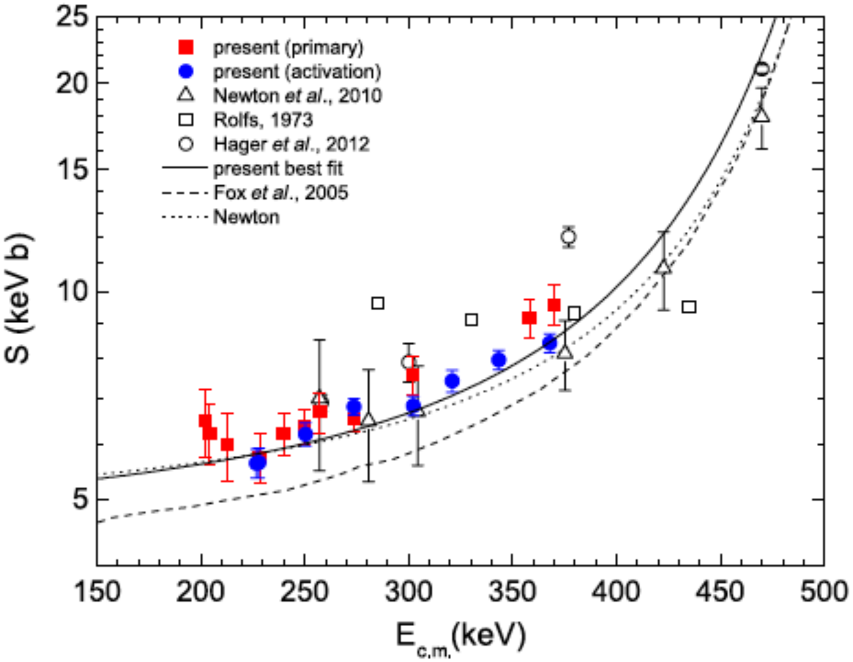




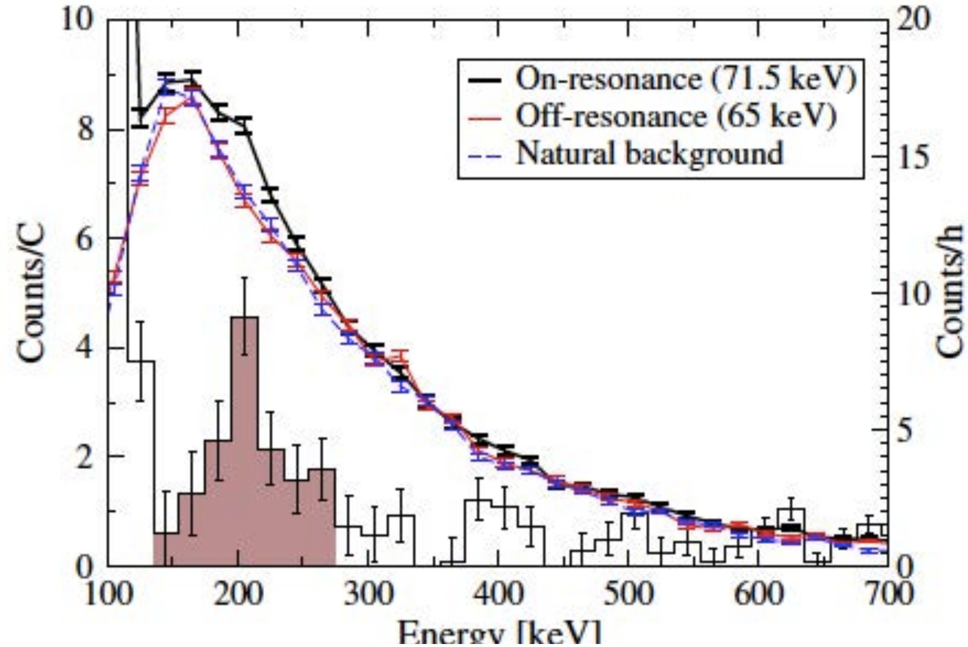
Bruno et al EJPA 51 (2015) 94

- protective aluminized Mylar foils (2.4 μm) before each detector
- expected alpha particle energy E ~ 200 keV (from 70 keV resonance)

$^{17}O(p,\gamma)^{18}F$ and $^{17}O(p,\alpha)^{14}N$ reactions



First measurement within Novae Gamow window



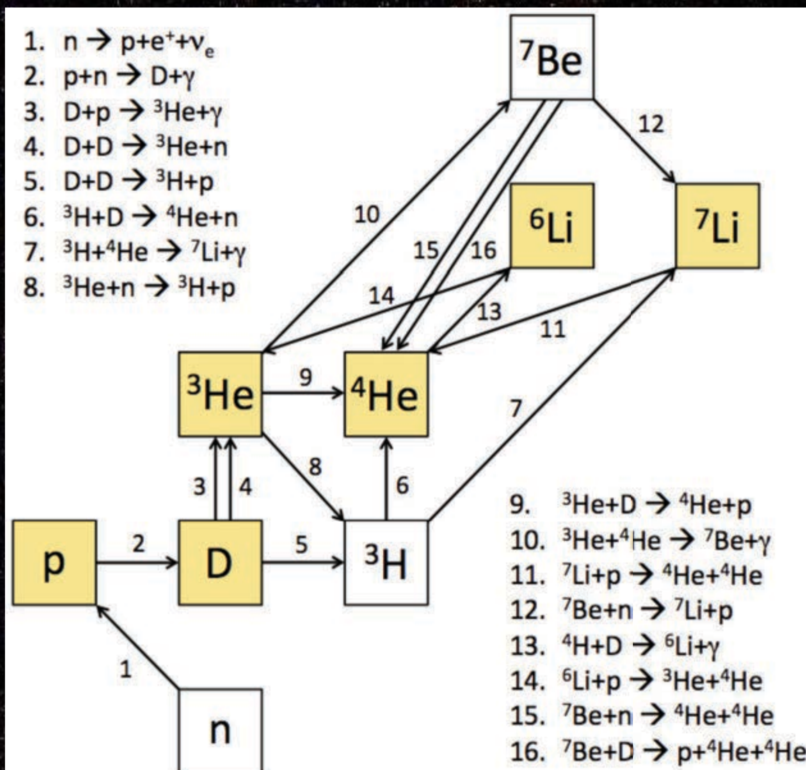
LUNA rate is a factor of 2 higher than the rate previously adopted, compatible with the hypothesis of oxygen enriched pre-solar grains in group II produced by massive AGB stars

Di Leva et al., PRC 89 (1) (2014) 015803
Scott et al., PRL 109 (20) (2012) 202501

Bruno et al., PRL 117, 142502 (2016)
Lugaro et al., Nature Astronomy 1, 0027 (2017)

Big Bang Nucleosynthesis

BBN is the result of the competition between the relevant nuclear processes and the expansion rate of the early universe:



$$H^2 = \frac{8\pi}{3} G\rho$$

$$\rho = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

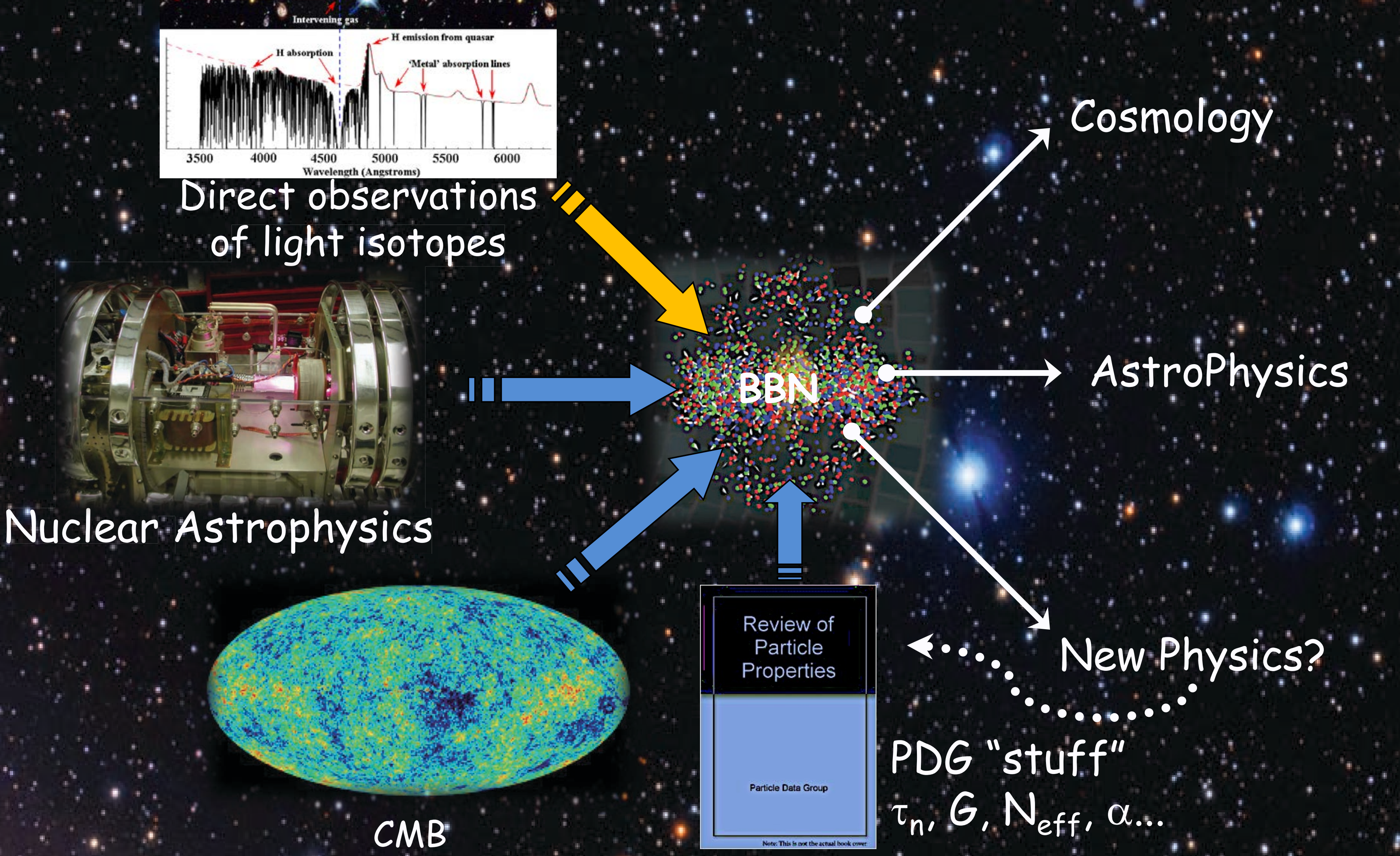
Calculation of primordial abundances only depends on:

-Baryon density Ω_b

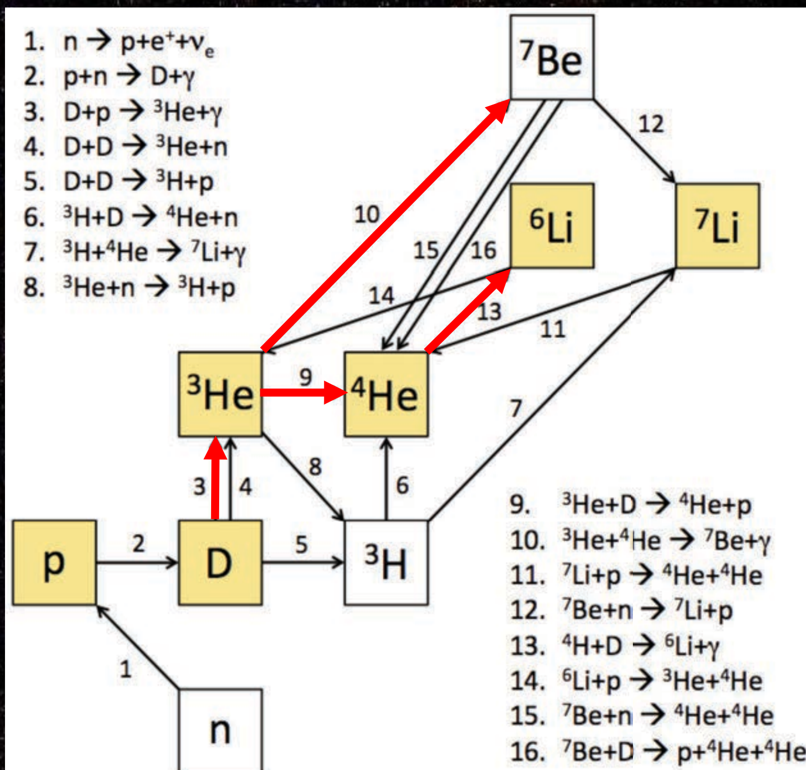
-Particle Physics (N_{eff}, α..)

-Nuclear Astrophysics, i.e. Cross sections of relevant processes at BBN energies

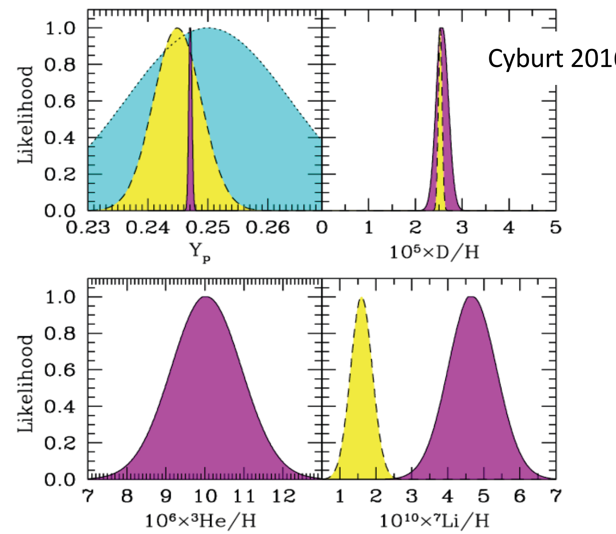
BBN “Flowchart”



Theory Vs observations



Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.05)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
^{3}He/H	$(1.00\pm0.01)\times10^{-5}$	$(0.9\pm1.3)\times10^{-5}$
^{7}Li/H	$(4.68\pm0.67)\times10^{-10}$	$(1.23\ ^{+0.68}_{-0.32})\times10^{-10}$
^{6}Li/^{7}Li	$(1.5\pm0.3)\times10^{-5}$	$<\sim10^{-2}$



^{4}He, D, ^{3}He abundances measurements are (broadly) consistent with expectations.
^{7}Li: Long standing "Lithium problem"
^{6}Li: "Second Lithium problem"?

$^3He(\alpha,\gamma)^7Be$ reaction

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.05)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
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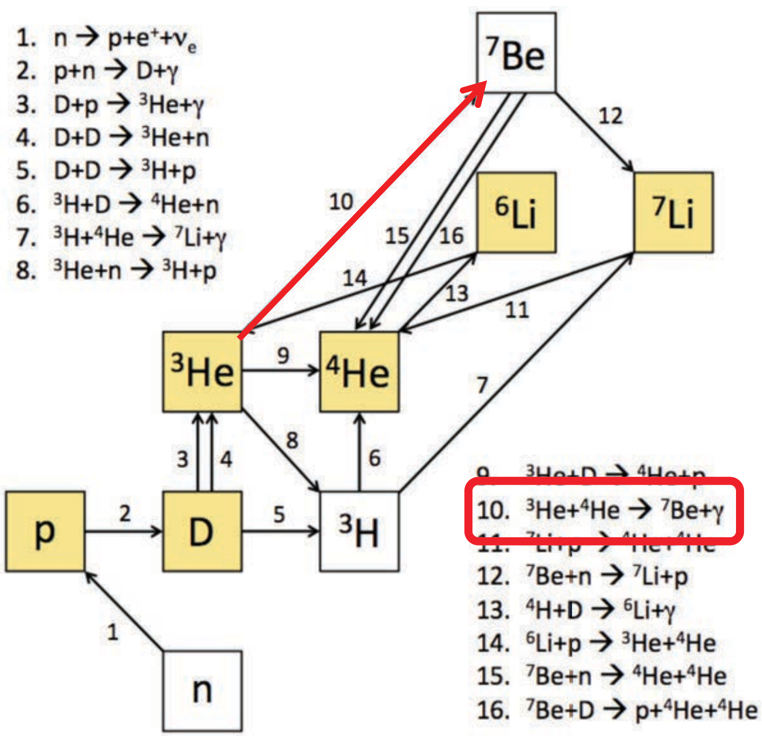

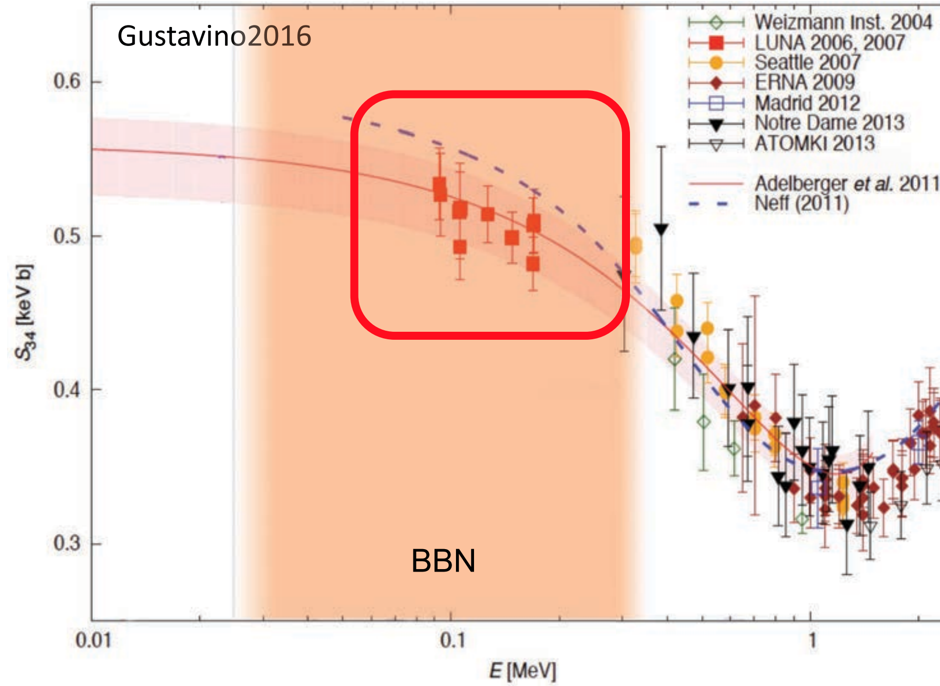

-LUNA data well inside the BBN energy region
-Low uncertainty (4%)
-Simultaneous measurement of prompt and delayed γs
→ Consolidation of "Lithium Problem"

D(α,γ)^{6}Li reaction

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.05)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
^{3}He/H	$(1.00\pm0.01)\times10^{-5}$	$(0.9\pm1.3)\times10^{-5}$
^{7}Li/H	$(4.68\pm0.67)\times10^{-10}$	$(1.23\ ^{+0.68}_{-0.32})\times10^{-10}$
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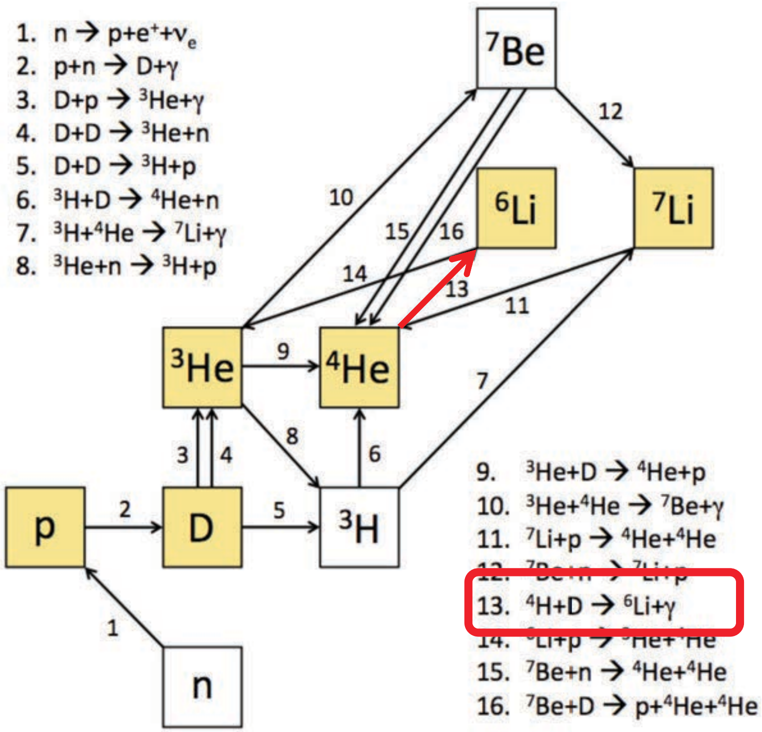

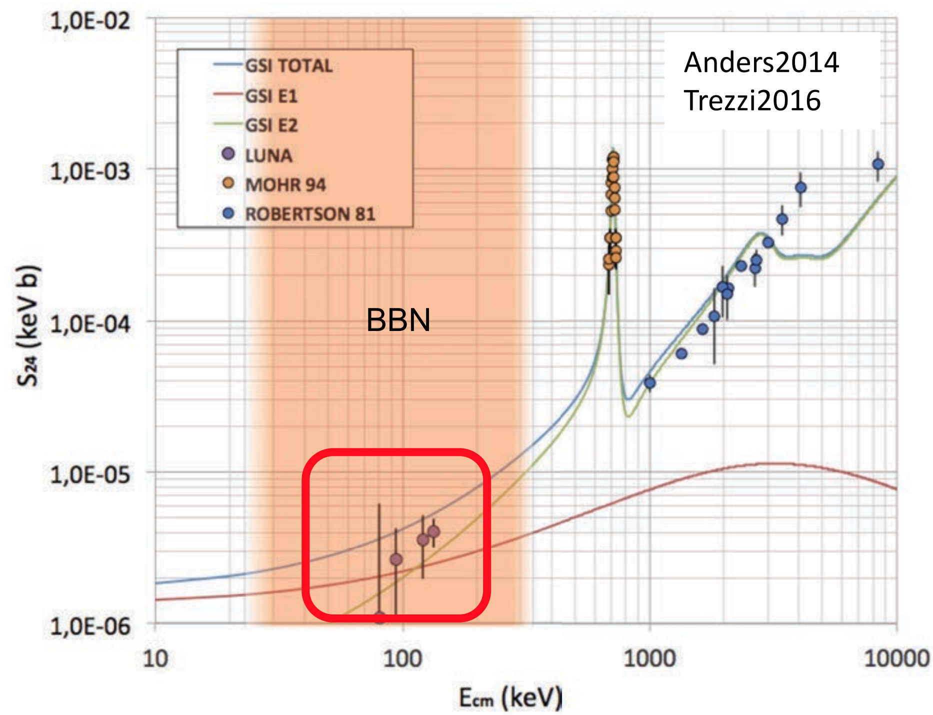

First direct measurement in the BBN energy region

→LUNA data exclude a nuclear solution for the purported ^{6}Li problem...

D(p,γ)^{3}He reaction

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.05)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
^{3}He/H	$(1.00\pm0.01)\times10^{-5}$	$(0.9\pm1.3)\times10^{-5}$
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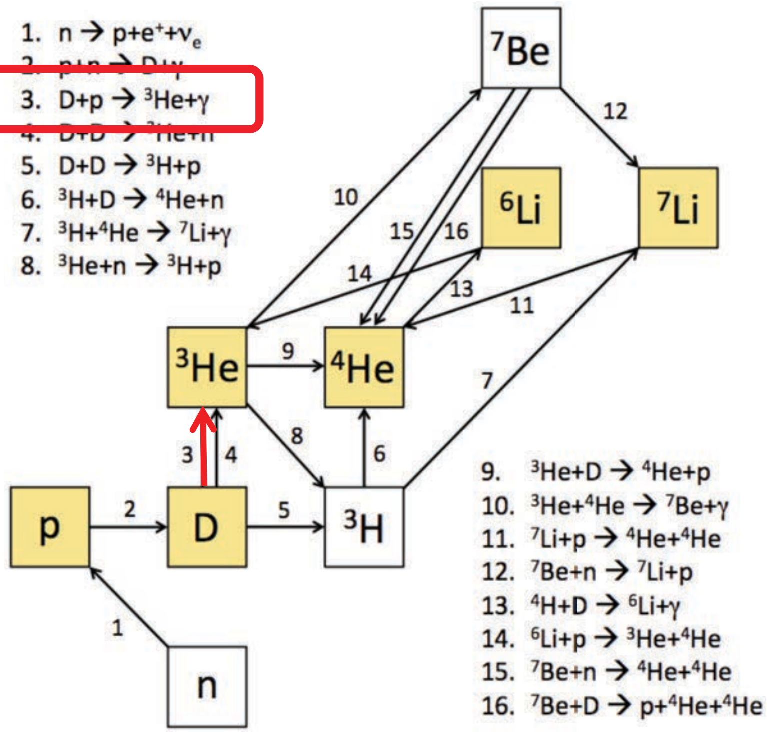
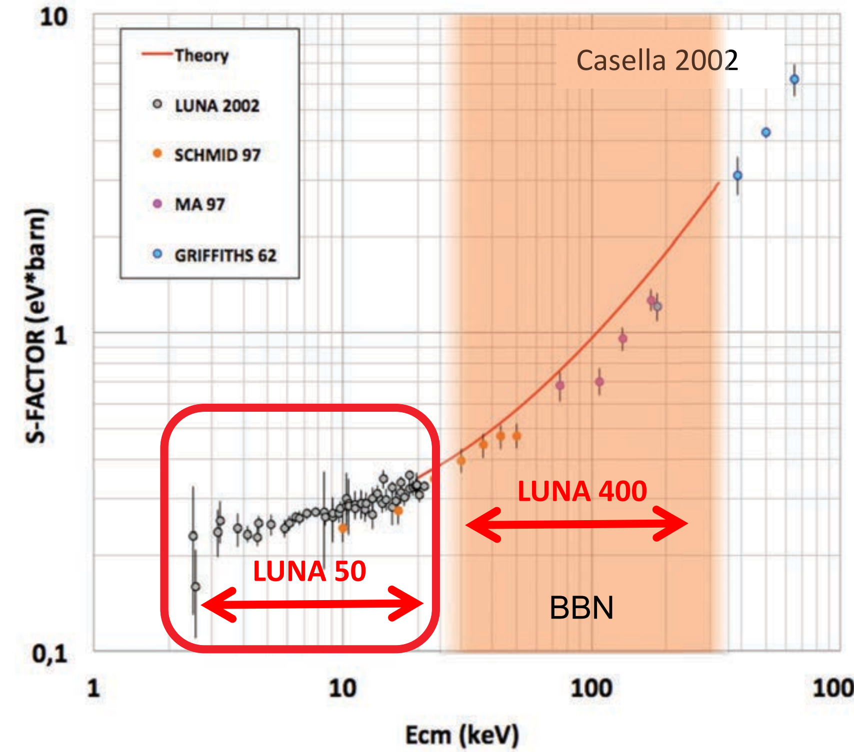




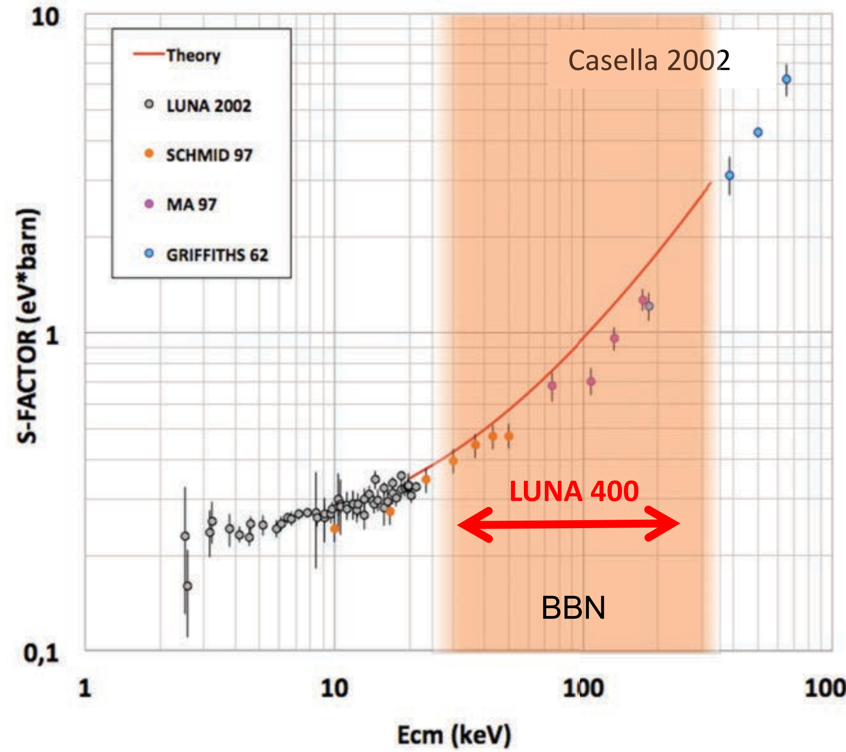
Reduction of $(D/H)_{BBN}$ error of a factor 3 with LUNA 50 kV

D(p,γ)^{3}He reaction @ LUNA400

Reaction	Rate Symbol	$\sigma_{^2H/H} \cdot 10^5$
$p(n,\gamma)^2$H	R_1	± 0.002
$d(p,\gamma)^3$He	R_2	± 0.062
$d(d,n)^3$He	R_3	± 0.020
$d(d,p)^3$H	R_4	± 0.013

(Di Valentino, C.G. et al. 2014)

-The error budget of computed abundance of deuterium is mainly due to the D(p,γ)^{3}He reaction
-measurements (9% error) NOT in agreement with recent ”Ab-Initio” calculations.



Measurement goal:

-Cross section measurement at $30 < E_{cm}(\text{keV}) < 260$ with ~ 3% accuracy
-Differential cross section measurement at $100 < E_{cm} < 260$

Physics:

-Cosmology: measurement of Ω_b.
-Neutrino physics: measurement of N_{eff}.
-Nuclear physics: comparison of data with “ab initio” predictions.

D(p,γ)^{3}He reaction @ LUNA400

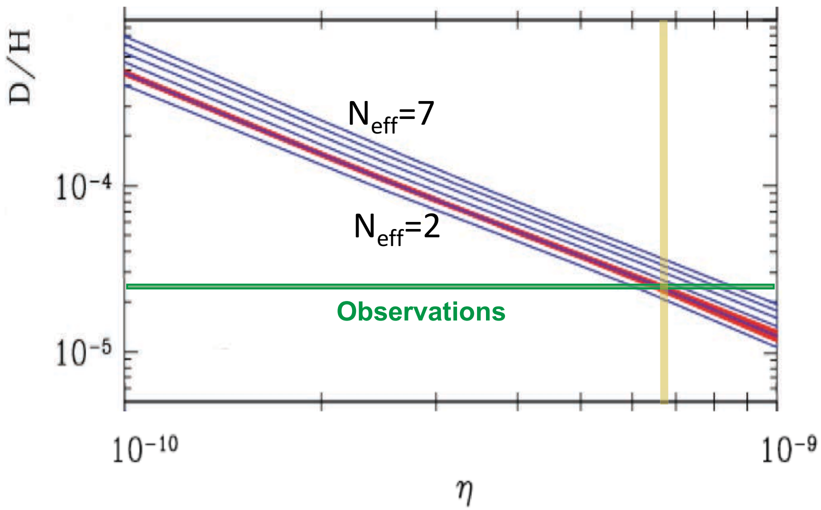
-BBN provides a precise estimate of Baryon density Ω_b , through the comparison of $(D/H)_{BBN}$ and $(D/H)_{obs}$:

Dpγ data fit

$100\Omega_{b,0}h^2$(BBN)=2.20±0.04±0.02 (Cooke2013)
$100\Omega_{b,0}h^2$(BBN)=2.16±0.01±0.02 (Cooke2016)

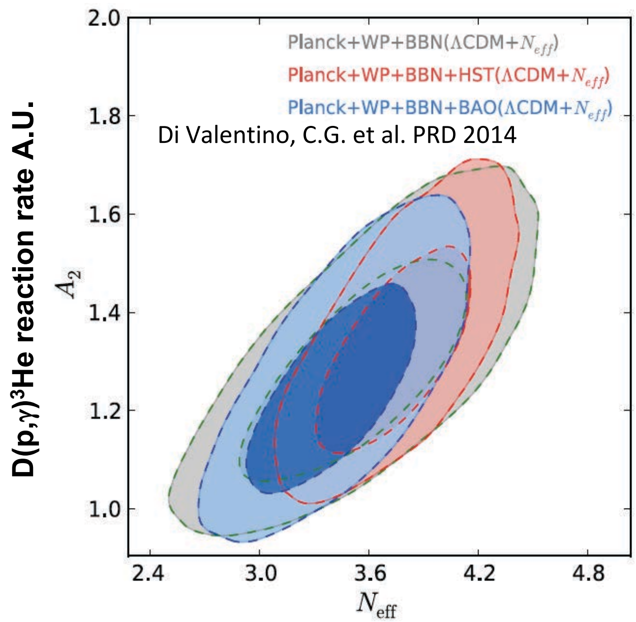
Dpγ "ab-initio"
D/H observations

From CMB data:
$100\Omega_{b,0}h^2$(CMB)=2.237±0.015 (PLANCK2018)

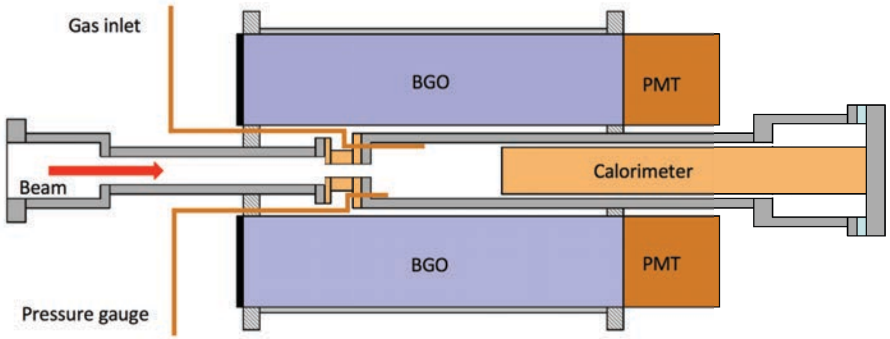


-Deuterium abundance also depends on the density of relativistic particles, (photons and 3 neutrinos in SM). Therefore it is a tool to constrain "dark radiation".

Assuming literature data for the D(p,γ)^{3}He reaction:
N_{eff} (BBN) = 3.57±0.18 (Cooke&Pettini 2013)
N_{eff} (CMB) = 3.36±0.34 (PLANCK 2013)
N_{eff} (SM) = 3.046

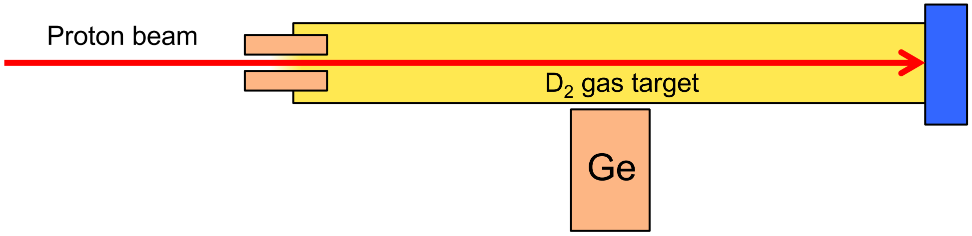


D(p,γ)^{3}He reaction: setup



High efficiency (~60%, ~4π acceptance)

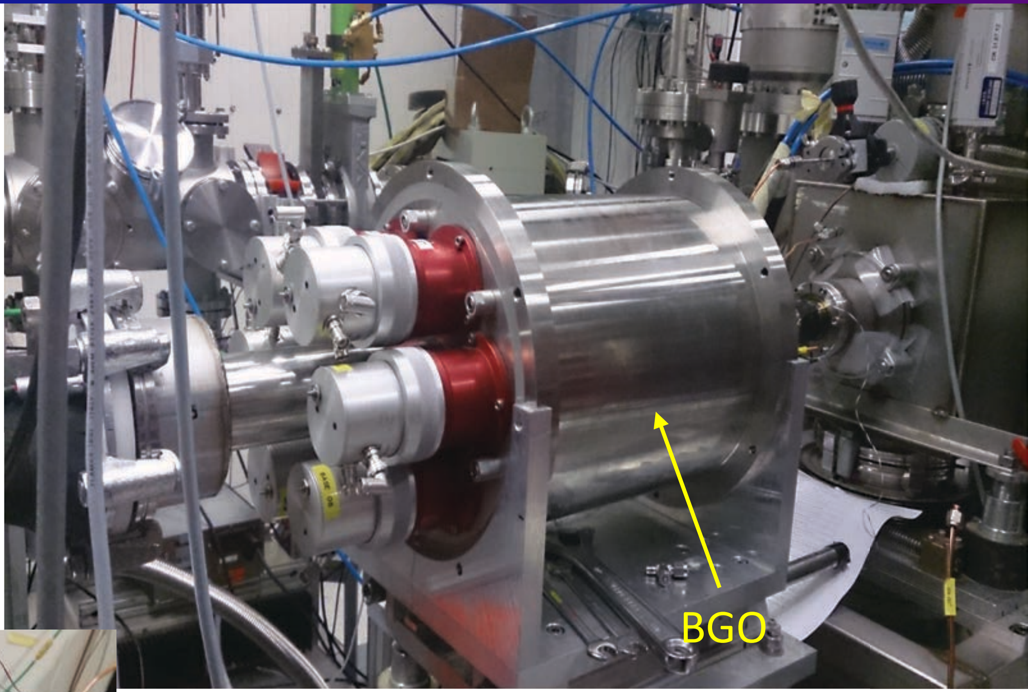
BGO detector

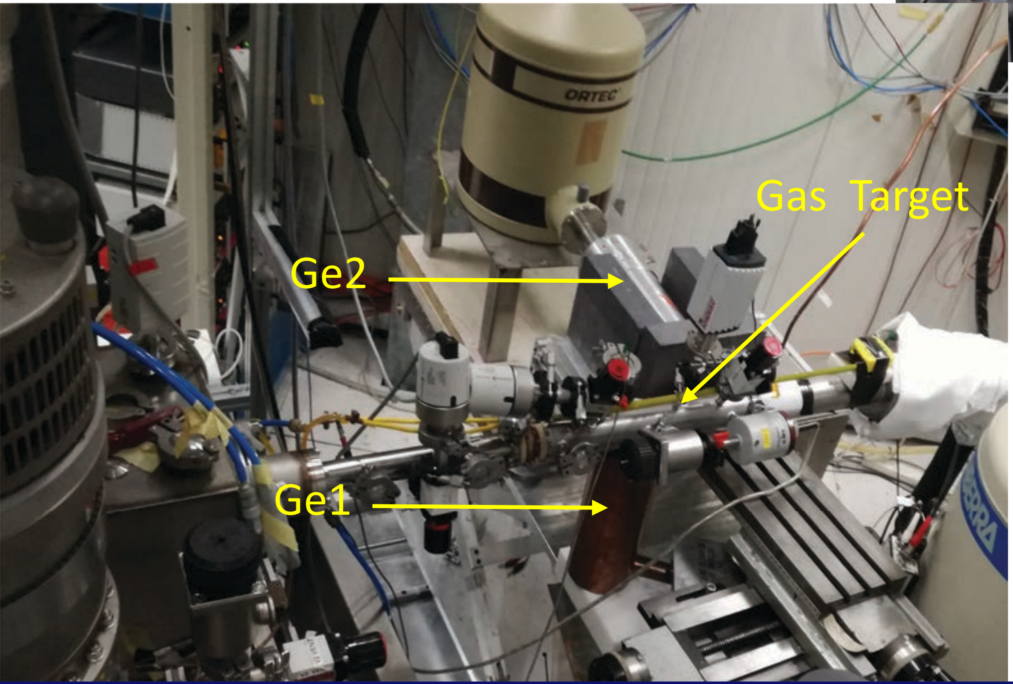


High energy resolution (~10 keV @ 6 MeV)

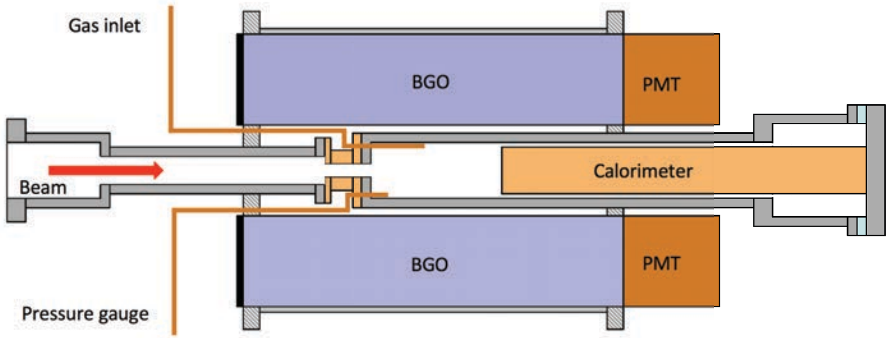
Ge(Li) detector

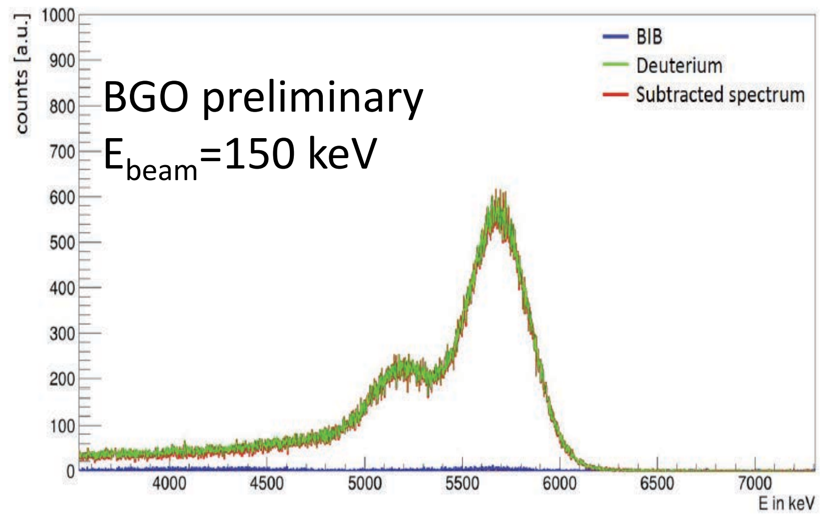
D(p,γ)^{3}He reaction: setup



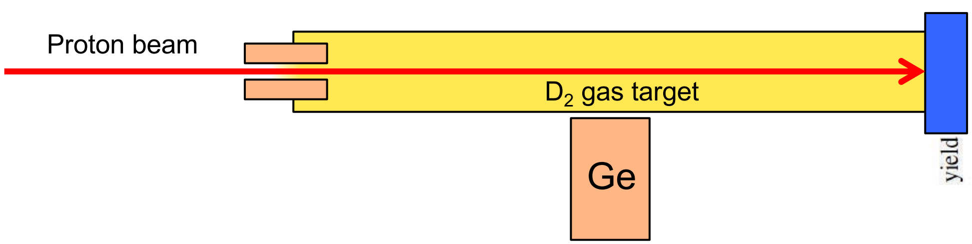


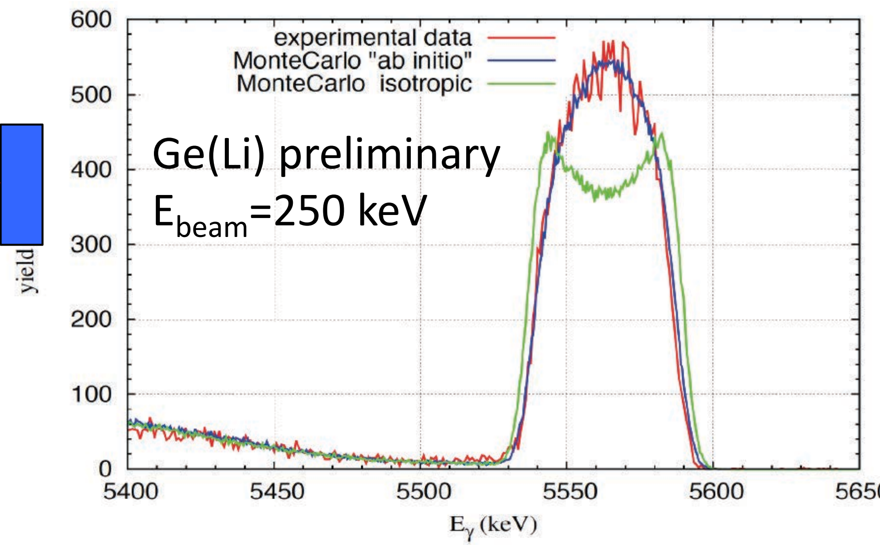
Preliminary results





BGO detector





Ge(Li) detector

LUNA

Next: LUNA MV

HIGH VOLTAGE ENGINEERING EUROPA B.V.
Amsterdamseweg 63, 3812 RR Amersfoort, P.O. Box 99, 3800 AB Amersfoort, The Netherlands
Phone: +31-33-4619741. Fax +31-33-4615291. Trade register Amersfoort nr. 31014544
E-mail: info@highvolteng.com – Web: www.highvolteng.com

March 19, 2018

FACTORY ASSEMBLY PROTOCOL
3.5 MV Singletron accelerator system

End-User/Consignee: Laboratory Nazionale del Gran Sasso, Assergi, Italy

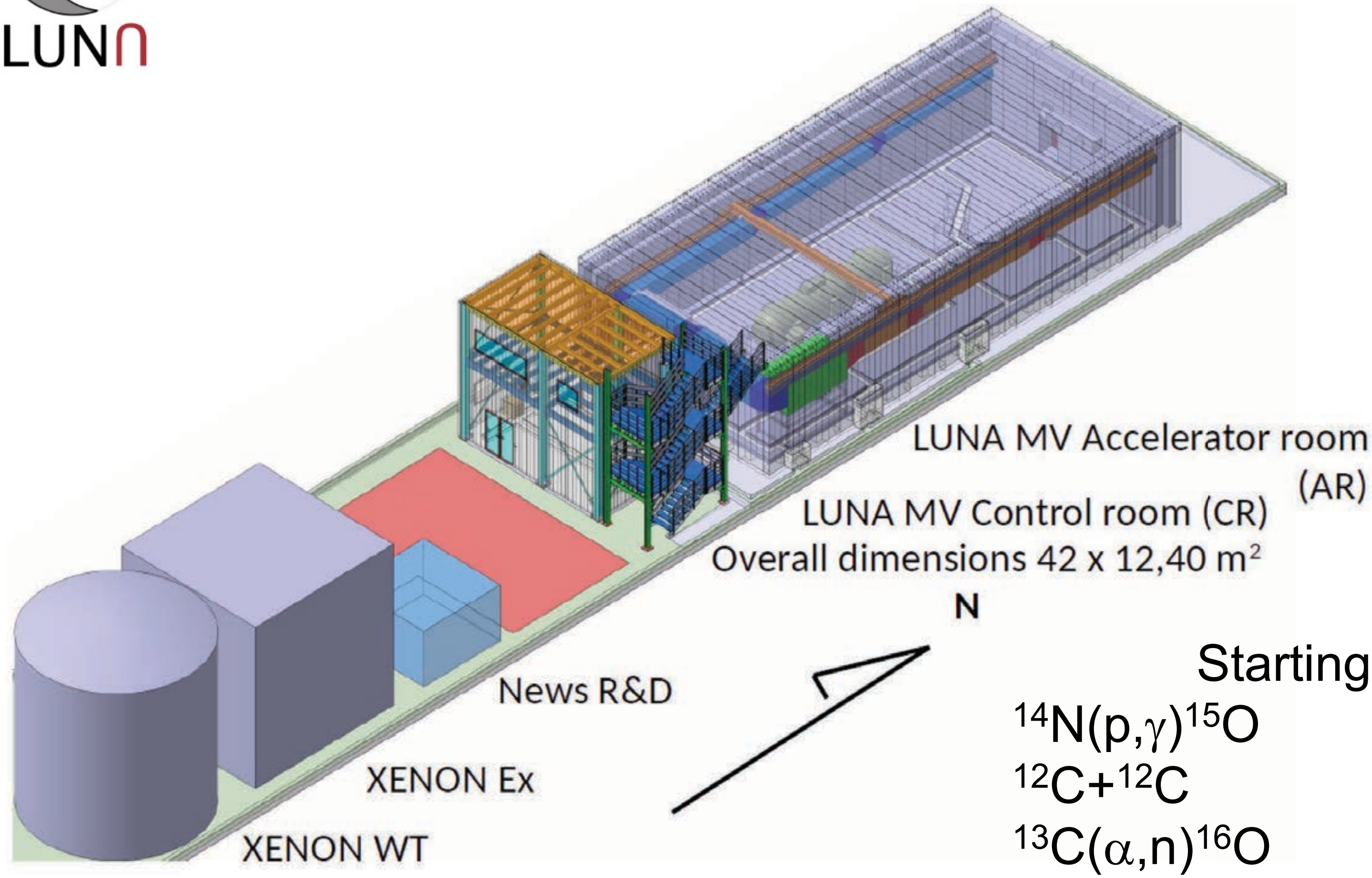
Contract number: CIG No. 62076380EF and CUP No. 154G14000140005
CIG No. 62076380EF Amdt. No. 1

HVEE ref.: B9051

Delivery at LNGS: january 2019

Gran Sasso Assergi, Italy is fully assembled at HVE Amersfoort, The Netherlands.

Next: LUNA MV



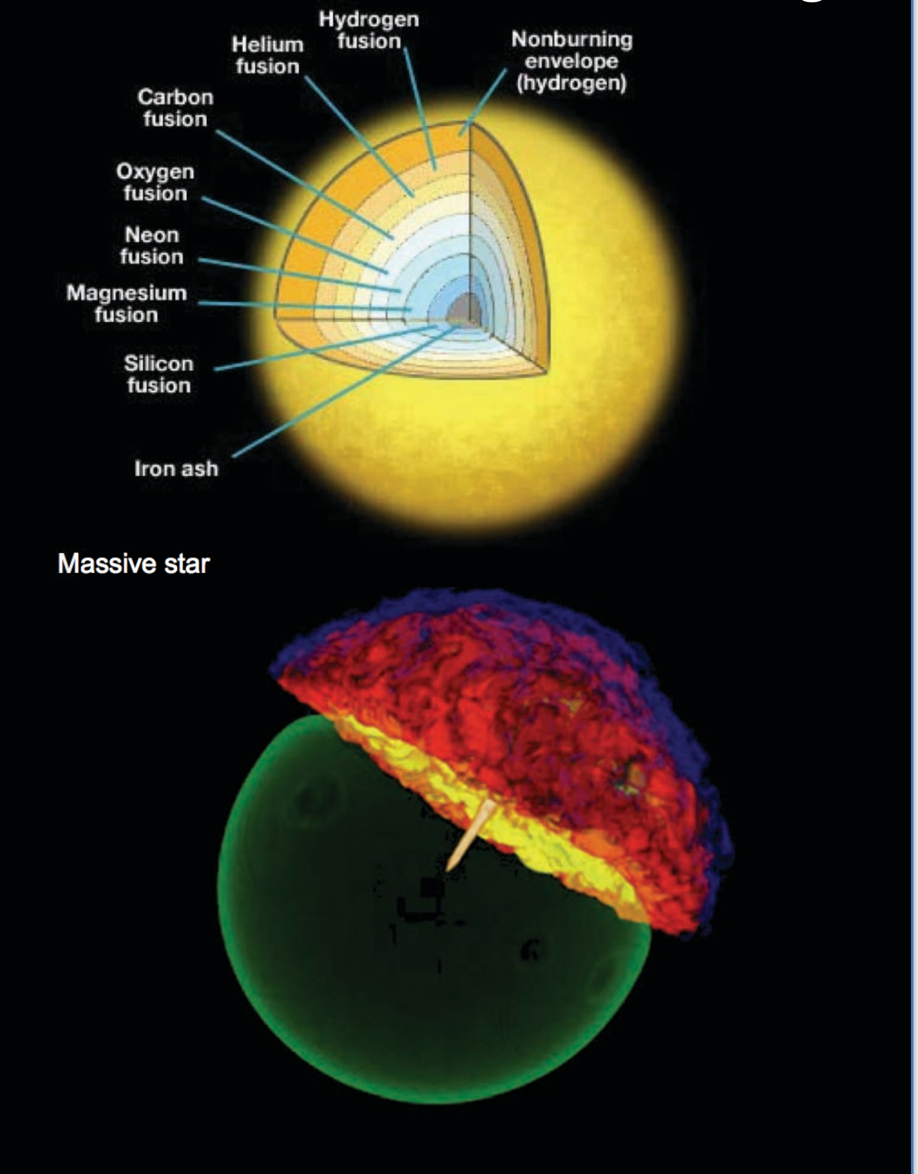
Starting program:

$^{14}N(p,\gamma)^{15}O$	(CNO I Cycle)
$^{12}C+^{12}C$	(Carbon burning)
$^{13}C(\alpha,n)^{16}O$	(s-process)
$^{22}Ne(\alpha,n)^{25}Mg$	(s-process)
$^{12}C(\alpha,\gamma)^{16}O$	(Helium burning)
First run:	june 2019.

Terminal Voltage ≈ 0.2 – 3.5 MV

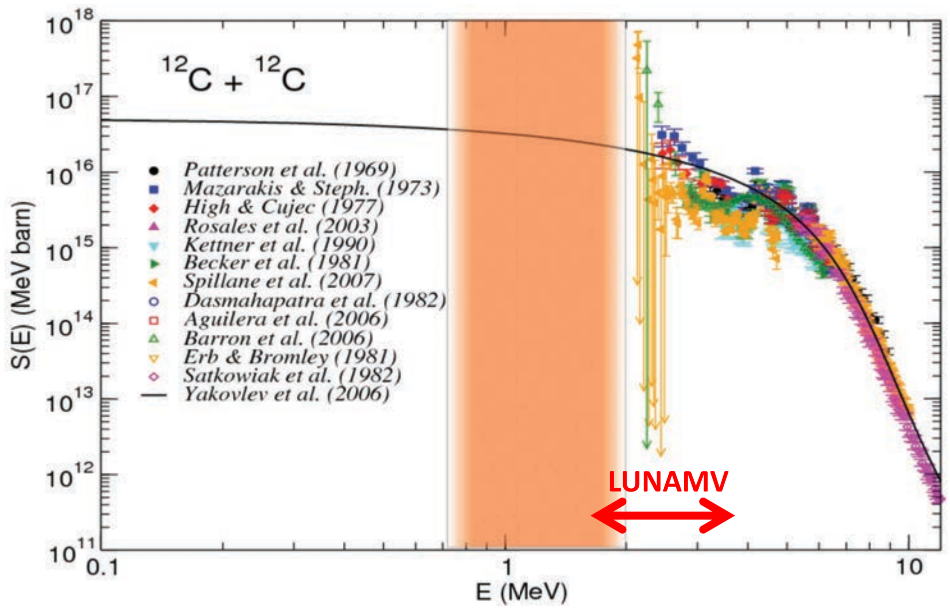
I_{max} ≈ 100-1000 μA protons, ^{4}He, $^{12}C^{+}$, $^{12}C^{++}$

Carbon Burning & type Ia supernovae



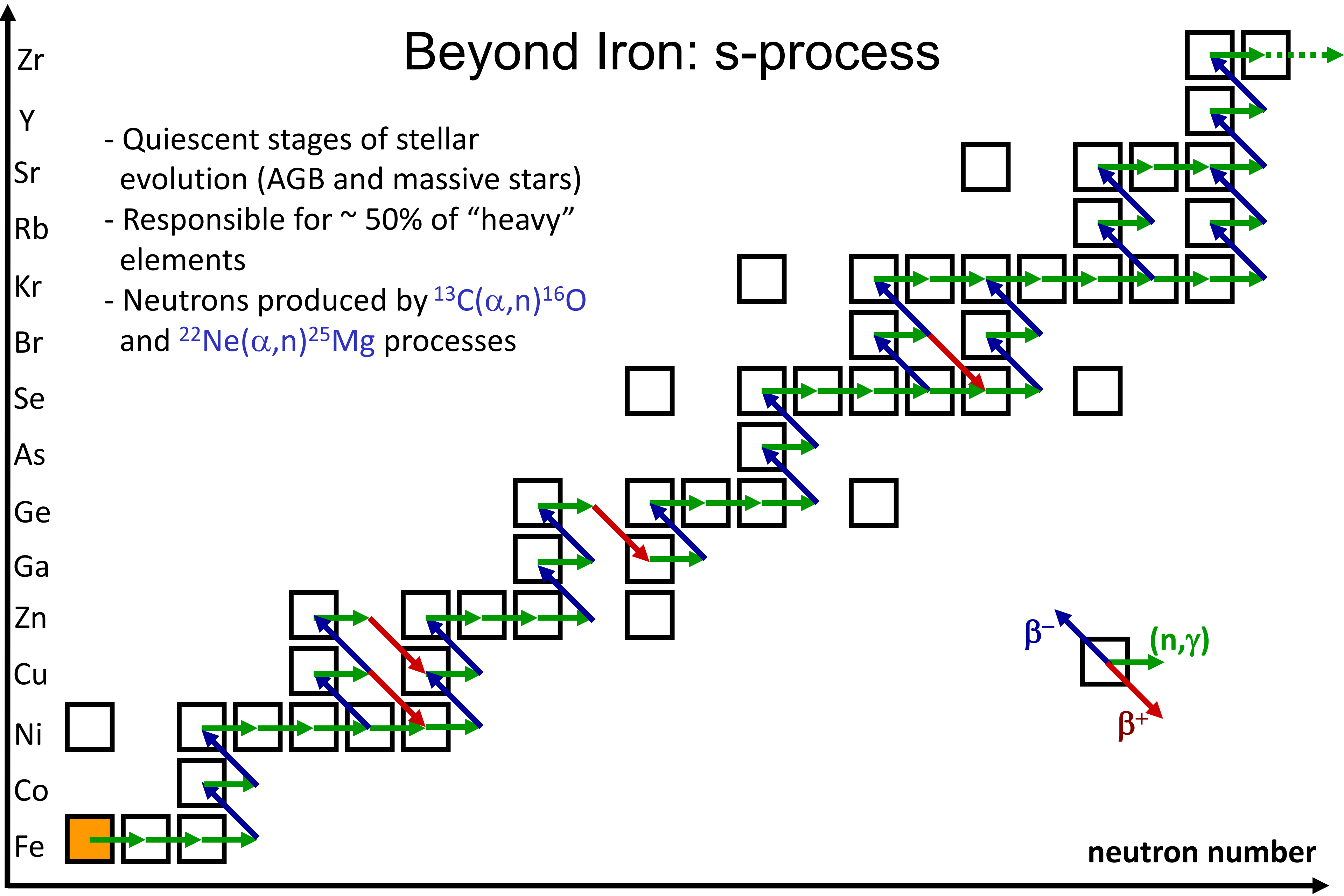
$$
\begin{aligned}
{}^{12}C + {}^{12}C &\rightarrow {}^{16}O + 2\,{}^{4}He \\
&\rightarrow {}^{20}Ne + {}^{4}He \\
&\rightarrow {}^{23}Na + p^{+} \\
&\rightarrow {}^{23}Mg + n \\
&\rightarrow {}^{24}Mg + \gamma
\end{aligned}
$$

- Critical mass for the fate of a star
- Population of WD, novae, SN1a, SN, NS and BH.
- Duration of quiescent carbon burning
- Complex chains involving C→Si nuclei
- Affects s-process
- Strongly affects the abundance of elements
- Type 1a supernovae outcomes



Beyond Iron: s-process

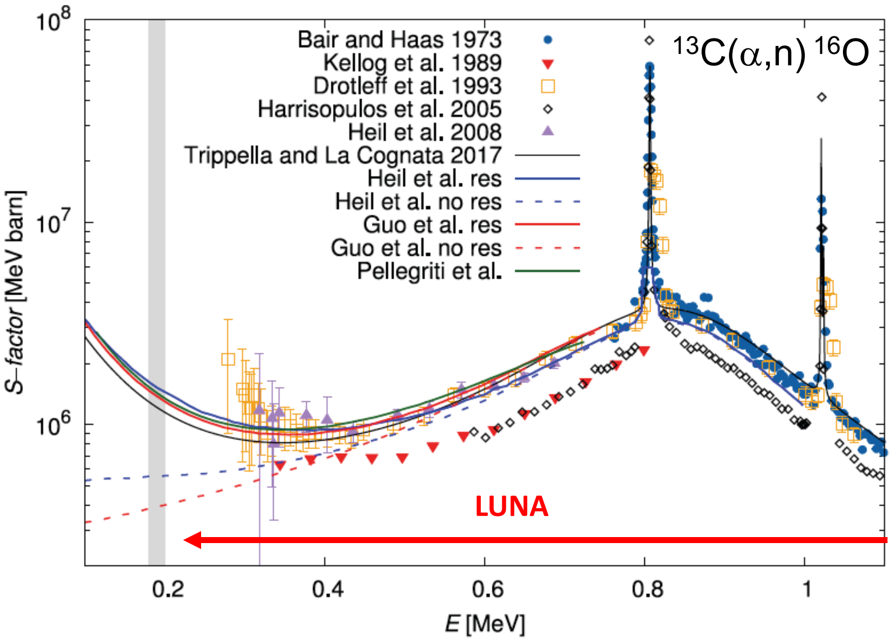
- Quiescent stages of stellar evolution (AGB and massive stars)
- Responsible for ~ 50% of “heavy” elements
- Neutrons produced by $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ processes

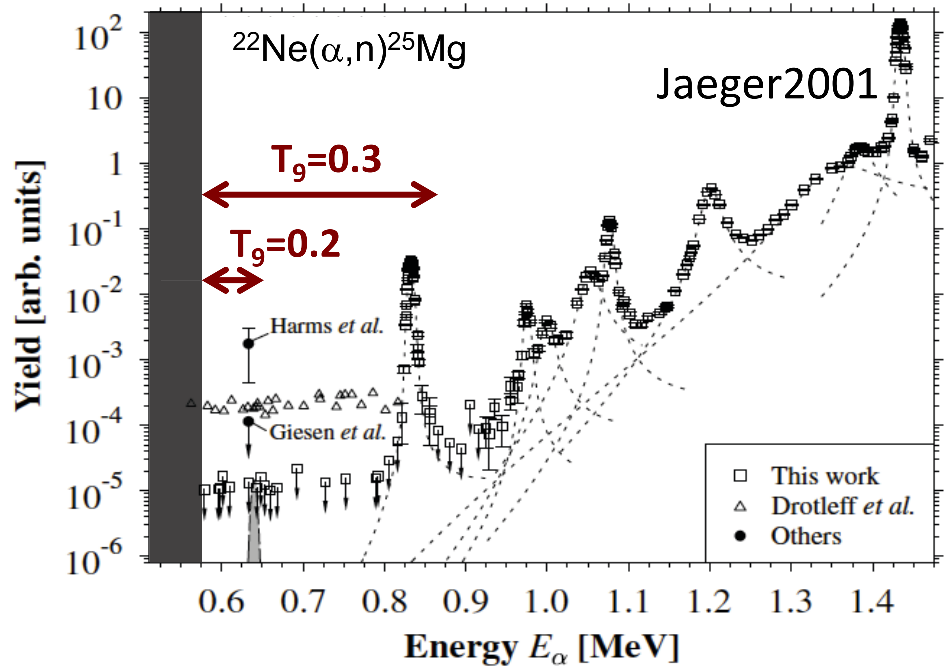


Neutron sources: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$

$^{13}C(\alpha,n)^{16}O$ → LUNA 400 and LUNA-MV

$^{22}Ne(\alpha,n)^{25}Mg$ → LUNA-MV





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Thanks for the attention!