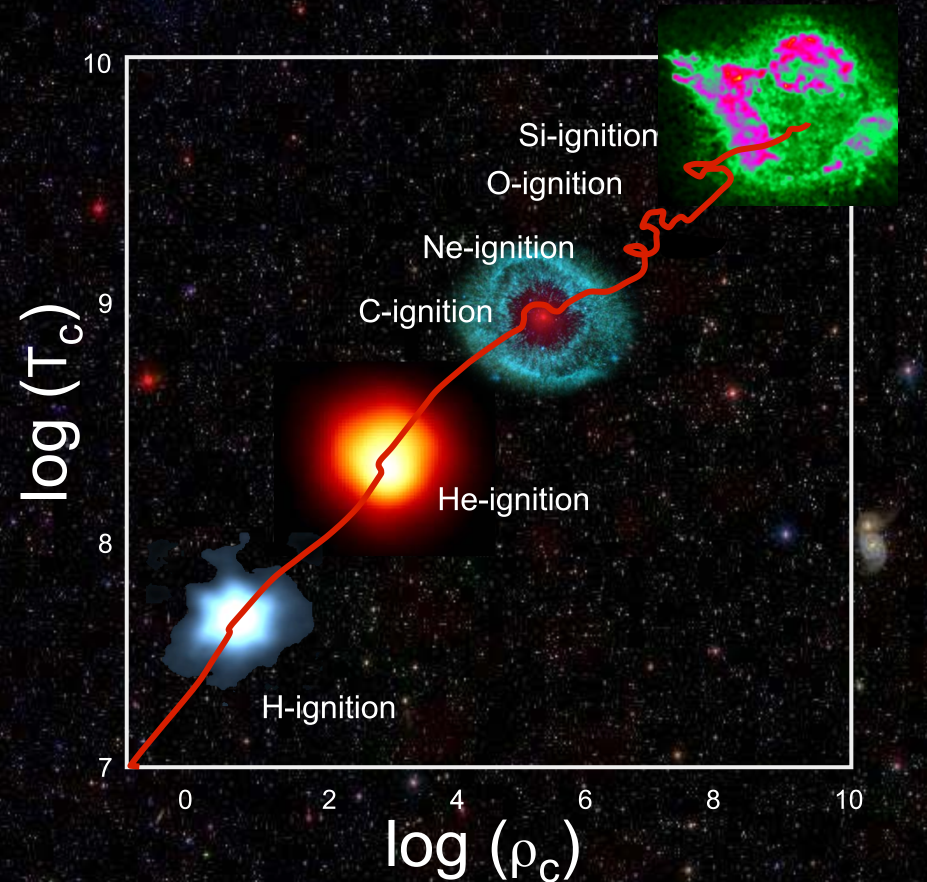
Underground Nuclear Astrophysics: Present and future of the LUNA experiment

Carlo Gustavino
INFN Roma

Why Nuclear astrophysics?

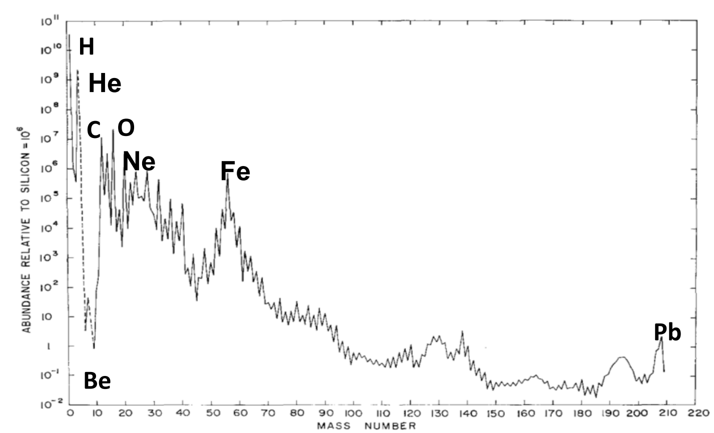


For a 15 M_{sun} star:

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

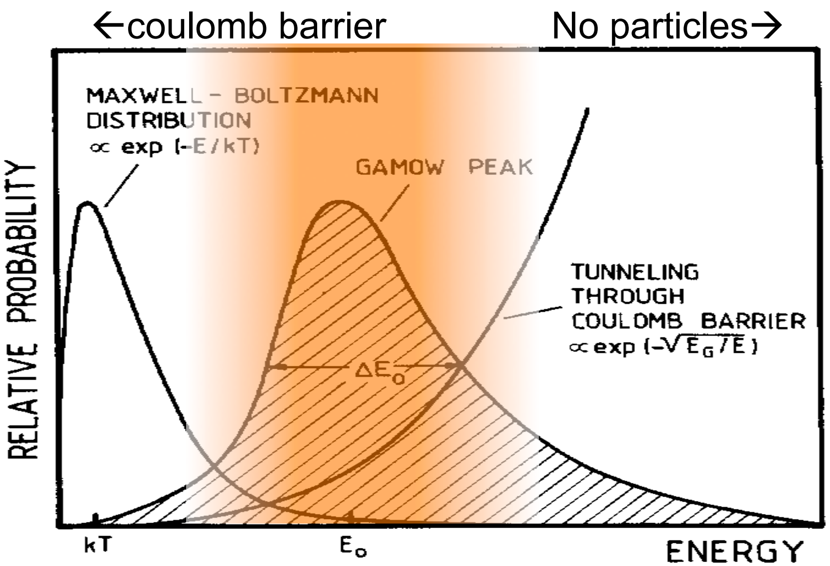
- Understanding the Sun
- Stellar population
- Evolution and fate of stars
- Big Bang Nucleosynthesis
- Isotopic abundances in the cosmos
- Cosmology
- Particle Physics
- Theoretical nuclear physics

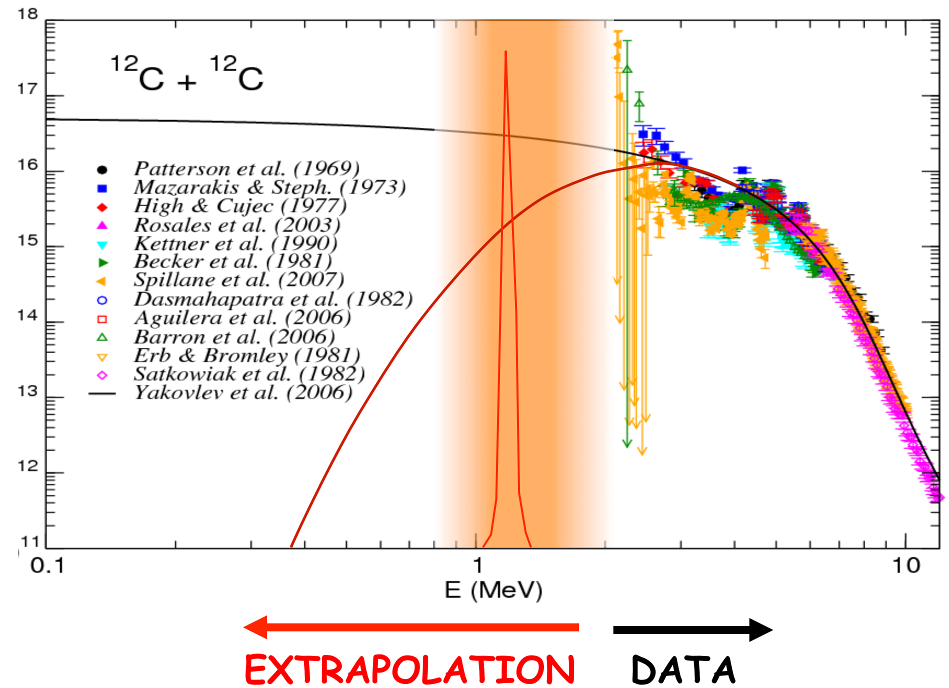


Why Underground Measurements?

Very low cross sections because of the Coulomb barrier

Underground accelerator to reduce the background induced by Cosmic Rays





Astrophysical Factor

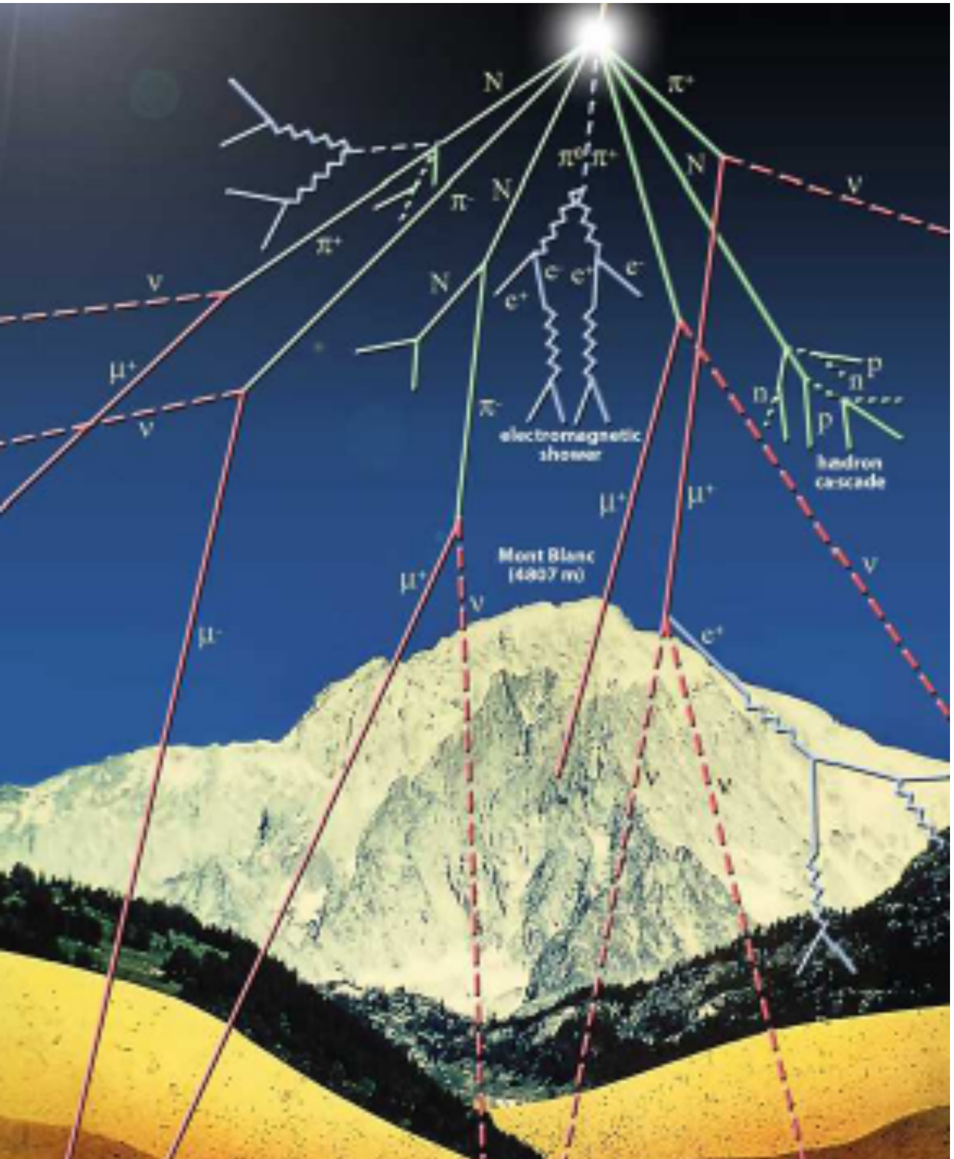
Coulomb Barrier

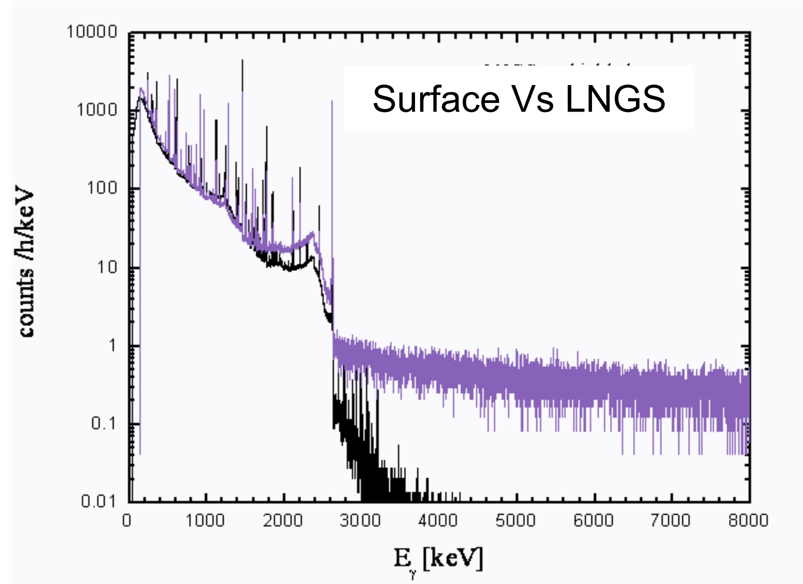
$$\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}$$

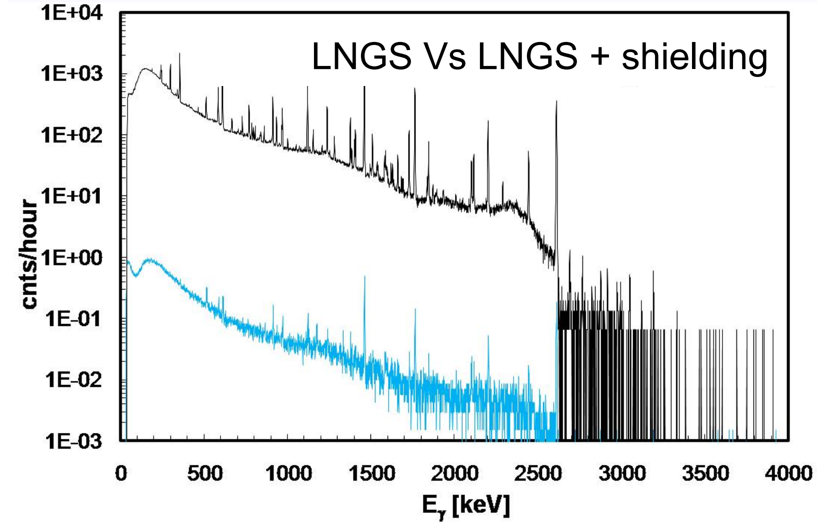
Gran Sasso National Laboratories

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

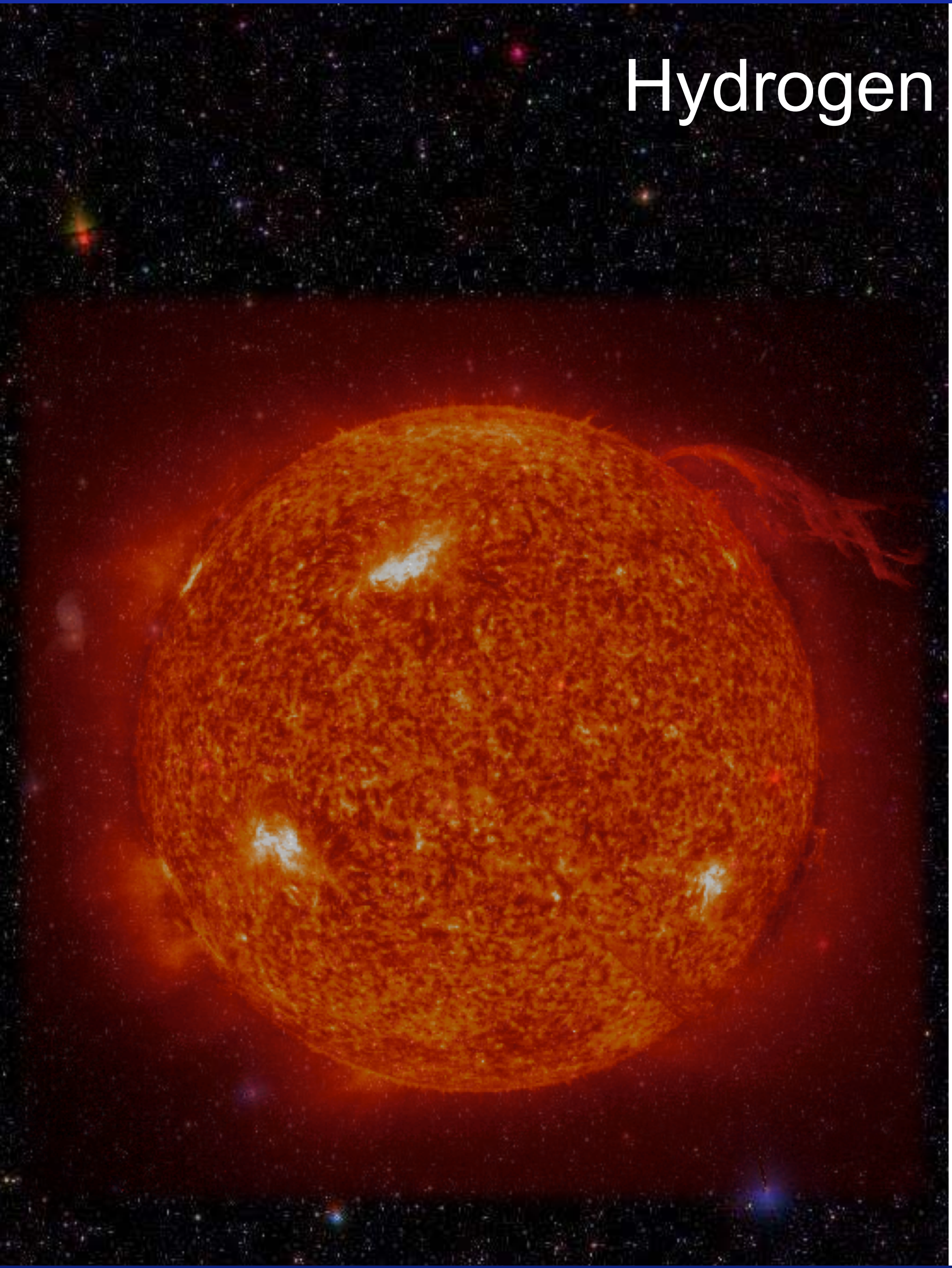






Passive shielding is more effective underground since the μ flux, that create secondary γs, is suppressed.

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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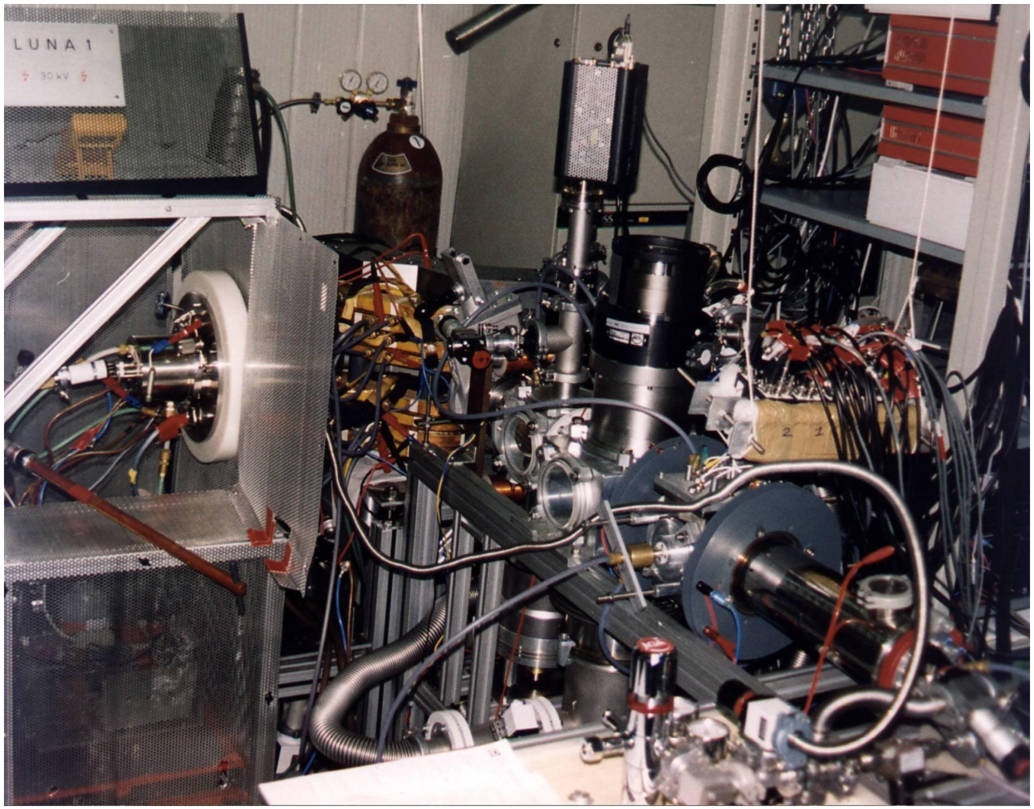
LUNA 50 kV

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

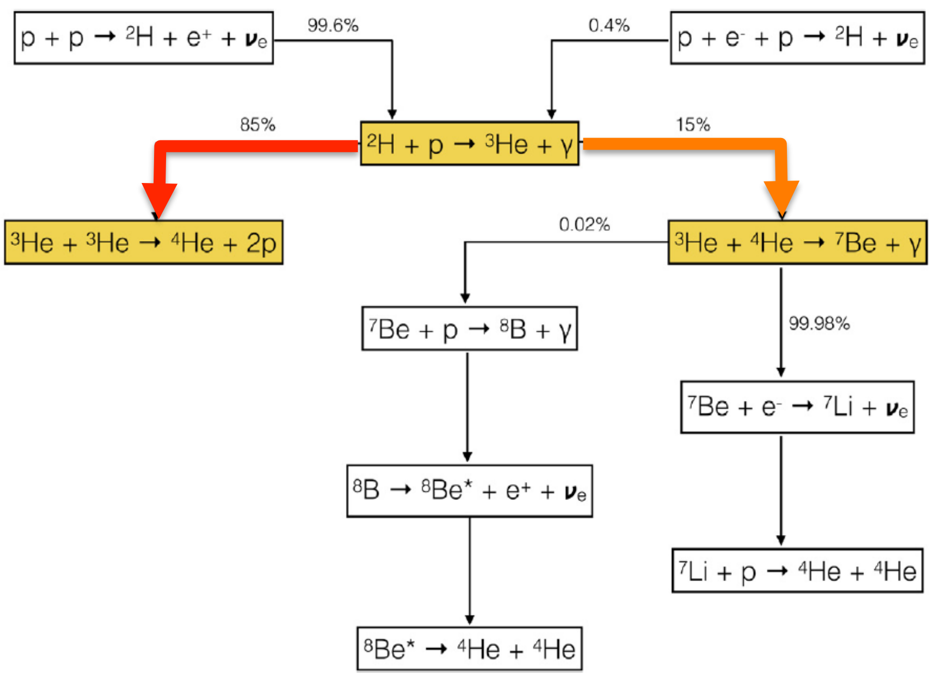


$^{3}He(^{3}He,2p)^{4}He$ (solar ν)
$^{2}H(p,\gamma)^{3}He$ (BBN)

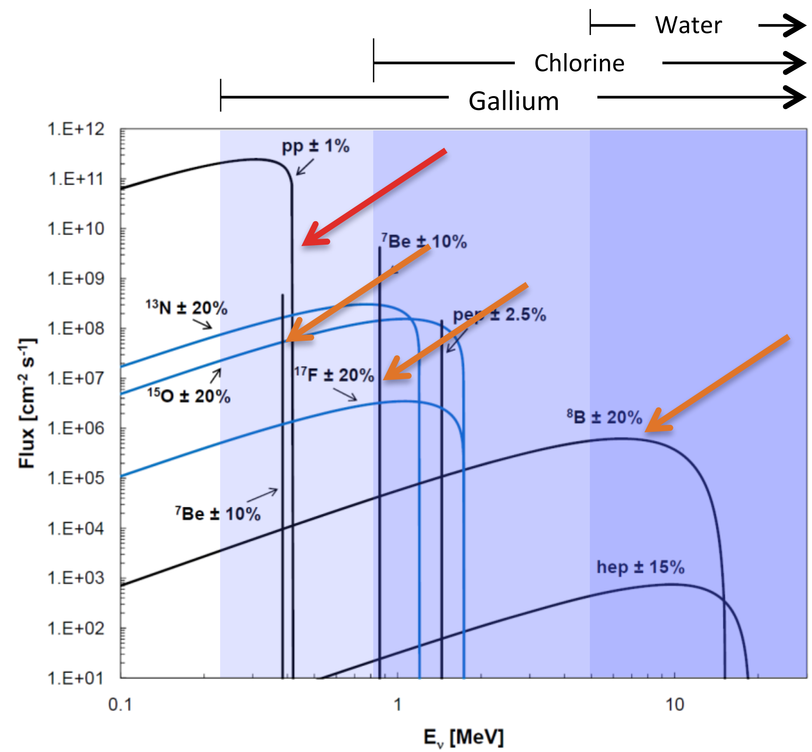
$E_{beam} \approx 1 - 50$ keV
$I_{max} \approx 500$ μA protons, ^{3}He
Energy spread $\approx$ 20 eV

Solar Neutrinos

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

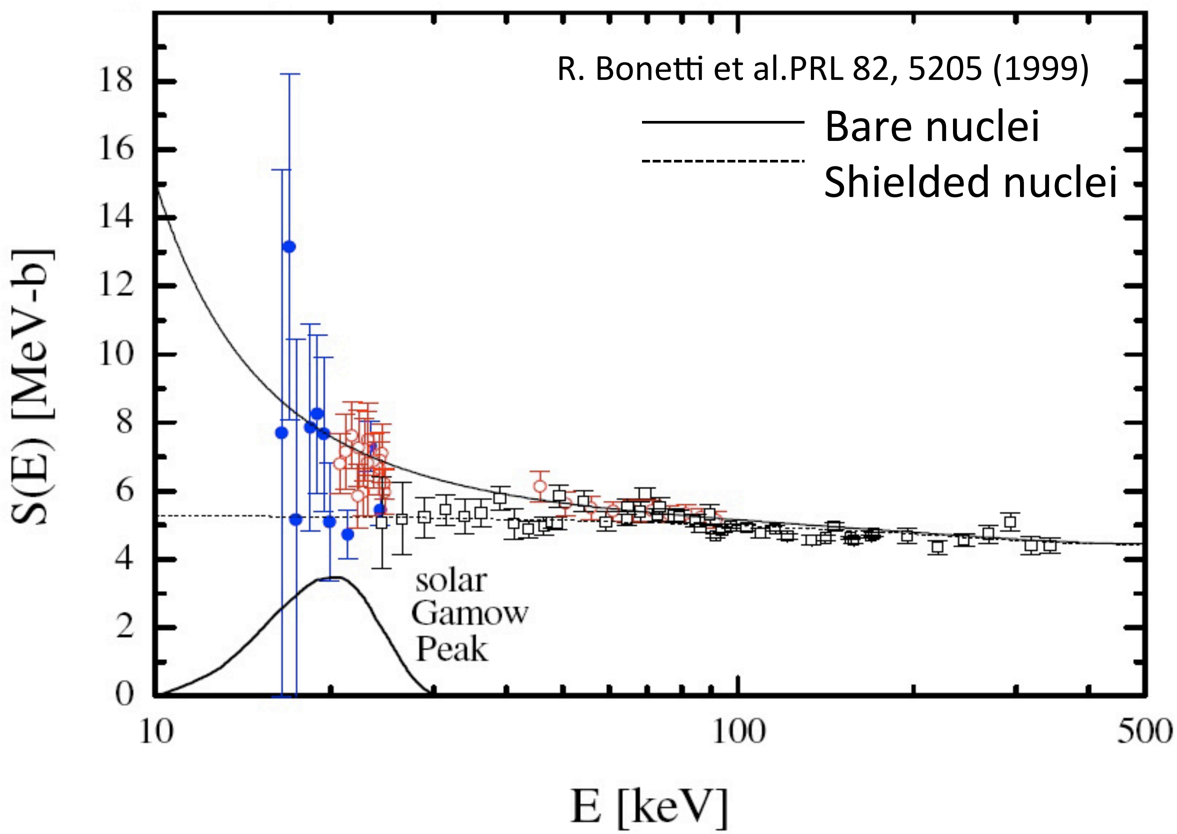


p-p chain



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

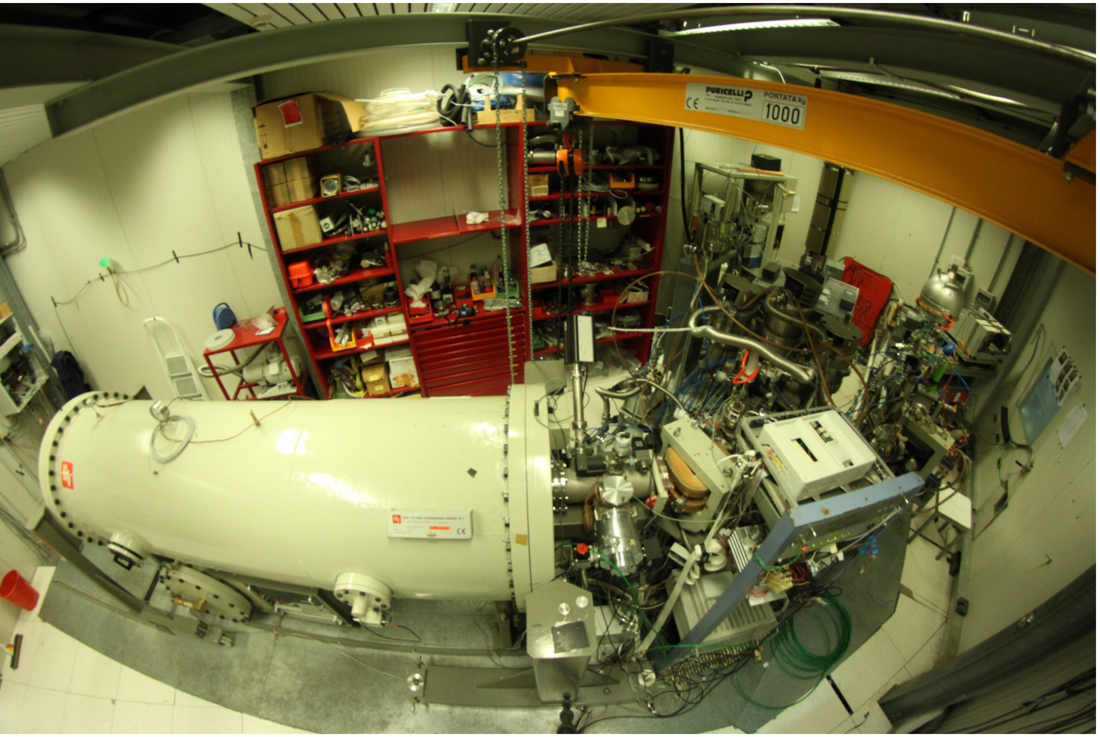
$^3He(^3He,2p)^4He$ reaction



-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 ν's mixing parameters

LUNA 400 kV

Still the word’s only underground accelerator



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

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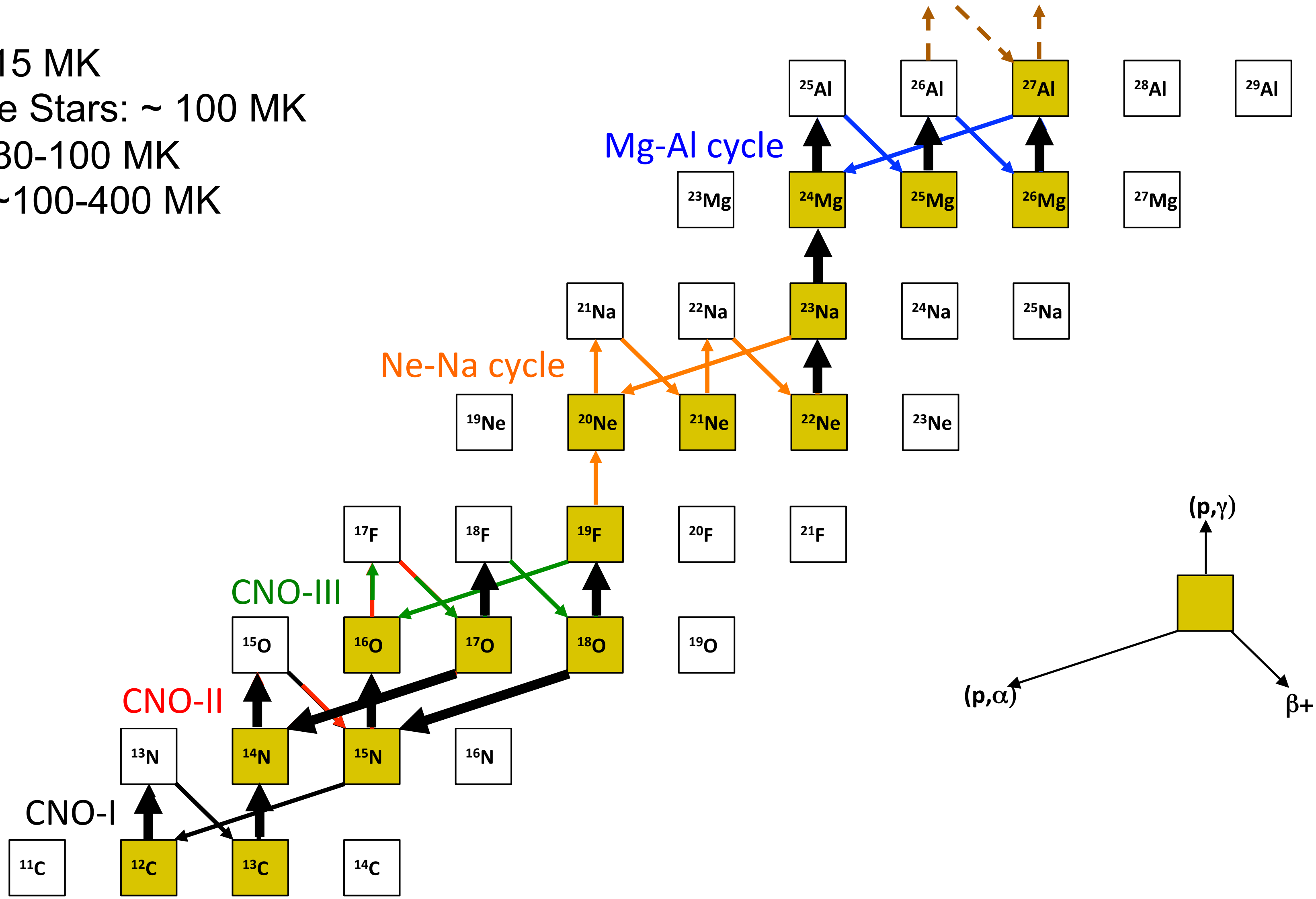
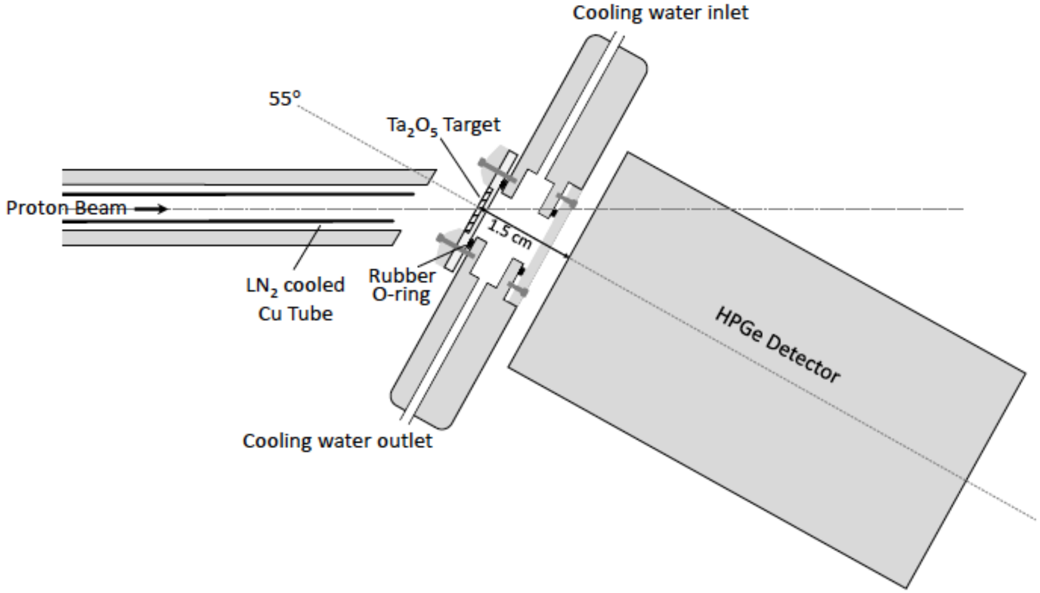
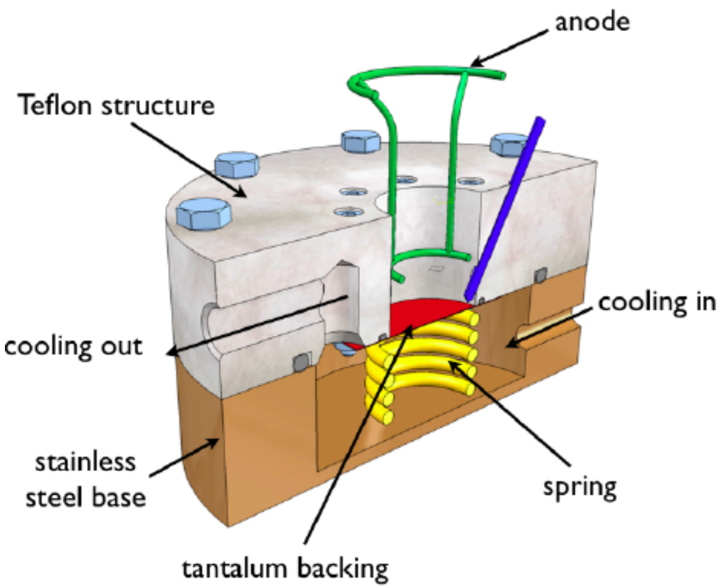


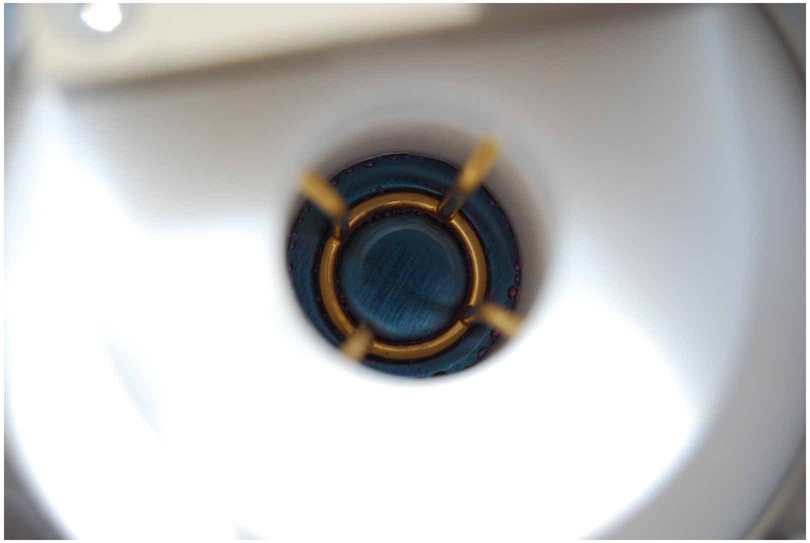
$^{17}O(p,\gamma)^{18}F$ and $^{17}O(p,\alpha)^{14}N$ reactions

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

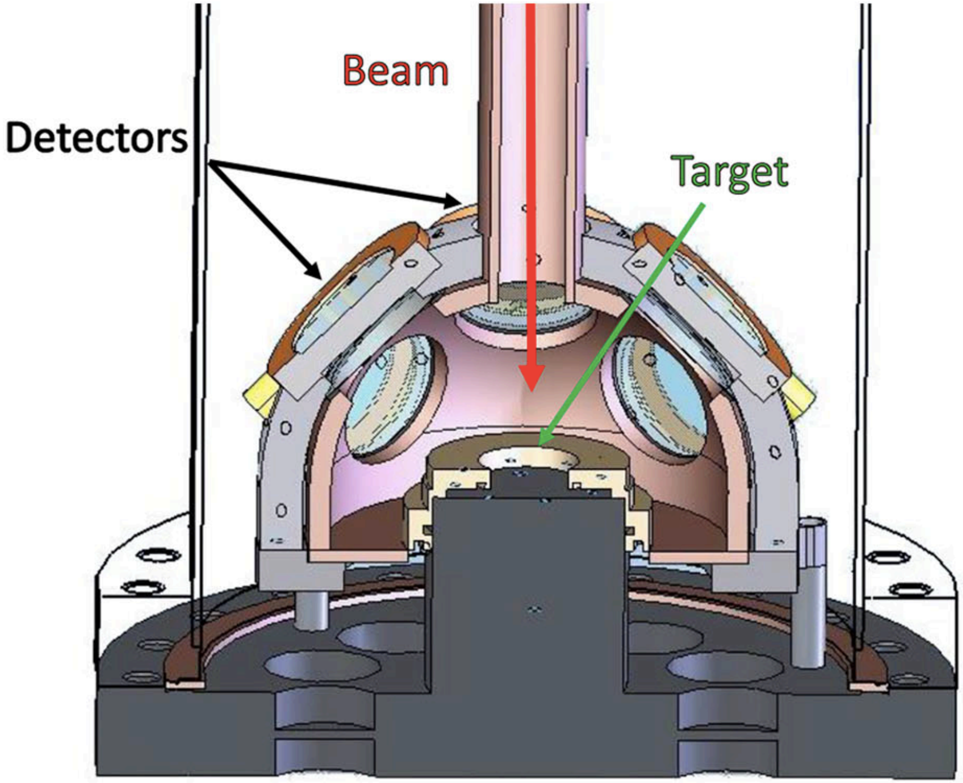
Caciolli et al. EPJA 48 (2012) 144

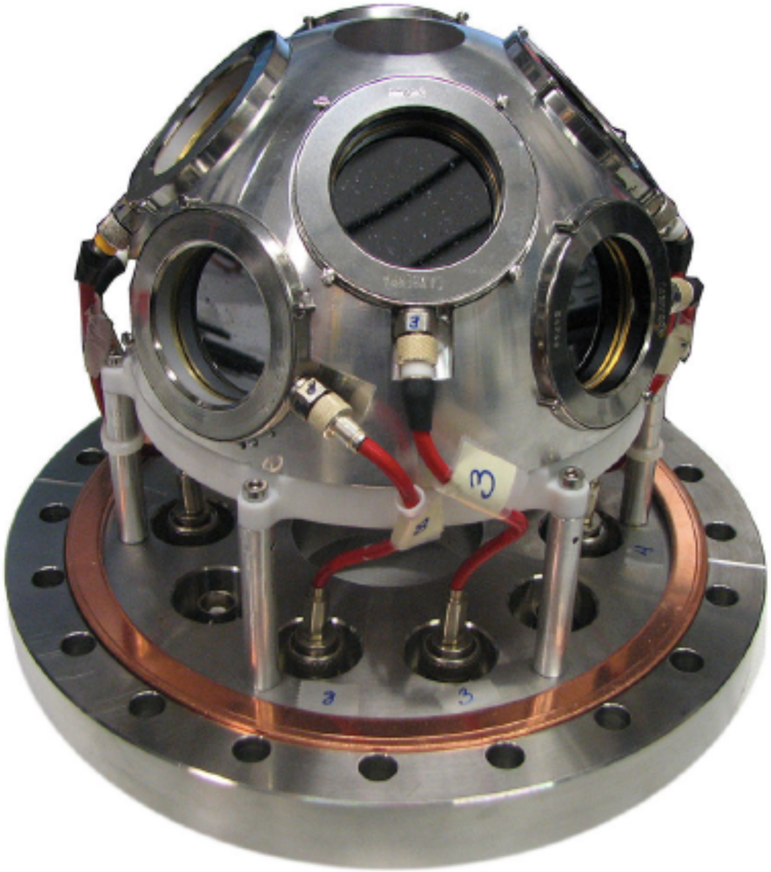






$^{17}O(p,\gamma)^{18}F$ and $^{17}O(p,\alpha)^{14}N$ reactions

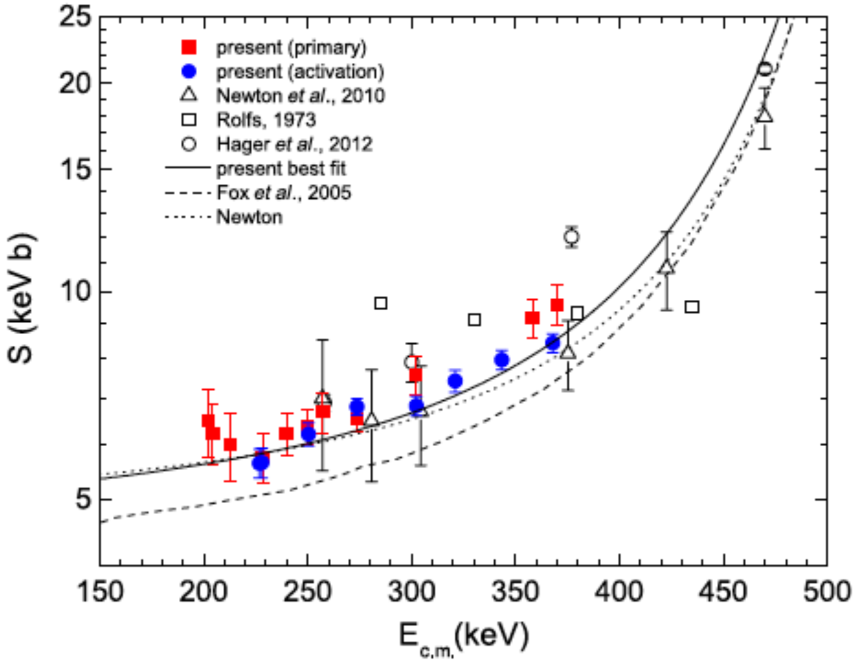




Bruno et al EJPA 51 (2015) 94

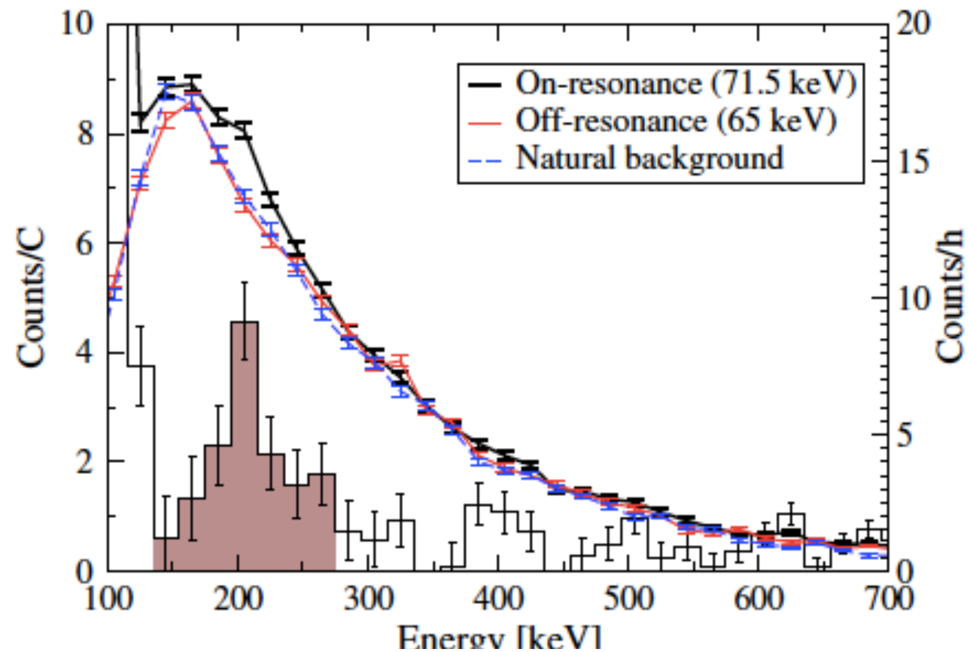
- protective aluminized Mylar foils (2.4 μm) before each detector
- expected alpha particle energy E ~ 200 keV (from 70 keV resonance)

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



First measurement within Novae Gamow window

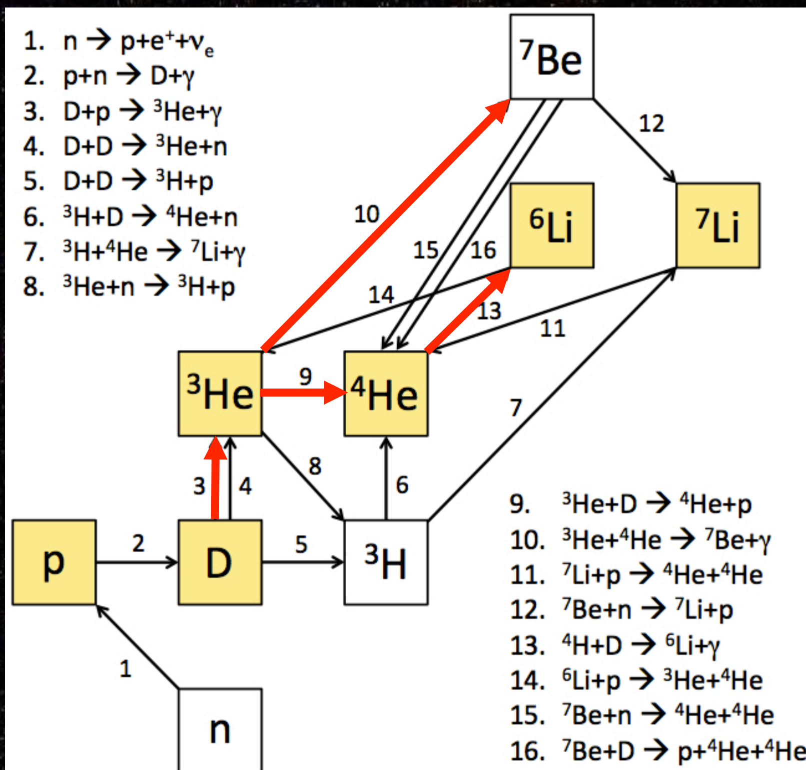
Di Leva et al., PRC 89 (1) (2014) 015803
Scott et al., PRL 109 (20) (2012) 202501



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

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:

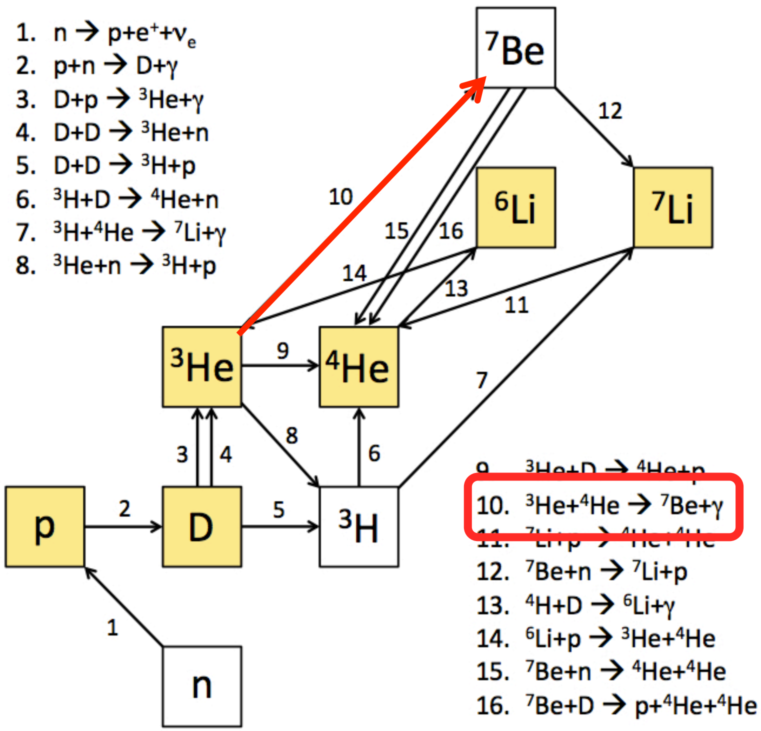
-Baryon density Ω_b

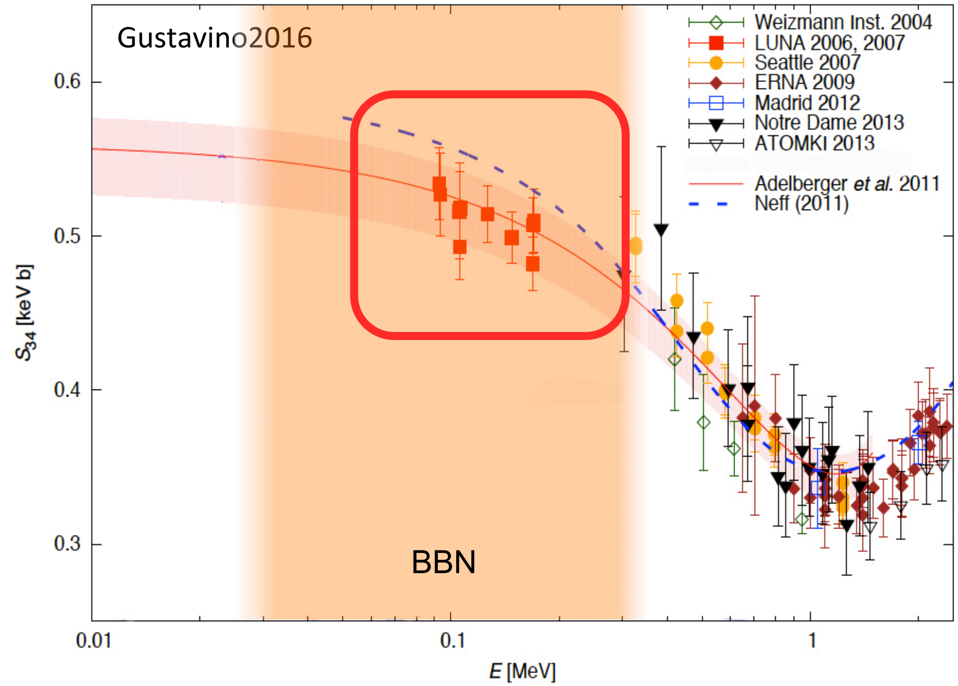
-Particle Physics (N_{eff}, α..)

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

^{3}He(α,γ)^{7}Be 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	$(4.68\pm0.67)\times10^{-10}$	$(1.23^{+0.68}_{-0.32})\times10^{-10}$
^{6}Li/^{7}Li	$(1.5\pm0.3)\times10^{-5}$	$<\sim10^{-2}$





-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	$(2.41\pm0.05)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
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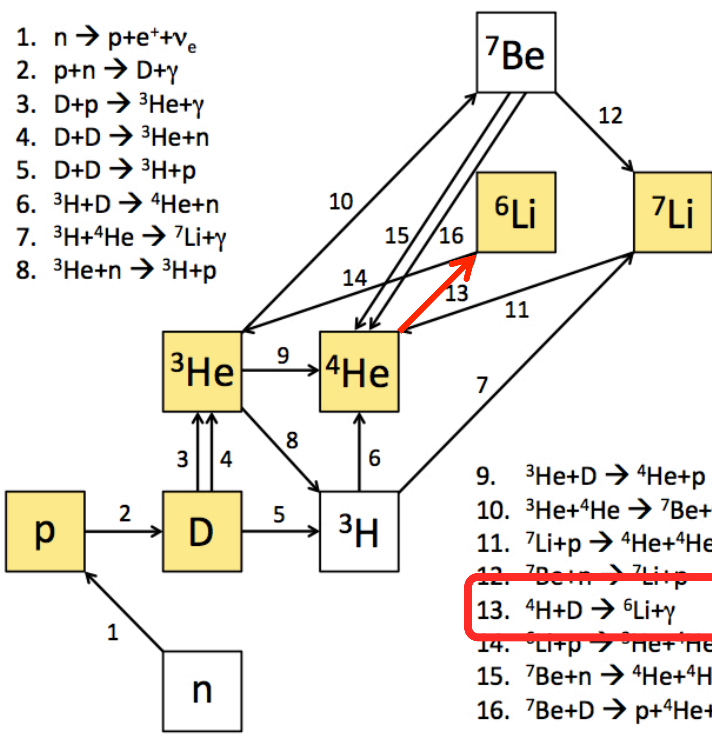
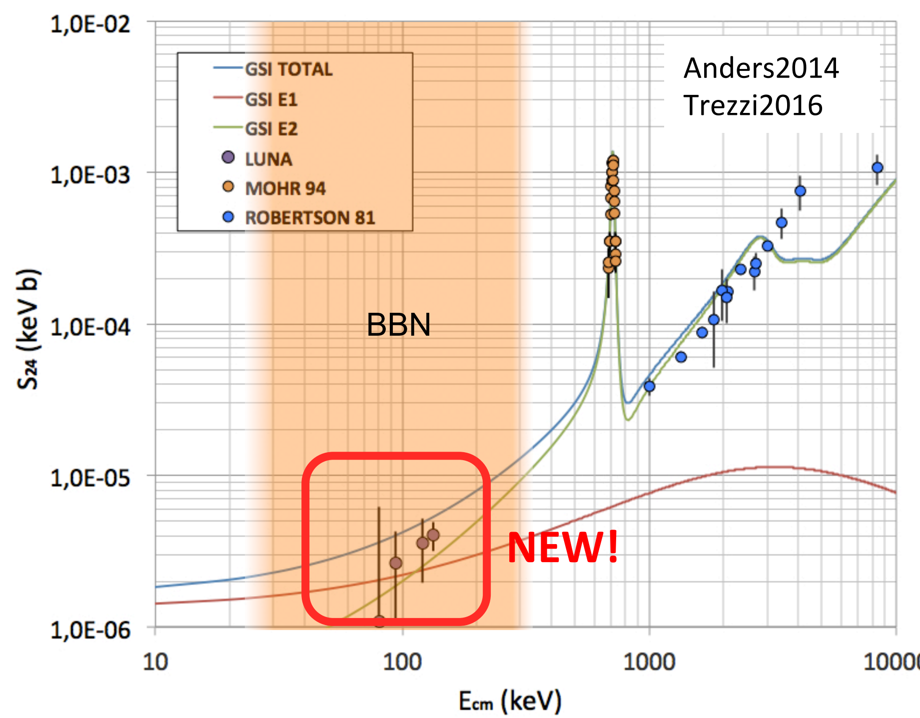
^{6}Li/^{7}Li	$(1.5\pm0.3)\times10^{-5}$	$<\sim10^{-2}$

1. n → p+e$^+$+ν$_e$
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}He → ^{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}H+D → ^{6}Li+γ
14. ^{6}Li+p → ^{3}He+^{4}He
15. ^{7}Be+n → ^{4}He+^{4}He
16. ^{7}Be+D → p+^{4}He+^{4}He



First measurement in the BBN energy region
→LUNA data exclude a nuclear solution for the ^{6}Li problem...

D(p,γ)^{3}He reaction

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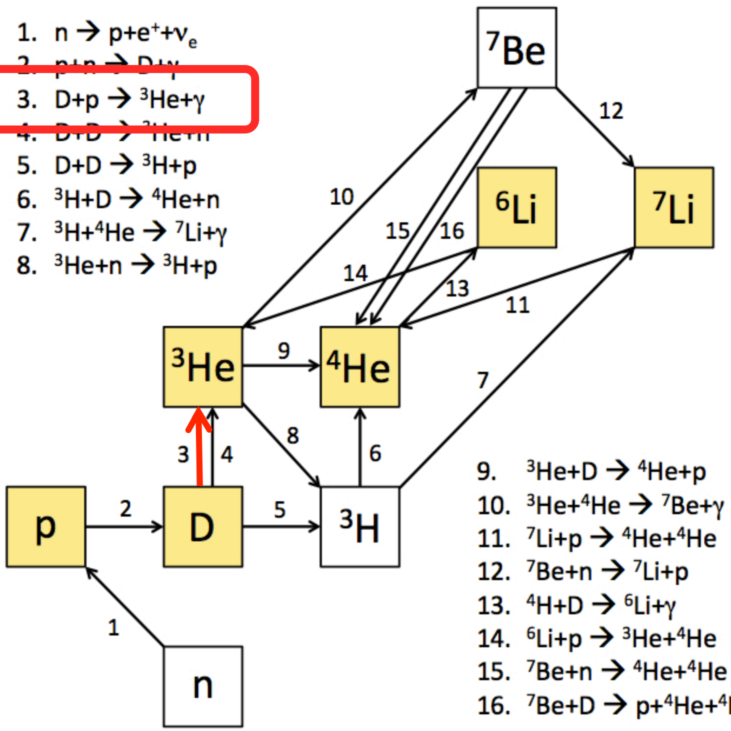
^{7}Li/H	$(4.68\pm0.67)\times10^{-10}$	$(1.23\,^{+0.68}_{-0.32})\times10^{-10}$
^{6}Li/^{7}Li	$(1.5\pm0.3)\times10^{-5}$	<~10^{-2}

1. n → p+e$^+$+ν_e
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}He → ^{7}Li+γ
8. ^{3}He+n → ^{3}H+p



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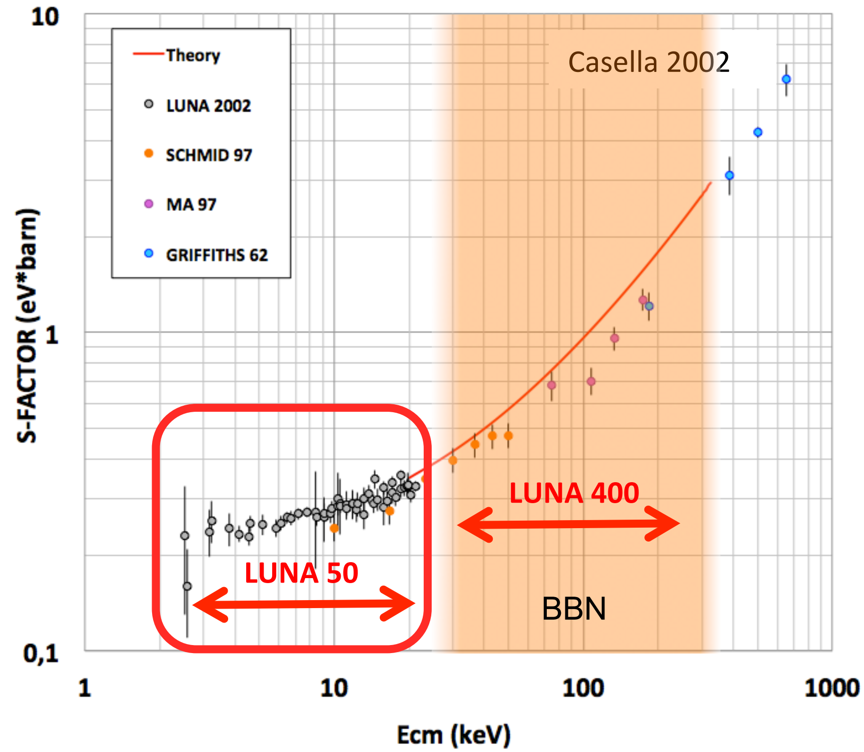
13. ^{4}H+D → ^{6}Li+γ
14. ^{6}Li+p → ^{3}He+^{4}He
15. ^{7}Be+n → ^{4}He+^{4}He
16. ^{7}Be+D → p+^{4}He+^{4}He



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

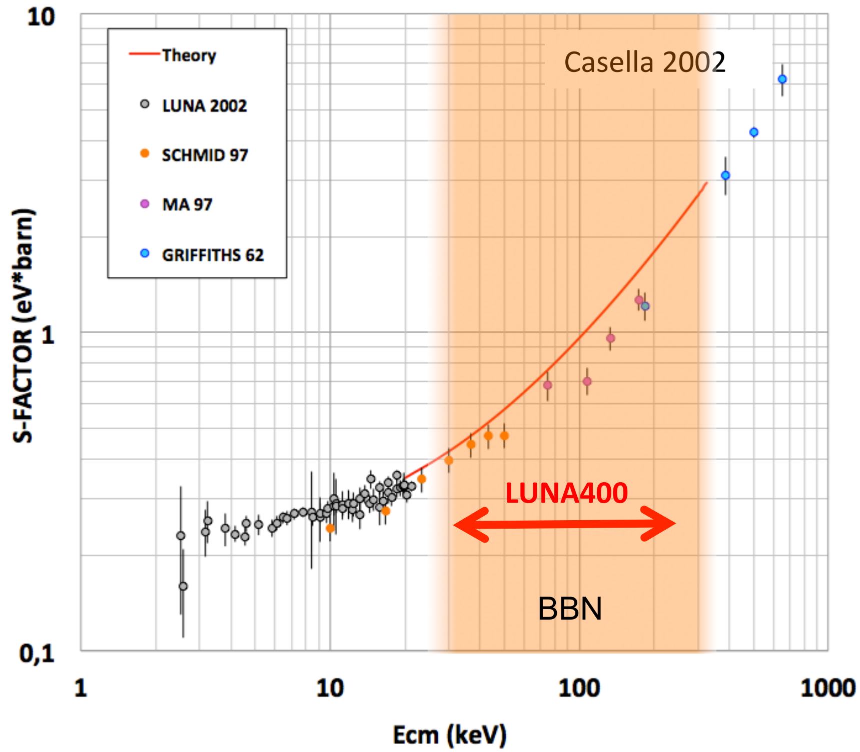
$D(p,\gamma)^3He$ reaction @ LUNA400

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

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

-The error budget of computed abundance of deuterium is mainly due to the $D(p,\gamma)^3He$ reaction

-measurements (9% error) NOT in agreement with recent "Ab-Initio" calculations.



Measurement goal:

-Cross section measurement at $30<E_{cm}<260$ 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.

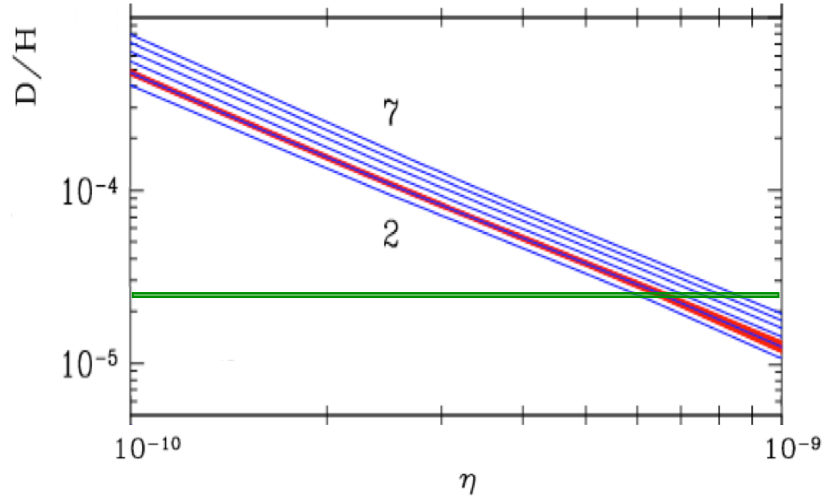
D(p,γ)^{3}He reaction: Ω_b and N_{eff}

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

Dpγ data fit

$100\Omega_{b,0}h^2(BBN)=2.20\pm0.04\pm0.02$ (Cooke2013)
$100\Omega_{b,0}h^2(BBN)=2.16\pm0.01\pm0.02$

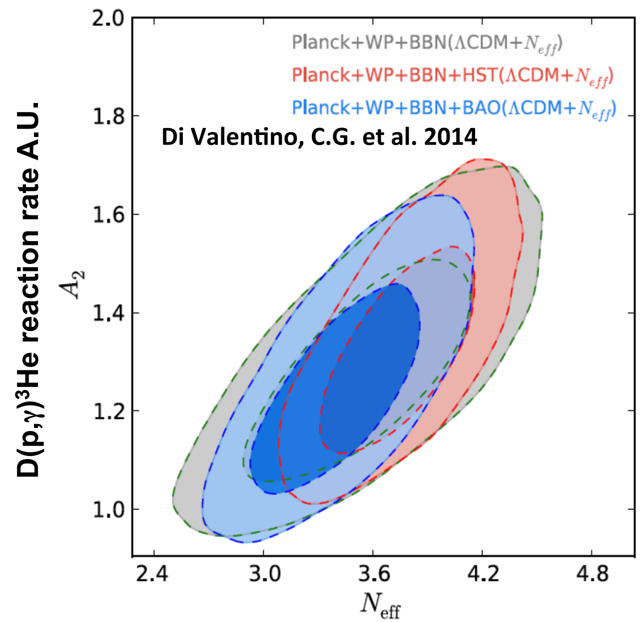
Dpγ "ab-initio"
D/H observations



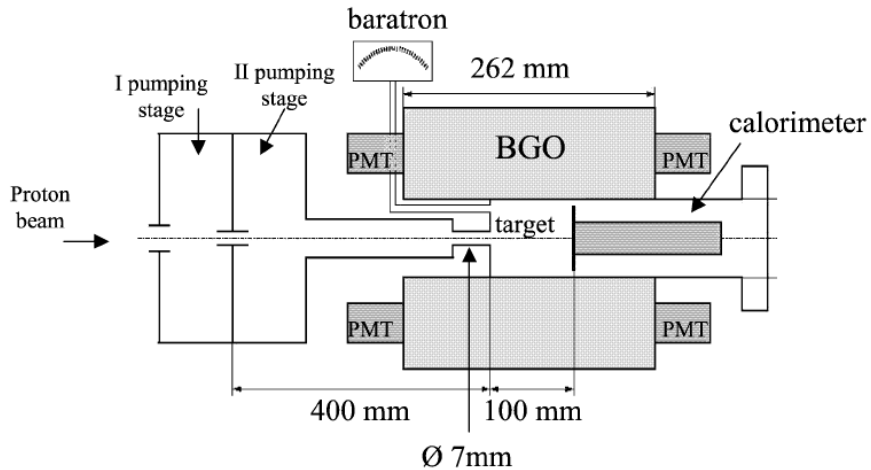
From CMB data:
$100\Omega_{b,0}h^2(CMB)=2.22\pm0.02$ (PLANCK2015)

-Deuterium adundance 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,g)^{3}He reaction:

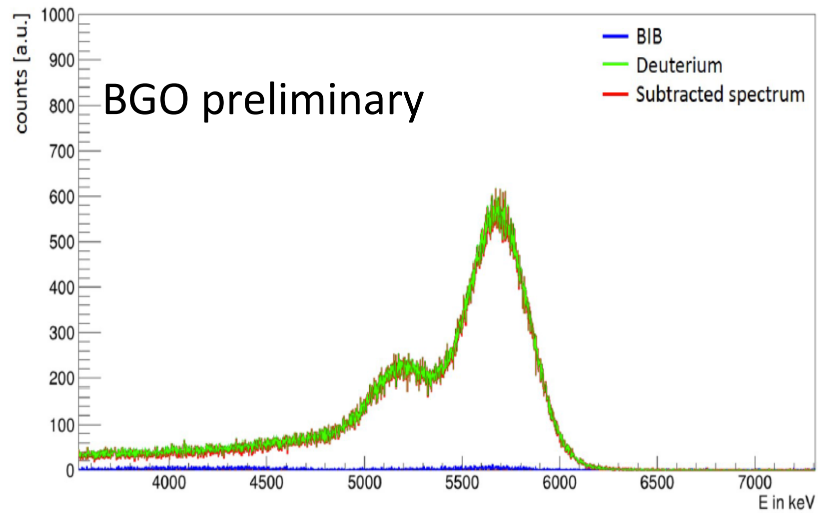
N_{eff} (BBN) = 3.57±0.18 (Cooke&Pettini 2013)
N_{eff} (CMB) = 3.36±0.34 (PLANCK 2013)
N_{eff} (SM) = 3.046



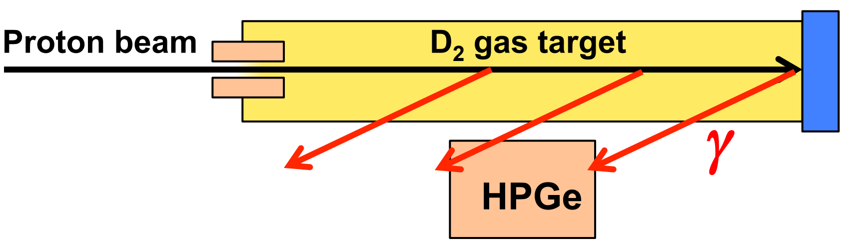
D(p,γ)^{3}He reaction: setup



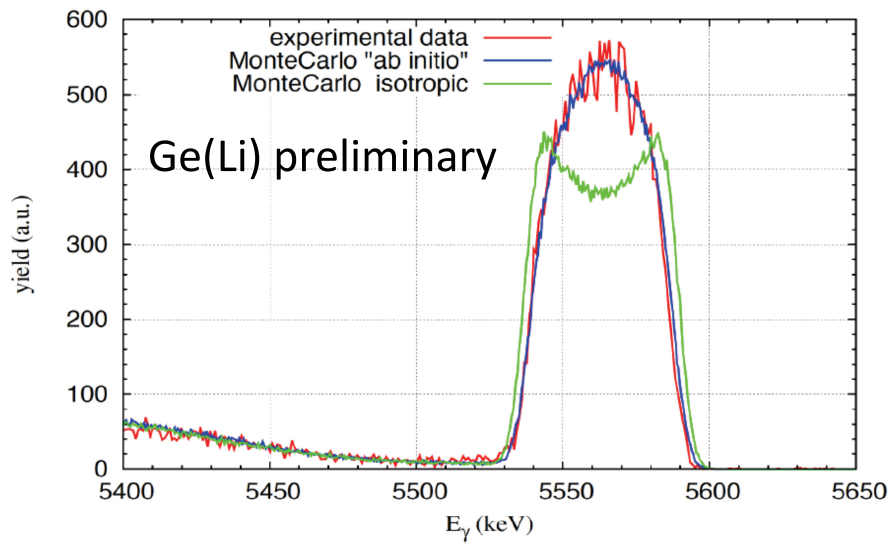
BGO detector



$$E_\gamma = \frac{m_p^2 + m_d^2 - m_{He}^2 + 2E_p m_d}{2(E_p + m_d^2 - p_p cos(\theta_{cm}))}$$

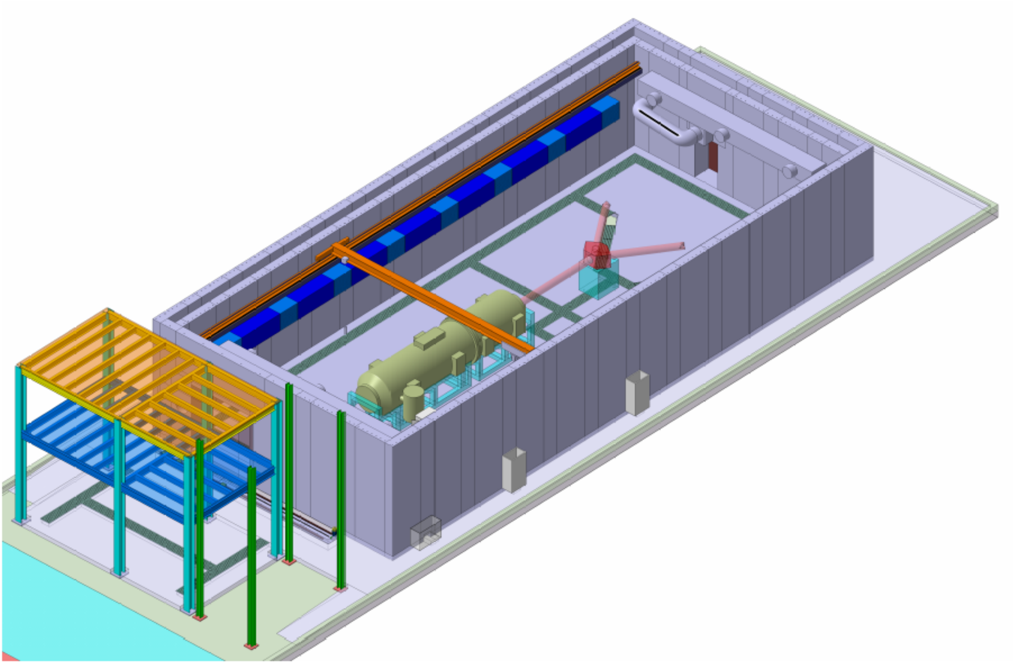


Ge(Li) detector



Next: LUNA MV

Funded by the Italian Research Ministry as a “premium project”.
First run scheduled in june 2019.

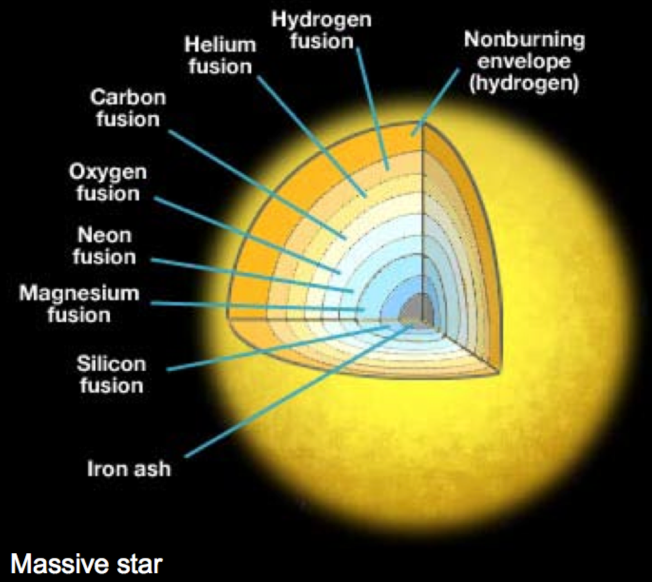


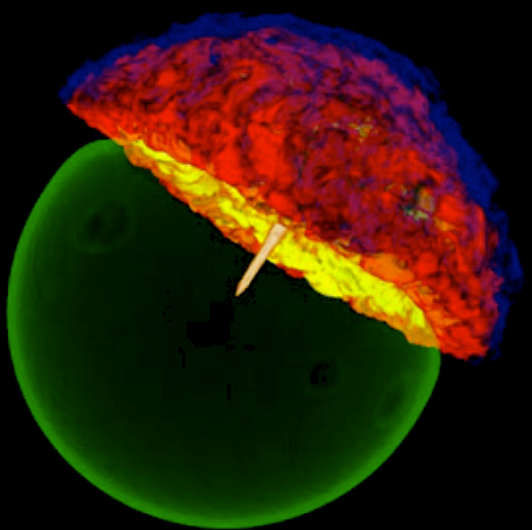
Starting program:

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

Terminal Voltage ≈ 0.2 – 3.5 MeV
I_{max} ≈ 100-1000 μA   protons, ^{4}He, $^{12}C^{+}$, $^{12}C^{++}$

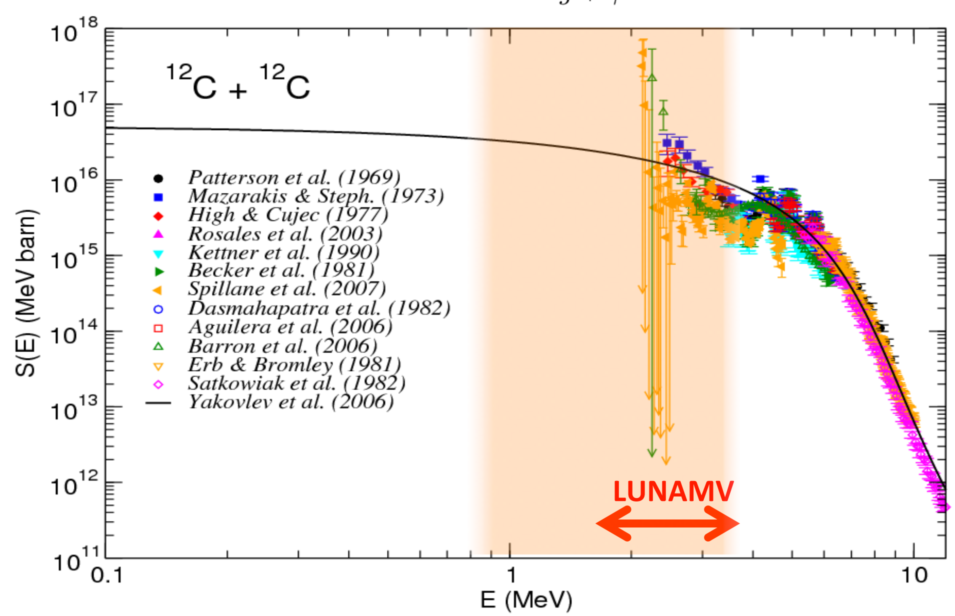
Carbon Burning & type Ia supernovae





- 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

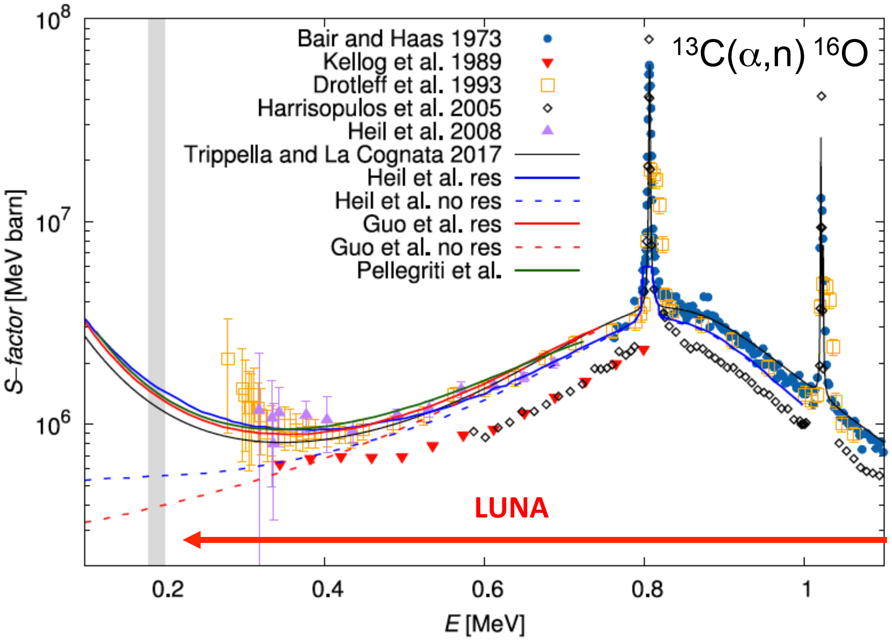
$$
\begin{aligned}
{}^{12}C + {}^{12}C &\rightarrow {}^{16}O + 2\,{}^{4}He \\
&\rightarrow {}^{20}Ne + {}^{4}He \\
&\rightarrow {}^{23}Na + p^{+} \\
&\rightarrow {}^{23}Mg + n \\
&\rightarrow {}^{24}Mg + \gamma
\end{aligned}
$$

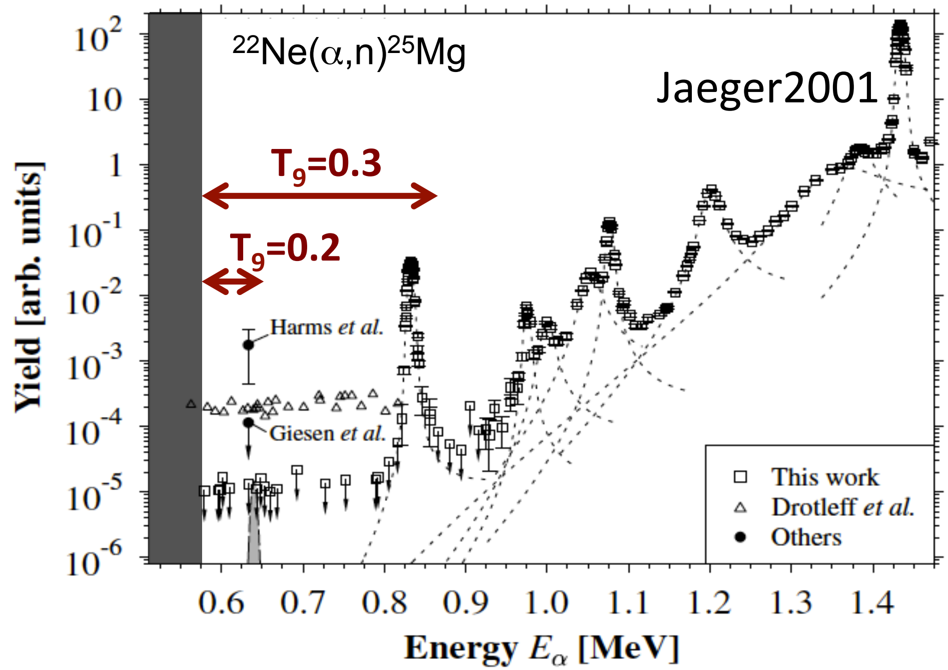


s-process

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

$^{22}Ne(\alpha,n)^{25}Mg$ →LUNA-MV





The LUNA collaboration

- A. Best, A. Boeltzig*, G.F. Ciani*, A. Formicola, I. Kochanek, M. Junker, L. Leonzi | INFN LNGS /*GSSI, Italy
- D. Bemmerer, M. Takacs, T. Szucs | HZDR Dresden, Germany
- C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy
- Z. Elekes, Zs. Fülöp, Gy. Gyurky| MTA-ATOMKI Debrecen, Hungary
- M. Lugaro | Monarch University Budapest, Hungary
- O. Straniero | INAF Osservatorio Astronomico di Collurania, Teramo, Italy
- F. Cavanna, P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli | Università di Genova and INFN Genova, Italy
- A. Guglielmetti, D. Trezzi | Università di Milano and INFN Milano, Italy
- A. Di Leva, G. Imbriani, | Università di Napoli and INFN Napoli, Italy
- G. Gervino | Università di Torino and INFN Torino, Italy
- M. Aliotta, C. Bruno, T. Davinson | University of Edinburgh, United Kingdom
- G. D'Erasmo, E.M. Fiore, V. Mossa, F. Pantaleo, V. Paticchio, R. Perrino, L. Schiavulli, A. Valentini| Università di Bari and INFN Bari, Italy