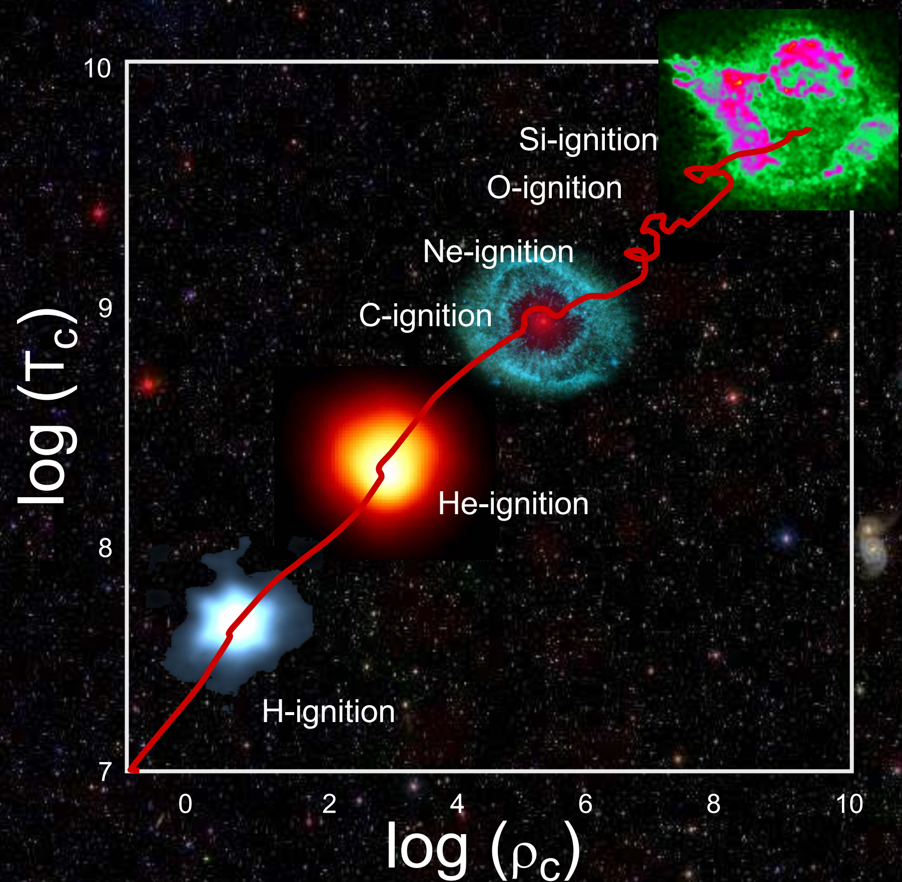
BBN, Nuclear Astrophysics and neutrinos

Carlo Gustavino
INFN Roma
For the LUNA Collaboration

- Solar neutrinos
- Cosmic Neutrino Background (CNB)

Nuclear astrophysics



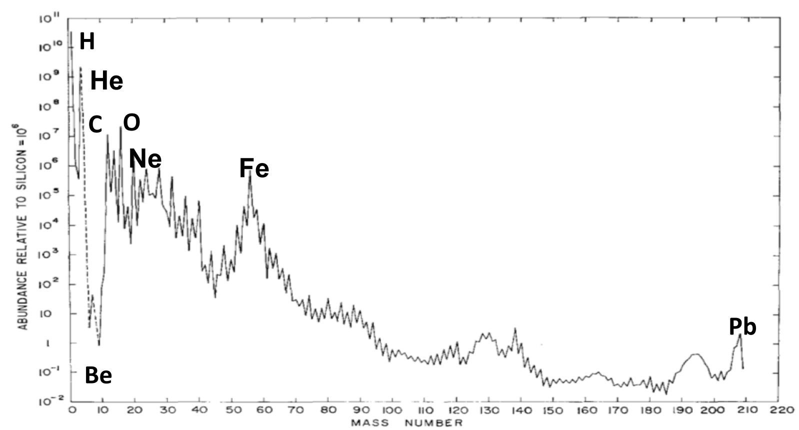
For a 15 M_{sun} star:

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 Big Bang Nucleosynthesis and determine the evolution and fate of celestial bodies

- Big Bang Nucleosynthesis
- Evolution and fate of stars
- the Sun

- Cosmology
- Astrophysics
- Particle Physics
- Theoretical nuclear physics



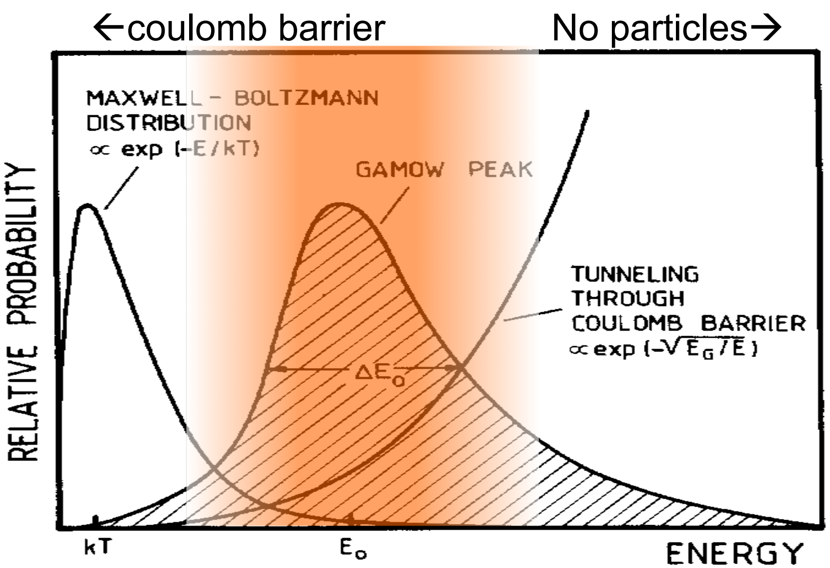
Why Underground Measurements?

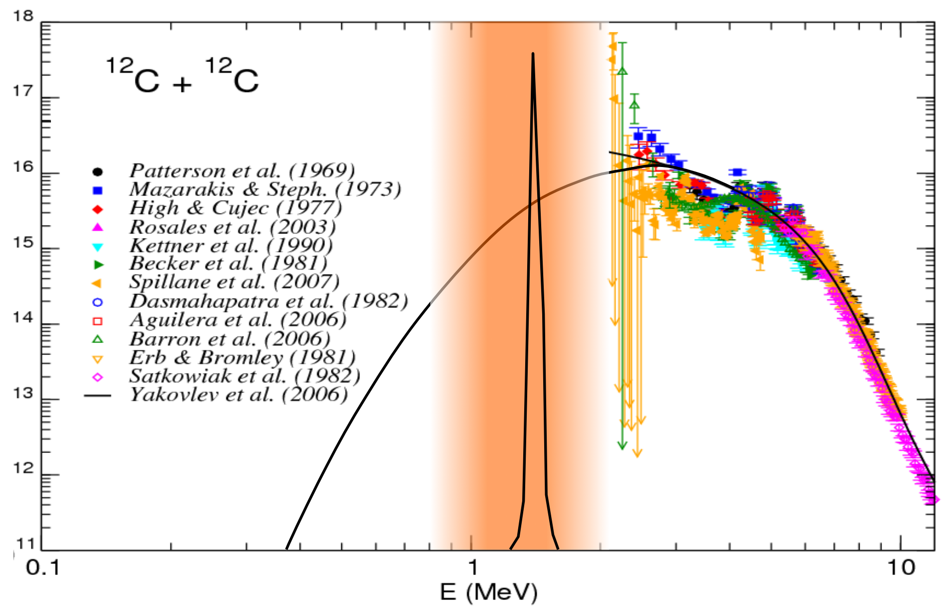
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu}} (k_B T)^{-3/2} \int_0^\infty \sigma(E)\, E \, \exp[-E/k_B T]\, dE$$

Astrophysical Factor

Coulomb Barrier

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



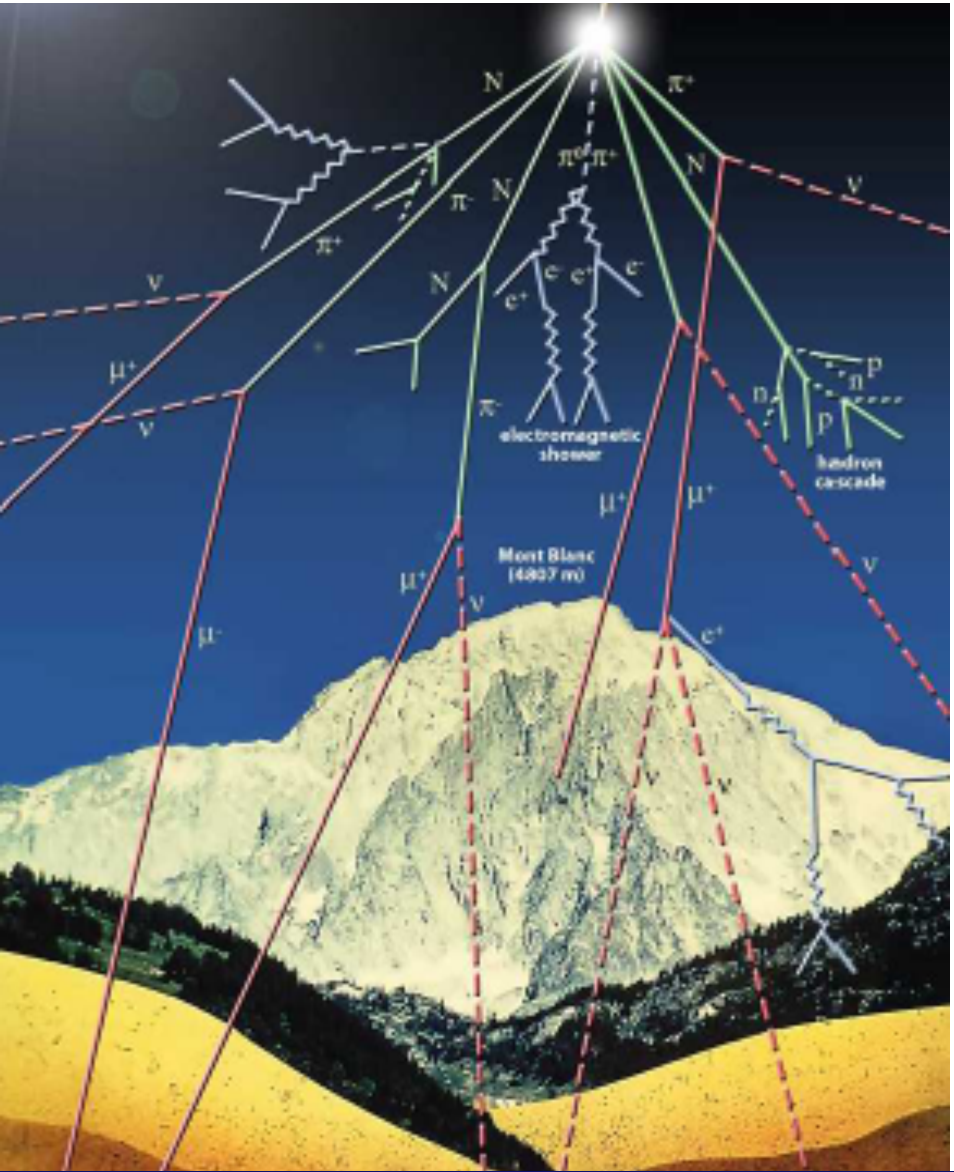


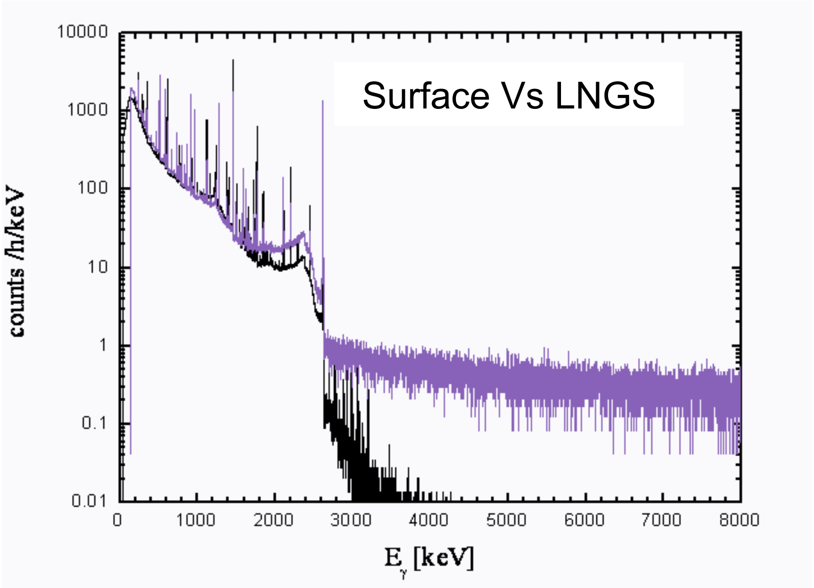
Measurements at low energies

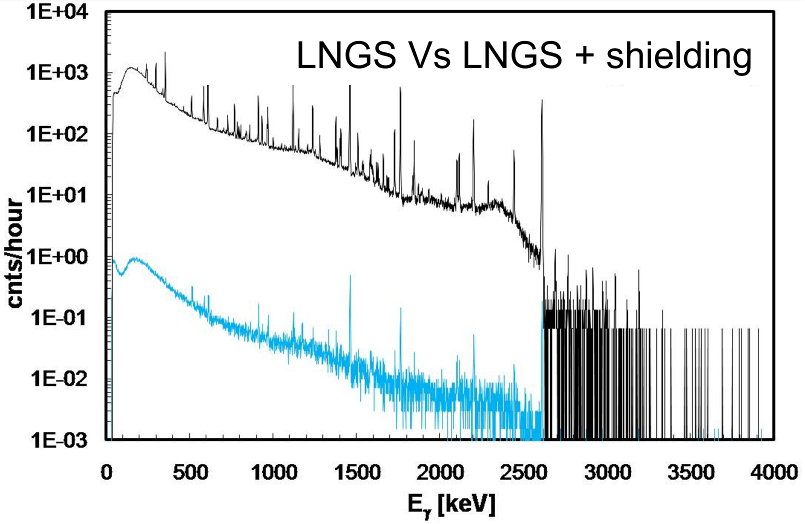
Low cross sections because of the Coulomb barrier

→Underground accelerator to reduce the background induced by Cosmic Rays

Background @ Gran Sasso



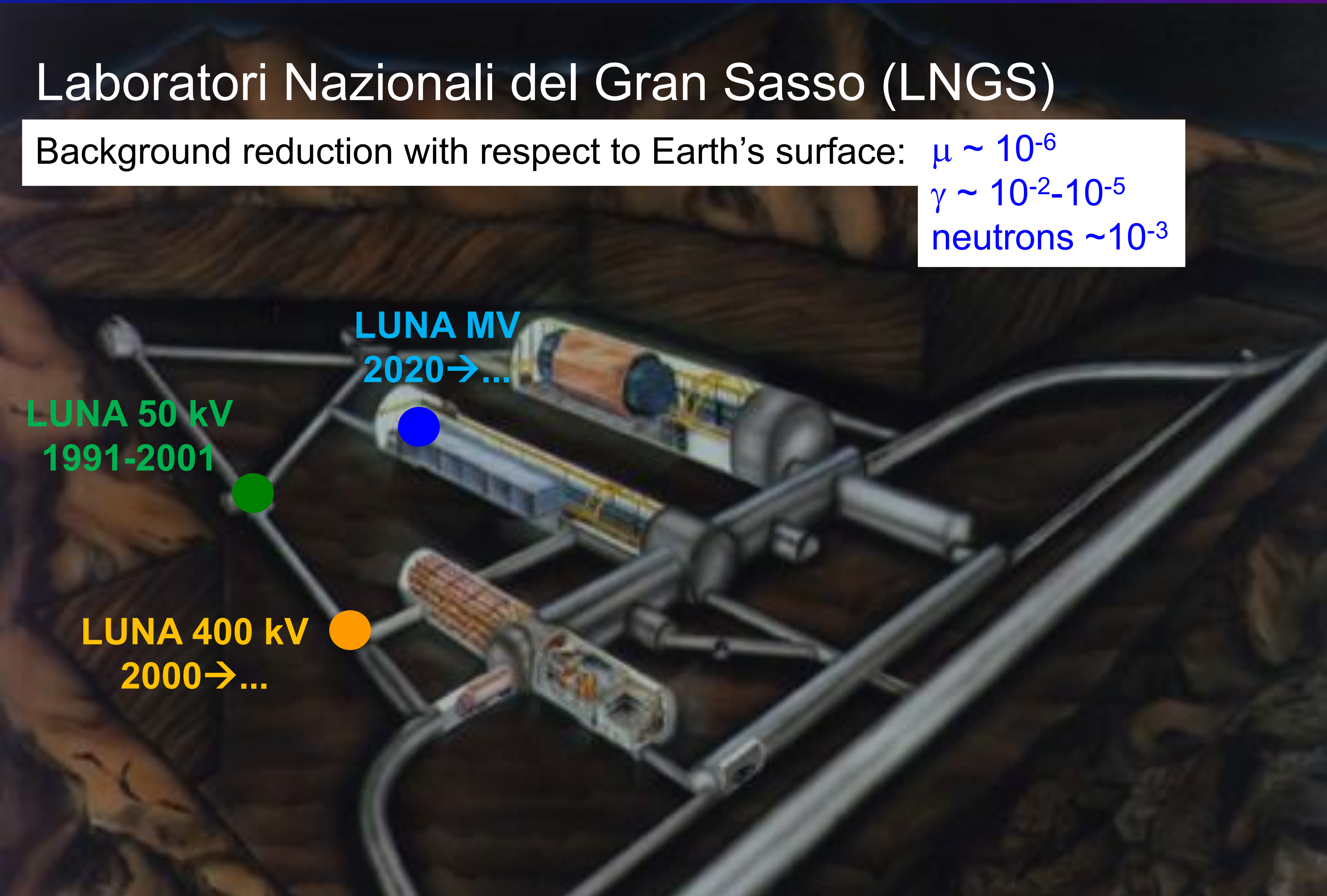




Passive shielding is more effective underground since the μ flux, that create secondary γs, is suppressed.

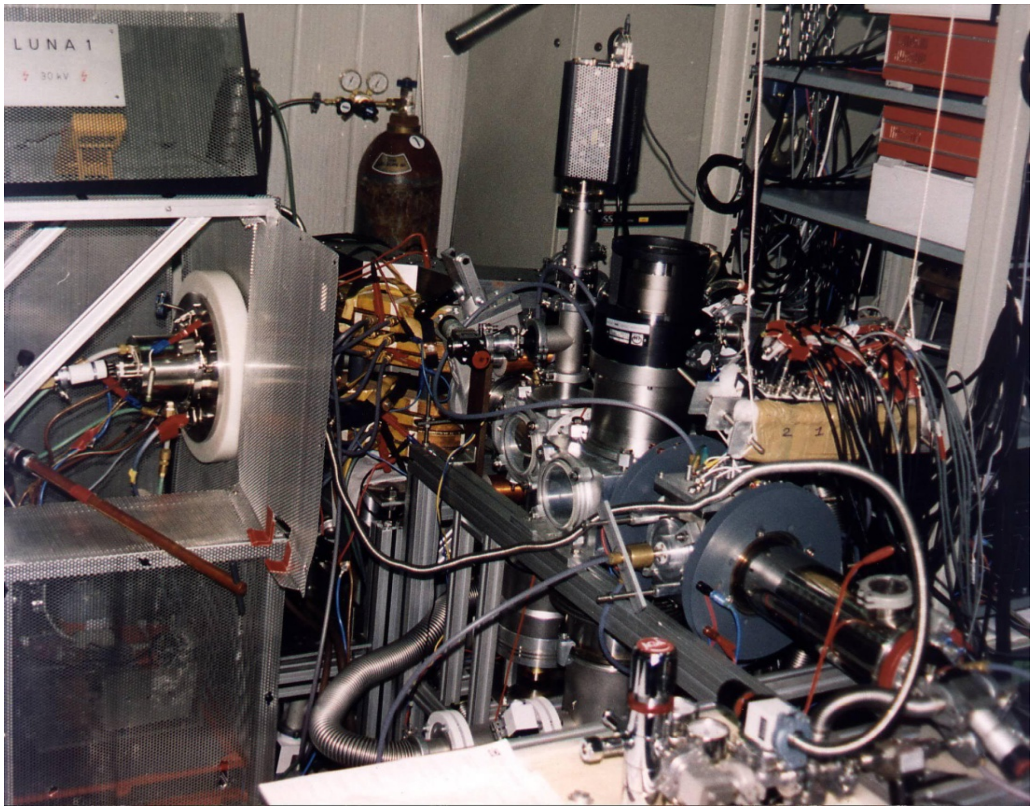
Laboratori Nazionali del Gran Sasso (LNGS)

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



LUNA 50 kV

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



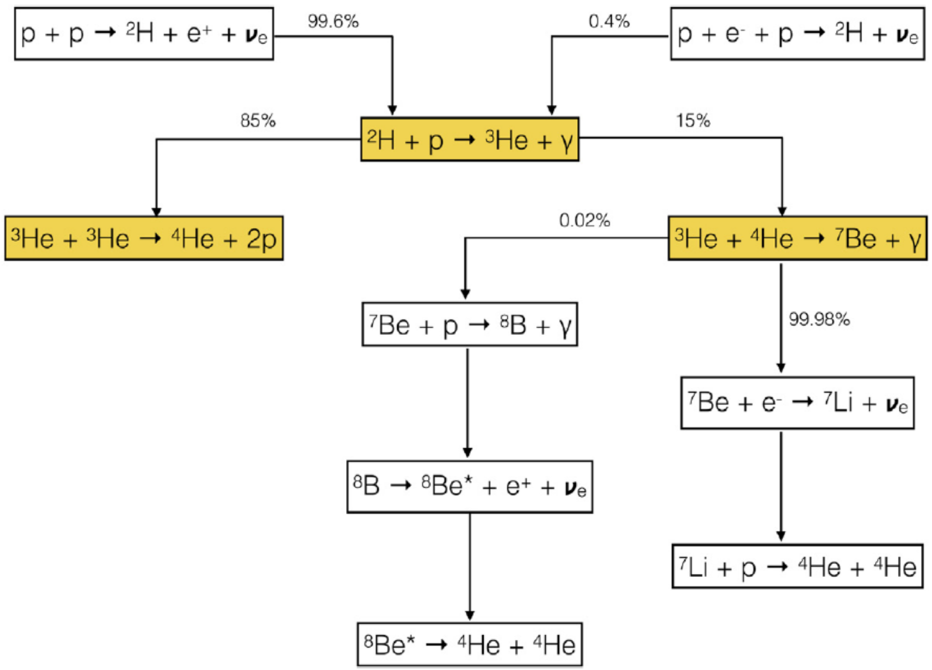
$E_{beam} \approx 1 – 50$ keV
$I_{max} \approx 500\ \mu A$ protons, ^3He
Energy spread ≈ 20 eV

Claus Rolfs

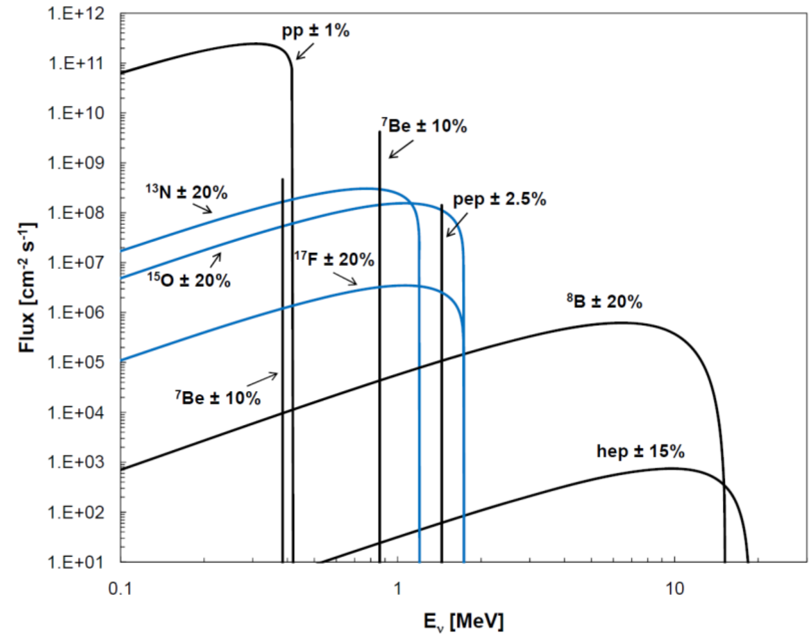
Goal: Understanding the hydrogen burning in the Sun through the study of the $^3He(^3He,2p)^4He$ reaction at low energies

SSM and the Solar Neutrino deficit

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



p-p chain



As suggested by Fowler, a natural way to explain the observed neutrino deficit could be due to a narrow resonance inside the unexplored ^{3}He+^{3}He solar gamow peak

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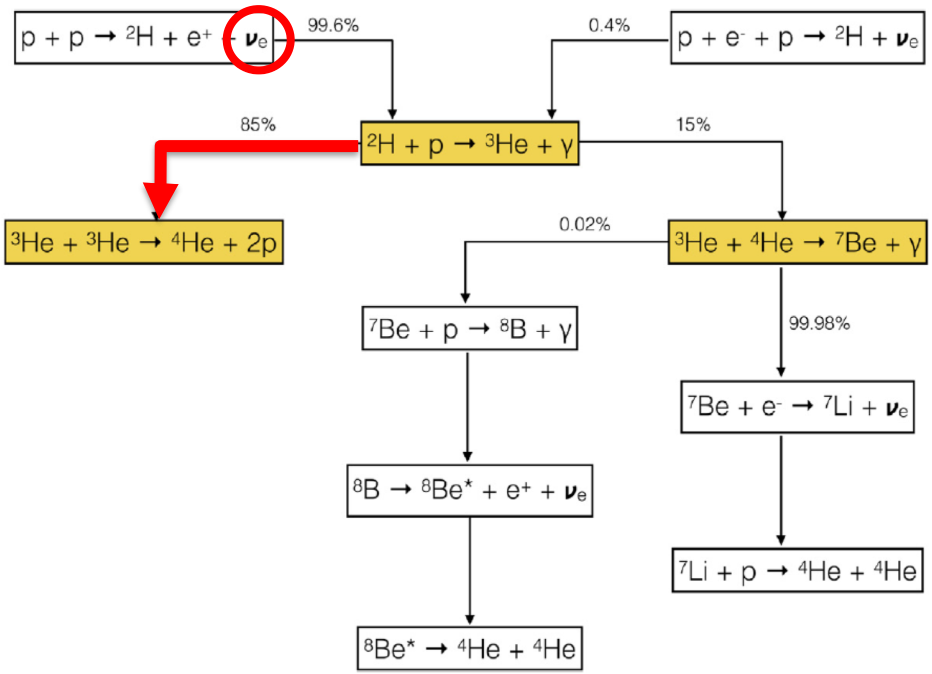

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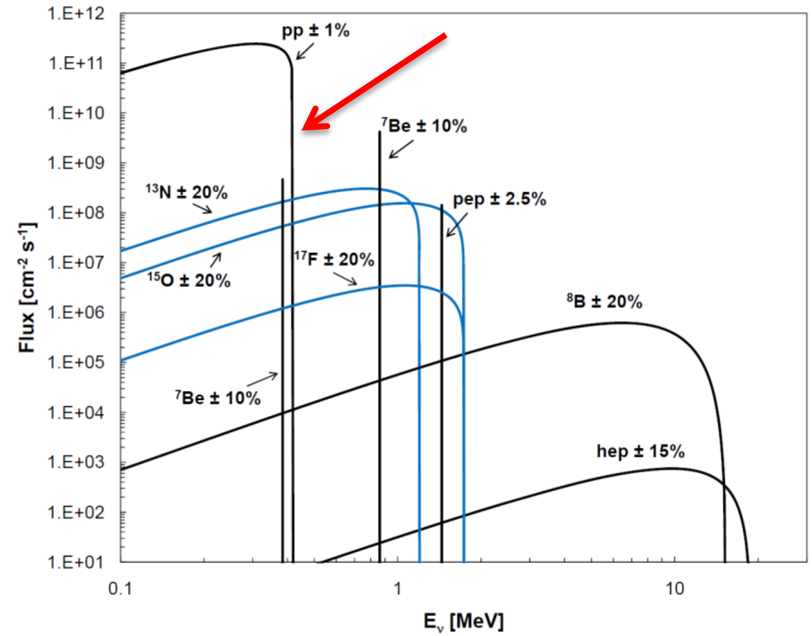

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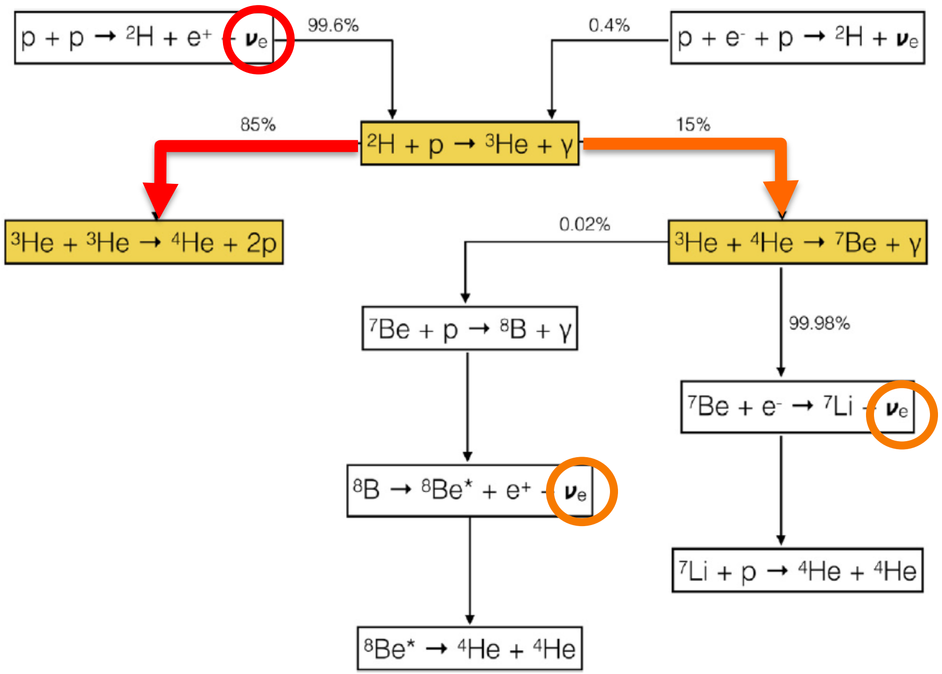
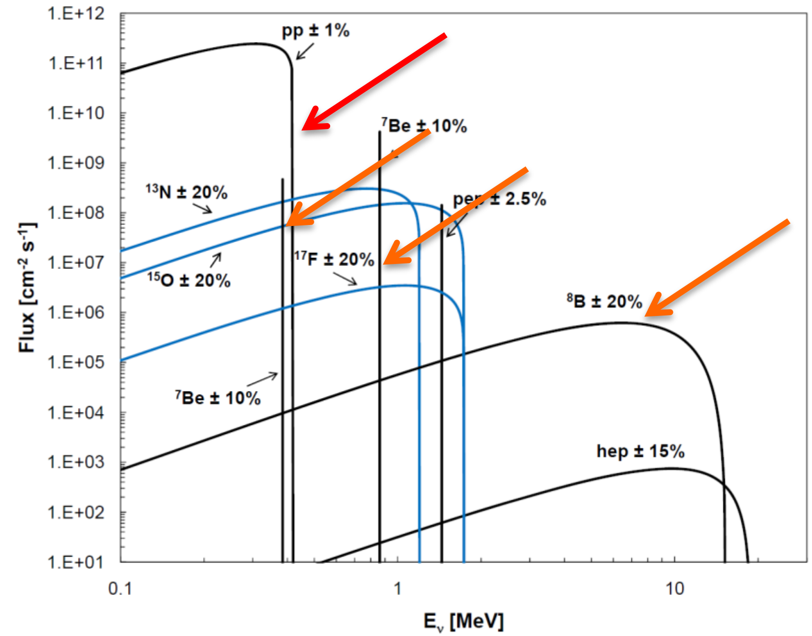


p-p chain



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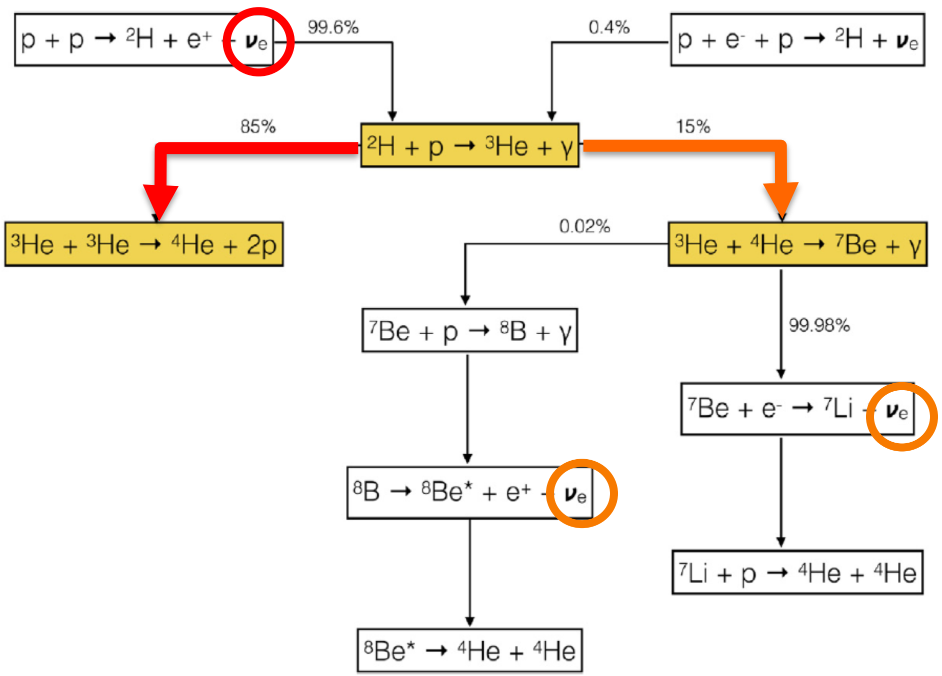

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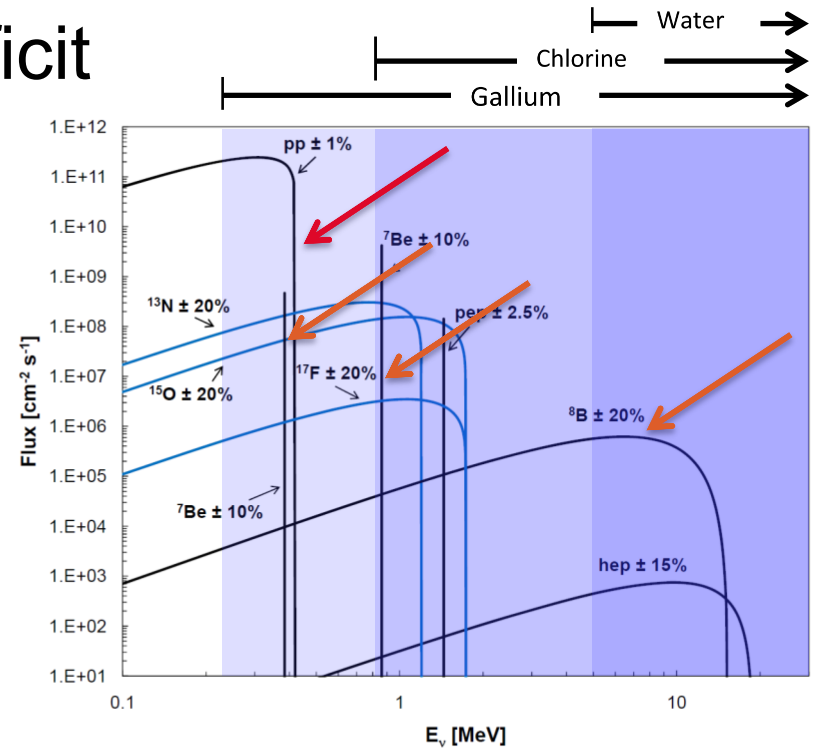

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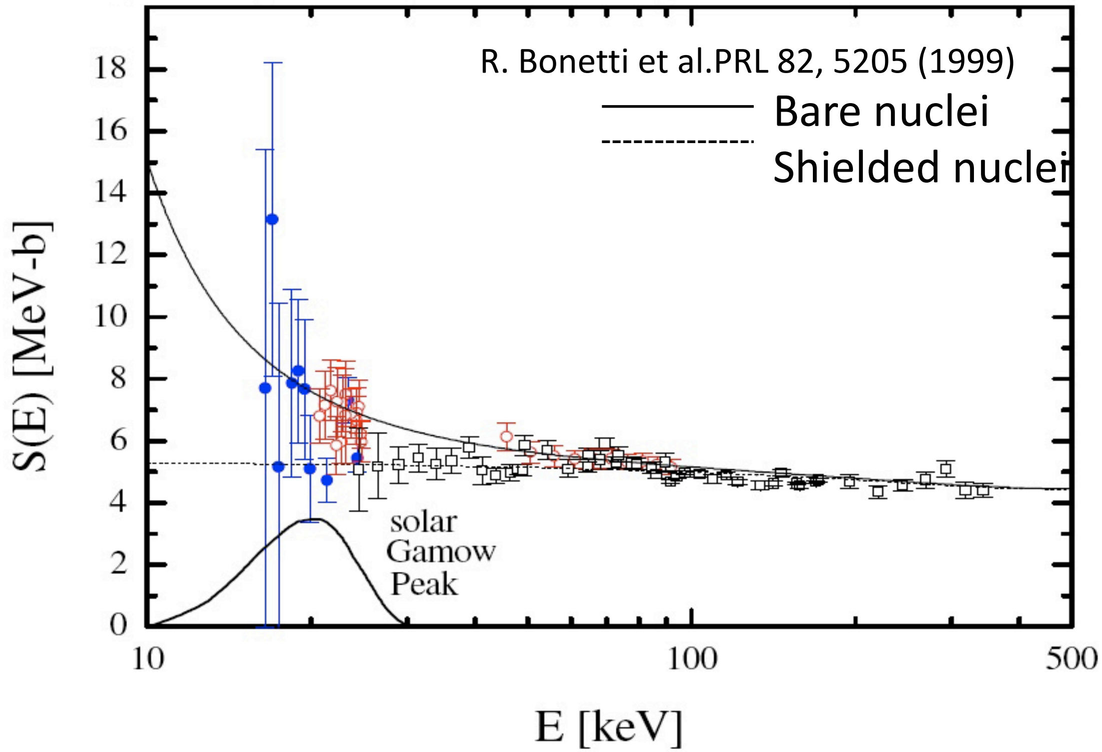
$^3He(^3He,2p)^4He$ reaction



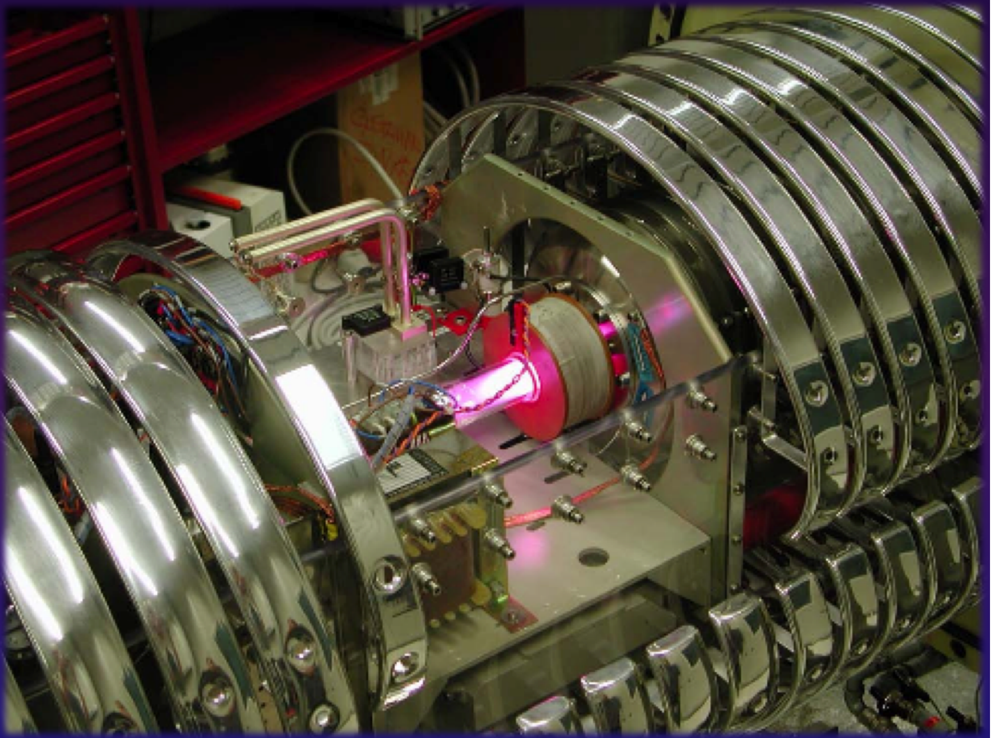
-First measurement below the Gamow peak

-σ(16,5 keV)=20±10 fb 2 events/month!!

-No evidence for a narrow resonance → SSM validation

→second generation of experiments (Borexino, Kamland, SNO) addressed to prove the neutrino oscillation (and to measure the neutrino mixing parameters).

LUNA 400 kV



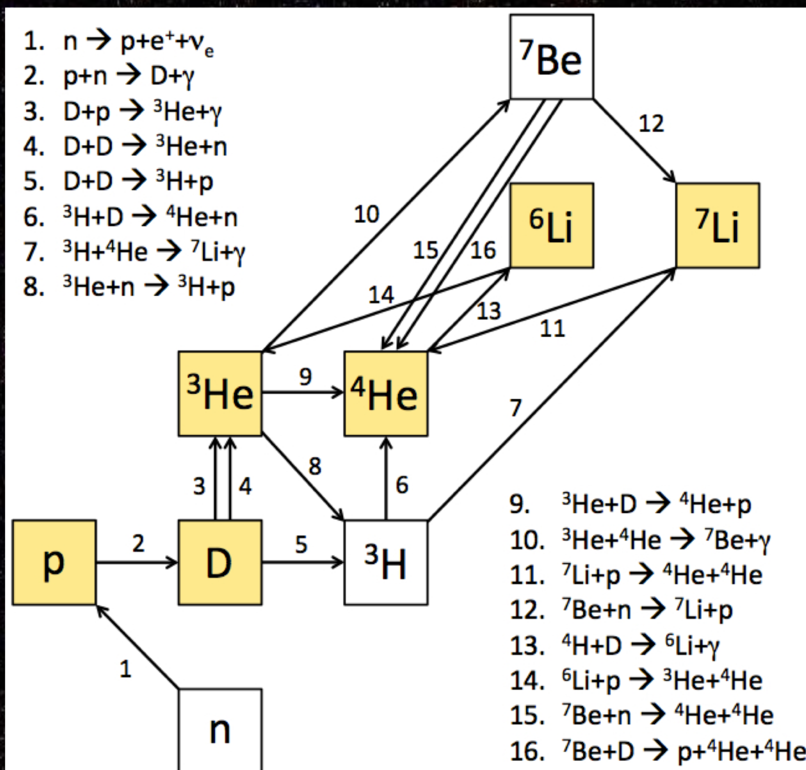
- $^{14}N(p,\gamma)^{15}O$ (Sun,CNO-I cycle)
- $^{3}He(^{4}He,\gamma)^{7}Be$ (Sun, BBN)
- $^{25}Mg(p,\gamma)^{26}Al$ (Mg-Al Cycle)
- $^{15}N(p,\gamma)^{16}O$ (CNO-II Cycle)
- $^{17}O(p,\gamma)^{18}F$ (CNO-III Cycle)
- $^{2}H(^{4}He,\gamma)^{6}Li$ (BBN)
- $^{22}Ne(p,\gamma)^{23}Na$ (Ne-Na Cycle)
- $^{2}H(p,\gamma)^{3}He$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

Mixing parameters of solar neutrinos
Temperature and metallicity of Sun
Stellar evolution
Universal chemical composition
Age of Universe
Cosmology
Theoretical Nuclear physics

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

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

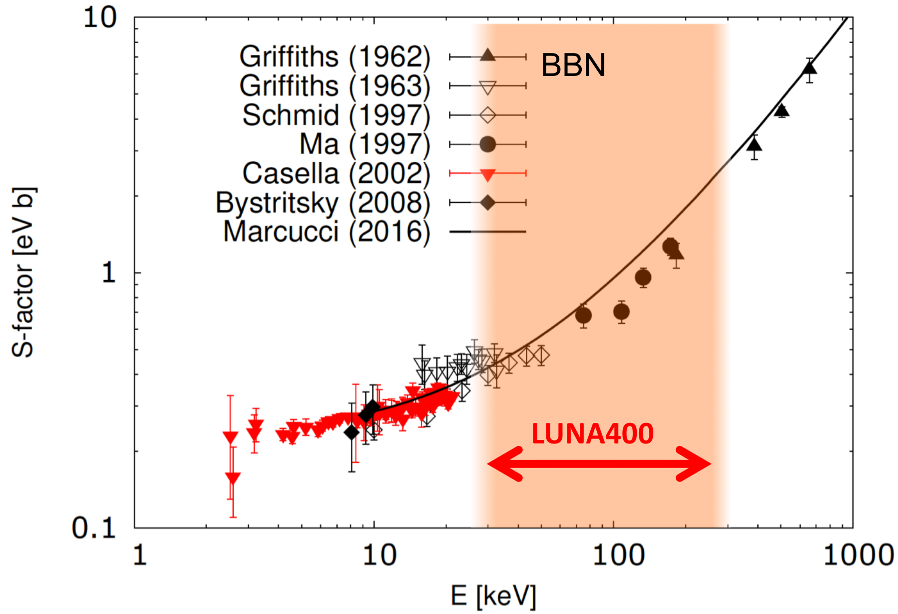
-Particle Physics (N_{eff}, α..)

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

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

Reaction	$\Delta(D/H)_{BBN}/(D/H)_{BBN}$
$p(n,\gamma)D$	0.08%
$D(p,\gamma)^3He$	$\boxed{2.34\%}$
$D(d,n)^3He$	0.75%
$D(d,p)^3H$	0.49%

(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 $30<E_{cm}[keV]<270$ with ~ 3% accuracy
- Differential cross section measurement at $50<E_{cm}[keV]<270$

Physics:

- *Cosmology: measurement of Ω_b*
- *Neutrino physics: measurement of N_{eff}*
- *Nuclear physics: comparison of data with "ab initio" predictions*

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

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

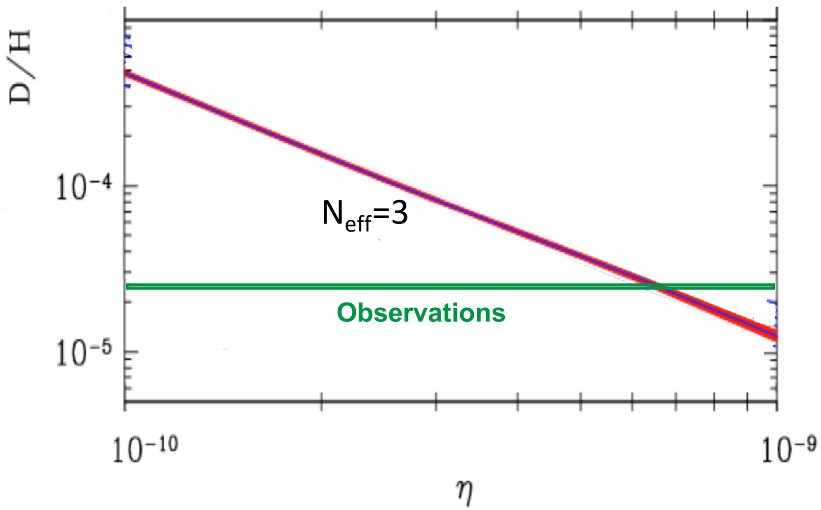
Dpγ data fit

$100\Omega_{b,0}h^2(BBN)=2.235\pm0.033\pm0.016$ (Cooke2018)

$100\Omega_{b,0}h^2(BBN)=2.166\pm0.011\pm0.015$ (Cooke2018)

Dpγ "ab-initio"

D/H observations



From CMB data:

$100\Omega_{b,0}h^2(CMB)=2.236\pm0.015$ (PLANCK2019)

D(p,γ)^{3}He reaction @ LUNA400

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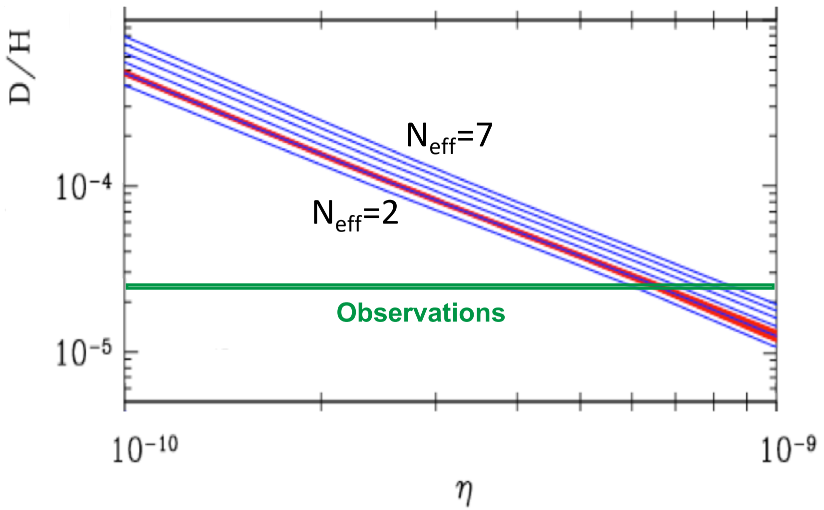
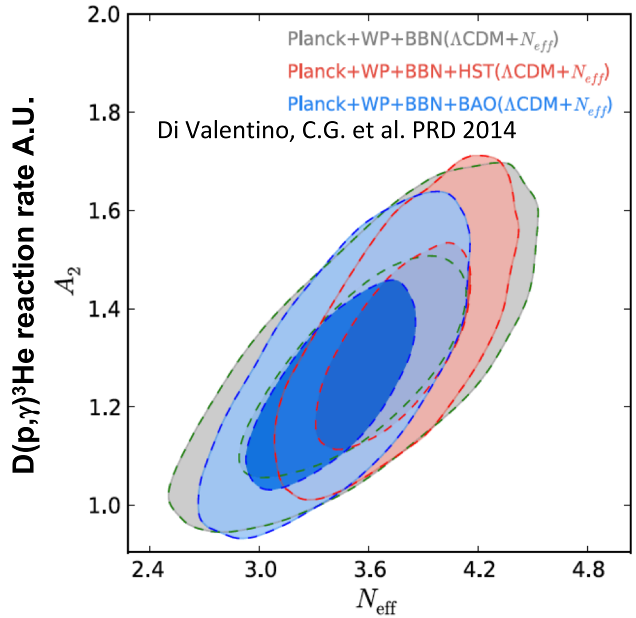


From CMB data:

$100\Omega_{b,0}h^2$(CMB)=2.236±0.015 (PLANCK2019)

❖ 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".



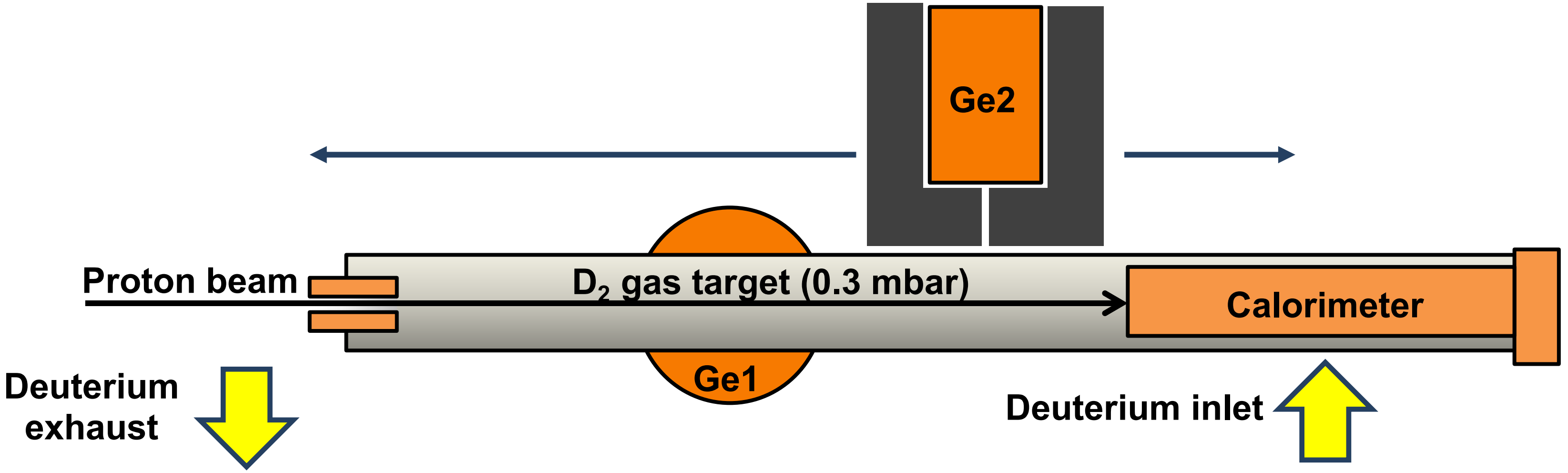
Assuming literature data for the D(p,γ)^{3}He reaction:

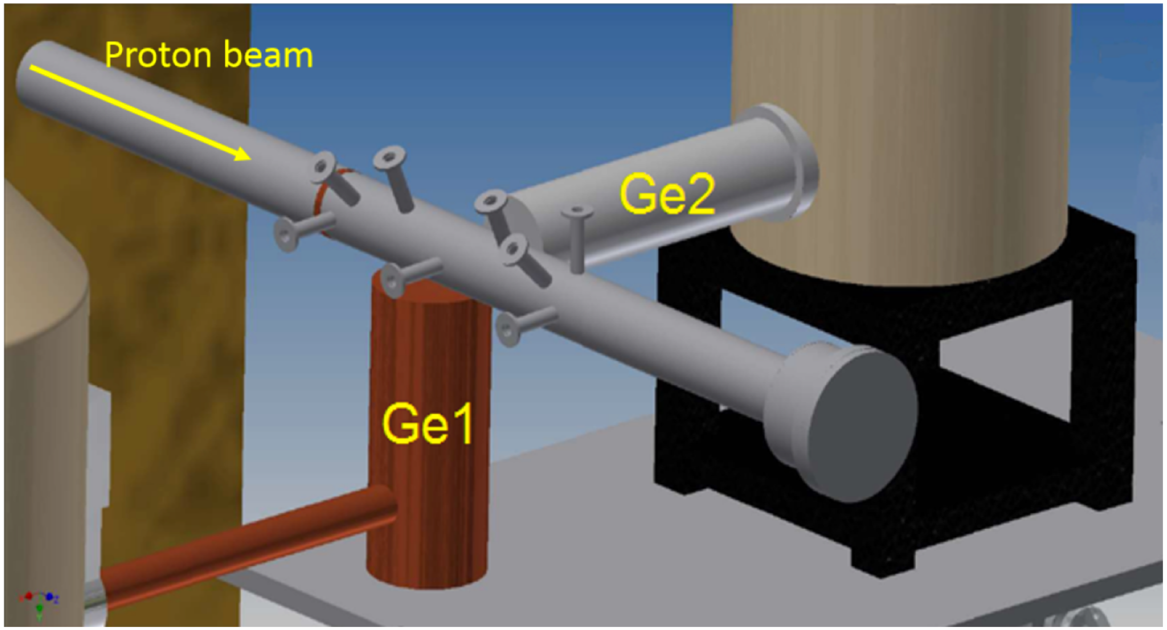
N_{eff} (BBN) = 3.57±0.18 (Cooke&Pettini 2013)

N_{eff} (CMB) = 2.89±0.37 (PLANCK 2019)

N_{eff} (SM) = 3.046

D(p,γ)^{3}He reaction: setup

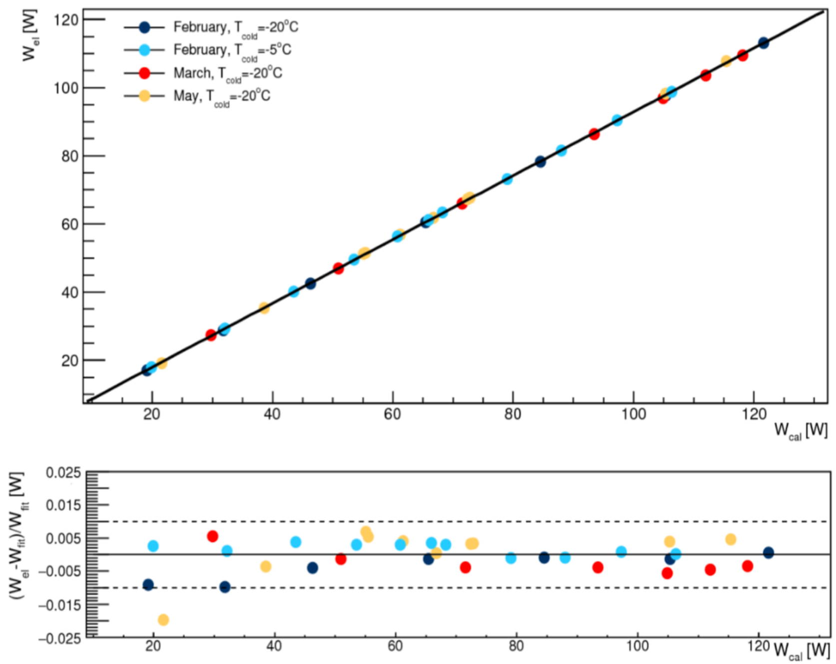




Systematics: Beam Current

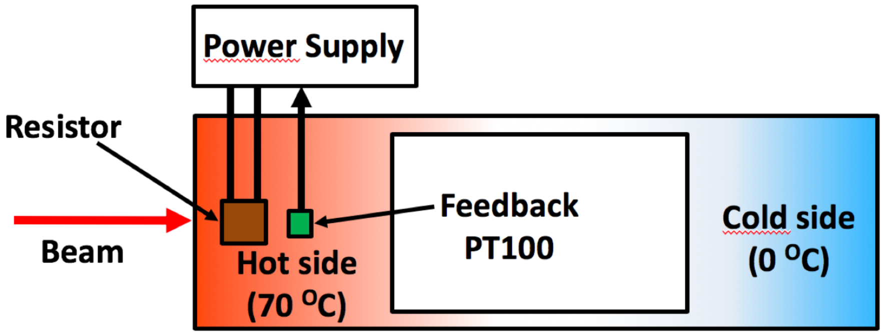
$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \cdot \boxed{I_{beam}} \cdot \rho(z) \cdot \varepsilon(z)} W(\vartheta\,(z))\,dz$$

HPGe Source	Method
BEAM CURRENT	Calibration with Faraday cup
TEMPERATURE PROFILE	Direct Measurement
PRESSURE PROFILE	Direct Measurement
BEAM HEATING	Rate Vs Current measurement
DETECTOR EFFICIENCY	Calibration with $^{14}N(p,g)^{15}O$ reaction
ANGULAR DISTRIBUTION	Peak Shape Analysis



Constant temperature gradient calorimeter

$$I_{beam} = \frac{W_0 - W_{beam}}{E_p/e}$$



Systematics: Target Density

$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \; \boxed{I_{beam}} \cdot \boxed{\rho(z)} \cdot \varepsilon(z)} W(\vartheta\,(z))\,dz$$

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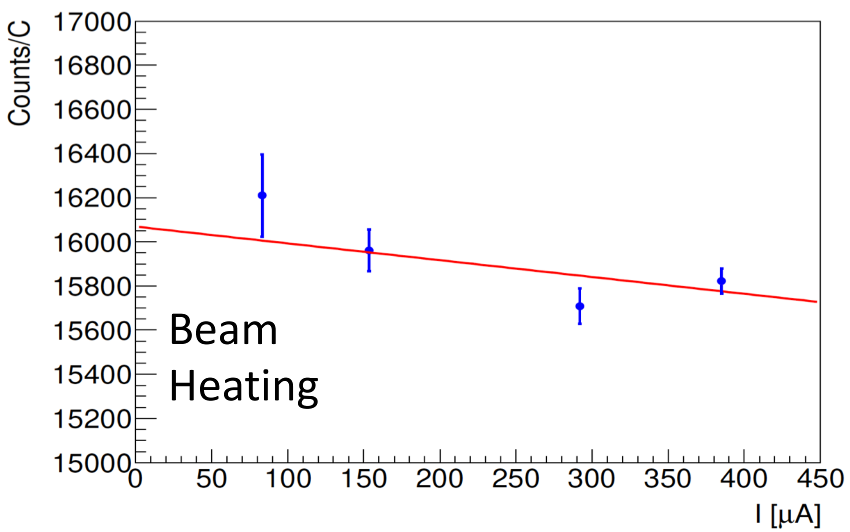

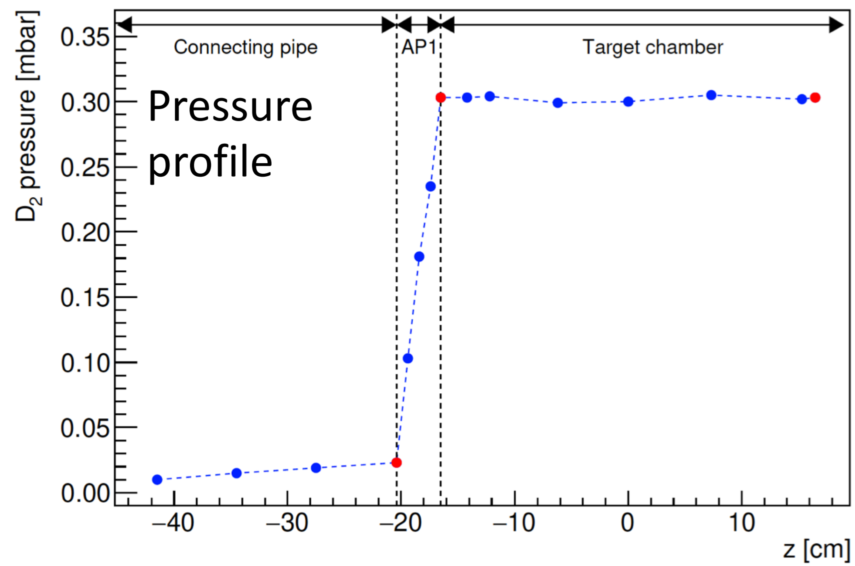

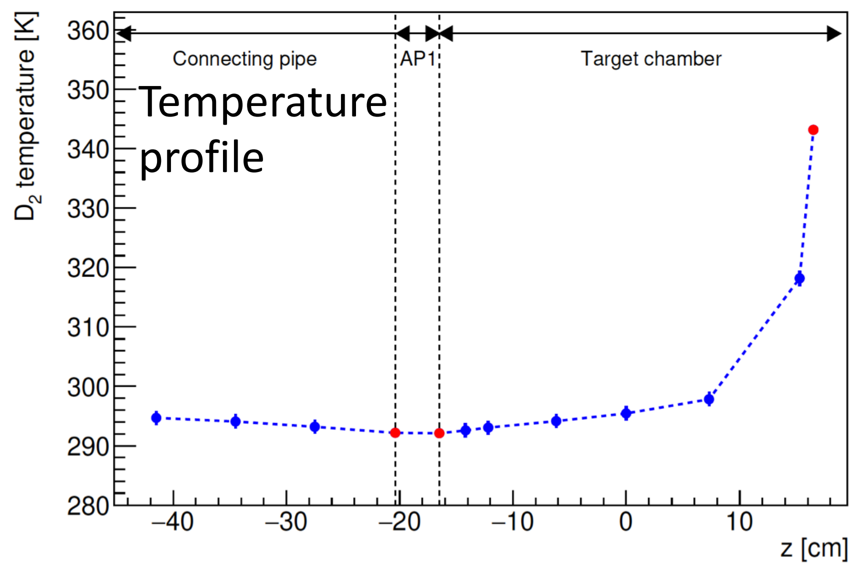

Systematics: Detector Efficiency

$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \cdot \boxed{I_{beam}} \cdot \boxed{\rho(z)} \cdot \boxed{\varepsilon(z)}} W(\vartheta\,(z))\,dz$$

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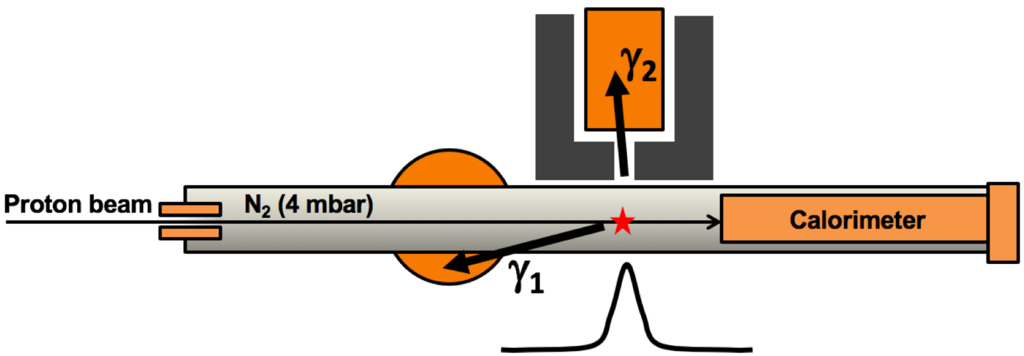
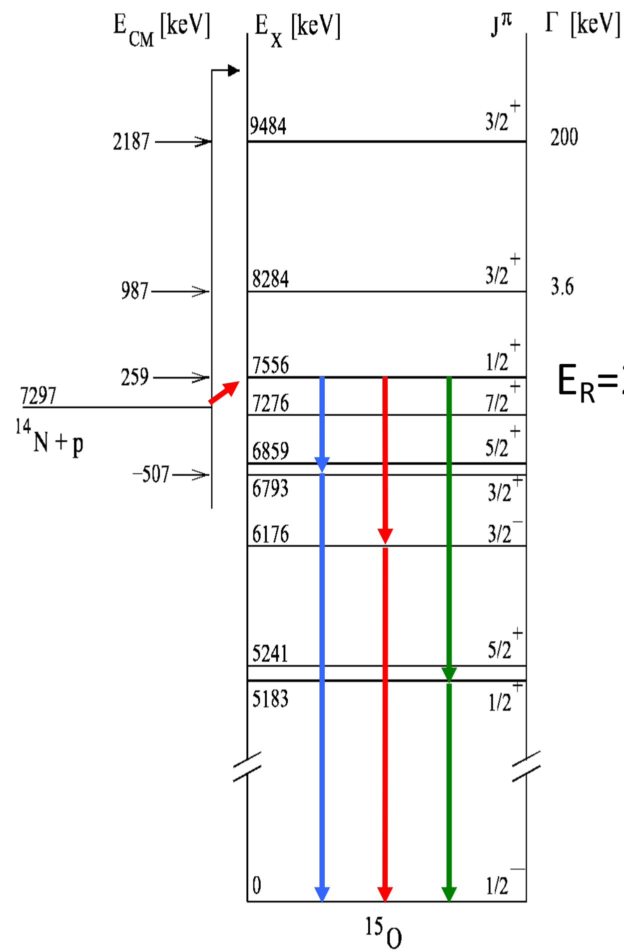
Calibration exploiting the reaction: $^{14}N+p \rightarrow {}^{15}O+\gamma_1+\gamma_2$





E_R=259 keV

Eγ (keV)	BR (%)
765+6791	22.9
1384+6172	57.8
2375+5181	17.1

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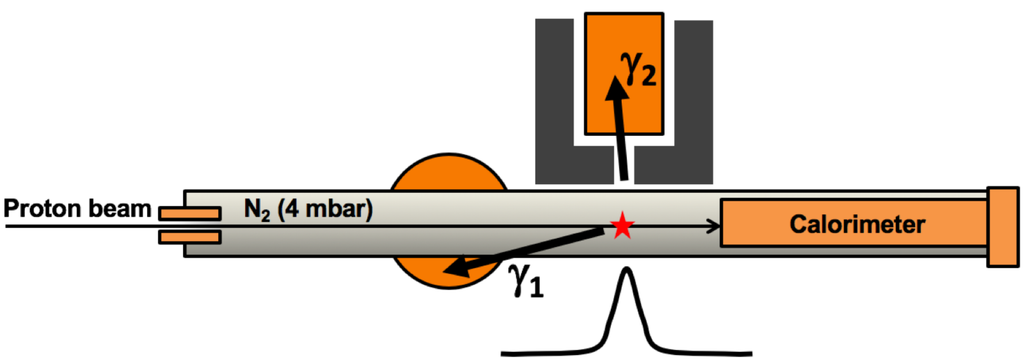
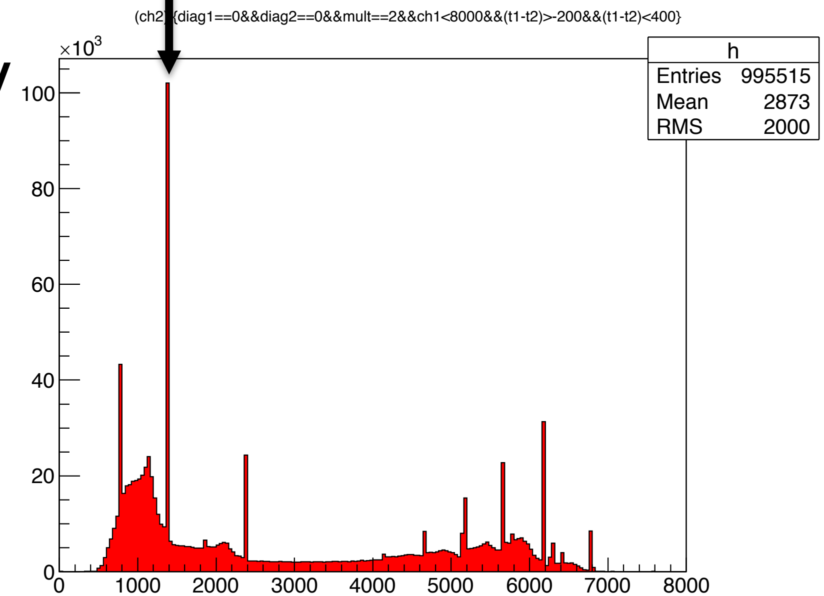
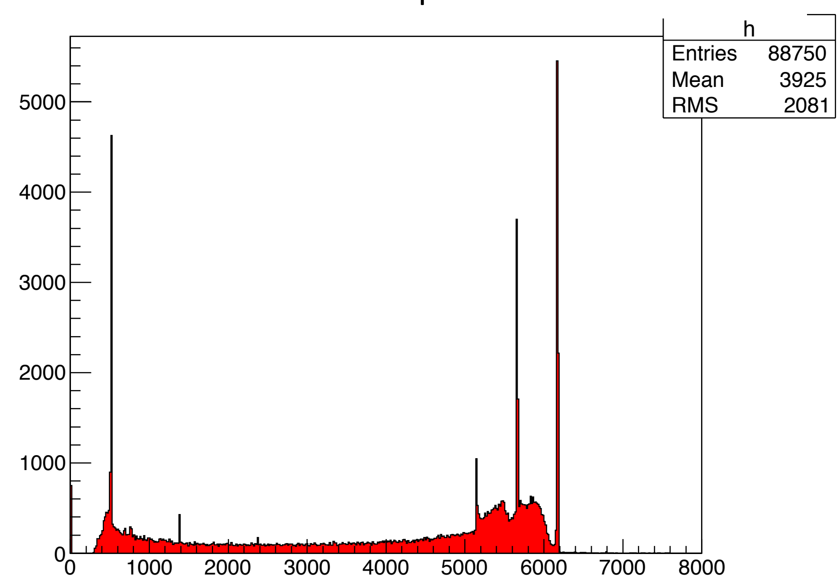




Ge2 Inclusive spectrun



Ge1 Coinc. spectrum

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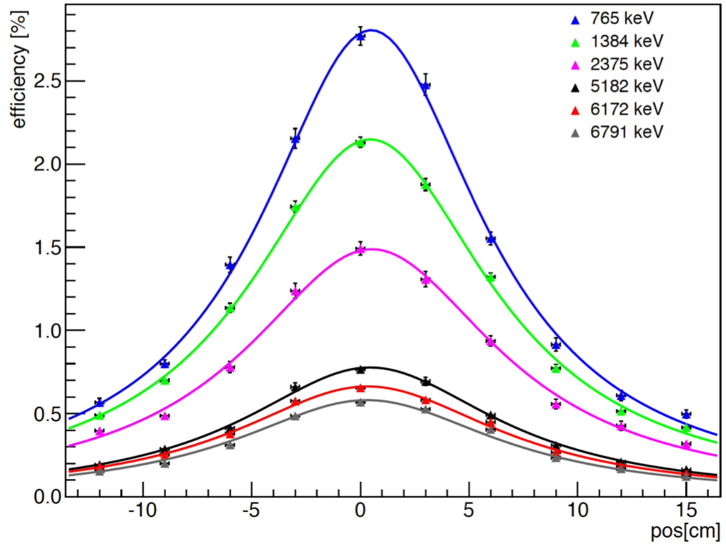

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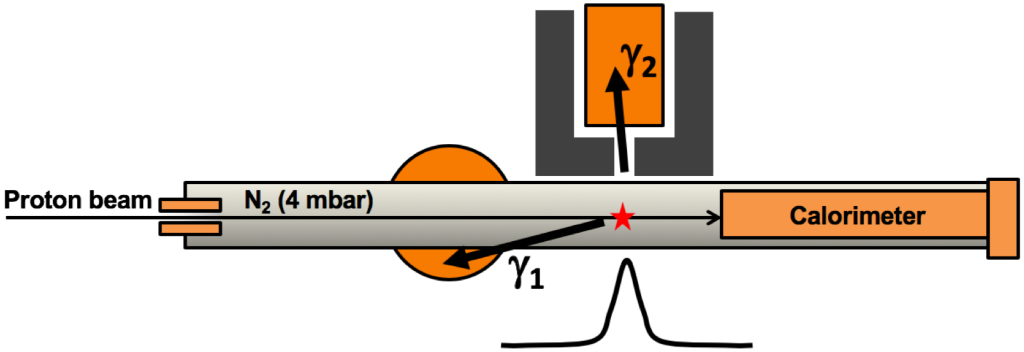

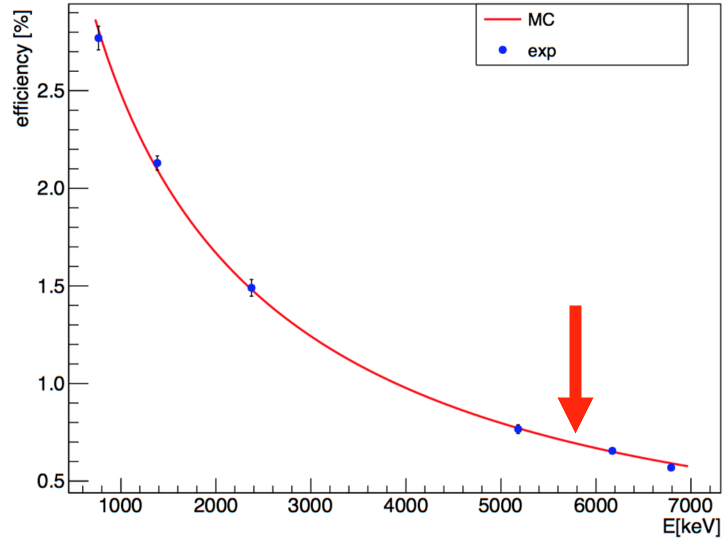

Systematics: Angular Distribution

$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \boxed{I_{beam}} \cdot \boxed{\rho(z)} \cdot \boxed{\varepsilon(z)}} \boxed{W(\vartheta\,(z))}\, dz$$

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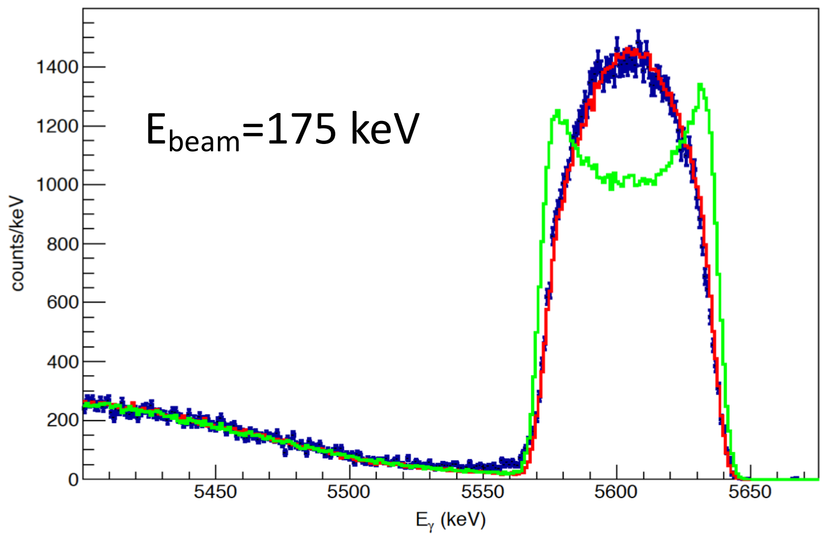
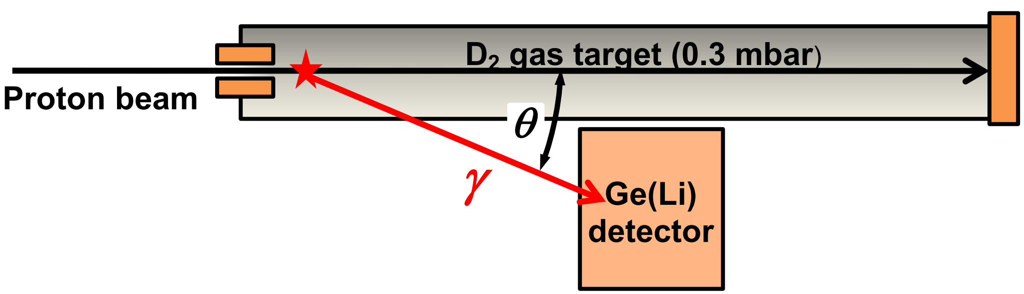


$$\boxed{E_\gamma} = \frac{m_p^2 + m_d^2 - m_{He}^2 + 2E_p m_d}{2(E_p + m_d + p_p \boxed{\cos(\vartheta_{lab})})}$$



Total error budget

$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \; \boxed{I_{beam}} \cdot \boxed{\rho(z)} \cdot \boxed{\varepsilon(z)}} \boxed{W(\vartheta(z))} \, dz$$

Source	Method	$\Delta S/S$
Beam energy	Direct measurement	$\ll 1\%$
Energy loss	Low pressure	$\ll 1\%$
T and P profiles	Direct measurement	1.0%
Beam heating	Direct measurement	0.5%
Gas purity	Data sheet	$\ll 1\%$
Beam current	Calorimeter calibration	1.0%
Efficiency	Direct measurement	2.0%
Instrumental effects	Pulser method	$\ll 1\%$
Angular distribution	Peak shape analysis	0.5%
Total		2.6%

$E_{cm}[keV]$	$\Delta S_{sys}/S$	$\Delta S_{stat}/S$
32.36	2.6%	3.6%
66.68	2.4%	1.4%
99.48	2.4%	0.9%
115.88	2.5%	0.9%
132.91	2.9%	0.4%
149.29	2.5%	0.5%
166.09	2.9%	0.3%
182.70	2.4%	0.4%
199.47	2.4%	0.2%
222.82	2.5%	0.3%
232.89	2.9%	0.6%
252.86	2.5%	0.6%
262.88	2.5%	0.9%

Moreover:

- Beam induced background → Dedicated measurements
- Instrumental bias (dead time, pile-up,..) → Pulser method
- Energy loss → Ziegler formulae/direct measurements
- Detailed simulation to correct second order effects
-
-

Conclusions

In recent years spectacular improvements have been reached in Cosmology. In particular:
-Cosmic baryon density Ω_b is derived with a precision of <1% percent, thanks to the PLANCK mission.
-Primordial abundance of Deuterium D/H_{obs} is now known at ~1% from astronomical observations.

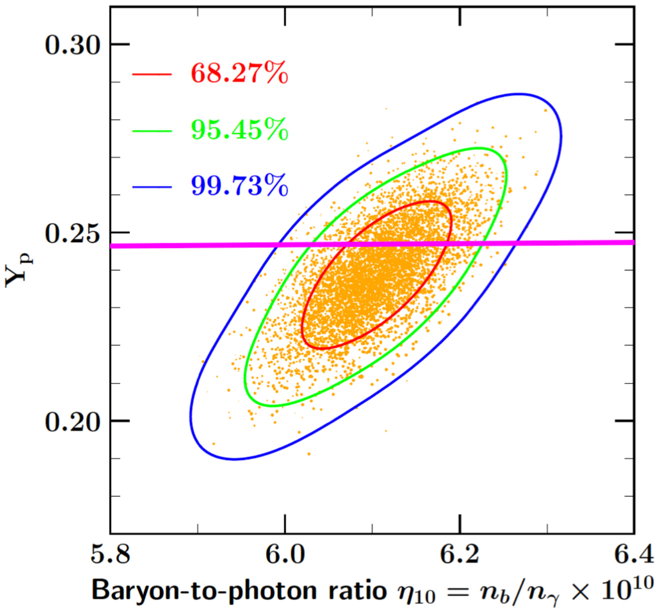
The new LUNA measurement allows to determine D/H_{BBN} with high accuracy, affected previously by the poorly known $D(p,\gamma)^3He$ cross section at BBN energies. Consequences of particular interest are:

- The accurate determination of Ω_b (BBN), assuming standard (3ν) BBN.
- The comparison of Ω_b(CMB) (i.e. 380.000 years after the Big Bang) and Ω_b(BBN) (few minutes after the birth of Universe).
- The number of neutrino families ($\Delta N_{eff}/N_{eff}$~7%).

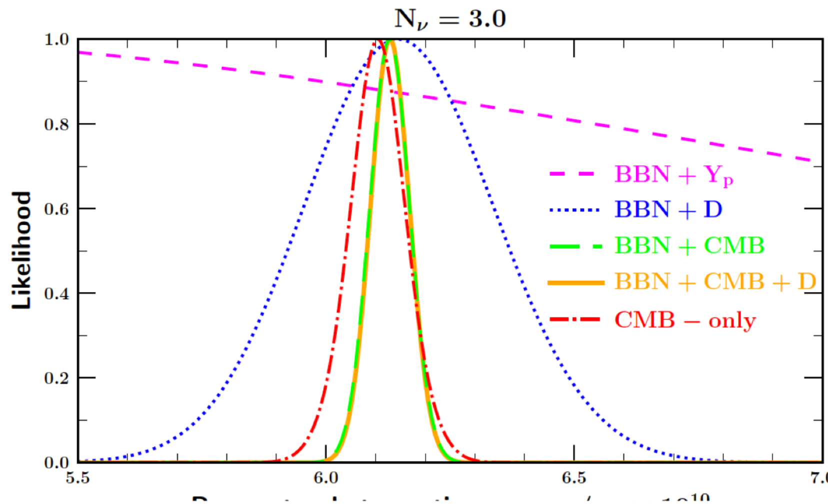
…Soon a paper on the Cosmology *Vs* $D(p,\gamma)^3He$ cross section measured at LUNA.

Thanks for the attention!

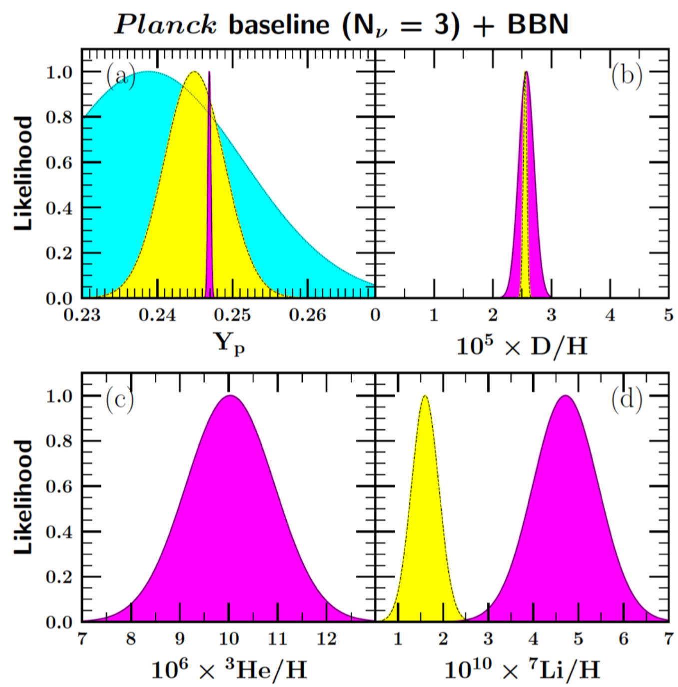
Fields2019



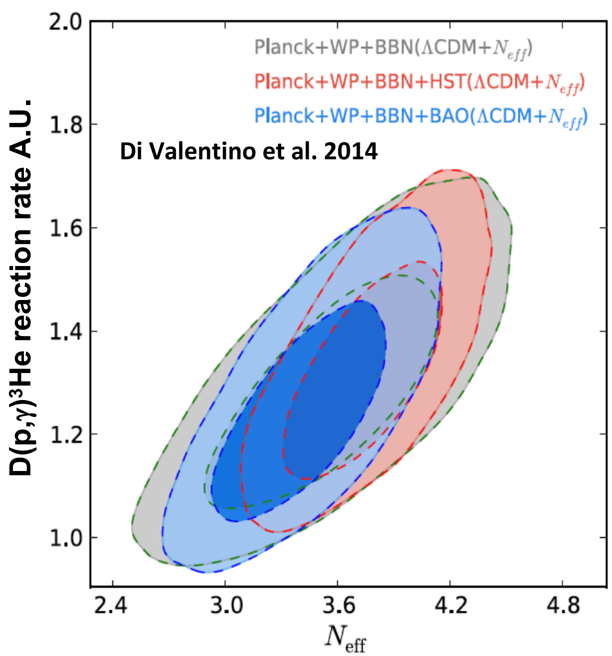
68.27%
95.45%
99.73%
0.30
0.25
0.20
Y_p
5.8
6.0
6.2
6.4
Baryon-to-photon ratio $\eta_{10} = n_b/n_\gamma \times 10^{10}$

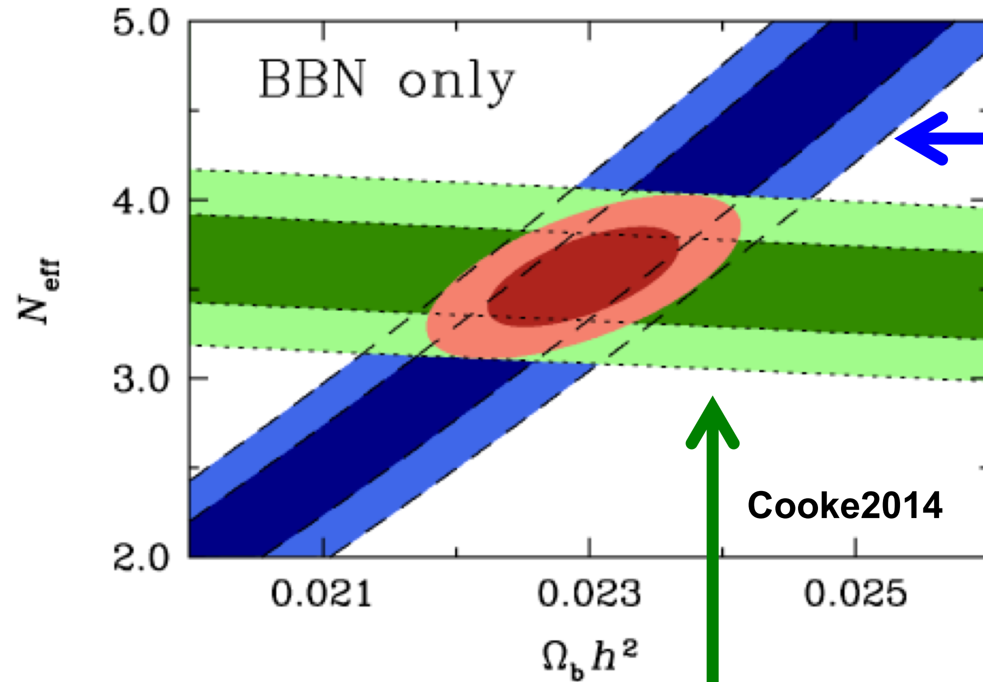


$N_\nu = 3.0$
Likelihood
BBN + Y_p
BBN + D
BBN + CMB
BBN + CMB + D
CMB − only
5.5
6.0
6.5
7.0



Planck baseline (N_ν = 3) + BBN
(a)
(b)
(c)
(d)
Likelihood
Y_p
$10^5 \times D/H$
$10^6 \times {}^3He/H$
$10^{10} \times {}^7Li/H$





Y_p error band mainly due to systematics of direct observations.

D/H error band is mainly due to the D(p,γ)^{3}He reaction.

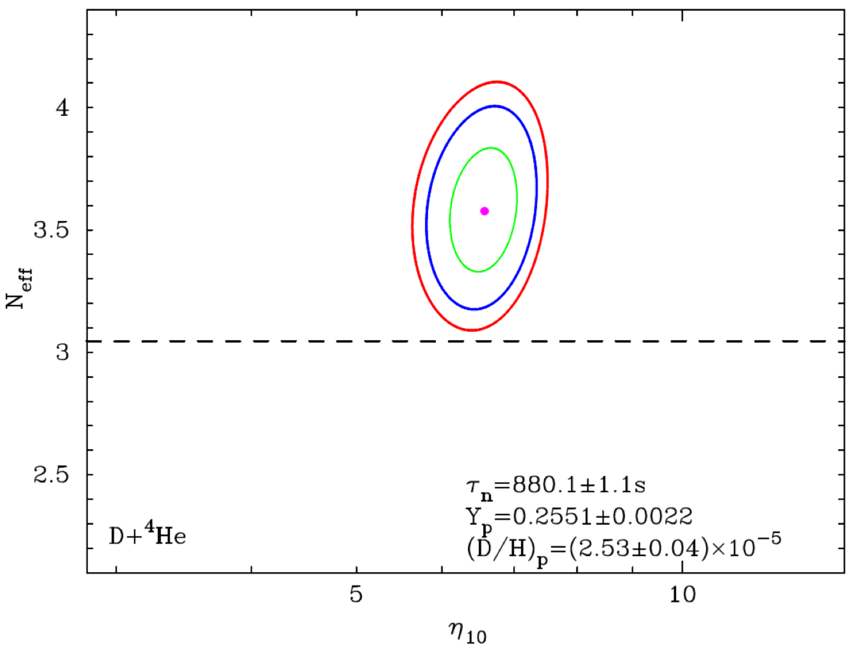
Assuming literature data for the D(p,γ)^{3}He reaction:

N_{eff} (CMB) = 3.36±0.34 (PLANCK 2013)

N_{eff} (BBN) = 3.57±0.18 (Cooke&Pettini 2014)

N_{eff} (SM) = 3.046

IZOTOV 2014
Yp=0.2551±0.0022
Neff=3.58±0.25



PEIMBERT 2016
Yp=0.2446±0.0029
Neff=2.90±0.22

Y_P VALUES AND PREDICTED EQUIVALENT NUMBER OF NEUTRINO FAMILIES, ΔN_ν, BEYOND THE SBBN

Y_P(H II)	Y_P(H II+CMB)	ΔN_ν(H II)	ΔN_ν(H II+CMB)	Y_P source
0.2446 ± 0.0029	0.2449 ± 0.0029	-0.16 ± 0.22	-0.14 ± 0.22	This paper
0.2449 ± 0.0040	0.2455 ± 0.0040	-0.14 ± 0.30	-0.09 ± 0.30	Aver et al. (2015)
0.2551 ± 0.0022	0.2550 ± 0.0022	$+0.63 \pm 0.16$	$+0.62 \pm 0.16$	Izotov et al. (2014)

Next: LUNA MV

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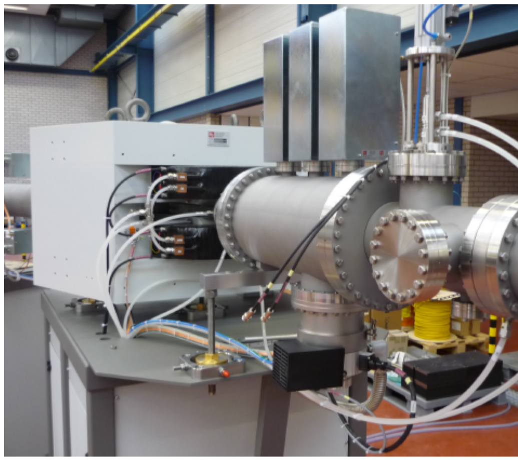
March 19, 2018

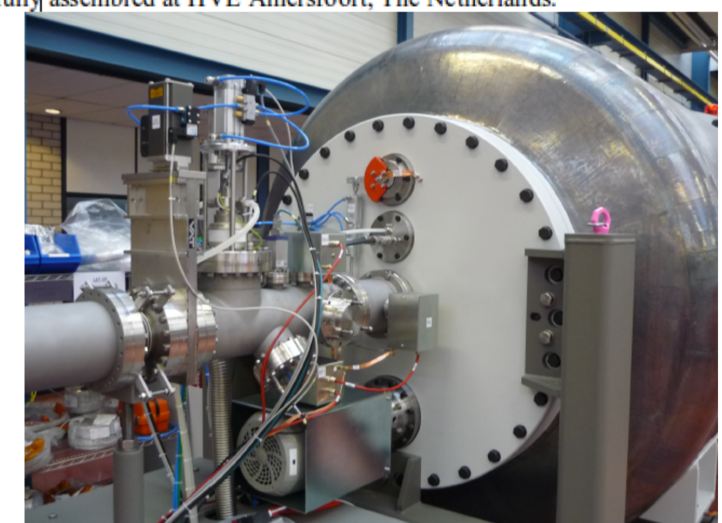
FACTORY ASSEMBLY PROTOCOL

3.5 MV Singletron accelerator system

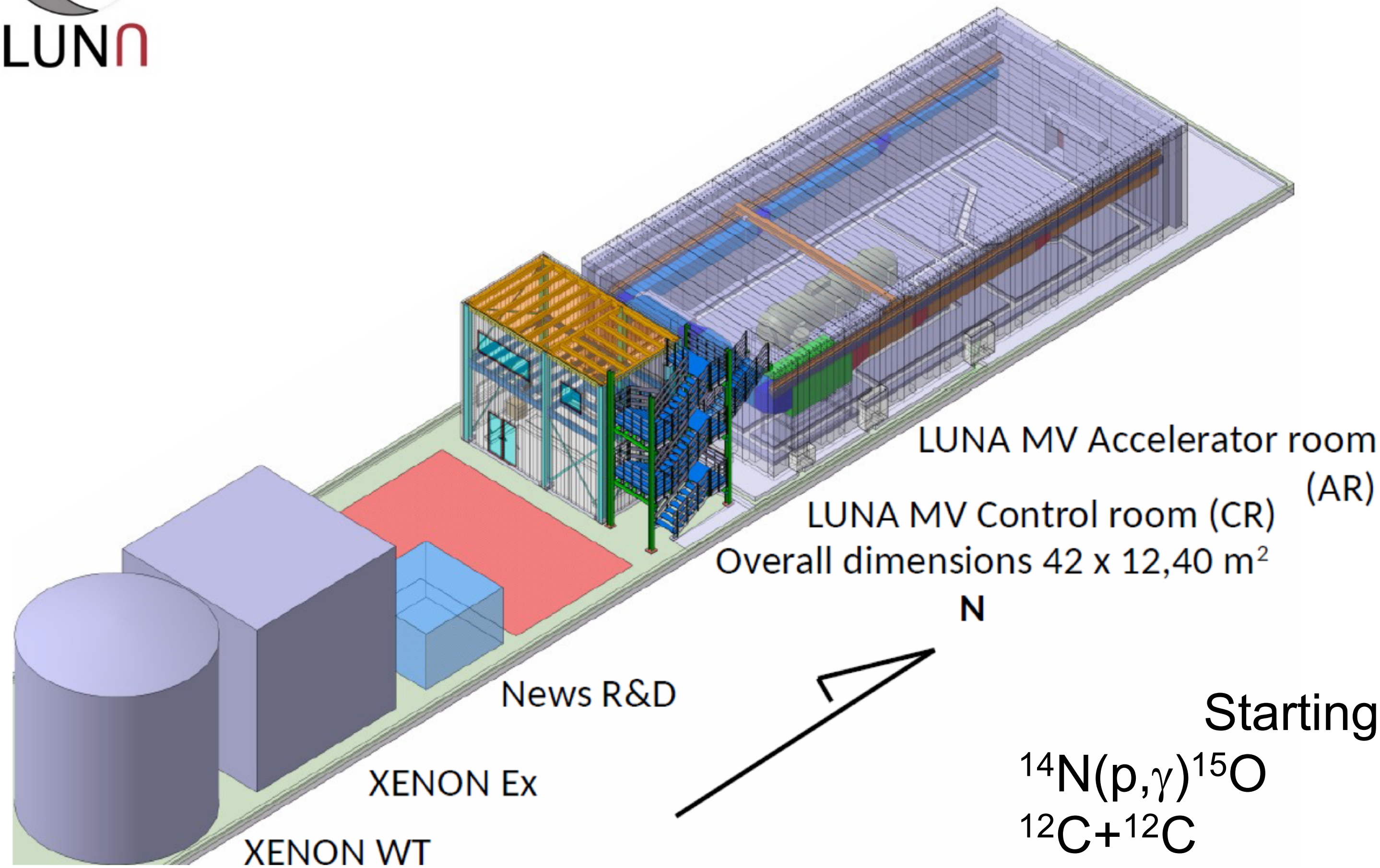
End-User/Consignee:	Laboratory Nazionale del Gran Sasso, Assergi, Italy
Contract number:	CIG No. 62076380EF and CUP No. 154G14000140005 CIG No. 62076380EF Amdt. No. 1
HVEE ref.:	B9051

We herewith confirm that the 3.5 MV Singletron accelerator system for Laboratory Nazionale del Gran Sasso Assergi, Italy is fully assembled at HVE Amersfoort, The Netherlands.





Next: LUNA MV



Terminal Voltage ≈ 0.2 – 3.5 MV

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

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)