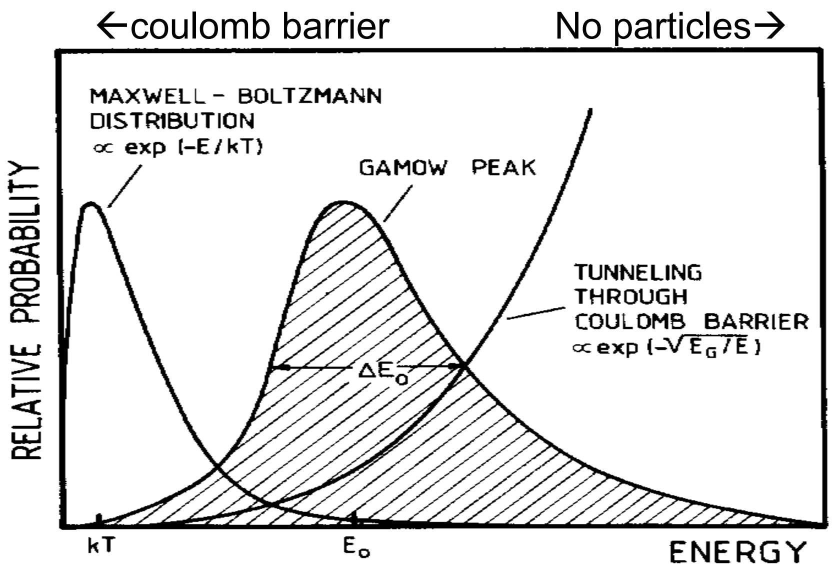
Probing Big Bang Nucleosynthesis Deep Underground

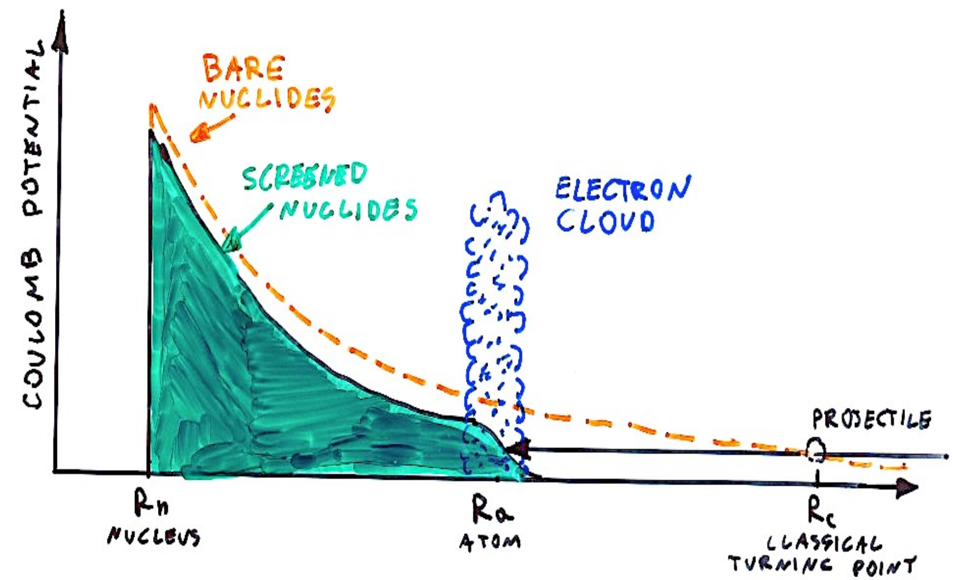
C. Gustavino (for the LUNA collaboration)
INFN-Roma

The LUNA experiment at LNGS
Big Bang Nucleosynhesis
BBN at LUNA
d(p,γ)^{3}He reaction

INPC, september 15th 2016, Adelaide

Why Underground measurements?





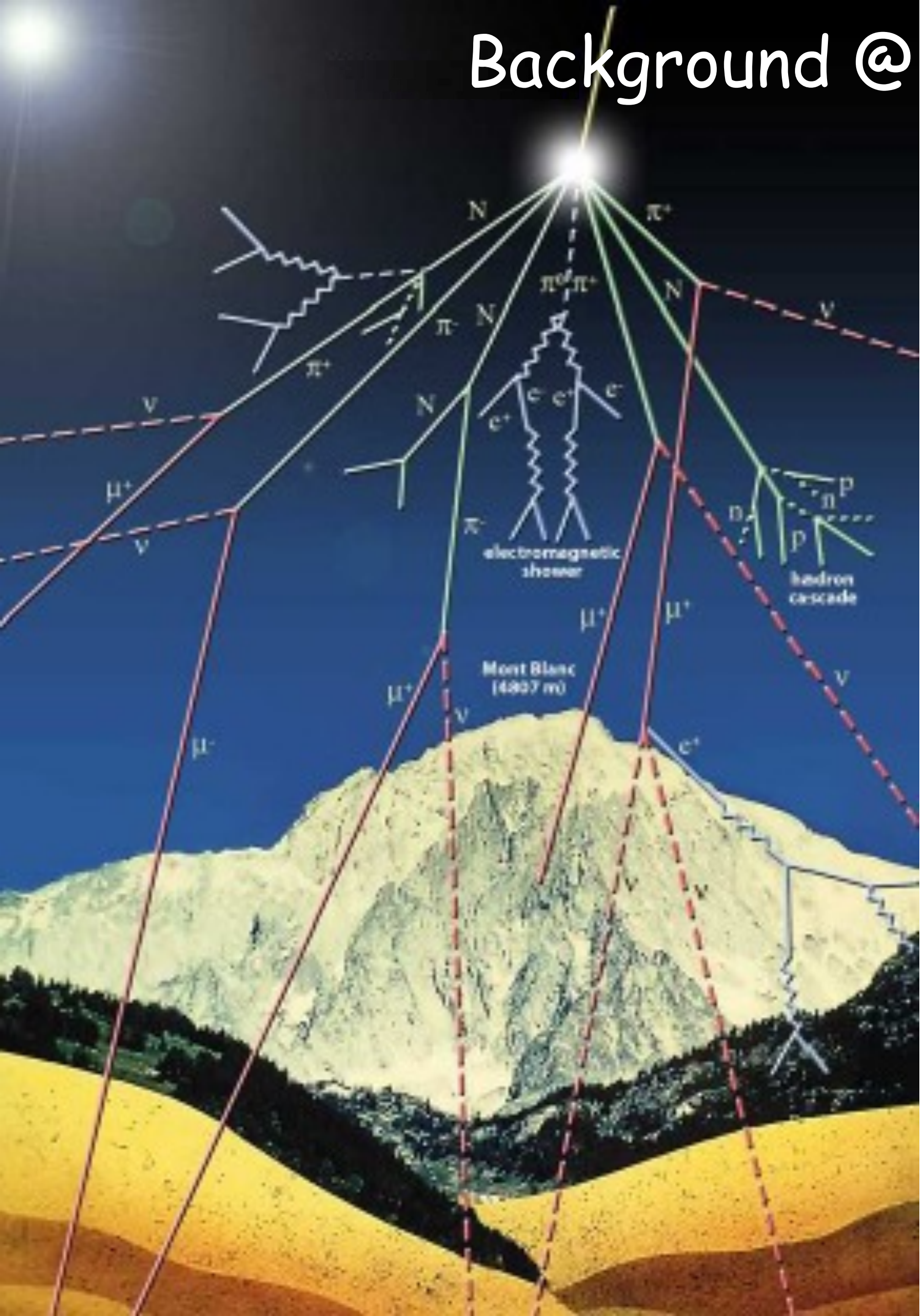
Astrophysical Factor

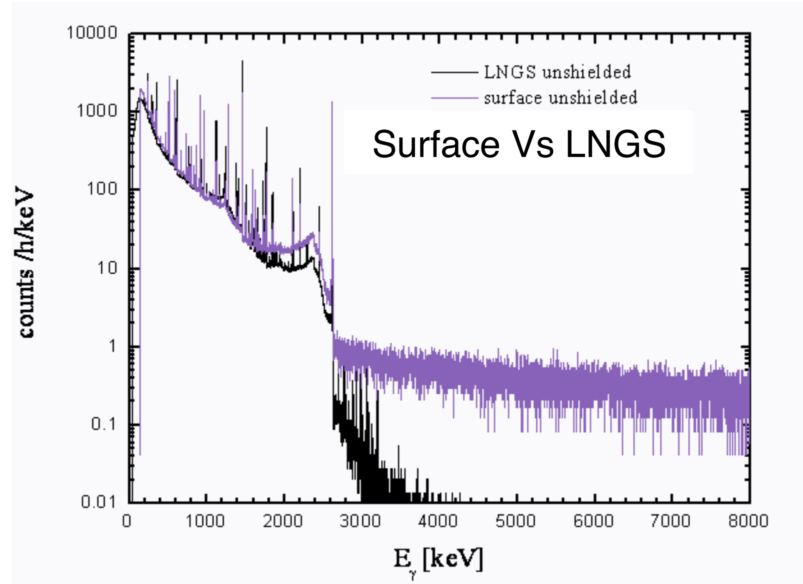
Coulomb Barrier

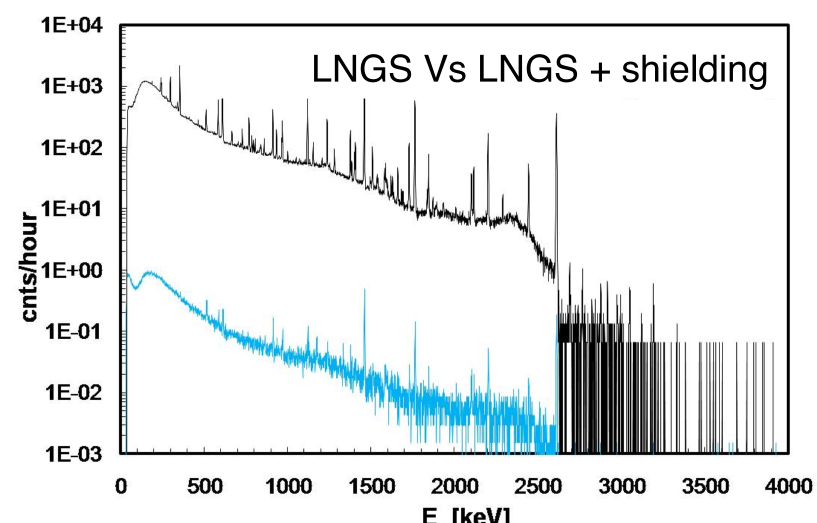
$$\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}$$

Very low cross sections because of the coulomb barrier
→UNDERGROUND accelerator to reduce the background induced by cosmic rays

Background @ Gran Sasso

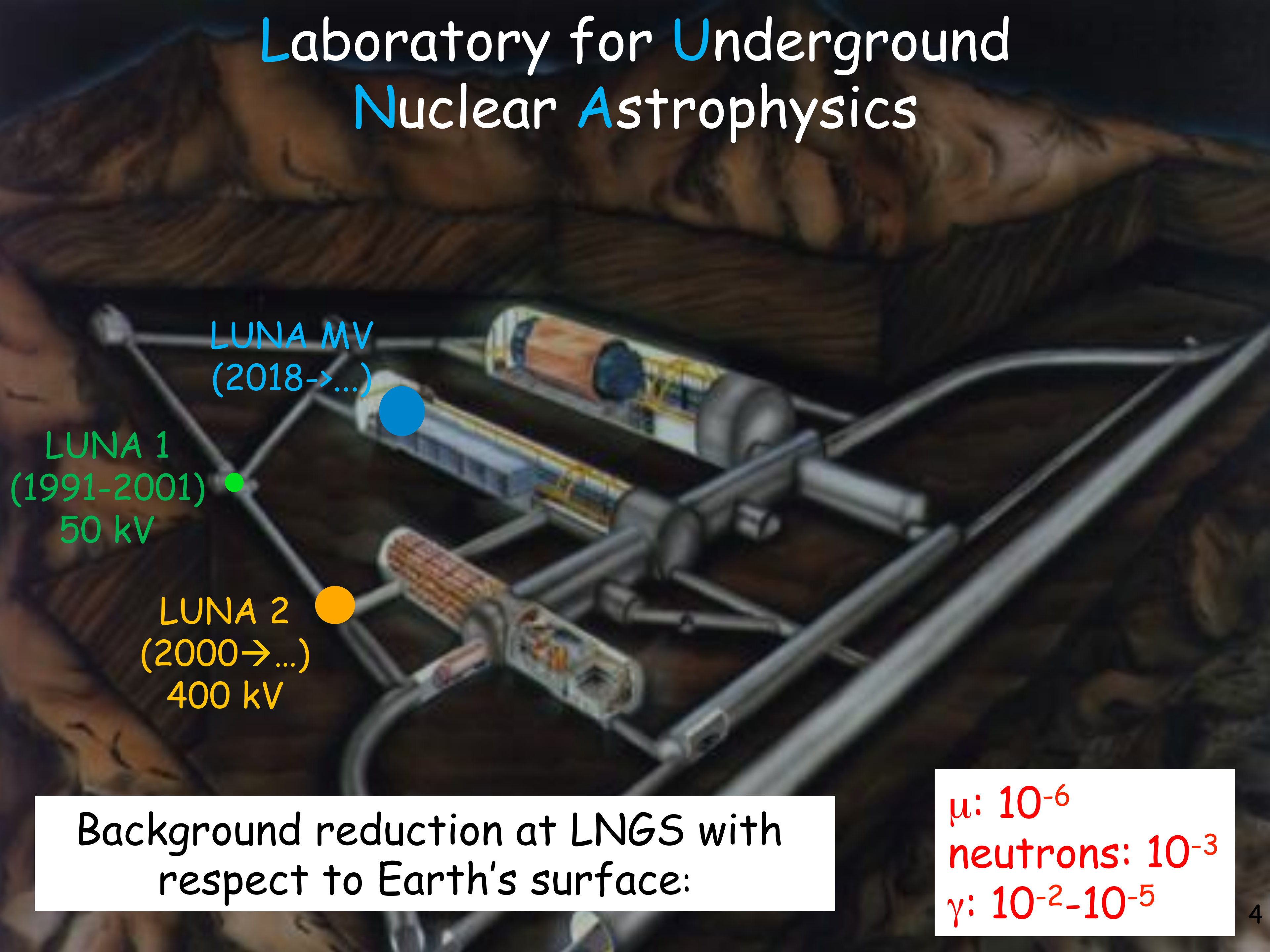






Passive shielding is more effective underground since the μ flux, that create secondary γs, is suppressed.

Laboratory for Underground Nuclear Astrophysics

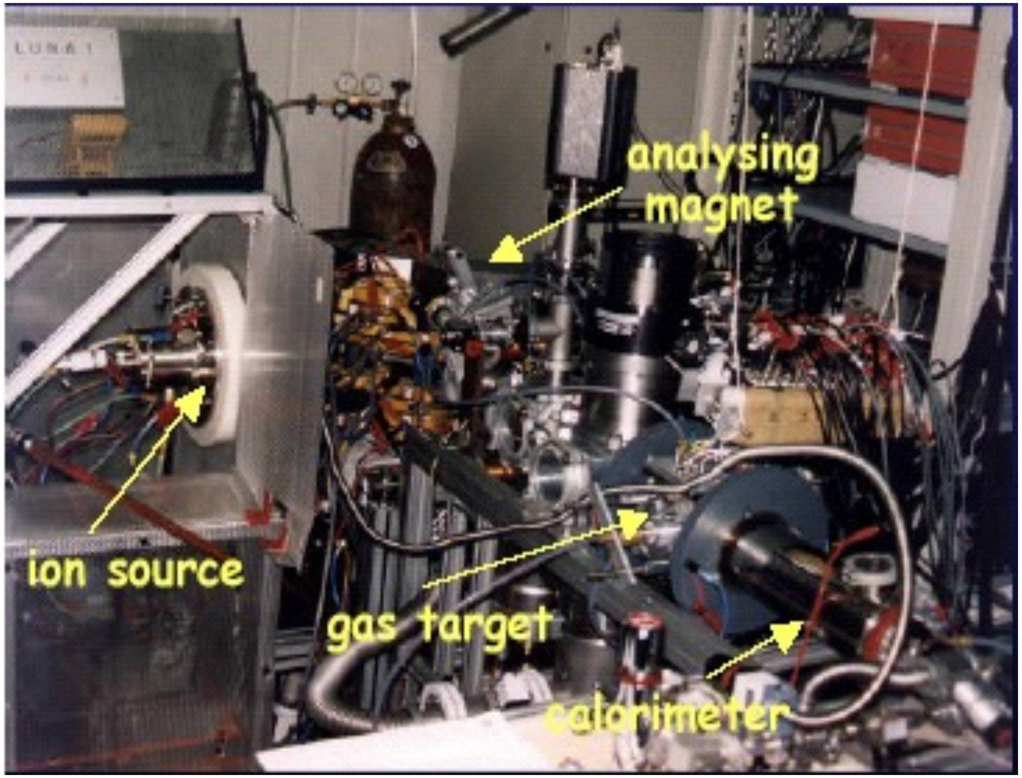


Background reduction at LNGS with respect to Earth's surface:

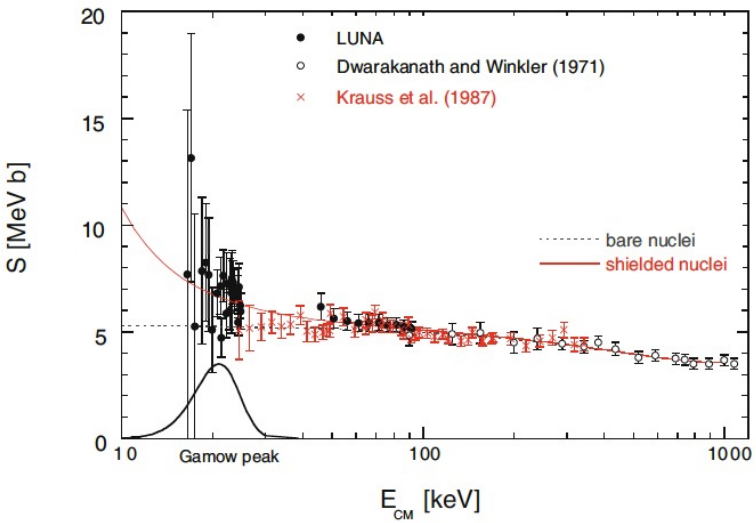
μ: 10^{-6}
neutrons: 10^{-3}
γ: 10^{-2}–10^{-5}

LUNA 50 kV

1991: Birth of underground Nuclear Astrophysics.



$^3He(^3He,2p)^4He$ (solar ν)



$E_{beam} \approx 1 - 50$ keV

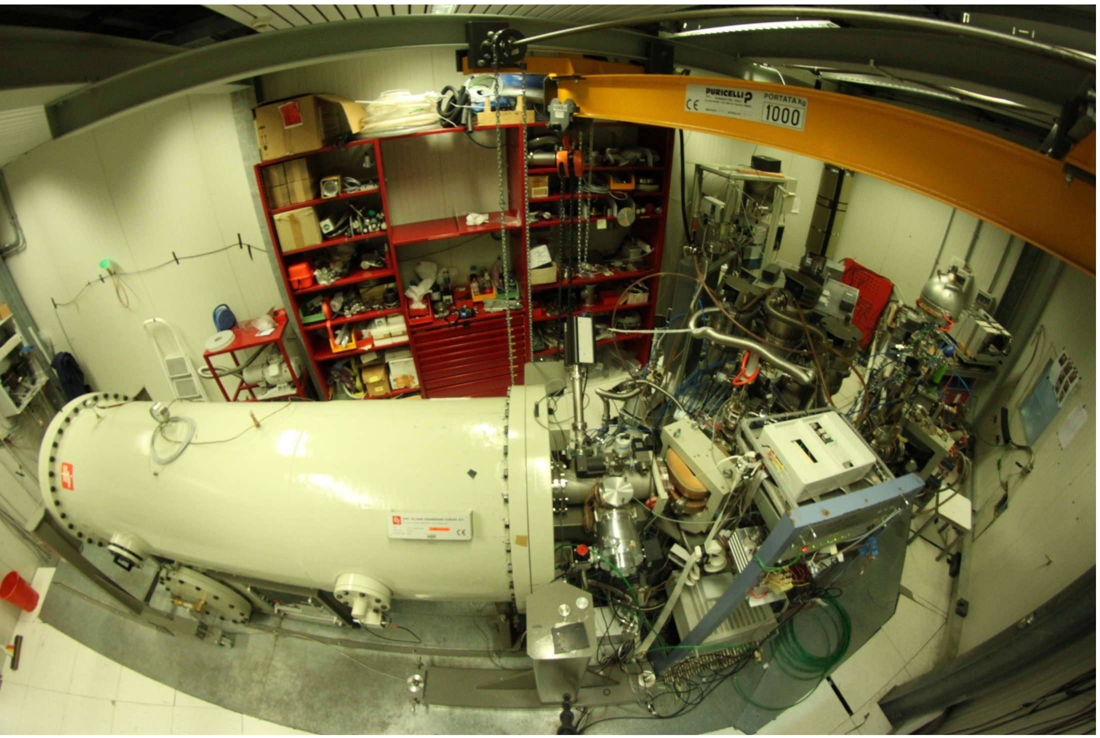
$I_{max} \approx 500\ \mu A$ protons, ^3He

Energy spread ≈ 20 eV

Long term stability (8 h) ≈ $5*10^{-5}$

LUNA-400

2016: Still the only underground accelerator in the world.



$^{14}N(p,\gamma)^{15}O$	(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)
$d(^{4}He,\gamma)^{6}Li$	(BBN)
$^{22}Ne(p,\gamma)^{23}Na$	(Ne-Na Cycle)
$d(p,\gamma)^{3}He$	(BBN)

$E_{beam} \approx 50 - 400$ keV

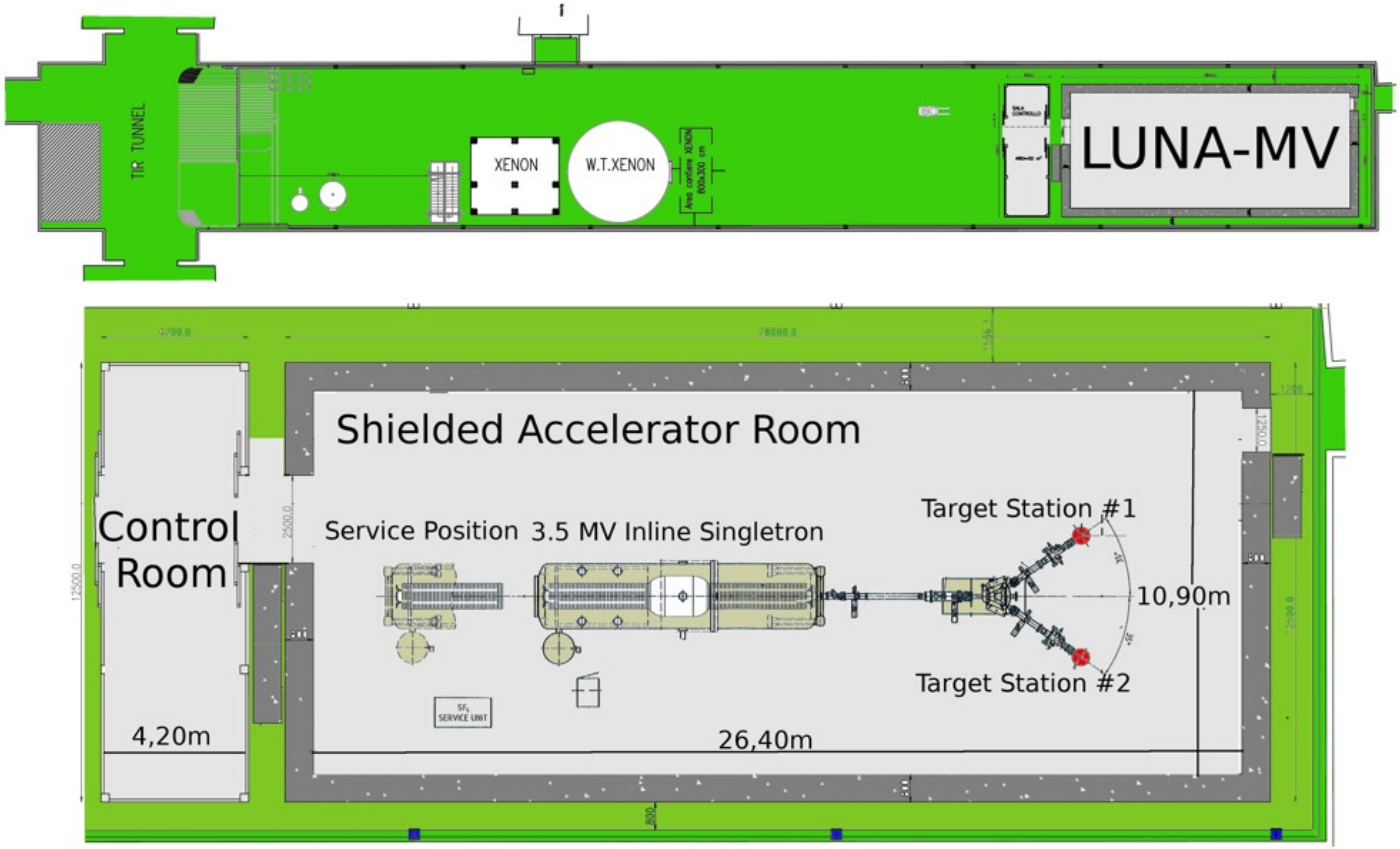
$I_{max} \approx 300\ \mu A$ protons, ^{4}He

Energy spread ≈ 70 eV

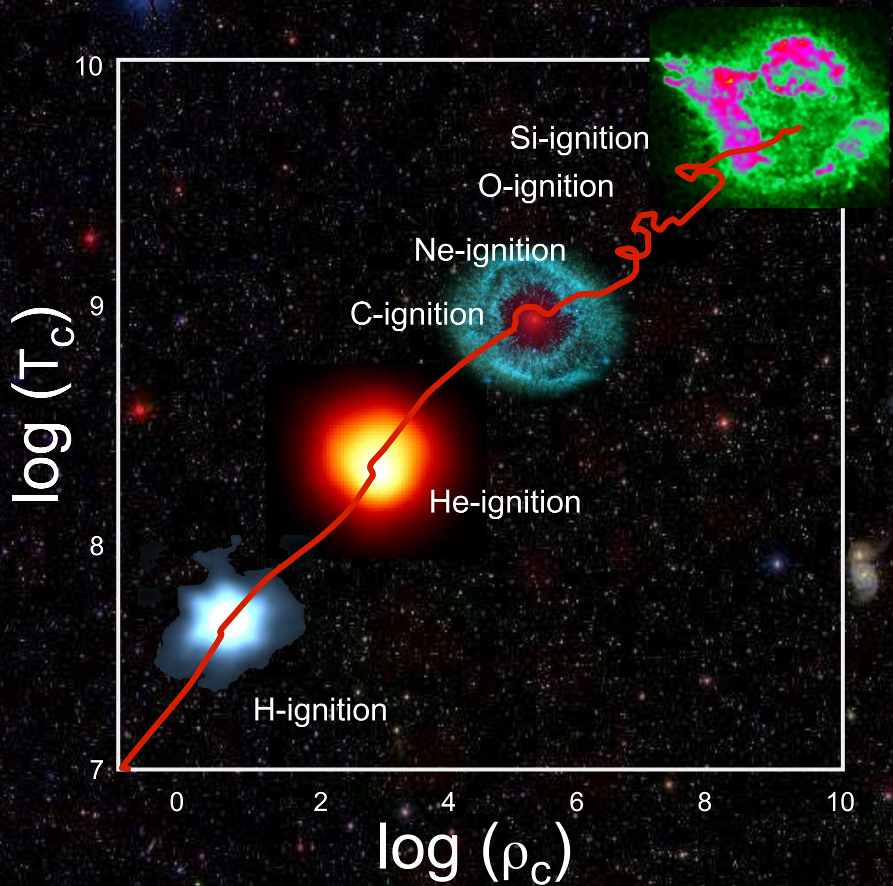
Long term stability ≈ 5eV/h

LUNA-MV

Funded by the Italian Research Ministry as a "premium project".
First run scheduled in 2018.



LUNA program



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

LUNA400 (2016-2018):

$^{13}C(\alpha,n)^{16}O$
$^{12}C(p,\gamma)^{13}N$
$^{13}C(p,\gamma)^{14}N$
$d(p,\gamma)^{3}He$ (this talk)
$^{22}Ne(p,\gamma)^{23}Na$ (Ferraro's talk)
$^{6}Li(p,\gamma)^{7}Be$

- Hydrogen burning in massive stars
- BBN

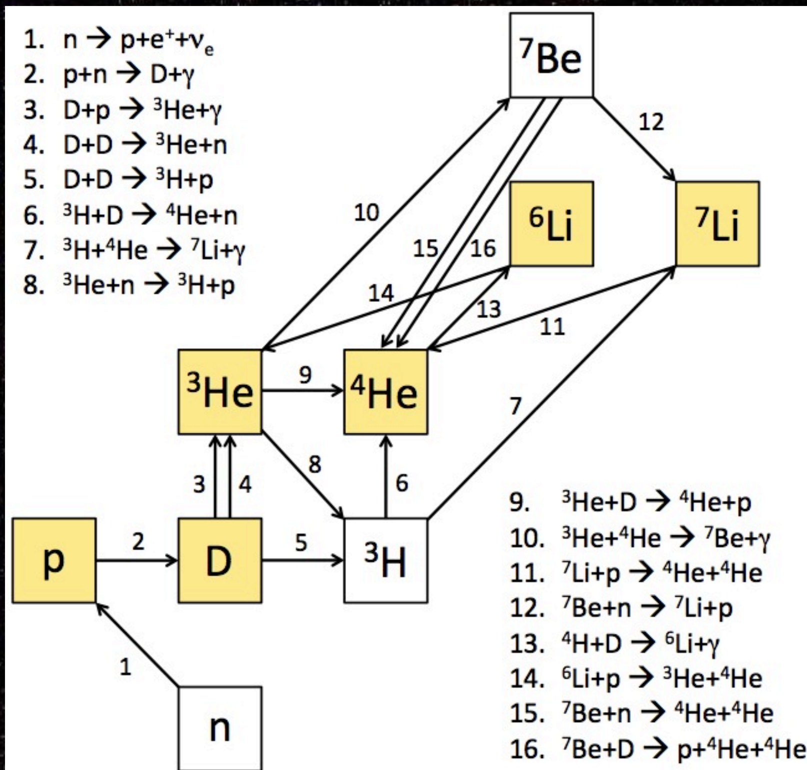
LUNA-MV (2019-2022):

$^{12}C+^{12}C$
$^{12}C(\alpha,\gamma)^{16}O$
$^{13}C(\alpha,n)\,^{16}O$
$^{22}Ne(\alpha,n)^{25}Mg$

- Star evolution after Hydrogen burning
- S-process

Workshop at LNGS on LUNA-MV (1-2 december) + celebration of the first 25-years of LUNA ("*Silver Moon*").

Big Bang Nucleosynthesis



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

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

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

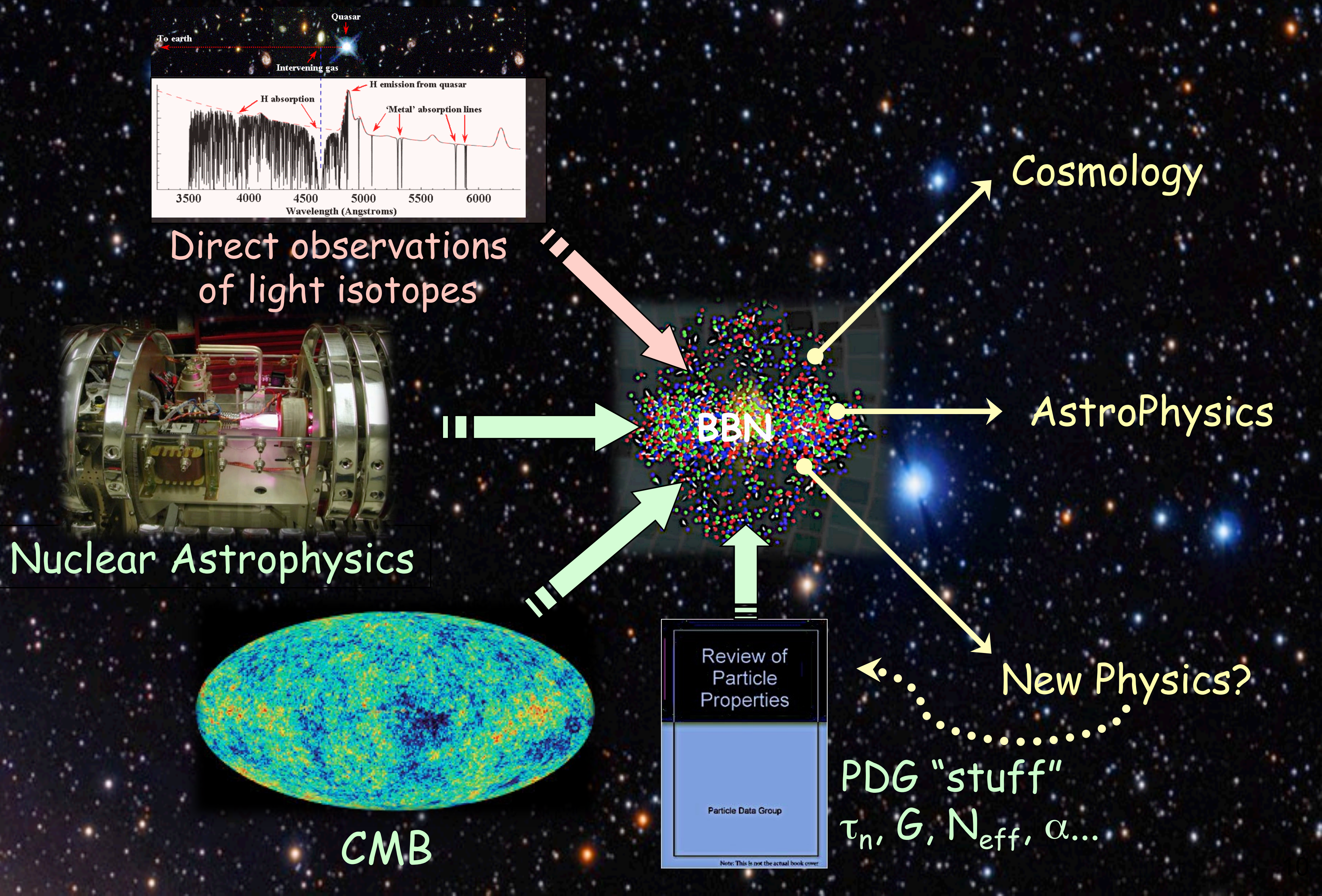
Calculation of primordial abundances only depends on:

-Baryon density Ω_b

-Particle Physics (N_{eff}, α..)

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

BBN "Flowchart"



BBN predictions

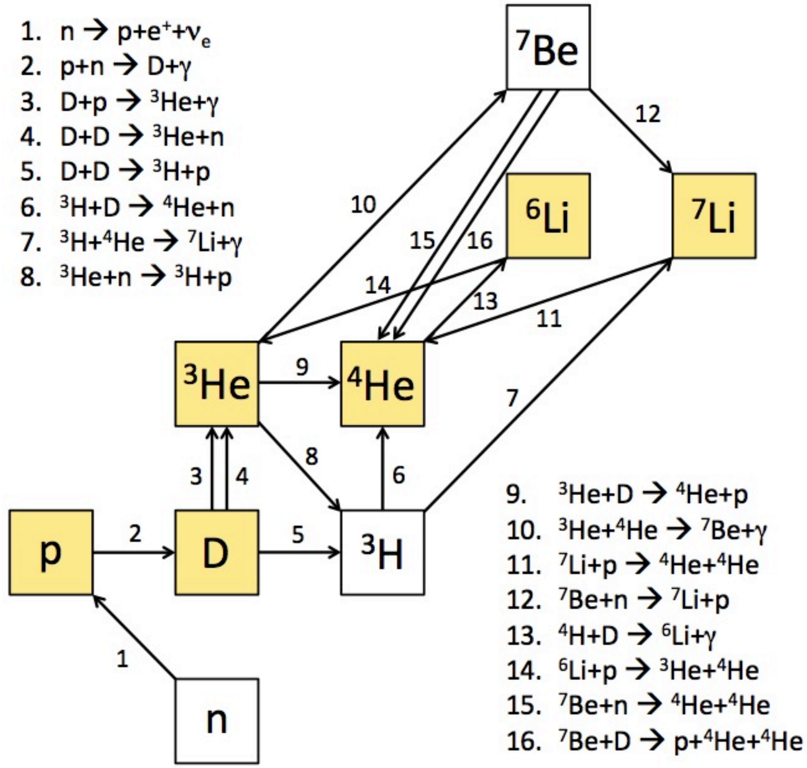
-The BBN begins with the formation of Deuterium.

-Nearly all the free neutrons end up bound in the most stable light element ^{4}He.

-Small abundance ^{7}Li and ^{6}Li because of the absence of stable nuclei with mass number 5.

-Negligible amount of heavier elements because the lack of A=8 isotopes.

Accuracy mainly depends on nuclear cross section knowledge
→ Direct measurements at BBN energies.



BBN uncertainties:

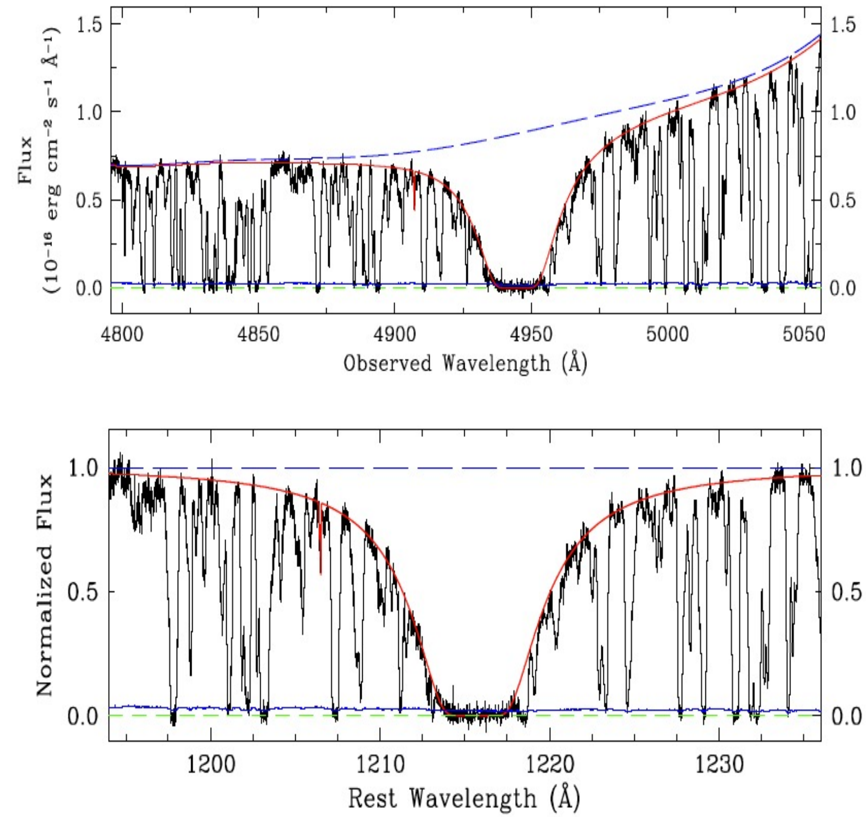
^{4}He:	Almost entirely due to $\Delta\tau_n$
D:	Mainly due to the D(p,γ)^{3}He reaction
^{3}He:	Mainly due to the ^{3}He(d,p)^{4}He reaction
^{6}Li:	Mainly due D(a,γ)^{6}Li reaction
^{7}Li:	..Many reactions of the BBN network

Astronomical observations

-Observation of metal-poor and faraway sites

-Extrapolate to zero metallicity:
Fe/H, O/H, Si/H → 0

-Systematics mainly due to post-primordial processes



Observation errors:

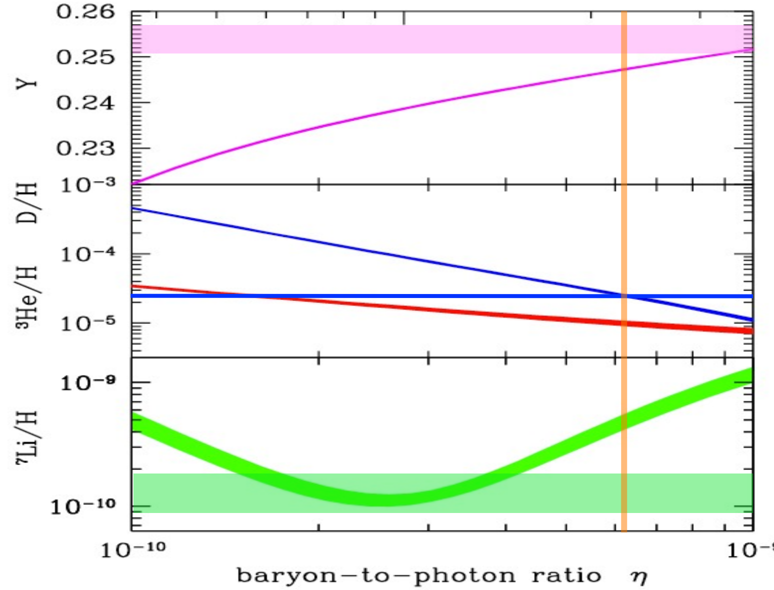
^{4}He: Observation in H_{II} regions, quite large systematics.
D: Observation of absorption lines in DLA systems. Accurate measurements.
^{3}He: Solar System, very large systematics, not a powerful probe for BBN.
^{7}Li: observation of metal poor stars absorption line (Spite plateau)
^{6}Li: observation of metal poor stars absorption lines (controversial)

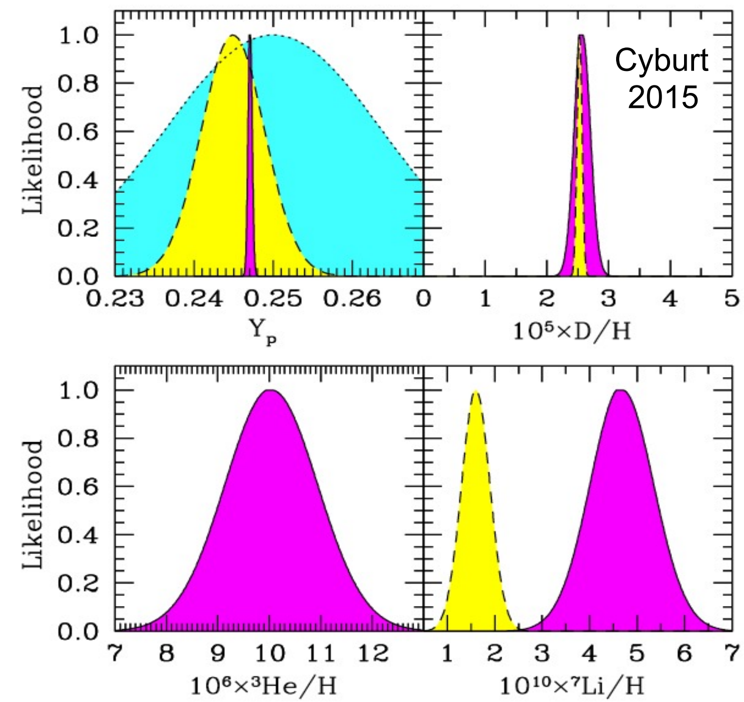
Theory Vs Observations

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.005)\times10^{-5}$	$(2.55\pm0.03)\times10^{-5}$
^{3}He/H	$(1.00\pm0.01)\times10^{-5}$	$\lesssim 2.2\times10^{-5}$
^{7}Li/H	$(4.68\pm0.67)\times10^{-10}$	$(1.23\ ^{+0.68}_{-0.32})\times10^{-10}$
^{6}Li/^{7}Li	$(1.5\pm0.3)\times10^{-5}$	$\lesssim 10^{-2}$

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

A coherent theory (Cosmology, Astrophysics, Particle physics, Gravitation…) must provide the matching between theory and observations for all the primordial light isotopes.

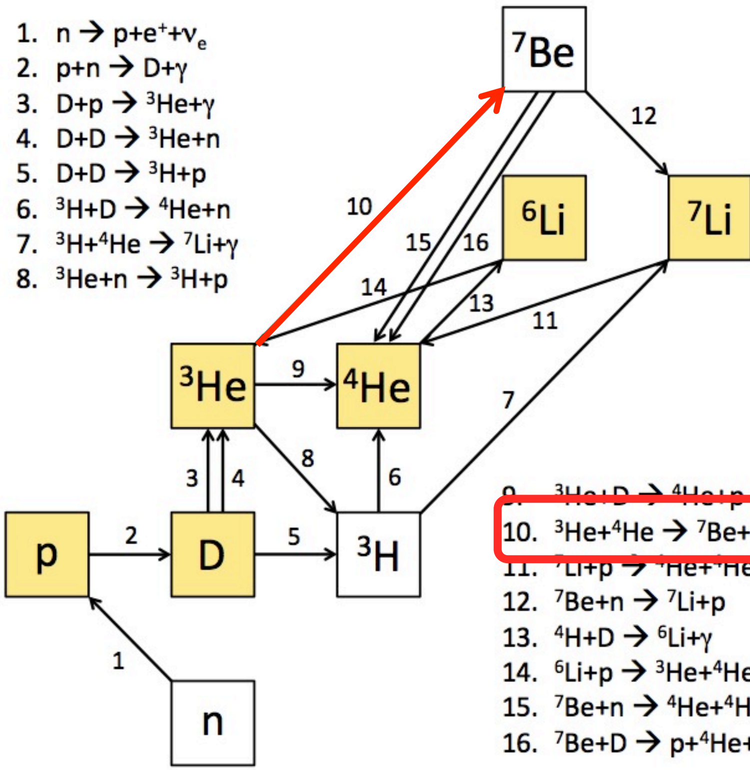




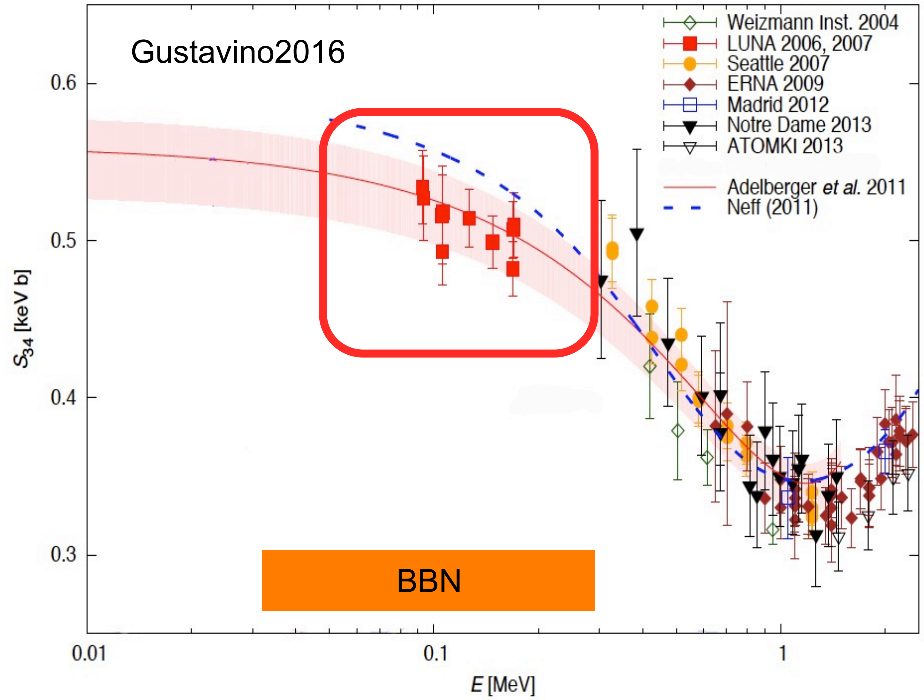
$^3He(\alpha,\gamma)^7Be$ reaction @ LUNA 400

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.005)\times10^{-5}$	$(2.55\pm0.03)\times10^{-5}$
$^3He/H$	$(1.00\pm0.01)\times10^{-5}$	$(0.9\pm1.3)\times10^{-5}$
$^7Li/H$	$(4.68\pm0.67)\times10^{-10}$	$(1.23^{+0.68}_{-0.32})\times10^{-10}$
$^6Li/^7Li$	$(1.5\pm0.3)\times10^{-5}$	$<\sim10^{-2}$

1. $n \rightarrow p+e^+ +\nu_e$
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. ${}^3H+{}^4He \rightarrow {}^7Li+\gamma$
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. ${}^4H+D \rightarrow {}^6Li+\gamma$
14. ${}^6Li+p \rightarrow {}^3He+{}^4He$
15. ${}^7Be+n \rightarrow {}^4He+{}^4He$
16. ${}^7Be+D \rightarrow p+{}^4He+{}^4He$



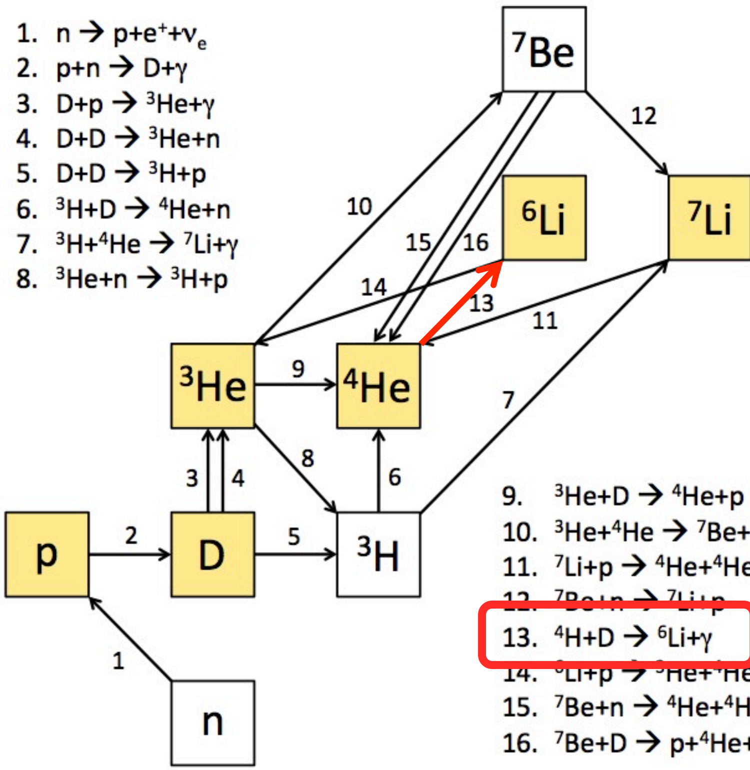
-LUNA data well inside the BBN energy region
-Low uncertainty (4%)
-Simultaneous measurement of prompt and delayed γs

→ Consolidation of "Lithium Problem"

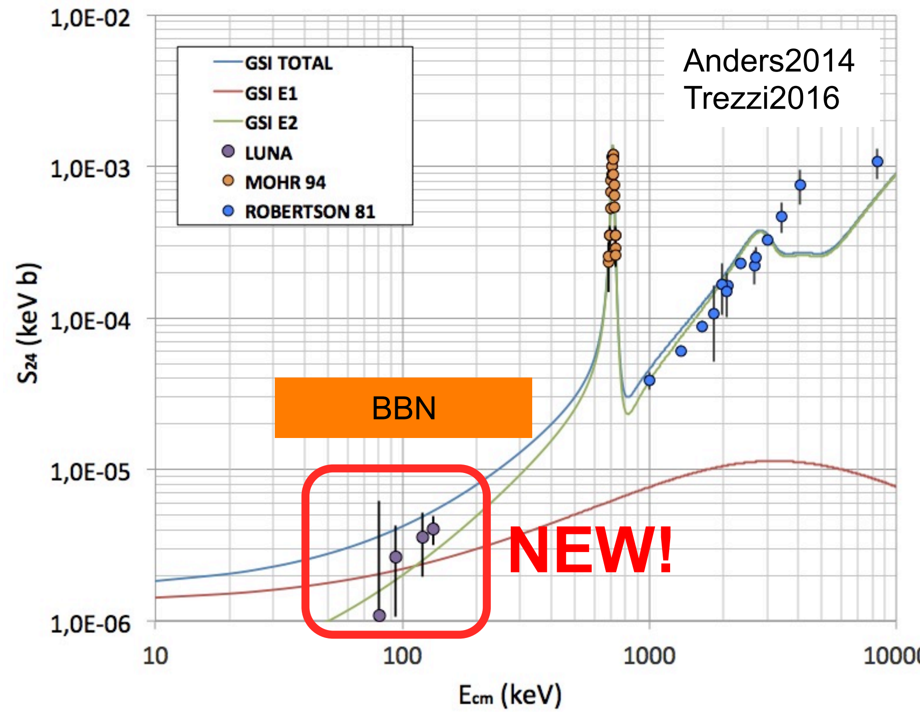
D(α,γ)^{6}Li reaction @ LUNA 400

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.005)\times10^{-5}$	$(2.55\pm0.03)\times10^{-5}$
^{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	$(1.5\pm0.3)\times10^{-5}$	$<\sim10^{-2}$

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

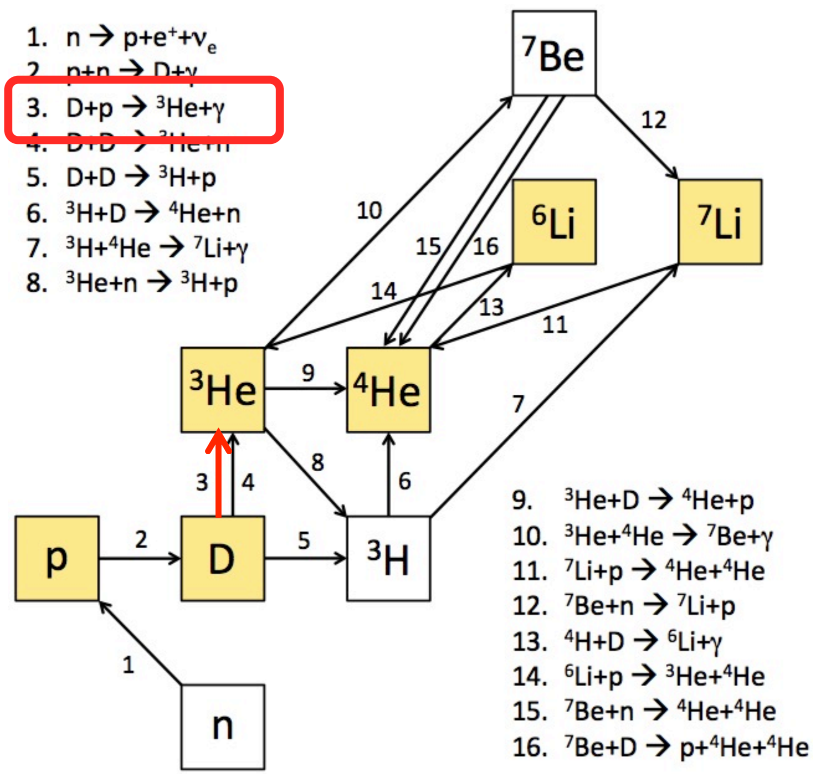


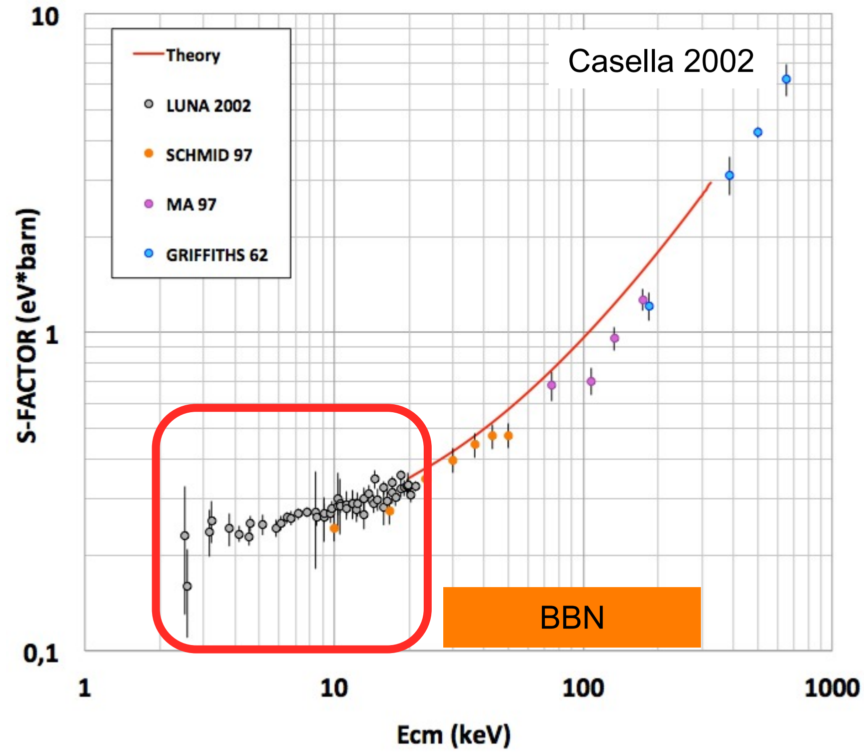
-LUNA data provide the first measurement in the BBN energy window

→A nuclear solution is ruled out to explain the ^{6}Li problem...

$D(p,\gamma)^3He$ reaction @ LUNA 50

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.005)\times10^{-5}$	$(2.55\pm0.03)\times10^{-5}$
$^3He/H$	$(1.00\pm0.01)\times10^{-5}$	$(0.9\pm1.3)\times10^{-5}$
$^7Li/H$	$(4.68\pm0.67)\times10^{-10}$	$(1.23^{+0.68}_{-0.32})\times10^{-10}$
$^6Li/^7Li$	$(1.5\pm0.3)\times10^{-5}$	<~10^{-2}





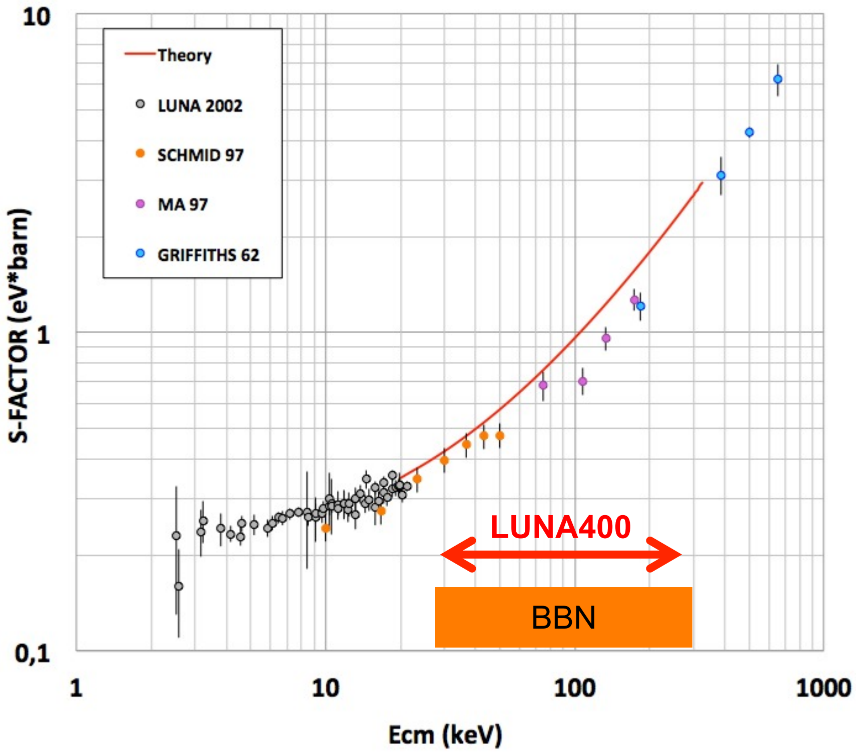
$(D/H)_{BBN}$ error reduction of a factor 3 with low energy LUNA data

In progress: D(p,γ)^{3}He reaction @ LUNA400

Reaction	Rate Symbol	$\sigma_{^2\mathrm{H/H}} \cdot 10^5$
$p(n,\gamma)^2\mathrm{H}$	R_1	± 0.002
$d(p,\gamma)^3\mathrm{He}$	R_2	± 0.062
$d(d,n)^3\mathrm{He}$	R_3	± 0.020
$d(d,p)^3\mathrm{H}$	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 (1% error).

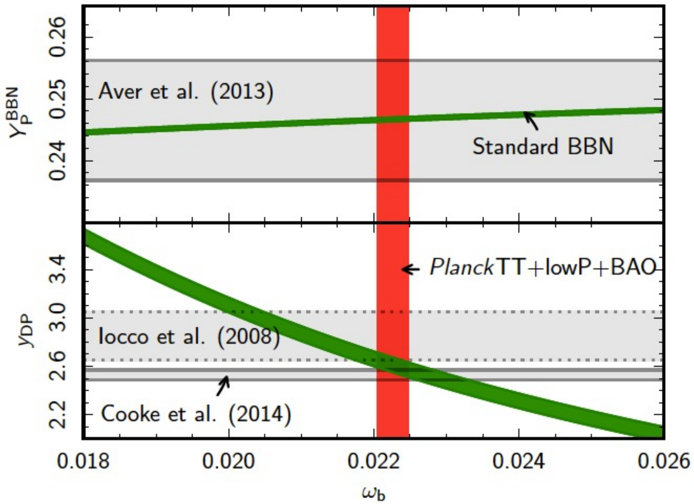


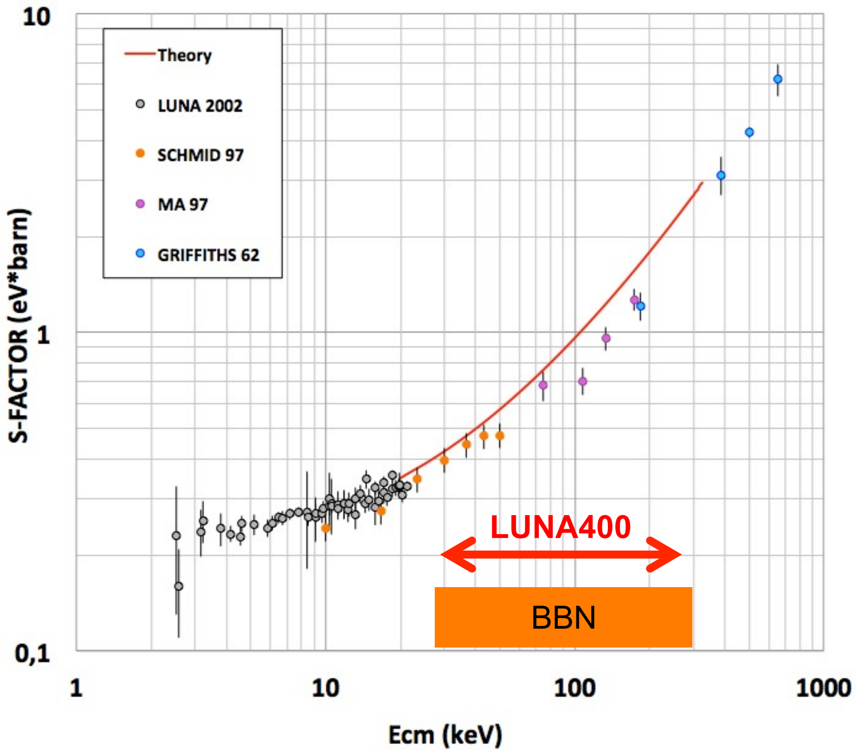
Measurement goal:
-Cross section measurement at $30<E_{cm}<260$ with ~3% accuracy
-Differential cross section measurement at $100<E_{cm}<260$

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

data taking and analysis in progress

$D(p,\gamma)^3He$: Baryon Density





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

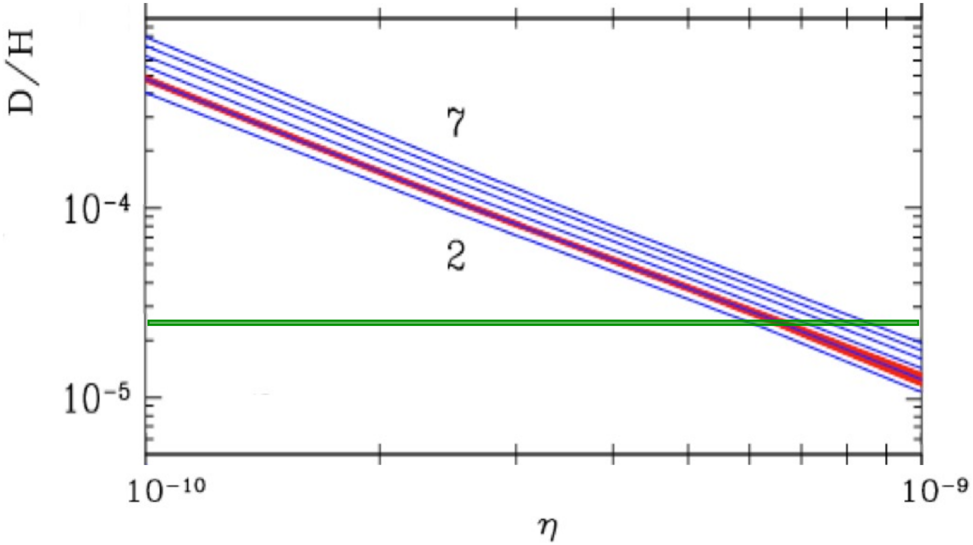
From CMB data:

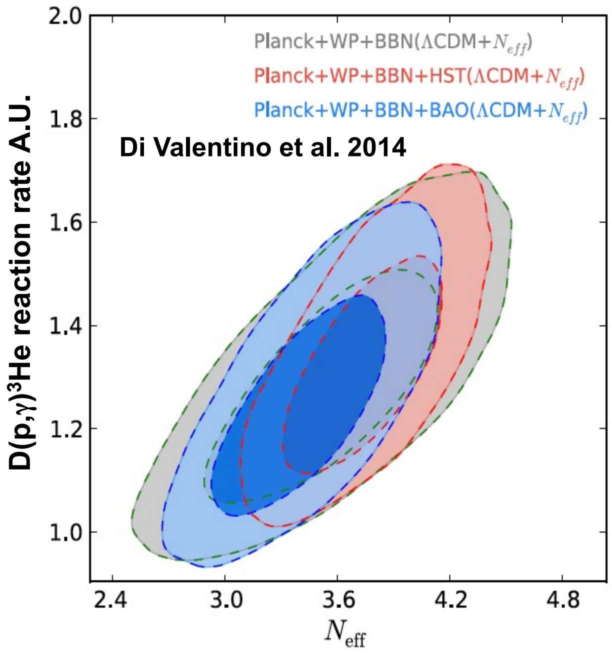
$100\Omega_{b,0}h^2(CMB)=2.22\pm0.02$ (PLANCK2015)

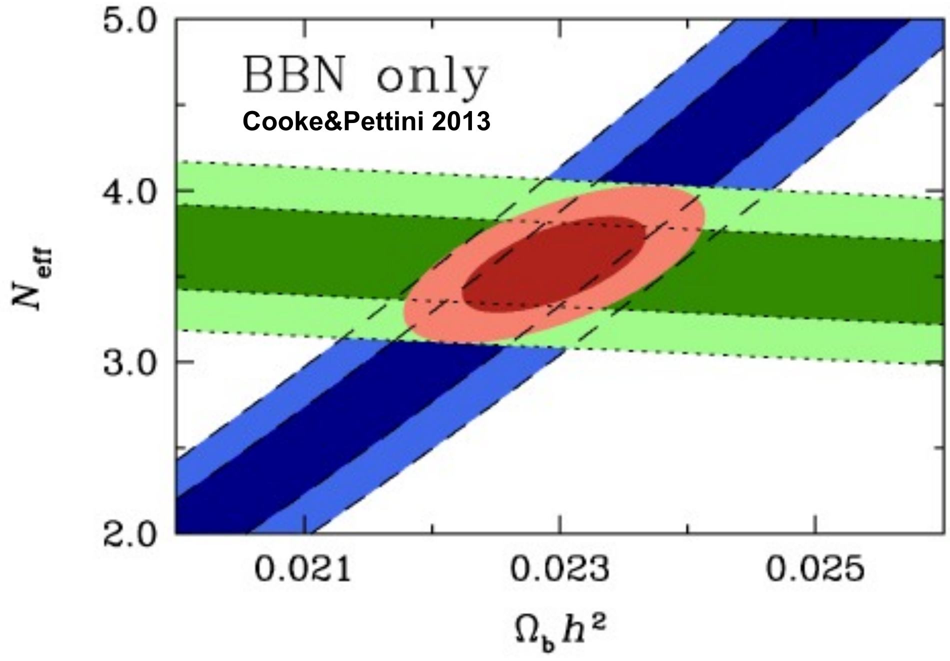
D(p,γ)^{3}He: N_{eff}

Deuterium adundance 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 reation:

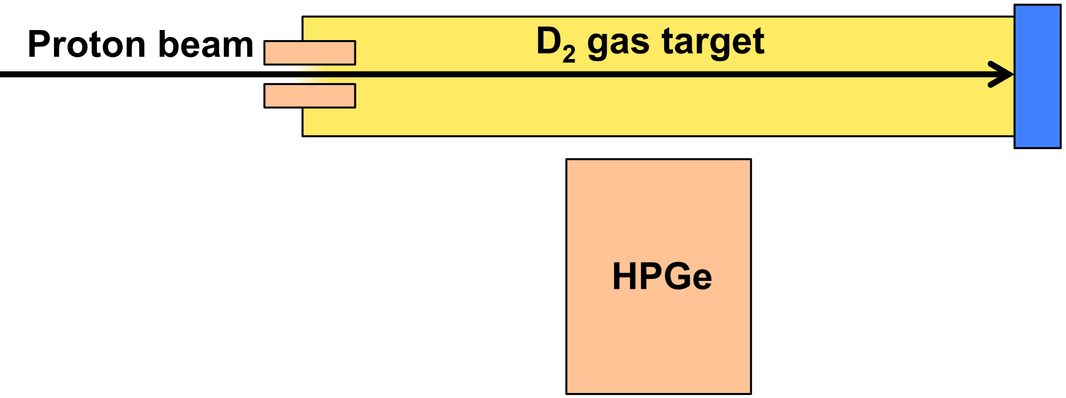
N_{eff} (BBN) = 3.57±0.18 (Cooke&Pettini 2013)
N_{eff} (CMB) = 3.36±0.34 (PLANCK 2013)
N_{eff} (SM) = 3.046

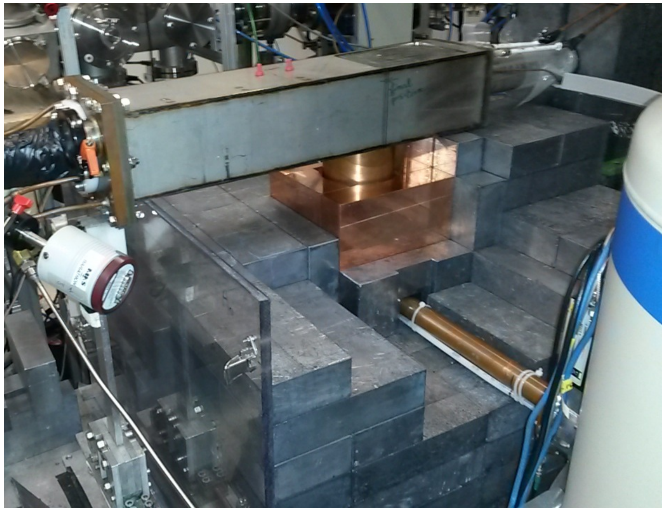




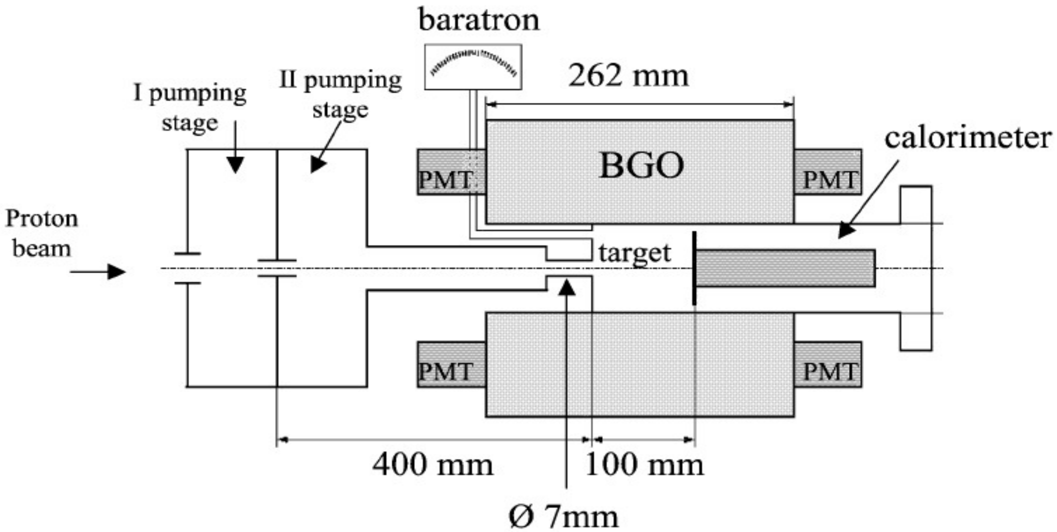


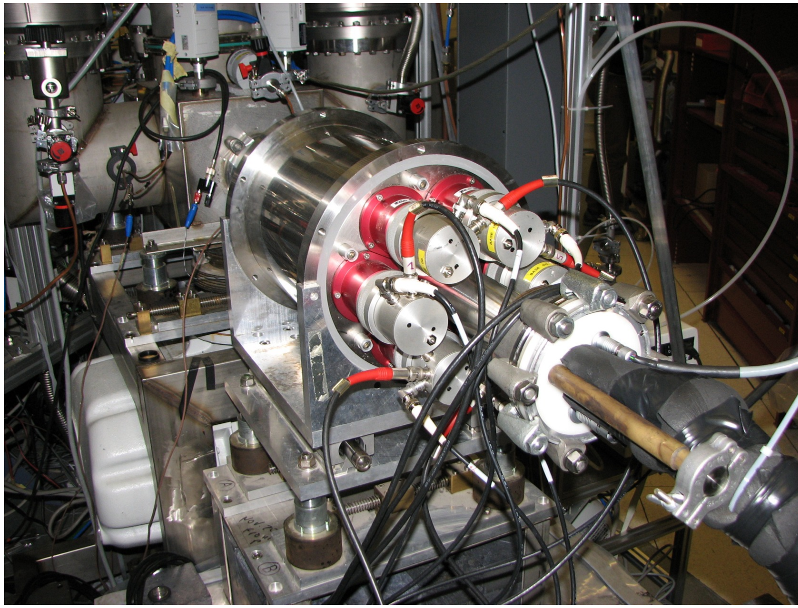
Experimental setup





Ge(Li) detector: **Angular distribution of emitted photons**



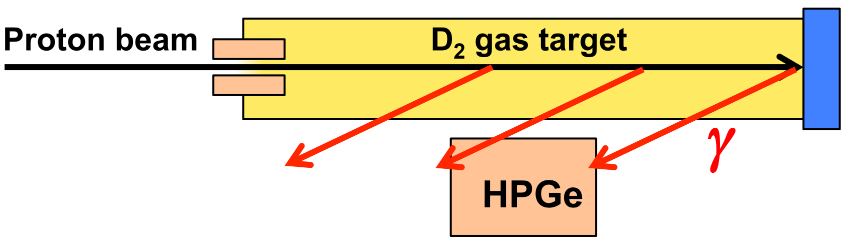


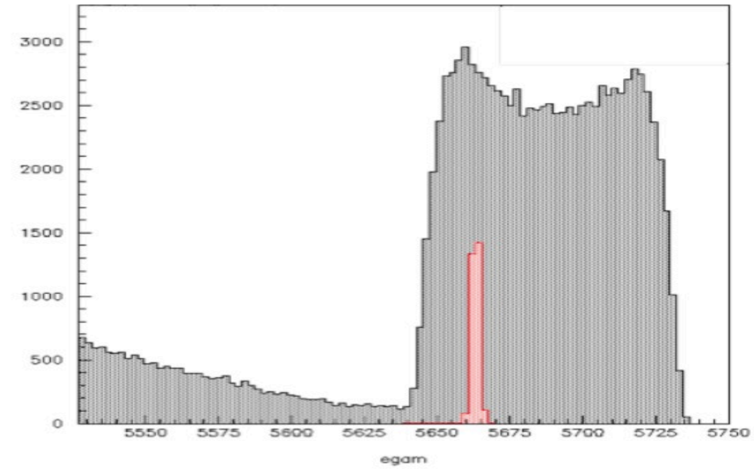
4π BGO detector: **Total cross section Vs Energy**

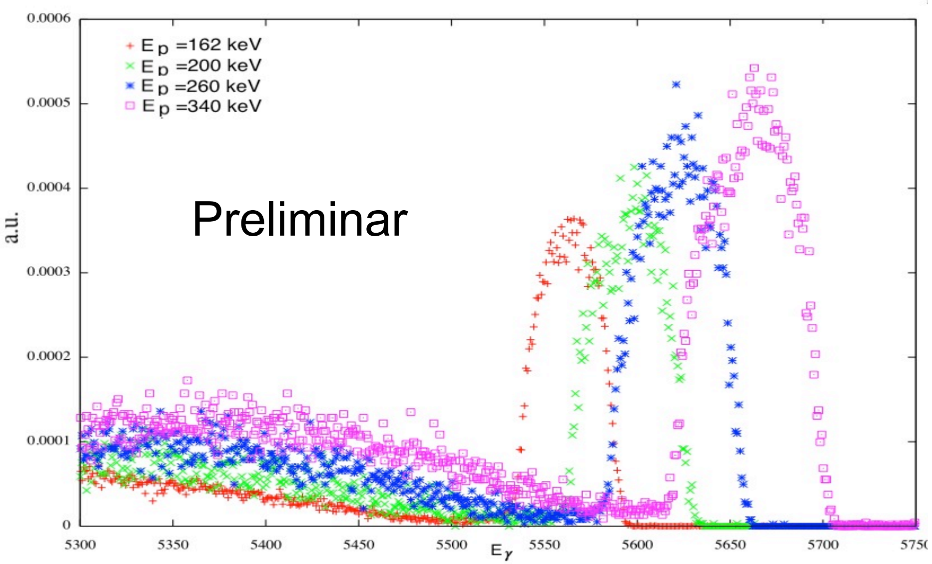
HPGe Preliminary results

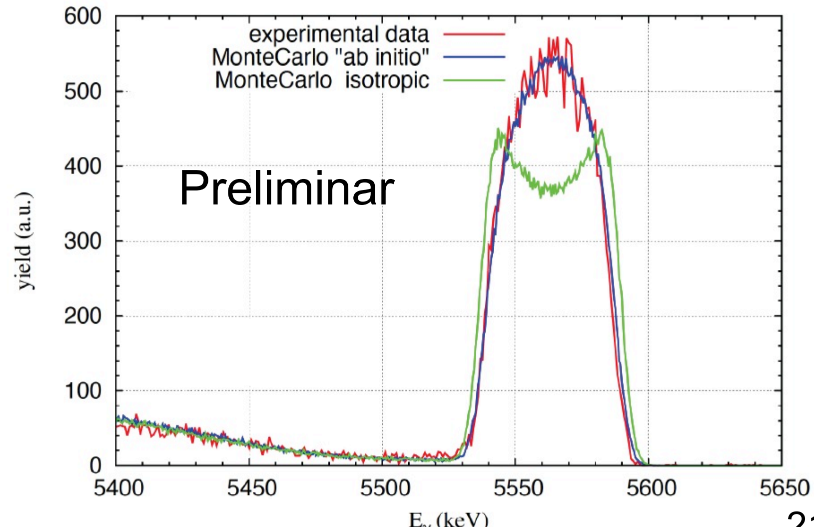
The high resolution of Germanium detector allows to measure the angular distribution of photons emitted by the $d(p,\gamma)^3He$ reaction exploiting the doppler effect:

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

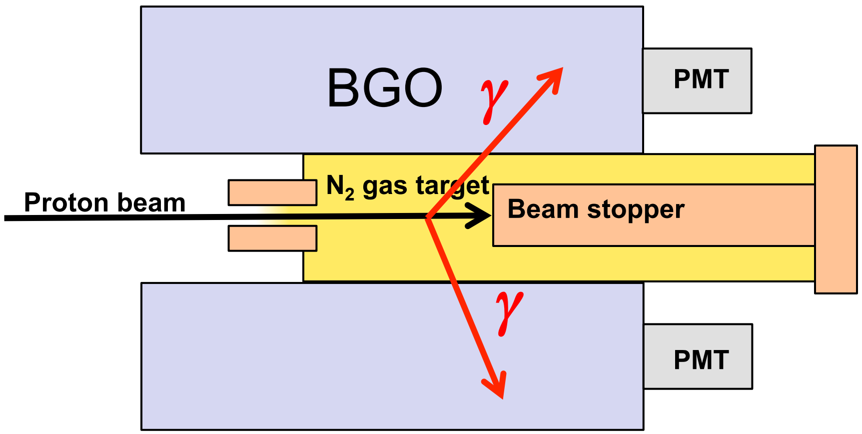


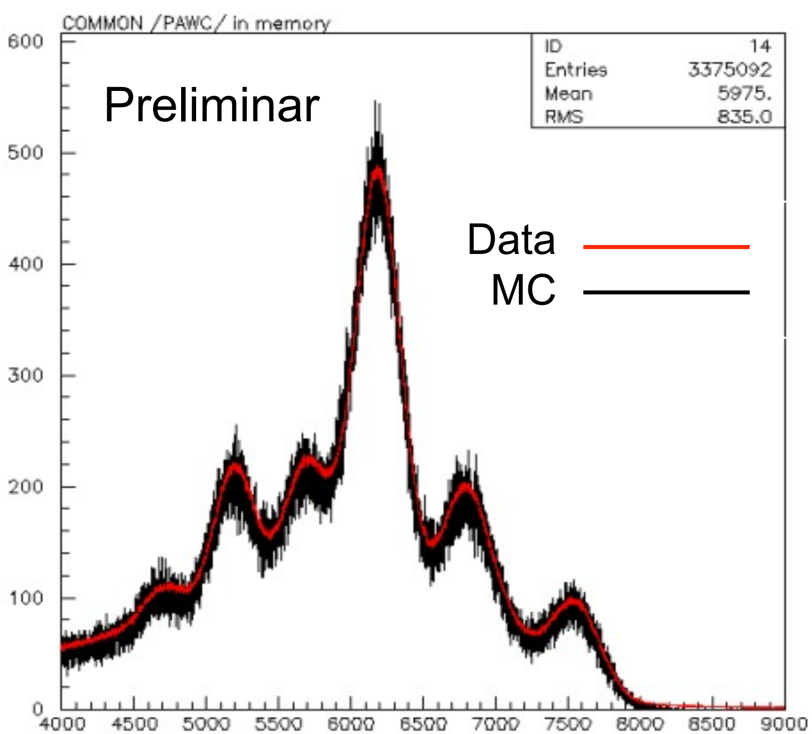


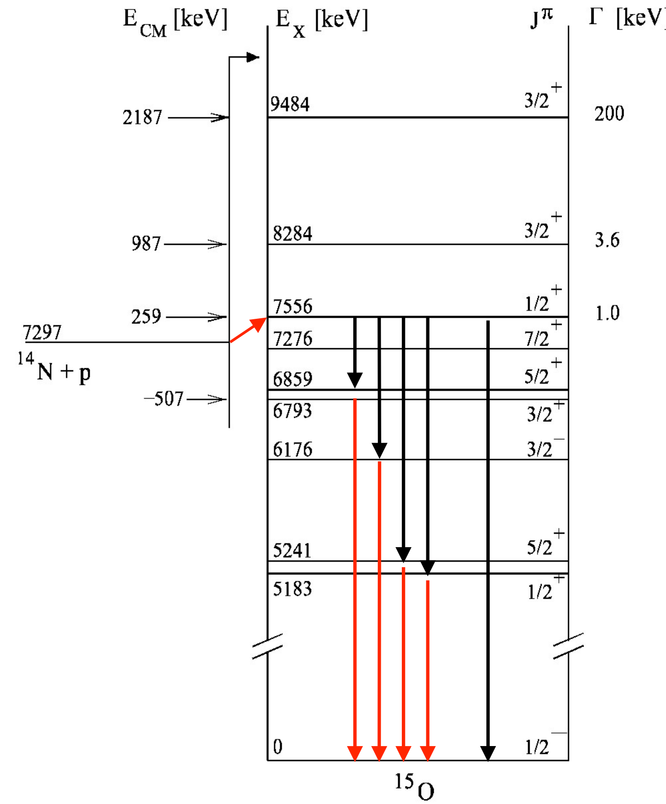




BGO Preliminary results







Eγ (keV)	Branching (%)
5181+2375 (14N)	17.1±0.2 (1.2%)
5241+2315	0.6±0.3 (50%)
6172+1384	57.8±0.3 (0.5%)
6791+765	22.9±0.3 (1.3%)
7556+0	1.6±0.1 (6.2%)

Systematics error budget

Source	BGO phase	HPGe phase
Angular distribution	<<1 %	2.0 %
Detector Efficiency	1.0 %	3.0 %
Beam current	1.5 %	1.5 %
Target density	<1.0 %	<1.0 %
Target lenght	2.0 %	1.0 %
Gas purity	<<1.0 %	<< 1.0 %
Beam energy	<<1.0 %	<< 1.0 %
TOTAL	**≲ 3.0 %**	**≲ 4.0 %**

Systematics will be evaluated through dedicated measurements, minimazing the use of simulations and literature data

- Temperature profile measurements
- Pressure profile
- Reaction yield Vs Pressure
- Reaction yield Vs Current
- Calibration with ^{60}Co, ^{88}Y, ^{137}Cs
- Calibration with $^{14}N(p,\gamma)^{15}O$
- Interplay between BGO and HPGe results
- …

Conclusions

There have been tremendous improvements in recent years in the determination of cosmological parameters from astrophysical measurements. In particular:
-The cosmic density of baryons Ω_b is now known to percent level thanks to the PLANCK mission.
-The primordial abundance of deuterium has been deduced from observations of pristine gas at high redshifts with similar accuracy.

These measurements offer the means to test sensitively cosmology and particle physics. Of particular importance are:
-The comparison of Ω_b(CMB) and Ω_b (BBN).
-The precise estimate of effective number of neutrino families N_{eff}.

The most important obstacle to improve present constraints is the poorly known S-factor of the $d(p,\gamma)^3He$ reaction at BBN energies.
...But a precision study of $d(p,\gamma)^3He$ reaction at BBN energies is in progress at LUNA.

Data taking with dedicated setup: sept 2016 < T < may 2017

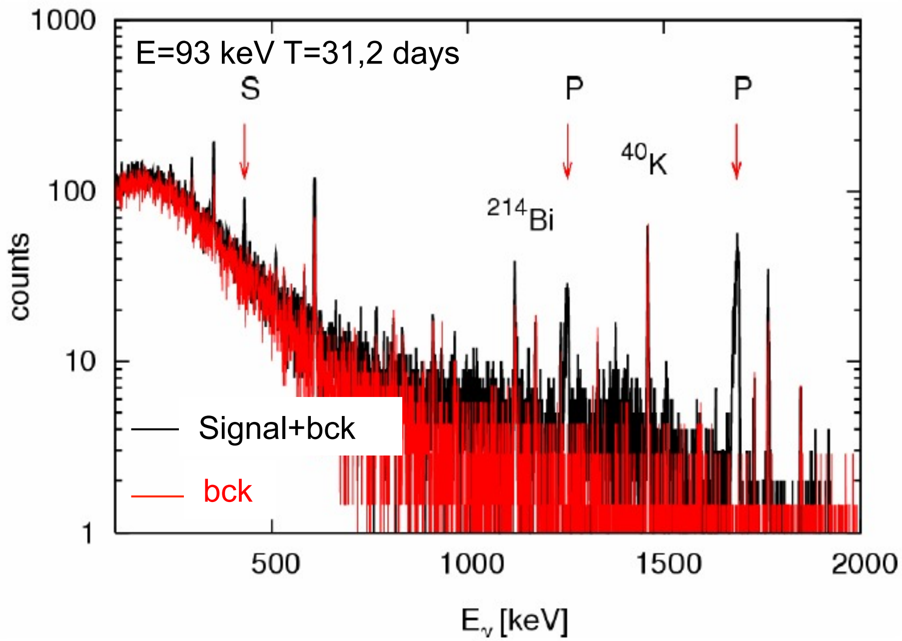
STAY TUNED!

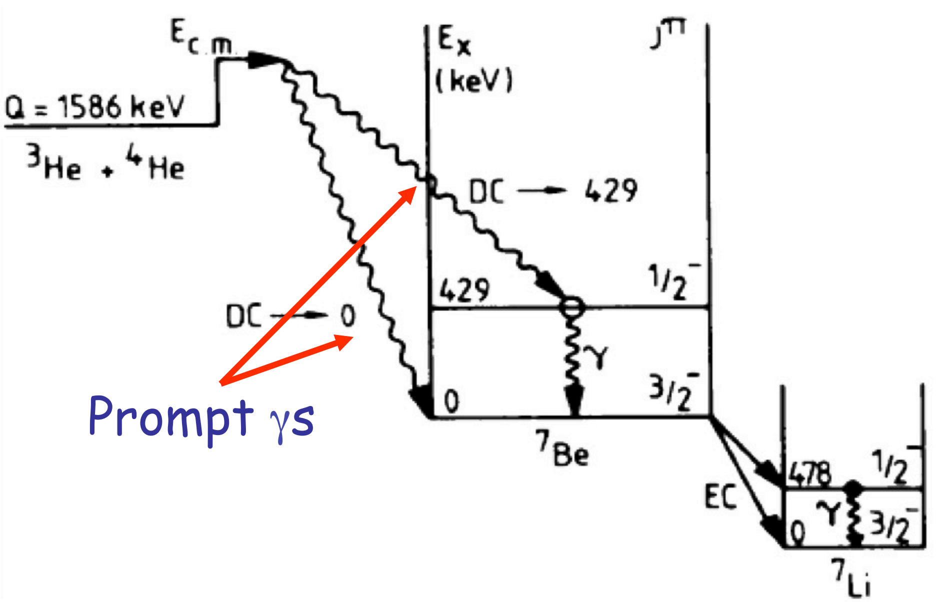
The LUNA collaboration

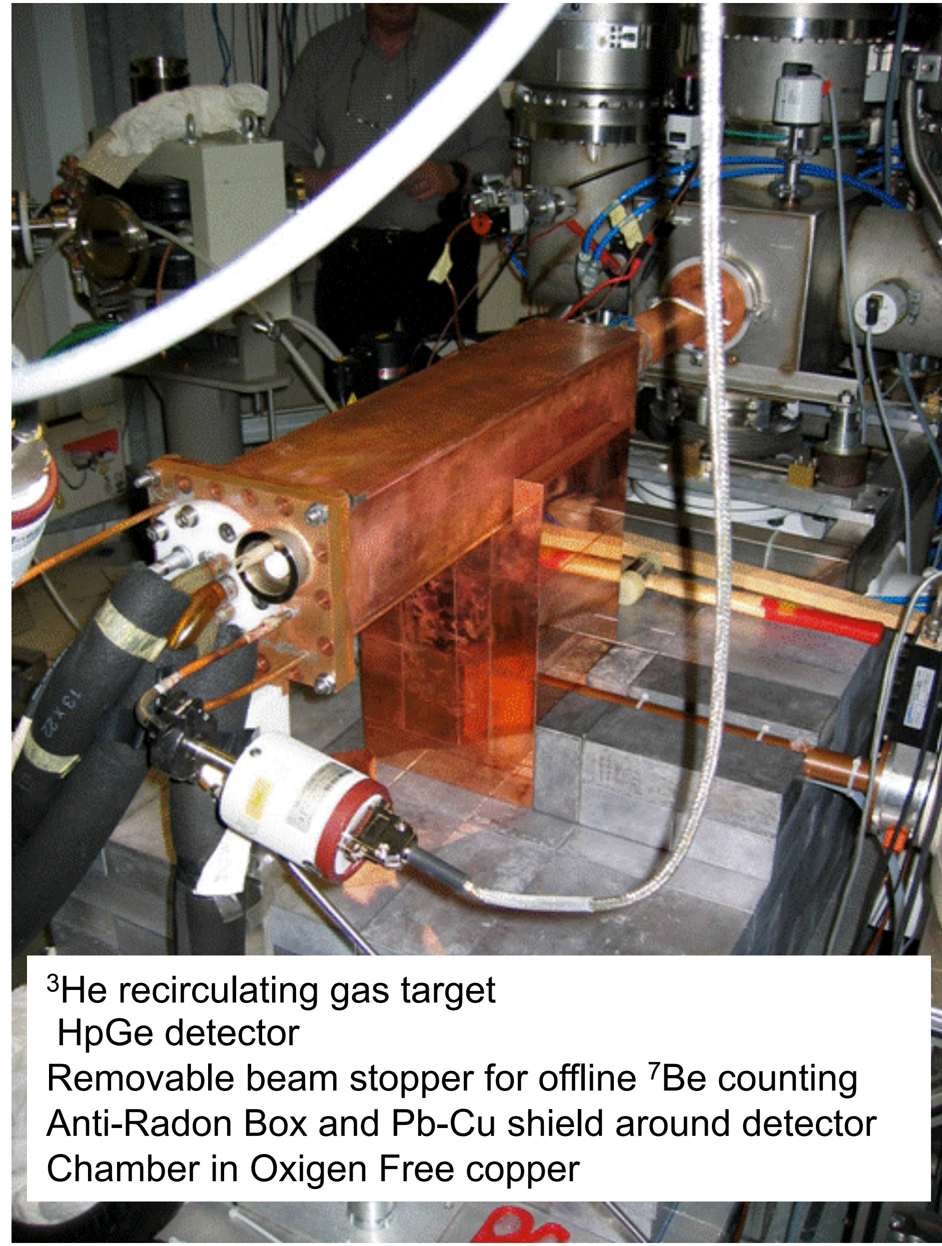
- A. Best, A. Boeltzig*, G.F. Ciani*, A. Formicola, I. Kochanek, M. Junker, L. Leonzi | INFN LNGS / *GSSI, Italy
- D. Bemmerer, M. Takacs, T. Szucs | HZDR Dresden, Germany
- C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | 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

SPARES

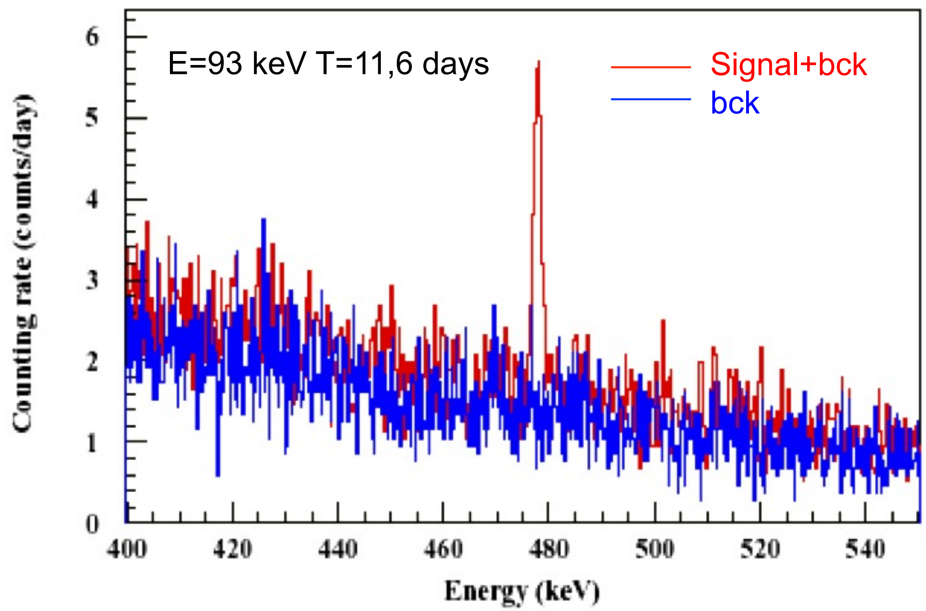
$^3He(\alpha,\gamma)^7Be$ at LUNA: prompt γ's

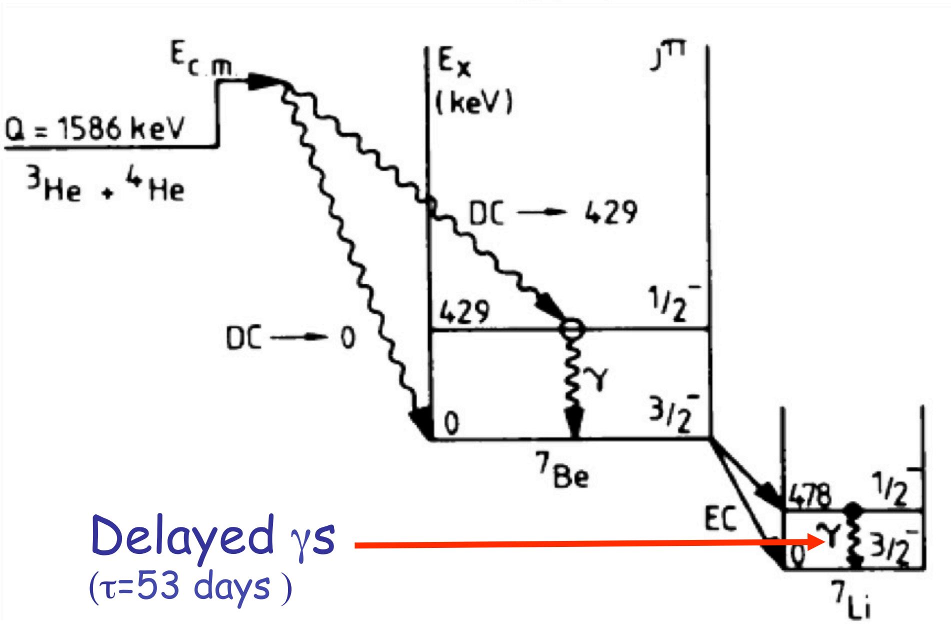


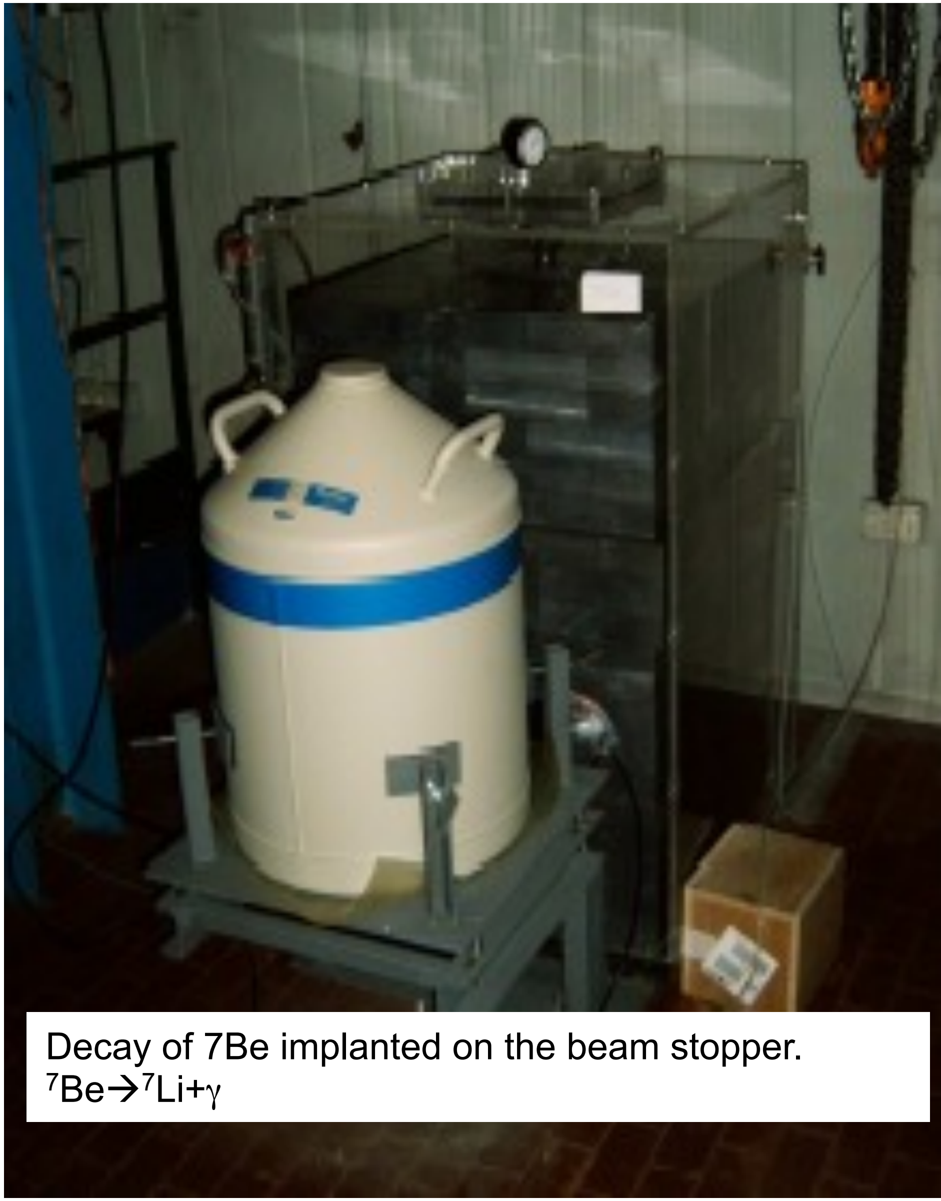




$^3He(\alpha,\gamma)^7Be$ at LUNA: delayed γ's



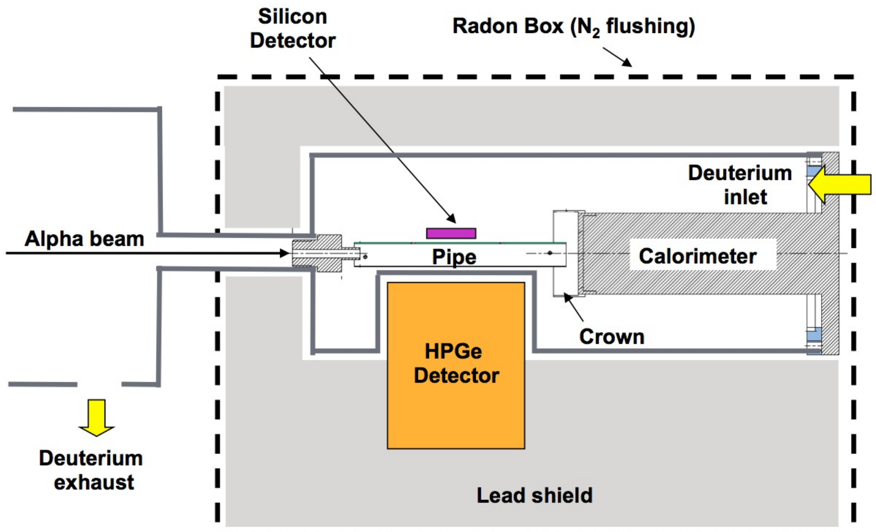


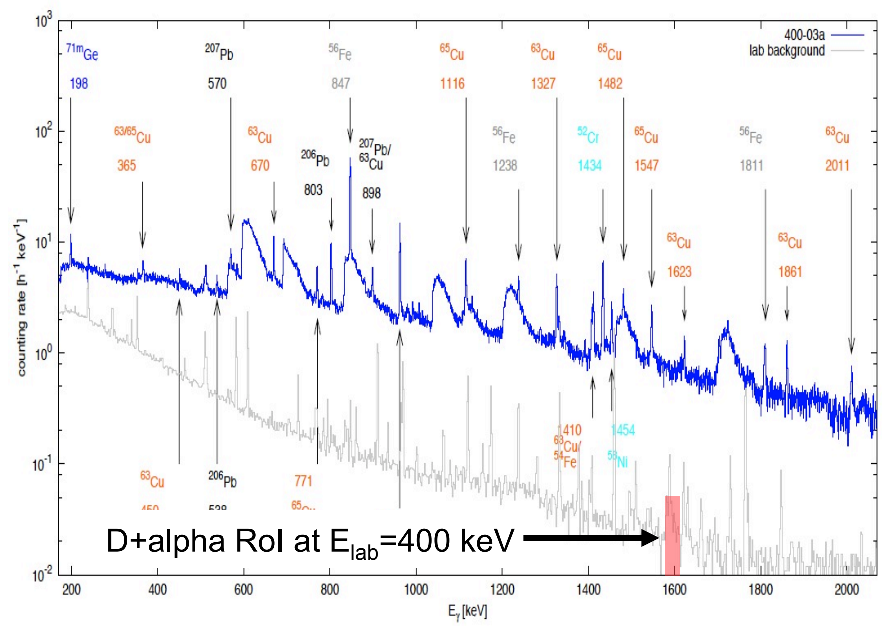


Decay of 7Be implanted on the beam stopper.
$^7Be \rightarrow ^7Li + \gamma$

D(α,γ)⁶Li reaction @ LUNA 400

Main problem: beam induced background

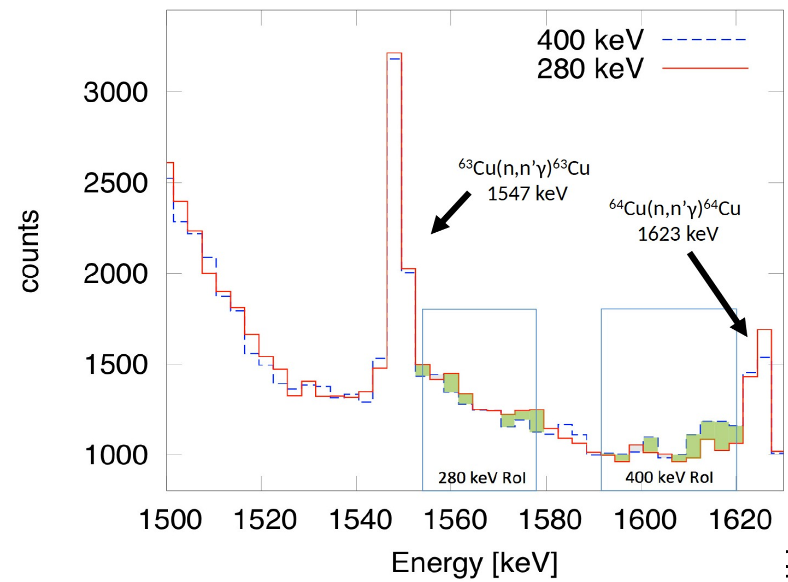




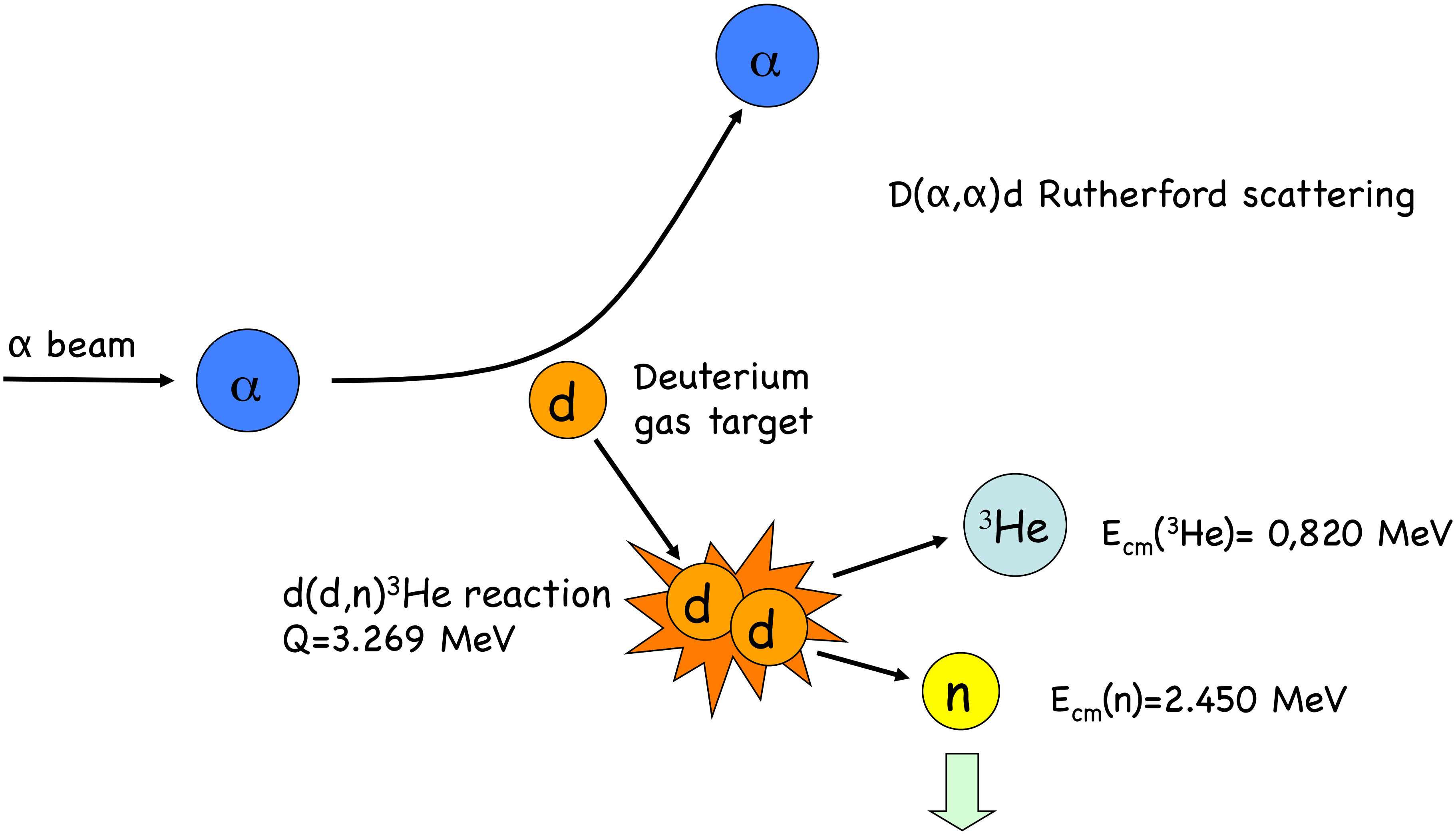
Method:

1. Measurement with E_α=400 keV on D_2 target. Signal is expected in a well defined RoI (1587-1625 keV).
2. Same as 1., but with E_α =280 keV. The Background is essentially the same as before, while the gammas from the D(α,γ)⁶Li reaction are expected at 1550-1580 keV.

→D(α,γ)⁶Li Signal is obtained by subtracting the two spectra



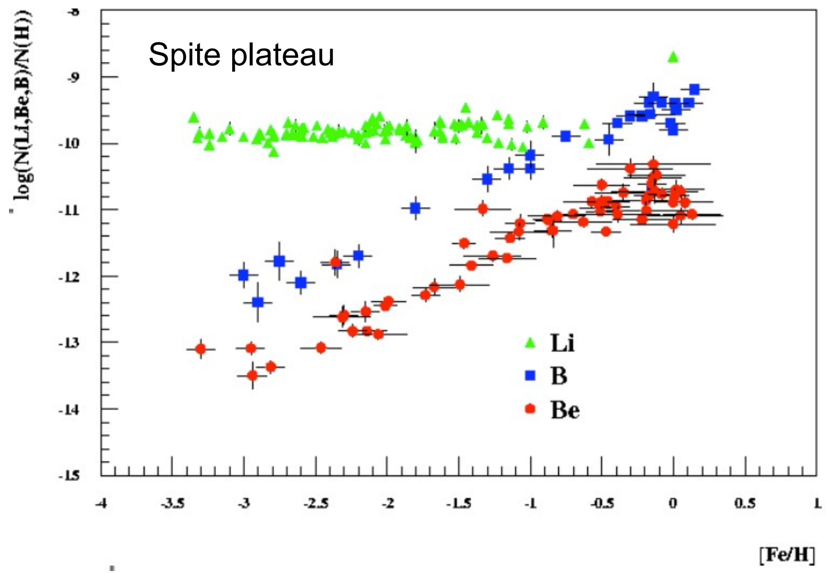
Beam Induced Background



(n,n'γ) reaction on the surrounding materials (lead, steel, copper and germanium)
γ-ray background in the RoI for the $D(\alpha,\gamma)^6Li$ DC transition (~1.6 MeV)

The Lithium problem(s)

- Observed ^{7}Li abundance is about 3 times lower than foreseen: Well established "Lithium problem".
- Debated claim of a huge abundance of ^{6}Li (Asplund2006).

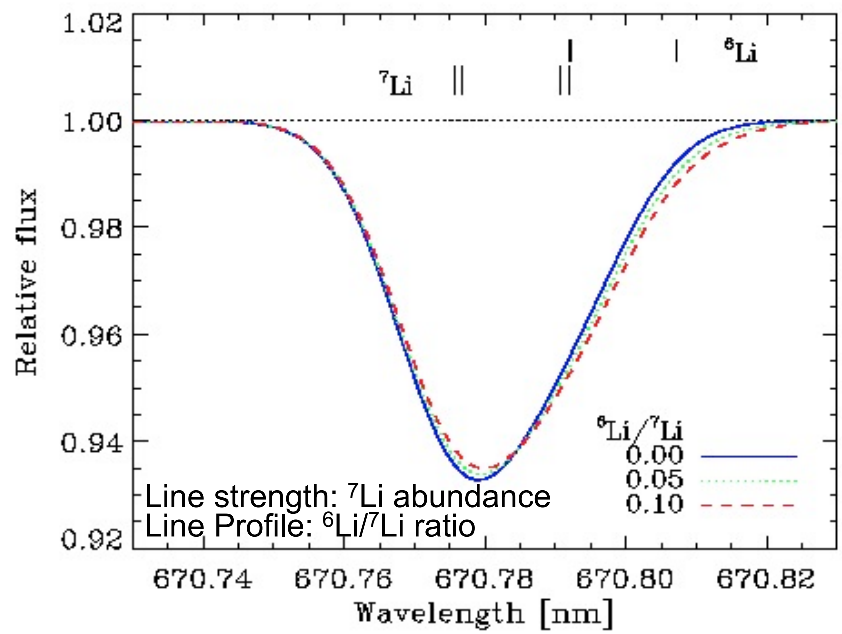


•Systematics in the measured ^{7}Li, ^{6}Li and abundances in the metal-poor stars of our Galaxy.

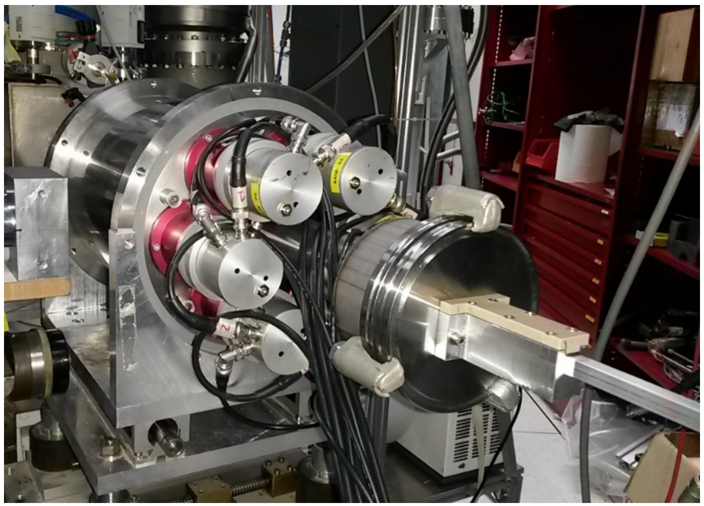
•Unknown processes before the birth of the galaxy

•New physics, e.g. sparticle annihilation/ decay (Jedamzik2008), long lived negatively charged particles (Kusakabe2010)

•…Nuclear physics, i.e. the lack of knowledge of the relevant nuclear reactions.

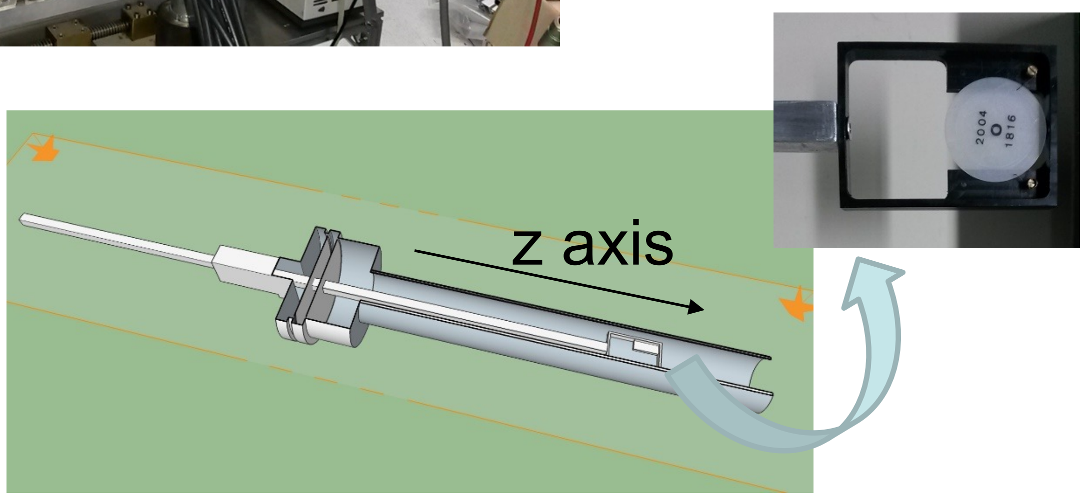


EFFICIENCY MEASUREMENT



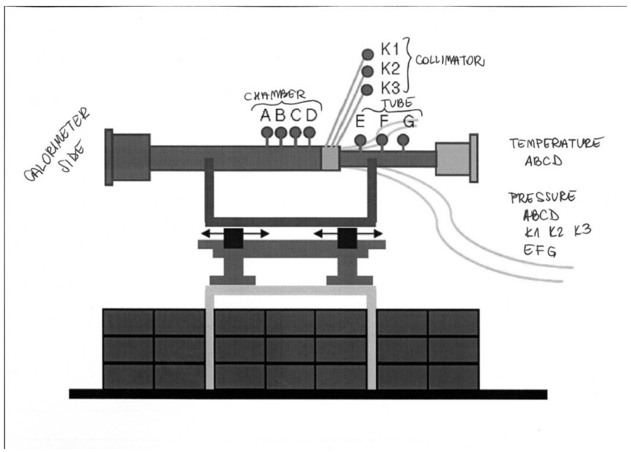
Low energy measurements / 1% statistical error:

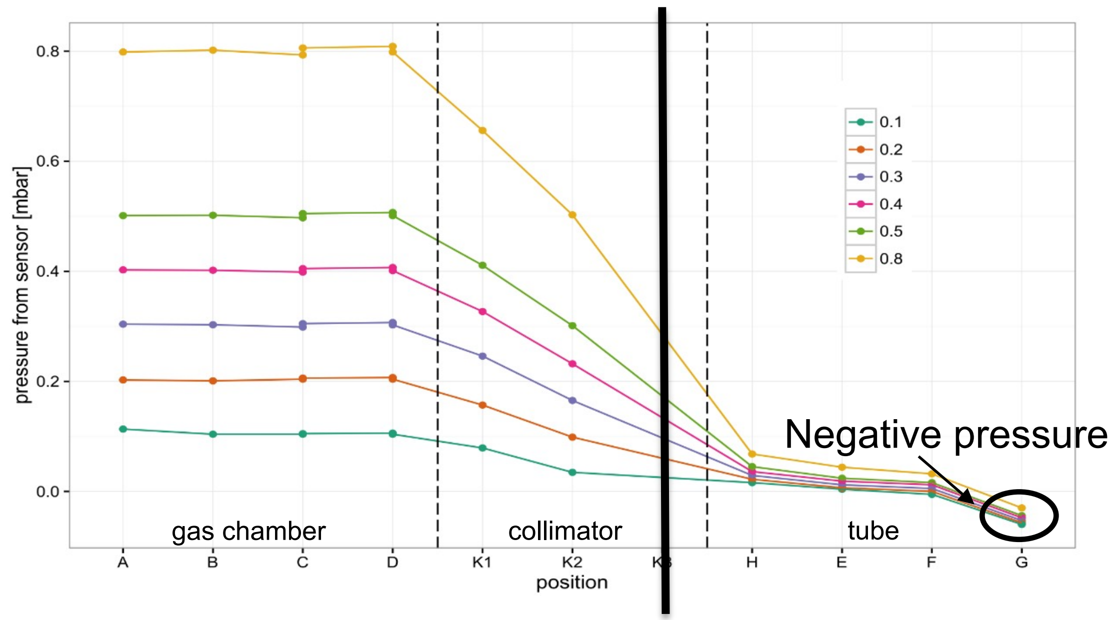
- ^{137}Cs (662 keV)
- ^{60}Co (1173 keV – 1332 keV)
- ^{88}Y (898 keV – 1836 keV)



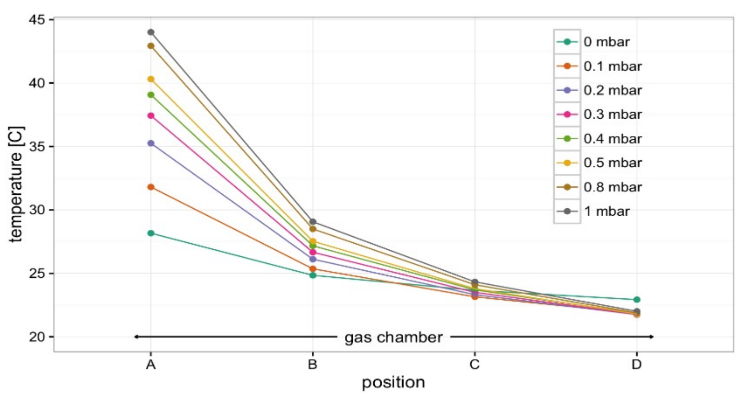
d	position [mm]
0	22,4
1	32,4
2	42,4
3	52,4
4	62,4
5	72,4
6	82,4
7	92,4
8	102,4
9	112,4
10	122,4
11	132,4

TEMPERATURE AND PRESSURE PROFILES



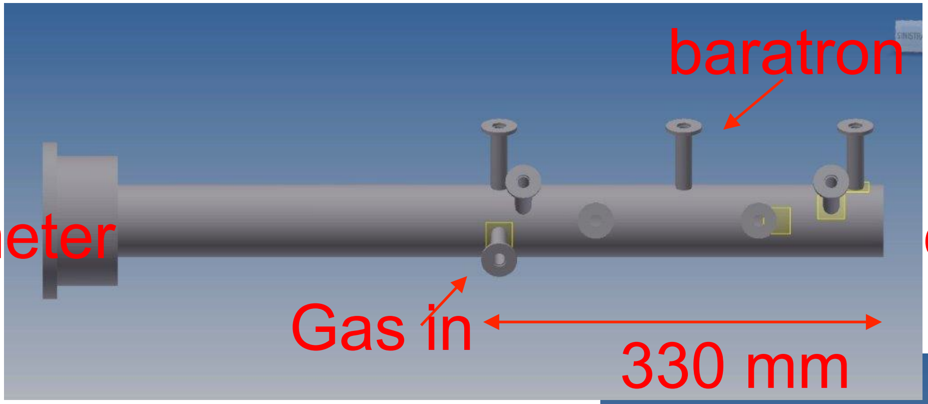


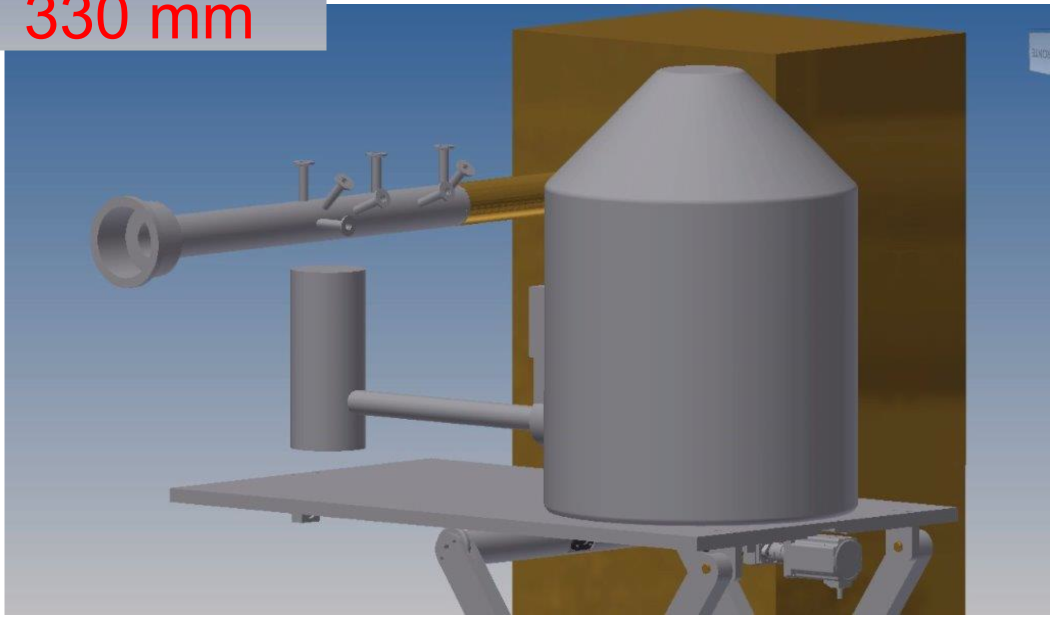
Not available (vacuum leak)



Temperatures have been measured along the gas chamber (only)

2. HPGe PHASE





Particle Data Group: Review of Particle physics (2014).

The nuclear reaction cross sections important for BBN have all been measured at the relevant energies. We will see, however, that recently there have been substantial advances in the precision of light element observations (e.g., D/H) and in cosmological parameters (e.g., from *Planck*). This motivates corresponding improvement in BBN precision and thus in the key reaction cross sections. For example, it has been suggested [30] that $d(p,\gamma)^3$He measurements may suffer from systematic errors and be inferior to *ab initio* theory; if so, this could alter D/H abundances at a level that is now significant.

E. Di Valentino et al., PRD 90, 023543 (2014)

provides some piece of information on the radiative capture reaction $d(p,\gamma)^3$He, converting deuterium into helium. The value of the rate for this process represents the main source of uncertainty to date in the BBN computation of the primordial deuterium abundance within a given cosmological scenario, parametrized by the baryon density $\Omega_b h^2$ and effective neutrino number $N_{\rm eff}$. The corresponding cross section has not been measured yet with a sufficiently low uncertainty and normalization errors in the BBN center-of-mass energy range, 30–300 keV. In addition to

PLANCK collaboration, arXiV:1502.01589v2 [astro-ph.CO] (2015).

The posteriors for A_2 are shown in Fig. 37. These results suggest that the d(p, γ)^{3}He reaction rate may be have been underestimated by about 10 %. Evidently, tests of the standard BBN picture appear to have reached the point where they are limited by uncertainties in nuclear reaction rates. There is therefore a strong case to improve the precision of experimental measurements (e.g., Anders et al. 2014) and theoretical computations of key nuclear reaction rates relevant for BBN.

R. J. Cooke, ApJL 812, L12 (2015).

New experimental data for the crucial d(p,γ)^{3}He reaction, which contributes the dominant uncertainty for both the D/H and ^{3}He/^{4}He abundance ratios, are currently being acquired by the Laboratory for Underground Nuclear Astrophysics (LUNA; Broggini et al. 2010; Di Valentino et al. 2014). New data for the remaining reaction rates are now needed.

A. Coc et al., Eur. Phys. J. A 51 34 (2015)

lithium problem. We just point out that if the new observations of deuterium are confirmed, high precision ($\sim 1\%$) will be required on the main cross sections involved in deuterium destruction [171]. The most recent measurements concerning these cross sections have been done directly at LUNA (^{2}H(p, γ)^{3}He) [21] and TUNL (^{2}H(d, n)^{3}He and ^{2}H(d, p)^{3}H) [172]. These latter were very recently, determined using the Trojan Horse Method [173] and theoretically through *ab initio* calculations [174].

L. Marcucci et al., PRL 116, 102501 (2016).

tent during BBN. Of course, our results ought to be confirmed by direct measurement of the $d(p,\gamma)^3$He S-factor, as it is planned at the Gran Sasso National Laboratories (Italy), by the LUNA Collaboration. Such a measurement will therefore turn out to be crucial in this context and an improved accuracy at few percent would provide an independent handle to assess the overall consistency of the standard cosmological model. Finally, it should be

R. H. Cyburt et al., Rev. Mod. Phys. 88, 015004 (2016).

which yield high precision D/H abundances. Moreover, the nuclear physics uncertainties in D/H now dominate the error budget. Thus there is strong motivation for future measurements of the rates most important for deuterium: $d(p,\gamma)^3$He, as well as $d(d,n)^3$He, $d(d,n)t$, and $n(p,\gamma)$D (Nollett and Holder, 2011; Di Valentino *et al.*, 2014). We can hope that