BBN, neutrinos and Nuclear Astrophysics

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Big Bang Nucleosynthesis

BBN is the result of the competition between the relevant nuclear processes and the expansion rate of the early universe, governed by the Freidmann Equation:

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

H = Hubble constant

G = Newton's gravitational constant

ρ **= energy density (i.e. photons and neutrinos density in the early Universe)**

Therefore, the abundance of primordial isotopes ONLY depends on:

- **Baryon density Ω_b (BBN and CMB experiments)**
- **Particle Physics (τ_n, N_{eff}, α..)**
- **Nuclear astrophysics, i.e. cross sections of BBN nuclear reactions**

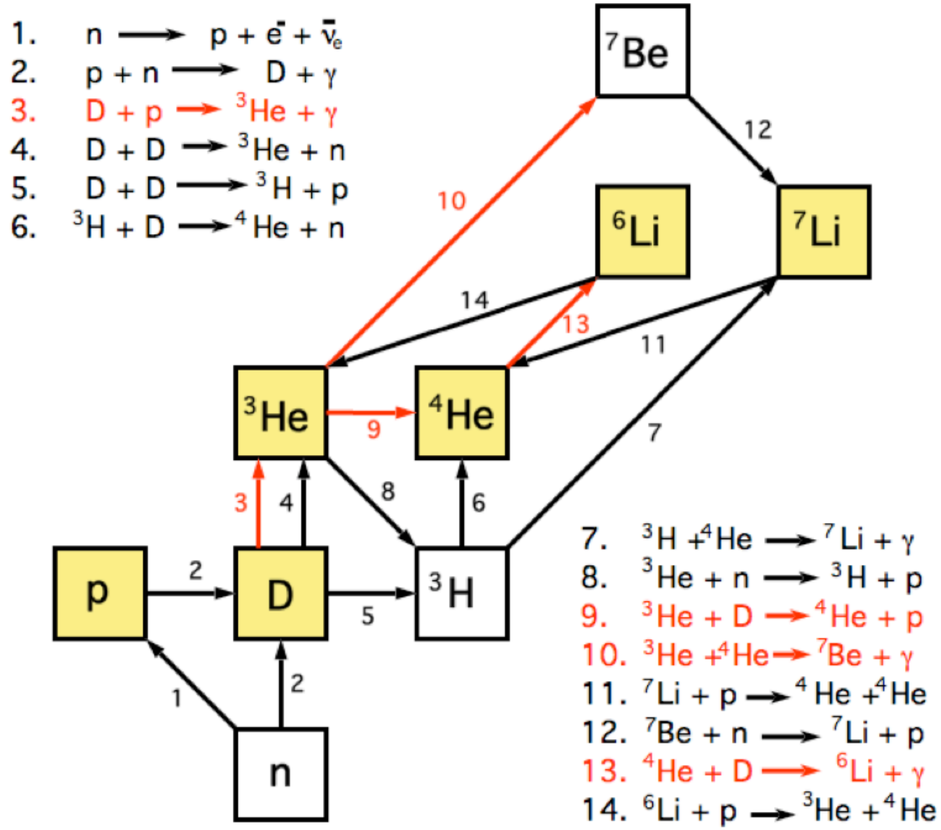
Big Bang Nucleosynthesis

-The BBN begins with the formation of **Deuterium**.

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

- ^{7}Li and ^{6}Li have small abundance because of the absence of stable nuclei with mass number 5 or 8.

- Direct observations are restricted to stable elements (D, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li)



BBN error budgets:

^{4}He:	Almost entirely due to $\Delta\tau_n$ (1)
D:	Mainly due to the D(p,γ)^{3}He reaction (3)
^{3}He:	Mainly due to the ^{3}He(d,p)^{4}He reaction (9)
^{6}Li:	Mainly due D(α,γ)^{6}Li reaction (13)
^{7}Li:	..Many reactions of the BBN network (10, 9, 3,...)

Determination of primordial abundances

Direct Observations:

- **Observation of a set of primitive objects (born when the universe was young)**
- **Extrapolate to zero metallicity: Fe/H, O/H, Si/H → 0**
- **Systematics mainly due to post-primordial processes**

^{4}He: Observation in H_{II} regions, quite large systematics.
D: Observation of absorption lines in QSO. 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)

^{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 Vs observation for the abundances of all the primordial light isotopes.

Baryon density

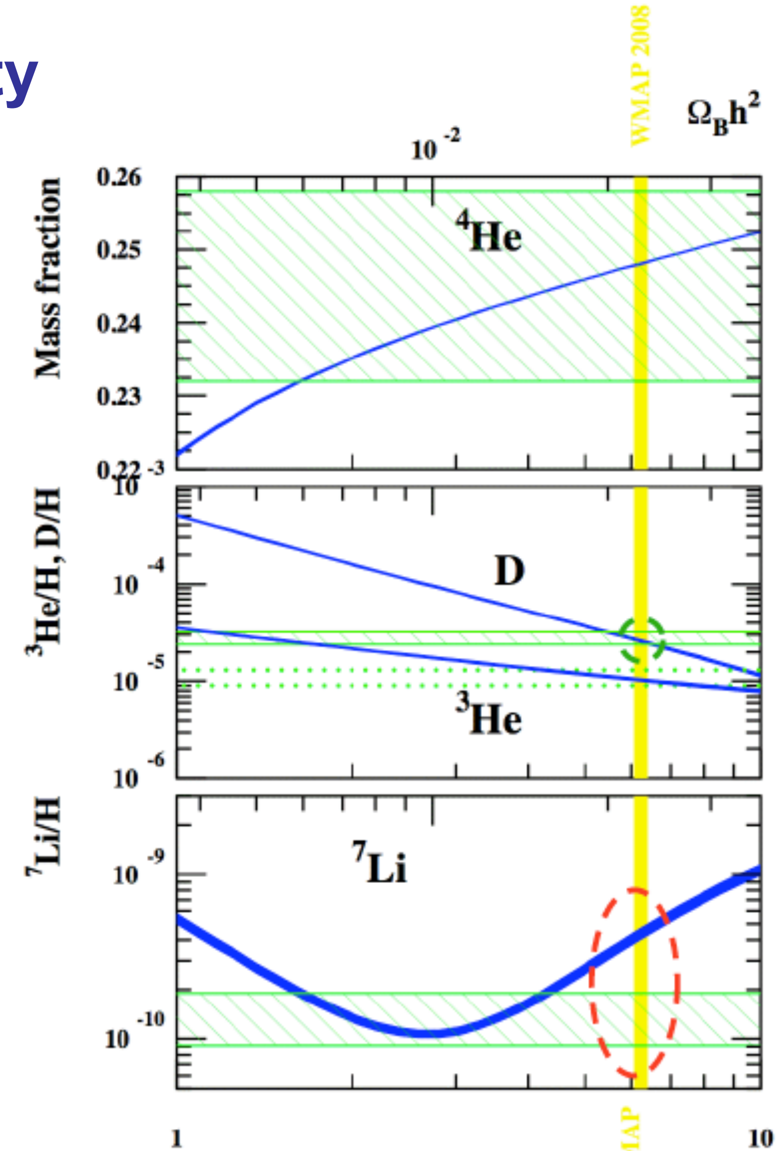
The cosmic baryon density Ω_b is a key parameter, and it is independently measured via CMB and BBN.
CMB and BBN results are in good agreement, suggesting that the number of relativistic species did not change between the time of BBN (~10 min) and the time of recombination (~400.000 years).
Assuming Standard Model (3 neutrino species):

$100\Omega_{b,0}h^2$(CMB)=2.20±0.03 (PLANCK2013)

$100\Omega_{b,0}h^2$(D/H)=2.20±0.02±0.04 (Cooke2013)

D/H observations

Nuclear Astrophysics (Dpγ reaction uncertainty)

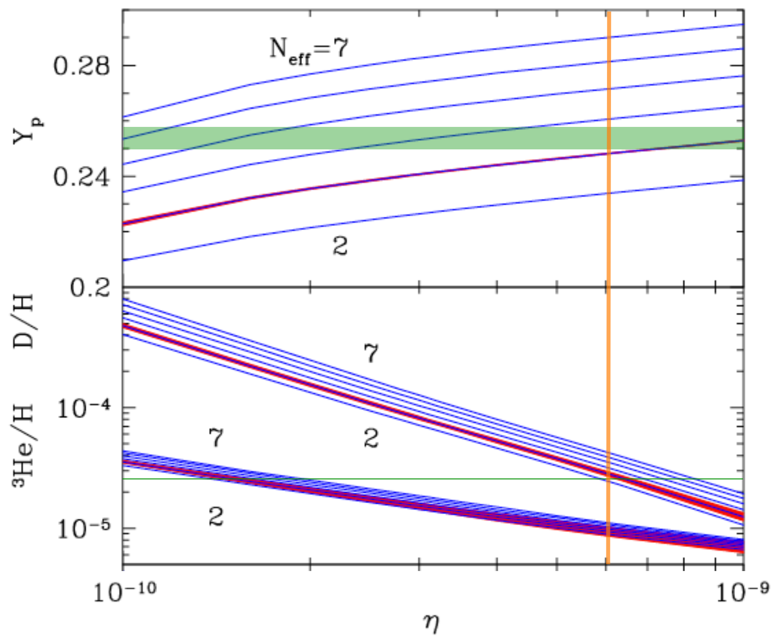


$\Omega_{b,0}h^2$(BBN) is obtained by comparing D/H$_{obs}$ and D/H$_{BBN}$. The Ω_b(BBN) uncertainty is mainly due to the poor knowledge of D(p,γ)^{3}He reaction at BBN energies.

BBN and neutrinos

^{4}He abundance (Y_p) strongly depends on the expansion rate, i.e. on the number of neutrino families N_{eff}. Unfortunately, direct measurements are affected by large systematical errors.

(D/H) is somewhat less sensitive to the number of neutrinos (or any other relativistic species) but direct (D/H) measurements are very accurate.



$$Y_P = 0.2469 \pm 0.0006 + 0.0016\,(\eta_{He} - 6)$$
where: $\eta_{He} = \eta_{10} + 100(S - 1) - 575\xi/4$

$$(D/H)_P = 2.55\times10^{-5}\,(6/\eta_D)1.6\ \times(1 \pm 0.03)$$
where: $\eta_D = \eta_{10} - 6(S - 1)+5\xi/4$

$\eta_{10} = 273.9\times\Omega_{b,0}\ h^2$
$S = [1 + 7(N_{eff} - 3.046)/43]^{1/2}$

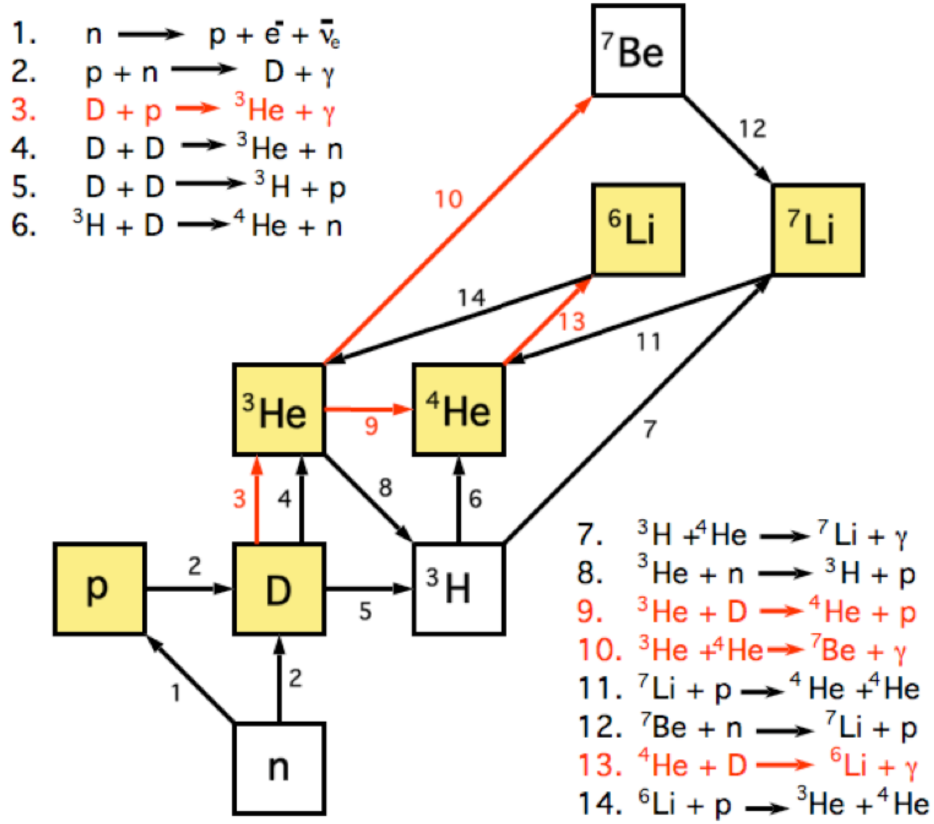
N_{eff}= number of neutrino families (or any other relativistic species)
ξ=neutrino degeneracy (matter/antimatter asymmetry in the neutrino sector)

Standard Model: N_{eff}=3.046, ξ=0

The D(p,γ)^{3}He reaction and Deuterium abundance

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

Primordial Deuterium error budget (Di Valentino et al. 2014)



→Presently, the error budget of deuterium abundance is essentially due to the paucity of data at BBN energies relative to the D(p,γ)^{3}He reaction.

The $D(p,\gamma)^3He$ reaction and Deuterium abundance

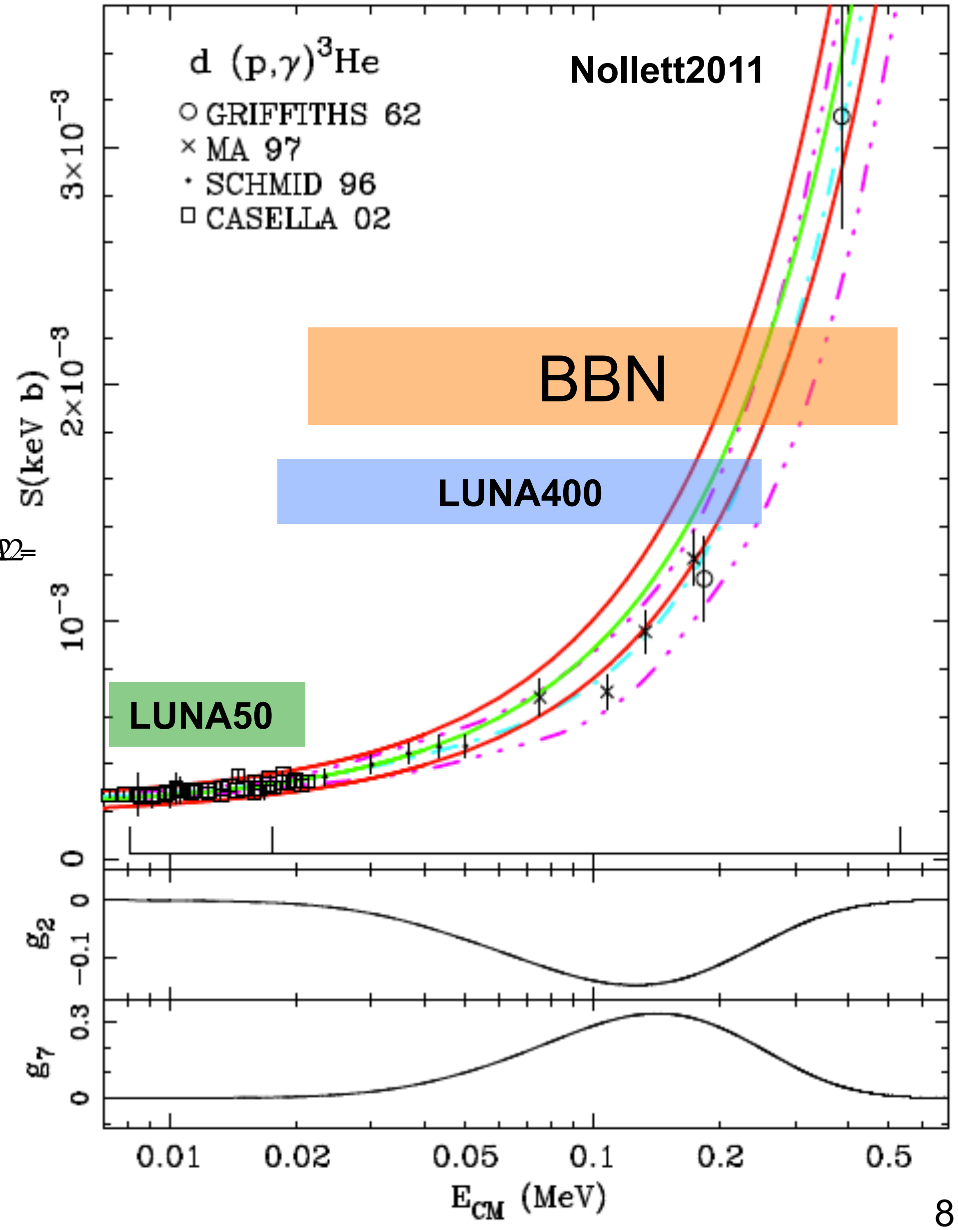
- **Present data have a $D(p,\gamma)^3He$ (claimed) systematic error of 9% (2 σs error bars in the figure).**
- **Theoretical *"ab initio"* and experimental values of the S_{12} factor differ at the level of 20%.**

→ A renewed and accurate measurement of the $D(p,\gamma)^3He$ reaction at the BBN energy range is necessary.

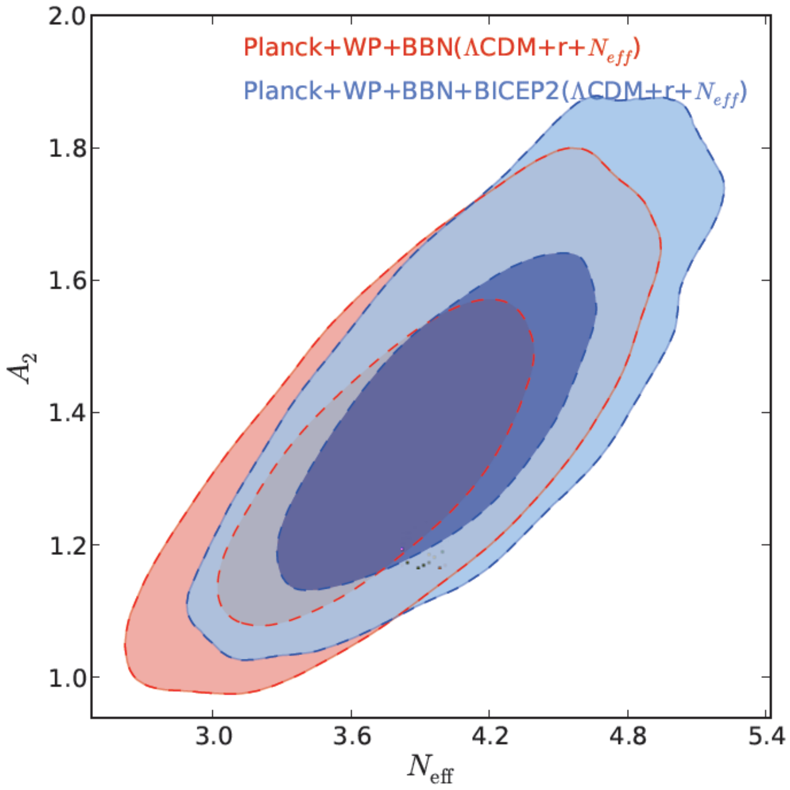
LUNA 400 kV at LNGS is well suited to do it ($20<E_{cm}(keV)<260$).

We can define:

$$A_2 = \frac{R_2^{th}(T)}{R_2^{exp}(T)}$$



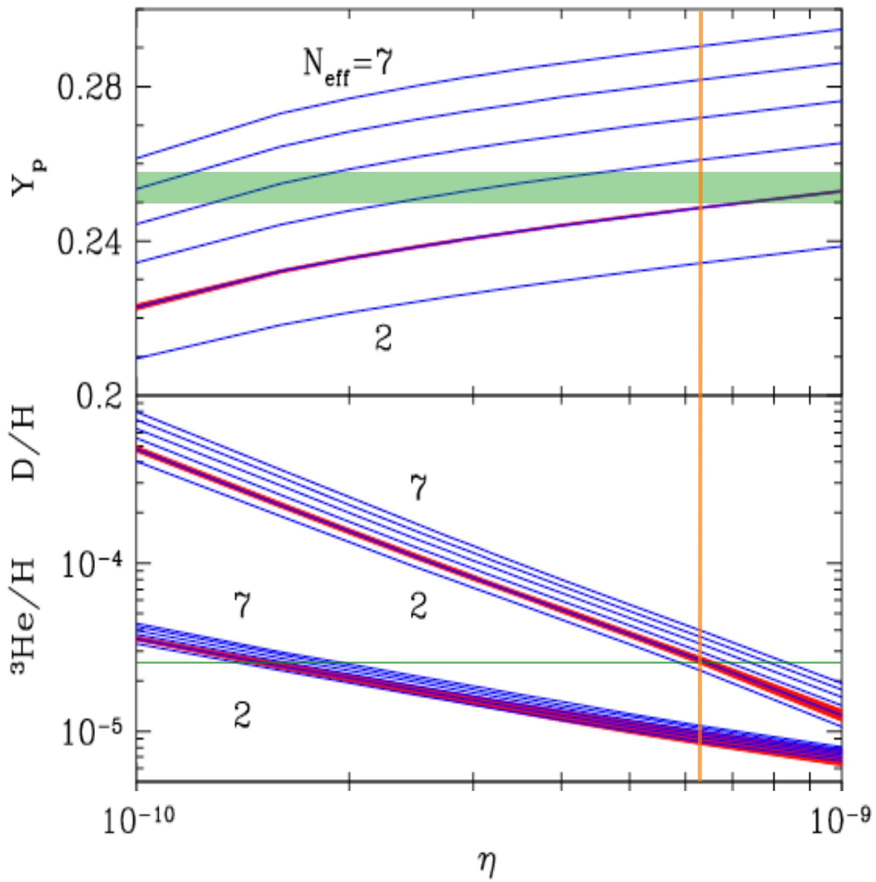
CMB, neutrinos and $D(p,\gamma)^3He$ reaction

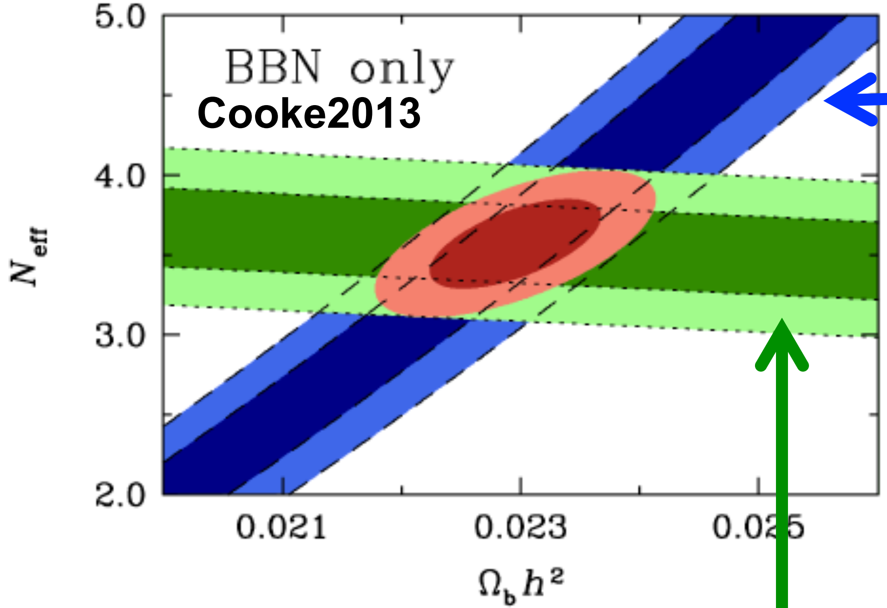


arXiv:1404.7848v1 [astro-ph.CO] 30 Apr 2014

CMB experiments (Planck, WMAP, BICEP2) provide an estimate of Ω_b (and other parameters). The tension towards higher $D(p,\gamma)^3He$ cross section and $N_{eff}>3$ is quite apparent.

BBN and neutrinos





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.

Ω_b and N_{eff} can be inferred with BBN theory alone, by comparing BBN calculations and direct observations of ^{4}He and D.

Physics case summary

-D abundance is sensitive to Ω_b, N_{eff}, ξ.

-BBN parameters, such as Ω_b, $(D/H)_p$, are known with high (and increasing) precision:

Ω_b error: 4.3% (WMAP2003)→ 1.4% (PLANCK2013)
$(D/H)_p$ error: 8% (Cyburt 2006)→1.6% (Cooke&Pettini 2013)

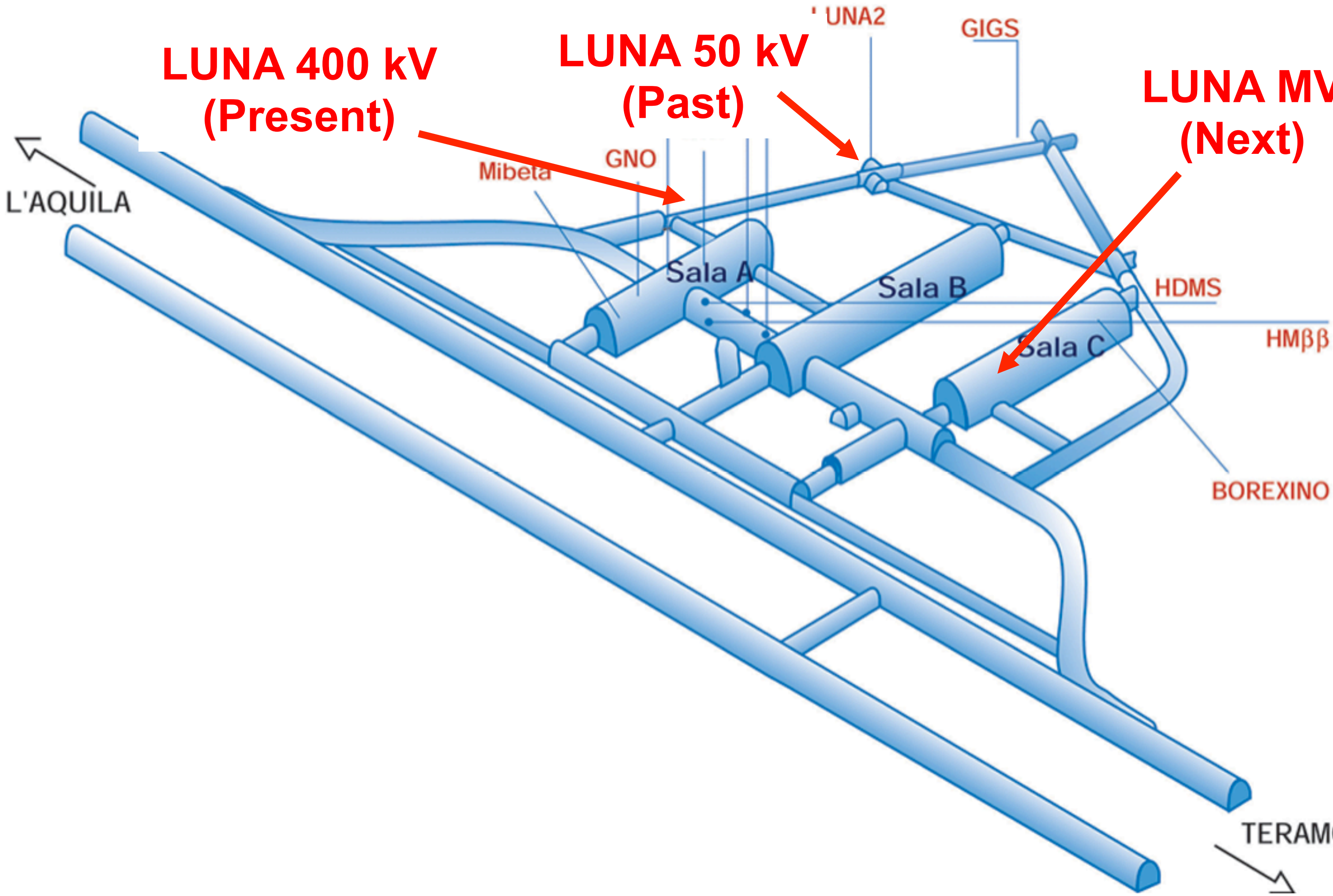
With the present $^2H(p,\gamma)^3He$ data at BBN energies we have:

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

→Result from BBN and CMB are in excellent agreement providing a suggestive, but still inconclusive, hint of the presence of dark radiation.

The accurate study of the $^2H(p,\gamma)^3He$ reaction at BBN energies is necessary, because its poorly known cross-section represent the single most important obstacle to improve the BBN contraints on the existence of "dark radiation".

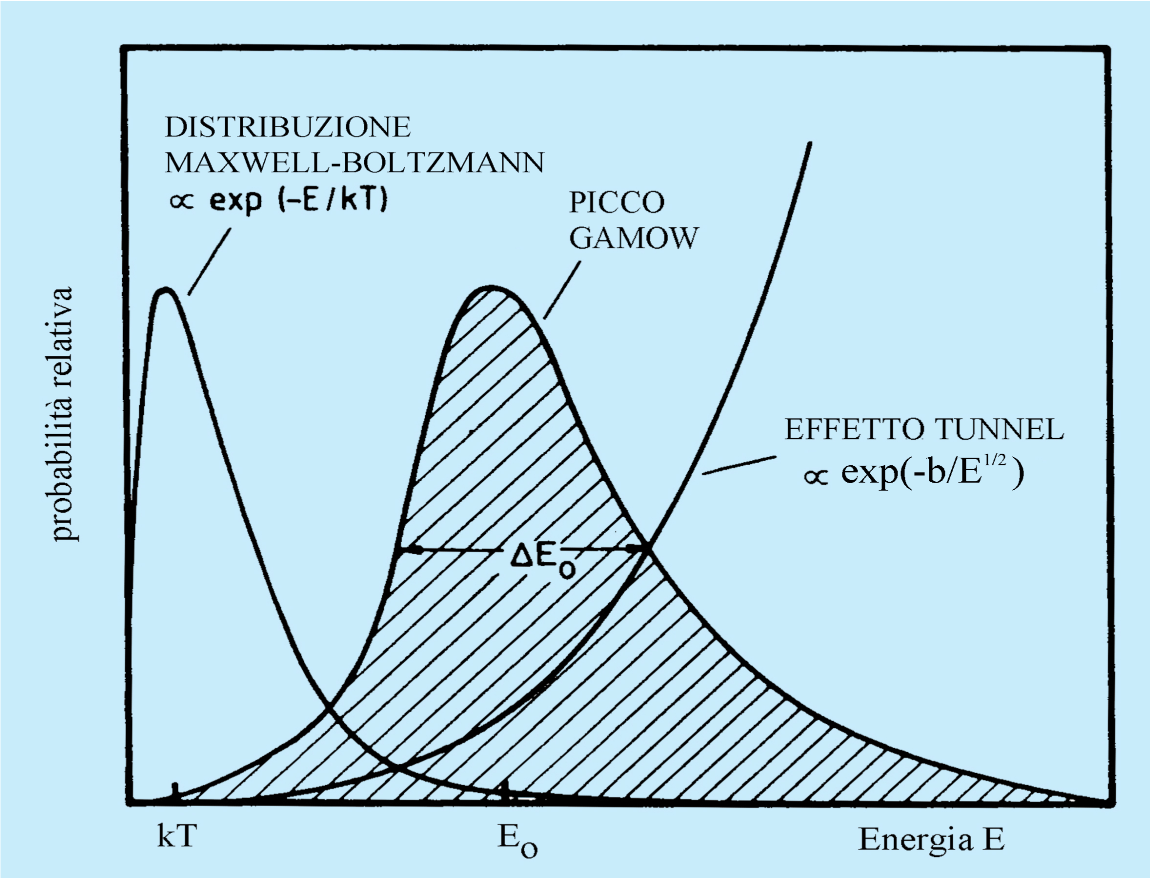
Gran Sasso National Laboratory (LNGS)



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

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

Why Underground measurements?



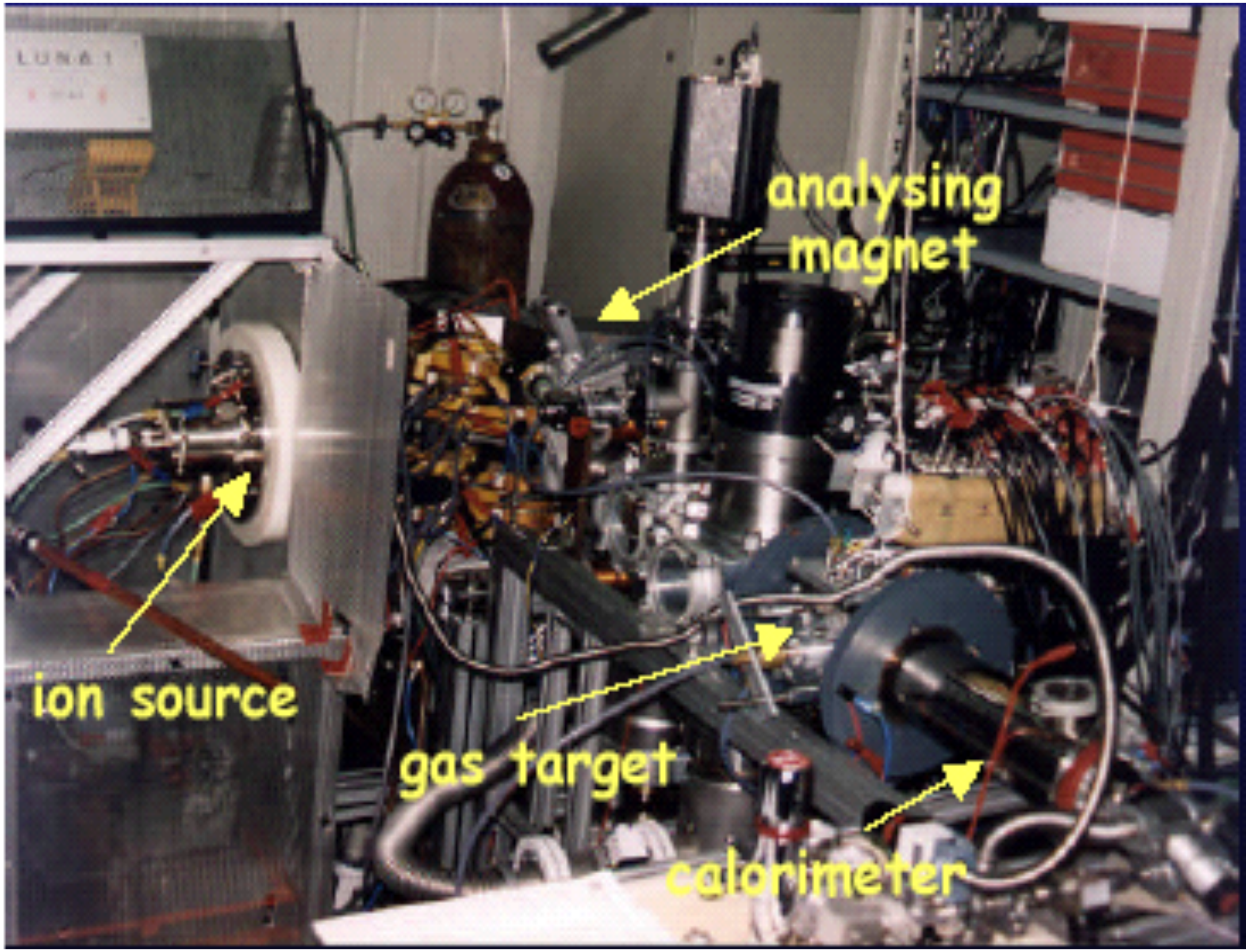
Astrophysical Factor

Coulomb Barrier

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

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

LUNA 50 kV



$^{3}He(^{3}He,2p)^{4}He$ (solar neutrinos)

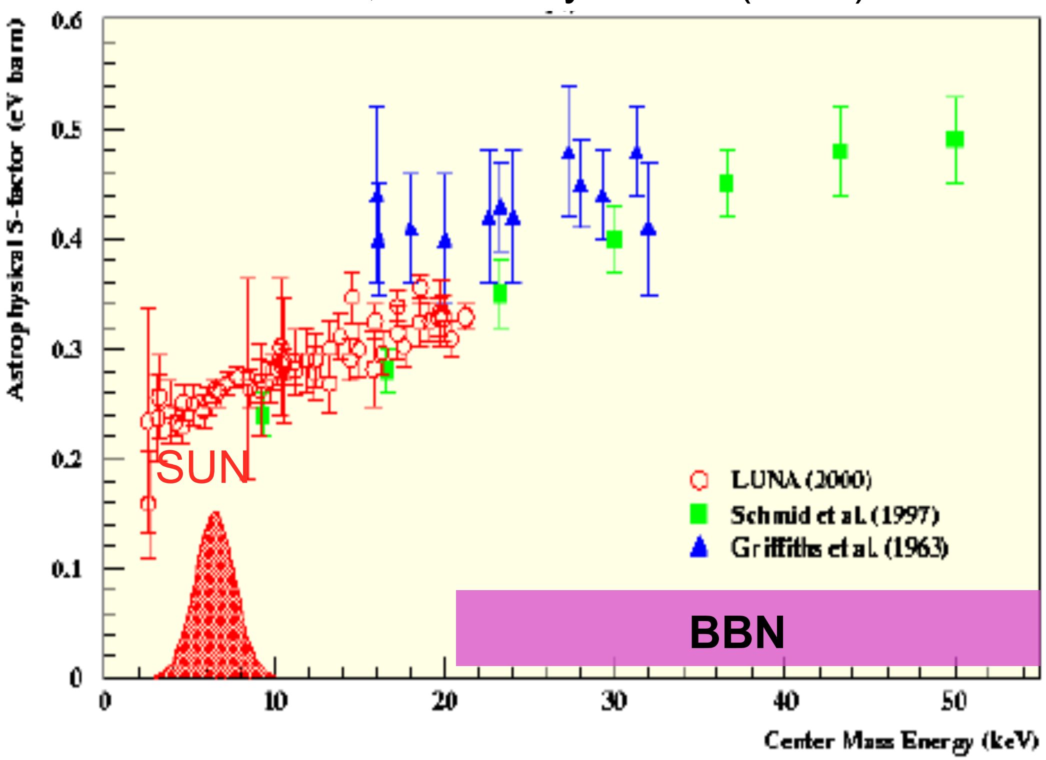
$D(p,\gamma)^{3}He$ (BBN, proto-Stars, p-p chain)

D(p,γ)^{3}He @ LUNA50

Low energy LUNA50 data have reduced the primordial abundance error of:

- **D/H (factor 3)**
- **^{3}He/H (factor 2)**
- **^{7}Li/H (factor 1.2)**

C.Casella et al., Nucl. Phys. A706(2002)203

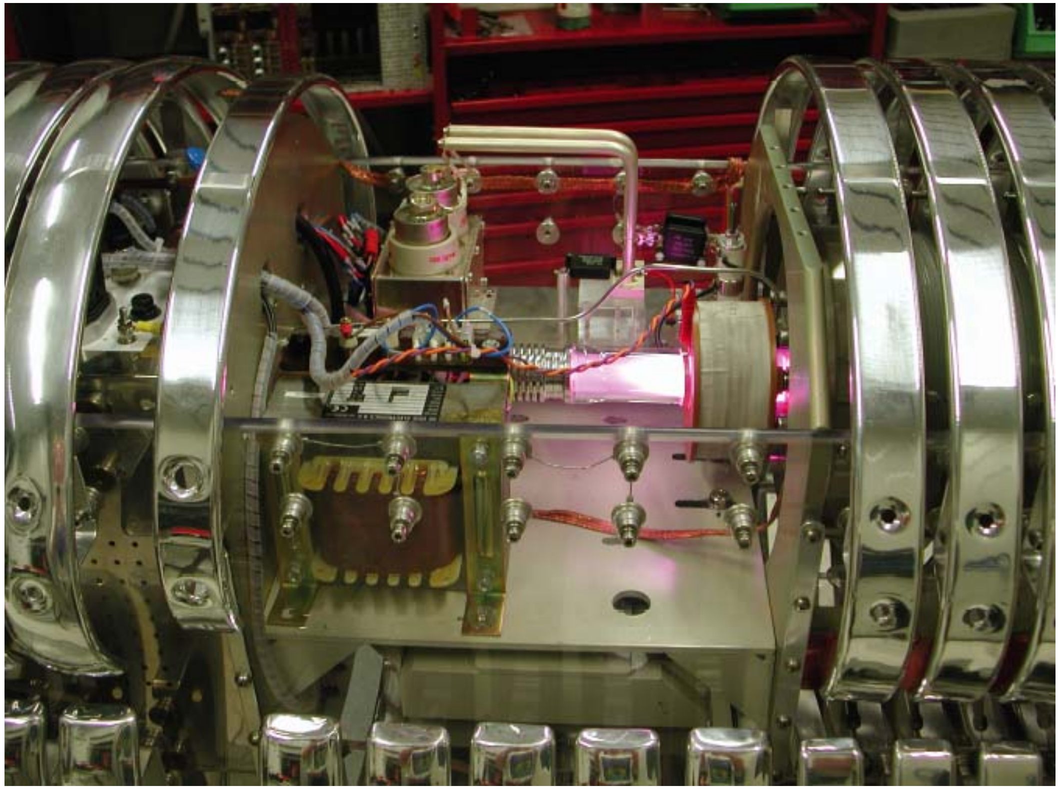


Q = 5.5 MeV

S(0)=0.216± 0.006 eV·barn

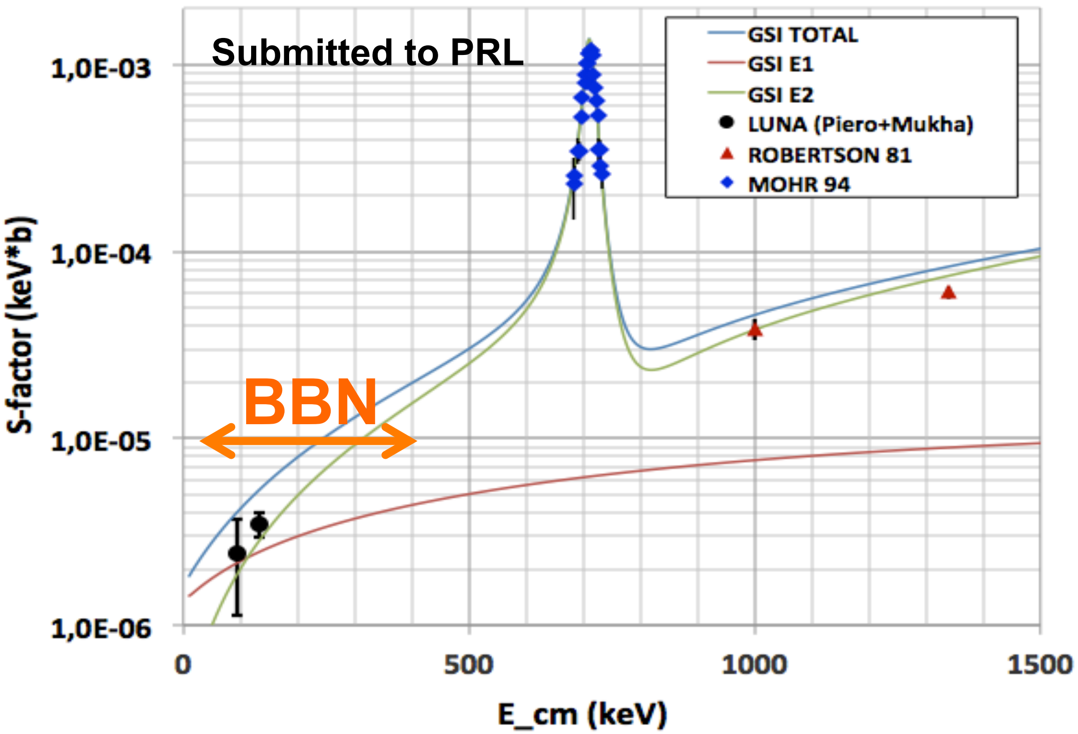
LUNA 400 kV

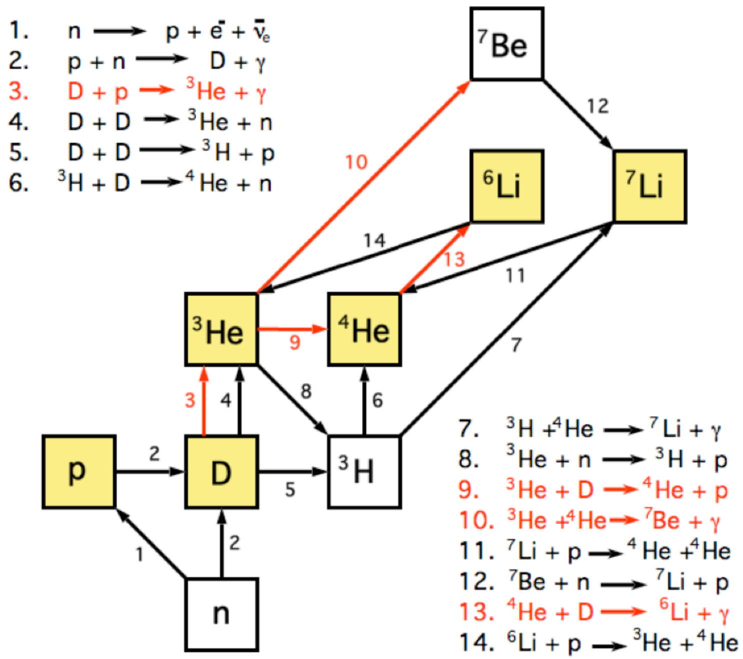
Presently, LUNA is the world's only underground accelerator at LNGS, Italy, with a maximal energy of E_{beam}=400 keV
Many accelerators have been proposed in the world, operating up to several MeV, i.e. well suited to study BBN reactions.



$^{14}N(p,\gamma)^{15}O$
$^{3}He(^{4}He,\gamma)^{7}Be$
$^{25}Mg(p,\gamma)^{26}Al$
$^{15}N(p,\gamma)^{16}O$
$^{17}O(p,\gamma)^{18}F$
$D(^{4}He,\gamma)^{6}Li$ (just done)
$^{22}Ne(p,\gamma)^{23}Na$ (in progress)
$D(p, \gamma)^{3}He$ (next)

D(α,γ)^{6}Li: The ^{6}Li/H abundance





First D(α,γ)^{6}Li cross section measurement at BBN energies

→ ^{6}Li/H = (0.74±16)x10^{-14}

→ ^{6}Li/^{7}Li = (1.5±0.3)x10^{-5}

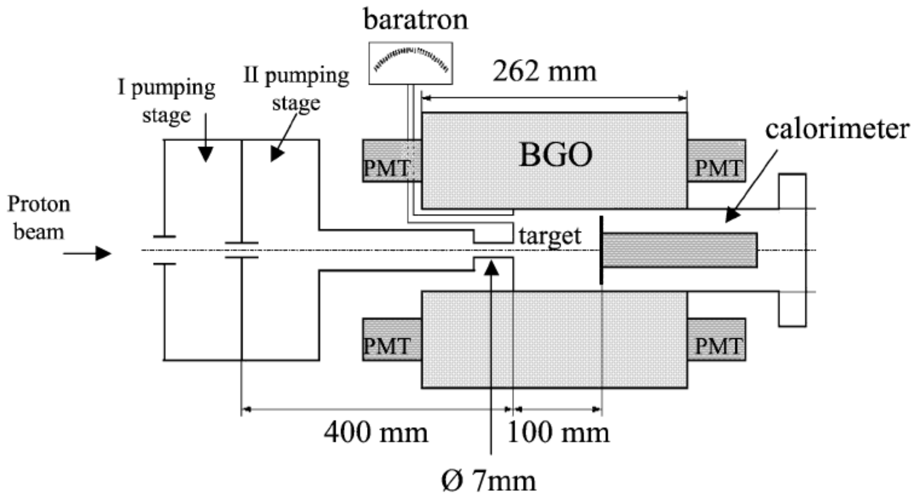
D(p,γ)^{3}He reaction: Possible Set-up

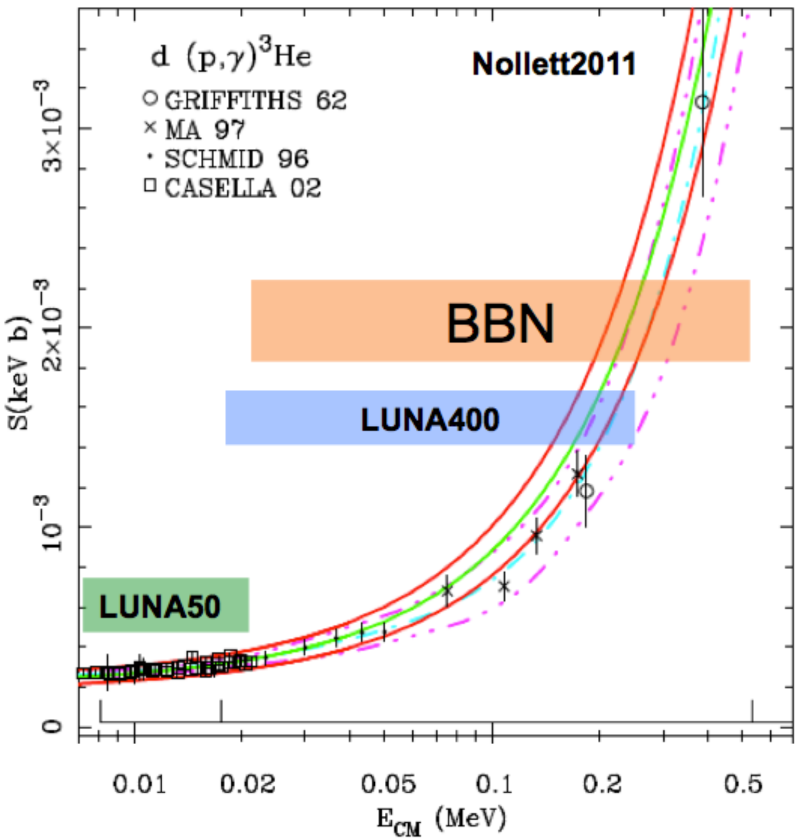
BGO detector

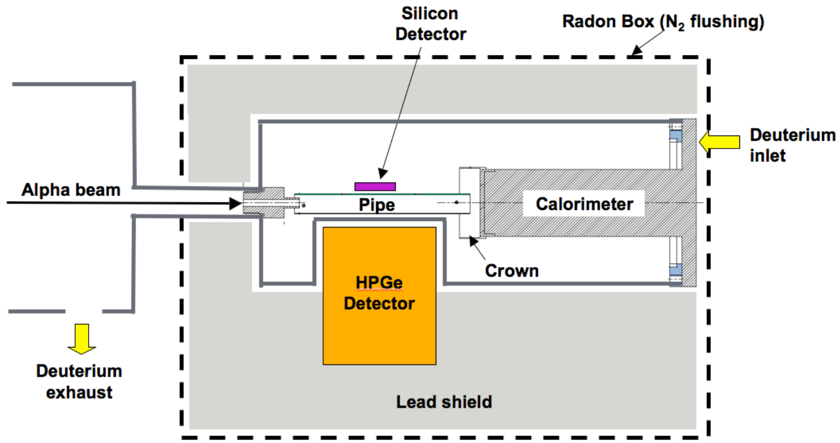
Accurate Total cross section Vs Energy ($20<E_{cm}keV<266$)

Ge(Li) detector

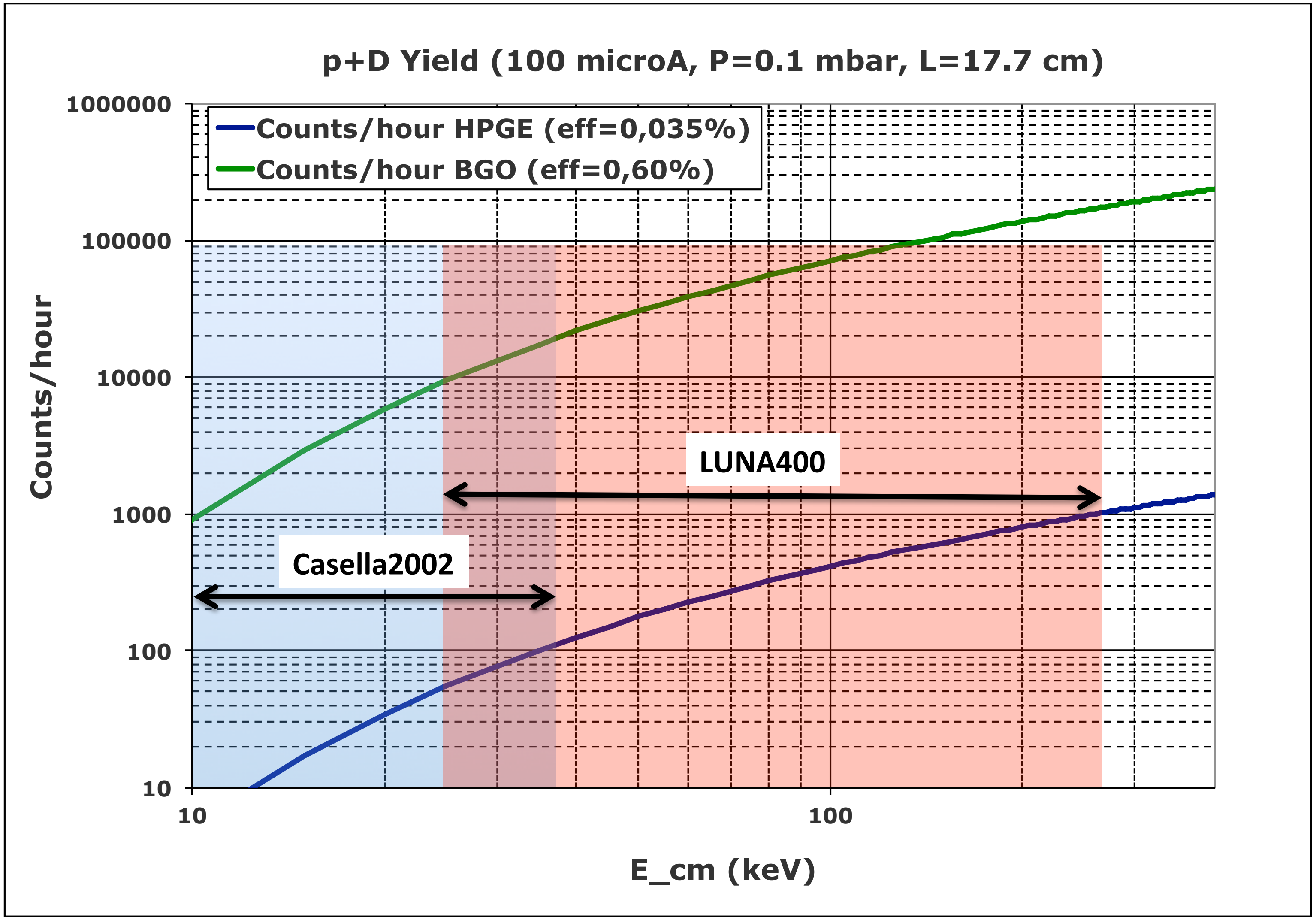
Study of angular emission of photons to study nuclear physics aspects







D(p,γ)^{3}He reaction: Possible Set-up



HPGe: 10^3-10^4 events/day ($100<E_{cm}(keV)<263$)
BGO: 10^4-10^5 events/hour ($20<E_{cm}(keV)<263$)

Conclusions

-We are in the "Precision Era" of Cosmology. BBN parameters, such as Ω_b, Y_p, $(D/H)_p$ are known with high (and increasing) precision. Uncertainties of calculations are often limited by the poor knowledge of the cross section of few reaction, at BBN energies.

-Accurate measurements at low energy must be done with Underground accelerators, with present (LUNA) or future accelerators (e.g. the approved LUNA-MV project).

-Of crucial importance is the accurate measurement of the $D(p,\gamma)^3He$ cross section, To calculate the D abundance and therefore to increase the BBN and CMB sensitivity to N_{eff} and lepton degeneracy.

-Other BBN key processes are in the LUNA program.

The first direct measurement of the $^2H(\alpha,\gamma)^6Li$ at BBN energy ($^6Li/H$, "second lithium problem") has been recently performed at LUNA400.

Desirable (but not so urgent) is the study of the $D(^3He,p)^4He$ process ($^3He/H$), and a renewed measurement of the $^3He(^4He,\gamma)^7Be$ reaction ($^7Li/H$, "Lithium problem").