Neutrinos, BBN and Nuclear Astrophysics

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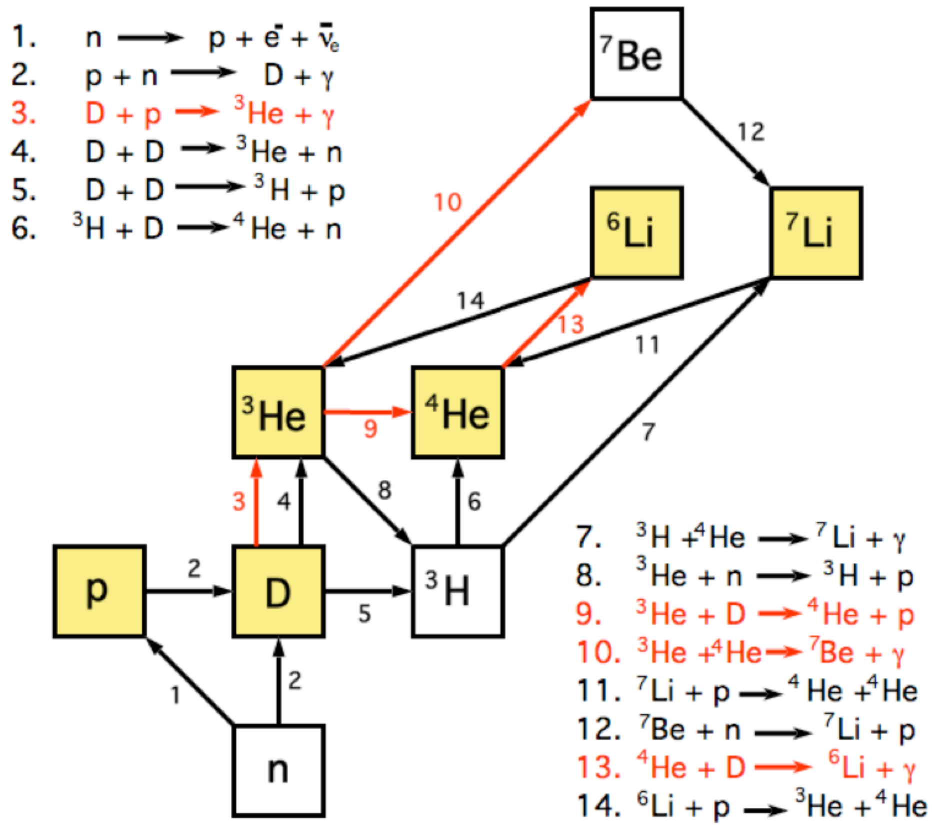
Big Bang Nucleosynthesis

The primordial abundance of isotopes depends on the competition between the relevant nuclear processes and the expansion rate of the early universe. In the standard scenario, it depends **ONLY** on:

- Baryon density ω_b
- Standard Model (τ_n, N_{eff}, α..)
- Nuclear astrophysics, i.e. cross sections of nuclear reactions in the BBN chain

-The chain begins with the formation of D (reaction 2).
-Nearly all the free neutrons end up bound in the most stable light element ^{4}He.
-Heavier nuclei such as ^{7}Li and ^{6}Li have small abundance because of the absence of stable nuclei with mass number 5 or 8 and of the large Coulomb barriers for reactions such as reactions 7 and 10 .



Direct observations are restricted to the stable isotopes, i.e. D, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li.

BBN theory Vs Direct Observations

BBN error budget:

^{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

^{7}Li: …Many reactions of the BBN network.

^{6}Li: Mainly D(α,γ)^{6}Li reaction

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 due to unknown post-primordial processes difficult to be evaluated

^{4}He: Observation in H_{II} regions, quite large systematics.

D: Observation of absorption lines in QSO. Accurate measurements (percent level)

^{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 in good agreement with expectations.

^{7}Li: Long standing "Lithium problem"

^{6}Li: "Second Lithium problem"?

Baryon density

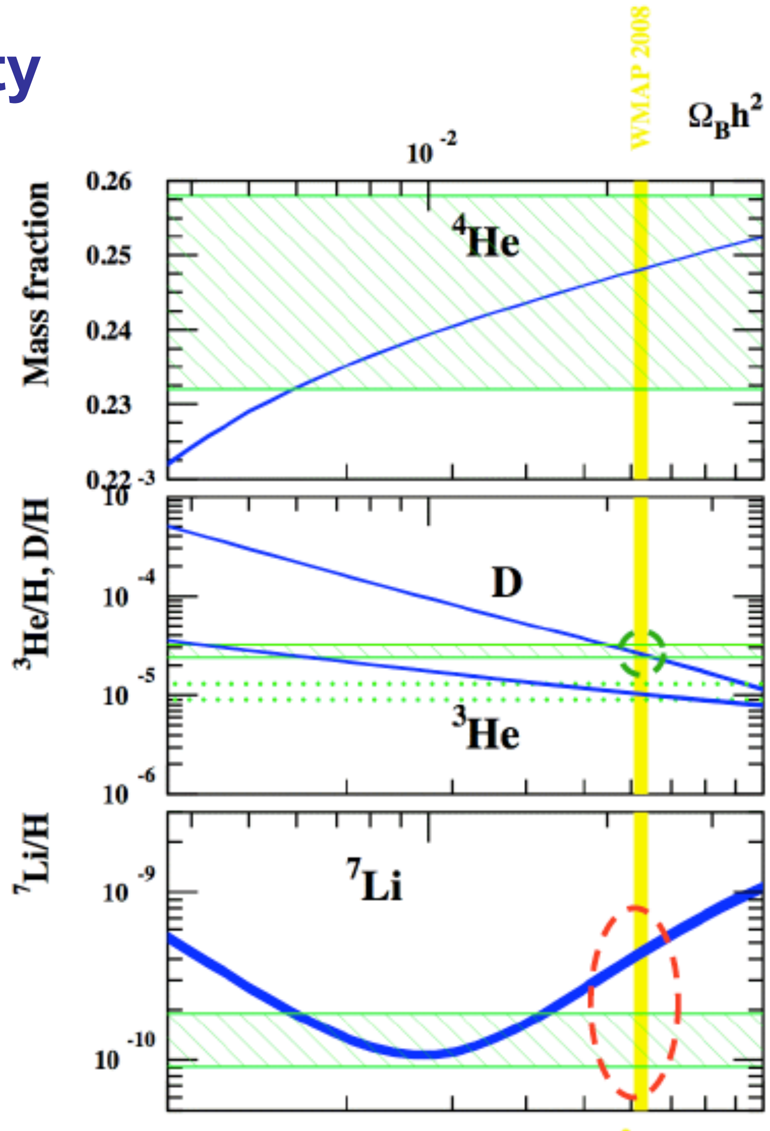
The cosmic baryon density Ω_b is independently measured via CMB and BBN. CMB and BBN results are in good agreement, suggesting that the number of relativistic species did not change between the time of BBN (~10 min) and the time of recombination (~400.000 years).

$100\Omega_{b,0}h^2$(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 (D+p reaction uncertainty)



PLANCK experiment is taking data, $\Omega_{b,0}h^2$(CMB) error will presumably improve in the next years…

$\Omega_{b,0}h^2$(BBN) is essentially obtained with the comparison of D/H_{obs} and D/H_{BBN}. It is mainly limited by the knowledge of $D(p,\gamma)^3He$ reaction.

BBN and neutrinos

The ^{4}He abundance (Y_p) strongly depends on the number of neutrino families, but direct measurements of this isotopes is affected by a large systematical error. Instead, (D/H) is less sensitive to the number of neutrinos (or any other relativistic species) but it has the advantage of an accurate direct measurements.

$$Y_P = 0.2469 \pm 0.0006 + 0.0016\,(\eta_{He} - 6)$$

and

$$(D/H)_P = 2.55\times10^{-5}\,(6/\eta_D)1.6\,\times(1 \pm 0.03)$$

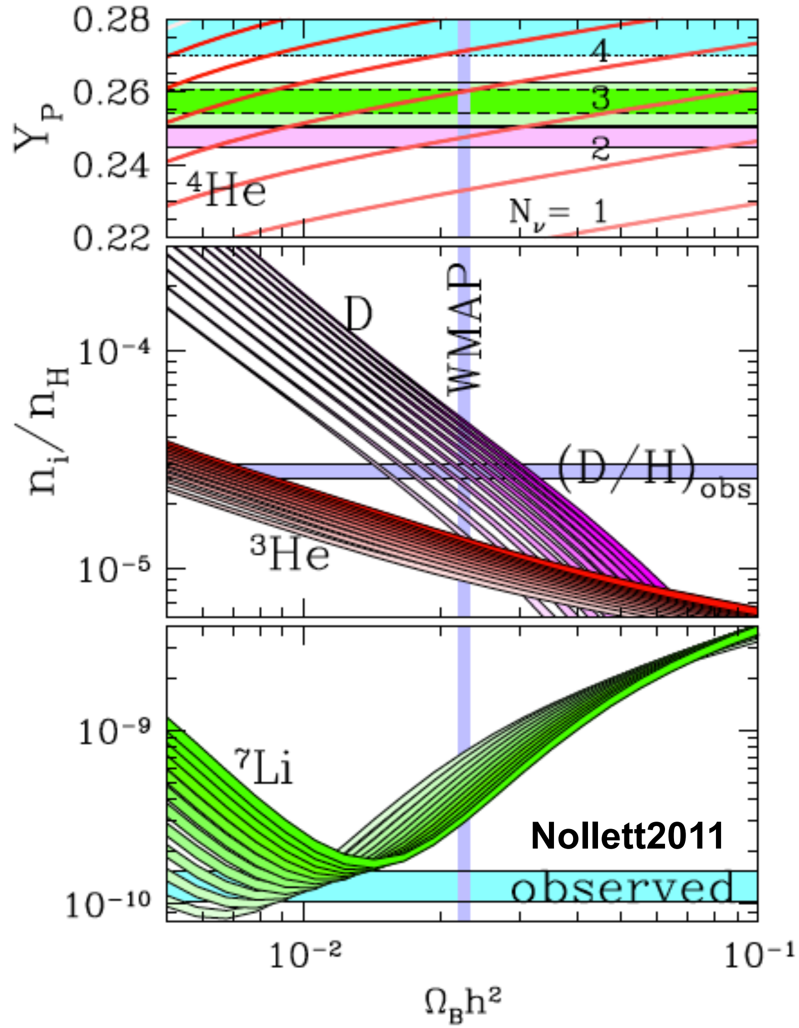
where:

$$\eta_{He} = \eta_{10} + 100(S - 1) - 575\xi/4$$

$$\eta_D = \eta_{10} - 6(S - 1) + 5\xi/4$$

$$S = [1 + 7(N_{eff} - 3.046)/43]^{1/2}$$

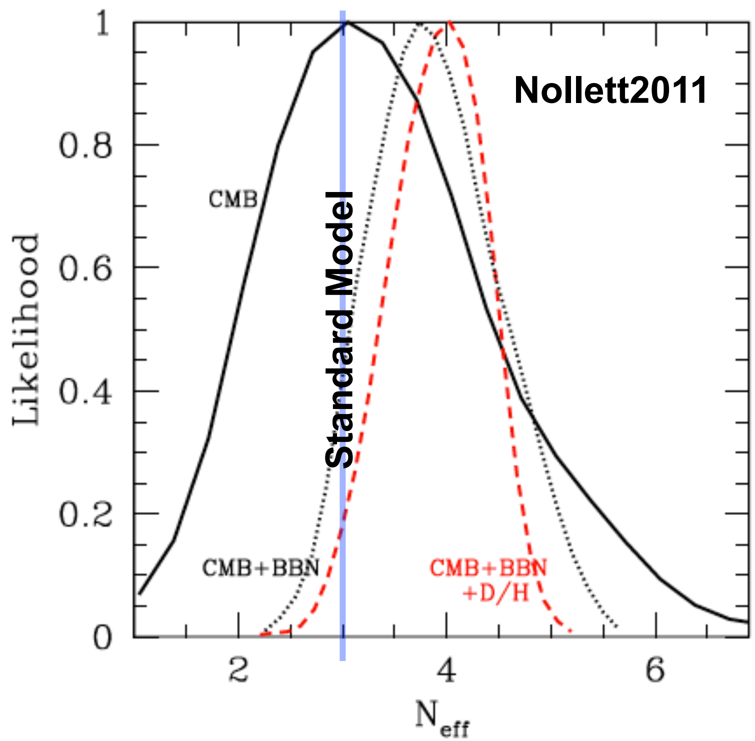
$$\eta_{10} = 273.9\times\Omega_{b,0}\,h^2$$

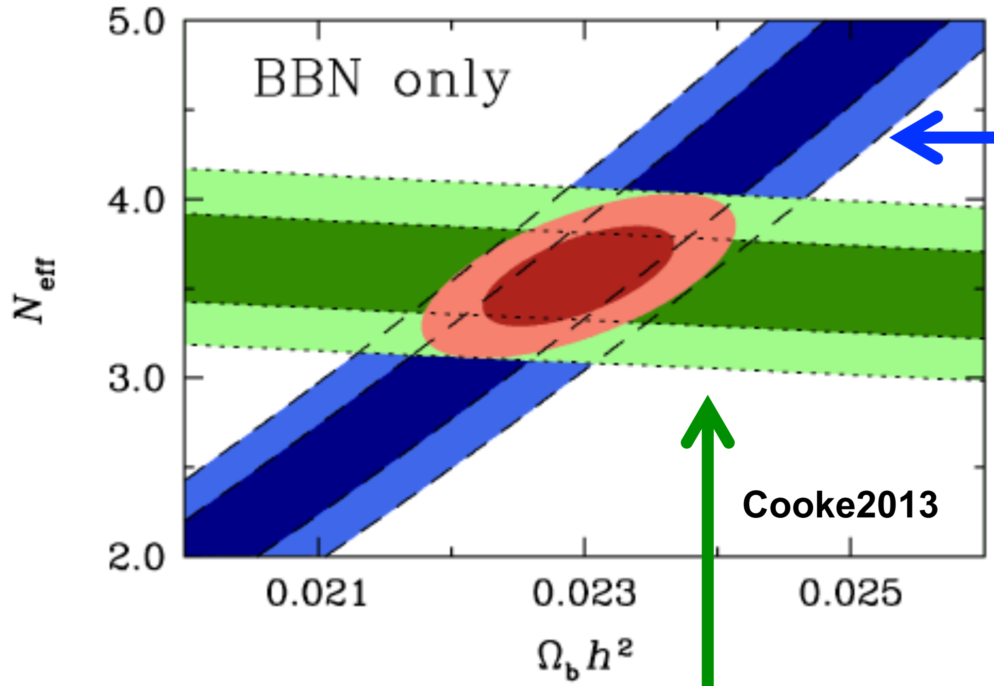


N_{eff}= number of actice neutrino species (or any other relativistic species)
ξ=neutrino degeneracy (matter/antimatter asymmetry)

in the Standard Model: N_{eff}=3.046, ξ=0

BBN and neutrinos





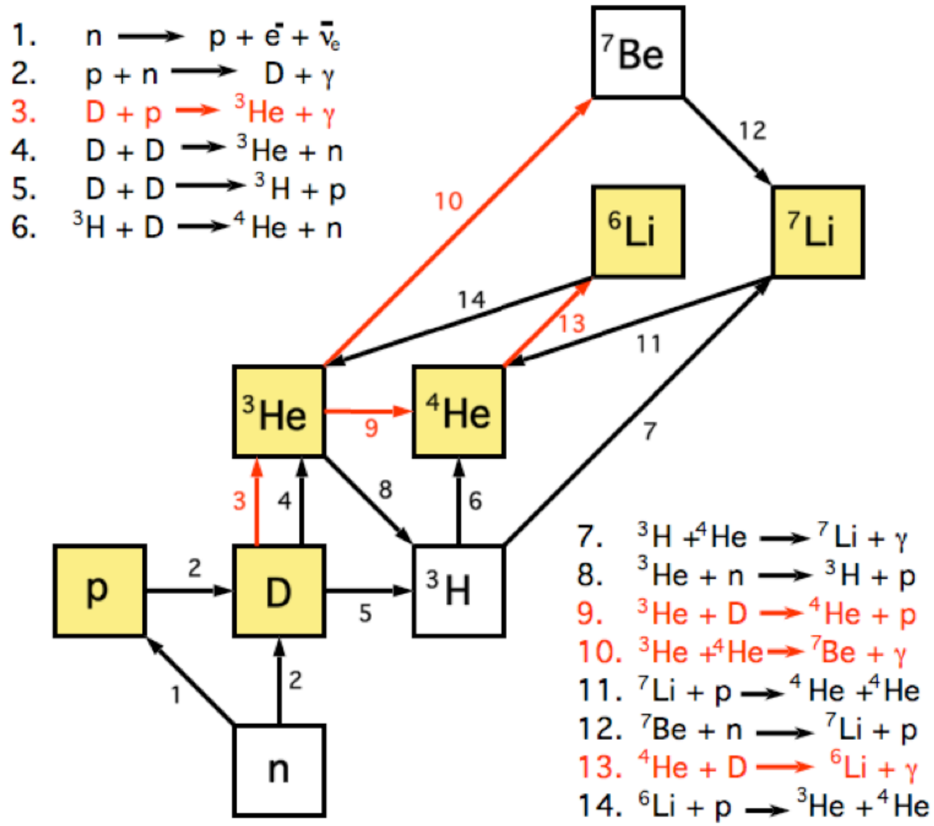
Y_p error band mainly due to systematics of direct observations.
D/H error band is mainly due to the $D(p,\gamma)^3He$ reaction.

Although the existence of a "dark radiation" is somewhat favoured by BBN, the data are also consistent with no extra-relativistic species, within 95% confidence. But accuracy of BBN (as well as CMB results) is rapidly improving…

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

rate	$\delta\sigma^2_{^2H^2H}/\sigma^2_{^2H^2H}(\%)$
$dp\gamma$	49
ddn	37
ddp	14

From Serpico2004



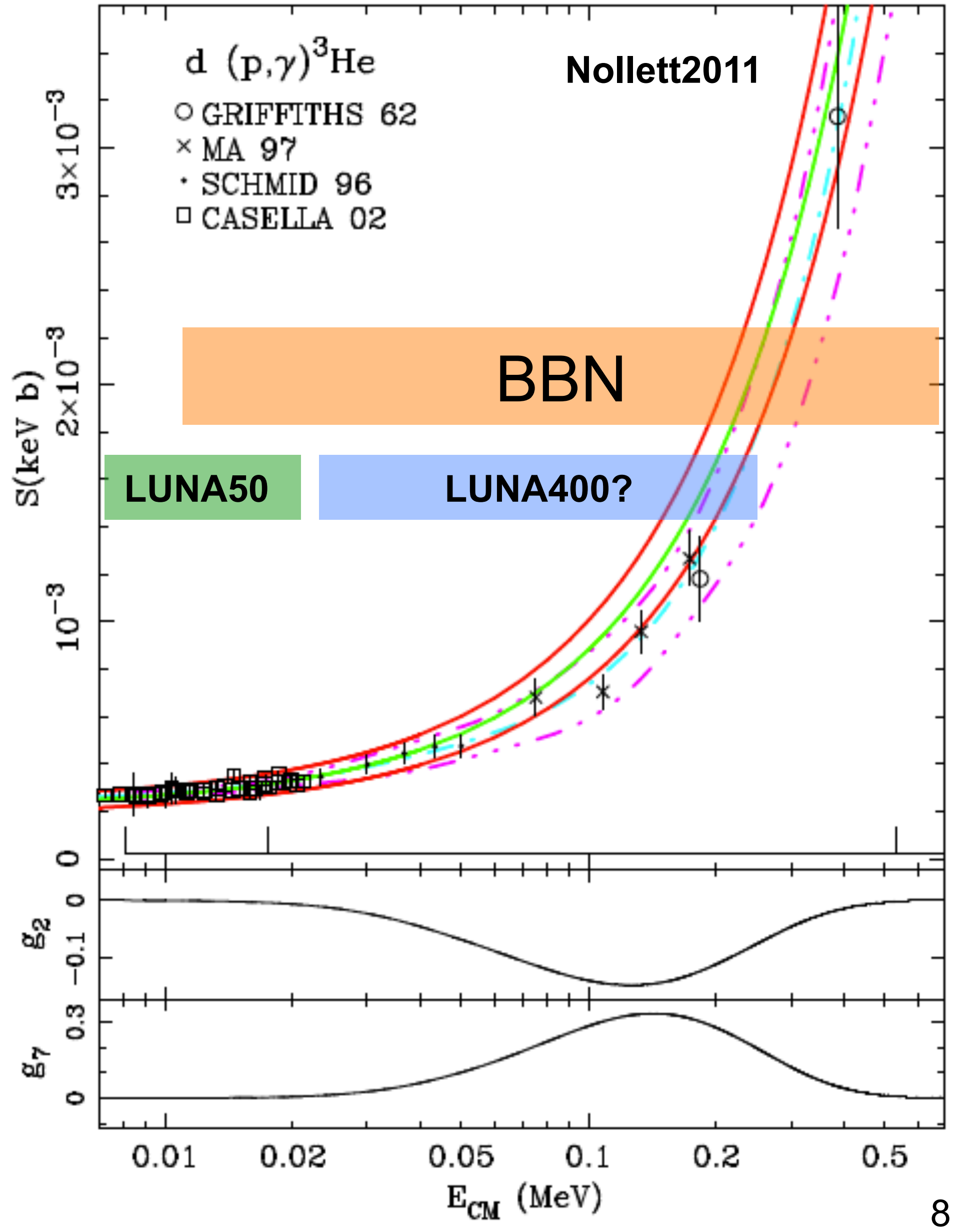
N.B. The tables do not include the Leonard2006 mesurement, in which the accuracy of $D(d,n)^3He$ and $D(d,p)^3H$ reactions was improved by a factor 3, with respect to Serpico2004.

→Presently, the error budget is dominated by the $D(p,\gamma)^3He$ reaction.

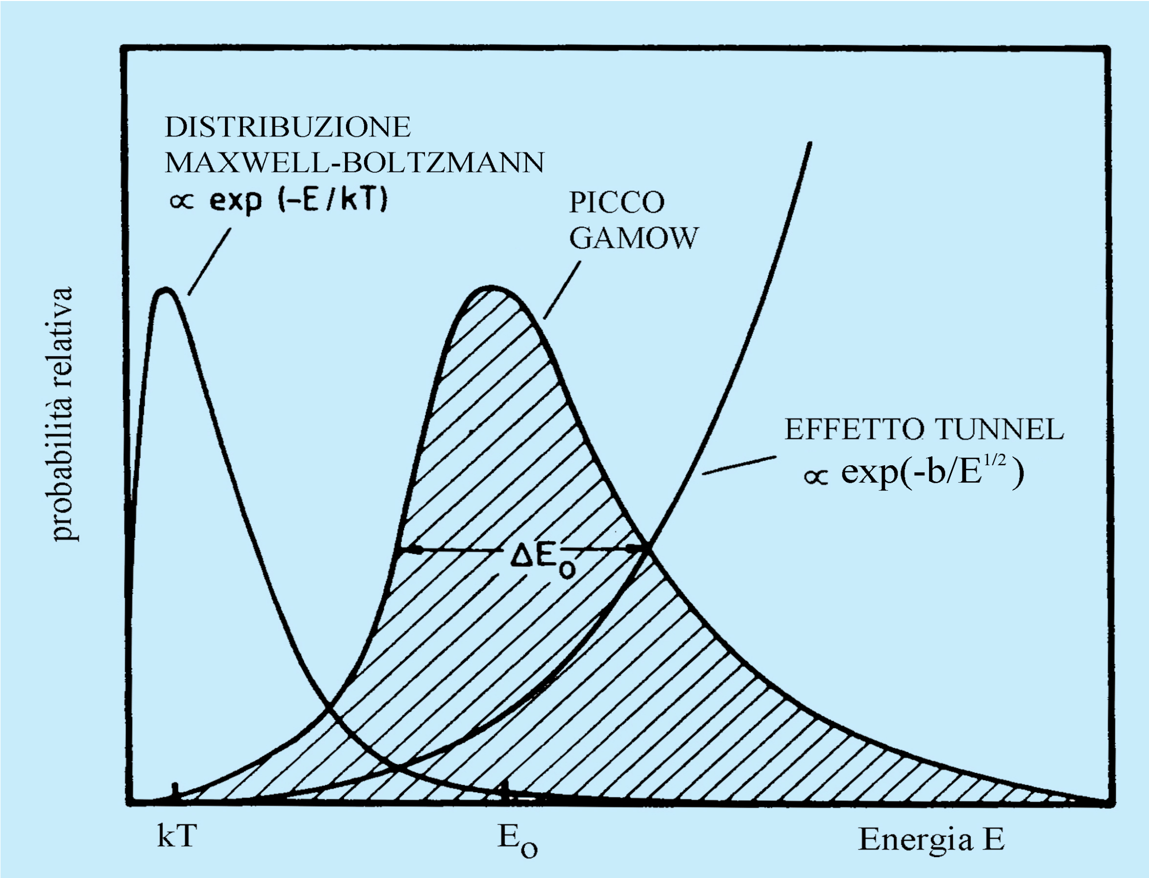
Deuterium abundance and the $D(p,\gamma)^3He$ reaction

The present data have a (claimed) systematic error of 9%. However they show tension with theory (the error bar in the figure are of 2 σs).

A renewed measurement of the $D(p,\gamma)^3He$ at the BBN energy range with a percent accuracy is mandatory. The best is to use an Underground accelerator. LUNA 400 kV at LNGS is well suited to do do it ($20<E_{cm}(keV)<260$). The present data have a claimed systematic error of 9%, showing some tension with theory (the error bar in the plot are of 2 σs).



Nuclear Astrophysics



Astrophysical Factor

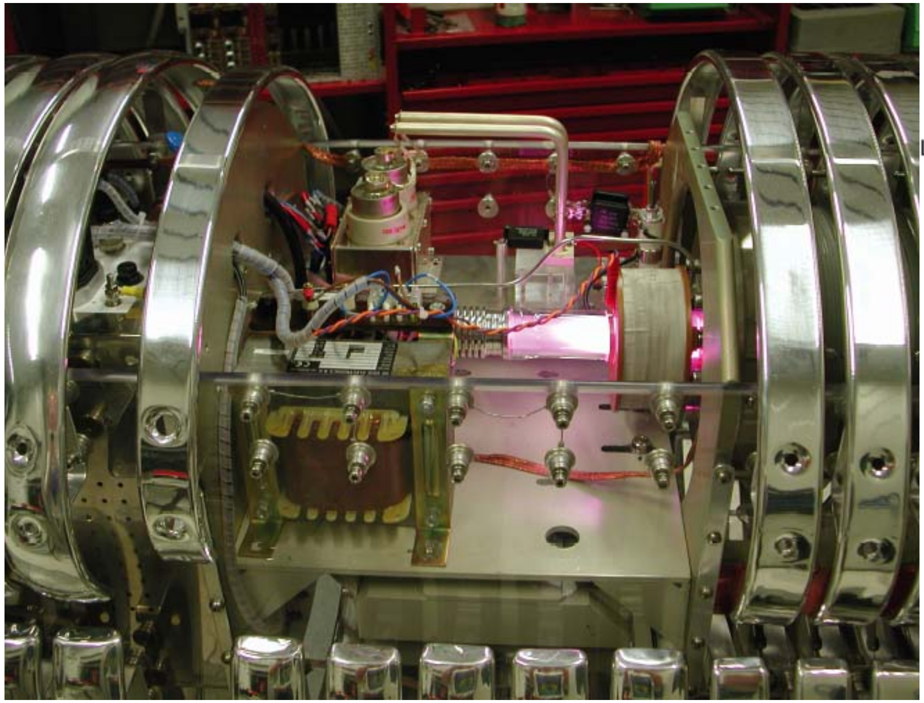
Coulomb Barrier

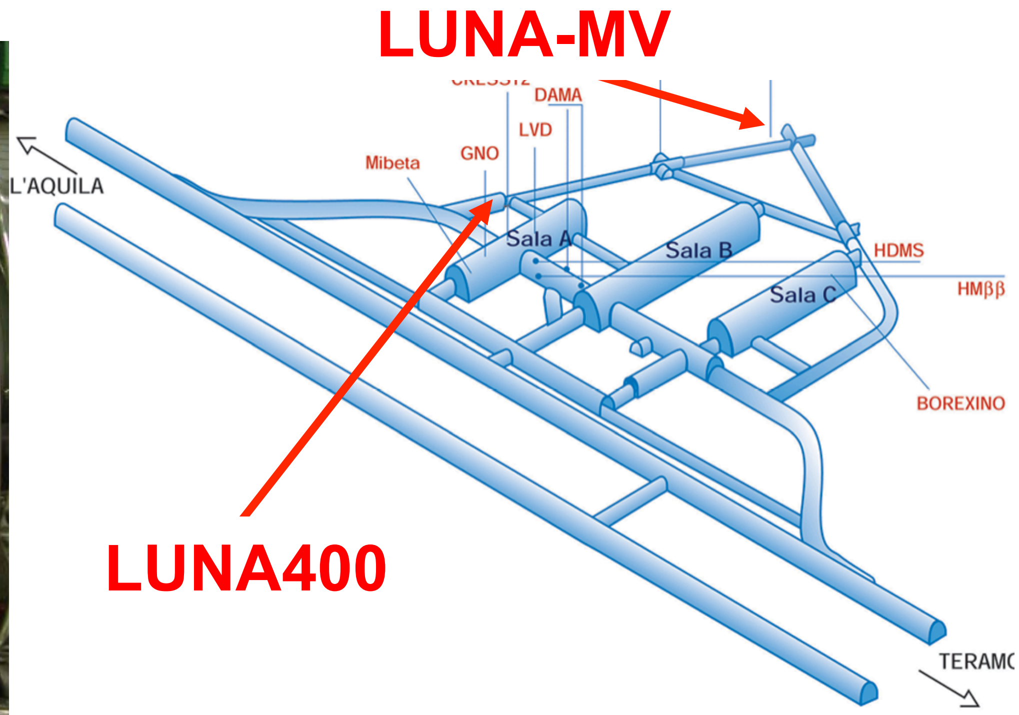
$$\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}$$

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

The LUNA accelerator

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.





Background reduction at LUNA400 with respect to Earth's surface:

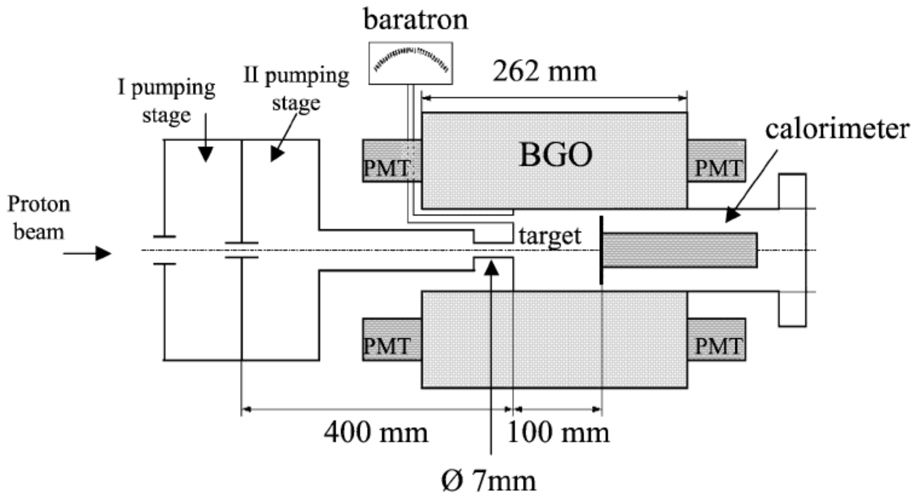
- **μ: 10^{-6}**
- **neutrons: 10^{-3}**
- **γ: 10^{-2}-10^{-5}**

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

An accurate measurement with LUNA 400 is highly desirable.

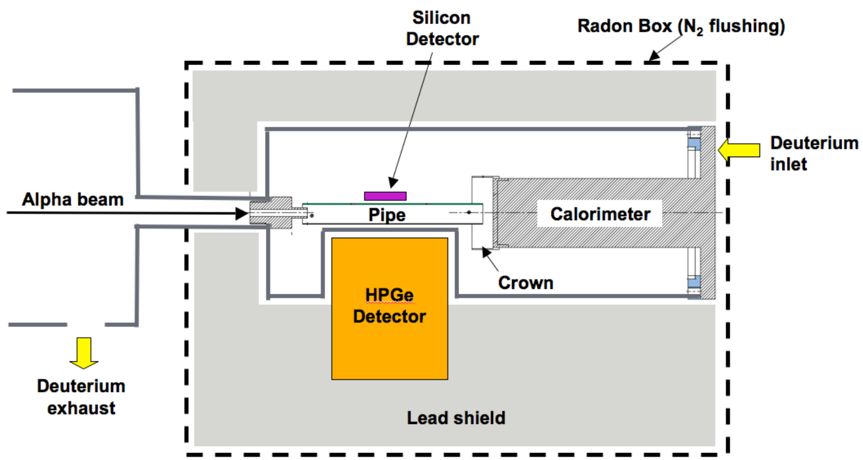
First step: 4π BGO detector

Accurate Total cross section Vs Energy (30<E_{cm}keV<266)



Second Step: Ge(Li) detector

Study of nuclear effects exploiting the energy shape of D(p,γ)^{3}He γ-rays.



Same accuracy (at least) of Casella2002 is expected (factor 3 improvement).

The Lithium problem(s)

Lithium observations

•^{7}Li primordial abundance: observation of the absorption lines at the surface of metal-poor stars in the halo of our Galaxy

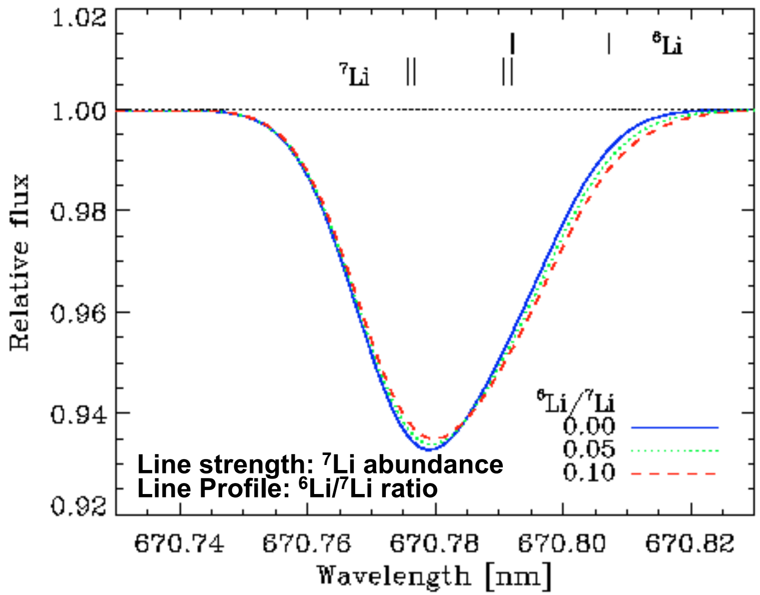
•^{6}Li abundance : observation of the asymmetry of the ^{7}Li absorption lines.

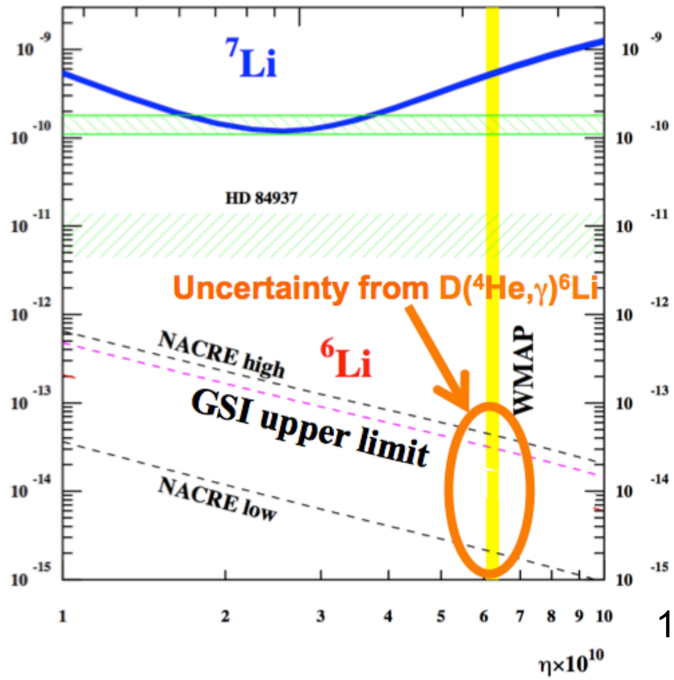
Observed ^{7}Li abundance is ~3 times lower than foreseen: Well established "^{7}Li problem".

Observed ^{6}Li abundance orders of magnitude higher than expected (Asplund2006). However the "Second Lithium problem" is debated, because:

1) convective motions on the stellar surface can give an asymmetry of the absorption line, mimicking the presence of ^{6}Li.

2) The BBN prediction for ^{6}Li is affected by a very large error, due to the poor knowledge of the D(^{4}He,γ)^{6}Li reaction





The D(α, γ)^{6}Li reaction

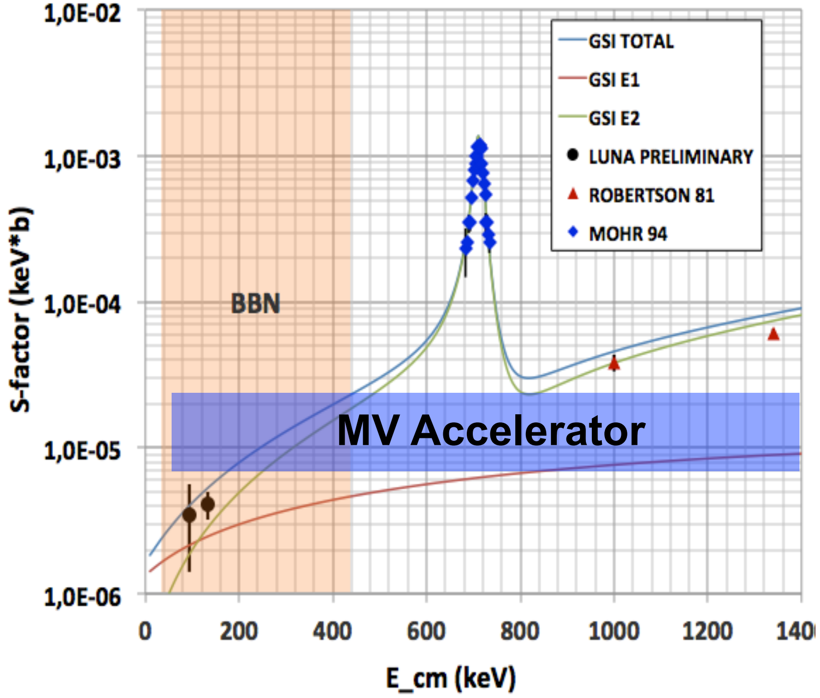
The ^{6}Li abundance in metal-poor stars is very large (Asplund2006) compared to BBN predictions. The possible reasons are:

•Systematics in the ^{6}Li observation in the metal-poor stars

•Unknown ^{6}Li sources older than the birth of the galaxy

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

•…Lack of the knowledge of the D(^{4}He,γ)^{6}Li reactions



IN FACT:

NO DIRECT MEASUREMENTS in the BBN energy region in literature (large uncertainty due to extrapolation)

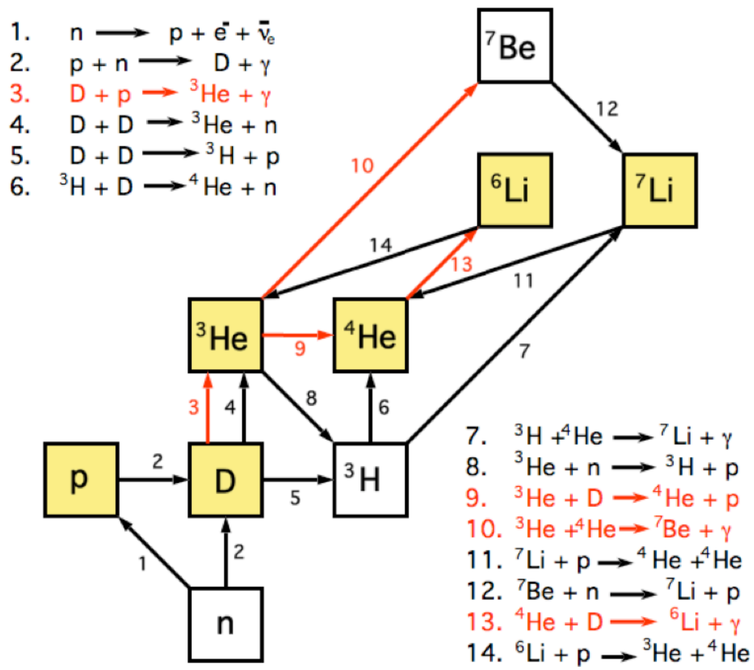
INDIRECT coulomb dissociation measurements (Kiener91, Hammache2010) are not reliable because the nuclear part is dominant, and give only upper limits.

VERY RECENTLY, LUNA showed the first direct measurement of the D(α,γ)^{6}Li reaction at BBN energy, showing that DIRECT MEASUREMENTs are feasible, if performed underground. A future underground accelerator operating in the MeV region will allow a detailed study of this reaction in a wide energy range, thus providing a solid (i.e. direct) experimental footing to calculate the primordial ^{6}Li abundance.

Conclusions

-^{4}He and D abundances are sensitive to N_{eff} and lepton degeneracy.

-The disagreement between observed and computed abundances of ^{6}Li and ^{7}Li, "the Lithium Problems" may be a hint for new physics (e.g. sparticles).



-Presently, we are in the "Precision Era" of Cosmology. BBN parameters, such as Ω_b, Y_p, $(D/H)_p$, $(^7Li/H)_p$, $(^6Li/H)_p$ are known with high (and increasing) precision.

-Concerning Nuclear astrophysics, it is convenient (if not mandatory) to perform accurate measurements Underground, with present (LUNA) or future accelerator.

-Of crucial importance are the $D(p,\gamma)^3He$ reaction and $D(\alpha,\gamma)^6Li$ reactions, to calculate the D and ^{6}Li abundance, respectively.

-Desirable (but not so urgent) is the study of the $D(^3He,p)^4He$ (for the ^{3}He abundance), and $^3He(^4He,\gamma)^7Be$ (for the ^{7}Li abundance) reactions, again by using of underground facilities.