Status of Big Bang Nucleosynthesis

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Introduction

Big Bang Nucleosynthesis (BBN) is one of the solid pillars of the Standard Cosmological model:

✓ BBN predicts the primordial abundances of light elements (^{4}He, D, ^{3}He, ^{7}Li).

✓ Predictions span 9 orders of magnitude.
Good (reasonable) agreement with observational data.

Theory: well defined, very precise

Observations: two problems
- systematics
- evolutionary effects

The Physics of BBN

The abundances of ^{4}He, D, ^{3}He, ^{7}Li produced by BBN depends on the following quantities:

Deuterium bottleneck $T_N \approx -\frac{B_d}{\ln(\eta)} \approx 0.1\text{ MeV}$

- Baryon density

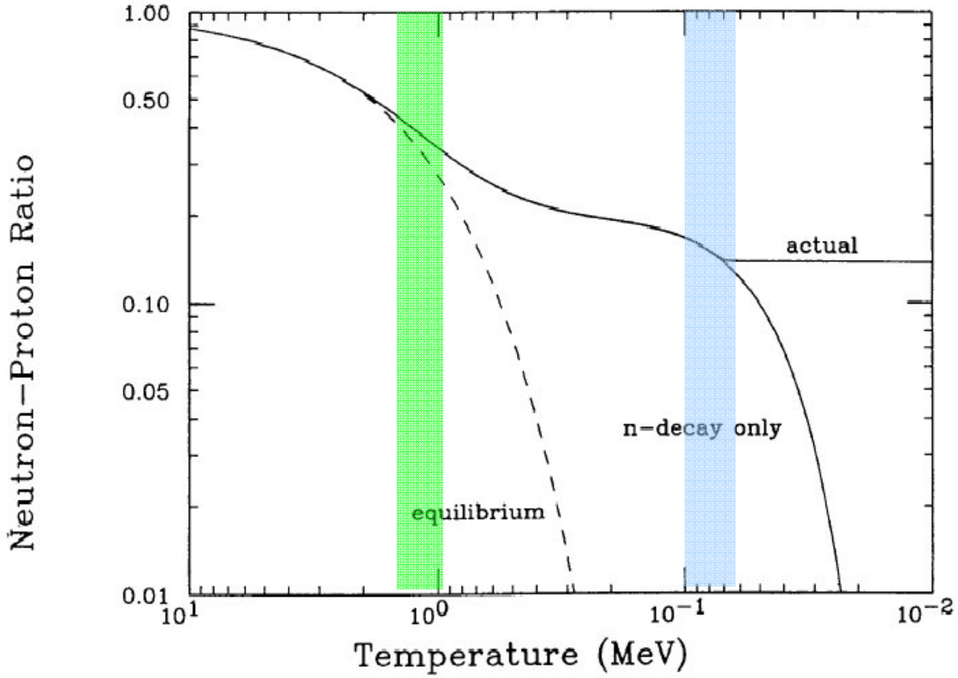
$$\eta \equiv \frac{n_B}{n_\gamma} \qquad \Omega_B h^2 \approx 3.7\;10^7\,\eta$$

- Hubble expansion rate

$$H \approx g_*^{1/2}\, G_N^{1/2}\, T^2$$

$$g_* = 10.75 + \frac{7}{4}(N_\nu - 3)$$

Γ_W = Weak rate (ν_e +n ←→ p+e)



$H/\Gamma_W = 1$ → Weak interaction freeze-out $T_W \approx 1\text{ MeV}\cdot(g_*/10.75)^{1/6}$

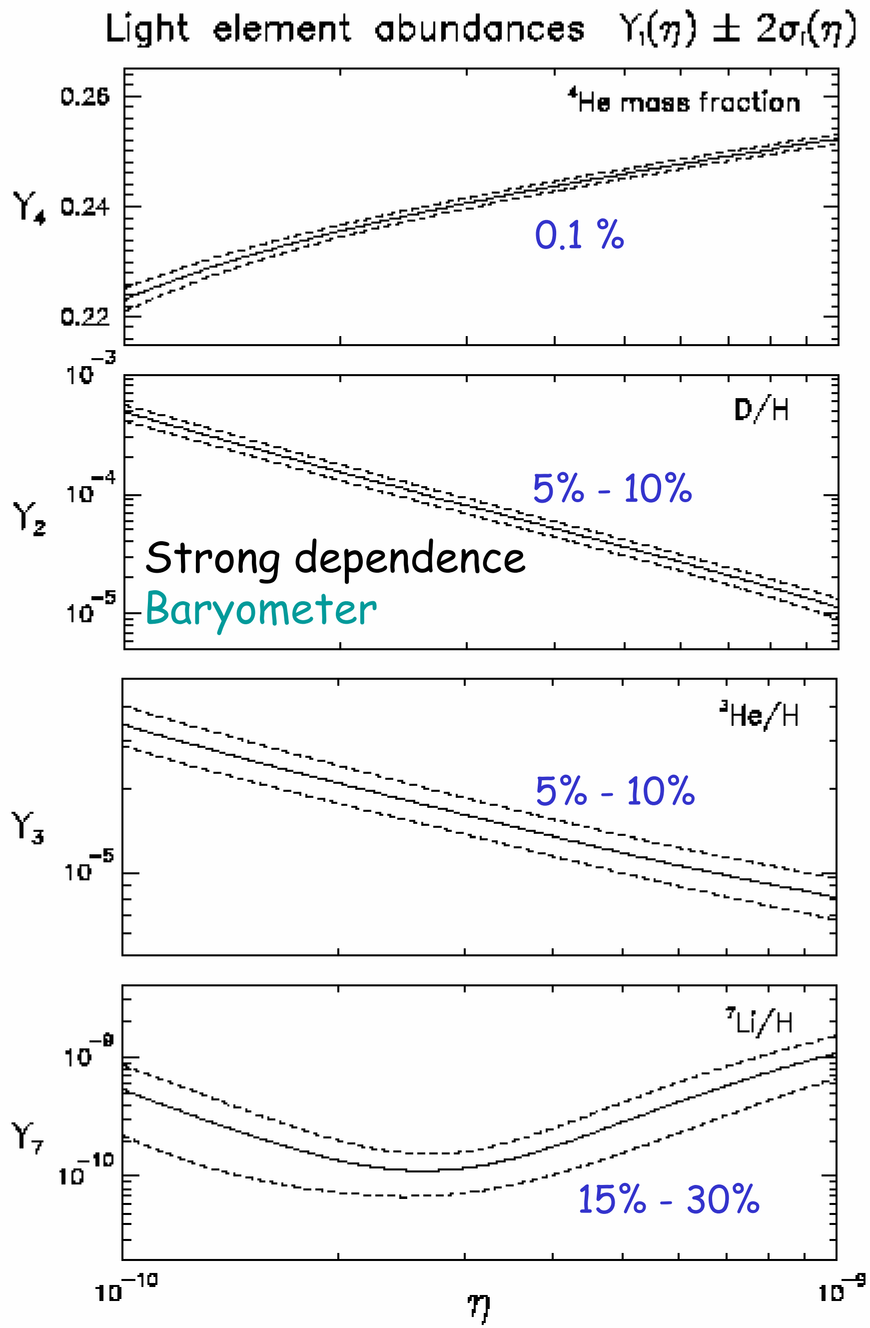
- Essentially all neutrons surviving till the onset of BBN used to build ^{4}He
- D, ^{3}He, ^{7}Li are determined by a complex nuclear reaction network.

Accuracy of theoretical calculations

Accuracy of ^4He calculation at the level of 0.1%.

High precision codes (Lopez & Turner 1999, Esposito et al. 1999) take directly into account effects due to :
- zero and finite temperature radiative processes;
- non equilibrium neutrino heating during e± annihilation;
- finite nucleon masses;
- ....

These effects are included "a posteriori" in the "standard" code (Wagoner 1973, Kawano 1992).



Theoretical uncertainties

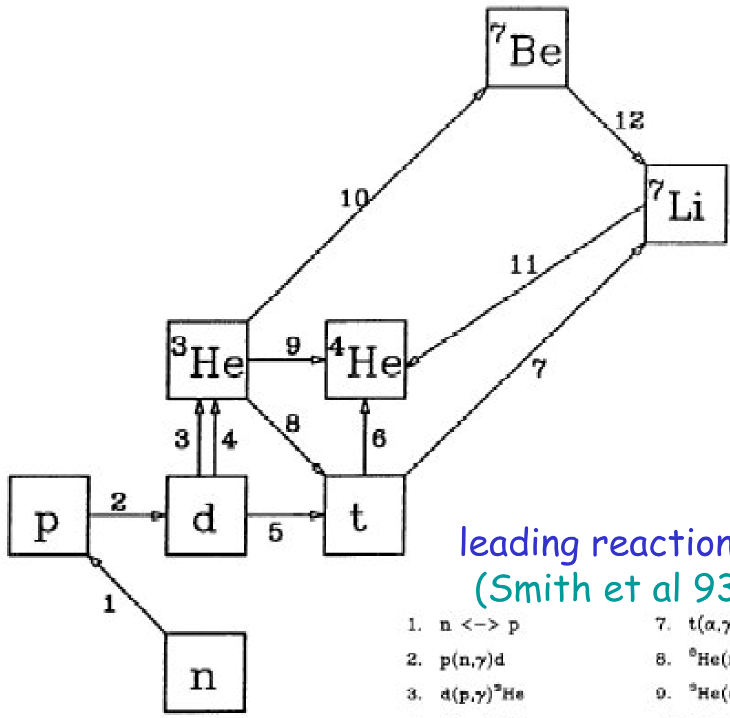
Reaction rate uncertainties translate into uncertainties in theoretical predictions:

Monte-Carlo evaluation of uncertainties
Krauss & Romanelli 90,
Smith et al 93,
Kernan & Krauss 94

Semi-analytical evaluation of the error matrix
Fiorentini et al 98
Lisi et al. 00

Re-analysis of nuclear data
Nollet & Burles 00, Cyburt et al 01,
Descouvement et al. 04, Cyburt et al. 04,
Serpico et al. 04

Recent new data and compilations
NACRE Coll. Database
LUNA: $D(p,\gamma)^3He$, $^3He(a,\gamma)^7Be$



leading reactions
(Smith et al 93)

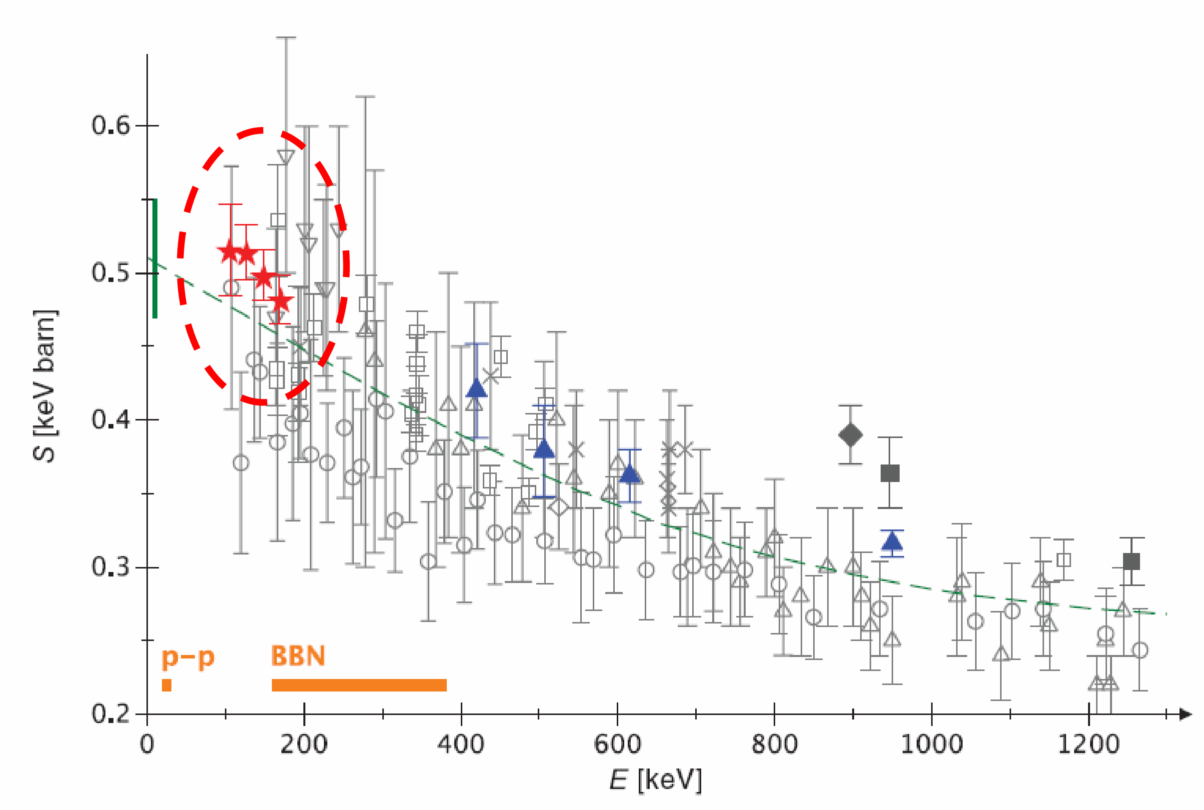
1. $n \leftrightarrow p$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3He$
4. $d(d,n)^3He$
5. $d(d,p)t$
6. $t(d,n)^4He$
7. $t(\alpha,\gamma)^7Li$
8. $^3He(n,p)t$
9. $^3He(d,p)^4He$
10. $^3He(\alpha,\gamma)^7Be$
11. $^7Li(p,\alpha)^4He$
12. $^7Be(n,p)^7Li$

Sub-leading reactions
(see Serpico et al. 04)

Recent LUNA results

- ^{7}Li is the decay product of ^{7}Be;
- At high η ^{7}Be is mainly produced by:

$^3He + ^4He \rightarrow ^7Be + \gamma$



Nuclear cross sections and BBN abundances

Based on Fiorentini et al, 1998

Relative errors on σ and their relative contribution to the theoretical uncertainty on BBN abundances

Inputs can be taken from different analysis of nuclear data

k	Reaction	Des04 dR/R
1	n lifetime	0,0009
2	p(n,g)d	0,040
3	d(p,g)3He	0,050
4	d(d,n)3He	0,030
5	d(d,p)t	0,020
6	t(d,n)4He	0,020
7	t(a,g)7Li	0,040
8	3He(n,p)t	0,015
9	3He(d,p)4He	0,040
10	3He(a,g)7Be	0,080
11	7Li(p,a)4He	0,060
12	7Be(n,p)7Li	0,007

Contributo all'errore totale ($\Delta Y_k / \Delta Y$)

He4	D	Li	He3
0,92	0,01	0,00	0,00
0,27	0,29	0,51	0,10
0,00	0,64	0,28	0,54
0,25	0,61	0,19	0,15
0,14	0,35	0,01	0,14
0,00	0,00	0,00	0,00
0,00	0,00	0,01	0,00
0,00	0,01	0,04	0,07
0,00	0,02	0,28	0,81
0,00	0,00	0,73	0,00
0,00	0,00	0,02	0,00
0,00	0,00	0,05	0,00

Errore Teorico Percentuale ΔY (%)

He4	D	Li	He3
0,07	2,6	10,7	3,7

k	Reaction	SKM93	Cyburt01	Des04	Cyburt04
1	n lifetime				
2	p(n,g)d	0,07	0,0445	0,0400	0,0250
3	d(p,g)3He	0,10	0,1320	0,0500	0,0698
4	d(d,n)3He	0,10	0,0310	0,0300	0,0545
5	d(d,p)t	0,10	0,0159	0,0200	0,0693
6	t(d,n)4He	0,08	0,0401	0,0200	0,0516
7	t(a,g)7Li	0,26	0,0421	0,0400	0,2313
8	3He(n,p)t	0,10	0,0352	0,0150	0,0440
9	3He(d,p)4He	0,08	0,0915	0,0400	0,0730
10	3He(a,g)7Be	0,16	0,1060	0,0800	0,1692
11	7Li(p,a)4He	0,08	0,1140	0,0600	0,0802
12	7Be(n,p)7Li	0,09	0,0387	0,0070	0,0625

Summarizing …
Theoretical uncertainties at the level of:

^{4}He	0.1% - 0.2%
D	5% - 10%
^{3}He	5% - 10%
^{7}Li	15% - 30%

depending on the analysis of nuclear data.

See also: Serpico et al. 04 - Sub-leading reactions contributions to uncertainties

Observations

Observations: deuterium

Deuterium = baryometer

No astrophysical sources of deuterium → Any D/H measurement provide a lower limit for $(D/H)_p$. → Upper limit for η.

Local ISM value for D/H : $(1.5 \pm 0.1) * 10^5$ Linsky et al. 1998

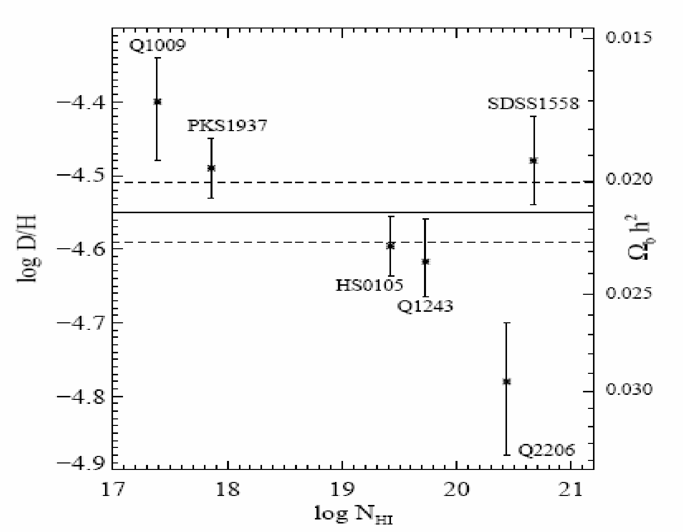
In recent years, deuterium has been observed in the high resolution spectra of QSO absorption systems at high redshift:

Lyman Limit systems (LLS):
Neutral hydrogen clouds with column density $N(HI) > 10^{17}$ cm^{-2}

Damped Lyman α systems (DLA):
Neutral hydrogen clouds with column density $N(HI) > 10^{20}$ cm^{-2}
Possible advantages: more precise H abundance, metallicity more accurate, "interloper" less probable.

Note: D isotope shift = -82 km/s → Clouds with simple velocity structure are needed.

Observations: deuterium



$(D/H) = (1.5 \pm 0.1) * 10^{-5}$ Local ISM Linsky et al. 1998

	$(20 \pm 5) * 10^{-5}$	*z=0.701*	*Webb et al.*	*1997*	*LLS*	
	$(3.98 \pm 0.65) * 10^{-5}$	z=2.504	O'Meara et al.	2001	LLS	*
	$(3.25 \pm 0.3) * 10^{-5}$	z=3.572	O'Meara et al.	2001	LLS	*
(D/H) =	$(2.54 \pm 0.23) * 10^{-5}$	z=2.356	O'Meara et al.	2001	DLA	*
	$(1.65 \pm 0.35) * 10^{-5}$	z=2.701	Pettini, Bowen	2001	DLA	*
	$(2.24 \pm 0.67) * 10^{-5}$	z=3.025	D'Odorico et al.	2001	DLA	
	$(3.75 \pm 0.25) * 10^{-5}$	z=3.025	Levshakov et al.	2001	DLA	
	$(2.42 \pm 0.35) * 10^{-5}$	z=2.526	Kirkman et al.	2003	DLA	*
	$(1.60 \pm 0.28) * 10^{-5}$	z=2.703	Crighton et al.	2004	LLS	
	$(3.34 \pm 0.46) * 10^{-5}$	z=2.703	O'Meara et al.	2006	DLA	*

"Average" value – $(D/H) = (2.83 \pm 0.26) * 10^{-5}$ O'Meara et al. 2006

$\Omega_B h^2 = 0.0213 \pm 0.0013$ (obs.) ± 0.0004 (nuc.)

$(\Omega_B h^2)_{CMB} = 0.0223 \pm 0.0008$

Observations: Helium-4

Y_p is determined by extrapolating to Z=0 the (Y,Z) relation or by averaging Y in extremely metal poor objects (N and O used as metallicity tracers).
In particular:

- ✓ ^{4}He is observed in clouds of ionized hydrogen (HII regions).
- ✓ The most metal poor HII regions are in Dwarf Blue Compact Galaxies (BCGs).

Present situation:

- ✓ Individual determinations of Y_p at the level of 1%
- ✓ Disagreement at the level of 1-2%
- ✓ Several physical mechanism acting in HII regions still not completely understood (ionization correction factor, underlying stellar absorption, temperature structure …).

Observations: Helium-4

0.244 ± 0.002	Izotov et al. 1998	Regression using 45 BCGs – O/H
0.245 ± 0.001		N/H
Y_p = 0.235 ± 0.003	Olive et al. 1997	Regression using 62 BCGs
0.238 ± 0.002	Fields and Olive 1998	Re-analysis (update) of Olive et al. 1997
0.2345 ± 0.0026	Peimbert et al 2000	HII regions of the Small Magellanic Cloud
0.2384 ± 0.0025	Peimbert et al 2001	Average of the 5 most metal poor BCGs
0.239 ± 0.002	Luridiana et al 2003	5 metal poor HII regions

0.249 ± 0.009	Olive et al. 2004	Re-analysis of a subsample of Izotov et al. 1998
0.2472 ± 0.0012	Izotov et al. 2007	Regression using 86 extra-galactic HII regions
0.2516 ± 0.0011		
0.2474 ± 0.0028	Peimbert et al 2007	5 metal poor extra-galactic HII regions

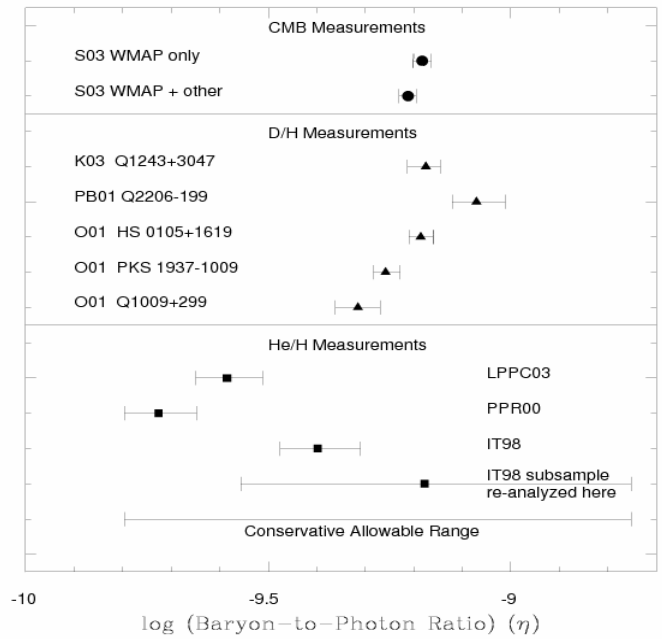
Y_p = 0.249 ± 0.009 (syst)   Fields & Sarkar - PDG 2006

N_ν^{eff} = 3.1 ± 1.3   (95% C.L.)   BBN

N_ν^{eff} = 5.2 ± 2.4   (95% C.L.)   CMB + LSS

Slight tension (2σ) between the relativistic content at early (BBN) and late (CMB+LSS) epochs.

See: Mangano et al. 2007, Seljak et al. 2006



Observations: Lithium-7 and Helium-3

Lithium-7

Observations in metal poor stars in the Halo of our galaxy ($Z \sim 10^{-4} - 10^{-5} Z_o$)

Spite plateau: Li abundance does not vary significantly for $Z < 1/30\ Z_o$:

	$(1.23 \pm 0.06)\ 10^{-10}$	Ryan et al. 00
$^7Li/H =$	$(2.19 \pm 0.28)\ 10^{-10}$	Bonifacio et al. 02
	$(2.34 \pm 0.06)\ 10^{-10}$	Melendez et al. 04

$^7Li/H = \quad (1.7 \pm 0.02\ ^{+1.1}_{-0})\ 10^{-10}$ Field e Sarkar – PDG06

SBBN ($N_\nu^{eff}=3$) and CMB data would require: $^7Li/H \sim 4.5\ 10^{-10}$ (depletion?)

Helium-3

Observations available in Solar System and high metallicity HII regions in our galaxy

Stellar nucleosynthesis models in conflict with observations

Upper bound for primordial abundance: $3He/H < (1.1 \pm 0.2)\ 10^{-5}$ Bania et al. 02

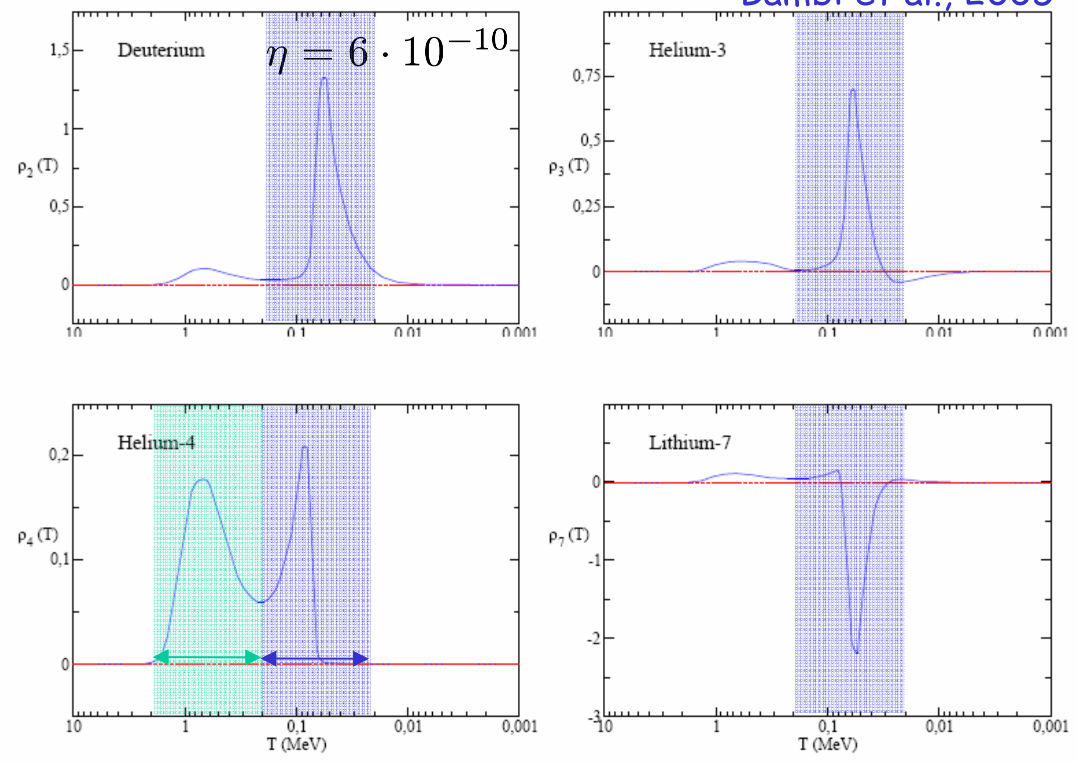
May be relevant for N_ν^{eff} (Mangano et al. 07).

BBN as a probe of the early Universe

$$\delta Y_i(\eta, \delta H(T)) = 2 \int \varrho_i(\eta, T)\, \delta H(T)\, \frac{dT}{T}$$

$\delta H(T) \equiv$ variation of Universe exp. rate

Bambi et al., 2005



BBN is sensitive to a variety of non standard effects:

- Variations of "fundamental" constants;
- new light particles;
- ν_e and $\nu_{\mu\tau}$ degeneracy;
- Active-Sterile neutrino oscillations;
- …

T ~ 1 MeV - Hubble/Weak rate

$$\frac{H}{\Gamma_{\rm W}} \sim \frac{\sqrt{g_* G_{\rm N}}\, T^2}{G_{\rm F}^2 T^5}$$

T~ 0.1 MeV Hubble/Nuclear rate

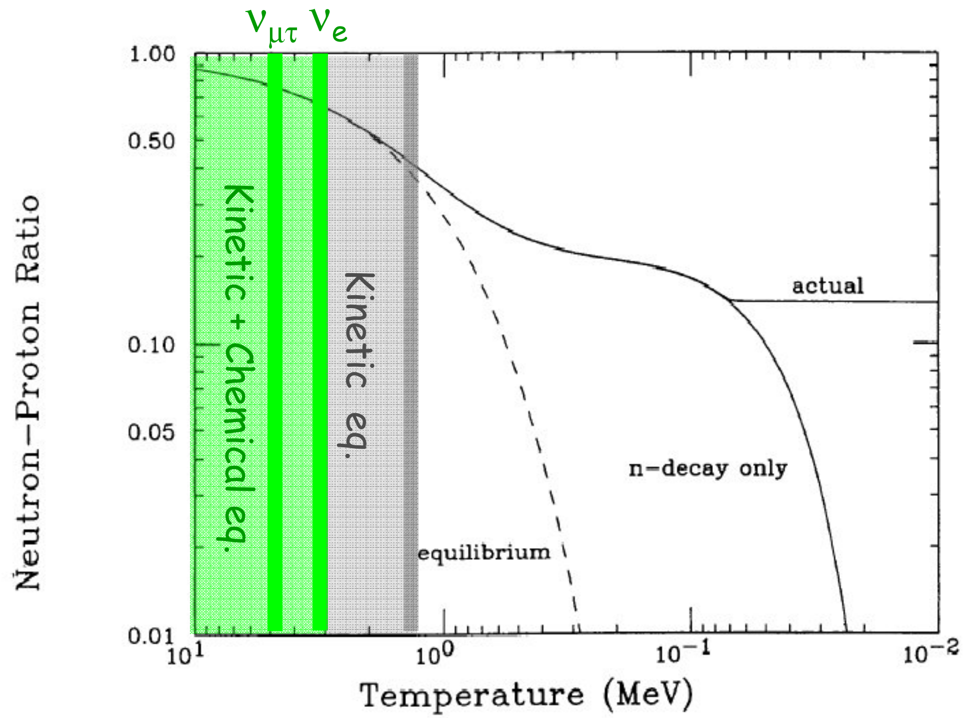
$$\frac{H}{\Gamma_{\rm nuc}} \propto \frac{\sqrt{g_* G_{\rm N}}\, T^2}{\eta n_\gamma \langle \sigma v \rangle}$$

Active-sterile ν-oscillations

Kinetic + chemical equilibrium
Ann./creat. neutrino reactions
$\nu\nu \leftrightarrow \ell\ell$

Kinetic equilibrium
Elastic scattering
$\nu \ell \leftrightarrow \nu \ell$

ν_{act} - ν_s oscillations before chemical decoupling → ν_s brought into equilibrium
→ boost the Universe exp. rate



ν_e - ν_s oscillations after chemical decoupling → ν_e number density reduction
→ affect n/p interconversion rate.

Energy density increase

$$\Delta N_\nu^{\rm BBN} = \frac{4}{7}\left[\frac{10.75 + (7/4)\Delta N_\nu}{((1+n_e)/2)^2} - 10.75\right]$$

ν_e depletion

ν_e - ν_s oscillations after kinetic decoupling → ν_e spectral distorsion
→ affect n/p interconversion rate.

See Dolgov 03 for a recent review and for references

Neutrino oscillations: 3 active + 1 sterile

Active neutrinos are now known to be mixed.
Their mixing should be taken into account together with $\nu_{act} - \nu_s$ mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} & U_{ACT} & & \eta_1 \\ & & & \eta_2 \\ & & & \eta_3 \\ \varepsilon_1 & \varepsilon_2 & \varepsilon_3 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$\vec{\eta} = -\overleftrightarrow{U}_{ACT} \cdot \vec{\varepsilon}$$

4 — $(\delta m^2)_{14} =$ variable

3 — $(\delta m^2)_{23} = (\delta m^2)_{atmo}$

2 —
1 — $(\delta m^2)_{12} = (\delta m^2)_{solar}$

ν_s mixing with one flavour eigenstate (e.g. $\eta_1 \neq 0$, $\eta_2, \eta_3 = 0$)
→ three different δm^2 ($\varepsilon_1, \varepsilon_2, \varepsilon_3 \neq 0$), new resonances ....

ν_s mixing with one mass eigenstate (e.g. $\varepsilon_1 \neq 0$, $\varepsilon_2, \varepsilon_3 = 0$)
→ one δm^2, oscillation into mixed flavours ($\eta_1, \eta_2, \eta_3 \neq 0$)

All results in
Dolgov and Villante 2003
See also:
Cirelli et al. 2004

N.B. Mixing among active neutrinos cannot be rotated away, because BBN is flavour sensitive.

Conclusions

Standard BBN:

Very accurate, very precise
Costant progress in the last decade

BBN and AstroParticle:

BBN is a unique window to early universe.
Sensitive to a variety of non-standard effects

- Variations of “fundamental” constants;
- new light particles;
- ν_e and $\nu_{\mu\tau}$ degeneracy;
- Active-Sterile neutrino oscillations;
- ……

Observations:

Progress in (D/H) determination;
Necessary to improve Y_p ($\delta Y_p/Y_p \sim 0.02 \rightarrow \Delta N\nu \sim 1$ at 2σ)
Necessary to understand ^3He and ^7Li