Constraints on Ω_B from Standard Big Bang Nucleosynthesis (SBBN) and CMB observations

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- Determinations of Ω_B (SBBN, CMB)
- Observational data (^{7}Li, D and ^{4}He)
- Nuclear data (recent compilations)
- Comparisons of Ω_B ranges and discussion

Density components of the Universe

A natural reference : the critical density :

$$\rho_C = \frac{3H_0^2}{8\pi G} = 1.88\, h^2 \times 10^{-29}\ \mathrm{g/cm^3} \text{ or } 2.9\, h^2 \times 10^{11}\ M_\odot/\mathrm{Mpc}^3$$

(h=H_0/100 km/s/Mpc h=0.71)

$$\boxed{\Omega \equiv \rho/\rho_C}$$

Some Ω values		
Visible matter	Ω_L	~0.002
Baryons	Ω_b	0.044±0.004
Matter	Ω_m	0.27±0.04
Vacuum	Ω_Λ	0.73±0.04
Total	Ω_T	1.02±0.02

Number of baryons per photon : $\eta \equiv n_b/n_\gamma$ et $\Omega_b h^2 = 3.65\times10^7\, \eta$

Ω_b determination

- Standard Big Bang Nucleosynthesis

Calculated and observed ^4He, D, ^3He, ^7Li primordial abundances
$\Rightarrow \eta$ (or $\Omega_B h^2$)

Need good:

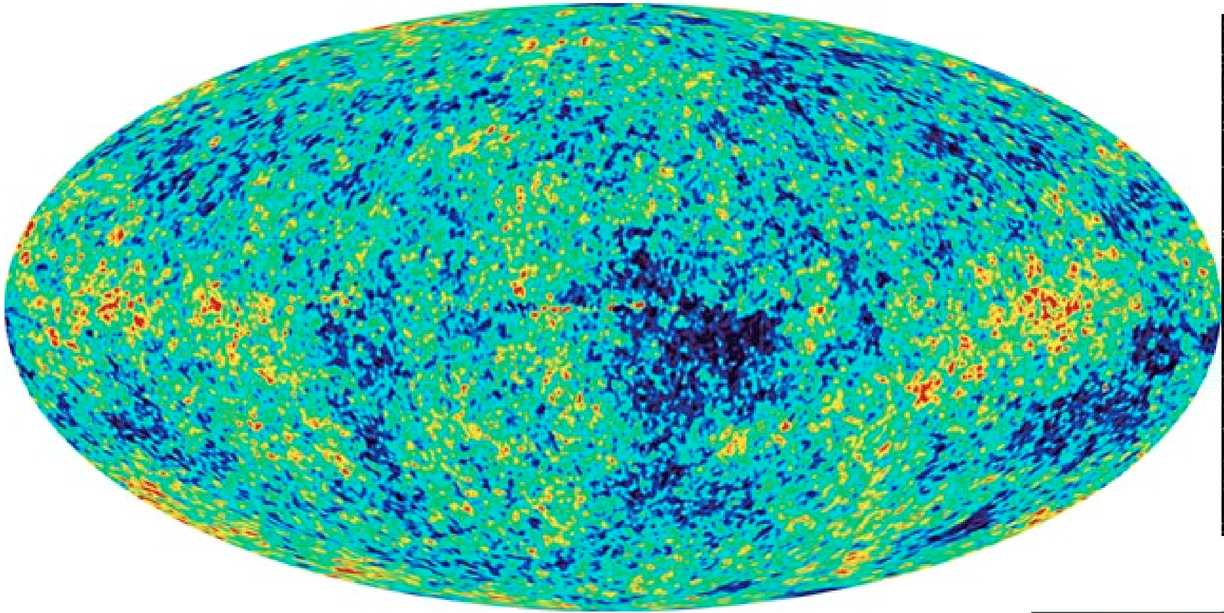
- Observational data
- Nuclear data

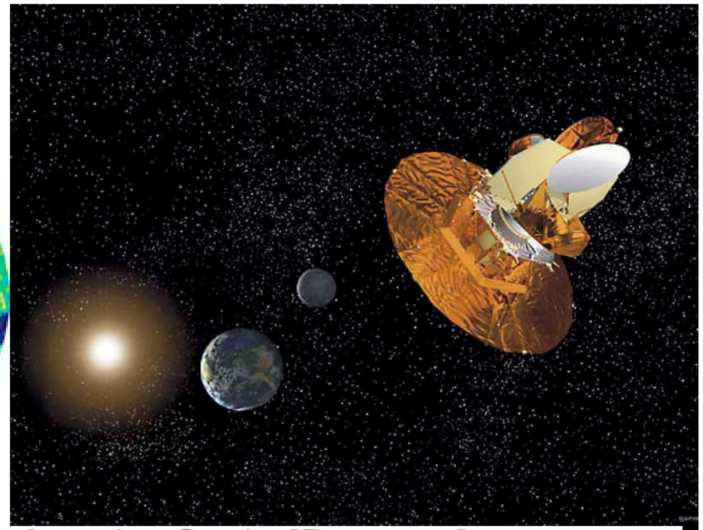
- HI and HeII Lyman-α forest absorption (on the line of sight of quasars)

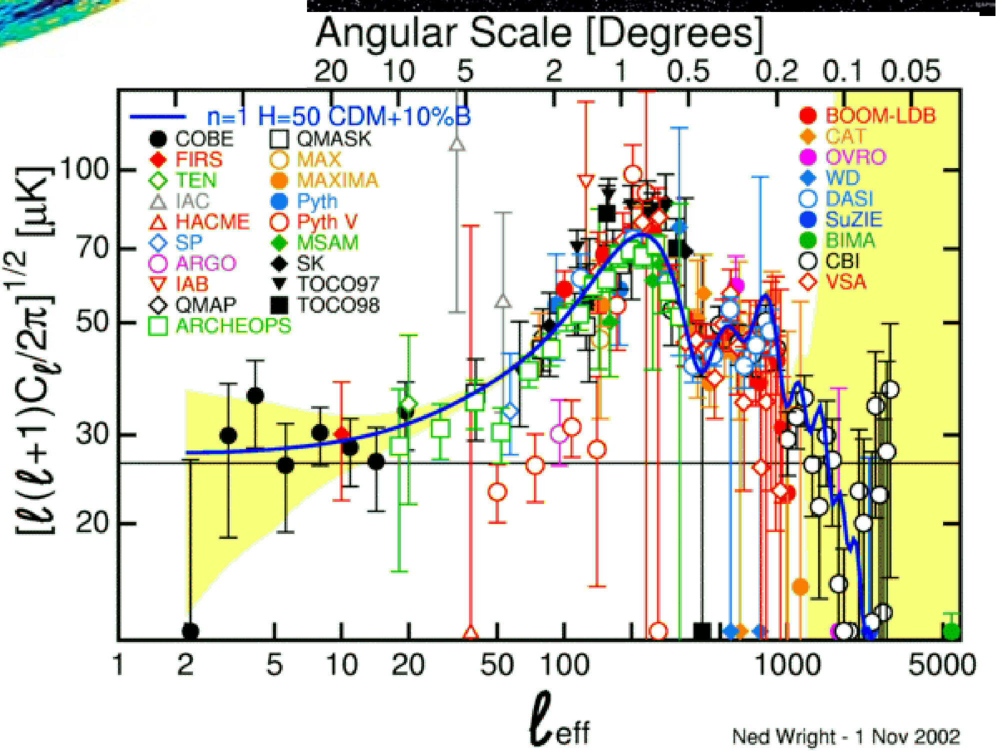
- Anisotropies in the Cosmic Microwave Background radiation

BOOMERanG, CBI, DASI, MAXIMA, ARCHEOPS, WMAP,…..

Anisotropies of the Cosmic Microwave Background (CMB)







At t≈0.3 Ma, and T≈3000 K : recombination, the Universe becomes transparent (presently 2.725 K)

Following COBE, new generations of instruments (BOOMERanG, CBI, DASI, MAXIMA, ARCHEOPS), now WMAP and soon Plank Surveyor are dedicated to the study of CMB anisotropies.

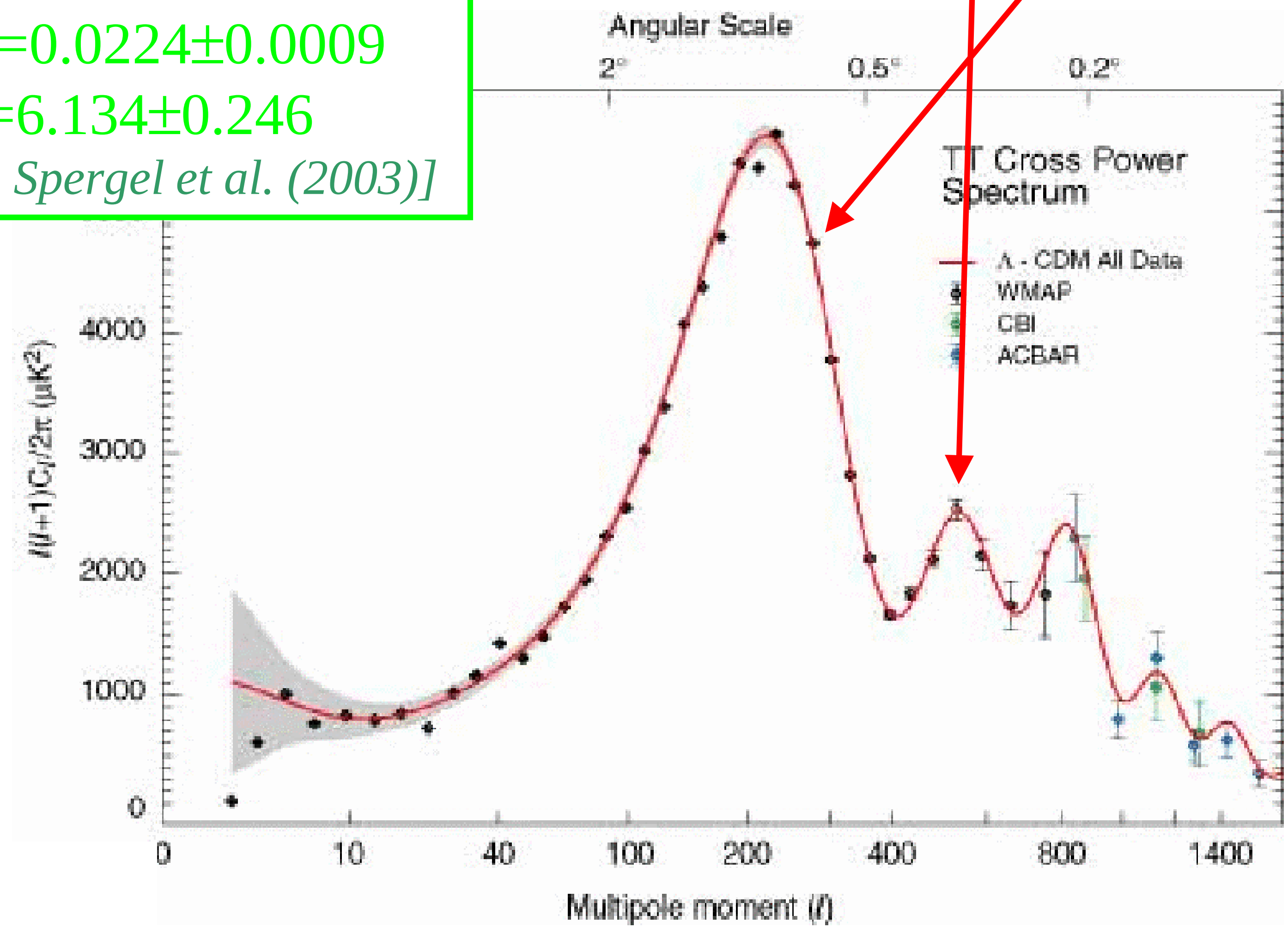
Anisotropies of the Cosmic Microwave Background (CMB)

Spatial fluctuation spectrum of CMB →
(Inertia of baryons)

Ø Geometry ($\Omega_T \approx 1$), 1st peak

Ø Ω_B (2nd/1st peaks)

$\Omega_B h^2 = 0.0224 \pm 0.0009$
$\eta = 6.134 \pm 0.246$
[WMAP: Spergel et al. (2003)]



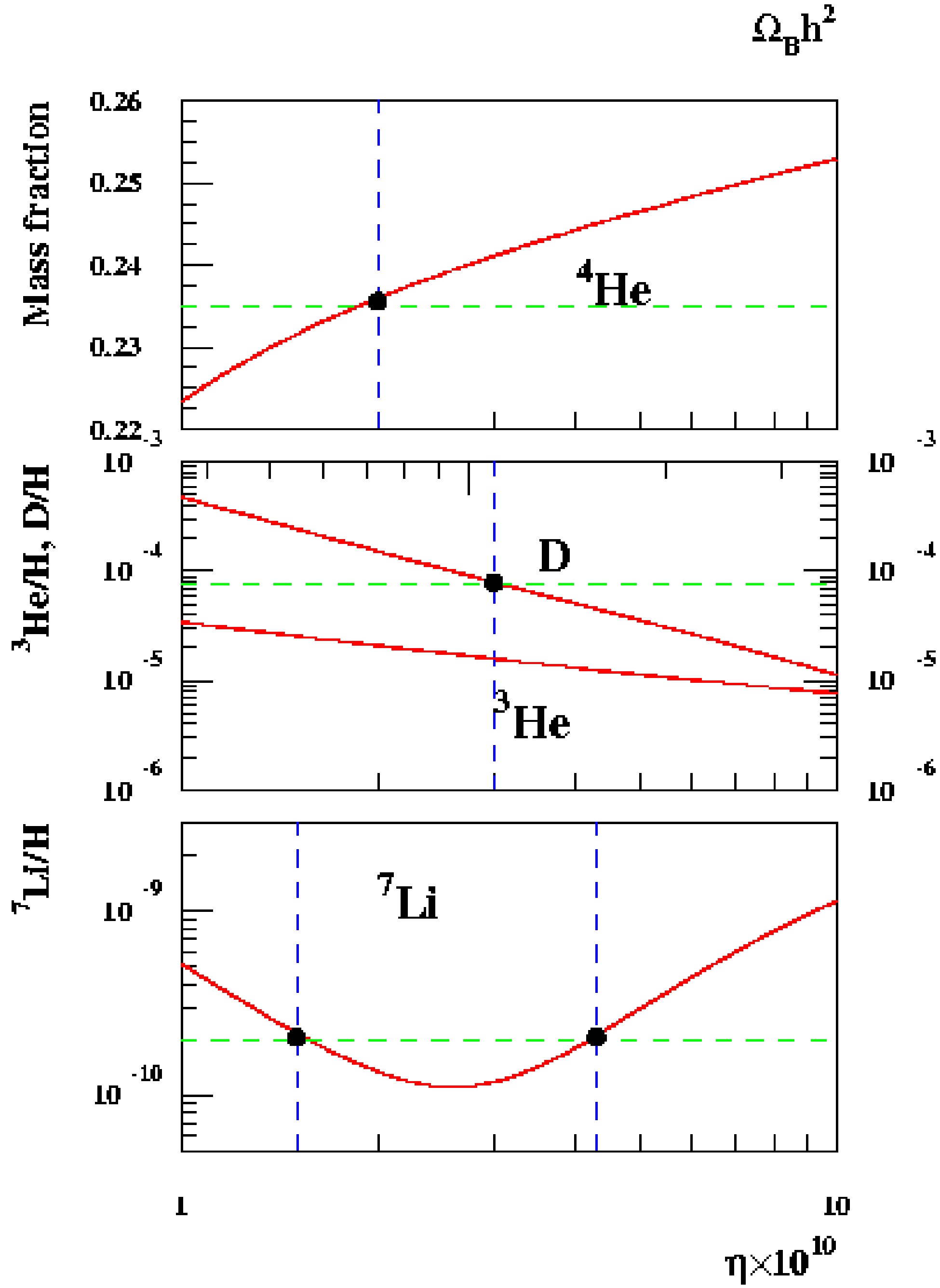
Best isotope to constrain η ?

^{4}He : little sensitive to η

^{3}He : stellar production / destruction not well understood.

D : seems the best candidate: a strong monotonic evolution with η and no stellar production.

^{7}Li : main drawback: a non monotonic evolution with η; two η values for a given Li/H



Deuterium primordial abundance

Fragile isotope : only destroyed after BBN

$\Rightarrow$ use highest observed value

1. Local interstellar medium (present) :
   $D/H=1.5\ 10^{-5}$
2. Protosolar cloud (4.6 Gyr ago) :
   $D/H=2.1\ 10^{-5}$
3. Remote cosmological clouds on the line of sight of quasars

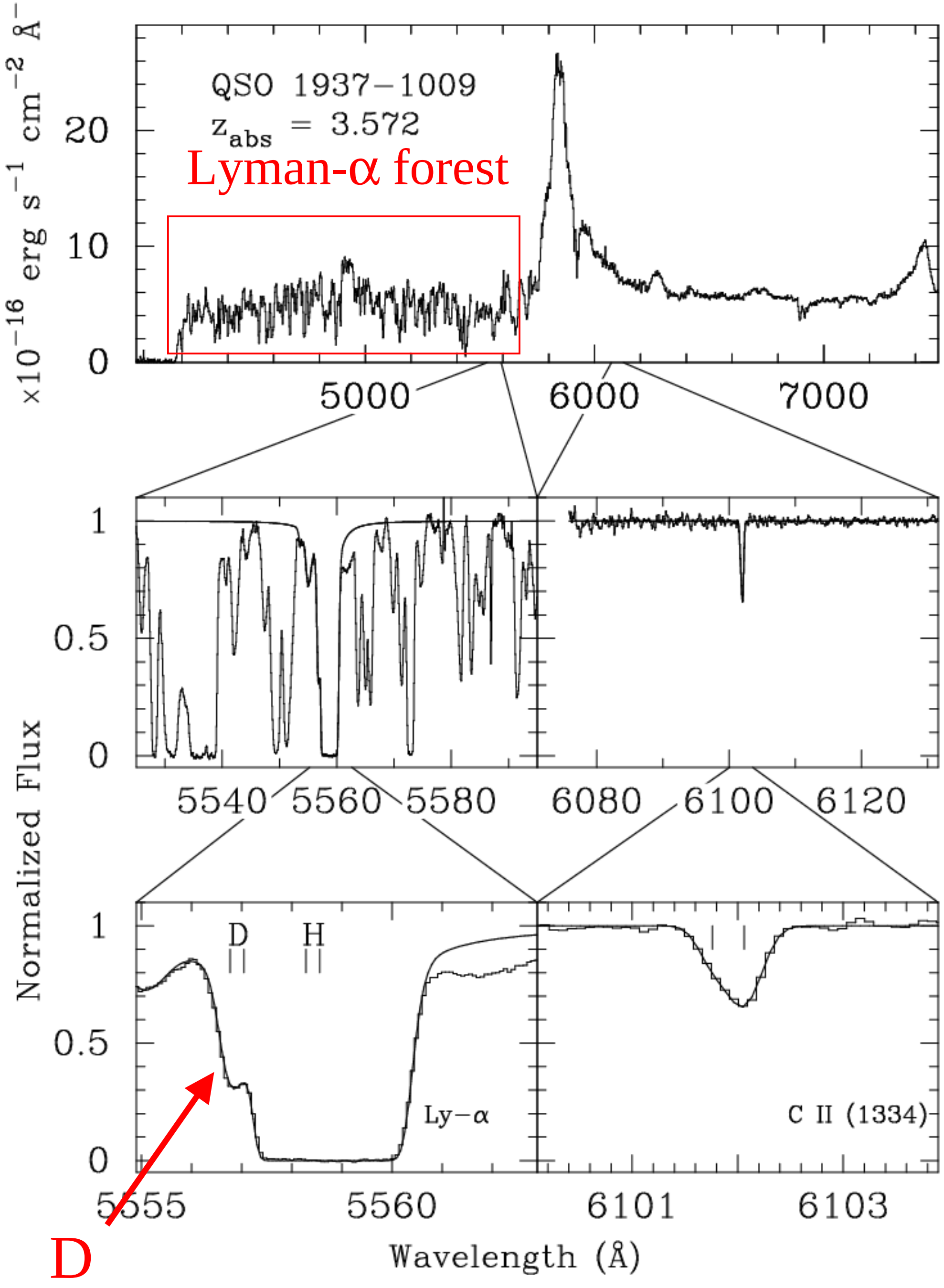
D/H observations in a cosmological cloud

Cloud at redshift of $z = 3.6$ on the line of sight of quasar QSO 1937-1009

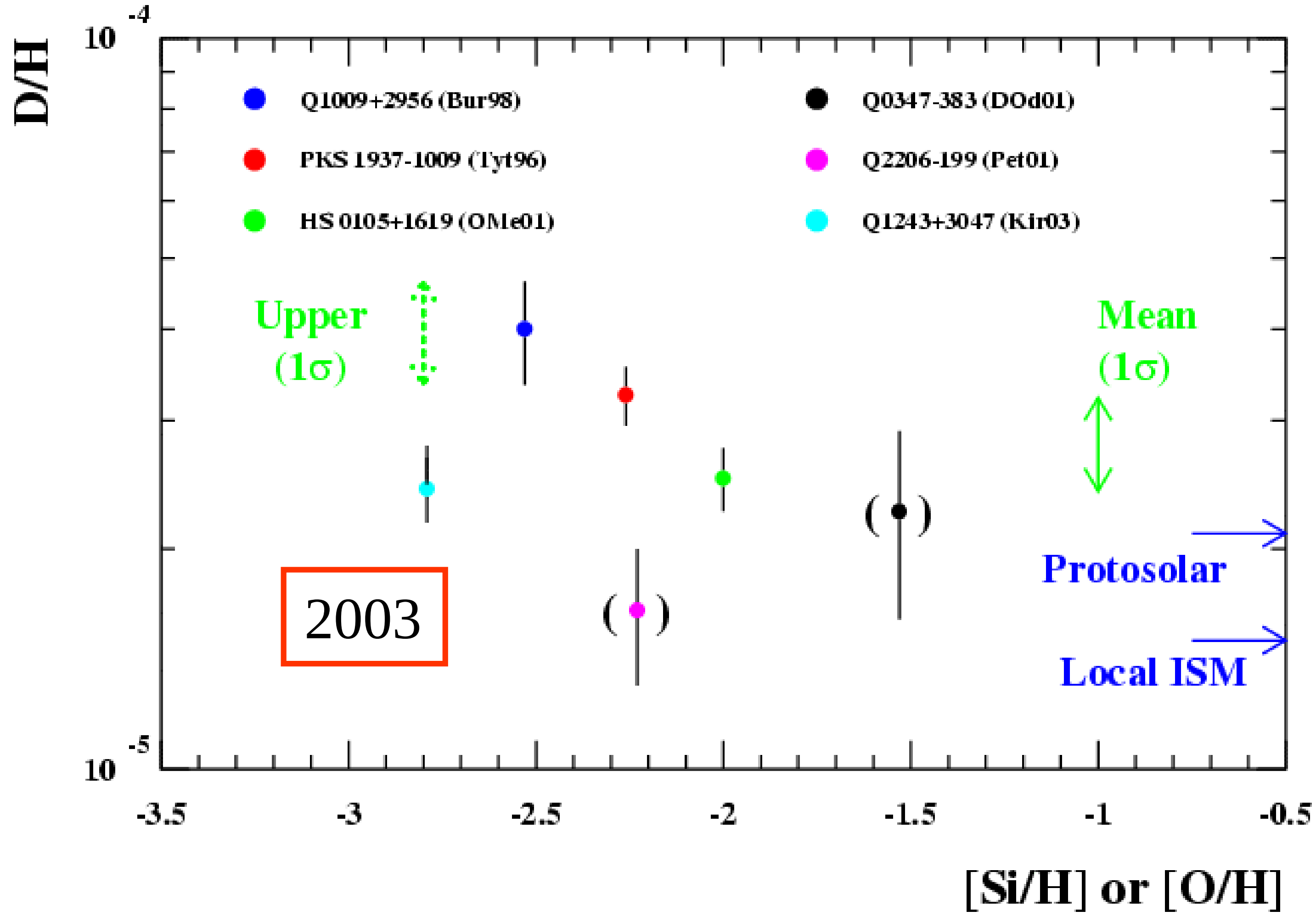
Observations :

- D/H ratio at high redshift from the depth/width of absorption lines
- Baryonic density (Ω_b) from the census of the « Lyman-α Forest » lines

[Burles & Tytler 1998]



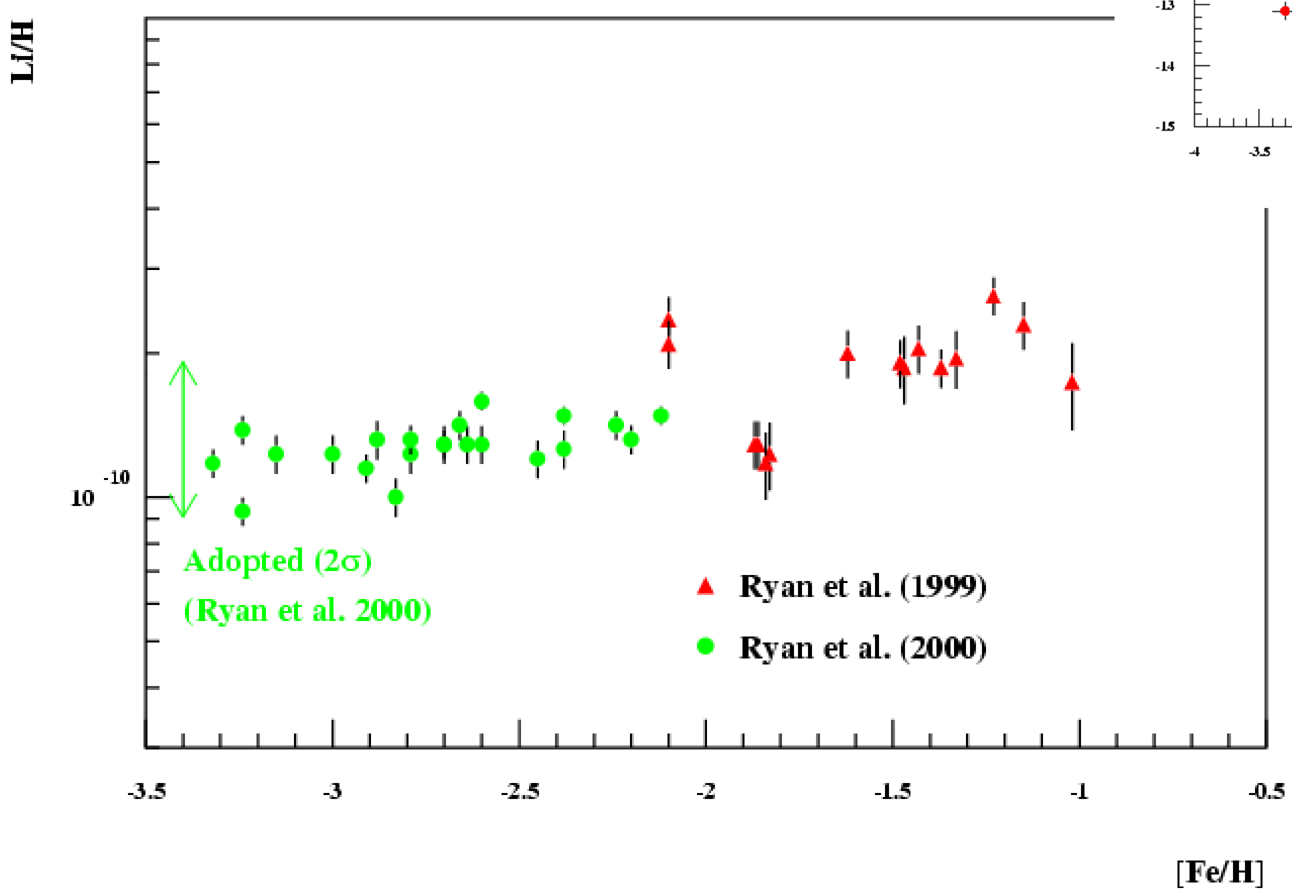
D/H observations in cosmological clouds

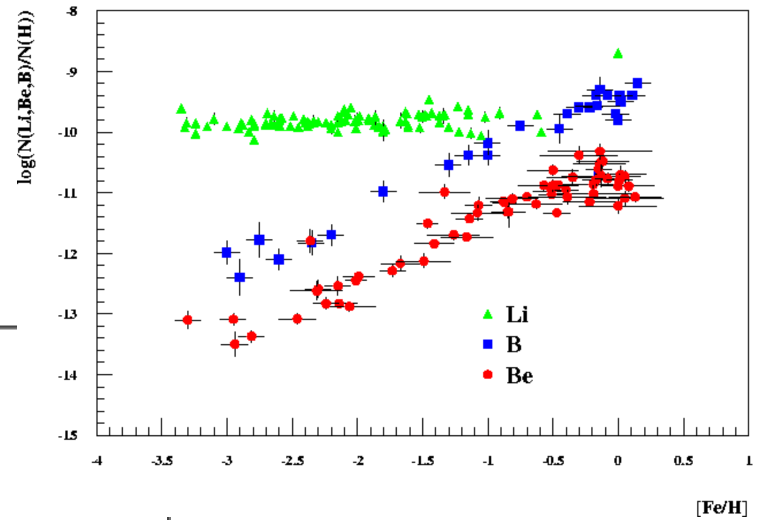


Burles & Tytler 1998; Tytlet et al. 1996; O'Meara et al. 2001; D'Odorico et al. 2001; Pettini & Bowen 2001; Kirkman et al. 2003

Observation of lithium abundances in low metallicity stars

•Spite plateau: Li/H versus metallicity (time)
[Spite & Spite, 1982]





•Low dispersion

•^{6}Li observations (^{6}Li/^{7}Li$\approx 10^{-2}$)
[Cayrel et al., 1999]

$\Rightarrow$ low Li destruction

$\Rightarrow$Reliable primordial abundance

TABLE 1

INFERRED PRIMORDIAL LITHIUM ABUNDANCE: OBSERVED (RNB) ABUNDANCE IS $\langle A(\mathrm{Li})\rangle_{-2.8} = 2.12 \pm 0.02$

Corrections to Apply Logarithmically	Value	Estimated Uncertainty
(1) GCE/GCR:		
Previous analyses (RNB)	−0.14 to −0.05	
Log data fit (eq. [1])	−0.20 to −0.09	
Linear data fit (eq. [2])	−0.12 to −0.04	
Linear data fit (eq. [3])	−0.16 to −0.05	
Model fits (eqs. [2]–[3])	−0.05 to −0.04	
Adopted (excludes model)		$-0.11^{+0.07}_{-0.09}$
(2) Stellar depletion		$+0.02^{+0.08}_{-0.02}$
(3a) T_{eff}-scale zero point		$+0.08 \pm 0.08$
(3b) One-dimensional atmosphere models		$+0.00^{+0.10}_{-0.00}$
(3c) Convective treatment		$+0.00^{+0.08}_{-0.00}$
(3d) Non-LTE		-0.02 ± 0.01
(3e) *gf*-values		$+0.00 \pm 0.04$
(4) Anomalous objects		$+0.00 \pm 0.01$
Total		$-0.03^{+0.19}_{-0.13}$
Inferred $A(\mathrm{Li}_p)$		$+2.09^{+0.19}_{-0.13}$

NOTE.—The weighted mean and 95% CL uncertainty of observed Li abundances for a very metal-poor sample of halo main-sequence turnoff stars (RNB) with $\langle[\mathrm{Fe/H}]\rangle = -2.8$ and the corrections required to deduce the primordial value.

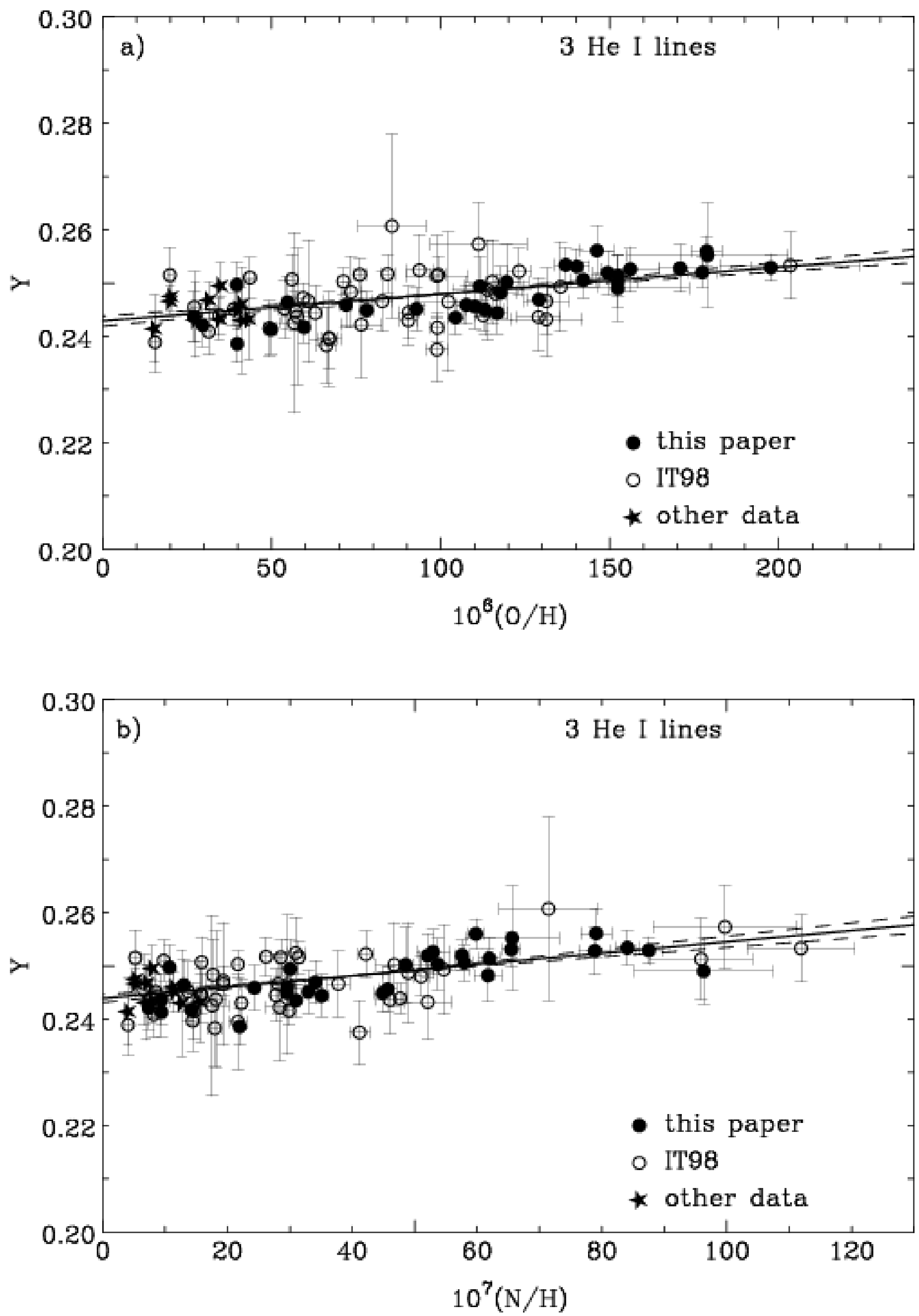
Deduced primordial abundance : Li/H = $(0.91–1.91)\times10^{-10}$
after correction for systematic effects [Ryan et al., 2000]

^{4}He observations in blue compact galaxies

From a sample of 82 H II regions in 76 blue compact galaxies:

$Y_p = 0.2421 \pm 0.0021$

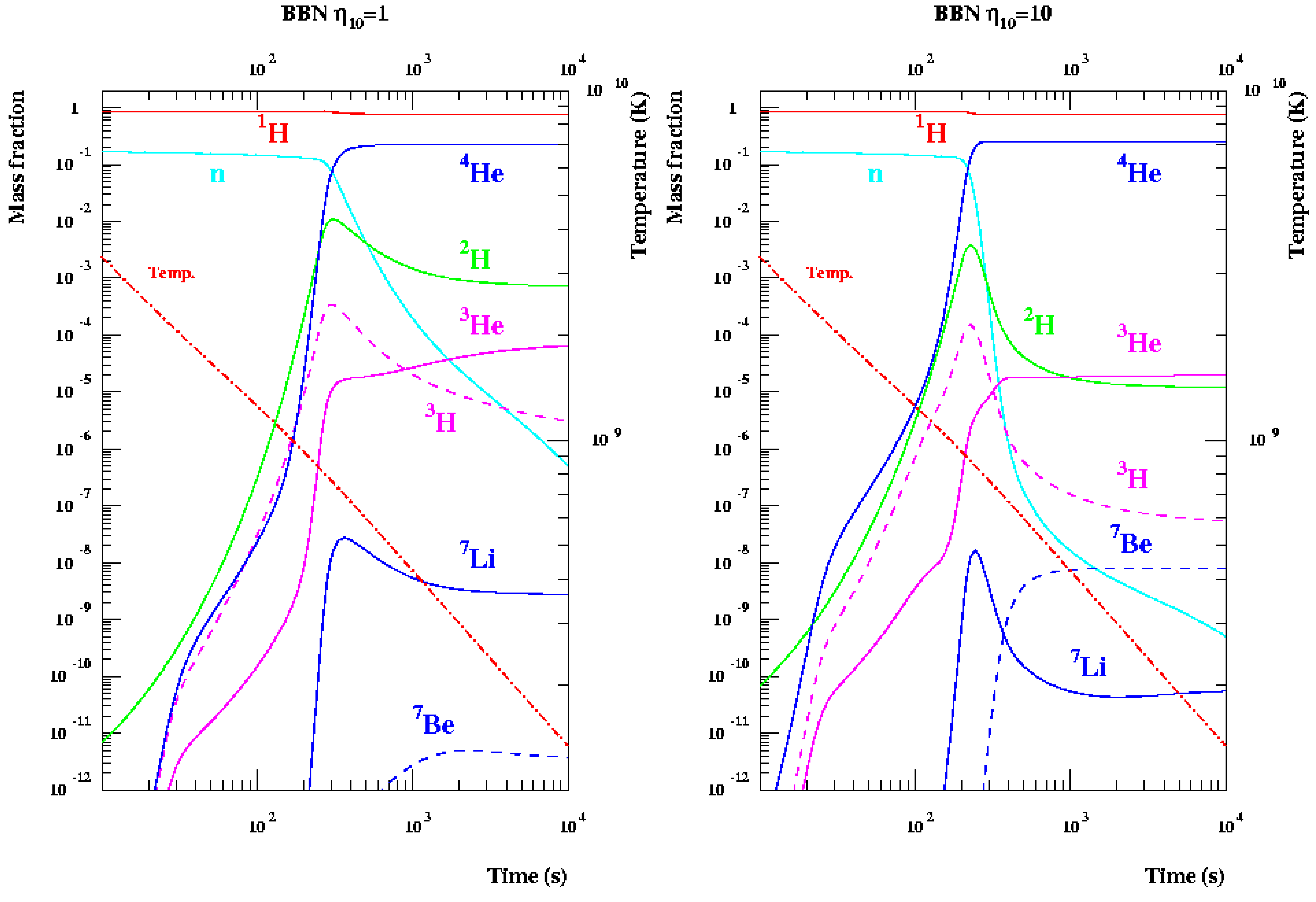
[Izotov & Thuan 2003]



Previously used values :

- $Y_p = 0.2452 \pm 0.0015$ *[Izotov et al. (1999)]*
- $Y_p = 0.2391 \pm 0.0020$ *[Peimbert et al. (2002)]*

Primordial nucleosynthesis with $\eta_{10} = 1$ et 10



The 12 reactions of standard BBN

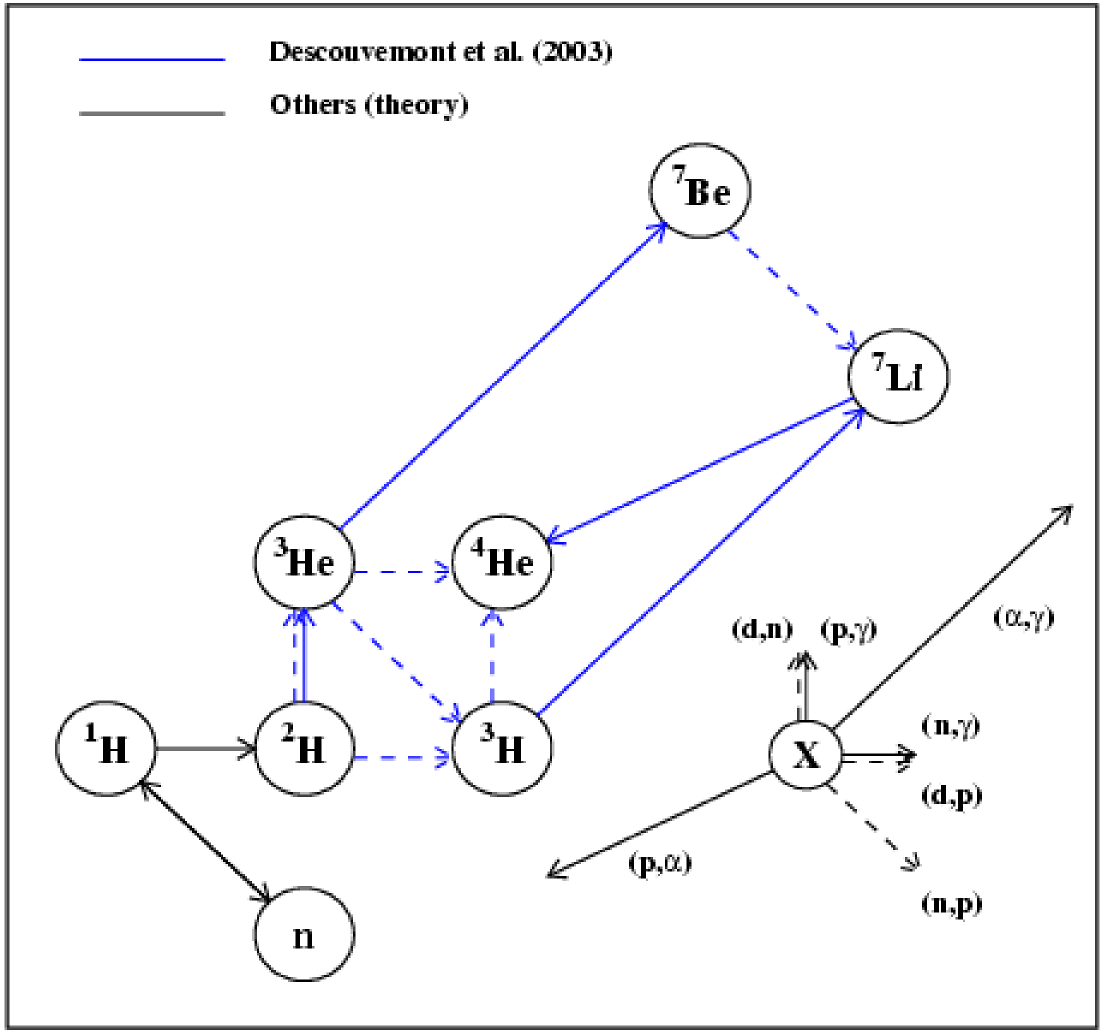
Origin of reaction rates

Theoretical:

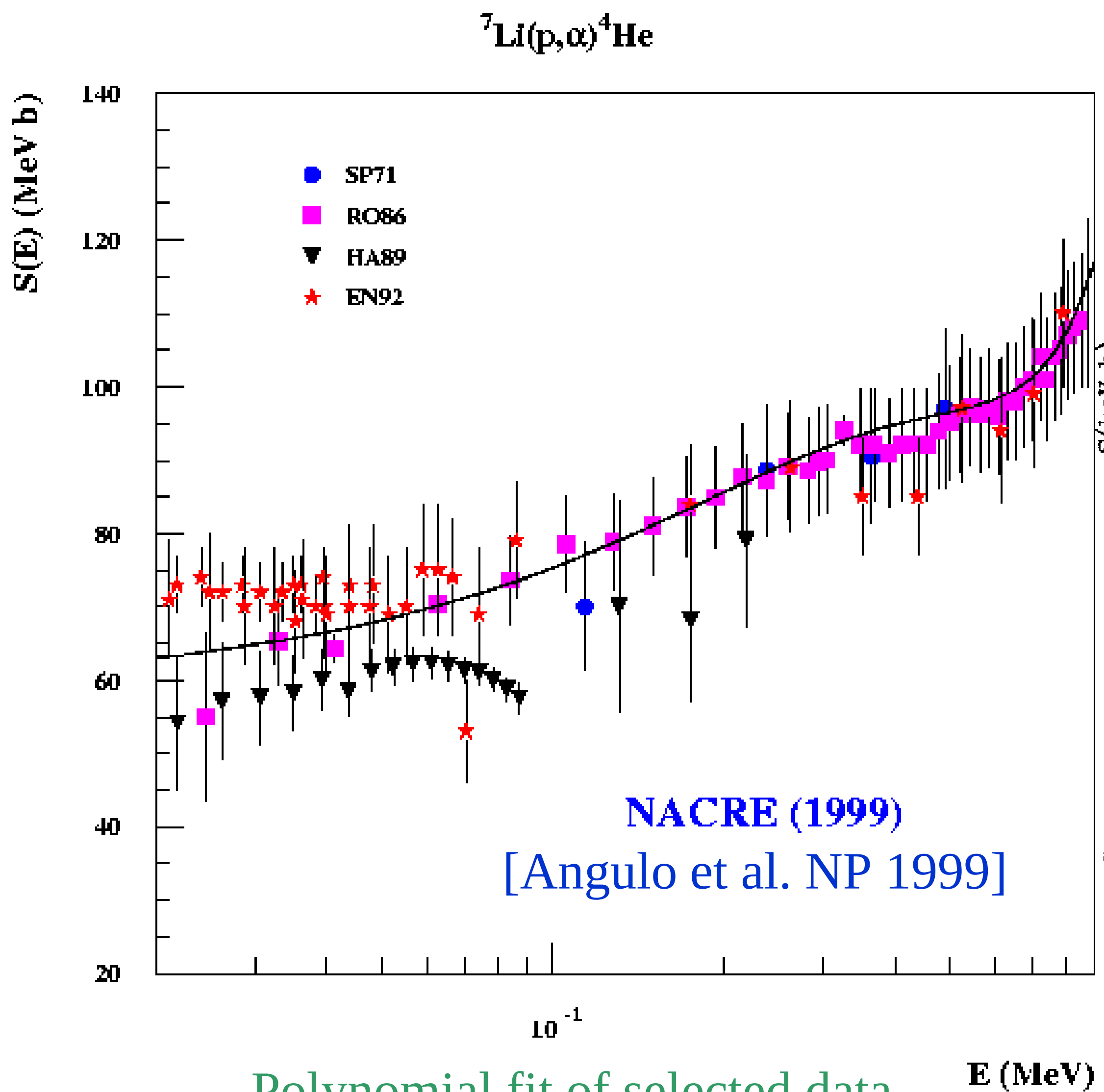
- $n \leftrightarrow p$: with $\tau_n = 886.7 \pm 1.9$ s *[PDG 2000]*, very small uncertainty *[Brown & Sawyer (2001)]*
- $^{1}H(n,\gamma)^{2}H$: Two nucleons effective field theory *[Chen & Savage (1999)]*

New compilation:

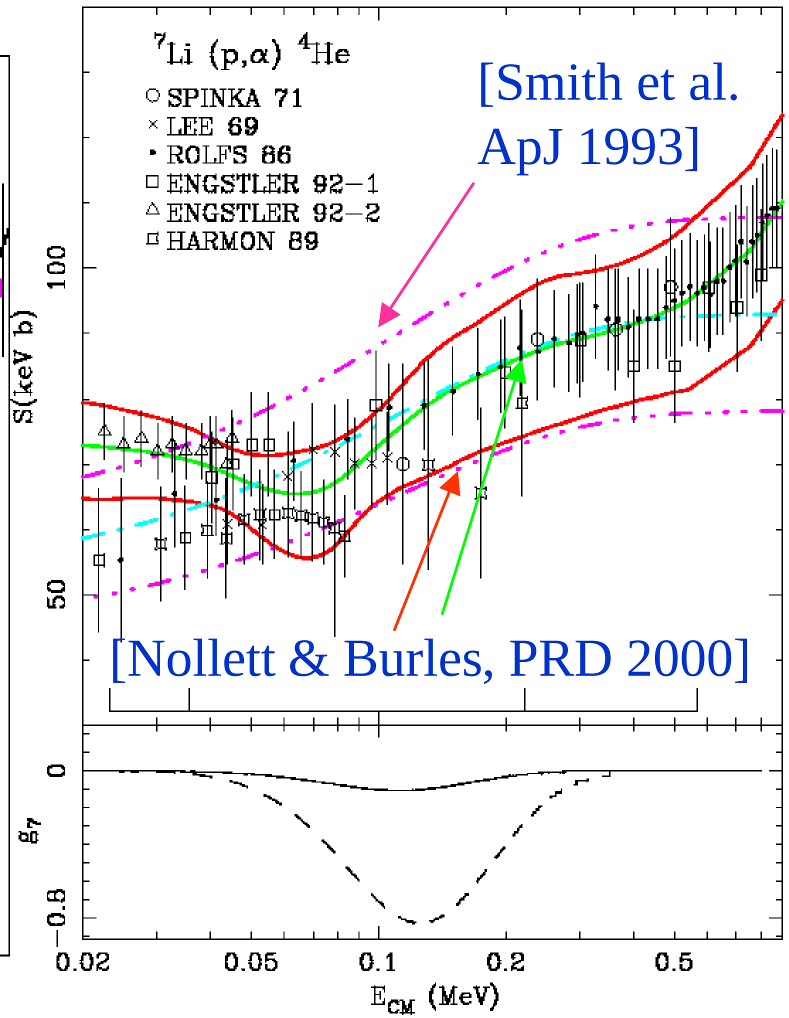
[Descouvemont, Adahchour, Angulo, Coc & Vangioni-Flam (2003), submitted]



Data evaluation for the $^{7}Li(p,\alpha)^{4}He$ reaction



Polynomial fit of selected data

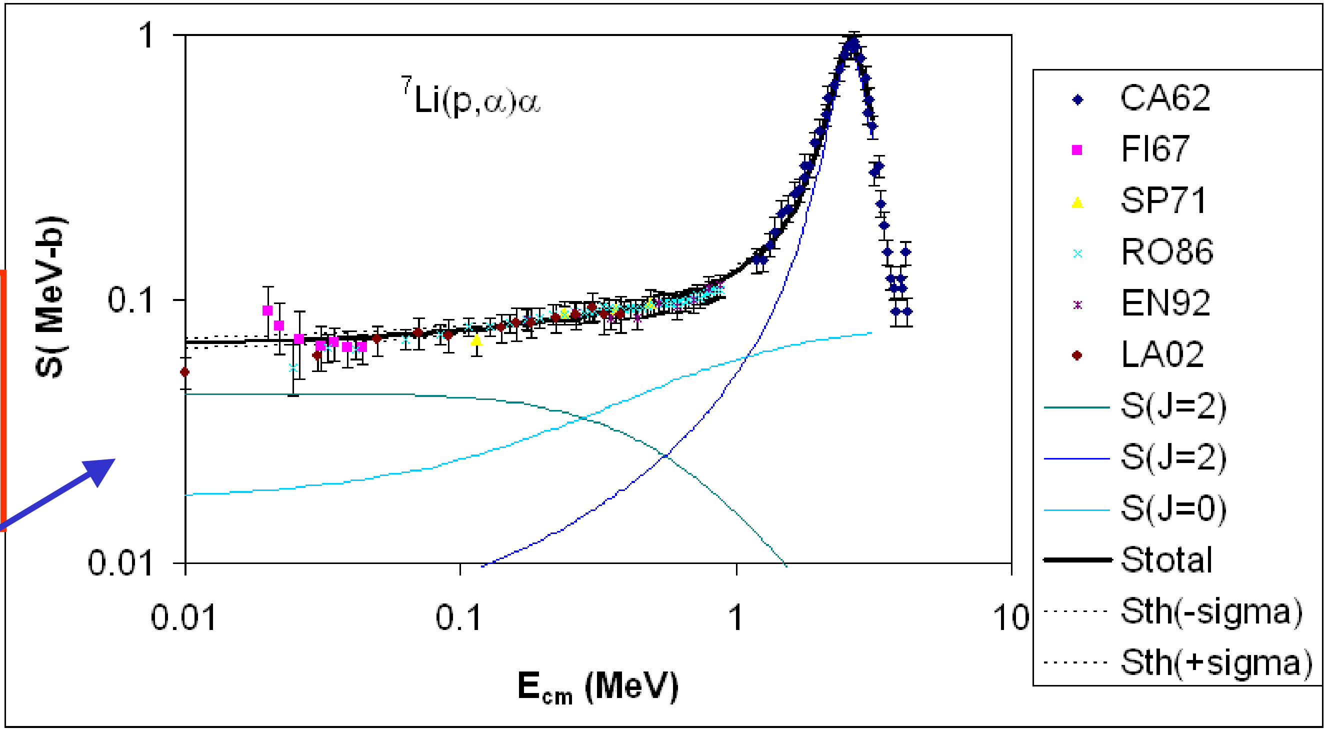


Spline fit of all data

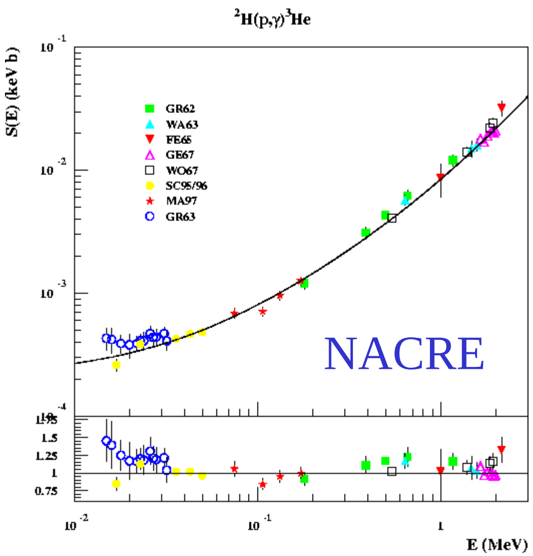
(See also Cyburt, Fields & Olive, 2001)

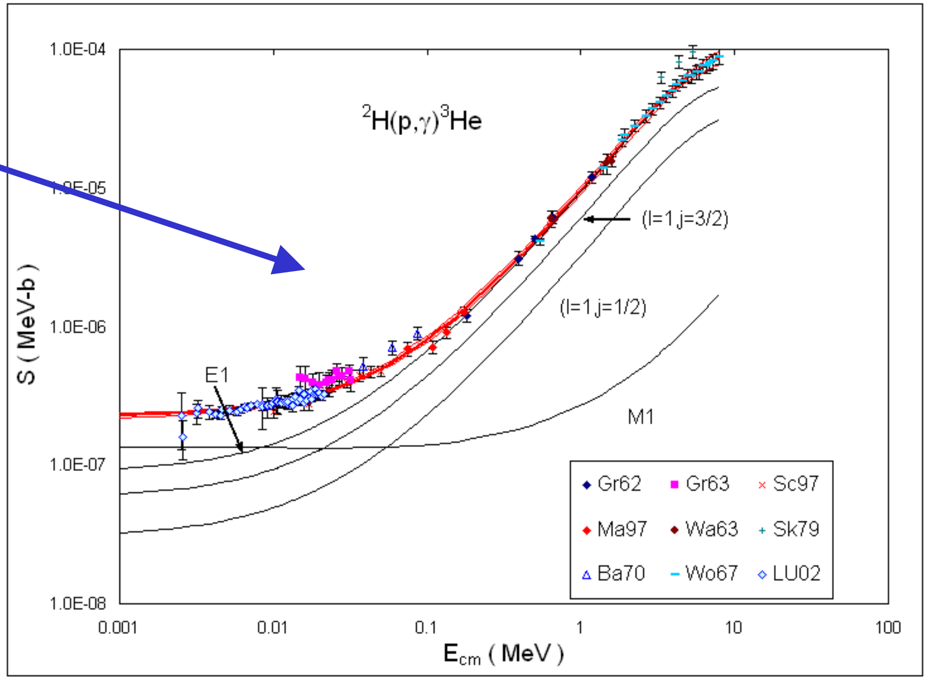
New analysis of BBN rates

[DAACV] Descouvemont, Adahchour, Angulo, Coc & Vangioni-Flam (2003), submitted



« R-Matrix » formalism: S-factors fits of data constrained by theory





Influence of nuclear uncertainties

$$\log(X_H/X_L)|_{MAX} \equiv \log(X(\text{rate}+1\sigma)/X(\text{rate}-1\sigma))$$

$$(\text{maximum for } 1 \le \eta_{10} \le 10)$$

$$\bullet \equiv |\log(X_H/X_L)|_{MAX} < 0.001$$

Reaction/ΔY/Y	Ref.	limits	^{4}He	D	^{3}He	^{7}Li
			$(X_H\text{-}X_L)_{MAX}$	$\log(X_H/X_L)\|_{MAX}$		
^{2}H(p,γ)^{3}He	DAACV (2003)	±1σ	•	-0.030	0.022	0.034
^{2}H(d,n)^{3}He	DAACV (2003)	±1σ	•	-0.009	0.007	0.011
^{2}H(d,p)^{3}H	DAACV (2003)	±1σ	•	-0.008	-0.008	0.003
^{3}H(d,n)^{4}He	DAACV (2003)	±1σ	•	•	-0.003	-0.004
^{3}H(α,γ)^{7}Li	DAACV (2003)	±1σ	•	•	•	0.038
^{3}He(n,p)^{3}H	DAACV (2003)	±1σ	•	•	-0.018	-0.017
^{3}He(d,p)^{4}He	DAACV (2003)	±1σ	•	•	-0.006	-0.004
^{3}He(α,γ)^{7}Be	DAACV (2003)	±1σ	•	•	•	0.049
^{7}Li(p,α)^{4}He	DAACV (2003)	±1σ	•	•	•	-0.039
^{7}Be(n,p)^{7}Li	DAACV (2003)	±1σ	•	•	•	-0.003

Comparison between observed and calculated abundances

Limits (1-σ) obtained by Monte-Carlo from *DAACV* reaction rate uncertainties.

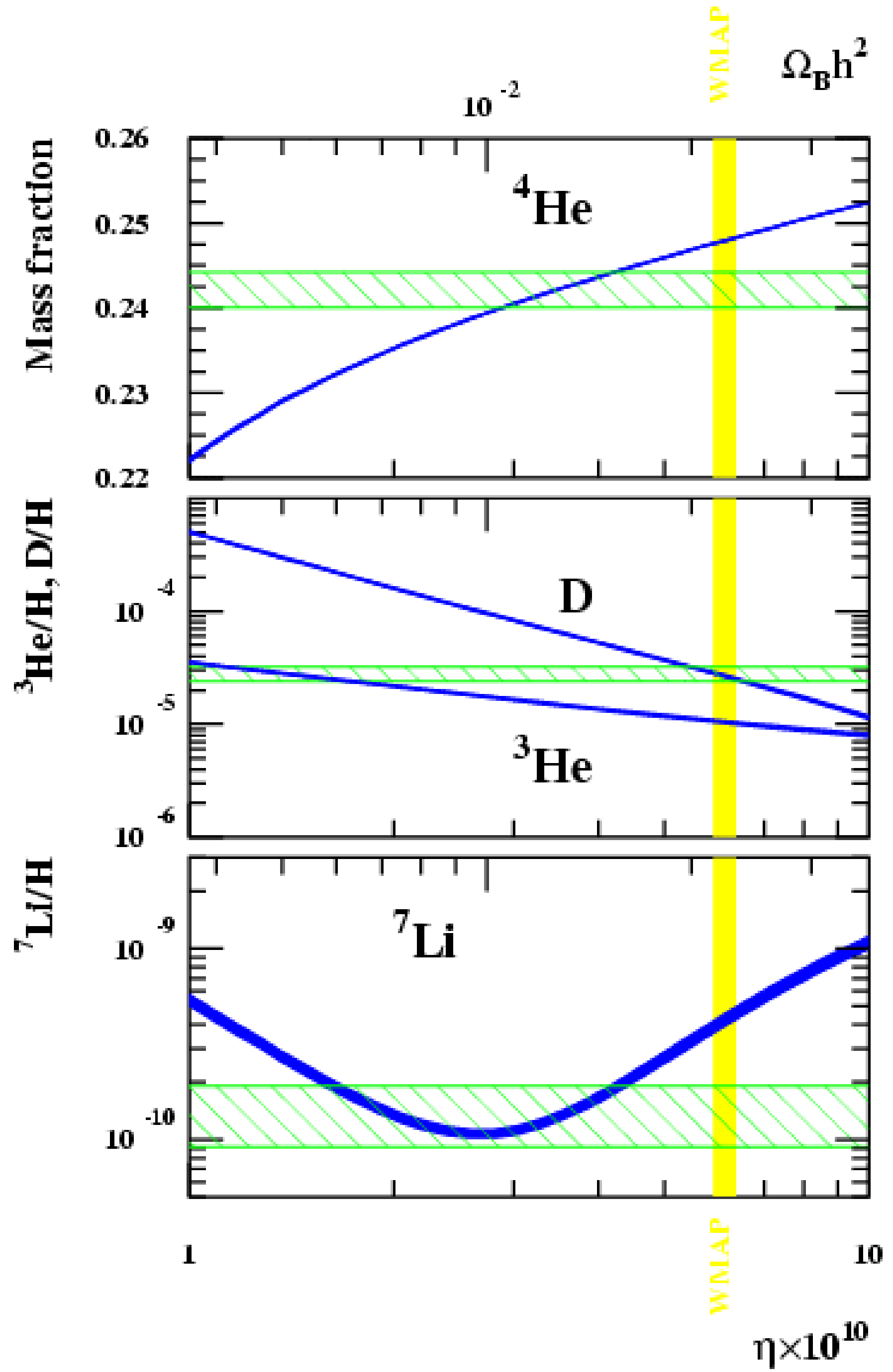
Primordial abundances

•^{4}He : $Y_p = 0.2421 \pm 0.0021$ *[Izotov et al. (2003)]*

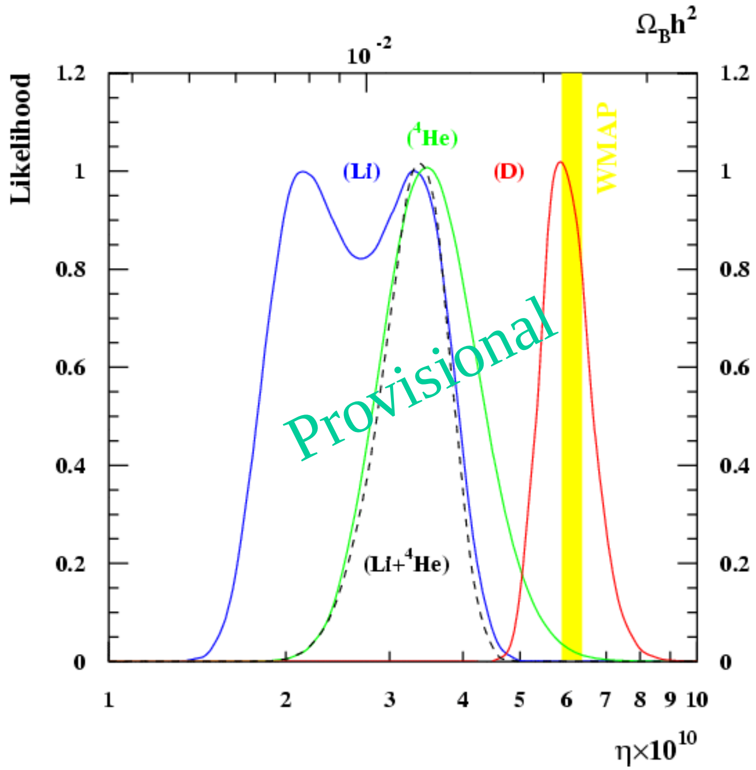
•D : D/H = $(2.78^{+0.44}_{-0.38}) \times 10^{-5}$ (1σ) *[Kirkman et al. (2003)]*

•^{7}Li : Li/H = $(1.23^{+0.68}_{-0.32}) \times 10^{-10}$ (2σ) *[Ryan et al. (2000)]*

•$\Omega_B h^2 = 0.0224 \pm 0.0009$, *[WMAP: Spergel et al. (2003)]*



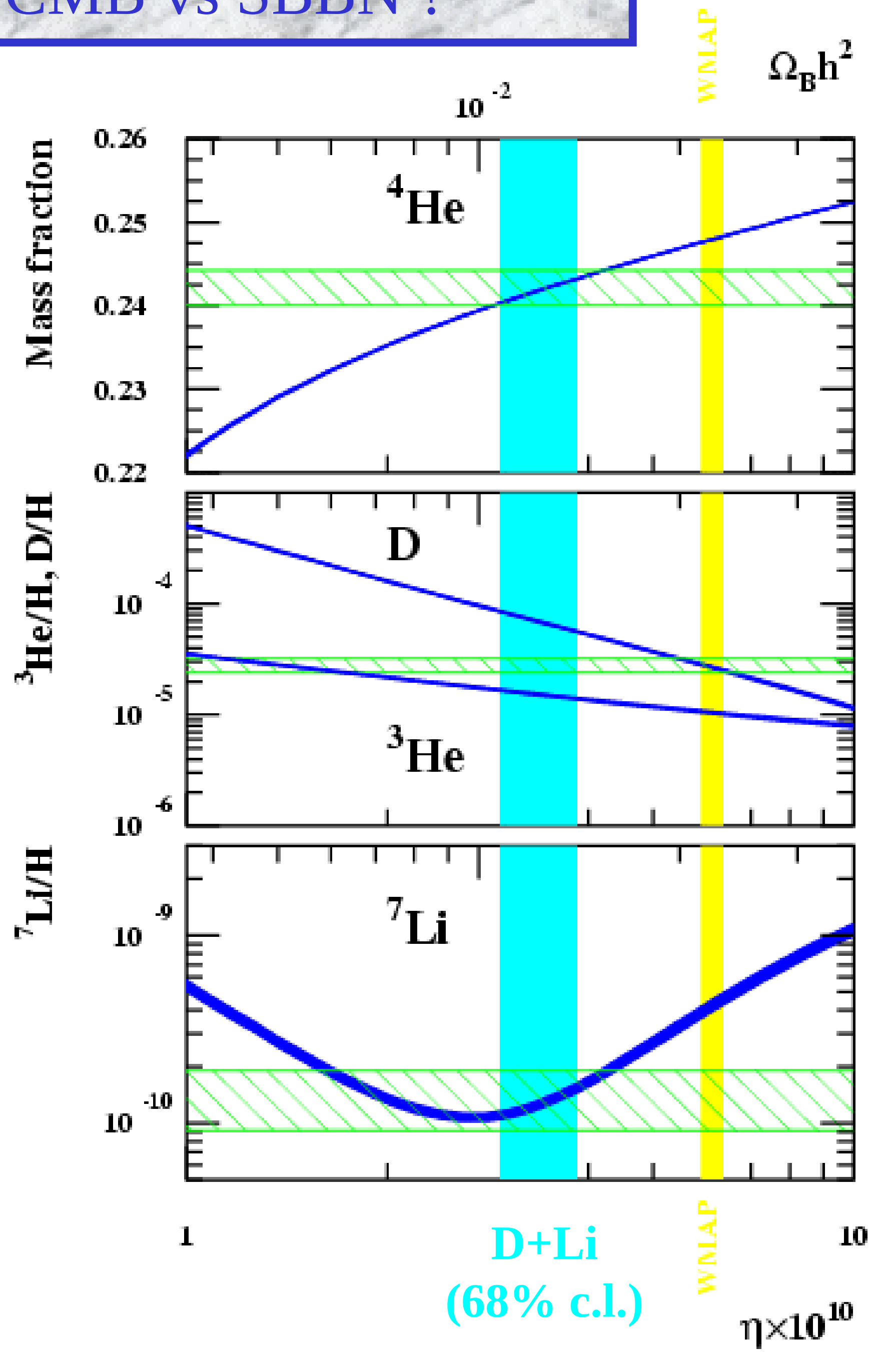
Baryonic density : CMB vs SBBN ?



η_{10} = 6.134±0.246 (WMAP)

SBBN + (D, Li, ^{4}He), 95% c.l. :

$5.0<\eta_{10}<7.3$	(D only)
$1.6<\eta_{10}<4.3$	(Li only)
$2.45<\eta_{10}<5.20$	(^{4}He only)
$2.45<\eta_{10}<4.20$	(Li & ^{4}He)



Primordial abundances from CMB value of $\Omega_b h^2$ and SBBN

Using $\Omega_B h^2 = 0.0224 \pm 0.0009$, *[WMAP: Spergel et al. (2003)]* and *DAACV* rates in SBBN calculations give:

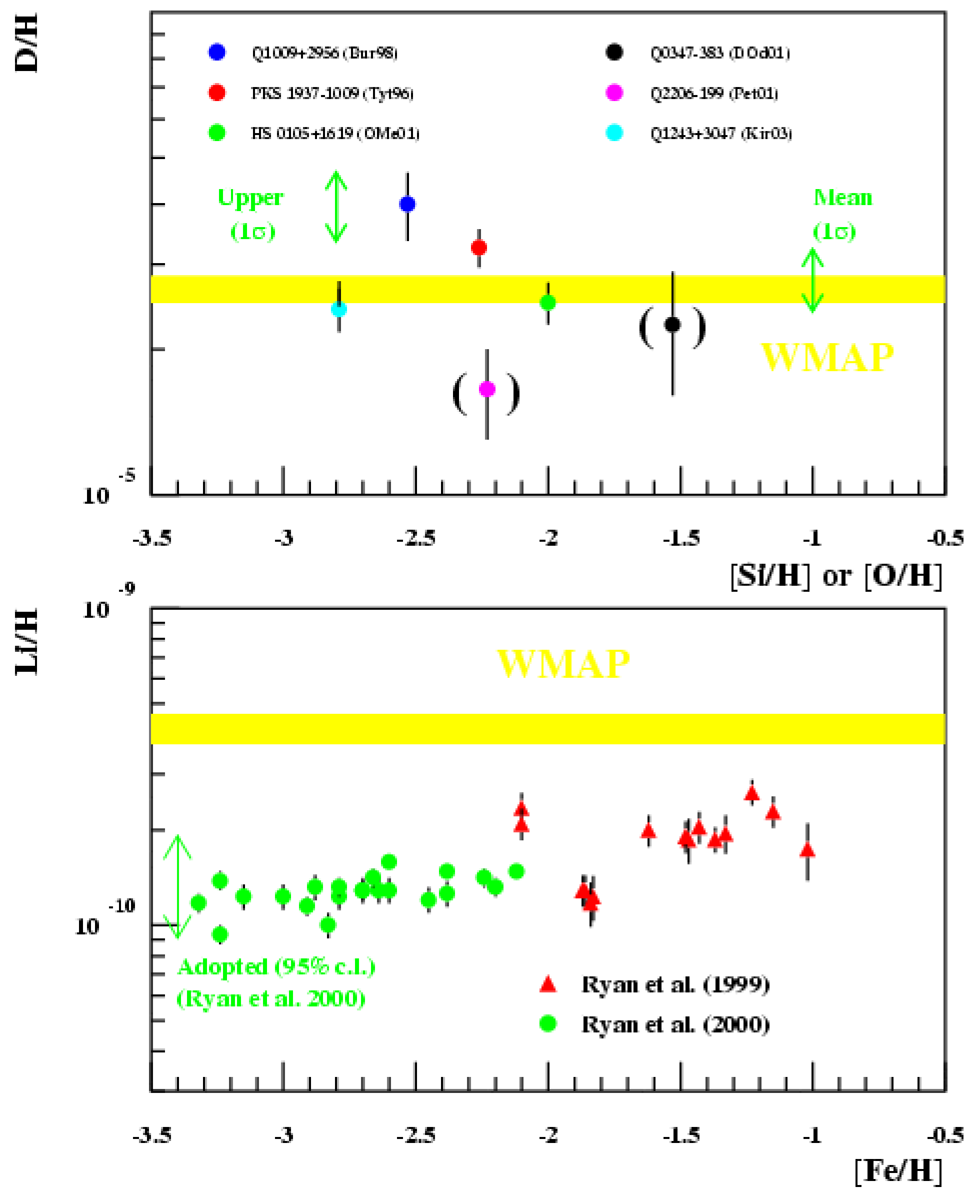
•$D/H = (2.66 \pm 0.17) \times 10^{-5}$ (1σ)
Fully compatible with D/H measured values in cosmological clouds.

• $Li/H = (4.18 \pm 0.46) \times 10^{-10}$ (1σ)
A factor of ≈ 3.4 higher than the value deduced from observations

See also Cyburt, Fields & Olive, astro-ph/0302431 (≈NACRE)

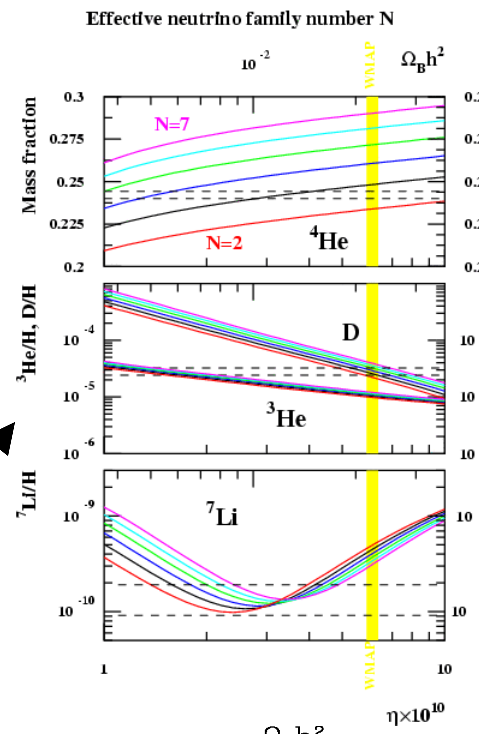
$D/H = (2.74^{+0.26}_{-0.16}) \times 10^{-5}$ (1σ)

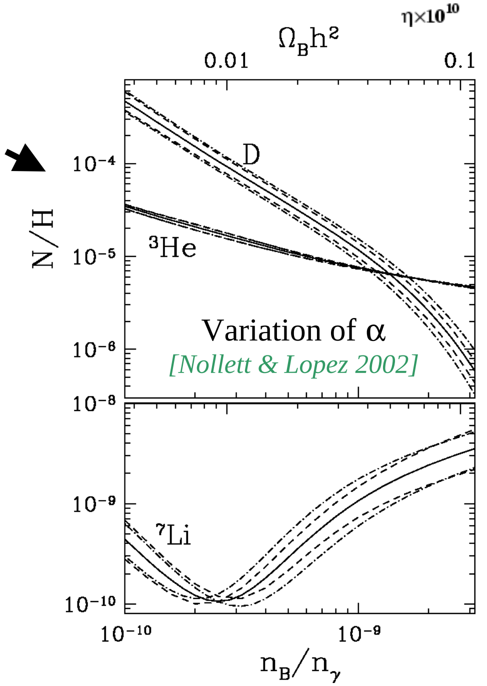
$Li/H = (3.76^{+1.03}_{-0.38}) \times 10^{-10}$ (1σ)



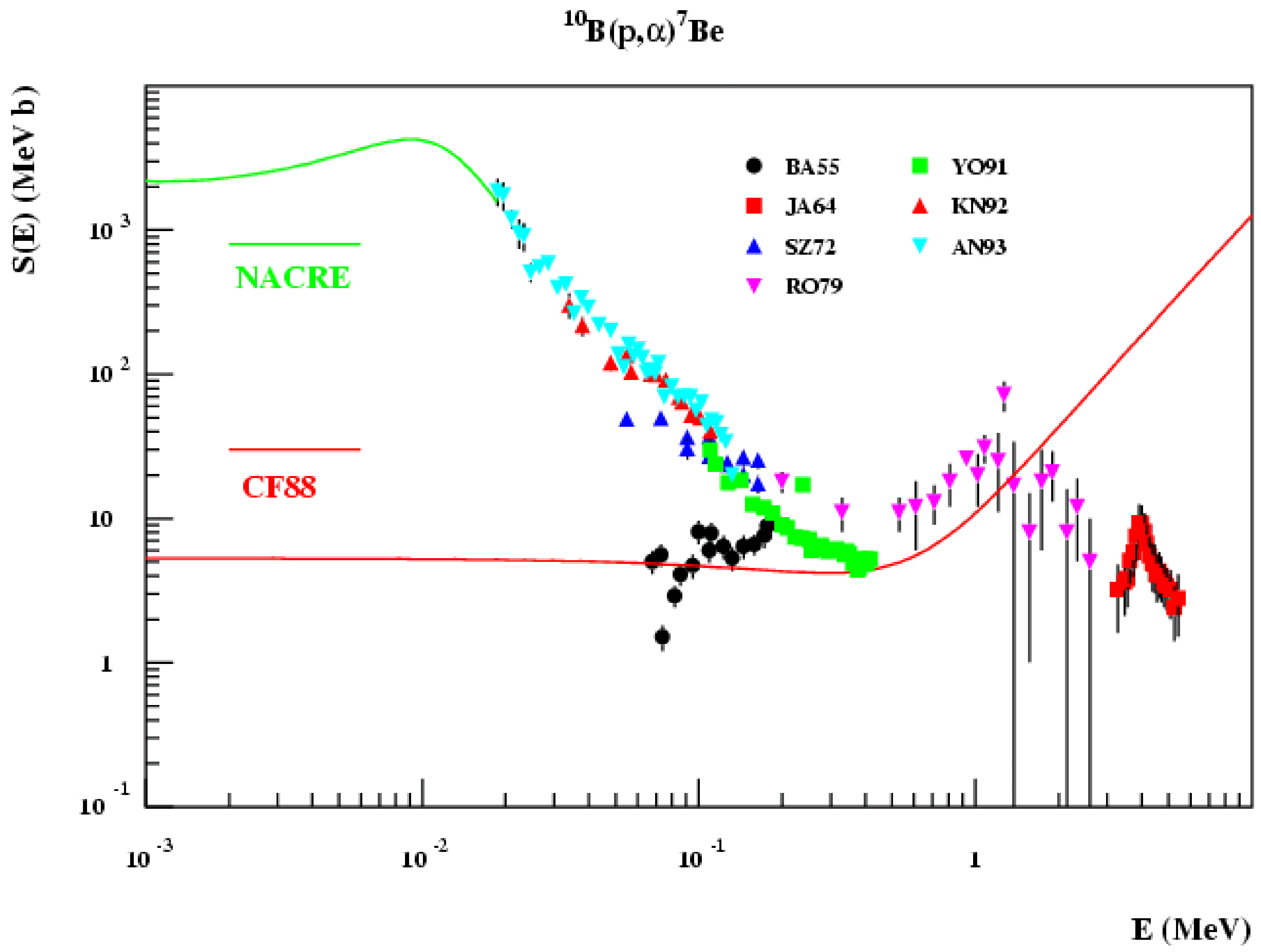
Origin of CMB/SBBN discrepancies ?

- Stellar ?
  - Observational bias: 1D/3D, LTE/NLTE model atmospheres
  - Li stellar destruction (^{6}Li observations, however)
- Cosmology ?
  - Extension of General Relativity, Quintessence, Branes, Lepton asymmetry, Inhomogeneous BBN, Variation of fundamental couplings,….
  - Blazars contamination of CMB *[astro-ph/0306206]*
- Pregalactic evolution ? (not affecting D!)
  - Spallation by cosmological cosmic rays
  - First generation stars
- Nuclear ?



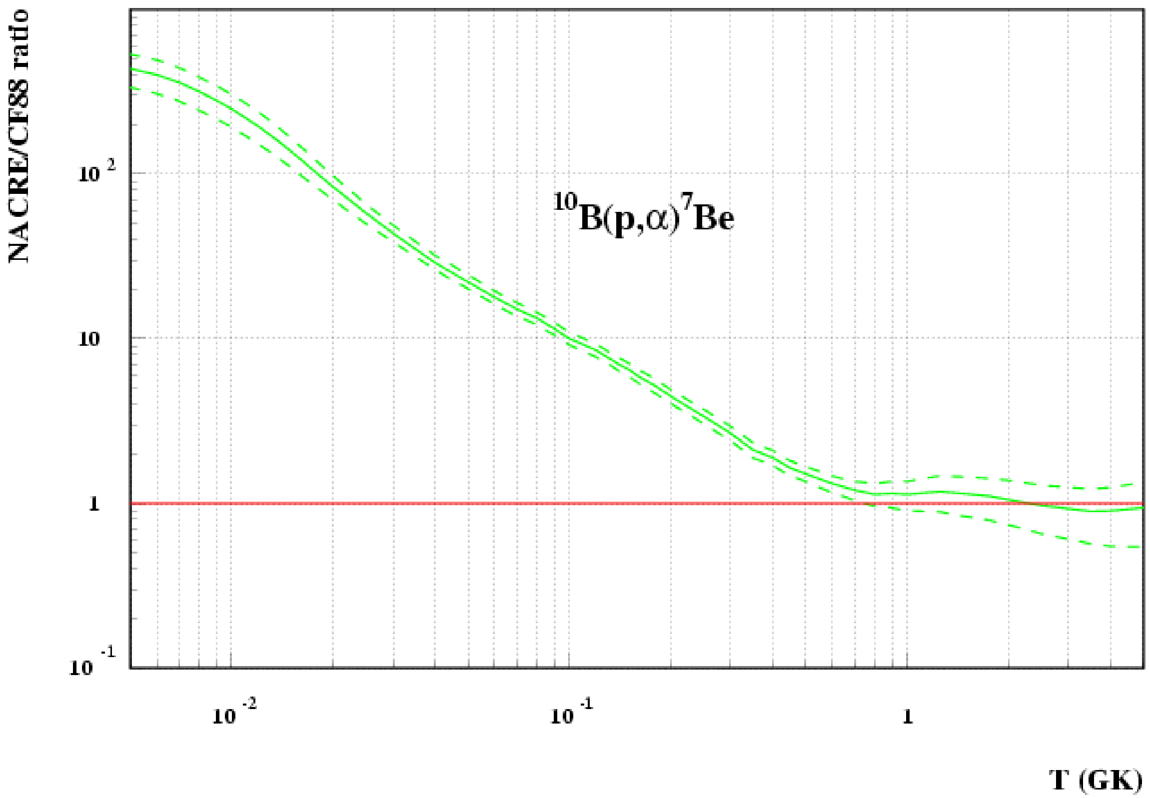


Experimental data on $^{10}B(p,\alpha)^{7}Be$ reaction



Evolution of the $^{10}B(p,\alpha)^7Be$ rate

The ratio between the NACRE (Angulo et al., 1999) rate and the CF88 (Caughlan & Fowler, 1988) one.

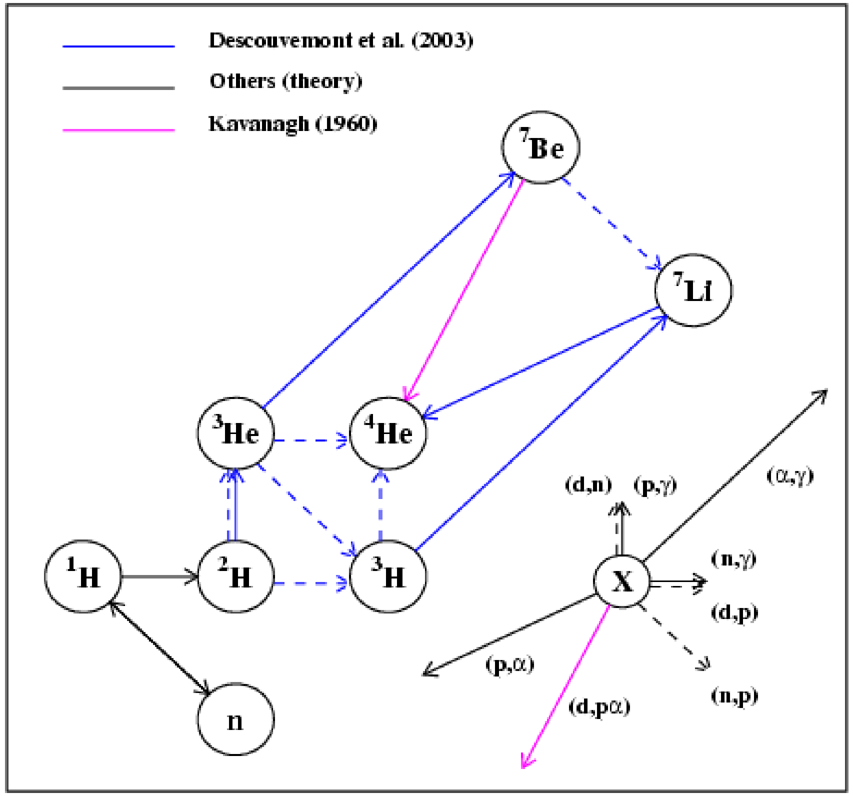


A factor of ≈10 in the SBBN production of ^{10}B

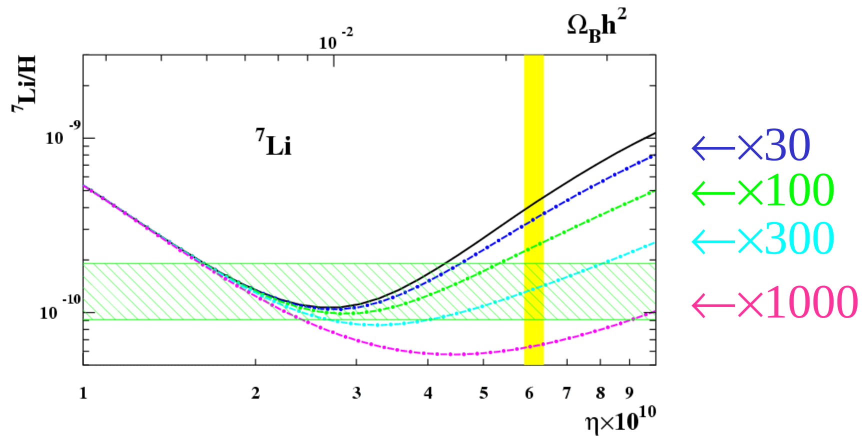
Reaction rates can change by huge factors from old estimates to new ones (new data). An other example $^{18}F(p,\alpha)$ in novae.

Other nuclear reaction rates

- About 100 other reactions involved in SBBN from H to B
- Among them ≈40 remain whose uncertainty on rate is not available
- Systematic check by varying the rates by factors of 10, 100, 1000.



An interesting case :
the ^{7}Be(d,p)2α reaction



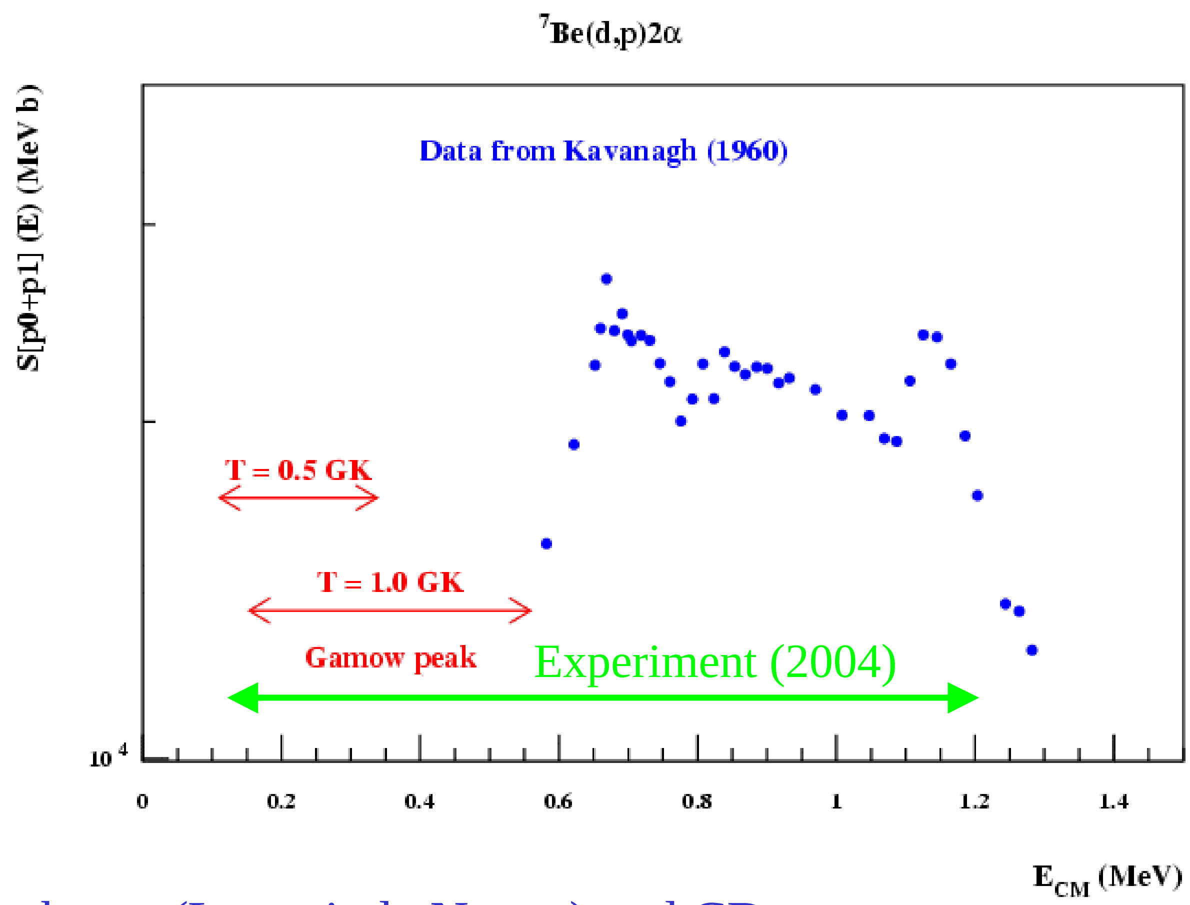
Experimental data on $^{7}Be(d,p)2\alpha$ reaction

$^{7}Be(d,p)^{8}Be^{*} \rightarrow 2\alpha$

Reaction rate *[CF88]* from an estimate *[Parker, 1972]* based on partial experimental data *[Kavanagh, 1960]*

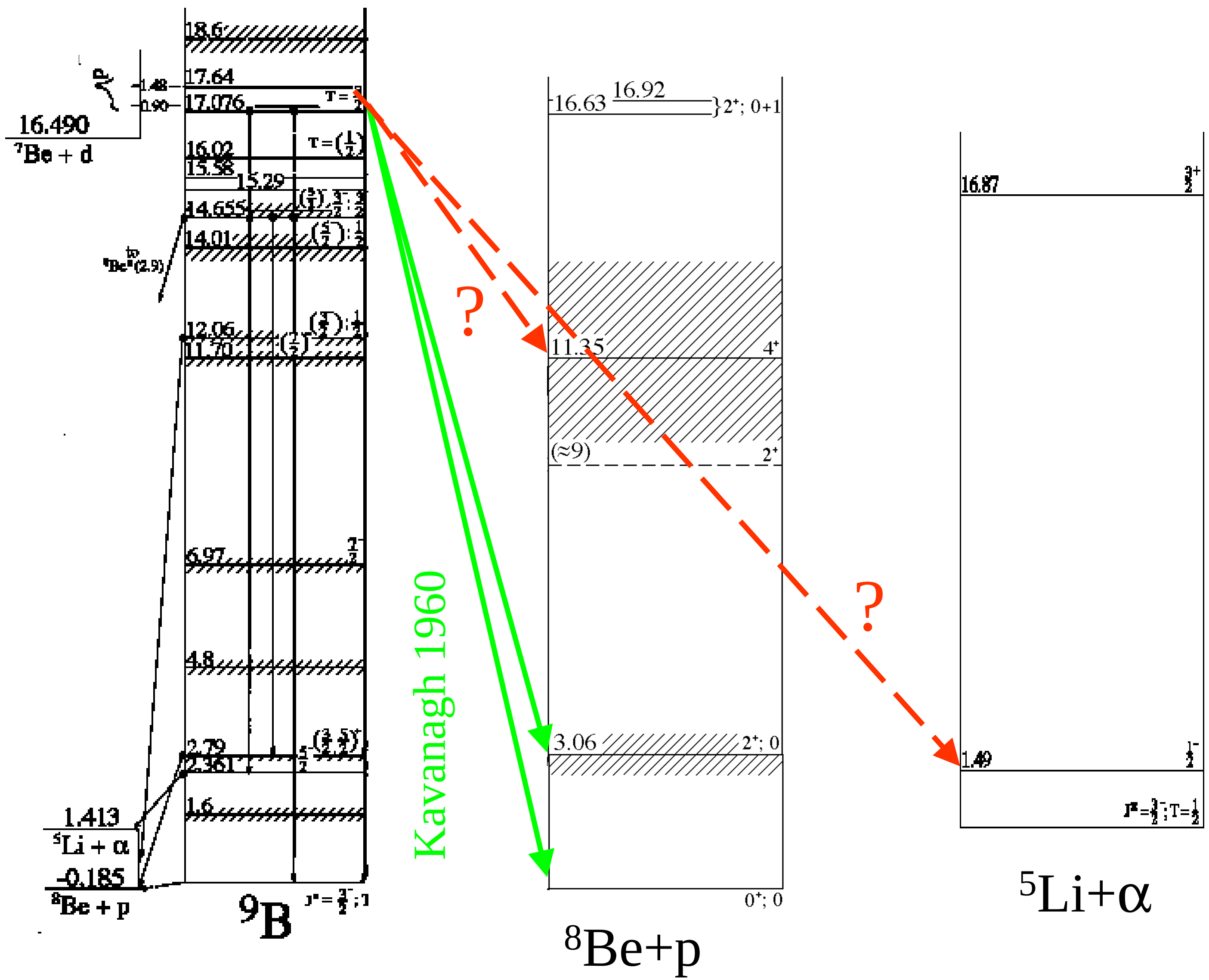
No data at BBN energies!

Experiment in 2004 at Louvain la Neuve



1. Reverse kinematics : ^{7}Be beam (Louvain la Neuve) and CD_2 target. (*CRC (Louvain LN), CSNSM, Edinburgh, ULB*)
2. Direct measurement radioactive ^{7}Be target and *d* beam (*CENBG 2005 ?*)

The $^7Be(d,p)2\alpha$ and $^7Be(d,\alpha)^5Li$ reactions



Conclusions

- First SBBN calculations with « main » nuclear reaction rates
  - Ø Constrained by R-matrix theory
  - Ø Statistically evaluated uncertainties
- Confirms good agreement for Ω_B values deduced from :
  1. CMB,
  2. SBBN (D),
  3. Lyman-α
- However disagreement between :
  - v SBBN (^{7}Li+^{4}He) and CMB
    - Ø Stellar, cosmology, pre-galactic, origin ?
- Need to exclude nuclear origin
  - v Systematic errors *[e.g.* $^3He(\alpha,\gamma)^7Be$*)]* but not a factor of 3!!!
  - v Investigate « new » SBBN reactions *[* ^7Be+d *]*
- May be some interesting new (astro)physics