BBN : SUCCESSES AND CHALLENGES

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COSMOLOGICAL LIMITS TO THE NUMBER OF MASSIVE LEPTONS

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BBN & The CBR Provide Complementary Probes Of The Early Universe

Do predictions and observations of the baryon density (η) and of the expansion rate of the Universe (H) agree at 20 minutes and at 400 kyr ?

Baryon Density Parameter

$$\eta \equiv n_N / n_\gamma \; ; \quad \eta_{10} \equiv 10^{10}\eta = 274\,\Omega_B h^2$$

$$\text{where : } \Omega_B \equiv \rho_B / \rho_c$$

$$\text{and : } h \equiv H_0 / 100 \text{ km/s/Mpc} \approx 0.7$$

$$\text{also : } \omega_B \equiv \Omega_B h^2$$

Note : Baryons $\Rightarrow$ Nucleons

DEUTERIUM --- The Baryometer Of Choice

- As the Universe evolves, D is only DESTROYED $\Rightarrow$

  * Anywhere, Anytime : $(D/H)_t \leq (D/H)_P$

  * For $t << t_0$ $(Z << Z_\odot)$: $(D/H)_t \rightarrow (D/H)_P$

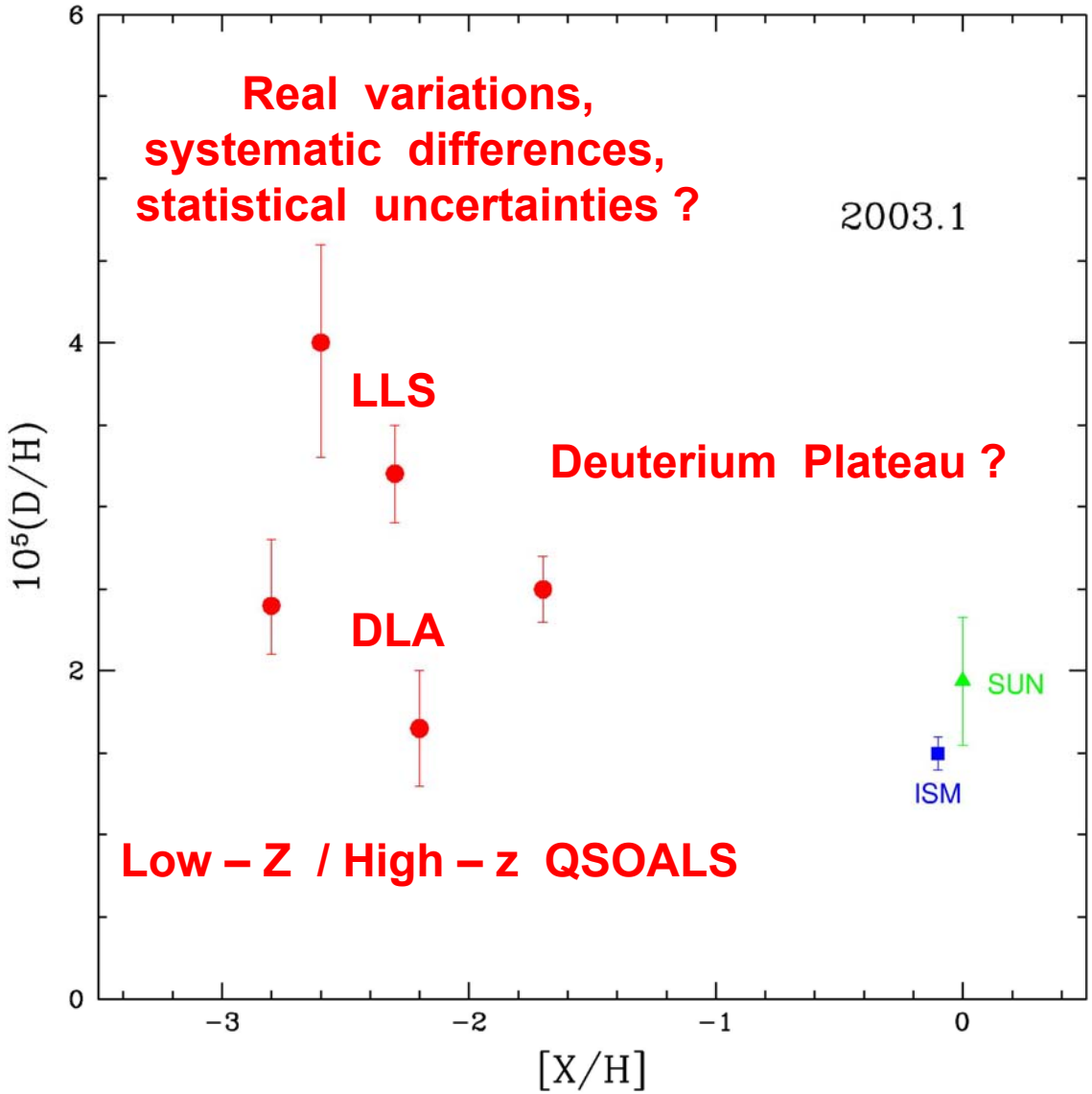
  $\Rightarrow$ Deuterium Plateau

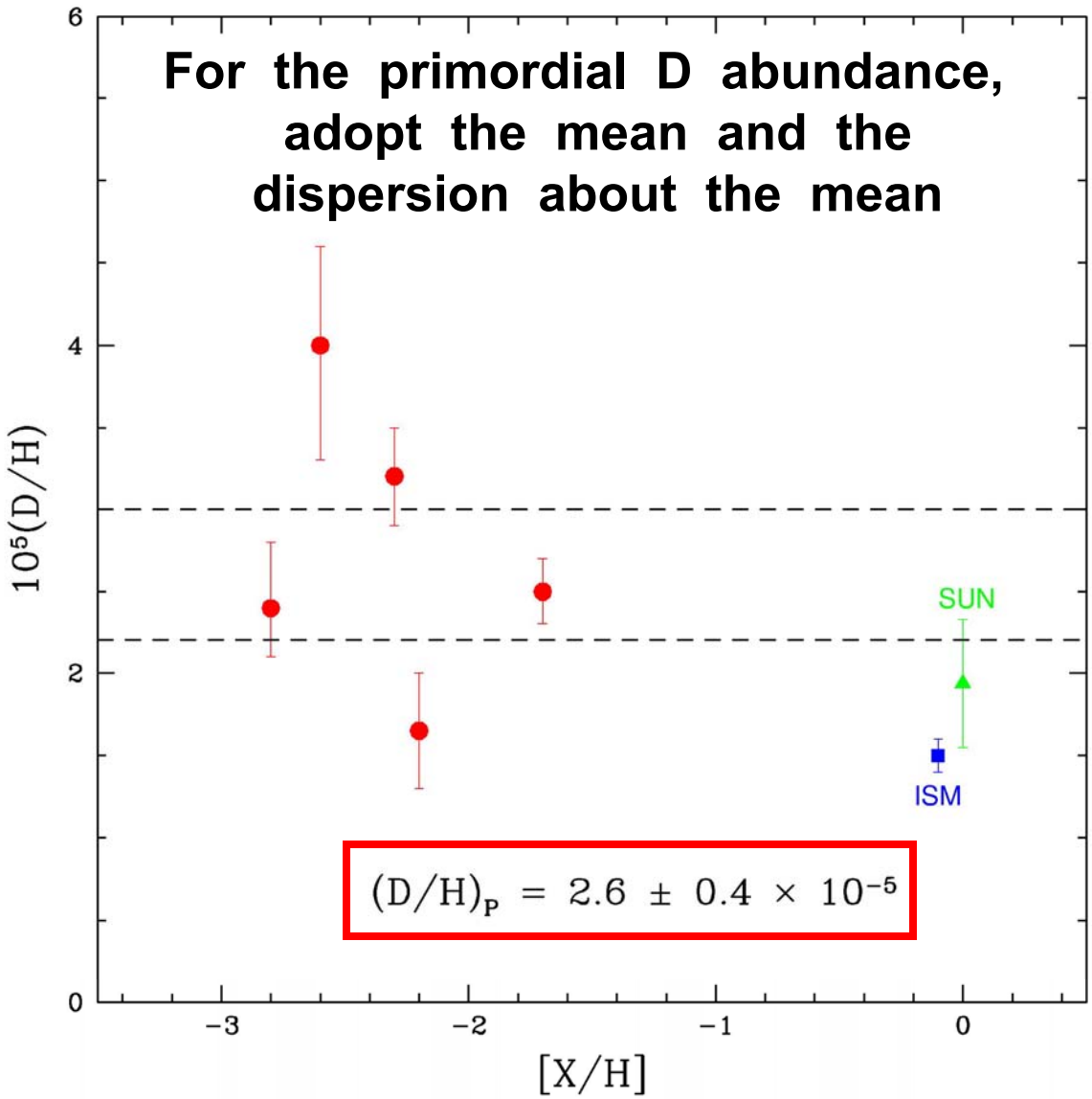
- $(D/H)_P$ is sensitive to the baryon density ($\propto \eta_{10}^{-1.6}$)
- H I and D I are seen in Absorption BUT ...

  * H I and D I spectra are identical $\Rightarrow$ H I Interlopers?

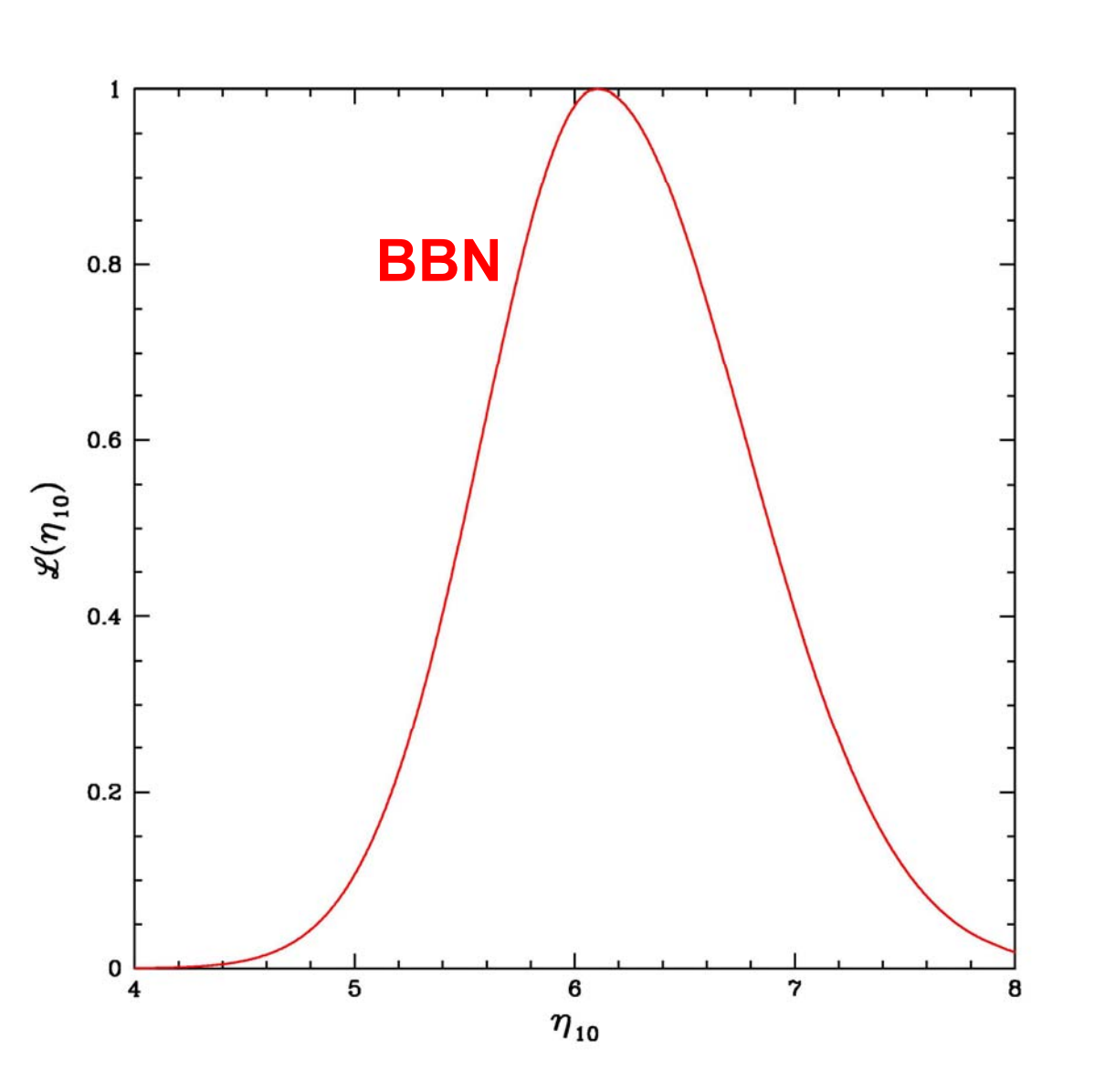
  * Unresolved velocity structure $\Rightarrow$ Errors in N(H I) ?

D/H vs. Metallicity



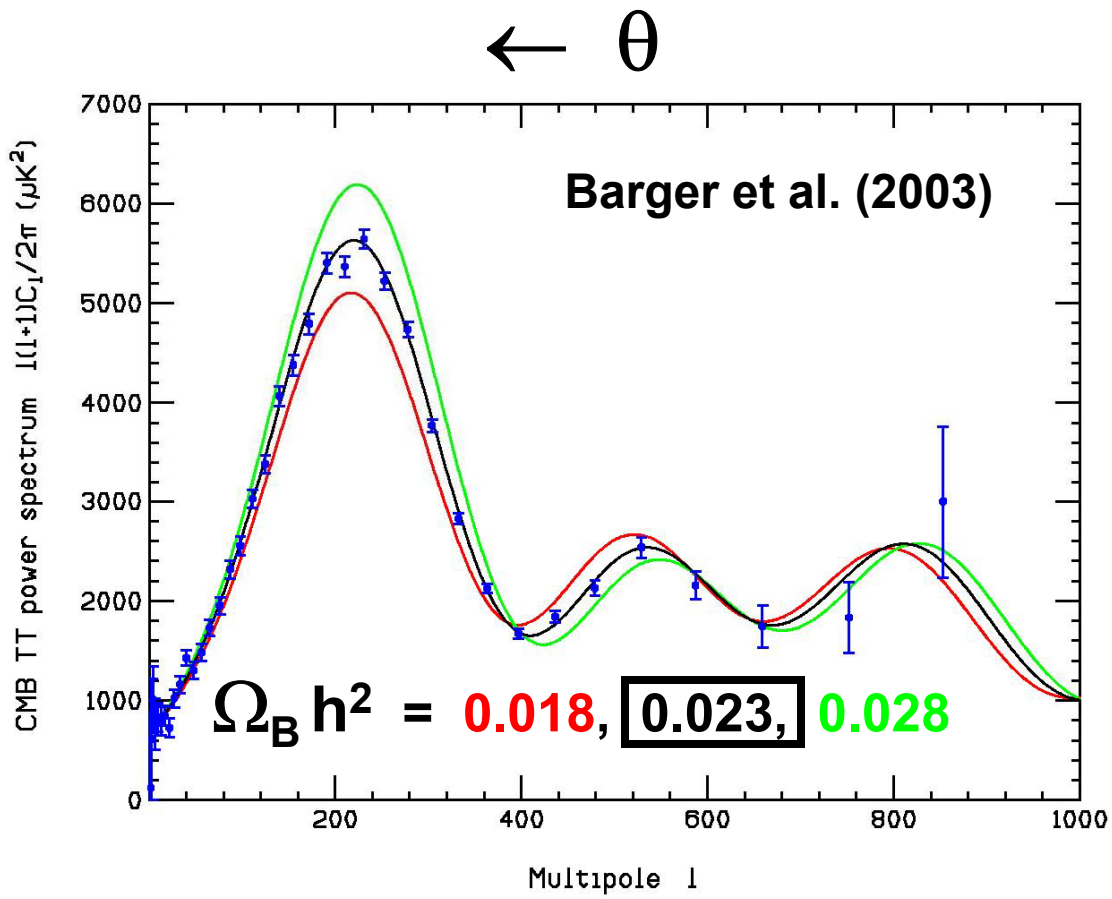

For the primordial D abundance, adopt the mean and the dispersion about the mean
SUN
ISM
$(D/H)_P = 2.6 \pm 0.4 \times 10^{-5}$
$10^5(D/H)$
[X/H]
6
4
2
0
−3
−2
−1
0

$(D/H)_P = 2.6 \pm 0.4 \times 10^{-5}$ + SBBN $\Rightarrow \eta_{10} = 6.1 \pm 0.6$



CBR Temperature Anisotropy Spectrum

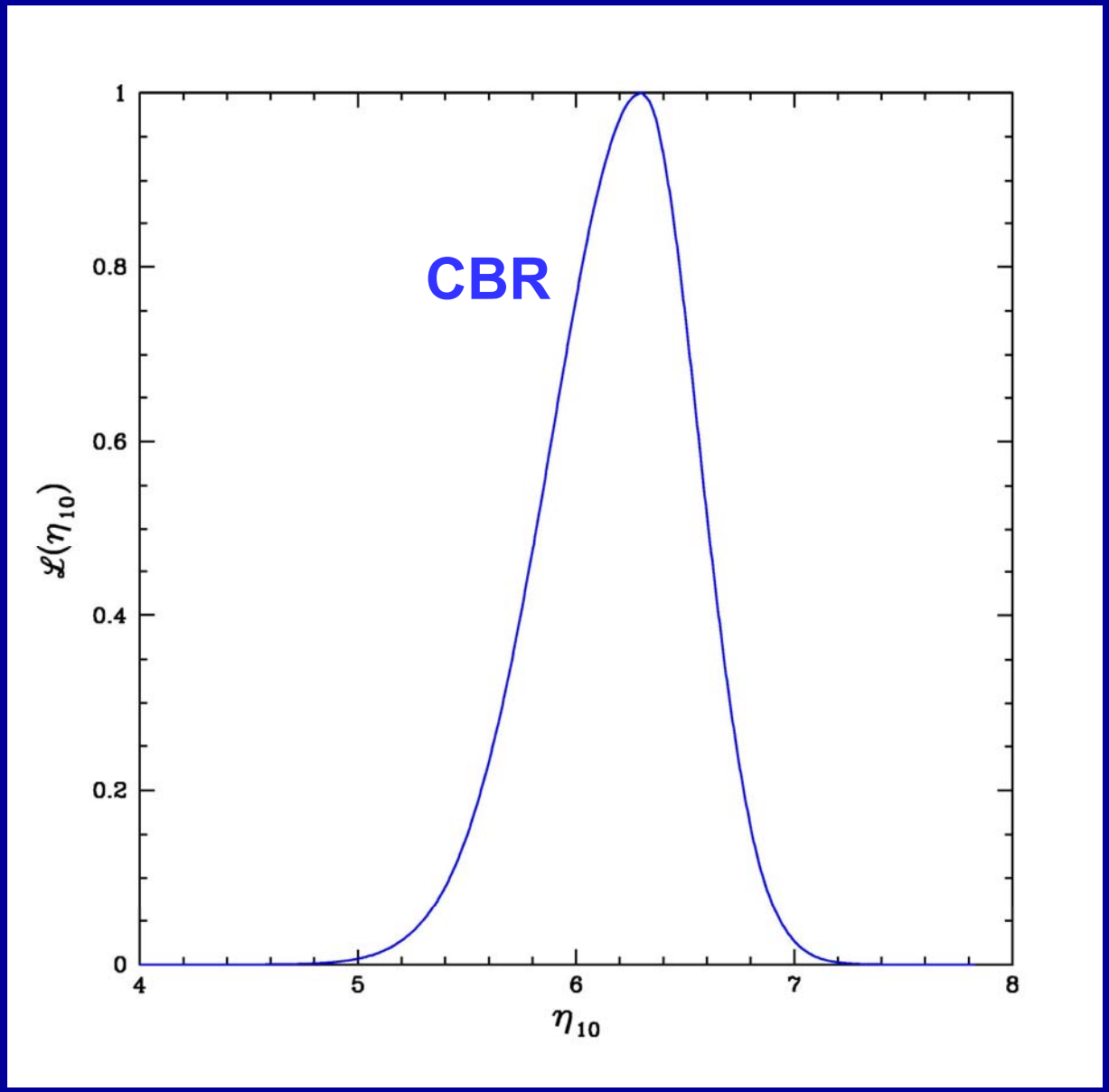
(ΔT^2 vs. θ) Encodes The Baryon Density (ω_B)



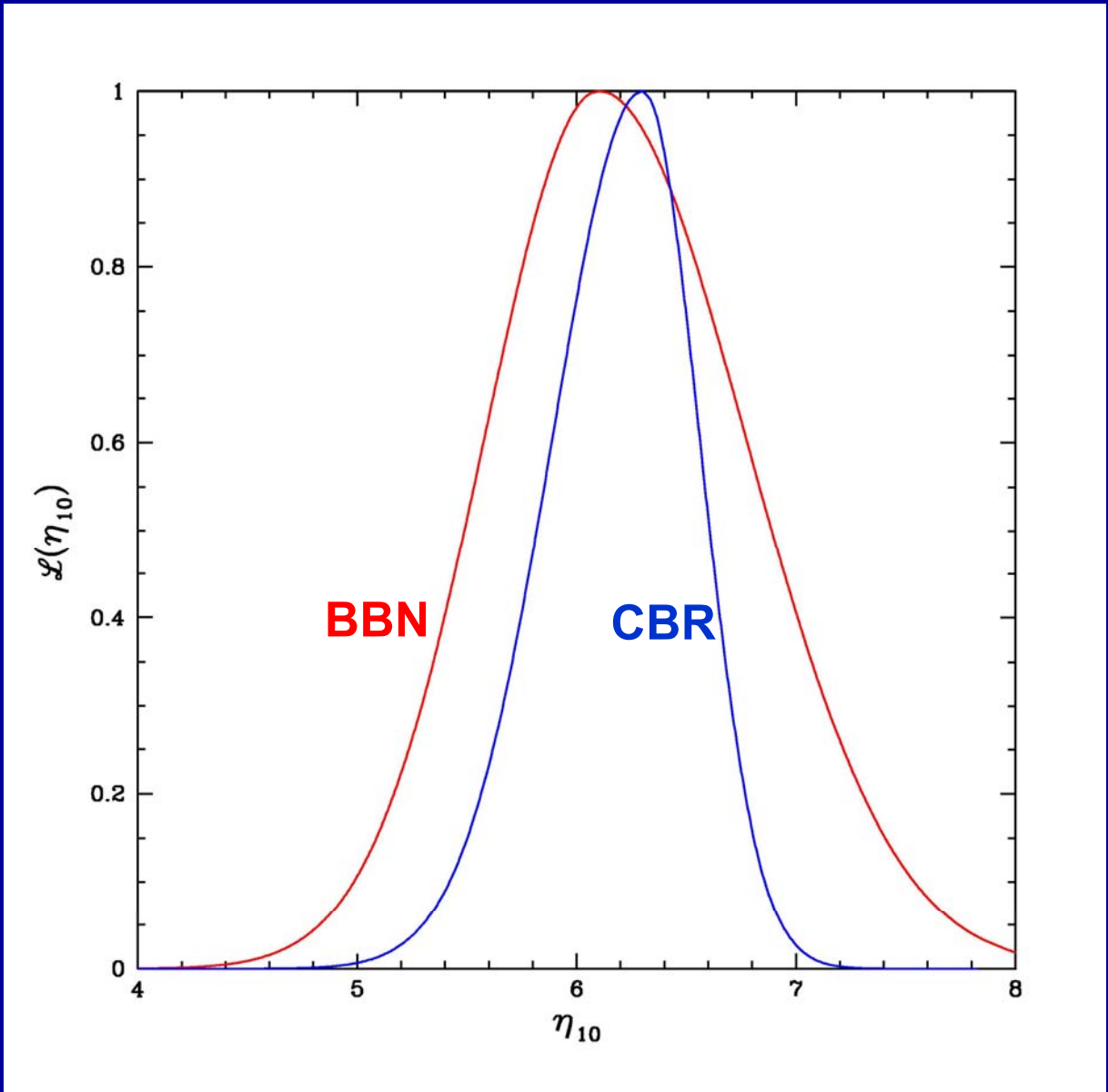
CBR (WMAP) constrains $\Omega_B h^2$

The CBR is (also) an early - Universe Baryometer

CBR (WMAP ALONE !) $\Rightarrow \eta_{10} = 6.3 \pm 0.3$



BBN (20 min) & CBR (380 kyr) AGREE !

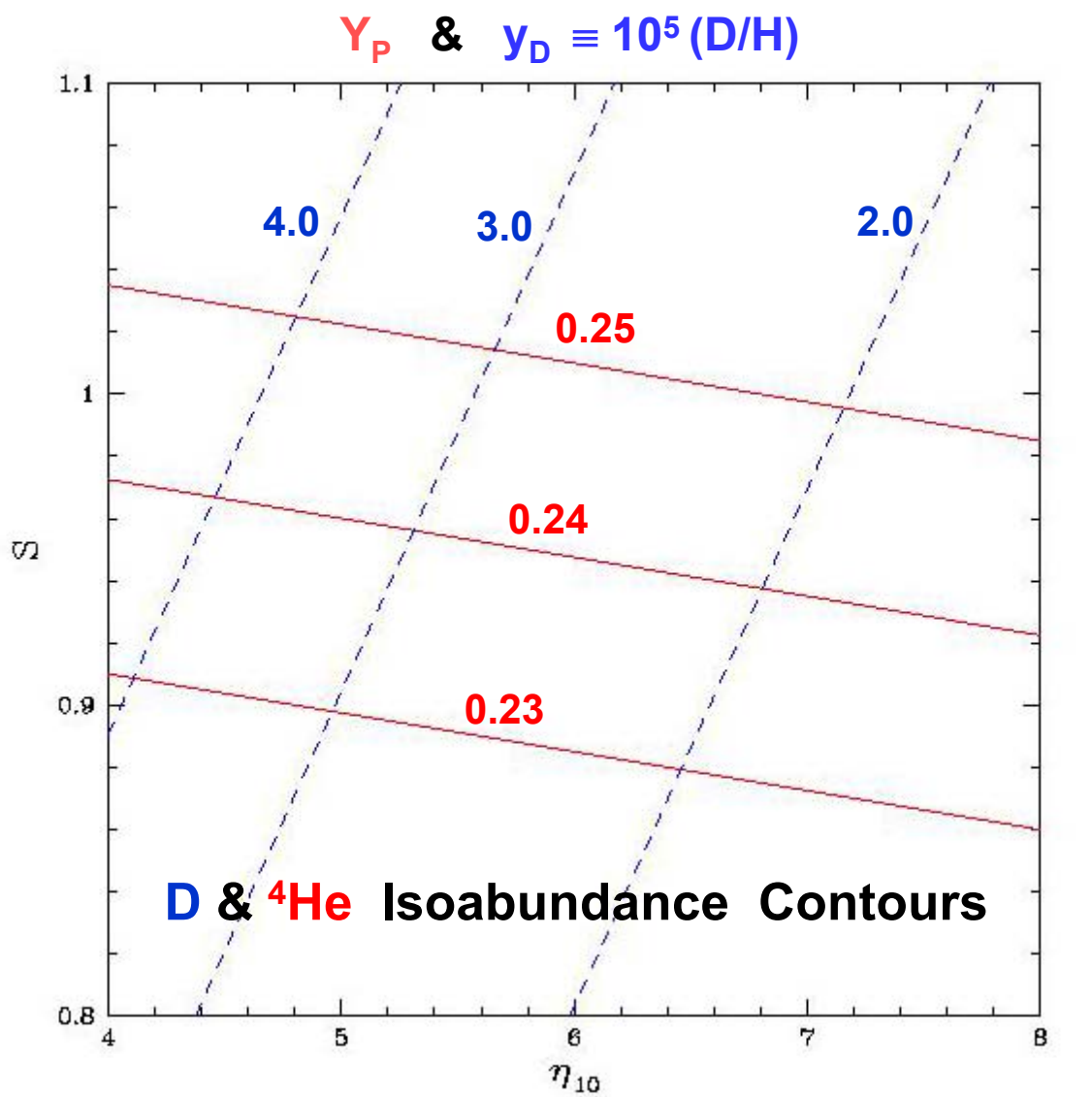


The Expansion Rate Provides A

Probe Of Non-Standard Physics

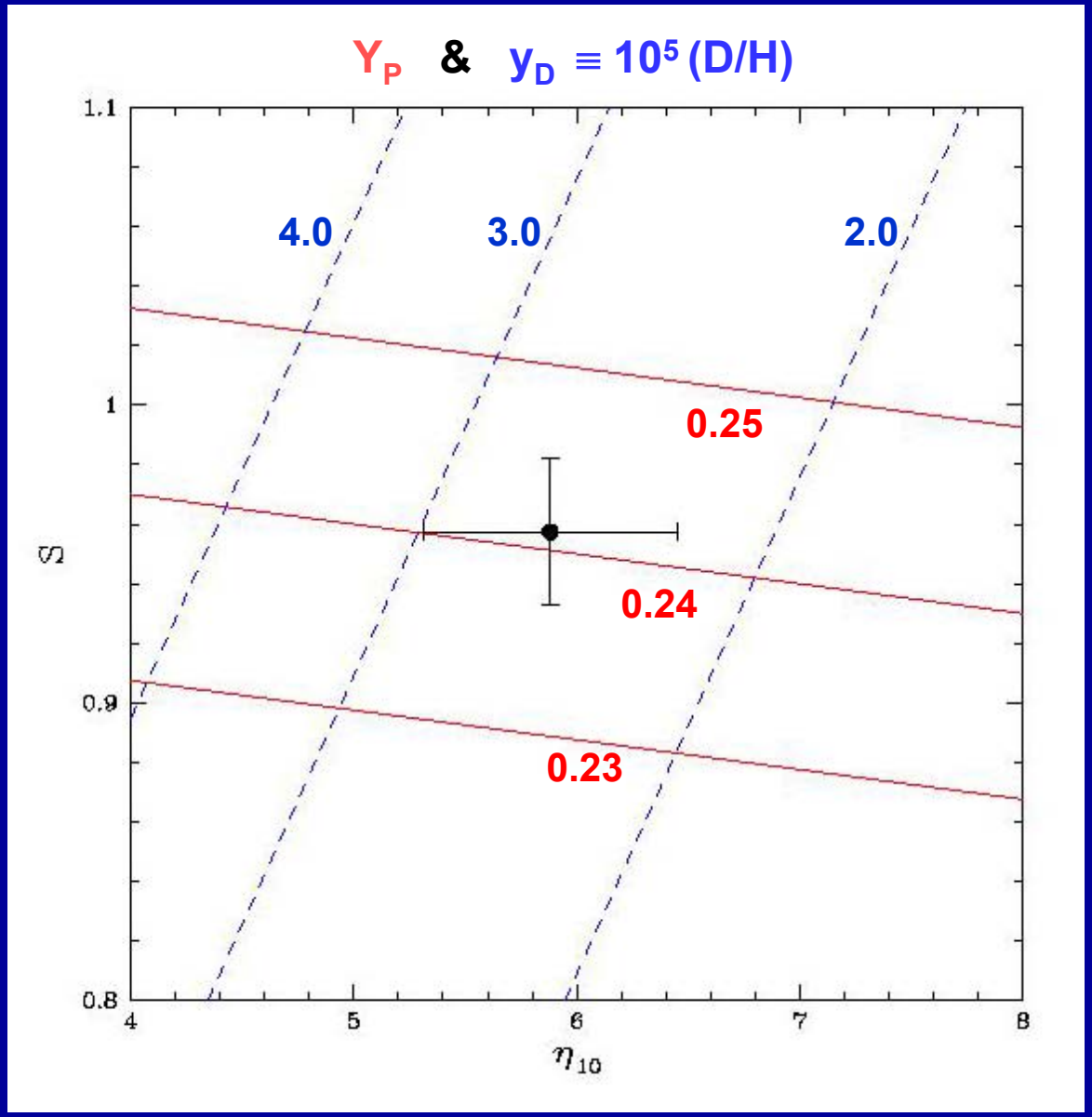
$$S \equiv H'/H \equiv (G'\rho'/G\rho)^{1/2} \equiv (1 + 7\Delta N_\nu/43)^{1/2}$$

^{4}He is sensitive to S & D probes η



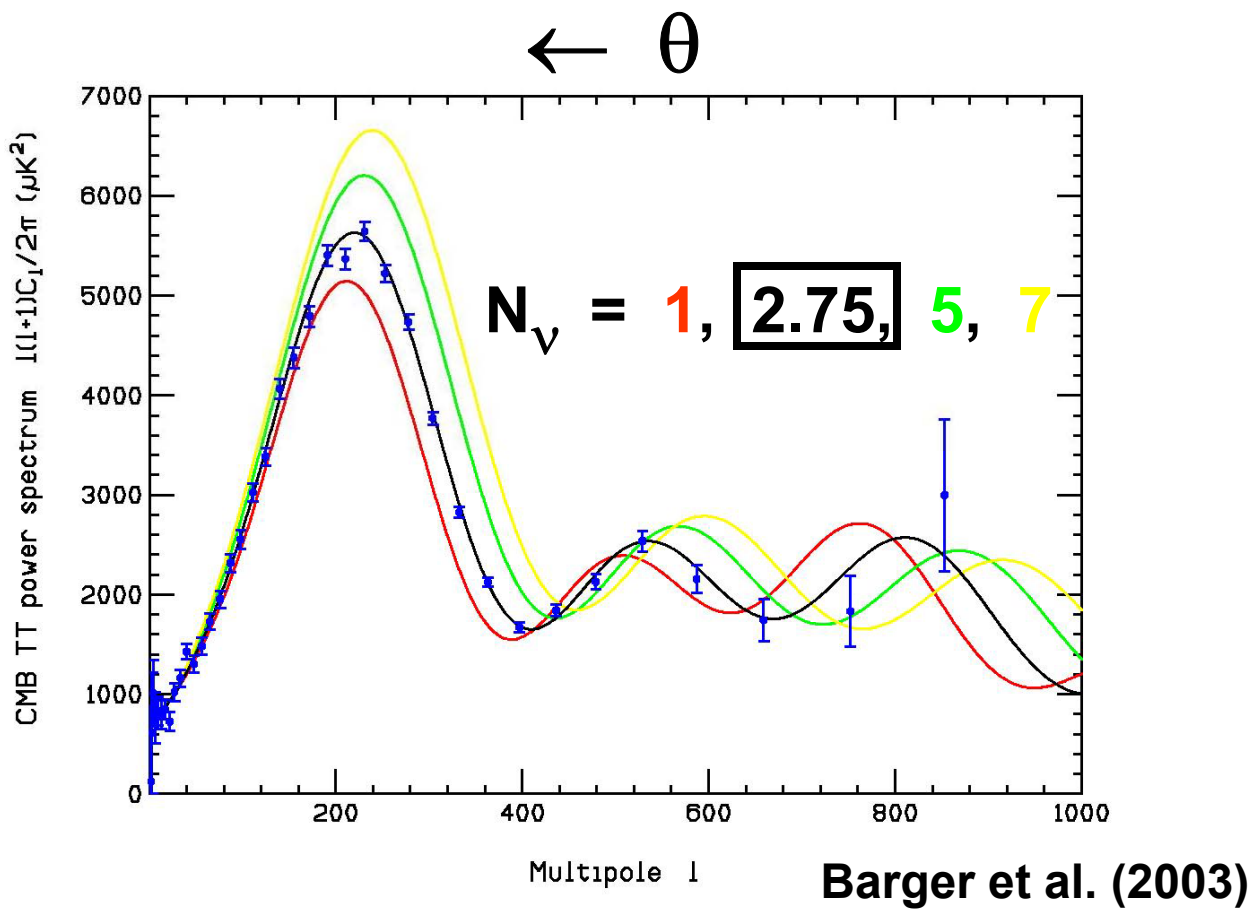
Kneller & Steigman (2004)

BBN (D, ^{4}He) ✓ For $N_\nu \approx 2.5 \pm 0.3$



CBR Temperature Anisotropy Spectrum (ΔT^2 vs. θ)

Encodes the Radiation Density ρ_R (ΔN_ν)

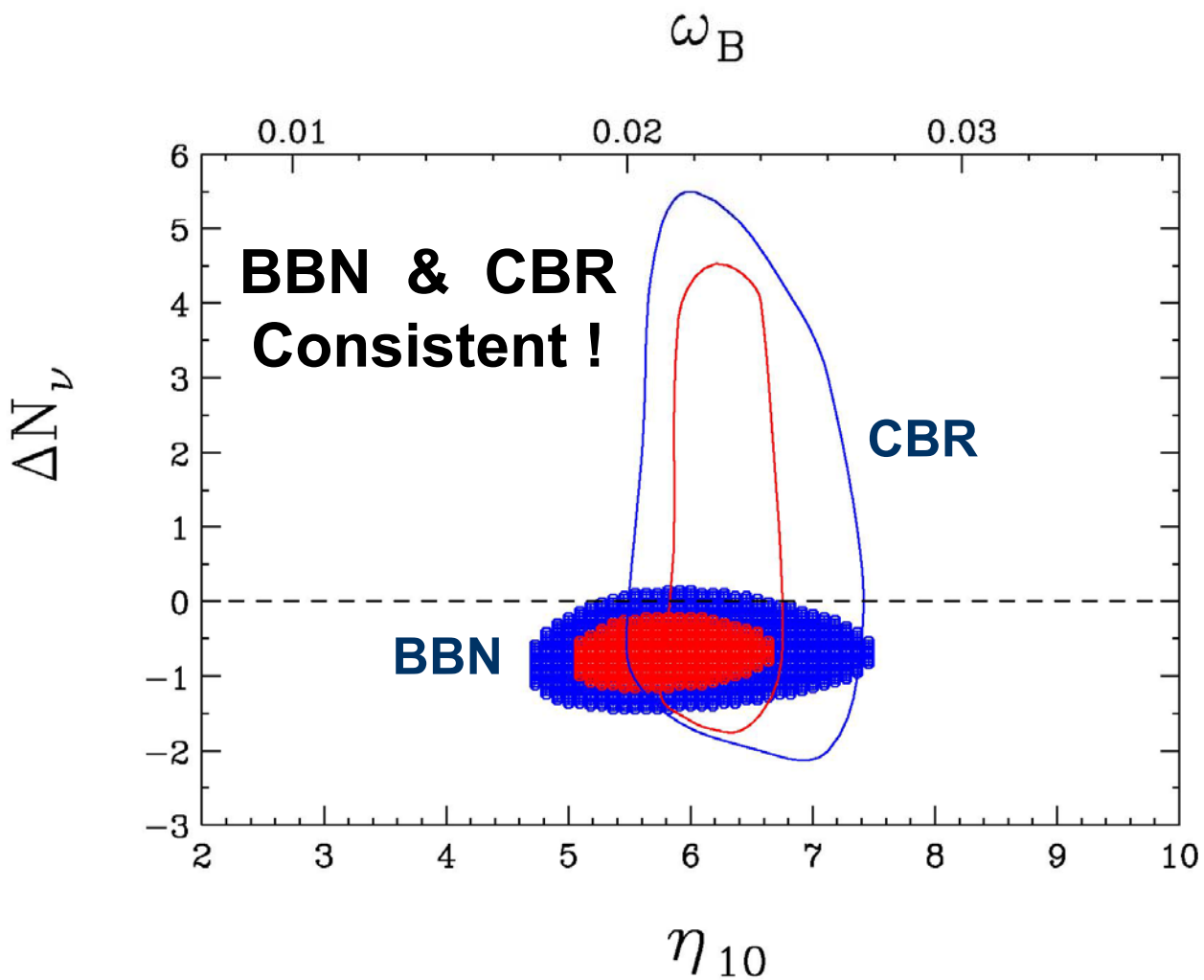


Barger et al. (2003)

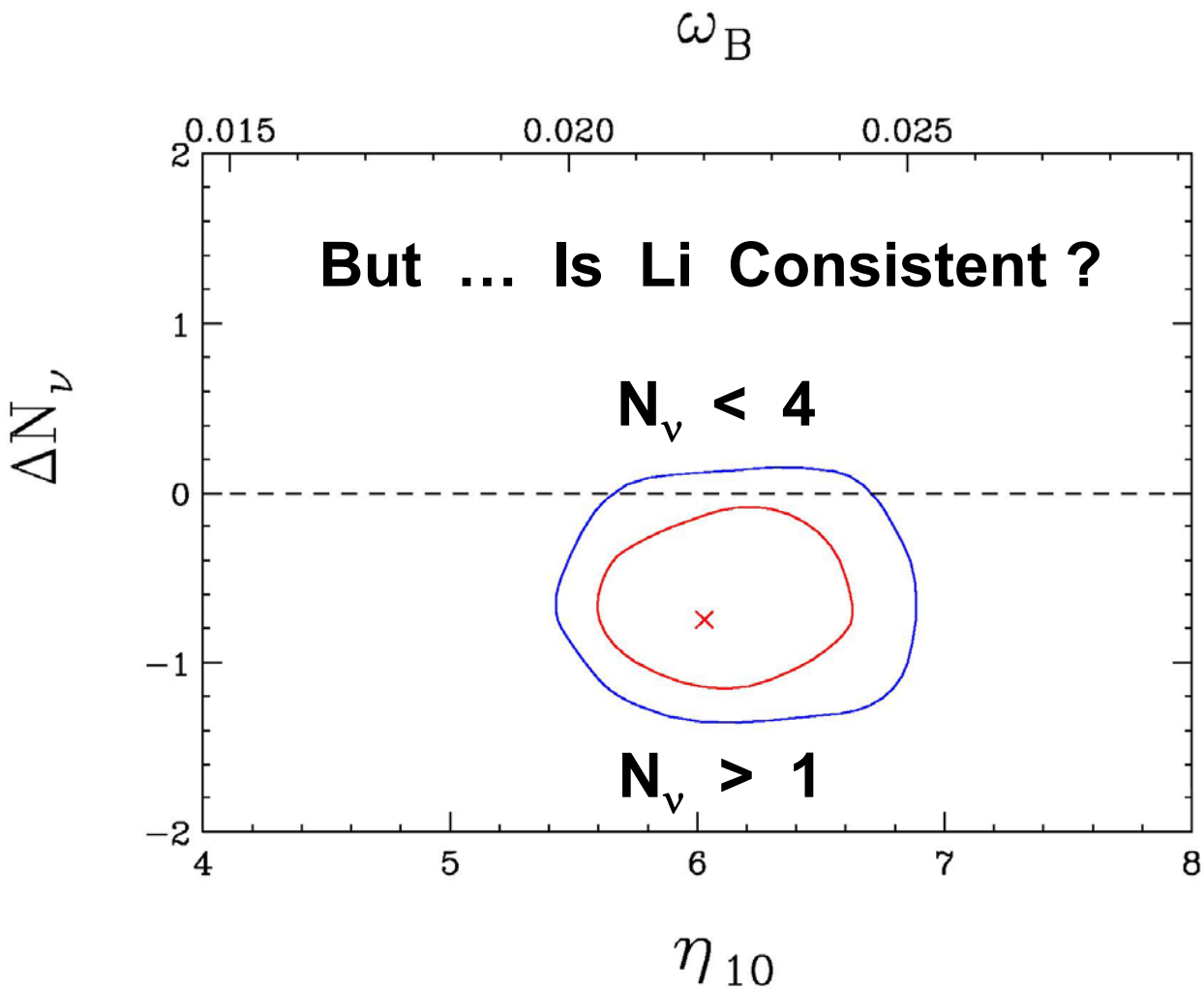
CBR (WMAP) constrains N_ν (S)

The CBR is an early - Universe Chronometer

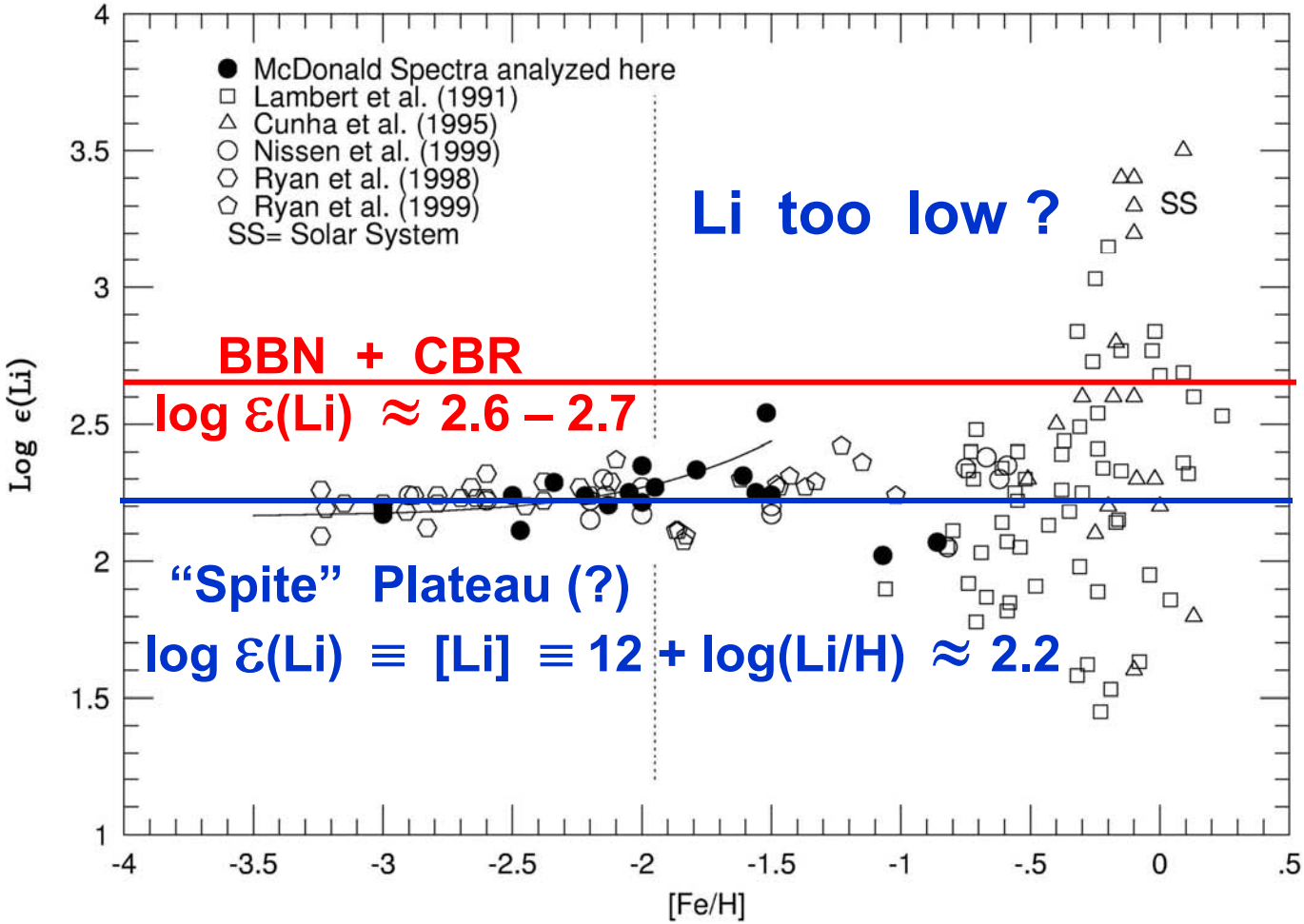
BBN (D & ^{4}He) + CBR (WMAP)



Joint BBN (D & ^{4}He) & CBR Fit



Li/H vs. Fe/H


McDonald Spectra analyzed here
Lambert et al. (1991)
Cunha et al. (1995)
Nissen et al. (1999)
Ryan et al. (1998)
Ryan et al. (1999)
SS= Solar System
Li too low ?
SS
BBN + CBR
log ε(Li) ≈ 2.6 – 2.7
"Spite" Plateau (?)
log ε(Li) ≡ [Li] ≡ 12 + log(Li/H) ≈ 2.2
Log ε(Li)
[Fe/H]
4
3.5
3
2.5
2
1.5
1
-4
-3.5
-3
-2.5
-2
-1.5
-1
-.5
0
.5

Even for $N_\nu \neq 3$

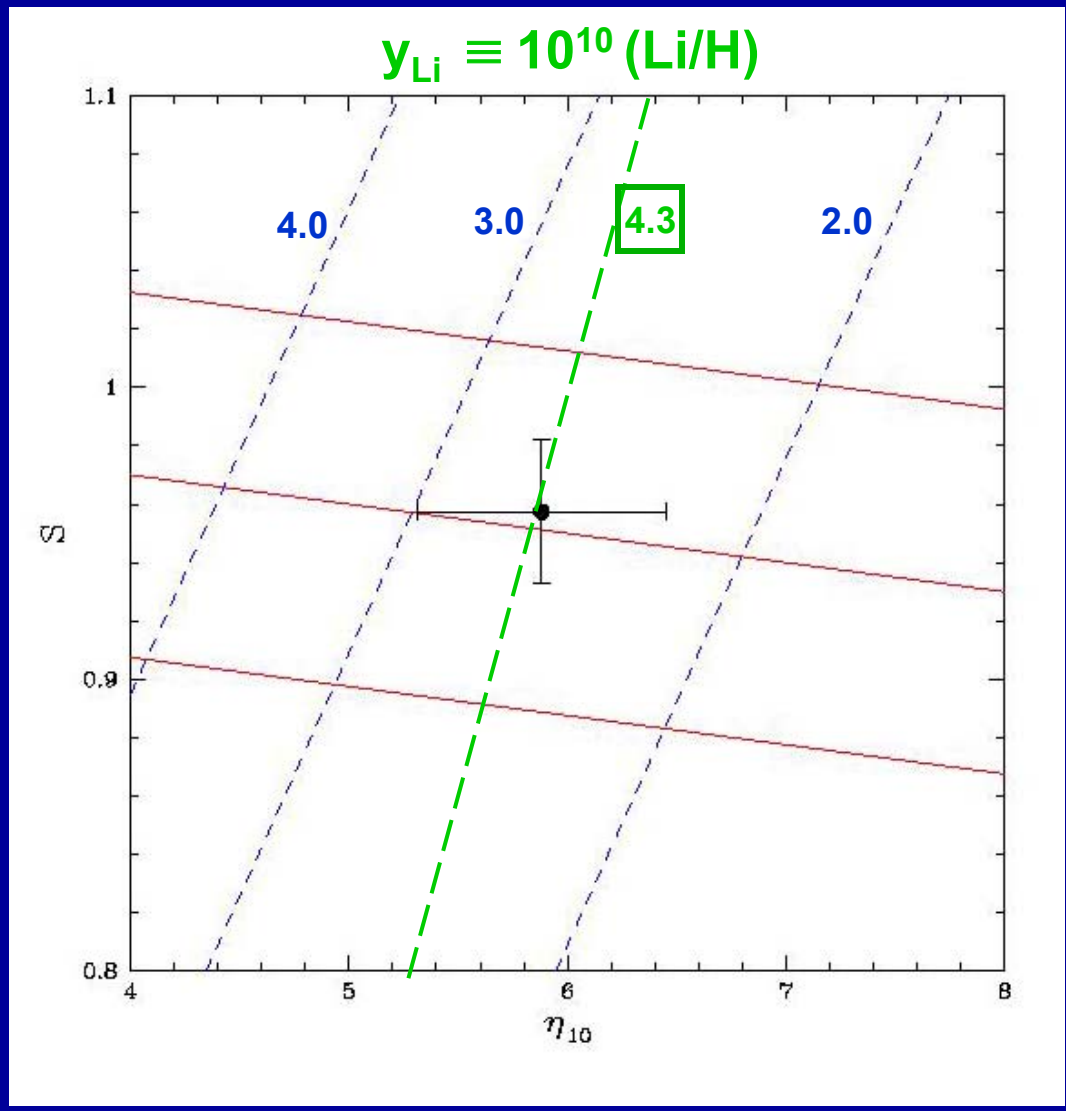
$Y + D/H \Rightarrow$

$Li/H \approx 4.3 \pm 0.9 \times 10^{-10}$

$\Rightarrow \log \varepsilon(Li) \approx 2.6 \pm 0.1$

Li depleted / diluted

in Pop II stars ?



SUCCESSES

- SBBN ($N_\nu = 3$) D / H & CBR (WMAP) ✓

- BBN (D & ^{4}He) & CBR agree for :

$\eta_{10} \approx 6.1$ ($\Omega_B h^2 \approx 0.022$) & $N_\nu \approx 2.5$

* 95% Ranges :

$1.9 \leq N_\nu \leq 3.1$ &

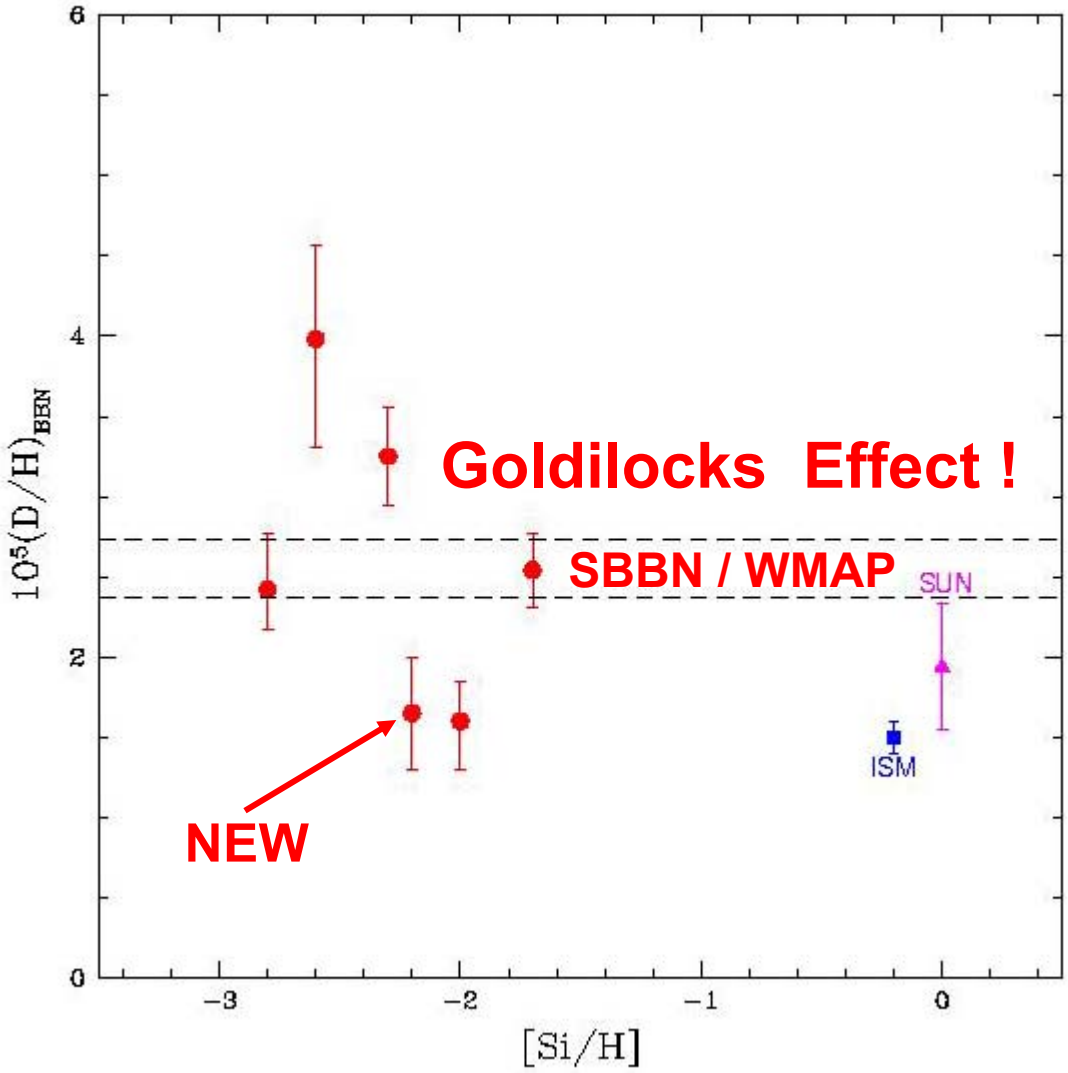
$5.5 \leq \eta_{10} \leq 6.6$ ($0.020 \leq \Omega_B h^2 \leq 0.025$)

Challenge:

- Dispersion in D/H too large ?

- Need more data

  - - - be careful what you wish for !


Goldilocks Effect !
SBBN / WMAP
SUN
ISM
NEW
$10^5(D/H)_{BBN}$
[Si/H]
6
4
2
0
−3
−2
−1
0

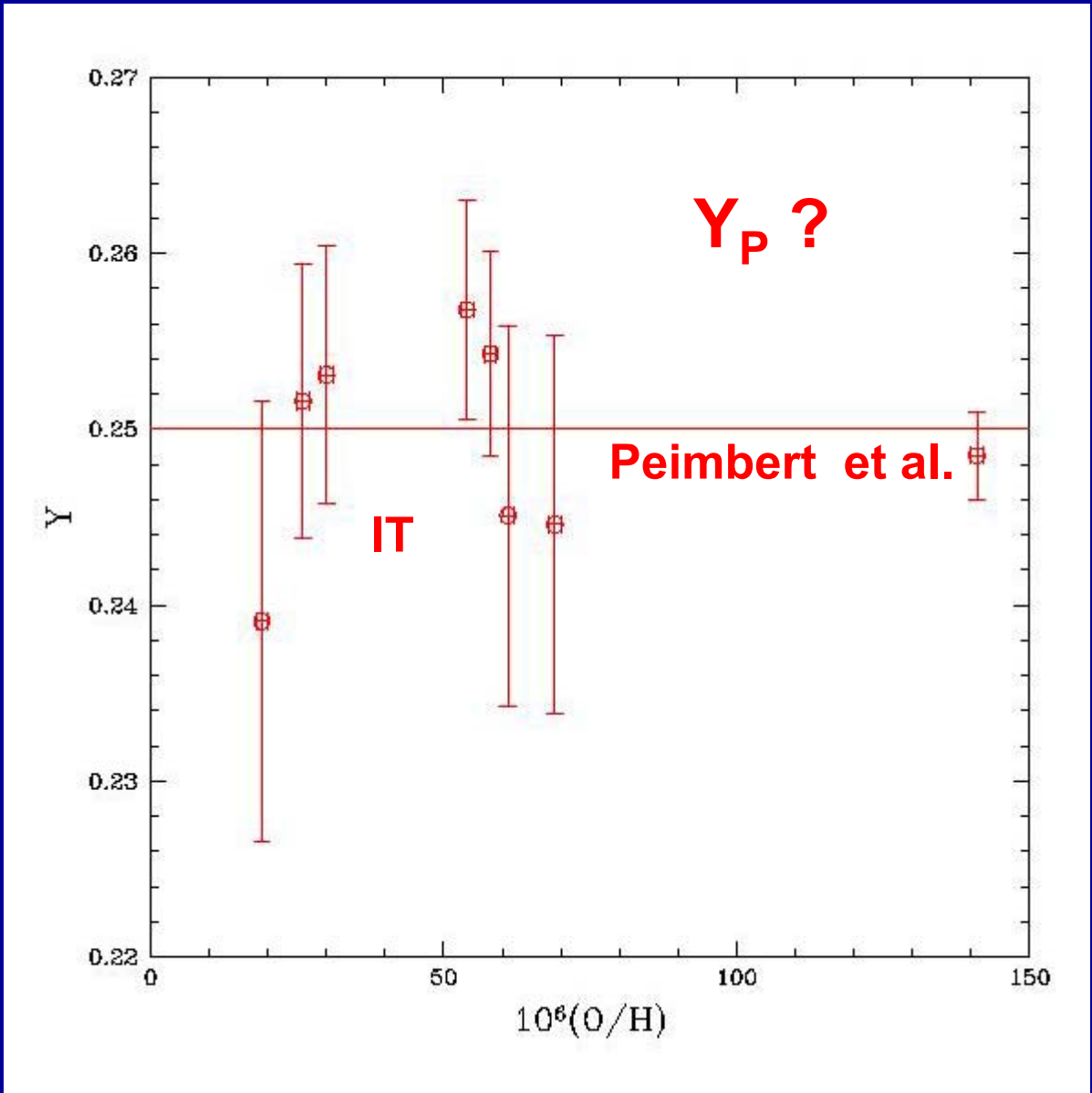
Challenge:

- Observed ^{4}He too low ?

- Olive & Skillman reanalysed Izotov & Thuan and Peimbert et al. (SMC) data

  $\Rightarrow$ Errors in Y should be increased

Y(OS) vs. O/H from IT & Peimbert et al. data

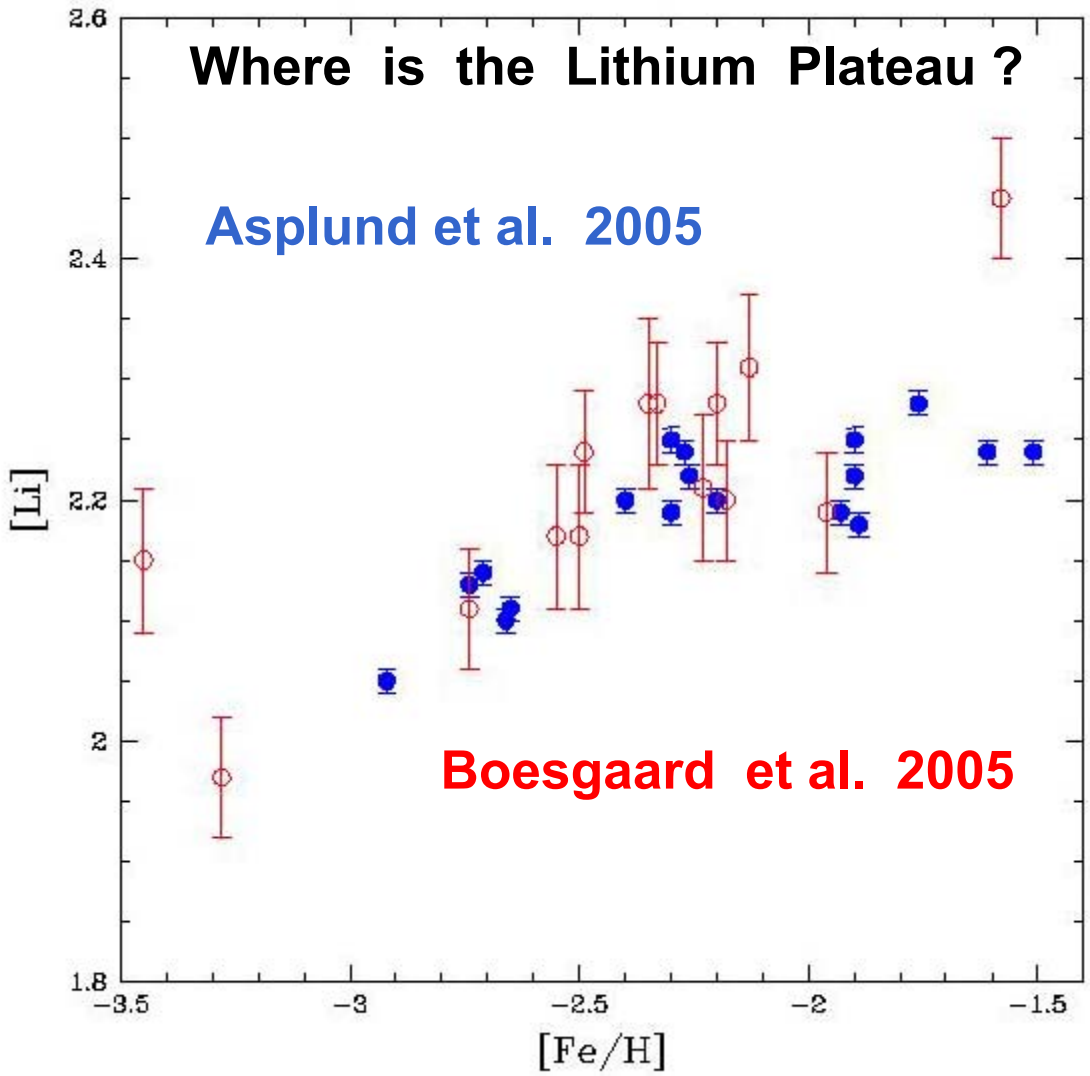


Challenge:

- Observed Li too low ?

- New Observations :

  Asplund et al. & Boesgaard et al.


Where is the Lithium Plateau ?
Asplund et al. 2005
Boesgaard et al. 2005
[Li]
[Fe/H]
2.6
2.4
2.2
2
1.8
−3.5
−3
−2.5
−2
−1.5

SUCCESS

BBN and the CBR Agree !

CHALLENGE

(The Theorist's Mantra)

More / Better Data Are Needed !

Precision ≡ Accuracy ?