NEUTRINOS, BBN, and the CBR

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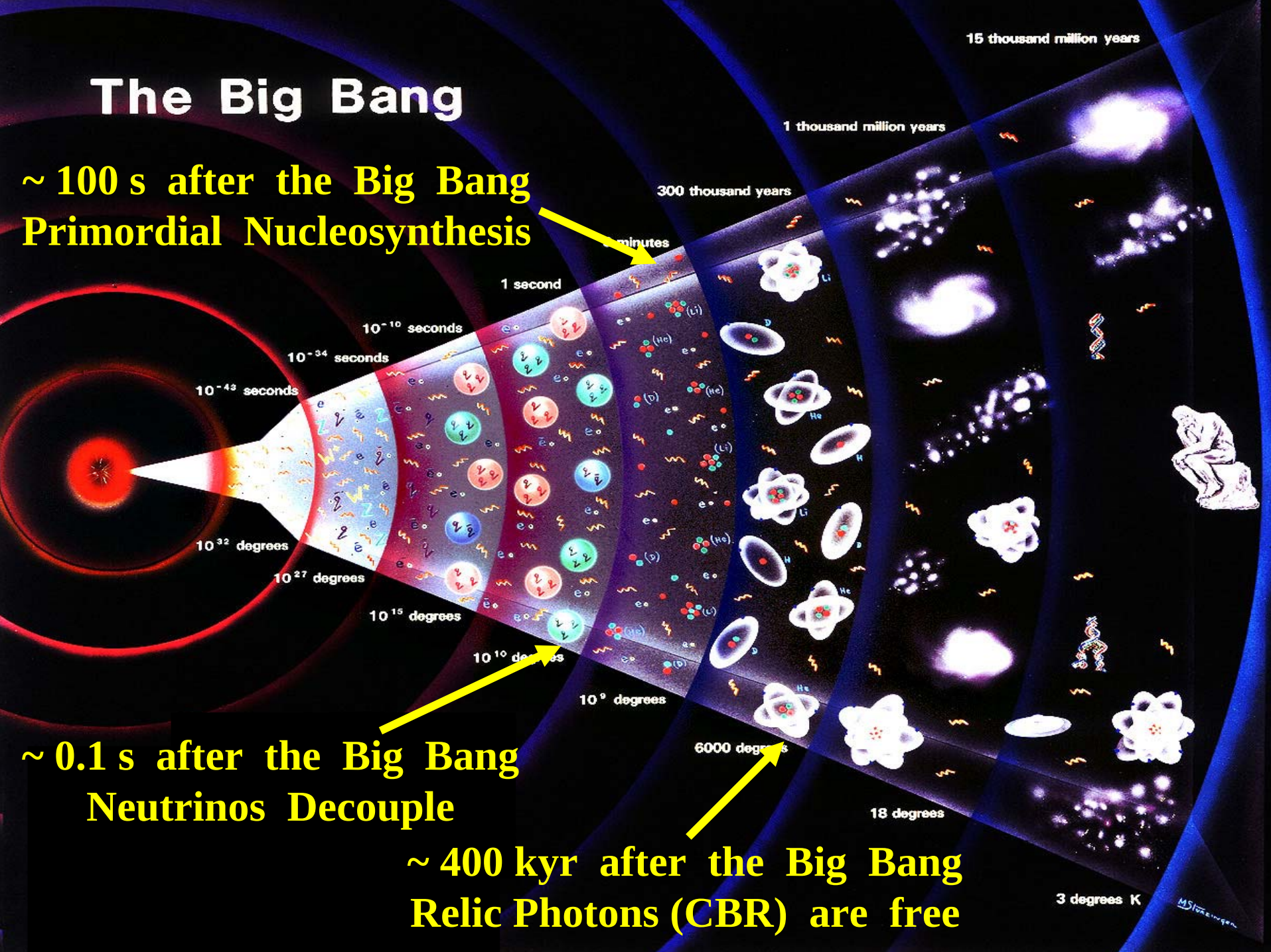

The Big Bang
~ 100 s after the Big Bang
Primordial Nucleosynthesis
~ 0.1 s after the Big Bang
Neutrinos Decouple
~ 400 kyr after the Big Bang
Relic Photons (CBR) are free
15 thousand million years
1 thousand million years
300 thousand years
minutes
1 second
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K

BBN & The CBR Provide Complementary Probes Of The Early Universe

Do predictions and observations of the baryon density and the expansion rate agree at 20 minutes and at 400 kyr ?

Baryon Density Parameter

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

where : $\Omega_B \equiv \rho_B / \rho_c$

and : $h \equiv H_0 / 100$ km / s / Mpc ≈ 0.7

also : $\omega_B \equiv \Omega_B h^2$

Note : Baryons $\Rightarrow$ Nucleons

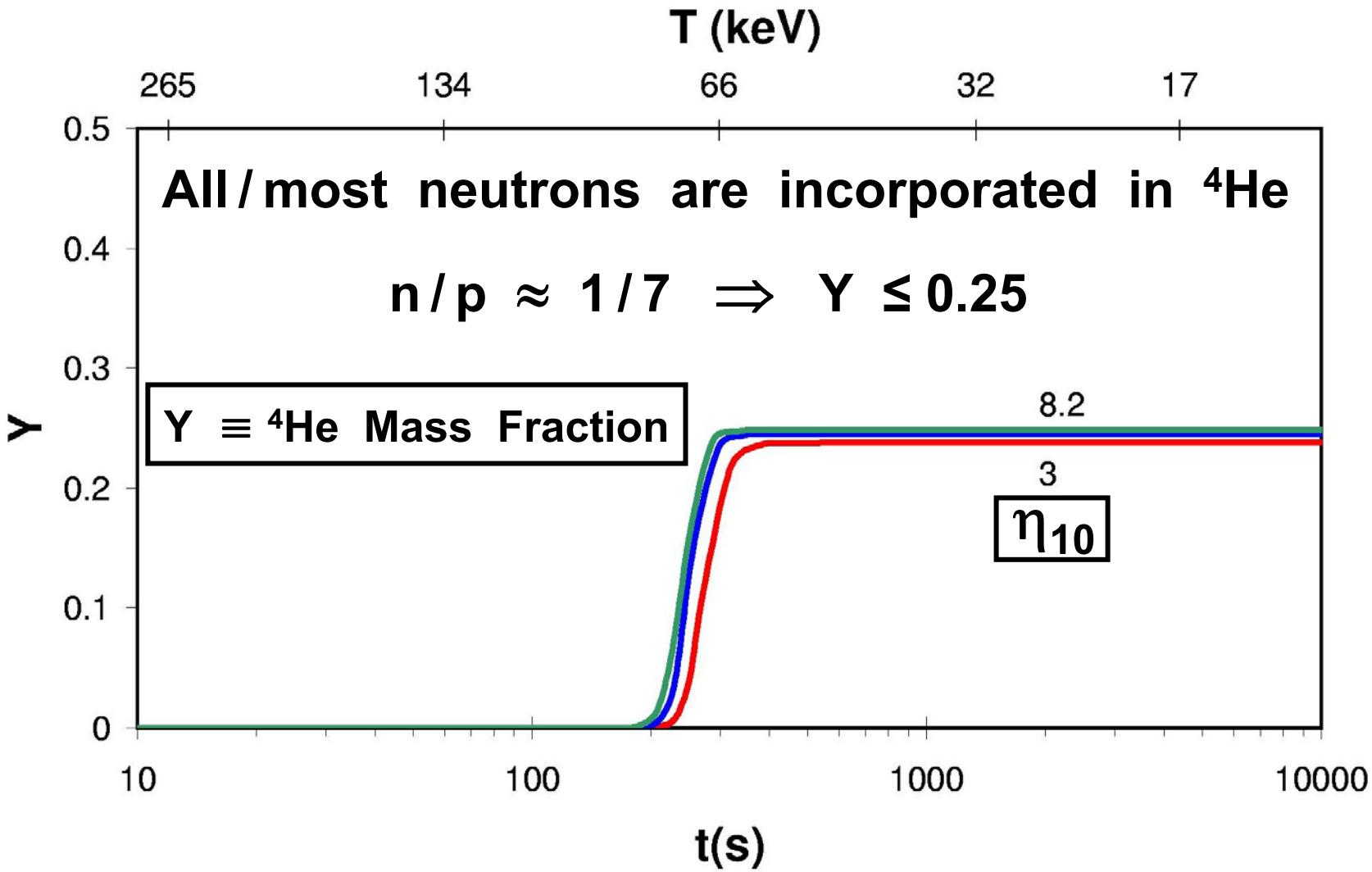
BBN "begins" at $T \approx 70$ keV

when $n / p \approx 1 / 7$

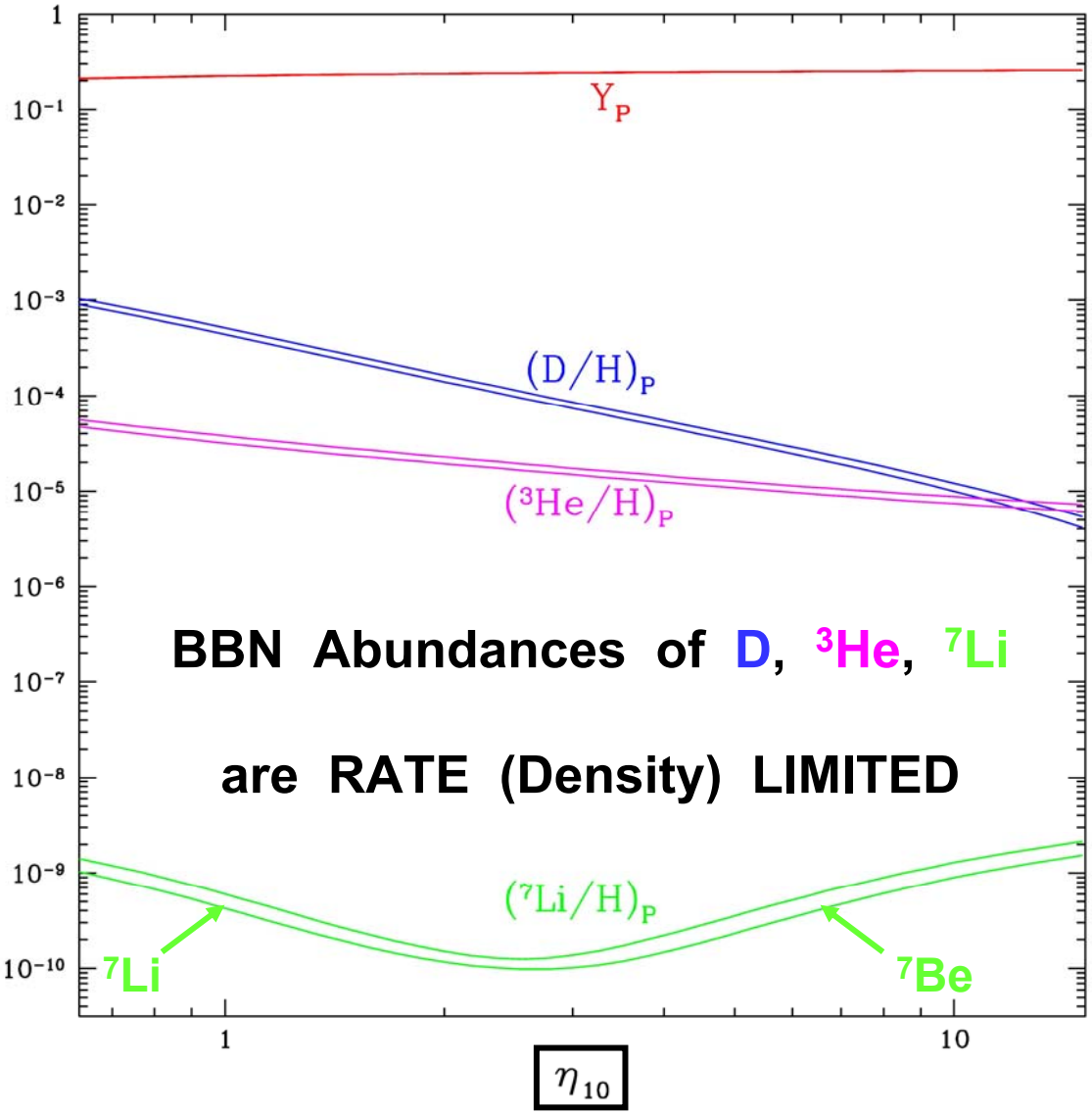
Coulomb Barriers and the absence of free neutrons terminate BBN at $T \approx 30$ keV

$$\Rightarrow t_{BBN} \approx 4 \rightarrow 24 \text{ min.}$$

Y is VERY WEAKLY dependent on the nucleon abundance



BBN – Predicted Primordial Abundances



BBN Abundances of D, ^{3}He, ^{7}Li

are RATE (Density) LIMITED

D, ^{3}He, ^{7}Li are potential BARYOMETERS

- ^{4}He (mass fraction Y) is NOT Rate Limited

- ^{4}He IS n/p Limited $\Rightarrow$ Y is sensitive to the

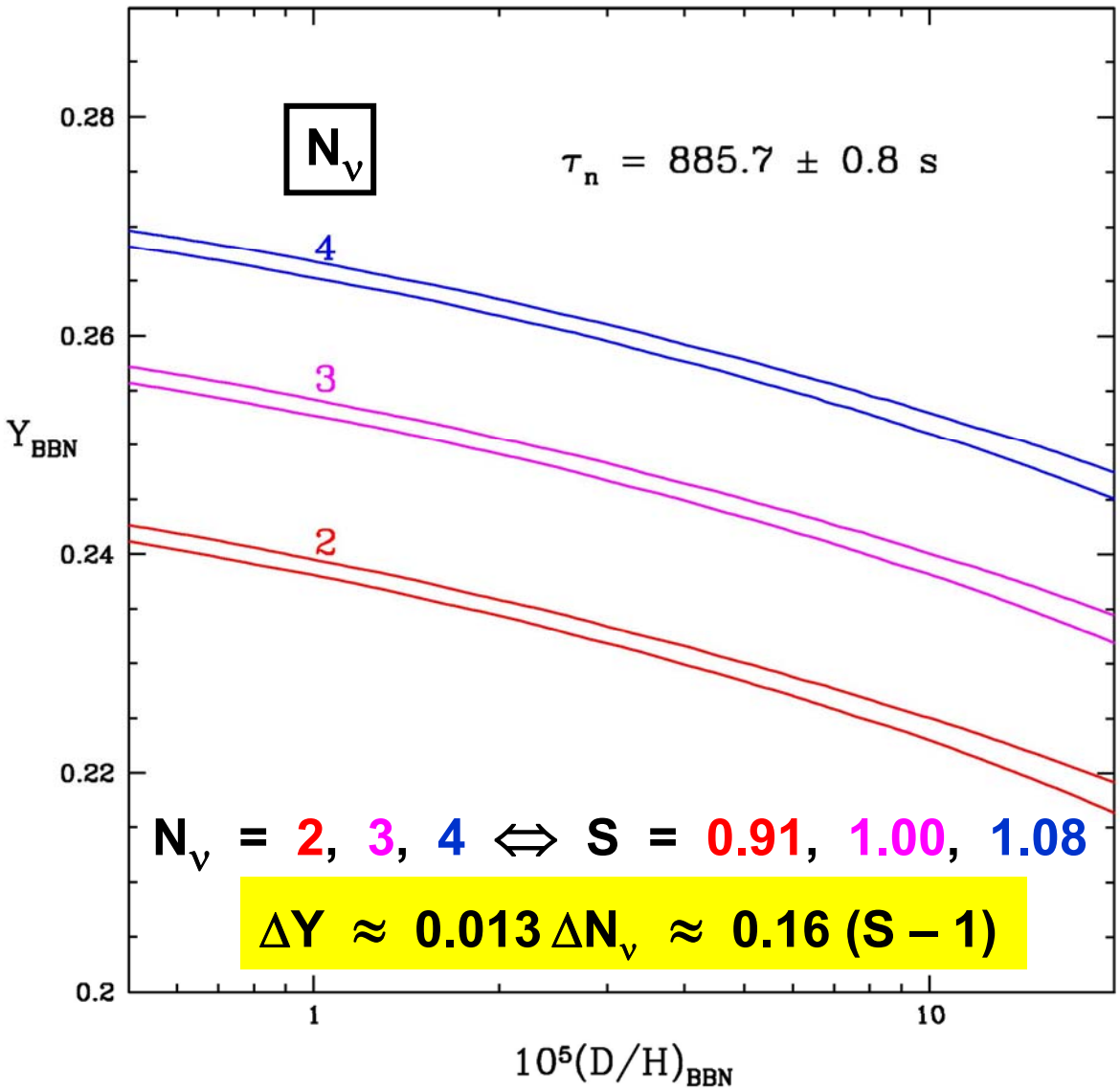
  EXPANSION RATE ($H \propto \rho^{1/2}$)

  - Expansion Rate Parameter : $S \equiv H'/H$

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

    where : $\rho' \equiv \rho + \Delta N_\nu \rho_\nu$ and $N_\nu \equiv 3 + \Delta N_\nu$

Y vs. D/H for N_ν = 2, 3, 4



N_ν = 2, 3, 4 ⇔ S = 0.91, 1.00, 1.08

$\Delta Y \approx 0.013\,\Delta N_\nu \approx 0.16\,(S-1)$

^{4}He is an early – Universe Chronometer

Non-Standard BBN (An Example)

Late Decay of a

Massive Particle

&

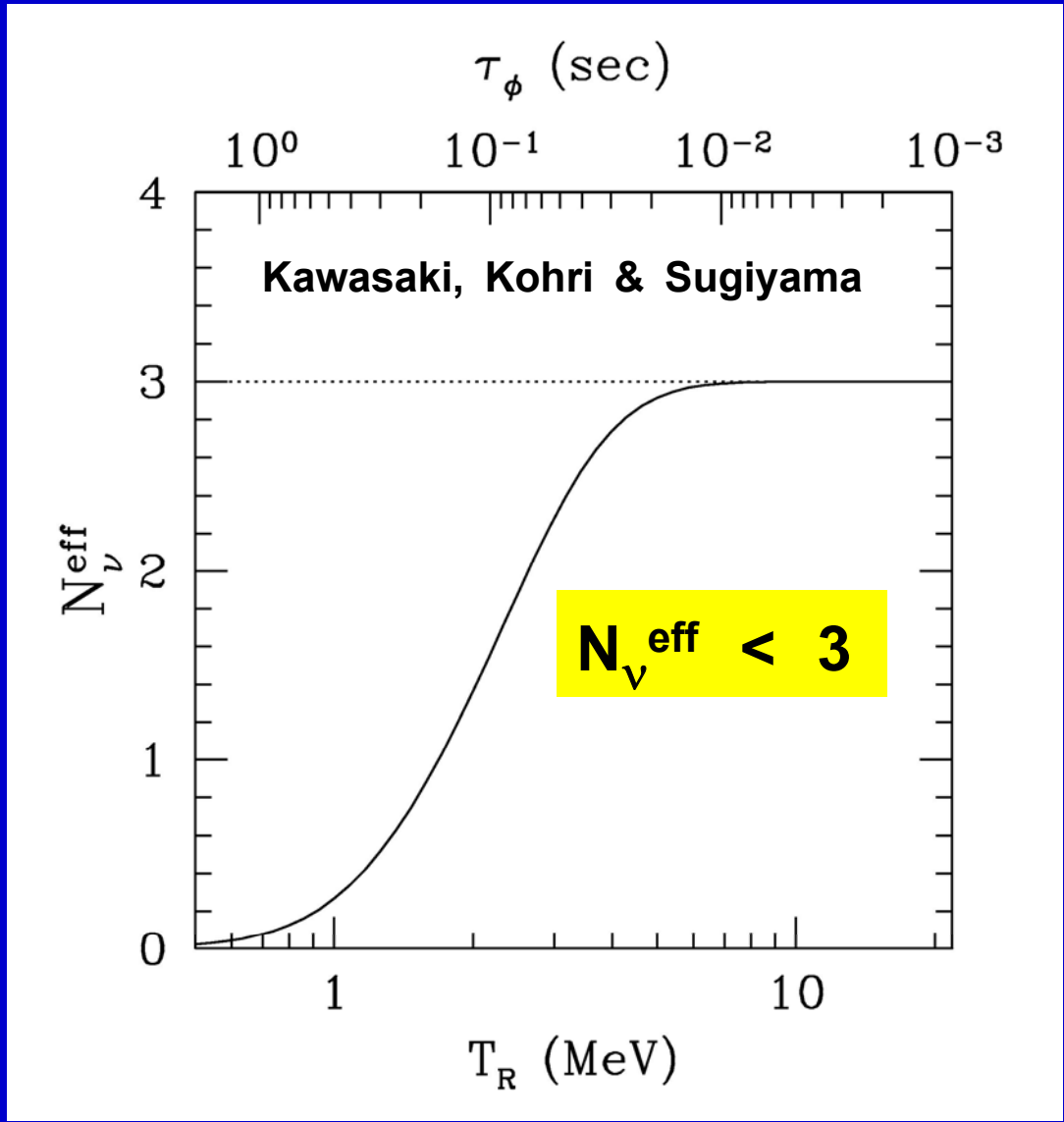
Low Reheat Temp.

(T_R ~ MeV)

$\Rightarrow$

Relic Neutrinos Not

Fully (Re) Populated



Alternative to $N_\nu \neq 3$

e – Neutrino Degeneracy (Non – Zero Lepton Number)

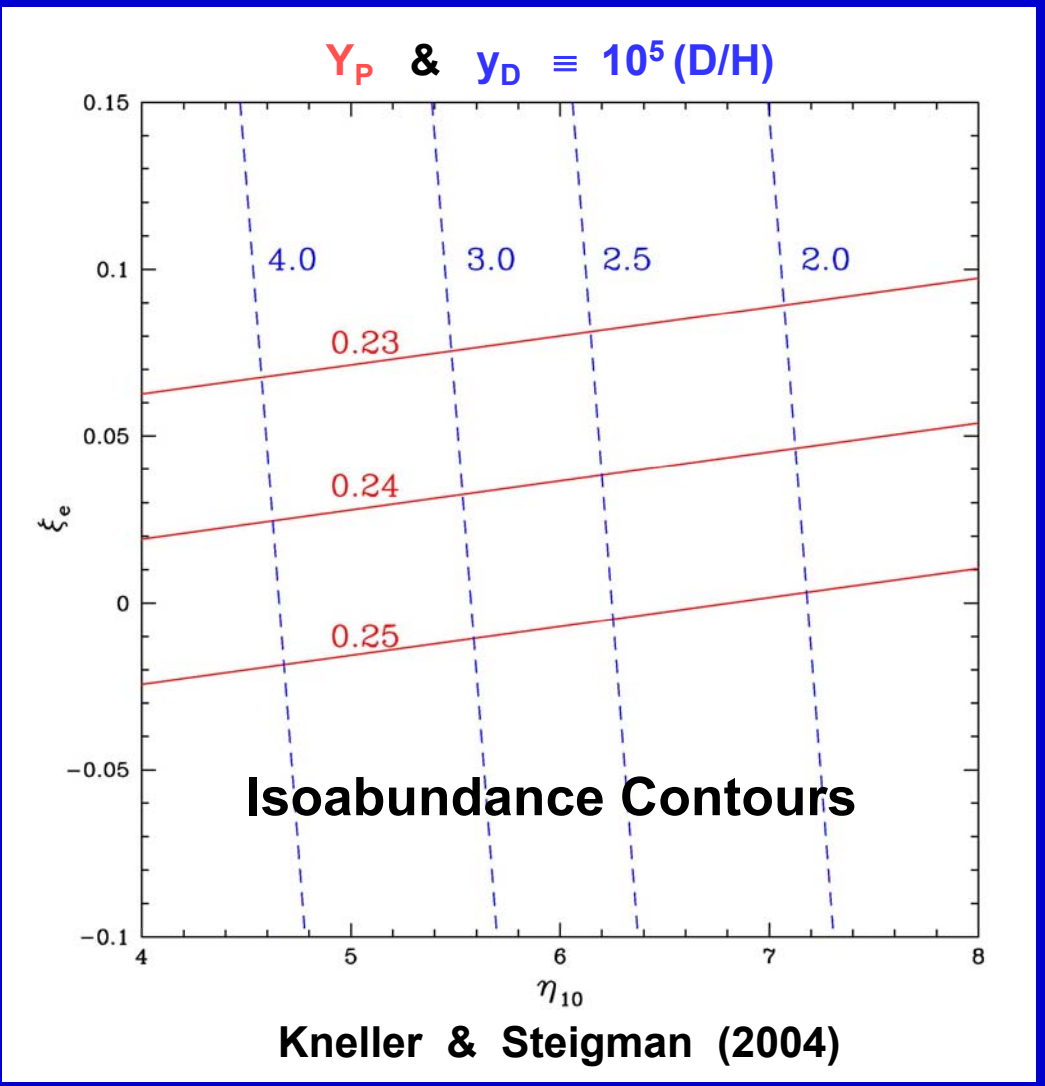
For $\xi_e = \mu_e/kT > 0$

(more ν_e than anti - ν_e)

$n/p \approx \exp(-\Delta m/kT - \xi_e)$

$\Rightarrow$ n/p $\downarrow$ $\Rightarrow$ $Y_P \downarrow$

Y_P is a **neutron** probe



Kneller & Steigman (2004)

DEUTERIUM --- The Baryometer Of Choice

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

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

  * For $t << t_0$ ($Z << Z_\odot$; $z >> 0$) : $(D/H)_t \rightarrow (D/H)_P$

- $(D/H)_P$ is sensitive to the baryon density ($\propto \eta_{10}^{-1.6}$)

- BUT ...

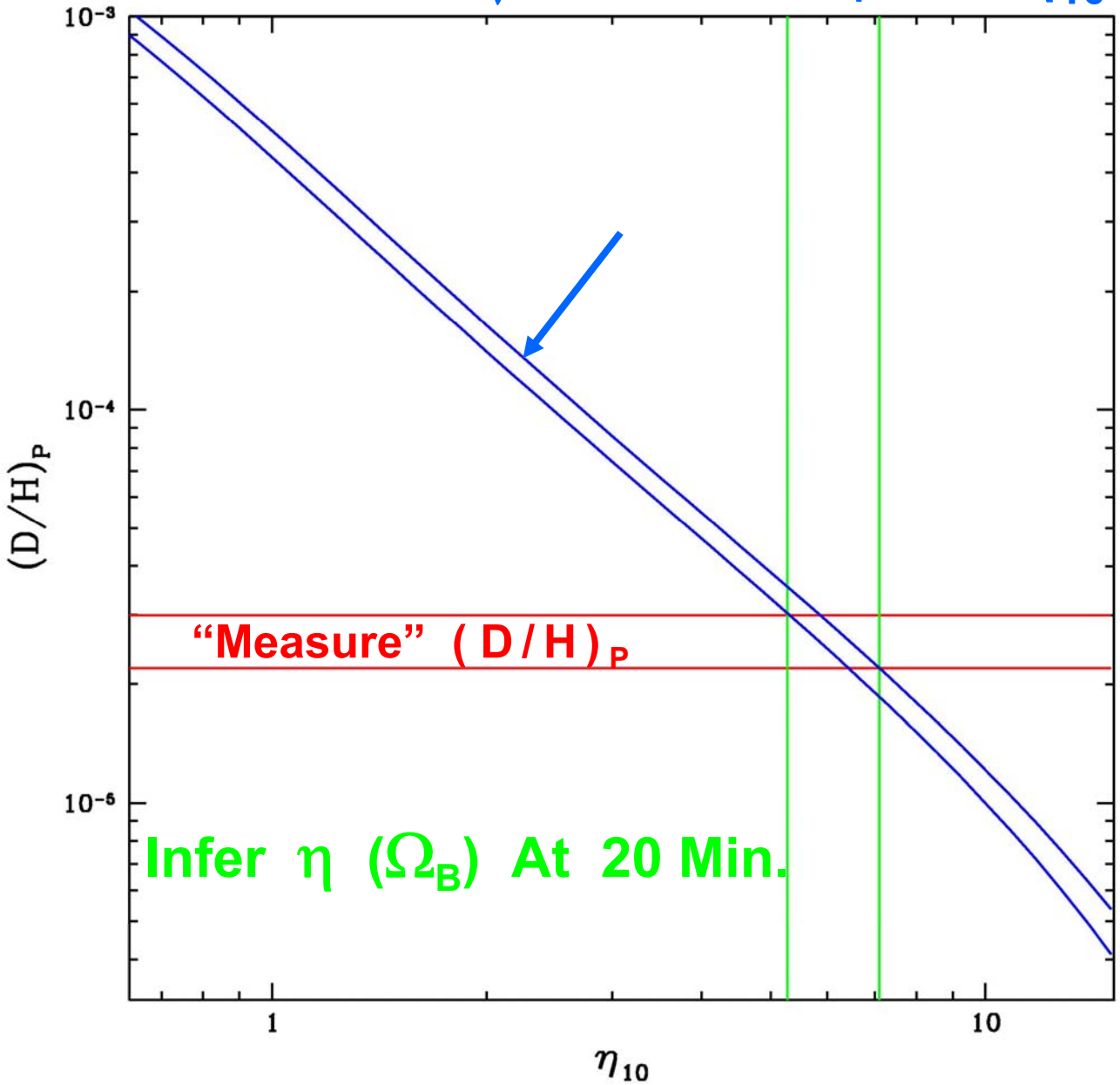
  * H I and D I spectra are identical $\Rightarrow$ H I Interlopers?

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

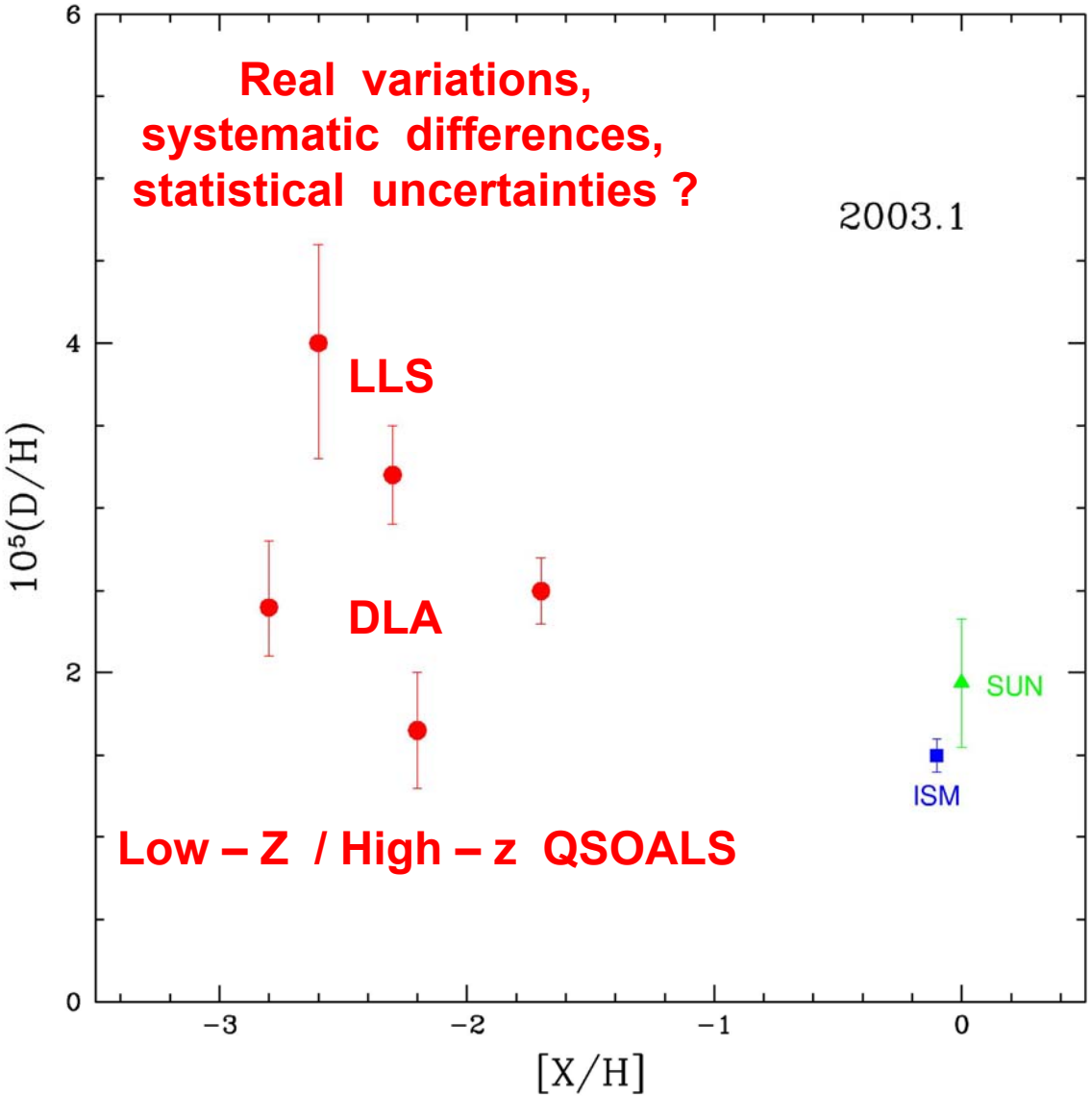
Primordial D & BBN Constrain

The Baryon Density

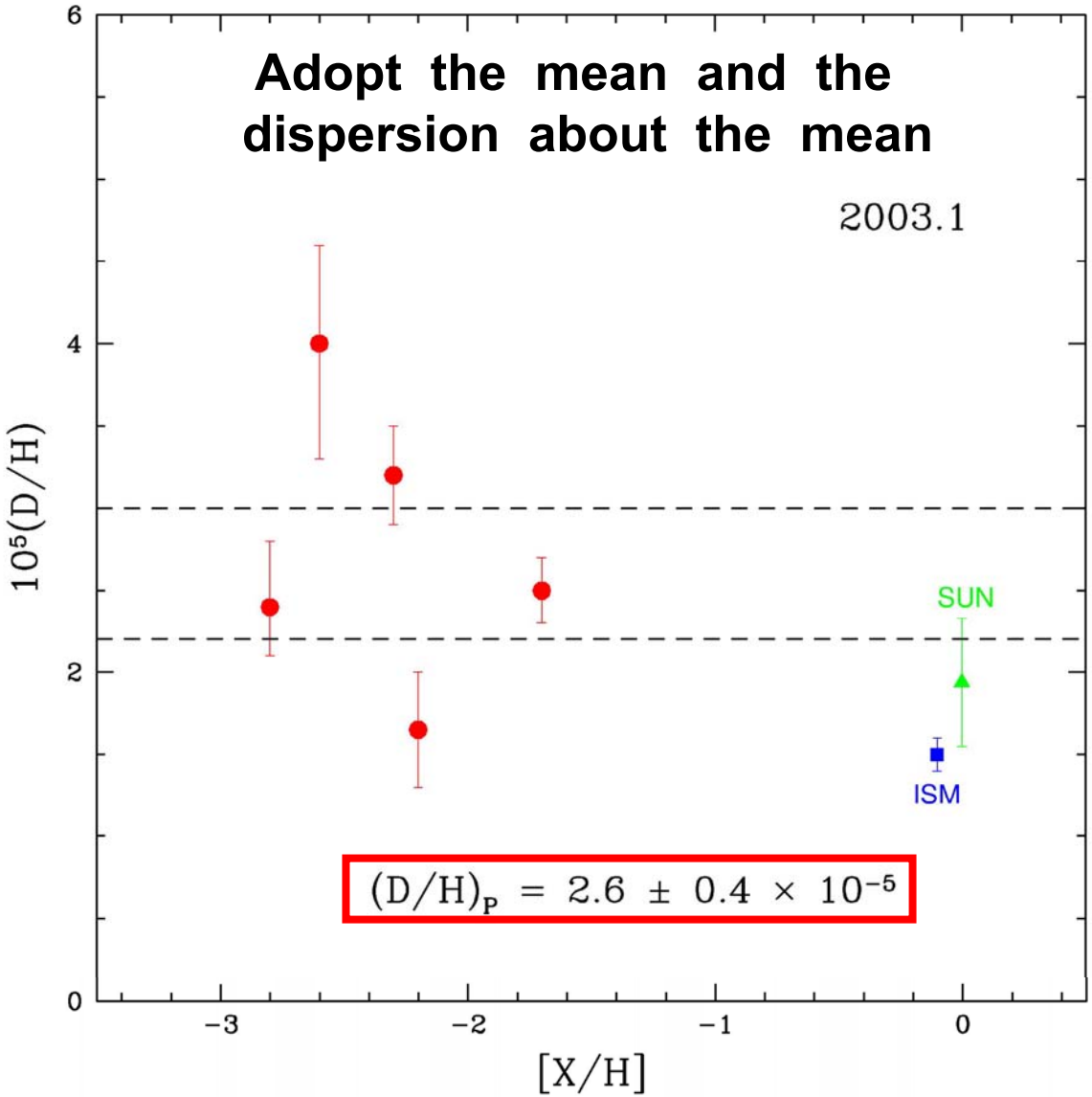
Use SBBN ($N_\nu = 3$) $(D/H)_P$ vs. η_{10}



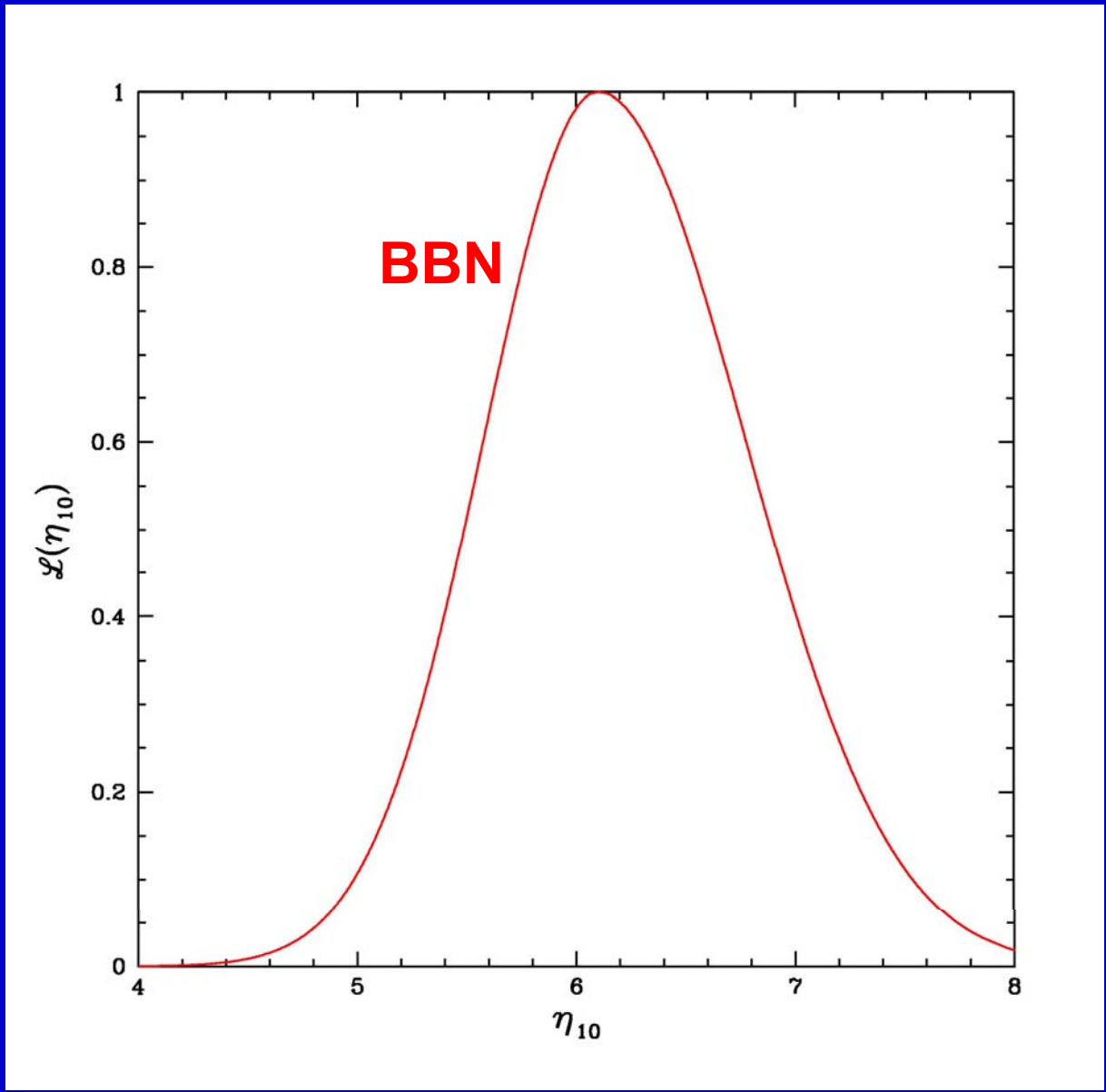
D - Abundance Data



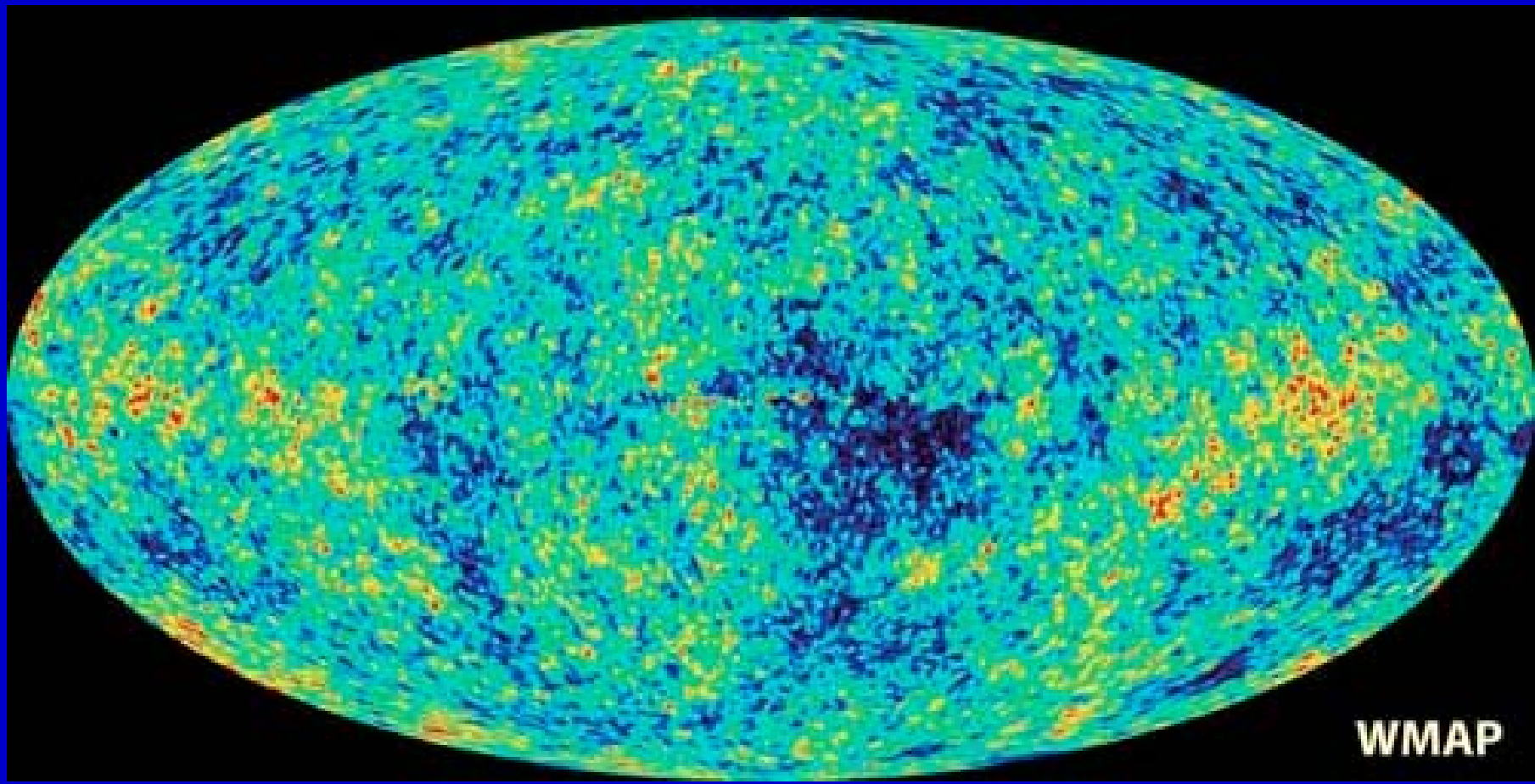
X = O, Si, …


Adopt the mean and the dispersion about the mean
2003.1
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 $\Rightarrow$ $\eta_{10} = 6.1 \pm 0.6$

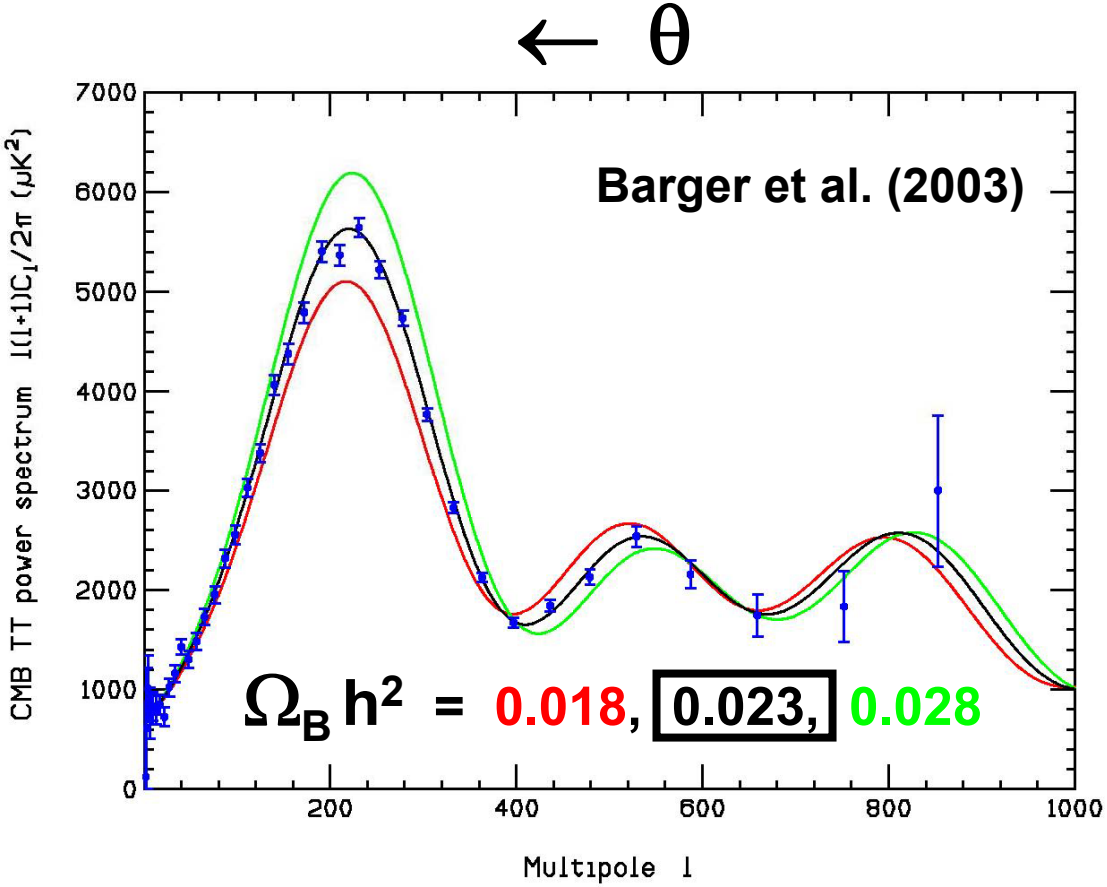


CBR



CBR Temperature Anisotropy Spectrum

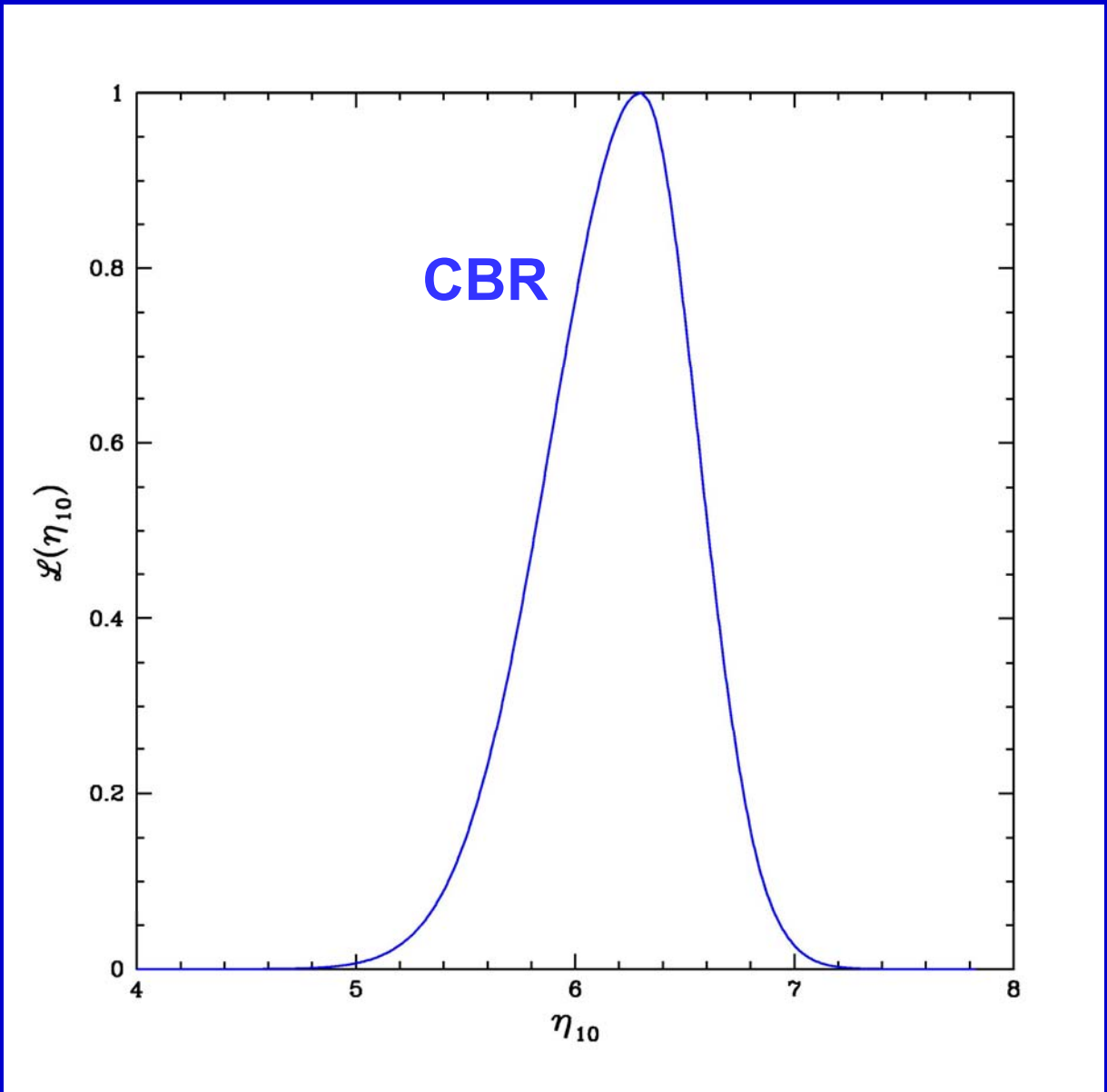
(ΔT^2 vs. θ) Encodes The Baryon Density (ω_B)



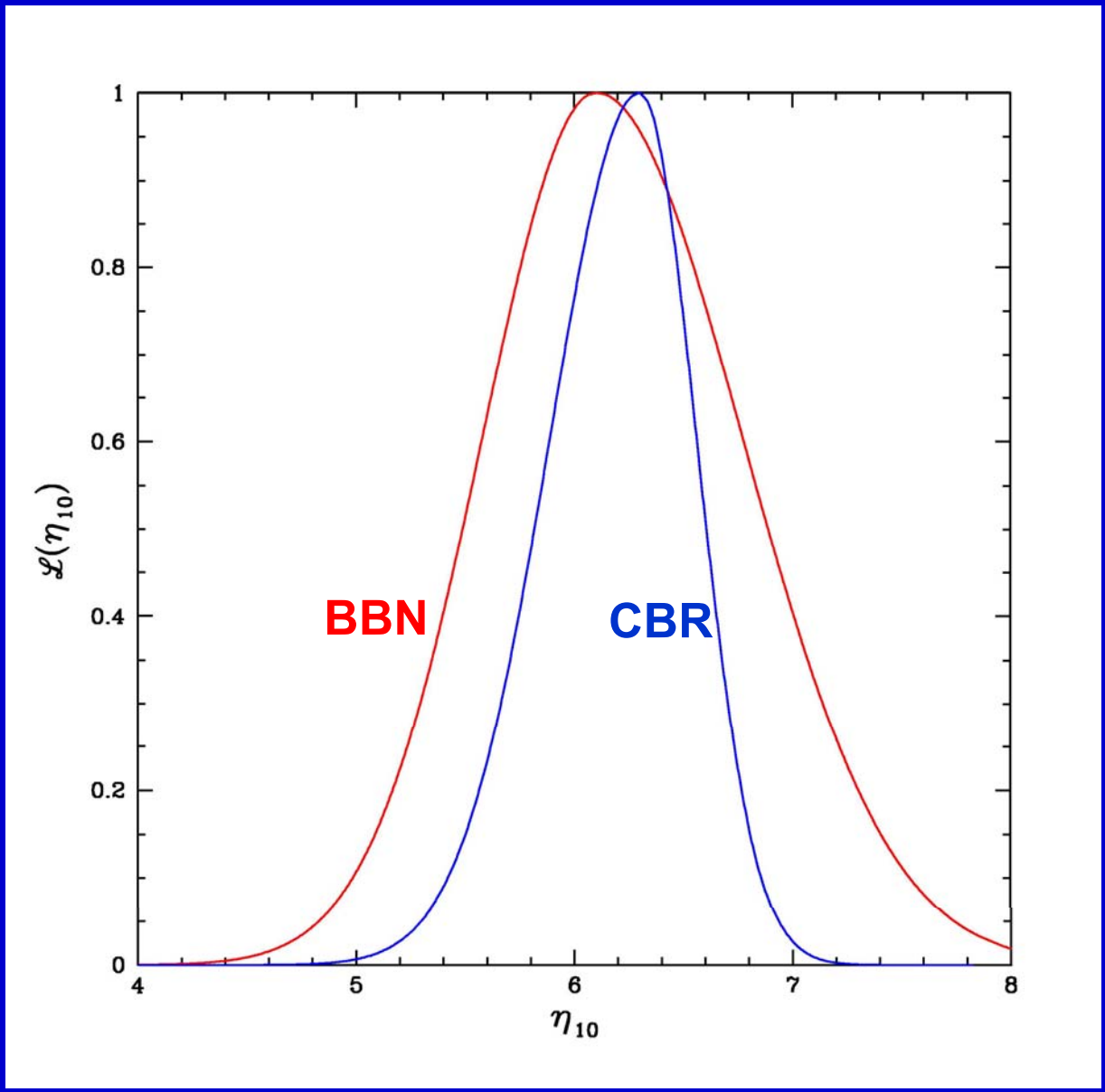
CBR (WMAP) constrains $\Omega_B h^2$

The CBR is (also) an early - Universe Baryometer

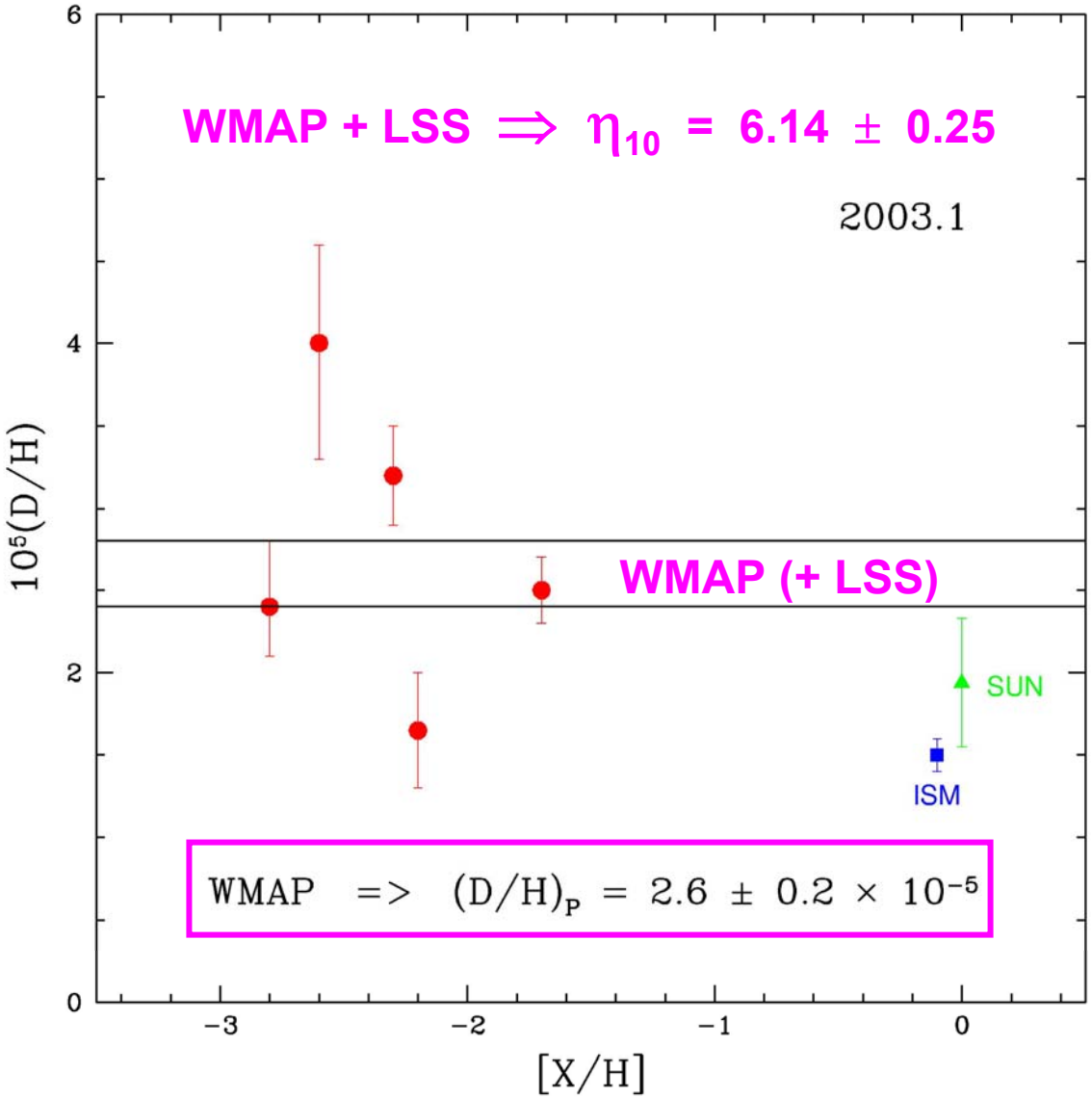
CBR & WMAP (ALONE !) $\Rightarrow \eta_{10} = 6.3 \pm 0.3$

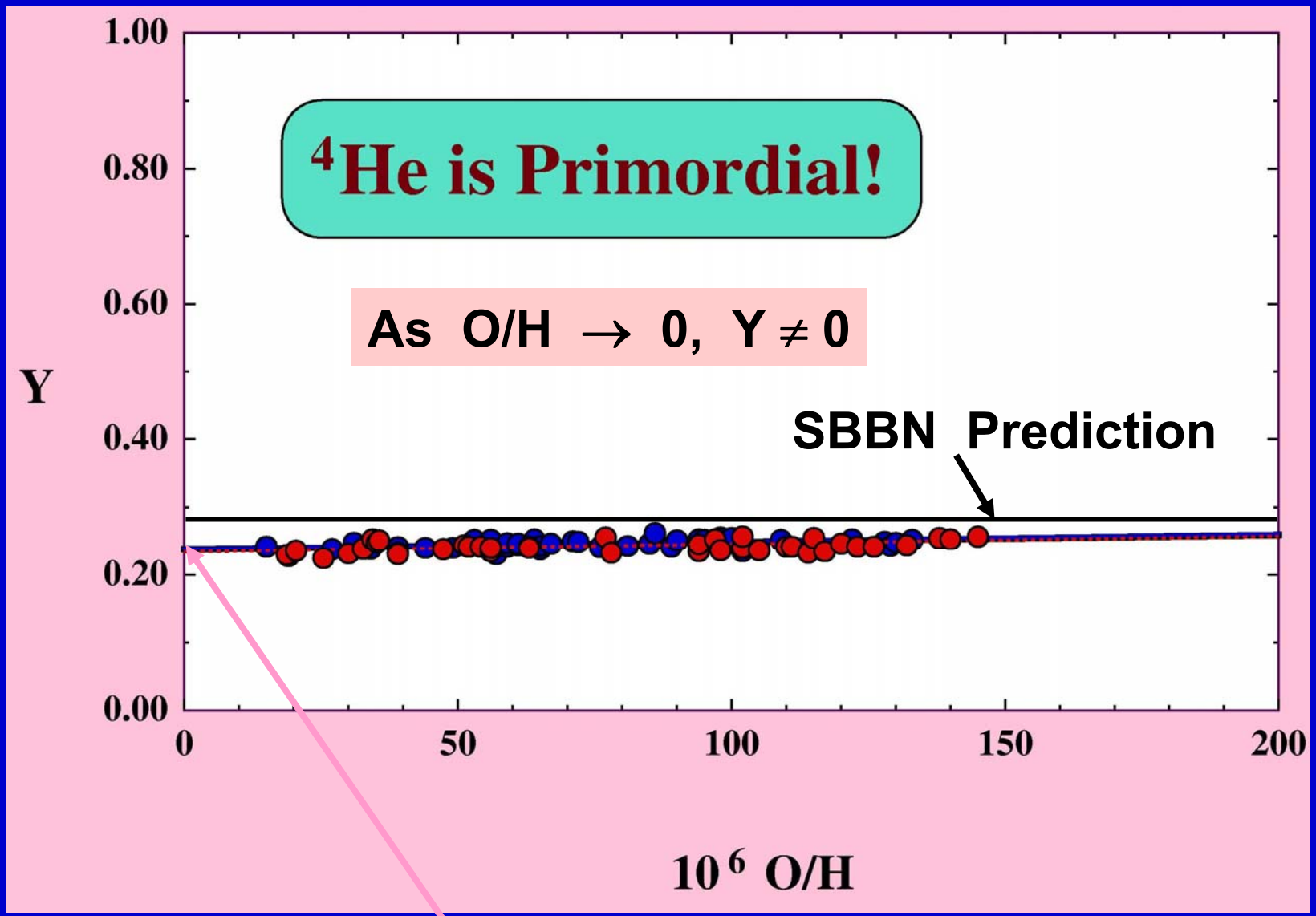


BBN (20 min) & CBR (380 kyr) AGREE !



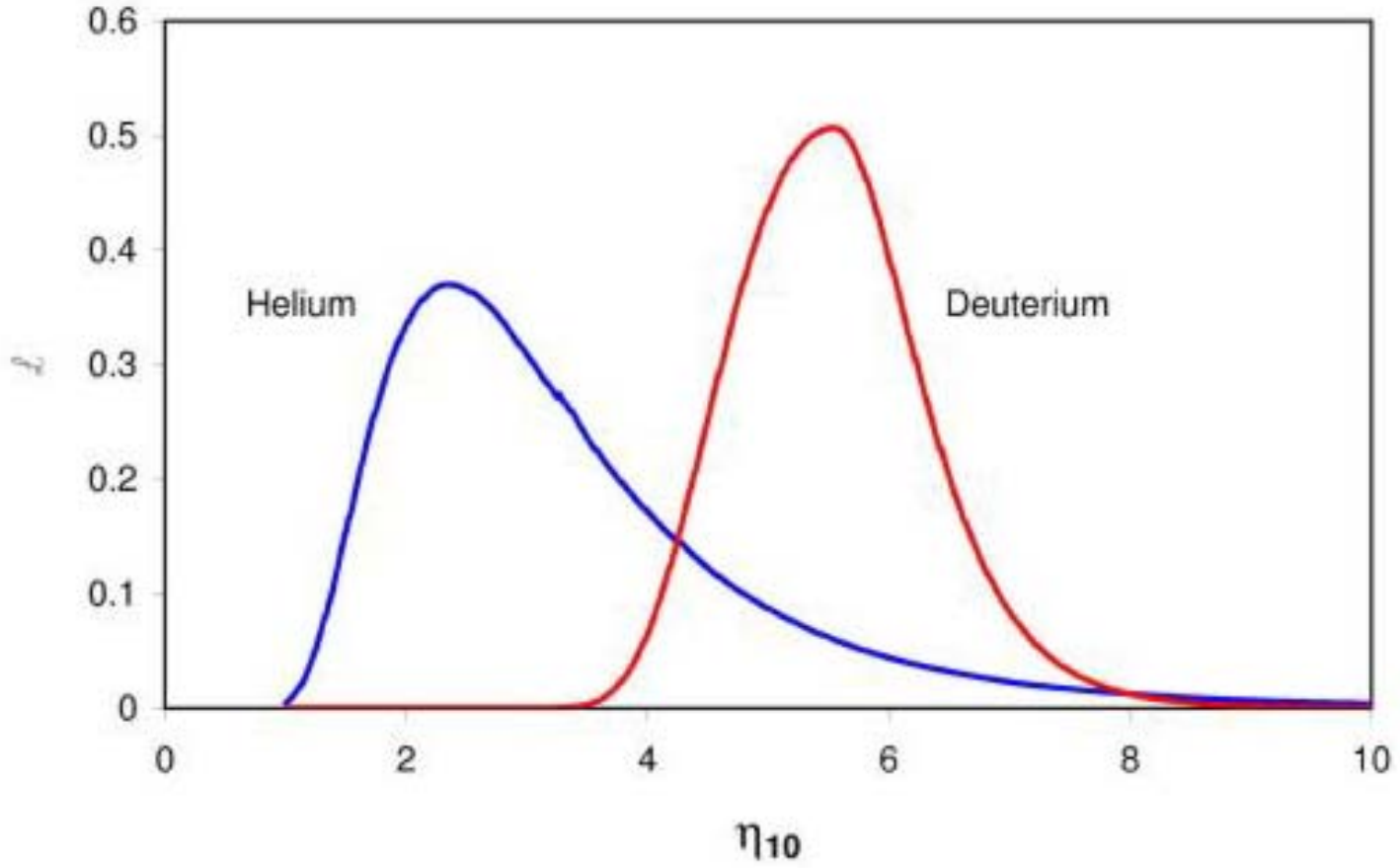
The CBR is a good Deuteronometer !



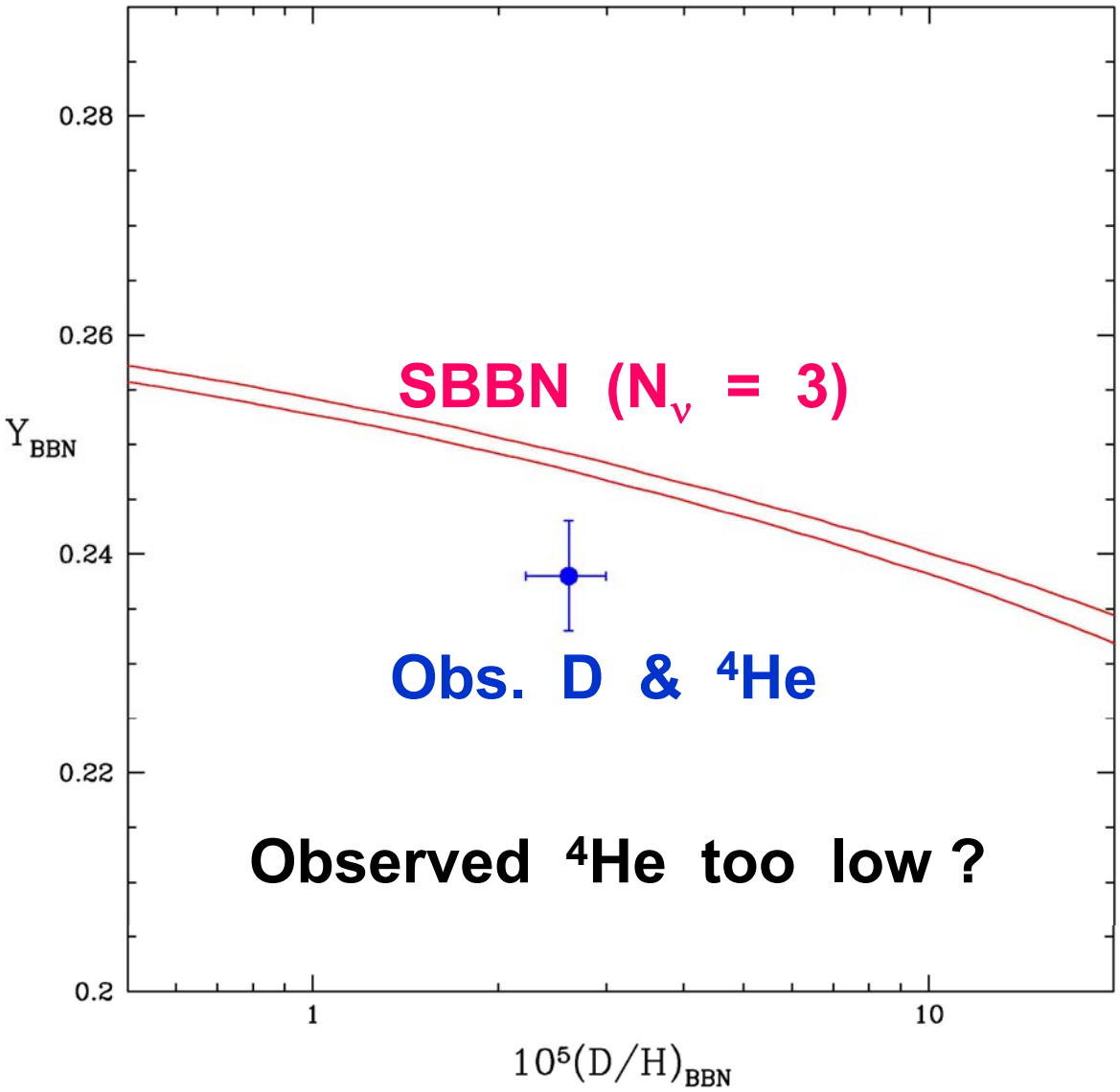


"2σ" range for Y_P : 0.228 ↔ 0.248 (OSW)

η Likelihoods from D and ^{4}He

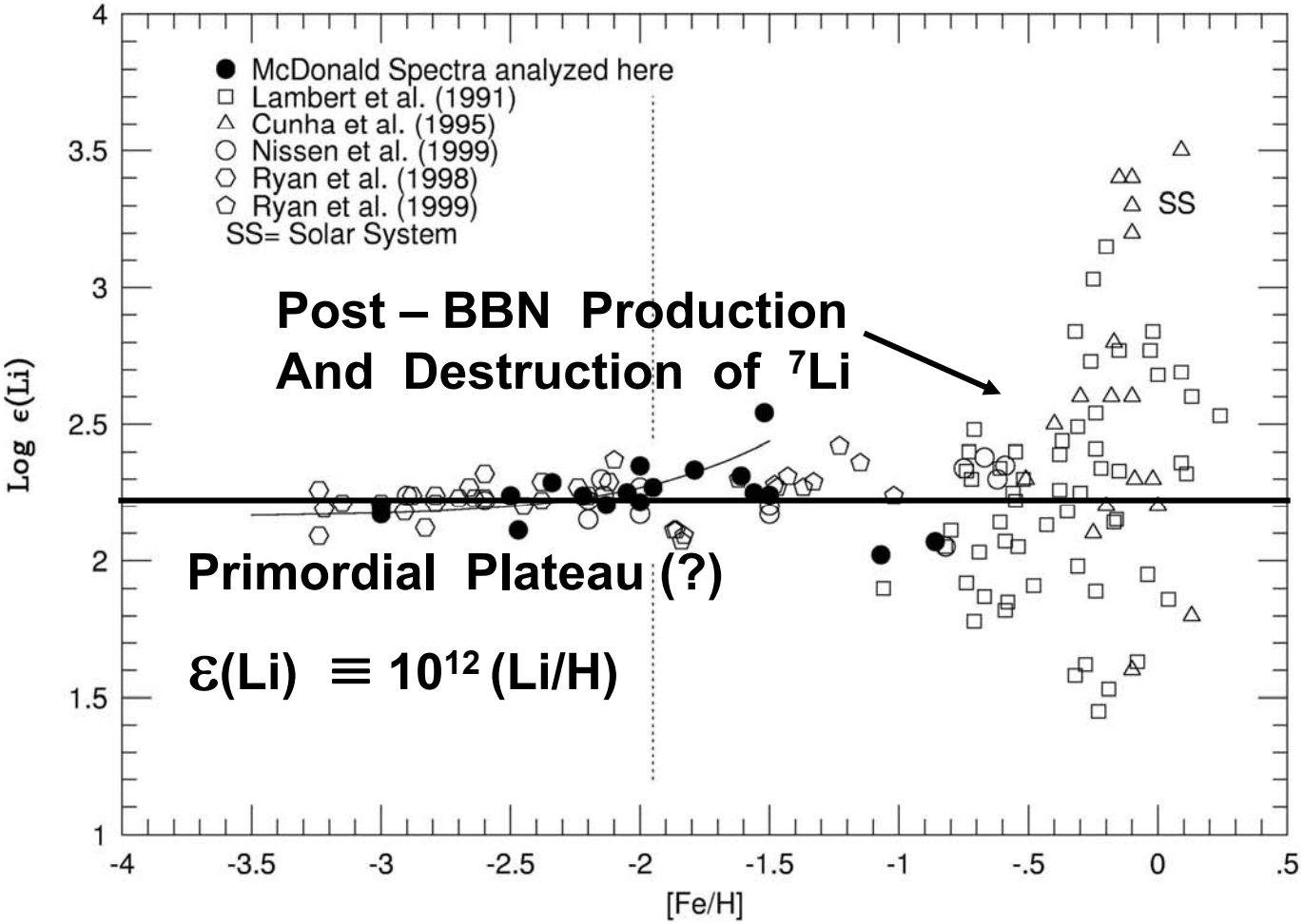


Y vs. D/H

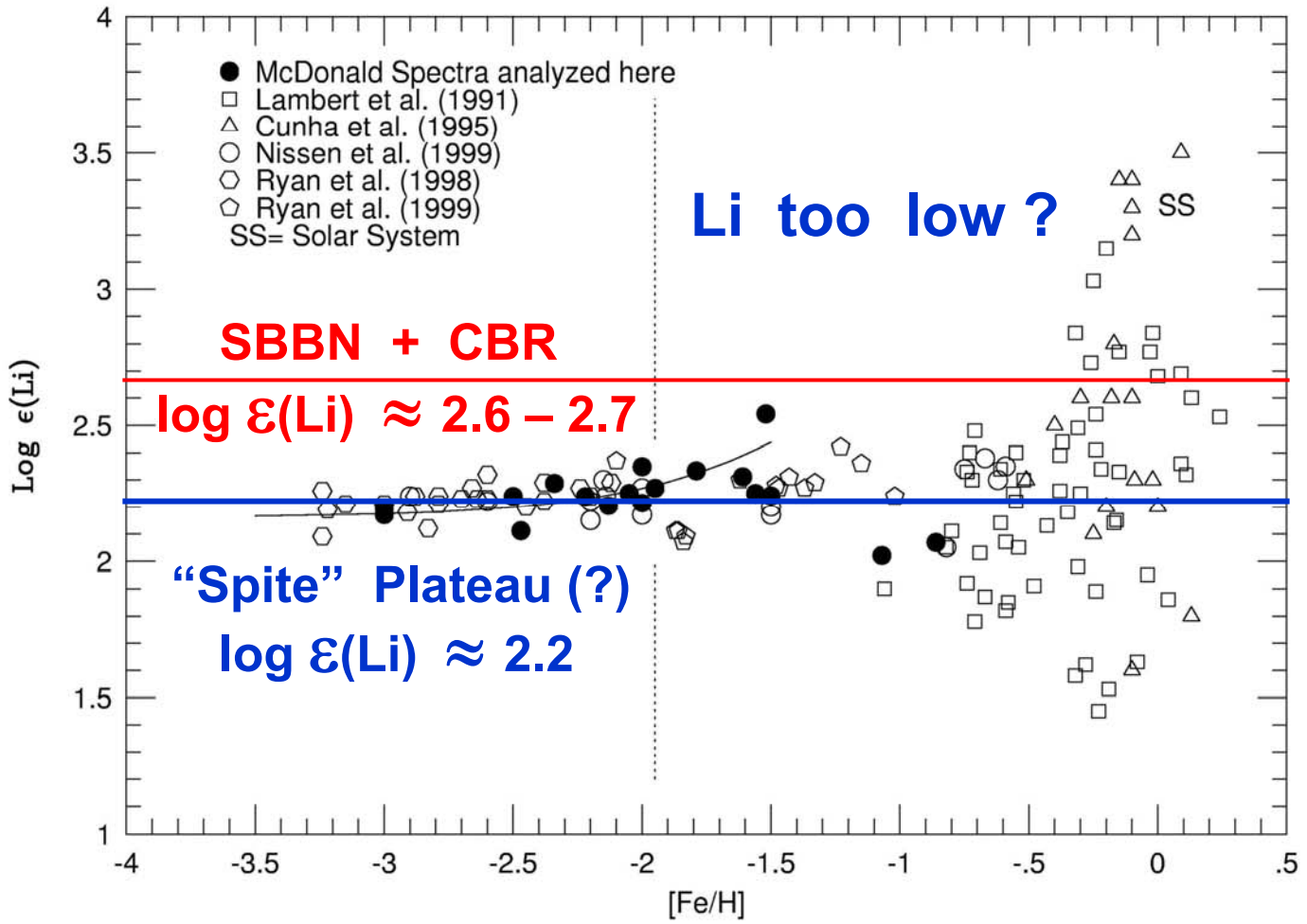


Observed ^{4}He too low ?

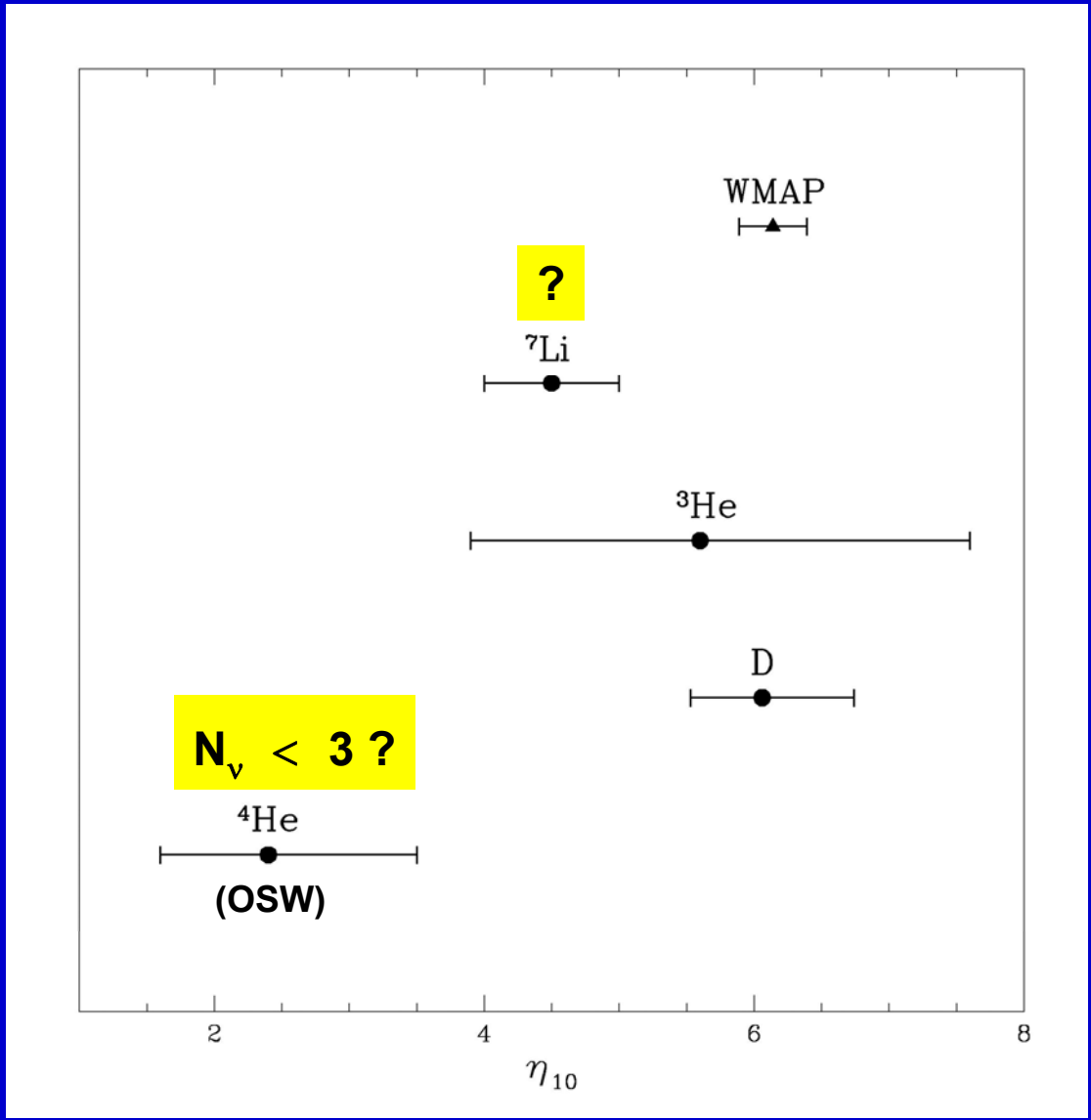
Lithium vs. Fe / H



BBN and Primordial (Pop II) Lithium ?

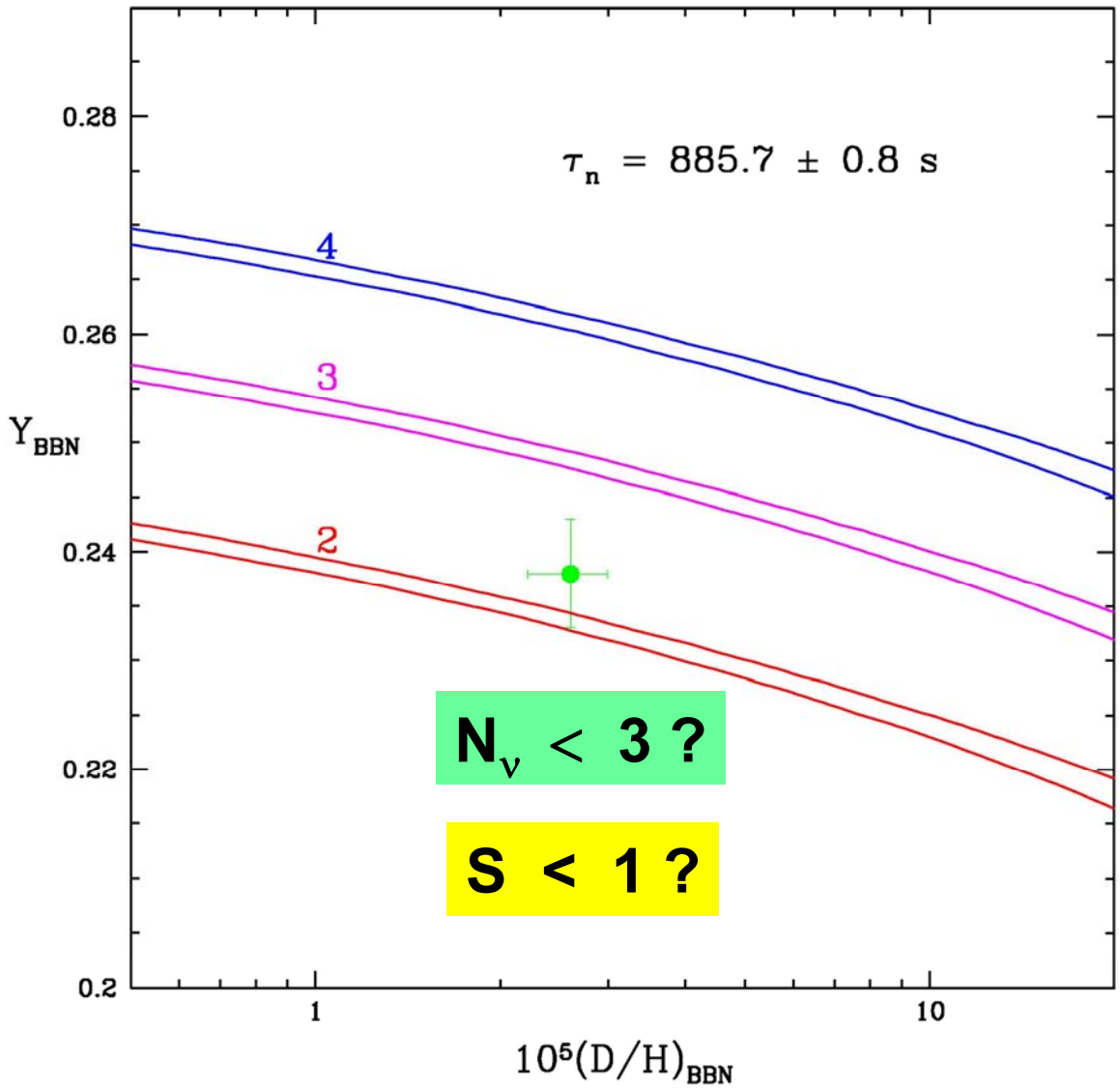


Baryon Density Determinations



Observational Uncertainties Or New Physics?

N_ν = 2, 3, 4

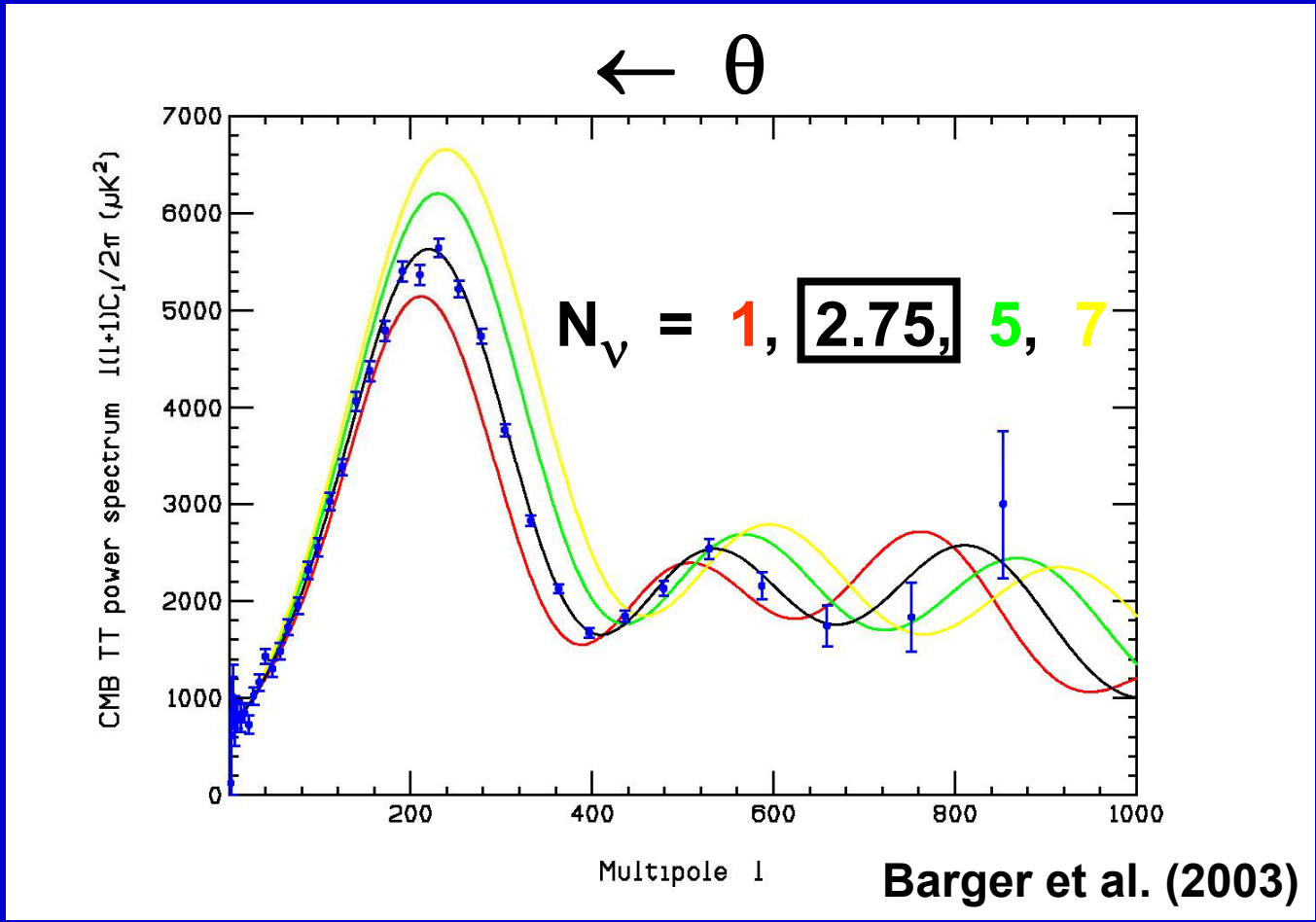


N_ν < 3 ?

S < 1 ?

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

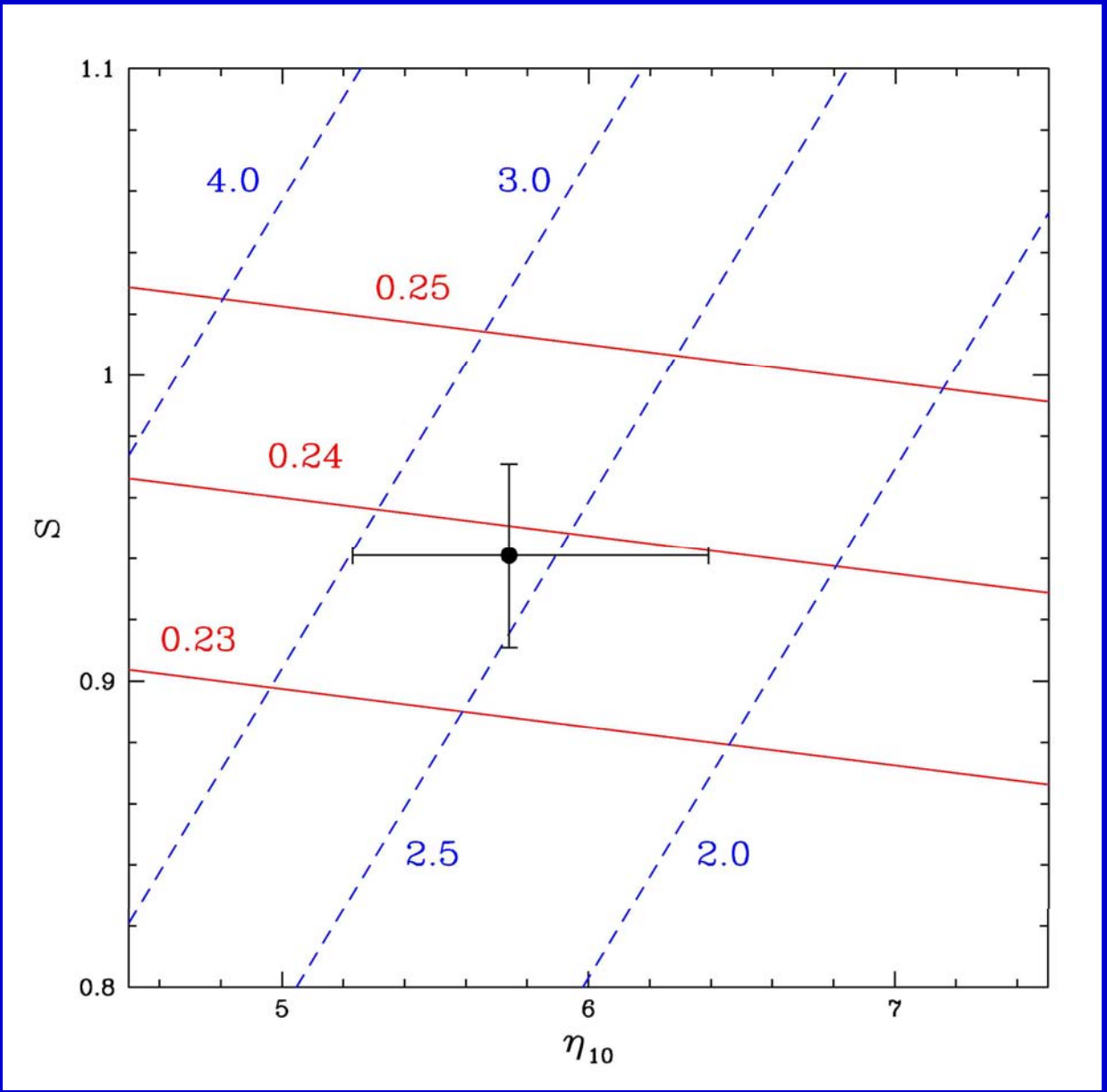
Encodes the Radiation Density ρ_R (ΔN_ν)



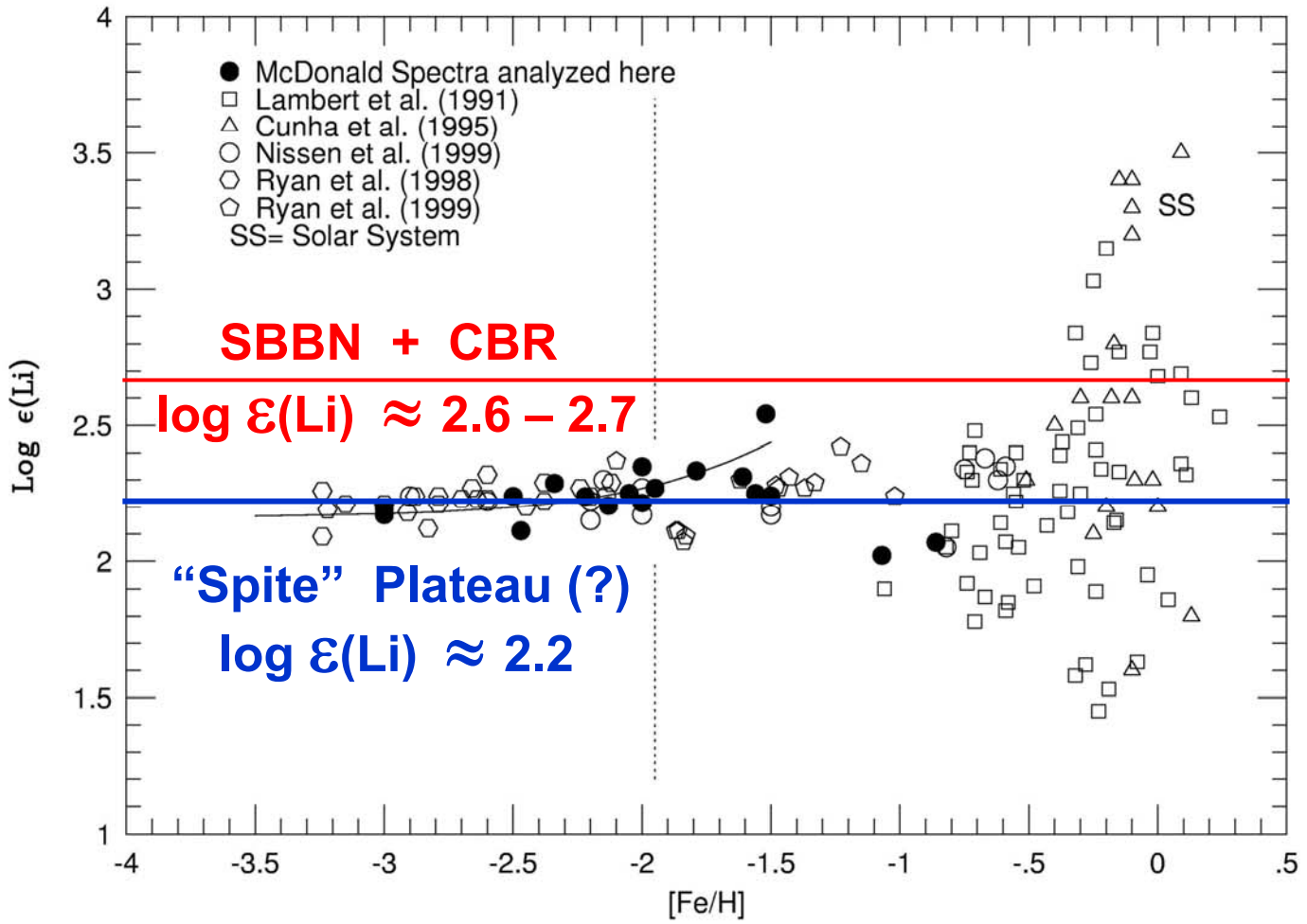
CBR (WMAP) constrains N_ν (S)

The CBR is an early - Universe Chronometer

BBN (D, ^{4}He) & CBR ✓ But, Li ?



BBN and Primordial (Pop II) Lithium ?



Even for $N_\nu \neq 3$

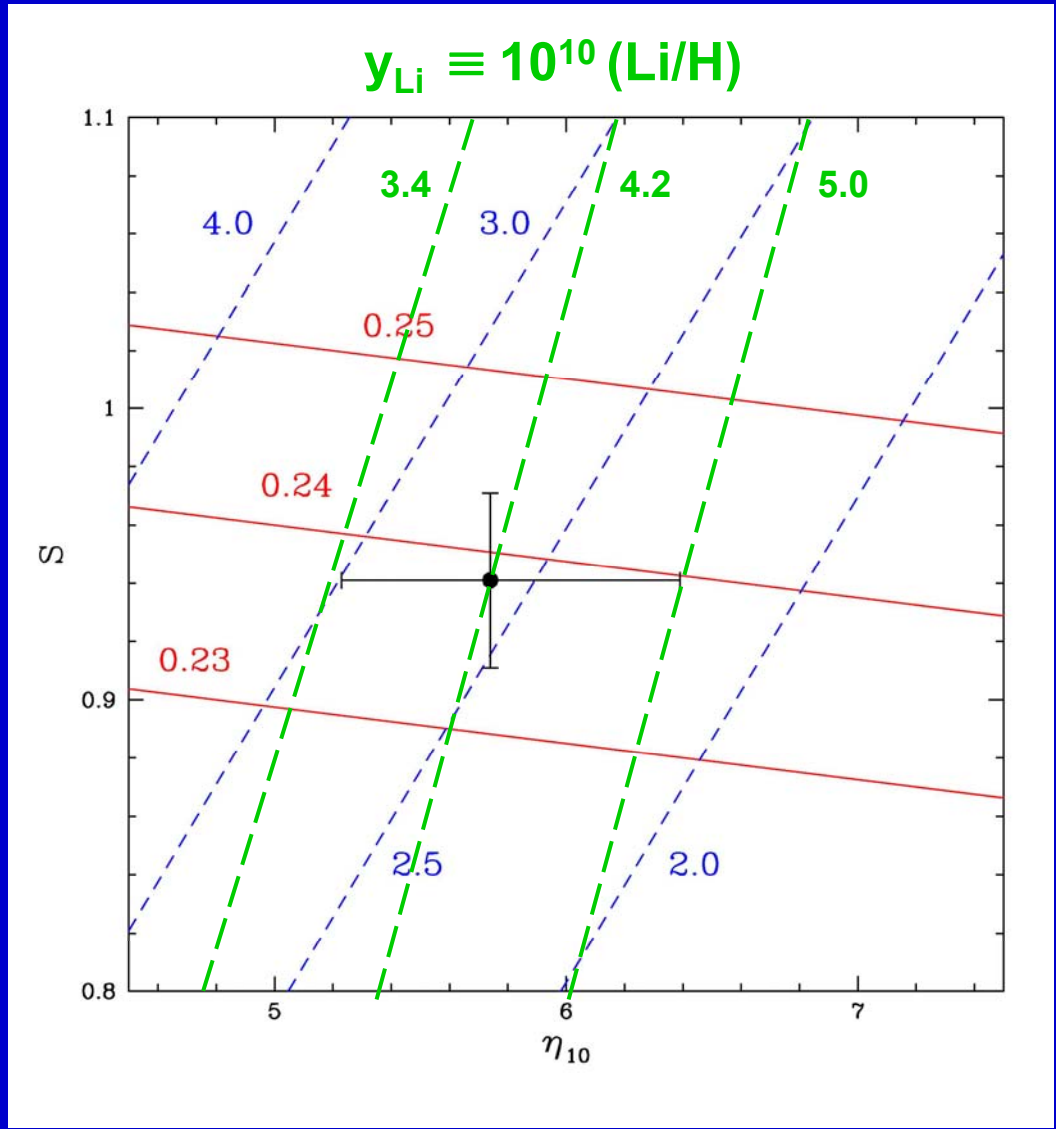
Y_{OSW} + D / H $\Rightarrow$

Li / H $\approx 4.2 \pm 0.8 \times 10^{-10}$

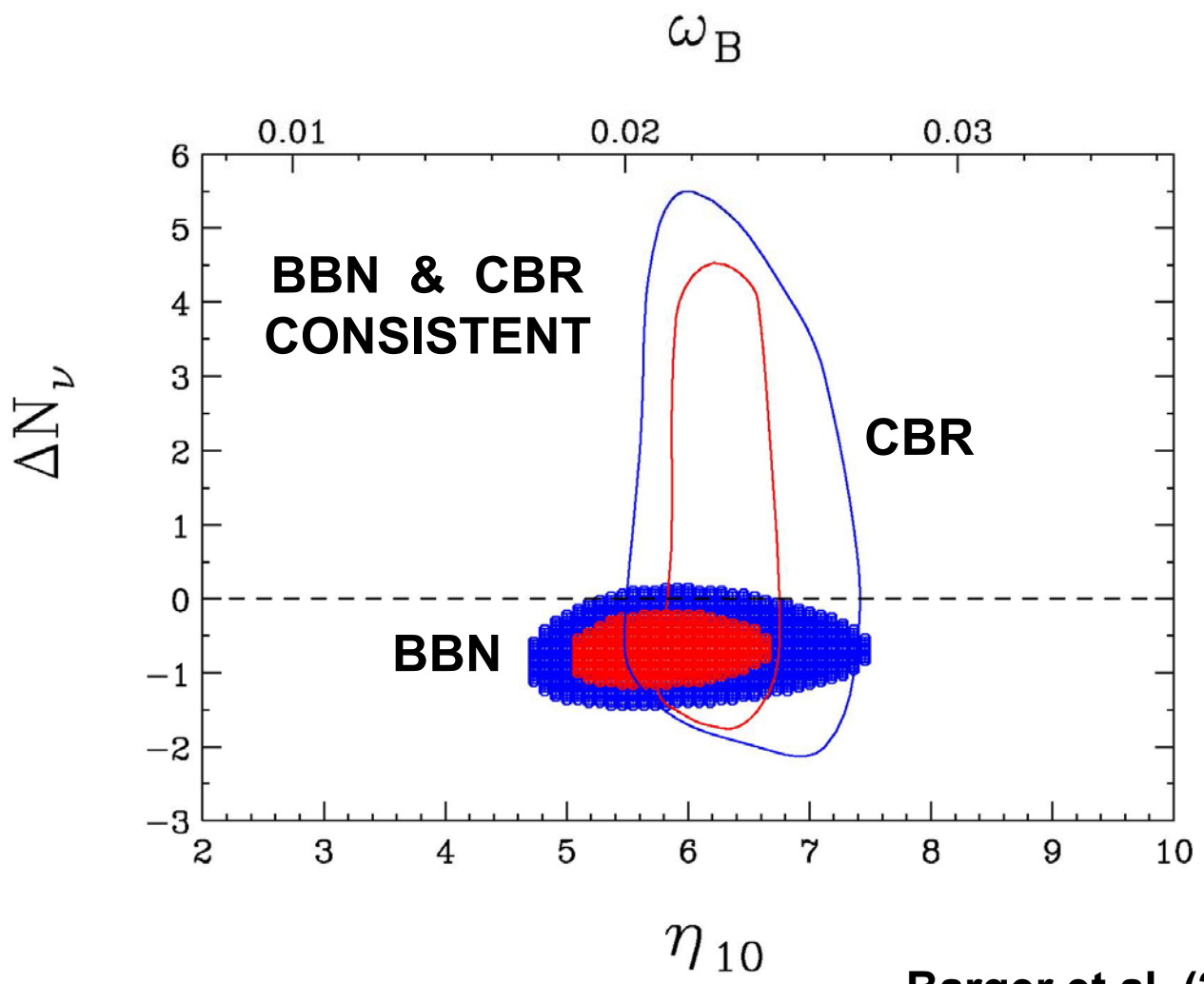
$\Rightarrow$ log ε(Li) $\approx 2.6 \pm 0.1$

Li depleted / diluted

in Pop II stars ?

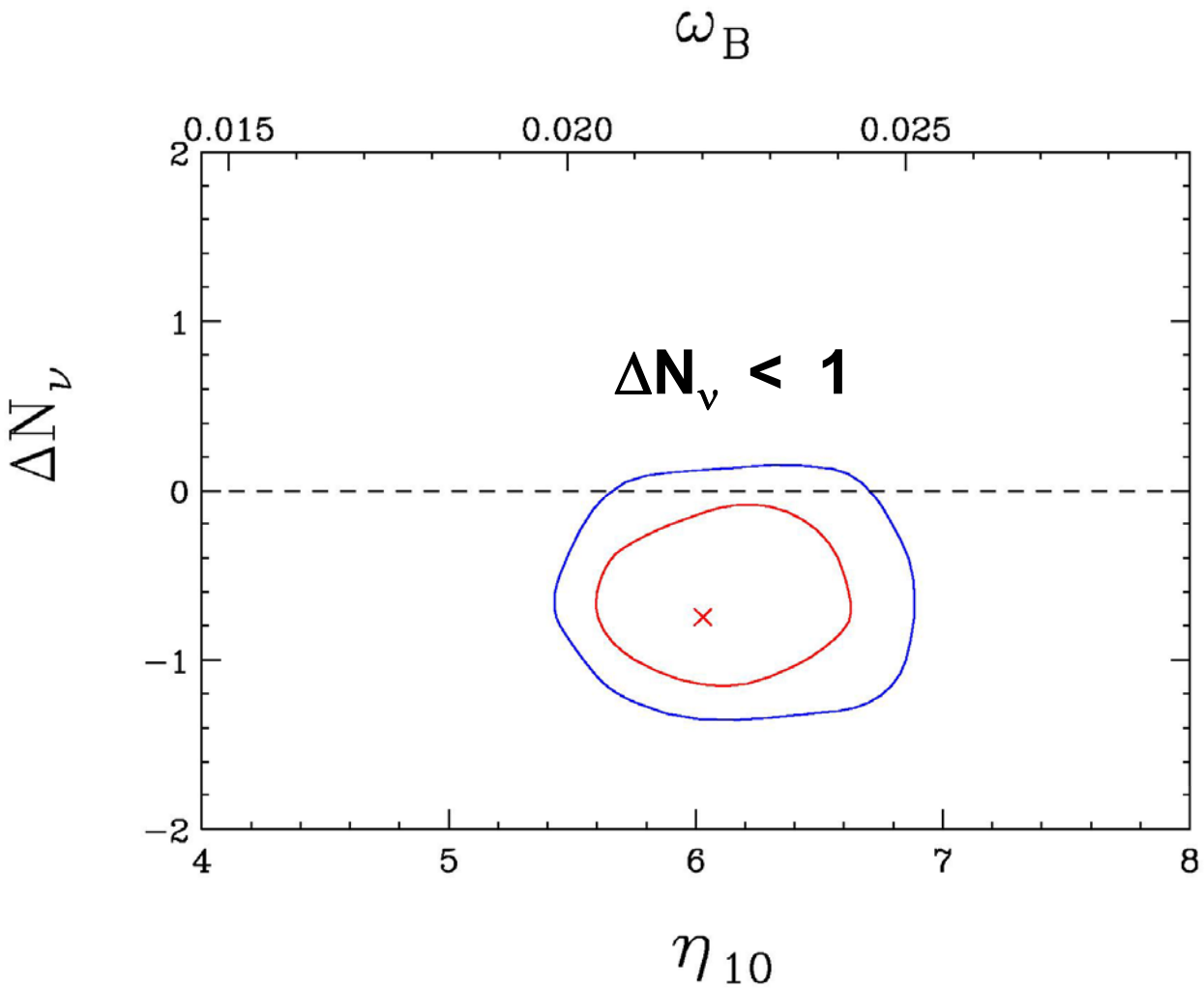


BBN (D & OSW ^{4}He) + CBR (WMAP)



Barger et al. (2003)

Joint BBN & CBR Fit



Barger et al. (2003)

Conclusions ($\xi_{e} = 0$)

- SBBN ($N_\nu = 3$) D / H & CBR (WMAP) ✓
- BBN (D, ^{4}He) & CBR agree for :

  $\eta_{10} = 6.03$ ($\Omega_B h^2 = 0.0220$) & $N_\nu = 2.25$

  95% Ranges : $1.65 \leq N_\nu \leq 3.03$

  $5.53 \leq \eta_{10} \leq 6.76$

  $(0.0202 \leq \Omega_B h^2 \leq 0.0247)$

e – Neutrino Degeneracy

$\Rightarrow \xi_e \approx 0.044 \pm 0.022$

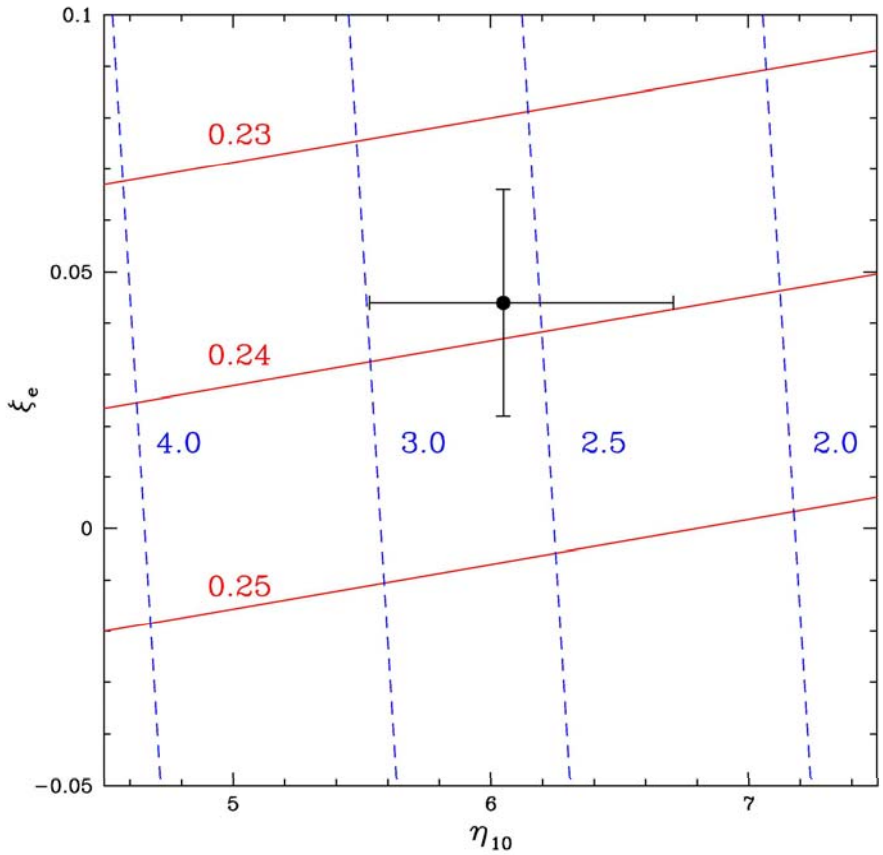
$\Rightarrow \Omega_B h^2 \approx 0.022 \pm 0.002$

$(\eta_{10} = 6.0 \pm 0.6$ ✓$)$

But …

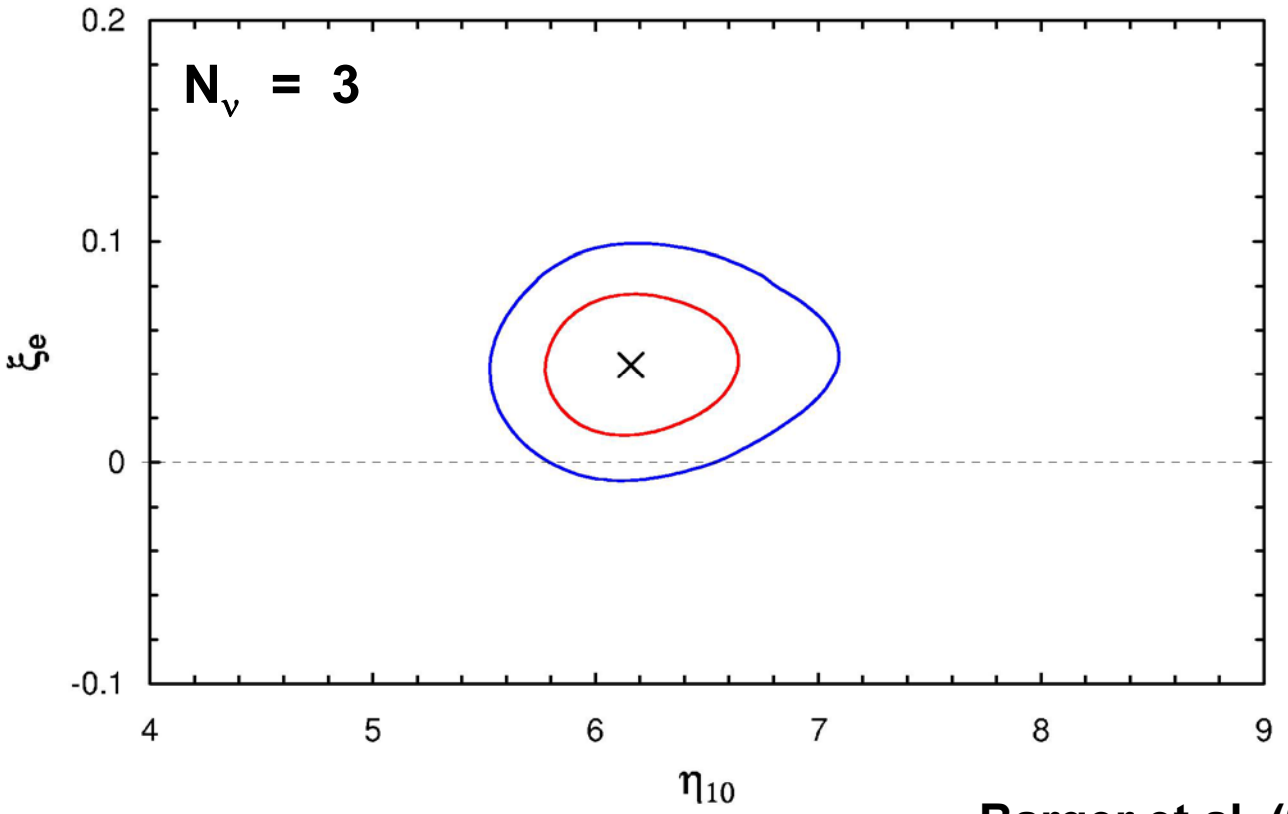
log ε(Li) ≈ 2.6 ± 0.1

Y_P & $y_D \equiv 10^5$ (D/H)



Kneller & Steigman (2004)

CBR + BBN



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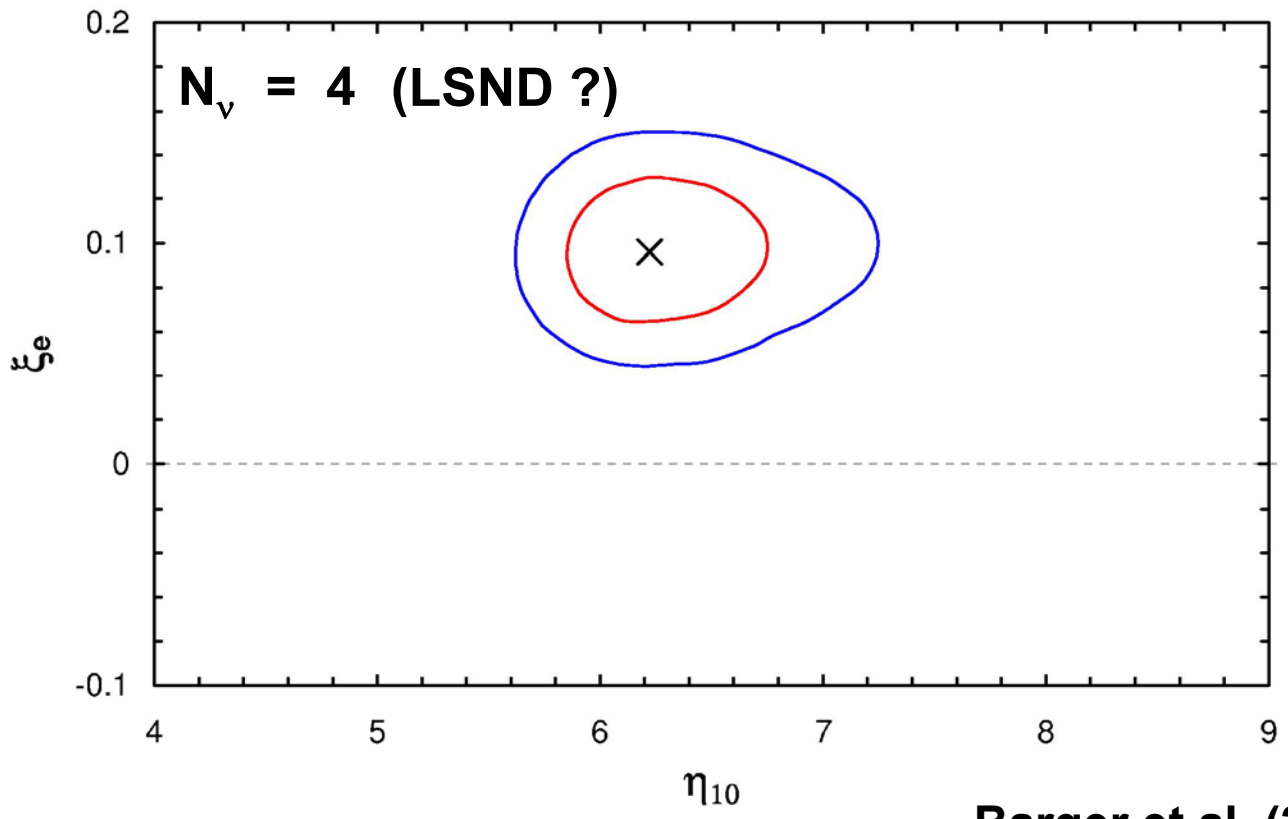


Barger et al. (2003)

SUMMARY AND CONCLUSIONS

BBN and CBR are consistent :

Predictions of the Universe at

20 min and at 380 kyr AGREE !

- **For $\xi_e = 0$: $1.7 \leq N_\nu \leq 3.0$ allowed @ ~ 95%**
- **For $\xi_e \neq 0 \Rightarrow$ more freedom for $N_\nu \Rightarrow$**

  $-0.1 \leq \xi_e \leq 0.3$ & $1 \leq N_\nu \leq 8$ @ ~ 95%

SUMMARY AND CONCLUSIONS

BBN and CBR are consistent :

Predictions of the Universe at

20 min and at 380 kyr AGREE !

- **For $\xi_e = 0$: $1.7 \leq N_\nu \leq 3.0$ allowed @ ~ 95%**
- **For $N_\nu = 3$: $0 \leq \xi_e \leq 0.09$ allowed @ ~ 95%**
- **For $\xi_e \neq 0 \Rightarrow$ more freedom for $N_\nu \Rightarrow$ $-0.1 \leq \xi_e \leq 0.3$ & $1 \leq N_\nu \leq 8$ @ ~ 95%**

Challenges :

- Dispersion in D/H too large ?

  Systematic errors in N(D I) and/or N(H I) ?

- Observed ^{4}He too low ?

  Underlying stellar absorption ?

- Observed Li too low ?

  Stellar dilution/depletion ?

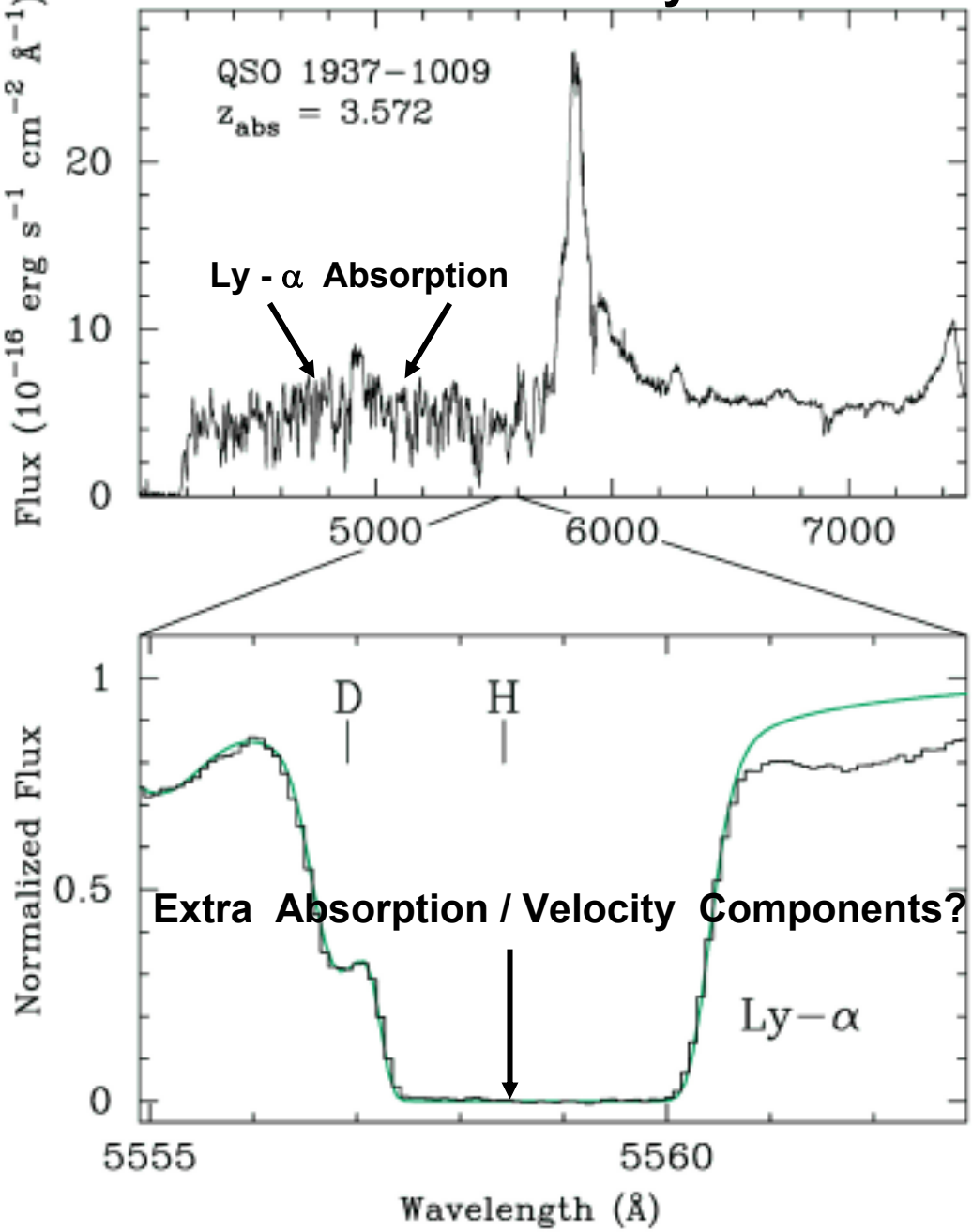
Recent Y_P Determinations

- Prior to 2000, $Y_P \leq 0.238$ @ 2σ
- OSW 00 : $Y_P = 0.238 \pm 0.005$
- PPR 00 : $Y_{SMC} = 0.2405 \pm 0.0018$
  $\Rightarrow Y_P \leq 0.244$ @ 2σ
- IT 04 : $Y_P = 0.243 \pm 0.001$ (!)
- OS 04 : $0.232 \leq Y_P \leq 0.258$ @ 2σ (?)
- OS 04 + GSV 02 : $0.225 \leq Y_P \leq 0.253$ @ 2σ (?)

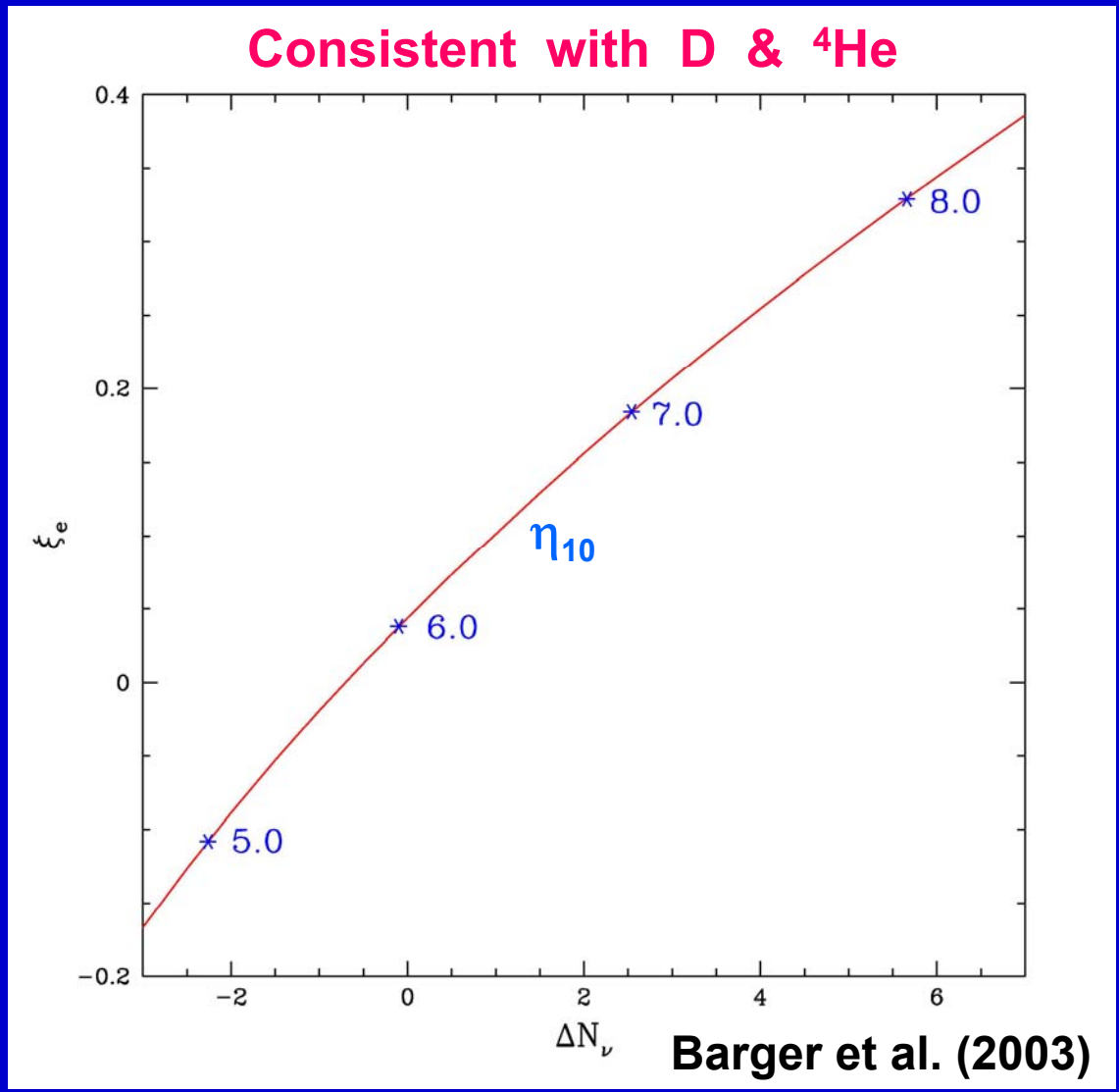
Corresponding N_ν Determinations

- Prior to 2000, $N_\nu \leq 2.2$ @ 2σ (Crisis ?)
- OSW 00 : $N_\nu = 2.2 \pm 0.4$
- PPR 00 : $N_\nu \leq 2.7$ @ 2σ
- IT 04 : $N_\nu = 2.6 \pm 0.1$
- OS 04 : $1.8 \leq N_\nu \leq 3.8$ @ 2σ (?)
- OS 04 + GSV 02 : $1.4 \leq N_\nu \leq 3.4$ @ 2σ (?)

Look for D in the Ly - α Forest



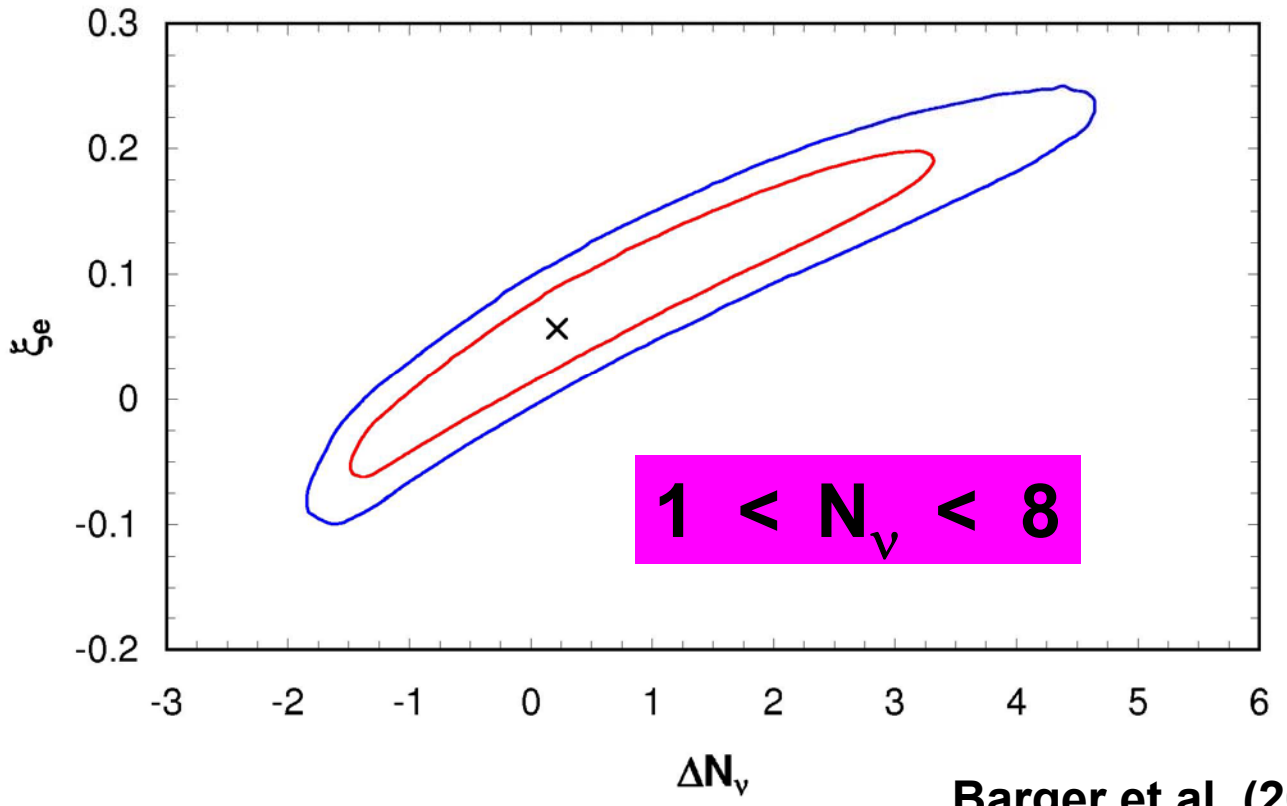
- As N_ν increases, so too do ξ_e and η_{10}



- But, the CBR (WMAP) limits N_ν and η_{10}

JOINT BBN & CBR CONTOURS

(η_{10}, ξ_e, ΔN_ν ALL FREE)



Barger et al. (2003)