PROBING THE UNIVERSE AT 20 MINUTES AND 400 THOUSAND YEARS

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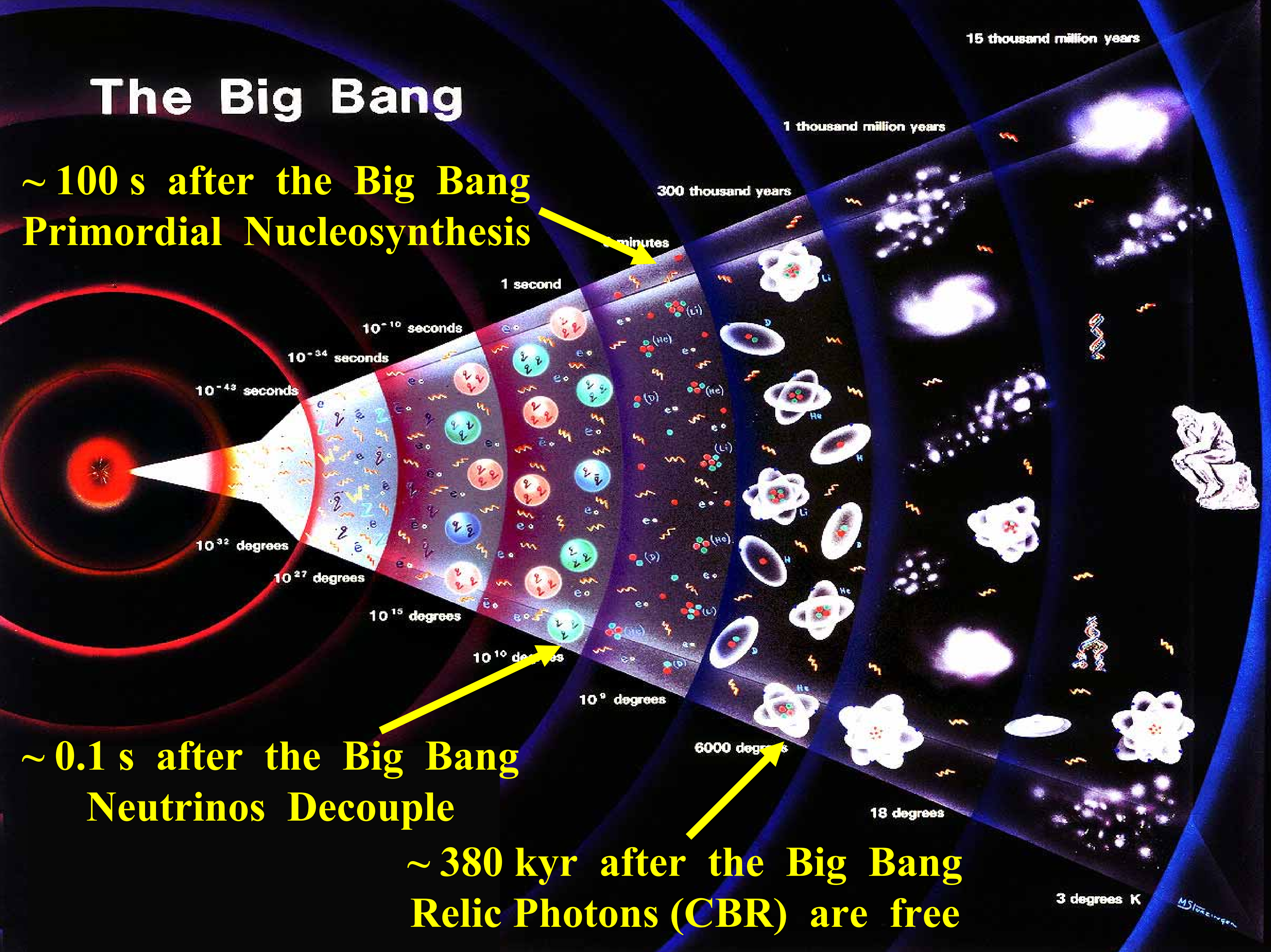
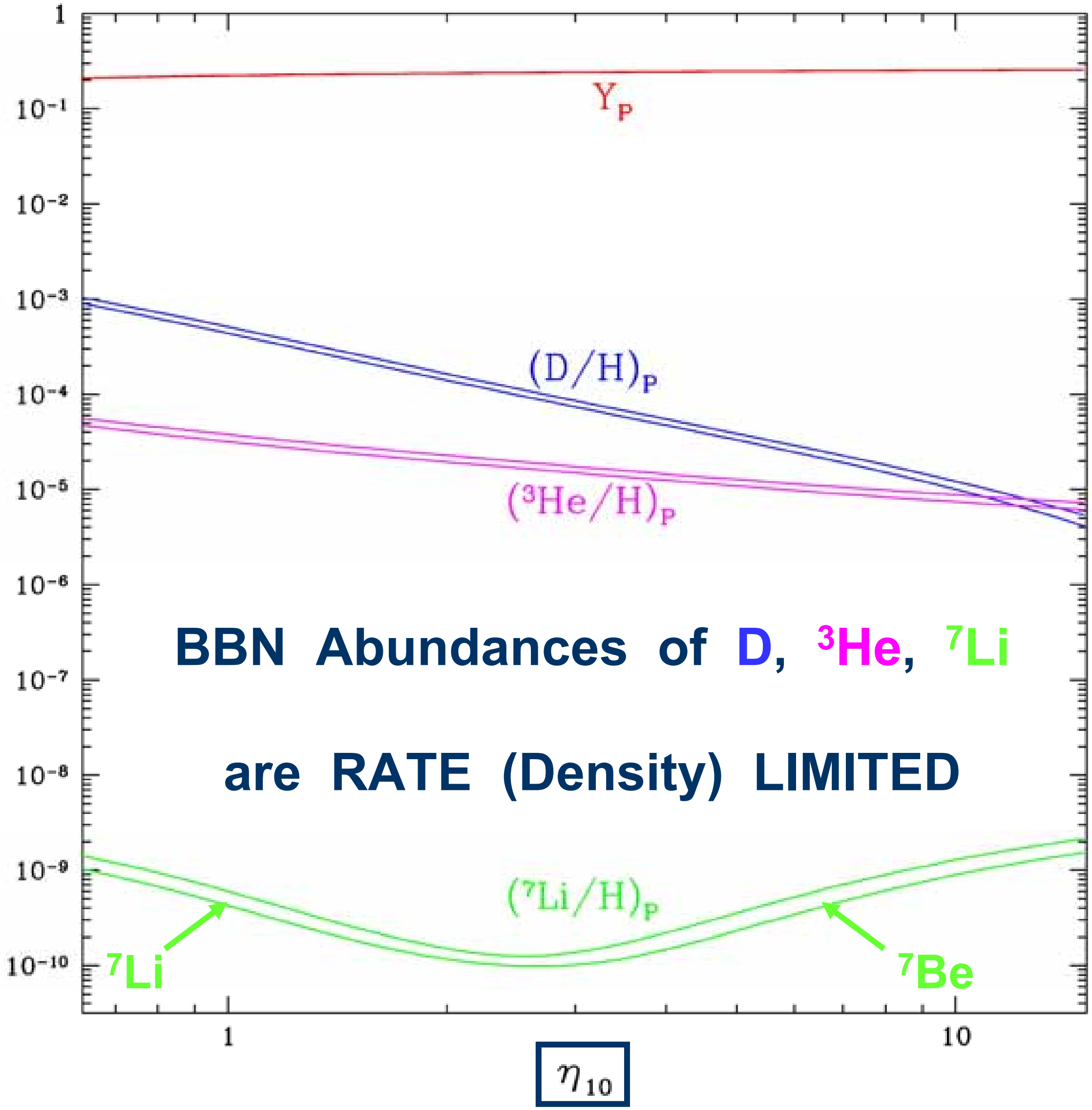

The Big Bang
~ 100 s after the Big Bang
Primordial Nucleosynthesis
~ 0.1 s after the Big Bang
Neutrinos Decouple
~ 380 kyr after the Big Bang
Relic Photons (CBR) are free
15 thousand million years
1 thousand million years
300 thousand years
minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{9} degrees
18 degrees
3 degrees K

BBN & The CBR Provide Complementary Probes Of The Early Universe

Do the predictions and observations of the baryon density ($\eta_{10} \equiv 10^{10}(n_B/n_\gamma)_0 = 274\ \Omega_B h^2$) and the expansion rate (H) of the Universe agree at 20 minutes (BBN) and at 380 kyr (CBR) ?

BBN – Predicted Primordial Abundances



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

DEUTERIUM --- The Baryometer Of Choice

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

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

  * For $Z \ll Z_\odot$: $(D/H)_t \rightarrow (D/H)_P$ (Deuterium Plateau)

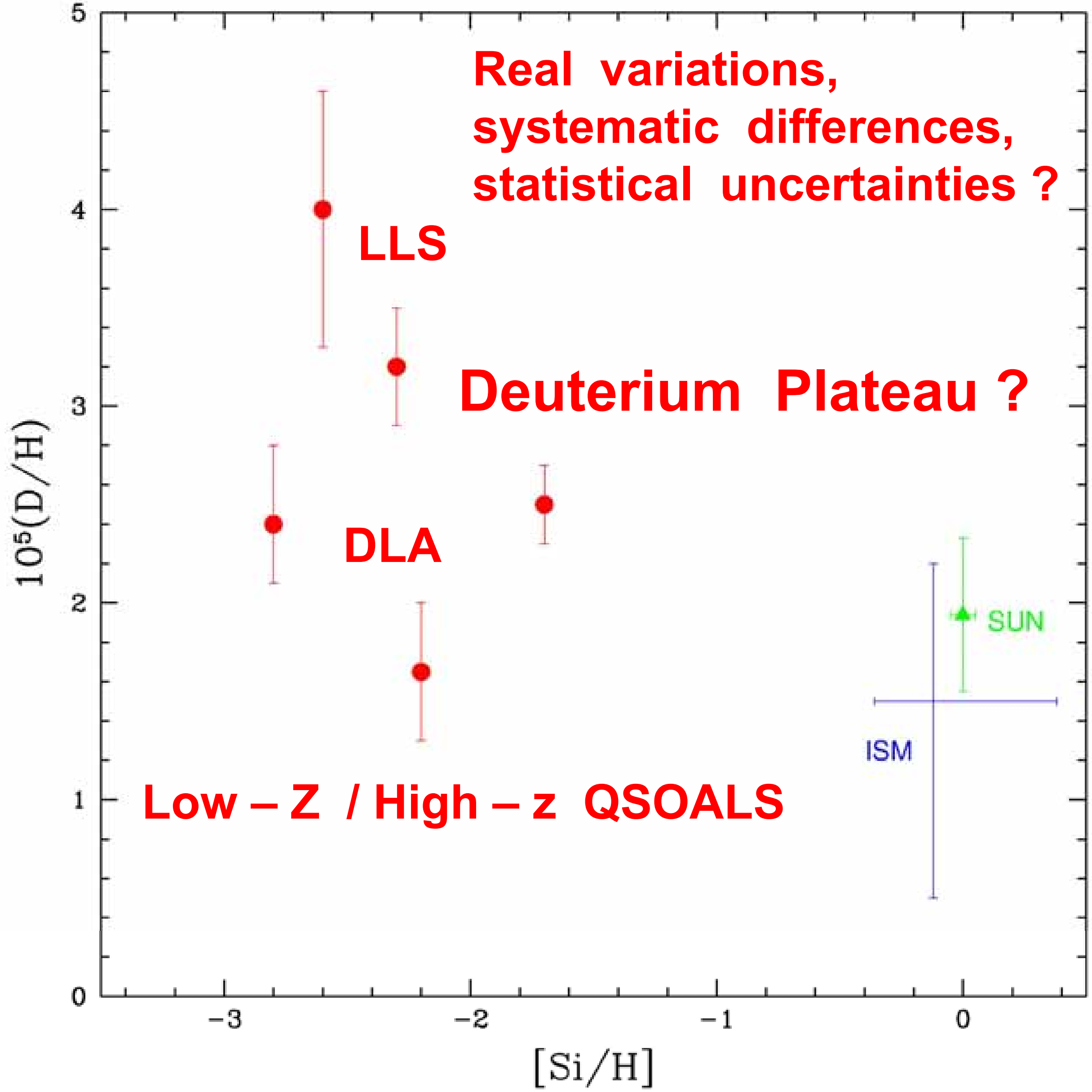
- $(D/H)_P$ is sensitive to the baryon density ($\propto \eta_{10}^{-1.6}$)

- H I and D I are seen in Absorption, BUT …

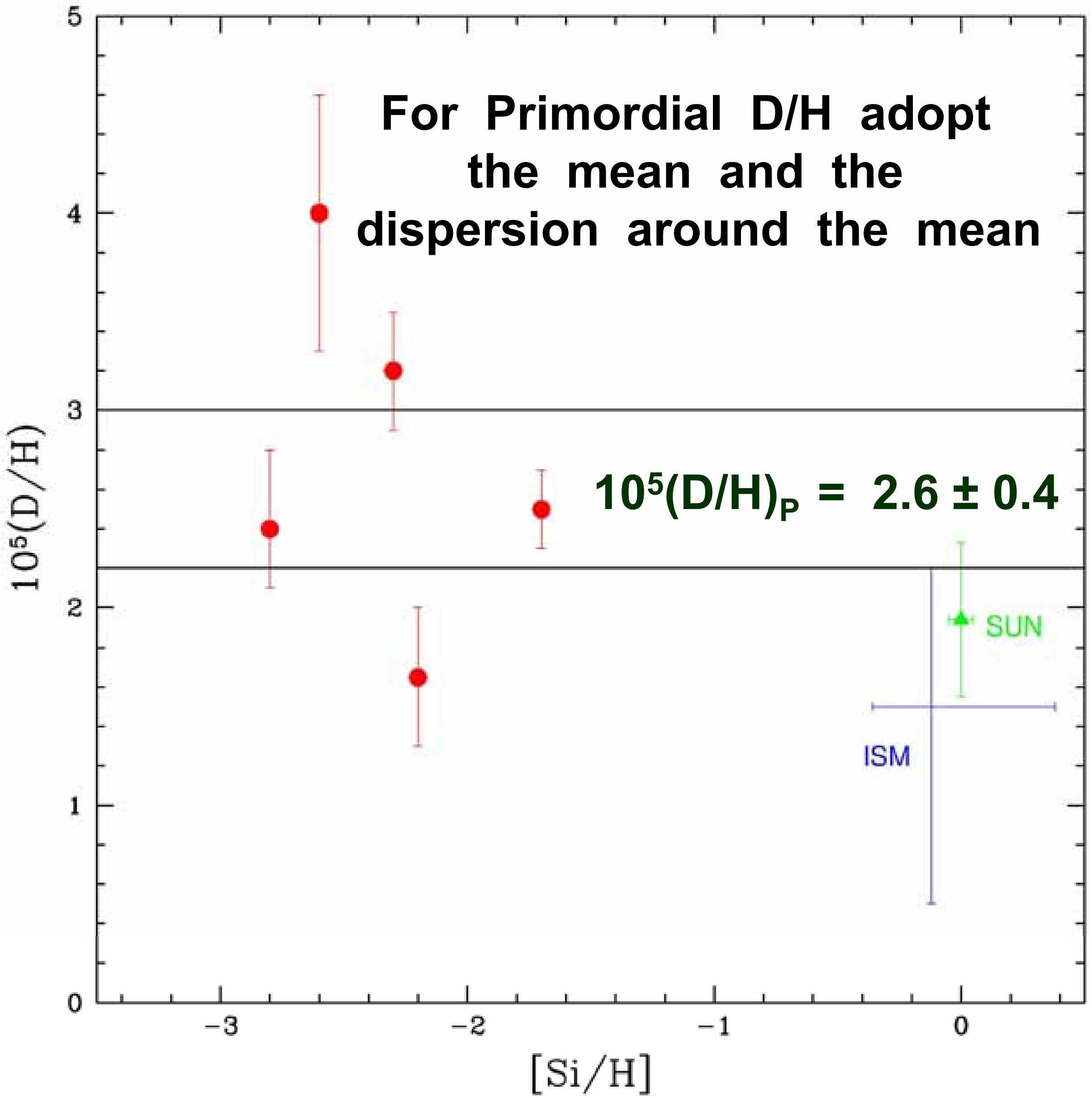
  * H I and D I spectra are identical $\Rightarrow$ H I Interlopers?

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

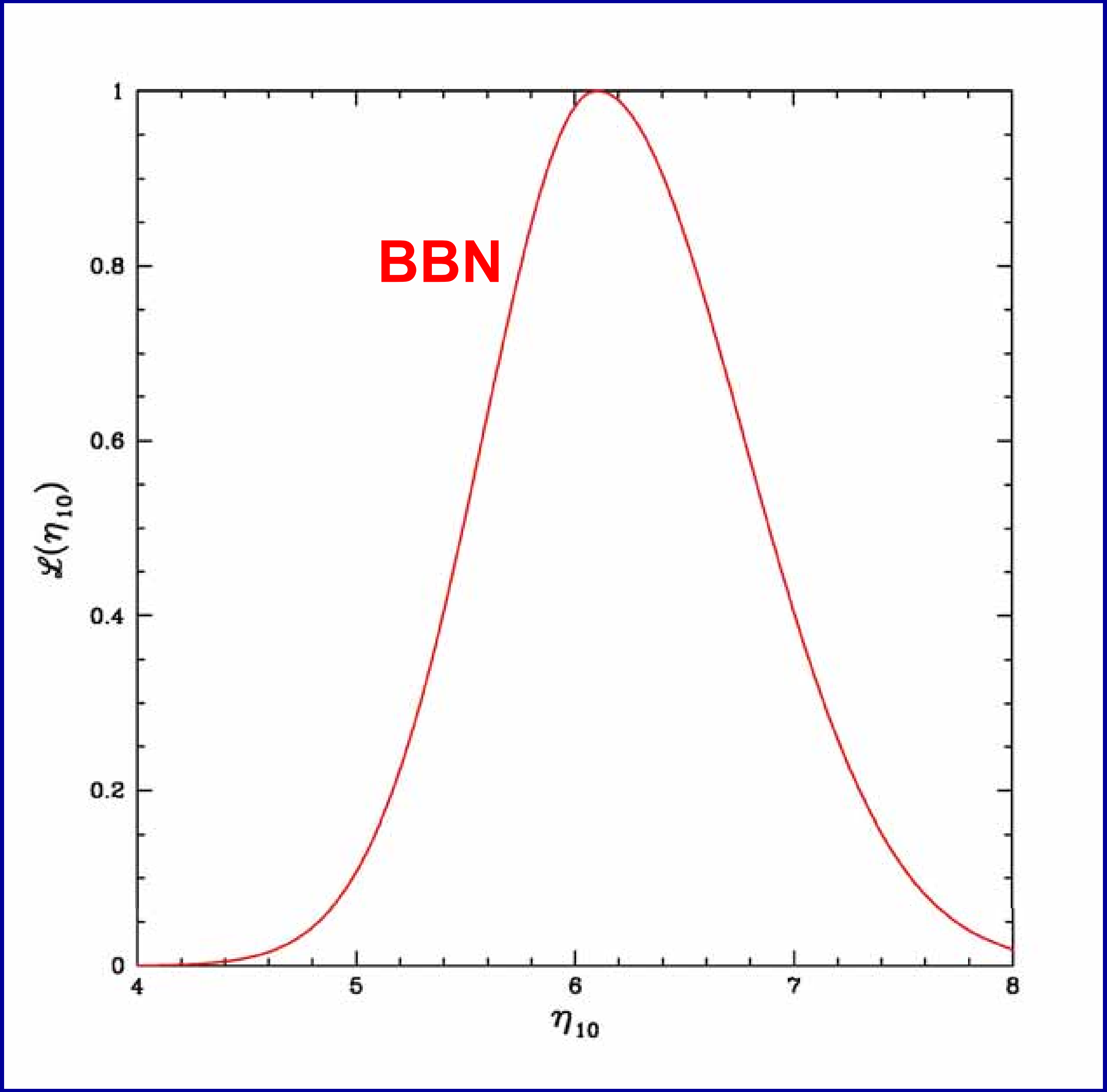
D/H vs. Metallicity



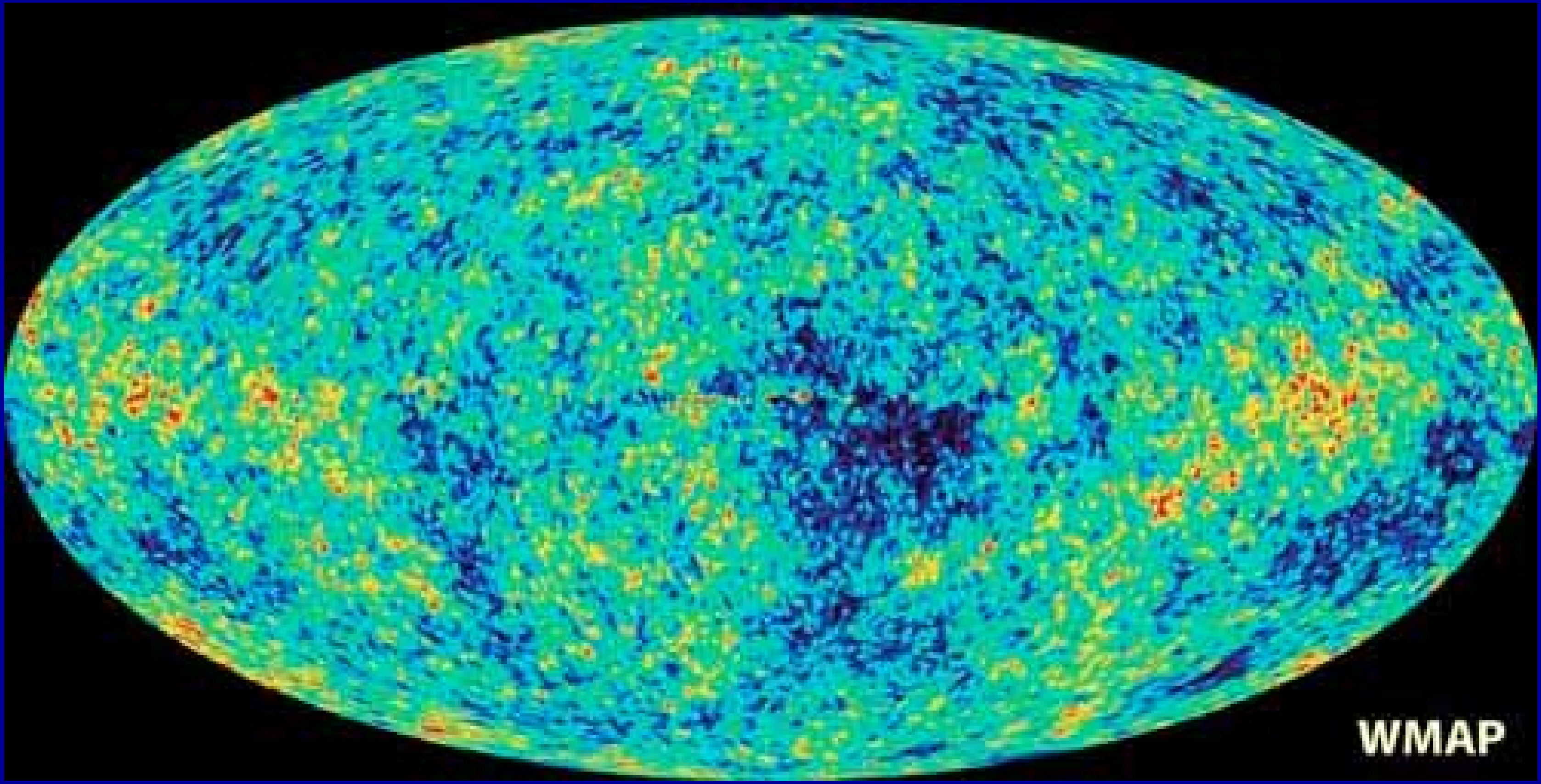
D/H vs. Metallicity



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

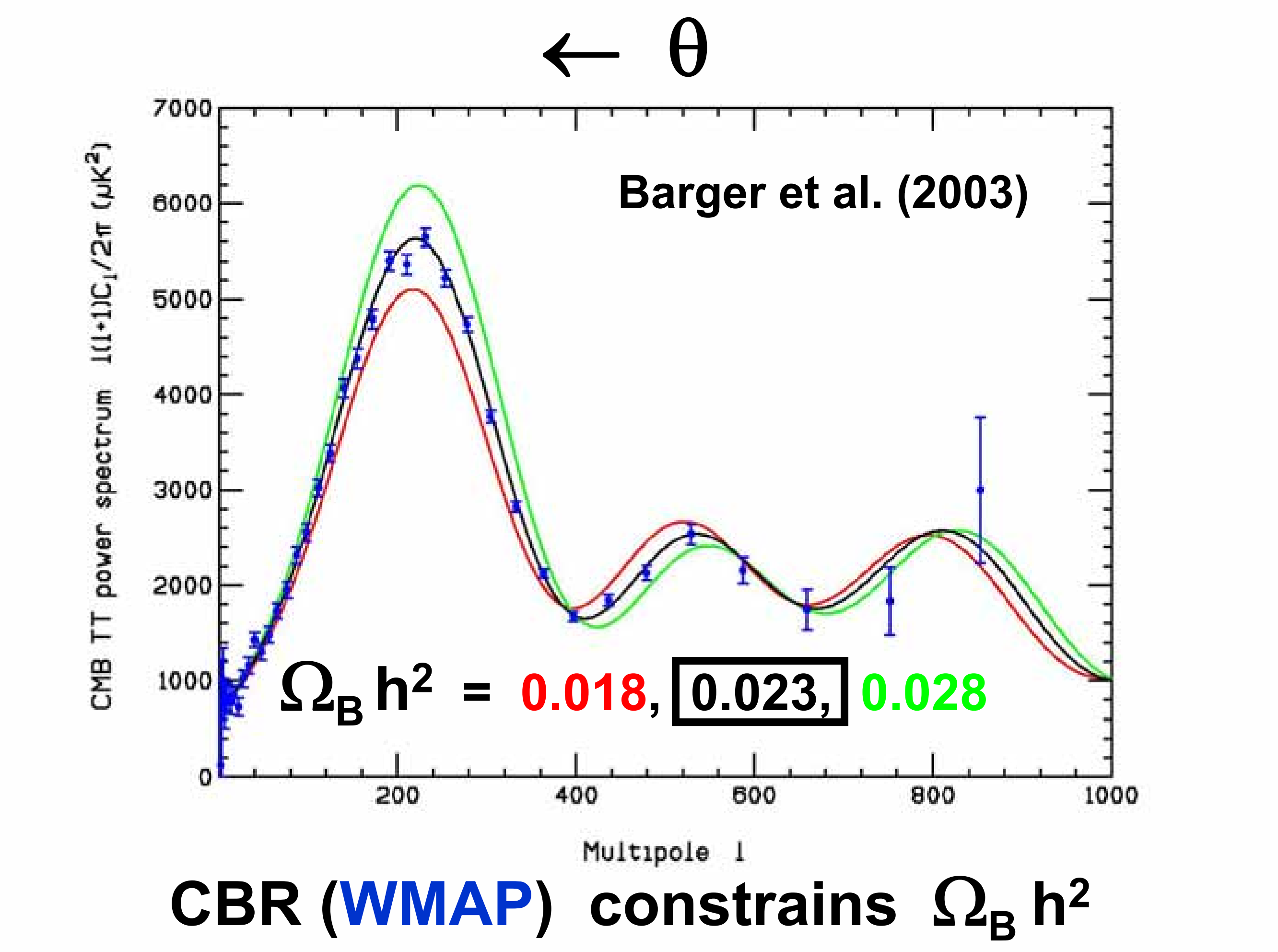


CBR



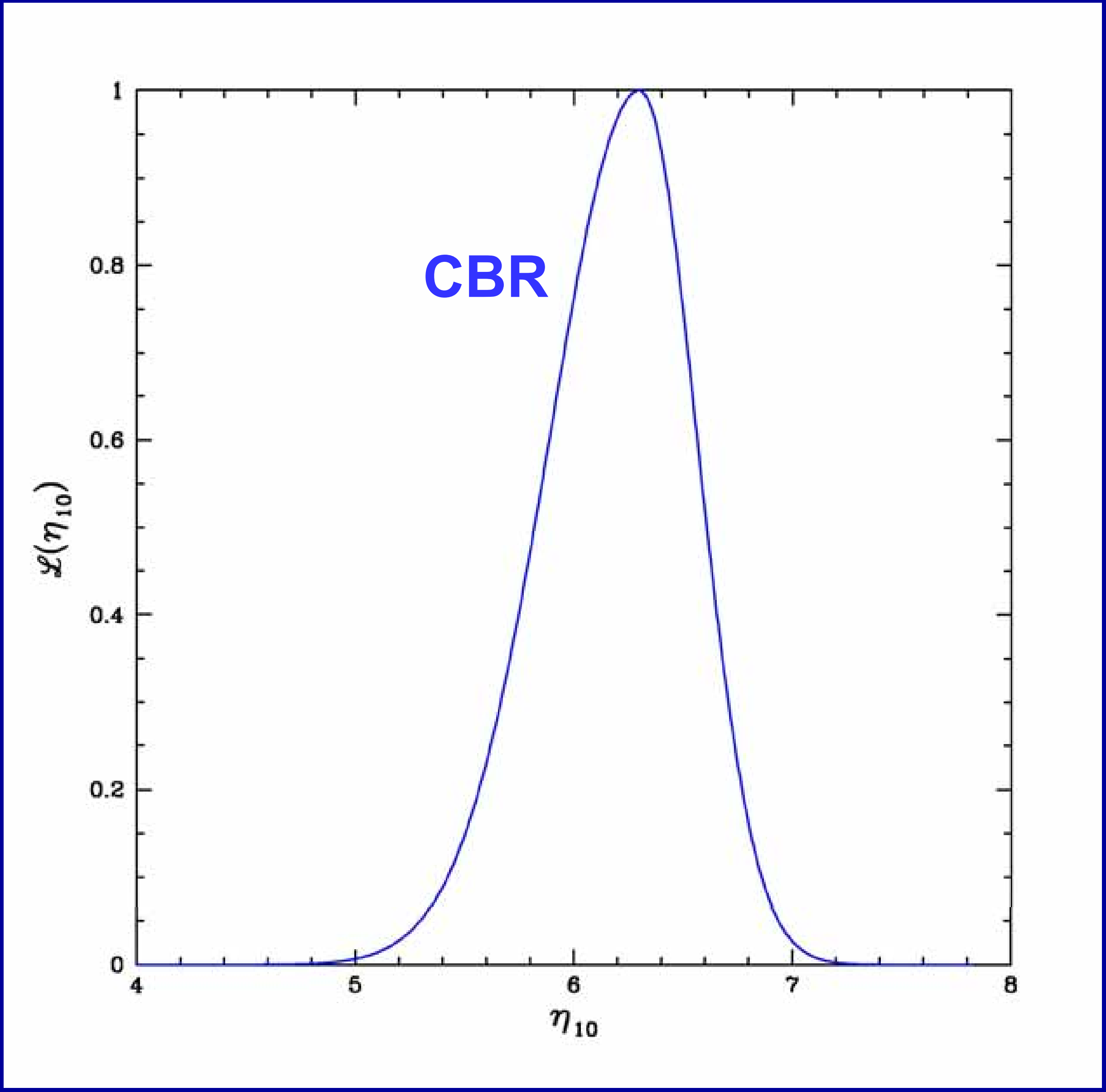
CBR Temperature Anisotropy Spectrum (2003)

(ΔT^2 vs. θ) Depends On The Baryon Density

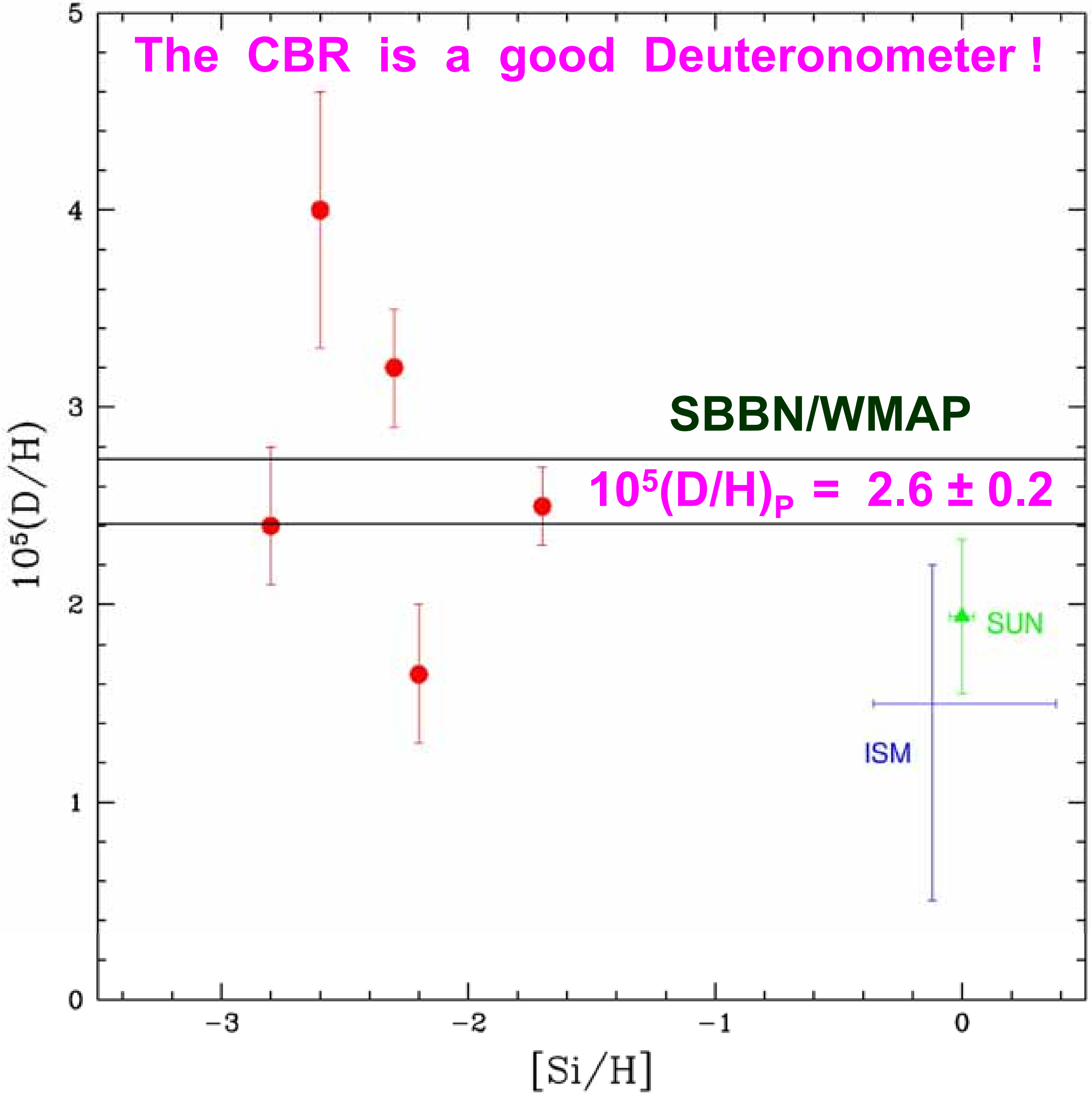


The CBR is an early - Universe Baryometer

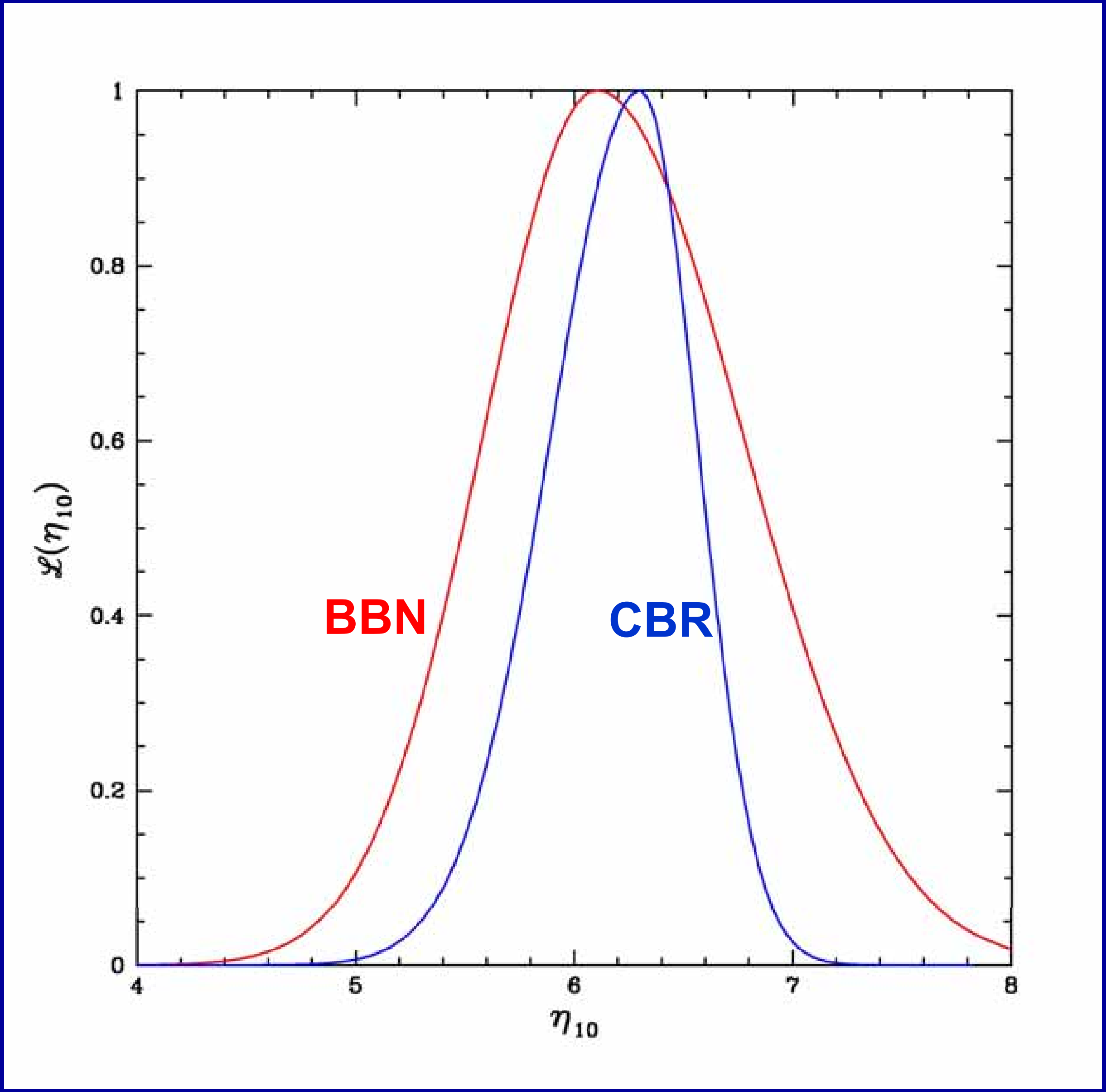
CBR (WMAP – 2003 ALONE) $\Rightarrow \eta_{10} = 6.3 \pm 0.3$



D/H vs. Metallicity



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



The Expansion Rate (H) Provides

A Probe Of Non-Standard Physics

^{4}He production is n/p Limited $\Rightarrow$ Y_P is

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

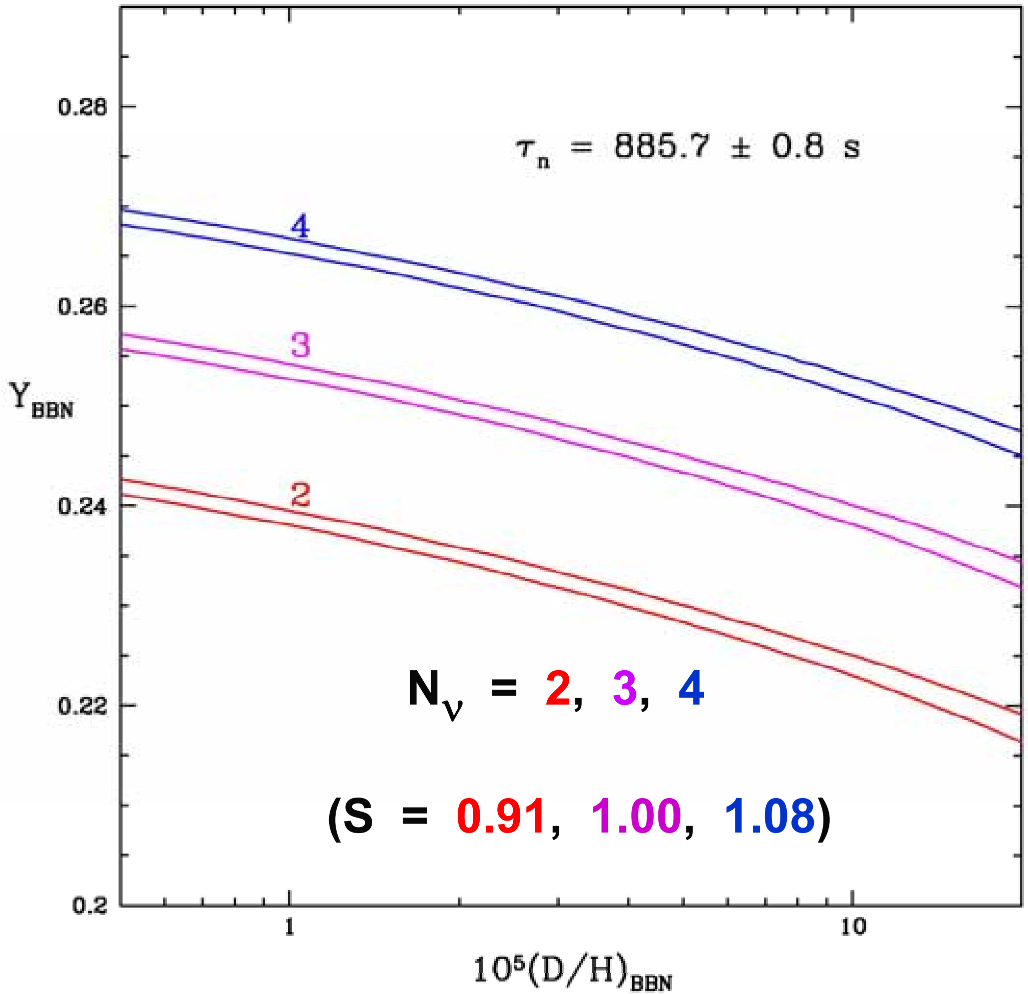
$$S \equiv H'/H \equiv (\rho'/\rho)^{1/2} \equiv (1 + 7\Delta N_\nu/43)^{1/2}$$

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

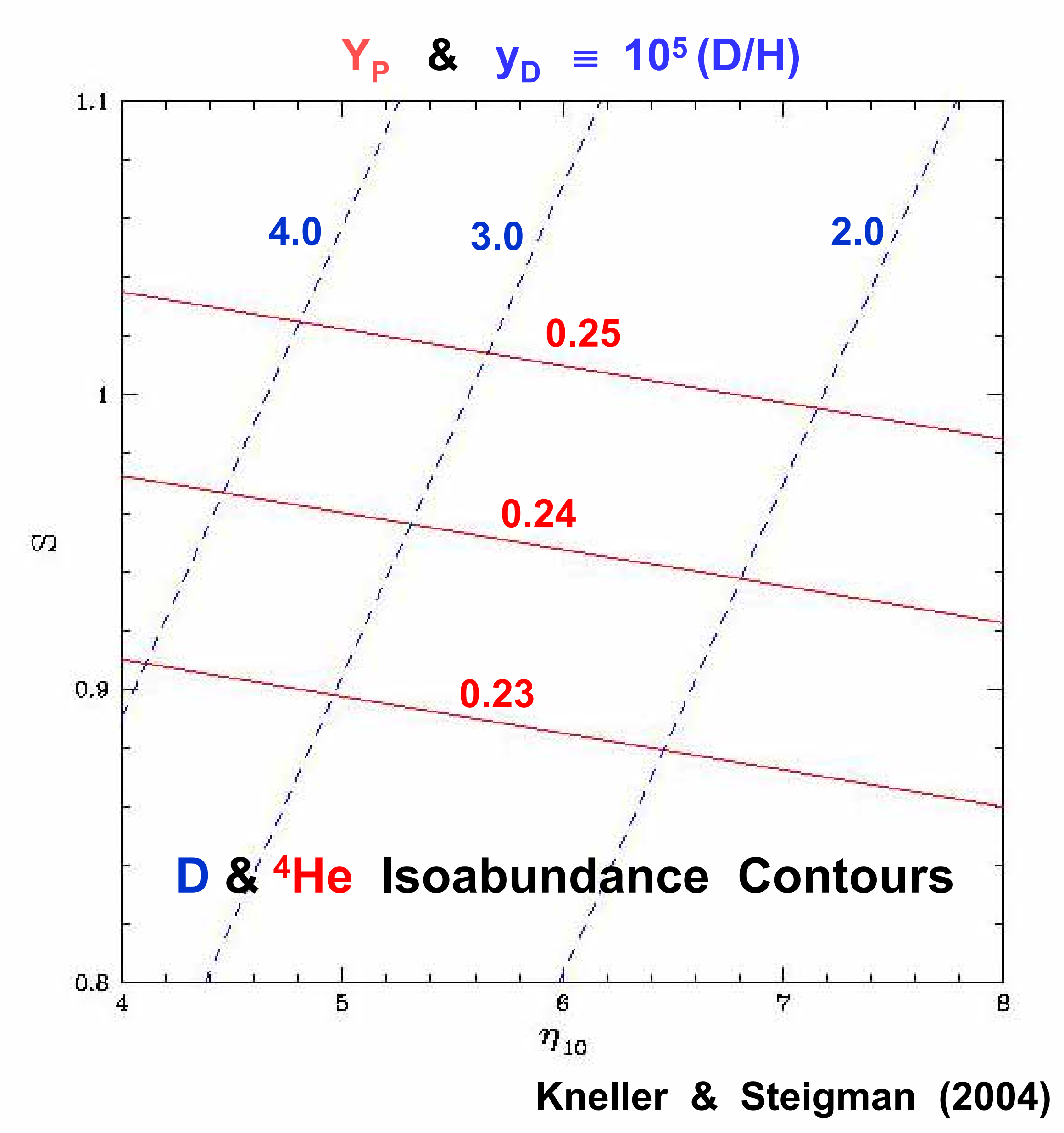
$\Rightarrow$ S (or N_ν) is constrained by Y_P

^{4}He is an early – Universe Chronometer

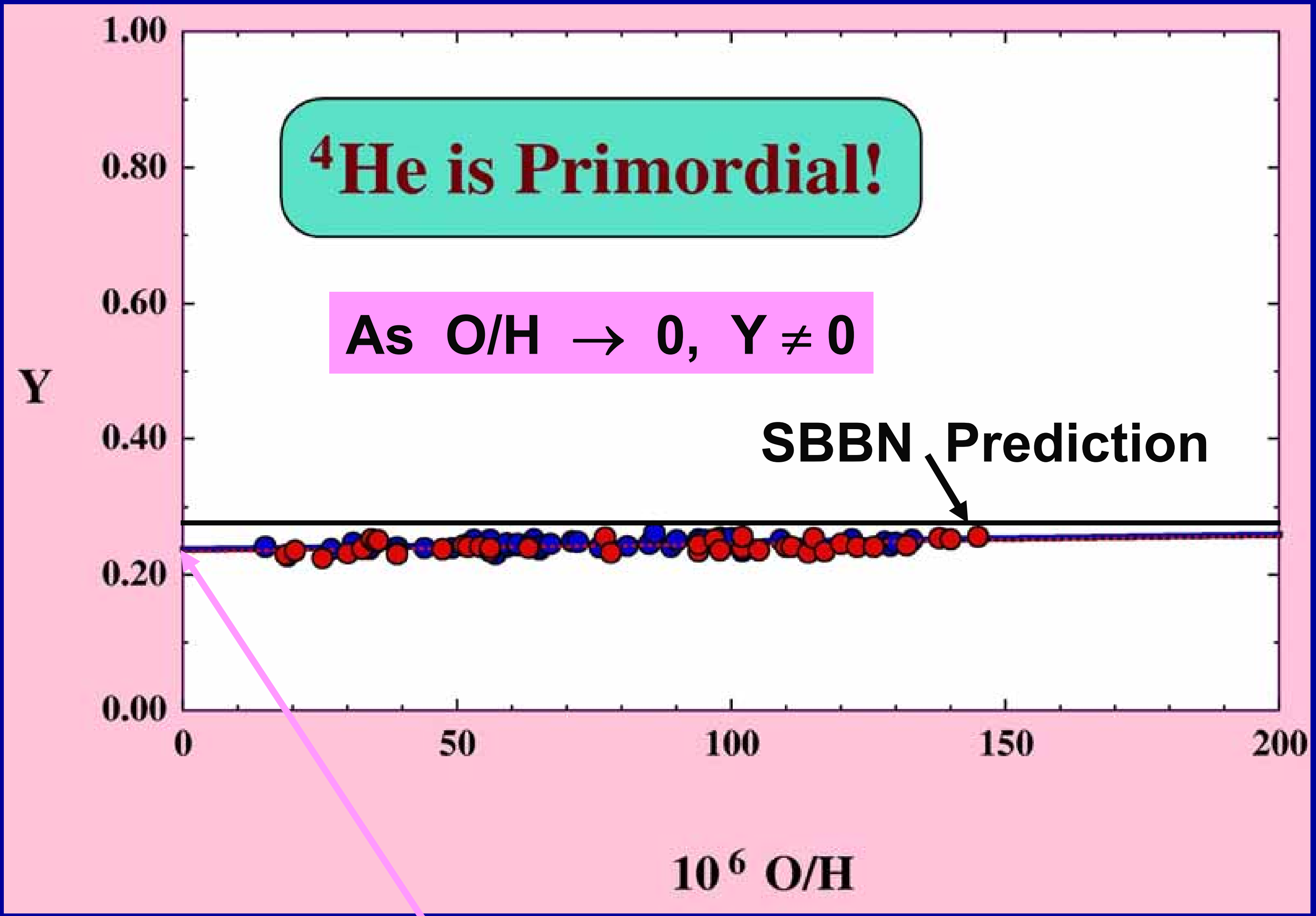
Y vs. D / H



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

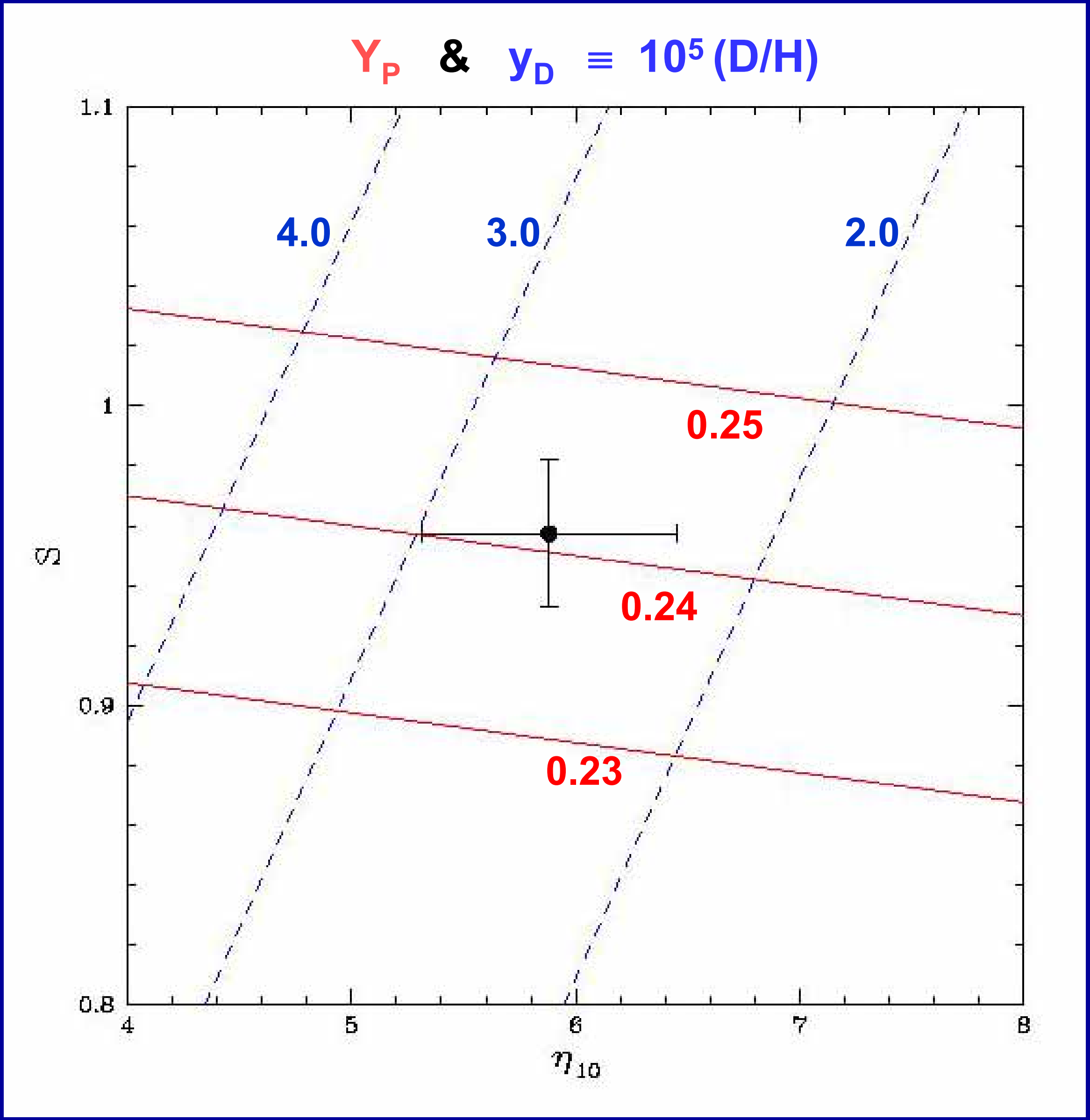


Y_P & $y_D \equiv 10^5$ (D/H)
1.1
1
0.9
0.8
S
4
5
6
7
8
η_{10}
4.0
3.0
2.0
0.25
0.24
0.23
D & ^{4}He Isoabundance Contours
Kneller & Steigman (2004)



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

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



A Non-Standard BBN Example ($N_\nu^{eff} < 3$)

Late Decay of a

Massive Particle

&

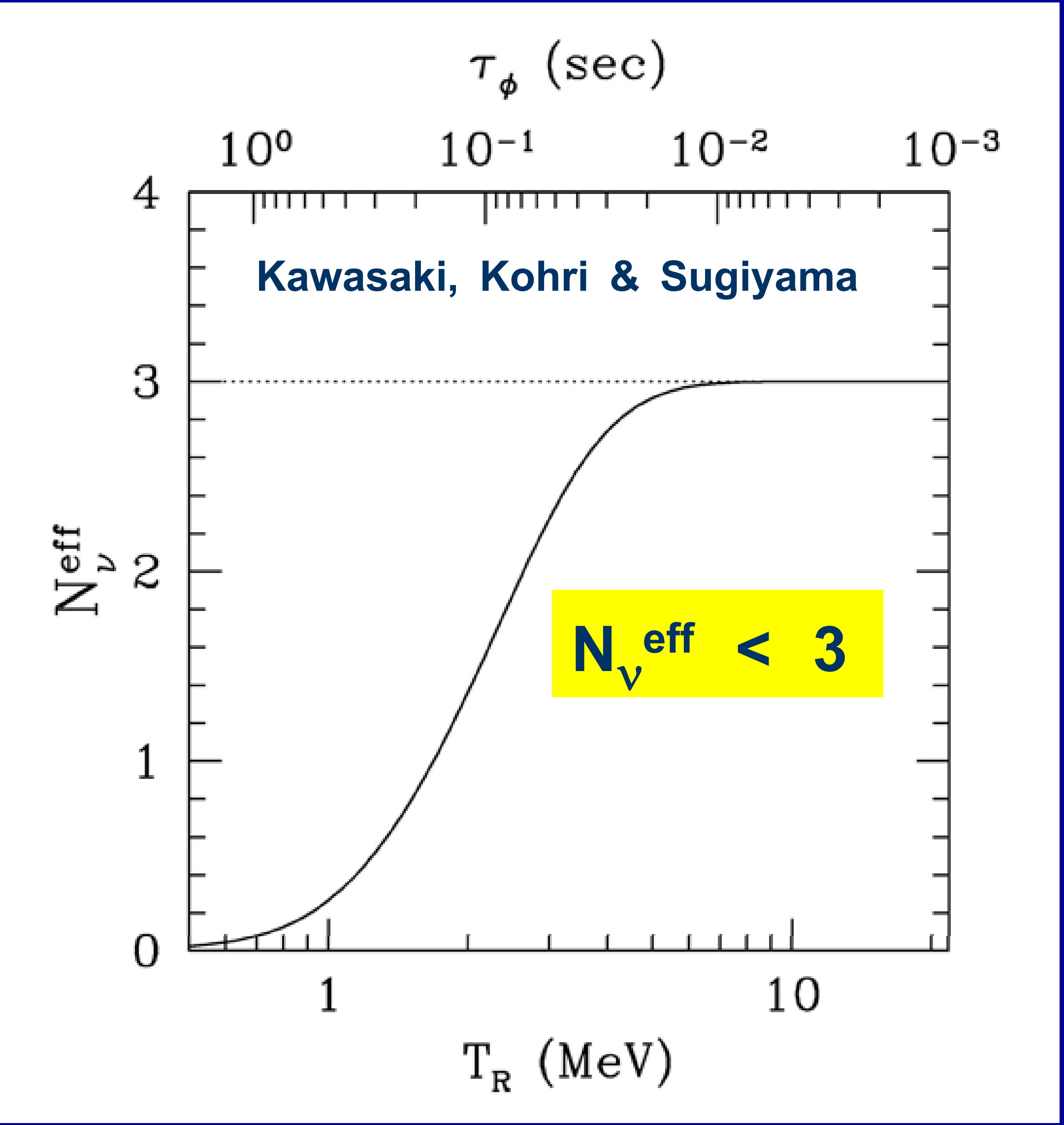
Low Reheat Temp.

($T_R \sim$ MeV)

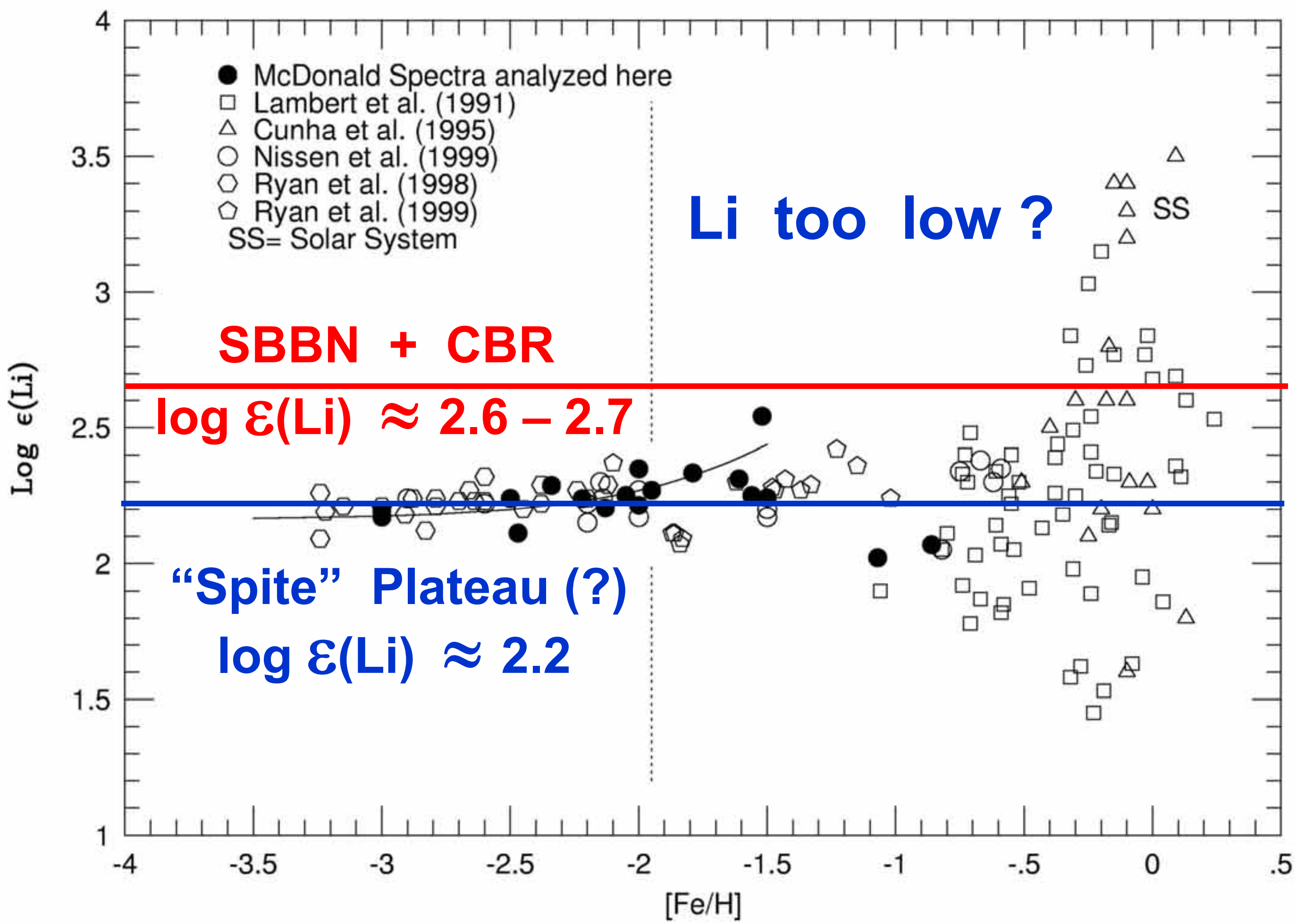
$\Rightarrow$

Relic Neutrinos Not

Fully (Re) Populated



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
SS
Li too low ?
SBBN + CBR
log ε(Li) ≈ 2.6 – 2.7
"Spite" Plateau (?)
log ε(Li) ≈ 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 $N_\nu \neq 3$

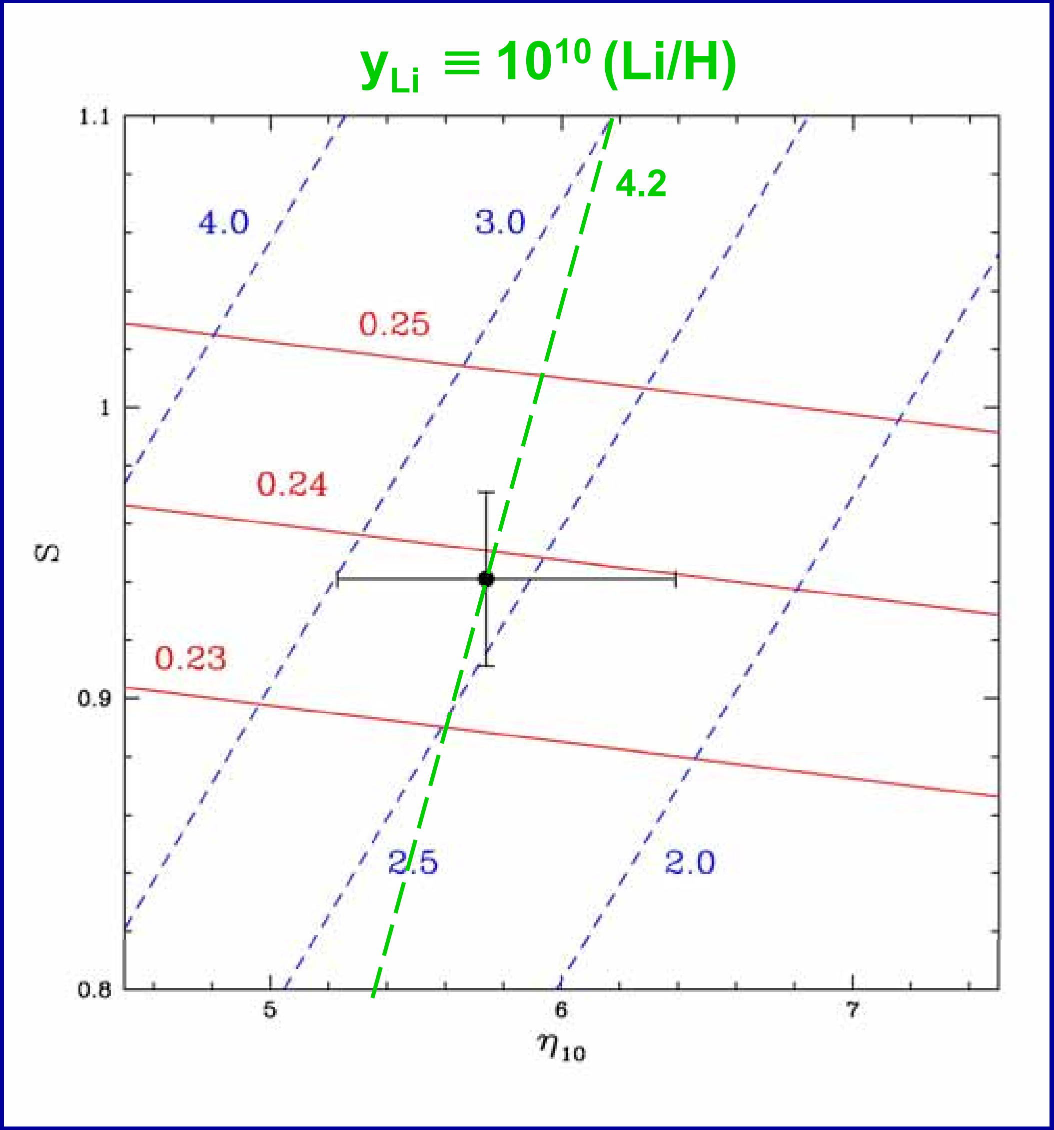
Y_{OSW} + D / H $\Rightarrow$

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

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

Li depleted / diluted

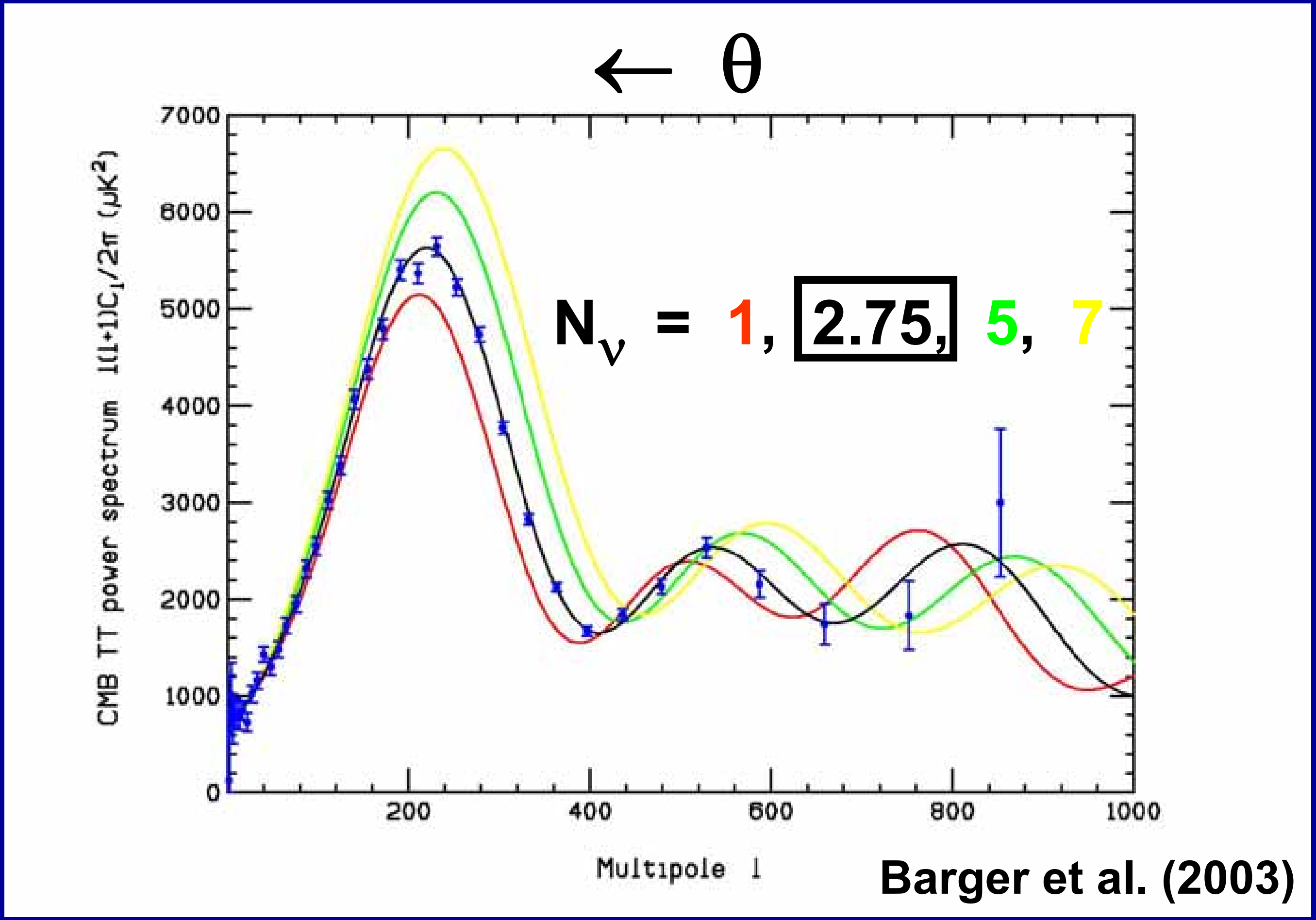
in Pop II stars ?



Or, Late Decay of the NLSP ?

CBR Temperature Anisotropy Spectrum (2003)

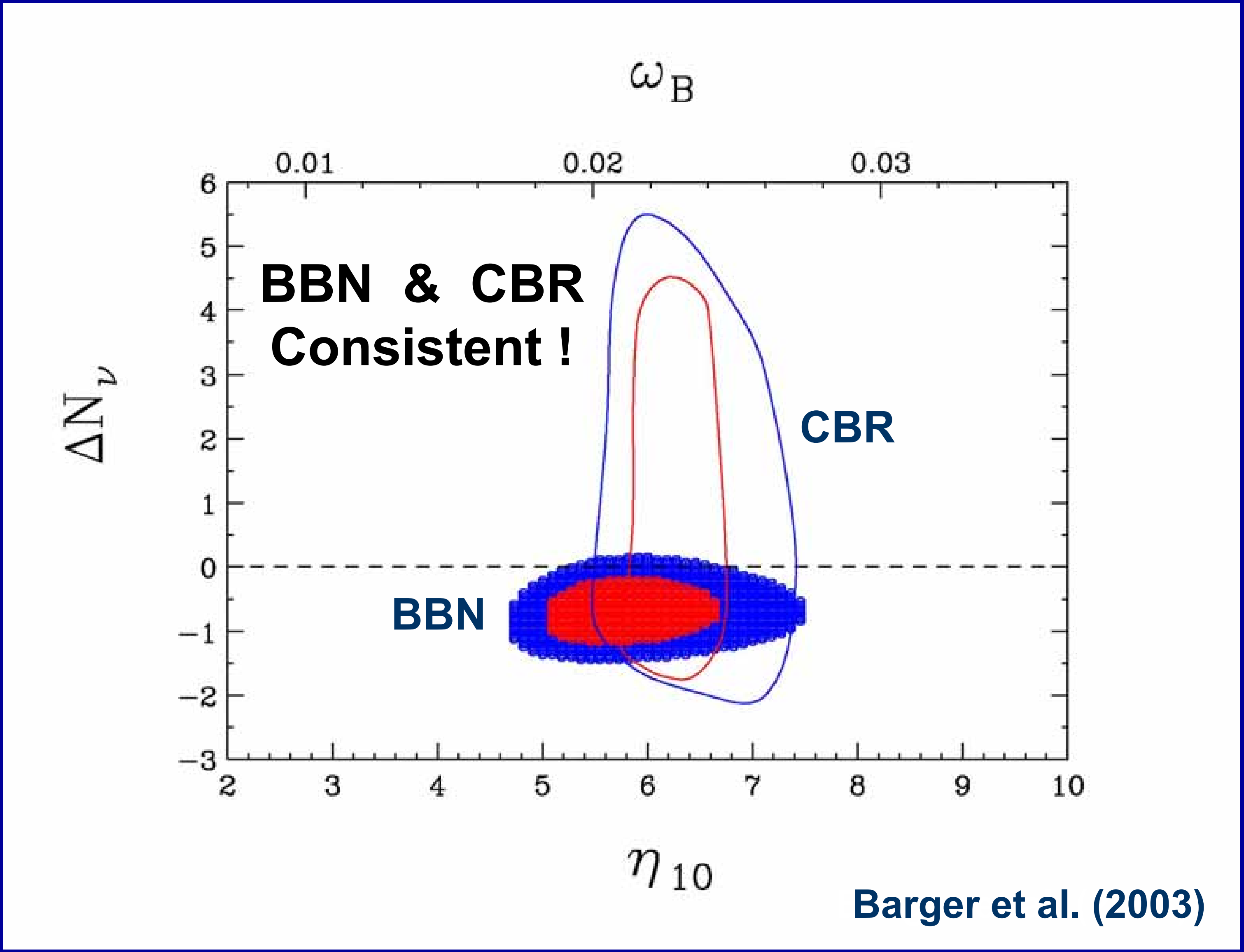
Depends on the Radiation Density ρ_R (S or N_ν)



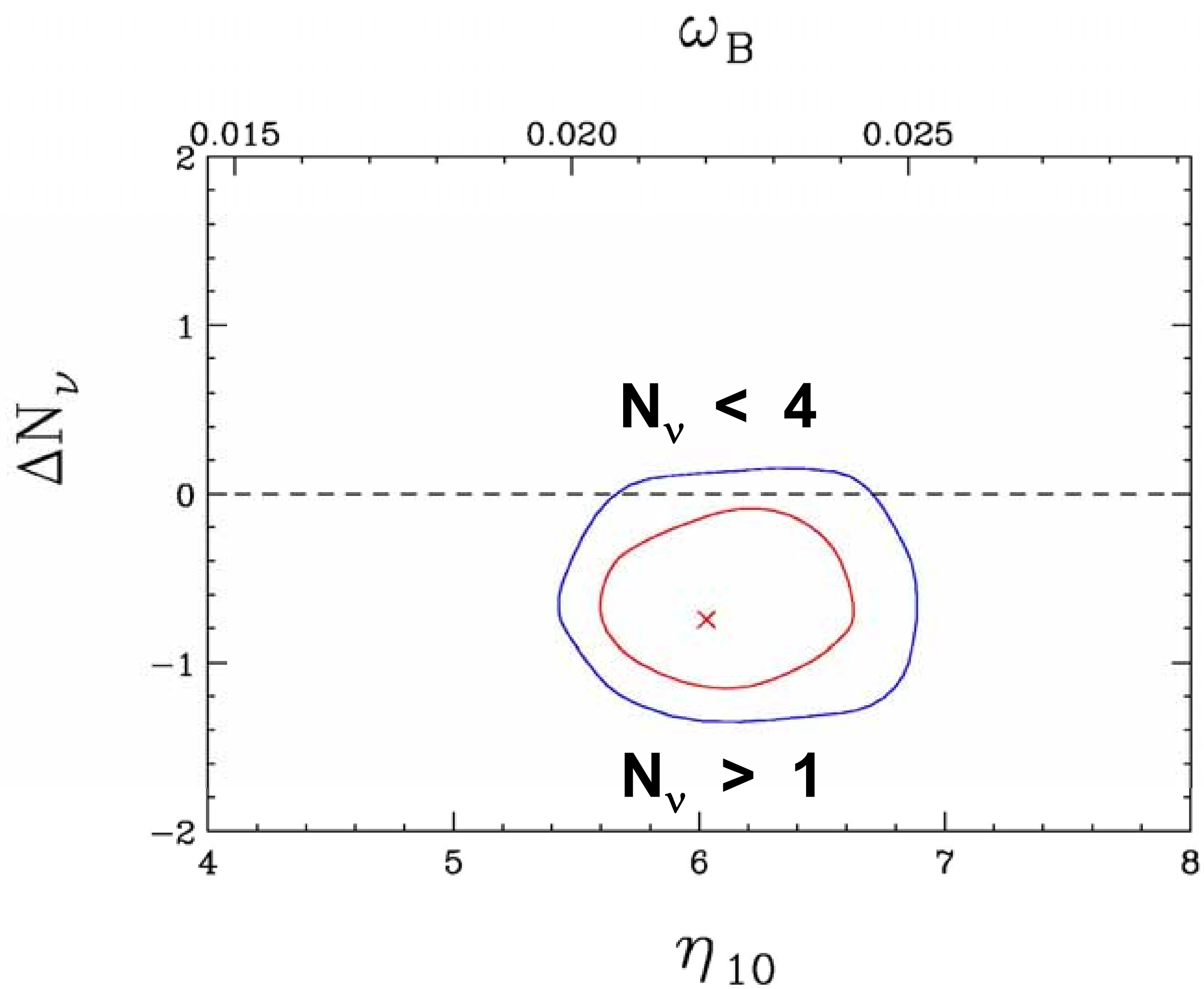
CBR (WMAP) constrains N_ν (S)

The CBR is an early - Universe Chronometer

BBN (D & ^{4}He) + CBR (WMAP – 2003)

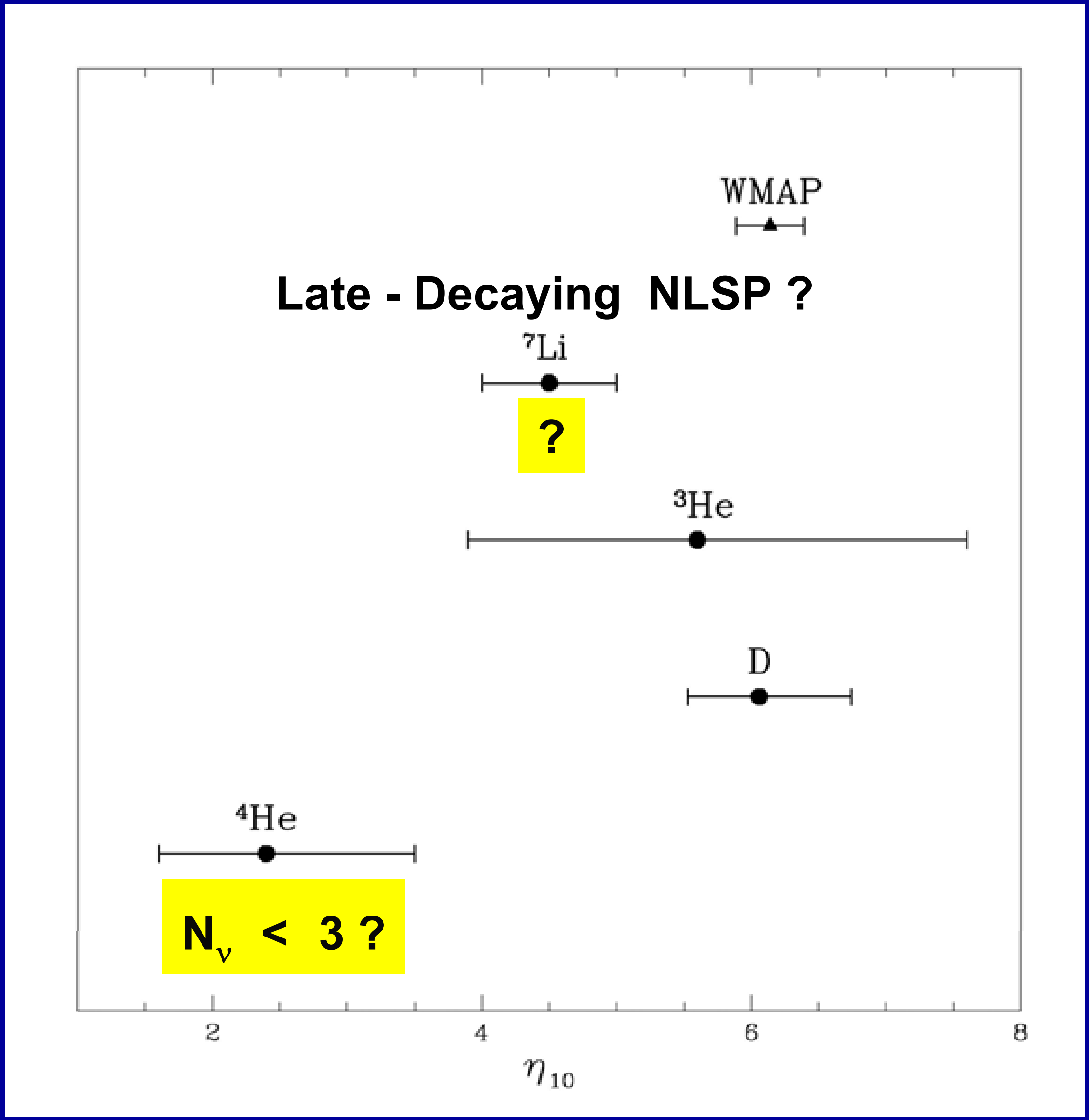


Joint BBN (D & ^{4}He) & CBR (WMAP) Fit



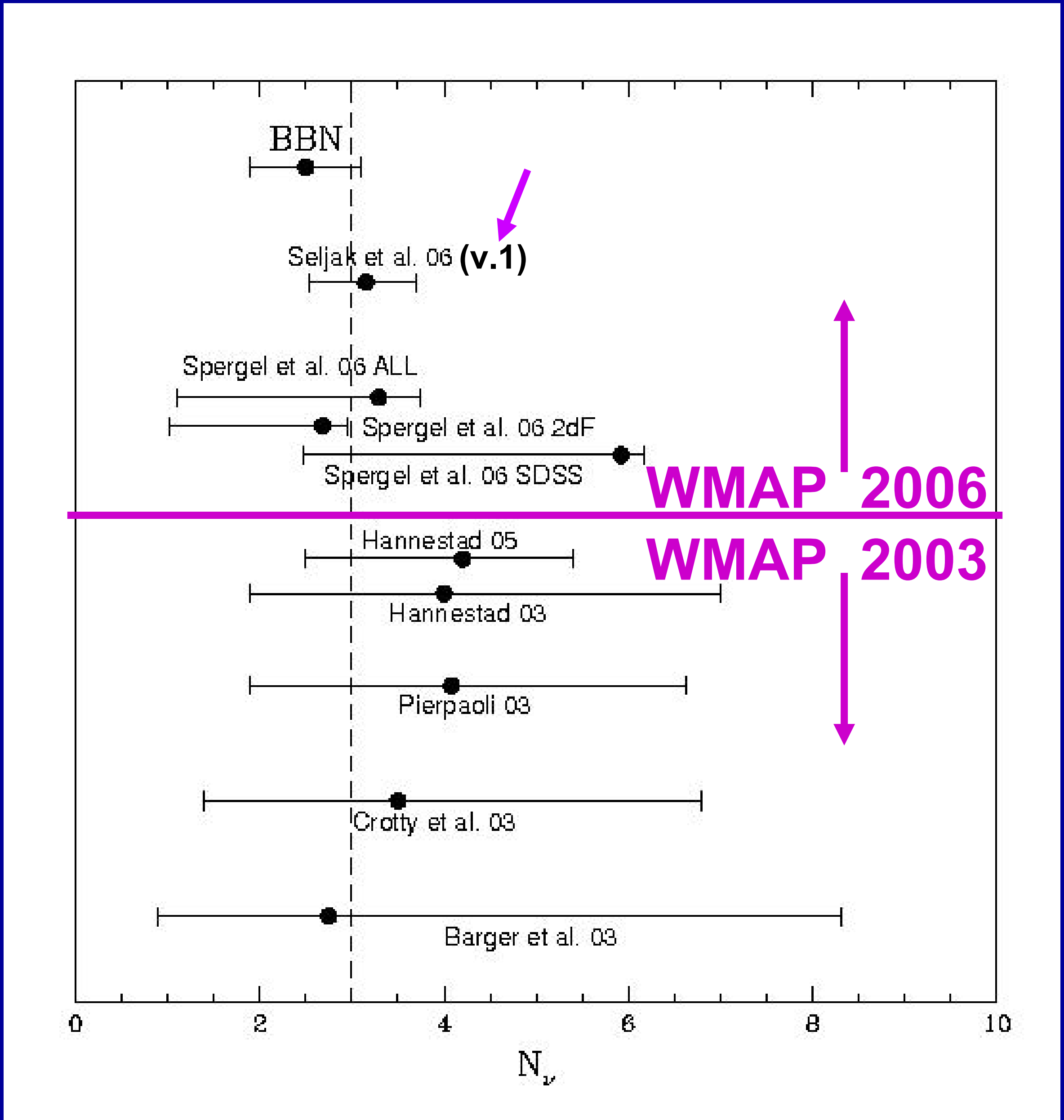
Barger et al. (2003)

Baryon Density Determinations: Consistent ?

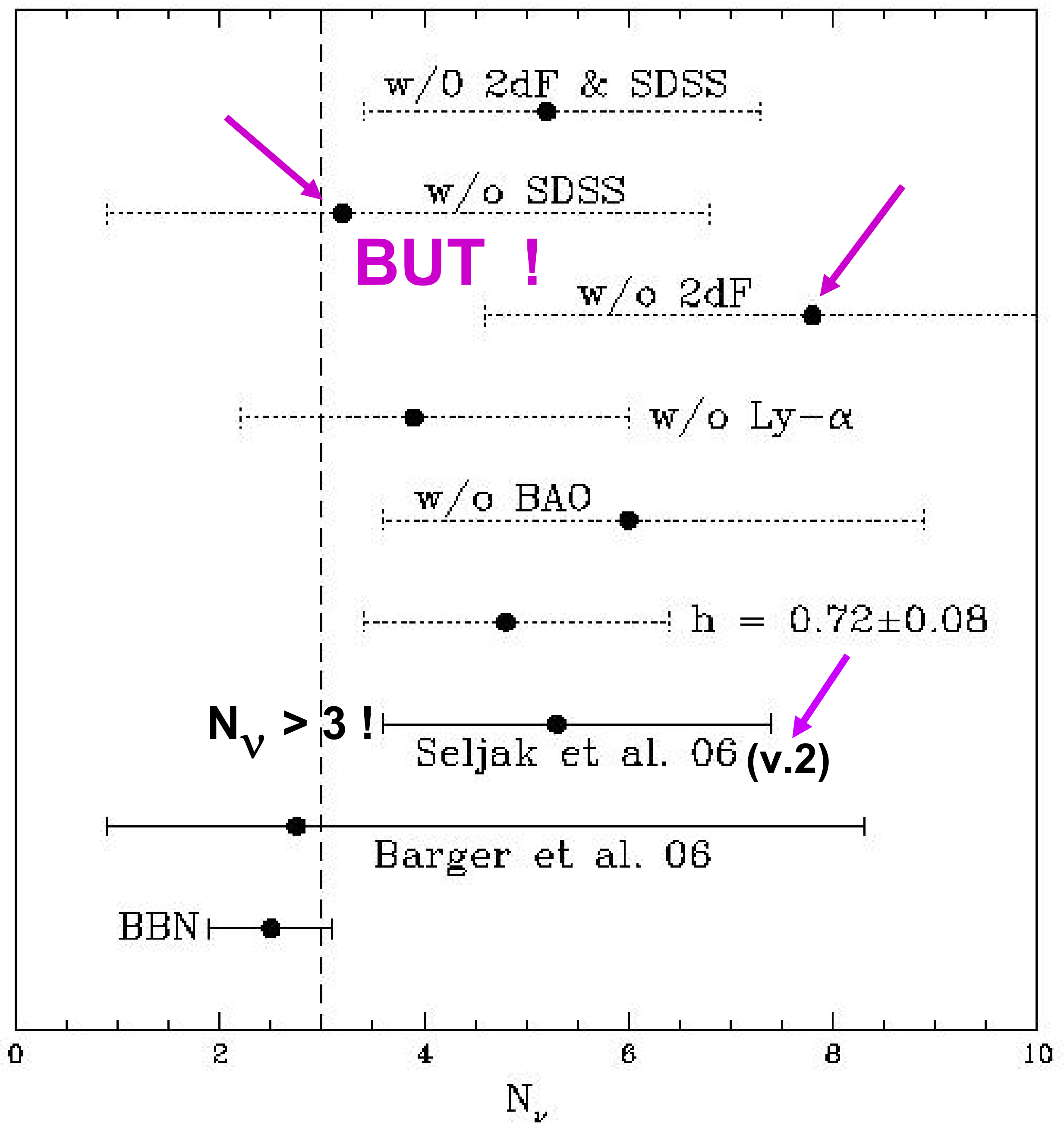


Observational Uncertainties Or New Physics?

N_ν Determinations (95 % CL Ranges)



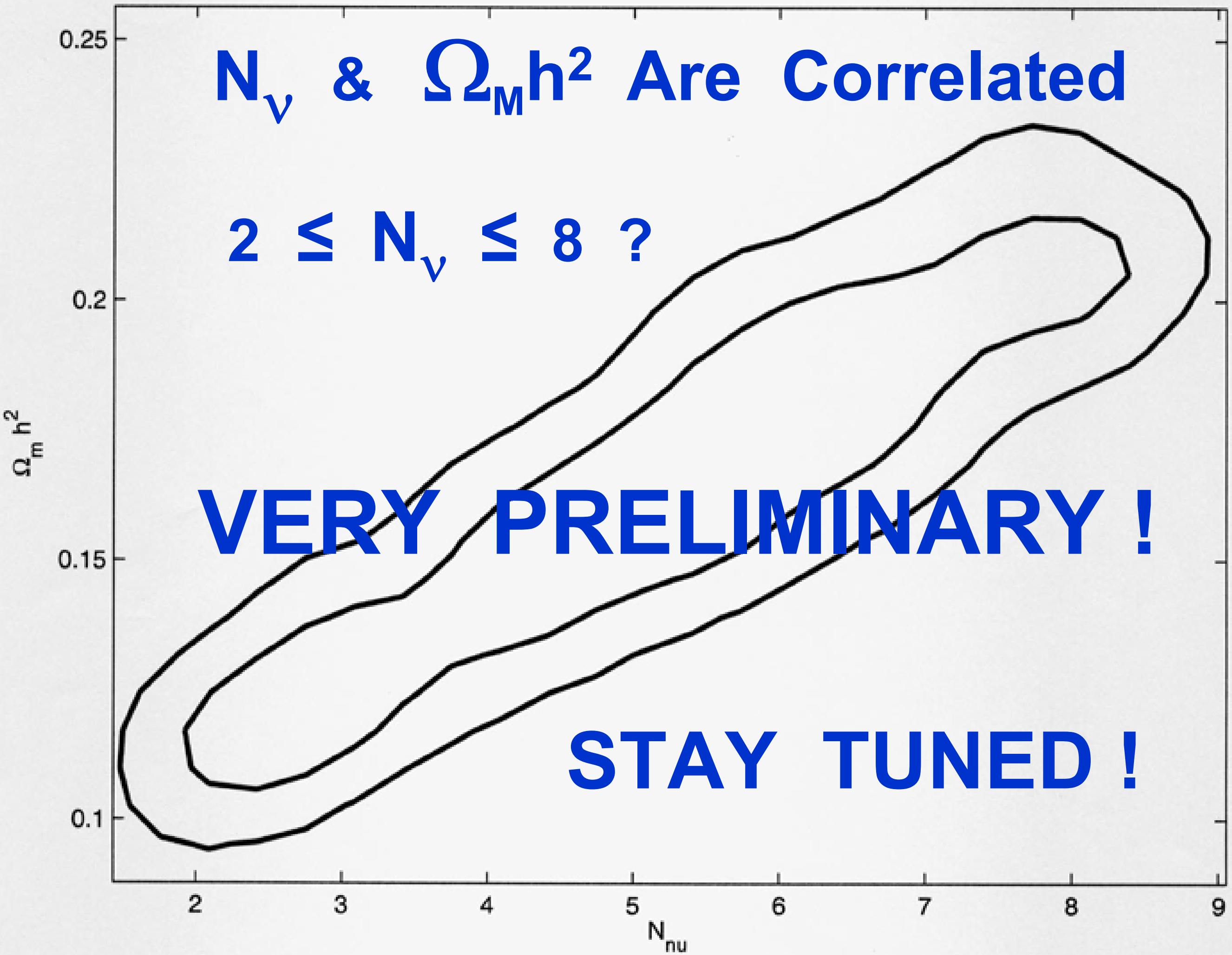
Seljak et al. Revised



V. Simha & G. S.

N_ν & $\Omega_M h^2$ Are Correlated

$2 \le N_\nu \le 8$?



VERY PRELIMINARY !

STAY TUNED !

The CMB Is A Relatively Poor Chronometer

CONCLUSIONS

(Pre – WMAP 2006)

BBN (~ 20 min.) And The CBR (~ 400 kyr)

Are CONSISTENT !

$1.9 \leq N_\nu \leq 3.1$ allowed @ ~ 95%

(Also : $\eta_{10} = 6.1 \pm 0.2$)