BIG BANG NUCLEOSYNTHESIS

AND NEUTRINOS

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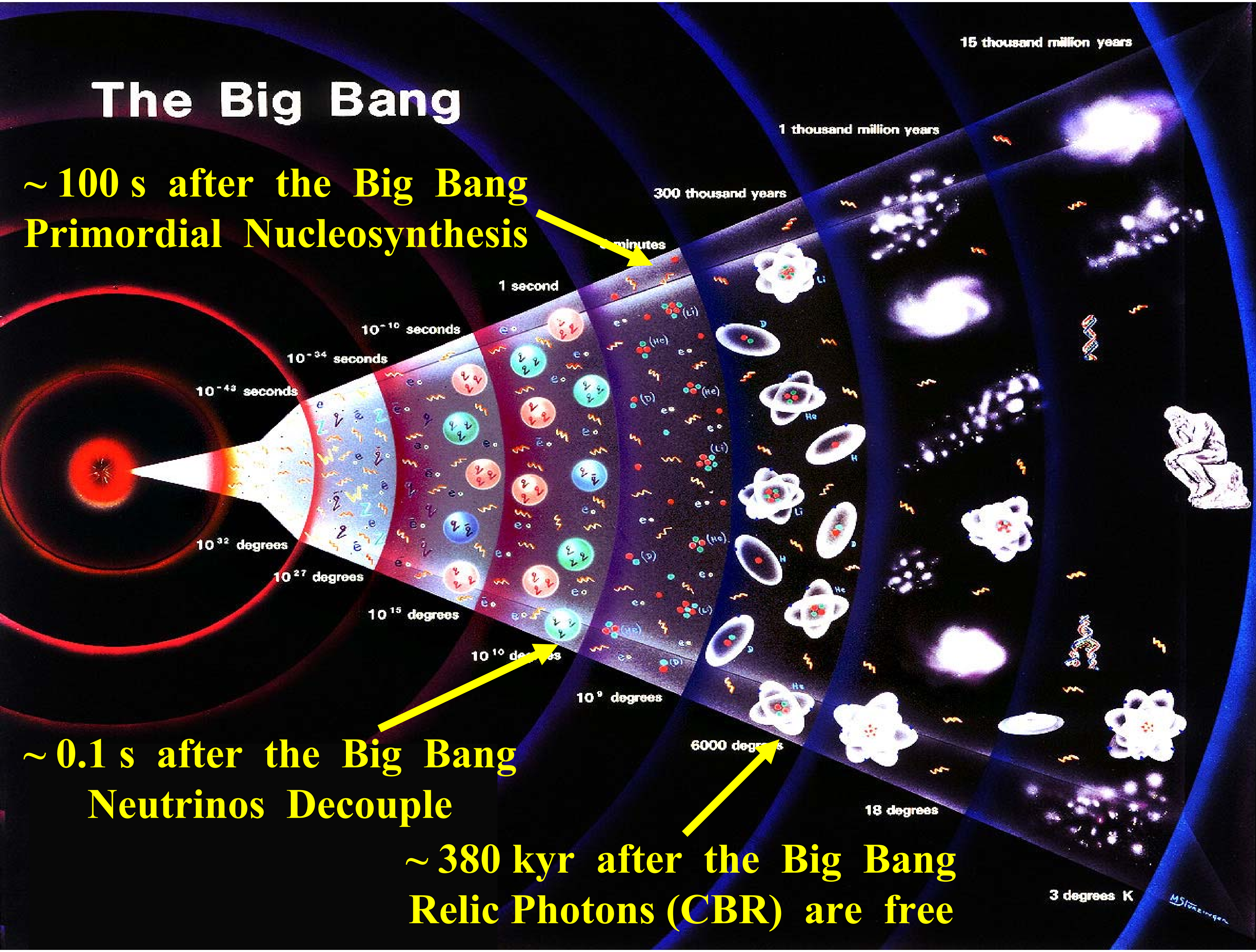

The Big Bang
~ 100 s after the Big Bang
Primordial Nucleosynthesis
~ 0.1 s after the Big Bang
Neutrinos Decouple
~ 380 kyr after the Big Bang
Relic Photons (CBR) are free
15 thousand million years
1 thousand million years
300 thousand years
minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K

BBN (@ ~ 20 Minutes) & The CBR (@ ~ 400 kyr)

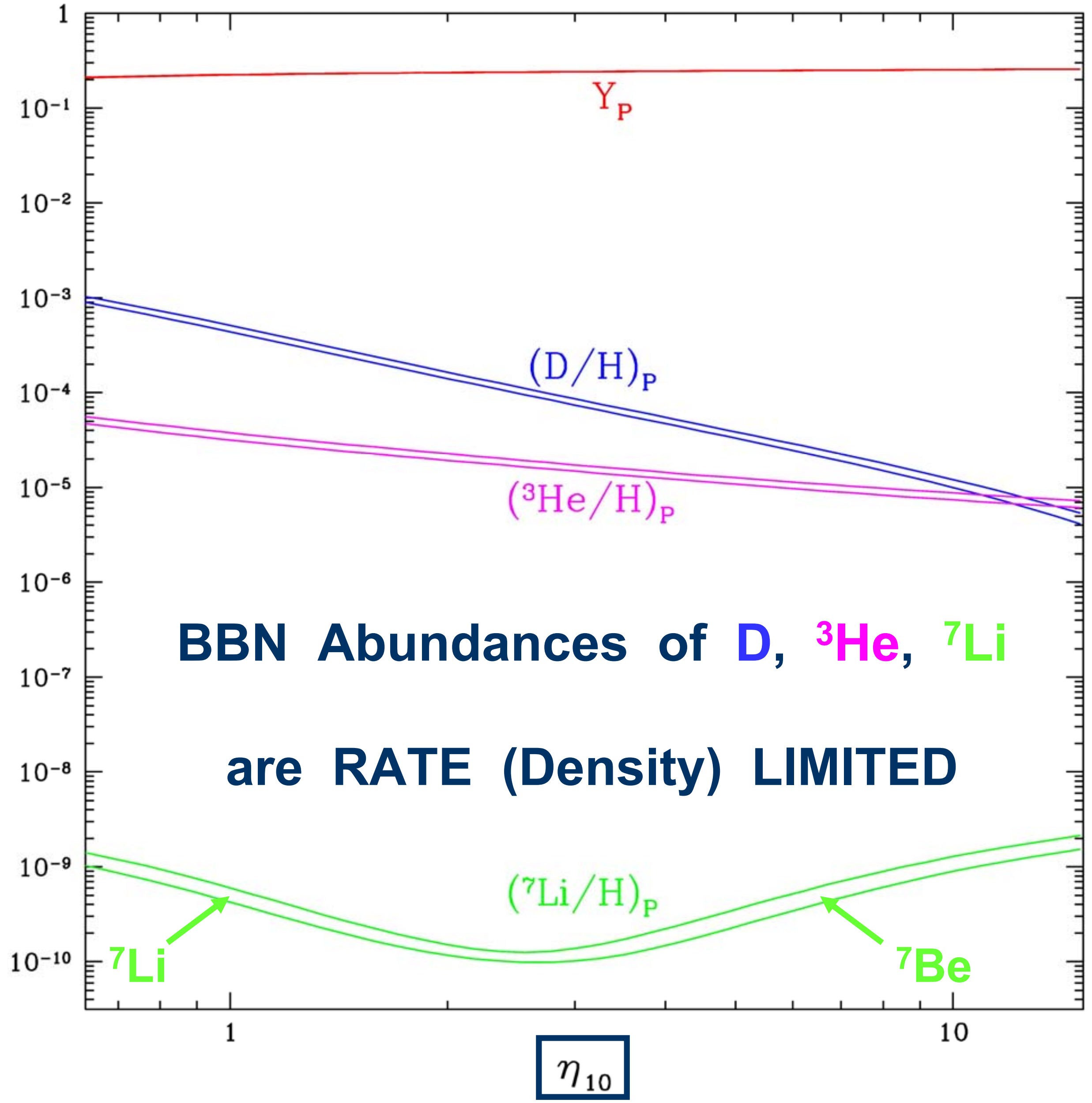
Provide Complementary Probes Of The

Early Evolution Of The Universe

*** Neutrinos Play Important Roles At Both Epochs**

Do predictions and observations of the baryon density ($\eta_{10} \equiv 10^{10}(n_B/n_\gamma)_0 = 274\,\Omega_B h^2$) and expansion rate (H) of the Universe agree at these different epochs?

BBN – Predicted Primordial Abundances



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

DEUTERIUM --- The Baryometer Of Choice

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

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

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

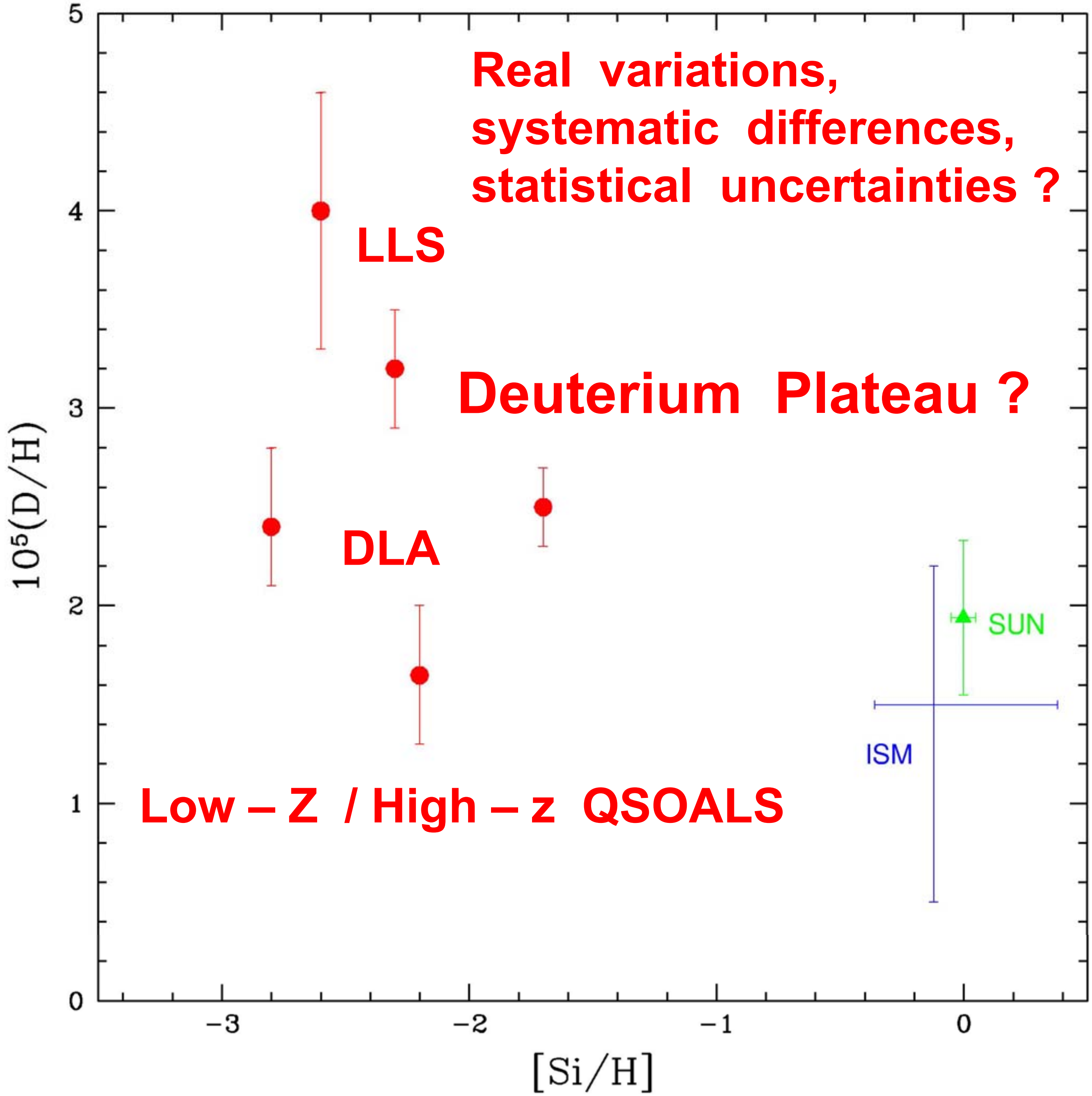
- **$(D/H)_P$ is sensitive to the baryon density ($\propto \eta_{10}^{-1.6}$)**

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

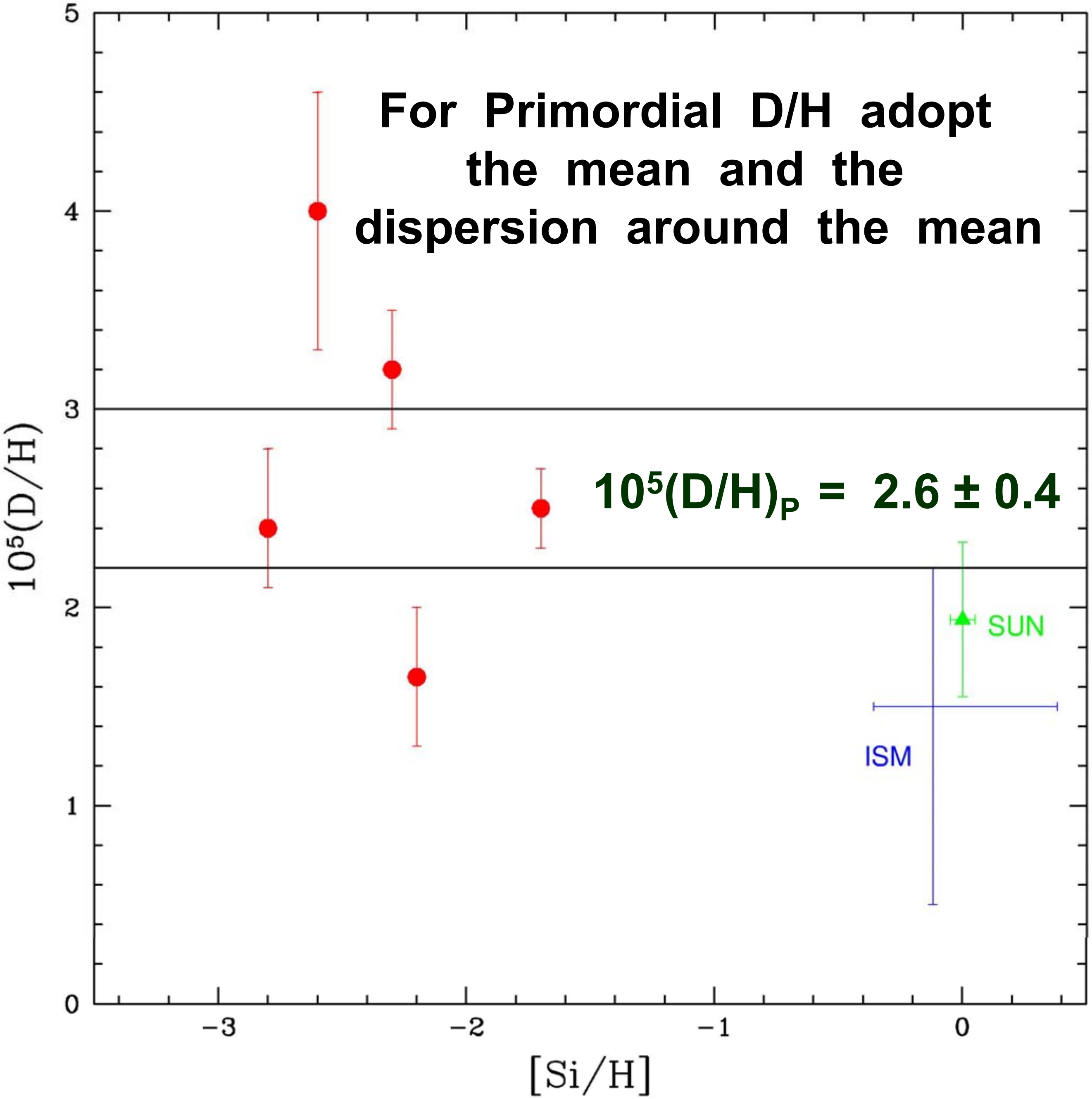
  * **H I and D I spectra are identical $\Rightarrow$ H I Interlopers?**

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

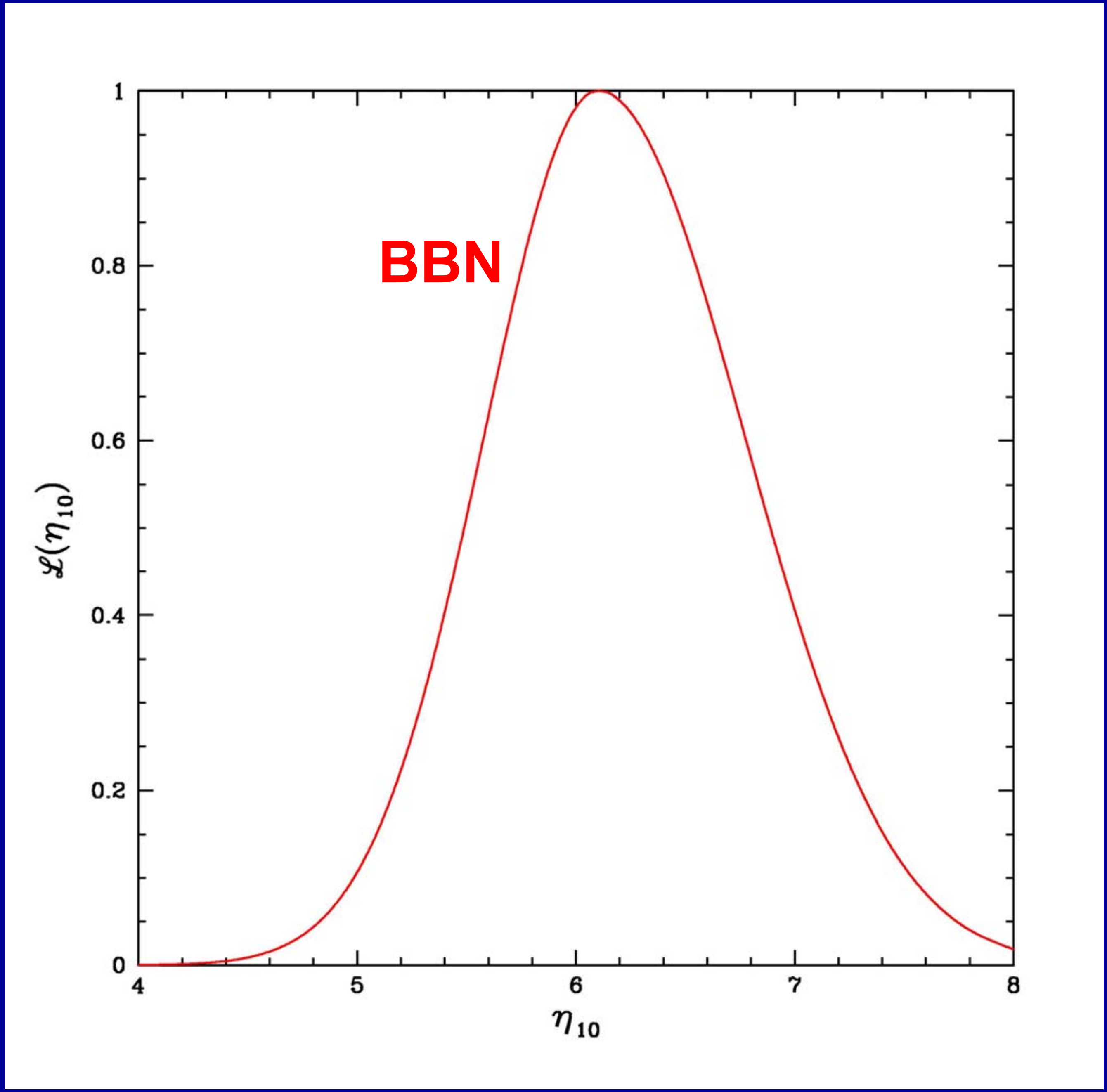
D/H vs. Metallicity



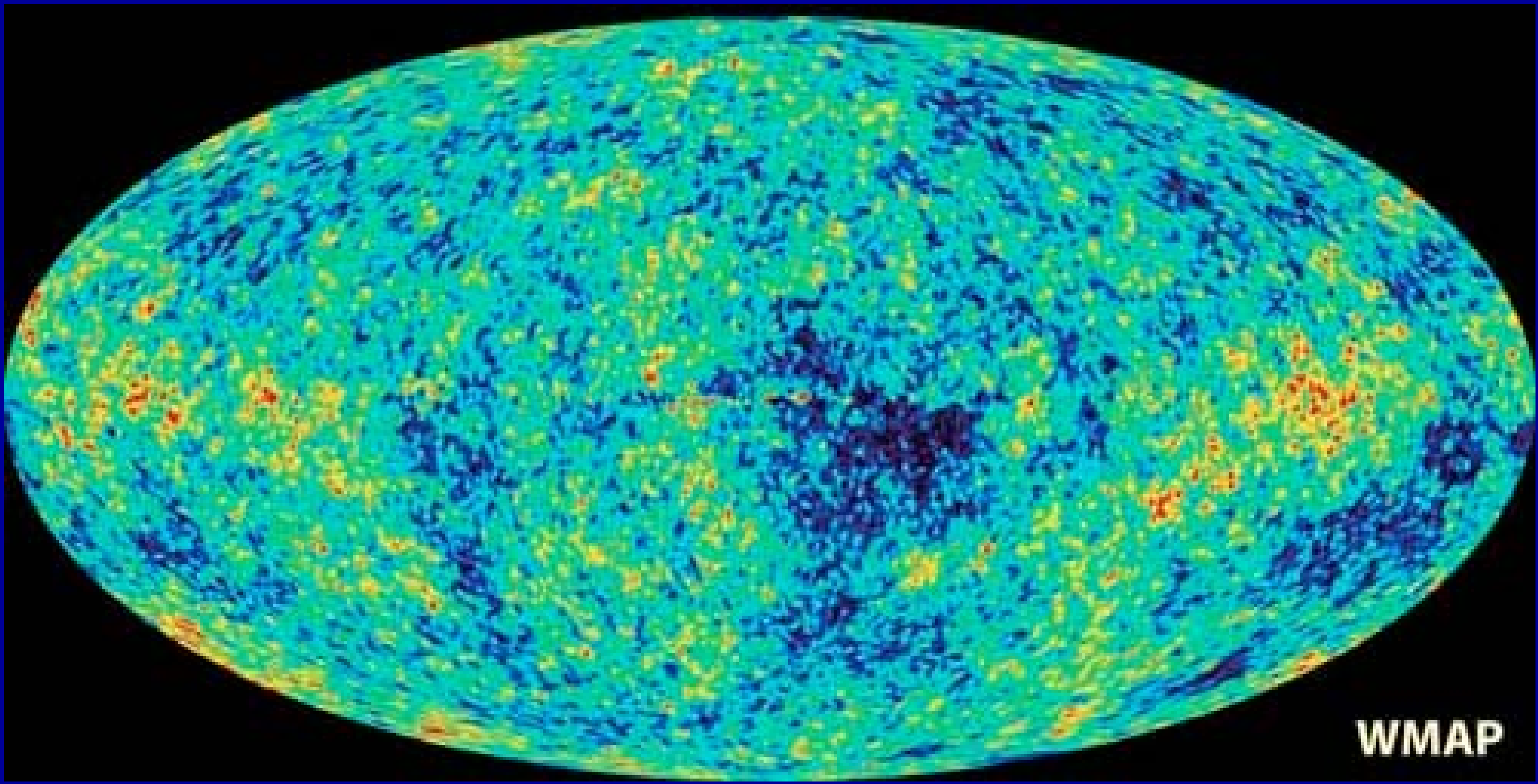
D/H vs. Metallicity



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

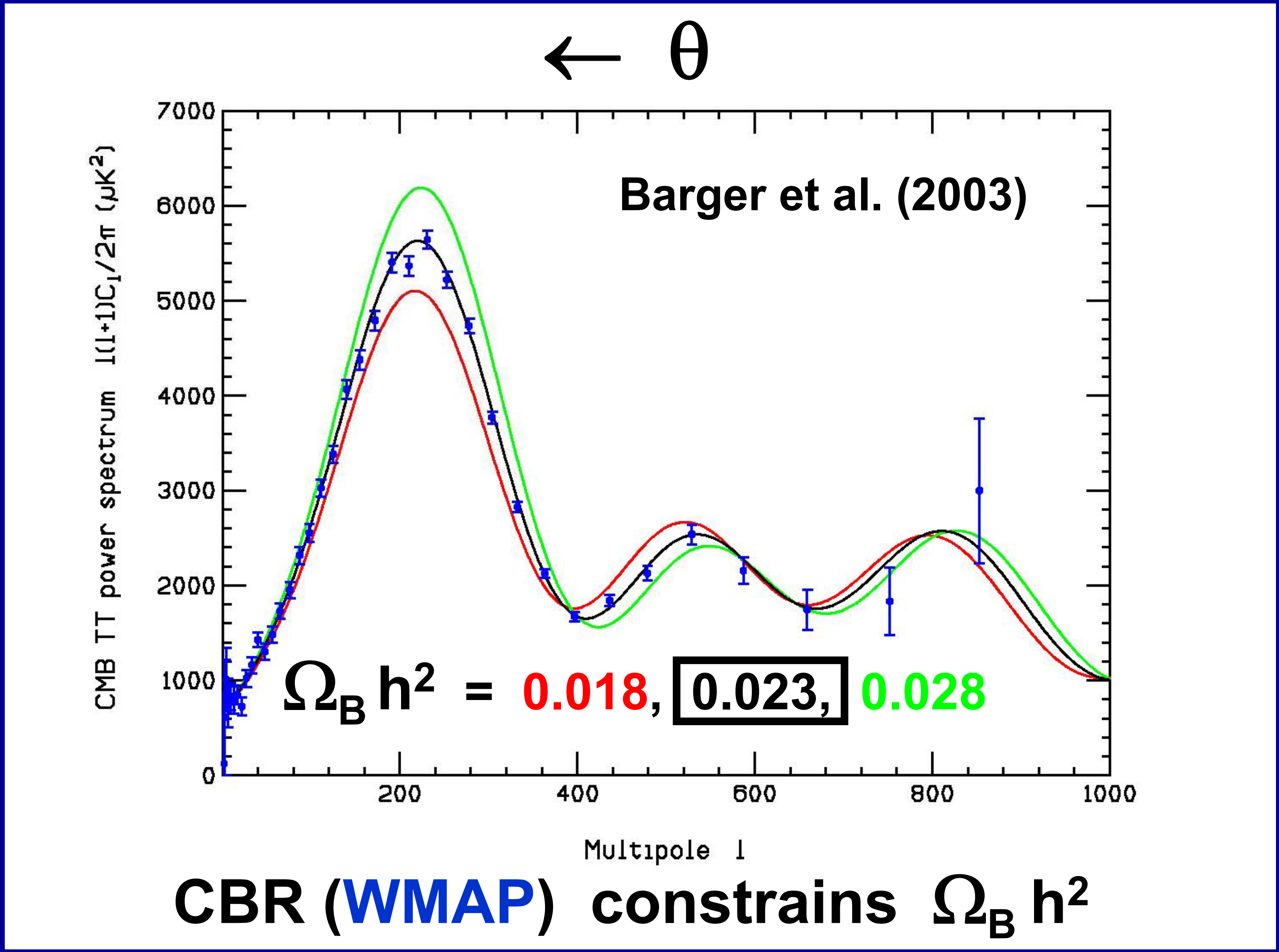


CBR



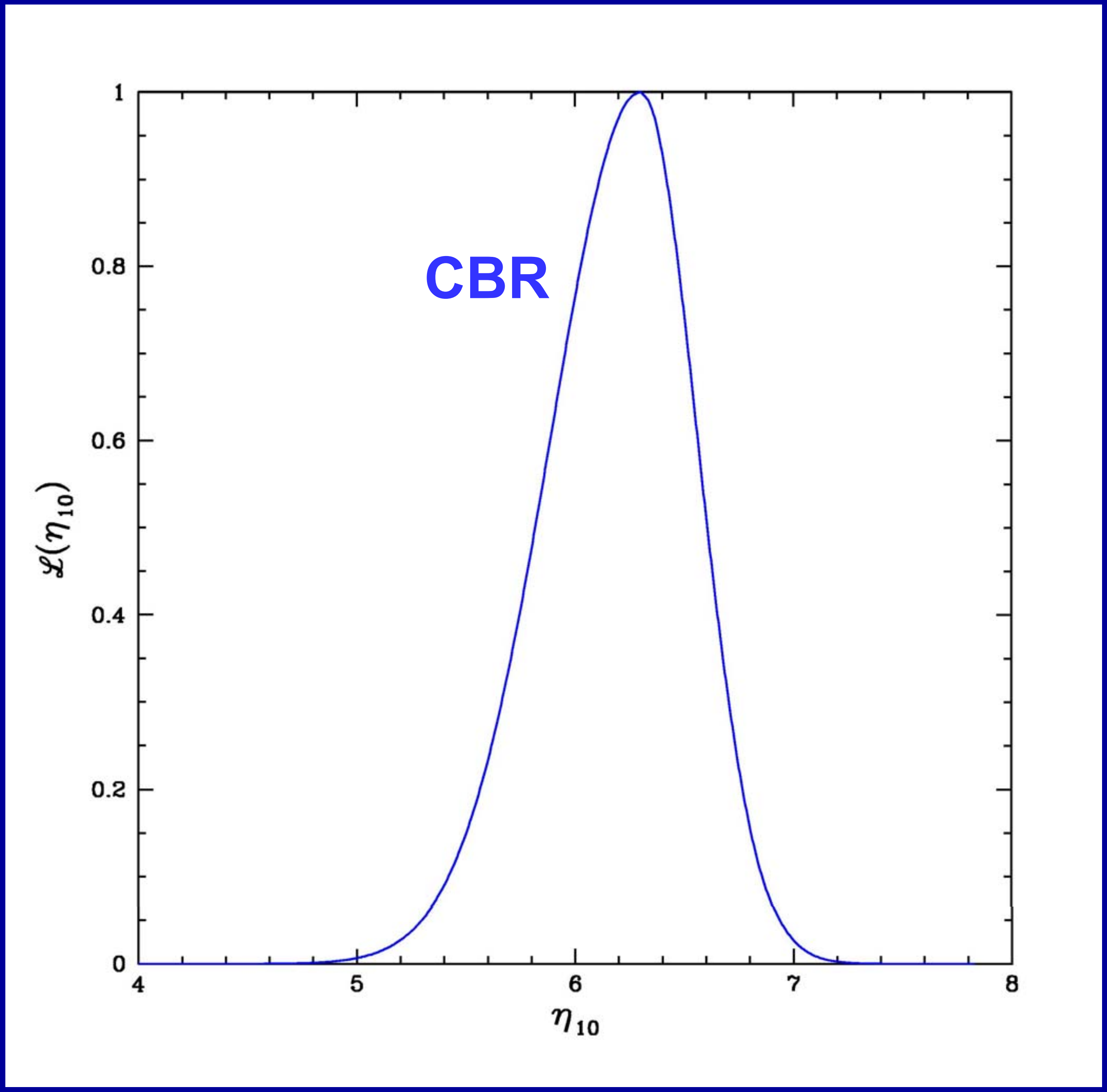
CBR Temperature Anisotropy Spectrum (2003)

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

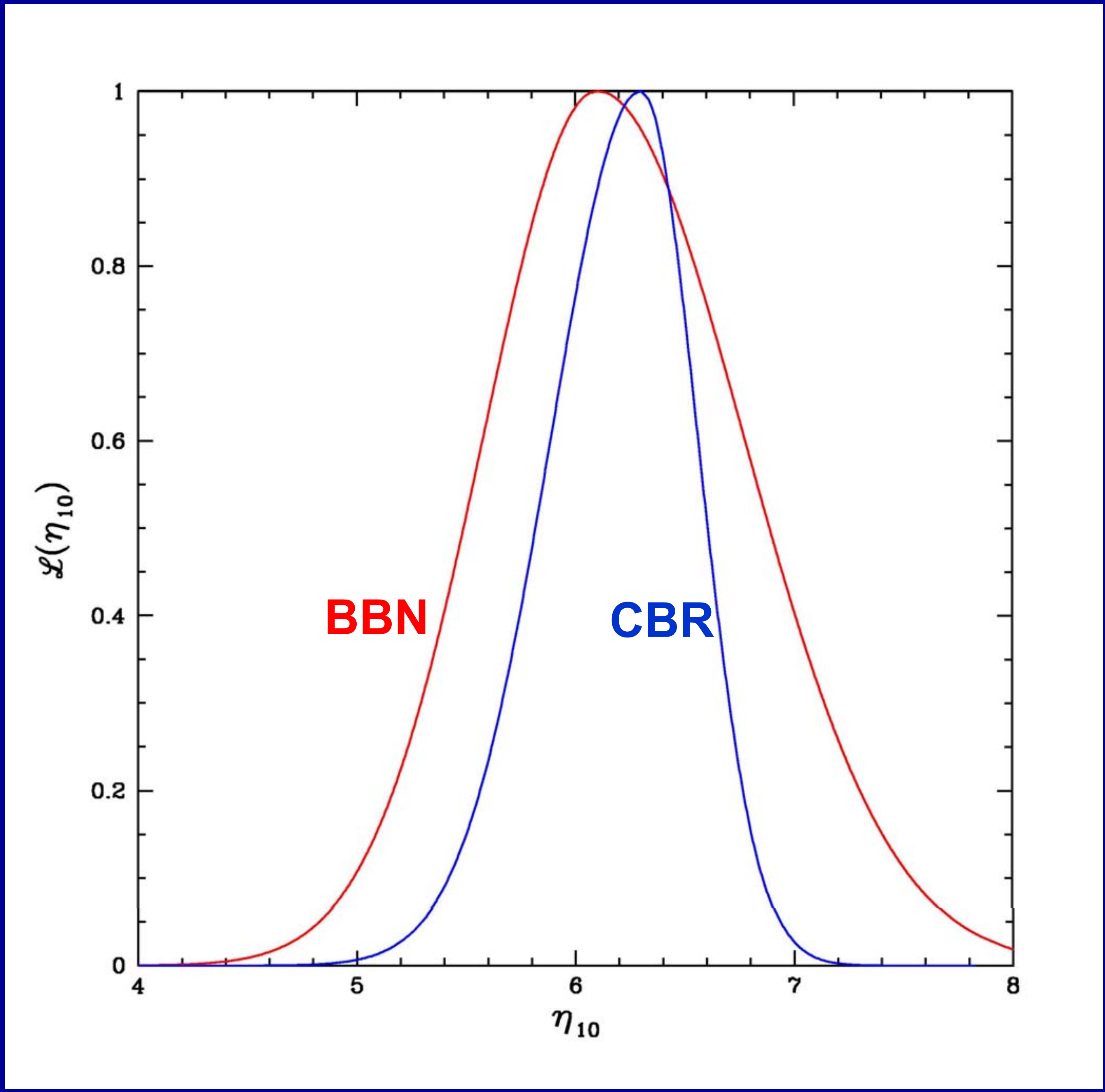


The CBR is an early - Universe Baryometer

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



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



The Expansion (H) Rate Provides

A Probe Of Non-Standard Physics

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

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

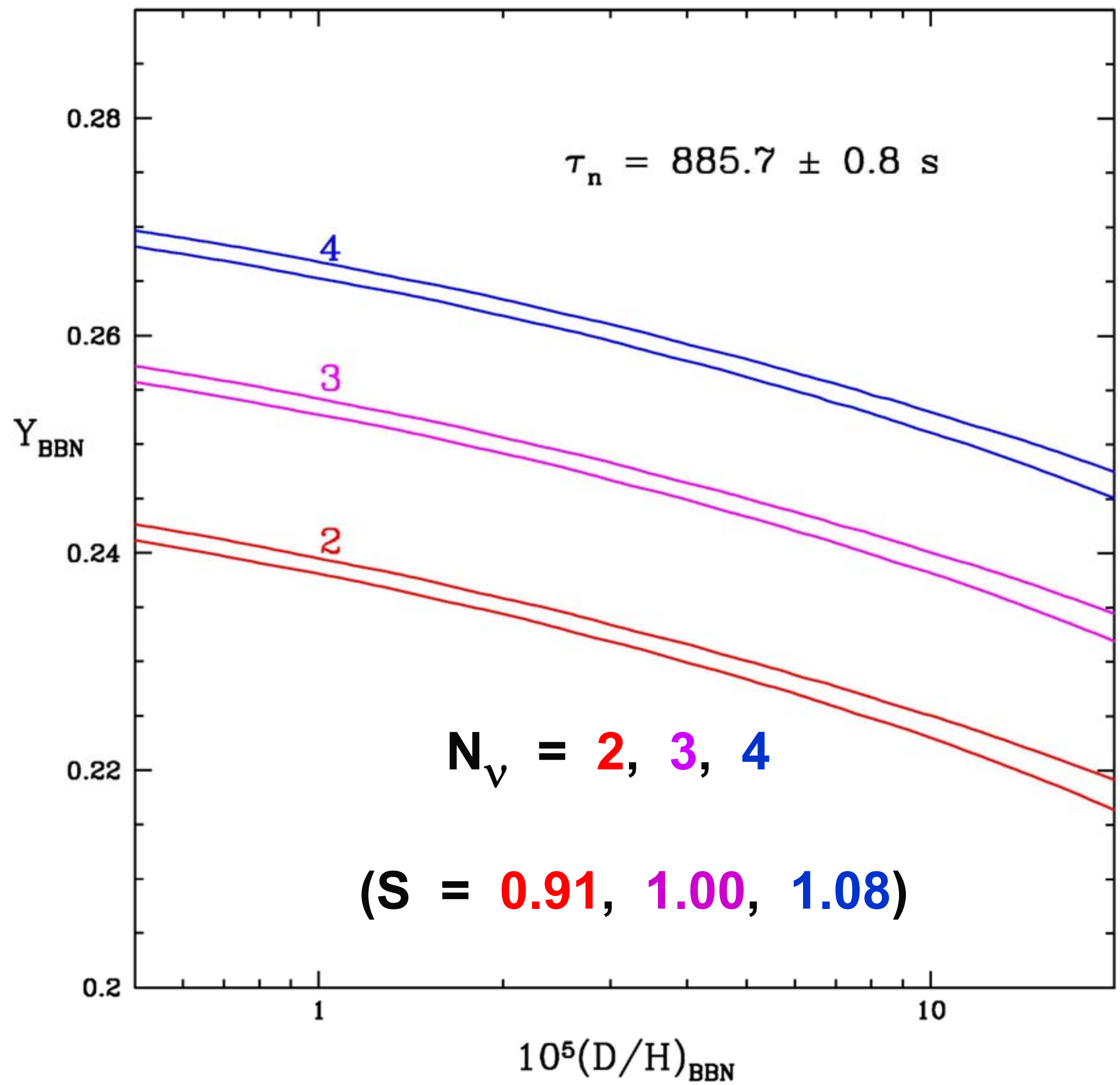
$$S \equiv H'/H \equiv (\rho'/\rho)^{1/2} \equiv (1 + 7\Delta N_\nu / 43)^{1/2}$$

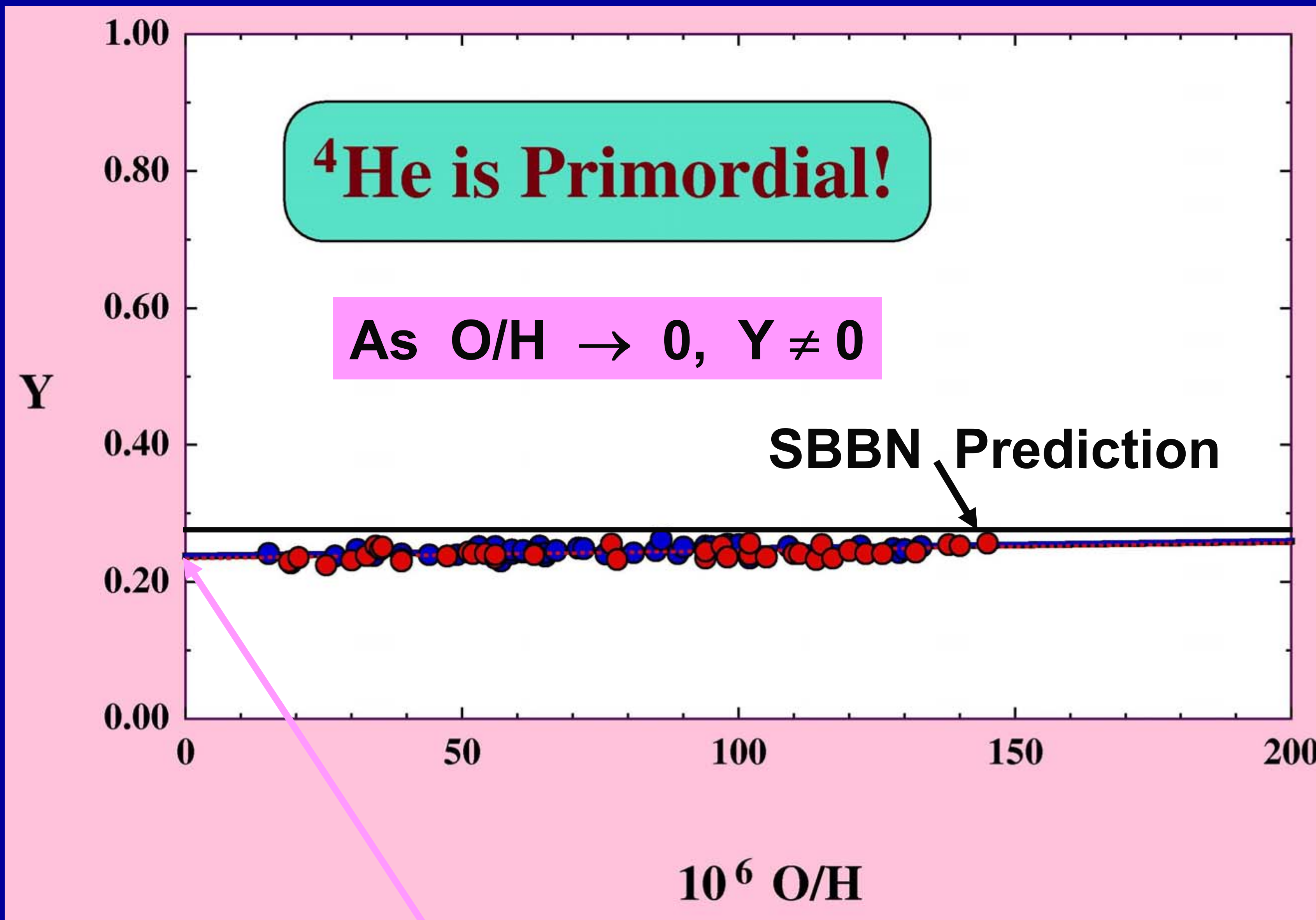
where $\rho' \equiv \rho + \Delta N_\nu \, \rho_\nu$ and $N_\nu \equiv 3 + \Delta N_\nu$

$\Rightarrow$ $S(N_\nu)$ is constrained by Y_P

^{4}He is an early – Universe Chronometer

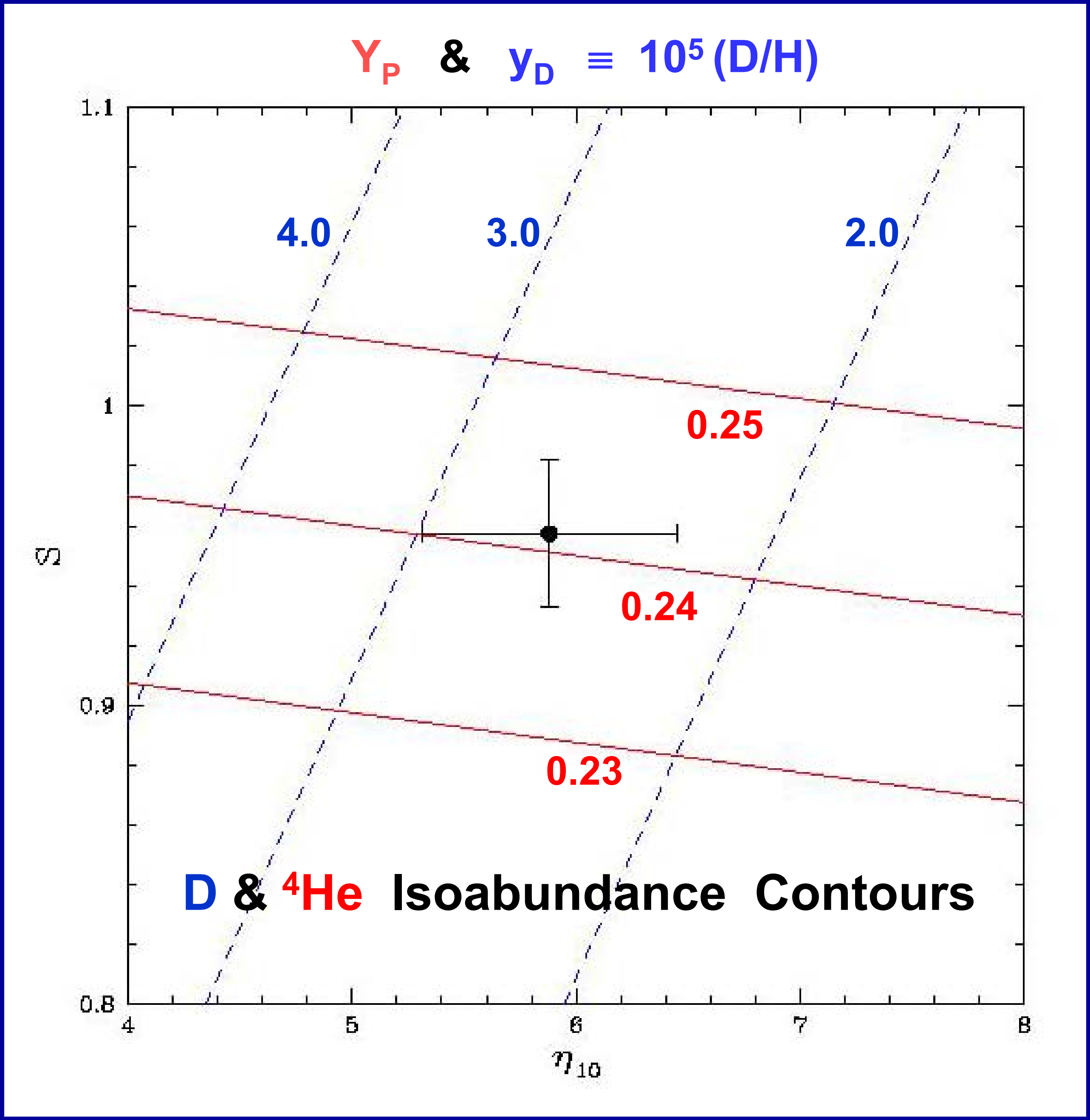
Y vs. D / H





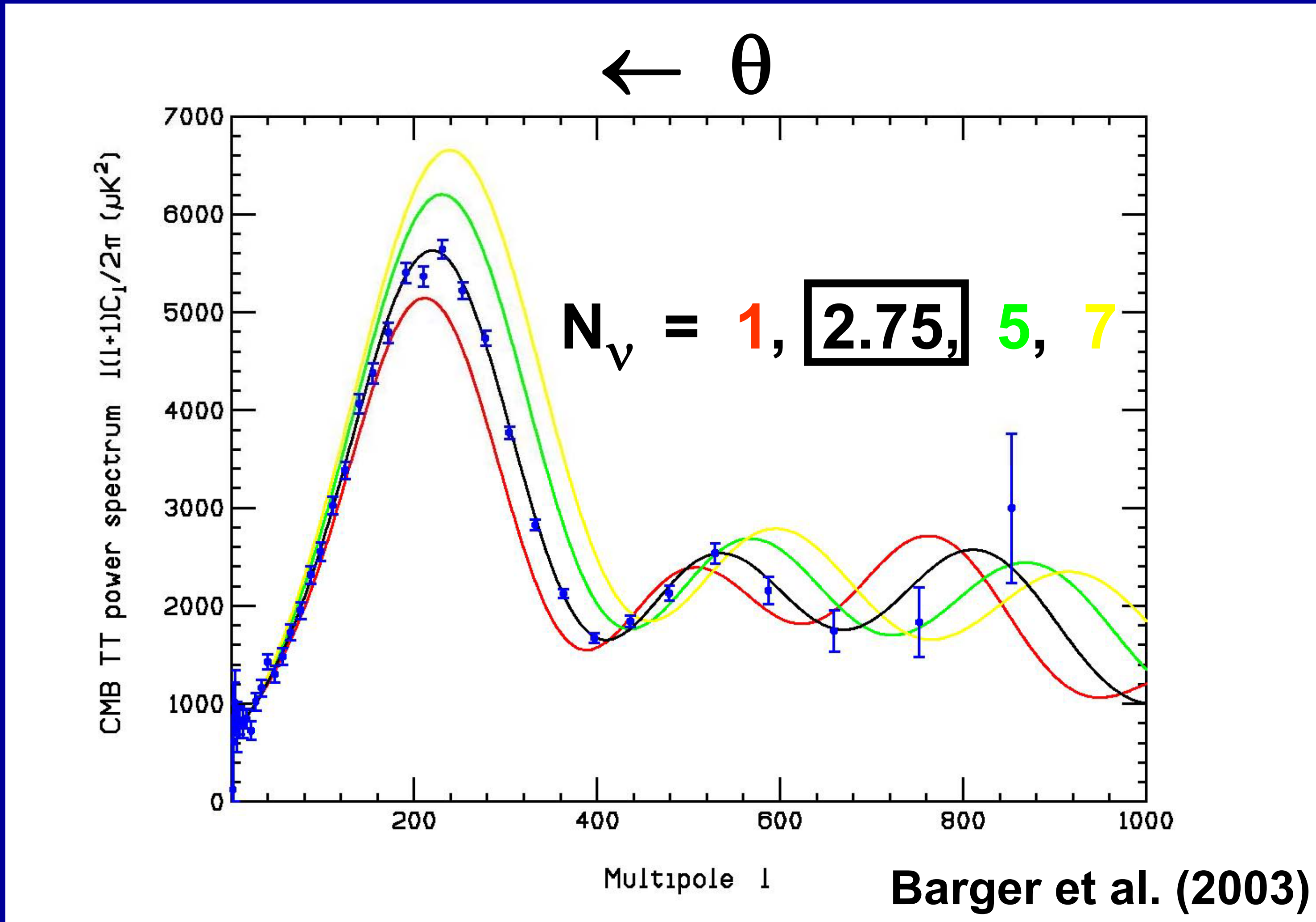
"2σ" range for Y_P : 0.228 $\leftrightarrow$ 0.248 (OSW)

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



CBR Temperature Anisotropy Spectrum (2003)

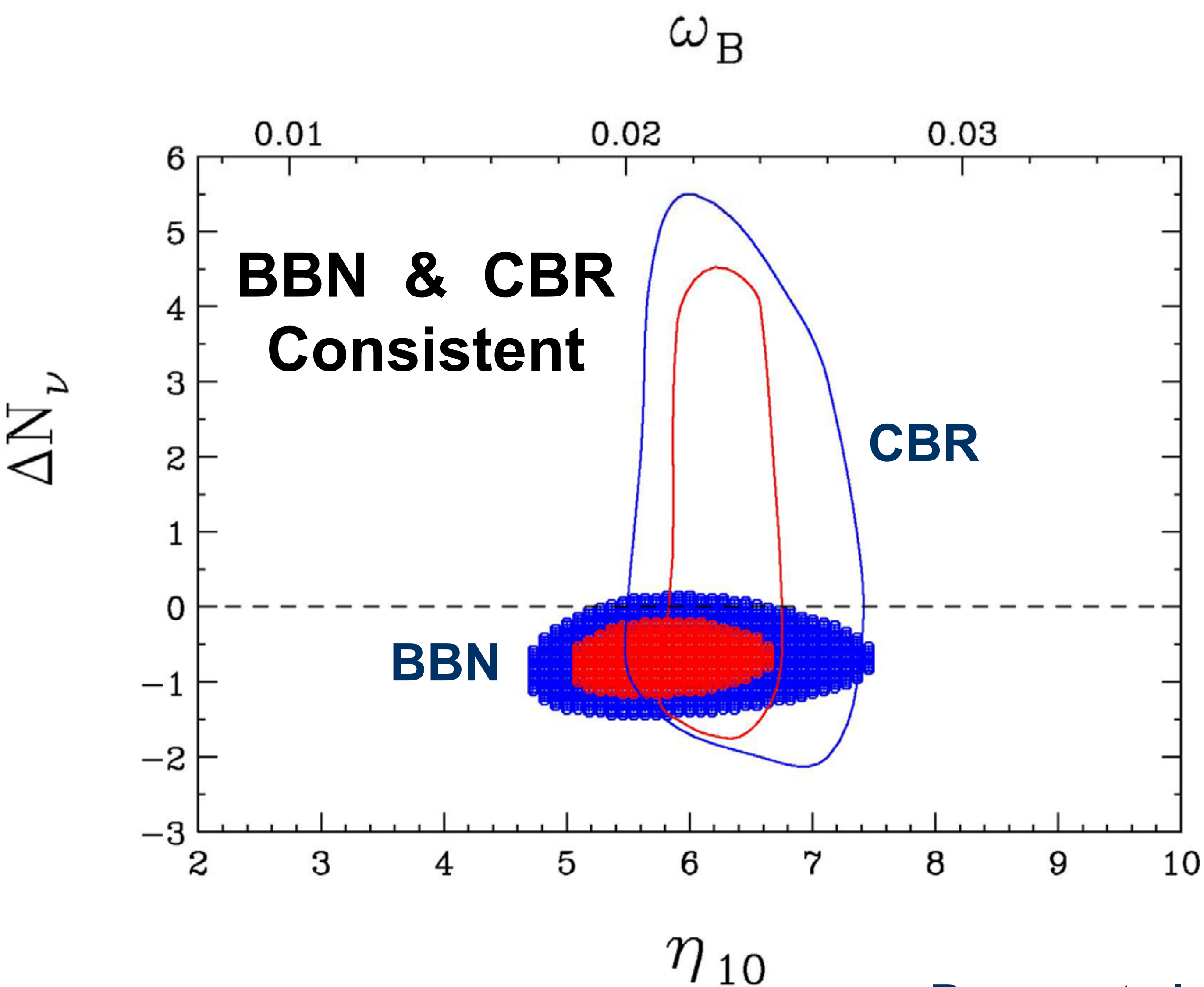
Depends on the Radiation Density ρ_R (S or N_ν)



CBR (WMAP) constrains N_ν (S)

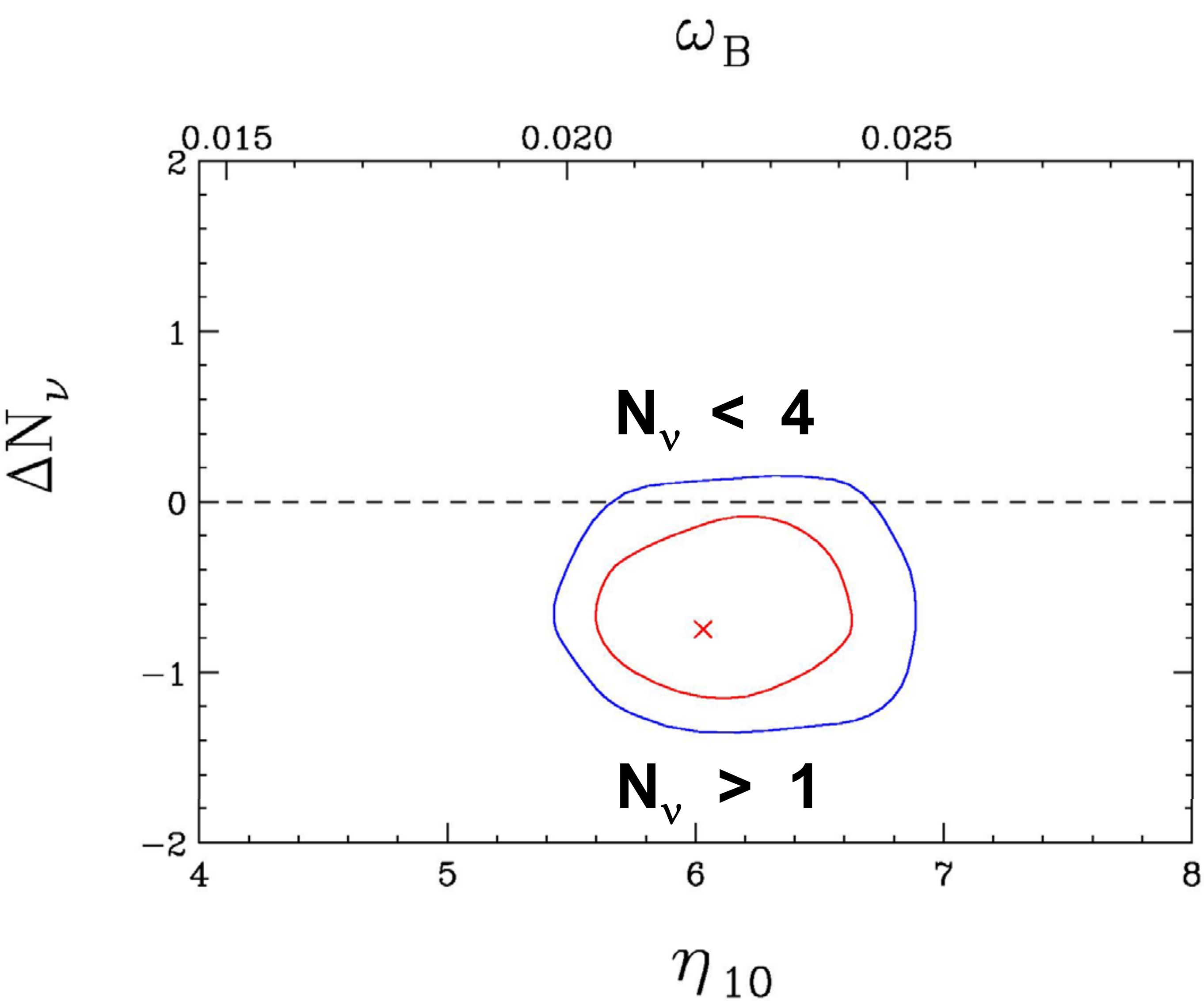
The CBR is an early - Universe Chronometer

BBN (D & ^{4}He) + CBR (WMAP – 2003)



Barger et al. (2003)

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



Barger et al. (2003)

Alternative to $N_\nu \neq 3$ $(S \neq 1)$

ν_e Degeneracy (Non – Zero Lepton Number)

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

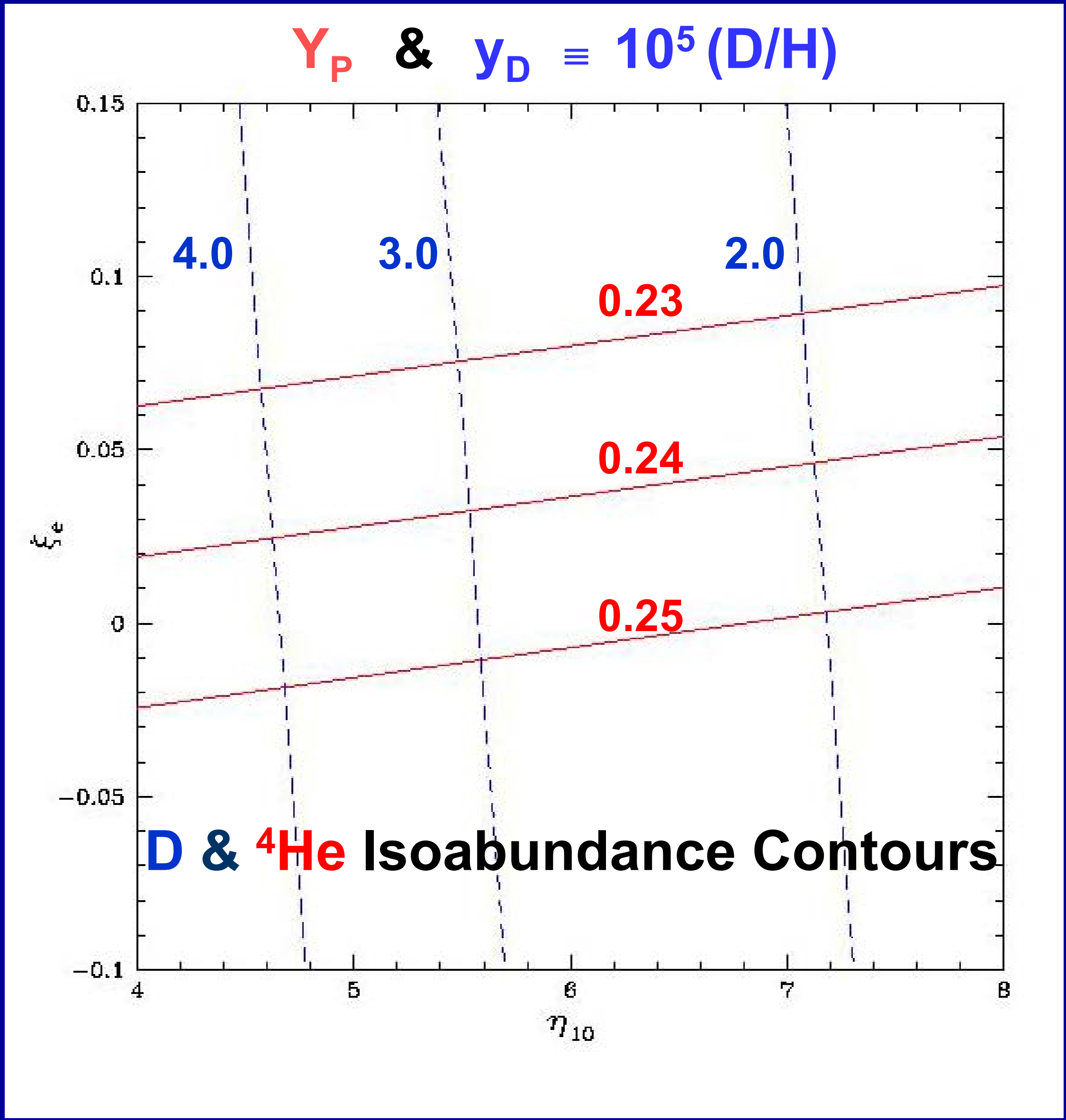
(more ν_e than anti - ν_e)

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

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

Y_P probes

Lepton Asymmetry



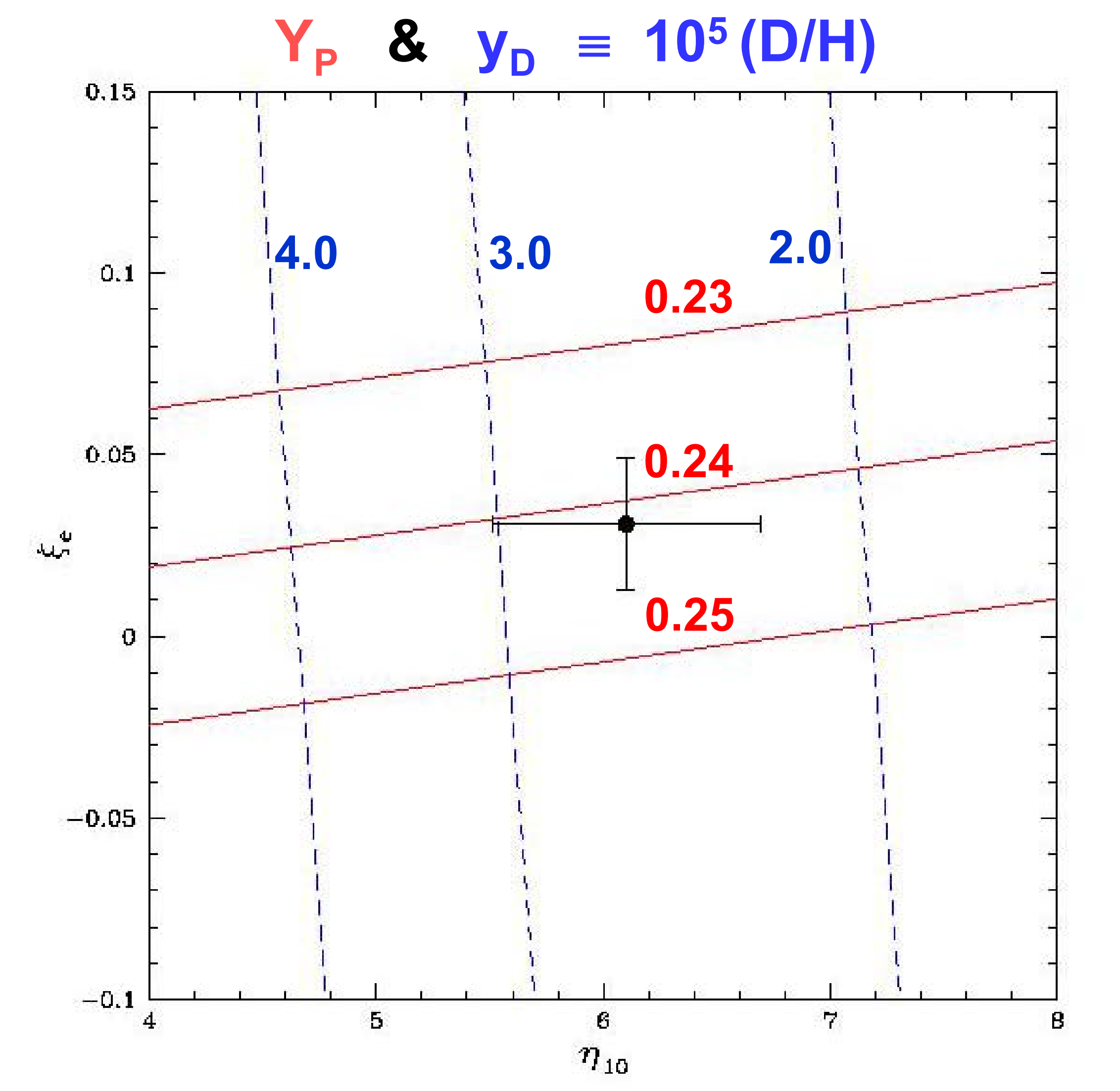
ν_e Degeneracy (Non – Zero Lepton Number)

$$\xi_e \approx 0.031 \pm 0.018$$

&

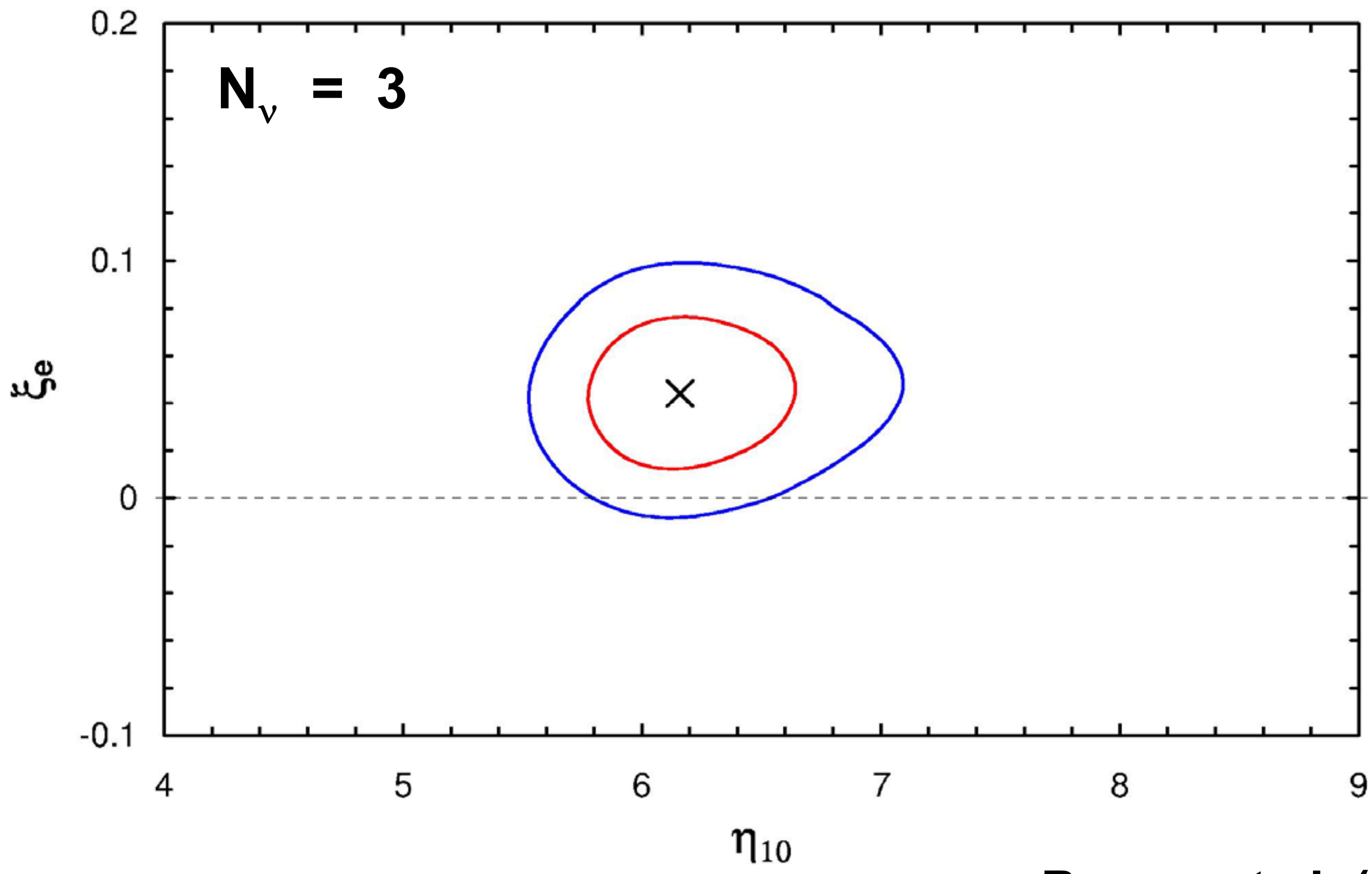
$$\Omega_B h^2 \approx 0.022 \pm 0.002$$

$$(\eta_{10} = 6.1 \pm 0.6 \checkmark)$$



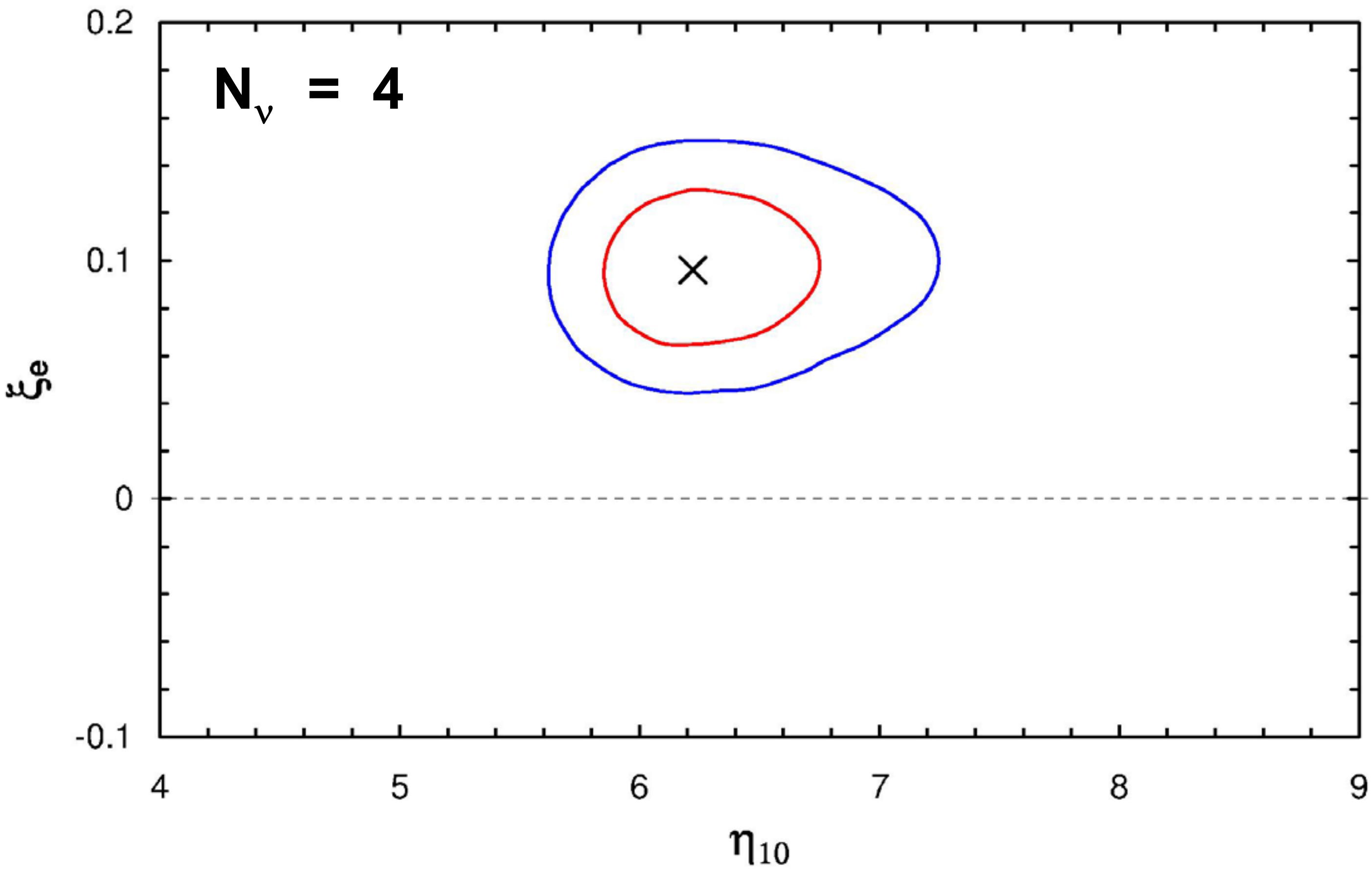
Kneller & Steigman (2004)

CBR + BBN



Barger et al. (2003)

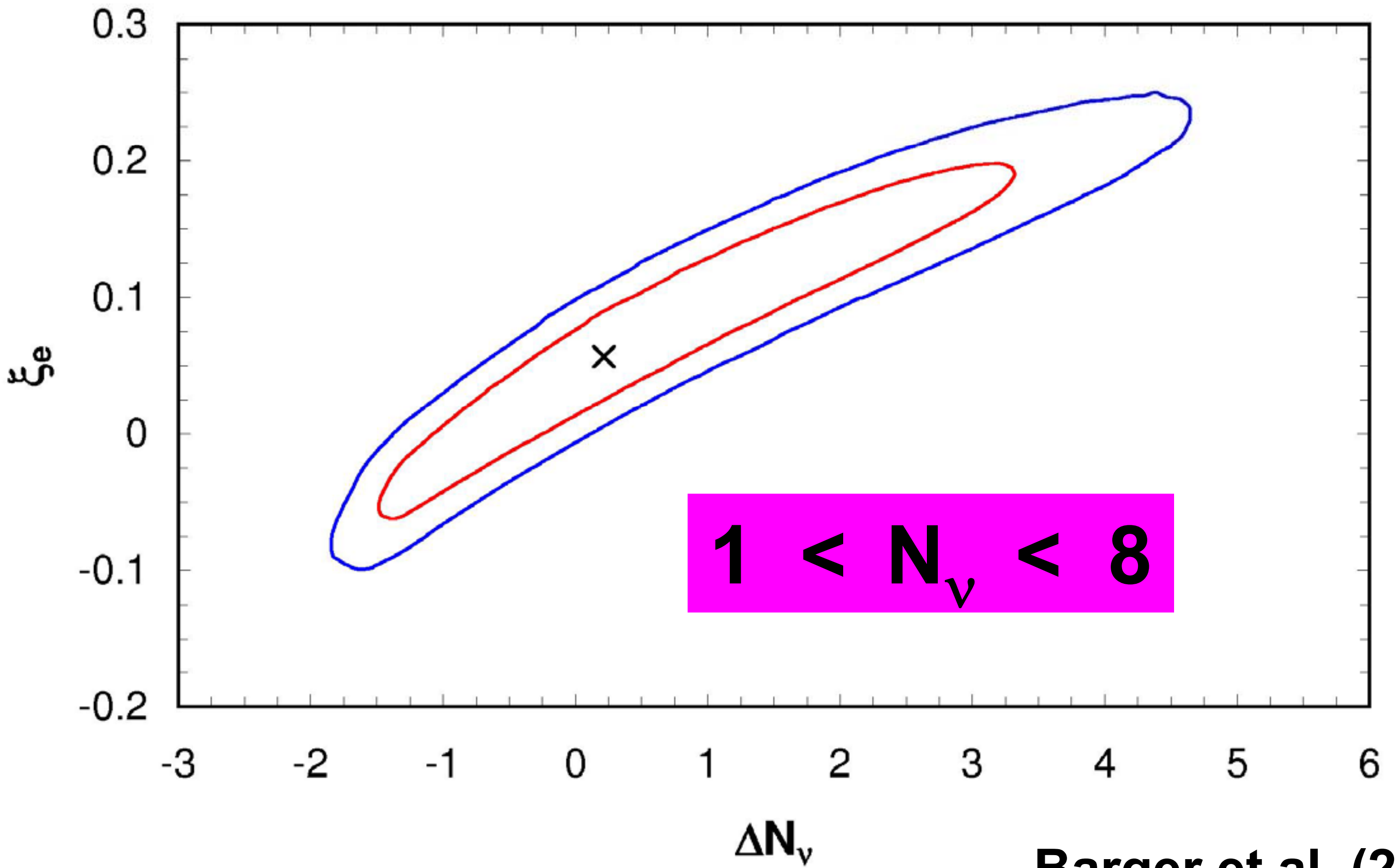
CBR + BBN



Barger et al. (2003)

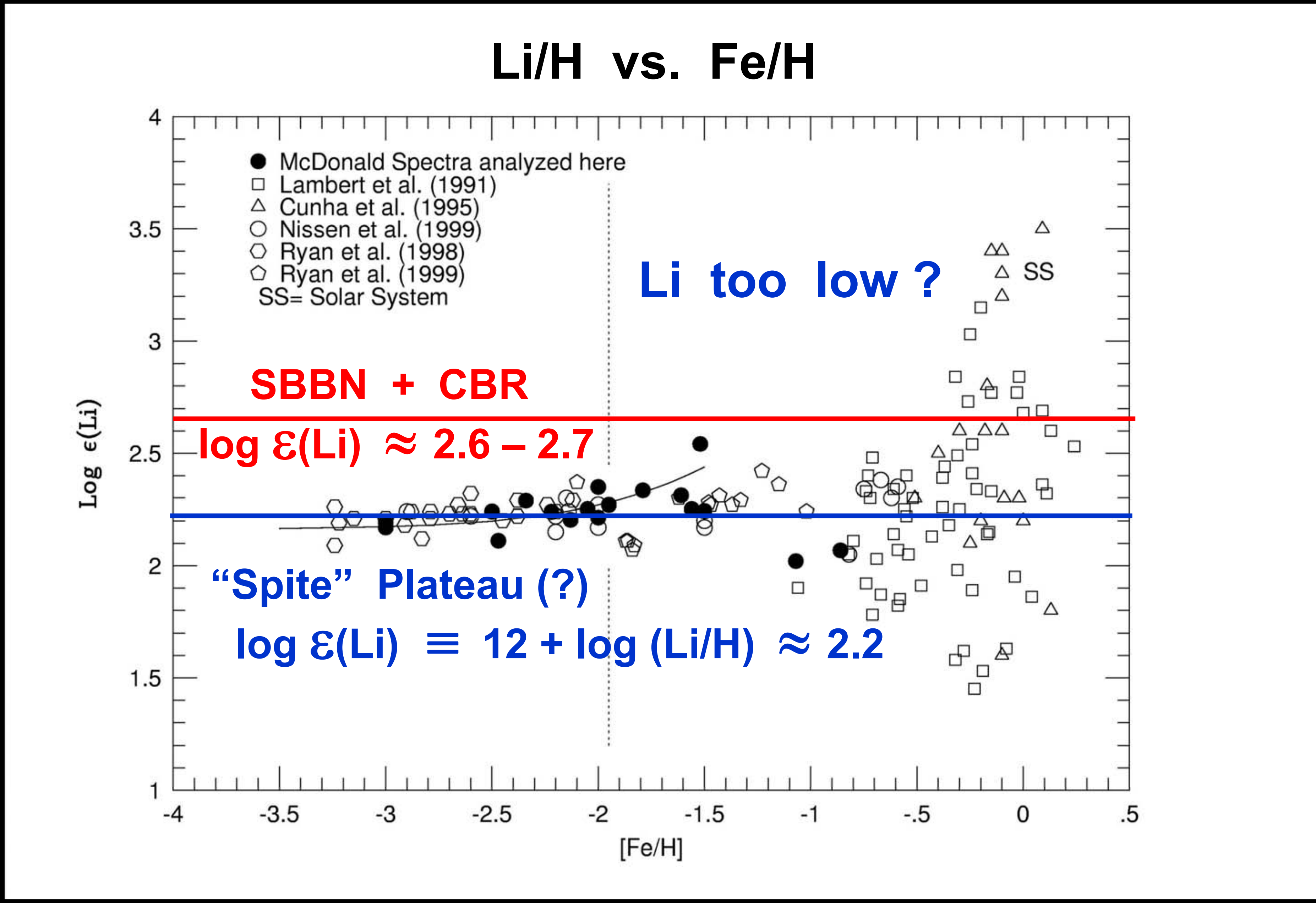
JOINT BBN & CBR CONTOURS

With η_{10}, ξ_e, ΔN_ν ALL FREE



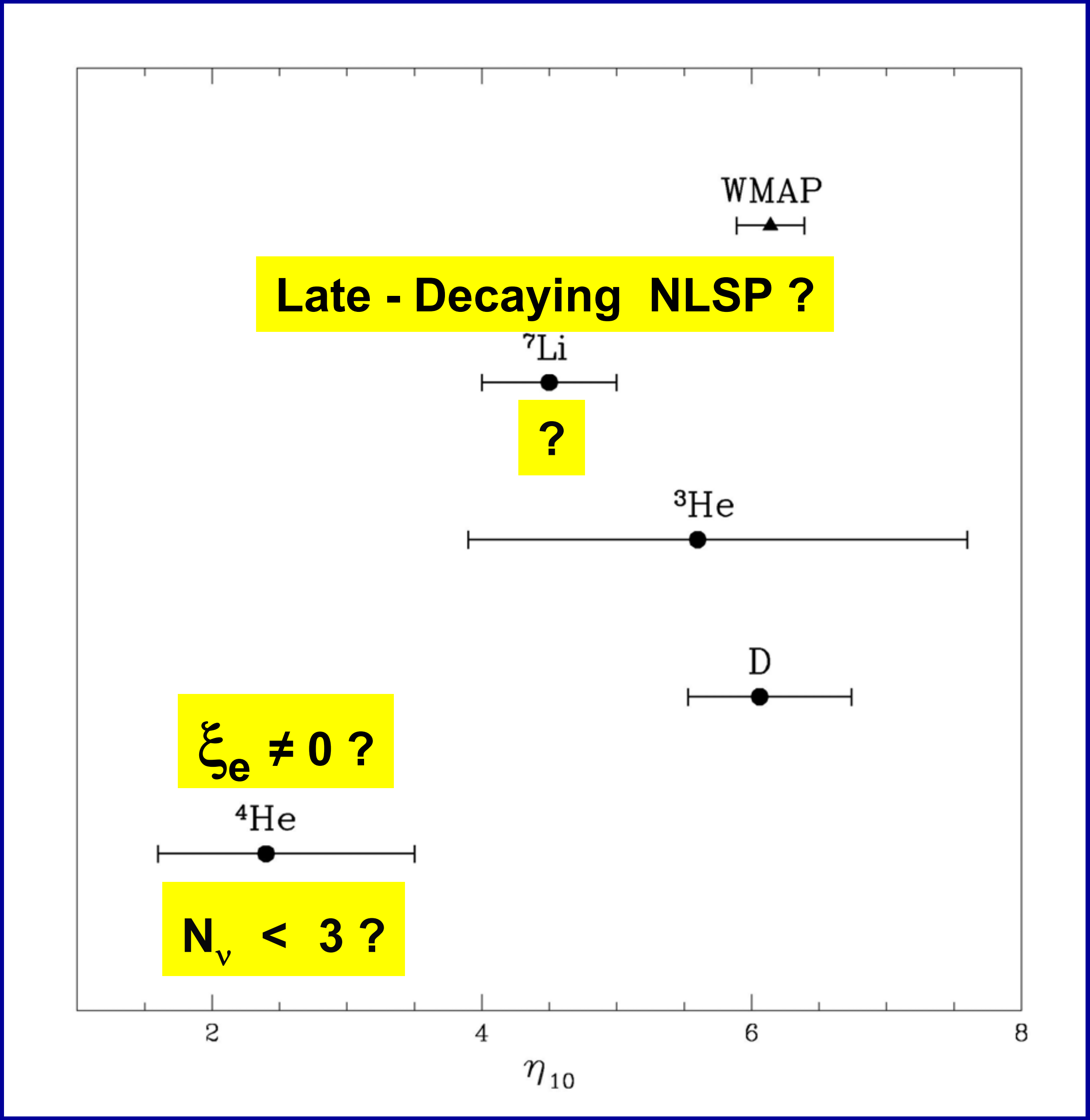
Barger et al. (2003)

LITHIUM - The Fly In The Ointment



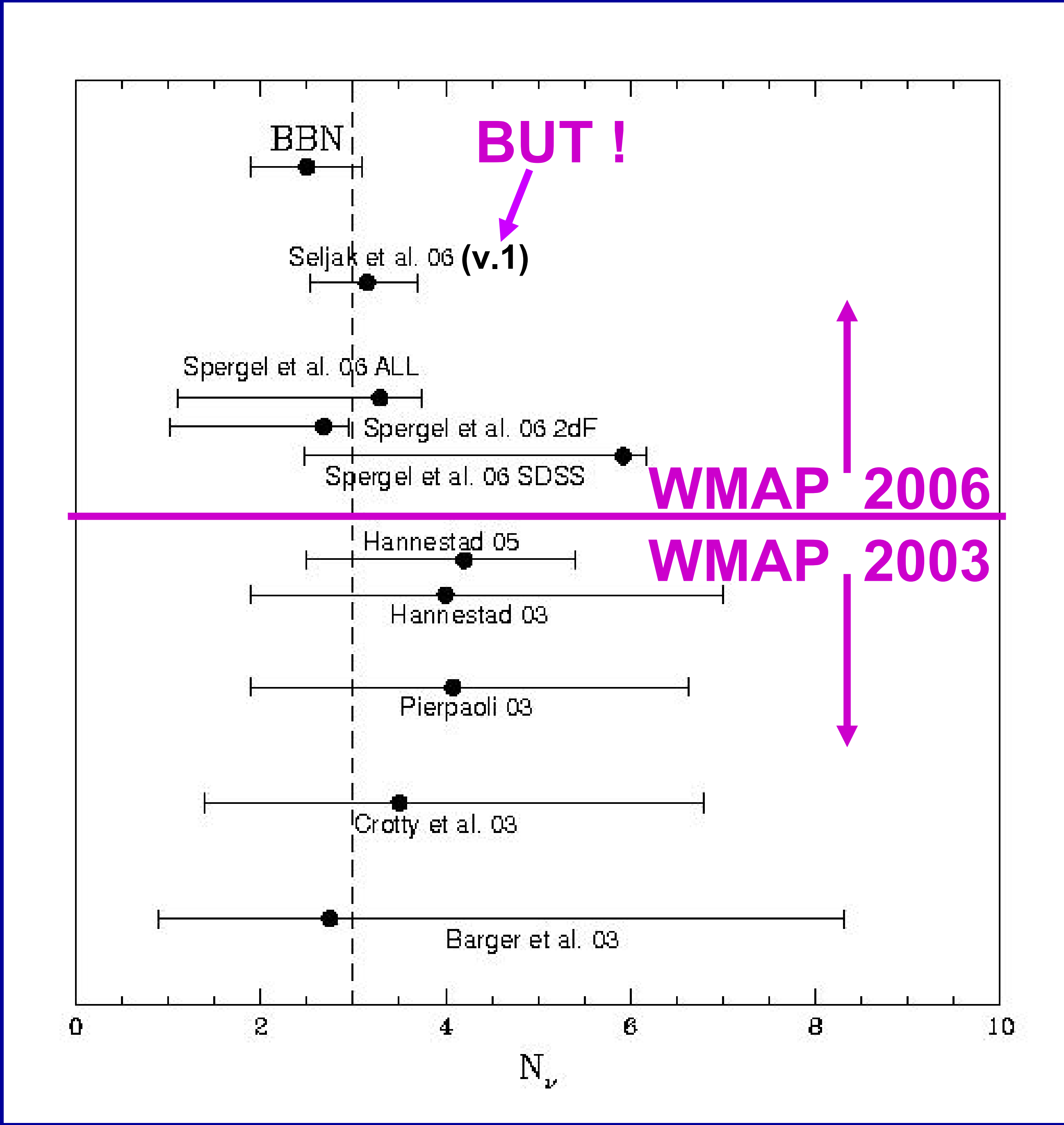
Neither $N_\nu \neq 3$ Nor $\xi_e \neq 0$ Can Resolve Li Problem

Baryon Density Determinations: Consistent ?

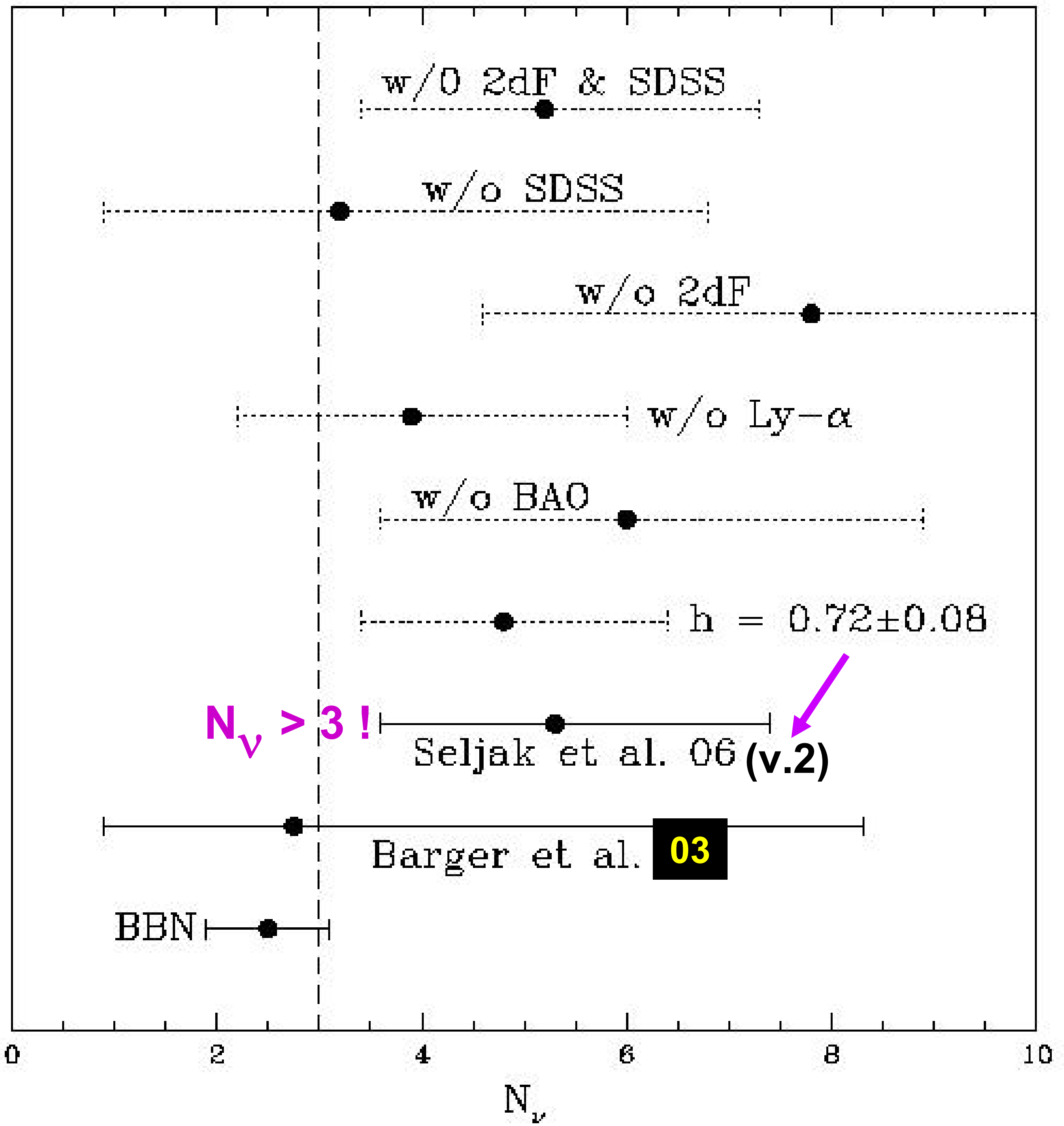


Observational Uncertainties Or New Physics?

N_ν Determinations (95 % CL Ranges)



Seljak et al. Revised



SUMMARY AND CONCLUSIONS

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

Are CONSISTENT

- **For $\xi_e = 0 : 1.9 \le N_\nu \le 3.1$ allowed @ ~ 95%**

- **For $\xi_e \neq 0 \Rightarrow$ more freedom for $N_\nu \Rightarrow$**

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