BBN & THE CMB / LSS CONSTRAIN THE UNIVERSAL BARYON DENSITY

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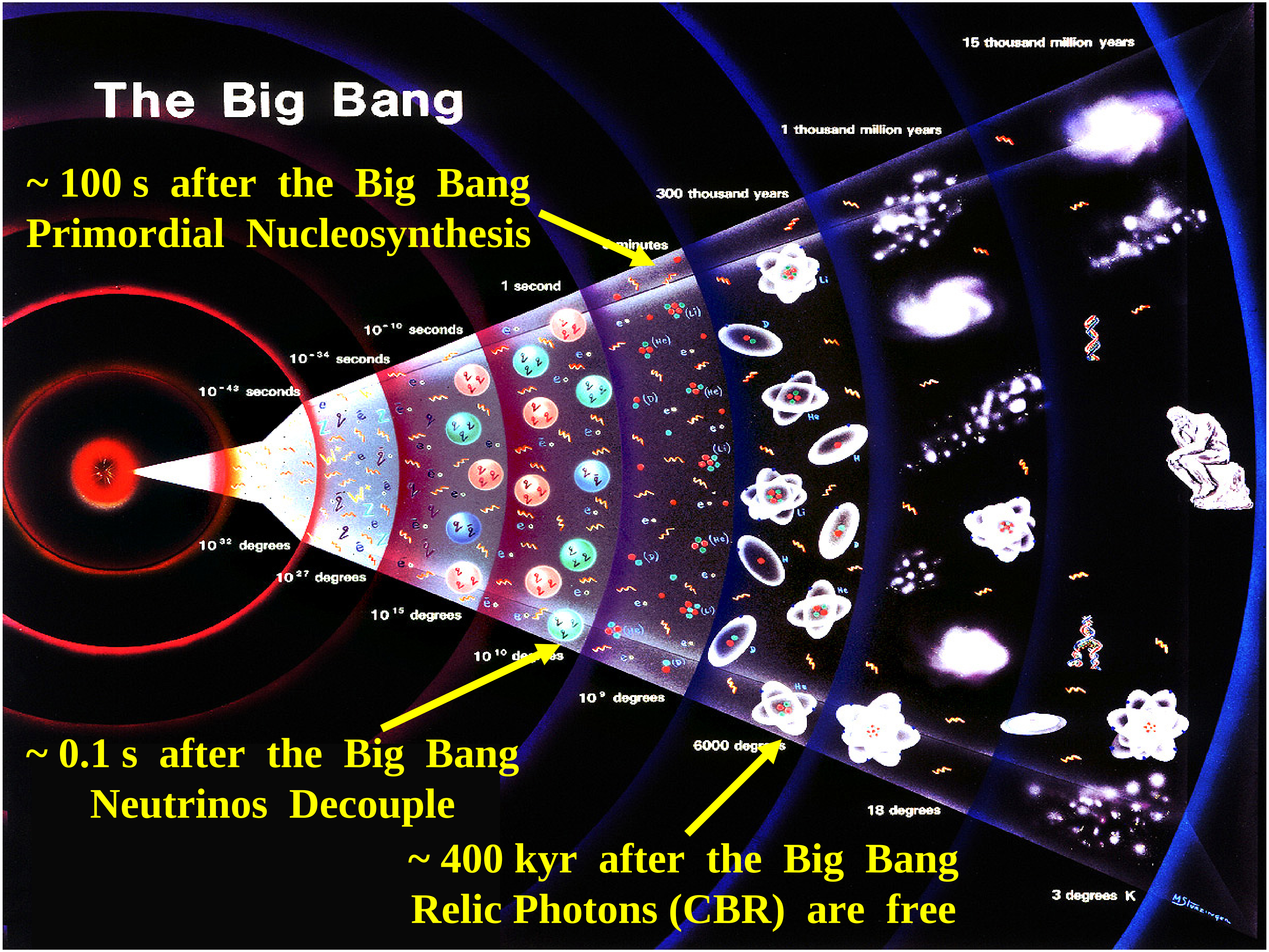


The Big Bang
~ 100 s after the Big Bang
Primordial Nucleosynthesis
~ 0.1 s after the Big Bang
Neutrinos Decouple
~ 400 kyr after the Big Bang
Relic Photons (CBR) are free
15 thousand million years
1 thousand million years
300 thousand years
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{9} degrees
18 degrees
3 degrees K

BBN & The CMB Provide Complementary Probes Of The Early Universe

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

Baryon Density Parameter

Note : Baryons $\Rightarrow$ Nucleons

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

where : $\Omega_B \equiv \rho_B / \rho_c$; $\rho_c \equiv$ critical density

Hubble parameter : $h \equiv H_0 / 100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

$$h \approx 0.7 \; ; \; H_0^{-1} = 9.8 / h \approx 14\ \mathrm{Gyr}$$

The Early, Hot, Dense Universe

Is A Cosmic Nuclear Reactor

As the Universe expands and cools, BBN

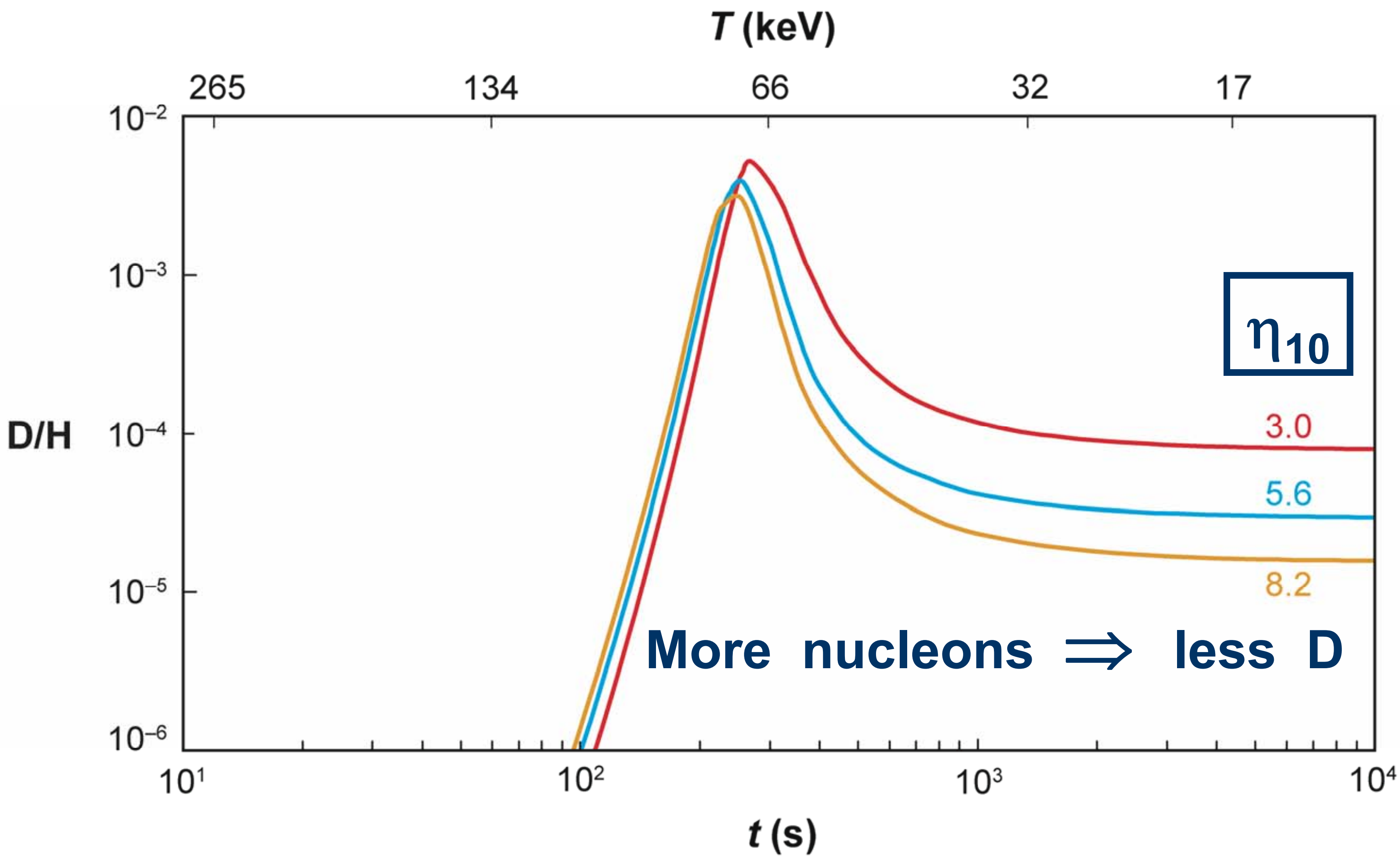
"begins" at $T \approx 70$ keV (when $n / p \approx 1 / 7$)

Coulomb barriers and the absence of

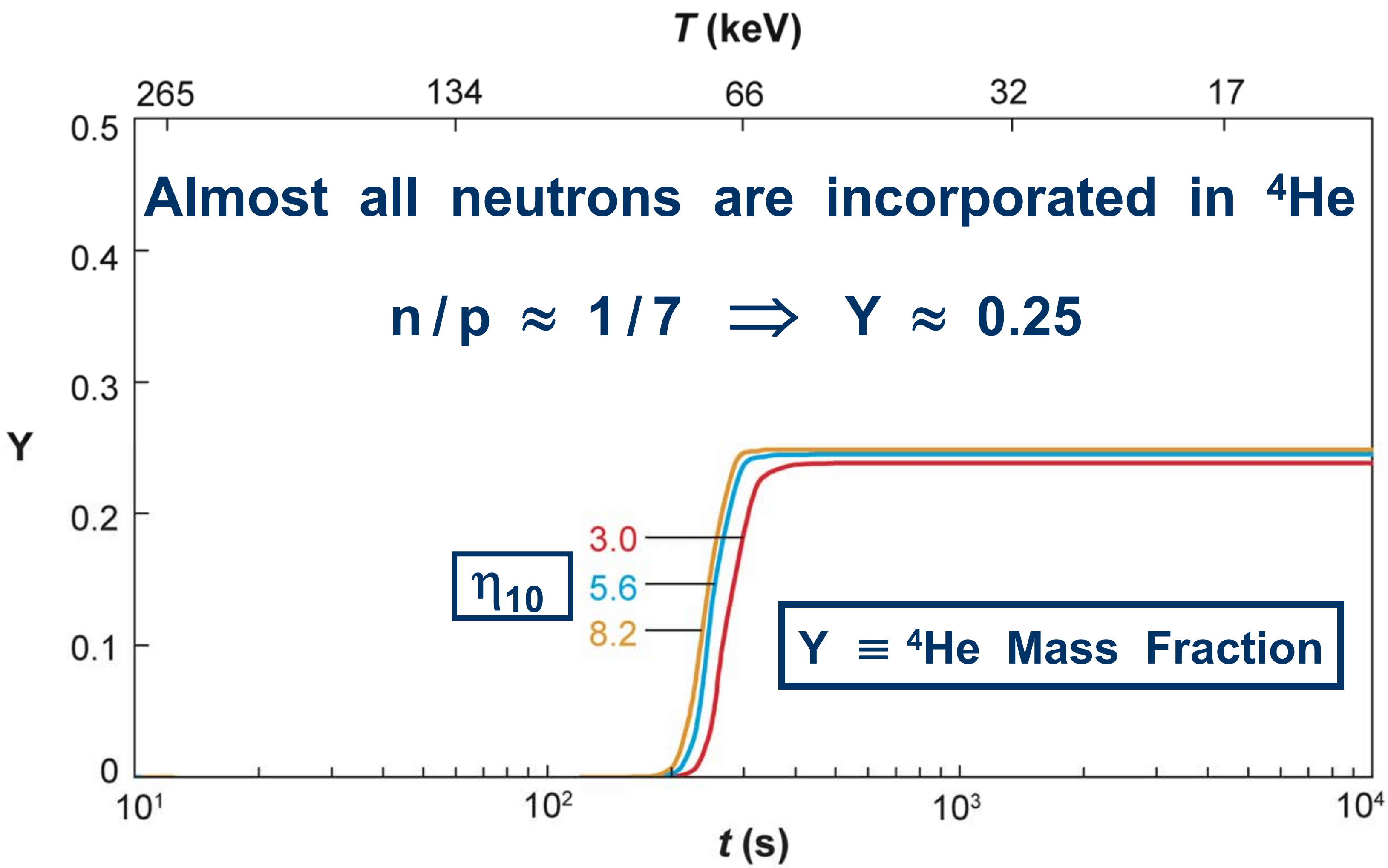
free neutrons end BBN at $T \approx 30$ keV

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

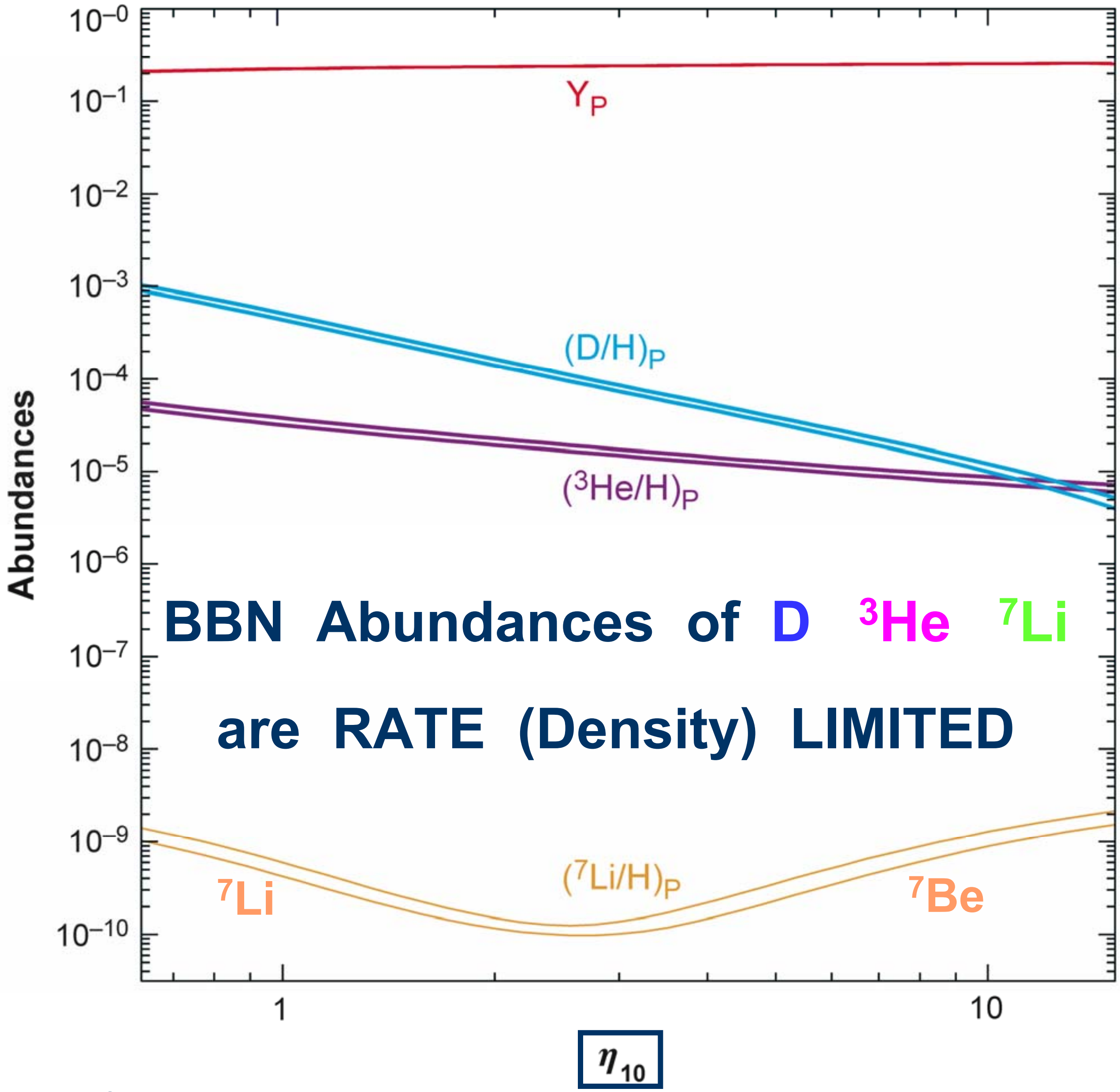
Evolution of Deuterium



Y depends on the nucleon abundance VERY WEAKLY

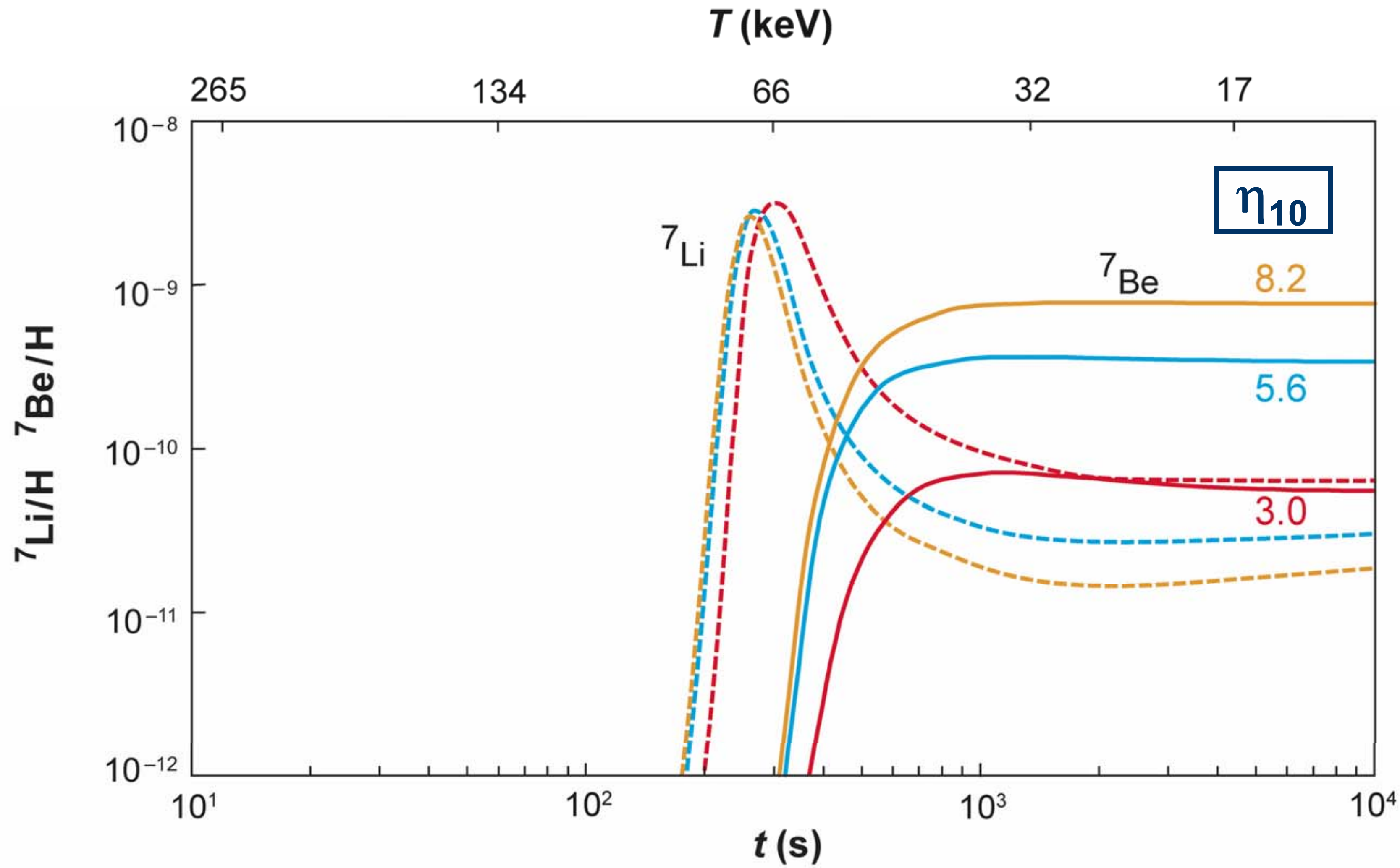


BBN – Predicted Primordial Abundances



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

Two pathways to mass - 7



DEUTERIUM --- The Baryometer Of Choice

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

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

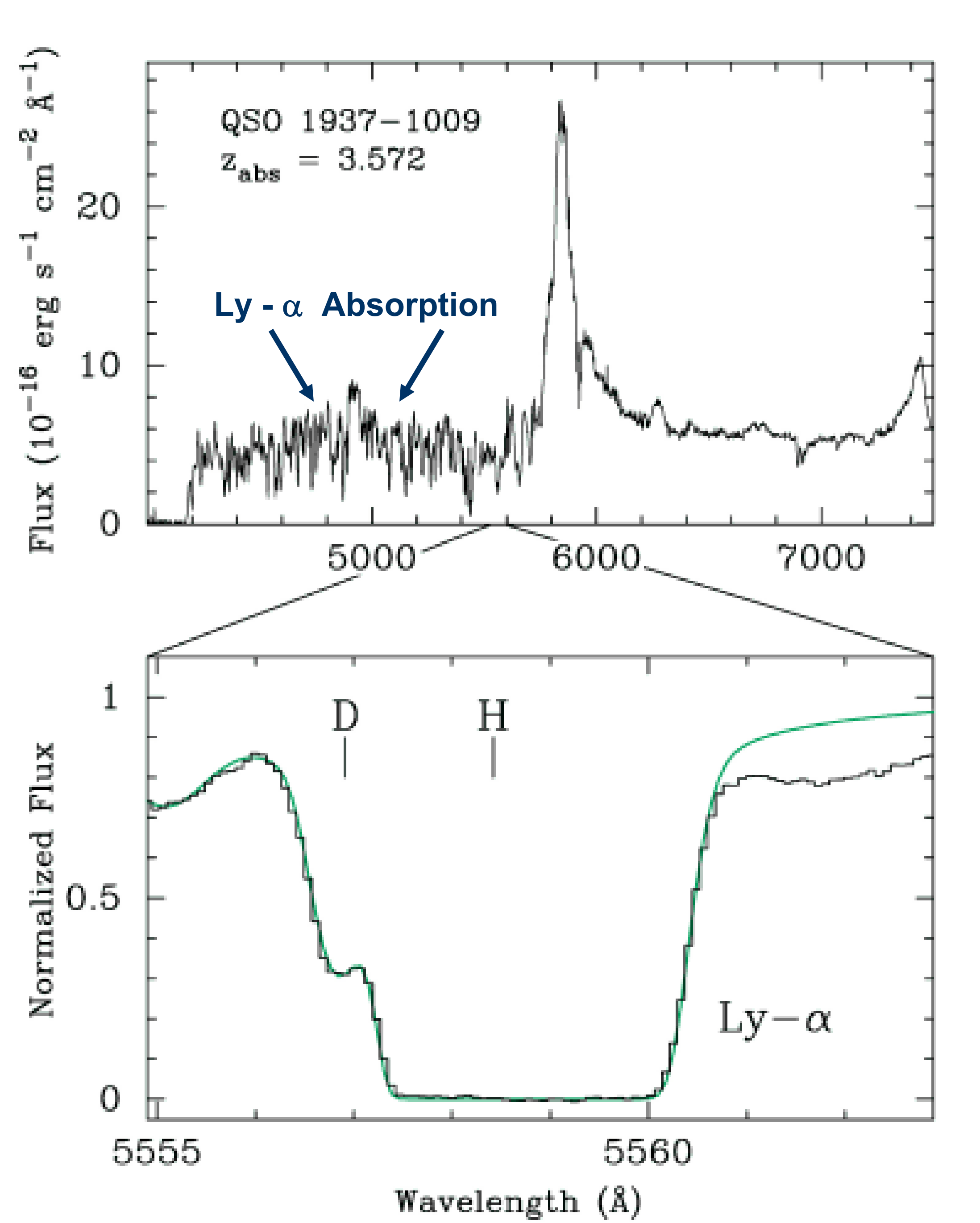
  * For $Z \ll Z_\odot$: $(D/H)_t \rightarrow (D/H)_P$ (Deuterium Plateau)

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

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

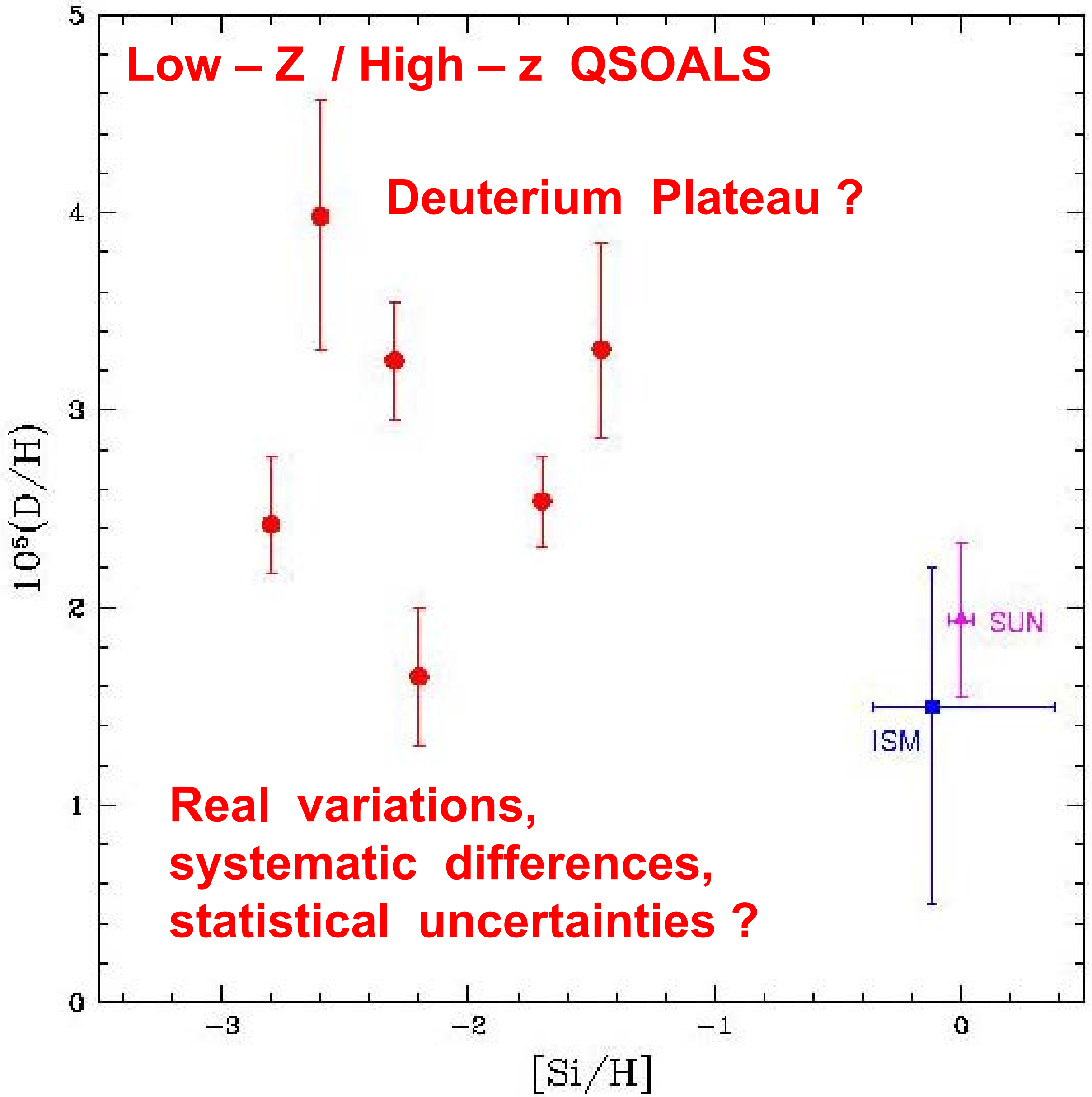
  * H I and D I spectra are identical $\Rightarrow$ H I Interlopers?

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

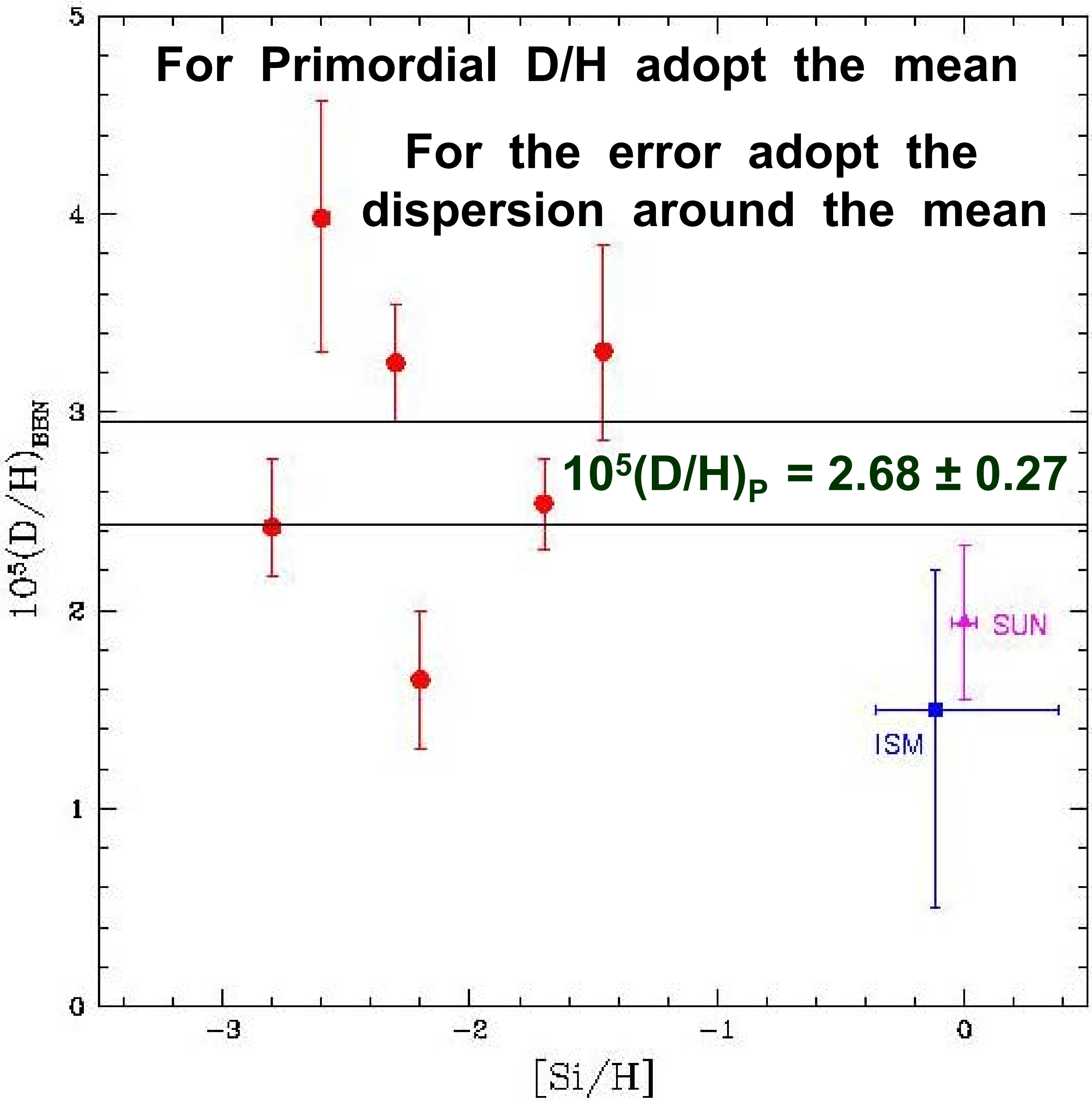


QSO 1937−1009
z_{abs} = 3.572
Ly - α Absorption
Flux (10^{-16} erg s^{-1} cm^{-2} Å^{-1})
0
10
20
5000
6000
7000
D
H
Ly−α
Normalized Flux
0
0.5
1
5555
5560
Wavelength (Å)

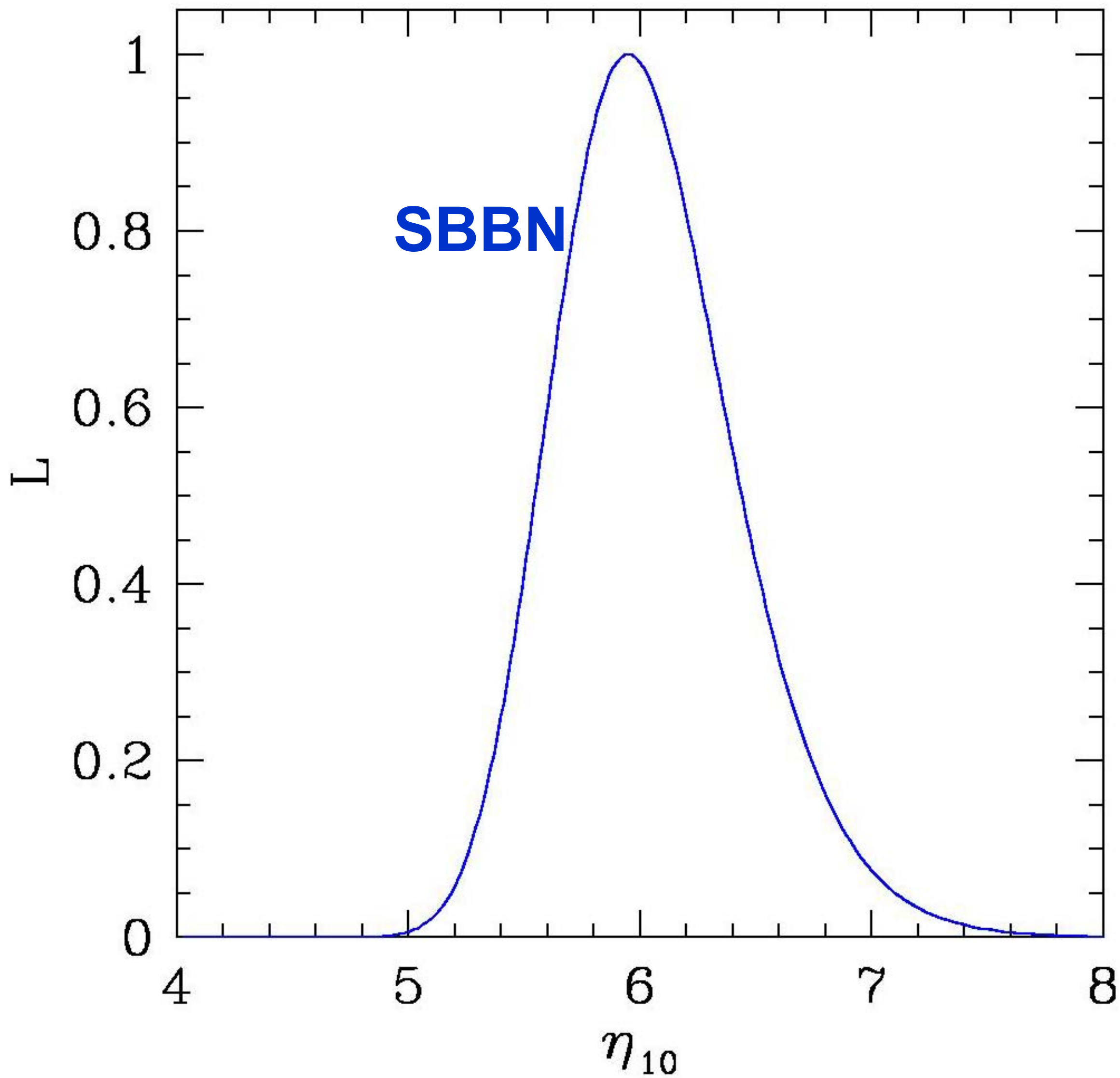
D/H vs. Metallicity



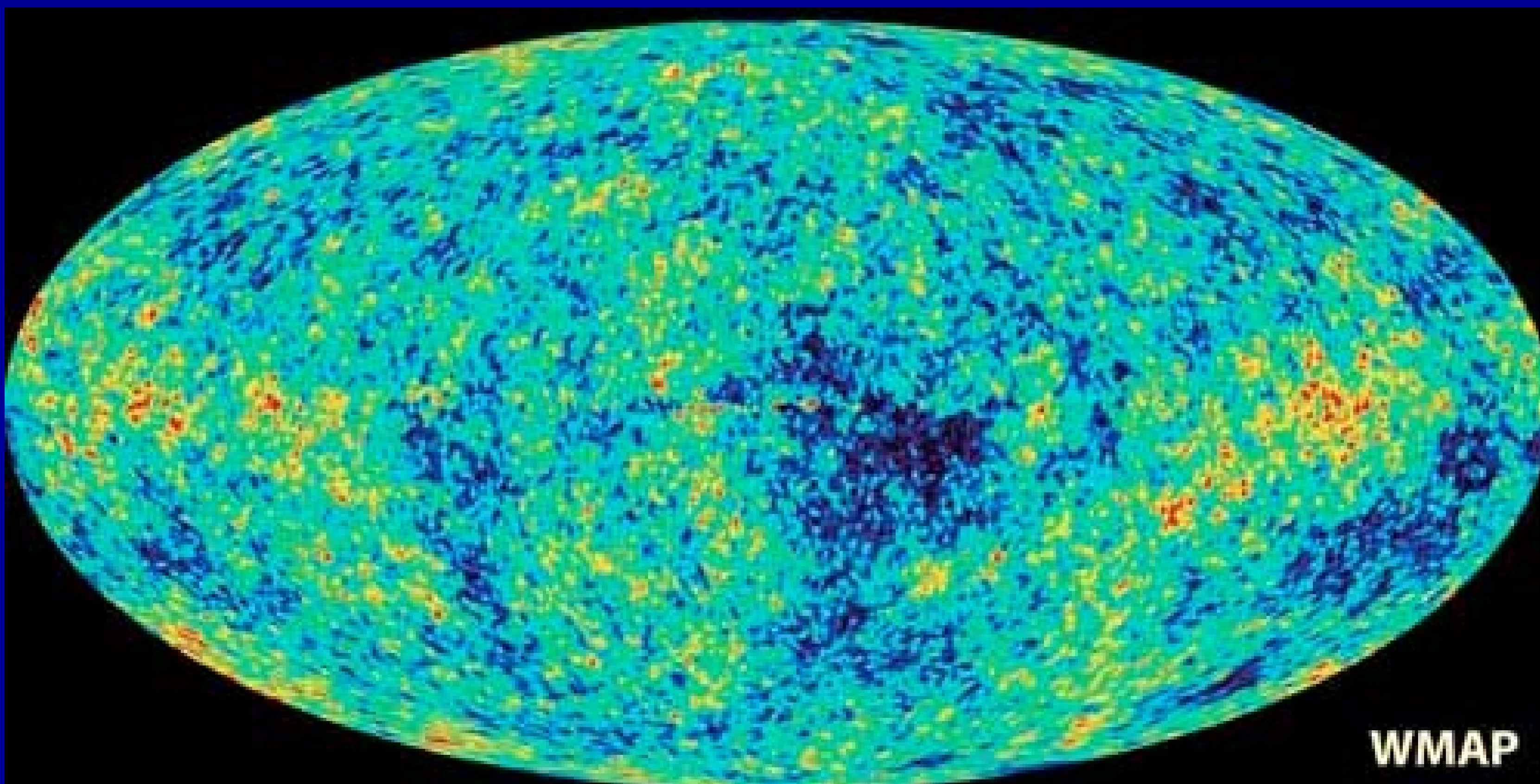
D/H vs. Metallicity



D + SBBN $\Rightarrow$ η_{10} = 6.0 ± 0.4

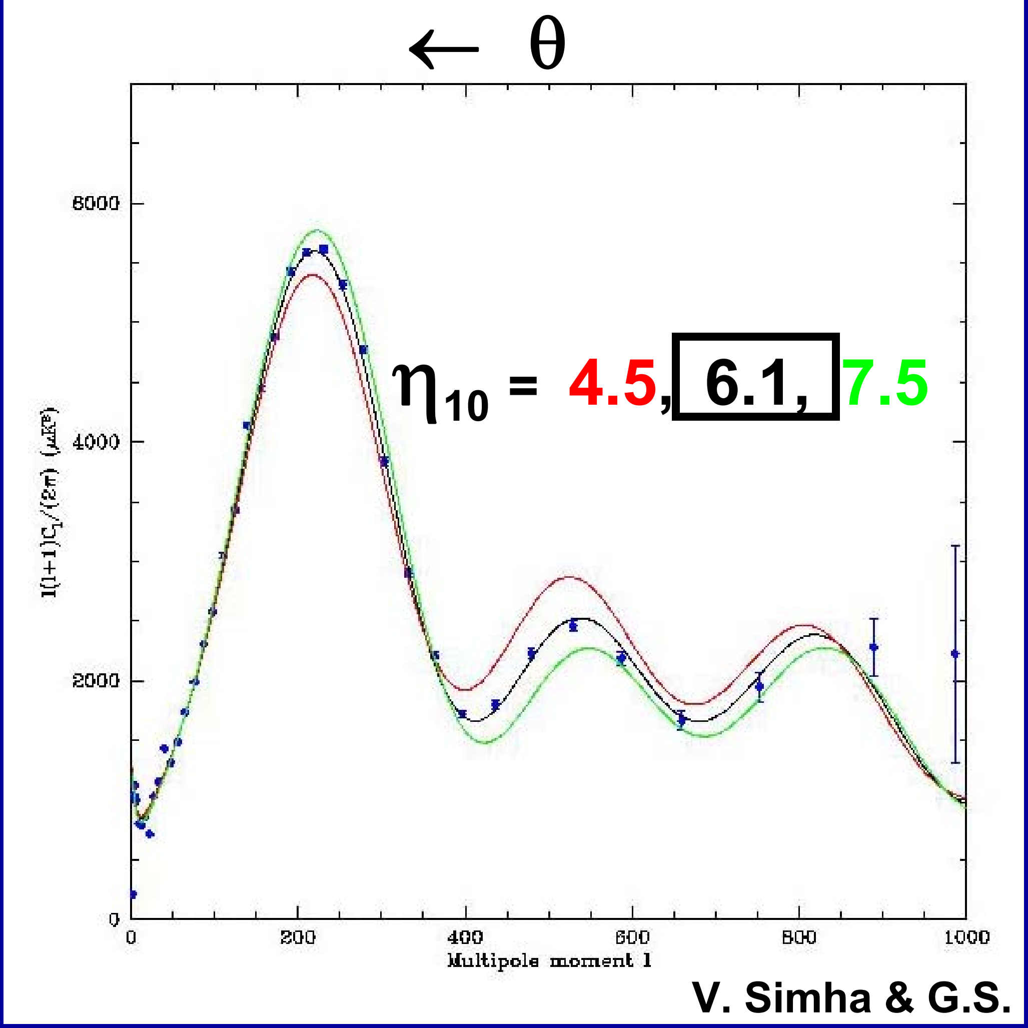


CMB



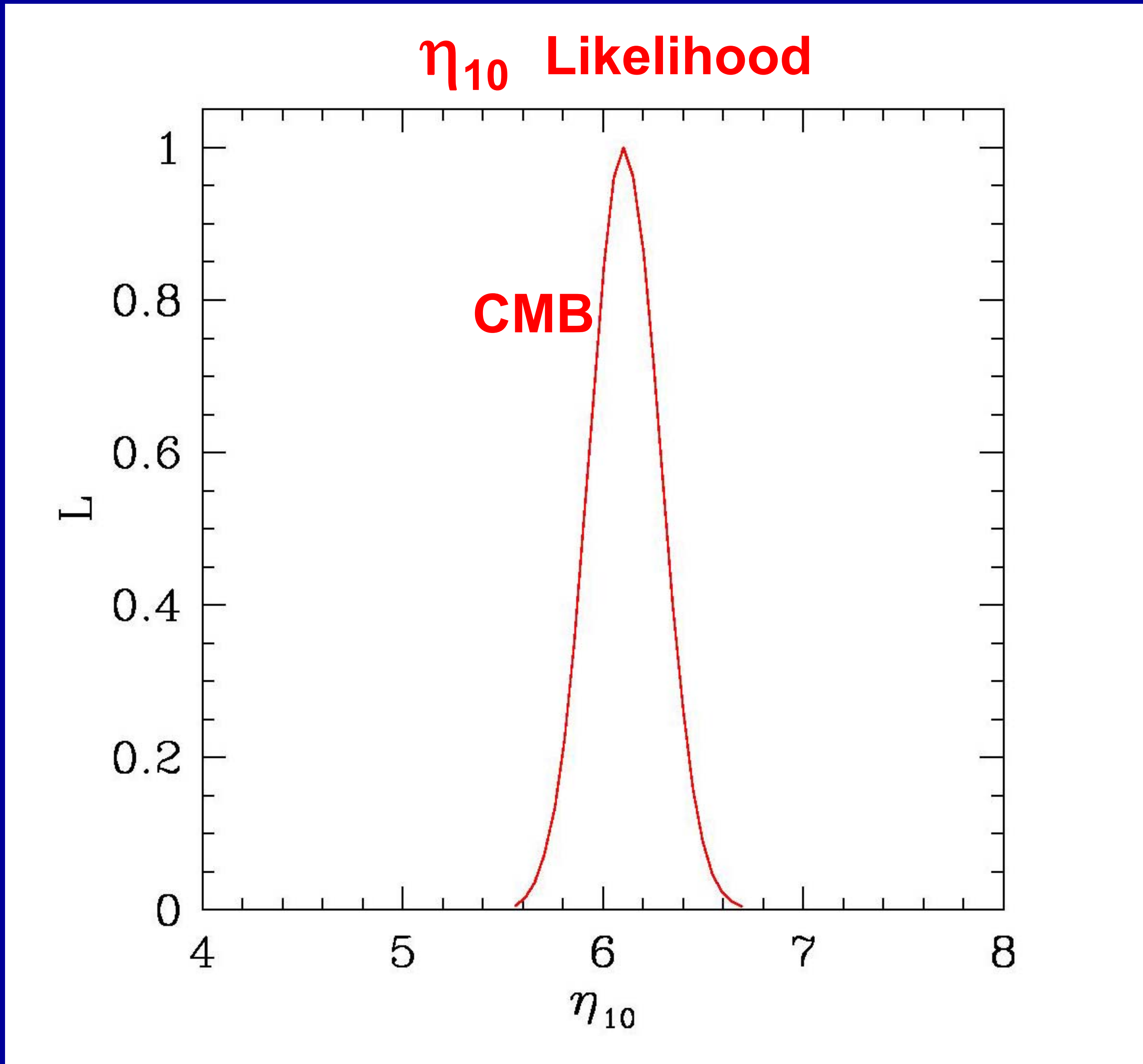
CMB Temperature Anisotropy Spectrum

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

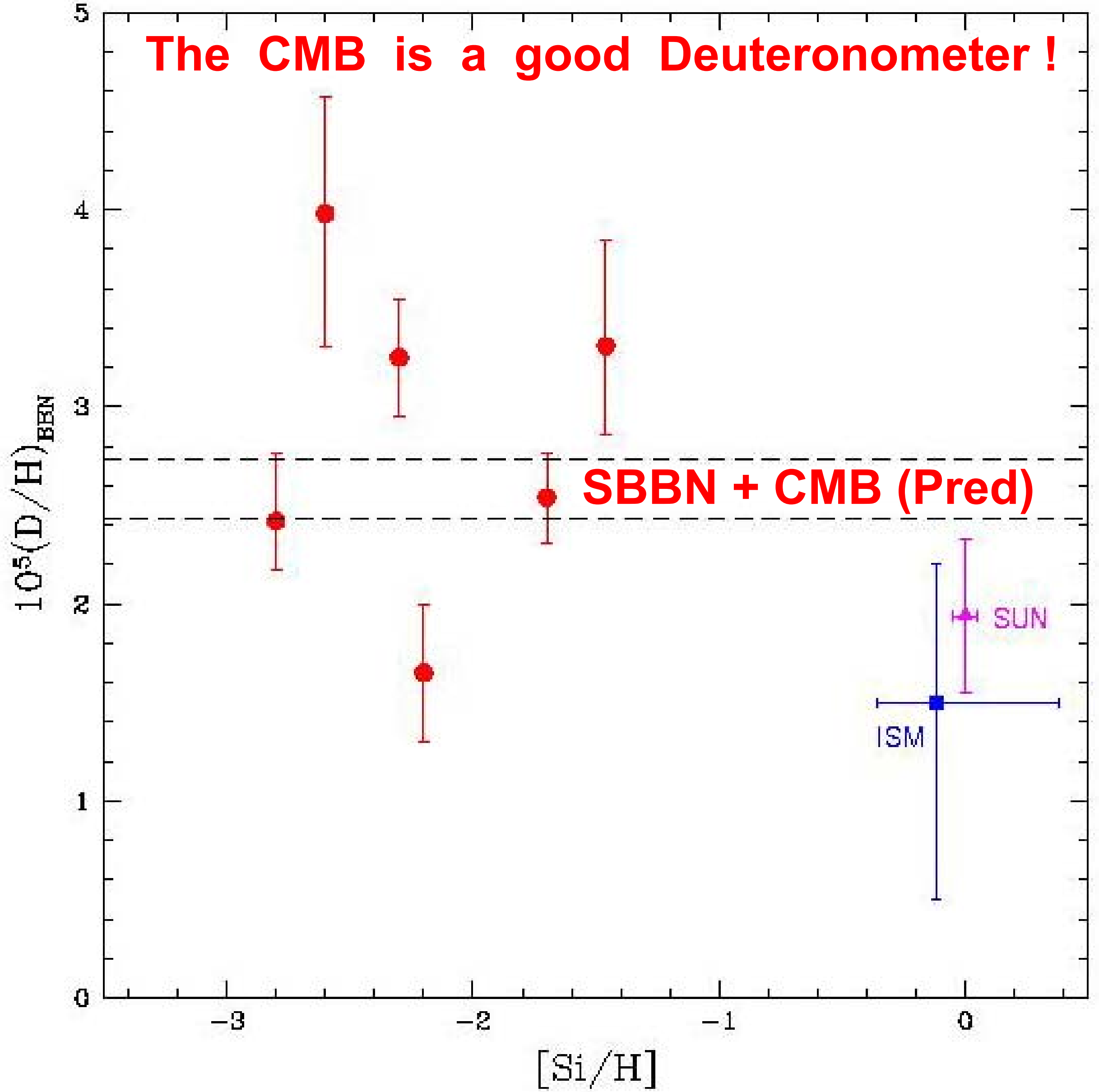


The CMB is an early - Universe Baryometer

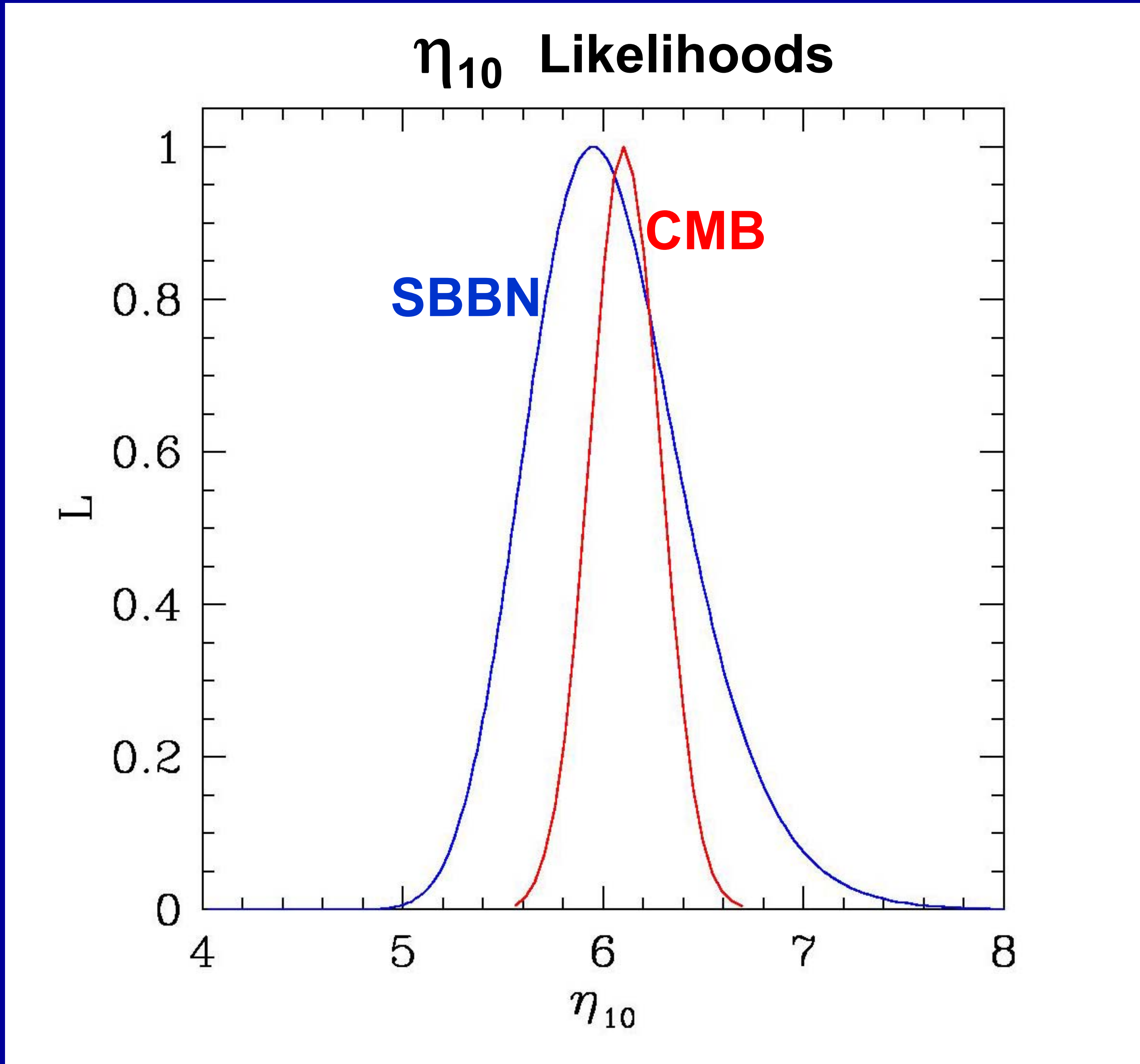
CMB $\Rightarrow$ η_{10} = 6.1 ± 0.2



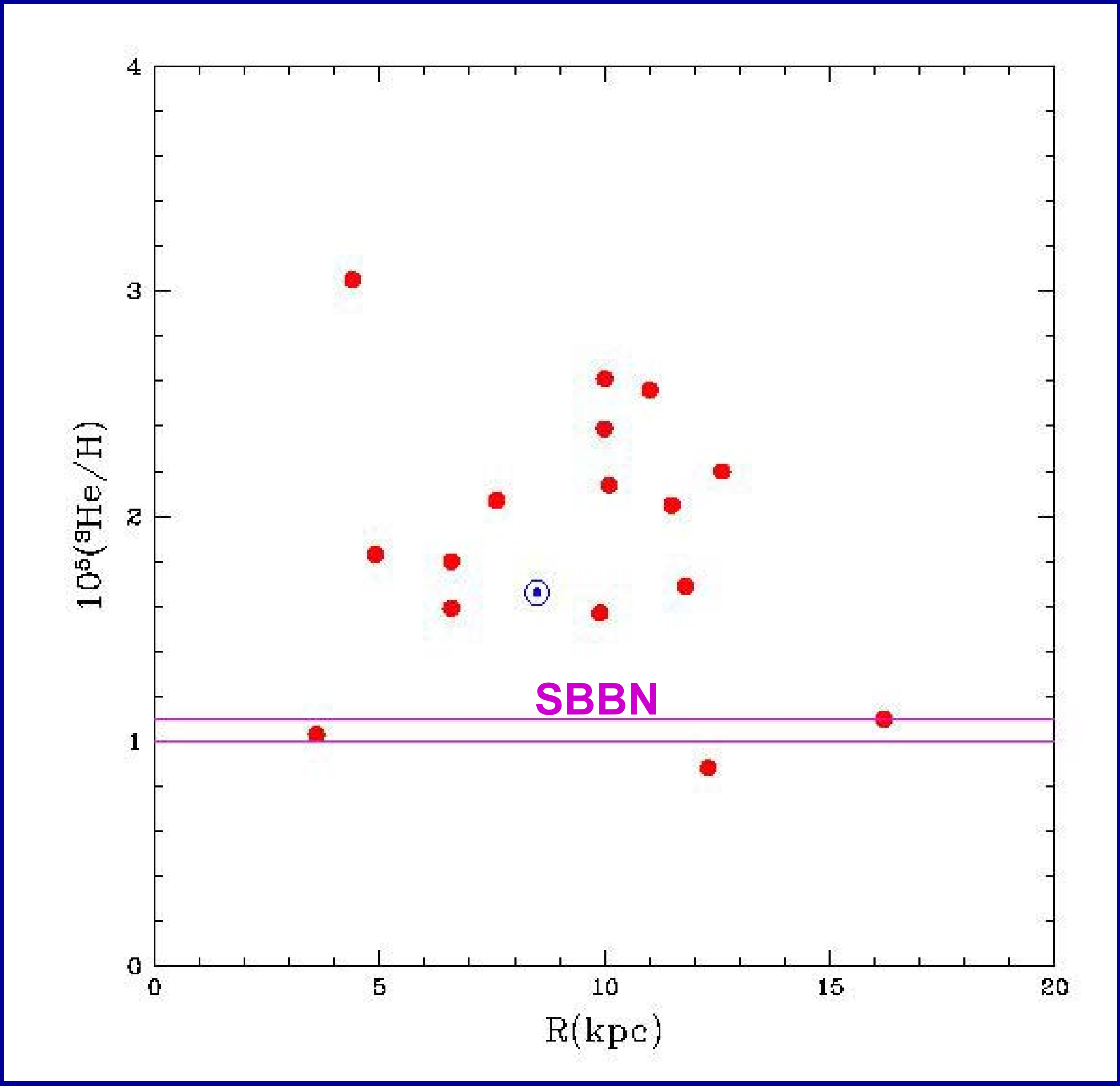
D/H vs. Metallicity



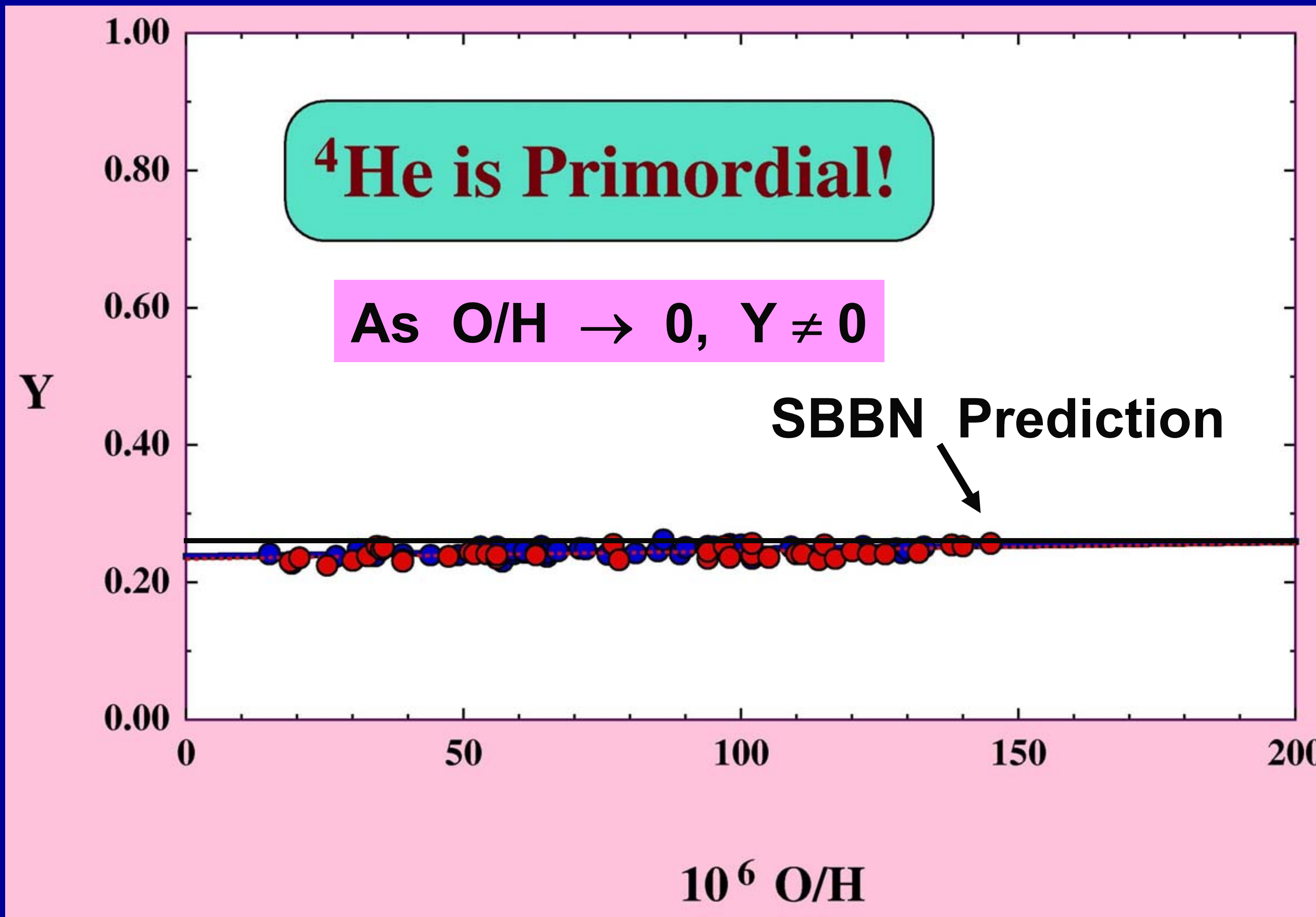
BBN (20 min) & CMB (380 kyr) AGREE !



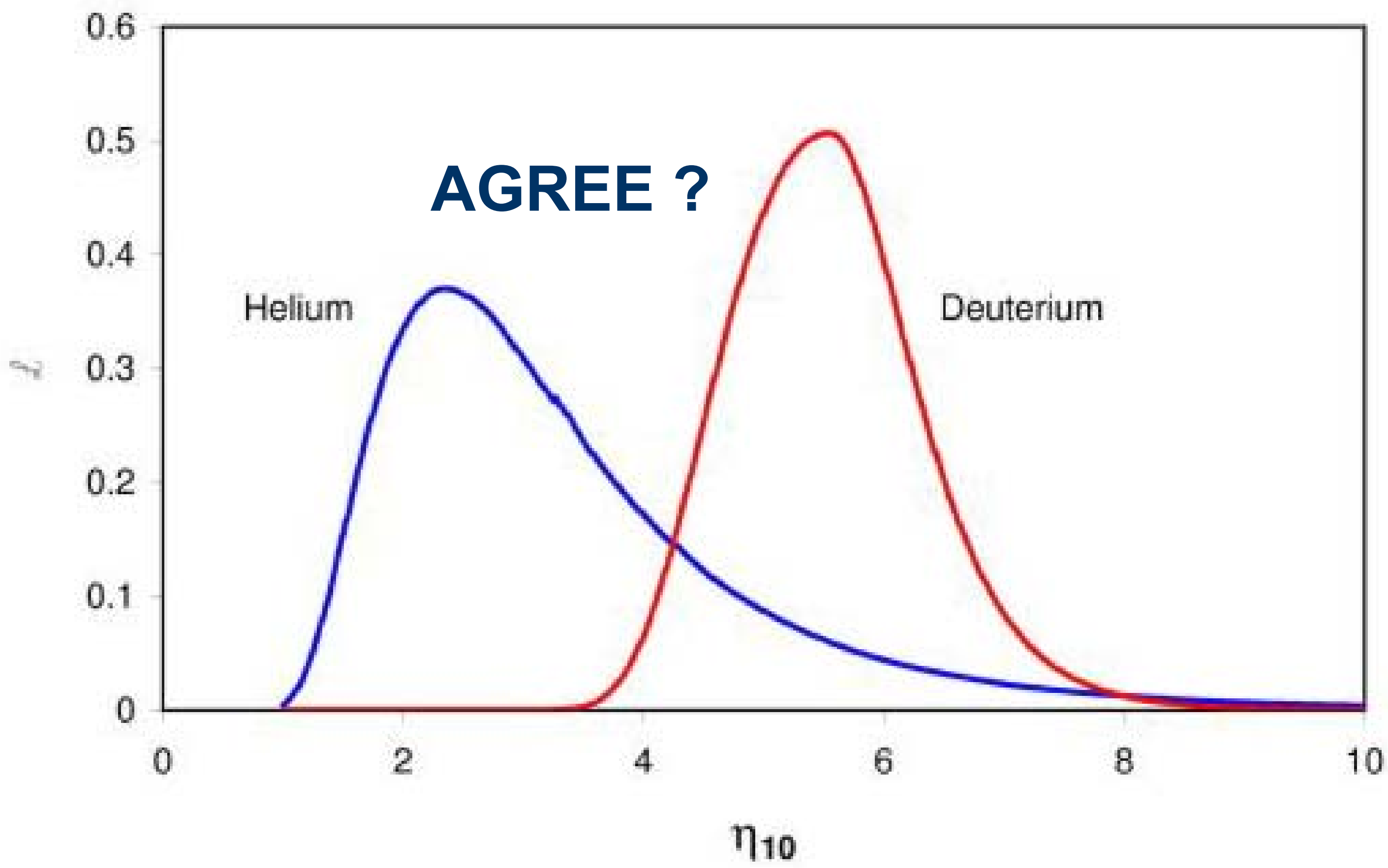
Galactic ^{3}He Observations (H II Regions)



Extragalactic ^{4}He Observations (H II Regions)

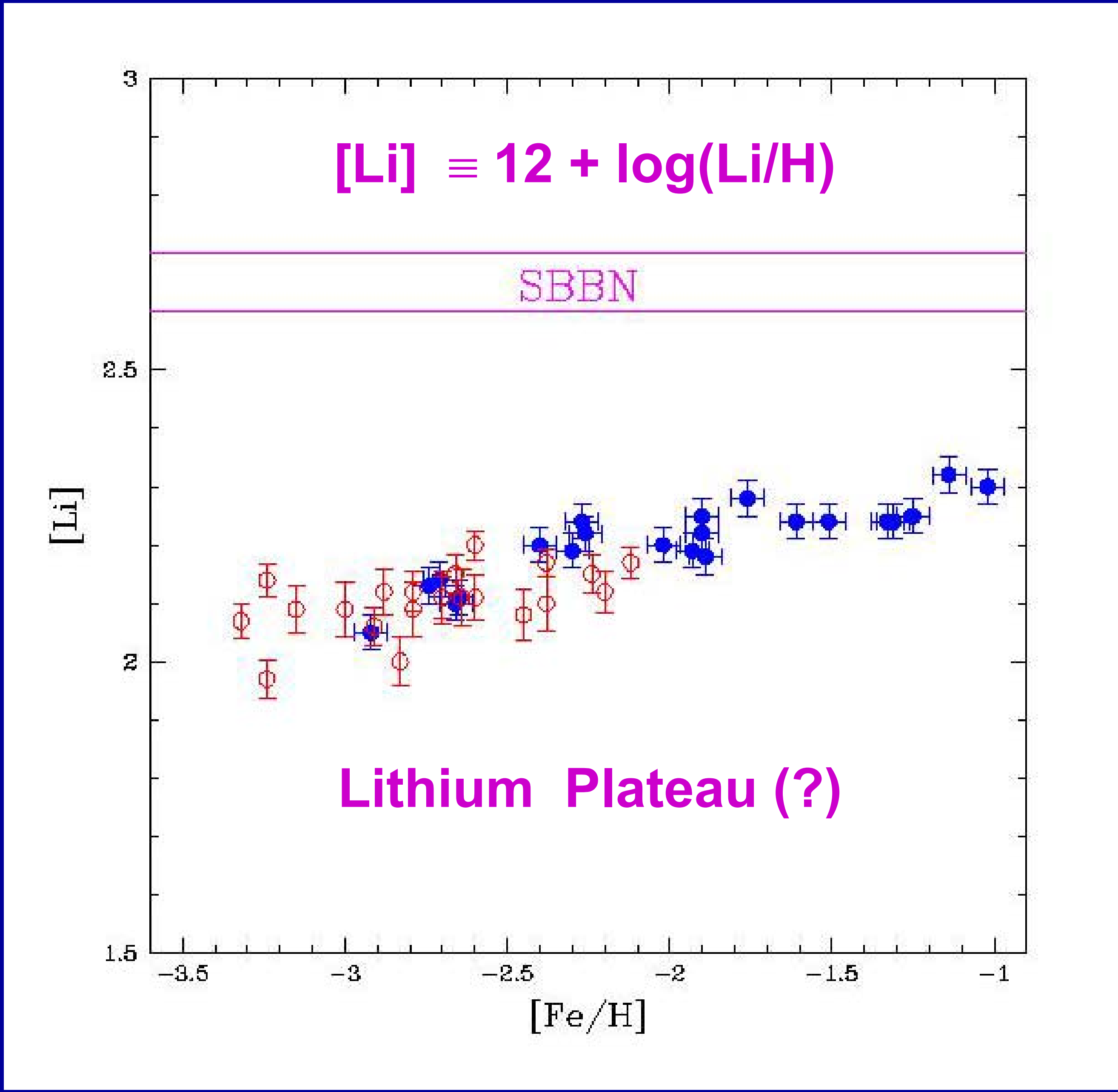


η Likelihoods from D and ^{4}He

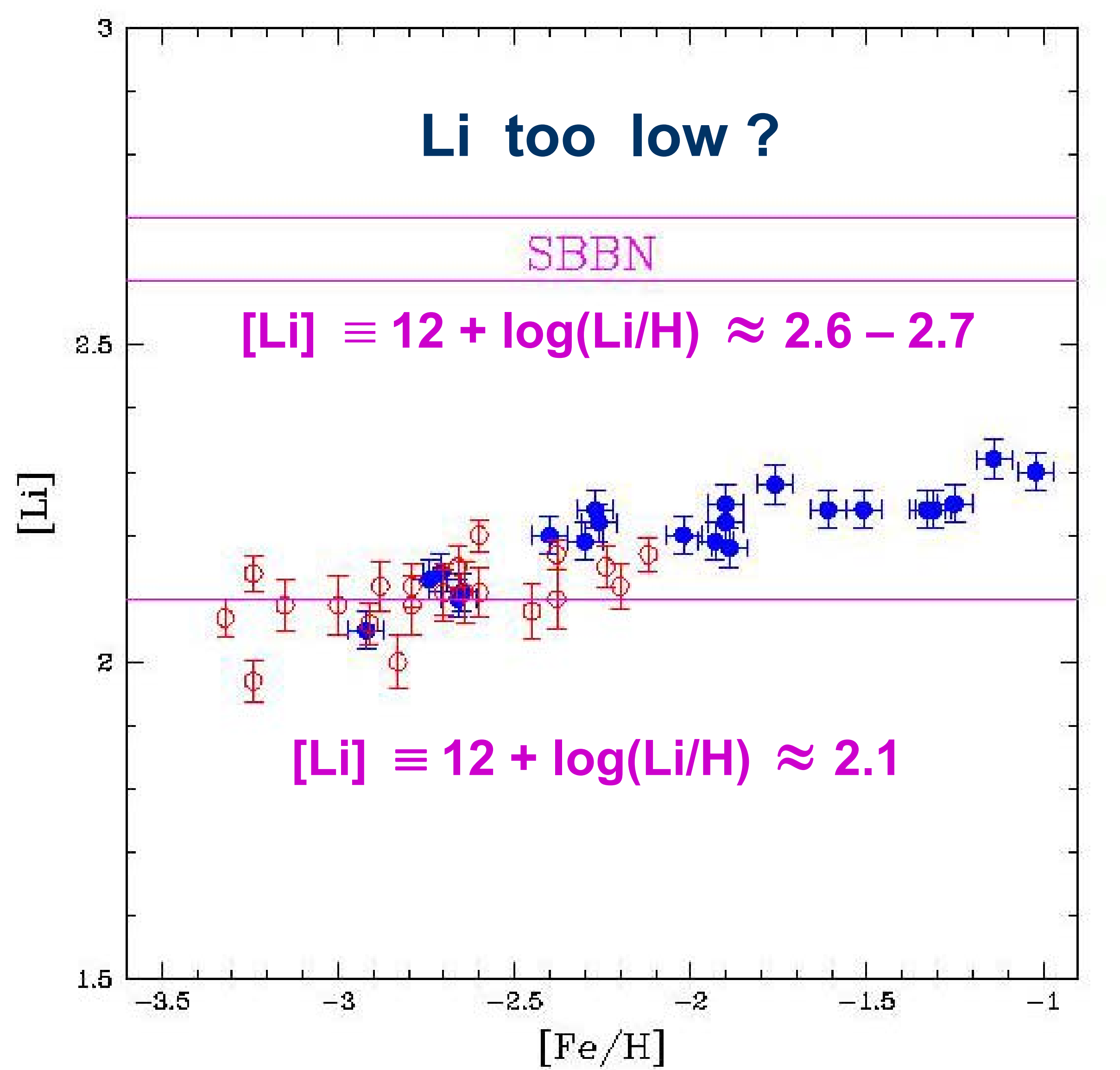


to be continued …

Lithium Observations in Galactic Halo Stars



BBN and Primordial (Pop II) Lithium



to be continued …

The Expansion Rate (H ≡ Hubble Parameter)

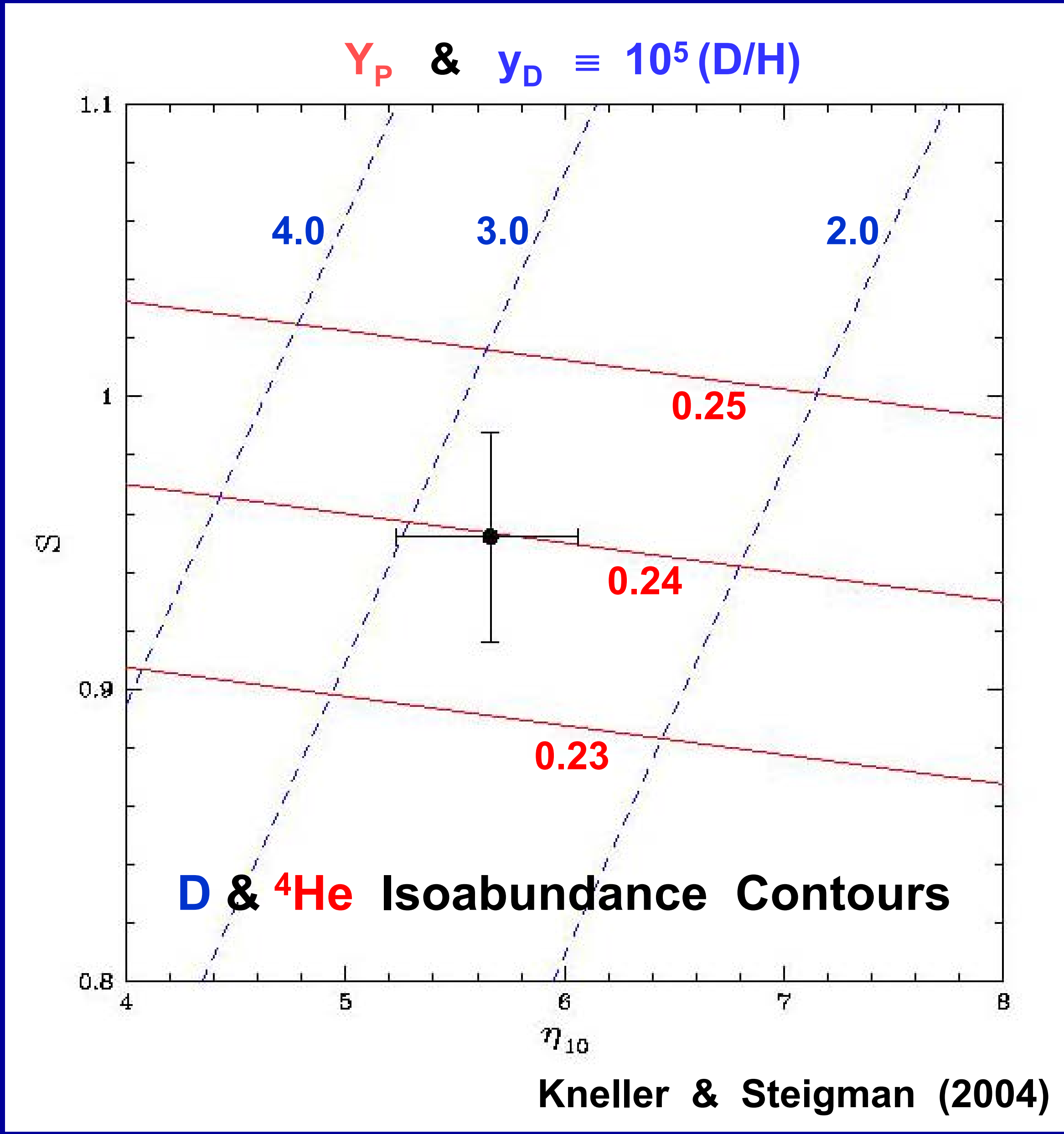
provides a probe of Non-Standard Physics

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

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

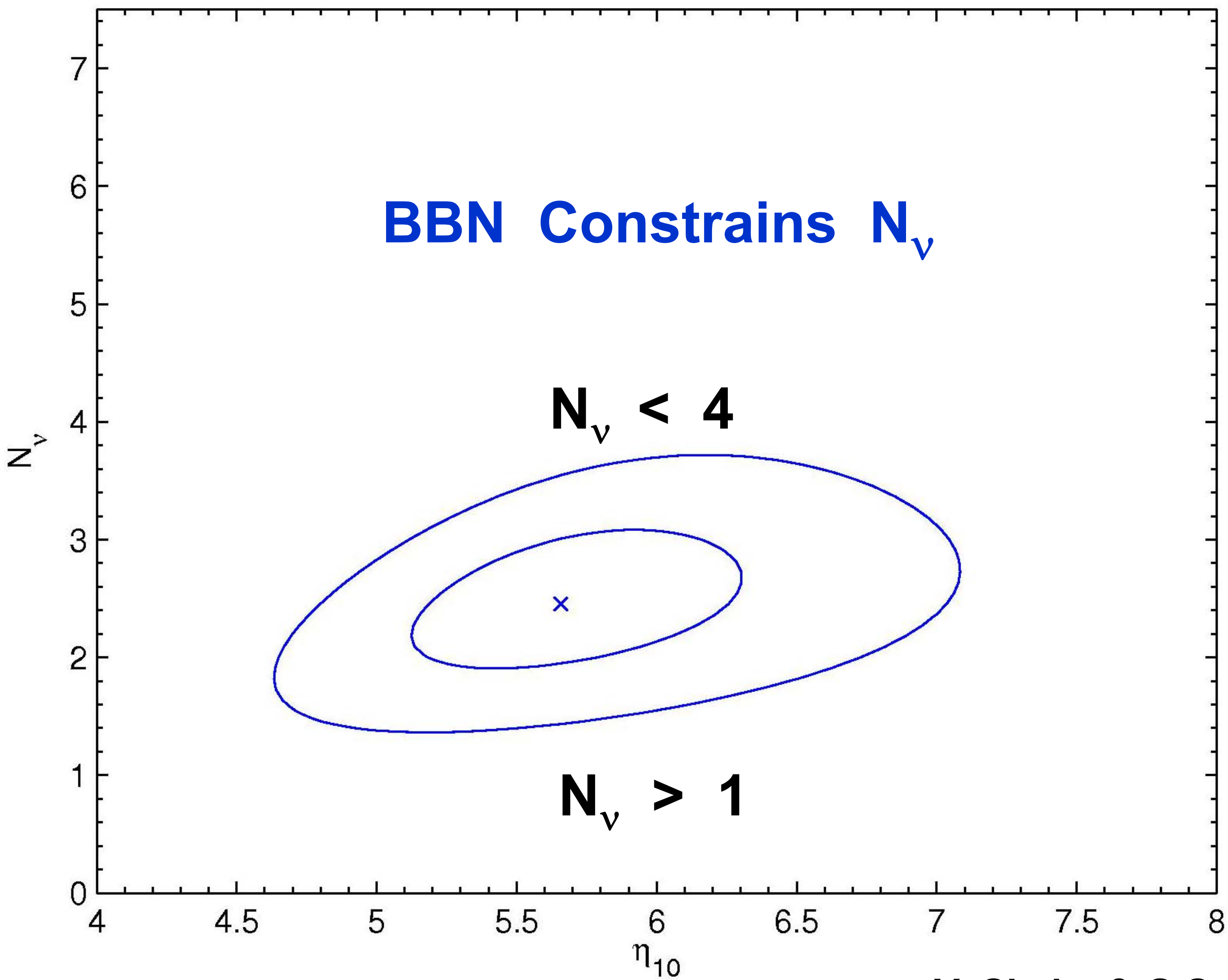
- ^{4}He is sensitive to S while D probes η

BBN (D, ^{4}He) ✓ For $N_\nu \approx 2.4 \pm 0.4$



BBN (D & ^{4}He)

N_ν vs. η_{10}



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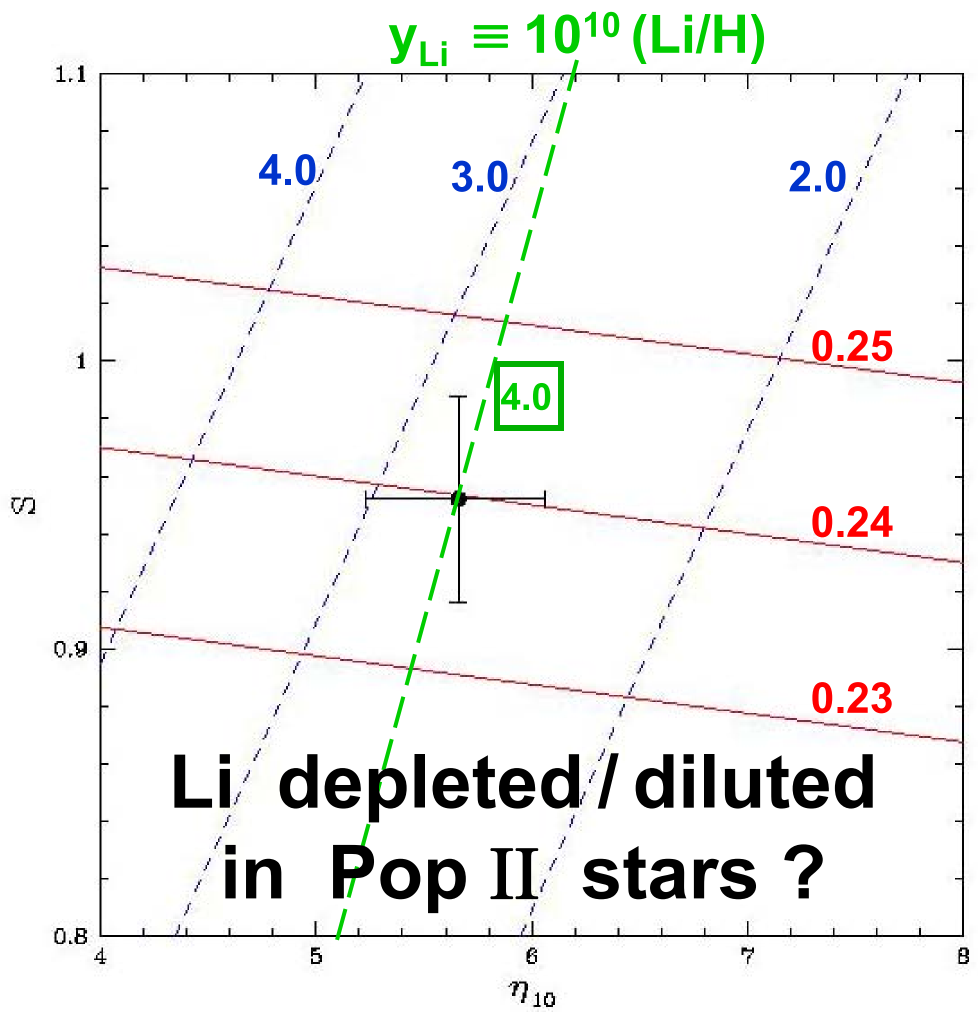
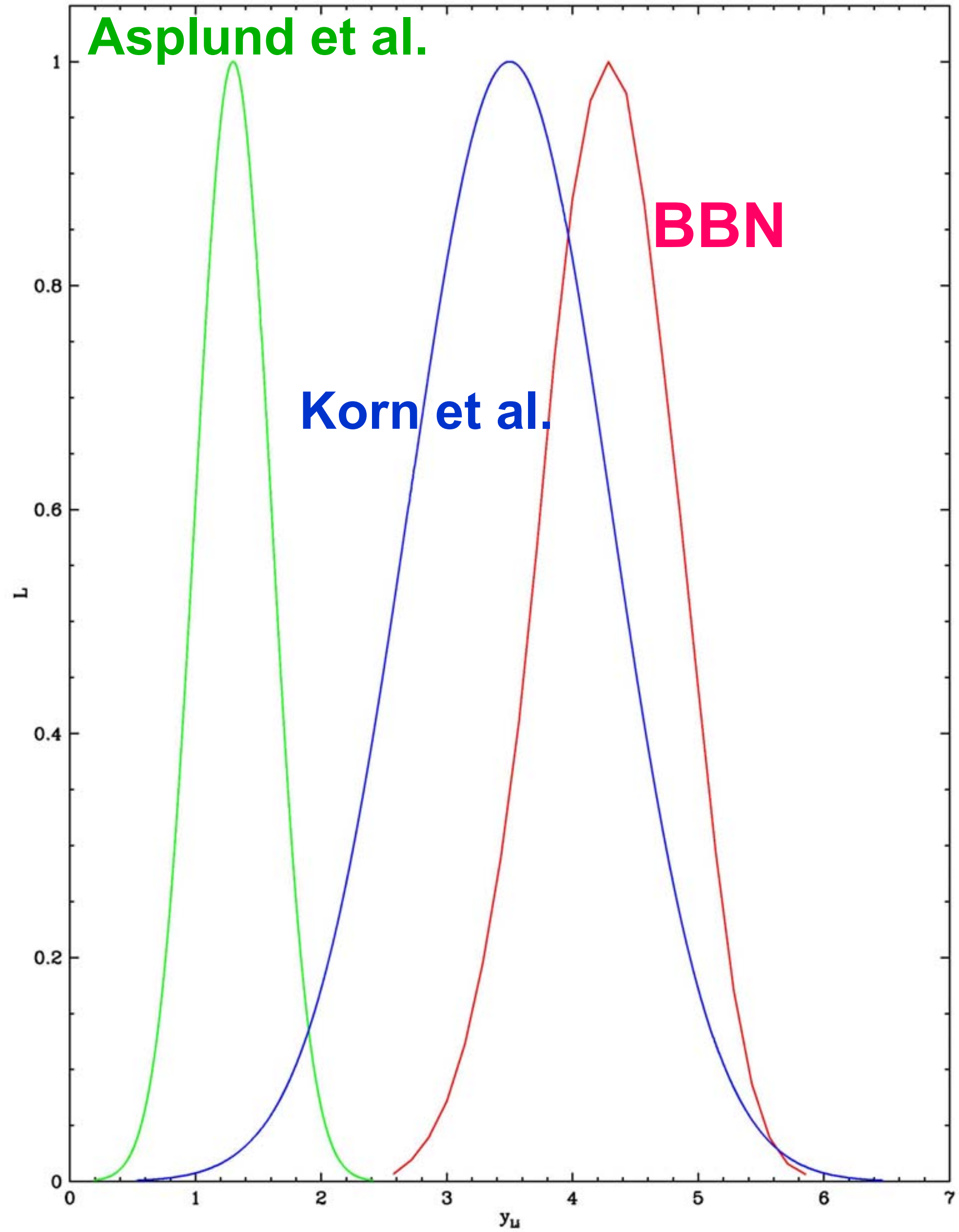
But , even for $N_\nu \neq 3$

$Y + D/H \Rightarrow Li/H \approx 4.0 \pm 0.7 \times 10^{-10}$



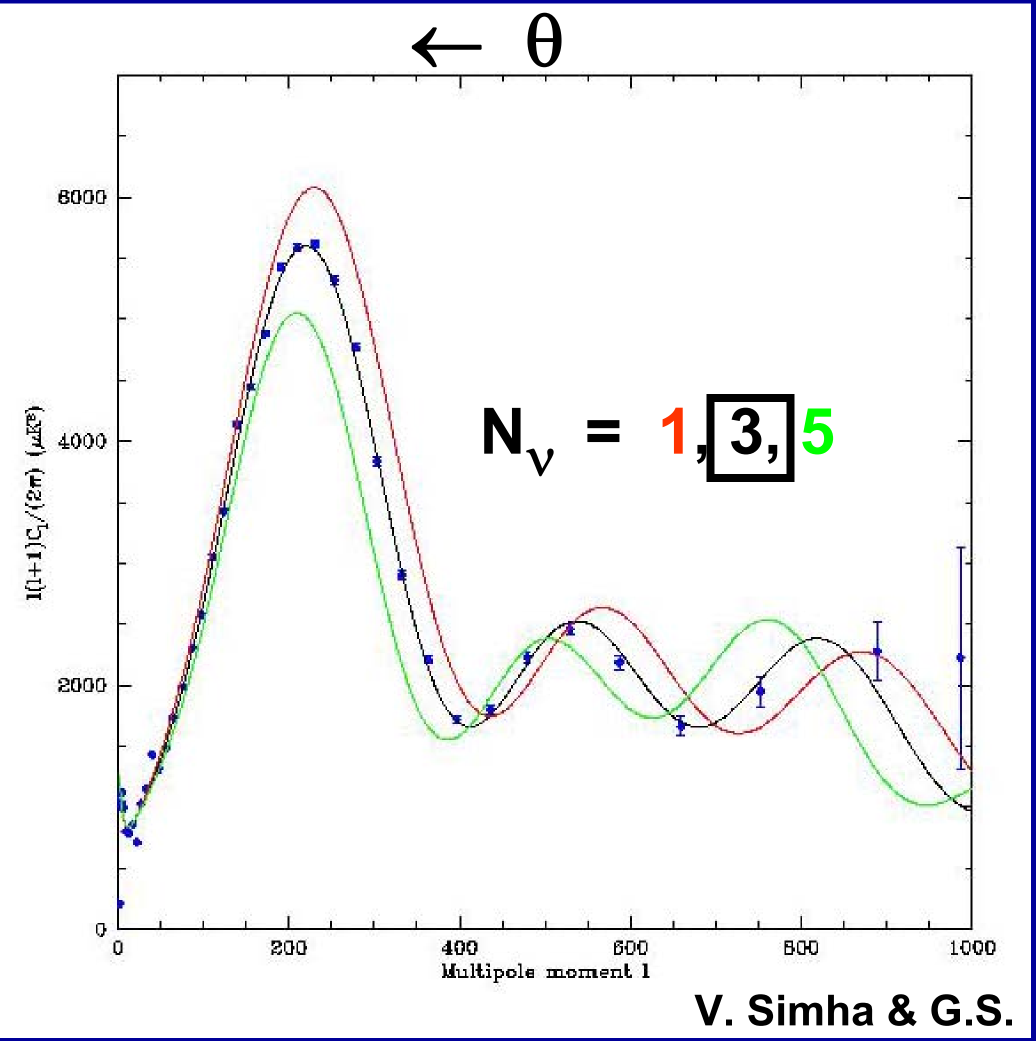
Kneller & Steigman (2004)

Lithium Likelihoods



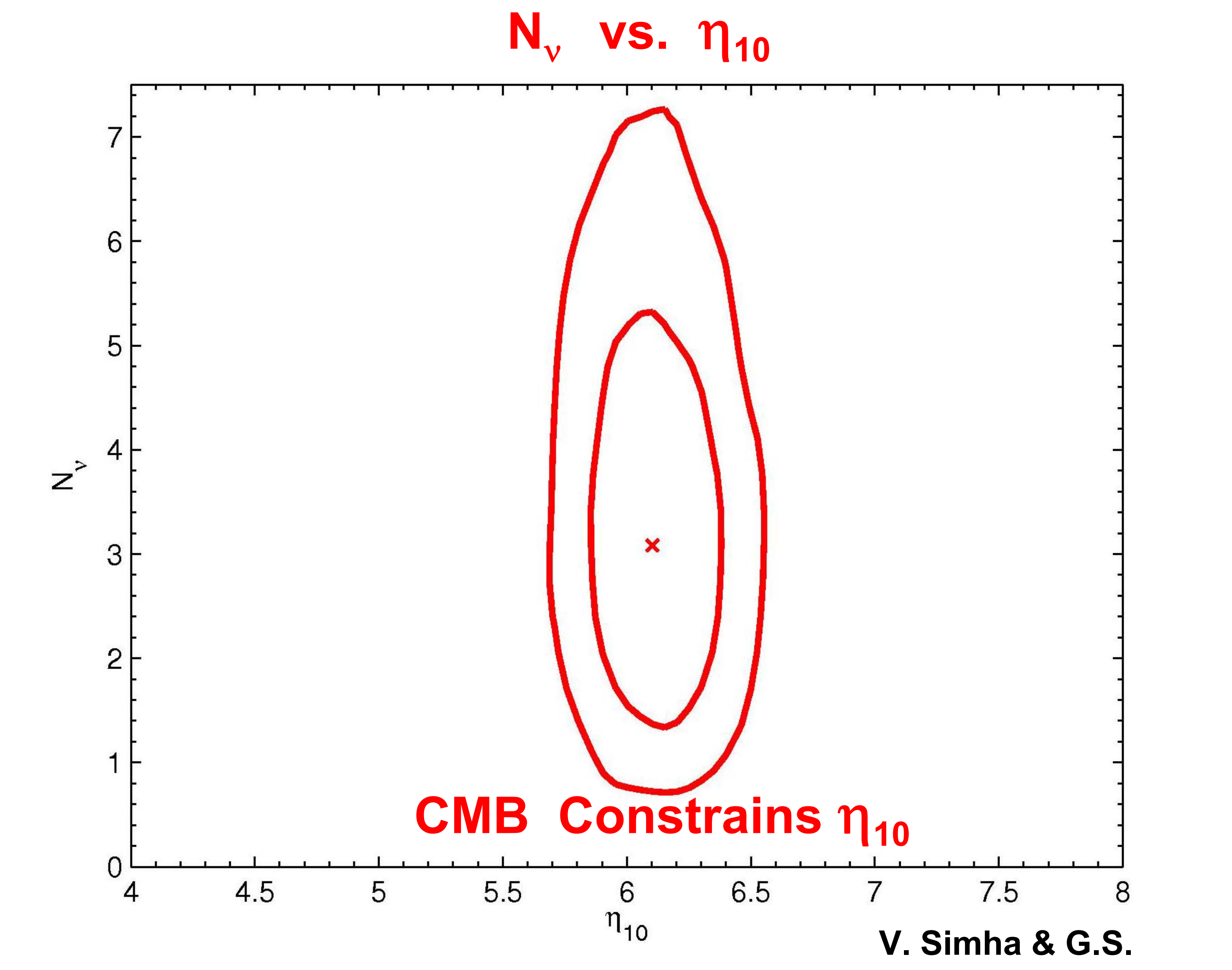
CMB Temperature Anisotropy Spectrum

Depends on the Radiation Density ρ_R (S or N_ν)



The CMB is an early - Universe Chronometer

CMB


N_ν vs. η_{10}
7
6
5
4
3
2
1
0
N_ν
4
4.5
5
5.5
6
6.5
7
7.5
8
η_{10}
CMB Constrains η_{10}
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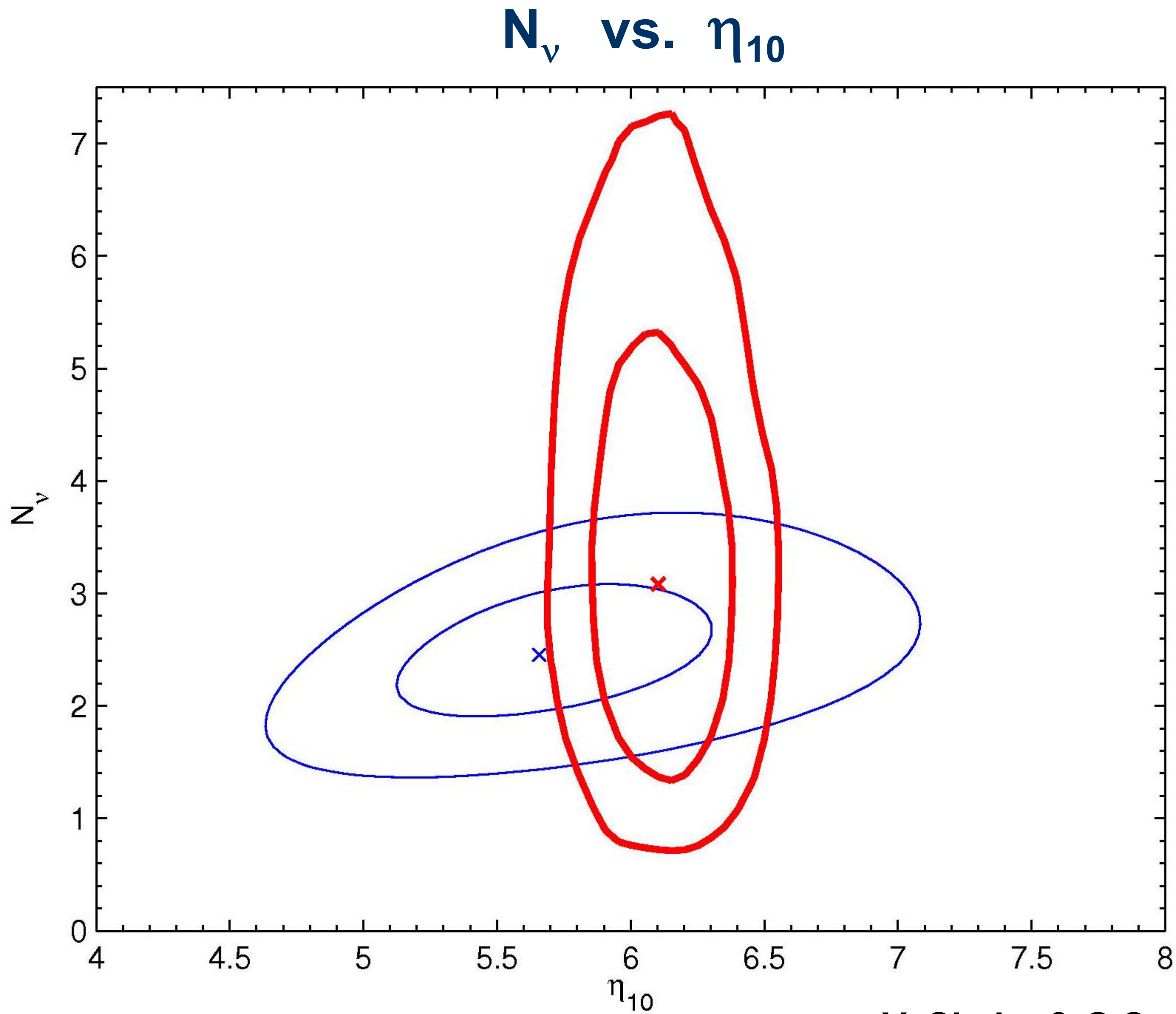
BBN (D & ^{4}He) & CMB AGREE !



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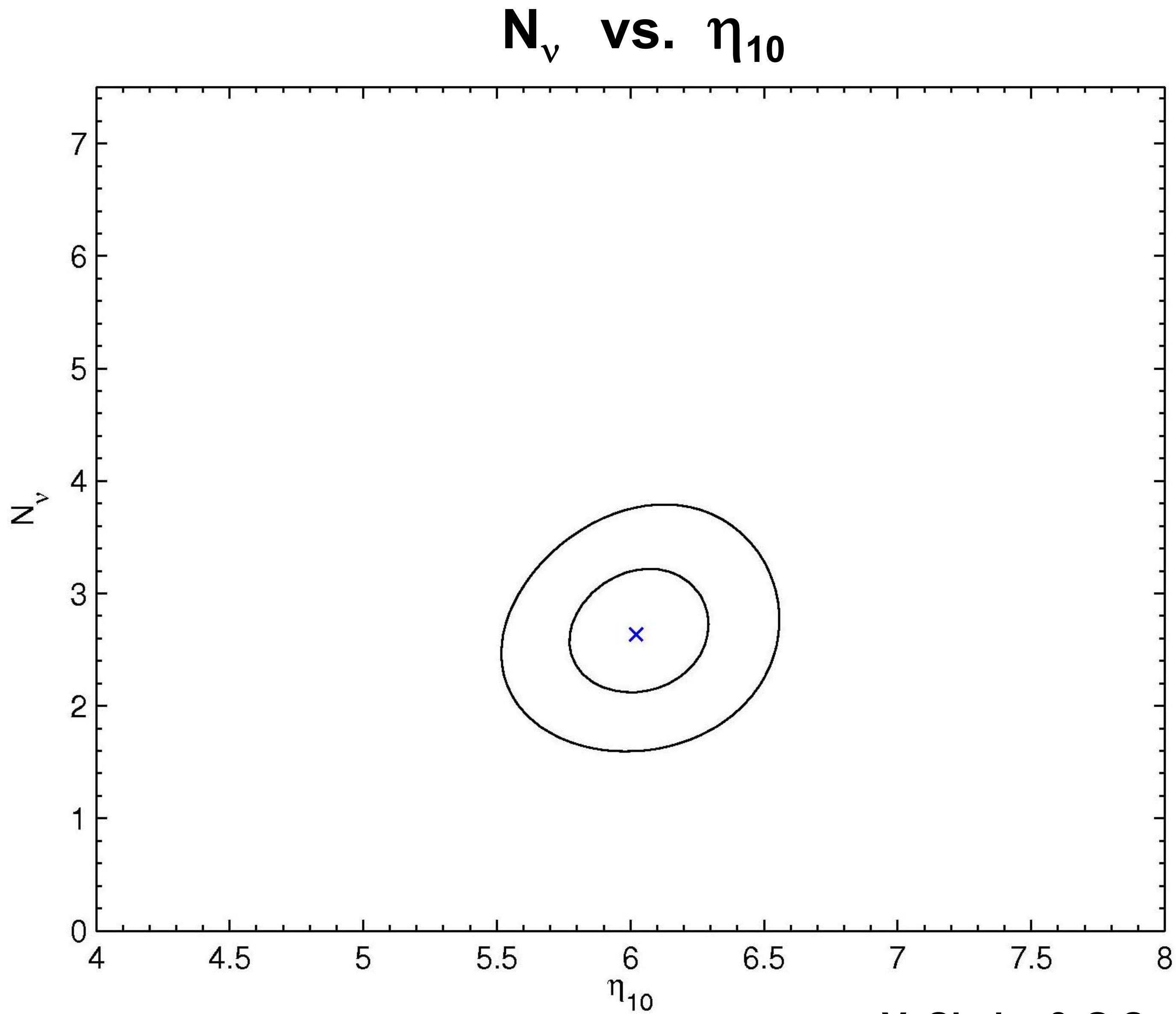
BBN + CMB Combined Fit



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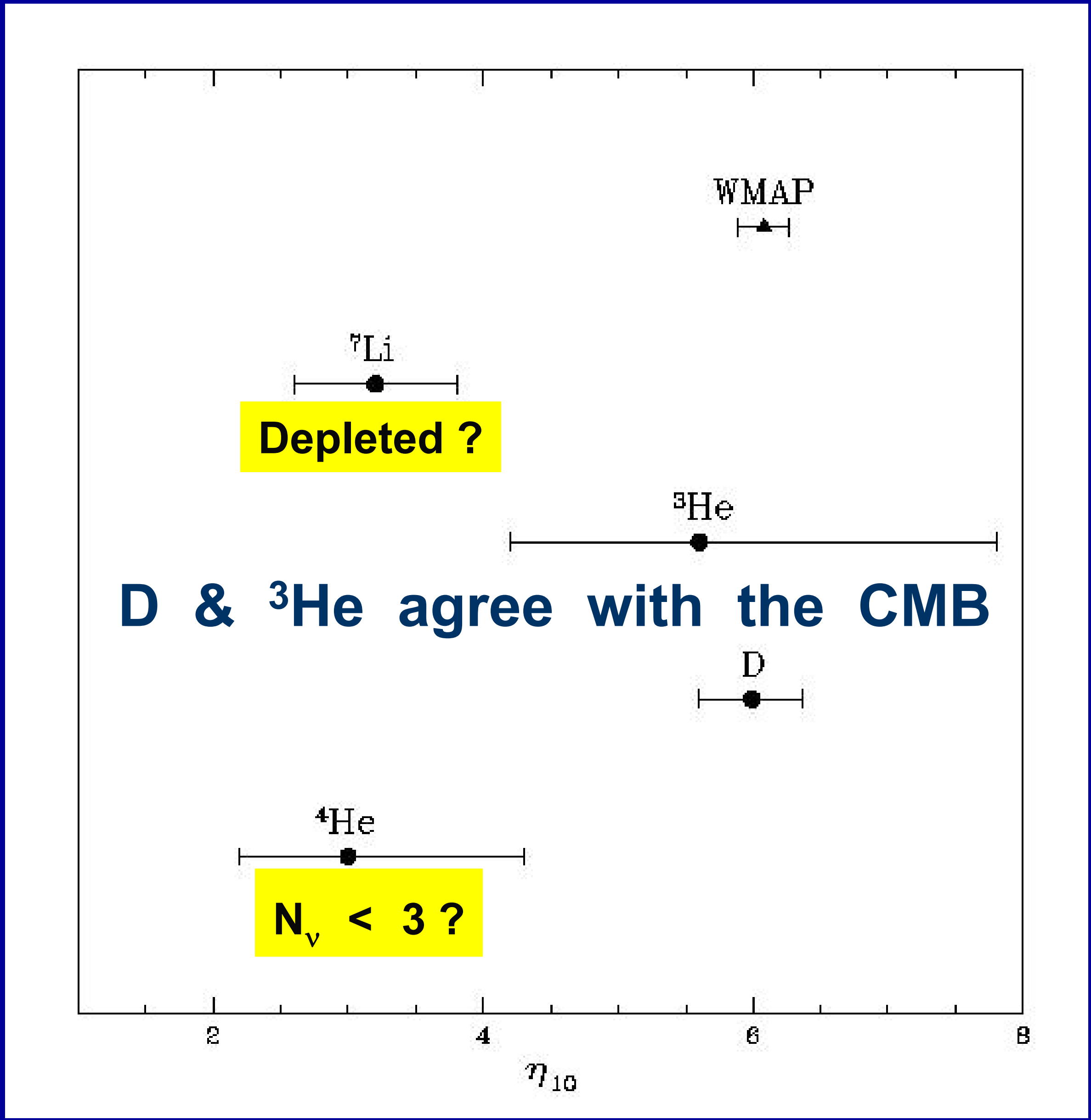
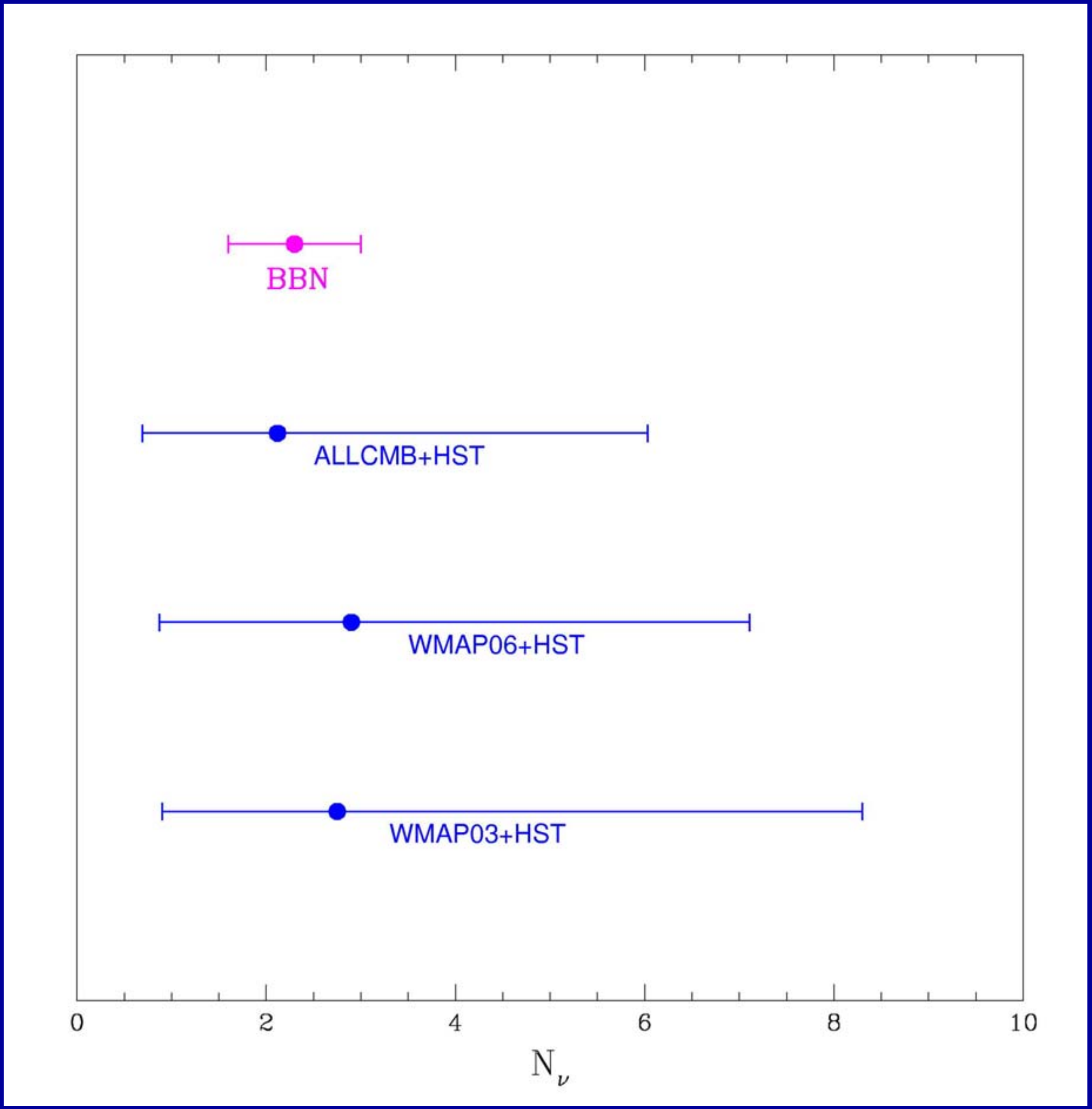
Baryon Density Parameter Determinations



N_ν (S) Determinations ✓



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)

$\xi_e \approx 0.035 \pm 0.026$

&

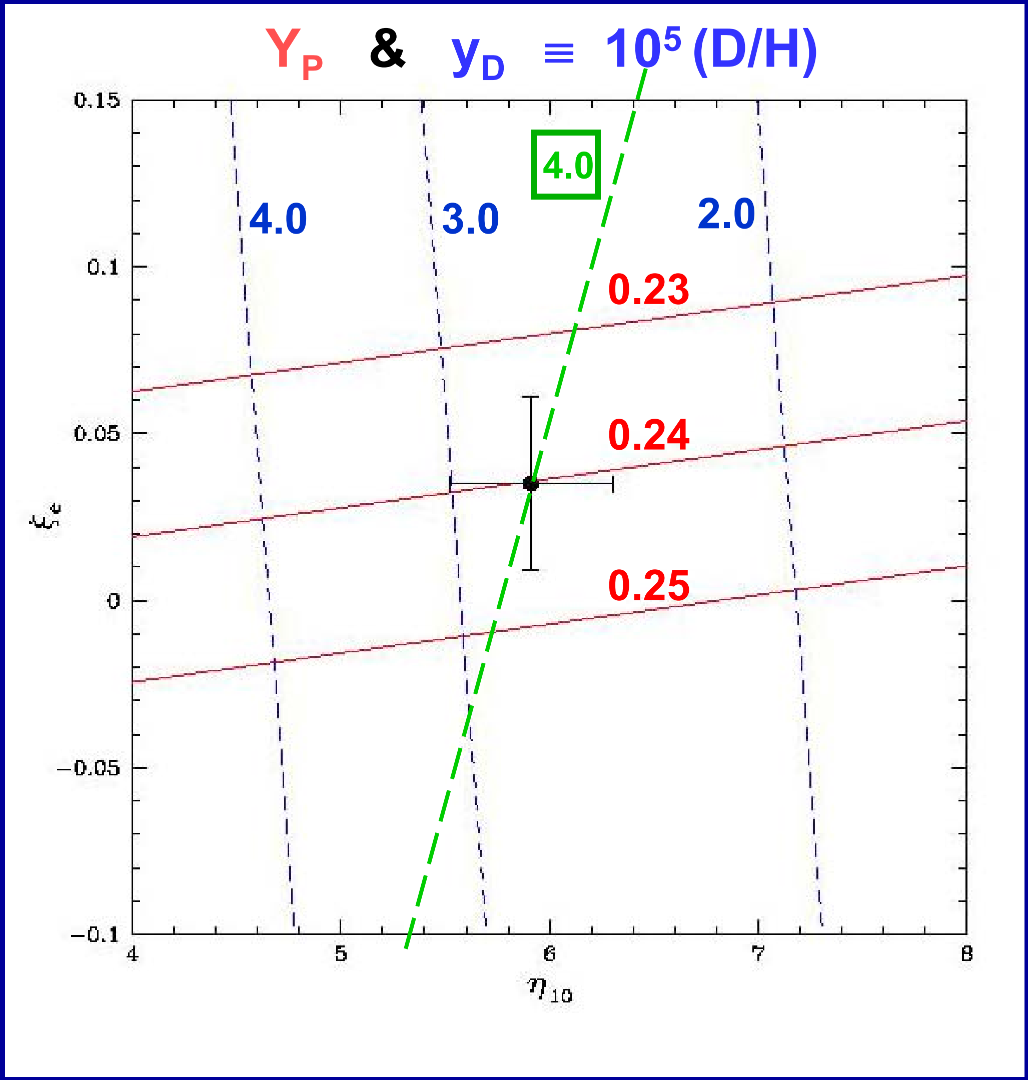
$\eta_{10} = 5.9 \pm 0.4$ ✓

But, [Li] = 2.6 ± 0.7

Still !

Li depleted / diluted

in Pop II stars ?



SUCCESS

BBN (D & ^{4}He) and the CMB Agree !

But, Lithium ?

CHALLENGE

(The Theorist's Mantra)

More & Better Data Are Needed !