PRIMORDIAL NUCLEOSYNTHESIS :

PREDICTED AND OBSERVED ABUNDANCES

AND THEIR COSMOLOGICAL CONSEQUENCES

Gary Steigman

Departments of Physics and Astronomy

Center for Cosmology and Astro-Particle Physics

Ohio State University

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Baryon Density Parameter : η_B

Note : Baryons $\equiv$ Nucleons

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

(η_B not predicted (yet) by fundamental theory)

Hubble Parameter : H = H(z)

In The Early Universe : $H^2 \propto G\rho$

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

$S \neq 1$ is a Probe of Non-Standard Physics

- $S^2 = G'\rho'/G\rho \equiv 1 + 7\boxed{\Delta N_\nu}/43$

$\Delta N_\nu \equiv (\rho' - \rho)/\rho_\nu$ and $N_\nu \equiv 3 + \Delta N_\nu$

- $S \Leftrightarrow N_\nu$

NOTE : If $\rho' = \rho$, $G'/G = S^2 = 1 + 7\Delta N_\nu / 43$

- ^{4}He is sensitive to $S\,(N_\nu)$; D probes η_B

“Standard” Big Bang Nucleosynthesis (SBBN)

An Expanding Universe Described By General Relativity, With S = 1 (N_ν = 3)

Relic abundances of D, ^{3}He, ^{4}He, ^{7}Li depend only on η_B

Big Bang Nucleosynthesis (BBN) : S ≠ 1

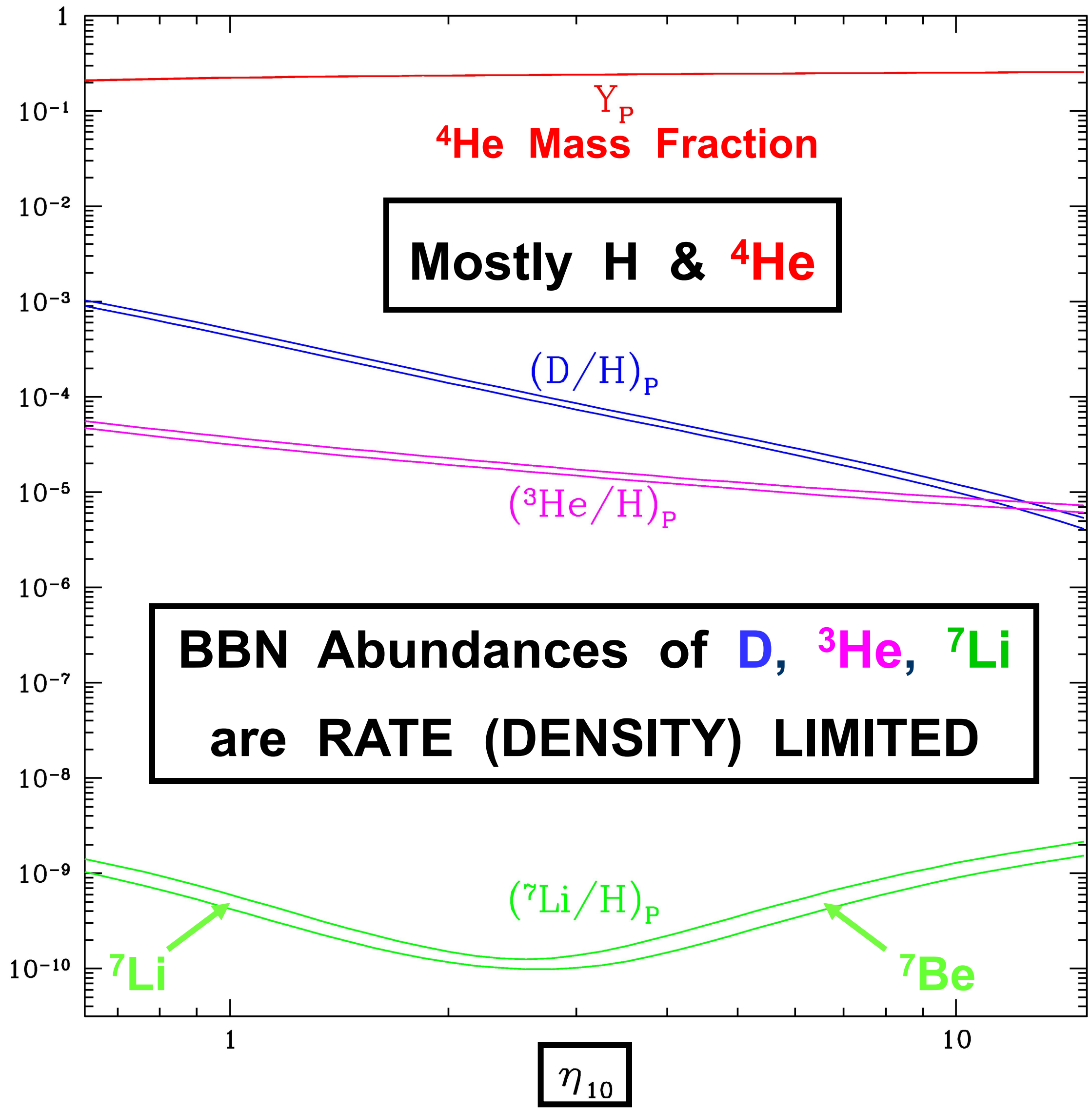
Relic abundances depend on η_B and S (N_ν)

BBN (~ 3 Minutes) , The CMB (~ 400 kyr) , LSS (~ 10 Gyr) Provide Complementary Probes Of The Early Evolution Of The Universe

* Do the BBN - predicted abundances agree with observationally - inferred primordial abundances ?

- Do the BBN and CMB values of η_B agree ?
- Do the BBN and CMB values of S (N_ν) agree ?
- Is S_{BBN} = S_{CMB} = 1 ?

SBBN – Predicted Primordial Abundances



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

Post – BBN Evolution of the Relic Abundances

- As gas cycles through stars, D is only DESTROYED
- As gas cycles through stars, ^{3}He is DESTROYED, PRODUCED and, some prestellar ^{3}He SURVIVES
- Stars burn H to ^{4}He (and produce heavy elements)

  $\Rightarrow$ ^{4}He INCREASES (along with CNO …)
- Cosmic Rays and SOME Stars PRODUCE ^{7}Li BUT, ^{7}Li is DESTROYED in most stars

DEUTERIUM Is The Baryometer Of Choice

- The Post – BBN Evolution of D is Simple :

  As the Universe evolves, D is only DESTROYED $\Longrightarrow$

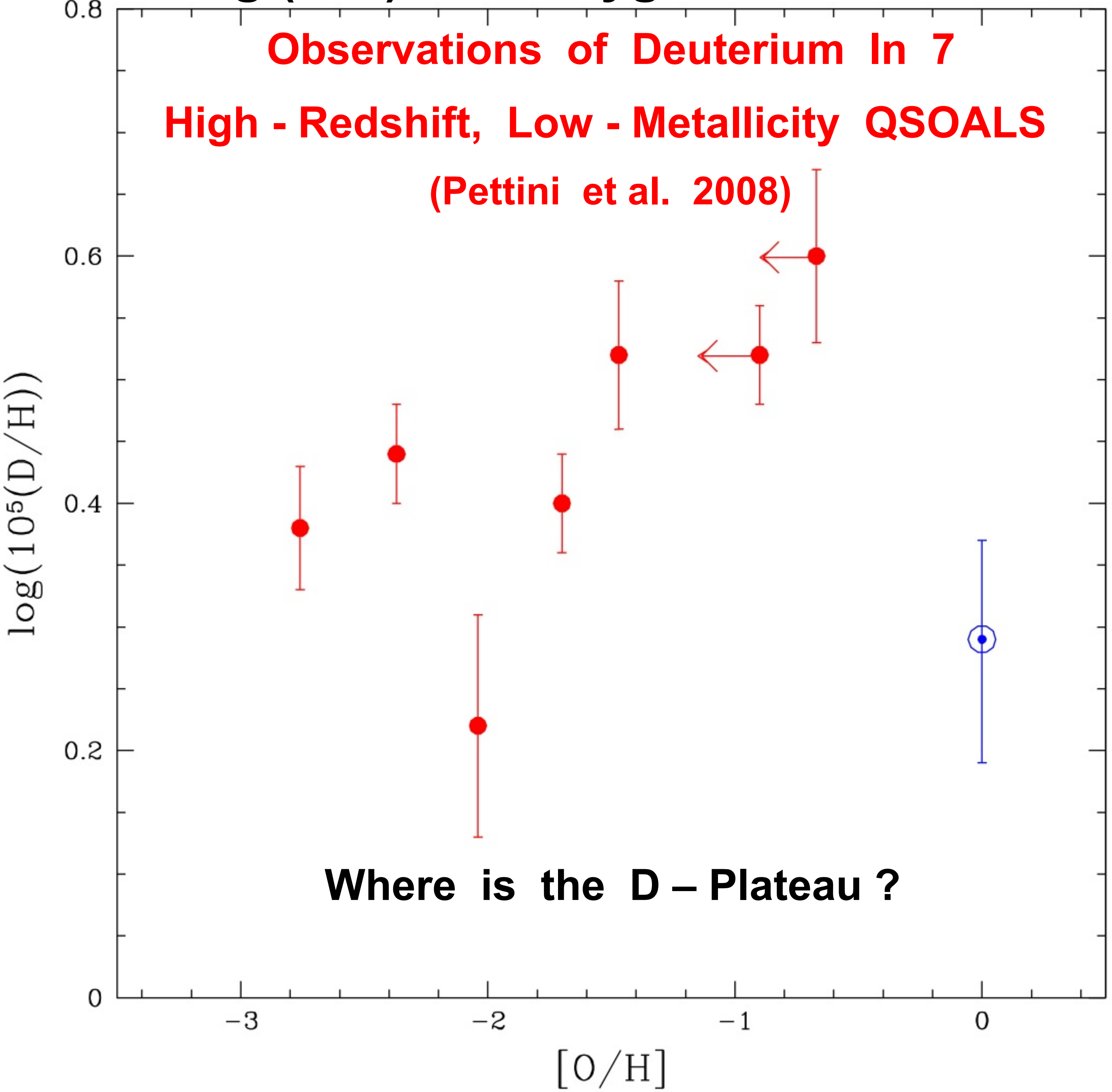
  * Anywhere, Anytime : $(D/H)_t \leq (D/H)_P$

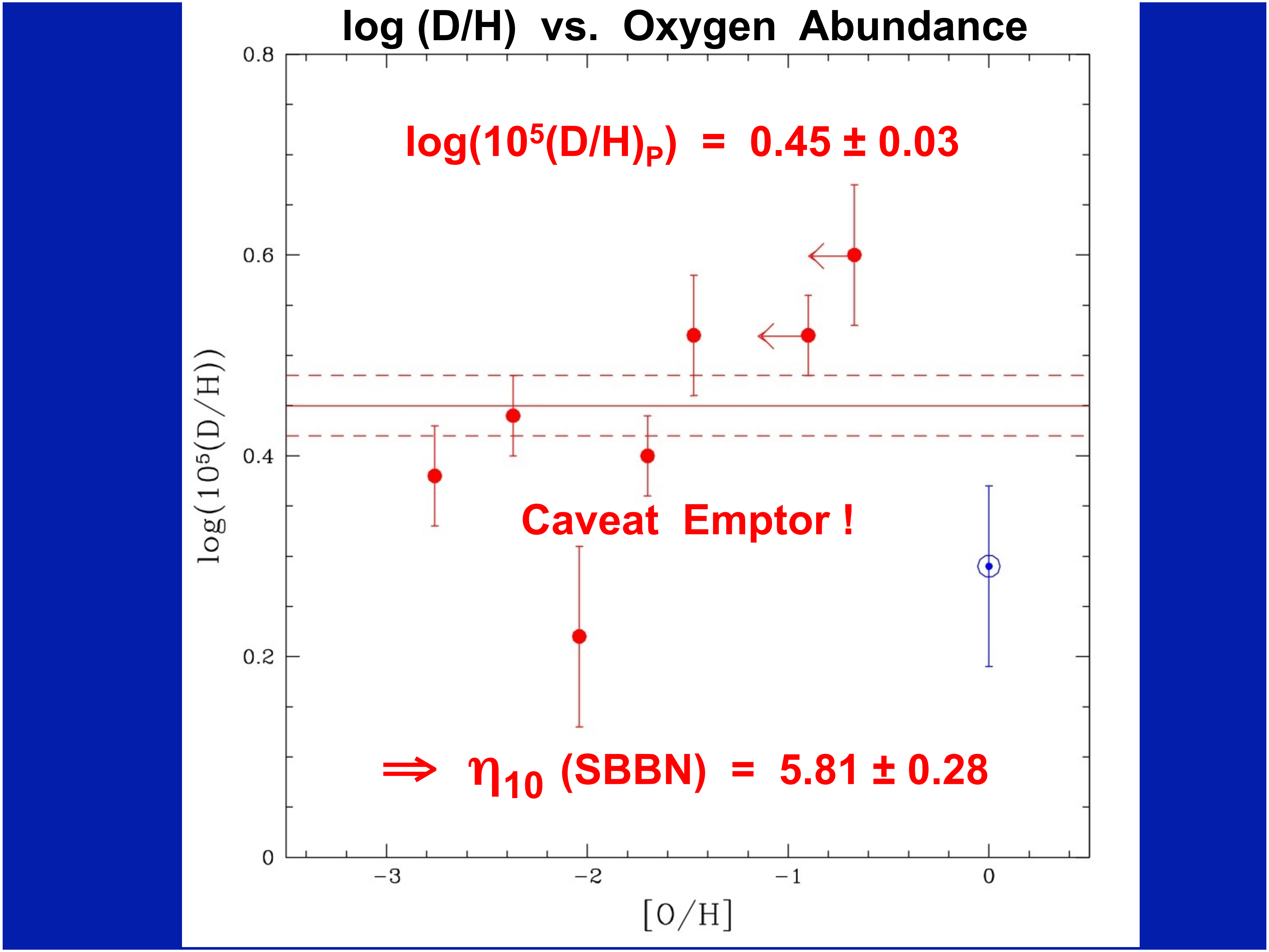
  * For $Z \ll Z_{\odot}$: $(D/H)_t \longrightarrow (D/H)_P$ (Deuterium Plateau)

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

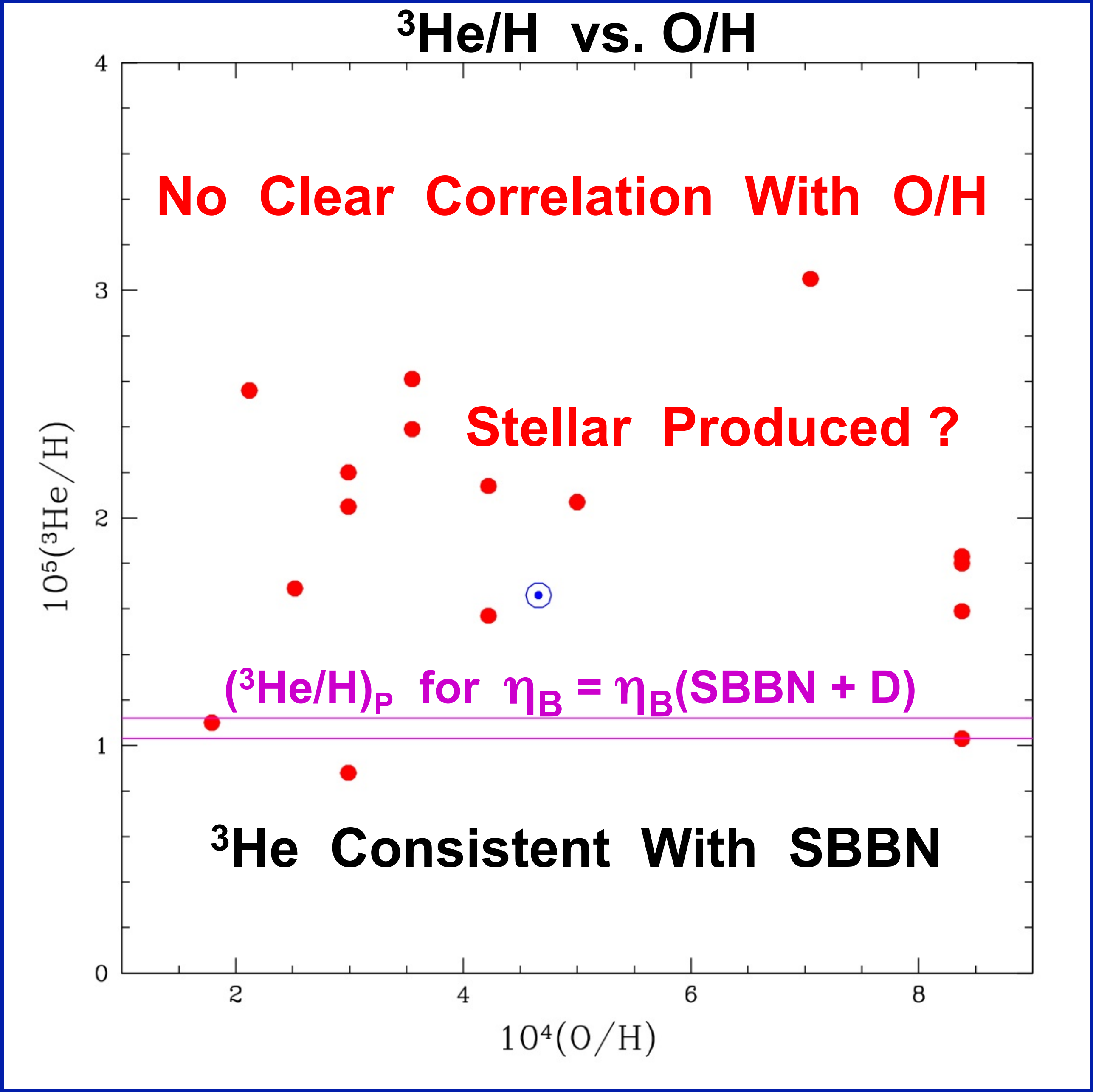
- H I and D I are observed in Absorption in High – z, Low – Z, QSO Absorption Line Systems (QSOALS)

log (D/H) vs. Oxygen Abundance

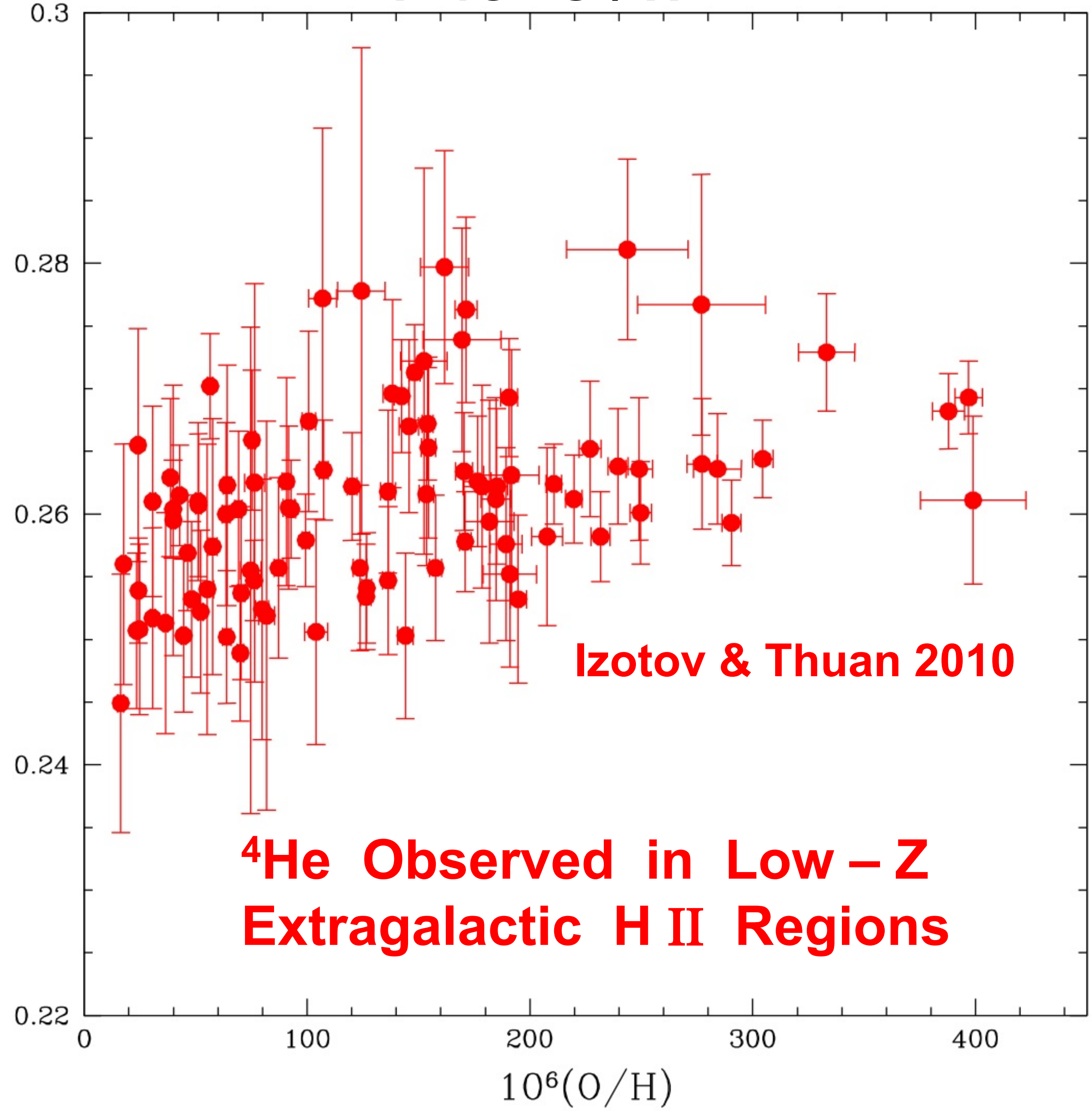


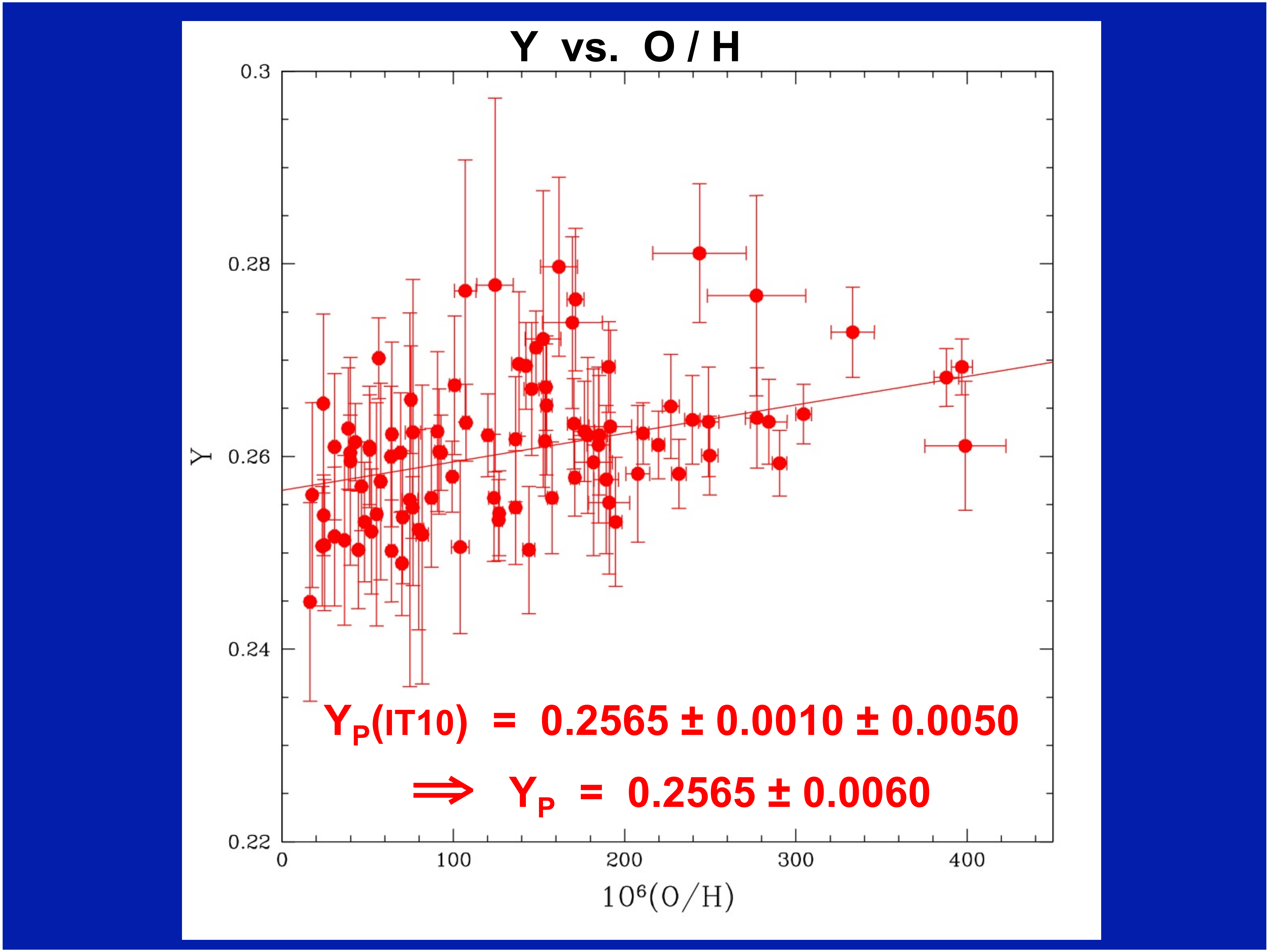

log (D/H) vs. Oxygen Abundance
log(10^5(D/H)_P) = 0.45 ± 0.03
Caveat Emptor !
⇒ η10 (SBBN) = 5.81 ± 0.28
0.8
0.6
0.4
0.2
0
−3
−2
−1
0
log(10^5(D/H))
[O/H]

^{3}He Observed In Galactic H II Regions



Y vs. O / H


0.3
0.28
0.26
0.24
0.22
Y
0
100
200
300
400
10⁶(O/H)
Izotov & Thuan 2010
⁴He Observed in Low – Z
Extragalactic H II Regions


Y vs. O / H
0.3
0.28
0.26
0.24
0.22
Y
0
100
200
300
400
10⁶(O/H)
Y_P(IT10) = 0.2565 ± 0.0010 ± 0.0050
⟹ Y_P = 0.2565 ± 0.0060

For SBBN (N_ν = 3)

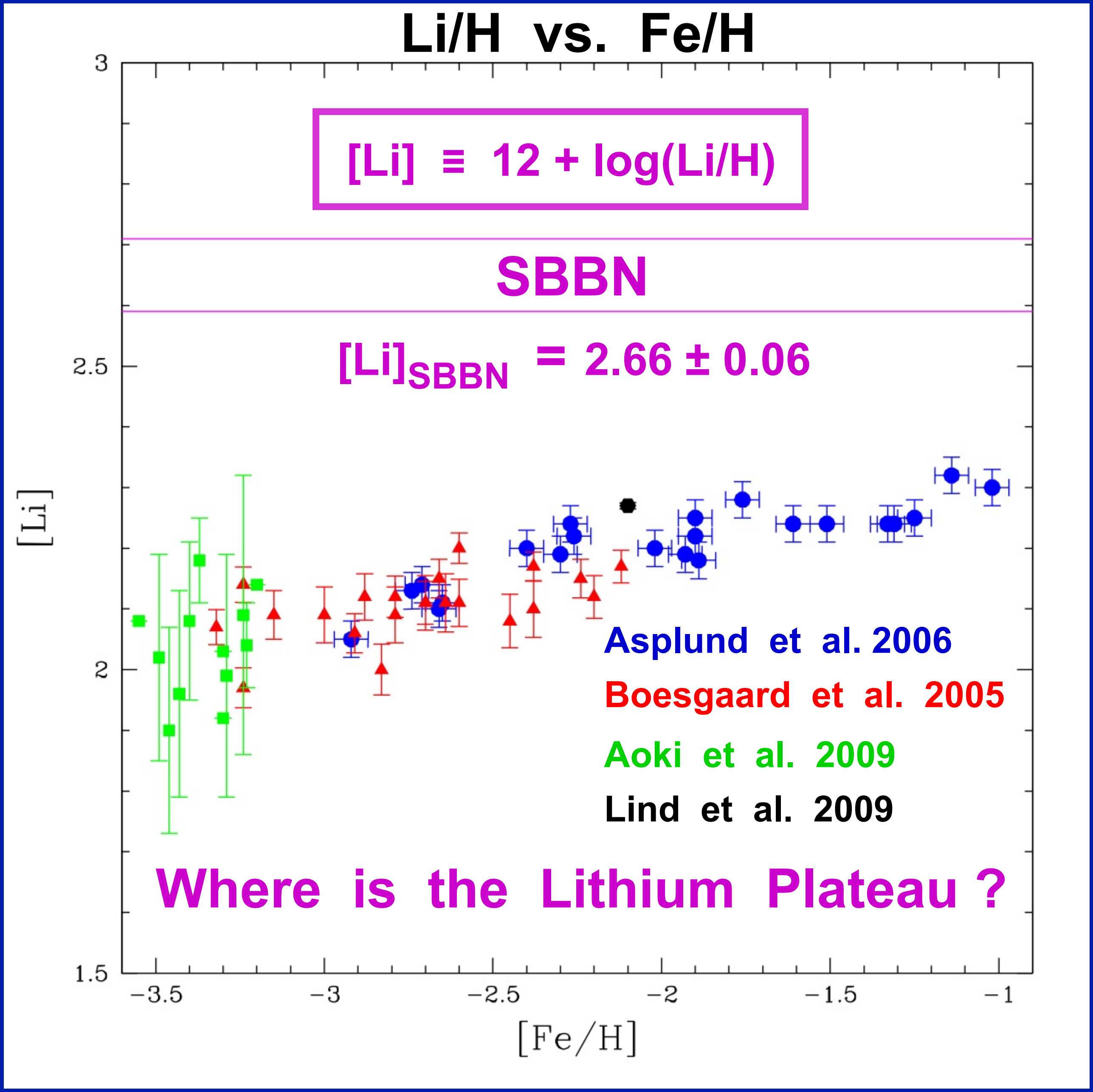
If : $5 + \log(D/H)_P = 0.45 \pm 0.03 \Longrightarrow$

$\eta_{10} = 5.81 \pm 0.28 \Longrightarrow Y_P = 0.2482 \pm 0.0005$

$Y_P(OBS) - Y_P(SBBN) = 0.0083 \pm 0.0060$

$\Longrightarrow Y_P(OBS) = Y_P(SBBN)$ @ $\sim 1.4\,\sigma$

But ! Lithium – 7 Is A Problem



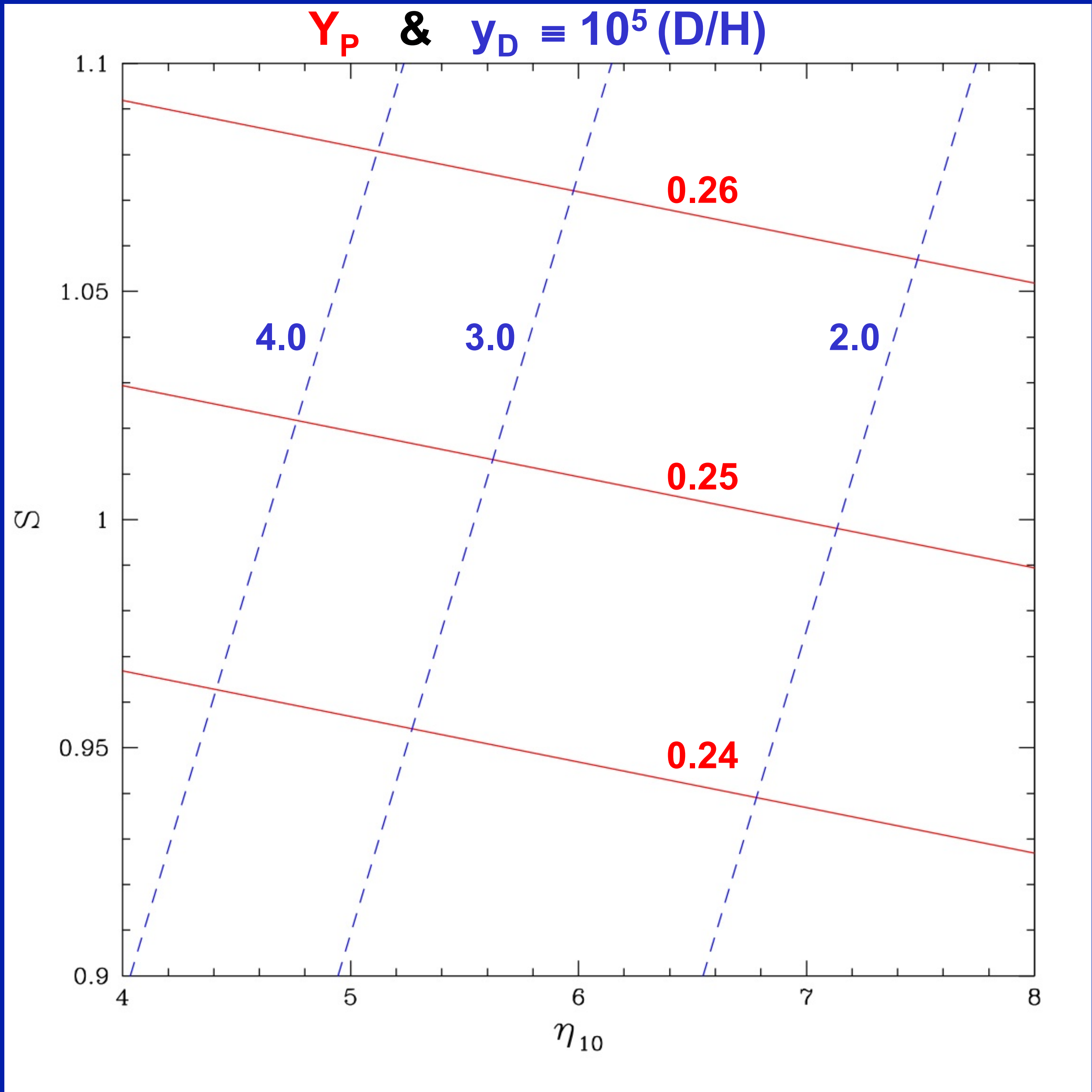
SBBN Predictions Agree With Observations Of

D, ^{3}He, ^{4}He, But NOT With ^{7}Li

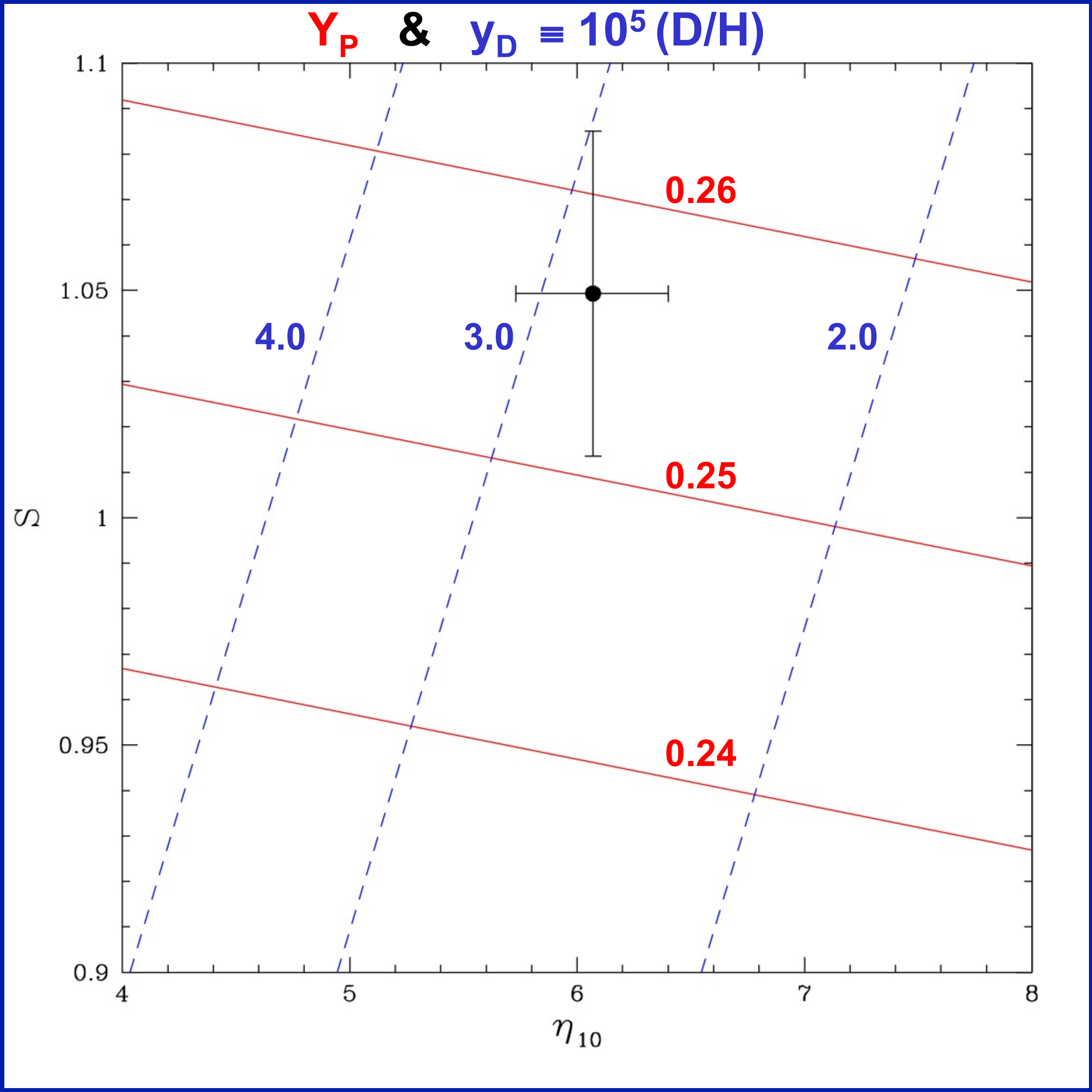
For BBN (with η_{10} & N_ν (S) as free parameters)

BBN Abundances Are Functions of η_{10} & S

Isoabundance Contours for $10^5(D/H)_P$ & Y_P



Isoabundance Contours for $10^5(D/H)_P$ & Y_P

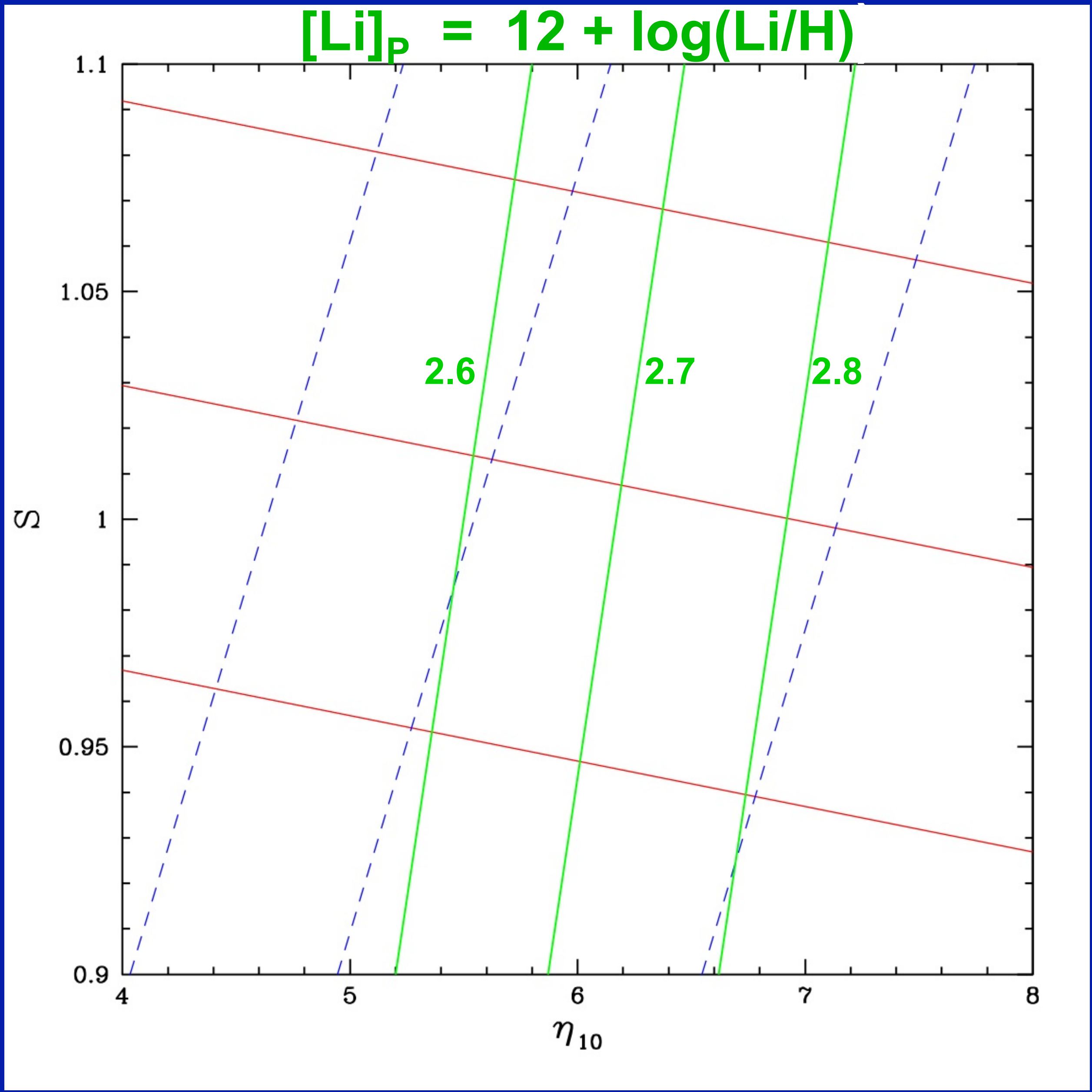


$$5 + \log(D/H)_P = 0.45 \pm 0.03 \;\; \& \;\; Y_P = 0.2565 \pm 0.0060$$

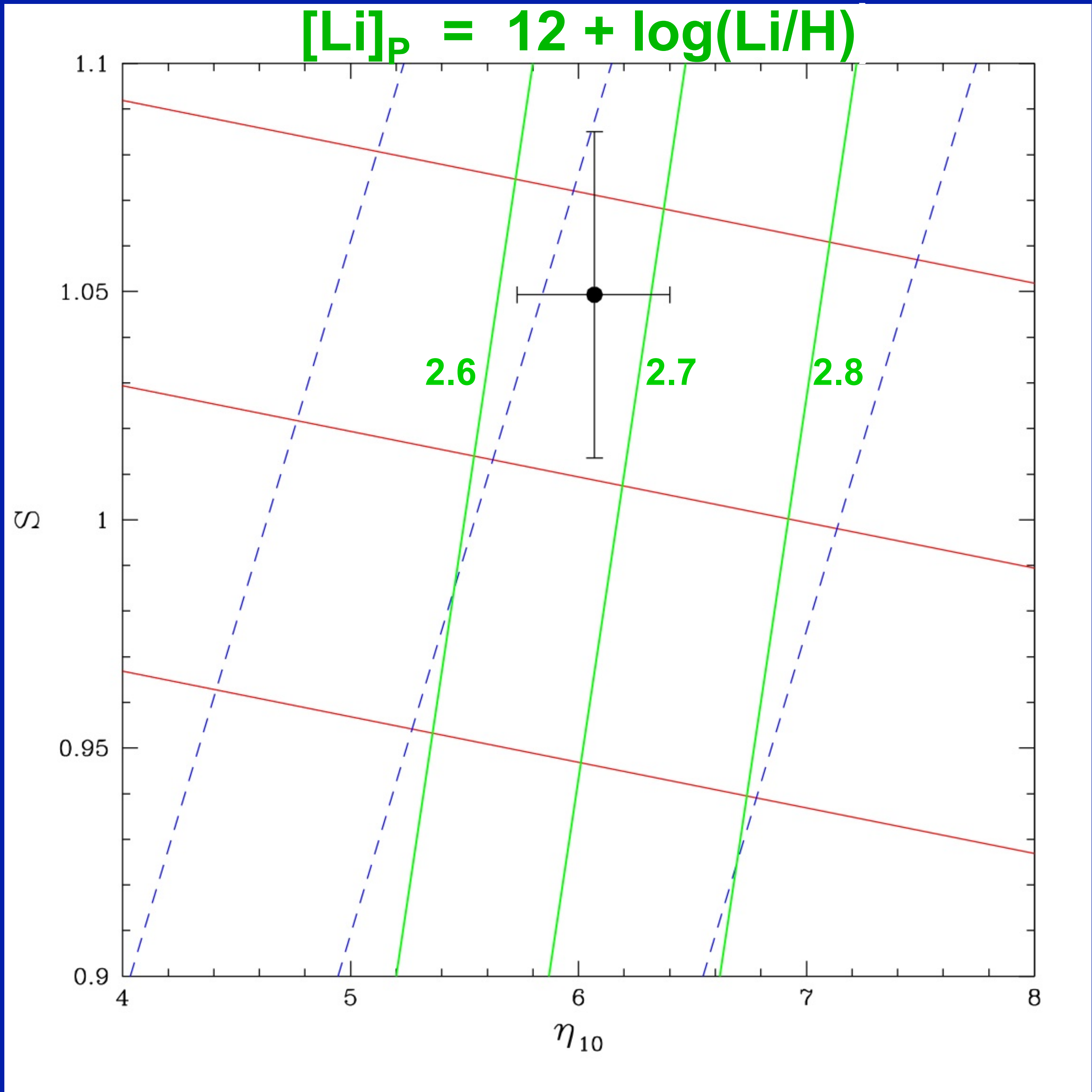
$$\Rightarrow \eta_{10} = 6.07 \pm 0.34 \;\; \& \;\; N_\nu = 3.62 \pm 0.46$$

$$\Rightarrow N_\nu = 3 \;\; @ \sim 1.3\,\sigma$$

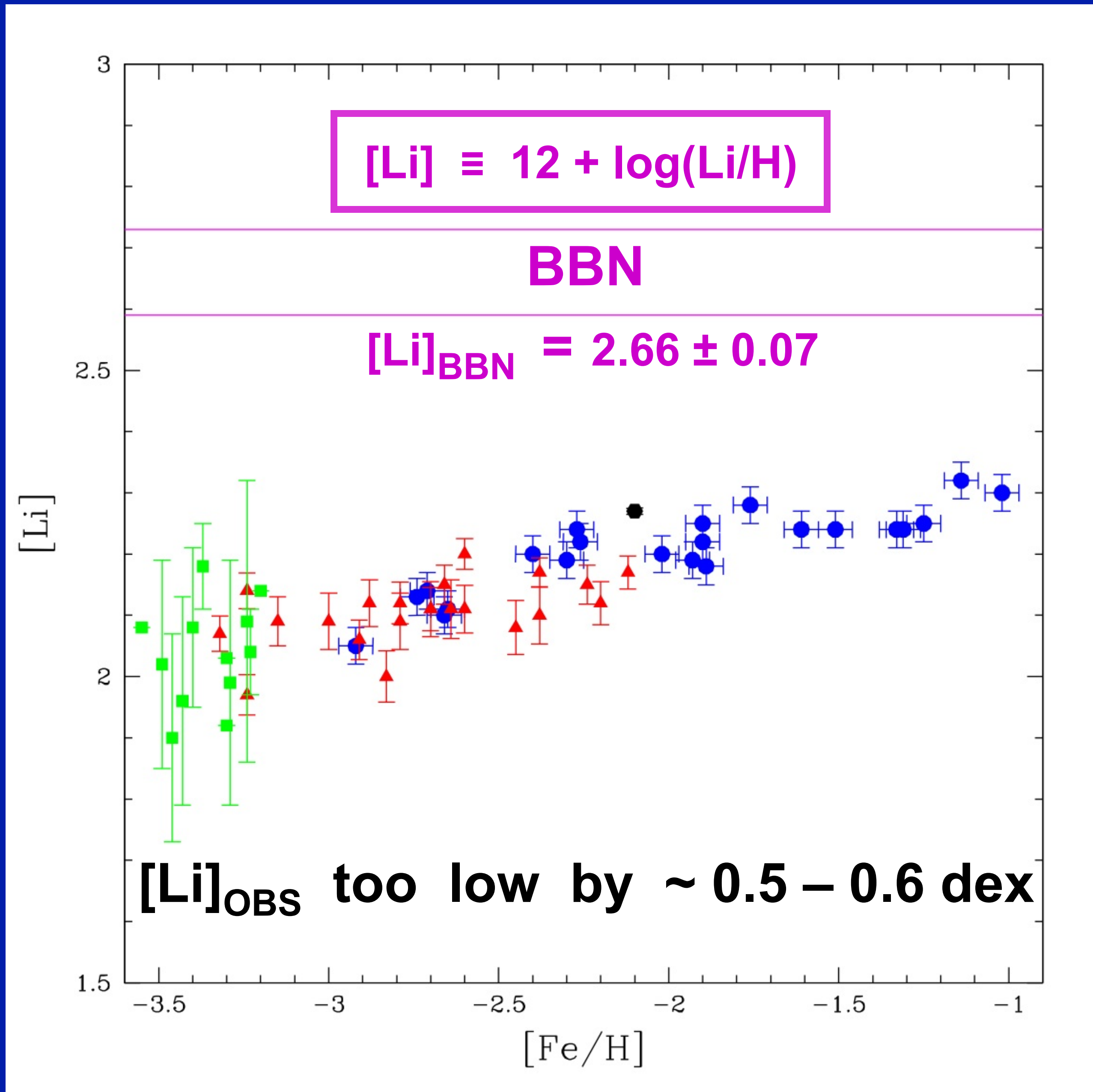
Lithium Isoabundance Contours



Even for $N_\nu \neq 3$, $[Li]_P > 2.6$



Lithium – 7 Is STILL A Problem



CMB Temperature Anisotropy Spectrum Depends On The Baryon Density

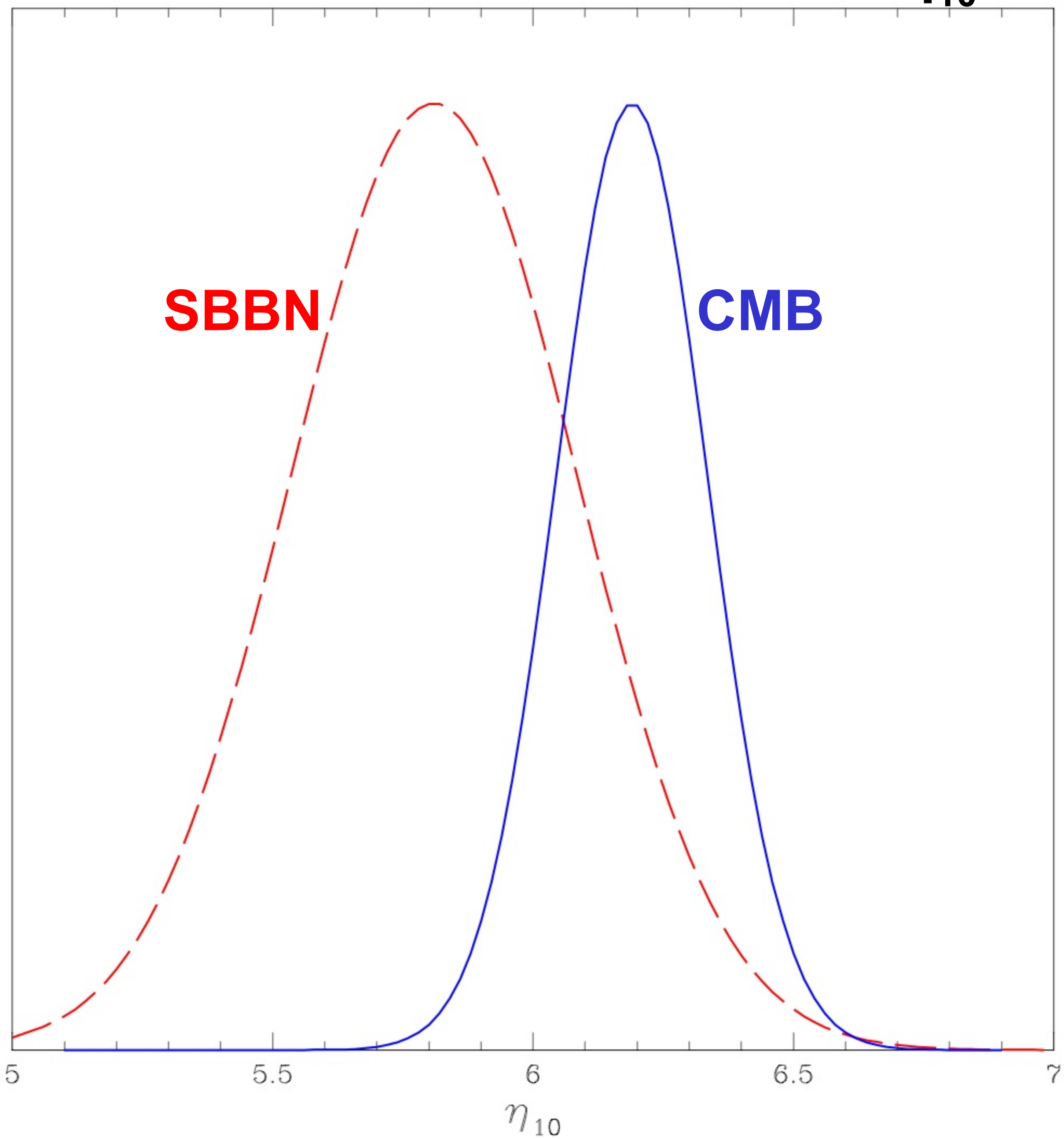
η_{10} (CMB) = 6.190 ± 0.145 (Komatsu et al. 2010)

For N_ν = 3, is η_B (CMB) = η_B (SBBN) ?

η_{10} (SBBN) = 5.81 ± 0.28

SBBN & CMB Agree Within ~ 1.2 σ

Likelihood Distributions For η_{10}



At <u>BBN</u>, With η_{10} & N_ν As Free Parameters

$$\eta_{10}(BBN) = 6.07 \pm 0.34$$

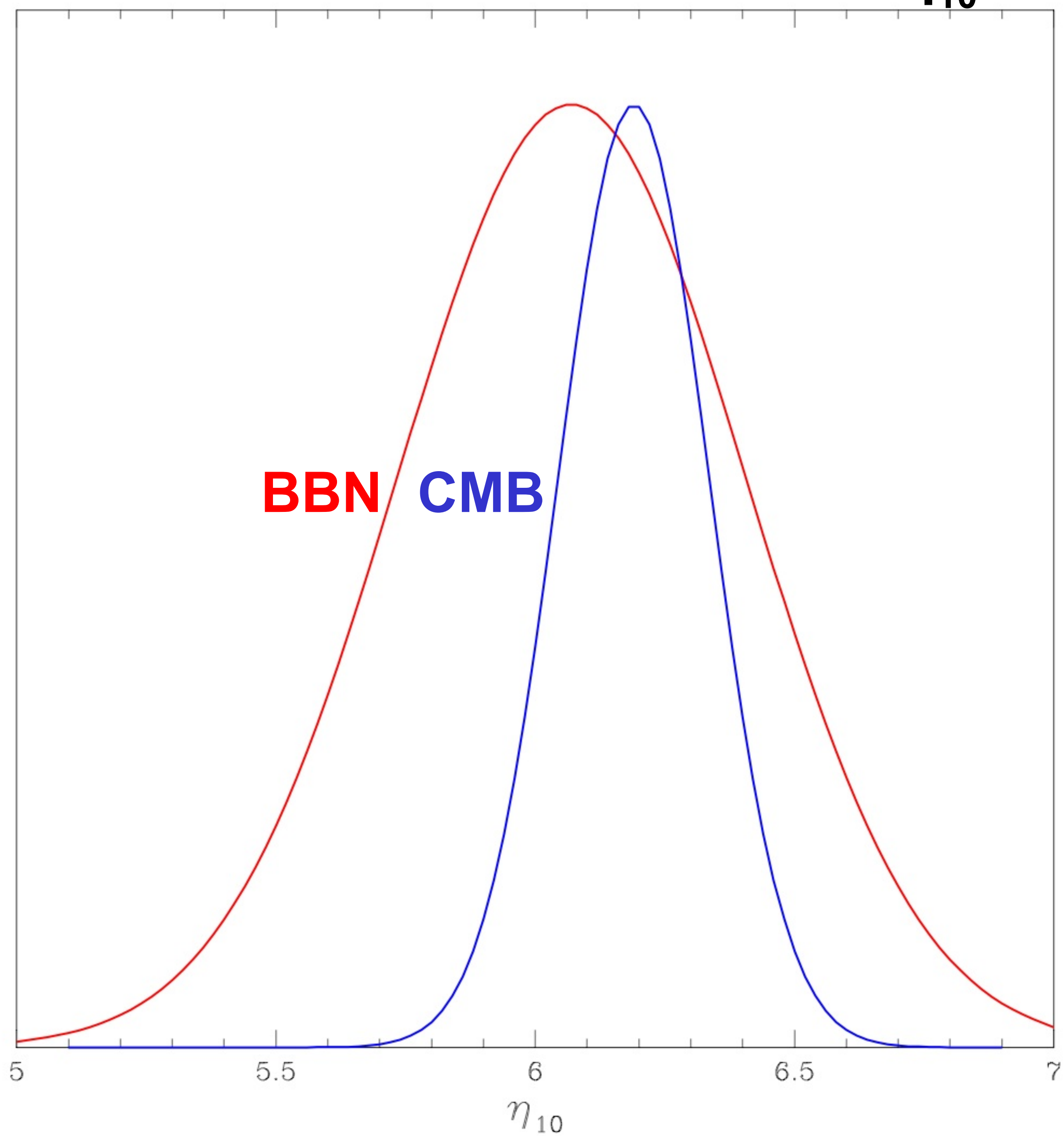
At <u>REC</u>, With CMB (WMAP 7 Year Data) + LSS

$$\eta_{10}(REC) = 6.190 \pm 0.145$$

$\eta_{10}(BBN)$ & $\eta_{10}(REC)$ Agree

$$\Rightarrow \quad \eta_{10}(REC) - \eta_{10}(BBN) = 0.12 \pm 0.37$$

Likelihood Distributions For η_{10}



At BBN, With η_{10} & N_ν As Free Parameters

N_ν(BBN) = 3.62 ± 0.46 ⇒ N_ν(BBN) = 3 @ ~ 1.3 σ

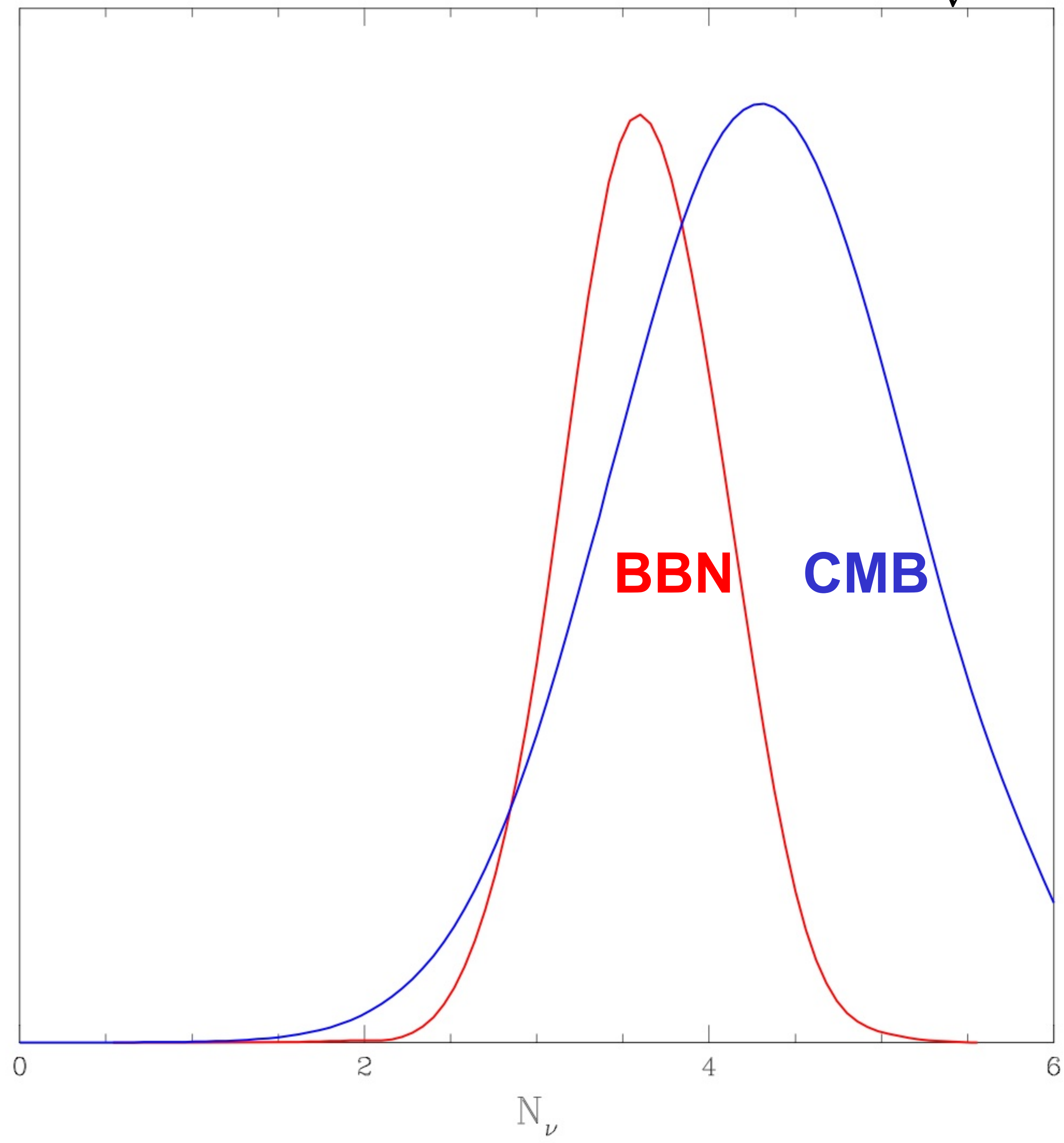
At REC, With CMB (WMAP 7 Year Data) + LSS

N_ν(REC) = 4.30 ± 0.87 ⇒ N_ν(REC) = 3 @ ~ 1.5 σ

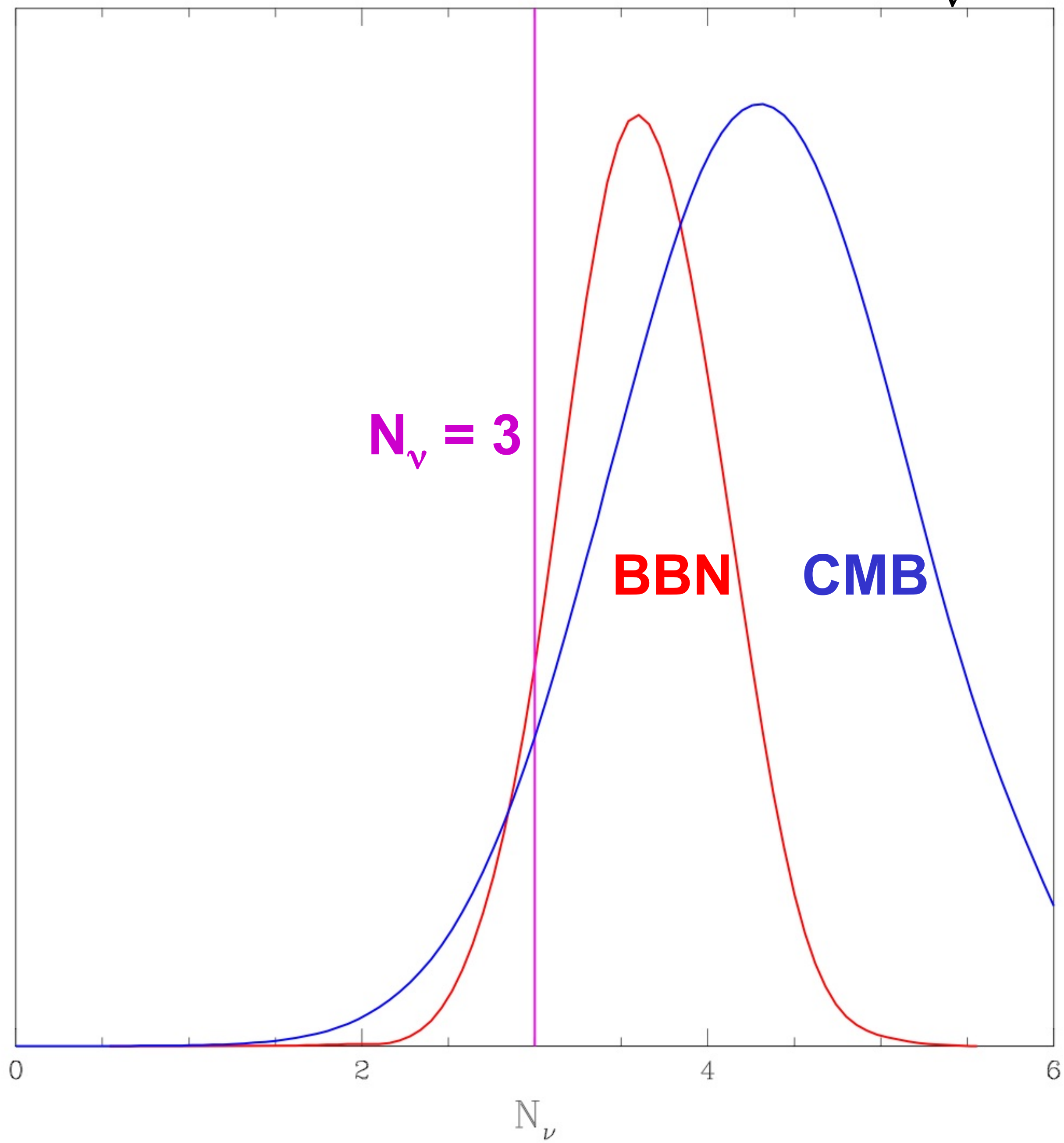
N_ν(BBN) & N_ν(REC) Agree

⇒ N_ν(REC) – N_ν(BBN) = 0.68 ± 0.98

Likelihood Distributions For N_ν



Likelihood Distributions For N_ν



CONCLUSION # 1

<u>SBBN</u> <u>IS</u> Consistent With D, ^3He, ^4He

<u>And</u> Agrees With The CMB + LSS + H_0

(<u>But</u> , Lithium Is A Problem !)

- Li depleted / diluted in Pop II Stars ?
- Post – BBN Decay of Massive Particles ?
- Annihilation of Dark Matter Relics ?

CONCLUSION # 2

Non - standard BBN ($N_\nu \neq 3$, $S \neq 1$) With

$\eta_{10} = 6.07 \pm 0.34$ & $N_\nu = 3.62 \pm 0.46$

IS Consistent With D, ^{3}He, & ^{4}He

And With The CMB + LSS (But, ^{7}Li ?)

BBN + CMB Combined Can Constrain

Non-standard Cosmology & Particle Physics

Comparing BBN And The CMB

Entropy (CMB Photon) Conservation

* In a comoving volume, $N_\gamma = N_B / \eta_B$
* For conserved baryons, N_B = constant
* Comparing η_B at BBN and at Recombination

$\Rightarrow N_\gamma(\text{REC}) / N_\gamma(\text{SBBN}) = 0.94 \pm 0.05$

$\Rightarrow N_\gamma(\text{REC}) / N_\gamma(\text{BBN}) = 0.98 \pm 0.06$

Variation of the Gravitational Constant Between BBN, Recombination, and Today ?

$$G' / G = S^2 = 1 + 7\Delta N_\nu / 43$$

$$G(\text{BBN}) / G_0 = 1.10 \pm 0.08$$

$$G(\text{REC}) / G_0 = 1.21 \pm 0.14$$

"Extra" Radiation Density ?

Example : Late decay of a massive particle

Recall that : $\rho'_R / \rho_R = S^2 \equiv 1 + 7\Delta N_\nu / 43$

In the absence of the creation of new radiation (via decay ?), $S\,(\mathrm{BBN}) = S\,(\mathrm{REC})$

Comparing N_ν at BBN and at Recombination

$$\Rightarrow \quad N_\nu(\mathrm{REC}) - N_\nu(\mathrm{BBN}) = 0.68 \pm 0.98$$

CONCLUSIONS

For $N_\nu \approx 3$, BBN (D, ^3He, ^4He)

Agrees With The CMB + LSS

(But , Lithium Is A Problem !)

BBN + CMB + LSS Constrain

Cosmology & Particle Physics

CHALLENGES

- Why is the spread in D abundances so large ?

- Why is $^3He/H$ uncorrelated with O/H and / or R ?

- What (how big) are the systematic errors in Y_P ?
  Are there observing strategies to reduce them ?

- What is the primordial abundance of ^7Li (^6Li) ?

★ We (theorists) need more (better) data !