PRIMORDIAL NUCLEOSYNTHESIS : A COSMOLOGICAL PROBE

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Baryon Density Parameter : η_B

Note : Baryons ≡ Nucleons

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

Hubble Parameter : H = H(z)

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

Expansion Rate Parameter : S

S is a Probe of Non - Standard Physics

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

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

- $S \Leftrightarrow N_\nu$

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

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

“Standard” Big Bang Nucleosynthesis (SBBN)

An Expanding Universe Described By General Relativity, Filled With Radiation, Including [3] Flavors Of Light Neutrinos ($N_\nu = 3$)

The relic abundances of D, ^{3}He, ^{4}He, ^{7}Li are predicted as a function of only one parameter :

*** The baryon to photon ratio : η_B**

Big Bang Nucleosynthesis (BBN)

An Expanding Universe Described By

General Relativity, Filled With Radiation,

Including N_ν Flavors Of Light Neutrinos

The relic abundances of D, ^{3}He, ^{4}He, ^{7}Li are

predicted as a function of two parameters :

* The baryon to photon ratio : η_B

* The effective number of neutrinos : N_ν

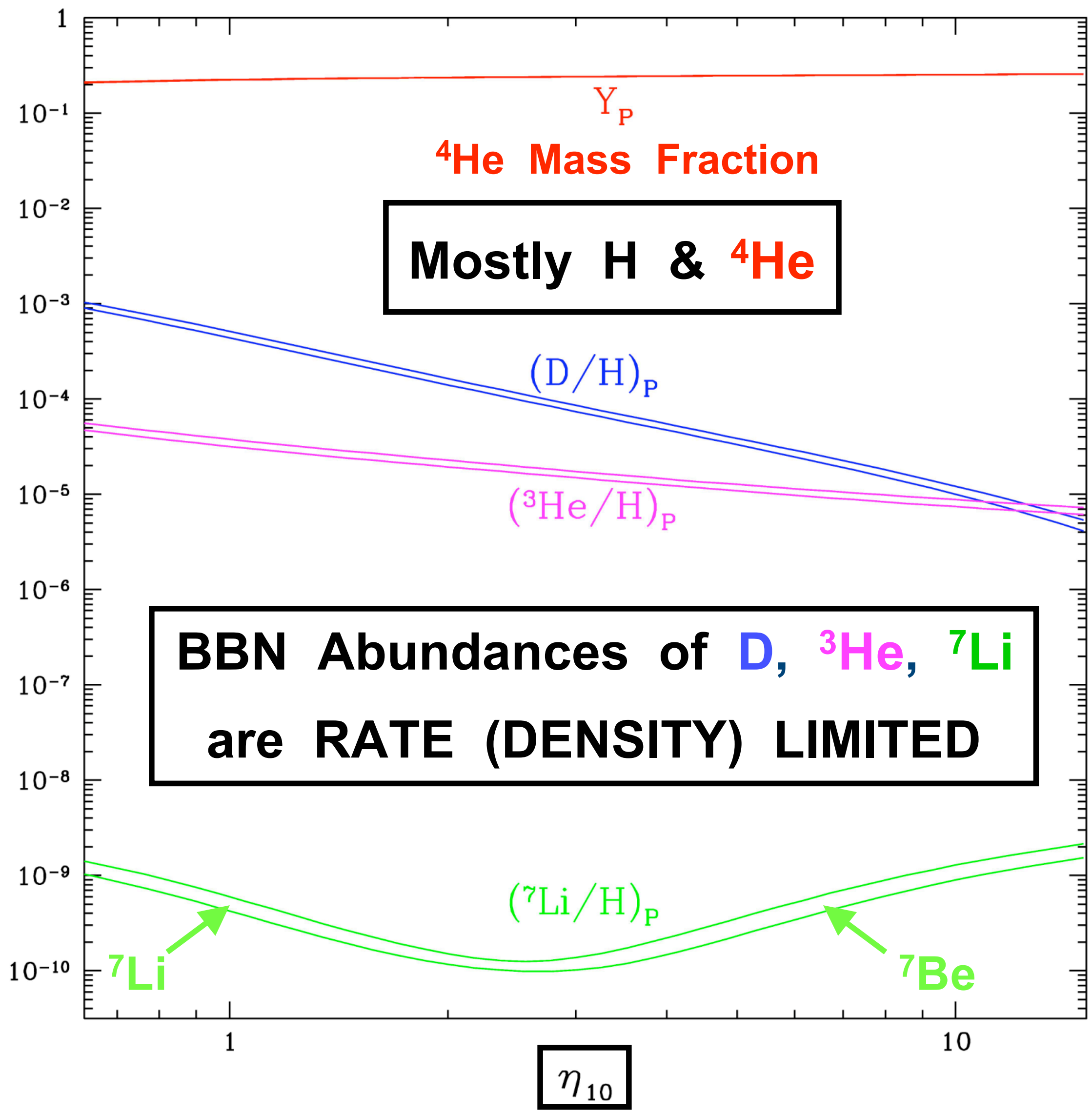
BBN Provides A Key Probe Of The Physics And Early Evolution Of The Universe

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 values of η_B and S (N_ν) agree with independent (non-BBN) observations (e.g., from the CMB and LSS) ?**

SBBN – Predicted Primordial Abundances



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

DEUTERIUM Is The Baryometer Of Choice

- **The Post – BBN Evolution of D is Simple :**
  As the Universe evolves, D is only DESTROYED $\Longrightarrow$

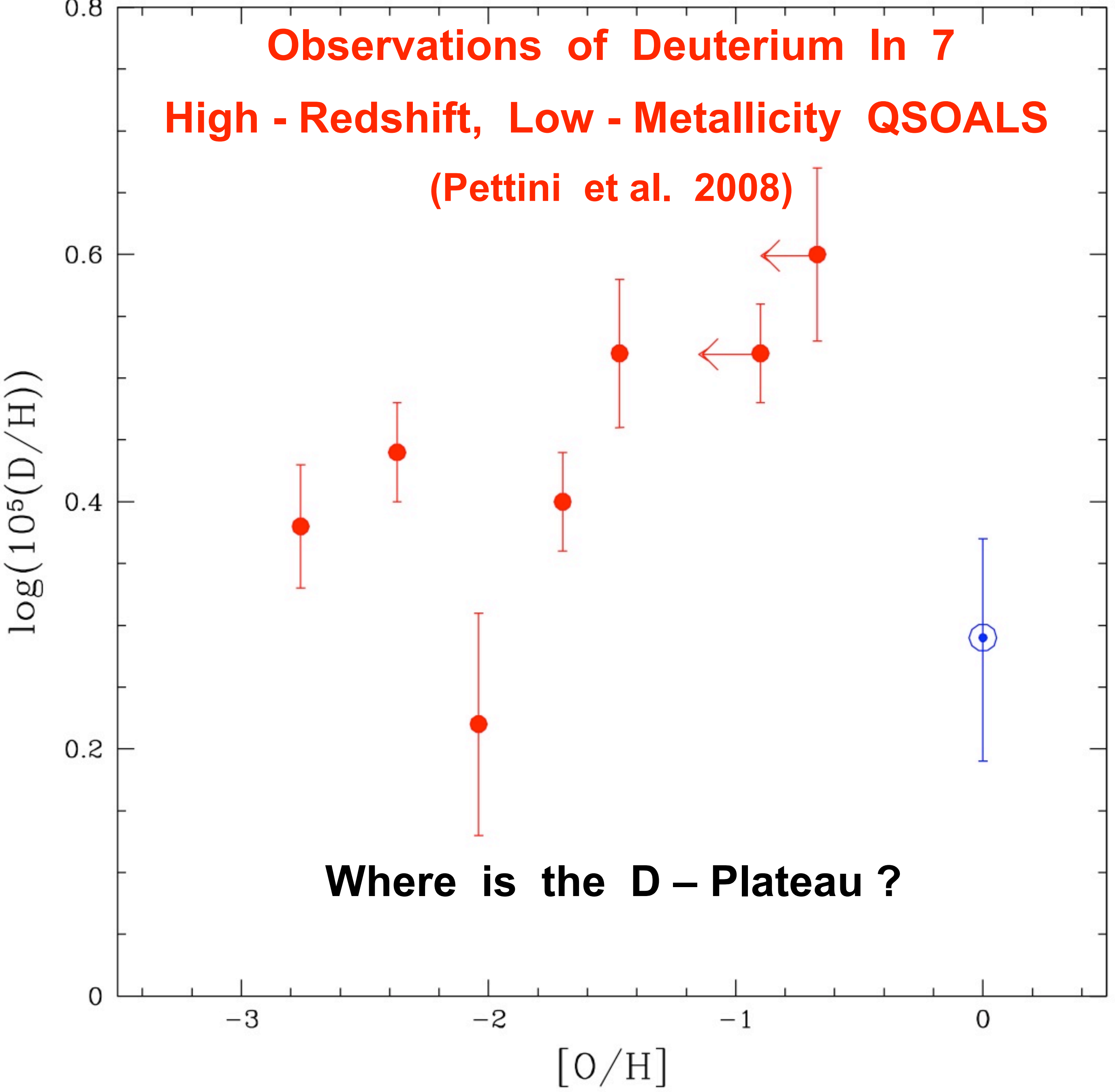
  * **Anywhere, Anytime : $(D/H)_t \leq (D/H)_P$**

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

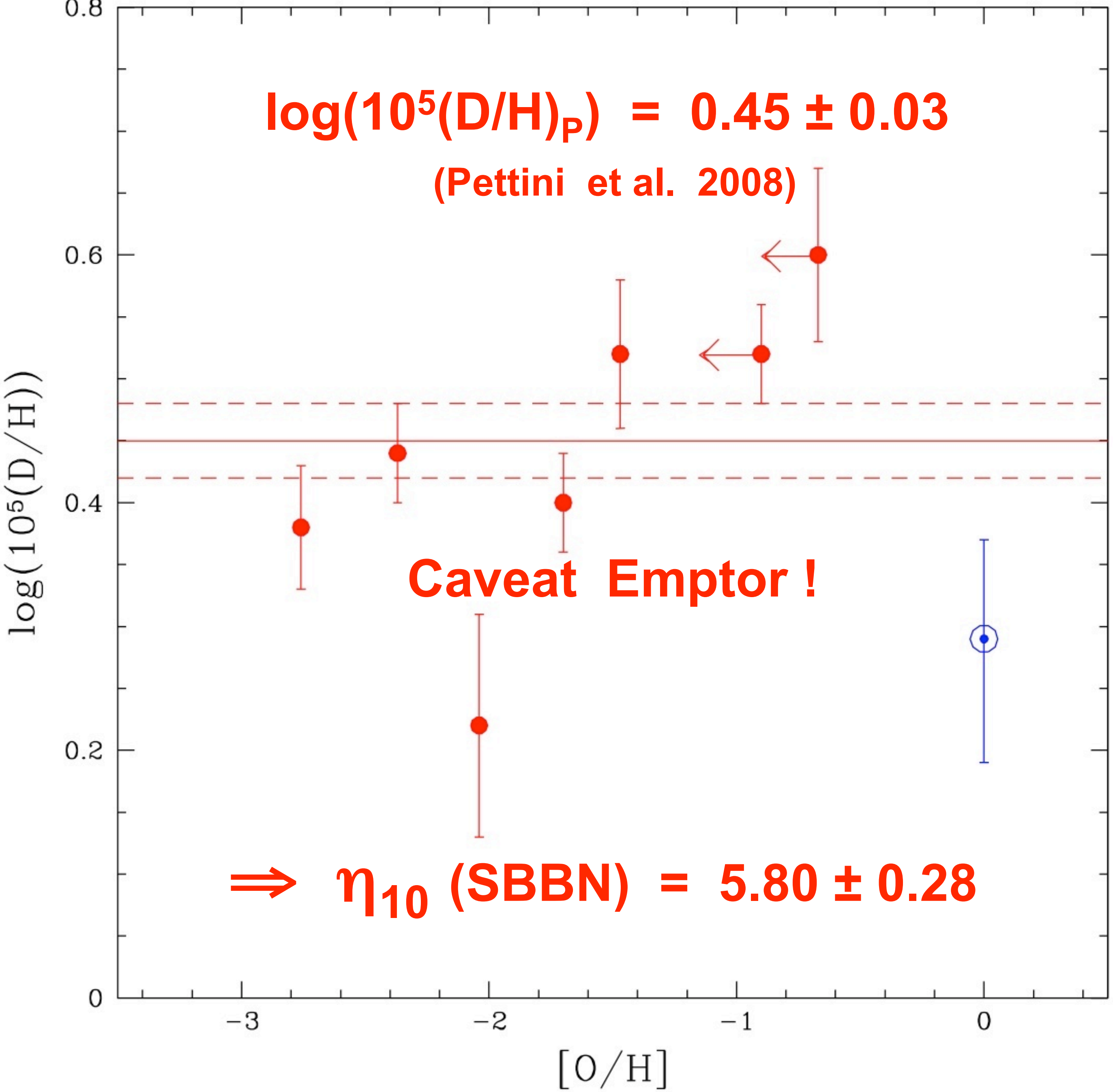
- **$(D/H)_P$ is sensitive to the baryon density ($\propto \eta_B^{-1.6}$)**

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

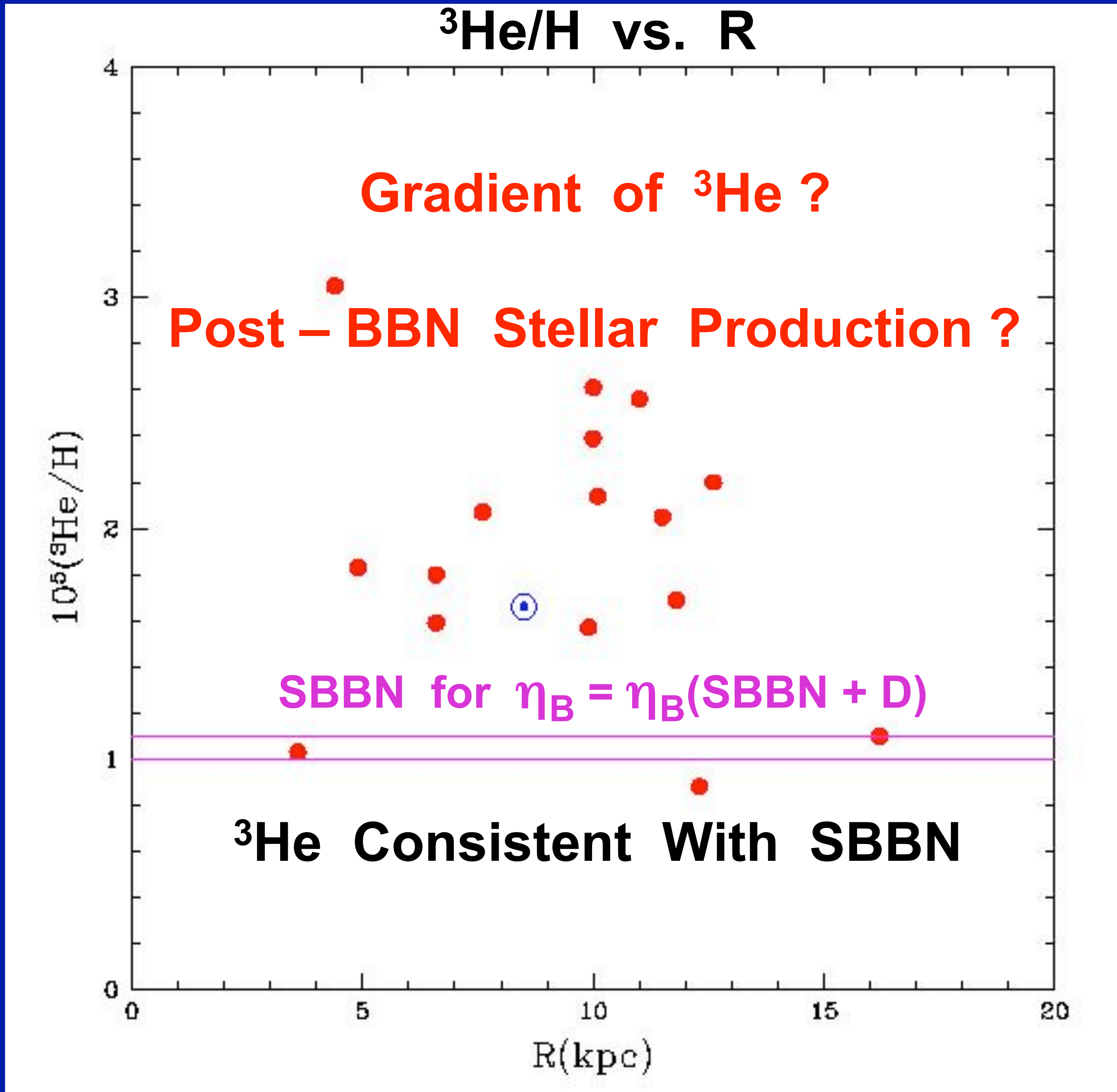
log (D/H) vs. Oxygen Abundance



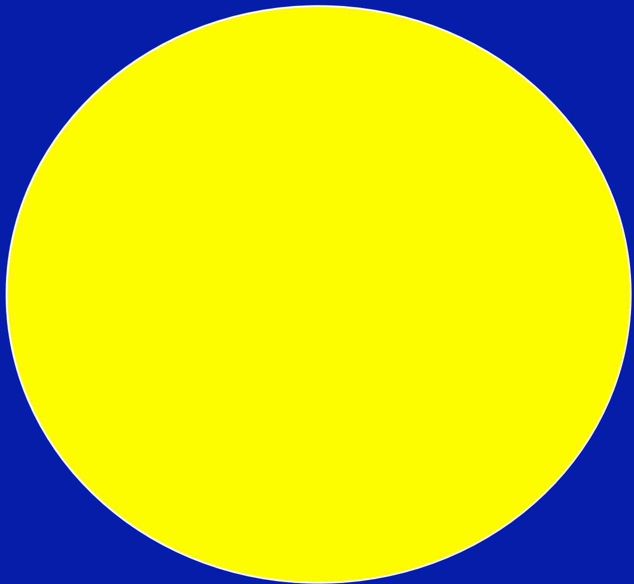
log (D/H) vs. Oxygen Abundance



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



The ^{4}He abundance is measured via H and He recombination lines from metal-poor, extragalactic H II regions (Blue Compact Galaxies).



Theorist's H II Region

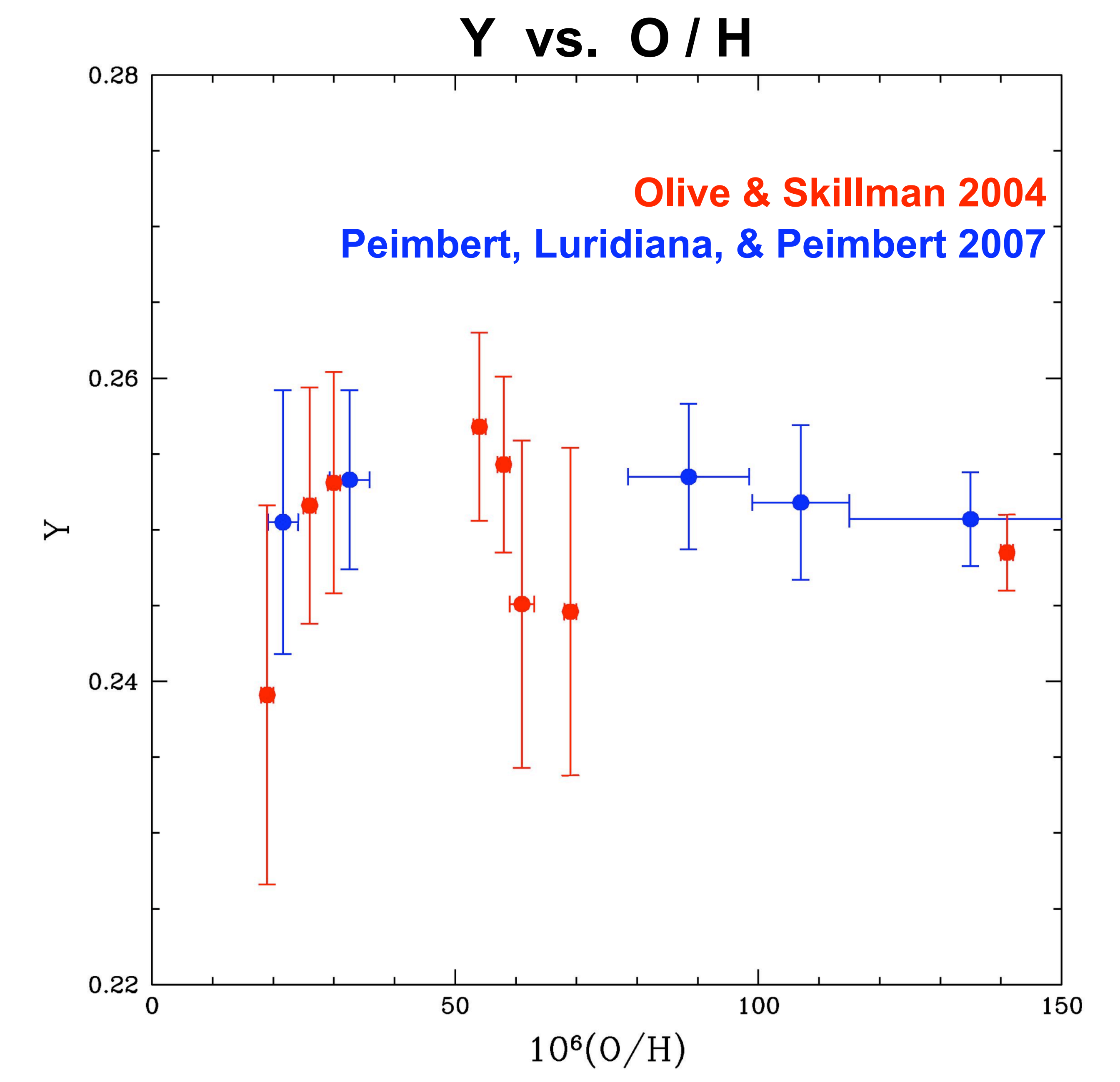
Real H II Region

In determining the primordial helium abundance, systematic errors (underlying stellar absorption, temperature variations, ionization corrections, atomic emissivities, inhomogeneities, ….) dominate over the statistical errors and over the uncertain extrapolation to zero metallicity.

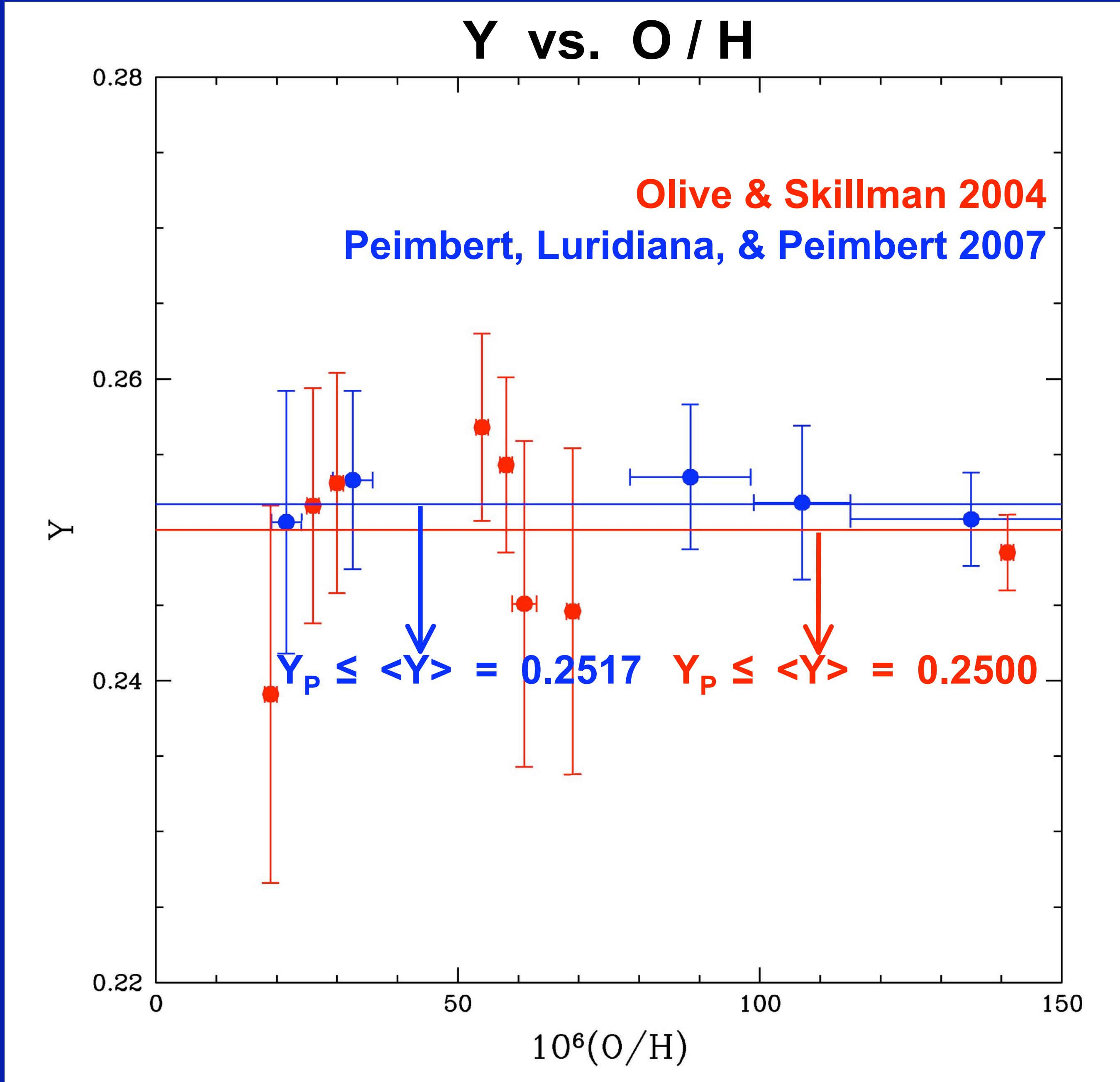
$$\sigma(Y_P) \approx 0.006, \text{ \underline{NOT} } < 0.001 \text{ !}$$

Note : $\Delta Y = (\Delta Y / \Delta Z)\, Z < \sigma(Y_P)$

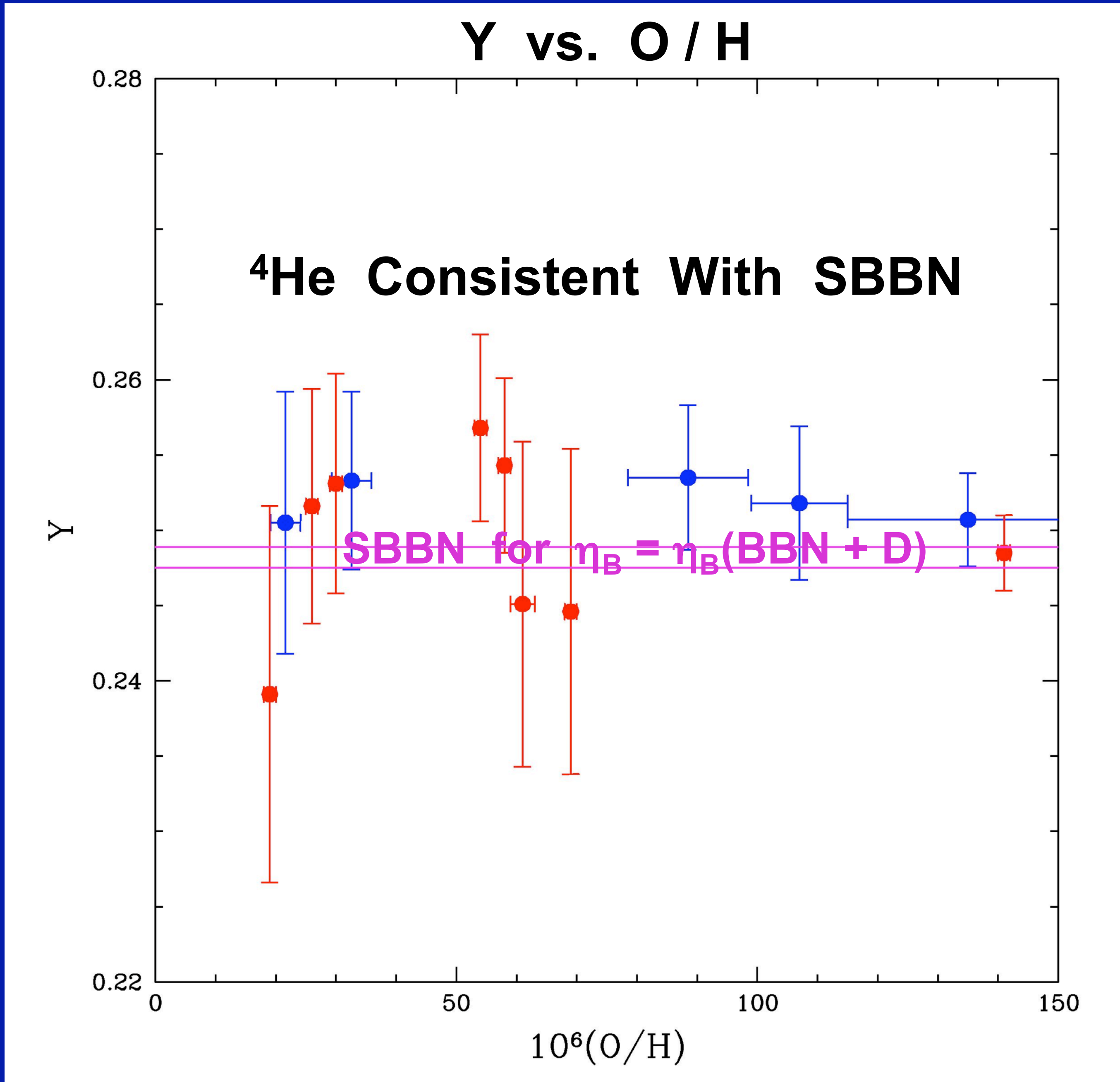
^{4}He (Y) From Low – Z Extragalactic H II Regions



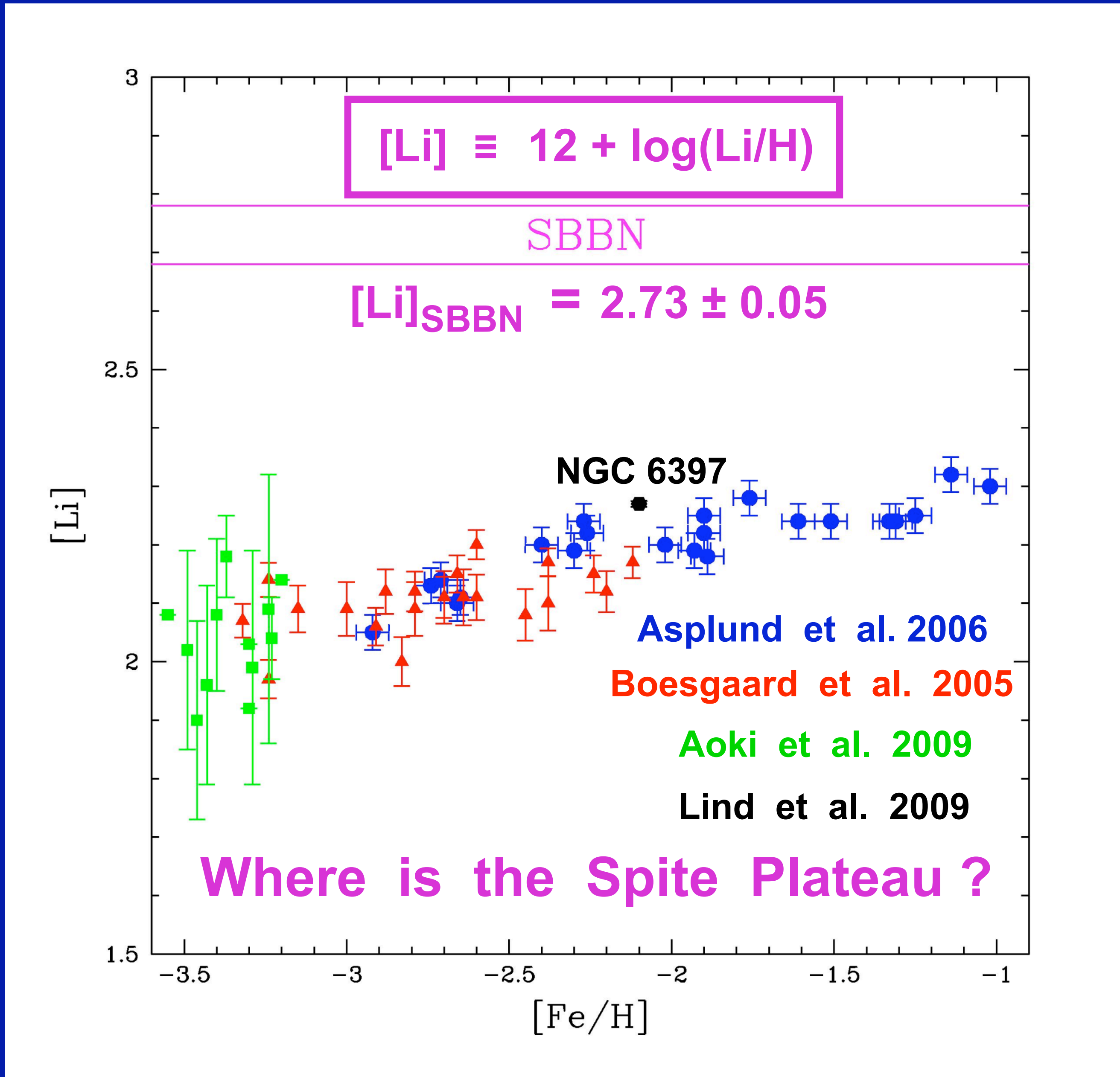
^{4}He (Y) From Low – Z Extragalactic H II Regions



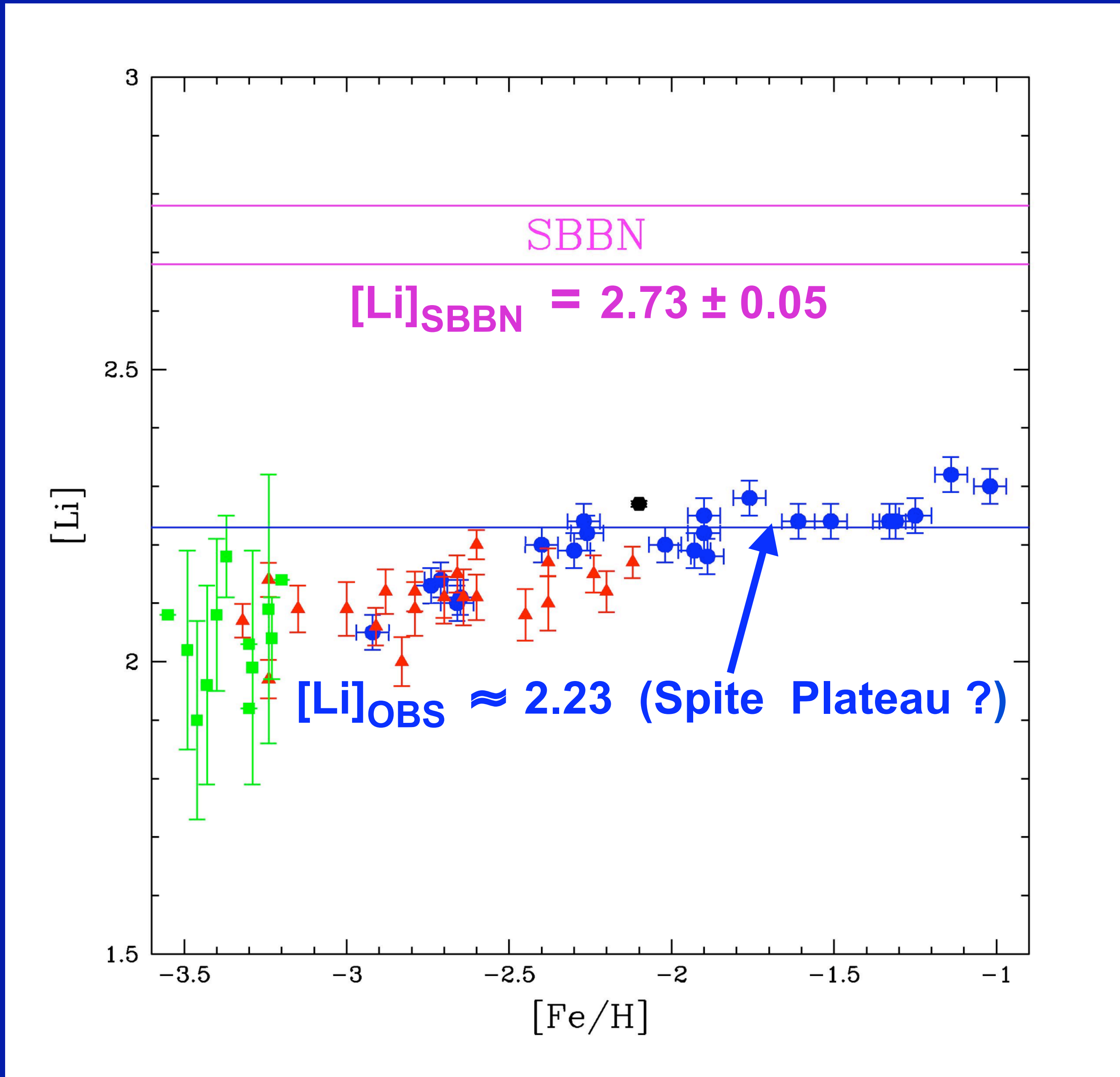
^{4}He (Y) From Low – Z Extragalactic H II Regions



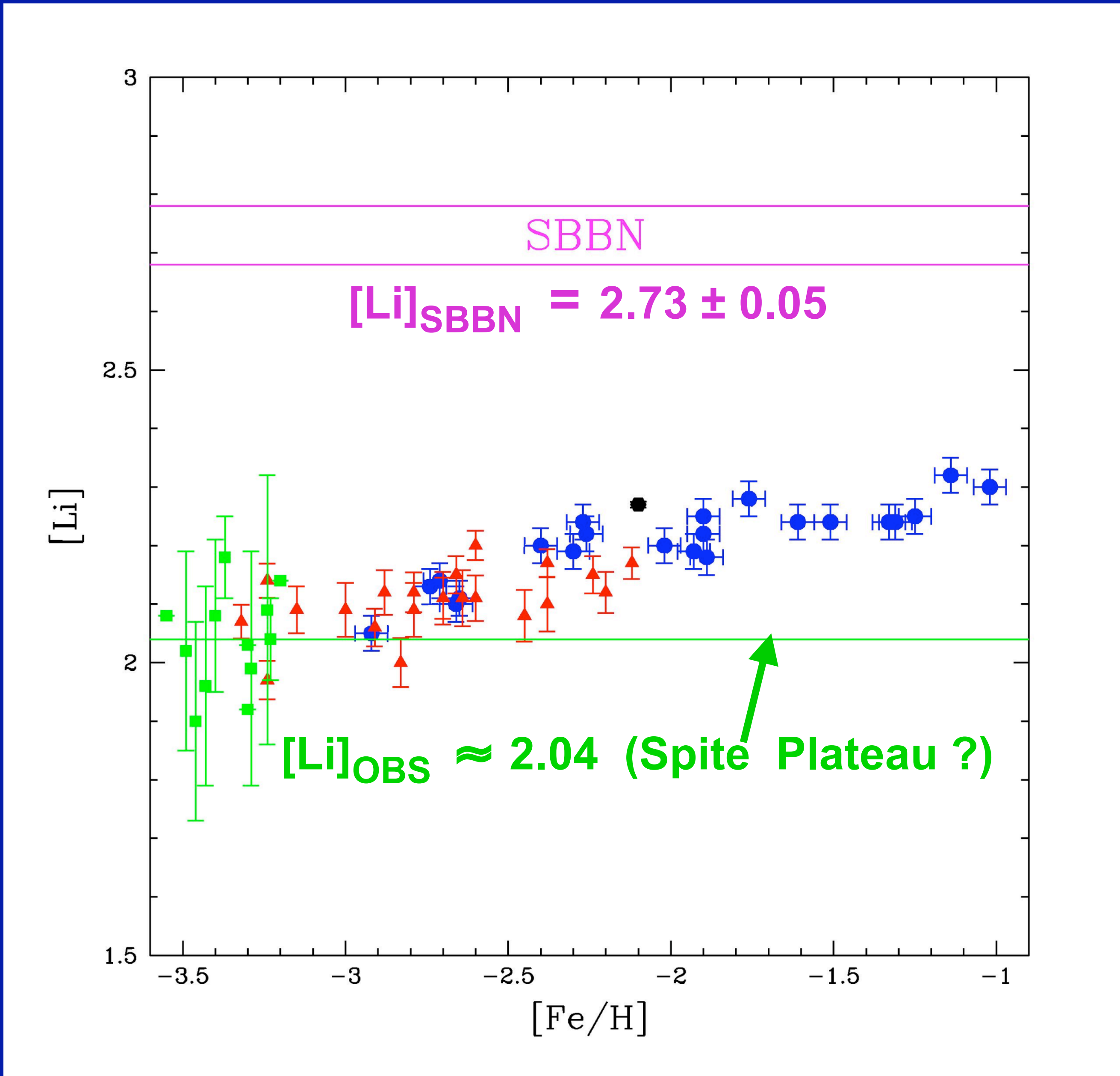
But ! Lithium – 7 Is A Problem



Lithium too low by a factor of ~ 3 !



Lithium too low by a factor of ~ 5 !



CMB Temperature Anisotropy Spectrum Depends On The Baryon Density

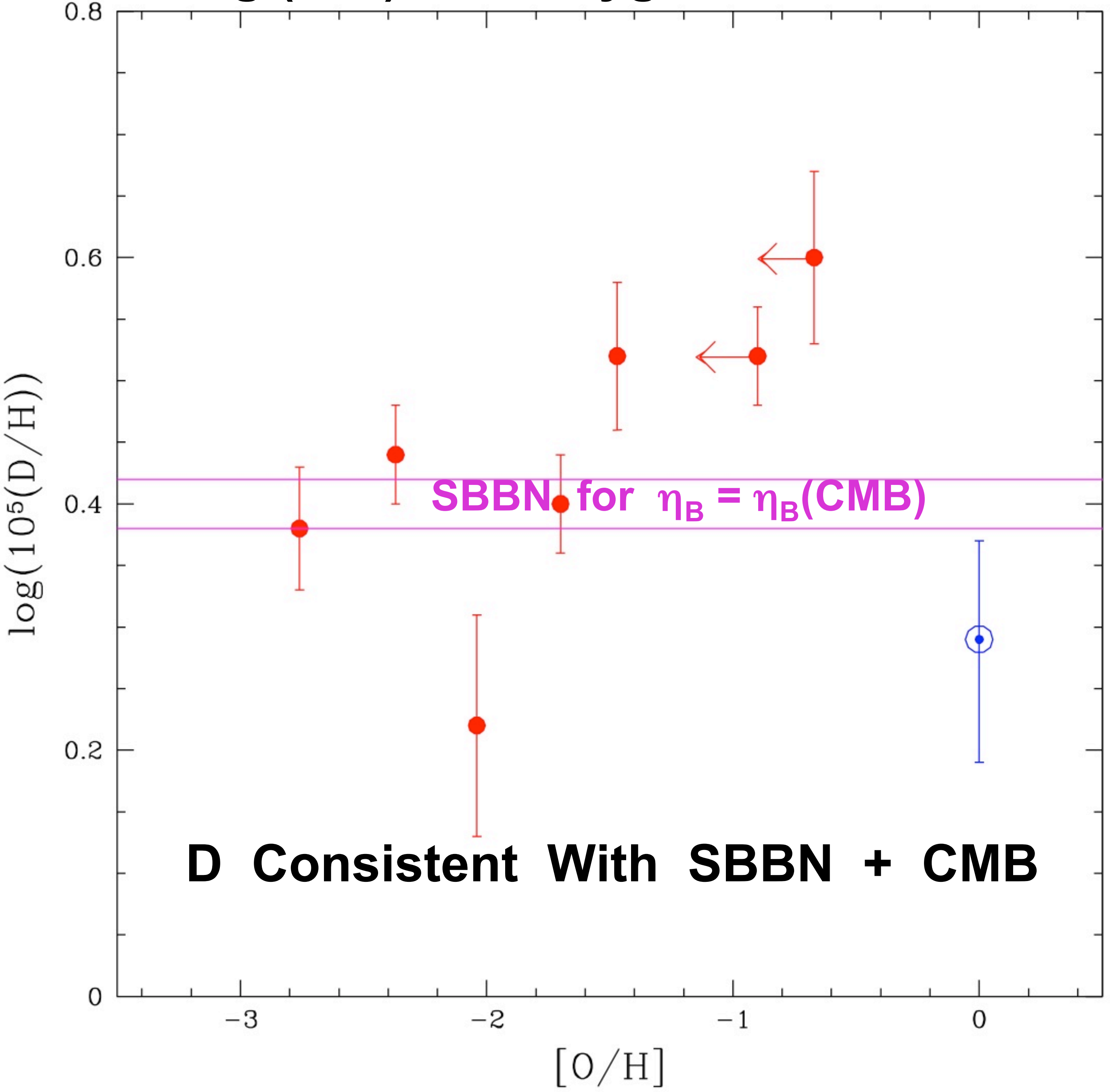
η_{10} (CMB) = 6.22 ± 0.16 (Dunkley et al. 2008)

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

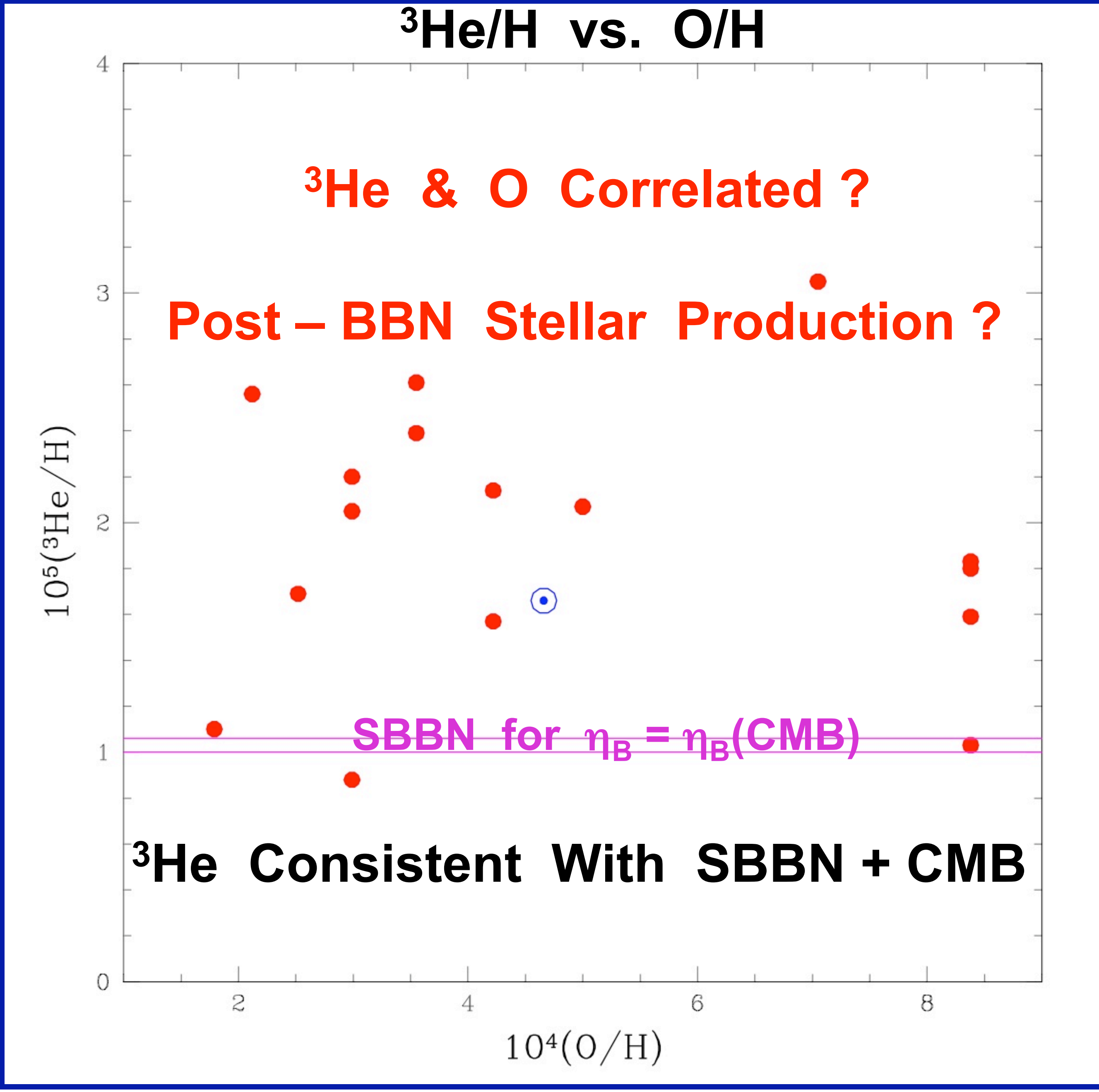
η_{10} (SBBN + $(D/H)_P$) = 5.80 ± 0.28

SBBN & CMB Agree Within ~ 1.5 σ

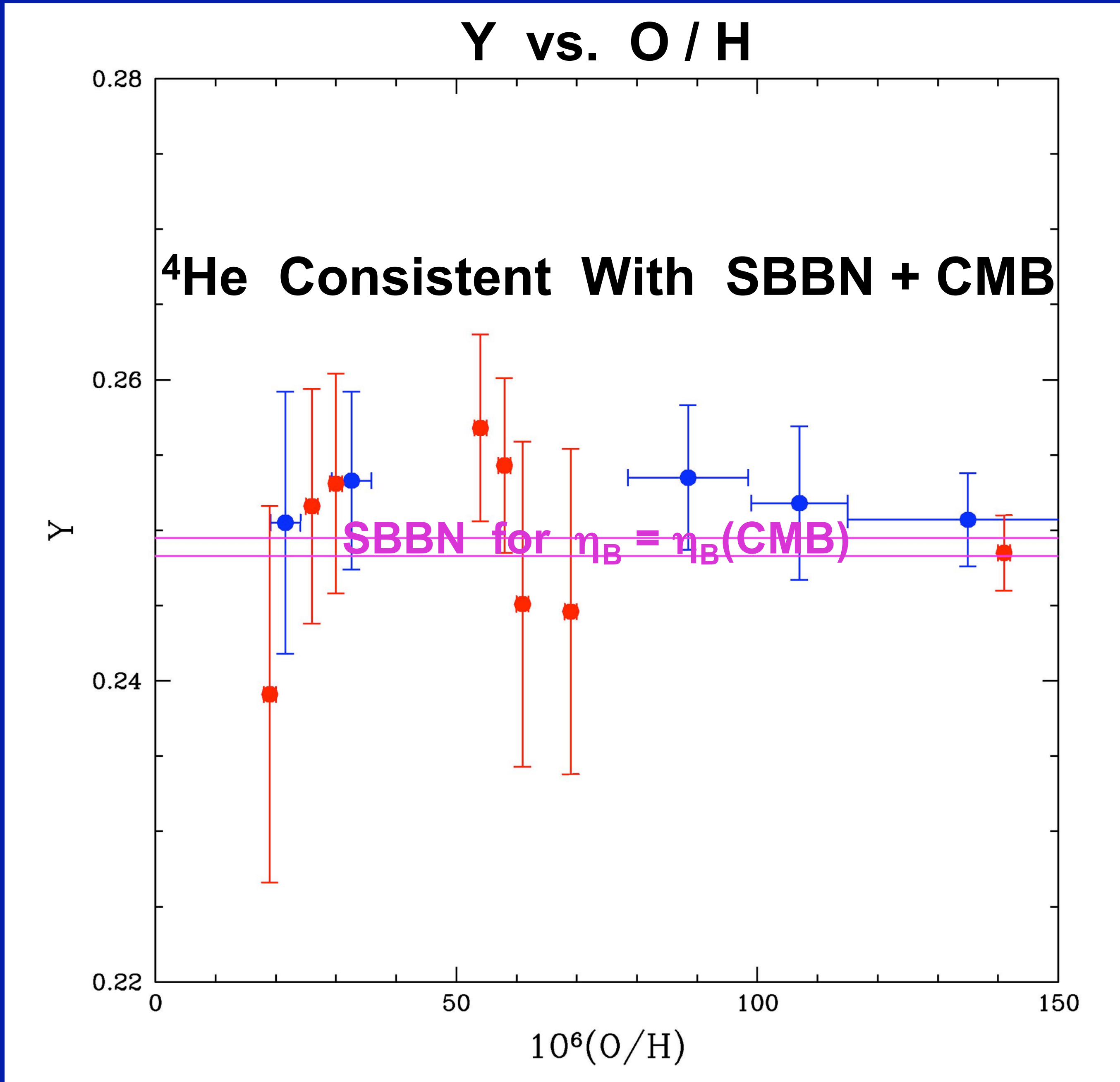
log (D/H) vs. Oxygen Abundance



^3He Observations (Galactic H II Regions)



^{4}He (Y) From Low – Z Extragalactic H II Regions



CONCLUSION

For N_ν = 3, BBN (D, ^{3}He, ^{4}He)

Agrees With The CMB + LSS + H_0

(But , Lithium Is A Problem !)

BBN + CMB Constraint On N_ν

For non – standard BBN ($N_\nu \neq 3$)

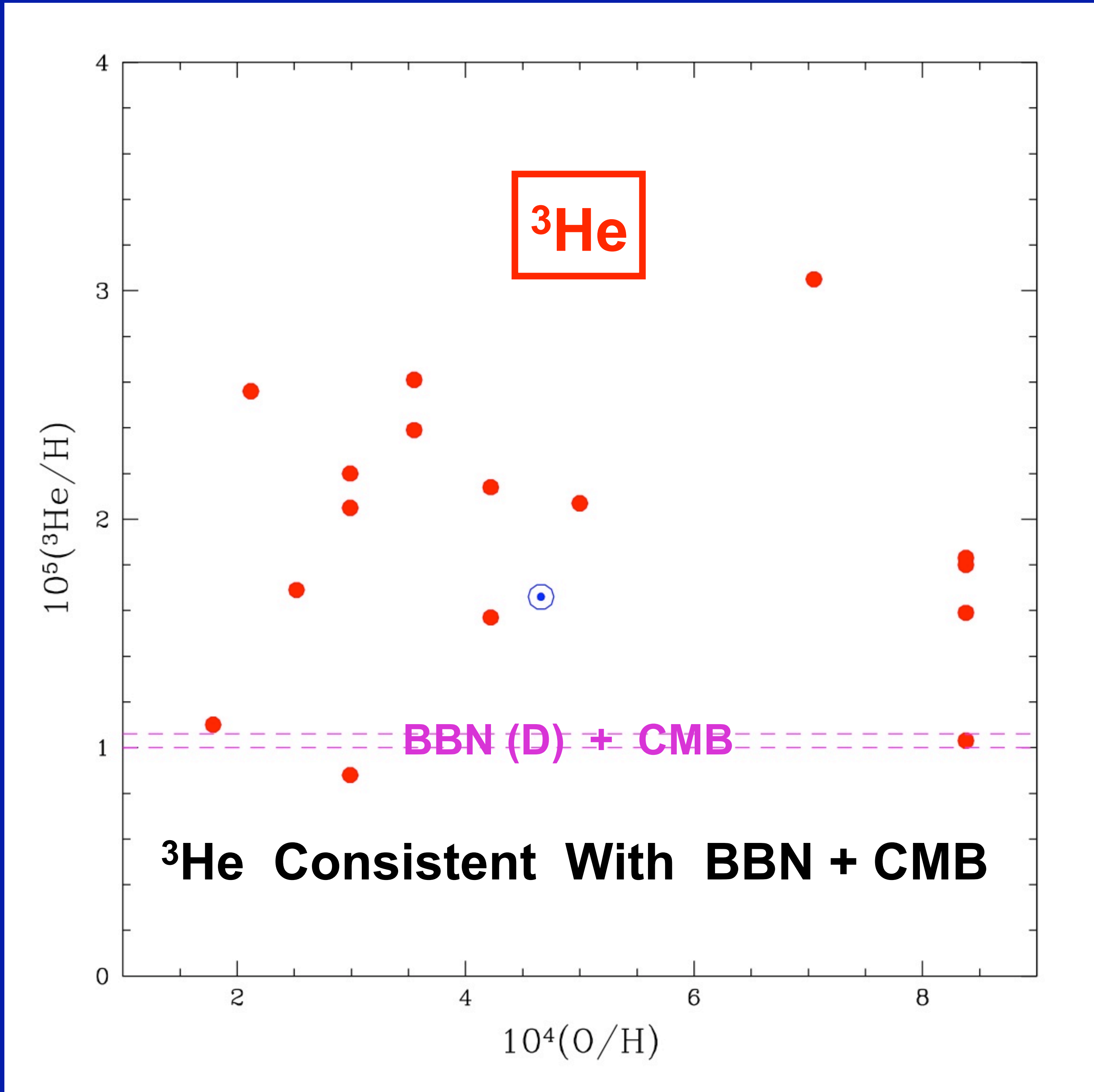
$(D/H)_P \;\alpha\; \eta_D^{-1.6}$, where $\eta_D \equiv \eta_D(\eta_{10}, N_\nu)$

$N_\nu \neq 3$ may reflect a real (?) difference between η_D & η_{10}. But, $(D/H)_P$ depends weakly on N_ν, which inflates any $N_\nu \neq 3$ determined this way.

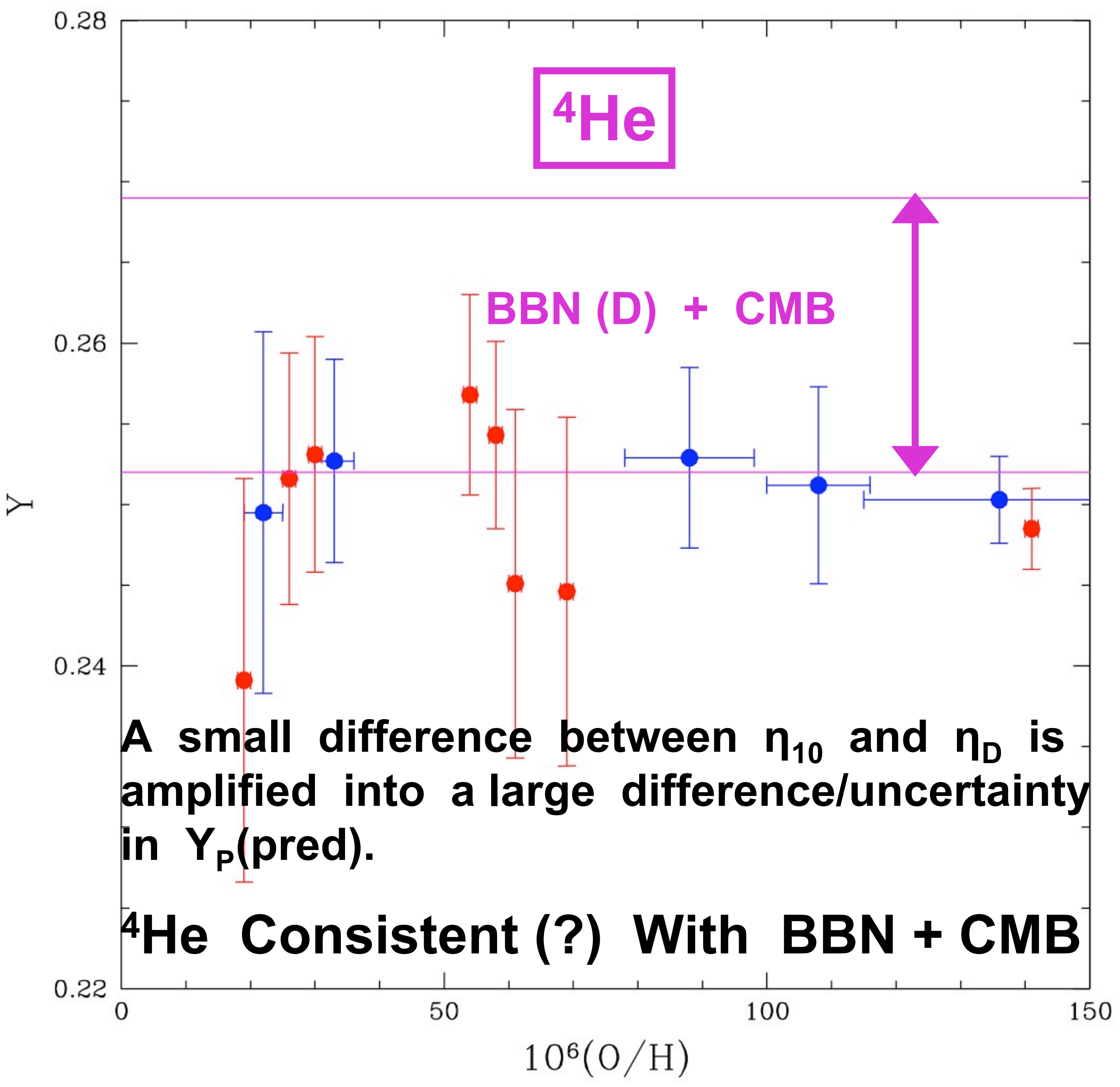
If $\eta_{10} \equiv \eta_{10}(CMB) \Rightarrow N_\nu = 4.0 \pm 0.7$

$\Rightarrow N_\nu = 3$ @ ~ 1.4 σ

BBN with $\eta_{10}(CMB) = 6.22 \pm 0.16$ & $N_\nu = 4.0 \pm 0.7$

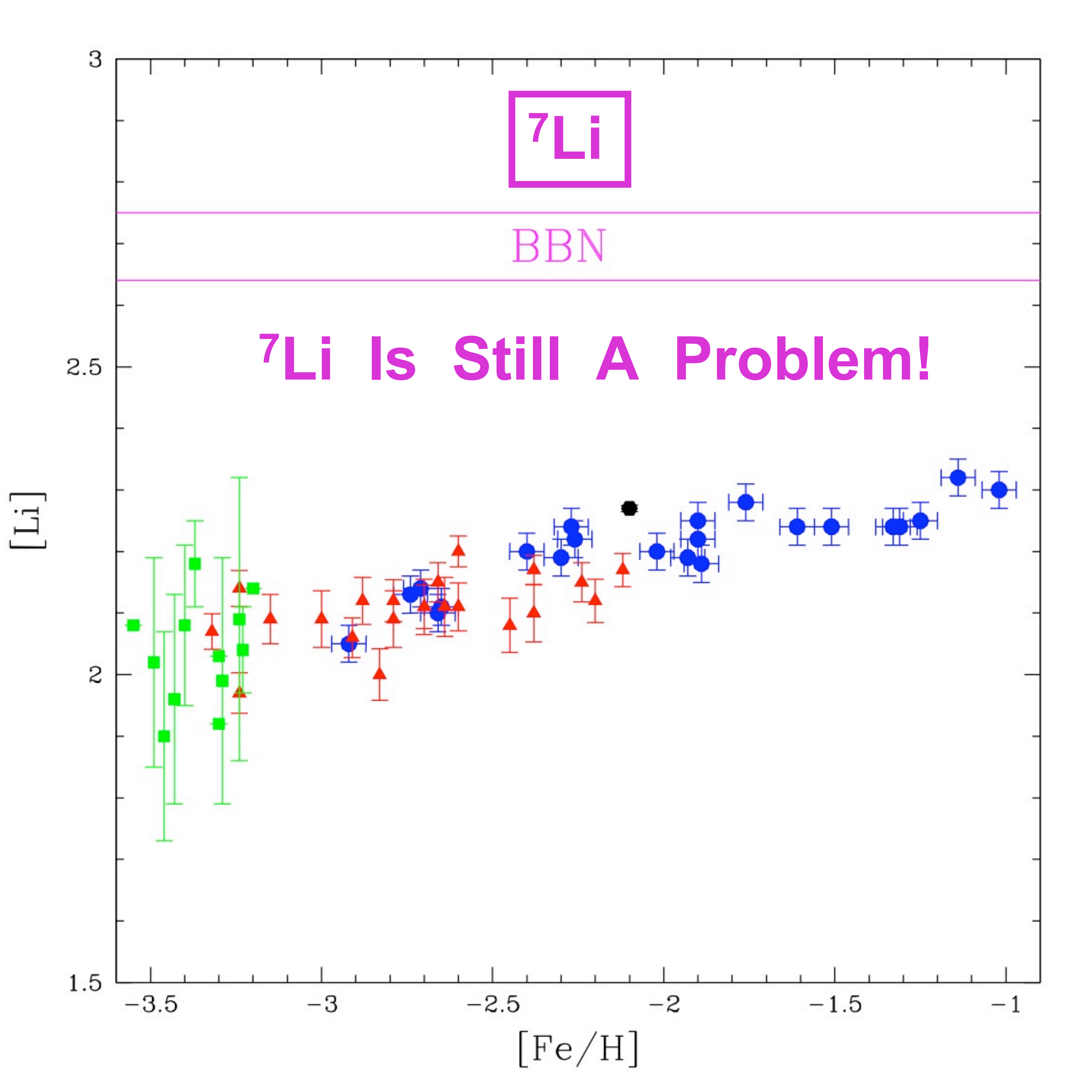


3He
BBN (D) + CMB
3He Consistent With BBN + CMB
10⁵(³He/H)
10⁴(O/H)
0
1
2
3
4
2
4
6
8



A small difference between η_{10} and η_D is amplified into a large difference/uncertainty in Y_P(pred).

^{4}He Consistent (?) With BBN + CMB



^{7}Li
BBN
^{7}Li Is Still A Problem!
3
2.5
2
1.5
[Li]
−3.5
−3
−2.5
−2
−1.5
−1
[Fe/H]

CONCLUSION

Non – standard BBN ($N_\nu \neq 3$) with

η_{10} (CMB) = 6.22 ± 0.16 & N_ν = 4.0 ± 0.7

is consistent with D, ^{3}He, & ^{4}He (But, ^{7}Li ?)

BBN + CMB Combined Can Constrain

Non-standard Cosmology & Particle Physics

CHALLENGES

- Why is the spread in D abundances so large ?
- Why is ^{3}He/H uncorrelated with O/H and/or R ?
- What are the systematic errors in Y_P ?
  Are there observing strategies to reduce them ?
- What is the primordial abundance of ^{7}Li (^{6}Li) ?

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

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

$$\Rightarrow \Delta N_\gamma / N_\gamma (\mathrm{BBN}) = -\,0.07 \pm 0.05$$

$$\Rightarrow \Delta N_\gamma = 0 \;@\; \sim 1.4\,\sigma$$

"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 ?), N_ν (BBN) = N_ν (CMB)

Comparing N_ν at BBN and at recombination

$$\Rightarrow \; 0.94 \leq N_\nu \text{(BBN)} / N_\nu \text{(CMB)} \leq 1.23$$