CONSTRAINING NEUTRINOS WITH BBN (WITH A LITTLE HELP FROM THE CMB)

GGI NEUTRINO WORKSHOP & SMIRNOV FEST

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BBN – Predicted Primordial Abundances Depend On Three Physical / Cosmological Parameters :

Baryon Density (Asymmetry) Parameter :

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

Expansion Rate (Dark Radiation) Parameter :

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

Lepton (Neutrino) Asymmetry Parameter :

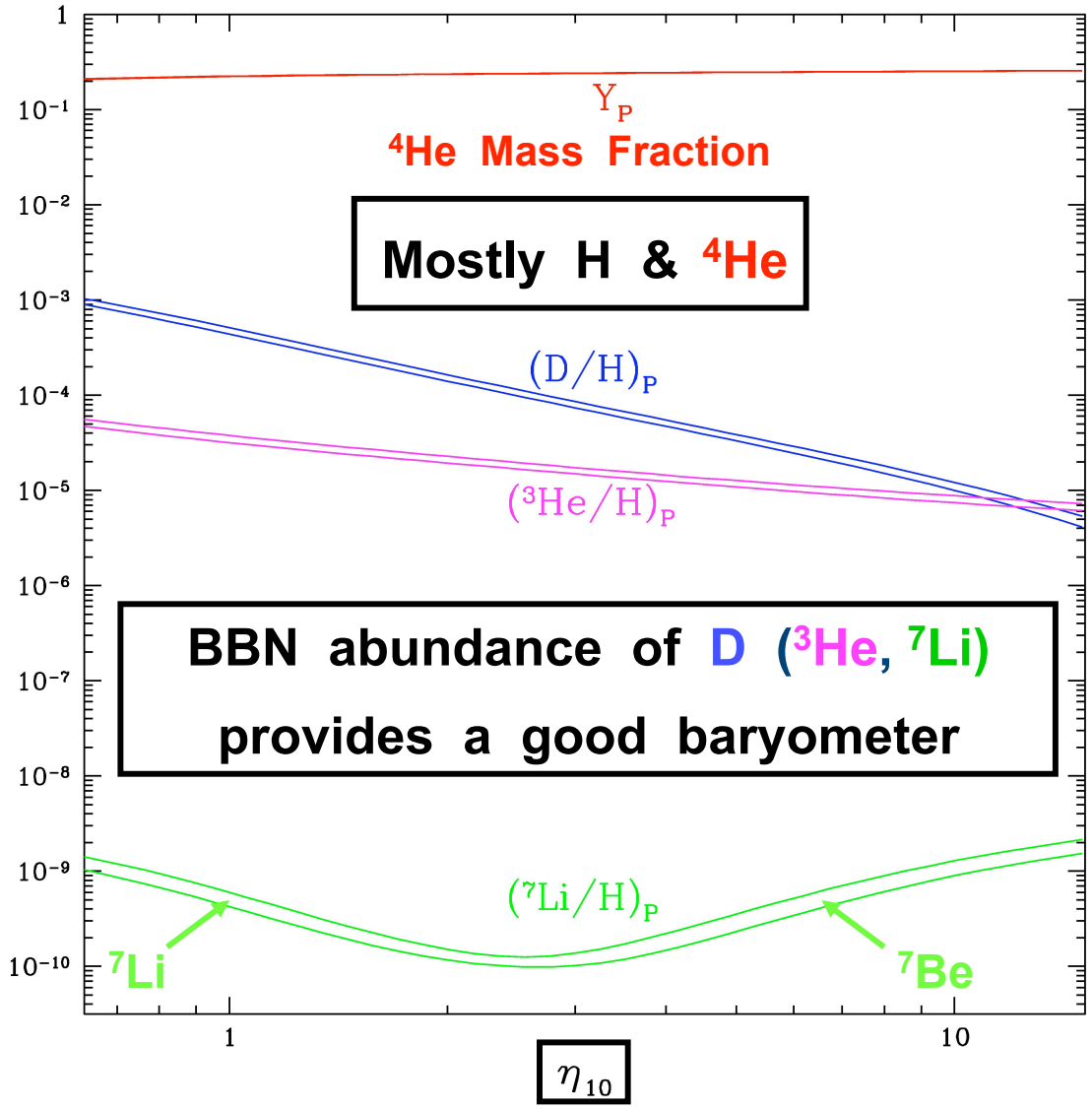
- $\xi = \xi_\nu = \mu_\nu / T_\nu$ $(\xi_\nu = \xi_{\nu e} = \xi_{\nu\mu} = \xi_{\nu\tau})$

"Standard" Big Bang Nucleosynthesis (SBBN)

For An Expanding Universe Described By General Relativity, With $S = 1$ ($\Delta N_\nu = 0 = \xi$)

The Relic Abundances Of D, ^{3}He, ^{4}He, ^{7}Li Depend Only On $\eta_B = \eta_{10}$

SBBN – Predicted Primordial Abundances



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)

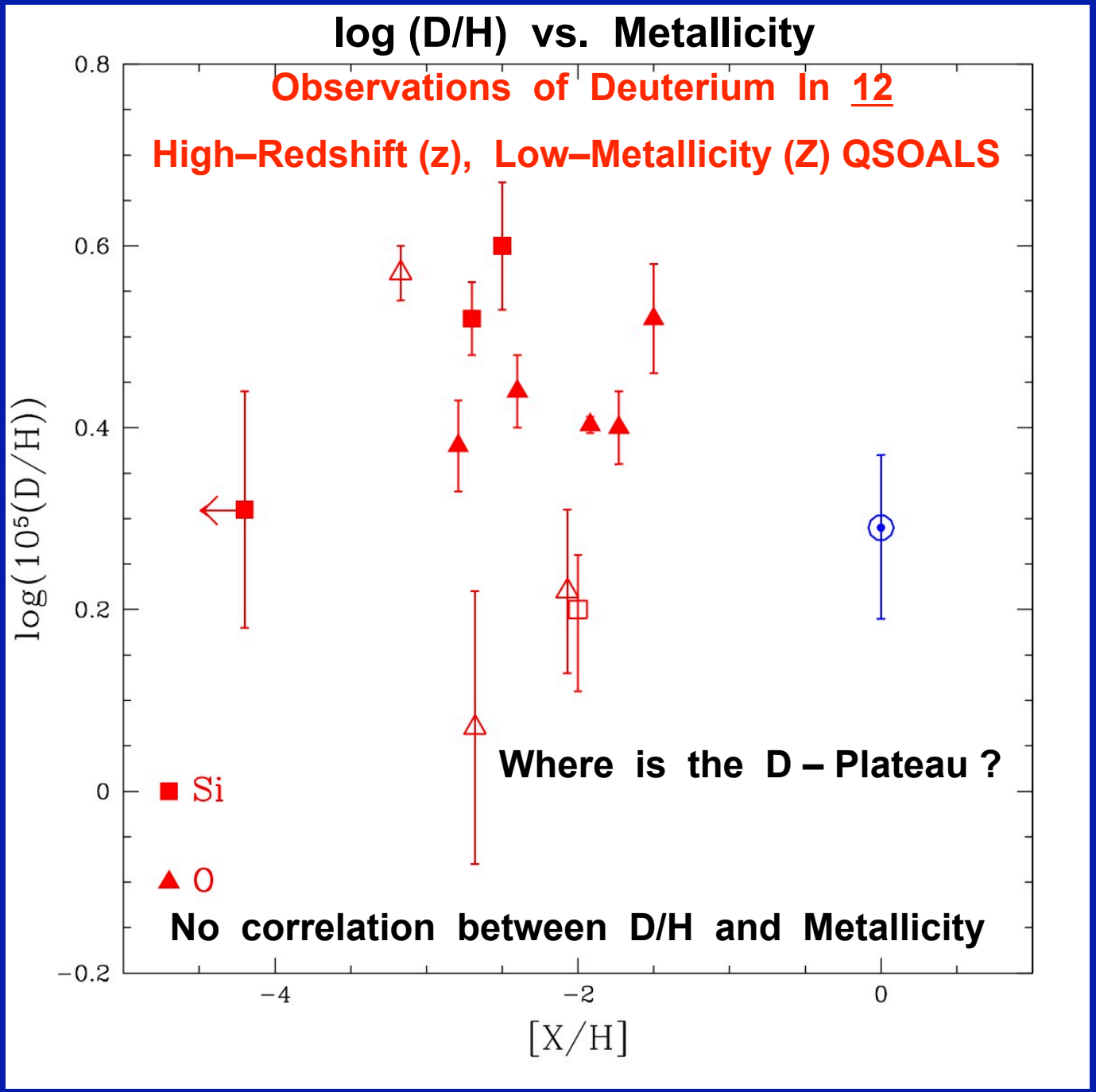
  $\Rightarrow$ ^{4}He INCREASES (along with CNO …)
- Cosmic Rays and SOME Stars PRODUCE ^{7}Li BUT, ^{7}Li is DESTROYED in most stars

* Use D to constrain η_B (mainly)

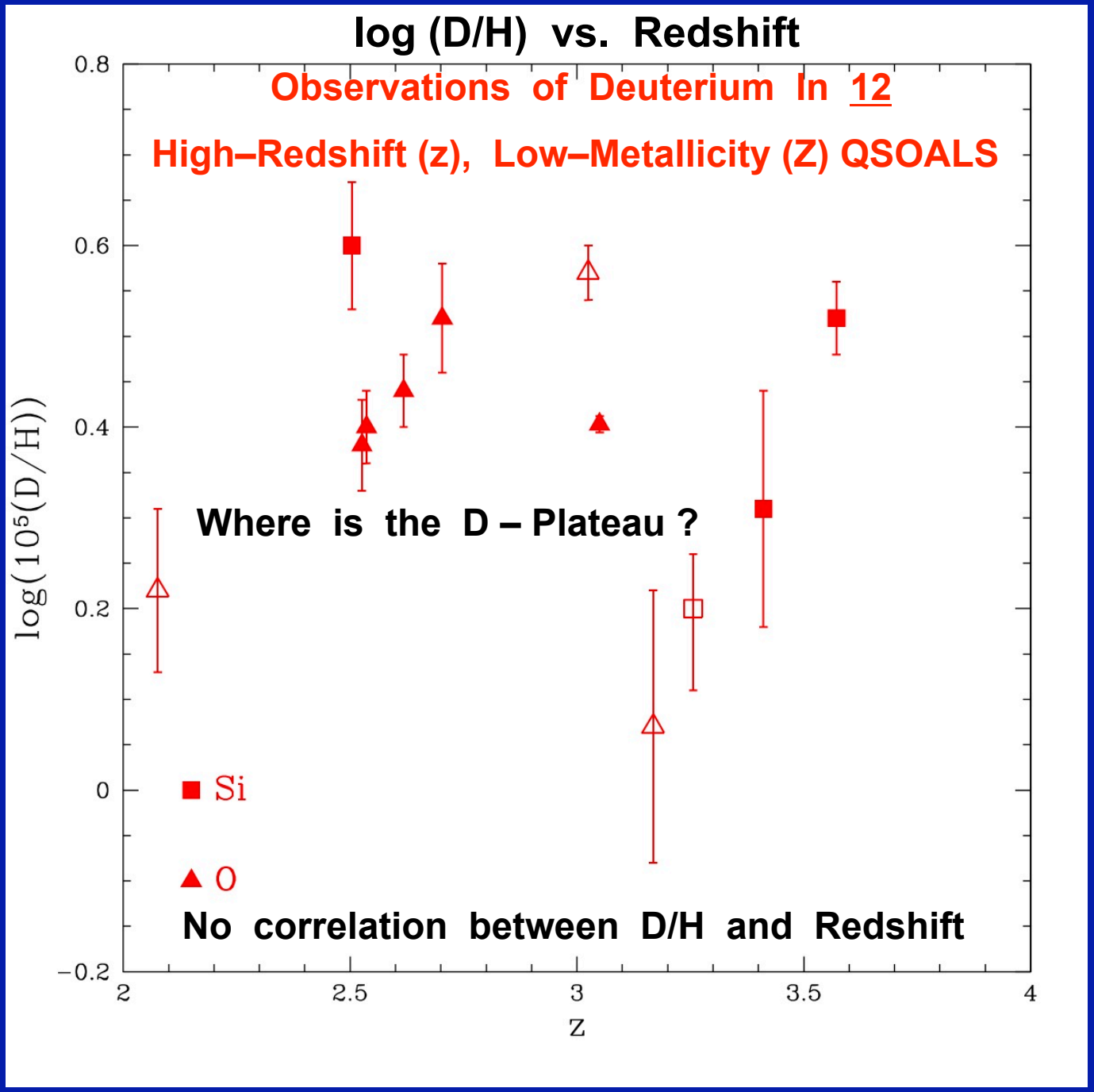
* Use ^{4}He to constrain ΔN_ν or ξ (mainly)

(Use η_B and ΔN_ν or ξ to predict BBN ^{7}Li)

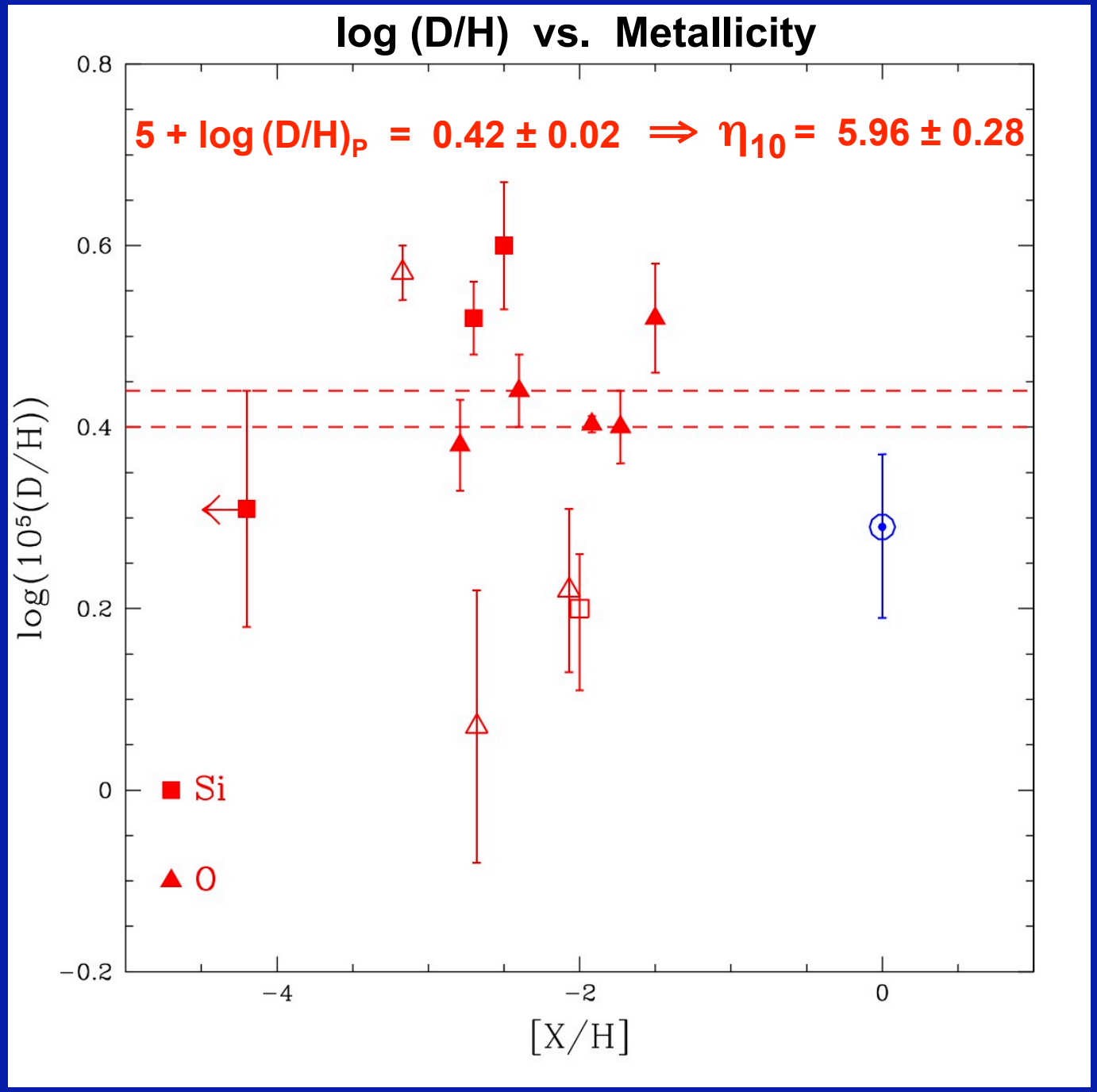
log (D/H) vs. Metallicity

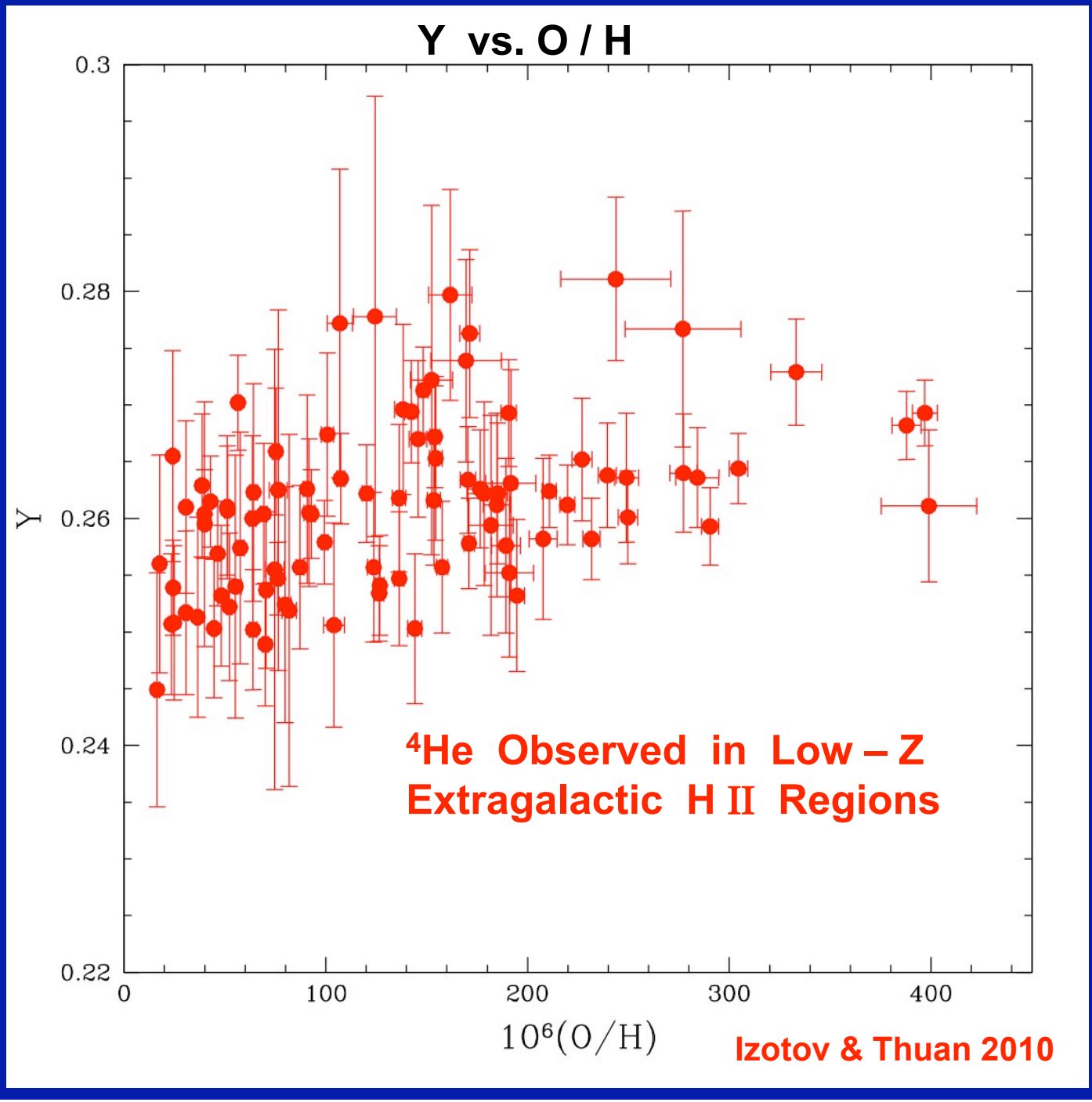


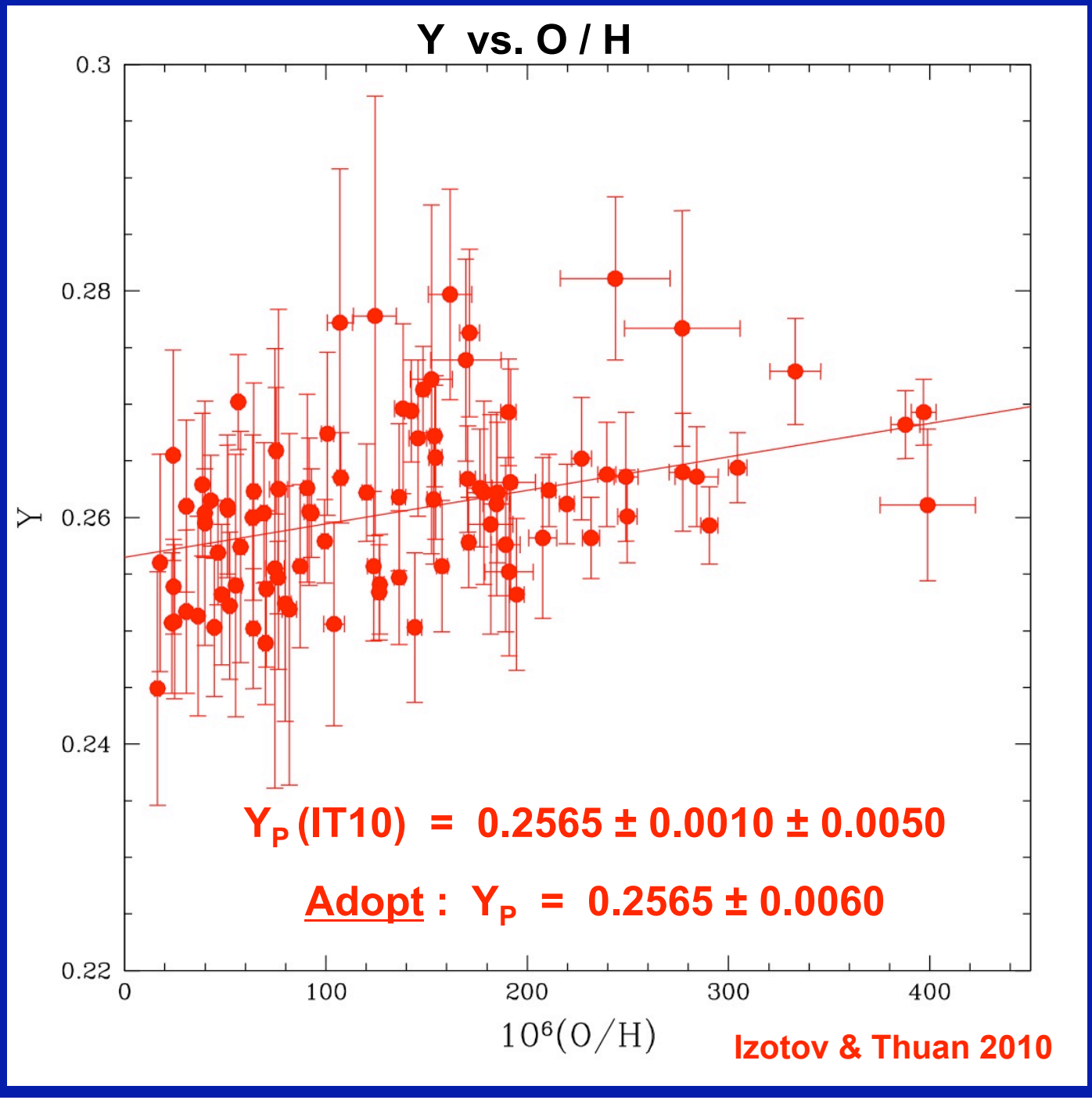
log (D/H) vs. Redshift



log (D/H) vs. Metallicity




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


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
Adopt : Y_P = 0.2565 ± 0.0060
Izotov & Thuan 2010

SBBN ($\Delta N_\nu = 0 = \xi$)

IF : $5 + \log(D/H)_P = 0.42 \pm 0.02 \Longrightarrow$

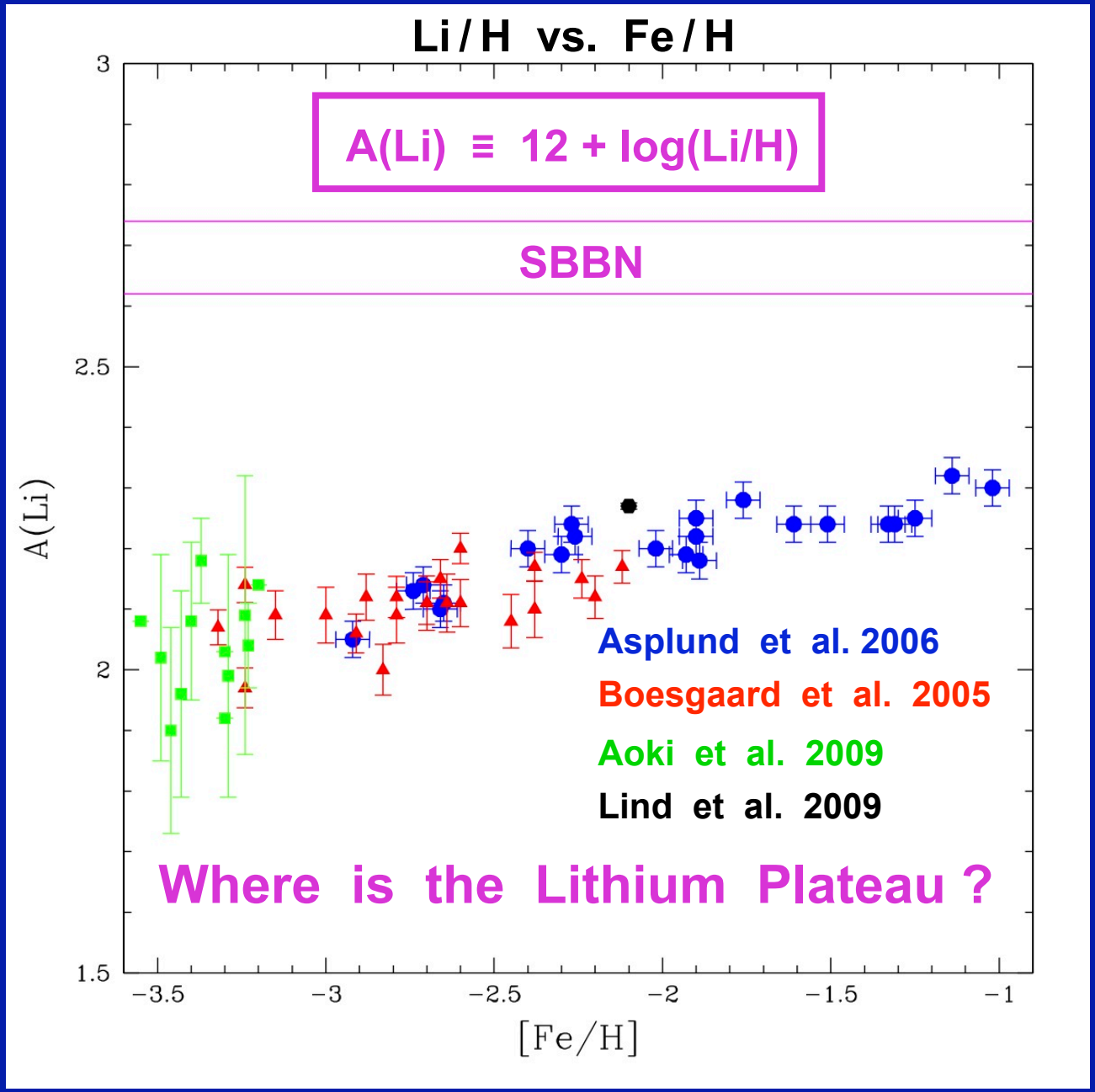
$\eta_{10} = 5.96 \pm 0.28 \Longrightarrow Y_P = 0.2476 \pm 0.0007$

$Y_P(\mathrm{OBS}) - Y_P(\mathrm{SBBN}) = 0.0089 \pm 0.0060$

$\Longrightarrow Y_P(\mathrm{OBS}) = Y_P(\mathrm{SBBN})$ @ $\sim 1.5\,\sigma$

IF $Y_P = 0.2565 \pm 0.0060 \Longrightarrow \eta_{10} = 11.50 \pm 3.77$

But ! Lithium – 7 Is A Problem

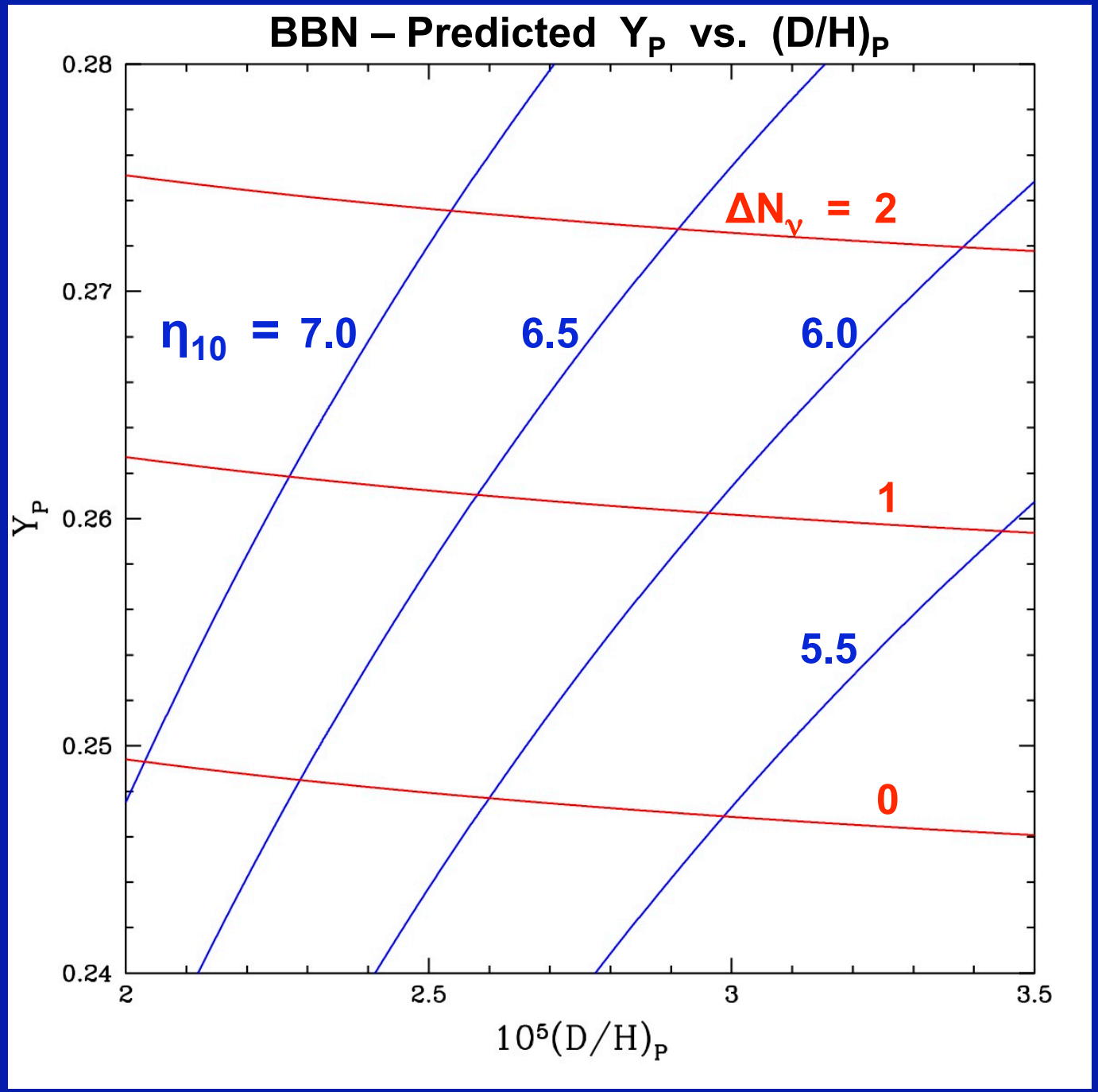


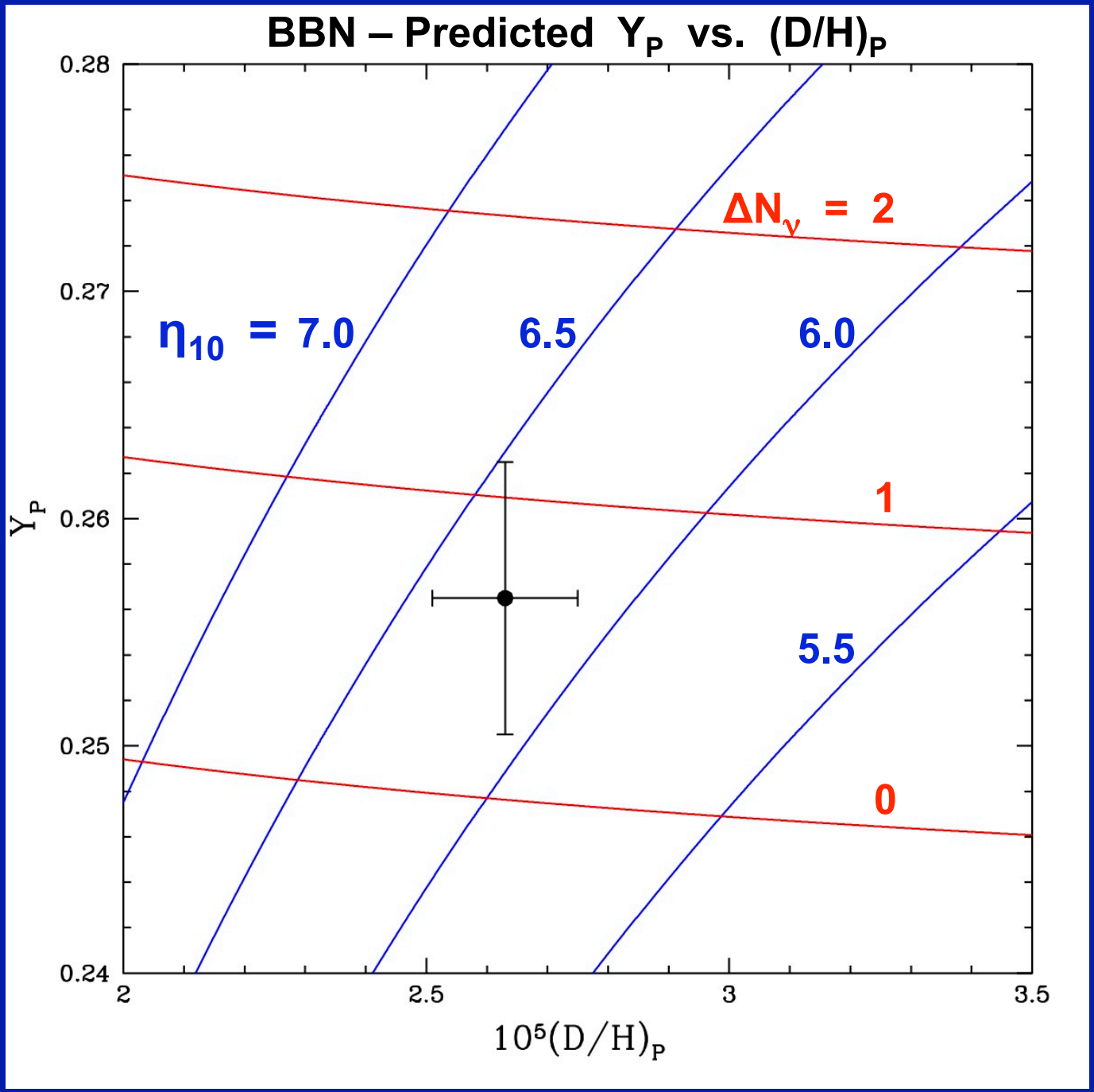
SBBN Predictions Agree With Observations Of D, ^{3}He, ^{4}He, But NOT With ^{7}Li

When η_{10}, ΔN_ν, ξ are free parameters

BBN abundances are functions of η_{10}, ΔN_ν, ξ

Explore the constraints provided by D (D/H) and ^{4}He (Y_P) and use them to predict ^{7}Li (Li/H)


BBN – Predicted Y_P vs. $(D/H)_P$
0.28
0.27
0.26
0.25
0.24
Y_P
2
2.5
3
3.5
$10^5(D/H)_P$
ΔN_ν = 2
η_{10} = 7.0
6.5
6.0
1
5.5
0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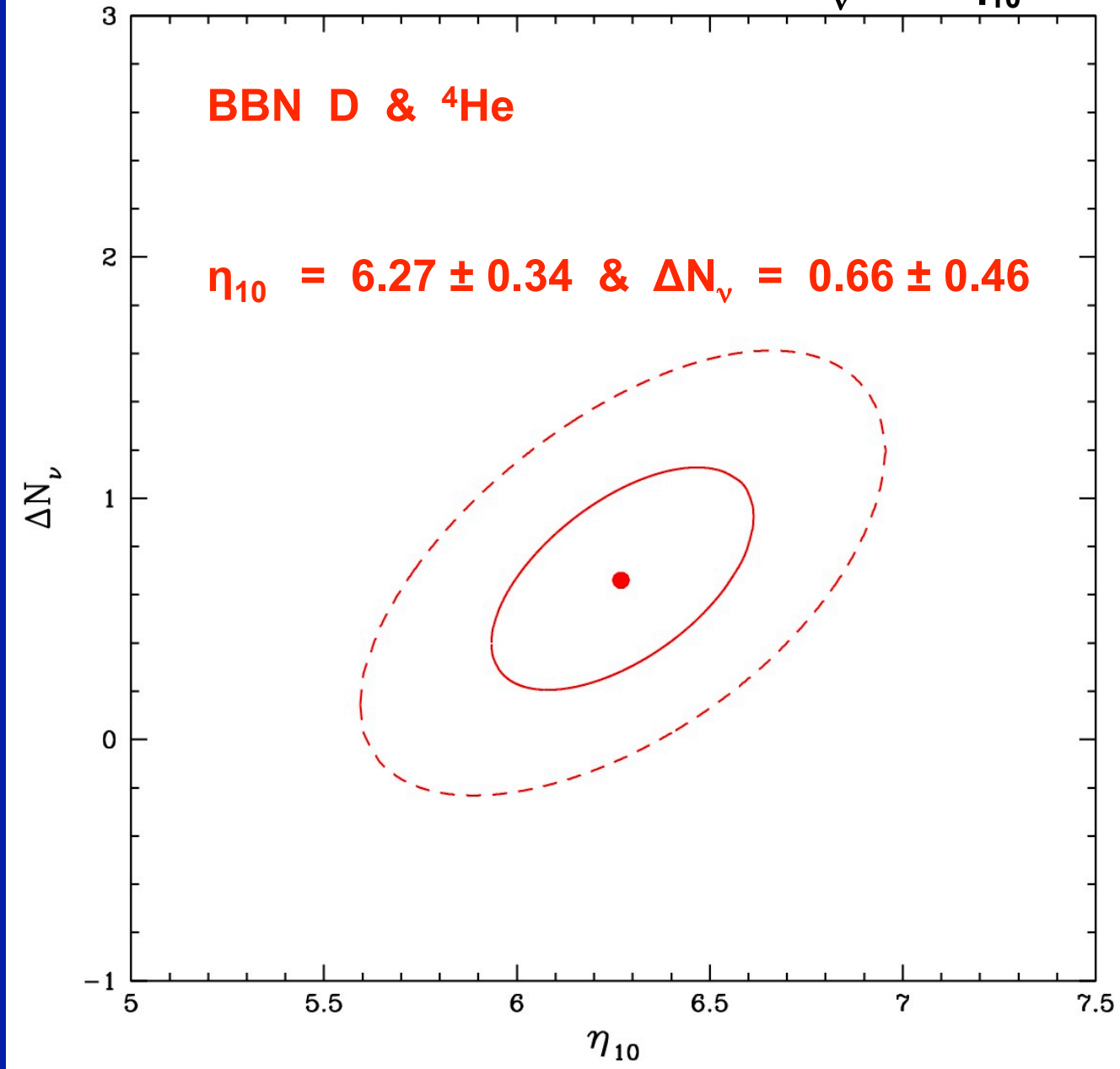
0.28
0.27
0.26
0.25
0.24
Y_P
2
2.5
3
3.5
$10^5(D/H)_P$
$\Delta N_\nu = 2$
1
0
$\eta_{10} = 7.0$
6.5
6.0
5.5

68 % & 95 % Contours of ΔN_ν vs. η_{10}



For BBN ($\Delta N_\nu \neq 0$, $\xi = 0$)

$\Rightarrow$ $\eta_{10} = 6.27 \pm 0.34$ & $\Delta N_\nu = 0.66 \pm 0.46$

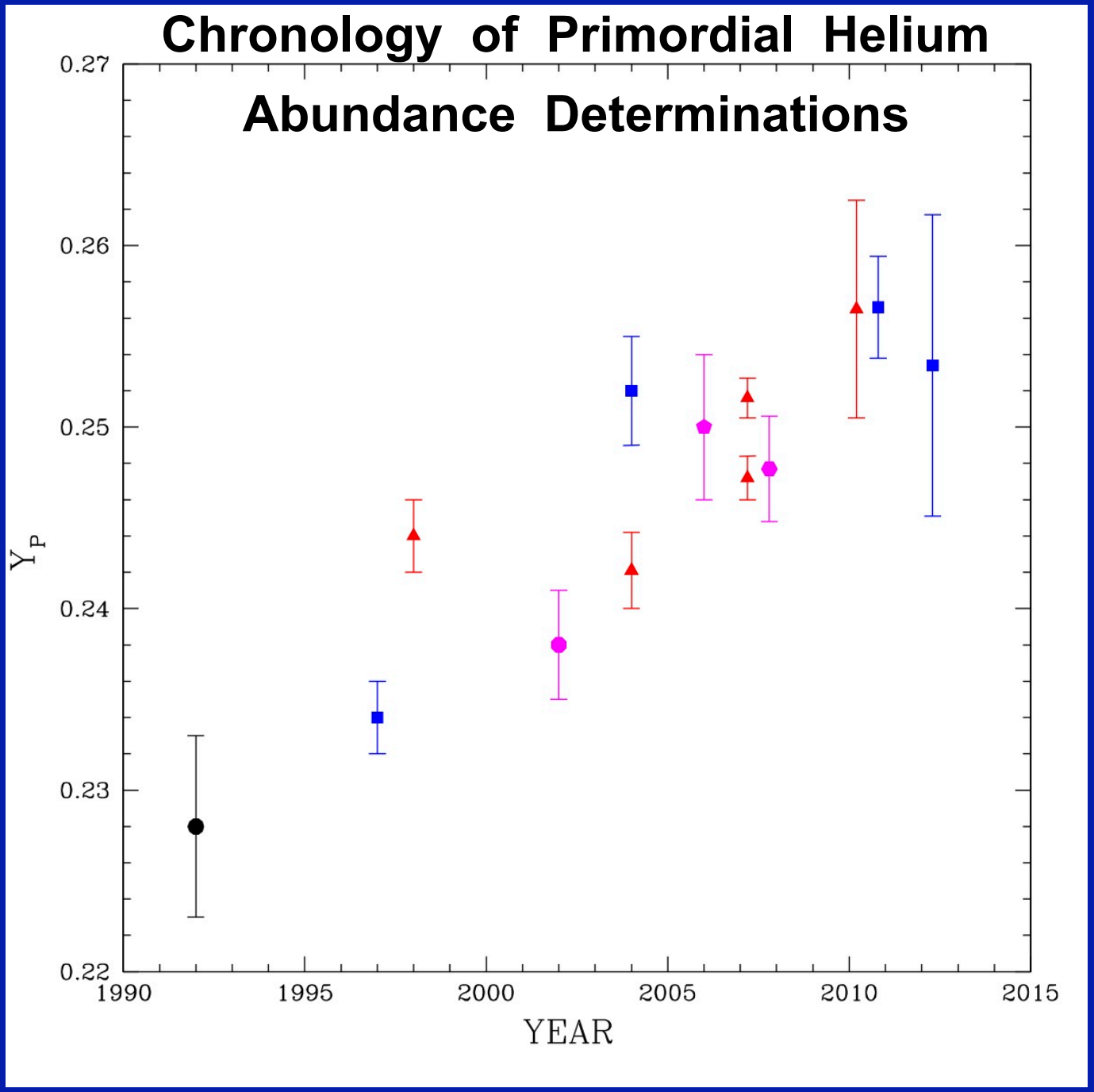
$\Rightarrow$ $\Delta N_\nu = 0$ @ $\sim 1.4\,\sigma$

(Or $\Rightarrow$ $G_{BBN} / G_0 = 1.11 \pm 0.07$)

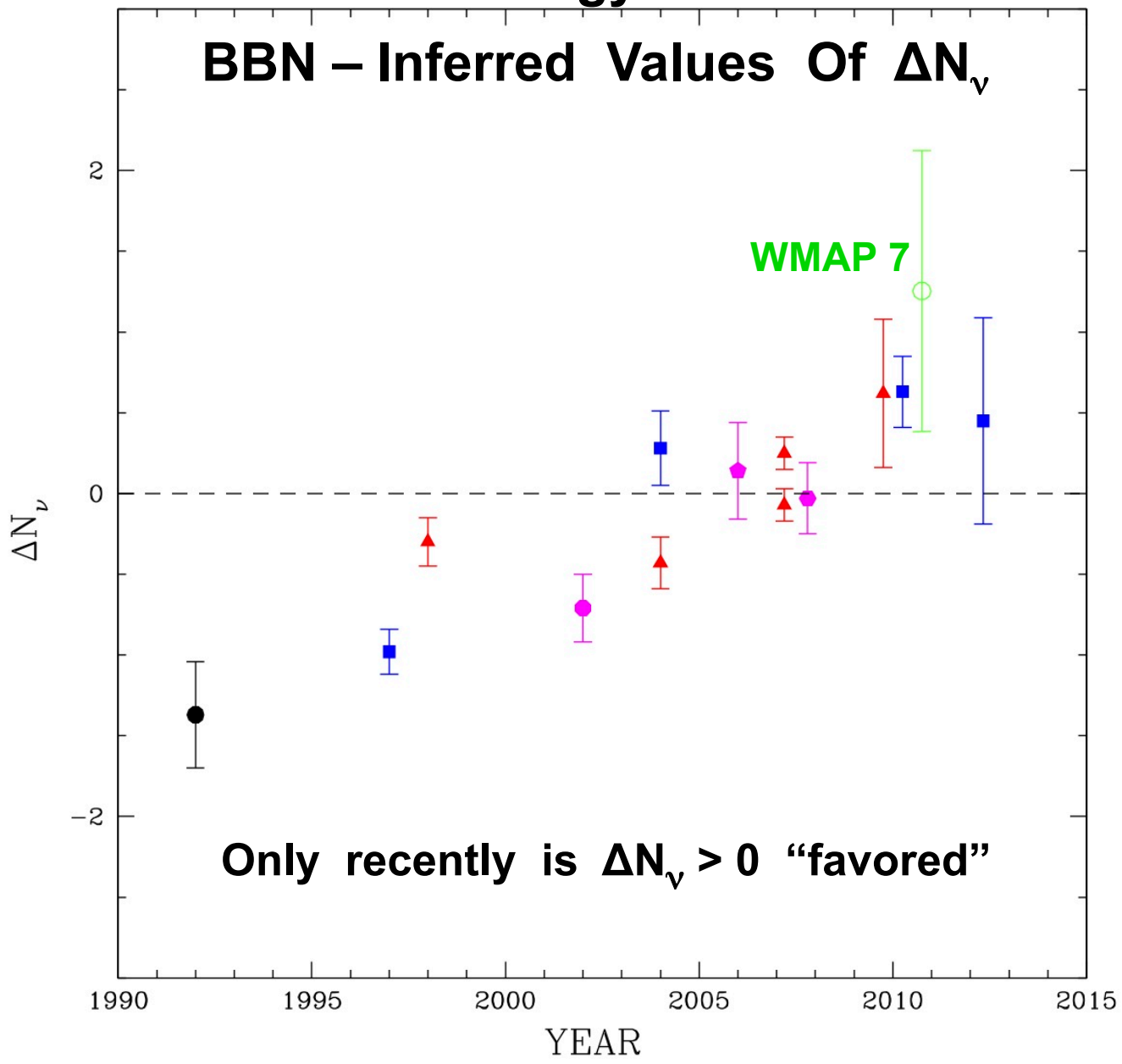
But, what about Lithium ?

$\Rightarrow$ A(Li) = 2.70 ± 0.06 (Too High !)

Chronology of Primordial Helium



Chronology Of The BBN – Inferred Values Of ΔN_ν

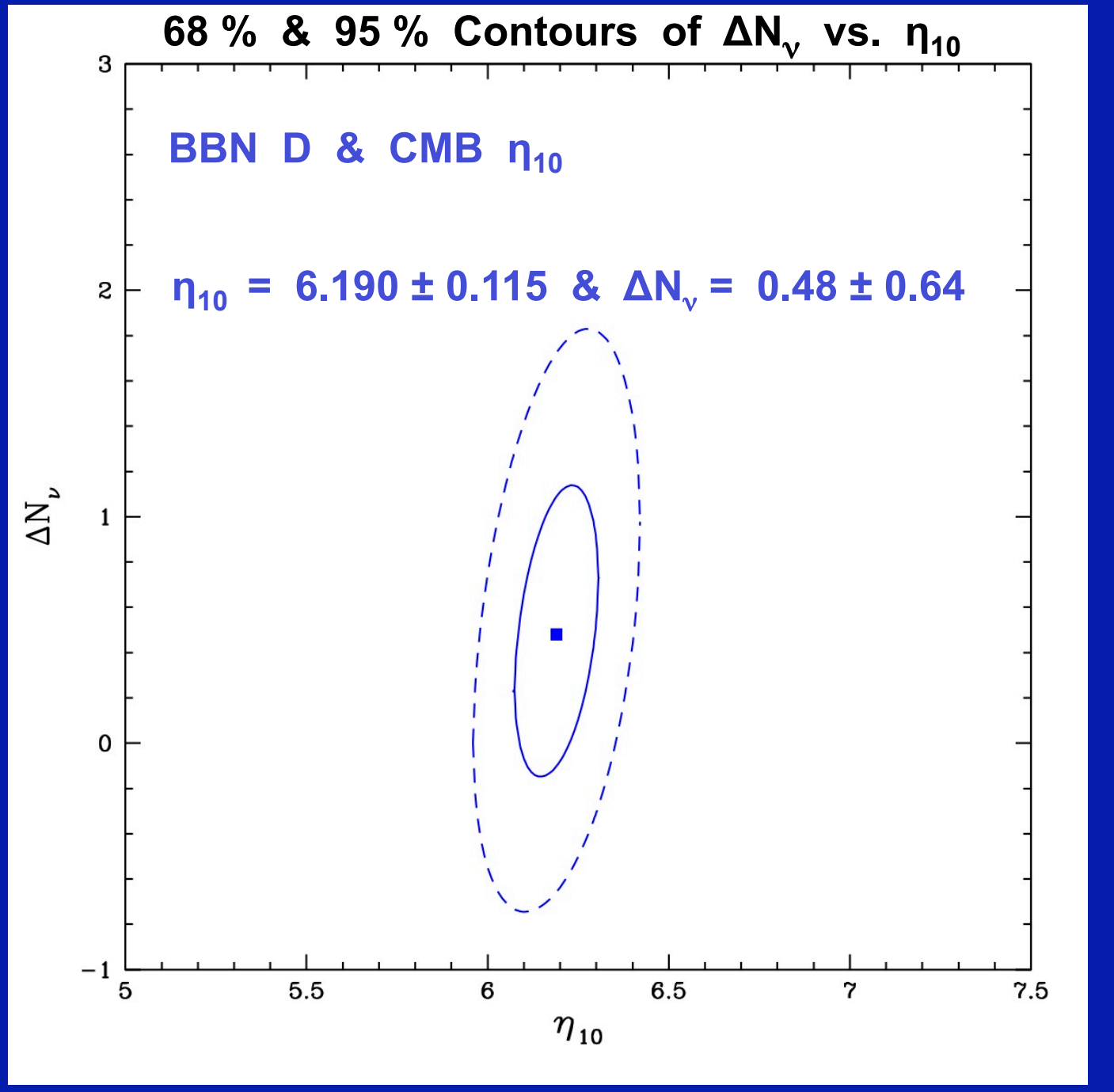


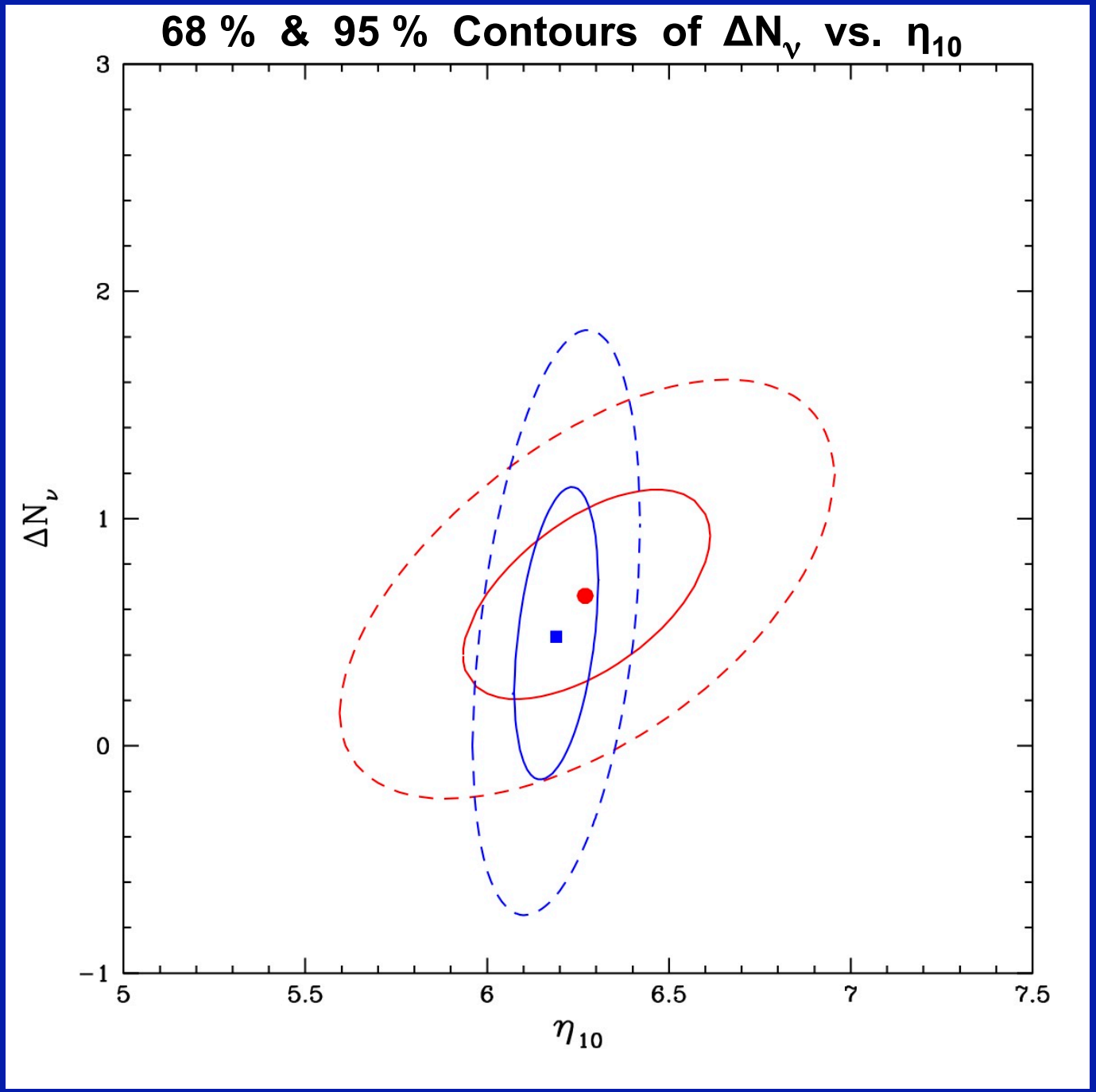
Only recently is $\Delta N_\nu > 0$ "favored"

The recent BBN support for $\Delta N_\nu > 0$ is driven by the recent (uncertain) estimates of Y_P

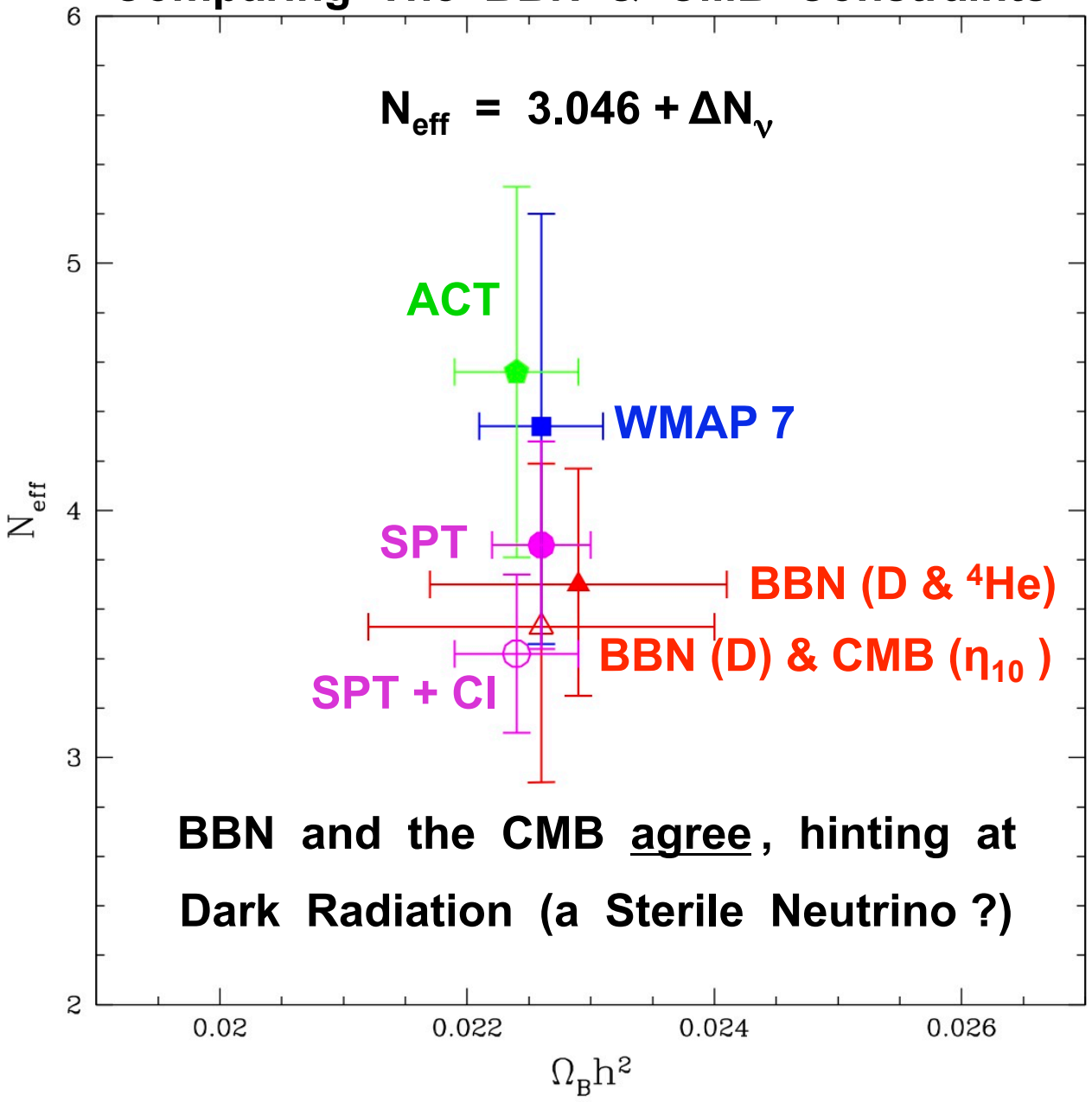
Avoid the uncertainties in Y_P by replacing BBN ^{4}He with CMB – determined η_{10}

68 % & 95 % Contours of ΔN_ν vs. η_{10}



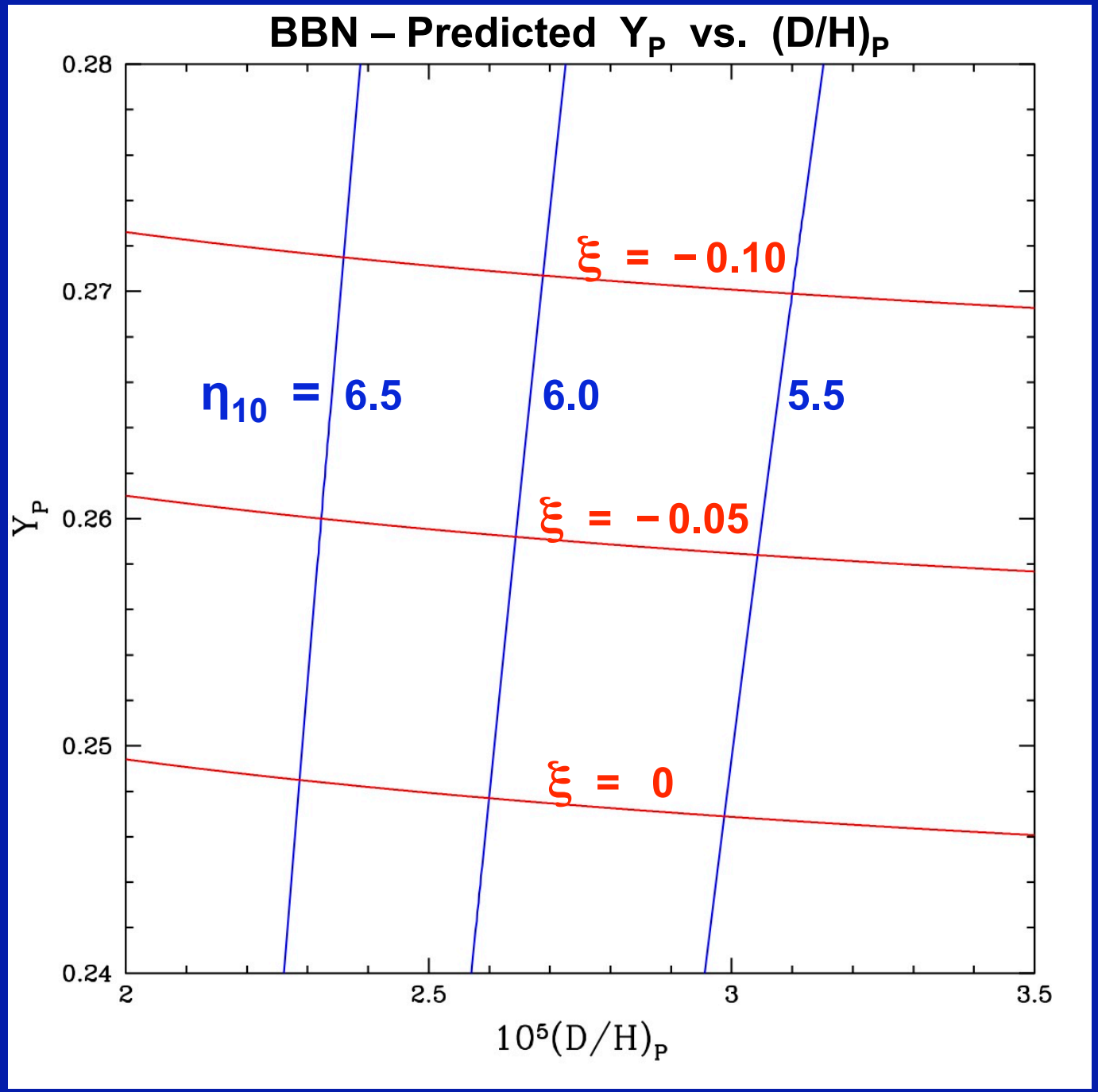

68 % & 95 % Contours of ΔN$_\nu$ vs. η$_{10}$
3
2
1
0
−1
5
5.5
6
6.5
7
7.5
ΔN$_\nu$
η$_{10}$

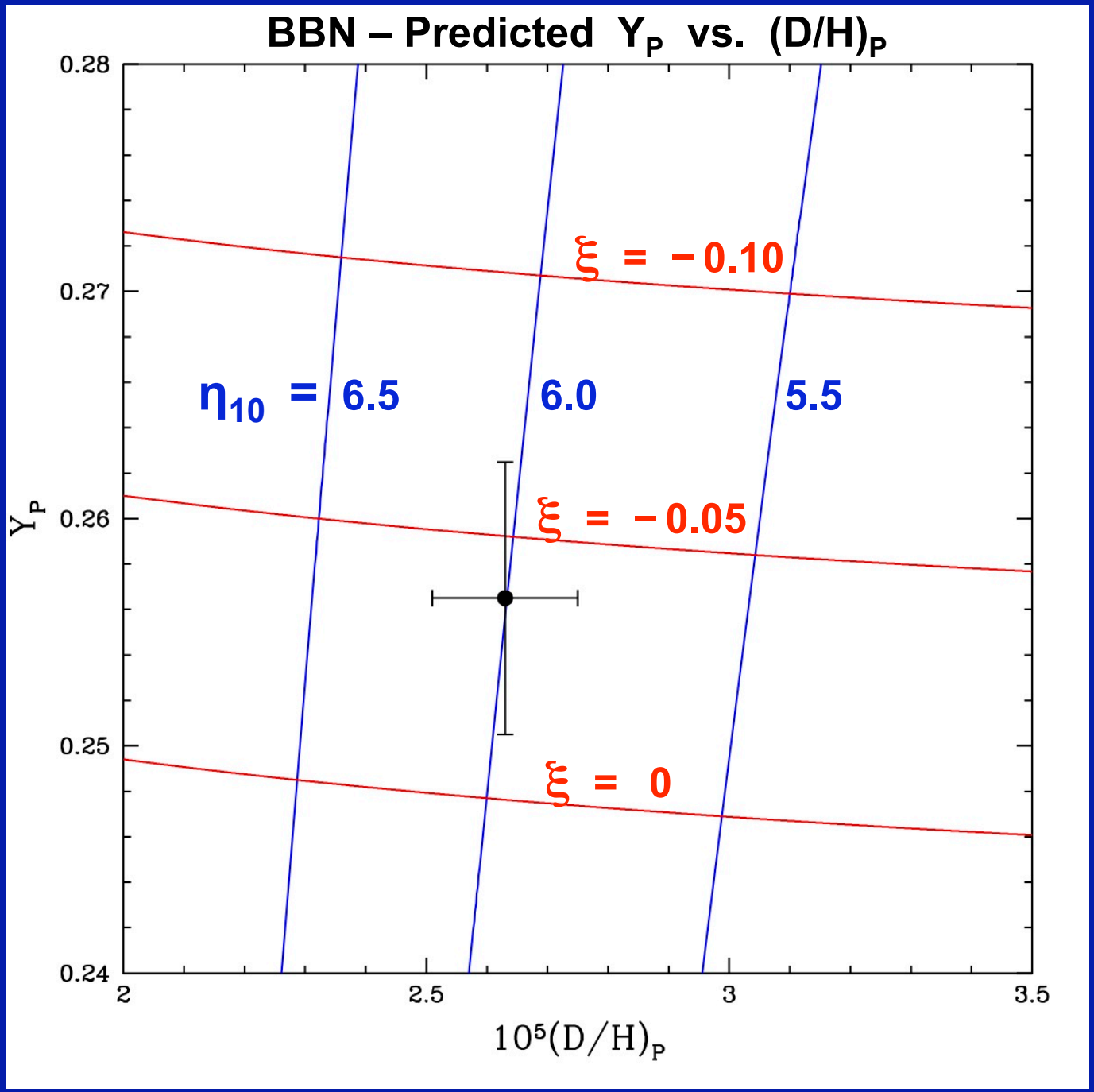
Comparing The BBN & CMB Constraints

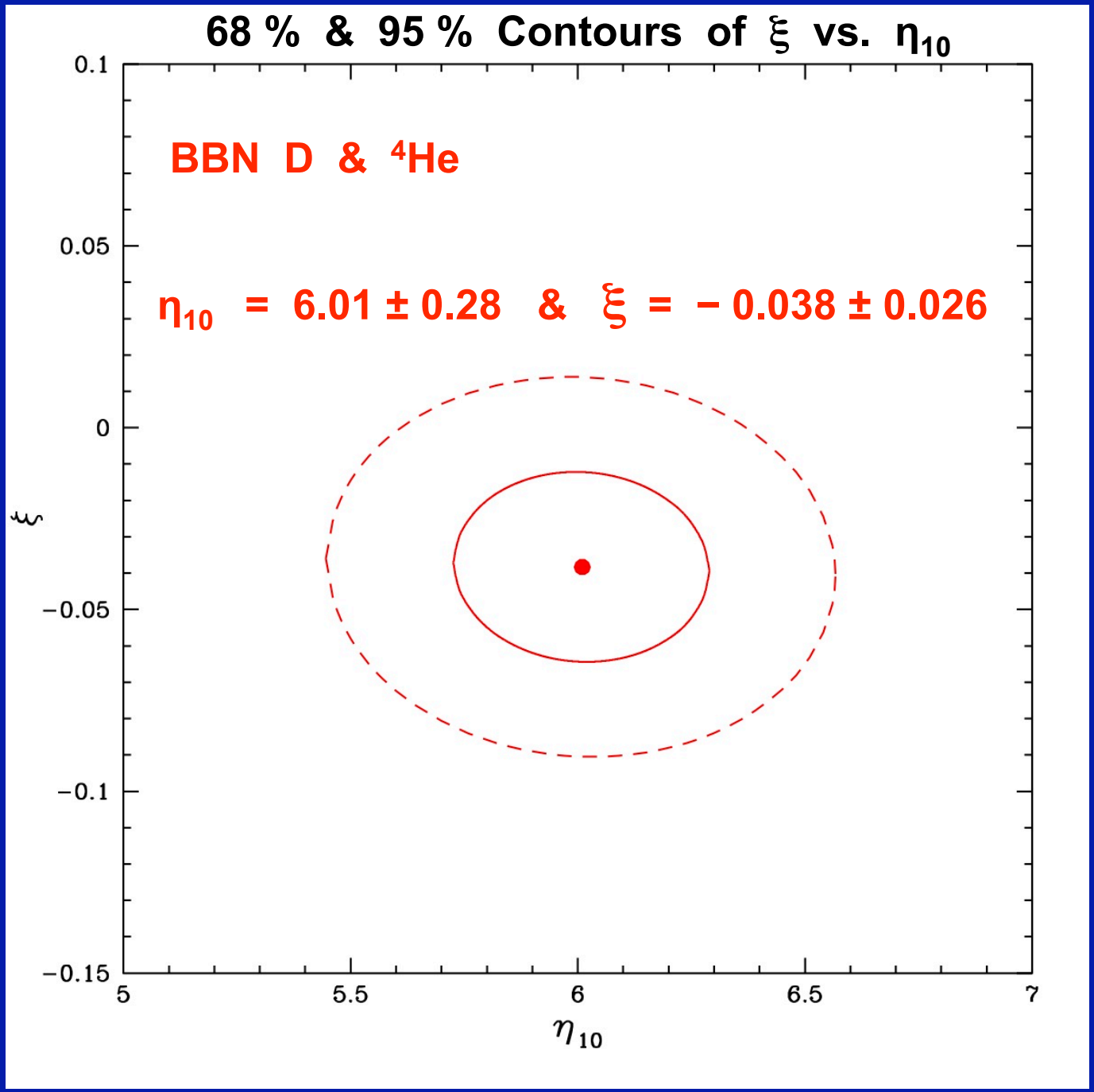


BBN (D & 4He) Allowing For Lepton Asymmetry

(No Dark Radiation : $\Delta N_\nu = 0$)


BBN – Predicted Y_P vs. $(D/H)_P$
0.28
0.27
0.26
0.25
0.24
Y_P
2
2.5
3
3.5
$10^5(D/H)_P$
η_{10} = 6.5
6.0
5.5
ξ = −0.10
ξ = −0.05
ξ = 0


BBN – Predicted Y_P vs. $(D/H)_P$
0.28
0.27
0.26
0.25
0.24
Y_P
2
2.5
3
3.5
$10^5(D/H)_P$
ξ = −0.10
ξ = −0.05
ξ = 0
η_{10} = 6.5
6.0
5.5


68 % & 95 % Contours of ξ vs. η10
BBN D & 4He
η10 = 6.01 ± 0.28 & ξ = − 0.038 ± 0.026
0.1
0.05
0
−0.05
−0.1
−0.15
ξ
5
5.5
6
6.5
7
η10

For BBN ($\Delta N_\nu = 0$, $\xi \neq 0$)

$\Rightarrow$ $\eta_{10} = 6.01 \pm 0.28$ & $\xi = -0.038 \pm 0.026$

$\Rightarrow$ $\xi = 0$ @ $\sim 1.5\,\sigma$

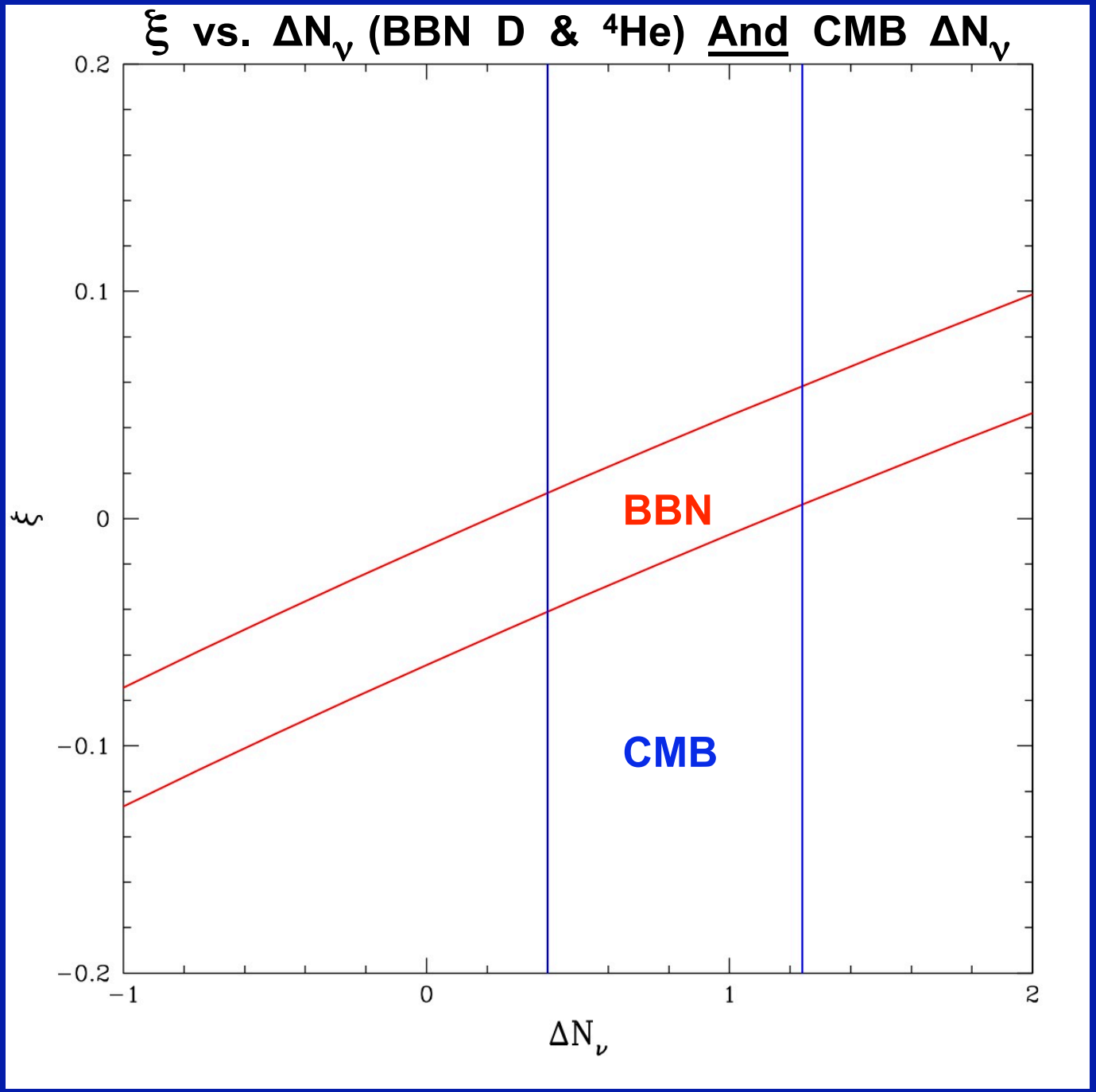
But, what about Lithium ?

$\Rightarrow$ A(Li) = 2.69 ± 0.05 (Too High !)

BBN (D & ^{4}He) Allowing For

Lepton Asymmetry And Dark Radiation

Supplemented By A CMB Constraint On ΔN_ν


ξ vs. ΔN_ν (BBN D & ⁴He) And CMB ΔN_ν
0.2
0.1
0
−0.1
−0.2
ξ
−1
0
1
2
ΔN_ν
BBN
CMB

For BBN ($\Delta N_\nu \neq 0$, $\xi \neq 0$)

And CMB ($\Delta N_\nu = 0.82 \pm 0.64$)

$\Rightarrow$ $\eta_{10} = 6.34 \pm 0.32$ & $\xi = 0.009 \pm 0.035$

But, what about Lithium ?

$\Rightarrow$ A(Li) = 2.70 ± 0.06 (Still Too High !)

CONCLUSIONS

For $\Delta N_\nu \approx 0$ & $\xi = 0$, BBN (D, ^{3}He, ^{4}He)

Agrees With The CMB + LSS

(But , Lithium Is A Problem !)

BBN + CMB + LSS Constrain

Cosmology & Particle Physics