G. Steigman

The Cosmic Nuclear Reactor

$t \approx 0.1 - 1000$ sec. ; $T \approx 3$ MeV $-$ 30 keV

D, ^3He, ^4He, ^7Li synthesized

- **Abundances depend on "1"* parameter**

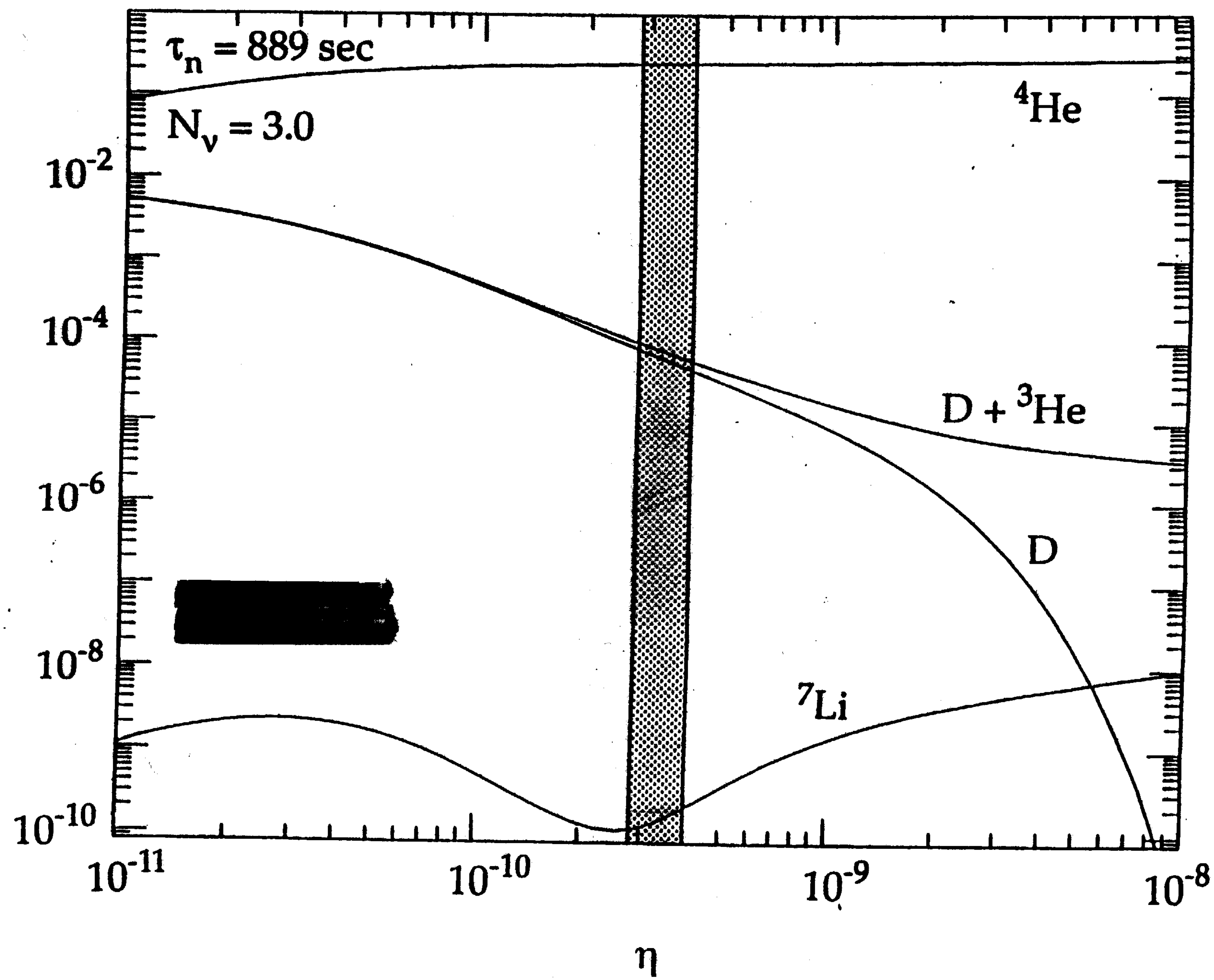
$$\eta \equiv n_N / n_\gamma \quad ; \quad \eta_{10} \equiv 10^{10} \eta$$

$$\Omega_B h^2 = \eta_{10} / 273$$

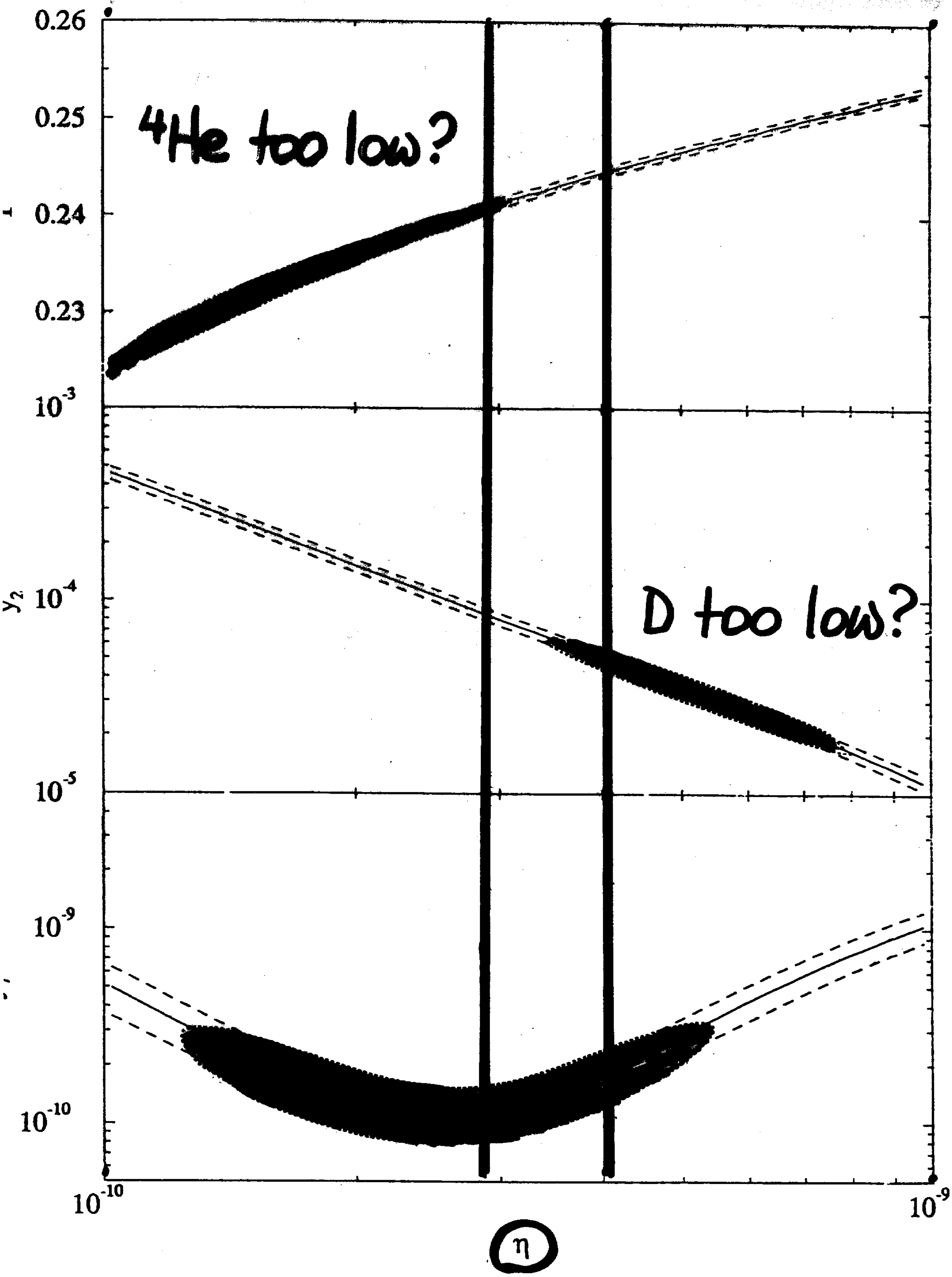
- $\Omega_B \equiv \rho_B / \rho_{crit}$
- $H_0 \equiv 100\, h$ km s^{-1} Mpc^{-1}

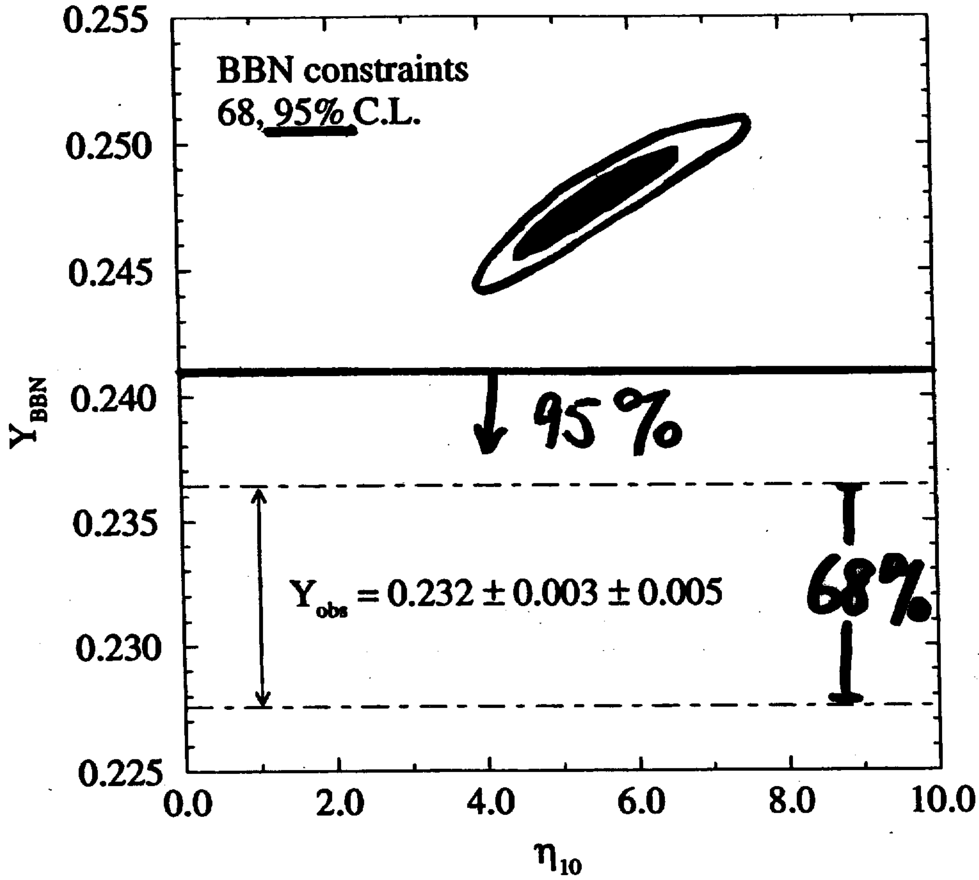
$(H_0^{-1} = 9.8\, h^{-1}$ Gyr$)$

* $N_\nu = 3$ at BBN


$\tau_n = 889$ sec
$N_\nu = 3.0$
^4He
$D + ^3He$
D
^7Li
[redacted]
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
η

Hata et al. PRL '95 ("Crisis")





- Use D, ^3He, ^7Li to constrain η_{10}
- Predict $Y_{BBN}(\eta)$
- Compare to Y_p^{OBS}

3 Resolutions Of The BBN Crisis

- **"Observed" Abundance Of ^4He Too Small?**

  $Y_p = 0.25$ vs. 0.23 ?

- **"Inferred" Abundance (Primordial) Of D Too Small?**

  $D/H = 2 \times 10^{-4}$ vs. 2×10^{-5} ?

- **"New Physics"?**

  Is The Tau-Neutrino Massive?

  ($N_\nu^{BBN} = 2.1 \pm 0.3$)

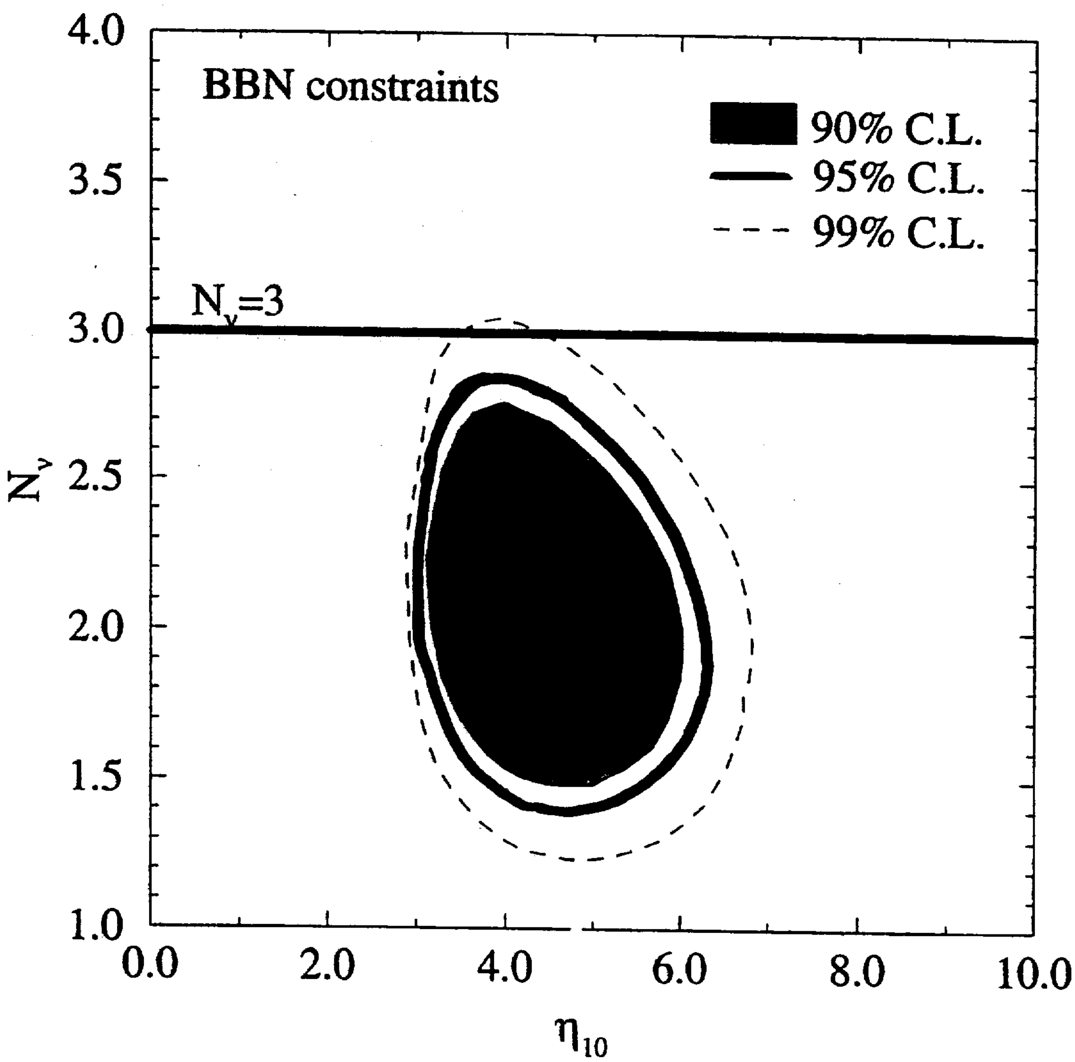
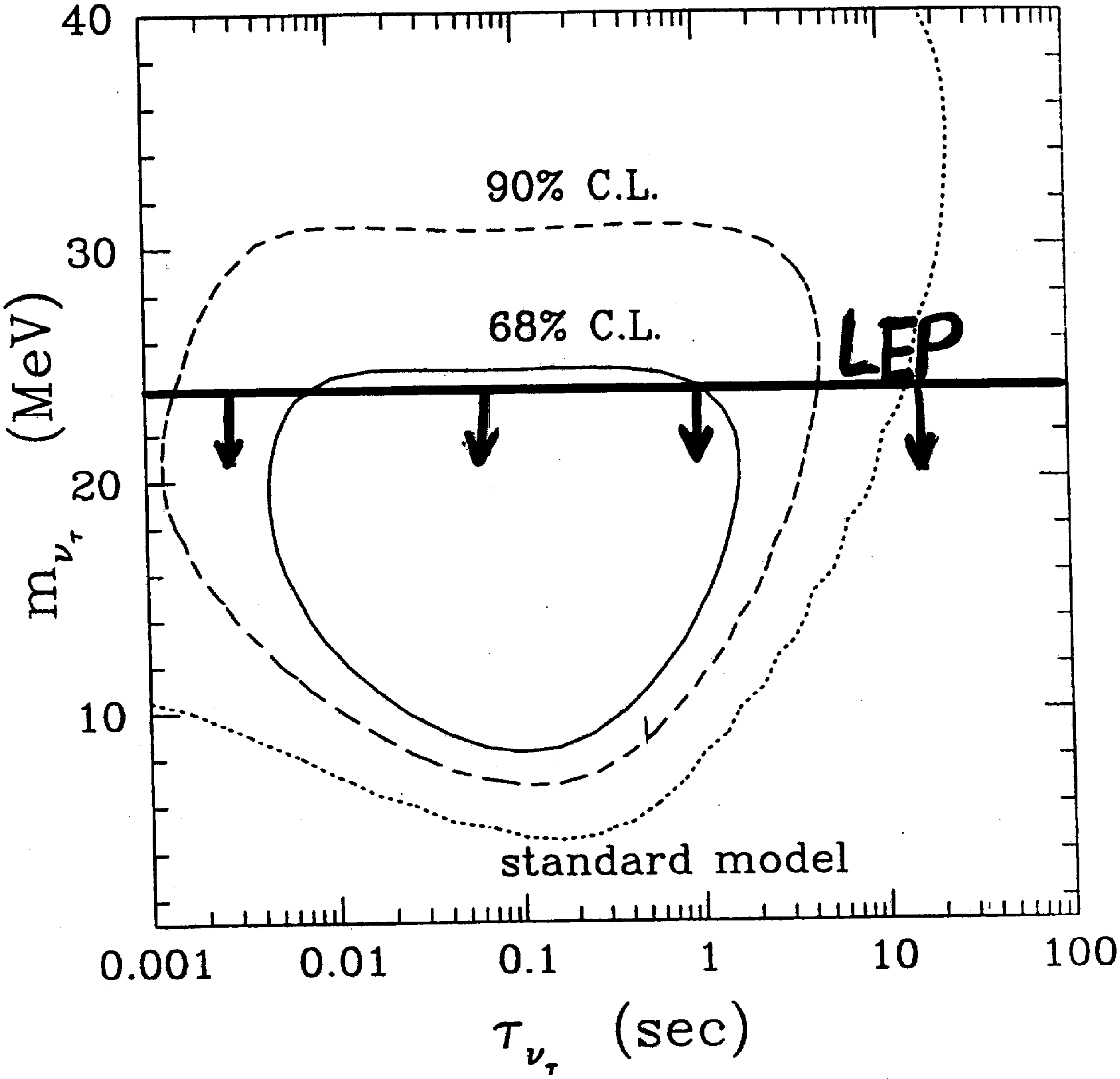

BBN constraints
90% C.L.
95% C.L.
99% C.L.
N_ν=3
N_ν
η_{10}
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.0
2.0
4.0
6.0
8.0
10.0

Figure 3

Resolving the Crisis?



$$\nu_\tau \to \nu_\mu + \phi$$

Kawasaki et al.

STATUS QUO ANTE*

- Consistency
- $\eta_{10} = 3.4 \pm 0.3$ $(\Omega_B h^2 \approx 0.01)$
- $N_\nu \lesssim 3.4$

* Walker et al. 1991 (WSSOK)

"NEW" (Dichotomies)

- Deuterium
  - High-D $\Rightarrow$ Low-η_{10} ($\lesssim 1.7$)
    $\Rightarrow Y_p \lesssim 0.235$
  - Low-D $\Rightarrow$ High-η_{10} ($\gtrsim 4.5$)
    $\Rightarrow Y_p \gtrsim 0.245$
- Lithium (PWSN)
  - $2.2\times10^{-10} \lesssim (\mathrm{Li/H})_P \lesssim 5.6\times10^{-10}$
  - Low-η_{10} ($\lesssim 1.7 \Rightarrow$ High-D)
  - High-η_{10} ($\gtrsim 3.7 \Rightarrow$ Low-D)

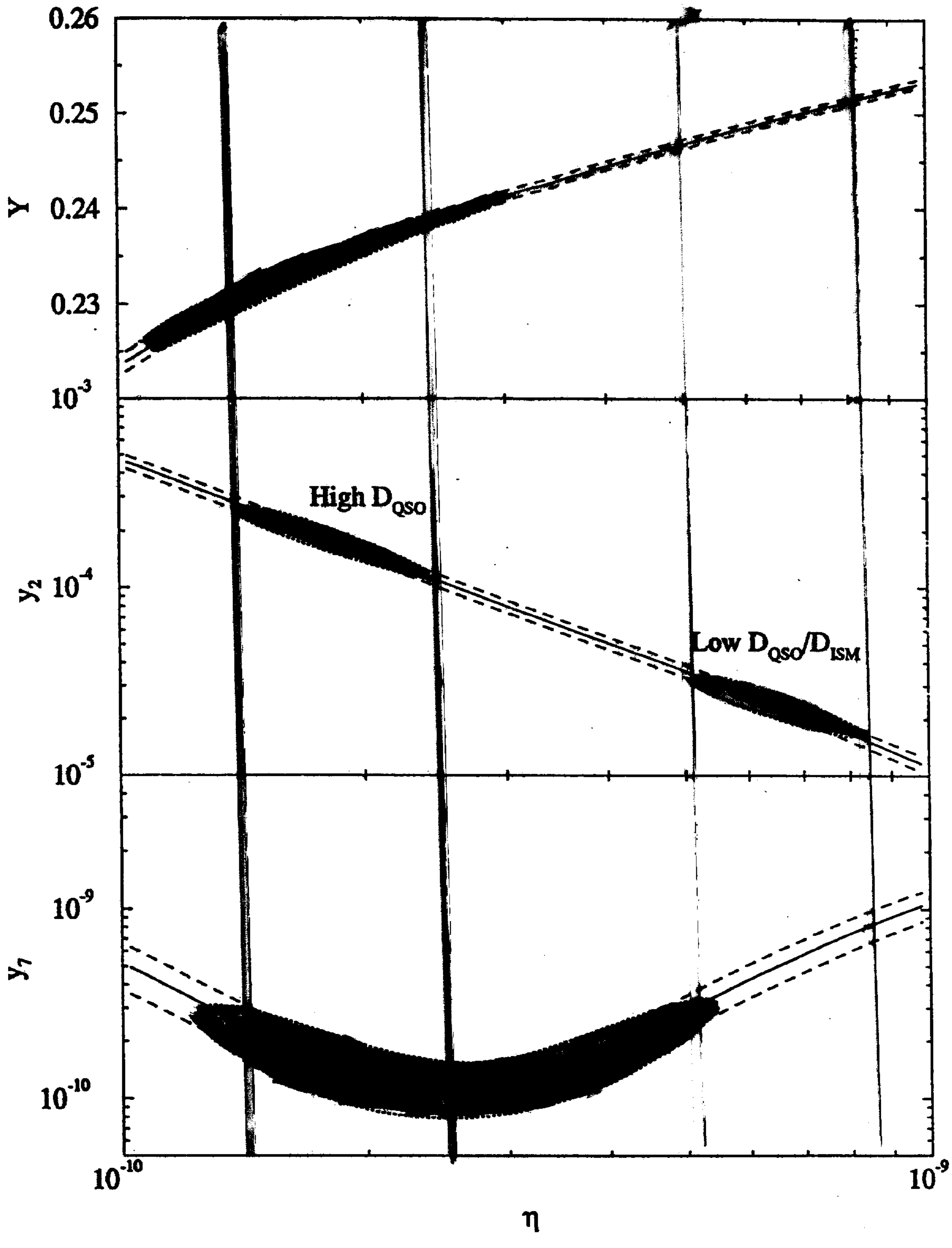
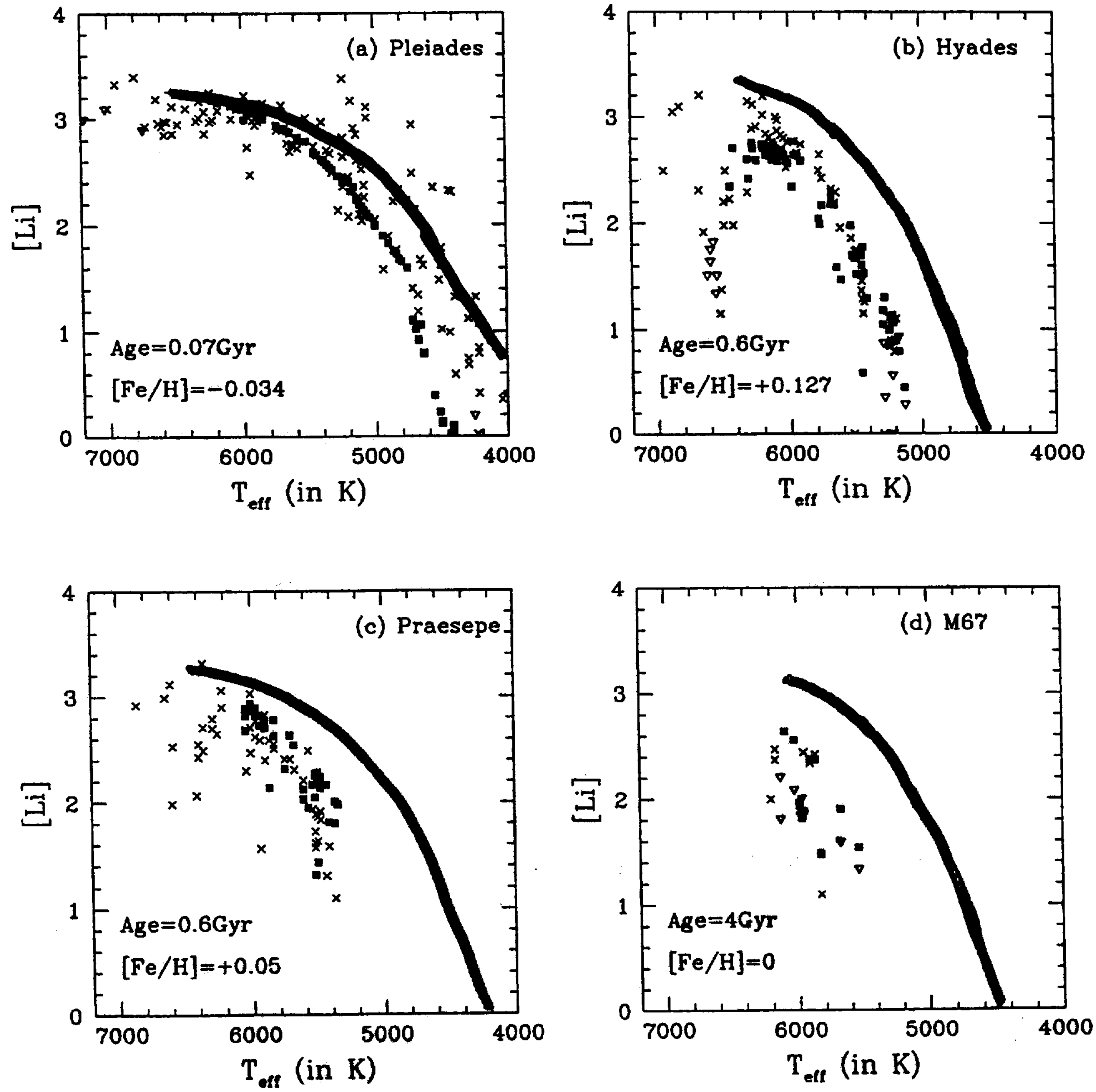
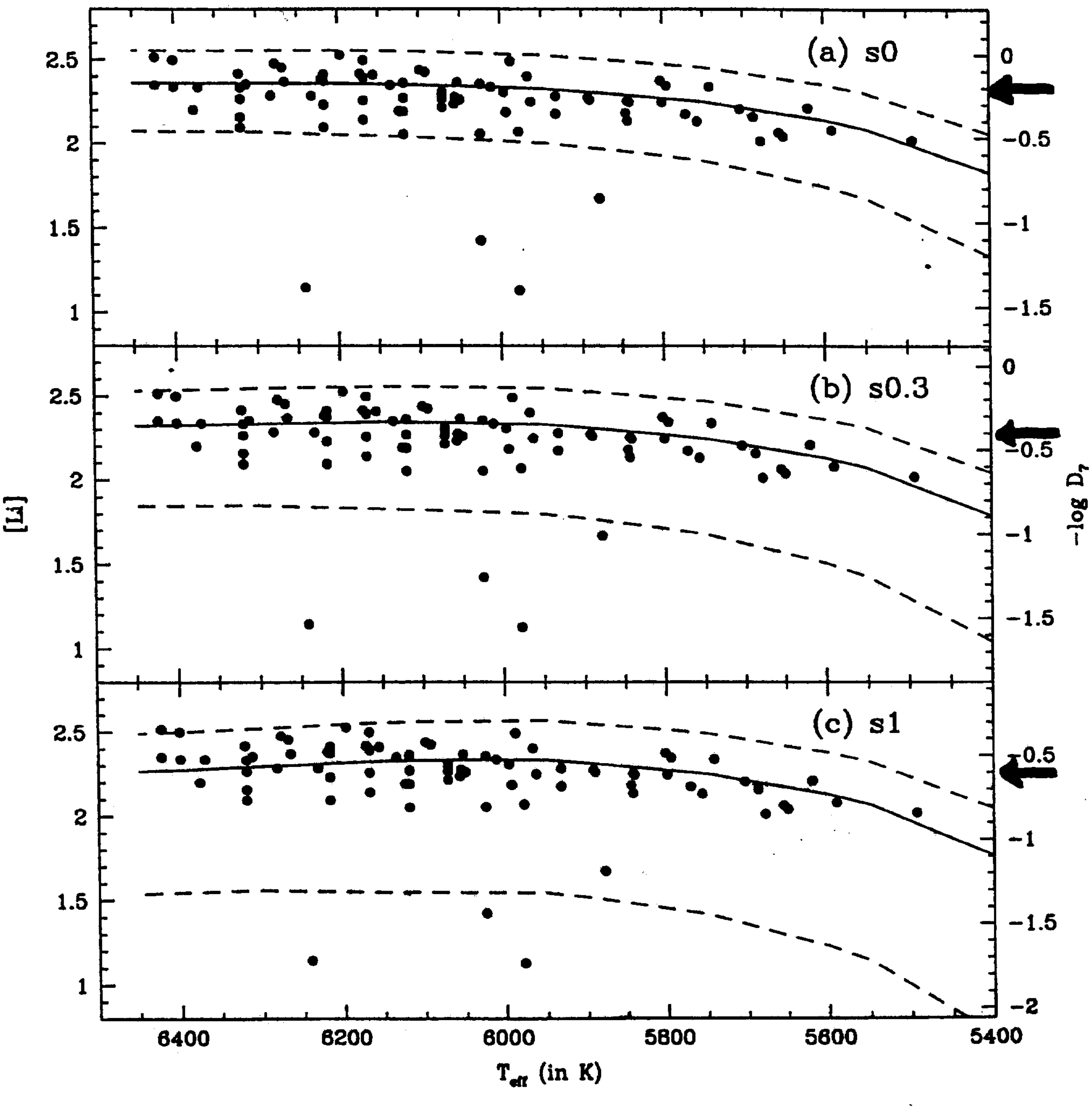

0.26
0.25
0.24
0.23
Y
10^{-3}
High D_{QSO}
y_2 10^{-4}
Low D_{QSO}/D_{ISM}
10^{-5}
10^{-9}
y_7
10^{-10}
10^{-10}
10^{-9}
η

Figure 1

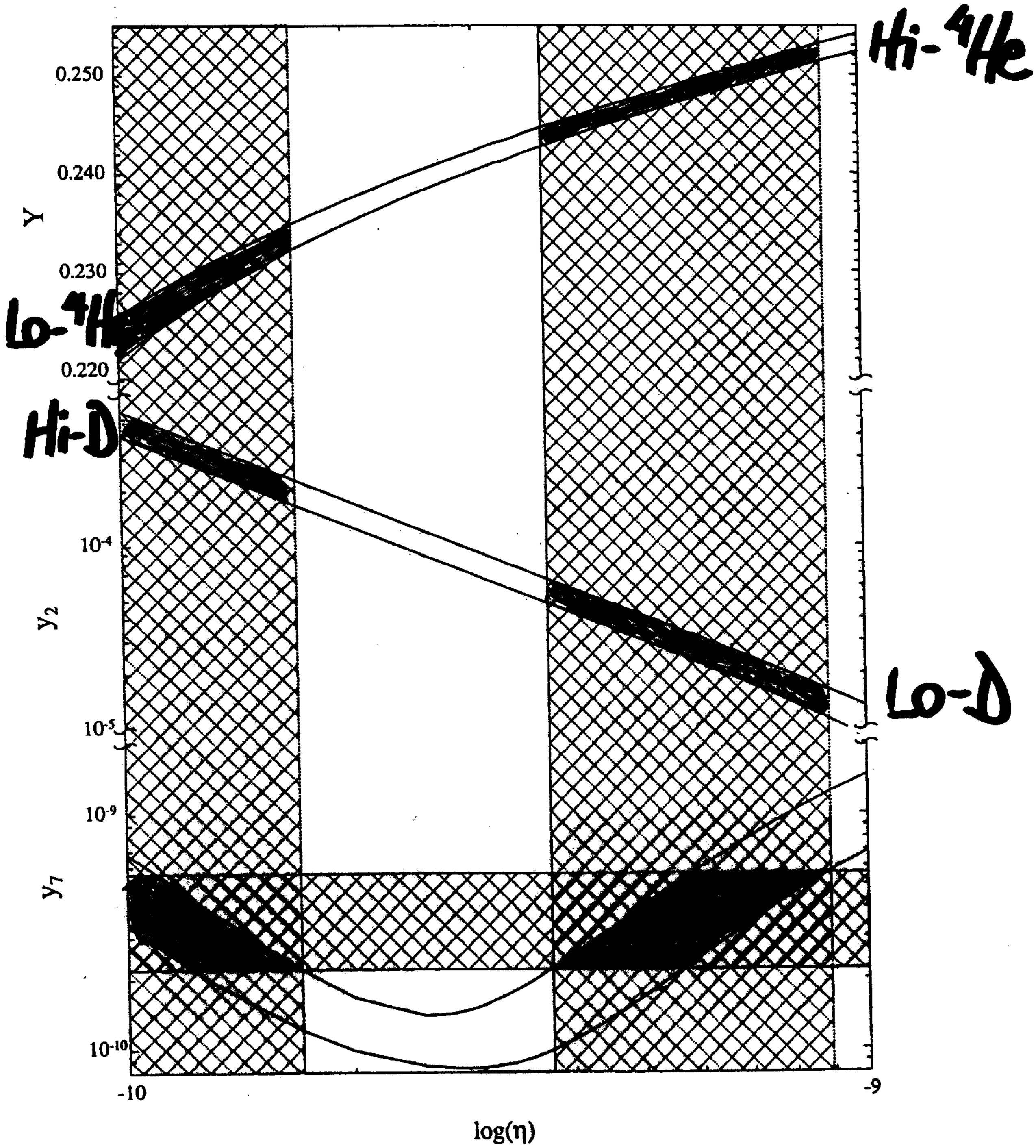


× Data
■ Rotating Models
• Non-rotating Model



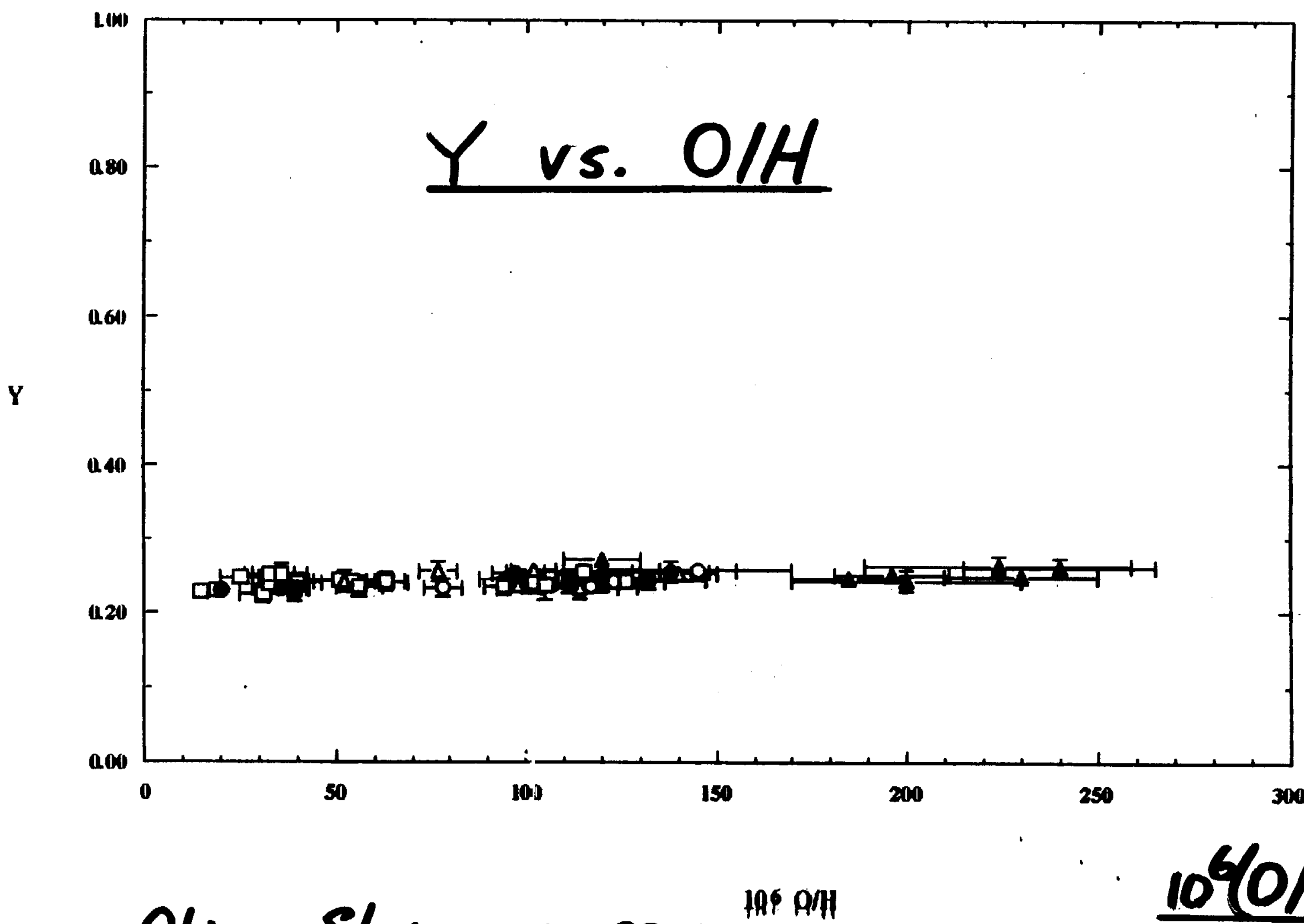
$0.2 \lesssim \log D_7 \lesssim 0.4$

Low η : $\eta_{10} = 0.8 - 1.7$



High η : $\eta_{10} = 3.7 - 9.0$

Metal - Poor HII Regions



Olive + Steigman 1995

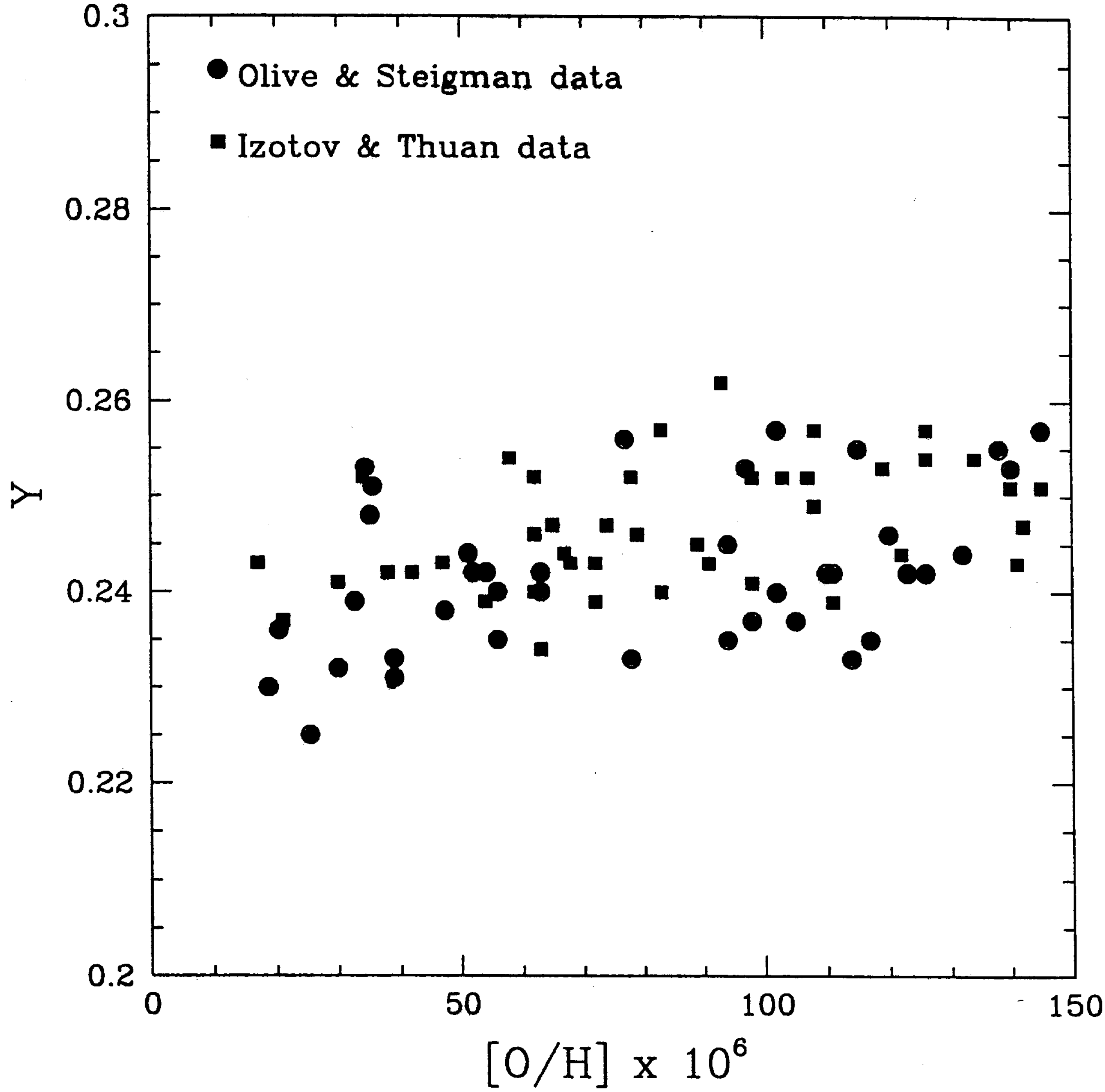
$10^6 (O/H)_\odot \approx 800$

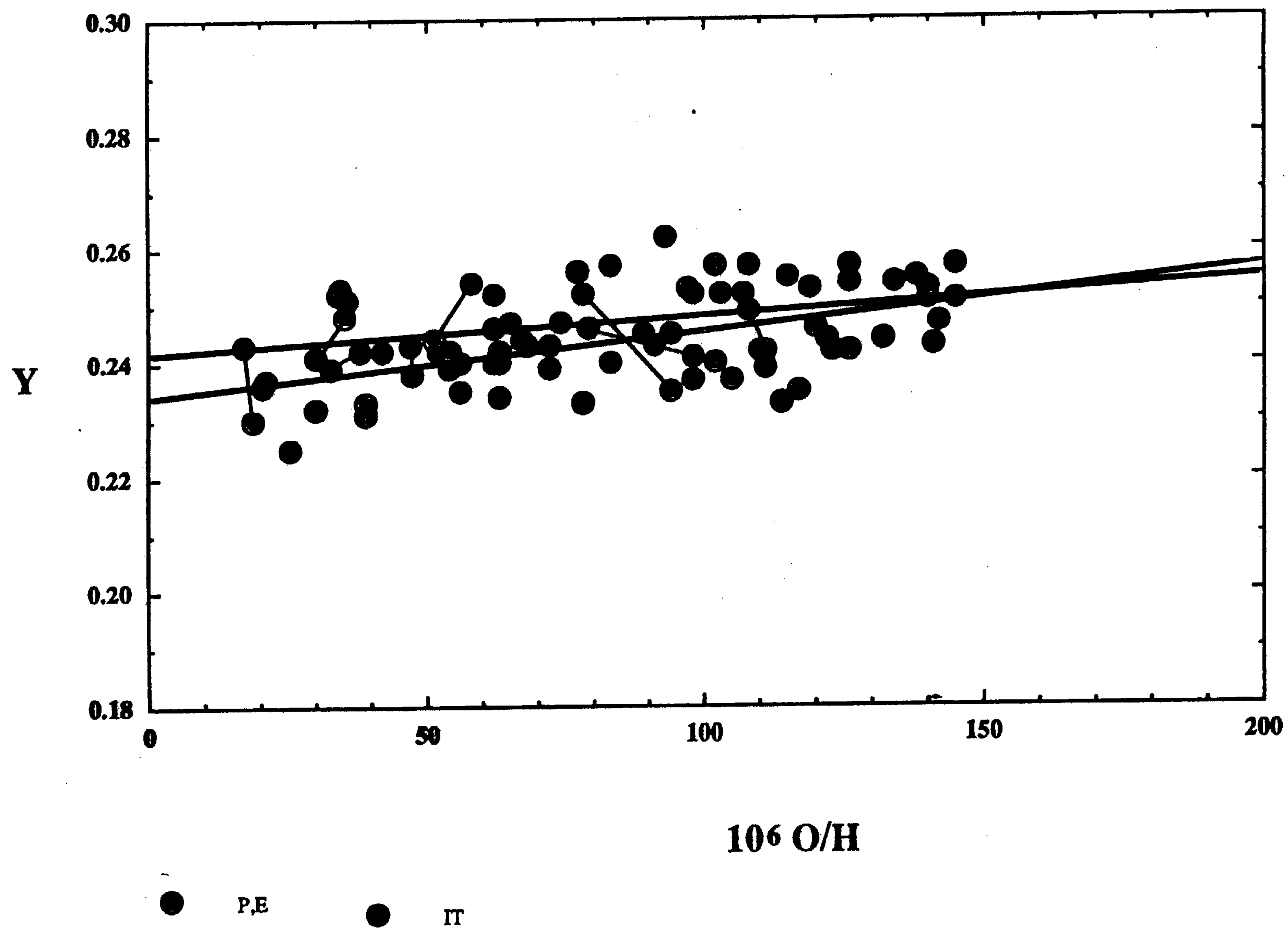
Potential Sources Of Systematic Error

- Ionization Corrections
- Collisional Excitation
- Temperature Fluctuations *
- **Stellar Absorption**
- Atomic Data (Singlet/Triplet)

* $\chi^2/DOF \approx 0.5$

* Variance of the residuals of $Y - Y(fit) = 0.007$ ($\langle\sigma\rangle = 0.010$)


Olive & Steigman data
Izotov & Thuan data
0.3
0.28
0.26
0.24
0.22
0.2
Y
0
50
100
150
[O/H] x 10^6


0.30
0.28
0.26
0.24
0.22
0.20
0.18
Y
0
50
100
150
200
10⁶ O/H
P,E
IT

- **Helium**
  - OSS: $Y_p \lesssim 0.243 \Rightarrow \eta_{10} \lesssim 3.7$
  - IT: $Y_p \lesssim 0.248 \Rightarrow \eta_{10} \lesssim 6.0$

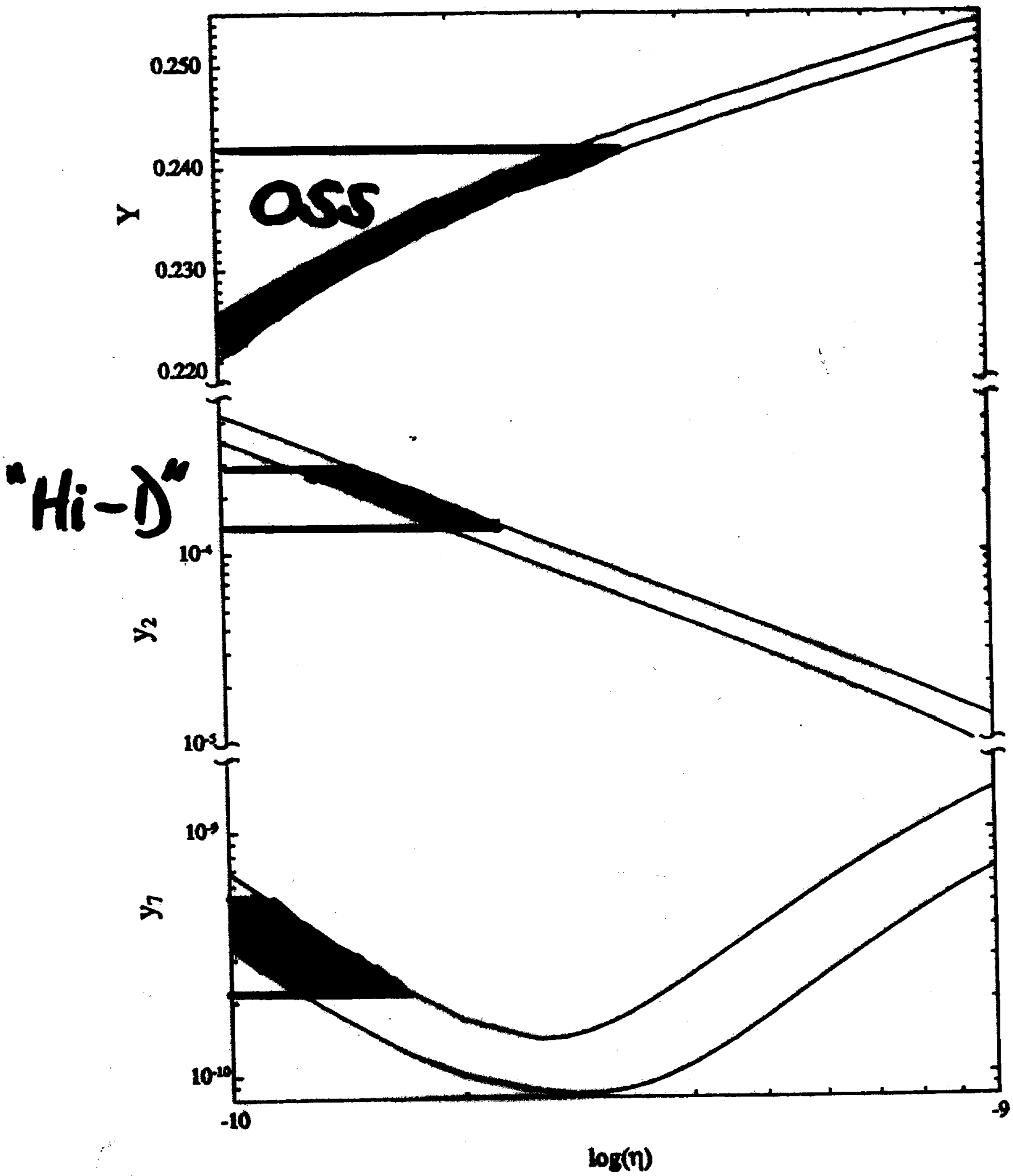
* Low-η_{10} (D, ^{4}He, ^{7}Li)

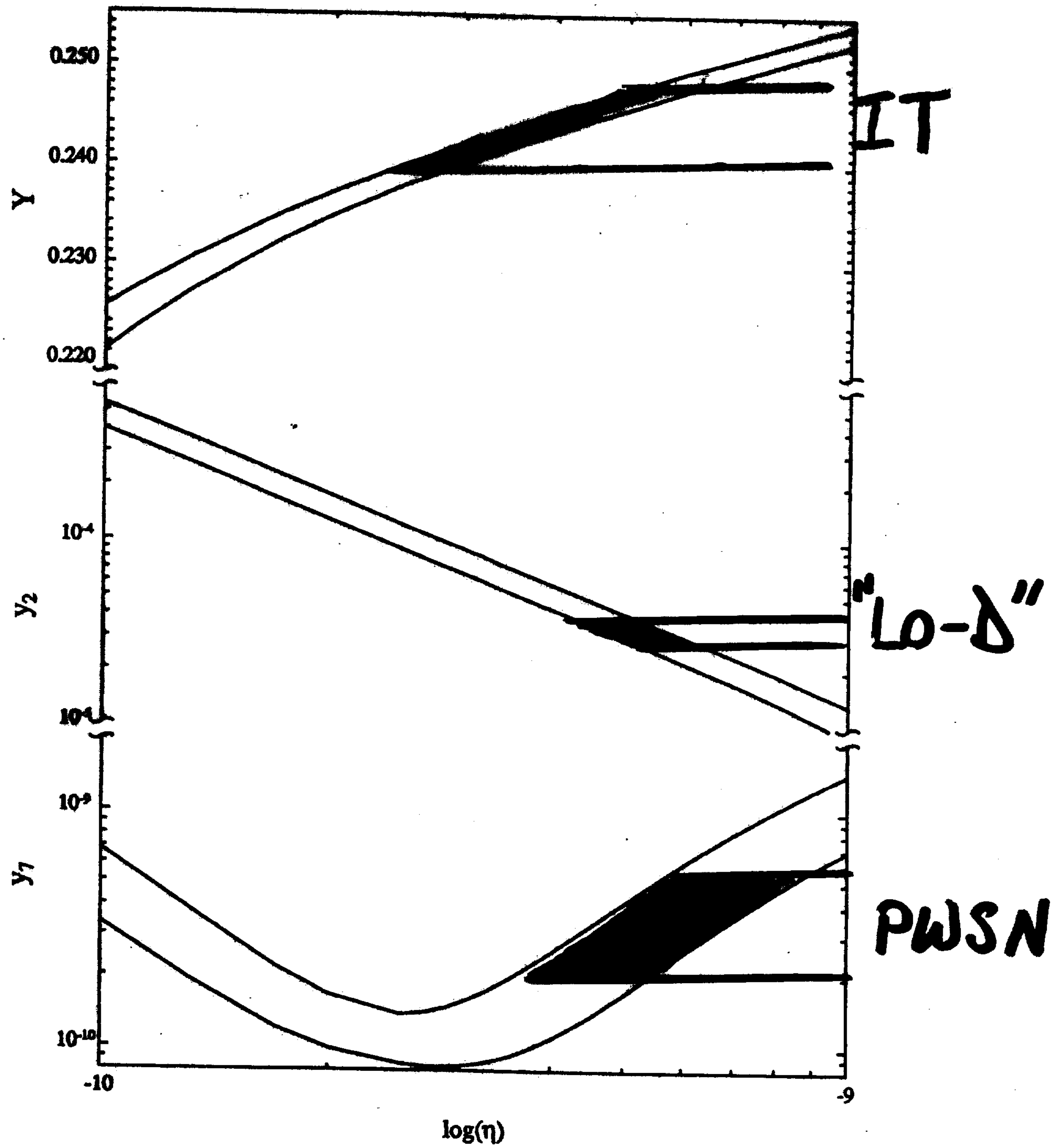
  $\Rightarrow \eta_{10} \lesssim 1.7$; $\Omega_B h^2 \lesssim 0.006$

* High-η_{10} (D, ^{7}Li ; ^{4}He ??)

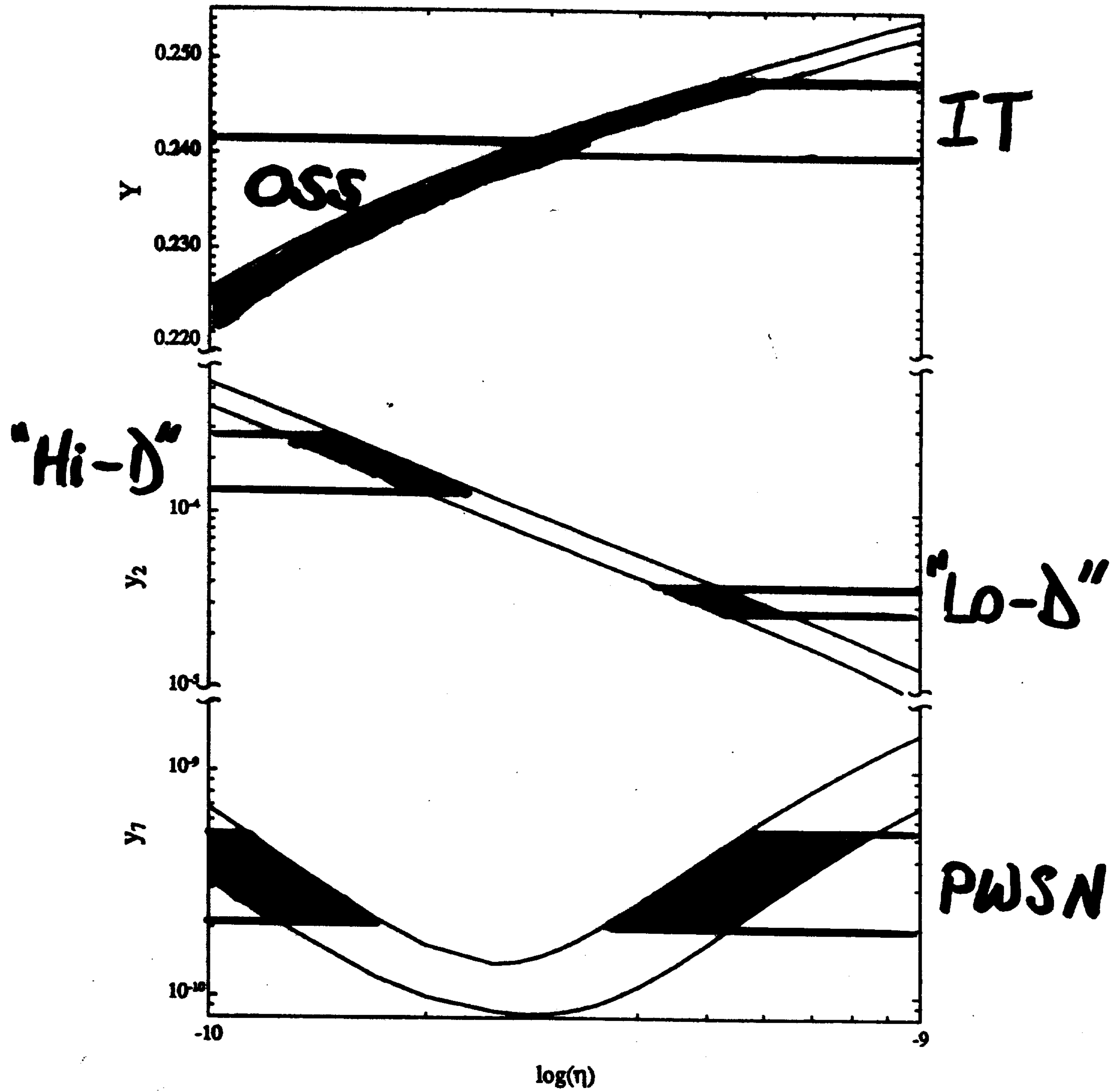
  $\Rightarrow \eta_{10} \gtrsim 4.5$; $\Omega_B h^2 \gtrsim 0.016$

  (But, $Y_p \gtrsim 0.245$??)


0.250
0.240
0.230
0.220
Y
OSS
"Hi-D"
10^{-4}
y_2
10^{-5}
10^{-9}
y_7
10^{-10}
-10
-9
log(η)



0.250
0.240
0.230
0.220
Y
IT
10^{-4}
y_2
"LO-D"
10^{-9}
y_7
PWSN
10^{-10}
-10
-9
log(η)



0.250
0.240
0.230
0.220
Y
OSS
IT
"Hi-D"
"Lo-D"
10^{-4}
10^{-5}
y_2
10^{-9}
10^{-10}
y_7
PWSN
-10
-9
log(η)

Cosmological Observables

- $H_0 = 100h = 70 \pm 15$ km/s/Mpc
- $t_0 = H_0^{-1} f(\Omega_M) = 14^{+7}_{-2}$ Gyr
- **Baryon Fraction** (Clusters)

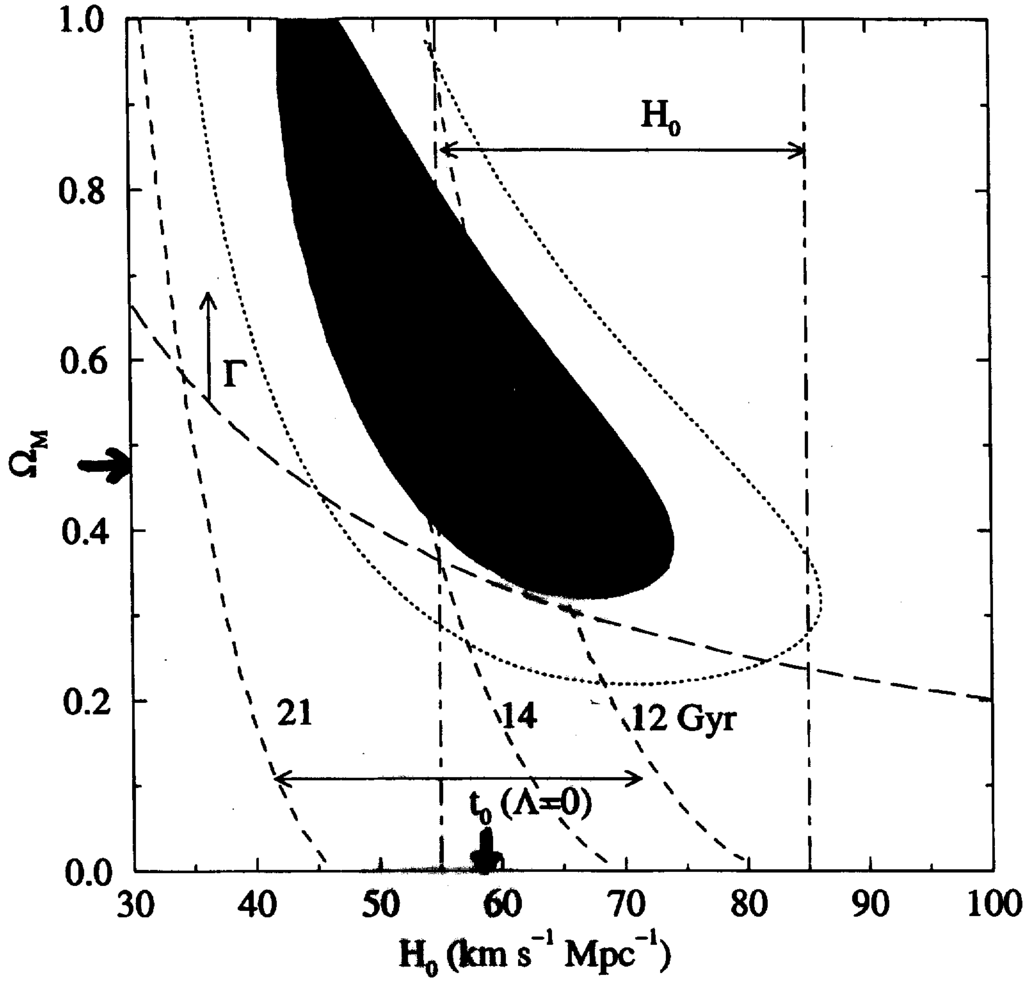
  $$\Omega_B = (f_{HG} + f_{GAL})\,\Omega_M / \Upsilon$$

  - $f_{HG}\, h^{3/2} = 0.06(1 \pm 0.1)$
  - $f_{HG} / f_{GAL} = 5.5\, h^{-3/2}$
  - $\Upsilon = 0.9\ (1.3)$

- Shape Parameter : $\Gamma = 0.255 \pm 0.017$

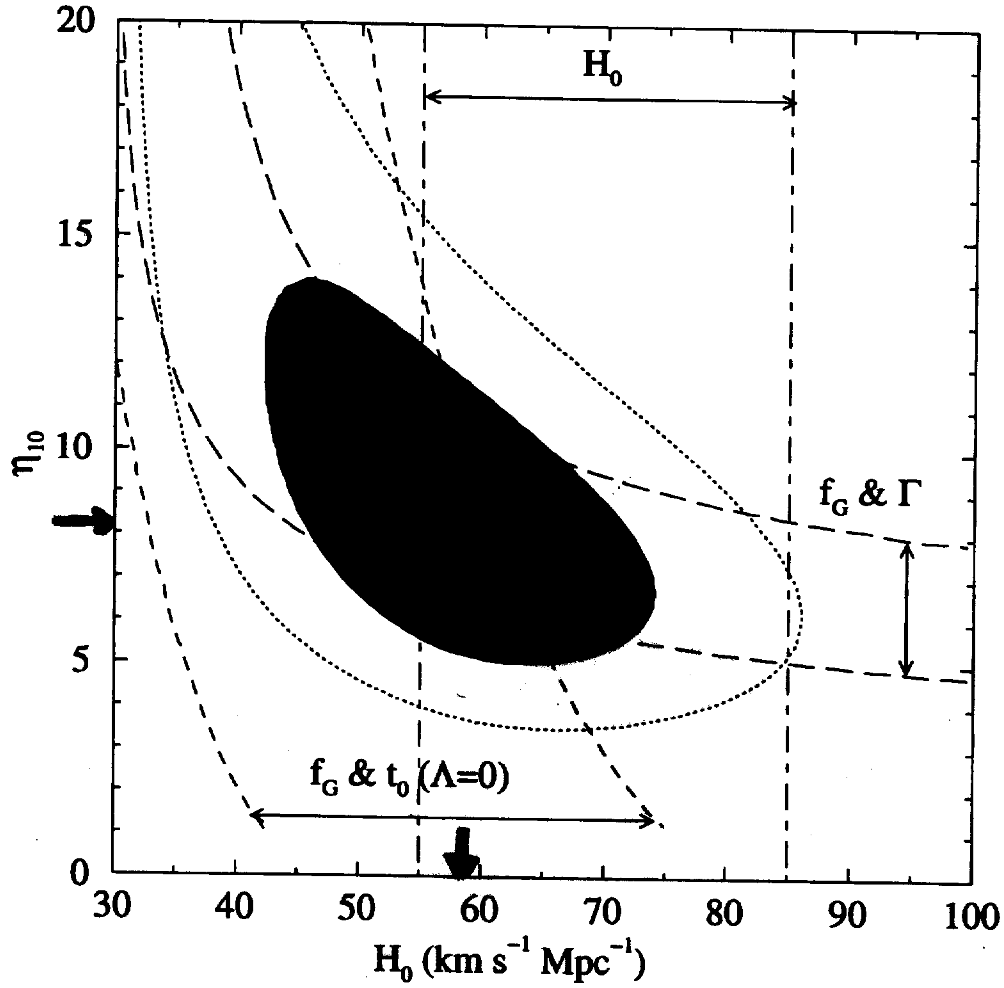
  $$\Gamma = \Omega_M h \exp[-\Omega_B(1 + (h/0.5)^{1/2}/\Omega_M)]$$
  $$-0.32(n^{-1} - 1)$$

  - "Tilt": $n = 1\ (0.8)$



$\Gamma = 0.25 \pm 0.05$

* $\eta_{10} = 8.2$, $\Omega_M = 0.48$, $H_0 = 58$

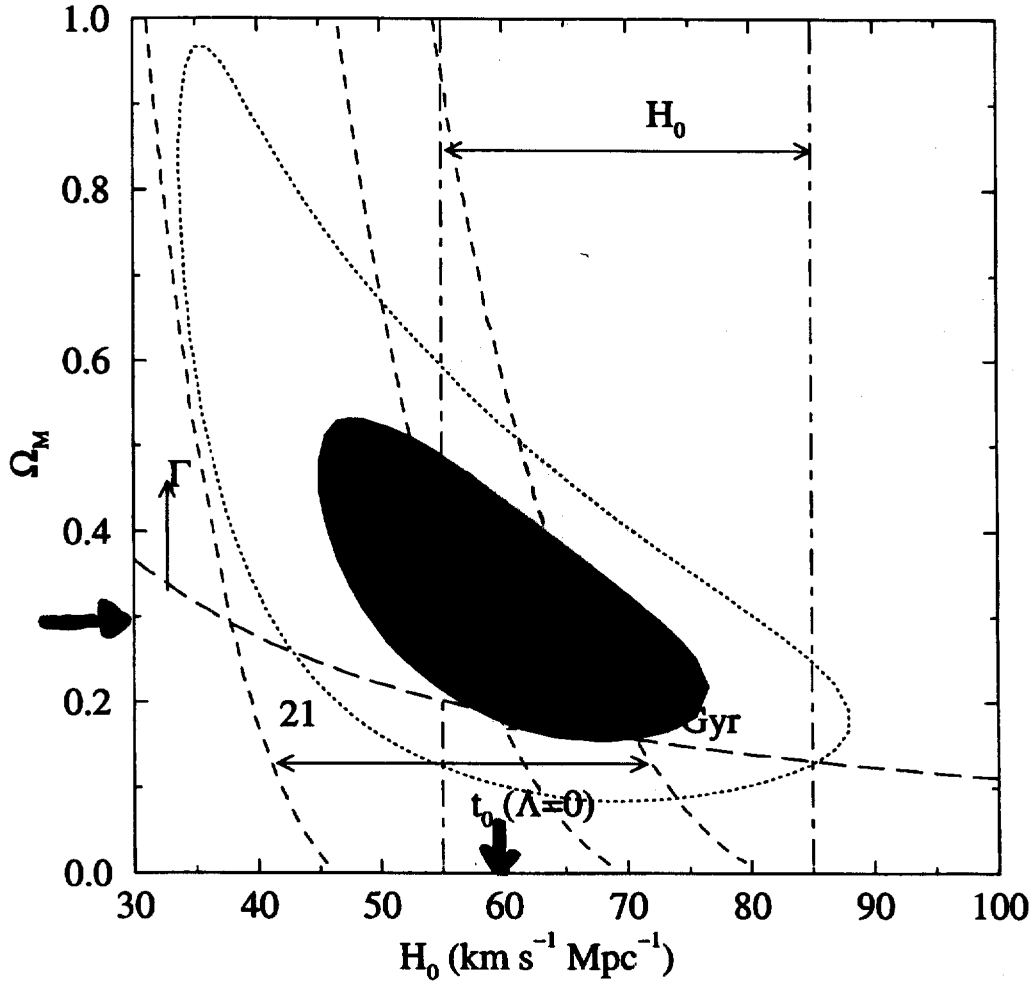


$\Gamma = 0.25 \pm 0.05$

$\Rightarrow \eta_{10} = 8.2$

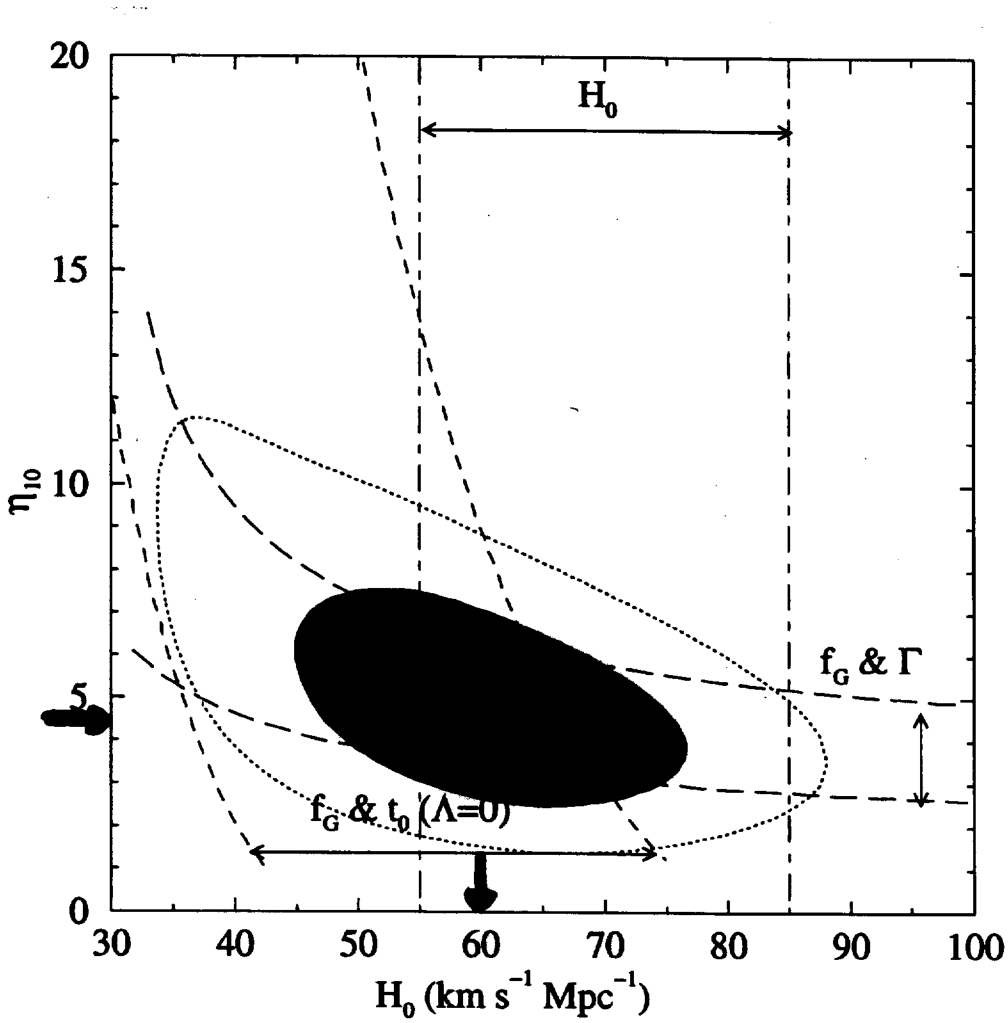
$\Gamma = 0.15 \pm 0.04$,

* $\eta_{10} = 4.6$, $\Omega_M = 0.30$, $H_0 = 60$



$\Gamma = 0.15 \pm 0.04$

$\Rightarrow \eta_{10} = 4.6$

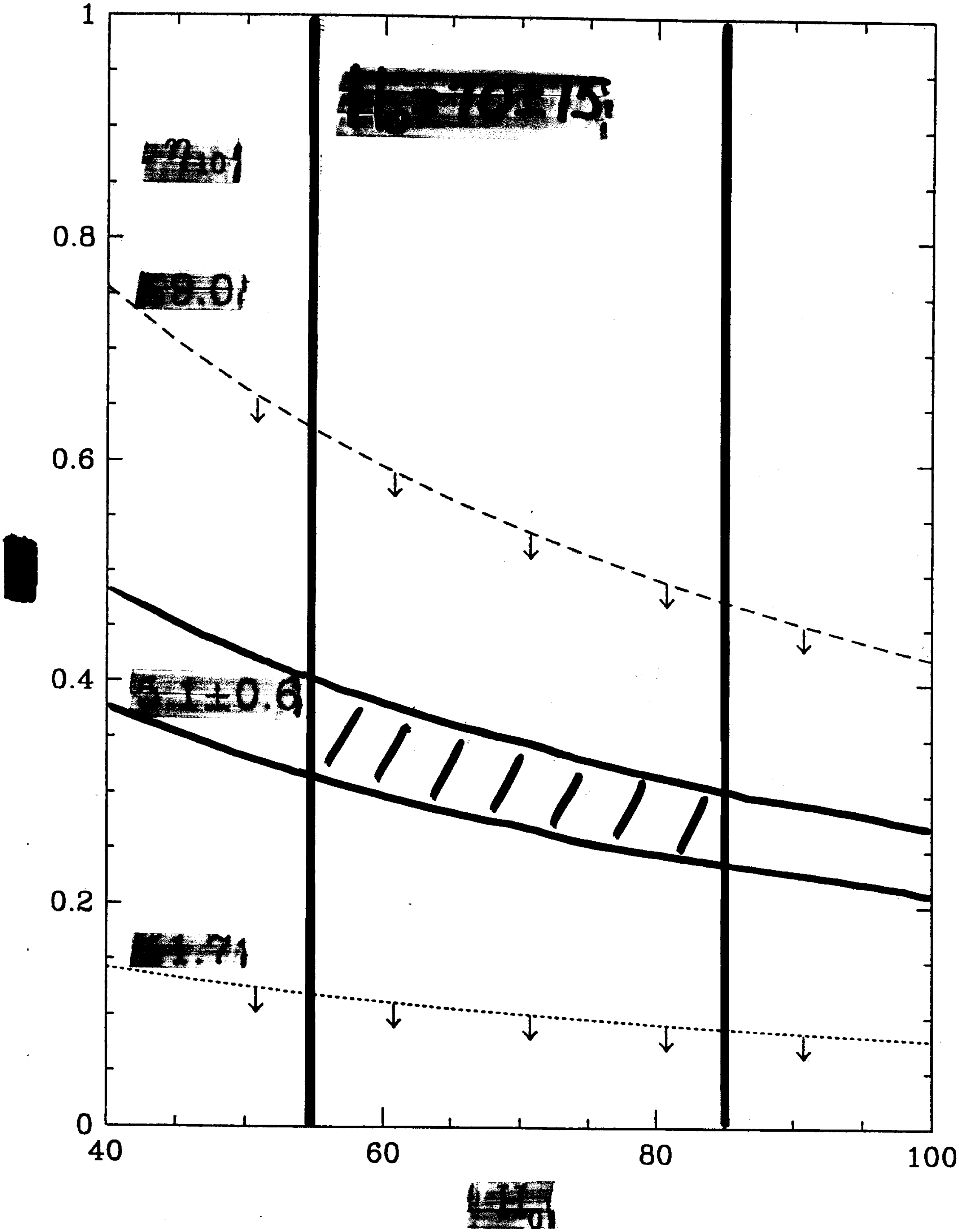


Baryon Density & Ω

- $\Omega = \Omega_B / f_B$
  - $\Omega_B h^2 = \eta_{10}/273$
  - $f_B h^{3/2} = \frac{f_{HG}}{\Upsilon} h^{3/2} \left(1 + \frac{M_*}{M_{HG}}\right)$
  - $H_0 = 100h = 70 \pm 15$ km/s/Mpc
- Burles & Tytler D/H

  $\Rightarrow \eta_{10} = 5.1 \pm 0.6 \ (2\sigma)$
- Ly-α Forest

  $\Rightarrow \eta_{10} \approx 8h^{1/2} \ (\pm \gtrsim 50\%)$


[redacted]
[redacted]
[redacted]
[redacted]
[redacted]
[redacted]
[redacted]
1
0.8
0.6
0.4
0.2
0
40
60
80
100

BBN Is Observationally Challenged!

- Bad Data? (D?, ^4He?)
- Bad Extrapolation From Here And Now To There And Then?
- New Physics? ($m_{\nu_\tau} \approx 10\,MeV$?)

Options	D	^4He	^7Li	Non-BBN
Lo-η	✓(?)	✓(?)	✓	X (?)
Hi-η	✓(?)	✓(?)	✓	✓ (?)

* More Data Needed! (D, ^4He)

666* - A Devilishly Good Model

* $\eta_{10} = 6$; $\Omega_M = 0.6$; $h = 0.6$

- $\Omega_B = \eta_{10}/273 = 0.06$*
- $f_B \equiv \Omega_B/\Omega_M = 0.10$ $(f_B h^{3/2} = 0.05)$
- $\Gamma = \Omega_M h \exp\left[-\Omega_B\left(1 + \frac{(2h)^{1/2}}{\Omega_M}\right)\right] = 0.30$
- $\eta_{10} = 8h^{1/2}$ (Ly-α ; $\Omega_B h^{3/2} = 0.03$)
- $\begin{cases} t_0 = 12 \text{ Gyr} & (\Lambda = 0) \\ t_0 = 13 \text{ Gyr} & (k = 0) \end{cases}$
- $(D/H)_P = 2.7 \times 10^{-5}$

  $Y_P = 0.249$ (??)

  $(Li/H)_P = 4.3 \times 10^{-10}$