Big Bang Nucleosynthesis-Post Planck

- BBN and the WMAP/Planck determination of η, $\Omega_B h^2$
- Observations and Comparison with Theory

  - D/H   - ^{4}He   - ^{7}Li

- The Li Problem

- Neutrinos

Historical Perspective

Intimate connection with CMB

Alpher
Herman
Gamow

Conditions for BBN:

Require $T > 100$ keV $\Rightarrow t < 200$ s

$$\sigma v(p + n \rightarrow D + \gamma) \approx 5 \times 10^{-20}\ \mathrm{cm^3/s}$$

$$\Rightarrow n_B \sim 1/\sigma v t \sim 10^{17}\ \mathrm{cm^{-3}}$$

Today:

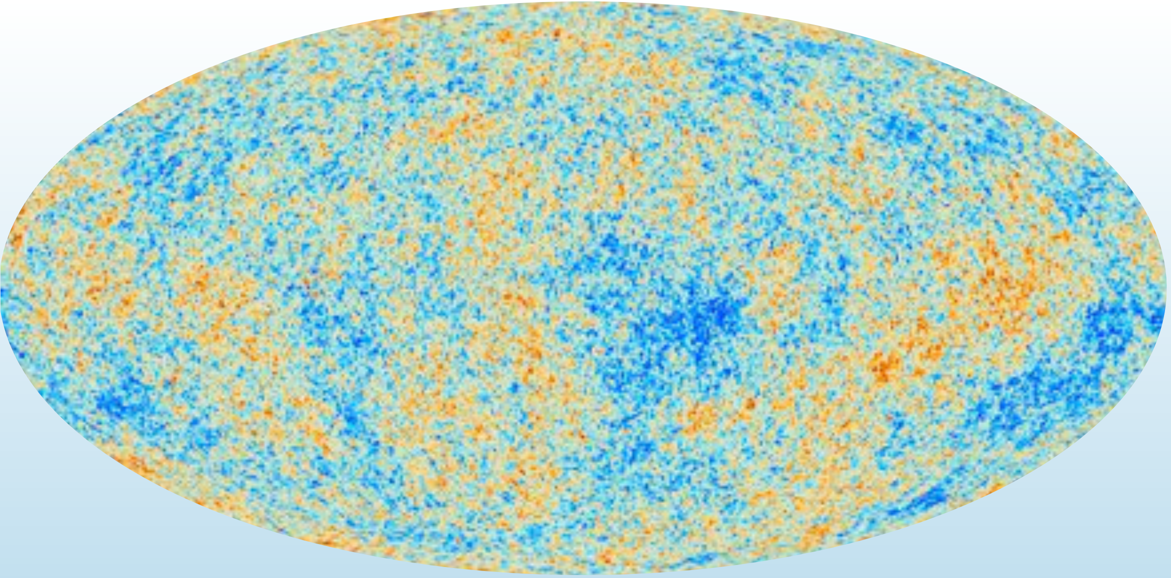
$$n_{Bo} \sim 10^{-7}\ \mathrm{cm^{-3}}$$

and

$$n_B \sim R^{-3} \sim T^3$$

Predicts the CMB temperature

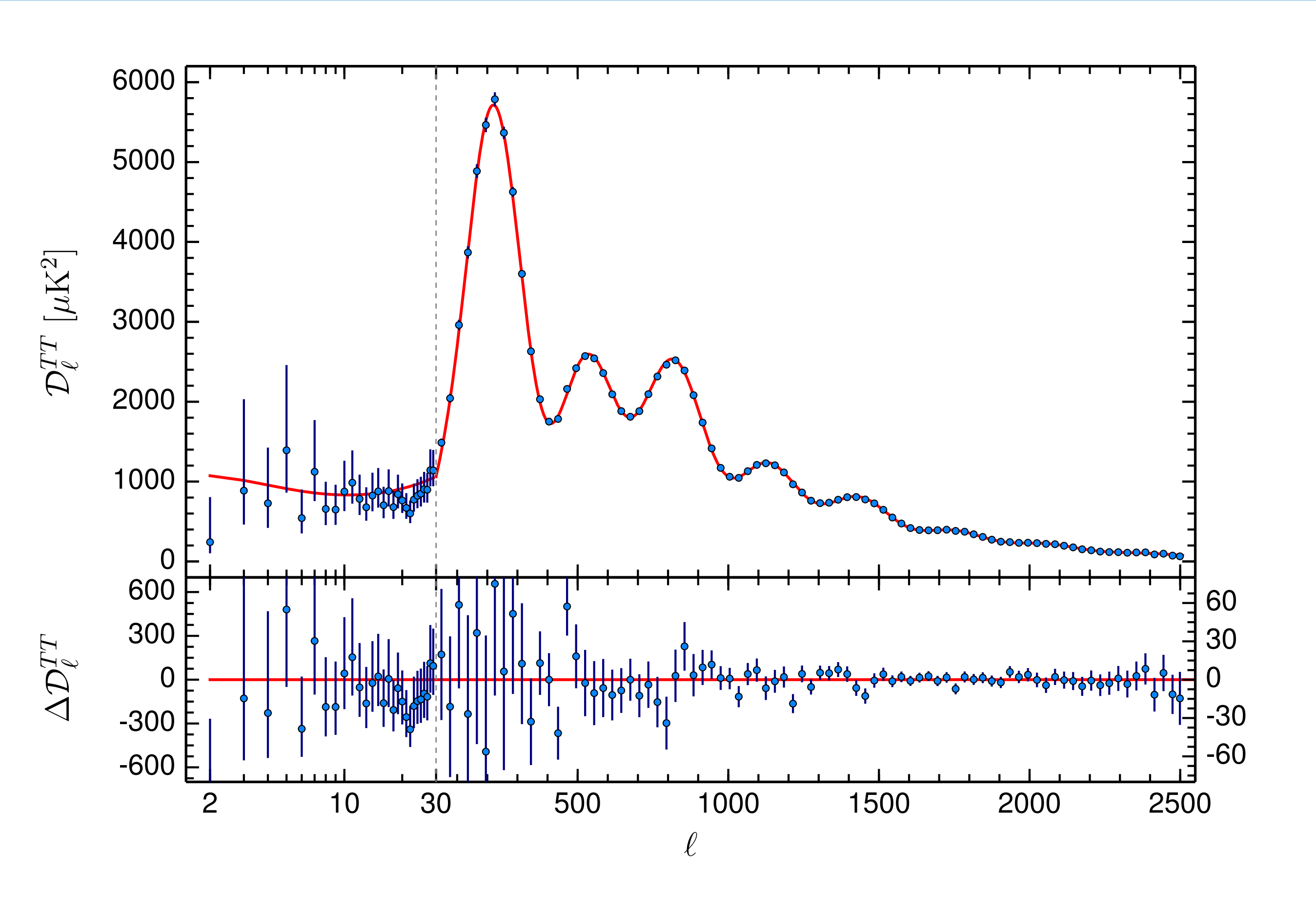
$$T_o = (n_{Bo} / n_B)^{1/3}\, T_{BBN} \sim 10\ \mathrm{K}$$

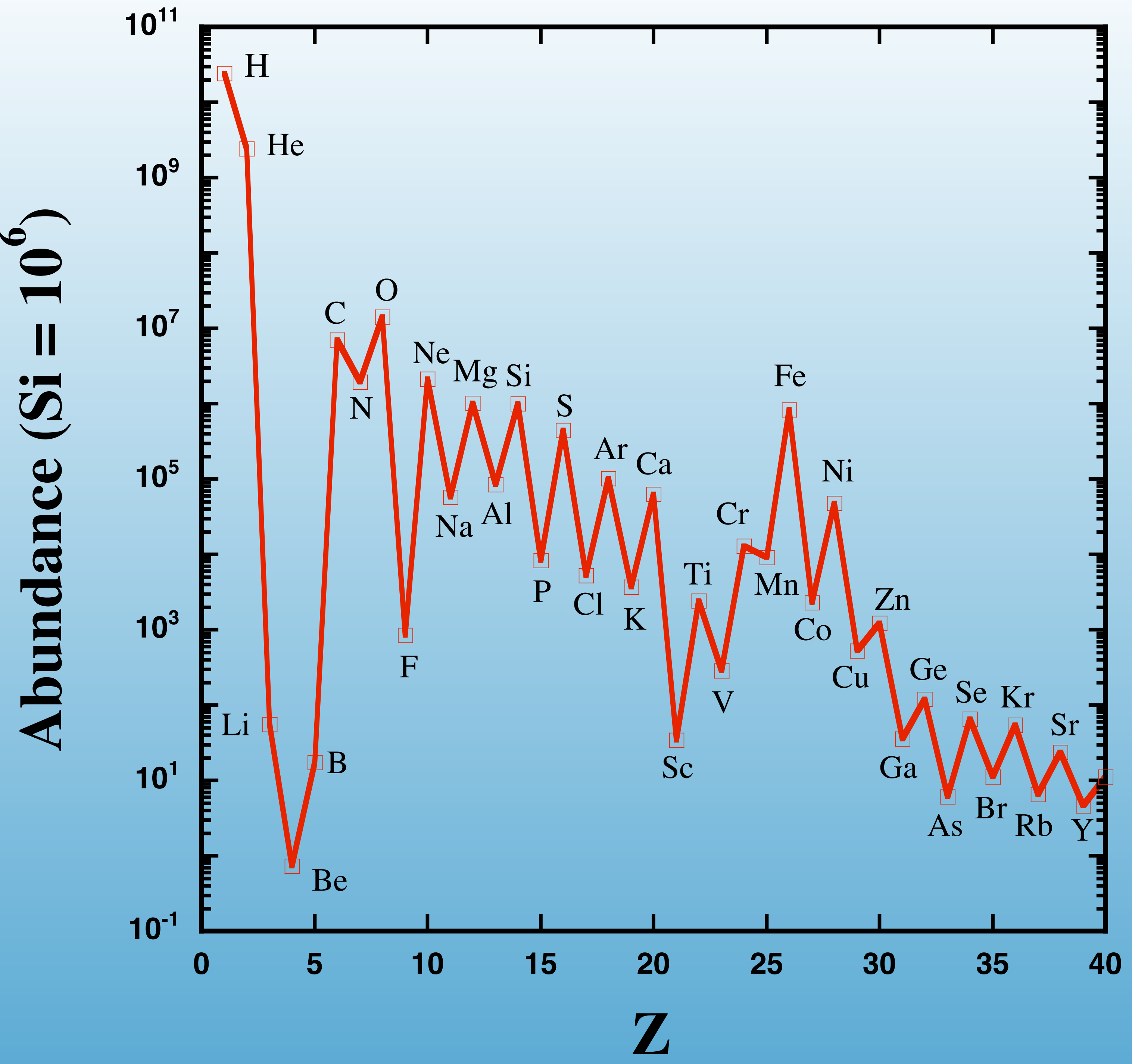


Planck best fit

$\Omega_B h^2 = 0.02226 \pm 0.00023$

$\eta_{10} = 6.09 \pm 0.06$





Abundance (Si = 10^6)
Z
10^{11}
10^9
10^7
10^5
10^3
10^1
10^{-1}
0
5
10
15
20
25
30
35
40
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y

BBN could <u>not</u> explain the abundances (or patterns) of <u>all</u> the elements.

$\Longrightarrow$ growth of stellar nucleosynthesis

But,

Questions persisted:

25% (by mass) of ^{4}He ?

D?

Resurgence:

BBN could successfully account for the abundance of

D, ^{3}He, ^{4}He, ^{7}Li.

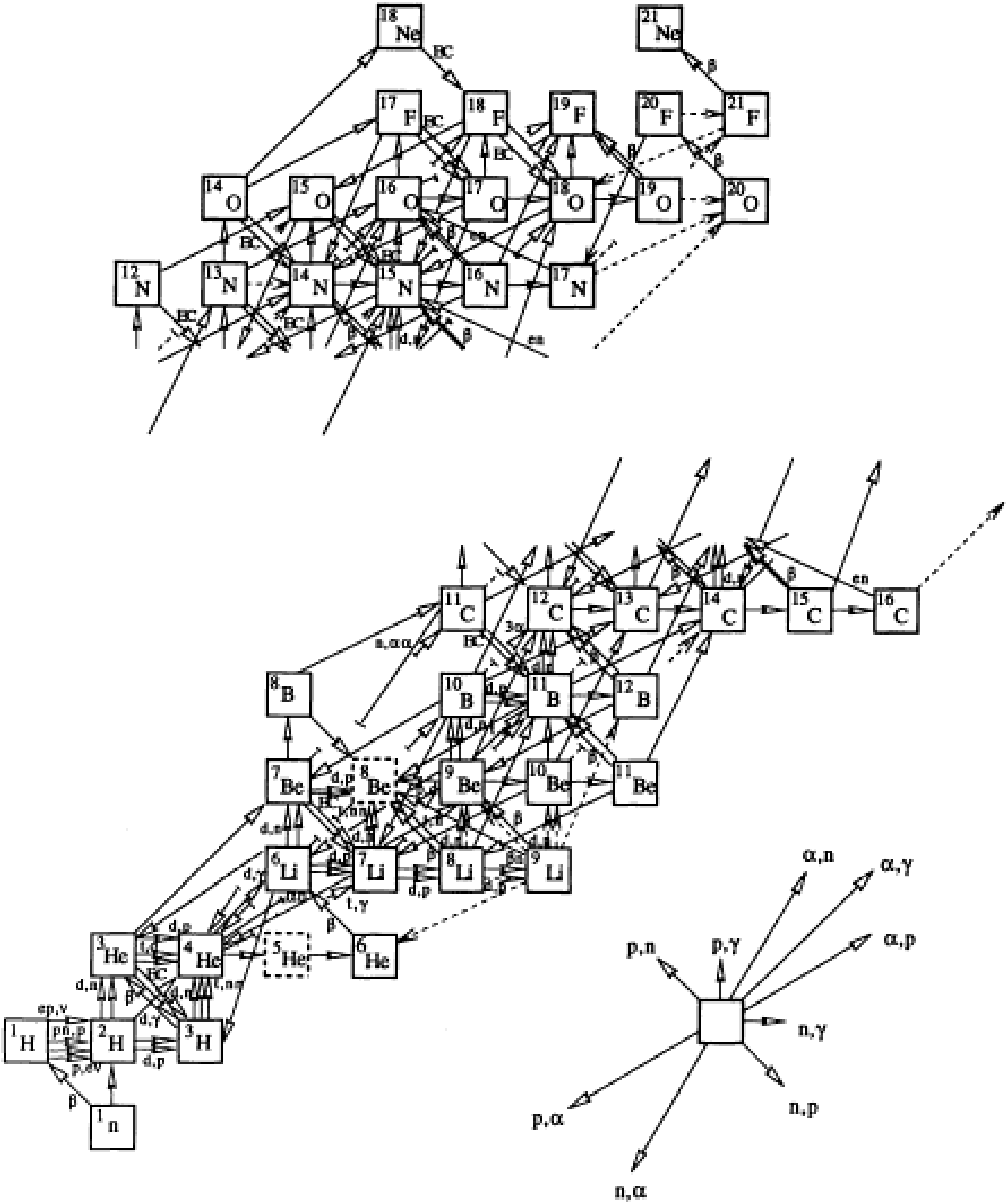
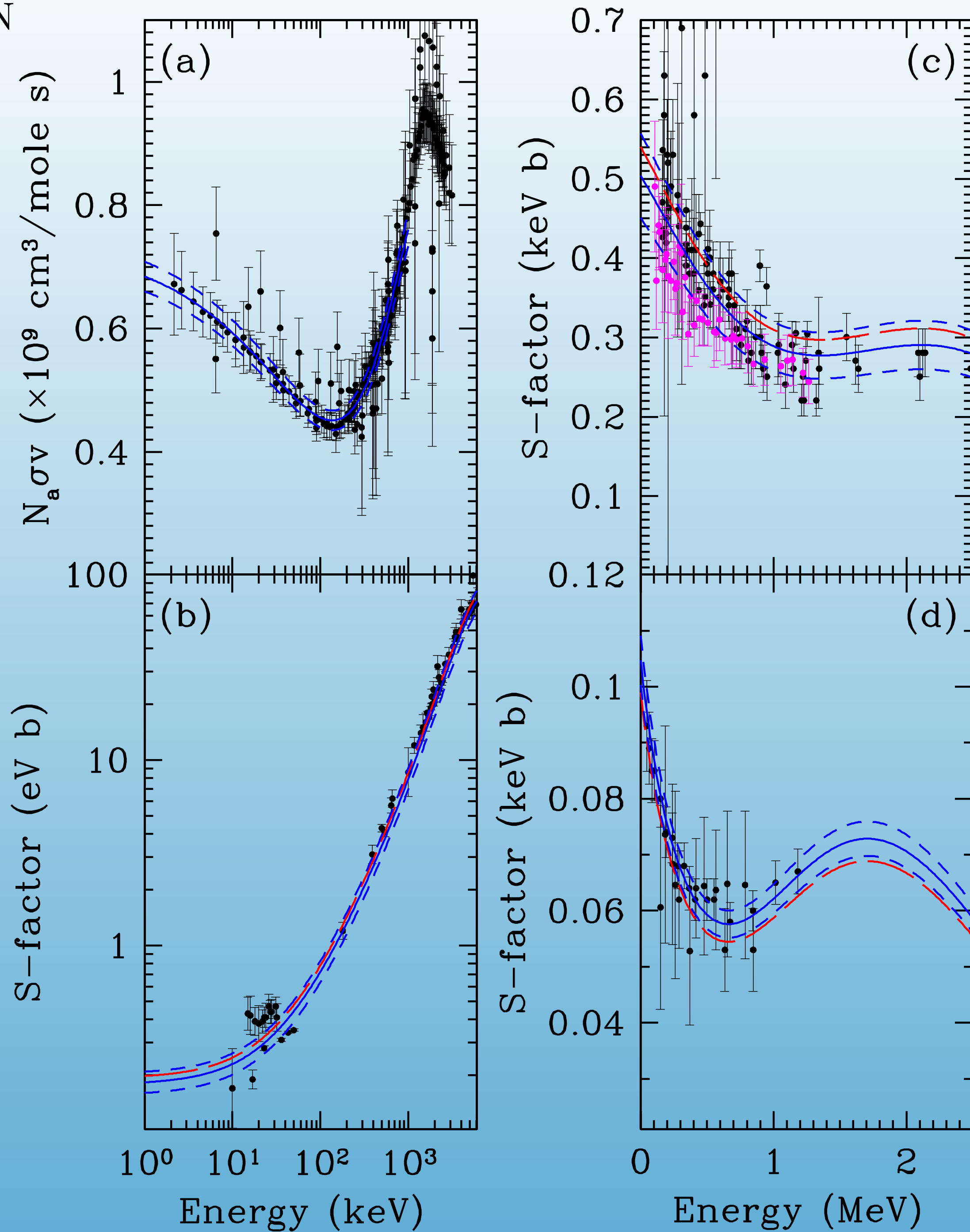


FIG. 1.—Reaction network used in the code. Estimated reactions are shown with dashed lines.

Table 1: Key Nuclear Reactions for BBN

Source	Reactions	
NACRE	$d(p,\gamma)^3$He	(b)
	$d(d,n)^3$He	
	$d(d,p)t$	
	$t(d,n)^4$He	
	$t(\alpha,\gamma)^7$Li	(d)
	^{3}He$(\alpha,\gamma)^7$Be	(c)
	^{7}Li$(p,\alpha)^4$He	
SKM	$p(n,\gamma)d$	
	^{3}He$(d,p)^4$He	
	^{7}Be$(n,p)^7$Li	
This work	^{3}He$(n,p)t$	(a)
PDG	τ_n	

NACRE
Cyburt, Fields, KAO
Nollett & Burles
Coc et al.



Conditions in the Early Universe:

$$T \gtrsim 1 \textbf{ MeV}$$

$$\rho = \frac{\pi^2}{30}(2 + \frac{7}{2} + \frac{7}{4}N_\nu)T^4$$

$$\eta = n_B/n_\gamma \sim 10^{-10}$$

β-Equilibrium maintained by weak interactions

Freeze-out at ~ 1 MeV determined by the competition of expansion rate $H \sim T^2/M_p$ and the weak interaction rate $\Gamma \sim G_F^2 T^5$

$$\begin{aligned} n + e^+ &\leftrightarrow p + \bar{\nu}_e \\ n + \nu_e &\leftrightarrow p + e^- \\ n &\leftrightarrow p + e^- + \bar{\nu}_e \end{aligned}$$

At freezeout n/p fixed modulo free neutron decay, $(n/p) \simeq 1/6 \rightarrow 1/7$

Nucleosynthesis Delayed (Deuterium Bottleneck)

$p + n \rightarrow \mathbf{D} + \gamma$ $\quad\quad\quad \Gamma_p \sim n_B \sigma$

$p + n \leftarrow \mathbf{D} + \gamma$ $\quad\quad\quad \Gamma_d \sim n_\gamma \sigma e^{-E_B/T}$

Nucleosynthesis begins when $\Gamma_p \sim \Gamma_d$

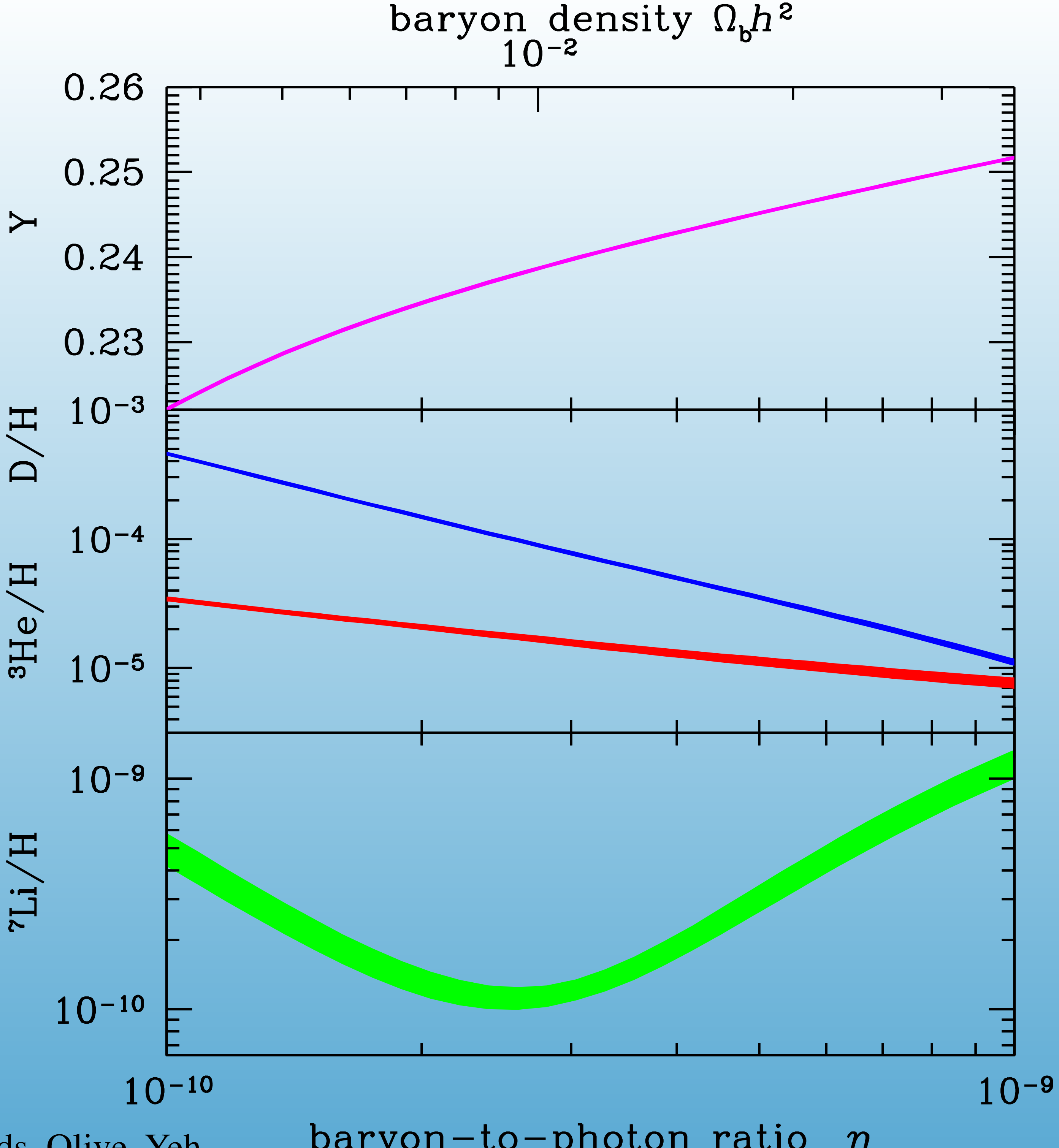
$\frac{n_\gamma}{n_B} e^{-E_B/T} \sim 1$ $\quad\quad$ **@** $T \sim 0.1$ **MeV**

All neutrons $\rightarrow$ ^{4}**He**

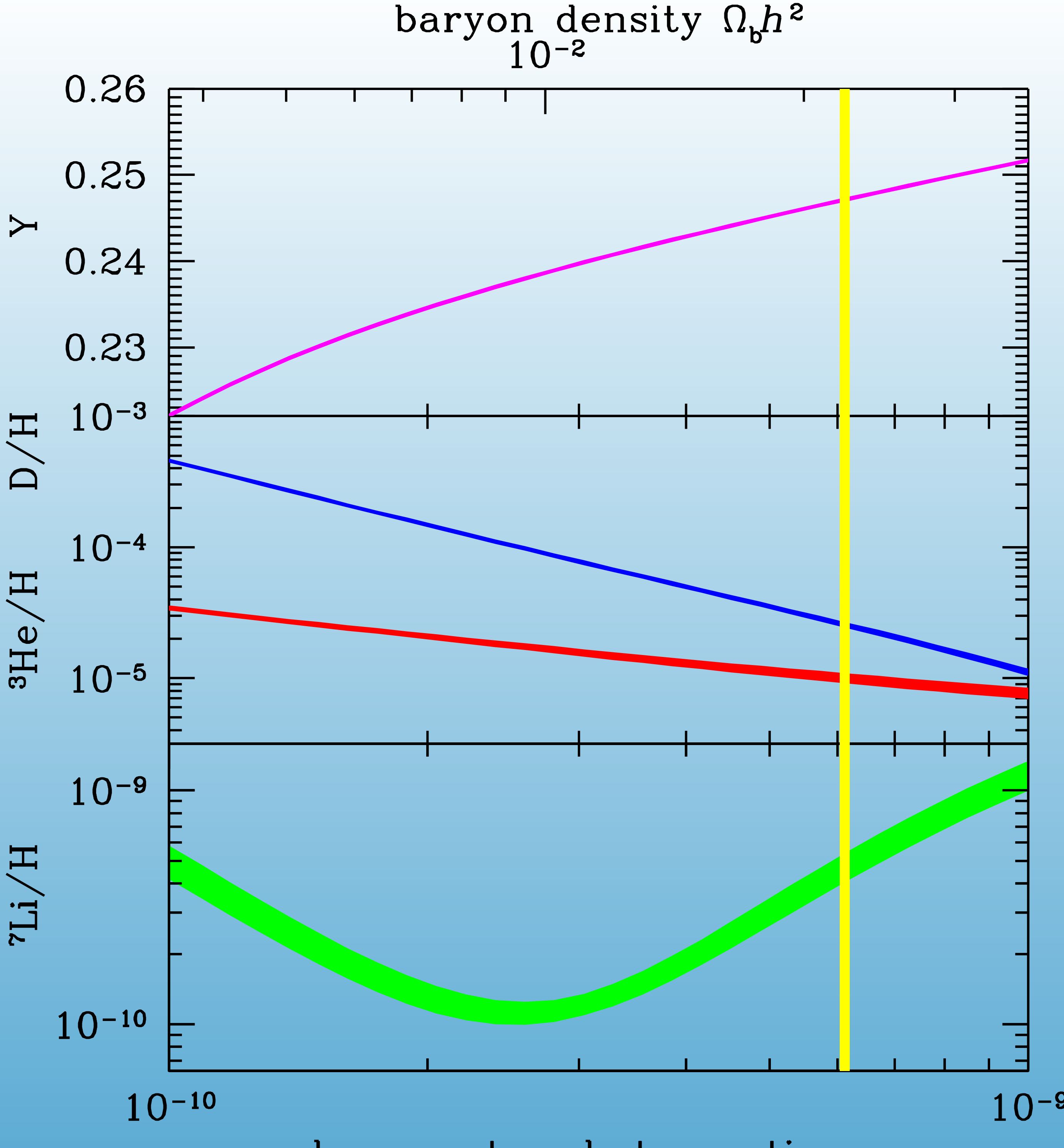
$$Y_p = \frac{2(n/p)}{1 + (n/p)} \simeq 25\%$$

Remainder:

D, ^{3}**He** $\sim 10^{-5}$ **and** ^{7}**Li** $\sim 10^{-10}$ **by number**



Cyburt, Fields, Olive, Yeh



Cyburt, Fields, Olive, Yeh

Big Bang Nucleosynthesis

- Production of the Light Elements: D, ^{3}He, ^{4}He, ^{7}Li
  - ^{4}He observed in extragalctic HII regions:
    abundance by mass = 25%
  - ^{7}Li observed in the atmospheres of dwarf halo stars:
    abundance by number = 10^{-10}
  - D observed in quasar absorption systems (and locally):
    abundance by number = 3×10^{-5}
  - ^{3}He in solar wind, in meteorites, and in the ISM:
    abundance by number = 10^{-5}

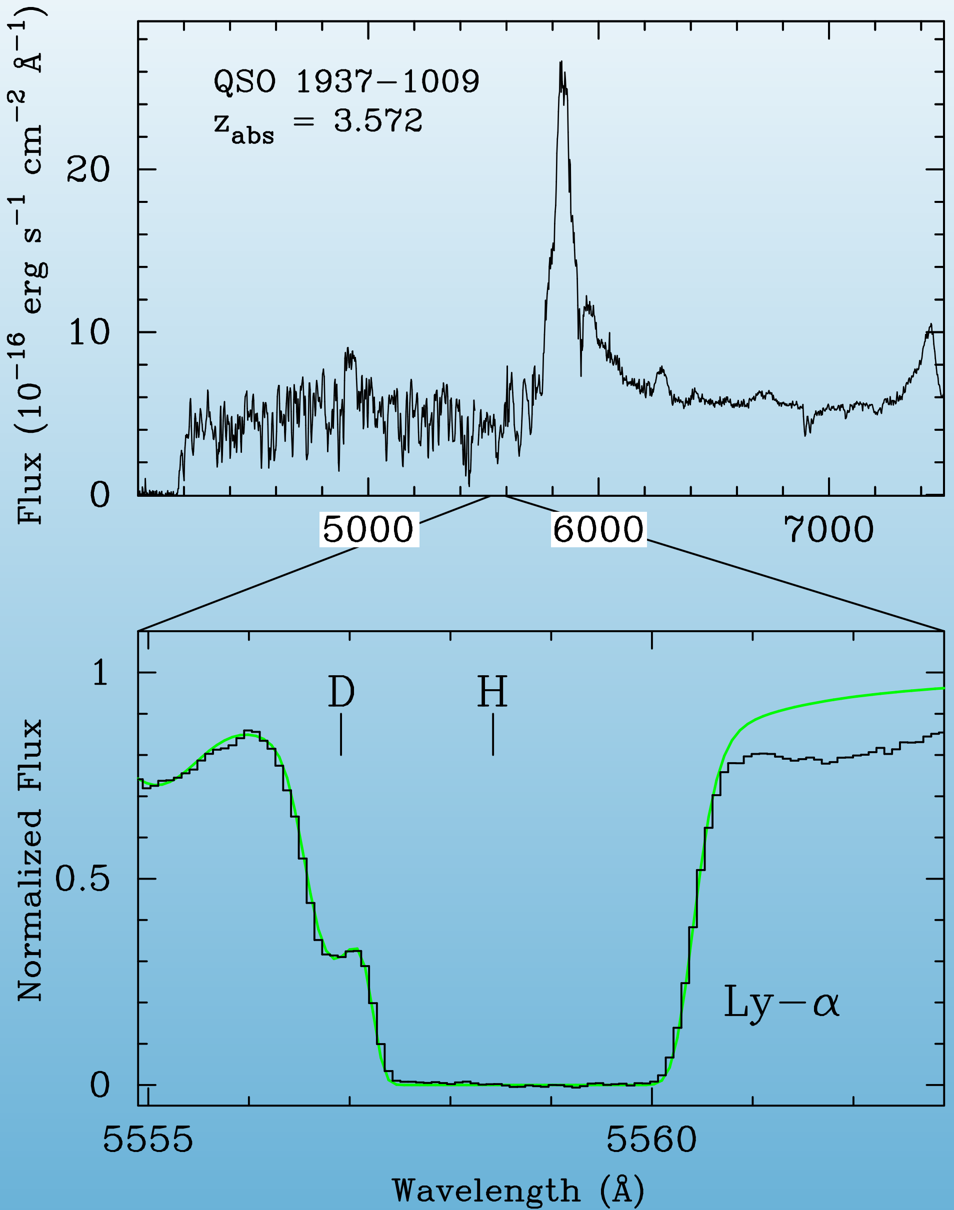
D/H

- All Observed D is Primordial!
- Observed in the ISM and inferred from meteoritic samples (also HD in Jupiter)
- D/H observed in Quasar Absorption systems

THE PRECISION SAMPLE OF D/H MEASUREMENTS IN QSO ABSORPTION LINE SYSTEMS

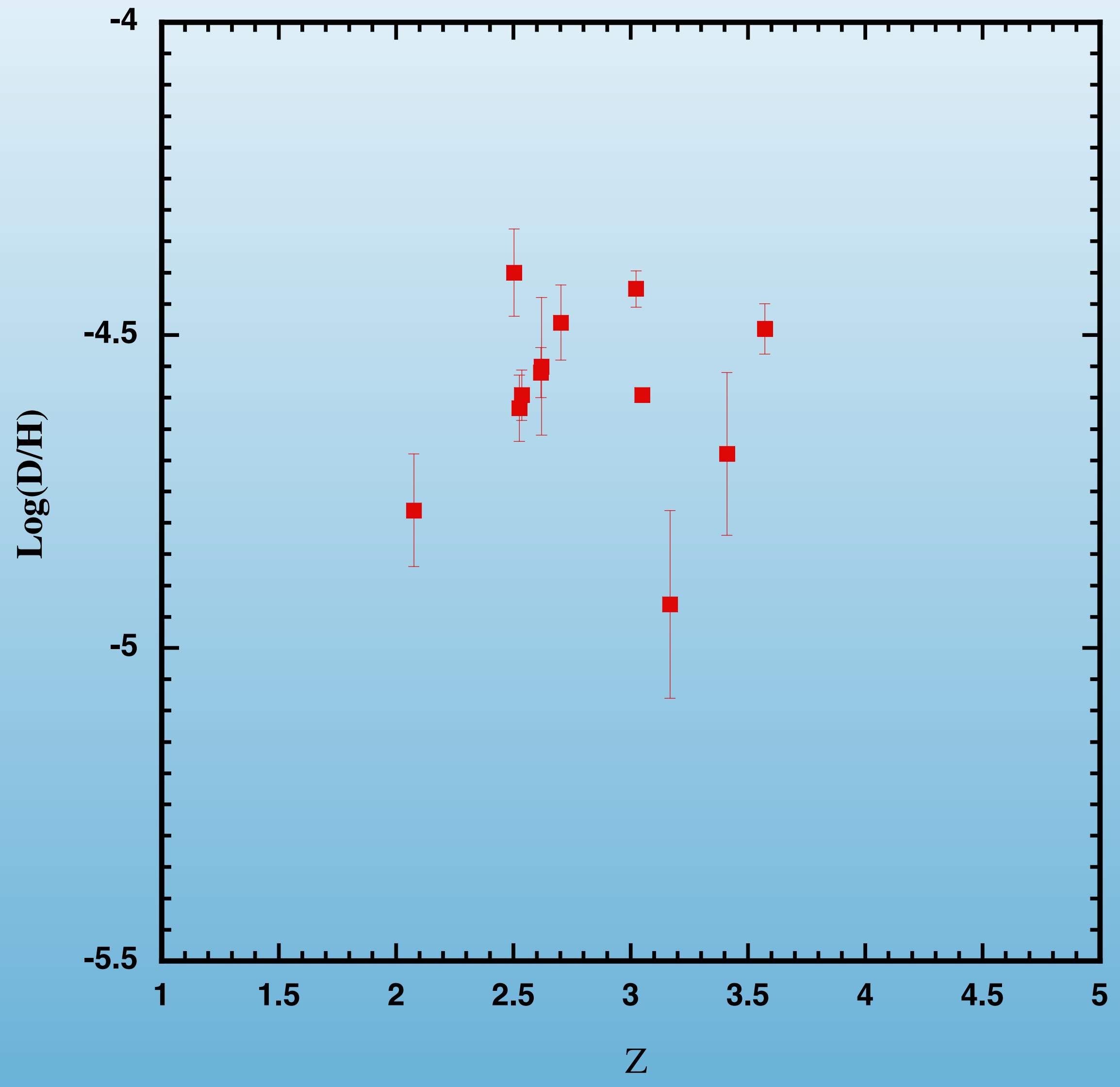
QSO	z_{em}	z_{abs}	[O/H][a]	Literature log N(H I) (cm^{-2})	Literature log (D/H)	This work log N(H I) (cm^{-2})	This work log (D/H)	Ref.[b]
HS 0105+1619	2.652	2.53651	−1.77	19.42 ± 0.01	−4.60 ± 0.04	19.426 ± 0.006	−4.589 ± 0.026	1, 2
Q0913+072	2.785	2.61829	−2.40	20.34 ± 0.04	−4.56 ± 0.04	20.312 ± 0.008	−4.597 ± 0.018	1, 3, 4
SDSS J1358+6522	3.173	3.06726	−2.33	...	...	20.495 ± 0.008	−4.588 ± 0.012	1
SDSS J1419+0829	3.030	3.04973	−1.92	20.391 ± 0.008	−4.596 ± 0.009	20.392 ± 0.003	−4.601 ± 0.009	1, 5, 6
SDSS J1558−0031	2.823	2.70242	−1.55	20.67 ± 0.05	−4.48 ± 0.06	20.75 ± 0.03	−4.619 ± 0.026	1, 7

Cooke et al.



Tytler, O'Meara, Suzuki, Lubin

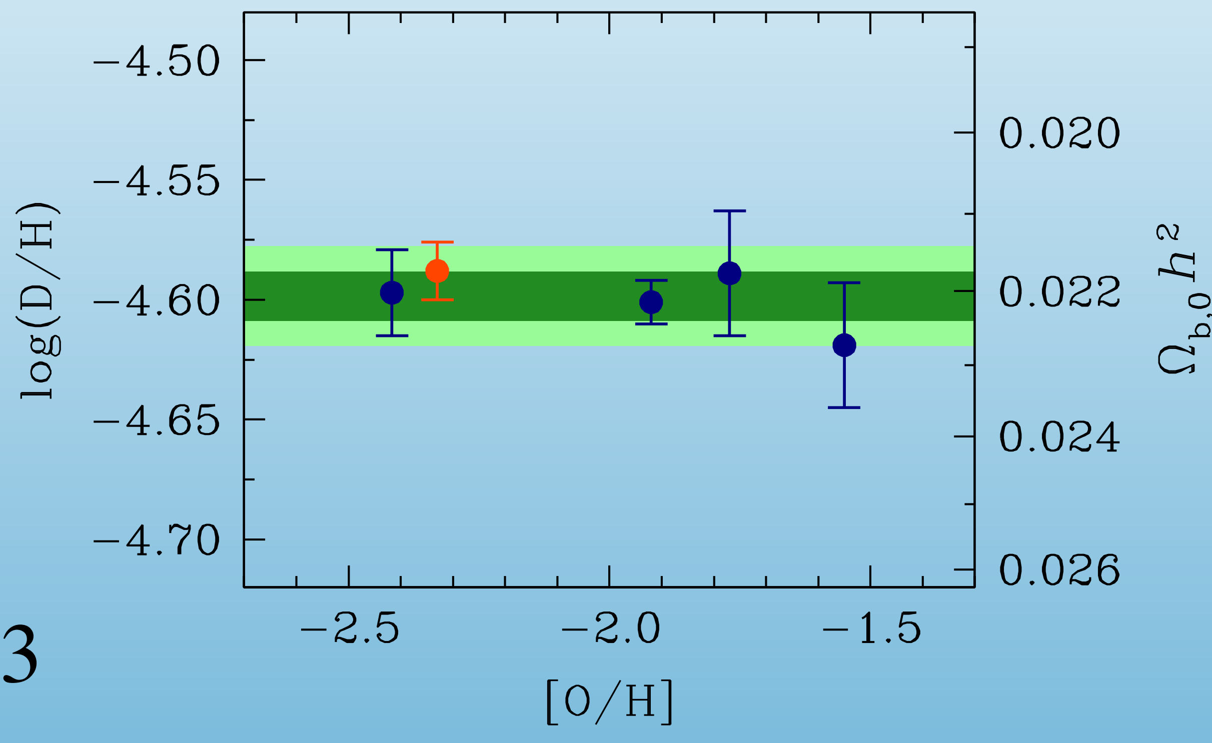
D/H abundances in Quasar absorption systems



BBN Prediction:
10^5 D/H = 2.58 ± 0.13

Obs Average:
10^5 D/H = 3.01 ± 0.21
(0.68 sample variance)

D/H abundances in Quasar absorption systems



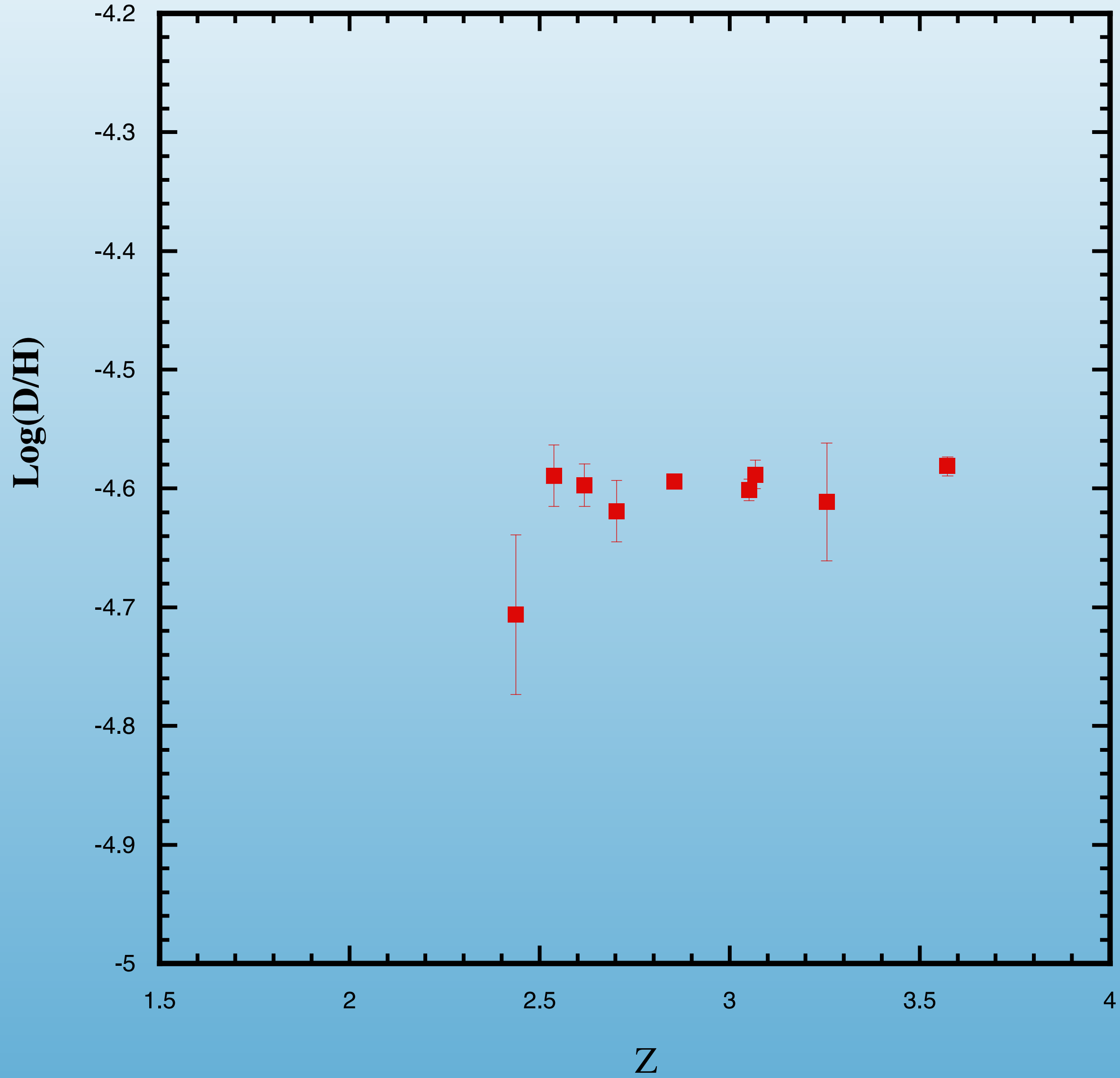
BBN Prediction:

10^5 D/H = 2.58 ± 0.13

Obs Average:

10^5 D/H = 2.53 ± 0.04

Updated
D/H abundances in Quasar absorption systems

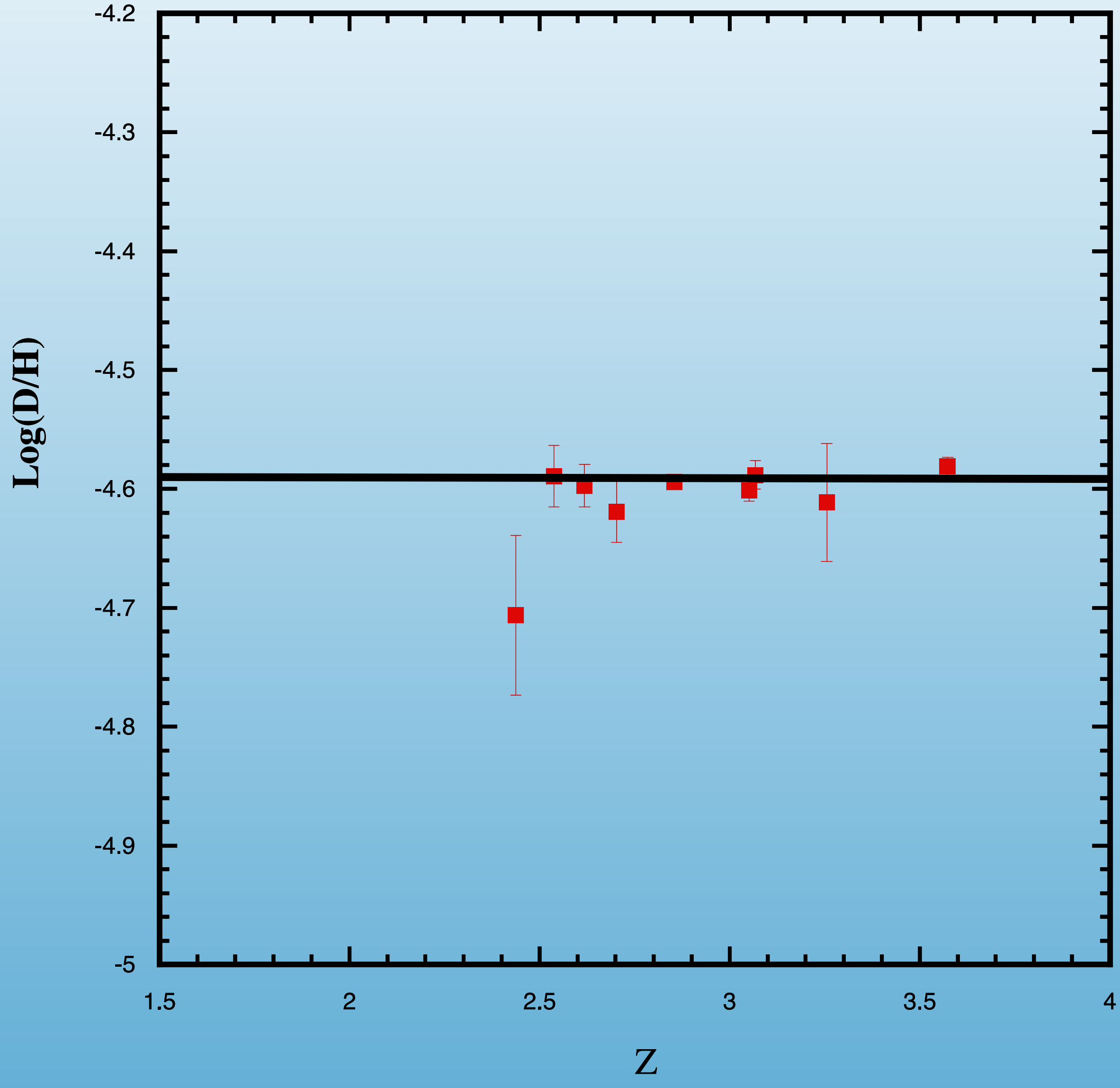


BBN Prediction:
10^5 D/H = 2.58 ± 0.13

Obs Average:
10^5 D/H = 2.55 ± 0.02

Reimer-Sorensen et al.

Updated D/H abundances in Quasar absorption systems



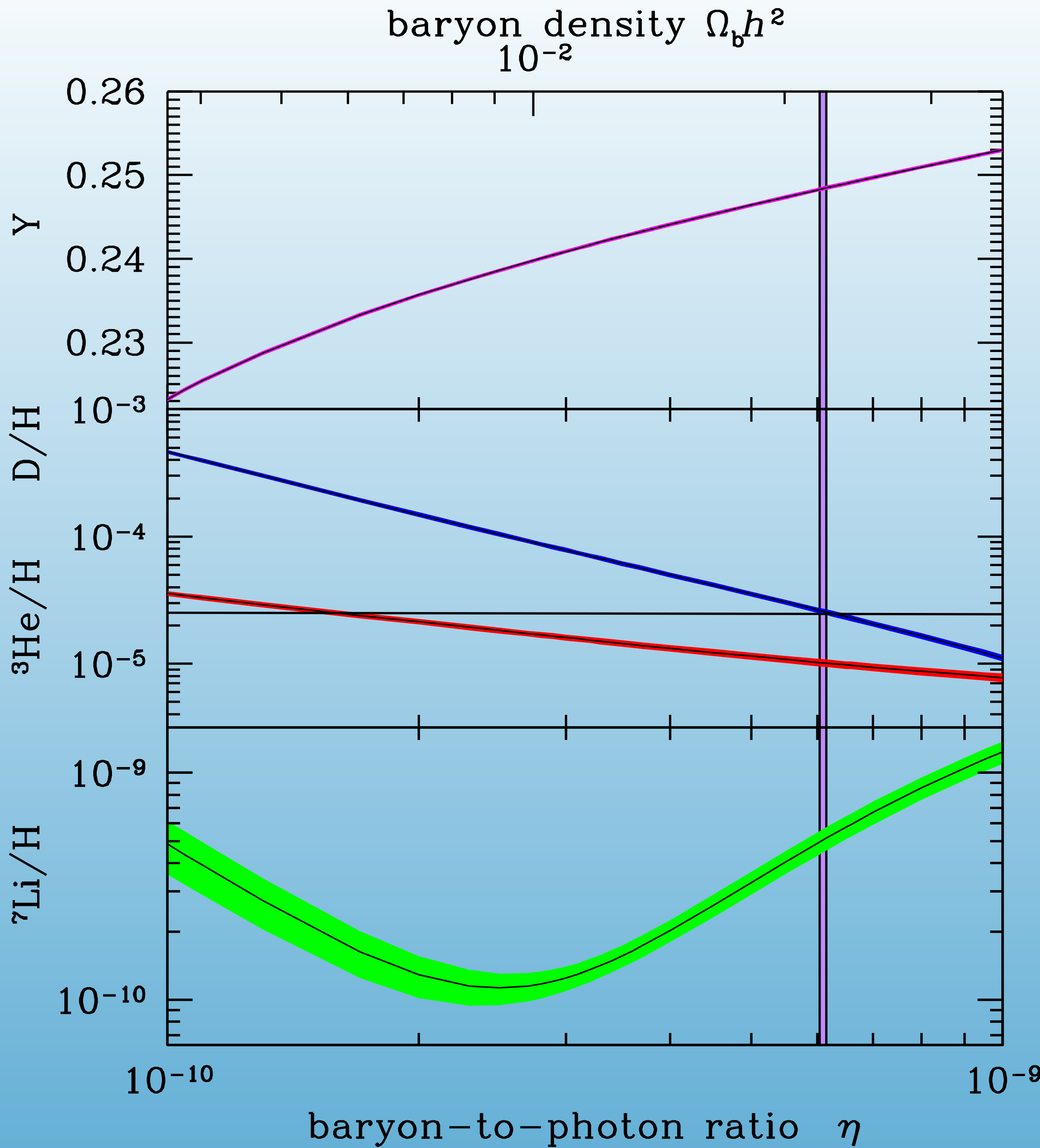
BBN Prediction:

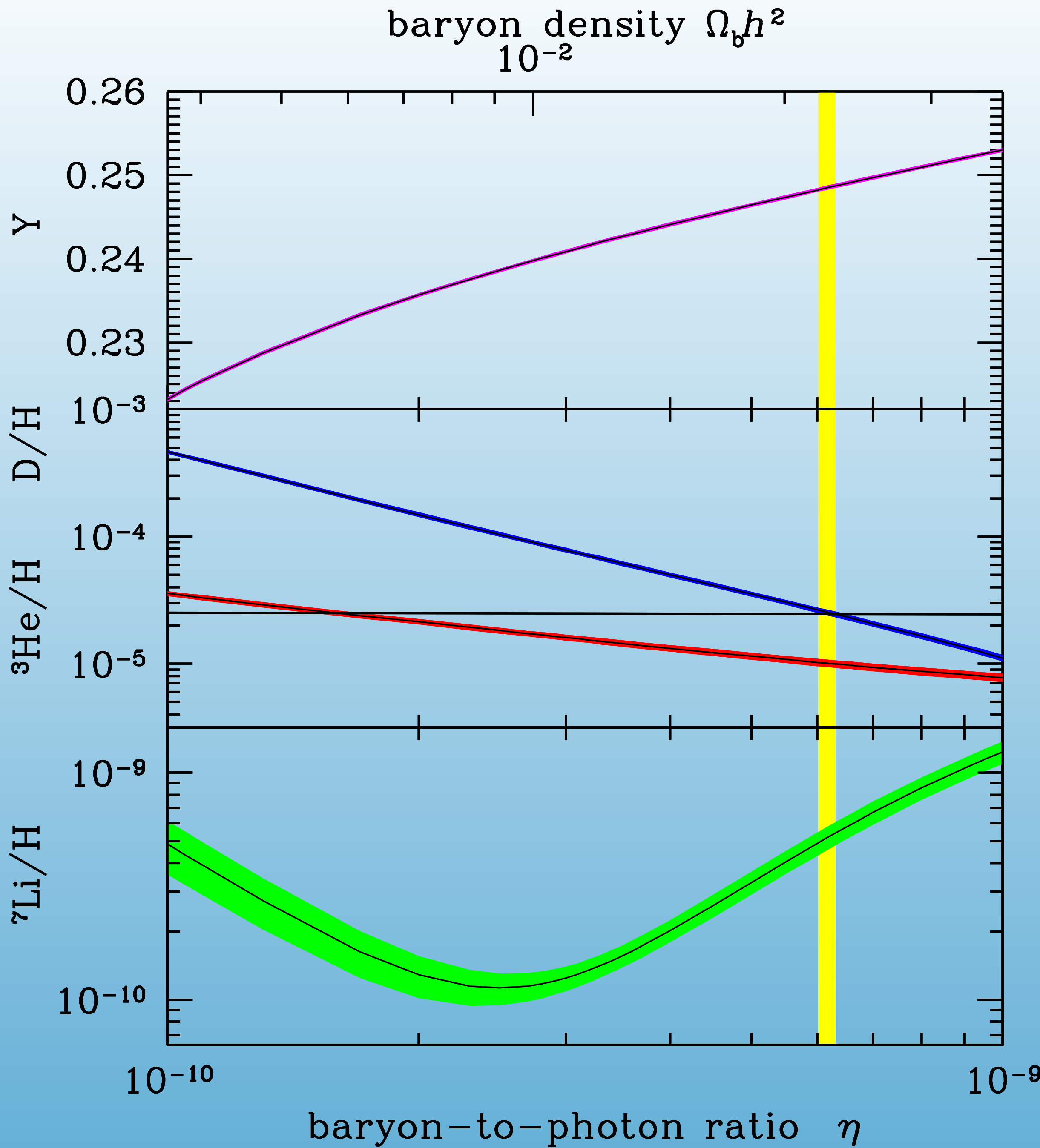
10^5 D/H = 2.58 ± 0.13

Obs Average:

10^5 D/H = 2.55 ± 0.02

Reimer-Sorensen et al.


baryon density $\Omega_b h^2$
10^{-2}
0.26
0.25
0.24
0.23
Y
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon–to–photon ratio η



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10^{-2}
0.26
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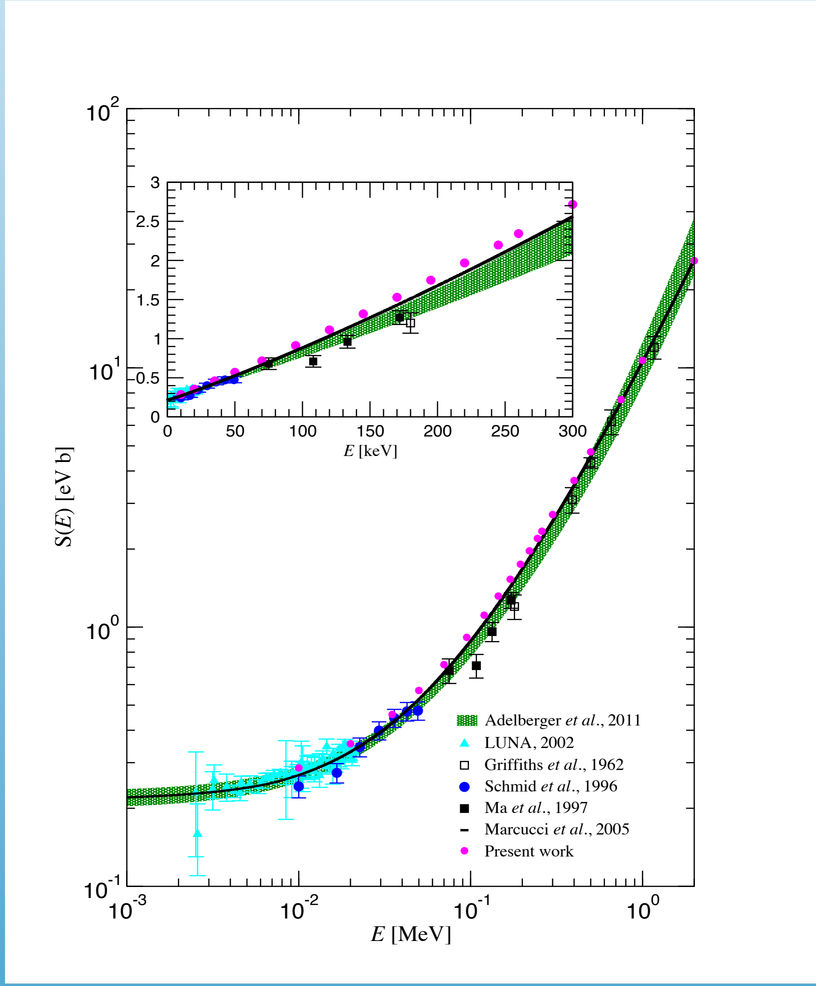
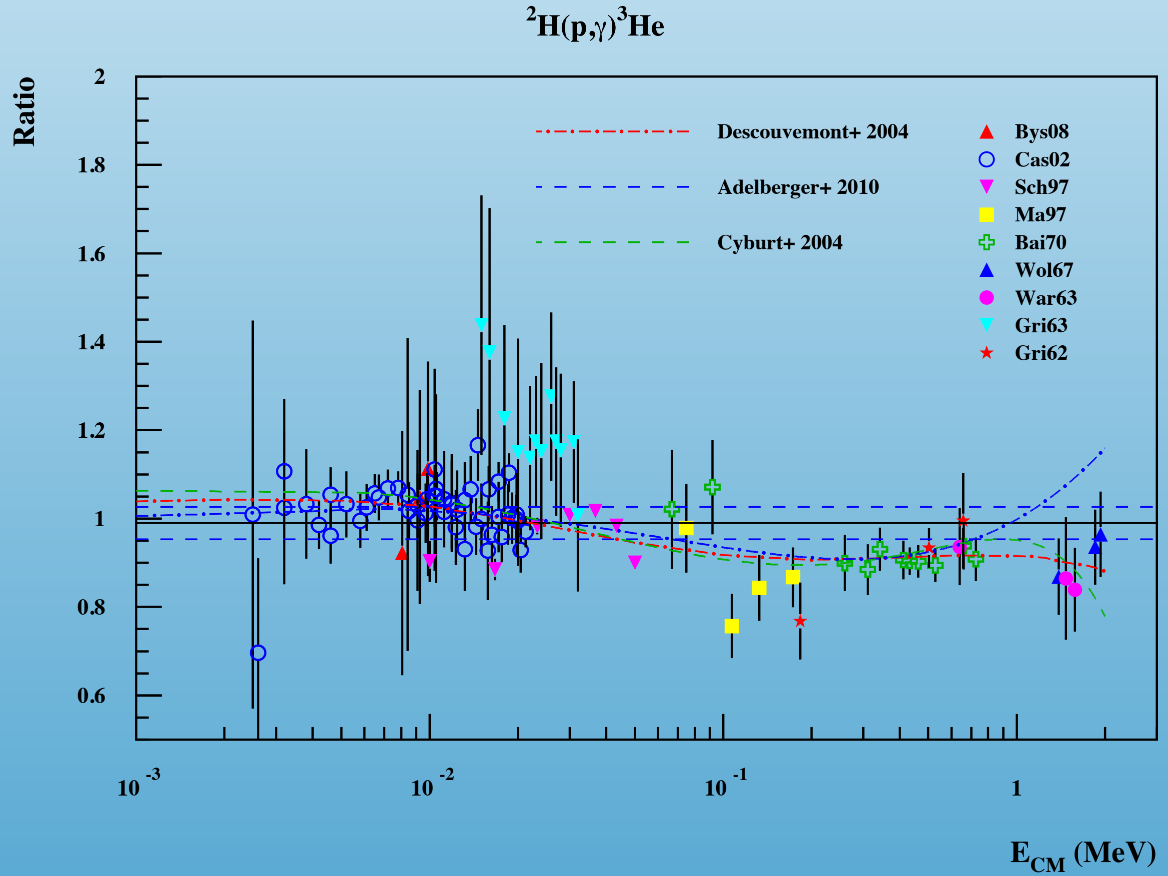
Y
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon−to−photon ratio η

A word about d(p,γ)^{3}He

Some recent claims (Coc et al.; Cooke et al.) claim a discrepancy with theory and observation in D/H.

Based on fit to theoretical S-factor (Marucci et al.)

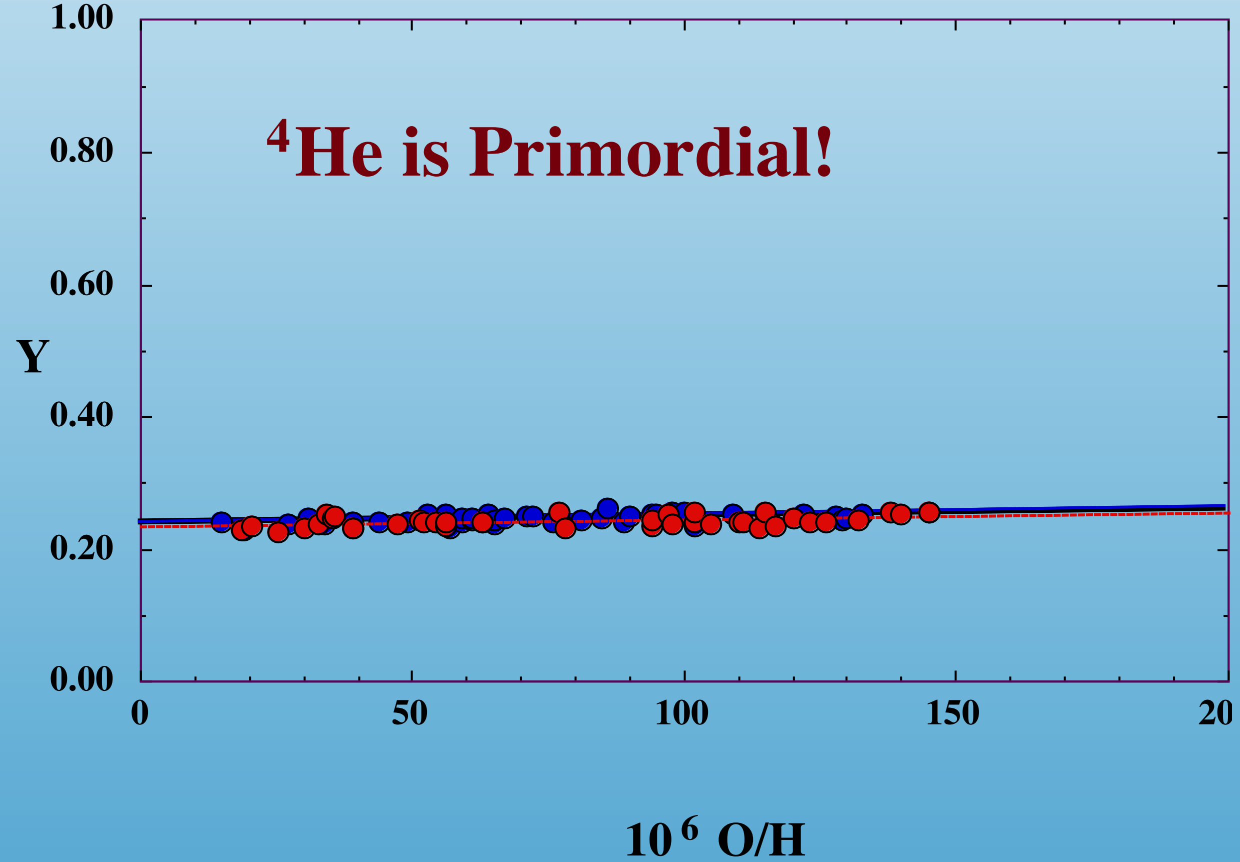


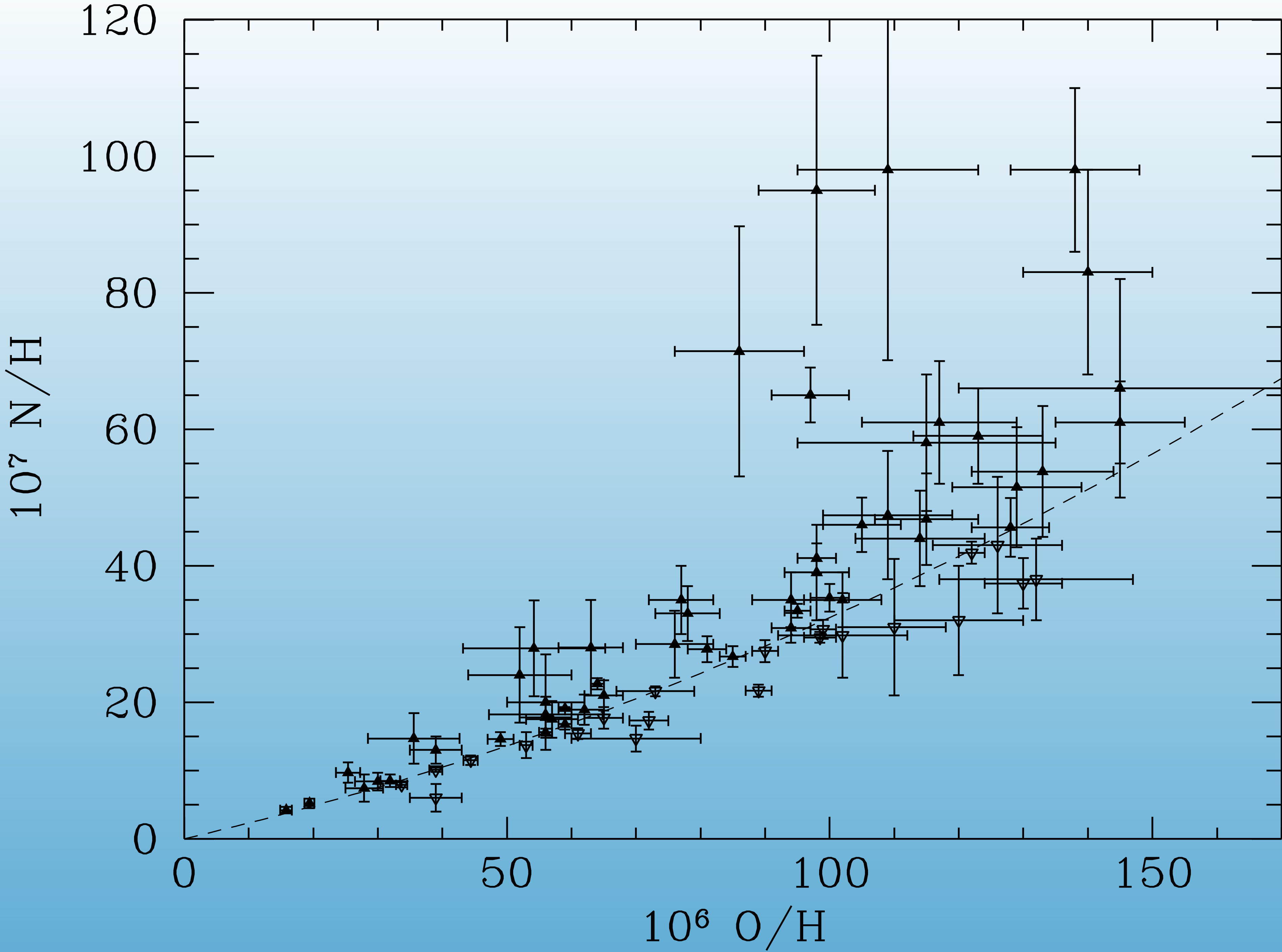


^{4}He

Measured in low metallicity extragalactic HII regions (~100) together with O/H and N/H

$$Y_P = Y(O/H \to 0)$$





120
100
80
60
40
20
0
0
50
100
150
10⁷ N/H
10⁶ O/H

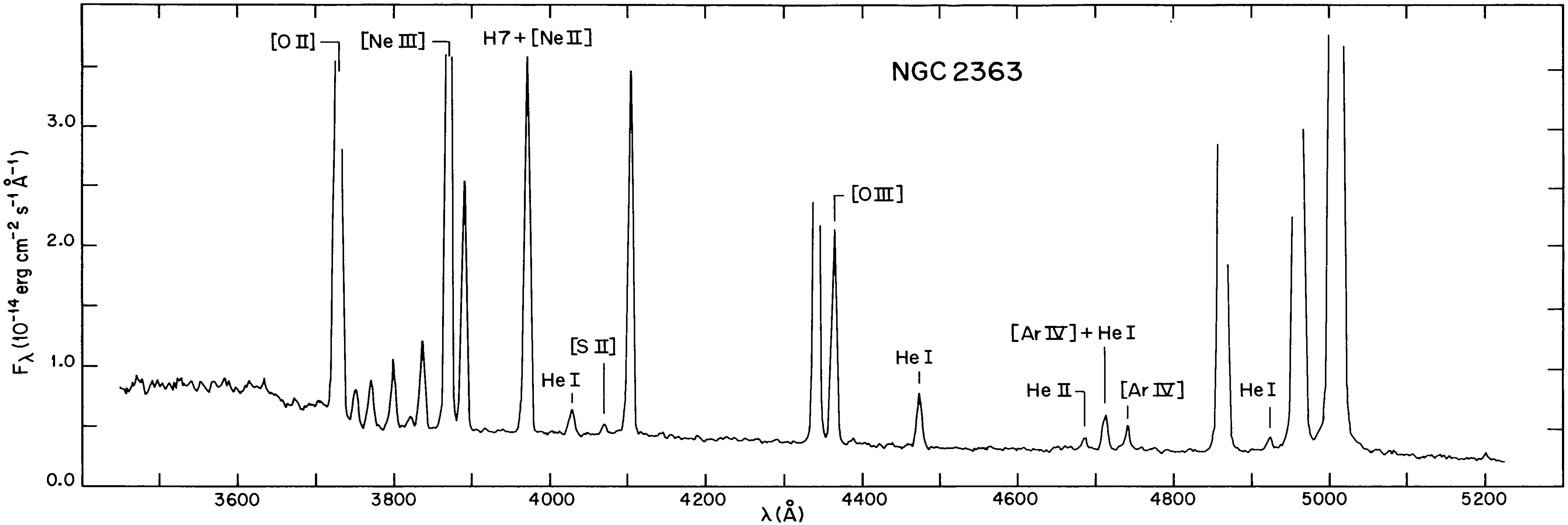


Fig. 1. Low dispersion blue spectrogram of NGC 2363, showing the faintest lines measured

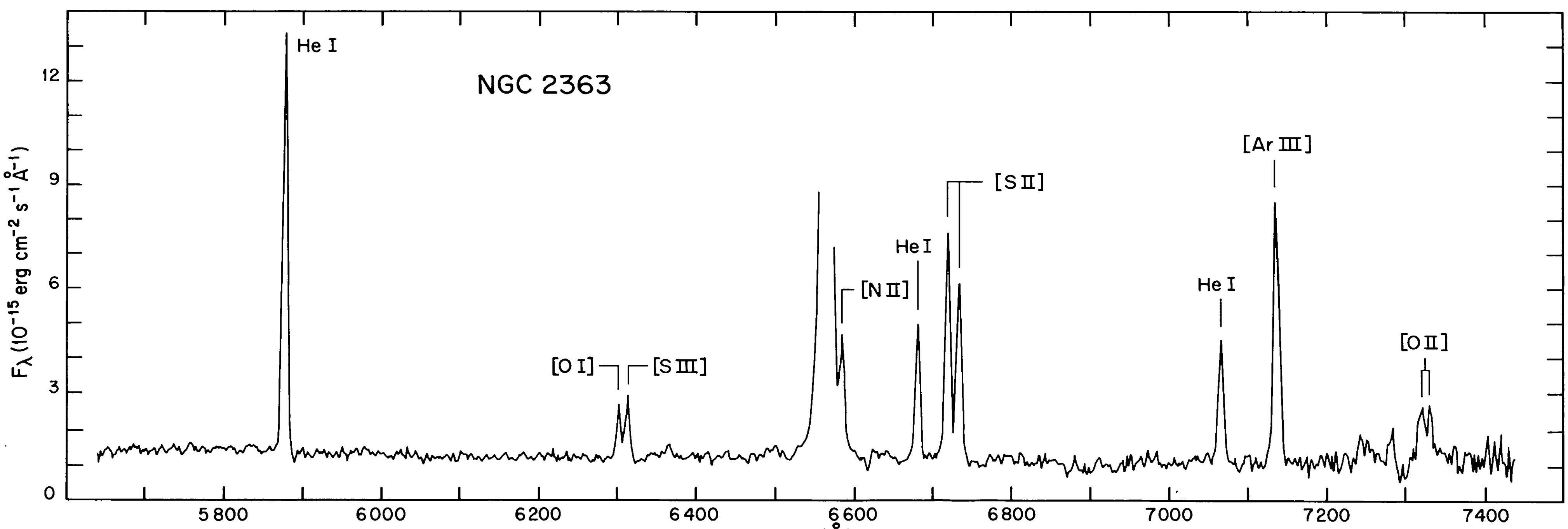
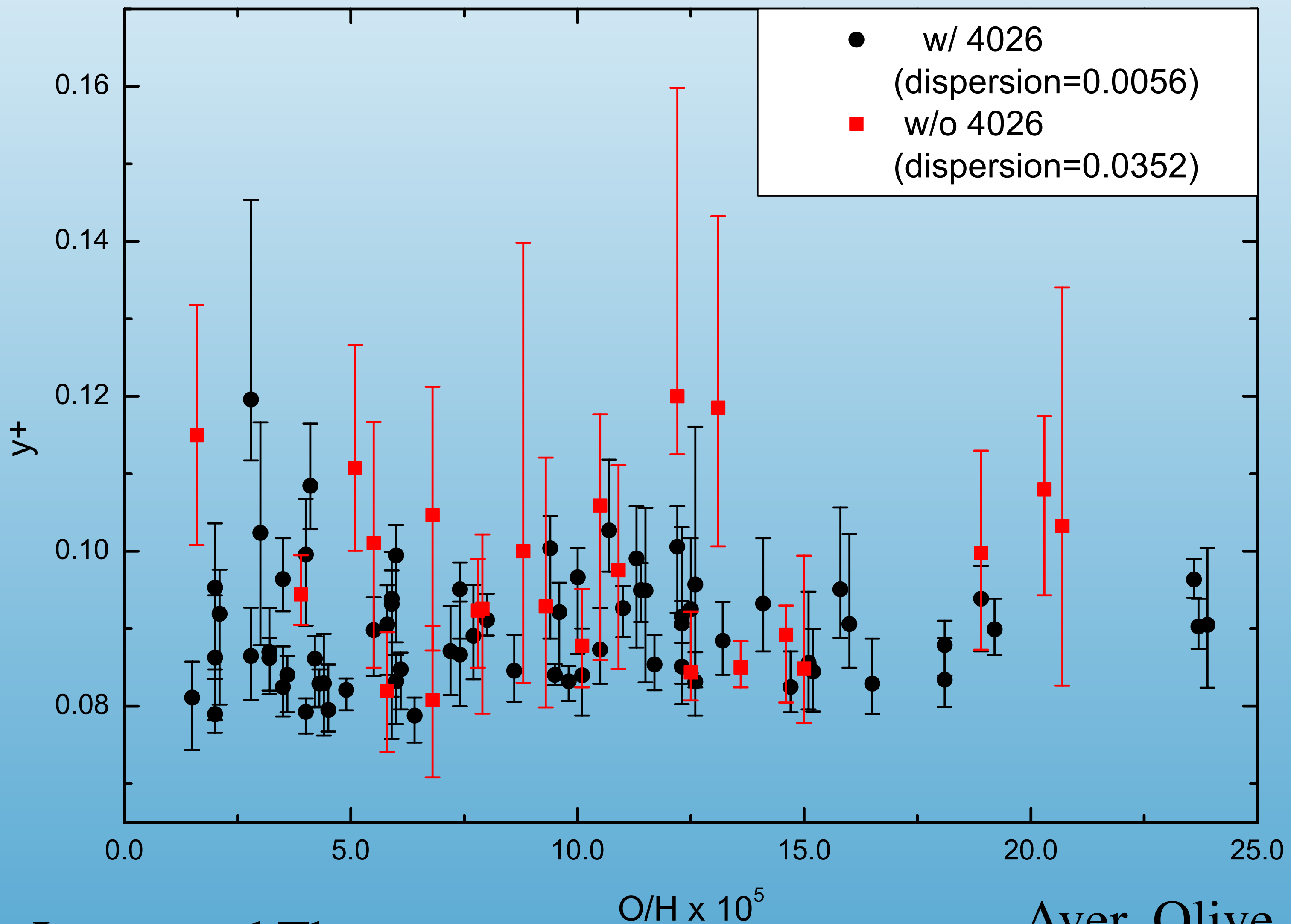


Fig. 2. Low dispersion red spectrogram of NGC 2363

^4He

Importance of a full set of line fluxes

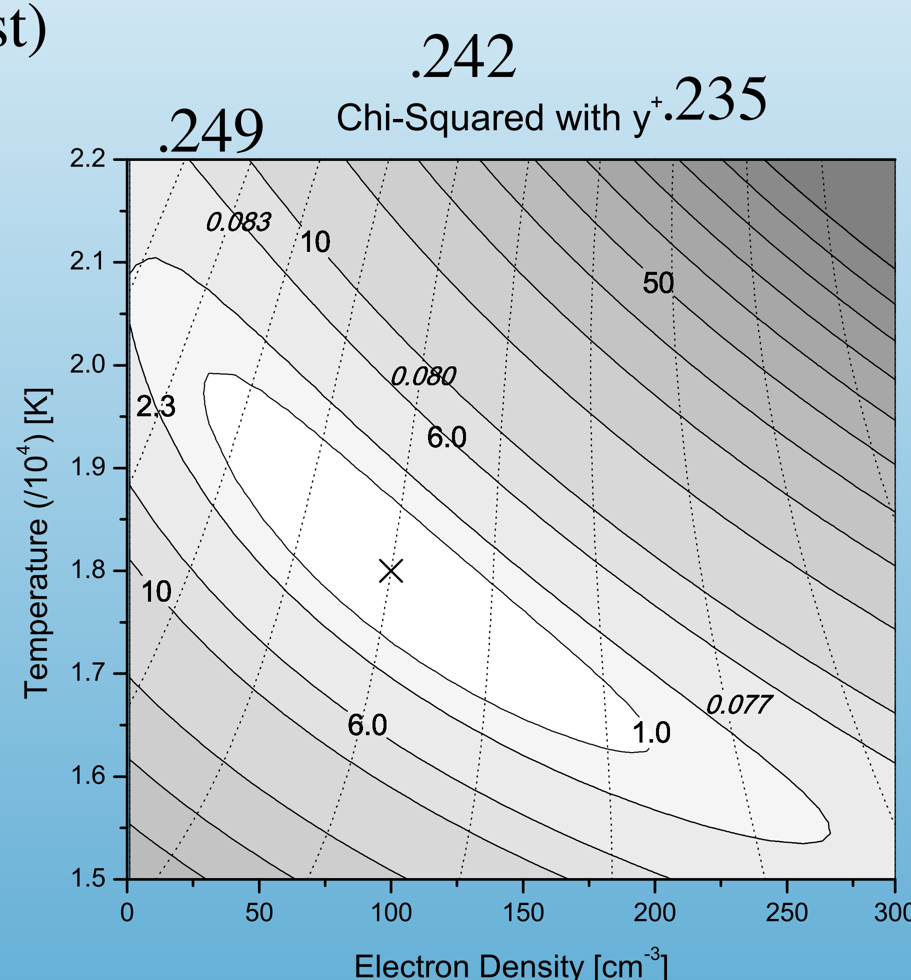


Data from Izotov and Thuan

Aver, Olive, Skillman

Results for He dominated by systematic effects

- Interstellar Redding (scattered by dust)
- Underlying Stellar Absorption
- Radiative Transfer
- Collisional Corrections



MCMC statistical techniques have proven effective in parameter estimation

$$\frac{F(\lambda)}{F(H\beta)} = y^{+}\frac{E(\lambda)}{E(H\beta)}\frac{\frac{W(H\beta)+a_H(H\beta)}{W(H\beta)}}{\frac{W(\lambda)+a_{He}(\lambda)}{W(\lambda)}}f_{\tau}(\lambda)\frac{1+\frac{C}{R}(\lambda)}{1+\frac{C}{R}(H\beta)}10^{-f(\lambda)C(H\beta)}$$

$$(\mathrm{y}^{+},\, \mathrm{n}_e,\, \mathrm{a}_{He},\, \tau,\, \mathrm{T},\, \mathrm{C}(\mathrm{H}\beta),\, \mathrm{a}_H,\, \xi)$$

Aver, Olive, Skillman

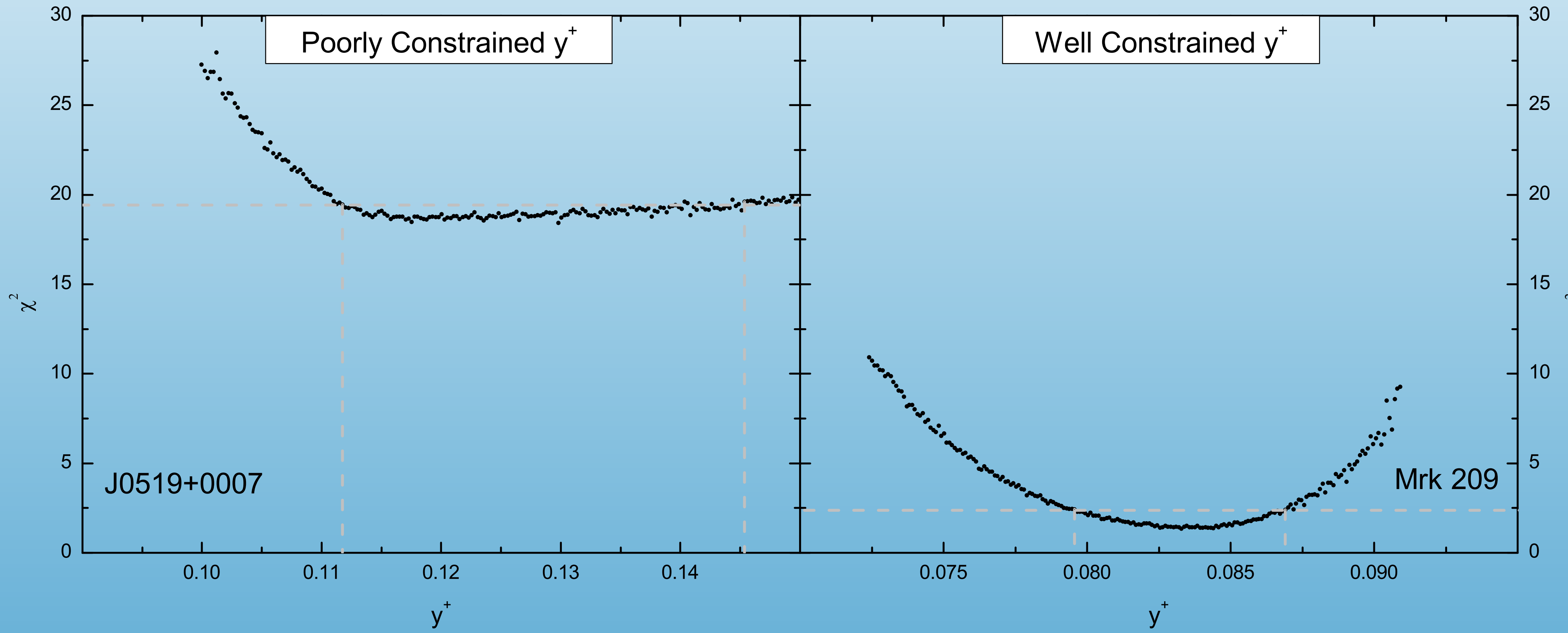
Results for He dominated by systematic effects

$$\chi^2 = \sum_\lambda \frac{\left(\frac{F(\lambda)}{F(H\beta)} - \frac{F(\lambda)}{F(H\beta)}_{\text{meas}}\right)^2}{\sigma(\lambda)^2}$$

9 observables

$$(\mathrm{y}^+,\ \mathrm{n}_e,\ \mathrm{a}_{He},\ \tau,\ \mathrm{T},\ \mathrm{C}(\mathrm{H}\beta),\ \mathrm{a}_H,\ \xi)$$

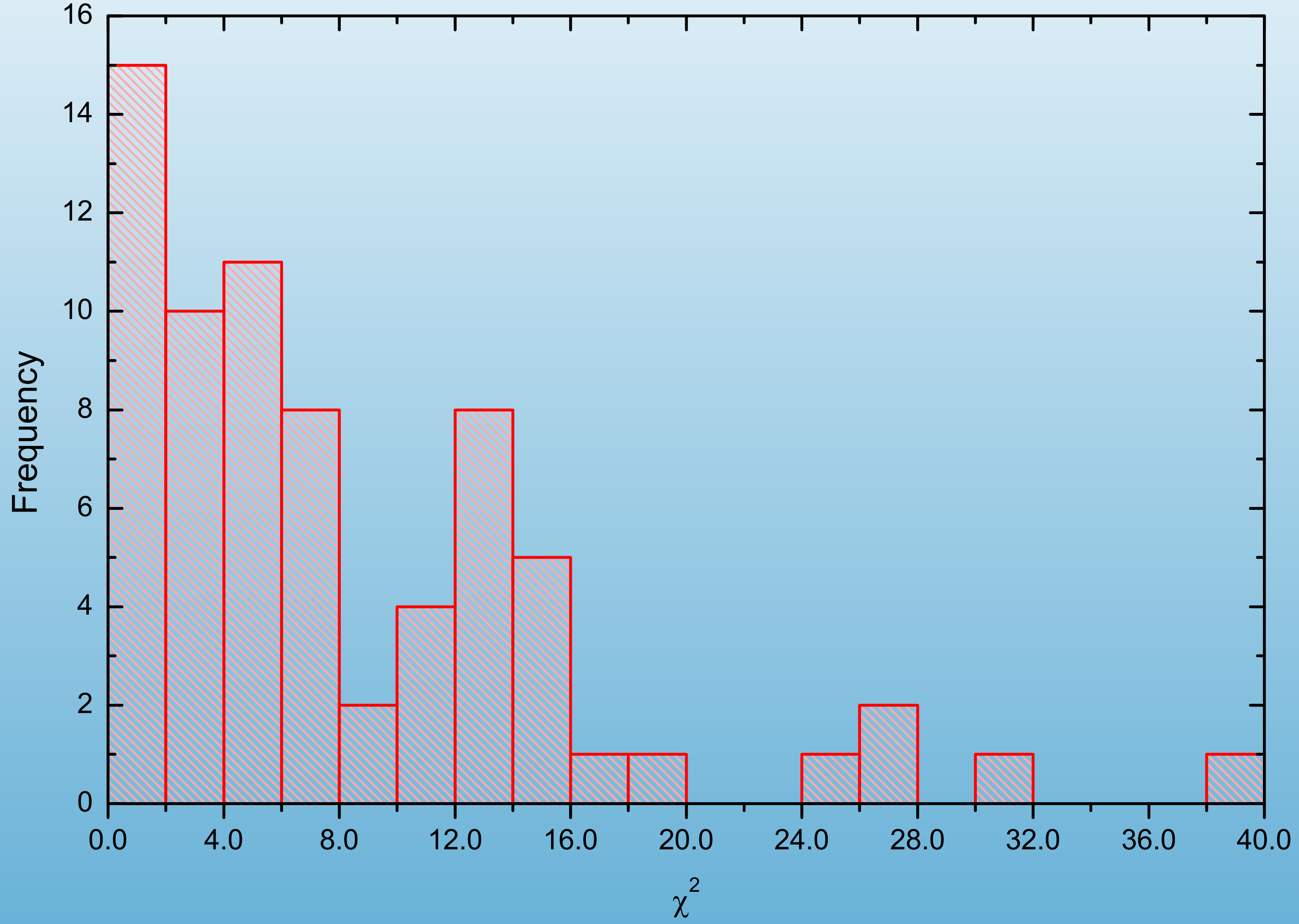
8 parameters



$$\frac{F(\lambda)}{F(H\beta)} = y^+ \frac{E(\lambda)}{E(H\beta)} \frac{\frac{W(H\beta)+a_H(H\beta)}{W(H\beta)}}{\frac{W(\lambda)+a_{He}(\lambda)}{W(\lambda)}} f_\tau(\lambda) \frac{1+\frac{C}{R}(\lambda)}{1+\frac{C}{R}(H\beta)} 10^{-f(\lambda)C(H\beta)}$$

Aver, Olive, Skillman

Using χ^2 as a discriminator

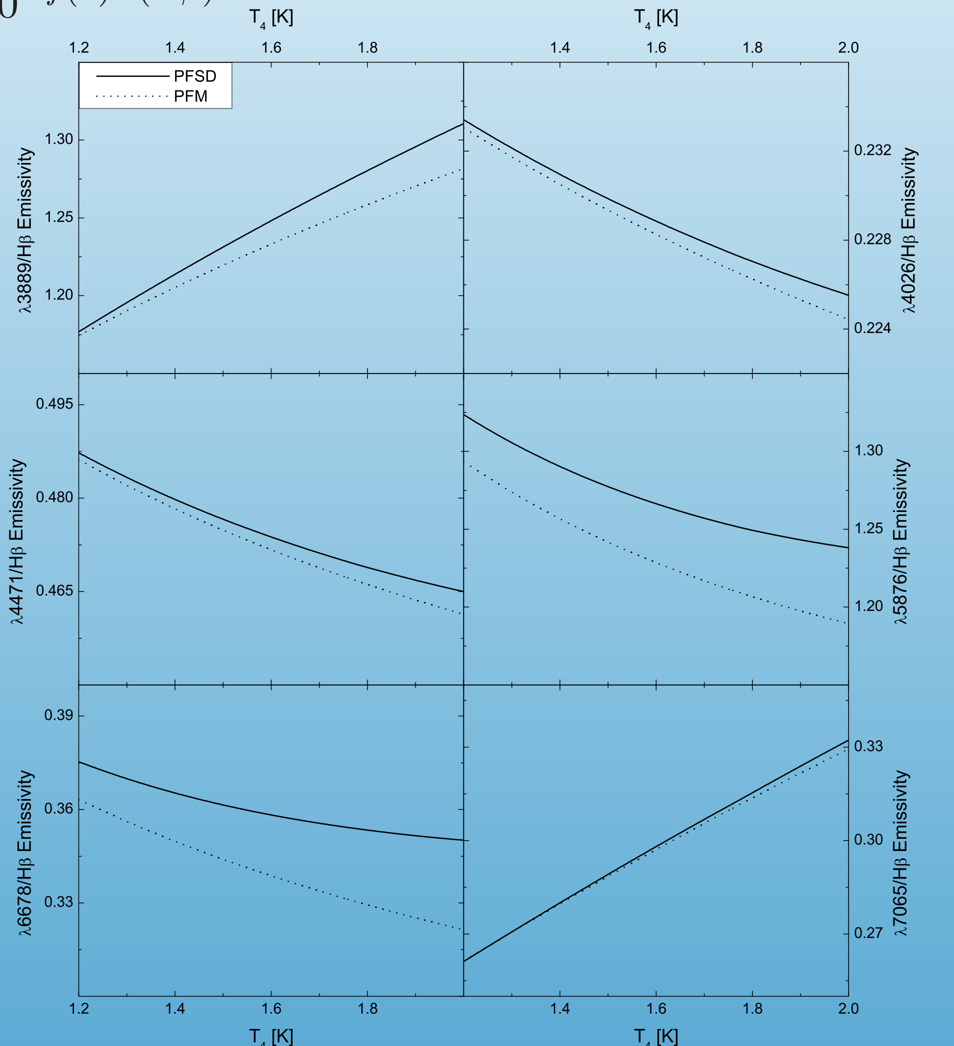


Aver, Olive, Skillman

New Emissivities

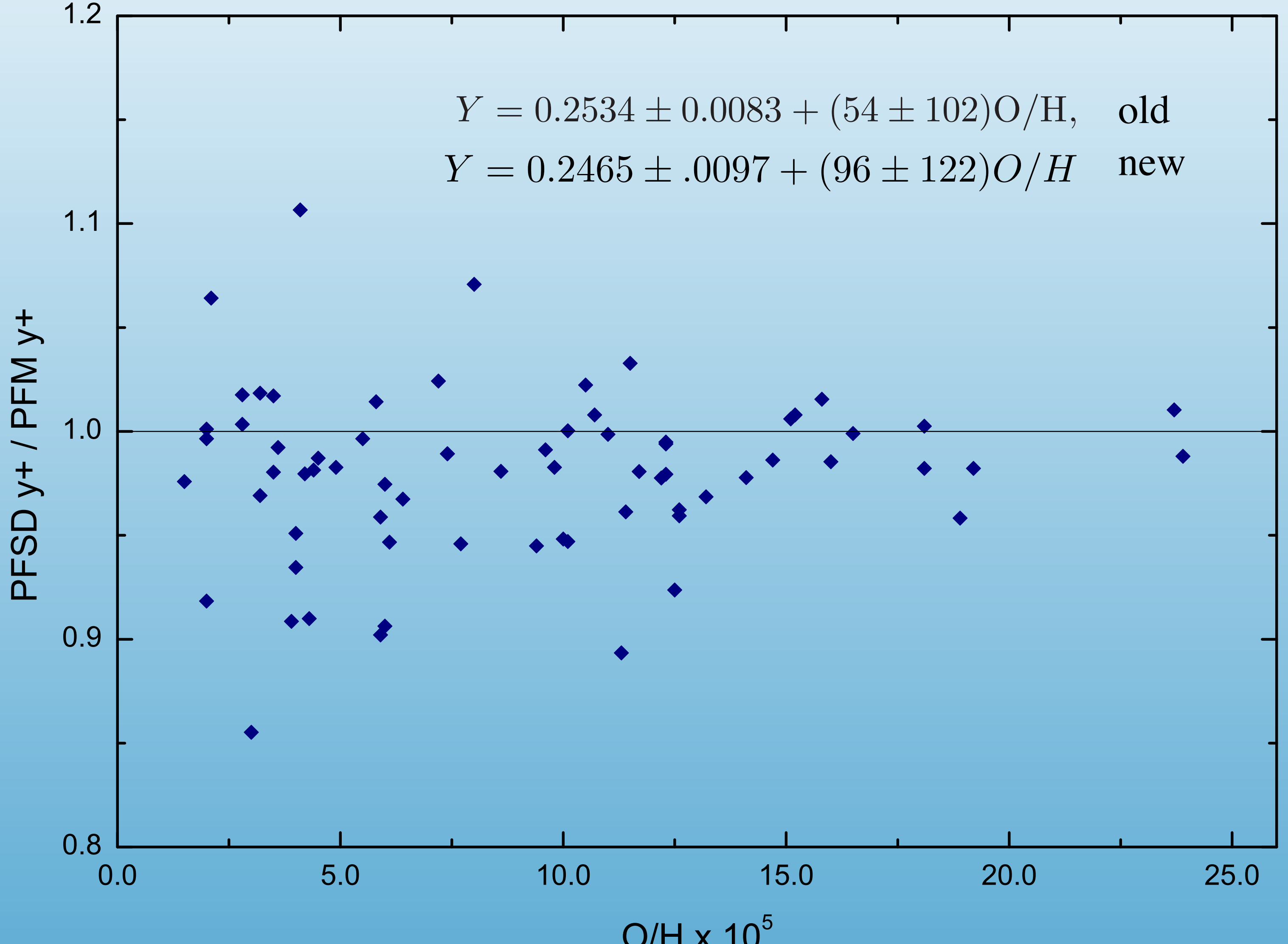
$$\frac{F(\lambda)}{F(H\beta)} = y^+ \frac{E(\lambda)}{E(H\beta)} \frac{\frac{W(H\beta)+a_H(H\beta)}{W(H\beta)}}{\frac{W(\lambda)+a_{He}(\lambda)}{W(\lambda)}} f_\tau(\lambda) \frac{1+\frac{C}{R}(\lambda)}{1+\frac{C}{R}(H\beta)} 10^{-f(\lambda)C(H\beta)}$$

New emissivities from Porter et al. (2012,2013) using improved cross sections (and corrected errors!)



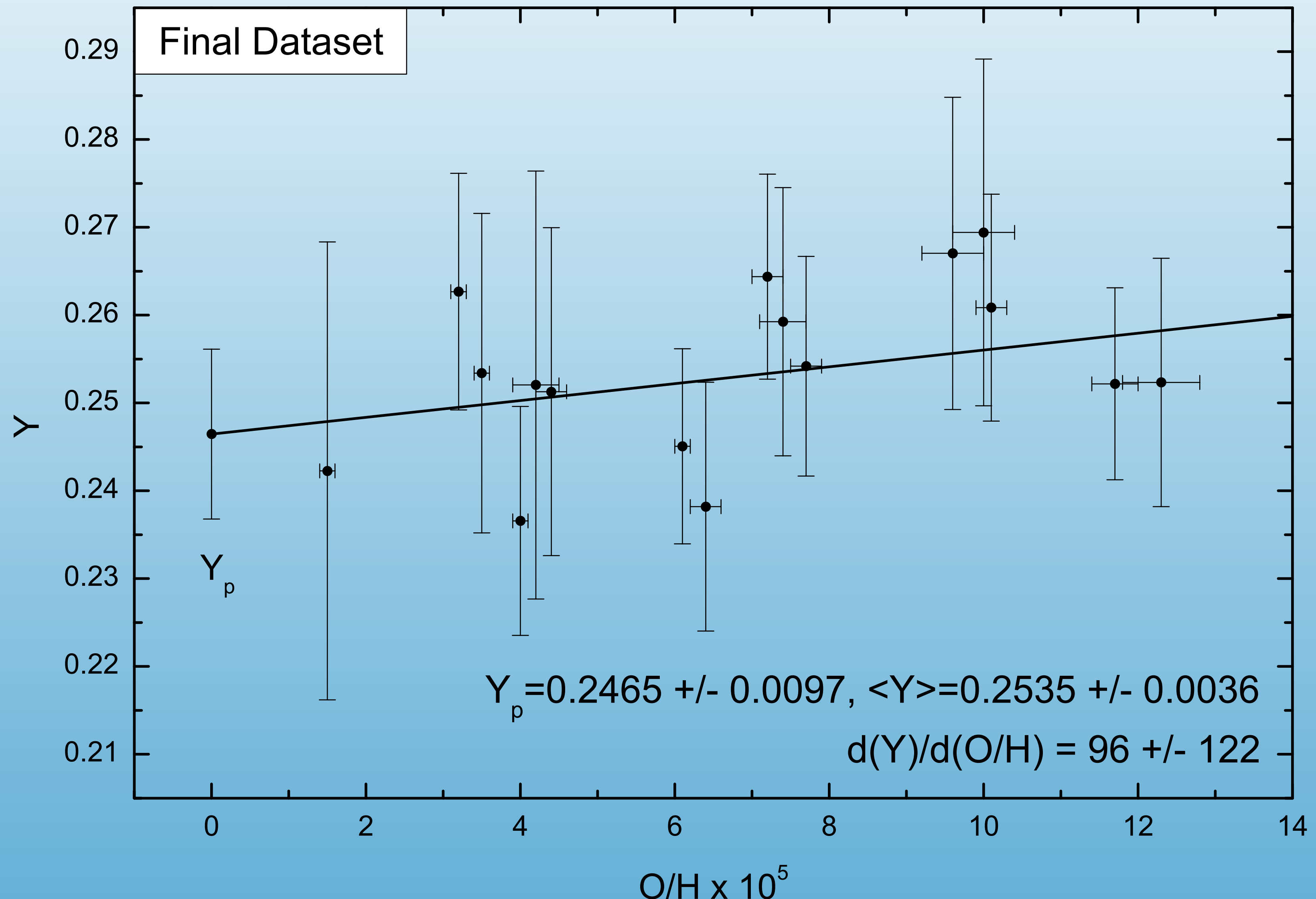
Aver, Olive, Porter, Skillman

Higher emissivities ⇒ lower
He abundances



Aver, Olive, Porter, Skillman

^{4}He



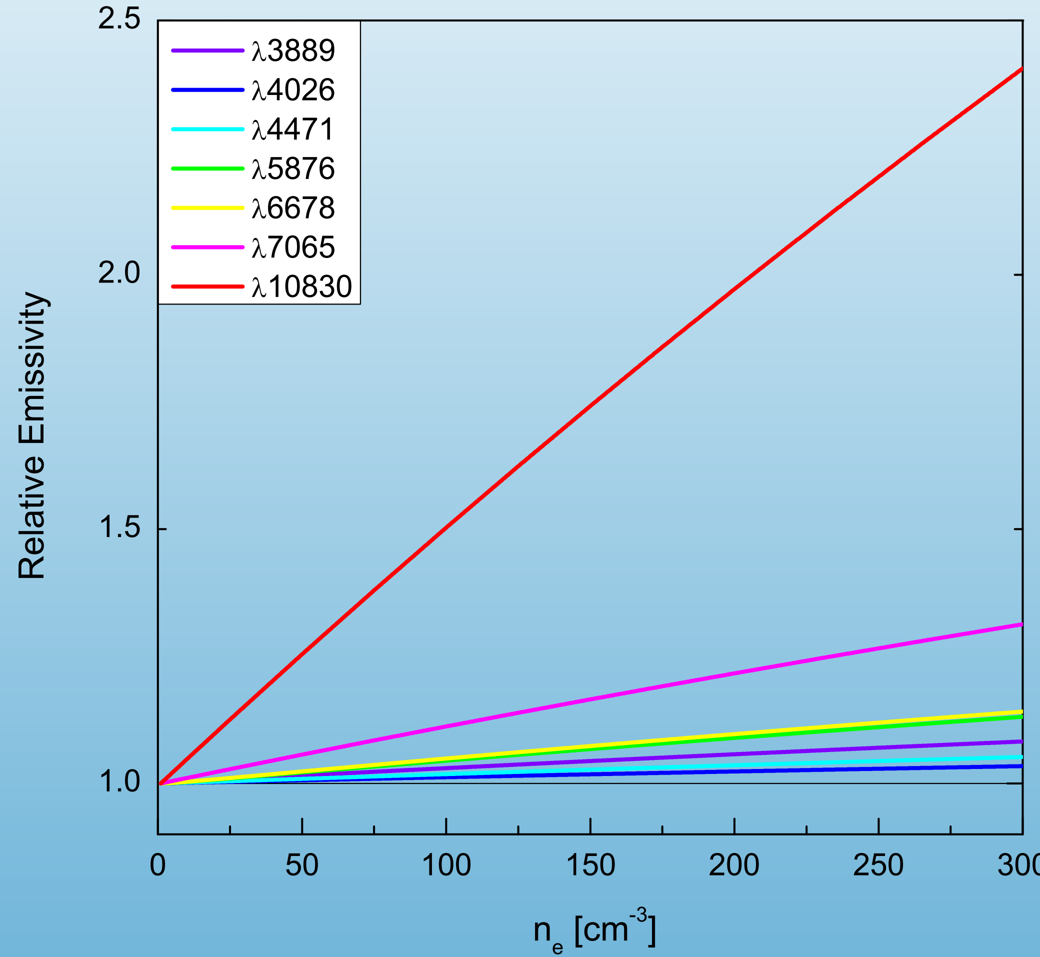
old emissivities: Y_P = .2534 ± 0.0083

Aver, Olive, Porter, Skillman

Adding λ10380

Izotov, Thuan, Guseva

Increased sensitivity to n_e

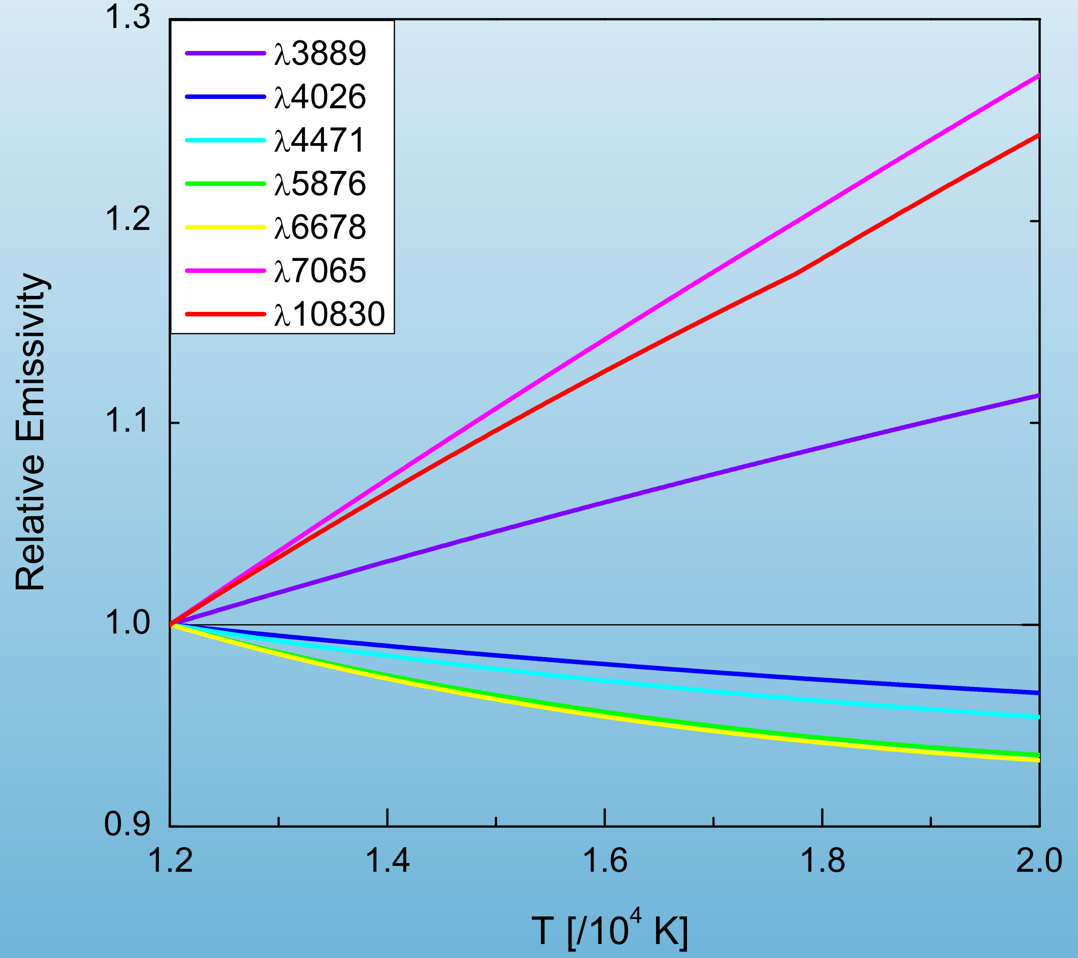


Aver, Olive, Skillman

Adding λ10380

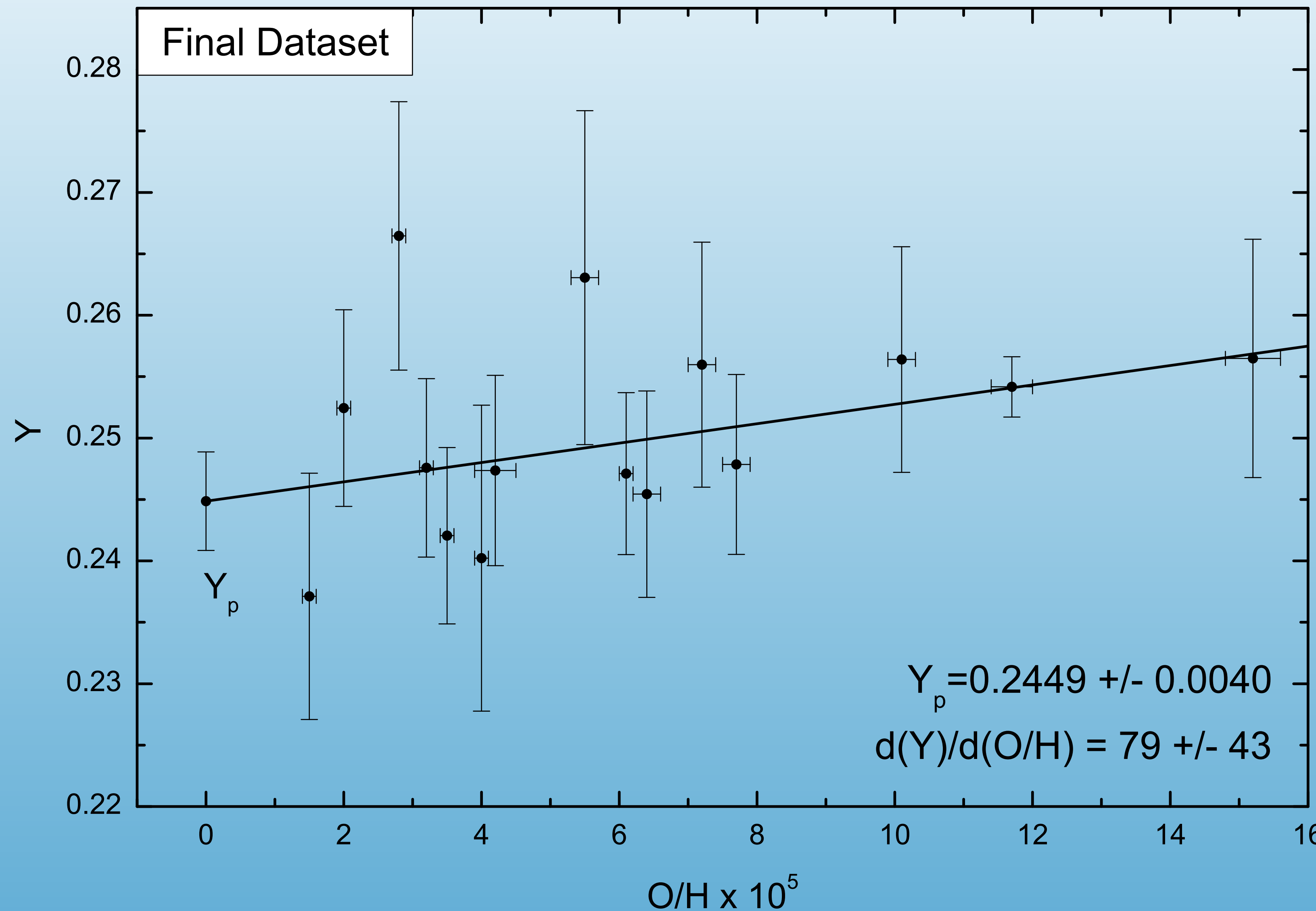
Izotov, Thuan, Guseva

Strong sensitivity to T



Aver, Olive, Skillman

^{4}He



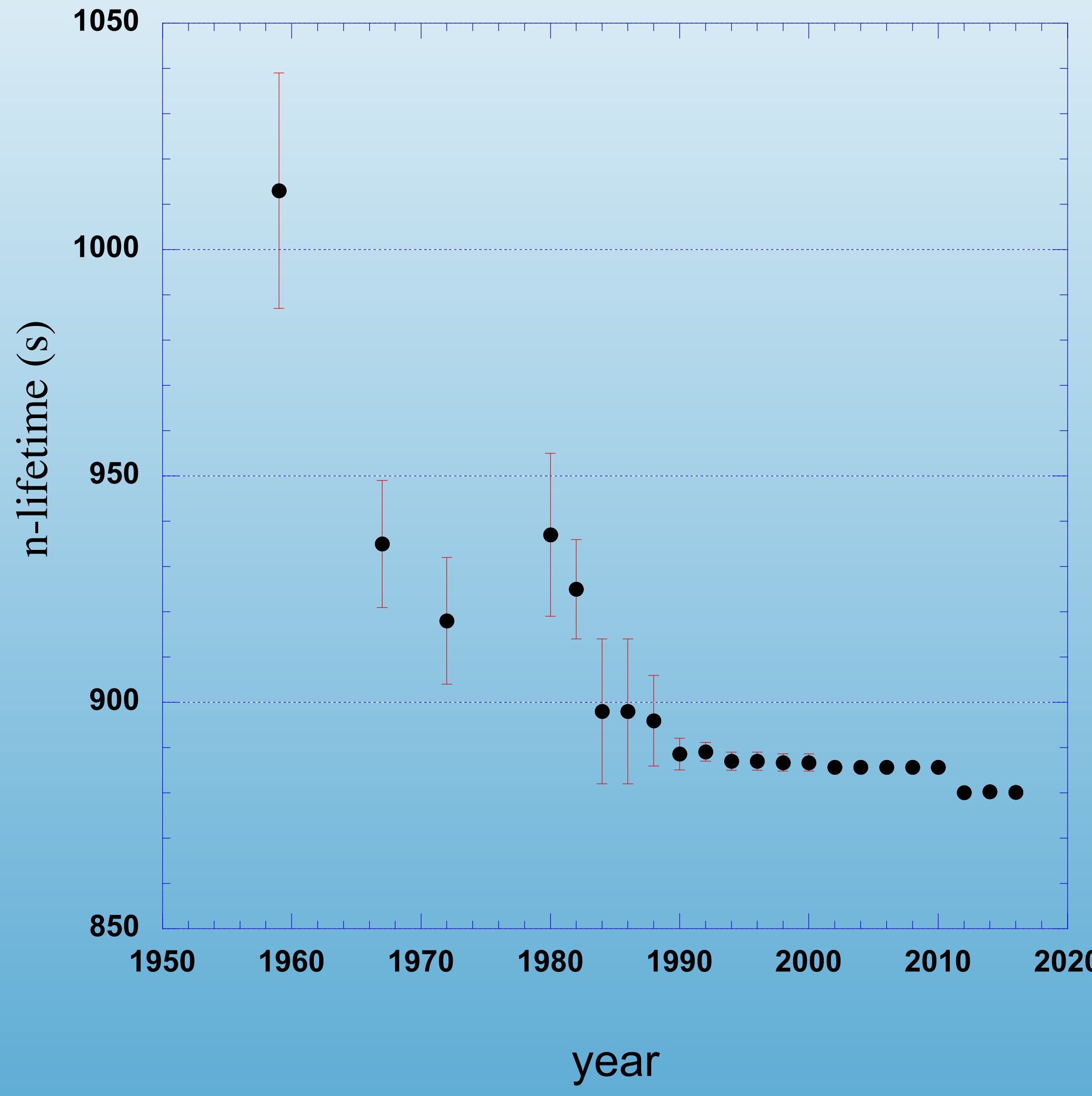
without 10830: Y_P = .2465 ± 0.0097

Aver, Olive, Skillman

Neutron Lifetime

$\tau = 885.7 \rightarrow Y = .2481$

$\tau = 880.2 \rightarrow Y = .2470$



Neutron Lifetime

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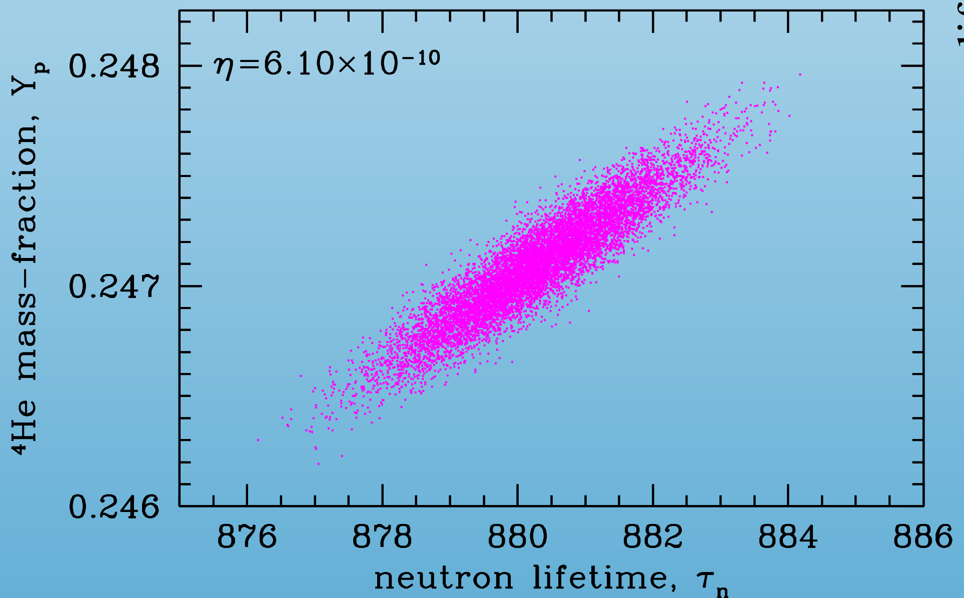
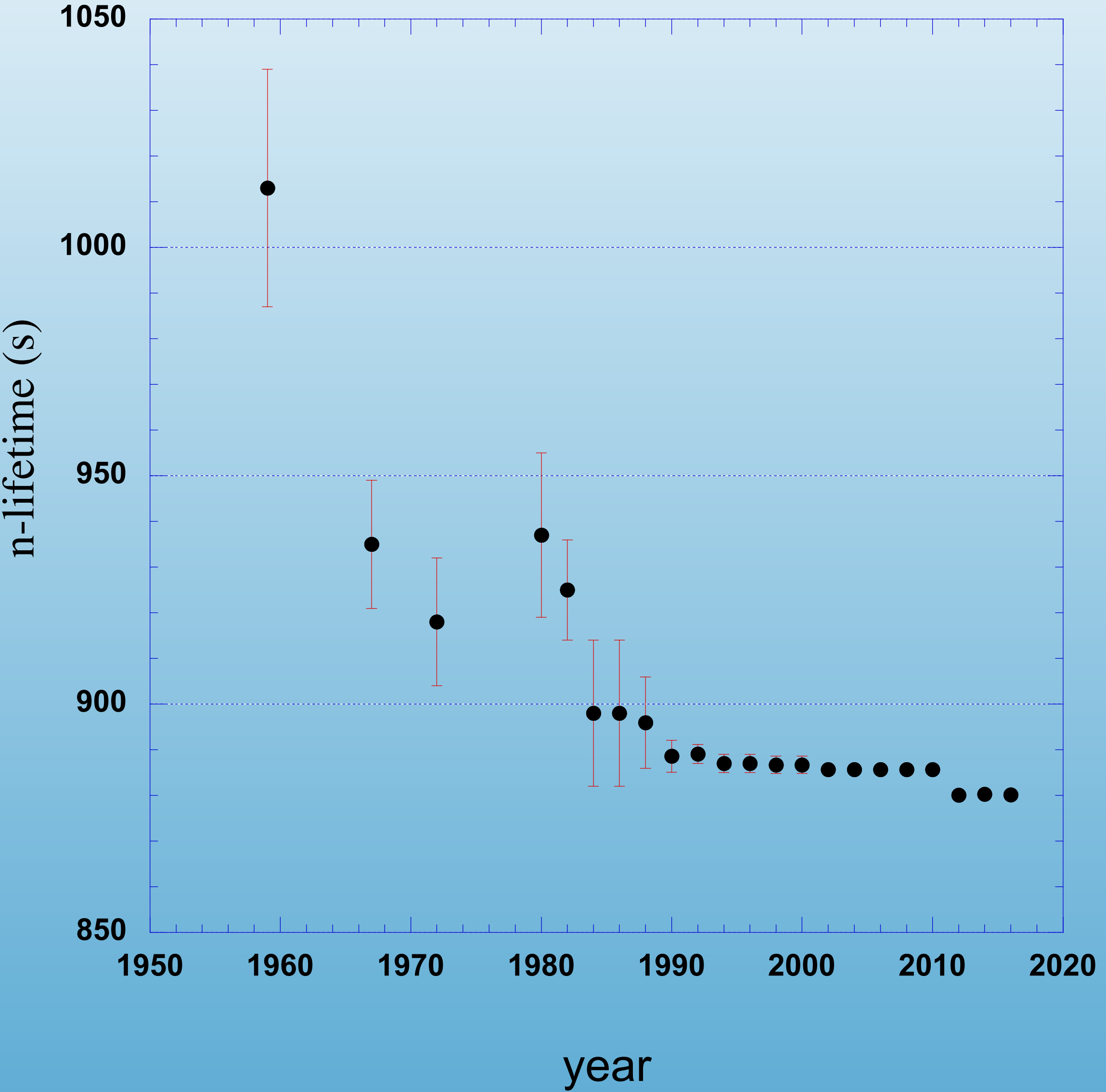
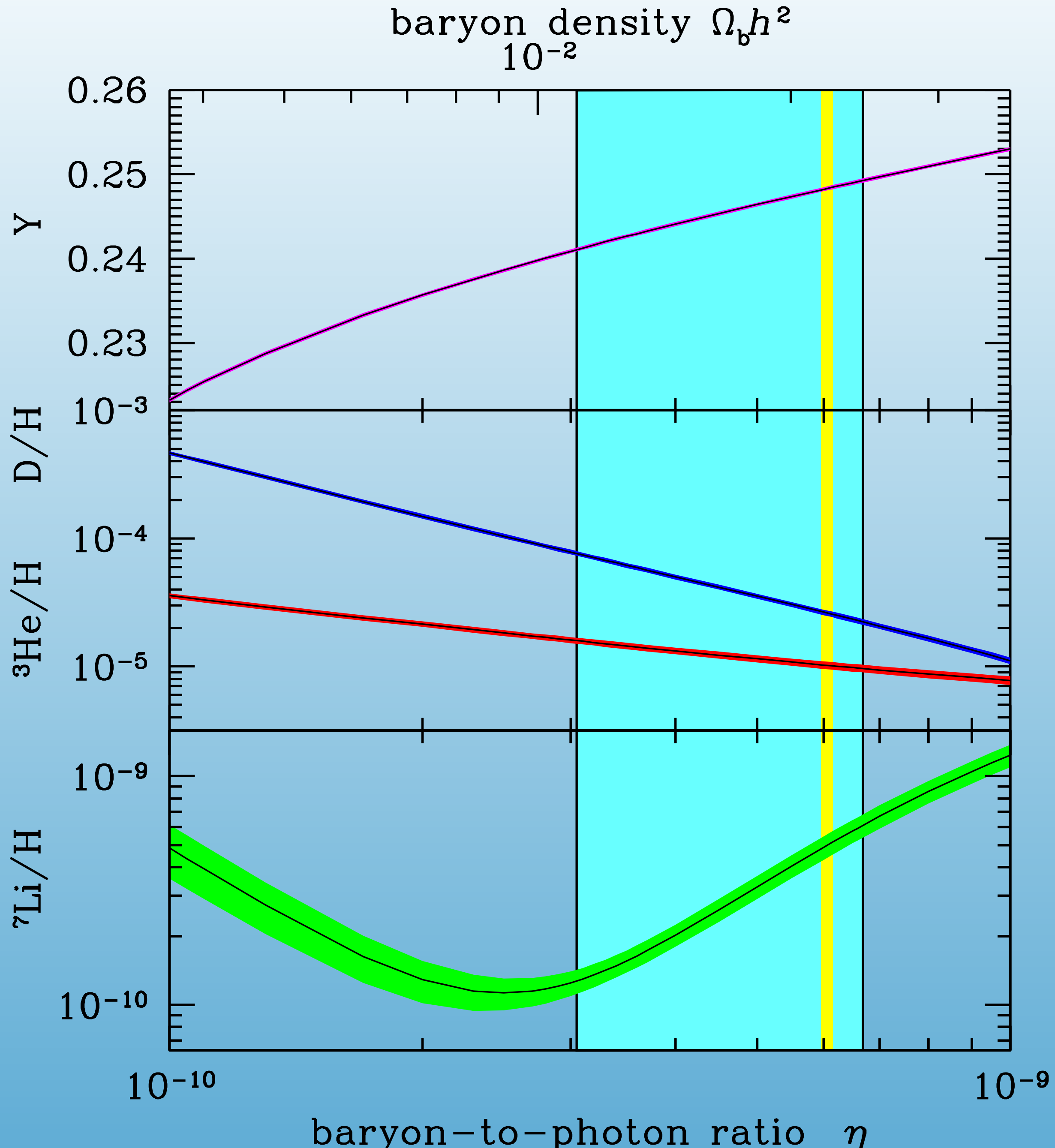




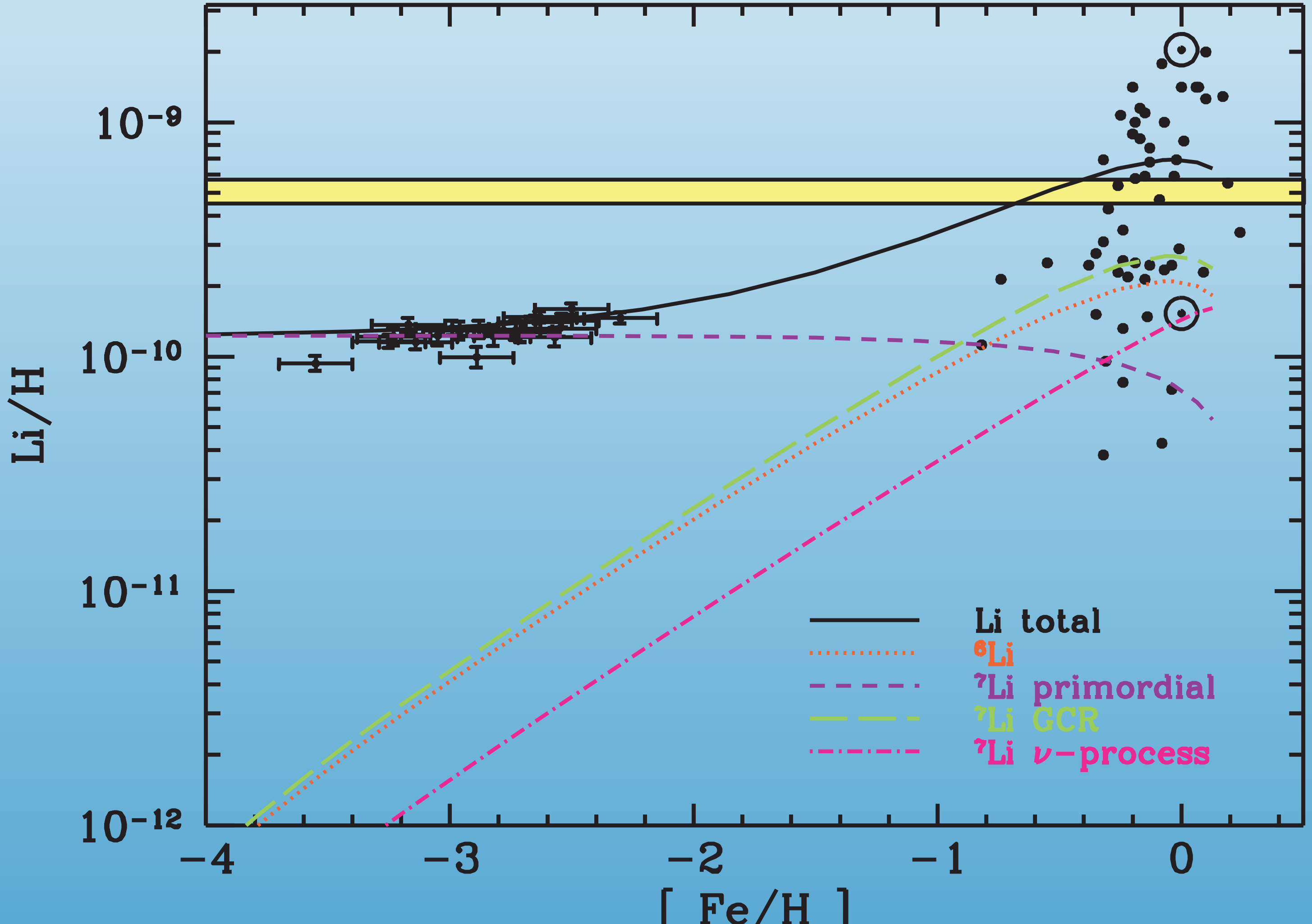
^{4}He Prediction:
0.2471 ± 0.0002

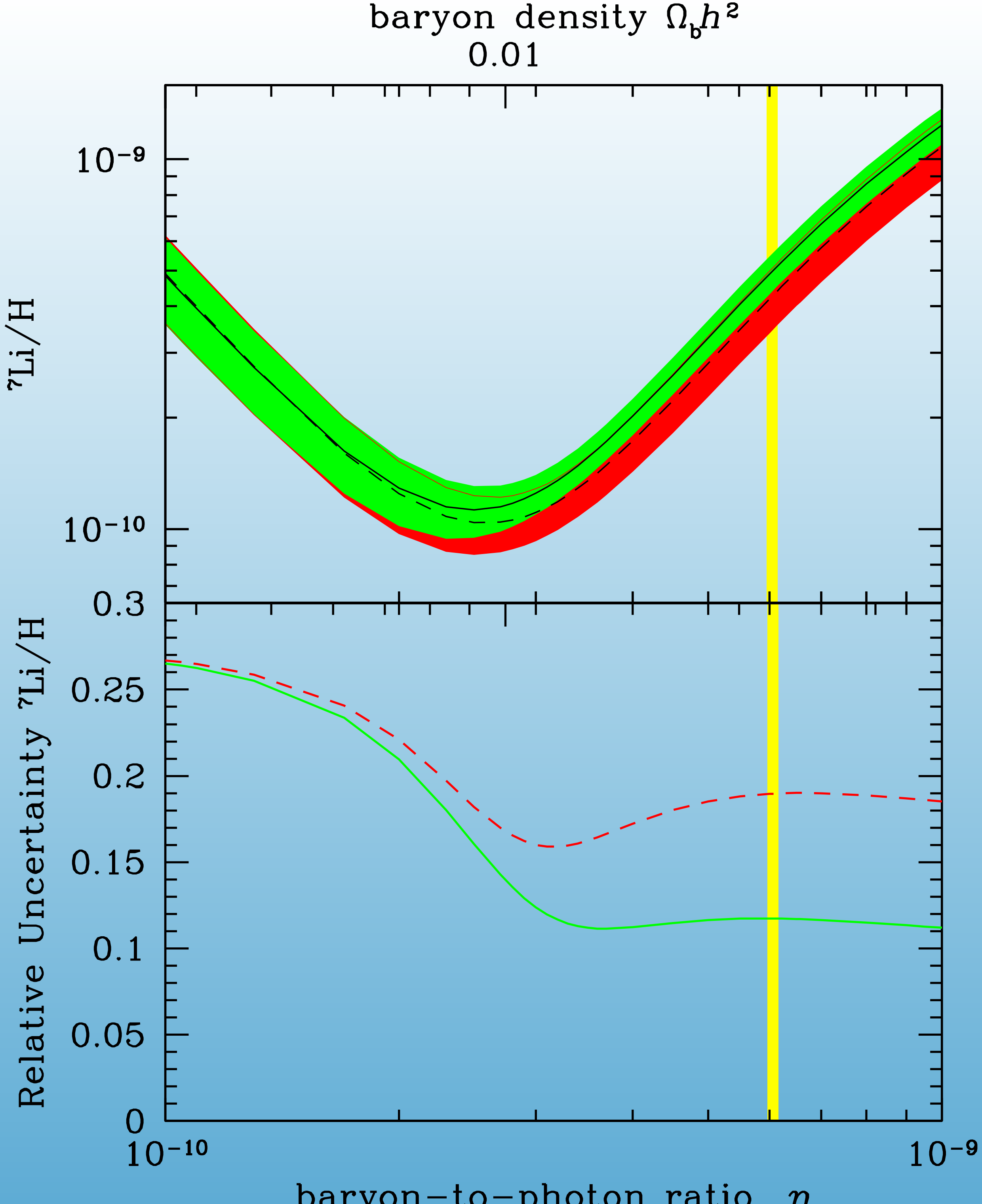
Data: Regression:
0.2449 ± 0.0040



Li/H

Measured in low metallicity dwarf halo stars
(over 100 observed)





At the Planck value for η:
Li/H =

$$(4.88^{+0.71}_{-0.62}) \times 10^{-10}$$

cf. data at

$$\left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{halo}\star} = (1.23^{+0.34}_{-0.16}) \times 10^{-10},$$

$$\left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{Gl.Cl.}} = (2.34 \pm 0.05) \times 10^{-10},$$

improved ^{3}He(α,γ)^{7}Be

Cyburt, Fields, KAO

Possible sources for the discrepancy

- Nuclear Rates
  - Restricted by solar neutrino flux

Coc et al.
Cyburt, Fields, KAO
Boyd, et al.

Resonant Reactions

Is there a missing excited state providing a resonant reaction?

$$^{7}\mathrm{Be} + A \rightarrow C^{*} \rightarrow B + D$$

If energy released in producing C* is

$$Q_C = \Delta(^{7}\mathrm{Be}) + \Delta(A) - \Delta(C^{\mathrm{g.s.}})$$

$$\Delta = m - Am_{\mathrm{u}}$$

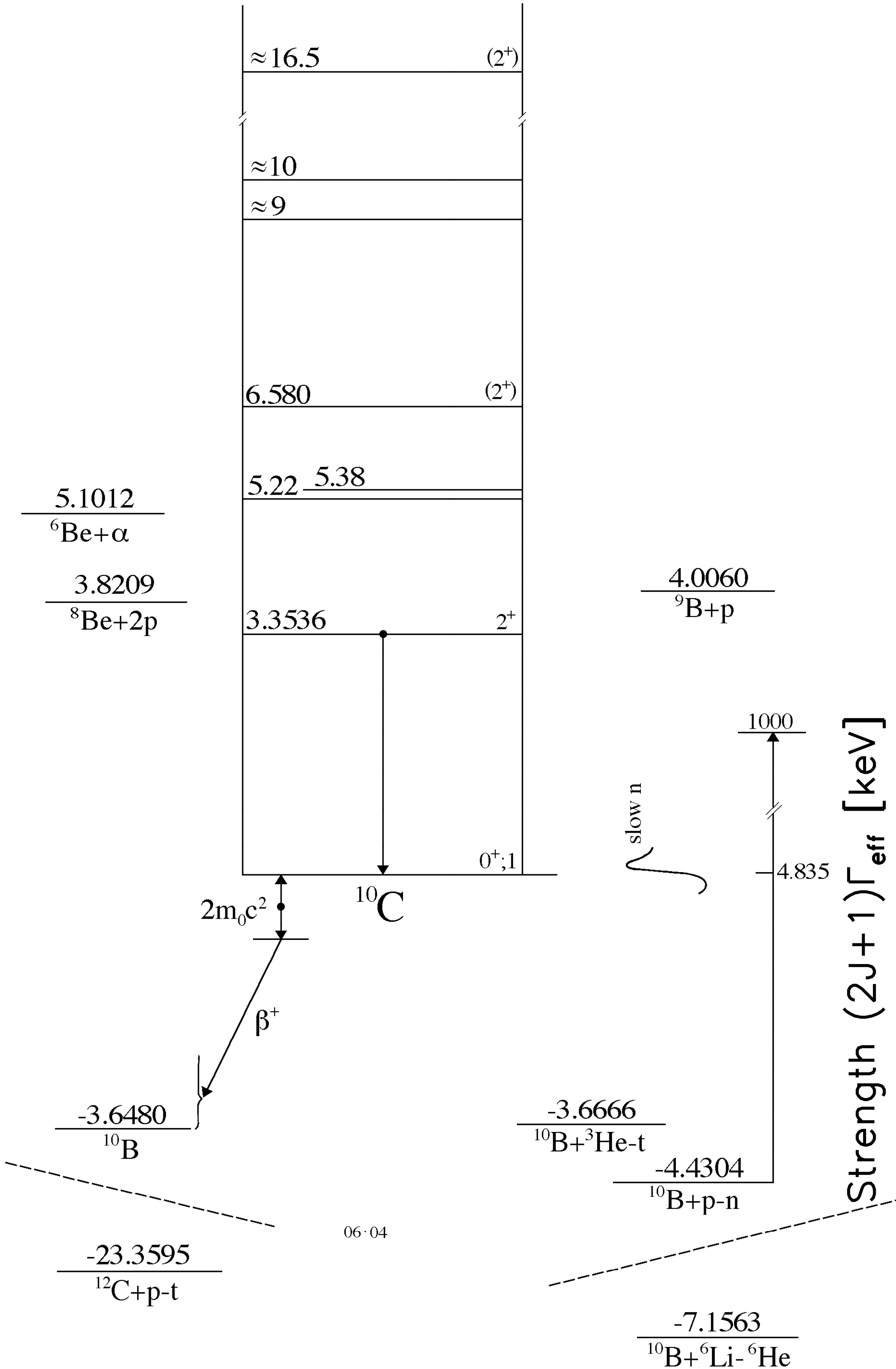
mass defect

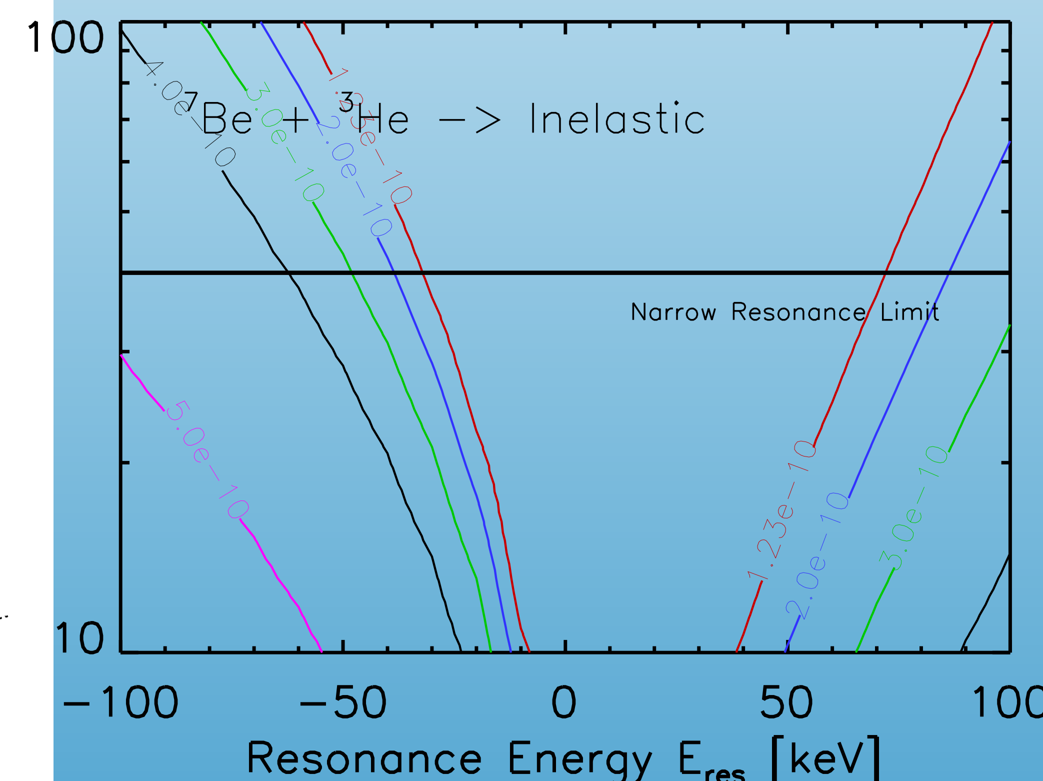
Then the resonant energy is

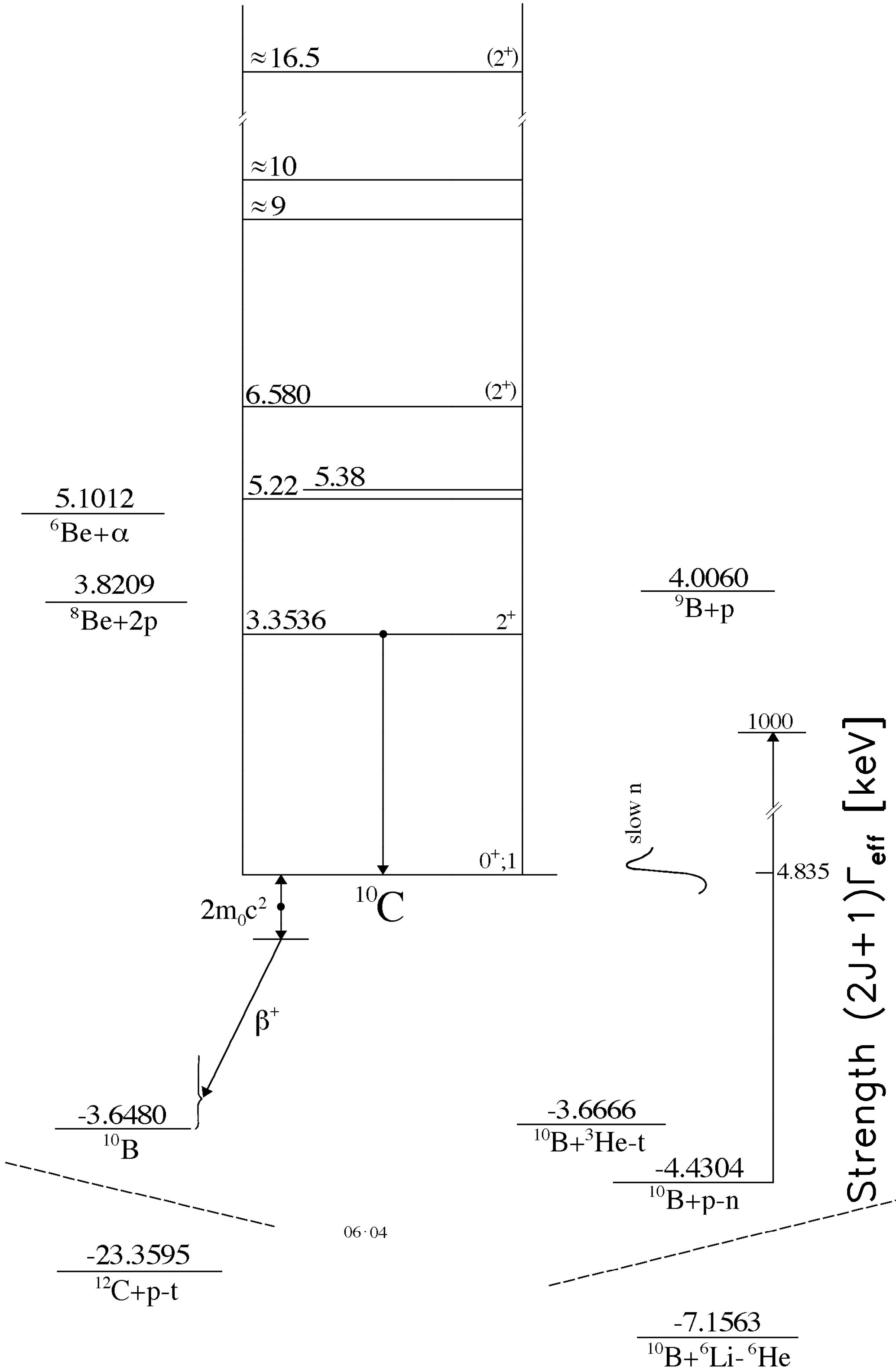
$$E_{\mathrm{res}} \equiv E_{\mathrm{ex}} - Q_C$$

In principle, long list of possible resonance candidates

- Excited states of ^{8}Li (included)
- ^{8}Be (some included) - large E_{res}
- ^{8}B (included)
- ^{9}B - interesting state at 16.71 MeV
- ^{10}B - interesting state at 18.80 MeV
- ^{10}C - potentially interesting state at 15 MeV
- ^{11}C - negligible effect


≈16.5
(2+)
≈10
≈9
6.580
(2+)
5.22
5.38
5.1012
6Be+α
3.8209
8Be+2p
3.3536
2+
4.0060
9B+p
1000
slow n
4.835
0+;1
2m0c2
10C
β+
-3.6480
10B
-3.6666
10B+3He-t
-4.4304
10B+p-n
06·04
-23.3595
12C+p-t
-7.1563
10B+6Li-6He

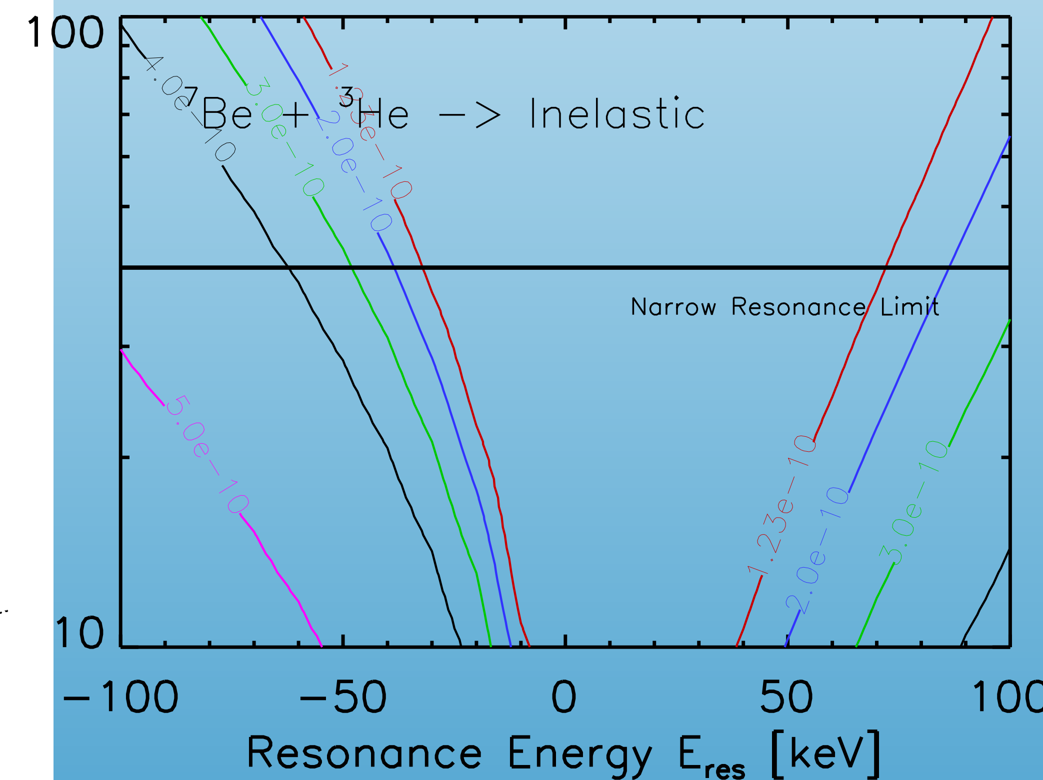

7Be + 3He -> Inelastic
Narrow Resonance Limit
Strength (2J+1)Γeff [keV]
Resonance Energy Eres [keV]
100
10
-100
-50
0
50
100
5.0e-10
4.0e-10
3.0e-10
2.0e-10
1.23e-10

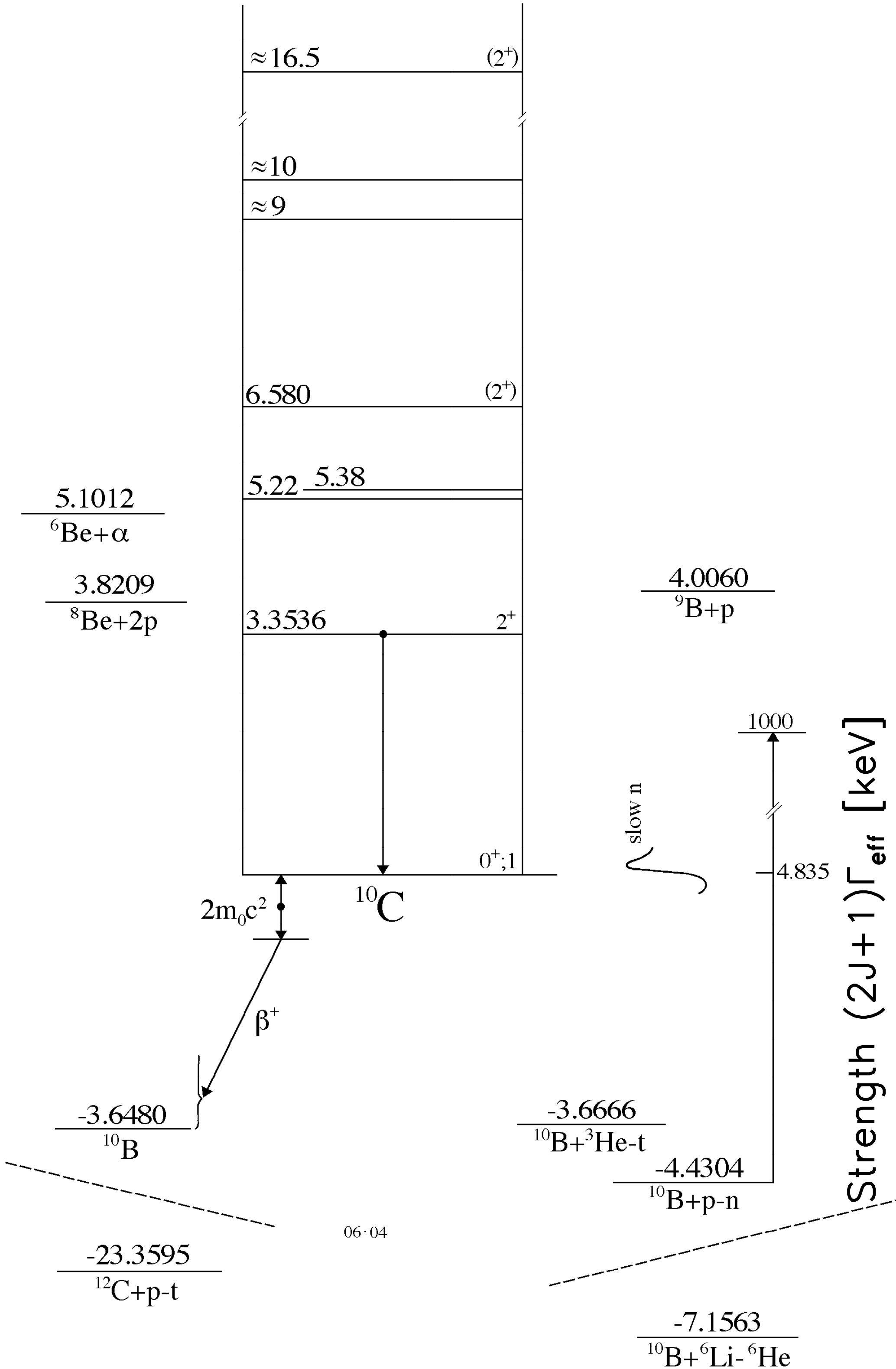


15.0

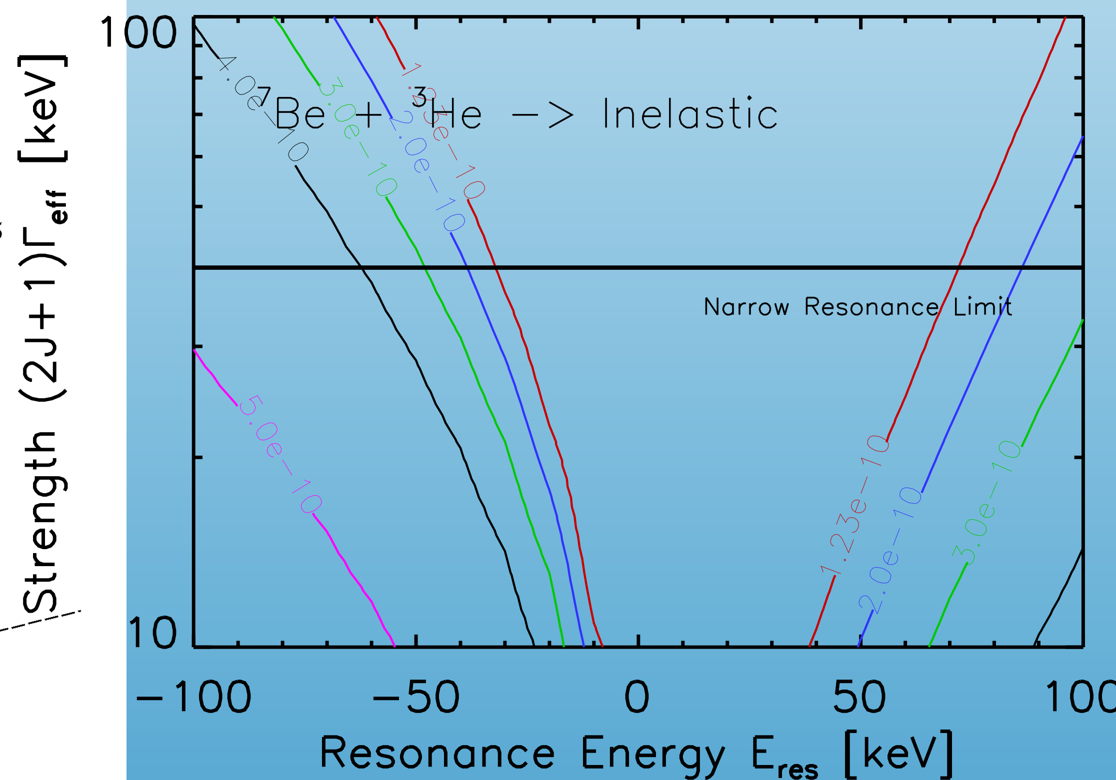
^{7}Be + ^{3}He

eg. if a 1^{-} or 2^{-} excited state of ^{10}C were near 15.0 MeV .....





But, Not seen in recent experiments (Hammache et al. 2013)



Limits on Unstable particles due to

Electromagnetic/Hadronic Production and Destruction of Nuclei

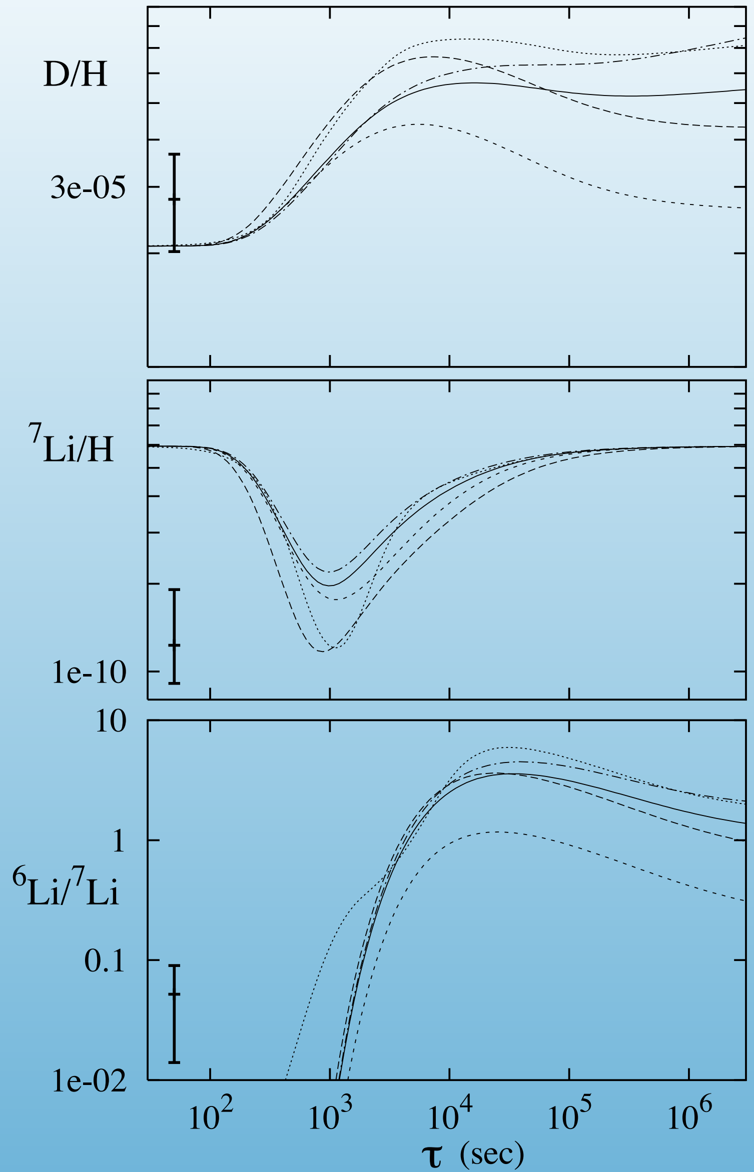
3 free parameters

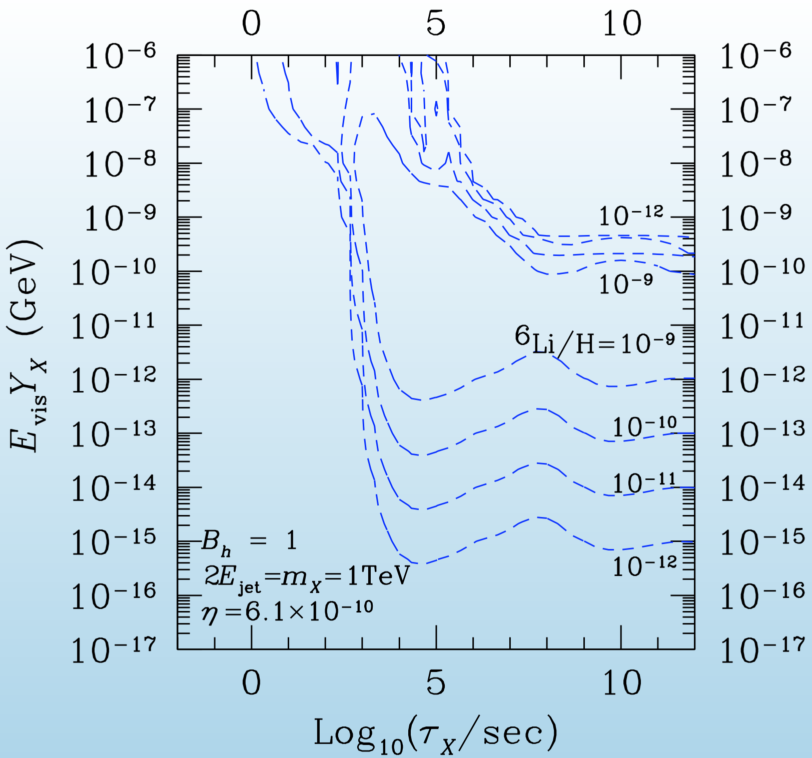
$\zeta_X = n_X m_X / n_\gamma = m_X Y_X \eta$, m_X ,

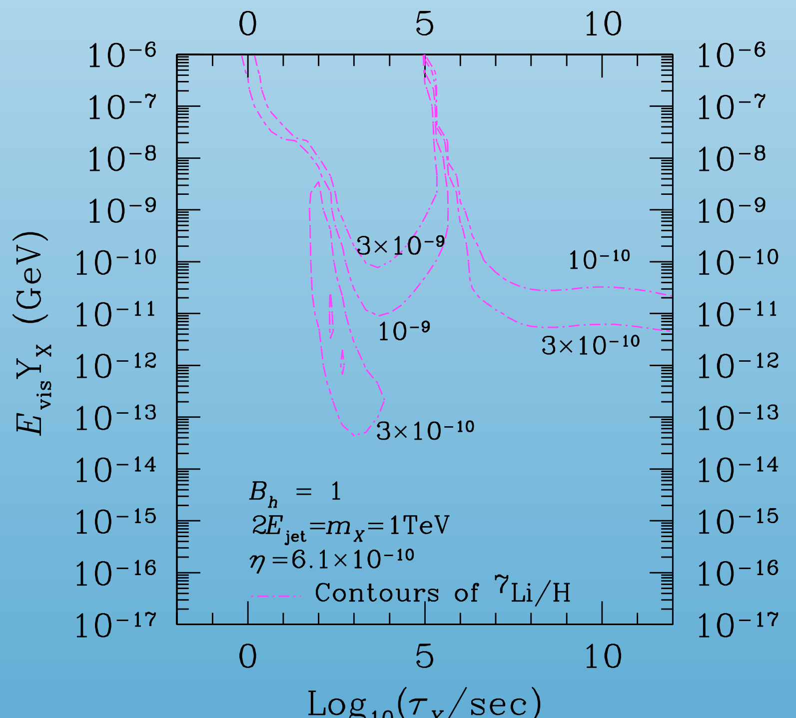
and τ_X

- Start with non-thermal injection spectrum (Pythia)

- Evolve element abundances including thermal (BBN) and non-thermal processes.

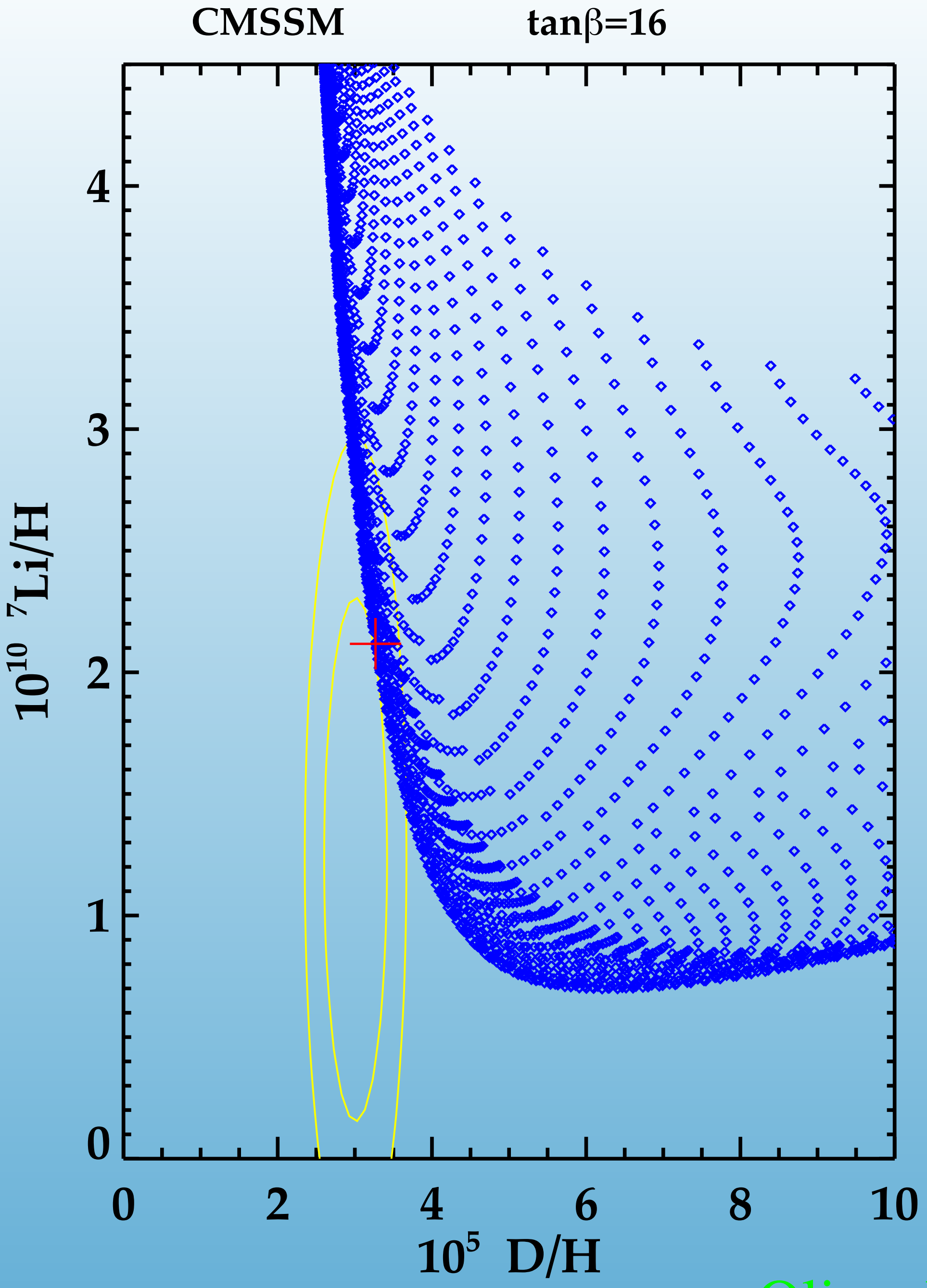






Jedamzik

Kawasaki, Kohri, Moroi

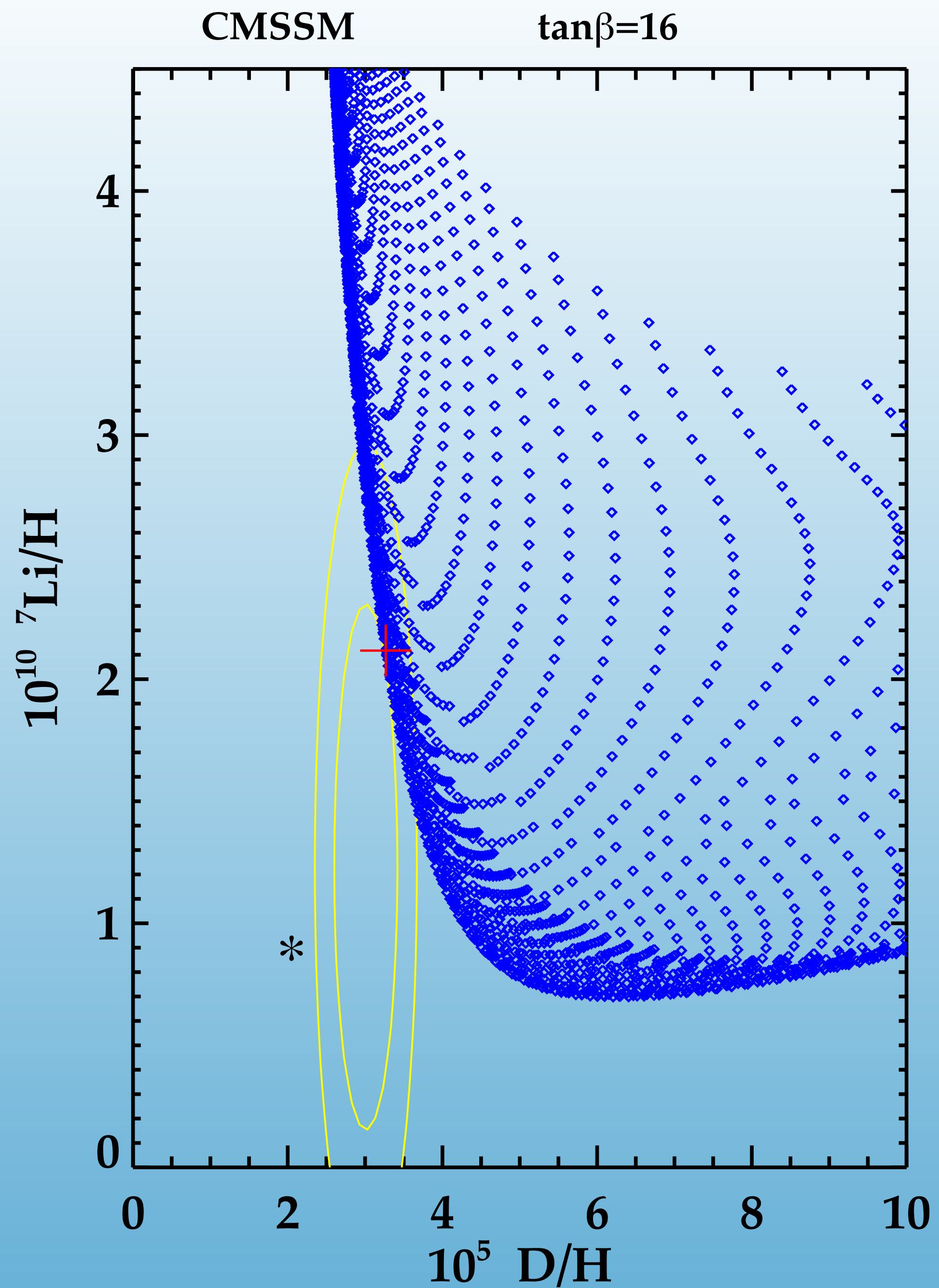


Injection of p,n with timescale of ~1000 s

$^7Be(n,p)^7Li$ followed by $^7Li(p,\alpha)^4He$

Olive, Petitjean, Vangioni, Silk

Cyburt, Ellis, Fields, Luo, Olive, Spanos



Injection of p,n with timescale of ~1000 s

$^7Be(n,p)^7Li$
followed by
$^7Li(p,\alpha)^4He$

*Uses $\sigma_{D/H} = \pm\ 0.27$ should now be ± 0.13

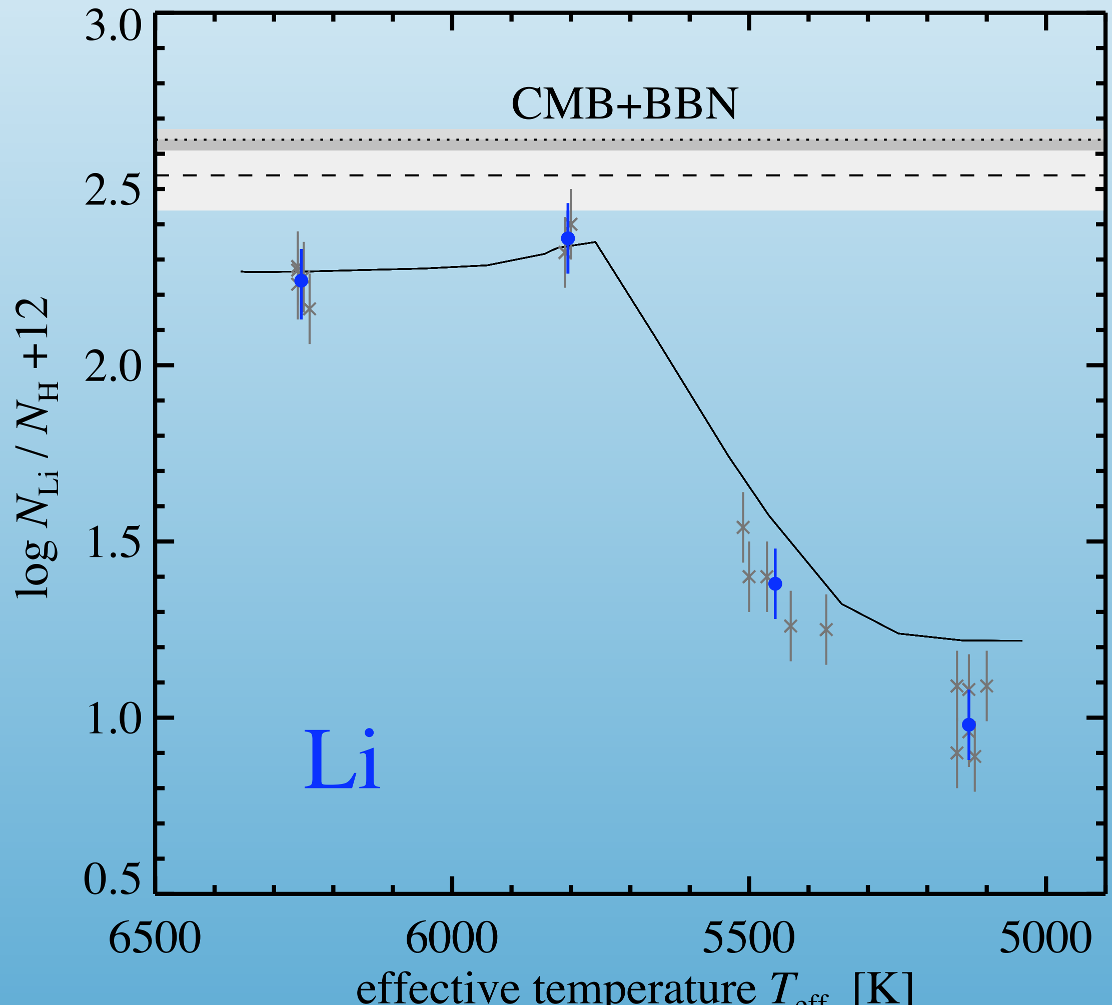
Olive, Petitjean, Vangioni, Silk
Cyburt, Ellis, Fields, Luo, Olive, Spanos

Possible sources for the discrepancy

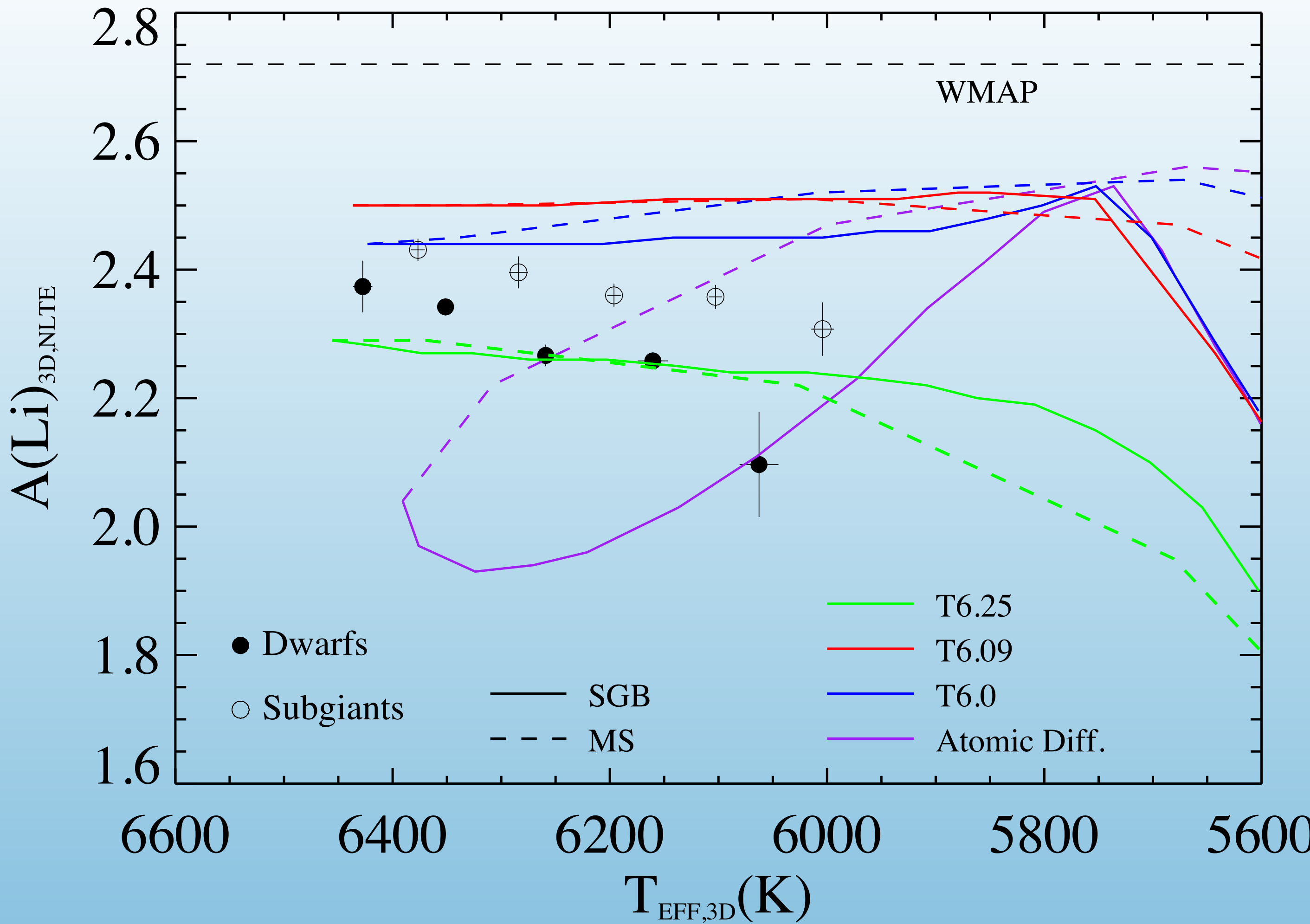
- Stellar Depletion
  - lack of dispersion in the data, ^{6}Li abundance
  - standard models (< .05 dex), models (0.2 - 0.4 dex)

Vauclaire & Charbonnel
Pinsonneault et al.
Richard, Michaud, Richer
Korn et al.

Stellar Depletion in the Turbulence Model of Korn et al.

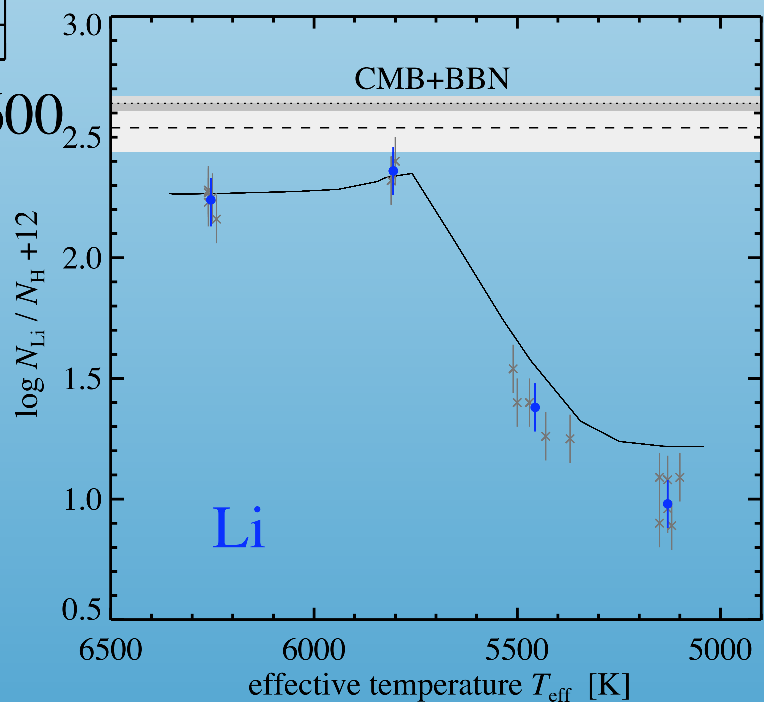


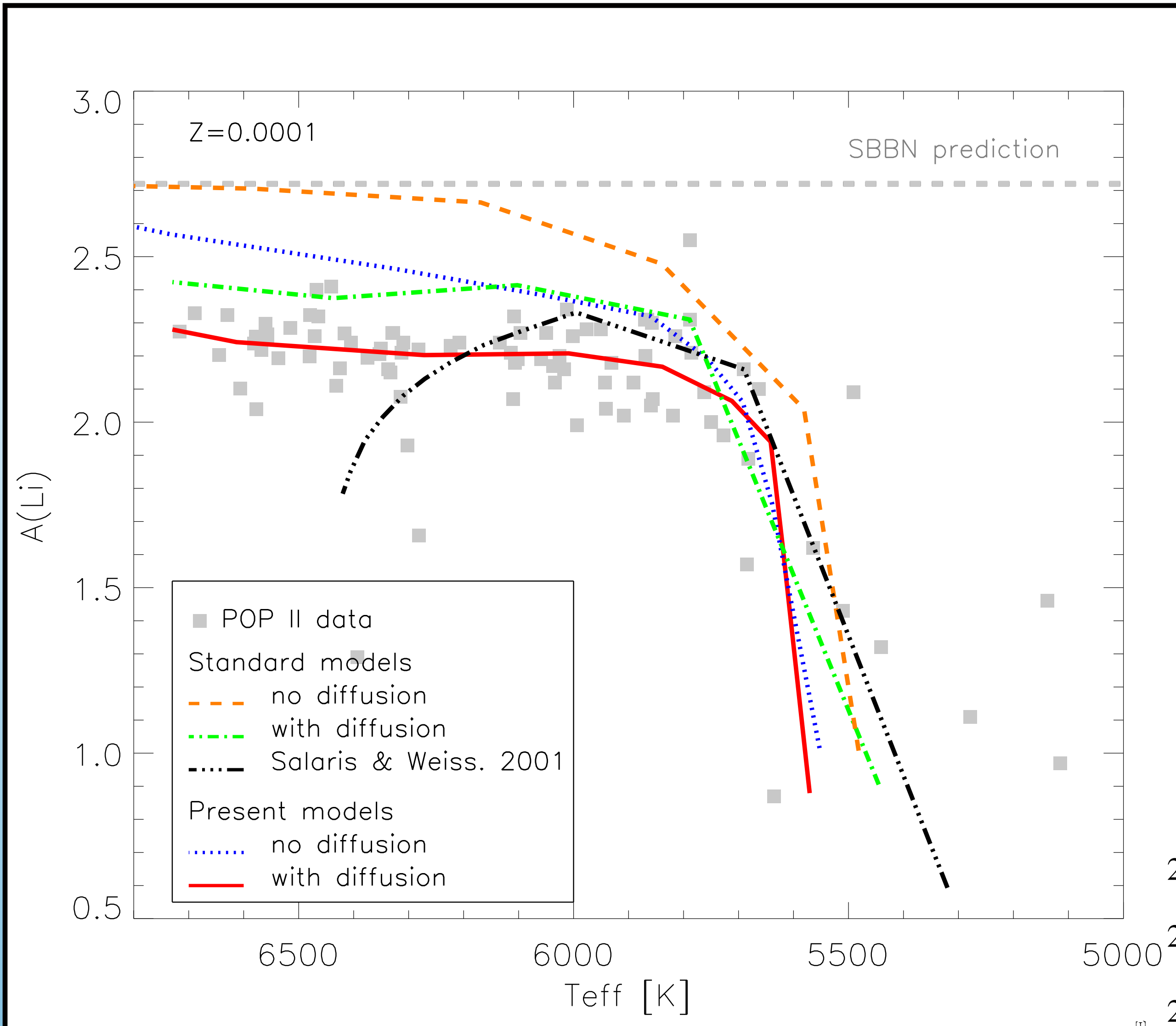
Note new BBN Li result pushes primordial value up from 2.63 to 2.72



But,

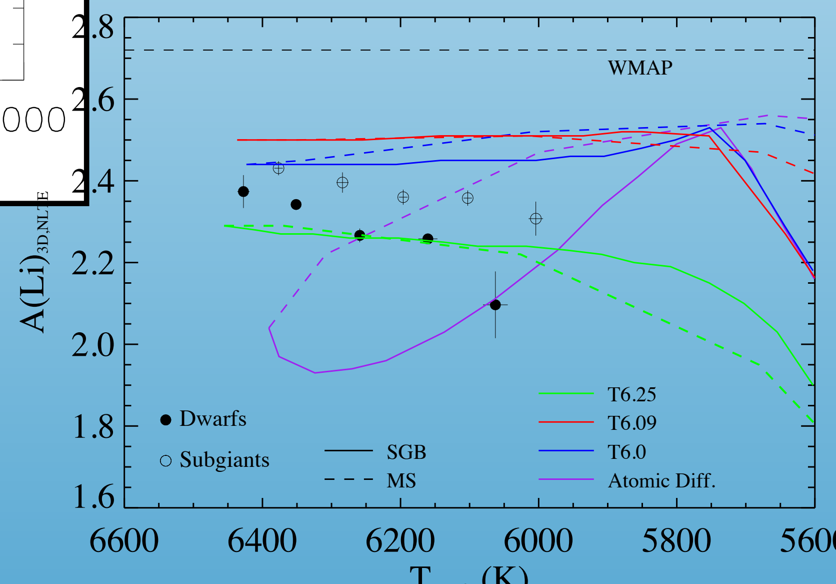
from Gonzáles Hernández et al. (2009)





But,

from Fu et al. (2015)

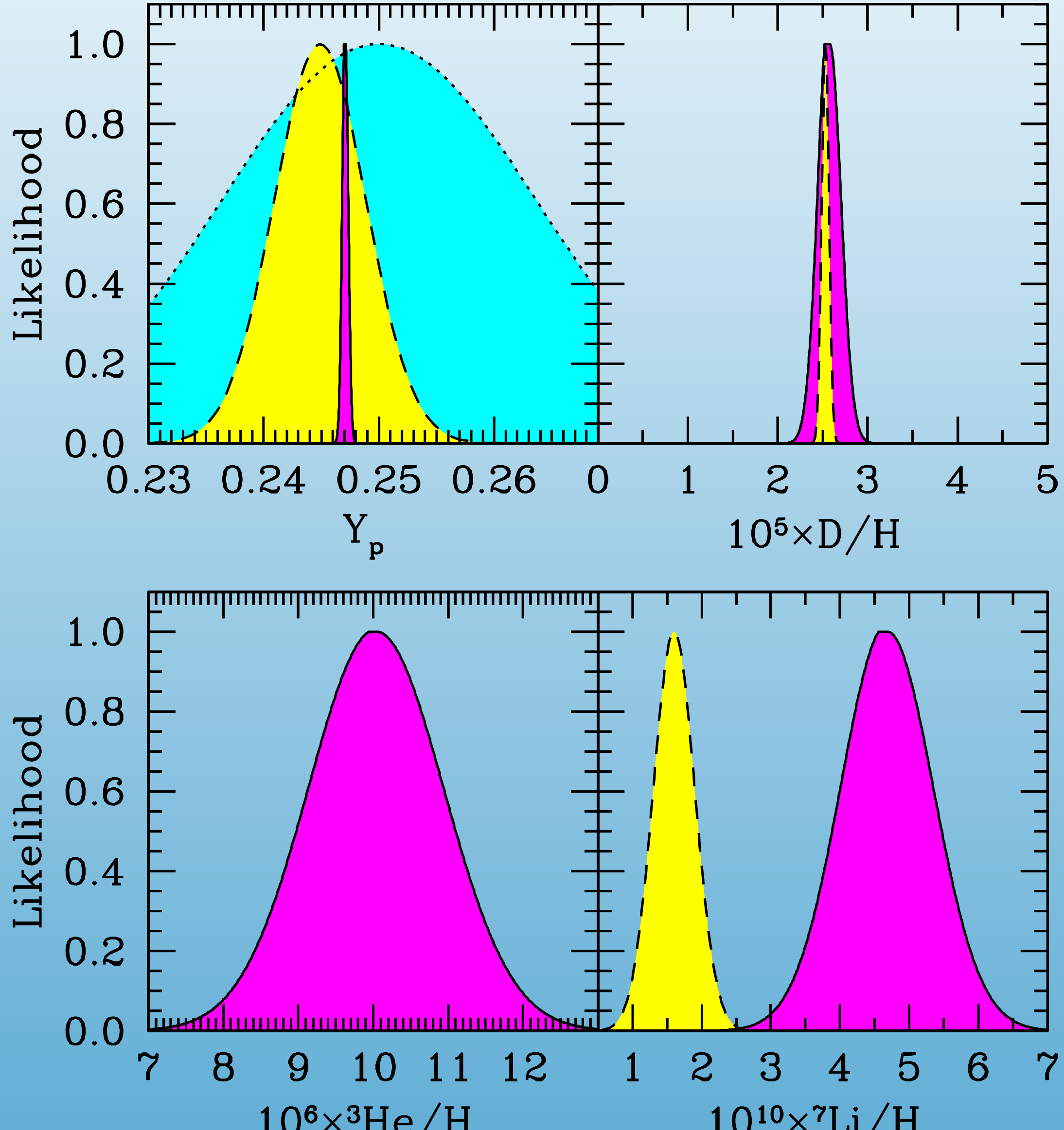


Other possible sources for the discrepancy

- Stellar parameters
- Axion Cooling
- Variable Constants

BBN and the CMB

Monte-Carlo approach combining BBN rates, observations and CMB



Cyburt, Fields, Olive, Yeh

BBN and the CMB

Sensitivities

$$Y_p = 0.24703 \left(\frac{10^{10}\eta}{6.10}\right)^{0.039} \left(\frac{N_\nu}{3.0}\right)^{0.163} \left(\frac{G_N}{G_{N,0}}\right)^{0.35} \left(\frac{\tau_n}{880.3s}\right)^{0.73}$$
$$\times\, [p(n,\gamma)d]^{0.005}\, [d(d,n)^3\mathrm{He}]^{0.006}\, [d(d,p)t]^{0.005}$$

$$\frac{\mathrm{D}}{\mathrm{H}} = 2.579 \times 10^{-5} \left(\frac{10^{10}\eta}{6.10}\right)^{-1.60} \left(\frac{N_\nu}{3.0}\right)^{0.395} \left(\frac{G_N}{G_{N,0}}\right)^{0.95} \left(\frac{\tau_n}{880.3s}\right)^{0.41}$$
$$\times\, [p(n,\gamma)d]^{-0.19}\, [d(d,n)^3\mathrm{He}]^{-0.53}\, [d(d,p)t]^{-0.47}$$
$$\times\, [d(p,\gamma)^3\mathrm{He}]^{-0.31}\, [^3\mathrm{He}(n,p)t]^{0.023}\, [^3\mathrm{He}(d,p)^4\mathrm{He}]^{-0.012}$$

$$\frac{^3\mathrm{He}}{\mathrm{H}} = 9.996 \times 10^{-6} \left(\frac{10^{10}\eta}{6.10}\right)^{-0.59} \left(\frac{N_\nu}{3.0}\right)^{0.14} \left(\frac{G_N}{G_{N,0}}\right)^{0.34} \left(\frac{\tau_n}{880.3s}\right)^{0.15}$$
$$\times\, [p(n,\gamma)d]^{0.088}\, [d(d,n)^3\mathrm{He}]^{0.21}\, [d(d,p)t]^{-0.27}$$
$$\times\, [d(p,\gamma)^3\mathrm{He}]^{0.38}\, [^3\mathrm{He}(n,p)t]^{-0.17}\, [^3\mathrm{He}(d,p)^4\mathrm{He}]^{-0.76}\, [t(d,n)^4\mathrm{He}]^{-0.009}$$

$$\frac{^7\mathrm{Li}}{\mathrm{H}} = 4.648 \times 10^{-10} \left(\frac{10^{10}\eta}{6.10}\right)^{2.11} \left(\frac{N_\nu}{3.0}\right)^{-0.284} \left(\frac{G_N}{G_{N,0}}\right)^{-0.73} \left(\frac{\tau_n}{880.3s}\right)^{0.43}$$
$$\times\, [p(n,\gamma)d]^{1.34}\, [d(d,n)^3\mathrm{He}]^{0.70}\, [d(d,p)t]^{0.065}$$
$$\times\, [d(p,\gamma)^3\mathrm{He}]^{0.59}\, [^3\mathrm{He}(n,p)t]^{-0.27}\, [^3\mathrm{He}(d,p)^4\mathrm{He}]^{-0.75}\, [t(d,n)^4\mathrm{He}]^{-0.023}$$
$$\times\, [^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}]^{0.96}\, [^7\mathrm{Be}(n,p)^7\mathrm{Li}]^{-0.71}\, [^7\mathrm{Li}(p,\alpha)^4\mathrm{He}]^{-0.056}\, [t(\alpha,\gamma)^7\mathrm{Li}]^{0.030}$$

Cyburt, Fields, Olive, Yeh

BBN and the CMB

Convolved Likelihoods

From Planck:

$$\mathcal{L}_{\mathrm{PLA-base\_yhe}}(\omega_b, Y_p) \text{ and } \mathcal{L}_{\mathrm{PLA-base\_nnu\_yhe}}(\omega_b, Y_p, N_\nu)$$

$$\omega_b = 0.022305 \pm 0.000225$$

$$Y_p = 0.25003 \pm 0.01367$$

$$\omega_b = 0.022212 \pm 0.000242$$

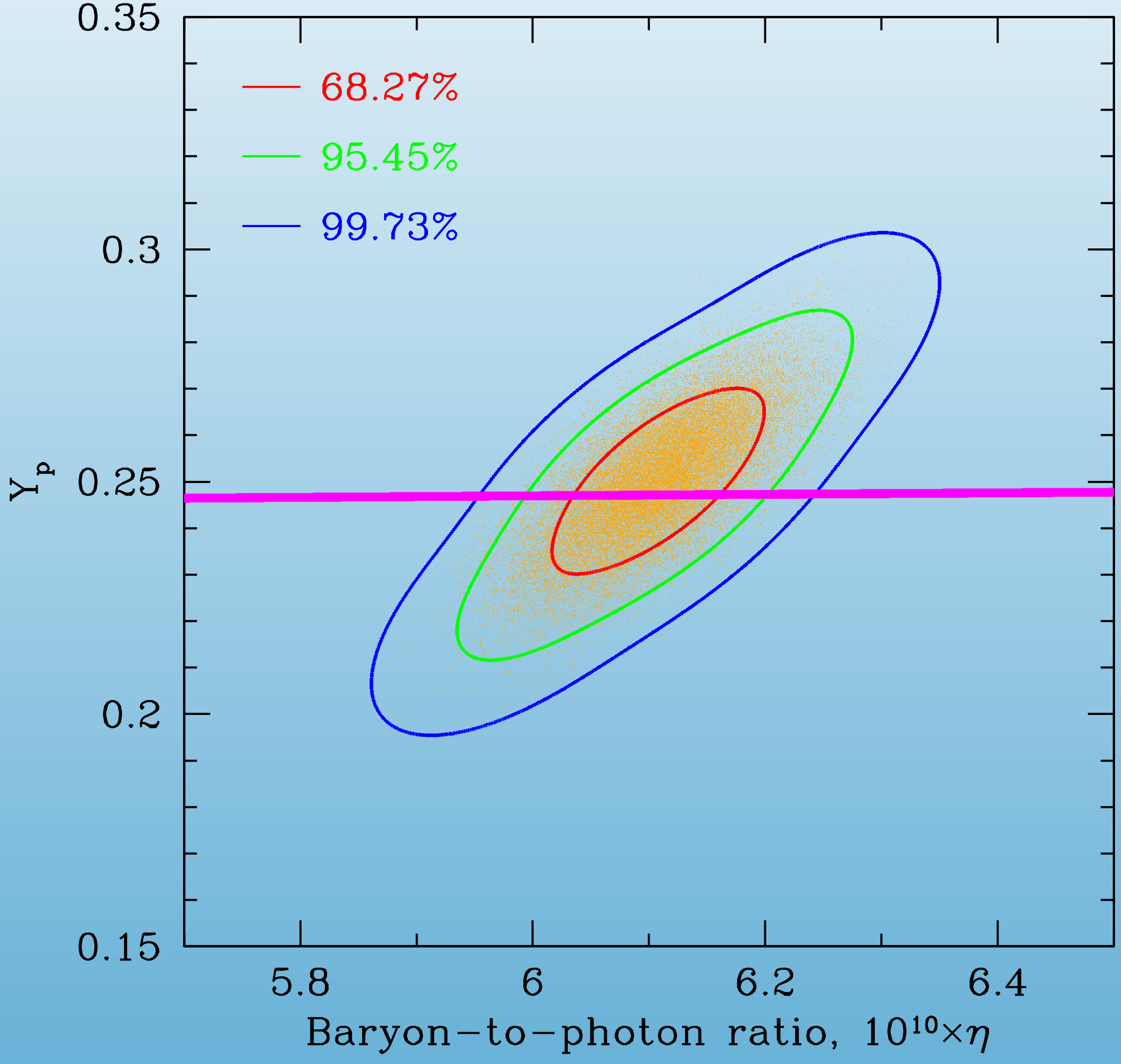
$$N_{\rm eff} = 2.7542 \pm 0.3064$$

$$Y_p = 0.26116 \pm 0.01812$$

Cyburt, Fields, Olive, Yeh

BBN and the CMB

$N_\nu = 3$



CMB only determination of η and Y_P

3σ BBN Prediction

Cyburt, Fields, Olive, Yeh

BBN and the CMB

Results for η (N_ν)

Constraints Used	$\eta \times 10^{10}$
CMB-only	6.108 ± 0.060
BBN+Y_p	$4.87^{+2.46}_{-1.54}$
BBN+D	6.180 ± 0.195
BBN+Y_p+D	6.172 ± 0.195
CMB+BBN	6.098 ± 0.042
CMB+BBN+Y_p	6.098 ± 0.042
CMB+BBN+D	6.102 ± 0.041
CMB+BBN+Y_p+D	6.101 ± 0.041

Convolved Likelihoods

Constraints Used	η_{10}	N_ν
CMB-only	6.08 ± 0.07	$2.67^{+0.30}_{-0.27}$
BBN+Y_p+D	6.10 ± 0.23	2.85 ± 0.28
CMB+BBN	6.08 ± 0.07	2.91 ± 0.20
CMB+BBN+Y_p	6.07 ± 0.06	2.89 ± 0.16
CMB+BBN+D	6.07 ± 0.07	2.90 ± 0.19
CMB+BBN+Y_p+D	6.07 ± 0.06	2.88 ± 0.16

Cyburt, Fields, Olive, Yeh

BBN and the CMB

Results for η (N_ν)

Constraints Used	$\eta \times 10^{10}$
CMB-only	6.108 ± 0.060
BBN+Y_p	$4.87^{+2.46}_{-1.54}$
BBN+D	6.180 ± 0.195
BBN+Y_p+D	6.172 ± 0.195
CMB+BBN	6.098 ± 0.042
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CMB+BBN+D	6.102 ± 0.041
CMB+BBN+Y_p+D	6.101 ± 0.041

Convolved Likelihoods

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BBN+Y_p+D	6.10 ± 0.23	2.85 ± 0.28
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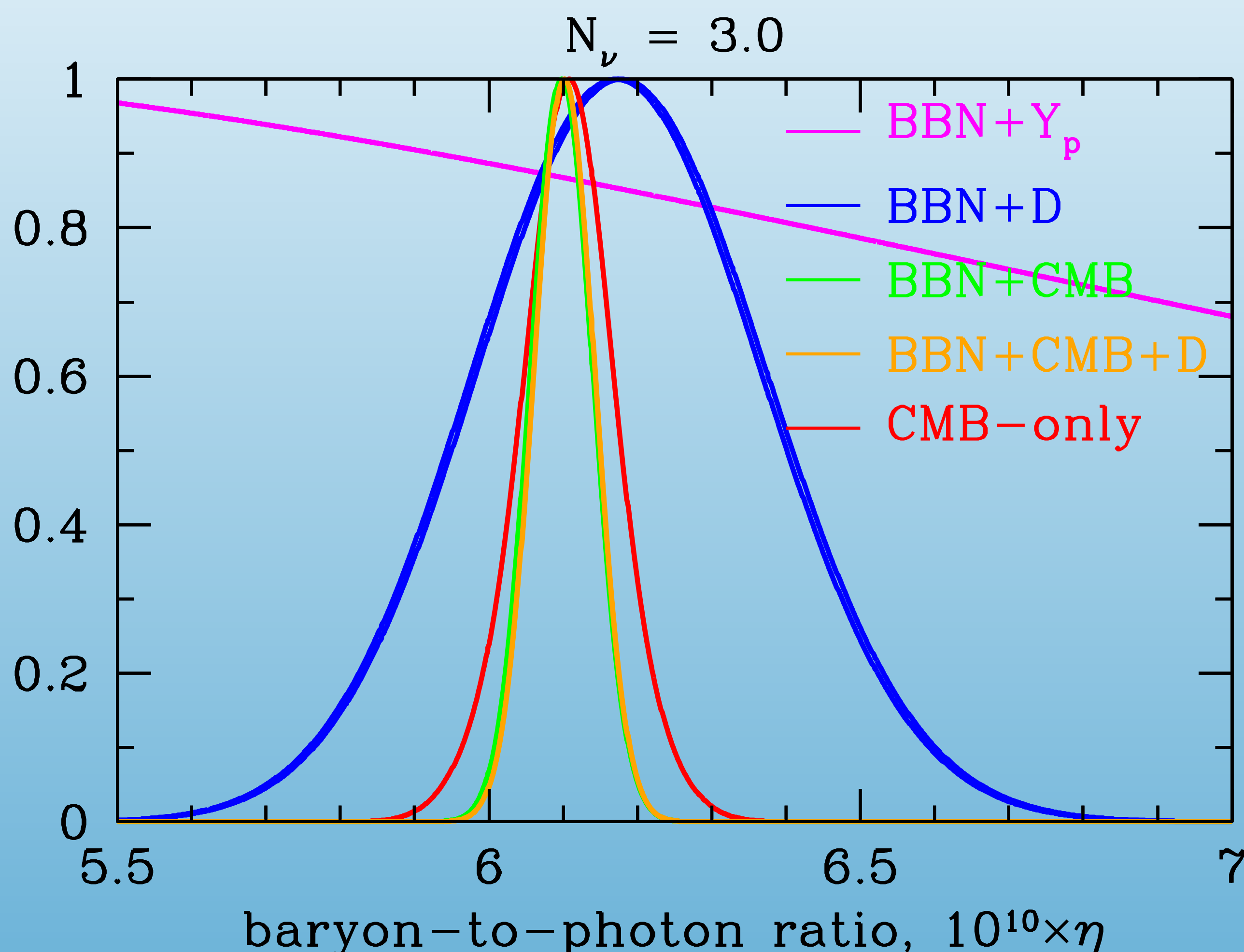
CMB+BBN+Y_p	6.07 ± 0.06	2.89 ± 0.16
CMB+BBN+D	6.07 ± 0.07	2.90 ± 0.19
CMB+BBN+Y_p+D	6.07 ± 0.06	2.88 ± 0.16

$N_\nu < 3.2$ (95% CL)

Cyburt, Fields, Olive, Yeh

BBN and the CMB

Convolved Likelihoods

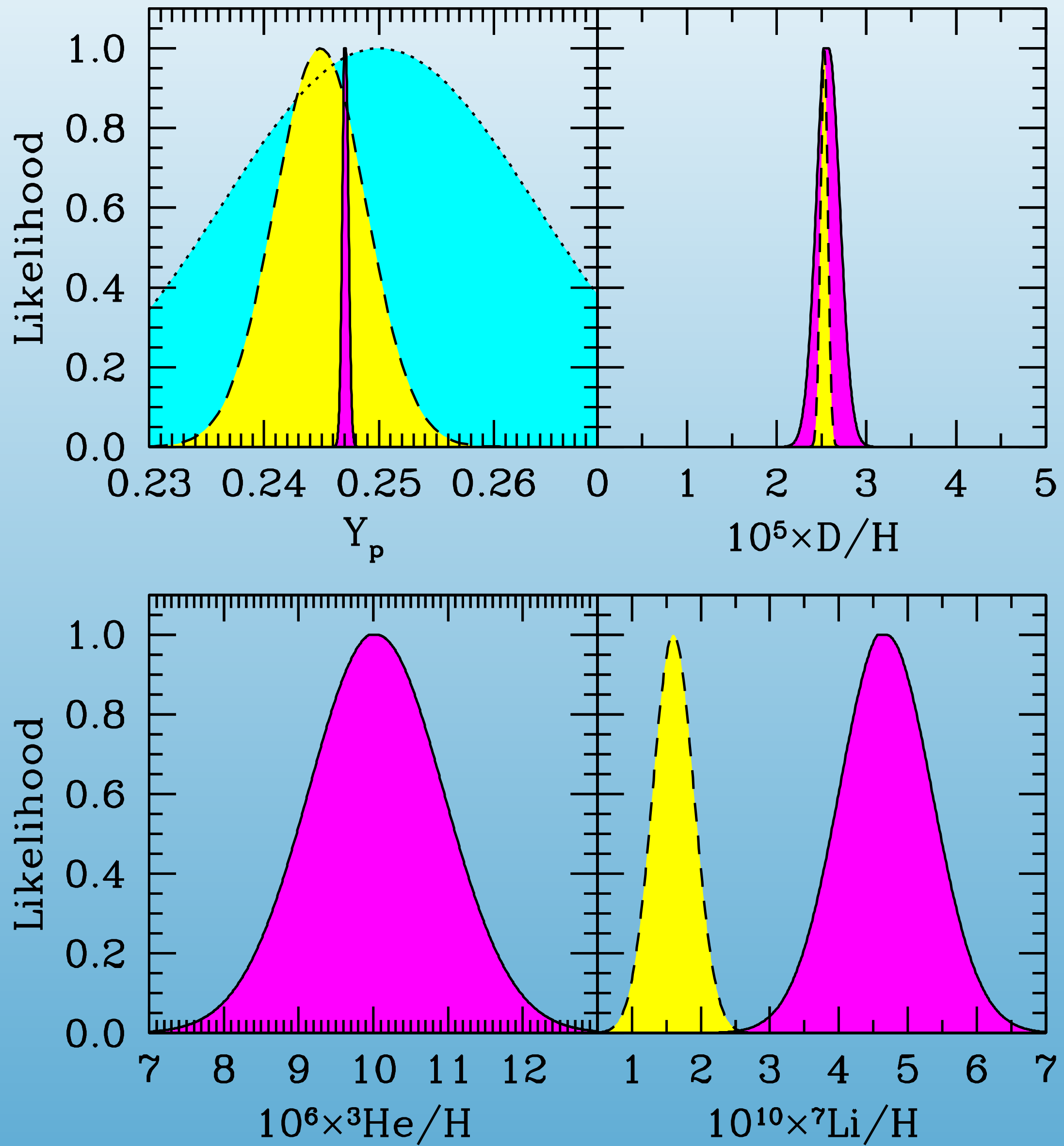


Determination of η

Cyburt, Fields, Olive, Yeh

BBN and the CMB

$$\mathcal{L}(X_i) \propto \int \mathcal{L}_{\mathrm{PLA-base\_yhe}}(\omega_b, Y_p)\ \mathcal{L}_{\mathrm{BBN}}(\eta; \{X_i\})\ d\eta$$



recall ω_b and η are related

$$Y_p = 0.24709 \pm 0.00025$$

$$\mathrm{D/H} = (2.58 \pm 0.13) \times 10^{-5}$$

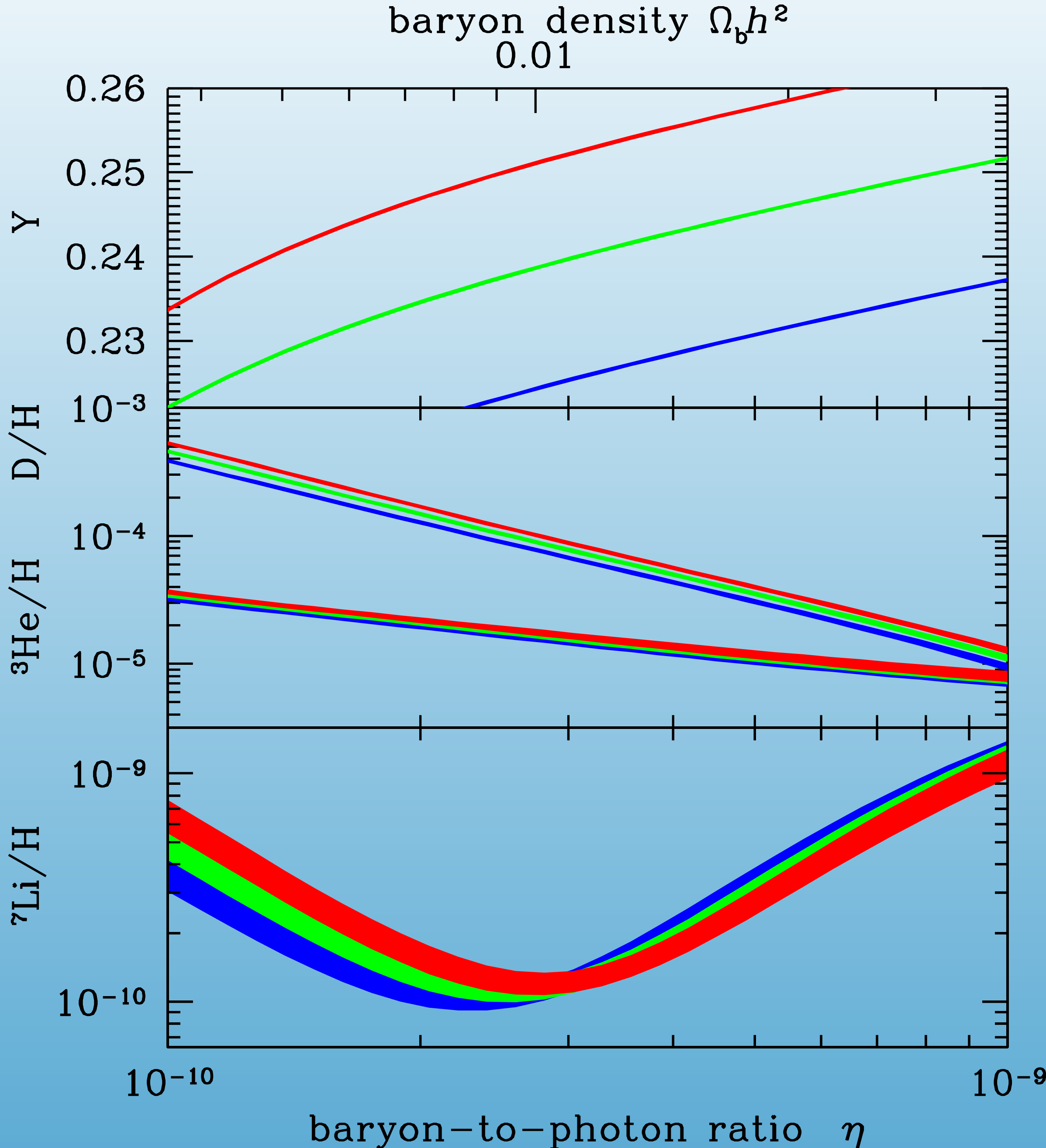
$$^3\mathrm{He/H} = (10.039 \pm 0.090) \times 10^{-5}$$

$$^7\mathrm{Li/H} = (4.68 \pm 0.67) \times 10^{-10}$$

$$\log_{10}(^6\mathrm{Li/H}) = -13.89 \pm 0.20$$

Cyburt, Fields, Olive, Yeh

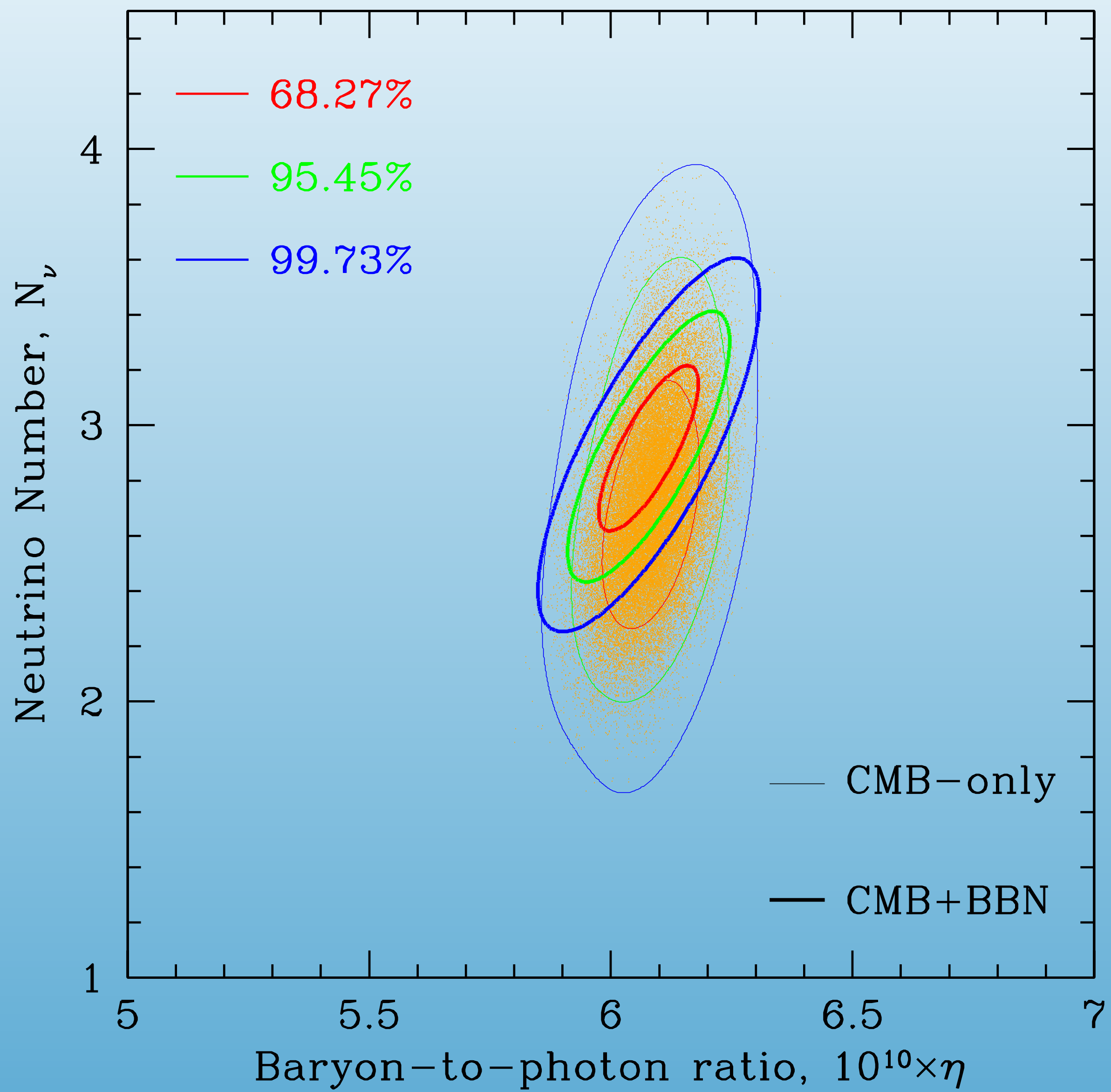
BBN and the CMB



Sensitivity to N_ν

Cyburt, Fields, Olive, Yeh

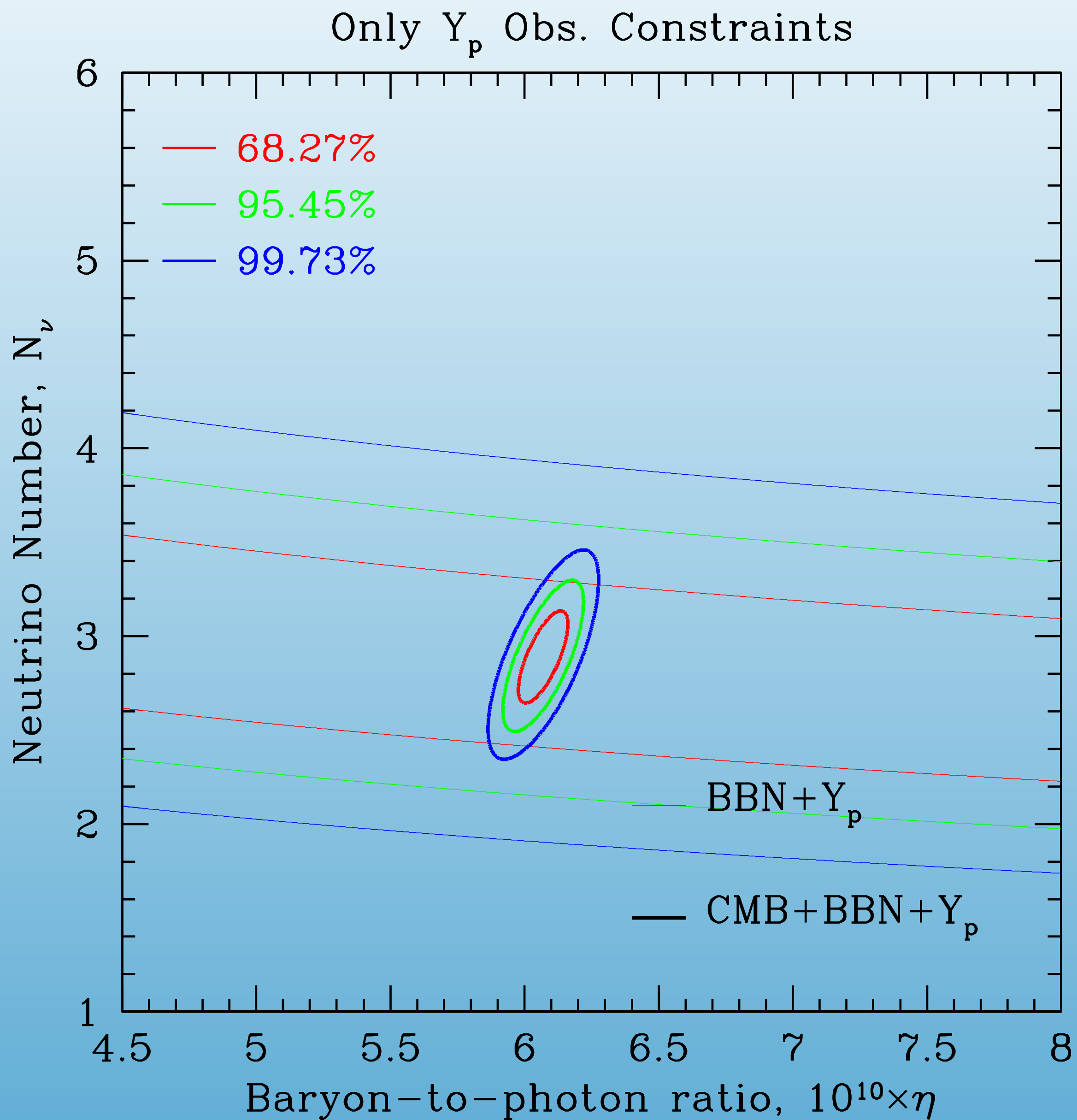
BBN and the CMB



CMB only determination of η and N_ν

Cyburt, Fields, Olive, Yeh

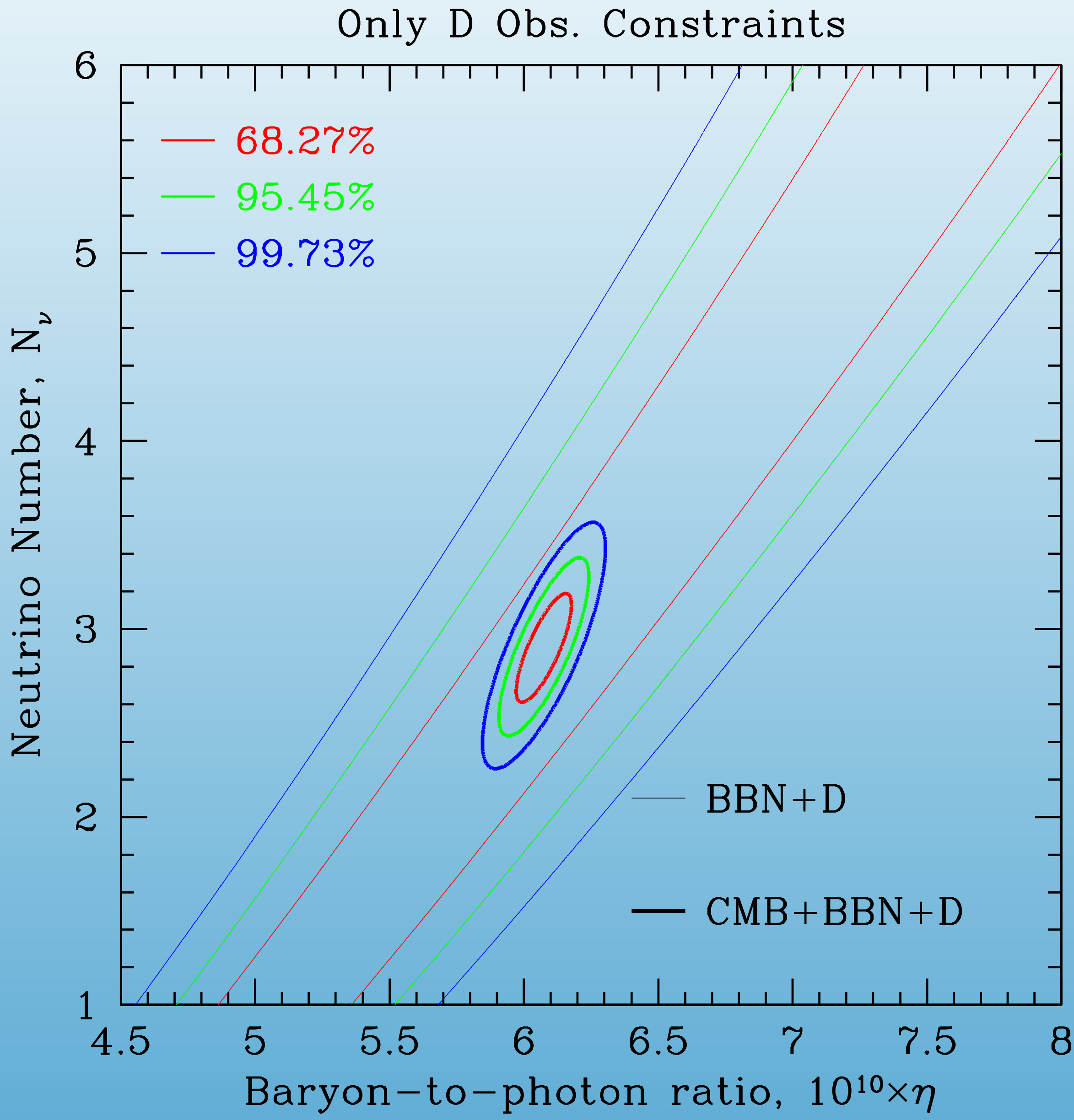
BBN and the CMB



CMB and BBN determination of η and N_ν

Cyburt, Fields, Olive, Yeh

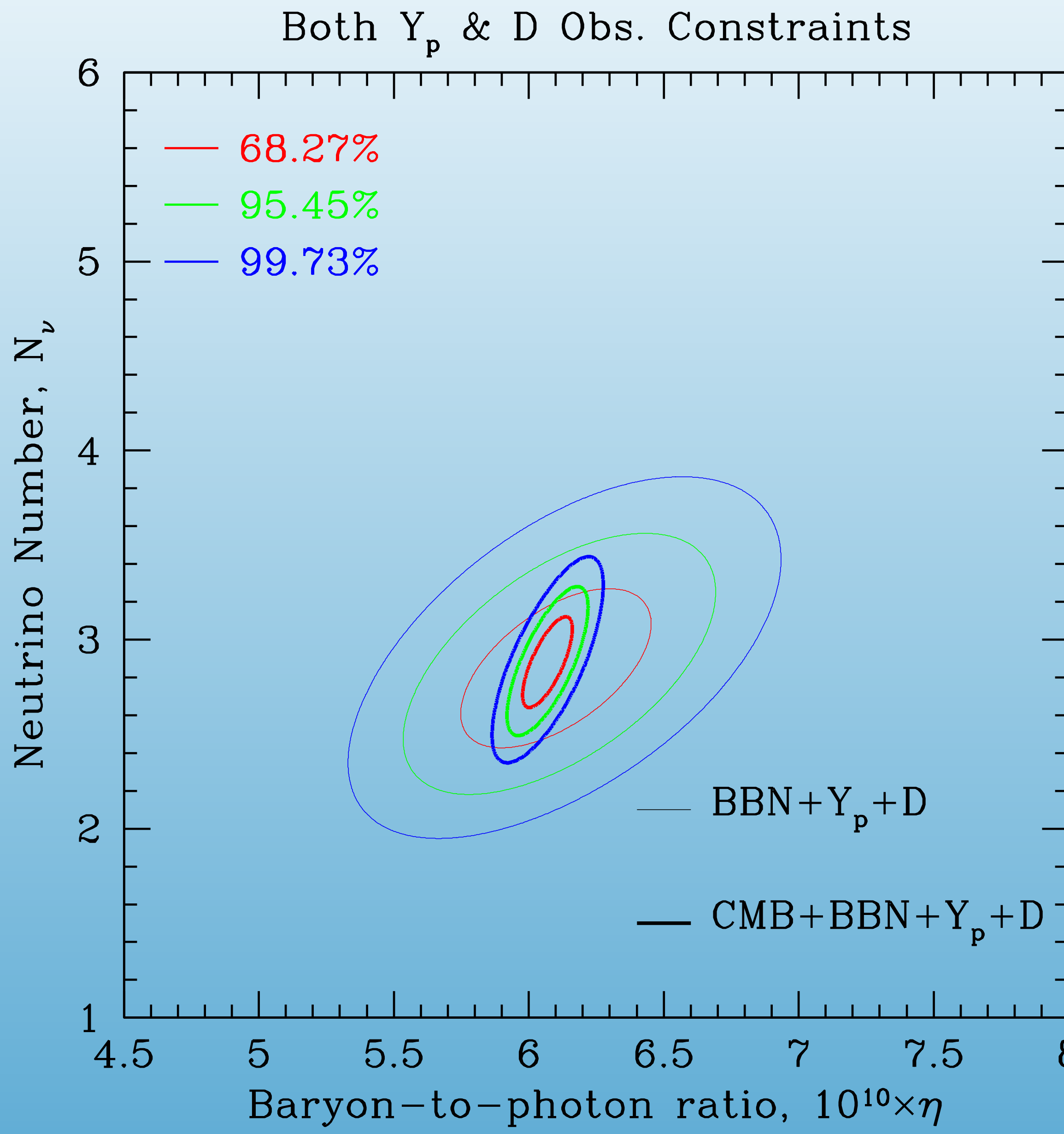
BBN and the CMB



CMB and BBN determination of η and N_ν

Cyburt, Fields, Olive, Yeh

BBN and the CMB



CMB and BBN determination of η and N_ν

Cyburt, Fields, Olive, Yeh

Summary

- BBN and CMB are in excellent agreement wrt D and He

- Li: Problematic
  - BBN ^{7}Li high compared to observations
- Important to consider:
  - Nuclear considerations
  - Depletion (tuned)
  - BSM solutions?

- Standard Model ($N_\nu = 3$) is looking good!