BBN and the Status of D, He4, and Li7 Observations

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

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

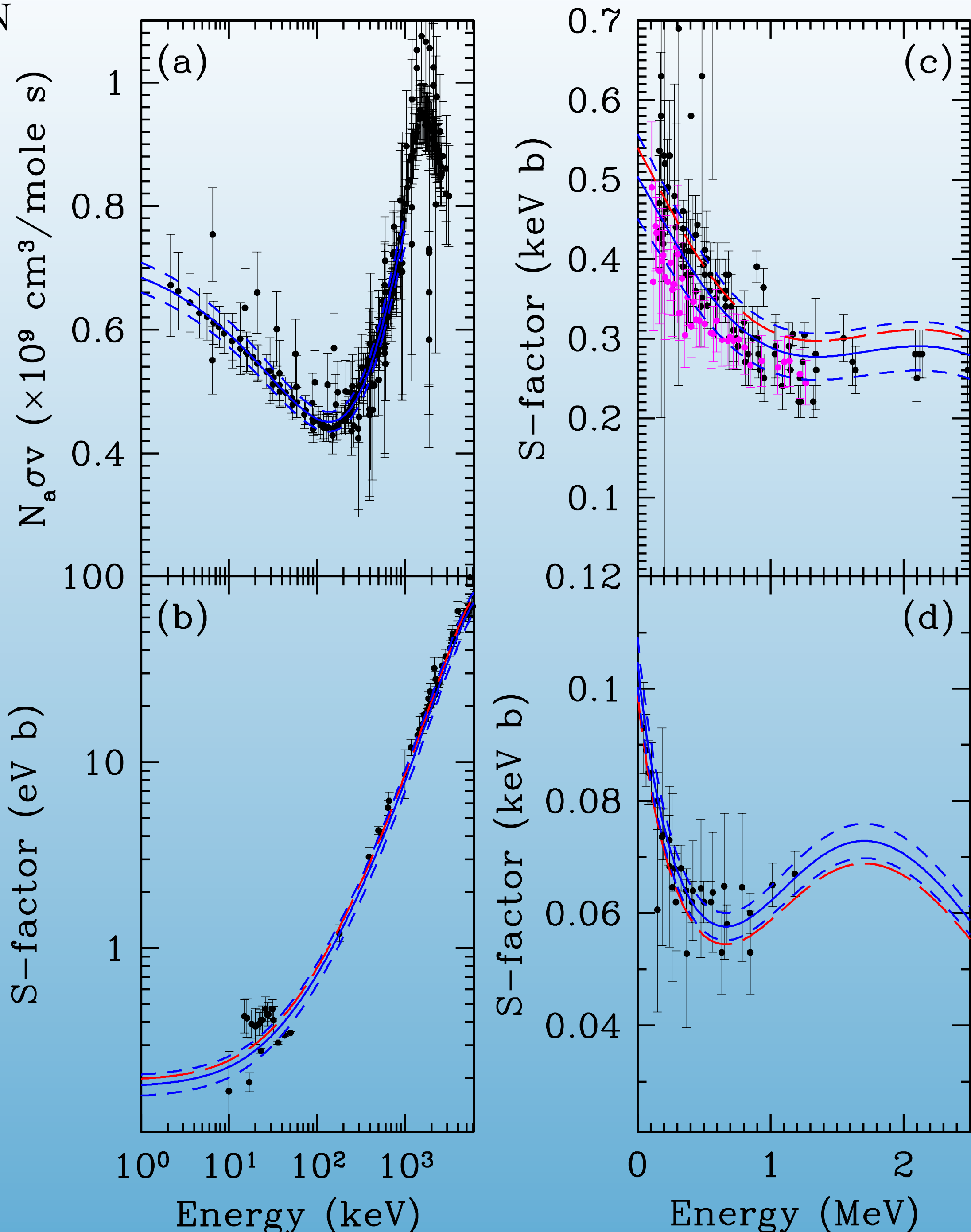
- The Li Problem

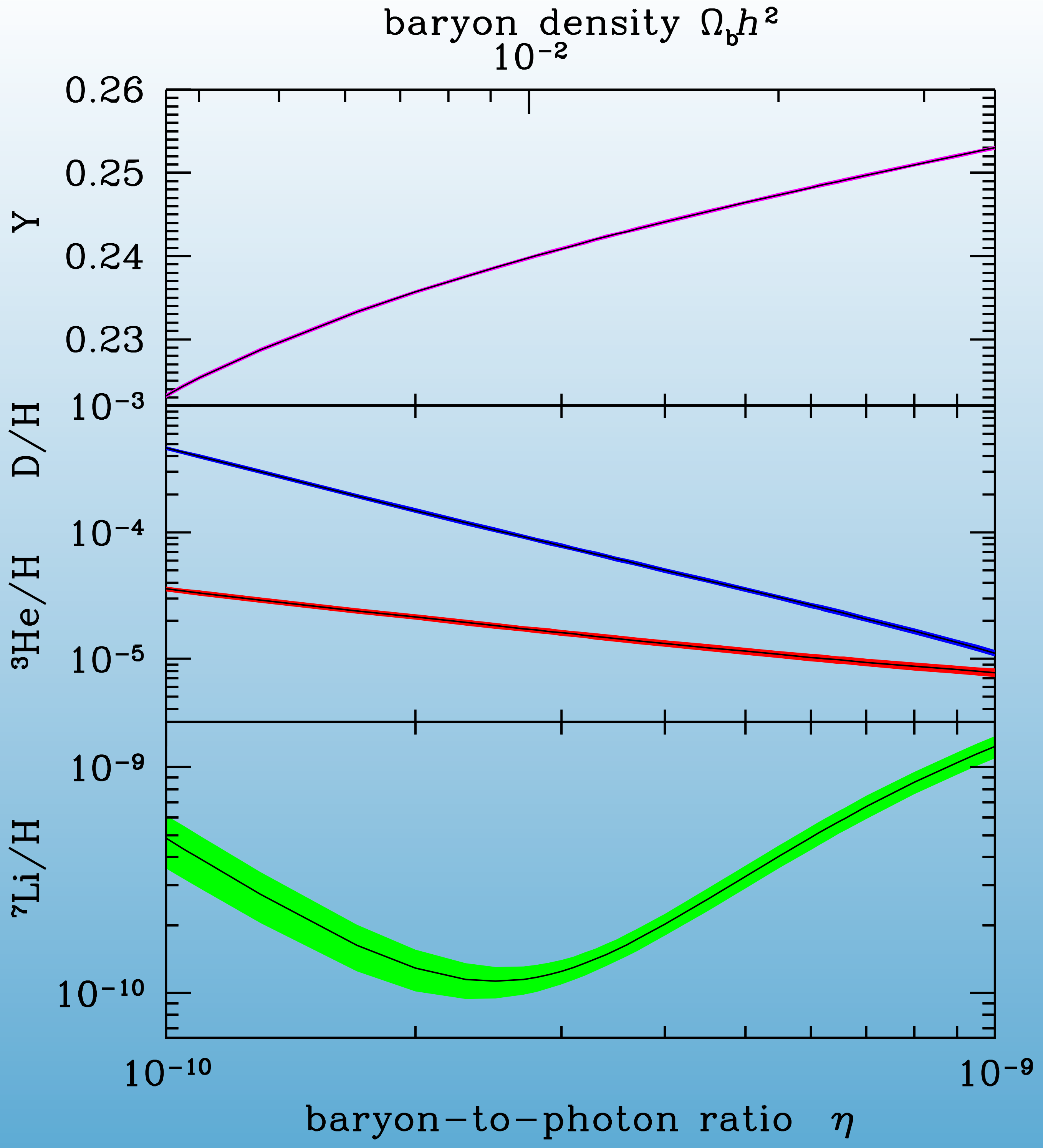
- Solutions?

Table 1: Key Nuclear Reactions for BBN

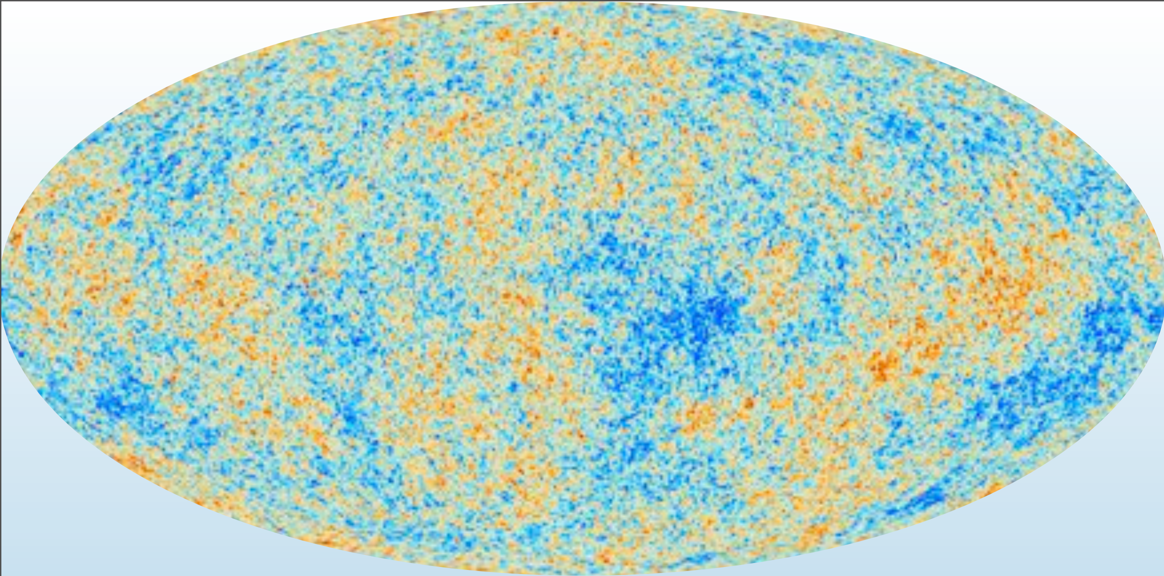
Source	Reactions	
NACRE	$d(p,\gamma)^3\mathrm{He}$	(b)
	$d(d,n)^3\mathrm{He}$	
	$d(d,p)t$	
	$t(d,n)^4\mathrm{He}$	
	$t(\alpha,\gamma)^7\mathrm{Li}$	(d)
	$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$	(c)
	$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$	
SKM	$p(n,\gamma)d$	
	$^3\mathrm{He}(d,p)^4\mathrm{He}$	
	$^7\mathrm{Be}(n,p)^7\mathrm{Li}$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

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





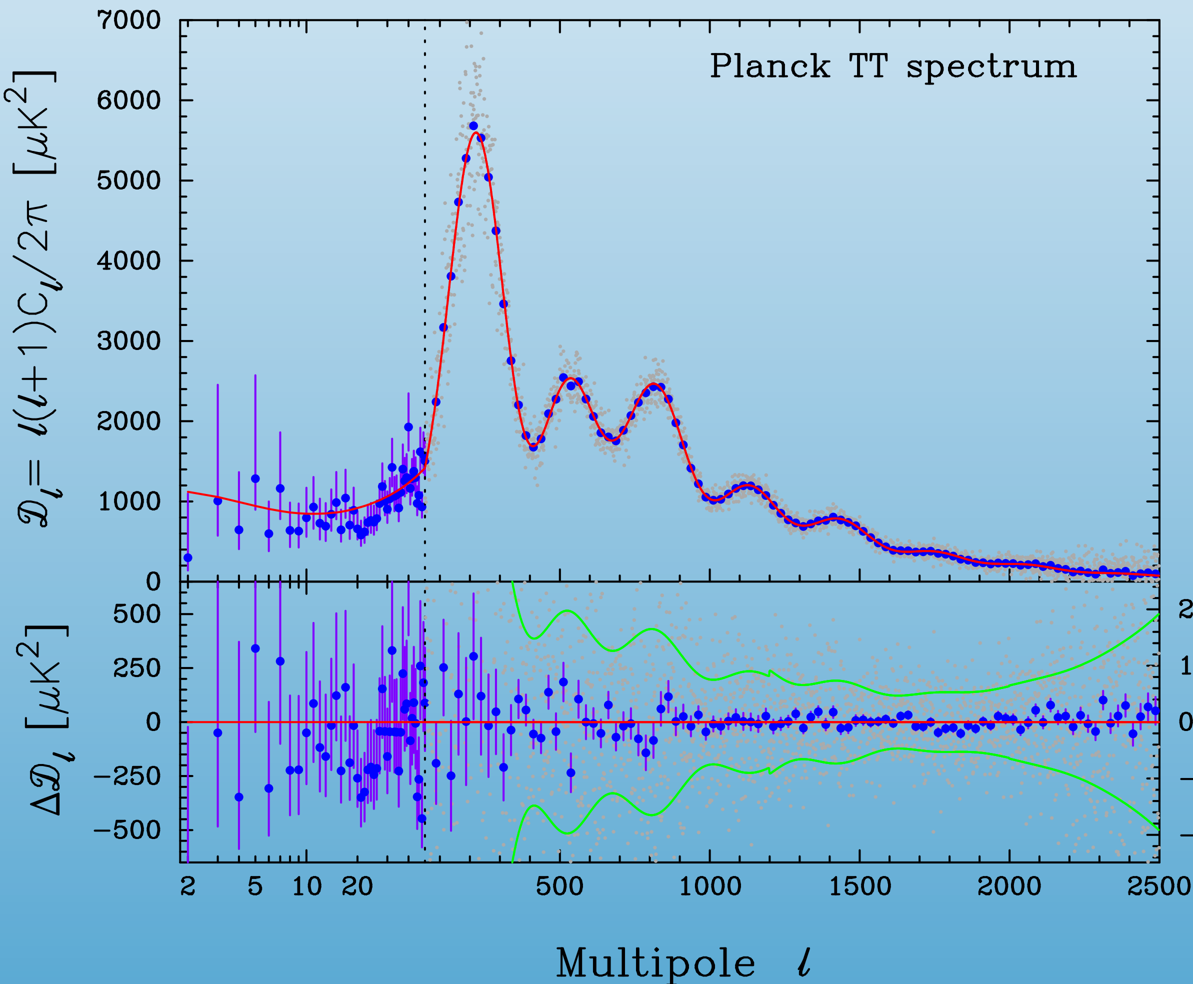
baryon density $\Omega_b h^2$
10^{-2}
0.26
0.25
0.24
0.23
Y
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon–to–photon ratio η

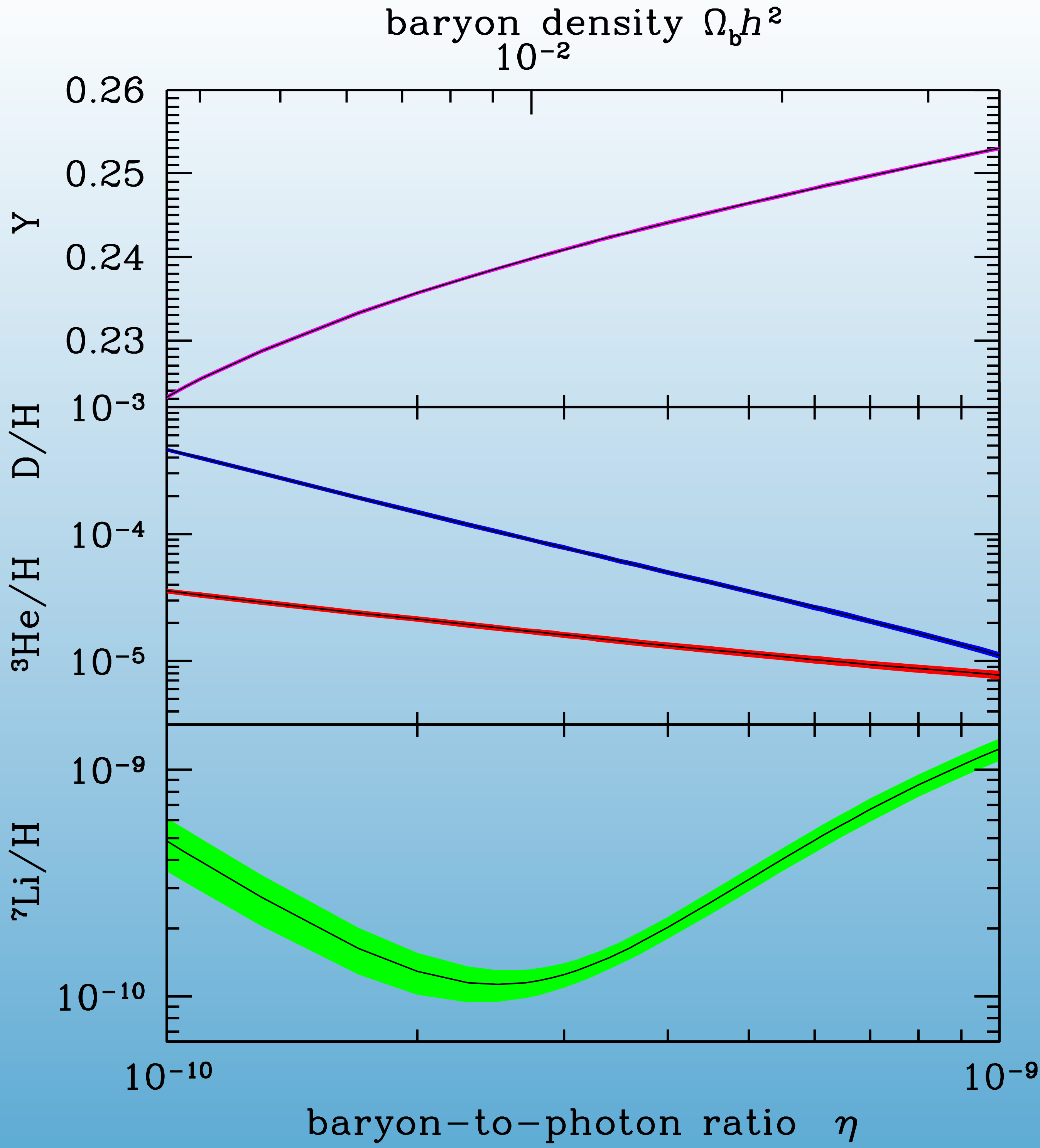


Planck best fit

$\Omega_B h^2 = 0.0221 \pm 0.0003$

$\eta_{10} = 6.05 \pm 0.08$





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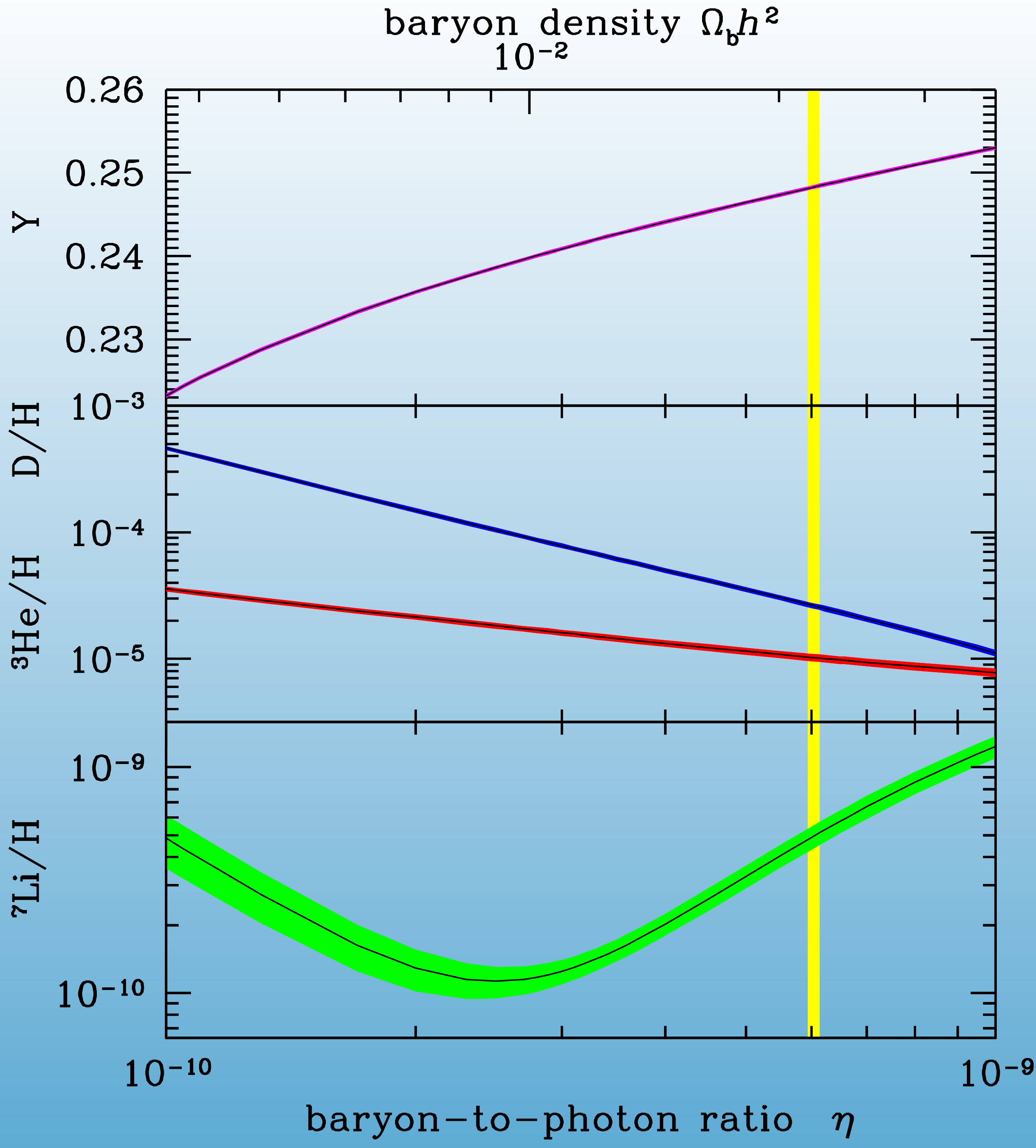
baryon−to−photon ratio η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10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio η

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

QSO	z_{em}	z_{abs}	$\log N(\mathrm{H\,I})$ (cm^{-2})	[O/H][a]	$\log(\mathrm{D/H})$
HS 0105+1619	2.640	2.53600	19.42 ± 0.01	-1.73	-4.60 ± 0.04
Q0913+072	2.785	2.61843	20.34 ± 0.04	-2.40	-4.56 ± 0.04
Q1009+299	2.640	2.50357	17.39 ± 0.06	< -0.70[c]	-4.40 ± 0.07
SDSS J1134+5742	3.522	3.41088	17.95 ± 0.05	< -1.9[d]	-4.69 ± 0.13
Q1243+307	2.558	2.52566	19.73 ± 0.04	-2.79	-4.62 ± 0.05
SDSS J1337+3152	3.174	3.16768	20.41 ± 0.15	-2.68	-4.93 ± 0.15
SDSS J1419+0829	3.030	3.04984	20.391 ± 0.008	-1.92	-4.596 ± 0.009
SDSS J1558−0031	2.823	2.70262	20.67 ± 0.05	-1.50	-4.48 ± 0.06
Q1937−101	3.787	3.57220	17.86 ± 0.02	< -0.9	-4.48 ± 0.04
Q2206−199	2.559	2.07624	20.43 ± 0.04	-2.07	-4.78 ± 0.09
Q347−3819	3.23	3.0245	20.626 ± 0.005	-0.82	-4.426 ± 0.029
CTQ 247	3.02	2.621	20.45 ± 0.1	-1.99	-4.55 ± 0.11

D/H abundances in Quasar apsorption systems

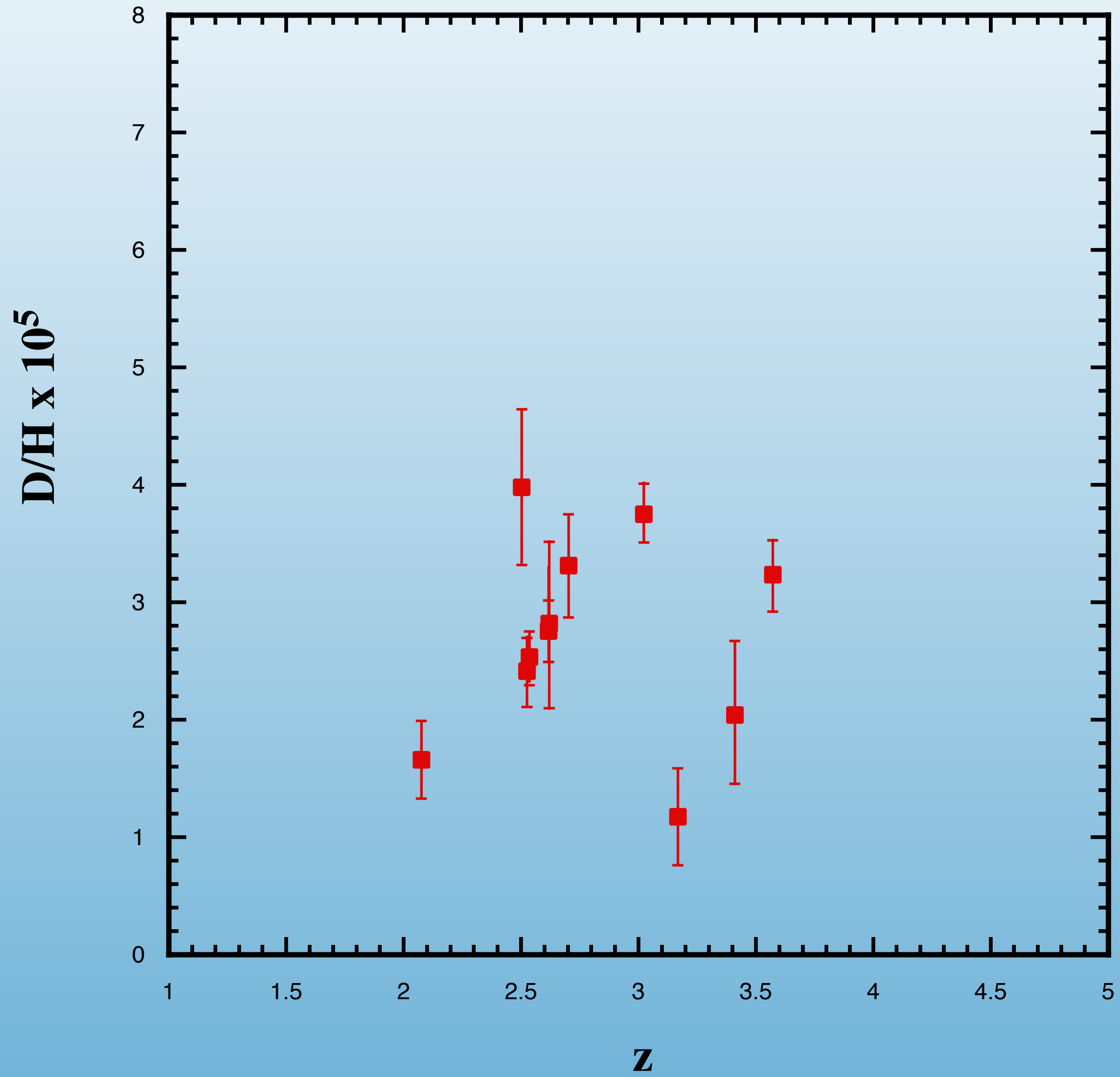
BBN Prediction:

10^5 D/H = 2.59 ± 0.17*

Obs Average:

10^5 D/H = 3.01 ± 0.21

(sample variance of 0.68)



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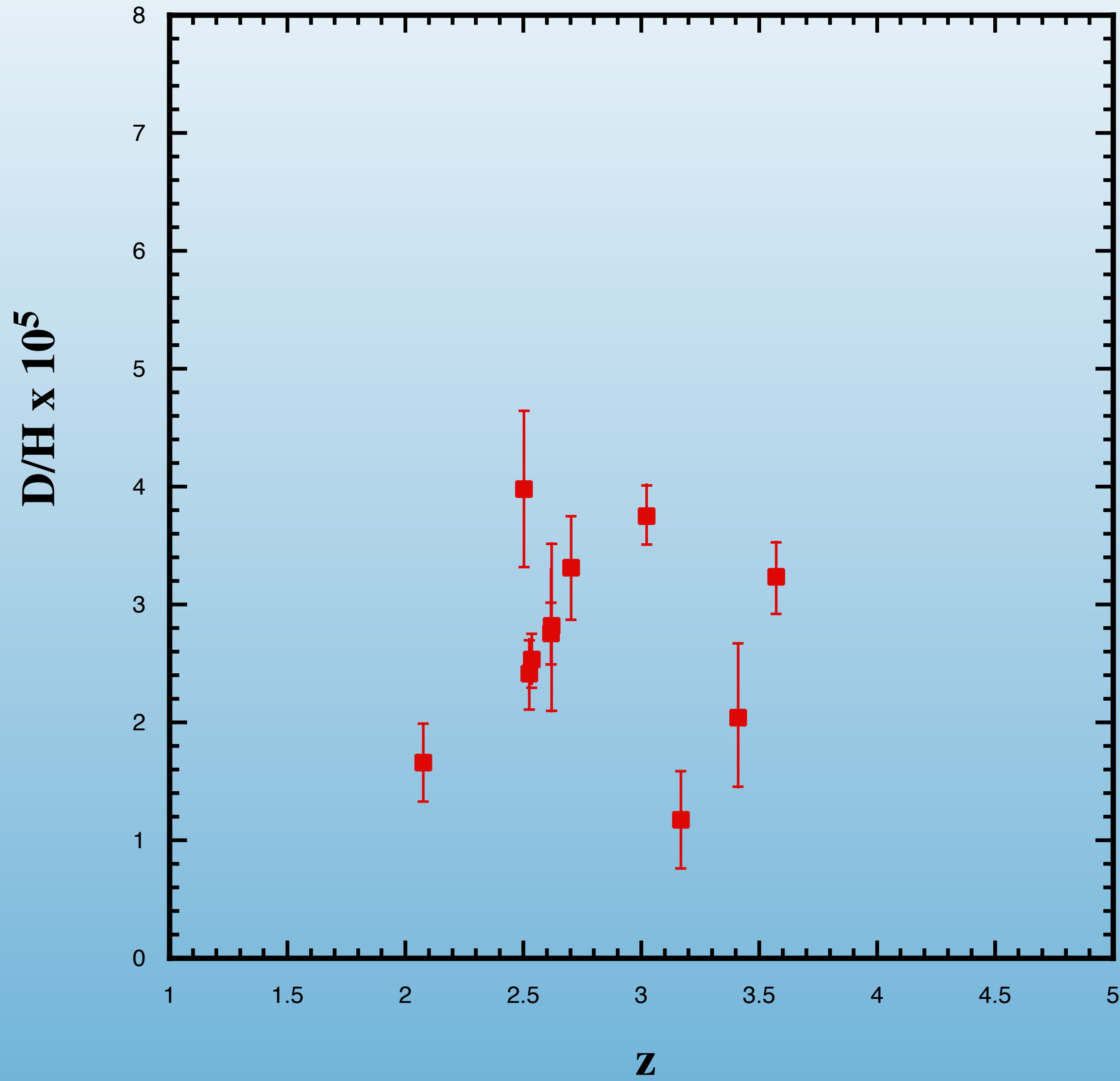
*uncertainty reduced to .14 with Planck determination of η



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10^5 D/H = 2.65 ± 0.11
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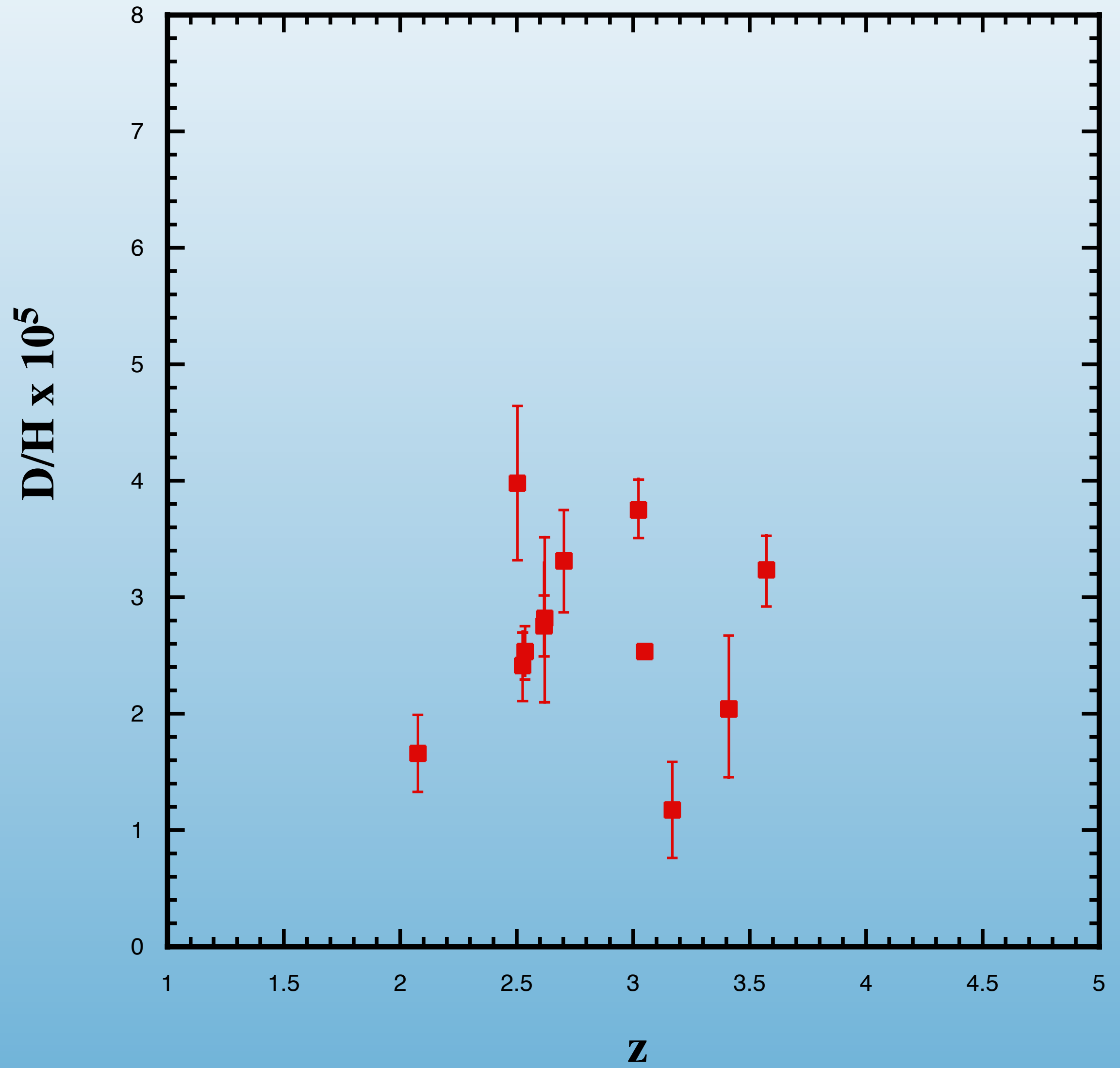

New Point from Pettini and Cooke

$z_{em} = 3.03$

$z_{abs} = 3.04984$

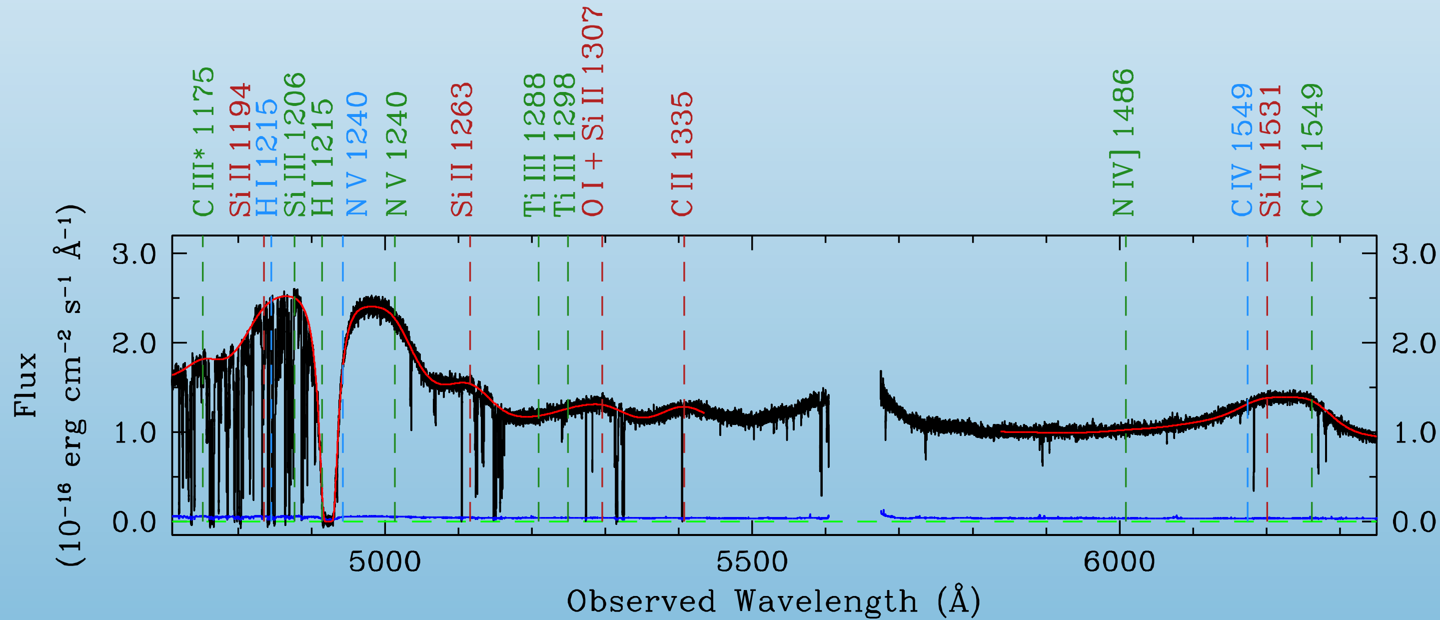

Fig. 2.— Portion of the UVES spectrum of the QSO SDSS J1419+0829 (black), together with the model fit (red). The 1σ error spectrum is shown in blue (near the zero level). Vertical dash lines mark the positions of QSO spectral features, as indicated. Green labels denote emission lines at $z_{em} = 3.04224$, light blue labels emission lines at $z_{em} = 2.98576$, and red labels emission lines at $z_{abs} = 3.04954$.

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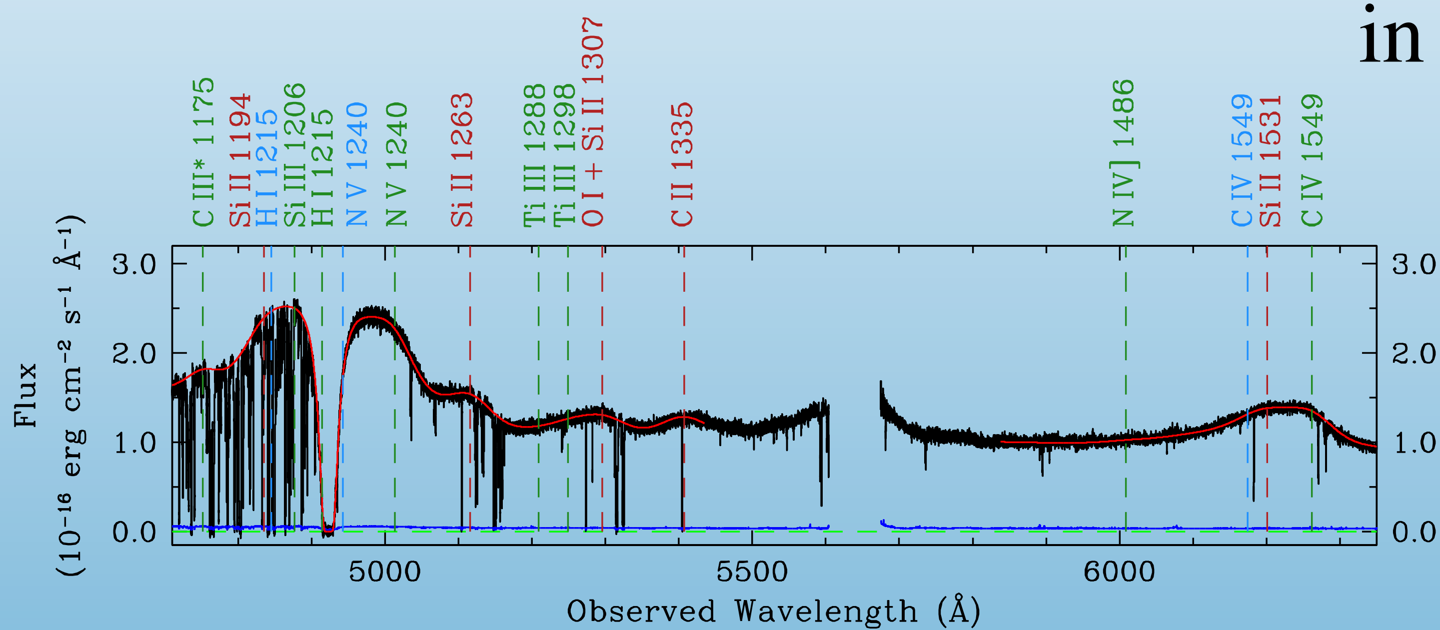
Is the uncertainty in the continuum included?



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Kirkman et al.

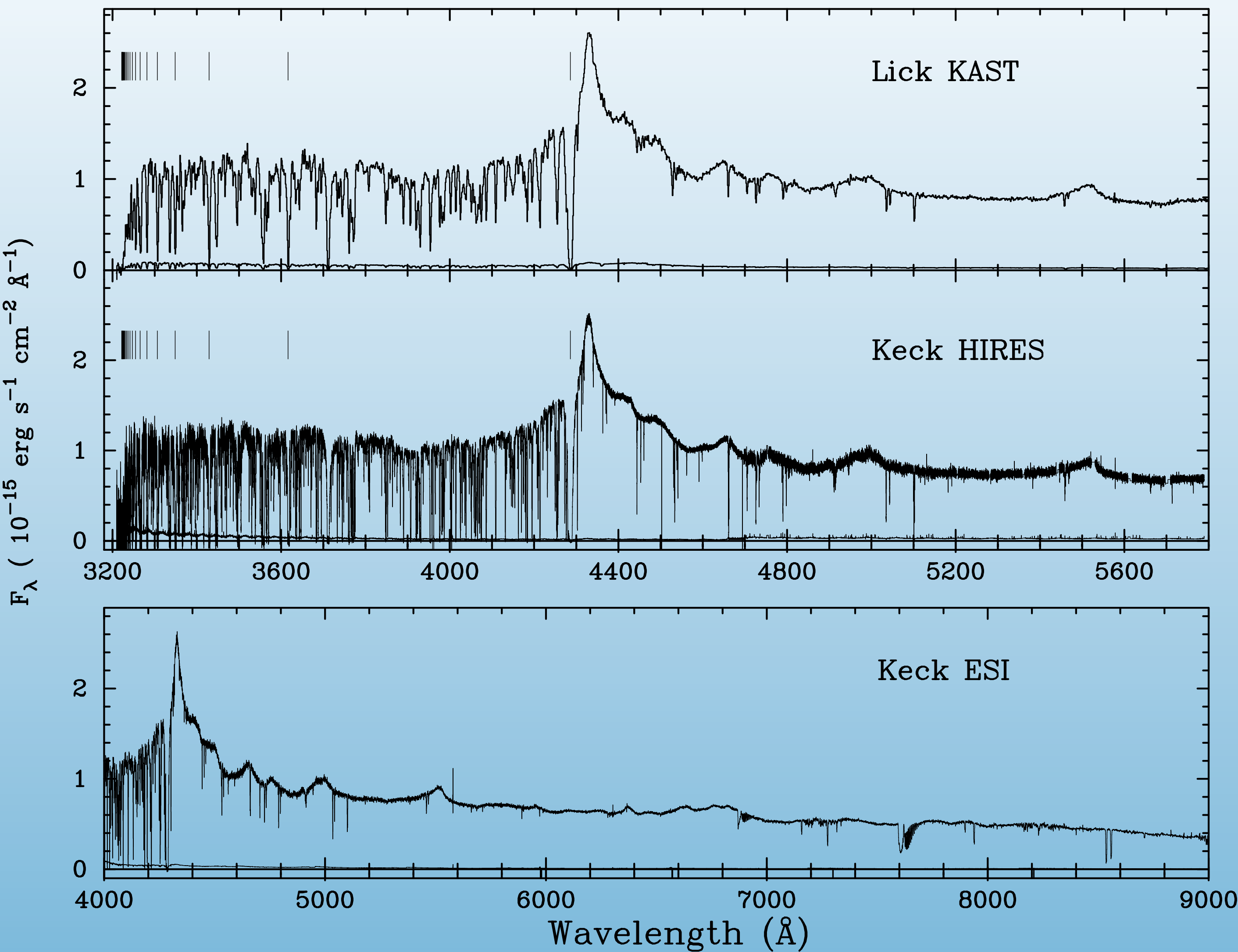

FIG. 1.—Spectra of Q1243+3047 from the KAST spectrograph (*top*), HIRES (*middle*), and ESI (*bottom*). We show the complete wavelength coverage for the Kast and HIRES spectra, but not for the ESI, which extends to 10,000 Å. We have applied relative flux calibration to all three spectra. The emission lines blend to give a continuously undulating continuum level from 4400–5000 Å. The vertical marks above the Kast and HIRES spectra show the positions of the Lyman series lines in the absorption system at $z = 2.526$ that gives the D/H-value. The Lyα absorption line of this system, from which we get the H I column density, is near 4285 Å, just to the left of the peak of the Lyα emission line.

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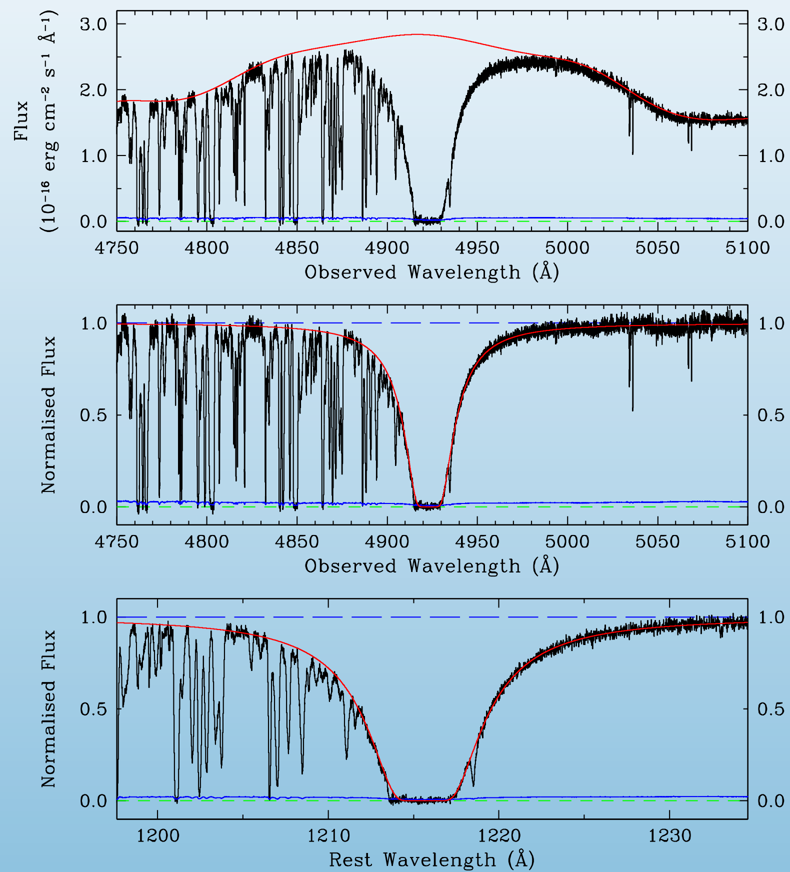
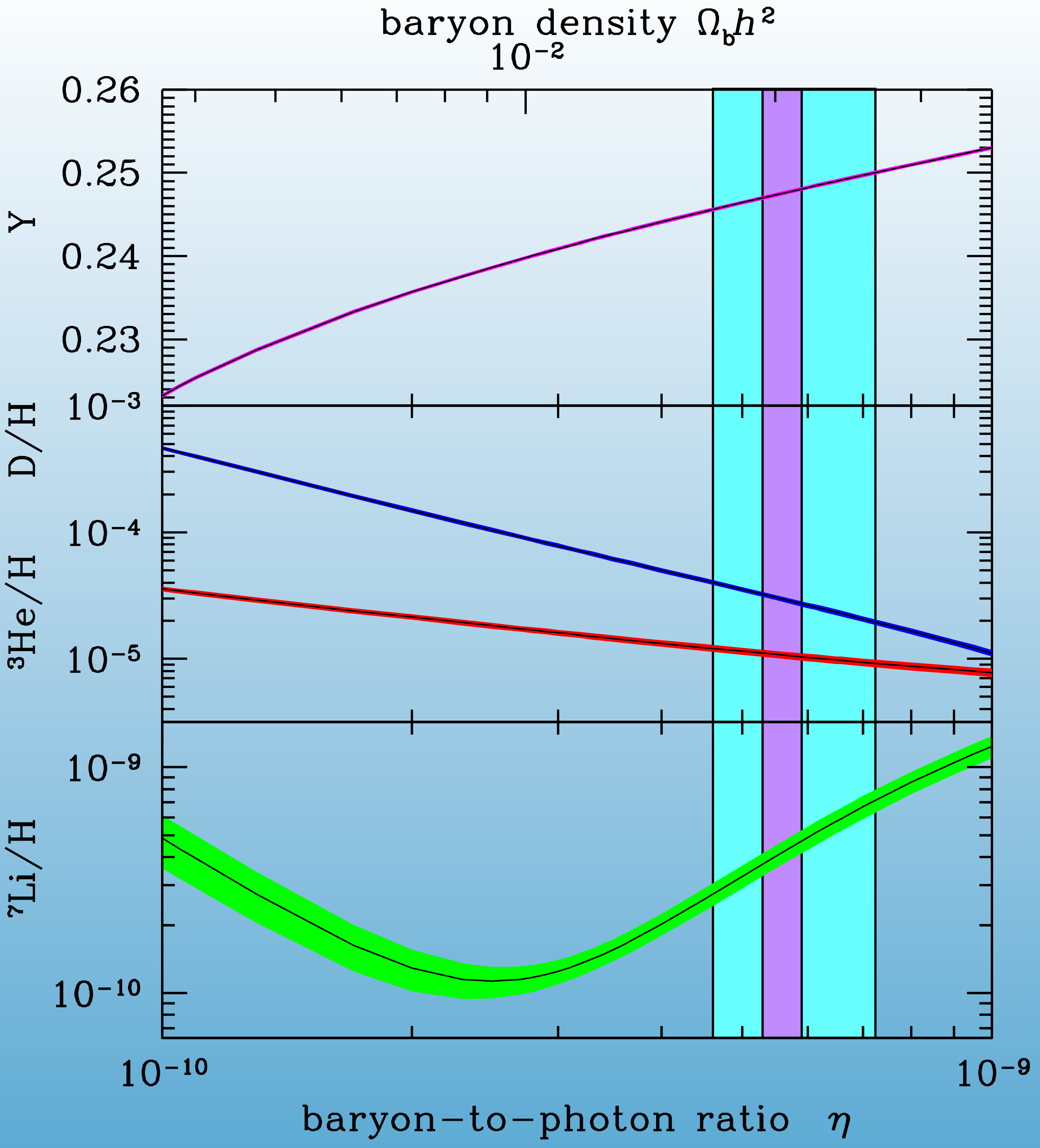


Is the uncertainty in the continuum included?

Fig. 3.— The Lyα region in J1419+0829. *Top panel:* Observed QSO spectrum in black and best-fitting model spectrum in red. *Middle panel:* The normalized QSO spectrum, obtained by dividing the observed spectrum by the model spectrum, is shown in black together with the best fitting damped Lyα absorption profile (see section 3.2) in red. The neutral hydrogen column density is $\log N(\mathrm{H\,I})/\mathrm{cm}^{-2} = 20.391 \pm 0.008$. *Bottom panel:* Expanded central portion of the middle panel. In all three panels the 1σ error spectrum is shown in blue.



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10^{-2}
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D/H
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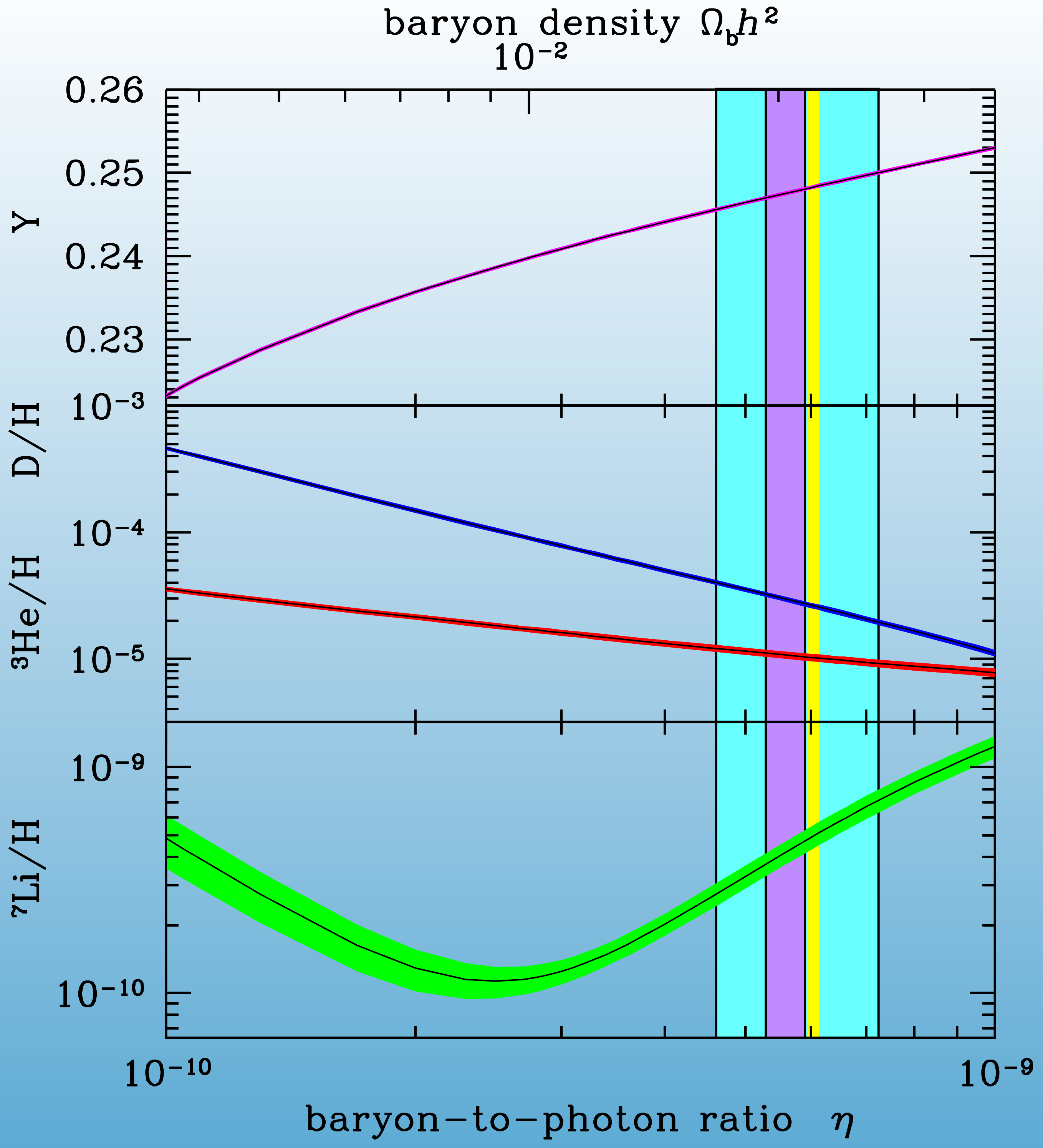
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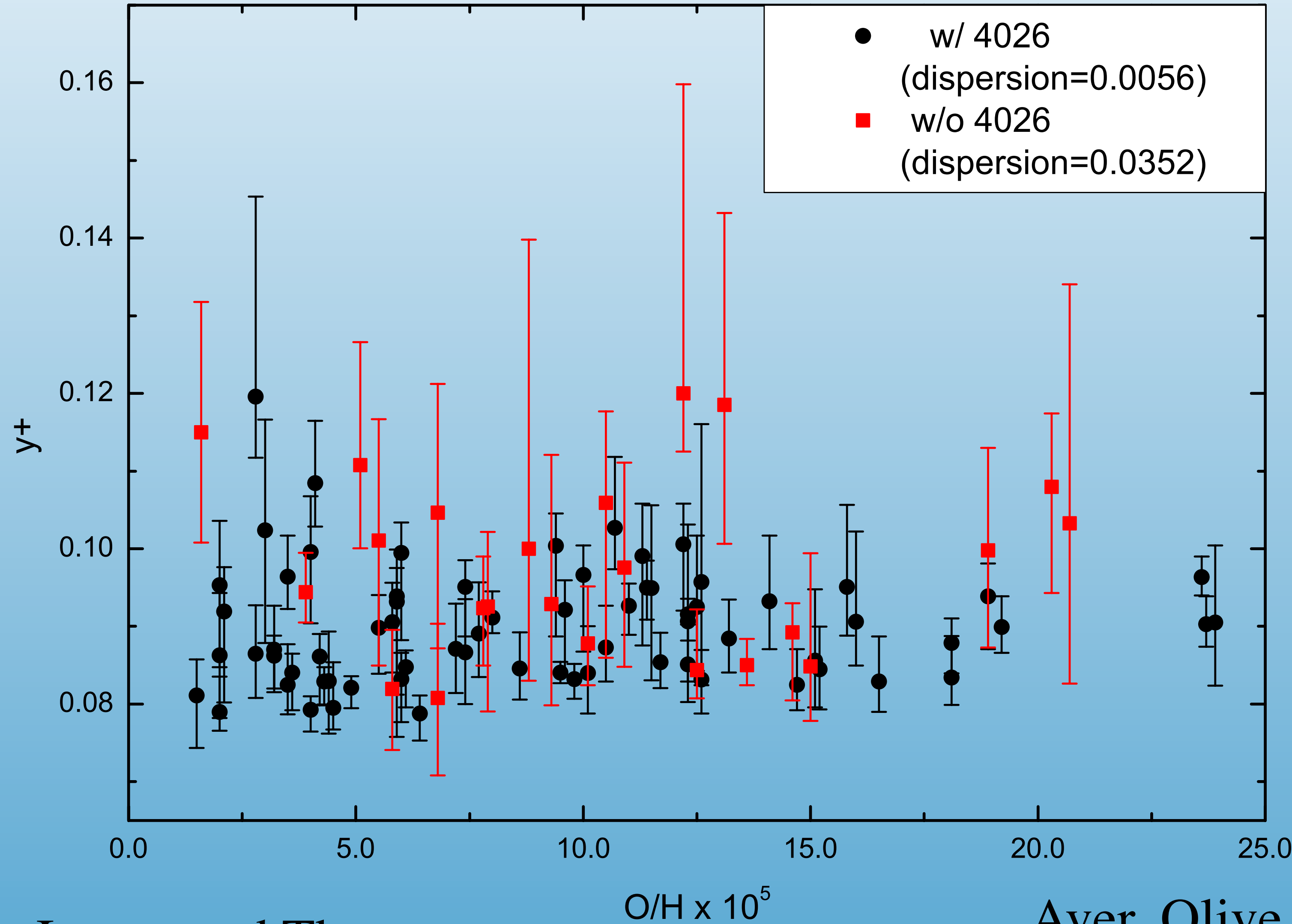
^4He

Measured in low metallicity extragalactic HII regions together with O/H and N/H

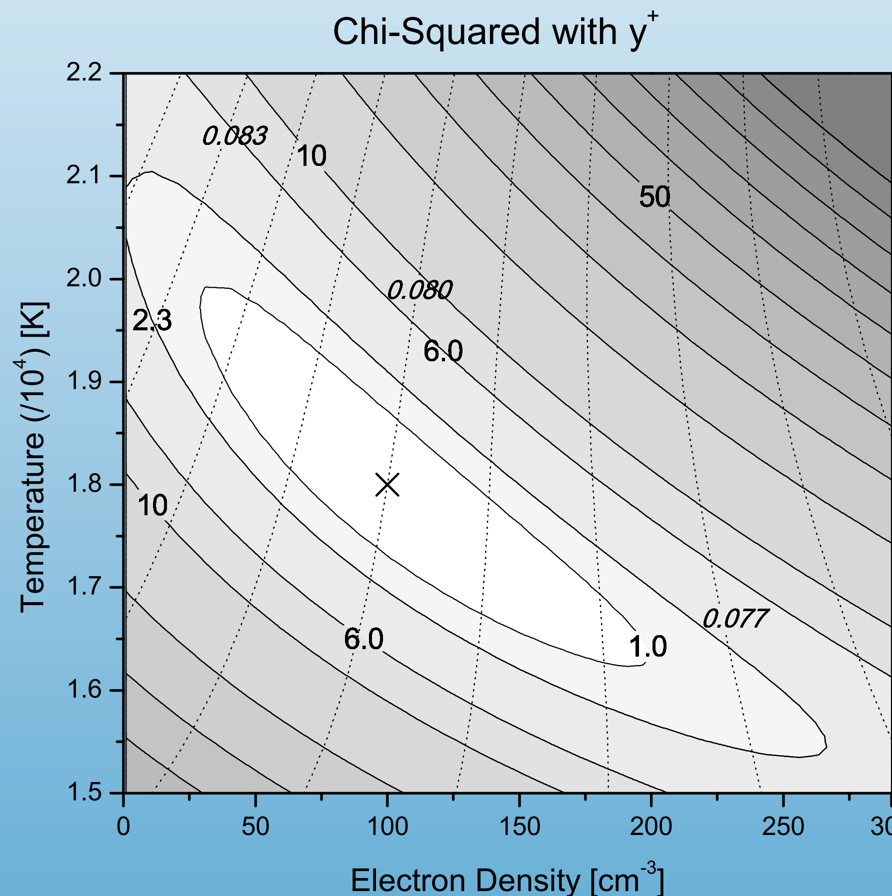


Data from Izotov and Thuan

Aver, Olive, Skillman

Results for He dominated by systematic effects

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

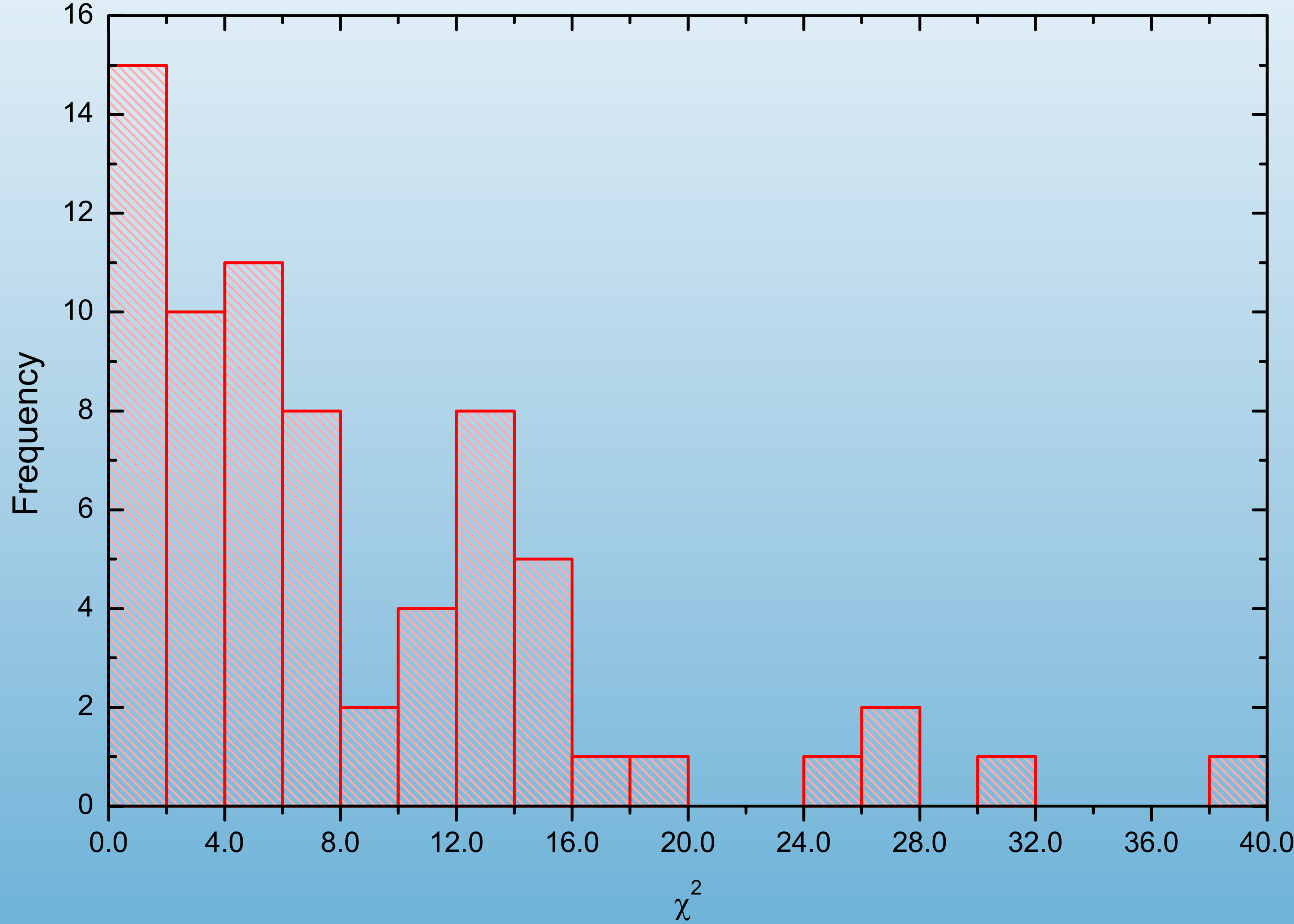


MCMC statistical techniques have proven effective in parameter estimation

$$(y^+, n_e, a_{He}, \tau, T, C(H\beta), a_H, \xi)$$

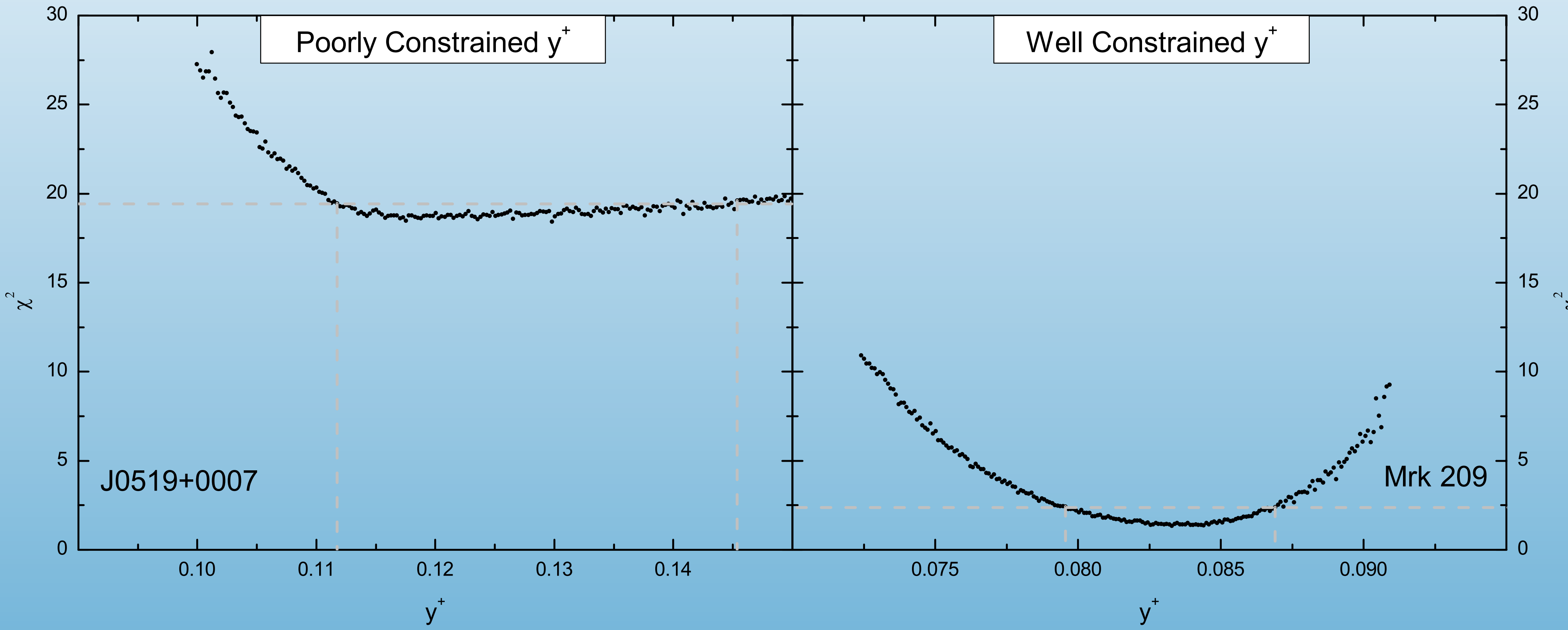
Aver, Olive, Skillman

Using χ^2 as a discriminator



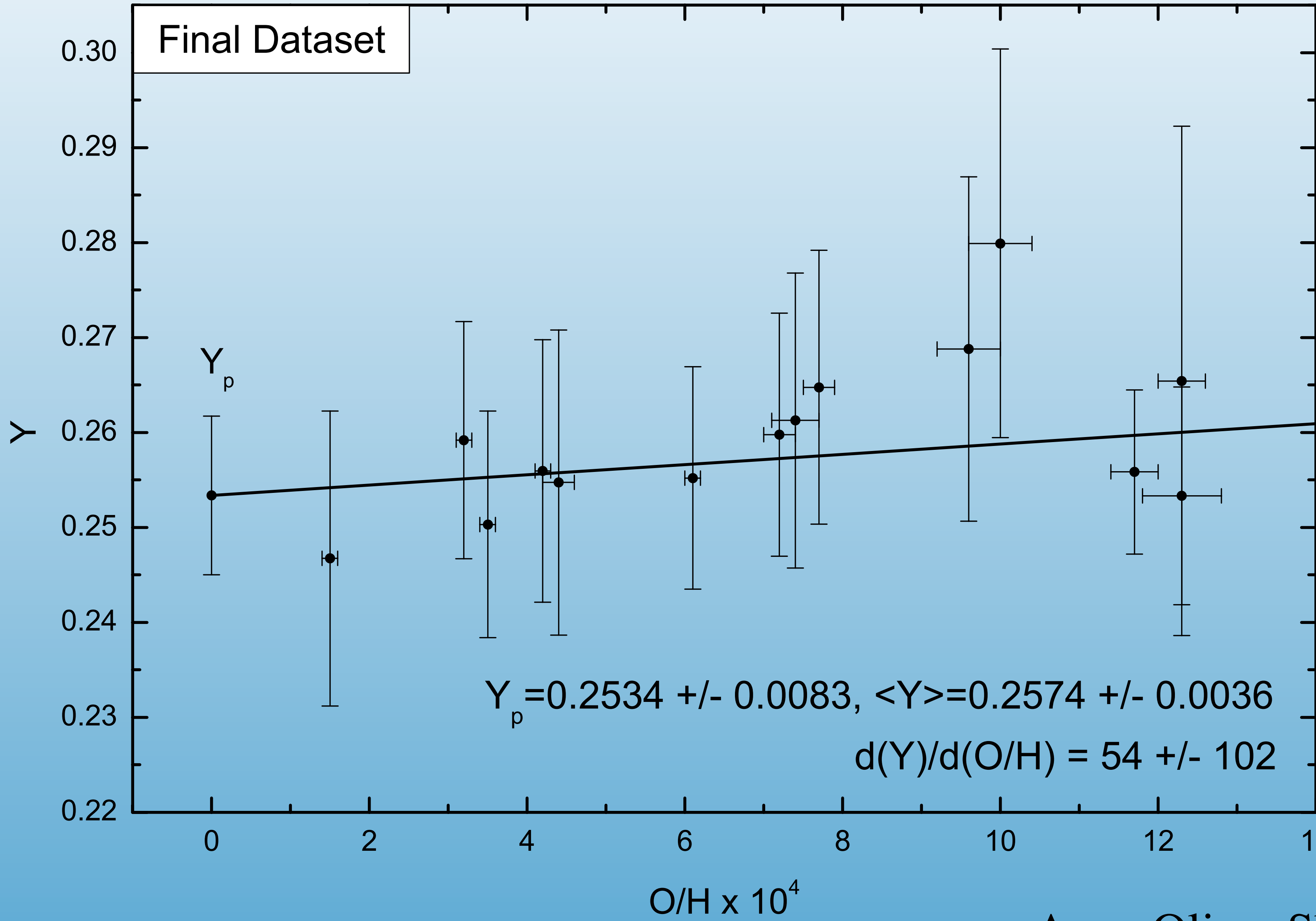
Aver, Olive, Skillman

Marginalized χ^2 He from MCMC analysis: the bad and the good



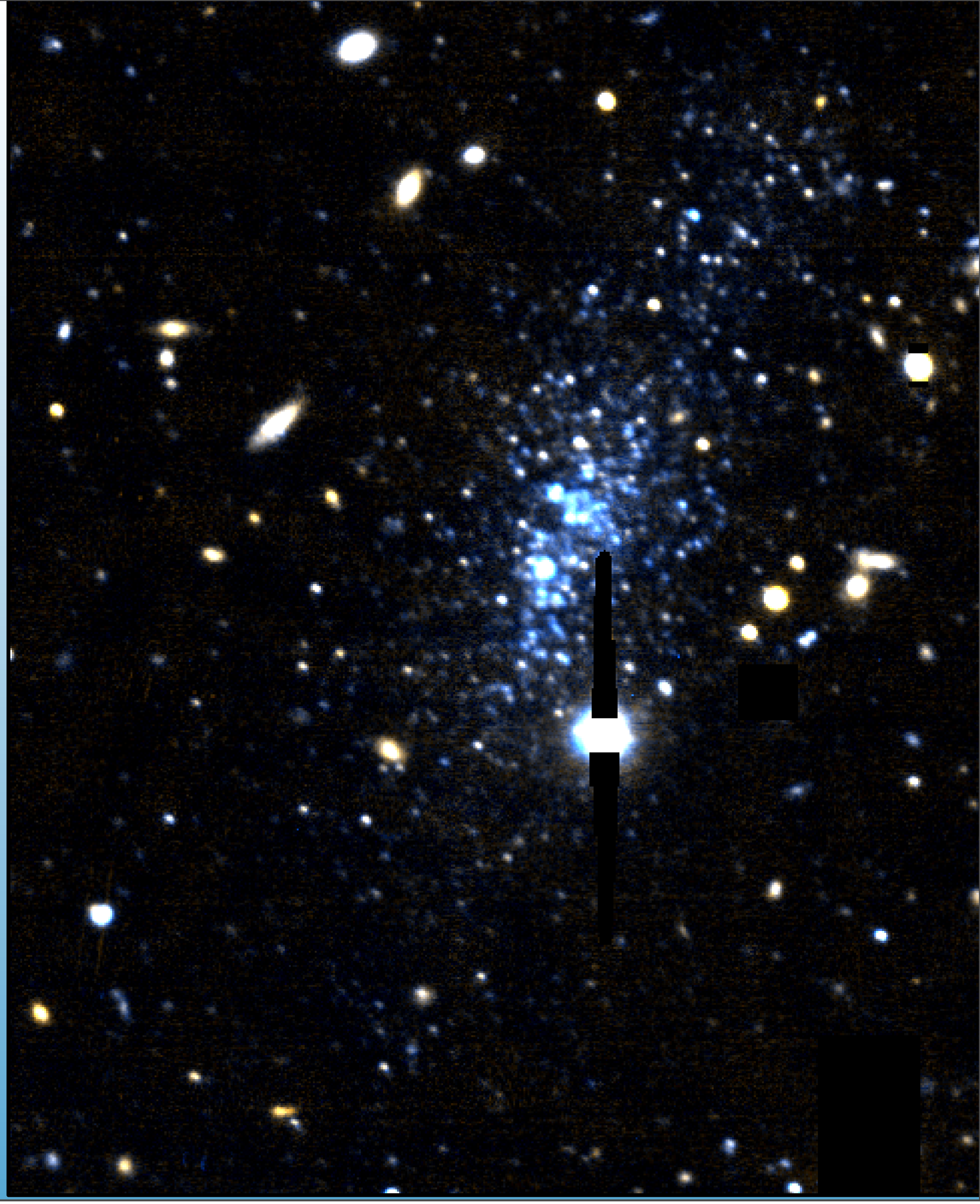
Aver, Olive, Skillman

Final Result

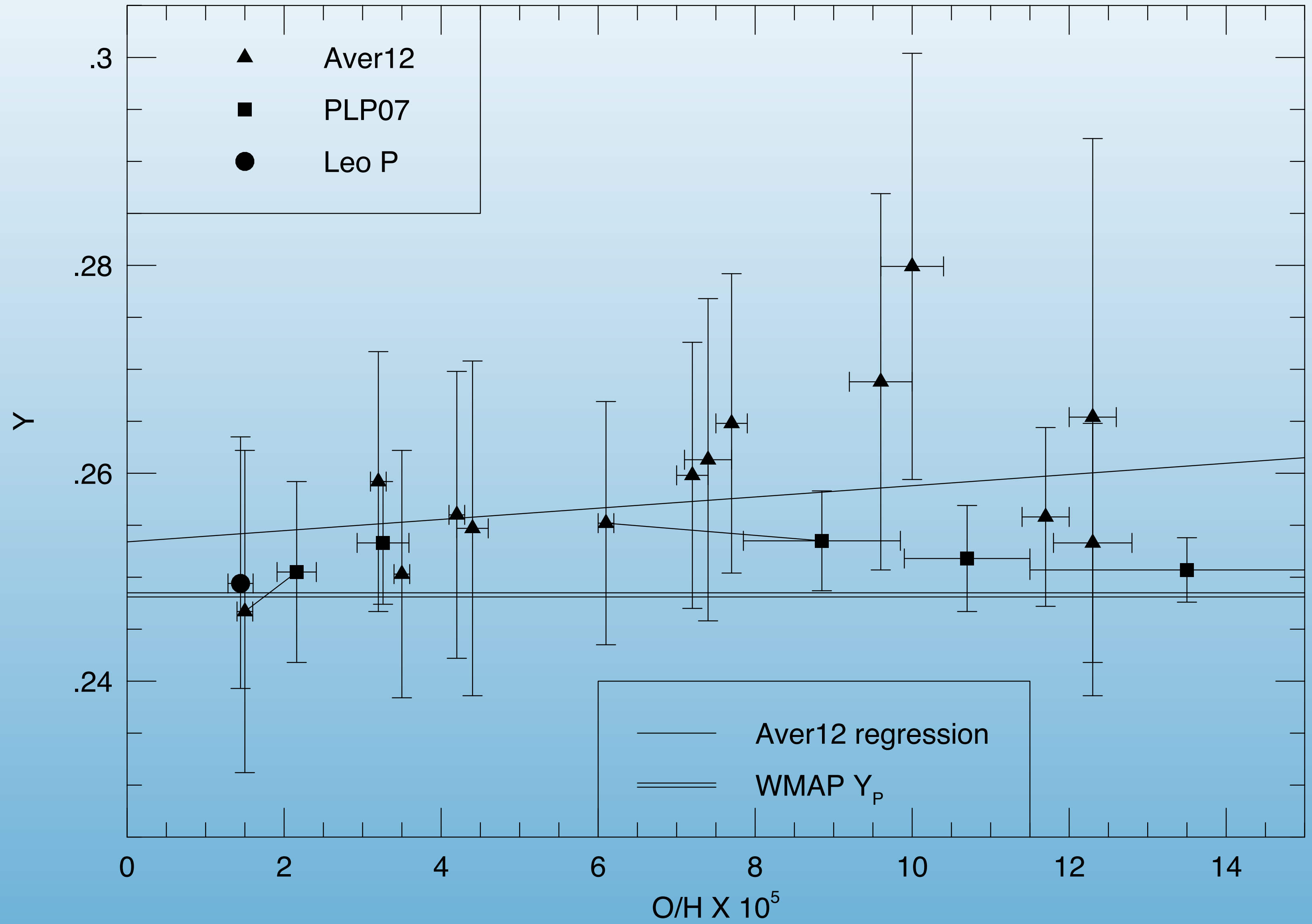


Aver, Olive, Skillman

Leo P: A new extremely metal poor galaxy (Giovanelli et al. - 2012)



Newer Final Result



$Yp = 0.2520 \pm 0.0072 + (69 \pm 90)\ (O/H)$

Skillman et al.

^{4}He Prediction:

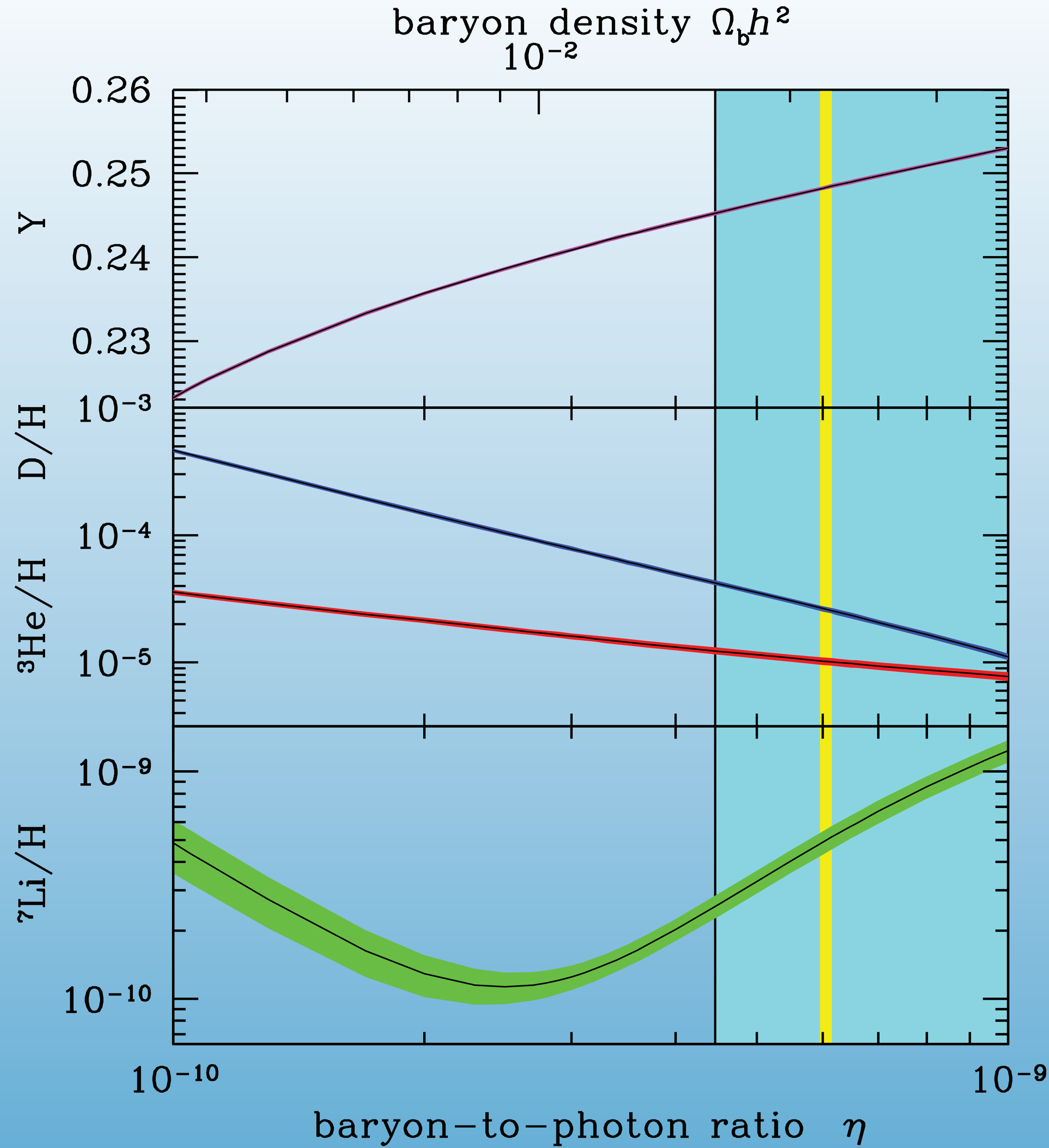
0.2485 ± 0.0002

Data: Regression:

0.2520 ± 0.0072

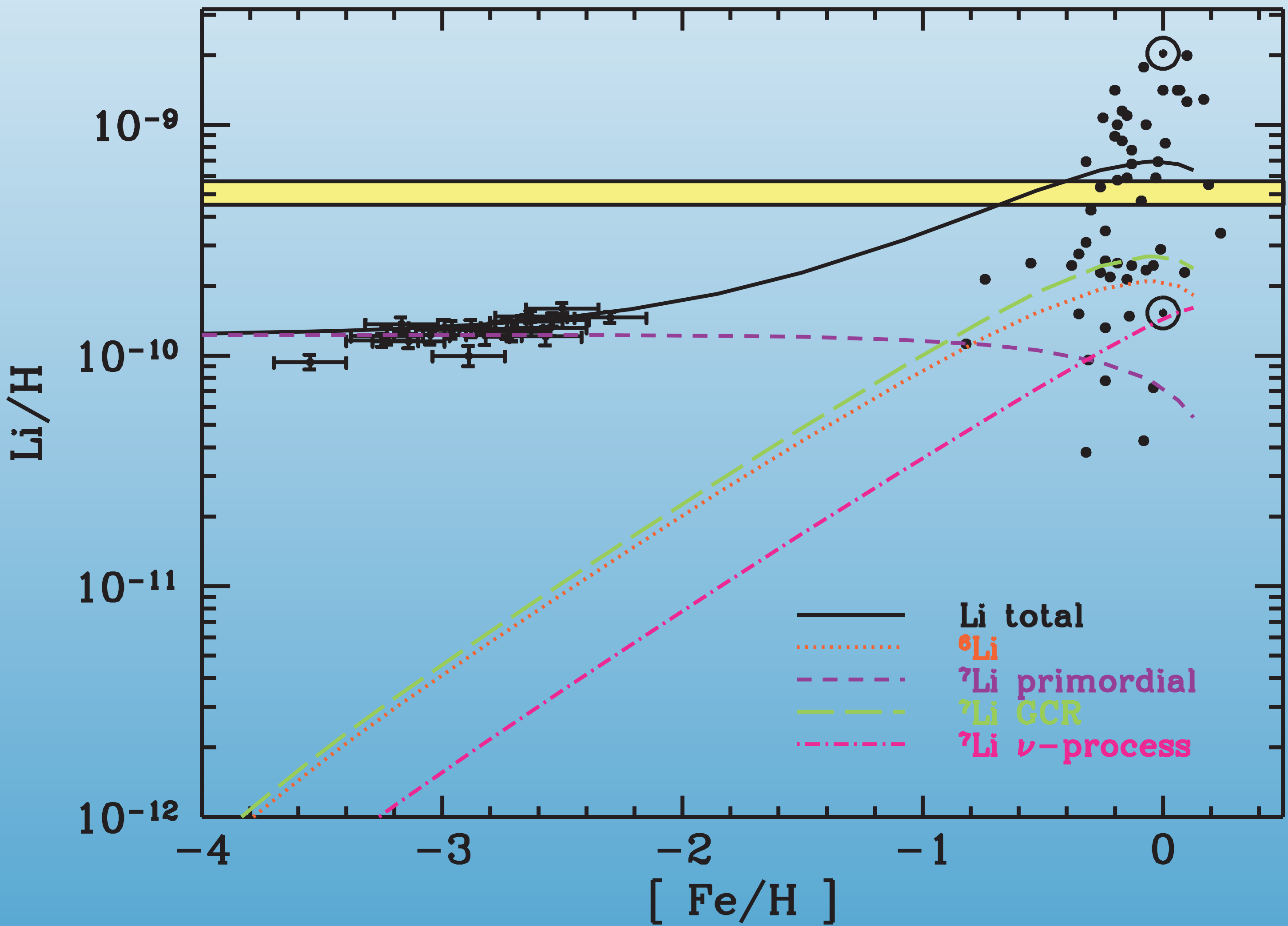
Mean:

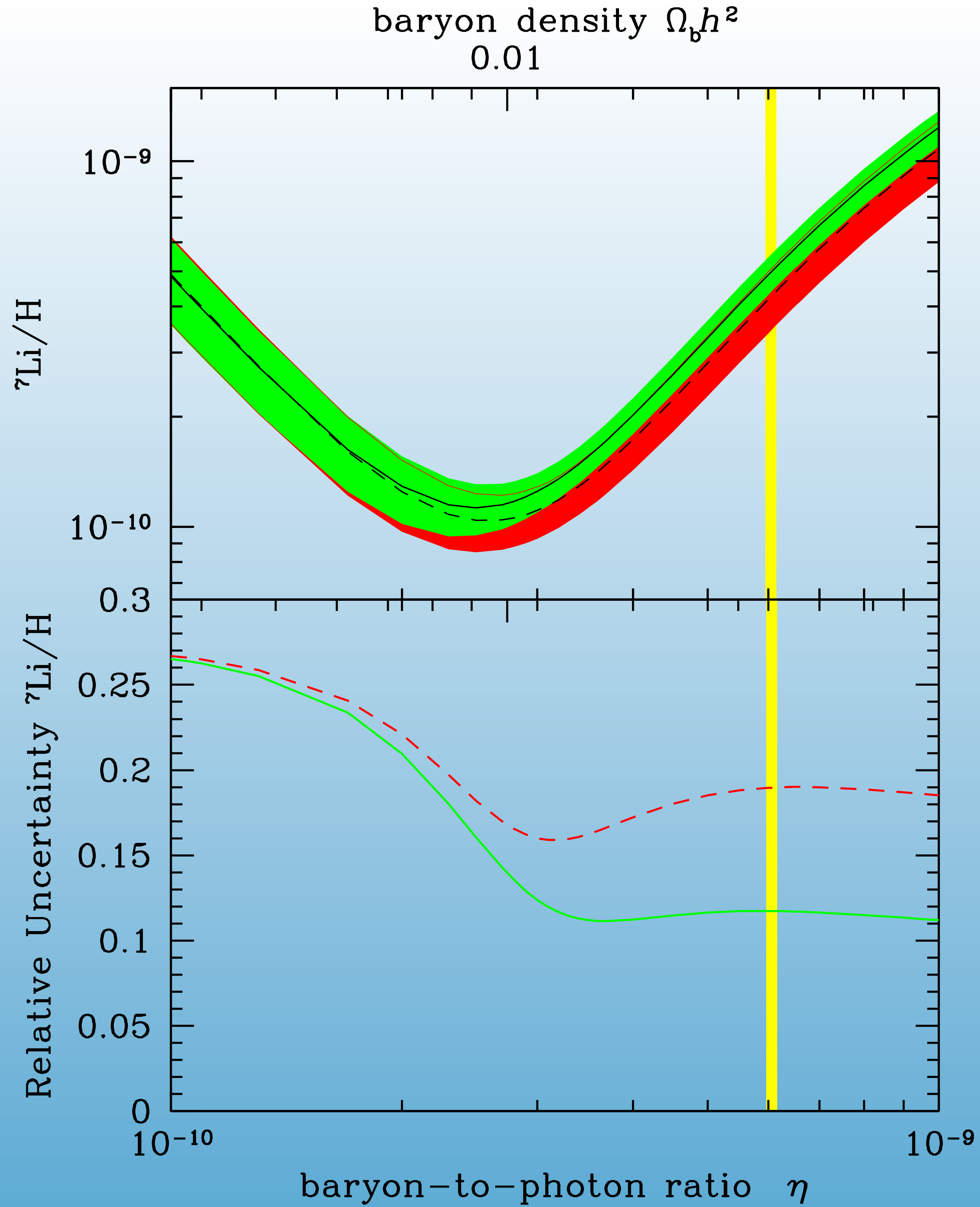
0.2567 ± 0.0034



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

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

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

Cyburt, Fields, KAO

Possible sources for the discrepancy

- Nuclear Rates
  - Restricted by solar neutrino flux

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

BBN Li sensitivites

$$^7Li/^7Li_0 = \Pi_i R_i^{\alpha_i}$$

Key Rates:

^{3}He (α,γ) ^{7}Be

Reaction/Parameter	sensitivities (α_i)
$\eta_{10}/6.14$	$+2.04$
$n(p,\gamma)d$	$+1.31$
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$	$+0.95$
$^3\mathrm{He}(d,p)^4\mathrm{He}$	-0.78
$d(d,n)^3\mathrm{He}$	$+0.72$
$^7\mathrm{Be}(n,p)^7\mathrm{Li}$	-0.71
Newton's G_N	-0.66
$d(p,\gamma)^3\mathrm{He}$	$+0.54$
n-decay	$+0.49$
$N_{\nu,eff}/3.0$	-0.26
$^3\mathrm{He}(n,p)t$	-0.25
$d(d,p)t$	$+0.078$
$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$	-0.072
$t(\alpha,\gamma)^7\mathrm{Li}$	$+0.040$
$t(d,n)^4\mathrm{He}$	-0.034
$t(p,\gamma)^4\mathrm{He}$	$+0.019$
$^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$	-0.014
$^7\mathrm{Be}(d,p)2^4\mathrm{He}$	-0.0087

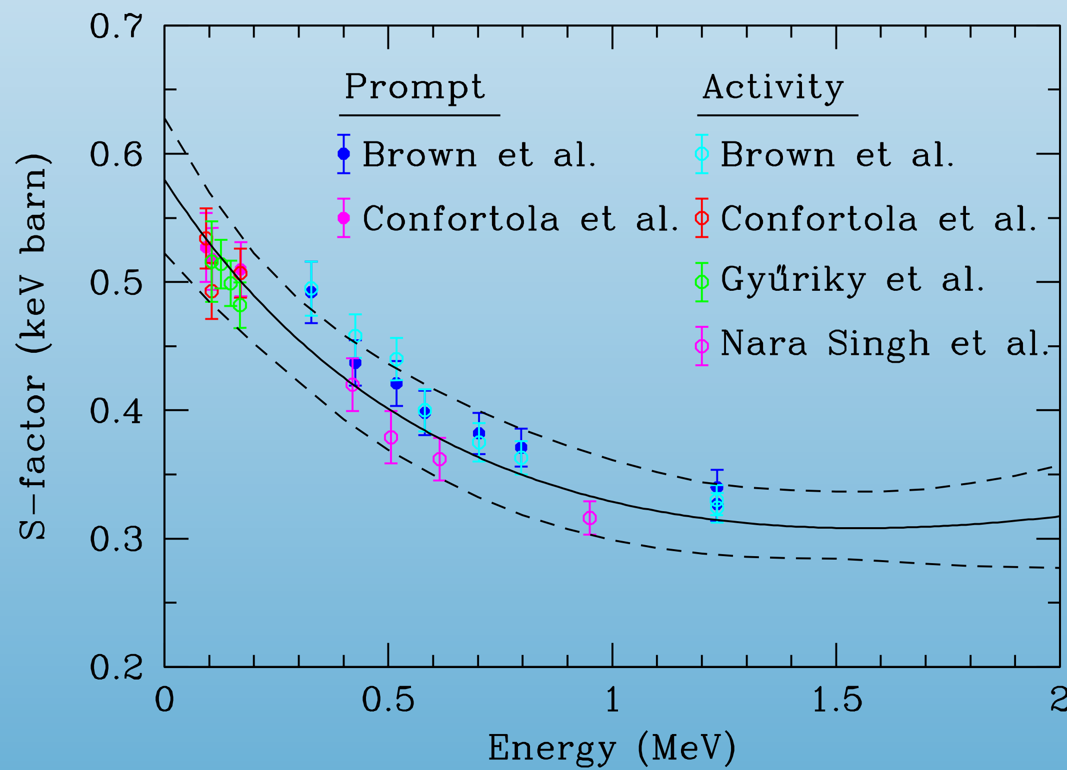
Require:

$$\left.\begin{aligned} S_{34}^{NEW}(0) &= 0.267 \text{ keVb} \\ \frac{\Delta S_{34}}{S_{34}} &= -0.47 \end{aligned}\right\} \text{globular cluster Li}$$

or

$$\left.\begin{aligned} S_{34}^{NEW}(0) &= 0.136 \text{ keVb} \\ \frac{\Delta S_{34}}{S_{34}} &= -0.73 \end{aligned}\right\} \text{halo star Li}$$

New $^3He(\alpha,\gamma)^7Be$ measurements



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or

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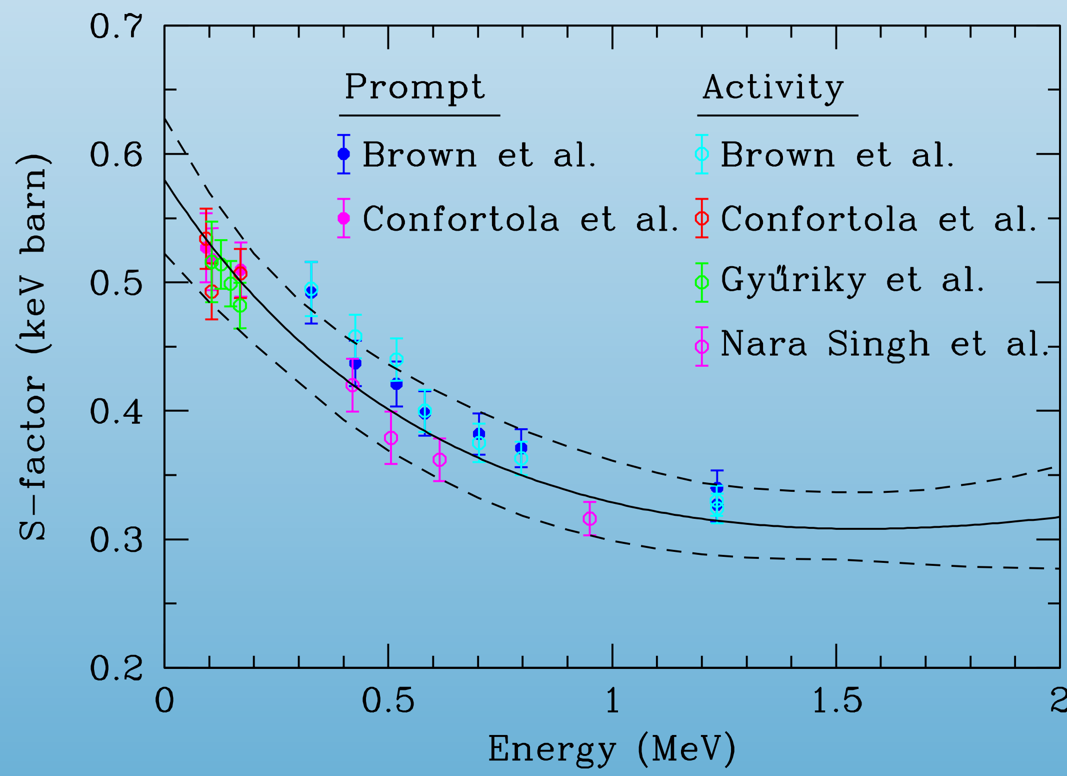
Constrained from solar neutrinos

$$S_{34} > 0.35 \text{ keV barn}$$

at 95% CL

New $^3He(\alpha,\gamma)^7Be$ measurements



Resonant Reactions

Cyburt, Pospelov
Chakraborty, Fields, Olive
Broggini, Canton, Fiorentini, Villante

Is there a missing excited state providing a resonant reaction?

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

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In principle, long list of possible resonance candidates

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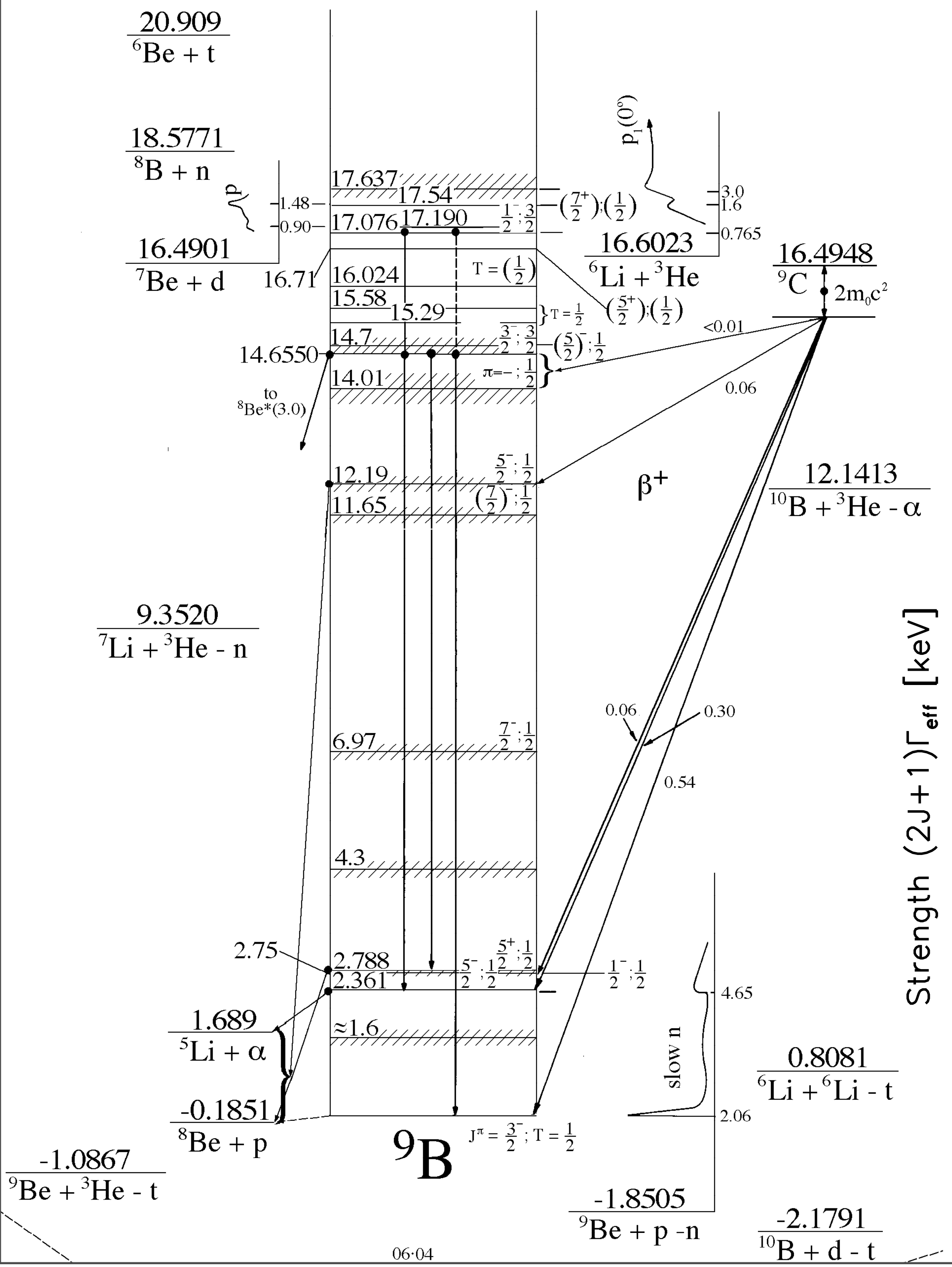
Is there a missing excited state providing a resonant reaction?

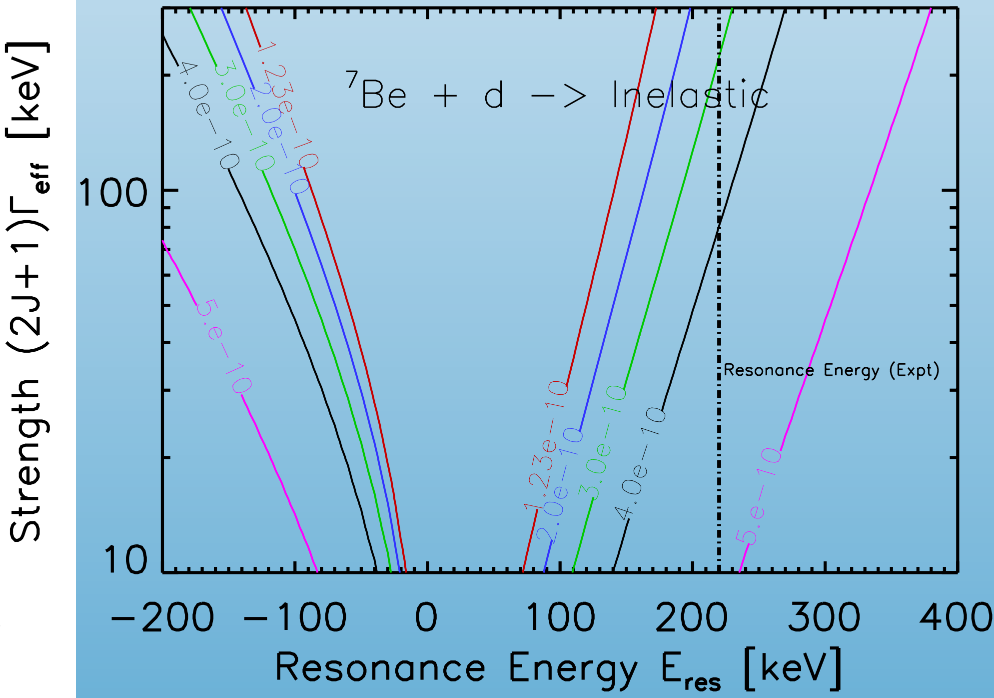
$$^7\mathrm{Be} + A \rightarrow C^* \rightarrow B + D$$

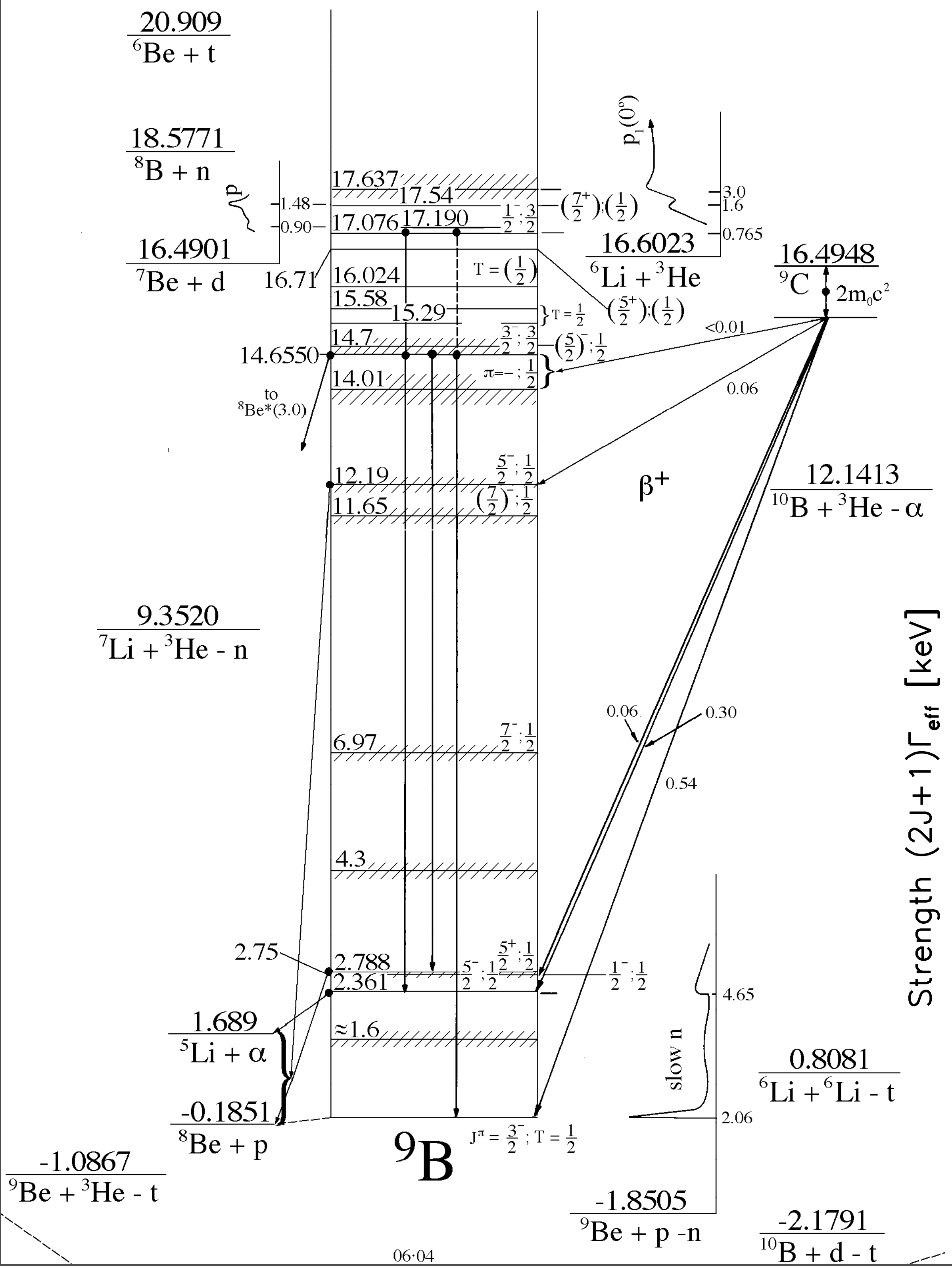
In principle, long list of possible resonance candidates

- Excited states of ^{8}Li (included)
- ^{8}Be (some included) - large E_{res}
- ^{8}B (included)
- ^{9}B - interesting state at 16.71 MeV

$^{7}Be + d \rightarrow {}^{9}B$ (16.71)





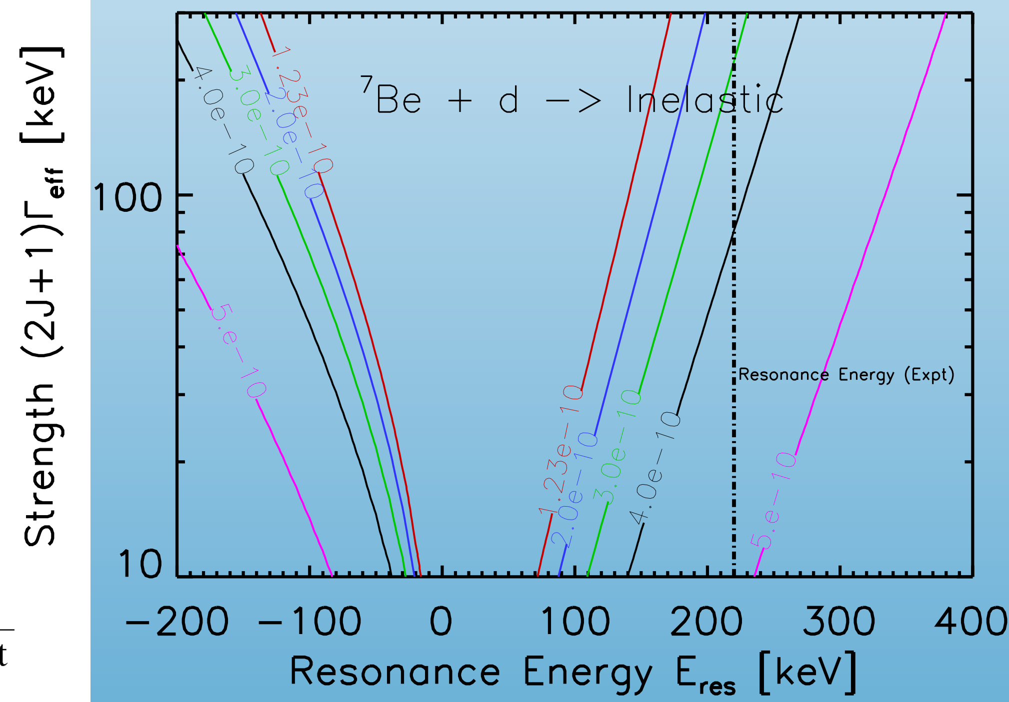


$^7Be + d \rightarrow {}^9B$ (~~16.71~~)

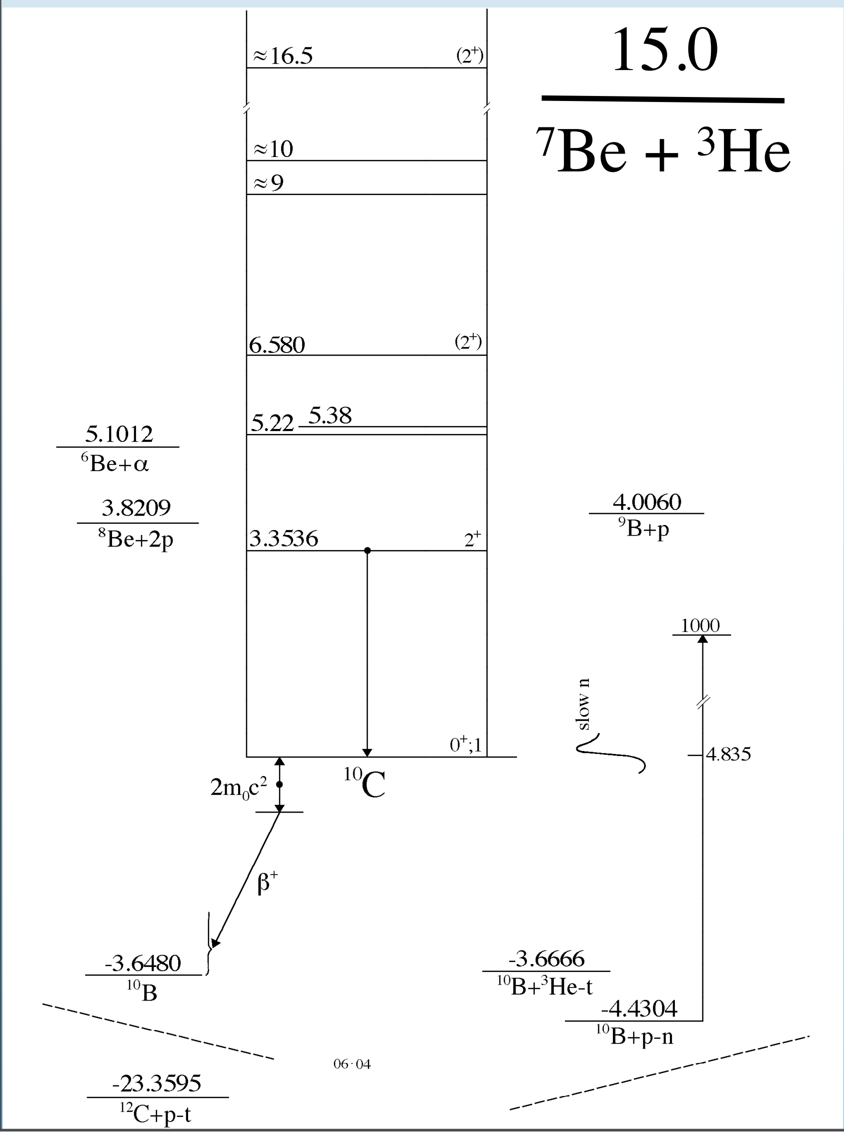
Recent results place state at 16.80

Scholl et al. 2011

cf. Kirsebom and Davids



- ^{10}B - interesting state at 18.80 MeV
- ^{10}C - potentially interesting state at 15 MeV
- ^{11}C - negligible effect



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

Preliminary report from

ORSAY SPLIT-POLE spectrometer

Possible E_x=15.05 MeV (E_r=50 keV) level

reported by A. Coc - Paris Feb/12

Possible sources for the discrepancy

- Nuclear Rates
  - Restricted by solar neutrino flux
- 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.

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

$$\frac{dLi}{dlng} = \frac{.09}{.5} \qquad \frac{dLi}{dT} = \frac{.08}{100K}$$

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

- Stellar parameters

$$\frac{dLi}{dlng} = \frac{.09}{.5} \qquad \frac{dLi}{dT} = \frac{.08}{100K}$$

- Particle Decays

Limits on Unstable particles due to

Electromagnetic/Hadronic Production and Destruction of Nuclei

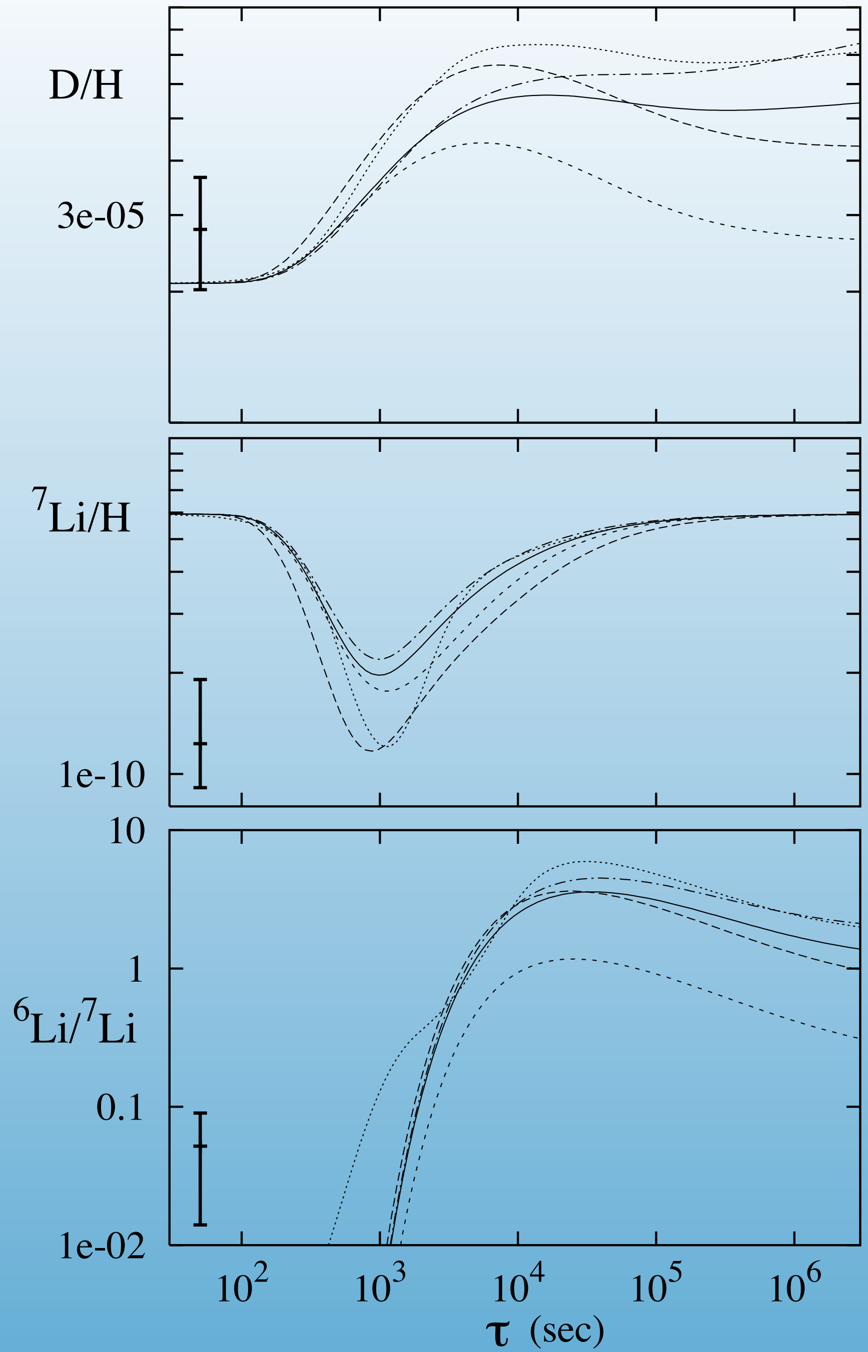
3 free parameters

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

and τ_X

- Start with non-thermal injection spectrum (Pythia)

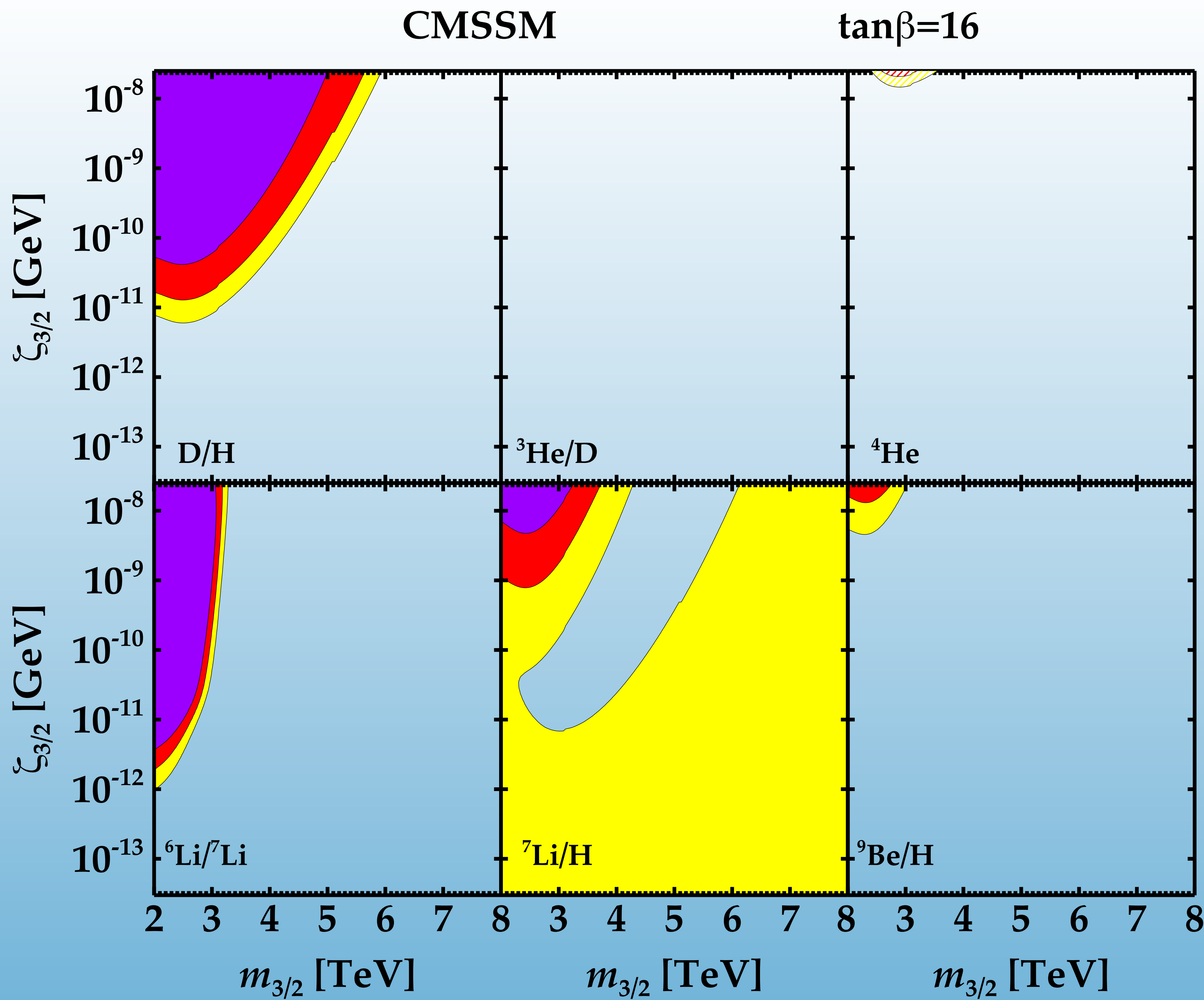
- Evolve element abundances including thermal (BBN) and non-thermal processes.



Injection of p,n with timescale of ~1000 s

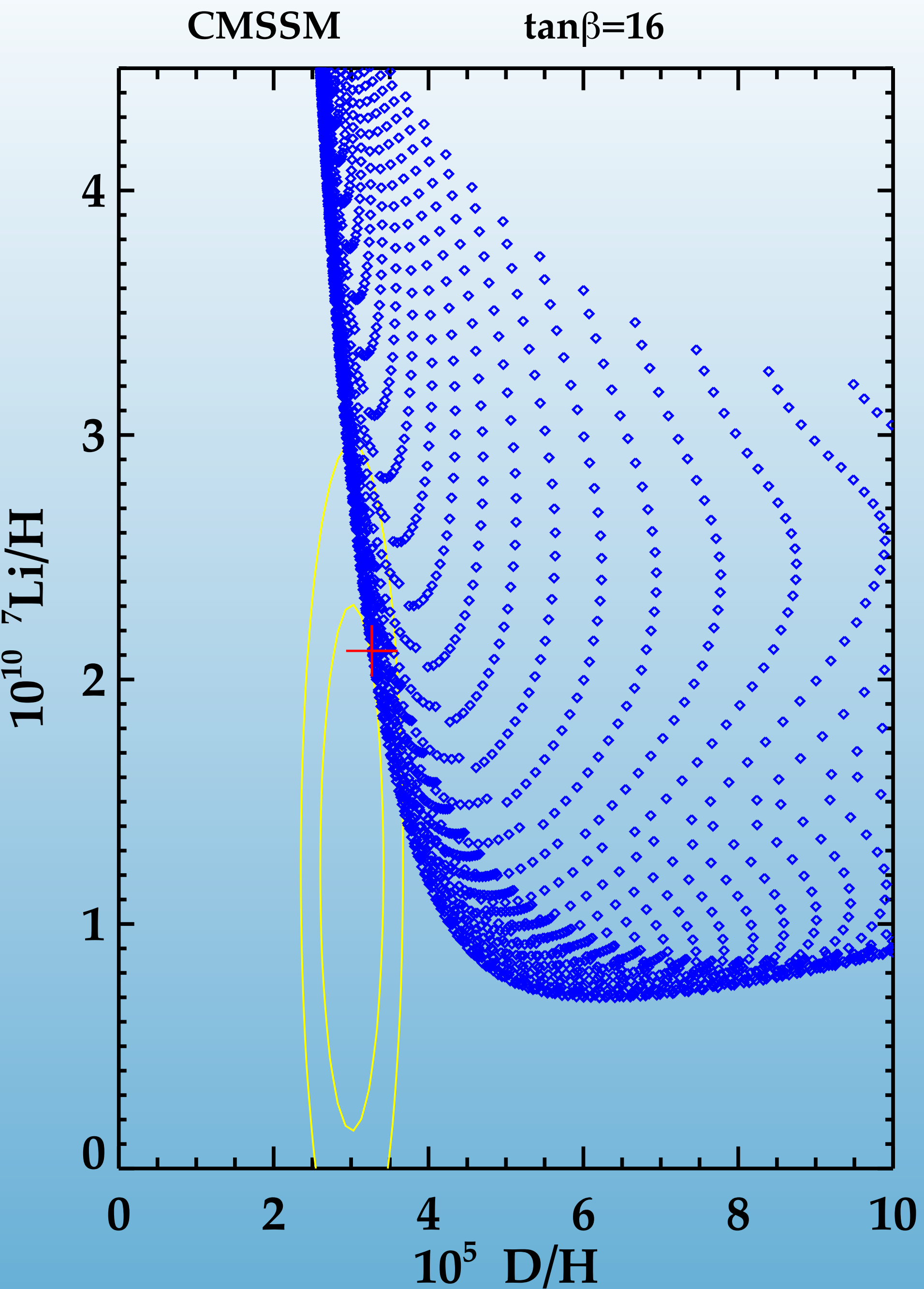
^{7}Be(n,p)^{7}Li followed by ^{7}Li(p,α)^{4}He

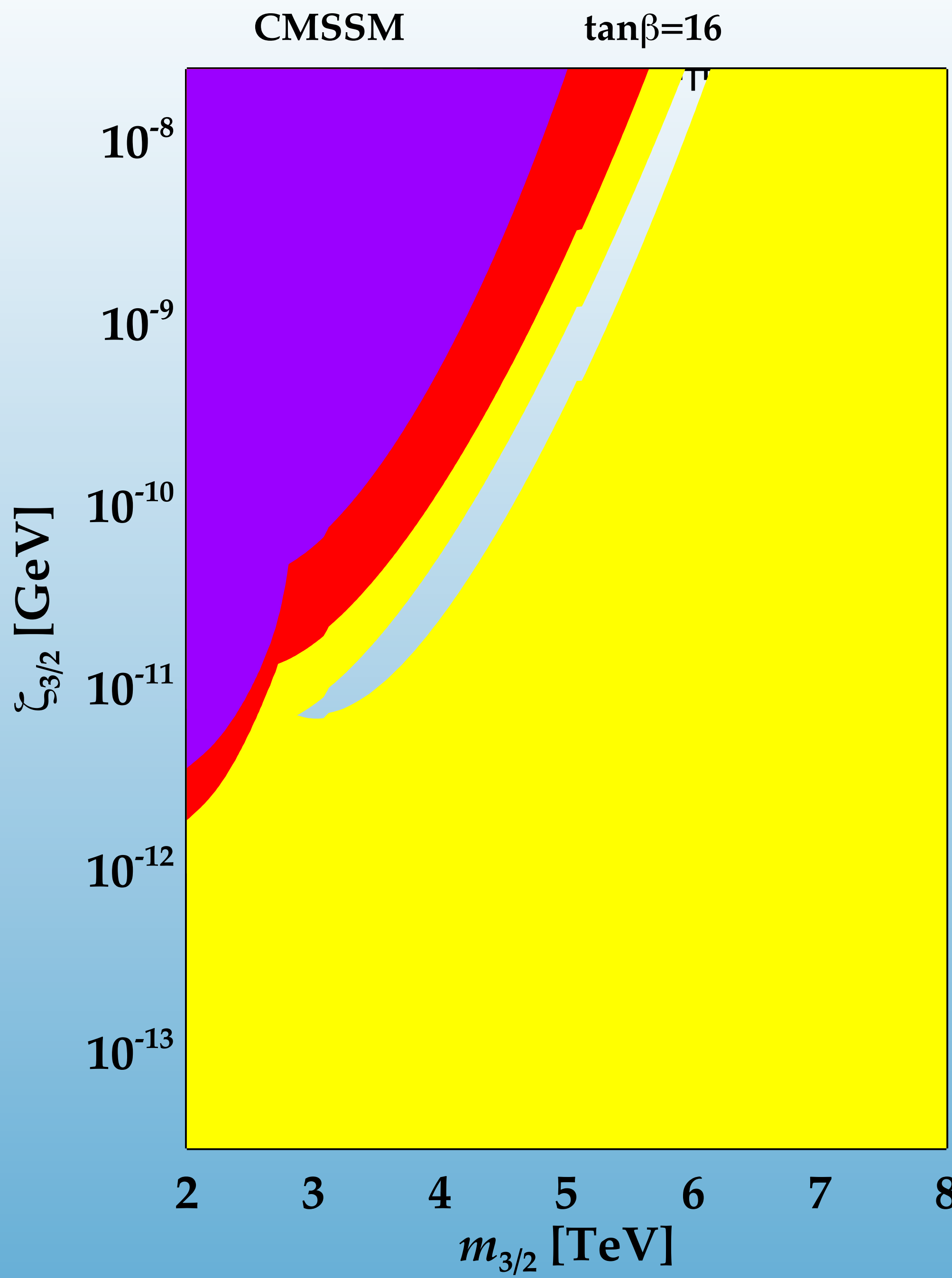
Jedamzik



CMSSM - Mastercode Best Fit Post LHC 2012

Cyburt, Ellis, Fields, Luo, Olive, Spanos





Olive, Petitjean, Vangioni, Silk

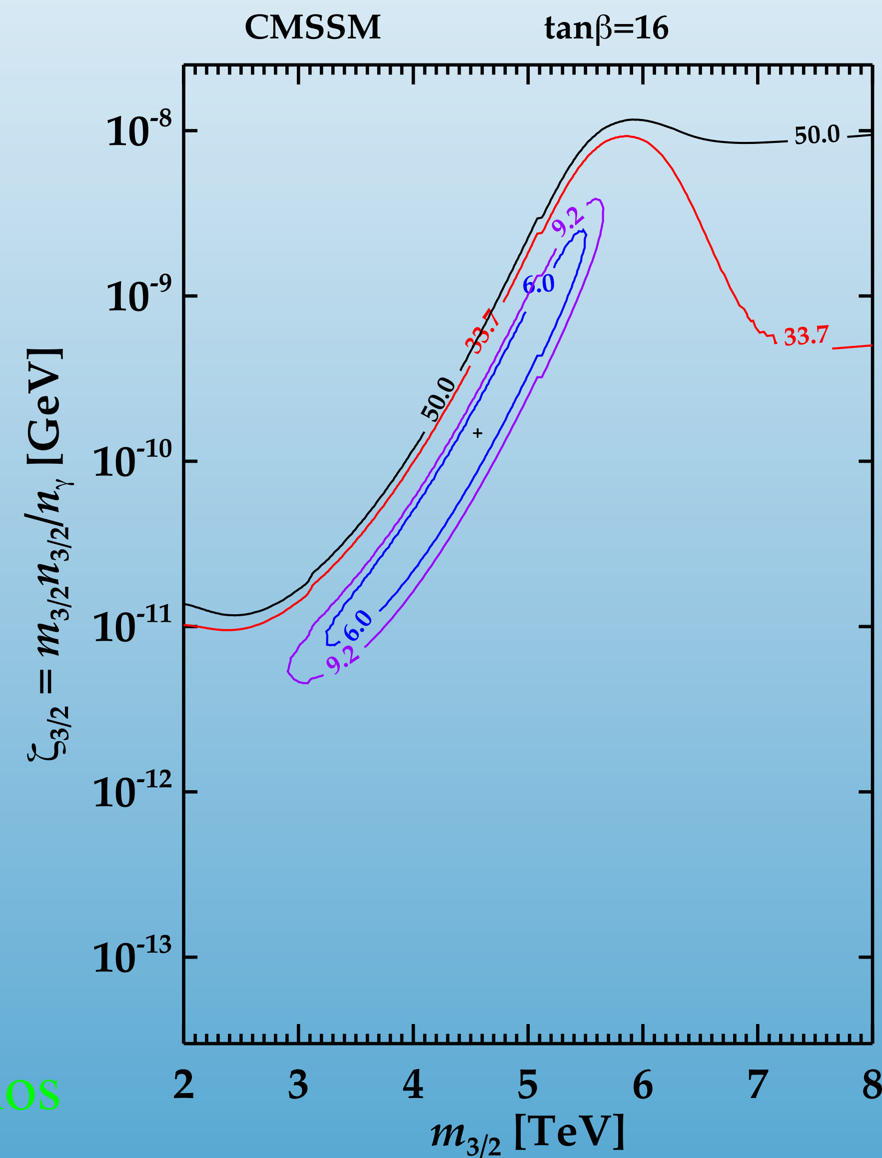
Cyburt, Ellis, Fields, Luo, Olive, Spanos

How well can you do

$$\chi^2 \equiv \left(\frac{Y_p - 0.2534}{0.0083}\right)^2 + \left(\frac{\mathrm{D/H} - 3.01\times10^{-5}}{0.27\times10^{-5}}\right)^2 + \left(\frac{{}^7\mathrm{Li/H} - 1.23\times10^{-10}}{0.71\times10^{-10}}\right)^2 + \left(\frac{\Omega_\chi^{(3/2)}h^2}{0.0045}\right)^2,$$

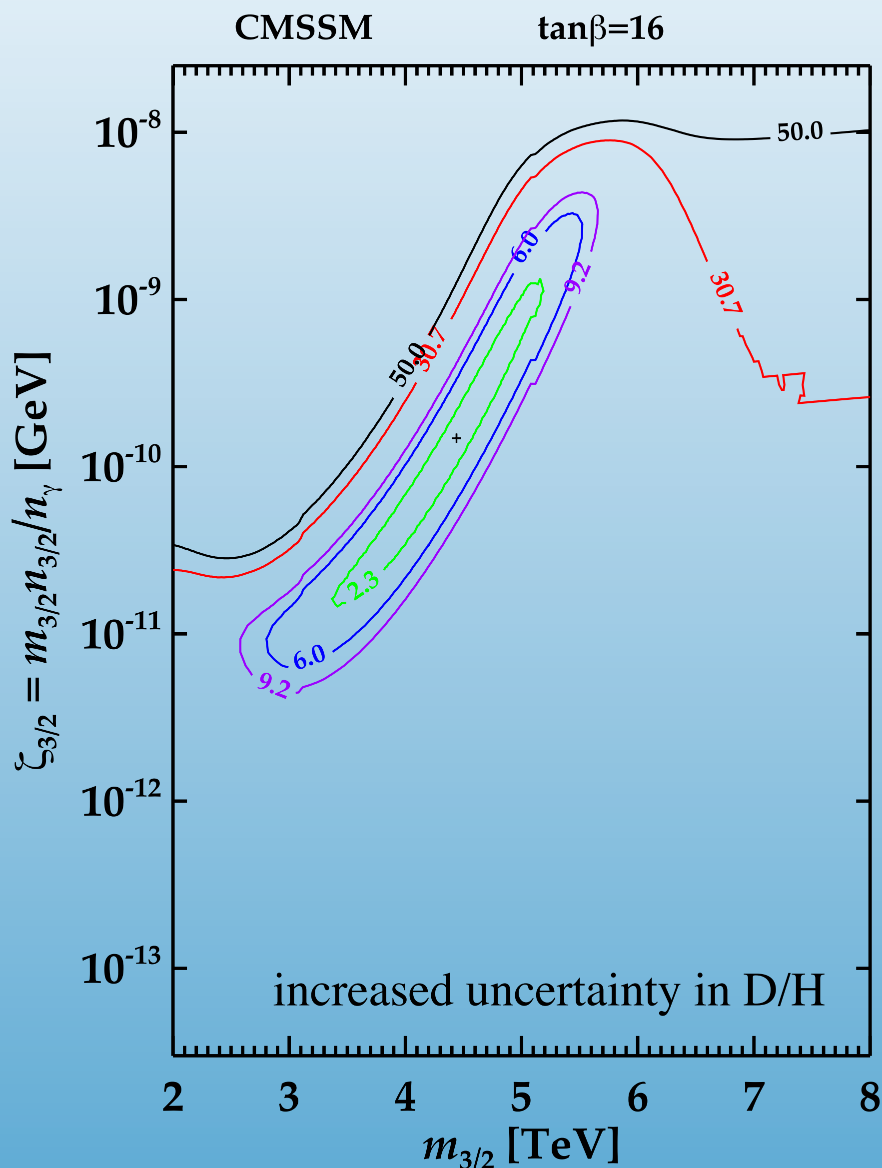
SBBN: χ^2 = 33.7 - field stars

SBBN: χ^2 = 23.8 - GC stars



Cyburt, Ellis, Fields, Luo, Olive, Spanos

ID	Y_p	10^5 D/H	10^{10} ^{7}Li/H	$\Omega_\chi^{(3/2)} h^2$	$\chi^2_{\rm min}$
1	0.2487	3.27	2.12	5.0×10^{-4}	2.81
2	0.2487	3.28	2.09	1.1×10^{-3}	2.86
3	0.2487	3.26	2.14	4.4×10^{-4}	2.82
4	0.2487	3.29	2.11	2.1×10^{-3}	3.14
5	0.2487	3.32	2.01	6.5×10^{-4}	2.87
6	0.2487	3.27	2.11	1.0×10^{-3}	2.86
7	0.2487	3.29	2.08	4.7×10^{-4}	2.87
8	0.2487	3.25	2.16	1.8×10^{-3}	2.96
9	0.2487	3.31	2.04	1.2×10^{-3}	2.91
10	0.2487	3.28	2.09	1.4×10^{-3}	2.89
11	0.2487	3.55	1.63	5.1×10^{-4}	1.25
12	0.2487	3.10	2.50	3.5×10^{-3}	0.52
13	0.2487	3.15	2.40	2.5×10^{-4}	0.37



Cyburt, Ellis, Fields, Luo, Olive, Spanos

Possible sources for the discrepancy

- Particle Decays
- Axion Cooling

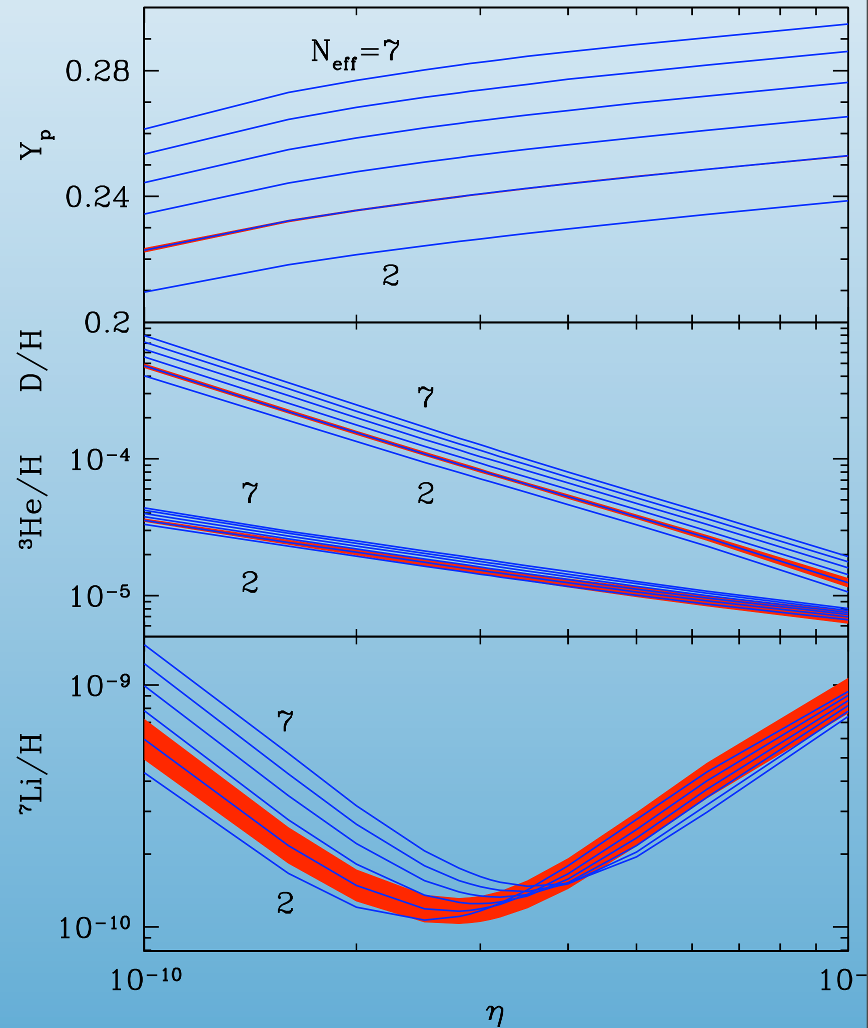
Erkin, Sikivie, Tam, Yang
Kusakabe, Balantekin, Kajino, Pehlivan

- Variable Constants

Limits on N_ν

$$G_F T^5 \sim \Gamma(T_f) \sim H(T_f) \sim \sqrt{G_N N}\, T_f^2$$

Observations	$\eta_{10} \equiv 10^{10}\eta$	N_ν	$\delta N_{\nu,max}$
Y_p + D/H$_A$	$5.94^{+0.56}_{-0.50}$	$3.14^{+0.70}_{-0.65}$	1.59
$Y_p + \eta_{CMB}$	6.14 ± 0.25	$3.08^{+0.74}_{-0.68}$	1.63
D/H$_A + \eta_{CMB}$	6.16 ± 0.25	$3.59^{+1.14}_{-1.04}$	2.78
Y_p + D/H$_A + \eta_{CMB}$	$6.10^{+0.24}_{-0.22}$	$3.24^{+0.61}_{-0.57}$	1.44



“current” upper limit from He:
$\delta N_\nu < 1.45$

Cyburt, Fields, KAO, Skillman

Summary

- D, He are ok -- issues to be resolved
- Li: Problematic
  - BBN ^{7}Li high compared to observations
- Important to consider:
  - Nuclear considerations
    - Resonances ^{10}C (15.04) !
  - Depletion (tuned)
  - Li Systematics - T scale - unlikely
  - Particle Decays?
  - Axion cooling??
  - Variable Constants???
- ^{6}Li: Another Story