BBN Concordance: What's the Matter with Li?

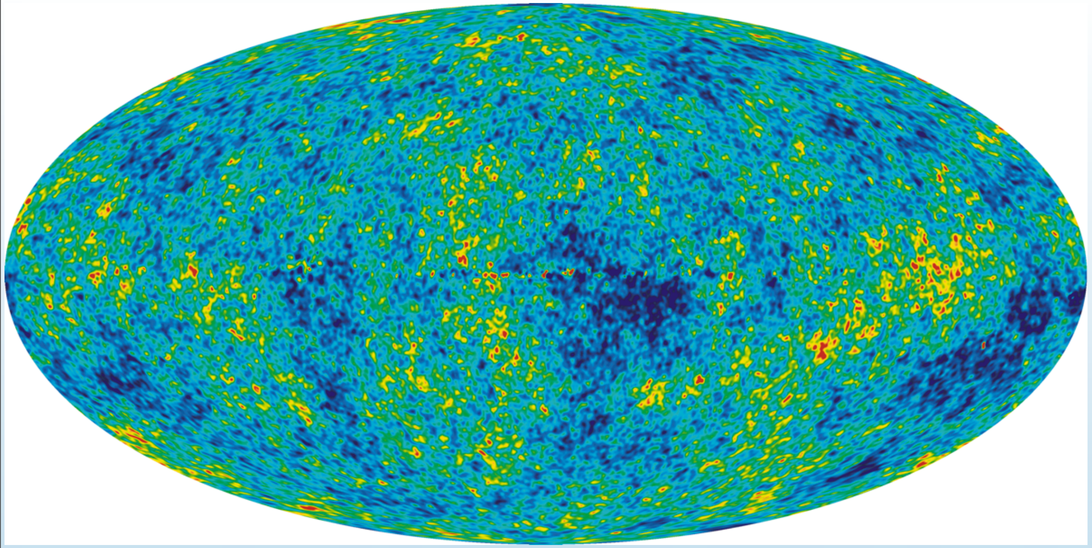
- BBN and the WMAP determination of η, $\Omega_B h^2$
- Observations and Comparison with Theory

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

- The Li Problem

- Cosmic-ray nucleosynthesis

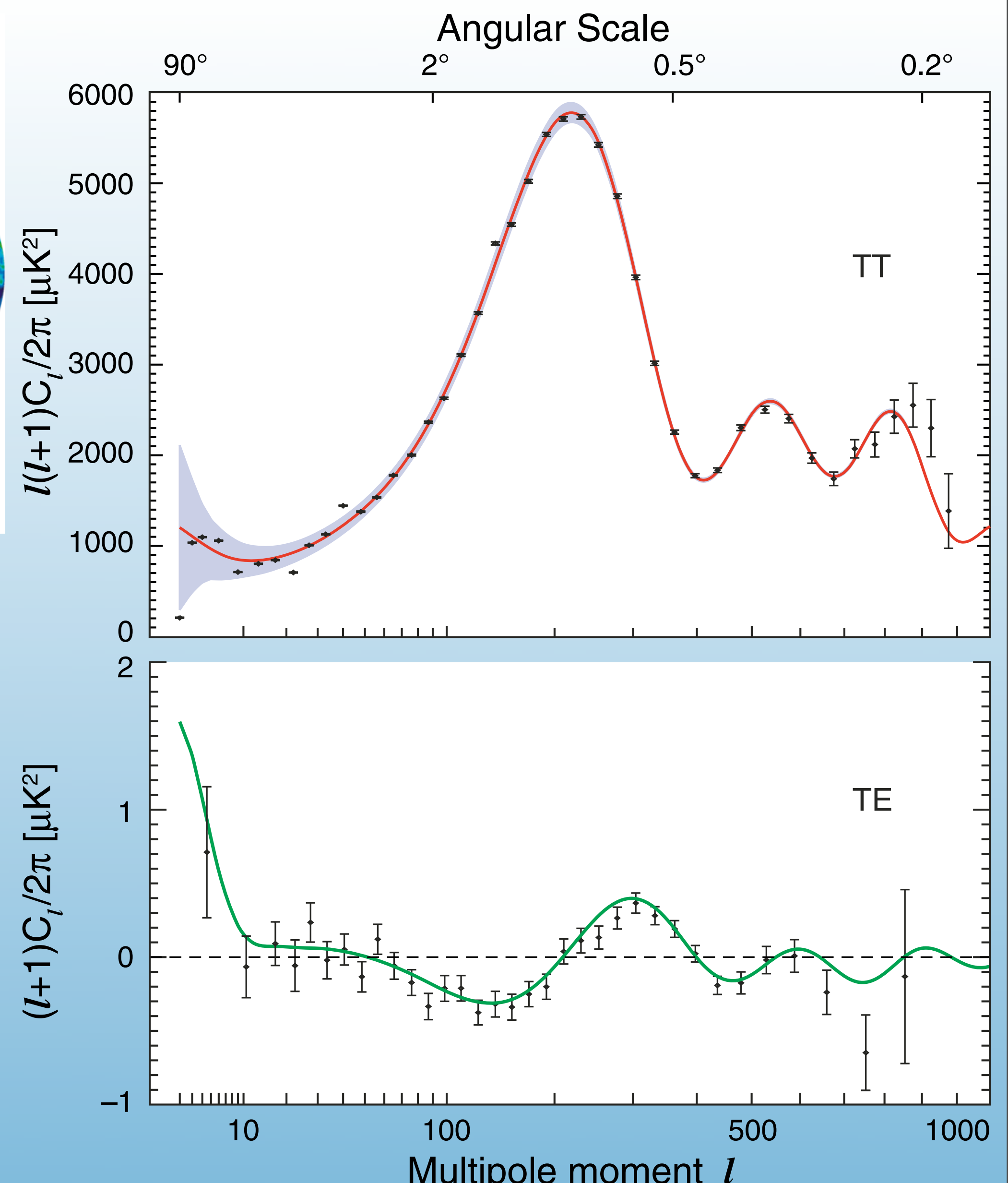
  - ^{6,7}Li - BeB

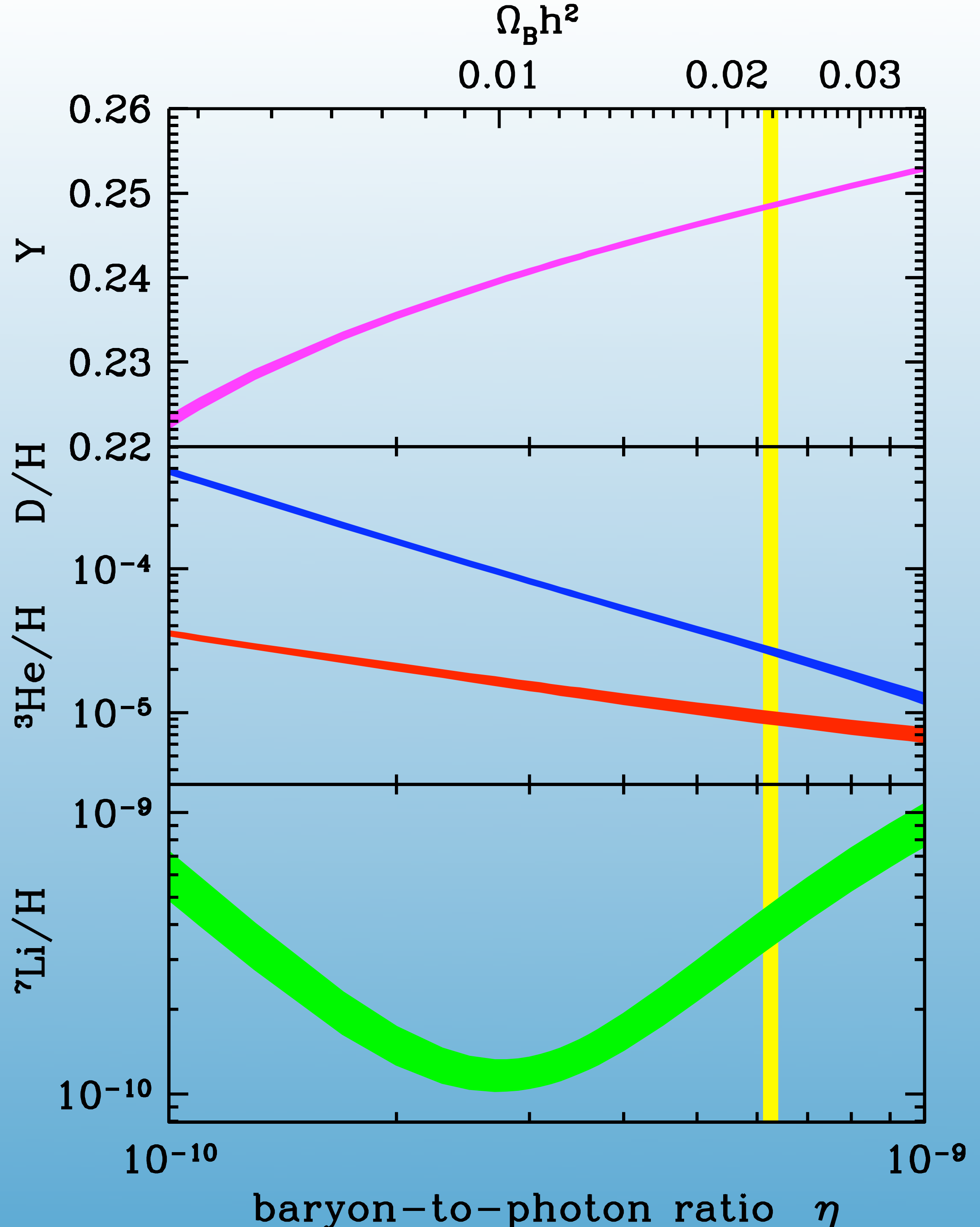


WMAP best fit

$$\Omega_B h^2 = 0.0227 \pm 0.0006$$

$$\eta_{10} = 6.22 \pm 0.16$$



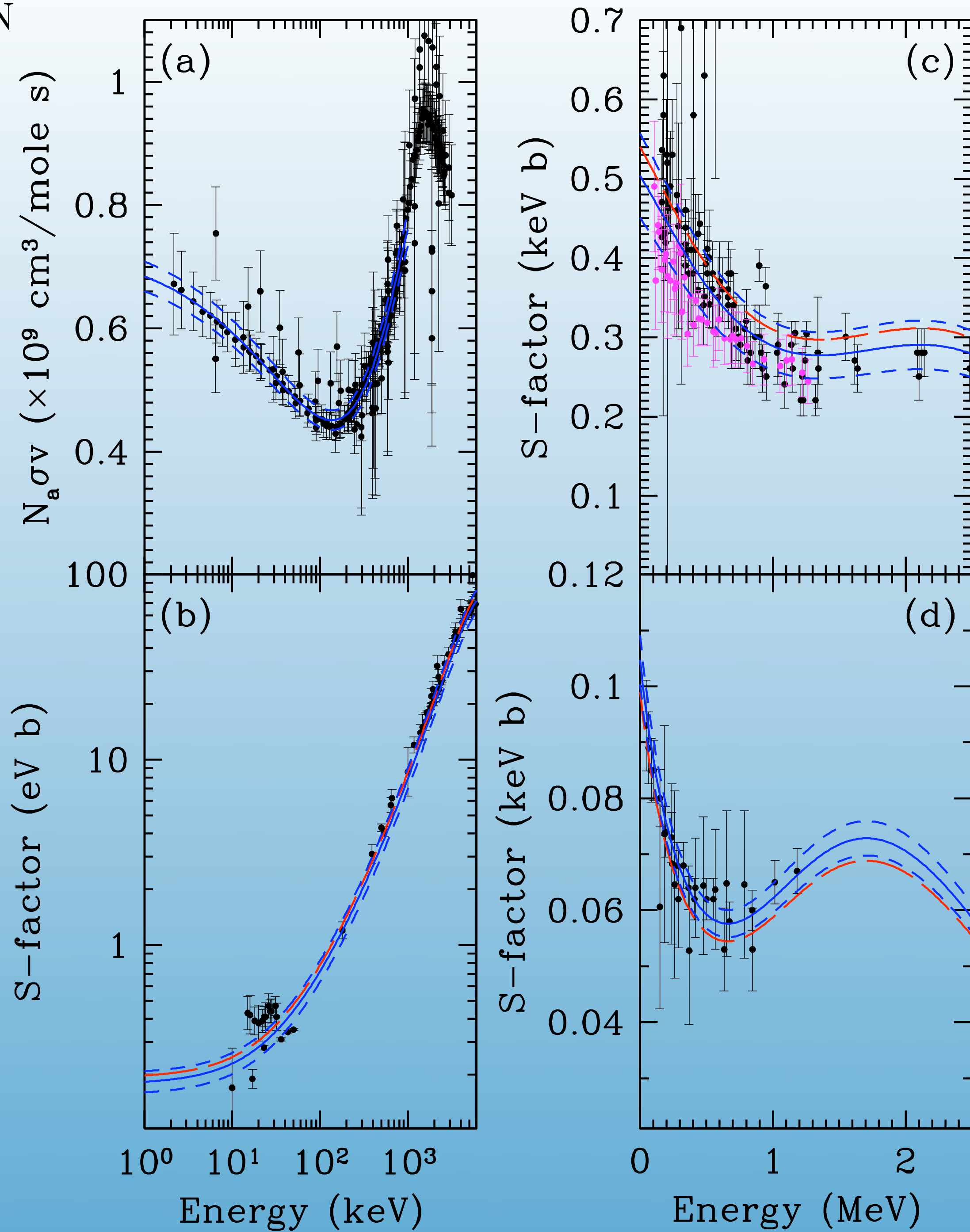


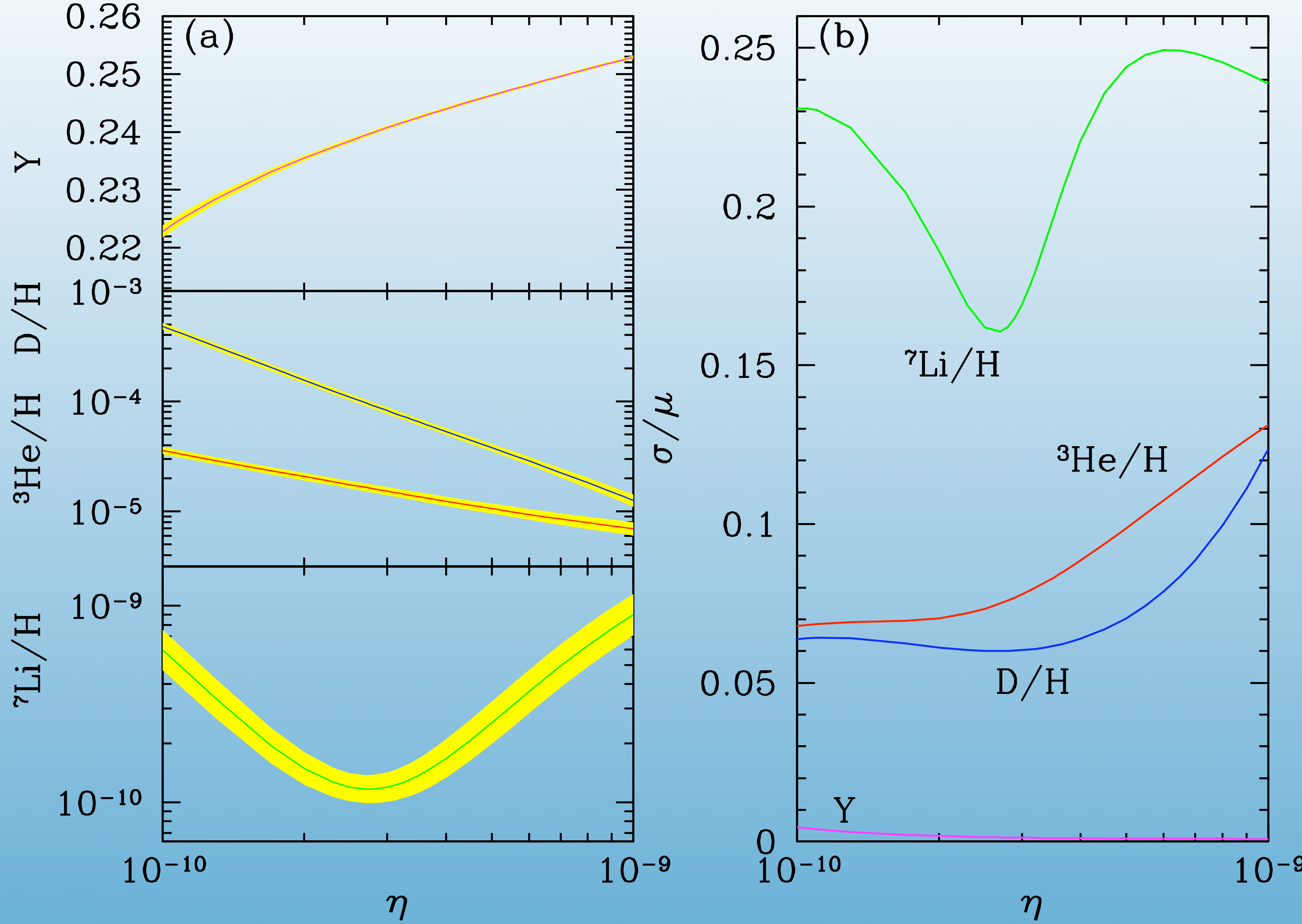
$\Omega_B h^2$
0.01
0.02
0.03
0.26
0.25
0.24
0.23
0.22
Y
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon−to−photon ratio η

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.





(a)
Y
0.26
0.25
0.24
0.23
0.22
D/H
10^{-3}
^{3}He/H
10^{-4}
10^{-5}
^{7}Li/H
10^{-9}
10^{-10}
10^{-10}
10^{-9}
η
(b)
0.25
0.2
0.15
0.1
0.05
0
σ/μ
^{7}Li/H
^{3}He/H
D/H
Y
10^{-10}
10^{-9}
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}	$\log N(\text{H I})$ (cm^{-2})	[O/H][b]	log (D/H)
HS 0105+1619	2.640	2.53600	19.42 ± 0.01	-1.70	-4.60 ± 0.04
Q0913+072	2.785	2.61843	20.34 ± 0.04	-2.37	-4.56 ± 0.04
Q1009+299	2.640	2.50357	17.39 ± 0.06	< -0.67[c]	-4.40 ± 0.07
Q1243+307	2.558	2.52566	19.73 ± 0.04	-2.76	-4.62 ± 0.05
SDSS J155810.16−003120.0	2.823	2.70262	20.67 ± 0.05	-1.47	-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	-2.04	-4.78 ± 0.09

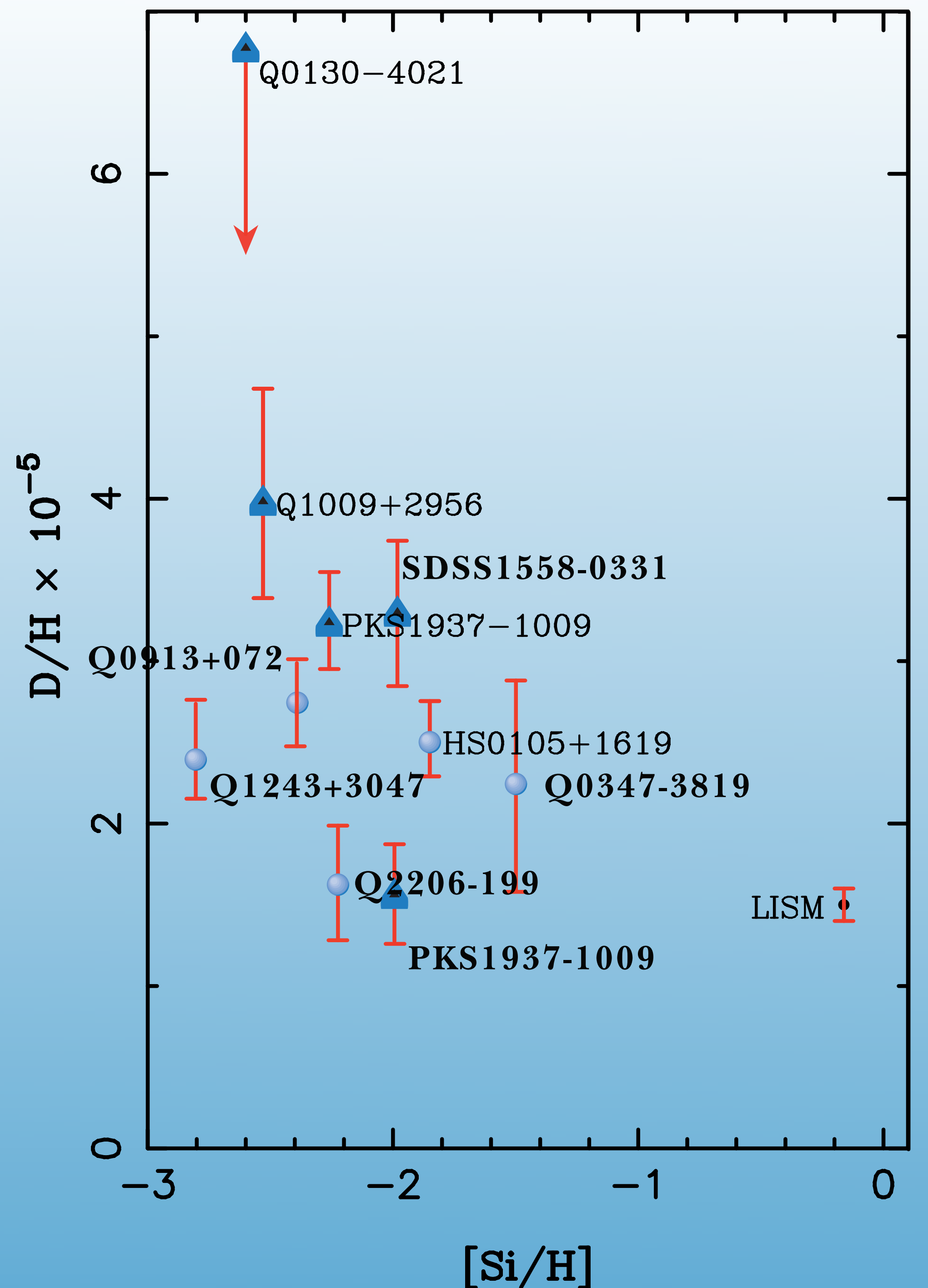
D/H abundances in Quasar apsorption systems

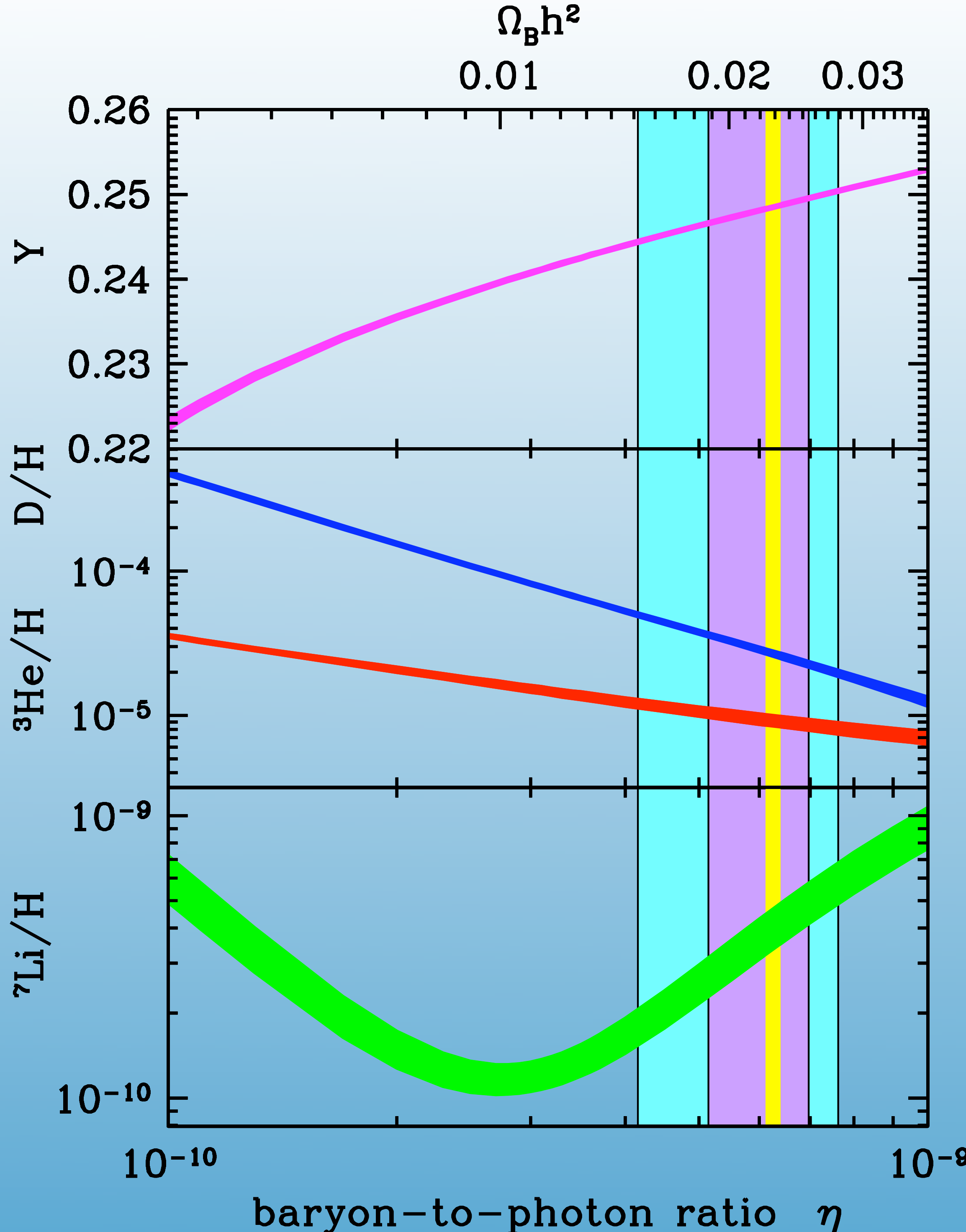
BBN Prediction:

$$10^5\,D/H = 2.74^{+0.26}_{-0.16}$$

Obs Average:

$$10^5\,D/H = 2.82 \pm 0.21$$



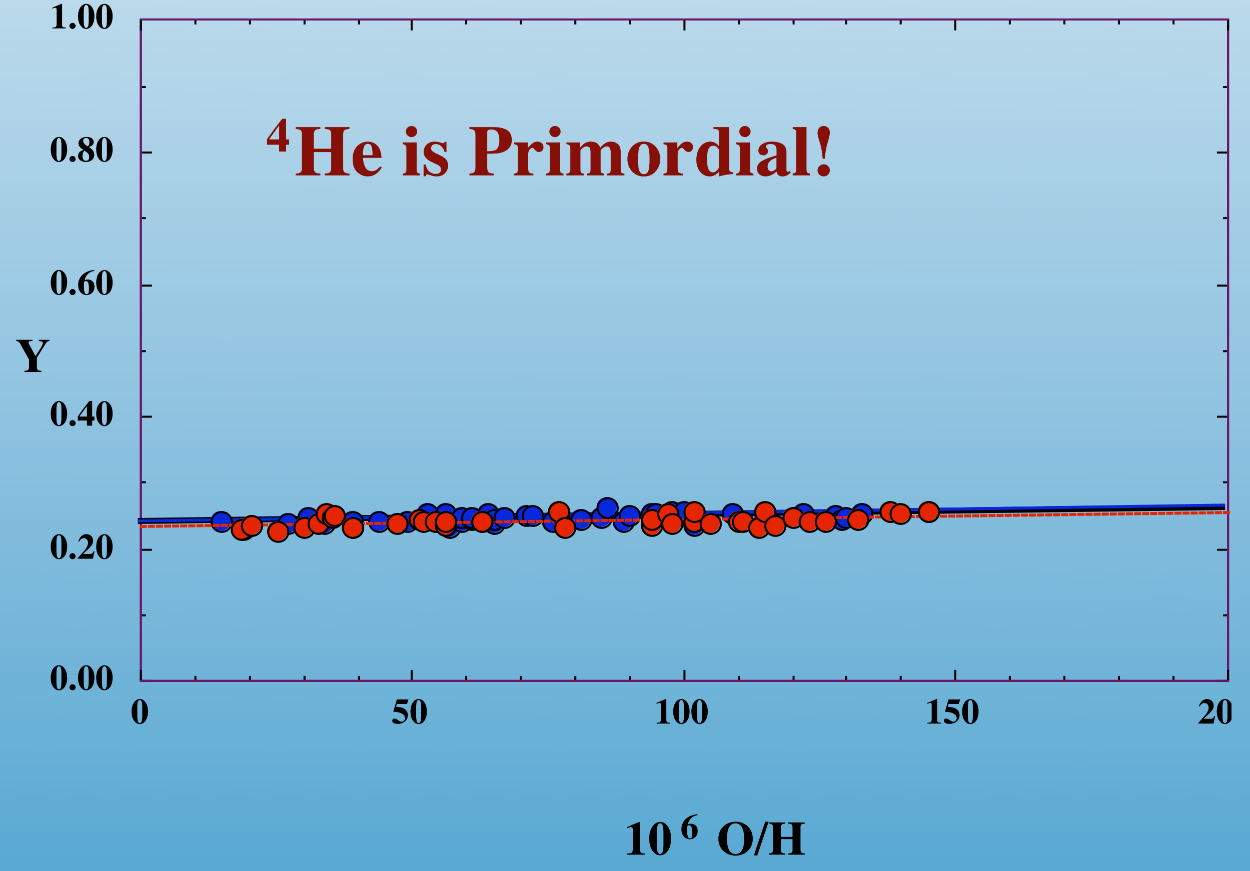


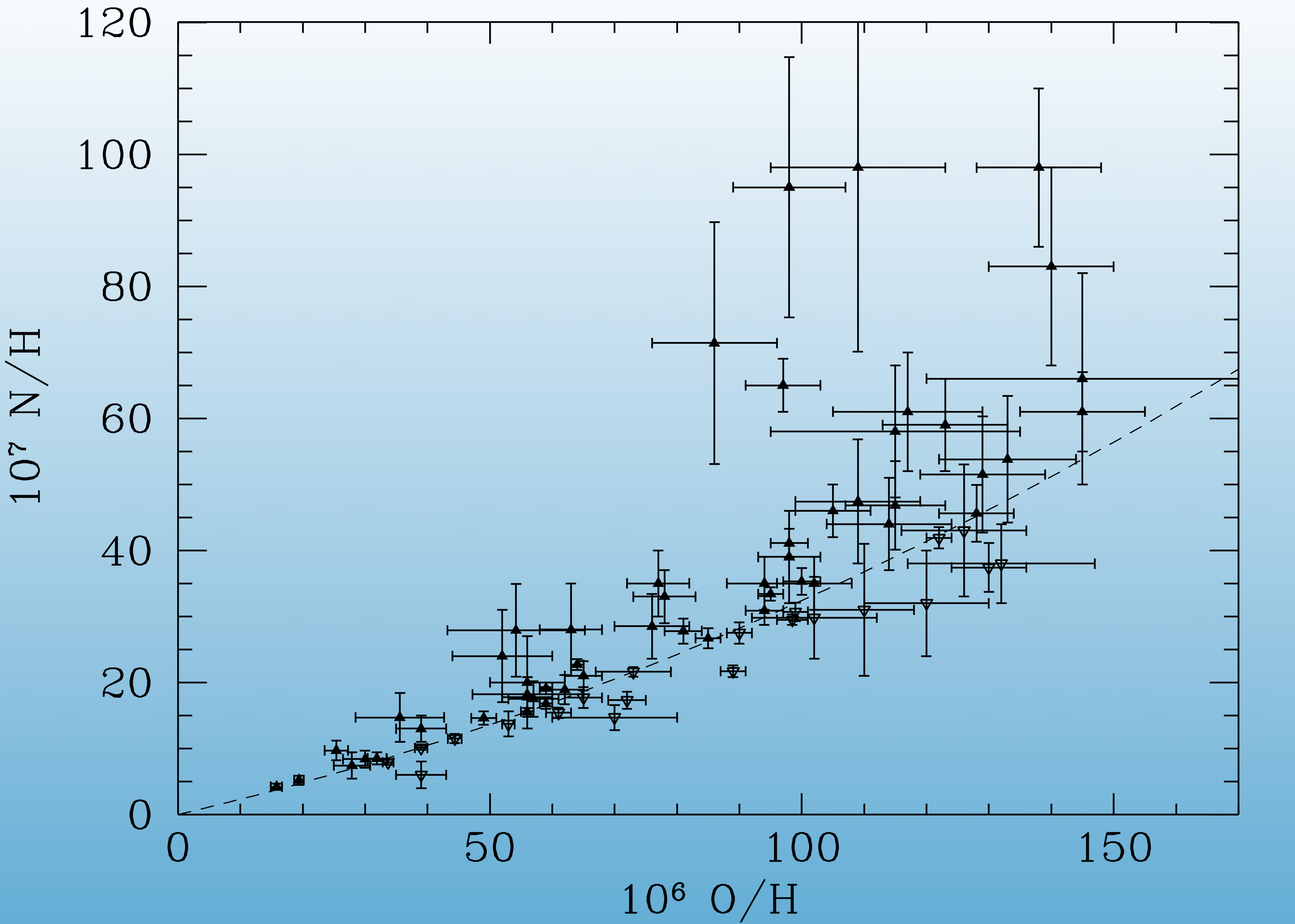
$\Omega_B h^2$
0.01
0.02
0.03
0.26
0.25
0.24
0.23
0.22
Y
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio η

^{4}He

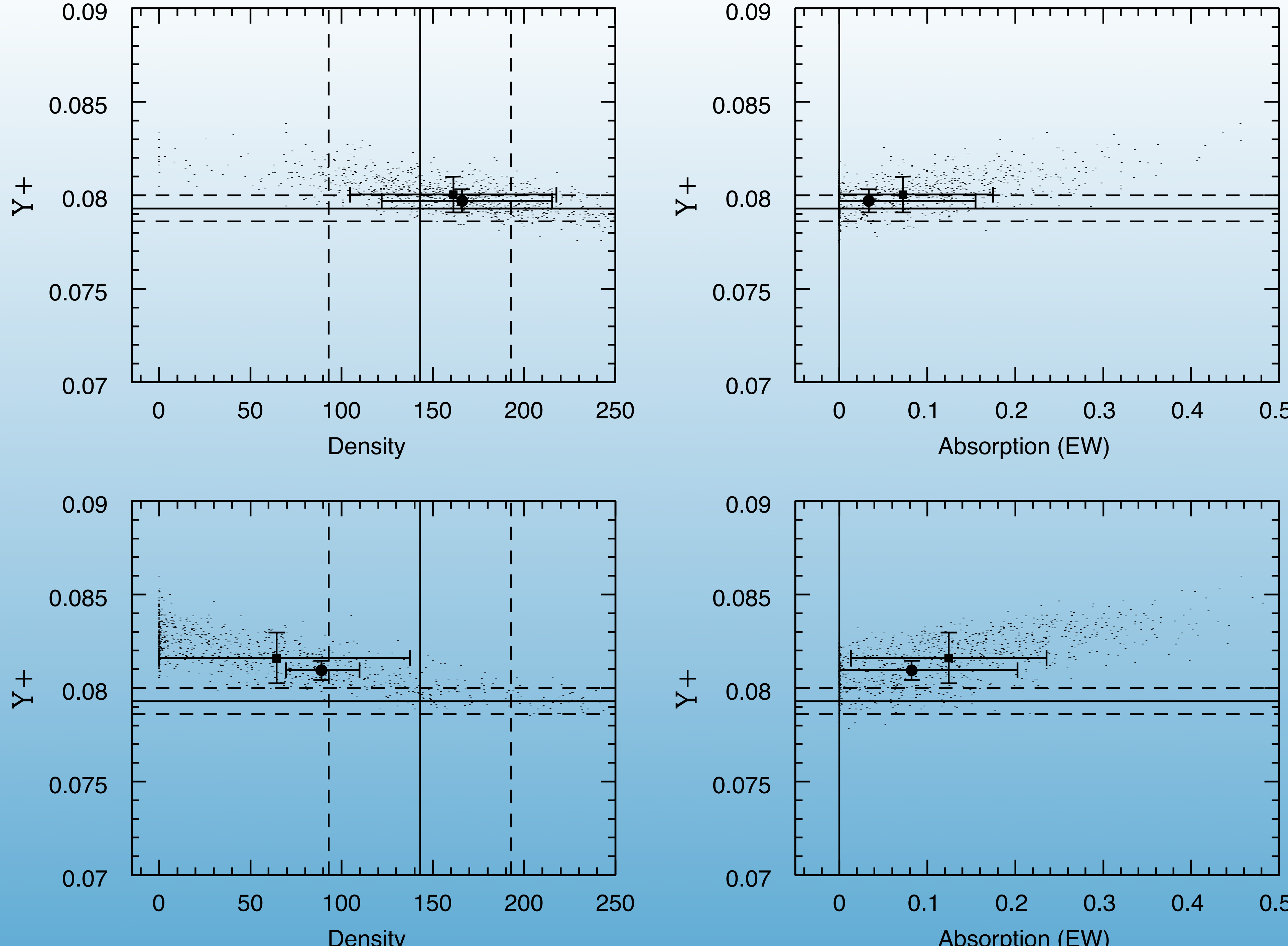
Measured in low metallicity extragalactic HII regions (~100) together with O/H and N/H

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

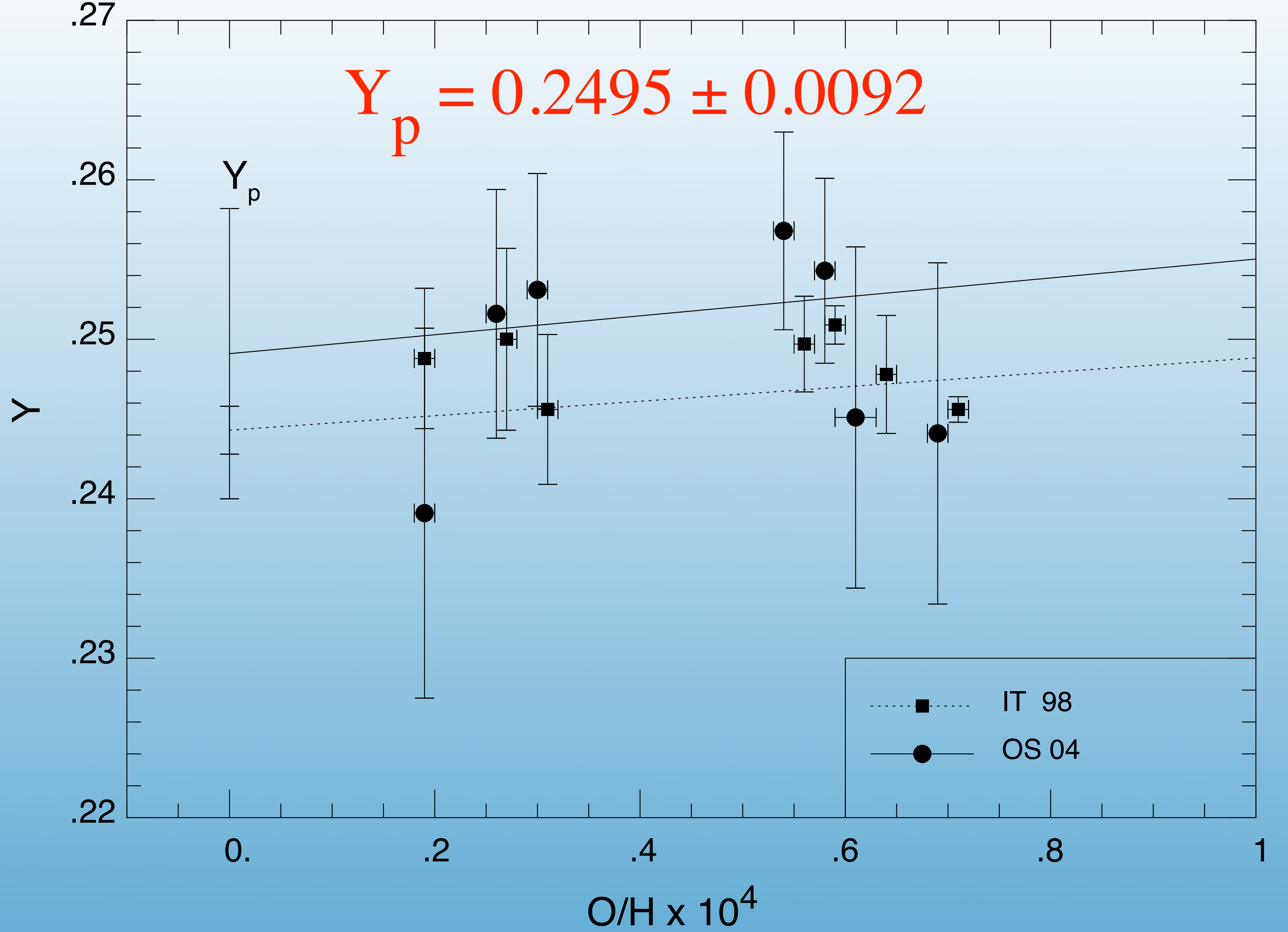




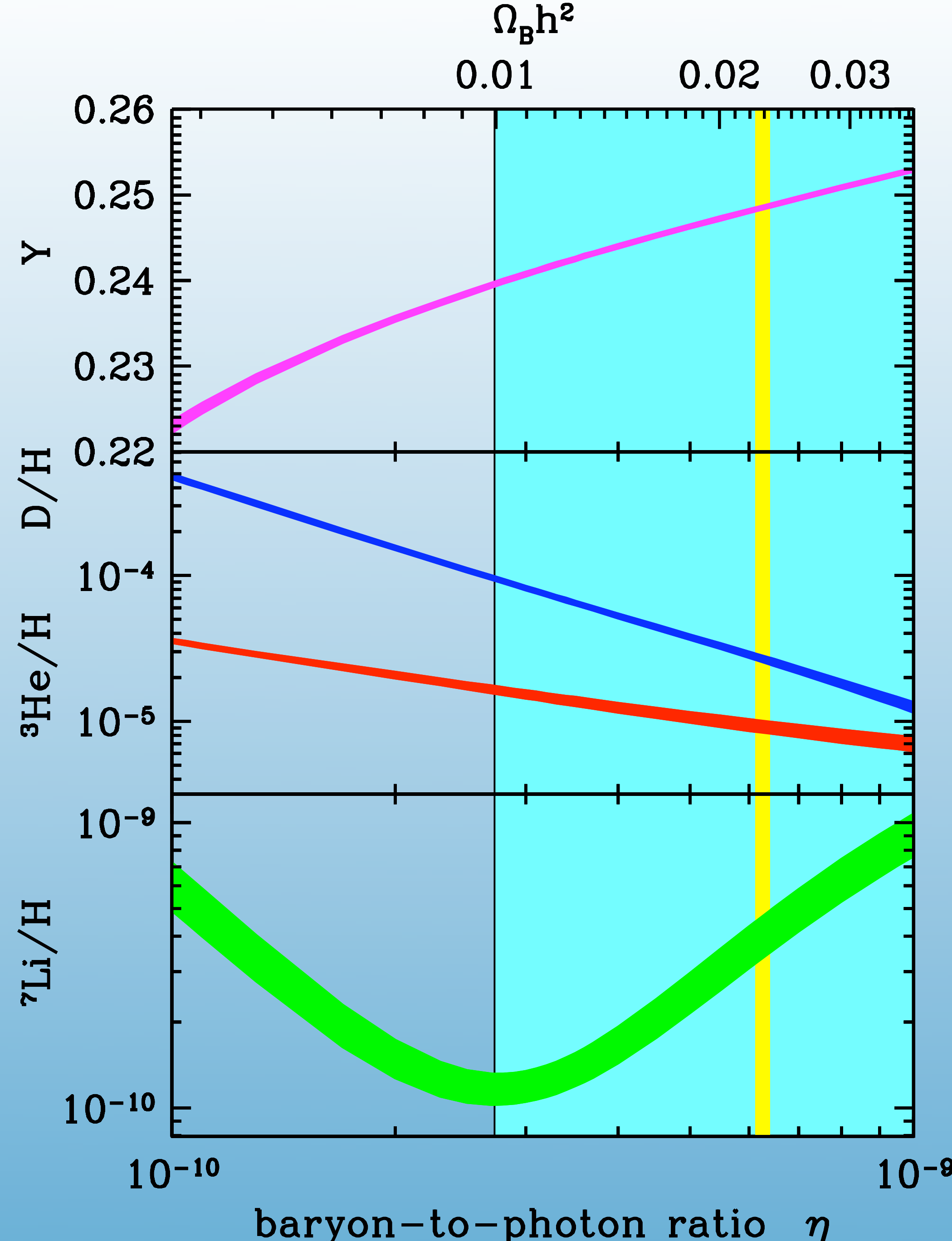
120
100
80
60
40
20
0
0
50
100
150
10⁷ N/H
10⁶ O/H



KAO + Skillman



$Y_p = 0.2495 \pm 0.0092$
Y_p
Y
.27
.26
.25
.24
.23
.22
0.
.2
.4
.6
.8
1
O/H x 10^4
IT 98
OS 04



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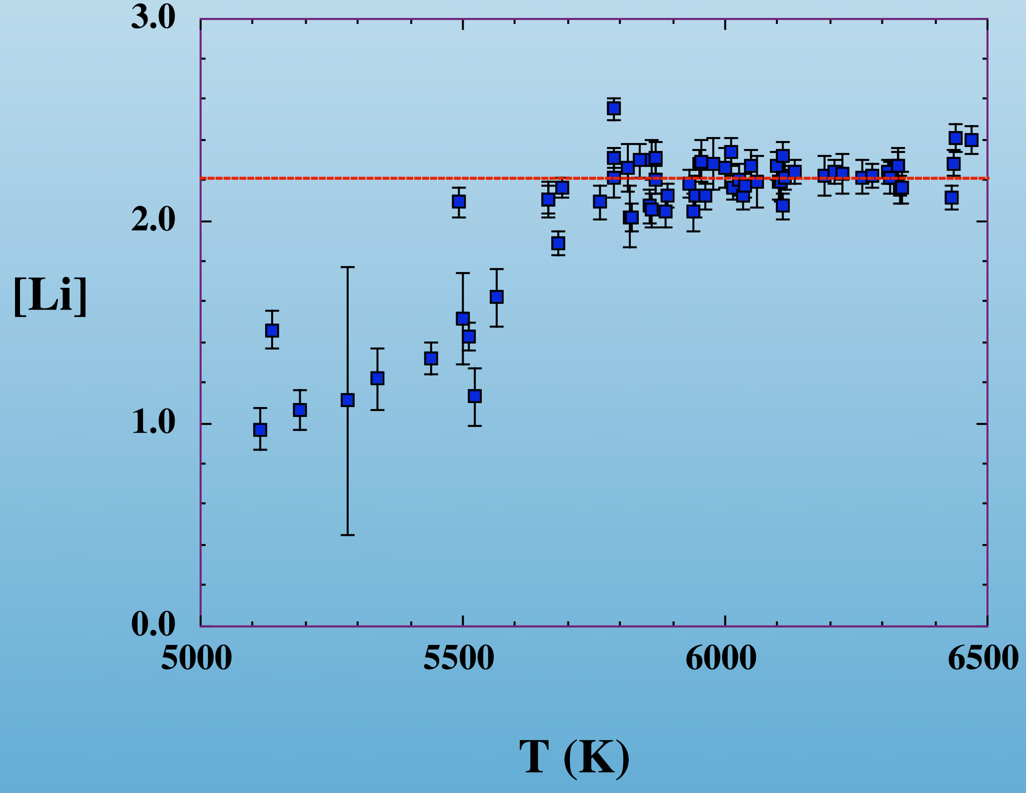
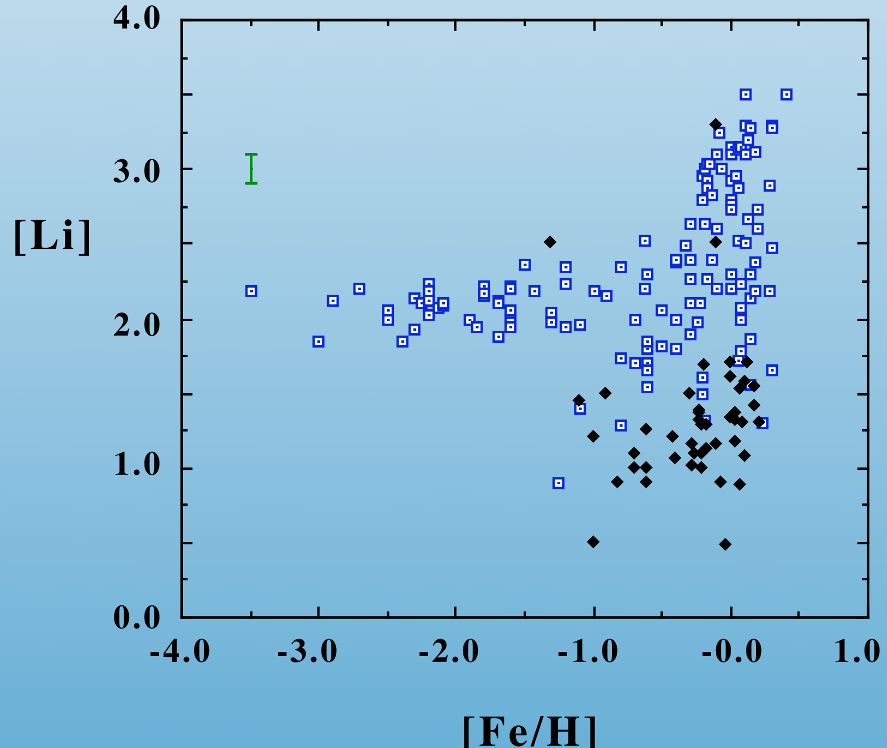
Y
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon−to−photon ratio η

Li/H

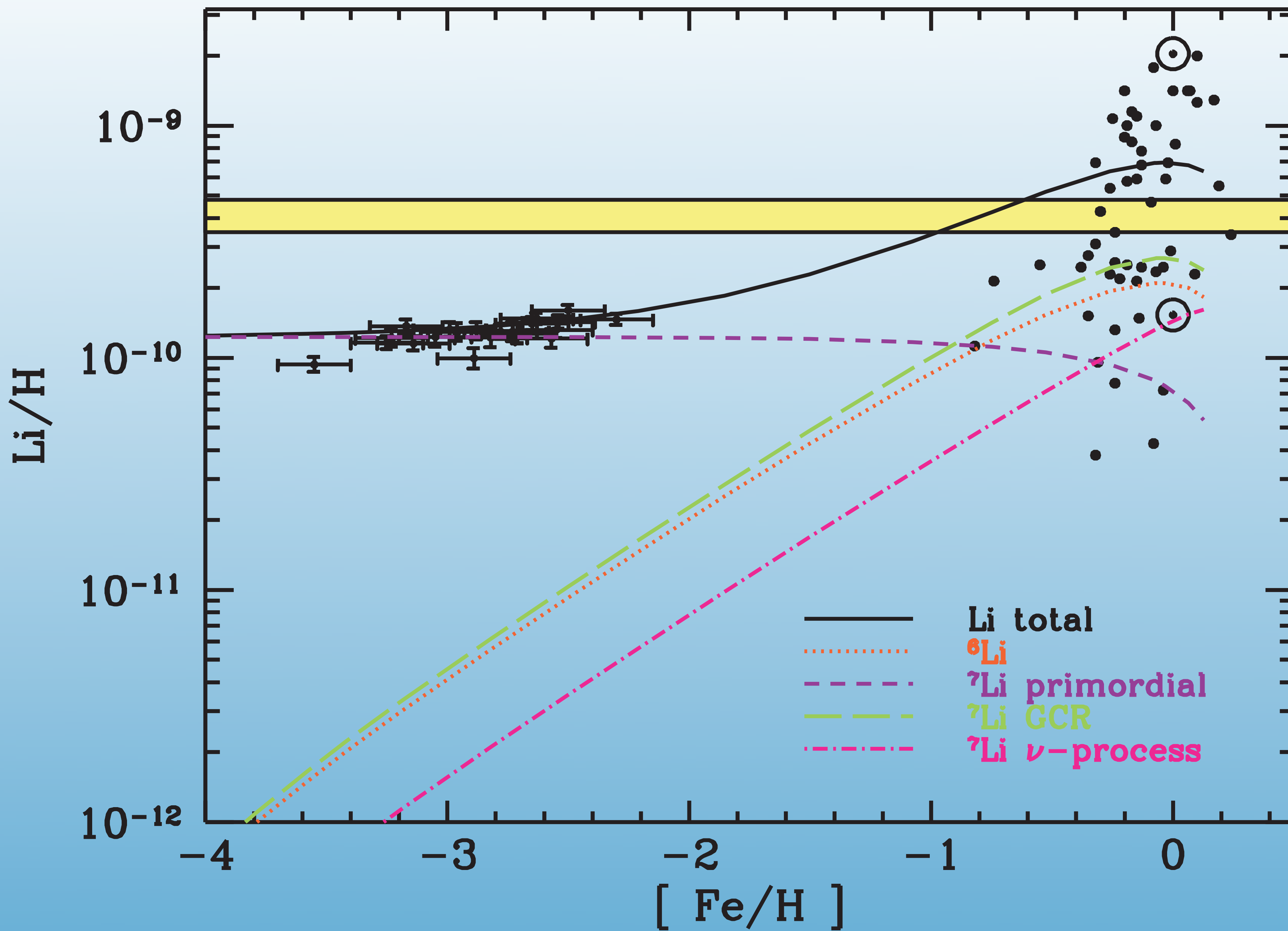
Measured in low metallicity dwarf halo stars
(over 100 observed)





Li Woes

- Observations based on
  - "old": Li/H = 1.2×10^{-10} Spite & Spite +
  - Balmer: Li/H = 1.7×10^{-10} Molaro, Primas & Bonifacio
  - IRFM: Li/H = 1.6×10^{-10} Bonifacio & Molaro
  - IRFM: Li/H = 1.2×10^{-10} Ryan, Beers, KAO, Fields, Norris
  - Hα (globular cluster): Li/H = 2.2×10^{-10} Bonifacio et al.
  - Hα (globular cluster): Li/H = 2.3×10^{-10} Bonifacio
  - λ6104: Li/H ~ 3.2×10^{-10} Ford et al.
- Li depends on T, ln g, [Fe/H], depletion, post BBN-processing, ...
- Strong systematics



10−9
10−10
10−11
10−12
Li/H
−4
−3
−2
−1
0
[Fe/H]
Li total
6Li
7Li primordial
7Li GCR
7Li ν−process

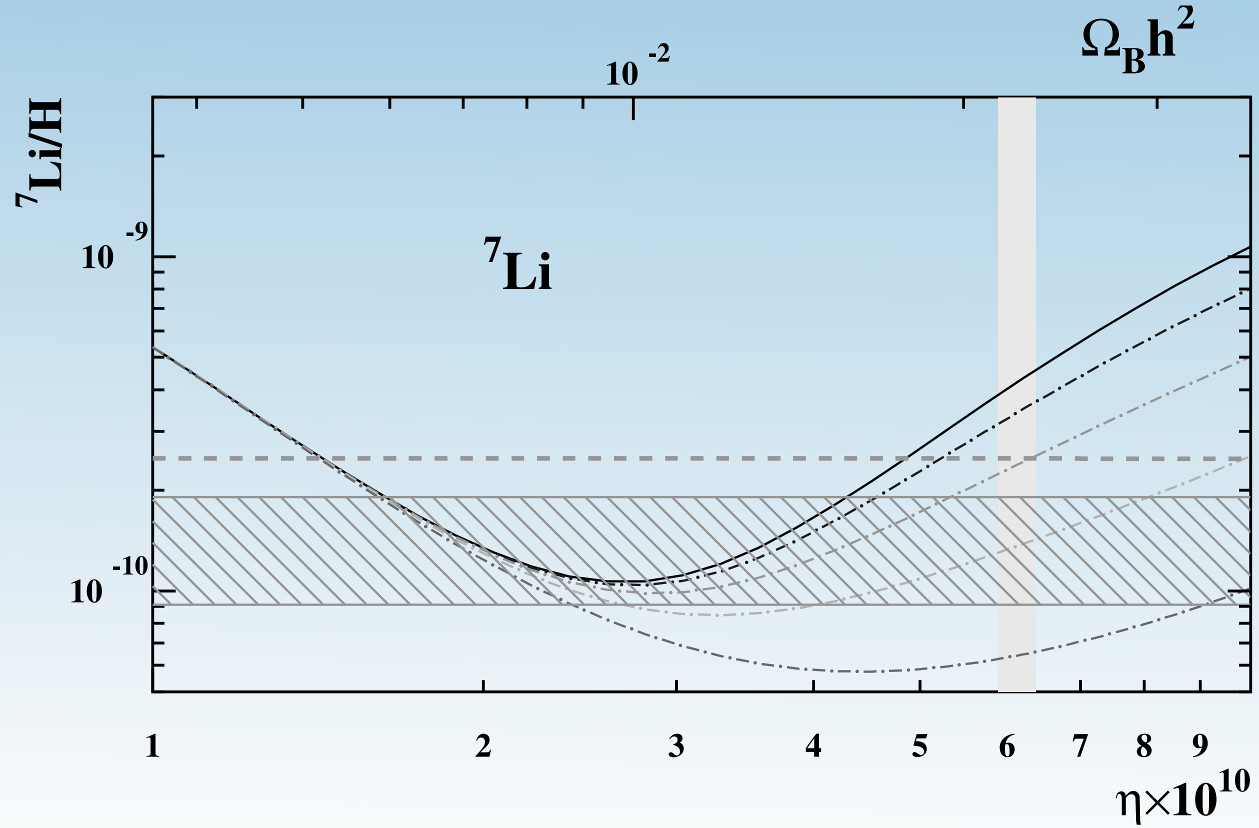
Possible sources for the discrepancy

- Nuclear Rates
  - Restricted by solar neutrino flux

Coc et al.
Cyburt, Fields, KAO

Coc et al. consider large variations of certain rates.

$^3H\ (p,\gamma)\ ^4He$	increase x1000	low η	XX
$^4He\ (\alpha,n)\ ^7Be$	small compared with	destruction	X
$^7Li\ (d,n)\ 2\,^4He$	increase x100	low η	XX
$^7Be\ (d,p)\ 2\,^4He$	increase >x100	high η	✓? X



BBN Li sensitivites

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

Key Rates:

^{3}He (α,γ) ^{7}Be

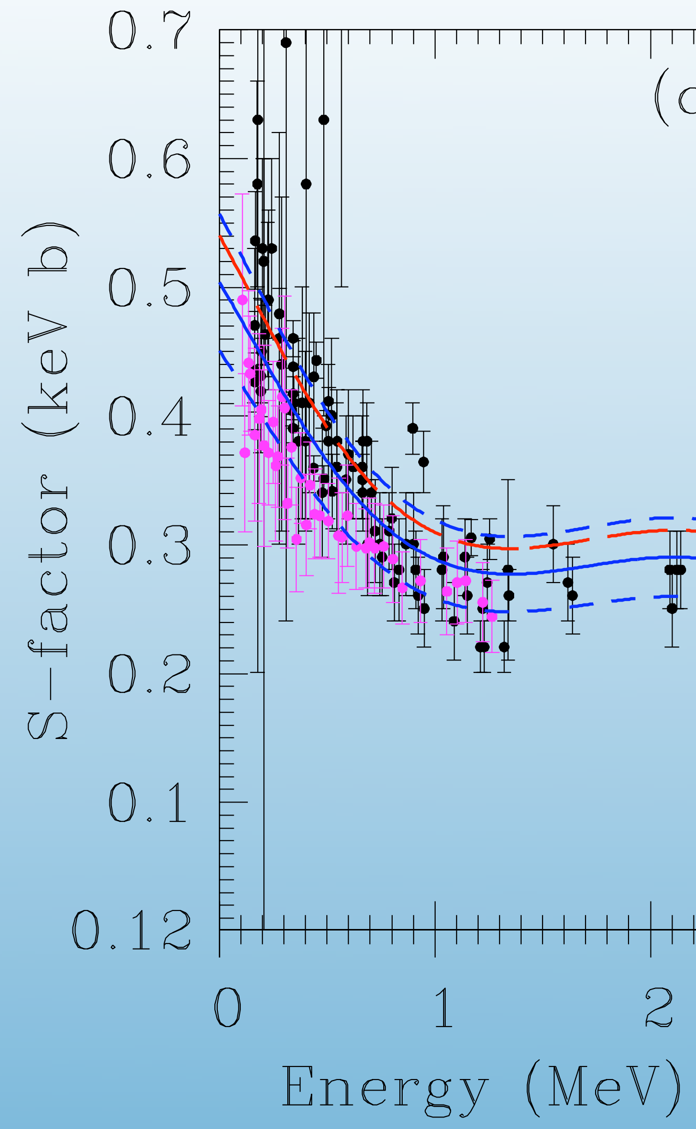
Reaction/Parameter	sensitivities (α_i)
$\eta_{10}/6.14$	+2.04
$n(p,\gamma)d$	+1.31
^{3}He$(\alpha,\gamma)^7$Be	+0.95
^{3}He$(d,p)^4$He	−0.78
$d(d,n)^3$He	+0.72
^{7}Be$(n,p)^7$Li	−0.71
Newton's G_N	−0.66
$d(p,\gamma)^3$He	+0.54
n-decay	+0.49
$N_{\nu,eff}/3.0$	−0.26
^{3}He$(n,p)t$	−0.25
$d(d,p)t$	+0.078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

Require:

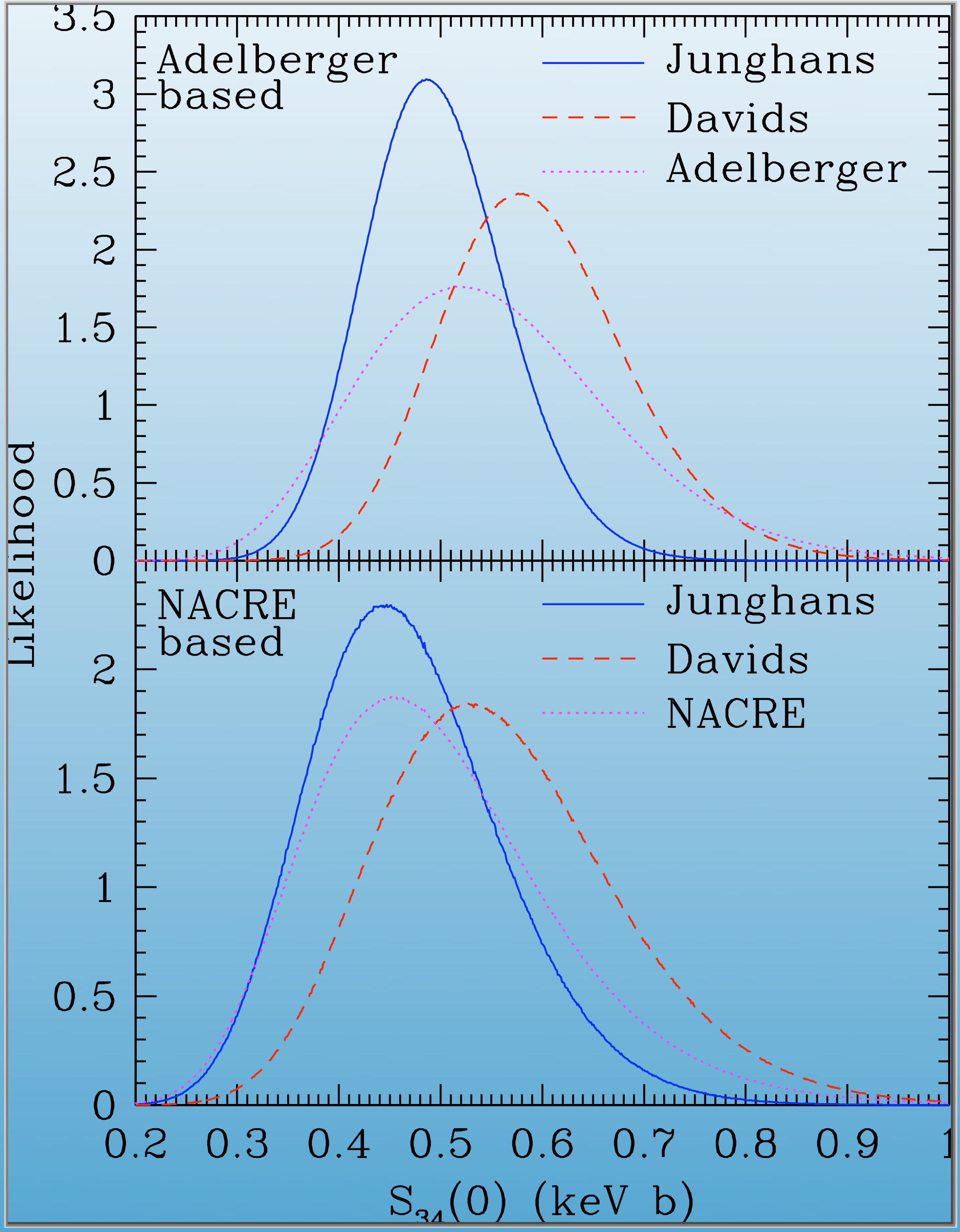
$$\left.\begin{aligned} S_{34}^{NEW}(0) &= 0.267 \text{ keVb} \\ \frac{\Delta S_{34}}{S_{34}} &= -0.47 \end{aligned}\right\} \text{globular cluster Li}$$

or

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



Constraints from solar ν's



$S_{34} > 0.35$ keV barn

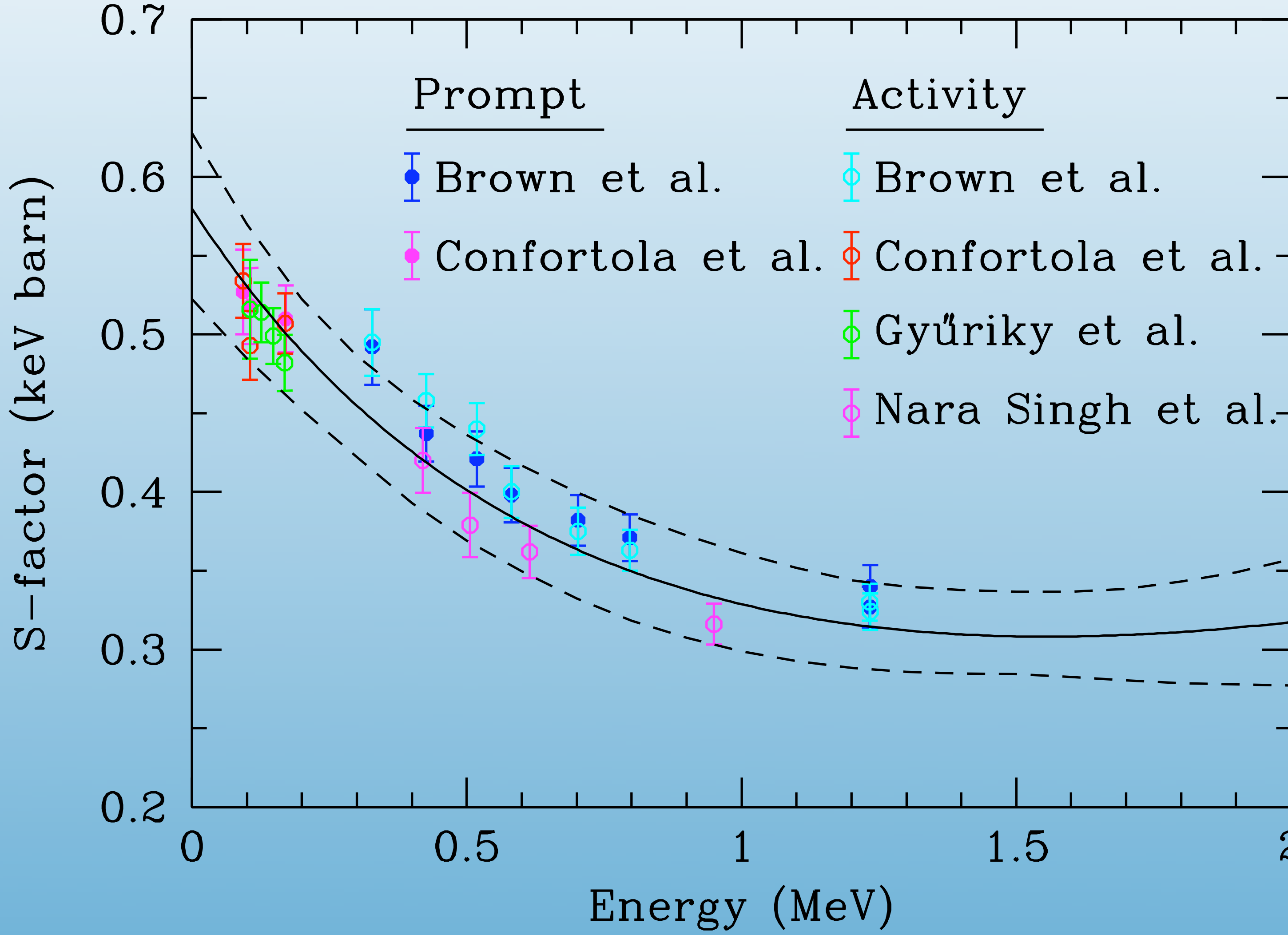
at 95% CL

Needed

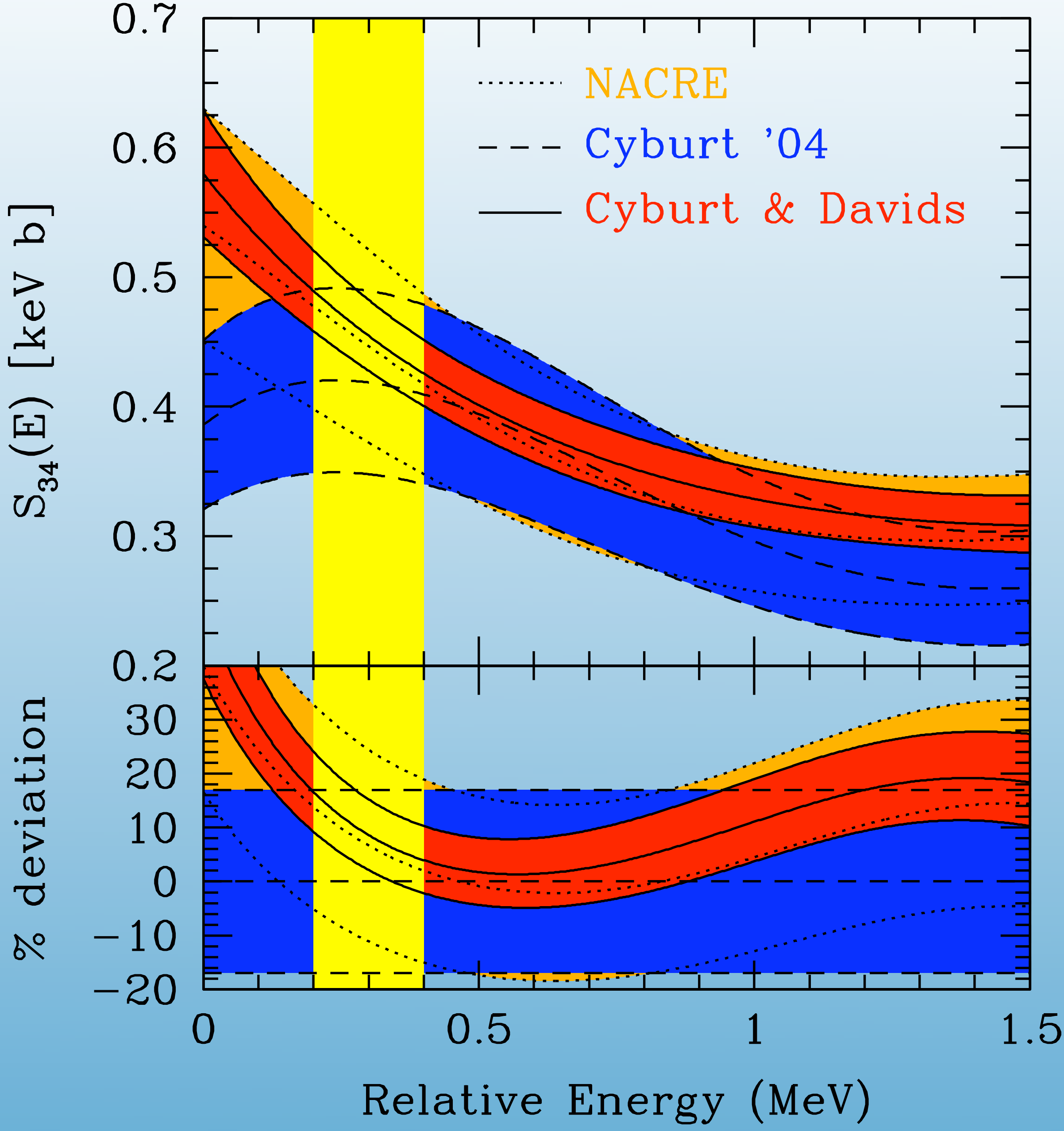
S_{34} < 0.27 or 0.14 keV bn

CFO

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

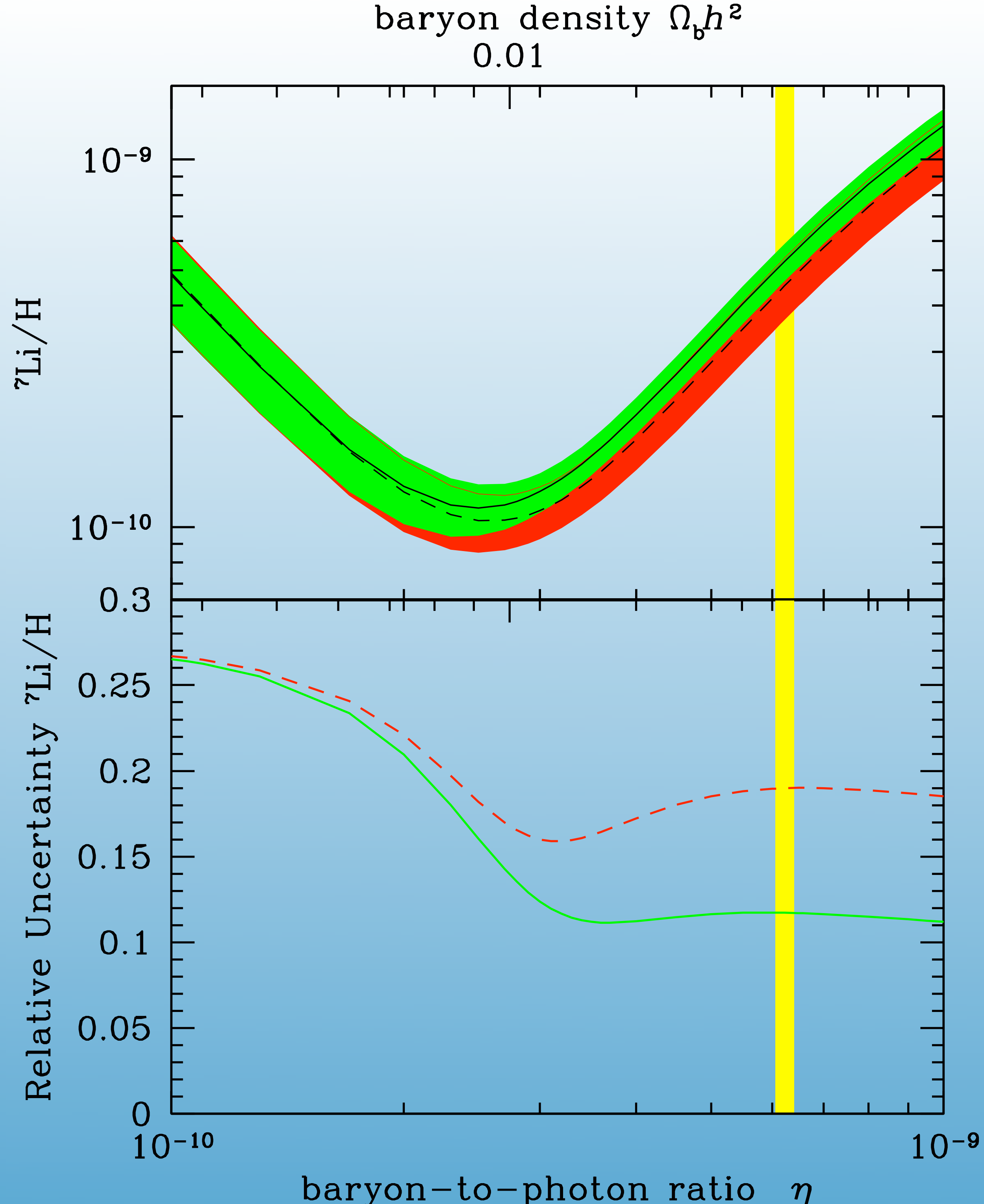


Cyburt and Wands



17% increase in S

⇒ 16% increase in Li



In addition, 1.5% increase in η, leads to 3% increase in Li (Li ~ $\eta^{2.12}$) plus another ~1% from pn

Net change in Li:
4.26×10^{-10} to
5.24×10^{-10} or 23%

Cyburt, Fields, KAO

Possible sources for the discrepancy

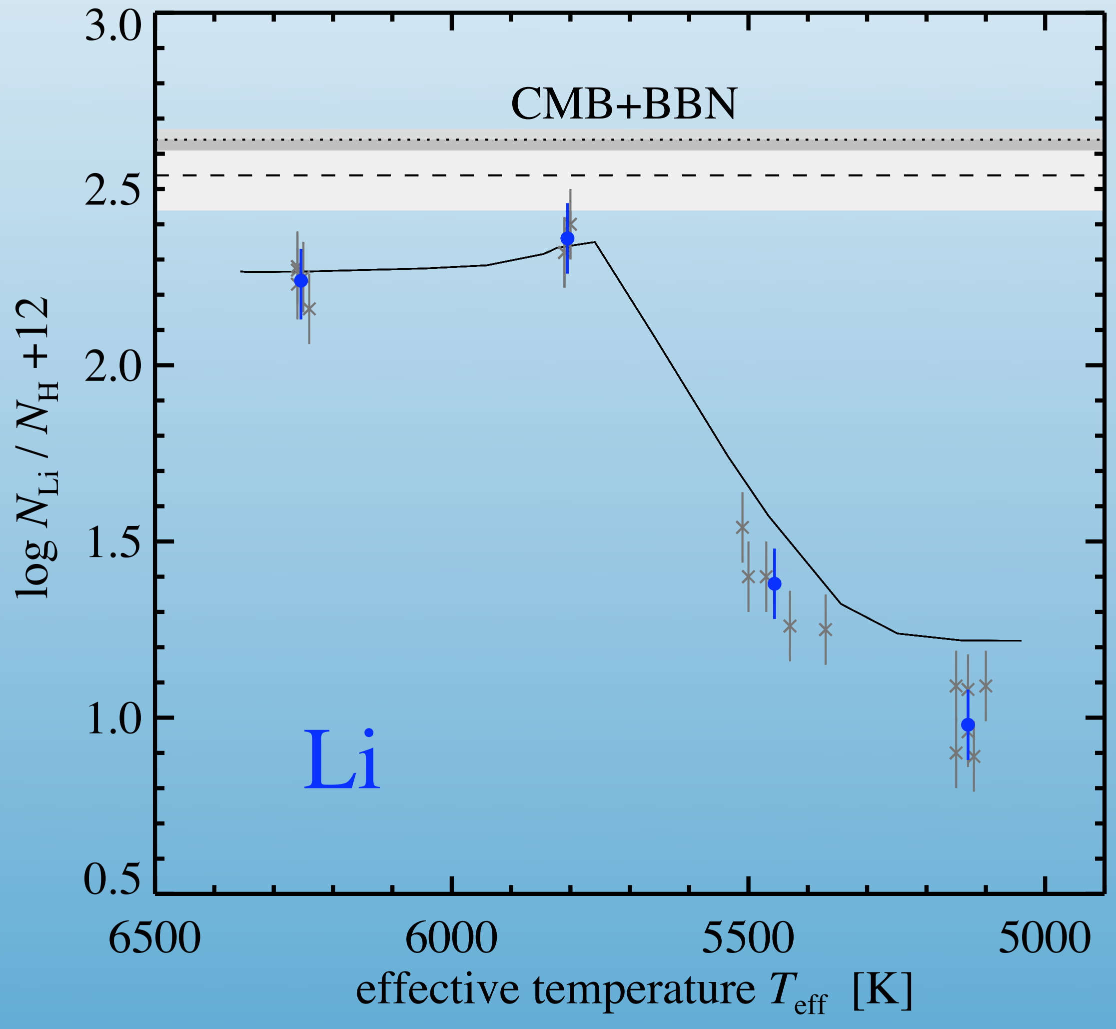
- Nuclear Rates
  - Restricted by solar neutrino flux

Coc et al.
Cyburt, Fields, KAO

- 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

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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)

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

- Stellar parameters

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

Reappraising the Spite Lithium Plateau: Extremely Thin and Marginally Consistent with WMAP

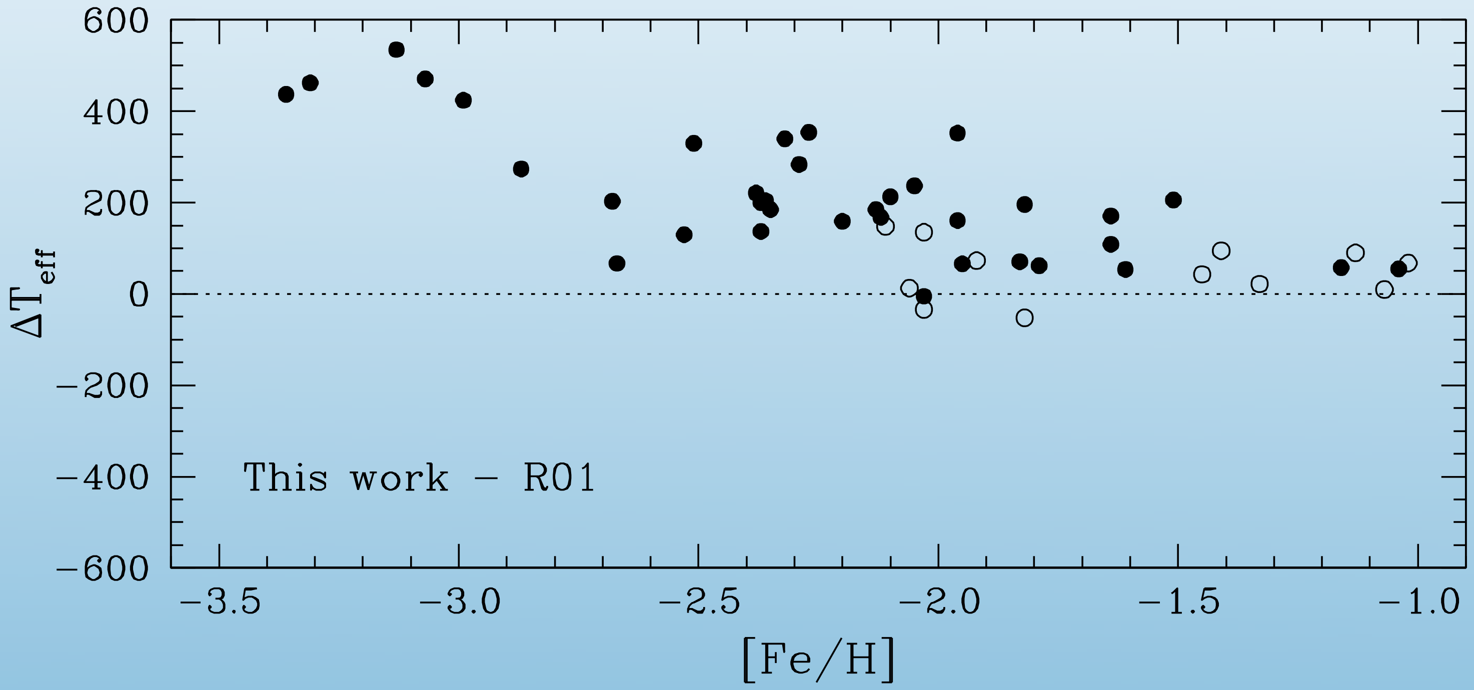
Jorge Meléndez[1] and Iván Ramírez[2]

New evaluation of surface temperatures in 41 halo stars with systematically higher temperatures (100-300 K)

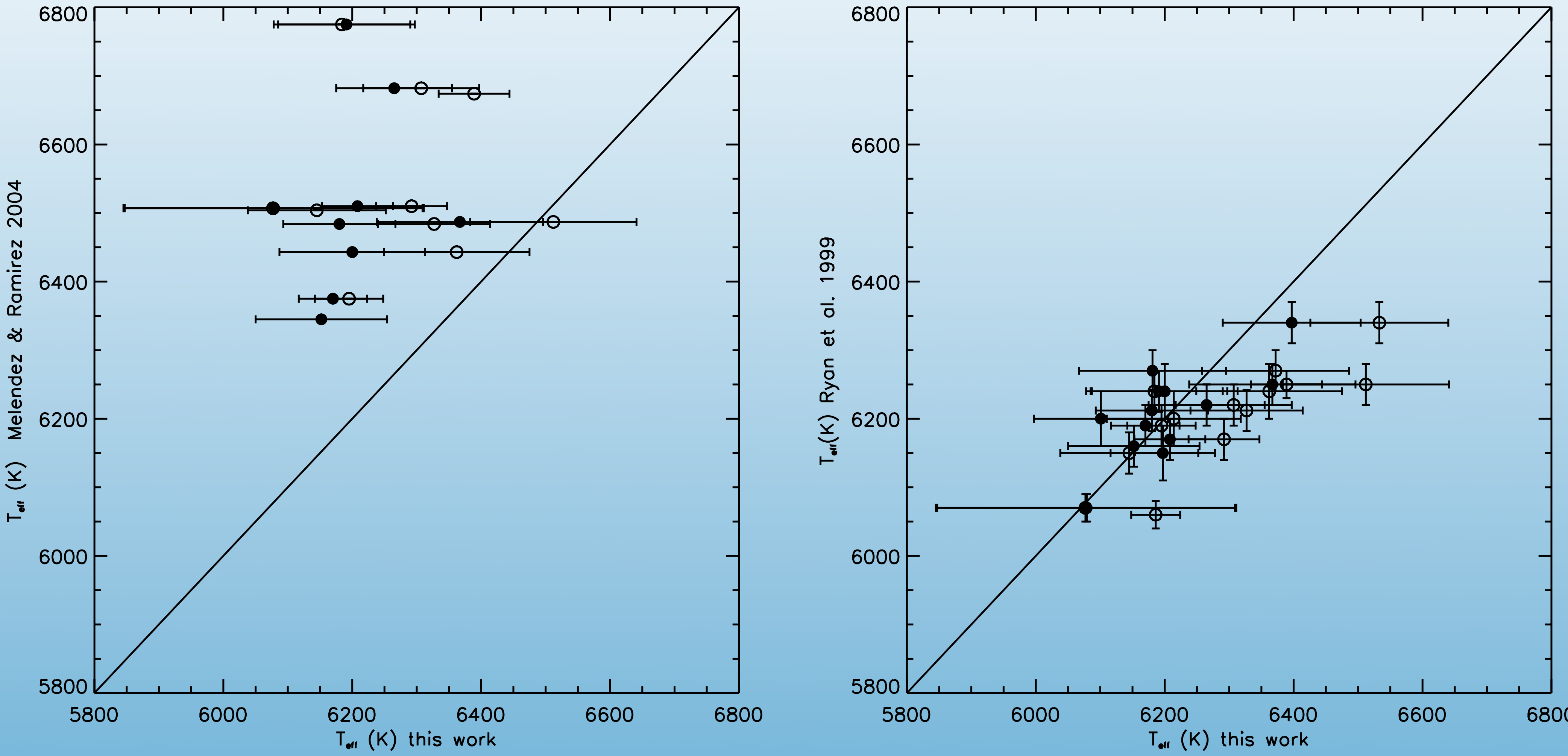
$[Li] = 2.37 \pm 0.1$

$Li/H = 2.34 \pm 0.54 \times 10^{-10}$

BBN Prediction: $10^{10}\, Li/H = 4.26^{+0.73}_{-0.60}$

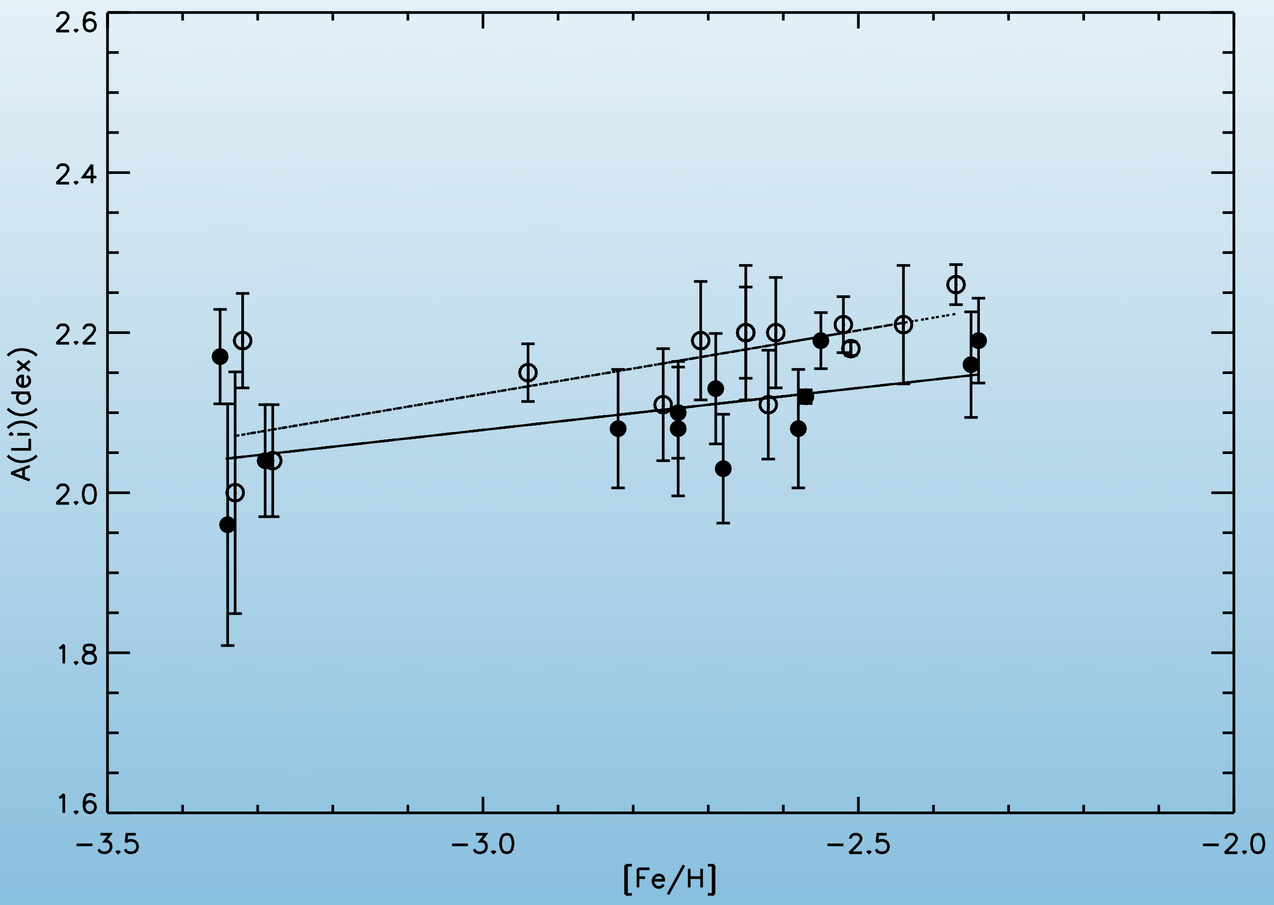

600
400
200
0
−200
−400
−600
ΔT_eff
This work − R01
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
[Fe/H]

Recent dedicated temperature determinations (excitation energy technique)



Hosford, Ryan, Garcia-Perez, Norris, Olive

Resulting Li:



[Li] = 2.16 ± 0.07 MS

= 2.10 ± 0.07 SGB

Hosford, Ryan, Garcia-Perez, Norris, Olive

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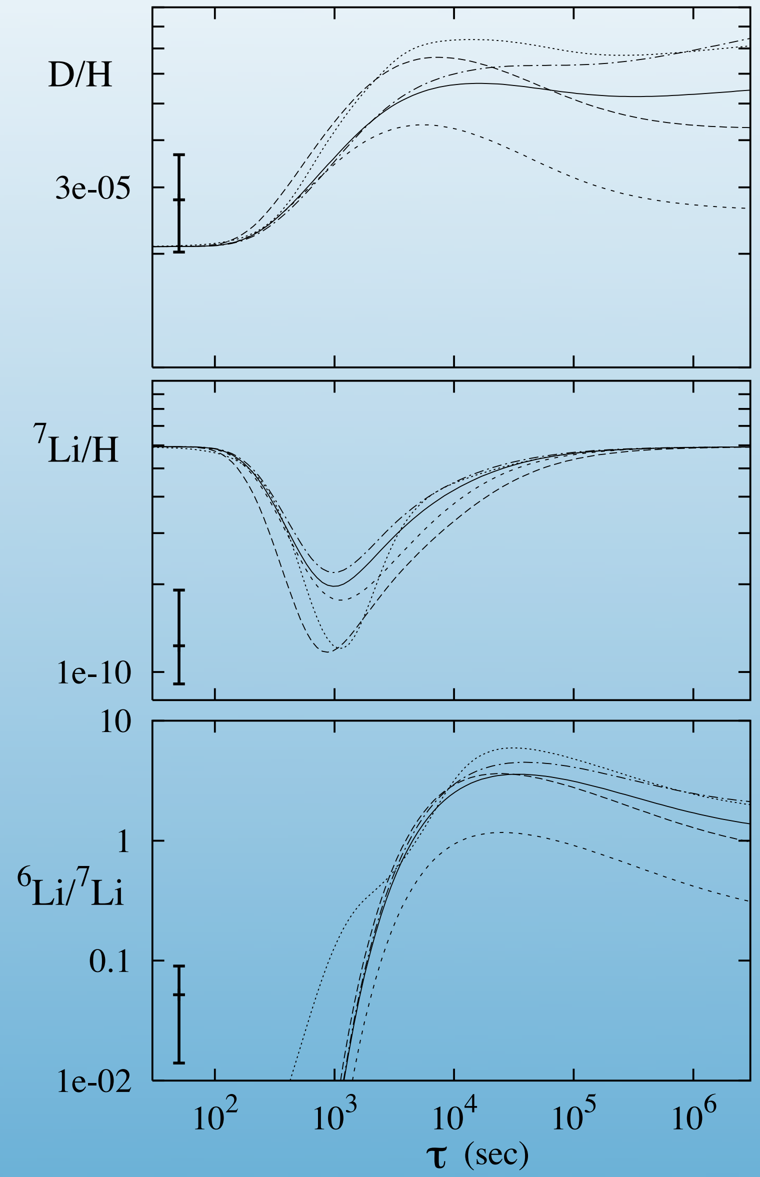
Coc et al.
Cyburt, Fields, KAO

- Stellar parameters

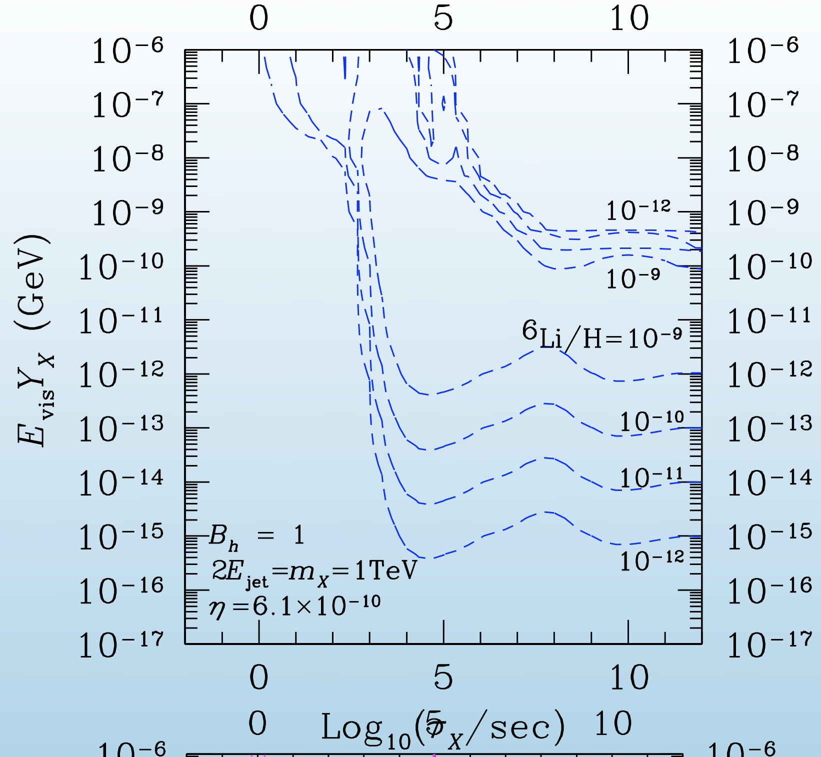
$$\frac{dLi}{dlng} = \frac{.09}{.5} \qquad \frac{dLi}{dT} = \frac{.08}{100K}$$

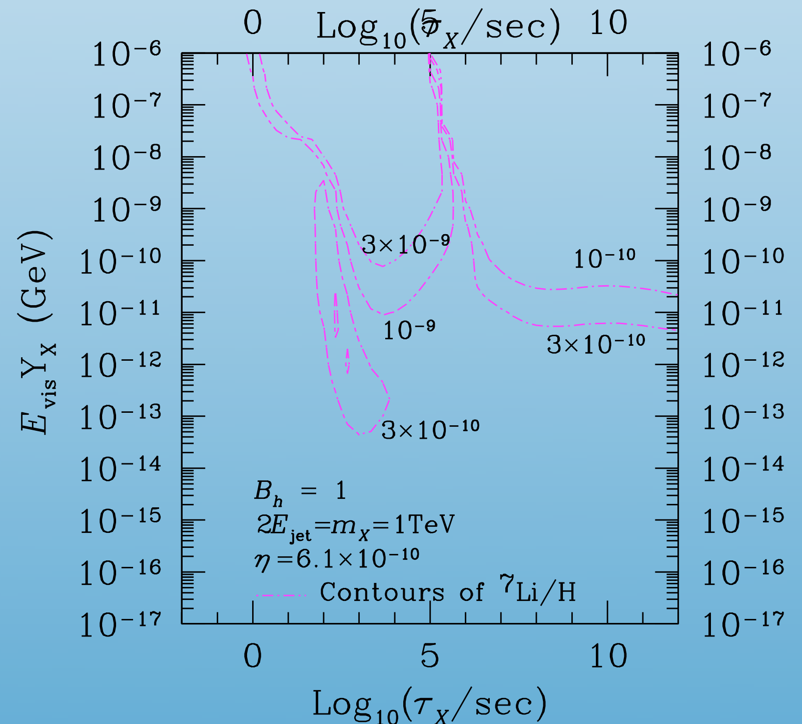
- Particle Decays

Solution 1: Particle Decays



Jedamzik

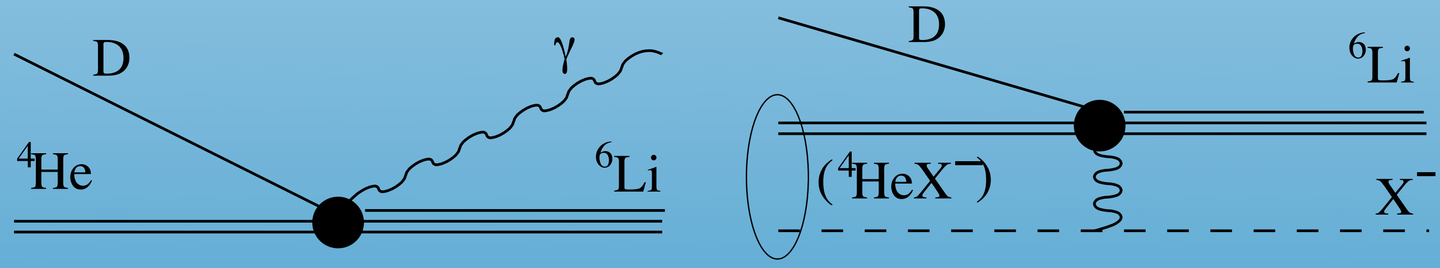




Kawasaki, Kohri, Moroi

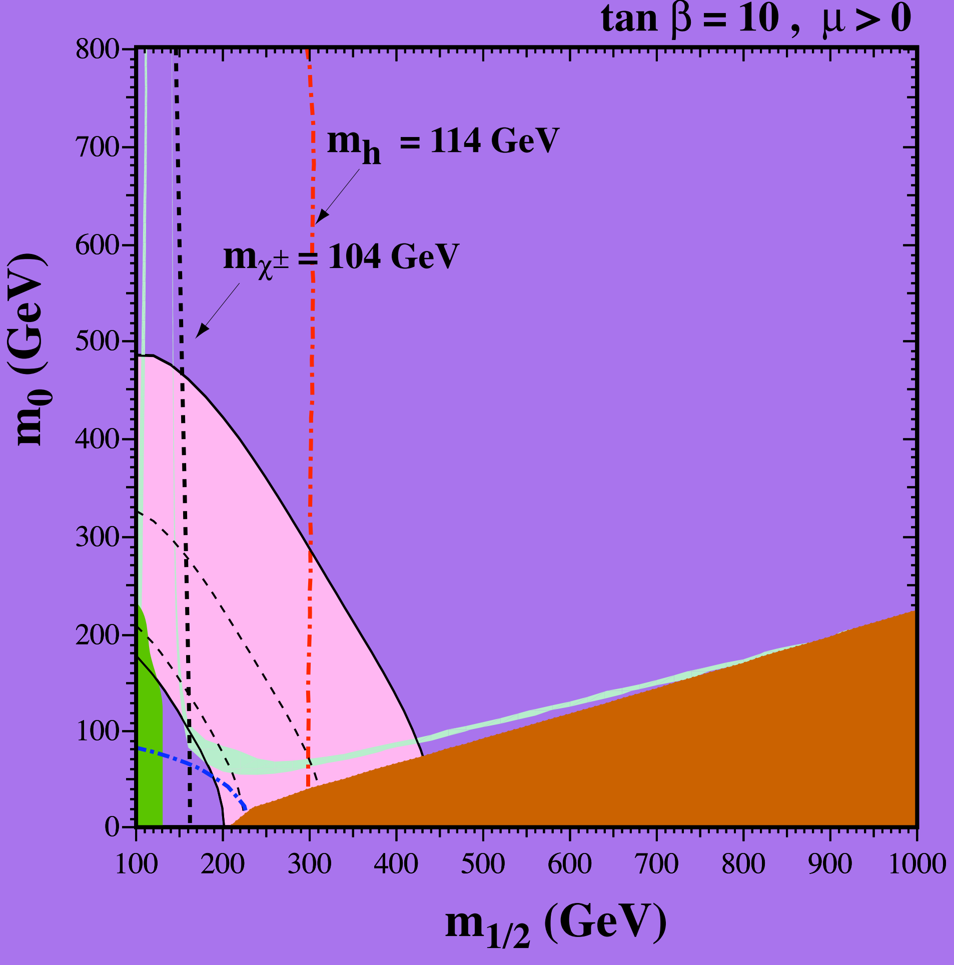
Effects of Bound States

- In SUSY models with a $\tilde{\tau}$ NLSP, bound states form between ^{4}He and $\tilde{\tau}$
- The ^{4}He (D, γ) ^{6}Li reaction is normally highly suppressed (production of low energy γ)
- Bound state reaction is not suppressed

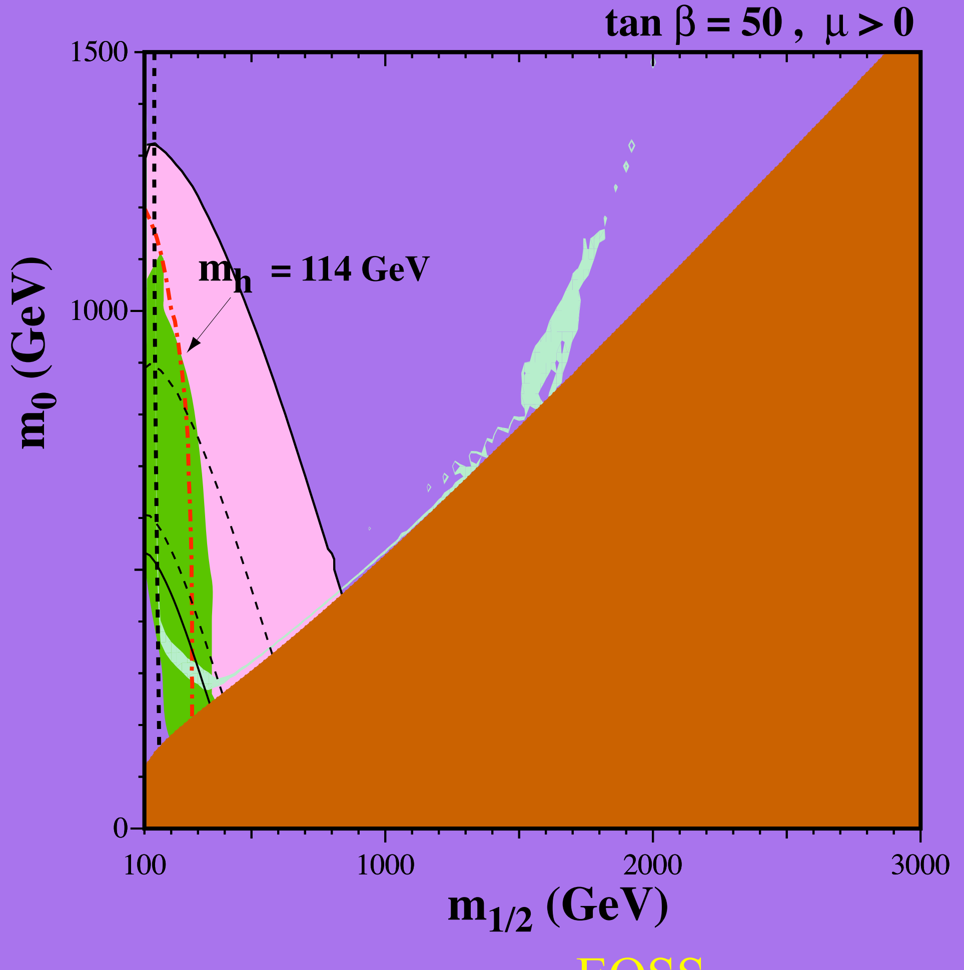


Pospelov

CMSSM

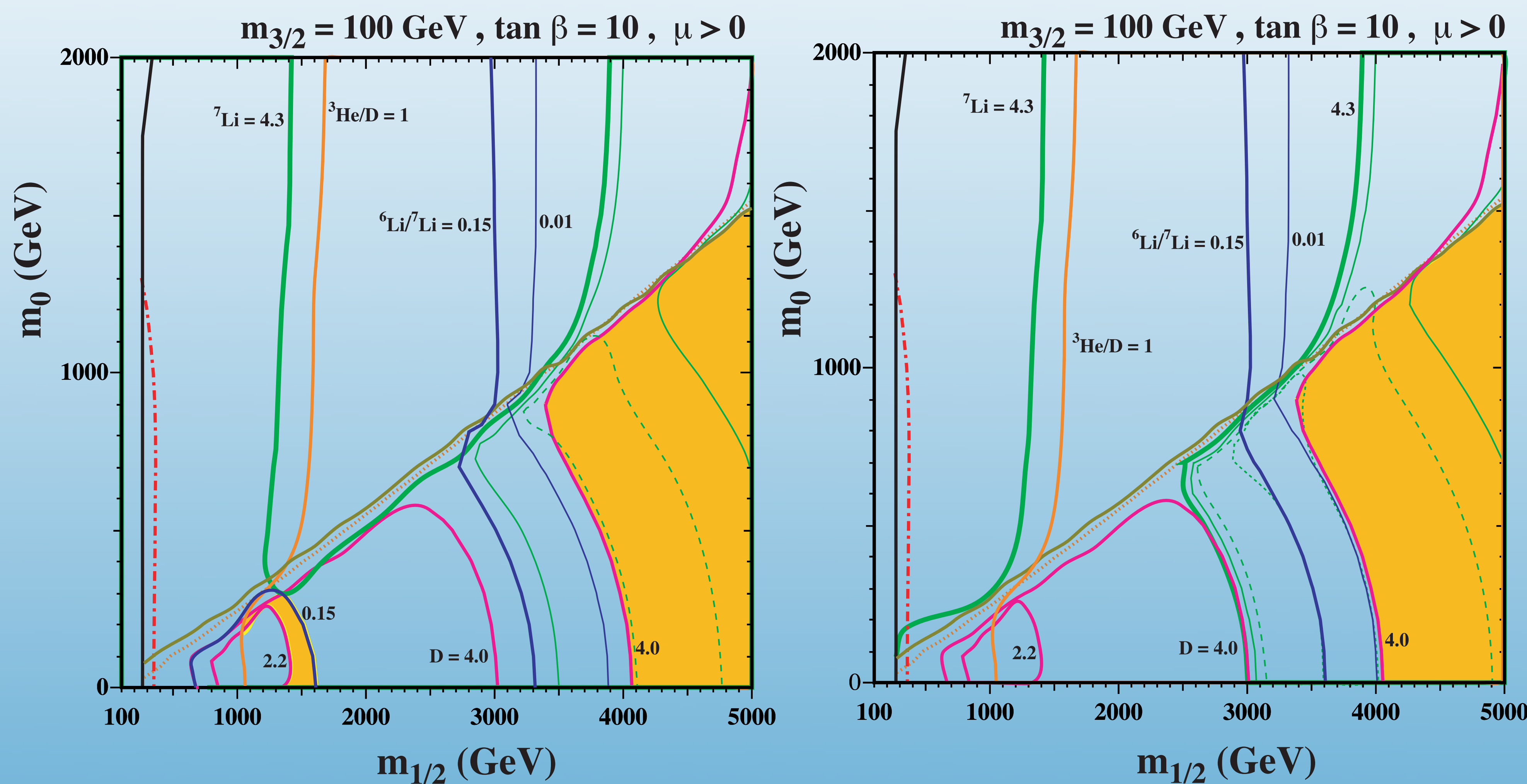


tan β = 10 , μ > 0
m_h = 114 GeV
m_χ± = 104 GeV
m_0 (GeV)
m_1/2 (GeV)
0
100
200
300
400
500
600
700
800
900
1000

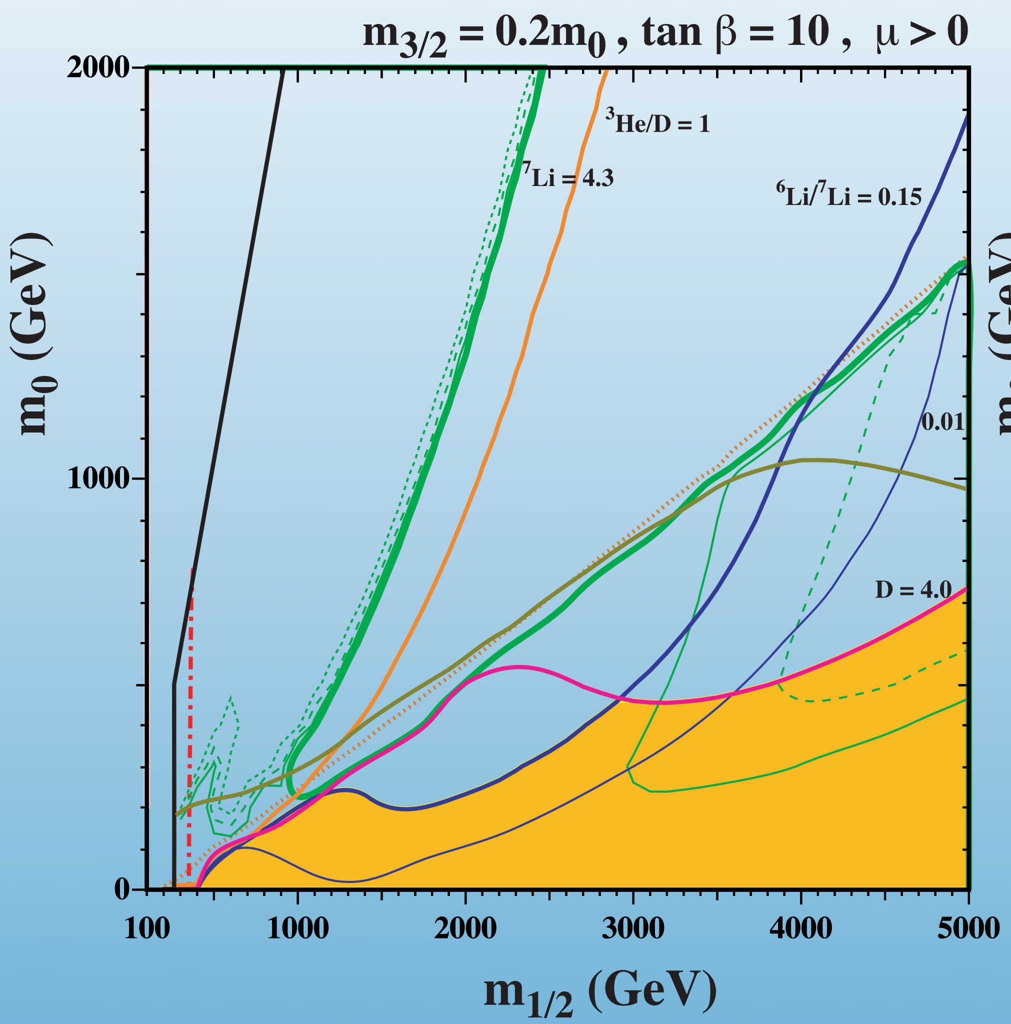


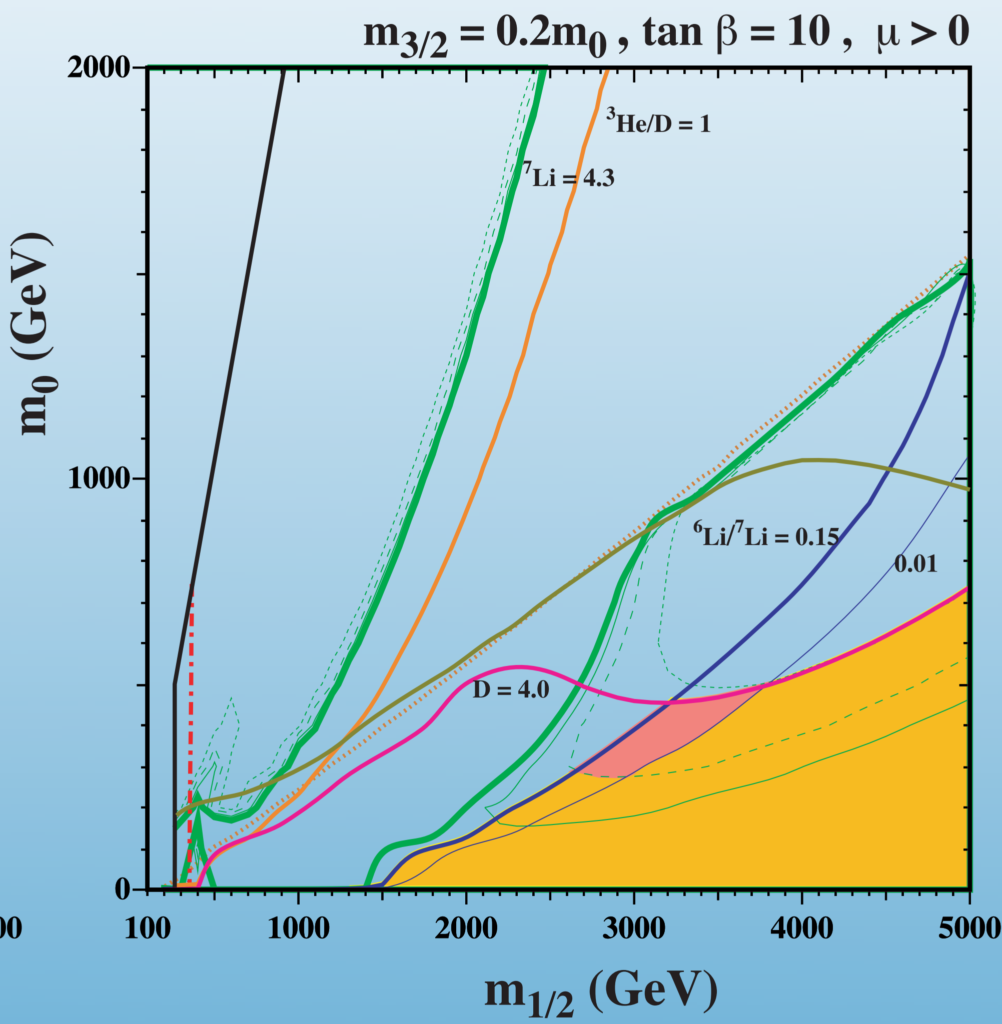
tan β = 50 , μ > 0
m_h = 114 GeV
m_0 (GeV)
m_1/2 (GeV)
0
1000
1500
100
2000
3000

EOSS



Cyburt, Ellis, Fields, KO, Spanos





Cyburt, Ellis, Fields, KO, Spanos

Possible sources for the discrepancy

- Stellar parameters

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

- Particle Decays

- Variable Constants

How could varying α affect BBN?

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

Recall in equilibrium,

$$\frac{n}{p} \sim e^{-\Delta m/T}$$

fixed at freezeout

Helium abundance,

$$Y \sim \frac{2(n/p)}{1+(n/p)}$$

If T_f is higher, (n/p) is higher, and Y is higher

Limits on α from BBN

Contributions to Y come from n/p which in turn come from Δm_N

Contributions to Δm_N:

Kolb, Perry, & Walker
Campbell & Olive
Bergstrom, Iguri, & Rubinstein

$$\Delta m_N \sim a\alpha_{em}\Lambda_{QCD} + bv$$

Changes in α, Λ_{QCD}, and/or v all induce changes in Δm_N and hence Y

$$\frac{\Delta Y}{Y} \simeq \frac{\Delta^2 m_N}{\Delta m_N} \sim \frac{\Delta\alpha}{\alpha} < 0.05$$

If $\Delta\alpha$ arises in a more complete theory the effect may be greatly enhanced:

$$\frac{\Delta Y}{Y} \simeq O(100)\frac{\Delta\alpha}{\alpha} \textbf{ and } \frac{\Delta\alpha}{\alpha} < \textbf{few } \times 10^{-4}$$

Approach:

Consider possible variation of Yukawa, h,
or fine-structure constant, α

Include dependence of Λ on α; of v on h, etc.

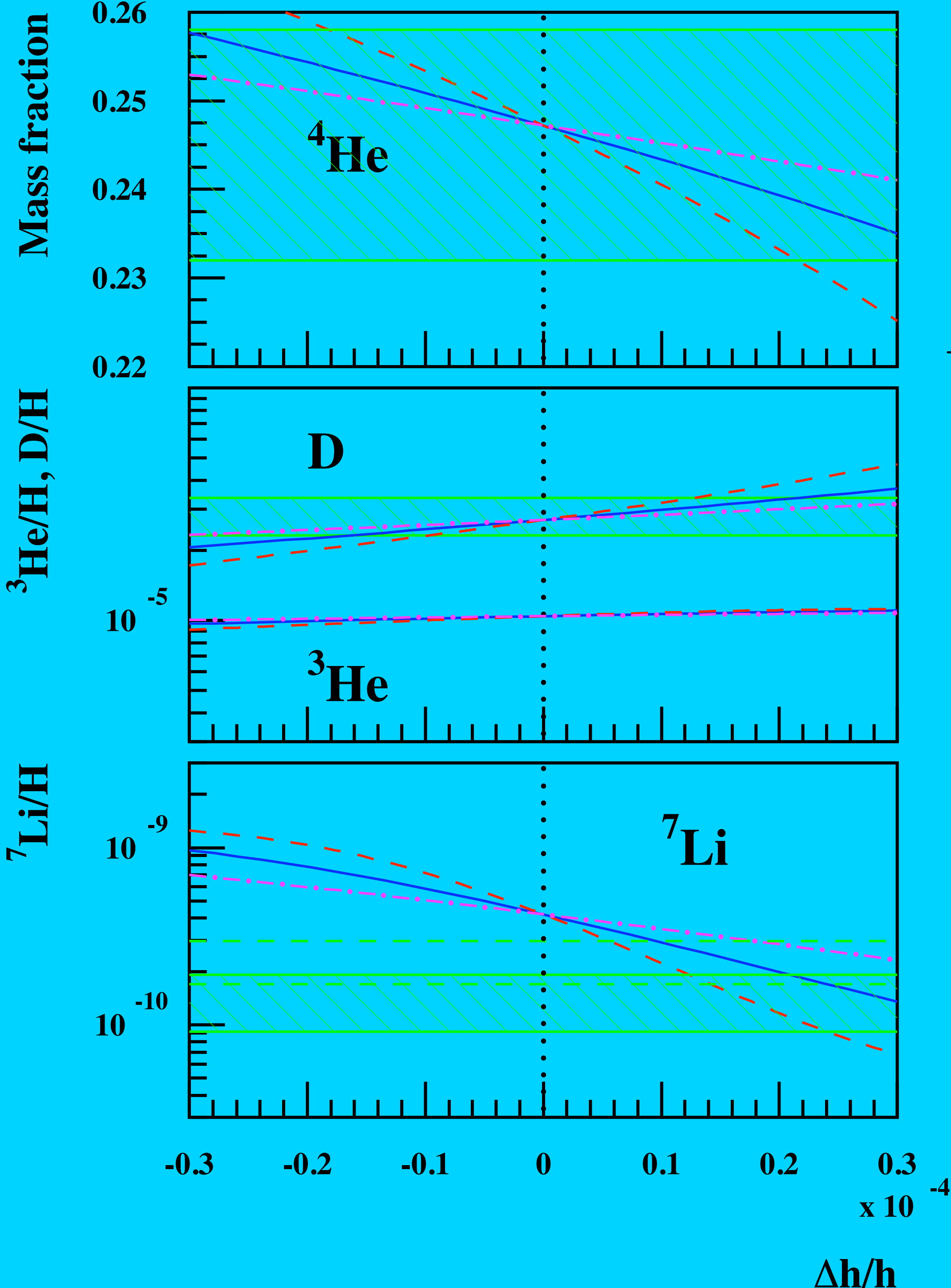
Consider effects on: $Q = \Delta m_N$, τ_N, B_D

and with $\frac{\Delta h}{h} = \frac{1}{2}\frac{\Delta\alpha_U}{\alpha_U}$

$$
\begin{aligned}
\frac{\Delta B_D}{B_D} &= -[6.5(1+S) - 18R]\frac{\Delta\alpha}{\alpha} \\
\frac{\Delta Q}{Q} &= (0.1 + 0.7S - 0.6R)\frac{\Delta\alpha}{\alpha} \\
\frac{\Delta\tau_n}{\tau_n} &= -[0.2 + 2S - 3.8R]\frac{\Delta\alpha}{\alpha}\,,
\end{aligned}
$$

Coc, Nunes, Olive, Uzan, Vangioni
Dmitriev & Flambaum

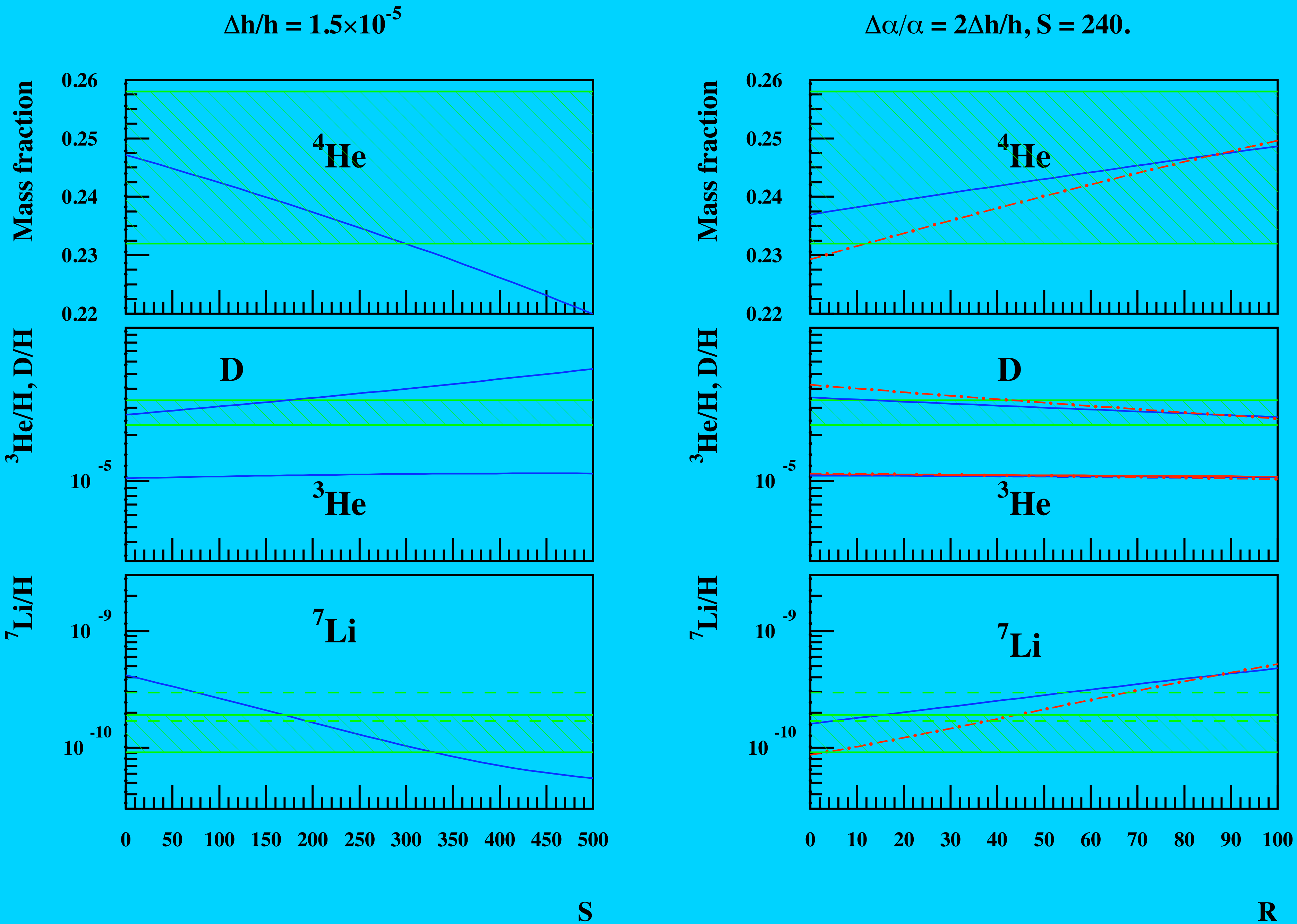
S = 240, R = 0, 36, 60, Δα/α=2Δh/h



For S = 240, R = 36,

$$-1.6 \times 10^{-5} < \frac{\Delta h}{h} < 2.1 \times 10^{-5}$$

Finally,



Δh/h = 1.5×10^-5
Δα/α = 2Δh/h, S = 240.
Mass fraction
0.26
0.25
0.24
0.23
0.22
4He
D
3He/H, D/H
10^-5
3He
7Li/H
10^-9
10^-10
7Li
0
50
100
150
200
250
300
350
400
450
500
S
10
20
30
40
50
60
70
80
90
100
R

Summary

- D, He are ok -- issues to be resolved

- Li: 2 Problems
  - BBN ^{7}Li high compared to observations
  - BBN ^{6}Li low compared to observations
    ^{6}Li plateau?
- Important to consider:
  - Depletion
  - Li Systematics - T scale
  - Particle Decays?
  - Variable Constants?
  - PreGalactic production of ^{6}Li (and BeB)