The production of the light elements from D to B

- BBN and the early Universe
- WMAP determination of η, $\Omega_B h^2$
- Observations and Comparison with Theory
  - D/H
  - ^4He
  - ^7Li
- Cosmic-ray nucleosynthesis
  - $^{6,7}Li$
  - BeB

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, $(n/p) \simeq 1/6 \to 1/7$

Nucleosynthesis Delayed (Deuterium Bottleneck)

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

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

Nucleosynthesis begins when $\Gamma_p \sim \Gamma_d$

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

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

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

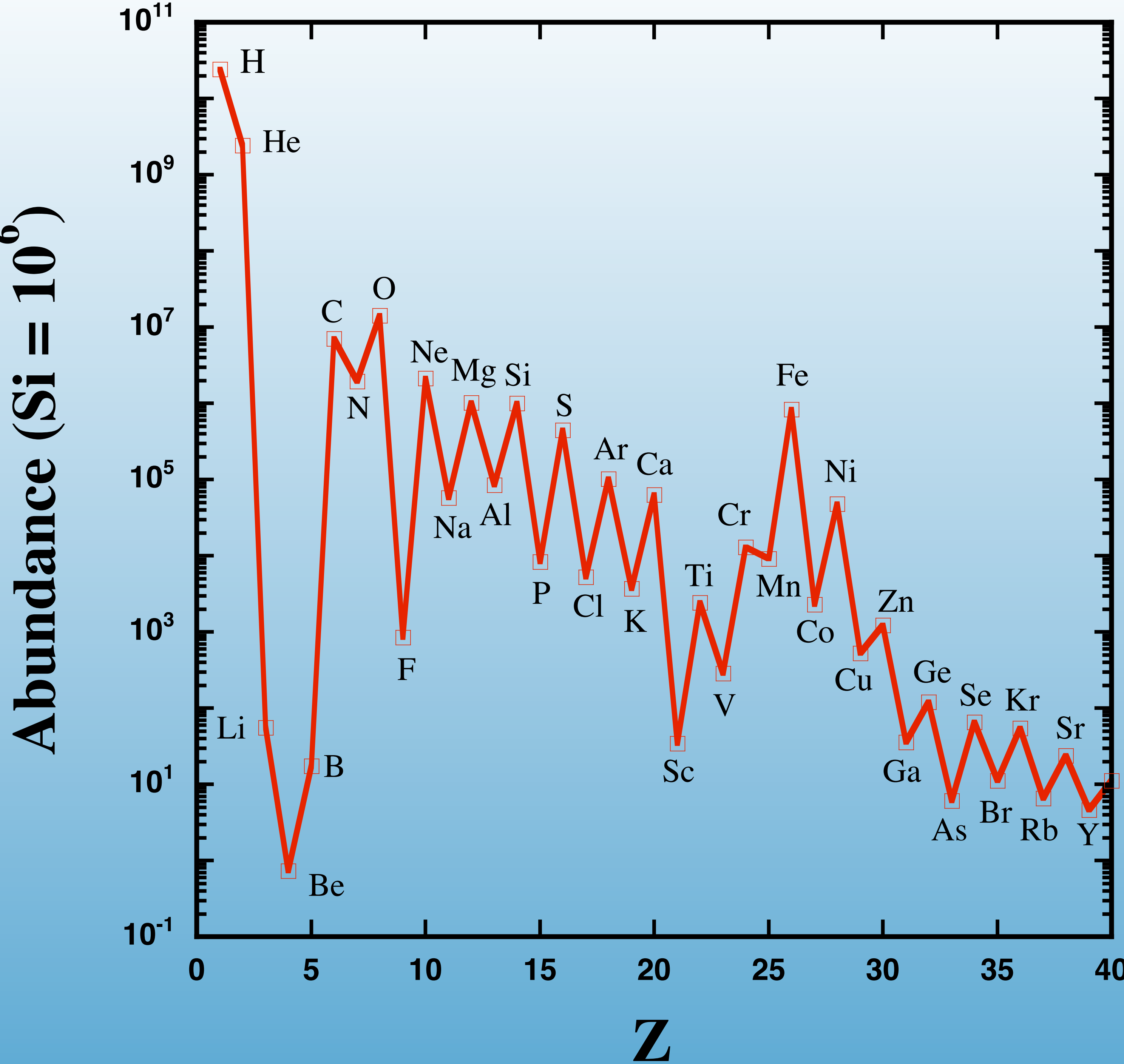
Remainder:

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

Decline:

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

⇒ growth of stellar nucleosynthesis



Abundance (Si = 10^6)
10^{11}
10^9
10^7
10^5
10^3
10^1
10^{-1}
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
0
5
10
15
20
25
30
35
40
Z

Decline:

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

$\Rightarrow$ 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.

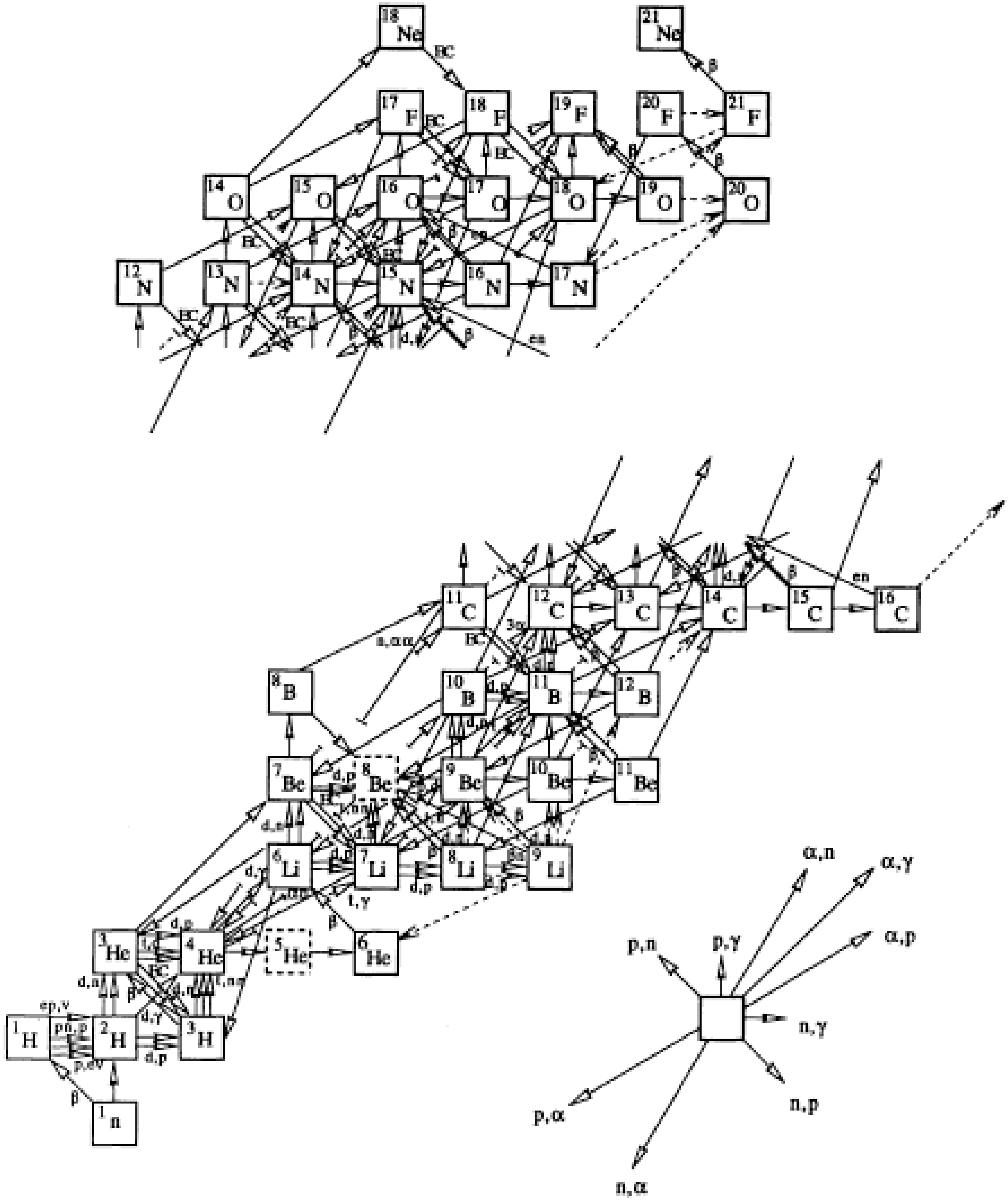
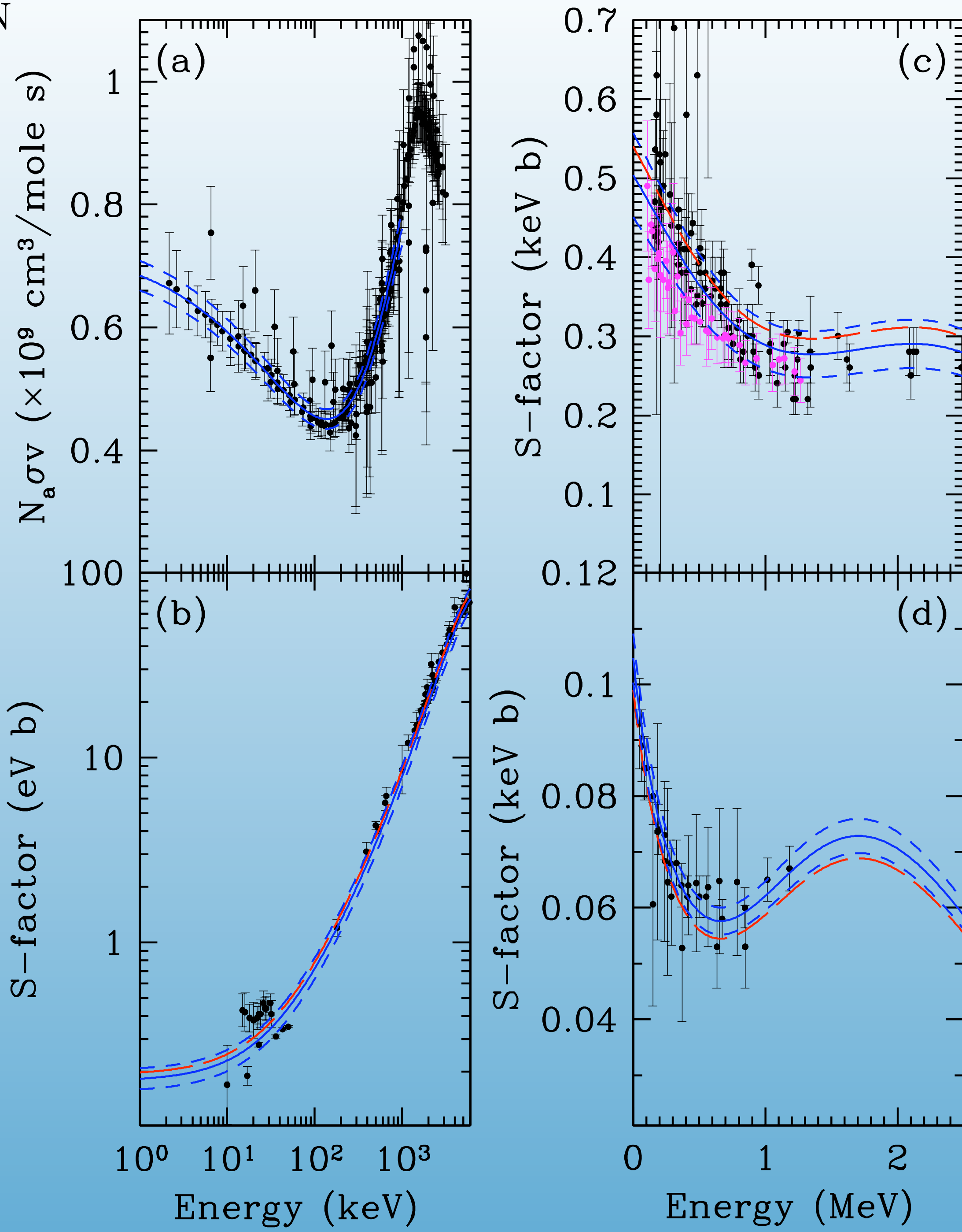


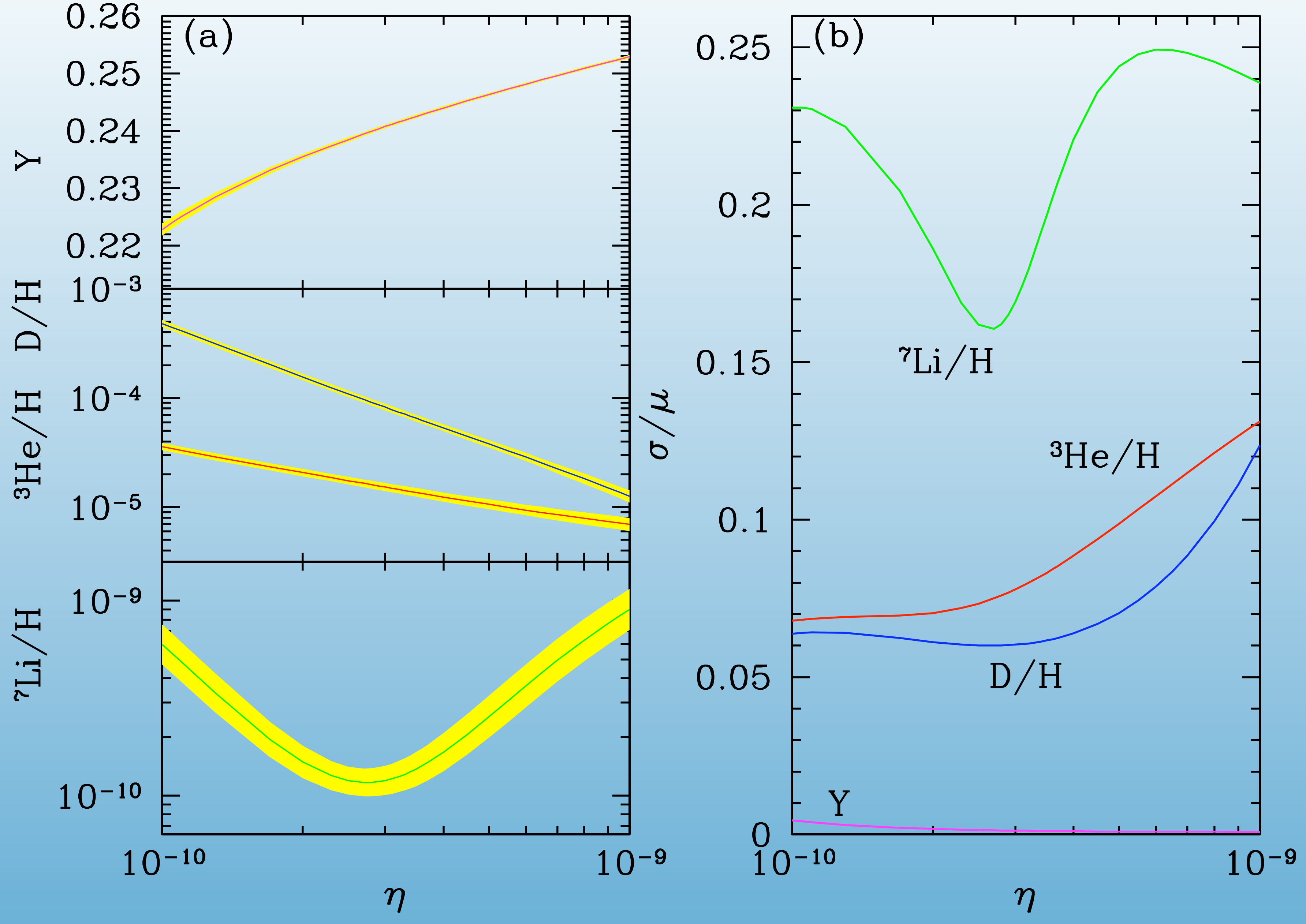
FIG. 1.—Reaction network used in the code. Estimated reactions are shown with dashed lines.

Table 1: Key Nuclear Reactions for BBN

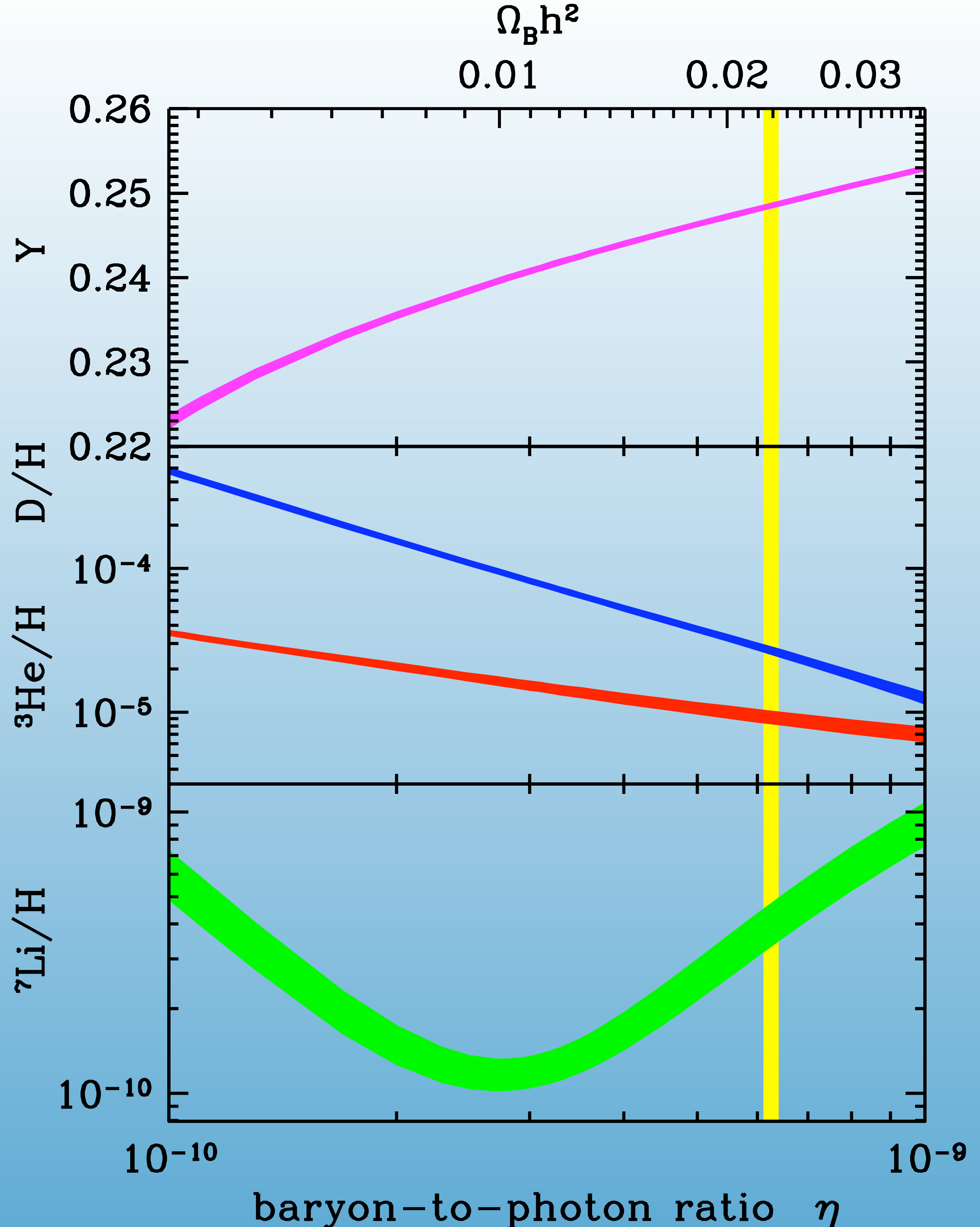
Source	Reactions	
NACRE	$d(p,\gamma)^3\mathrm{He}$	(b)
	$d(d,n)^3\mathrm{He}$	
	$d(d,p)t$	
	$t(d,n)^4\mathrm{He}$	
	$t(\alpha,\gamma)^7\mathrm{Li}$	(d)
	$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$	(c)
	$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$	
SKM	$p(n,\gamma)d$	
	$^3\mathrm{He}(d,p)^4\mathrm{He}$	
	$^7\mathrm{Be}(n,p)^7\mathrm{Li}$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

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





(a)
Y
0.26
0.25
0.24
0.23
0.22
D/H
^{3}He/H
10^{-3}
10^{-4}
10^{-5}
^{7}Li/H
10^{-9}
10^{-10}
10^{-10}
10^{-9}
η
(b)
σ/μ
0.25
0.2
0.15
0.1
0.05
0
^{7}Li/H
^{3}He/H
D/H
Y
10^{-10}
10^{-9}
η



$\Omega_B h^2$
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

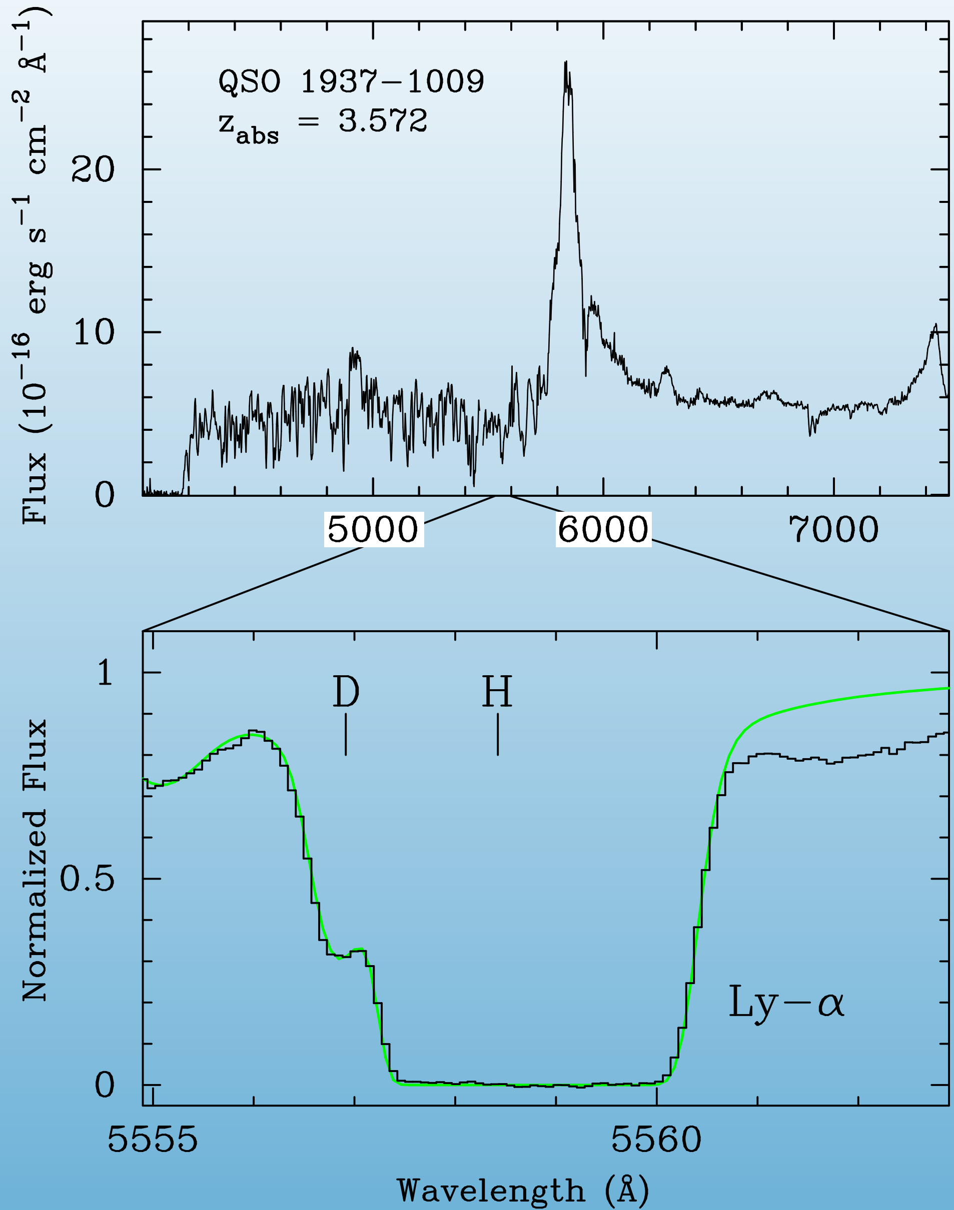
Big Bang Nucleosynthesis

- Production of the Light Elements: D, ^3He, ^4He, ^7Li
  - ^4He observed in extragalctic HII regions:
    abundance by mass = 25%
  - ^7Li 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}
  - ^3He 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

QSO	z_{em}	z_{abs}	$\log N(\mathrm{H\,I})$ (cm^{-2})	$[\mathrm{O/H}]^{b}$	$\log(\mathrm{D/H})$
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



Tytler, O'Meara, Suzuki, Lubin

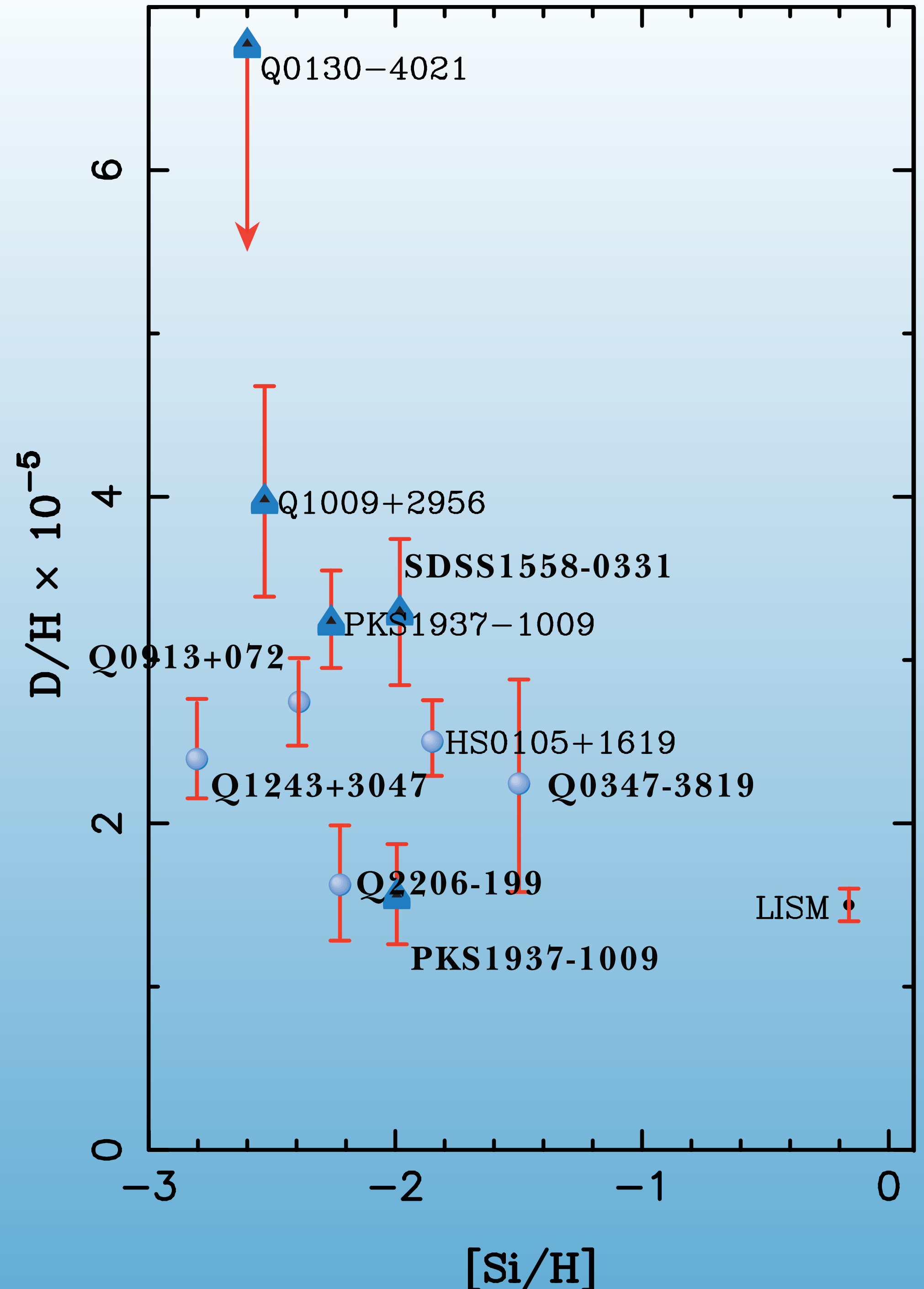
D/H abundances in Quasar apsorption systems

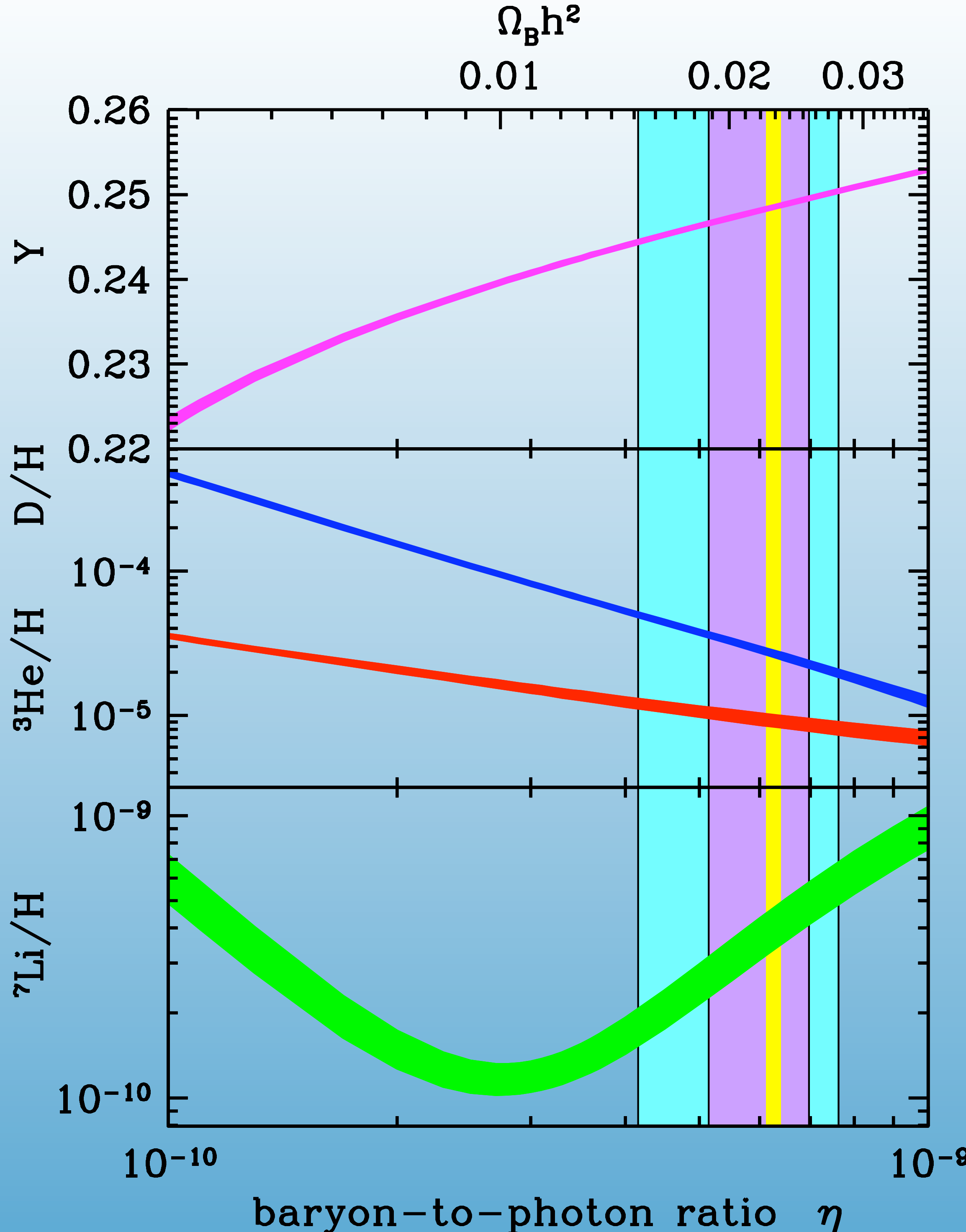
BBN Prediction:

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

Obs Average:

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



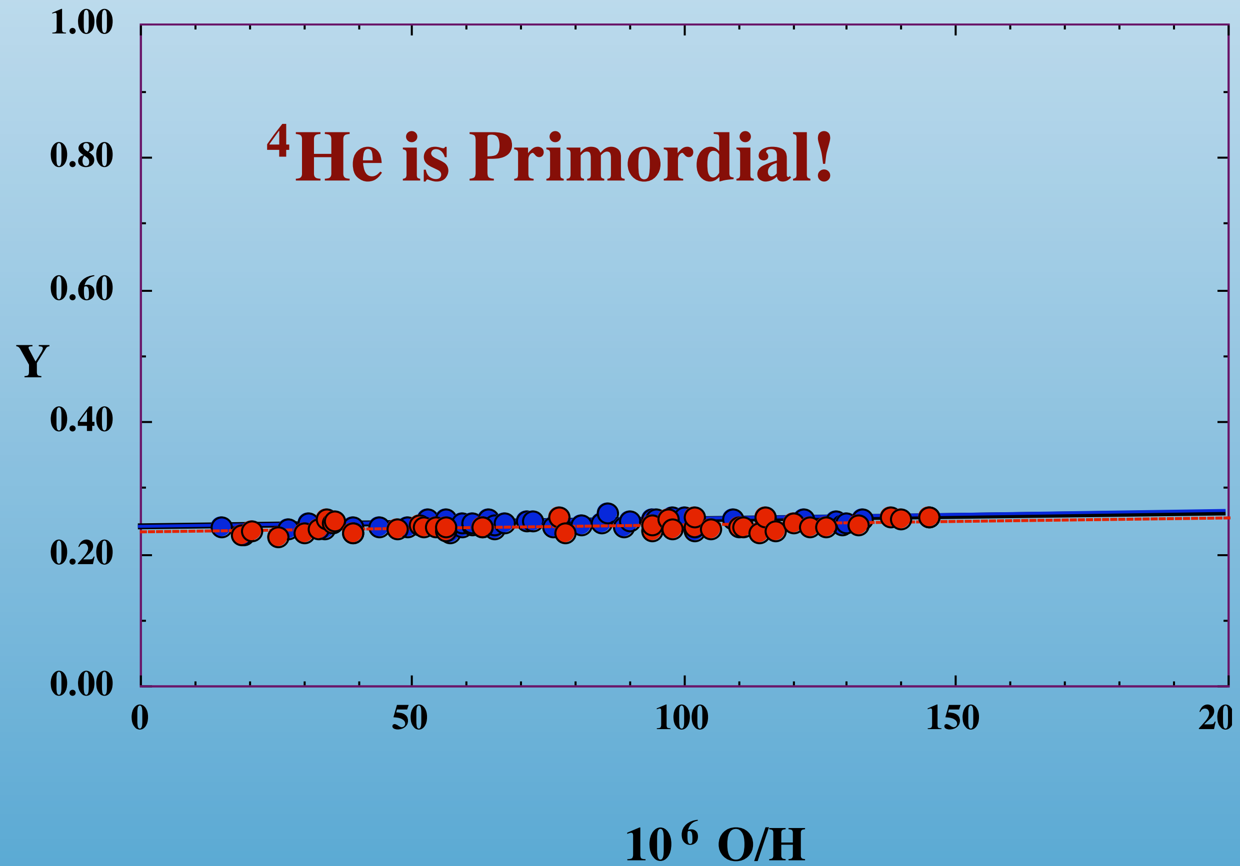


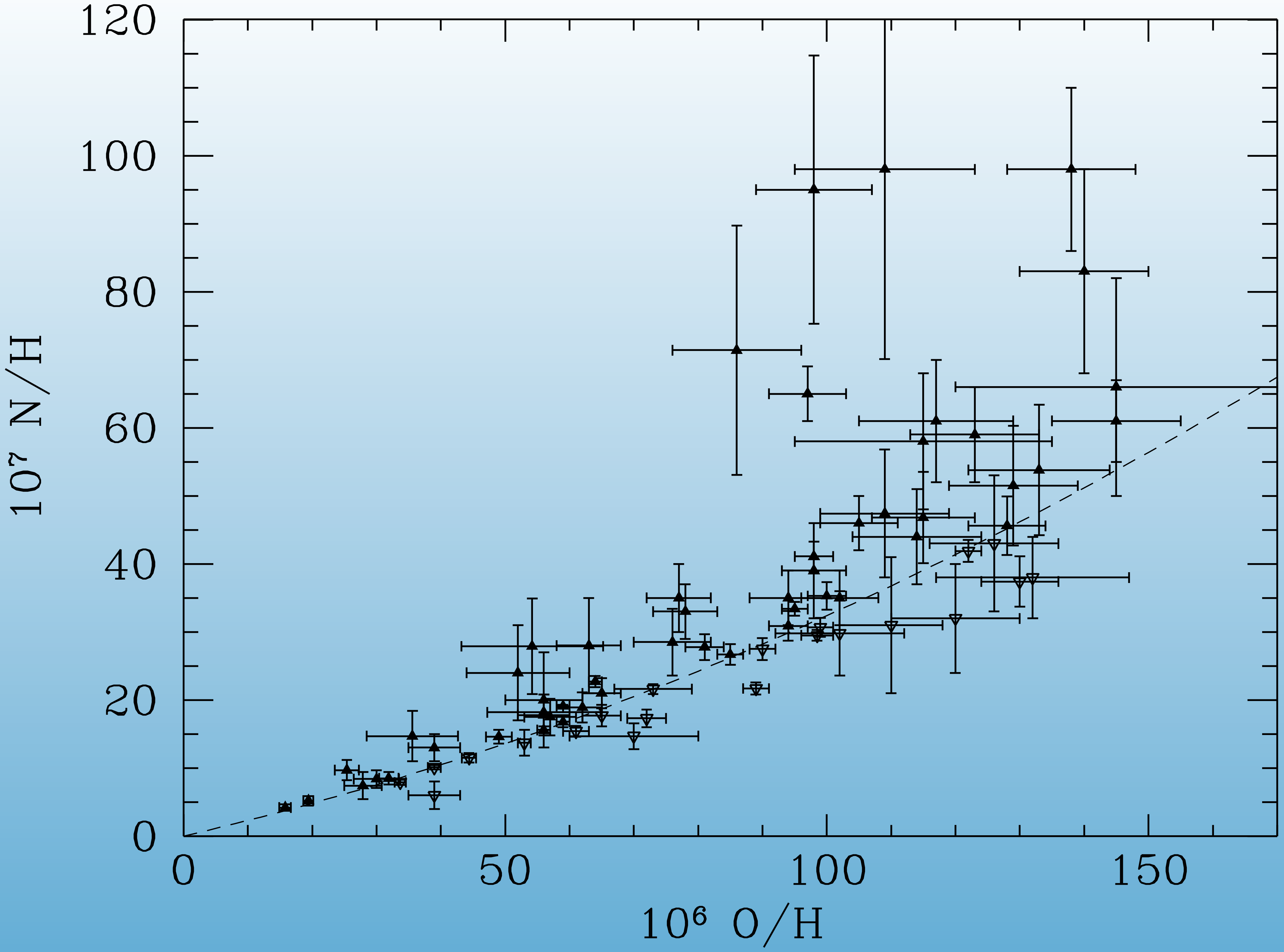
$\Omega_B h^2$
0.01
0.02
0.03
0.26
0.25
0.24
0.23
0.22
Y
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio η

^{4}He

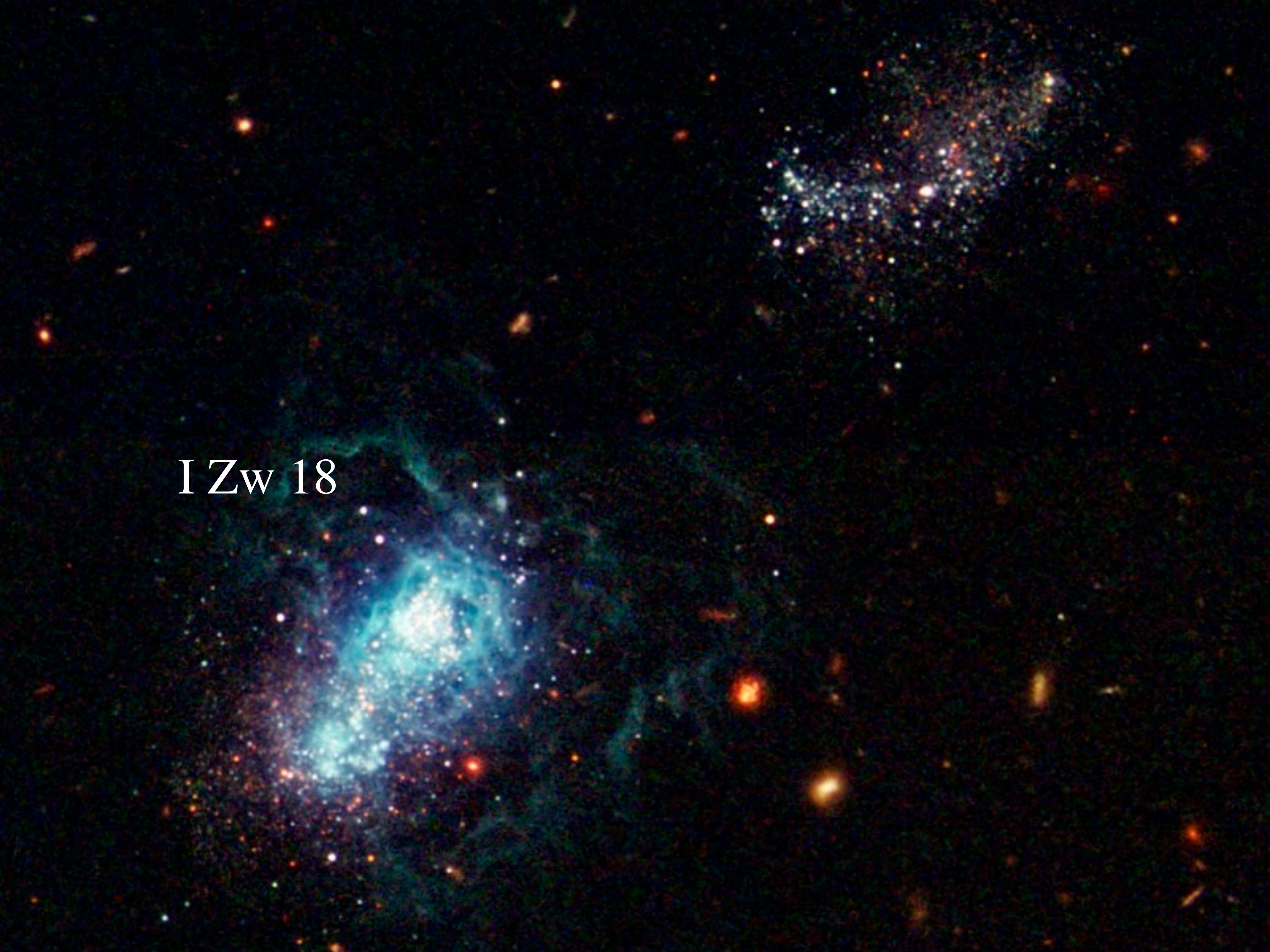
Measured in low metallicity extragalactic HII regions (~100) together with O/H and N/H

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





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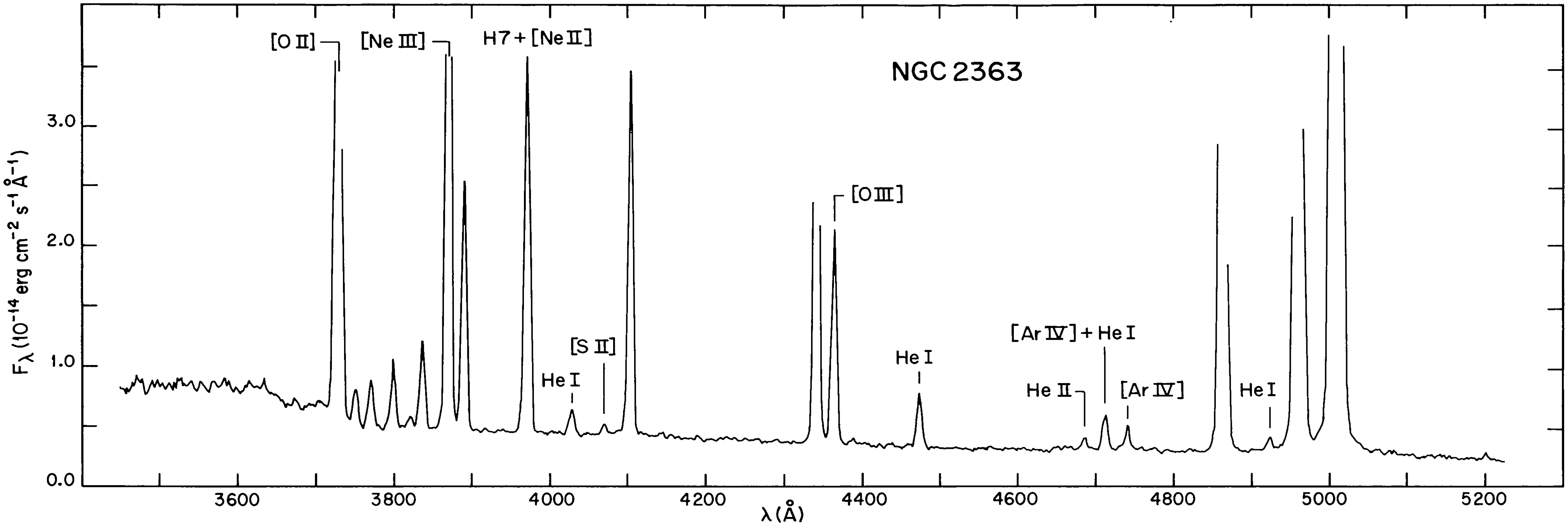


Fig. 1. Low dispersion blue spectrogram of NGC 2363, showing the faintest lines measured

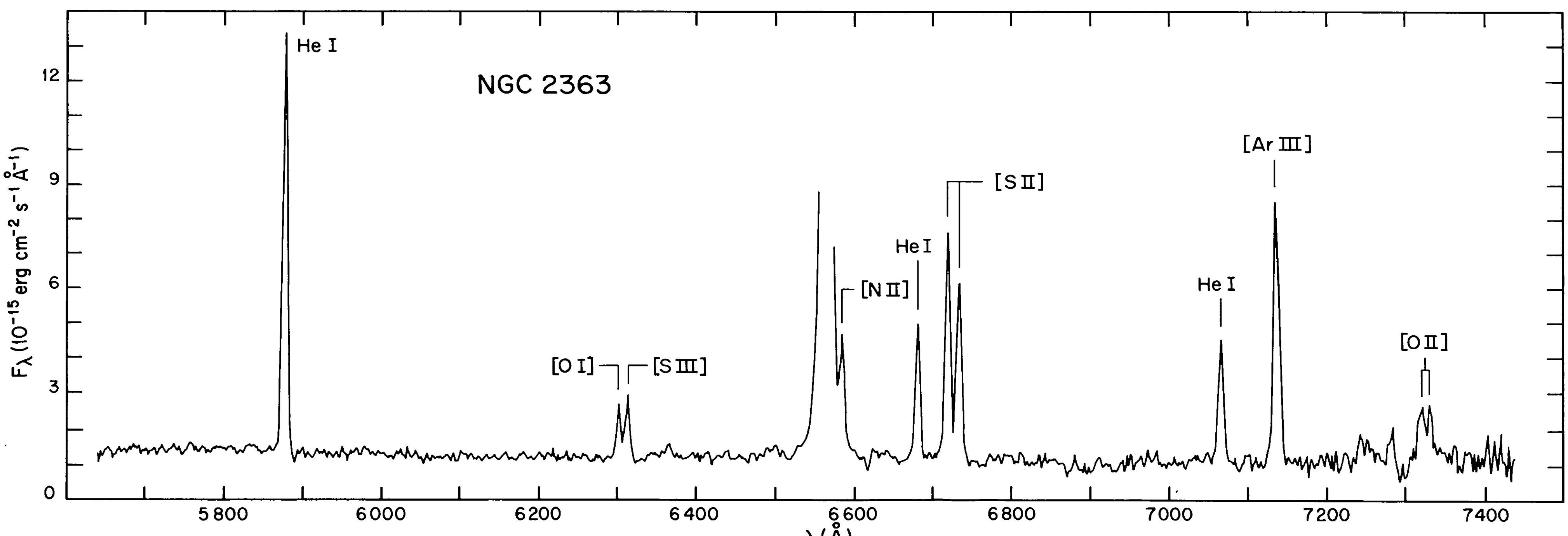
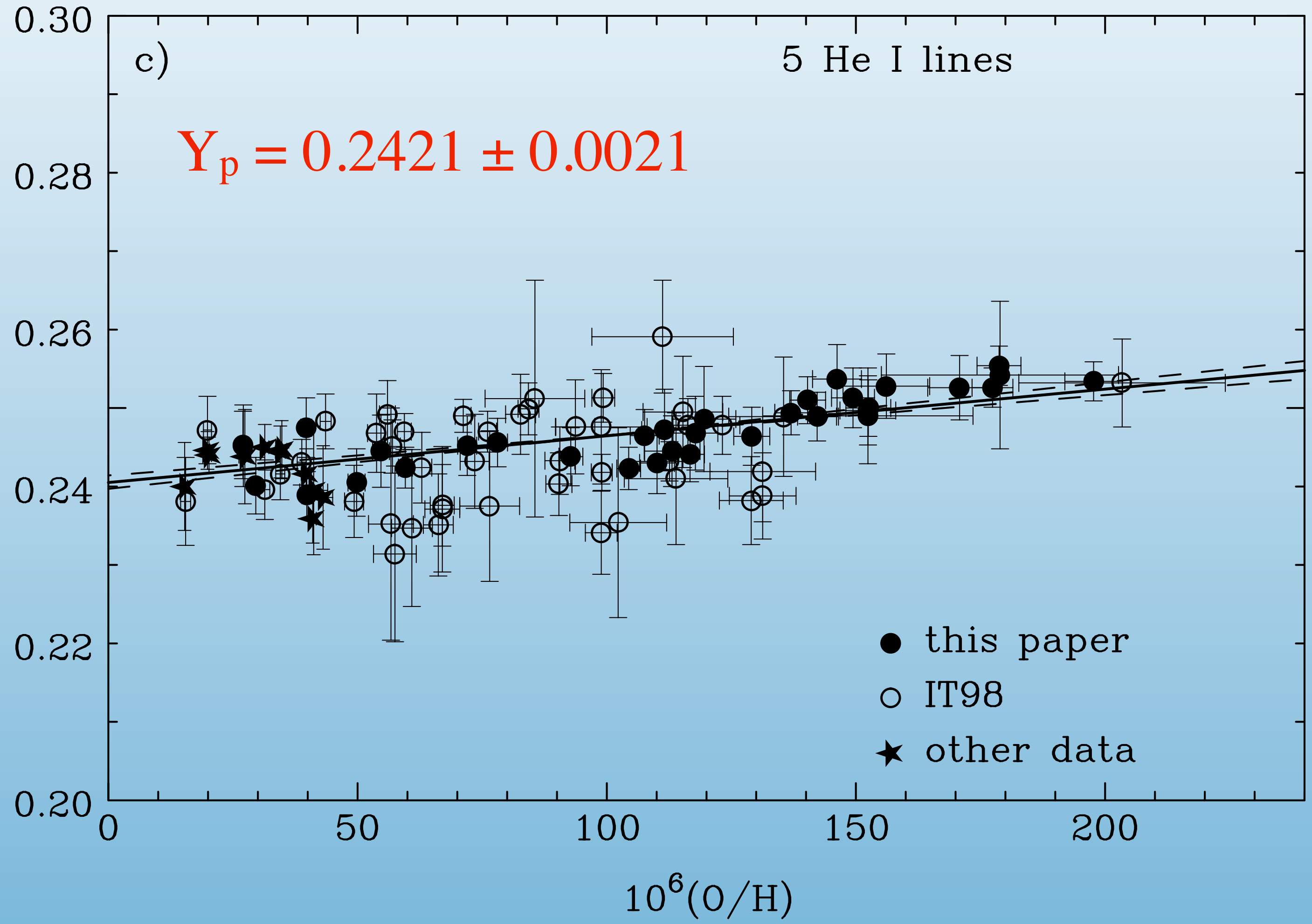


Fig. 2. Low dispersion red spectrogram of NGC 2363

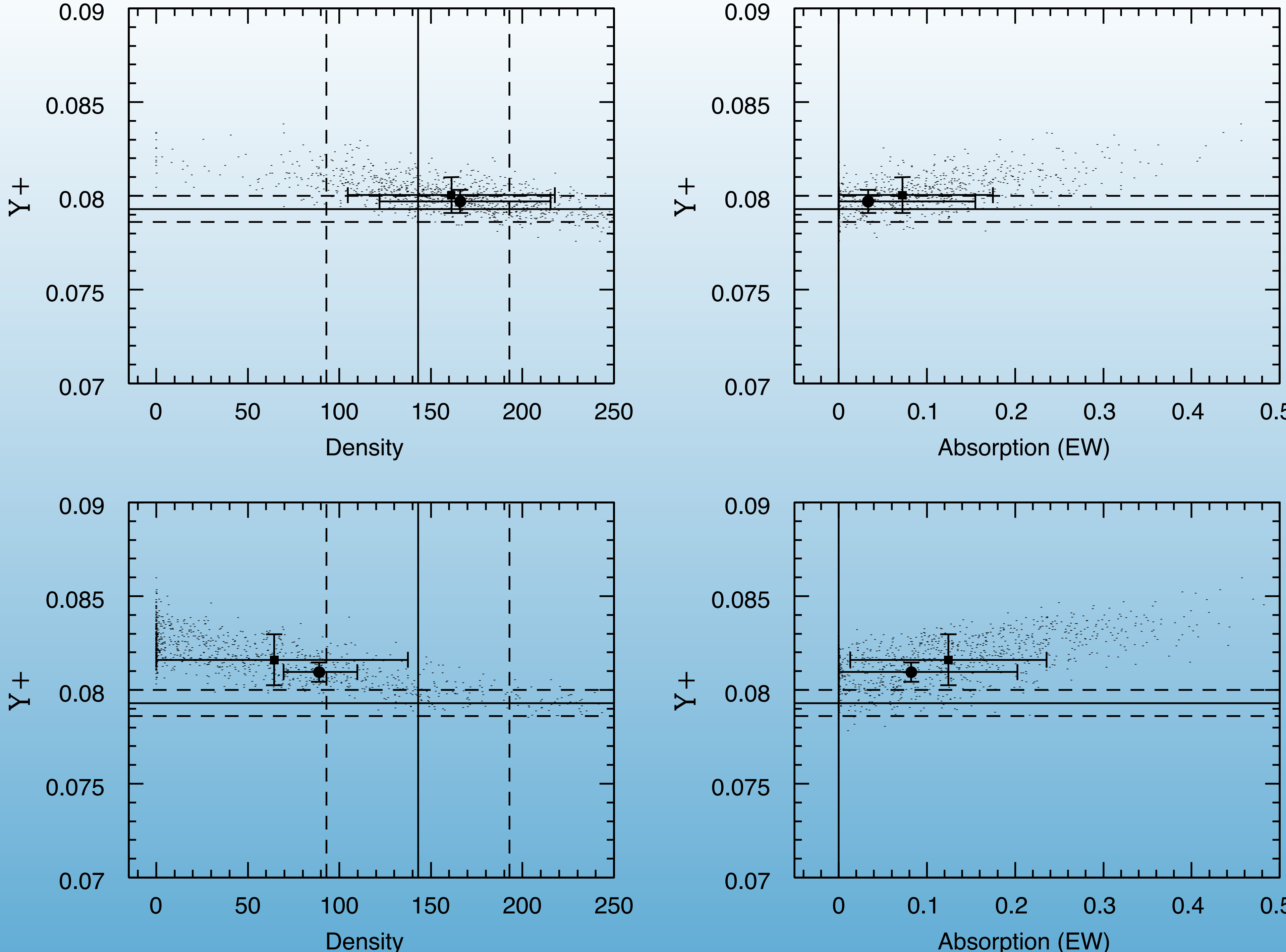
^{4}He



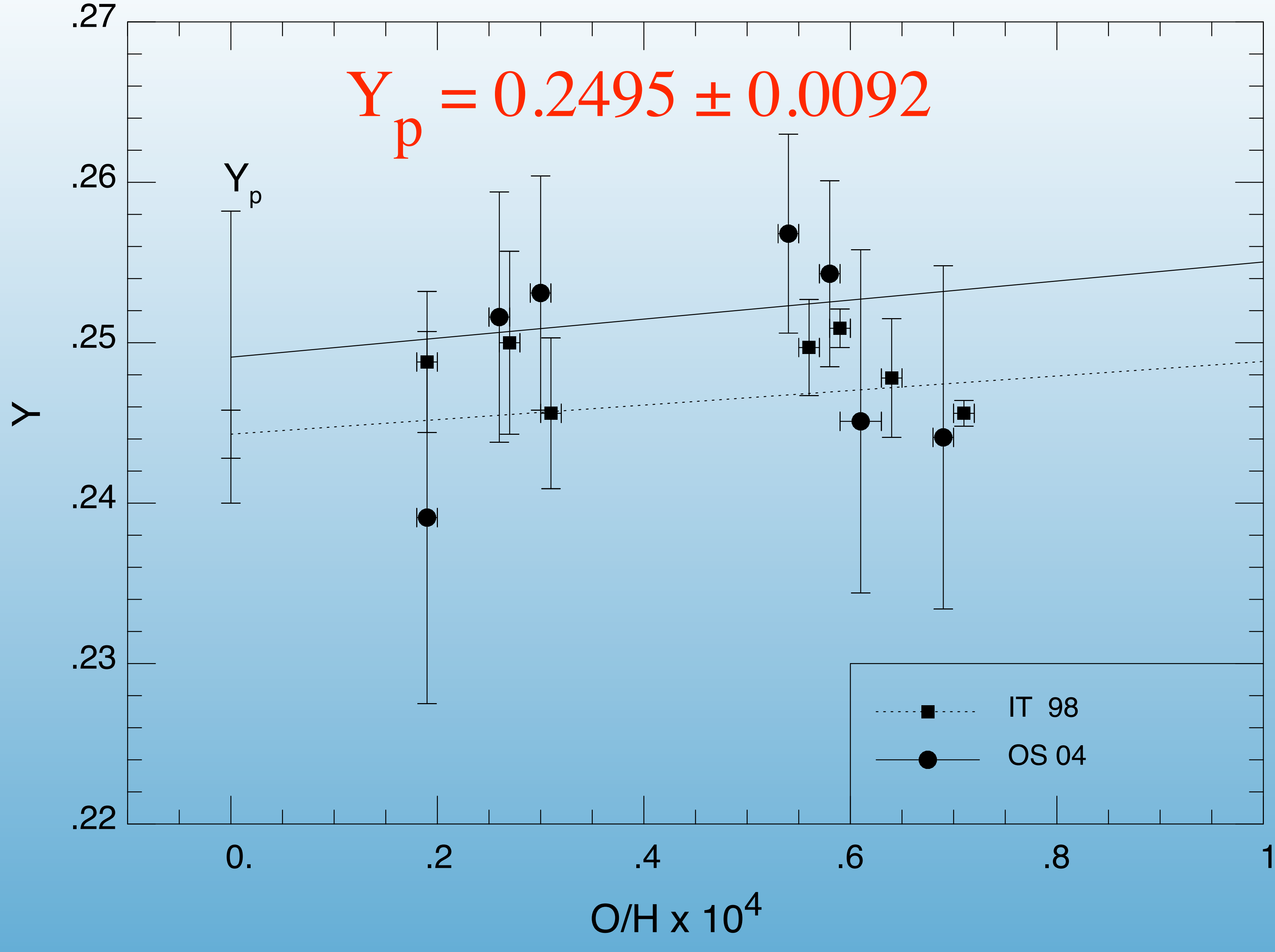
Izotov & Thuan

Method:

- Intensity and Eq. Width for H and He
- Determine H reddening and underlying absorption
- Use 6 He emission lines to determine physical parameters:
  - denisty, optical depth, temperature, underlying He absorption, ^{4}He abundance
- Severe degeneracies revealed by Monte Carlo anaysis



KAO + Skillman

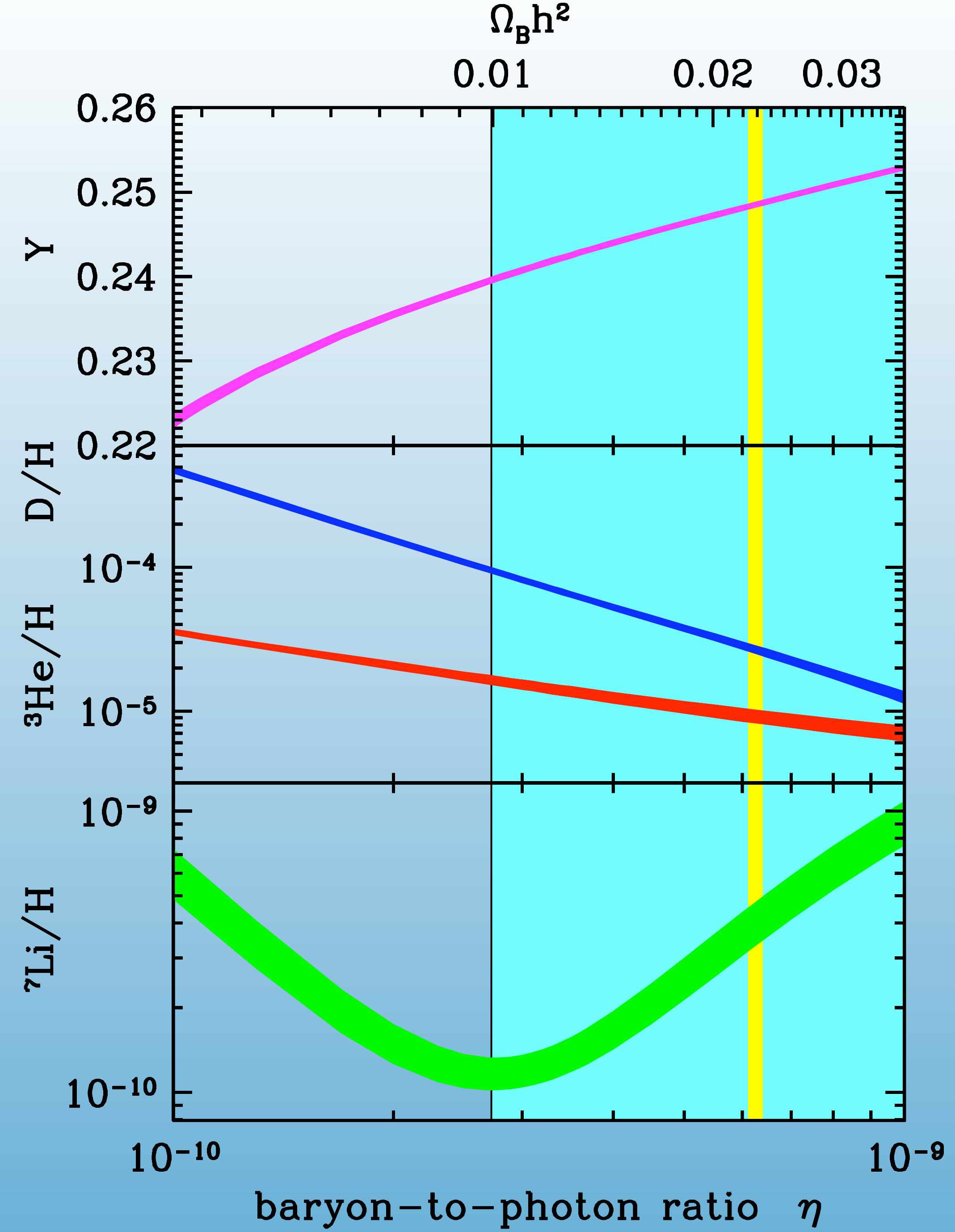


$Y_p = 0.2495 \pm 0.0092$
.27
.26
.25
.24
.23
.22
Y_p
Y
IT 98
OS 04
0.
.2
.4
.6
.8
1
O/H x 10^4

^{4}He Prediction:
0.2484 ± 0.0005

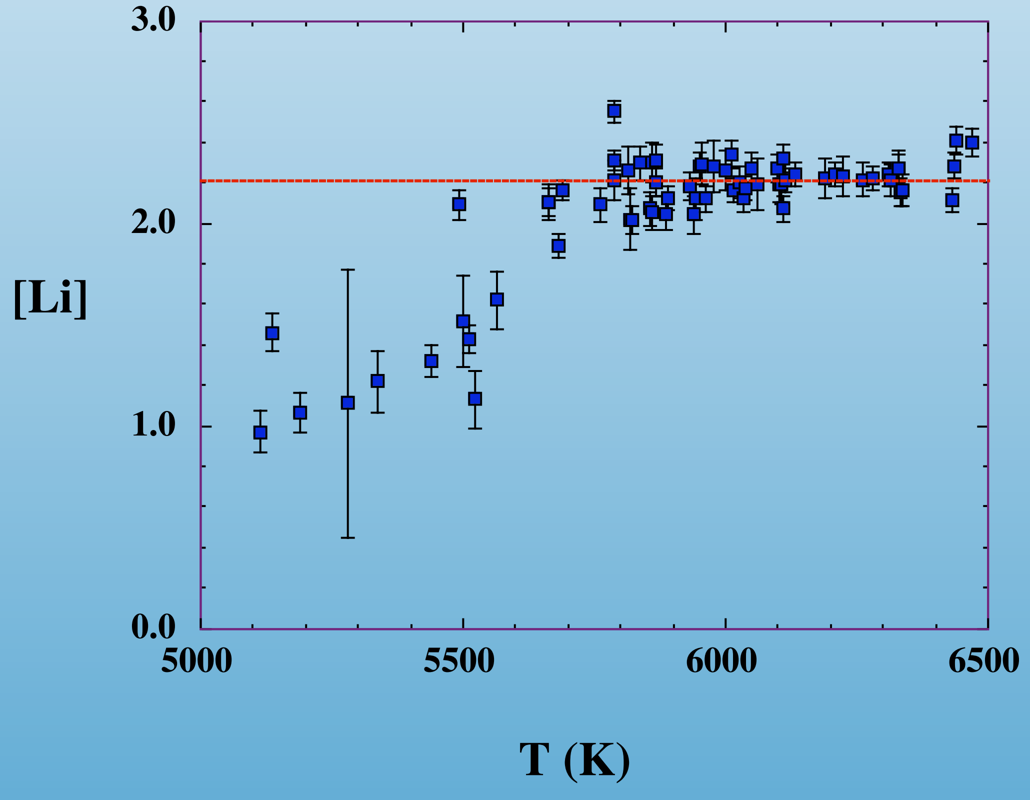
Data: Regression:
0.2495 ± 0.0092

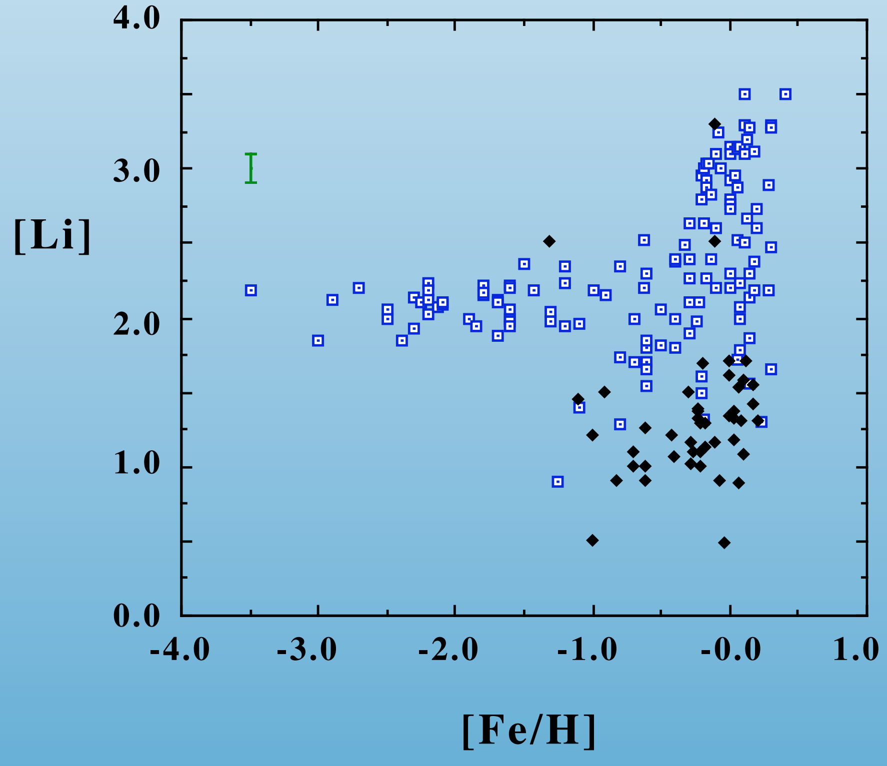
Mean:
0.2520 ± 0.0030



Li/H

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

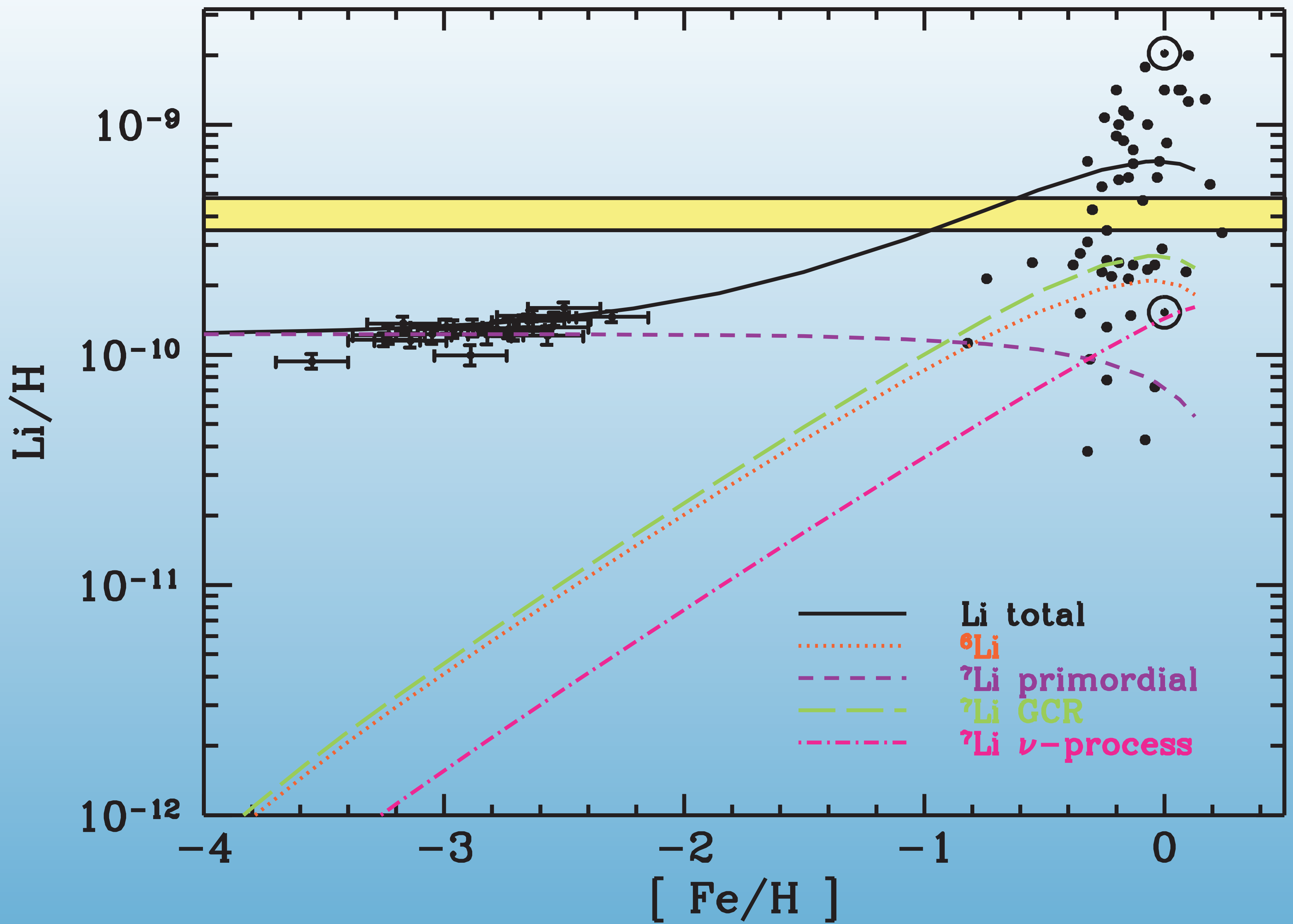




Li Woes

- 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
  - $H\alpha$ (globular cluster): Li/H = 2.2×10^{-10} Bonifacio et al.
  - $H\alpha$ (globular cluster): Li/H = 2.3×10^{-10} Bonifacio
  - $\lambda 6104$: Li/H ~ 3.2×10^{-10} Ford et al.

- Li depends on T, ln g, [Fe/H], depletion, post BBN-processing, ...
- Strong systematics



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

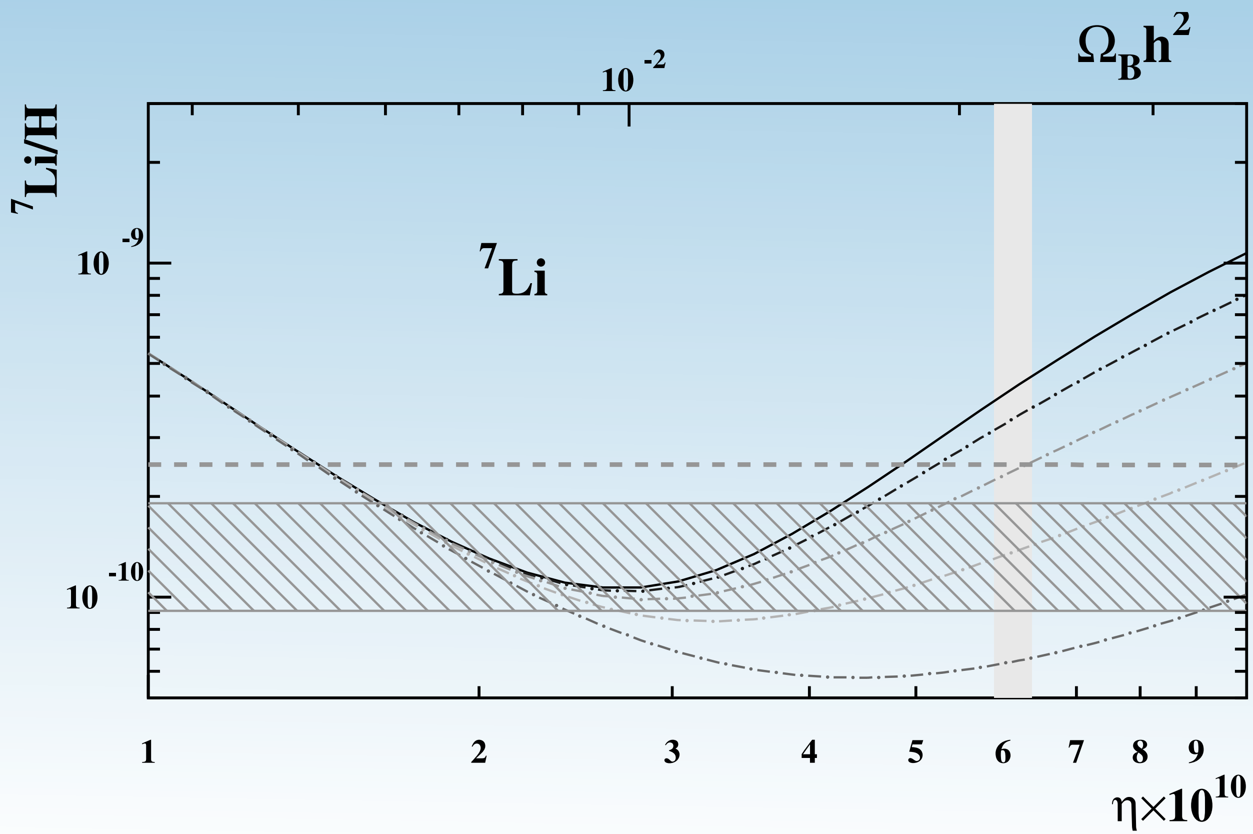
Possible sources for the discrepancy

- 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

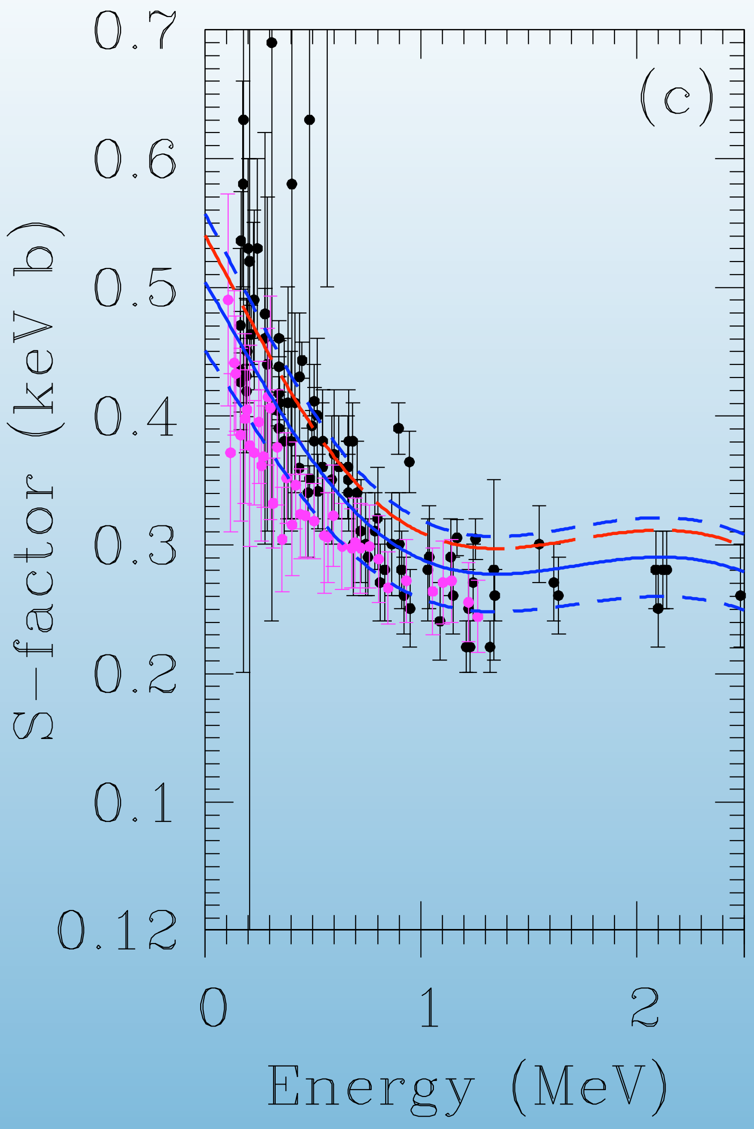
Reaction/Parameter	sensitivities (α_i)
$\eta_{10}/6.14$	$+2.04$
$n(p,\gamma)d$	$+1.31$
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$	$+0.95$
$^3\mathrm{He}(d,p)^4\mathrm{He}$	-0.78
$d(d,n)^3\mathrm{He}$	$+0.72$
$^7\mathrm{Be}(n,p)^7\mathrm{Li}$	-0.71
Newton's G_N	-0.66
$d(p,\gamma)^3\mathrm{He}$	$+0.54$
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:

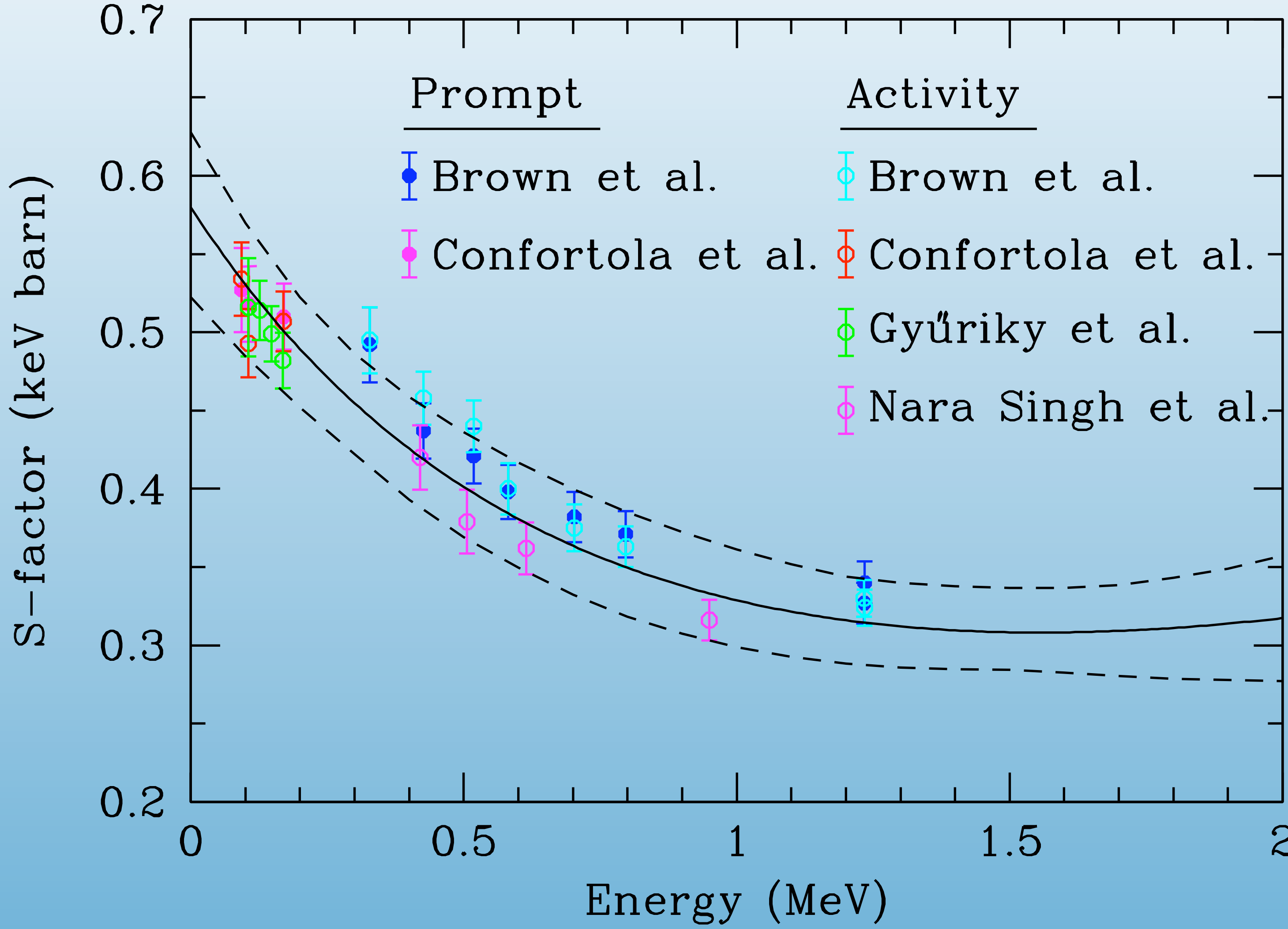
$$\left.\begin{aligned} S_{34}^{NEW}(0) &= 0.267 \text{ keVb} \\ \frac{\Delta S_{34}}{S_{34}} &= -0.47 \end{aligned}\right\} \text{globular cluster Li}$$

or

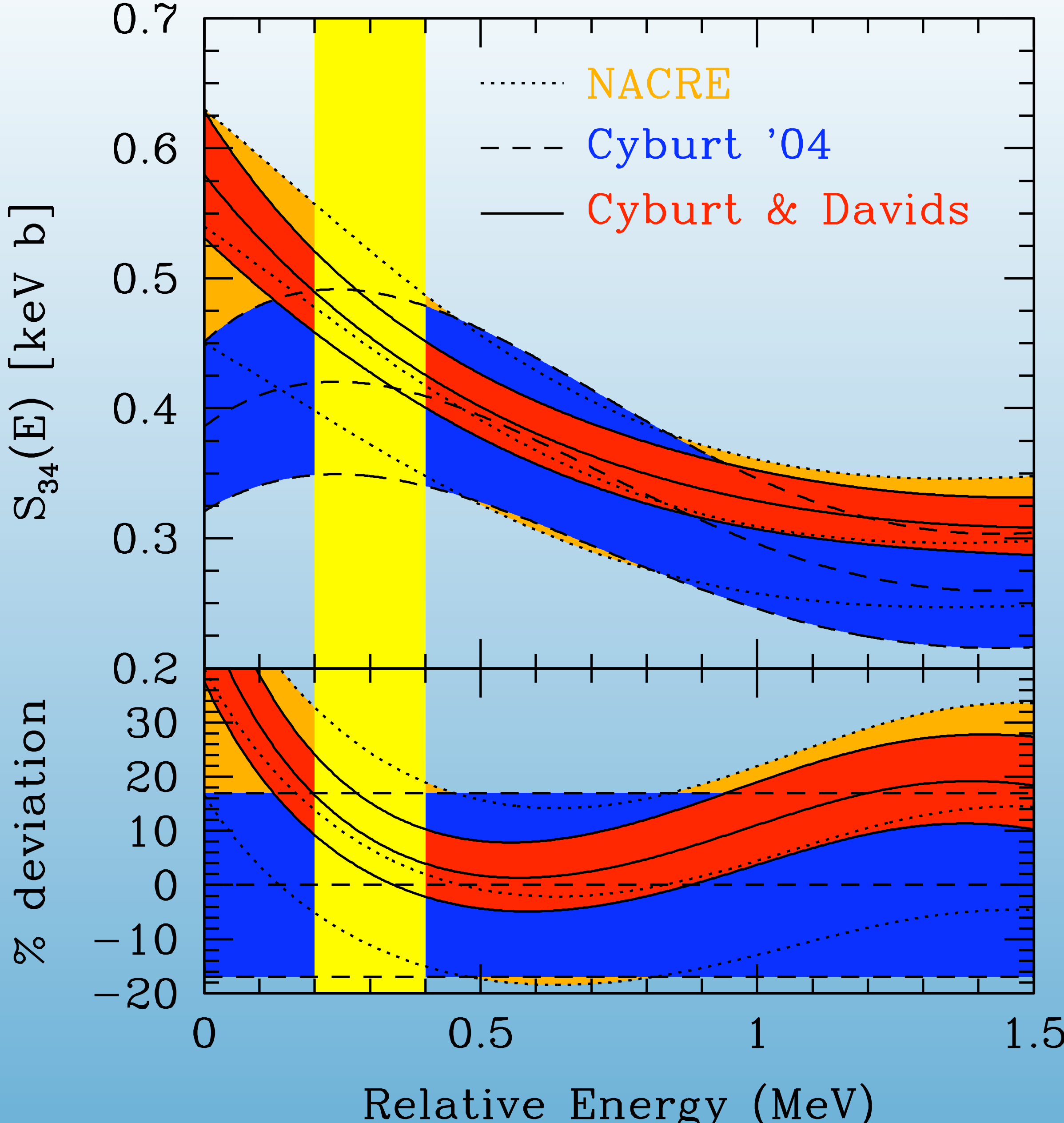
$$\left.\begin{aligned} S_{34}^{NEW}(0) &= 0.136 \text{ keVb} \\ \frac{\Delta S_{34}}{S_{34}} &= -0.73 \end{aligned}\right\} \text{halo star Li}$$



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

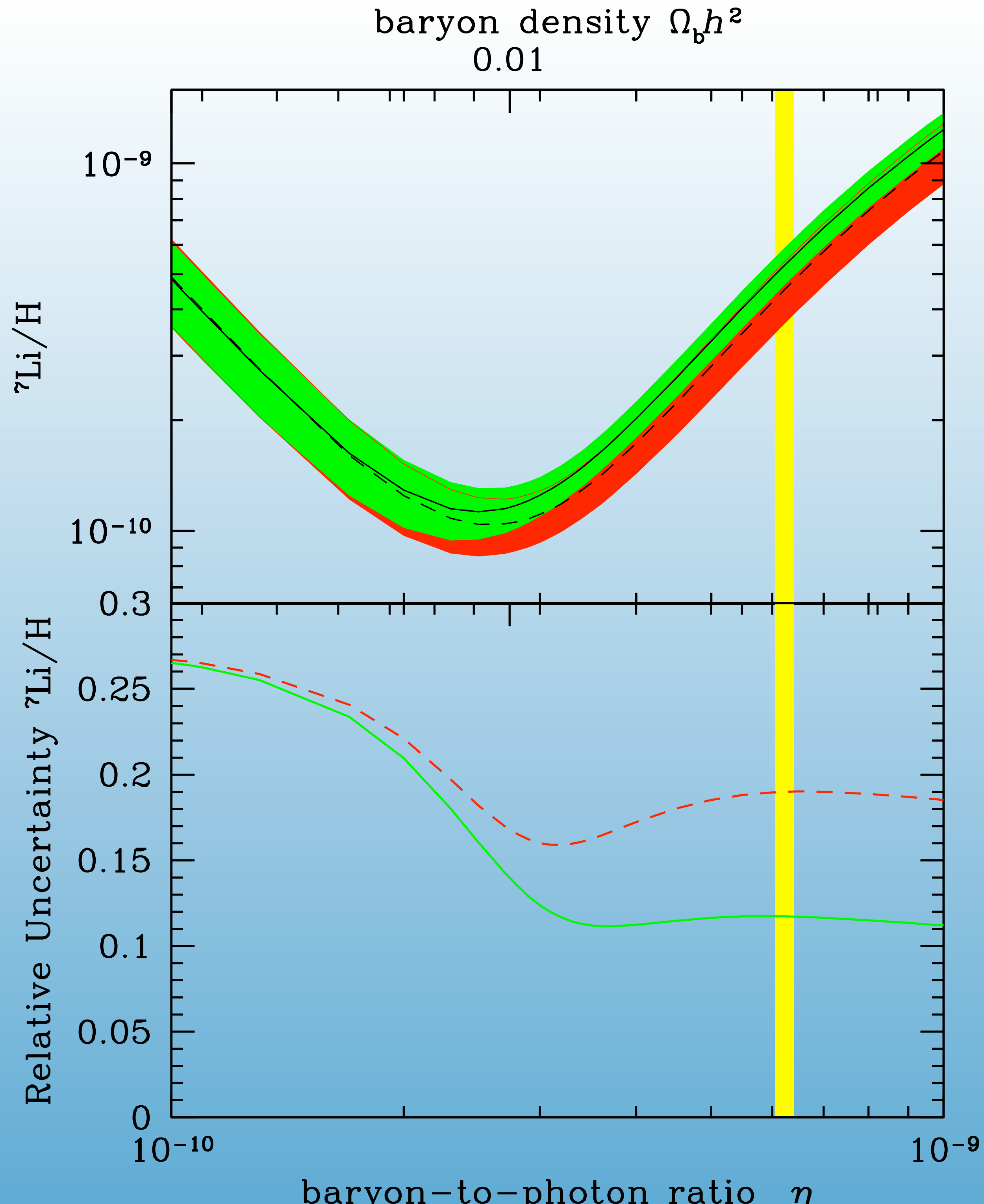


Cyburt and Wands



17% increase in S

$\Rightarrow$ 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

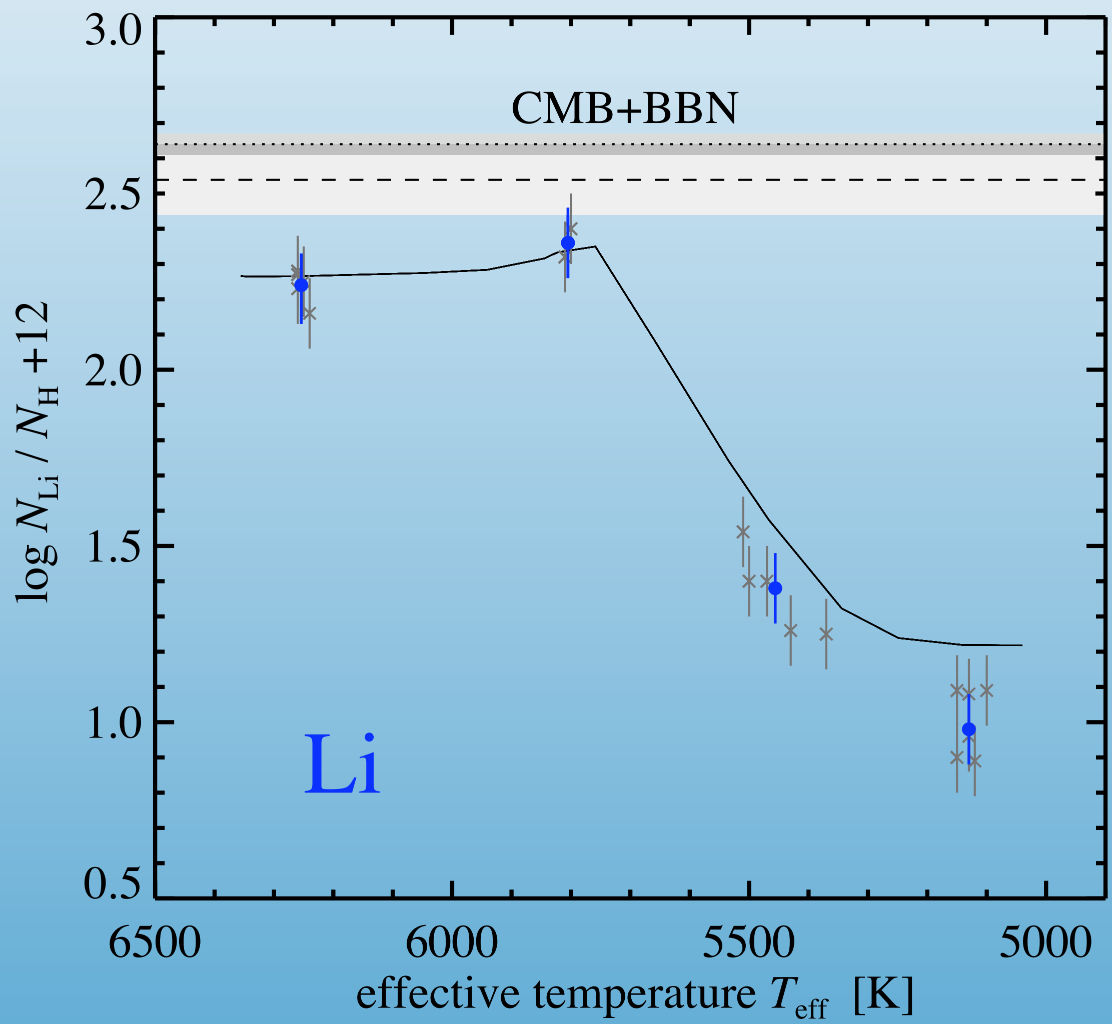
- Nuclear Rates
  - Restricted by solar neutrino flux

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

Possible sources for the discrepancy

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  - 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

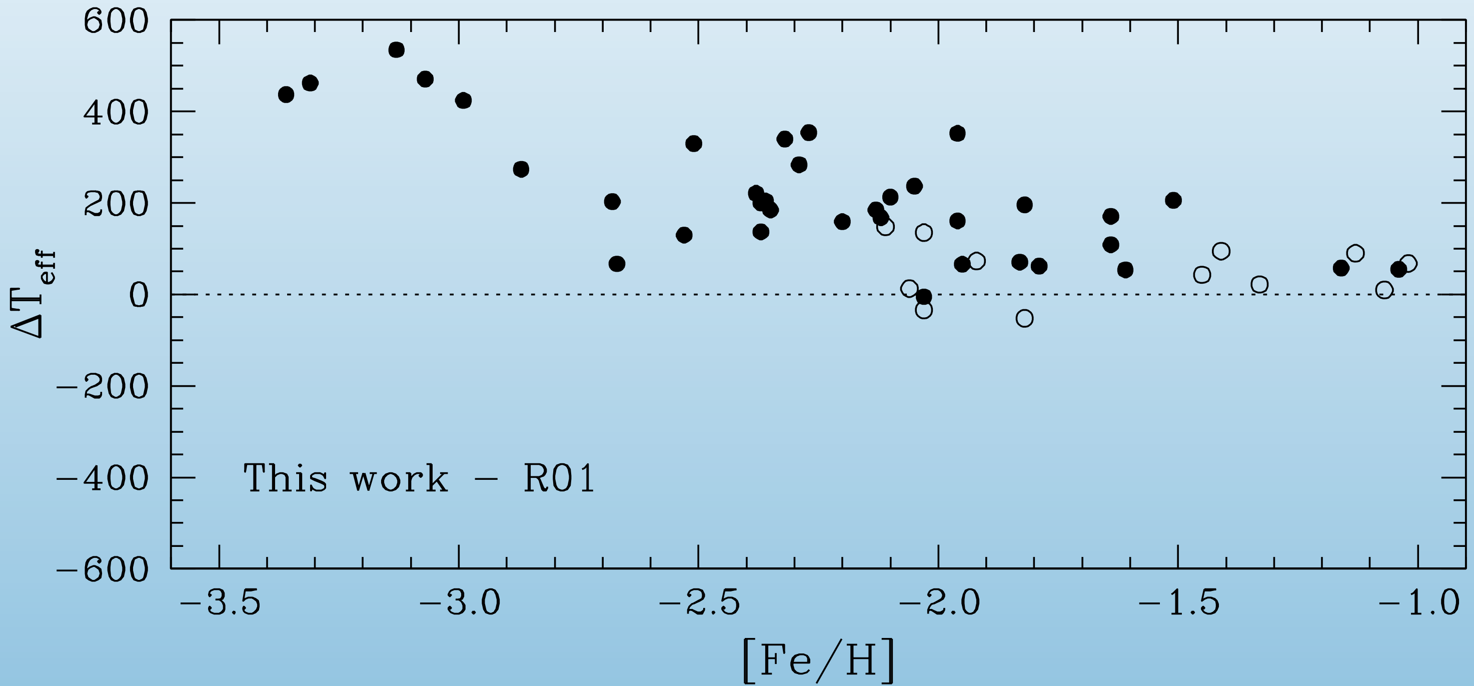
Jorge Meléndez[1] and Iván Ramírez[2]

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

$$[\mathrm{Li}] = 2.37 \pm 0.1$$

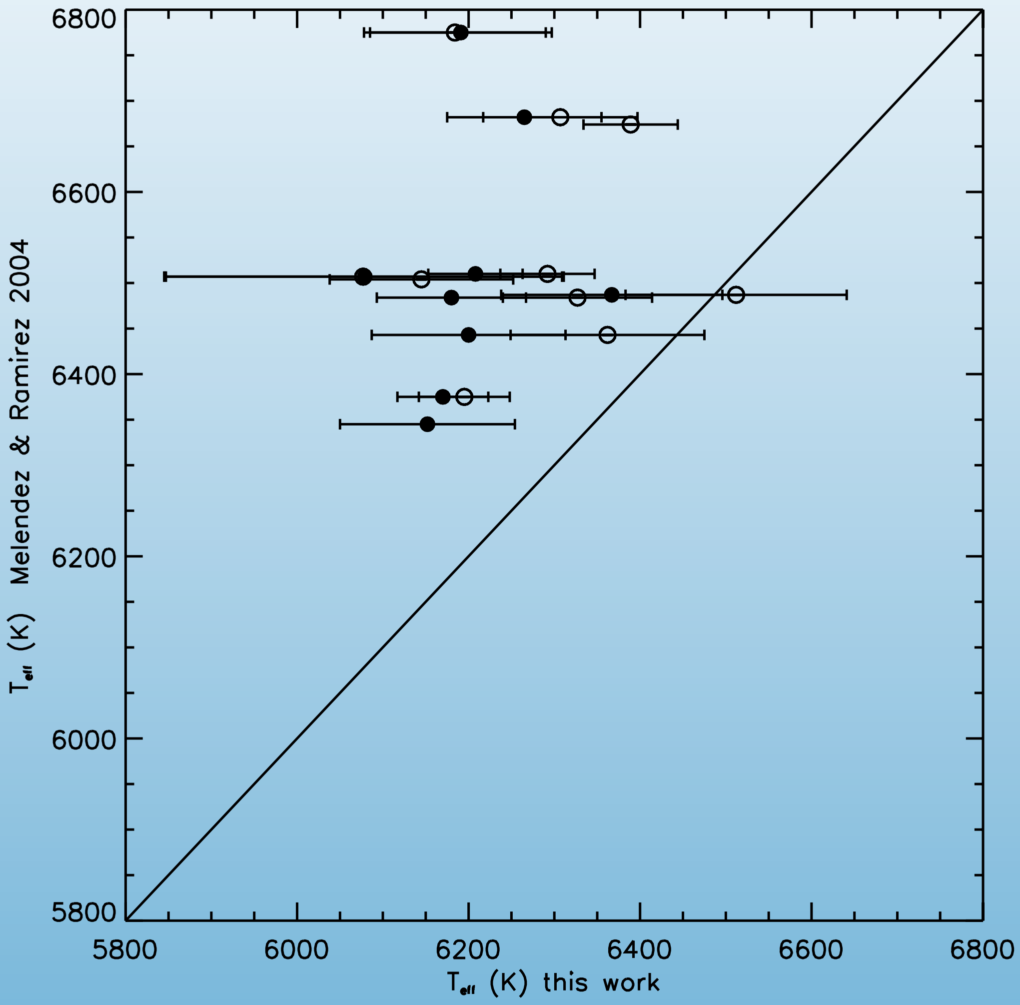
$$\mathrm{Li/H} = 2.34 \pm 0.54 \times 10^{-10}$$

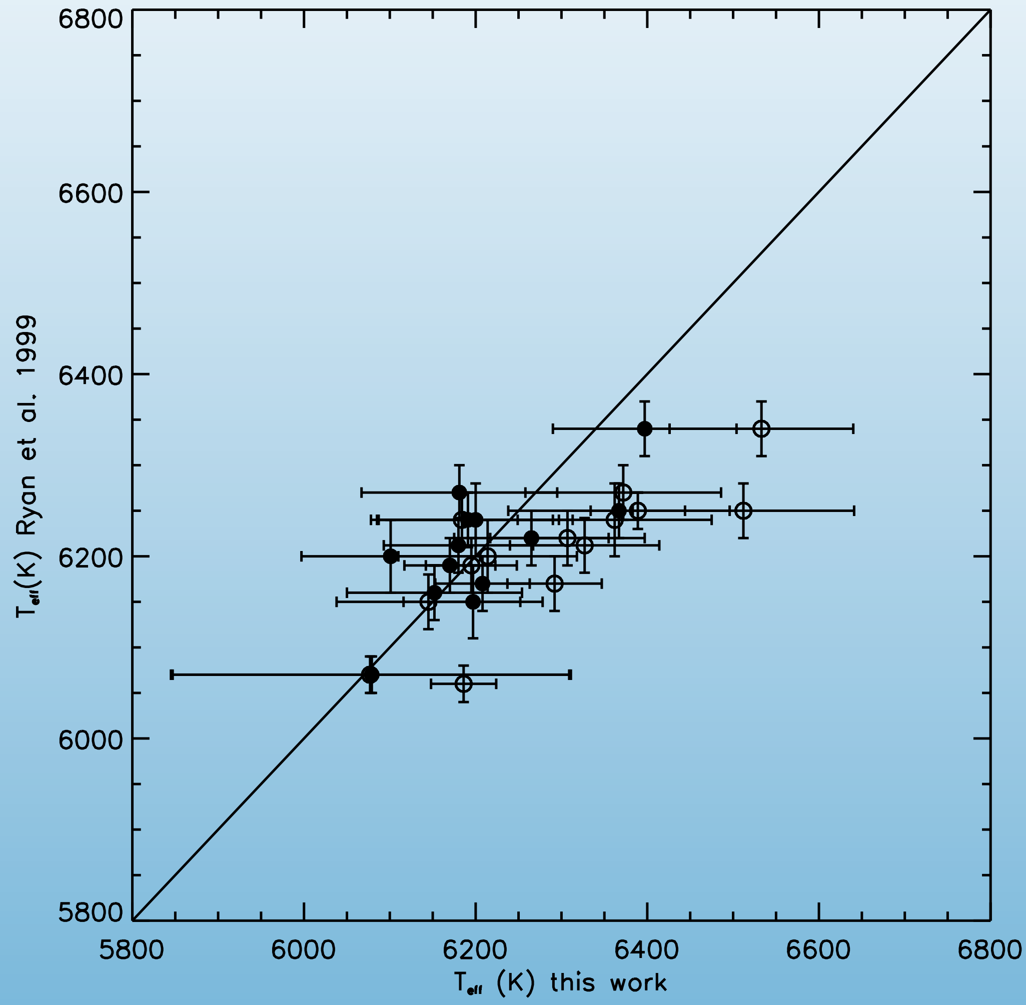
BBN Prediction: $10^{10}\,\mathrm{Li/H} = 4.26^{+0.73}_{-0.60}$



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]

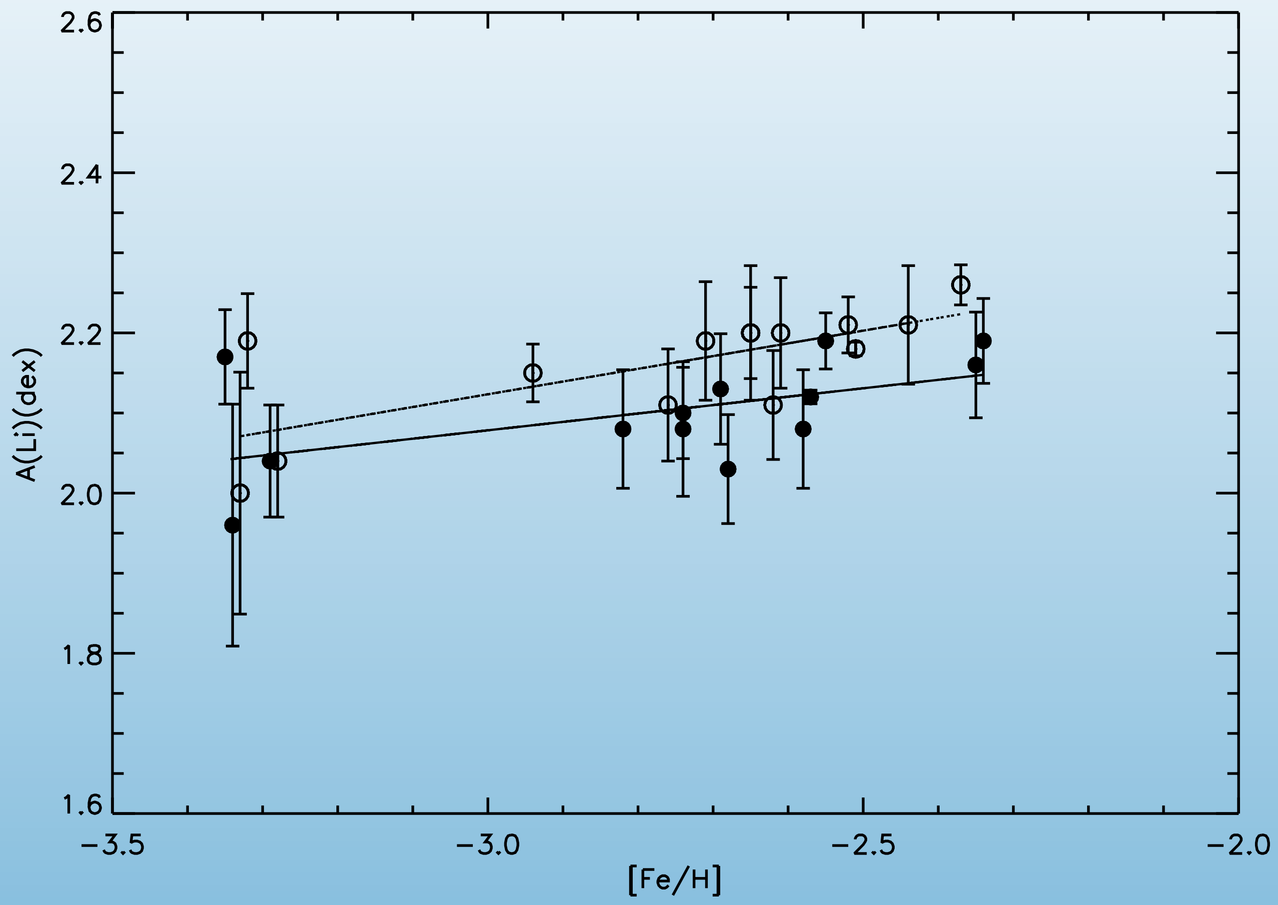
Recent dedicated temperature determinations (excitation energy technique)





Hosford, Ryan, Garcia-Perez, Norris, Olive

Resulting Li:



$[Li] = 2.16 \pm 0.07$ MS

$= 2.10 \pm 0.07$ SGB

Hosford, Ryan, Garcia-Perez, Norris, Olive

Possible sources for the discrepancy

- Nuclear Rates
  - Restricted by solar neutrino flux

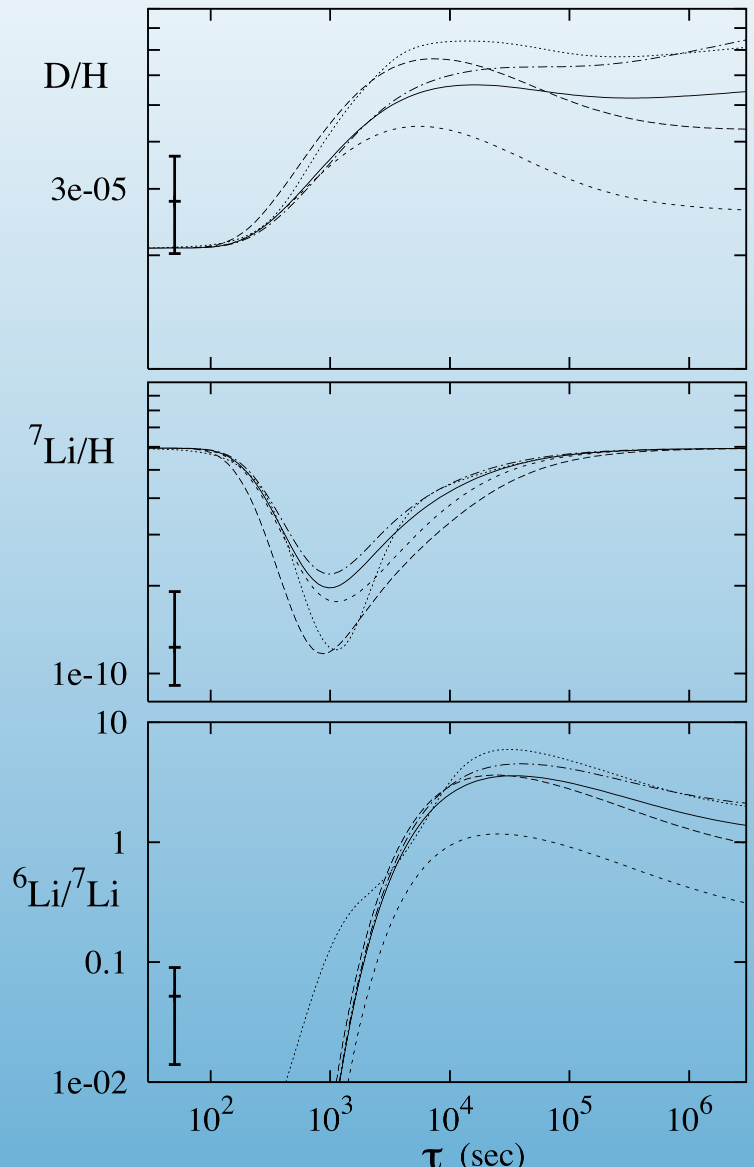
Coc et al.
Cyburt, Fields, KAO

- Stellar parameters

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

- Particle Decays

Solution 1: Particle Decays



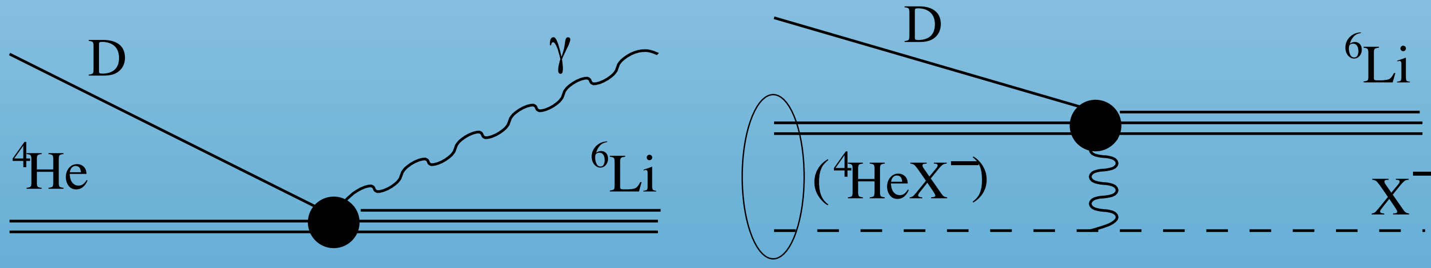
Jedamzik

Effects of Bound States

- In SUSY models with a $\tilde{\tau}$ NLSP, bound states form between ^{4}He and $\tilde{\tau}$

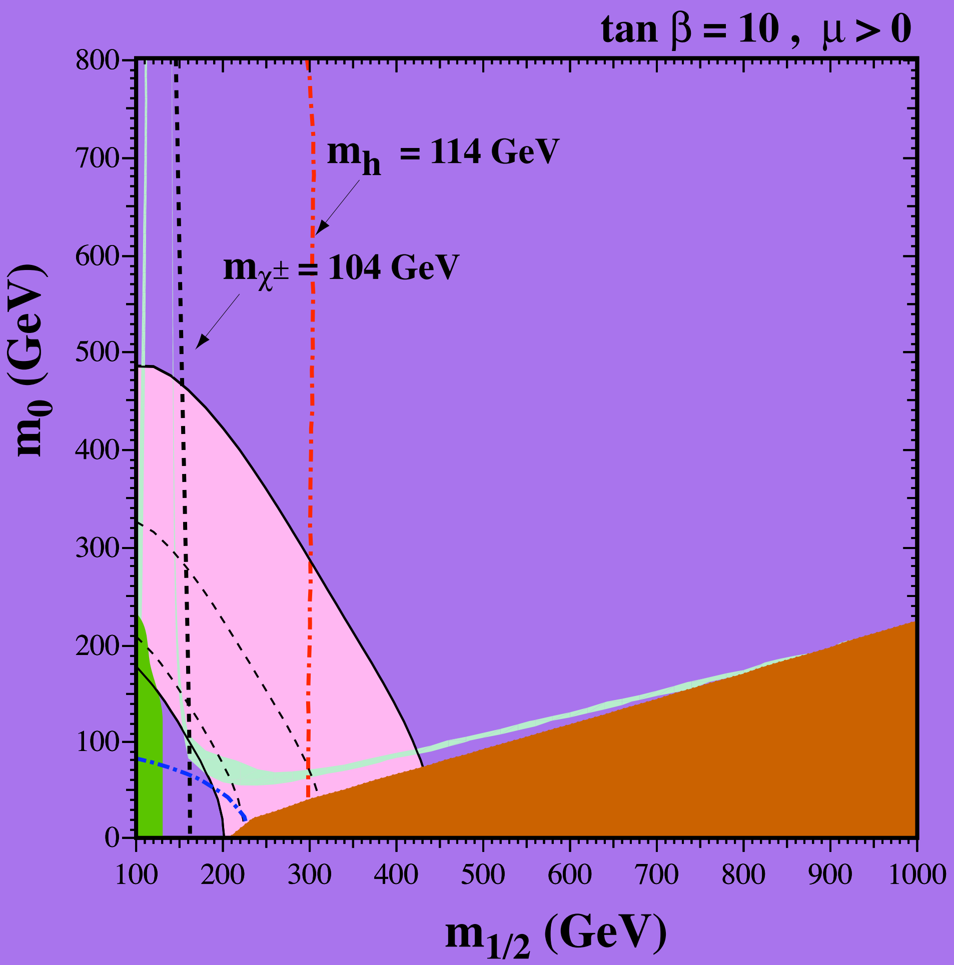
- The ^{4}He (D, γ) ^{6}Li reaction is normally highly suppressed (production of low energy γ)

- Bound state reaction is not suppressed

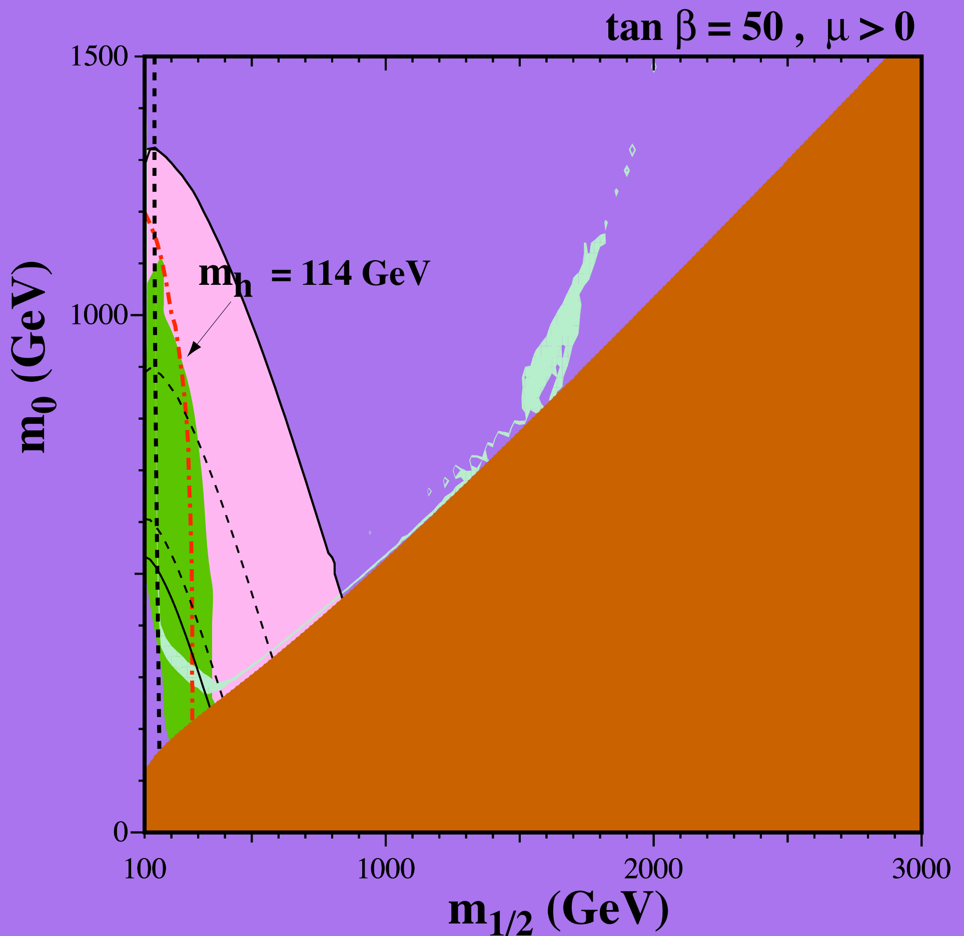


Pospelov

CMSSM

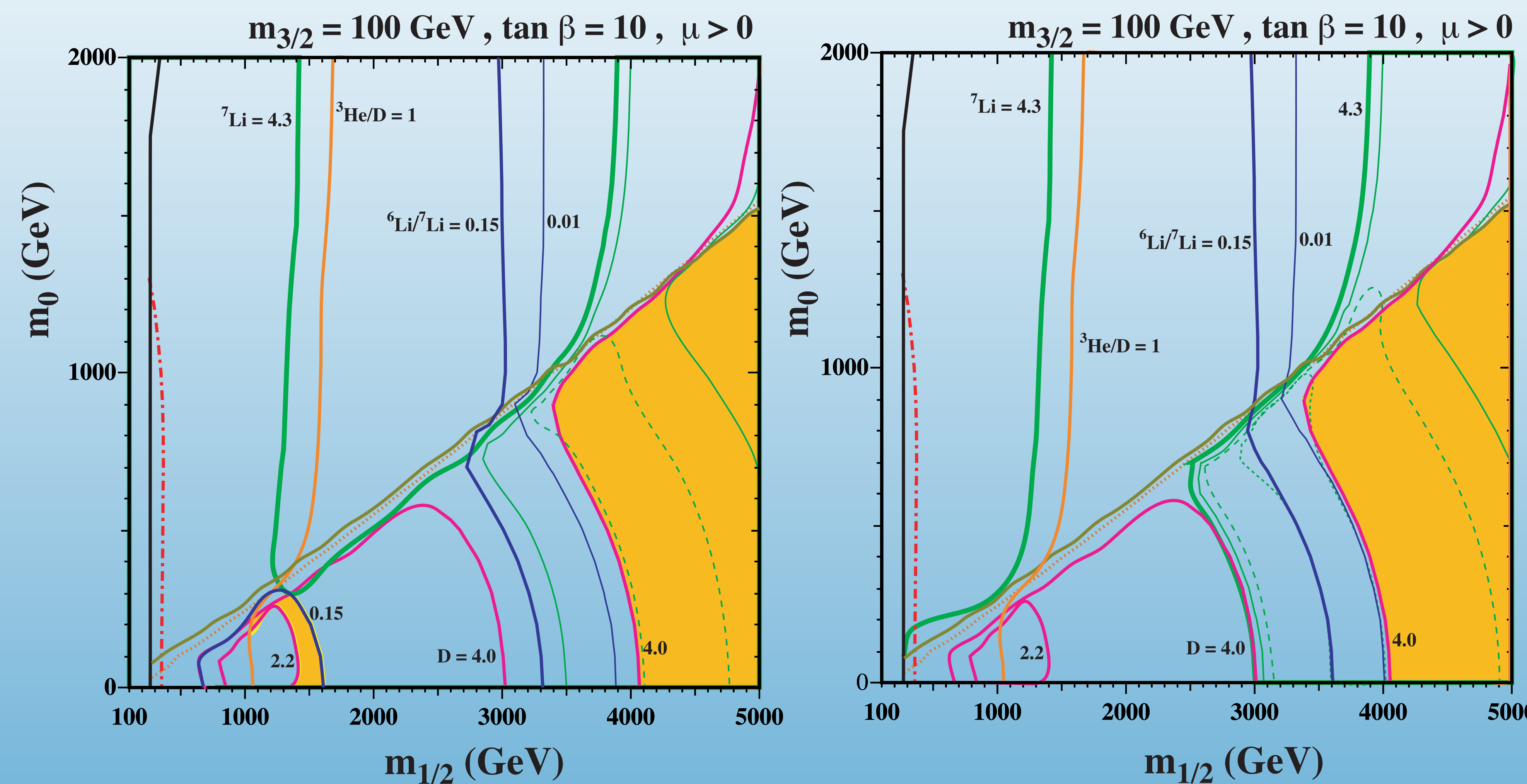


tan β = 10 , μ > 0
m_h = 114 GeV
m_χ± = 104 GeV
m_0 (GeV)
m_1/2 (GeV)
0
100
200
300
400
500
600
700
800
900
1000

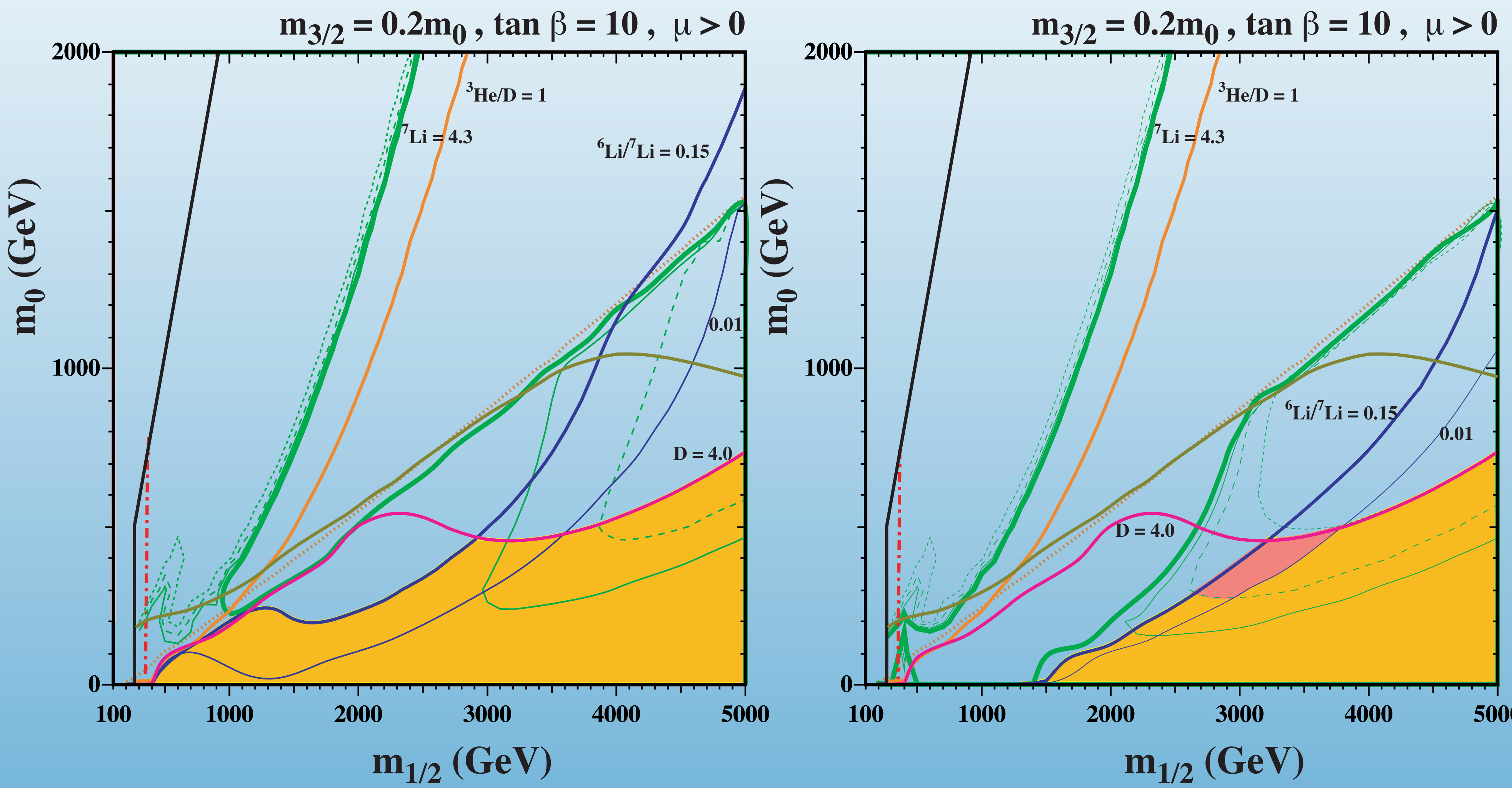


tan β = 50 , μ > 0
m_h = 114 GeV
m_0 (GeV)
m_1/2 (GeV)
0
1000
1500
100
2000
3000

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

Limits on the variations of α

- Cosmology
  - BBN
  - CMB
- The Oklo Reactor
- Meteoritic abundances
- Atomic clocks

How does a Fundamental Constant Change?

$$\mathcal{L} \sim \phi R \qquad \langle \phi \rangle = \frac{1}{16\pi G_N} = \frac{M_P^2}{16\pi}$$

$$\mathcal{L} \sim \phi F^2 \qquad \langle \phi \rangle = \frac{1}{4e^2} = \frac{1}{16\pi\alpha}$$

Does this ever happen?

e.g. JBD Theory

$$S = \int d^4x \sqrt{g} \left[\phi R - \frac{\omega}{\phi} \partial_\mu \phi \partial^\mu \phi + \mathcal{L}_m \right]$$

$$\mathcal{L}_m = -\frac{1}{4e^2} F^2 - \frac{1}{2} \partial_\mu y \partial^\mu y - V(y)$$

$$-\overline{\Psi} \not{D} \Psi - m \overline{\Psi} \Psi + \Lambda$$

with a conformal rescaling,

$$S = \int d^4x \sqrt{\overline{g}} \left[\overline{R} - (\omega + \tfrac{3}{2}) \frac{(\partial_\mu \phi)^2}{\phi^2} \right.$$

$$- \frac{1}{2} \frac{(\partial_\mu y)^2}{\phi} - \frac{V(y)}{\phi^2} - \frac{\overline{\Psi} \not{D} \Psi}{\phi^{3/2}}$$

$$\left. - \frac{m \overline{\Psi} \Psi}{\phi^2} - \frac{1}{4e^2} F^2 + \frac{\Lambda}{\phi^2} \right]$$

now, $M_p(G_N)$, and α are fixed but particle masses scale with ϕ,

$$m \sim 1/\phi^{1/2}$$

the same is true for the Higgs expectation value,

$$G_F \sim \frac{1}{v^2} \sim 1/\phi$$

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

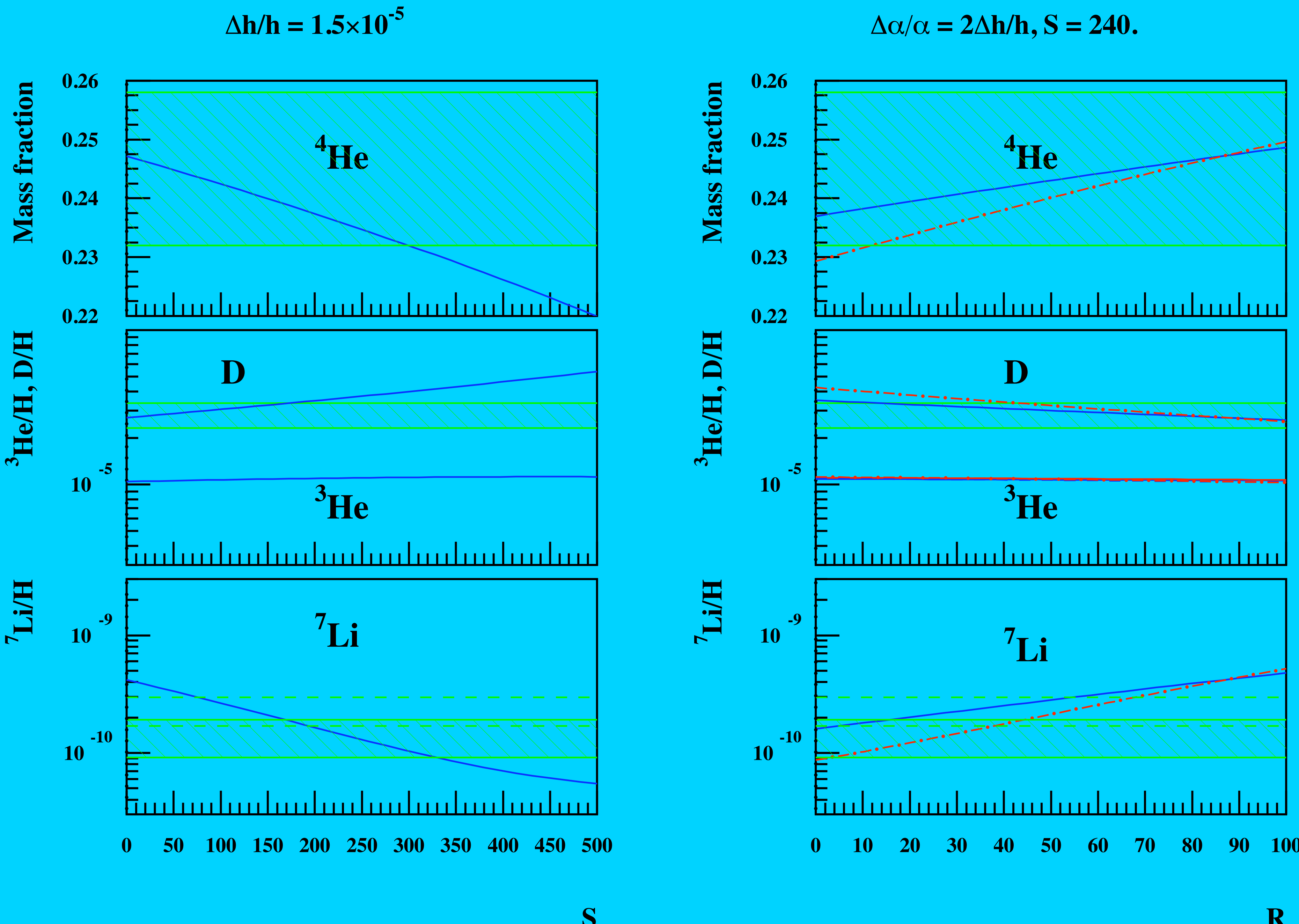
Include dependence of Λ on α; of v on h, etc.

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



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

^{6}LiBeB

For $\eta_{10} \approx 6$

^{6}Li/H $\approx 10^{-14}$

^{9}Be/H $\approx 0.5 - 5 \times 10^{-19}$

^{10}B/H $\approx 2 \times 10^{-20}$

^{11}B/H $\approx 3 \times 10^{-16}$

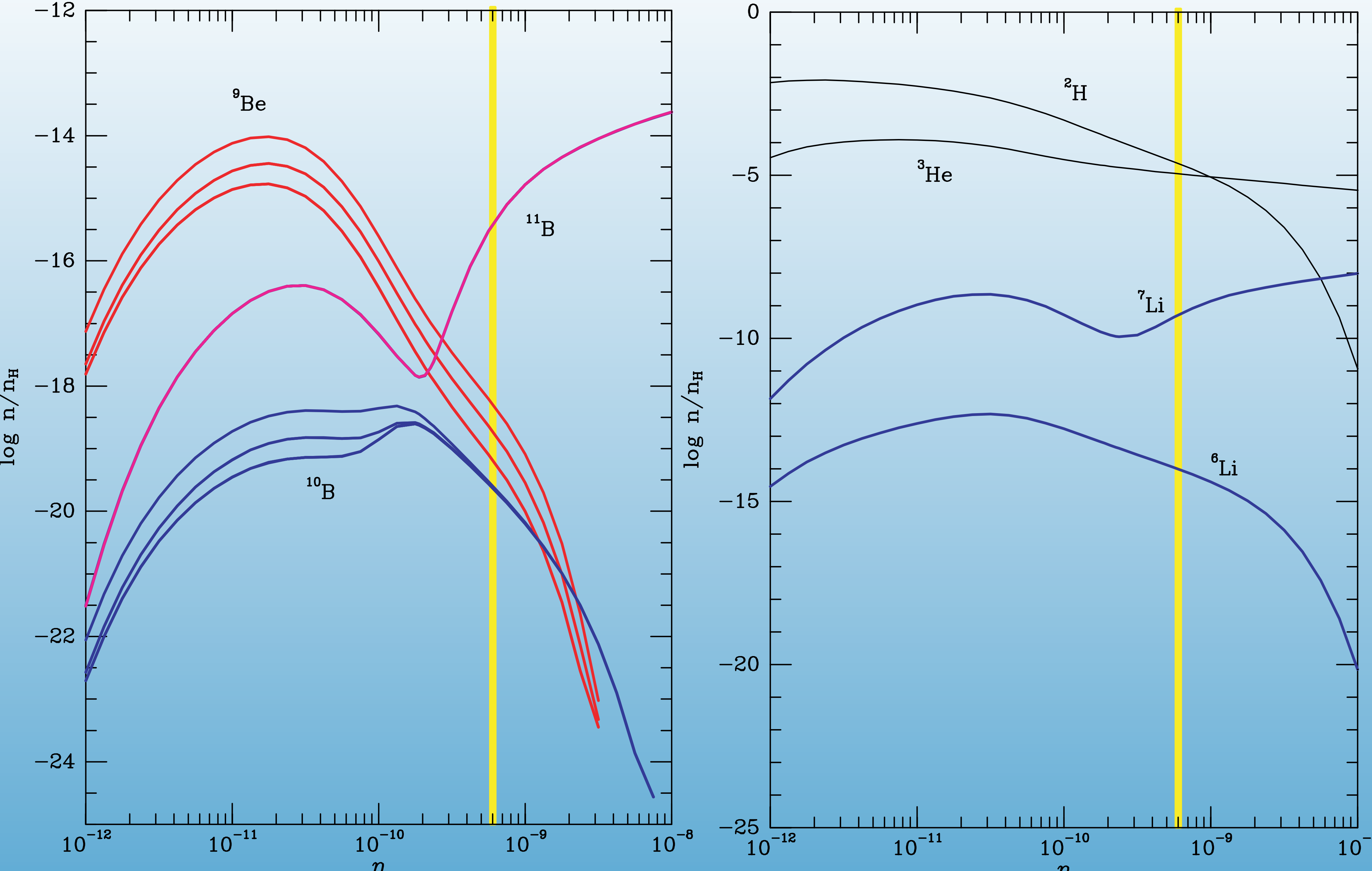
Far Below the observed values in Pop II stars

^{6}Li/H $\approx$ few $\times 10^{-12}$

^{9}Be/H $\sim 1 - 10 \times 10^{-13}$ B/H $\sim 1 - 10 \times 10^{-12}$

These are not BBN produced.

GCR Nucleosynthesis



−12
−14
−16
−18
−20
−22
−24
^{9}Be
^{11}B
^{10}B
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
η
log n/n_H
0
−5
−10
−15
−20
−25
^{2}H
^{3}He
^{7}Li
^{6}Li

^{6}Li

In the happy but not too distant past:

$$^6\mathbf{Li}\ (\mathbf{@}\ [\mathbf{Fe/H}] \sim -2.3)\mathbf{:}$$

$$\mathbf{HD\ 84937:\ ^6Li/Li = 0.054 \pm 0.011}$$

$$\mathbf{BD}\ 26^o3578\mathbf{:\ ^6Li/Li = 0.05 \pm 0.03}$$

SLN

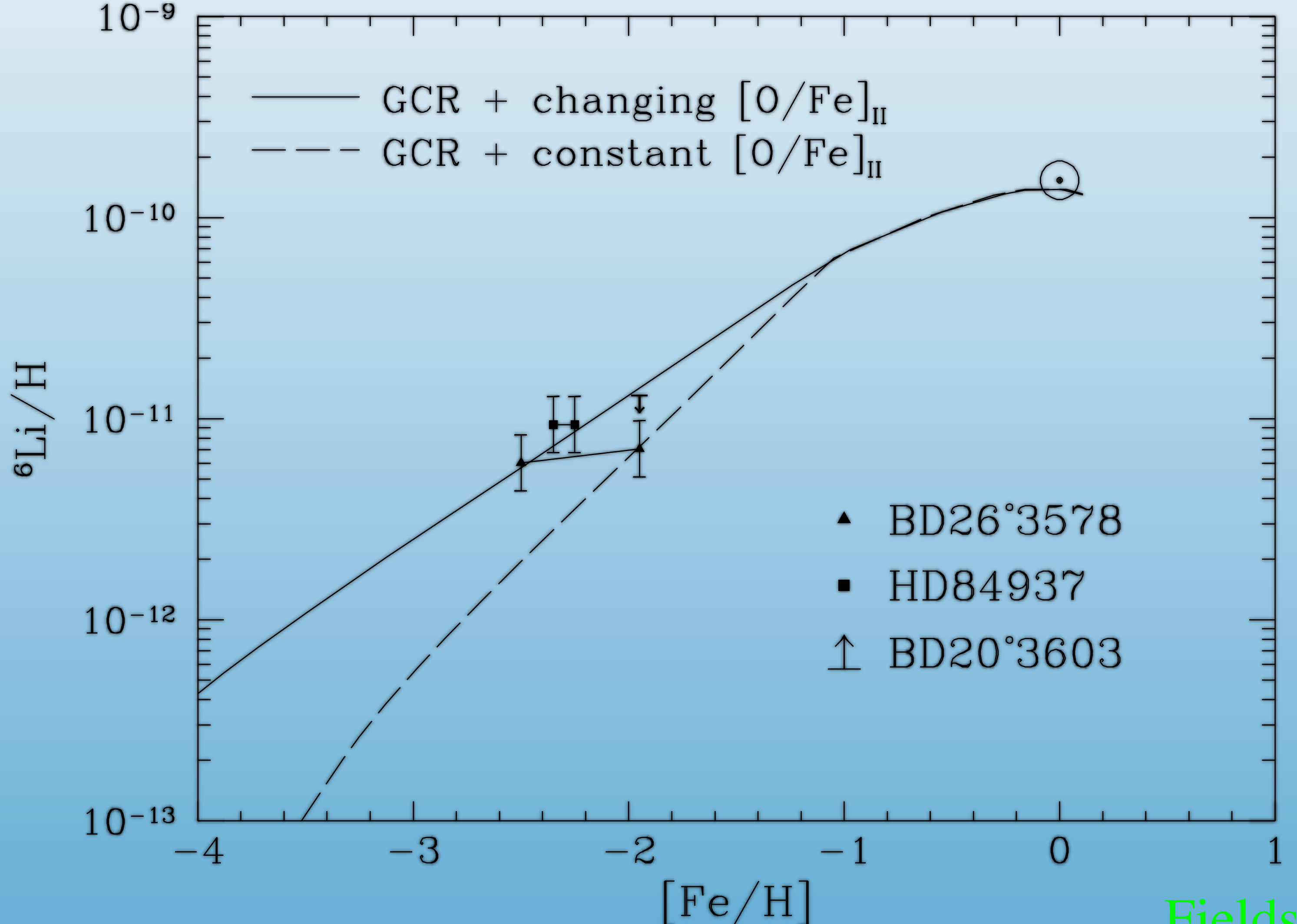
Hobbs & Thorburn

Cayrel etal

cf. BBN abundance of about ^{6}Li/H = 10^{-14}

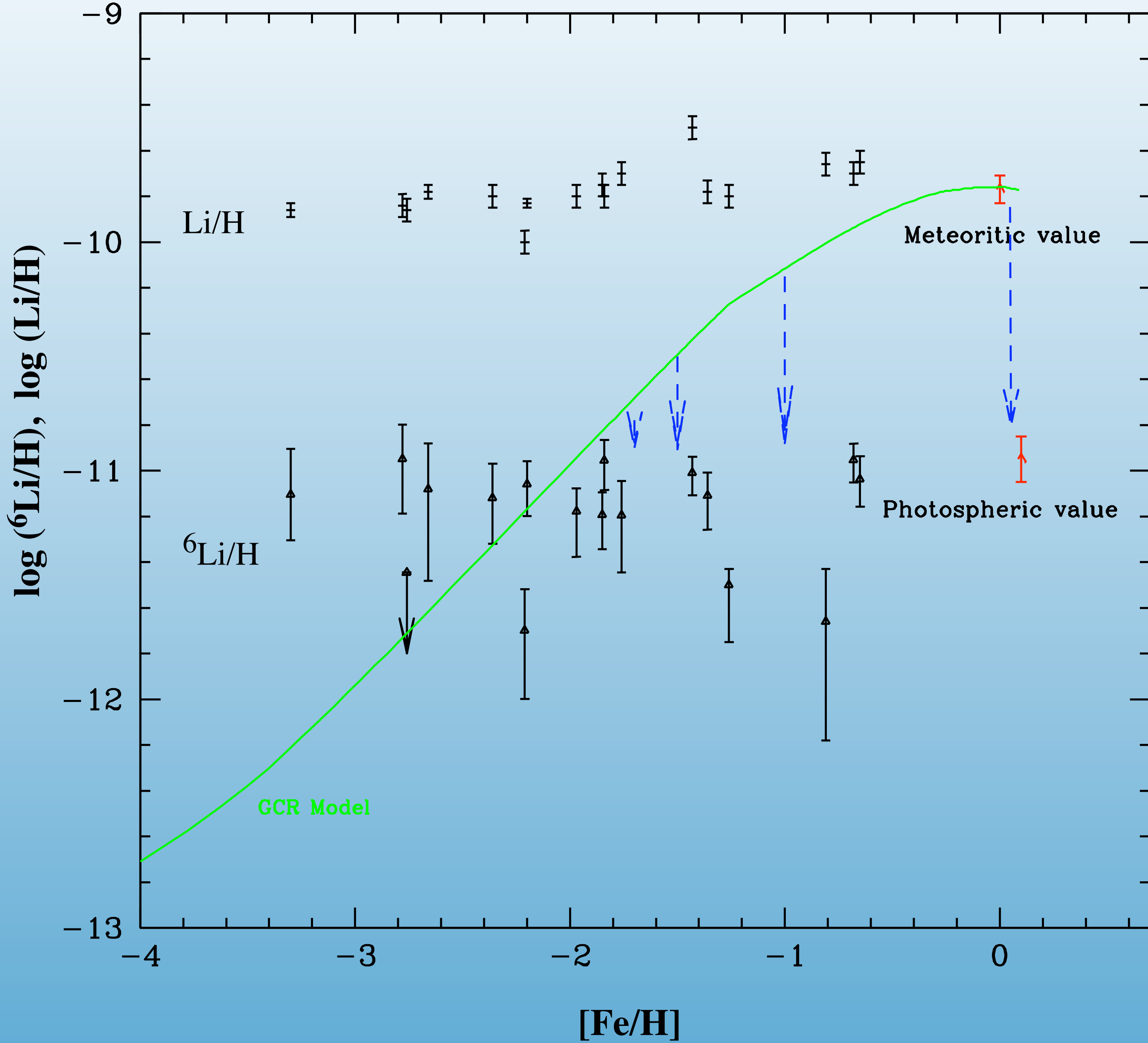
or ^{6}Li/Li < 10^{-4}

These data nicely accounted for by Galactic Cosmic Ray Nucleosynthesis



Fields and Olive
Vangioni et al.

Problem 2: There appears to be a ^{6}Li plateau

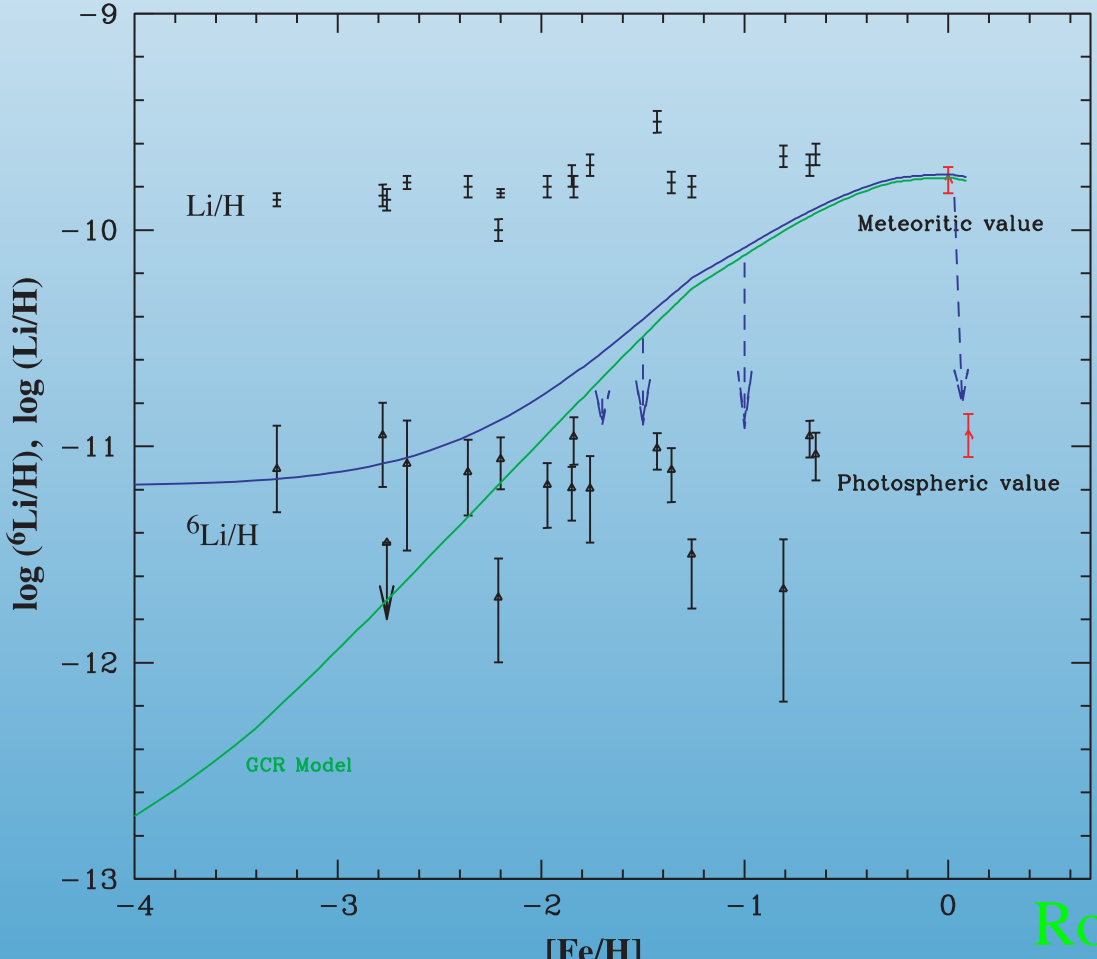


Data from Asplund et al and Inoue

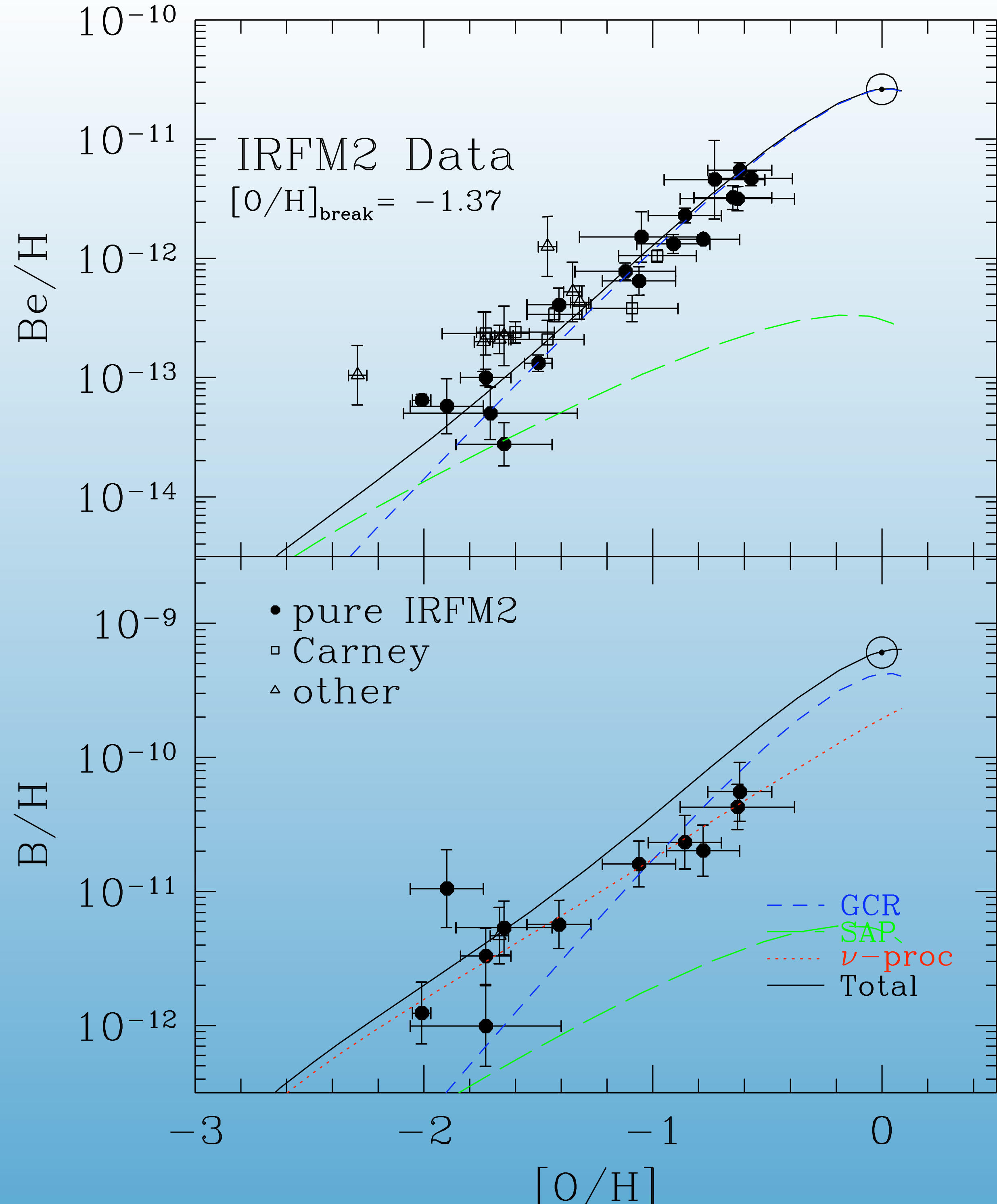
Possible Solutions

1. Particle decays - could solve both Li isotope problems

2. Cosmological Cosmic Rays



Rollinde, Vangioni, Olive



GCRN production of Be and B including primary and secondary sources

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)