Title: Big Bang Nucleosynthesis: Concordance of Theory and Observations

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Abstract:

Big Bang Nucleosynthesis: Concordance of Theory and Observations

- 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

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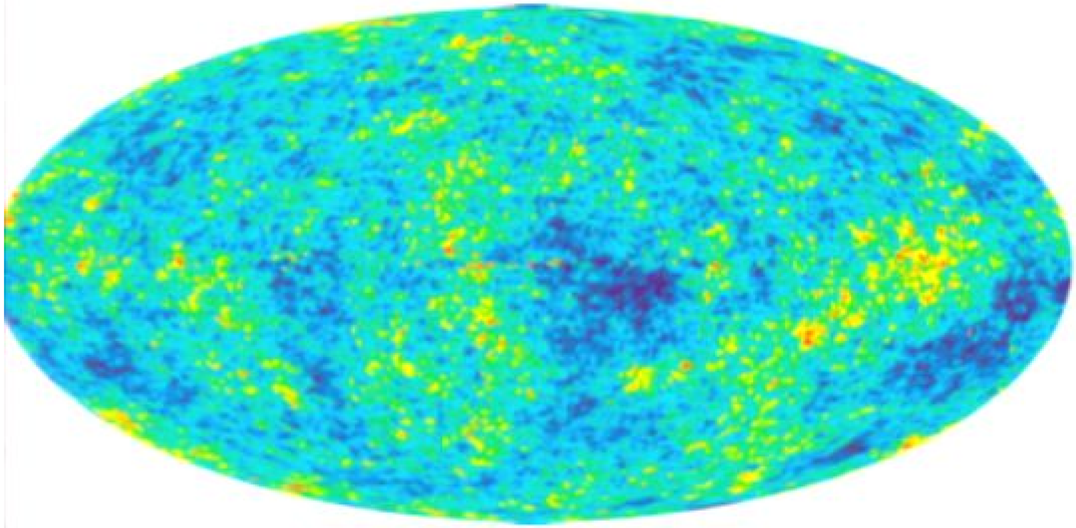
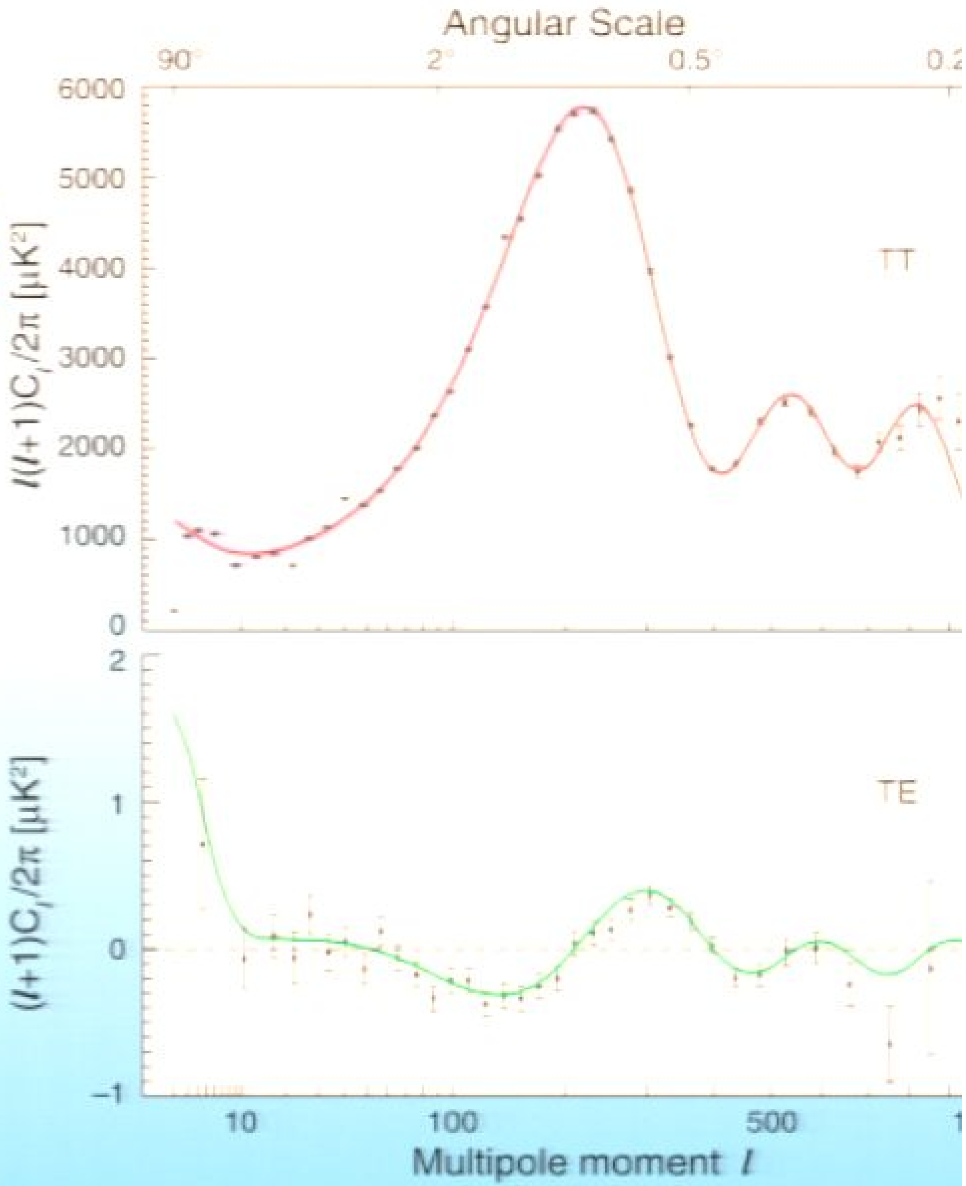




WMAP best fit

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

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

Conditions in the Early Universe:

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

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

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

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 $\Gamma \sim G_F^2 T^5$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$n + \nu_e \leftrightarrow p + e^-$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

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

Nucleosynthesis Delayed
(Deuterium Bottleneck)

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

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

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

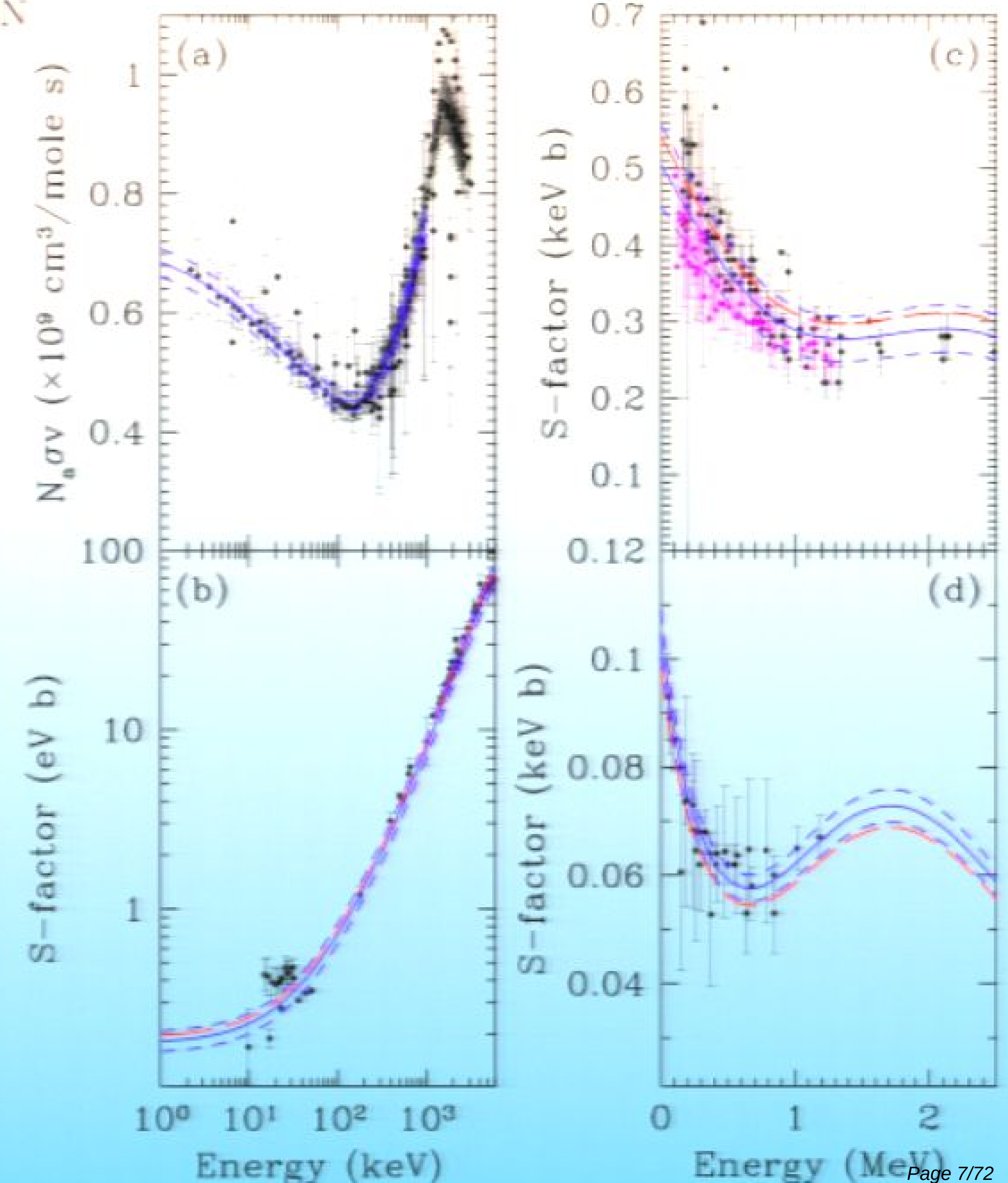
$$Y_p = \frac{2(n/p)}{1 + (n/p)} \simeq 25\%$$

Remainder:

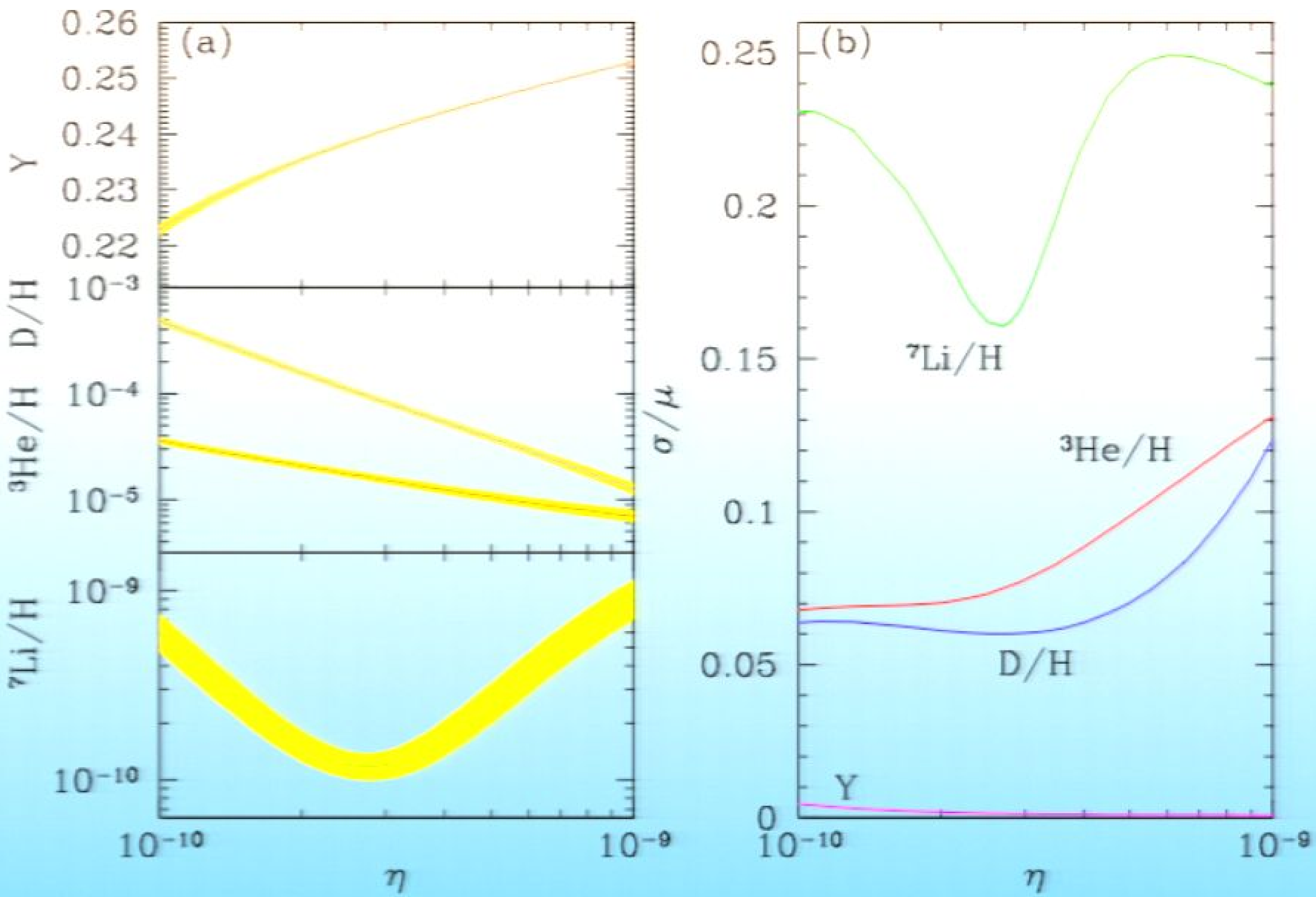
D, ^{3}He $\sim 10^{-5}$ and ^{7}Li $\sim 10^{-10}$ by numbe

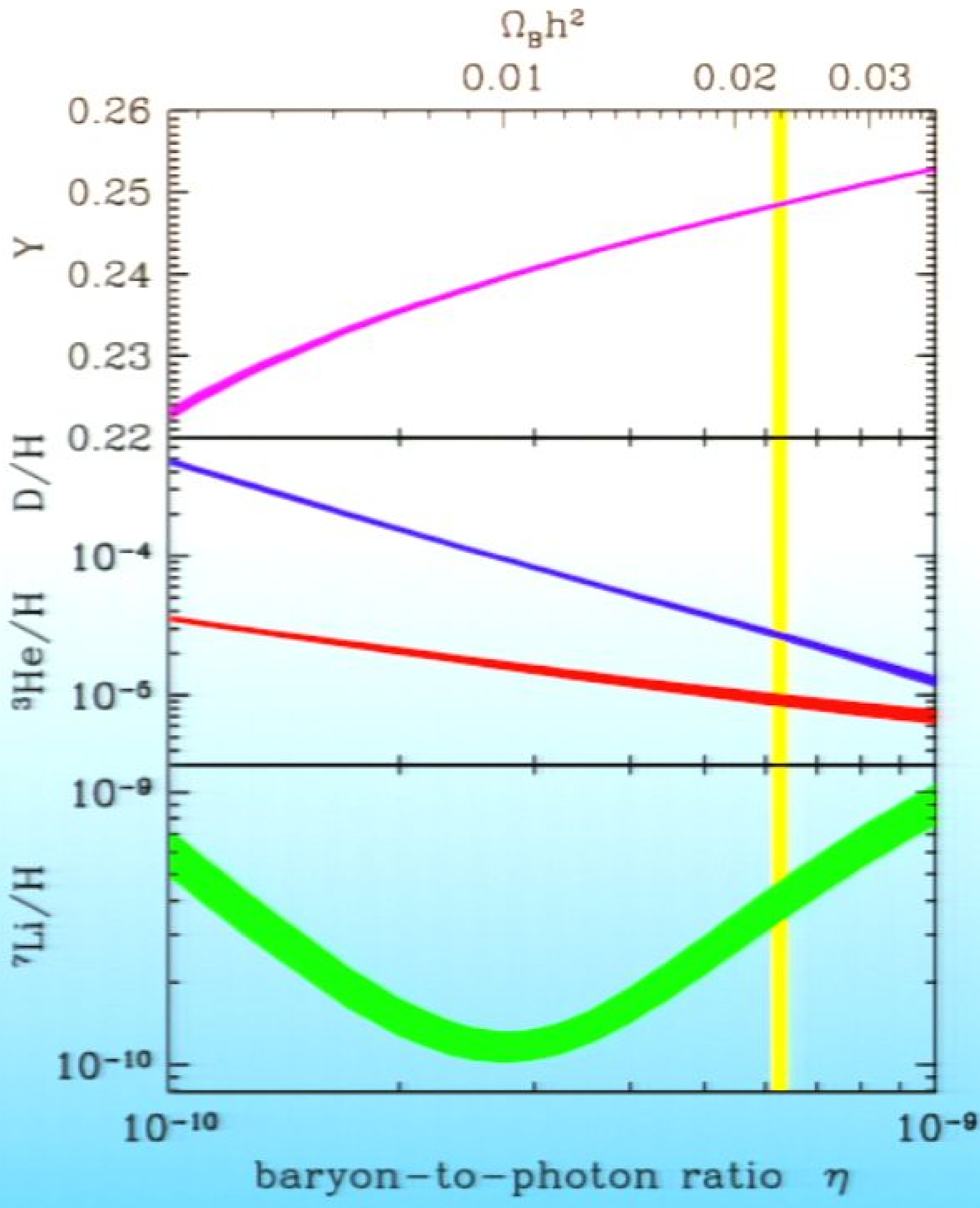
Table 1: Key Nuclear Reactions for BBN

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
D/H
^{3}He/H
^{7}Li/H
0.26
0.25
0.24
0.23
0.22
10^{-3}
10^{-4}
10^{-5}
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, ^{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

D/H

- All Observed D is Primordial!

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- Observed in the ISM and inferred from meteoritic samples (also HD in Jupiter)

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- D/H observed in Quasar Absorption systems

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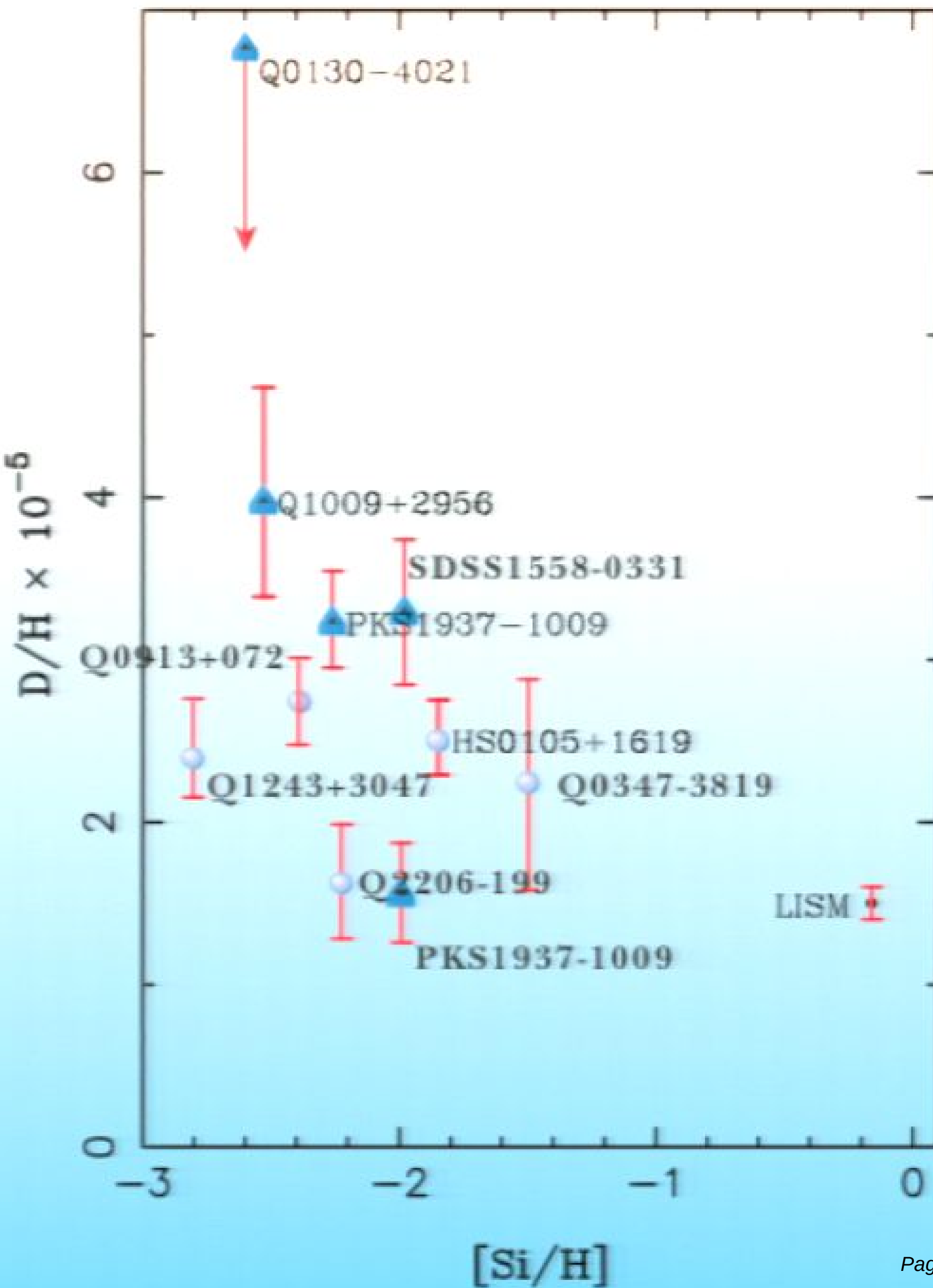
- D/H observed in Quasar Absorption systems

QSO	z_{em}	z_{abs}	log N(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



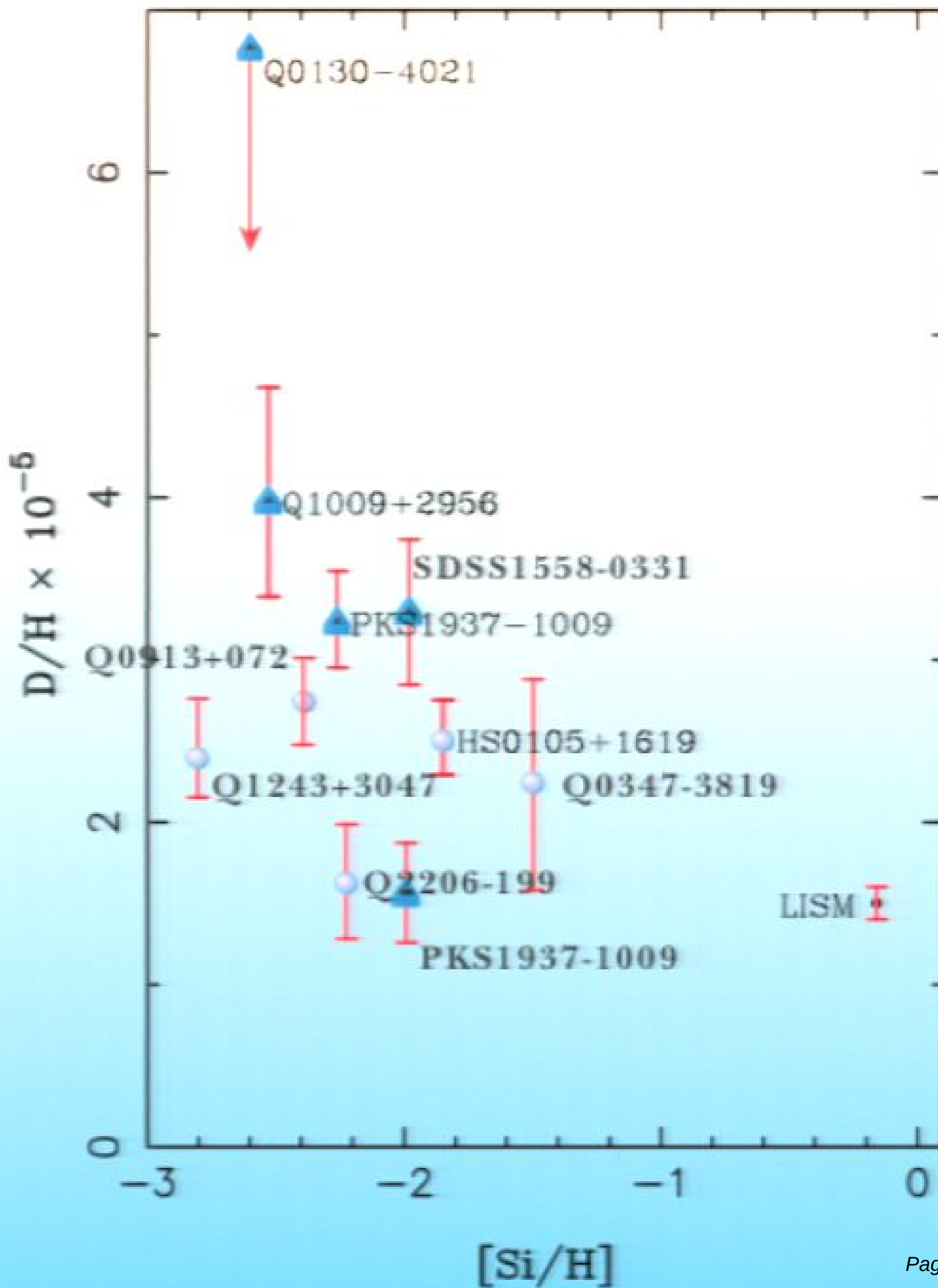
D/H abundances in Quasar apsorption systems

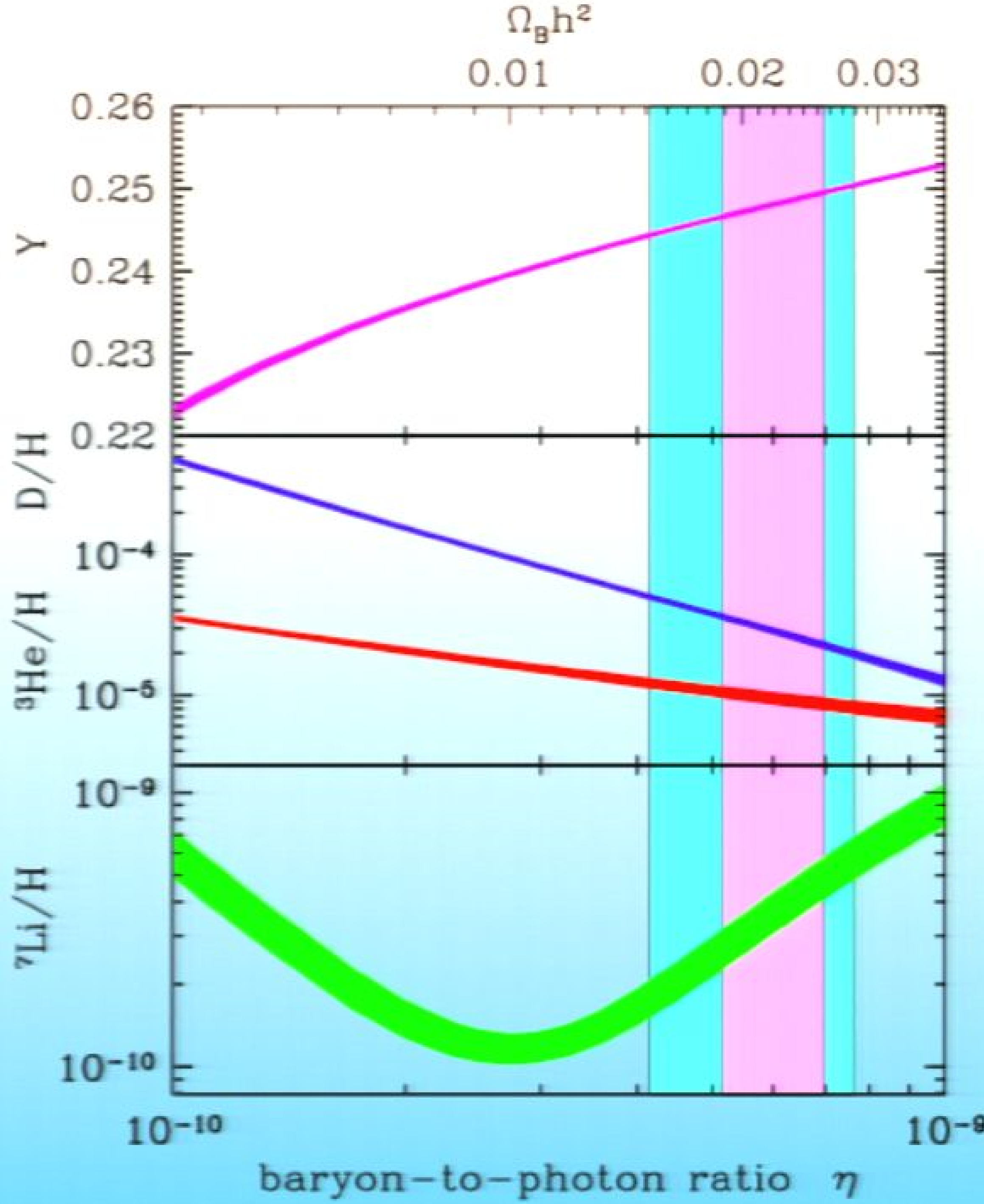
BBN Prediction:

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

Obs Average:

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





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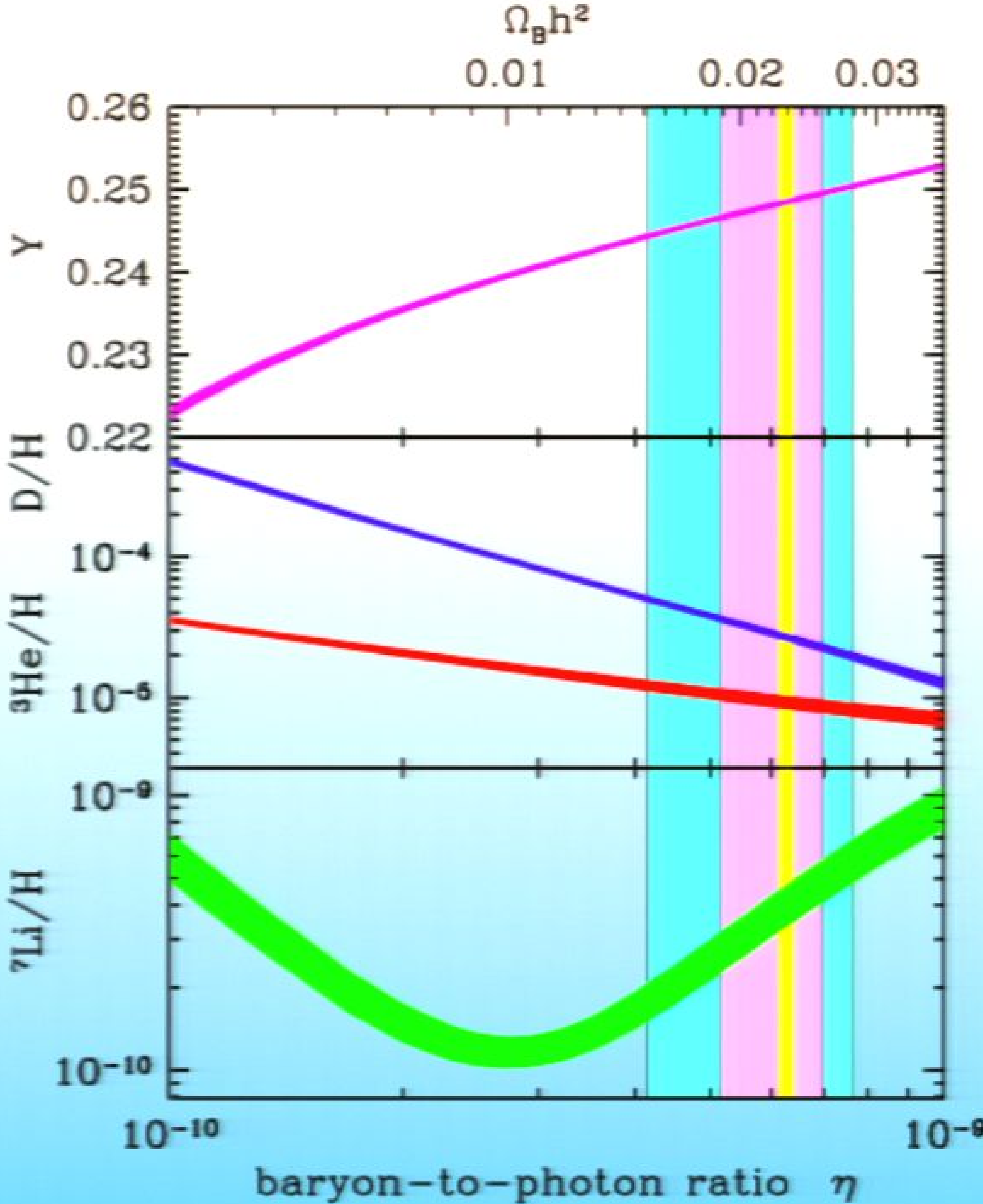
baryon–to–photon ratio η



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10^{-9}
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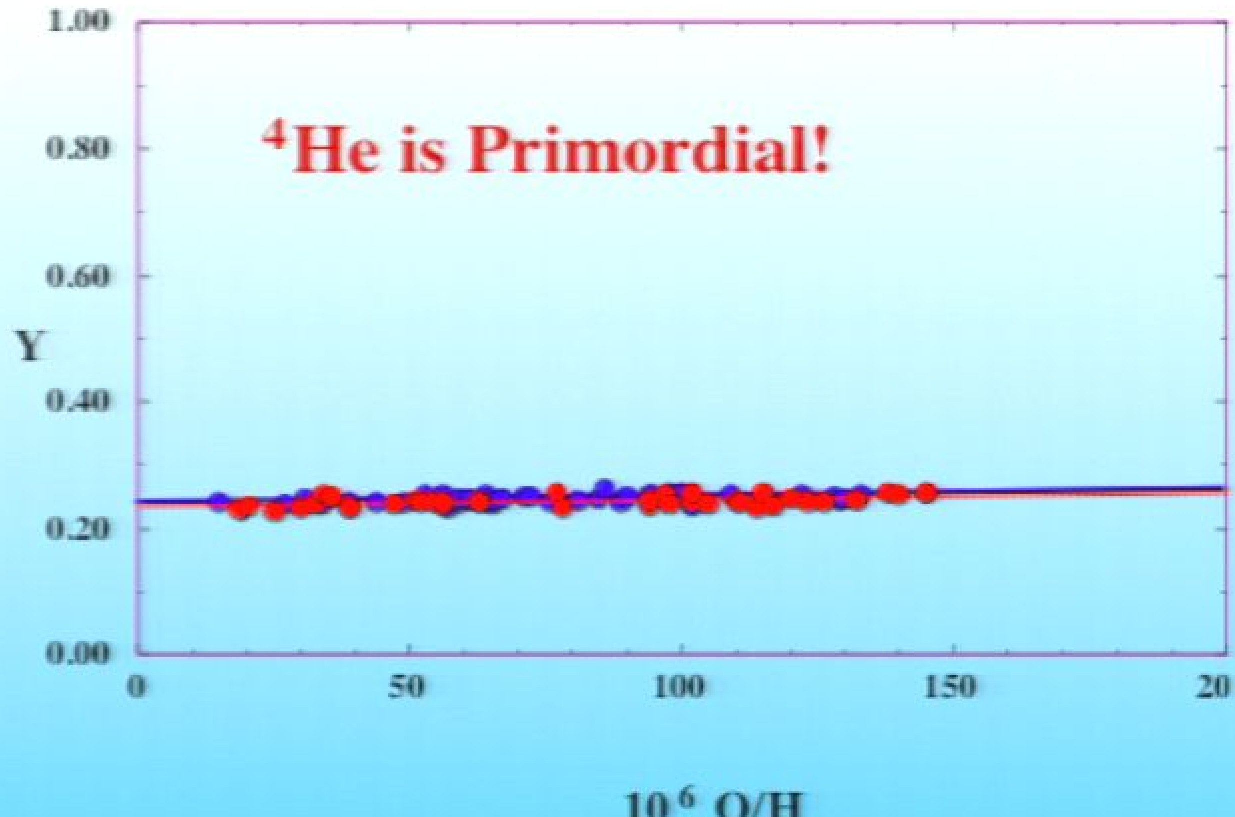
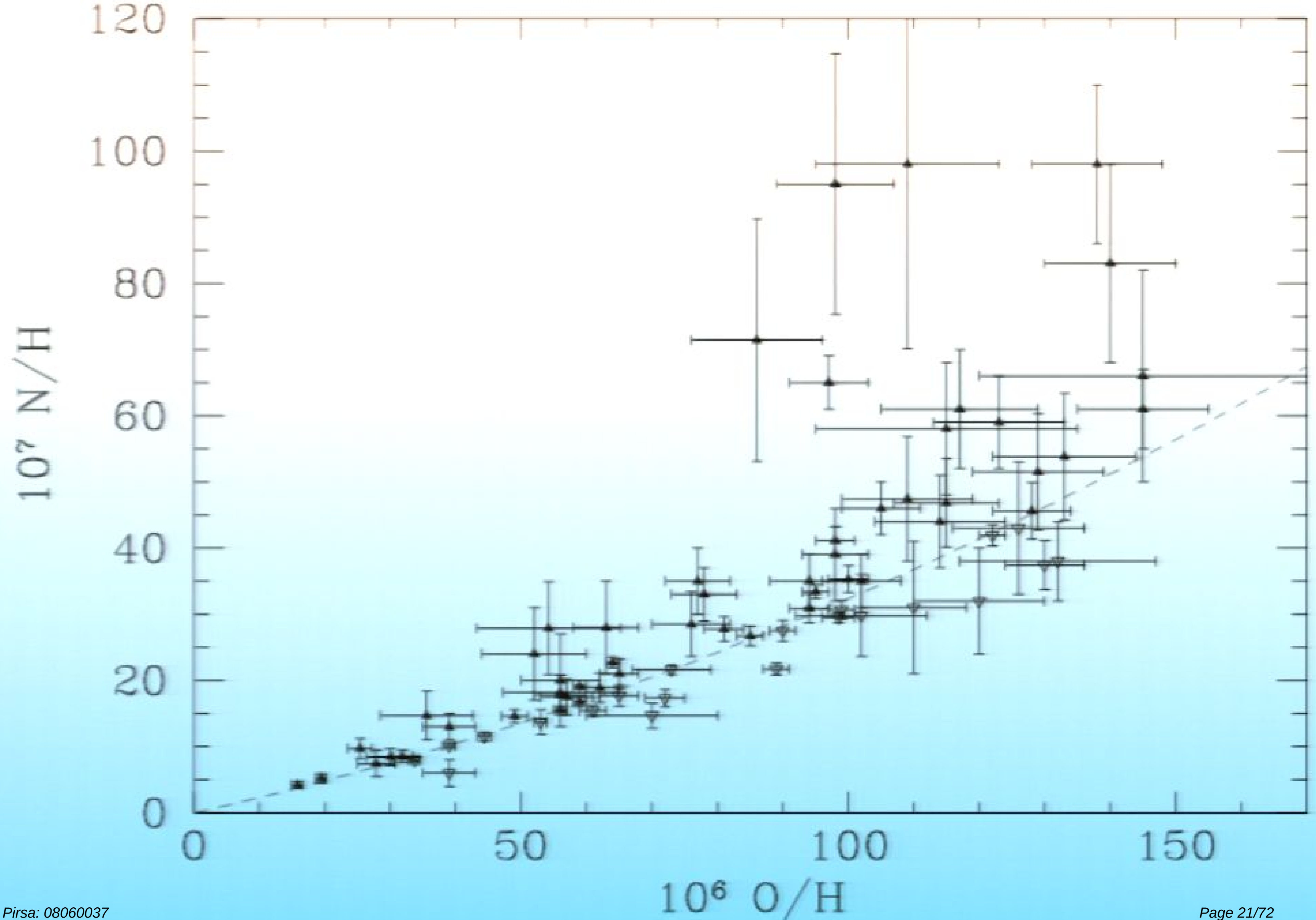
^{4}He

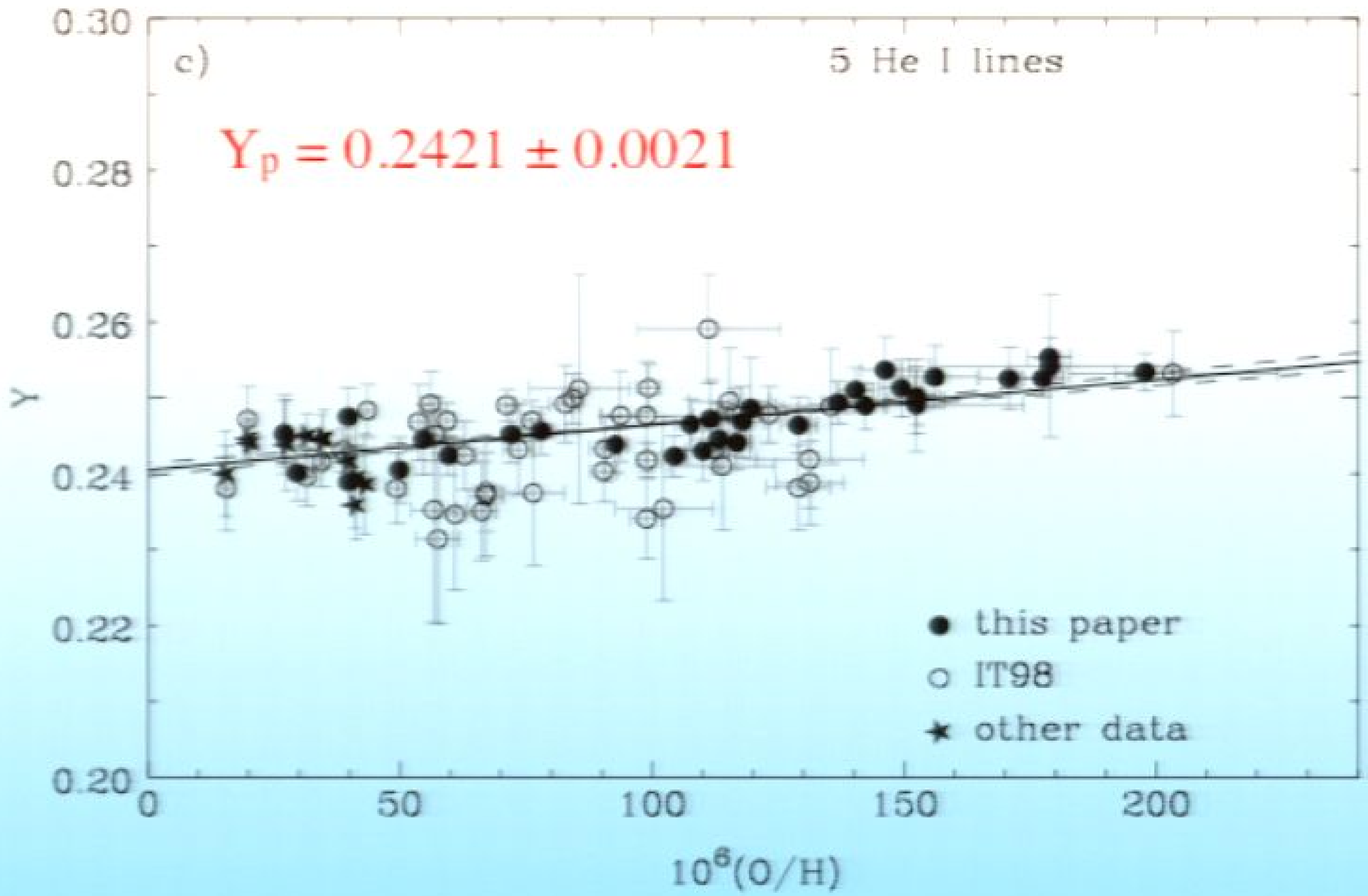
Measured in low metallicity extragalactic HII regions (~100) together with O/H and N/H

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




120
100
80
60
40
20
0
0
50
100
150
10^7 N/H
10^6 O/H

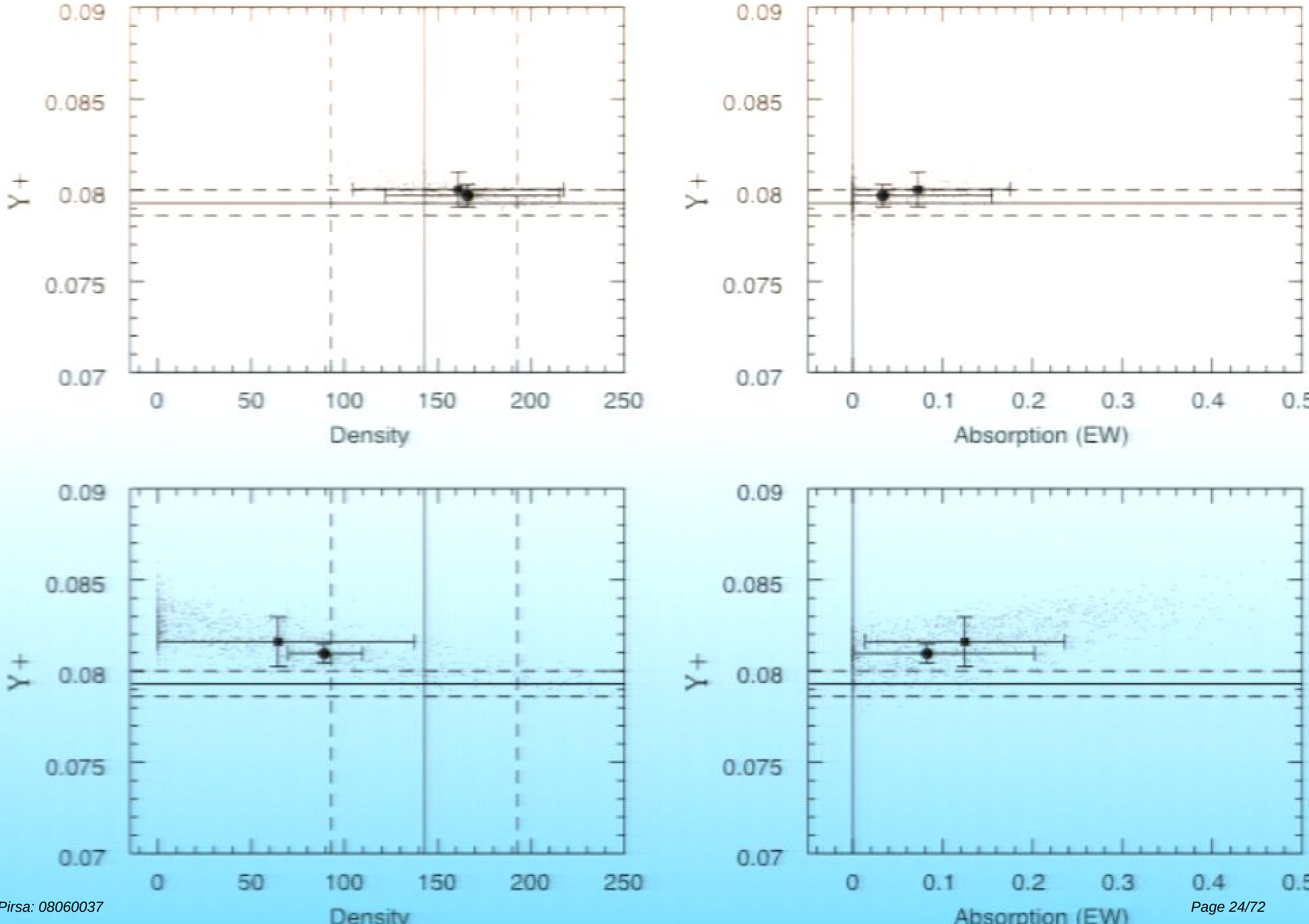
^{4}He



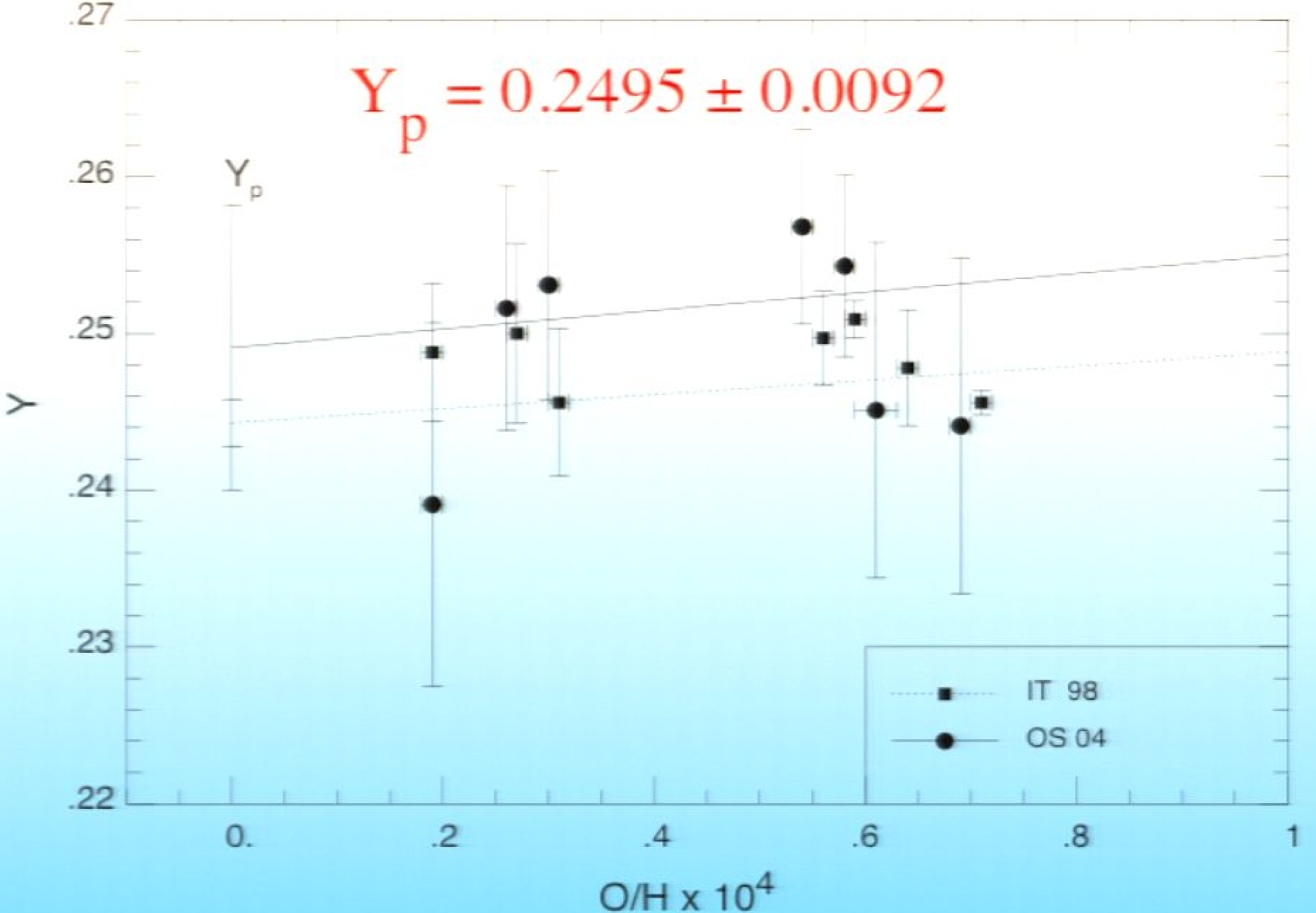
Izotov & Thuan

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
Y_p
0.
.2
.4
.6
.8
1
O/H x 10^4
IT 98
OS 04

Self-consistent H and He

- Determine H and He properties from 9 lines (6 He and 3 H) using MC

- (Preliminary) no new degeneracies but previous degeneracies remain.

Aver, Olive, Skillman

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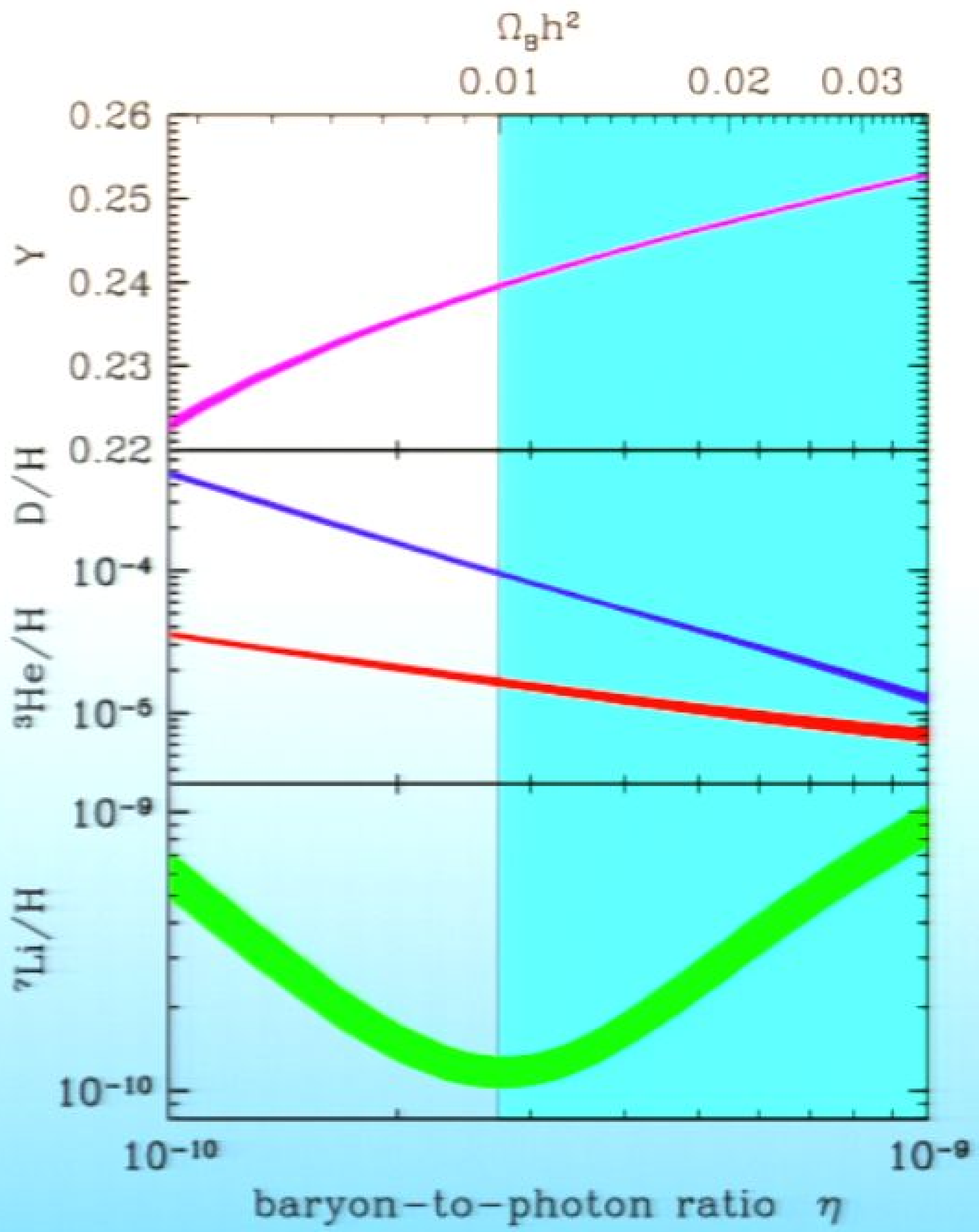
^{4}He Prediction: 0.2484 ± 0.0005

Data: Regression: 0.2495 ± 0.0092

Mean: 0.2520 ± 0.0030



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0.24
0.23
0.22
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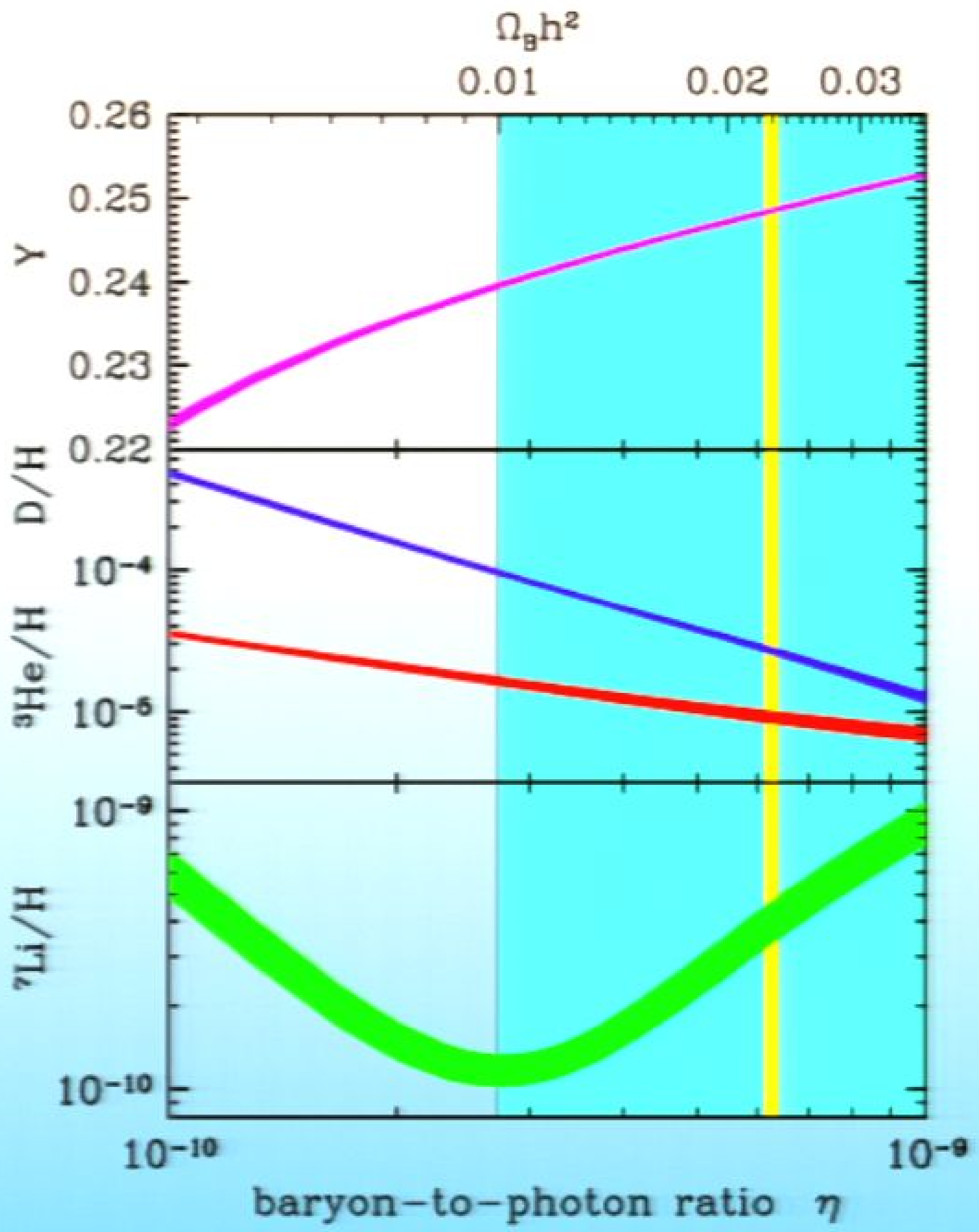
baryon–to–photon ratio η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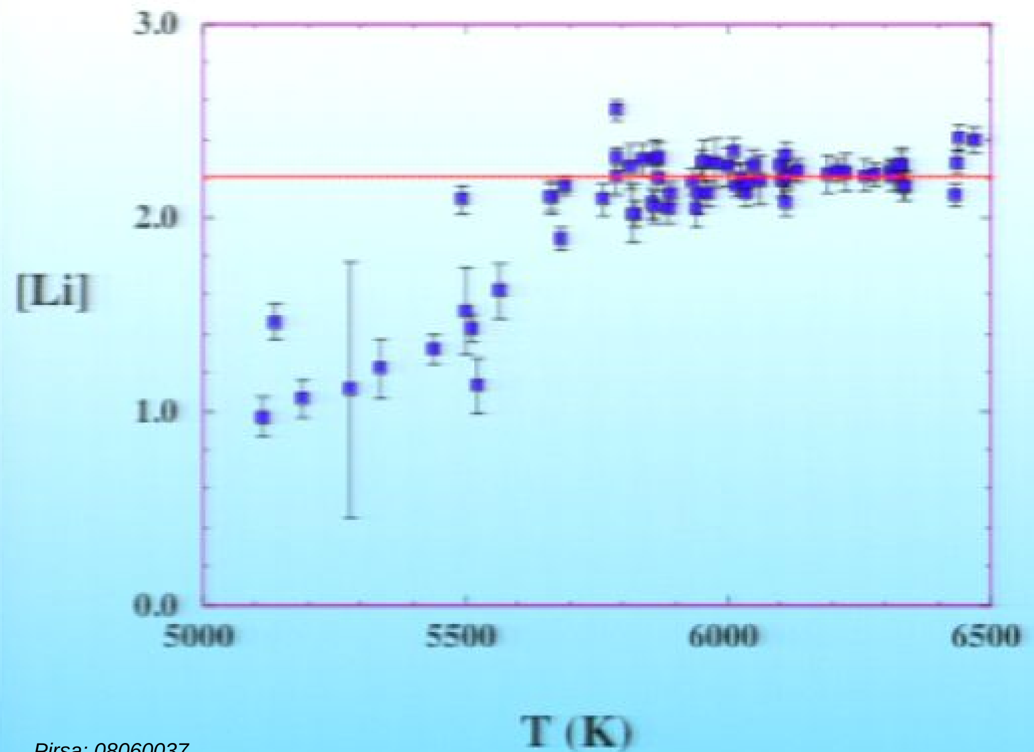
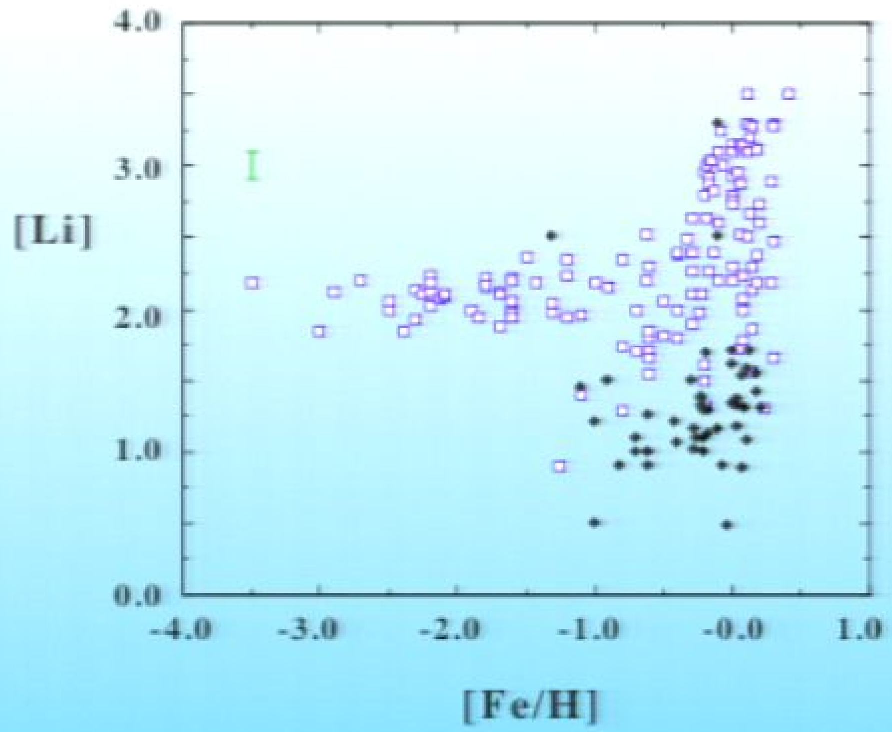
Li/H

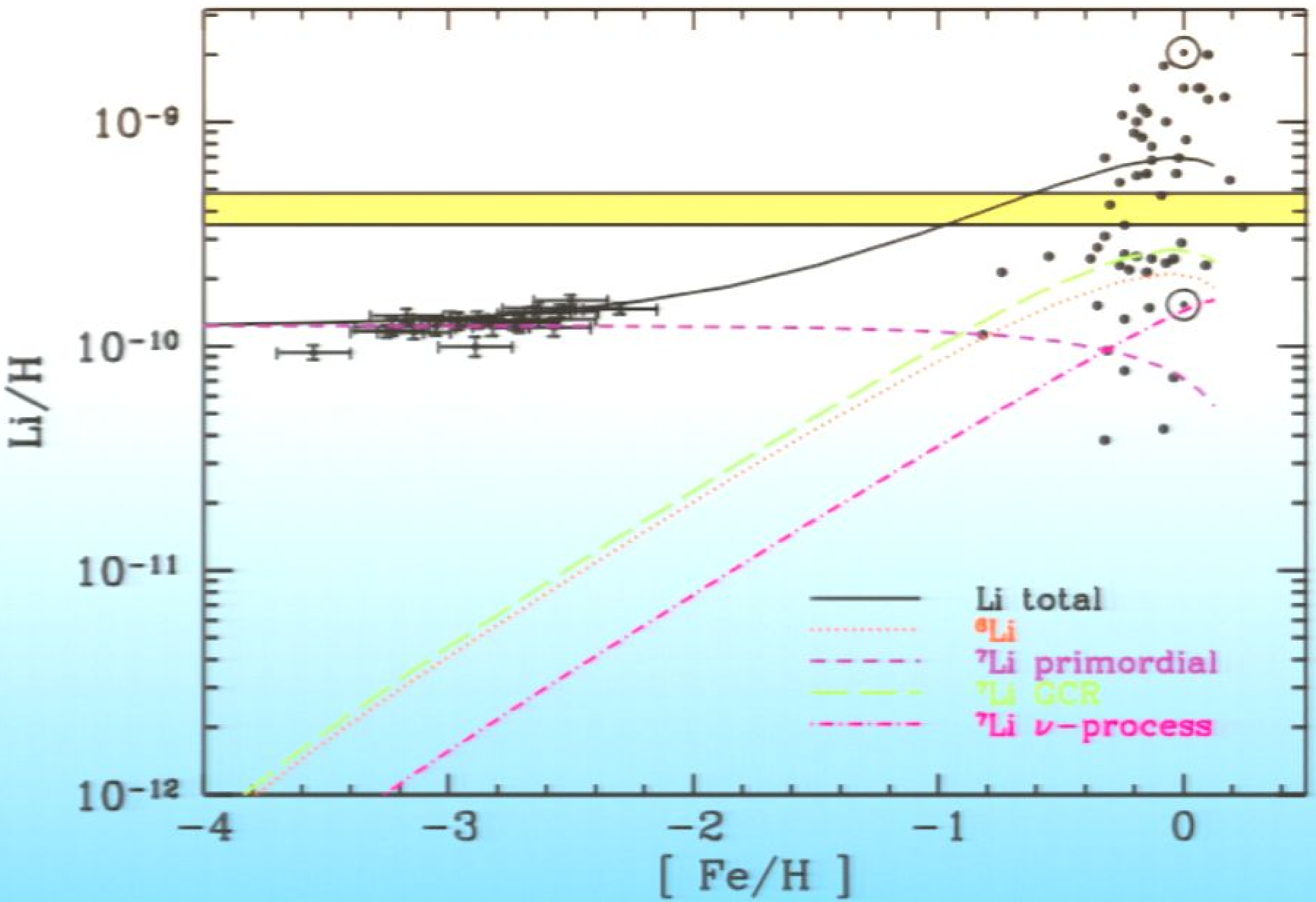
Measured in low metallicity dwarf halo stars (over 100 observed)





Li Woes

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



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

Possible sources for the discrepancy

- Stellar Depletion

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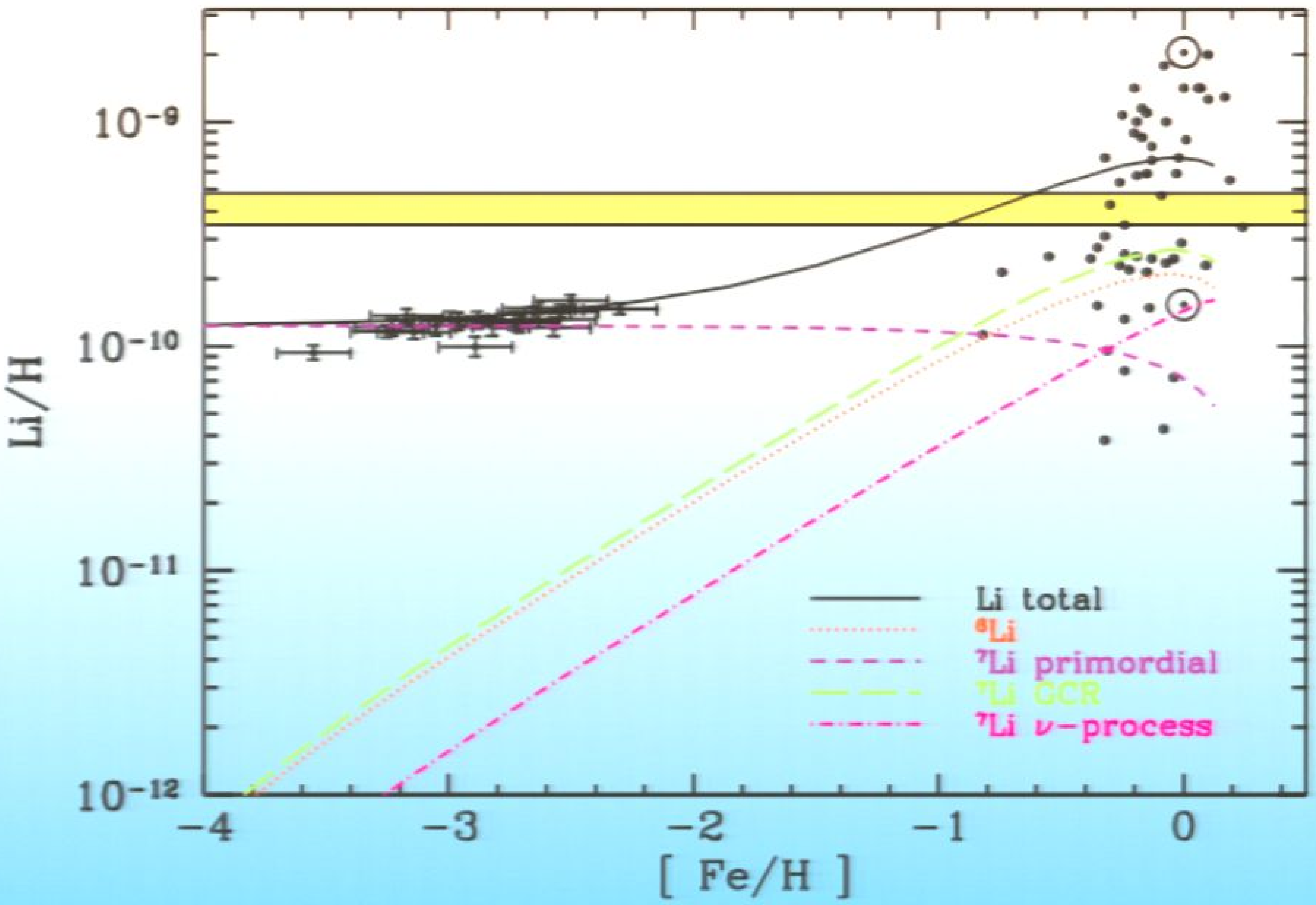
  - lack of dispersion in the data, ^6Li abundance



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- Stellar parameters

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

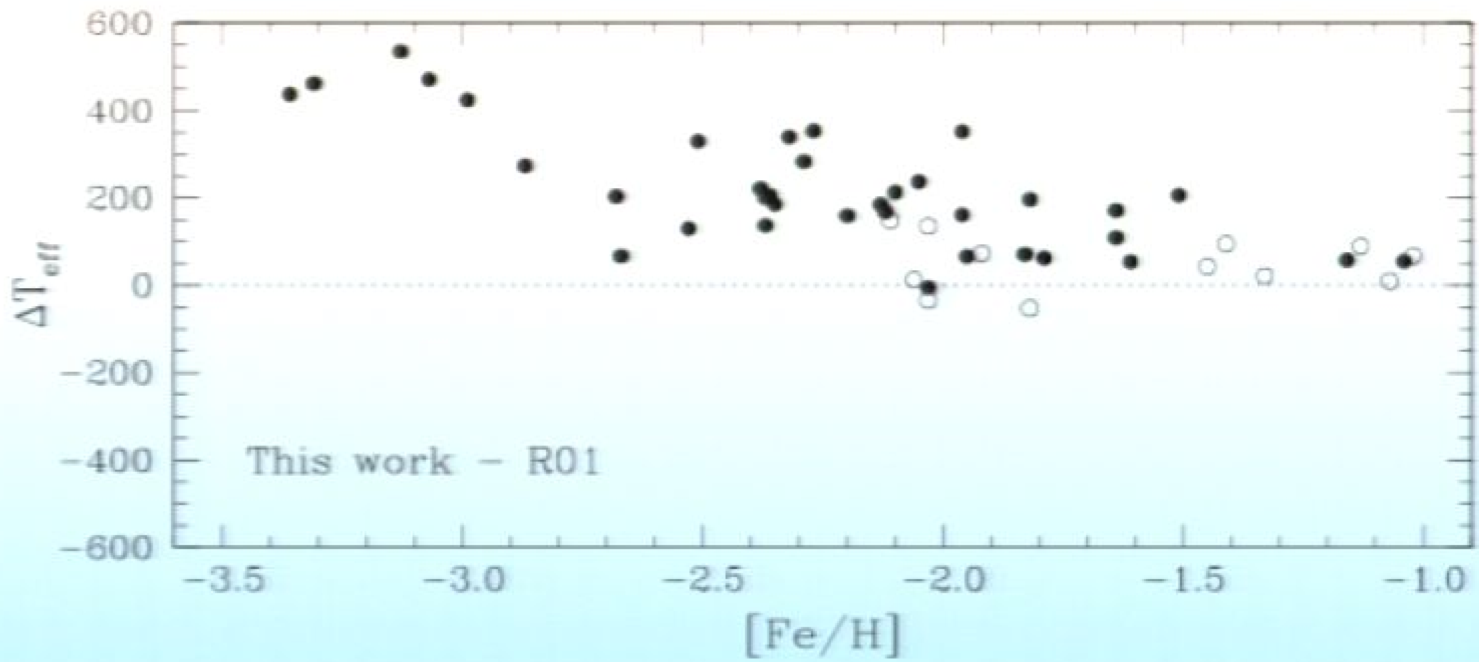
Jorge Meléndez[1] and Iván Ramírez[2]

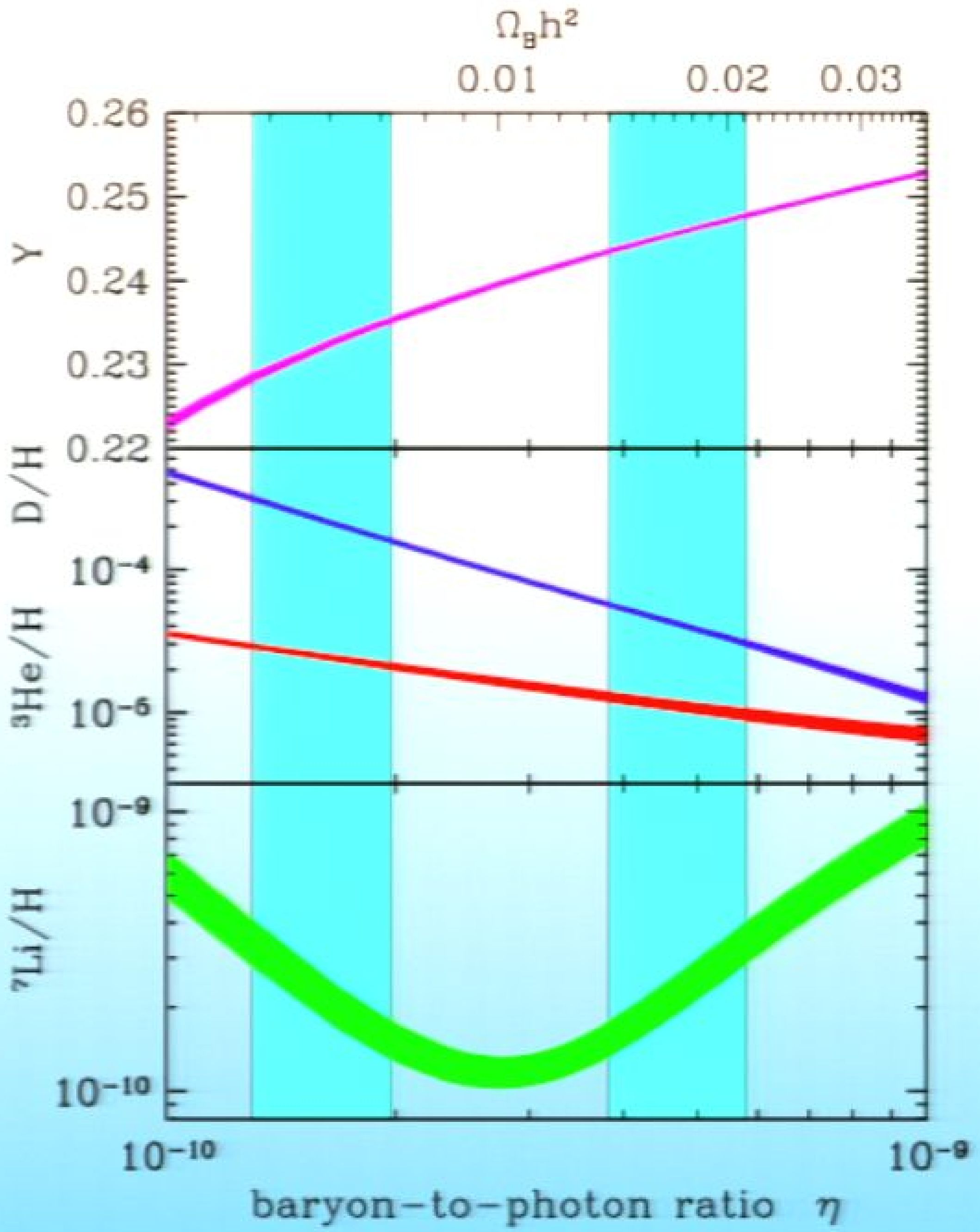
New evaluation of surface temperatures in 41 halo stars with systematically higher temperatures (100-300 K)

$$[Li] = 2.37 \pm 0.1$$

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

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]



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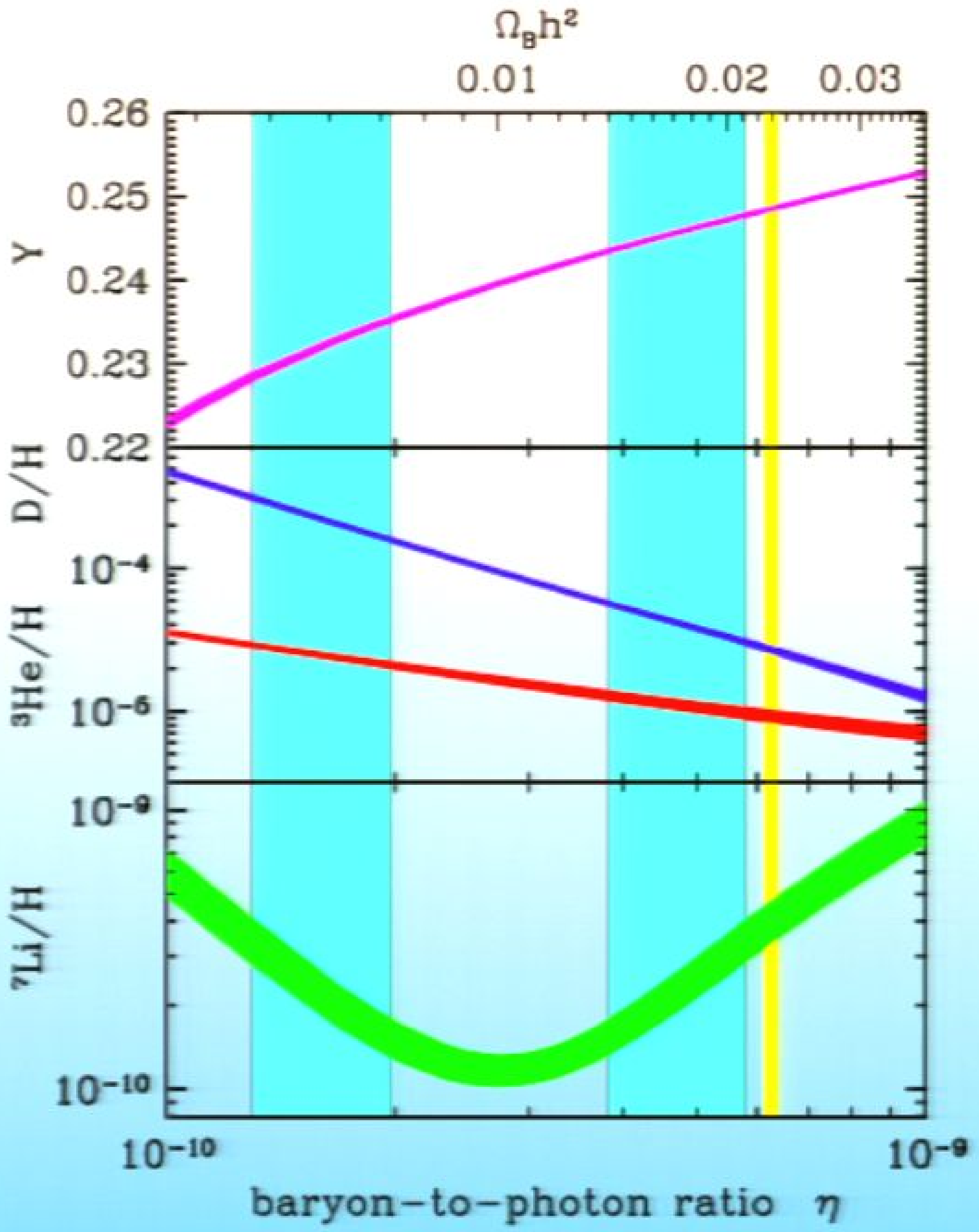
baryon−to−photon ratio η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10^{-4}
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10^{-5}
10^{-9}
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10^{-10}
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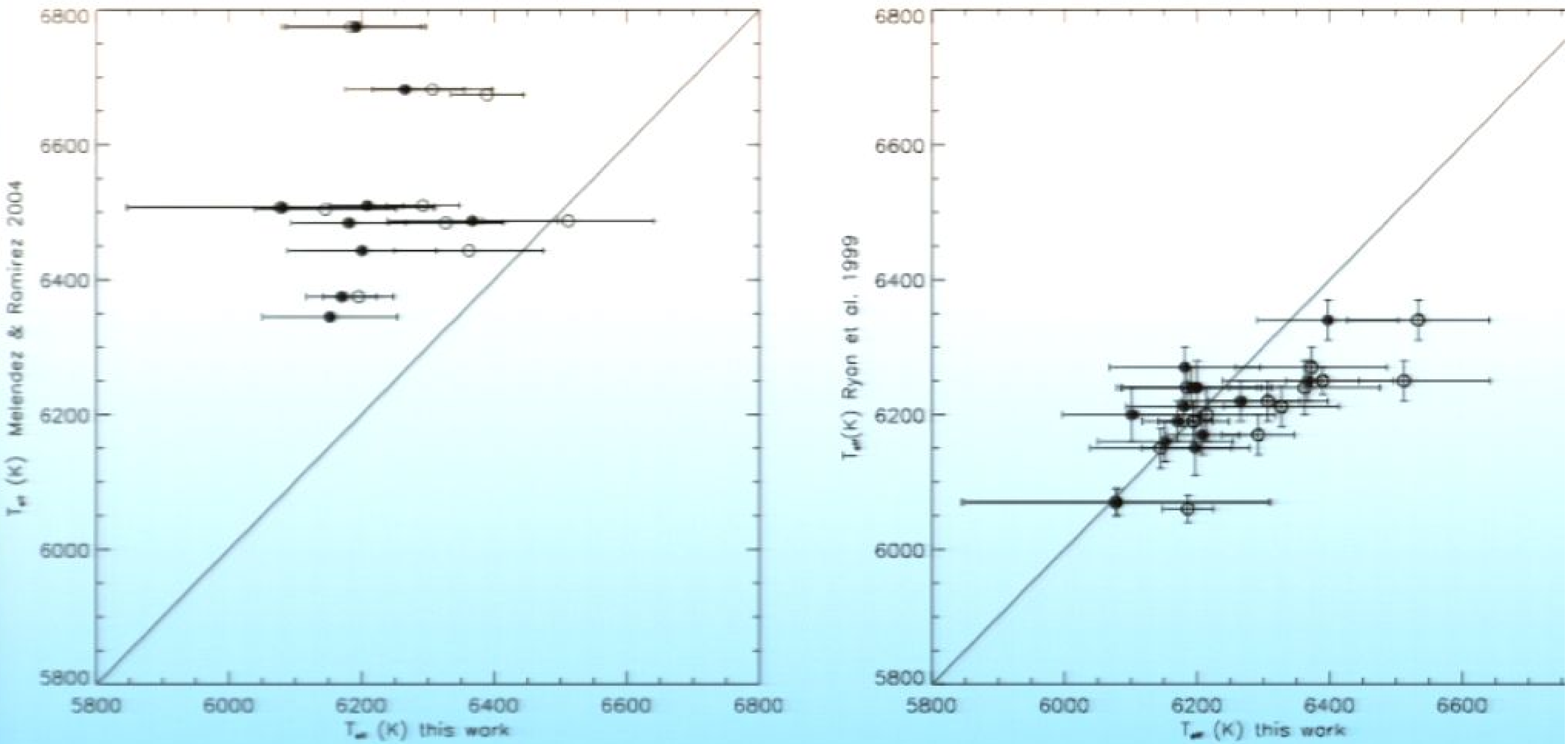
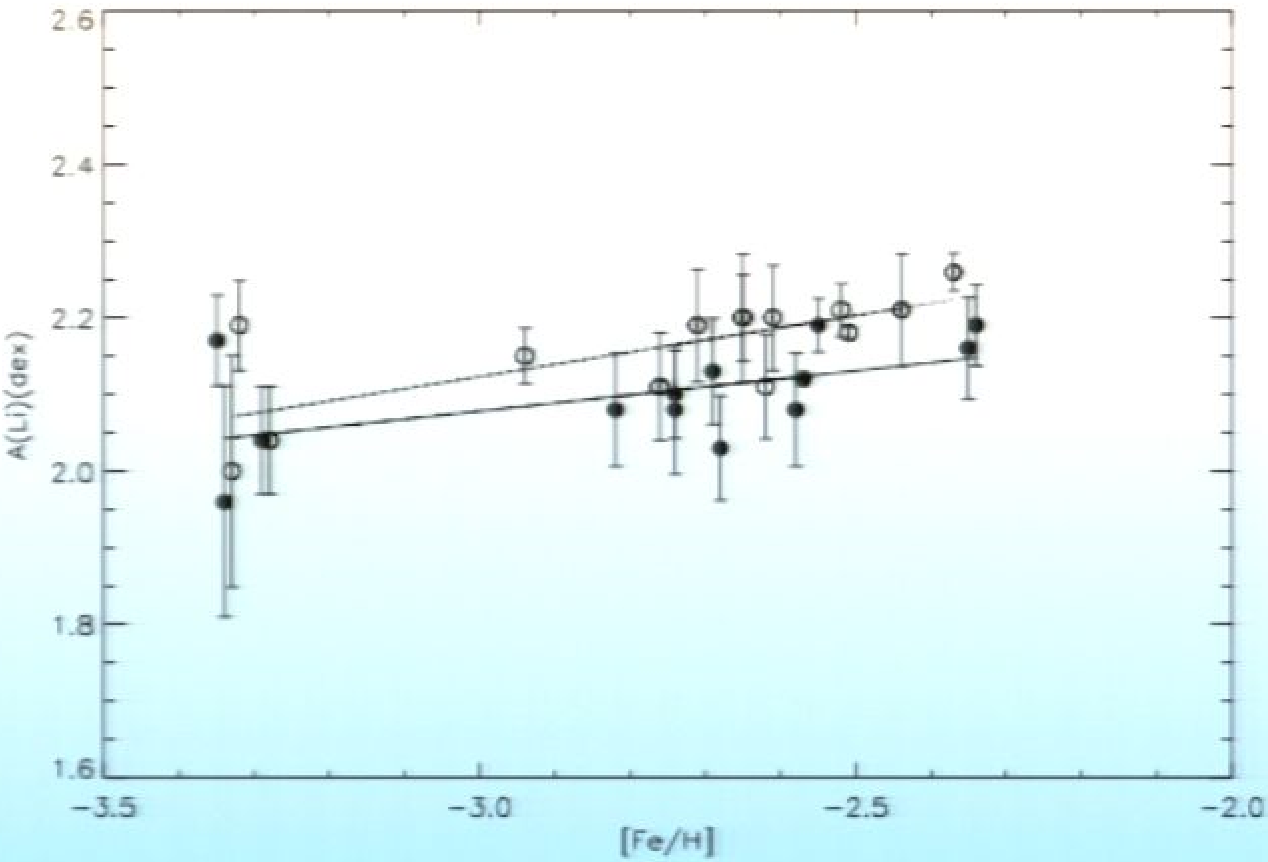
10^{-9}
baryon−to−photon ratio η

Recent dedicated temperature determinations (excitation energy technique)



Hosford, Ryan, Garcia-Perez, Norris, Oliv

Resulting Li:



$[Li] = 2.16 \pm 0.07$ MS

$= 2.10 \pm 0.07$ SGB

Hosford, Ryan, Garcia-Perez, Norris, Oliv

Possible sources for the discrepancy

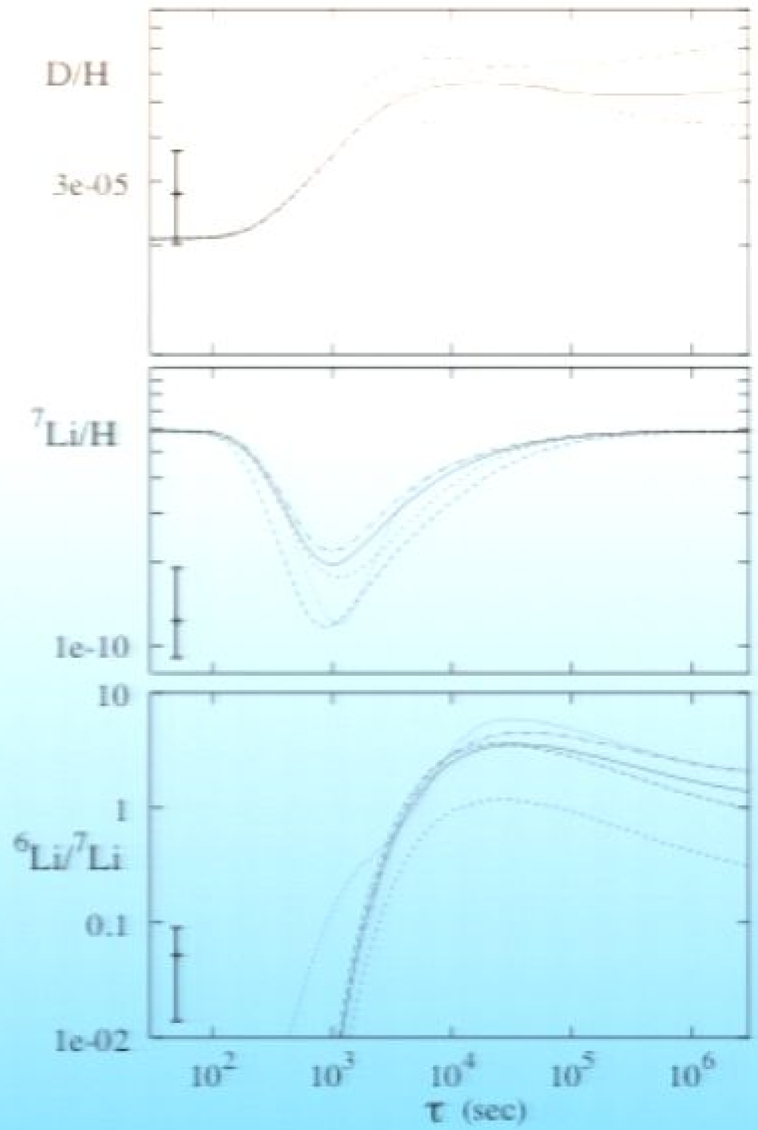
- Nuclear Rates
  - Restricted by solar neutrino flux

- Stellar parameters

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

- Particle Decays

Solution 1: Particle Decays



Jedamzik

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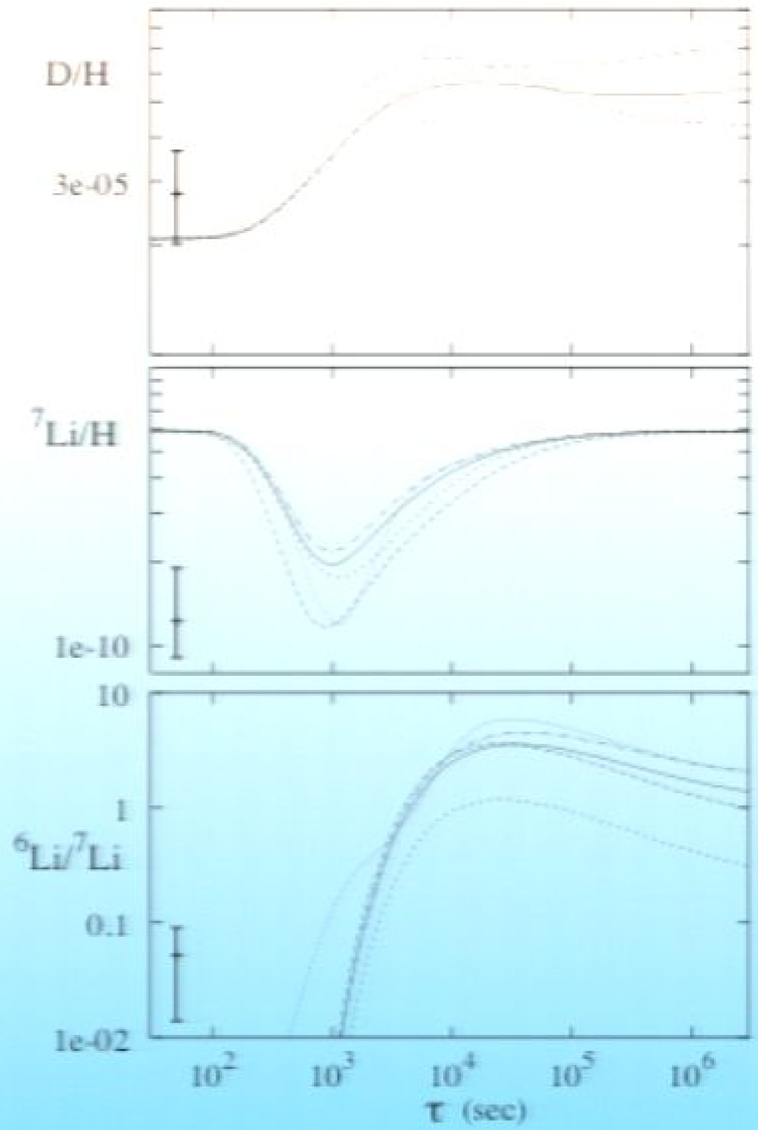


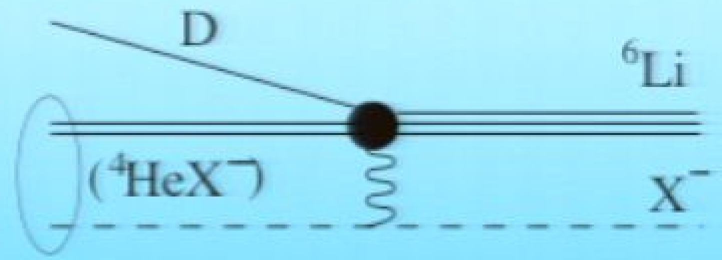
Jedamzik

Effects of Bound States

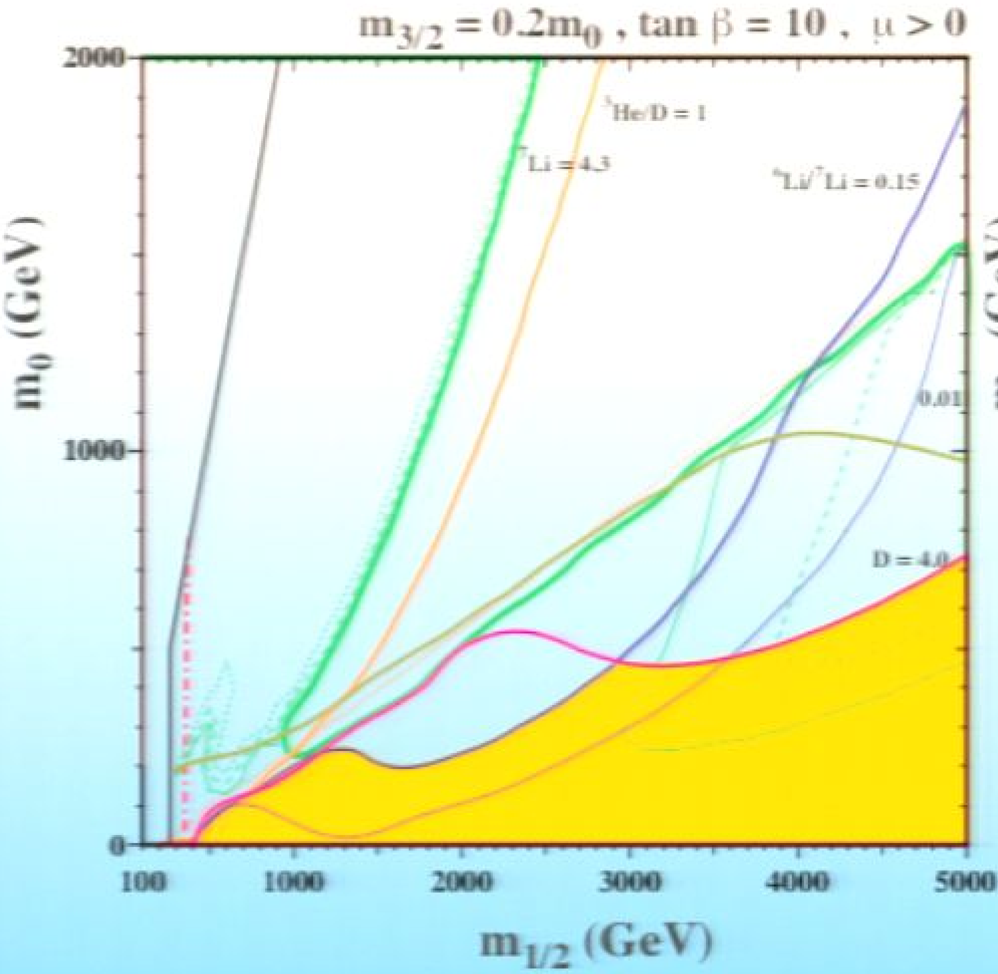
• In SUSY models with a $\tilde{\tau}$ NLSP, bound states form between ^{4}He and $\tilde{\tau}$

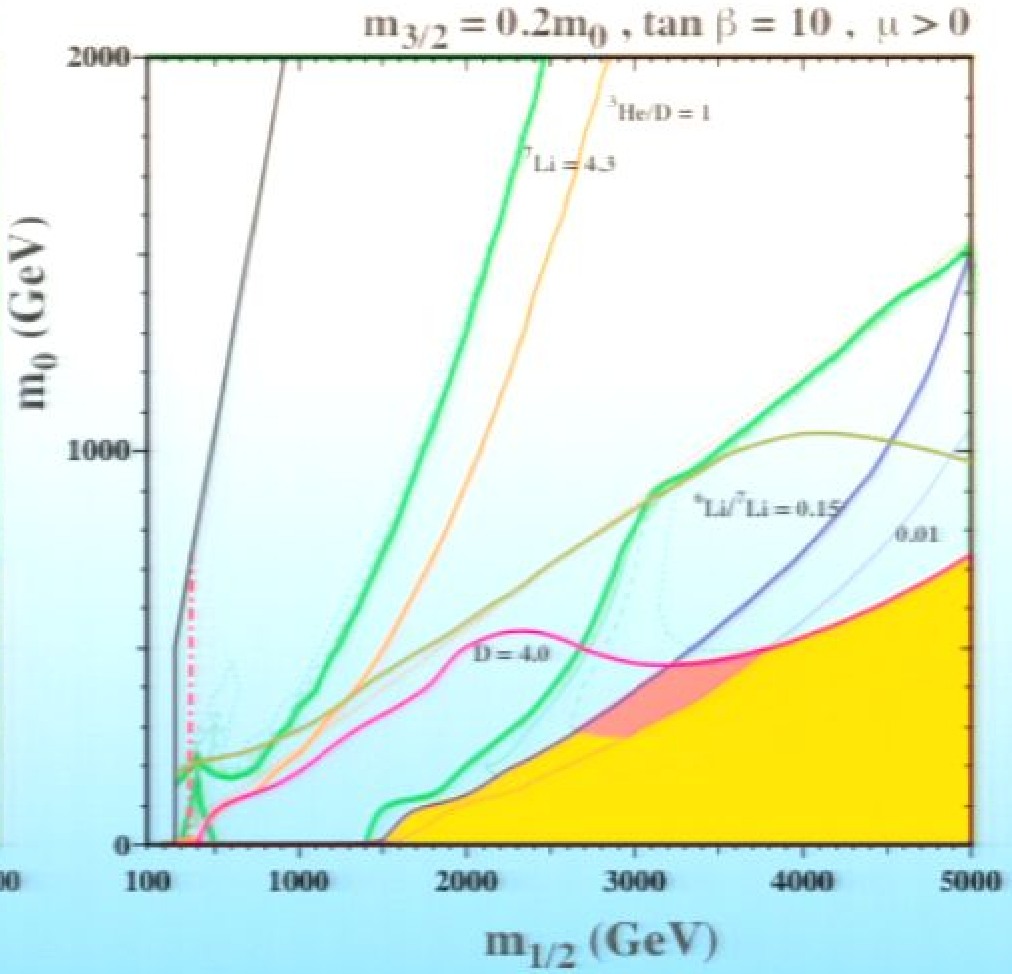
•The ^{4}He (D, γ) ^{6}Li reaction is normally highly suppressed (production of low energy γ)

•Bound state reaction is not suppressed



Pospelov





Cyburt, Ellis, Fields, KO, Span

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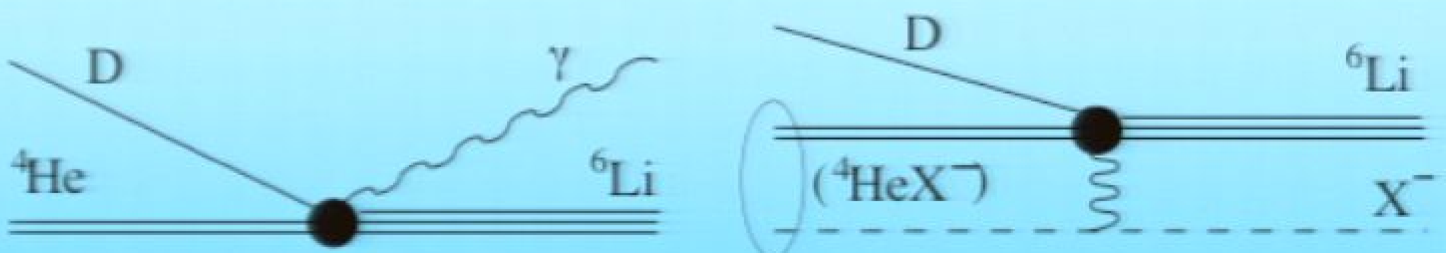
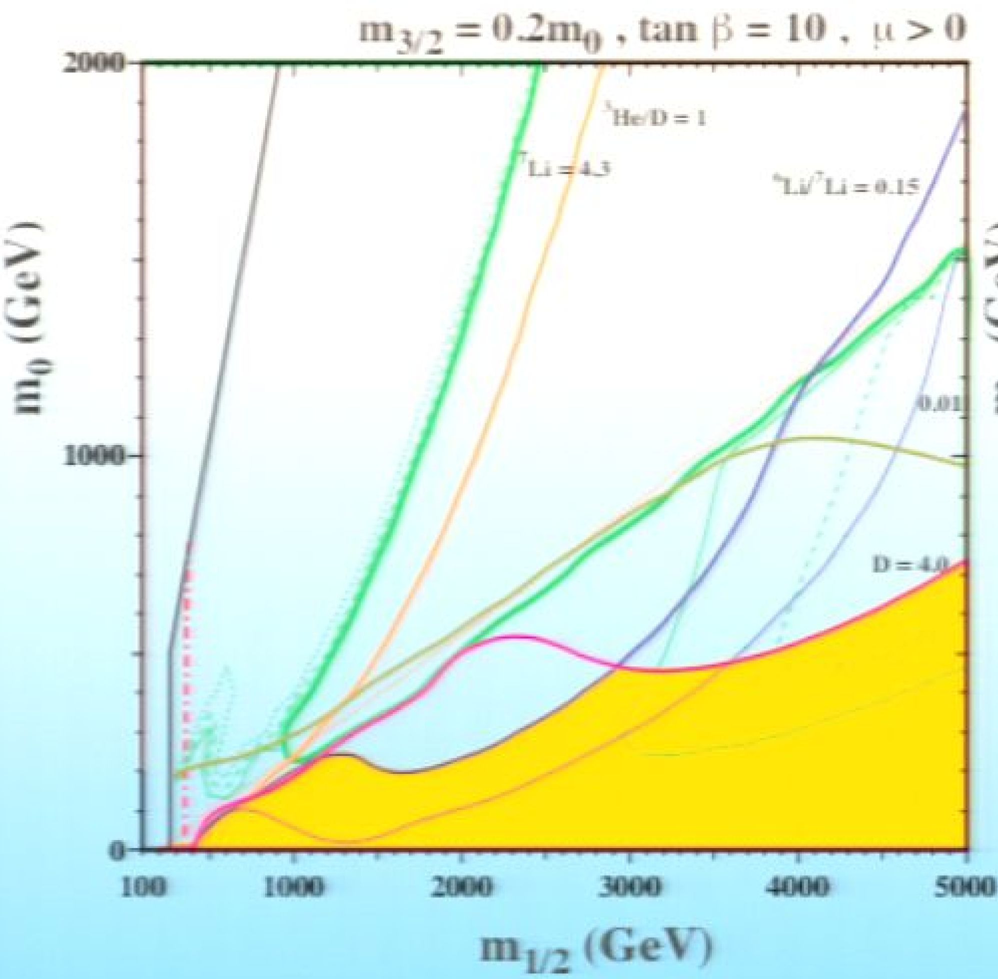
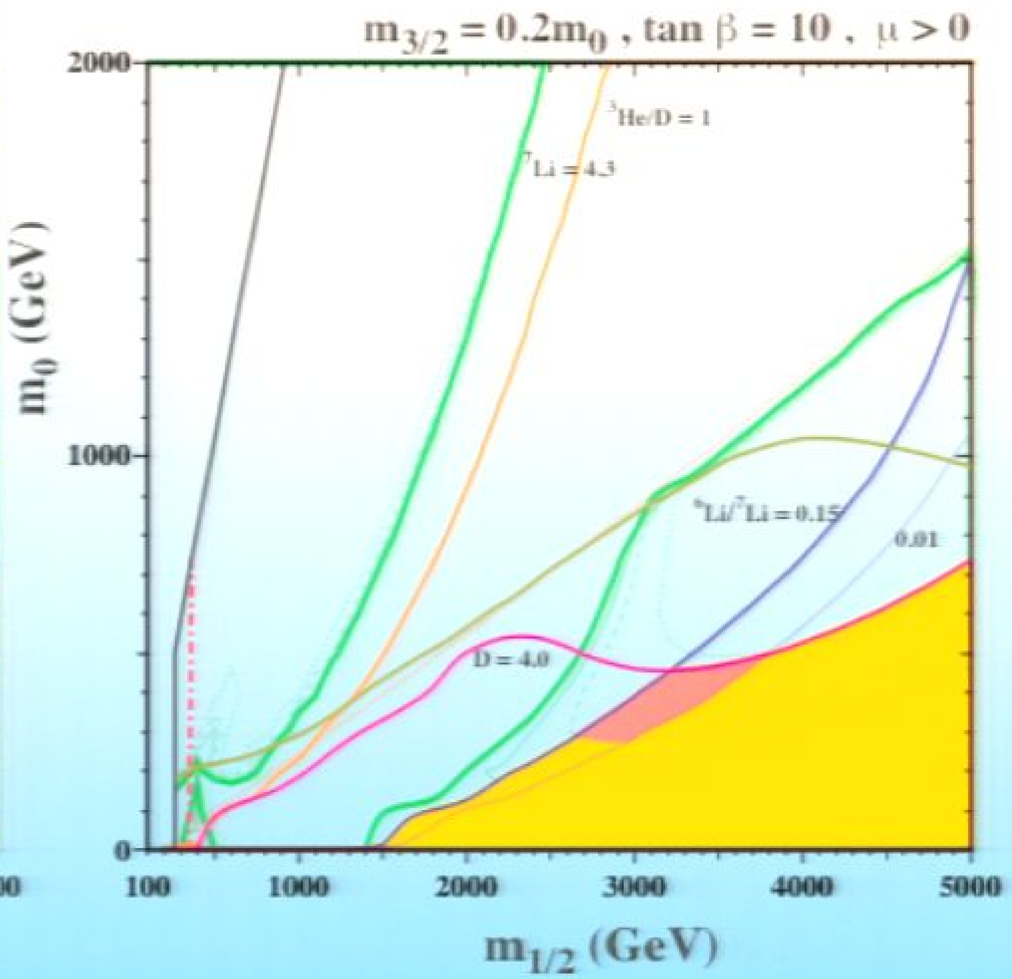


Pospelov





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- 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,

$$\frac{n}{p} \sim e^{-\Delta m/T} \qquad \text{fixed at freezeout}$$

Helium abundance,

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

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

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: $Q = \Delta m_N,\ \tau_N,\ B_D$

Coc, Nunes, Olive, Uzan, Vangio

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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

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Coc, Nunes, Olive, Uzan, Vangioni
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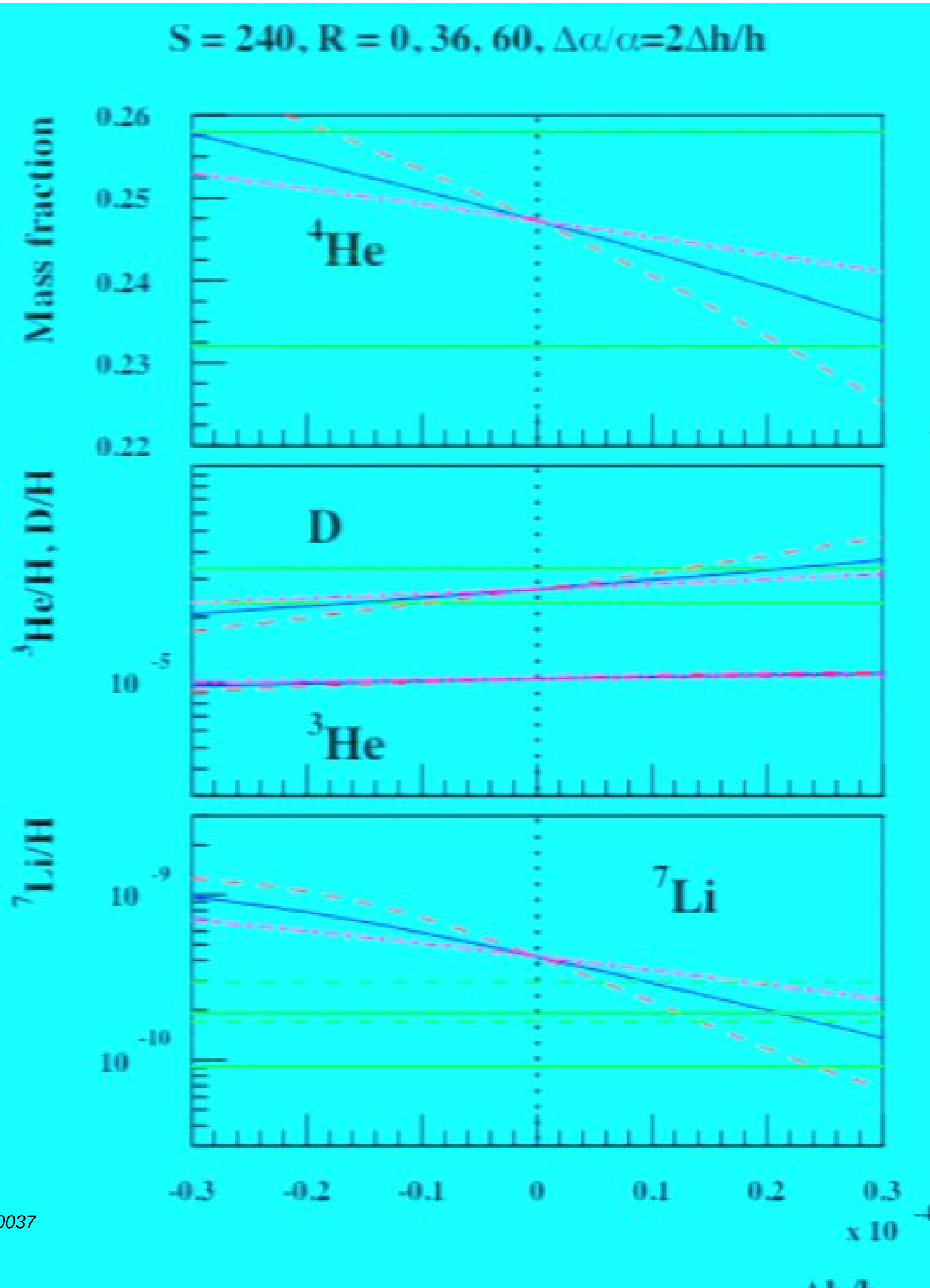
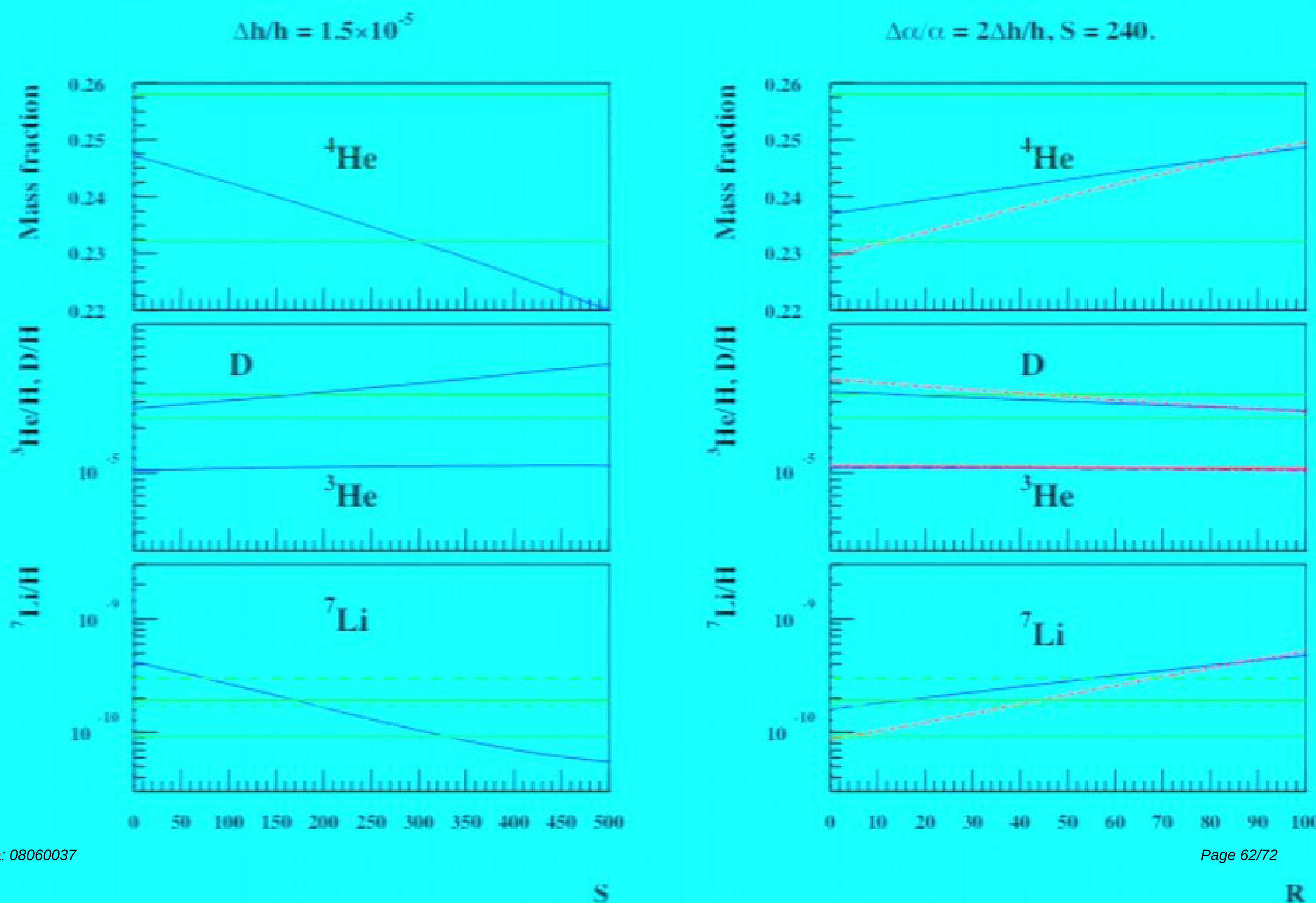


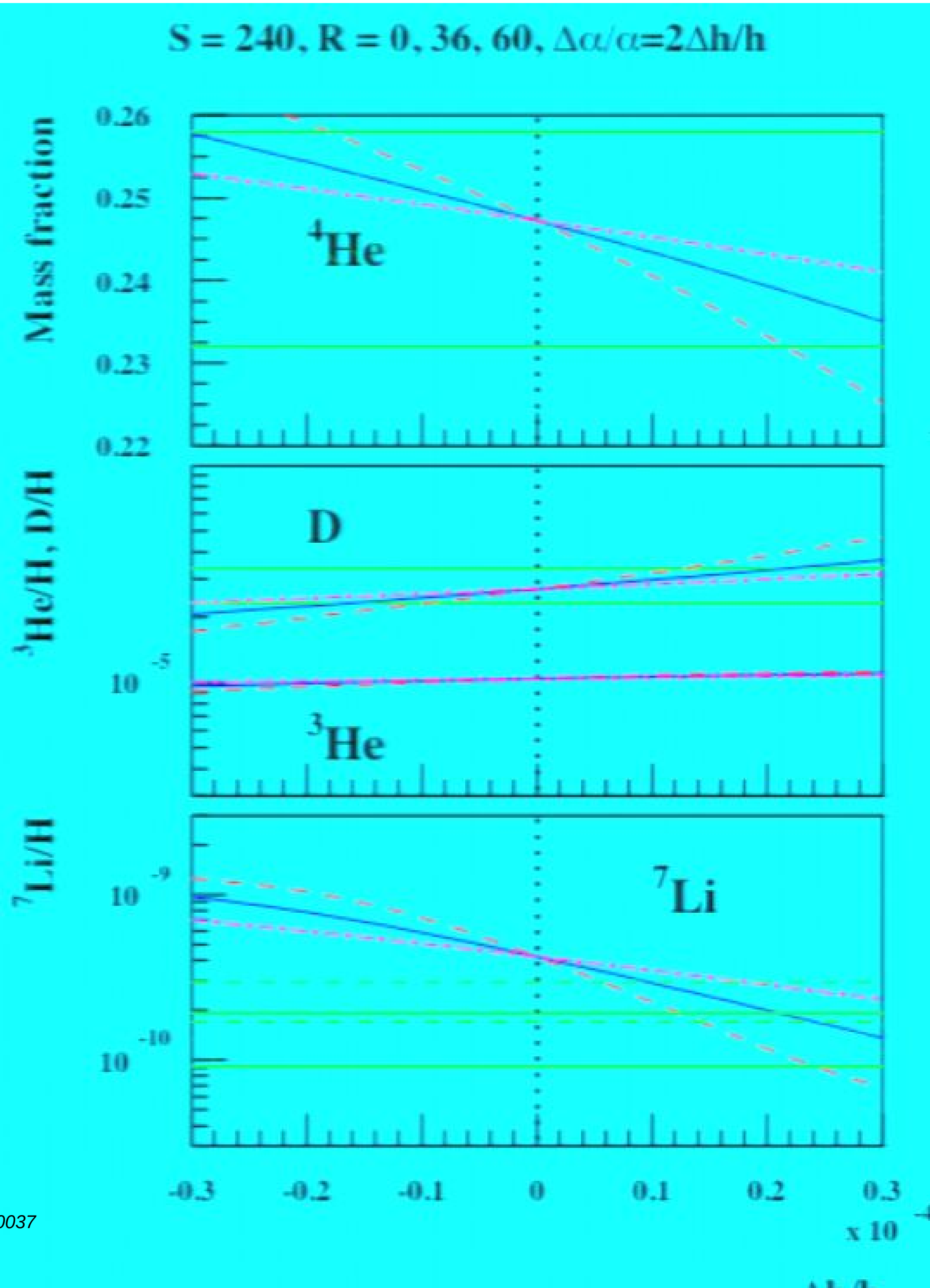
For S = 240, R = 36,

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

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
0 10 20 30 40 50 60 70 80 90 100
S
R



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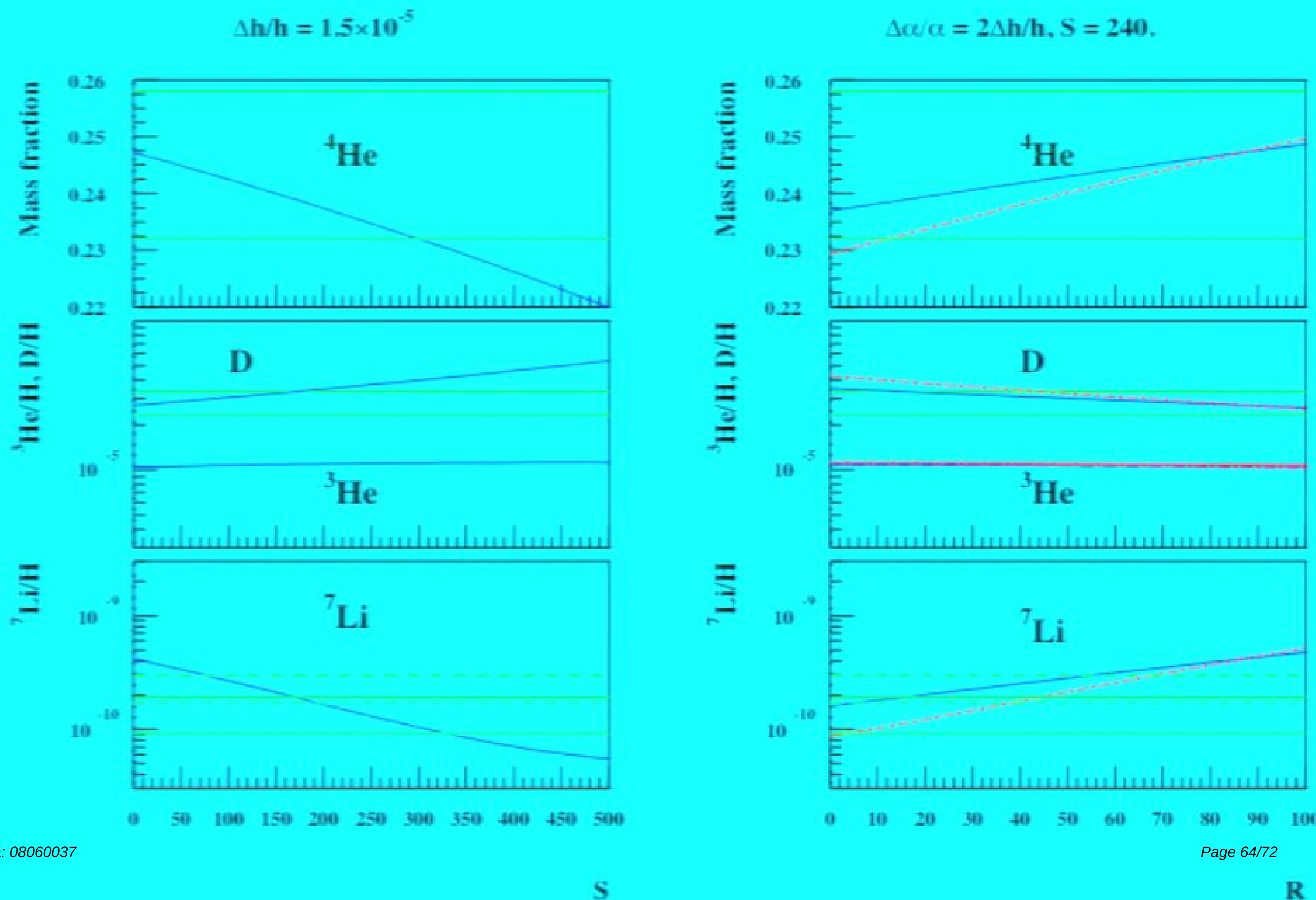

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0 50 100 150 200 250 300 350 400 450 500
0 10 20 30 40 50 60 70 80 90 100
S
R

^{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 $\times 10^{-12}$

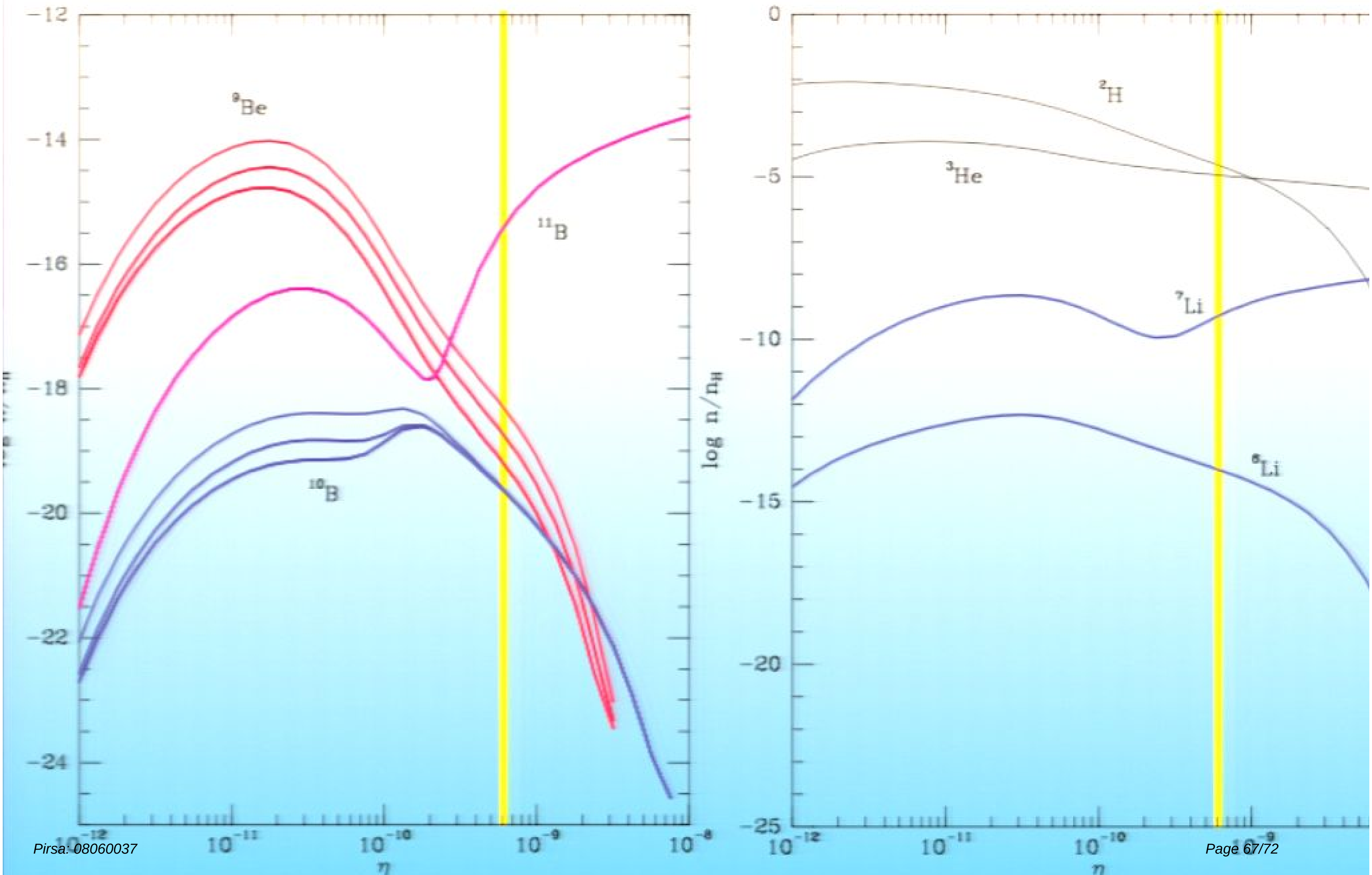
^{9}Be/H $\sim 1 - 10 \times 10^{-13}$ B/H $\sim 1 - 10 \times 10^{-12}$

These are not BBN produced.

GCR Nucleosynthesis

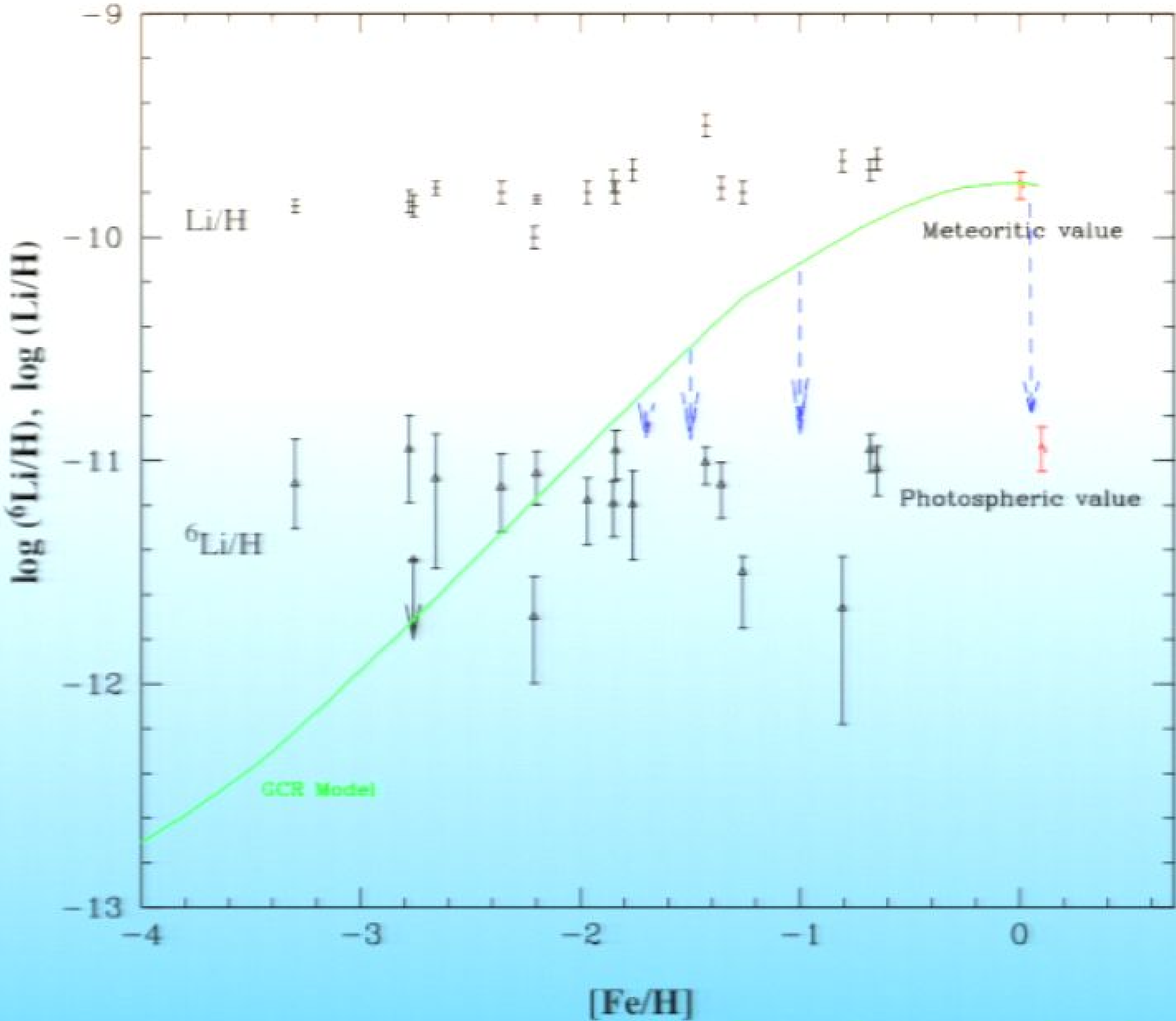
Summary

- 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)



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

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



Data from Asplund et al and Inou

Summary

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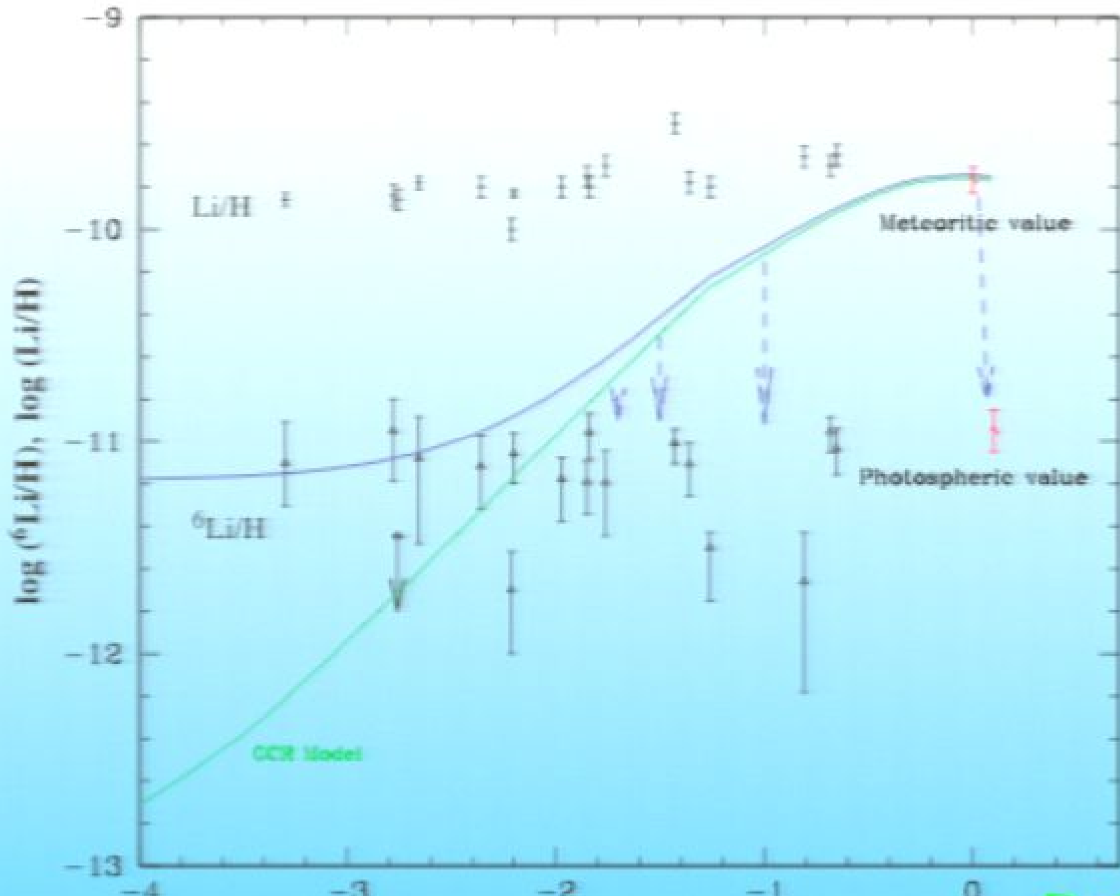
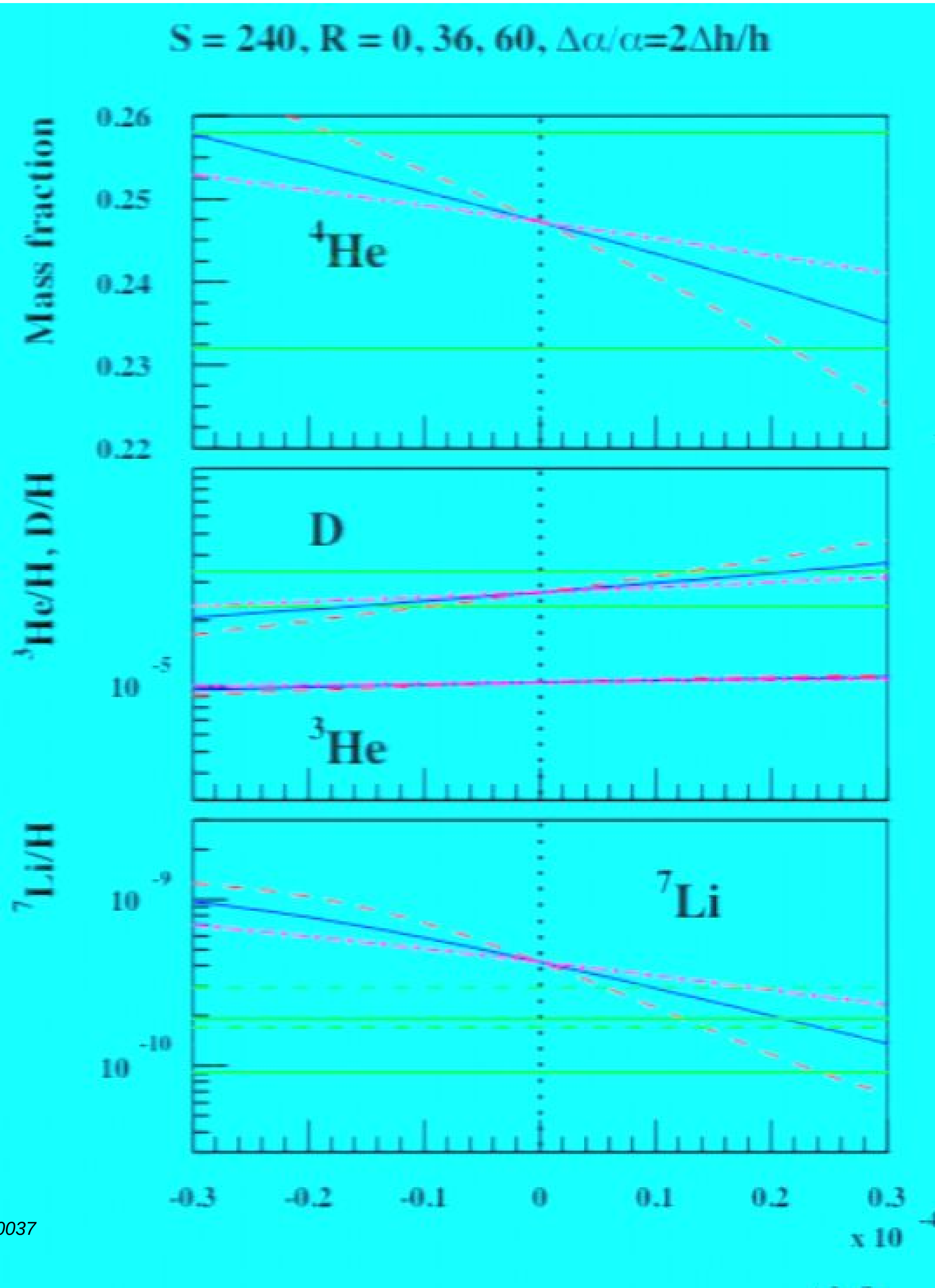
Possible Solution: Cosmological Cosmic Rays (to problem two only)

- Cosmic Chemical Evolution
- Early Reionization and Massive Stars
- Cosmic Ray Production and Propagation in an expanding Universe



Rollinde, Vangioni, Oliv



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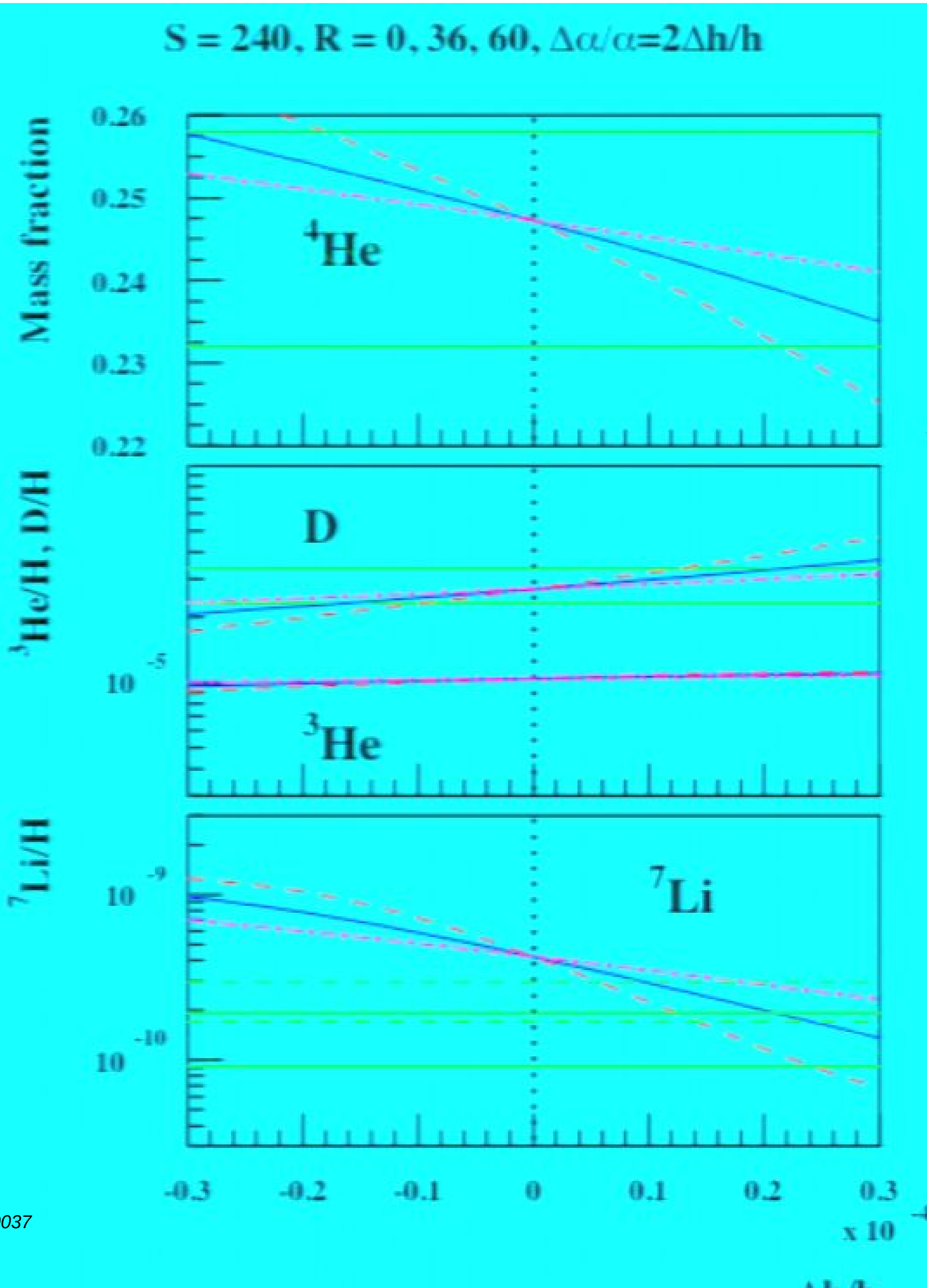

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