Big Bang Nucleosynthesis

- BBN and the early Universe

- Observations and Comparison with Theory
  - D/H
  - ^{4}He
  - ^{7}Li

Historical Perspective

Intimate connection with CMB

Alpher
Herman
Gamow

Conditions for BBN:

Require T > 100 keV ⇒ t < 200 s

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

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

Today:

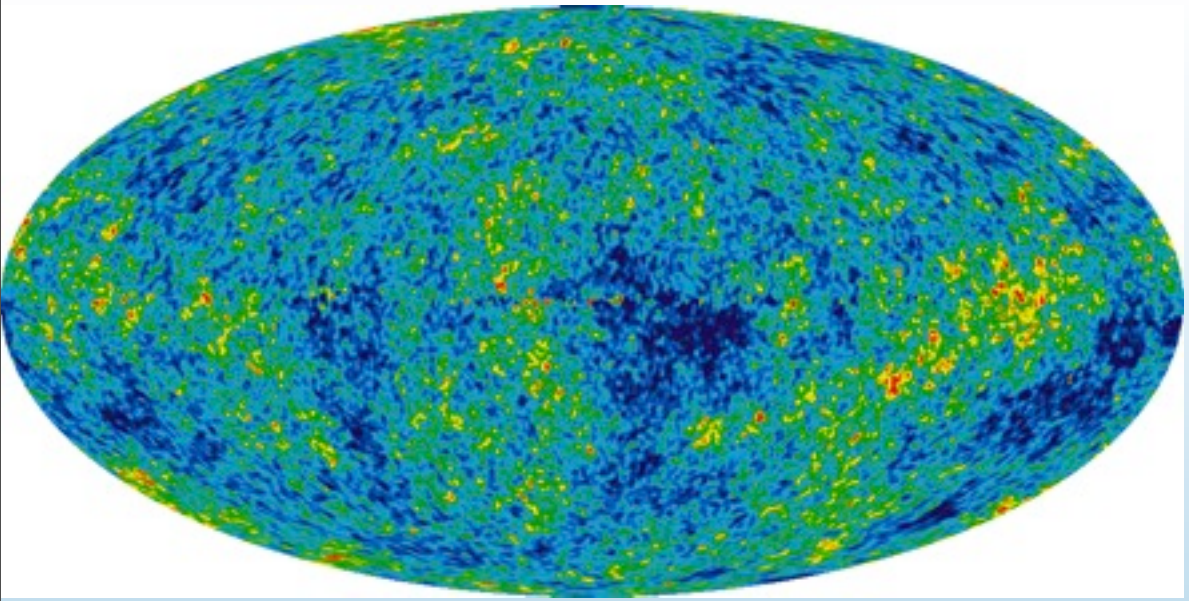
$n_{Bo} \sim 10^{-7}\ \mathrm{cm}^{-3}$

and

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

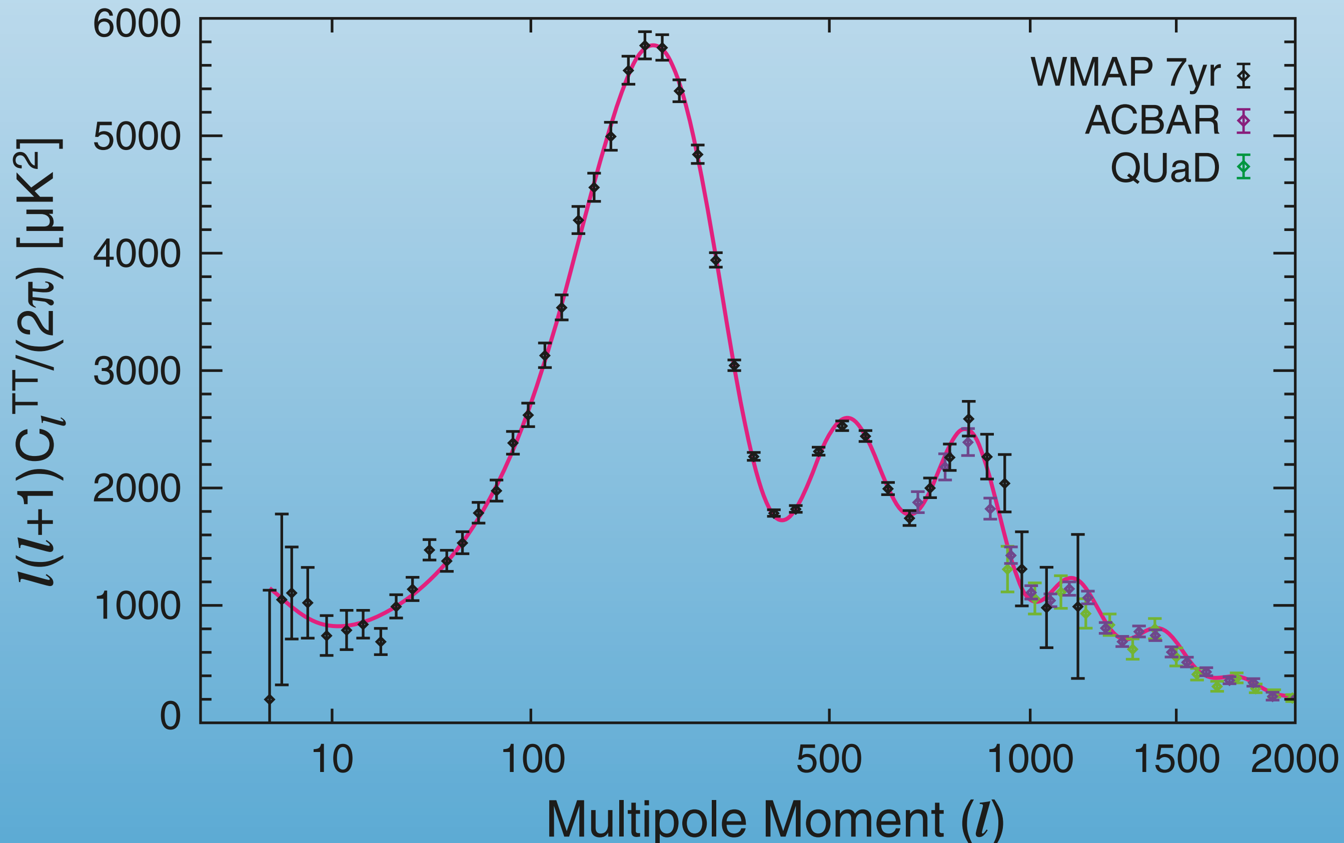
Predicts the CMB temperature

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



WMAP best fit

$$\Omega_B h^2 = 0.0225 \pm 0.0006$$
$$\eta_{10} = 6.16 \pm 0.16$$



Conditions in the Early Universe:

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

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

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

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)

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

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

Nucleosynthesis begins when $\Gamma_p \sim \Gamma_d$

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

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

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

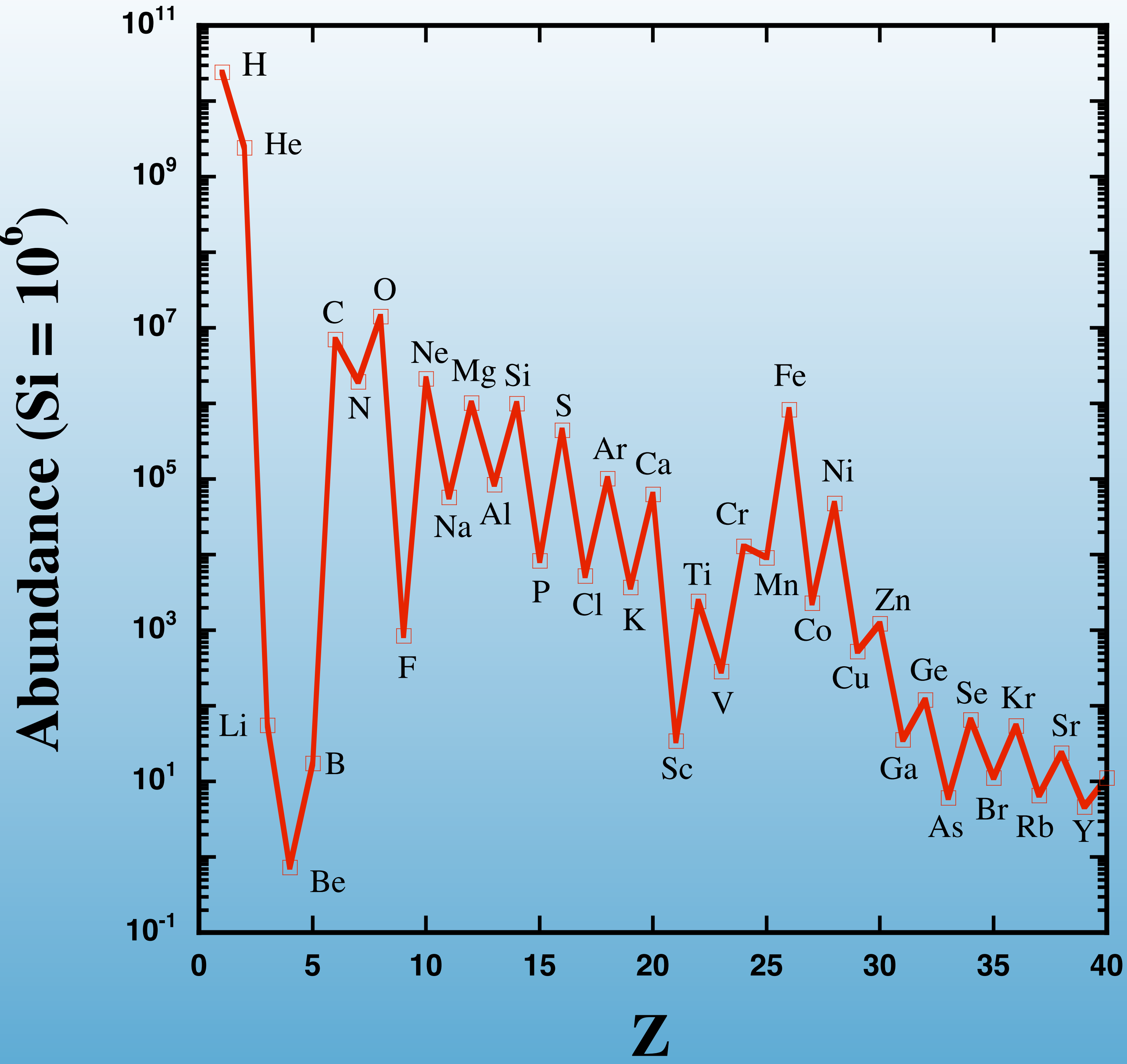
Remainder:

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

Decline:

BBN could not explain the abundances (or patterns) of all the elements.

$\Longrightarrow$ growth of stellar nucleosynthesis



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

Decline:

BBN could not explain the abundances (or patterns) of all 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.

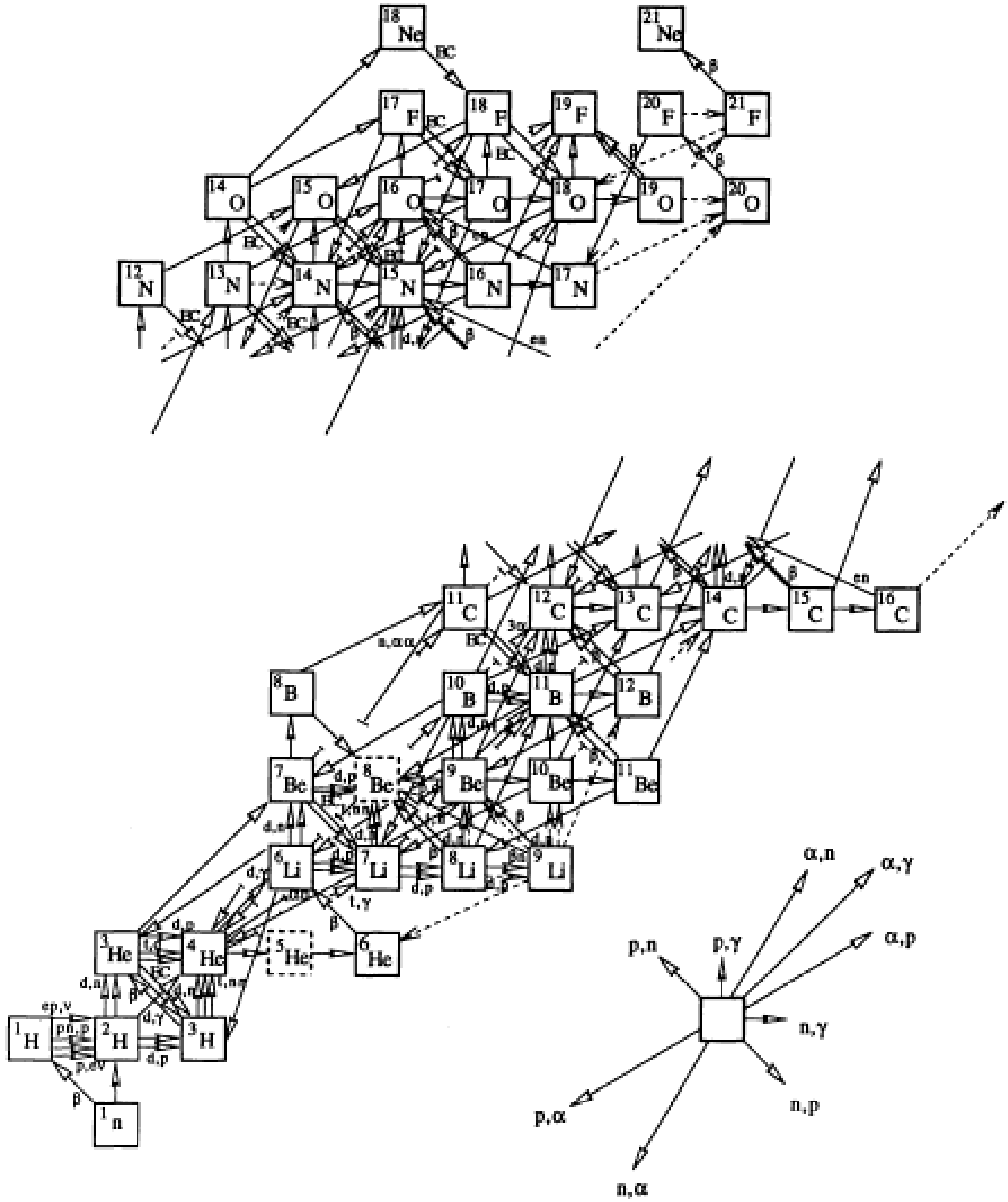
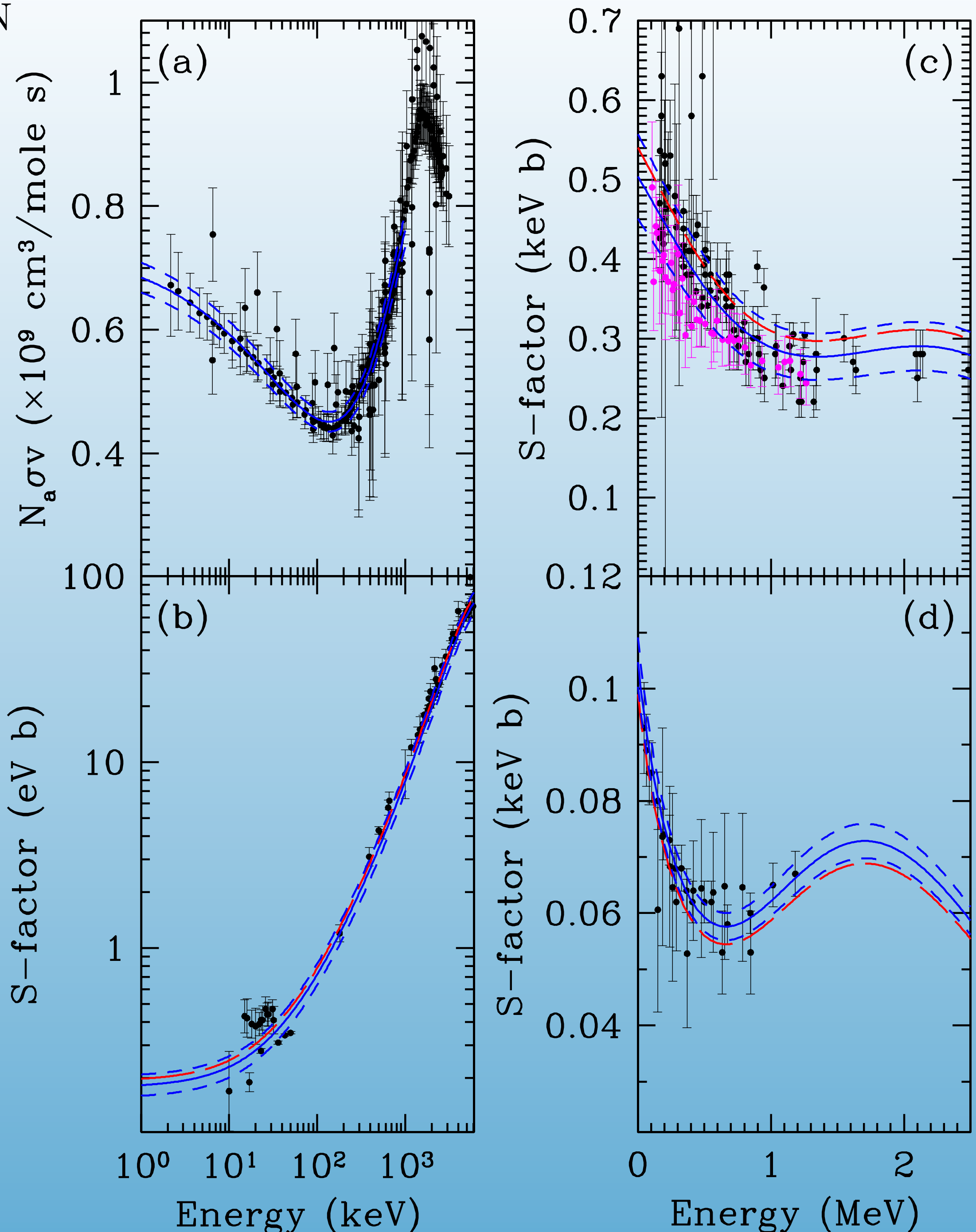


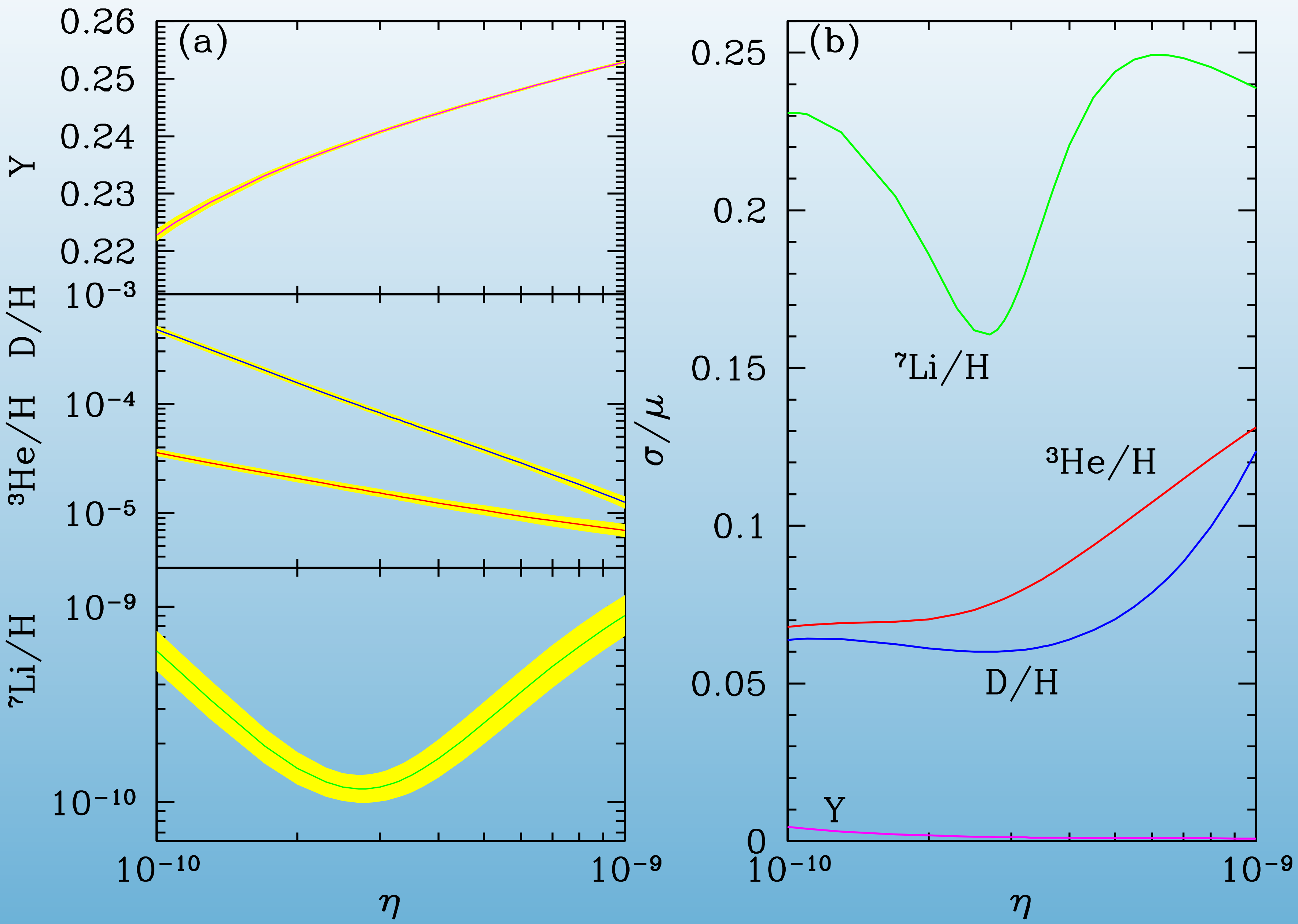
FIG. 1.—Reaction network used in the code. Estimated reactions are shown with dashed lines.

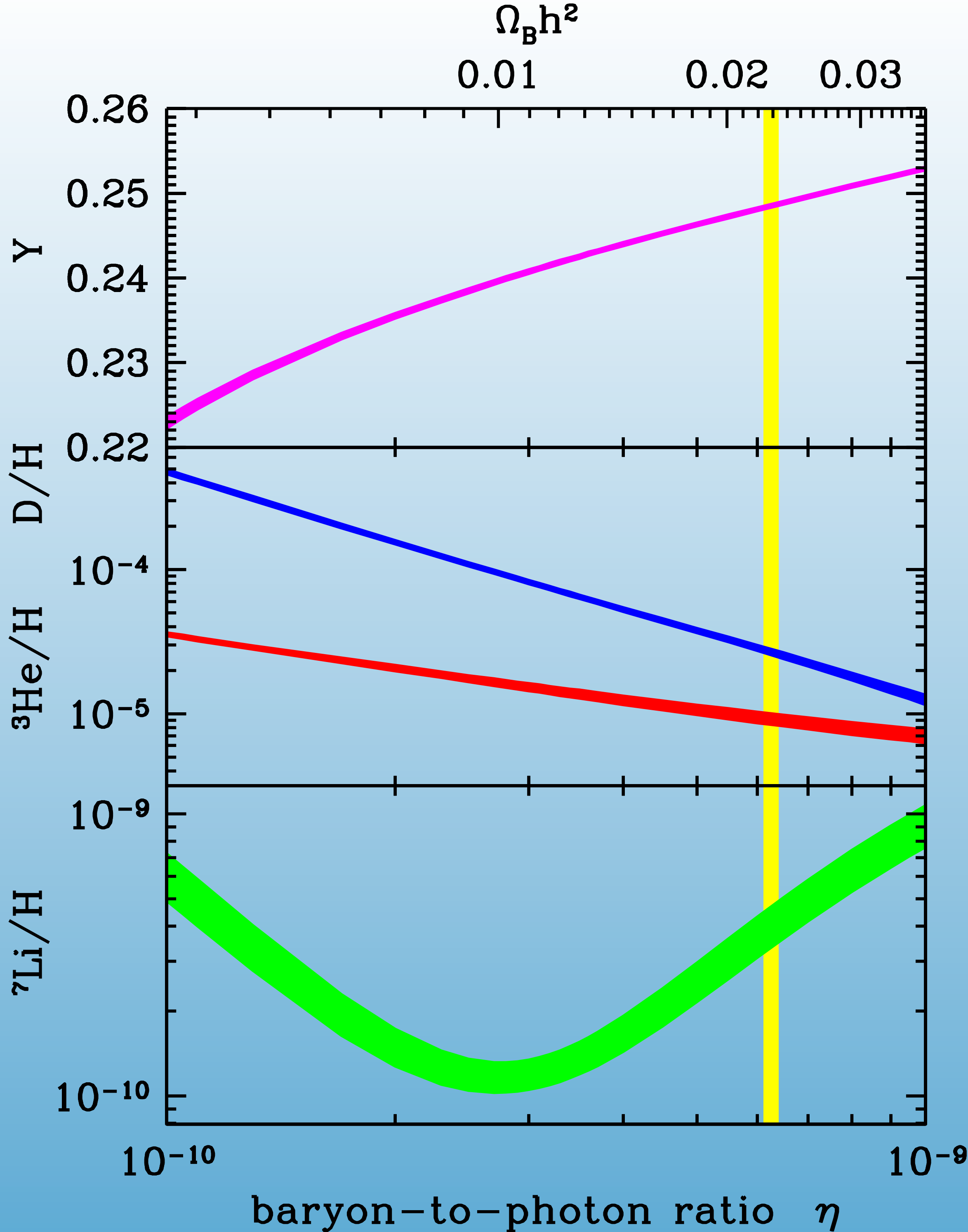
Table 1: Key Nuclear Reactions for BBN

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.


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

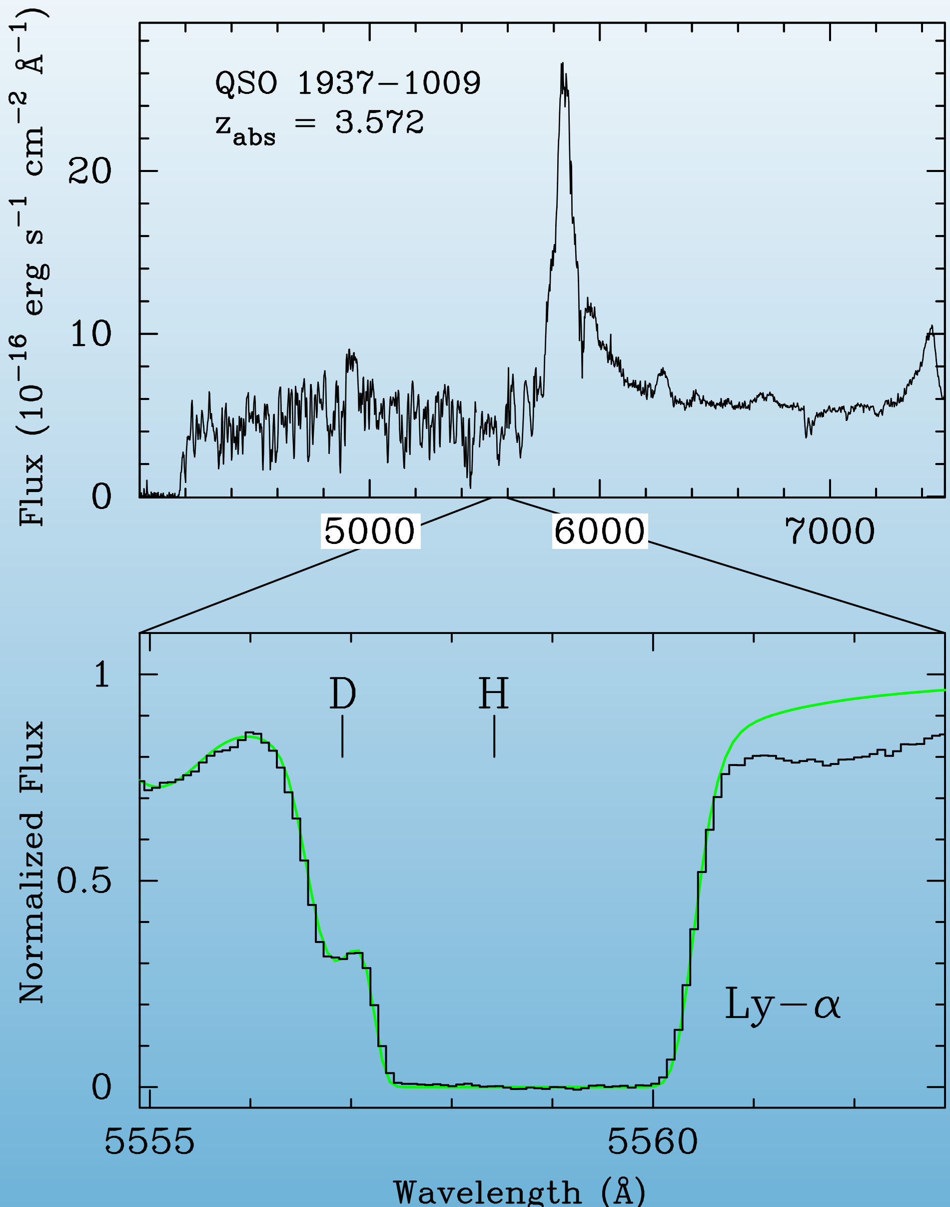
Big Bang Nucleosynthesis

- 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 x 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

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

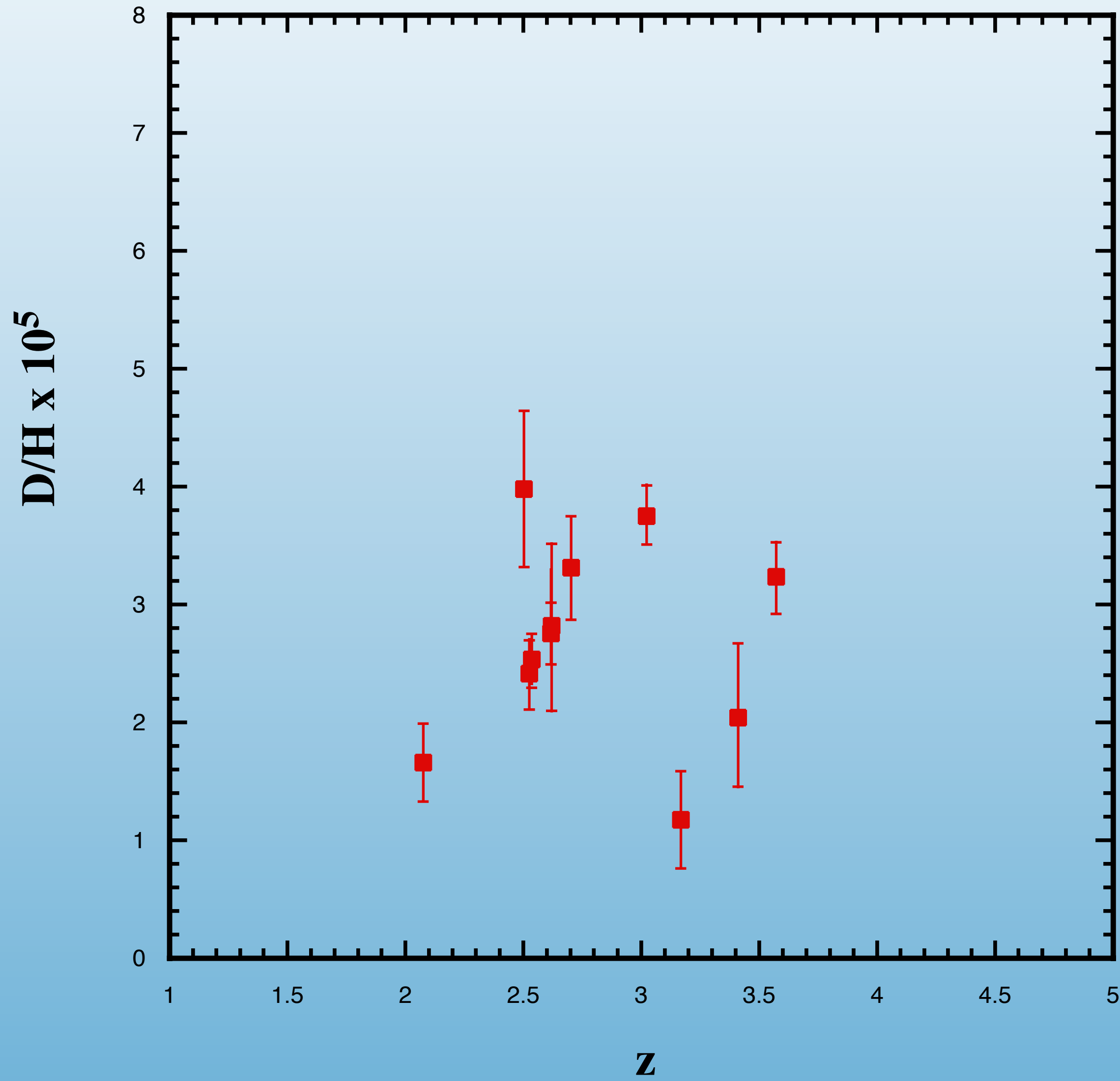


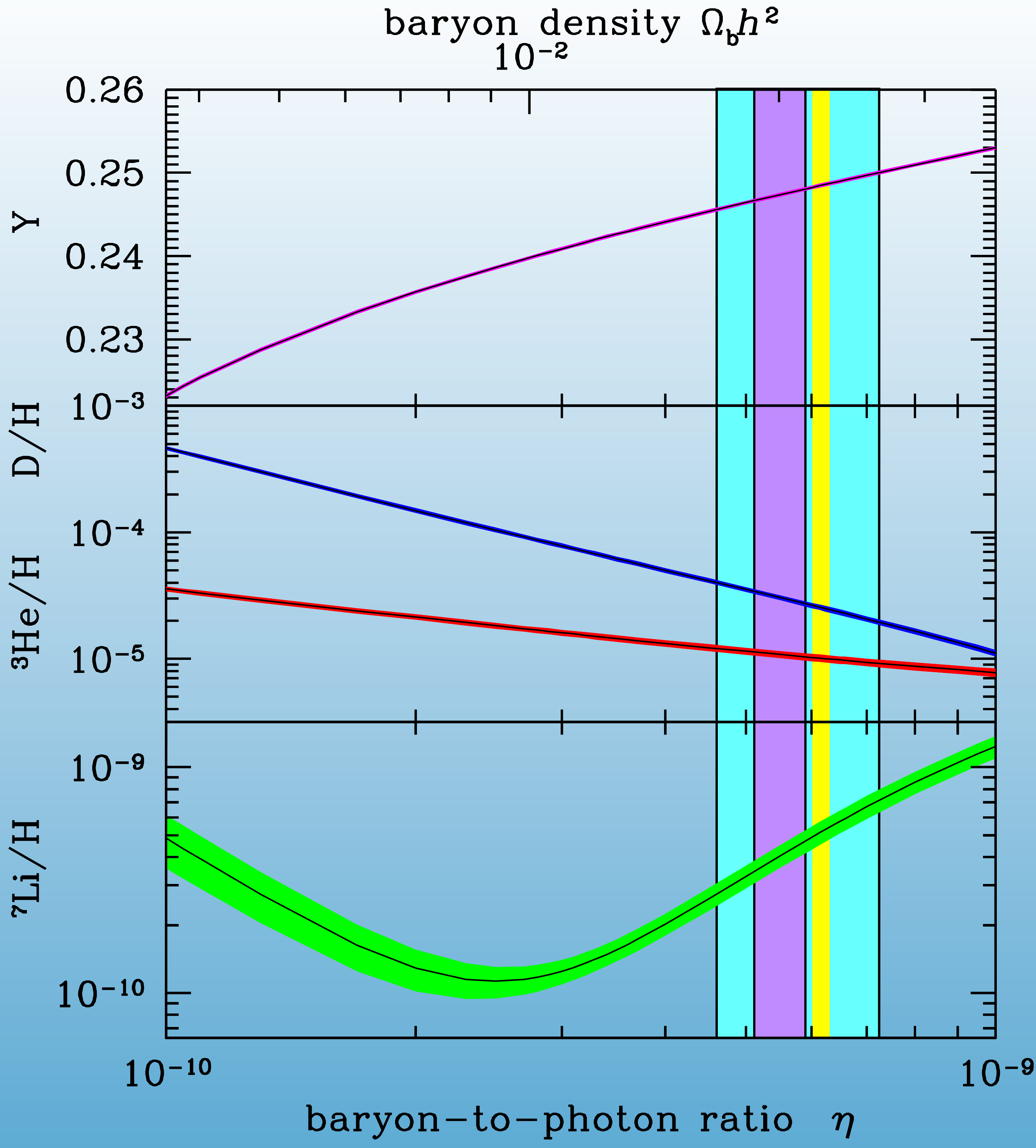
Tytler, O'Meara, Suzuki, Lubin

D/H abundances in Quasar apsorption systems

BBN Prediction:
10^5 D/H = 2.54 ± 0.17

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

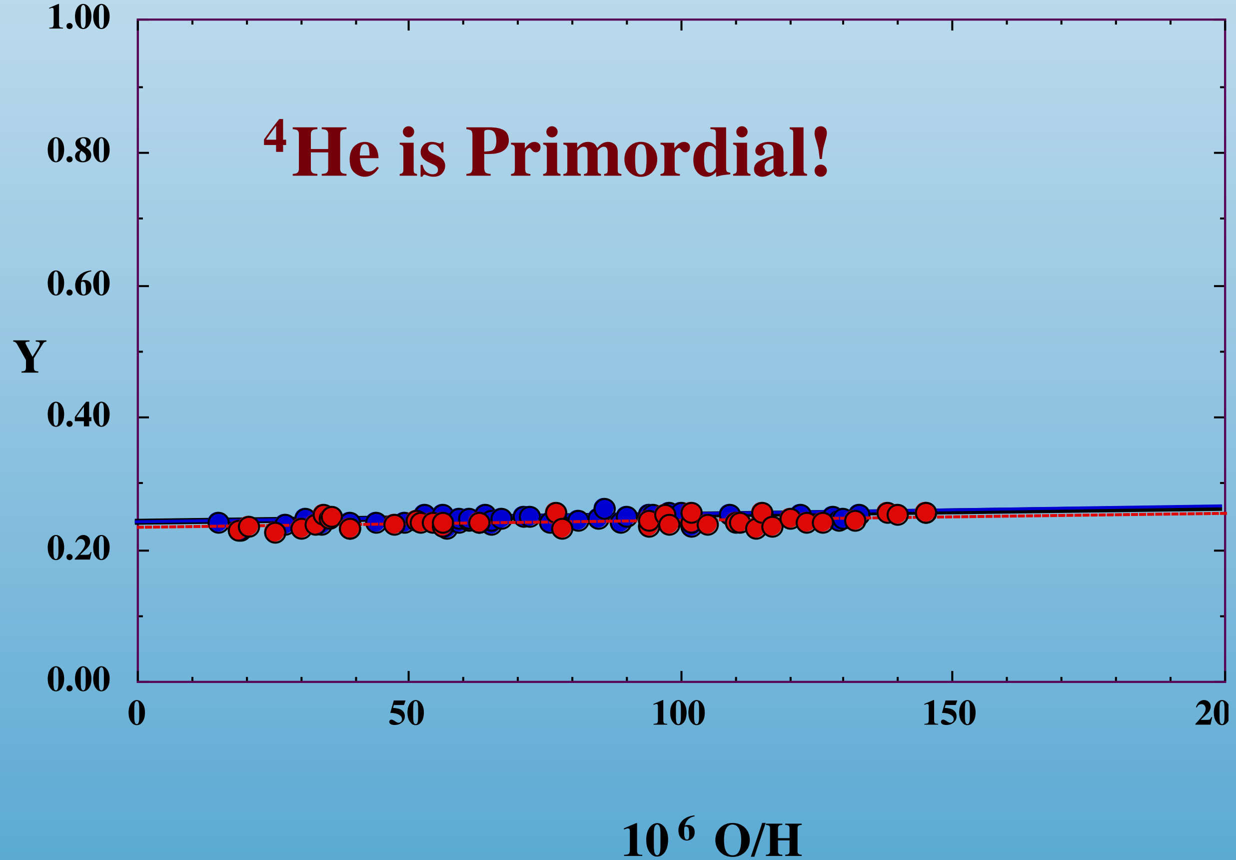


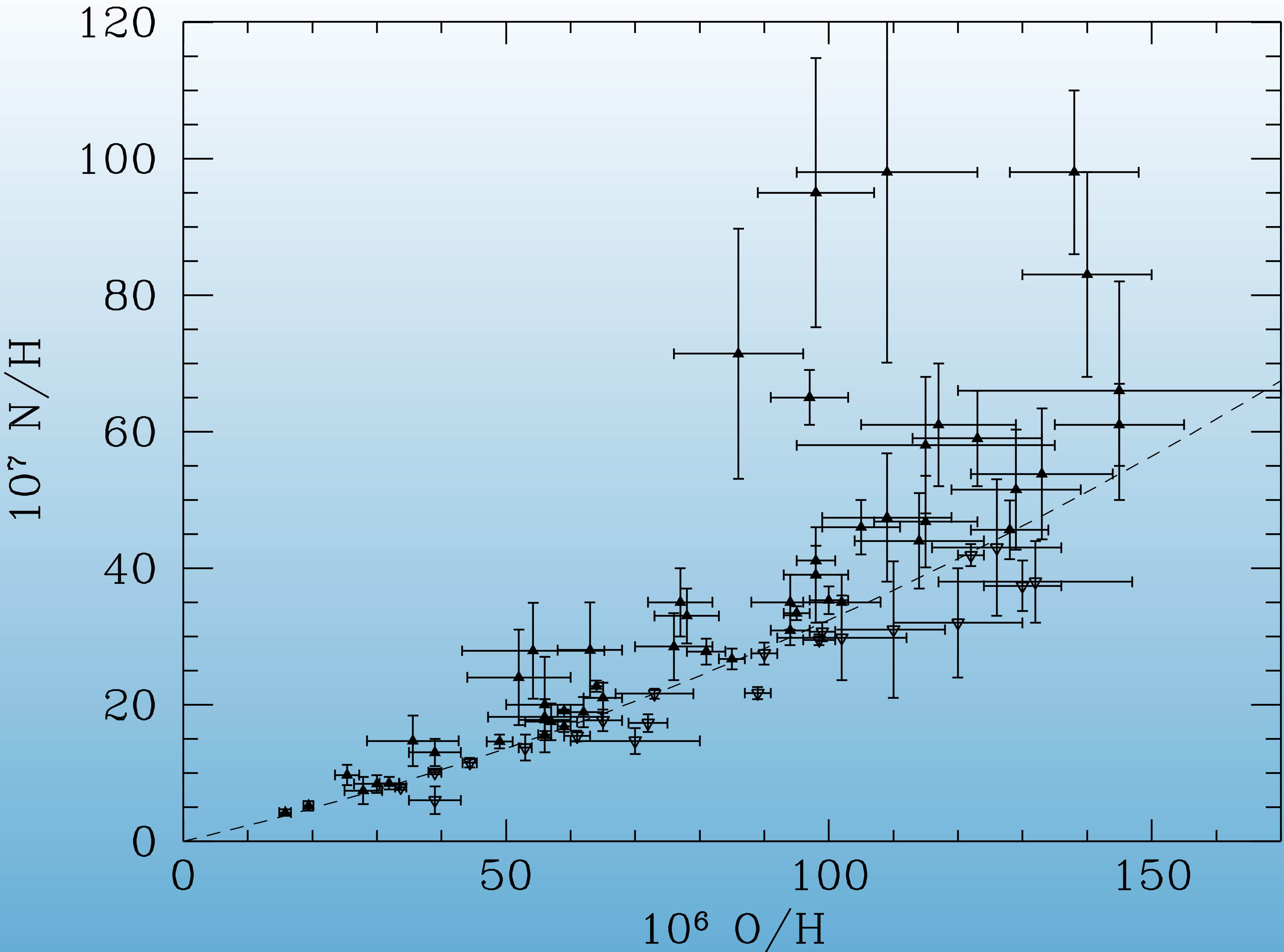

baryon density $\Omega_b h^2$
10^{-2}
0.26
0.25
0.24
0.23
Y
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio η

^{4}He

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

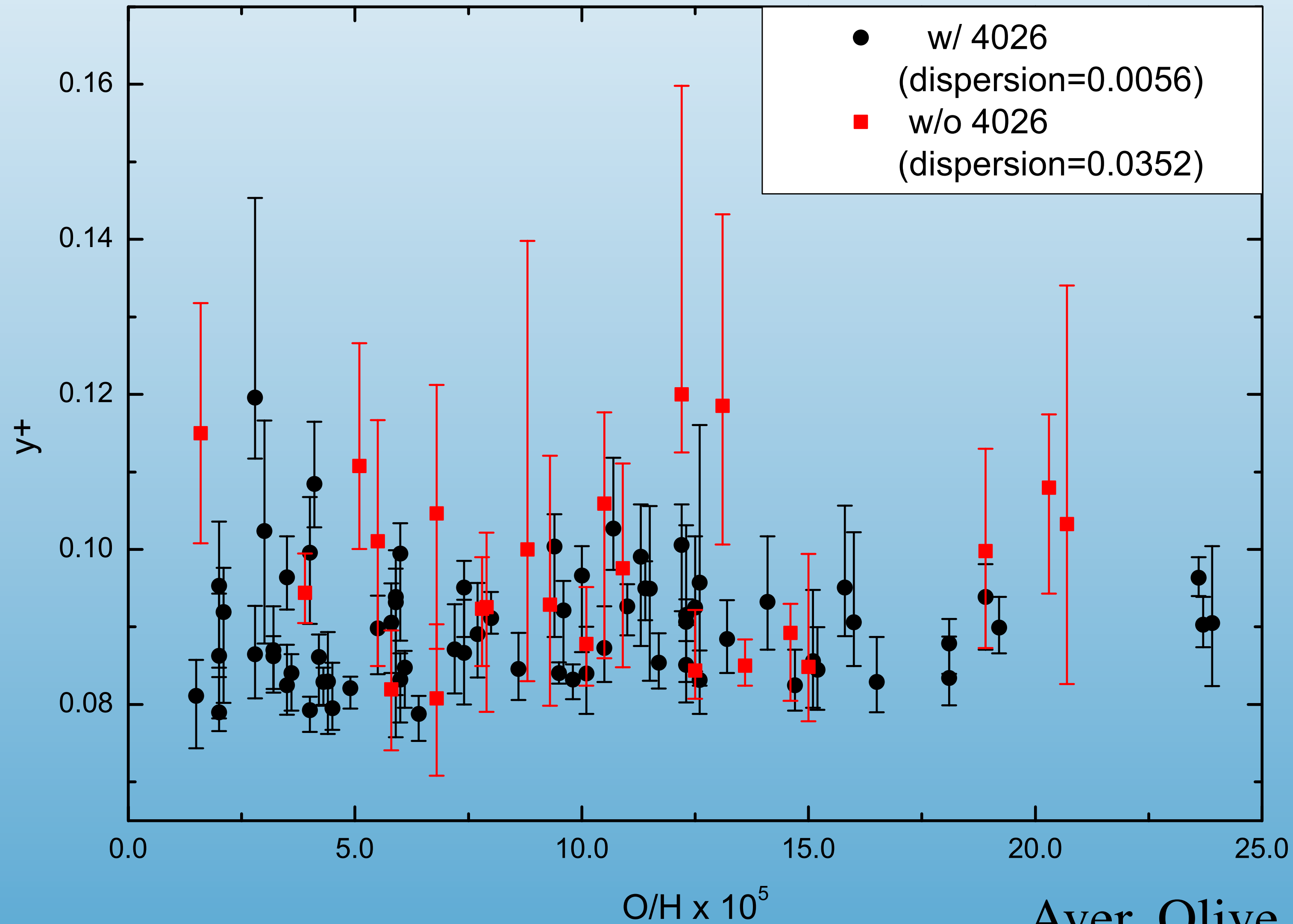
$$Y_P = Y(O/H \rightarrow 0)$$




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

^{4}He

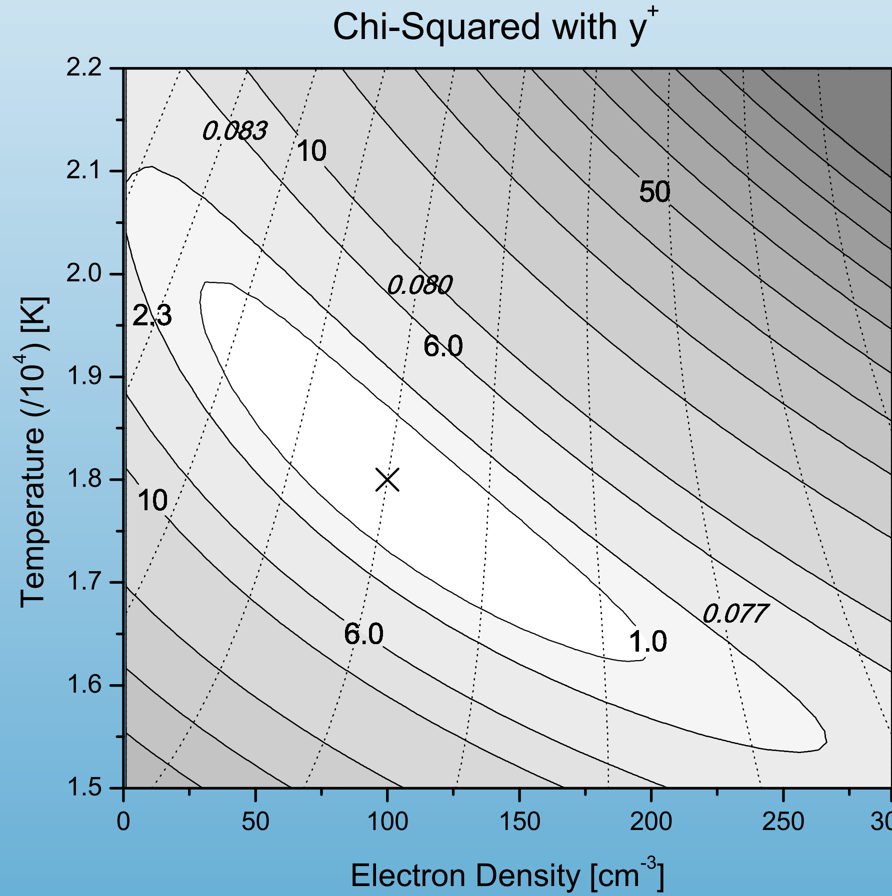
Measured in low metallicity extragalactic HII regions together with O/H and N/H



Aver, Olive, Skillman

Results for He dominated by systematic effects

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

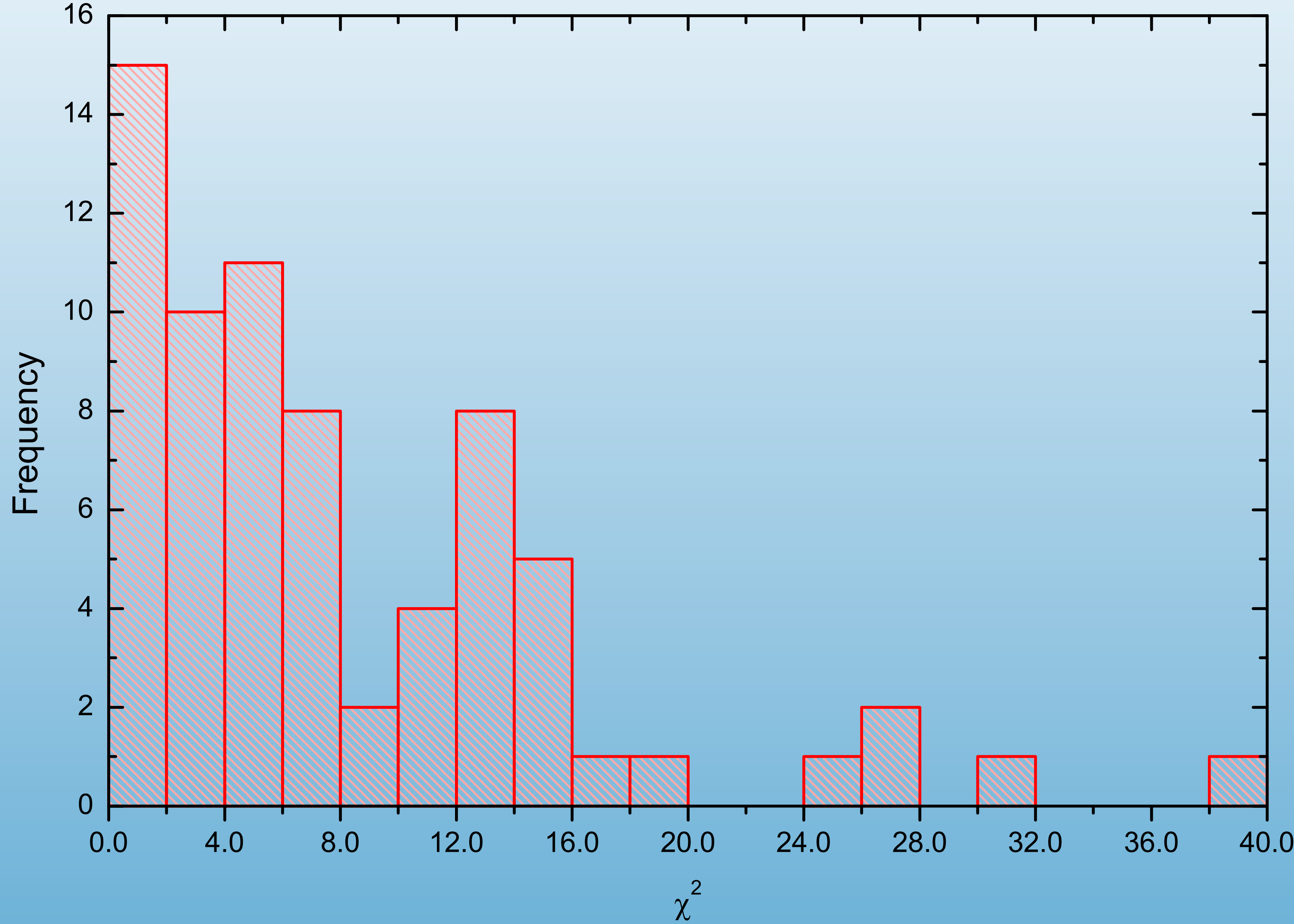


MCMC statistical techniques have proven effective in parameter estimation

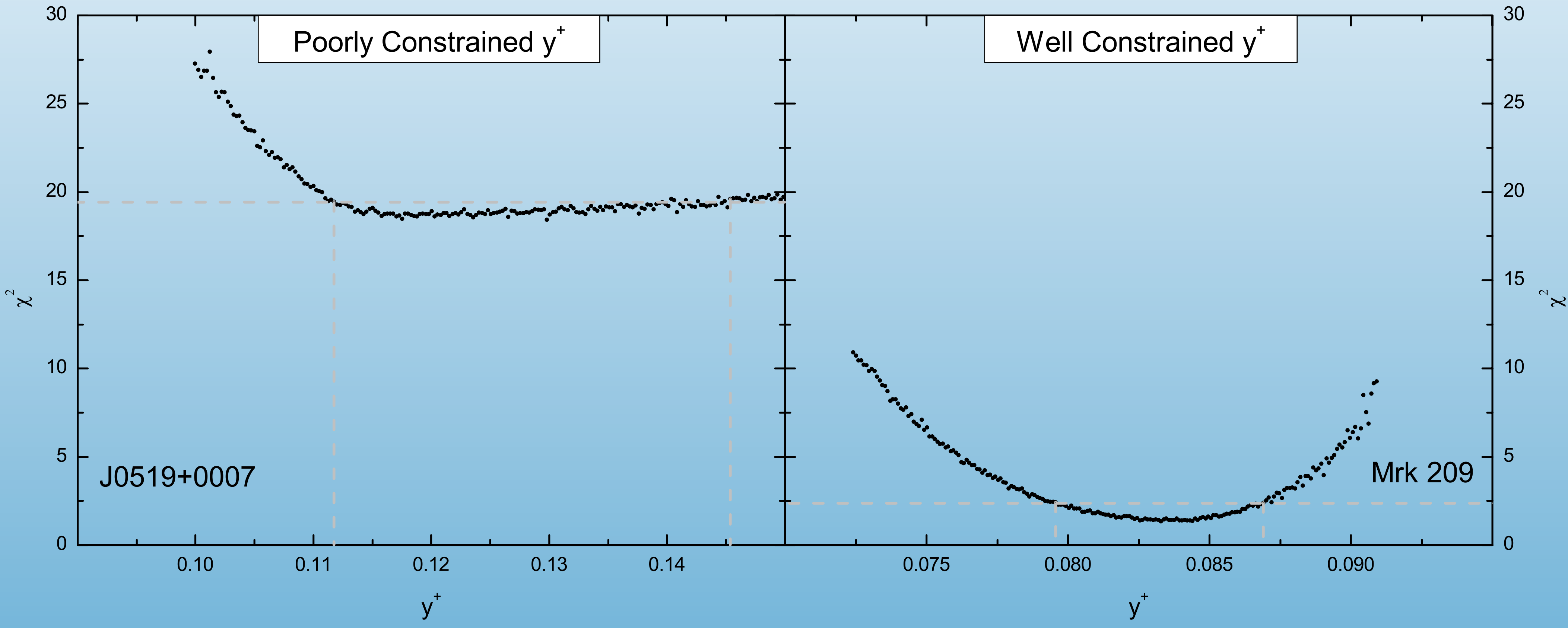
$$(y^+, n_e, a_{He}, \tau, T, C(H\beta), a_H, \xi)$$

Aver, Olive, Skillman

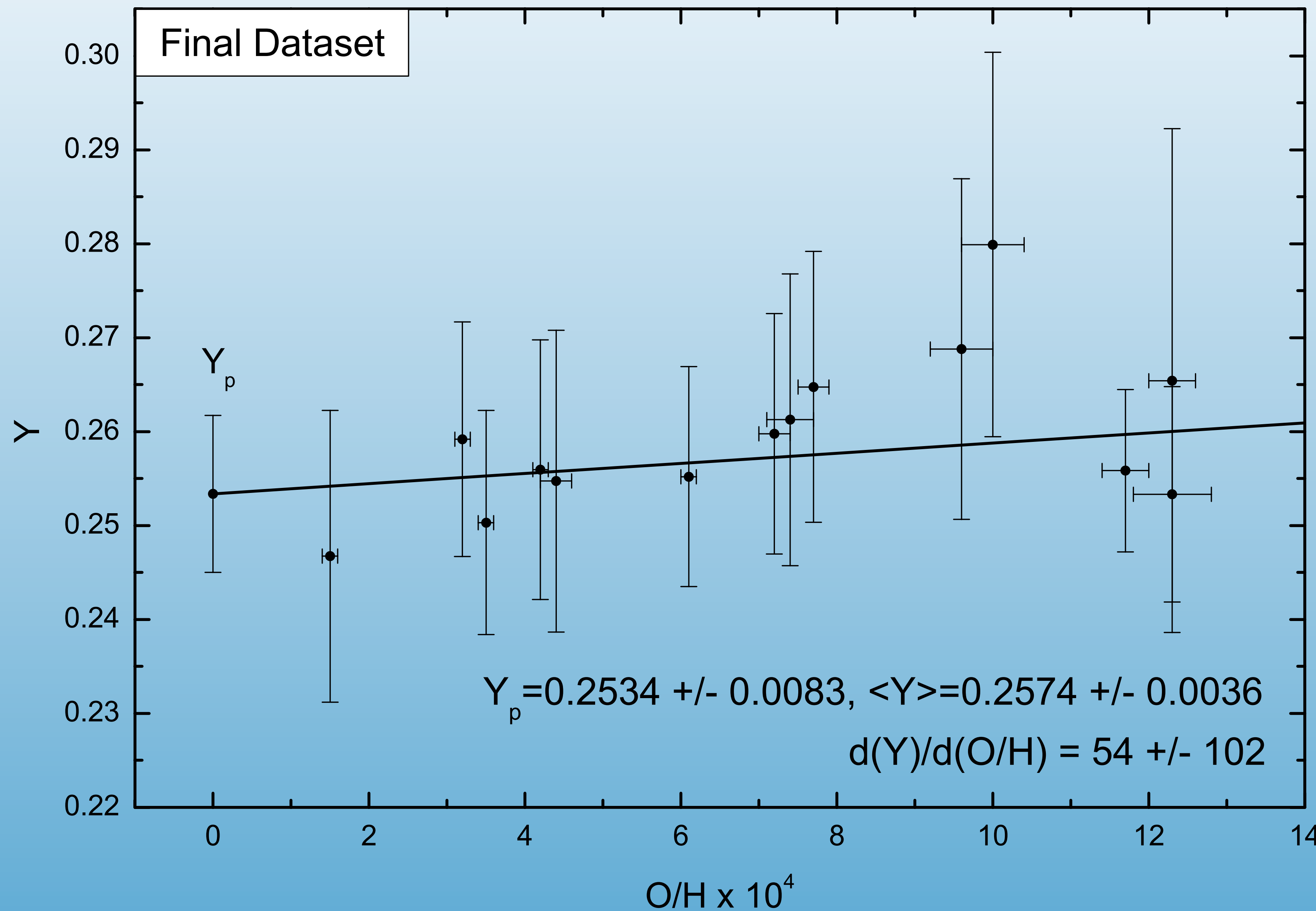
Using χ^2 as a discriminator



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



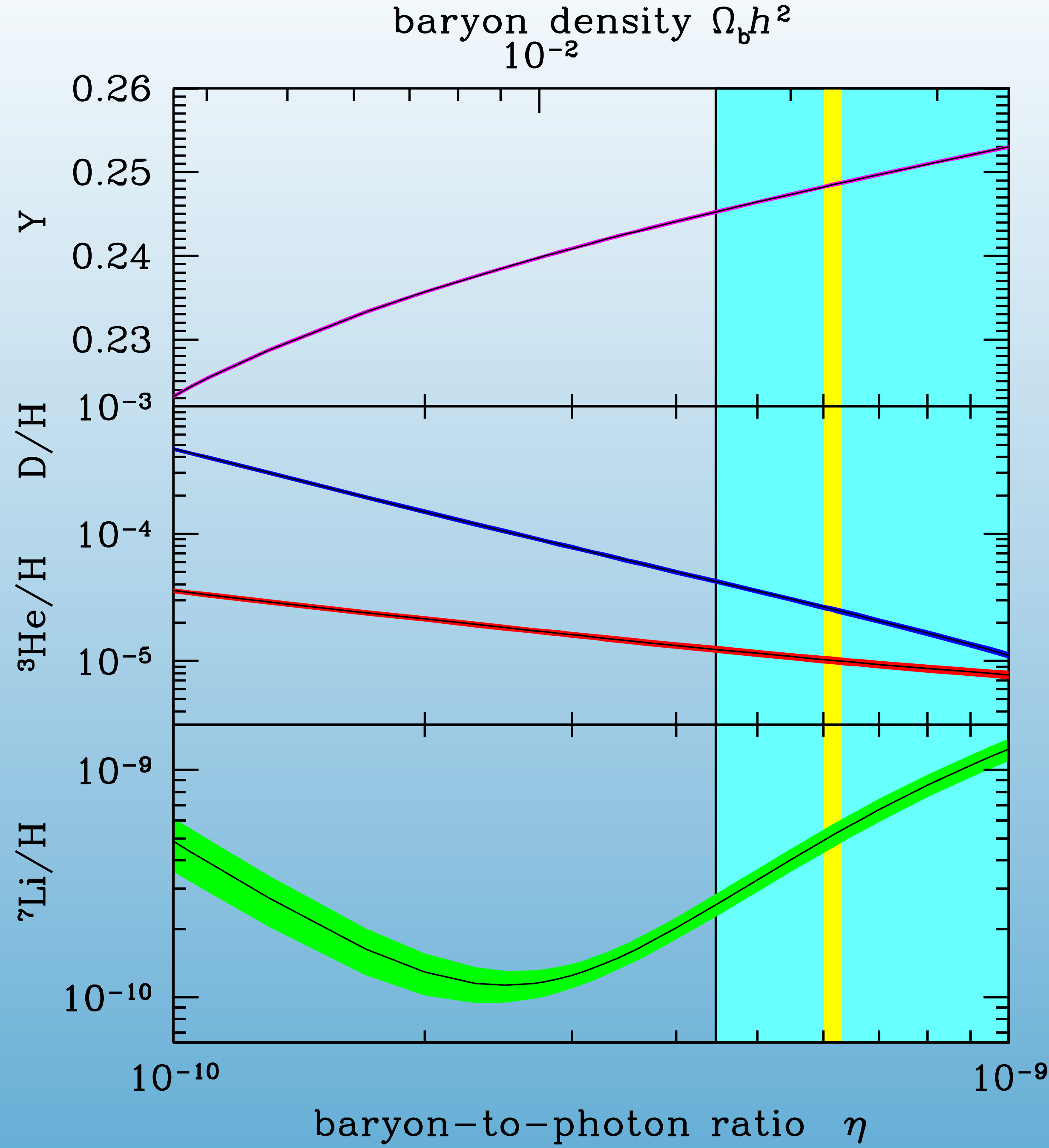
Final Result



^{4}He Prediction:
0.2487 ± 0.0002

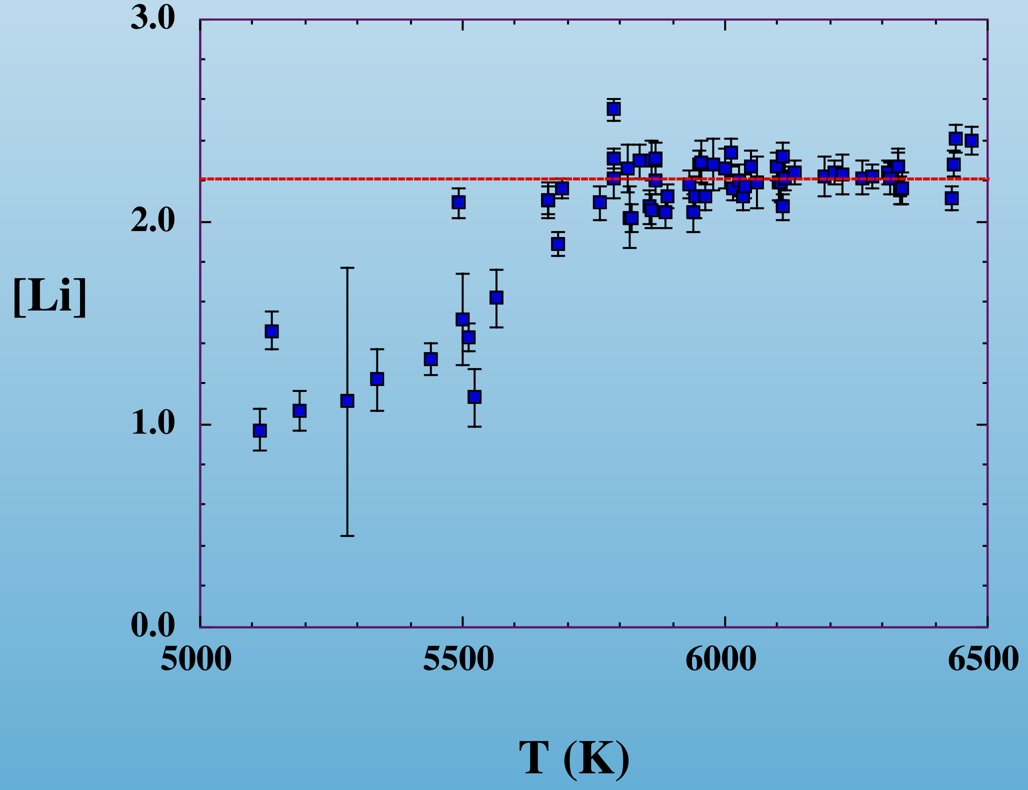
Data: Regression:
0.2534 ± 0.0083

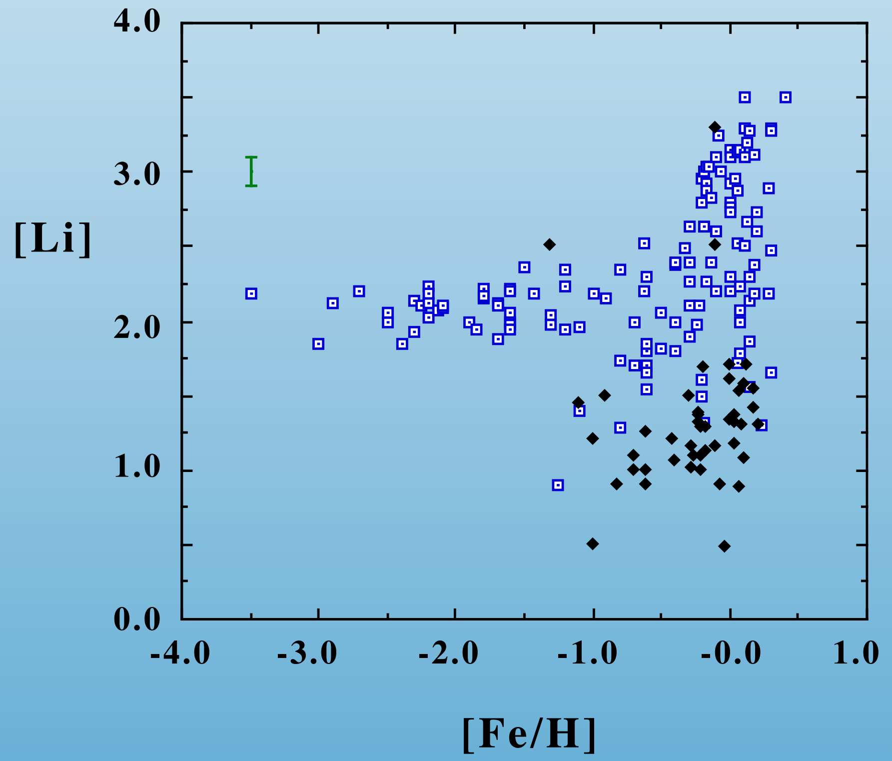
Mean:
0.2574 ± 0.0036

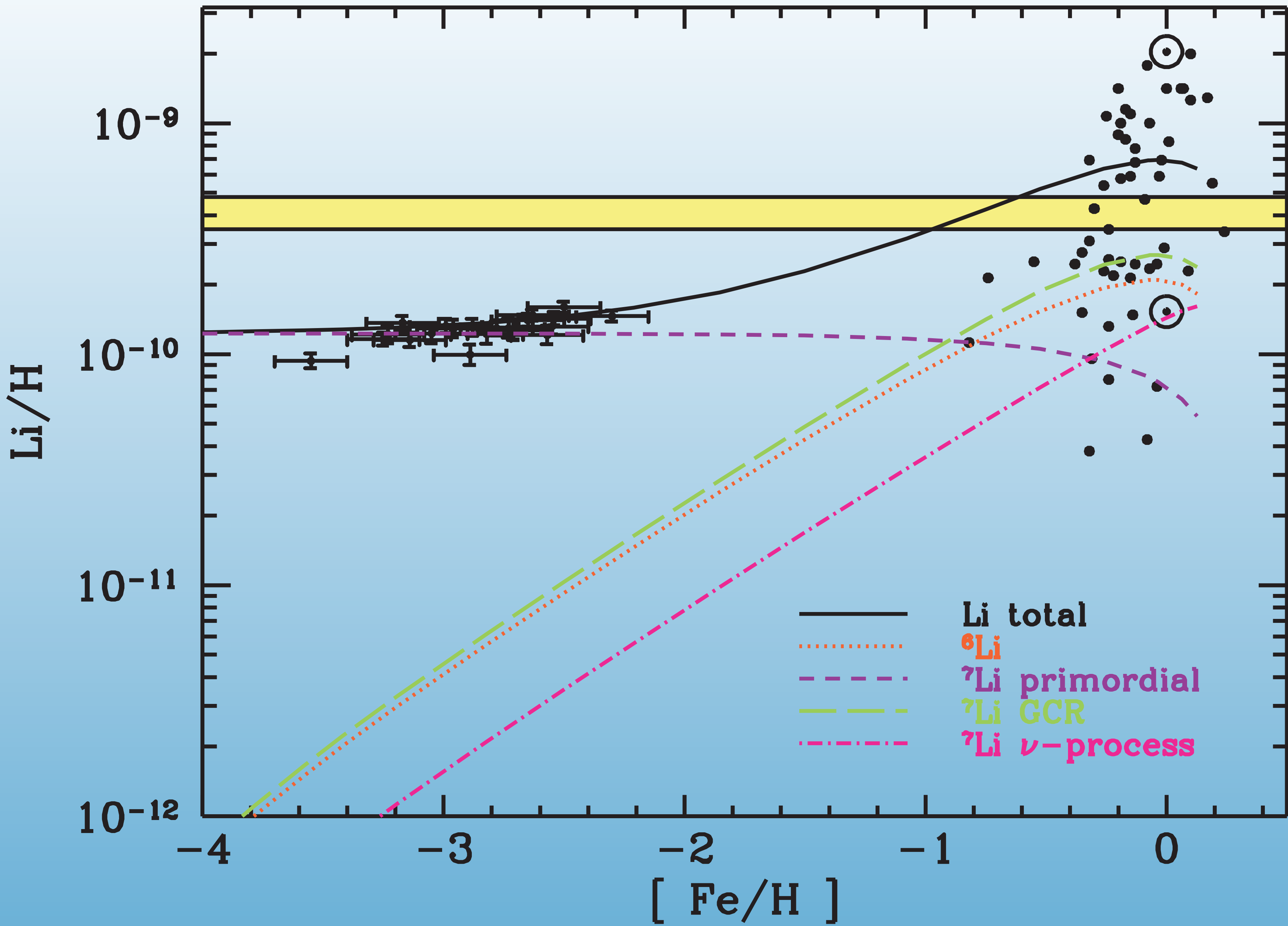


Li/H

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







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

- Nuclear Rates
  - Restricted by solar neutrino flux

Coc et al.
Cyburt, Fields, KAO

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:

$$S_{34}^{NEW}(0) = 0.267 \text{ keVb}, \quad \frac{\Delta S_{34}}{S_{34}} = -0.47 \quad \Big\} \text{ globular cluster Li}$$

or

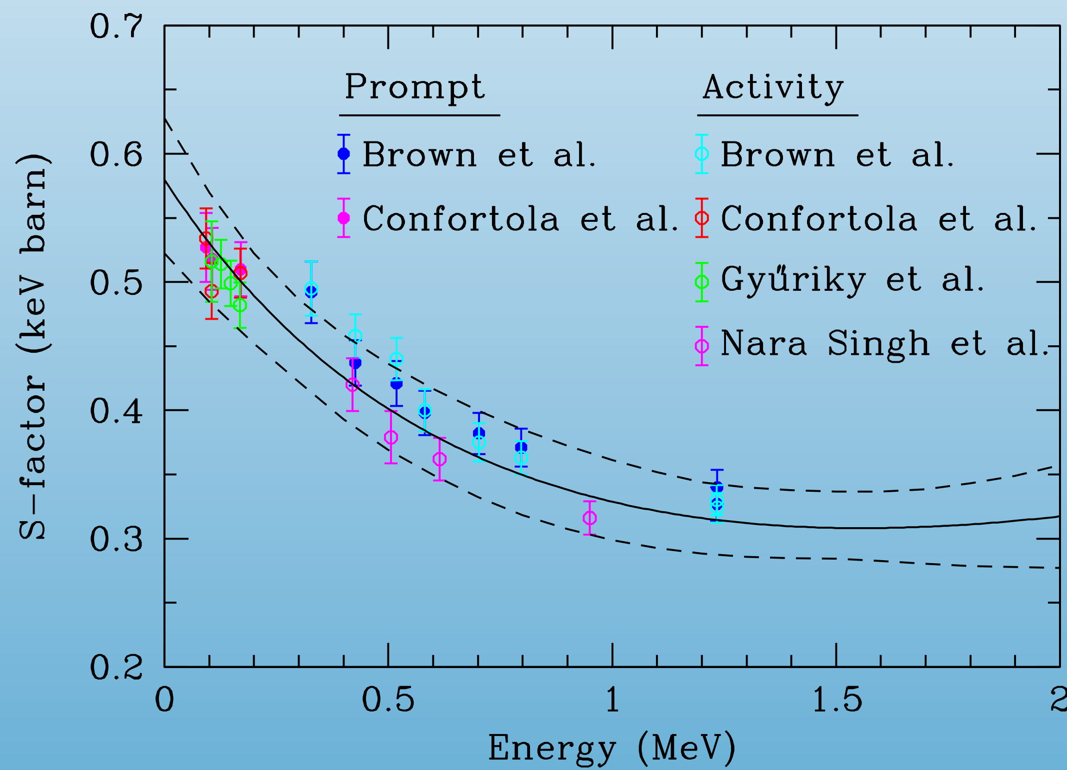
$$S_{34}^{NEW}(0) = 0.136 \text{ keVb}, \quad \frac{\Delta S_{34}}{S_{34}} = -0.73 \quad \Big\} \text{ halo star Li}$$

Constrained from solar neutrinos

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

at 95% CL

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



Resonant Reactions

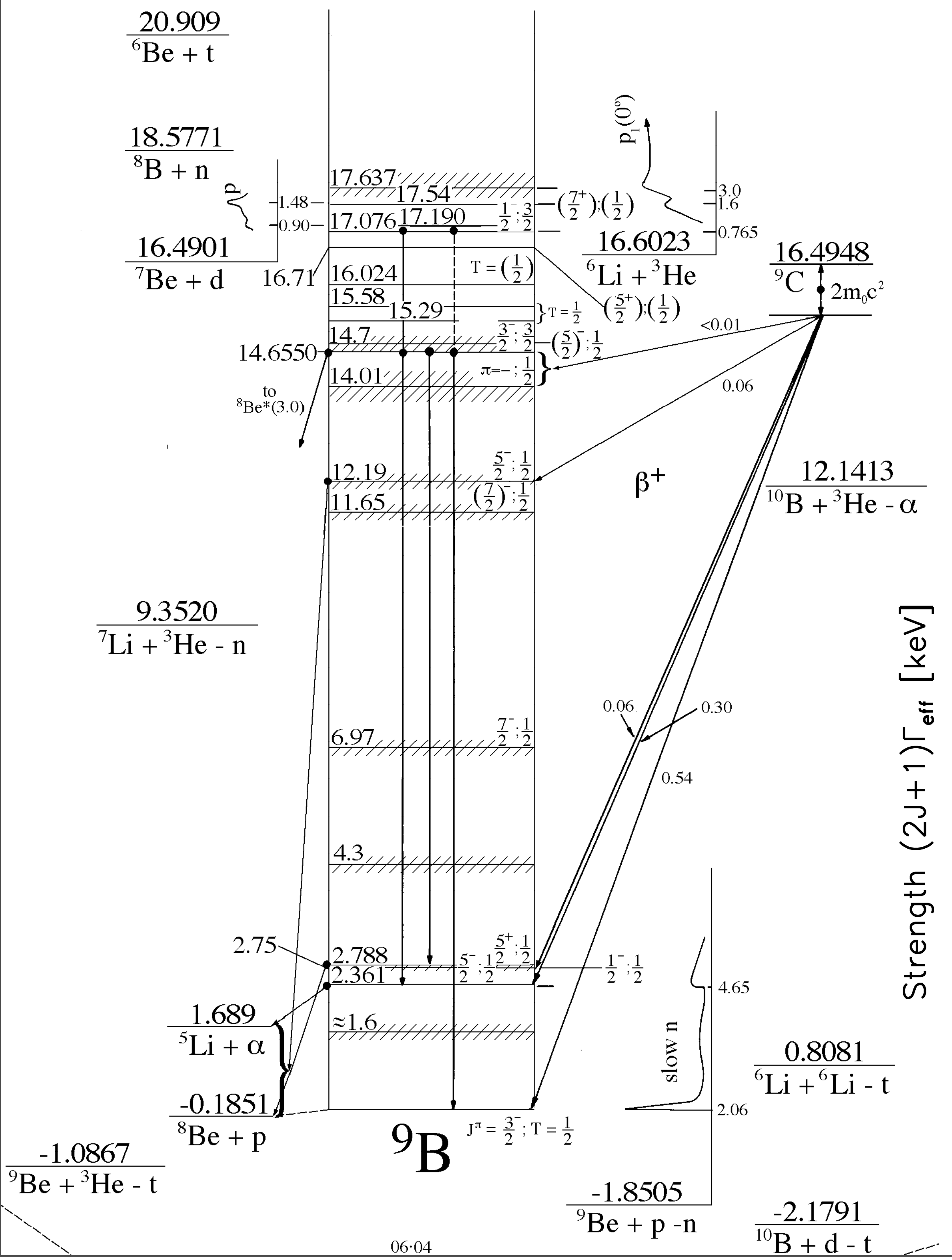
Cyburt, Pospelov
Chakraborty, Fields, Olive
Broggini, Canton, Fiorentini, Villante

Is there a missing excited state providing a resonant reaction?

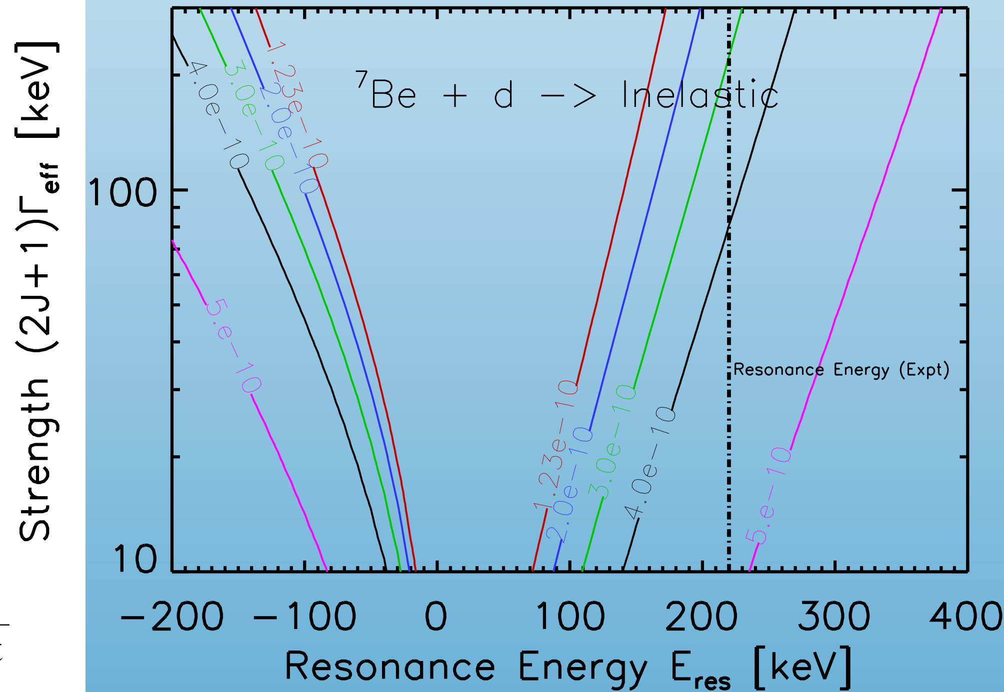
$$^{7}\mathrm{Be} + A \longrightarrow C^{*} \longrightarrow B + D$$

In principle, long list of possible resonance candidates

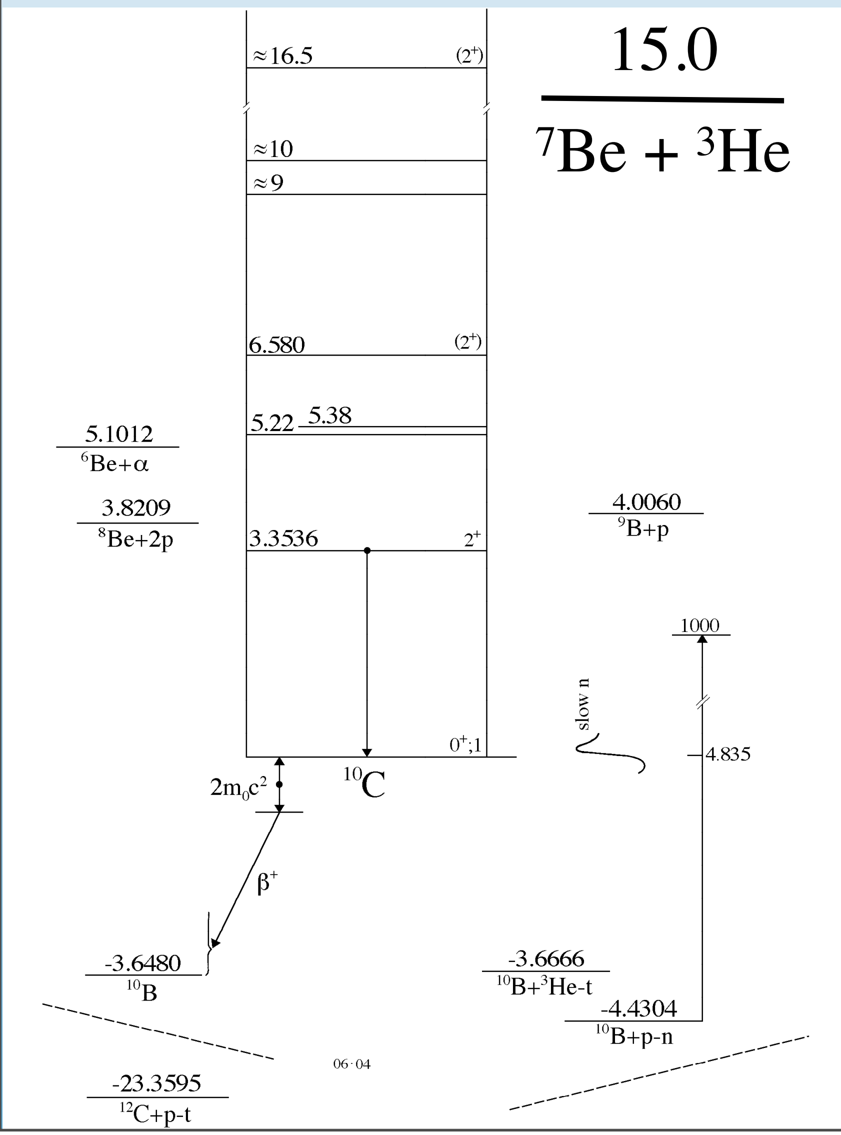
- Excited states of ^{8}Li (included)
- ^{8}Be (some included) - large E_{res}
- ^{8}B (included)
- ^{9}B - interesting state at 16.71 MeV



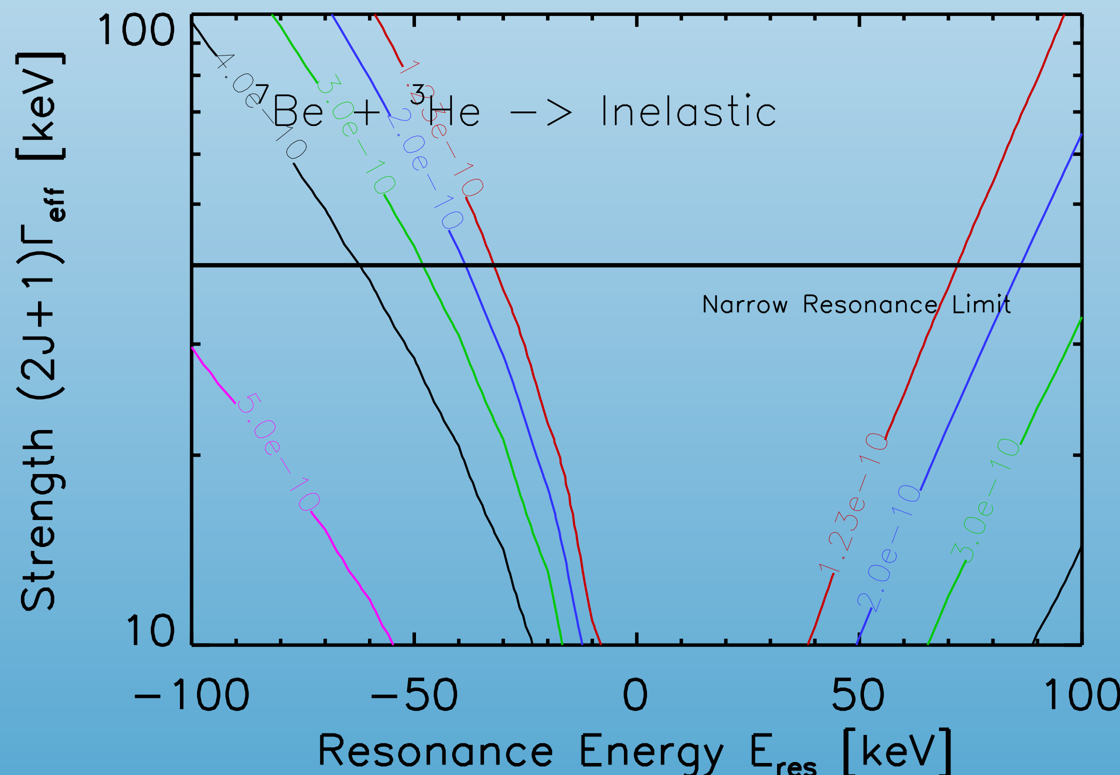
^{7}Be + d $\rightarrow$ ^{9}B (16.71)



- ^{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 .....



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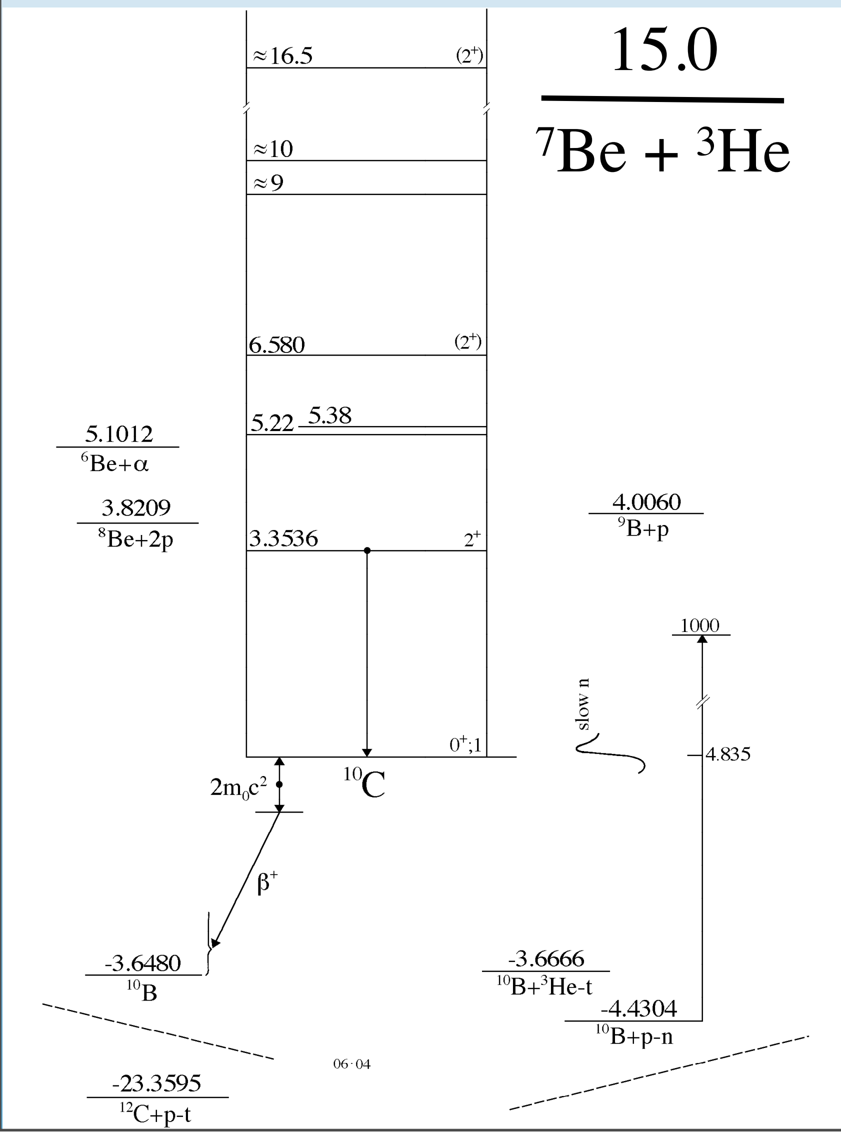

eg. if a 1^- or 2^- excited state of ^{10}C were near 15.0 MeV .....

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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Coc et al.
Cyburt, Fields, KAO

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  - standard models (< .05 dex), models (0.2 - 0.4 dex)

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

- Stellar parameters

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

Possible sources for the discrepancy

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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

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

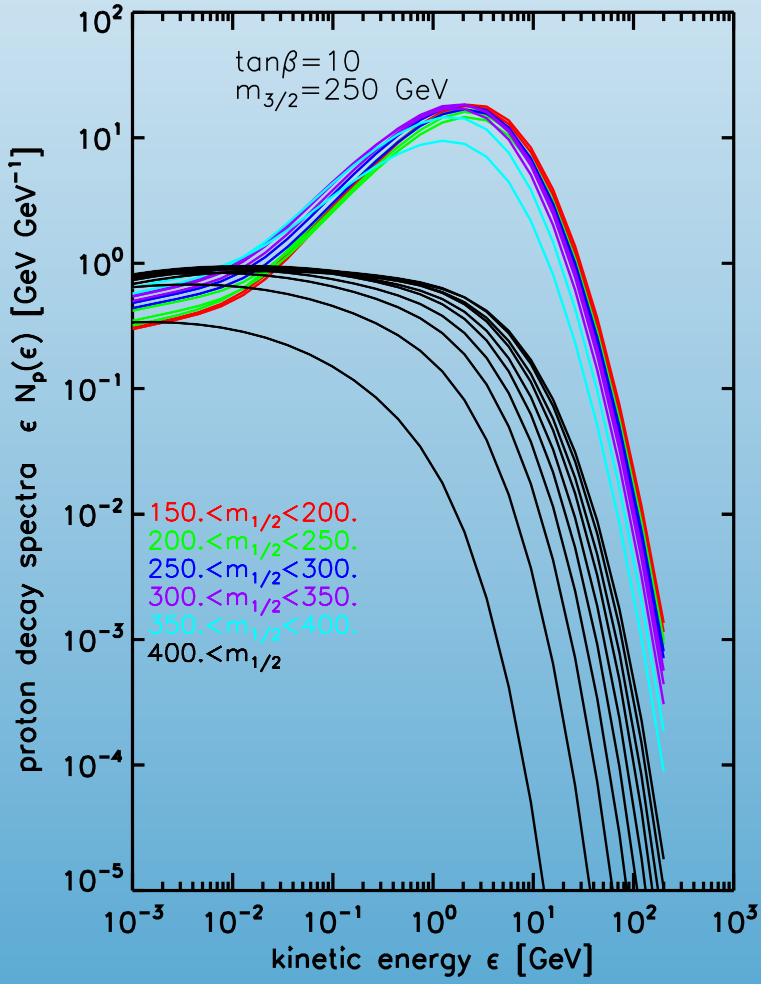
- Start with non-thermal injection spectrum (Pythia)
- Evolve element abundances including thermal (BBN) and non-thermal processes.

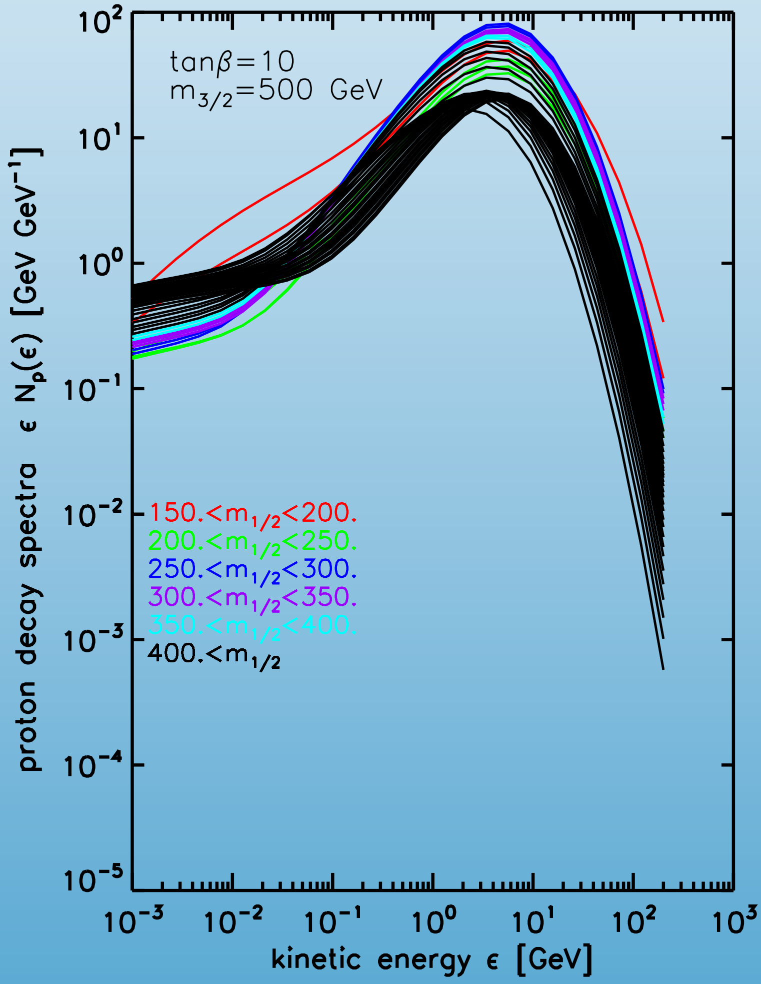
E.g., Gravitino decay

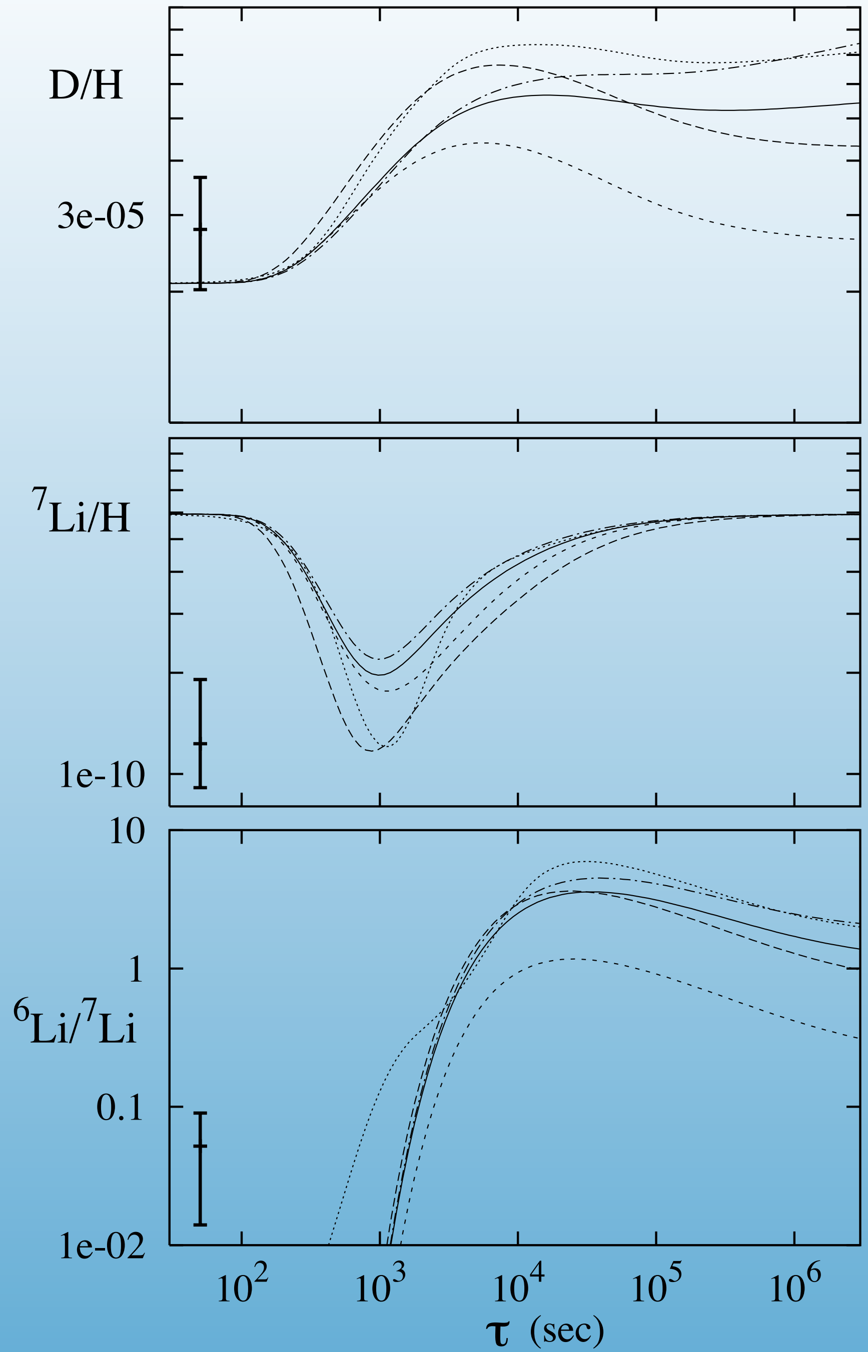
Cyburt, Ellis, Fields, Luo, Olive, Spanos

$$\widetilde{G} \to \tilde{f}\, f, \widetilde{G} \to \tilde{\chi}^{+}\, W^{-}(H^{-}), \widetilde{G} \to \tilde{\chi}^{0}_{i}\, \gamma(Z), \widetilde{G} \to \tilde{\chi}^{0}_{i}\, H^{0}_{i}\widetilde{G} \to \tilde{g}\, g.$$

plus relevant 3-body decays



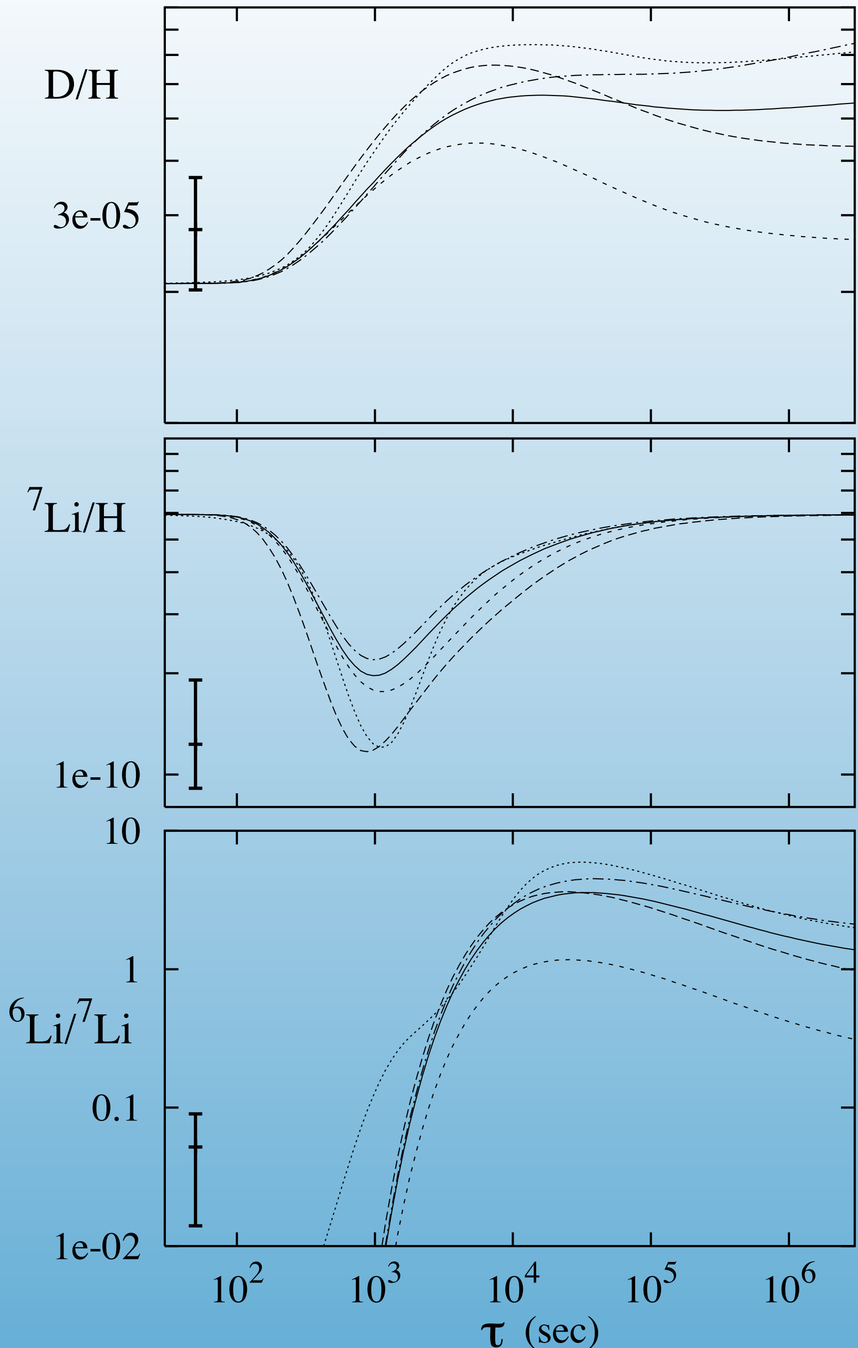




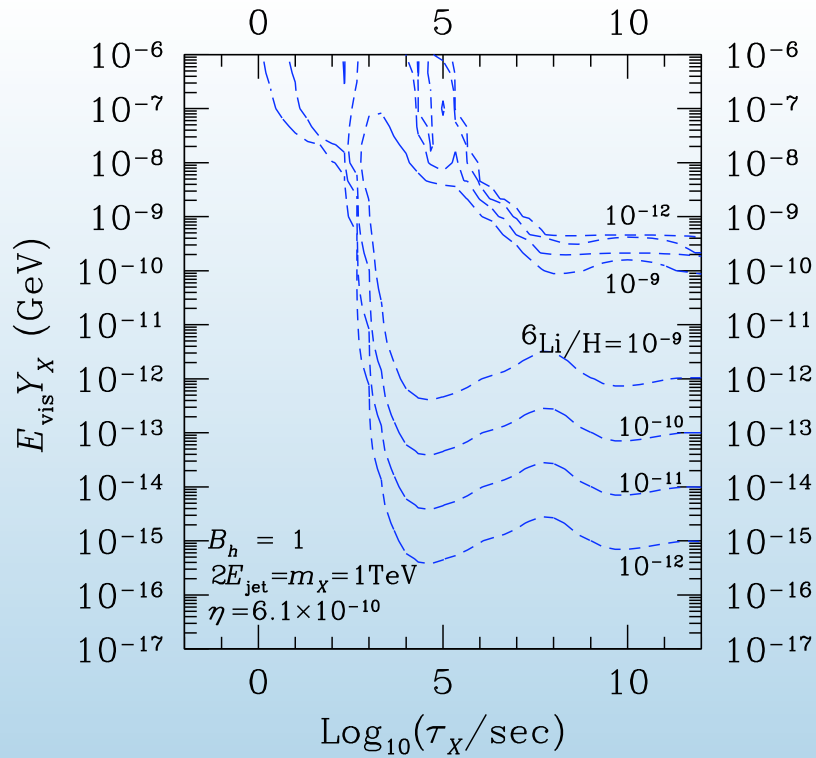
Injection of p,n with timescale of ~1000 s

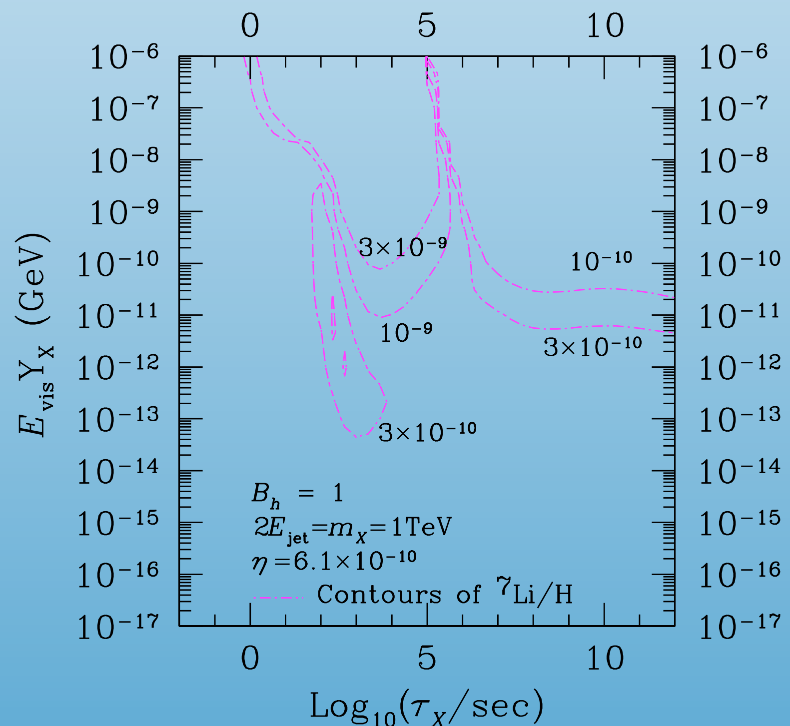
$^7Be(n,p)^7Li$ followed by $^7Li(p,\alpha)^4He$

Jedamzik



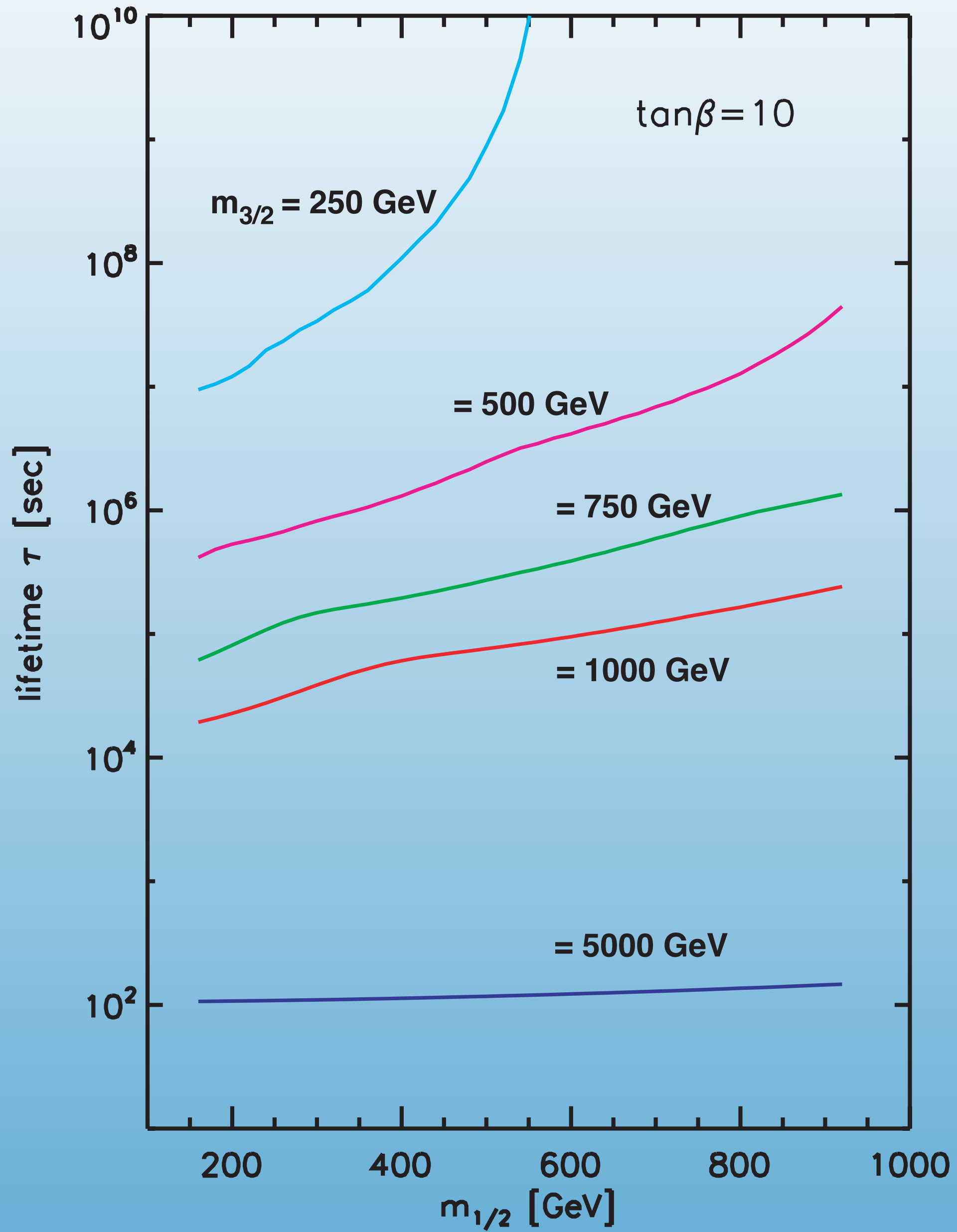
Jedamzik

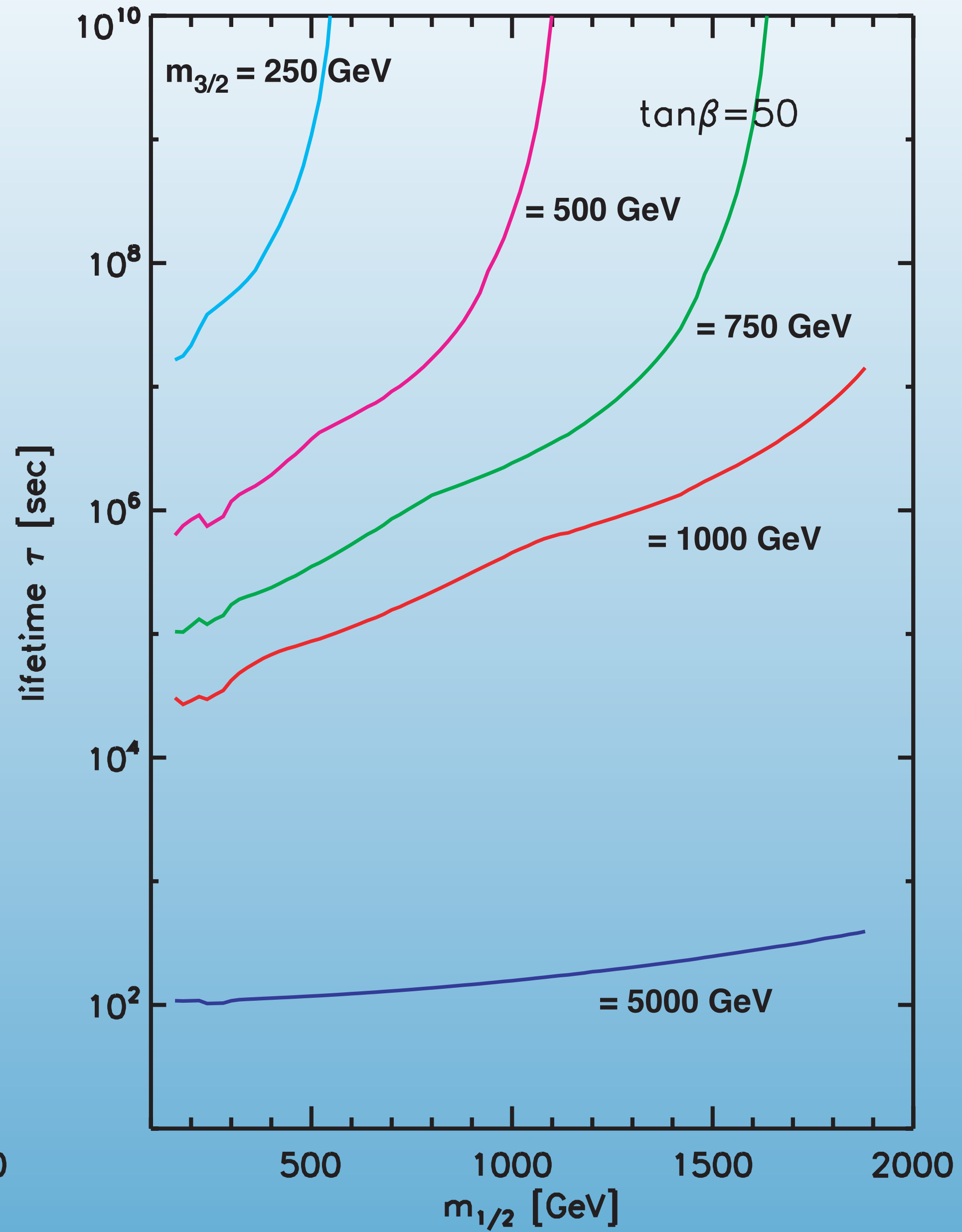




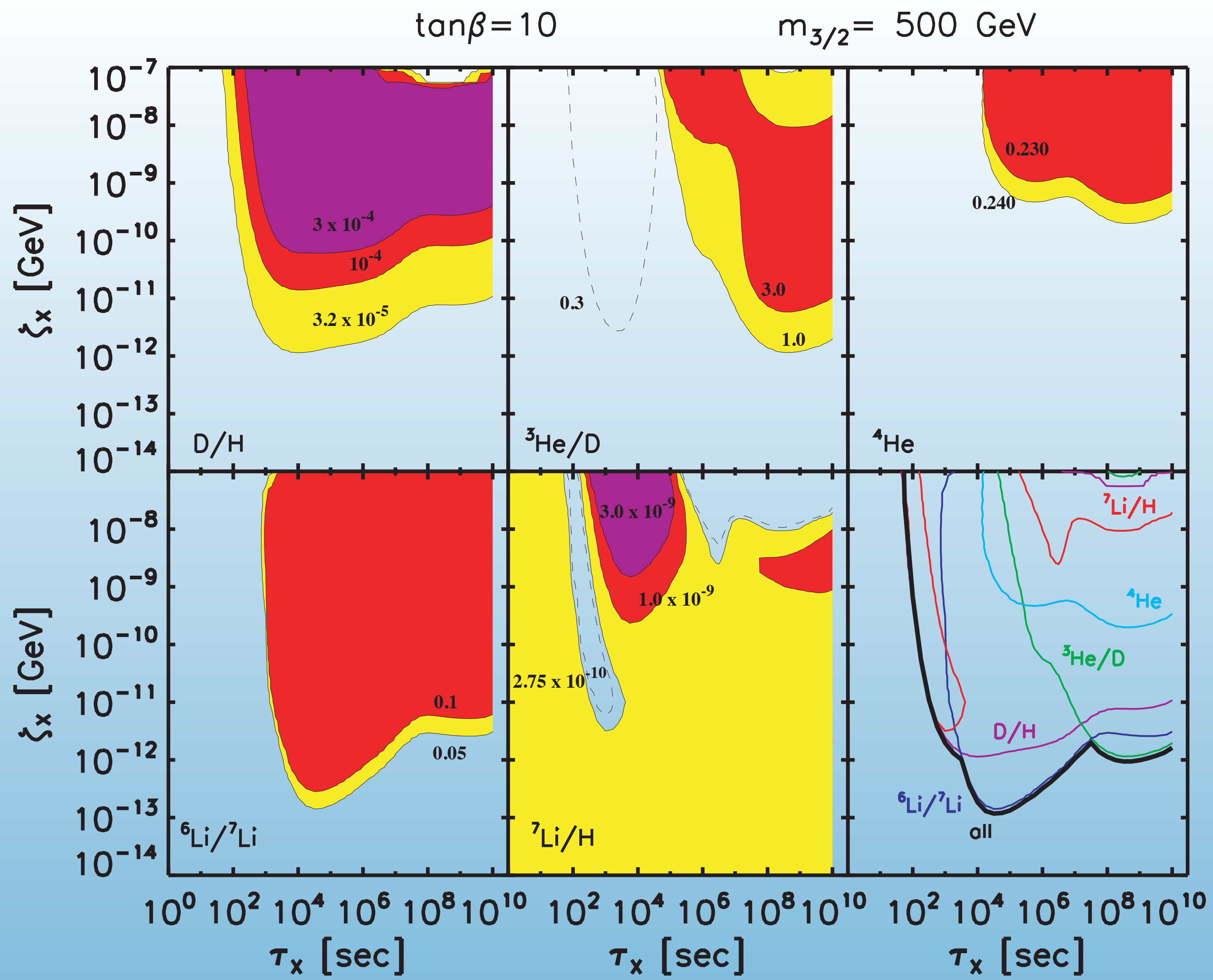
Kawasaki, Kohri, Moroi

Gravitino Decays and Li

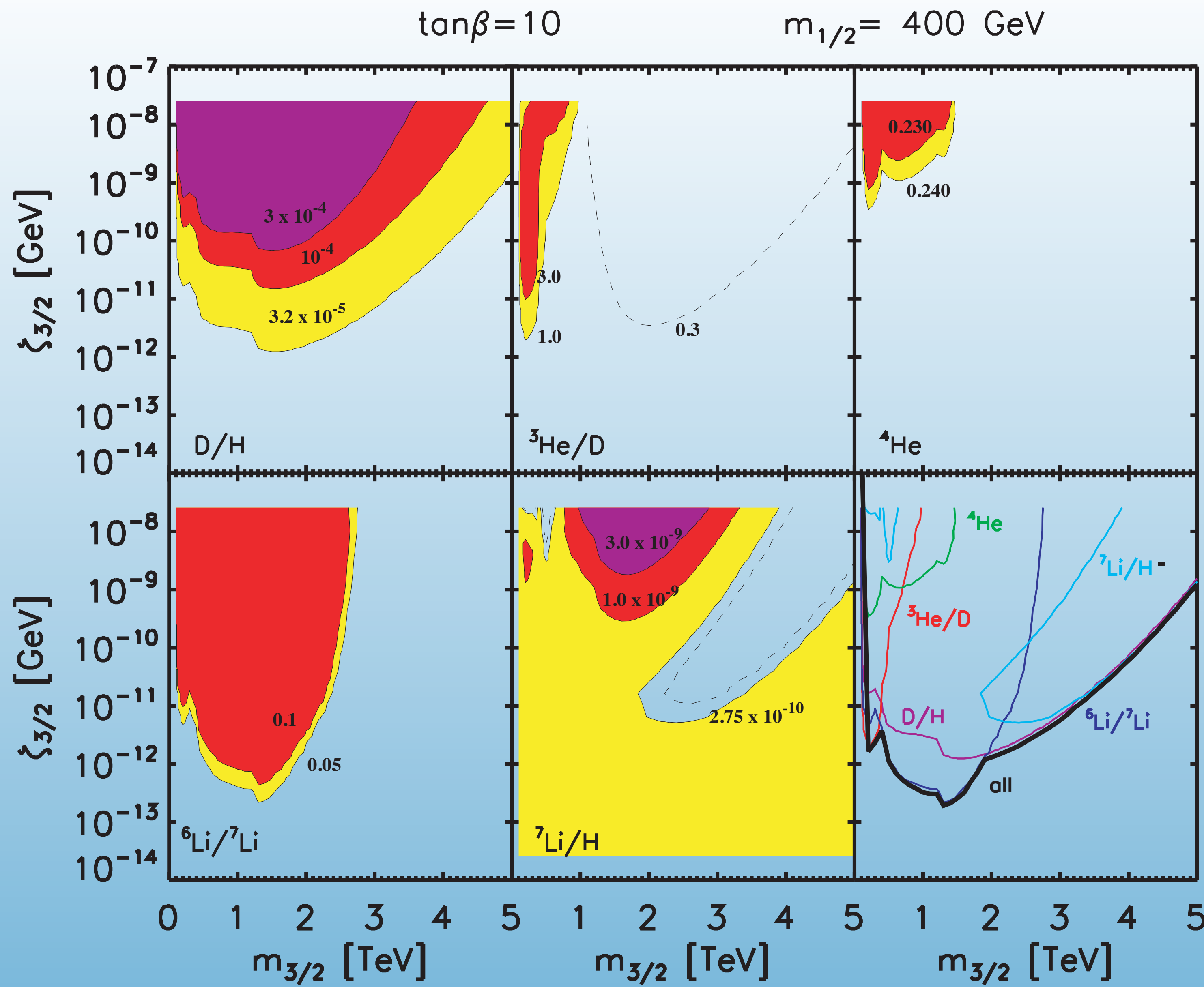




Cyburt, Ellis, Fields, Luo, Olive, Spanos



Based on $m_{1/2}$ = 300 GeV, tan β =10 ; B_h ~ 0.2



Benchmark point C, tan β =10 ; $m_{1/2}$ = 400 GeV

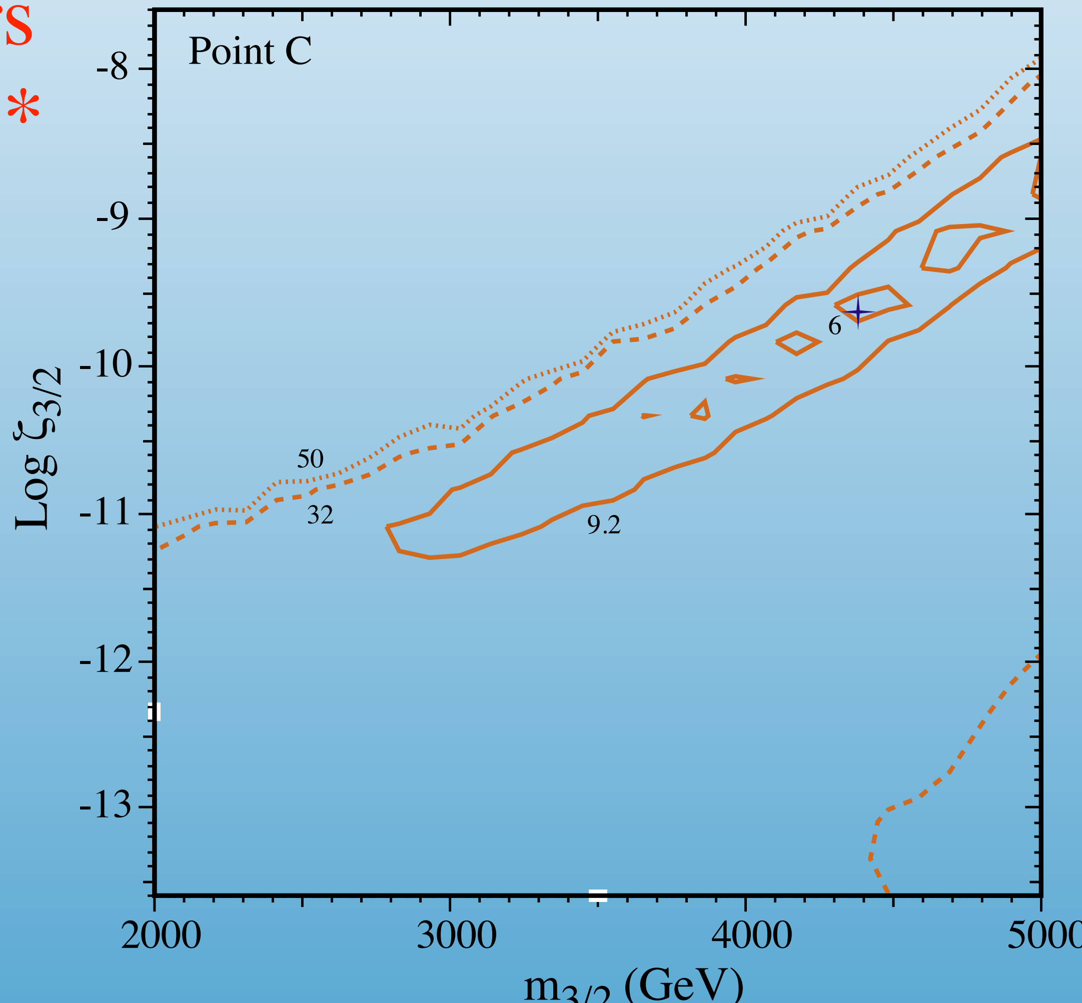
How well can you do

$$\chi^2 \equiv \left(\frac{Y_p - 0.256}{0.011}\right)^2 + \left(\frac{\frac{D}{H} - 2.82\times10^{-5}}{0.27\times10^{-5}}\right)^2 + \left(\frac{\frac{^7\mathrm{Li}}{H} - 1.23\times10^{-10}}{0.71\times10^{-10}}\right)^2 + \sum_i s_i^2,$$

SBBN: χ^2 = 31.7 - field stars

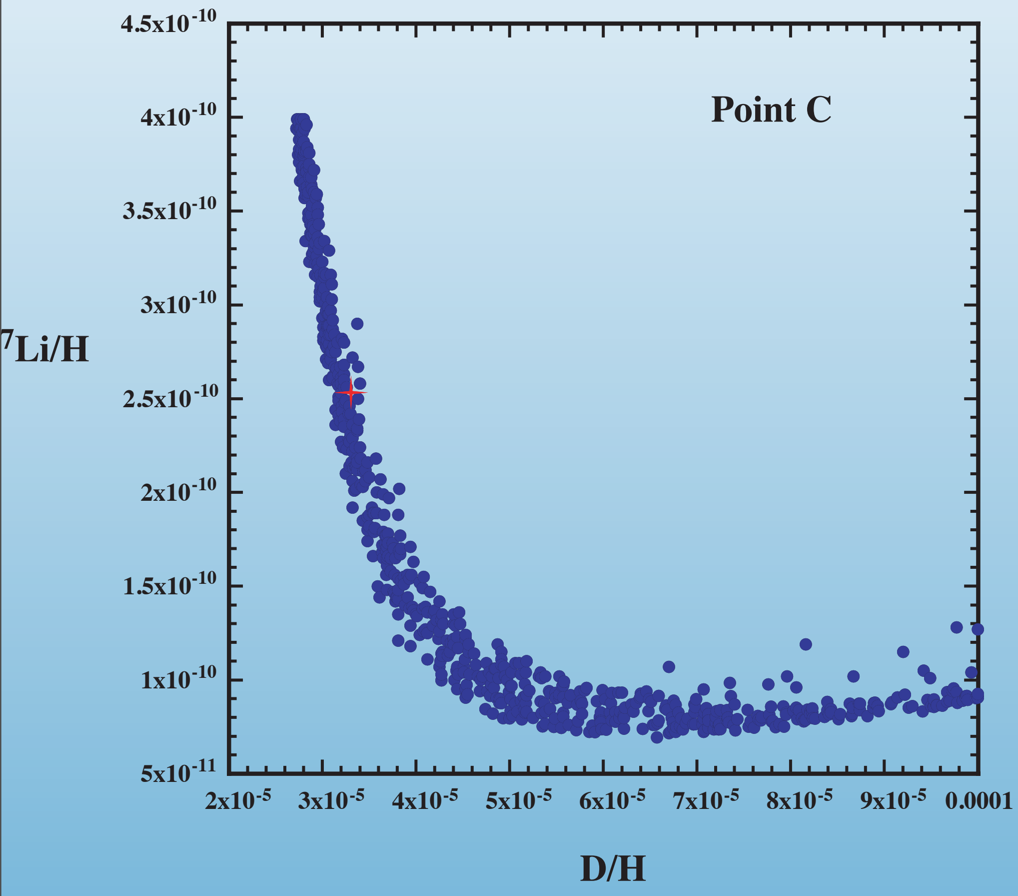
SBBN: χ^2 = 21.8 - GC stars*

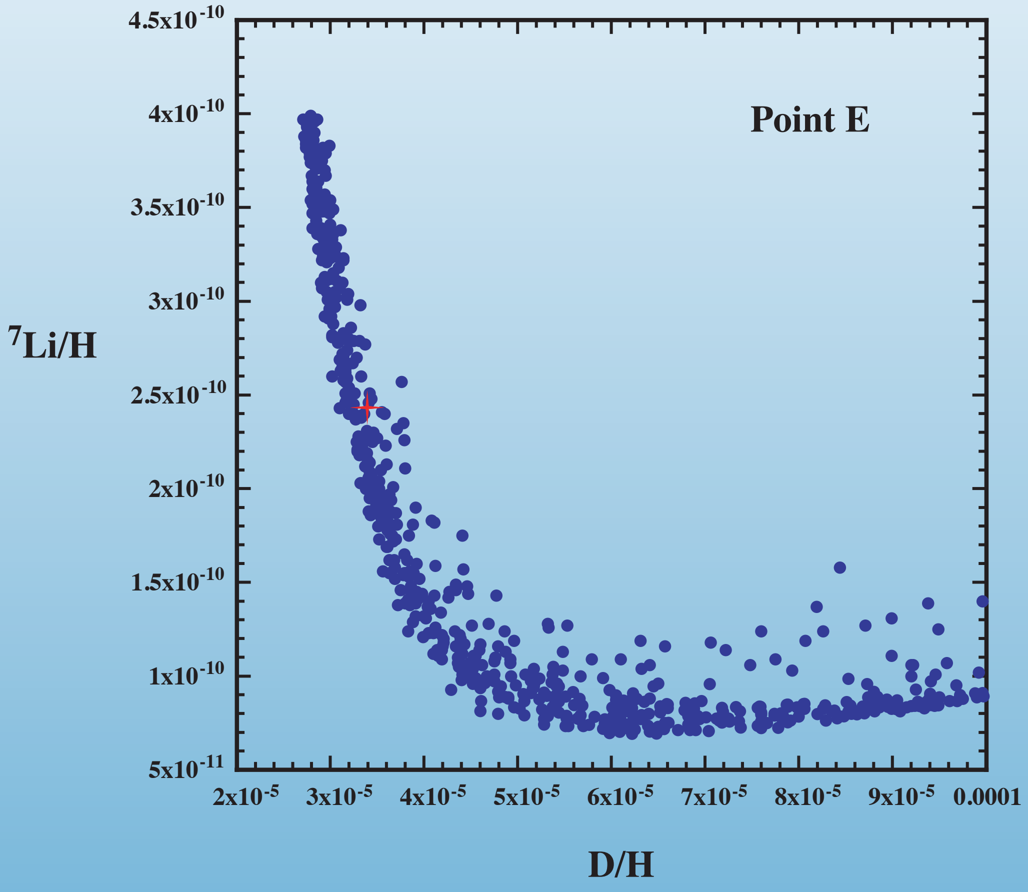
NGC 6397 appears to have a higher Li content than field stars of the same metallicity. This needs to be confirmed by a homogeneous analysis of field stars, with the same models and methods. This may or may not be related to the fact that this cluster is nitrogen rich, compared to field stars of the same metallicity (Pasquini et al. 2008).



* from Gonzales Hernandez et al.

General feature of "fixing" Li: Increased D/H

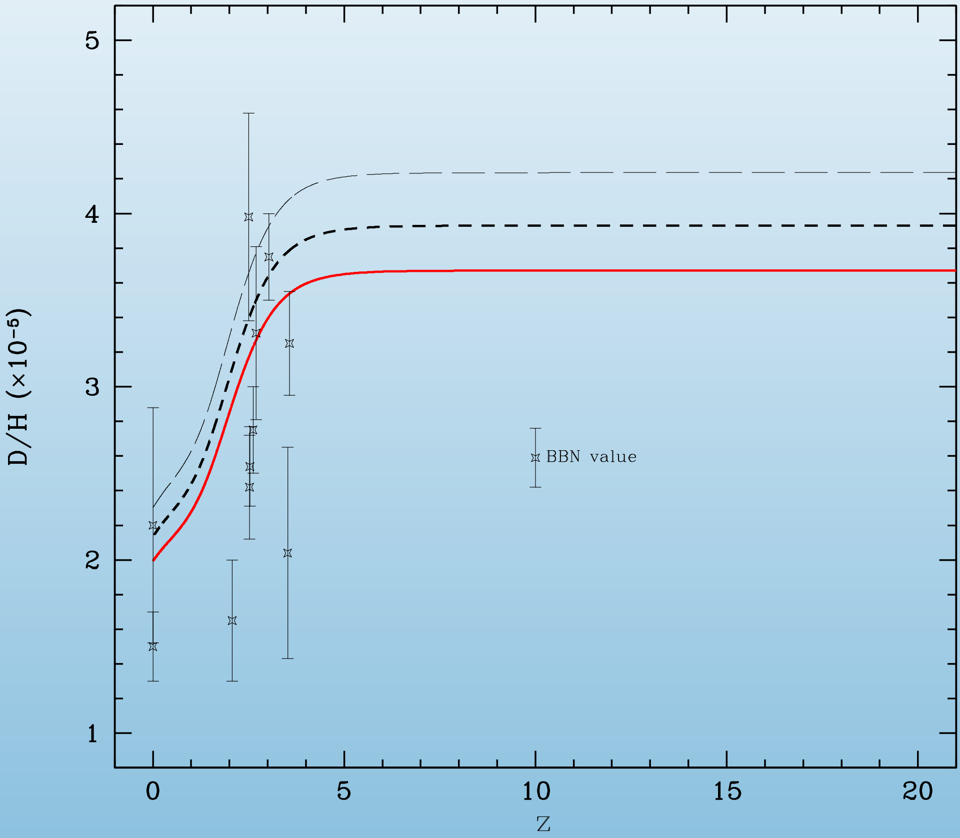


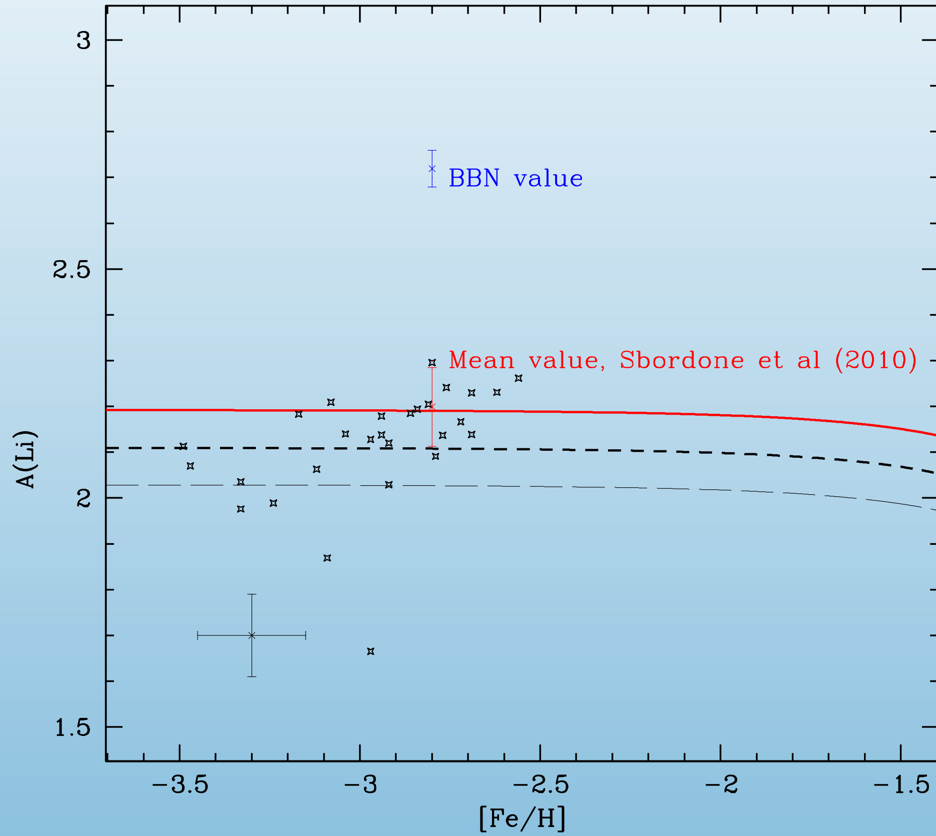


Cyburt, Ellis, Fields, Luo, Olive, Spanos

Olive, Petitjean, Vangioni, Silk

Evolution of D, Li





With post BBN processing of Li, D/H reproduces upper end of absorption data - dispersion due to in situ chemical destruction

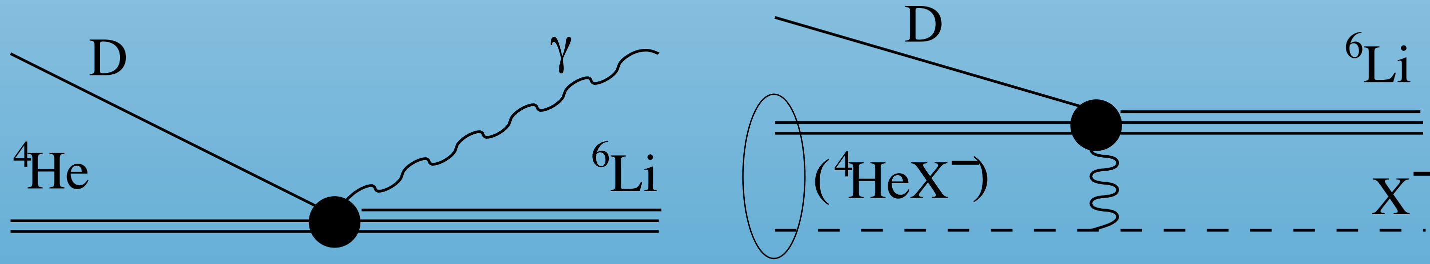
Olive, Petitjean, Vangioni, Silk

Effects of Bound States

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

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

- Bound state reaction is not suppressed



Pospelov

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

Constraints from balance of weak rates vs Hubble rate

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

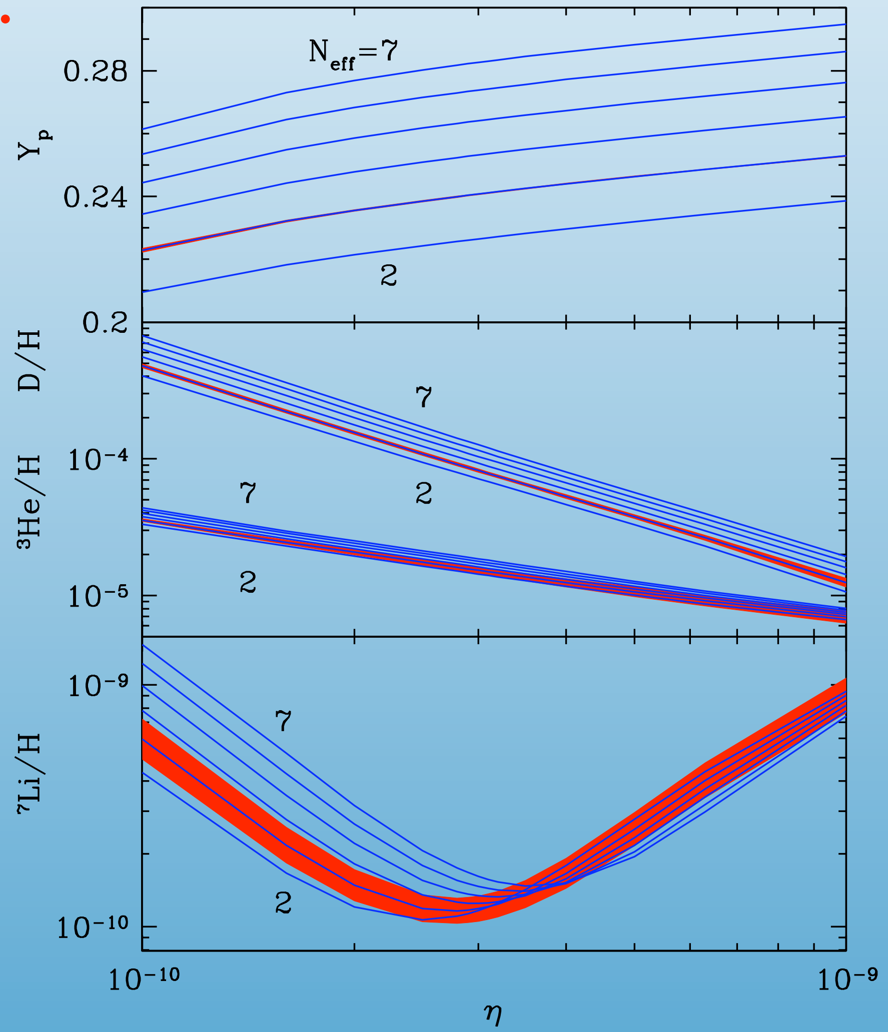
through He abunance

$\frac{n}{p} \sim e^{-\Delta m/T}$ **fixed at freezeout** $Y \sim \frac{2(n/p)}{1+(n/p)}$

Sets constraints on G_F, G_N, N, etc.

Limits on Particle Properties

- BBN Concordance rests on balance between interaction rates and expansion rate.
- Allows one to set constraints on:
  - Particle Types
  - Particle Interactions
  - Particle Masses
  - Fundamental Parameters



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.

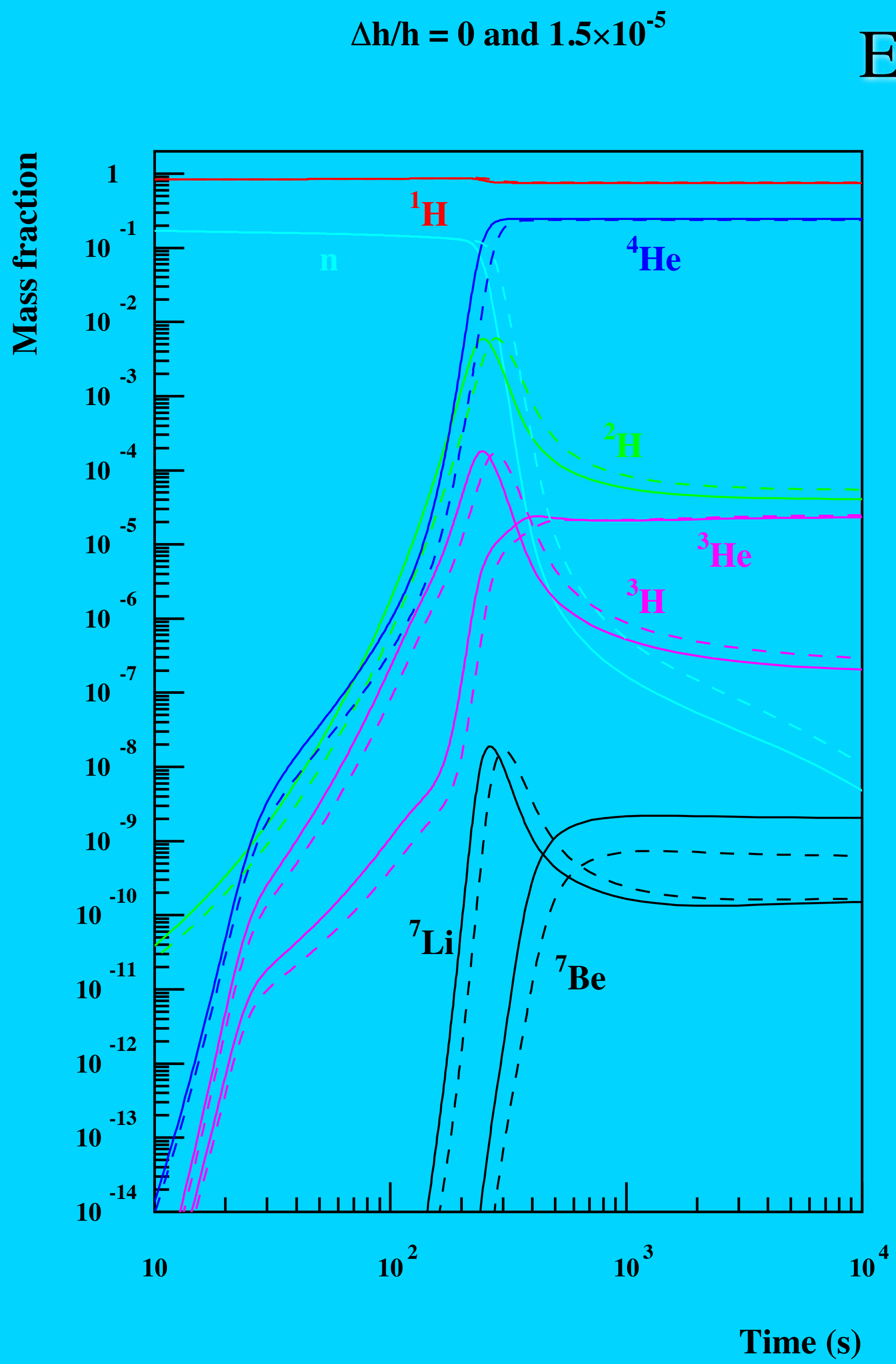
Consider effects on: $Q = \Delta m_N, \tau_N, B_D$

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

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

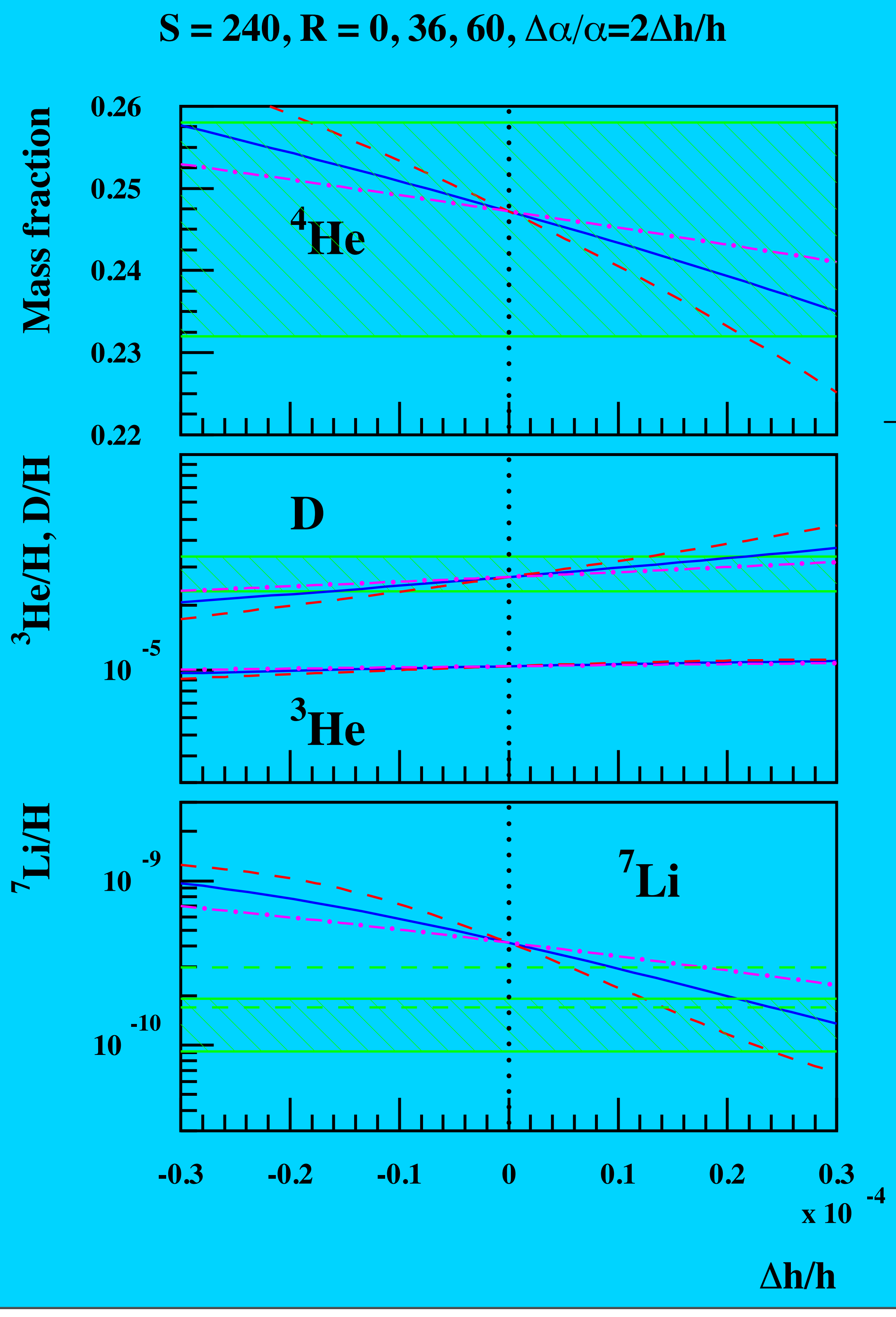
Coc, Nunes, Olive, Uzan, Vangioni
Dmitriev & Flambaum

Effect of variations of h (S = 160)



Notice effect on ^{7}Li

Coc, Nunes, Olive, Uzan, Vangioni



For S = 240, R = 36,

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

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???