Massive gravitino decays and the cosmological lithium problem

- 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
- Solutions?

Massive gravitino decays and the cosmological lithium problem

or

- BBN and the WMAP determination of η, $\Omega_B h^2$
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  - D/H - ^{4}He - ^{7}Li
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Massive gravitino decays and the cosmological lithium problem

or

How to best reconcile Big Bang Nucleosynthesis with Li abundance determinations

- BBN and the WMAP determination of η, $\Omega_B h^2$
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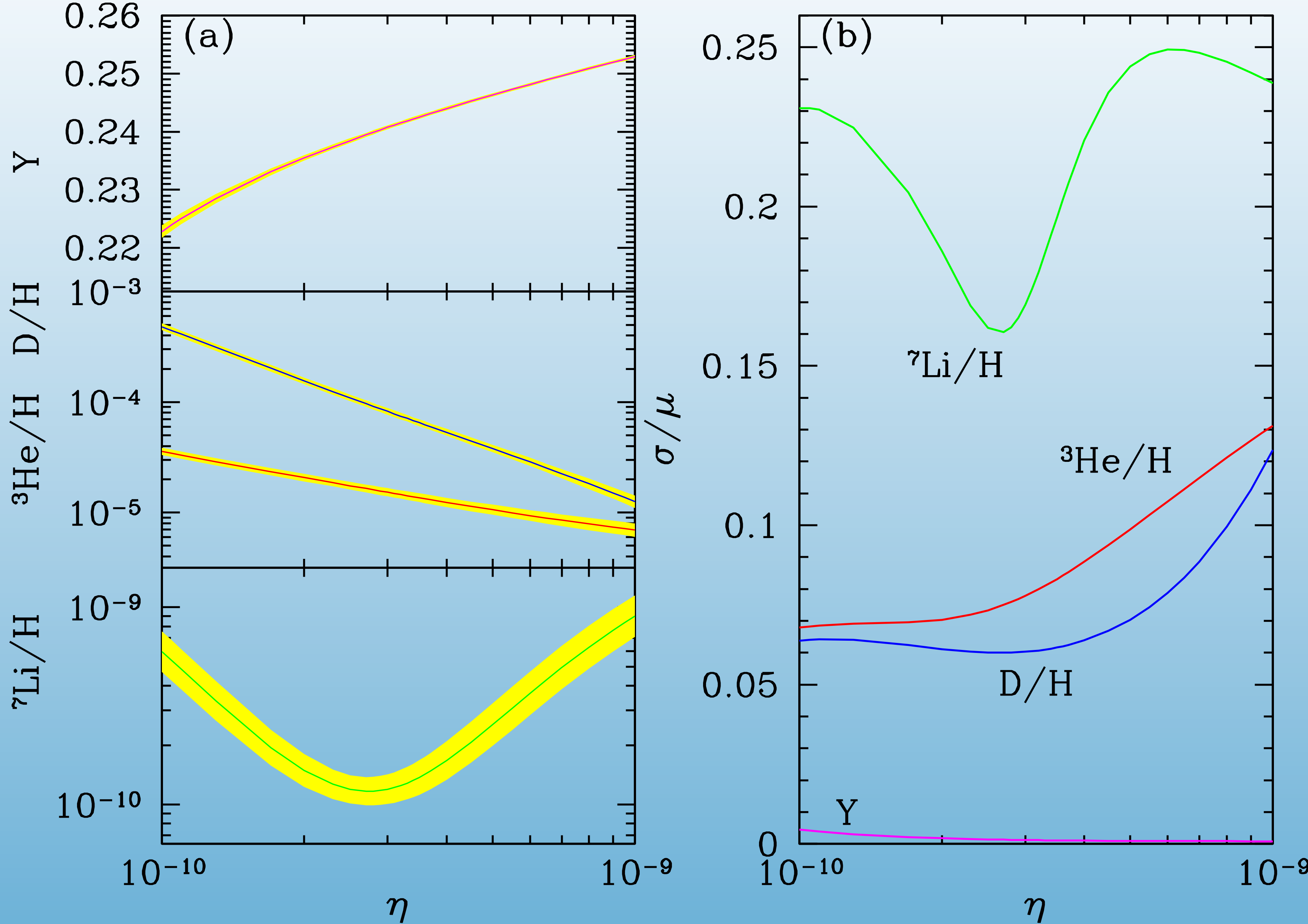
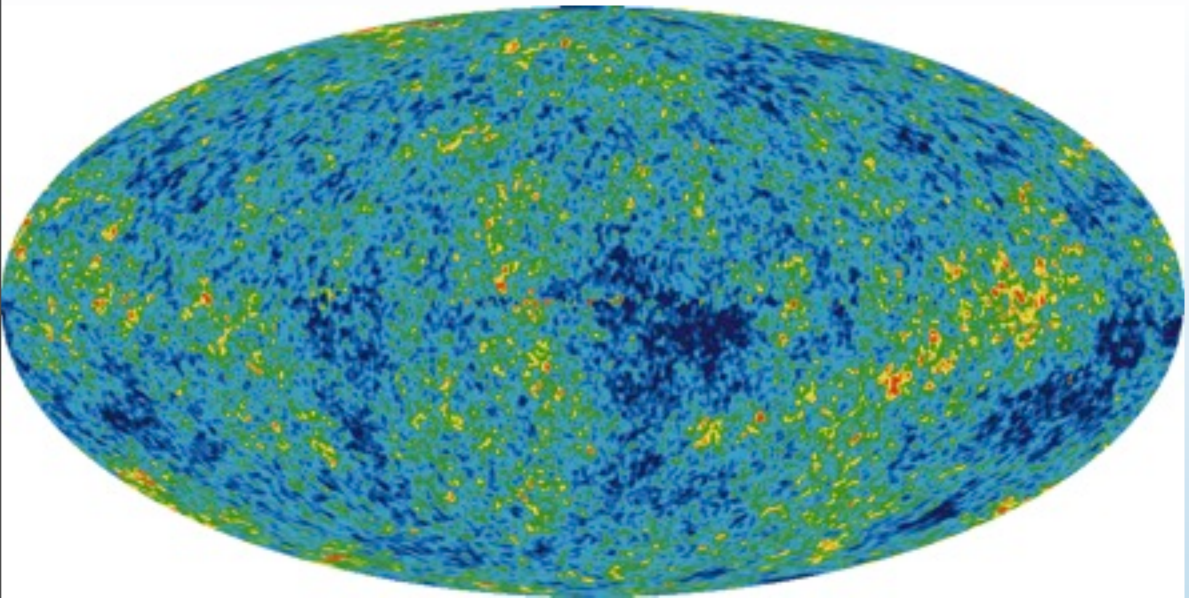
  - D/H - ^{4}He - ^{7}Li

- The Li Problem

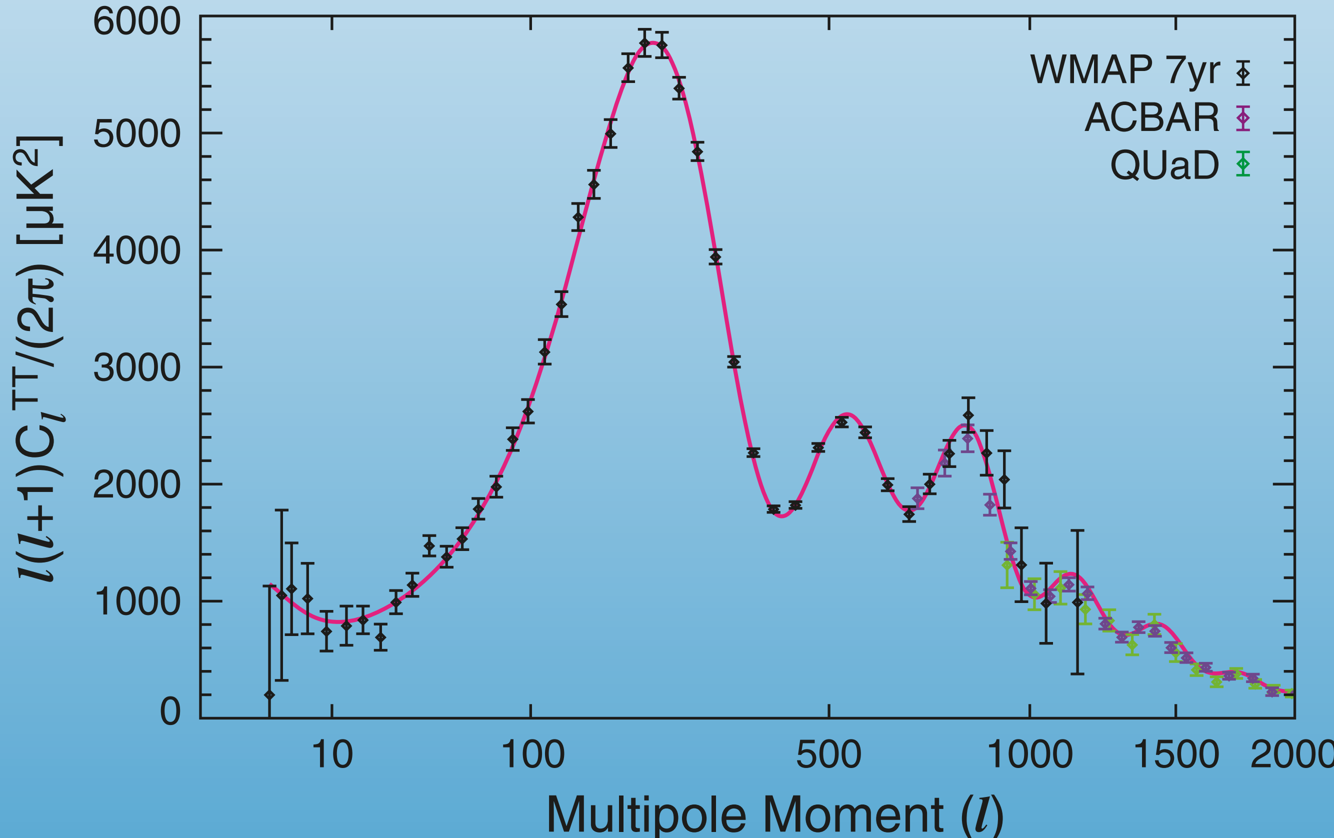
- Solutions?

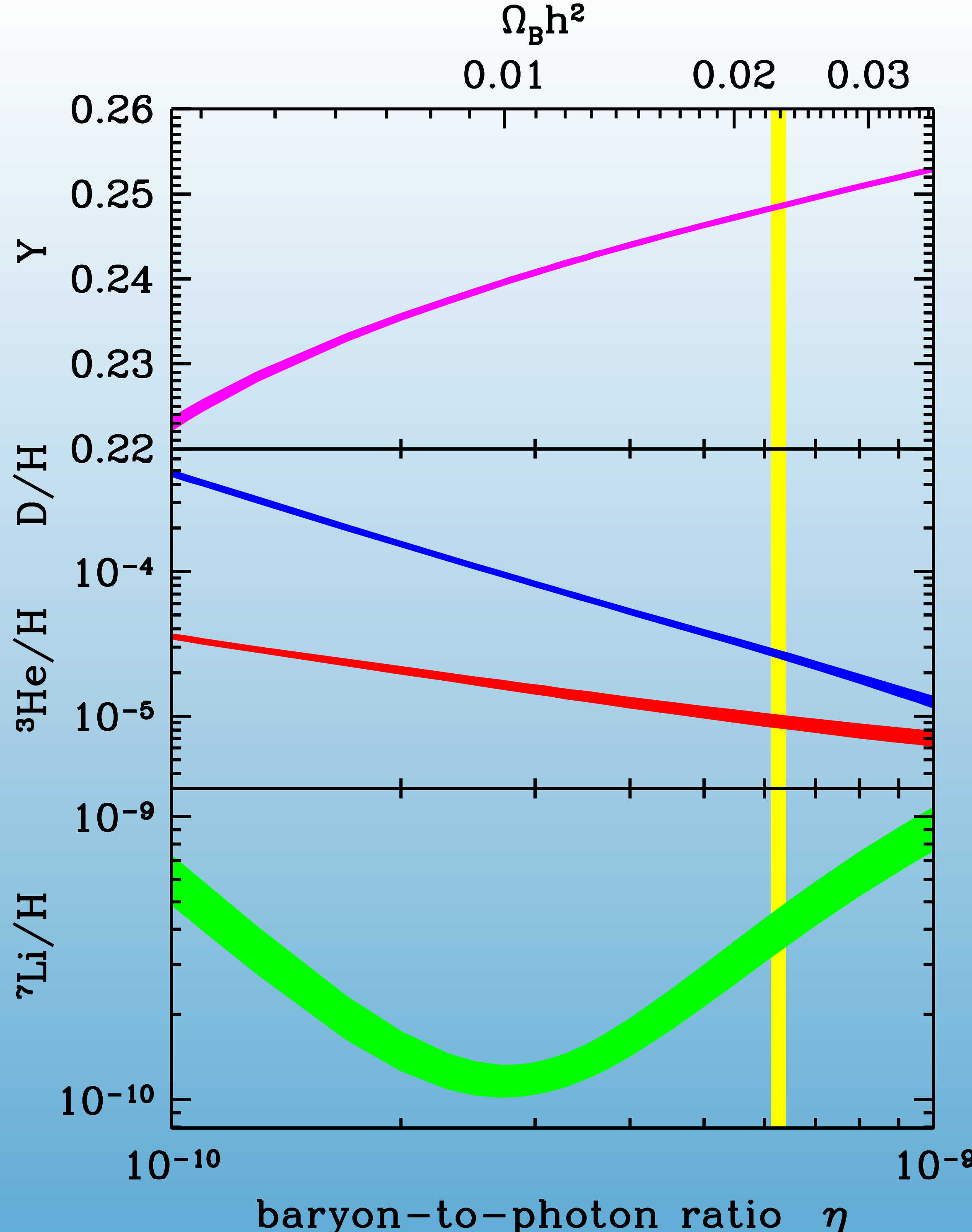

(a)
Y
0.26
0.25
0.24
0.23
0.22
D/H
^{3}He/H
10^{-3}
10^{-4}
10^{-5}
^{7}Li/H
10^{-9}
10^{-10}
10^{-10}
10^{-9}
η
(b)
σ/μ
0.25
0.2
0.15
0.1
0.05
0
^{7}Li/H
^{3}He/H
D/H
Y
10^{-10}
10^{-9}
η



WMAP best fit

$$\Omega_B h^2 = 0.0226 \pm 0.0005$$
$$\eta_{10} = 6.19 \pm 0.15$$




$\Omega_B h^2$
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

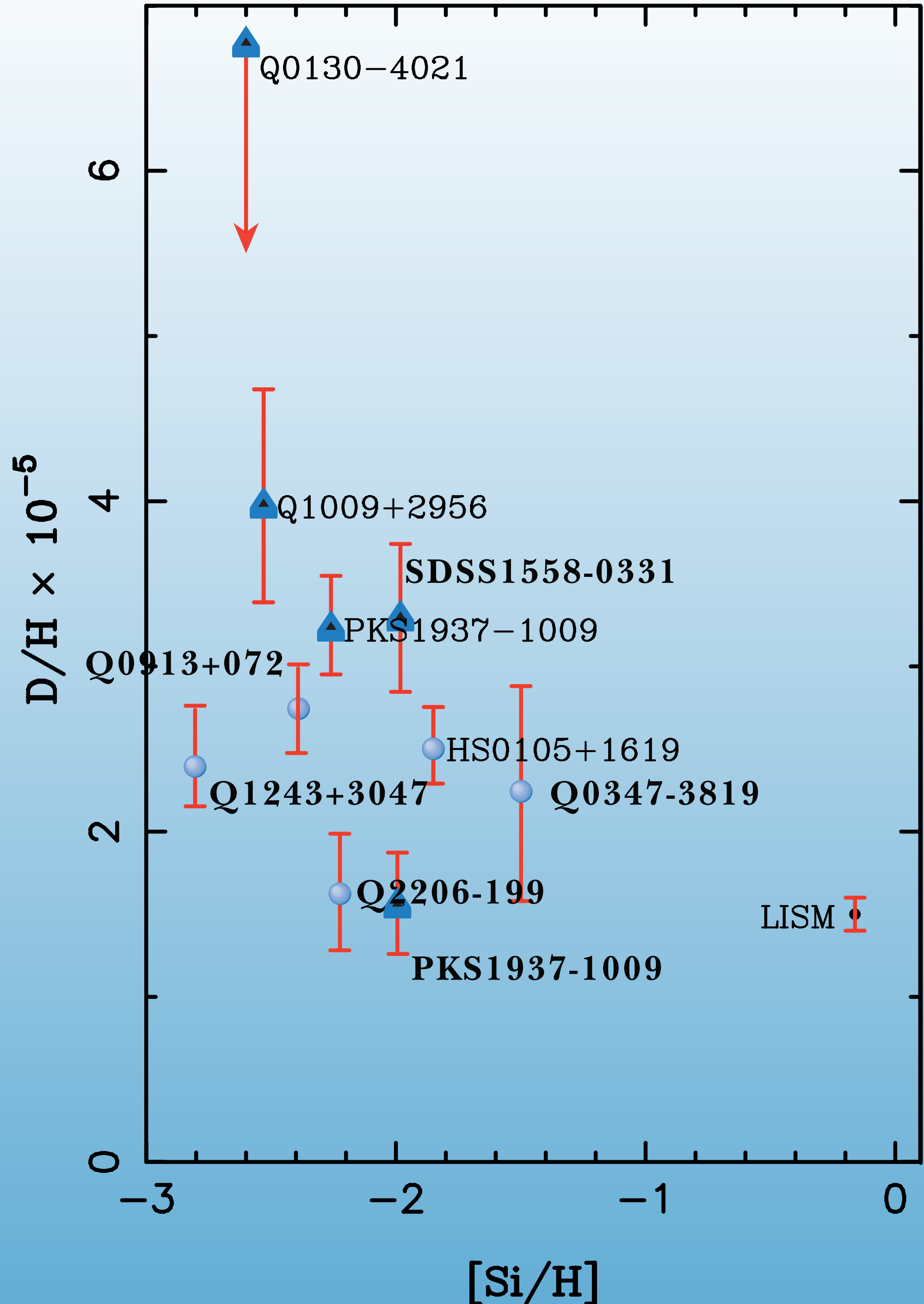
D/H abundances in Quasar apsorption systems

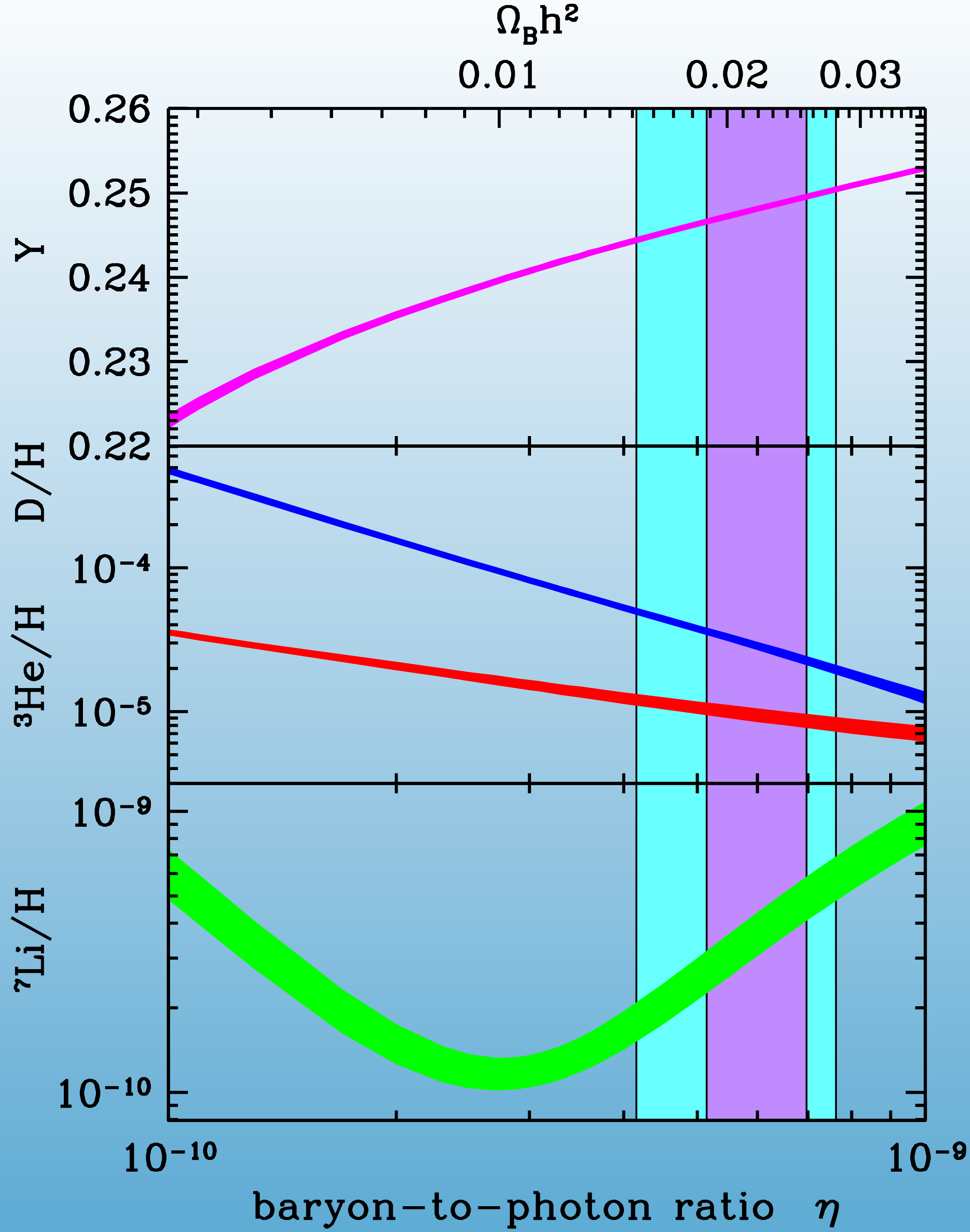
BBN Prediction:

10^5 D/H = 2.52 ± 0.17

Obs Average:

10^5 D/H = 2.82 ± 0.21





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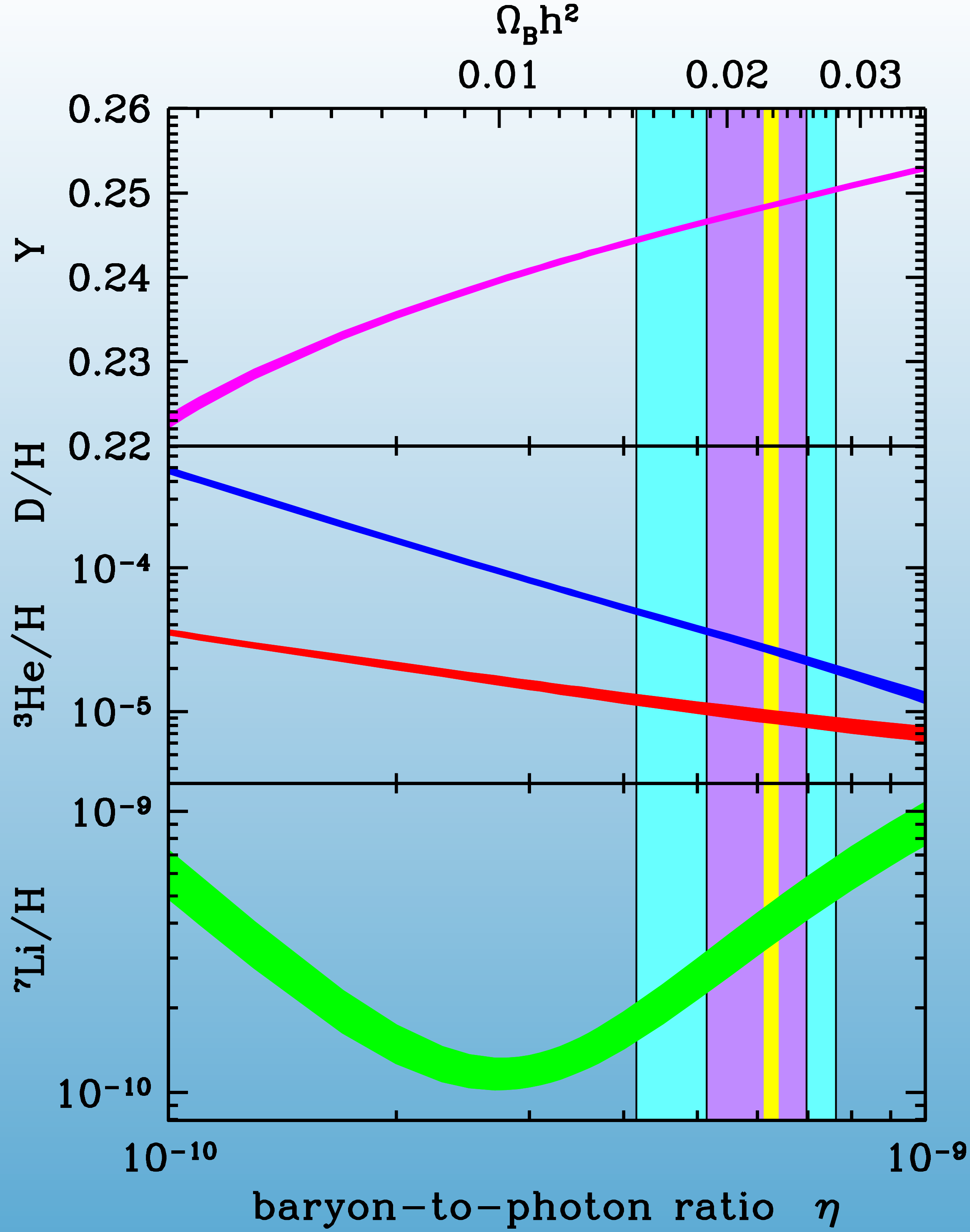
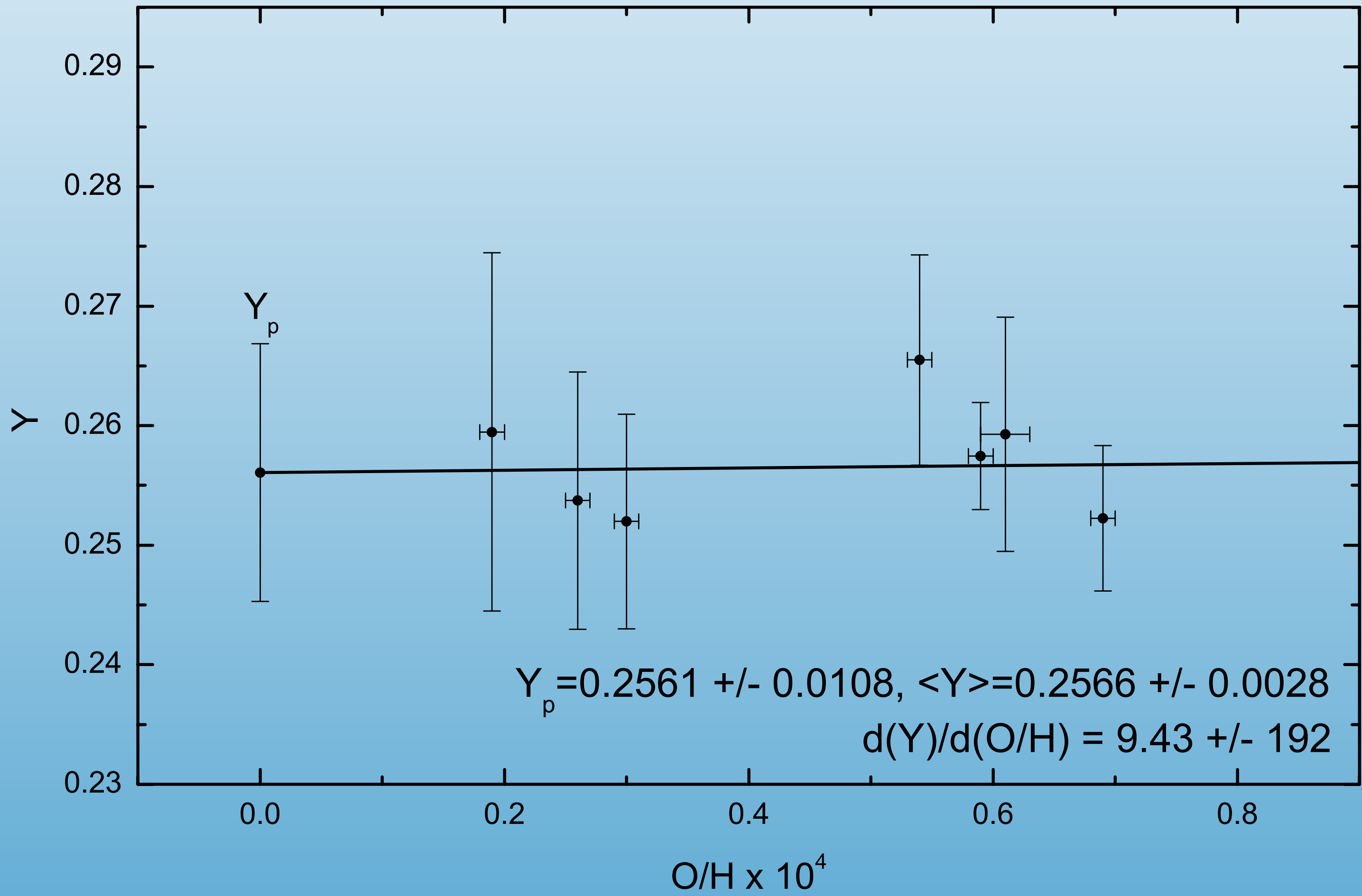
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon−to−photon ratio η



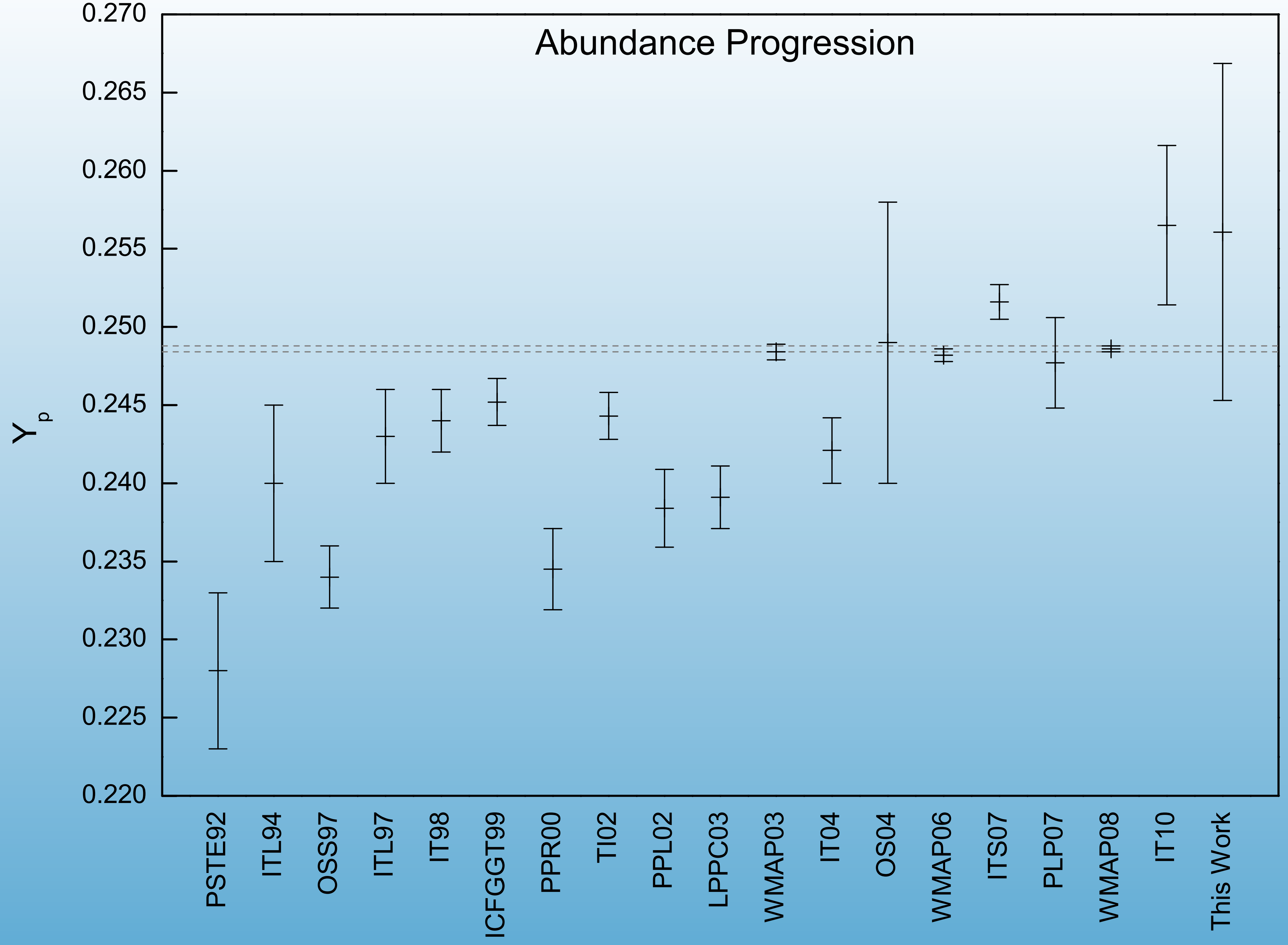
$\Omega_B h^2$
0.01
0.02
0.03
0.26
0.25
0.24
0.23
0.22
Y
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio η

^{4}He

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



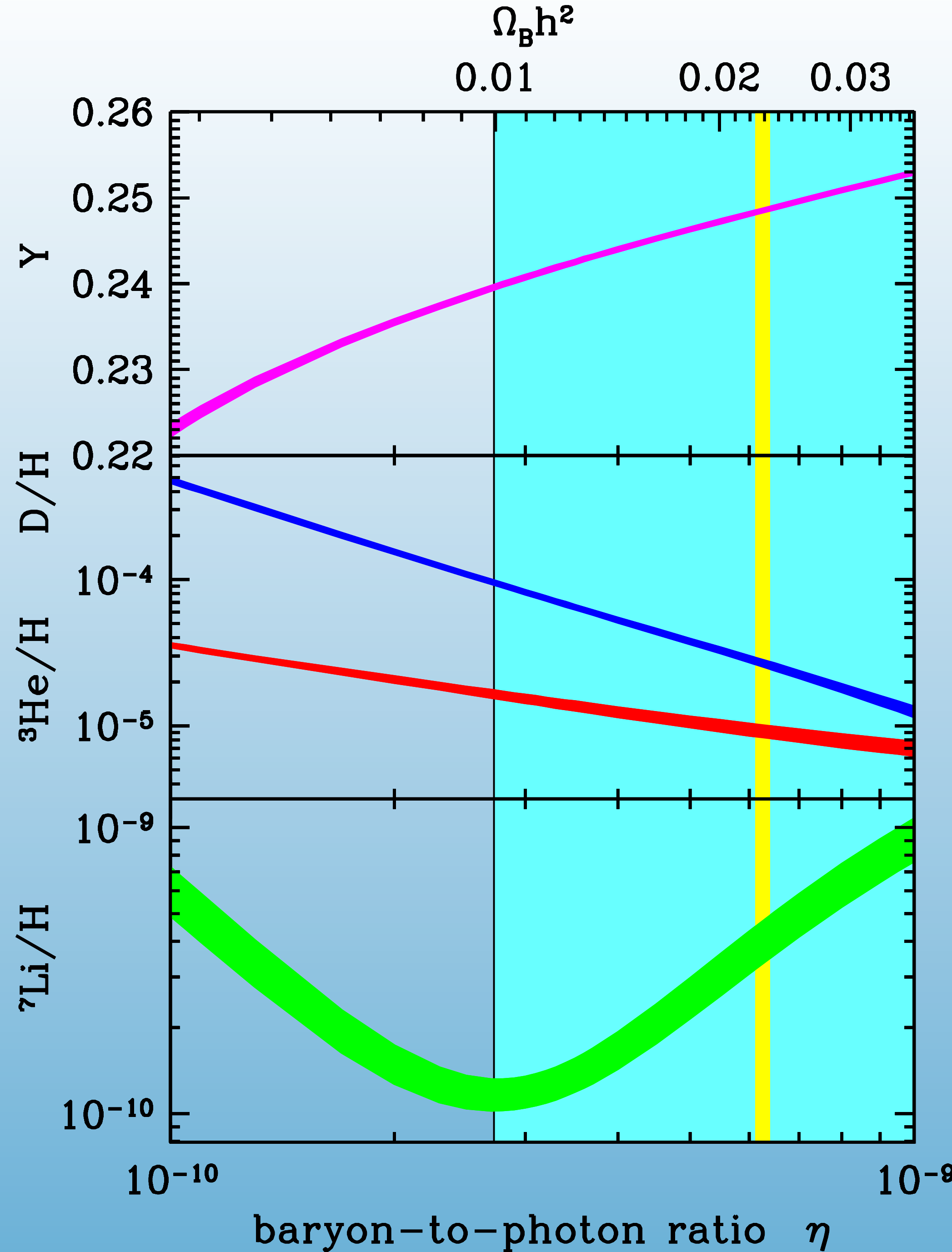
Aver, Olive, Skillman


Abundance Progression
Y p
0.270
0.265
0.260
0.255
0.250
0.245
0.240
0.235
0.230
0.225
0.220
PSTE92
ITL94
OSS97
ITL97
IT98
ICFGGT99
PPR00
TI02
PPL02
LPPC03
WMAP03
IT04
OS04
WMAP06
ITS07
PLP07
WMAP08
IT10
This Work

^{4}He Prediction:
0.2487 ± 0.0002

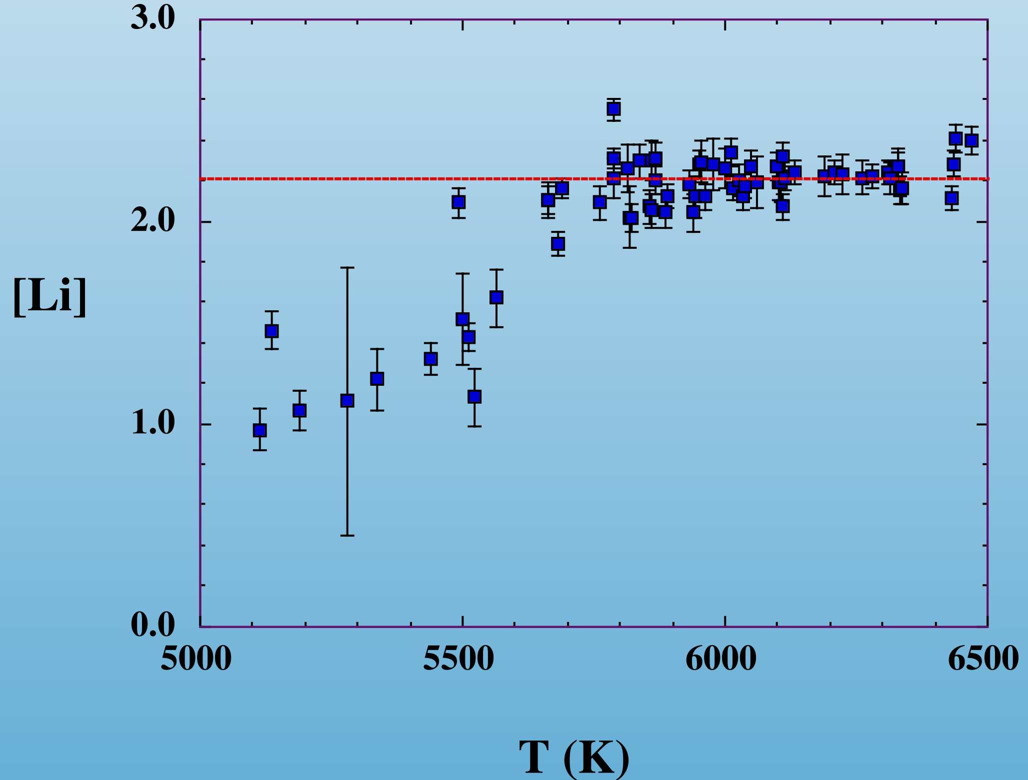
Data: Regression:
0.2561 ± 0.0108

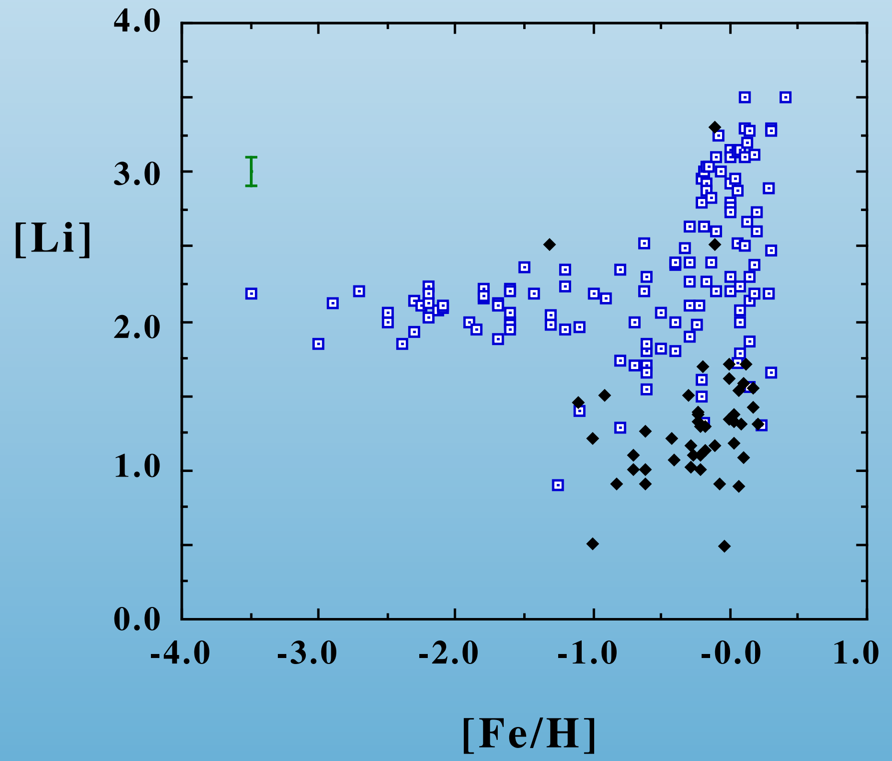
Mean:
0.2566 ± 0.0028

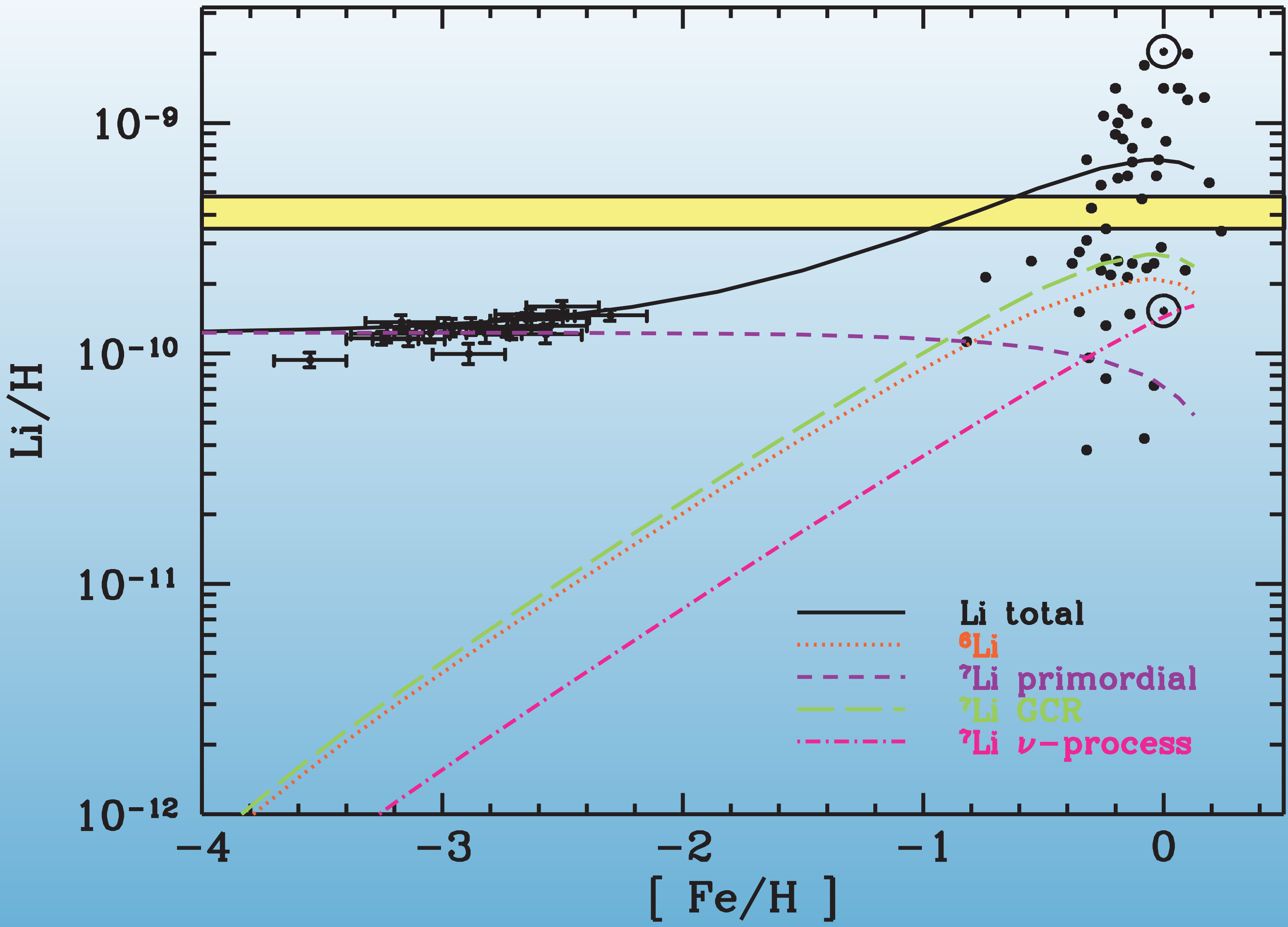


Li/H

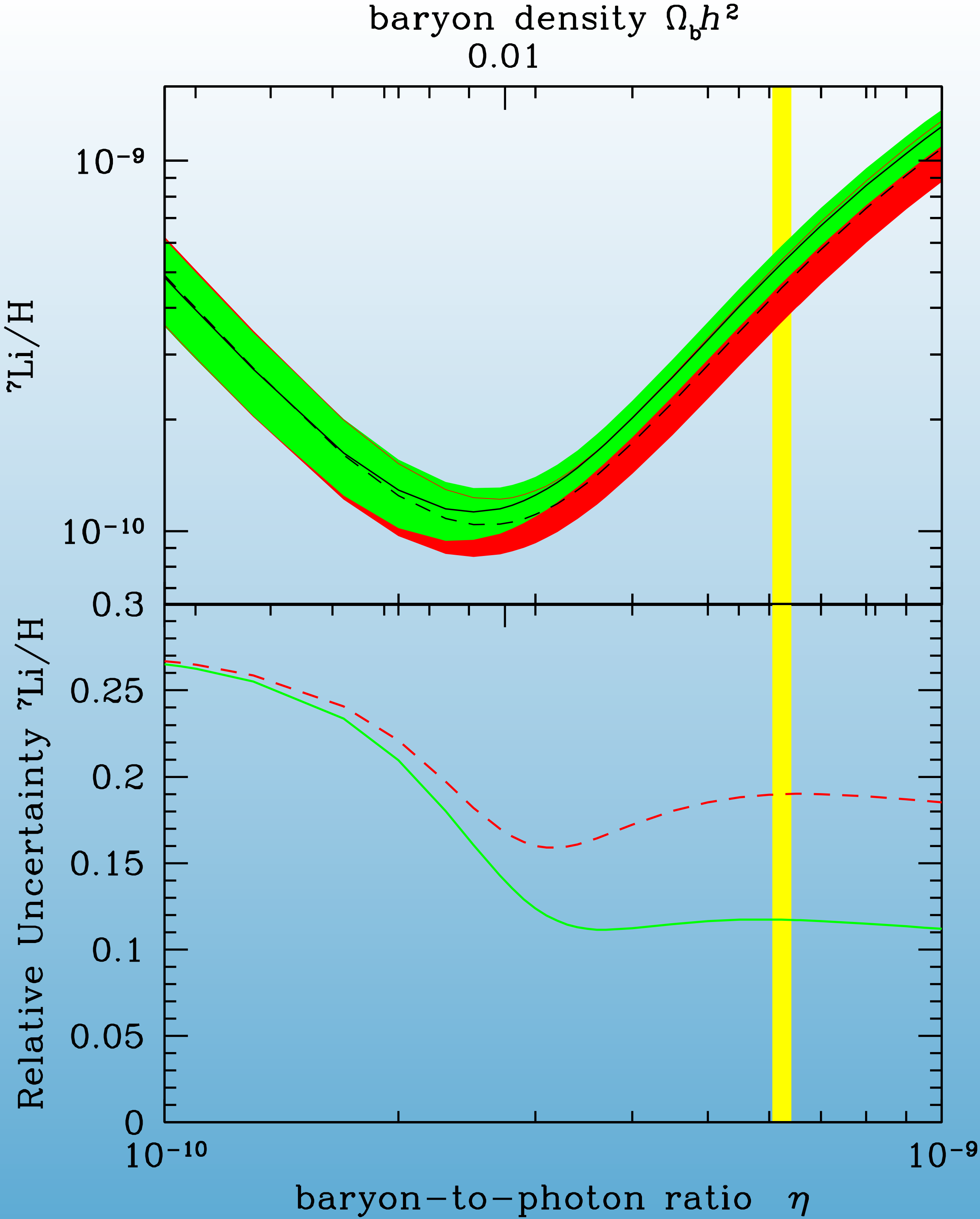
Measured in low metallicity dwarf halo stars (over 100 observed)





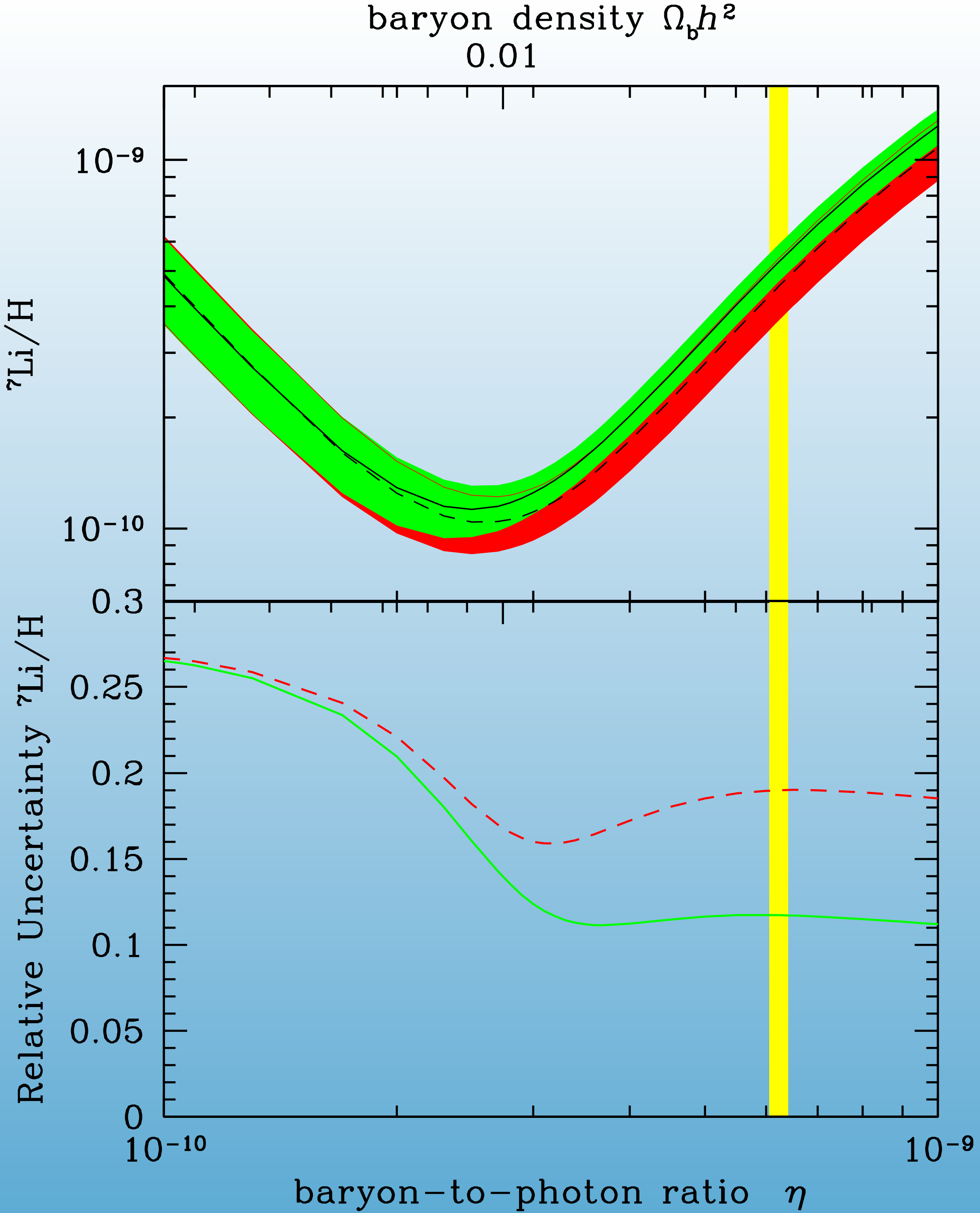


10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
Li/H
−4
−3
−2
−1
0
[Fe/H]
Li total
⁶Li
⁷Li primordial
⁷Li GCR
⁷Li ν−process



17% increase in the cross section
$\Rightarrow$ 16% increase in Li

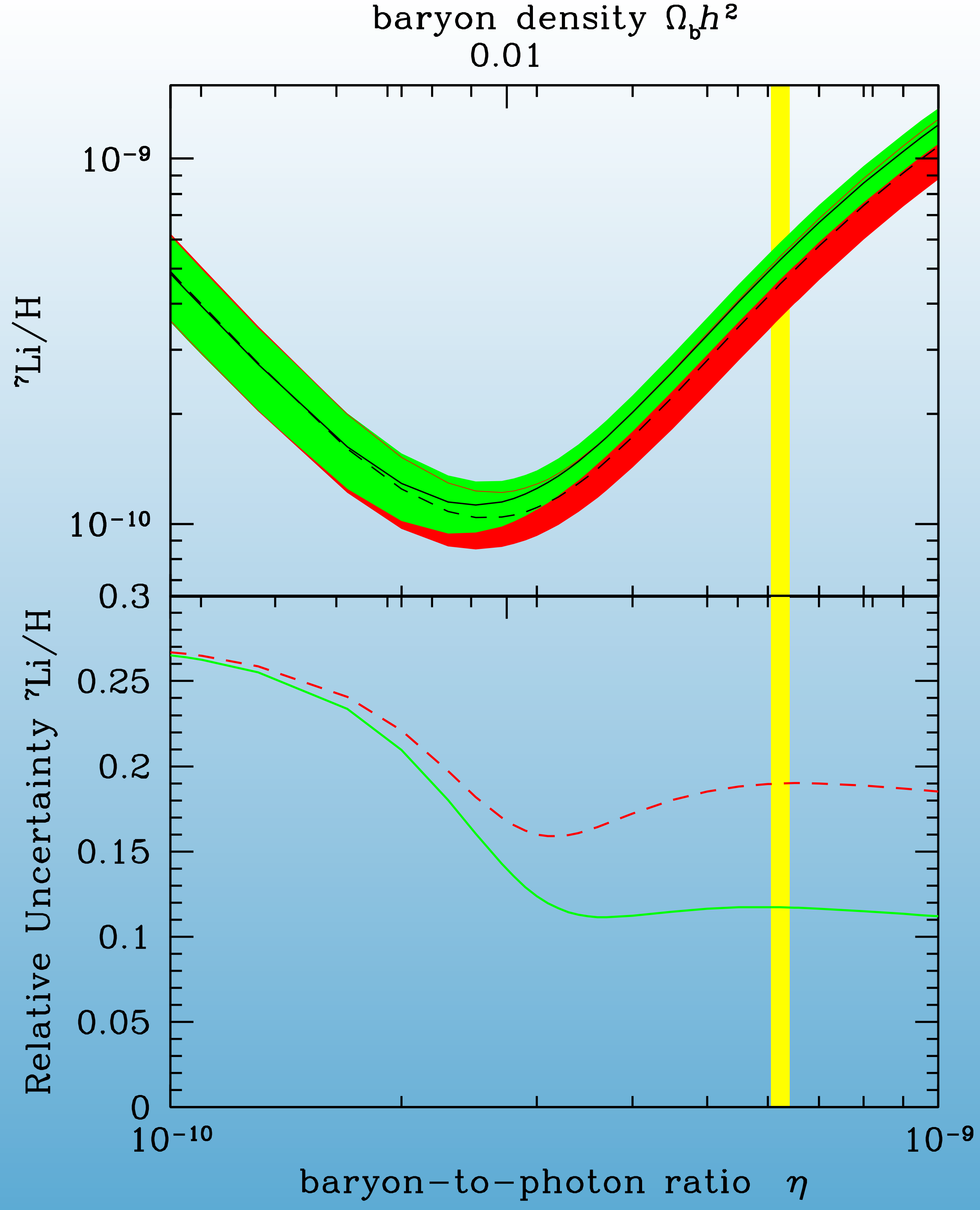
Cyburt, Fields, KAO



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

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

Cyburt, Fields, KAO



At the WMAP7 value for η:

Li/H =

$$(5.12^{+0.71}_{-0.62}) \times 10^{-10}$$

Cyburt, Fields, KAO

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

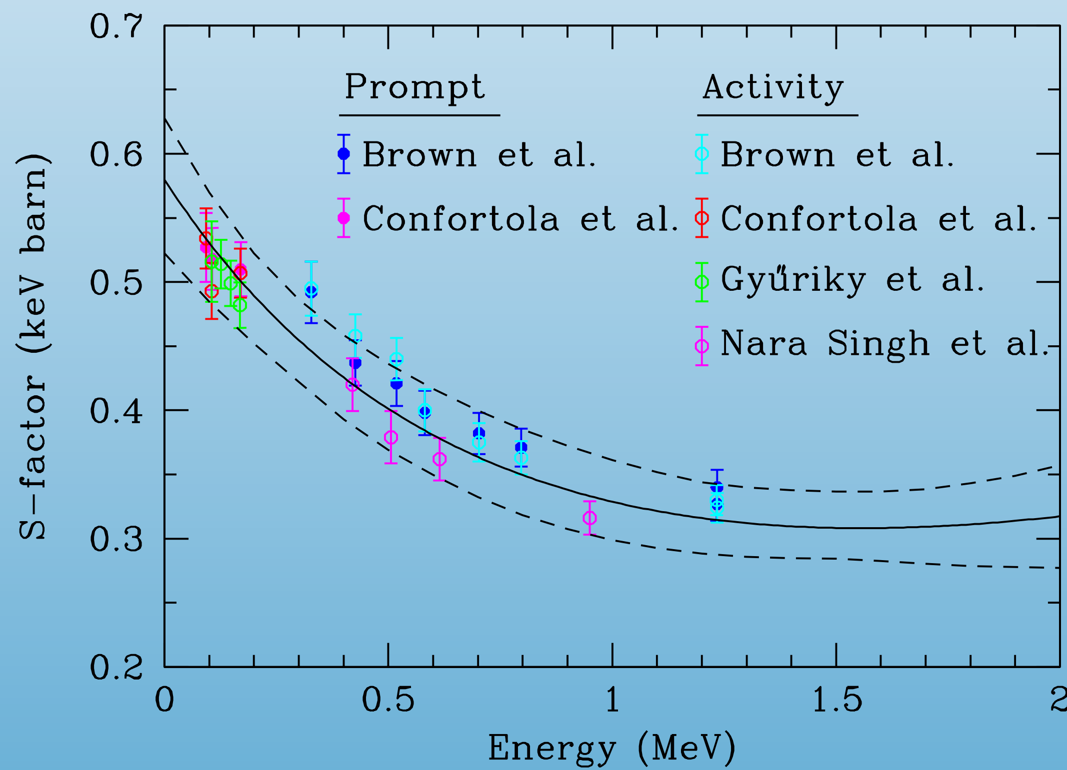
Require:

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

or

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

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



Require:

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

or

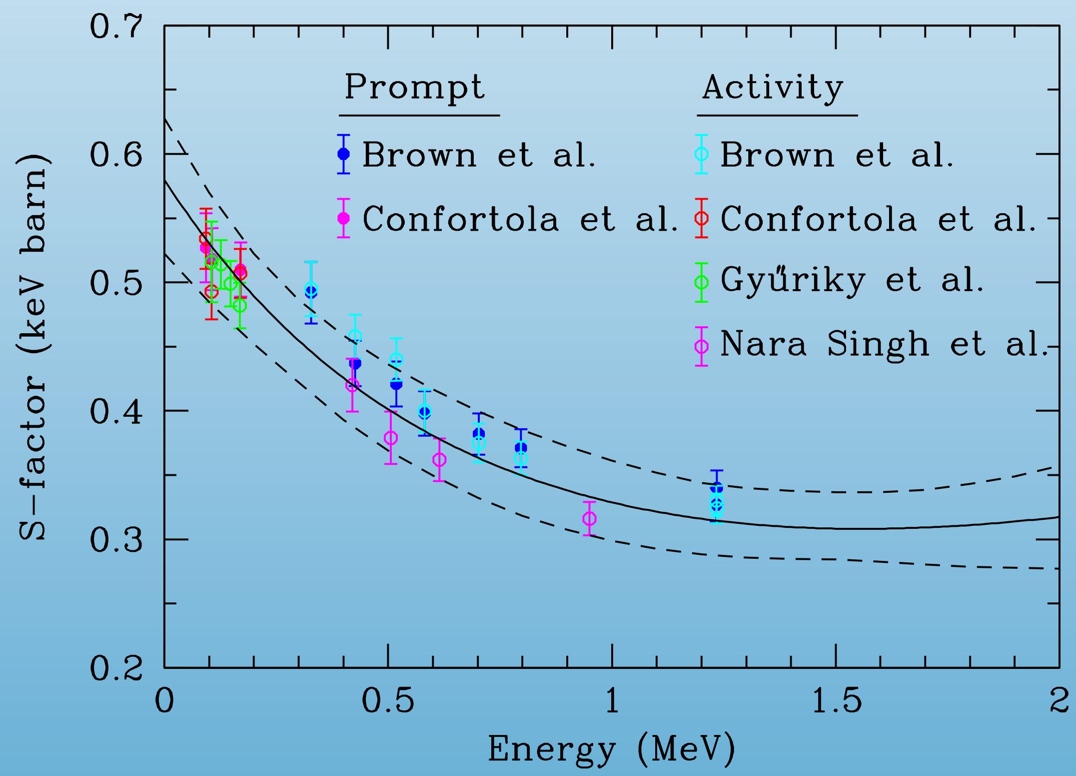
$$\left.\begin{array}{rcl} S_{34}^{NEW}(0) & = & 0.136 \text{ keVb} \\ \frac{\Delta S_{34}}{S_{34}} & = & -0.73 \end{array}\right\} \text{halo star Li}$$

Constrained from solar neutrinos

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

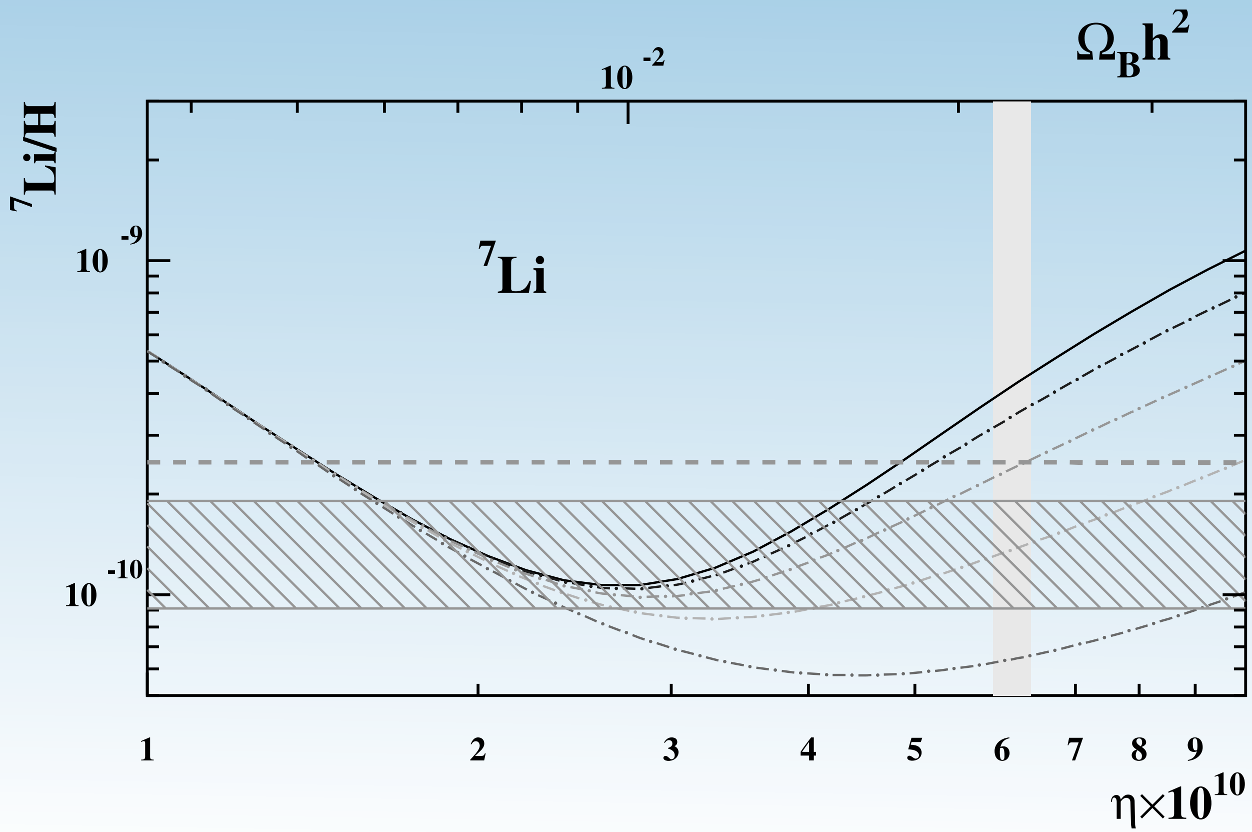
at 95% CL

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



Coc et al. consider large variations of certain rates.

^{3}H (p,γ) ^{4}He	increase x1000	low η	XX
^{4}He (α,n) ^{7}Be	small compared with	destruction	X
^{7}Li (d,n) 2^{4}He	increase x100	low η	XX
^{7}Be (d,p) 2^{4}He	increase >x100	high η	✓? X



Resonant Reactions

Cyburt, Pospelov
Chakraborty, Fields, Olive

Is there a missing excited state providing a resonant reaction?

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

If energy released in producing C* is

$$Q_C = \Delta(^{7}\mathrm{Be}) + \Delta(A) - \Delta(C^{\mathrm{g.s.}})$$

$$\Delta = m - A m_{\mathrm{u}}$$

mass defect

Then the resonant energy is

$$E_{\mathrm{res}} \equiv E_{\mathrm{ex}} - Q_C$$

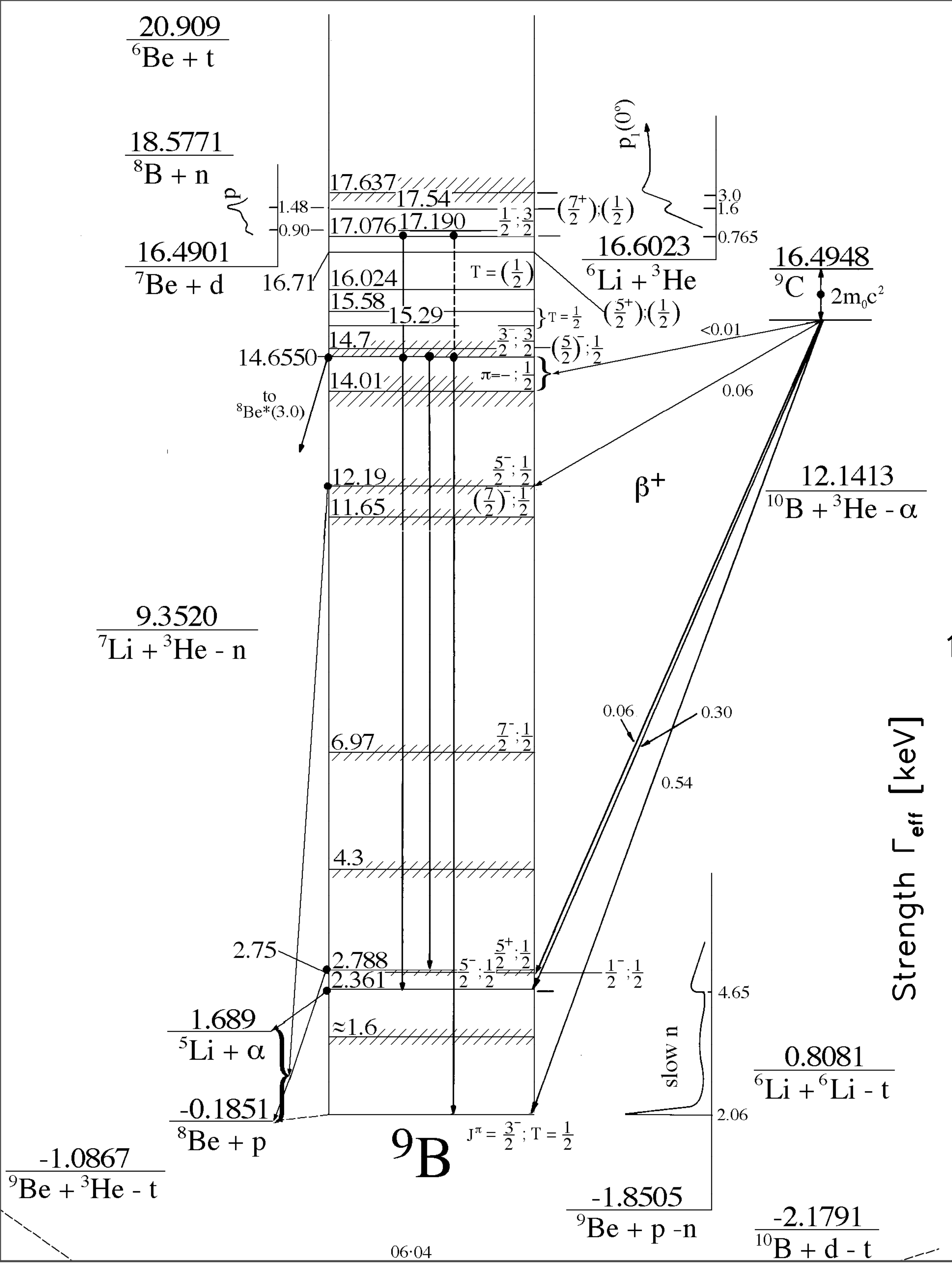
Resonant enhancements will occur if $|E_{res}| \lesssim \Gamma_{init}$

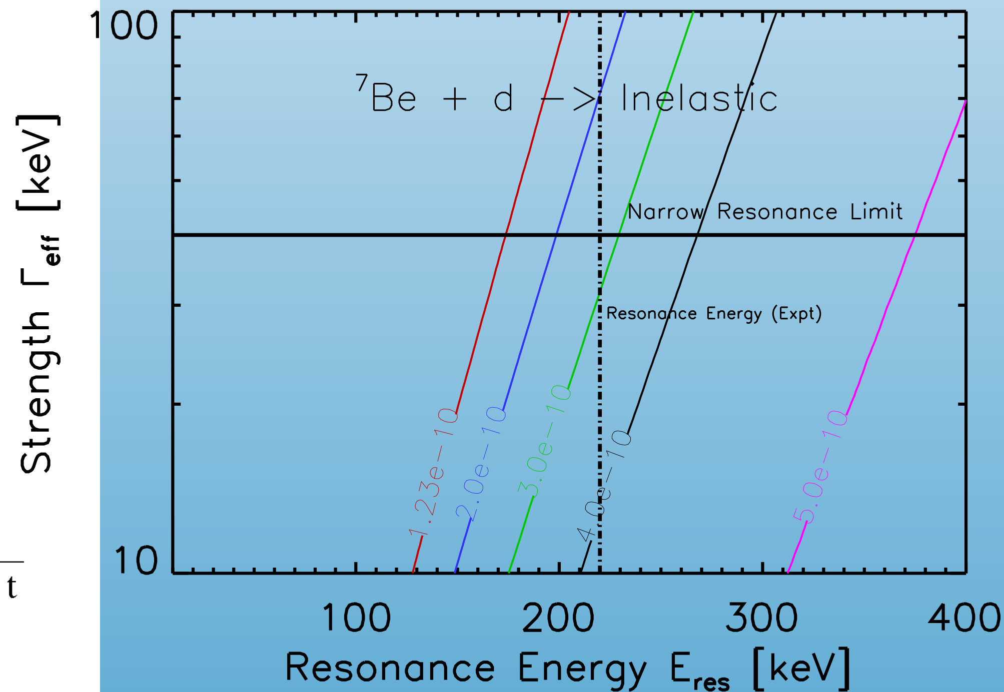
$$\sigma(E) = \frac{\omega}{8\pi\mu E}\frac{\Gamma_{\rm init}\Gamma_{\rm fin}}{(E-E_{\rm res})^2-(\Gamma_{\rm tot}/2)^2}$$

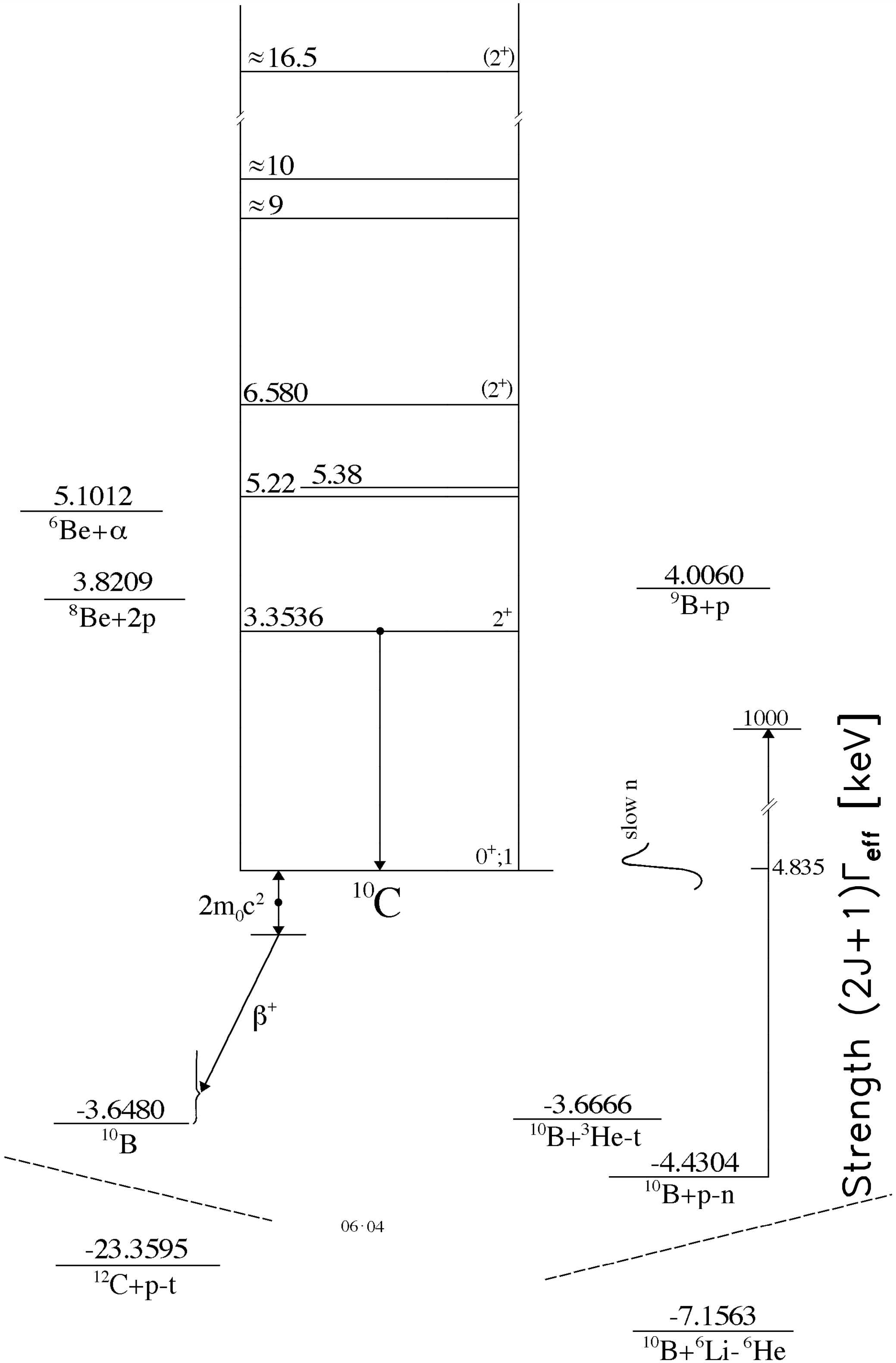
leading to a thermally averaged cross section
(in the narrow width approximation)

$$\langle\sigma v\rangle \;\;=\;\; \left(\frac{2\pi}{\mu T}\right)^{3/2}\hbar^2(\omega\;\Gamma_{\rm eff})_{res}\exp\left(-\frac{\rm E_{res}}{T}\right)$$

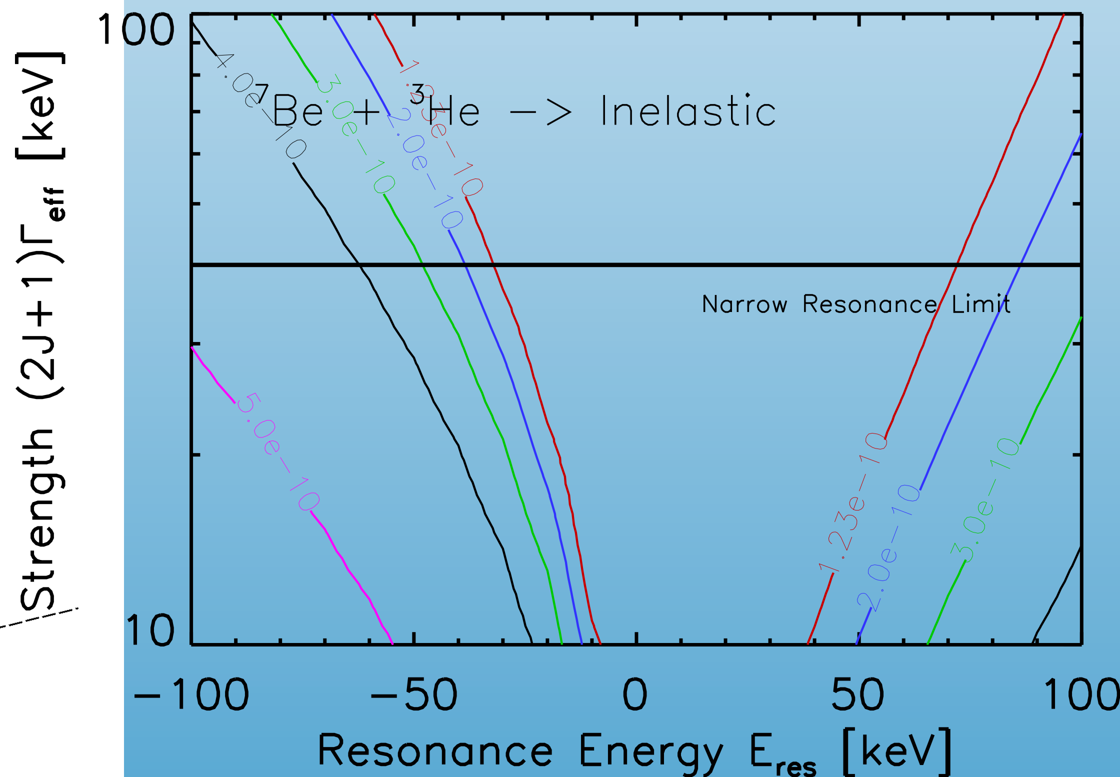
^{7}Be + d $\rightarrow$ ^{9}B (16.71)



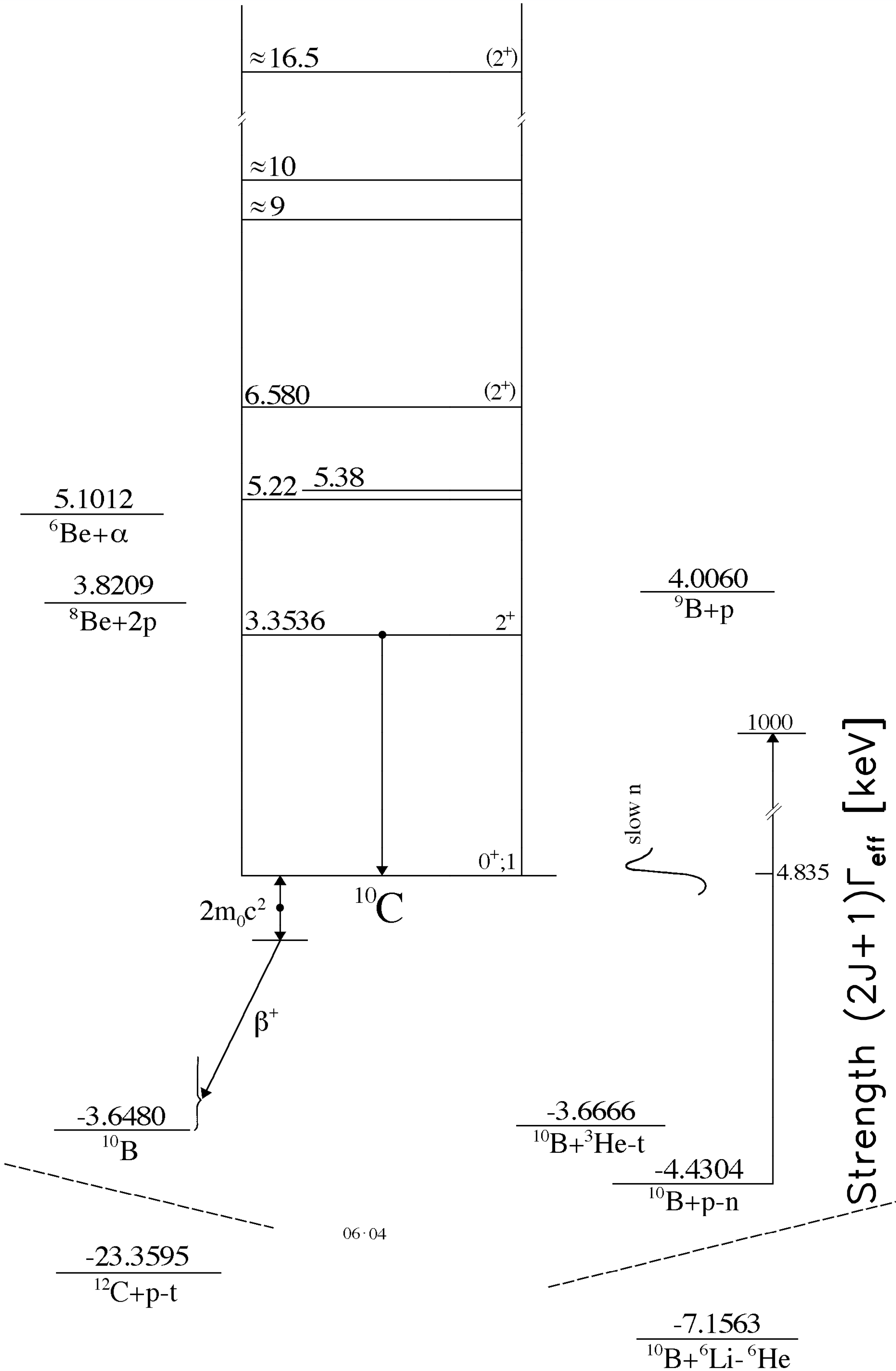




≈16.5
(2+)
≈10
≈9
6.580
(2+)
5.22
5.38
5.1012
6Be+α
3.8209
8Be+2p
3.3536
2+
4.0060
9B+p
1000
slow n
4.835
0+;1
2m0c2
10C
β+
-3.6480
10B
-3.6666
10B+3He-t
-4.4304
10B+p-n
06·04
-23.3595
12C+p-t
-7.1563
10B+6Li-6He



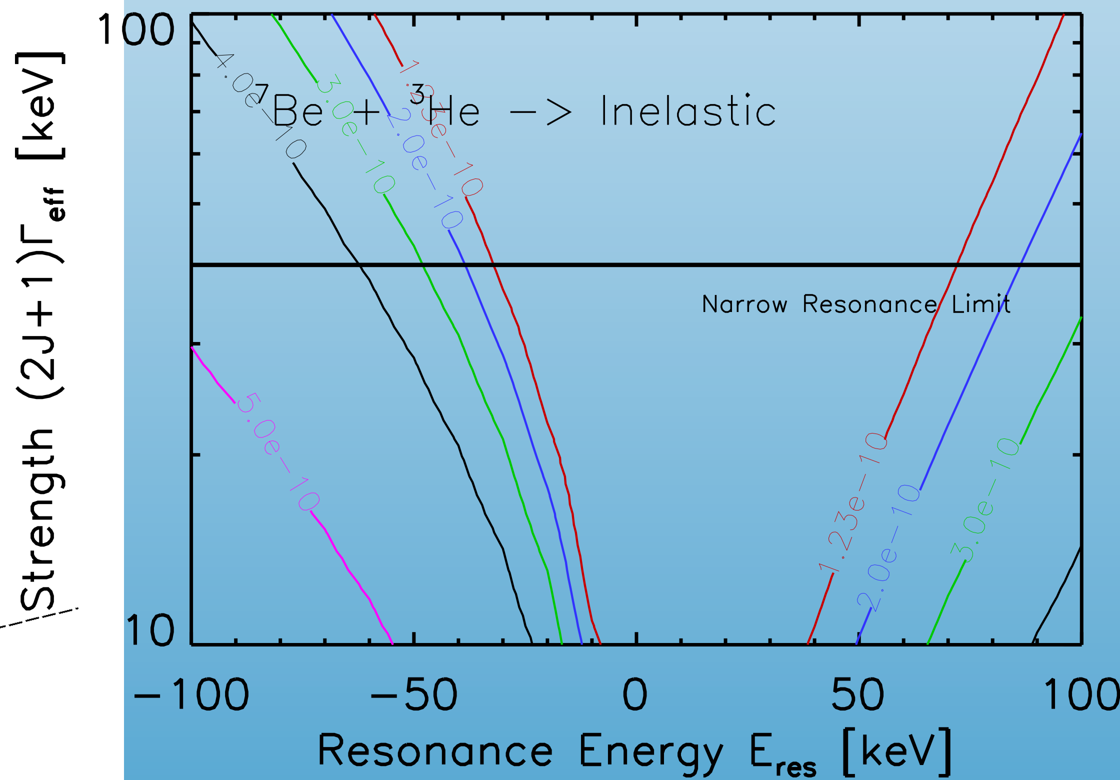
7Be + 3He -> Inelastic
Narrow Resonance Limit
4.0e-10
3.0e-10
2.0e-10
1.23e-10
5.0e-10
1.23e-10
2.0e-10
3.0e-10
100
10
-100
-50
0
50
100
Strength (2J+1)Γeff [keV]
Resonance Energy Eres [keV]



15.0

^{7}Be + ^{3}He

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



Possible sources for the discrepancy

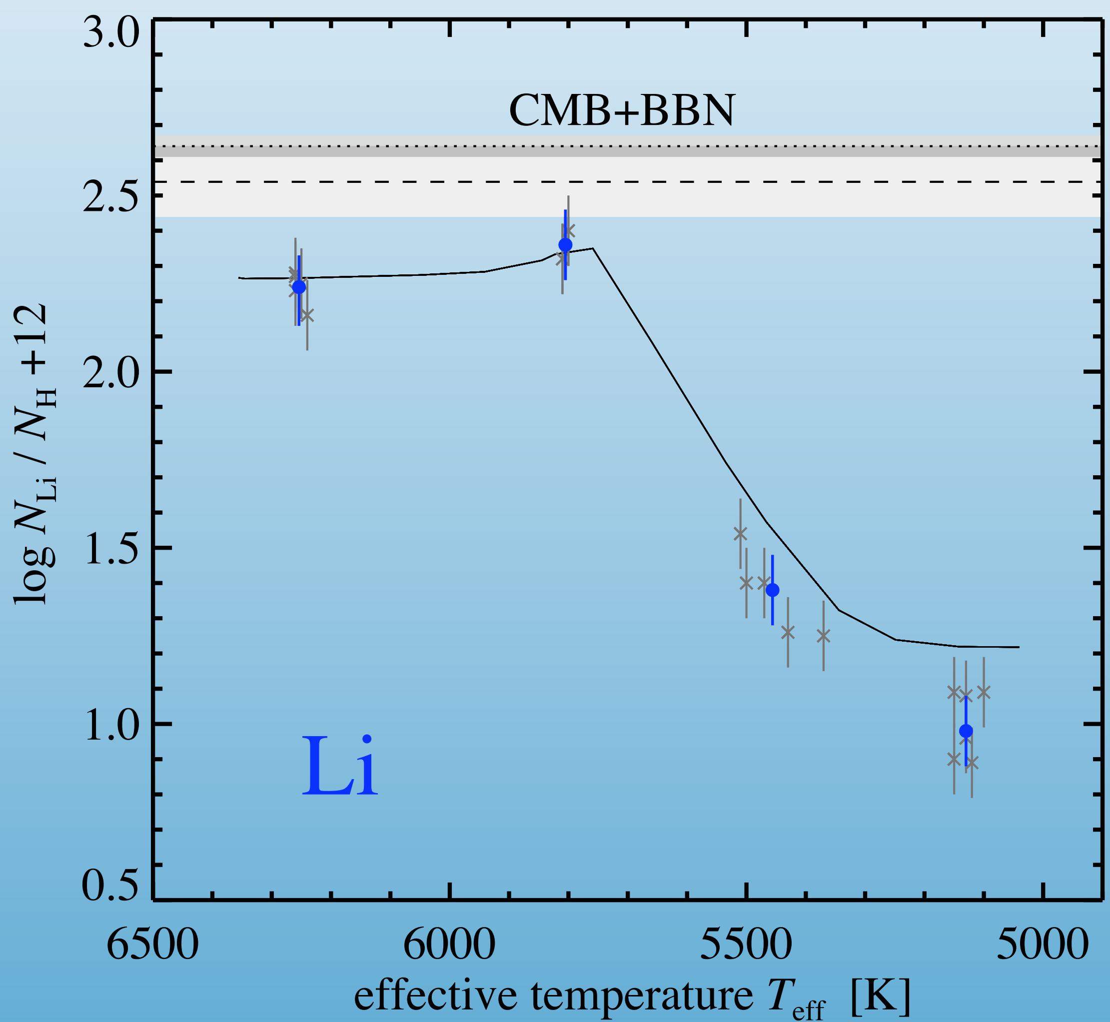
- Nuclear Rates
  - Restricted by solar neutrino flux

Coc et al.
Cyburt, Fields, KAO

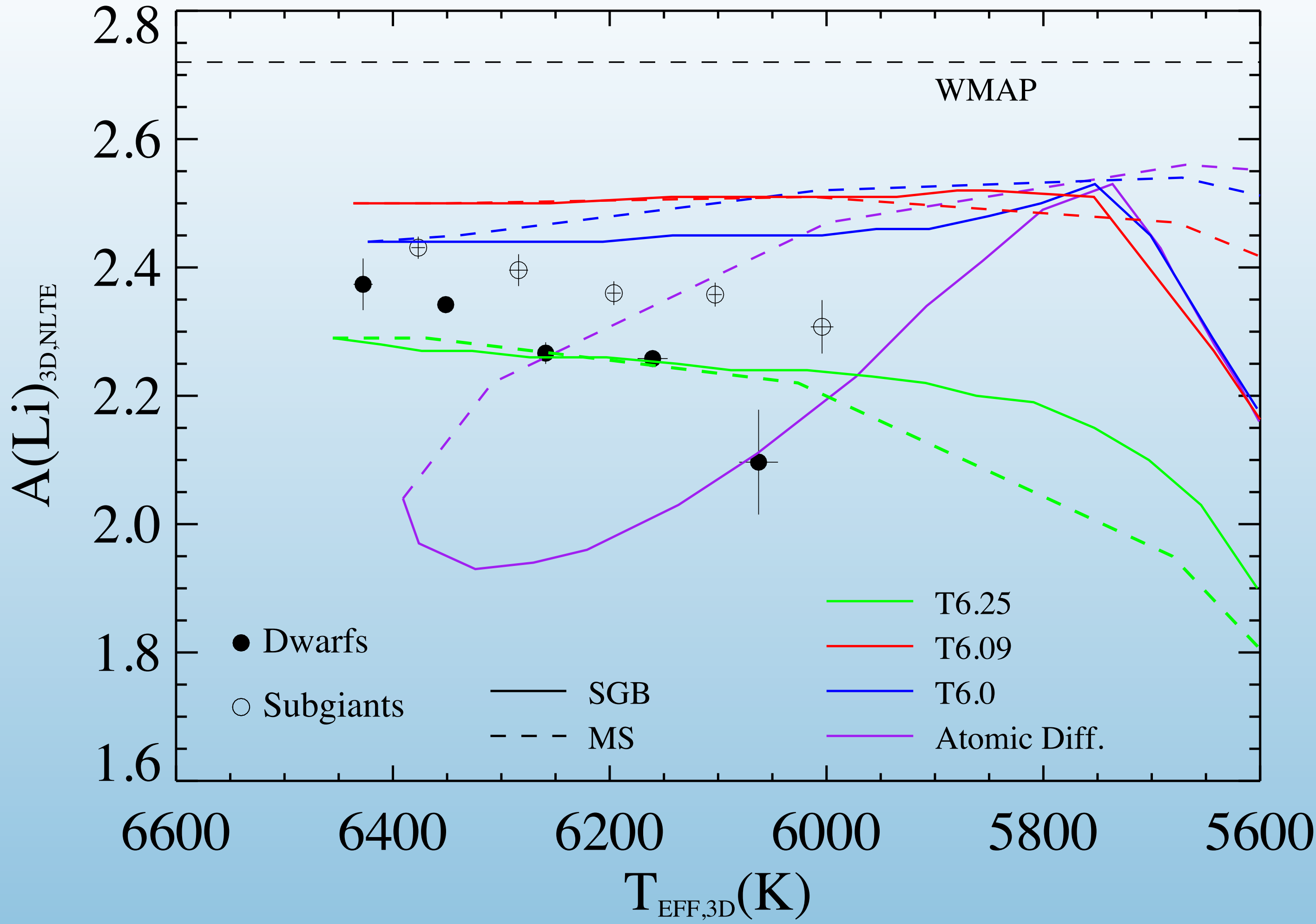
- Stellar Depletion
  - lack of dispersion in the data, ^{6}Li abundance
  - standard models (< .05 dex), models (0.2 - 0.4 dex)

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

Stellar Depletion in the Turbulence Model of Korn et al.

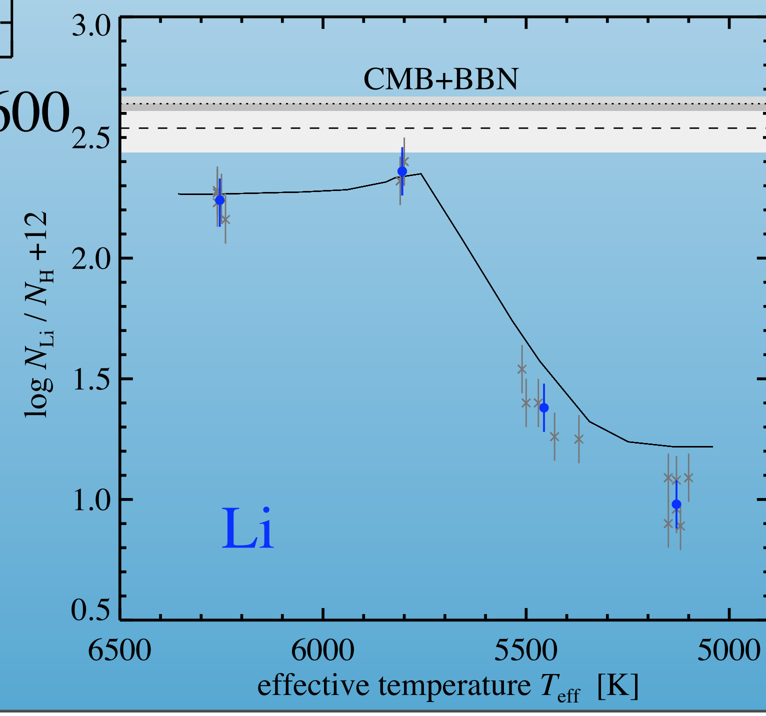


Note new BBN Li result pushes primordial value up from 2.63 to 2.72



But,

from Gonzáles Hernández et al.



Tuesday, October 19, 2010

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

- Stellar parameters

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

Claim:

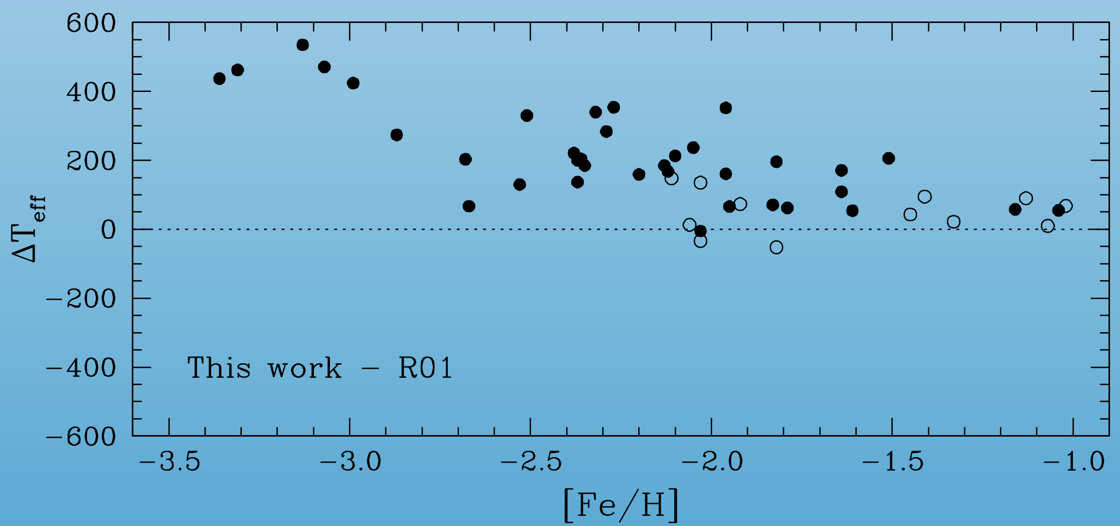
New evaluation of surface temperatures in 41 halo stars with systematically higher temperatures (100-300 K)

Melandez & Ramirez

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

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

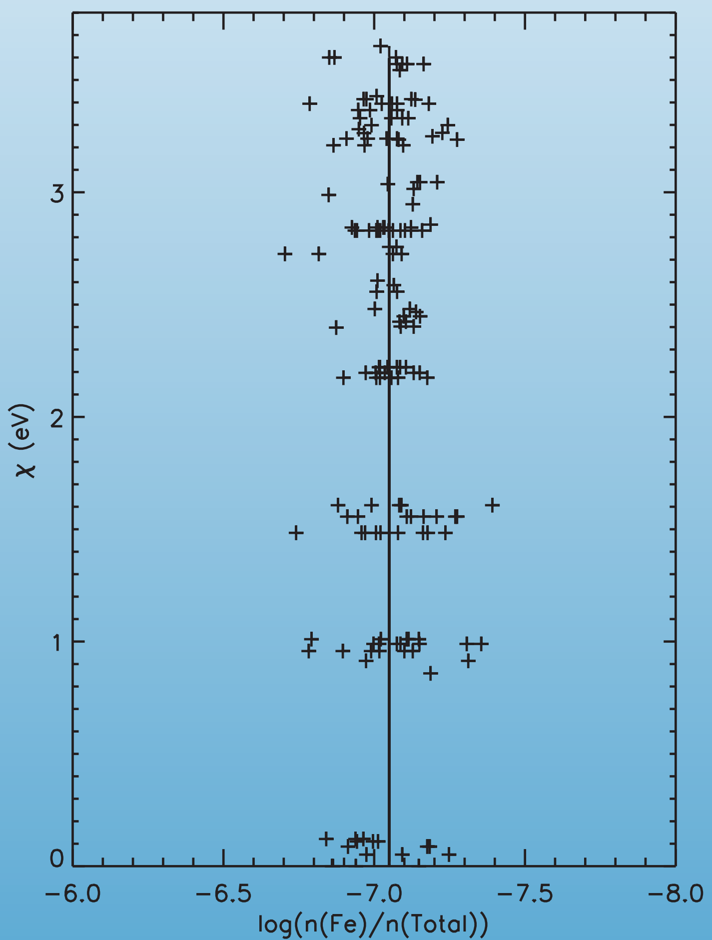
BBN Prediction: 10^{10} Li/H = $(5.12^{+0.71}_{-0.62}) \times 10^{-10}$



Recent dedicated temperature determinations (excitation energy technique)

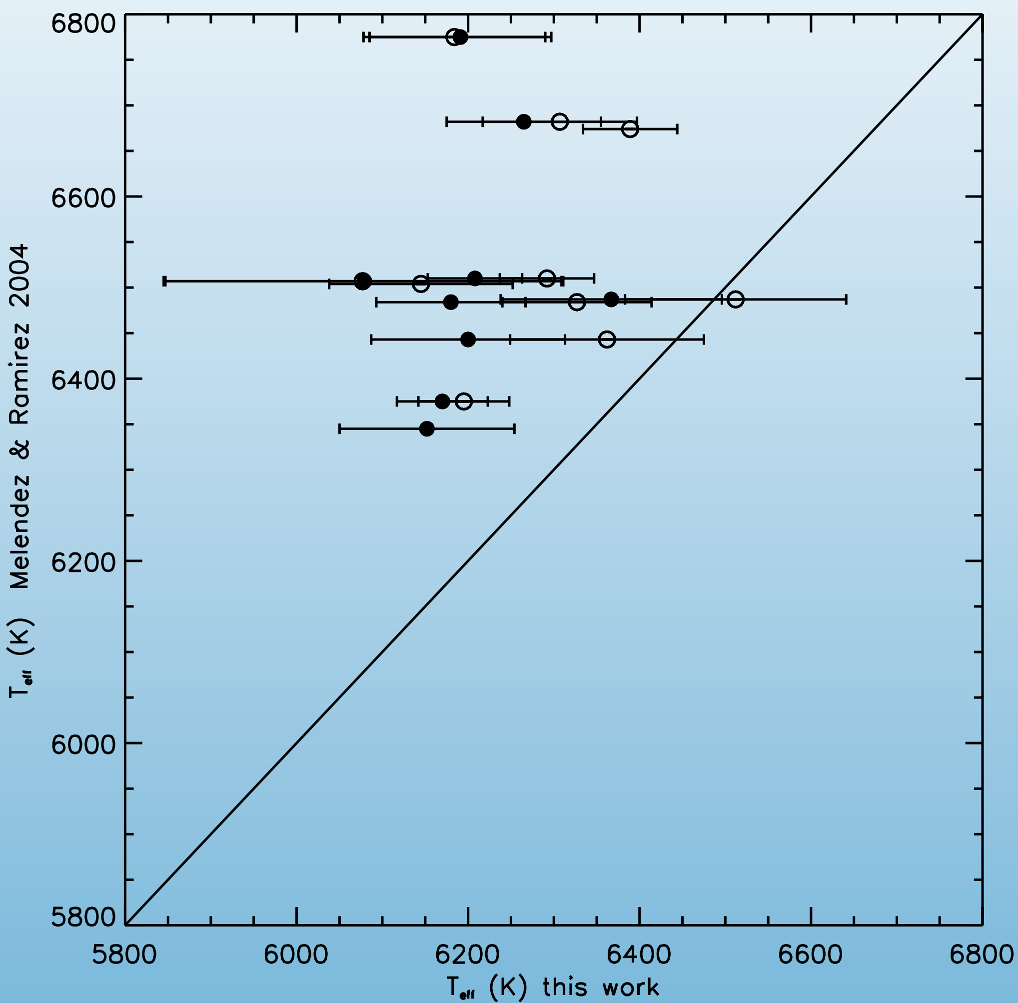
Use Fe I lines:

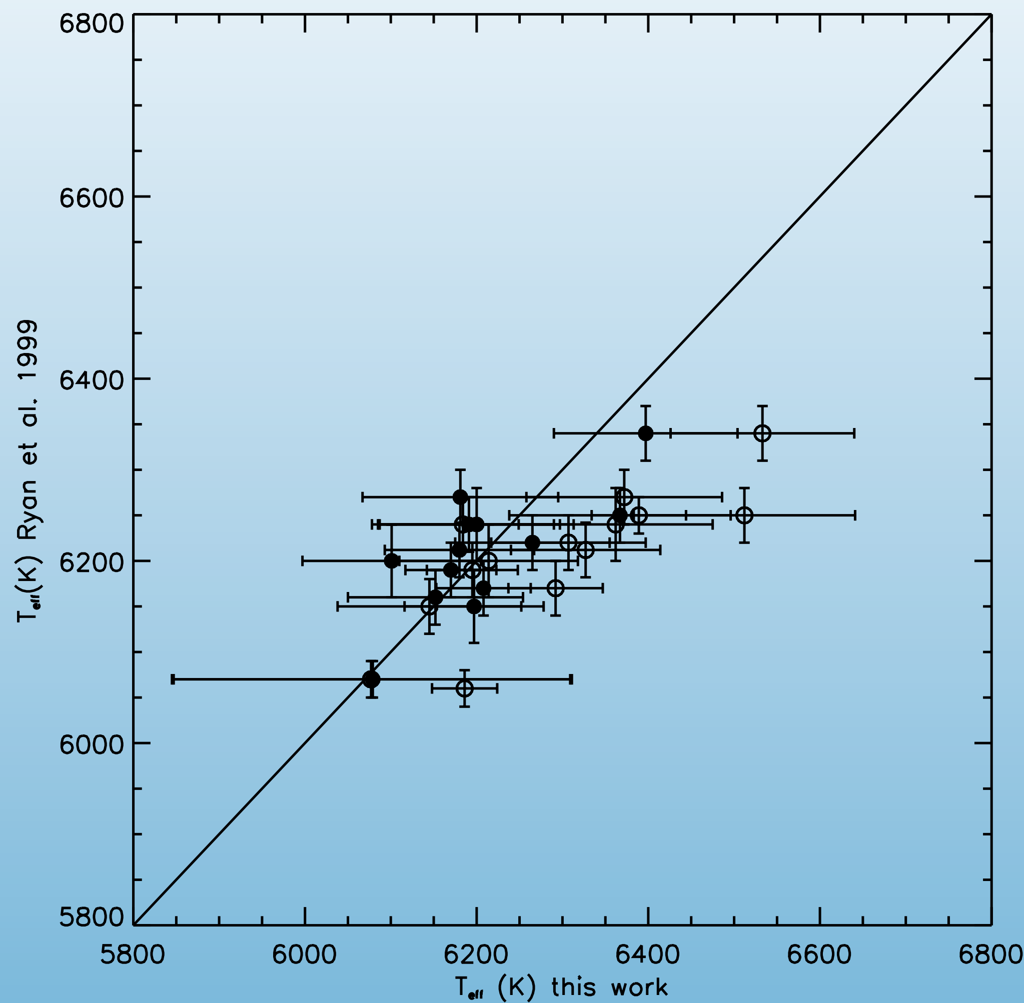
population of a given state ∝ $\exp(-\chi_i/T)$



Hosford, Ryan, Garcia-Perez, Norris, Olive

Comparison





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Cyburt, Fields, KAO

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

- 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)

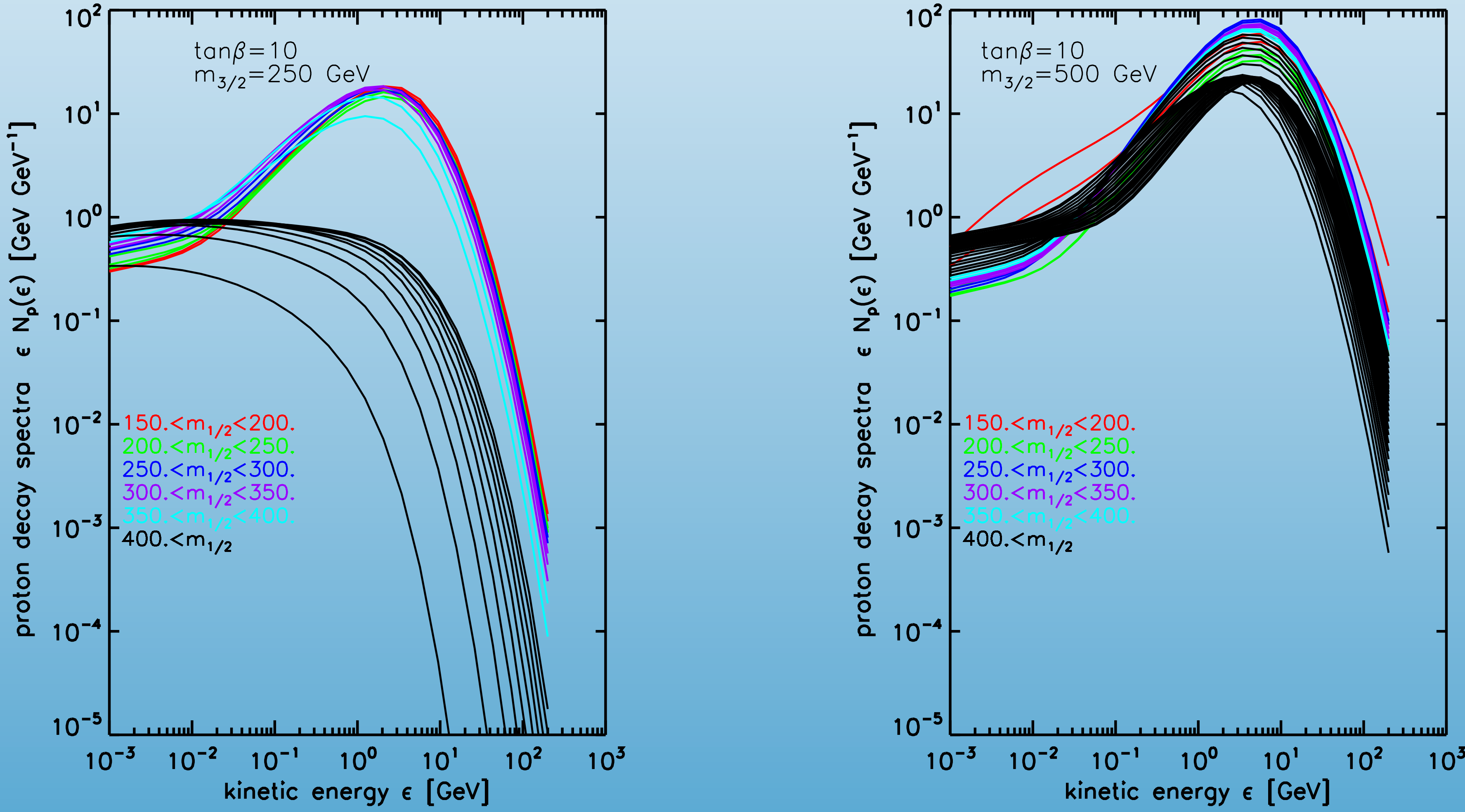
- Evolve element abundances including thermal (BBN) and non-thermal processes.

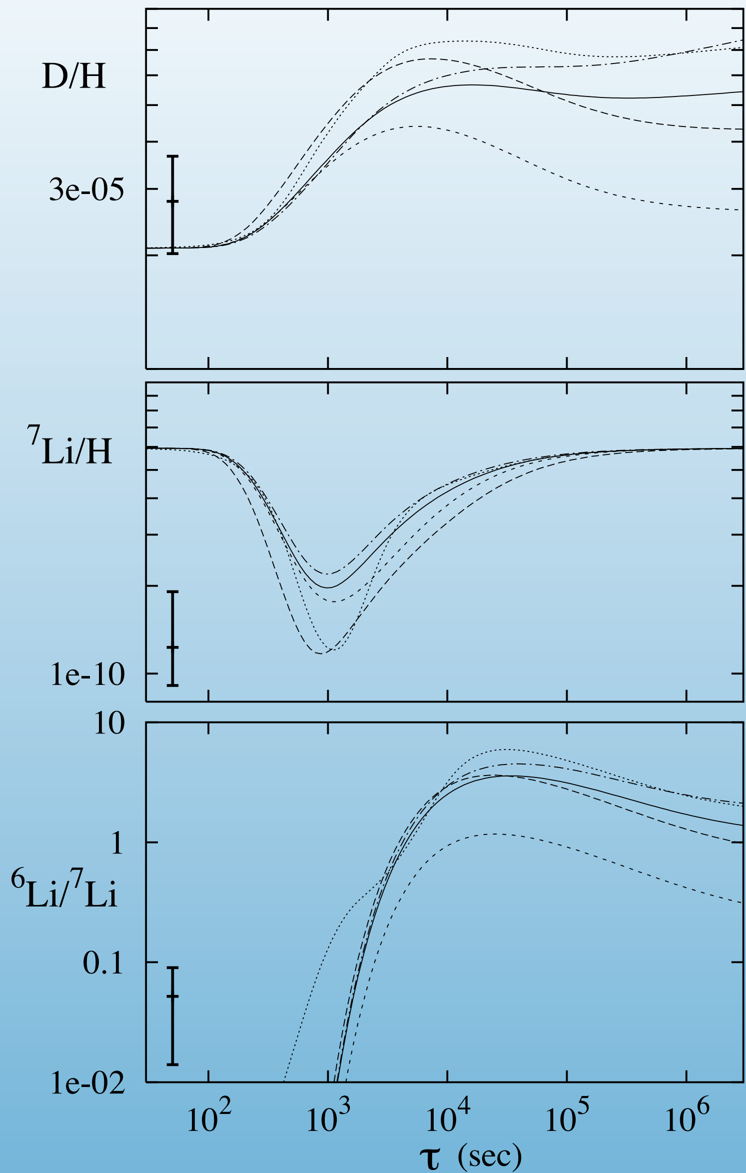
E.g., Gravitino decay

Cyburt, Ellis, Fields, Luo, Olive, Spanos

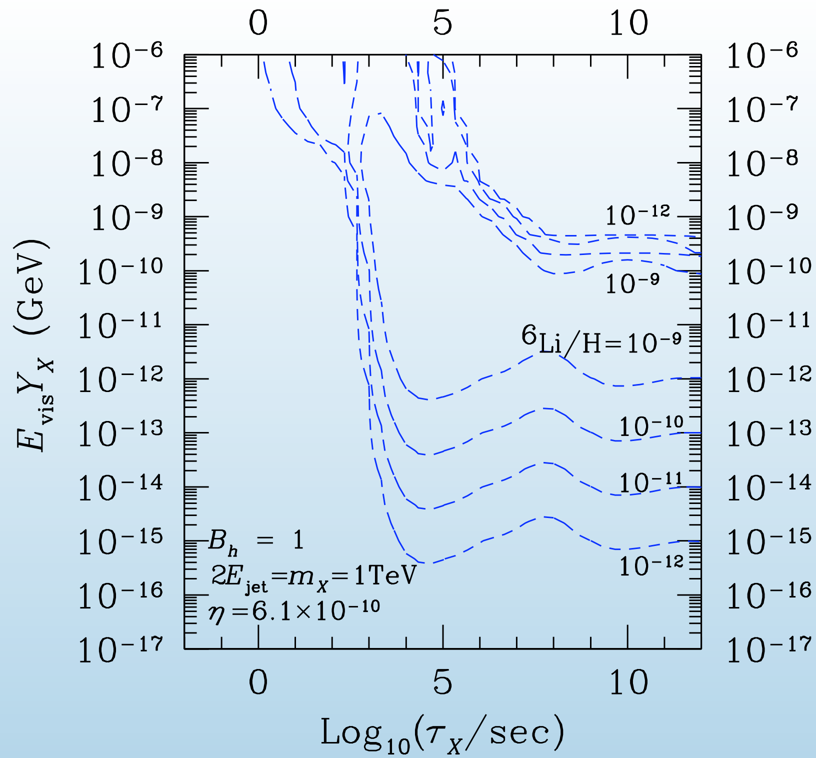
$$\widetilde{G} \to \tilde{f}\, f, \widetilde{G} \to \tilde{\chi}^{+}\, W^{-}(H^{-}), \widetilde{G} \to \tilde{\chi}^{0}_{i}\, \gamma(Z), \widetilde{G} \to \tilde{\chi}^{0}_{i}\, H^{0}_{i} \widetilde{G} \to \tilde{g}\, g.$$

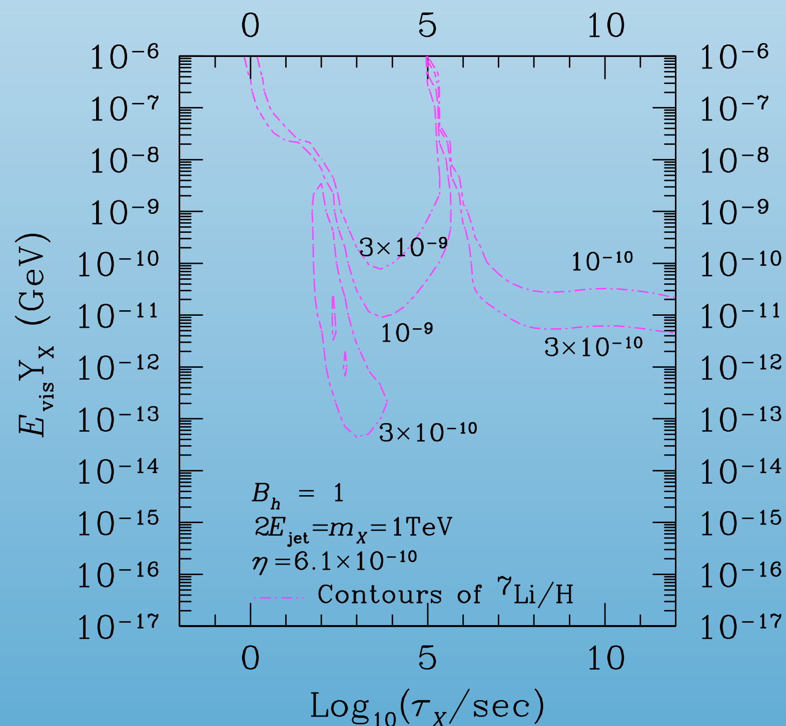
plus relevant 3-body decays



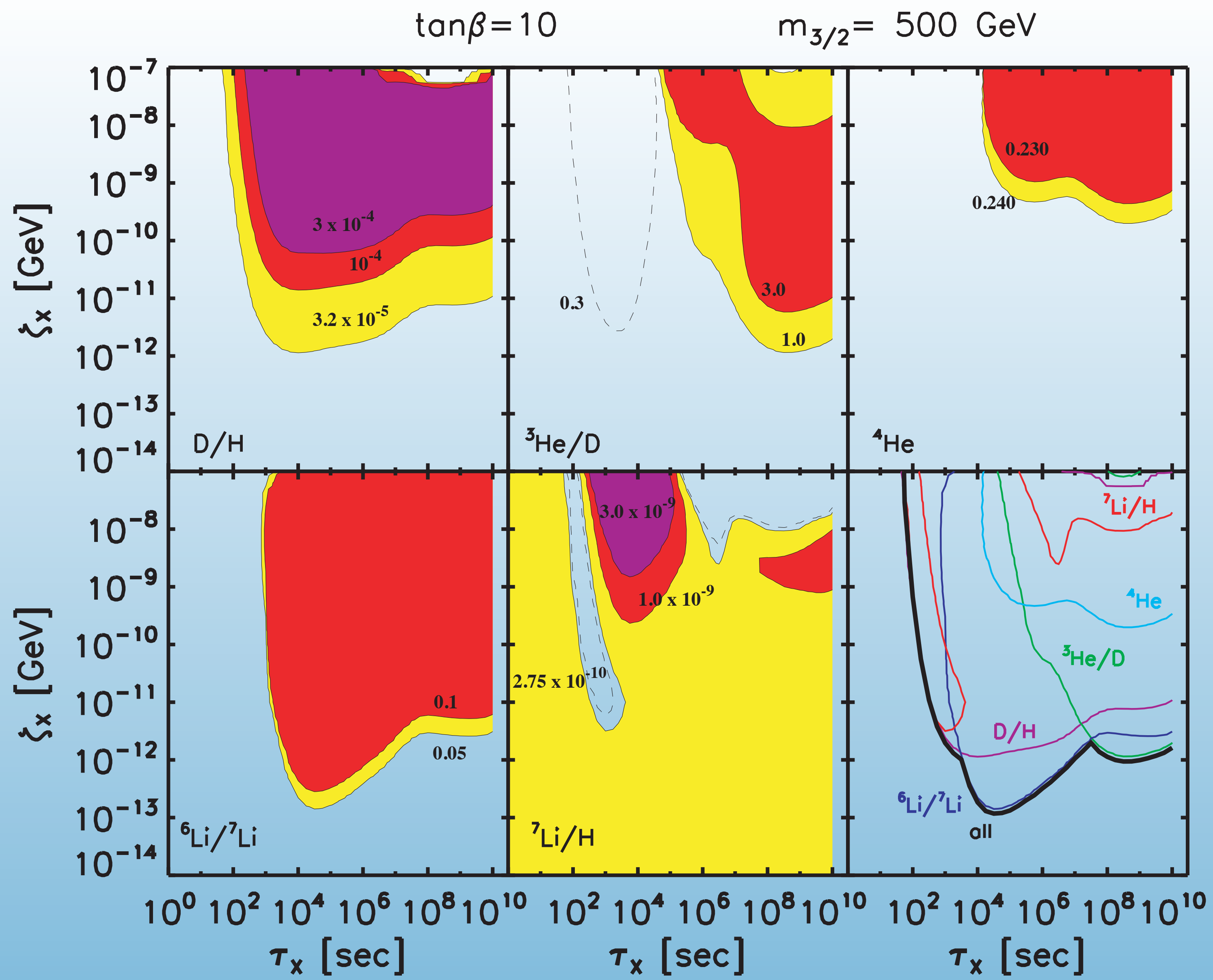


Jedamzik



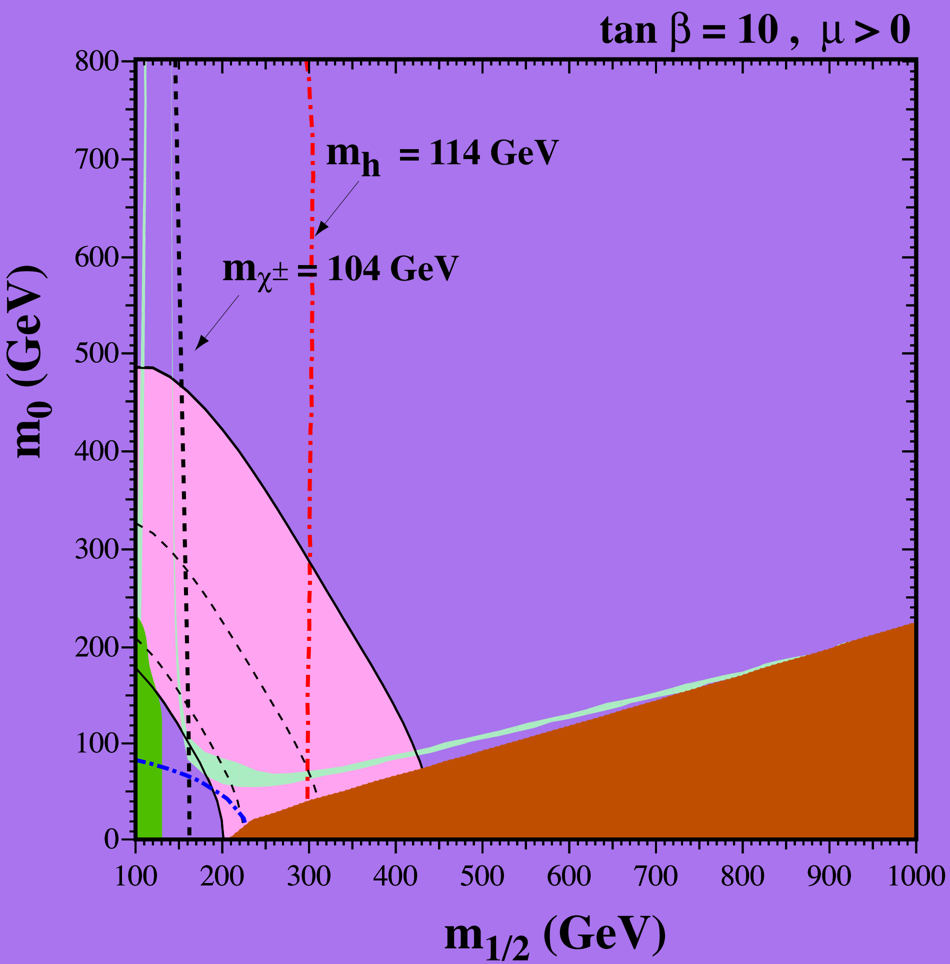


Kawasaki, Kohri, Moroi

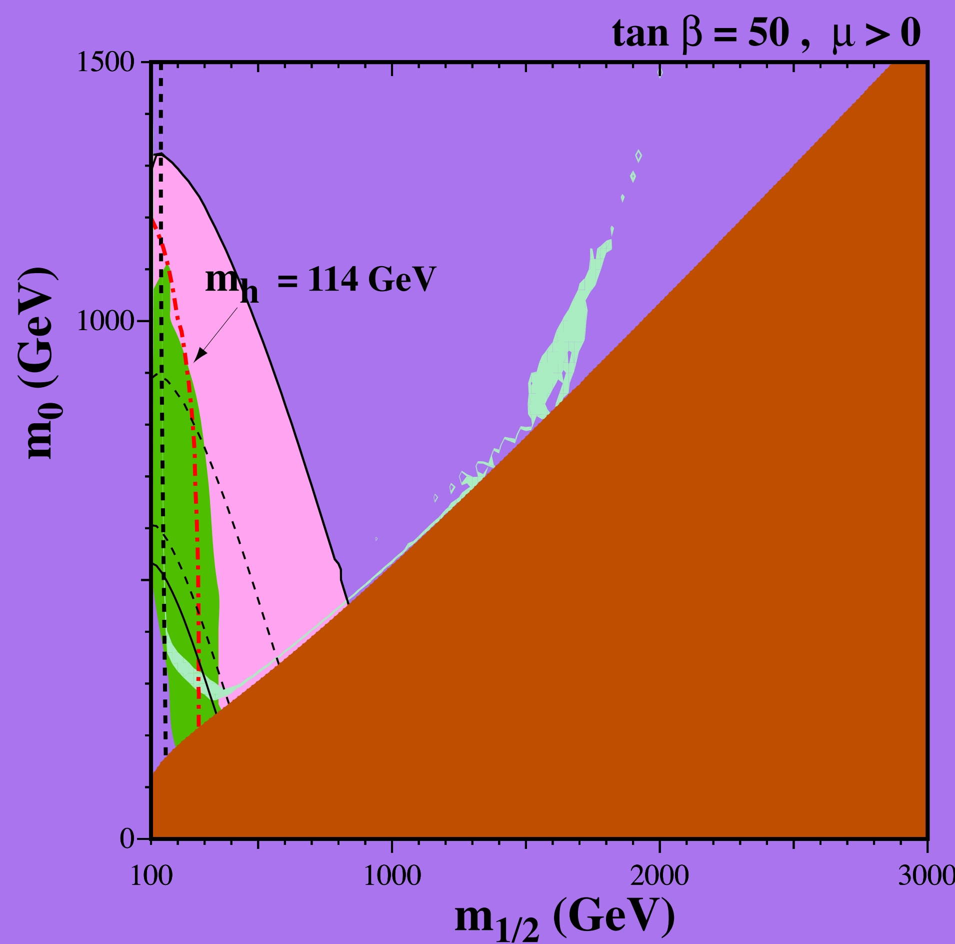


Based on $m_{1/2}$ = 300 GeV, tan β =10 ; $B_h \sim 0.2$

CMSSM

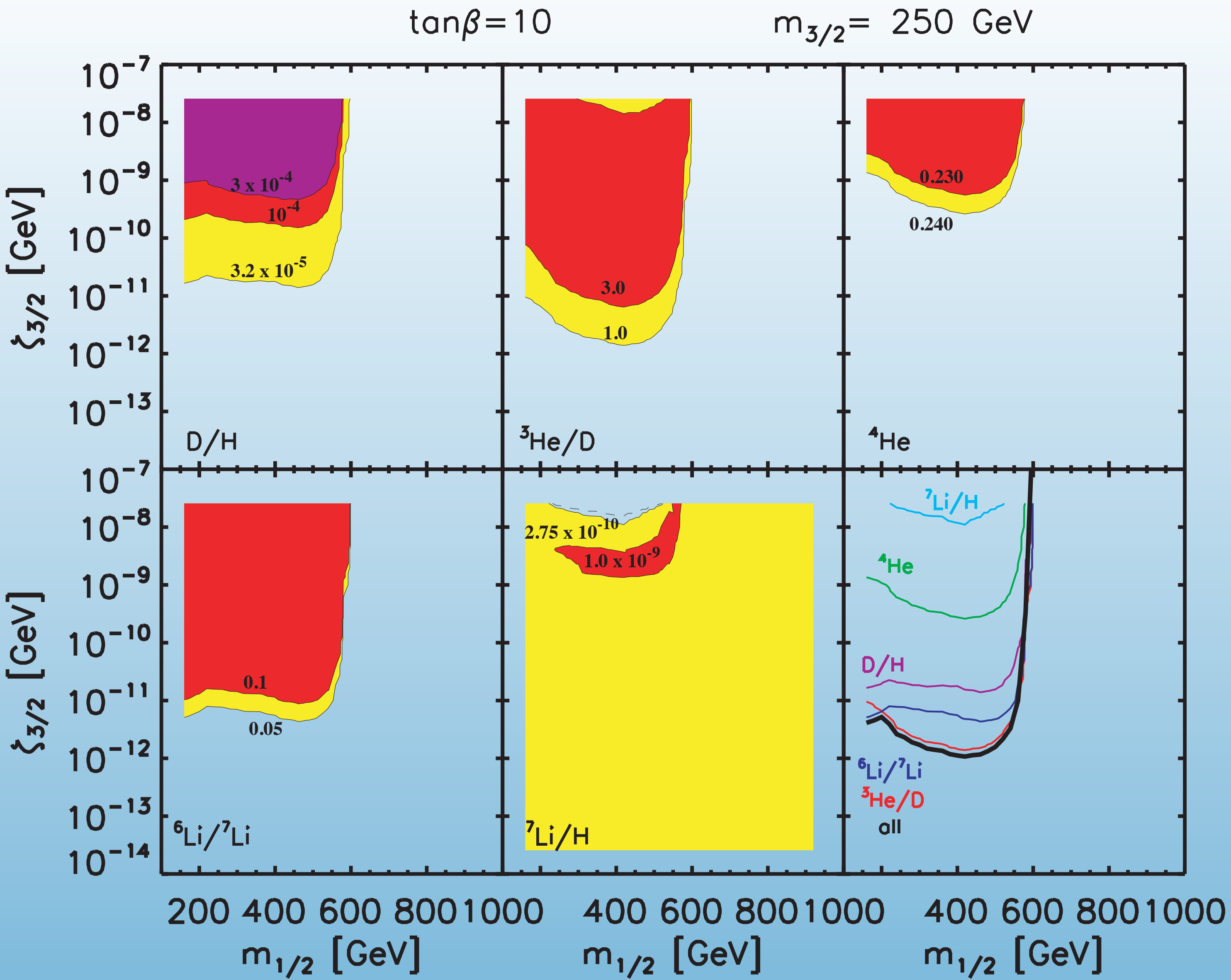


tan β = 10 , μ > 0
m_h = 114 GeV
m_χ± = 104 GeV
m_0 (GeV)
m_1/2 (GeV)
800
700
600
500
400
300
200
100
0
100
200
300
400
500
600
700
800
900
1000

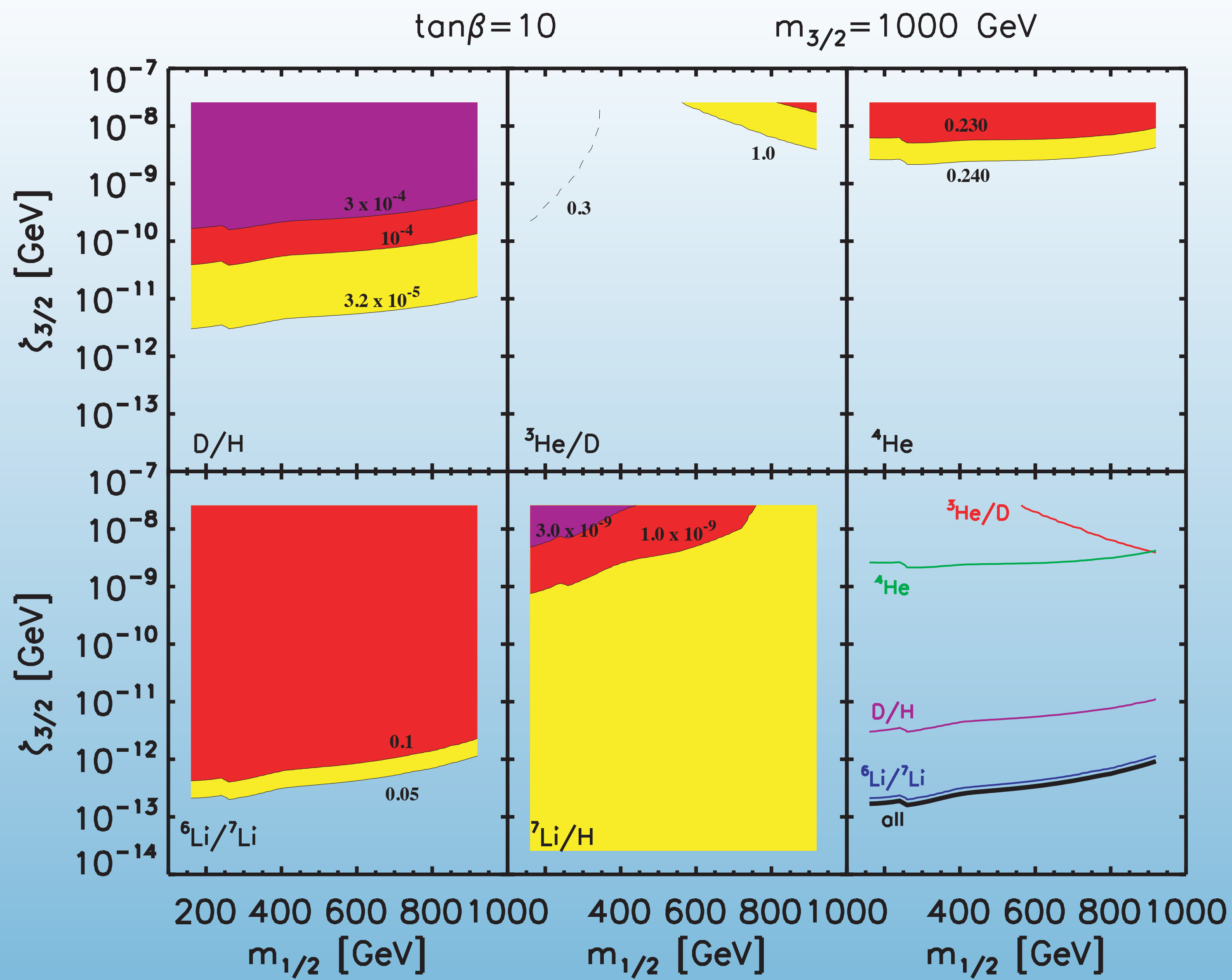


tan β = 50 , μ > 0
m_h = 114 GeV
m_0 (GeV)
m_1/2 (GeV)
1500
1000
0
100
1000
2000
3000

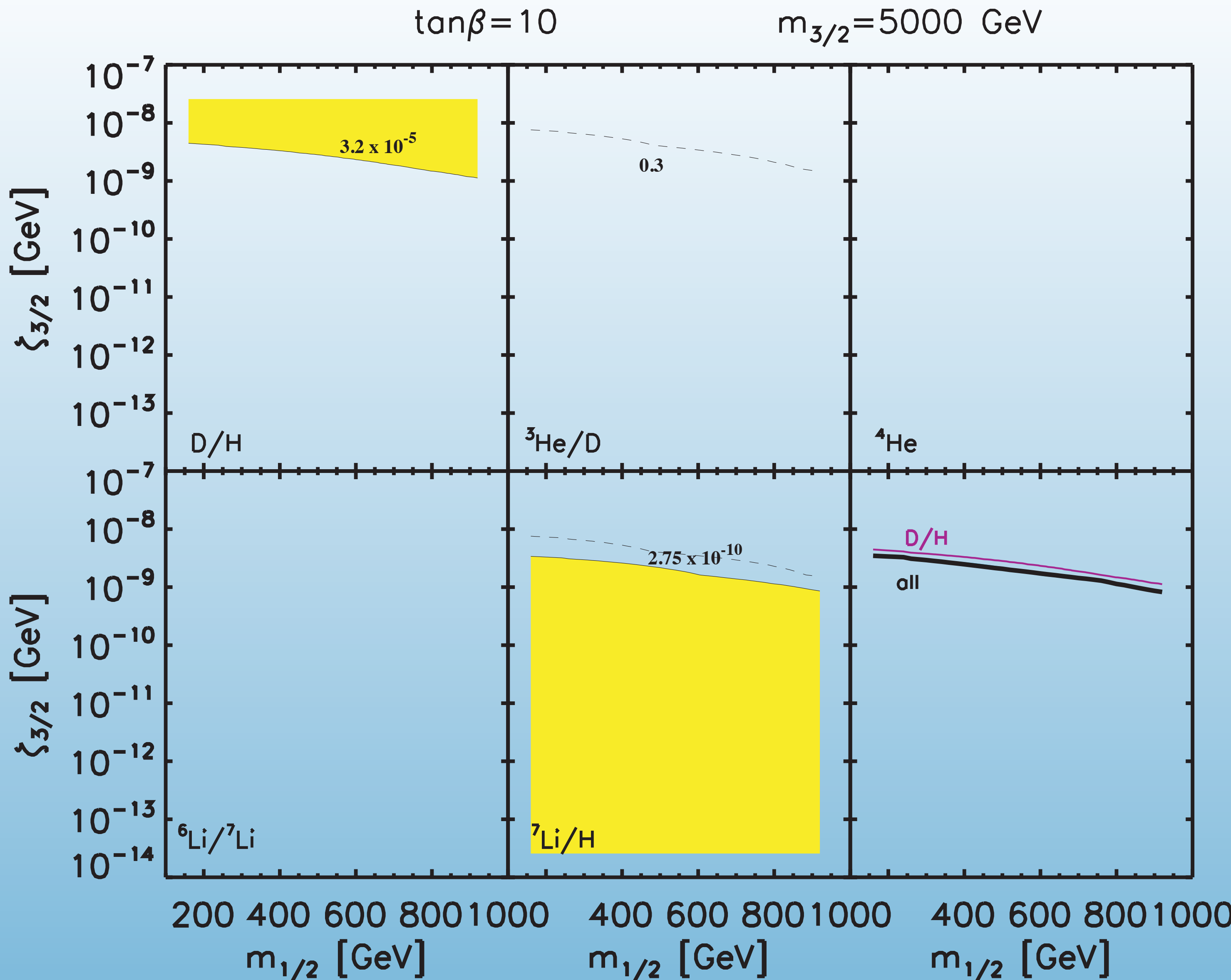
EOSS



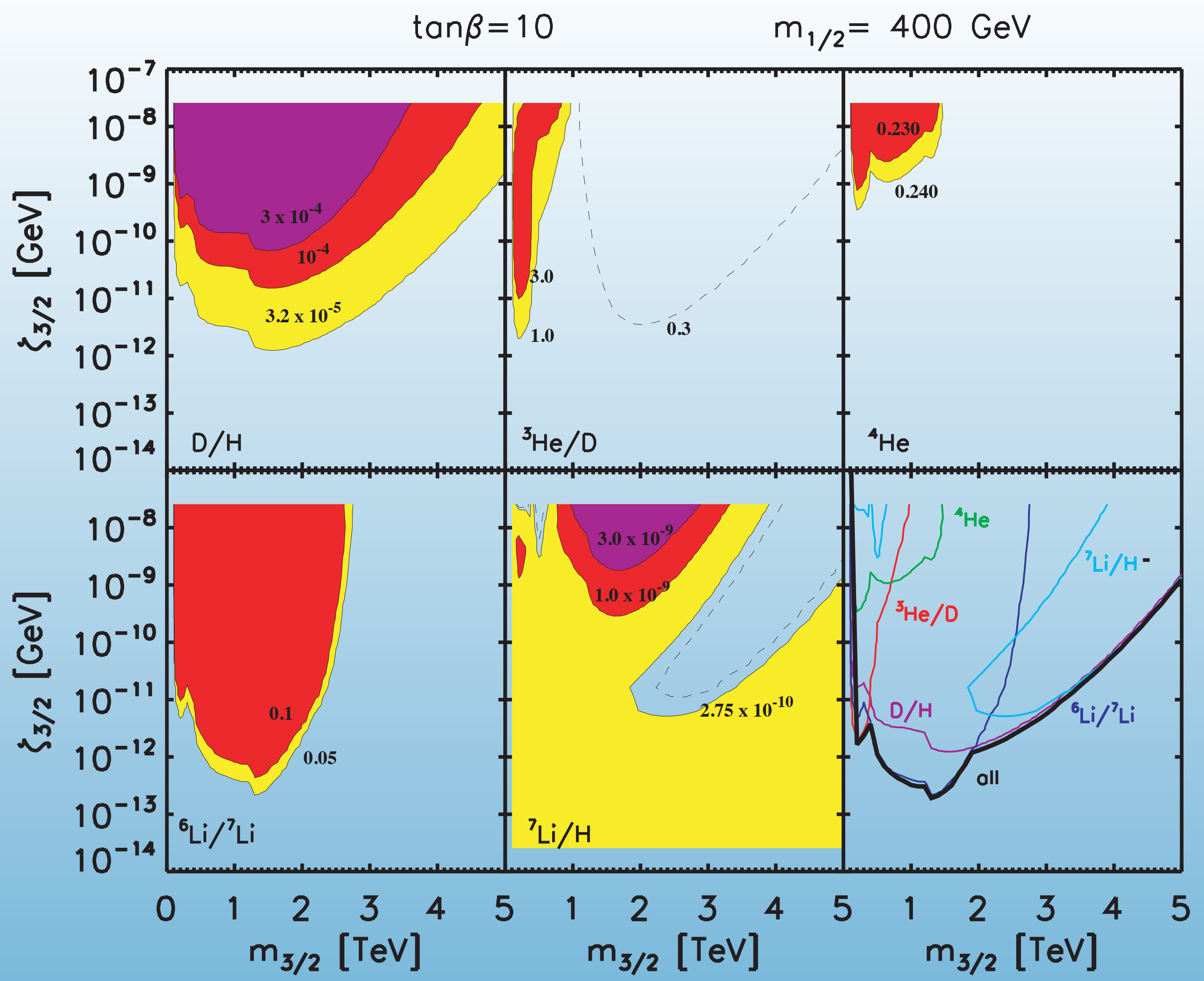
co-annihilation strip, tan β =10 ; $m_{3/2}$ = 250 GeV



co-annihilation strip, tan β =10 ; $m_{3/2}$ = 1000 GeV



co-annihilation strip, tan β =10 ; $m_{3/2}$ = 5000 GeV



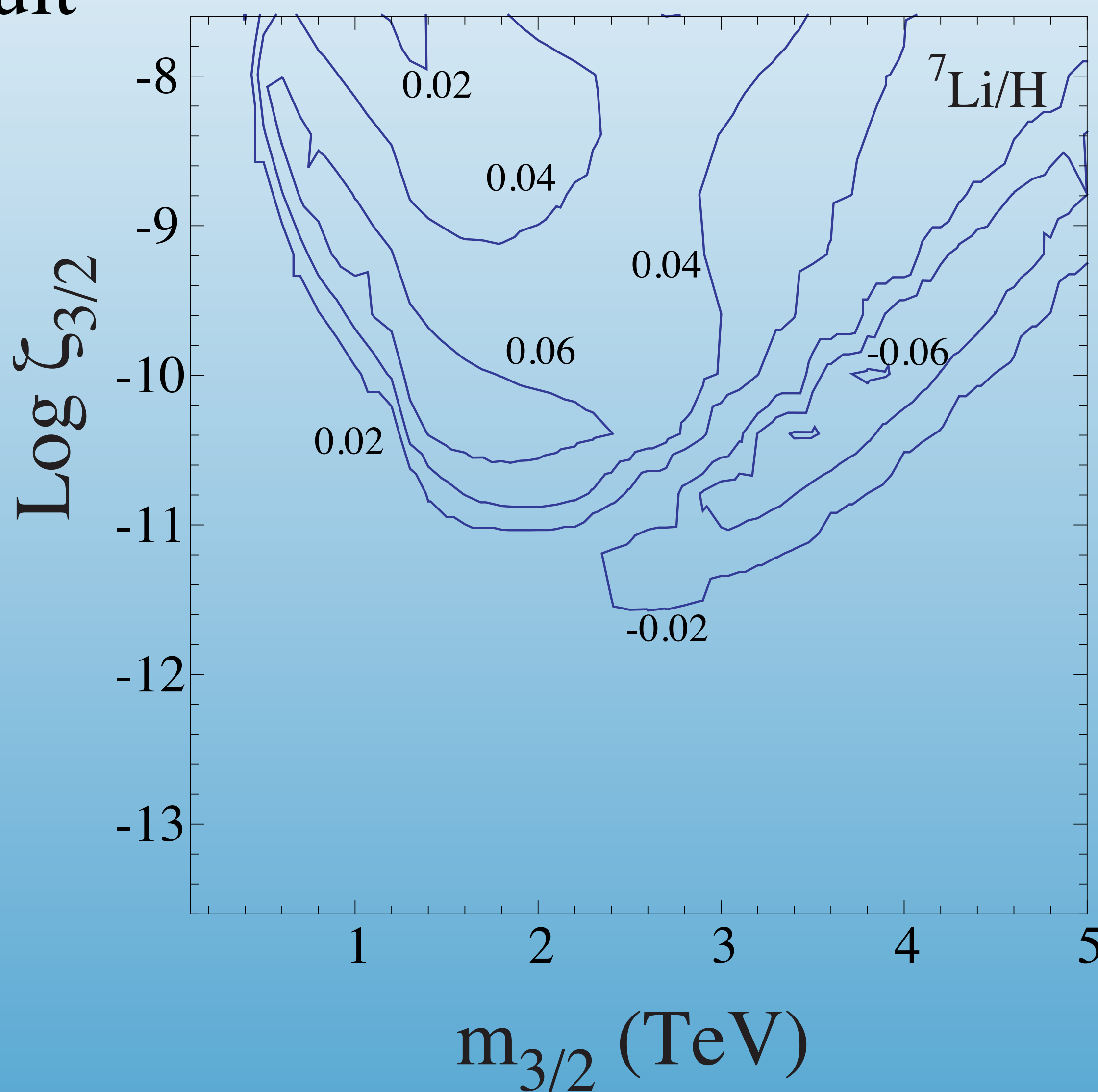
Benchmark point C, tan β =10 ; $m_{1/2}$ = 400 GeV

Uncertainties

There are only a few non-thermal rates which affect the result

$p\,^4\mathrm{He} \to np\,^3\mathrm{He}$	20%
$p\,^4\mathrm{He} \to ddp$	40%
$p\,^4\mathrm{He} \to dnpp$	40%
$t\,^4\mathrm{He} \to \,^6\mathrm{Li}n$	20%
$^3\mathrm{He}\,^4\mathrm{He} \to \,^6\mathrm{Li}p$	20%
$n\,^4\mathrm{He} \to npt$	20%
$n\,^4\mathrm{He} \to ddn$	40%
$n\,^4\mathrm{He} \to dnnp$	40%
$p\,^4\mathrm{He} \to ppt$	20%
$n\,^4\mathrm{He} \to nn\,^3\mathrm{He}$	20%

$(n\,^4\mathrm{He} \to npt)$

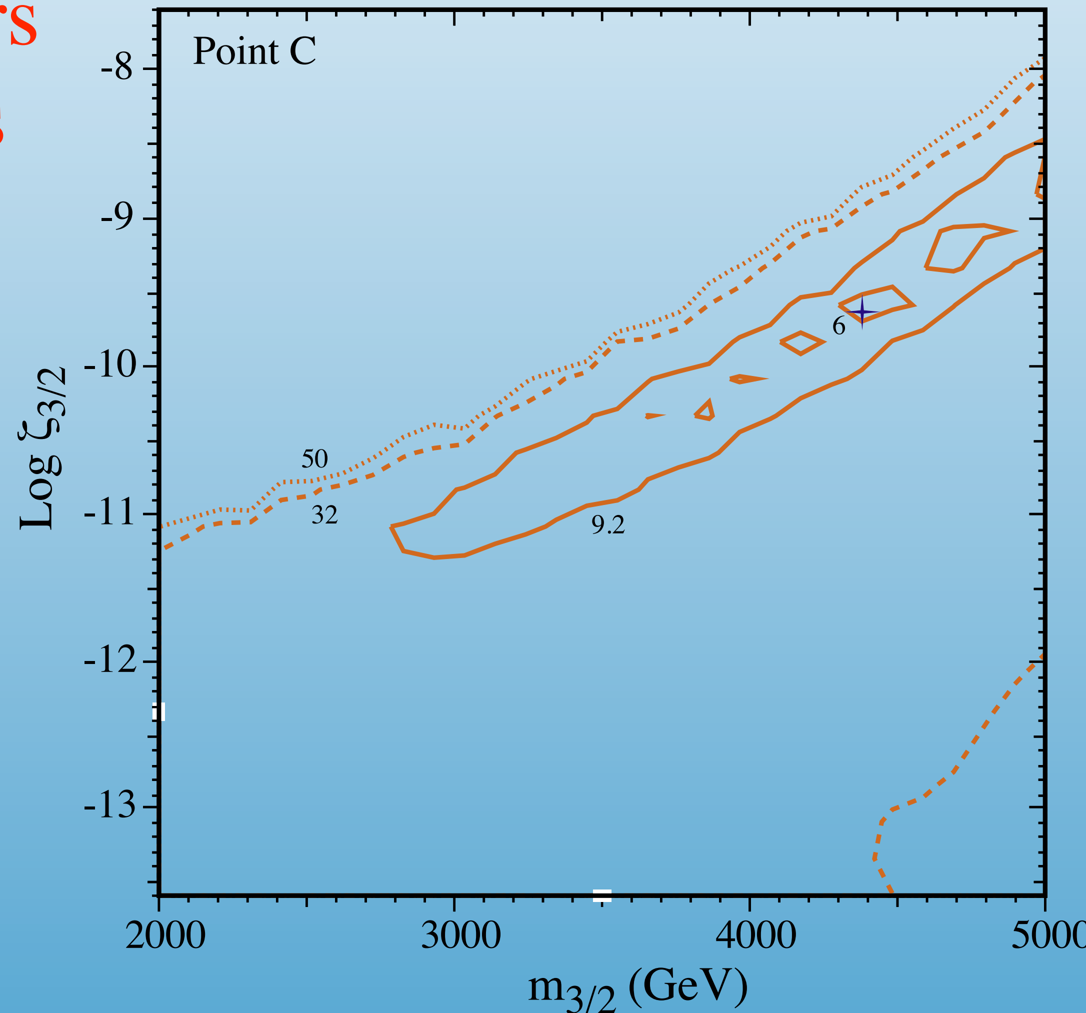


How well can you do

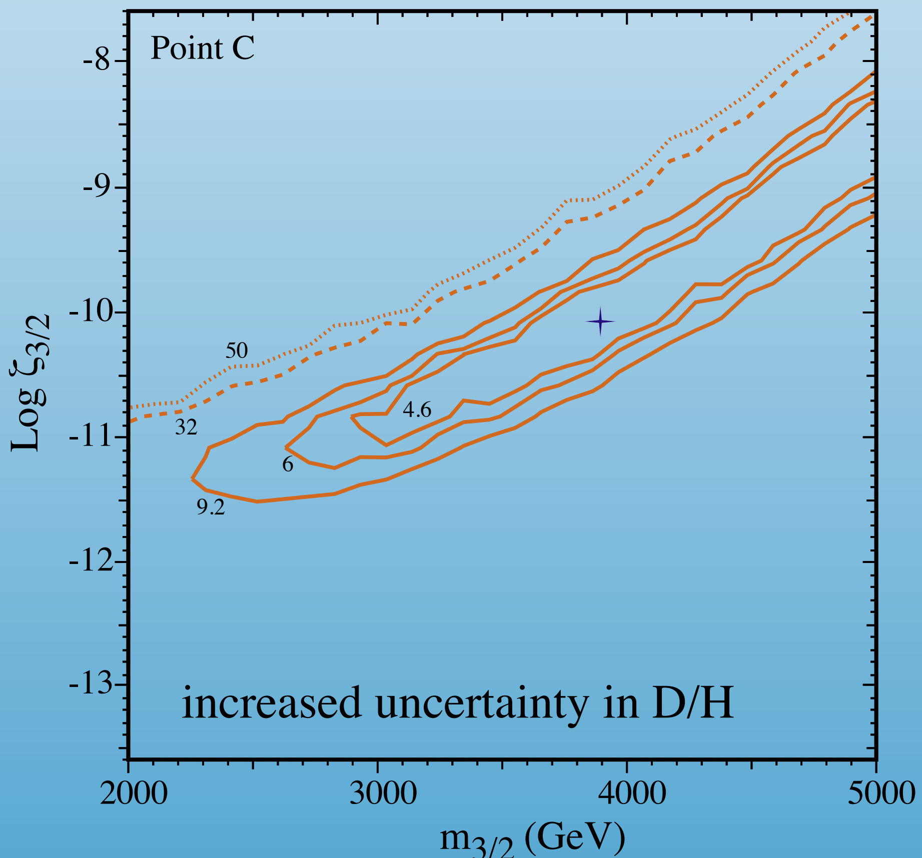
$$\chi^2 \equiv \left(\frac{Y_p - 0.256}{0.011}\right)^2 + \left(\frac{\frac{D}{H} - 2.82\times10^{-5}}{0.27\times10^{-5}}\right)^2 + \left(\frac{\frac{^7\mathrm{Li}}{H} - 1.23\times10^{-10}}{0.71\times10^{-10}}\right)^2 + \sum_i s_i^2,$$

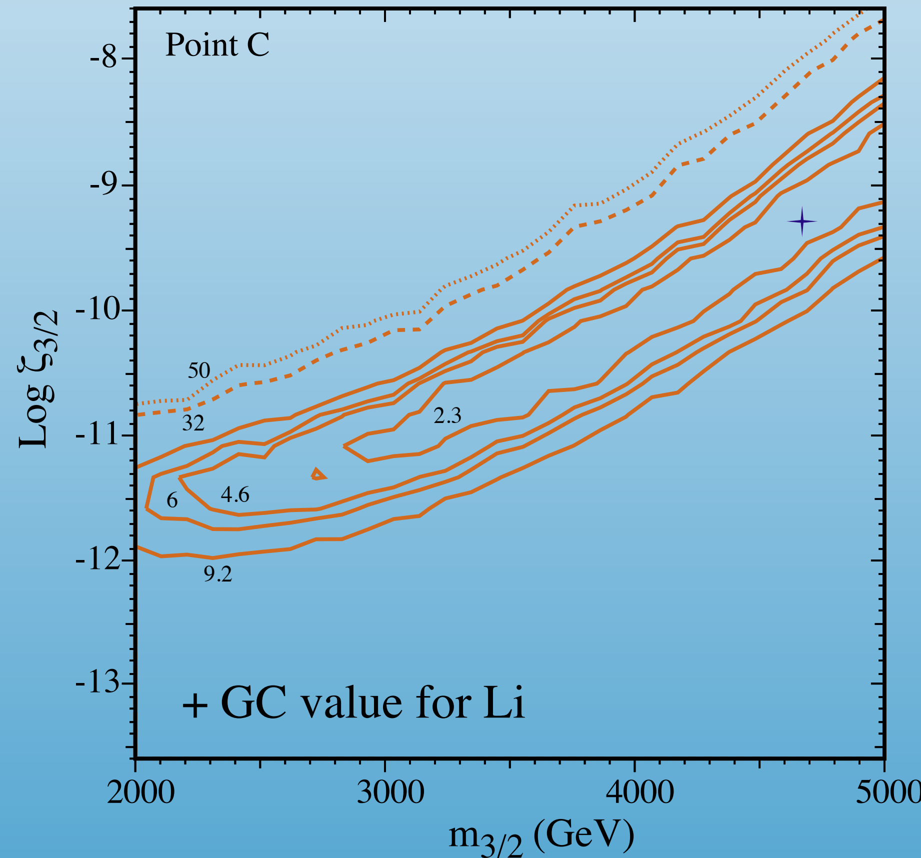
SBBN: χ^2 = 31.7 - field stars

SBBN: χ^2 = 21.8 - GC stars



	$m_{3/2}$[GeV]	$\text{Log}_{10}(\zeta_{3/2}/[\text{GeV}])$	Y_p	D/H ($\times 10^{-5}$)	^{7}Li/H ($\times 10^{-10}$)	$\sum s_i^2$	χ^2
BBN	——	——	0.2487	2.52	5.12	——	31.7
C	4380	−9.69	0.2487	3.15	2.53	0.26	5.5
E	4850	−9.27	0.2487	3.20	2.42	0.29	5.5
L	4380	−9.69	0.2487	3.21	2.37	0.26	5.4
M	4860	−10.29	0.2487	3.23	2.51	1.06	7.0
C	4680	−9.39	0.2487	3.06	2.85	0.08	2.0
M	4850	−10.47	0.2487	3.11	2.97	0.09	2.7
C	3900	−10.05	0.2487	3.56	1.81	0.02	2.8
C	4660	−9.27	0.2487	3.20	2.45	0.16	1.1



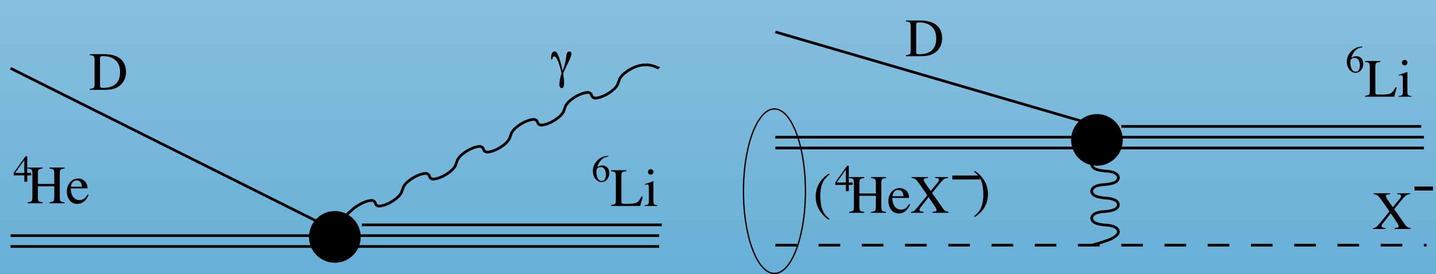


Effects of Bound States

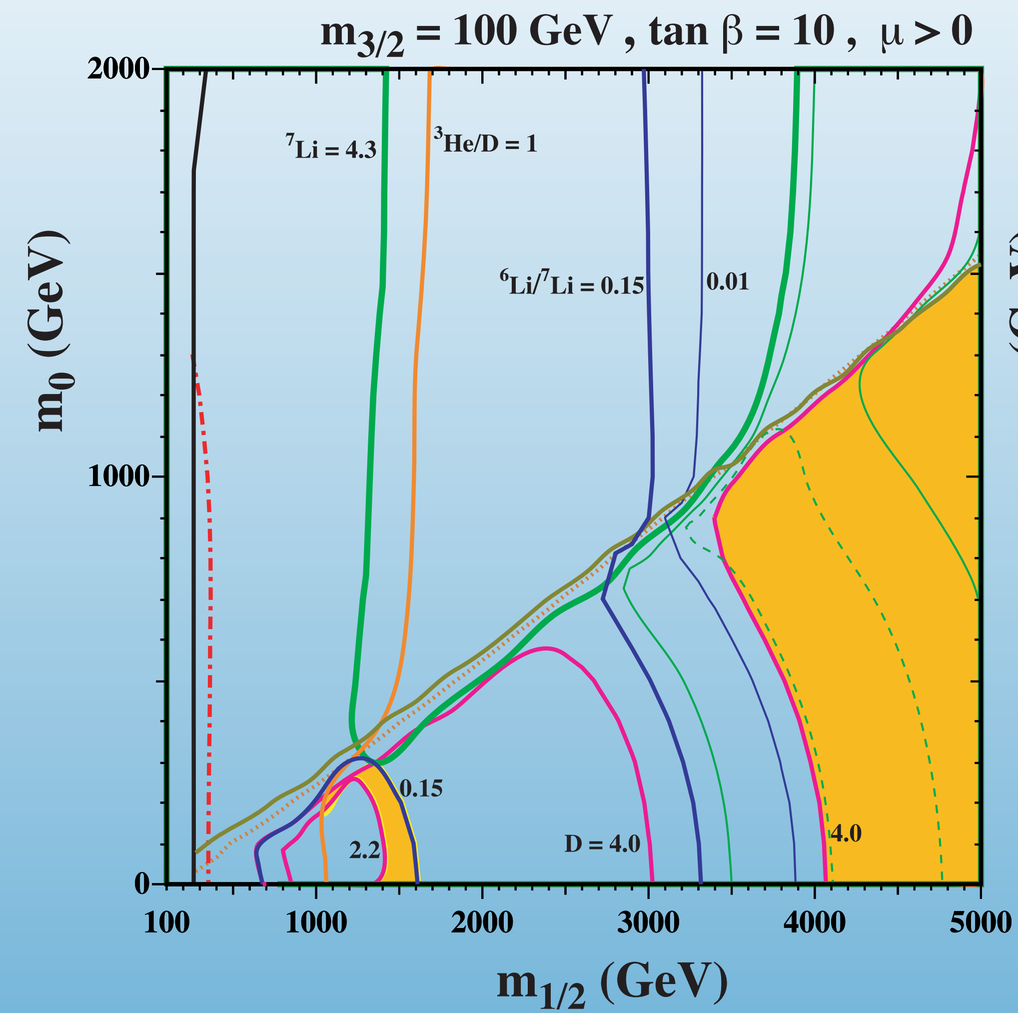
• In SUSY models with a $\tilde{\tau}$ NLSP, bound states form between ^{4}He and $\tilde{\tau}$

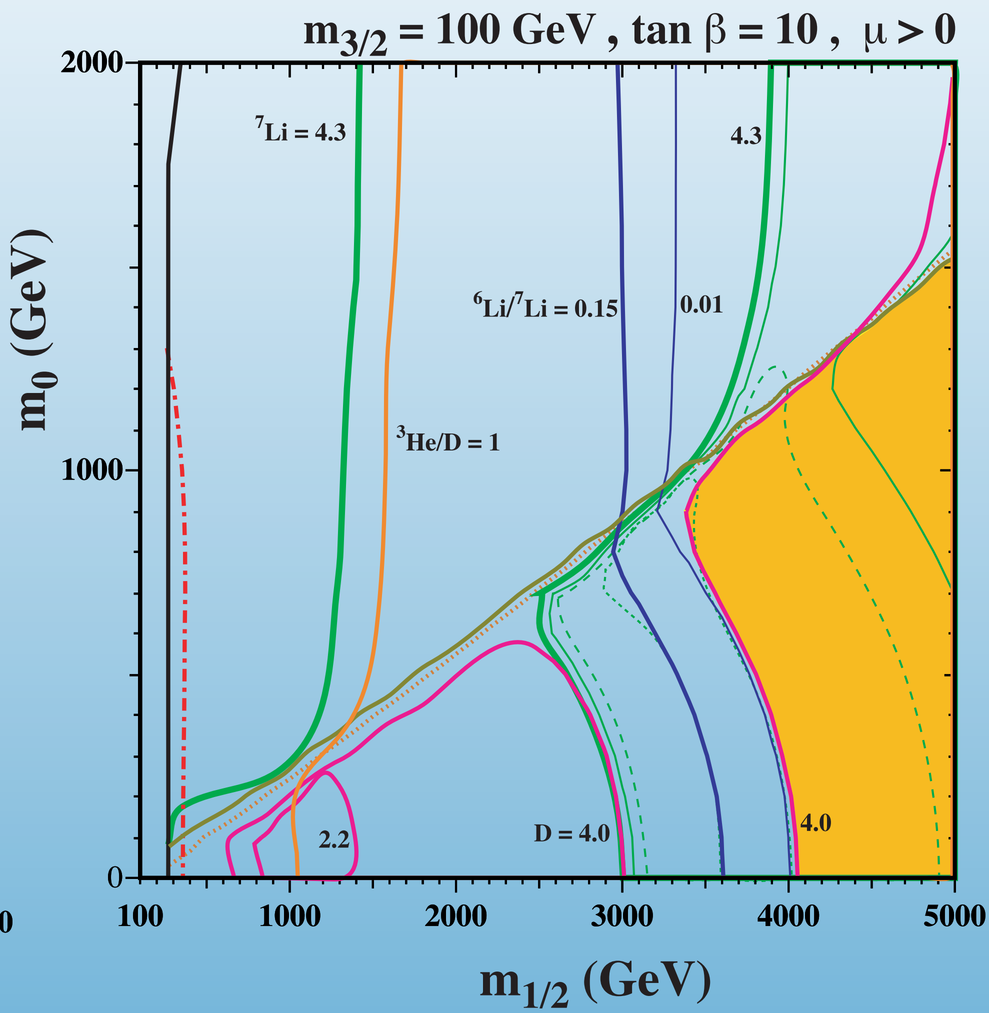
• The ^{4}He (D, γ) ^{6}Li reaction is normally highly suppressed (production of low energy γ)

• Bound state reaction is not suppressed

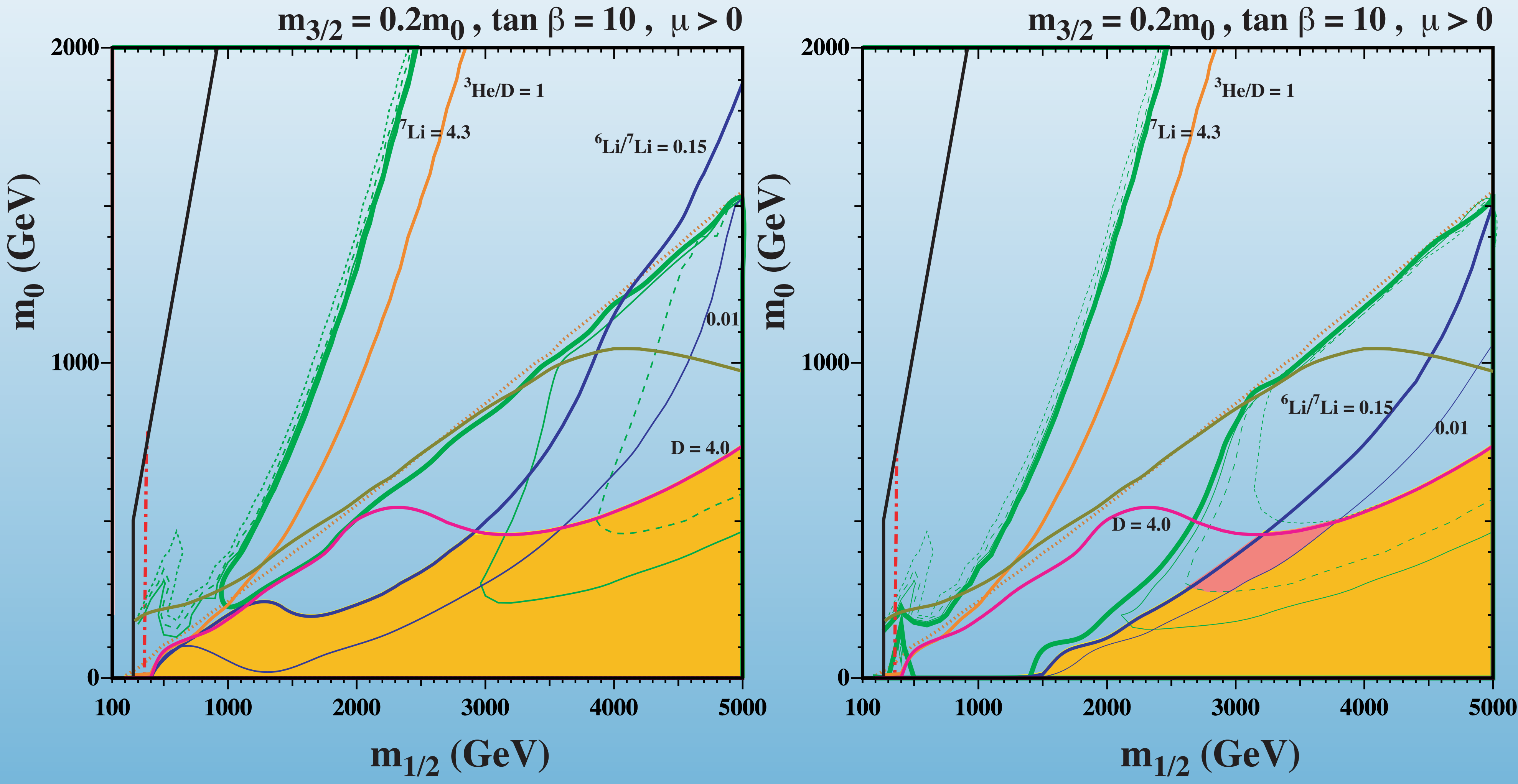


Pospelov





Cyburt, Ellis, Fields, KO, 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 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

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

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

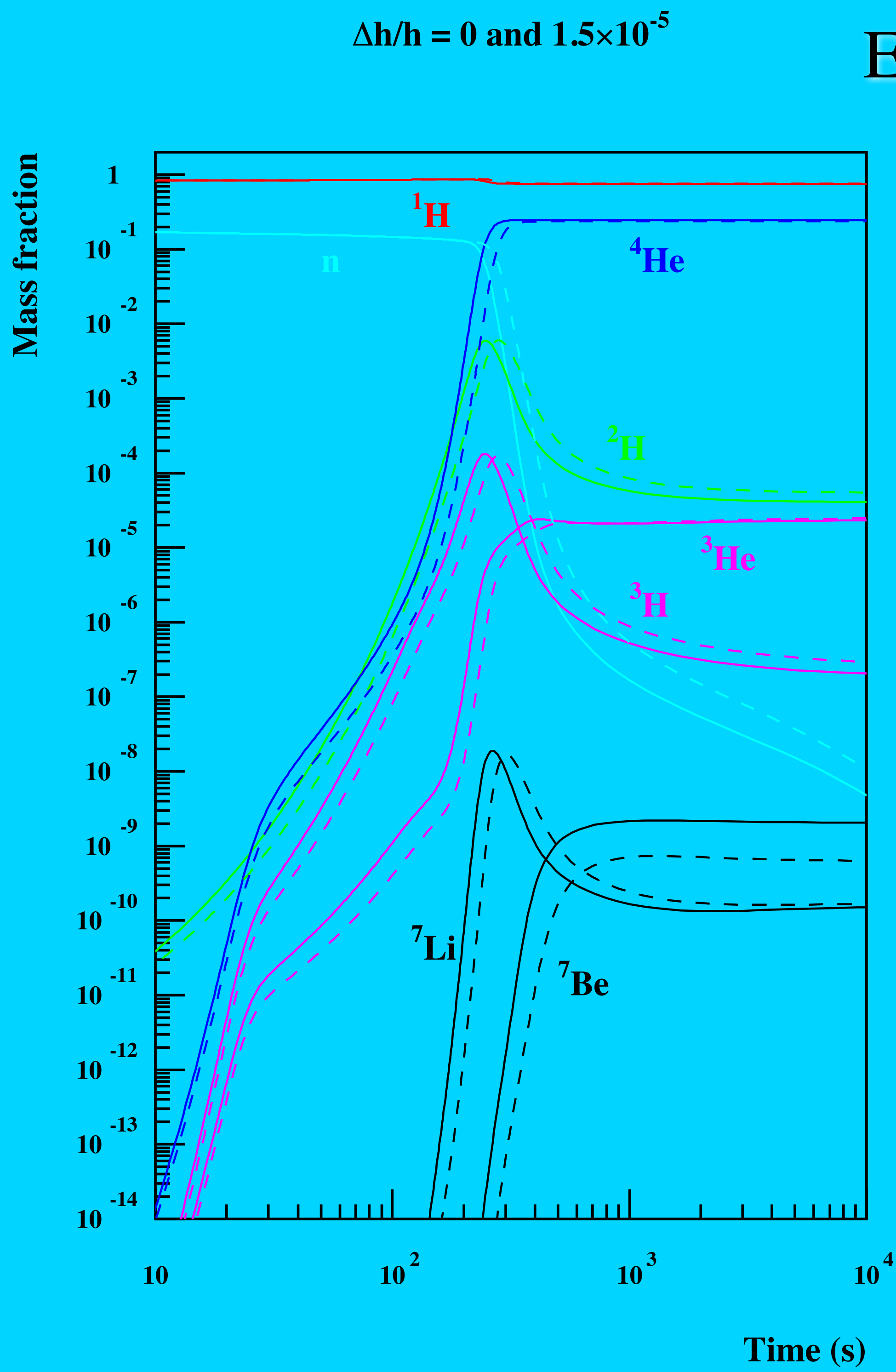
$$\frac{\Delta B_D}{B_D} = -[6.5(1+S) - 18R]\frac{\Delta \alpha}{\alpha}$$

$$\frac{\Delta Q}{Q} = (0.1 + 0.7S - 0.6R)\frac{\Delta \alpha}{\alpha}$$

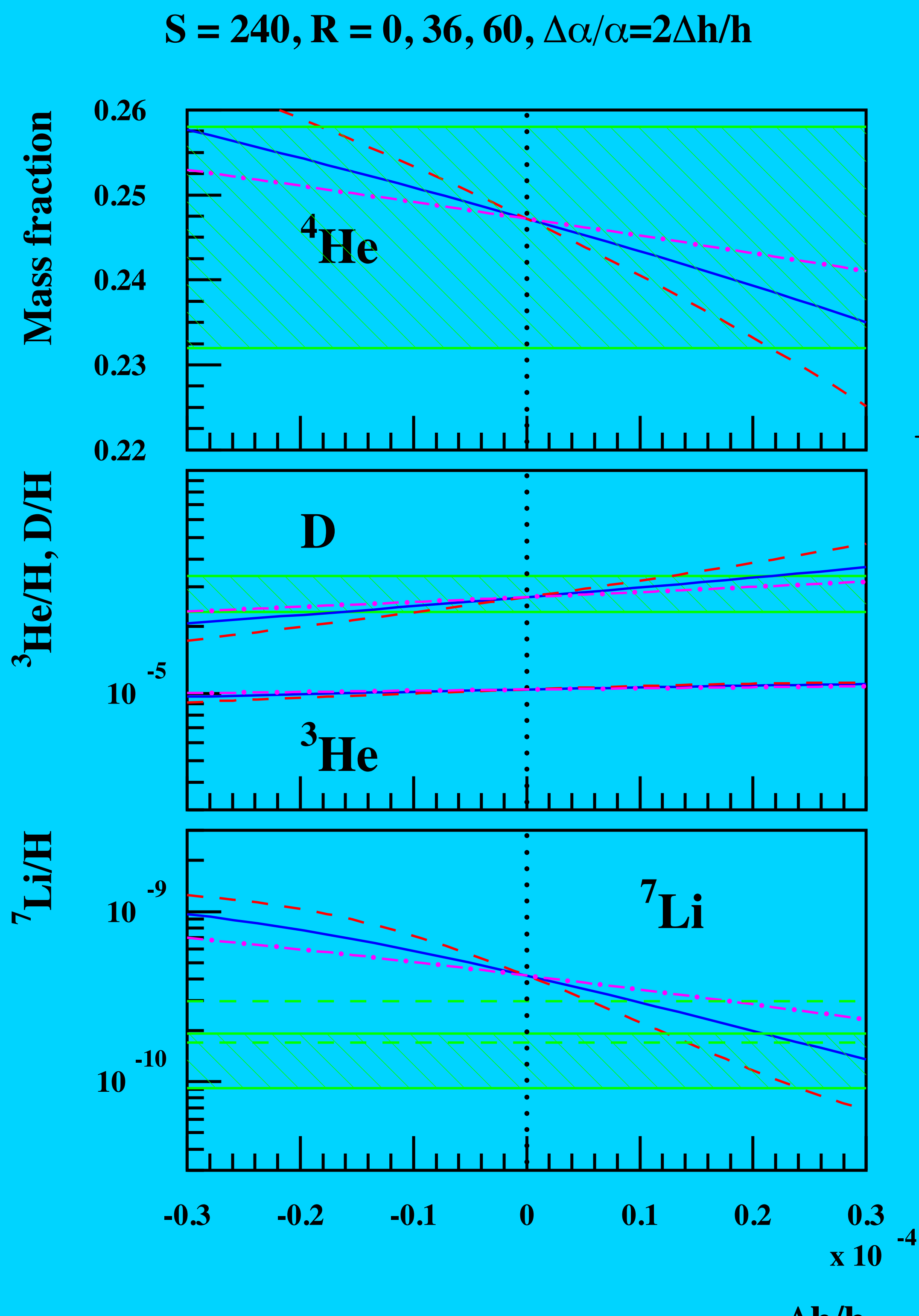
$$\frac{\Delta \tau_n}{\tau_n} = -[0.2 + 2S - 3.8R]\frac{\Delta \alpha}{\alpha},$$

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

Effect of variations of h (S = 160)



Notice effect on ^{7}Li



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?
  - Variable Constants???
- ^{6}Li: Another Story