The BBN/CMB connection: Post Planck

- BBN and the WMAP/Planck determination of η, $\Omega_B h^2$
- Input cross sections

- Observations and Comparison with Theory

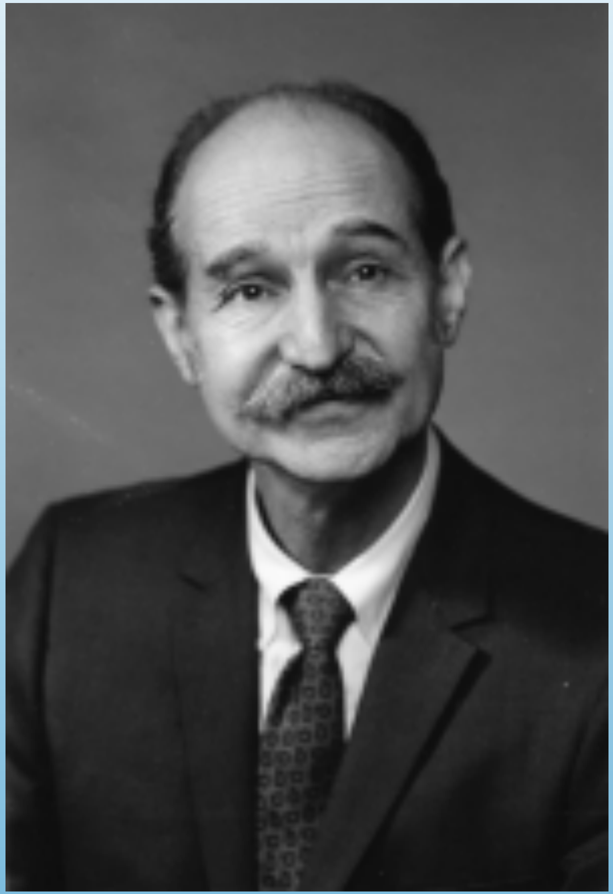
  - D/H - ^{4}He - ^{7}Li

- Neutrinos
- Constraints on BSM physics
- The Future (CMB-S4)

It all started with:

George Gamow

Ralph Alpher



Robert Herman

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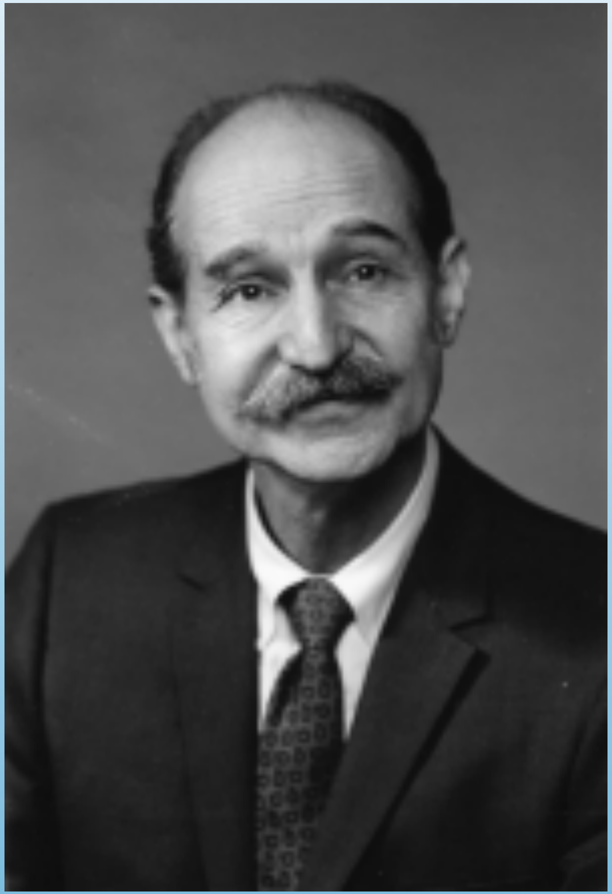

Robert Herman

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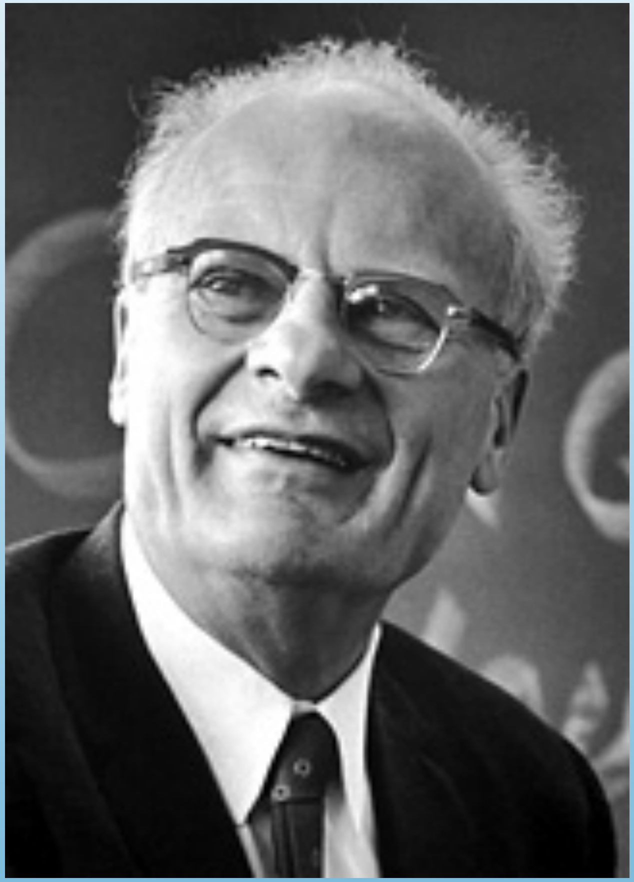


Hans Bethe

George Gamow

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. BETHE
Cornell University, Ithaca, New York

AND

G. GAMOW
The George Washington University, Washington, D. C.

February 18, 1948

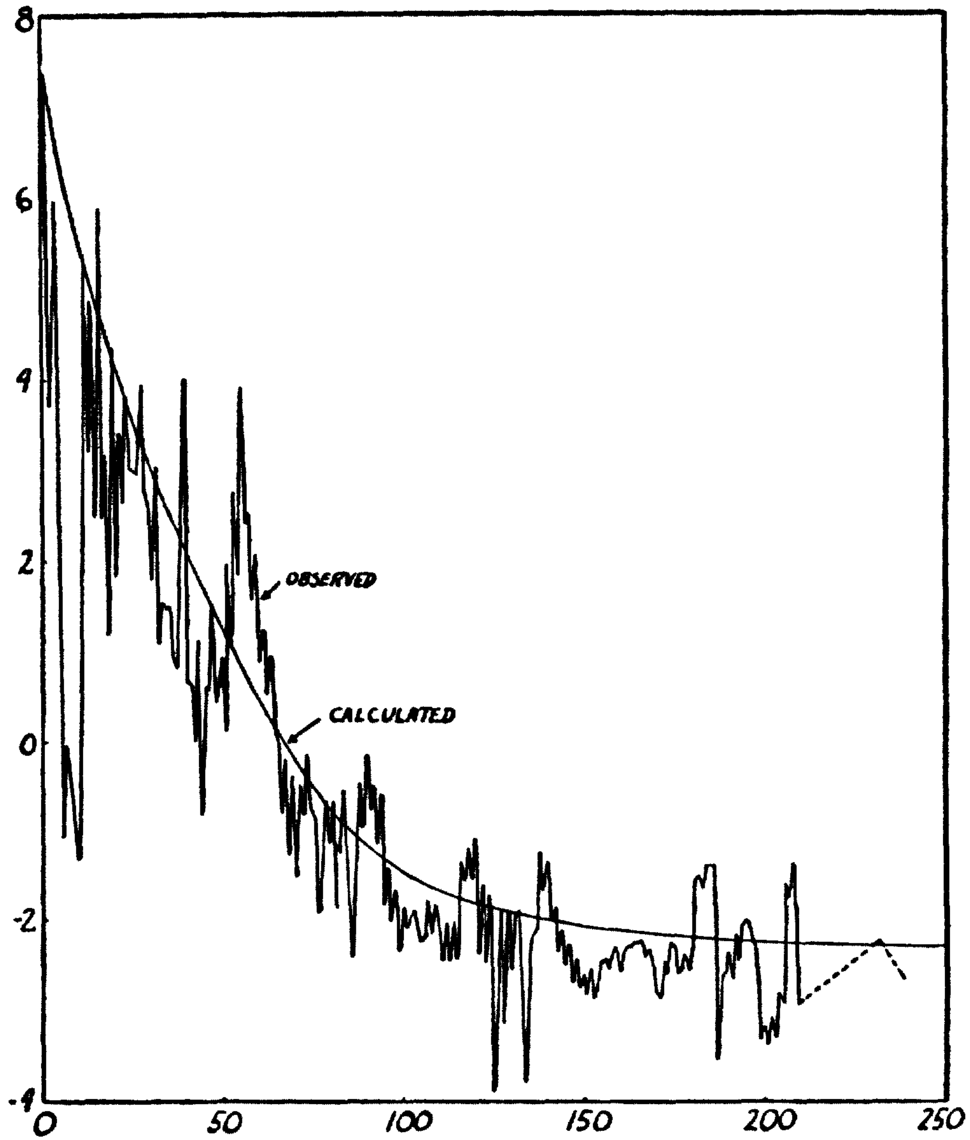
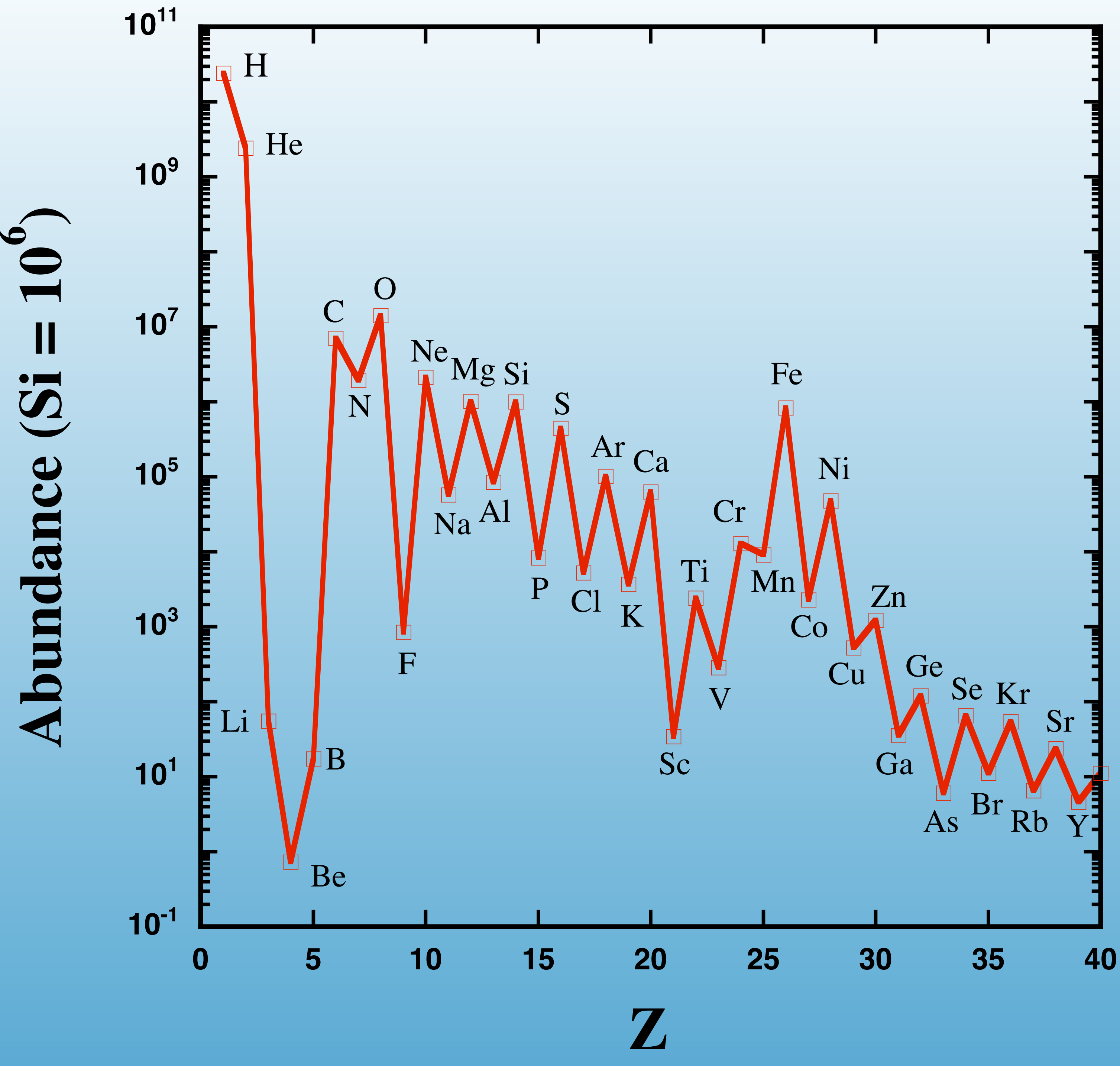


FIG. 1.

Log of relative abundance

Atomic weight



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

Historical Perspective

Intimate connection with CMB

Alpher
Herman
Gamow

Conditions for BBN:

Require $T > 100$ keV $\Rightarrow t < 200$ 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

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

Remarks on the Evolution of the Expanding Universe*,†

Ralph A. Alpher and Robert C. Herman
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
(Received December 27, 1948)

Because of Eq. (4) a knowledge of $\rho_{m'}$ and $\rho_{r'}$ during the element forming period together with $\rho_{m''}$ fixes a value for $\rho_{r''}$, the present radiation density, which is perhaps the least well-known quantity.

In accordance with Eq. (4), the specification of $\rho_{m''}$, $\rho_{m'}$, and $\rho_{r'}$ fixes the present density of radiation, $\rho_{r''}$. In fact, we find that the value of $\rho_{r''}$ consistent with Eq. (4) is

$$\rho_{r''} \cong 10^{-32}\ \text{g/cm}^3, \qquad (12d)$$

which corresponds to a temperature now of the order of 5°K. This mean temperature for the universe is to be interpreted as the background temperature which would result from the universal expansion alone. However, the thermal energy resulting from the nuclear energy production in stars would increase this value.

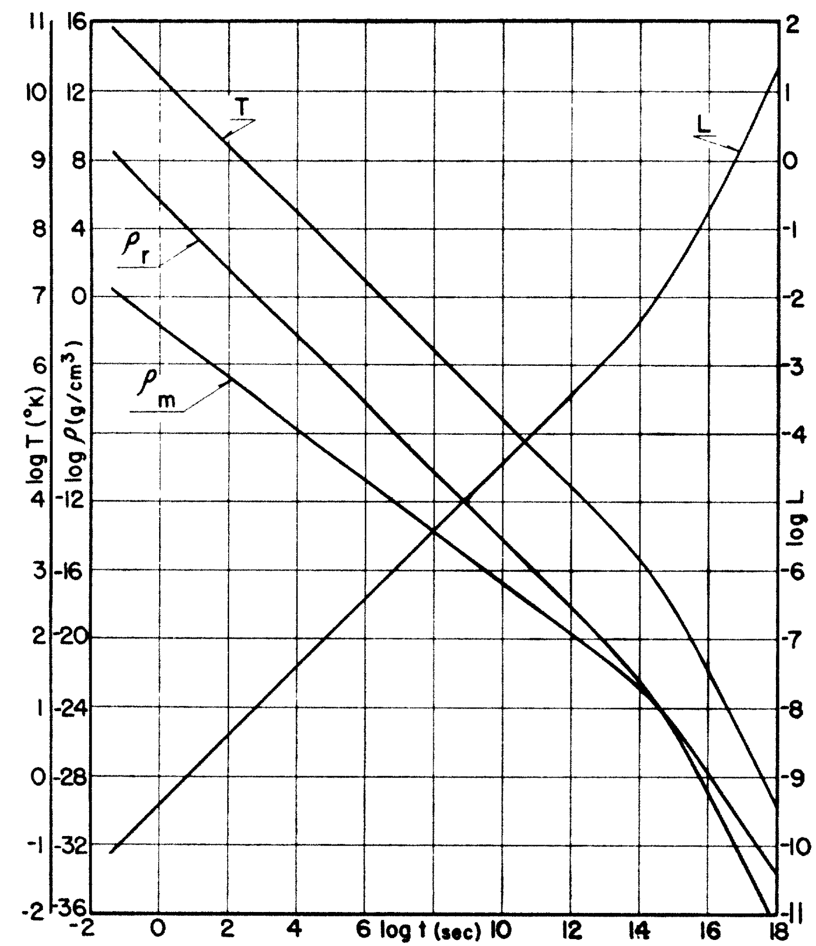


FIG. 1. The time dependence of the proper distance L, the densities of matter and radiation, ρ_m, and ρ_r, as well as the temperature, T, are shown for the case where $\rho_{m''} \cong 10^{-30}$ g/cm³, $\rho_{r''} \cong 10^{-32}$ g/cm³, $\rho_{m'} \cong 10^{-6}$ g/cm³, and $\rho_{r'} \cong 1$ g/cm³. [See Eq. (12).]

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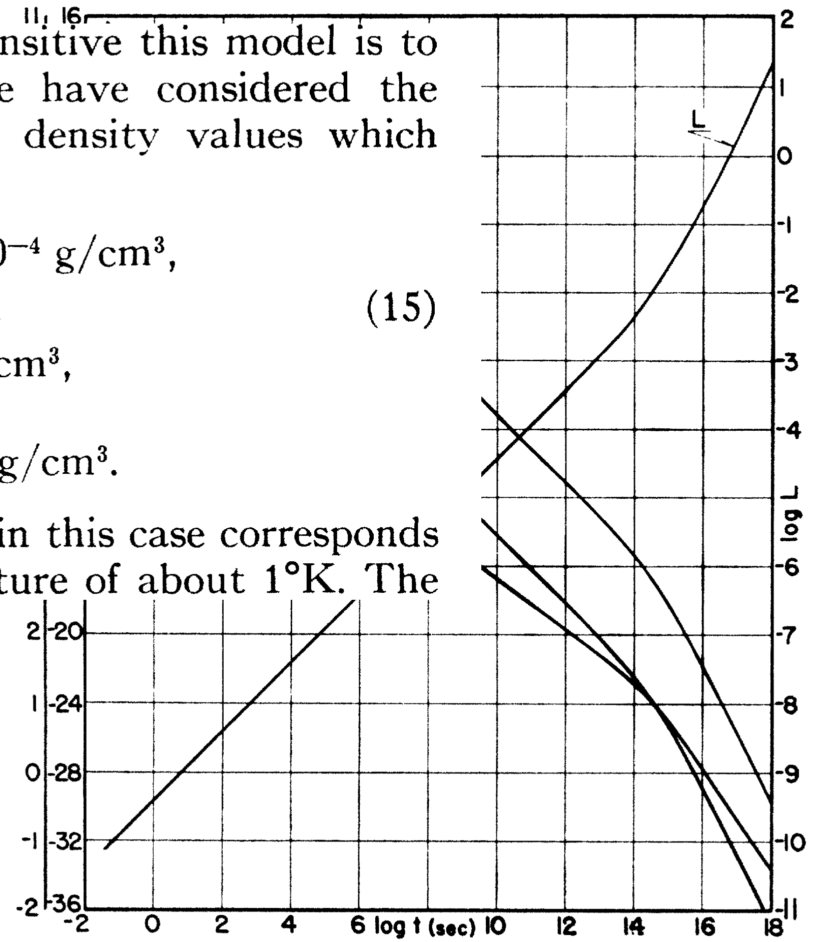
In order to study how sensitive this model is to the choice of densities, we have considered the following additional set of density values which satisfy Eq. (4):

$$\begin{aligned} \rho_{m'} &\cong 1.78\times 10^{-4}\ \mathrm{g/cm^3},\\ \rho_{r'} &\cong 1\ \mathrm{g/cm^3},\\ \rho_{m''} &\cong 10^{-30}\ \mathrm{g/cm^3}, \end{aligned} \tag{15}$$

and

$$\rho_{r''} \cong 10^{-35}\ \mathrm{g/cm^3}.$$

The value obtained for $\rho_{r''}$ in this case corresponds to a present mean temperature of about 1°K. The



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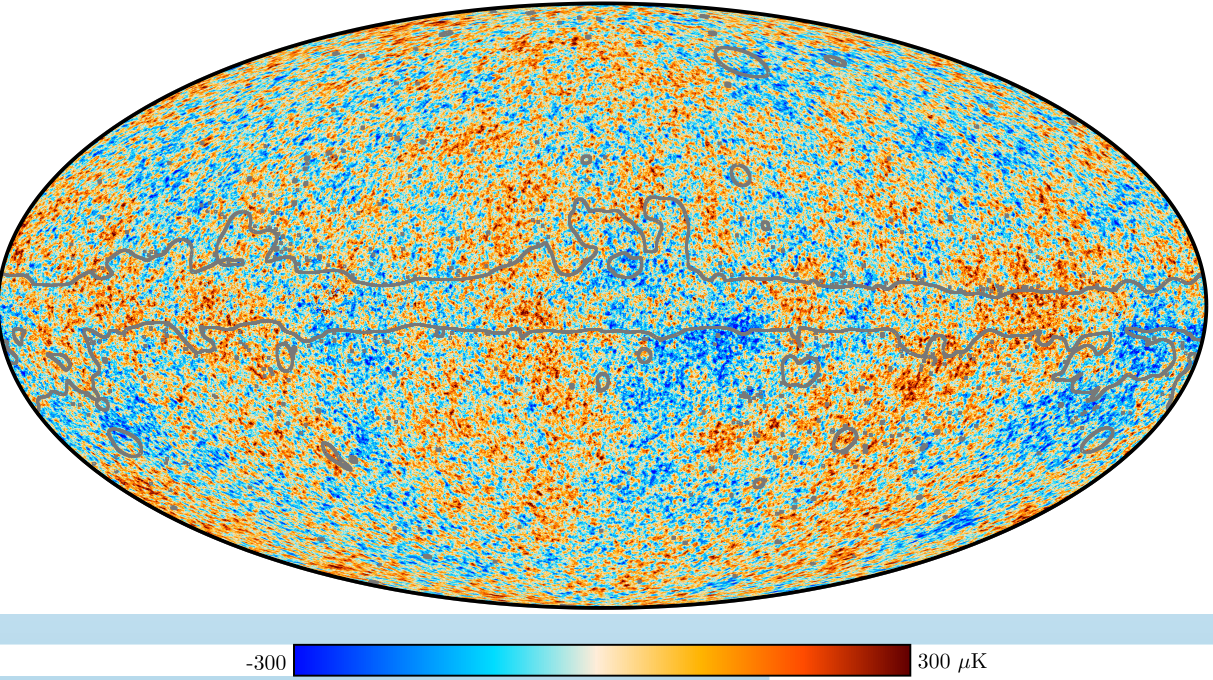
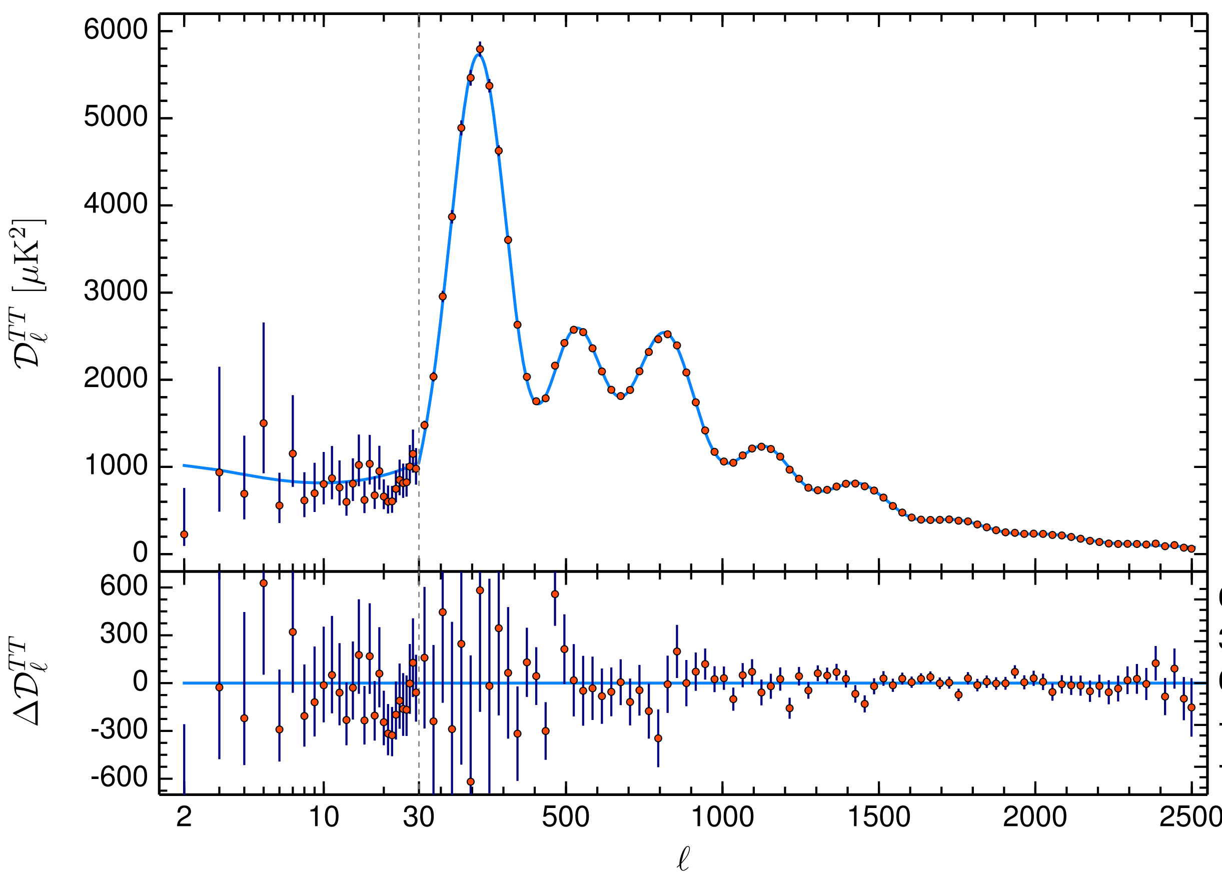


Planck best fit

$$\Omega_B h^2 = 0.02237 \pm 0.00015$$

$$\eta_{10} = 6.12 \pm 0.04$$

$$T = 2.7255 \pm 0.0006 \text{ K}$$



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 $\Gamma_p \sim \Gamma_d$

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

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**

- Weak Freeze-out (T~.84 MeV)
- D Bottleneck (T~.064 MeV)
- Free neutron decay n/p ≈ 1/4.66 to ≈ 1/7.2

$$y = \frac{n_{He}}{n_H} \approx \frac{\frac{1}{2}n}{p-n} \approx 0.081$$

$$Y \approx \frac{2n}{p+n} \approx 0.245$$

$$\approx \frac{4y}{1+4y}$$

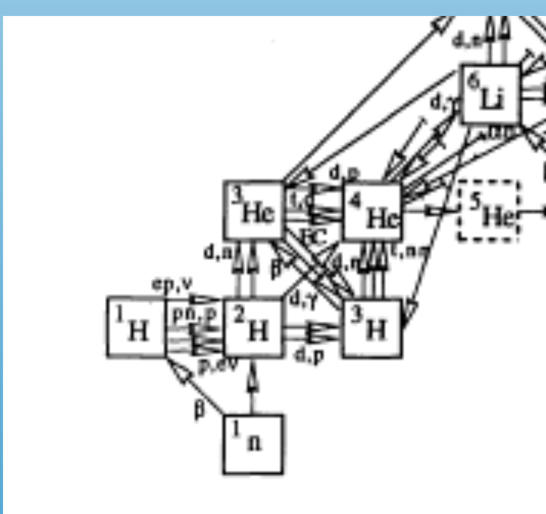
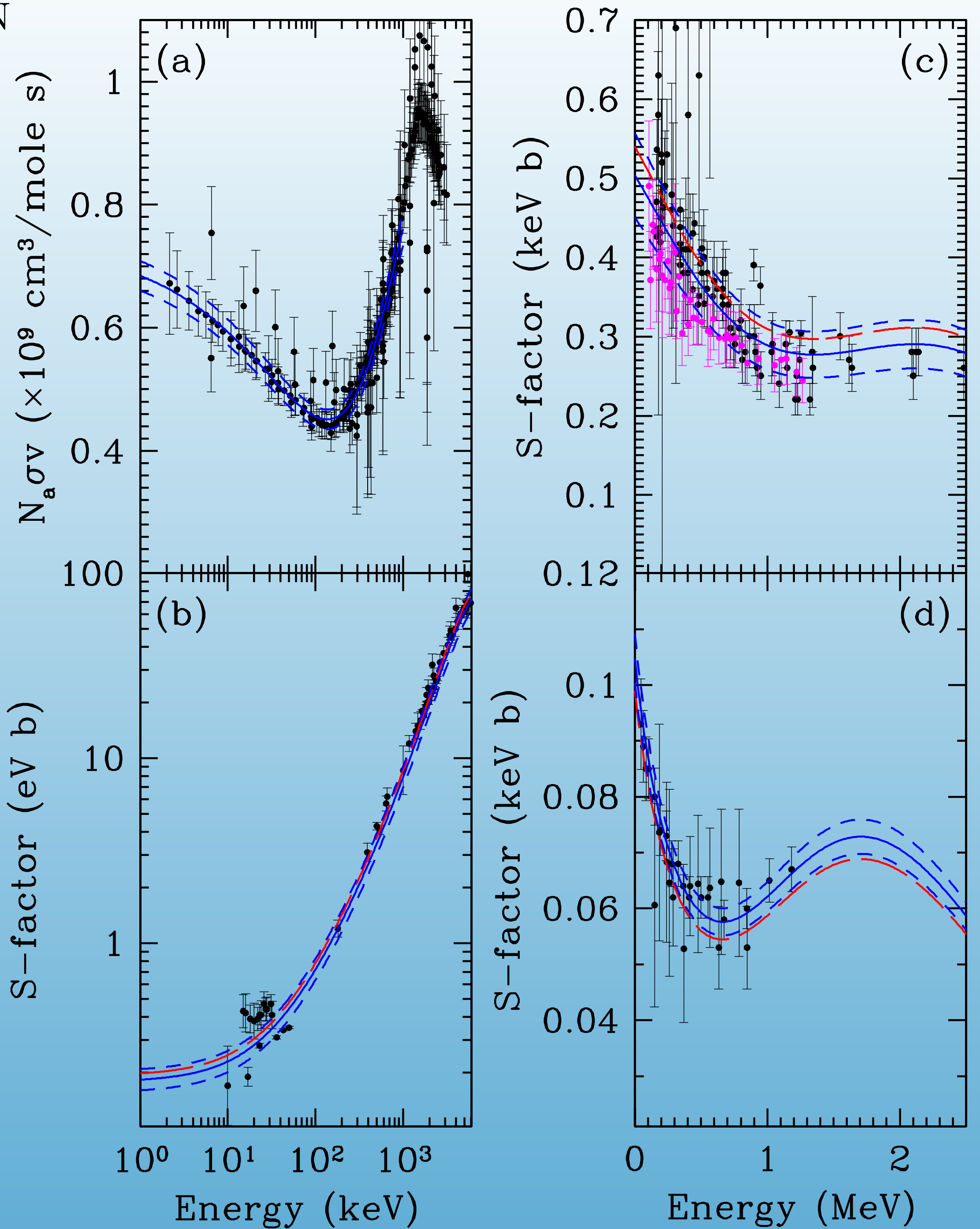


Table 1: Key Nuclear Reactions for BBN

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	(See below)
This work	^{3}He$(n,p)t$	(a)
PDG	τ_n	

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



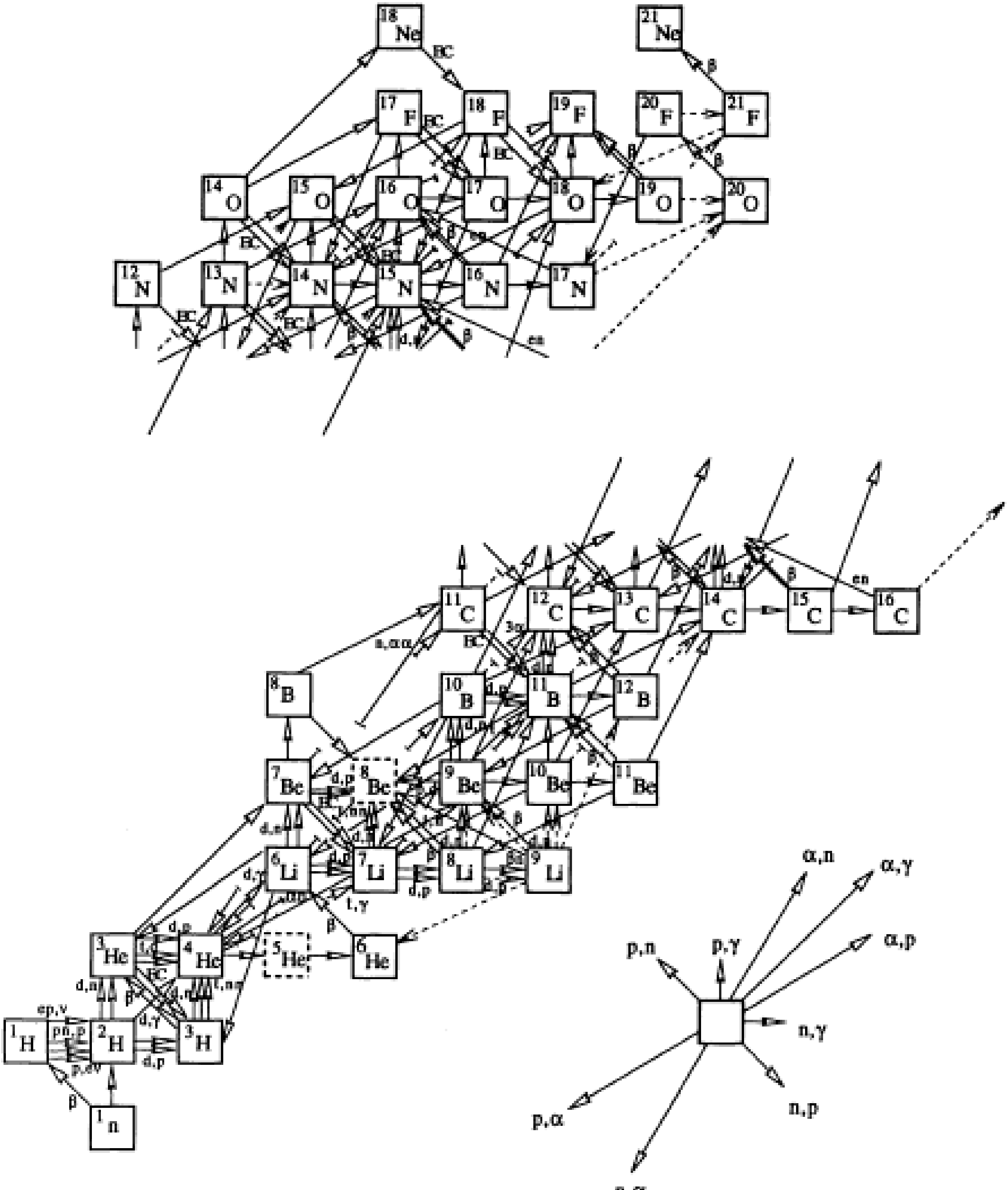
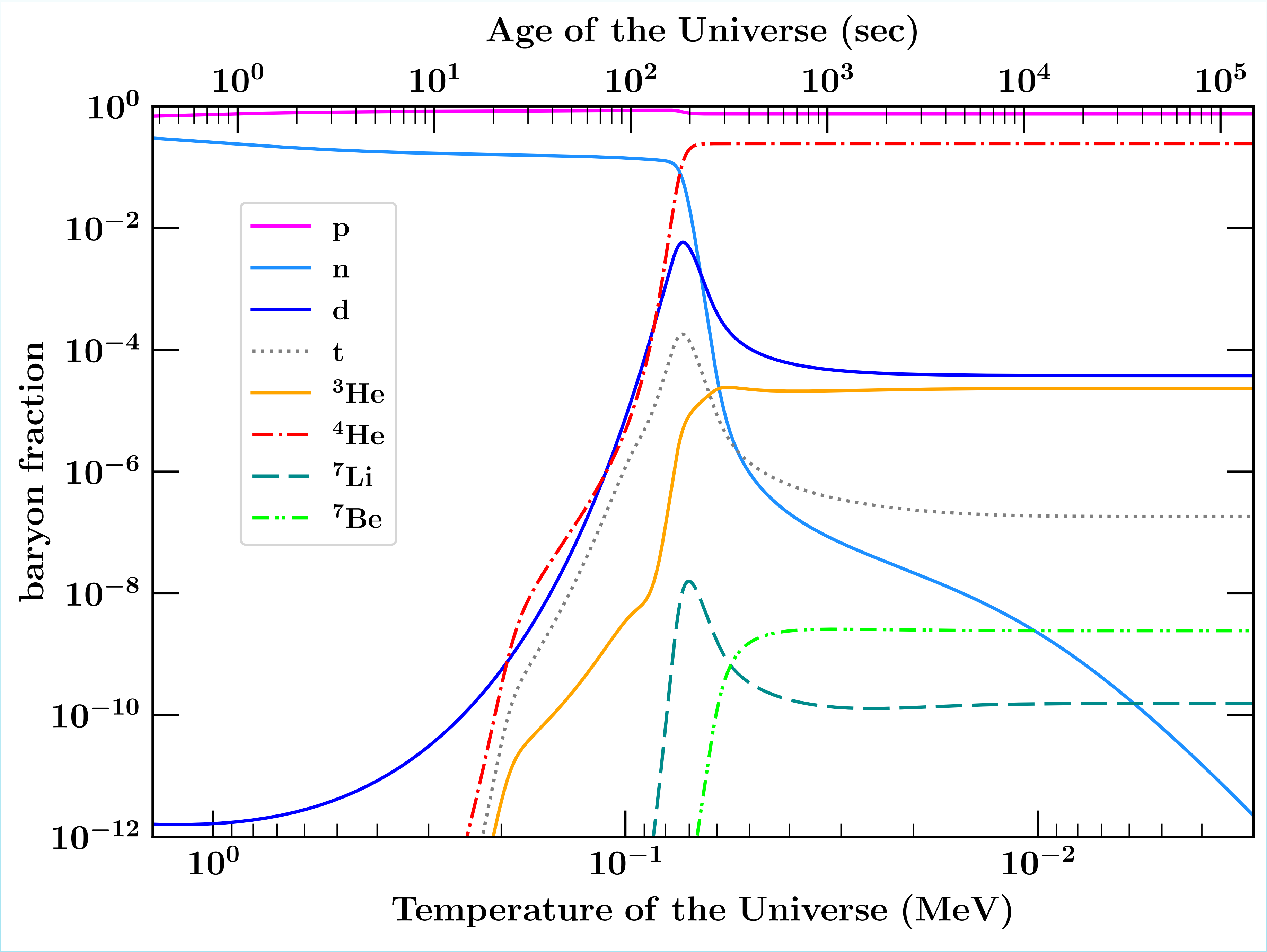


FIG. 1.—Reaction network used in the code. Estimated reactions are shown with dashed lines.

Evolution of the nuclear chain

Yeh



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

$\Longrightarrow$ growth of stellar nucleosynthesis

But,

Questions persisted:

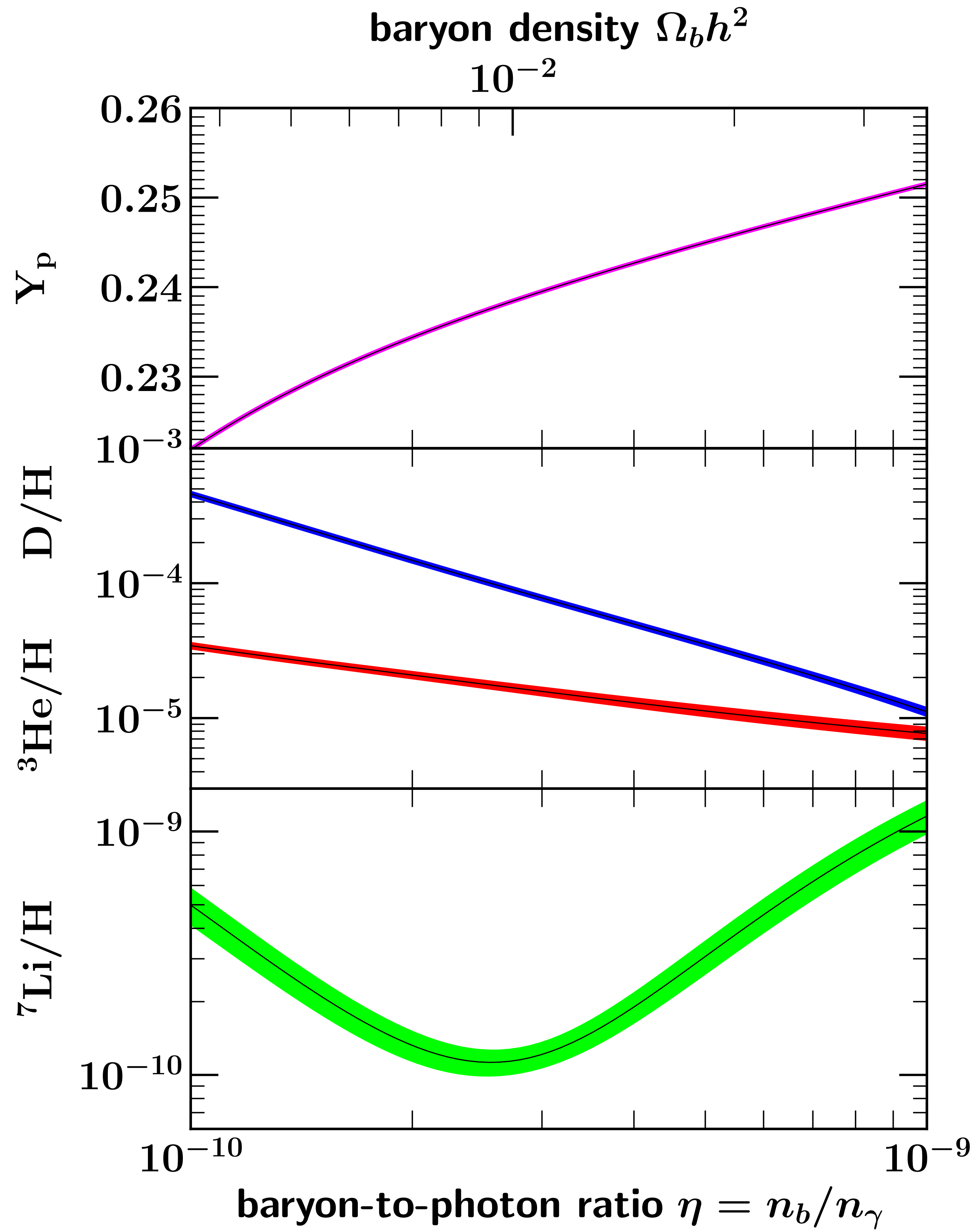
25% (by mass) of ^{4}He ?

D?

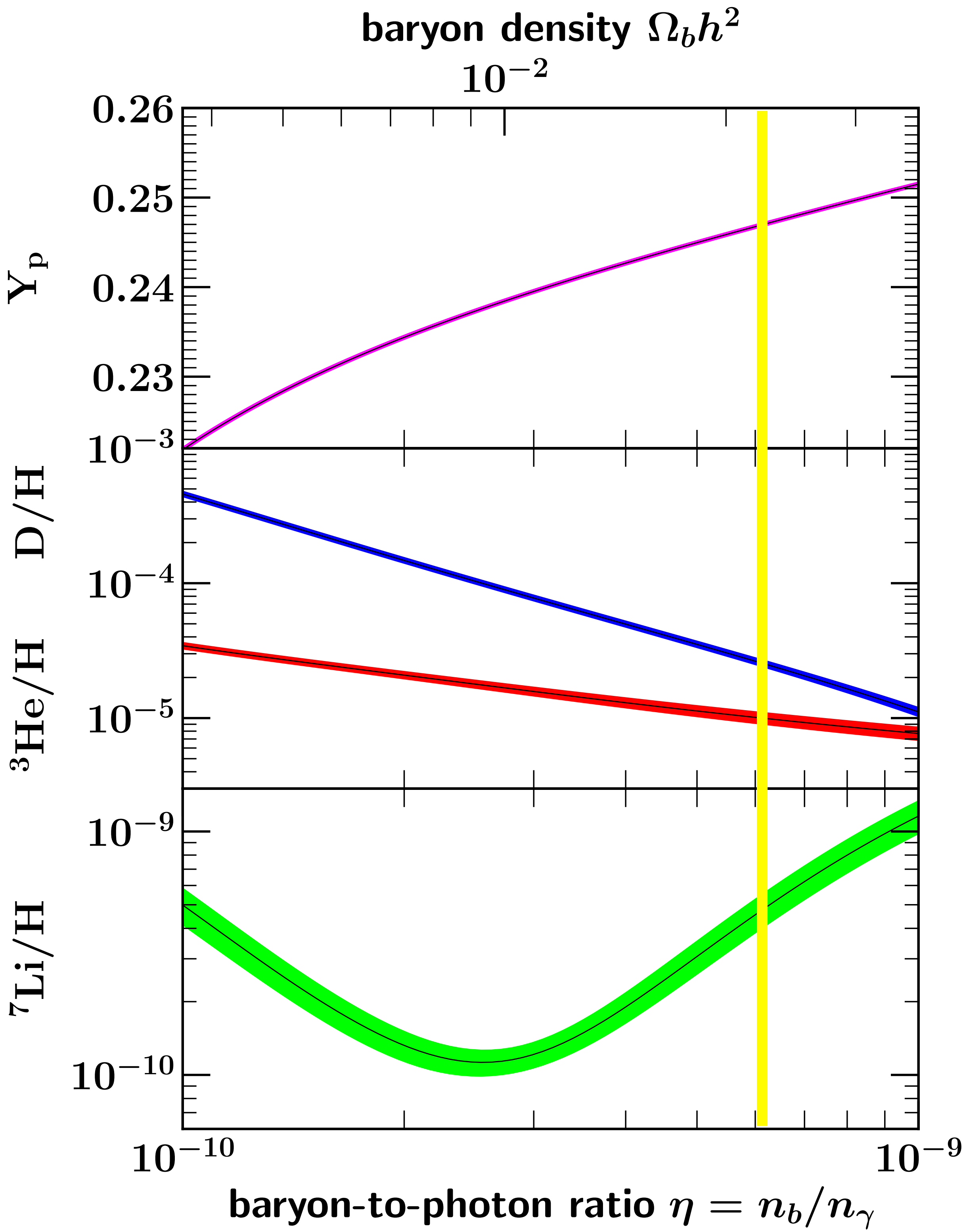
Resurgence:

BBN could successfully account for the abundance of

D, ^{3}He, ^{4}He, ^{7}Li.

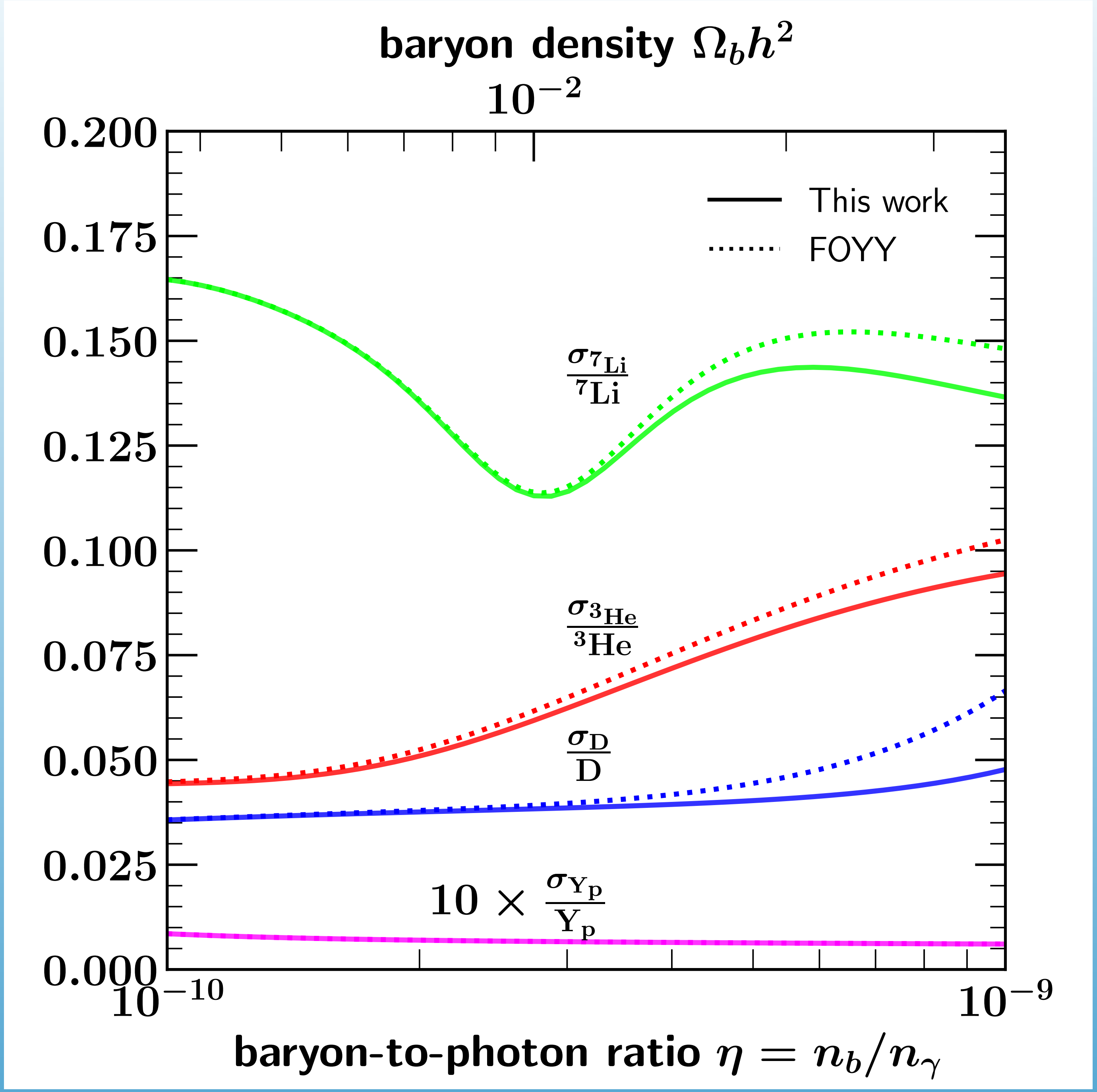


Fields, Olive, Yeh, Young



Fields, Olive, Yeh, Young

Uncertainties



Yeh, Olive, Fields

Observations

- 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

- 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

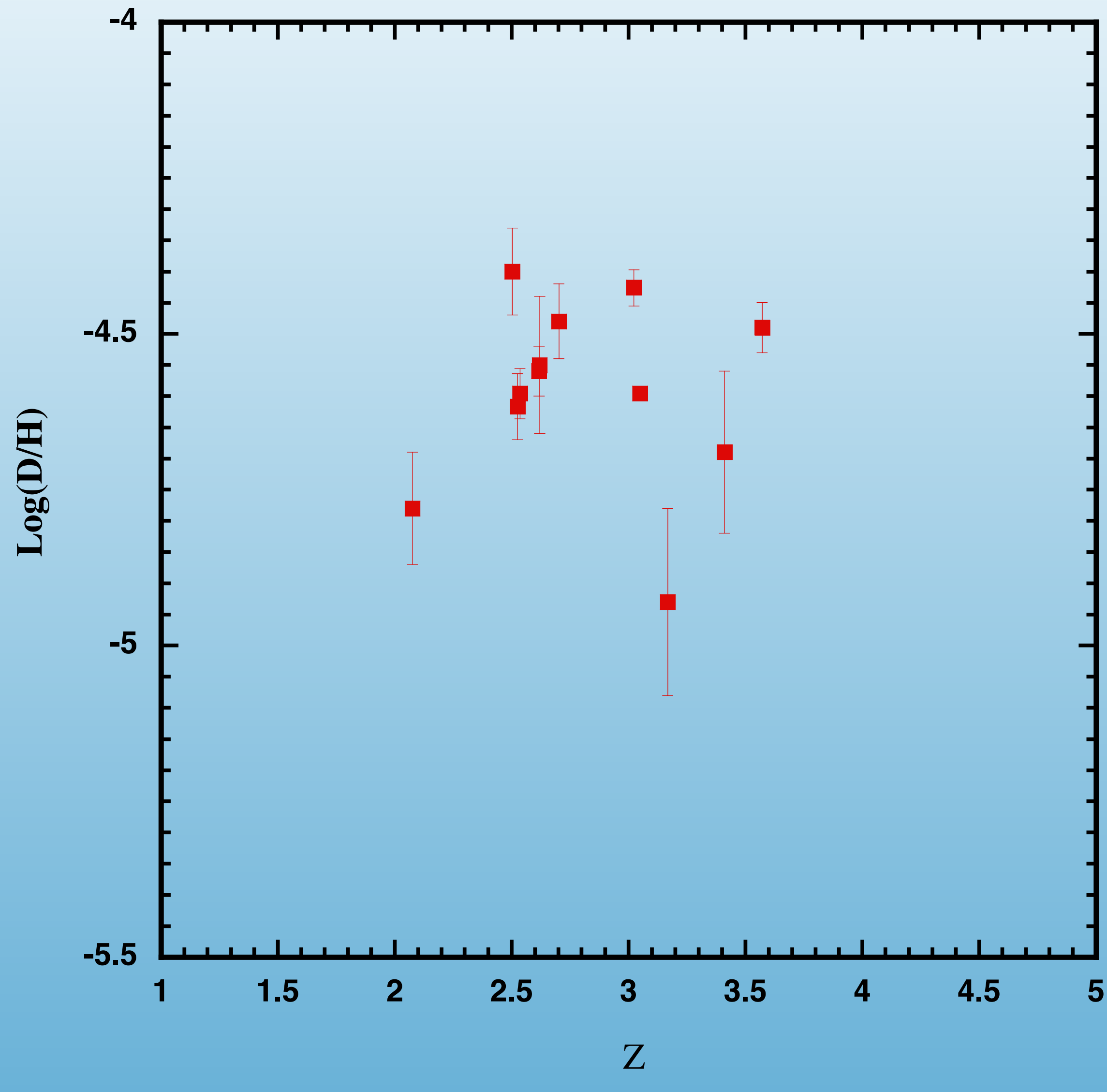
Table 3. PRECISION D/H MEASURES CONSIDERED IN THIS PAPER

QSO	z_{em}	z_{abs}	$\log_{10} N(\mathrm{H\,I})/\mathrm{cm}^{-2}$	[O/H][a]	$\log_{10} N(\mathrm{D\,I})/N(\mathrm{H\,I})$
HS 0105+1619	2.652	2.53651	19.426 ± 0.006	−1.771 ± 0.021	−4.589 ± 0.026
Q0913+072	2.785	2.61829	20.312 ± 0.008	−2.416 ± 0.011	−4.597 ± 0.018
Q1243+307	2.558	2.52564	19.761 ± 0.026	−2.769 ± 0.028	−4.622 ± 0.015
SDSS J1358+0349	2.894	2.85305	20.524 ± 0.006	−2.804 ± 0.015	−4.582 ± 0.012
SDSS J1358+6522	3.173	3.06726	20.495 ± 0.008	−2.335 ± 0.022	−4.588 ± 0.012
SDSS J1419+0829	3.030	3.04973	20.392 ± 0.003	−1.922 ± 0.010	−4.601 ± 0.009
SDSS J1558−0031	2.823	2.70242	20.75 ± 0.03	−1.650 ± 0.040	−4.619 ± 0.026

[a]We adopt the solar value $\log_{10}$ (O/H) + 12 = 8.69 (Asplund et al. 2009).

Cooke et al.

D/H abundances in Quasar absorption systems



BBN Prediction:

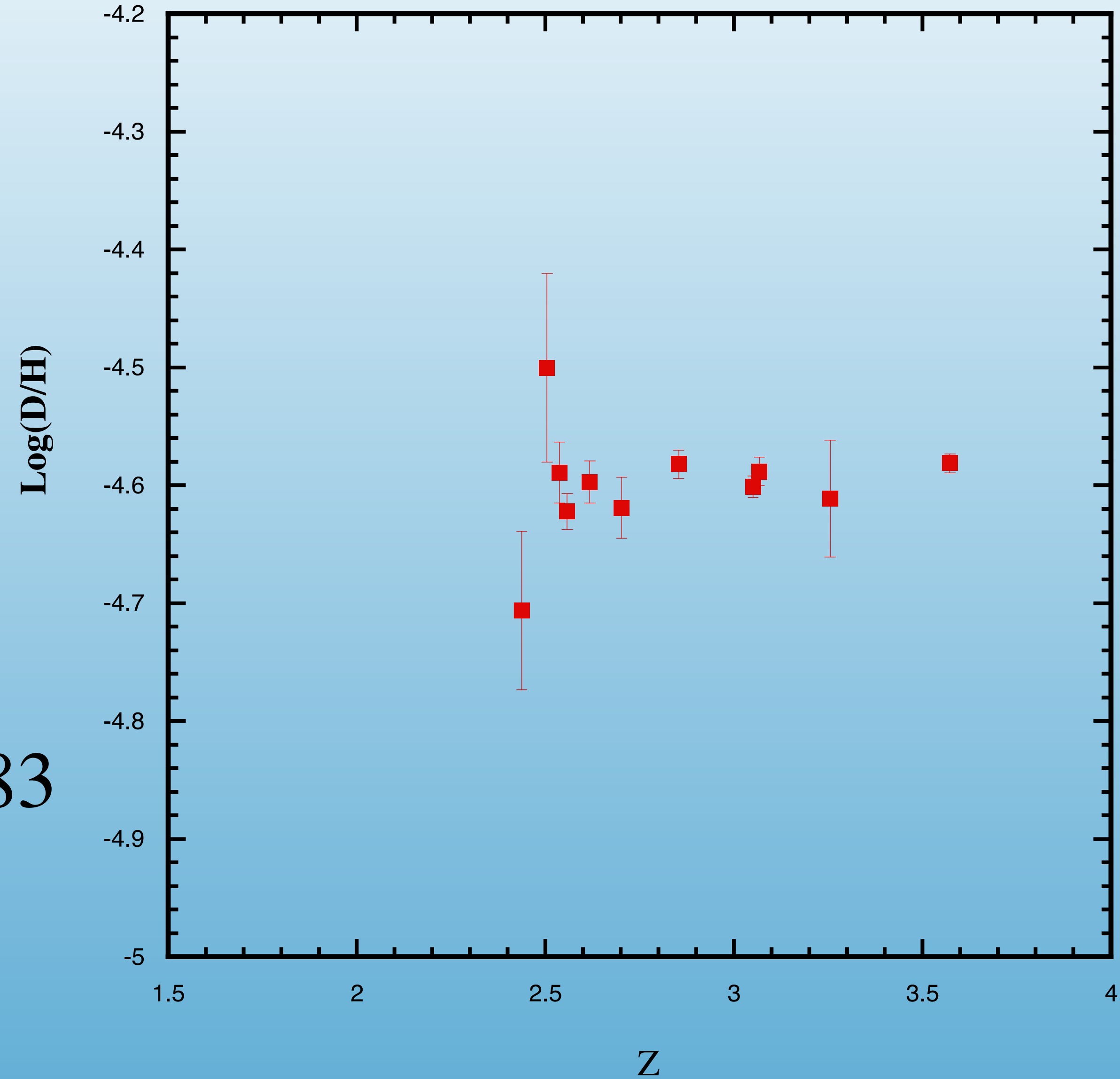
10^5 D/H = 2.58 ± 0.13

Obs Average:

10^5 D/H = 3.01 ± 0.21

(0.68 sample variance)

Updated D/H abundances in Quasar absorption systems



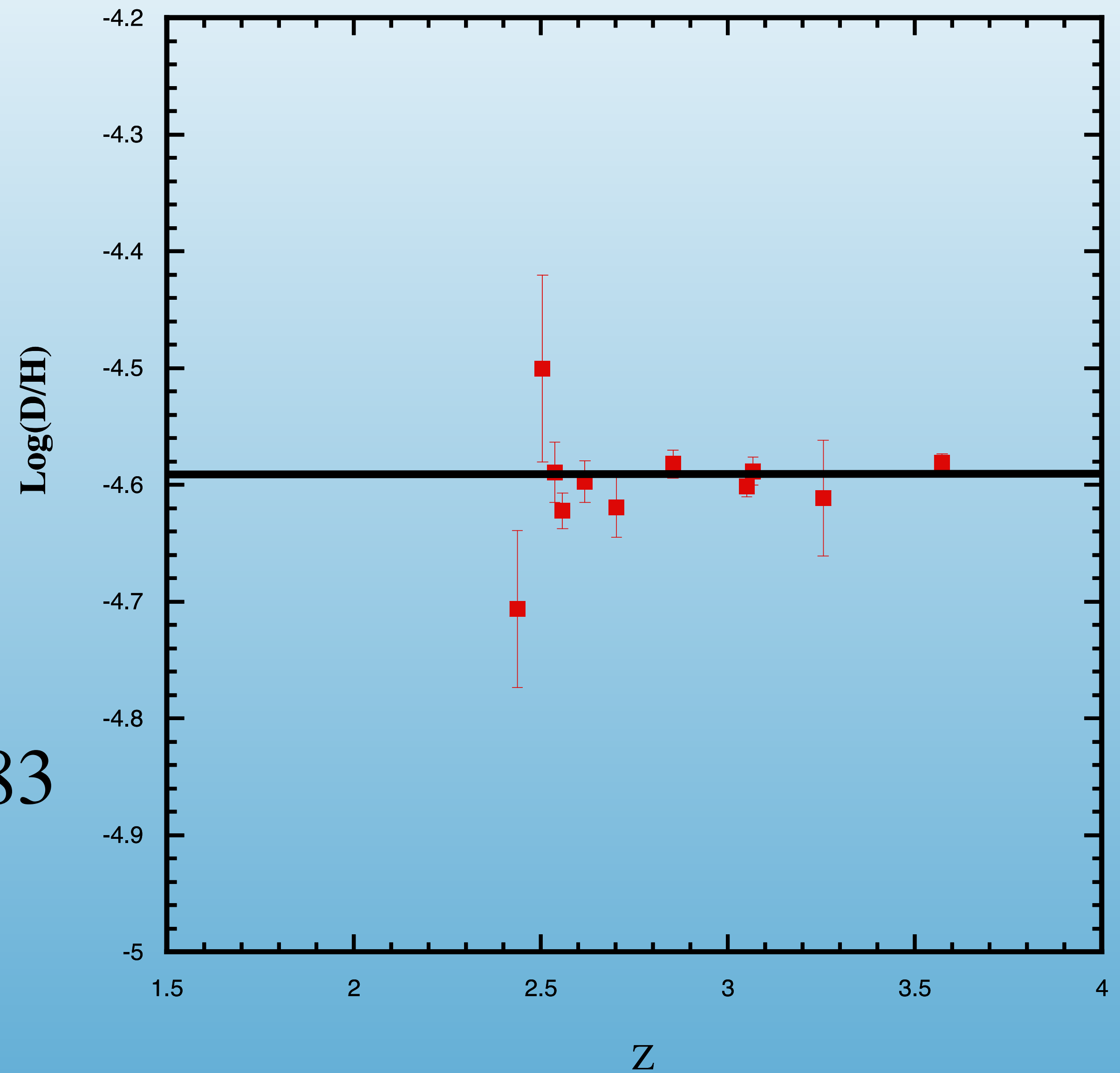
BBN Prediction:

10^5 D/H = 2.506 ± 0.083

Obs Average:

10^5 D/H = 2.55 ± 0.03

Updated
D/H abundances in
Quasar absorption
systems



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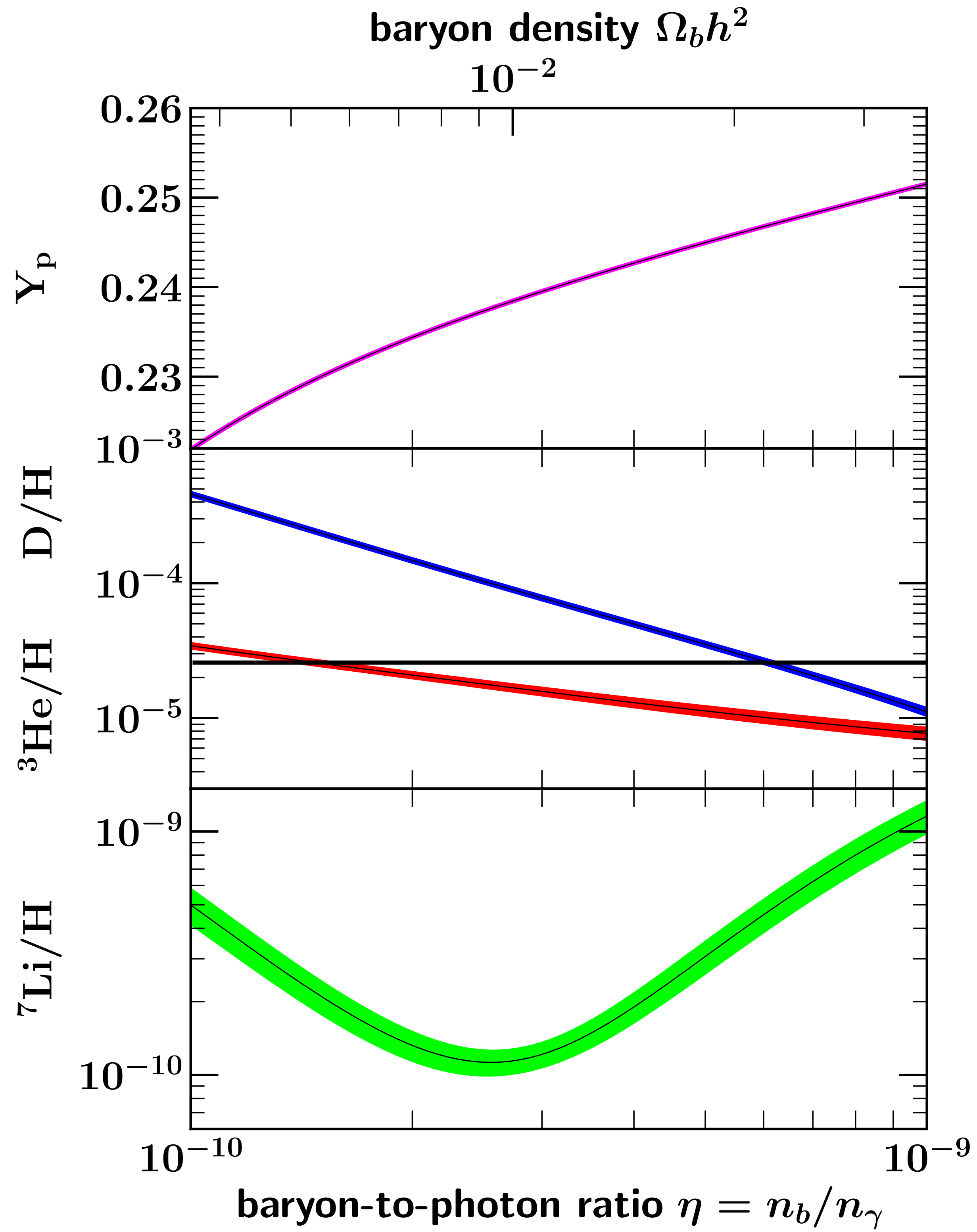
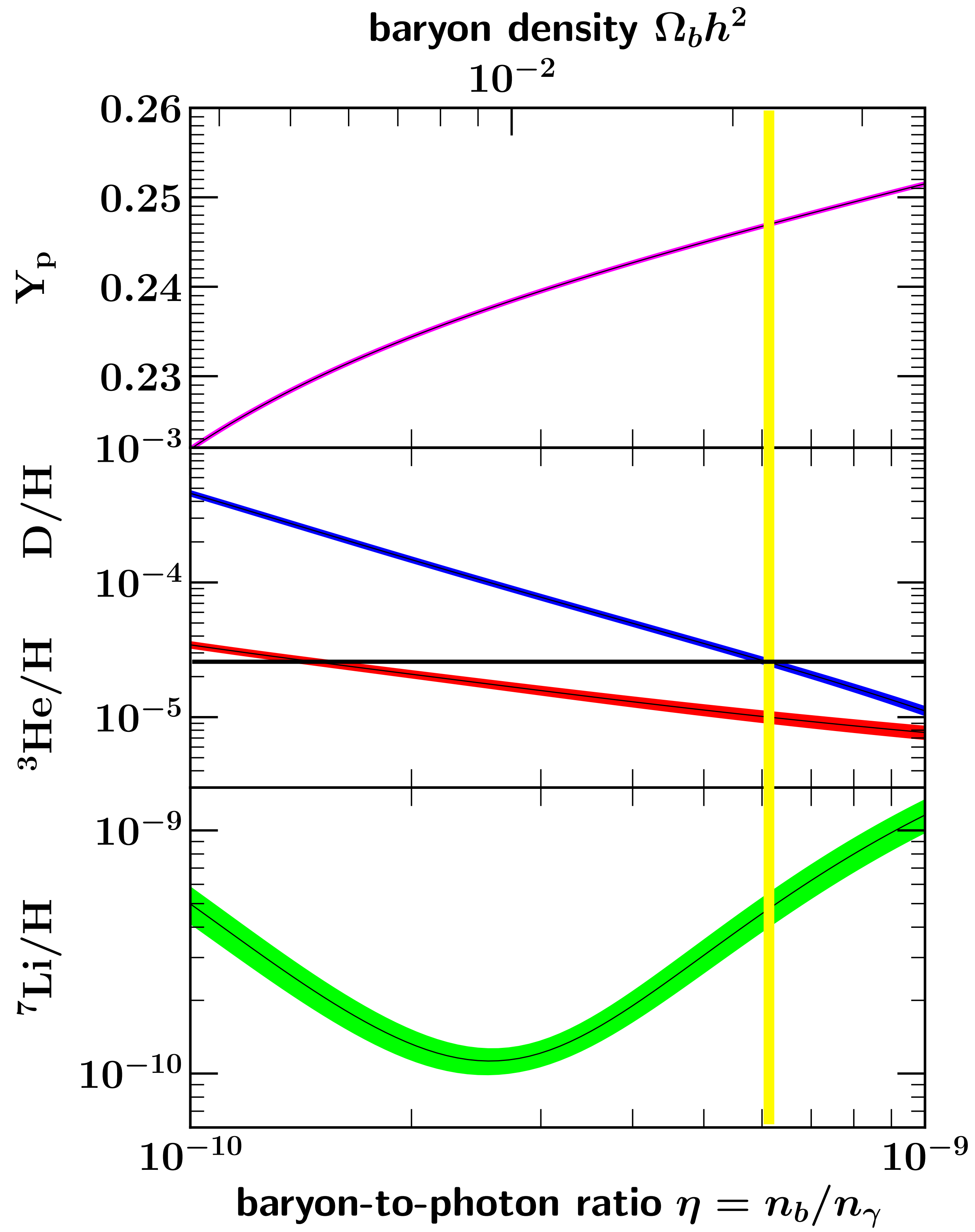
10^5 D/H = 2.506 ± 0.083

Obs Average:
10^5 D/H = 2.55 ± 0.03



Fields, Olive, Yeh, Young

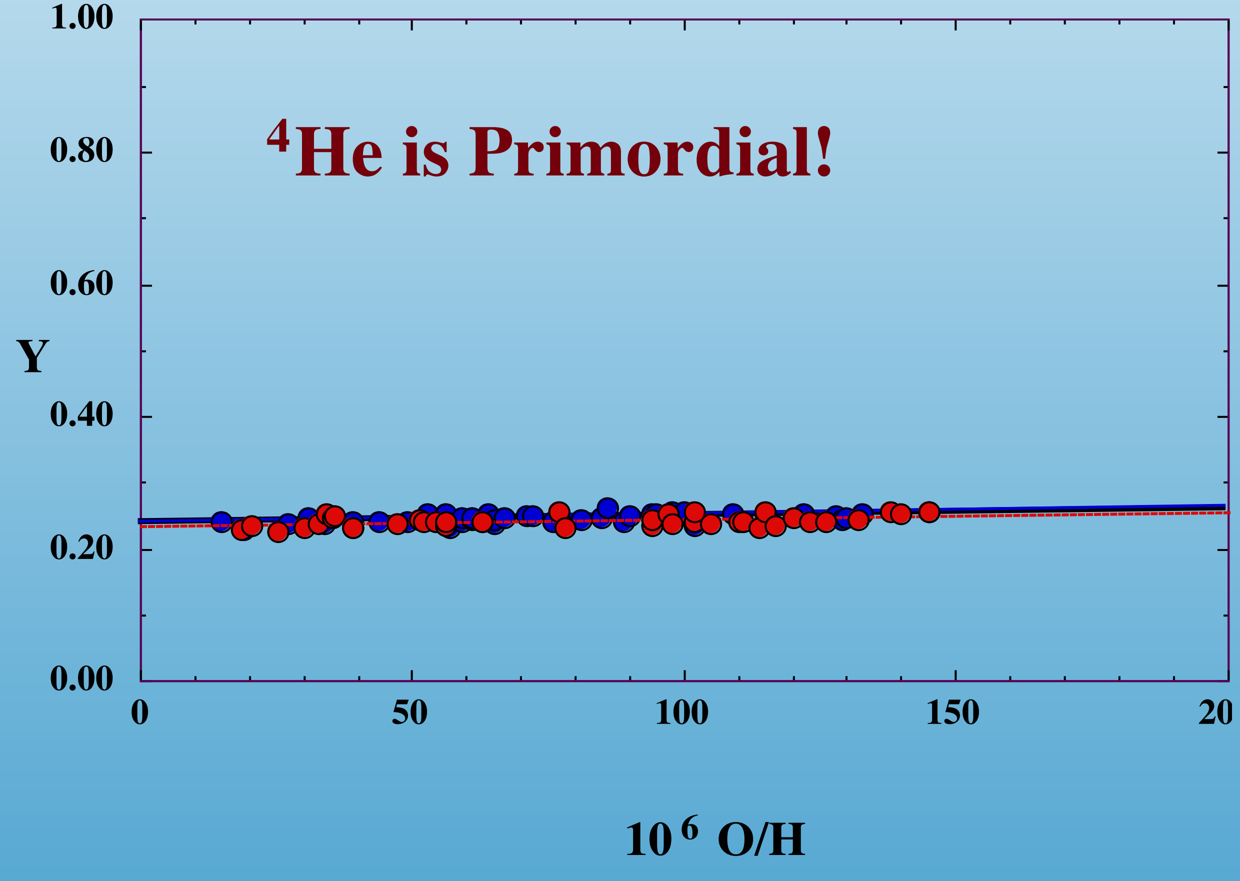


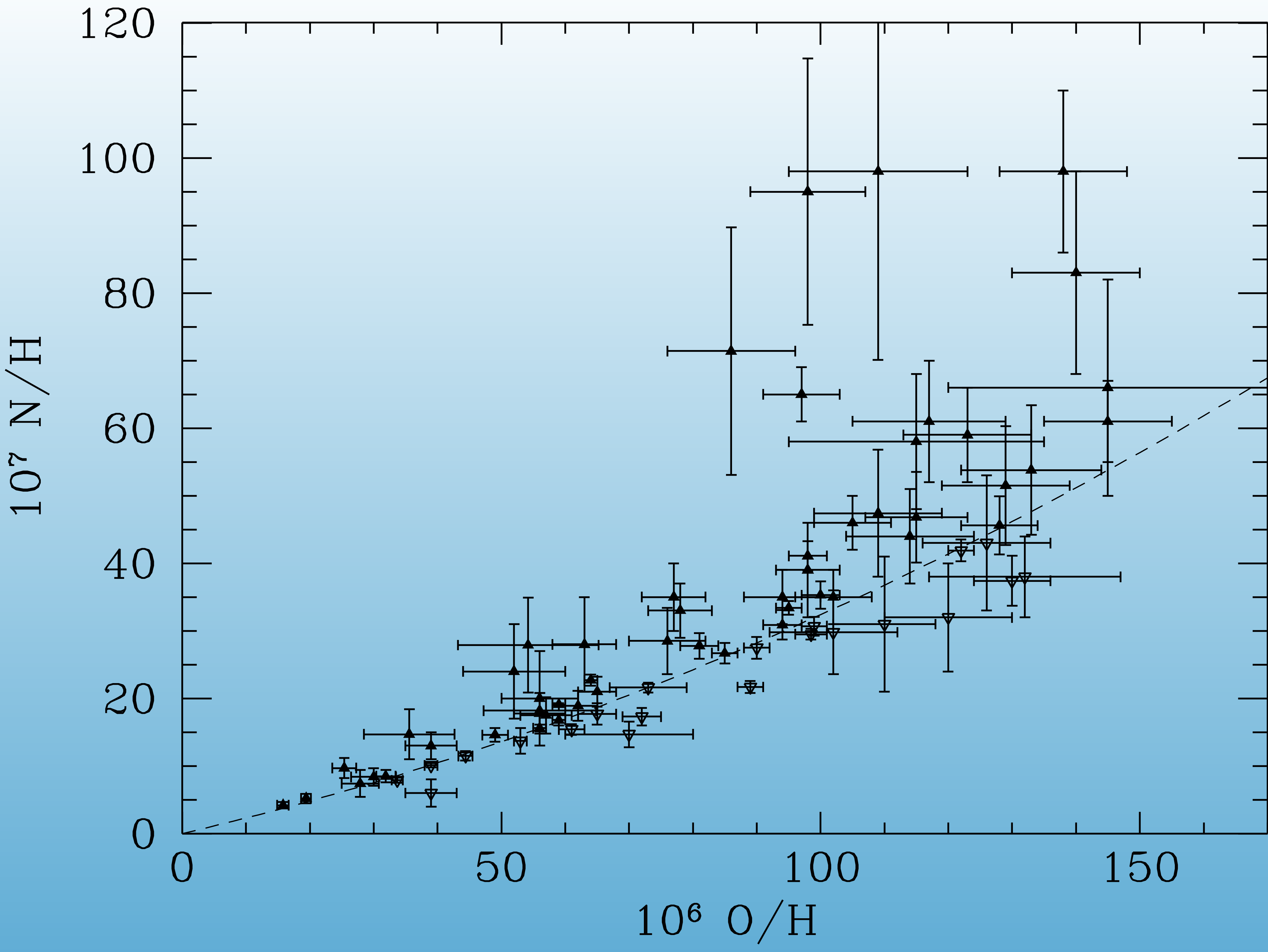
Fields, Olive, Yeh, Young

^4He

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

Systematics

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

$$\frac{F(\lambda)}{F(H\beta)} = y^{+}\frac{E(\lambda)}{E(H\beta)}\frac{\frac{W(H\beta)+a_H(H\beta)}{W(H\beta)}}{\frac{W(\lambda)+a_{He}(\lambda)}{W(\lambda)}} f_{\tau}(\lambda)\frac{1+\frac{C}{R}(\lambda)}{1+\frac{C}{R}(H\beta)}10^{-f(\lambda)C(H\beta)}$$

Systematics

- Interstellar Redding (scattered by dust)
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- Collisional Corrections

$$\frac{F(\lambda)}{F(H\beta)} = y^{+} \frac{E(\lambda)}{E(H\beta)} \frac{\frac{W(H\beta)+a_H(H\beta)}{W(H\beta)}}{\frac{W(\lambda)+a_{He}(\lambda)}{W(\lambda)}} f_{\tau}(\lambda) \frac{1+\frac{C}{R}(\lambda)}{1+\frac{C}{R}(H\beta)} 10^{-f(\lambda)C(H\beta)}$$

Calculate fluxes rather than y

$$(\mathrm{y}^{+}, \mathrm{n}_e, \mathrm{a}_{He}, \tau, \mathrm{T}, \mathrm{C}(\mathrm{H}\beta), \mathrm{a}_H, \xi)$$

Parameters now inlcude y

$$\chi^2 = \sum_{\lambda} \frac{\left(\frac{F(\lambda)}{F(H\beta)} - \frac{F(\lambda)}{F(H\beta)}_{\mathrm{meas}}\right)^2}{\sigma(\lambda)^2}$$

8 parameters; 9 observations

Improvements

New emissivities

Aver, Olive, Porter, Skillman
2013

Adding new He line

7 He, 3 H lines to fit 8 parameters

Izotov, Thuan, Guseva

Aver, Olive, Skillman
2015

Adding new H and He lines

Add 2 He, and 9 H lines (H9-12, and P8-12)

For a total of 21 observables to fit 9 parameters (a_P added).

Aver, Berg, Olive, Pogge, Salzer, Skillman
2021

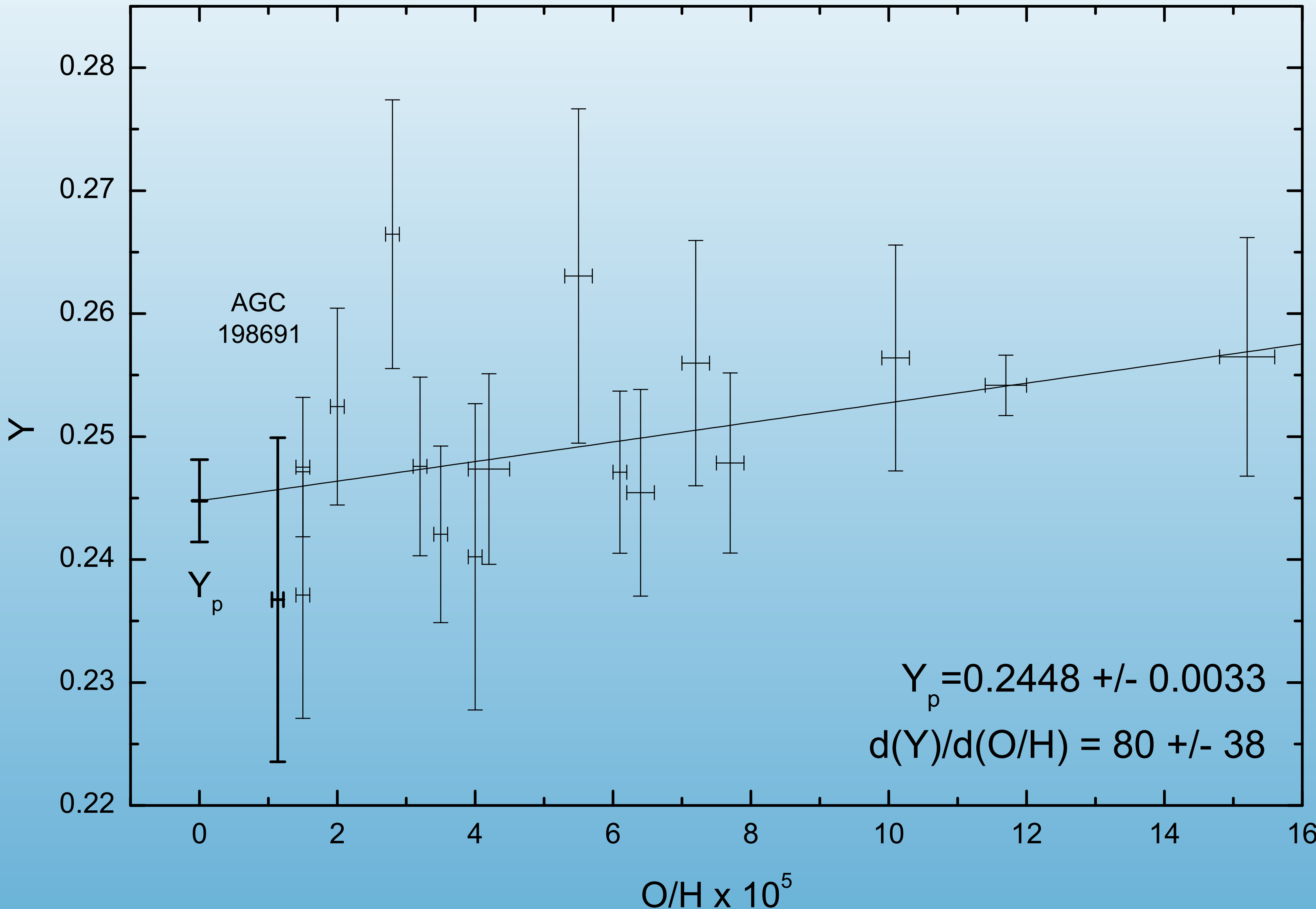
Applied to Leo P

Aver, Berg, Olive, Pogge,
Salzer, Skillman

	Skillman et al. [66]	This Work
Emission lines	9	21
Free Parameters	8	9
d.o.f.	1	12
95% CL χ^2	3.84	21.03
He^+/H^+	$0.0837^{+0.0084}_{-0.0062}$	$0.0823^{+0.0025}_{-0.0018}$
n_e [cm^{-3}]	1^{+206}_{-1}	39^{+12}_{-12}
a_{He} [Å]	$0.50^{+0.42}_{-0.42}$	$0.42^{+0.11}_{-0.15}$
τ	$0.00^{+0.66}_{-0.00}$	$0.00^{+0.13}_{-0.00}$
T_e [K]	$17{,}060\ ^{+1900}_{-2900}$	$17{,}400\ ^{+1200}_{-1400}$
C(Hβ)	$0.10^{+0.03}_{-0.07}$	$0.10^{+0.02}_{-0.02}$
a_H [Å]	$0.94^{+1.44}_{-0.94}$	$0.51^{+0.17}_{-0.18}$
a_P [Å]	-	$0.00^{+0.52}_{-0.00}$
$\xi \times 10^4$	0^{+156}_{-0}	0^{+7}_{-0}
χ^2	3.3	15.3
p-value	7%	23%
O/H $\times 10^5$	1.5 ± 0.1	1.5 ± 0.1
Y	0.2509 ± 0.0184	0.2475 ± 0.0057

13.7 for 68%

Most recent addition: AGC 198691 (2021)

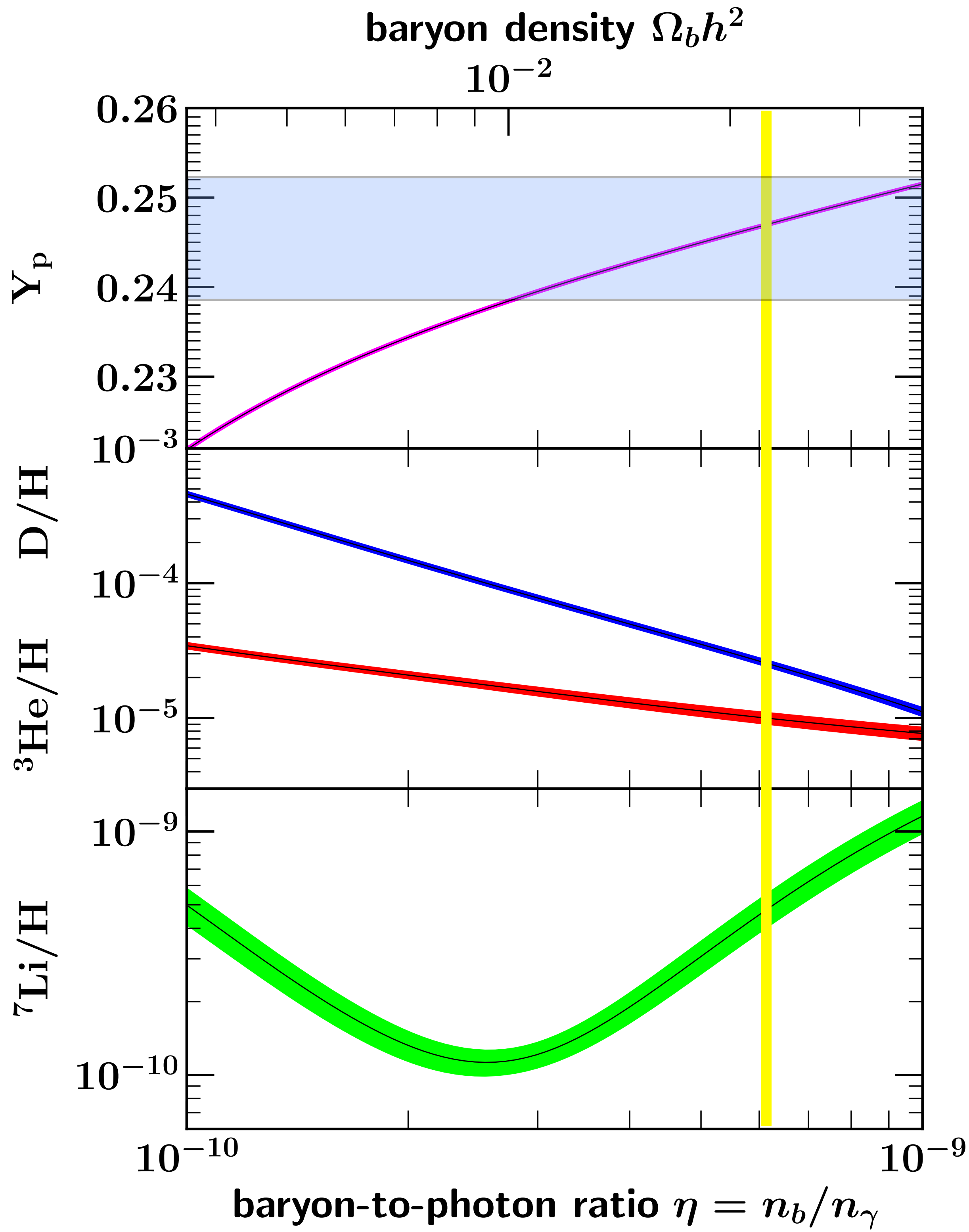


Aver, Berg, Hirschauer, Olive, Pogge, Rogers, Salzer, Skillman

prior: $Y_P = .2453 \pm 0.0034$

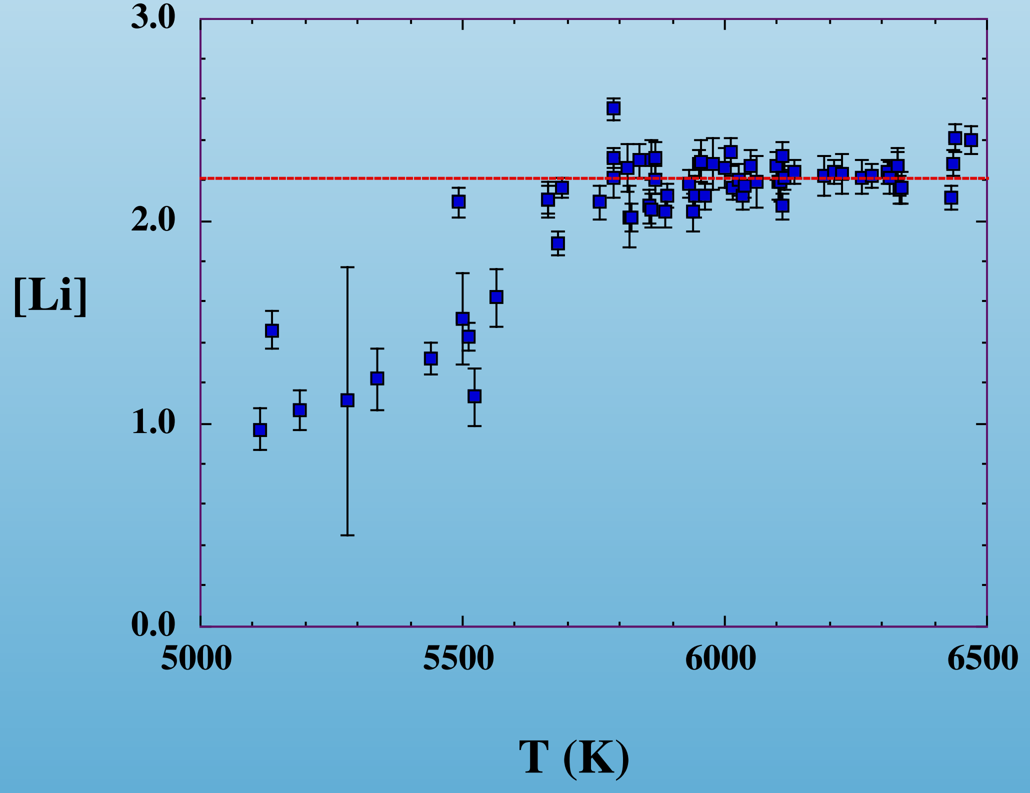
^{4}He Prediction:
0.2467 ± 0.0002

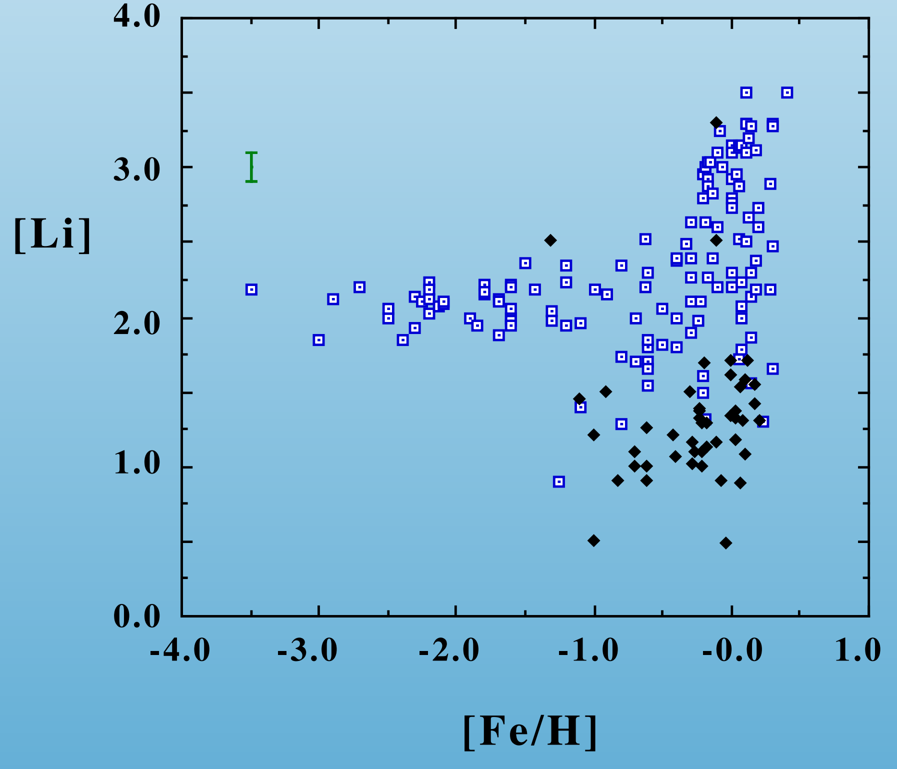
Data: Regression:
0.2448 ± 0.0033

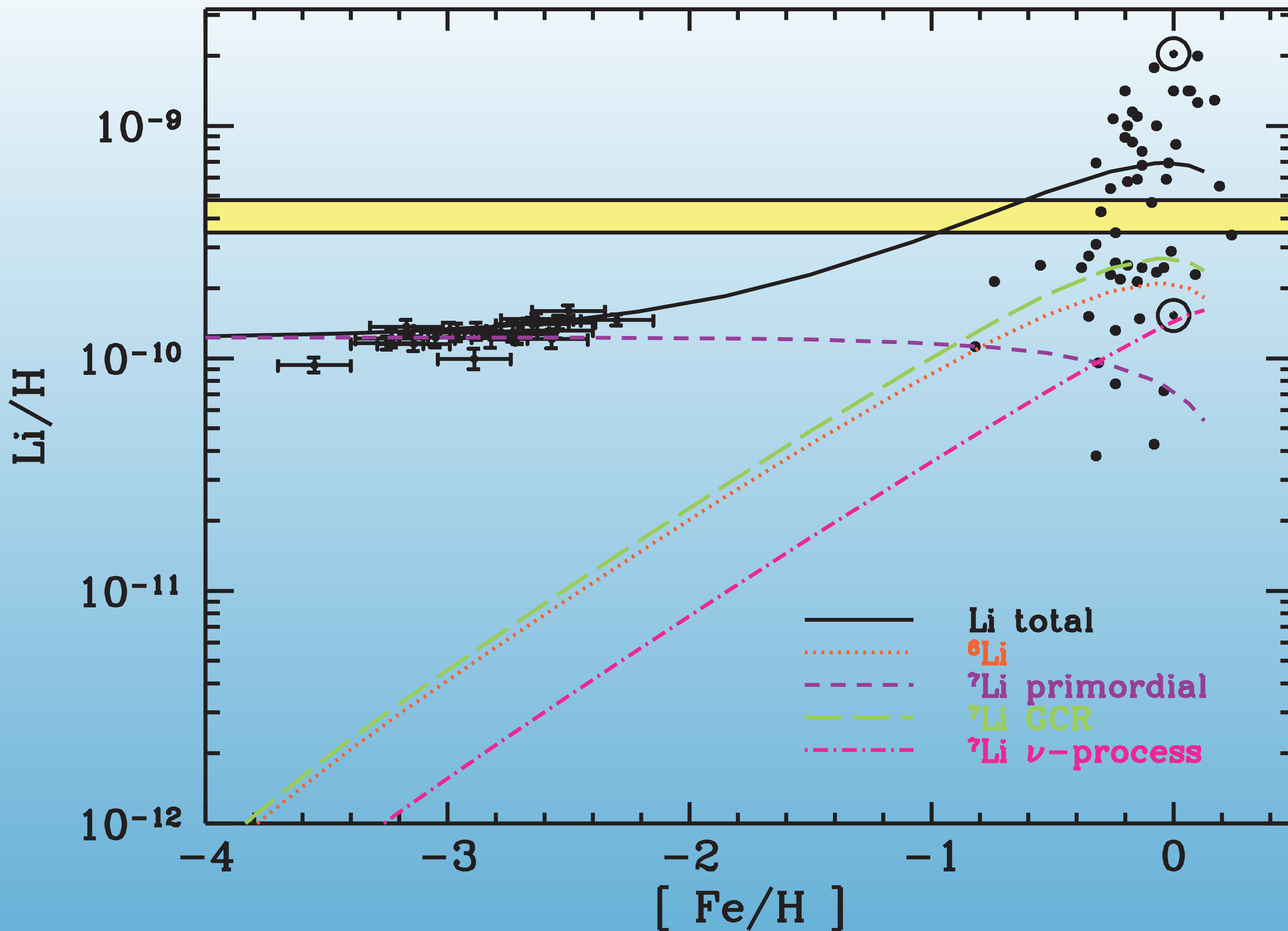


Li/H

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







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

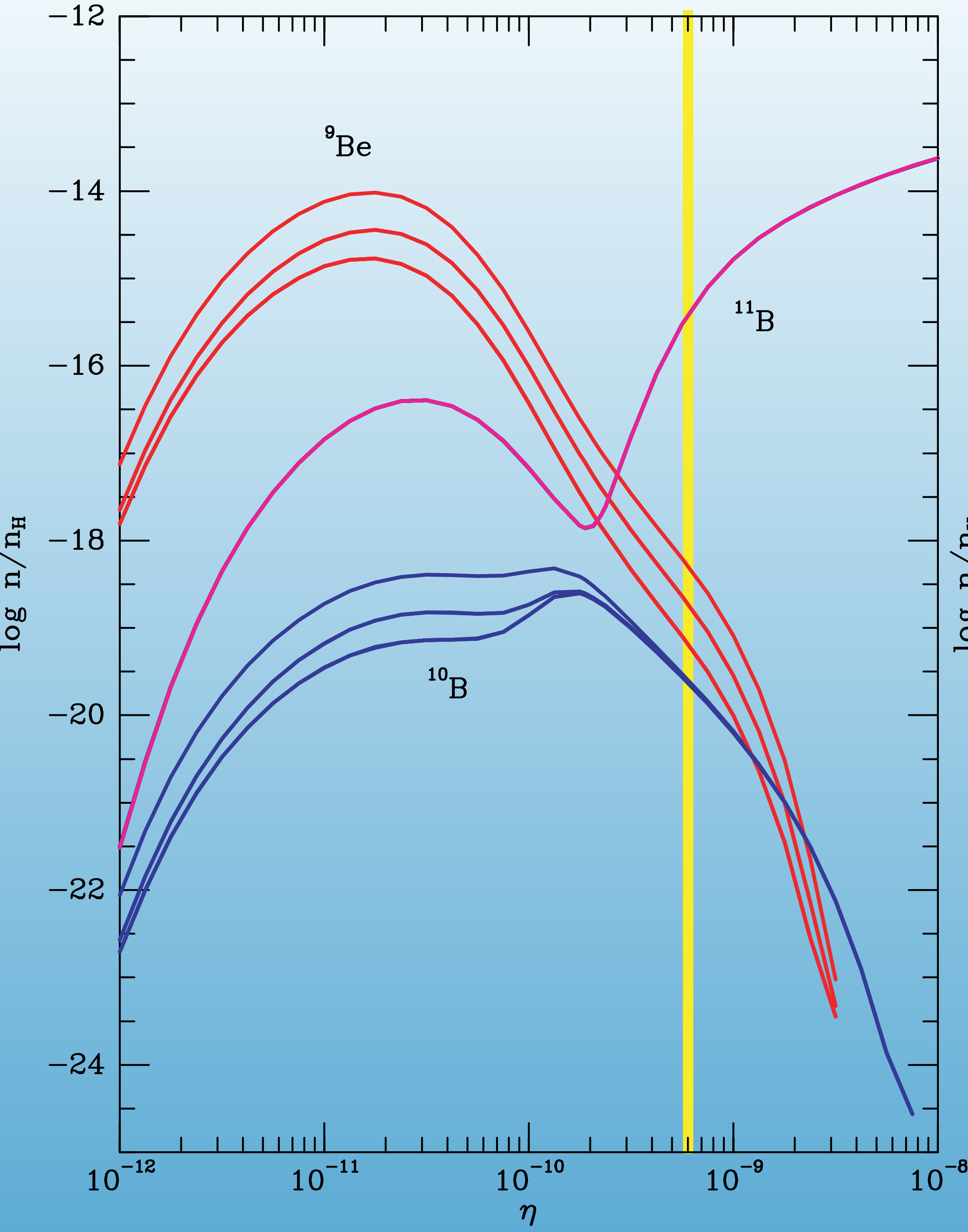
Possible sources for the discrepancy

- Nuclear Rates/Resonant reactions
- Stellar parameters
- Stellar Depletion

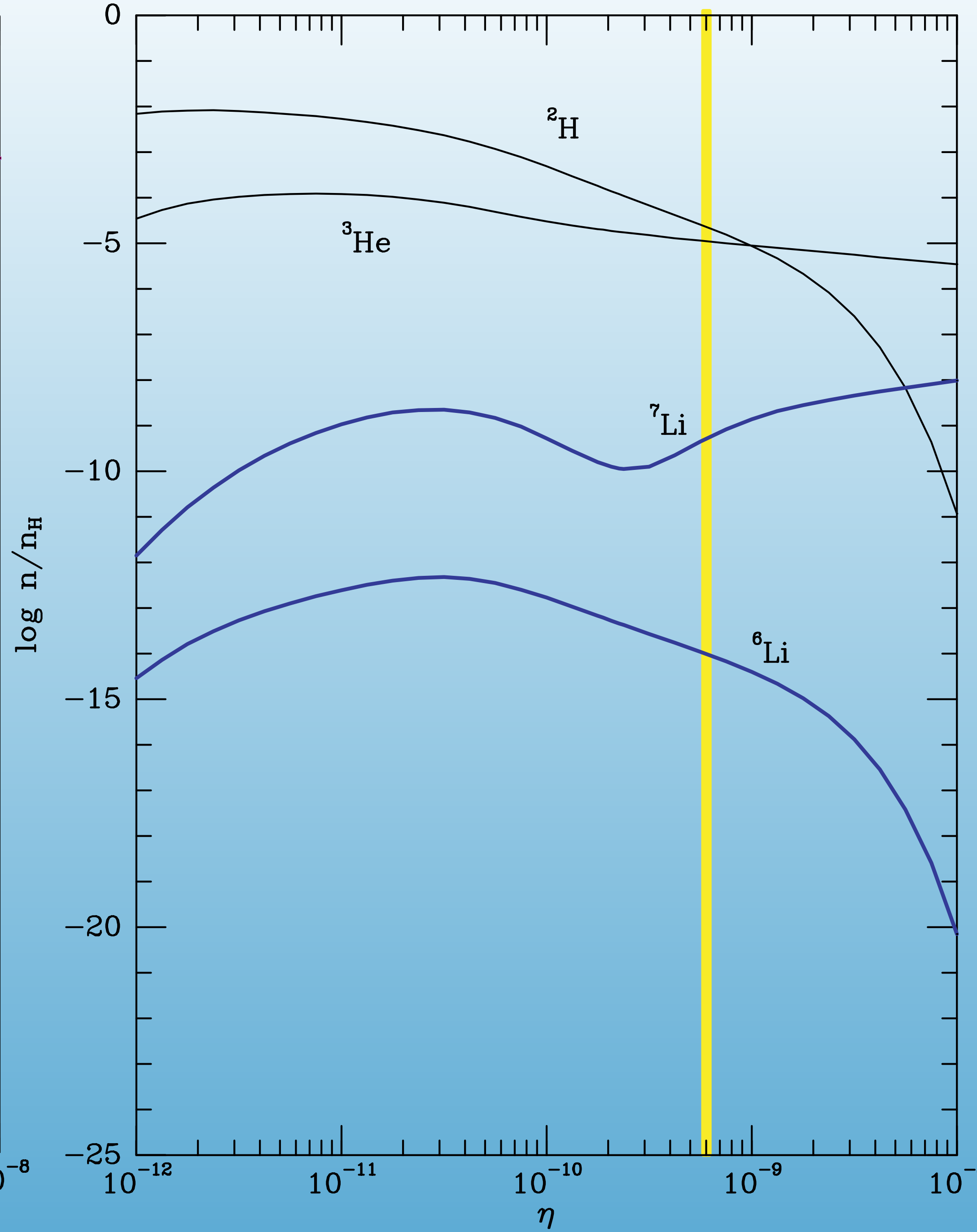
- Decaying Particles
- Axion Cooling
- Variable Constants

Arguments against stellar depletion

- Lack of dispersion in the plateau
- Observation of ^{6}Li



-12
-14
-16
-18
-20
-22
-24
log n/n_H
^{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
10^-12
10^-11
10^-10
10^-9
η

^{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

^{6}Li

In the happy but distant past:

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

$$\mathbf{HD\ 84937:\ ^6Li/Li = 0.054 \pm 0.011}$$
$$\mathbf{BD}\ 26^o3578\mathbf{:\ ^6Li/Li = 0.05 \pm 0.03}$$

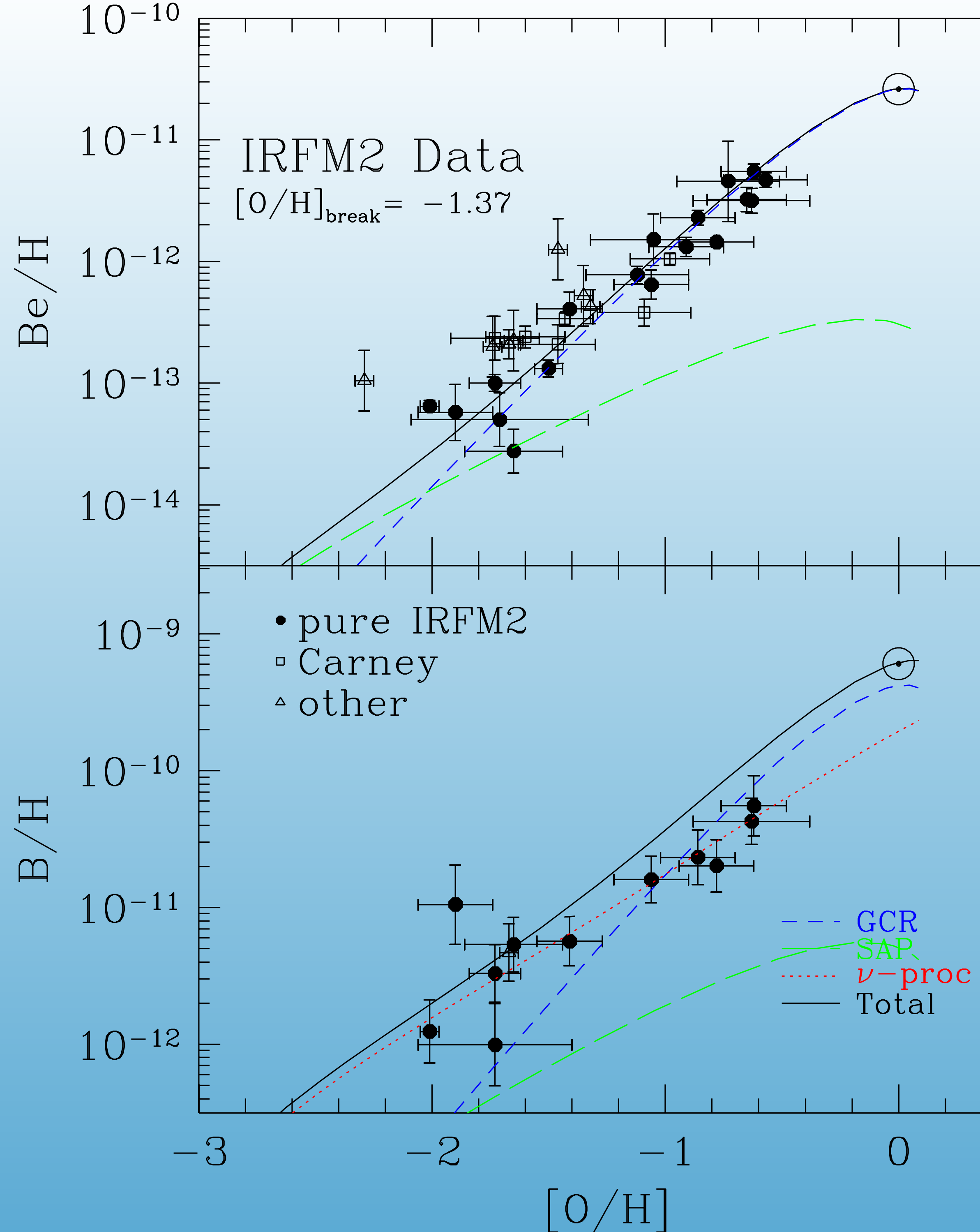
SLN

Hobbs & Thorburn

Cayrel etal

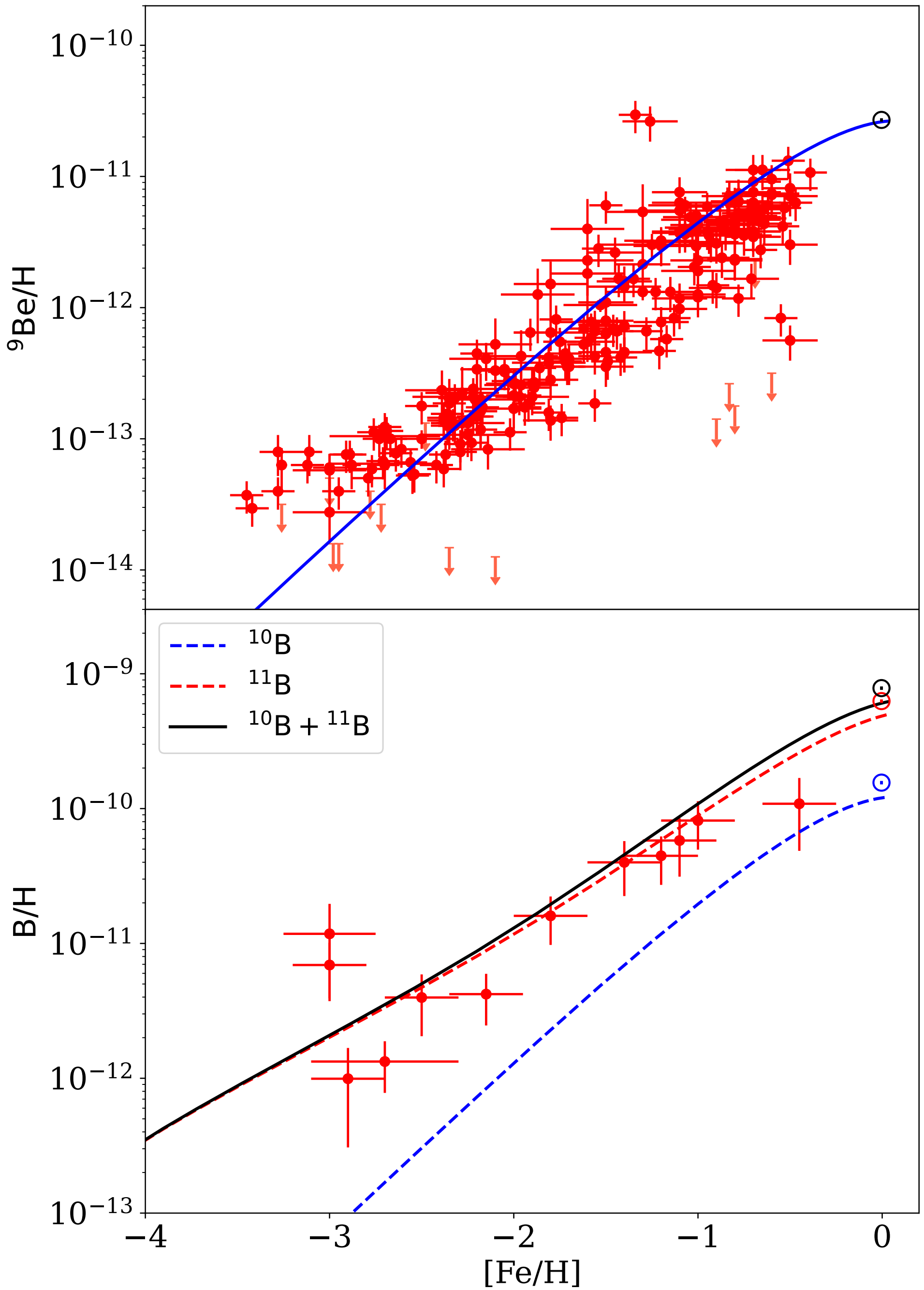
cf. BBN abundance of about ^{6}Li/H = 10^{-14}

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



GCRN production of Be and B including primary and secondary sources

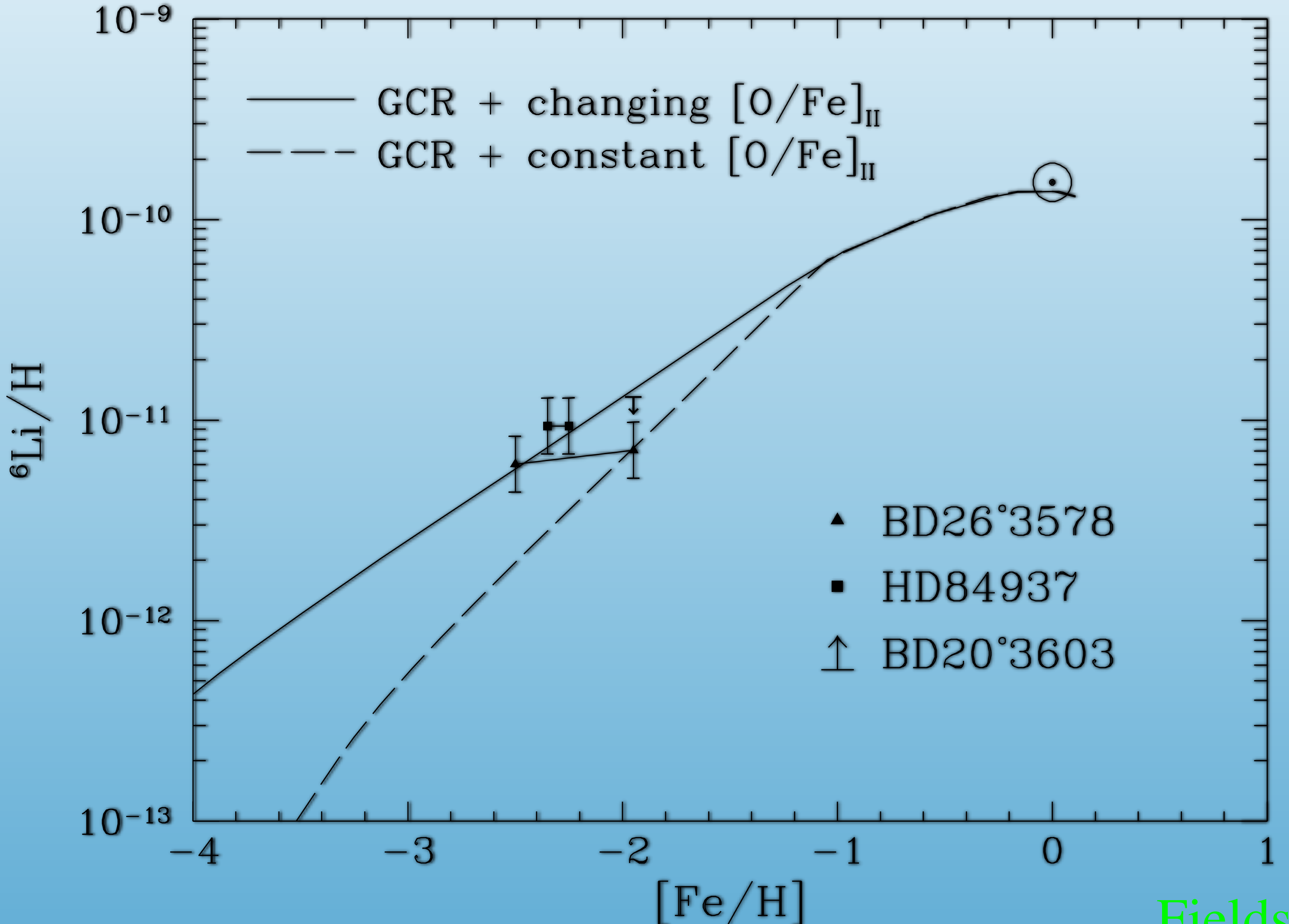
Fields & Olive



GCRN production of Be and B including primary and secondary sources

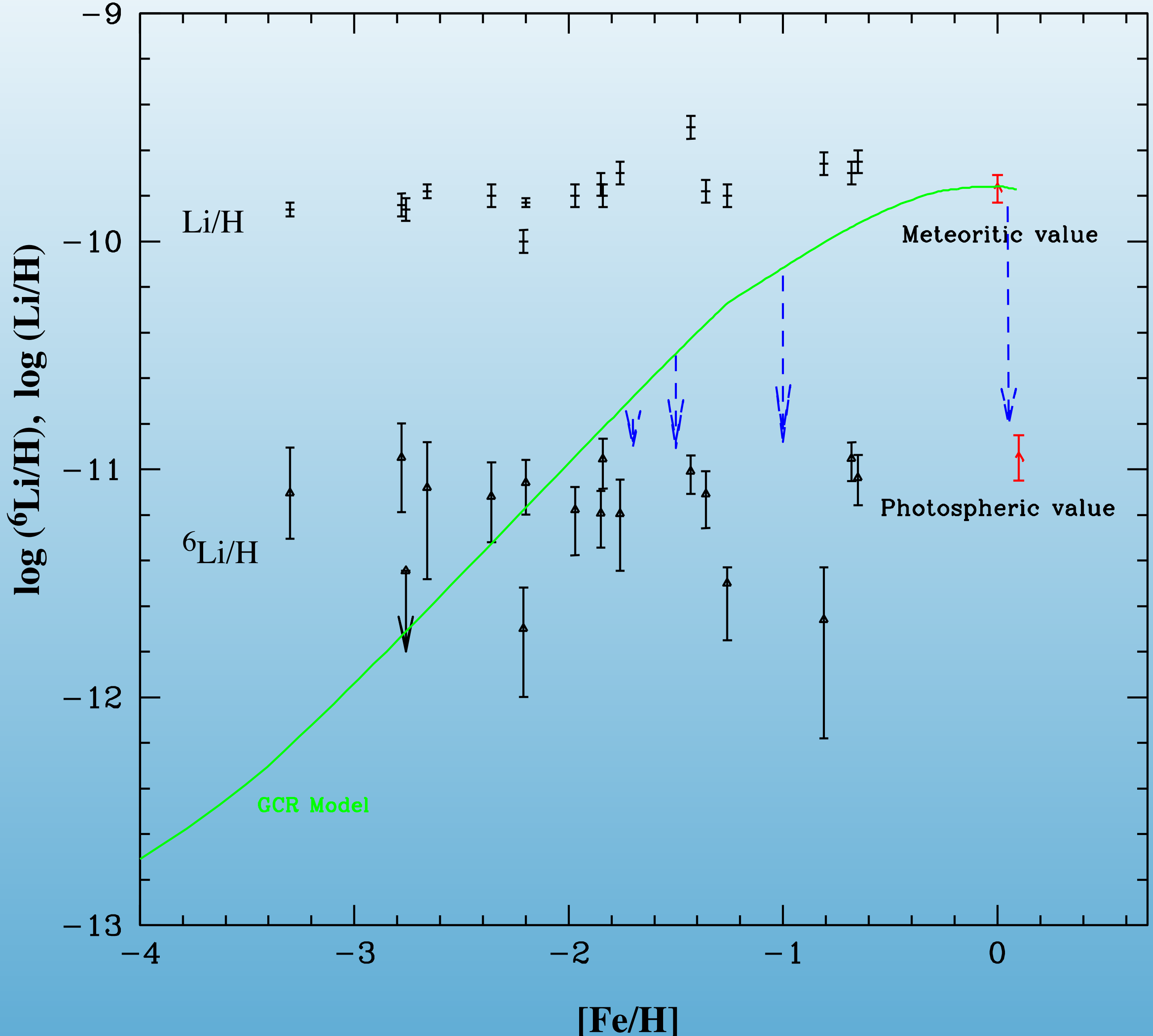
Fields & Olive

These data nicely accounted for by Galactic Cosmic Ray Nucleosynthesis



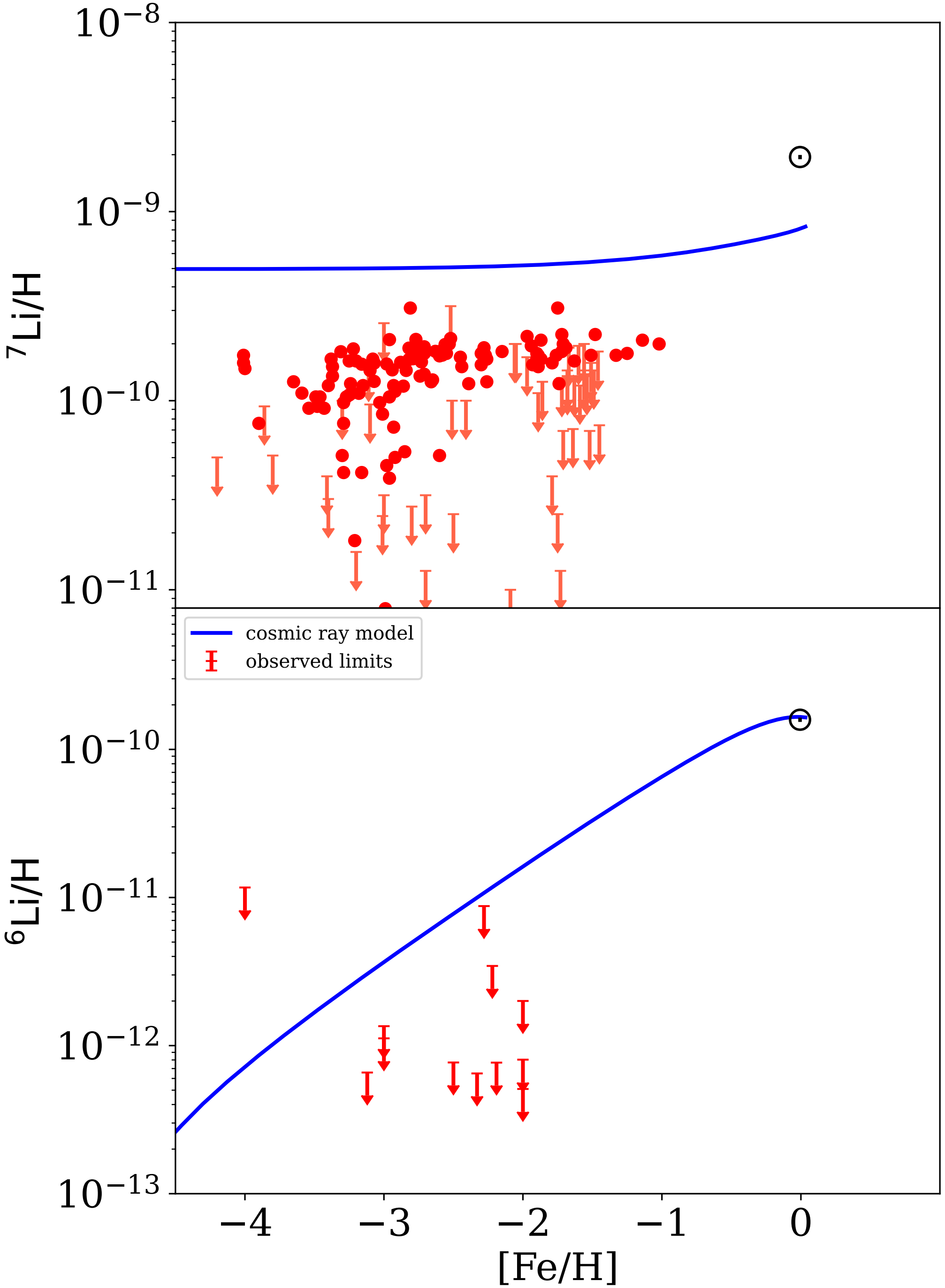
Fields and Olive
Vangioni et al.

a ^{6}Li plateau?



Data from Asplund et al and Inoue

Both ^{6}Li and ^{7}Li appear to be destroyed



Fields & Olive

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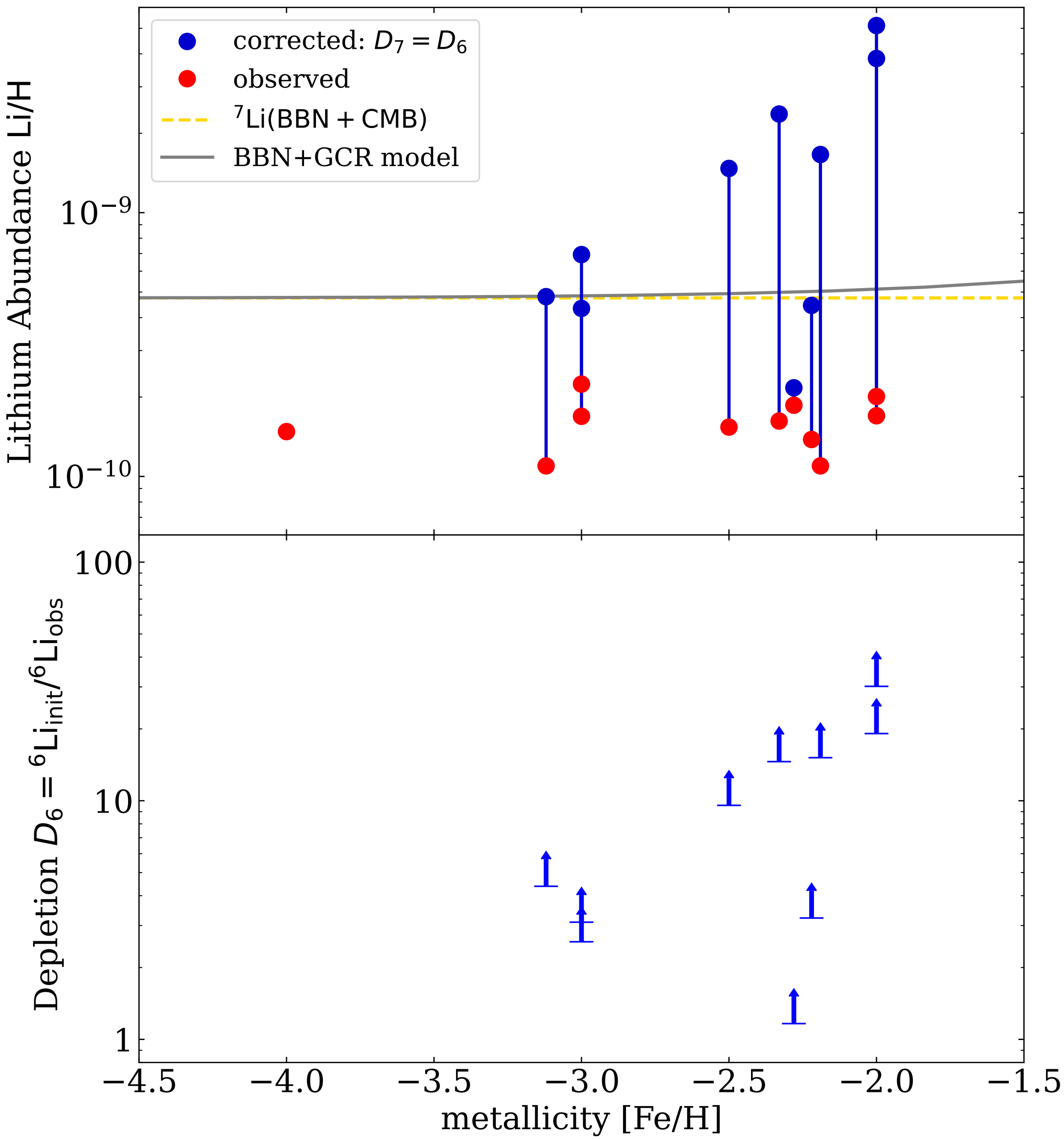
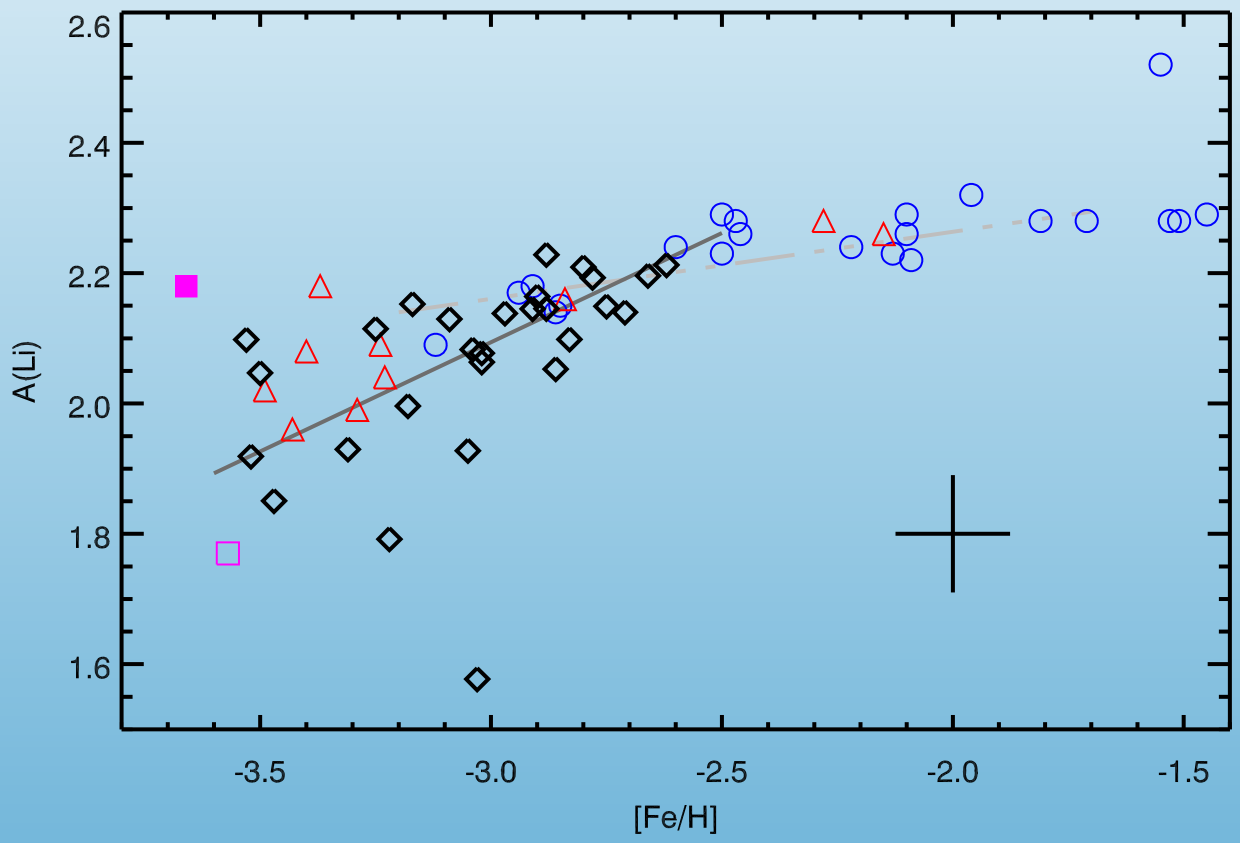


Implied Depletion

Fields & Olive

Broken Spite plateau

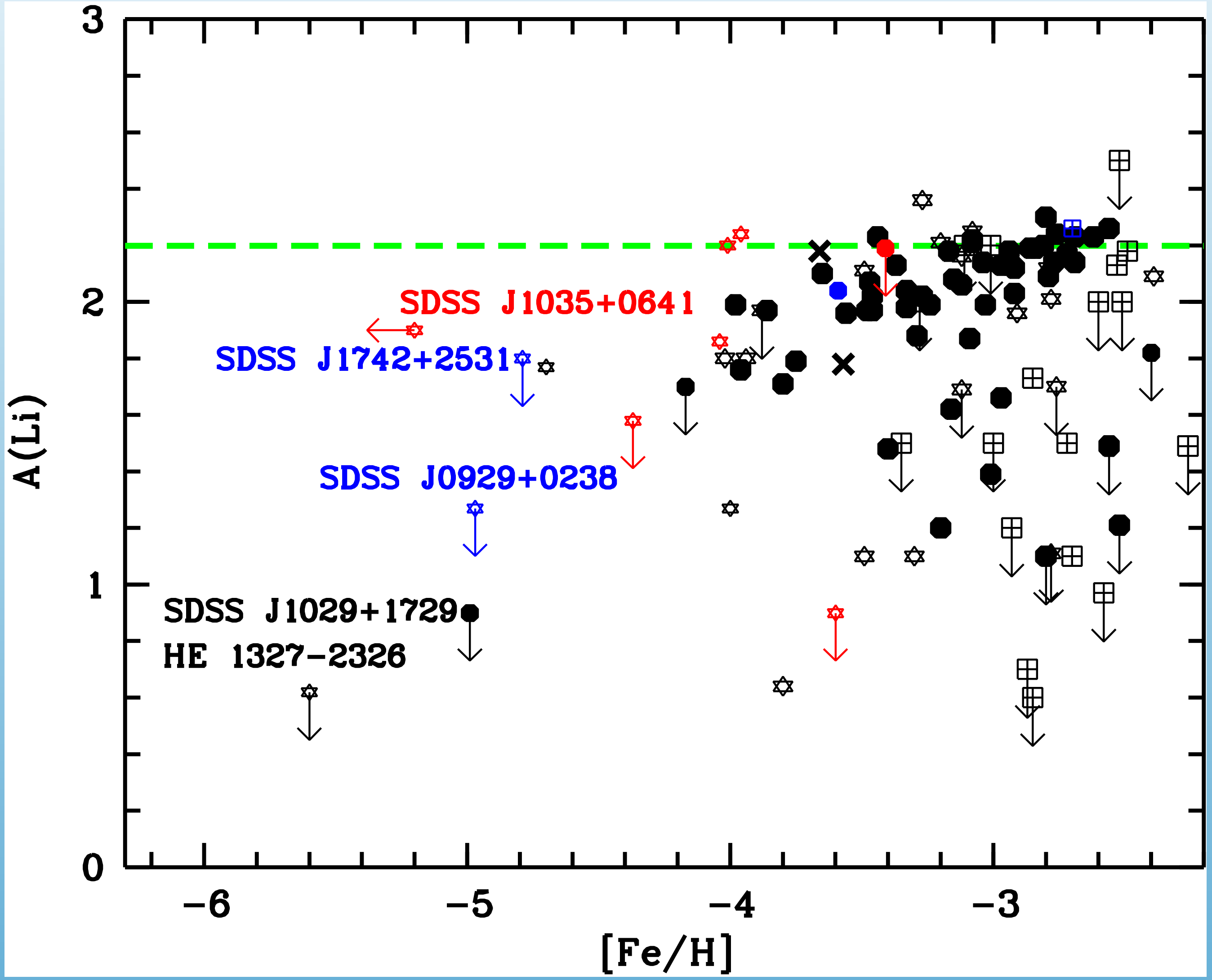
Note significant dispersion



Sbordone et al. (2010)

Broken Spite plateau

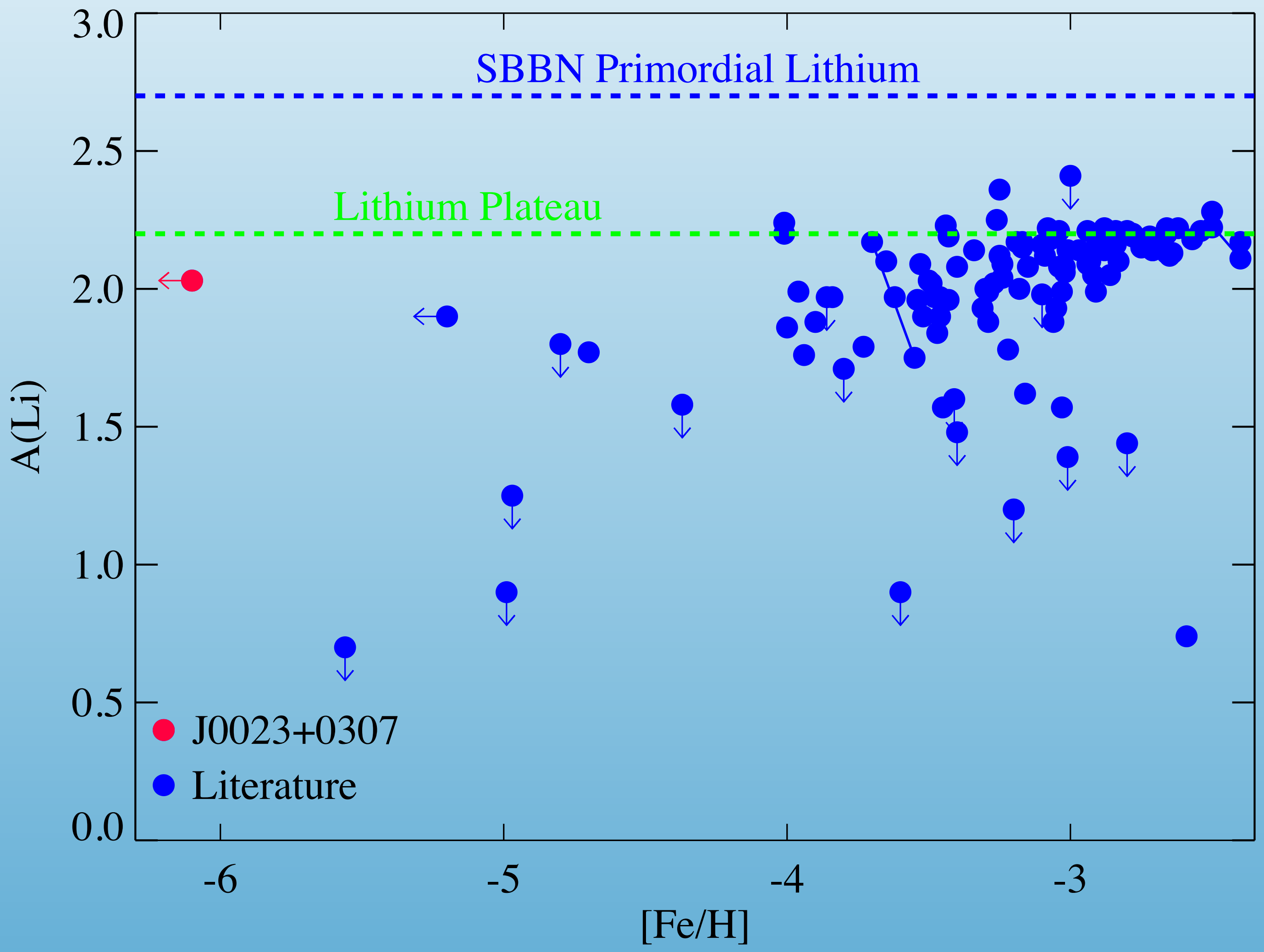
Note significant dispersion



Bonifacio et al. (2018)

Broken Spite plateau

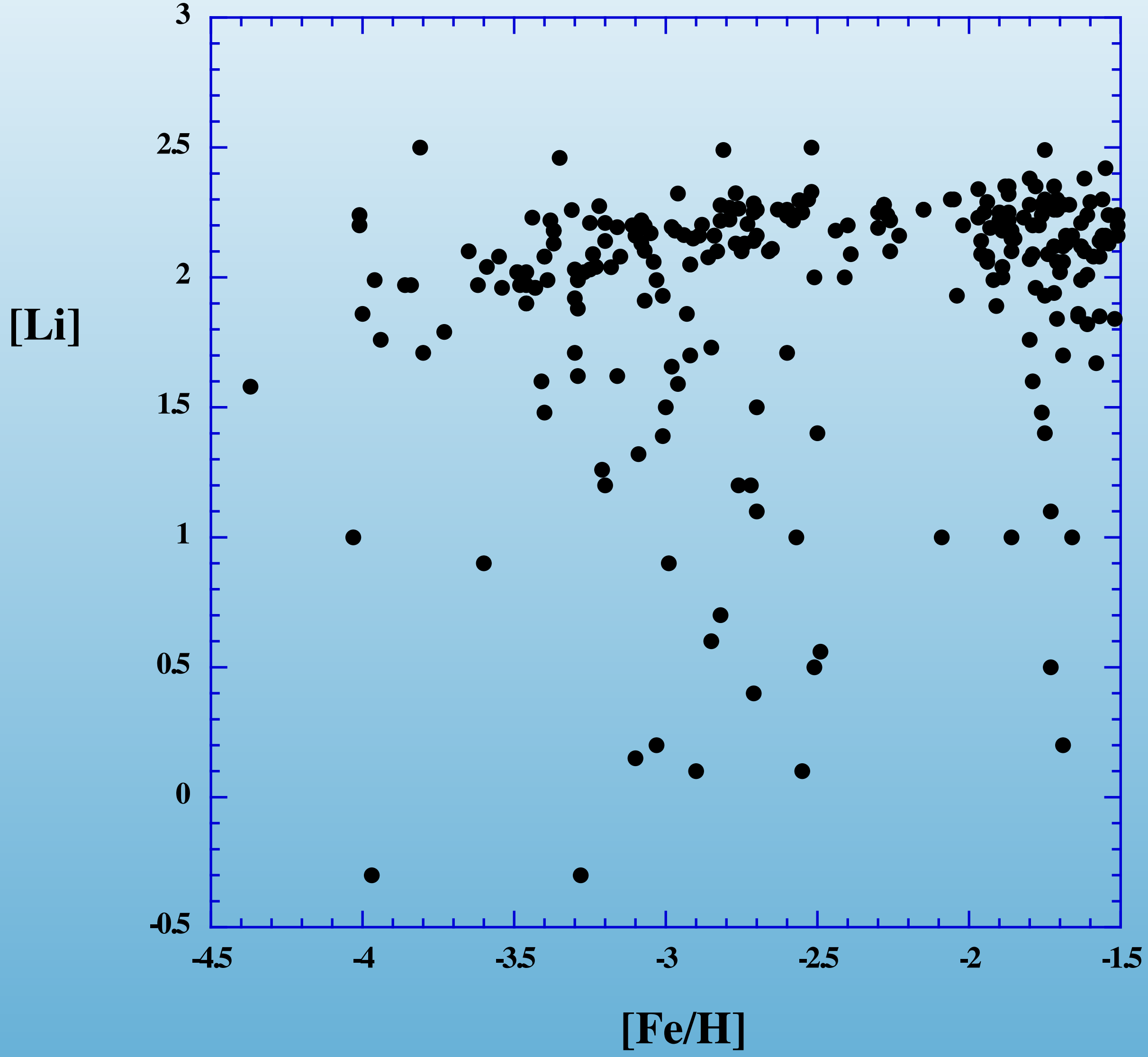
Note significant dispersion



Aguado et al. (2019)

Broken Spite plateau

Note significant dispersion



Maybe NO Li Problem

BBN and the CMB

Convolved Likelihoods

From Planck:

$$\mathcal{L}_{\rm CMB}(\eta, Y_p)$$

$$\mathcal{L}_{\rm NCMB}(\eta, Y_p, N_\nu)$$

$$\omega_b = 0.022212 \pm 0.000242$$

$$\omega_b = 0.022305 \pm 0.000225$$

$$N_{\rm eff} = 2.7542 \pm 0.3064$$

$$Y_p = 0.25003 \pm 0.01367$$

$$Y_p = 0.26116 \pm 0.01812$$

Cyburt, Fields, Olive, Yeh

From Planck 2018:

$$\omega_{\rm b}^{\rm CMB} = 0.022298 \pm 0.000200$$

$$\omega_{\rm b}^{\rm CMB} = 0.022242 \pm 0.000221$$

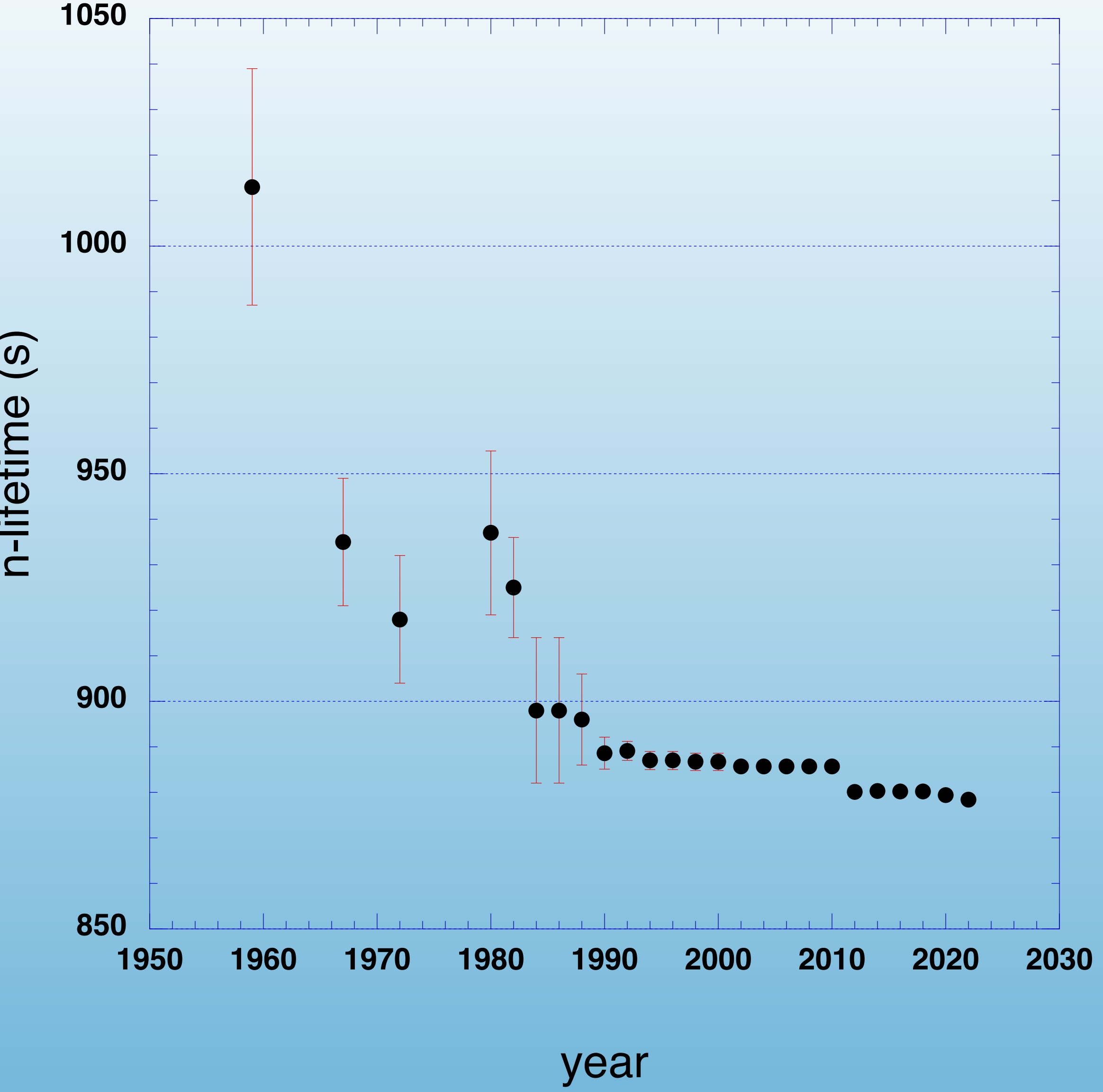
$$Y_{p,\rm CMB} = 0.247 \pm 0.018$$

$$Y_p = 0.239 \pm 0.013$$

$$N_{\rm eff} = 2.841 \pm 0.298$$

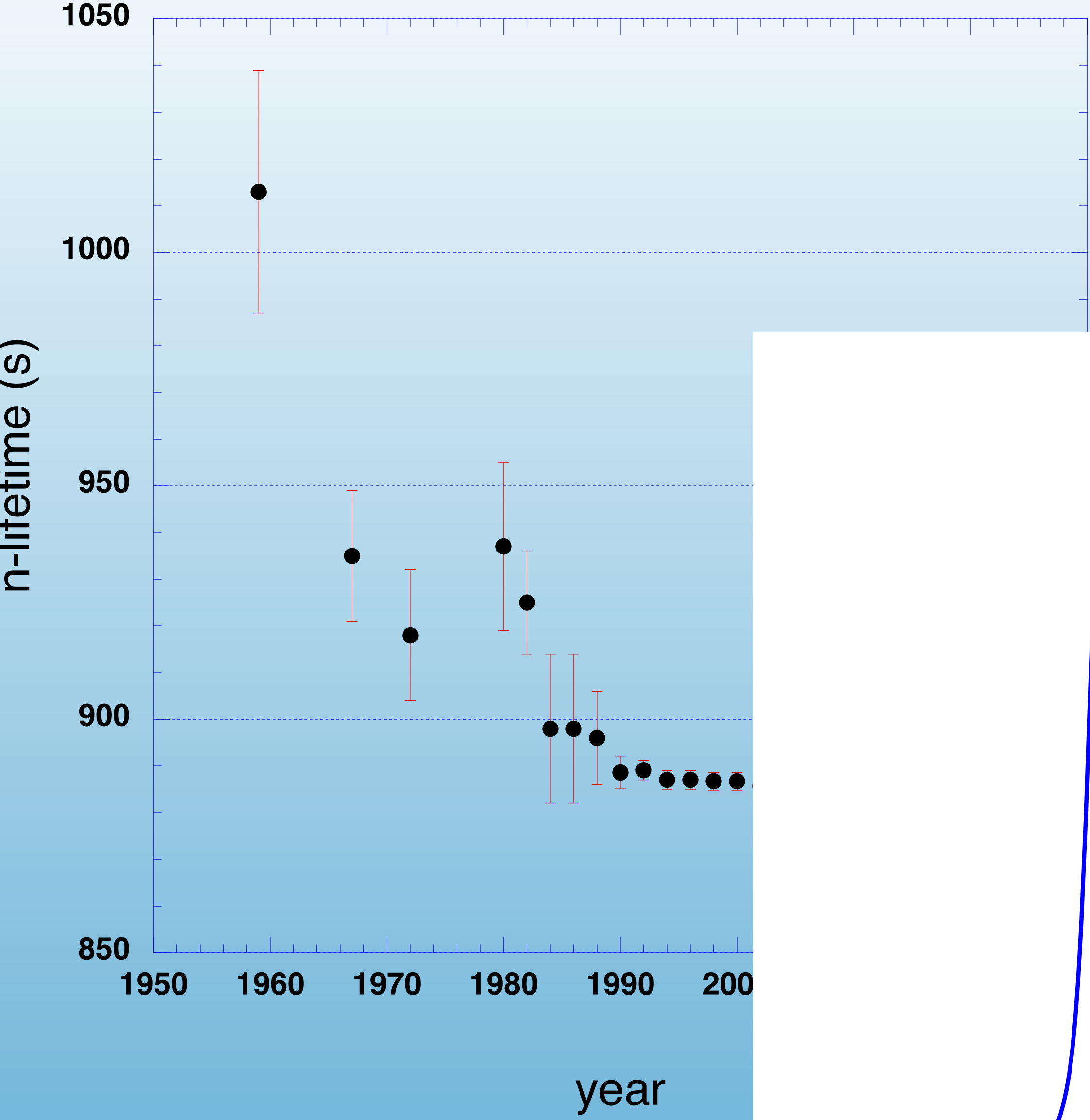
Fields, Olive, Yeh, Young

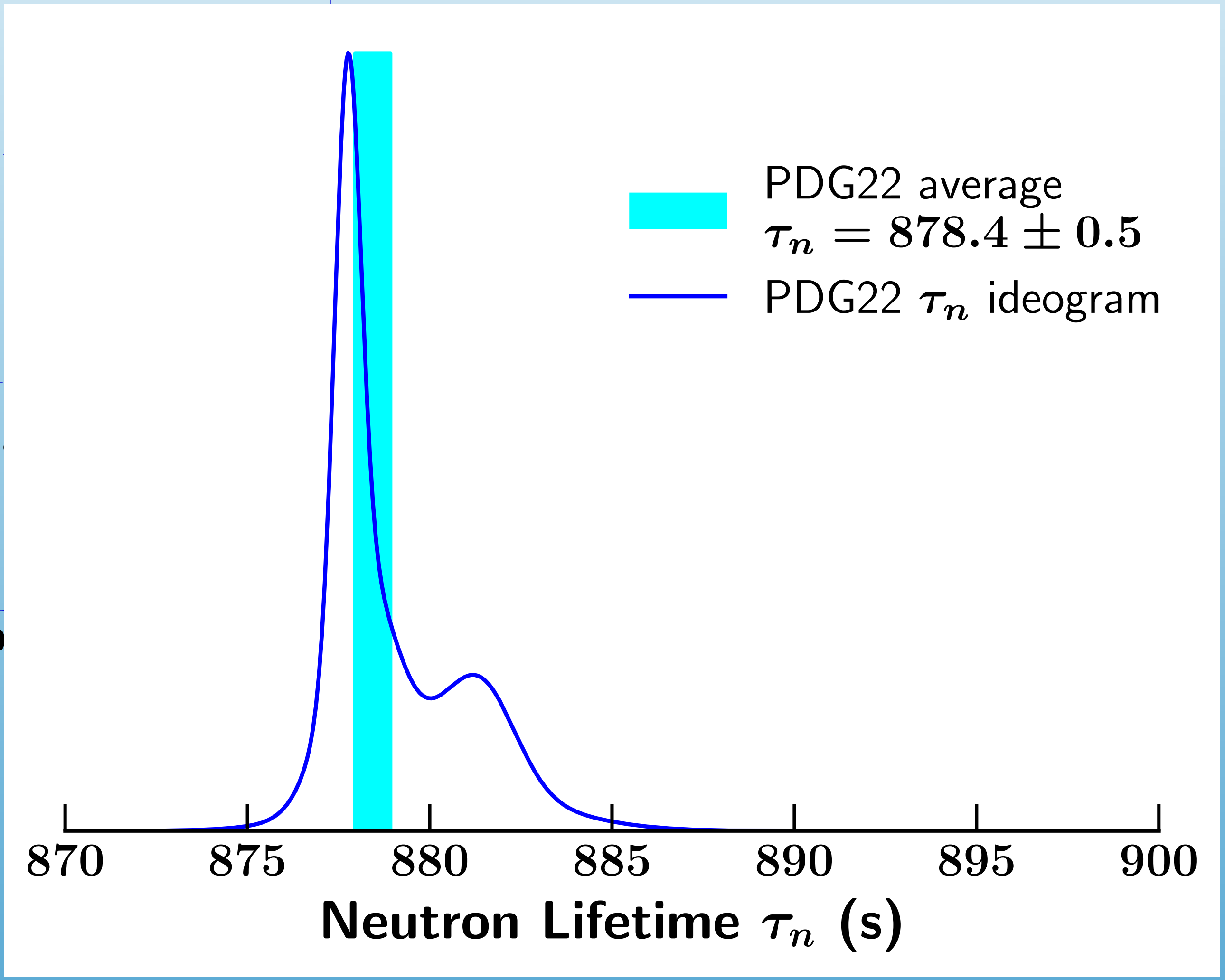
The neutron Mean-life



Yeh, Olive, Fields

The neutron Mean-life





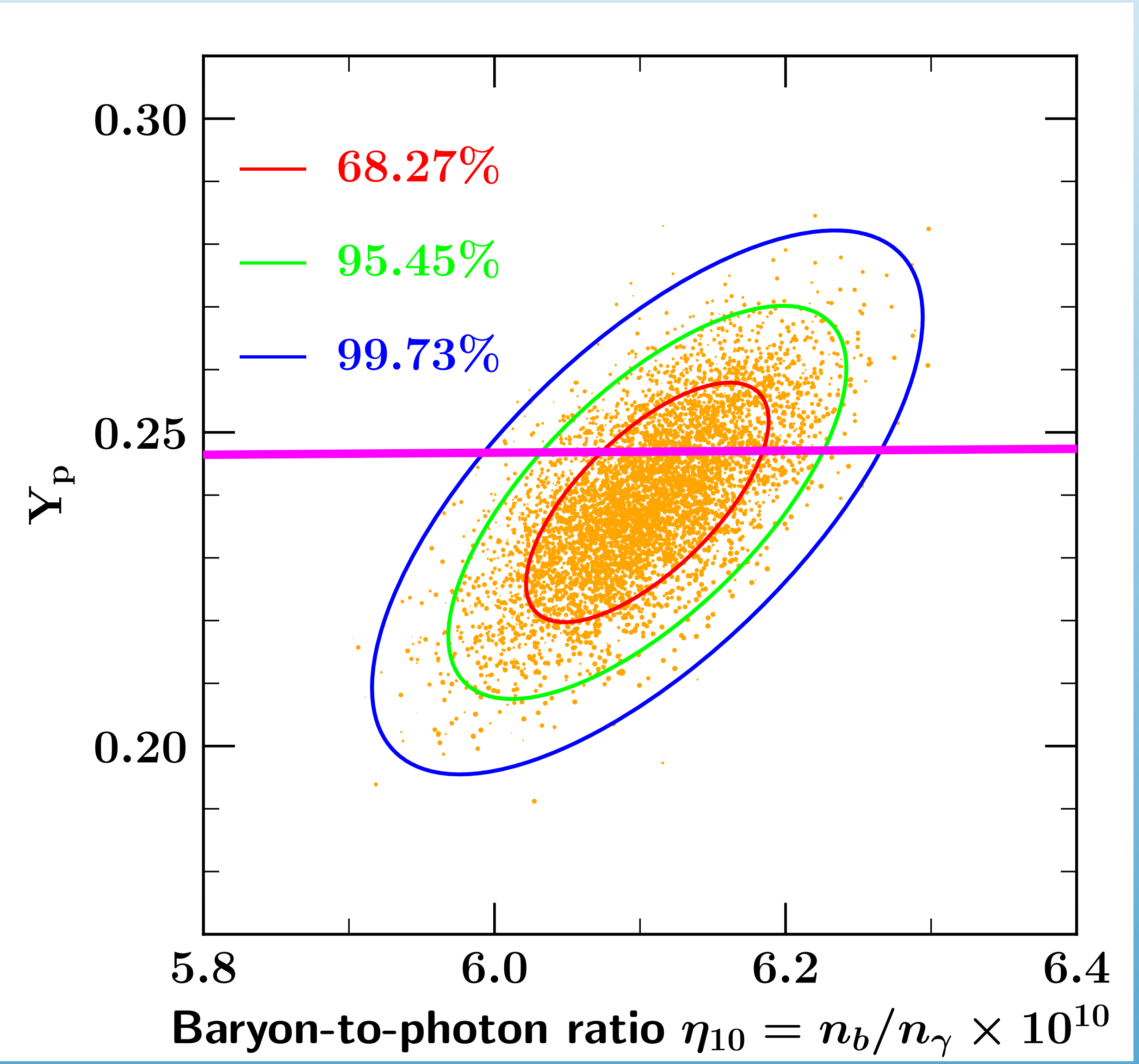
Yeh, Olive, Fields

BBN and the CMB

$N_\nu = 3$

CMB only determination of η and Y_P

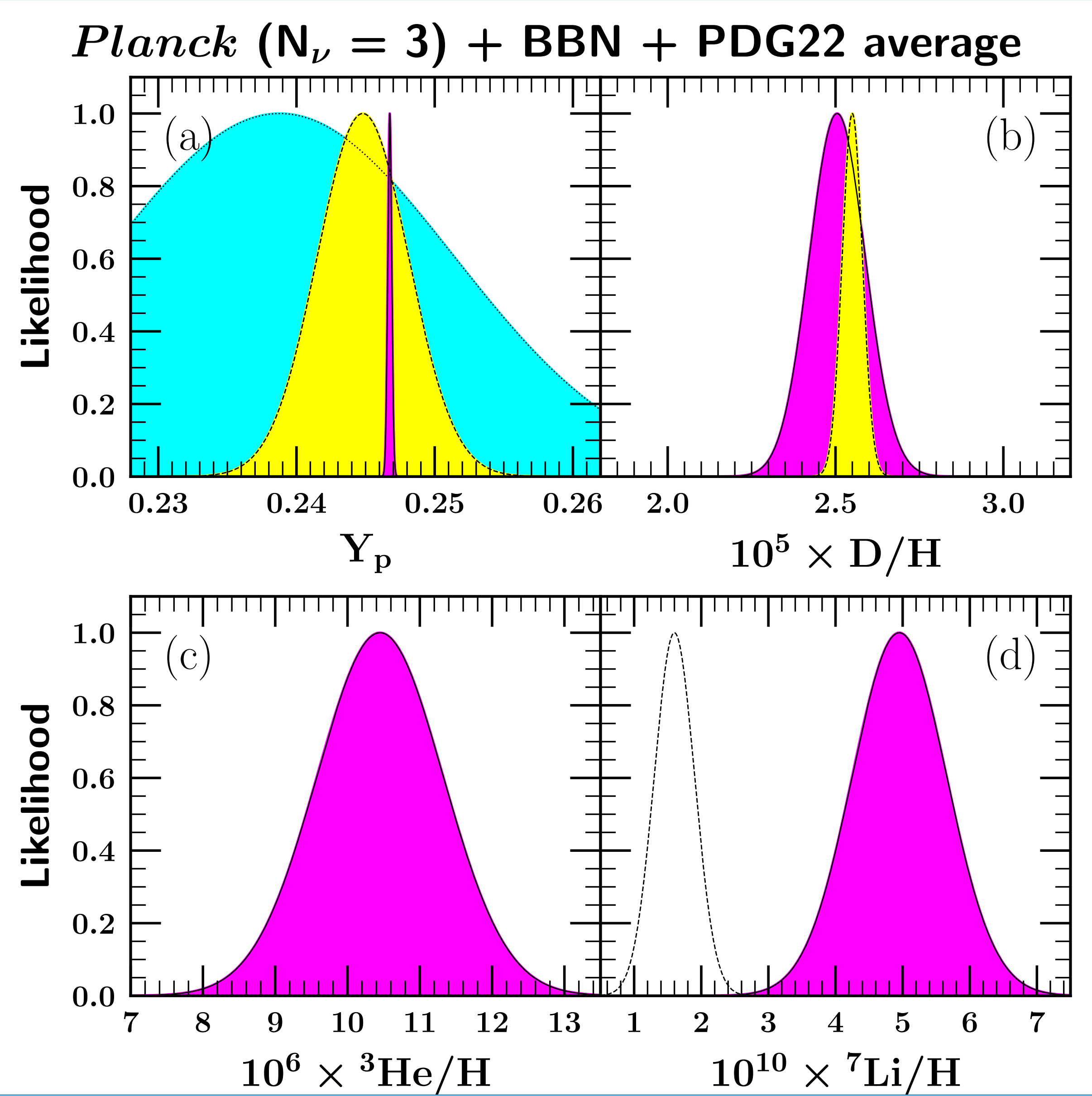
3σ BBN Prediction



Fields, Olive, Yeh, Young

BBN and the CMB

Monte-Carlo approach combining BBN rates, observations and CMB



$\mathcal{L}_{\rm OBS}(X)$ Yellow

$$\mathcal{L}_{\rm CMB}(Y_p) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\, d\eta\,.$$

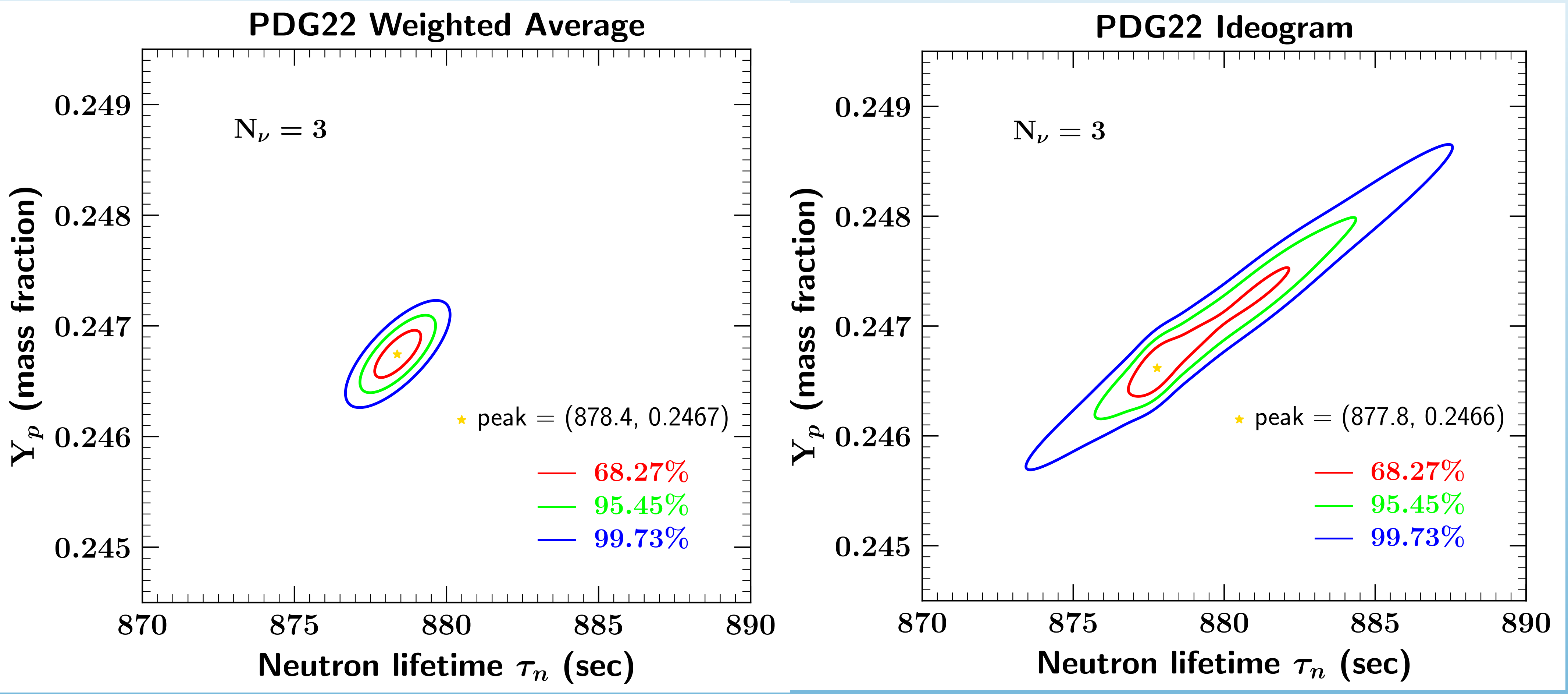
Cyan

$$\mathcal{L}_{\rm CMB-BBN}(X_i) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\ \mathcal{L}_{\rm BBN}(\eta; X_i)\ d\eta$$

Purple

Fields, Olive, Yeh, Young

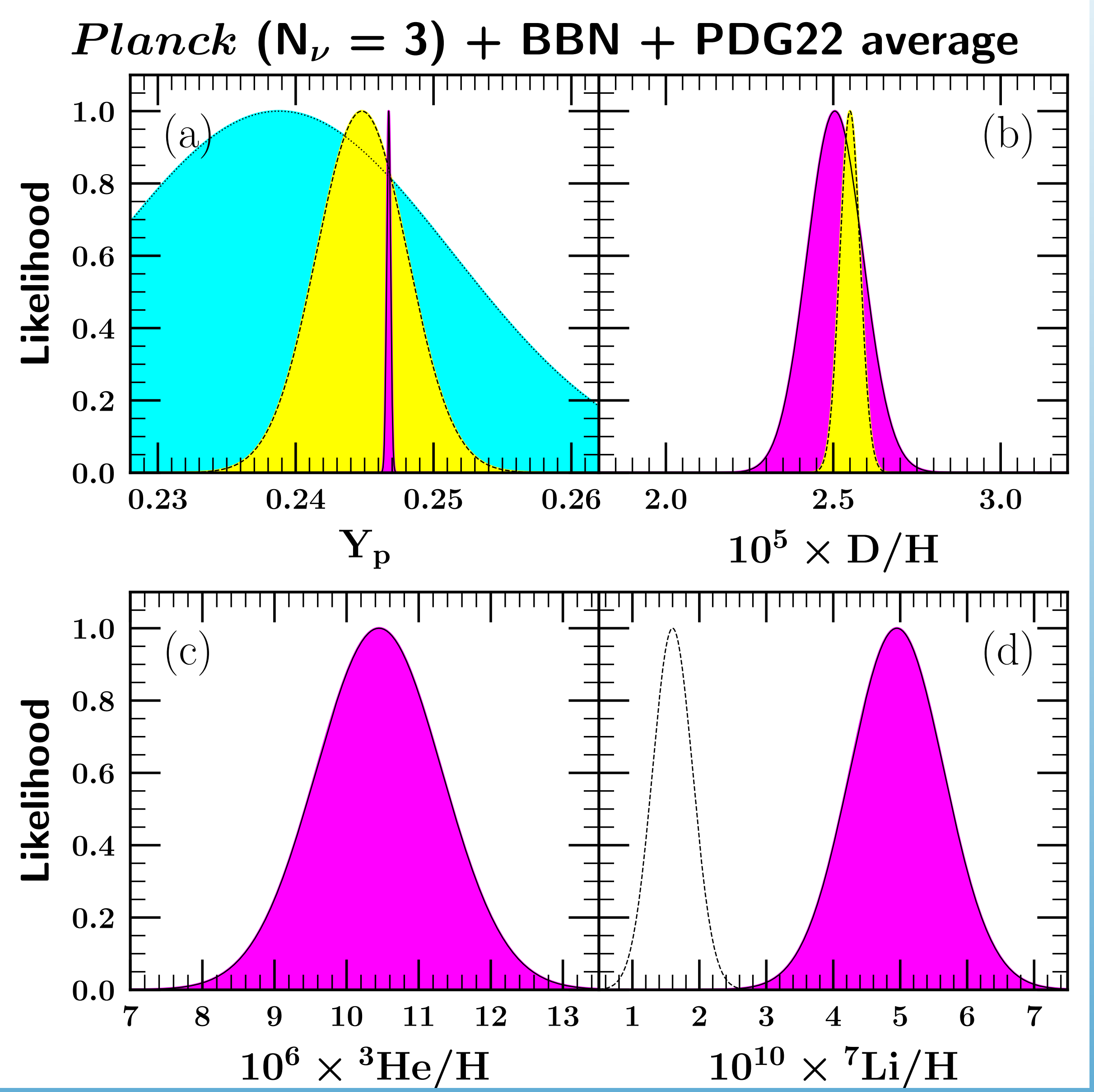
BBN and τ_n



Yeh, Olive, Fields

BBN and the CMB

Monte-Carlo approach combining BBN rates, observations and CMB

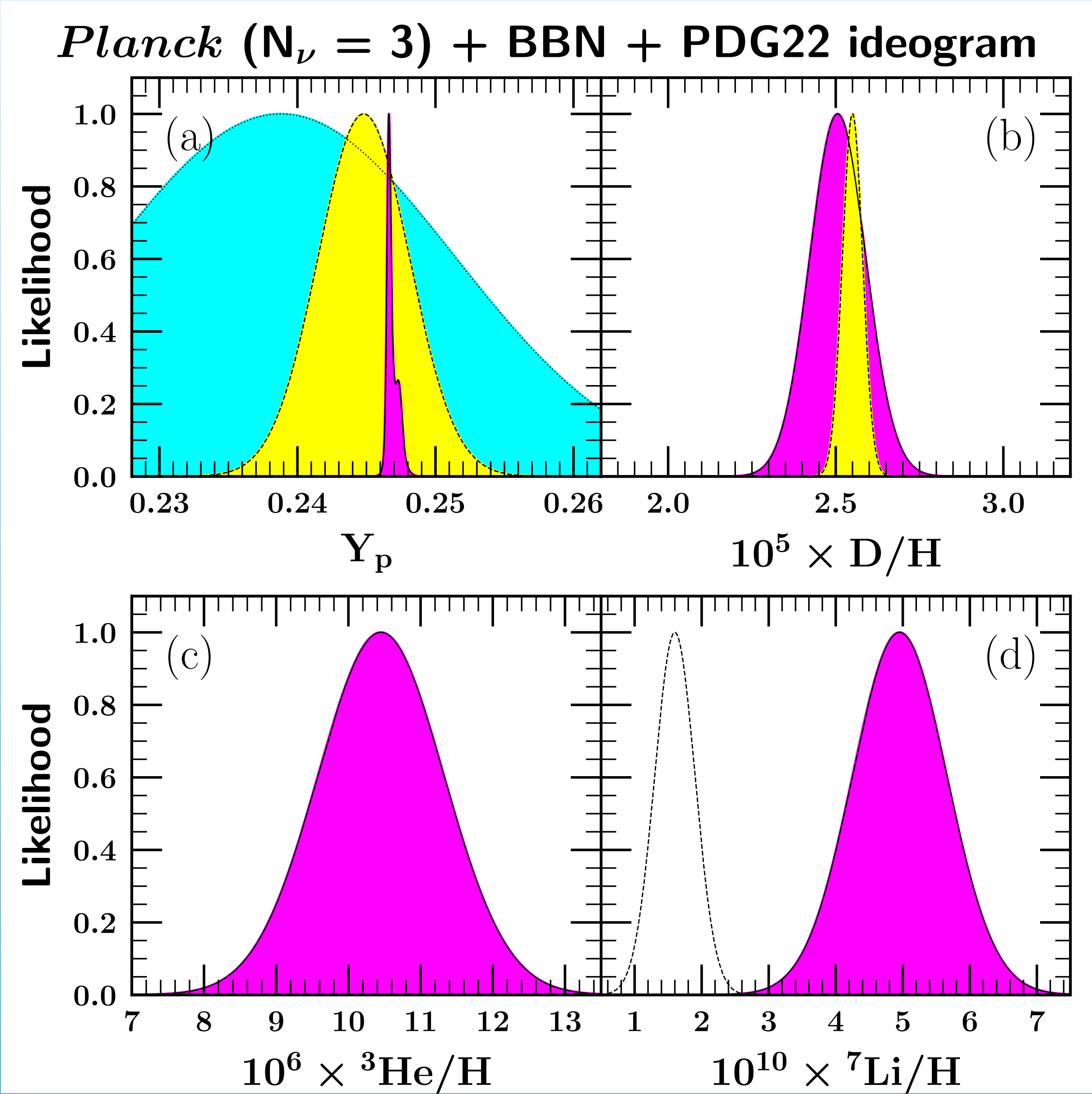


$$
\begin{aligned}
Y_p &= 0.2467 \pm 0.0002 && (0.2467) \\
\mathrm{D/H} &= (2.506 \pm 0.083) \times 10^{-5} && (2.505 \times 10^{-5}) \\
{}^3\mathrm{He/H} &= (10.45 \pm 0.87) \times 10^{-6} && (10.45 \times 10^{-6}) \\
{}^7\mathrm{Li/H} &= (4.96 \pm 0.70) \times 10^{-10} && (4.95 \times 10^{-10})
\end{aligned}
$$

Yeh, Olive, Fields

BBN and the CMB

Monte-Carlo approach combining BBN rates, observations and CMB



$$
\begin{aligned}
Y_p &= 0.2469 \pm 0.0004 && (0.2466) \\
D/H &= (2.507 \pm 0.083) \times 10^{-5} && (2.505 \times 10^{-5}) \\
{}^3He/H &= (10.45 \pm 0.87) \times 10^{-6} && (10.45 \times 10^{-6}) \\
{}^7Li/H &= (4.96 \pm 0.70) \times 10^{-10} && (4.95 \times 10^{-10})\,.
\end{aligned}
$$

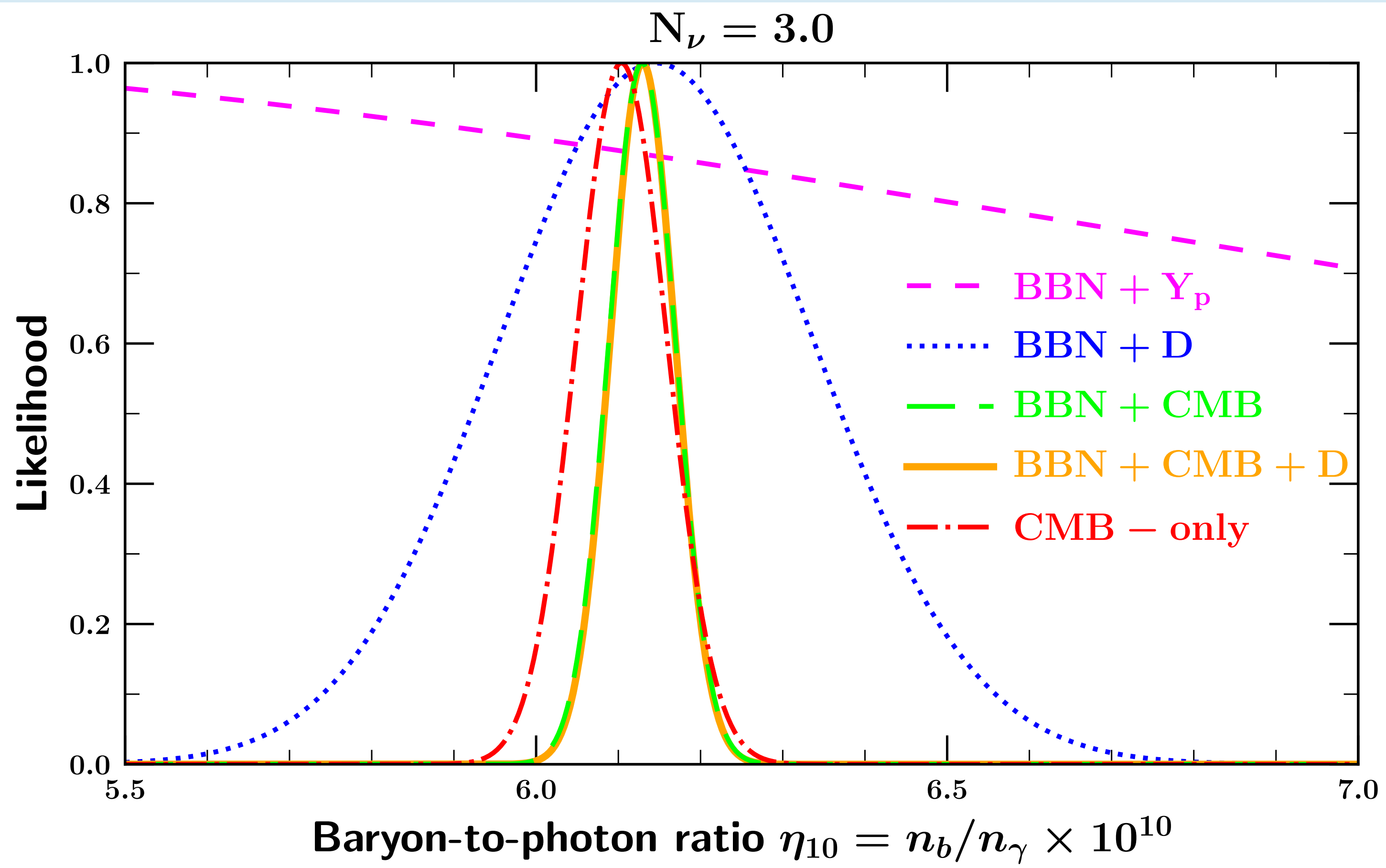
Yeh, Olive, Fields

BBN and the CMB

Convolved Likelihoods

$$\mathcal{L}_{\rm CMB}(\eta) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\ dY_p\,.$$

$$\mathcal{L}_{\rm CMB-BBN}(\eta) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\ \mathcal{L}_{\rm BBN}(\eta; Y_p)\ dY_p$$



Determination of η

$$\mathcal{L}_{\rm BBN-OBS}(\eta) \propto \int \mathcal{L}_{\rm BBN}(\eta; X_i)\ \mathcal{L}_{\rm OBS}(X_i)\ dX_i$$

$$\mathcal{L}_{\rm CMB-BBN-OBS}(\eta) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\mathcal{L}_{\rm BBN}(\eta; X_i)\ \mathcal{L}_{\rm OBS}(X_i)\ \prod_i dX_i$$

Fields, Olive, Yeh, Young

BBN and the CMB

Fields, Olive, Yeh, Young

Results for η_{10}

Constraints Used	mean η_{10}	peak η_{10}
CMB-only	6.104 ± 0.055	6.104
BBN+Y_p	$6.741^{+1.220}_{-3.524}$	4.920
BBN+D	6.148 ± 0.191	6.145
BBN+Y_p+D	6.143 ± 0.190	6.140
CMB+BBN	6.129 ± 0.041	6.129
CMB+BBN+Y_p	6.128 ± 0.041	6.128
CMB+BBN+D	6.130 ± 0.040	6.129
CMB+BBN+Y_p+D	6.129 ± 0.040	6.129

Convolved Likelihoods

$$\mathcal{L}_{\rm CMB}(\eta) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\; dY_p\,.$$

$$\mathcal{L}_{\rm CMB-BBN}(\eta) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\; \mathcal{L}_{\rm BBN}(\eta; Y_p)\; dY_p$$

$$\mathcal{L}_{\rm BBN-OBS}(\eta) \propto \int \mathcal{L}_{\rm BBN}(\eta; X_i)\; \mathcal{L}_{\rm OBS}(X_i)\; dX_i$$

$$\mathcal{L}_{\rm CMB-BBN-OBS}(\eta) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\mathcal{L}_{\rm BBN}(\eta; X_i)\; \mathcal{L}_{\rm OBS}(X_i)\; \prod_i dX_i$$

Limits on Particle Properties

$$G_F^2 T^5 \sim \Gamma_{\rm wk}(T_f) = H(T_f) \sim G_N^{1/2} T^2,$$

$$H^2 = \frac{8\pi}{3} G_N \rho$$

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

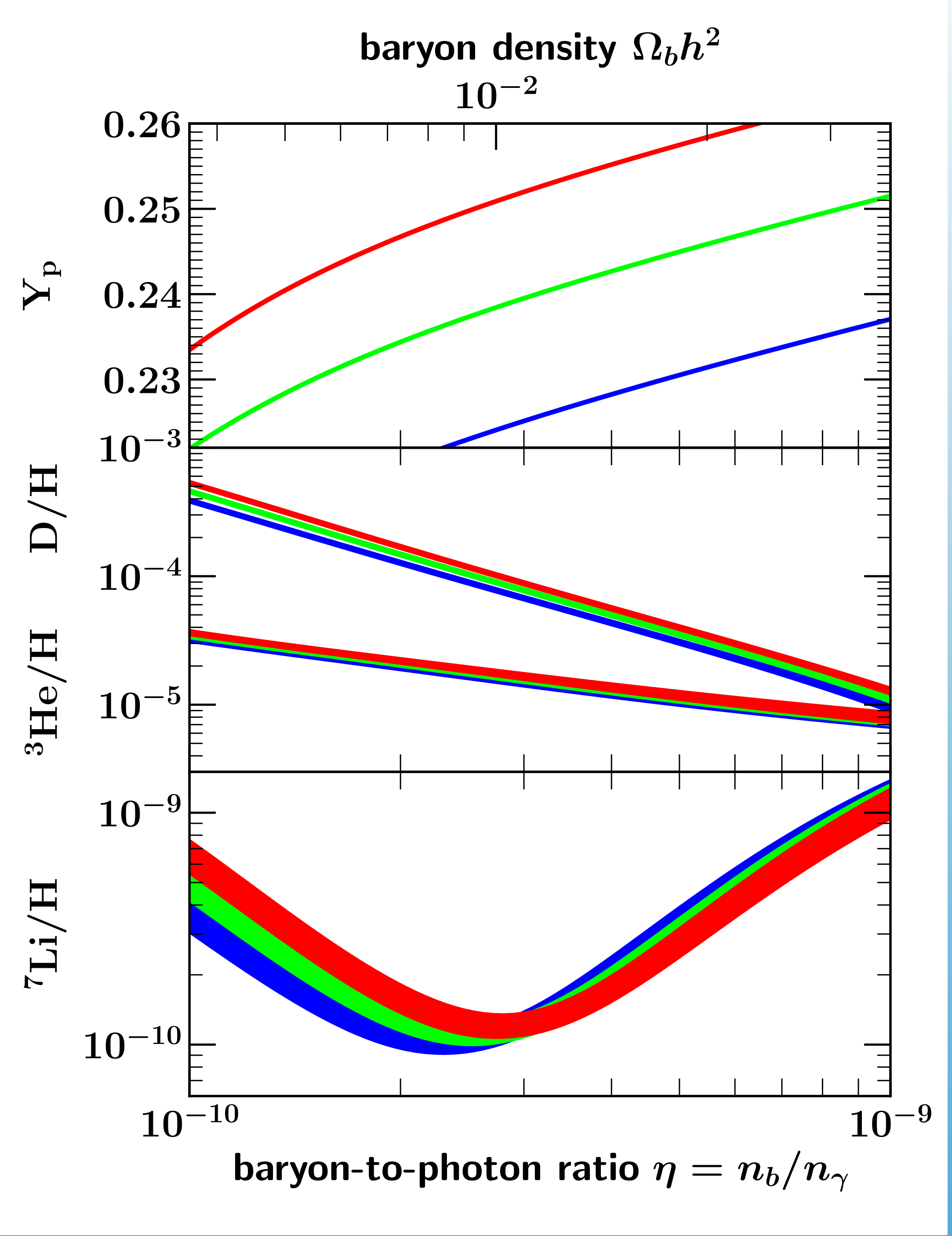
$$\frac{n}{p} \sim e^{-\Delta m / T}$$

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

- 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: G_N, G_F, α

e.g. $\frac{\Delta\alpha}{\alpha} < \text{few} \times 10^{-4}$

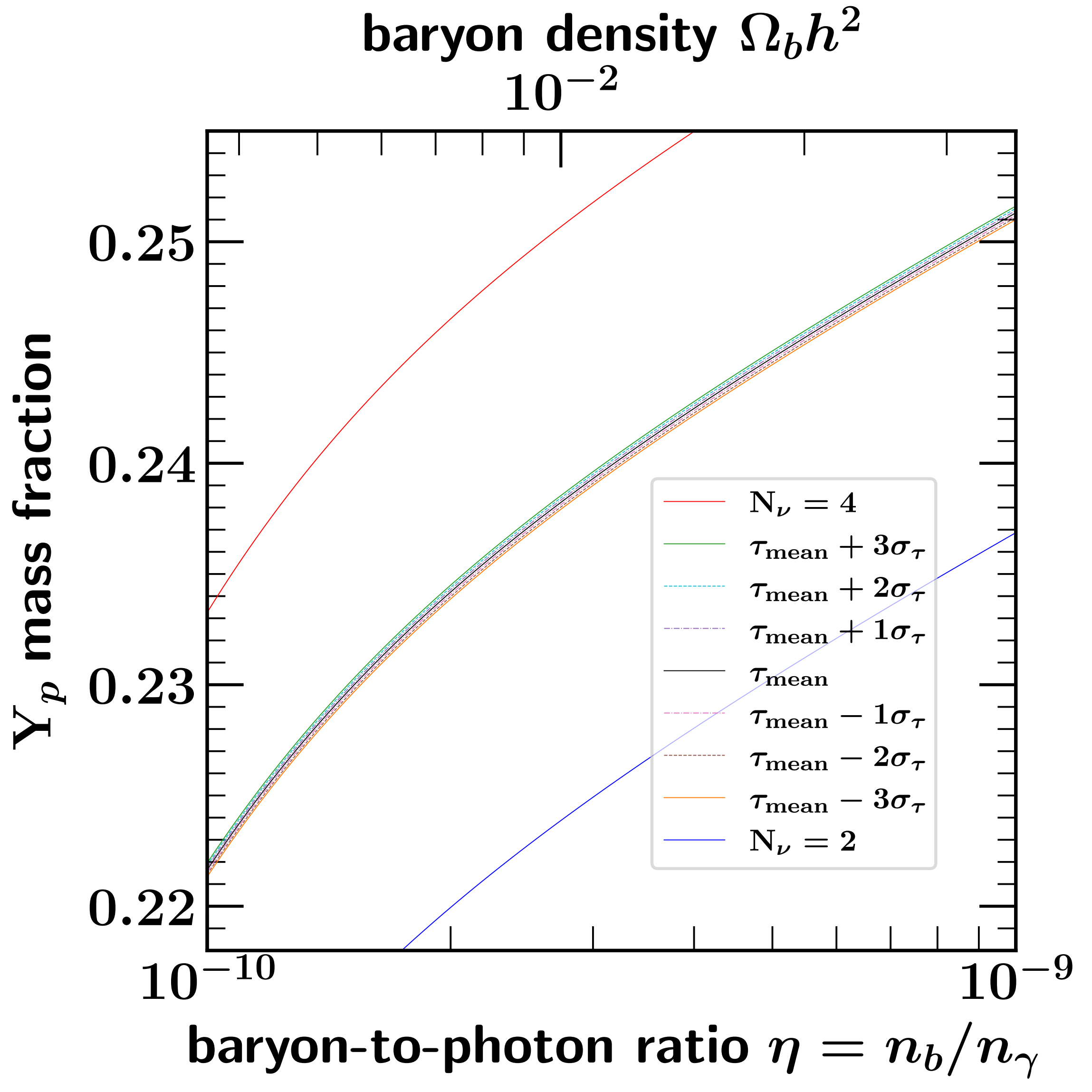
BBN and the CMB



Sensitivity to N_ν

Fields, Olive, Yeh, Young

BBN and the CMB

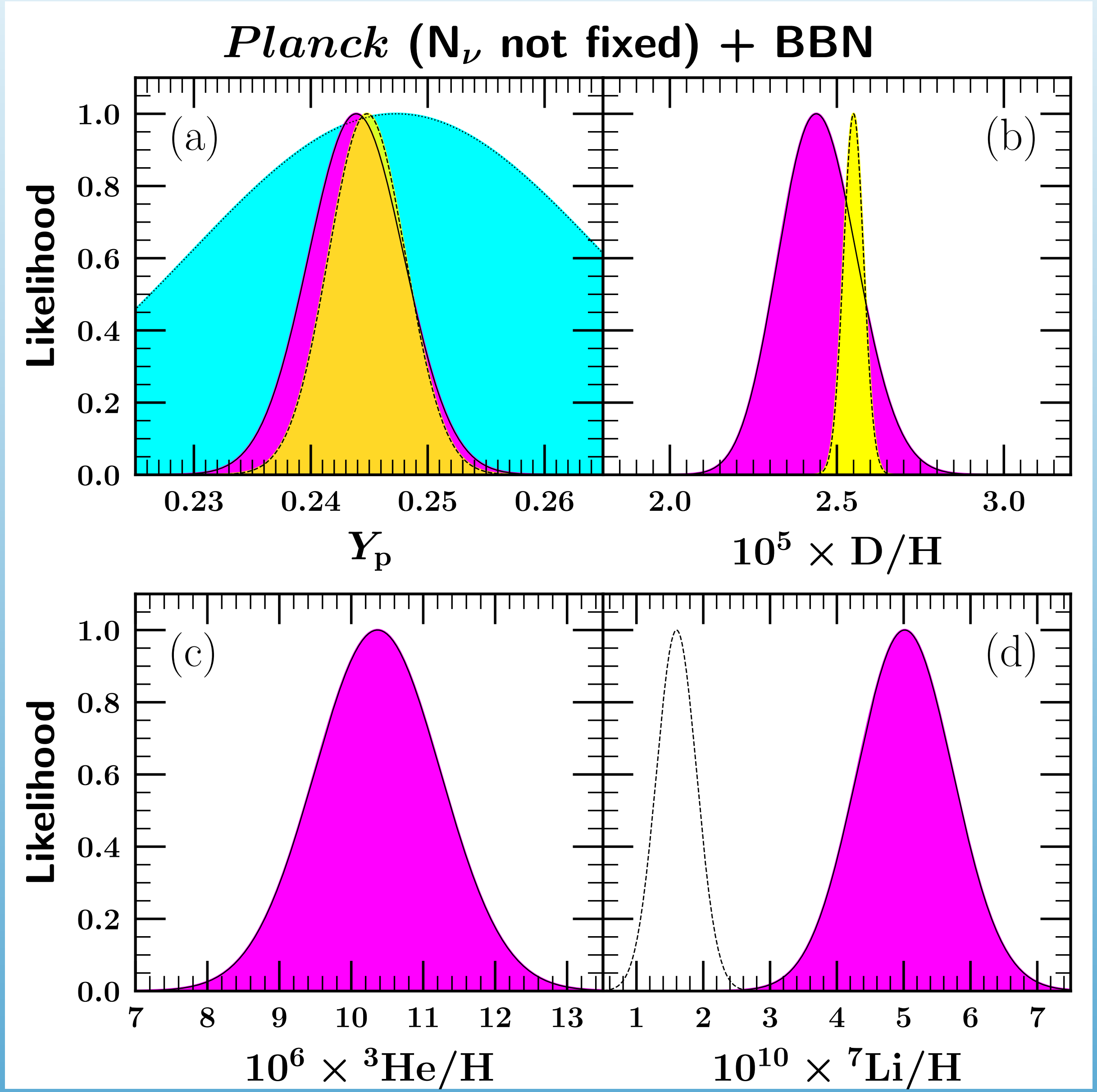


Sensitivity to N_ν

Fields, Olive, Yeh, Young

BBN and the CMB

Monte-Carlo approach combining BBN rates, observations and CMB



$\mathcal{L}_{\rm OBS}(X)$ Yellow

$$\mathcal{L}_{\rm NCMB}(\eta) \propto \int \mathcal{L}_{\rm NCMB}(\eta, Y_p, N_\nu)\; dY_p\; dN_\nu\,,$$

Cyan

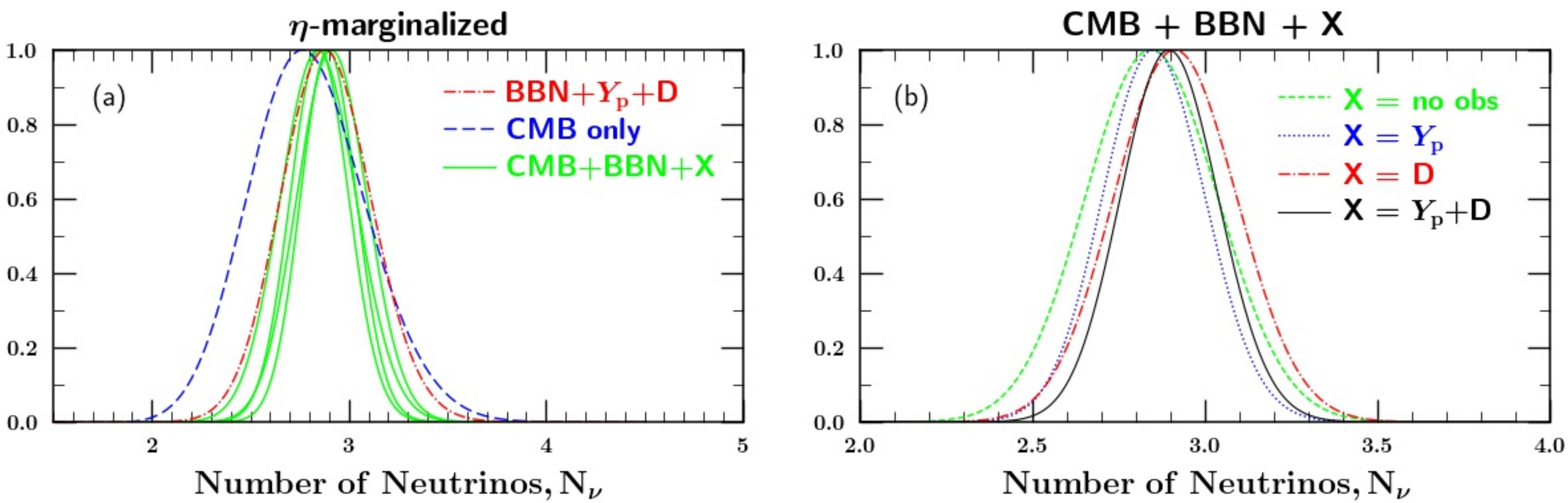
$$\mathcal{L}_{\rm NCMB-NBBN}(\eta) \propto \int \mathcal{L}_{\rm NCMB}(\eta, Y_p, N_\nu)\mathcal{L}_{\rm NBBN}(\eta, N_\nu; X_i)\; dY_p dN_\nu\,,$$

Purple

Fields, Olive, Yeh, Young

BBN and the CMB

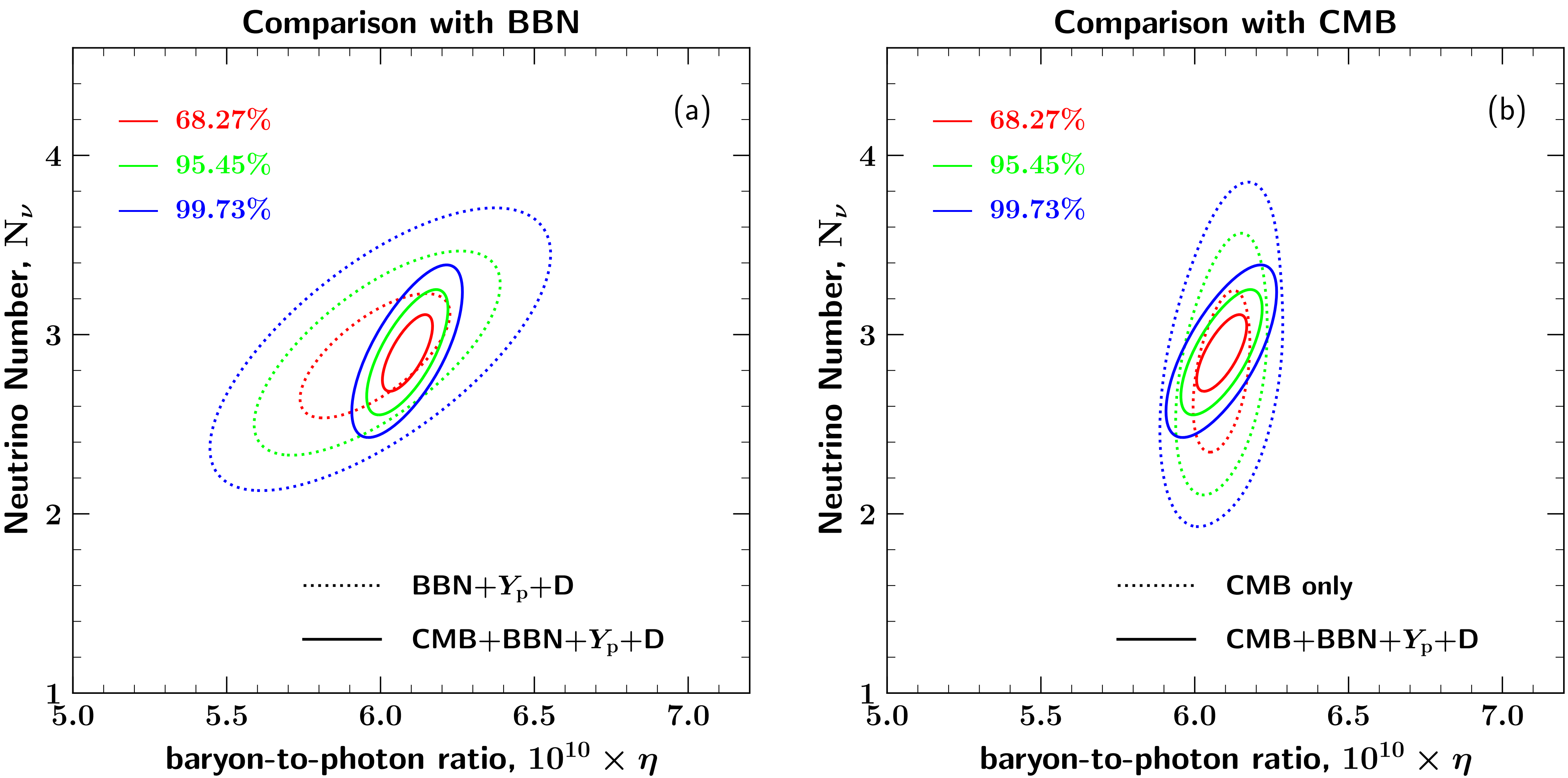
CMB and BBN determination of N_ν



Yeh, Shelton, Olive, Fields

BBN and the CMB

CMB and BBN determination of η and N_ν



Yeh, Shelton, Olive, Fields

BBN and the CMB

Convolved Likelihoods

Results for η (N_ν)

Constraints Used	mean η_{10}	peak η_{10}	mean N_ν	peak N_ν	δN_ν
CMB-only	6.090 ± 0.061	$6.090^{+0.061}_{-0.062}$	2.800 ± 0.294	$2.764^{+0.308}_{-0.282}$	0.513
BBN+Y_p+D	5.986 ± 0.161	$5.980^{+0.163}_{-0.159}$	2.889 ± 0.229	$2.878^{+0.232}_{-0.226}$	0.407
CMB+BBN	6.087 ± 0.061	$6.088^{+0.061}_{-0.062}$	2.848 ± 0.190	$2.843^{+0.192}_{-0.189}$	0.296
CMB+BBN+Y_p	6.089 ± 0.053	$6.089^{+0.054}_{-0.054}$	2.853 ± 0.148	$2.850^{+0.149}_{-0.148}$	0.221
CMB+BBN+D	6.092 ± 0.060	$6.093^{+0.061}_{-0.060}$	2.916 ± 0.176	$2.912^{+0.178}_{-0.175}$	0.303
CMB+BBN+Y_p+D	6.088 ± 0.054	$6.088^{+0.054}_{-0.054}$	2.898 ± 0.141	$2.895^{+0.142}_{-0.141}$	0.226

Yeh, Shelton, Olive, Fields

BBN and the CMB

Convolved Likelihoods

Results for η (N_ν)

Constraints Used	mean η_{10}	peak η_{10}	mean N_ν	peak N_ν	δN_ν
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$N_\nu < 3.180$ (95% CL)

Yeh, Shelton, Olive, Fields

BBN and the CMB

Convolved Likelihoods

Results for η (N_ν)

Constraints Used	mean η_{10}	peak η_{10}	mean N_ν	peak N_ν	δN_ν
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CMB+BBN+Y_p+D	6.088 ± 0.054	$6.088^{+0.054}_{-0.054}$	2.898 ± 0.141	$2.895^{+0.142}_{-0.141}$	0.226

$N_\nu < 3.180$ (95% CL)

1-sided limit assuming $N_\nu \geq 3$ $N_\nu < 3.226$ (95% CL)

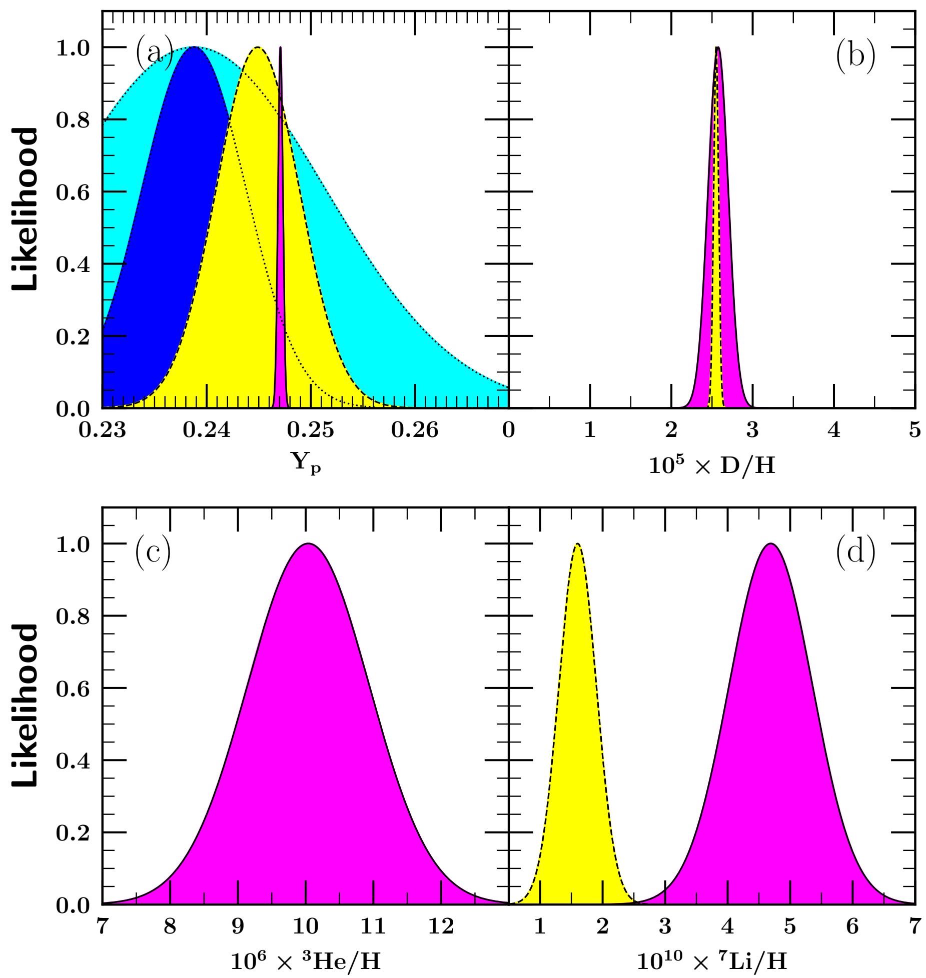
Yeh, Shelton, Olive, Fields

Limits:

- Right-handed neutrinos and extra gauge boson masses
- Dark Radiation
- Stochastic Gravitational Wave Background
- Vacuum Energy - Trackers
- Primordial Magnetic Fields
- Limits on Changes in η and N_ν between BBN and CMB
- Changes in Fundamental Constants

Yeh, Shelton, Olive, Fields

BBN and the CMB



CMB-S4 promises significantly improved BBN parameters

$$\sigma_{\rm S4}(Y_p) \simeq 0.005$$

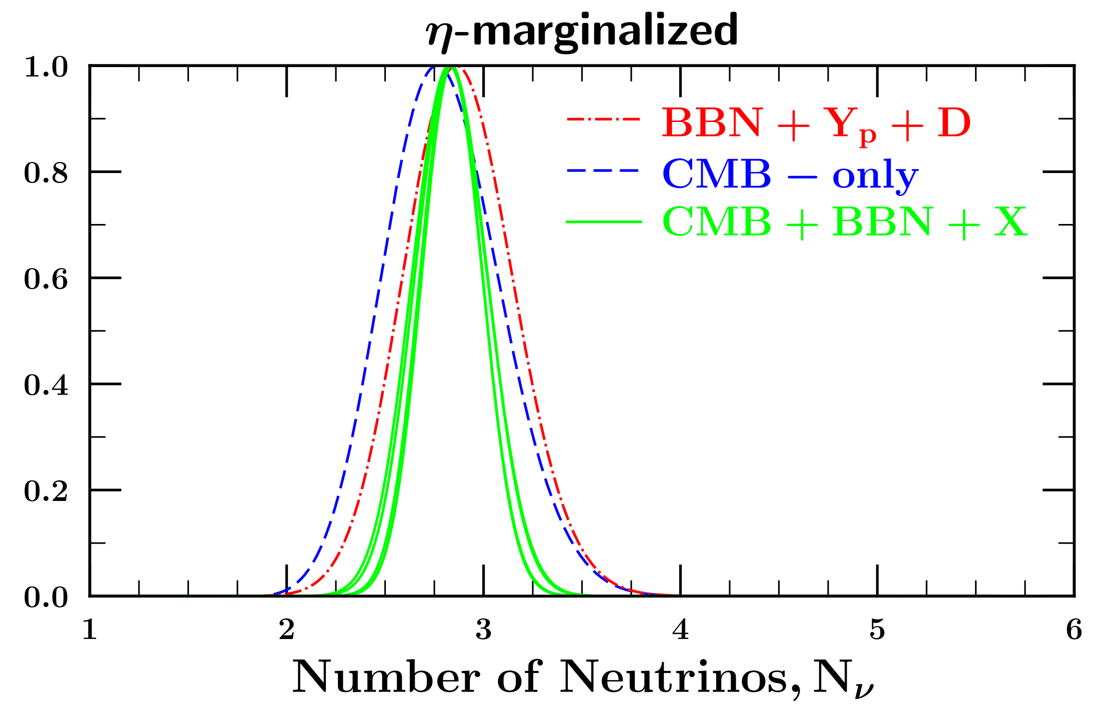
K. N. Abazajian *et al.* [CMB-S4 Collaboration]

CMB-S4:

$$\sigma_{\rm S4}(N_{\rm eff}) \simeq 0.09$$

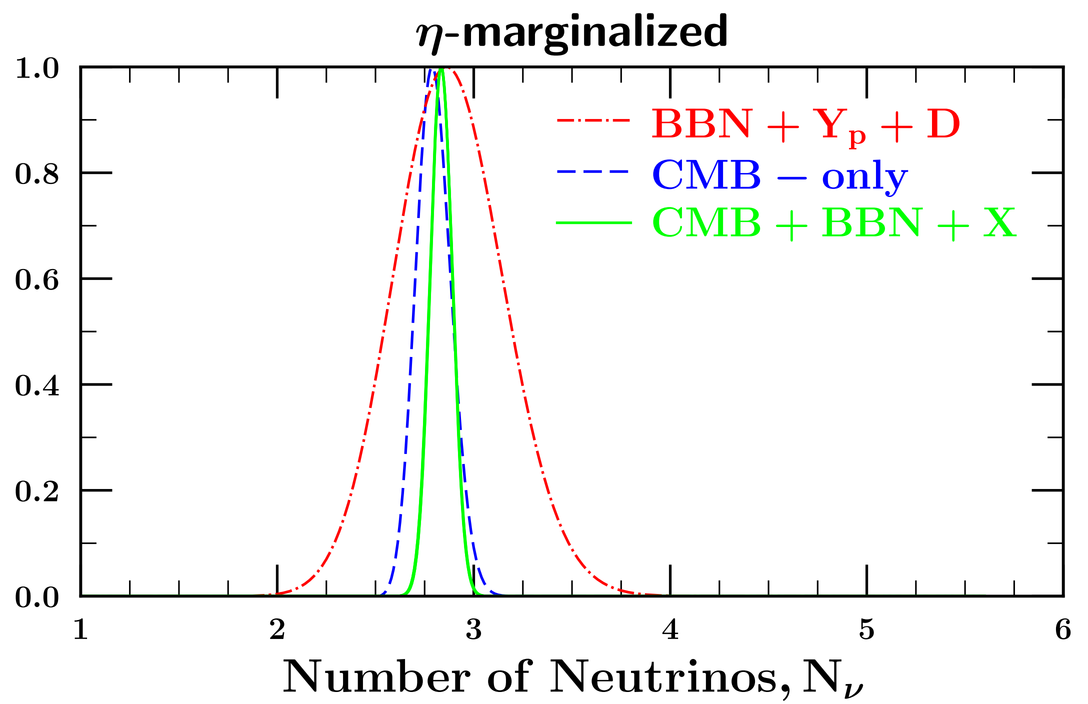
Fields, Olive, Yeh, Young

BBN and the CMB



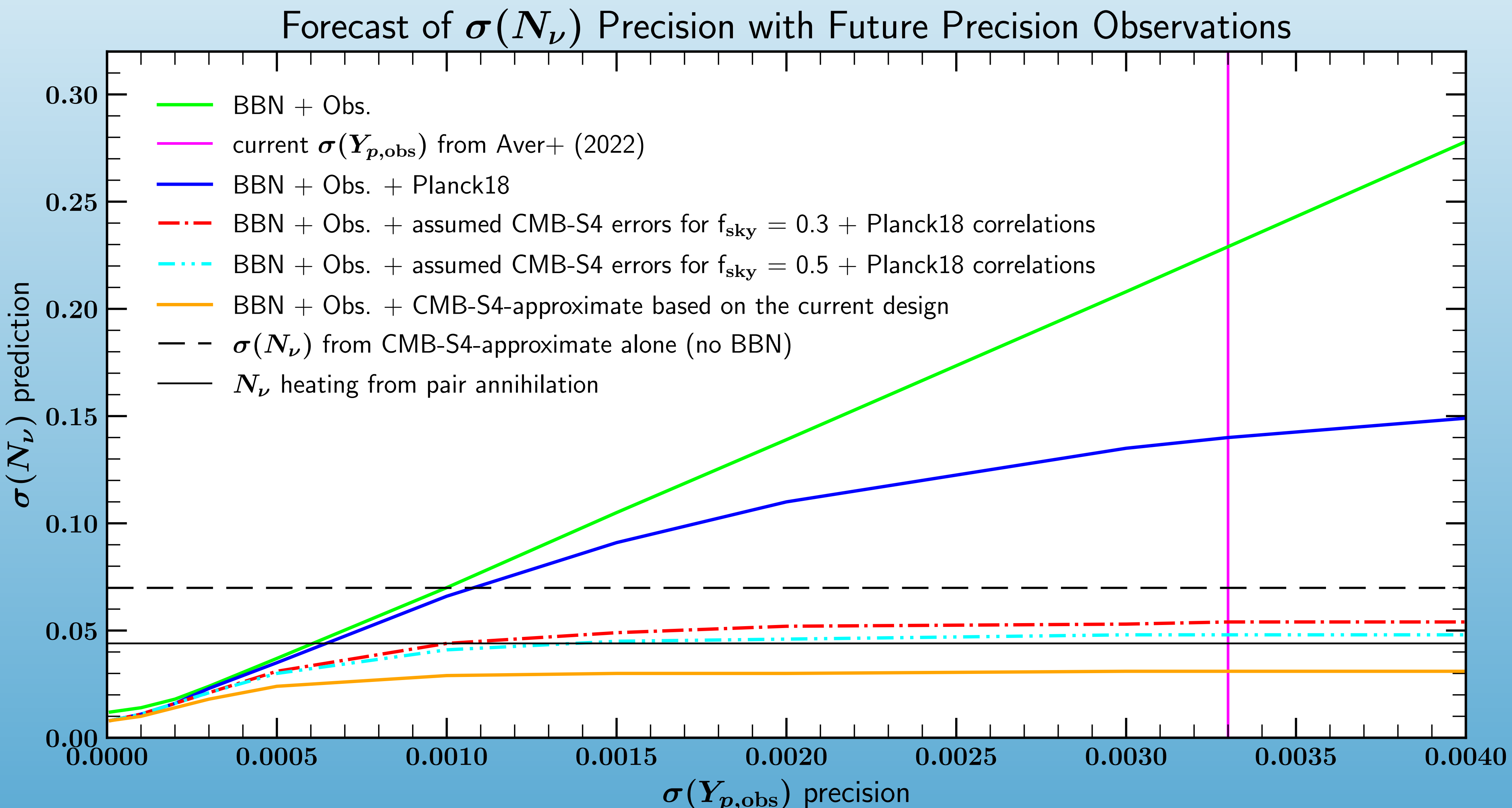
Planck 2018

CMB-S4 uncertainty

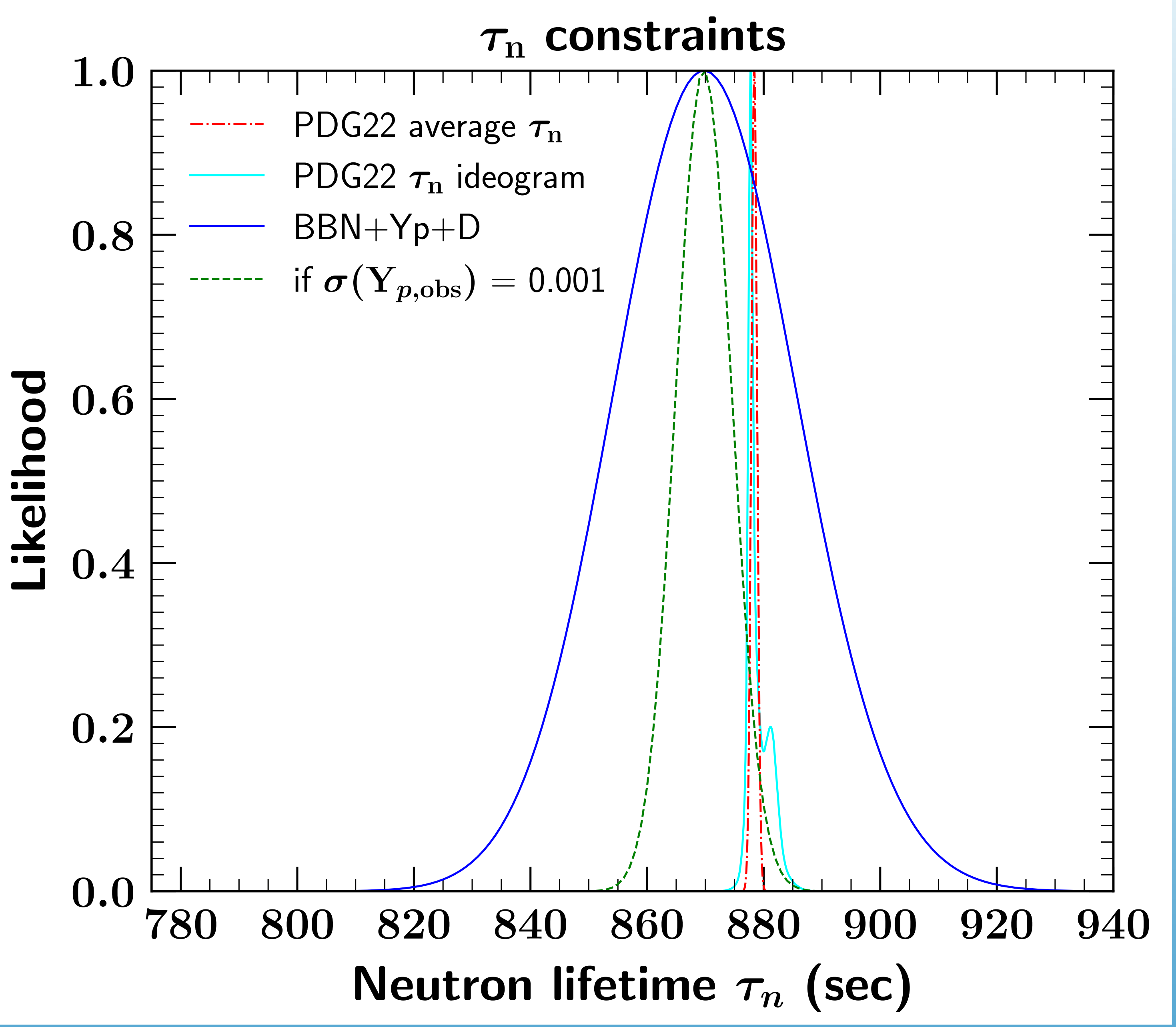


BBN and the CMB

more recent projection $\sigma_{S4}(N_{\rm eff}) \simeq 0.07$



BBN and the CMB
Predicting τ_n



Summary

- BBN and CMB are in excellent agreement wrt D and He
- Li: Was Problematic
  - Most certainly now due to stellar depletion
- Wish list:
  - New cross sections measurements for D(D,p) and D(D,n)
  - New high precision measurements of He
- Standard Model ($N_\nu = 3$) is looking good!