Big Bang Nucleosynthesis-Post Planck

- BBN and the WMAP/Planck determination of η, $\Omega_B h^2$
- Observations and Comparison with Theory

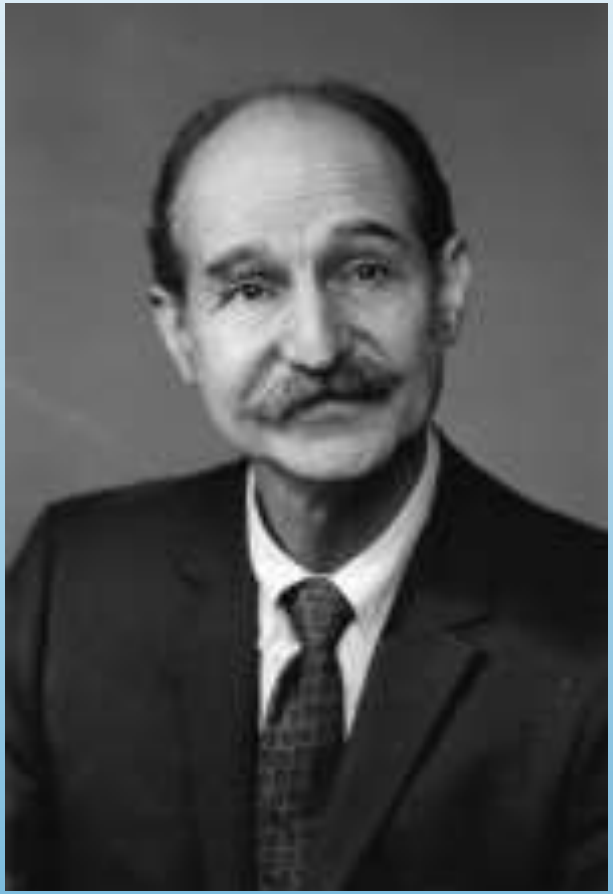
  - D/H   - ^{4}He   - ^{7}Li

- Impact of new cross section measurements
- Neutrinos
- Constraints on BSM physics
- The Future (CMB-S4)

It all started with:

George Gamow

Ralph Alpher



Robert Herman

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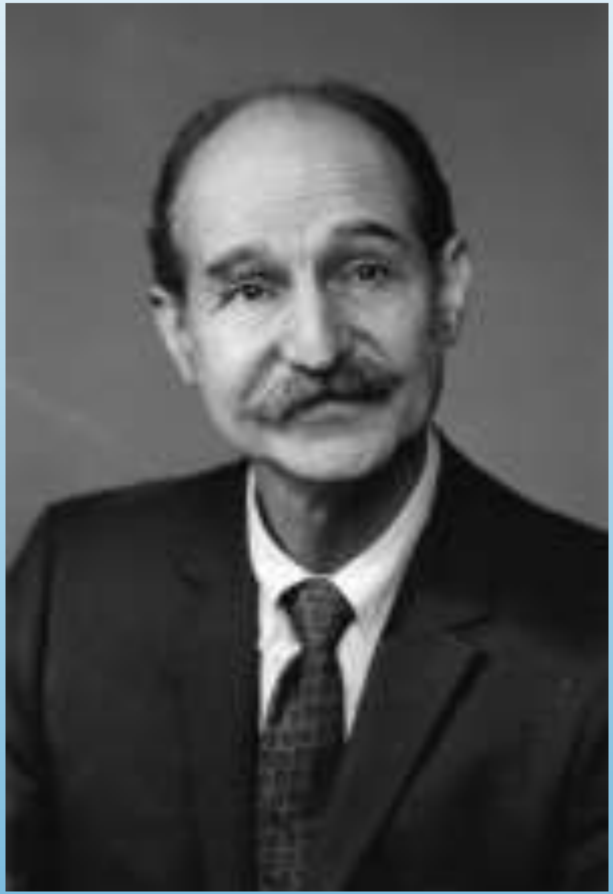

Robert Herman

It all started with:

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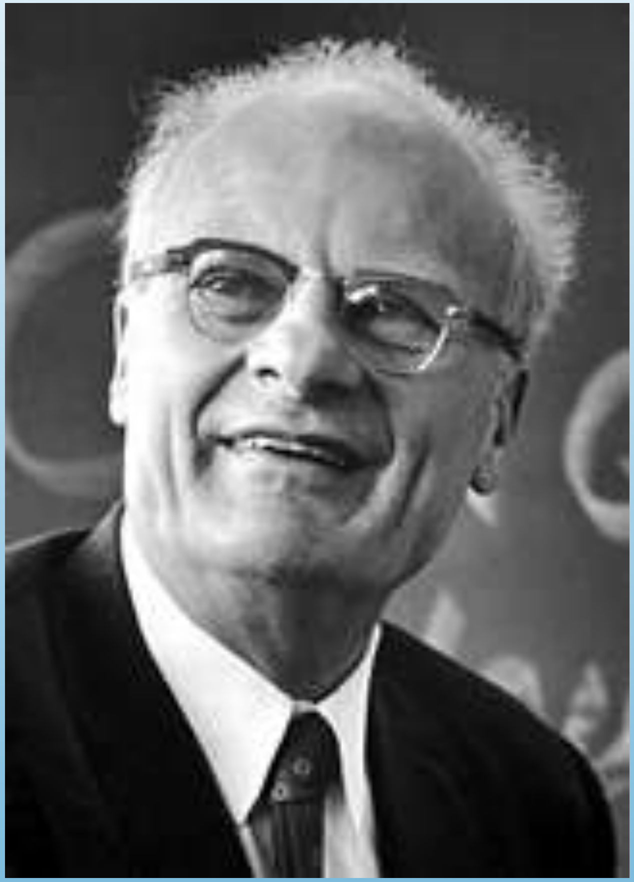


Hans Bethe

George Gamow

PHYSICAL REVIEW VOLUME 7

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

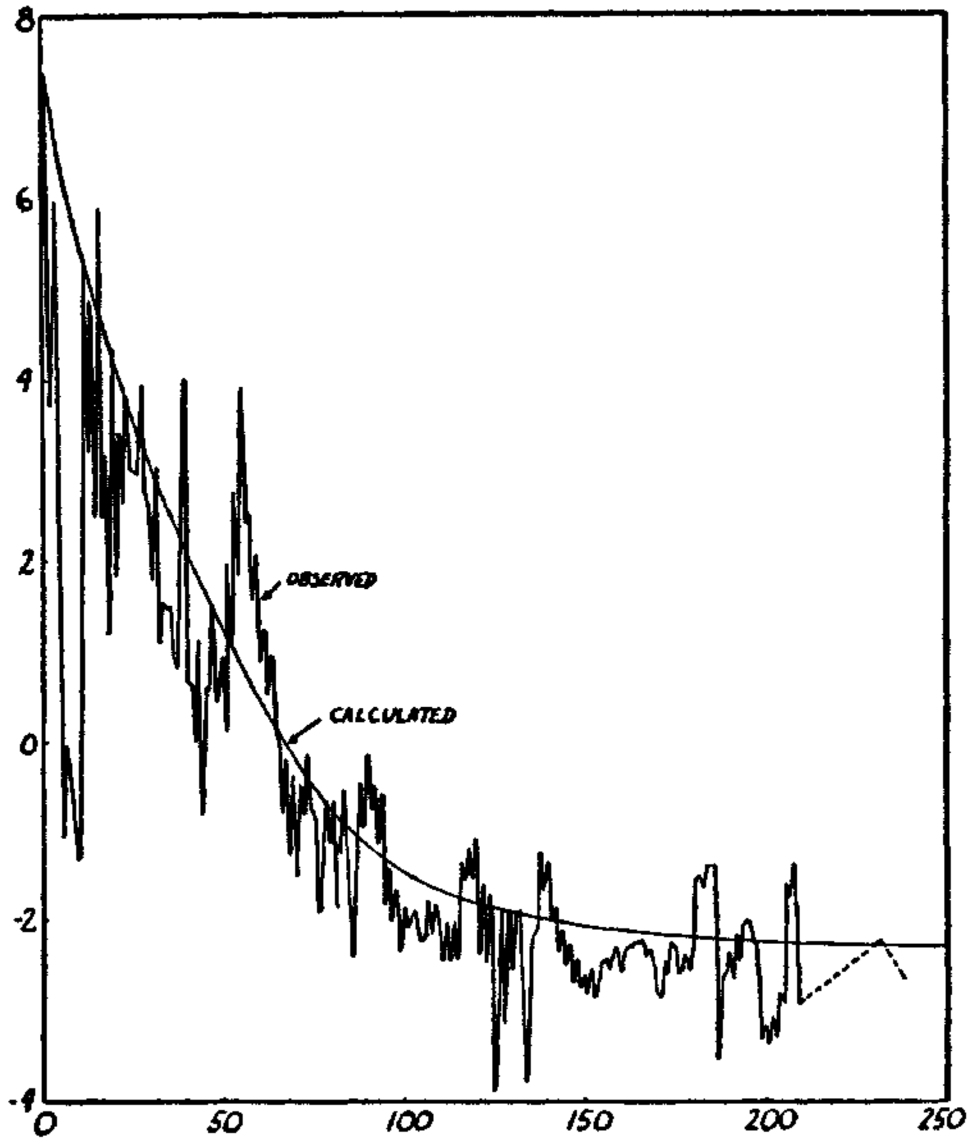
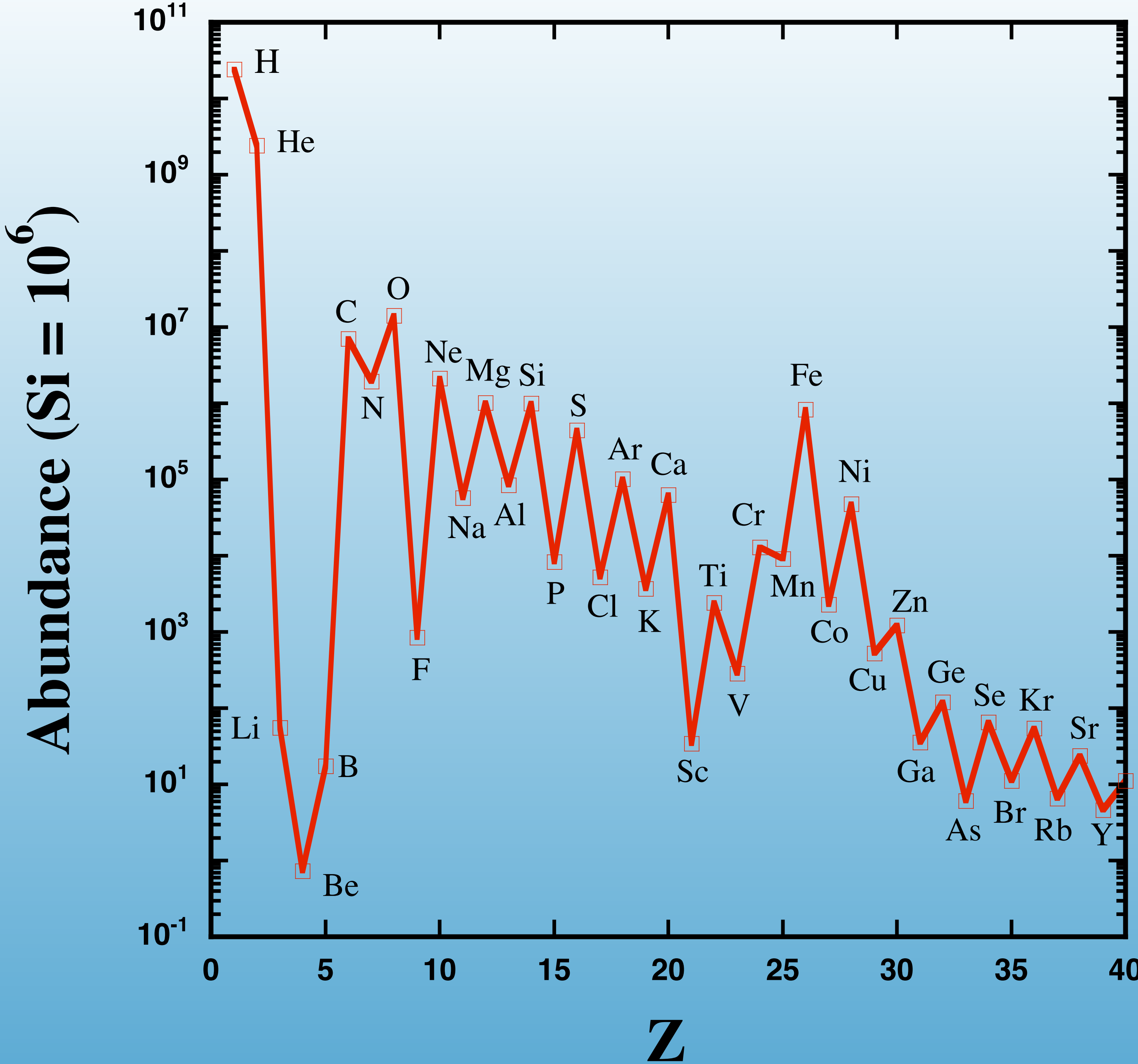


FIG. 1.

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

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

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

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

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

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.

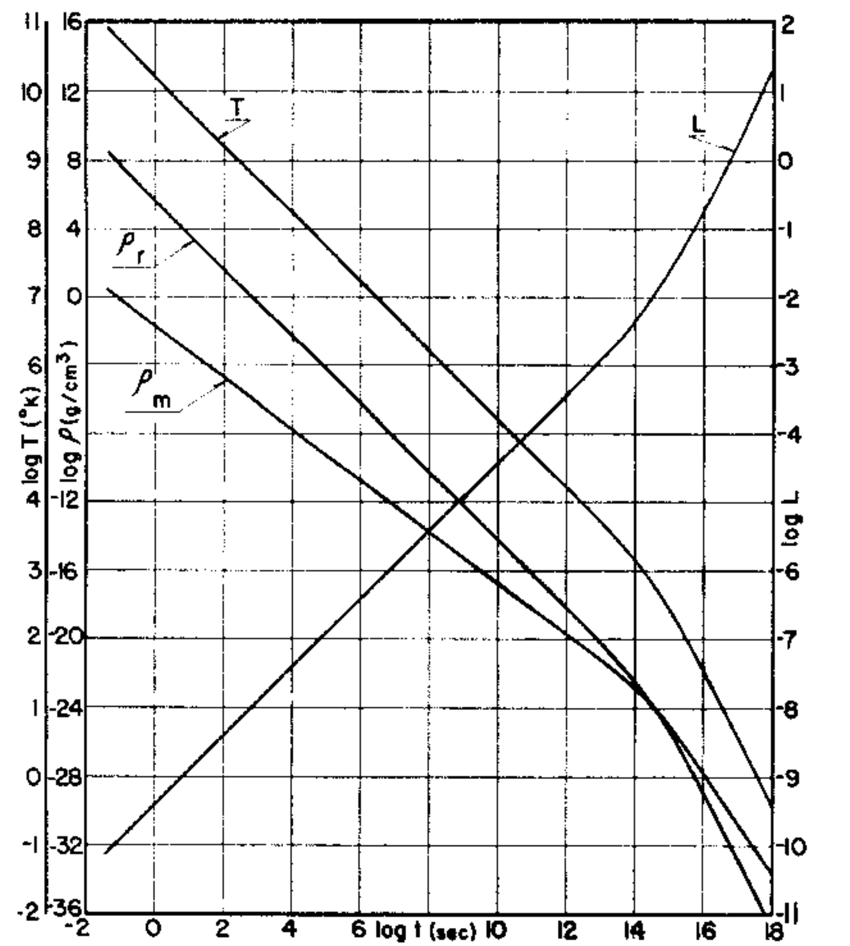


FIG. 1. The time dependence of the proper distance L, the densities of matter and radiation, ρ_m, and ρ_r, as well as the temperature, T, are shown for the case where $\rho_{m''} \cong 10^{-30}$ g/cm³, $\rho_{r''} \cong 10^{-32}$ g/cm³, $\rho_{m'} \cong 10^{-6}$ g/cm³, and $\rho_{r'} \cong 1$ g/cm³.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

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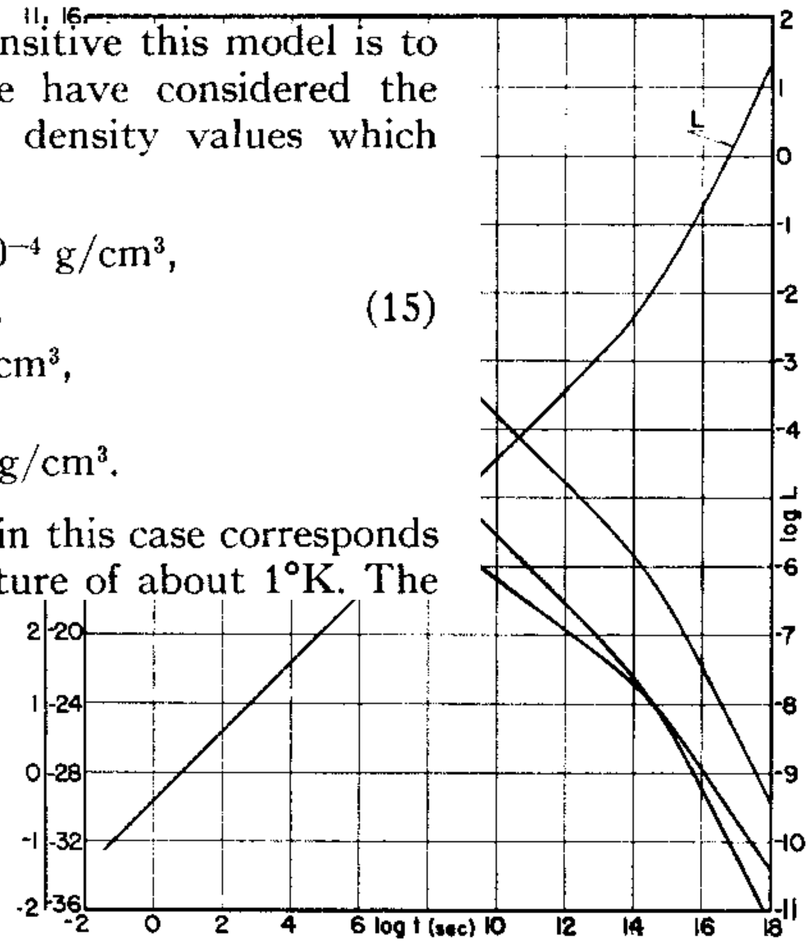
In order to study how sensitive this model is to the choice of densities, we have considered the following additional set of density values which satisfy Eq. (4):

$$\rho_{m'} \cong 1.78\times 10^{-4}\ \text{g/cm}^3,$$
$$\rho_{r'} \cong 1\ \text{g/cm}^3, \qquad (15)$$
$$\rho_{m''} \cong 10^{-30}\ \text{g/cm}^3,$$

and

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

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



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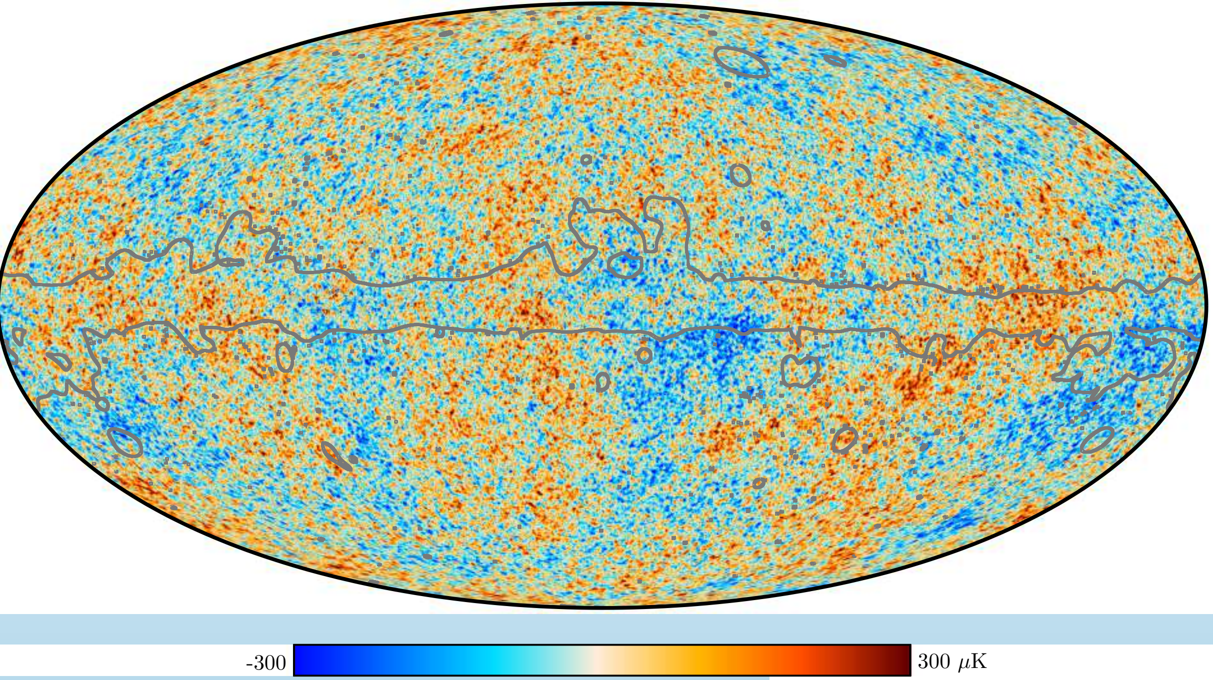
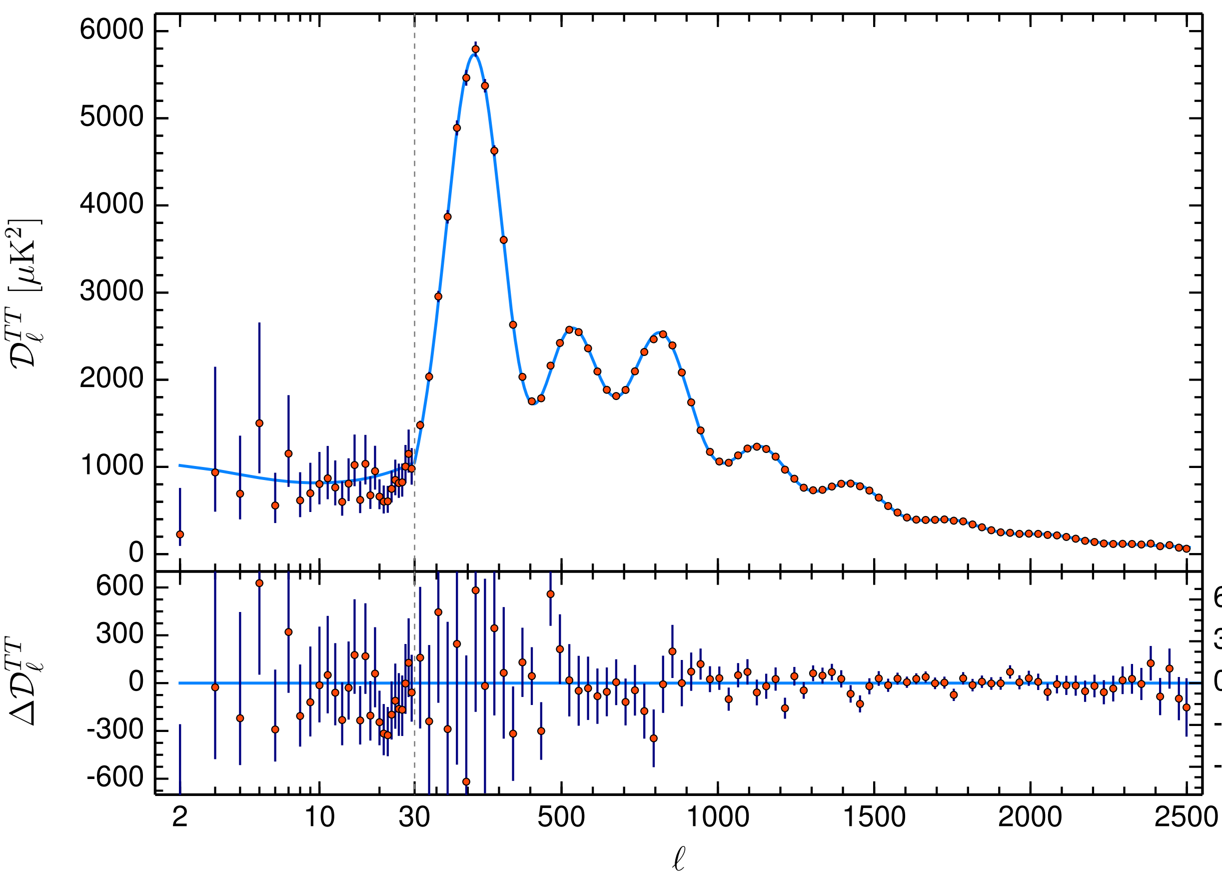


Planck best fit

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

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



Conditions in the Early Universe:

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

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

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

β-Equilibrium maintained by weak interactions

Freeze-out at ~ 1 MeV determined by the competition of expansion rate $H \sim T^2/M_p$ and the weak interaction rate $\Gamma \sim G_F^2 T^5$

$$\begin{aligned} n + e^+ &\leftrightarrow p + \bar{\nu}_e \\ n + \nu_e &\leftrightarrow p + e^- \\ n &\leftrightarrow p + e^- + \bar{\nu}_e \end{aligned}$$

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

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 number**

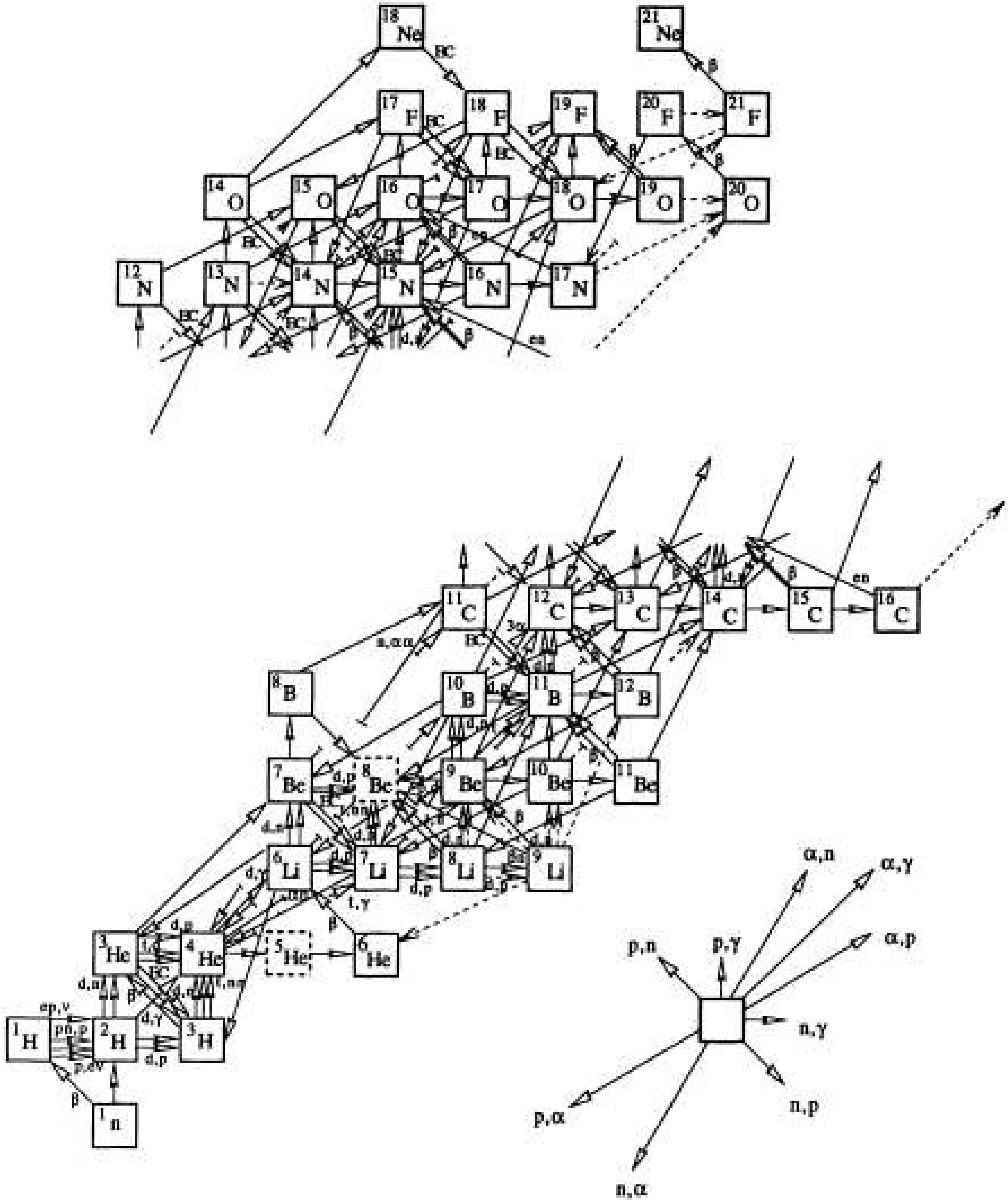


FIG. 1.—Reaction network used in the code. Estimated reactions are shown with dashed lines.

Table 1: Key Nuclear Reactions for BBN

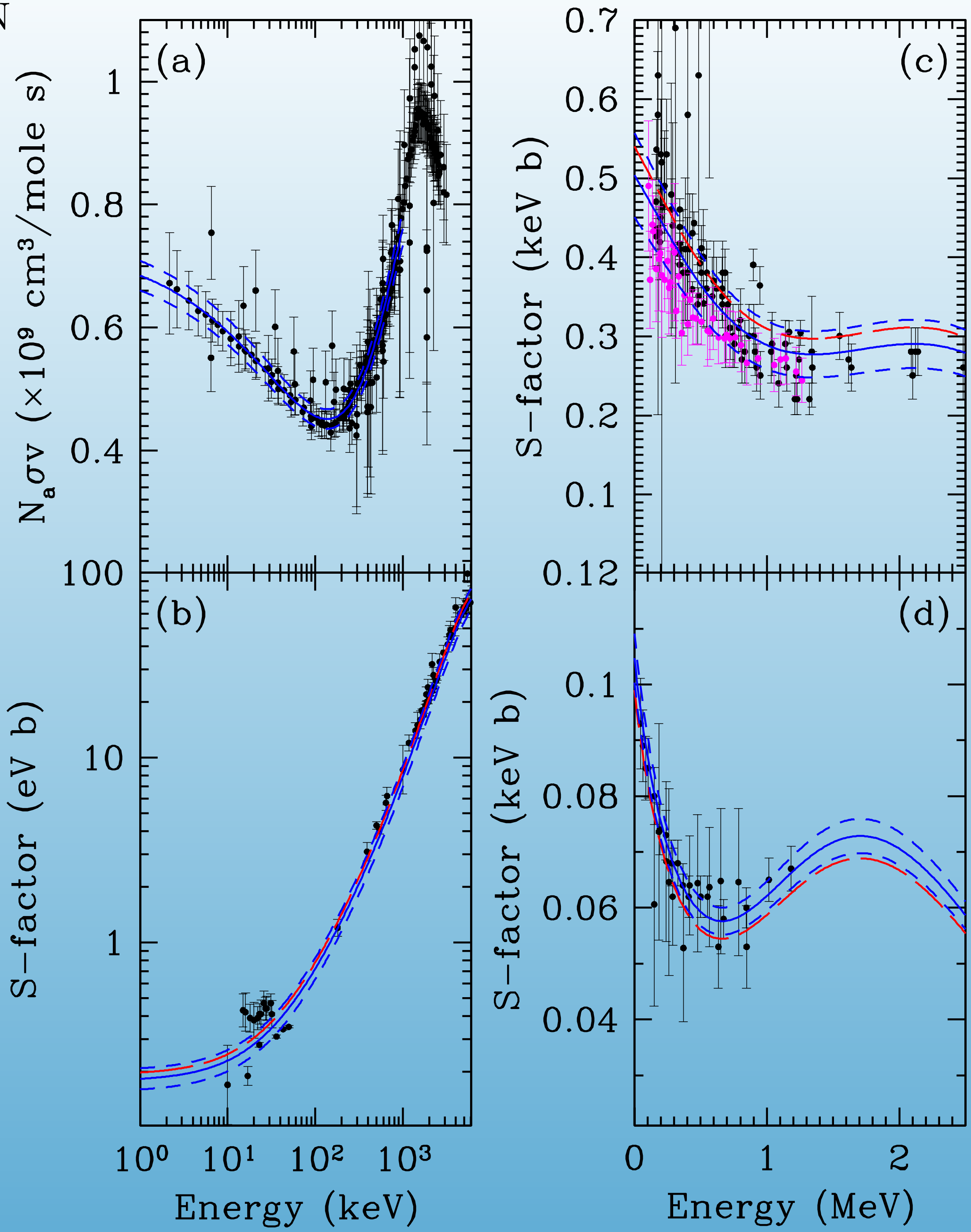
Source	Reactions	
NACRE	$d(p,\gamma)^3$He	(b)
	$d(d,n)^3$He	
	$d(d,p)t$	
	$t(d,n)^4$He	
	$t(\alpha,\gamma)^7$Li	(d)
	^{3}He$(\alpha,\gamma)^7$Be	(c)
	^{7}Li$(p,\alpha)^4$He	
SKM	$p(n,\gamma)d$	
	^{3}He$(d,p)^4$He	
	^{7}Be$(n,p)^7$Li	(See below)
This work	^{3}He$(n,p)t$	(a)
PDG	τ_n	

NACRE

Cyburt, Fields, KAO

Nollett & Burles

Coc et al.



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

$\Longrightarrow$ growth of stellar nucleosynthesis

But,

Questions persisted:

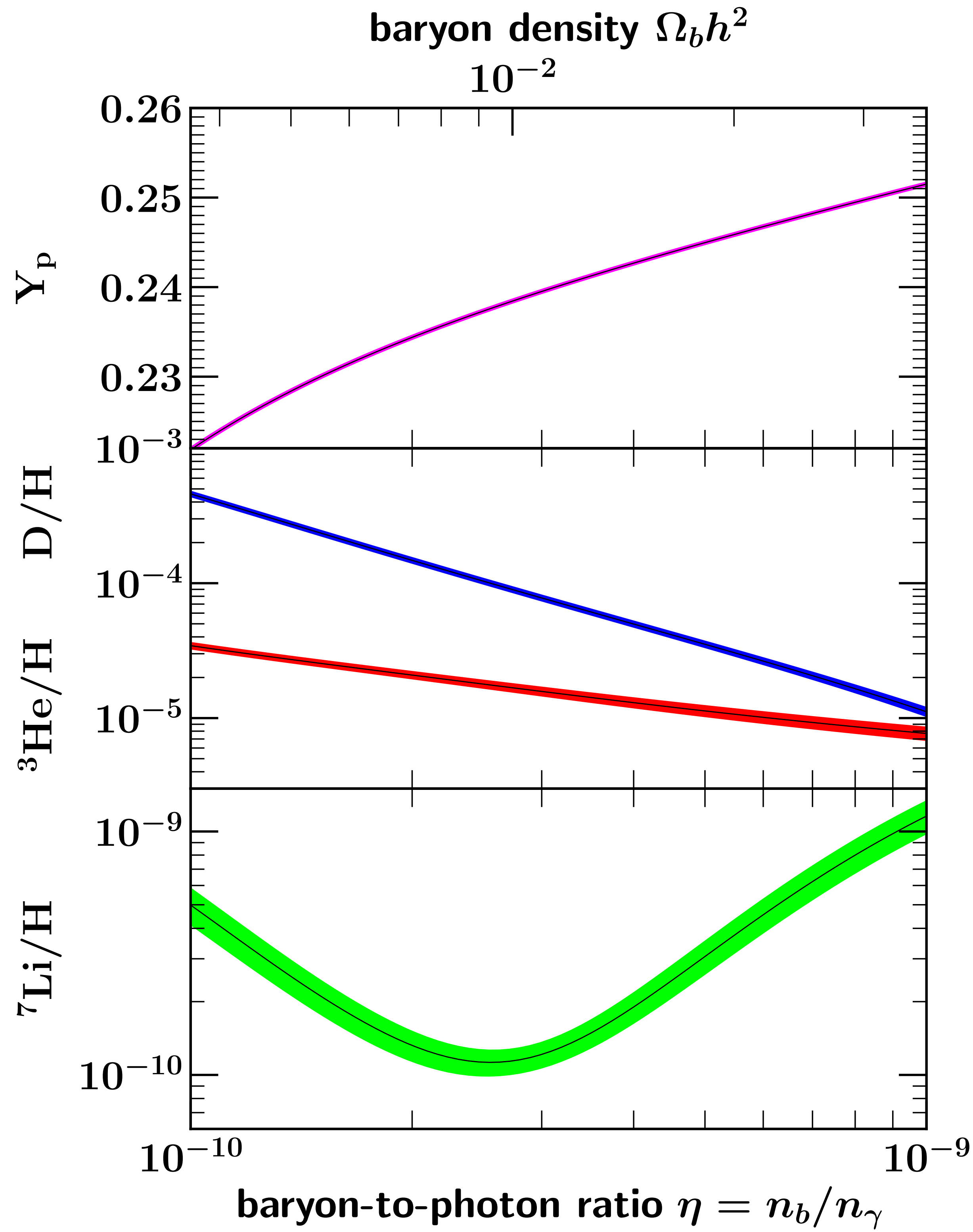
25% (by mass) of ^{4}He ?

D?

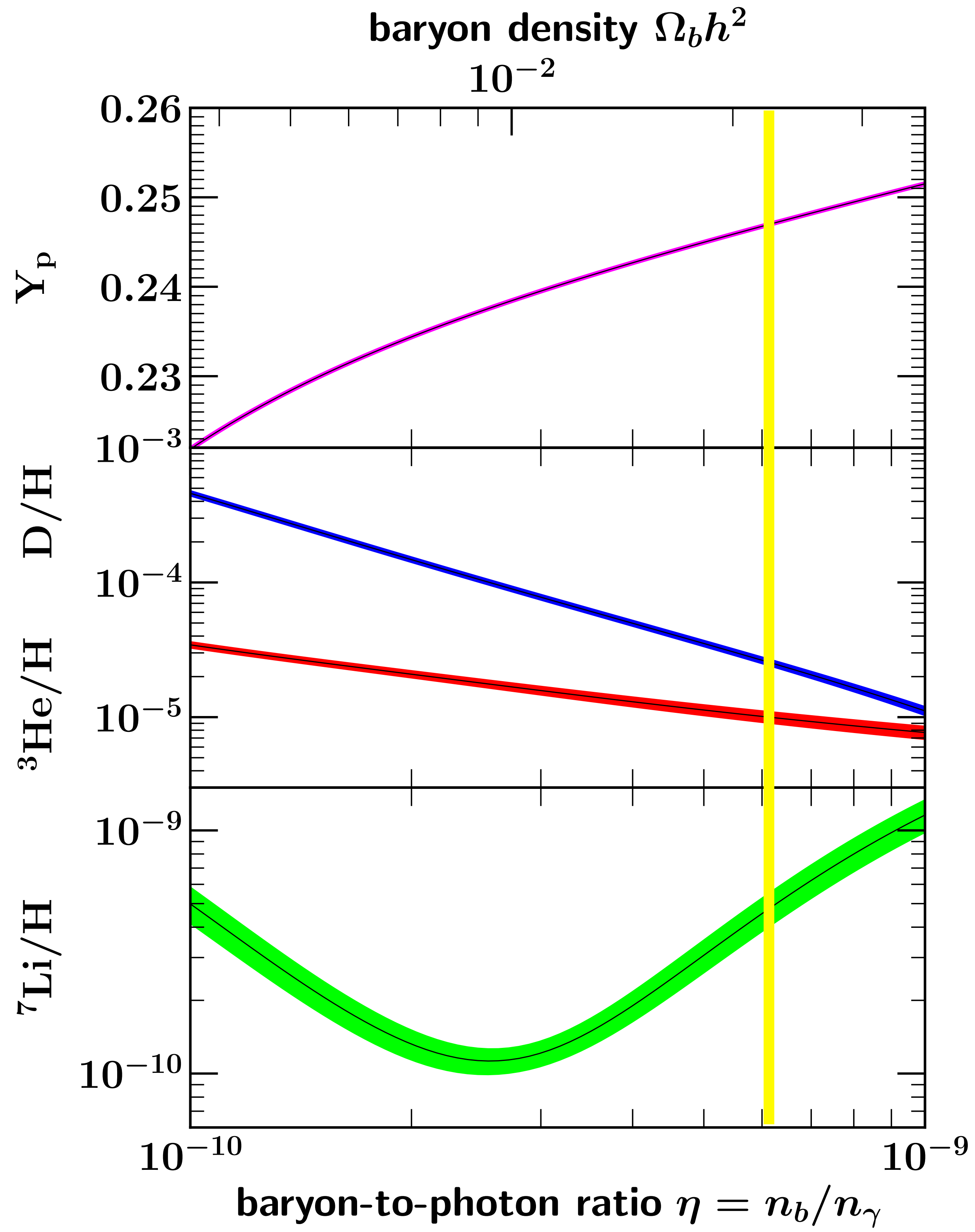
Resurgence:

BBN could successfully account for the abundance of

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

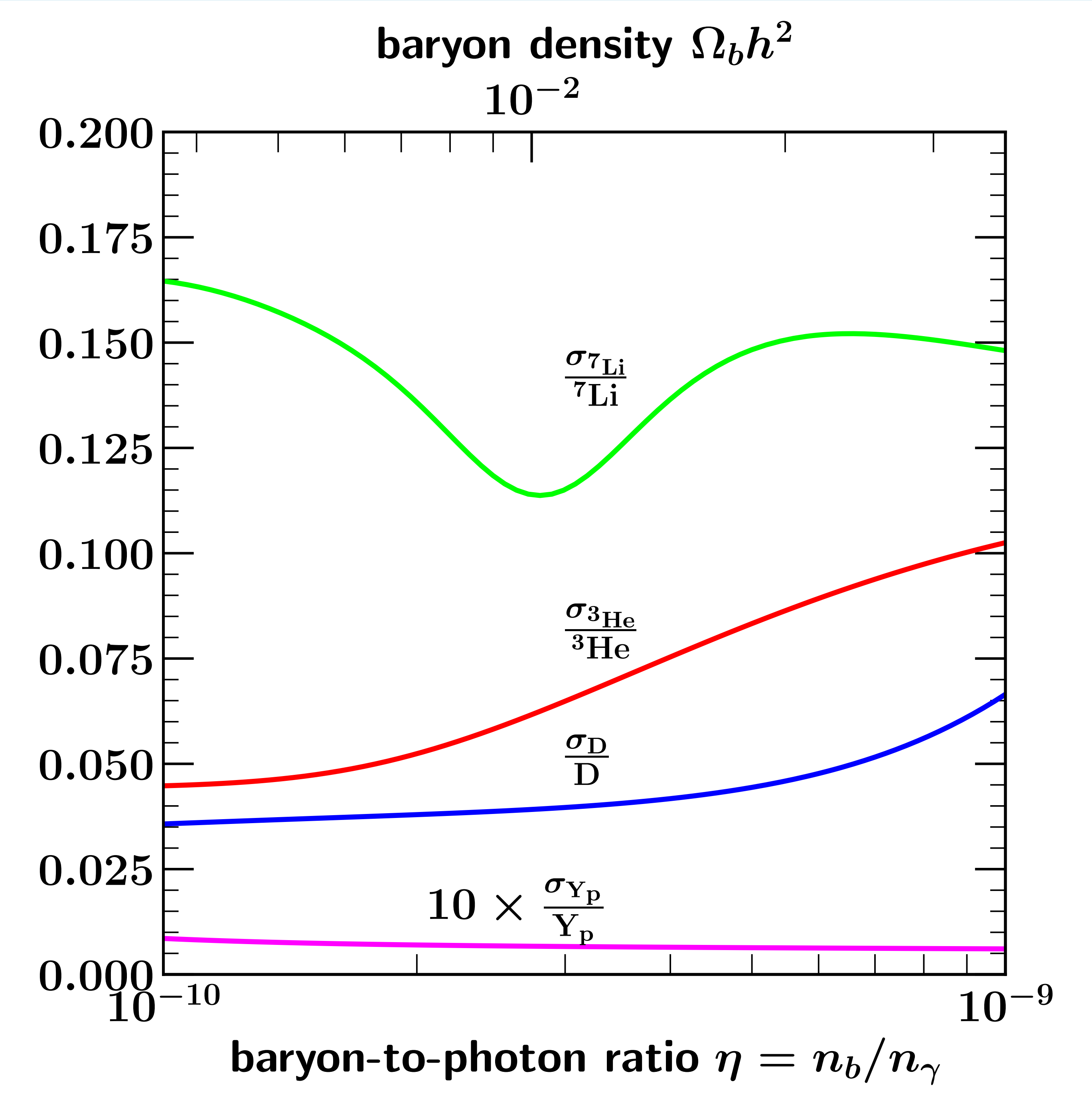


Fields, Olive, Yeh, Young



Fields, Olive, Yeh, Young

Uncertainties



Fields, Olive, Yeh, Young

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

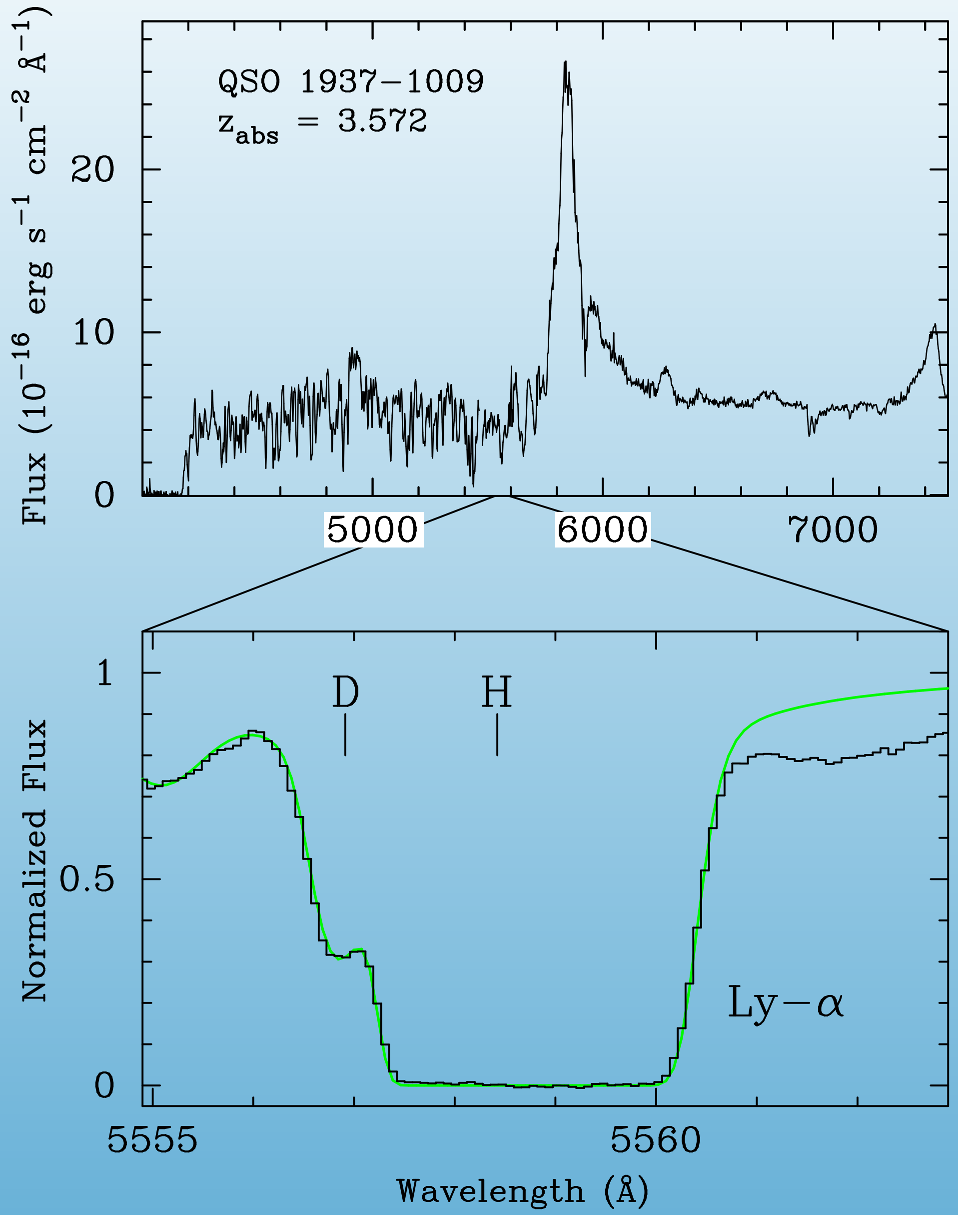
- All Observed D is Primordial!
- Observed in the ISM and inferred from meteoritic samples (also HD in Jupiter)
- D/H observed in Quasar Absorption systems

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

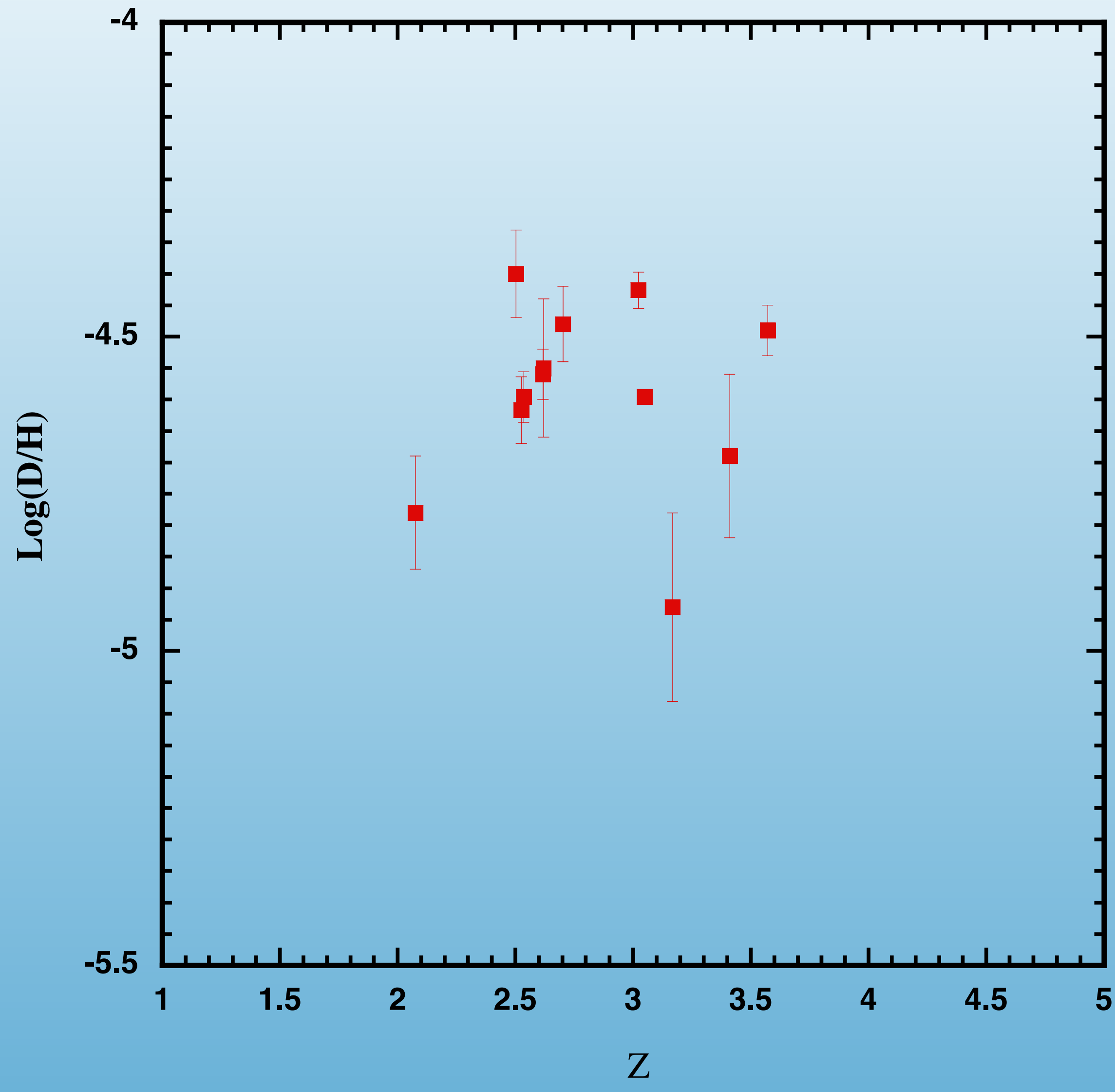
[a]We adopt the solar value $\log_{10}$ (O/H) + 12 = 8.69 (Asplund et al. 2009).

Cooke et al.



Tytler, O'Meara, Suzuki, Lubin

D/H abundances in Quasar absorption systems



BBN Prediction:

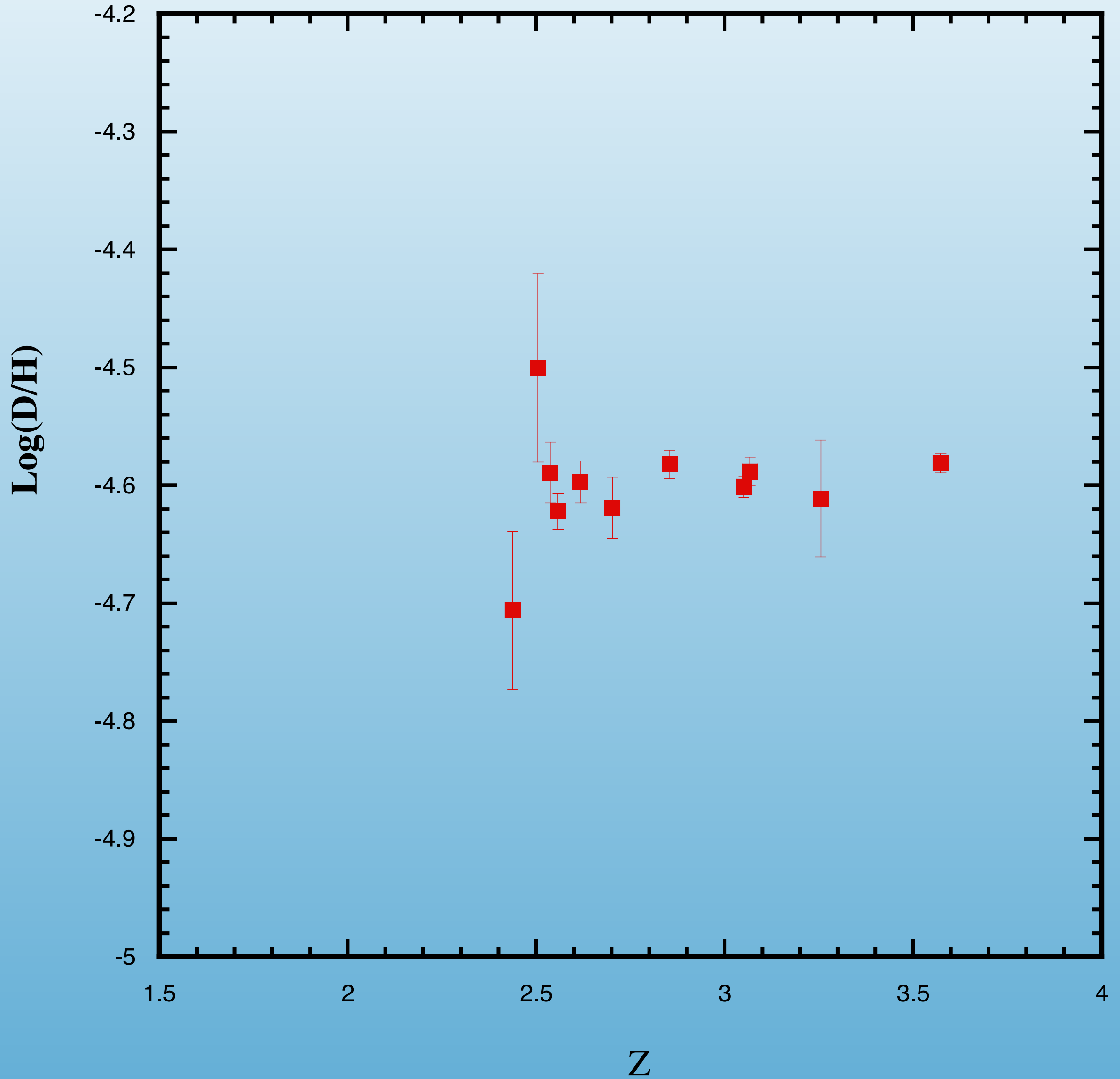
10^5 D/H = 2.58 ± 0.13

Obs Average:

10^5 D/H = 3.01 ± 0.21

(0.68 sample variance)

Updated D/H abundances in Quasar absorption systems



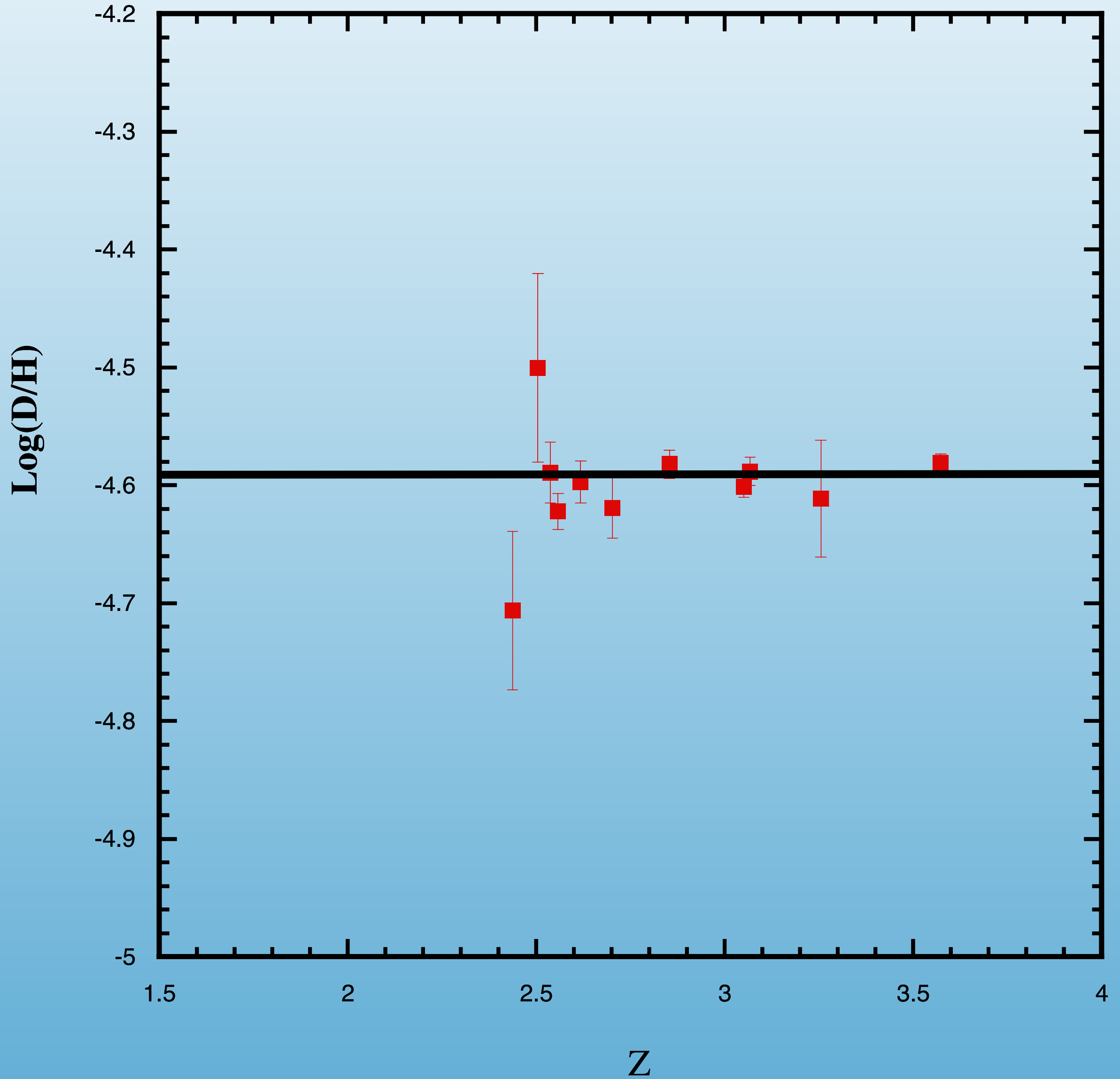
BBN Prediction:

10^5 D/H = 2.51 ± 0.11

Obs Average:

10^5 D/H = 2.55 ± 0.03

Updated D/H abundances in Quasar absorption systems



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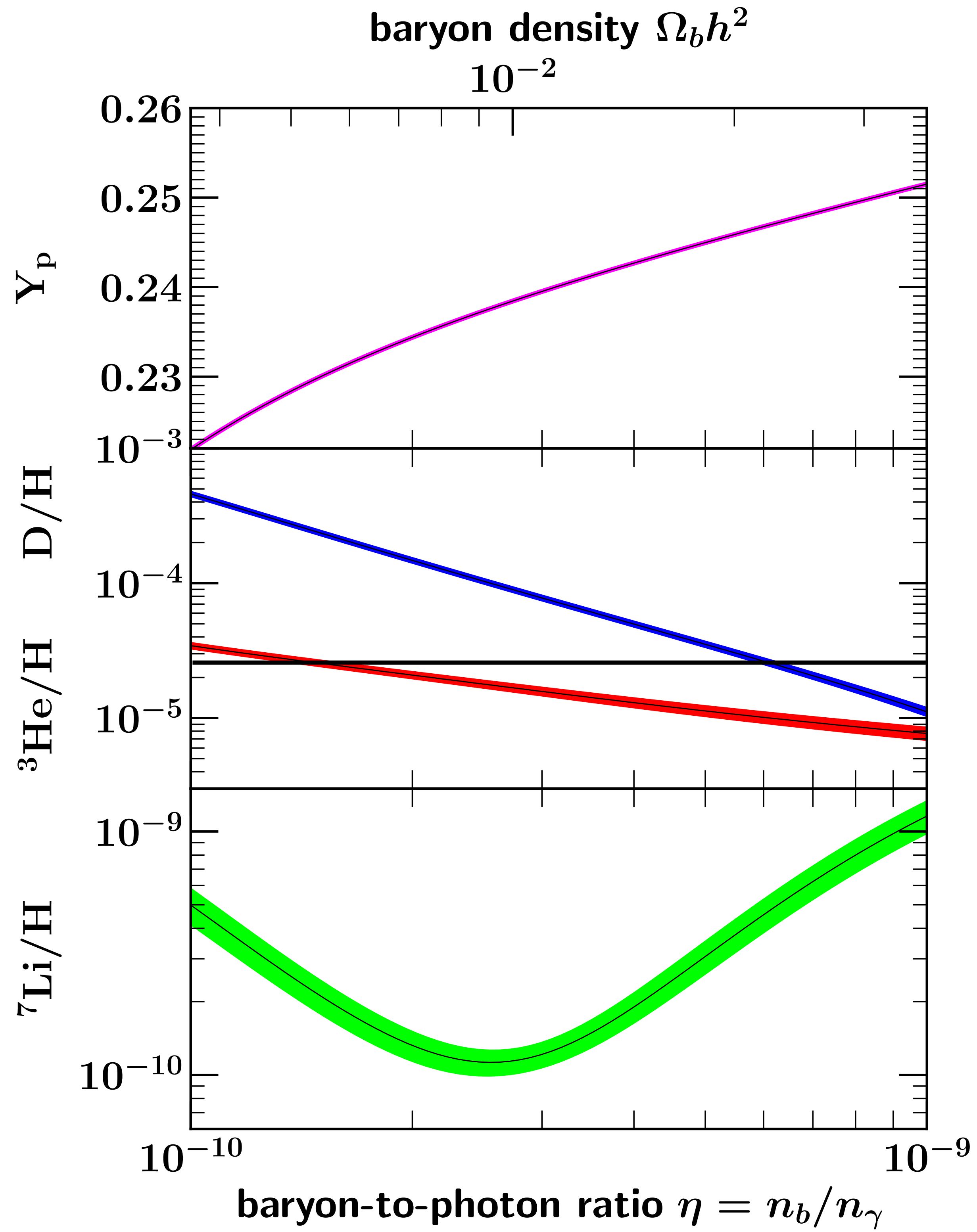
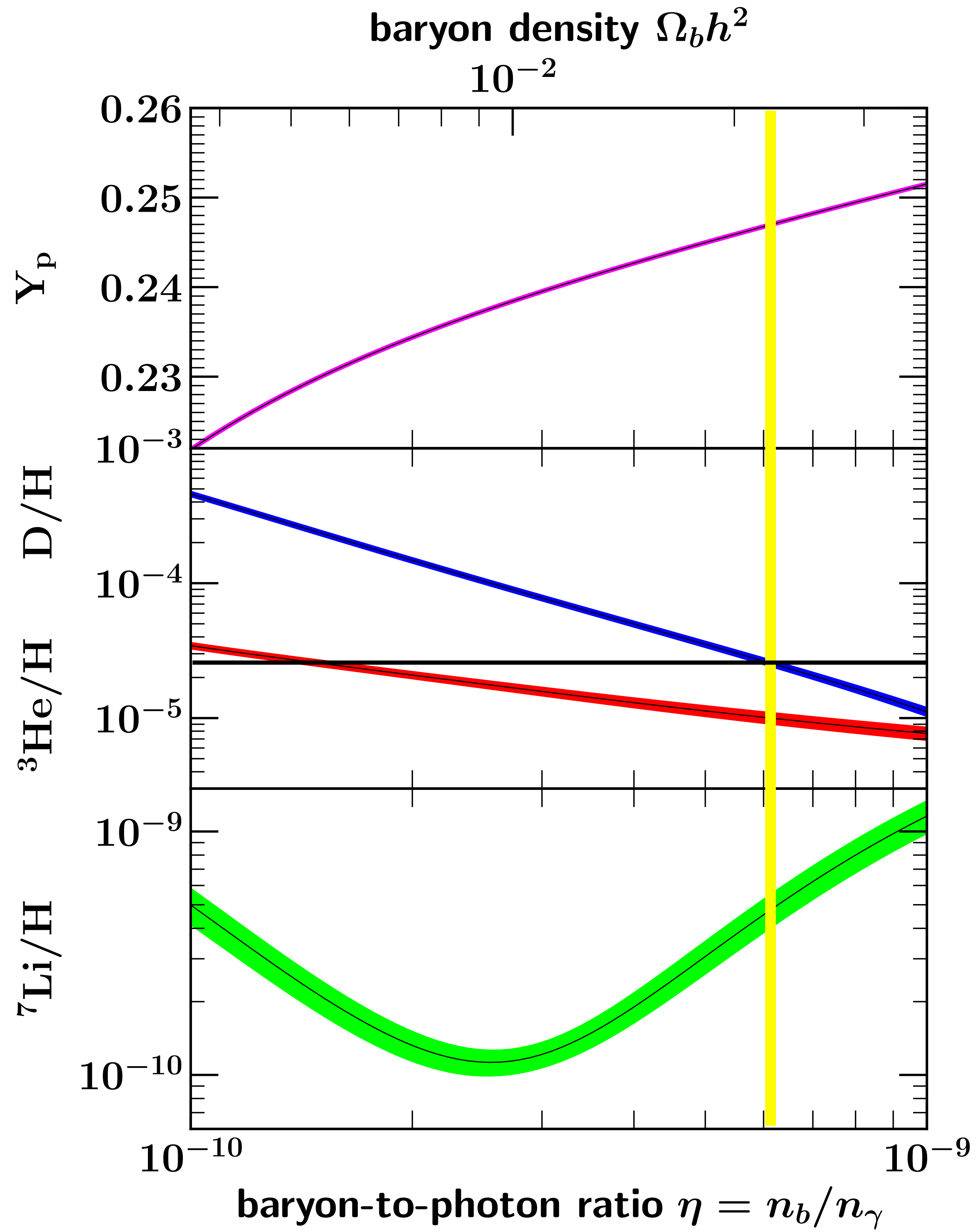
10^5 D/H = 2.55 ± 0.03



Fields, Olive, Yeh, Young

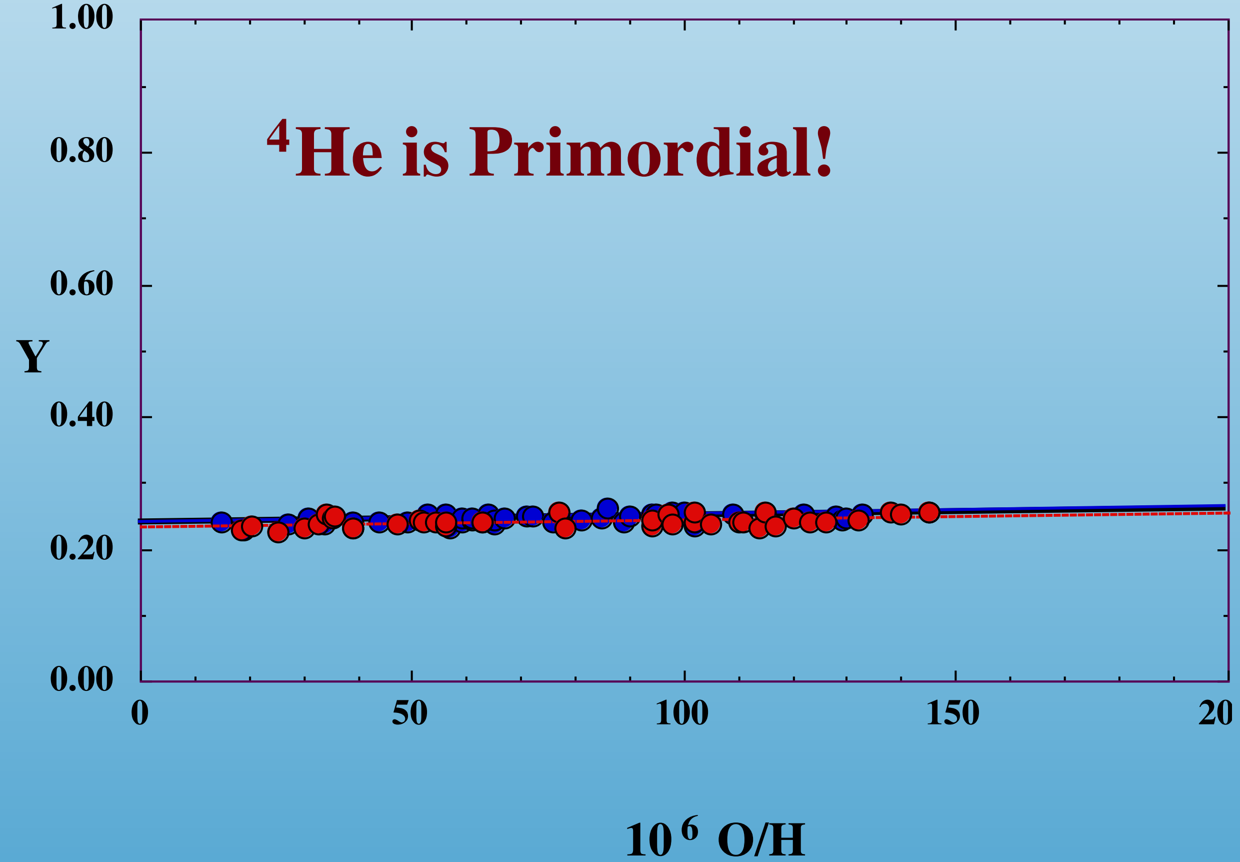


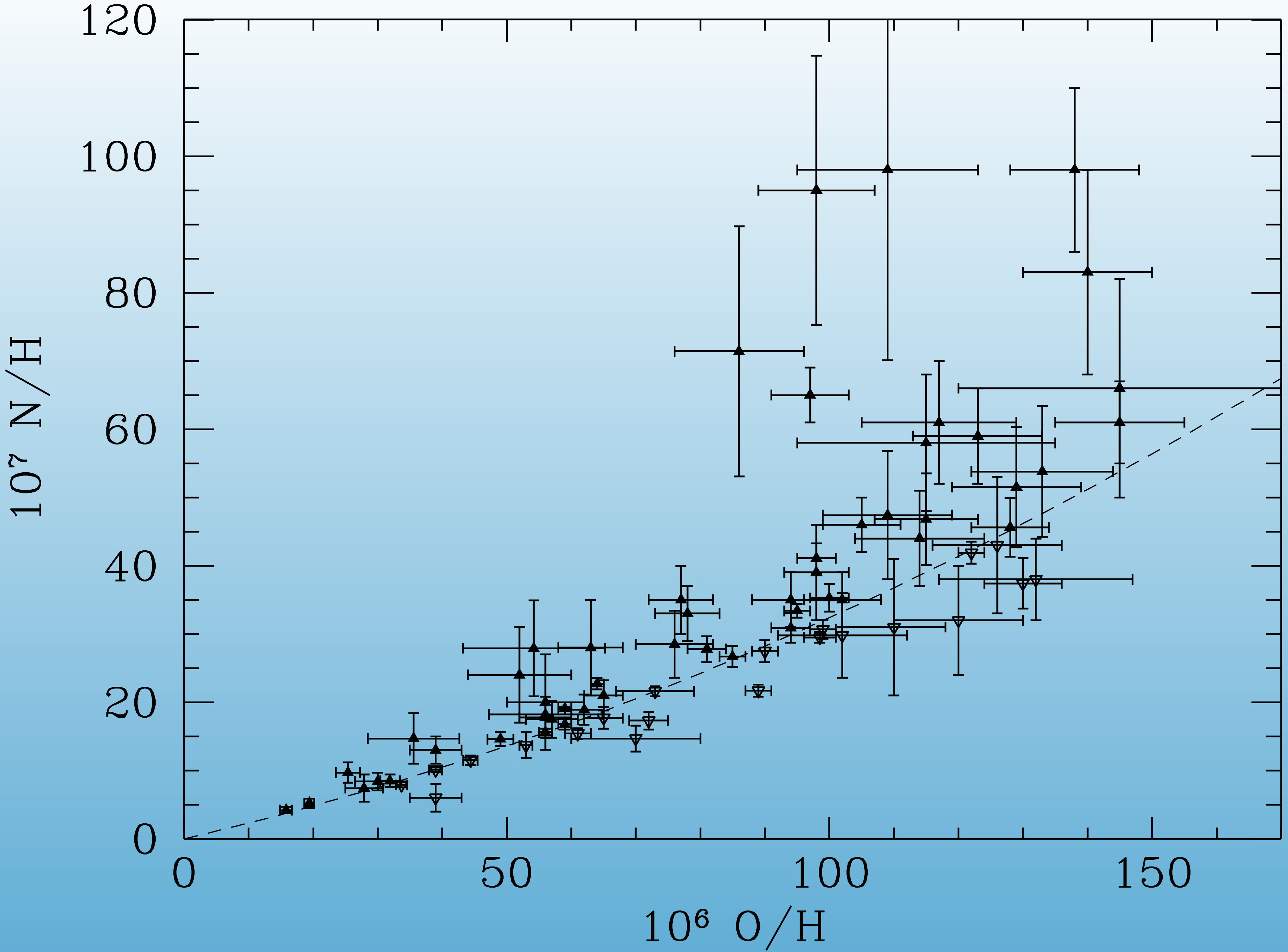
Fields, Olive, Yeh, Young

^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
10⁷ N/H
10⁶ O/H

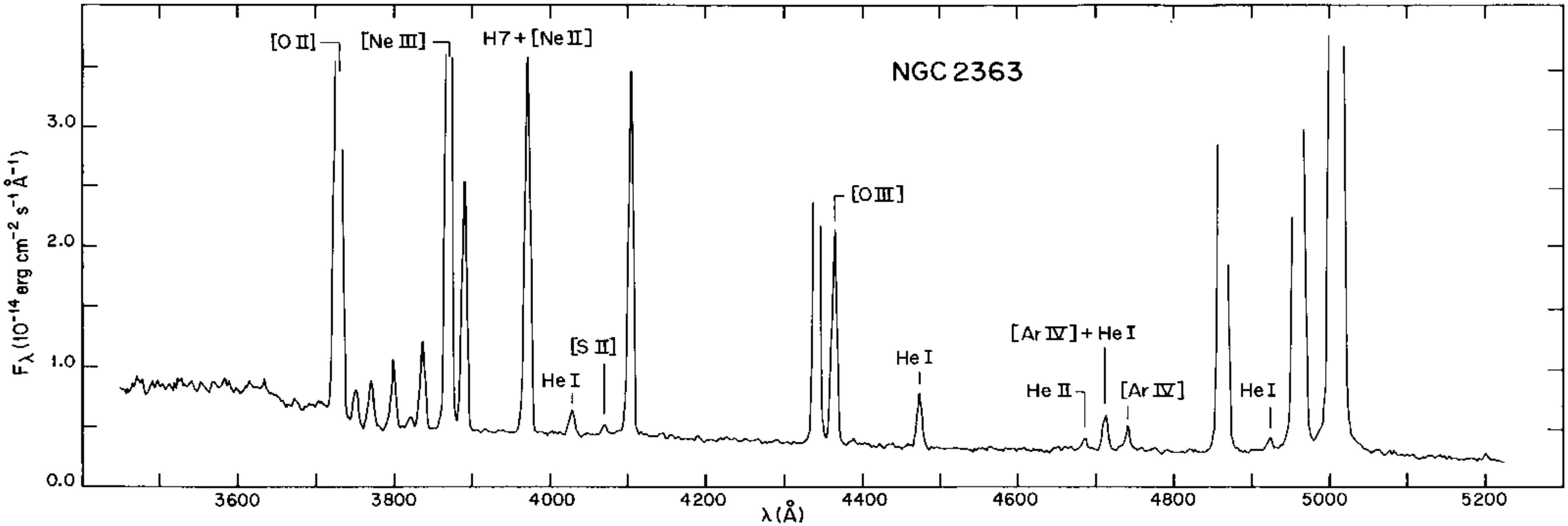


Fig. 1. Low dispersion blue spectrogram of NGC 2363, showing the faintest lines measured

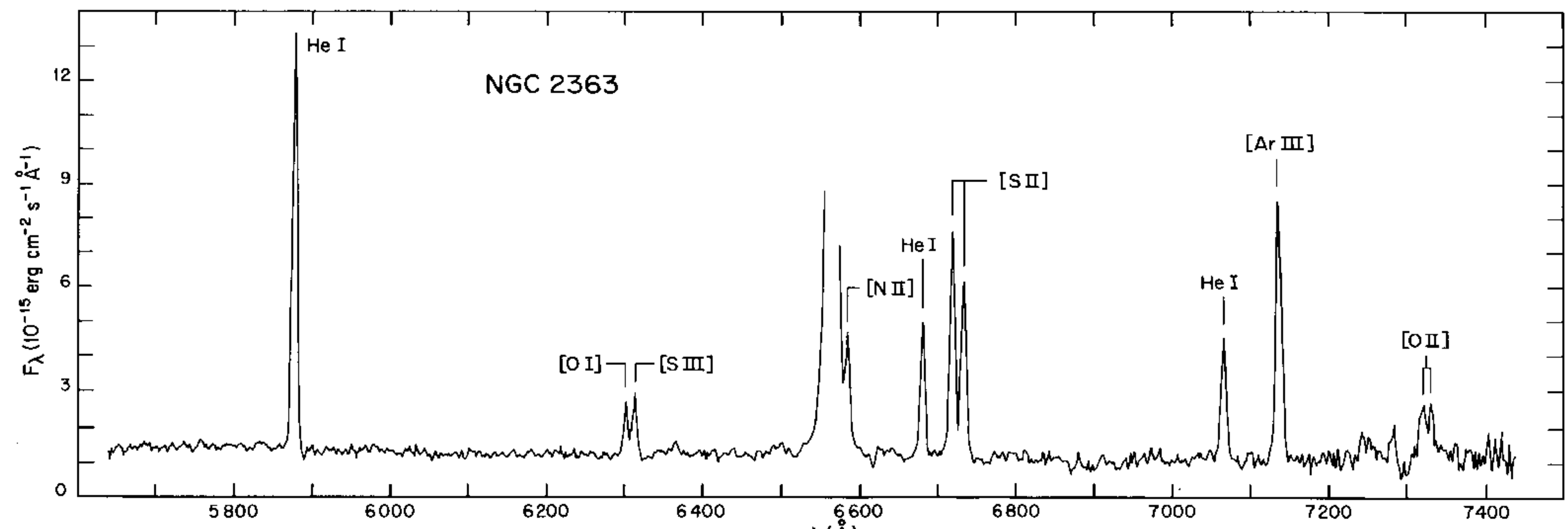


Fig. 2. Low dispersion red spectrogram of NGC 2363

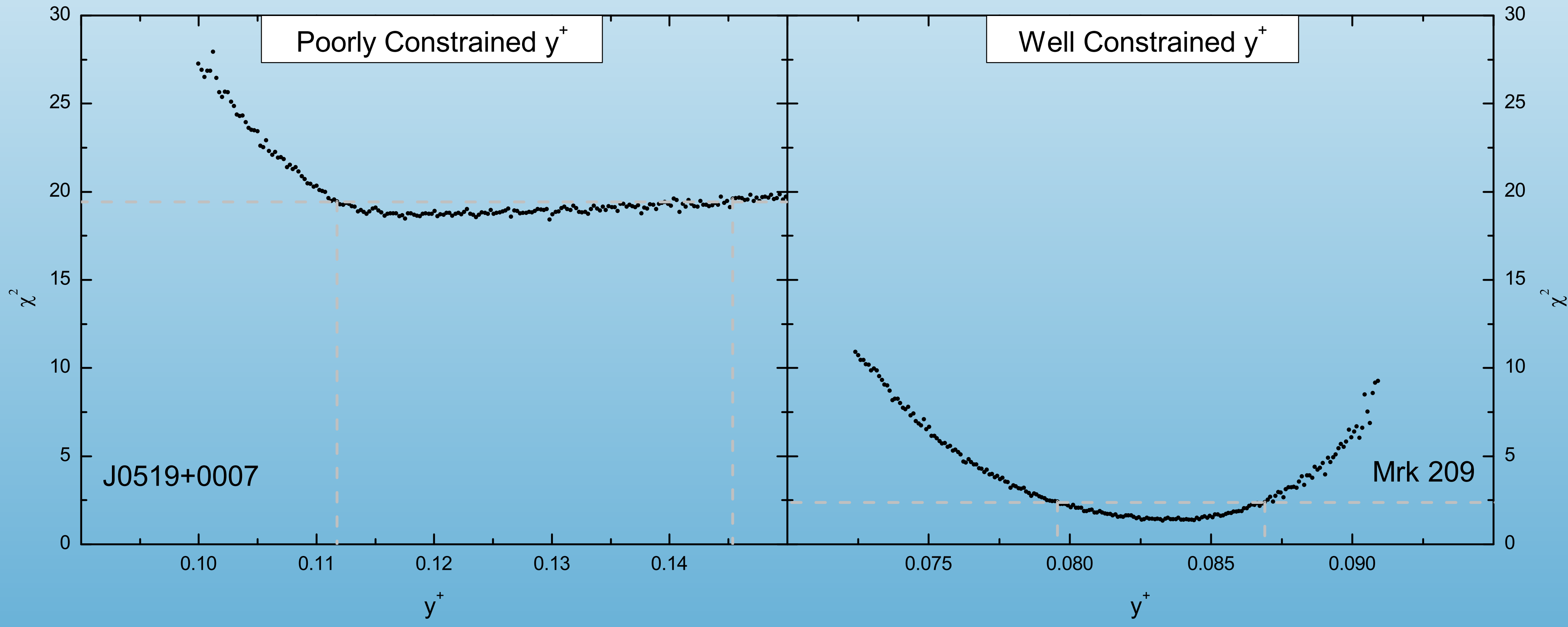
Results for He dominated by systematic effects

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

9-10 observables

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

8 parameters



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

Aver, Olive, Skillman

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).

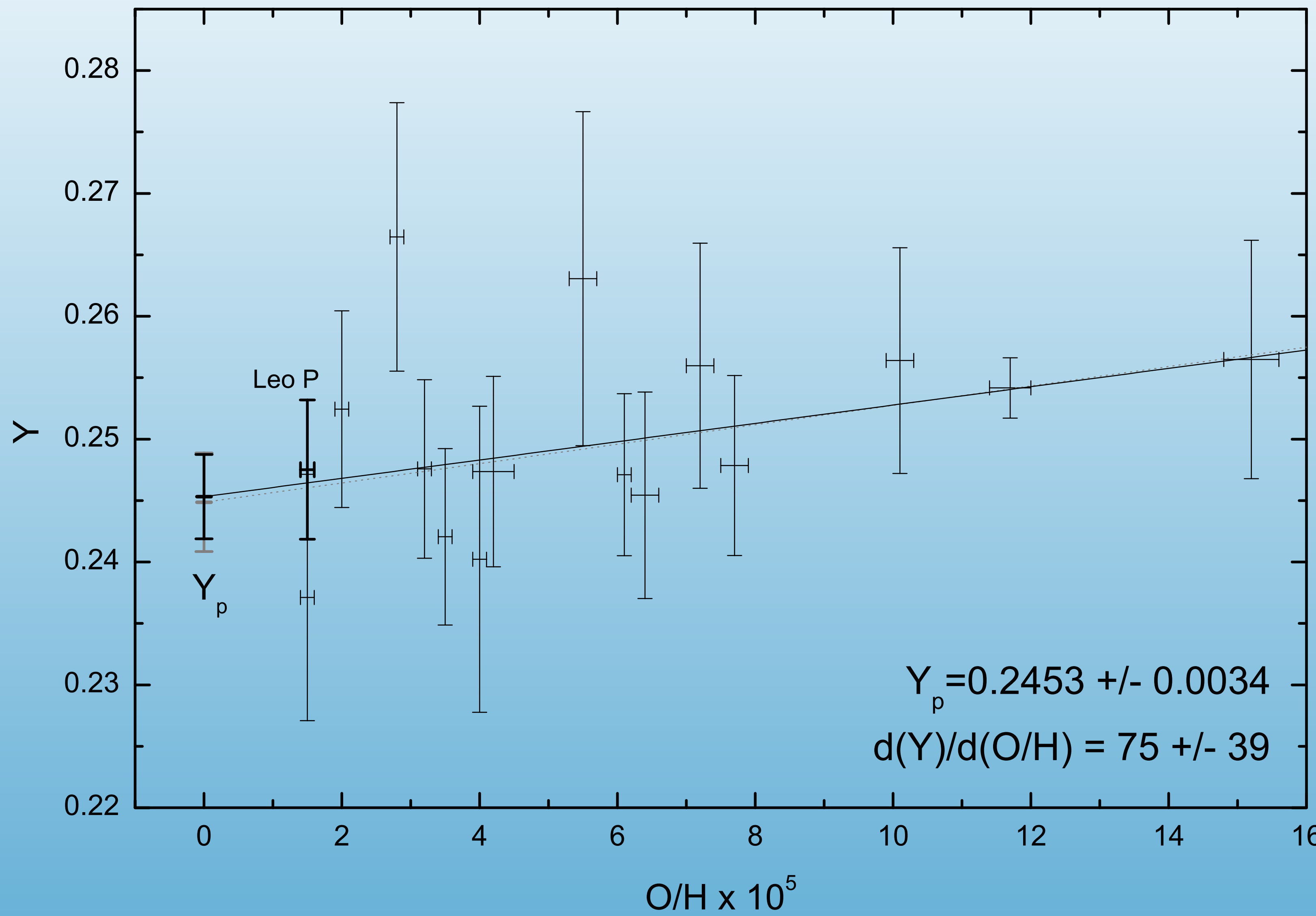
Aver, Berg, Olive, Pogge, Salzer, Skillman
2021

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%

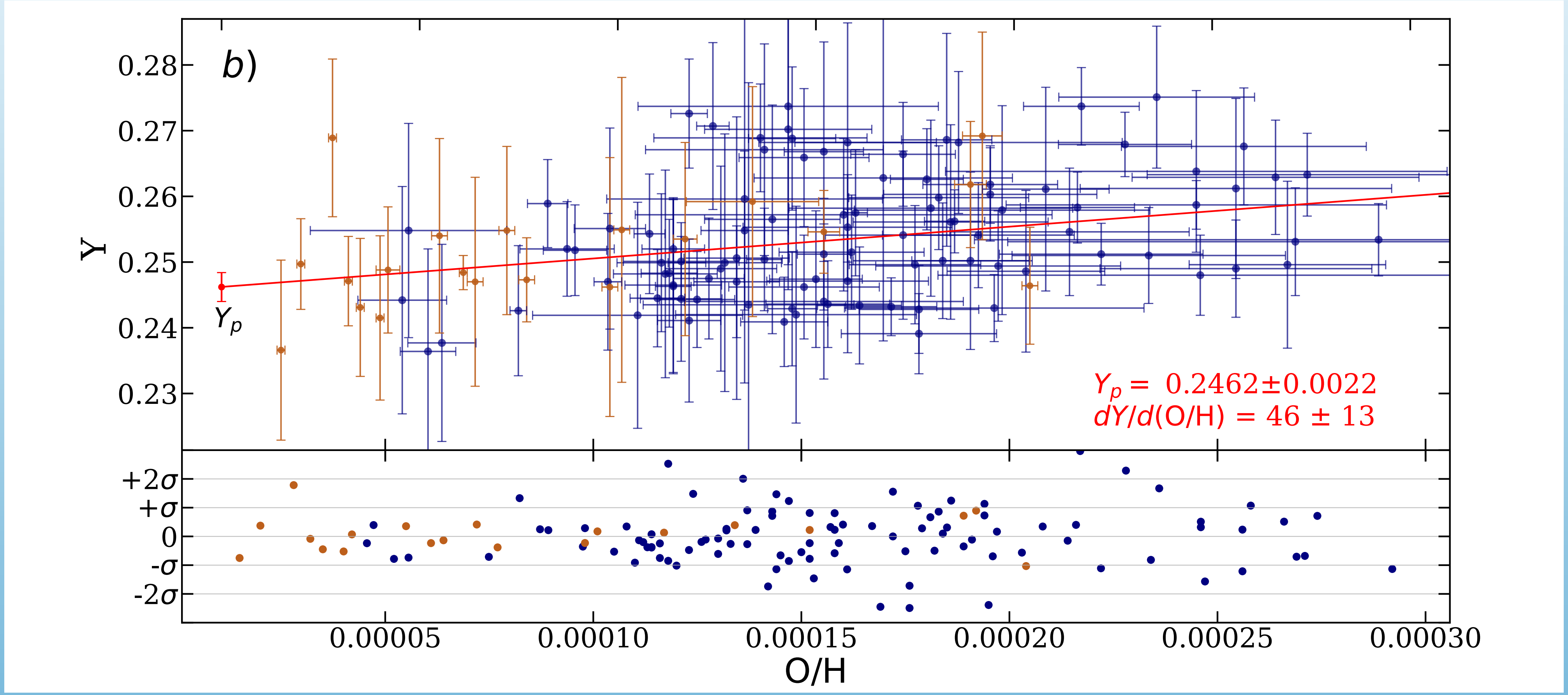


Aver, Berg, Olive, Pogge, Salzer, Skillman

prior: $Y_P = .2449 \pm 0.0040$

Adding higher metallicity regions from SDSS data

Kurichin, Kislitsyn, Klimenko
Balashev, Ivanchik



cf. Aver et al. Y_p=0.2453 +/- 0.0034

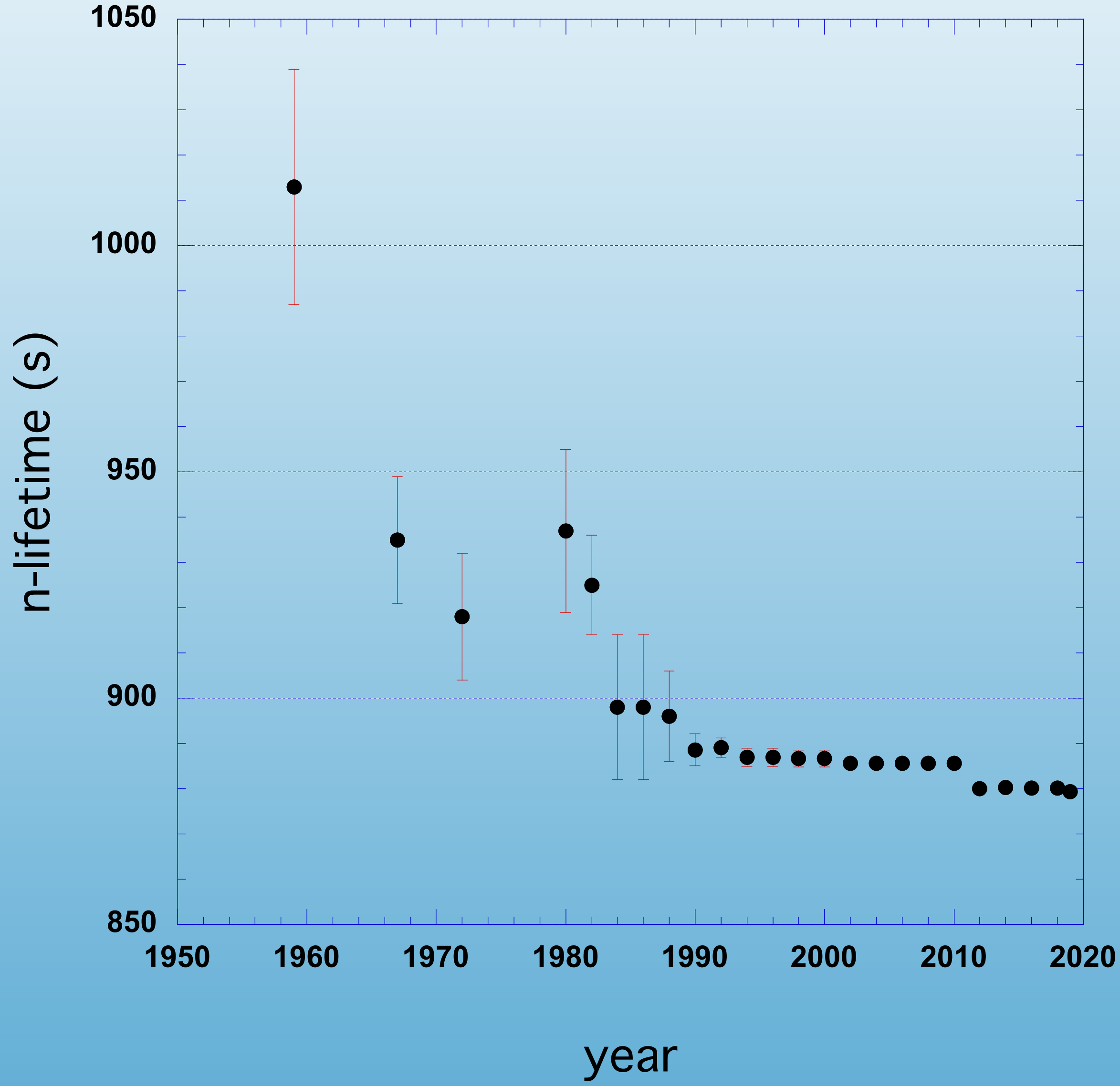
d(Y)/d(O/H) = 75 +/- 39

Neutron Lifetime

$\tau = 885.7 \rightarrow Y = .2481$

$\tau = 880.2 \rightarrow Y = .2470$

$\tau = 879.4 \rightarrow Y = .2468$



Neutron Lifetime

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$\tau = 880.2 \rightarrow Y = .2470$
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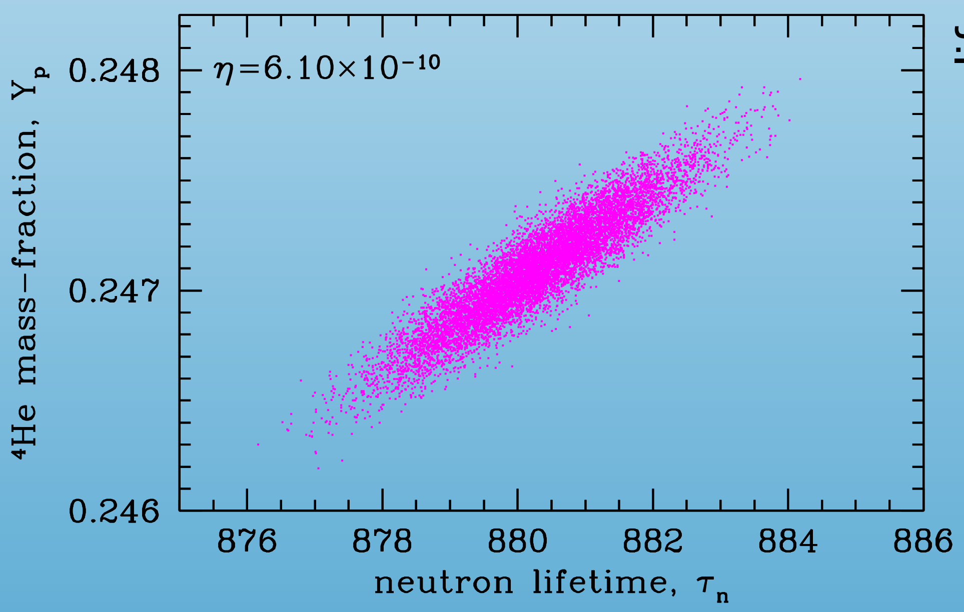
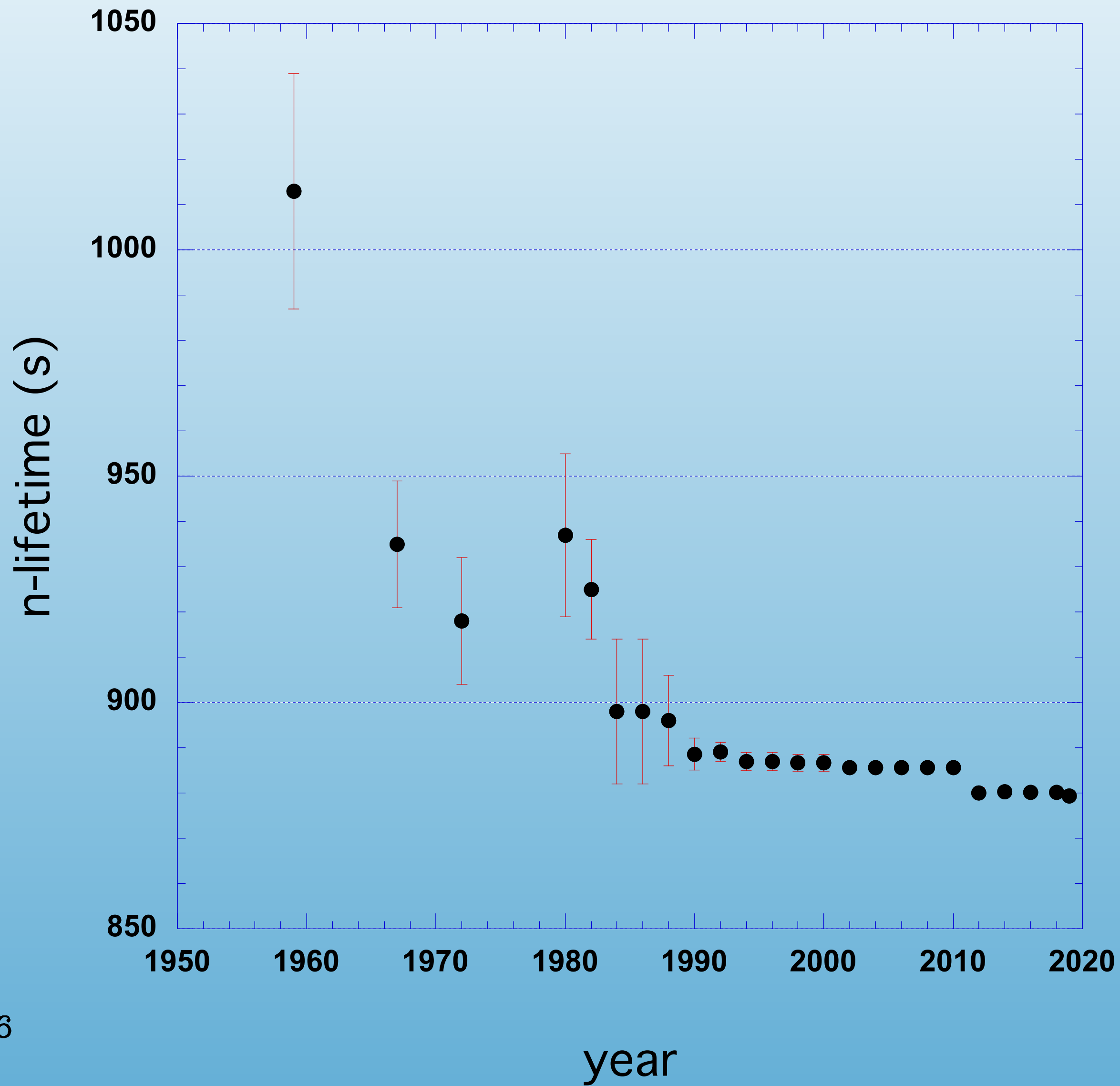
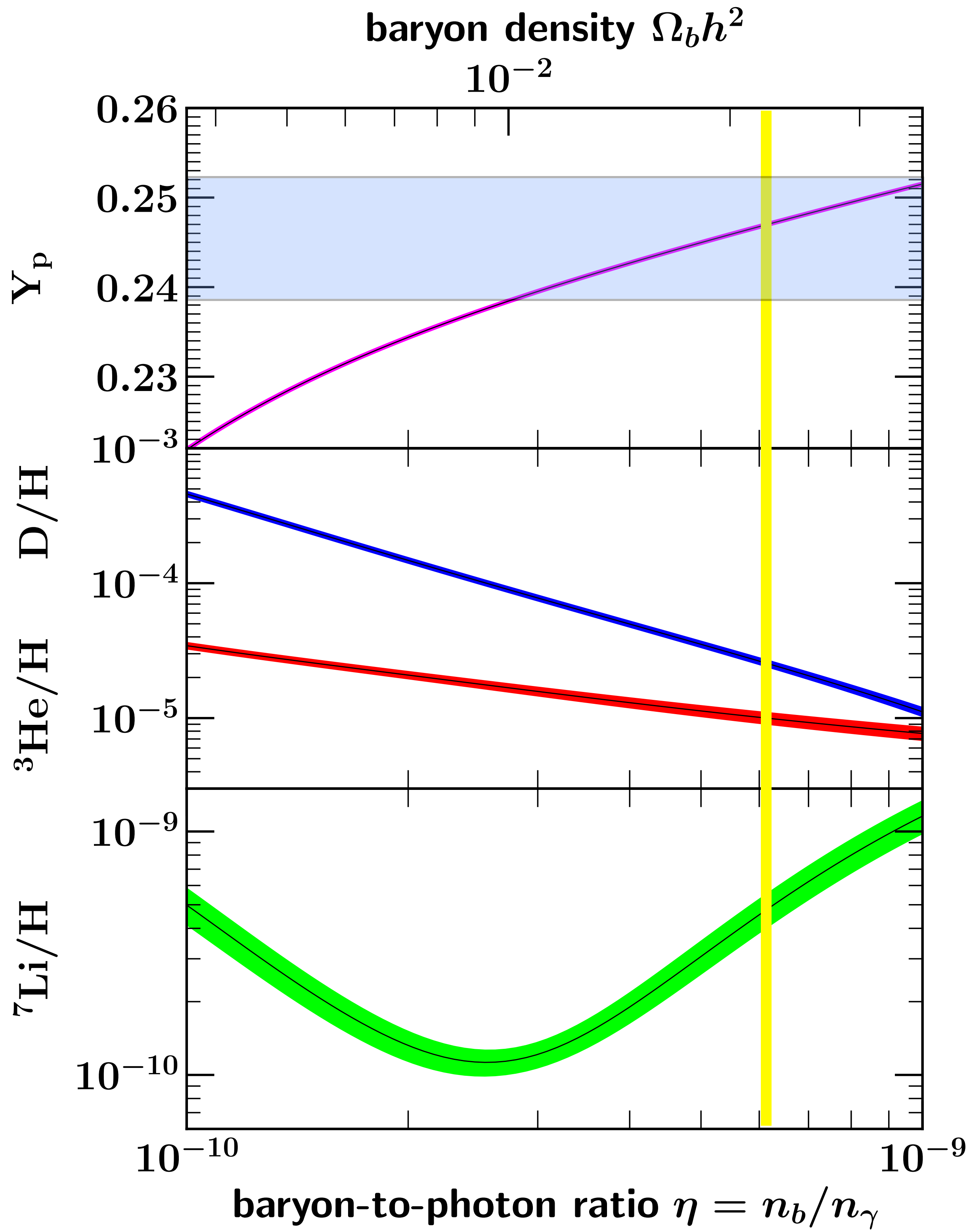




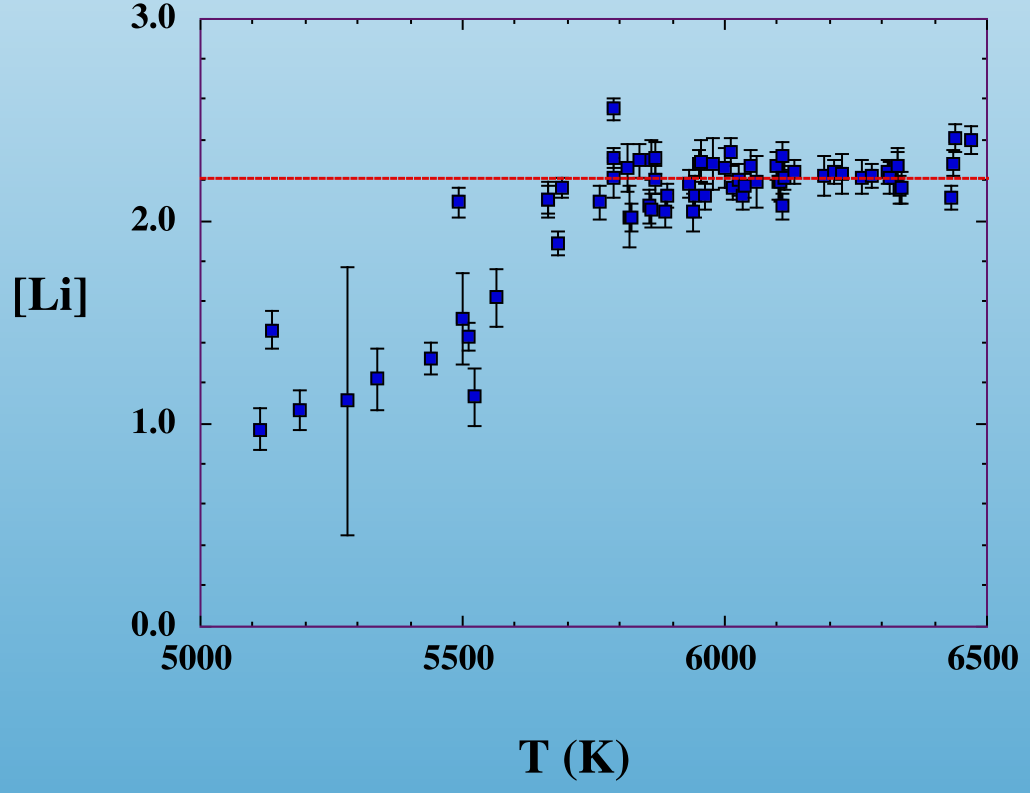
^{4}He Prediction:
0.2469 ± 0.0002

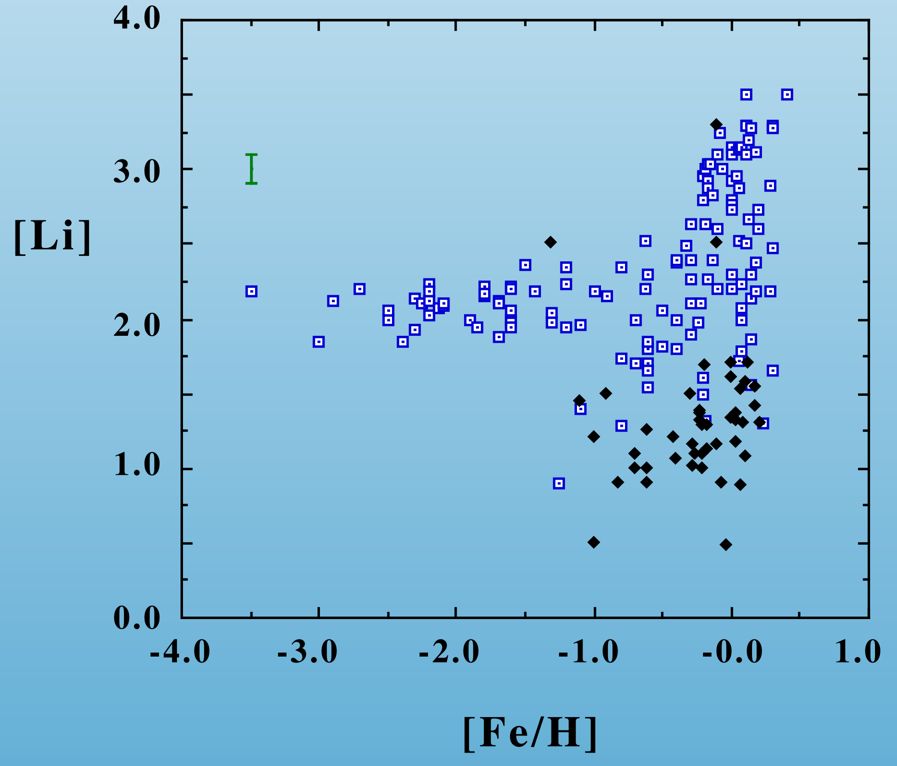
Data: Regression:
0.2453 ± 0.0034

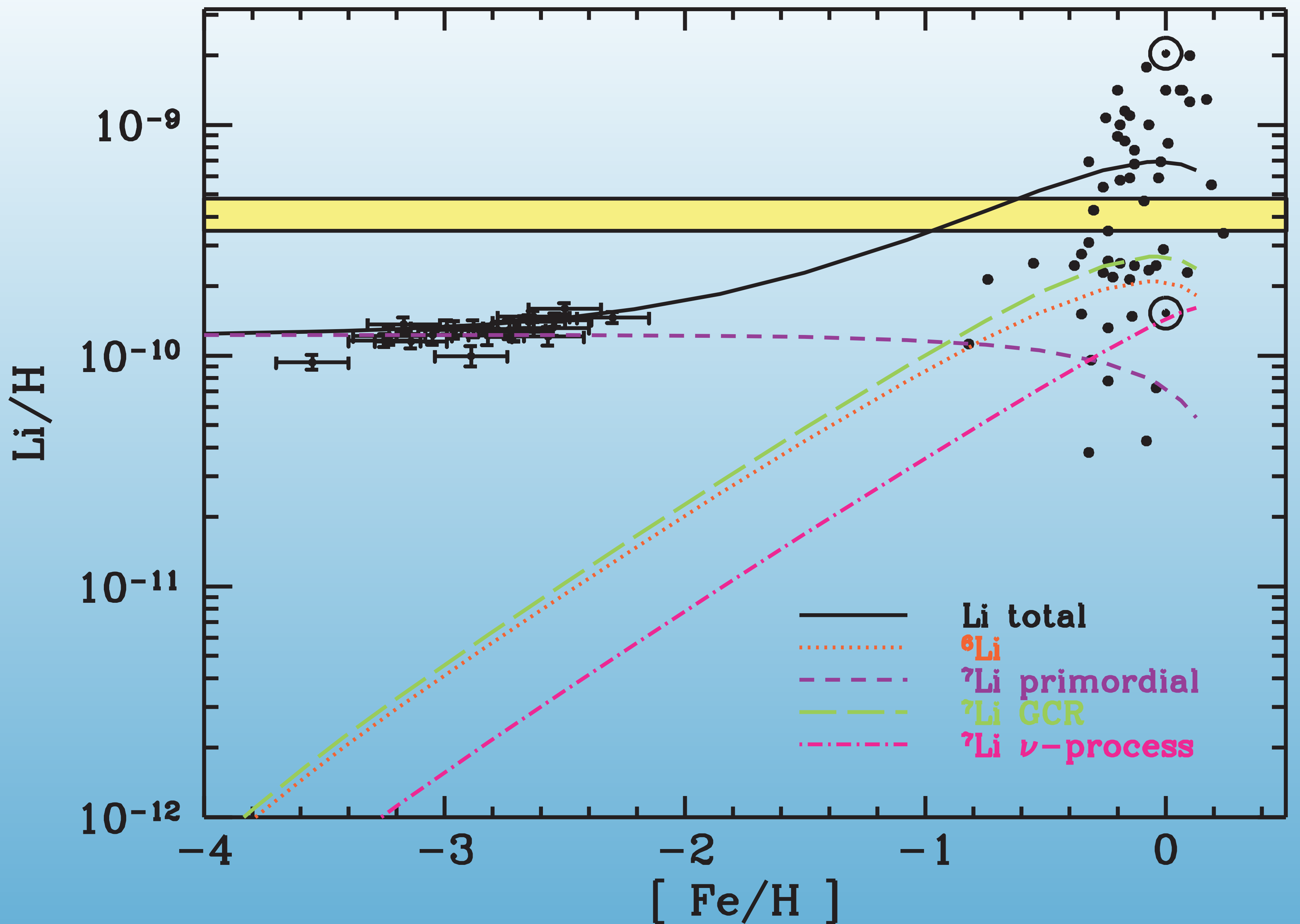


Li/H

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
^{6}Li
^{7}Li primordial
^{7}Li GCR
^{7}Li ν−process

Possible sources for the discrepancy

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- Nuclear Rates

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- Nuclear Rates
  - Restricted by solar neutrino flux

Coc et al.
Cyburt, Fields, KAO
Boyd, et al.

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  - New Measurements of $^7Be(n,p)^7Li$
  - Others: $^7Be(n,\alpha)^4He$, $^7Be(d,p)^4He^4He$

Coc et al.
Cyburt, Fields, KAO
Boyd, et al.

n-TOF;
Hou et al.
Kawabata et al.
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- Resonant reactions

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

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n-TOF;
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Rigal et al.

- Resonant reactions
  - $^7\mathrm{Be} + {}^3\mathrm{He} \rightarrow {}^{10}\mathrm{C}$

Cyburt, Pospelov
Chakraborty, Fields, Olive
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Possible sources for the discrepancy

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  - Restricted by solar neutrino flux
  - New Measurements of ^{7}Be(n,p)^{7}Li
  - Others: ^{7}Be(n,α)^{4}He, ^{7}Be(d,p)^{4}He^{4}He

Coc et al.
Cyburt, Fields, KAO
Boyd, et al.

n-TOF;
Hou et al.
Kawabata et al.
Lamia et al.
Rigal et al.

- Resonant reactions
  - ^{7}Be + ^{3}He $\rightarrow$ ^{10}C
  - Resonance at 15 MeV not seen by experiment

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

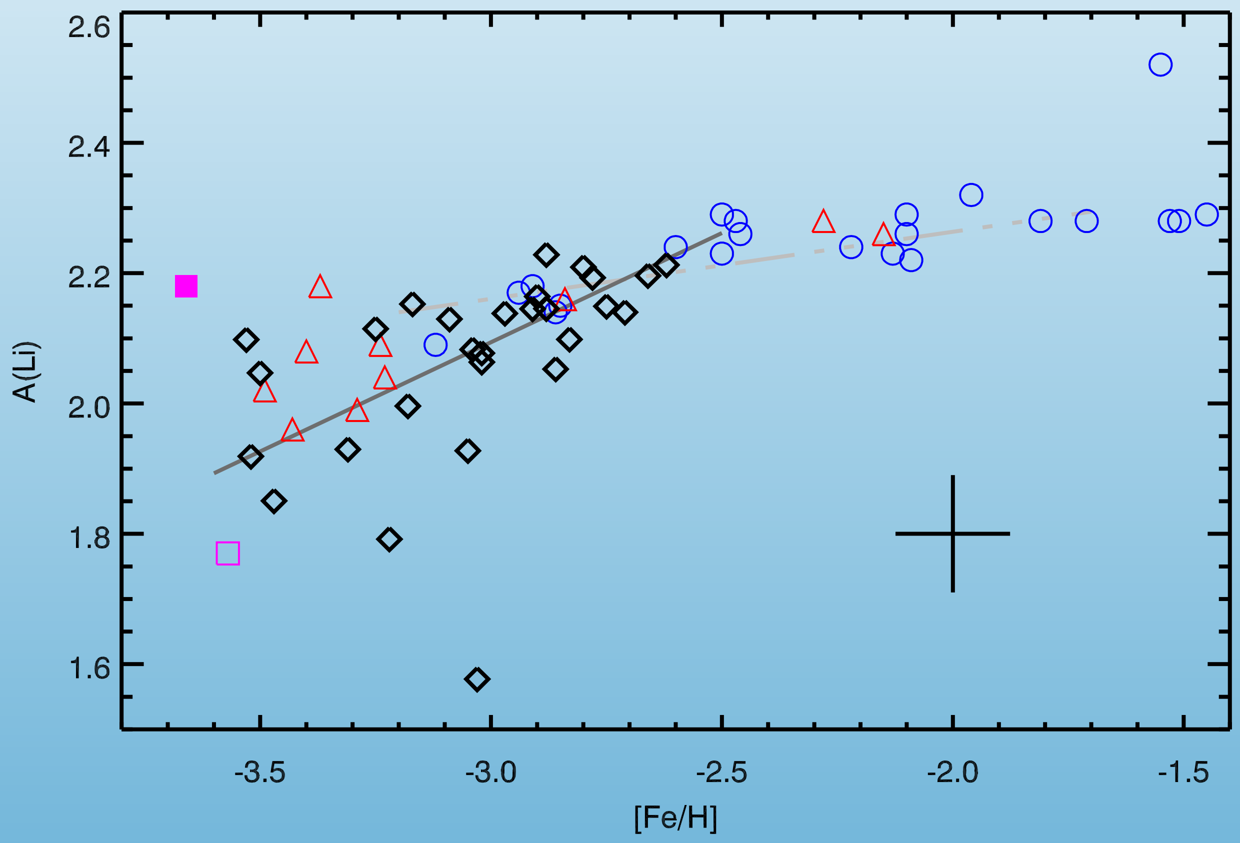
Possible sources for the discrepancy

- 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.
Fu et al.

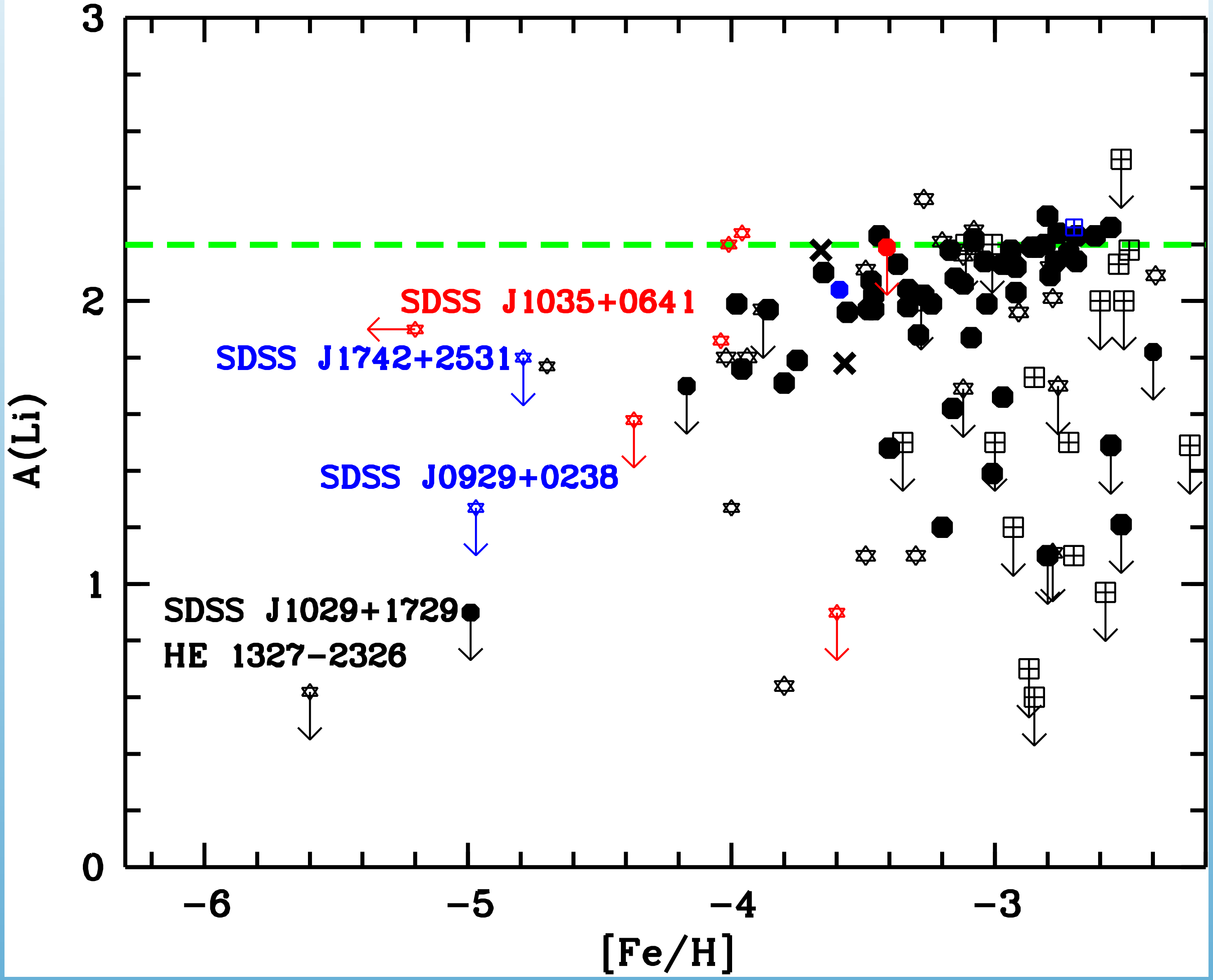
Broken Spite plateau

Note significant dispersion



Sbordone et al. (2010)

Broken Spite plateau

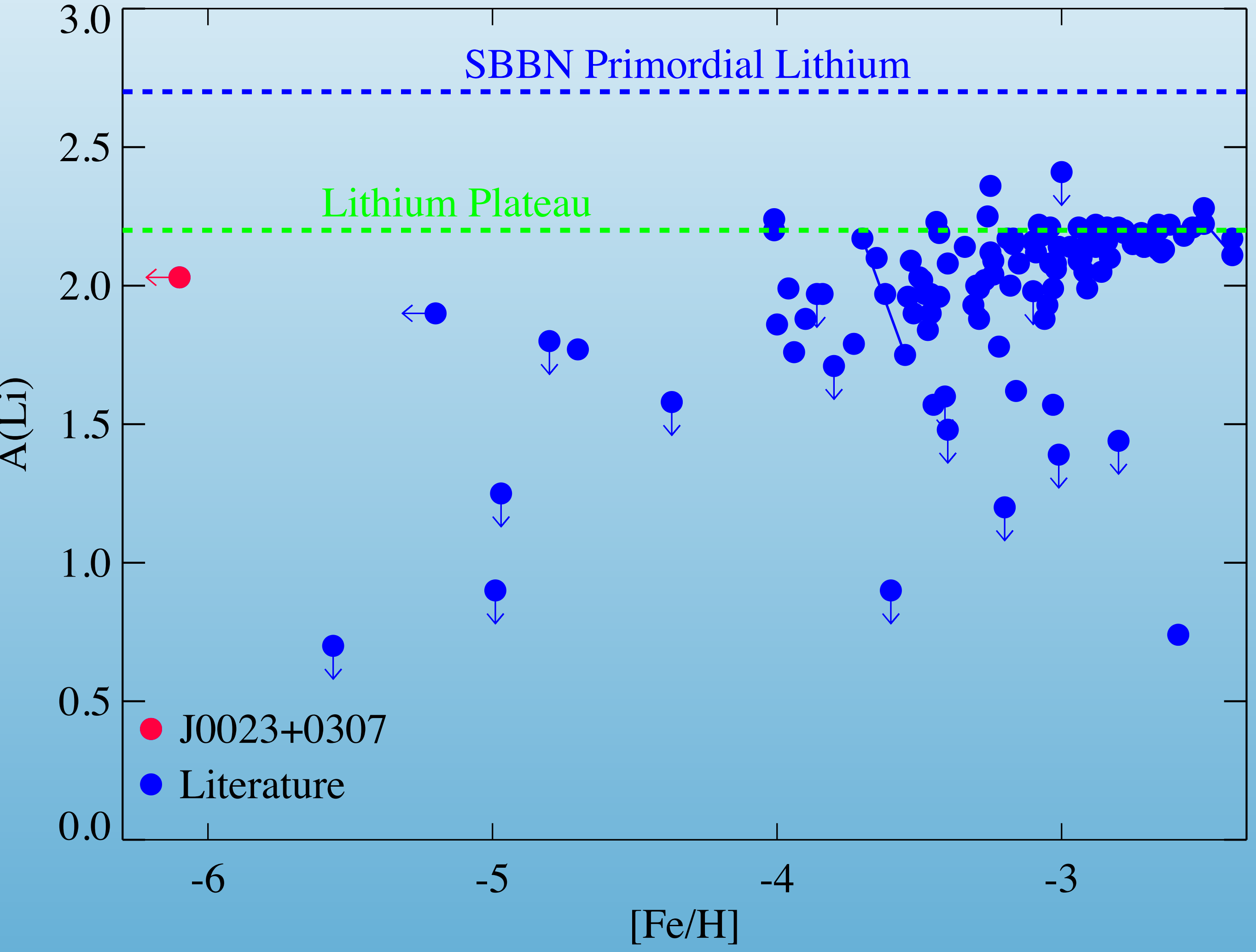


Note significant dispersion

Bonifacio et al. (2018)

Broken Spite plateau

Note significant dispersion



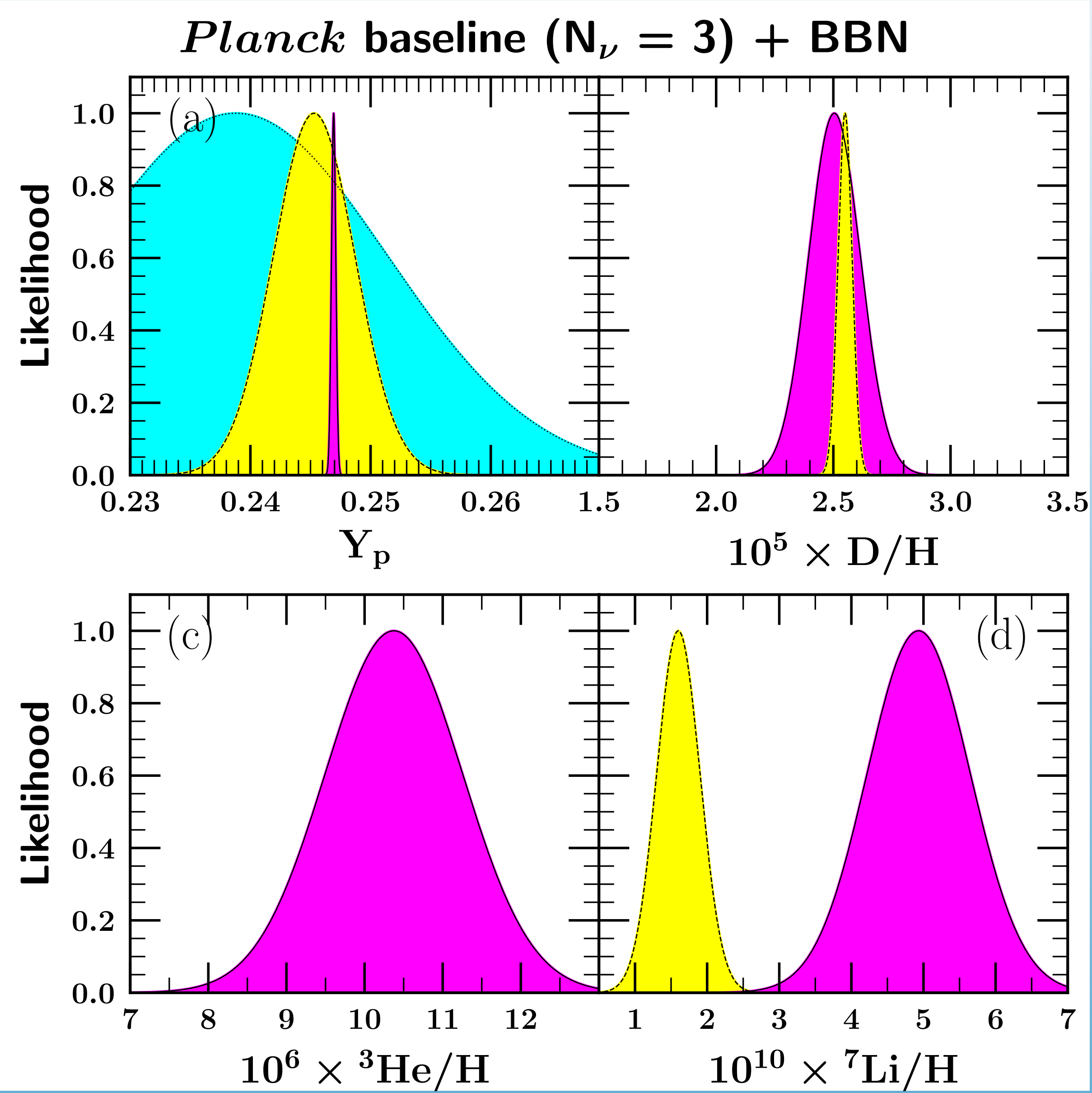
Aguado et al. (2019)

Other possible sources for the discrepancy

- Stellar parameters
- Decaying Particles
- Axion Cooling
- Variable Constants

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

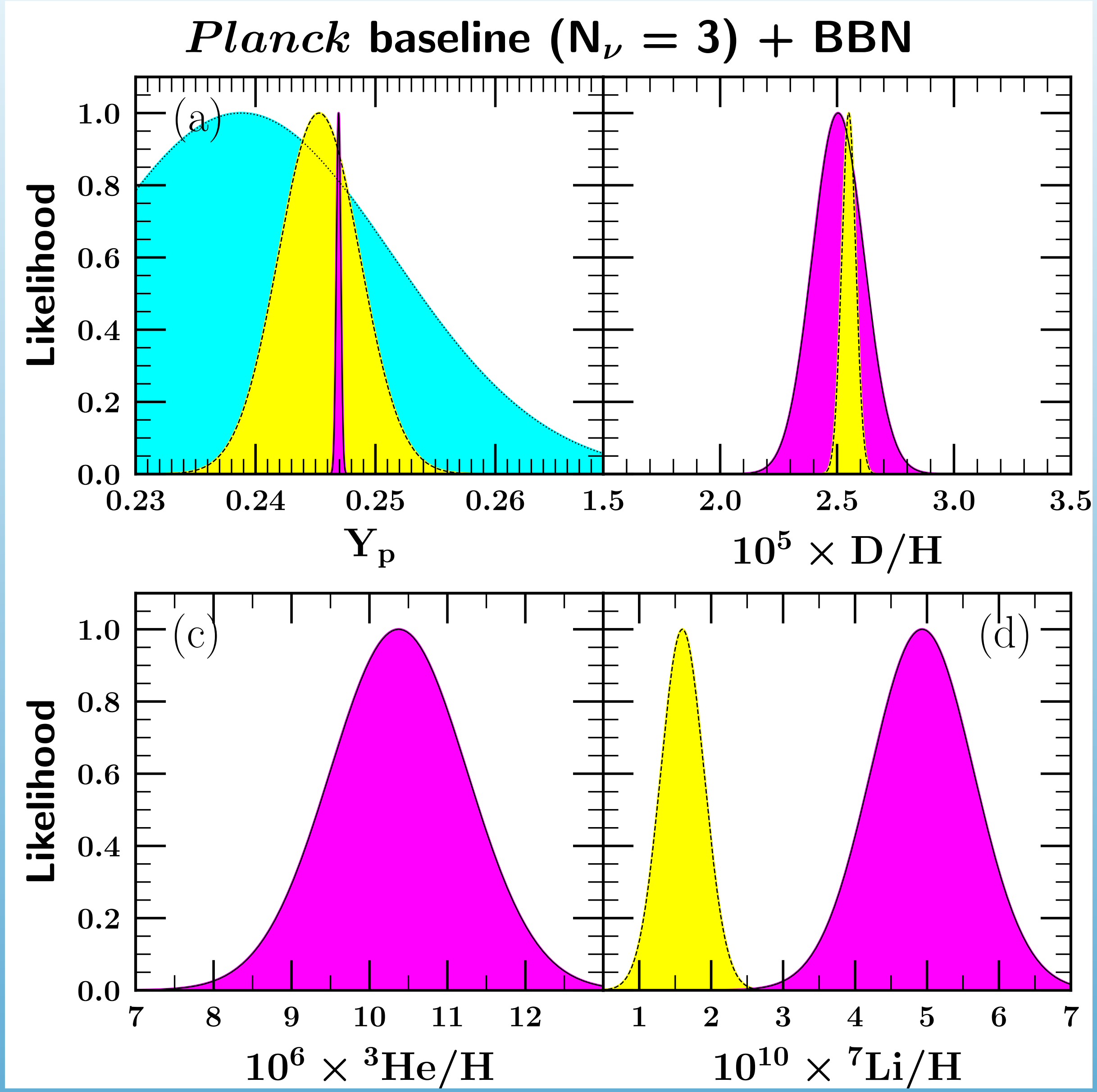
$$\mathcal{L}_{\rm CMB-BBN}(X_i) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\, \mathcal{L}_{\rm BBN}(\eta; X_i)\, d\eta$$

Purple

Fields, Olive, Yeh, Young

BBN and the CMB

Monte-Carlo approach combining BBN rates, observations and CMB



$$Y_p = 0.24693 \pm 0.00018 \qquad (0.24693)$$
$$\mathrm{D/H} = (2.51 \pm 0.11) \times 10^{-5} \qquad (2.50 \times 10^{-5})$$
$${}^3He/\mathrm{H} = (10.4 \pm 0.88) \times 10^{-6} \qquad (10.4 \times 10^{-6})$$
$${}^7Li/\mathrm{H} = (4.94 \pm 0.72) \times 10^{-10} \qquad (4.93 \times 10^{-10})$$

Fields, Olive, Yeh, Young

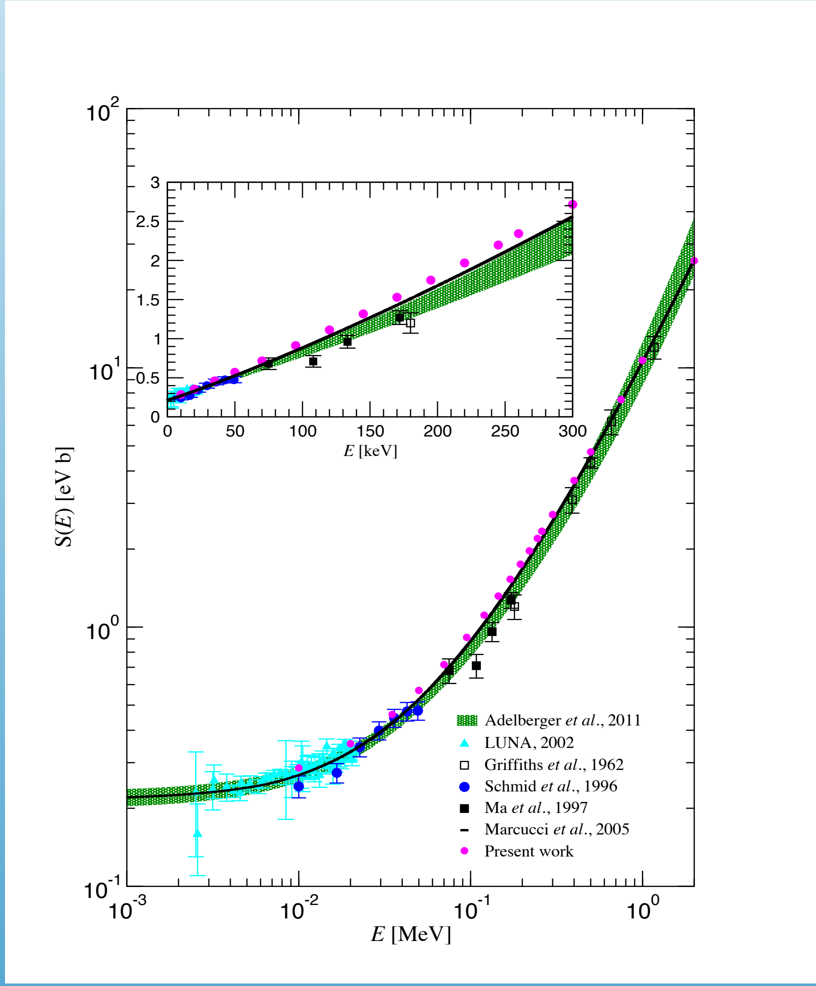
Importance of $D(p,\gamma)^3He$

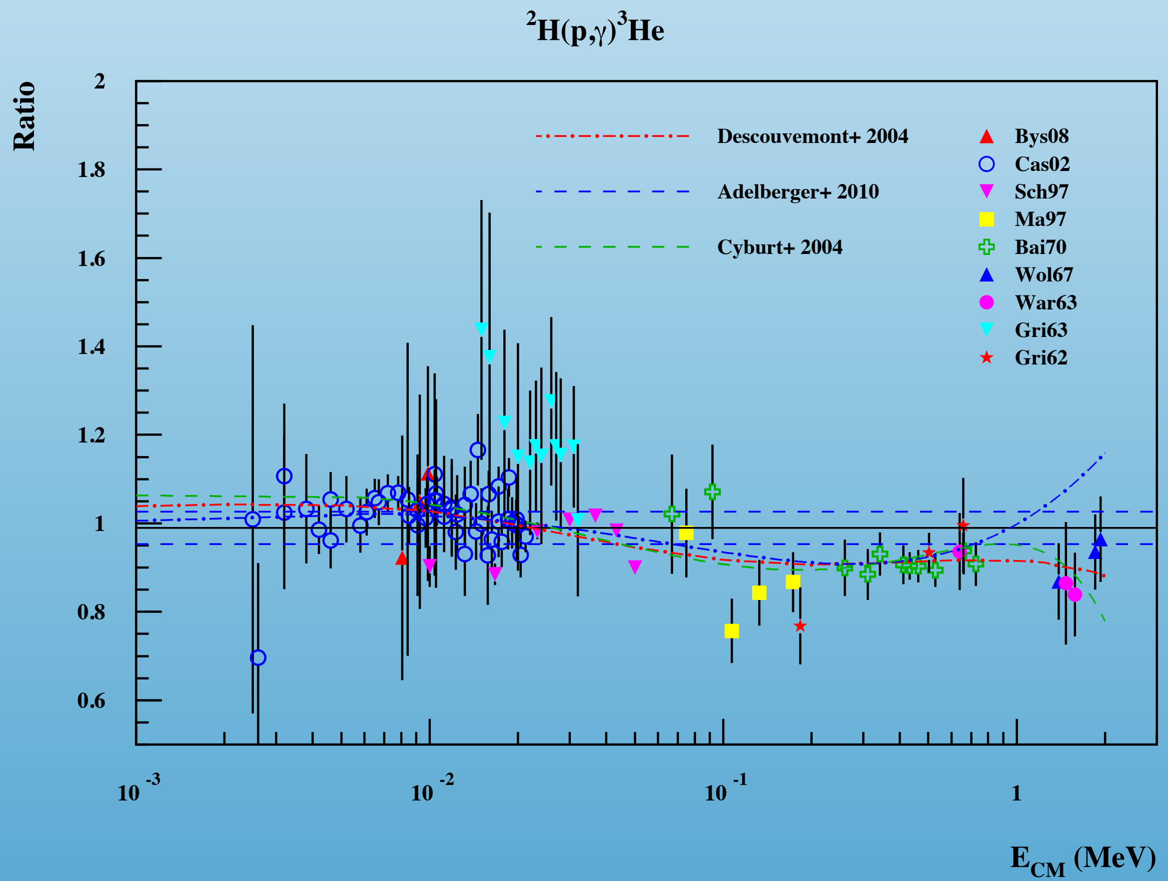
TABLE III. Comparison of BBN Results

	η_{10}	N_ν	Y_p	D/H	^{3}He/H	^{7}Li/H
CFOY-2016	6.10	3	0.2470	2.579×10^{-5}	0.9996×10^{-5}	4.648×10^{-10}
Pitrou-2018	6.091	3	0.2471	2.459×10^{-5}	1.074×10^{-5}	5.624×10^{-10}
FOYY-2020	6.129	3	0.2470	2.559×10^{-5}	0.9965×10^{-5}	4.702×10^{-10}

Some recent claims (Coc et al.; Cooke et al.) claim a discrepancy with theory and observation in D/H.

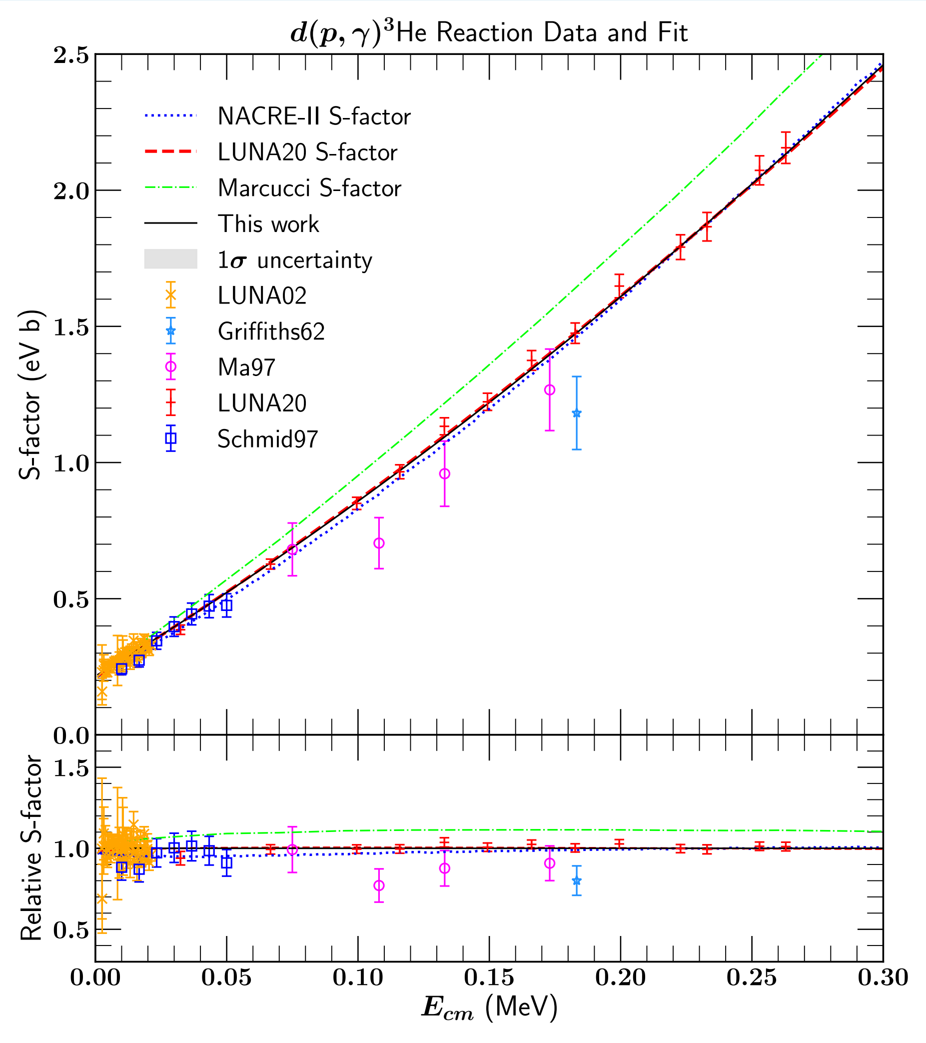
Based on fit to theoretical S-factor (Marucci et al.)

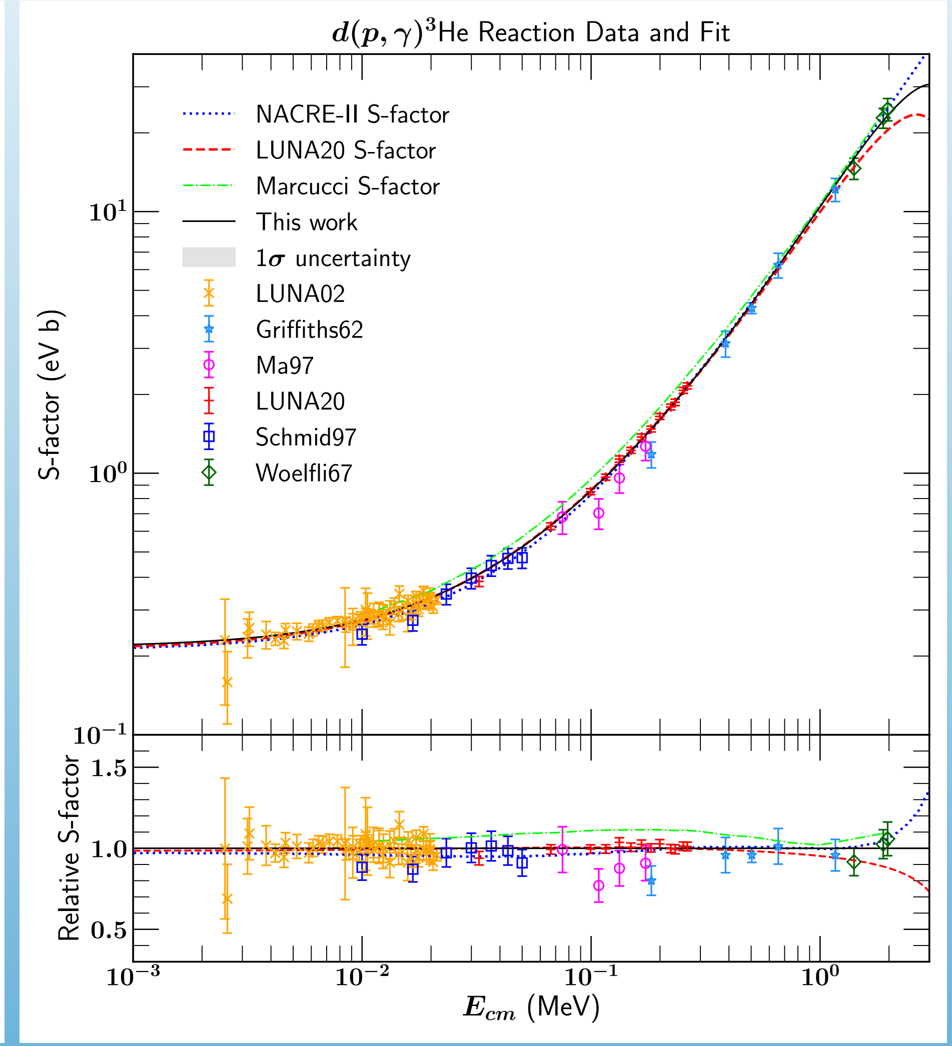




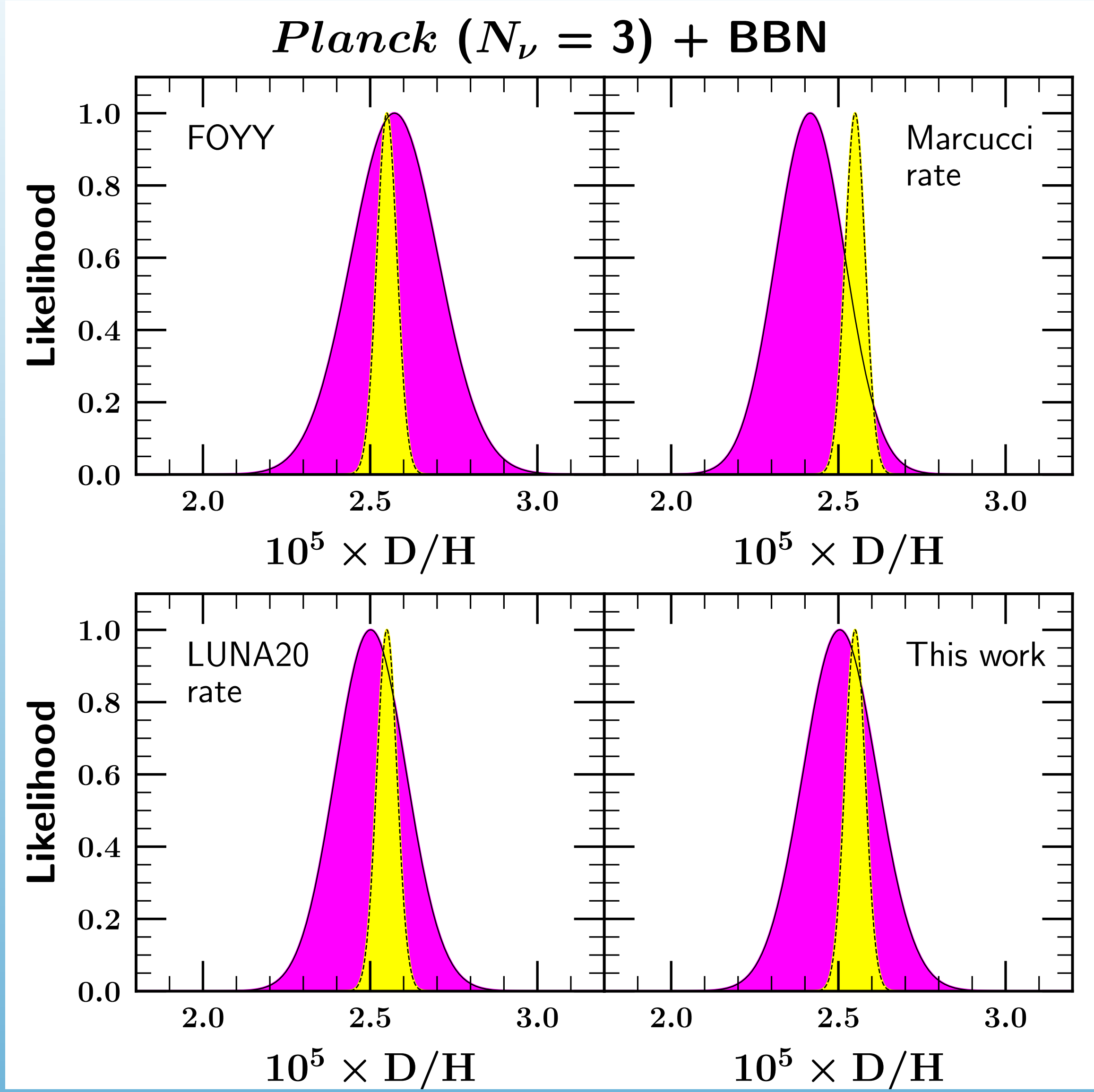
New cross section measurement

LUNA





Yeh, Olive, Fields



$d(p,\gamma)^3$He rate	mean D/H $\times 10^5$	peak D/H $\times 10^5$
FOYY [19]	2.574 ± 0.129	2.572
Theory [43]	2.417 ± 0.103	2.416
LUNA20 [47]	2.503 ± 0.106	2.502
This Work	2.506 ± 0.110	2.504

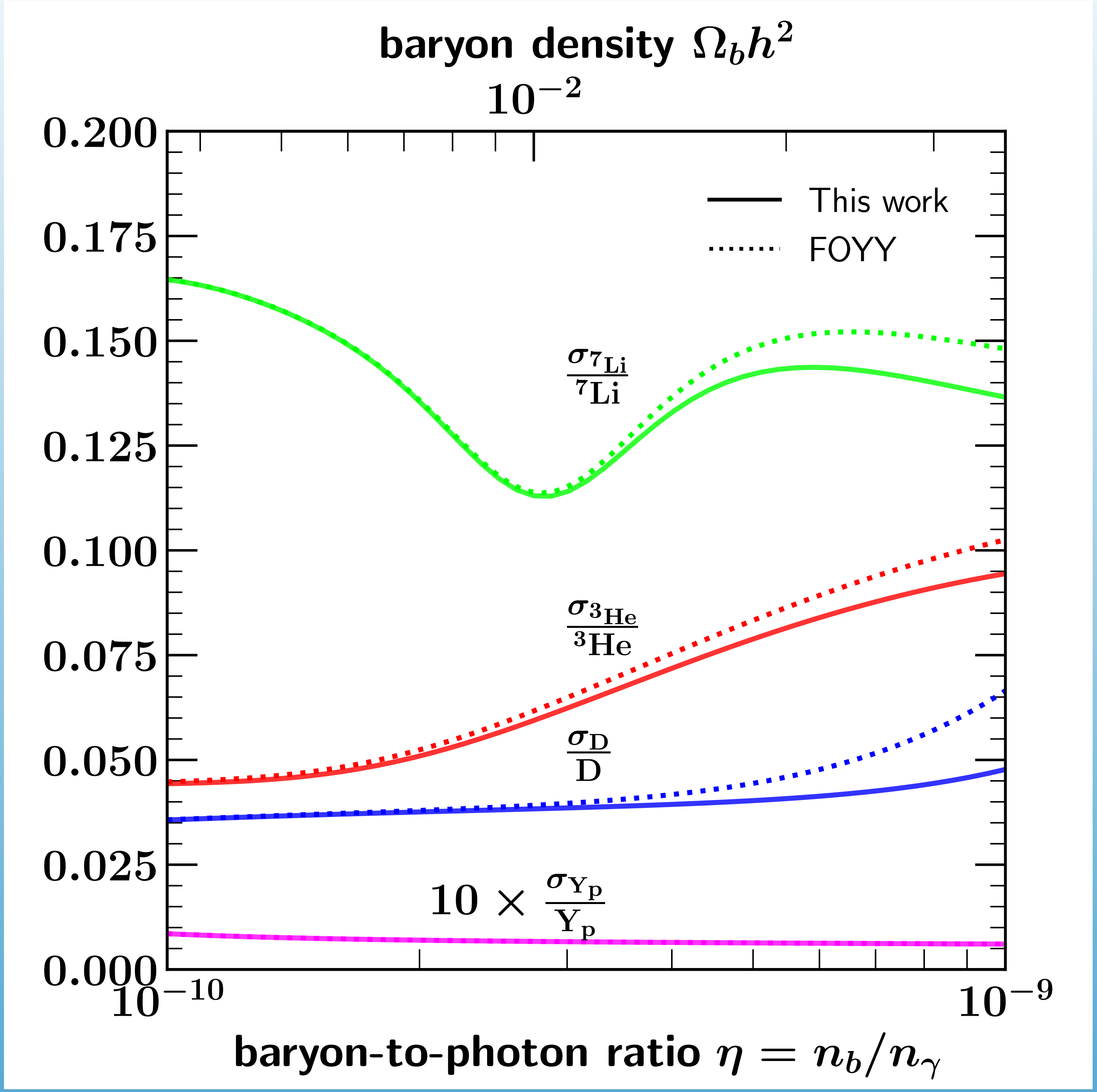
Yeh, Olive, Fields

Importance of $D(p,\gamma)^3He$

TABLE I. Comparison of BBN Results

	η_{10}	N_ν	Y_p	D/H	^{3}He/H	^{7}Li/H
CFOY-2016	6.10	3	0.2470	$2.579\ (130) \times 10^{-5}$	0.9996×10^{-5}	4.648×10^{-10}
Pitrou-2018	6.091	3	0.2471	$2.459\ (046) \times 10^{-5}$	1.074×10^{-5}	5.624×10^{-10}
FOYY-2020	6.129	3	0.2470	$2.559\ (129) \times 10^{-5}$	0.9965×10^{-5}	4.702×10^{-10}
Pisanti-2021	6.138	3	0.2469	$2.51(07) \times 10^{-5}$		
Pitrou-2021	6.138	3	0.2472	$2.439\ (037) \times 10^{-5}$	1.039×10^{-5}	5.464×10^{-10}
YOF-2021	6.123	3	0.2470	$2.493\ (110) \times 10^{-5}$	1.033×10^{-5}	4.926×10^{-10}

Uncertainties



Yeh, Olive, Fields

BBN and the CMB

From Planck:

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

$$\omega_b = 0.022305 \pm 0.000225$$

$$Y_p = 0.25003 \pm 0.01367$$

Convolved Likelihoods

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

$$\omega_b = 0.022212 \pm 0.000242$$

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

$$Y_p = 0.26116 \pm 0.01812$$

Cyburt, Fields, Olive, Yeh

From Planck 2018:

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

$$Y_p = 0.239 \pm 0.013$$

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

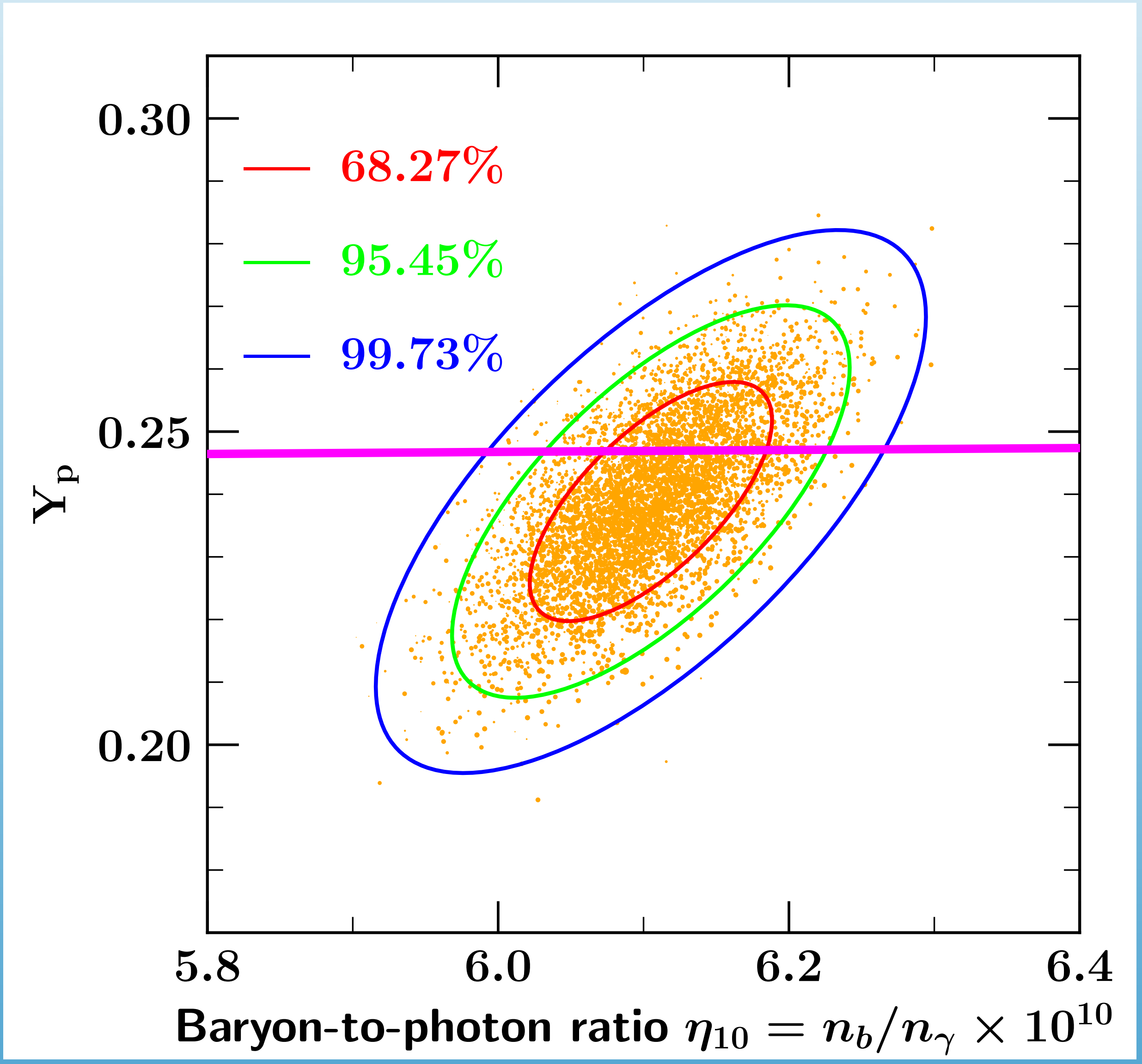
$$Y_{p,\rm CMB} = 0.247 \pm 0.018$$

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

Fields, Olive, Yeh, Young

BBN and the CMB

$N_\nu = 3$



CMB only determination of η and Y_P

3σ BBN Prediction

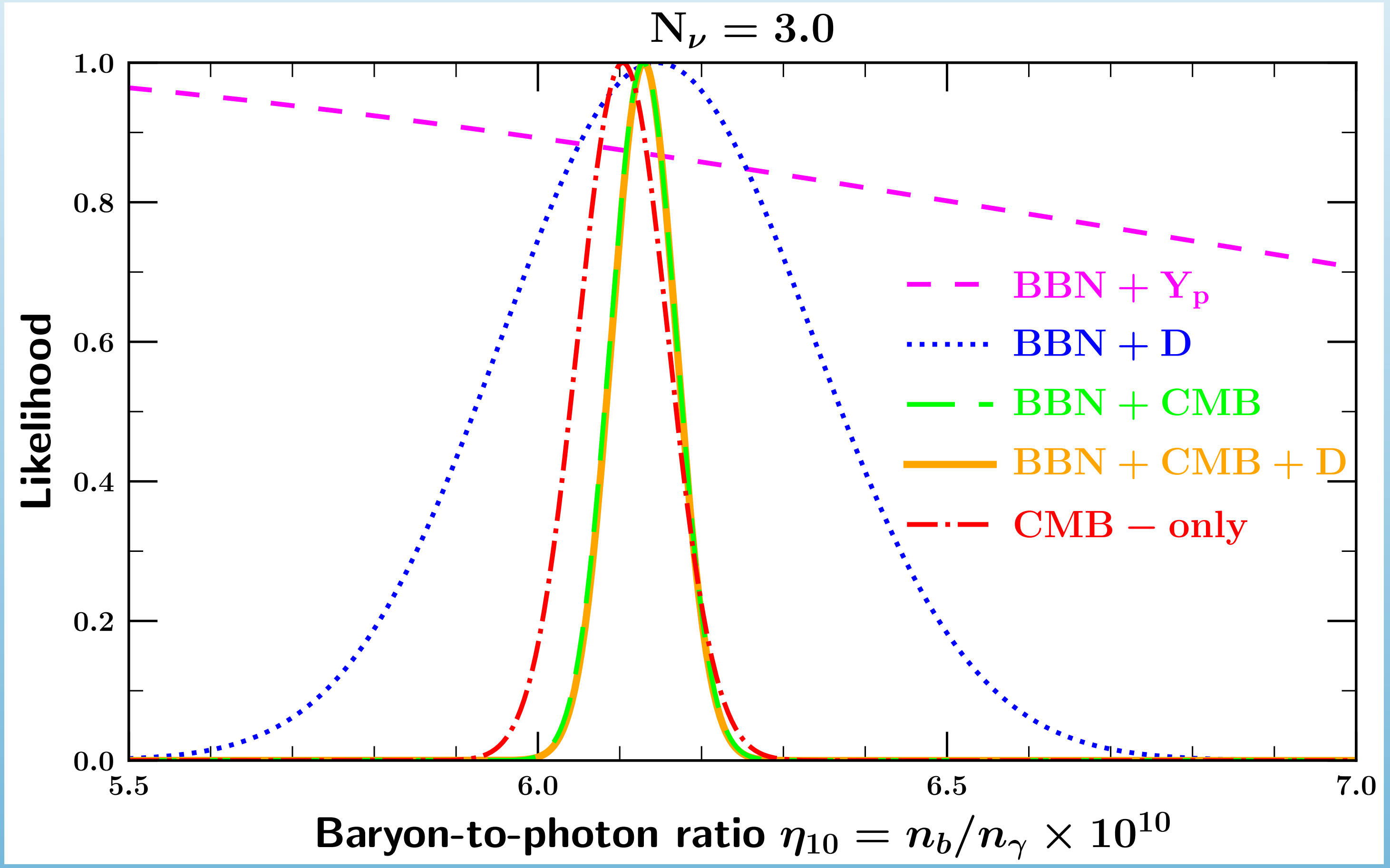
Fields, Olive, Yeh, Young

BBN and the CMB

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

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

Convolved Likelihoods



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

Convolved Likelihoods

Results for η

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

Fields, Olive, Yeh, Young

Limits on Particle Properties

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

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

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

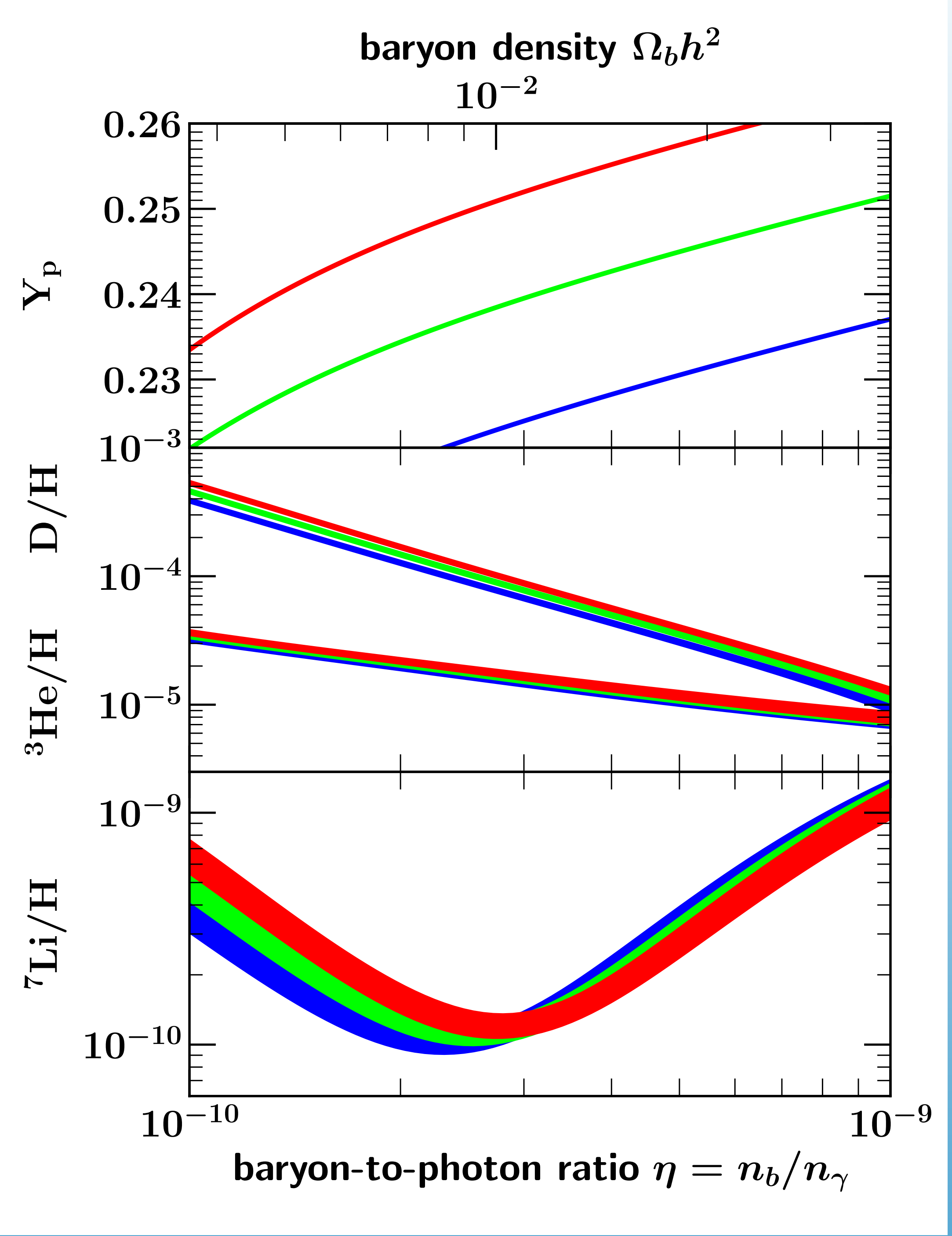
$$\frac{n}{p} \sim e^{-\Delta m/T}$$

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

- 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

What does N > 3 mean?

Today,

$$\rho_{rad} = \frac{\pi^2}{30}\left(2 + \frac{7}{4}N_\nu(\frac{T_\nu}{T_\gamma})^4\right)T_\gamma^4$$

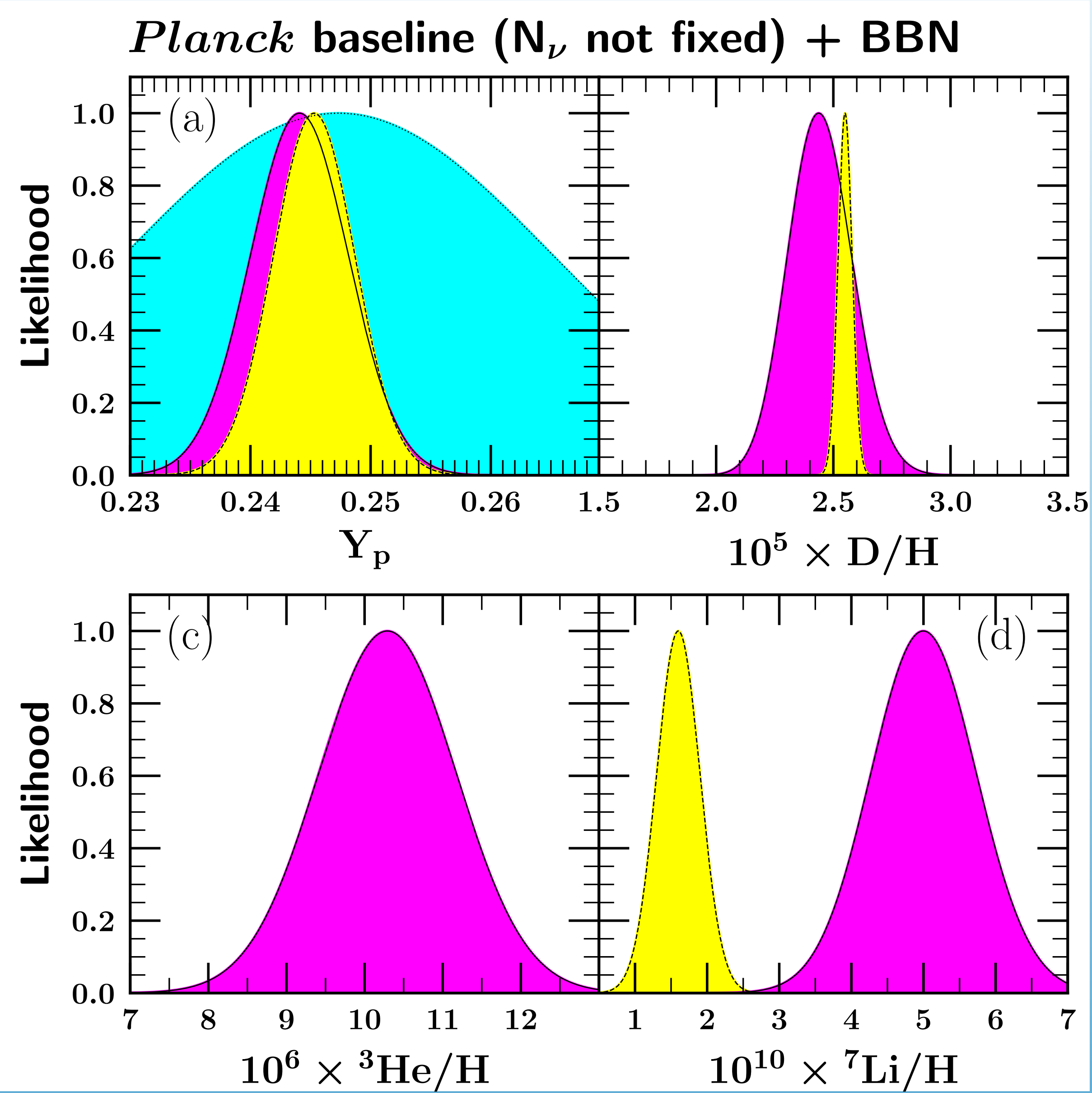
$$= \frac{\pi^2}{30}\left(2 + \frac{21}{4}(\frac{4}{11})^{4/3} + \frac{7}{4}\Delta N(\frac{T_{\Delta N}}{T_\gamma})^4\right)T_\gamma^4$$

Scalars: $\Delta N = 4/7$

Dirac Fermion: $\Delta N = 2$

BBN and the CMB

Monte-Carlo approach combining BBN rates, observations and CMB



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

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

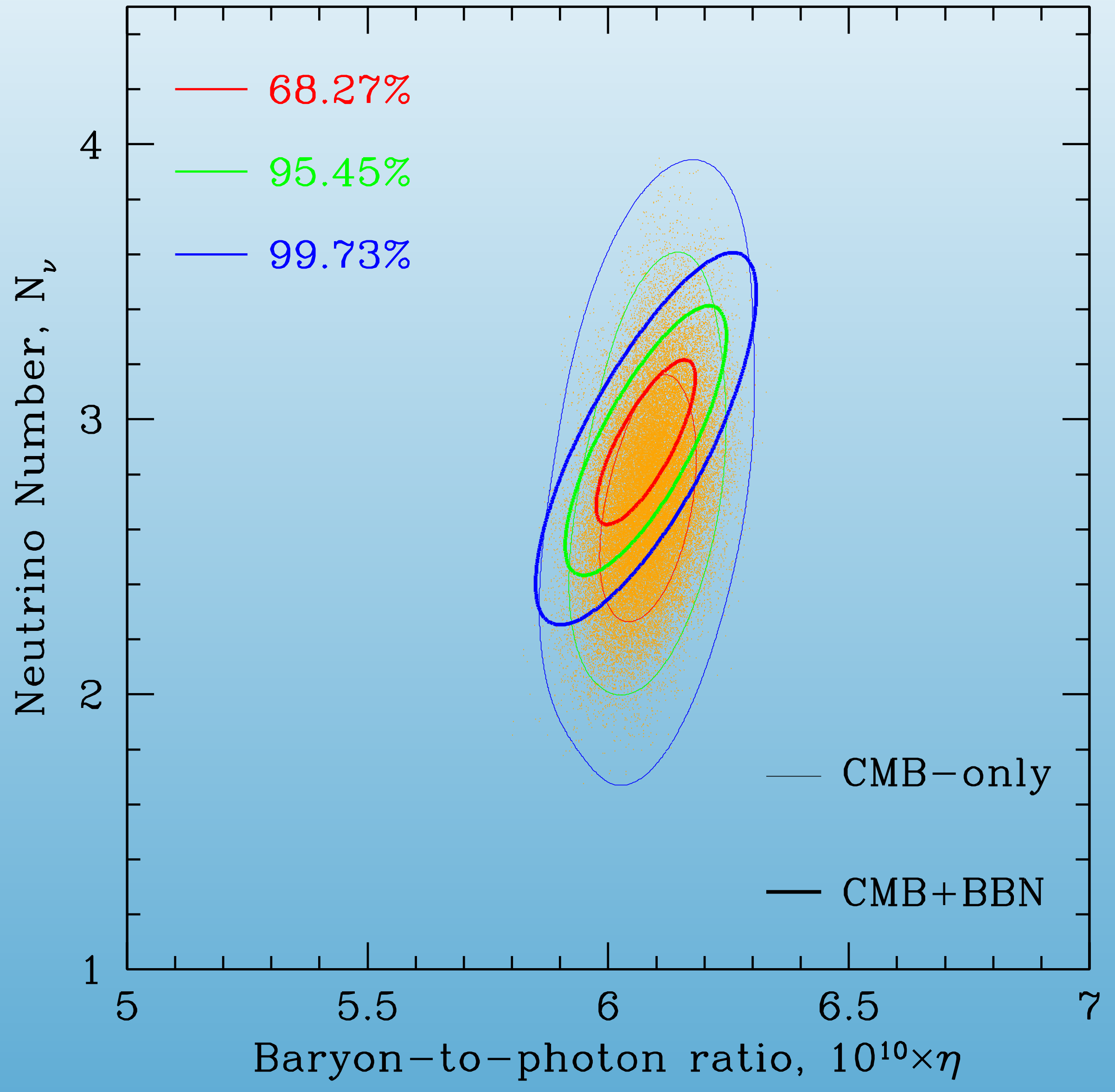
Cyan

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

Purple

Fields, Olive, Yeh, Young

BBN and the CMB



CMB only determination of η and N_ν

$$\omega_b^{CMB} = 0.022242 \pm 0.000221$$

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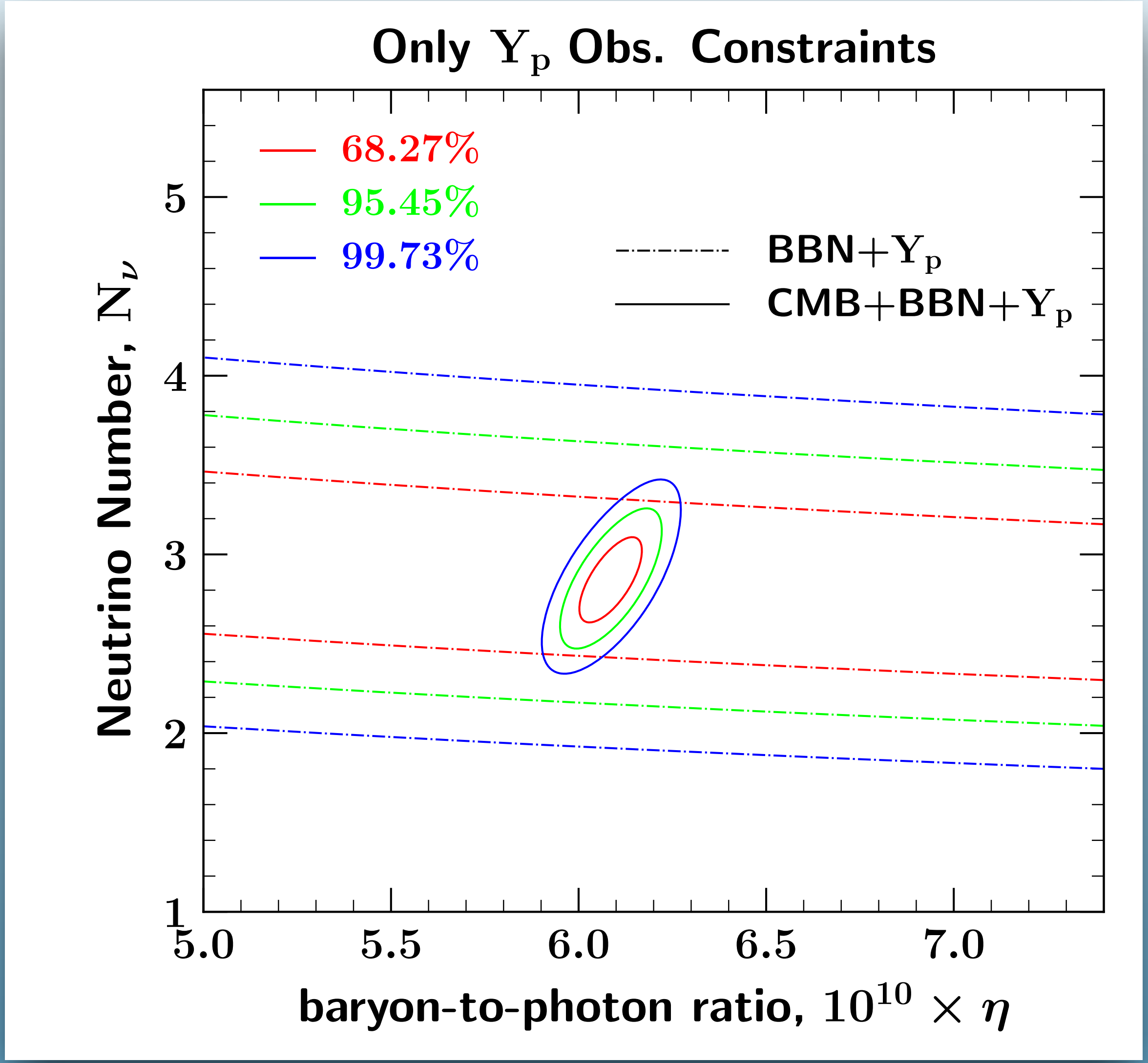
Cyburt, Fields, Olive, Yeh

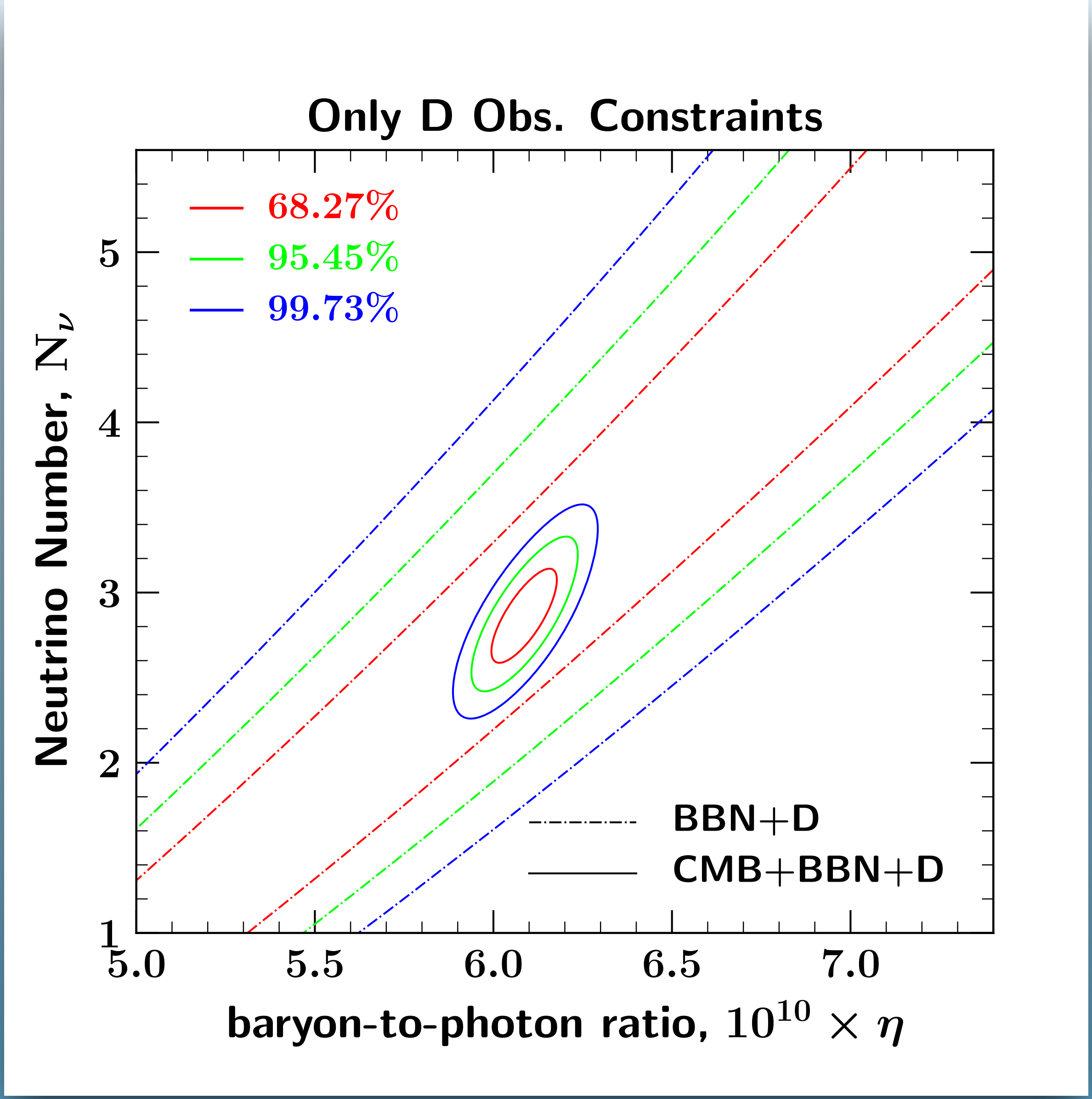
BBN and the CMB



CMB and BBN determination of η and N_ν

Fields, Olive, Yeh, Young

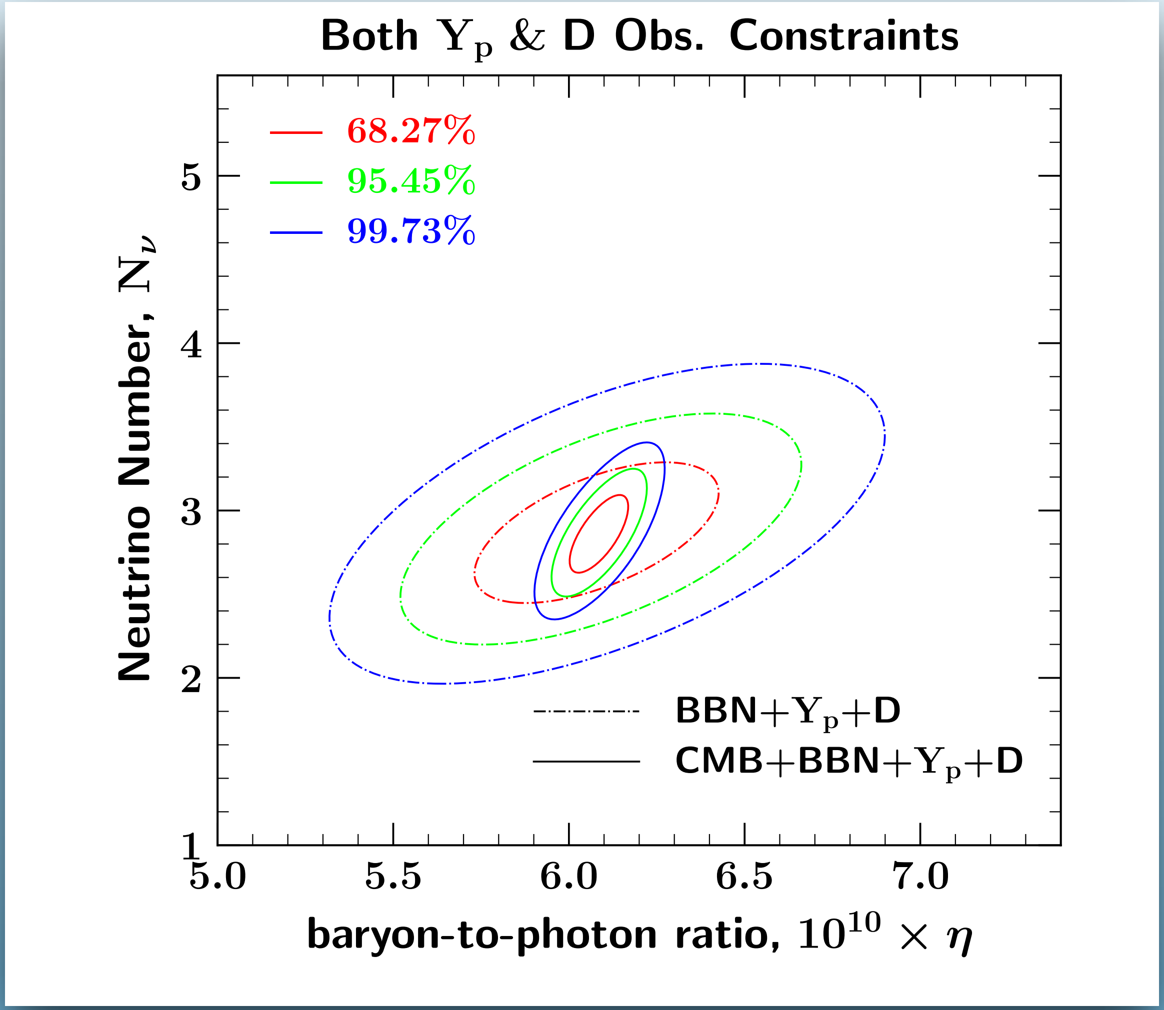
BBN and the CMB



CMB and BBN determination of η and N_ν

Cyburt, Fields, Olive, Yeh

BBN and the CMB



CMB and BBN determination of η and N_ν

Fields, Olive, Yeh, Young

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
CMB-only	6.090 ± 0.061	6.090	2.799 ± 0.294	2.763
BBN+Y_p+D	6.084 ± 0.230	6.075	2.878 ± 0.278	2.861
CMB+BBN	6.088 ± 0.060	6.088	2.830 ± 0.189	2.825
CMB+BBN+Y_p	6.090 ± 0.055	6.090	2.838 ± 0.158	2.833
CMB+BBN+D	6.088 ± 0.060	6.089	2.838 ± 0.182	2.833
CMB+BBN+Y_p+D	6.090 ± 0.055	6.090	2.843 ± 0.154	2.839

Fields, Olive, Yeh, Young

BBN and the CMB

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$N_\nu < 3.15$ (95% CL)

Fields, Olive, Yeh, Young

BBN and the CMB

Convolved Likelihoods

Results for η (N_ν)

$d(p,\gamma)^3$He rate	mean η_{10}	peak η_{10}	mean N_ν	peak N_ν
FOYY [19]	6.090 ± 0.055	6.090	2.843 ± 0.154	2.839
updated Y_P [19, 29]	6.093 ± 0.054	6.093	2.855 ± 0.146	2.851
Theory [43]	6.092 ± 0.054	6.092	2.918 ± 0.144	2.915
LUNA20 [47]	6.092 ± 0.054	6.093	2.883 ± 0.144	2.879
This Work	6.092 ± 0.054	6.093	2.880 ± 0.144	2.876

Yeh, Olive, Fields

BBN and the CMB

Convolved Likelihoods

Results for η (N_ν)

$d(p,\gamma)^3$He rate	mean η_{10}	peak η_{10}	mean N_ν	peak N_ν
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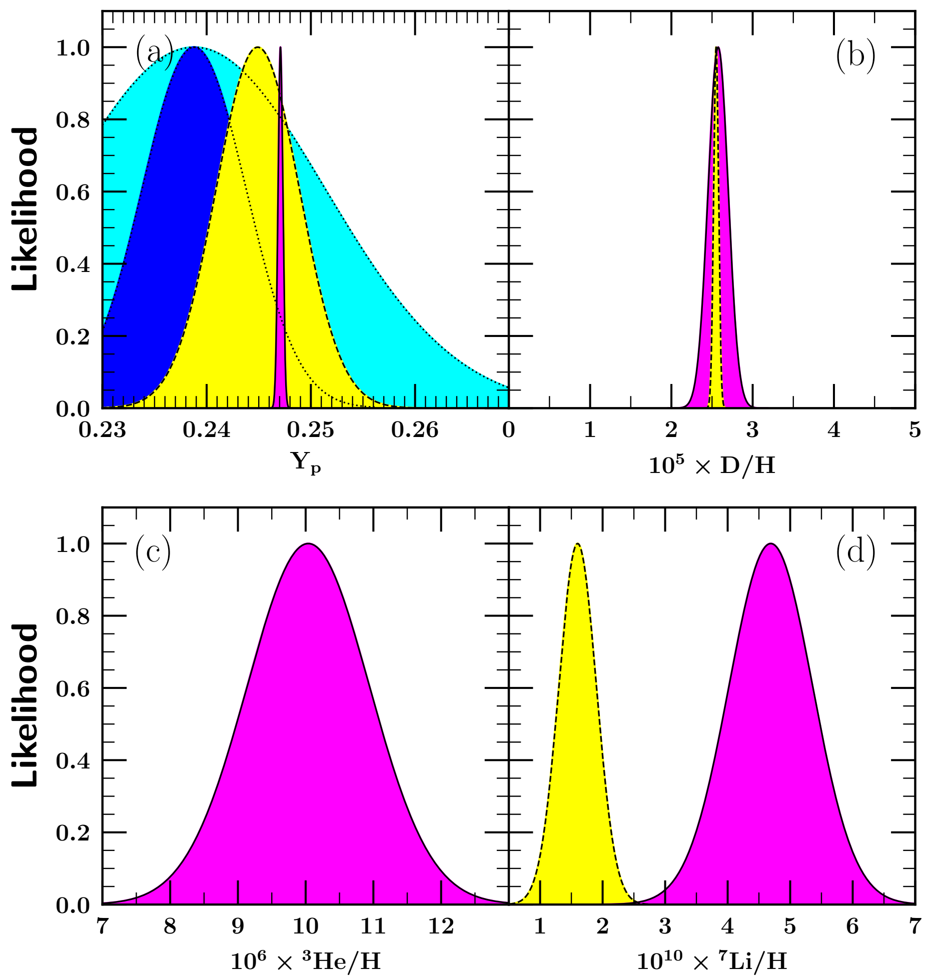
This Work	6.092 ± 0.054	6.093	2.880 ± 0.144	2.876

$N_\nu < 3.17$ (95% CL)

Yeh, Olive, Fields

BBN and the CMB



CMB-S4 promises significantly improved BBN parameters

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

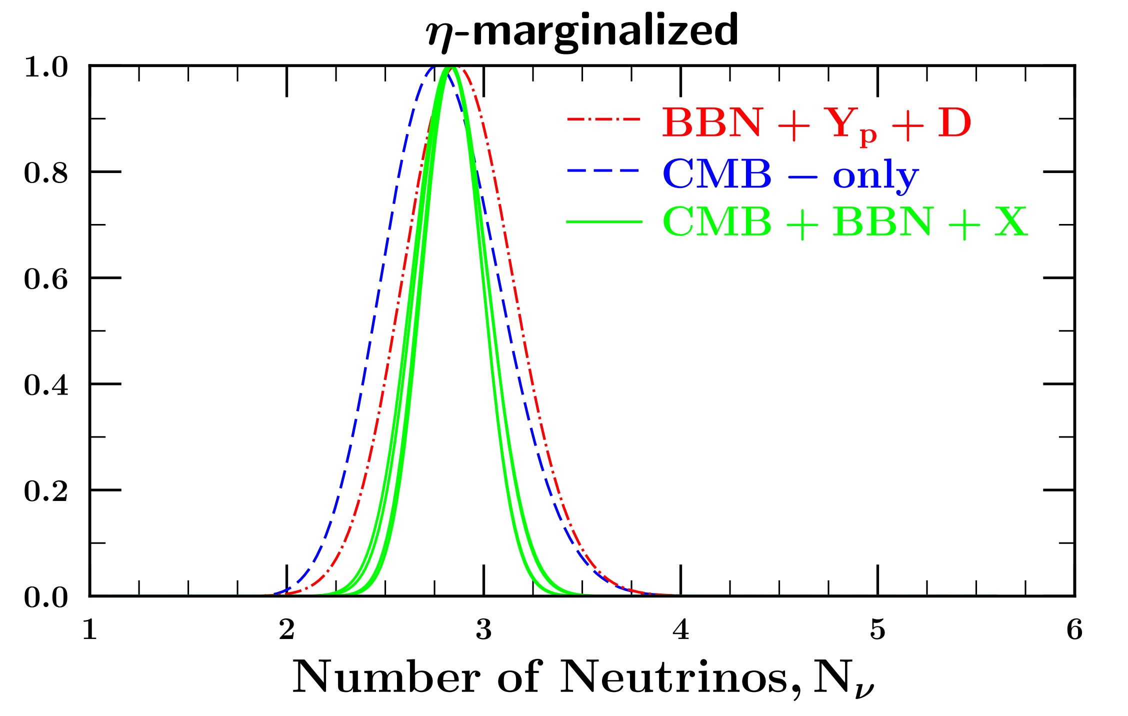
K. N. Abazajian *et al.* [CMB-S4 Collaboration]

CMB-S4:

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

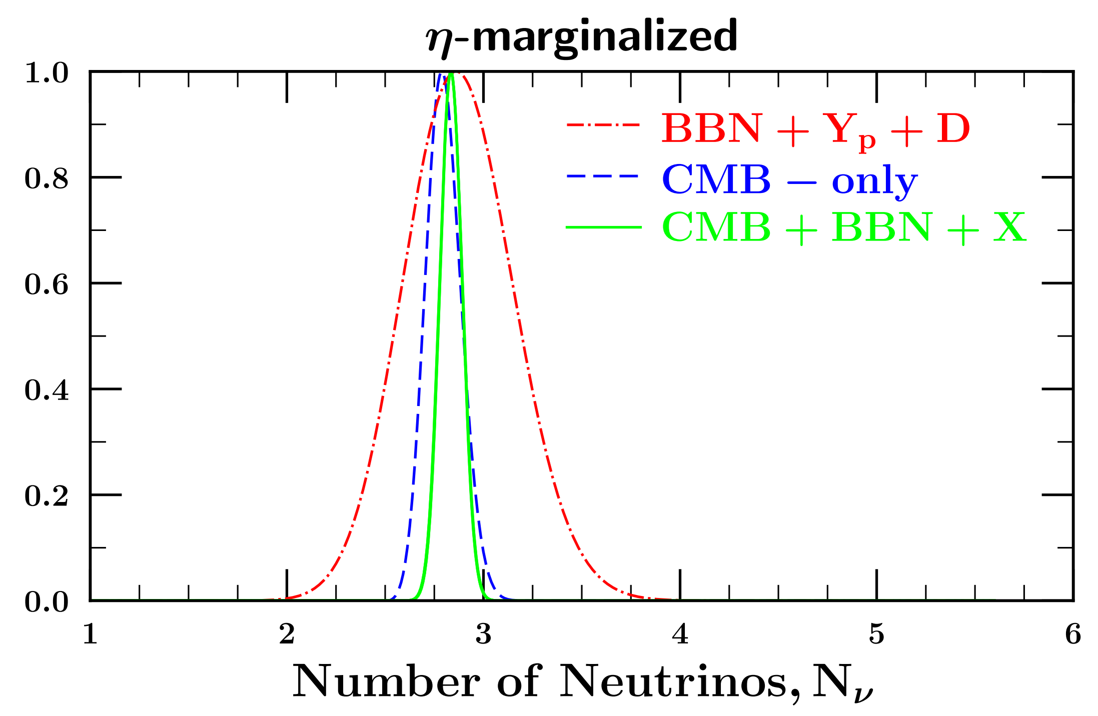
Fields, Olive, Yeh, Young

BBN and the CMB



Planck 2018

CMB-S4 uncertainty



Summary

- BBN and CMB are in excellent agreement wrt D and He

- Li: Problematic
  - BBN ^{7}Li high compared to observations

- 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!