Happy Retirement(?) Subir

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Our work together:

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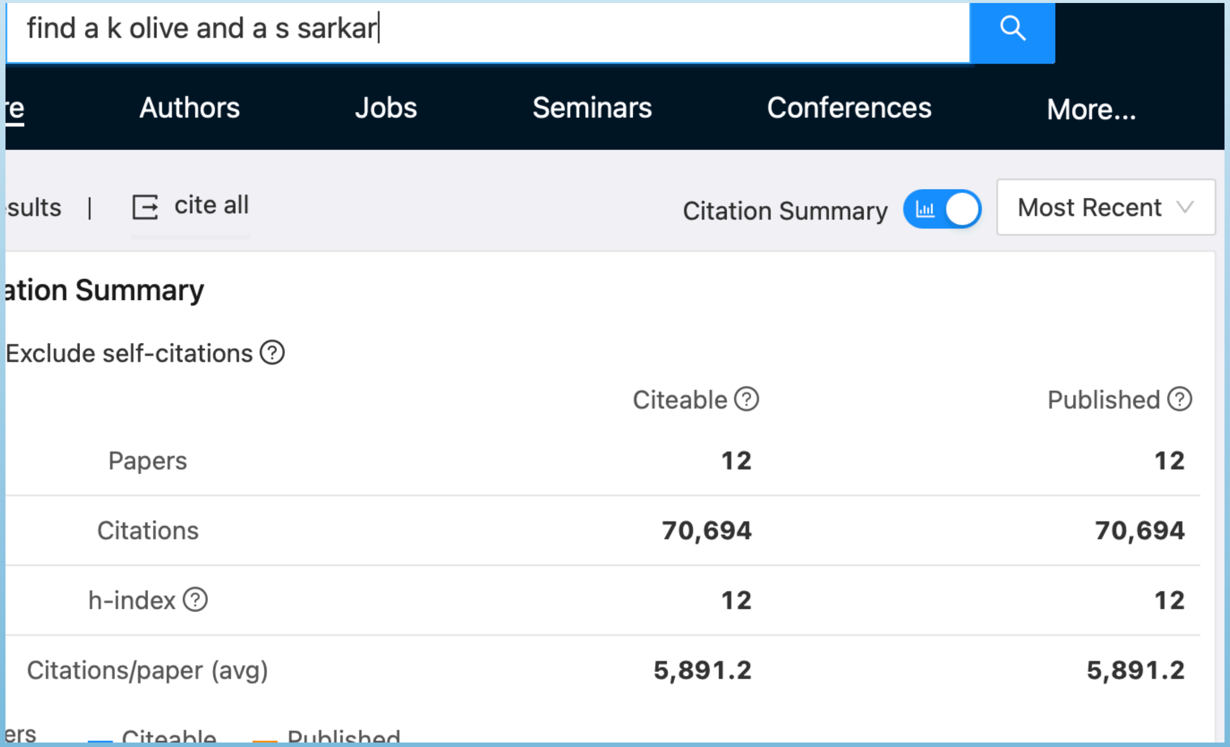

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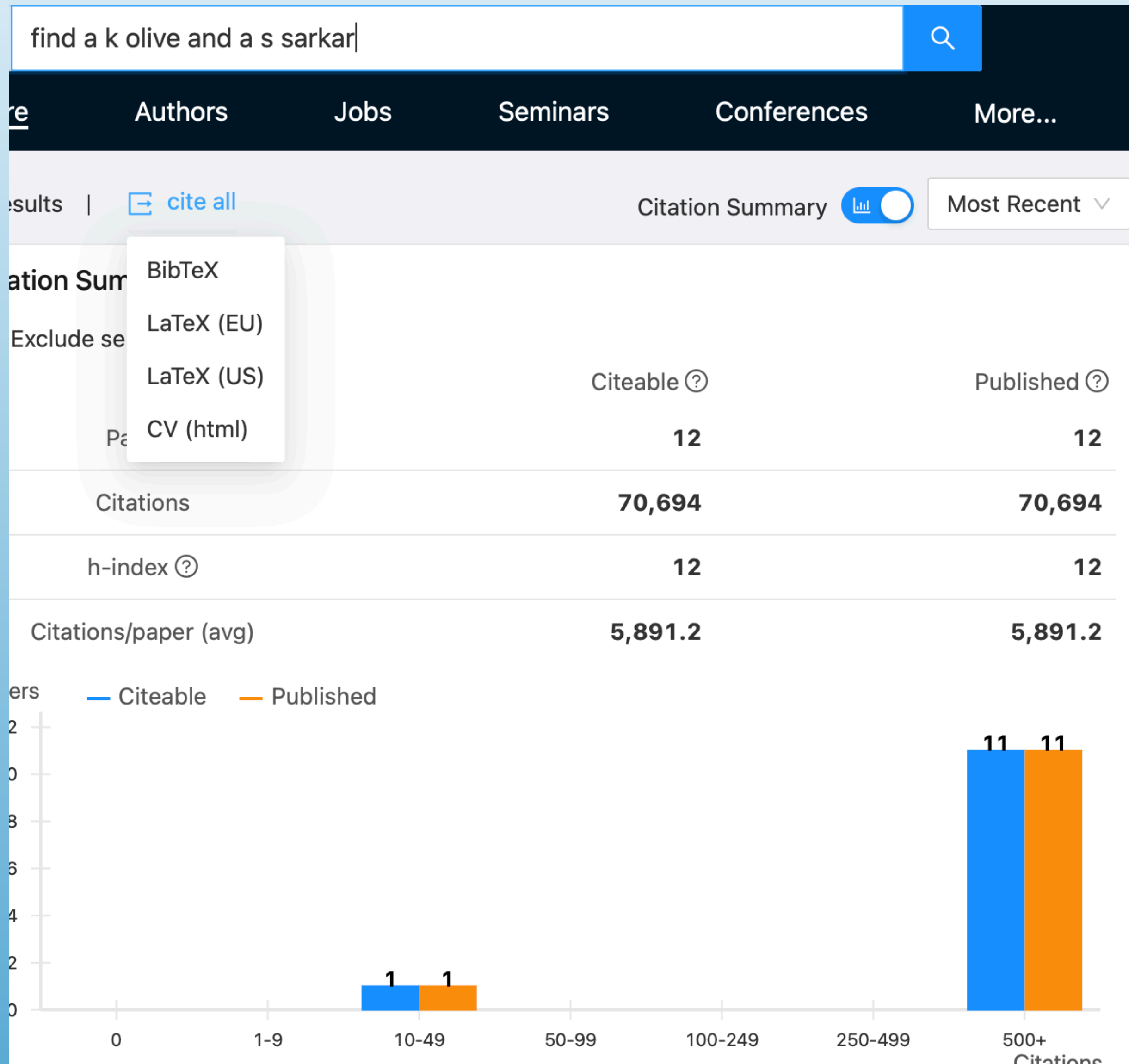

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LOW-MASS PHOTINOS AND SUPERNOVA 1987A

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and

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International School of Advanced Studies, Strada Costiera 11, I-34014 Trieste, Italy and DAMTP and Institute of Astronomy, Cambridge CB3 9EW, UK

Received 16 September 1988

Photinos or higgsinos with mass O(100) eV are not excluded by cosmological considerations, and their radiative decays could be responsible for the surprisingly large ultra-violet background recently detected at a red-shift $z \sim 4$. The agreement of the neutrino data from supernova 1987A with standard expectations severely restricts the energy which could have been emitted via such light photinos or higgsinos, and hence constrains the parameters of models in which they appear. In the low-mass photino case, we find that squark masses between ~ 60 GeV and ~ 2.5 TeV are excluded. This together with laboratory limits excludes the range of squark masses generally favoured by naturalness arguments. In the low-mass higgsino case, we exclude much of the range of ratios of Higgs VEVs favoured by many models.

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$$m_{\tilde{q}} > 2.5 \text{ TeV}$$

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Recent updates to Big Bang Nucleosynthesis

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

- Planck 2018
- Towards Precisions abundances for ^4He
- New Cross section measurements

- Concordance
- Neutrinos and Constraints on BSM physics

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

Nucleosynthesis Delayed
(Deuterium Bottleneck)

$p + n \rightarrow$ **D** $+ \gamma$ $\qquad \Gamma_p \sim n_B \sigma$

$p + n \leftarrow$ **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

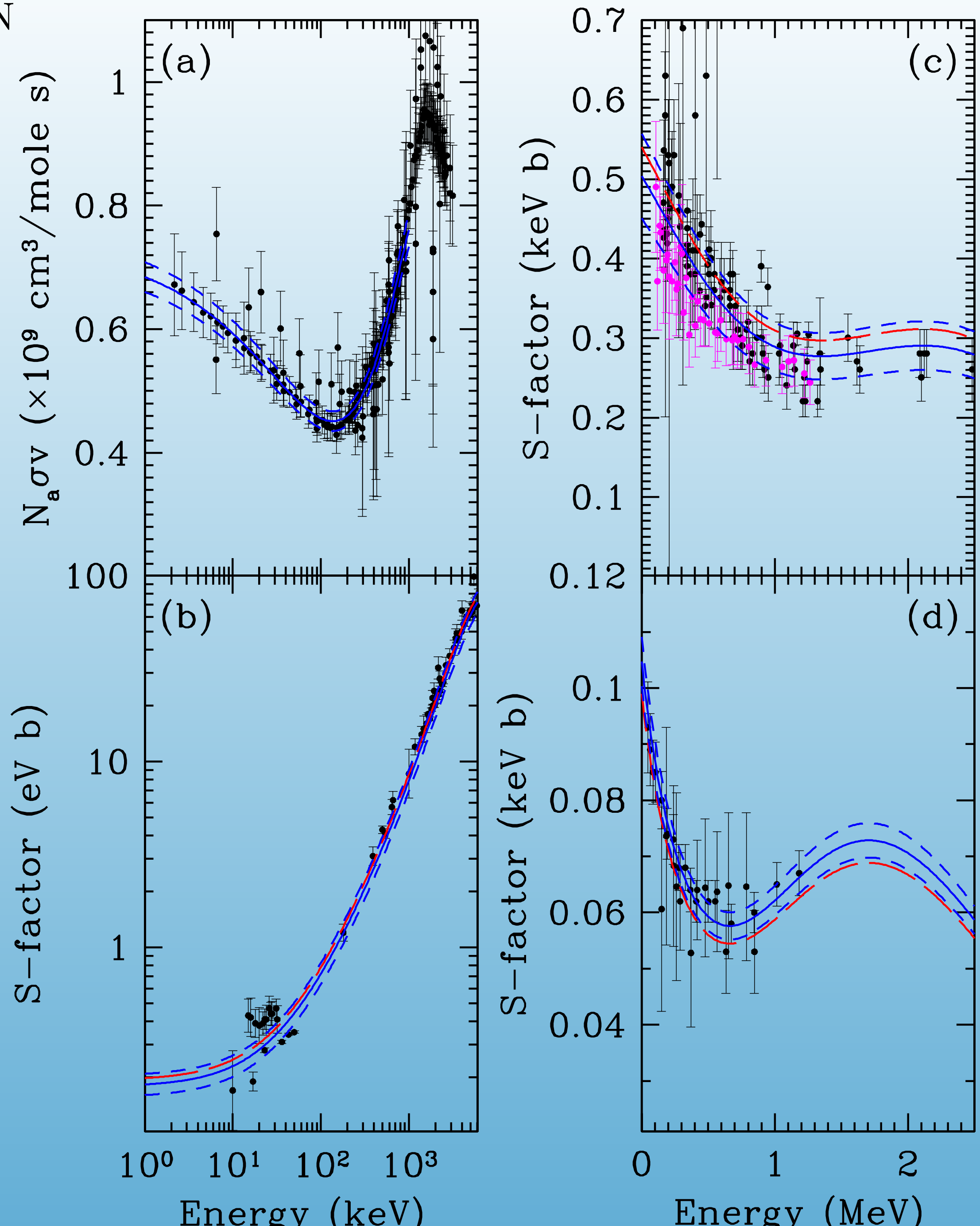
$$Y_p = \frac{2(n/p)}{1 + (n/p)} \simeq 25\%$$

Remainder:

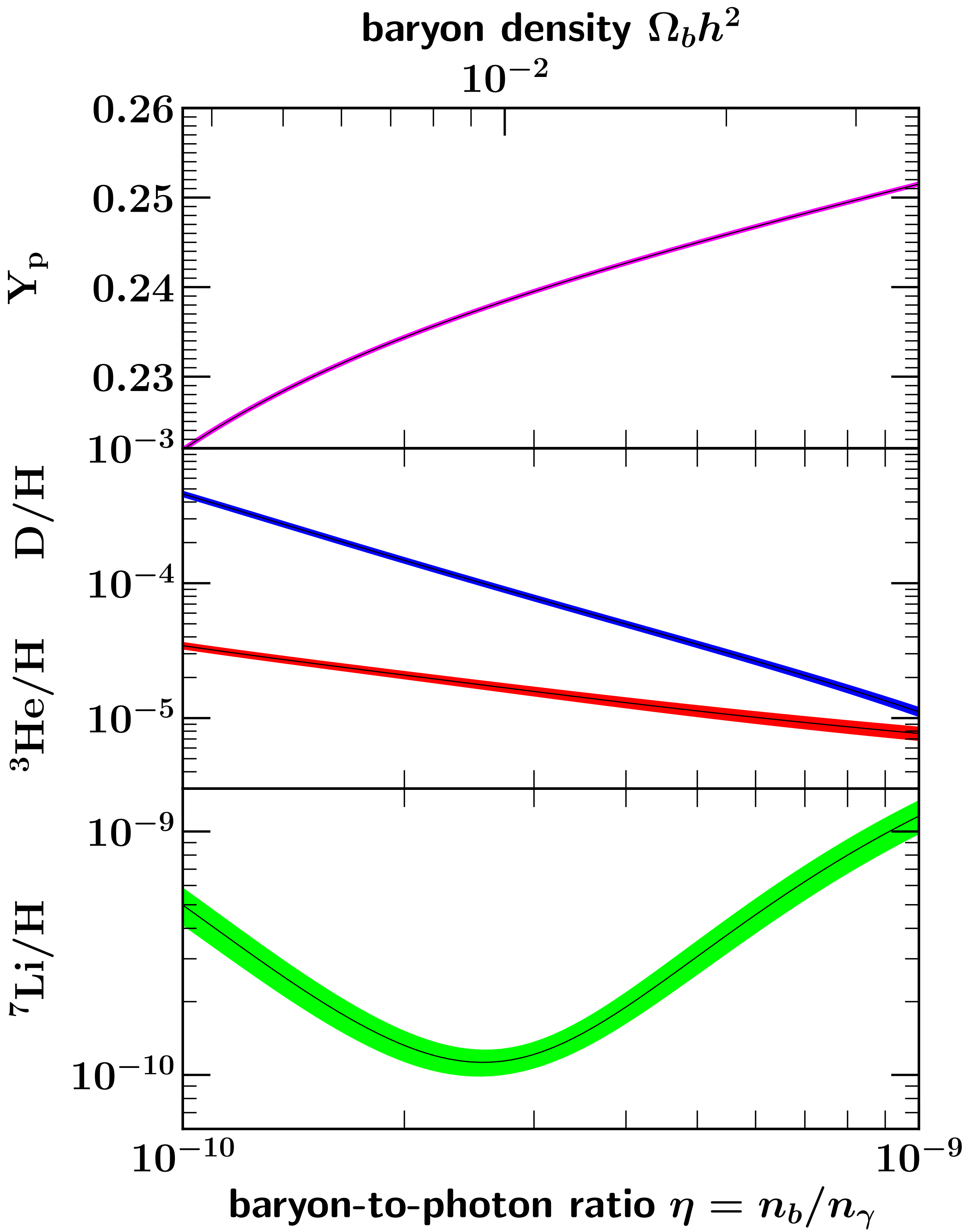
D, ^{3}He $\sim 10^{-5}$ and ^{7}Li $\sim 10^{-10}$ by number

Table 1: Key Nuclear Reactions for BBN

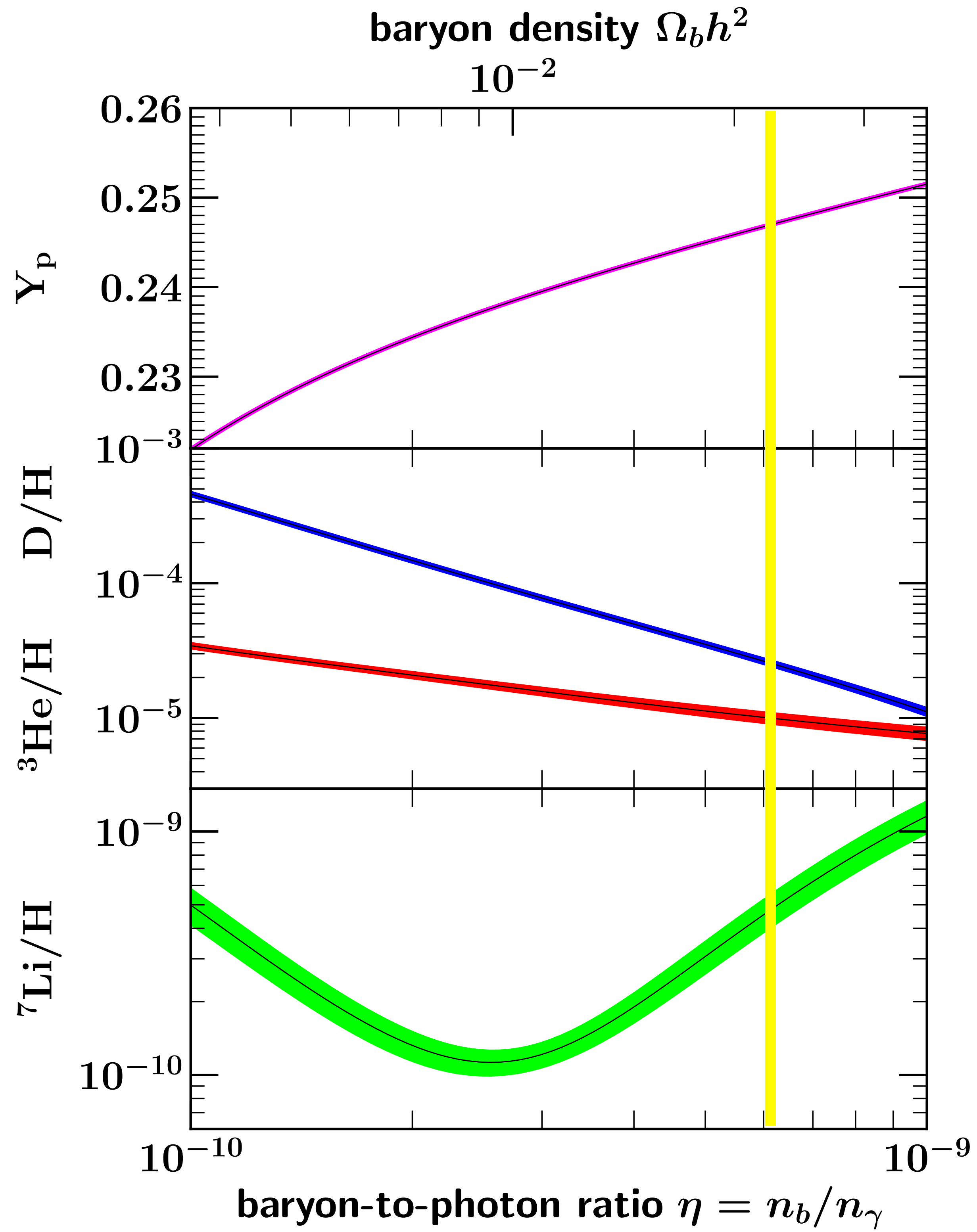
Source	Reactions	
NACRE	$d(p,\gamma)^3\text{He}$	(b)
	$d(d,n)^3\text{He}$	
	$d(d,p)t$	
	$t(d,n)^4\text{He}$	
	$t(\alpha,\gamma)^7\text{Li}$	(d)
	$^3\text{He}(\alpha,\gamma)^7\text{Be}$	(c)
	$^7\text{Li}(p,\alpha)^4\text{He}$	
SKM	$p(n,\gamma)d$	
	$^3\text{He}(d,p)^4\text{He}$	
	$^7\text{Be}(n,p)^7\text{Li}$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



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

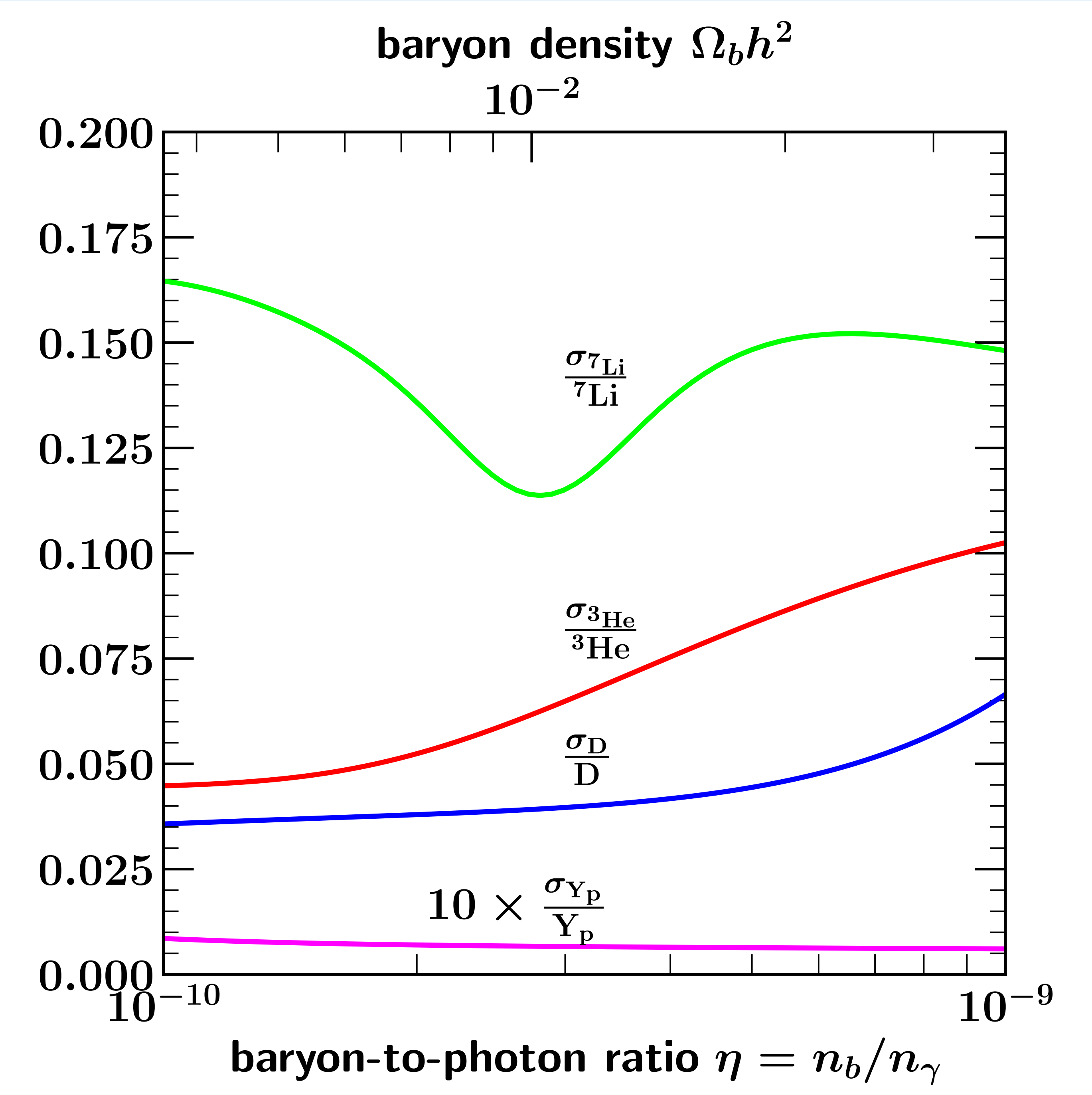


Fields, Olive, Yeh, Young



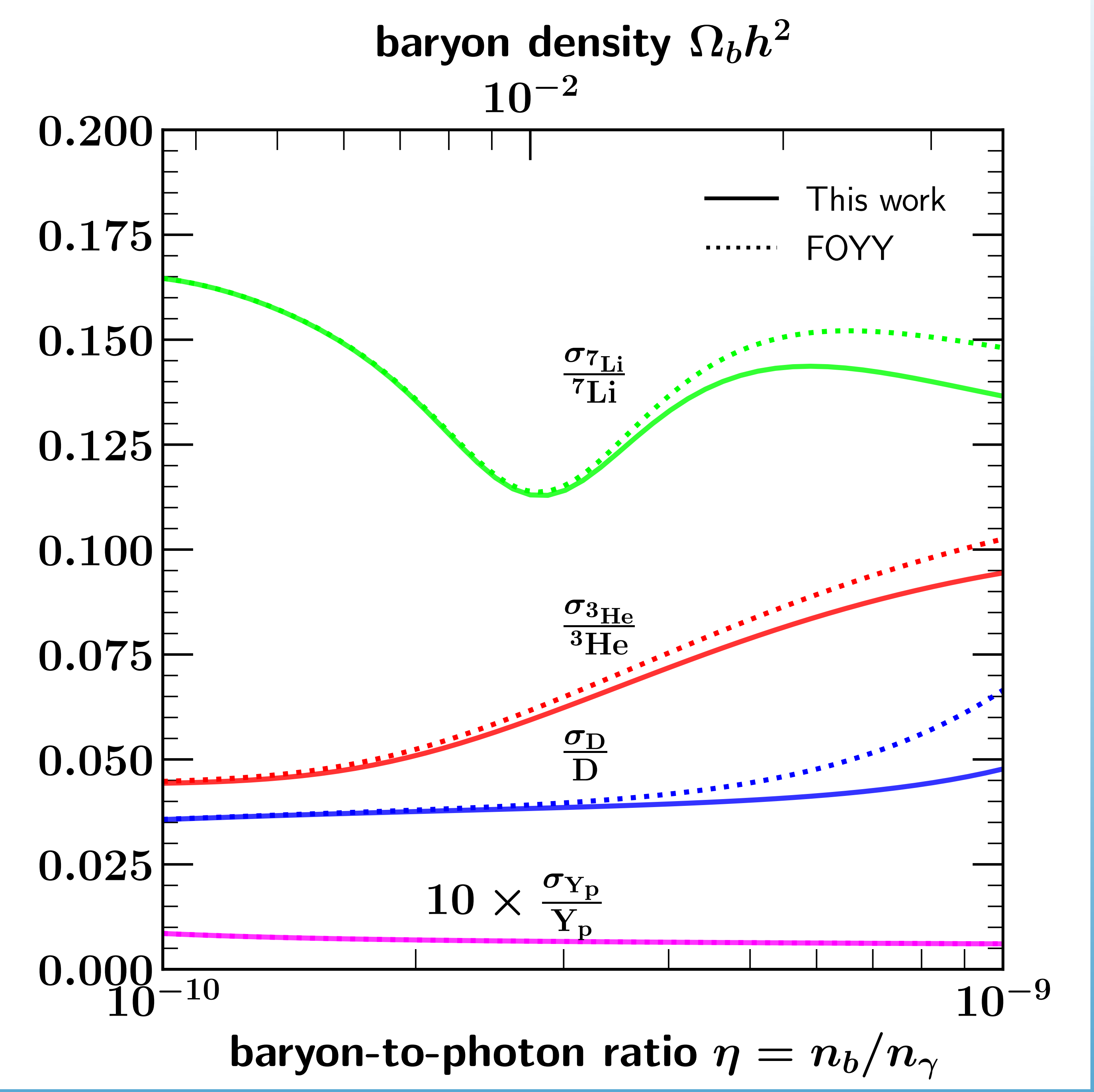
Fields, Olive, Yeh, Young

Uncertainties



Fields, Olive, Yeh, Young

Uncertainties



Yeh, Olive, Fields

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

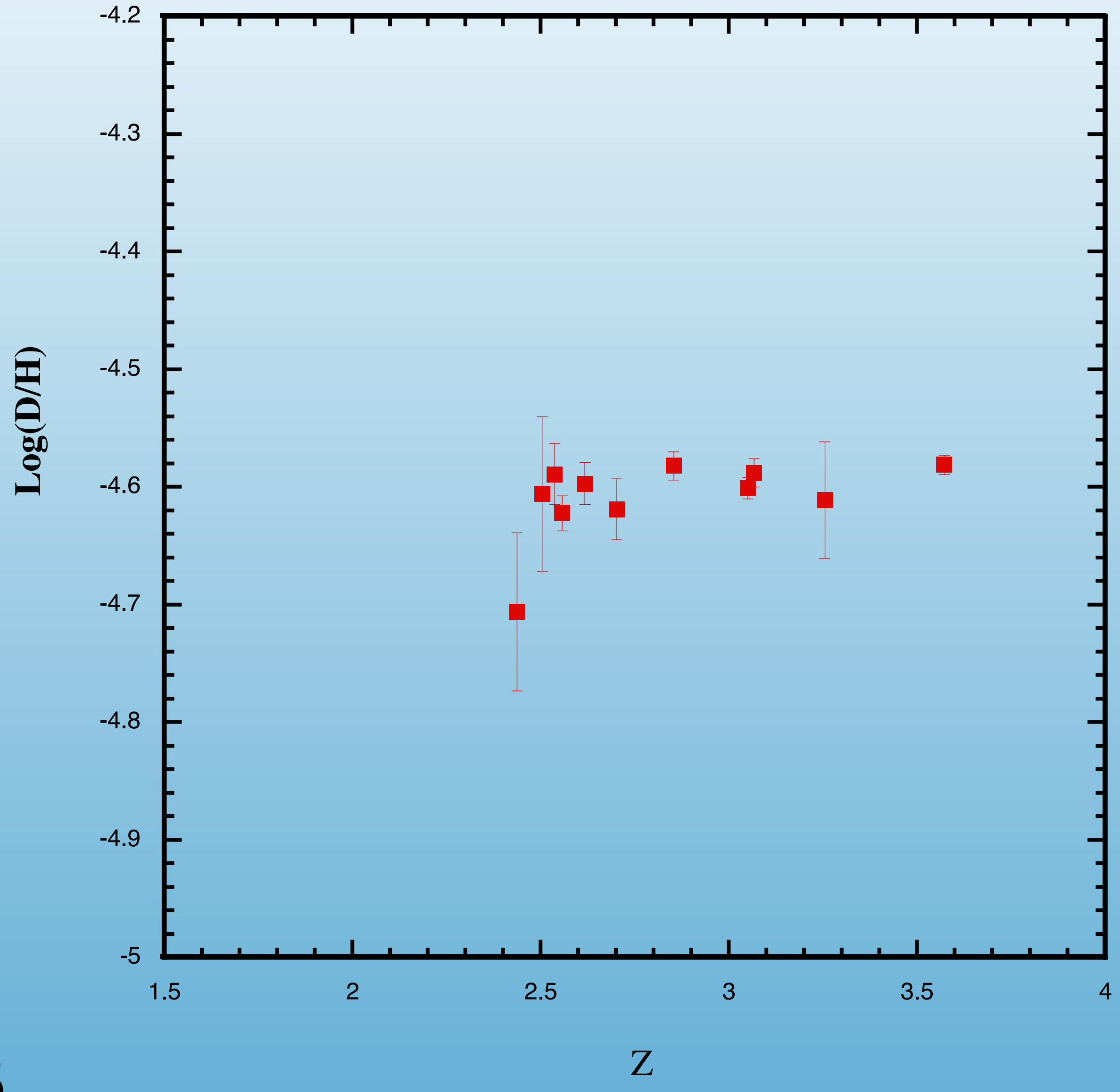
Table 3. PRECISION D/H MEASURES CONSIDERED IN THIS PAPER

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 $\log_{10}(\mathrm{O/H}) + 12 = 8.69$ (Asplund et al. 2009).

Cooke et al.

Updated D/H abundances in Quasar absorption systems



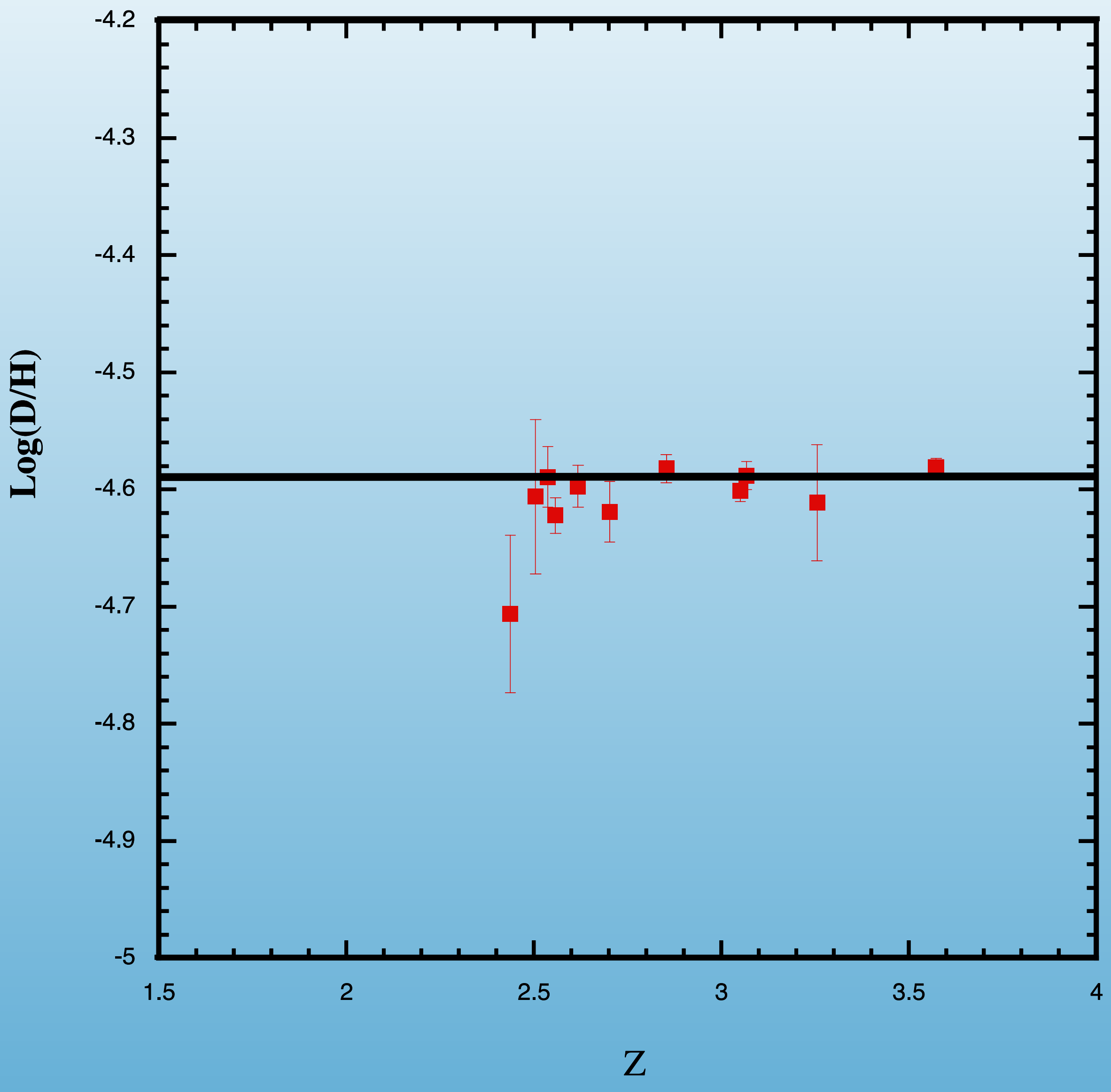
BBN Prediction:

10^5 D/H = 2.51 ± 0.08

Obs Average:

10^5 D/H = 2.55 ± 0.03

Updated D/H abundances in Quasar absorption systems



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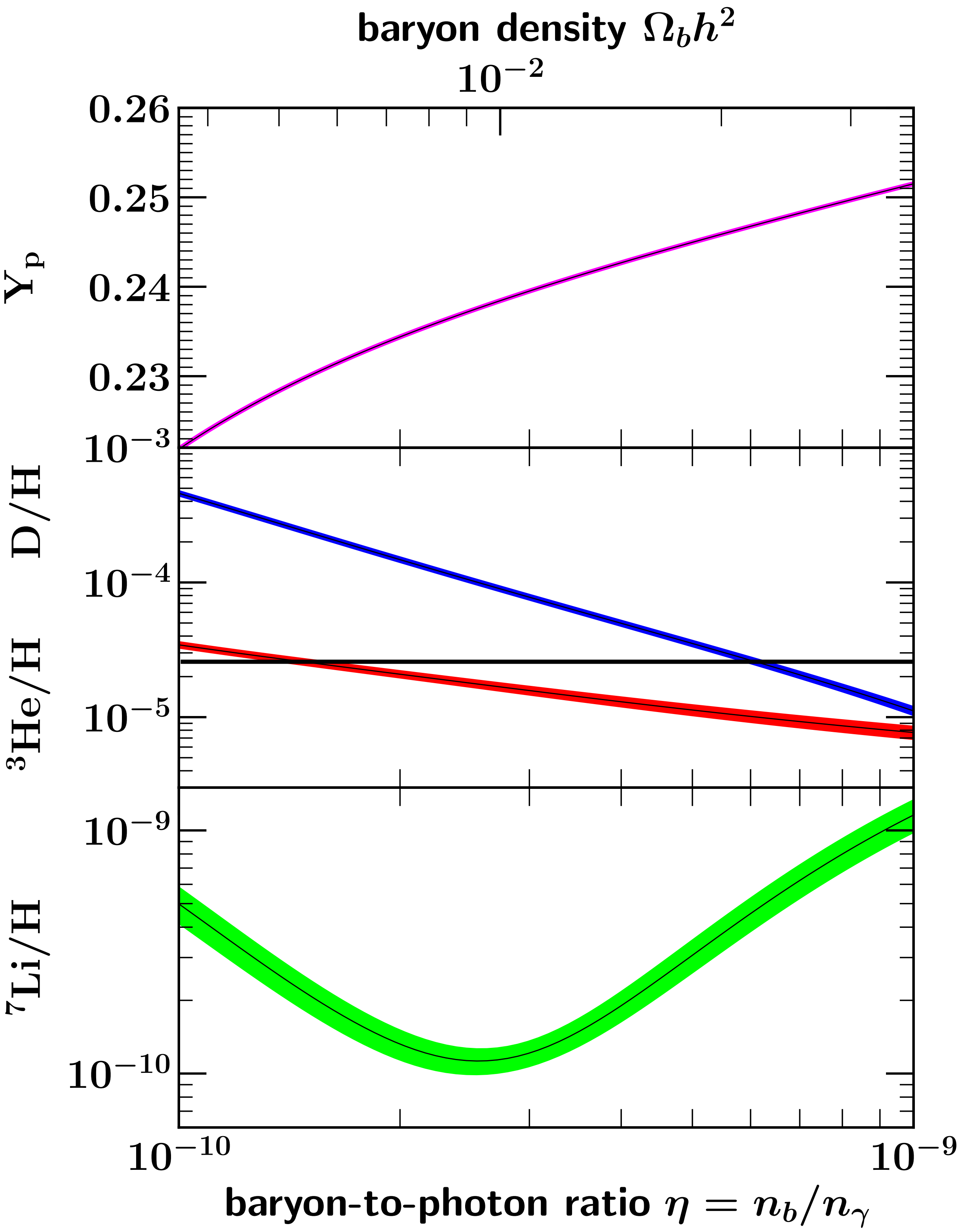
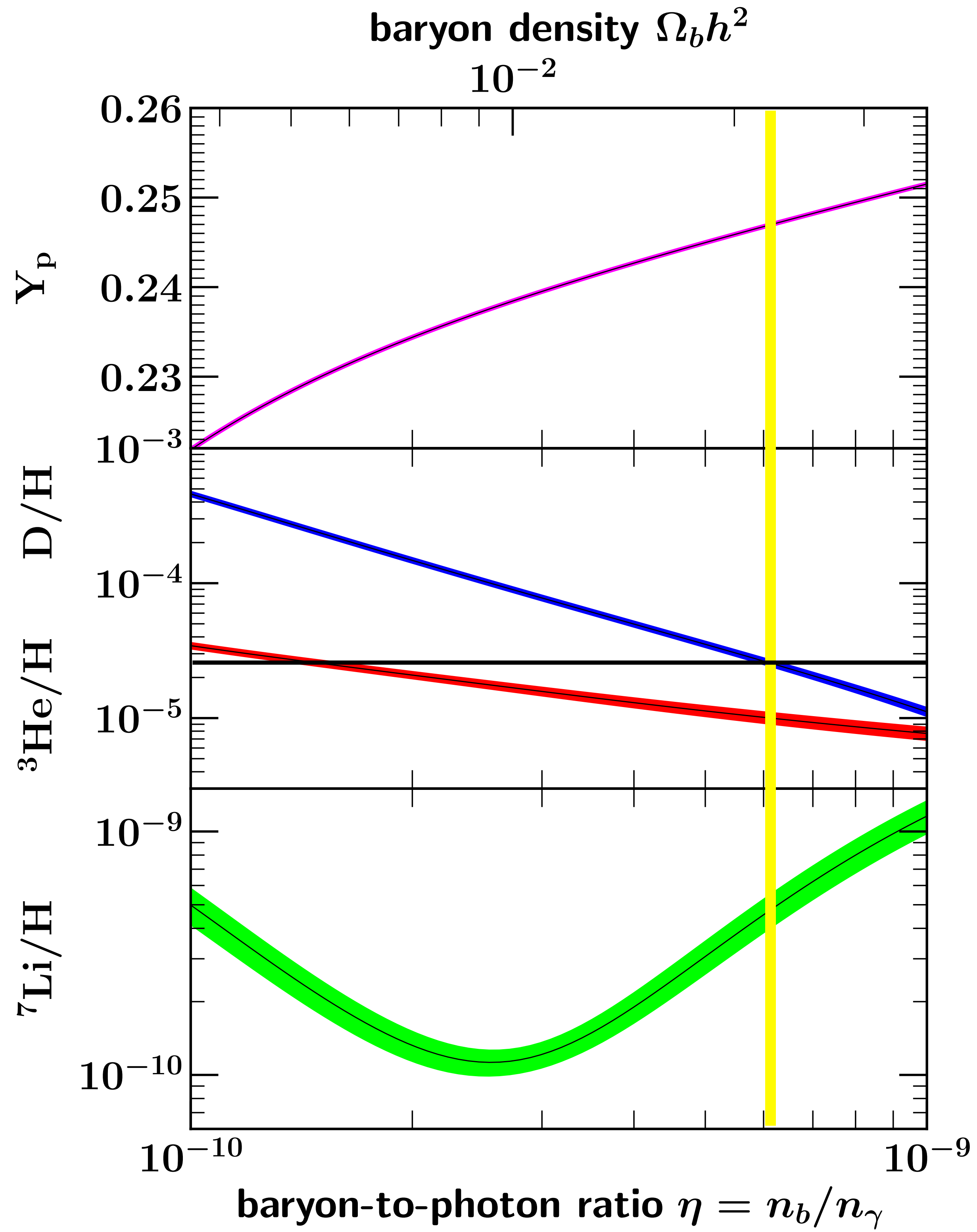


Fields, Olive, Yeh, Young

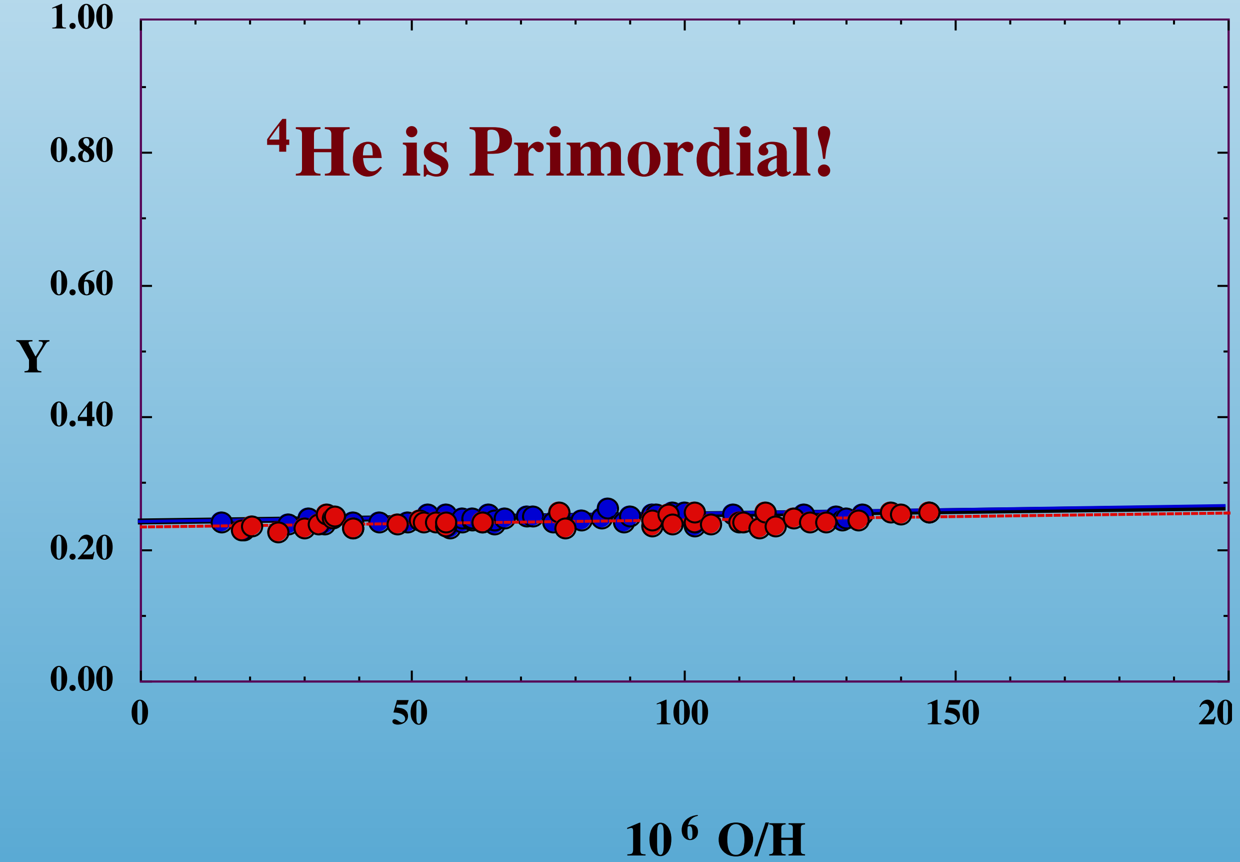


Fields, Olive, Yeh, Young

^{4}He

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

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



Results for He dominated by systematic effects

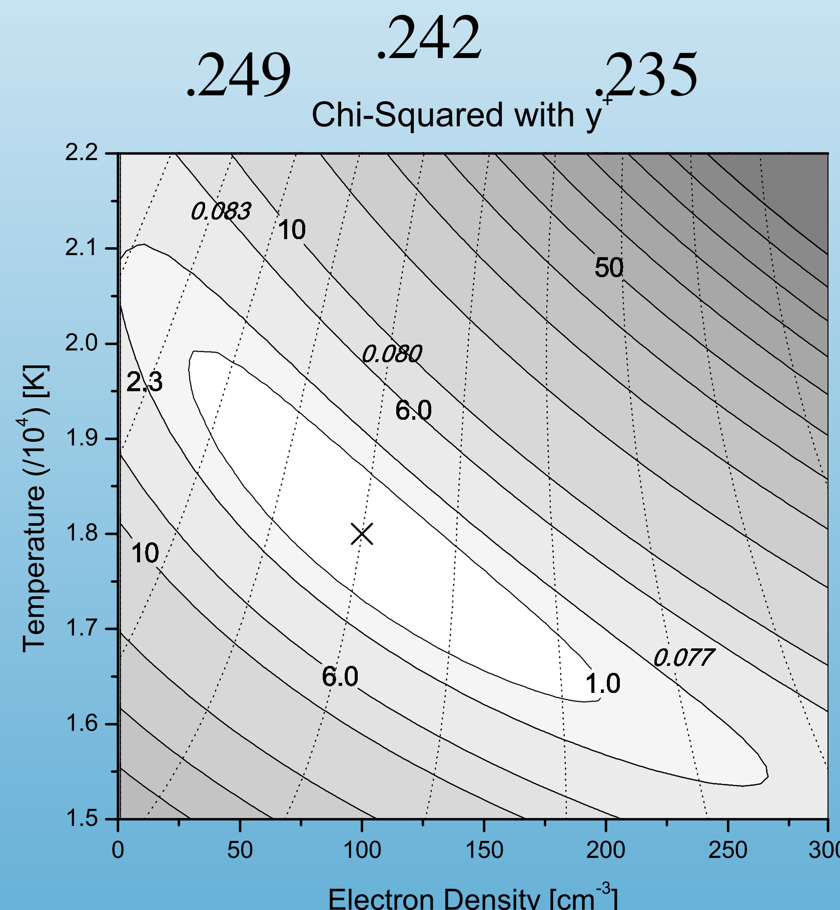
- Interstellar Redding (scattered by dust)
- Underlying Stellar Absorption
- Radiative Transfer
- Collisional Corrections

MCMC statistical techniques have proven effective in parameter estimation

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

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

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



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

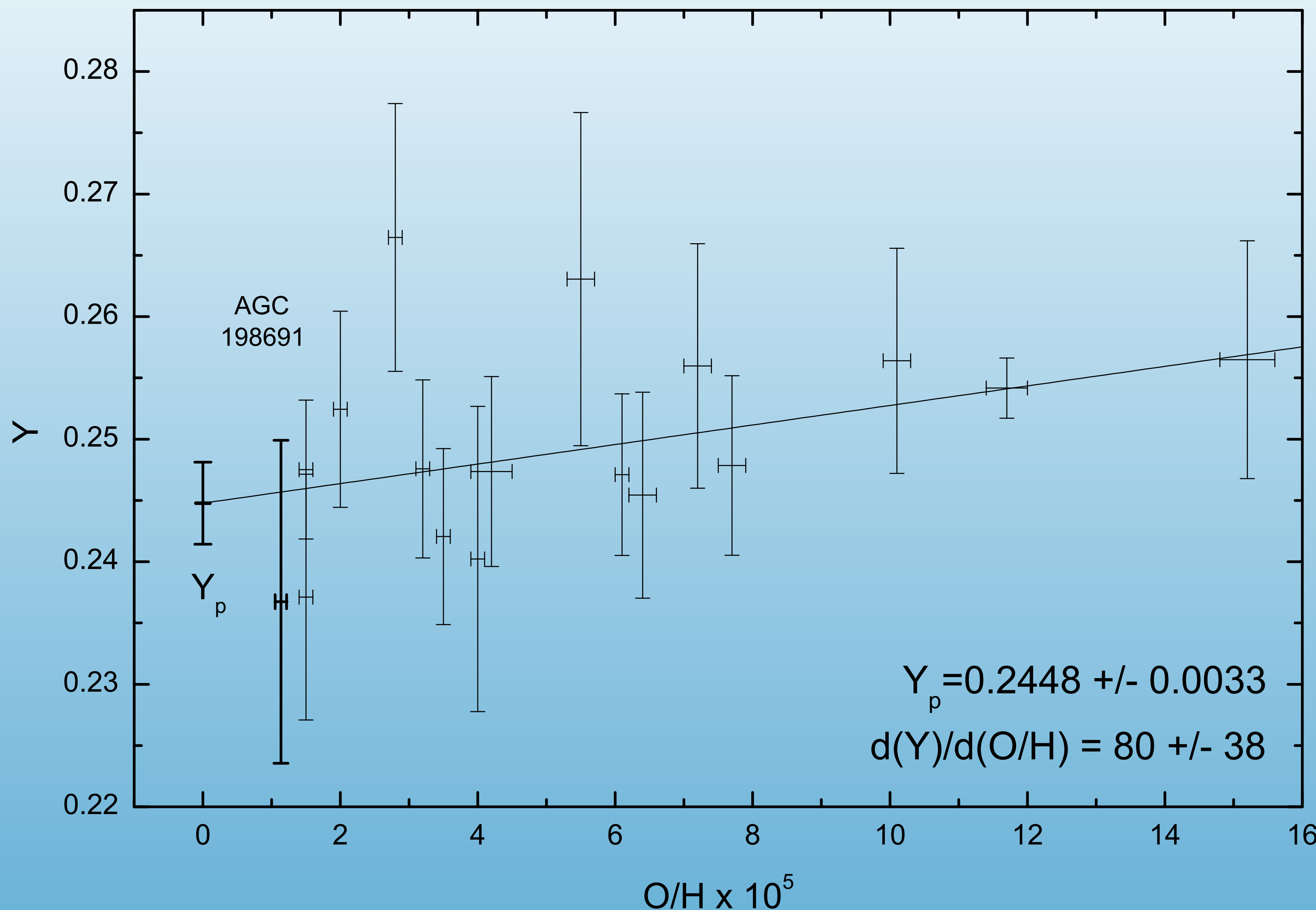
Applied to Leo P

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%

Most recent addition: AGC 198691 (2021)

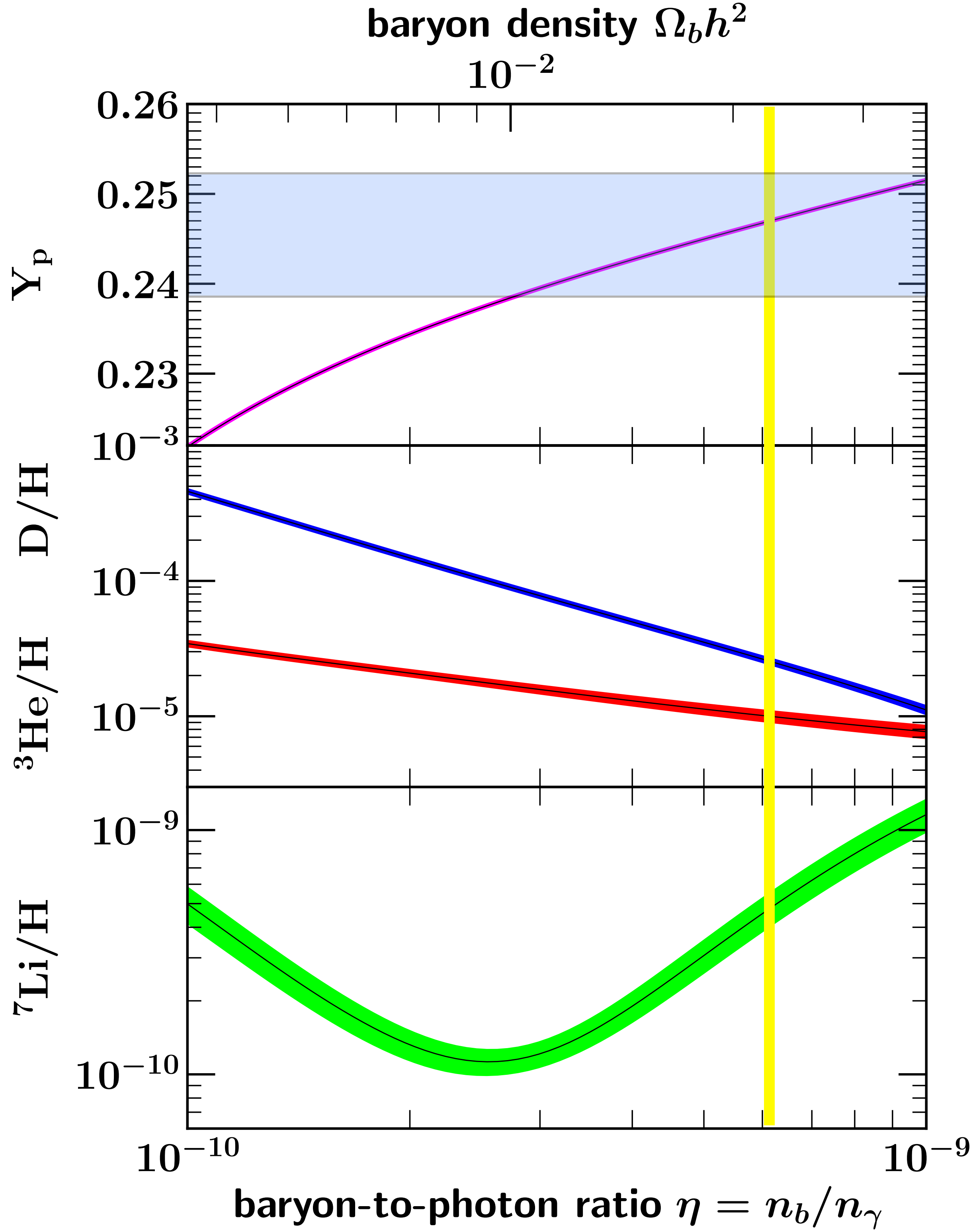


Aver, Berg, Hirschauer, Olive, Pogge, Rogers, Salzer, Skillman

prior: $Y_P = .2453 \pm 0.0034$

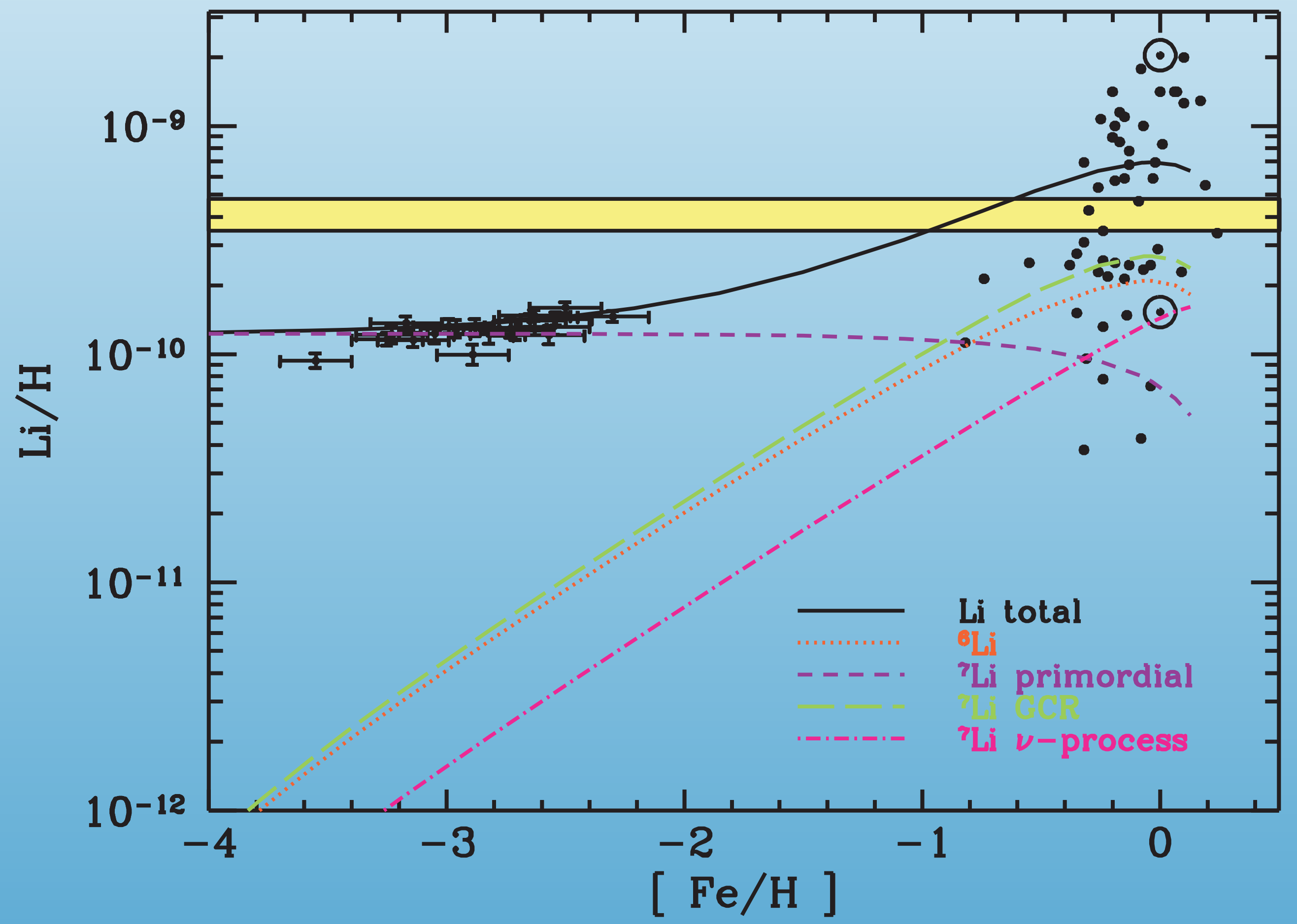
^{4}He Prediction:
0.2469 ± 0.0002

Data: Regression:
0.2448 ± 0.0033



Li/H

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



Possible sources for the discrepancy

- Nuclear Rates
- Resonant reactions
- Stellar Depletion

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

Arguments against stellar depletion

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

^{6}Li

In the happy but distant past:

^{6}Li (@ [Fe/H] ~ -2.3):

HD 84937: $^6\mathrm{Li/Li} = 0.054 \pm 0.011$

BD 26^o3578: $^6\mathrm{Li/Li} = 0.05 \pm 0.03$

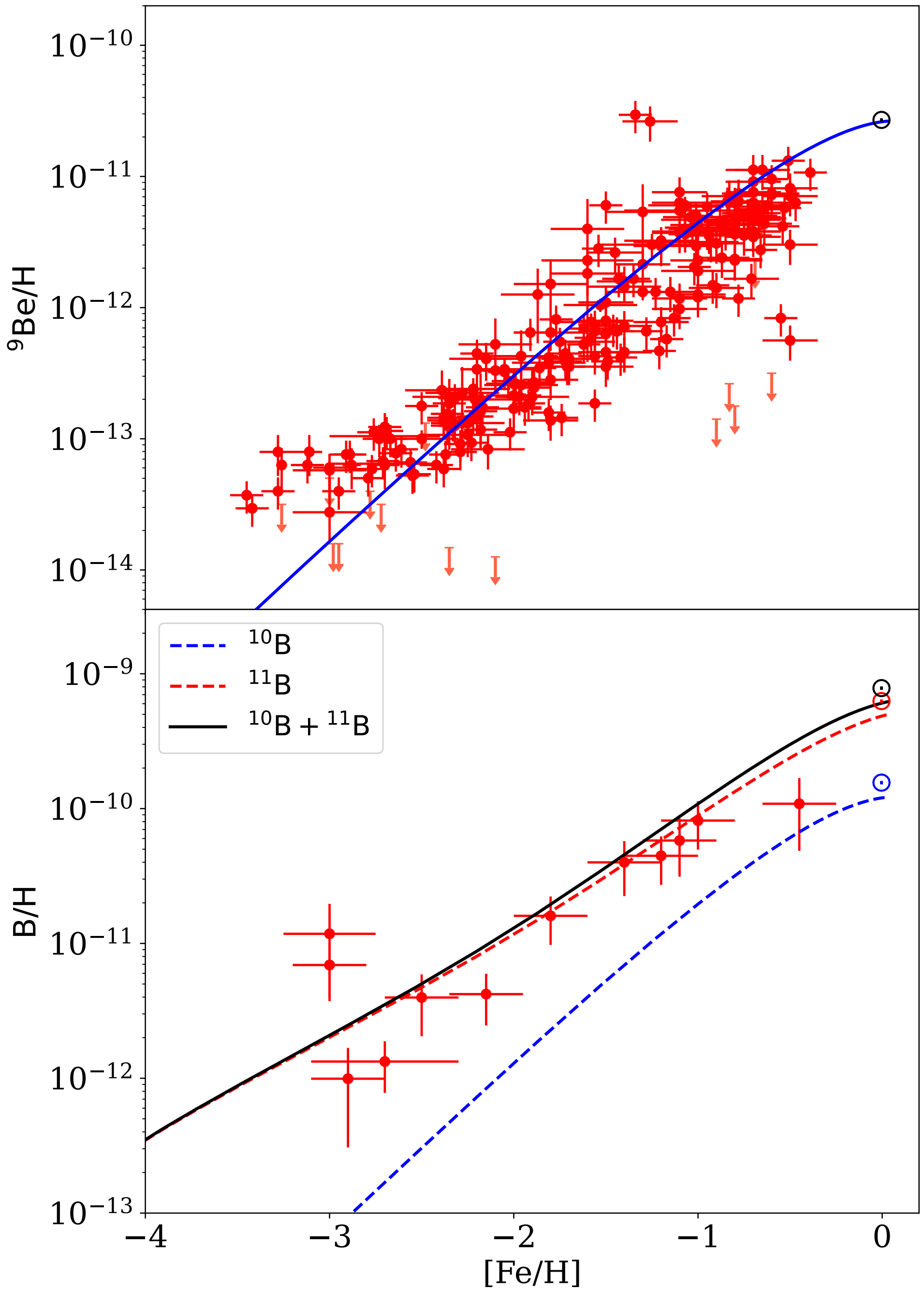
SLN

Hobbs & Thorburn

Cayrel etal

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

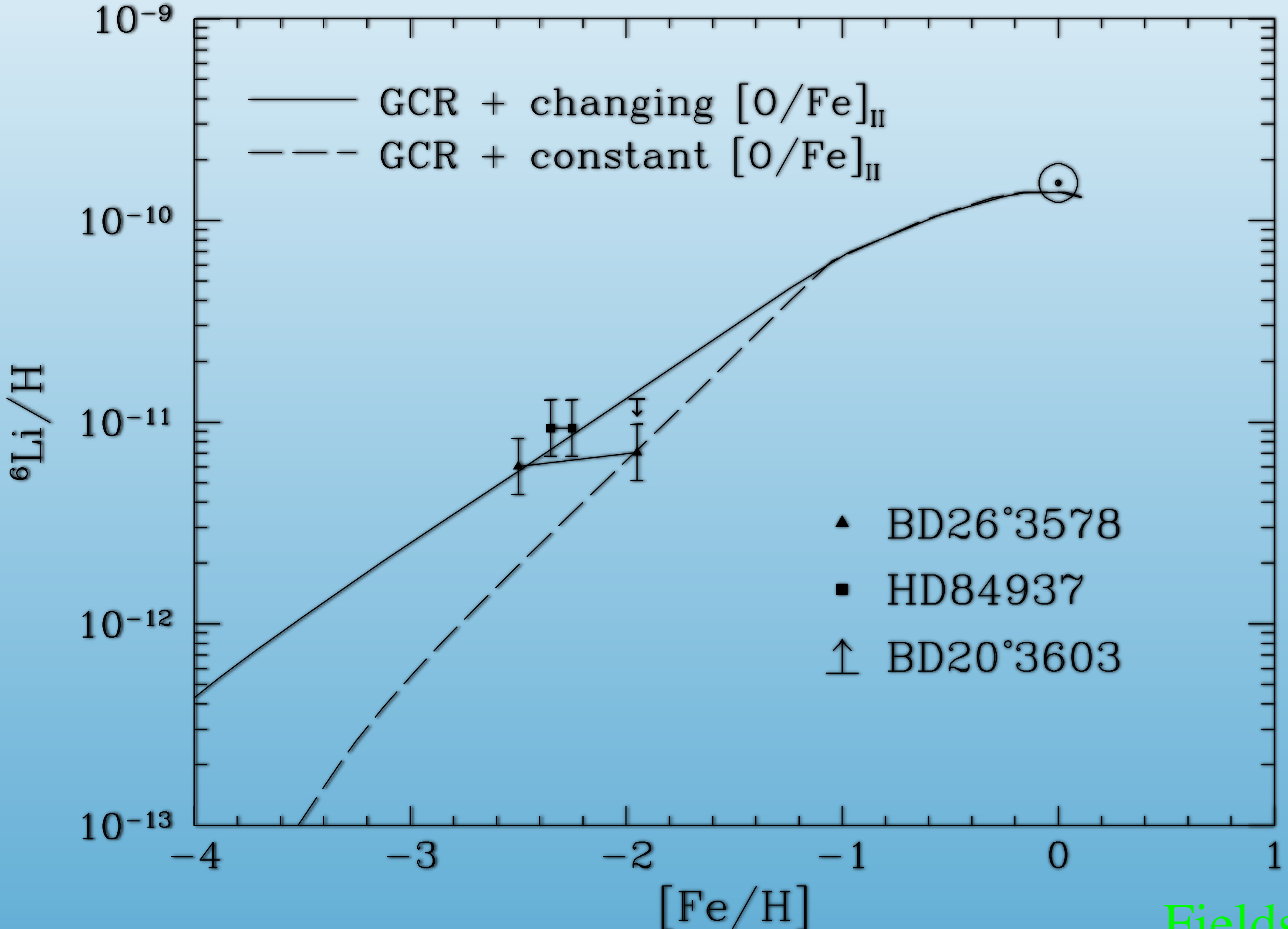
or $^6\mathrm{Li/Li} < 10^{-4}$



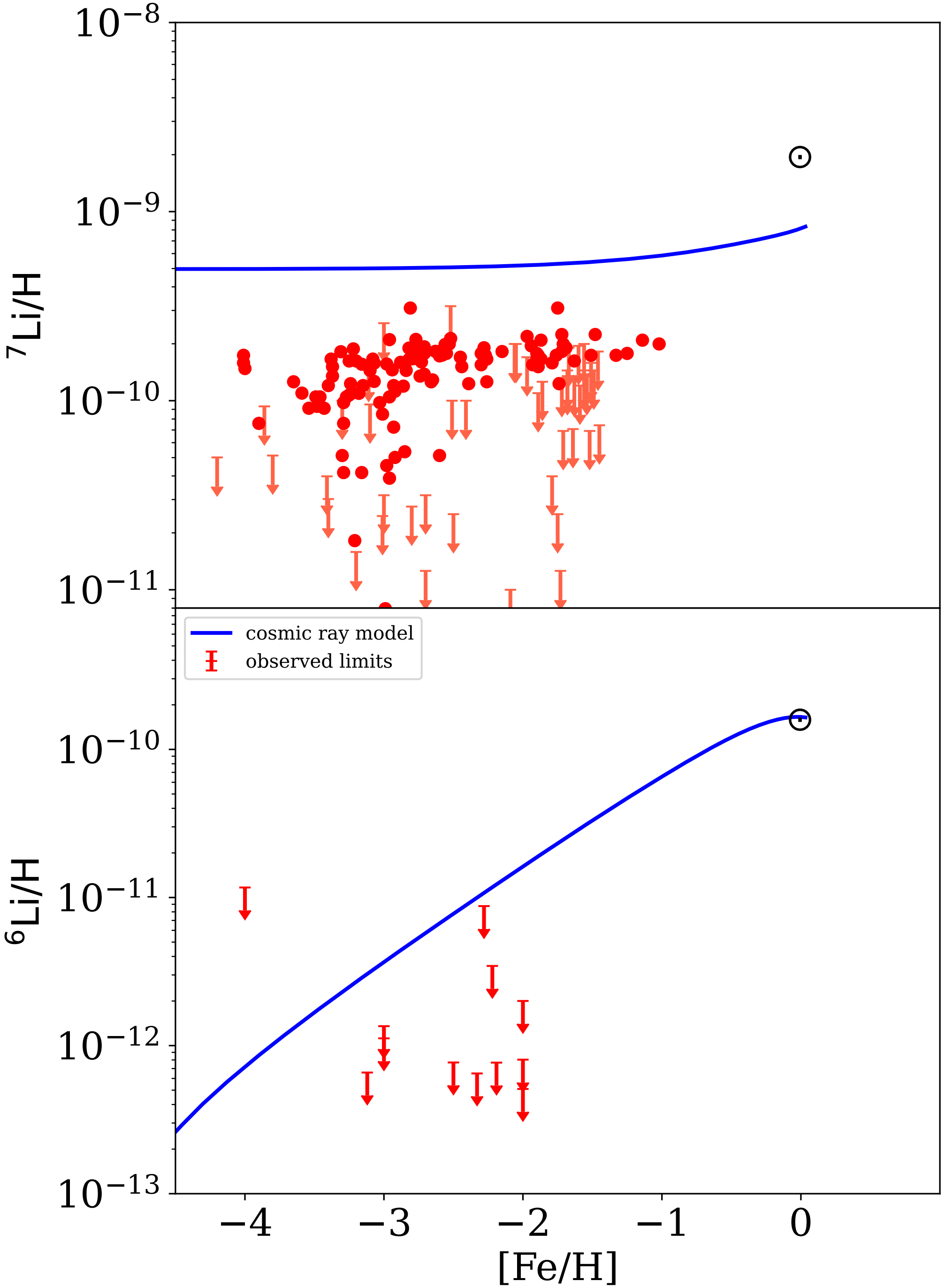
GCRN production of Be and B including primary and secondary sources

Fields & Olive

These data nicely accounted for by Galactic Cosmic Ray Nucleosynthesis

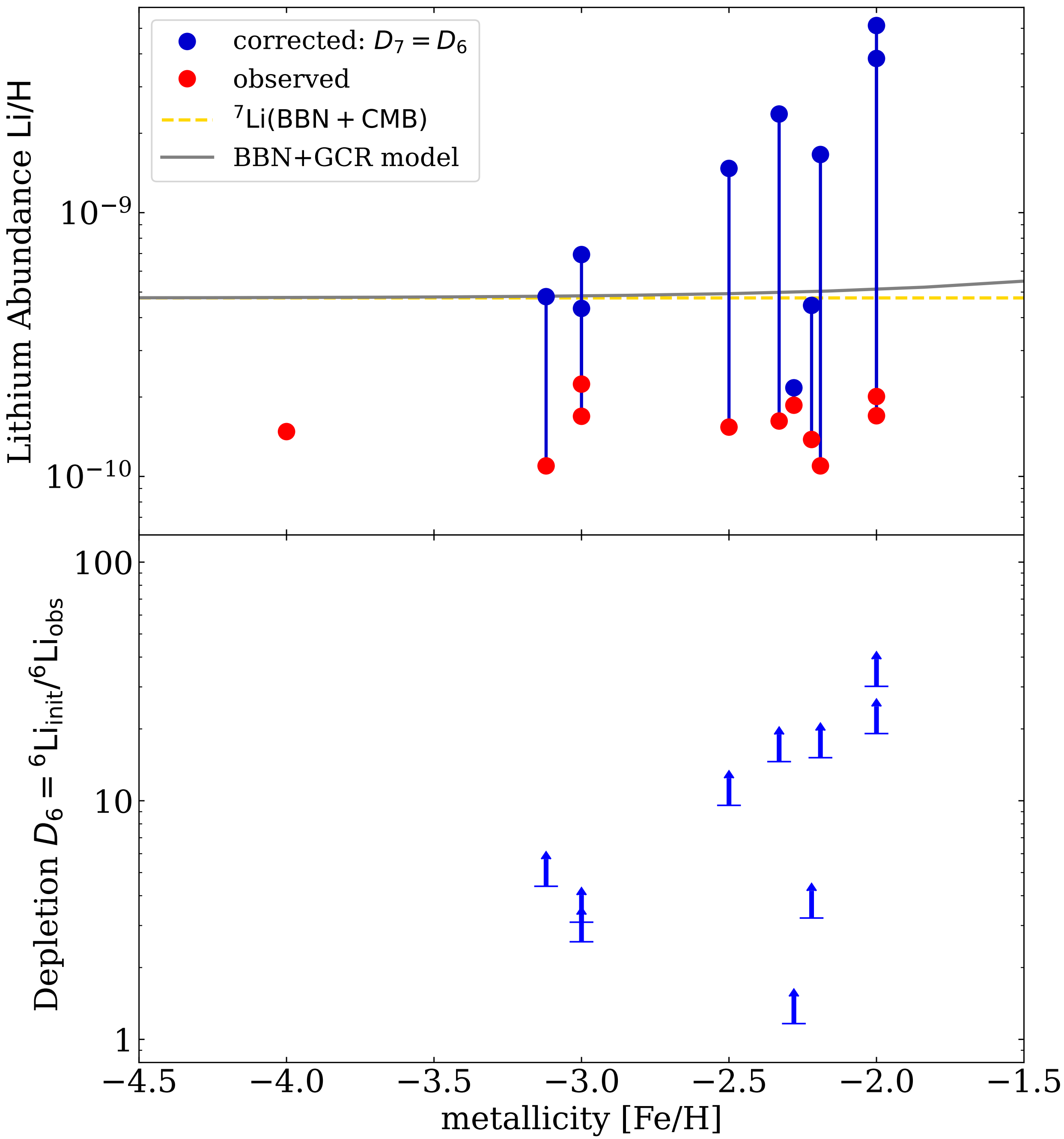


Fields and Olive
Vangioni et al.



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

Fields & Olive



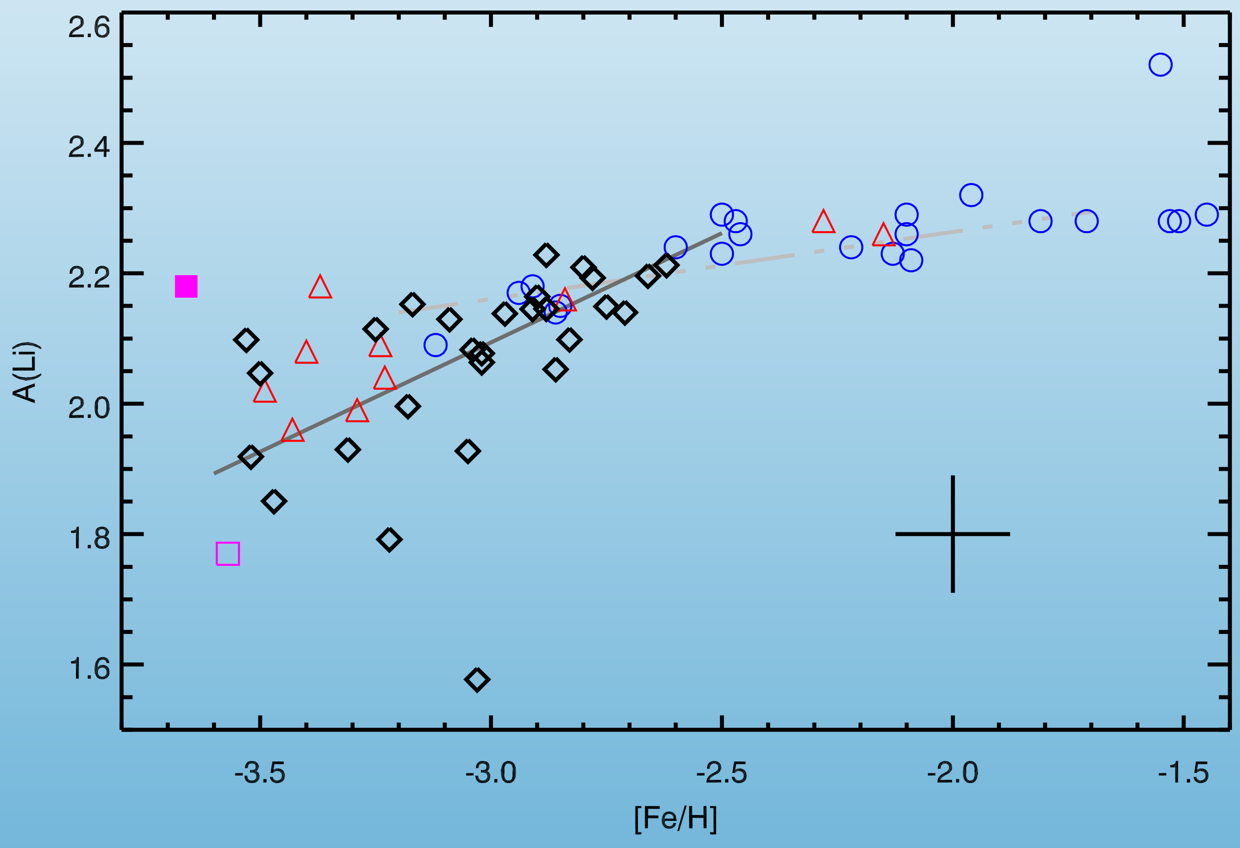
Both ^{6}Li and ^{7}Li appear to be destroyed

Implied Depletion

Fields & Olive

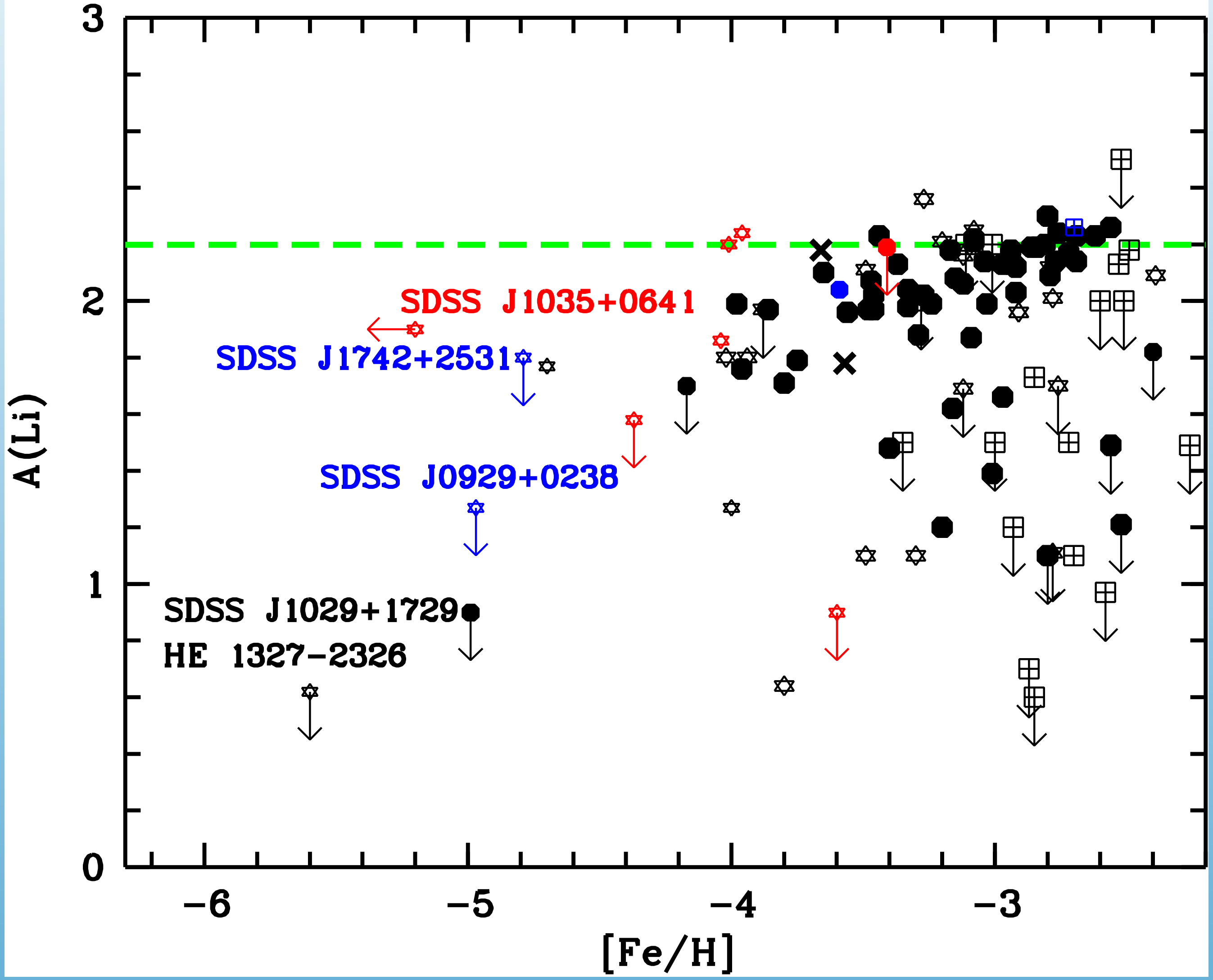
Broken Spite plateau

Note significant dispersion



Sbordone et al. (2010)

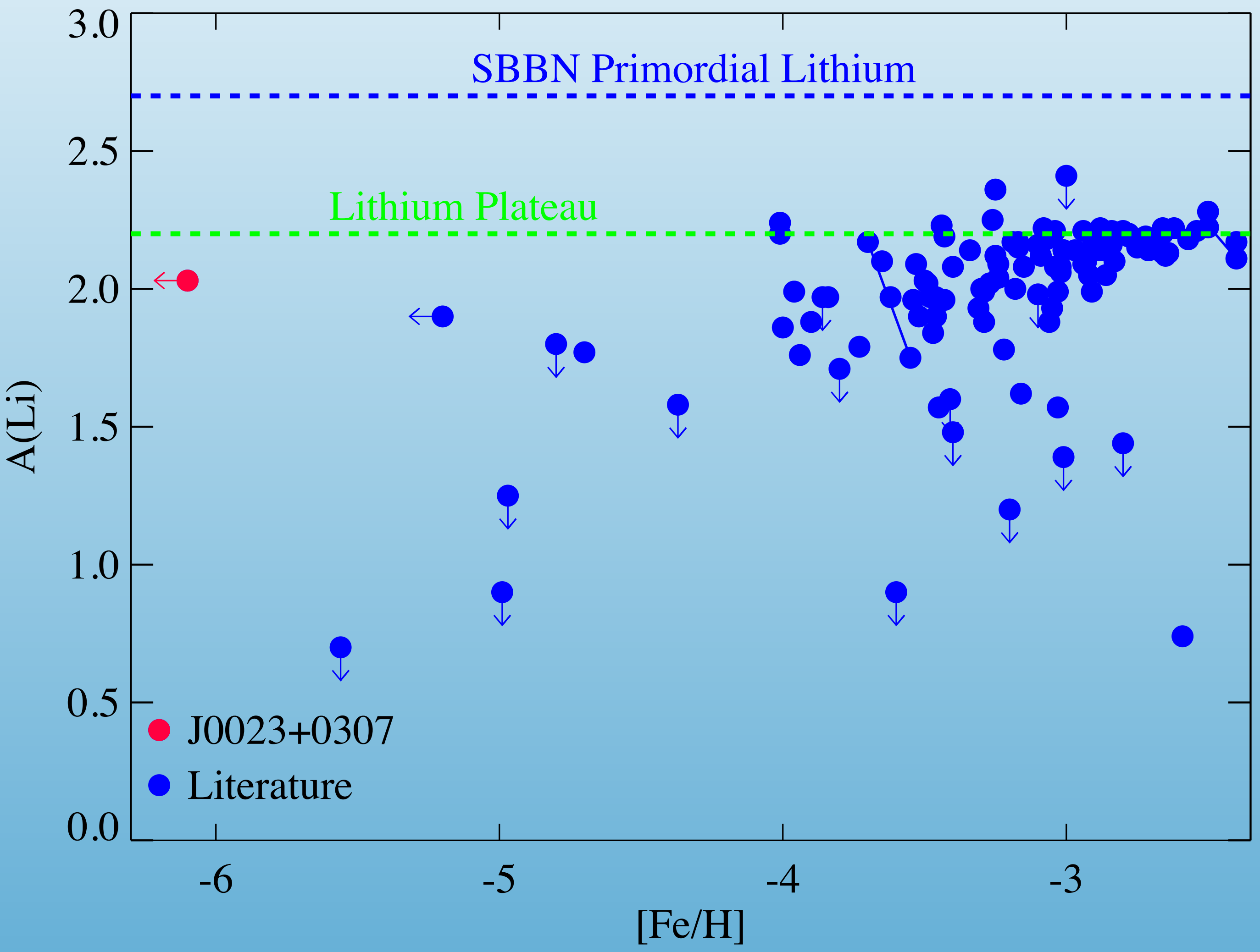
Broken Spite plateau



Note significant dispersion

Bonifacio et al. (2018)

Broken Spite plateau

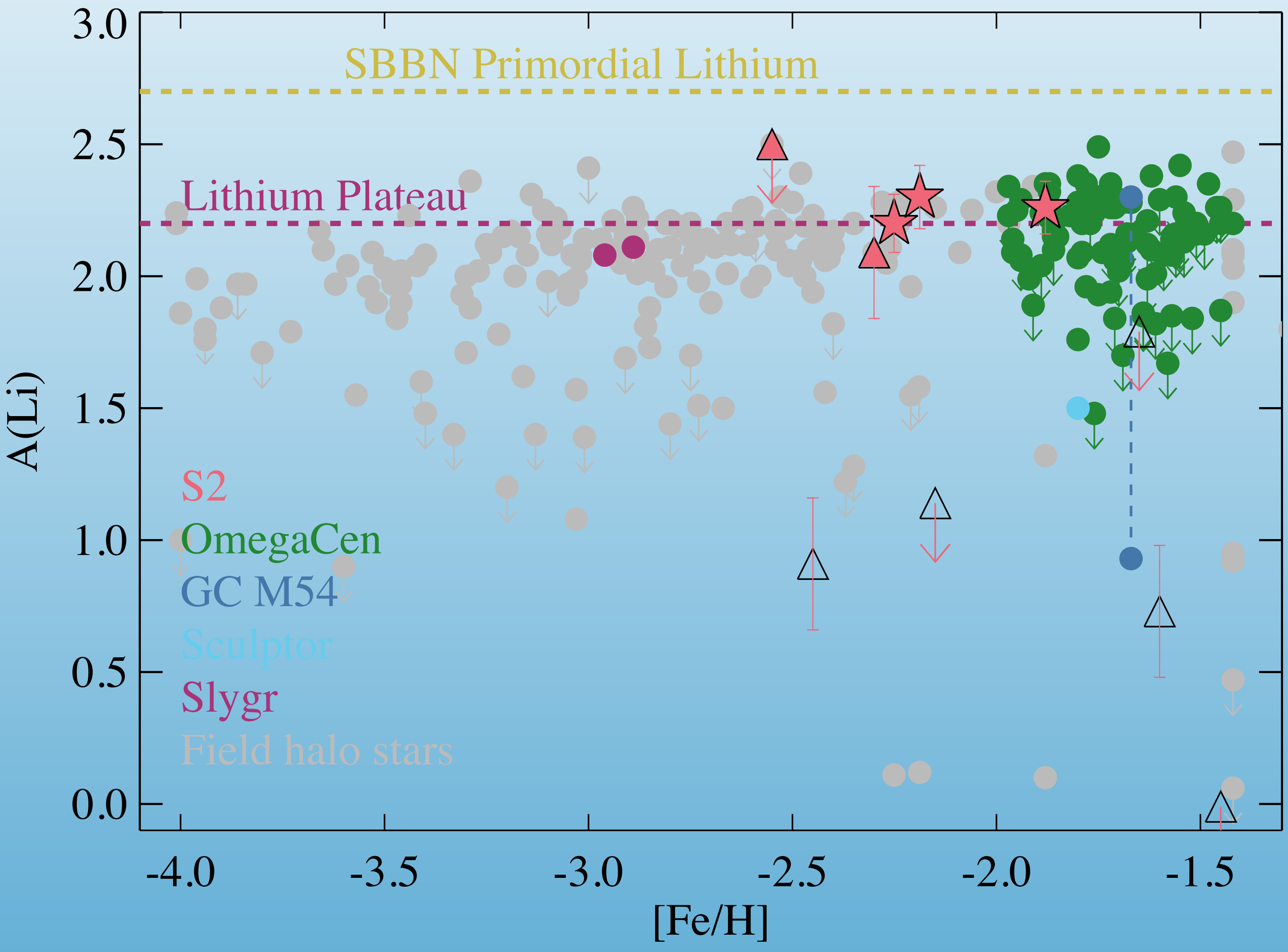


Note significant dispersion

Aguado et al. (2019)

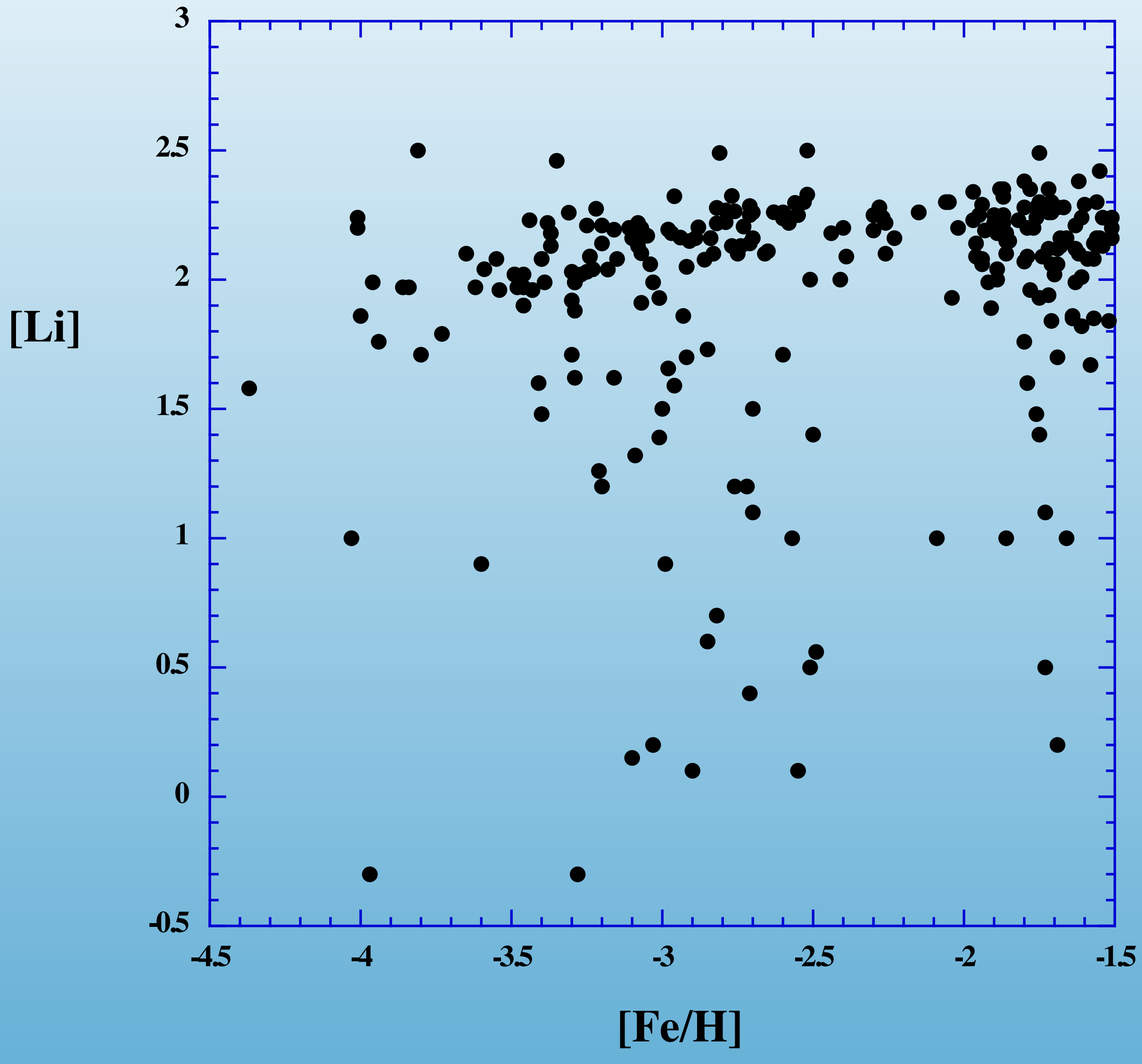
Broken Spite plateau

Note significant dispersion



Aguado et al. (2020)

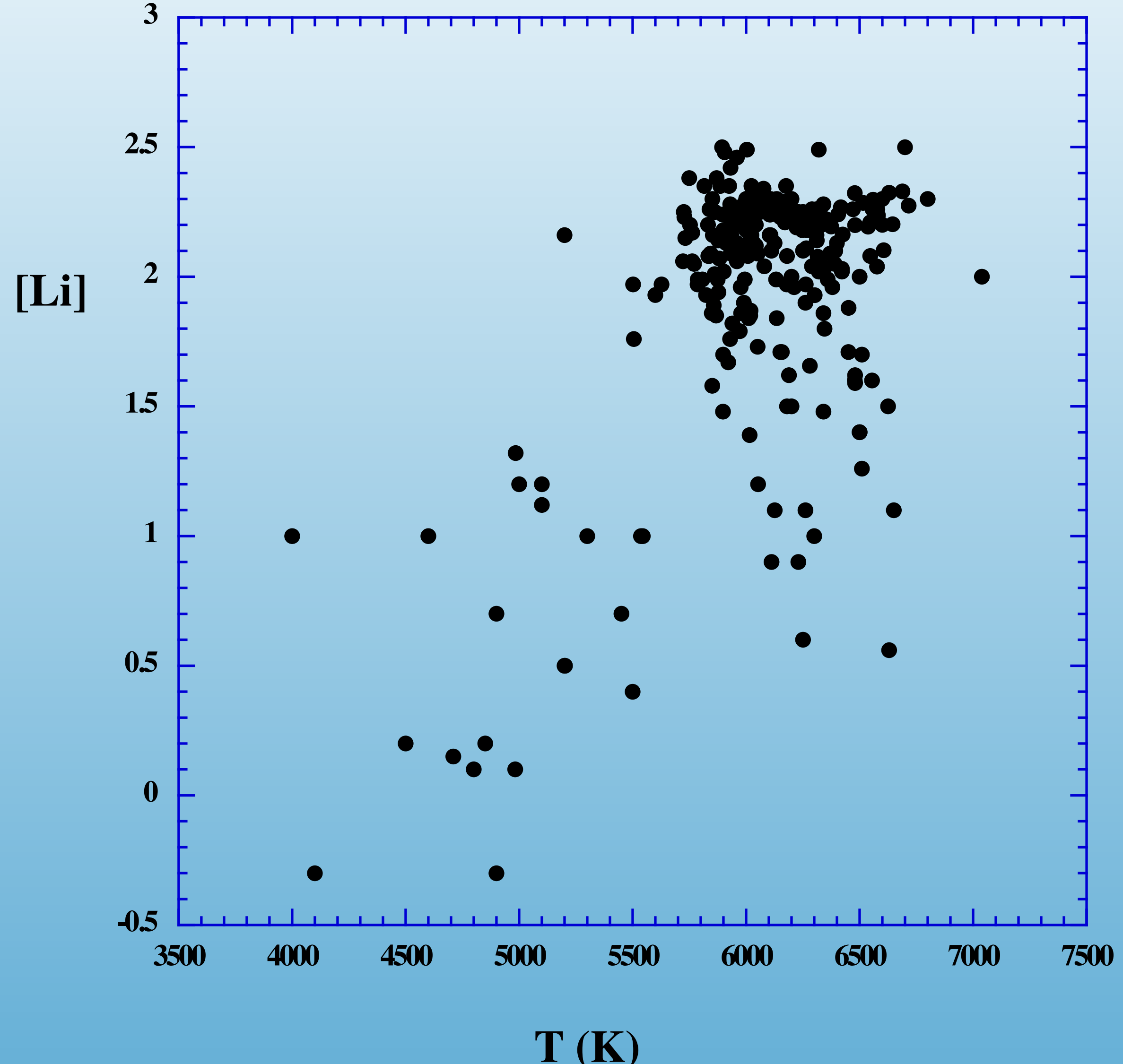
Broken Spite plateau



Note significant dispersion

Broken Spite plateau

Note significant dispersion



BBN and the CMB

From Planck (2015):

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

$$\omega_b = 0.022305 \pm 0.000225$$

$$Y_p = 0.25003 \pm 0.01367$$

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:

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

$$Y_p = 0.239 \pm 0.013$$

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

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

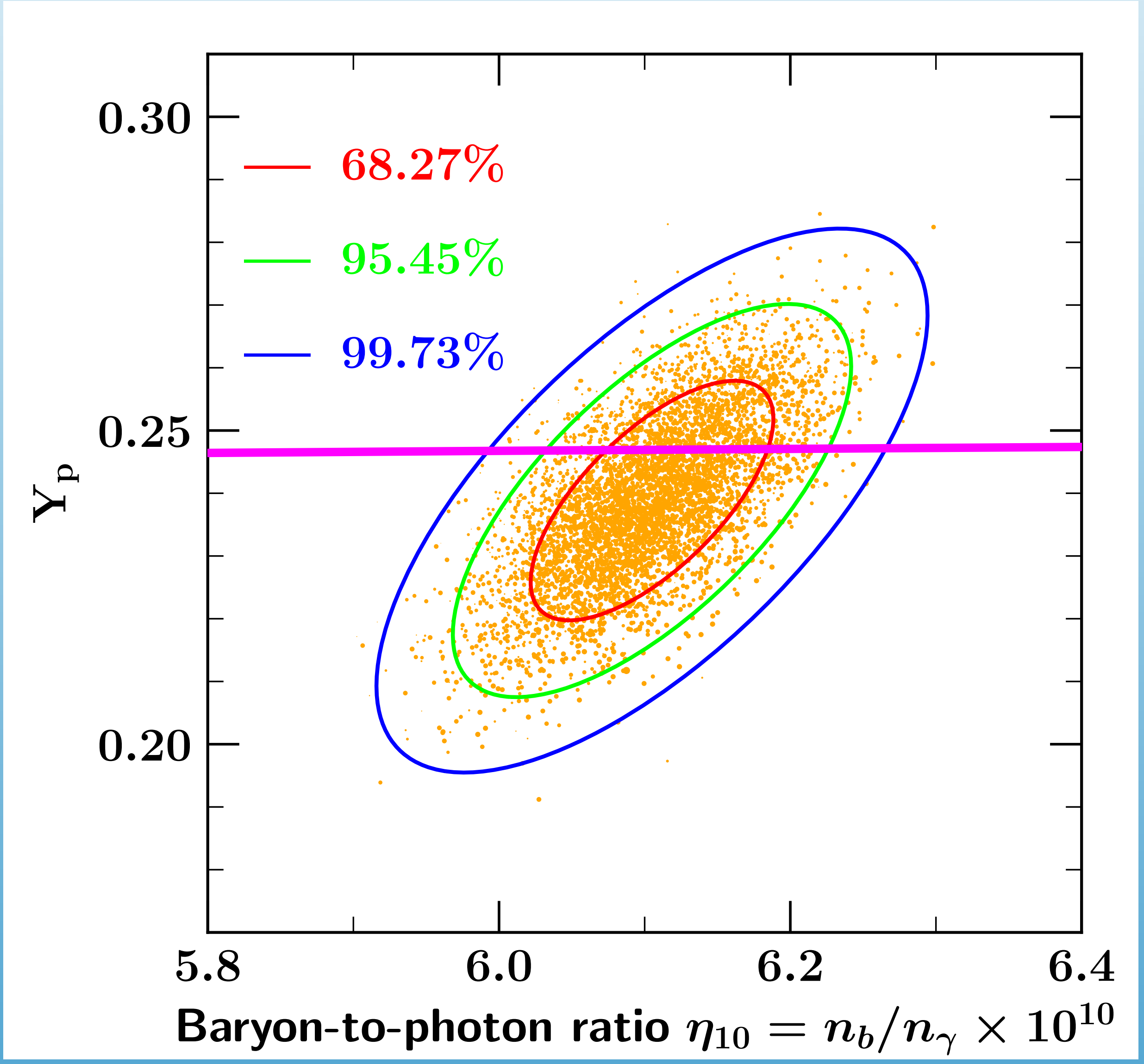
$$N_{\rm eff} = 2.841 \pm 0.298$$

Fields, Olive, Yeh, Young

BBN and the CMB

$N_\nu = 3$

CMB only determination of η and Y_P

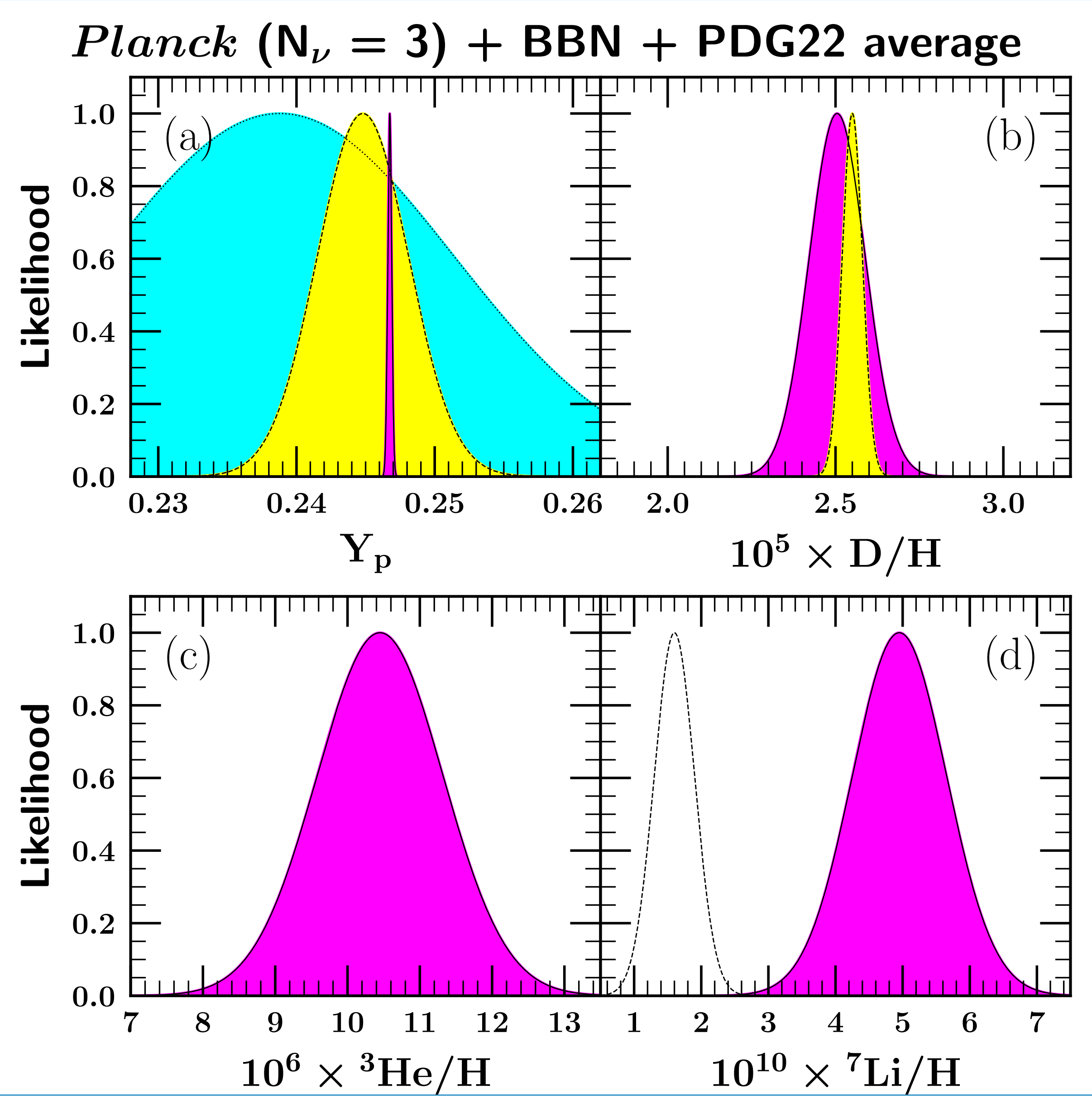


3σ BBN Prediction

Fields, Olive, Yeh, Young

BBN and the CMB

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

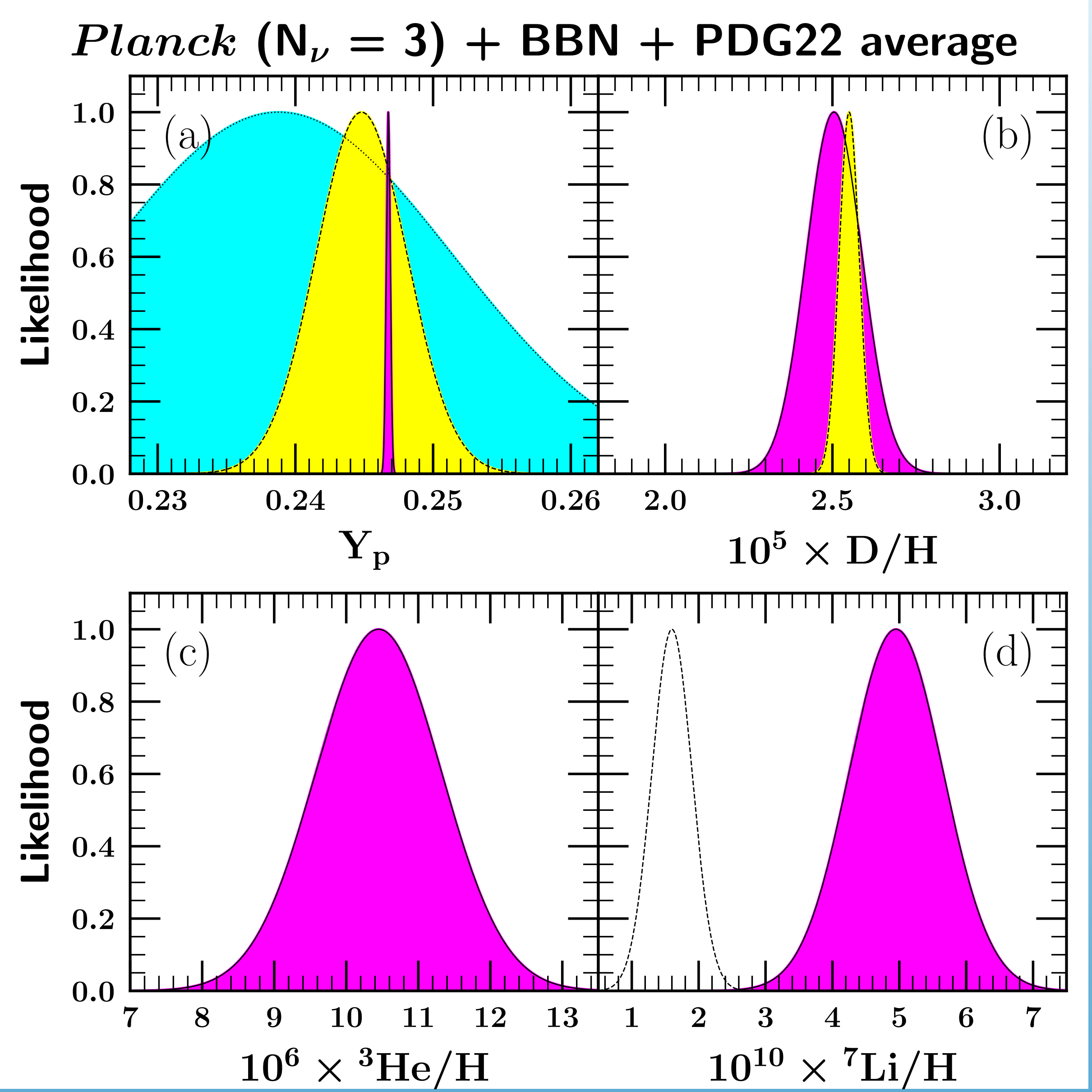
$$\mathcal{L}_{\rm CMB-BBN}(X_i) \propto \int \mathcal{L}_{\rm CMB}(\eta, Y_p)\, \mathcal{L}_{\rm BBN}(\eta; X_i)\, d\eta$$

Purple

Yeh, Olive, Fields

BBN and the CMB

Monte-Carlo approach combining BBN rates, observations and CMB



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

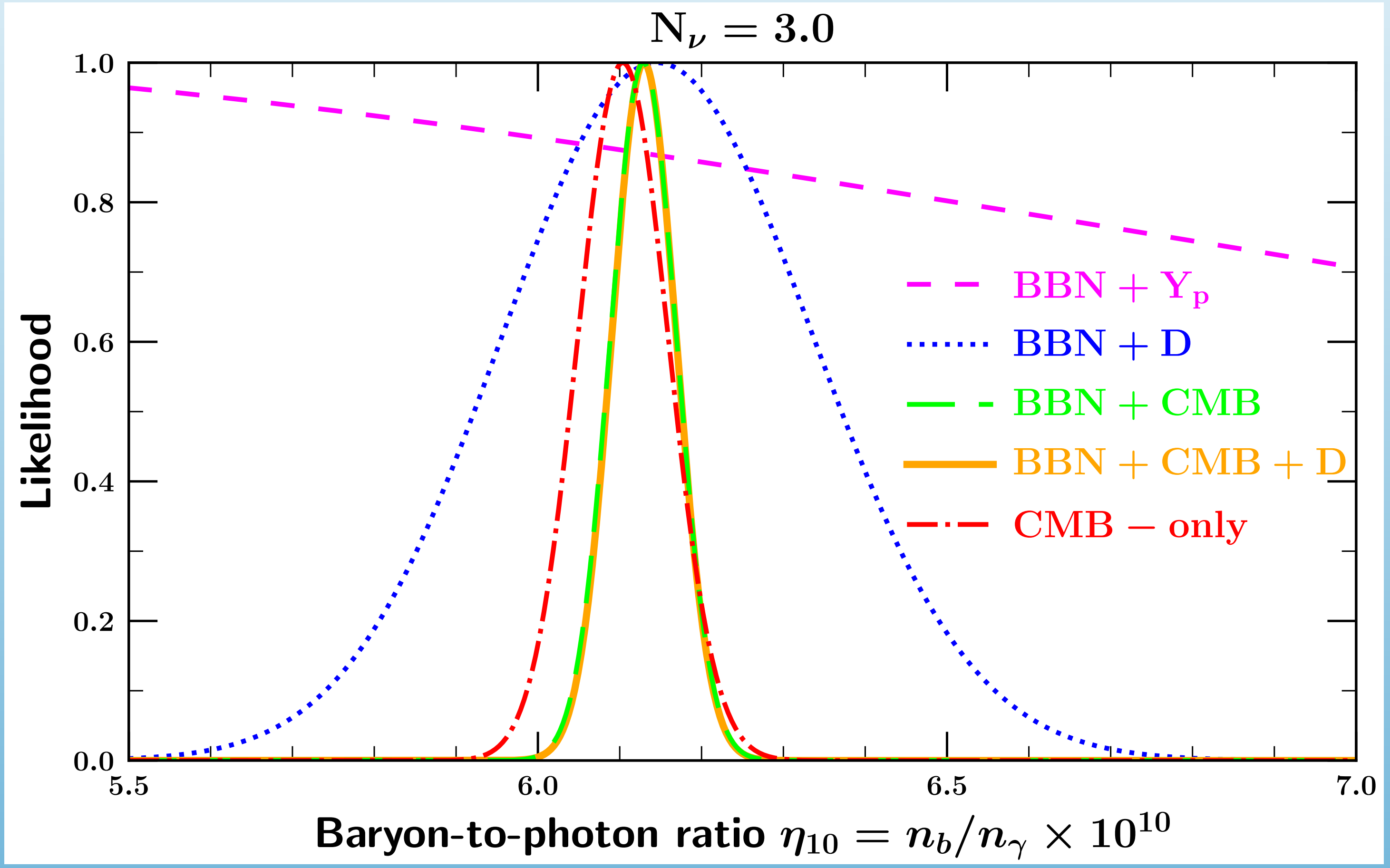
Yeh, Olive, Fields

BBN and the CMB

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

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

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

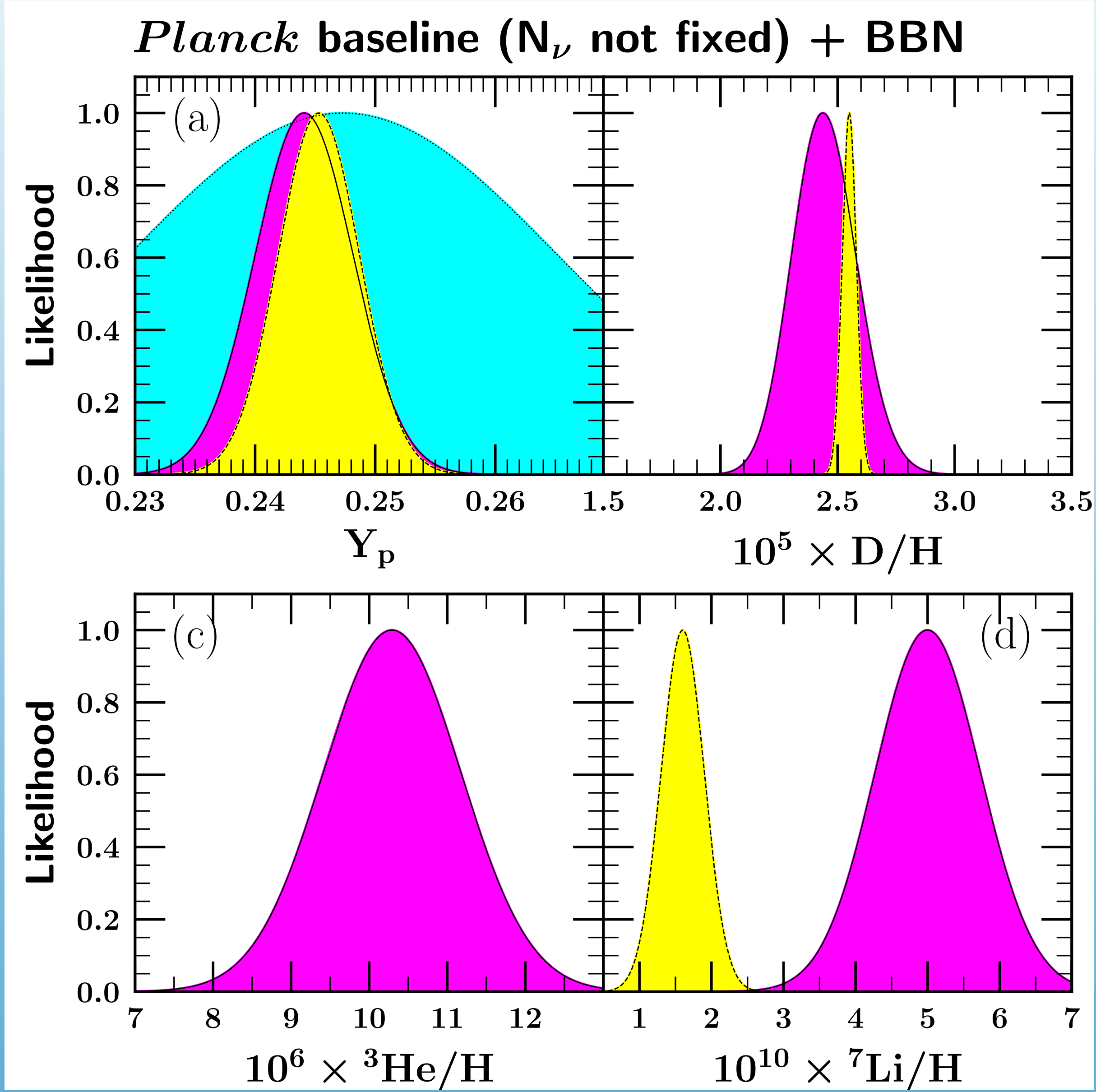
Results for η

Constraints Used	mean $10^{10}\eta$	peak $10^{10}\eta$
CMB-only	6.104 ± 0.055	6.104
BBN+Y_p	$6.239^{+1.202}_{-2.741}$	5.031
BBN+D	6.042 ± 0.118	6.041
BBN+Y_p+D	6.040 ± 0.118	6.039
CMB+BBN	6.124 ± 0.040	6.124
CMB+BBN+Y_p	6.124 ± 0.040	6.124
CMB+BBN+D	6.115 ± 0.038	6.115
CMB+BBN+Y_p+D	6.115 ± 0.038	6.115

Yeh, Shelton, Olive, Fields

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

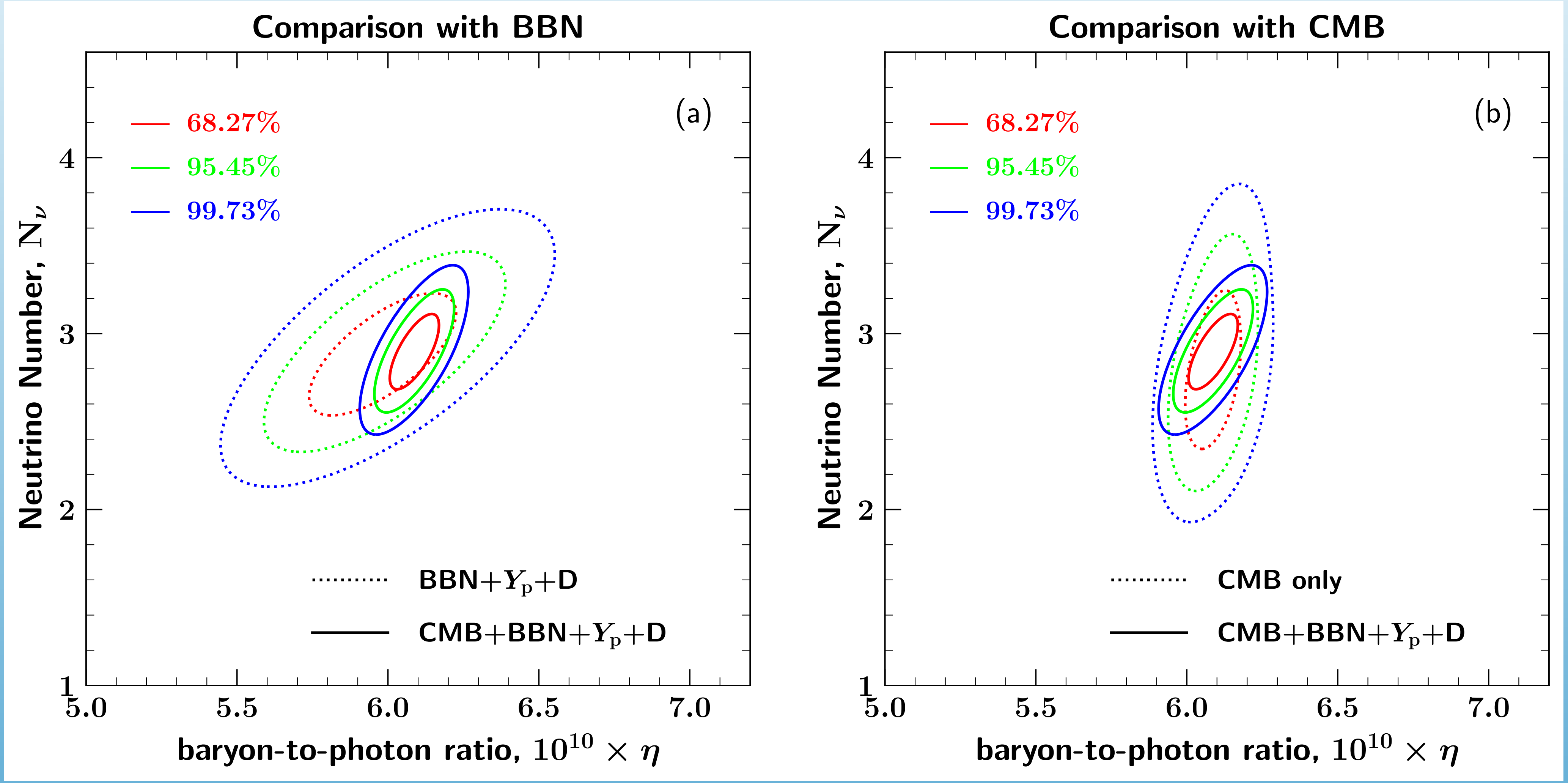
$$\mathcal{L}_{\rm NCMB-NBBN}(\eta) \propto \int \mathcal{L}_{\rm NCMB}(\eta, Y_p, N_\nu)\mathcal{L}_{\rm NBBN}(\eta, N_\nu; X_i)\, dY_p dN_\nu \,,$$

Purple

Fields, Olive, Yeh, Young

BBN and the CMB

CMB and BBN determination of η and N_ν



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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

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$N_\nu < 3.18$ (95% CL)

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Summary

- BBN and CMB are in excellent agreement wrt D and He
- Li: Problematic
  - most likely 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!

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