What did the light nuclides know and when did they know it?

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BBN in three easy steps

At temperatures above $T \sim 10^{10}$ K, the ratio of neutrons to protons is governed by equilibrium enforced by weak interactions:

$$\nu_e + n \longleftrightarrow p + e^-$$

and "crossed" diagrams

Nucleosynthesis starts at $T \sim 10^{10}$ K, when the rates for processes maintaining equilibrium become slower than the universal expansion

The neutron/proton ratio freezes out at

$$\frac{n_n}{n_p} = \exp[-(m_n - m_p)/kT] \sim \frac{1}{7}$$

followed by free neutron decay

This is Weak Freezeout

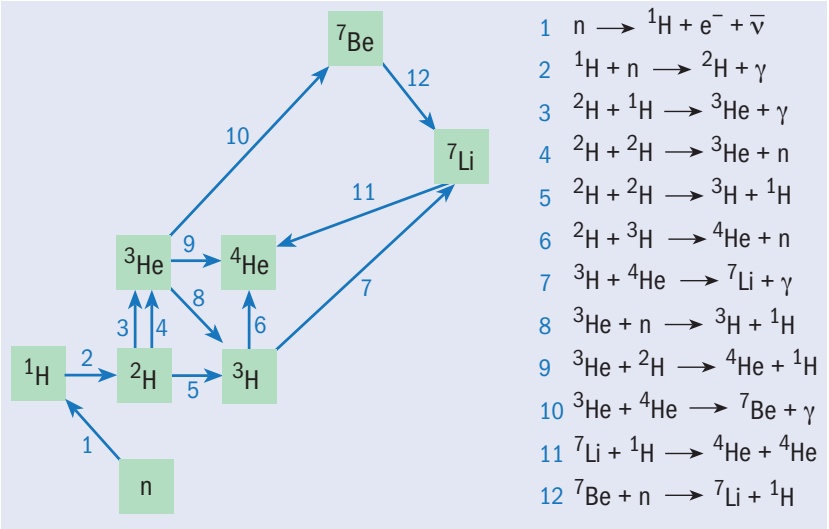
BBN in three easy steps

At the time of weak freezeout, relative amounts of light nuclei are in Nuclear Statistical Equilibrium (NSE)

Almost all nucleons are free, small amounts of D, ^{3}He, ^{3}H, and ^{4}He

Dropping T gradually favors $A = 3$ and 4

At $\sim$ 5 minutes, almost all neutrons are in ^{4}He (large per-particle binding energy)



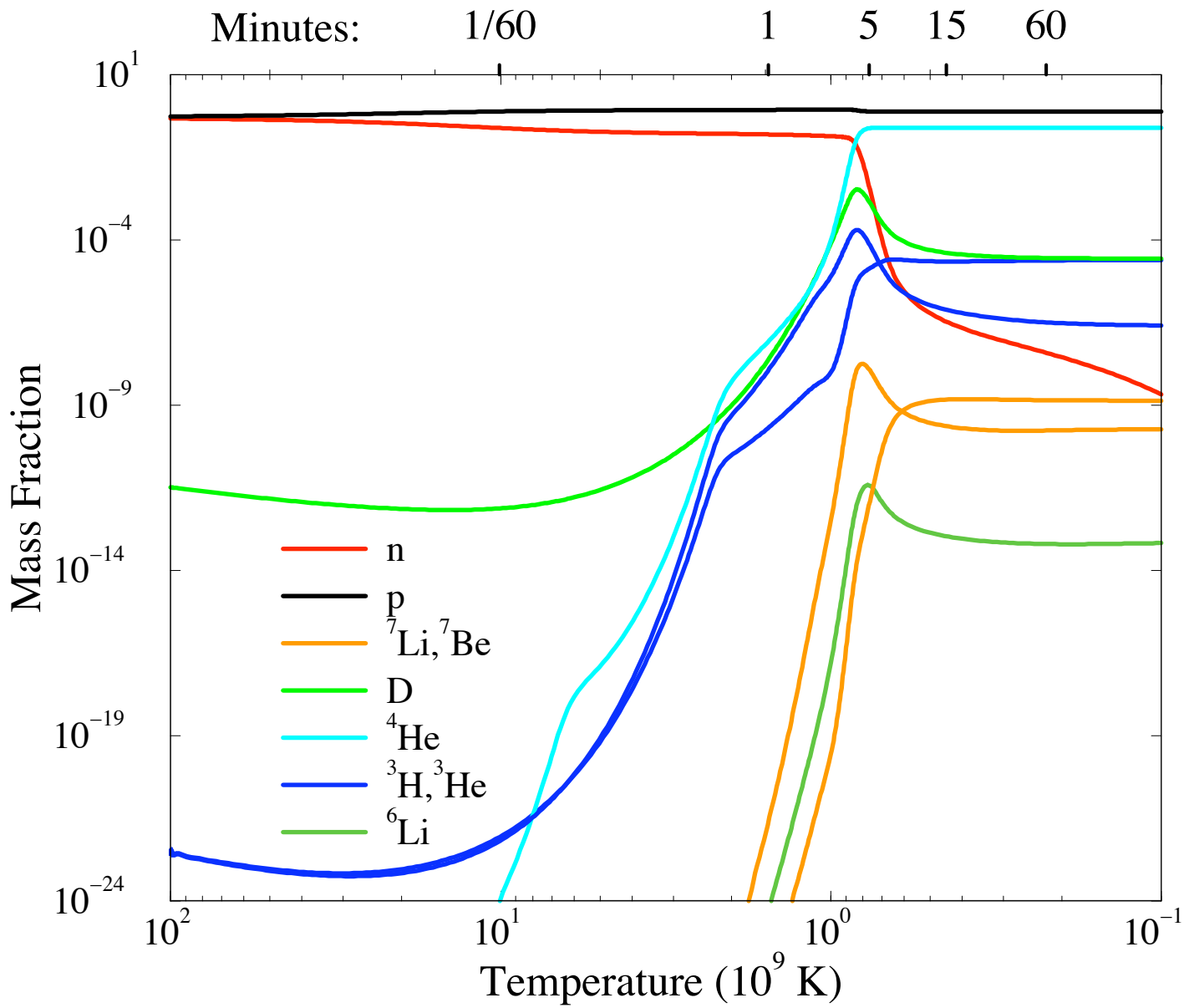
Low ρ and T, Coulomb barriers, disappearance of neutrons, fragility to proton reactions, and lack of stable $A = 5, 8$ nuclei all cause Final Freezeout

BBN in a nutshell

1. Weak Freezeout
   ($\sim$ 1 second)

2. Statistical equilibrium & quasi-equilibrium
   ($\sim$ 1 second to 5 minutes)

3. Final Freezeout
   ($>$ 5 minutes)



BBN today

The Big Question is now

Are the primordial abundances consistent with the standard cosmology?

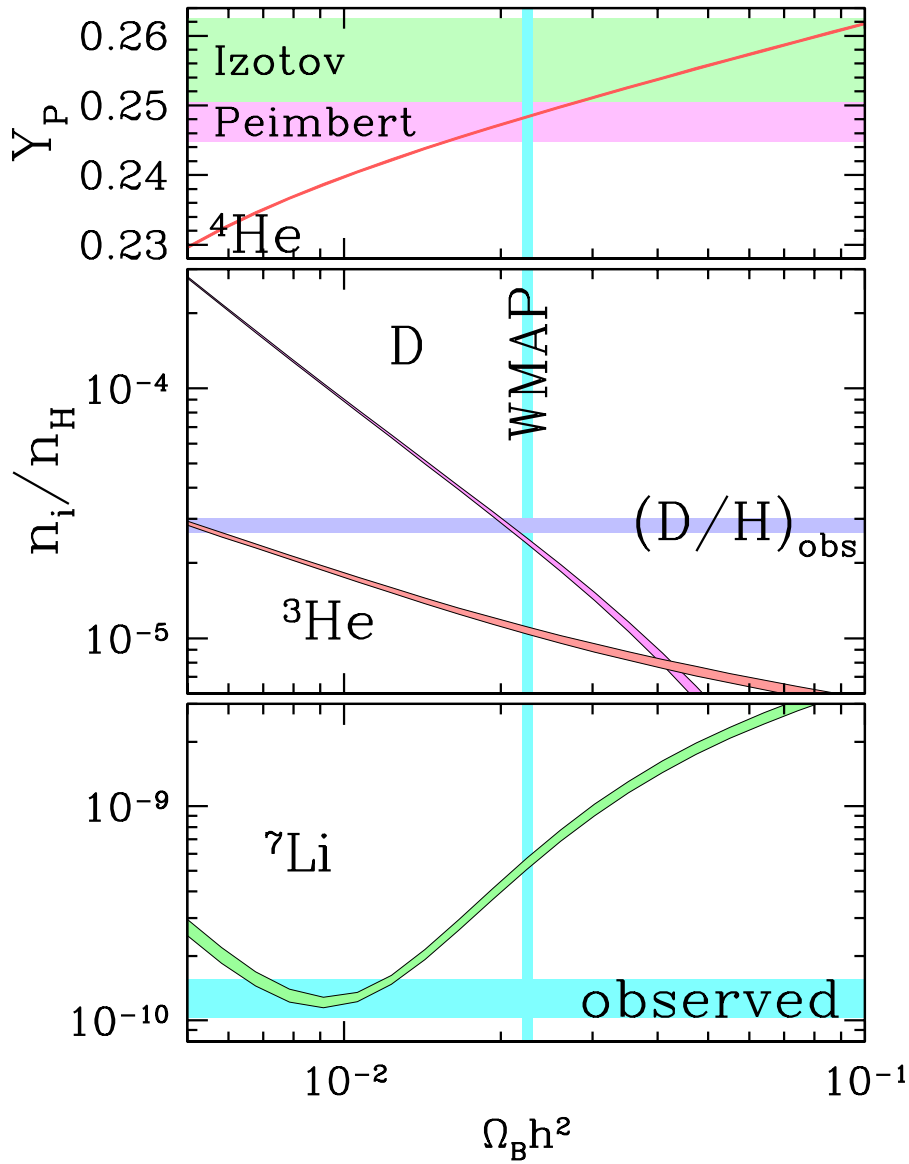
The only ΛCDM parameter that BBN depends on is $\Omega_B h^2 \propto n_B/n_\gamma$

With 2% precise $\Omega_B h^2$ from CMB, BBN gives very precise predictions

If the answer is "no," there are interesting things to be learned about:

neutrinos	model atmospheres
gravity	stellar evolution
all of the above	none of the above

...but we can't tell *a priori* which one(s)



Standard BBN as a precise theory

Y_P counts neutrons, only cares about weak freezeout

$Y_P = 0.2484 \pm 0.0002(\text{theory}) \pm 0.0003(\tau_\text{n}) \pm 0.0002(\Omega_\text{B}\text{h}^2)$

Deuterium nuclear inputs have improved considerably in the last decade, now dominated by $d + p \longrightarrow {}^3\text{He} + \gamma$

$\text{D/H} = (2.42 \pm 0.11) \times 10^{-5}$ (2.5% nuclear, 4% $\Omega_B h^2$)

${}^3\text{He/H} = (1.07 \pm 0.04) \times 10^{-5}$, mostly nuclear

A major logjam in ${}^3\text{He} + \alpha \longrightarrow {}^7\text{Be} + \gamma$ precision broke in the '00s

$\text{Li/H} = (5.5 \pm 0.4) \times 10^{-10}$, only 2% from $\Omega_B h^2$

BBN: The neutrino's point of view

Neutrinos do two things in BBN:

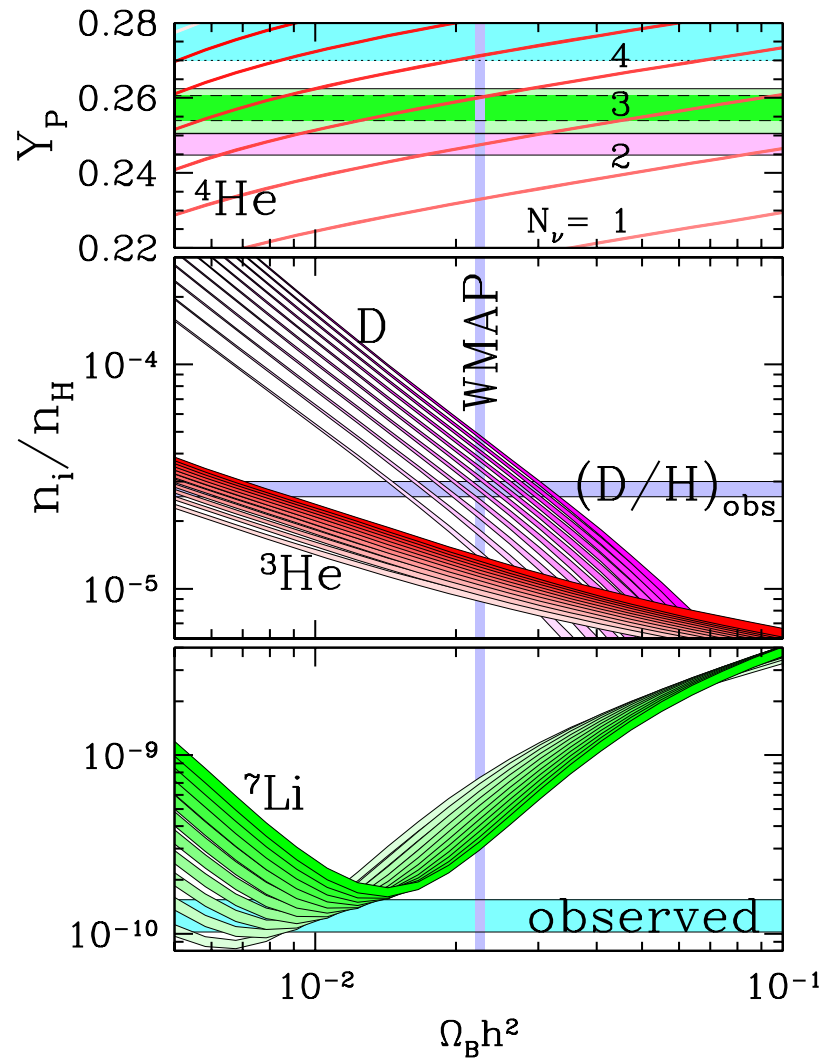
Each (doublet) species carries $\sim 15\%$ of energy density
$\longrightarrow$ the sum sets expansion timescales

ν_e participate in the weak $n \longleftrightarrow p$ rates that set n/p ratio & Y_P

They also affect BBN at two clearly distinct times:

Y_P depends on the number of neutrons, set at 1 second

Other yields depend on nuclear burning at 5–30 minutes



$N_{\rm eff} = 0$ to 10 shown

Counting neutr(on|ino)s

BBN has a long history of ν counting based on the sensitivity at 1 second

More neutrinos $\longrightarrow$ faster expansion $\longrightarrow$ weak freezeout at higher T
$\longrightarrow$ more neutrons $\longrightarrow$ higher Y_P

Since Y_P also depends (weakly) on $\Omega_B h^2$, another input is needed

We can use $\Omega_B h^2$ from CMB + assumption that n_B/n_γ is unchanged

Or we can fit jointly with another light-element yield (which mostly drives $\Omega_B h^2$)

Deuterium & lithium as clocks

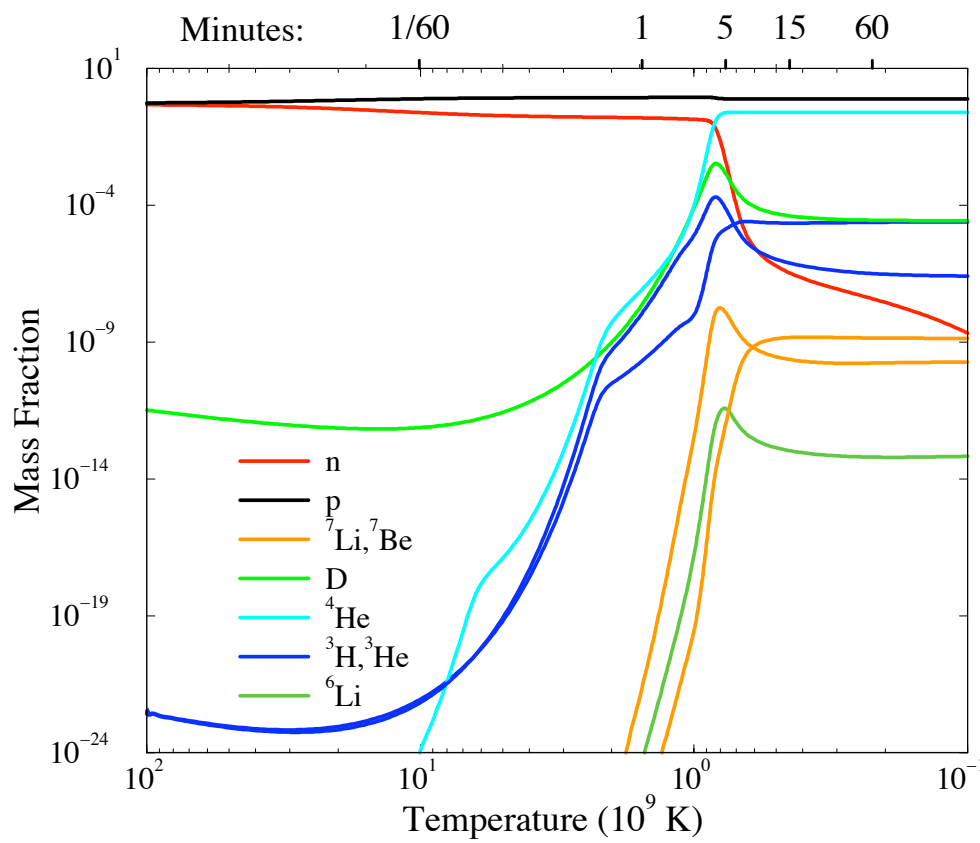
Nuclear processing of scraps continues after ^{4}He has been assembled

D burns via $d(p,\gamma)^3$He, $d(d,n)^3$He, $d(d,p)^3$H

^{3}He is destroyed via ^{3}He$(n,p)^3$H & ^{3}He$(d,p)^4$He

^{7}Li burns via ^{7}Li$(p,\alpha)^4$He

^{7}Be is produced via ^{3}He$(\alpha,\gamma)^7$Be



Faster expansion means less time for this

$\longrightarrow$ more D & ^{3}He, less ^{7}Li (at CMB $\Omega_B h^2$)

Tipping the scales

The baryon number of the universe is small, $n_B/n_\gamma \sim 10^{-10}$

A much larger lepton asymmetry could hide in the neutrinos: $n_\nu \equiv n_\nu - n_{\bar{\nu}} \neq 0$

$|n_\nu/n_\gamma| \gtrsim 10$ affects BBN timescales noticeably (through ρ via μ_ν)

A bigger effect (Kang, Abazajian, Mangano...):

$n_{\nu_e} \neq n_{\bar{\nu}_e}$ favors either n or p by $\exp[-(\Delta m - \mu_\nu/kT)]$ at early times

Particularly with $\theta_{13} \neq 0$, an asymmetry in one SM ν flavor infects them all

$|n_\nu/n_\gamma| \gtrsim 0.05$ shifts Y_P significantly

$n_\nu \neq 0$ can patch BBN models or make them (with ν_s) more interesting

Helium: Percent compositions from 70 Mpc away?

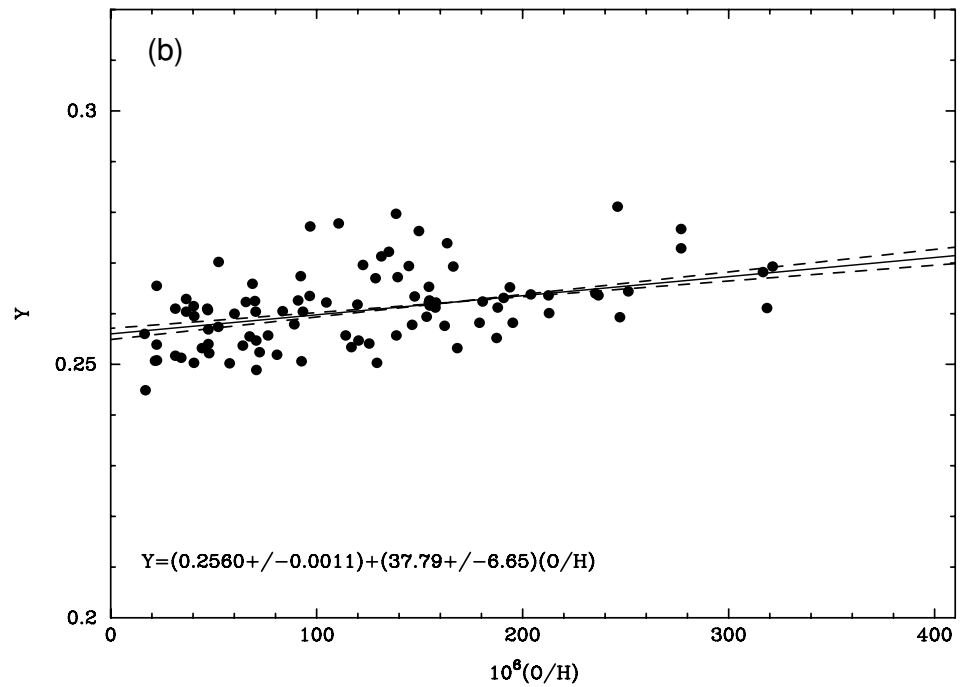
He/H is inferred from nebular emission in blue compact dwarf galaxies (BCD)

Peimbert et al. 2007 study 5 objects in some detail, 0.2477 ± 0.0029

Izotov & Thuan (most recently 2010) study 86 objects, 0.2565 ± 0.006

Aver, Olive, Skillman have explored error estimation for subsets of Izotov, currently 0.2574 ± 0.0036

$Y_{\mathrm{BBN}} = 0.2483 \pm 0.0006$



Izotov & Thuan 2010

Errors as small as 0.0015 have been claimed in the past

Changes in atomic data shifted everyone up $\Delta Y_P \sim 0.010$ a few years ago

Helium: Percent compositions from somewhere?

The history of Y_P error estimation is not encouraging

The nebular lines won historically with small errors, low metallicity

Extended nebulae or ensembles thereof are unresolved

Nothing smaller than Izotov ± 0.005 atomic-data systematics seems prudent

Less-primordial Y were used before – should we go back?

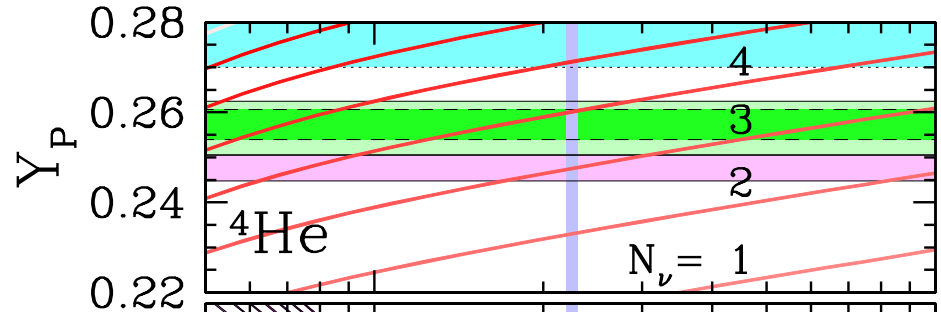


Table 1
Estimates of primordial helium mass fraction

Objects	Y_P	Method	Ref.[a]	Problems
Sun	$< 0.28 \pm 0.02$	Interior	1	κ; Eq. of st; ν prob.
Sun	$< 0.28 \pm 0.05$	Prom. He I	2	Level pops.
B stars	$< 0.30 \pm 0.04$	Abs. lines	3	Precision
μ Cas	0.23 ± 0.05	Bin. orbit	4	Precision
Field sd	0.19 ± 0.05	Main seq.	5	Plx; $T_{\rm eff}$; conv.
Globular clusters	0.23:	RR, Δm	6	Physical
	0.23 ± 0.02	N(HB)/N(RG)	7	basis of stellar evolution
	0.23 ± 0.02:	M15 HB	8	
	$\leq 0.24 \pm 0.02$	47 Tuc HB	9	
Gal.	0.22 ± 0.02	Plan. neb.	10	Self + gal enr.
neb.	0.22:	H II reg.	11	He^0; gal. enr.
Extra-galactic	0.233 ± 0.005	Irr. + BCG	12	He^0; data
	$< 0.243 \pm 0.010$	BCG	13	II Zw 40
	0.228 ± 0.005	Irr. + BCG	14	I Zw 18
H II regions	0.234 ± 0.002	Irr. + BCG	15	
	0.244 ± 0.002	BCG	16	

[a] References: 1. Turck-Chièze and Lopez (1993). 2. Heasley and Milkey (1978). 3. Kilian (1992). 4. Haywood et al. (1992). 5. Carney (1983). 6. Caputo et al. (1987). 7. Buzzoni et al. (1983). 8. Dorman et al. (1991). 9. Dorman et al. (1989). 10. Peimbert (1983). 11. Mezger and Wink (1983). 12. Lequeux et al. (1979). 13. Kunth and Sargent (1983). 14. Pagel et al. (1992). 15. Olive et al. (1997). 16. Izotov and Thuan (1998a).

Helioseismology + solar models are particularly promising (thanks, Mike):

$Y_\odot = 0.2703 \pm 0.0072$

Deuterium: The baryon density across the universe

Very few quasars are suitable for D/H measurement

D/H has been convincingly measured in 8 systems (+2 today)

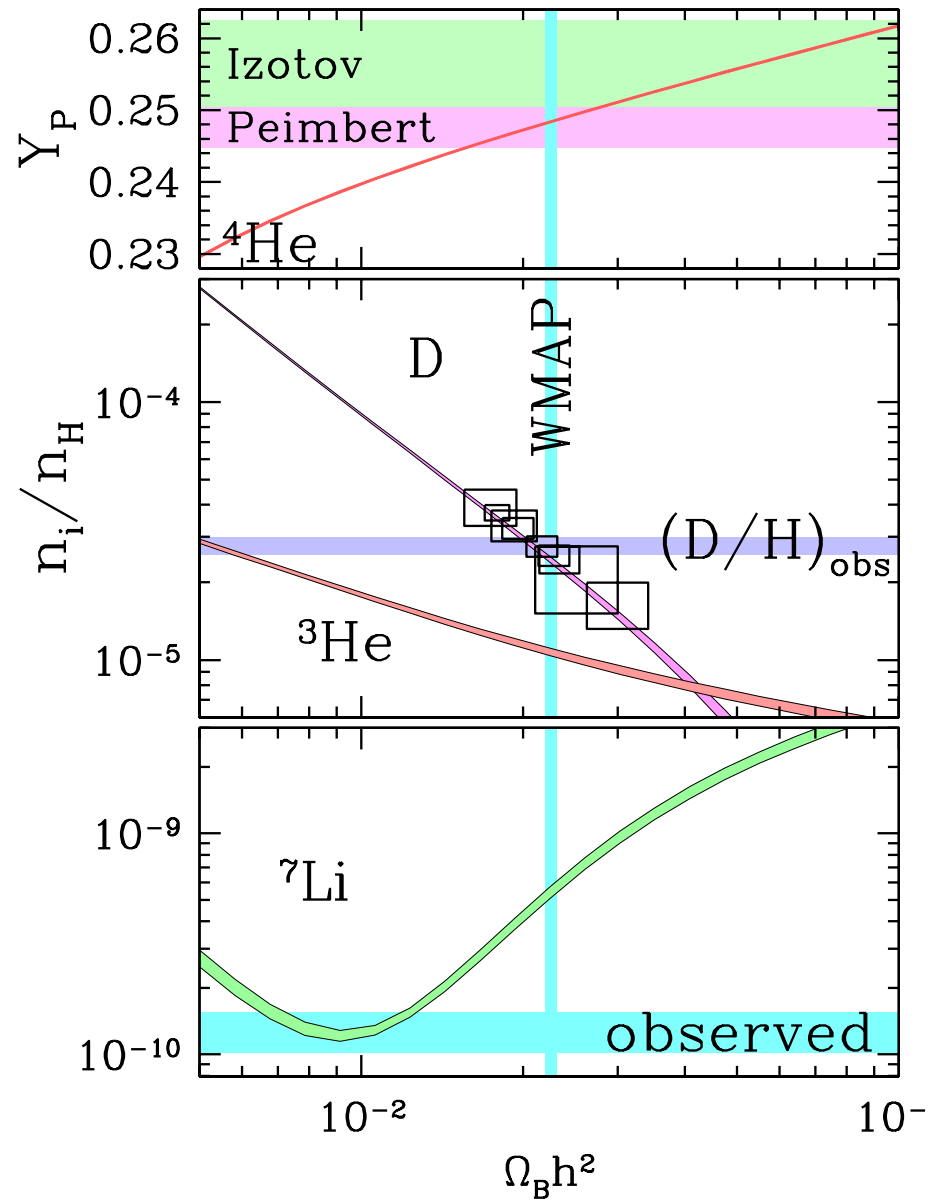
Dispersion suggests slightly underestimated errors

There is imperfect agreement between BBN prediction and measurement:

Standard BBN says $(2.42 \pm 0.11) \times 10^{-5}$

Spectra said $(2.78 \pm 0.22) \times 10^{-5}$

Today (Pettini): $(2.63 \pm 0.12) \times 10^{-5}$



^{7}Li: Neutrinos don't help

Charbonnel & Primas mean of many metal-poor stars:

$\mathrm{Li/H} = (1.6^{+0.4}_{-0.3}) \times 10^{-10}$

(fairly stable over 30 years)

Theory gave $(5.5 \pm 0.4) \times 10^{-10}$

Factor of 3.4 (5σ) mismatch

So what gives?

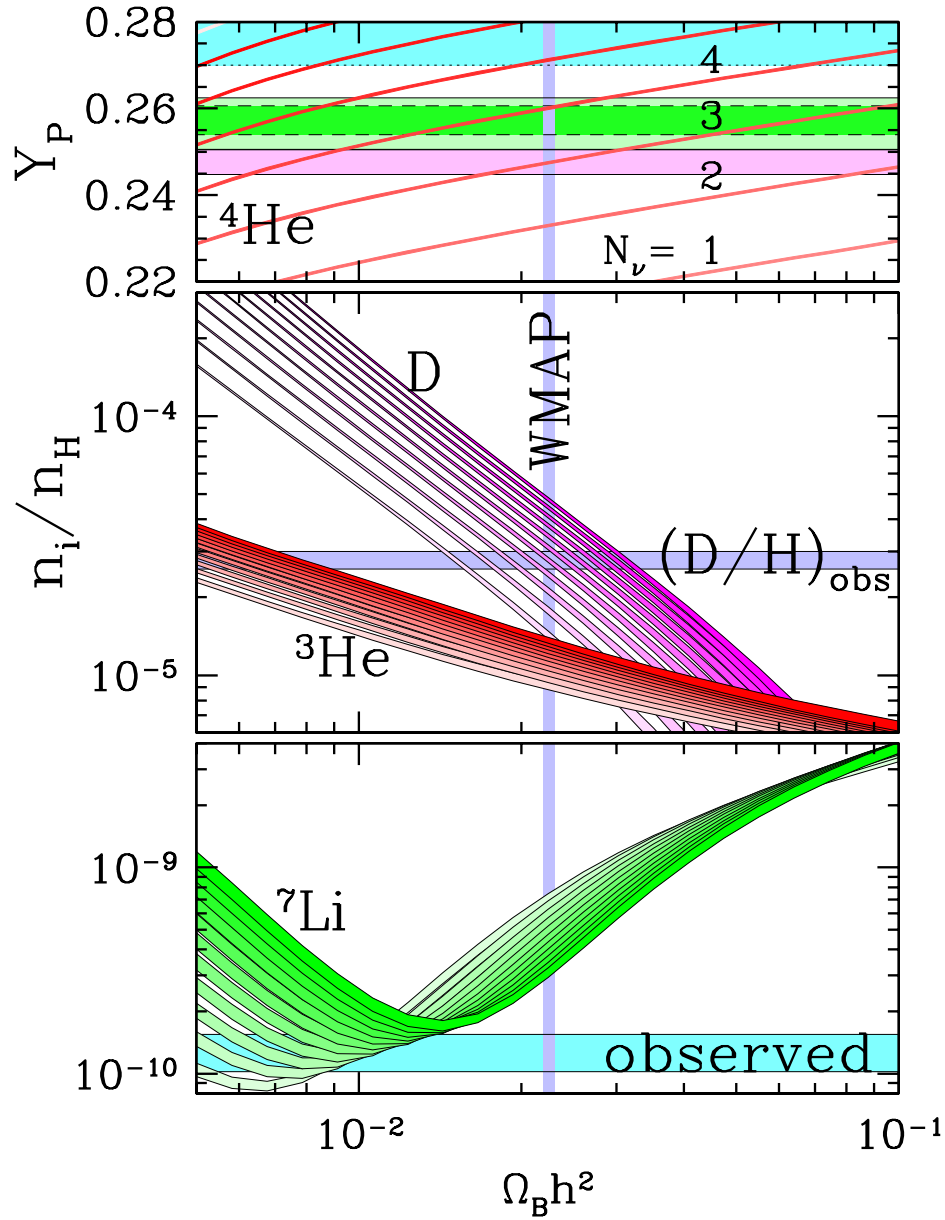
Bad cross sections? Unlikely

Missing cross sections? Unlikely

Misinterpreted spectra? Unlikely

Exotic particle physics? Possible

Deep mixing in the stars? Maybe



$N_{\mathrm{eff}} = 0$ to 10 shown

Digesting the data: A simple model

Gil & I have concentrated on a simple model:

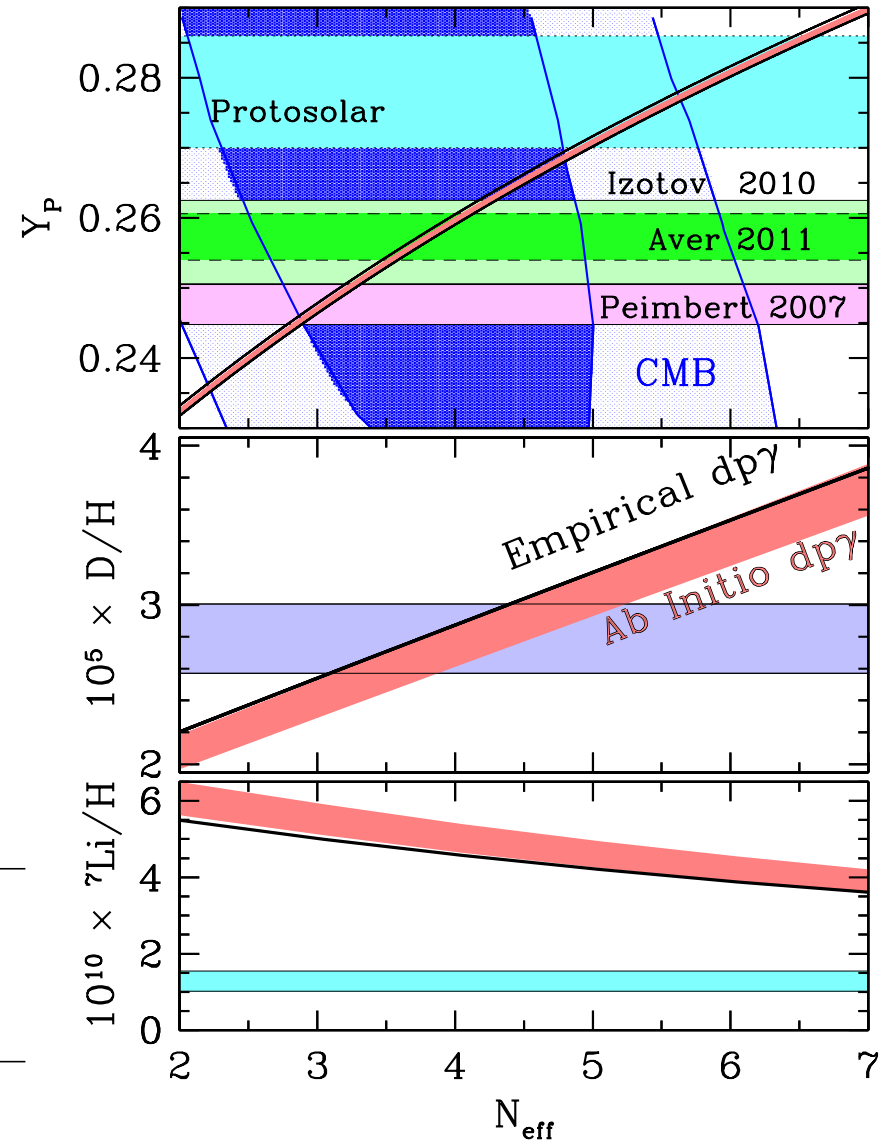
$$\rho_\nu = \frac{N_{\rm eff}}{3}\rho_{\nu,0};$$ also, Hamann et al.

First check: Are BBN & CMB consistent?

Second: Can the data be combined in useful ways?

Third: Can we avoid Y_P?

Constraint	N_ν
CMB, no Y_P constraint	3.4 ± 1.0
BBN + D/H + Y_P(Izotov)	3.82 ± 0.45
BBN + D/H + Y_P(Peimbert)	3.13 ± 0.21
CMB & $0.22 < Y_P < Y_{\rm proto}$	3.87 ± 0.81
CMB with BBN consistency	3.89 ± 0.60
CMB + BBN + D/H	3.90 ± 0.44



arXiv:1112.2683[astro-ph.CO]

Blue region is WMAP+SPT

D-burning rate matters, τ_n not so much

What next?

D/H sample is expanding again, maybe gaining precision (0.01 dex today!)

Improvement in Y_P would also be nice:

Asteroseismology? Revisit stellar evolution? High resolution spectra?

Making best use of the data:

Leverage on specific models at distinct times (1 second, 5 minutes, 400 000 years)

n_B/n_γ can vary between BBN & CMB, but generally comes with other effects
(early matter domination, nuclide reprocessing from late decays)

Standard ΛCDM at least provides a good null hypothesis