Calibrating weak rates for the big bang

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Measuring the Neutron Lifetime
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Precision in astrophysical weak interactions

Today's theories (& input data) for most astrophysical environments don't offer much payoff for high precision weak rates

Rates in many places involve large nuclei, so they're necessarily either measured directly or estimated with a lot of nuclear theory

Theory with percent-level precision (unless I'm missing something) only enters in the Sun and the big bang – simple environments

In the Sun, the uncertainty on the $p + p \longrightarrow d + e^+ + \nu_e$ rate is 0.9%, dominated by two-body physics (in both strong & weak forces)

The amount of helium made in the big bang can be computed to within $< 1\%$, and weak coupling constants from τ_n are vital to the calculation

Big-bang nucleosynthesis (BBN) as a pillar of cosmology

BBN is the production of the original chemical composition of the universe, during the very hot & dense first ~ 20 minutes

The composition went from free neutrons & protons to mainly hydrogen & helium, with a little D & Li

BBN yields depend on the universal mean baryon density ρ_B, so for a long time BBN was the main handle on ρ_B

BBN took place at ~ 1 second to 20 minutes, so the light-element yields provide a very early window on the universe

In the end, there are only four observables (& perhaps some non-observables)

Ingredients of BBN

1. General relativity

Friedmann-Robertson-Walker metric

$$ds^2 = dt^2 - [R(t)]^2 \left[\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right]$$

describes homogeneous & isotropic universe, sizes scale with $R(t)$

Insertion into Einstein equations gives the expansion rate

$$\left(\frac{R'(t)}{R(t)} \right)^2 = \frac{8\pi G}{3} \rho$$

with $\rho = \rho_B + \rho_\gamma + \rho_\nu + \rho_e + \cdots$

In minimal model, densities are assumed homogeneous (doesn't matter much)

Ingredients of BBN

2. Statistical mechanics of Fermi & Bose gases that fill the universe

$$\rho_x = \frac{g_x}{8\pi^3} \int \frac{E}{\exp\left[(E-\mu_x)/kT\right] \pm 1} d^3p$$

Initial conditions are assumed to be equilibrium at a single very high T

Each species (baryons, photons, electrons, 3 neutrino flavors) evolves at a well-defined temperature

T declines during isentropic expansion, since $\rho_x \propto R^{-4}$ for $m_x \ll kT$ (γ, ν) and $\rho_x \propto R^{-3}$ for $m_x \gtrsim kT$

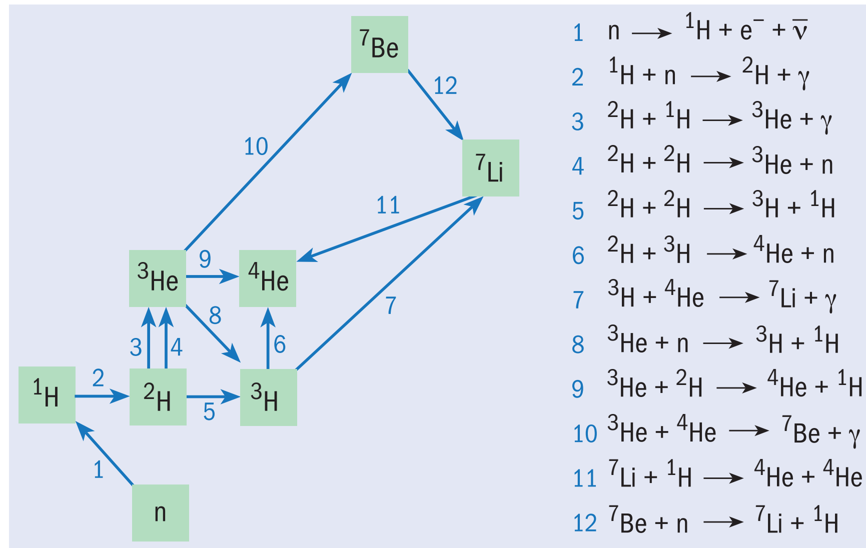
Ingredients of BBN

3. Nuclear cross sections

Abudance evolution proceeds through nuclear collisions

Cross sections are mainly empirical

Only 12 processes matter*, enumerated by Smith, Kawano, Malaney (1993)



Calculations with huge reaction networks and nuclei to CNO region have been done

Weak $p + l \leftrightarrow n + l'$ rates are all normalized to neutron lifetime & computed from weak-interaction physics

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: $\Gamma_{n \leftrightarrow p} < R'/R$

The neutron/proton ratio freezes out at

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

This is Weak Freezeout

Some destruction of neutrons by $e^+ + n \to p + \bar{\nu}_e$ and $\nu_e + n \to p + e^-$ and free decay follows, but it doesn't have much time

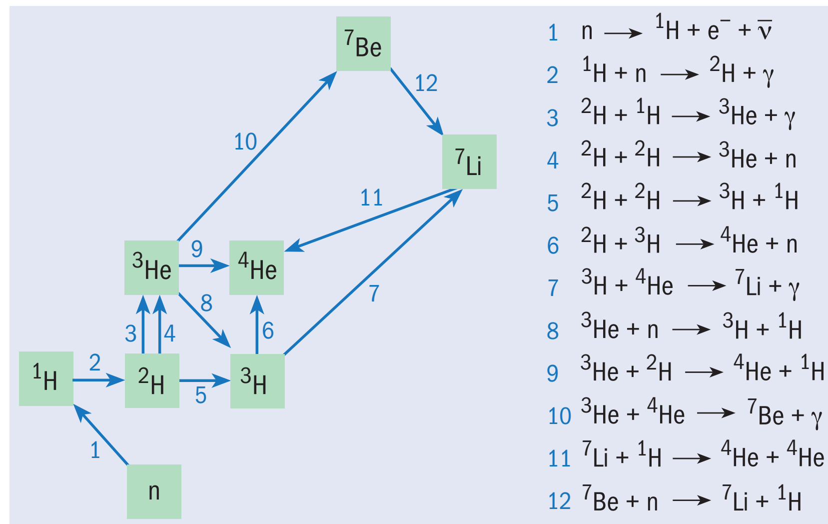
BBN in three easy steps

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)



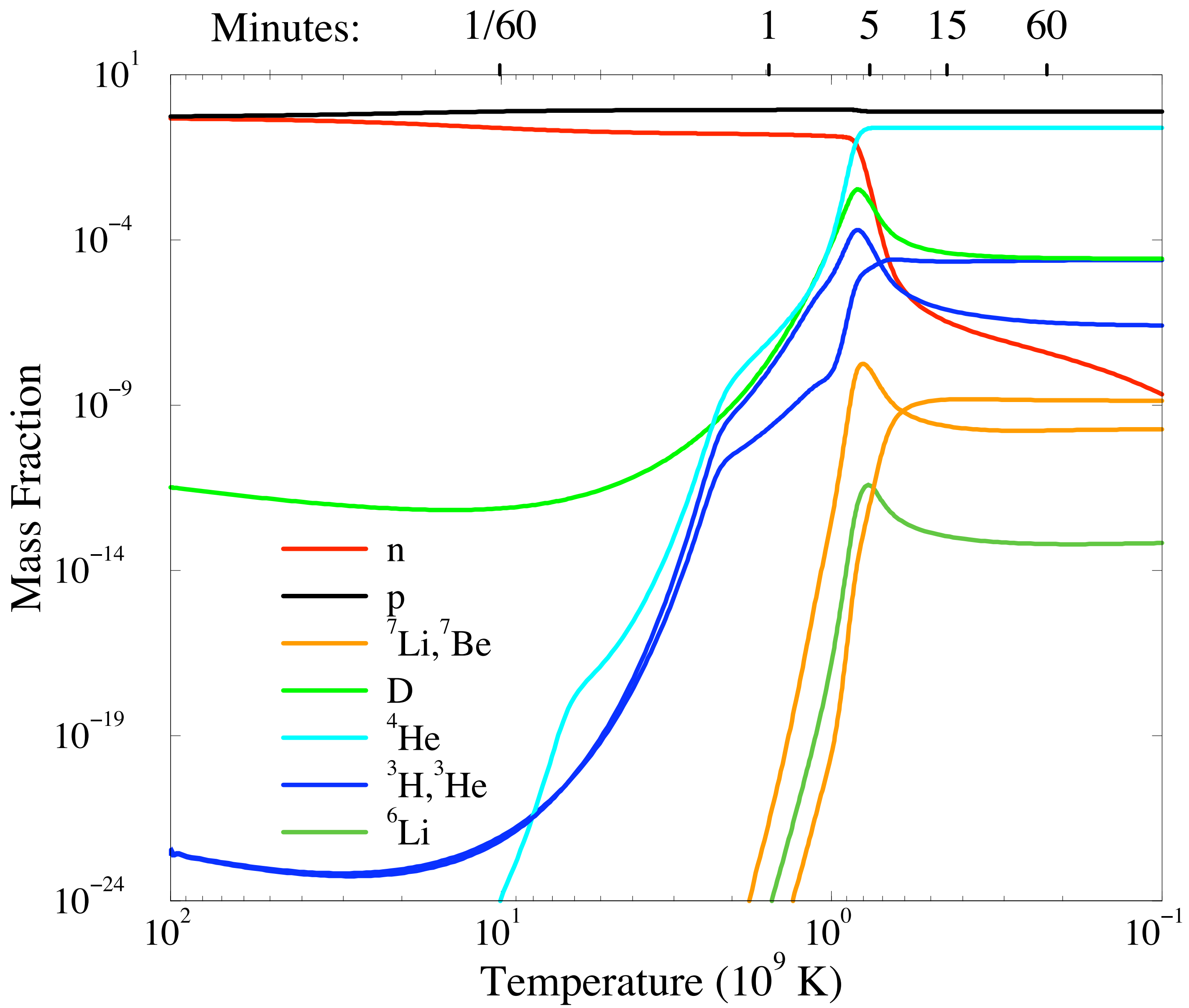
Low ρ and T, Coulomb barriers, disappearance of neutrons, fragility to proton reactions, and lack of stable $A = 5, 8$ nuclei all cause Final Freezeout

BBN in a nutshell

1. Weak Freezeout
   (∼ 1 second)

2. Statistical equilibrium &
   quasi-equilibrium
   (∼ 1 second
   to 5 minutes)

3. Final Freezeout
   (> 5 minutes)



The “Schramm plot”

Yields depend on one variable, n_B/n_γ

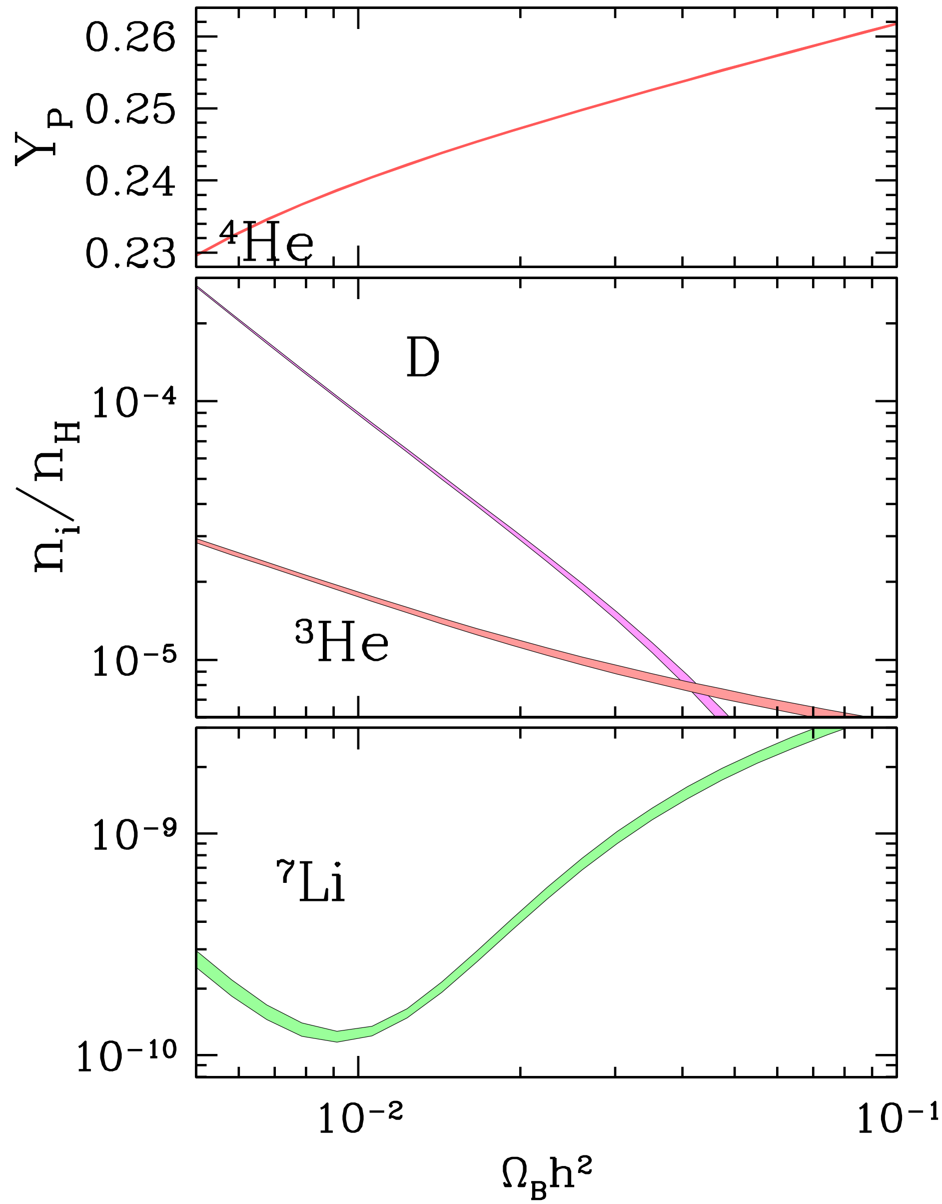
Conventional units are $\Omega_B \equiv \rho_B/\rho_{\rm crit}$

$\Omega_B h^2 =$
$8\pi G\rho_B/(3\times 10^4\ {\rm km}^2\ {\rm s}^{-2}\ {\rm Mpc}^{-2})$

$h \sim 0.7$ is Hubble’s constant in customary units, so $h^2 \sim 1/2$

Widths of curves reflect nuclear inputs (More on this in a few minutes...)

Need to find matter that has not been processed post-BBN & compare



BBN today

The Big Question is now

Are the primordial abundances consistent with the standard cosmology?

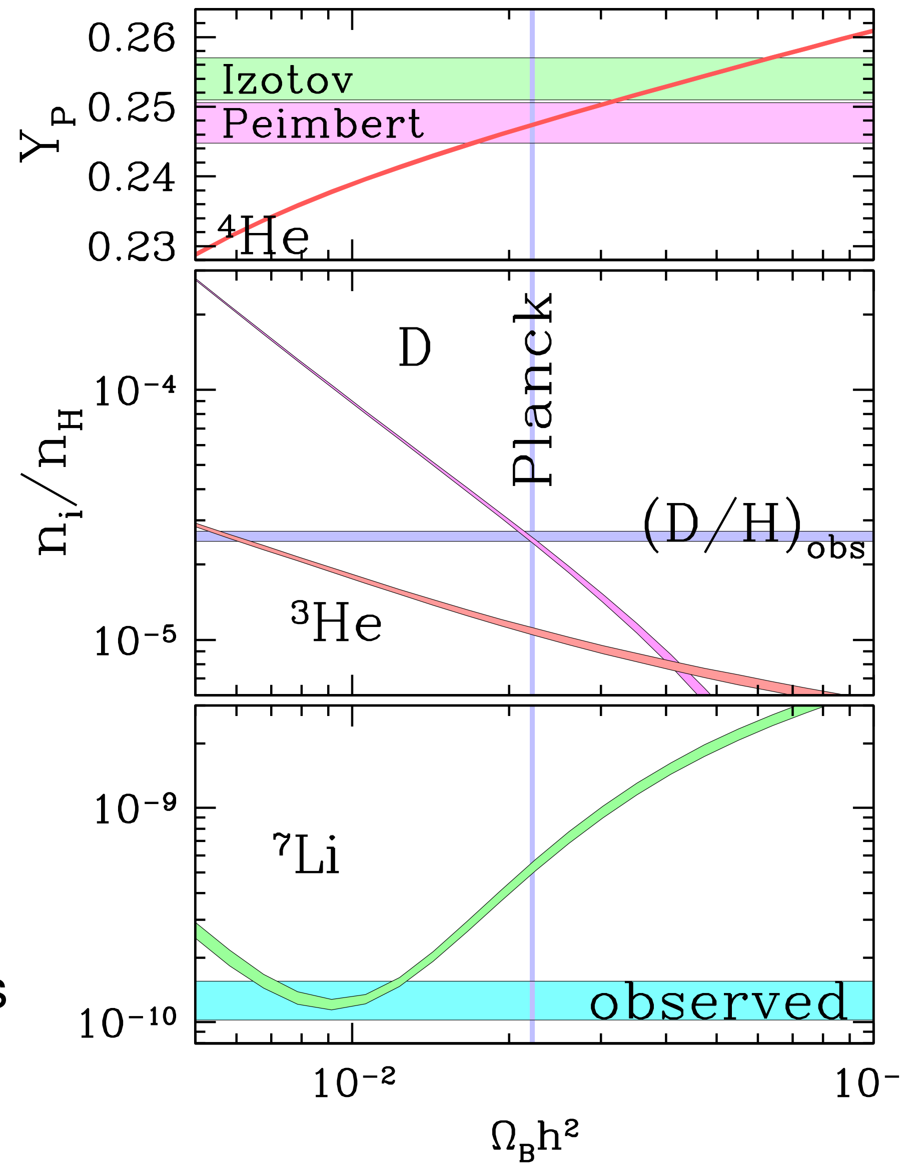
The only ΛCDM parameter that BBN depends on is $\Omega_B h^2 \propto n_B/n_\gamma$

With 1.3% 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

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

$\text{D/H} = (2.51 \pm 0.08) \times 10^{-5}$ (2.5% nuclear, 2% $\Omega_B h^2$)

Primordial ^{3}He is not yet observable; it depends on much of the same nuclear data & is kind of flat in $\Omega_B h^2$

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

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

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

(Li probably could be handled better – long story)

BBN post-WMAP: Precise ^{4}He predictions

Convention is to consider Primordial He mass fraction Y_P

This is not my fault – observation & theory give $n_{\mathrm{He}}/n_{\mathrm{H}}$ more naturally

At the end of BBN, all but $\sim 10^{-5}$ of neutrons are in ^{4}He
(Y_P specifies the isospin density of the universe)

Y_P thus probes weak-interaction freezeout at ~ 1 second, insensitive to Ω_B

The ratio of weak rates to the expansion rate at ~ 1 s determines the freezeout temperature & therefore Y_P

Neutron “decay” in BBN

Weak rates are all $\propto G_V^2 + 3G_A^2$, matched to τ_n at the start of a BBN calculation

Supposedly G_V & G_A/G_V are now known to a precision equivalent to $\Delta\tau_n \sim 2$ s
– there’s not much history of using them instead

The (shallow) dependence of Y_P on $\Omega_B h^2$ is mainly through neutron destruction after freezeout

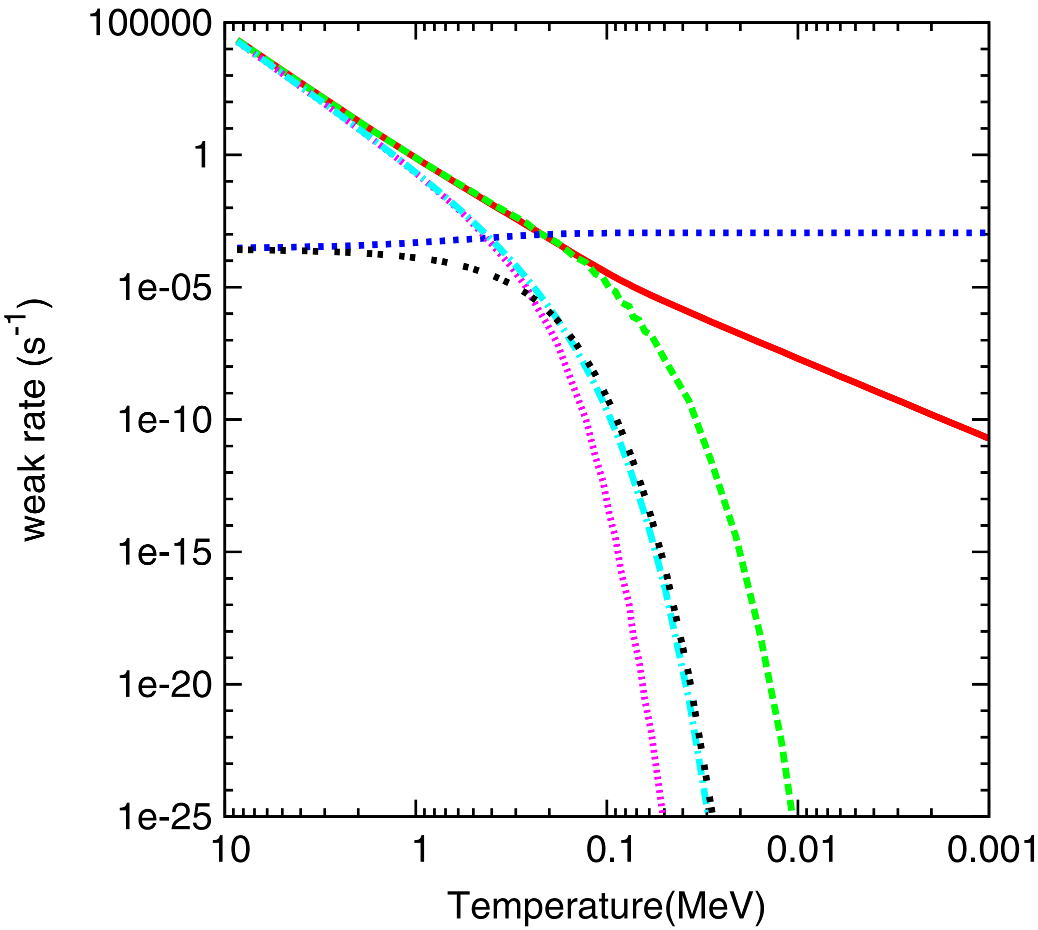
But even that includes interactions with the lepton gases

Blue: free decay

Red: $n + \nu_e \longrightarrow p + e^-$

Green: $n + e^+ \longrightarrow p + \bar{\nu}_e$

Others: n production



Smith & Fuller, PRD 81, 065027 (2010)

BBN post-WMAP: Precise ^{4}He predictions

Y_P cares a lot about fine details of weak rates and early thermal conditions

	Y_P	Cumulative		Effect Alone	
		$\delta Y_P(\times 10^{-4})$	$\delta Y_P/Y_P(\%)$	$\delta Y_P(\times 10^{-4})$	$\delta Y_P/Y_P(\%)$
Baseline	0.2414				
Coulomb and $T=0$ radiative	0.2445	+31	+1.28	+31	+1.28
finite mass	0.2457	+43	+1.78	+12	+0.50
finite T radiative	0.2460	+46	+1.90	+3	+0.12
QED plasma	0.2461	+47	+1.94	+1	+0.04
residual ν-heating	0.2462	+49	+2.00	+1.5	+0.06

Lopez & Turner 1999

Lopez & Turner (1999) computed Y_P with an error budget of $\Delta Y_P = 0.0002$

Olive, Steigman, & Walker (2000) agree to $\Delta Y_P = 0.0001$

Mangano & collaborators (more independent) agree to $\Delta Y_P = 0.0004$

The Mangano code is coming into wide use & the issue is in danger of being lost (Lopez now does high-frequency trading)

BBN post-WMAP: Precise ^{4}He predictions

The neutron lifetime is a big part of the (small) error budget

Source	τ_n	ΔY_P
PDG 2004–10	885.7 ± 0.8 sec	0.00016
Serebrov 2005	878.5 ± 1.0	0.00020
Pichlmaier 2010	880.7 ± 2.5	0.00050
PDG 2012	880.1 ± 1.1	0.00022
PDG 2014	880.3 ± 1.1	0.00022

Total spread across the table is $\Delta Y_P = 0.0015$

Planck gives $\Omega_B h^2 = 0.02214 \pm 0.00024$, robust against varying assumptions

$dY_P/d(\Omega_B h^2) = 0.43$ so $\Delta Y_P = 0.00010$ from $\Omega_B h^2$

In sum, $Y_P = 0.2471 \pm 0.0002(\text{theory}) \pm 0.0002(\tau_\text{n}) \pm 0.0001(\text{CMB})$ (using 2014 PDG)

So Y_P is an astronomical quantity predicted to $< 0.5\%$ – unique outside orbital mechanics?

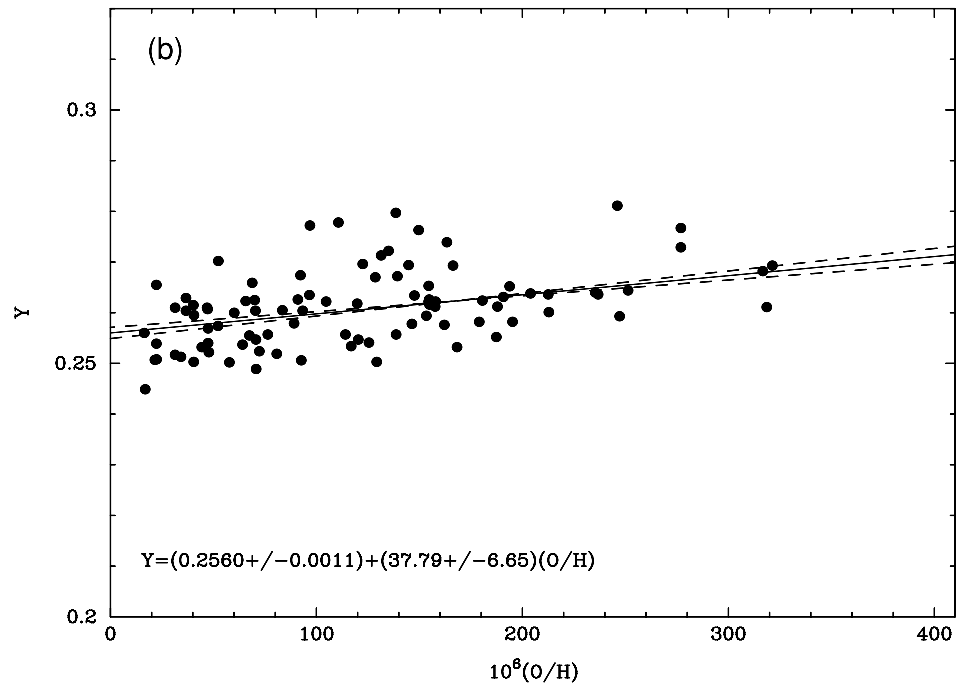
Helium: Percent compositions from 70 Mpc away?

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

$Y_{\mathrm{BBN}} = 0.2471 \pm 0.0005$

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

Izotov & Thuan (2013) study 111 objects, 0.254 ± 0.003 (August 2014 paper I haven't digested has 0.2551 ± 0.0022)



Izotov & Thuan 2010

Aver, Olive, Skillman have explored error estimation for subsets of Izotov, currently $0.2535 \pm 0.0036^{\dagger}$

Errors as small as 0.0015 have been claimed in the past; underlying atomic data may have problems amounting to $\Delta Y_P \sim 0.005$

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

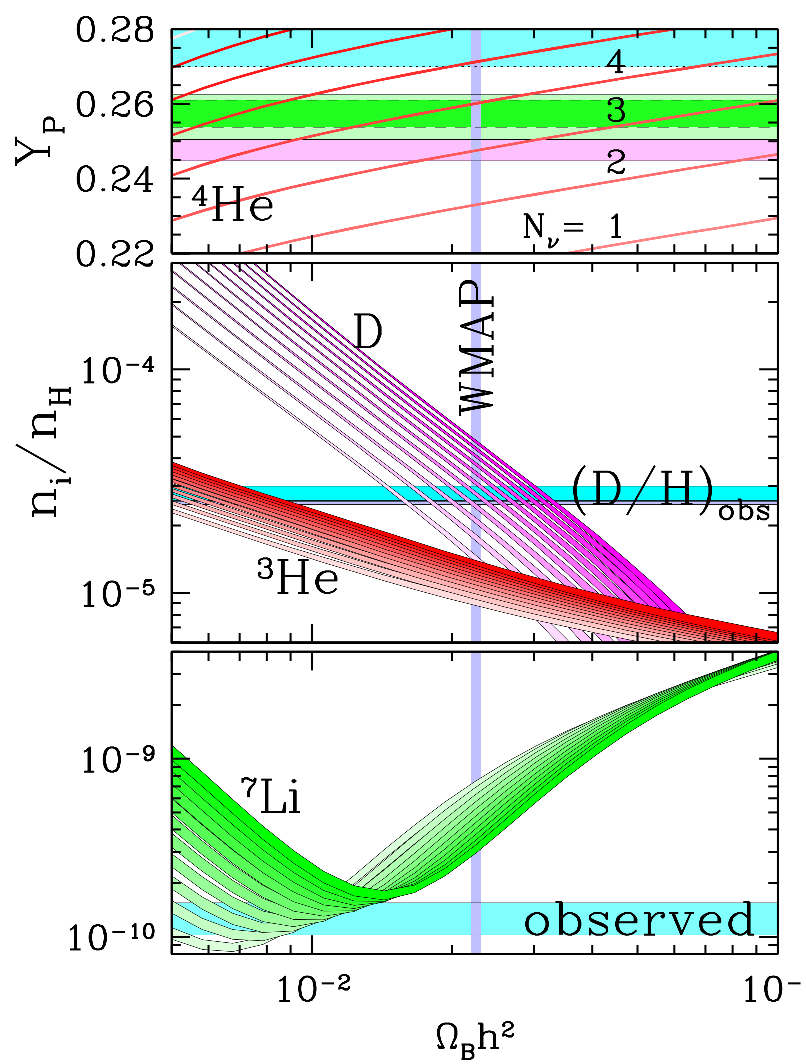
A timely example: BBN from a neutrino's point of view

BBN has a long history of constraining neutrino-like species using the sensitivity at 1 second

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

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



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

Counting neutr(on|ino)s using helium

We can use $\Omega_B h^2$ from CMB + assumption of unchanging n_B/n_γ after BBN

Or we can fit Y_P jointly with D/H (assumes less)

This program has received new interest now that the CMB probes the expansion rate at the time of CMB formation

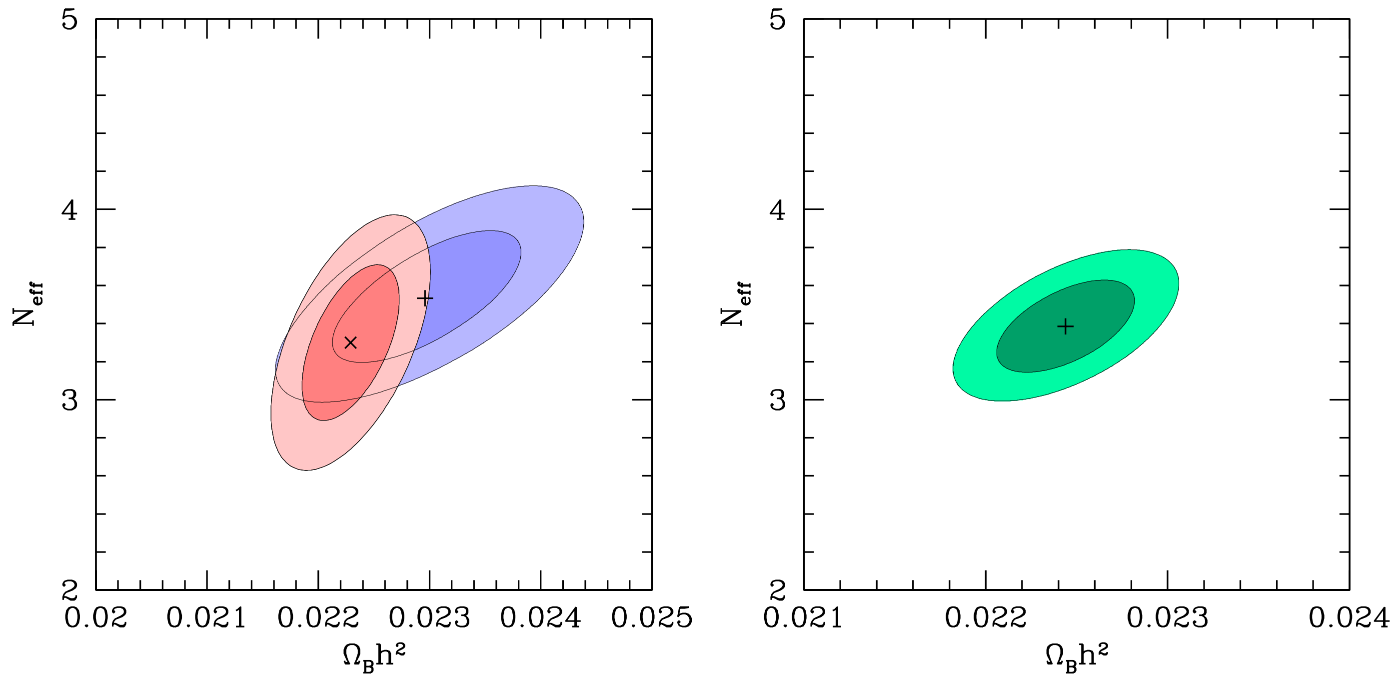
Cosmologists tend to measure the expansion rate as an equivalent number of thermally-populated neutrino species

$N_{\rm eff} = 3.046$ in the standard model (after small corrections)

Neutrino counting with BBN & the CMB

A couple of years ago, there were hints from the CMB that $N_{\mathrm{eff}} \sim 3.8 \pm 0.4$

Now we have:



The data agree, but together they like neither $N_\nu = 3$ nor $N_\nu = 4$

Salmon: CMB only   Blue: BBN only   Green: combined

update of Nollett & Steigman, arXiv:1312.5725

$N_{\mathrm{eff}} = 3.30 \pm 0.27$ (CMB), $N_{\mathrm{eff}} = 3.56 \pm 0.23$ (BBN), $N_{\mathrm{eff}} = 3.40 \pm 0.16$ (joint)

Yes, noninteger N_{eff} is meaningful – e.g. light scalar particles

Comparison of τ_n with what we're trying to do

At fixed $\Omega_B h^2$, one additional neutrino species produces $\Delta Y_P \simeq 0.013$

An additional second of neutron lifetime produces $\Delta Y_P \simeq 0.00021$

The full difference between the "old" PDG lifetime & the Serebrov lifetime is $\Delta Y_P = 0.0015$ (from $\Delta\tau_n = 6.8$ s)

So the τ_n spread gives $\Delta N_{\text{eff}} \sim 0.0015/0.013 \sim 0.12$

By comparison, the CMB is unlikely to measure N_{eff} to within much better than $\Delta N_{\text{eff}} \sim 0.20$

This all compares with reasonable observational errors today of $\Delta Y_P \sim 0.005$

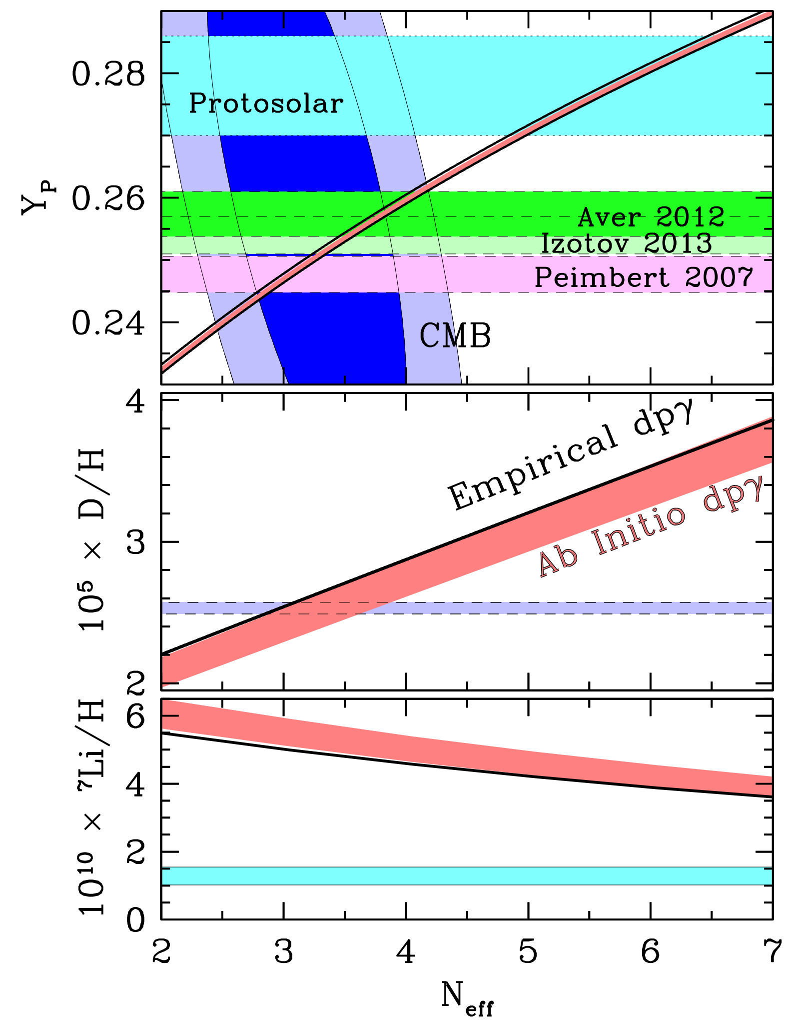
The same information, graphically

Here are abundances as functions of $N_{\rm eff}$
($\Omega_B h^2$ slightly outdated)

Pink band in Y_P shows errors around 2011
PDG recommended τ_n

Black lines on either side are 2004-2010
PDG & Serebrov

(Black lines in lower panels reflect other
nuclear uncertainties)



Nollett & Holder (2012), partial update

What I would like to see

The best thing for me would be an agreed τ_n with an error of ~ 1 s (again)

BBN has intrinsic interest as a source of very precise predictions arising from the standard cosmology, probing very early times

Even if astronomers can't match the theory's precision now, it's good to have the target out there (0.2% prediction!)

Any problem with τ_n sits below my predictions & skews my conclusions by $\sim \sigma/2$

Y_P also feeds into modeling of CMB anisotropies (which currently constrain Y_P by ± 0.06!)

I'm not sure they'll ever be sensitive at the percent level, though