BBN and the Status of D, He4, and Li7

Observations

• BBN and the WMAP/Planck determination of $\eta$, $\Omega_B h^2$
• Observations and Comparison with Theory
  - D/H  - $^4\text{He}$  - $^7\text{Li}$
• The Li Problem
• Solutions?
Table 1: Key Nuclear Reactions for BBN

<table>
<thead>
<tr>
<th>Source</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACRE</td>
<td>$d(p, \gamma)^3\text{He}$</td>
</tr>
<tr>
<td></td>
<td>$d(d, n)^3\text{He}$</td>
</tr>
<tr>
<td></td>
<td>$d(d, p)t$</td>
</tr>
<tr>
<td></td>
<td>$t(d, n)^4\text{He}$</td>
</tr>
<tr>
<td></td>
<td>$t(\alpha, \gamma)^7\text{Li}$</td>
</tr>
<tr>
<td></td>
<td>$^3\text{He}(\alpha, \gamma)^7\text{Be}$</td>
</tr>
<tr>
<td></td>
<td>$^7\text{Li}(p, \alpha)^4\text{He}$</td>
</tr>
<tr>
<td>SKM</td>
<td>$p(n, \gamma)d$</td>
</tr>
<tr>
<td></td>
<td>$^3\text{He}(d, p)^4\text{He}$</td>
</tr>
<tr>
<td></td>
<td>$^7\text{Be}(n, p)^7\text{Li}$</td>
</tr>
<tr>
<td>This work</td>
<td>$^3\text{He}(n, p)t$</td>
</tr>
<tr>
<td>PDG</td>
<td>$\tau_n$</td>
</tr>
</tbody>
</table>

NACRE
Cyburt, Fields, KAO
Nollett & Burles
Coc et al.
$\Omega_B h^2 = 0.0221 \pm 0.0003$

$\eta_{10} = 6.05 \pm 0.08$
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>
<thead>
<tr>
<th>QSO</th>
<th>$z_{em}$</th>
<th>$z_{abs}$</th>
<th>log $N$(H\textsc{i}) (cm$^{-2}$)</th>
<th>[O/H]$^a$</th>
<th>log (D/H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS 0105+1619</td>
<td>2.640</td>
<td>2.53600</td>
<td>19.42 ± 0.01</td>
<td>−1.73</td>
<td>−4.60 ± 0.04</td>
</tr>
<tr>
<td>Q0913+072</td>
<td>2.785</td>
<td>2.61843</td>
<td>20.34 ± 0.04</td>
<td>−2.40</td>
<td>−4.56 ± 0.04</td>
</tr>
<tr>
<td>Q1009+299</td>
<td>2.640</td>
<td>2.50357</td>
<td>17.39 ± 0.06</td>
<td>&lt; −0.70$^c$</td>
<td>−4.40 ± 0.07</td>
</tr>
<tr>
<td>SDSS J1134+5742</td>
<td>3.522</td>
<td>3.41088</td>
<td>17.95 ± 0.05</td>
<td>&lt; −1.9$^d$</td>
<td>−4.69 ± 0.13</td>
</tr>
<tr>
<td>Q1243+307</td>
<td>2.558</td>
<td>2.52566</td>
<td>19.73 ± 0.04</td>
<td>−2.79</td>
<td>−4.62 ± 0.05</td>
</tr>
<tr>
<td>SDSS J1337+3152</td>
<td>3.174</td>
<td>3.16768</td>
<td>20.41 ± 0.15</td>
<td>−2.86</td>
<td>−4.93 ± 0.15</td>
</tr>
<tr>
<td>SDSS J1419+0829</td>
<td>3.030</td>
<td>3.04984</td>
<td>20.391 ± 0.008</td>
<td>−1.92</td>
<td>−4.596 ± 0.009</td>
</tr>
<tr>
<td>SDSS J1558−0031</td>
<td>2.823</td>
<td>2.70262</td>
<td>20.67 ± 0.05</td>
<td>−1.50</td>
<td>−4.48 ± 0.06</td>
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<tr>
<td>Q1937−101</td>
<td>3.787</td>
<td>3.57220</td>
<td>17.86 ± 0.02</td>
<td>&lt; −0.9</td>
<td>−4.48 ± 0.04</td>
</tr>
<tr>
<td>Q2206−199</td>
<td>2.559</td>
<td>2.07624</td>
<td>20.43 ± 0.04</td>
<td>−2.07</td>
<td>−4.78 ± 0.09</td>
</tr>
<tr>
<td>Q347−3819</td>
<td>3.23</td>
<td>3.0245</td>
<td>20.626 ± 0.005</td>
<td>−0.82</td>
<td>−4.426 ± 0.029</td>
</tr>
<tr>
<td>CTQ 247</td>
<td>3.02</td>
<td>2.621</td>
<td>20.45 ± 0.1</td>
<td>−1.99</td>
<td>−4.55 ± 0.11</td>
</tr>
</tbody>
</table>

$^a$ Relative to the solar value log(O/H)$^\odot$ +1.2 = 8.69 (Asplund et al. 2009).


$^c$ This is a very conservative upper limit on the metallicity. Burles & Tytler (1998) estimate [Si/H] $\simeq$ −2.5 and [C/H] $\simeq$ −2.9 from photoionisation modelling.

$^d$ This is a conservative upper limit on the metallicity. Fumagalli et al. (2011) estimate [Si/H] $\simeq$ −4.2 from photoionisation modelling.
D/H abundances in Quasar absorption systems

BBN Prediction: $10^5 \text{D/H} = 2.59 \pm 0.17^*$

Obs Average: $10^5 \text{D/H} = 3.01 \pm 0.21$
(sample variance of 0.68)
D/H abundances in Quasar absorption systems

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$10^5 \frac{D}{H} = 2.59 \pm 0.17^*$

Obs Average:
$10^5 \frac{D}{H} = 3.01 \pm 0.21$
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*uncertainty reduced to .14 with Planck determination of $\eta$
D/H abundances in Quasar absorption systems

BBN Prediction:
\[ 10^5 \frac{D}{H} = 2.59 \pm 0.17 \]

Obs Average:
\[ 10^5 \frac{D}{H} = 2.65 \pm 0.11 \]
(sample variance of 0.36)

*uncertainty reduced to .14
with Planck determination of \( \eta \)
New Point from Pettini and Cooke

\[ z_{\text{em}} = 3.03 \]
\[ z_{\text{abs}} = 3.04984 \]

Fig. 1.— Selected metal lines in the \[ z_{\text{abs}} = 3.04984 \] DLA in the QSO SDSS J1419+0829, reproduced from Cooke et al. (2011). In each panel, the black histogram is the observed spectrum and the red continuous line is the theoretical line profile fitted to the data. Vertical tick marks above the spectrum indicate the velocities of the two absorption components, with parameters listed in section 2. The \( y \)-axis scale is residual intensity. The normalized quasar continuum and zero level are shown by the blue long-dashed and green dashed lines, respectively.

Fig. 2.— Portion of the UVES spectrum of the QSO SDSS J1419+0829 (black), together with the model fit (red). The 1\( \sigma \) error spectrum is shown in blue (near the zero level). Vertical dash lines mark the positions of QSO spectral features, as indicated. Green labels denote emission lines at \( z_{\text{em}} = 3.04224 \), light blue labels emission lines at \( z_{\text{em}} = 2.98576 \), and red labels emission lines at \( z_{\text{abs}} = 3.04954 \).
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Is the uncertainty in the continuum included?

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Hi and the D should have identical velocity distributions, except for the effects of thermal broadening. However, the H lines give little information because they are all saturated, broad, and blended. Instead, we use the unsaturated metal lines, especially the O\textsc{i} lines, as guides.

We do not know how closely the metal lines will trace the velocity structure of the H\textsc{i} and D\textsc{i}. We expect O\textsc{i} wherever we find metals, but the metal lines can have different velocity distributions in detail because the ionization and metal abundance can vary from component to component, and perhaps with velocity inside a component.

In Figure 3, we present the regions of the spectrum in which we expect metal line absorption. We observe strong absorption in only a few metal ions: O\textsc{i}, C\textsc{ii}, and Si\textsc{ii}. C\textsc{iii} and Si\textsc{iii} also show absorption but are poorly constrained since their lines appear saturated and may be highly contaminated by Ly/C11 forest absorption. We see weak C\textsc{iv} and Si\textsc{iv} absorption that has very different velocity structure from the low-ionization metals.

The O\textsc{i} absorption suggests that two components will be needed to model the velocity distribution of the gas that shows the D. O\textsc{i} provides the best indication of the velocity distribution of the H\textsc{i} and D\textsc{i} absorption, because O\textsc{i}/H\textsc{i} is similar to O/H in gas of low ionization (O’Meara et al. 2001). The O\textsc{i} 1302 transition is in a high S/N region of the spectrum well separated from other lines. In Figure 4 we see that this line is asymmetric, with extra absorption at larger wavelengths. We fit the O\textsc{i} with the two components that we list in Table 3.

The O\textsc{i} might have different velocity structure from the H\textsc{i} and the D\textsc{i} if O/H varies and is correlated with velocity. For example, we can imagine that all of the H\textsc{i}, D\textsc{i}, and O\textsc{i}...
New Point from Pettini and Cooke

\[ Z_{em} = 3.03 \]
\[ Z_{abs} = 3.04984 \]

Is the uncertainty in the continuum included?

Fig. 3.— The Ly\(\alpha\) region in J1419+0829. Top panel: Observed QSO spectrum in black and best-fitting model spectrum in red. Middle panel: The normalized QSO spectrum, obtained by dividing the observed spectrum by the model spectrum, is shown in black together with the best fitting damped Ly\(\alpha\) absorption profile (see section 3.2) in red. The neutral hydrogen column density is \[ \log N(\text{H}^{})/\text{cm}^{-2} = 20.391\pm0.008 \]. Bottom panel: Expanded central portion of the middle panel. In all three panels the 1\(\sigma\) error spectrum is shown in blue.
4He

Measured in low metallicity extragalactic HII regions together with O/H and N/H

Data from Izotov and Thuan

Aver, Olive, Skillman

Wednesday, May 22, 13
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

\[(y^+, n_e, a_{He}, \tau, T, C(H\beta), a_H, \xi)\]

Aver, Olive, Skillman
Using $\chi^2$ as a discriminator
Marginalized $\chi^2$ He from MCMC analysis: the bad and the good

Aver, Olive, Skillman
Final Result

Final Dataset

\[ Y_p = 0.2534 \pm 0.0083, \quad <Y> = 0.2574 \pm 0.0036 \]

\[ \frac{d(Y)}{d(O/H)} = 54 \pm 102 \]

Aver, Olive, Skillman

Wednesday, May 22, 13
Leo P: A new extremely metal poor galaxy (Giovanelli et al. - 2012)
Fig. 8.— The helium mass fraction (Y) and oxygen abundance for Leo P compared to the abundances in emission line galaxies from the sample of Izotov et al. (2007b) as analyzed by Aver et al. (2012, Aver12) and the sample from Peimbert et al. (2007, PLP07). The single line is the regression to the data from Aver et al. (2012). Note that the low value of O/H and the comparable error in Y for Leo P make this an important contribution in the determination of the primordial He abundance. Two of the galaxies are common to both comparison samples, I Zw 18 (at low O/H) and Haro 29 (also known as I Zw 36 and Mrk 209, at intermediate O/H) and their points are connected by lines. The narrow band marked WMAP7 is the range of values (±1σ) estimated for the primordial helium abundance following the calculation by Cyburt et al. (2008) from the 7-year WMAP value for the baryon-to-photon ratio (Komatsu et al. 2011) and assuming the neutron mean life from the Particle Data Group collaboration (Nakamura et al. 2010).

\[ Y_p = 0.2520 \pm 0.0072 + (69 \pm 90) \text{ (O/H)} \]
$^4$He Prediction: 0.2485 ± 0.0002

Data: Regression: 0.2520 ± 0.0072

Mean: 0.2567 ± 0.0034

baryon density $\Omega_b h^2$
Li/H

Measured in low metallicity dwarf halo stars (over 100 observed)
At the Planck value for η:
\[
\frac{\text{Li}}{\text{H}} = (4.88^{+0.71}_{-0.62}) \times 10^{-10}
\]

cf. data at
\[
\left( \frac{\text{Li}}{\text{H}} \right)_{\text{halo*}} = (1.23^{+0.34}_{-0.16}) \times 10^{-10},
\]
\[
\left( \frac{\text{Li}}{\text{H}} \right)_{\text{Gl.Cl.}} = (2.34 \pm 0.05) \times 10^{-10},
\]

Cyburt, Fields, KAO
Possible sources for the discrepancy

- Nuclear Rates
  - Restricted by solar neutrino flux

Coc et al.
Cyburt, Fields, KAO
Boyd, et al.
BBN Li sensitivities

\[ \frac{^7\text{Li}}{^7\text{Li}_0} = \prod_i R_i^{\alpha_i} \]

Key Rates:

\[ ^3\text{He} (\alpha, \gamma) ^7\text{Be} \]

<table>
<thead>
<tr>
<th>Reaction/Parameter</th>
<th>sensitivities ($\alpha_i$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{10}/6.14$</td>
<td>+2.04</td>
</tr>
<tr>
<td>$n(p, \gamma)d$</td>
<td>+1.31</td>
</tr>
<tr>
<td>$^3\text{He}(\alpha, \gamma)^7\text{Be}$</td>
<td>+0.95</td>
</tr>
<tr>
<td>$^3\text{He}(d,p)^4\text{He}$</td>
<td>-0.78</td>
</tr>
<tr>
<td>$d(d,n)^3\text{He}$</td>
<td>+0.72</td>
</tr>
<tr>
<td>$^7\text{Be}(n,p)^7\text{Li}$</td>
<td>-0.71</td>
</tr>
<tr>
<td>Newton's $G_N$</td>
<td>-0.66</td>
</tr>
<tr>
<td>$d(p, \gamma)^3\text{He}$</td>
<td>+0.54</td>
</tr>
<tr>
<td>n-decay</td>
<td>+0.49</td>
</tr>
<tr>
<td>$N_{\nu, eff}/3.0$</td>
<td>-0.26</td>
</tr>
<tr>
<td>$^3\text{He}(n,p)t$</td>
<td>-0.25</td>
</tr>
<tr>
<td>$d(d,p)t$</td>
<td>+0.078</td>
</tr>
<tr>
<td>$^7\text{Li}(p, \alpha)^4\text{He}$</td>
<td>-0.072</td>
</tr>
<tr>
<td>$t(\alpha, \gamma)^7\text{Li}$</td>
<td>+0.040</td>
</tr>
<tr>
<td>$t(d,n)^4\text{He}$</td>
<td>-0.034</td>
</tr>
<tr>
<td>$t(p, \gamma)^4\text{He}$</td>
<td>+0.019</td>
</tr>
<tr>
<td>$^7\text{Be}(n, \alpha)^4\text{He}$</td>
<td>-0.014</td>
</tr>
<tr>
<td>$^7\text{Be}(d, p)^2^4\text{He}$</td>
<td>-0.0087</td>
</tr>
</tbody>
</table>
Require:

\[
\begin{align*}
S_{34}^{NEW}(0) &= 0.267 \text{ keVb} \\
\frac{\Delta S_{34}}{S_{34}} &= -0.47 \\
\end{align*}
\]  \{ \text{globular cluster Li} \}

or

\[
\begin{align*}
S_{34}^{NEW}(0) &= 0.136 \text{ keVb} \\
\frac{\Delta S_{34}}{S_{34}} &= -0.73 \\
\end{align*}
\]  \{ \text{halo star Li} \}

New \(^3\text{He}(\alpha,\gamma)^7\text{Be} \) measurements

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{S-factor (keV barn) vs. Energy (MeV) for \(^3\text{He}(\alpha,\gamma)^7\text{Be} \) reaction.}
\end{figure}
Require:

\[
\begin{align*}
S_{34}^{NEW}(0) & = 0.267 \text{ keVb} \\
\frac{\Delta S_{34}}{S_{34}} & = -0.47 \\
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S_{34}^{NEW}(0) & = 0.136 \text{ keVb} \\
\frac{\Delta S_{34}}{S_{34}} & = -0.73 \\
\end{align*}
\]

\{ \text{halo star Li} \}

Constrained from solar neutrinos

\[
S_{34} > 0.35 \text{ keV barn} \\
\text{at 95\% CL}
\]
Is there a missing excited state providing a resonant reaction?

\[ ^7\text{Be} + A \rightarrow C^* \rightarrow B + D. \]
Is there a missing excited state providing a resonant reaction?

\[ ^7\text{Be} + A \rightarrow C^* \rightarrow B + D \]

In principle, long list of possible resonance candidates
Is there a missing excited state providing a resonant reaction?

\[ ^7\text{Be} + A \rightarrow C^* \rightarrow B + D \]

In principle, long list of possible resonance candidates

- Excited states of \(^8\text{Li}\) (included)
- \(^8\text{Be}\) (some included) - large \(E_{\text{res}}\)
- \(^8\text{B}\) (included)
- \(^9\text{B}\) - interesting state at 16.71 MeV
\[ \frac{7}{9}Be + d \rightarrow \frac{9}{10}B (16.71) \]
\[ \text{Be} + d \rightarrow \text{B} (16.71) \]

Recent results place state at 16.80

Scholl et al. 2011
cf. Kirsebom and Davids

\[
\begin{align*}
\text{6Be} + t & \quad 20.909 \\
\text{8B} + n & \quad 18.5771 \\
\text{7Be} + d & \quad 16.4901 \quad 16.71 \\
\text{7Li} + ^3\text{He} & \quad 9.3520 \\
\text{5Li} + \alpha & \quad 1.689 \\
\text{9Be} + p & \quad -1.0867 \\
\text{9Be} + ^3\text{He} & \quad -0.1851 \\
\end{align*}
\]
- $^{10}\text{B}$ - interesting state at 18.80 MeV
- $^{10}\text{C}$ - potentially interesting state at 15 MeV
- $^{11}\text{C}$ - negligible effect

Preliminary report from

**ORSAY SPLIT-POLE spectrometer**

Possible $E_x = 15.05$ MeV ($E_r = 50$ keV) level

reported by A. Coc - Paris Feb/12
Possible sources for the discrepancy

• Nuclear Rates
  – Restricted by solar neutrino flux

• Stellar Depletion
  – lack of dispersion in the data, $^6\text{Li}$ abundance
  – standard models (< .05 dex), models (0.2 - 0.4 dex)

Vauclaire & Charbonnel
Pinsonneault et al.
Richard, Michaud, Richer
Korn et al.
Possible sources for the discrepancy

- **Nuclear Rates**
  - Restricted by solar neutrino flux

- **Stellar Depletion**
  - Lack of dispersion in the data, $^6\text{Li}$ abundance
  - Standard models (< .05 dex), models (0.2 - 0.4 dex)

- **Stellar parameters**

  \[
  \frac{dL_i}{dl_{ng}} = \frac{0.09}{0.5}, \quad \frac{dL_i}{dT} = \frac{0.08}{100K}
  \]
Possible sources for the discrepancy

- Stellar Depletion
  - lack of dispersion in the data, $^6\text{Li}$ abundance
  - standard models (< .05 dex), models (0.2 - 0.4 dex)

- Stellar parameters

\[
\frac{dLi}{d\ln g} = 0.09 \quad \frac{dLi}{dT} = \frac{0.08}{100K}
\]

- Particle Decays
Limits on Unstable particles due to
Electromagnetic/Hadronic Production and
Destruction of Nuclei

3 free parameters

$$\xi_X = n_X m_X / n_\gamma = m_X Y_X \eta, \quad m_X, \quad \text{and } \tau_X$$

• Start with non-thermal injection spectrum (Pythia)

• Evolve element abundances including thermal (BBN) and non-thermal processes.
Injection of p,n with timescale of \(~1000\) s

\(^7\text{Be(n,p)}^7\text{Li} \quad \text{followed by} \quad \ ^7\text{Li(p,\(\alpha\)}^4\text{He}

\[ \text{D/H} \]

\[ ^7\text{Li/H} \]

\[ ^6\text{Li/}^7\text{Li} \]

\(\tau\) (sec)
How well can you do

\[ \chi^2 \equiv \left( \frac{Y_p - 0.2534}{0.0083} \right)^2 + \left( \frac{D/H - 3.01 \times 10^{-5}}{0.27 \times 10^{-5}} \right)^2 + \left( \frac{^{7}\text{Li}/H - 1.23 \times 10^{-10}}{0.71 \times 10^{-10}} \right)^2 + \left( \frac{\Omega_{\chi}^{(3/2)/2} h^2}{0.0045} \right)^2, \]

SBBN: \( \chi^2 = 33.7 \) - field stars
SBBN: \( \chi^2 = 23.8 \) - GC stars

**Cyburt, Ellis, Fields, Luo, Olive, Spanos**
<table>
<thead>
<tr>
<th>ID</th>
<th>$Y_p$</th>
<th>$10^5$ D/H</th>
<th>$10^{10}$ $^7$Li/H</th>
<th>$\Omega^{(3/2)}_\chi h^2$</th>
<th>$\chi^2_{\text{min}}$</th>
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<tbody>
<tr>
<td>1</td>
<td>0.2487</td>
<td>3.27</td>
<td>2.12</td>
<td>$5.0 \times 10^{-4}$</td>
<td>2.81</td>
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<tr>
<td>2</td>
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<td>3.28</td>
<td>2.09</td>
<td>$1.1 \times 10^{-3}$</td>
<td>2.86</td>
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<tr>
<td>3</td>
<td>0.2487</td>
<td>3.26</td>
<td>2.14</td>
<td>$4.4 \times 10^{-4}$</td>
<td>2.82</td>
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<td>4</td>
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<td>2.11</td>
<td>$2.1 \times 10^{-3}$</td>
<td>3.14</td>
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<tr>
<td>5</td>
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<td>2.01</td>
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<td>2.87</td>
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<tr>
<td>6</td>
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<td>3.27</td>
<td>2.11</td>
<td>$1.0 \times 10^{-3}$</td>
<td>2.86</td>
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<tr>
<td>7</td>
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<td>3.29</td>
<td>2.08</td>
<td>$4.7 \times 10^{-4}$</td>
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<tr>
<td>8</td>
<td>0.2487</td>
<td>3.25</td>
<td>2.16</td>
<td>$1.8 \times 10^{-3}$</td>
<td>2.96</td>
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<tr>
<td>9</td>
<td>0.2487</td>
<td>3.31</td>
<td>2.04</td>
<td>$1.2 \times 10^{-3}$</td>
<td>2.91</td>
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<tr>
<td>10</td>
<td>0.2487</td>
<td>3.28</td>
<td>2.09</td>
<td>$1.4 \times 10^{-3}$</td>
<td>2.89</td>
</tr>
<tr>
<td>11</td>
<td>0.2487</td>
<td>3.55</td>
<td>1.63</td>
<td>$5.1 \times 10^{-4}$</td>
<td>1.25</td>
</tr>
<tr>
<td>12</td>
<td>0.2487</td>
<td>3.10</td>
<td>2.50</td>
<td>$3.5 \times 10^{-3}$</td>
<td>0.52</td>
</tr>
<tr>
<td>13</td>
<td>0.2487</td>
<td>3.15</td>
<td>2.40</td>
<td>$2.5 \times 10^{-4}$</td>
<td>0.37</td>
</tr>
</tbody>
</table>
Possible sources for the discrepancy

• Particle Decays

• Axion Cooling

• Variable Constants

Erkin, Sikivie, Tam, Yang
Kusakabe, Balantekin, Kajino, Pehlivan
Limits on $N_{\nu}$

$$G_F T^5 \sim \Gamma (T_f) \sim H (T_f) \sim \sqrt{G_N N} \ T_f^2$$

<table>
<thead>
<tr>
<th>Observations</th>
<th>$\eta_{10} \equiv 10^{10} \eta$</th>
<th>$N_{\nu}$</th>
<th>$\delta N_{\nu, max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_p + D/H_A$</td>
<td>$5.94^{+0.56}_{-0.50}$</td>
<td>$3.14^{+0.70}_{-0.65}$</td>
<td>1.59</td>
</tr>
<tr>
<td>$Y_p + \eta_{CMB}$</td>
<td>$6.14 \pm 0.25$</td>
<td>$3.08^{+0.74}_{-0.68}$</td>
<td>1.63</td>
</tr>
<tr>
<td>$D/H_A + \eta_{CMB}$</td>
<td>$6.16 \pm 0.25$</td>
<td>$3.59^{+1.14}_{-1.04}$</td>
<td>2.78</td>
</tr>
<tr>
<td>$Y_p + D/H_A + \eta_{CMB}$</td>
<td>$6.10^{+0.24}_{-0.22}$</td>
<td>$3.24^{+0.61}_{-0.57}$</td>
<td>1.44</td>
</tr>
</tbody>
</table>

“current” upper limit from He:
$\delta N_{\nu} < 1.45$

Cyburt, Fields, KAO, Skillman
Summary

• D, He are ok -- issues to be resolved

• Li: Problematic
  - BBN $^7$Li high compared to observations

• Important to consider:
  - Nuclear considerations
    - Resonances $^{10}$C (15.04)!
  - Depletion (tuned)
  - Li Systematics - T scale - unlikely
  - Particle Decays?
  - Axion cooling??
  - Variable Constants???

• $^6$Li: Another Story