Precision measures of the primordial abundance of Deuterium

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Primordial nucleosynthesis
Big Bang Nucleosynthesis (BBN) Ingredients

Input parameters

- The expansion rate of the Universe
- Baryon density parameter
- Neutrino Degeneracy (i.e. lepton asymmetry)

Standard Model Assumptions

- Laboratory measured reaction cross-sections
- General Relativity (i.e. the Friedmann Equations)
- 3 families of neutrinos
- No lepton Asymmetry
These are the DLAs we're after.

\[ \eta_{10} = 274 \Omega_b h^2 \]

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How do we measure \((D/H)p\)?

Via absorption lines in near-pristine gas clouds at high redshift.
Cosmological redshifts give us a view of the Universe at different cosmic epochs.
A sample portion of a quasar absorption spectrum

10m Keck telescope + HIRES
A sample portion of a quasar absorption spectrum showing HI Lyman alpha (1215.67 Å) absorption lines
A sample portion of a quasar absorption spectrum

Lya forest: low-density, ionised, intergalactic gas
Energy Levels

$n = 8$  $n = 8$
$n = 7$  $n = 7$
$n = 6$  $n = 6$
$n = 5$  $n = 5$
$n = 4$  $n = 4$
$n = 3$  $n = 3$
$n = 2$  $n = 2$
$n = 1$  $n = 1$

blue-shift of 82 km/s
A sample portion of a quasar absorption spectrum

**Lya forest:** low-density, ionised, intergalactic gas
A sample portion of a quasar absorption spectrum

Damped Lya: high-density, neutral, galactic (?) gas
Metallicity Distribution

These are the DLAs we’re after

Rafelski et al. 2012
Very Metal Poor DLAs are the choice astrophysical environments for measuring the primordial abundance of deuterium.

Low metallicities imply negligible astration of D.

Prantzos & Ishimaru 2001
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- Low metallicities imply negligible astration of D
- Narrow absorption lines make it possible to resolve the -82 km/s isotope shift between D and H
- High H I column densities give detectable D I lines in many transitions of the Lyman series
J1419+0829, z= 3.050, Fe/H = 1/200 solar
Spectral analysis tailored specifically to the determination of D/H and its error

Pettini & Cooke 2012
Spectral analysis tailored specifically to the determination of D/H and its error
\( \gamma_p \equiv (^{4}\text{He}/\text{H})_p \)

\[ \eta_{10} = 274 \Omega_b h^2 \]

\[ (\text{D}/\text{H})_p = 2.55 \times 10^{-5} (6/\eta_{10})^{1.6} \]
Precision Measures of (D/H) [Cooke et al. 2014]

\[(D/H)_{DLA} = (2.53 \pm 0.04) \times 10^{-5}\]
Precision Measures of \((D/H)\) [Cooke et al. 2014]

\[100 \Omega_b h^2 = 2.202 \pm 0.045\]

(Random + Systematic Error)
1. $p \rightarrow n$
2. $p(n, \gamma)d$
3. $d(p, \gamma)^3\text{He}$
4. $d(d, n)^3\text{He}$
5. $d(d, p)t$
6. $t(d, n)^4\text{He}$
7. $t(\alpha, \gamma)^7\text{Li}$
8. $^3\text{He}(n, p)t$
9. $^3\text{He}(d, p)^4\text{He}$
10. $^3\text{He}(\alpha, \gamma)^7\text{Be}$
11. $^7\text{Li}(p, \alpha)^4\text{He}$
12. $^7\text{Be}(n, p)^7\text{Li}$

Nollett & Burles 2000
But don’t we know it all from the CMB anyway?
$100 \Omega_b h^2 (\text{CMB}) = 2.205 \pm 0.028$

Planck XVI 2013
$100 \Omega_b h^2 (BBN) = 2.202 \pm 0.045$

(Random + Systematic Error)
BBN and CMB measurements have now reached a level of accuracy sufficient to start testing for departures from the `standard model'.

In particular, test for the possible existence of `dark radiation', i.e. any hidden radiation decoupled from photons.

If dark matter, why not `dark radiation'?
Departures from the standard model are often parameterised by the effective number of neutrino species.

\[ N_{\text{eff}} = 3.046 \text{ in standard BBN} \]

The expansion rate factor \( S \) is altered by the presence of additional radiation components:

\[ S = \left( 1 + \frac{7\Delta N_{\text{eff}}}{43} \right)^{1/2} \]
Joint D/H and CMB Constraints on `dark radiation'

\[ N_{\text{eff}} = 3.28 \pm 0.28 \]

Cooke et al. 2014
BBN Constraints on 'dark radiation'

\[ N_{\text{eff}} = 3.50 \pm 0.20 \]

Cooke et al. 2014
Summary

There exists a population of neutral gas clouds which at redshifts $z = 2 - 4$ had undergone minimal enrichment by stellar nucleosynthesis.

Chemical studies of these `Extremely Metal-Poor Damped Lyman Alpha Systems' complement very effectively analogous measures in old stars of the Milky Way and nearby galaxies.
Main Results: Deuterium

Concordance between values of $\Omega_b h^2$ from CMB and D/H in metal-poor DLAs.

In future, offers the means to test for non-standard physics, e.g. axions.
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The End