BIG-BANG NUCLEOSYNTHESIS: THEORETICAL INPUTS AND UNCERTAINTIES: COMPARISON WITH THE DEUTERIUM OBSERVATIONS TOWARDS QSOs

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Improved light element yields are calculated in the context of standard big bang nucleosynthesis using a direct Monte Carlo treatment for 12 critical nuclear reaction rates. By combining these predictions with the recent measurements of extragalactic deuterium, the baryon density is constrained to better than 10% at 95% confidence: $\Omega_b h^2 = 0.020 \pm 0.002$. This constraint will provide, for the first time, a quantitative test of the hot big-bang model when compared with the latest observations from the cosmic microwave background.

1 Introduction

Standard big bang nucleosynthesis (BBN), the cosmological synthesis of the light elements ($A < 7$) during the first 10,000 seconds, is a pillar of the current hot big bang cosmological model. Starting with the pioneering work of Gamow[1] and his collaborators almost 60 years ago (for a historical review see the recent book by Alpher & Herman[2]), calculations of BBN have been very successful in the explaining the abundance patterns of the lightest isotopes. The current status of light element abundances have been recently reviewed on both the observational[3] and theoretical[4,5,6,7,8,9] sides.

To place constraints on cosmological models, we must assess the predictions and uncertainties in the nuclear inputs which is covered in the next section. This is then combined with the best constraints on the primordial isotopic abundance estimates. I will cover the recent observations of the deuterium to hydrogen ratio (D/H) as measured in high redshift, low metallicity intervening absorption systems observed towards more distant, ultra-luminous QSOs. For

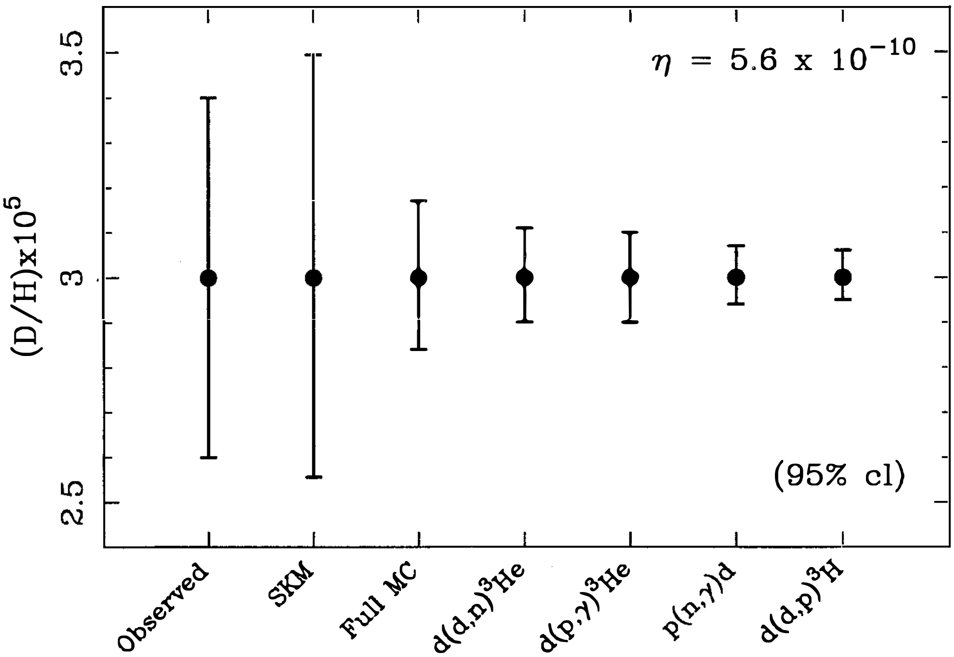

Figure 1: Important contributions to the error budget for standard BBN abundance of deuterium: see text for discussion.

reviews of observations of the other isotopes important in BBN, see discussions of Helium-3, Helium-4 and Lithium-7 by Bania, Luridiana, and Vauclair, respectively in these proceedings.

2 Nuclear Inputs

For standard Big Bang Nucleosynthesis, there are 12 critical reactions which need to be carefully treated to obtain reliable abundances. Krauss and Romanelli [10] studied 10 of these reactions and the effective individual uncertainties on Lithium-7. Smith, Kawano, & Malaney[11] produced the industry standard predictions by an in-depth analysis of all 12 reactions. Recently, other groups have addressed updated reaction rates[12,13]. Here, I will overview our treatment of the nuclear inputs and the total uncertainties in the final isotopic yields[14,15,16].

By introducing new, direct empirical fits to the experimental nuclear cross-section data, there has been a dramatic reduction in the final light element abundance uncertainties predicted with standard BBN, a reduction of more than a factor of 2[14]. The improvement can be explained by the following reasons: 1) New data became available in the interim, which lead to better and tighter characterization of the cross sections important for deuterium, and 2) even more significant, the new technique directly relates the final abundance uncertainty to the original nuclear cross section data at the energies exactly relevant for standard BBN.

The highlights of the direct Monte Carlo technique are 1) correct treatment of the random and correlated errors in nuclear data sets, 2) an aggressive assessment of the statistical uncertainties extracted with a direct Monte Carlo of the individual data points, 3) flexible spline fitting to allow for possible variations in the cross-section uncertainties as a function of energy. 4) The reaction rates are numerically integrated from the splined cross-section realizations, which

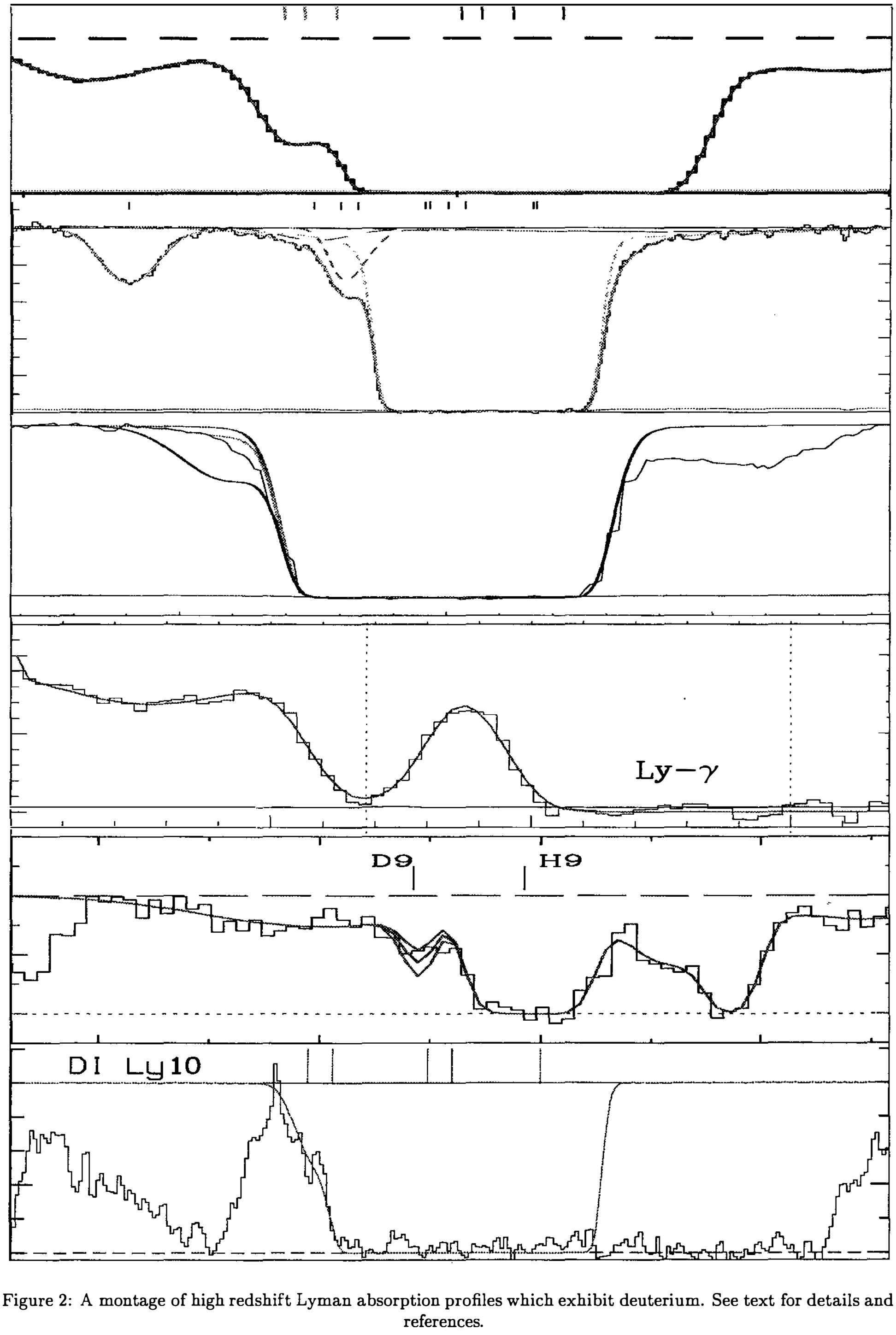

Figure 2: A montage of high redshift Lyman absorption profiles which exhibit deuterium. See text for details and references.

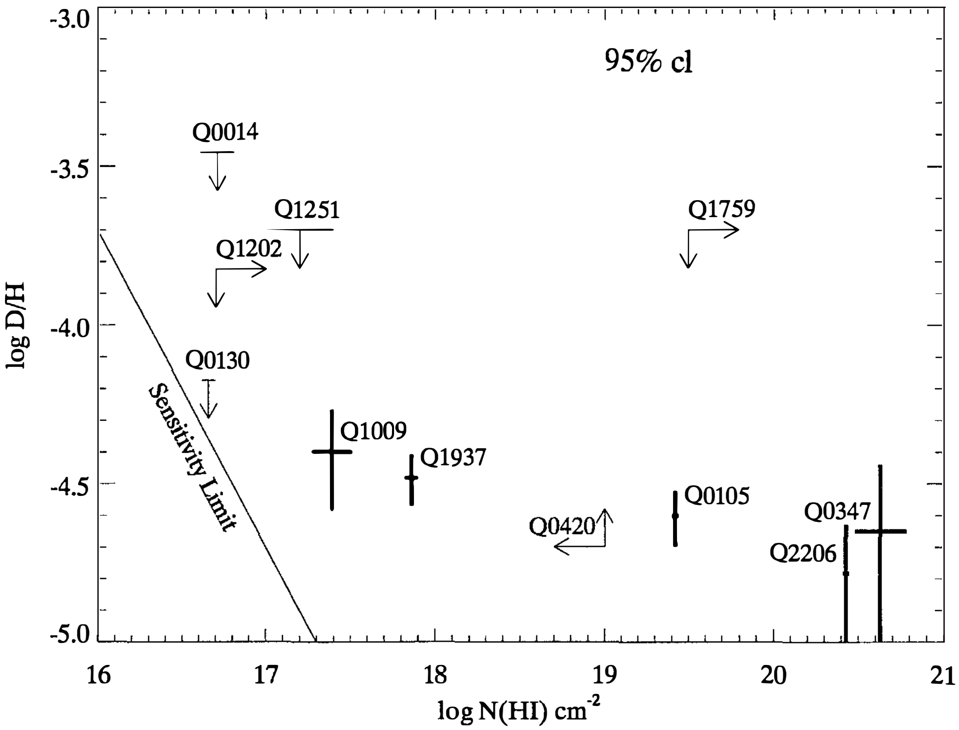

Figure 3: Extragalactic deuterium measurements and limits from Lyman absorption towards high redshift QSOs. The best published constraints at 95% confidence level are shown as $\log_{10}$ D/H versus neutral hydrogen column density. The diagonal line shows the sensitivity limit for Lyman absorption analyses, measurements closer to this line are more susceptible to excess hydrogen masquerading as deuterium.

complements functional derivative studies of the cross-sections versus energy.

In Figure 1, I show the contributions to error budget corresponding to the standard BBN abundance of deuterium for a baryon to photon ratio, $\eta = 5.6 \times 10^{-10}$ ($\Omega_b h^2 = 0.020$). All displayed uncertainties represent deuterium abundance intervals of 95% confidence. The first uncertainty shows the most recent weighted constraints from high redshift deuterium measurements discussed in the next section. The next uncertainty is from the earlier work of Smith, Kawano, and Malaney[11] which is as large as the current astrophysical abundance uncertainty. The next error represents the full combined deuterium abundance uncertainty from the direct Monte Carlo method. The remaining four smaller error bars show the individual contribution of each reaction which plays a significant role in the reliable prediction of a standard BBN deuterium abundance.

3 Deuterium Observations

The technique of measuring the isotopic abundance ratio of hydrogen, the number ratio of deuterium to hydrogen (D/H), was first carried out in the local interstellar medium by Rogerson and York[17] and will be expanded on in these proceedings with new FUSE results presented by Guillaume Hebrard. In 1976, Thomas Adams[18] proposed the same technique be applied to high-redshift QSO absorption systems. In this section, I will discuss the current state of affairs of the extragalactic deuterium measurements, and use the latest results to constrain standard BBN.

An in-situ measurement of deuterium in high-redshift absorption systems is very appealing for a few reasons: 1) the universe is less than about 2 billion years old, and the post-BBN processing should be much less than present-day astrophysical environments, 2) the absorption line systems are very metal-poor, usually less than 1/100 solar, which gives more reason to suspect very limited post-BBN processing (c.f. Jedamzik & Fuller[19] for further discussion), and 3) observationally, for redshifts greater than 2.5, the entire Lyman series is redshifted into the visible band and can be observed with large ground based apertures, and 4) the ratio of neutral deuterium to neutral hydrogen in extragalactic environment represents the total ratio (including ionized D & H) to better than 0.4

In Figure 2, I present a montage of the five best deuterium measurements and one stringent upper limit. Each of the panels in figure 2 corresponds to a different QSO line of sight, each with its own absorption redshift, column density and kinematic structure. From top to bottom, the panels display absorption profiles of 1) Lyman-α towards Q1937-1009 [21], 2) Lyman-α towards Q1009+2956 [22], 3) an upper limit on D Lyman-α towards Q0130-4031 [23], 4) Lyman-γ towards Q0105-1619 [24], 5) Lyman-9 in a damped Ly-α system towards Q2206-3819 [25], 6) Lyman-10 in a damped Ly-α system towards Q0347-3819 [26].

Each of these systems have been measured using Voigt profile analysis and constraining the assuming a common redshift for the absorption of Deuterium and Hydrogen features. Although deuterium is detected or severely limited in each case, the uncertainty on the final deuterium to hydrogen ratio varies dramatically between the measurements. In Figure 3, I highlight the five measurements and display the best fit values with corresponding 95% error bars as a function of neutral hydrogen column density. In addition to the bonafide measurements, I also show limits on D/H in other lines of sight, from systems which were slightly less than ideal and could not produce a robust measurement[27]. This is not intended to confuse the reader, for constraints on D/H one should use the best measurements, but this reveals the amount of effort which has gone into extragalactic measurements of D/H over the past 8 years. Each measurement and limit can represent up to 20 hours of world class telescope time, and up to a year of analysis to finally arrive at a constraint on the observed D/H ratio.

The extragalactic D/H measurements shown in figure 2 place strong constraints on a single value for the cosmological D/H ratio in low metallicity, high-redshift absorption systems. Taking each of the likelihoods on D/H to be log-normal (or normally distributed as shown in figure 2), one finds the variance weighted D/H at 95% confidence:

$$\log_{10}\mathrm{D/H} = -4.53 \pm 0.06 \qquad \text{(stat)} \tag{1}$$

$$\mathrm{D/H} = (3.0 \pm 0.4) \times 10^{-5}, \tag{2}$$

since the final error is small, we can report the linear analog: One may be (and should be) concerned about the scatter in the measurements, a simple calculation shows the 5 measurements give a total $\chi^2 = 15.9$. Of this total, the measurement towards Q2206 contributes $\chi^2 = 8$. This measurement already has large quoted uncertainties, but the central value is very low, and falls near the value measured in the local interstellar medium. The assumption of normally distributed errors about the central value may not hold in the case of Q2206, and the authors did not attempt to measure the likelihood function about their central value, nor did they attempt more sophisticated profile models to explain their result. Upon excluding the low value of Q2206, one finds a large χ^2, but with less than 2σ significance.

Clearly, additional high quality measurements of deuterium will resolve the question of possible scatter in the extragalactic measurements. But with the data and results in hand to date, with the possible exclusion of normally distributed errors on the measurement towards Q2206, we can place a very tight constraint on the assumption of a single cosmological abundance of deuterium in high redshift absorbers. In the final section, I will apply this constraint to

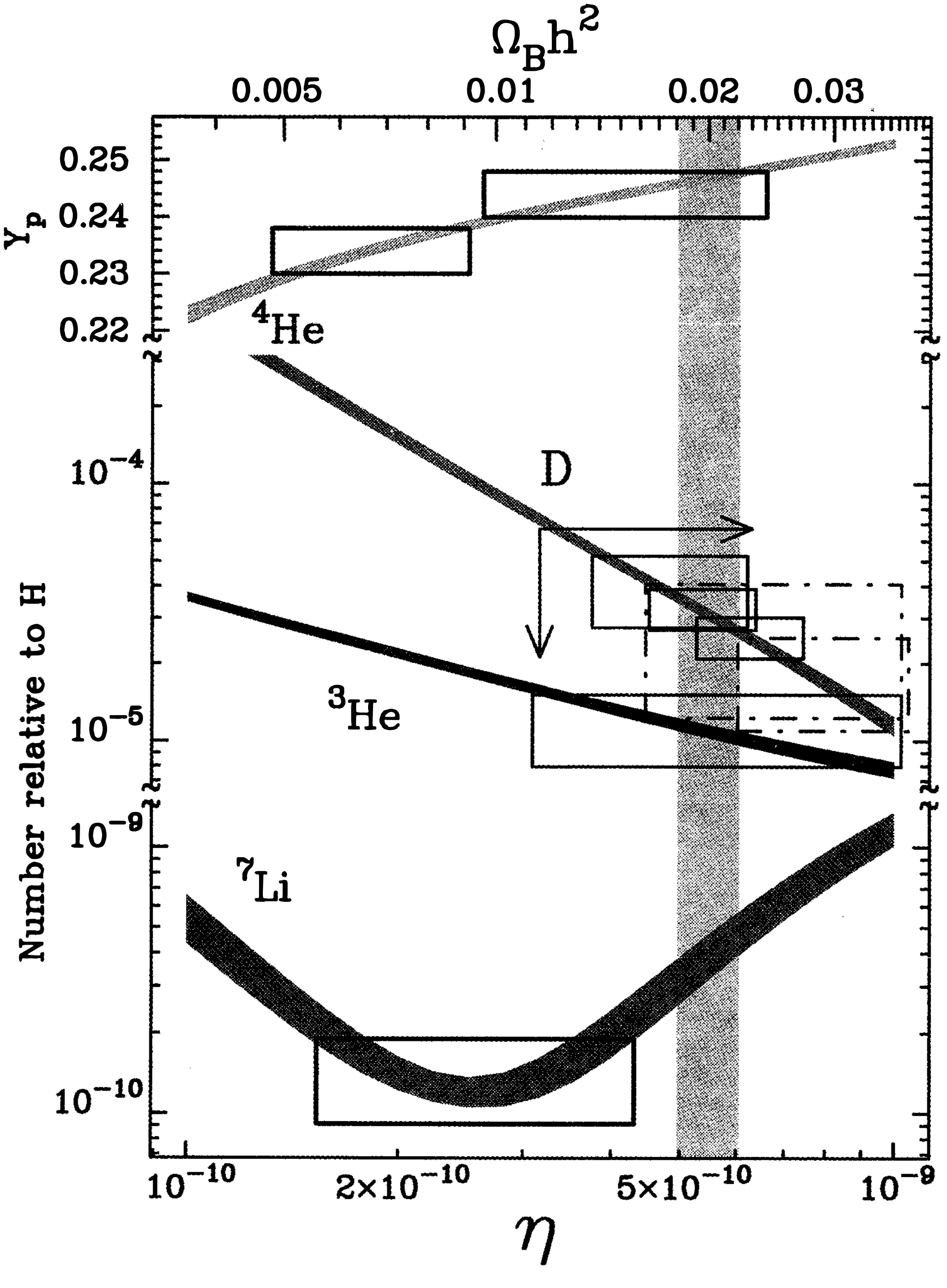

Figure 4: The light elements yields of standard BBN as a function of η (bottom) and $\Omega_b h^2$ (top). The thickness of the curves represents 95% uncertainties from the nuclear inputs. The boxes represent observational constraints discussed in the text (95% statistical errors), and the vertical band gives the weighted constraint from deuterium.

models of standard BBN and briefly compare with other light element abundances and very recent results from precise measurements of cosmic microwave background.

4 Conclusions

With a weighted average of extragalactic D/H measurements, along with the best abundance predictions from standard BBN, we can extract constraints of the baryon-to-photon ratio and the present-day baryon density: $\Omega_b h^2$. Figure 4 summarizes the current state of light element abundances and the predictions of standard BBN. The light stable isotopes are shown as number abundance relative to hydrogen, except for He4 which is given as mass fraction, Y_p. The thickness of the curves shows the 95% confidence limits given by the direct Monte Carlo method. The boxes show recent determinations of light element abundances. The vertical position and height of each box gives the statistical 95% confidence interval in the inferred primordial abundance. The horizontal extent of the box corresponds to the confidence interval (95%) on $\Omega_b h^2$ and the baryon-to-photon ratio, η.

The vertical blue band shows the final 95% limit based on the weighted cosmological deuterium abundance alone. At this level, it provides a statistical precision of 10% on the single free parameter in standard BBN:

$$\Omega_b h^2 = 0.020 \pm 0.002 \quad (95\% \text{ cl}) \tag{3}$$
$$\eta = (5.6 \pm 0.6) \times 10^{-10} \quad (95\% \text{ cl}) \tag{4}$$

Boxes representing the mass fraction of He4 are shown for two independent compilations of abundance determinations in extragalactic metal-poor H II regions, the upper box from Izotov & Thuan[28] and the lower from Olive, Skillman, & Steigman[29]. The apparent discrepancy in these results is discussed by Luridiana in the proceedings. The box falling on the He3 prediction represents the 95% confidence limit on a recent measurement in S209[30] as detailed by Bania in these proceedings. And the box covering the minimum in the Lithium-7 prediction is taken from a recent detailed study of metal-poor field halo stars[31].

In addition, there are new independent constraints on $\Omega_b h^2$ from the latest balloon borne and interferometric observations of the cosmic microwave background. Together with new results presented at this meeting, the power spectrum of temperature fluctuations agrees very well with the deuterium-inferred standard BBN baryon density. For the first time, we are on the threshold of a precision test on a single cosmological parameter measured in two distinct epochs which stand as pillars of the hot big bang cosmology. With more results on the cosmic microwave background on the way (c.f. talks by Bouchet and Peterson), as well as new light element measurements, we should expect a quantitative test of the standard big bang cosmology to a level of precision better than 5%.

Acknowledgments

I would like to thank all of the organizers for a wonderful Moriond meeting, in particular J. Tran Thanh Van and Sylvie Vauclair for the invitation.

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