

# **Constraining Primordial Helium-4 Abundance by Cosmic Microwave Background Radiation Anisotropies**

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## **Abstract**

I give a brief review of Big Bang Nucleosynthesis (BBN) and of the Cosmic Microwave Background Radiation (CMBR). The methods used to constrain  $Y_P$  by the CMBR are then discussed, including methods later discarded in favor of others. To conclude, I give limits found by our analysis and discuss the implications of said limits.

## INTRODUCTION

Approximately 15 billion years ago, the universe emerged from a singularity in a cataclysmic event called the Big Bang. This explosion of space, radiation, and matter cooled rapidly, allowing for the formation of elementary particles amidst an ever-changing spectrum of the forces that governed their interaction. Most of these changes occurred in the first 0.001 seconds after the bang (ATB) (see Table 1). From ~0.01 to ~100 seconds ATB the universe had cooled sufficiently for protons and neutrons to bind together to form atomic nuclei.

While the rate of interconversion between neutrons and protons was faster than the expansion rate of the universe, the ratio of the two particles remained in chemical equilibrium according to the equation

$$\frac{n}{p} = \exp\left[-\frac{(m_p - m_n)c^2}{kT}\right]. \quad [1]$$

Once the expansion rate exceeded that of the interconversion, however, the ratio of neutrons to protons “froze out” at the value given by the temperature at that stage, about 1/6. Deuterium could then have started forming if it weren’t for the large photon-to-

| $t (s^{-1} \text{ ATB})$                         | <i>Event</i>                      |
|--|-----------------------------------|
| $10^{-43}$                                       | Theory of Everything (TOE) Ends   |
| $10^{-34}$                                       | Grand Unified Theory (GUT) Ends   |
| $10^{-12}$                                       | Electroweak Ends                  |
| <b><math>10^{-2}</math> to <math>10^2</math></b> | <b>Primordial Nucleosynthesis</b> |
| $10^{11}$  | Matter Domination                 |
| <b><math>10^{13}</math></b>                      | <b>Decoupling / Recombination</b> |
| $10^{16}$  | Galaxy Formation                  |
| $10^{17}$  | Solar System Formation            |

**Table 1** -- Brief cosmological chronology, with events important to this discussion in bold type [1].

baryon ratio, which caused a large rate photodissociation. By the time the temperature of the universe cooled to 80 keV [2], at which point deuterium could only be dissociated by the most energetic photons, all neutrons were involved in the formation of helium-4 nuclei. The extreme stability of helium-4 ensures that essentially all neutrons will remain as part of those nuclei. Also within this time, the neutron-to-proton ratio fell to 1/7 due to neutron decay. From this figure a simple calculation yields a helium-4 abundance of

$$Y_p \approx \frac{2n}{p+n} = \frac{2\left(\frac{n}{p}\right)}{1+\left(\frac{n}{p}\right)} = \frac{2\left(\frac{1}{7}\right)}{1+\left(\frac{1}{7}\right)} = 25\%.$$

Approximately one million years later, the average temperature was low enough for electrons to bind with the nuclei, forming the first neutral atoms. At the same time as this event, termed “recombination” (even though the electrons and nuclei had never been combined before), the decoupling of matter and radiation occurred. Until this moment, photons were constantly interacting with free electrons by Thomson scatter. Now, because the number of free electrons was reduced so drastically and the cross-section of interactions with other particles was so small, the mean free path of photons was nearly the length of the universe. As such, the average photon hasn’t interacted with matter since the moment of decoupling. The 2.75 Kelvin Cosmic Microwave Background Radiation (CMBR) is the product of these photons, red-shifted over the past several billions of years. Because these photons haven’t been scattered since decoupling, the CMBR can give information on the state of the universe at that time; and because nucleosynthesis occurred before decoupling, the CMBR can be expected to contain information on the primordial helium-4 abundance.

The temperature of the CMBR is anisotropic: a graph of the  $C_{ls}$  (coordinate-system independent coefficients of spherical harmonics) that describe the angular power spectrum shows a number of peaks and troughs. (The value of  $\frac{l(l+1)C_l}{2\pi}$  can be taken roughly as the average temperature difference at that angular scale, where  $\theta = \frac{\pi}{l}$ . [3])

The height and position of these peaks is sensitive to the helium-4 abundance. A greater value of  $Y_p$  yields an earlier time of decoupling because electrons are bound more strongly to helium nuclei. The earlier decoupling leads to a smaller surface of last scatter, which shifts the position and strength of the peaks.

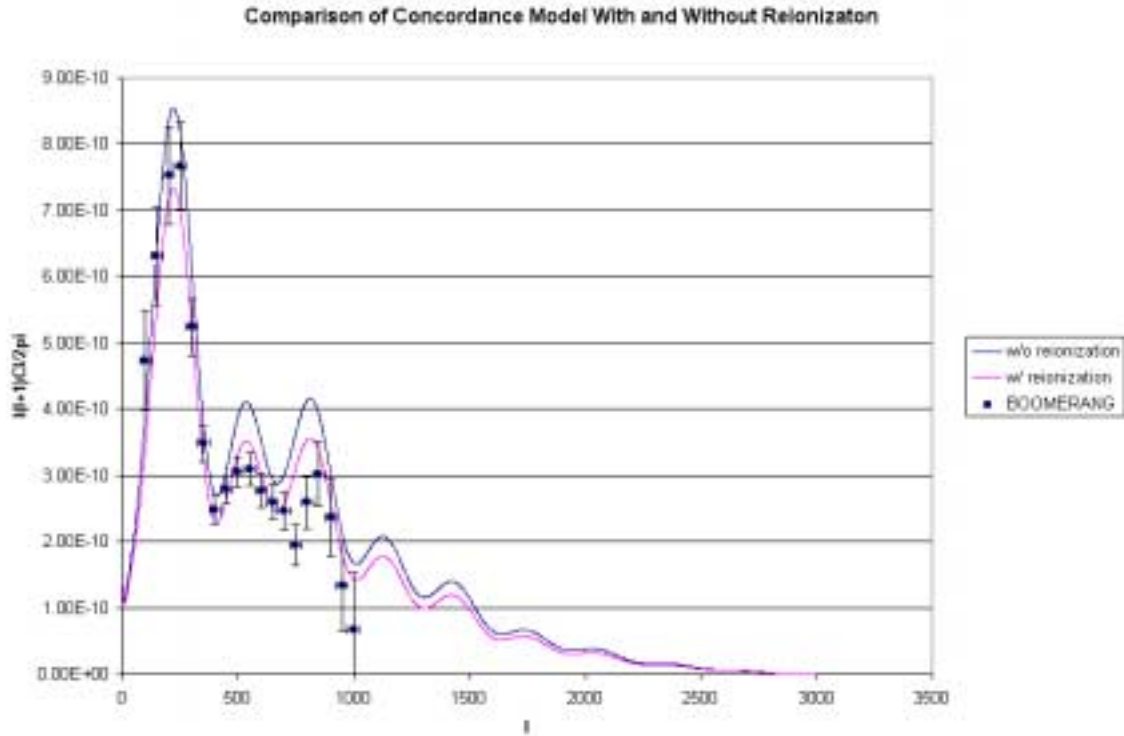
## **PURPOSE**

The objective of our research was to attempt to constrain the possible values of the primordial helium-4 abundance using only CMBR anisotropy data. Big-Bang Nucleosynthesis (BBN) theory can predict the correct helium-4 abundance by using equations of chemical equilibrium, along with the neutron decay rate, and by assuming that all neutrons are involved in the formation of helium-4 nuclei (as discussed above); however, we wanted to explore the possibility that CMBR data and related theory can be used to place limits on  $Y_p$  without other elements of Big Bang theory. We realized that these limits were unlikely to be as precise as those developed under BBN, but we hoped to demonstrate that this approach is valid for further research.

## METHOD

We ran models for the CMBR using a program called CMBFAST, developed by Seljak and Zaldarriaga (see [4]). The program, used extensively in theoretical CMBR research, allows the user to enter various cosmological parameters (Hubble constant, baryon density, etc.) including helium-4 abundance. It then uses these parameters to calculate a model of CMBR anisotropies, which can be compared with data recorded by satellites such as BOOMERANG, DASI, and MAXIMA to check the model's validity. CMBFAST uses the helium-4 abundance to calculate the fraction of free electrons to total electrons, which affects the timing of decoupling and in turn affects the CMBR. As such, the model predictions are independent of BBN helium synthesis theory. By running models for different values of  $Y_p$ , we can thereby find values that produce a good fit to current data.

First, we ran CMBFAST models using concordance parameters published by Netterfield, *et al.* in their analysis of the BOOMERANG experiment (see [5]). We compared these models to BOOMERANG data to verify that the program was working as expected. Originally, we had determined to assume for simplicity that no reionization occurred in the early universe, but we found that reionization is necessary to match the concordance model – otherwise the models always produced values of  $C_l$  that were too high (see Figure 1). Also, we found that CMBFAST behaves erratically for  $Y_p$  values over 90%, so we decided to limit the scope of our research to models having a helium-4 abundance under 85%.



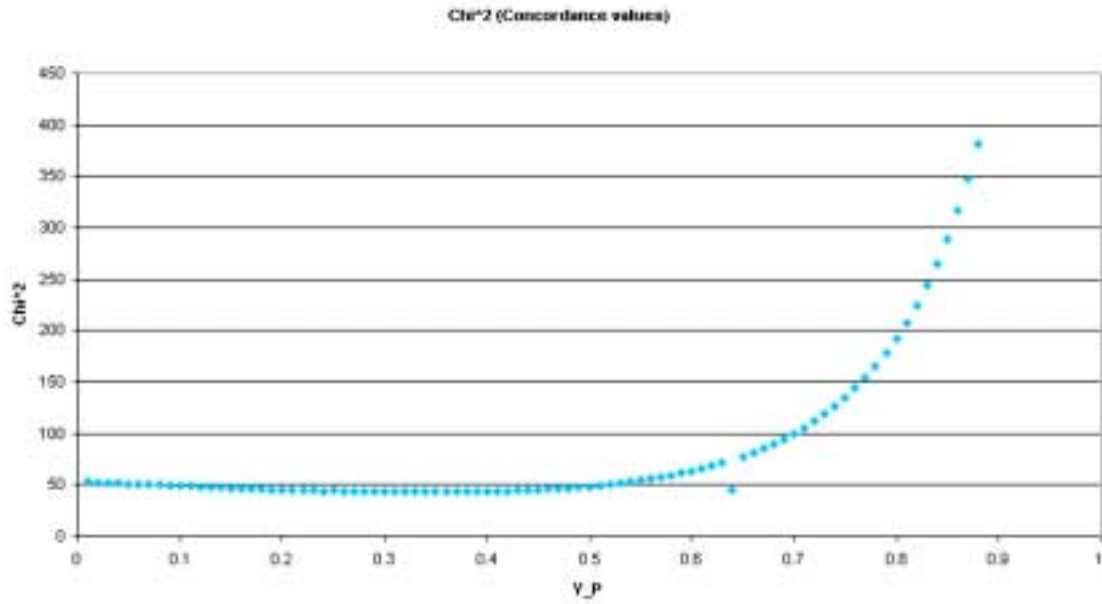
**Figure 1** – Concordance models with and without reionization.

For each of the models we assumed a flat universe ( $\Omega_{\text{TOT}} = 1$ , where  $\Omega_{\text{TOT}}$  is the density of the universe as a fraction of the critical density). We also assumed that the universe is isentropic (adiabatic), that the temperature of the CMBR is known at 2.726 Kelvin, and that the values of  $\Omega_{\nu}$  (neutrino density as fraction of critical density),  $N_{\nu}$  – massless (equivalent number of massless neutrino species), and  $N_{\nu}$  – massive (equivalent number of massive neutrino species) are 0, 3.04, and 0, respectively. All models were produced using the Peebles recombination calculation and a single spatial spectral index (tilt), which was allowed to vary. This left  $\Omega_b$  (baryon density),  $\Omega_c$  (cold dark matter density),  $\Omega_{\Lambda}$  (vacuum energy density),  $H_0$  (Hubble constant)  $\tau_c$  (optical depth at

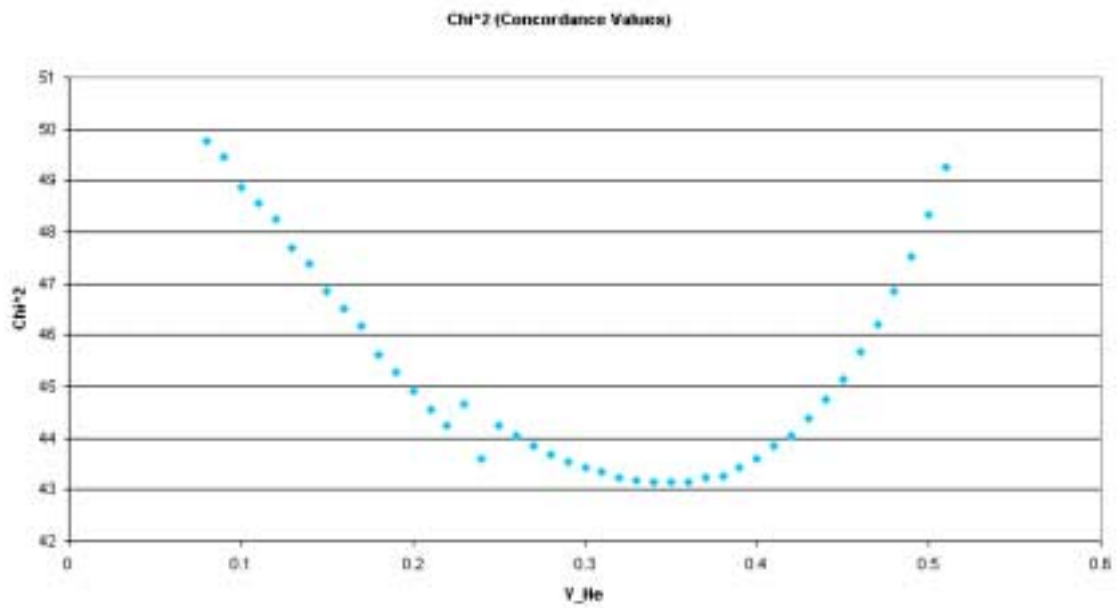
reionization), and  $n_s$  (tilt) to be varied. (Note:  $\Omega_b$  and  $\Omega_\Lambda$  were varied directly, and  $\Omega_c$  was defined as  $\Omega_c = 1 - (\Omega_b + \Omega_\Lambda)$  to ensure a flat model.

We had initially planned to do a  $\chi^2$ -analysis on our models using the RADical Compression Analysis PACKage (RADPACK) program, developed by Lloyd Knox (see [6]). RADPACK runs the analysis taking into account that the  $C_l$ s (actually  $l(l+1)C_l/2\pi$ ) aren't Gaussian as is needed for a standard  $\chi^2$  calculation; the  $C_l$ s are variances, which complicates the  $\chi^2$ -analysis. RADPACK performs all the calculations required to make the necessary adjustments ([7]). The program has the capability to run the analysis on single experimental data sets or any combination of all data sets currently available, with the additional option to assign different weights to each experiment. We planned to run the analysis against BOOMERANG, MAXIMA, and DASI, each weighted equally. I wrote a UNIX script with several nested loops to automate the process of running CMBFAST with several values for each of the five varying parameters, repeating the process for each  $Y_p$  ranging from 0.01 to 0.85 at steps of 0.01. The program would also run the RADPACK analysis on each of these models (see Figures 2 and 3). However, once I had this program ready we decided to drop this technique in favor of another that would give better results.

We turned instead to a Monte-Carlo analysis, using only BOOMERANG data. For this technique we assumed that the probability of values for each of the five varying parameters followed a Gaussian distribution centered on the concordance value, with the  $\sigma$  value given by Netterfield *et al.* (see again [5]). Gregory Mack wrote a Fortran program that would randomly select the values for these parameters following this distribution. When  $\sigma$  differed between the positive and negative directions we used the average of the



**Figure 2** –  $\chi^2$  of concordance models with varying  $Y_p$ .



**Figure 3** – Graph of  $\chi^2$  values on smaller range.

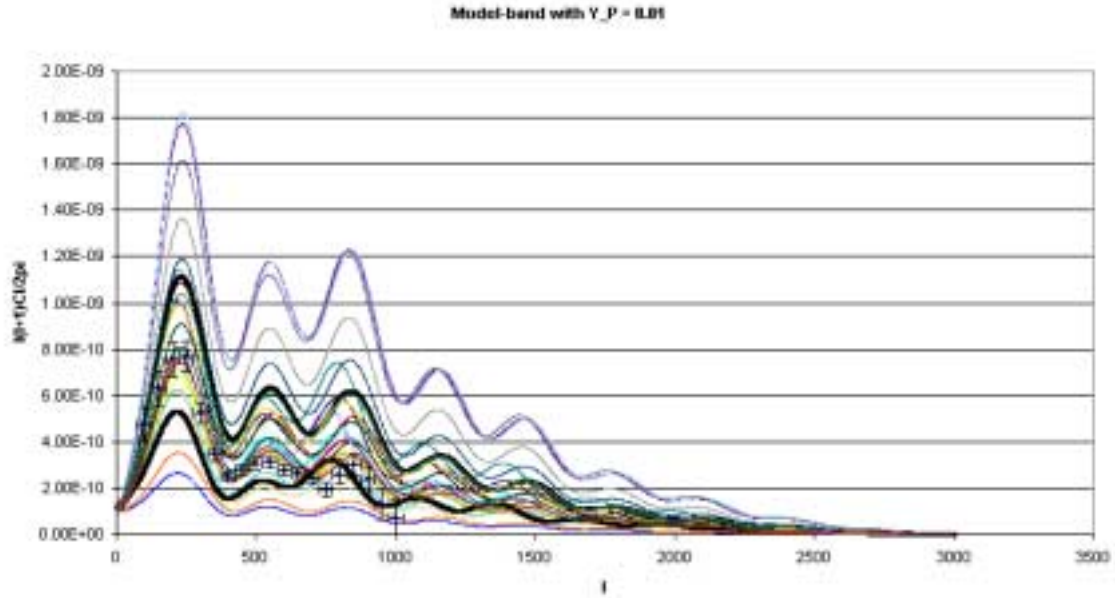
two (see Table 2 for values used). I then re-wrote my UNIX script to run Greg's program for the parameter values then use these values for the CMBFAST inputs. The script can repeat this process any number of times for desired values of  $Y_p$ . When all the models for a particular helium-4 abundance are graphed together they form a band of possible CMBR anisotropies that can be compared by eye to the BOOMERANG data. Any abundance value can be ruled out if it yields a band that doesn't include the data points. The large  $\sigma$  values for the Netterfield concordance model produced a large amount of scatter in the models, so we were forced to define a band with 66% of the models, allowing us to exclude abundances with a 66% confidence level.

| <i>Parameter</i> | <i>Value</i>    |
|------------------|-----------------|
| $\Omega_b$       | $0.05 \pm 0.01$ |
| $\Omega_\Lambda$ | $0.66 \pm 0.05$ |
| $H_0$            | $66 \pm 5$      |
| $n_s$            | $1.03 \pm 0.1$  |
| $\tau_c$         | $0.15 \pm 0.13$ |

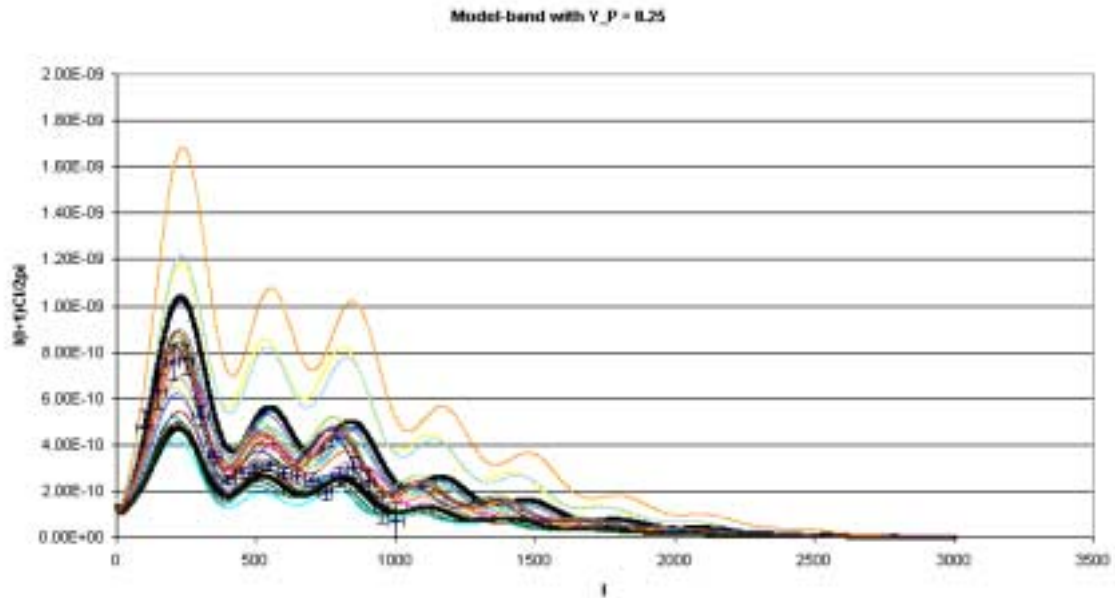
**Table 2** – Values used for Gaussian distribution of parameters.

## RESULTS

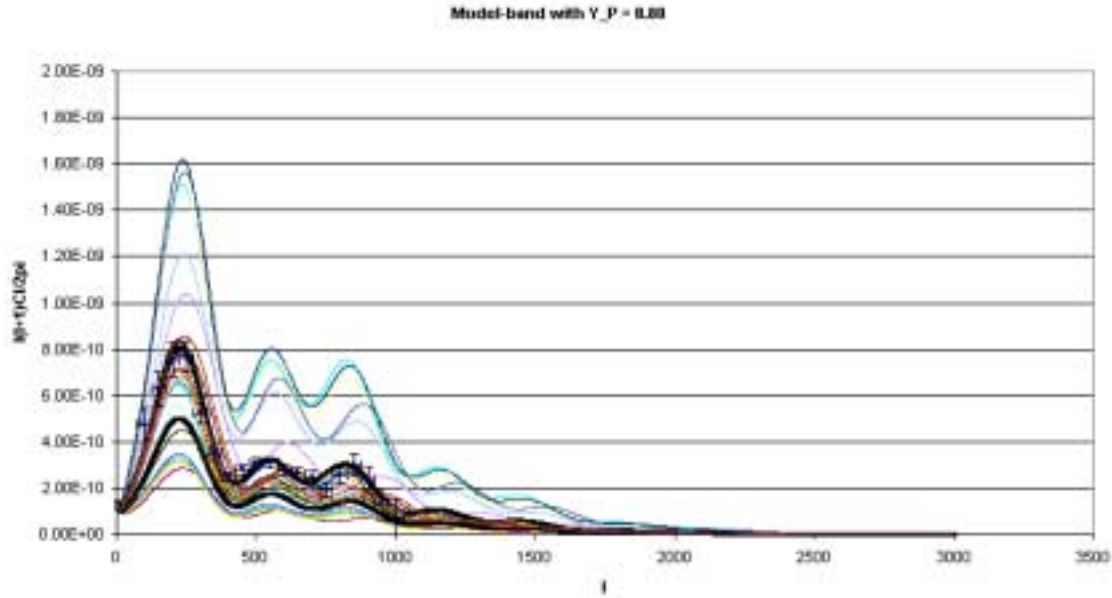
We were unable to set a lower limit of the helium-4 abundance, as the band of models generated for a 1% abundance wasn't defined enough to preclude even that low abundance; there was just too much uncertainty (see Figure 4). We were able, however, to establish an upper limit of 80% (with 66% confidence) (see Figures 5 and 6).



**Figure 4** – Model-band for  $Y_p = 0.01$ , with 66% confidence band outlined in black. Compared with BOOMERANG data.



**Figure 5** – Model-band for  $Y_p = 0.80$ .



**Figure 6** – Model-band for  $Y_p = 0.25$ .

While this result leaves a much larger range of possible  $Y_p$  values than standard BBN theory, it demonstrates that CMBR anisotropy data can limit helium-4 abundance! The inaccuracy of the current satellite data allows for too much spread to allow tighter limits ( $\sigma$  values for the various parameters are typically 10%, with one as high as 86%!).

With better data, the error bars in which acceptable model-bands must fall would be smaller, restricting allowable models. More importantly, better data would allow for a concordance model with smaller  $\sigma$  values for the parameters. This would lead to model-bands that are more compact and better defined, allowing more values of  $Y_p$  to be ruled out at 100% confidence. The MAP experiment, launched in early July 2001, is expected to give data accurate to within 1% [8]. This would dramatically improve results given by a Monte-Carlo analysis. During the next couple of months, our research group will

continue with a Fisher matrix analysis. This technique should allow us to predict how accurately we could confine the  $Y_p$  if our data were of unlimited accuracy.

## **ACKNOWLEDGMENTS**

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