Computational Implementation of the Restriction of Cosmological Parameters

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Introduction

In this project, it is proposed the study of the constraint on cosmological parameters using data from Cosmic Microwave Background radiation and Baryon Acoustic Oscillations. In addition to the data mentioned, data from forecasts of the 21-cm data from the BINGO radio telescope within the context of interaction in the dark sector of the Universe will also be used. This project aims to deepen the student's knowledge of statistical methods applied in the UCLCl code, which focuses on estimating the cosmological parameters of interest through the combination of the data previously mentioned. To accomplish this, the study of the physical theory behind interacting models, 21-cm neutral hydrogen radiation data for simulations, Bayesian statistics, and the use of Monte Carlo Markov Chain via the Nested Sampling method will be necessary, as well as programming in C++ and Python for data analysis.

Data and Methodology

In the project, two different and independent types of data and BINGO simulations will be used:

Cosmic Microwave Background

The Cosmic Microwave Background (CMB) data used will be from the latest data release of the Planck experiment (Collaboration 2019). CMB is radiation, detectable on Earth or in space, emitted as the interaction rate between matter and radiation becomes smaller than the expansion rate of the Universe.

Baryon Acoustic Oscillations

Baryon Acoustic Oscillations (BAO) are fluctuations in baryonic matter density. That can be used as a "standard ruler" (Kazin 2014). Some examples of survey data used include the Sloan Digital Sky Survey (SDSS and SDSS-III; Alam (2017); Ross (2015)), 6dFGS (Beutler 2011), and WiggleZ Dark Energy Survey (Kazin 2014).

21-cm Radiation - BINGO

Simulations of data obtained by BINGO in which the redshift range is divided into 30 bins using angular power spectra of 21-cm from the UCLCℓ code (Costa et al. 2022) to generate maps according to lognormal distributions (Marins & Filipe B. Abdalla 2022).

To be able to restrict the parameters, the Markov Chain Monte Carlo (MCMC) method is used to to extract usual statistical quantities, such as the mean and variance of the cosmological parameters of interest. In the project, the MCMC analysis will be performed using the PLINY code (Skilling 2004) - a sampler designed for parallel computing - with Nested Sampling (Buchner 2023). This generates a set of points in the parameter space whose probability distribution function has a density equal to the likelihood.

The UCLCℓ code enabled the creation of images to analyse the constraint of cosmological parameters by performing a MCMC analysis on the likelihood functions, comparing Universe description models presented in Costa et al. (2017). These fenomenological models assume the existence of interaction between dark matter and dark energy, satisfying continuity equations.

Results and Conclusions

In order to obtain the comparative images, the code was run using four models of Universe description, each with different values for the cosmological parameters:

Table 1. Stable phenomenological models.

Model	Parameter	Best fit	68% limits
I	$3\lambda_2 H\rho_d$	$-1<\omega<0$	$\lambda_2<0$
II	$3\lambda_2 H\rho_d$	$\omega<-1$	$0<\lambda_2<-2\omega\Omega_c$
III	$3\lambda_1 H\rho_c$	$\omega<-1$	$0<\lambda_1<-\omega/4$
IV	$3\lambda H(\rho_d+\rho_c)$	$\omega<-1$	$0<\lambda<-\omega/4$

To complement the analysis, the ΛCDM model was used as the "standard model", in which there is no interaction between dark energy and dark matter, hence no calculation of ω and λ. This model is used both for qualitative comparisons based on plots and quantitatively through evidence analysis.

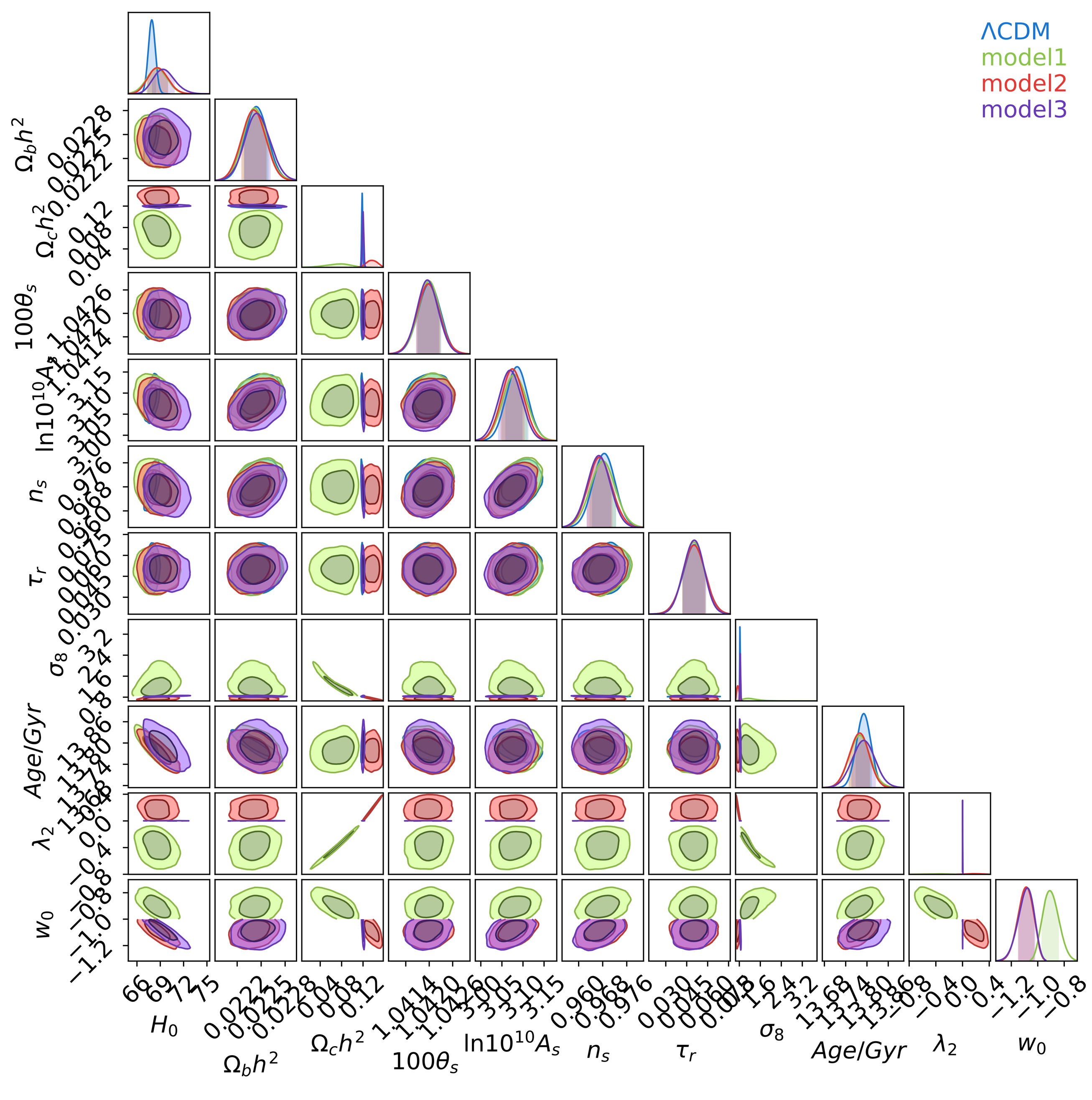

Figure 1. Comparison plot generated by UCLCℓ of the 3 models and the ΛCDM model with data from CMB + BAO.

The best fit -mean value- and 68% limits -values in Figure 1- for each cosmological parameter are in Table 2:

Table 2. Cosmological parameters - CMB + BAO

Parameter	ΛCDM		Model1		Model 2		Model 3	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
H_0	68.06	67.91 ± 0.45	68.61	68.50 ± 1.30	68.51	$68.60^{+1.30}_{-1.20}$	68.65	$69.40^{+1.40}_{-1.30}$
$\Omega_b h^2$	0.0225	0.0224 ± 0.0001	0.0225	$0.0224^{+0.0002}_{-0.0001}$	0.0224	0.0224 ± 0.0002	0.0224	$0.0224^{+0.0002}_{-0.0002}$
$\Omega_c h^2$	0.118	$0.118^{+0.0001}_{-0.001}$	0.108	$0.078^{+0.018}_{-0.025}$	0.132	$0.136^{+0.010}_{-0.010}$	0.119	$0.120^{+0.001}_{-0.001}$
$100\theta_S$	1.042	$1.042^{+0.0003}_{-0.0003}$	1.042	$1.042^{+0.0003}_{-0.0003}$	1.042	1.042 ± 0.0003	1.042	$1.042^{+0.0003}_{-0.0003}$
$ln(10^{10}A_s)$	3.074	3.086 ± 0.026	3.076	$3.079^{+0.030}_{-0.027}$	3.075	$3.074^{+0.027}_{-0.026}$	3.083	$3.069^{+0.028}_{-0.026}$
n_s	0.969	$0.969^{+0.004}_{-0.004}$	0.965	$0.968^{+0.004}_{-0.004}$	0.968	$0.967^{+0.004}_{-0.004}$	0.966	$0.967^{+0.004}_{-0.004}$
τ	0.053	$0.051^{+0.008}_{-0.008}$	0.051	$0.050^{+0.008}_{-0.008}$	0.056	$0.050^{+0.008}_{-0.008}$	0.049	$0.050^{+0.007}_{-0.008}$
λ_i	-	-	-0.1051	$-0.34^{+0.14}_{-0.18}$	0.1325	$0.169^{+0.110}_{-0.098}$	0.0002	$0.0011^{+0.0010}_{-0.0009}$
ω_0	-	-	-0.996	$-0.910^{+0.063}_{-0.056}$	-1.068	$-1.087^{+0.055}_{-0.058}$	-1.040	$-1.079^{+0.054}_{-0.062}$
σ_8	0.817	$0.823^{+0.010}_{-0.010}$	0.896	$1.13^{+0.34}_{-0.24}$	0.762	$0.739^{+0.052}_{-0.039}$	0.834	0.834 ± 0.015
Age	13.78	$13.79^{+0.02}_{-0.02}$	13.78	13.78 ± 0.03	13.78	$13.78^{+0.03}_{-0.03}$	13.79	$13.79^{+0.03}_{-0.03}$

Analyzing the overlapping ellipses of the three models, not considering the standard model, Model 3 is more suitable, as it restricts the probability space for the value of each parameter more effectively, providing a better sampling of the numerical value. The difference in the position of each ellipse for the coupling constants and dark energy equation of state can be explained by the differences in the priors for each model.

In order to better evaluate the probability of each model occurring compared to the standard ΛCDM, it was necessary to write a code in `Python` to calculate the evidence of each model to be able to conduct this analysis.

The analysis is based on the assumption that if $-1 < B < 1$, the studied model may be more feasible; however, if B is outside this range (meaning $B < -1$ or $B > 1$), the ΛCDM model is more likely; where B is the Bayes value.

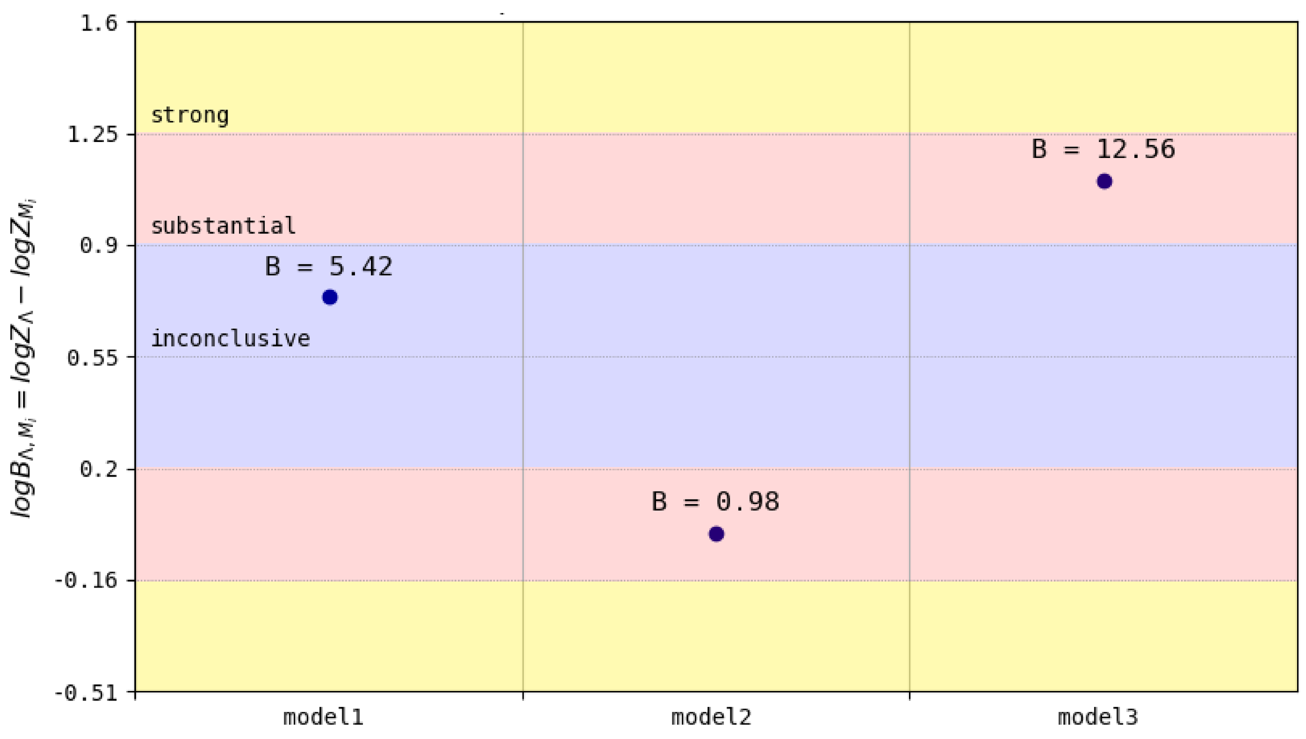

Figure 2. Evidence plot made in *Python* for CMB + BAO.

From the comparisons with the studied models, it is possible, through the analysis of evidence and the physical theory behind each proposed model, to conclude that the standard model is still the most likely. Even in the case of evidence, where Model 2 has a B value within the range $[-1, 1]$, combining this analysis with the values calculated by UCLCℓ reveals significant divergences, indicating an inadequacy of this model in describing the Universe. The other models, despite showing some agreement in the values of cosmological constants with those found for ΛCDM, have a B value greater than 1, highlighting their inadequacy.

In conclusion, despite finding values close to the actual cosmological parameters, the standard ΛCDM Model remains the most plausible in describing the Universe when the interaction between the dark sectors of the Universe is not considered. Furthermore, when additional experimental data beyond Planck is included, an improvement in the numerical calculation for the studied models can be observed. However, that does not invalidate the importance of studying these and other models, as these theories can contribute to the discussion to address the ΛCDM coincidence problem and potentially lead to the discovery of a more suitable description of the Universe.

Future Work

In order to complement the research, the next steps include using the simulated 21-cm radiation from BINGO's forecasts alongside the data mentioned and other consolidated cosmological data available in the literature. This will deepen the understanding of the telescope influence in the observed data and how to conduct further analyses.

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