Extragalactic Astronomy I Project

Constraining cosmological parameters using SN and BAO data

This documents provides the idea to carry out the project for the Extragalactic Astronomy I course of the IUCAA-NCRA graduate school, taken by Prof. Surhud More. This document provides a step by step guide to constrain the cosmological parameters using Type Ia supernovae and Baryon Acoustic Oscillations (BAO). We request everyone to work on the exercises individually, as it directly provides a way to work with data to do science. You are required to use your own code which you developed for the assignments to find the cosmological distances. The class notes can be referred to and is available at https://surhudm.github.io/Cosmology_IUCAA_2025/. For any help, the TAs will be available for discussion. (The updated version of this document will always be live at https://github.com/PhysicistSouravDas/sn_bao_cosmology_2024).

Data

All the data required to carry out the exercises are available at https://github.com/PhysicistSouravDas/sn_bao_cosmology_2024. The project has to be done by utilizing two datasets, one from Type Ia SN observations, and one from BAO observations. For the SN data, you are provided with the Joint Light-Curve Analysis (JLA) dataset (Betoule et al. 2014) at `data/JLA`. The JLA dataset contains data for 740 Type Ia SN, along with the covariance matrices. The data, including B band magnitude (m_B) with redshift (z), along with the corresponding errors, is contained in `jla_lcparams.txt`, and the information about the covariance matrices is contained in `jla.dataset`. For this project, you are expected to use the magnitude covariance matrix. The magnitude covariance matrix element $C_{i,j}$ represents the covariance between m_B measurements at i^{th} and j^{th} redshift.

The BAO data is from the first year of observations from the Dark Energy Spectroscopic Instrument (DESI) (Collaboration et al. 2024) located at `data/DESI2024`. The BAO data at different redshift along with the distance value and the type of distance quantity is contained in file `desi_2024_gaussian_bao_ALL_GCcomb_mean.txt`, and the corresponding covariance matrix at `desi_2024_gaussian_bao_ALL_GCcomb_cov.txt`. There are the following distance quantities:

- D_M/r_s: The transverse comoving distance $D_M(z)$, normalized by radius of the sound horizon r_s.
- D_H/r_s: Hubble distance $D_H(z)$ normalized by radius of the sound the horizon.
- D_V/r_s: Angle averaged distance that quantifies the average of the distances measured along and perpendicular to the line of sight of the observer,

$$D_V(z) = \left(zD_M(z)^2 D_H(z)\right)^{1/3}$$

normalized by the radius of the sound horizon.

The angular diameter distance (D_A) is related to D_M by

$$D_M = (1+z)D_A$$

You have to use this relation to use D_M values from the dataset along with the corresponding covariance matrix values, to compute D_A. One thing to note here is that the dataset has no values for r_s, but it can be factored out by taking the ratio of D_A at different redshifts.

All the data files and example programs can be downloaded from the GitHub link. A guide to download files from GitHub is also available at the given GitHub link.

Exercises

- Plot m_B vs z with errors on m_B.
- Compute the distance modulus μ, given by

  $$\mu = m - M = 5\log_{10} D_L(\text{in pc}) - 5$$

  There are no measurements on the absolute magnitude M, and it needs to be estimated and treated as a parameter along with other cosmological parameters. Here, D_L is the luminosity distance.

  Assume a Gaussian likelihood and define a log likelihood function using

  $$\chi^2 = r^\dagger C^{-1} r$$
  $$r = y_{\text{obs}} - y_{\text{model}}$$

  Here, C denotes the covariance matrix. The $\dagger$ implies the transpose operation on r.

  Define logprior function, using uniform priors on $\Omega_m = (0.0, 1.0)$, $\Omega_\Lambda = (0.0, 1.0)$, and M. Define log posterior/log probability using log likelihood and log prior for running the MCMC. It is recommended to use `emcee` package of Python3 to achieve this task. You may quote the values of Ω_m, Ω_Λ and M by maximizing the log probability before running the MCMC.

  Plot μ vs z along with the errors on μ, and convert to D_L to plot D_L vs z with the errors on D_L.

- Put ΛCDM predictions using three different values for the Ω parameters with the Hubble parameter $h = 0.703$, and plot μ vs z.
  - $\Omega_m = 0.05$, $\Omega_\Lambda = 0.4$
  - $\Omega_m = 0.2$, $\Omega_\Lambda = 0.6$
  - $\Omega_m = 0.4$, $\Omega_\Lambda = 0.9$

  Compute the χ^2 values for each model and tell us what do you understand from it.

- Generate a contour plot for SN as shown in figure 1a, showing 1σ and 2σ contours. Python3 package `corner` may be used.

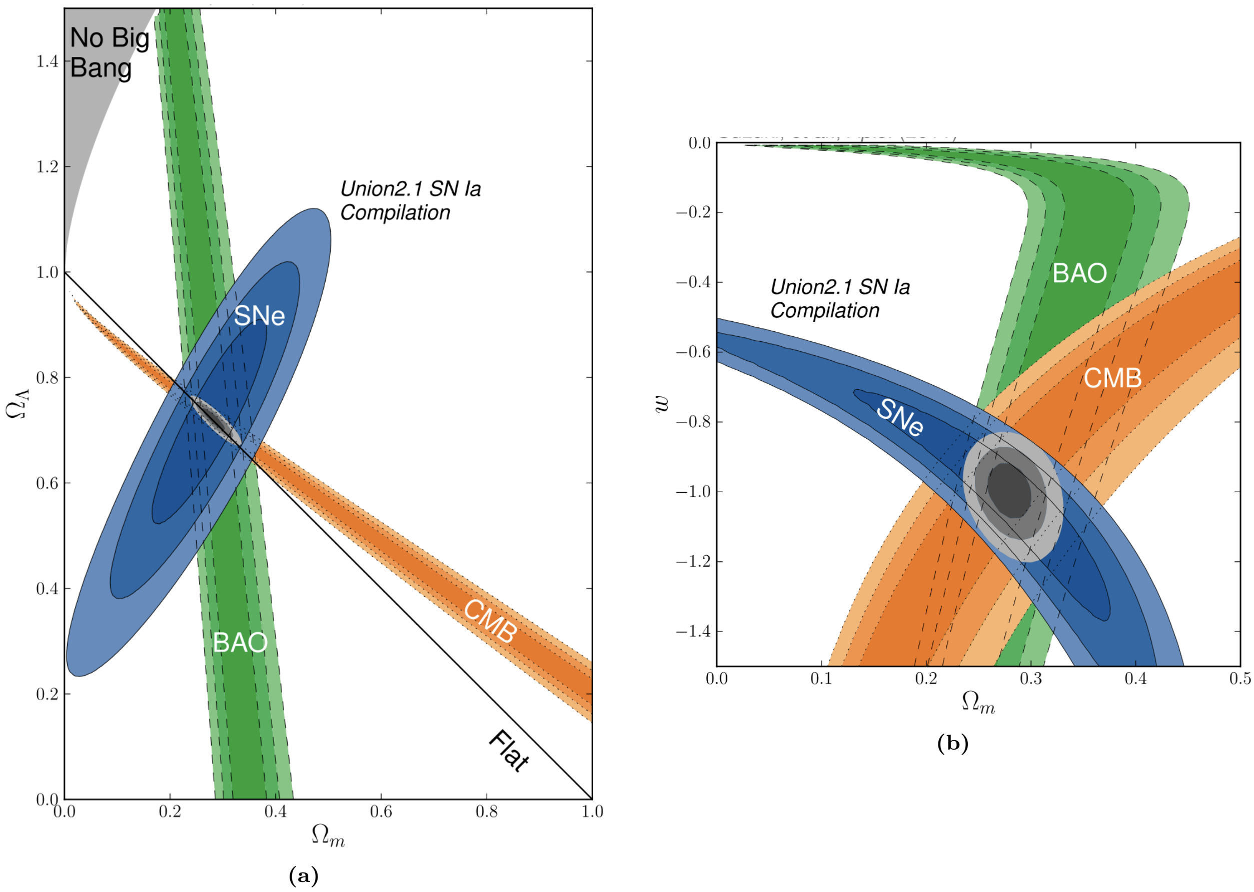

Figure 1: Contours from different datasets to constrain the cosmological parameters assuming (a) CDM model and (b) wCDM model.

- For BAO, plot D_A vs z, and propagate the errors. The errors on D_M can be computed from the diagonal elements of the covariance matrix, given that the off-diagonal elements are very small. Estimate the cosmological parameters from BAO data, assuming a Gaussian likelihood, and do a corner plot for BAO as shown in figure 1a. Quote the values of the cosmological parameters constrained.
- Combine both the SN and BAO observations to further constrain the cosmological parameters as shown in figure 1a.
- **Bonus:** Try to carry out similar tasks assuming wCDM model to generate contour plots shown in figure 1b. This part is not compulsory but will be treated as a bonus exercise.

References

Betoule, M. et al. (Aug. 2014). "Improved cosmological constraints from a joint analysis of the SDSS-II and SNLS supernova samples". In: *Astronomy amp; Astrophysics* 568, A22. ISSN: 1432-0746. DOI: 10.1051/0004-6361/201423413. URL: http://dx.doi.org/10.1051/0004-6361/201423413.

Collaboration, DESI et al. (2024). *DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations.* arXiv: 2404.03002 [astro-ph.CO]. URL: https://arxiv.org/abs/2404.03002.