Semester report
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PhD program: Astronomy and Space Physics
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Ph.D. Thesis title: Cosmic Dipole, Hubble-tension, cosmic coincidence – tests and attempts to solve the problems of the ΛCDM cosmological model

Introduction

Although the current concordance cosmological model, the Lambda Cold Dark Matter (ΛCDM) model, is in very good agreement with observations, it relies on the introduction of not yet fully understood constituents and mechanisms – such as dark matter, dark energy and cosmic inflation – to explain these observations. Despite its success, the model faces several known unsolved problems, including discrepancies between early- and late-universe observations, such as the Hubble-tension (Riess 2020) and S_8-tension (Di Valentino 2021), as well as anomalies like the cosmic dipole (Secrest 2021). Additionally, other persistent issues (Casado 2020, Perivolaropoulos & Skara 2022) suggest that further refinements to the theory may be necessary.

Investigating alternative cosmological models, such as coasting cosmologies or the AvERA model proposed by ELTE researchers (Rácz et al. 2017), can provide valuable insights into the theoretical challenges within standard cosmology. Coasting cosmologies, in particular, avoid several unresolved problems of the ΛCDM model, without requiring dark matter or dark energy, while still demonstrating remarkably good agreement with observational datasets used to test cosmological models (Melia 2018).

Description of research work carried out in current semester

During this semester, we further investigated the Pantheon+ supernovae database and the proper methodology for fitting cosmological models to it. Based on these studies, I refined my `Python` code, which was already capable of fitting supernova (SN) and quasar (QSO) datasets using an MCMC algorithm. I made necessary corrections and improvements to enhance its accuracy and usability. With this updated version, we tested the Flat ΛCDM and coasting cosmological models under different curvature assumptions. The results and conclusions of these analyses were published in January 2025. Additionally, I optimized the code to be more compact and readable, providing detailed instructions on configuration and execution to facilitate public accessibility.

As part of our publication, we also tested the models on the cosmic chronometer (CC) database using a publicly available `emcee` code. To support this work, I studied the `emcee` package in `Python` and customized the existing public code for our specific requirements. I also prepared tables and figures for inclusion in the publication and conducted additional analyses based on the reviewer's feedback.

Furthermore, we established contact with the inventors of AvERA cosmology at ELTE. After studying the AvERA model, I conducted tests on various realizations of it – assuming different coarse-graining scales – using the CC and SN datasets with my testing code. We discussed the results and outlined the next steps, aiming for a forthcoming publication.

Another major focus of my research is developing a method to measure the cosmic dipole using gravitational-wave signals from compact binary mergers. This involves testing the method through simulations and, in the future, applying it to detected gravitational-wave signals. This work will result in a publication, for which I will be the first author. During the previous and current semesters, I have studied the core principles of this method, analysed the relevant datasets, and reviewed recent publications in this field. Additionally, I have mapped the differences between the methodologies used by various authors.

I have been a member of the LIGO Collaboration since January 2015. Through this membership, I will gain access to LIGO's simulation software and databases, which are essential for conducting my analyses on the cosmic dipole. In summer 2024, Gergely Dálya and I applied for a research funding grant to develop the theoretical framework for the use of galaxy-cluster catalogues in gravitational-wave cosmology. The funding decision is still pending, and if successful, this research will be carried out over the next two years.

Publications

I am a co-author of the following article, published on January 17, 2025, and the corresponding author of its code repository:

Raffai, P., Pataki, A., Böttger, R. L., Karsai, A., and Dálya, G. (2025). *"Cosmic Chronometers, Pantheon+ Supernovae, and Quasars Favor Coasting Cosmologies over the Flat ΛCDM Model."* The Astrophysical Journal, **979**(1), 51. DOI: 10.3847/1538-4357/ada249

Code repository: Zenodo - 14184660

Studies in current semester

- FIZ/5/003 Astrostatistics
- FIZ/5/017 Chapters in modern astronomy and cosmology

Teaching activity in current semester

- **Physics Laboratory 2:** I served as the instructor for four experiments, conducting sessions once a week for four hours. I also corrected and graded the submitted reports.
- I provided teaching assistance to my supervisor in two courses:
  - **Introduction to Astronomy:** Corrected homework and exams.
  - **Cosmology:** Supervised the written exam.

References

Casado, J.; Ap&SS 365, 1, 16 (2020)
Di Valentino, E.; Astroparticle Physics 131, 102604 (2021)
Melia, F.; MNRAS 481, 4, 4855 (2018)
Perivolaropoulos L. & Skara, F.; New Astron. Rev. 95, 101659 (2022)
Rácz, G., et al.; MNRAS Letters 469, 1, L1 (2017)
Riess, A. G.; Nature Reviews Physics 2, 10 (2020)
Secrest et al.; ApJL 908, 2, L51, (2021)