Semester report

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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

While the current standard cosmological framework, the Lambda Cold Dark Matter (ΛCDM) model, aligns well with a broad range of observations, it relies on components and mechanisms – such as dark matter, dark energy and cosmic inflation – that are not yet fully understood. Despite its success, ΛCDM continues to face several unresolved challenges, including tensions between early- and late-universe measurements, such as the Hubble-tension (Riess 2020) and the S_8-tension (Di Valentino 2021), as well as anomalies like the cosmic dipole (Secrest 2021). Additional persistent discrepancies (Casado 2020, Perivolaropoulos & Skara 2022) further indicate that refinements to the current paradigm may be required.

Exploring alternative cosmological models, including coasting cosmologies or the AvERA model developed by ELTE researchers (Rácz et al. 2017), offers promising avenues to address these theoretical issues. Coasting cosmologies, in particular, bypass several of ΛCDM's open problems without invoking dark matter or dark energy, yet still show impressive consistency with observational datasets used to test cosmological theories (Melia 2018).

Description of research work carried out in current semester

During this semester, my research was primarily dedicated to building a robust, fully Bayesian framework for cosmological model fitting and comparison, using the `Python` package `dynesty`, which implements the dynamic nested sampling algorithm. I studied the theoretical underpinnings of Bayesian inference, with a focus on the advantages of nested sampling in model selection and evidence calculation. This included understanding how Bayesian evidence can be used to objectively compare competing cosmological models, especially when evaluating non-standard scenarios that differ in their complexity or number of parameters.

Using this knowledge, I replaced our previously developed MCMC-based fitting code with a new implementation based on `dynesty`. I applied this framework to fit both the AvERA cosmologies and the standard flat ΛCDM model to the most recent Cosmic Chronometer (CC) and Type Ia Supernova (SNIa) datasets. The code was written to be modular, efficient, and well-documented, facilitating future extensions or reuse. The analysis pipeline allows for direct model comparison based on Bayesian evidence and provides parameter posteriors for the cosmological scenarios.

I am the first author of a publication presenting these results, which is now finalized and will be submitted to *Astronomy & Astrophysics* in the coming days. The H_0 value of the AvERA model – obtained from our SNIa fit – was included in the *CosmoVerse White Paper*, to which I contributed as a co-author.

In parallel, I continued developing the foundations for another key research direction: measuring the cosmic dipole using gravitational-wave signals from compact binary mergers. The work involves both simulations and, in later phases, the application to real gravitational-wave detections. I will lead the resulting publication as first author.

As a member of the LIGO Collaboration since January, I began learning how to work with the LIGO databases and the `gwcosmo` `Python` package. This preparatory work forms a critical basis for conducting the cosmic dipole analysis and integrating it with observational gravitational-wave data.

In addition, together with Gergő Dálya, we were awarded a research grant through the NKFIH bilateral scientific and technological cooperation program (NKFIH Kétoldalú tudományos és technológiai együttműködés támogatása, 2024-1.2.5-TÉT). The project, titled "New approaches to improve dark siren Hubble constant estimations," received 4,000,000 HUF in funding for the 2025–2026 period. The grant supports collaborative research with a French group and will fund, among other things, my research visit to Toulouse during the fall semester. The aim of the project is to develop a theoretical framework for incorporating galaxy-cluster catalogues into gravitational-wave cosmology. I have already familiarized myself with the project's scientific goals, and we have established a concrete work plan for the coming year.

Publications

I am the first author of the following article, which is currently being prepared for submission to *Astronomy & Astrophysics*:
Pataki, A., Raffai, P., Csabai, I., Rácz, G., and Szapudi, I. *" Constraints on AvERA Cosmologies from Cosmic Chronometers and Type Ia Supernovae"*
Code repository: Zenodo - 15478706

I am the co-author of the CosmoVerse White Paper, submitted to arXiv in April 2025:
Di Valentino, E., Said, J. L., Riess, A., ... Pataki, A., ... *„The CosmoVerse White Paper: Addressing observational tensions in cosmology with systematics and fundamental physics"*
DOI: 10.48550/arXiv.2504.01669

Studies in current semester

- FIZ/5/004 Astrostatistics II.
- FIZ/5/040 Exoplanets

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 for the **Astrophysics** course taught to Physics BSc students. My role involved assisting with the correction of written exams.

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)