DOCTORAL SCHOOL OF PHYSICS - EÖTVÖS LORÁND UNIVERSITY (ELTE)

MAPPING THE COSMIC WEB: FROM SIMULATIONS TO THE DEEPEST GALAXY SURVEYS

SEMESTER REPORT

BY

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Abstract

I started the third semester by attending a short-term (30-day) Erasmus program at CPPM Marseille in September which helped me to engage with experts in my field and build new collaborations. This semester, I also took one course, "New Results in Machine Learning," which I successfully completed with an "Excellent" grade. In addition, I was honored to receive the EGYETEMI KUTATÓI ÖSZTÖNDÍJ PROGRAM (EKÖP) scholarship and to become a member of the Euclid Consortium Early Career Committee (ECC), marking important steps in my professional development both in scientific aspects and management roles this semester.

Introduction

The main objective of my PhD proposal within the Lendület Large-Scale Structure research group, led by Dr. András Kovács, is to analyze data from galaxy and quasar surveys and explore their cross-correlations with the cosmic microwave background (CMB). To advance this objective and lay the groundwork for my PhD proposal, I dedicated the third semester to working with the pyGenISW tool and the Gower Street Simulation suite.

The Gower Street simulation suite consists of 791 full-sky dark matter simulations. These simulations explore a range of cosmological parameters, including variations in the dark energy equation of state parameter, w. The Gower Street simulations use a box size of $L = 1250h^{-1}Mpc$ and a particle count of $N = 1080$. Each simulation generates 100 lightcone files, evenly spaced in proper time between the initial redshift $z_0 = 49$ Jeffrey et al., 2025.

The pyGenISW tool estimates the ISW effect by combining large-scale structure simulations with linear theory to map the distribution of matter in the Universe. Using the density contrast map from a simulation's lightcones, pyGenISW projects the gravitational potential temporal derivative onto the sky using spherical Bessel functions. The output is a map of ISW temperature anisotropies Naidoo et al., 2021.

Methods

In Kovács et al., 2020, the authors studied the ISW effect induced by cosmic voids for the AvERA model. The general approach and their methodology are based on the principle that, since the ISW signal from a single void is weak, stacking ISW maps centered on multiple voids improves the signal-to-noise ratio. By studying how the ISW effect correlates with void properties, their method provides insight into the nature of dark energy models and large-scale structure formation.

With a similar approach in mind, I am currently working on the ISW maps derived from the Gower Street simulations as part of a collaborative effort with my colleague, Barbara Matećsa, who is investigating the voids within the same simulation.

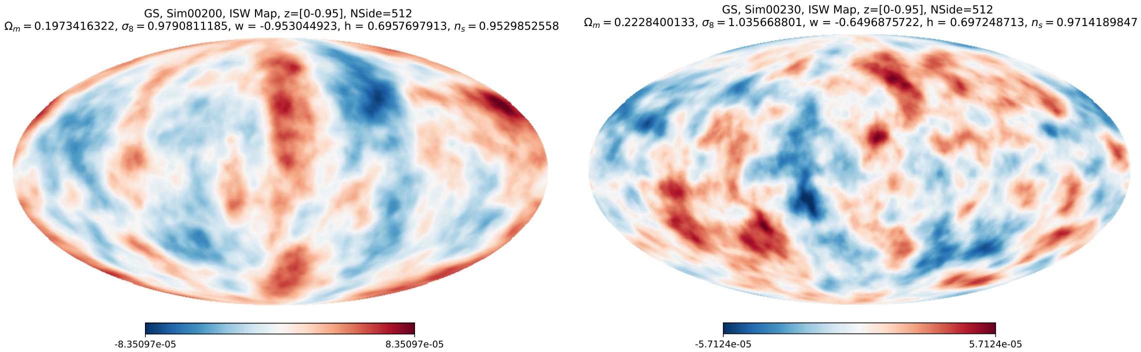

Figure 1: *Here are two examples of ISW maps that were produced using the Gower Street simulations. Our primary objective is to develop the ISW for each of the 791 simulations and study their correlations to voids in the same scenarios.*

Other Scientific Projects

Euclid CLOE and Void Integration

Following my short-term Erasmus program at CPPM, Marseille, under the supervision of Prof. Alice Pisani, I embarked on a new project that I am continuing to work on. Visiting international institutes is an important part of a researcher's career, and this chance led to a new collaboration. This project involves contributing to the CLOE (Cosmology Likelihood for Observables in Euclid) framework, a Python-based code designed to compute theoretical predictions for cosmological observables and evaluate them against data from Euclid surveys.

CLOE interfaces with parameter-sampling platforms like COBAYA and COSMOSIS, as well as Boltzmann solvers such as CAMB and CLASS. Using the linear matter power spectrum as input, CLOE computes the likelihood for Euclid's analysis setup. The current (yet unpublished) version of CLOE includes modules for CMB cross-correlations, non-linear effects, spectroscopic galaxy clustering, and cluster lensing profiles—capabilities that correspond to various scientific working groups within the Euclid consortium.

Given the increasing importance of cosmic voids in Euclid's scientific agenda, Prof. Pisani proposed integrating void-related analyses into CLOE to enhance its comprehensiveness. My primary task is to develop and implement void modules within CLOE. While this comes with challenges—particularly since CLOE is not fully published or complete—it presents an invaluable opportunity to deepen my understanding of void physics and develop expertise in managing large-scale, complex cosmological software.

This project began during my stay in Marseille, where I reviewed relevant literature on both void physics and CLOE's structure. I delivered two presentations at the Voids@CPPM biweekly meetings, where I discussed progress and initial findings. I continue to hold regular meetings with Prof. Pisani, where I report progress and ask technical questions. This project also led to my involvement in a key project within the Euclid Consortium, titled "*Cosmology with Cosmic Voids.*"

Recently, I presented this work as a lightning talk at the Euclid Galaxy Clustering meeting held from January 20–24, 2025, at MPE, Garching. This opportunity allowed me to share my

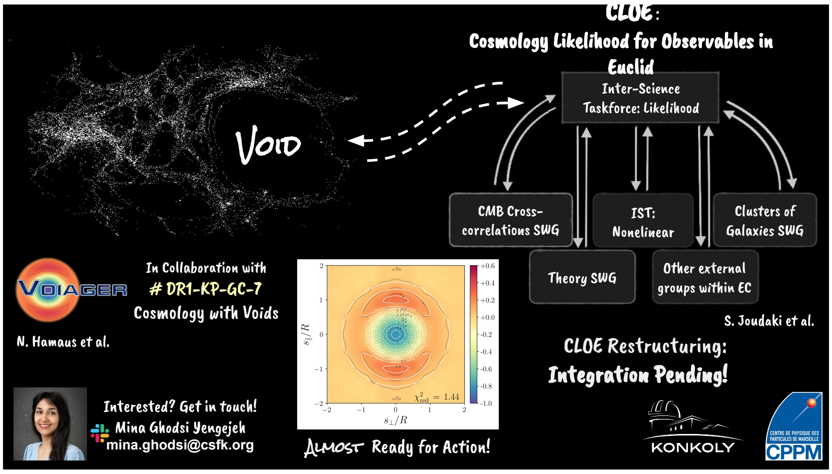

Figure 2: *Slide from my lightning talk at the Euclid Galaxy Clustering meeting, MPE, Garching, Munich (January 2025).*

ongoing research with the broader Euclid community and gather feedback.

EKÖP Scholarship Project

Under the EKÖP scholarship and the supervision of Dr. Sándor Frey, I am working on a project titled "*Revisiting the Angular Size–Redshift Relation of Compact Radio-Loud Active Galactic Nuclei as a Cosmological Test*." This project explores the use of the angular sizes of compact radio-loud active galactic nuclei (AGN) as standard rods to constrain cosmological parameters. By analyzing the relationship between the angular size (θ) of compact radio sources and their redshift (z), we aim to extract information about the Universe's expansion history.

Over 25 years ago, Gurvits et al., 1999 compiled the most comprehensive dataset available at the time, consisting of 330 Very Long Baseline Interferometry (VLBI)-imaged AGN. Today, the critical question is whether the observed angular size–redshift relation of compact (milliarcsecond-scale) radio structures can reliably constrain parameters of the ΛCDM cosmological model, independently of other observational methods. With advancements in VLBI and modern statistical techniques, we are now better positioned to overcome challenges such as astrophysical effects and the intrinsic evolution of these sources, enabling more precise measurements.

This project officially launched in September, while my work accelerated after my Erasmus program in October. It has evolved into a larger, international collaboration, involving the original authors who proposed this method, as well as a new generation of researchers from Russia and the USA. I developed Python codes to implement Markov Chain Monte Carlo (MCMC) methods, integrating the known physics of these objects and utilizing data provided by collaborators. The preliminary results are promising, producing reasonable outputs and convincing trends. Additionally, I restudied the Gurvits et al., 1999 analysis using a completely new approach in cosmological modeling and χ^2 calculation. The results closely match the original findings but with significantly improved error bars, which is an encouraging development.

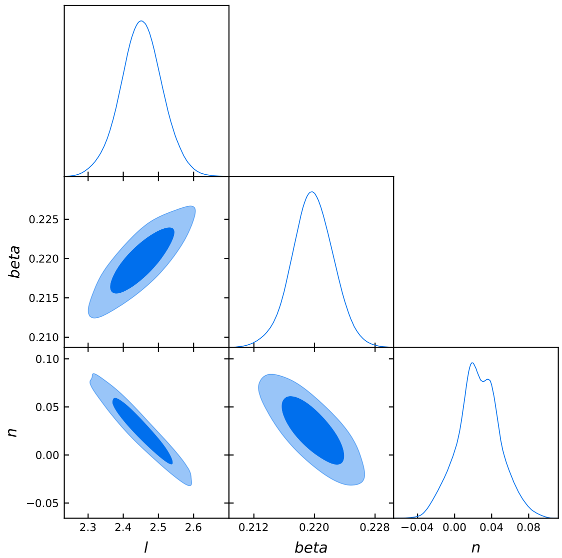

Figure 3: *Constraints on compact source parameters obtained from the analysis of 4000 data points, assuming cosmological parameters inferred from Planck 2018 data.*

To advance further, we are currently refining the dataset to address duplicate data and improve consistency in parameter estimation. This work is ongoing, and we have regular monthly meetings with collaborators to discuss progress, challenges, and next steps.

Management Roles within the Euclid Consortium

In addition to my scientific endeavors within the Euclid Consortium, I have taken on two volunteer management roles, serving on the Euclid Consortium Diversity Committee (ECDC) and the Early Career Committee (ECC). These roles reflect my commitment to contributing to the organizational and collaborative aspects of large-scale international projects.

Euclid Consortium Diversity Committee

As a member of the ECDC, I participate in ensuring diversity, equity, and inclusion within the Euclid Consortium. The committee plays a crucial role in decision-making processes, including the selection of new project leaders, organizing conferences and seminars, and approving public documents. Additionally, the ECDC is responsible for mediating and resolving any interpersonal or professional issues among consortium members, fostering a respectful and collaborative environment. This position requires regular participation in meetings, as well as handling offline tasks to maintain the integrity and inclusivity of the consortium.

Early Career Committee

Through my role on the ECC, I contribute to initiatives aimed at supporting early-career researchers (ECRs) in both the short and long term. The committee focuses on creating opportunities for ECRs to present their work, participate in conferences, and gain access to resources essential for professional development. Specific activities include facilitating fee waivers for conference attendance, organizing $Q\&A$ sessions on career development, and providing guidance on applications for grants, fellowships, and positions both inside and outside academia. These efforts are designed to ensure that ECRs in the consortium are well-equipped to succeed in their chosen career paths.

This role involves regular meetings and collaborative efforts, alongside independent tasks to implement various initiatives. My participation in these committees has not only allowed me to contribute to the broader goals of the consortium but has also provided insight into the operational aspects of managing an international scientific collaboration.

Proposals

During this semester, I also contributed to the preparation of the COST (European Cooperation in Science and Technology) Action proposal, "EuclidMap," led by Dr. András Kovács, where I was listed as a secondary proposer. COST Actions are funding programs that support interdisciplinary research networks across Europe, fostering collaboration among researchers. This proposal brought together scientists from eight different countries, providing me with an invaluable opportunity for international communication. My role involved reviewing the document, suggesting short passages, and assisting with the creation and formatting of references. This experience provided valuable insights into proposal writing and the collaborative process behind large-scale international research initiatives.

Publications

In preparation Cosmological aspects of Omnipotent Dark Energy and Λ_sCDM model
In preparation The CosmoVerse White Paper (https://cosmoversetensions.eu/)
In preparation Cosmology with cosmic voids
In preparation Revisiting the angular size-redshift relation of compact radio-loud active galactic nuclei as a cosmological test

Talks

- "*CLOE (Cosmology Likelihood for Observables in Euclid)*,
  Voids@CPPM, September 17, 2024
  CPPM, Marseille, France.
- "*Integration Void into CLOE*,
  Euclid Galaxy Clustering Meeting, Jan 23, 2025
  MPE, Garching, Germany.

Schools, Conferences, Seminars, and Scientific meetings

- Galaxy Clustering telecons, (Online)
- Void Cosmology telecons, (Online)
- WEAVE-QSO telecons, (Online)
- CosmoVerse Seminars, (Online)
- Konkoly Observatory Seminars
- Ortvay Seminar

Courses

- New Results in Machine Learning, FIZ/3/092

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Gurvits, L. I., K. I. Kellermann, and S. Frey (Feb. 1999). “The “angular size - redshift” relation for compact radio structures in quasars and radio galaxies”. In: 342, pp. 378–388. DOI: 10.48550/arXiv.astro-ph/9812018. arXiv: astro-ph/9812018 [astro-ph].

Jeffrey, N. et al. (2025). “Dark Energy Survey Year 3 results: likelihood-free, simulation-based wCDM inference with neural compression of weak-lensing map statistics”. In: *Mon. Not. Roy. Astron. Soc.* 536.2, pp. 1303–1322. DOI: 10.1093/mnras/stae2629. arXiv: 2403.02314 [astro-ph.CO].

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Naidoo, Krishna et al. (2021). “Full-sky integrated Sachs–Wolfe maps for the MICE grand challenge lightcone simulation”. In: *Mon. Not. Roy. Astron. Soc.* 506.3, pp. 4344–4353. DOI: 10.1093/mnras/stab1962. arXiv: 2103.14654 [astro-ph.CO].