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

During my first semester, I was actively involved in three courses where I had to give presentations and complete projects. This helped me to develop my practical skills and foundational knowledge, and I achieved an "Excellent" score in all of them. I regularly met with my supervisors to discuss research ideas and methodologies. Furthermore, through collaborative efforts with an international research group, we successfully authored and had a paper accepted by the "*Physics of the Dark Universe*" journal. My active participation in coursework, mentorship, and scholarly forums laid the foundation for my research journey.

## Introduction

As a Ph.D. student, I became a member of the Lendület Large-Scale Structure research group led by Dr. Andras Kovacs. The primary objectives include performing cosmic web analyses of state-of-the-art galaxy and quasar survey data sets and their cross-correlations with cosmic microwave background (CMB) anisotropy maps. In the long term, the research group also aims to characterize gravitational lensing, the Integrated Sachs-Wolfe (ISW) effect, and the thermal Sunyaev-Zeldovich (tSZ) effect.

In the journey from the last scattering surface to us, CMB photons move through gravitational potential wells, like the galaxy clusters. When photons move into a gravitational potential well, they become blueshifted. On the other hand, they will be redshifted as they move out of the gravitational potential. In symmetrical gravitational potential wells, the blueshift and redshift can cancel each other. However, during the late-time epoch, the accelerated expansion of the Universe causes alterations in gravitational potentials, leading to a secondary effect on the CMB photons known as the ISW effect (Fig. 1). Over approximately 13.5 billion years, these shifts accumulate along the observer's line of sight, potentially unveiling late-time Universe phenomenological aspects Sachs et al., 1967; Schaefer, 2008; Planck Collaboration et al., 2016.

## Methods

Initiating this project, I commenced working with cosmological packages—an integral component in the realm of observational cosmology due to the vast and diverse nature of the high volume and variety of datasets. In anticipation of forthcoming data from state-of-the-art surveys like Euclid and LSST, I began generating full-sky maps depicting the ISW effect. The density contrast used in the map is obtained from the WebSky halo catalog Stein et al., 2020. Employing the publicly available Python package, pyGenISW [1],

[1] https://github.com/knaidoo29/pyGenISW

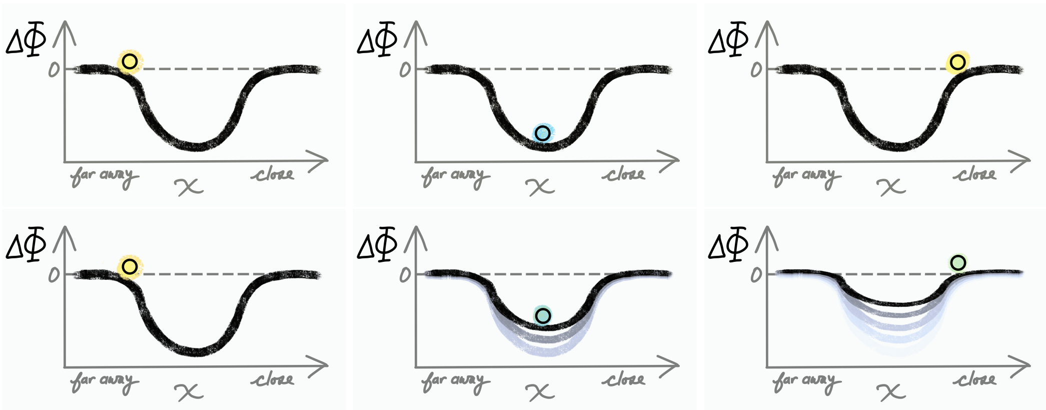


**Figure 1:** *In the matter-dominated era (***Top***), gravitational potentials remain static, whereas in the dark energy era (***Bottom***), evolving potentials induce asymmetry, leading to observable anisotropy in the cosmic microwave background (CMB). Credit: Jessie Muir*

I computed the ISW effect through the linear regime using spherical Bessel transforms (SBT), excluding the non-linear regime from smaller angular scales contributing to the Rees-Sciama effect (Fig. 2).

The significance of the SBT basis functions lies in their property as eigenfunctions of the Laplace operator within a ball-shaped domain. This characteristic makes them instrumental in various mathematical operations and signal analysis. This connection is significant because the Laplace operator in the Poisson equation links the gravitational potential (driving the evolution of gravitational potentials, resulting in the ISW effect) to overdensities (observable quantities) Naidoo et al., 2021.

The pyGenISW package relies on TheoryCL [2], a Python module computing theoretical auto- and cross-angular power spectra for the ISW effect. TheoryCL calculates the cross-correlation between CMB and large-scale structures with a specified redshift distribution. Additionally, pyGenISW necessitates the linear matter power spectrum for map generation, requiring the utilization of the Code for Anisotropies in the Microwave Background (CAMB) [3] to numerically compute the matter power spectrum within the standard model of cosmology or other alternative models.

Furthermore, this paper Camacho-Ciurana et al., 2023 was published under the guidance of my supervisors. Now, building upon this work, I have joined this group to extend the project by investigating not only the CMB lensing but also the tSZ signal of voids using simulations based on the concordance model of cosmology and data from the WISE-Pan-STARRS catalog. This initiative offers a unique opportunity to probe the intricate gas physics within cosmic voids, thereby complementing the previous research.

[2] https://github.com/knaidoo29/TheoryCL
[3] https://camb.readthedocs.io/en/latest/index.html

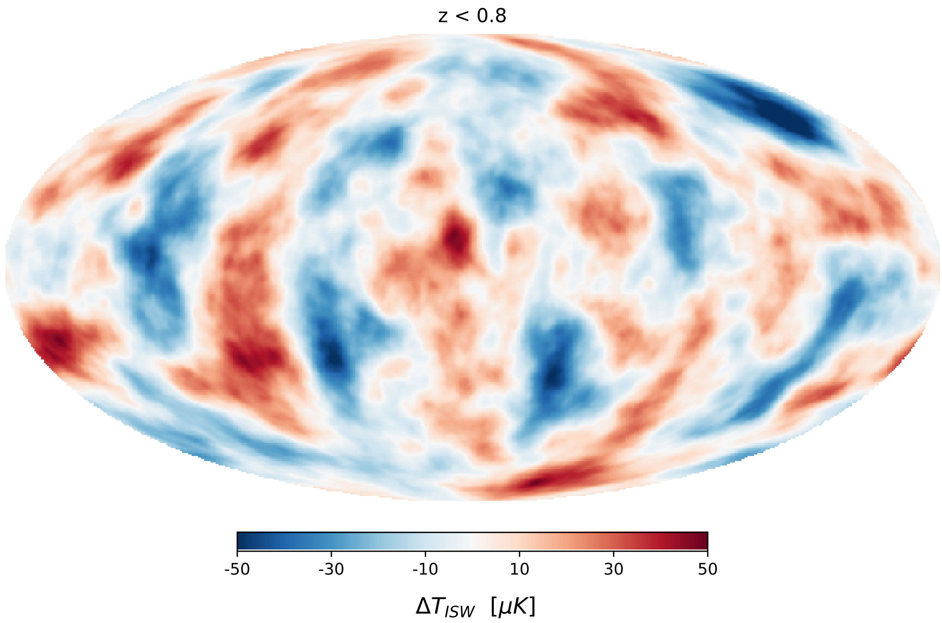


**Figure 2:** *The ISW effect for the WebSky Extragalactic CMB Mocks, constructed for contributions within the range of* $z \leq 0.8$ *utilizing an SBT with normal boundary conditions.*

# Publications

**A New Binning Method to Choose a Standard Set of Quasars**,"
M. G. Dainotti, A. L. Lenart, M. Godsi Yengejeh, S. Chakraborty, N. Fraija, E. Di Valentino, G. Montani
**Journal:** DOI: 10.1016/j.dark.2024.101428
**Preprint:** `arXiv:` 2401.12847

# Courses

- Solar System plasma physics, FIZ/5/055
- (Exo)planetary atmospheres seminar I., FIZ/5/043
- Radio astronomy I., FIZ/5/009

# Conferences

- WEAVE-QSO Meeting, 5-7th Dec, 2023, Paris, France (Online).
- CosmoVerse Seminars (Online).
- Weekly Seminars, Konkoly Observatory
- Ortvay Seminar
- Budapest Science Meetup

**Figure 3: Left:** *We donned Halloween costumes at the Svabhegy Observatory Halloween event, adding a dash of fun to the cosmic festivity.* **Right:** *Dr. Andras Kovacs skillfully navigating the space-time trampoline to explain the mysteries of the Universe on a large scale.*

## Further Activities

During my first semester, I joined the WEAVE-QSO survey, of which my supervisor is also a member. Starting in mid-2024, this project will delve into cosmic structures and intergalactic medium properties through advanced spectroscopic techniques Pieri et al., 2016.

Additionally, I undertook a short task to learn about the visual inspection of quasar spectra within optical spectroscopic data for the survey validation of the Dark Energy Spectroscopic Instrument (DESI) Alexander et al., 2023. This experience provided me with valuable hands-on experience, further enriching my expertise in the field.

Meanwhile, regular meetings with my supervisors and interactions with short-term visitors and graduate and undergraduate students at both ELTE and the Konkoly Observatory provided valuable opportunities for brainstorming and idea-sharing. These sessions facilitated interdisciplinary dialogue and set the stage for potential international collaborations, enhancing my academic journey.

Besides, at the Svabhegy Observatory Halloween event, I assisted in preparing for the outreach session where my supervisor explained the Universe's large-scale structure. Together, we brainstormed creative ways to simplify concepts like dark matter and dark energy, using the space-time trampoline analogy to make these ideas accessible and engaging for the audience Fig. 3.

# Bibliography


Alexander, David M. et al. (Feb. 2023). "The DESI Survey Validation: Results from Visual Inspection of the Quasar Survey Spectra". In: *The Astronomical Journal* 165.3, p. 124. ISSN: 1538-3881. DOI: 10.3847/1538-3881/acacfc. URL: http://dx.doi.org/10.3847/1538-3881/acacfc.

Camacho-Ciurana, G. et al. (Dec. 2023). "The CMB lensing imprint of cosmic voids detected in the WISE-Pan-STARRS luminous red galaxy catalog". In: arXiv: 2312.08483 [astro-ph.CO].

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Pieri, M. M. et al. (2016). *WEAVE-QSO: A Massive Intergalactic Medium Survey for the William Herschel Telescope*. arXiv: 1611.09388 [astro-ph.CO].

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Sachs, R. K. and A. M. Wolfe (Jan. 1967). "Perturbations of a Cosmological Model and Angular Variations of the Microwave Background". In: 147, p. 73. DOI: 10.1086/148982.

Schaefer, Bjoern Malte (2008). "The integrated Sachs-Wolfe effect in cosmologies with coupled dark matter and dark energy". In: *Mon. Not. Roy. Astron. Soc.* 388, pp. 1403–1408. DOI: 10.1111/j.1365-2966.2008.13521.x. arXiv: 0803.2239 [astro-ph].

Stein, George et al. (Oct. 2020). "The Websky extragalactic CMB simulations". In: *Journal of Cosmology and Astroparticle Physics* 2020.10, pp. 012–012. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2020/10/012. URL: http://dx.doi.org/10.1088/1475-7516/2020/10/012.