Doctoral School of Physics - Eötvös Loránd University (ELTE)

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

4th Semester Report

By

Mina Ghodsi Yengejeh

Email: mina.ghodsi @ csfk.org

Supervisors

Andras Kovacs, PhD
Email: kovacs.andras @ csfk.org

Istvan Csabai, PhD
Email: csabai @ elte.hu

Budapest, May 2025

Introduction

Understanding the large-scale structure of the Universe and its evolution remains a central objective in modern cosmology. One of the most powerful observational probes in this context is the Cosmic Microwave Background (CMB), which retains signatures from both the early Universe and its subsequent evolution. As CMB photons travel through the large-scale structure of the Universe, they experience secondary anisotropies, including the Integrated Sachs-Wolfe (ISW) effect, gravitational lensing, and the thermal Sunyaev-Zeldovich (tSZ) effect. These effects are sensitive to the geometry, expansion history, and energy content of the Universe, thereby providing key observational constraints on dark energy and alternative cosmological scenarios.

The ISW effect is particularly sensitive to the expansion history of the Universe and thus provides an important probe of dark energy and late-time cosmic acceleration. However, detecting the ISW effect directly is challenging due to its subtle imprint on the CMB. To enhance the signal-to-noise ratio, cross-correlation techniques are applied using large-scale structure data, such as galaxy surveys and cosmic void catalogs. Cosmic voids—vast underdense regions in the Universe—are of special interest because they can produce a measurable ISW imprint that is distinct from overdense structures.

My research, conducted within the Lendület Large-Scale Structure group led by Dr. András Kovács, aims to probe these phenomena using state-of-the-art cosmological simulations and cross-correlations between galaxy/quasar surveys and CMB data. A core focus is the study of the ISW effect and its correlation with cosmic voids, supported by the use of publicly available tools (e.g., pyGenISW and Core Cosmology Library) and large simulation suites (e.g., AbacusSummit, Gower Street, EuclidLargeMocks). Through this work, we aim to shed light on the nature of dark energy and improve our understanding of the late-time Universe.

Summary of research work carried out in the previous three semesters

Over the past three semesters, I have focused on theoretical, computational, and simulation-based studies of the ISW effect and its connection to cosmic voids.

Semester 1: I began by building foundational skills through coursework and hands-on experience with cosmological tools. I used the publicly available pyGenISW package to generate full-sky ISW maps based on the WebSky halo catalog, applying spherical Bessel transforms in the linear regime. This involved computing the ISW temperature anisotropies using theoretical matter power spectra from CAMB and cross-correlation functions from TheoryCL.

Semester 2: I expanded my simulation-based work using the AbacusSummit suite, which includes high-resolution N-body simulations suitable for analyzing galaxy clustering and large-scale structure. I studied the spatial distribution of halos, generated two-dimensional density maps, and computed the two-point correlation function (2PCF) to analyze the clustering features and extract the Baryon Acoustic Oscillation (BAO) signal. These methods provided a baseline for understanding matter distribution, which is essential for correlating structure with the ISW effect.

Semester 3: This semester, I focused on generating ISW maps using the Gower Street simulation suite, which consists of 791 full-sky dark matter simulations. Each simulation contains 100 lightcone slices that trace the evolution of matter over cosmic time. Using pyGenISW, I processed these lightcone density contrasts to produce ISW temperature maps for each simulation. This work is conducted in collaboration with my colleague Barbara Matécsa, who is analyzing the void catalogs in the same simulations. Together, we aim to study the correlation between voids and the ISW signal, using a stacking technique to enhance detectability, following methodologies from Kovács et al., 2020.

Description of research work carried out in the current semester

Building on the foundations laid in previous semesters, my research this term focused on computing and analyzing the cross-power spectra between ISW maps and density maps derived from large-scale structure simulations. Specifically, I focused on the Gower Street simulation suite, which includes 791 individual lightcone simulations, each based on a distinct set of cosmological parameters within the wCDM framework. These parameters—Ω_m, σ_8, h, ω, Ω_b, and n_s—are critical inputs for calculating the theoretical matter power spectrum and comoving distances, both of which directly influence the shape and amplitude of the ISW auto/cross-power spectrum.

One of the main challenges was ensuring that the cross-power spectra derived from different methods were consistent with theoretical expectations. On the theoretical side, I used two public cosmology packages—TheoryCL and the Core Cosmology Library (CCL)—to compute reference curves for the expected ISW cross-power spectra. These predictions were then compared to spectra obtained through a more observationally motivated pipeline using pyGenISW, which constructs ISW maps directly from the lightcone density contrast fields.

A key component of this analysis involved testing different binning strategies for the lightcones. Two pyGenISW-based approaches were implemented: one using narrow redshift slices, and another combining them into thicker $\Delta z \simeq 0.1$. Although narrow slicing offers finer redshift resolution, it can introduce additional noise into the reconstructed ISW signal. Further investigation is needed to determine the optimal trade-off between resolution and noise.

To create the LSS density maps, halo count maps were generated from each simulation's lightcone data. These density maps were then used in conjunction with the ISW maps—produced with the pyGenISW package—to compute the cross-power spectra. These spectra were compared against theoretical predictions to ensure internal consistency. A significant challenge in this process was managing and processing the large volume of data: 791 simulations, each approximately 3 GB in size, resulting in substantial computational and storage demands. To address this, I applied for and obtained a 6-month access grant to the

HUN-REN Cloud infrastructure, where I currently run my analysis on a virtual machine equipped with 32 GB of RAM and 8 virtual CPUs (vCPUs) for parallel computation and 1 TB of storage volume.

Figure 1, left panel, presents the cross-power spectrum $D_\ell^{ISW-halo}[\mu K]$ as a function of multipole moment ℓ, comparing theoretical predictions with simulated data. The dash-dot red curve shows the prediction obtained using TheoryCL, while the dashed blue curve represents the corresponding result from CCL. The solid black line depicts the cross-spectrum derived from simulated halo and ISW maps generated using pyGenISW. The middle panel illustrates the ratio of the simulated data to the TheoryCL prediction, and the bottom panel shows the ratio with respect to the CCL prediction. These ratio plots emphasize the level of agreement and highlight scale-dependent deviations between the simulations and theoretical models. At large angular scales (low ℓ), the predictions from TheoryCL exhibit notable deviations from the simulated data, suggesting that CCL provides a more accurate description of the ISW–halo cross-correlation in this regime. An additional advantage of using CCL lies in its flexibility: it supports a broader class of cosmological models, including wCDM and CPL parameterizations, thereby enabling more realistic and comprehensive investigations. In contrast, TheoryCL is currently limited to the baseline ΛCDM framework, which restricts its applicability in studies involving extended cosmological scenarios.

In parallel, we investigated two distinct strategies for constructing the ISW signal using pyGenISW: one based on finely sampled lightcones composed of narrow redshift slices, and another using coarser lightcones formed by merging adjacent slices. The resulting cross-power spectra, shown in the right panel of Figure 1, reveal similar overall trends, though with subtle differences in amplitude. The solid black line, corresponding to the finely sliced lightcone, exhibits a slightly higher amplitude across most multipoles, indicating a more detailed reconstruction of the ISW signal. The dash-dot orange line represents the merged-slice approach and shows a modest suppression, particularly at intermediate angular scales. Both curves are obtained by cross-correlating the respective ISW maps with the density (halo) map. For comparison, the blue dashed curve shows the theoretical prediction from CCL for the same cosmological model. The lower panel presents the ratio of the pyGenISW-based spectra to the CCL prediction, further quantifying the differences and highlighting the sensitivity of the ISW–halo cross-correlation to the choice of lightcone resolution.

In Figure 2, we present the cross-power spectra $D_\ell^{ISW-halo}[\mu K]$ comparing the ISW signal reconstructed with pyGenISW to theoretical predictions from CCL. The solid lines represent spectra derived from finely sliced lightcones cross-correlated with the halo density map, while the dashed lines show the corresponding theoretical prediction from CCL. The bottom panel shows the ratio of the pyGenISW-based spectra to the CCL expectation, emphasizing the effect of lightcone resolution on the ISW signal recovery. The curves are color-coded by the value of Ω_m, illustrating how matter density influences the ISW–halo correlation across simulations. The cosmological parameters for these simulations are listed in Table 1.

Overall, this semester's work has been dedicated to refining the cross-correlation methodology, validating theoretical models against simulated data, and preparing a robust frame-

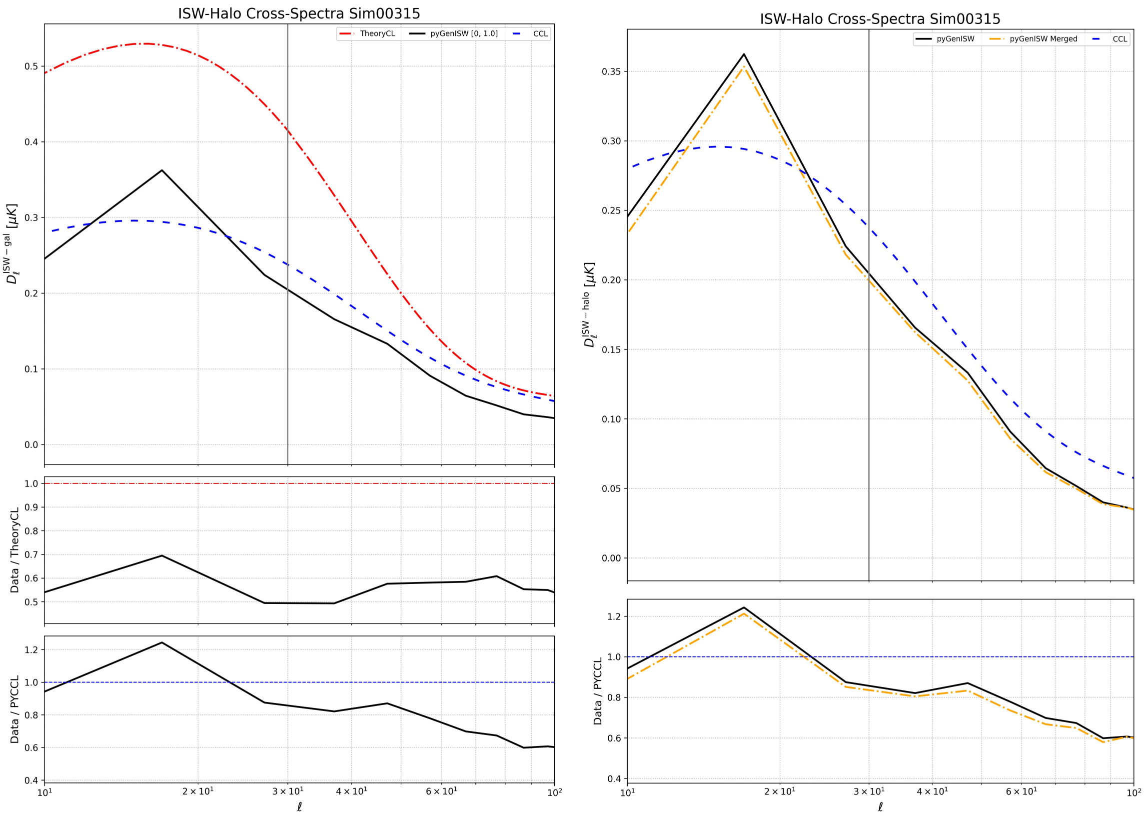

Figure 1: ***Left*** *Cross-power spectrum* $D_\ell^{ISW-halo}[\mu K]$ *as a function of multipole moment* ℓ*. The dash-dot red curve represents the theoretical prediction computed using TheoryCL, while the dashed blue curve corresponds to the prediction from CCL. The solid black line shows the cross-spectrum obtained from simulated data using the halo and ISW maps generated by pyGenISW. The middle panel displays the ratio of the data to the TheoryCL prediction (Data/TheoryCL), and the bottom panel shows the ratio of the data to the CCL prediction (Data/CCL), highlighting relative deviations across angular scales.* ***Right*** *Cross-power spectra* $D_\ell^{ISW-halo}[\mu K]$ *comparing two ISW reconstructions from pyGenISW: the solid black line uses finely sliced lightcones, while the dash-dot orange line uses merged, broader slices. Both are cross-correlated with the halo density map. The blue dashed curve shows the theoretical prediction from CCL. The lower panel displays the ratio of the pyGenISW-based spectra to the CCL prediction, highlighting the impact of lightcone resolution on the ISW signal.*

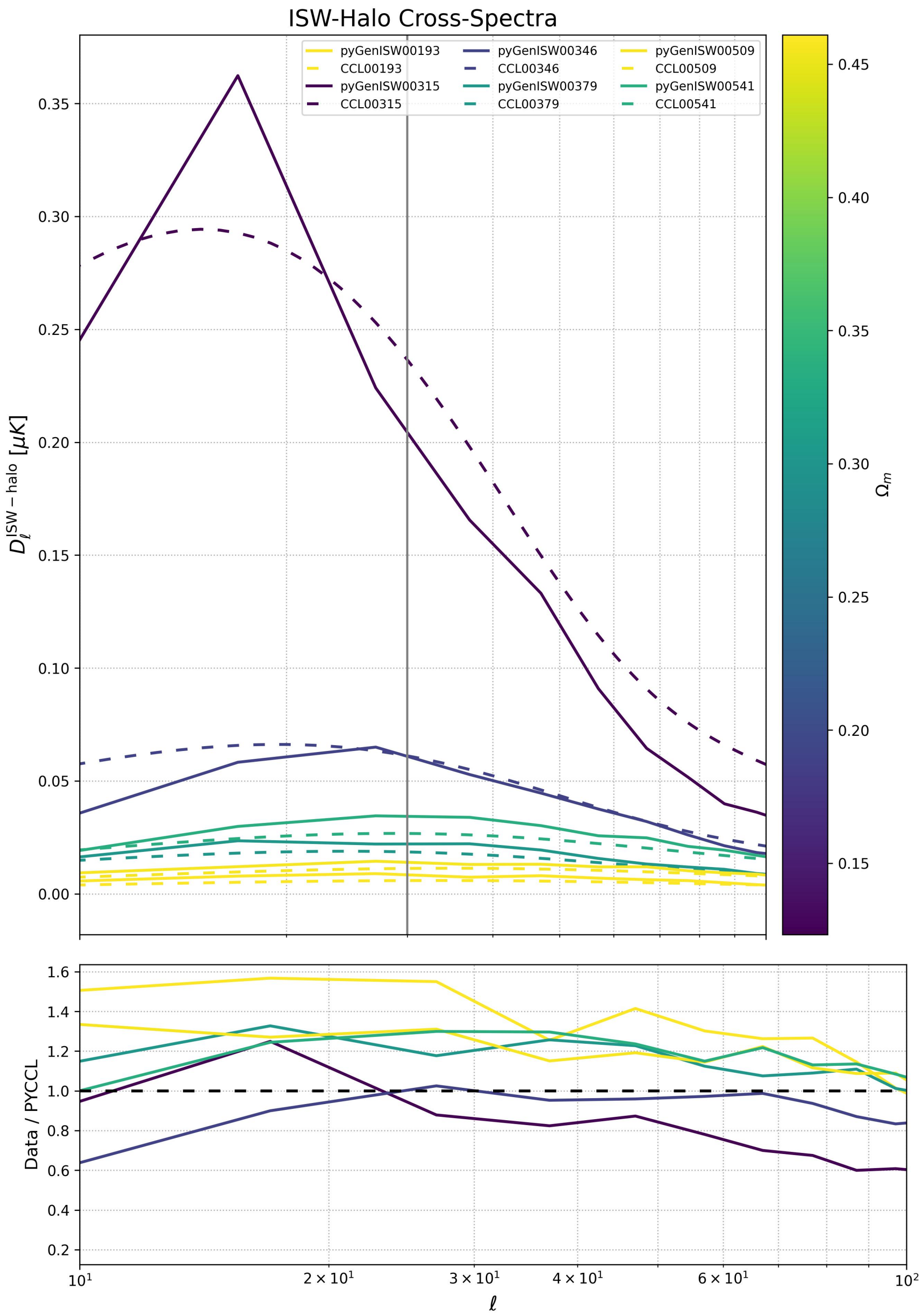

Figure 2: *Cross-power spectra $D_\ell^{ISW-halo}[\mu K]$ comparing ISW reconstructions from pyGenISW (solid lines) with theoretical predictions from CCL (dashed lines). The bottom panel shows the ratio of the reconstructed signal to the theory. Colors indicate Ω_m, highlighting its impact on the ISW signal and the role of lightcone resolution.*

Table 1: *Cosmological parameters from selected simulations.*

Simulation	Ω_m	σ_8	w	Ω_b	h	n_s	Ω_Λ
193	0.4610	0.4755	-1.0042	0.0467	0.6917	0.9644	0.4922
315	0.1232	1.1104	-1.0073	0.0420	0.7271	0.9715	0.8348
346	0.1905	0.7430	-0.9938	0.0437	0.7124	0.9656	0.7658
379	0.3026	0.5492	-0.9970	0.0505	0.6663	0.9607	0.6469
509	0.4571	0.6794	-1.0018	0.0429	0.7211	0.9685	0.5000
541	0.3364	0.7976	-0.9954	0.0415	0.7358	0.9706	0.6221

work for upcoming ISW–void stacking analyses.

The first paper, derived from my PhD proposal, titled ISW Maps from 791 wCDM Cosmologies: Methodology and Power Spectrum Validation (in preparation), focuses on generating ISW maps using the Gower Street simulation suite and the validation of the resulting cross-power spectra against theoretical predictions as mentioned above.

Building upon this foundation, the second planned paper will investigate the most extreme cold spots in the ISW maps across the 791 wCDM simulations. This study is motivated by the work of Kovács et al., 2020, who found that the observed coldest spot in the Planck CMB map could not be reproduced by any of the simulated ΛCDM realizations they analyzed, hinting at a possible tension with the standard cosmological model. By extending this analysis to a broader parameter space, the second paper aims to explore whether alternative dark energy models within the wCDM framework can offer a more consistent explanation for the anomalous cold spot, thereby providing further insights into the role of cosmological parameters in shaping secondary CMB anisotropies.

Other Scientific Projects

Euclid CLOE and Void Integration

As a continuation of the project initiated during my Erasmus stay at CPPM, Marseille, under the supervision of Dr. Alice Pisani, I am contributing to the development of void analysis modules within the CLOE framework—an internal Python-based likelihood code used by the Euclid Consortium. Following initial literature review, code exploration, and presentations at Voids@CPPM biweekly meetings, I have remained actively involved in the project. With the updated, more user-friendly version of CLOE now internally available via https://github.com/cloe-org, I have begun the implementation of void statistics, marking a key step toward integrating void cosmology into Euclid's analysis pipeline.

EKÖP Scholarship Project

This project, initiated under the guidance of Dr. Sándor Frey, revisits the angular size–redshift relation of compact radio-loud AGNs as a cosmological tool Gurvits et al., 1999, aiming to assess its viability for constraining cosmological parameters independently of more conventional probes. Building on the foundational dataset of VLBI-imaged AGNs compiled over two decades ago, we have incorporated new data and implemented modern statistical techniques, including MCMC-based parameter estimation, to reanalyze the relation in the context of the ΛCDM model.

A key development in our work is the use of different datasets derived from different methodologies to extract AGN core sizes. These datasets—based on varying definitions of "core size" and frequency regimes—allow us to approach the problem from distinct observational perspectives. This diversity has proven essential in identifying and characterizing potential sources of systematic uncertainty.

Our preliminary results reproduce the qualitative trends found in earlier work but with significantly improved error bars, owing to both refined data and more rigorous statistical treatment. However, our new preliminary analysis has revealed that the constraints on Ω_m, while statistically consistent, are potentially degenerate with astrophysical parameters that influence the observed angular size.

This degeneracy may arise because the angular size of compact sources does not solely depend on cosmological distances but is also shaped by underlying AGN physics that are not fully disentangled from redshift-dependent trends. This complicates the direct interpretation of the angular size–redshift relation as a clean cosmological probe. Therefore, part of our ongoing effort involves re-expressing the model equations to more carefully account for these astrophysical contributions and to better isolate the cosmological signal—particularly the sensitivity to Ω_m.

Management Roles within the Euclid Consortium

I am a member of two Euclid Consortium committees in volunteer management roles. These roles involve supporting equity, inclusion, and early-career development through organizing events, contributing to policy decisions, and facilitating professional opportunities. My work includes regular meetings and independent tasks, reflecting my commitment to the collaborative and structural goals of large-scale scientific projects.

Publications

Published

- *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: Physics of the Dark Universe, DOI: 10.1016/j.dark.2024.101428

Accepted

- *The CosmoVerse White Paper: Addressing observational tensions in cosmology with systematics and fundamental physics*
  E. Di Valentino et al.
  Accepted in: Physics of the Dark Universe
  Preprint: arXiv:2504.01669

In Preparation

- *ISW maps from 791 wCDM Cosmologies: Methodology and Power Spectrum Validation*
  (Expected submission: December 2025)
- *The coldest spots on the ISW maps in wCDM cosmologies*
  (Expected submission: Early 2026)
- *Cosmological Aspects of Omnipotent Dark Energy and Λ_sCDM Model*
  (Expected submission: August 2025)
- *Revisiting the Angular Size–Redshift Relation of Compact Radio-Loud Active Galactic Nuclei as a Cosmological Test*
  (Expected submission: August 2025)
- *Cosmology with Cosmic Voids* (As part of the Euclid Collaboration)

Conference and Seminar Participation with Presentations

- *"Revisiting the angular size-redshift relation of compact radio-loud AGN as a cosmological test"*,
  institutional EKÖP professional conference, August 29, 2025
  (virtual conference, Oral presentation)
- *"Searching for Cold Spots: ISW–Voids Cross-Analysis in wCDM Simulations"*,
  Cosmology from Home 2025, June 2025
  (virtual conference, Oral presentation)
- *"Revisiting the angular size-redshift relation of compact radio-loud AGN as a cosmological test"*,
  Konkoly Extragalactic Workshop, March 21, 2025, Budapest, Hungary
- *"ISW maps and stacked void signals using Gower St mocks"*,
  Voids@CPPM Workshop, February 25, 2025, Marseille, France
- *"Integration of Voids into CLOE"*,
  Euclid Galaxy Clustering Meeting, January 23, 2025, MPE, Garching, Germany
- *"CLOE (Cosmology Likelihood for Observables in Euclid)"*,
  Voids@CPPM, September 17, 2024, CPPM, Marseille, France
- *"A new binning method to choose a standard set of quasars"*,
  Konkoly Extragalactic Workshop, March 19, 2024, Budapest, Hungary

- *"The largest 3D map of our Universe and other interesting news"*,
  Pizza Seminars, April 30, 2024, ELTE, Budapest, Hungary

Conference and Seminar Participation

- *8th Institute of Space Sciences Summer School on Observational Cosmology*,
  July 7–18, 2025, Institute of Space Sciences (ICE/CSIC), Spain (Summer School)
- *CosmoVerse Workshop@Naples*,
  May 2025, Naples, Italy (Workshop)
- *CosmoVerse School: "From Fundamental Physics to Data Analysis in Cosmology"*,
  May 13–18, 2024, Corfu, Greece (Summer School)
- *Two 1-hour Webinar Tutorials on the Atacama Cosmology Telescope DR6*,
  April 18–19, 2024, Online (Tutorials)
- *Cosmology from Home 2024*,
  Online conference, Link (Conference)
- *WEAVE-QSO Meeting*,
  December 5–7, 2023, Paris, France (Online) (Meeting)

Teaching Activity

- **Seminar** : Data Mining in Astronomy Seminar (2024/25/2 term), 2 hours per week delivered, in collaboration with Dr. András Kovács and Prof. István Csabai.

Awards

- Awarded the **Stipendium Hungaricum** scholarship.
- Awarded the **Egyetemi Kutatói ÖsztÖndíj Program (EKÖP)** scholarship for the academic year **2024–2025**.
- Received a **COST Action grant** to attend CosmoVerseWorkshop@Naples, Naples, Italy, 21-23 May 2025.
- Received a **COST Action grant** to attend CosmoVerseSchool@Corfu, Corfu, Greece, 13 May - 18 May 2024.

Proposal

- Contributed as a secondary proposer to the COST Action proposal titled "*Mapping the Cosmos with the Euclid Space Telescope*", submitted in October 2024 for the 2025 call. The proposal was coordinated by Dr. András Kovács and involved collaborators from multiple European institutions.

Organizational Roles

- Serving as a member of the Scientific Organizing Committee (SOC) for the upcoming *DarkMap – Mapping the Dark Universe* conference, to be held September 1–5, 2025, in Budapest, Hungary.
- Co-organized *Early Career Workshop 9* (March 28, 2025), a two-part event featuring a panel discussion with astrophysicists from academia and industry, and a Q&A session with the Euclid Consortium Board Chair and Deputy.
- Co-organized the *Euclid Welcome Session* (22 November 2024), facilitating the integration of new members by presenting the consortium's structure, key projects, and collaboration opportunities.

Courses

- Exoplanetary Research, Fiz/5/04

Bibliography

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].

Kovács, András et al. (2020). “A common explanation of the Hubble tension and anomalous cold spots in the CMB”. In: *Mon. Not. Roy. Astron. Soc.* 499.1, pp. 320–333. DOI: 10.1093/mnras/staa2631. arXiv: 2004.02937 [astro-ph.CO].