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 second semester, I was actively involved in three courses where I had to give presentations and oral exams. 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're delving into two recently proposed cosmological models: rapid Universe transition from anti-de Sitter vacua to de Sitter vacua and non-monotonic energy densities. These models could alleviate the major cosmological tensions in modern cosmology. Moreover, winning the Stipendium Hungaricum scholarship, becoming a member of the Euclid Consortium and the Euclid Consortium Diversity Committee, participating in a summer school, winning Erasmus funding, and presenting at ELTE and Konkoly Observatory are some of my scientific activities this semester.

Introduction

The primary focus of my PhD proposal within the Lendület Large-Scale Structure research group led by Dr. Andras Kovacs involves examining data sets from galaxy and quasar surveys and their cross-correlations with the cosmic microwave background (CMB). Ultimately, our goal is to investigate other cosmological observables, including gravitational lensing, the integrated Sachs-Wolfe effect (ISW), and the thermal Sunyaev-Zeldovich (tSZ) effect.

Structure formation is the story that brings us from the initial conditions to the structure of the Universe, and it's a way to understand how our Universe works. The CMB fluctuations are the seeds for structure formation, which is where all our halos and galaxies come from. These fluctuations grow due to gravity; underdense regions lose matter, while overdense regions absorb more matter. As long as these perturbations are small (density contrast is smaller than unity), we can use a powerful tool called linear perturbation theory to describe how these perturbations grow. But when they get bigger than unity, it would be impossible to study them analytically. That's a reason why we need simulations to study non-linear physics.

Abacus is a highly efficient N-body code for cosmological simulations, capable of calculating over 100 billion pairwise force interactions per second on a single node Garrison et al., 2018. In 2020, Abacus was used to produce a new, larger set of simulations called AbacusSummit.

Methods

The halo occupation distribution (HOD) is a widely used model for analyzing galaxy surveys. Its empirical and flexible nature connects N-body simulations to galaxy clustering.

I used a subsample of halo particles, which has a box size L = 2000 Mpc/h with N = 2304^3 particles from the AbacusSummit suite. This file contains information on the central mass of around 17 million halos ([x, y, z] positions from -1000 to +1000 Mpc/h) and the number of particles. We can plot the halo field based on (x, y) positions of halos. Figure (1) displays a 2D histogram of the halo field, with the central mass of the halo positioned in (x, y), which seems like a Gaussian random field because we're looking into Gpc scales [2Gpc, 2Gpc]. In this scale, the variance of the density is small, so it looks like initial conditions.

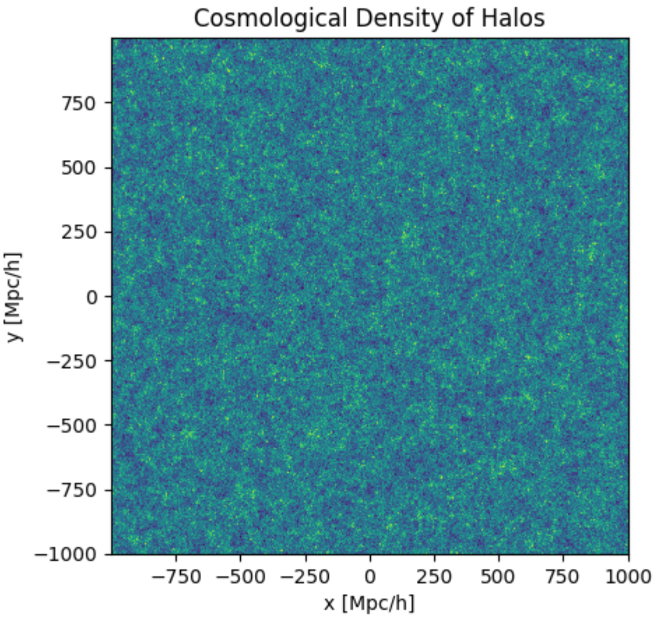

Figure 1: *The 2D histogram of the halo field at Gpc scales [2Gpc, 2Gpc]. It appears to resemble a Gaussian random field. This is because, at this scale, the density variance is small, giving the impression of initial conditions.*

The 2D histogram can be visualized with a 20 and 40 Mpc/h deep slice as well. This is shown in Fig. (2), where you can see the shape of the cosmic web more clearly.

For a Gaussian random field, the two-point correlation function (2PCF) completely describes its characteristics. It's used to measure galaxy clustering at different scales and can make the Baryon Acoustic Oscillation (BAO) peak visible, as you can see in Fig. (3). In this plot, we calculate the mass of each halo by multiplying the number of particles that each halo has by the particle mass in physical units, with a limit of $M > 10^{13} M_{\odot}/h$.

AbacusSummit includes various sets of cosmologies based on different models and parameters. For instance, the ΛCDM model with Planck2018 parameters, variations with massless and massive neutrinos, secondary cosmologies like wCDM, low-σ_8, primordial

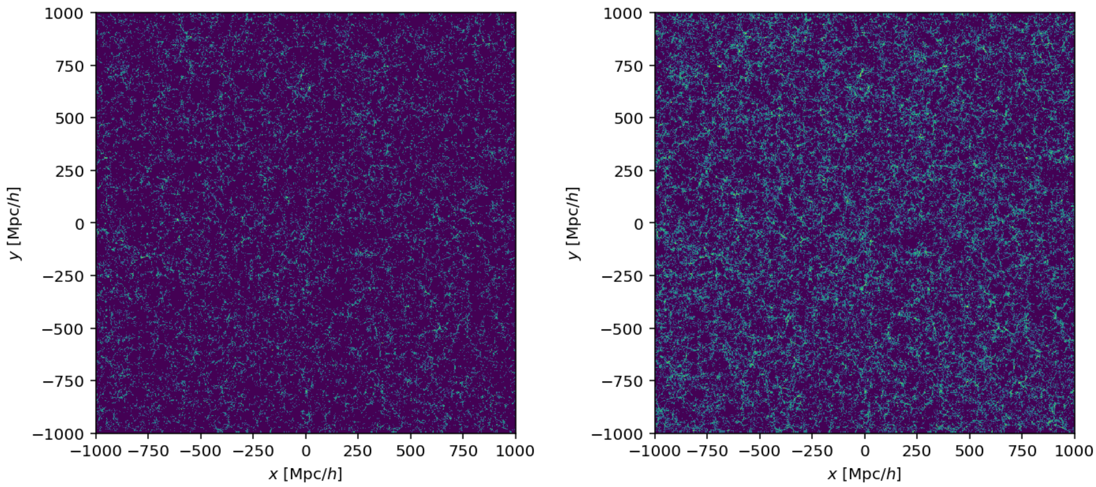

Figure 2: *The 2D histogram of the halo field at Gpc scales [2Gpc, 2Gpc] with a 20 Mpc/h (left) and 40 Mpc/h (right) deep slice. The structure of the cosmic web becomes more apparent within this thin slice.*

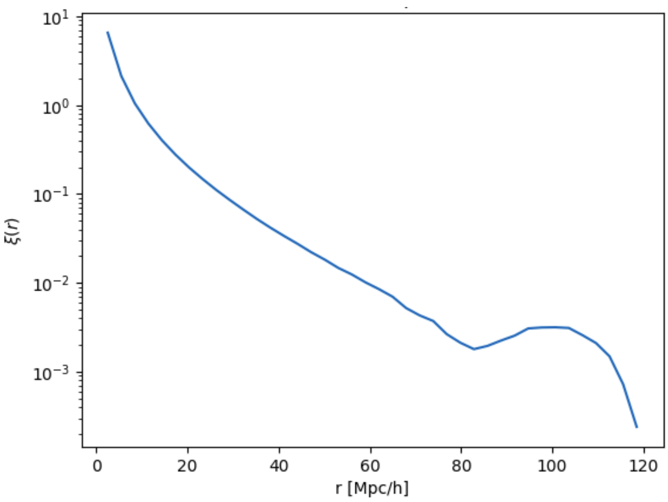

Figure 3: *The BAO peak at around 100 Mpc/h in the 2PCF indicates the distance that sound waves traveled in the early Universe.*

non-Gaussianity, and the Euclid flagship based on different values for σ_8. Overall, they ran nearly 180 different cosmologies.

Different cosmological parameters or models produce different amounts of clustering, which directly affect the results of the 2PCF. Through comparing these results, we can determine which model best fits the observed galaxy clustering. This forms the basis for the next step: utilizing pyGenISW to reconstruct the ISW maps for different cosmologies.

Along with my research related to my PhD proposal, I'm working with an international collaboration group from Iran and the UK on cosmological aspects of two recently proposed phenomenological models of cosmology, omnipotent dark energy (DE) Adil et al., 2024, and Λ_sCDM Akarsu et al., 2023. Omnipotent DE models are a group of models with energy densities that can cross between negative and positive values and correspond to the equation of state parameters featuring phantom divide line crossings. On the other hand, the Λ_sCDM model is based on the sign-switching ΛCDM model. It considers the possibility that the Universe at the late time, $z \sim 2$, experienced a rapid transition from anti-de Sitter vacua to de Sitter vacua, which means that the cosmological constant switched signs. These two recently introduced models show promise as candidates for a new concordance cosmological model of the Universe. This could help address cosmological tensions such as the H_0 and S_8 tensions. However, there are still more cosmological aspects to study. In this project, our aim is to examine these aspects using multiple cosmological observations.

Publications

In preparation Cosmological aspects of Omnipotent Dark Energy and Λ_sCDM model
In preparation The CosmoVerse White Paper (https://cosmoversetensions.eu/)

Talks

- "*The largest 3D map of our Universe and other interesting news from*",
  Pizza Seminars, 30th April, 2024, ELTE, Budapest, Hungary
- "*A new binning method to choose a standard set of quasars*",
  Konkoly Extragalactic Workshop, 19th March 2024, Budapest, Hungary

Schools, Conferences, and Seminars

- Cosmology From Home 2024, https://cosmologyfromhome.com/
- CosmoVerse School, "*From Fundamental Physics to Data Analysis in Cosmology*", 13-18 May, Corfu, Greece
- Two 1-hour webinar tutorials on the Atacama Cosmology Telescope DR6, 18 and 19 April 2024
- Konkoly Extragalactic Workshop, 19th March, 2024, Budapest, Hungary
- WEAVE-QSO Weekly telecons, (Online)
- CosmoVerse Weekly Seminars (Online)
- Konkoly Observatory Weekly Seminars

Courses

- At the edge of the Solar System II, FIZ/5/048
- The structure of compact stars, FIZ/5/025
- Radio astronomy II., FIZ/5/010

Further Activities

- I have been awarded the Stipendium Hungaricum scholarship.
- I have been awarded full financial support by the organizers to participate in the CosmoVerse School at Corfu.
- With the support of Dr. Andras Kovacs, the Euclid Consortium Board (ECB) representative for Hungary, I have recently become a member of the Euclid Consortium (https://www.euclid-ec.org/).
- A new member of the Euclid Consortium Diversity Committee (ECDC).
- I have been accepted as an Erasmus+ exchange mobility participant for short-term doctoral mobility at Aix-Marseille University.
- I applied for the Egyetemi Kutatói Ösztöndíj Program (EKÖP) scholarship with a proposal titled *"Revisiting the angular size-redshift relation of compact radio-loud active galactic nuclei as a cosmological test,"* under the supervision of Dr. Sandor Frey.

Bibliography

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