STACKING OF VOID GALAXIES

A Project Report Submitted
in Fulfillment of the Requirements
for Summer Internship

by

MAITREY SHARMA

under the guidance of

DR. TUHIN GHOSH

to the

School of Physical Sciences

National Institute of Science Education and Research

Bhubaneswar

March 13, 2023

DECLARATION

I hereby declare that I am the sole author of this report in fulfillment of the requirements for Summer Internship from National Institute of Science Education and Research (NISER). I authorize NISER to lend this report to other institutions or individuals for the purpose of scholarly research.

Signature of the Student
Date:

The work reported in the report entitled .... was carried out under my supervision, in the school of .... at NISER, Bhubaneswar, India.

Signature of the project supervisor
School:
Date:

ABSTRACT

In this work we first discuss the cosmological voids and the galaxies that are present in these crucial components of the Cosmic Web. We work through the arguments that solidify the importance of void galaxies to galaxy formation and the effects of their cosmological neighborhood on galaxy evolution. We discuss the cosmic microwave background radiation and how its anisotropies can be probed in void galaxies, with our interest being on the thermal Sunyaev-Zeldovich effect. After the theoretical basis we obtain a publicly available void galaxy catalog and create a filter to remove wall galaxies within a void so that we can increase the signal-to-noise ratio in our stacking techniques.

Contents

Chapter 1

Introduction

The Universe came to be from an homogeneous hot dense phase, a gravitational singularity where spacetime breaks down catastrophically to an heterogeneous vast and sparse state. Different types of cosmological formations took place as it cooled down and expanded over the course of billion years after the Big Bang. *Structure formation*, as it is called, is the formation of galaxies, galactic clusters and larger structures from small early density fluctuations. The study of these structures provide immense insight into the early Universe. Galactic formation and evolution is, thus, one of the most important areas of study of cosmology. Galaxies are diverse, with each class having their own set of properties and what they can reveal about the early Universe.

In this work we will first build our premise towards a special type of galaxies, defined by where they are found, discuss why they are so crucial and what probes we can use to study them. After that we will discourse the objective of this work, the methodologies used and then finally discuss the results and draw conclusions.

1.1 Cosmic Voids

Cosmic voids are vast spaces between galaxy filaments (the largest structures in the Universe) which contain very few or no galaxies. Voids are enormous regions with sizes in the range of 20-50 h^{-1} Mpc that are practically devoid of any galaxy, usually roundish in shape and occupying the major share of space in the Universe. There are a variety of reasons the study of voids is relevant to our understanding of the Universe (**van˙de˙weygaert˙cosmic˙2011**).

1. They are a prominent aspect of the Megaparsec Universe, instrumental in the spatial organization of the Cosmic Web.

2. Voids contain a considerable amount of information on the underlying cosmological scenario and on global cosmological parameters. Notable cosmological imprints are found in the outflow velocities and accompanying redshift distortions (**dekel˙omega˙1994**, **martel˙simulation˙1989**, **ryden˙voids˙1996**). Also their intrinsic structure, shape and mutual alignment are sensitive to the cosmology, including that of dark energy (**park˙void˙2007**; **lee˙constraining˙2009**; **platen˙alignment˙2008**).

3. The pristine low-density environment of voids represents an ideal and pure setting for the study of galaxy formation and the influence of cosmic environment on the formation of galaxies.

The last is particularly interesting and forms the basis of this work as we will see in the next section.

1.2 Void Galaxies

A void galaxy is a galaxy located in a cosmological void. Few galaxies exist in voids; most are located in sheets, walls and filaments that surround voids and supervoids. These galaxies are predominately low-mass and often brimming with star formation (**singari˙detection˙2018**). These galaxies are subject to dynamics that are unique to these underdense regions. They are generally late type disk galaxies that are gas rich, star-forming systems lying mainly on the blue cloud of galaxy evolution (**beygu˙void˙2017**; **kreckel˙only˙2011**)

Several surveys, thus, have been conducted in past few years to systematize the study of these galaxies, such as the Void Galaxy Survey (VGS) and Galaxy and Mass Assembly (GAMA) survey. So far we have established that void galaxies present a unique and interesting case to study galaxy formation, what effects the neighboring environment can have on it and the cosmos as a whole. For this work, we will be using a public catalog[1] prepared by **pan˙cosmic˙2012** (**pan˙cosmic˙2012**).

1.3 Cosmic Microwave Background

Cosmic microwave background, the relic radiation from the Universe is mostly isotropic, but not quite. Therefore, precise measurements of anisotropies in temperature, polarization and spectrum of the CMB are of immense interest in cosmology and it is the reason massive projects such as the Planck Collaboration exist.

CMB spectral distortions are tiny departures of the average cosmic microwave background (CMB) frequency spectrum from the predictions given by a perfect black body, and they were first starting with the seminal papers of Yakov B. Zeldovich and Rashid Sunyaev (**sunyaev˙small-scale˙1970**).

[1] http://www.physics.drexel.edu/~pan/VoidCatalog/

1.4 The Sunyaev-Zeldovich Effect and the Circum-galactic Medium

The Sunyaev–Zeldovich effect (abbreviated as the SZ effect from here) is the spectral distortion of the cosmic microwave background (CMB) through inverse Compton scattering by high-energy electrons in galaxy clusters, in which the low-energy CMB photons receive an average energy boost during collision with the high-energy cluster electrons.

If this distortion results from a large number of high energy electrons is known as the thermal Sunyaev–Zeldovich (tSZ) effect. The tSZ effect is the best probe of the large scale distribution of the diffuse hot gas component of our Universe, with temperature $T > 10^6$K. The tSZ effect has been recently used for detecting the circum-galactic medium (CGM) around massive galaxies usually for locally bright galaxies of stellar masses larger than $10^{11}\mathrm{M}_\odot$ (**planck˙collaboration˙planck˙2013**).

Since these void galaxies are isolated and have low stellar masses, they are ideal for studying the hot gas due to stellar feedback lying within the CGM of galaxies. In this work we will discuss the process of constraining our data of void galaxies from the catalog (**pan˙cosmic˙2012**) and then using stacking techniques with the all-sky Planck y-map.

Chapter 2

Methods

2.1 Distance Measures in Cosmology

Cosmological distances require special considerations as effects of general relativity, which is, expansion of spacetime becomes substantial that objects are very heavily redshifted. Hubble's law, also known as the Hubble–Lemaître law, is the observation in physical cosmology that galaxies are moving away from Earth at speeds proportional to their distance.

The Hubble constant H_0 is the constant of proportionality between recession speed v and distance d in the expanding Universe;

$$v = H_0 d \tag{2.1}$$

The subscripted "0" refers to the present epoch because in general H changes with time. The dimensions of H_0 are inverse time, but it is usually written

$$H_0 = 100\, h \,\mathrm{km\,s^{-1}\,Mpc^{-1}} \tag{2.2}$$

where h is a dimensionless Hubble constant and is often introduced to denote the "present" cosmology. We further define the Hubble distance as

$$d_H \equiv \frac{c}{H_0} = 9.26 \times 10^{25}\, h^{-1}\,\mathrm{m} \tag{2.3}$$

Then there are the density parameters Ω_r (radiation density), Ω_m (matter density), Ω_Λ (dark energy density) and Ω_k (curvature density) which together define the dimensionless Hubble parameter $E(z)$. All these quantites can be expressed as function of redshift z and summarised in the following equation;

$$E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda} \tag{2.4}$$

All of these form the basis of a more convenient way of dealing with distances in cosmology: comoving distances. *Proper distance* roughly corresponds to where a distant object would be at a specific moment of cosmological time, which can change over time due to the expansion of the universe. *Comoving distance* factors out the expansion of the universe, giving a distance that does not change in time due to the expansion of space. Mathematically, comoving distance d_C is given by

$$d_C(z) = d_H \int_0^z \frac{dz'}{E(z')} \tag{2.5}$$

2.2 Implementation

The first goal is to create a filter to increase the signal-to-noise ratio of the eventual stacking that will be done. The galaxies which are too near the walls of the voids, the wall galaxies are to be removed. For this following steps were taken:

Using the catalogues made available by **pan˙cosmic˙2012** (**pan˙cosmic˙2012**), data was imported for void centres (using `public_void_catalog.txt`) and void galaxies (using the `maglim_void_galaxies.txt`). To get the coordinates of void centres from here, the columns of x, y, z distances were used and column r was used to get void radius. To take the cosmology into account, the radius r by 0.7 (in accordance with the data). To find the comoving distances to void galaxies and void centres, we use $d = \sqrt{x^2 + y^2 + z^2}$ where (x, y, z) denote coordinates. The obtained comoving distances are now multiplied by 0.7 to take cosmology into account. After this, a simple program was written using the Astropy package[1] for Python, which basically calculates distance of every void centre and galaxy pair and returns the galaxy number corresponding to the void number which satisfies a given fractional distance condition (eg. all void galaxies which are at a distance from $0.5r$ where r is the void radius).

2.3 The code

The Python code, which implements the process described in the last section is given here:

```python
import numpy as np
from astropy.coordinates import SkyCoord
from astropy import units as u

# importing void and galaxy data
data_gal = np.loadtxt('maglim_void_galaxies.txt')
data_void = np.loadtxt('public_void_catalog.txt')

# stripping the data
ra_void = data_void[:, 0]
dec_void = data_void[:, 1]
ra_gal = data_gal[:, 0]
dec_gal = data_gal[:, 1]


x_void = data_void[:, 2]
y_void = data_void[:, 3]
z_void = data_void[:, 4]
void_radius = data_void[:, 5]*0.7
```

[1] http://www.astropy.org

```

x_gal = data_gal[:, 6]
y_gal = data_gal[:, 7]
z_gal = data_gal[:, 8]

#following code to check if comoving distances are same as given in catalog
cmvdist_gal = np.sqrt(x_gal**2+y_gal**2+z_gal**2)*0.7
cmvdist_void  = np.sqrt(x_void**2+y_void**2+z_void**2)*0.7

#the main part of the code
for i in range(len(coord_void)):#range(len(coord_void)):
  c2 = SkyCoord(ra=ra_gal*u.degree, dec=dec_gal*u.degree, distance=cmvdist_gal*u.Mpc)
  c1 = SkyCoord(ra=ra_void[i]*u.degree, dec=dec_void[i]*u.degree, distance=cmvdist_void[i]*u.Mpc)
  dist = c1.separation_3d(c2)
  frac_dist = dist.value/void_radius[i]
  a = np.where(frac_dist <= 0.5) #this is the case for 0.5r
  print("For void number #",i+1, a[0]+1)

```

Listing 2.1: Code for filtering wall galaxies

Chapter 3

Results and Discussion

After implementing the code, the filter can be generated as per user's requirements. Some plots are included with did not use the filter but represent the results which are obtained by stacking the void galaxies. MILCA refers to Modified Internal Linear Component Algorithm (**hurier˙milca˙2013**), which is a internal linear combination (ILC) method used to extract the CMB emission from the WMAP multifrequency data courtesy projects like the Planck survey. NILC stands for Needlet Internal Linear Combination (**remazeilles˙cmb˙2011**), a different technique used for same purpose.

Using the filter, similar stacking plots can be obtained. The filtering will aid in

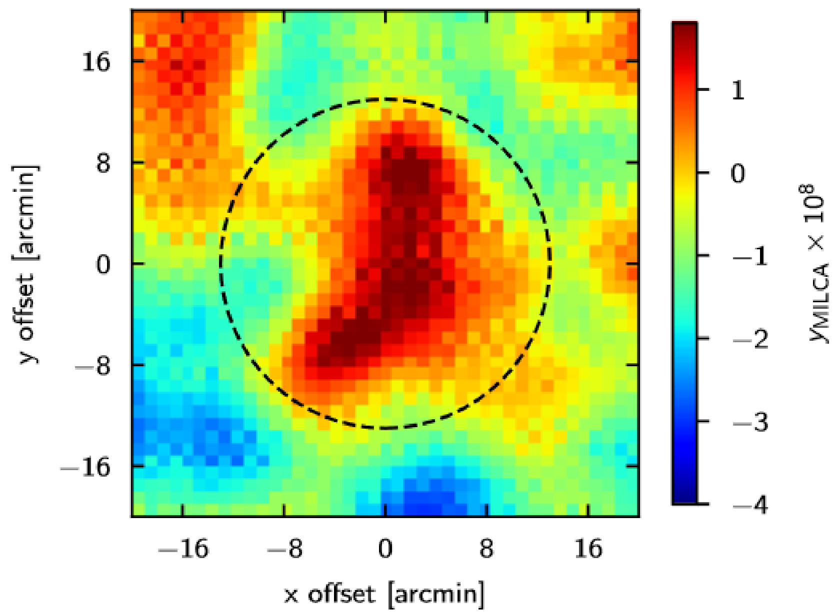

Figure 3.1: The normalized stacked y MILCA map at void galaxy locations at all z in our sample over 51% sky mask.

removing unwanted galaxies, that are too near the void walls.

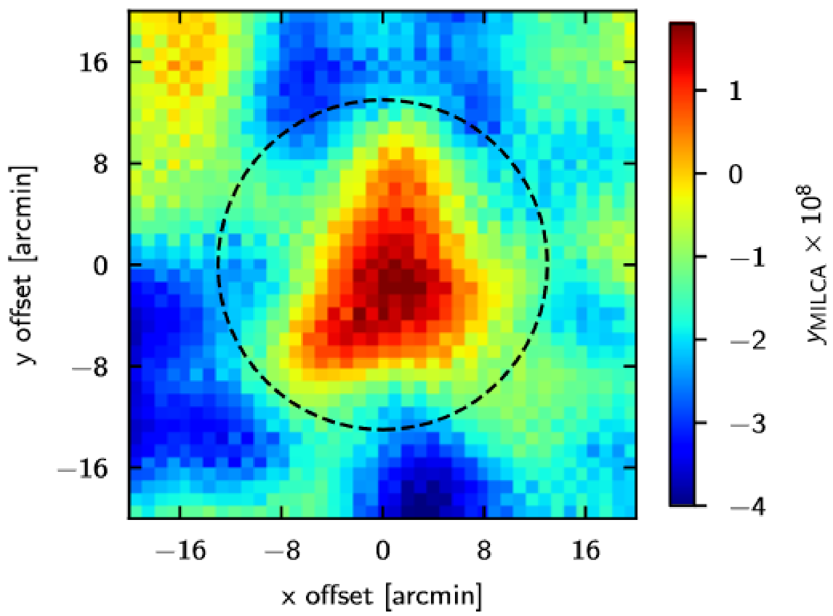

Figure 3.2: The normalized stacked y MILCA map at void galaxy locations at $z > 0.04$ in our sample over 51% sky mask.

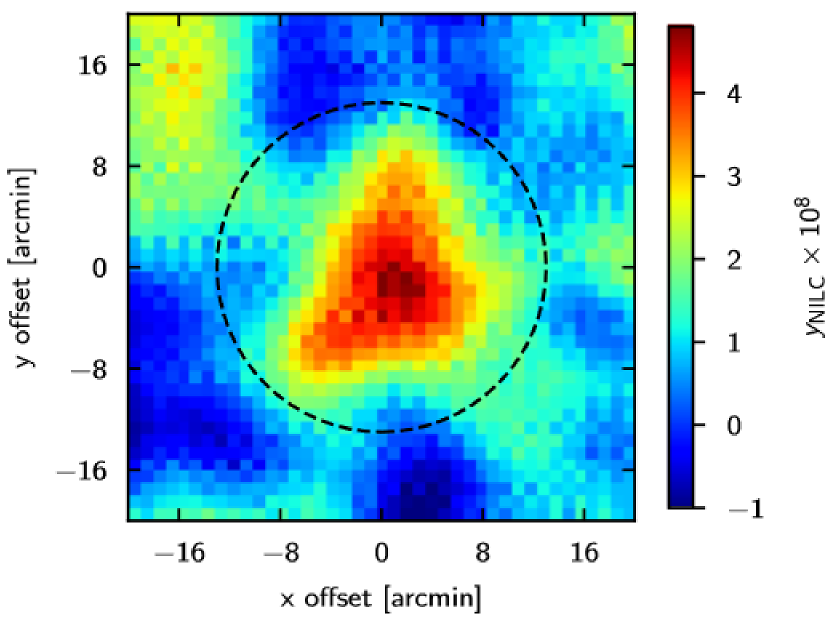

Figure 3.3: The normalized stacked y NILC map at void galaxy locations at $z > 0.04$ in our sample over 51% sky mask.

reference.bib