Integrated Sachs-Wolfe Effect and its Detectability on Galaxy-Redshift Surveys

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1 Project Description

1.1 Problem Proposition

Nowadays, the accepted cosmological model is the named Λ-Cold Dark Matter (ΛCDM), which was proposed as a model that fits to the observations and allows us to explain them based on the theory of the general relativity. In such a cosmological model, the universe is homogeneous and isotropic, and it is composed by different components: baryonic matter, dark matter, radiation and dark energy, of which the dark energy and dark matter are the main components [4].

Based on the observations of the Cosmic Microwave Background and the recession of the galaxies, the simplest accepted origin of the universe is a great explosion called Big Bang. After this great explosion, vacuum quantum fluctuations occured, from which large amounts of matter and antimatter were created. Both parts were annihilated creating photons, and due to the large amount of energy and high temperatures, matter (protons, electrons, etc.) and radiation were coupled. With the expansion of the universe, the temperature decreased, and radiation and matter decoupled, allowing radiation to travel free in the universe and fill it completely, while carrying information of the initial conditions of the universe at the moment in which radiation and matter decoupled [4]. Initially, this large termic bath, called Cosmic Microwave Background (CMB), was isotropic in the whole universe. However, it latter suffered from perturbations in this spatial distribution due to effects such as Baryonic Accoustic Oscillations before the surface of "last scattering", generating what is known as the primordial anisotropies of the CMB. Those anisotropies are fluctuations in the CMB temperature that deviates from the mean black-body temperature that CMB photons should have. This surface of last scattering is the set of points in the space at a distance such that nowadays we received photons from the CMB that were scattered by last time at the moment of decoupling [4].

Besides these primordial anisotropies of the CMB generated at the surface of last scattering, there were more anisotripies. Long after the decoupling time, the inflation era and the collapse of dark matter, protogalaxies anda galaxies were formed, and then the large-scale structures in the universe. Photons from CMB started to undergo perturbations due to the presence of these matter structures, causing the so-called late anisotropies on the CMB. These later anisotropies have a lower signal amplitude than the early anisotropies [6], but still detectable, although with some difficulties.

The study of the anisotropies of the CMB could be one of the evidences that allow to study the nature of the cosmological constant [1], [9]. This cosmological constant is introduced in the Einstein's field equations and the observations of the accelerated expansion of the universe fit very well to this model. The cosmological constant is associated to the dark energy in the ΛCDM cosmological model.
One of the late anisotropies in the CMB is caused by the called Integrated Sachs-Wolfe (ISW) effect, that is an effect that the photons of the CMB underwent when they pass accross regions of overdensities or underdensities of matter, changing its wavelength and energy. Such a perturbation on the CMB is due to the time-evolution of the gravitational potential wells of dark matter that form the Large-Scale Structures (LSS) that host the galaxies. The ISW effect, as a late anisotropy in the CMB, has a lower amplitude compared with the primordial anisotropies and this is the reason why it is too difficult to detect [6].

To date, many attempts to detect the ISW effect have been performed, by searching correlations between the CMB maps and the maps of the matter density field in the Universe, which is related with the local gravitational potential wells. Because the primordial anisotropies of the CMB are not correlated with the matter density field at present time, it is possible to find the correlations between the weak anisotropies of the late ISW effect and the matter density field [6].

Studies from diverse groups of authors have tried to find such correlations. Some studies have shown a correlation between the CMB maps and the density field with significances between 2-3σ level [2], [6], using data from the Wilkinson Microwave Anisotropy Probe (WMAP) and samples from galaxy surveys such as the Sloan Digital Sky Survey (SDSS). Results from those authors are consistent with the current cosmological model despite the low significance [16]. In turn, using 3D projections of the galaxies instead of the 2D density profiles for Luminous Red Galaxies (LRG) of the SDSS survey, and assuming the most extreme density perturbations, it has been achieved a significance level of 4.4σ in the temperature deviation on the CMB due to supervoid and superclusters, which is the largest significance related with the ISW effect found until now [7]. However, the same group of authors in a recent work found that their ISW map constructed from the same data of LRGs from the SDSS survey, showed no evidence for degree-scale cold and hot spots associated with supervoid and supercluster structures, although they find that the ISW measurement is a factor ~ 2.1 above the ΛCDM based simulation results [8]. On the other hand, some authors have found anti-correlations while studying the relation between CMB maps (from WMAP) with more than 1.5 million of galaxies of the same SDSS survey, rejecting the ΛCDM model [19]. Other authors even reject the hypothesis of the existence of the ISW effect, when using photometric measurements in galaxy redshift surveys as the Two Micron All-Sky Survey (2MASS) [5].

Other studies about the ISW effect tried to decompose the whole anisotropy signal into a signal associated to the primordial anisotropies and another signal related to the secondary anisotropies, in which the ISW effect has the major contribution. In [12], the authors used a likelihood method in order to separate the ISW contribution from maps of the CMB (from WMAP), with both, simulations and observational data (from 2MASS survey), obtaining constrains for the ISW component of the called Cold Spot in the CMB data.

By those reasons, the detectability of the ISW effect has become a great challenge, because even the same group of authors has obtained different results in their detections using the same observational data. Furthermore, in general, there is no agreement in the criterion about the detection of the ISW effect. Even, when comparing the signal of the ISW from observations with the expected value in the ΛCDM model from mock catalogues, the observations data show a signal that is above the expected value. A possible fact that induces such artifacts in the detections could be the galaxy bias. The galaxy bias of a given observational sample is obtained when comparing the clustering of observed galaxies with the clustering of dark matter; the latter is obtained from cosmological simulations and depends on the cosmological model used [11], and then turns into an important parameter in the model.

In this project, we intend to use cosmological simulations and observational data manipulated with the Halo Based Method (HBM), which is galaxy bias free-method, to obtain the density field of both catalogues, and to model the signal amplitude of the ISW effect due to those density fields. Given the posibility to detect it, we desire to estimate the differences between the signal from synthetic data and that from the observational data, to look for possible inconsistencies between both signals and give a conclusion about the detection of the ISW effect and, if possible, about the nature of the dark energy in our Universe.

Keywords: Cosmic Microwave Background, Late-Integrated Sachs-Wolfe Effect, Large-Scale Structures, Cosmology, Fourier Methods.

2 Hypothesis

Our work hypothesis is:

Using cosmological simulations and manipulating observational data with the Halo Based Method (HBM) to obtain the density fields, it would be possible to detect the late ISW effect signal due to the time-evolution of the gravitational potential wells induced by the expansion of the universe, and use such detections as direct evidence of the existence of dark energy.

3 Objectives

3.1 General Objectives

To use the Halo Based Method (HBM) to quantify the amount of late ISW signal in the Cosmic Microwave Background from local mass density perturbation in the Large Scale Structures.

3.2 Specific Objetives

- To study the theoretical foundations that support this work: foundations of the current cosmological model ΛCDM and its relation with dark energy, the CMB anisotropies and the LSS formation process.

- To quantify the observability of the ISW effect through correlations in mock catalogues obtained from computational simulations.
- To quantify the late ISW effect signal through correlations with the density field from observations of the SDSS galaxy survey.
- To compare the results of both kind of detections from observations and from mock catalogues to conclude about the detectability of the ISW effect.
- To see if the inconsistence in the ISW signal obtained by other authors is due to the galaxy bias and could be solved with the HBM.
- To write a master thesis reporting in detail the used procedures and results.

4 Theoretical Background

Because direct observation of small anisotropies in the CMB temperature due to ISW effect is complicated, the search of such effect has been concentrated to find correlations between the CMB temperature maps and the matter density maps that account for the local gravitational potential wells. In order to realize such a study, it is necessary to understand the basic concepts as the current accepted cosmological model, the different CMB anisotropies and the formation of LSS.

4.0.1 Cosmological Context:

Nowadays, the accepted cosmological model is the Standard Cosmological Model ΛCDM (Λ-Cold Dark Matter) in which the universe is composed by radiation (photons and neutrinos), baryonic matter (atoms, electrons and other particles that constitutes stars, planets and living beings), dark matter (which forms the LSS and give place to the gravitational potential wells that host the galaxies) and the dark energy. This dark energy, nowadays, is the major constituent of the Universe, being near of the 70% of its energy density, followed by the dark matter which constitutes approximately 26%, being the remainder percentage a majority of baryonic matter and, last and to a lesser extent, the radiation [4]. The dark energy is associated with the cosmological constant, which is an integration constant in Einstein's field equations; such a constant is interpreted as an entity with a constant energy density which composes the major contribution to the energy density in the Universe. Besides, observations fit very well with a cosmological model for the Universe that includes a cosmological constant.

The current cosmological model is justified in the observations that show an isotropic an homogeneous universe (at very large scales) with flat geometry and whose dynamics is governed by the ratios between the matter density and energy of the 4 constituents of the Universe mentioned above [4]. An isotropic and homogeneous universe is well described by the Friedmann-Lemaître-Robertson-Walker metric:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta\mathrm{d}\phi^2\right) \tag{1}$$

Where $a(t)$ is the scale factor, which characterizes the expansion of the universe, and k is the space-time curvature. Observations show that the Universe can be considered as having a flat geometry ($k = 0$). The dynamics of such a universe is studied from the Friedmann equations which allows to relate the densities of matter, radiation and dark energy that constitutes the universe with the scale factor and its rate of change in the following way:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2} \tag{2}$$

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}\left(\rho + \frac{3P}{c^2}\right) \tag{3}$$

Equation 2 is derived from the 00 component of Einstein's field equations. The Equation 3 is derived from Equation 2 with the trace of Einstein's field equations. Using conventions that are more adecuate to observables, the first equation can be transformed in the following:

$$\frac{H^2}{H_0^2} = \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda \tag{4}$$

Where Ω_i gives the density of each of the constituents of the universe: radiation ($i = r$), matter ($i = m$) and dark energy ($i = \Lambda$). H is the Hubble's parameter that is related with the expansion of the Universe. Such a parameter varies in time, being $H_0 = H(t_0)$ its value at present time t_0.

4.0.2 LSS Formation:

The ΛCDM model assumes that the structures we observe today in the Universe, grew from perturbations in the density field in a hierarchical way, that is, the first structures to be formed were the small ones, and then, through coalescence of this small structures, the big ones are formed [15]. In general, we can define the density contrast as:

$$\Delta(x) = \frac{\rho(x) - \overline{\rho}}{\overline{\rho}} \tag{5}$$

Where $\rho(x)$ is the density of one of the constituents of the Universe at a certain position x, $\overline{\rho}$ is the mean density of the respective constituent in all the Universe and $\Delta(x)$ is the called density contrast which measures the fluctuation of the density in a point x relative to the mean density [15]. Since we are interested in large structures, we will work with the densities and density contrast of dark matter.

The large-scale structures (LSS) emerge from overdensities in the dark matter density field, generated by primordial density field fluctuations, allowing the formation of gravitational potential wells or dark matter haloes. In those haloes, baryonic matter starts to cool and collapse. Once the collapse of baryonic matter starts, Jeans unstable hydrogen clouds begin to collapse independently, allowing the formation of the first stars and protogalaxies, which evolved from collisions and coalesence, in a hierarchichal formation scenario [15]. The collapse of baryonic matter starts after decoupling time, when the Universe's temperature has decreased enough such that Compton effect is no frequent any more, leaving the radiation free from its interaction with matter. As dark matter can not be observed directly, those overdensities may be inferred from the local number density of galaxies on the dark matter haloes [15].

One can write an equation for the evolution of the density contrast in the expanding Universe. Starting with the equation of conservation of mass (equation of continuity), the equation of motion for an element of a fluid (Euler's equation) and the equation for the gravitational potential in the presence of a mass density distribution ρ (Poisson's equation) [21]:

$$\frac{\mathrm{d}\rho(\mathbf{x},t)}{\mathrm{d}t} + \nabla\cdot(\rho(\mathbf{x},t)\mathbf{v}) = 0 \tag{6}$$

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{\nabla P}{\rho} - \nabla\Phi \tag{7}$$

$$\nabla^2\Phi = 4\pi G\rho \tag{8}$$

Where Equation 6 is the continuity equation, in which ρ represents the density in a certain point $\mathbf{x}$, and $\mathbf{v}$ is the peculiar velocity of the density distribution at this point. Equation 7 is the Euler's equation for the motion of an element of a fluid; here P is the pressure and Φ is the gravitational potential. Finally, Equation 8 is the Poisson's equation, where G is the gravitational constant.

Performing perturbations on those equations, one can find a general equation for the density contrast:

$$\frac{\mathrm{d}^2\Delta}{\mathrm{d}t^2} + 2\left(\frac{\dot{a}}{a}\right)\frac{\mathrm{d}\Delta}{\mathrm{d}t} - 4\pi G\overline{\rho}\Delta = 0 \tag{9}$$

Where $\overline{\rho}$ is the unperturbed density. When solving this equation, one can express $\Delta(x)$ in terms of the redshift z in this general way:

$$\Delta(z) = AD_1(z) + BD_2(z) \tag{10}$$

Where the partial solutions $D_1(z)$ and $D_2(z)$ are called the growing and decaying modes, respectively. In general, we will work only with the growing mode D_1, we will call it simply D. This is because the decaying mode $D_2(z)$ can be considered to have a negligible contribution as the Universe expands. We can express the growing mode in terms of the scale factor a, as follows:

$$D(a) = \frac{5}{2}\left(\frac{\Omega_{m,0}}{\Omega_{\Lambda,0}}\right)^{1/3}\frac{\sqrt{1+y^3}}{y^{3/2}}\int_0^y \frac{y'^{3/2}}{[1+y'^3]^{3/2}}\,\mathrm{d}y' \tag{11}$$

$$y \equiv a\left(\frac{\Omega_{\Lambda,0}}{\Omega_{m,0}}\right)^{1/3} \tag{12}$$

Where $\Omega_{m,0}$ and $\Omega_{\Lambda,0}$ are the so called density parameters of matter and cosmological constant, respectively, evaluated at the present time.

For $\Omega_m > 0.1$, the growing mode $D(a)$ can be accurately approximated by:

$$D(a) = \frac{(5/2)a\Omega_m}{\Omega_m^{4/7} - \Omega_\Lambda + (1+\Omega_m/2)(1+\Omega_\Lambda/70)} \tag{13}$$

With the matter density parameter Ω_m and cosmological constant density parameter Ω_Λ related with the scale factor as follows:

$$\Omega_m(a) = \frac{\Omega_{m,0}}{(1+y^3)} \tag{14}$$

$$\Omega_\Lambda(a) = 1 - \Omega_m(a) \tag{15}$$

$$\mathrm{d}s^2 = a^2(\eta)\left[-(1-2\Phi)\mathrm{d}\eta^2 + (1-2\Psi)\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j\right] \tag{16}$$

Where η is the conformal time, and Φ and Ψ are the so called Bardeen potentials, which are gauge invariant. From Equation 16, and studying the trajectory of a photon in this universe, it is possible to obtain Equation 19 by making the assumption that $|\Phi| \approx |\Psi|$ [10].

4.0.3 Perturbative General Relativity in ΛCDM:

In order to obtain the fluctuation in temperature produced by the ISW effect, as we will see in Equation 19, it is necessary to study the perturbations in the general relativity applied to the ΛCDM cosmological model. In particular, it is necessary to perform perturbations over the metric that describes the flat, homogeneous and isotropic Universe (Equation 1). Thus, the metric of such universe can be described by a perturbed FLRW metric (very near to an homogeneous and isotropic FRLW metric) and an unperturbed FLRW metric, as follows [10]:

$$g_{\mu\nu} = \overline{g}_{\mu\nu} + \delta g_{\mu\nu} \tag{17}$$

Where $\overline{g}_{\mu\nu}$ is the unperturbed metric and $\delta g_{\mu\nu}$ is the perturbation. Performing perturbations over the Einstein's field equations in the same way as in Equation 17 and with the help of the Friedmann equations, it is possible to study such kind of universe.

Taking into account that the perturbations on the metric $\delta g_{\mu\nu}$ can be decomposed into scalar, vectorial and tensorial perturbations and focusing only on the scalar perturbations, it is possible to obtain the line element of the perturbed universe [10]:

4.0.4 CMB and Anisotropies:

In 1964 two engineers, Arno Penzias and Robert Wilson, were working at Bell Laboratories in Holmdel, New Jersey, with a huge horn reflector antenna that had been used to communicate with the Telstar satellite. They found a persistent hiss in the signal that came from all directions and realize that a 3 K black-body radiation could be producing this interference. The engineers detected the black-body radiation that fills the Universe, with a peak wavelength of $\lambda_{\max} = 1.06$ mm in the microwave region of the electromagnetic spectrum, nowadays known as the Cosmic Microwave Background (CMB). In 1991, the COBE satellite measured a temperature of 2.725 K, while nowadays we know that the temperature of the black-body spectrum of the CMB is about 2.72548$\pm$0.00057 K [4].

Such radiation is isotropic in the whole Universe, but due to different factors as the movement of the observers or the presence of matter in the universe, this radiation presents different kinds of anisotropies. The first type of anisotropy is due to effects that emerged before the surface of last scattering, as the Baryon Accoustic Oscillations. Those anisotropies are called early anisotropies and are generated in the early moments in the history of the Universe (that means, at high redshift z).

Other types of anisotropies are the late ones, as the Doppler shift due to the peculiar velocity of each observer relative to the Hubble flux; this anisotropy causes that the observer measures a lower temperature if watching backward, while if watching forward he measures a higher temperature [4].

Also, there are another late anisotropies that have a lower amplitude than the primordial anisotropies in the CMB spectrum. One of those is the Sunyaev-Zel'dovich effect, which is related to the inverse Compton effect when photons pass through ionized hot gas clouds in galaxy clusters, which causes that high-energy electrons give their energies to those photons, increasing the energy of the latter. Because of that, the black-body spectrum of the CMB changes its shape and moves to higher frequencies, allowing a change ΔT in the temperature of the CMB from its mean temperature $\overline{T}_0$ [4].

Another effect that leads to late anisotropies in the CMB is the late Integrated Sachs-Wolfe (ISW) effect, due to gravitational redshifting when photons pass through gravitational potential wells that evolve in time. If dark matter dominates the universe, those potential wells will not evolve in time, but the presence of dark energy (or even by the space-time curvature), would make such potential wells to evolve, generating new fluctuations in the temperature (or secondary anisotropies) at low redshifts (the ISW effect is mainly given at redshift $z < 2$) when photons cross regions of overdensities or underdensities, and then, changing the energy of the photons [6].

It is possible to observe the ISW effect when studying the cosmic harmonics. The general pattern of the temperature variations of the CMB in the celestial sphere can be expressed in the following way [9]:

$$\frac{\delta T(\theta, \phi)}{T} = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} a_{l,m} Y_m^l(\theta, \phi) \tag{18}$$

Where the ISW effect is observed for $l < 50$ in the power spectrum of the CMB [4]. The coefficients $a_{l,m}$ are determined from the observations in the CMB and making measurements of $\delta T/T$ in all directions. Y_m^l are the spherical harmonics. In the particular case $l = 1$, one can obtain the dipole anisotropy of the CMB due to the Doppler shift by the observer's peculiar velocity.

The theoretical origin of the ISW effect dates back to 1966, when R. K. Sachs and A. M. Wolfe found solutions to linear perturbations of the Einstein's field equations, to obtain fluctuations in the density field [18]. This allow them to obtain the temperature fluctuations, related with the time evolution of the gravitational potential, as follows [3]:

$$\Delta T(\hat{n}) = \frac{2}{c^3}\overline{T}_0 \int_0^{r_L} \frac{\partial \Phi(r, z, \hat{n})}{\partial \eta} dr \tag{19}$$

Where $\hat{n}$ is a vector pointing along the line of sight, r_L is the comoving radial distance to the surface of last scattering, $\overline{T}_0$ is the mean CMB temperature, η is the conformal time and $\Phi(r, z, \hat{n})$ is the gravitational potential which is differentiated respect to η along the photon's geodesic. This equation gives the amplitude of the signal to be detected [16].

In order to obtain the gravitational potential Φ and its temporal evolution relative to conformal time η, we must solve the perturbed Poisson's equation, which allows us to relate the potential and the matter fluctuations [20]:

$$\nabla^2 \Phi(\mathbf{x}, t) = 4\pi G \overline{\rho}(t) \Delta(\mathbf{x}, t) a^2(t) \tag{20}$$

Where $\Delta(\mathbf{x}, t)$ will be found through the Halo Based Method (HBM) described in subsubsection 4.0.5. In the Fourier space, and after some algebra, Equation 20 becomes:

$$\Phi(\mathbf{k}, t) = -4\pi G \overline{\rho}(t) a^2(t) k^{-2} \Delta(\mathbf{k}, t) \tag{21}$$

Taking the time derivative respect to conformal time η, we obtain:

$$\dot{\Phi}(\mathbf{k}, t) = \frac{3}{2}\Omega_{m0} H_0^2 k^{-2} \left[\frac{H(t)}{a(t)} \Delta(\mathbf{k}, t) + \frac{i\mathbf{k} \cdot \mathbf{p}(\mathbf{k}, t)}{a(t)} \right] \tag{22}$$

Then, making an inverse Fourier transform of Equation 22 we can integrate Equation 19. As we desire to compare with the linear theory, we can assume that $\dot{\Delta}(\mathbf{k}, t) = \dot{D}(t)\Delta(\mathbf{k}, z = 0)$, and then, substituting in Equation 22, we obtain:

$$\dot{\Phi}(\mathbf{k}, t) = \frac{3}{2} H_0^2 k^{-2} \Omega_{m0} \frac{H(t)}{a(t)} \Delta(\mathbf{k}, t)[1 - f(t)] \tag{23}$$

Where $f(t)$ is the linear growth rate given by $f(t) = \mathrm{d}\ln D(t)/\mathrm{d}\ln a$.

Both Equation 22 and Equation 23 can be used as integrand in Equation 19 in order to compare the contributions of both regimes. As the ISW effect in the linear approximation has a higher contribution than high-order terms, then Equation 23 should give coherent results with those found with Equation 22 [3].

Finally, and related to Equation 18, we can study the power spectrum of the CMB, as shown in Figure 1. Each anisotropy has a contribution to the power spectrum, and the shape of this

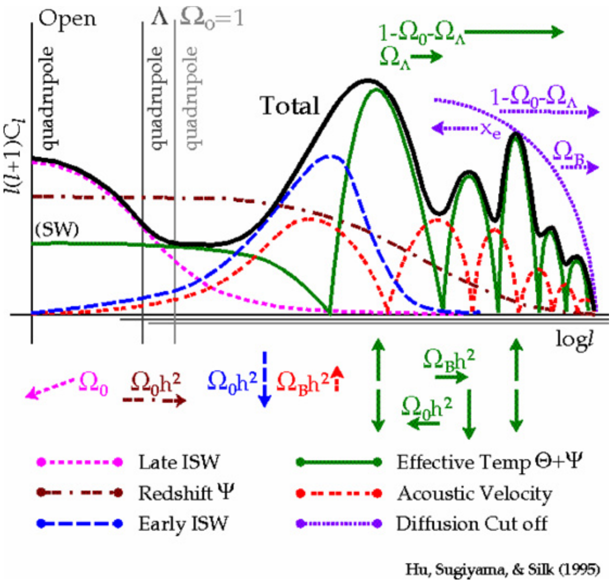

Figure 1: Power spectrum of the CMB

power spectrum depends on the contribution of each anisotropy as well as on the amount of baryonic matter, dark matter or dark energy in the Universe. As mentioned before, the ISW effect contribution is given at $l < 50$, which is related with large angles in the sky. At such low values of the multipole l (or angular frequency) the observations suffer of cosmic variance, making the ISW effect so difficult to detect. This is the reason to find a method that allows to determine the ISW signal, and the reconstruction of the density field of the large-scale structures to find correlations with the CMB maps has been the most studied until now.

4.0.5 Halo Based Method and Mass Density Reconstruction:

As mentioned in subsubsection 4.0.4, in order to detect the ISW effect we need to calculate the gravitational potential Φ and its time derivative $\dot{\Phi}$. The gravitational potential must be estimated from the density field $\rho(x)$ (related with the density contrast $\Delta(x)$) through the Poisson equation (Equation 20).

As our goal is to estimate the ISW signal from a cosmological simulation and from obsvervational data, then we need o estimate the the density field $\rho(x)$ in both cases. In the case of the observational data, the procedure must be complemented with some results from cosmological simulations as we will see soon.

To estimate the ISW signal from the density field of a cosmological simulation, we just need to use a mass assignment scheme, such as the Nearest-Grid Point (NGP) or the Cloud-in-Cell (CIC). When the density field is calculated, using the Poisson's equation in the Fourier space (see Equation 21) and then its time derivative (as in Equation 22). With an inverse Fourier transform, $\dot{\Phi}$ can be calculated and then, the ISW signal. This method, using the NGP mass assignment scheme was used in [21].

For the observational data, it should be reminded (subsection 1.1) that one of the possible facts that causes the inconsistencies between the works of different authors, even working with the same data, could be the assumptions in the galaxy bias. The galaxy bias pretends to relate the amount of baryonic matter observed with the possible amount of dark matter that host such quantity of baryonic matter. In other words, what we can see in the observations is just the baryonic matter that composes the galaxies, but not the amount of underlying dark matter; then, one must find a relation that allows to quantify the amount of dark matter from the observed baryonic matter. For this reason, several models for galaxy bias were constructed in order to estimate such relation.

In this work we will implement a different approach, that consist in the the methods used by the co-advisor Juan Carlos Muñoz Cuartas, whom have worked in the so-called Halo-Based Methods (HBM). This method is inspired in the Friends-of-Friends group finder and in the halo model [14]. Such a method has the advantage to be bias-free and does not assume ad hoc parameters in the manipulation of the observational data. With the galaxy distribution from a survey like the Sloan Digital Sky Survey (SDSS), the haloes of each galaxy are identified through a method described in [14]. In this method, the halo of each galaxy is identified and its characteristics such as virial radius and its mass are computed. Then, through an iterative method based on the FoF, the population of haloes is modified in order to identify the large-scale structures. The mass of the haloes is also modified iteratively.

Once the haloes are identified from the galaxy distribution, the reconstruction of the density field $\rho(x)$ will be performed. For this step, the method described in [13], that was also used by the co-advisor, will be implemented.

Theoretically, the cosmic mass distribution can be modelled as a smooth continuous function of the coordinates [13]. But this cosmic mass distribution must be inferred from the galaxy distribution, which is a distribution of discrete objects and is considered a tracer of the cosmic mass distribution. The majority of methods used to reconstruct the cosmic mass distribution infer it by smoothing the discrete data of the galaxy distribution on a grid and convolve it with a given smoothing kernel [13]. As those reconstructions are based on the distribution of galaxies, and they may be biased tracers of the cosmic mass distribution, assumptions on the shape and functional dependence of the bias factor are needed [13]. The Halo Based Reconstruction Method uses the haloes insted of the galaxies to perform the reconstruction procedure, while simultaenously enables the inclusion of environments on the mass distribution around these haloes.

In this method, it is assumed that the cosmic mass is distributed in haloes following a given mass density profile. Here, it is supposed that the density distribution $\eta(r, M)$ in and around a halo of given mass M is a function of the distance r to the center of the halo and of the halo mass M. Also, the spatial coordinates and masses of a set of dark mater haloes are given by a known function $\Psi(\mathbf{r}_i, M_i)$, where $\mathbf{r}_i$ and M_i are the individual coordinates and masses of the ith halo, respectively. This function $\Psi(\mathbf{r}_i, M_i)$ (called $\Phi(\mathbf{r}_i, M_i)$ in [13]) is the same identification of the haloes (with its mass and positions) performed in the previous step (described in [14]). Then, the mass density field around the ith halo is defined by the convolution of $\eta(r, M)$ with $\Psi(\mathbf{r}_i, M_i)$ in the following way:

$$\rho_i(\mathbf{r}_i, M_i) = \eta(r, M) \otimes \Psi(\mathbf{r}_i, M_i) \tag{24}$$

Where the function $\Psi(\mathbf{r}_i, M_i)$ that describes the positions and masses of the haloes is given by their coordinates and masses in the halo catalogue, i.e., in the catalogue of identified haloes;

and the typical mass distribution in a halo of mass M and its surroundings, $\eta(r, M)$, is computed from cosmological simulations. The total mass distribution $\rho(\mathbf{r})$ arising from a complete set of haloes is defined as:

$$\rho(\mathbf{r}) = \hat{\Sigma}\rho_i(\mathbf{r}_i, M_i) \tag{25}$$

For well-isolted haloes, the operator $\hat{\Sigma}$ will represent a summation of the density profiles at the different positions of the haloes. well-isolated haloes means that theirs domains don't overlap. The domain of a halo represents the unique region of the universe that is closest to the halo than to any other. But, as the domains of the haloes are going to overlap , the operator $\hat{\Sigma}$ has to be defined as the operation that composes the mass density distribution in and around haloes in and around haloes depending on the extension of the domain of the haloes and the environment where they are located [13].

With those methods for the identification of the haloes in a survey like the SDSS and the reconstruction of the density field, it would be possible to the gravitational potential and its time derivative in order to calculate the ISW signal in such data samples.

5 Antecedents

Since two years, the student began to work in the problem of the ISW effect. The student has studied the foundations of the cosmological model ΛCDM and a general theory about the CMB and its anisotropies, in order to understand the cosmological origin of the CMB and the difference between primordial and secondary anisotropies. Later, in a bachelor's thesis advised by the Dr. Juan Carlos Muñoz Cuartas (see [21]), the student studied the detectability of the late ISW effect in a cosmological simulation. From this work, the student obtained routines and tools that allow to obtain the density field of the particles in the simulation through a Nearest Grid Point (NGP) mass assignment scheme algorithm. Other routines constructed, allow to perform Fast Fourier Transforms (FFT) of this density field in order to obtain the gravitational potential Φ, its time derivative $\dot{\Phi}$ and some interpolation and integration routines necessary to know the ISW contribution given by Equation 19. Finally, routines that show the late ISW maps obtained from the study of the density field of the cosmological simulation were created. At the same time, the results of the thesis were shown in a seminar of the investigation group and in an international event.

Nowadays, a Cloud-In-Cell (CIC) mass assignment scheme is being studied instead of the NGP algorithm. Furthermore, a joint work with an undergraduate student has been being performed. In this work we study, based on the general theory of relativity, the perturbations to a Friedmann-Lemaître-Robertson-Walker metric. This work tries to understand the origins of the ISW effect from fundamental principles in a ΛCDM cosmological model.

On the other hand, the coadvisor, Dr. Juan Carlos Muñoz Cuartas has the necessary tools that perform the HBM method explained in subsubsection 4.0.5. These routines will be implemented in order to find the density field from galaxy-redshift surveys such as the SDSS without taking into account the galaxy bias, and perform the manipulation of the data in order to obtain the ISW signal from observational data.

With those reasons in mind, we can say that the student has the enough experience to continue his work in this subject in order to achieve the goal to obtain a comparison between the ISW signal from observational data and from the mock catalogue of the cosmological simulation.

6 Scientific Impact

In recent years, in order to find a model that fits with the cosmological observations, the ΛCDM model was proposed. This models assumes a flat universe which expands at an accelerated rate, and its formation from the Big Bang lead to Gaussian features in the temperature anisotropies of the CMB. But different probes, as the COsmic Background Explorer (COBE), the Wilkinson Microwave Anisotropy Probe (WMAP) and recently the Planck spacecraft, show that the CMB lacks from statistical isotropy, or have anisotropies on large scales [17].

However, recently there is much debate about the causes of these anomalies. Because of the statistical methods used and even the large cosmic variance on large scales, those anomalies can be due to a statistical fluke or even not be anomalous [17]. Then, deep studies about the CMB and its anisotropies (being primordial or secondary) are essential to understand one of the most important pillars of the ΛCDM model, because is the only model that has explained the CMB observations (and other cosmological observations) until now. Another cosmological model should be able to explain observations of the CMB and explain its origins.

Also, and related with the ΛCDM model, the ISW effect, being a secondary (or late) anisotropy given at low redshifts, may account for the effects of the cosmological constant (or dark energy) in our universe, and show us if indeed there is some entity associated with this cosmological constant that makes the Universe accelerate its expansion.

In order to study the late anisotropy induced by the ISW effect, a lot of effort has been performed in the development of methods and techniques that allow to observe and understand the relation between the density field of the LSS in the Universe and the photons of the CMB passing through the gravitational potential wells that contain this density field. Since results with mock catalogues from cosmological simulations based on the ΛCDM model show a lower ISW signal than the obtained from the manipulation of observational data, it has not been consistency until now. This inconsistence may be caused by the manipulation of the data, for example, due to the galaxy bias model used. It is of great importance to study for both, simulations and observational data, the relation between the density field and its imprint on the CMB anisotropies. As in this work, we are going to use a different method to manipulate the observational data with the HBM, that is a free-parameter method, we could overcome such inconsistencies between the signals obtained from the two kind of experiments performed. With such a study, it would be possible to determine if the ISW effect can indeed be detected and it could also lead us to a possible conclusion about the existence and precense of the dark energy, associated with the cosmological constant.

7 Expected Results

With the development of this work, we expect to obtain the following results:

- Tools that allows to obtain the ISW imprint on the CMB from the density field obtained from mock catalogues and from observational data.
- A conclusion about the possibility of detect the ISW signal from density fiels from cosmological simulations and from observational data.
- A comparison between the results from cosmological simulations and from observational data to analize the order of magnitude of both ISW signals and conclude about the general inconsistencies obtained in the works of other authors.
- A conclusion about the efficiency of the Halo Based Method, which is a free-parameter method, in the manipulation of the observational to find galaxy groups and associate the respective ISW signal.
- A M.Sc. thesis.
- Submit almost an article in a national or international journal or the participation (with an oral presentation or a poster) in a national or international event.

8 Methodology

The methodology we are going to use in this project is the common methodology used in computational physics. We will take a physical model under which numerical systems will be constructed, with the respective computational algorithms that will allow us to detect the ISW imprint on the CMB. This work has been made partially in the bachelor's thesis mentioned above. With this in mind, we can begin the project from a starting point in which we know some results that provide us with a way to continue the project and some ideas of how to go beyond in the next steps.

The project is divided in the stages presented below:

- **Bibliographic Analysis:** In this stage, we will look over the bibliography which refers to: Cosmology scenary, CMB and anisotropies (focusing in the ISW effect), LSS formation and the manipulation of the observational data that will be used. This bibliography includes the available papers and books.
- **Construction of Models:** The models found in the bibliographic search will be organized. Those models will facilitate the construction of a computational simulations that allows to model the ISW effect in maps of the CMB. On the other hand, the models created for the manipulation of the observational data could be coupled in some way to the models of the analysis of simulations, to understand and obtain maps of the ISW effect due to the observed density fields.
- **Survey's Simulation:** A cosmological simulations will be used in order to construct a replica of a survey (mock catalogue) of galaxies, and from it, construct the density field and the gravitational potential associated to this field. Such mock catalogue has been obtained from previous works and are available for its study by the student. Even so, the student must understand the way in which such catalogues were constructed. On the

other hand, the models obtained for the manipulation of the observational data will be implemented in this stage.

The following programming languages will be used for the simulations and manipulation of the observational data: C (version C11) and Python (version 3.3.1) and some available libraries for the simulation of the CMB maps as: GSL and FFTW for C and scipy, numpy and matplotlib for Python.

- **Model Implementation:** The mock catalogues from the last stage will be used to implement the created model for the ISW effect in the maps of CMB. What we desire to obtain is the signal amplitude of the ISW effect over the CMB to determine if it is detectable or not with the current technology or with the data from the galaxy surveys available today. As we have detected a signal on the mock catalogues (see [21]), the algorithms will be improved in order to improve the ISW imprint due to this synthetic density field. Later, the manipulated observational data of the density field will be used to obtain the ISW imprint over the CMB by a similar way as with the mock catalogues. The manipulation of this observational will be performed in this stage and later, its analysis by means of the model will be executed.

- **Analysis and Conclusions:** In this stage, the results obtained from the implementations of the models will be analyzed, in order to conclude if it is possible or not to detect the ISW effect in cosmological simulations and in galaxy surveys of observational data. This will allow us to conclude, if detected, that it is a way to evidence the existence of dark energy in our universe.

- **Thesis and Paper:** Results and conclusions will be written in a M.Sc. thesis and in a national or, if possible, international journal.

9 Summary

The main procedures we will follow in order to achieve the objectives of the project are:

- To use the density field and the gravitational potential from a cosmological simulation to simulate the trajectory of a photon and obtain the ISW imprint over the CMB due to those fields.

- Manipulate the observational data from galaxy surveys with the HBM to obtain the density field and the respective gravitational potential.

- To follow the same procedure of the first step, to try to detect the ISW effect with real data.

- To compare the results from the first and third steps to conclude about the detectability of the ISW effect in both, cosmological simulations and observational data.

- To conclude if the HBM indeed offers a better estimate of the ISW effect and allows to overcome the inconsistencies found until now in the works of other authors.

Actividades	Mes										
	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Bibliographic Analysis											
Construction of Models											
Survey's Simulations											
Model Implementation											
Analysis and Conclusions											
Thesis											
Paper											

Table 1: Cronograma

10 Cronogram of Activities

The next table shows the cronogram of activities as a summary of the methodology:

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