Testing cosmological models with the Integrated Sachs-Wolfe effect

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The cross correlation between the Cosmic Microwave Background and the Large Scale Structure of the Universe is a powerful probe to test our cosmological models. This correlation can be used to detect the Integrated Sachs-Wolfe effect, and it depends on both the geometry of the Universe and the properties of the clustering and evolution of structures; for this reason it can be used to test and constrain cosmological models and parameters as well as theories of gravity. In this proceeding we briefly introduce the ISW effect and present some of the recent cosmological tests done using it.

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I. INTRODUCTION

Around ten years ago our model for describing the universe profoundly changed; the observation that the expansion of the Universe is not slowing down but accelerating led to the formulation of the current accepted standard model of cosmology, the ΛCDM model. In this model, baryonic matter only contributes 5% of the matter-energy content of the universe, with Cold Dark Matter (the CDM in the acronym) and a Dark Energy component, in the form of a cosmological constant (the Λ in the acronym) providing the other 95%.

This Dark Energy component, in particular, is responsible for the acceleration of the expansion of the Universe; but, while its effects are observed, its nature is not yet understood, so one of the main challenge in the modern cosmology is to understand it and provide models to describe it. To do this cosmologists use many tests, one of them being the observation of the so called Integrated Sachs-Wolfe effect (1), which consists in a correlation between the Cosmic Microwave Background and the Large Scale Structure that only exists in presence of the dark energy component, given that we don't assume exotic models of the Universe.

II. THE INTEGRATED SACHS-WOLFE EFFECT

Just after the Big Bang, the Universe is hot and dense, and photons are strongly coupled to electrons and protons. Gradually the Universe becomes colder and less dense, until protons and electrons form hydrogen (recombination), so that photons are free to travel towards us. This moment is called last scattering, and the edge that we see looking back is called the last scattering surface. This is important because it carries informations about the state of the Universe at a relatively young age, around 380 K years after the Big Bang.

The photons leaving the last scattering surface form the Cosmic Microwave Background, which is extremely homogeneous, but has some small inhomogeneities due to physical effects at the last scattering surface. Travelling to us, CMB photons can experience other physical effects that will cause more inhomogeneities; one of these effects is the fact that travelling to us, CMB photons pass through potential wells of matter. In an Einstein-de Sitter universe the blueshift of a photon falling into a well is cancelled by the redshift as it climbs out. In presence of a dark energy component, instead, there is a time variation of the local gravitational potential Φ, so potential wells are stretched, and photons will experience a larger blue-shift than red-shift, leading to a net change in photon temperature, which accumulates along the photon path. This translates in CMB temperature anisotropies: \[ \delta T/T \propto \int \frac{d\Phi}{dt} dt \]. This is called the integrated Sachs-Wolfe effect, and it can contribute significantly to CMB fluctuations on large angular scales.

The ISW effect enhances only the low l multipoles, so is not easily detected directly in the CMB, due to other effects. As first pointed out by 2 a way of probing the linear Integrated Sachs-Wolfe effect is through correlations of Cosmic Microwave Background maps with tracers of large scale structure. Following the current cosmological model, cosmic structures form from overdensities, and hence the galaxies density traces the potential wells: if the evolu-
function of the wave number \( k \) logarithmic matter power spectrum today as a
function of the gravitational potential due to the influence of dark energy.

### III. THE ISW-LSS CROSS-CORRELATION FUNCTION

We can write the cross-correlation power spectrum between the surface density fluctuations of galaxies and CMB fluctuations as:

\[
C_{TT}^{gT} = \langle a_{lm}^g a_{lm}^T \rangle = 4\pi \int_{k_{\min}}^{k_{\max}} \frac{dk}{k} \Delta^2(k)f_l^g(k)f_l^T(k),
\]

where \( f_l^g \) and \( f_l^T \) are the galaxies and CMB filter functions, respectively, and \( \Delta^2(k) \) is the logarithmic matter power spectrum today as a function of the wave number \( k \).

The cross-correlation function as a function of the angular separation \( \theta \) is then obtained as:

\[
C_{NT}^{gT}(\theta) = \sum_l \frac{2l+1}{4\pi} C_{l}^{gT} P_l(\cos \theta),
\]

where \( P_l \) are the Legendre polynomials.

#### A. The galaxies filter function

Galaxy counts are a biased tracer of the underlying matter distribution, and thus the projected number density of radio sources per steradian, \( n(z, \hat{n}) \), is related to the matter distribution \( \delta(z, \hat{n}) \equiv \delta \rho / \rho \) via:

\[
n(z, \hat{n})d\Omega = \frac{dN}{dz}d\Omega + b_r(z)\delta(z, \hat{n})]d\Omega,
\]

where \( dN/dz \) is the mean number of sources per steradian at a redshift \( z \) and \( b_r(z) \) is the radio galaxy bias parameter. Thus, the observed fluctuation on the sky in projected source counts are given by:

\[
\delta N(\hat{n}) = \int dz b_r(z) \frac{dN}{dz} \delta(z, \hat{n});
\]

We are only interested in clustering on large scales, so the evolution of \( \delta \) factors as \( \delta(k, z) = D(z)\delta(k) \), and the galaxy filter function is written:

\[
f_l^g(k) = \int dz \frac{dN}{dz} b(z) D(z) j_l(\kappa \eta(z)),
\]

where \( (dN/dz)dz \) is the mean number of sources per steradian with redshift \( z \) within \( dz \), \( b(z) \) is the bias factor relating the source overdensity to the mass overdensity, assumed to be scale-independent, \( D(z) \) is the linear growth factor of mass fluctuations, \( j_l(\kappa) \) is the spherical Bessel function, and \( \eta(z) \) is the conformal look-back time:

\[
\eta(z) = \int_0^z \frac{dz'}{H(z')} = \int_0^z \frac{dz'}{H_0 E(z')}.
\]

#### B. The ISW filter function

The temperature anisotropies due to the ISW effect are expressed by an integral over the conformal lookback time:

\[
\delta T^{SW}(\hat{n}) = 2 \int_0^{\eta_0} \frac{d\eta}{\eta} \frac{\partial \Phi}{\partial \eta},
\]

The local gravitational potential is related to the matter distribution via the Poisson equation:

\[
\nabla^2 \Phi = 4\pi G a^2 \rho_m \delta_m,
\]

where the gradient is taken with respect to comoving coordinates. Fourier transforming, we have:

\[
\Phi(k, \eta) = -\frac{3}{2} \Omega_m \left( \frac{H_0}{k} \right)^2 g(\eta) \delta(k),
\]

where \( H_0 \) is the Hubble constant, \( \Omega_m H_0^2 = 8\pi G \rho_m^0/3 \), and \( g(\eta) \equiv D(\eta)/a(\eta) \) is the linear growth suppression factor. Hence:

\[
f_l^T(k) = 3\Omega_m \left( \frac{H_0}{k} \right)^2 \int d\eta \frac{d\eta}{\eta} j_l(\kappa \eta). \]

So the filter function for the ISW effect is:

\[
f_l^T(k) = 3T_{CMB} \Omega_m \left( \frac{H_0}{c k} \right)^2 \int d\eta \frac{d\eta}{\eta^2} j_l(\kappa \eta(z)).
IV. TESTING COSMOLOGICAL MODELS WITH THE ISW EFFECT

We have shown that the cross-correlation between the ISW effect and the Large Scale Structure of the Universe involve two windows functions that depend on the evolution of the gravitational potential and on the clustering of structures. For this reason, comparing the observed correlation with theoretical models can help us to constrain cosmological parameters and test models. In particular, the galaxy filter function tells us where the matter is, so changing this allows us to test models for the bias relating the visible matter to the mass (including Dark Matter) and the redshift distribution of galaxies, while the ISW filter tells us how the gravitational potential change, and modifying this we can test models of gravity.

Recently the ISW-LSS correlation has been used to test models of the evolution of radio galaxies and their bias ([5], [7]), to test the galaxy part of it, or, acting on the CMB temperature part, to constrain parameters in a Unified Dark Matter model ([8]), to test an Early Dark Energy model ([9]) and to test a Galileon model ([10]).

V. RESULTS

In Figs. 1, 2, 3 are shown some of the recent results obtained with the cross-correlation between the CMB and the LSS.

Acting on the window function of galaxies, in 5 we tested different models for the redshift distribution of radio sources and the evolution of their clustering. Figure 1 shows the predicted cross-correlation of WMAP ILC CMB maps with NVSS radiosources for three different models (Pure Luminosity Evolution and two Luminosity-Density Evolution models) and a redshift-dependent bias, compared with the prediction obtained using a constant bias and the Radio Luminosity Function model. In 7 we used the ISW effect to test a new evolutionary model that describes the population properties of radio sources at low frequency, and in this case the cross-correlation between CMB and LSS allowed to confirm the validity of the model tested; in Figure 2 is shown the comparison between the predicted CCF using this model and the observed NVSS-WMAP correlation.

Modifying the CMB window function make it possible to test alternative cosmologies; in 8 we studied the ISW effect in Unified Dark Matter scalar field cosmologies, where the cross-correlation between the CMB and the Large Scale Structure of the Universe depends on the speed of sound of the unified fluid. We compared the predicted cross-correlation function for different values of this speed of sound with observations from 6 different galaxy catalogues (NVSS, HEAO, 2MASS, and SDSS main galaxies, luminous red galaxies, and quasars); in Figure 3 it is shown the analysis for the NVSS catalog.

VI. CONCLUSIONS

Our understanding of the universe is still not complete and the models we have at the moment need to be tested and compared with observations; to do it we can use different sets of obser-
FIG. 3: Cross correlation function for a Unified Dark Matter scalar field cosmology, for different values of the \( c_\infty^2 \) parameter, from ([8]).

Observations, like the Cosmic Microwave Background and the Large Scale Structure of the Universe, The cross-correlation between them is an important tool, because, as we saw, it allows us to test both the geometry and the evolution of the Universe, and can help to constrain theories of gravity, models for the dark energy component of the Universe, and the evolution of clustering of galaxies. In this talk we pointed out the power of this tool and gave some examples of recent and ongoing tests that are being done using it.

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