Testing Dark Energy with HI Surveys:

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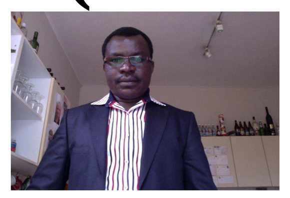

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Introduction

One of the key problems in cosmology today is to identify the source of the late time acceleration of the universe. Is it an anti- gravity field called dark energy? If so, what kind of dark energy - vacuum energy (the cosmological constant) or a dynamical scalar field (quintessence) or a field that interacts with dark matter? Given the lack of a fundamental theory for dark energy, an alternative is that the acceleration is driven by a relative weakening of gravity on large scales - i.e. a breakdown of general relativity in the infrared. Radio surveys of the HI signal provide a new frontier for putting these theoretical ideas to the test, complementing the current use of optical galaxy surveys. The MeerKAT HI survey will have a fairly small volume, but will be useful to testing techniques. LOFAR will provide large volumes, and the SKA will take this much further. Theoretical work needs to be done to prepare for implementing tests of models with data from these surveys.

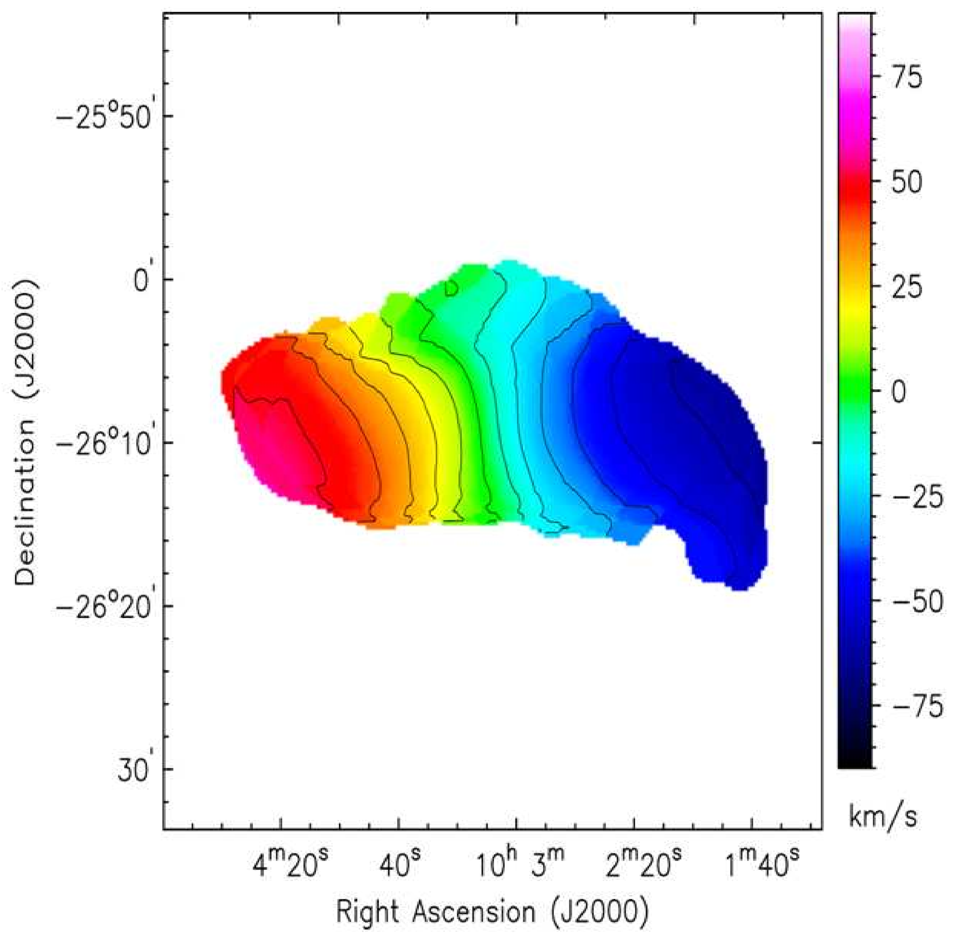

Figure 1: An HI gas Image of a rotating galaxy with blue showing motion towards us and red away from us. The rotation is not uniform- an indication of the structure and can be used to model matter distribution in the galaxy and hence probe the nature of dark energy and dark matter [4].

Problem Identification

We aim at the scientific exploitation of radio data from MeerKAT and the SKA with a focus on computing the predictions to be confronted with data. In particular, the distribution of HI is a tracer for the growth of large-scale structure in the universe and the rate of growth and other features such as peculiar velocities are highly sensitive to the nature of dark energy or modified gravity. Our work focuses on computing these indicators of growth of structure for a variety of models and help to devise tests that will rule out specific models or families of dark energy models.

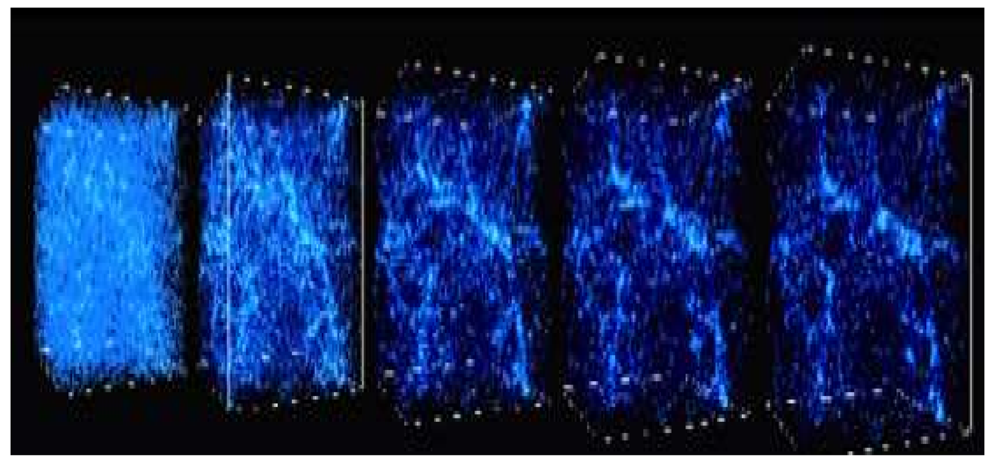

Figure 2: The process of structure formation in the universe: small over dense regions grow more over dense while small under dense regions grow more under dense.

Theory

We have computed the evolution of the density, velocity and curvature perturbations from the end of photon decoupling, for the Einstein de Sitter and ΛCDM cosmological models by numerically integrating the governing background and perturbation equations.

The Background Evolution Equations

We obtain two equations to describe evolution of the background universe, they are:

$$\Omega' = -3aH(1-\Omega)\Omega \quad \text{and} \quad H' = -\frac{3}{2}aH^2\Omega \tag{1}$$

and the background energy constraint equation:

$$\Omega_\Lambda = 1 - \Omega \tag{2}$$

where $\Omega = \frac{8\pi G\rho}{3H^2}$ is the dimensionless matter *density parameter* and the 'prime' denotes differentiation with respect to conformal time.

The Perturbed Equations

We start with the perturbed metric in the Newtonian Gauge [2]:

$$ds^2 = a^2[-(1+2\Phi)d\eta^2 + (1-2\Phi)dx^2] \tag{3}$$

and the energy momentum tensor for perfect fluid with zero anisotropic stresses:

$$T^\mu_\nu = (\rho + p)u^\mu u_\nu + p\delta^\mu_\nu \tag{4}$$

and obtain, the perturbation equations from the perturbed Einstein Field equations (see e.g [1]):

$$\Delta^2\Phi - 3\mathcal{H}(\Phi' + \mathcal{H}\Phi) = 4\pi Ga^2\delta\rho \tag{5}$$

$$\Phi' + \mathcal{H}\Phi = -4\pi Ga^2\bar{\rho}v \tag{6}$$

$$\Phi'' + 3\mathcal{H}\Phi' + 3\Omega_\Lambda\mathcal{H}^2\Phi = 0 \tag{7}$$

while the conservation equations:

$$\delta' = k^2 v + 3\Phi' \quad \text{and} \quad v' = -\mathcal{H}v - \Phi \tag{8}$$

follow from the vanishing covariant derivative of the energy momentum tensor (4).

The dimensionless background and perturbation equations

We transform the background evolution equations (1) and the perturbation equations (6) and (8) into the ordinary differential equations in redshift space:

$$\frac{d\Omega}{da} = -\frac{3}{a}(1-\Omega)\Omega \tag{9}$$

$$\frac{dh}{da} = -\frac{3}{2a}h\Omega \tag{10}$$

$$\frac{d\Phi}{da} = -\frac{3}{2}\Omega hu - \frac{\Phi}{a} \tag{11}$$

$$\frac{d\delta}{da} = -\frac{9}{2}hu\Omega + \frac{l^2}{a^2h}u - \frac{3}{a}\Phi \tag{12}$$

$$\frac{du}{da} = -\frac{1}{a}u + \frac{1}{a^2h}\Phi \tag{13}$$

and using equation (5) obtain the dimensionless relativistic Poisson equation:

$$\frac{l^2}{h^2}\Phi + \frac{3}{2}\Omega a^2\left[\delta - 3ah(1+w)u\right] = 0 \tag{14}$$

where $h = \frac{H}{H_0}$, $l = \frac{k}{H_0}$ and $u = H_0 v$ are dimensionless variables and H_0 is the Hubble rate today.

Initial Conditions

we use:

$$a_{in} = 10^{-3} \tag{15}$$

$$\begin{aligned} \Omega_{in} &= \frac{\Omega_0 a_{in}^{-3}}{\Omega_0 a_{in}^{-3} + \Omega_{\Lambda 0}} \\ \Omega_{\Lambda in} &= 1 - \Omega_{in} \\ h_{in} &= (\Omega_0 a^{-3} + \Omega_\Lambda)^{1/2} \\ \Phi_{in} &= 10^{-5} \\ \delta_{in} &= -2\Phi_{in}\left(1 + \frac{k^2}{3H_0\Omega_0}a_{in}\right) \\ u_{in} &= -\frac{2\Phi_{in}a_{in}^{1/2}}{3\Omega_0^{1/2}} \end{aligned} \tag{16}$$

The Growth Rate

Defining the comoving density contrast as:

$$\Delta = \delta - 3hu \tag{17}$$

we can derive the formular:

$$\Delta'' + 2\mathcal{H}'\Delta - 4\pi Ga^2\rho\Delta = 0 \tag{18}$$

This implies that:

$$\Delta(k, a) = D(a)\Delta(k, a_{in}) \tag{19}$$

where $D(a)$ is the growth function and a_{in} is the initial value of the scale factor a. Now, since the rate of growth of galaxies is given by

$$f = \frac{d\ln D}{d\ln a} \tag{20}$$

we can test dark energy models by comparing the growth function $f(a)$ with observations from HI surveys.

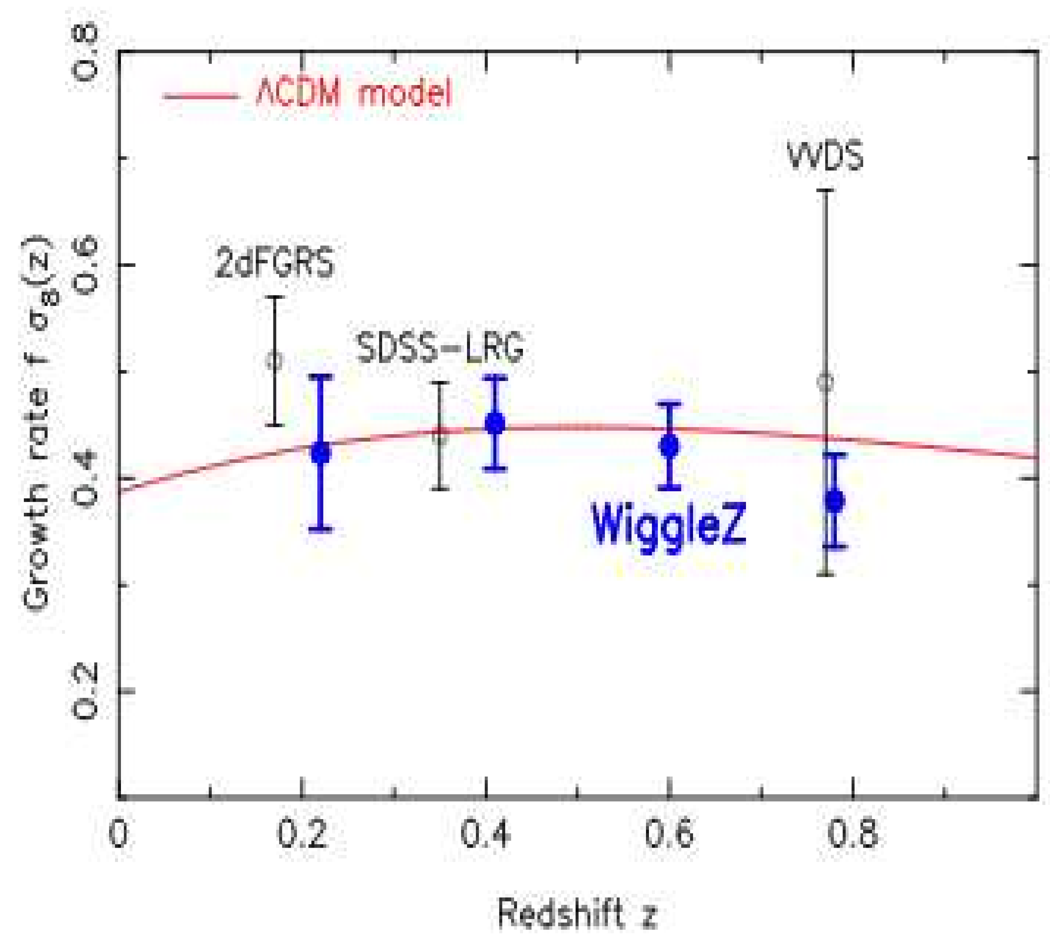

Figure 3: Measurements of the growth rate of structure weighted by a redshift-dependent normalization, $f(z)\sigma_8(z)$, obtained in four redshift slices by fitting WiggleZ Survey data showing the prediction of a flat ΛCDM cosmological model with m = 0.27 [3].

Acknowledgement

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References

[1] K. A. Malik. "Cosmological perturbations in an Inflationary Universe". *PhD thesis, University of Portsmouth UK*, 2001.

[2] L. Sriramkumar. "An Introduction to Inflation and Cosmological Perturbation Theory". *arXiv*, 0904:4584v1, 2009.

[3] C. Blake et.al. The WiggleZ Dark Energy Survey: the growth rate of cosmic structure since redshift z = 0.9.*Mon. Not. R. Soc.* arXiv no: 1104.2948v1, 2011

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