Observational tests of an inhomogeneous cosmology

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Abstract

One of the biggest mysteries in cosmology is Dark Energy, which is required to explain the accelerated expansion of the universe within the standard model. But maybe one can explain the observations without introducing new physics, by simply taking one step back and re-examining one of the basic concepts of cosmology. In standard cosmology, it is assumed that the universe is homogeneous, but this is not true at small scales ($\lesssim$ 200 Mpc). Since general relativity, which is the basis of modern cosmology, is a non-linear theory, one can expect some back reactions in the case of an inhomogeneous matter distribution. The magnitude of these back reactions is a topic of hot discussion and estimates range from insignificant to being perfectly able to explain the accelerated expansion of the universe. In the end, the only way to be sure is to test predictions of inhomogeneous cosmological theories, such as timescape cosmology, against observational data. If it is a valid description of the universe, one expects aside other effects, that there is a dependence of the Hubble parameter on the line of sight matter distribution. The redshift of a galaxy, which is located at a certain distance, is expected to be smaller if the environment in the line of sight is mainly high density (clusters), rather than mainly low density environment (voids). Here we present a test of this prediction using redshifts and fundamental plane distances of elliptical galaxies obtained from SDSS DR8 data. In order to get solid statistics, which can handle the uncertainties in the distance estimate and the natural scatter due to peculiar motions, one has to systematically study a very large number of galaxies. For this, the SDSS forms a perfect basis for testing timescape cosmology and similar theories. The preliminary results of this investigation are exciting and they might cast some light on the nature of Dark Energy.

Timescape cosmology

Inhomogeneous cosmology has been around since Tolman (1934) and Bondi (1947), but for a very long time it was a rather quiet and exotic topic. During the last 20 years significant advance were made on this field, mainly due to the work of Buchert et. al (1997, 2000, 2002, 2003, 2011), Räsänen (2004, 2006, 2009, 2011), Wiltshire (2007, 2008, 2009, 2010, 2011, 2012) and others. The basic assumption is that since general relativity is a non-linear theory, inhomogeneities like voids and cluster can cause some back reactions, which may explain the observed accelerated expansion of the universe. Buchert (2000) constructed a scheme, which is based on perturbation theory and general relativity, and they considered the inhomogeneities' influence on the average properties of cosmological parameters. In the simple case of a general relativistic dust, the equations, which describe the cosmic expansion, have to be modified to the Buchert's scheme:

$$3\left(\frac{\dot a}{a}\right)^2 = 8\pi G\left\langle\rho\right\rangle - \frac{1}{2}\left\langle R\right\rangle - \frac{1}{2}Q$$
$$3\frac{\ddot a}{a} = -4\pi G\left\langle\rho\right\rangle + Q$$
$$\partial_t\left\langle\rho\right\rangle + \frac{\dot a}{a}\left\langle\rho\right\rangle = 0$$
$$Q = \frac{2}{3}\left\langle\left(\theta - \left\langle\theta\right\rangle\right)^2\right\rangle - 2\left\langle\sigma\right\rangle^2$$

The backreaction Q is defined by the expansion θ and the shear σ. But the acceleration of the universe's expansion cannot be fully understood in a simple pertubative approach alone (Räsänen, 2006; Kolb et al., 2006; Ishibashi and Wald, 2006). One of the most advanced conceptions of an inhomogeneous cosmology, which can mimic dark energy, was created by Wiltshire (2007) and it is called "timescape cosmology". He uses a simple two-phase model consisting of a fractal bubble of empty voids and dense walls (clusters). Both regions are separated by the finite infinity boundary (see Fig.1), which encloses gravitationally bound regions and disconnects them from the freely expanding voids.

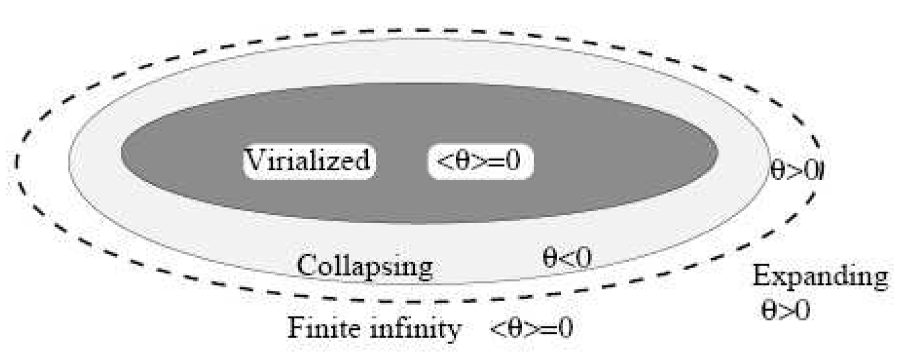

Figure 1: A schematic illustration of the concept of finite infinity (by David Wiltshire, 2007).

In this model, a back reaction also causes significant differences in the time flow, due to effects of quasilocal gravitational energy: the universe in the middle of a void is older than in the centre of a cluster. Due to this effect, this specific theory of inhomogeneous cosmology is also called timescape cosmology. **As a consequence of the importance of the local geometry in this model, the Hubble flow is not uniform anymore and the empty voids expand faster than the dense walls. At large scales these different expansion rates will lead to the signature of an overall accelerated expansion of the universe, because in timescape cosmology the fraction of the volume occupied by voids constantly increases with time.** According to Wiltshire, the dynamics of this fractal bubble model can be described by following equations:

$$\left(\frac{\dot{\bar a}}{\bar a}\right)^2 + \frac{\dot f_v^2}{9 f_v(1-f_v)} - \frac{\alpha^2 f_v^{\frac{1}{3}}}{\bar a^2} = \frac{8\pi G}{3}\bar\rho_0\frac{\bar a_0^3}{\bar a^3}$$
$$\ddot f_v + \frac{\dot f_v^2(2f_v-1)}{2f_v(1-f_v)} + 3\frac{\dot{\bar a}}{\bar a}\dot f_v - \frac{3\alpha^2 f_v^{\frac{1}{3}}(1-f_v)}{2\bar a^2} = 0$$

The variable f_v denotes the volume fraction of voids in the universe, which is of course time dependent. Recently there have been several papers (Bose & Majumdar, 2012; Clarkson et al., 2012, 2011, 2009; Wiltshire et al., 2012; Buchert, 2011; Clifton, 2011; Coley, 2010; van den Hoogen, 2010; Paranjape, 2009), which show that the magnitude and importance of these back reactions is still a topic of hot discussion. Timescape cosmology and similar inhomogeneous cosmologies may provide possible solutions for the dark energy problem, but the estimates of the magnitude of back reaction from voids and their influence on the expansion of the universe range from negligible to extremely important (Marra & Pääkkönen, 2010; Mattsson & Mattsson, 2010; Kwan et al., 2009; Clarkson et al., 2009; Paranjape, 2009; van den Hoogen, 2010). Therefore, observational tests are essential for the ongoing debate.

Predictions of the theory

There are several predictions of timescape cosmology, which can be used as potential tests. But most of them are extremely difficult and not possible nowadays or leave quite some space for interpretation and cannot produce striking evidence neither for nor against the theory. Here we focus on a very direct test proposed by Schwarz (2010) and Wiltshire (2009, 2011), namely measuring the different expansion rates of voids and walls directly. Those should differ by about 10 to 20%, in order to explain the observed accelerated expansion with timescape cosmology: **The Hubble parameter is larger, if the foreground is void dominated, rather than wall dominated.**

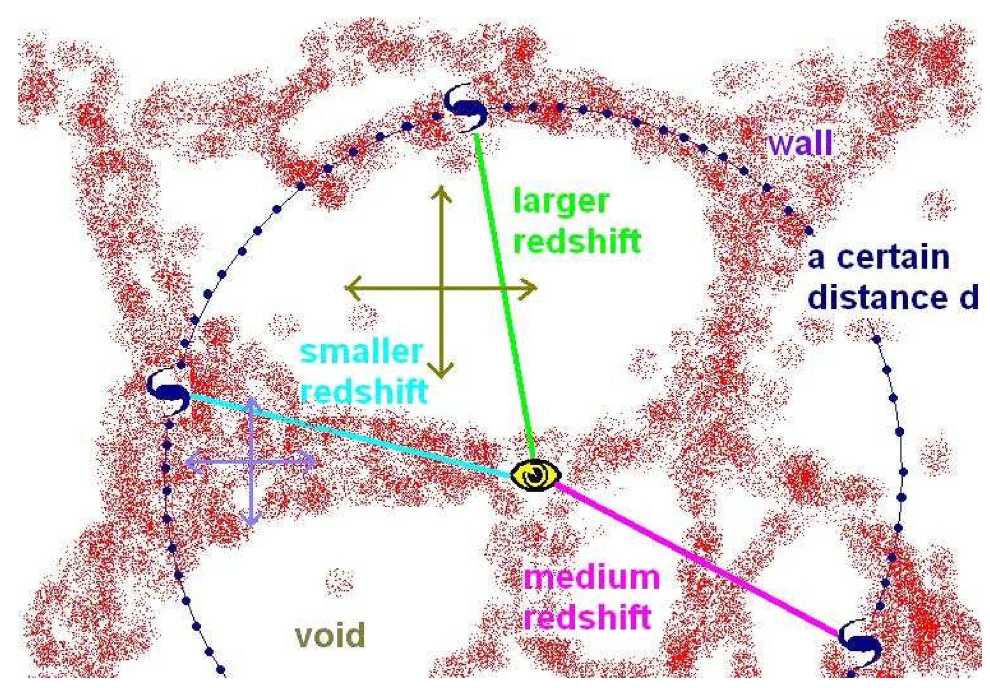

Figure 2: The measured redshift at a fixed distance depends on matter distribution in the line of sight.

This test requires:

- Redshift data
- A redshift independent distance indicator
- A model of the matter distribution in the line of sight

Potential problems:

- Uncertainty in the distance measurement
- Peculiar motions of the galaxies
- Mass estimates for matter distribution

These problems can be handled by using a large homogeneous sample.

Testing the predictions

Data from the Sloan Digital Sky Survey DR8 (SDSS)

- Spectroscopic data
  - Redshift
  - Central velocity dispersion
- Photometric data
  - Model magnitudes in 5 different filters
  - Effective radii of these models
  - Extinction map (Schlegel)
- SDSS-based third party data
  - Galaxy classifications (GalaxyZoo - Lintott et al. (2008, 2010))
  - Masses of groups and clusters (catalog by Yang et al. (2008))

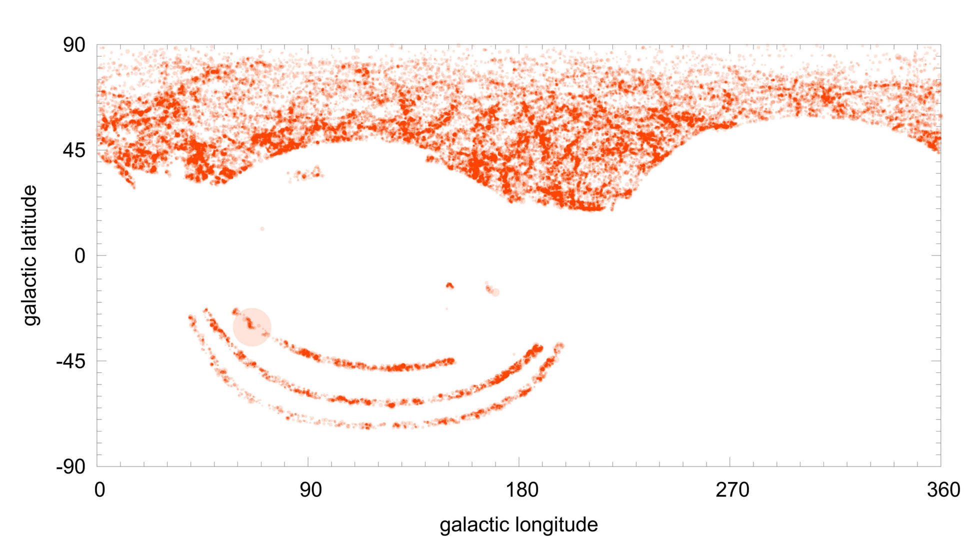

Figure 3: A part of the foreground model between 100 and 150 h^{-1} Mpc. One can also see the sky coverage of SDSS here.

- Foreground model (see Fig. 3)
  - More than 350 000 galaxies
  - Mass from Yang et al. (2008) or mass-light ratios
  - Homogeneous spheres with renormalized critical density
  - Distances from redshift-distance relation
- Fundamental plane model as a redshift independent distance indicator
  - $R_0 = a\cdot\log(I_0) + b\cdot\log(\sigma_0) + c$
  - Calibrated using about 70 000 elliptical galaxies (see Fig. 4)
  - Classifications from GalaxyZoo
  - All required parameters derived from SDSS data
  - Use it to calculate redshift independent distances for a quality selected sample of 10 000 ellipitcal galaxies

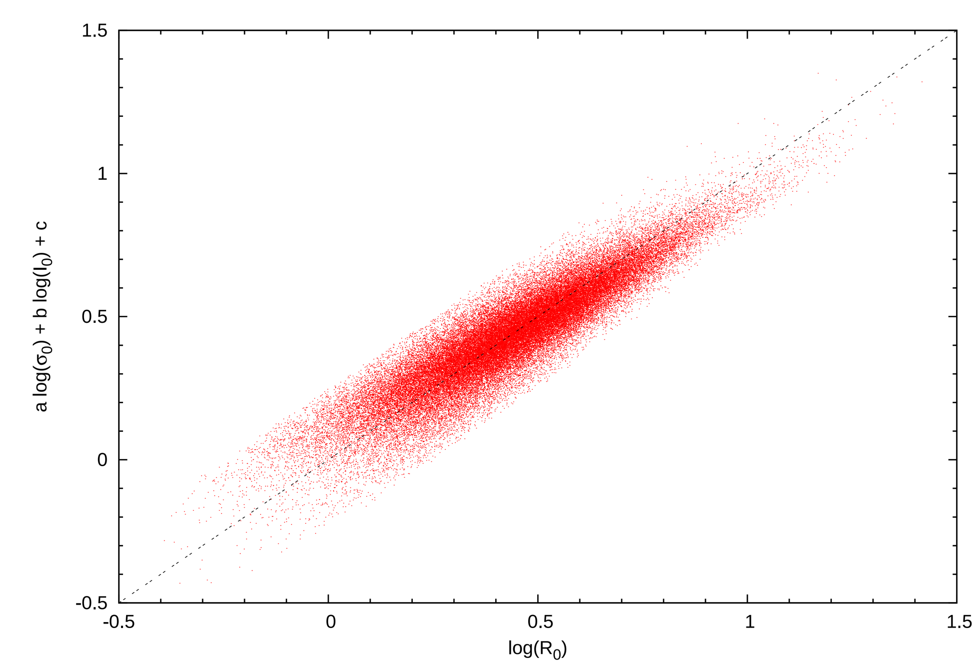

Figure 4: The fundamental plane of elliptical galaxies is an empirical relation between the effective radius R_0, the central velocity dispersion σ_0 and the average surface brightness I_0.

- Final analysis
  - Use redshifts and FP-distances to calculate "individual Hubble parameters" for every galaxy in the sample
  - Calculate the fraction of the line of sight, which is in wall environment (inside a finite infinity boundary) using the foreground model
  - Put the results in correlation

Preliminary results

- Systematically larger Hubble parameters for low density environment (voids) in the line of sight (see Fig. 5)
- The distribution is not as smooth as may be expected, given the dearth of galaxies for void foreground and below average Hubble parameter. This is still a matter of concern for us in this analysis.
  - Unknown biases?
  - Further improvements on the foreground model necessary?
  - Unknown systematic effects?

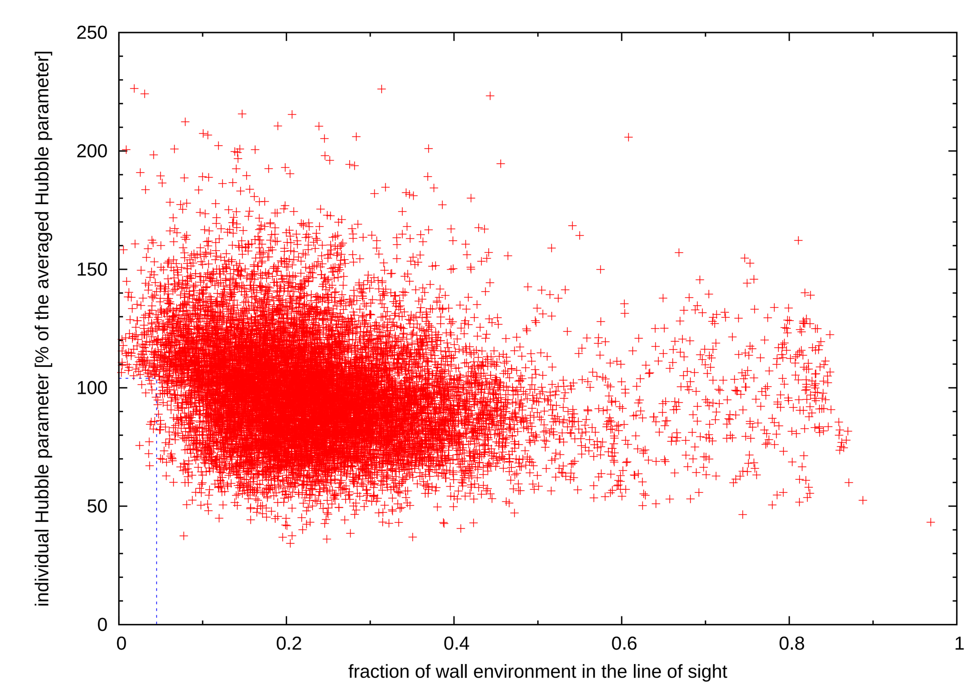

Figure 5: This plot shows the dependence of the Hubble parameter on the foreground matter distribution.

- Additional science output
  - New fits for the fundamental plane
  - Peculiar velocities
  - Data on the large scale structure of the local universe