arXiv:1205.4238v2 [astro-ph.CO] 12 Jun 2012

Mon. Not. R. Astron. Soc. **000**, 1–22 (2012)   Printed 13 June 2012   (MN LaTeX style file v2.2)

The darkness that shaped the void: dark energy and cosmic voids

E. G. Patrick Bos[1]*, Rien van de Weygaert[1], Klaus Dolag[2,3], Valeria Pettorino[4]
[1] *Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands*
[2] *Department of Physics, Ludwig-Maximilians-Universität, Scheinerstr. 1, 81679 München, Germany*
[3] *Max Planck Institut für Astrophysik, P.O. Box 1317, D-85741 Garching, Germany*
[4] *Université de Genève, Département de physique théorique, 24 Quai Ansermet, 1211, Genève, Switzerland*

13 June 2012

ABSTRACT

Aims: We assess the sensitivity of void shapes to the nature of dark energy that was pointed out in recent studies. We investigate whether or not void shapes are useable as an observational probe in galaxy redshift surveys. We focus on the evolution of the mean void ellipticity and its underlying physical cause. *Methods*: We analyse the morphological properties of voids in five sets of cosmological N-body simulations, each with a different nature of dark energy. Comparing voids in the dark matter distribution to those in the halo population, we address the question of whether galaxy redshift surveys yield sufficiently accurate void morphologies. Voids are identified using the parameter free Watershed Void Finder. The effect of redshift distortions is investigated as well. *Results*: We confirm the statistically significant sensitivity of voids in the dark matter distribution. We identify the level of clustering as measured by $\sigma_8(z)$ as the main cause of differences in mean void shape $\langle\epsilon\rangle$. We find that in the halo and/or galaxy distribution it is practically unfeasible to distinguish at a statistically significant level between the various cosmologies due to the sparsity and spatial bias of the sample.

Key words: Cosmology: theory – large-scale structure of universe – dark energy – methods: data analysis – numerical simulations

1 INTRODUCTION

One of today's greatest puzzles is that of the nature of the dark components of our universe: dark matter (DM) and dark energy (DE). According to concordance cosmology, these make up respectively 21.7% and 73.8% of the total cosmic energy content (Komatsu et al. 2011), a total of 95.5%. Yet, there are no compelling observational indications for the precise nature of dark matter and dark energy (Komatsu et al. 2011; Amanullah et al. 2010).

While there is considerable agreement on some of the physical properties of dark matter, the nature of dark energy remains a complete mystery. It is not even sure whether it really concerns an energy component to be associated to a new species in the universe or rather a modification of gravity itself, as in extensions of general relativity like scalar-tensor theories.

It is far from trivial to constrain the nature of dark energy, due to the relatively weak imprint of the equation of state of dark energy, in combination with sizeable observational errors (Frieman, Turner & Huterer 2008). Nonetheless, since the Supernova Cosmology Project and the High-z Supernova Search Team first hinted to the accelerated expansion of the universe (Riess et al. 1998; Perlmutter et al. 1999), a range of astrophysical probes have led to a considerable narrowing of the parameter space for the nature of dark energy. Weak gravitational lensing by the large scale matter

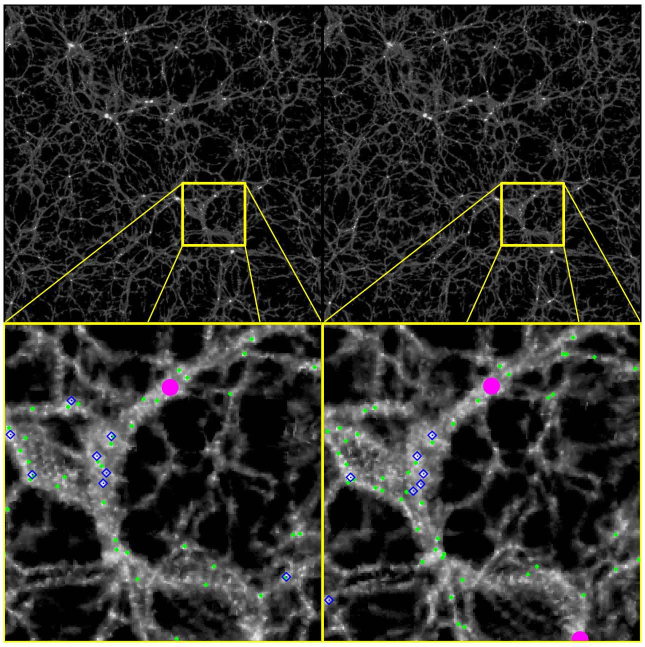

Figure 1. ΛCDM (left) and quintessence (right) cosmologies; dark matter density (grey) and galaxies (coloured dots). Differences are subtle; measuring them is the challenge of this paper.

---

* Email: pbos@astro.rug.nl

© 2012 RAS

distribution, baryonic acoustic oscillations (BAOs) and the redshift dependent number density of clusters of galaxies are well-known examples of dark energy probes. Based on these, a range of observational and experimental programs have been initiated in order to constrain the nature of dark matter and dark energy. Notable examples are BAO experiments like WiggleZ (Drinkwater et al. 2010), BOSS (Ross et al. 2010), the Dark Energy Survey and large weak lensing surveys like KiDS (de Jong et al. 2012). Ambitious projects like ESA's Euclid Mission (Laureijs et al. 2011) and the Large Synoptic Survey Telescope (LSST) will considerably sharpen and extend our knowledge on the dark energy content of the universe. Most of these probes directly relate to the cosmic distance measure.

Probes like the integrated Sachs Wolfe effect (ISW) (Dupé et al. 2011) and the structure formation growth rate (Linder 2006; Guzzo et al. 2008) offer alternative paths towards constraining dark energy. However, these probes are still ridden by considerable uncertainties. In preparation for the upcoming large dark energy experiments, it is therefore of great importance to find a wider range of reliable and independent probes for the determination of the dark energy equation of state. The combination of different and independent observations and measures of dark energy is crucial for breaking degeneracies and constraining the allowed parameter space. The recent study by Amanullah et al. (2010) illustrates the potential of such an approach to further pin down dark energy and other cosmological parameters.

1.1 Voids & cosmology

Here, we are particularly interested in the imprint of dynamical dark energy (Wetterich 1988).

Several recent studies have pointed out that cosmic voids not only represent a key constituent of the cosmic mass distribution, but that they are also one of the cleanest probes and measures of global cosmological parameters. Their structure, morphology and dynamics reflects the nature of dark energy (Park & Lee 2007; Lee & Park 2009; Lavaux & Wandelt 2010; Biswas, Alizadeh & Wandelt 2010; Lavaux & Wandelt 2011; Shoji & Lee 2012), dark matter (Hellwing, Juszkiewicz & van de Weygaert 2010; Li 2011) and that of the possibly non-Gaussian nature of the primordial perturbation field (Kamionkowski, Verde & Jimenez 2009). Lavaux & Wandelt (2010) demonstrated the extreme sensitivity of the evolving ellipticity of voids to the equation of state of dark energy. Biswas, Alizadeh & Wandelt (2010) even quoted the possibility of improving the Dark Energy Task Force figure of merit by a factor of a hundred for future experiments like Euclid.

Along a related and perhaps even more promising route, Lavaux & Wandelt (2011) demonstrated the potential of using an Alcock-Paczysnki test on the average shape of stacked voids (also see Shoji & Lee 2012). By stacking a large number of voids, one expects a spherical shape, so that size differences in radial and transverse direction can be directly related to the product of angular diameter distance and Hubble parameter. The claim is that for Euclid-like surveys stacked voids would outperform BAOs by an order of magnitude in accuracy (Lavaux & Wandelt 2011).

Other studies have explored the possibility to use voids for inferring information on the amount and nature of dark matter. Void outflow velocities and the accompanying redshift distortions might be used to determine Ω_m, the mass density of the universe, and infer the amount of dark matter (Martel & Wasserman 1990; Dekel & Rees 1994; Ryden & Melott 1996). However, void outflow velocities are difficult to measure, while void redshift distortions are restricted because of the naturally limited void outflow. Nonetheless, recent advances in the study of cosmic flows, have shown the prominent and clearly recognizable dynamical role of voids in the nearby universe (Courtois et al. 2012; Tully et al. 2008). Related observations have been made with respect to the sensitivity of voids to the identification of dark matter. The emptiness of voids would be a direct measure of the strength and screening length of the class of long-range scalar-interacting dark matter models that have been forwarded as a possible means of explaining several deficiencies of the concordance ΛCDM model (Farrar & Peebles 2004; Gubser & Peebles 2004; Nusser, Gubser & Peebles 2005; Peebles & Nusser 2010; Hellwing, Juszkiewicz & van de Weygaert 2010; Li 2011). Most prominent amongst these deficiencies is the observed dearth of dwarf galaxies in nearby voids (Peebles 2001). Given the extreme environment of voids, probing the tail of the cosmic density and halo mass distribution (Platen, van de Weygaert & Jones 2012), they form a natural resort for exploring the imprint of possible modifications of general relativity, such as $f(R)$ gravity (Li 2011) and MOND/TeVeS (Llinares 2011).

1.2 Voids

Voids form a prominent aspect of the megaparsec distribution of galaxies and matter (Chincarini & Rood 1975; Gregory & Thompson 1978; Einasto, Joeveer & Saar 1980; Kirshner et al. 1981; Kirshner et al. 1987; de Lapparent, Geller & Huchra 1986; van de Weygaert 1991; Colless et al. 2003; Tegmark et al. 2004; Furlanetto & Piran 2006; Huchra et al. 2012). They are enormous regions with sizes in the range of $20 - 50\ h^{-1}\mathrm{Mpc}$ that are practically devoid of any galaxy. They are usually roundish in shape and occupy the major share of space in the universe (see van de Weygaert & Platen 2011, for a recent review). Surrounded by elongated filaments, sheetlike walls and dense compact clusters, they weave the salient weblike pattern of galaxies and matter pervading the observable universe.

Voids in the galaxy distribution account for about 95% of the total volume (Jõeveer, Einasto & Tago 1978; Kauffmann & Fairall 1991; El-Ad, Piran & da Costa 1996; El-Ad & Piran 1997; Rojas et al. 2005; Pan et al. 2012). The typical sizes of voids in the galaxy distribution depend on the galaxy population used to define the voids. Voids defined by galaxies brighter than a typical L_* galaxy tend to have diameters of order $10 - 20\ h^{-1}\mathrm{Mpc}$, but voids associated with rare luminous galaxies can be considerably larger; diameters in the range of $20 - 50\ h^{-1}\mathrm{Mpc}$ are not uncommon (Hoyle & Vogeley 2002; Plionis & Basilakos 2002). Even larger voids can be recognized in the distribution of clusters (Bahcall 1988; Einasto et al. 1994, 2001).

Evolving out of primordial underdensities, voids become increasingly isotropic objects (Icke 1984) with a "bucket-shape" density profile whose density in the centre has a characteristic value of $\delta \approx -0.8$ (Sheth & van de Weygaert 2004). To a first approximation, (isolated) spherical underdensities will become more spherical as they expand (Icke 1984; van de Weygaert & van Kampen 1993). In reality, voids will never reach perfect sphericity. Their flattening is a result of large scale dynamical and environmental influences (Platen, van de Weygaert & Jones 2008). They will encounter surrounding structures such as overdense filaments or walls. Moreover, they retain an uncommonly large sensitivity to the dynamical influence of their large scale environment. In most situations this remains the dominant factor, to the extent that voids are found to become more anisotropic as time proceeds. Under realistic circumstances, the evolution of voids appears to reverse the simple spherical trend expected for isolated voids (Icke 1984).

The sensitivity of voids to global cosmological parameters is a result of their unique dynamical status. On the one hand, the dynamical evolution of voids is rather straightforward, in that they tend to evolve into expanding, extended, uniform, and underdense regions with a distinct bucket-shaped profile (Sheth & van de Weygaert 2004). On the other hand, they are distinctly nonlinear objects that mark the transition scale between linear and nonlinear evolution (Sahni, Sathyaprakah & Shandarin 1994). As such, their structure and morphology reflects and magnifies cosmological differences present in the primordial universe. Also, unlike the majority of evolving overdensities in the form of dark matter haloes and galaxies, their evolution retains the dominant influence of the inhomogeneous cosmological surroundings (Platen, van de Weygaert & Jones 2008). All these factors conspire to make voids into important and optimal cosmological sources of information.

1.3 Observing voids

The use of voids as a cosmological probe involves at least three major complicating factors.

A first point of attention is the very definition of a void. This involves the need for a clear and unambiguous detection and delineation of the near empty void regions. A range of studies have forwarded a large and diverse number of techniques and methods to accomplish this. For a complete overview of these algorithms we refer to the comparison study by Colberg et al. (2008) and to the study of Lavaux & Wandelt (2010). We will use the Watershed Void Finder, developed by our group (Platen, van de Weygaert & Jones 2007). This method allows a parameter-free determination of the size and shape of voids in the matter and galaxy distribution. We will discuss some of the relevant technical details in §4.

A second issue concerns the fact that the relevant observations of cosmic structure consist almost exclusively of galaxy redshift surveys. The use of redshifts for distance estimation distorts the observed shapes of structures (Shoji & Lee 2012). This is a consequence of the peculiar velocities in and around these objects. In the case of voids, matter and galaxies are flowing out of the density depressions as a result of the lower than average gravitational attraction. As a result, with respect to the Hubble flow we see galaxies at the frontside moving towards us and those at the backside moving away from us, stretching the void along the radial direction. A number of studies in the nineties proposed this as a possible means of extracting global cosmological information from voids (e.g Ryden & Melott 1996). Recent studies confirm this idea (Percival & White 2009; Jennings, Baugh & Pascoli 2011).

A third and major complicating factor for the study of voids in observations is the fact that we have to infer their properties from the diluted and possibly strongly biased population of galaxies. Galaxy redshift surveys are necessarily limited in their spatial resolution of cosmic structure. Even in the Sloan Digital Sky Survey (SDSS), structure is delineated by relatively bright galaxies. The spatial void distribution defines an intrinsically hierarchical complex of voids, in which a void consists of an assembly of subvoids (Sahni, Sathyaprakah & Shandarin 1994; Sheth & van de Weygaert 2004; Aragon-Calvo et al. 2010; Aragon-Calvo & Szalay 2012). Finer substructure can only be observed when sampling ever fainter objects. Hence, the brighter galaxies of SDSS only trace the rough outline of larger voids, with sizes in the order of $10 - 15\ h^{-1}\mathrm{Mpc}$. Even more complicating is the issue of the possible bias of galaxies with respect to the dark matter distribution. While moderate density regions ($\delta \sim 0-$ a few) appear to have a rather low level of bias, a range of studies have indicated a strong bias of galaxies in and around the lowest density regions. Peebles (2002) strongly emphasized the fact that dwarf galaxies seem to avoid the void regions, contrary to the expectations and predictions of most galaxy formation theories. This *void phenomenon* is one manifestation of what appears to be a rather puzzling situation with respect to the galaxy distribution in voids: different semi-analytical schemes of galaxy formation predict either bias or anti-bias (Platen 2009; Platen, van de Weygaert & Jones 2012).

In figure 1 the galaxies/haloes (points) are overlaid on the full density field, illustrating that the spatial distribution of the two don't match. This is an especially poignant example of the fact that void substructure is lost on small scales. The large void of $\sim 30\ h^{-1}\mathrm{Mpc}$ at the right of the figure is traced only on the outside by galaxy-like "haloes" (more on this in §3.2).

1.4 Voids in the halo distribution

In this study, we address the issue of whether it is feasible to infer the nature of dynamical dark energy from the evolving population of voids in the observational context of the voids being sampled by a dilute population of discrete objects, like dark matter haloes and galaxies.

In this, we follow the strategy of identifying voids only and solely on the basis of the spatial distribution of the sampled objects. From the distribution of galaxies or haloes, we outline voids with the help of the Watershed Void Finder (WVF). While under ideal circumstances, one might consider to use knowledge of the dynamical evolution of voids, we chose not to do so given the uncertainties about the bias of void galaxies: it would amplify any difference between the sampled halo/galaxy distribution and the underlying density field. Our plan is to follow the evolution of the shape of voids inferred from the spatial *dark matter* and *dark halo* distribution at each epoch and to compare the results obtained for different dynamical dark energy models. The void population in the *dark matter* distribution of the different dark energy cosmologies is expected to reflect the sensitivity to the nature of dark energy. How accurately the void population in the *dark halo distribution* manages to follow this sensitivity, is one of the main questions to be answered by this study.

Also, we investigate the origin of the dependence of voids to the nature of dark energy. We presume that the structure of voids at any cosmic epoch is a reflection of the stage of structure development in the corresponding dark energy cosmology. This suggests a strong relation between the amplitude of the density and velocity perturbations in the mass distribution and the structure, shape and profile of the voids. We therefore assess in how far the void shape evolution in different dark energy scenarios can be ascribed to σ_8, the root mean square density fluctuation within a sphere of radius $8\ h^{-1}\mathrm{Mpc}$, and whether there are other possible factors of influence.

1.5 Outline

The outline of this paper is as follows. In §2 we will treat cosmological models, four of which contain a time dependent dark energy component and discuss cosmic voids and their theoretical use in discerning between cosmological models. We will give a description of the data in §3. Void identification is invaluable to our analysis and we will elaborate on this in §4. In §5 we describe the void