Cold imprint of supervoids in the Cosmic Microwave Background re-considered with Planck and BOSS DR10

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Submitted 2015

ABSTRACT

We analyze publicly available void catalogs of the Baryon Oscillation Spectroscopic Survey Data Release 10 at redshifts $0.4 \leq z \leq 0.7$. The first goal of this paper is to extend the Cosmic Microwave Background stacking analysis of previous spectroscopic void samples at $z < 0.4$. In addition, the DR10 void catalog provides the first chance to spectroscopically probe the volume of the Granett et al. (2008) supervoid catalog that constitutes the only set of voids which has shown a significant detection of a cross-correlation signal between void locations and average CMB chill. We found that the positions of voids identified in the spectroscopic DR10 CMASS galaxy catalog typically do not coincide with the locations of the Granett et al. (2008) supervoids in the overlapping volume, in spite of the presence of large underdense regions of high void-density in DR10. The stacking of filtered CMB temperatures at these different void locations shows a $\Delta T = -6.2 \pm 3.4 \mu K$ signal for the 120 largest voids, otherwise the correlation is washed out by statistical uncertainties. This correlation is, however, significantly lower than the $\Delta T = -11.5 \pm 3.7 \mu K$ we found by stacking 35 of the 50 Granett et al. (2008) supervoids available in the DR10 volume. This failure to reproduce the signal with a different void catalog may be due to systematic differences in the detection of voids in photometric and spectroscopic samples.

Key words: surveys – cosmology: observations – large-scale structure of Universe – cosmic background radiation

1 INTRODUCTION

Large-scale structures at low redshift leave their mark on the Cosmic Microwave Background (CMB) radiation providing direct probes of the late time cosmic acceleration and the physics of Dark Energy [Aghanim et al. 2008]. In particular, large voids and clusters can imprint themselves to the primary fluctuations of the CMB via physical mechanisms called the Integrated Sachs-Wolfe effect (Sachs & Wolfe 1967, ISW) in the linear regime, and the Rees-Sciama effect (Rees & Sciama 1968, RS) on non-linear scales. The expected ISW correlation in the $\Lambda CDM$ model is on the order of $0.1 \mu K < |\Delta T| < 1 \mu K$ for typical voids [Cai et al. 2010], extending up to $|\Delta T| \approx 20 \mu K$ for the largest observable superstructures which are also the rarest (see e.g. Szapudi et al. 2014; Nadathur et al. 2014). The contribution of the non-linear RS effects remains typically at the $\sim 10\%$ level compared to the linear expectation [Cai et al. 2010]. However, the ISW and RS effects and their relative strength may be different in alternative cosmologies [Cai et al. 2014].

The typical ISW and RS imprints are thus small enough to be immeasurable. The traditional approach for detecting the weak signal is the angular cross-correlation measurement between galaxy density maps and the CMB. This detection strategy has been followed by a series of studies finding both marginally (see e.g. Francis & Peacock 2010, Kovács et al. 2013) and moderately significant (see e.g. Ho et al. 2008; Giannantonio et al. 2008, 2012; Planck Collaboration et al. 2014 and references therein) ISW-like signals.

Another approach is focused on the largest structures in the density field, where the ISW-RS effect is expected to be the strongest. Foremost, Granett et al. (2008) created a catalog of supervoids and superclusters [Gr08, hereafter] using the SDSS Data Release 4 (DR4) Mega-z photometric LRG catalog [Collister et al. 2007] with some additional area from DR 6. They used the ZOBOV algorithm [Neyrinck 1]

1 http://ifa.hawaii.edu/cosmowave/supervoids/
2 http://skysrv.pha.jhu.edu/neyrinck/voboz/
Figure 1. Void positions of the Gr08 sample (gold) vs. DR10 void catalog (purple). The underlying $N_{\text{side}} = 32$ HEALPix map is the DR10 void density sample smoothed with a $\sigma = 4^\circ$ Gaussian. Due to the hierarchical organisation of the void catalogue, an underdense region may be split into a number of voids of various sizes in the catalogue. Dark blue colors indicate higher void abundance thus lower average projected density.

Granett et al. (2008) found a $|\Delta T| = 9.6 \pm 2.2 \mu K$ signal for their 100 most significant (> $3\sigma$) superstructures using an aperture size of $R = 4^\circ$. This signal appears to be in ~ $2\sigma$ tension with $\Lambda$CDM predictions, as pointed out in several follow-up studies using theory and simulations (Pápai et al. 2011; Pápai & Szapudi 2010; Nadathur et al. 2012; Flender et al. 2013; Hernández-Monteagudo & Smith 2013; Hotchkiss et al. 2013; Aiola et al. 2014). Also, numerous additional tests have been performed to uncover possible systematic problems and statistical biases (Ilić et al. 2013; Planck Collaboration et al. 2014; Cai et al. 2013). It was found that varying the number of the objects in the stacking, or using different filter sizes typically lowers the overall significance. Otherwise the original Gr08 signal has survived every revisions and remained a puzzle. Additionally, Ilić et al. (2013) Planck Collaboration et al. (2014), and Cai et al. (2013) repeated the CMB stacking analysis of Granett et al. (2008) using complementary void catalogs (Sutter et al. 2012) based on spectroscopic measurements at $z < 0.4$. These studies, however, did not report a highly significant detection of the ISW-like effect found in Gr08.

In this paper we test the robustness of the Gr08 void catalog itself using the Baryon Oscillation Spectroscopic Survey (BOSS) DR10 CMASS void catalog provided by Sutter et al. (2014). On one hand, we are able to probe a significant fraction of the Gr08 volume (filled with photo-z data) with spectroscopic DR10 voids. On the other hand, we extend previous low-$z$ DR7 void stacking measurements to the range of $0.4 < z < 0.7$. Two distinct conclusions are possible: our stacking analysis could confirm the Granett et al. (2008) detection for the first time with an independent void catalog, or the ISW(-like) signal could disappear. In any case, some puzzle will certainly remain for future analyses with BOSS DR12 and Planck DR2.

The paper is organized as follows. Data sets, algorithms, and our observational results are presented in Section 2; the final section contains a summary, discussion and interpretation of our results.

2 DATA SETS AND MEASUREMENTS

2.1 CMB data

On the CMB side we use Planck’s SMICA\(^3\) map (Planck Collaboration et al. 2013) with resolution downgraded to $N_{\text{side}} = 512$ with the HEALPix (Gorski et al. 2005) pixelization. We mask out potentially contaminated

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\(^3\) http://www.cosmos.esa.int/web/planck
CMB pixels using the WMAP 9-year extended temperature analysis mask \cite[2013]{Hinshaw} at $N_{side} = 512$. It has already been pointed out by \cite{Granett}, and later confirmed by \cite{Planck}, \cite{Cai}, and \cite{Ilic} that the ISW-like cross-correlation signal detected at void locations is independent of the CMB data set when looking at WMAP Q, V, W, or \textit{Planck} SMICA temperature maps. We thus limit our analysis to the latest \textit{Planck} SMICA sky map.

2.2 Catalogs of cosmic voids

We use public void catalogs by \cite{Sutter} where the authors identified voids in BOSS DR10 spectroscopic galaxy samples \cite{Ahn}. The voids were identified with the ZOBV tool \cite{Neyrinck} within the VIDE framework \cite{Sutter}. The void-finder ZOBV is based on the watershed algorithm which builds a hierarchy of underdensities. Thus a large underdensity in the galaxy field may be represented in the catalogue by multiple voids contained by an encompassing void. We remove voids with size $R < 40 h^{-1}Mpc$ to cut the hierarchy. Furthermore, these small voids may occupy over dense regions (see \cite{Cai} for details). We also restrict our analysis to central voids to minimise possible contaminations caused by the survey mask (see e.g. \cite{Sutter} for details).

These moderately conservative cuts remove $\sim 65\%$ of the voids from the DR10 CMASS catalog. Our approach is to probe the $0.4 < z < 0.7$ redshift range thus we only consider CMASS data in our analysis.

The galaxy number density for the CMASS catalog peaks at $z=0.5$ with mean inter-galaxy separation $L \approx 16 h^{-1}Mpc$ which rises to $\sim 25 h^{-1}Mpc$ at $z = 0.65$, thus a lower cut of roughly twice this characteristic scale is a safe and reasonable choice to prune spurious void detections that would contribute only noise to the measurement \cite{Sutter}.

Following \cite{Sutter}, we divide the resulting DR10 void catalog into three subsamples; CMASS 1 at $z < 0.5$ (56 voids), CMASS 2 at $0.5 < z < 0.6$ (237 voids), and CMASS 3 at $0.6 < z < 0.7$ (172 voids). We analyze these catalogs both separately and jointly.

Finally, we removed 6 voids from the analysis, as their position was curiously outside of the rough $N_{side} = 32$ DR10 footprint by $\sim 2^\circ$. We checked the effects of these objects on our main results and found no difference.

We show our final sample together with the 50 Gr08 supervoids in Figure 1 (35 of the 50 Gr08 voids should be detectable in DR10, i.e. not masked out or residing close to the boundary). We found large regions of high density of DR10 voids, which typically do not overlap with the larger Gr08 supervoids. This somewhat counter-intuitive finding means that a potential (and expected) ISW-(like) signal in the shared DR10-Gr08 volume is in this case carried by voids at distinct locations in the sky. Also, DR10 voids are much smaller in angular and physical size than the Gr08 superstructures, due to the ability of resolving small-scale structures with spectroscopic redshifts. The number densities of the two catalogues are of similar order: while the CMASS tracer number density is $n_{1/3} \sim 14 - 22 h^{-1}Mpc$, the photometric LRG sample is $\sim 2.2$ times more dense with $n_{1/3} \sim 10 - 17 h^{-1}Mpc$.

The analysis of these issues is one of the main goals of this letter.

2.3 Methods & Results

Foremost, we repeated the stacking analysis of \cite{Granett} for the 35 supervoids available in the DR10 volume with constant $R = 4^\circ$ filter radius. The original signal of $\Delta T = -11.3 \pm 3.1 \mu K$ as measured by \cite{Granett} has changed to $\Delta T = -11.5 \pm 3.7 \mu K$. We then expected to detect a similar signal in the same physical volume with voids identified using spectroscopic redshift from the DR10 CMASS catalog.

In our methods, we closely follow \cite{Ilic} and \cite{Cai}. We first measure average temperatures in the SMICA map at void locations using the compensated top-hat filter technique applied by \cite{Granett}. We further scale the filter by angular size as advanced by \cite{Ilic} and \cite{Cai}. The same authors empirically found in data and in simulations that the optimal filter size to maximize the signal-to-noise in our tests. The resulting typical filter radius is $r_{mean} \approx 0.8^\circ$ for all CMASS sub-samples, i.e. 5 times smaller than the constant $R = 4^\circ$ filter of Gr08. \cite{Cai} also applied a weighting as a function of void probability, finding no significant difference in the signal they measured. Note that, however, other weightings, for instance weighting based on the expected signal to noise ratio, are possible, we restrict our analysis here to the simple sorting by void radius.

Our findings are presented in Figures 2 and 3, showing the void temperature measured as a function of void radius and redshift. These plots show the typical behavior of such top-hat filtered temperatures, as they contain large fluctuations for individual objects of both positive and negative signs. However, there is no obvious excess clustering or other oddity in these parameter spaces. Two exceptions are the slight average shift to the negative side for $R < 50 h^{-1}Mpc$ CMASS 2 objects, and the counteractive change at $R < 50 h^{-1}Mpc$ for CMASS 3. Note that these voids should carry the lowest ISW-RS signal among the catalog, and their robustness is questionable. \cite{Cai}.

We then average the filtered temperatures for the 465 CMASS voids, sorted by radius. We estimated statistical uncertainties by generating 1000 Gaussian CMB simulations with the HEALPix \cite{Gorski} synfast routine using the \textit{Planck} DR1 best fit CMB power spectrum \cite{Planck}. Gaussian simulations without considering instrument noise suffice because the CMB signal is dominated by cosmic variance on the scales we consider. We compare two error estimators. First, we repeated the stacking analysis 1000 times varying the CMB correlation signal detected at void locations is independent of the CMB data set when looking at WMAP Q, V, W, or \textit{Planck} SMICA temperature maps. We thus limit our analysis to the latest \textit{Planck} SMICA sky map.

\footnote{http://lambda.gsfc.nasa.gov/product/map/dr5/}

\footnote{http://www.cosmicvoids.net}
Figure 2. Filtered temperatures in re-scaled top-hats are shown as a function of their physical size. Color bars indicate the redshifts of the voids, without any apparent trend or clustering in this parameter space. We note, however, that there is a slight extra average cooling for small CMASS 2 voids. Interestingly, CMASS 3 voids behave inversely showing hotter temperature differences on average for the smallest voids. Shaded region mark out 2σ statistical uncertainties scaled with the number of objects considered, while solid lines indicate the stacked temperature for a given subsample.

Figure 3. Filtered temperatures in re-scaled top-hats are shown as a function of their redshift. No meaningful trend is observable, as all sub-samples show similar distributions. The grey shaded region marks the 1σ fluctuation $\sigma_{\Delta T} \approx 37 \mu K$ for a single object, as measured using CMB simulations.

Figure 4. Stacked CMB temperatures as a function of the number of the objects considered. A physically motivated ordering of the voids by radius is applied, as largest voids should leave the coldest imprints on the CMB. Orange points in panel 2 mark the errors obtained by measuring standard deviations for all filter sizes in simulations independently, which are in remarkably good agreement with the simplified error estimates based on 1000 randomly selected cases of slightly different angular filter size.
tainty for a single supervoid found by Granett et al. (2008), indicating larger average fluctuations in smaller filters.

We note the following features in the measurements

(i) Considering the combined sample (Fig 4, top panel), the signal fluctuates around the 1-σ level. The cold imprint peaks with an amplitude of $-6.2 \pm 3.1 \mu K$ at 1.8σ for the ~120 largest voids with sizes $R > 55 h^{-1} \text{Mpc}$. Counting all 465 voids down to $R = 40 h^{-1} \text{Mpc}$ the signal becomes $\Delta T \approx -1.5 \pm 1.7 \mu K$.

(ii) The CMASS 1 sample shows a rather constant $\Delta T \approx -5 \mu K$ signal, resulting in a final value of $\Delta T \approx -6.1 \pm 5.0 \mu K$ for the full sub-catalog with 56 void members.

(iii) The CMASS 2 sample with the largest number of voids contributes most strongly to the combined sample, thus the signal is similar to that described above. The significance rises to $S/N \approx 1.7$ when the smallest voids are included in the analysis, after fluctuating around zero (as expected) for $N_{\text{stack}} \approx 80 - 210$. The overall signal-to-noise with all voids included is $\Delta T \approx -4.1 \pm 2.4 \mu K$ for the 237 CMASS 2 objects.

(iv) The CMASS 3 temperature signal fluctuates around the 1-σ level. Adding smaller scale voids the signal becomes positive and results in a positive $\Delta T \approx 3.5 \pm 2.9 \mu K$. However, the galaxy number density is lowest in the CMASS 3 bin, so a larger fraction of the smallest voids may be spurious compared with the other more densely sampled redshift bins.

We find that there is a weak indication of the ISW(-like) signal considering the largest voids in the catalogue, however it remains below the threshold for a convincing detection. Therefore, we cannot confirm the signal found by Gr08 even with the statistical analysis of voids that fill the same physical volume. The fact that the two void catalogues trace different structures points to systematic differences in the galaxy catalogues and void finding algorithms.

3 CONCLUSIONS

We probed the volume of the supervoid catalog with the BOSS DR10 CMASS void catalog provided by Sutter et al. (2014). Our principal aim was to revisit the strong ISW(-like) signal found in Gr08 with a catalog that probes the same density field. We pruned the DR10 catalog following the protocol of Cai et al. (2013) and the suggestion of Sutter et al. (2014) for removing the smallest and least reliable voids which are also expected to produce the smallest ISW-RS signals in $\Lambda CDM$. The voids identified with spectroscopic redshifts in DR10 are smaller than the Gr08 structures traced with photometric redshifts. Even so, we find that the Gr08 supervoid positions do not coincide with the DR10 voids which indicates that the void finders are sensitive to different structures. This situation merits further study to understand the systematic differences between voids identified in spectroscopic versus photometric samples. However, the $\Delta T = -11.5 \pm 3.7 \mu K$ signal we measured for the 35 Gr08 supervoids in the DR10 footprint using the original filter size demonstrates that this volume shows higher-than-expected ISW(-like) signals which have not been understood.

In this spirit, we performed a stacking analysis using 465 DR10 voids and found a $\Delta T = -6.2 \pm 3.4 \mu K$ or 1.8σ signal for the largest 120 voids of size $R > 55 h^{-1} \text{Mpc}$ in the CMASS sample. Otherwise the detection significance remained marginal. However, even the 1.8σ correlation that emerged in the presence of the posteriori choices is far from a convincing new evidence to corroborate the Gr08 signal.

Our results, therefore, highlight that ISW detections with the stacking protocol strongly depend on the properties of the tracer population and the void finder. While the effect of photo-z errors on the performance of ZOB0V have not been tested, it was pointed out by Sutter et al. (2014), Sutter et al. (2014), and Sutter et al. (2014) that masking and the density of the tracer population strongly affects the resulting void catalogs. Furthermore systematic uncertainties remain in how the hierarchy of voids is cut and the location of void centers.

An alternative, but highly speculative view of the situation is that supervoids and voids differ not only in size but for example in the nature of their ISW(-like) effect. For instance, Szapudi et al. (2014) found a rare low-redshift supervoid aligned with the Cold Spot in the CMB (Cruz et al. 2004), but according to the comprehensive estimates of Nadathur et al. (2014) this supervoid is capable of producing only a $\Delta T \approx -20 \mu K$ imprint in the CMB via the standard ISW effect, while the Cold Spot’s decrement in its center is $\Delta T \approx -150 \mu K$. The situation is somewhat similar here, as regular voids cannot imprint themselves to the CMB effectively, although supervoids seem to produce a strong signal, for which the $\Lambda CDM$ model has no satisfactory answer.

ACKNOWLEDGMENTS

We thank Mark Neyrinck and Yanchuan Cai for giving comments that improved the paper. AK takes immense pleasure in thanking the support provided by the Campus Hungary fellowship program. Funding for this project was partially provided by the Spanish Ministerio de Economia y Competitividad (MINECO) under projects FPA2012-39684, and Centro de Excelencia Severo Ochoa SEV-2012-0234. BRG acknowledges support of the European Research Council through the Darklight ERC Advanced Research Grant (#291521).

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III web site is http://www.sdss3.org/. SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofisica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University,
the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

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