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On the void explanation of the Cold Spot

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ABSTRACT

The integrated Sachs–Wolfe (ISW) contribution induced on the cosmic microwave background by the presence of a supervoid as the one detected by Szapudi et al. (2015) is reviewed in this letter in order to check whether it could explain the Cold Spot (CS) anomaly. Two different models, previously used for the same purpose, are considered to describe the matter density profile of the void: a top hat function and a compensated profile produced by a Gaussian potential. The analysis shows that, even enabling ellipticity changes or different values for the dark-energy equation of state parameter ω, the ISW contribution due to the presence of the void does not reproduce the properties of the CS.

Key words: methods: data analysis – cosmic background radiation.

1 INTRODUCTION

The Cold Spot (CS), an extremely cold region centred on (b, ℓ) = (210°, −57°), was discovered in the *Wilkinson Microwave Anisotropy Probe* data using a multiscale analysis of the Spherical Mexican Hat Wavelet (SMHW) coefficients (Vielva et al. 2004; Cruz et al. 2005). Within the Λcold dark matter (ΛCDM) model, the significance of the occurrence of this feature in the cosmic microwave background (CMB) anisotropies was estimated between 1 per cent and 2 per cent (Cruz et al. 2006). As the Planck Collaboration confirmed, the CS shows unusual properties which come to light when the mean angular profile or the area of wavelet coefficients above a certain threshold on angular scales around 10° are analysed (Planck Collaboration XIII; Planck Collaboration XVI 2015). Besides the possibility that the CS could be a statistical fluke, different explanations have been proposed. Although this letter is focused on the void hypothesis, other physical mechanisms include a cosmic bubble collision (Czech et al. 2010; Feeney et al. 2011; McEwen et al. 2012), the gravitational evolution of a cosmic texture (Cruz et al. 2007), and alternative inflationary models (Bueno Sánchez 2014).

Recently, there has been a debate on whether the CS could be explained as a consequence of the presence of a large void, which was detected in the *WISE*–2MASS galaxy survey at the same direction (Szapudi et al. 2015; Finelli et al. 2016). Actually, this is not the first time in which a void arises as the possible origin of the CS (see e.g. Tomita 2005; Inoue & Silk 2006; Rudnick, Brown & Williams 2007; Cruz et al. 2008; Bremer et al. 2010; Granett, Szapudi & Neyrinck 2010). This low-density region is consistent with a supervoid centred at $z \approx 0.15$–0.25, depending on its characterization. The alignment of the void and the CS is pointed out as a hint of a physical connection between both phenomena. They built their argument based on a probabilistic discussion about this alignment and a particular case of the Lemaître–Tolman–Bondi (LTB) model with a Gaussian potential (Finelli et al. 2016) to infer the angular profile of the CMB imprint of a spherically symmetric supervoid in the number density of galaxies. In this latter paper, the connection between the supervoid detected in *WISE*–2MASS and the CS was analysed in the light of the integrated Sachs–Wolfe (ISW) and the Rees–Sciama contributions. However, Zibin (2014) and Nadathur et al. (2014) show independently that the first-order ISW contribution from the presence of this type of void is actually dominant with respect to the non-linear component (Rees–Sciama effect), and therefore the corresponding temperature decrement induced in the CMB by the presence of a void as the one mentioned above ($\approx -19\,\mu$K) would not be intense enough to account for the depth of the CS ($\approx -150\,\mu$K).

In this letter, we explore the latter argument through a supplementary analysis in the SMHW coefficients (Martínez-González et al. 2002) at the specific CS angular scale, since the anomaly is detected in the SMHW space. In addition, we extend the void models enabling ellipticity changes to check that a different geometry could not produce an ISW contribution which accounts for the CS. We also show that alternative simple models of dark energy cannot reconcile the CMB contribution from a supervoid and the observed CS temperature. Finally, we discuss the previous analyses.

2 THE VOID INFLUENCE ON THE CMB

As it is known, within the standard cosmological model, the contribution of any possible supervoid is already included in the total CMB anisotropies (as a part of the linear ISW contribution) and therefore the presence of a standard and linear underdensity cannot explain the anomalous temperature decrement of the CS. The assumption that the effect on the CMB photons due to the non-linear evolution of the potential is negligible with respect to the ISW contribution is based on previous analyses of the Rees–Sciama

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contribution, which becomes noticeable at multipoles $\ell > 80$ ($\lesssim 2°$), and even at these angular scales, its value is much lower than the ISW component at large scales (see e.g. Cai et al. 2010). Therefore, a rare void is needed in order to explain the CS with the ISW and Rees–Sciama effects. These non-standard scenarios are explored varying the void eccentricity up to very unlikely values. In any case, the angular size of the ISW effect of the voids considered in this work is greater than several degrees.

Besides the amplitude of this decrement, the profile of the CS is also important to characterize the anomaly because a particular shape is preferred when it is selected in the SMHW coefficients. In this section, we first review the main conclusions about the ISW contribution expected from the presence of a void as that detected by Szapudi et al. (2015). Subsequently, the impact of varying the ellipticity of the void is also explored. In addition, non-standard scenarios with different values of ω are considered to check whether the void prediction is able to cause a temperature decrement as that observed in the CS.

2.1 Spherical model

Because of symmetry assumptions, the ISW contribution to the CMB anisotropies caused by a large-scale structure (LSS) fluctuation can be written as:

$$\frac{\Delta T(\theta)}{T_{\rm CMB}} = -2\int {\rm d}z\,\frac{{\rm d}G(z)}{{\rm d}z}\,\Phi\left(\sqrt{\chi^2(z)+\chi_0^2-2\chi(z)\chi_0\cos\theta}\right), \qquad (1)$$

where θ denotes the angular distance from the centre of the void at $\chi_0 = \chi(z_0)$, in comoving distance. The gravitational potential $\Phi(\boldsymbol{r}, z)$ is factorized into the growth suppression factor $G(z)$ and a spatial dependence $\Phi(r)$ which, assuming $G(0) = 1$, represents the potential at $z = 0$.

In this letter, two different density profiles, which have been already used to the same purpose, are considered. On the one hand, a spherical top hat (TH) model (Szapudi et al. 2015), parametrized by its radius R. In this case, the potential can be written as

$$\Phi(r) = \begin{cases} \phi_0 R^2\left(3-\frac{r^2}{R^2}\right), & \text{if } r \le R \\ \phi_0\frac{2R^3}{r}, & \text{if } r > R, \end{cases} \qquad (2)$$

where r denotes the comoving distance from the centre of the void.

When distances greater than R are considered, this model behaves as a point-like particle: it presents an inverse dependence on distance, and therefore the gravitational effect is extended far beyond distances as the size of the void.

On the other hand, a particular case of LTB model is considered (Nadathur et al. 2014; Finelli et al. 2016). The potential is described in this case by a Gaussian profile:

$$\Phi(r) = \phi_0 {r_0}^2 \exp\left(-\frac{r^2}{{r_0}^2}\right), \qquad (3)$$

where r_0 accounts for the scale. Hereafter, this profile is referred as the Gaussian model, although the matter underdensity profile is not Gaussian in this case.[1]

It is easy to show that, whilst the density profile associated to the Gaussian potential is compensated, that associated to the TH model is not.

[1] Notice that this model is denoted simply as LTB in previous papers (Nadathur et al. 2014; Szapudi et al. 2015; Finelli et al. 2016).

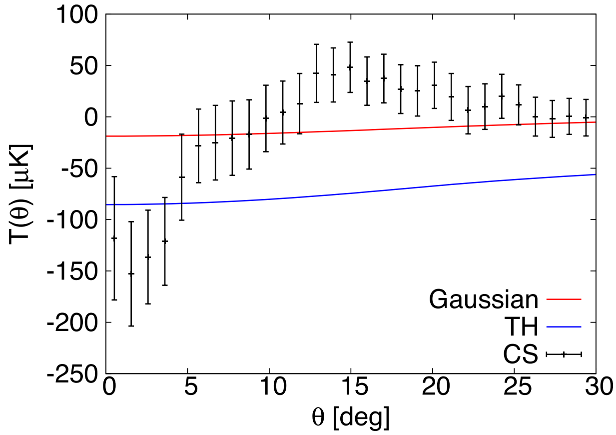

Figure 1. CMB temperature profiles induced by the presence of a supervoid modelled as a TH (in blue) and a Gaussian model (in red). The data points correspond to the CS profile from the Planck SMICA map, and the error bars represent the cosmic variance.

In both cases, the amplitude ϕ_0 is proportional to the matter density fluctuation at the void centre δ_0:

$$\phi_0 = \frac{\Omega_{\rm m}\delta_0}{4G(0)}\left(\frac{H_0}{c}\right)^2, \qquad (4)$$

where, in a flat universe, $\Omega_{\rm m} = 1 - \Omega_\Lambda$ denotes the matter energy density (in our case, with a fixed dark-energy density $\Omega_\Lambda = 0.685$), H_0 is the Hubble constant at present time and c is the speed of light in vacuum.

The best-fitting set of parameters is considered for each model. In particular, we take $R = (220 \pm 50)\,{\rm h}^{-1}$ Mpc, $\delta_0 = 0.14 \pm 0.04$, and $z_0 = 0.22 \pm 0.03$, for the TH model (Szapudi et al. 2015); and $r_0 = (195 \pm 35)\,{\rm h}^{-1}$ Mpc, $\delta_0 = 0.25 \pm 0.10$, and $z_0 = 0.155 \pm 0.037$, in the case of the LTB Gaussian model (Nadathur et al. 2014; Finelli et al. 2016).

In order to characterize the feature induced in the CMB temperature anisotropies by the presence of a supervoid, we compute its 1D shape. This profile can be expanded in terms of the Legendre polynomials:

$$\frac{\Delta T(\theta)}{T_{\rm CMB}} = \sum_{\ell=0}^{\infty}\sqrt{\frac{2\ell+1}{4\pi}}\,a_\ell P_\ell(\cos\theta), \qquad (5)$$

where a_ℓ denotes the coefficients of the expansion. In the particular case in which the void is aligned with the z-axis, the coefficients a_ℓ are equivalent to the spherical harmonic coefficients with $m = 0$. They can be therefore computed from the theoretical profile of equation (1) as

$$a_\ell = \sqrt{(2\ell+1)\pi}\int_{-1}^{1}{\rm d}(\cos\theta)\,\frac{\Delta T(\theta)}{T_{\rm CMB}}\,P_\ell(\cos\theta). \qquad (6)$$

The corresponding ISW profiles induced by each void model and the CS data are depicted in Fig. 1. The profiles are very different in terms of the amplitude. Within the considered ΛCDM model, the standard deviation of the ISW temperature fluctuations is estimated to be $\sigma_{\rm ISW} = 19.58\,\mu$K. Whilst the Gaussian model induces a profile whose value at $\theta = 0$ lies at the 1σ level when the standard deviation due exclusively to the ISW contribution is taken as reference, the TH profile at the centre reaches a 4.5σ level.

In terms of the standard deviation of the matter field convolved by a TH function of scale R, the corresponding value of δ_0 for the TH best-fitting profile lies at the $\approx 6\sigma$ level.[2] This could give a hint that the TH model is not a realistic description of a void expected within the standard model, although it is shown closer – but not enough yet – to explain the CS anomaly. Actually, this void description would imply an anomaly larger than the one that is expected to be explained. For the Gaussian model, the value of δ_0 is only at a $\approx 2\sigma$ level.

In addition to the amplitude, a deeper insight can be obtained by paying attention to the shape of the profile. The SMHW coefficient of the CS with scale $R = 300$ arcmin describes both the temperature at the centre and the hot ring at 15°, since the specific shape of the SMHW at this scale weighs these features in a single number. Therefore, if the theoretical profiles fit the CS data, they will have a similar value of the SMHW coefficient. It is also important to remark that the CS represents a $\approx 4.7\sigma$ fluctuation in terms of this coefficient, which implies that any theoretical model assumed for the CS must explain this large deviation. The value of the SMHW coefficient can be computed as

$$W_0 = \sum_{\ell=0}^{\infty} \sqrt{\frac{2\ell+1}{4\pi}} w_\ell a_\ell. \tag{7}$$

The standard deviation of the SMHW coefficients with $R = 300$ arcmin (the scale at which the CS anomaly is manifested) due to the ISW contribution is $\sigma_{\rm ISW}(W_0) = 0.94\ \mu$K. We obtain W_0 values at around $-1.07\ \mu$K for the TH description and $-0.54\ \mu$K for the Gaussian model, and both lie within the $\approx 1\sigma$ level when only the ISW contribution is taken into account. On the other hand, the SMHW coefficient associated to the CS is a 20σ fluctuation with respect to the ISW effect, and therefore is very unlikely to explain the CS only taking into account the ISW fluctuations of linear standard voids. Other possible scenario is that the CS is the sum of a primordial CMB fluctuation and the ISW effect of a void, but even in this case the probability of this event is small. The SMHW coefficient of the observed data, once the effect of the voids is subtracted, is still a $\approx 4.5\sigma$ fluctuation. Therefore, whilst the effect predicted by the theoretical models for this particular void is shown compatible with the expected ISW signal from typical LSS fluctuations within the ΛCDM, the CS appears anomalous in relation to both properties: shape and amplitude.

In principle, to consider the void as explanation of the CS, it would not be necessary that its contribution accounts for all the CS amplitude, but it should be intense enough to make anomalous the primordial fluctuation. In terms of the amplitude of the Gaussian model, the ISW contribution from the void represents a 13 per cent with respect to the temperature at the centre of the CS. However, in terms of W_0, this fraction drops to 2.8 per cent.

2.2 Ellipsoidal model

All previous conclusions are derived from a spherical void model, but we could wonder whether they remain when the void presents an ellipsoidal geometry. For this purpose, we decompose the radial coordinate $\boldsymbol{r}$ of the matter density profile, defined from the centre of the void, into a component parallel to the line of sight $r_\parallel$ and another orthogonal to it $\boldsymbol{r}_\perp$, which is a 2D vector in the normal plane, such that:

$$r = \sqrt{r_\parallel^2\left(1-e^2\right) + r_\perp^2}, \tag{8}$$

where e denotes the ellipticity. This toy model allows us to stretch the void along the line of sight in terms of the ellipticity, whereas the semiminor axis is fixed to the scale of the density profile (R for the TH and r_0 for the Gaussian model, respectively), implying an increase of the volume. The centre position of the void is also kept at z_0. This configuration favours the increase of the ISW contribution due to the presence of the void, because the void influence is kept in a greater redshift interval along the line of sight.

Although the standard model imposes limits to the ellipticity (e.g. Icke 1984; Bardeen et al. 1986), three values are considered such that the semimajor axis is increased by one, two, and three times the error bar of r_0 (the value of $35h^{-1}$Mpc is taken in both models for simplicity). A comparison between CMB temperature profiles caused by supervoids with different ellipticity is shown in Fig. 2. As expected, the absolute value of the amplitude at $\theta = 0$ increases as the ellipticity grows. In the case of the TH model, the radial profile at the centre of the void reaches a value close to the CS temperature decrease when an ellipticity of $e = 0.76$ is considered, whilst these values remain unreachable with the Gaussian model. However, all the SMHW coefficients lie within the 1σ level of the ISW contribution, as in the spherical case. This means that the shape of the profiles differs from that shown by the CS. The W_0 value for all cases are given in Table 1. They should be compared with the

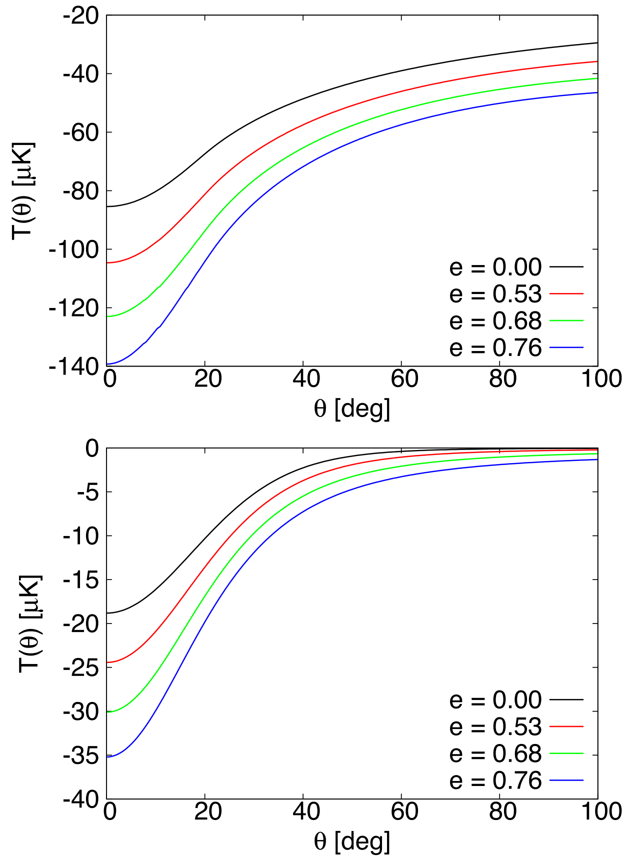

Figure 2. Comparison of CMB temperature profiles induced by the presence of an elliptical supervoid modelled as a TH (top panel) and a Gaussian model (bottom panel) with different values of ellipticity.

[2] Notice that Szapudi et al. (2015) provide a value of at least 3.3σ based on a more conservative estimate of the rareness of the void which takes into account a 1σ deviation of the TH best-fitting parameters.

Table 1. SMHW coefficients W_0 induced by elliptical voids modelled by TH and Gaussian profiles with different ellipticity. All coefficients correspond to a wavelet scale $R = 300$ arcmin. The W_0 computed at the CS location in the *Planck* temperature data is -19.3 ± 4.1 μK.

e	TH (μK)	Gaussian (μK)
0.00	−1.07	−0.54
0.53	−1.42	−0.71
0.68	−1.81	−0.85
0.76	−2.20	−1.03

SMHW coefficient at the CS location in the *Planck* temperature data whose value is estimated in -19.3 ± 4.1 μK.

2.3 Varying ω in the dark-energy equation of state

Assuming ΛCDM, Ω_Λ regulates the amplitude of the ISW effect produced by these void models. Considering dark energy, the ISW contribution also depends on its evolution. In this section, we extend the void models so that the dark-energy equation of state parameter ω can be set to another value different from -1. This dependence affects explicitly to the growth suppression factor $G(z)$ and the comoving distance $\chi(z)$. Decreasing the value of ω causes a stronger evolution in the density parameter of the dark energy, implying a larger ISW imprint. Actually, for our purposes, the assumption that the ω is different from -1 is only necessary at the redshift interval in which the CMB photon is suffering the effect of the void but not in the whole evolution of the Universe.

A comparison between CMB temperature profiles induced by the void corresponding to different values of ω is given in Fig. 3. The temperature at the centre reaches a similar value than that shown by the CS only for the TH model and considering a value of $\omega = -3.0$ which, obviously, is ruled out by current observations (e.g. Planck Collaboration XIII; Planck Collaboration XVI 2015). Similar intervals in ω does not correspond with similar increases of the absolute value of the amplitude of the profiles, but this increase is smaller as the values of ω become more extreme. However, the W_0 values for these profiles also lie within the 1σ level with respect to the standard deviation of the ISW signal. They are shown in Table 2.

3 DISCUSSION

We have reviewed the ISW contribution from a supervoid as the one detected by Szapudi et al. (2015) in the light of two different models previously considered: a TH matter density profile and a particular case of the LTB model with a Gaussian potential. The comparison between the feature induced on the CMB by the presence of a void as the one mentioned above and the CS has been focused both on the amplitude of the induced CMB temperature decrement and the shape of the radial profile. This is an important aspect, which is related to the anomalous nature of the CS that is manifested when the CMB is analysed in wavelet space. As was mentioned in Planck Collaboration XIII; Planck Collaboration XVI (2015), the shape of the CS radial profile is shown anomalous, and therefore the ability to relate this shape with the imprint of a supervoid would give weight to the hypothesis that there is a connection between both phenomena. However, an SMHW coefficient analysis shows that the imprint of the void does not fit the same pattern than the CS profile. All SMHW coefficients computed in this work lie within the 2.5σ level with respect to the standard deviation due to the ISW signal, even for extreme scenarios that, although discarded within the standard cosmological model, could provide CMB decrements at the centre of the CS of the order of the observed data. In the light of these models, it is important to recall that the ISW imprint from an individual void is indistinguishable from the primordial fluctuations.

Modifications of the LTB density profile have been considered to describe more accurately the particular shape of the CMB profile around the CS (see Finelli et al. 2016). However, the shape is modified at the expense of a lower value of the amplitude at the centre, and therefore this amplitude is not already significant. In fact, we have checked that the W_0 values associated with this profile are even smaller than those related to the cases considered in this work.

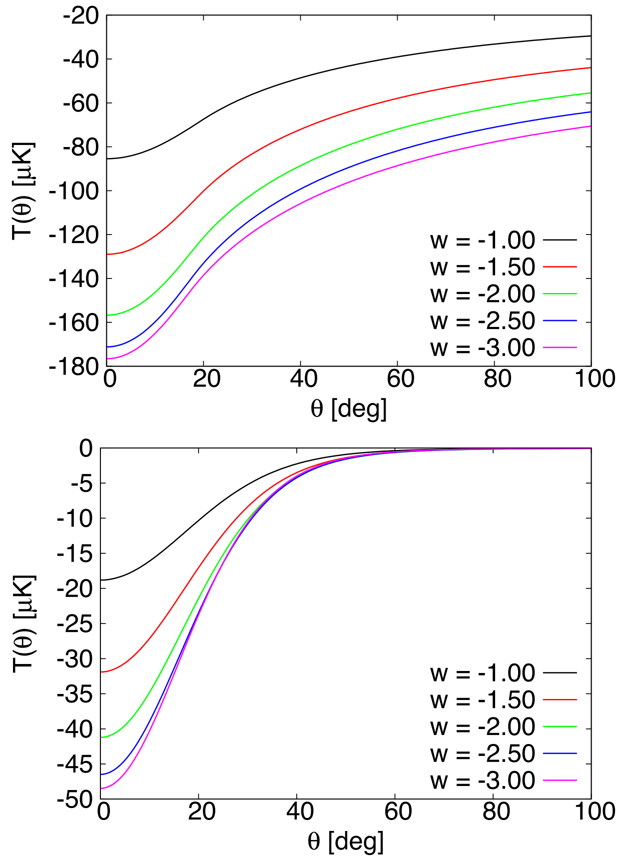

Figure 3. Comparison of CMB temperature profiles induced by the presence of a spherical supervoid modelled as a TH (top panel) and a Gaussian model (bottom panel) with different values of ω.

Table 2. SMHW coefficients W_0 induced by a spherical void as that detected by Szapudi et al. (2015) modelled by TH and Gaussian profiles for different values of ω. All coefficients correspond to a wavelet scale $R = 300$ arcmin. The W_0 computed at the CS location in the *Planck* temperature data is -19.3 ± 4.1 μK.

ω	TH (μK)	Gaussian (μK)
−1.00	−1.07	−0.54
−1.50	−1.74	−0.96
−2.00	−2.13	−1.28
−2.50	−2.34	−1.49
−3.00	−2.38	−1.60

In conclusion, we have shown that the ISW effect within the standard model is not a plausible explanation for the CS, not even considering the Rees–Sciama effect. Nevertheless, any hypothetical physical connection between the void and the CS should rely either on deviations from the standard cosmological model (e.g. non-Gaussian primordial density fluctuations) or on new physics.

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REFERENCES

Bardeen J. M., Bond J. R., Kaiser N., Szalay A. S., 1986, ApJ, 304, 15
Bremer M. N., Silk J., Davies L. J. M., Lehnert M. D., 2010, MNRAS, 404, L69
Bueno Sánchez J. C., 2014, Phys. Lett. B, 739, 269
Cai Y.-C., Cole S., Jenkins A., Frenk C. S., 2010, MNRAS, 407, 201
Cruz M., Martínez-González E., Vielva P., Cayón L., 2005, MNRAS, 356, 29
Cruz M., Tucci M., Martínez-González E., Vielva P., 2006, MNRAS, 369, 57
Cruz M., Turok N., Vielva P., Martínez-González E., Hobson M., 2007, Science, 318, 1612
Cruz M., Martínez-González E., Vielva P., Diego J. M., Hobson M., Turok N., 2008, MNRAS, 390, 913
Czech B., Kleban M., Larjo K., Levi T. S., Sigurdson K., 2010, J. Cosmol. Astropart. Phys., 12, 23
Feeney S. M., Johnson M. C., Mortlock D. J., Peiris H. V., 2011, Phys. Rev. Lett., 107, 071301
Finelli F., Garcia-Bellido J., Kovacs A., Paci F., Szapudi I., 2016, MNRAS, 455, 1246
Granett B. R., Szapudi I., Neyrinck M. C., 2010, ApJ, 714, 825
Icke V., 1984, MNRAS, 206, 1P
Inoue K. T., Silk J., 2006, ApJ, 648, 23
McEwen J. D., Feeney S. M., Johnson M. C., Peiris H. V., 2012, Phys. Rev. D, 85, 103502
Martínez-González E., Gallegos J. E., Argüeso F., Cayón L., Sanz J. L., 2002, MNRAS, 336, 22
Nadathur S., Lavinto M., Hotchkiss S., Räsänen S., 2014, Phys. Rev. D, 90, 103510
Planck Collaboration XIII, 2015, preprint (arXiv:1502.01589)
Planck Collaboration XVI, 2015, preprint (arXiv:1506.07135)
Rudnick L., Brown S., Williams L. R., 2007, ApJ, 671, 40
Szapudi I. et al., 2015, MNRAS, 450, 288
Tomita K., 2005, Phys. Rev. D, 72, 103506
Vielva P., Martínez-González E., Barreiro R. B., Sanz J. L., Cayón L., 2004, ApJ, 609, 22
Zibin J. P., 2014, preprint (arXiv:1408.4442)