Comment on “A Supervoid Imprinting the Cold Spot in the Cosmic Microwave Background”

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Recently Finelli et al. [arXiv:1405.1555] found evidence for a relatively nearby (z ≃ 0.16) void in a galaxy catalogue in the direction of the cosmic microwave background (CMB) Cold Spot. Using a perturbative calculation, they also claimed that such a void would produce a CMB decrement comparable to that of the observed Cold Spot, mainly via the nonlinear Rees-Sciama effect. Here I calculate the effect of such a void using a fully general relativistic model and show that, to the contrary, the linear integrated Sachs-Wolfe effect dominates and produces a substantially weaker decrement than observed.

INTRODUCTION

Recently Finelli et al. [1] (hereafter FGKPS) examined the WISE-2MASS galaxy catalogue and found evidence for a void in the direction of the cosmic microwave background (CMB) Cold Spot. They furthermore calculated the anisotropy generated by such a void on the CMB and claimed that the void could explain most of the Cold Spot decrement, mainly due to the nonlinear Rees-Sciama (RS) effect. In this brief Comment, I calculate the effect of such a void using a fully general relativistic model and show that, to the contrary, the linear integrated Sachs-Wolfe effect dominates and produces a substantially weaker decrement than observed.

THE FGKPS PROFILE

The spherically symmetric spacetime is described by the metric

\[ ds^2 = -dt^2 + \frac{Y^2}{1-K}dr^2 + Y^2 d\Omega^2, \]

for comoving coordinate \( r \) and radial derivative \( \prime = d/dr \). FGKPS adopt the curvature function profile

\[ K(r) = K_0 r^2 \exp \left( -\frac{r^2}{r_0^2} \right). \]

(2)

It is possible to show that, in the linear regime, the curvature function is related to the comoving curvature metric perturbation, \( \psi_q(r) \), via

\[ K(r) = 2r \psi_q(r). \]

(3)

Therefore the FGKPS profile corresponds to

\[ \psi_q(r) = -\frac{1}{4} K_0 r_0^2 \exp \left( -\frac{r^2}{r_0^2} \right). \]

(4)

The comoving perturbation \( \psi_q \) is time-independent in a dust or dust + \( \Lambda \) background, but is related to the time-dependent zero-shear (or longitudinal) gauge metric perturbation, \( \psi_\sigma \), via

\[ \psi_\sigma(t, r) = \frac{3}{5} g(t) \psi_q(r), \]

(5)

where \( g(t) \) is the growth factor for the suppression due to \( \Lambda \) domination. The relativistic Poisson equation gives for the comoving gauge matter perturbation

\[ \frac{\delta \rho_q(t, r)}{\rho_m} = \frac{2}{5} \frac{g(t)}{\Omega_m} \frac{\nabla^2}{a^2 H^2} \psi_q(r) \]

\[ = \frac{3}{5} \frac{g(t)}{a^2 H^2 \Omega_m} K_0 \left[ 1 - \frac{2}{3} \frac{r^2}{r_0^2} \right] \exp \left( -\frac{r^2}{r_0^2} \right). \]

(7)

This agrees with the form of the density contrast in FGKPS [their Eq. (2)], and allows us to identify their density contrast amplitude with

\[ \delta_0 = -\frac{3}{5} \frac{g(t)}{a^2 H^2 \Omega_m} K_0. \]

(8)

FGKPS calculate the RS anisotropy for this profile, and write its central amplitude \( A \equiv -\delta T(\theta = 0) \) as

\[ A = 51.0 \mu K \left( \frac{r_0 h}{155.3 \text{ Mpc}} \right)^3 \left( \frac{\delta_0}{0.2} \right)^2. \]

(Note that here I quote the updated relation from [5], which appears to agree better with the values plotted in Fig. 3 of FGKPS than the relation for \( A \) given in FGKPS.) The cubic dependence of \( A \) on the radius and
quadratic dependence on density contrast are well-known features of the RS effect in an Einstein-de Sitter (EdS) background (see, e.g., [6, 7]).

Finally, FGKPS fit their density profile to the WISE-2MASS galaxy distribution, and the predicted anisotropy to CMB data, finding best-fit parameters

\[
\delta_0 = 0.25 \pm 0.10, \quad r_0 h = (195 \pm 35) \text{ Mpc}, \quad z_0 = 0.155 \pm 0.037,
\]

where \(z_0\) is the redshift of the void centre. Eq. (9) then gives central amplitude \(A = 158 \mu K\) for the best-fit profile, which appears to be consistent with the anisotropy profiles plotted in Fig. 3 of FGKPS (assuming subdominant integrated Sachs-Wolfe (ISW) effect and minor effects due to angular binning).

**ALTB CALCULATION**

In order to calculate with the ALTB spacetime, we must fix the curvature function amplitude \(K_0\) in Eq. (2) [I will always fix the radius \(r_0\) to the FGKPS best-fit value Eq. (11)]. There are two ways to do this. First, we can use Eqs. (8) and (10) to produce a ALTB profile with the same linearized density contrast as the FGKPS best fit. The result is plotted in Fig. 1. In this case the nonlinear contrast is smaller than that of the FGKPS best fit, as expected since nonlinear growth suppresses underdense contrast. The other approach is to choose \(K_0\) so that the exact ALTB contrast matches the FGKPS best fit; this is plotted in Fig. 2. Note that the nonlinear growth changes the shape of the profile; I have chosen the amplitudes (central values) to match.

Although the difference between these two approaches is small, I choose the latter, i.e. I choose the exact ALTB contrast to match the FGKPS best fit. This is because this choice corresponds to a larger density contrast which will conservatively produce a larger CMB anisotropy (and in particular should produce a larger RS/ISW ratio). This corresponds to the value \(K_0 r_0^2 = -0.00087\).

Finally I am ready to calculate the CMB anisotropies. The ALTB solution is calculated as in [3] by numerically evolving Einstein’s equations using independent formulations as checks, including that described in [8]. I also monitor the constraints and compare with LTB (i.e. ALTB with \(\Lambda = 0\)) and linear theory in the appropriate regimes. The exact anisotropies are calculated by evolving null geodesics from the observer to the last scattering surface, as described in [9, 10].

The anisotropies due to the linearized ALTB solution [Eqs. (4) or (5)] can be calculated using

\[
\frac{\delta T}{T} = 2 \int \psi_\sigma dt + \left( \frac{5}{3g} - 1 \right) \frac{n_\mu \psi^{\mu}}{H},
\]

where \(n_\mu\) is the line-of-sight spatial direction [11]. The first term above is the familiar ISW effect, and the second term is the local dipole due to the “bulk flow” associated with the void. Even though the curvature profile is exponentially damped at large \(r\), we will see that at the FGKPS best-fit distance \(z_0\) the local dipole actually dominates over the ISW.

Figure 3 shows the anisotropy calculated exactly via raytracing in the ALTB spacetime as well as the linearized approximation using Eq. (13). We can see that the local dipolar anisotropy does indeed dominate. But we can also see that the linearized approximation (which does not incorporate the RS effect) agrees well with the exact calculation (which must include it), which suggests that the ISW dominates over RS.

We can see this more clearly by subtracting the local dipole contribution from both exact and linearized anisotropies, as in Fig. 4. Here we see that the anisotropy calculated from the exact ALTB solution agrees very well...
FIG. 3: Temperature anisotropy calculated exactly using the LTB solution (solid, black curve) and using the linearized relation, Eq. (13) (dashed, red). The two curves are almost indistinguishable and are dominated by the local dipole.

FIG. 4: As Fig. 3, but with the (linear) local dipole subtracted from both curves. The ISW clearly strongly dominates the total anisotropy.

FIG. 5: As Fig. 4, but for a profile with 10 times the amplitude of the FGKPS profile and located at \( z_0 = 1 \). The nonlinear contribution (RS effect) is now clearly apparent.

The question remains as to why the RS prediction of FGKPS, Eq. (9), is so much larger than the nonlinear effect seen in the full LTB calculation. Although the RS effect is well studied in an EdS (dust) background, leading, as already mentioned, to the dependences on radius and contrast seen in Eq. (9), the effect has been much less studied in a dust + \( \Lambda \) background. However, Ref. [13] studied the RS effect in this latter case, employing second order, thin shell, and fully nonlinear LTB methods. They found that the RS (nonlinear contribution to the anisotropies) is heavily suppressed in the realistic \( \Lambda \)CDM case with respect to the dust-dominated case, and that for comparable void size and depth to the FGKPS profile the linear (ISW) anisotropy dominates.

I have also repeated these calculations using different radial profiles \( K(r) \), including strongly non-compensated profiles, by fitting the profile parameters to closely match the density profile of FGKPS. In all cases I find that the ISW effect dominates over the RS effect and is of comparable magnitude to that of the FGKPS profile. Of course, it is entirely possible that the void discussed in FGKPS contributes partly to the Cold Spot anisotropy. But it is clear that most of the anisotropy must be sourced elsewhere, since the Cold Spot amplitude is considerably larger than \(-25 \mu K\): the Cold Spot has a deep “core” of roughly 5\(^\circ\) radius and \(\sim150 \mu K\) depth, surrounded by a shallower cold region out to perhaps 10\(^\circ\) radius (see, e.g., FGKPS or [14]). In addition, the angular size of the anisotropy shown in Fig. 4 (i.e. 30\(^\circ\)–40\(^\circ\)) is much larger than that of the observed Cold Spot. Although some exotic source is always a possibility, a combination of the local void with a fluke fluctuation at last scattering might appear most economical. Indeed such a scenario was found to be most likely in [15].
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