The ISW imprint of cosmic superstructures
a problem for ΛCDM

Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics

with Seshadri Nadathur & Shaun Hotchkiss, arXiv:1109.4126 (→ JCAP)

From the Planck scale to the electroweak scale, 28 May 2012, Warsaw

Summary

- An observation of the imprint on the CMB from superclusters and voids at $z \sim 0.5$ finds $\langle \Delta T \rangle \sim 10\ \mu$K, with 4.4σ significance.
- We (re)calculate the theoretical expectation for the 'late ISW effect' and find that the ΛCDM prediction is over 3σ *smaller* than the observed signal from voids, even with *conservative* assumptions.
- If the observed signal is due to the ISW effect, then very large and deep voids are far more abundant in the universe than expected.
- This is a challenge to the 'standard cosmological model' (e.g. the assumption of homogeneity on scales $\gtrsim 100h^{-1}$ Mpc) and suggests new physics (e.g. non-gaussianity of the primordial perturbations).

The late integrated Sachs-Wolfe effect

- When CMB photons traverse decaying potential fluctuations, secondary anisotropies are introduced $\rightarrow$ the late ISW effect:

$$\frac{\Delta T(\hat{n})}{T_0} = \frac{2}{c^3} \int_0^{r_{\mathrm{L}}} \dot{\Phi}(r, z, \hat{n}) a \, \mathrm{d}r.$$

- Potentials decay in presence of dark energy ($\Omega_\Lambda > 0$) or in an open universe ($\Omega_k > 0$), but not if $\Omega_{\mathrm{m}} = 1$.

The late integrated Sachs-Wolfe effect

- When CMB photons traverse decaying potential fluctuations, secondary anisotropies are introduced $\rightarrow$ the late ISW effect:

$$\frac{\Delta T(\hat{n})}{T_0} = \frac{2}{c^3} \int_0^{r_\mathrm{L}} \dot{\Phi}(r, z, \hat{n}) a \, \mathrm{d}r.$$

- Potentials decay in presence of dark energy ($\Omega_\Lambda > 0$) or in an open universe ($\Omega_k > 0$), but not if $\Omega_\mathrm{m} = 1$.
- Detection of this effect is an important *dynamical* test for dark energy (its *negative* pressure).
- Note that evidence for dark energy from the SN Ia Hubble diagram, CMB anisotropy and Baryon Acoustic Oscillations is based on an *assumed* FLRW metric ... can fit same data *without* dark energy by assuming a LTB metric (e.g. Seshadri & Sarkar, arXiv:1012.3460).

The late integrated Sachs-Wolfe effect

- Start from Poisson equation, $\nabla^2\Phi = 4\pi G\bar{\rho}a^2\delta$, where $\delta \equiv \rho/\bar{\rho} - 1$.
- In Fourier space this is:

$$\Phi(\mathbf{k}, t) = -\frac{3}{2}\left(\frac{H_0}{k}\right)^2 \Omega_{\rm m}\frac{\delta(\mathbf{k}, t)}{a}.$$

- Assume linear growth of inhomogeneities: $\delta(t) = D(t)\delta(z=0)$ as is valid on large scales ($\gtrsim 100$ Mpc today).
- Obtain:

$$\dot{\Phi}(\mathbf{k}, t) = \frac{3}{2}\left(\frac{H_0}{k}\right)^2 \frac{H(z)}{a}\Omega_{\rm m}\left(1 - \beta(z)\right) D(z)\delta(\mathbf{k}, z=0),$$

where $\beta(z) \equiv \frac{\mathrm{d}\ln D}{\mathrm{d}\ln a}$ is the linear growth rate.

The late integrated Sachs-Wolfe effect

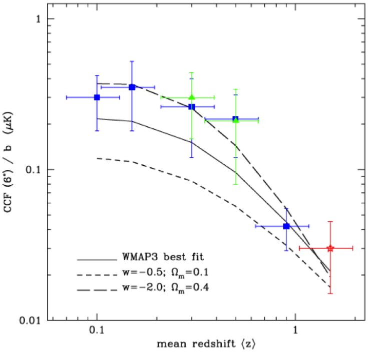
- H_0, Ω_{m}, $H(z)$, $\beta(z)$, $D(z)$ are given by the cosmological model.
- For any given δ we can calculate the temperature signal expected.
- The cosmological model will also predict expected δ.

The late integrated Sachs-Wolfe effect

- H_0, Ω_m, $H(z)$, $\beta(z)$, $D(z)$ are given by the cosmological model.
- For any given δ we can calculate the temperature signal expected.
- The cosmological model will also predict expected δ.
- N-body computer simulations show that non-linear (Rees-Sciama) effects are at most $\sim 10\%$ at low redshift $z < 1$ (Cai, Cole, Jenkins & Frenk, arXiv:1003.0974).
- Therefore our linear treatment is accurate to at least 10%.

Observing the late integrated Sachs-Wolfe effect

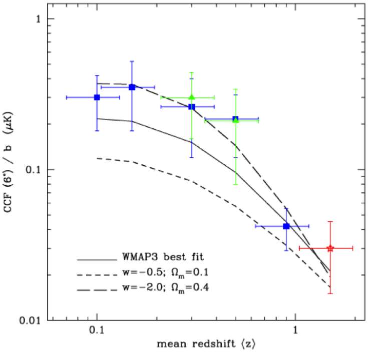
- Full sky analyses are tricky because of cosmic variance … several claimed detections but all are low significance and some are controversial (see Hernandez-Monteagudo, arXiv:0909.4294)



Gianantonio *et al*, astro-ph/0607572

Observing the late integrated Sachs-Wolfe effect

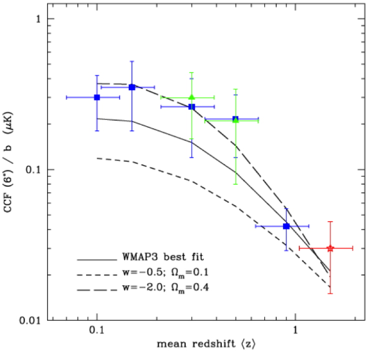
- Full sky analyses are tricky because of cosmic variance ... several claimed detections but all are low significance and some are controversial (see Hernandez-Monteagudo, arXiv:0909.4294)
- Most detections are *higher* than expected — consistent @ 1σ with ΛCDM (but consistent with *no* signal within $\sim 2\sigma$)!



Gianantonio *et al*, astro-ph/0607572

Observing the late integrated Sachs-Wolfe effect

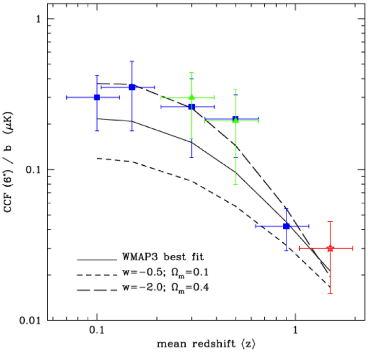
- Full sky analyses are tricky because of cosmic variance ... several claimed detections but all are low significance and some are controversial (see Hernandez-Monteagudo, arXiv:0909.4294)
- Most detections are *higher* than expected — consistent @ 1σ with ΛCDM (but consistent with *no* signal within $\sim 2\sigma$)!
- Some studies could not reject null hypothesis (Rassat *et al*, astro-ph/0610911, Francis & Peacock, arXiv:0909.2494)



Gianantonio *et al*, astro-ph/0607572

Observing the late integrated Sachs-Wolfe effect

- Full sky analyses are tricky because of cosmic variance … several claimed detections but all are low significance and some are controversial (see Hernandez-Monteagudo, arXiv:0909.4294)
- Most detections are *higher* than expected — consistent @ 1σ with ΛCDM (but consistent with *no* signal within $\sim 2\sigma$)!
- Some studies could not reject null hypothesis (Rassat *et al*, astro-ph/0610911, Francis & Peacock, arXiv:0909.2494)
- Another study found a $\sim 3\sigma$ *anti*-correlation (Sawangit *et al*, arXiv:0911.1352)



Gianantonio *et al*, astro-ph/0607572

Observing the late integrated Sachs-Wolfe effect

- Hence interesting to look at correlations between CMB and individual large structures in galaxy surveys such as SDSS.
- Such a study has been done (Granett, Neyrinck & Szapudi, arXiv:0805.2974, 0805.3695) with SDSS DR6 Luminous Red Galaxies.
- They report a $> 4\sigma$ detection of the ISW effect and state this is the *"clearest evidence of the ISW effect to date"*.

Physics World announces *"the most direct signal of dark energy"*

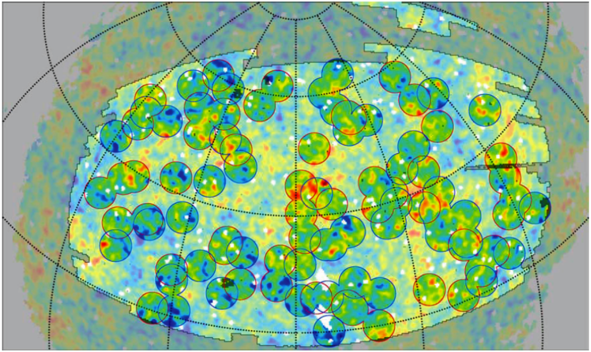


Figure 1: A map of the microwave sky over the SDSS area. The supervoids and superclusters used in our analysis are highlighted and outlined at a radius of 4°, blue for supervoids and red for superclusters. The compensated filter we use in our analysis approximately corrects for the large-angular-scale temperature variations that are visible across the map. The SDSS DR6 coverage footprint is outlined. Holes in the survey, *e.g.* due to bright stars, are displayed in black. Additionally, the WMAP Galactic foreground and point source mask is plotted (white holes). The disk of the Milky Way, which extends around the left and right border of the figure, is also masked. The map is in a Lambert azimuthal equal-area projection, centred at right ascension 180 and declination 35. The longitude and latitude lines are spaced at 30° intervals.

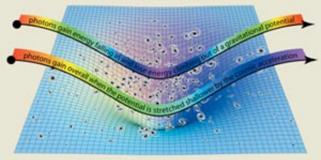
Grannett, Neyrinck & Szapudi, arXiv:0805.3695

Observing the late integrated Sachs-Wolfe effect

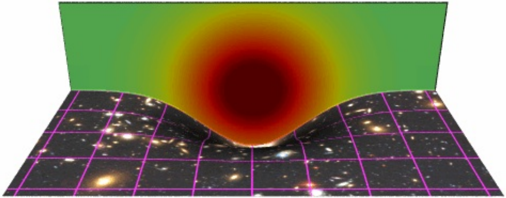
- Hence interesting to look at correlations between CMB and individual large structures in galaxy surveys such as SDSS.
- Such a study has been done (Granett, Neyrinck & Szapudi, arXiv:0805.2974, 0805.3695) with SDSS DR6 Luminous Red Galaxies.
- They report a $> 4\sigma$ detection of the ISW effect and state this is the *"clearest evidence of the ISW effect to date"*.

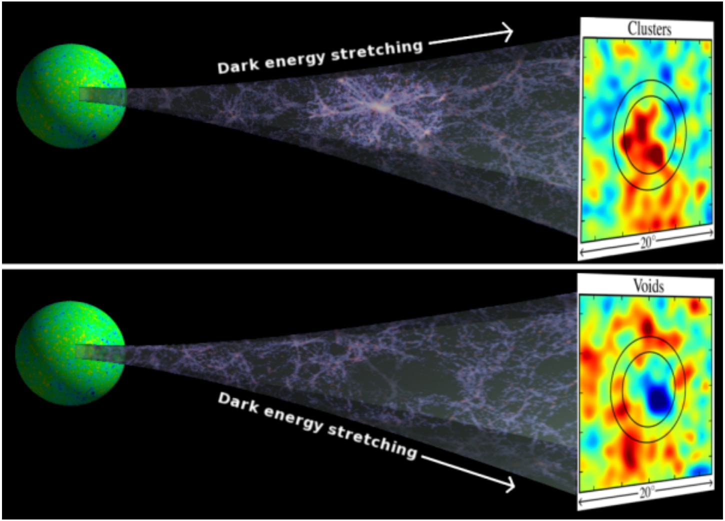
  Physics World announces *"the most direct signal of dark energy"*

- But is the detected signal consistent with ΛCDM?



In a potential well (cluster or void) which evolves as the CMB photon crosses it, the red/blue shifts do *not* cancel → “ring of fire” effect.





http://www.ifa.hawaii.edu/cosmowave/supervoids/

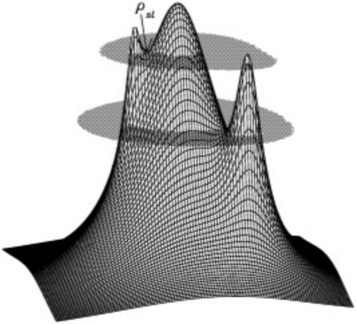
The observation by Granett *et al*

- The first step is to identify large-scale structures in the SDSS LRG sample ($0.4 < z < 0.75$ with median $z = 0.52$).
- This is done using structure-finding algorithms VOBOZ (for clusters) and ZOBOV (for voids).

The observation by Granett *et al*

- The first step is to identify large-scale structures in the SDSS LRG sample ($0.4 < z < 0.75$ with median $z = 0.52$).
- This is done using structure-finding algorithms VOBOZ (for clusters) and ZOBOV (for voids).

- Select structures based on "significance of detection", which is related to ratio of densities at centre and lip.
- Apply cutoff on "significance" to get 50 voids and 50 clusters.

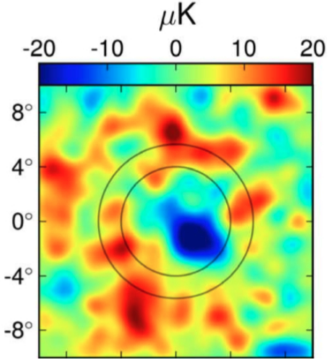


The observation by Granett *et al*

- Now average CMB temperature in direction of each object identified, and stack the images to increase signal-to-noise ratio.
- Use a compensated top-hat filter of radius 4° for the averaging to remove CMB fluctuations on larger scales.

The observation by Granett *et al*

- Now average CMB temperature in direction of each object identified, and stack the images to increase signal-to-noise ratio.
- Use a compensated top-hat filter of radius 4° for the averaging to remove CMB fluctuations on larger scales.



The observation by Granett *et al*

Results: found

- $\Delta T = -11.3 \pm 3.1\ \mu$K for voids,
- $\Delta T = 7.9 \pm 3.0\ \mu$K for clusters, and
- $\Delta T = 9.6 \pm 2.2\ \mu$K for both together i.e. clusters minus voids.

(Granett, Neyrinck & Szapudi, arXiv:0805.2974)

$\rightarrow$ high significance detection of a rather large signal!

The observation by Granett *et al*

Results: found

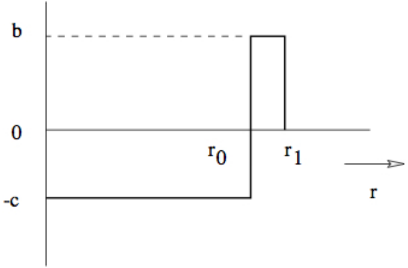
- $\Delta T = -11.3 \pm 3.1\ \mu$K for voids,
- $\Delta T = 7.9 \pm 3.0\ \mu$K for clusters, and
- $\Delta T = 9.6 \pm 2.2\ \mu$K for both together i.e. clusters minus voids.

(Granett, Neyrinck & Szapudi, arXiv:0805.2974)
$\rightarrow$ high significance detection of a rather large signal!

- But how big is the signal we expect to see?

ΛCDM prediction: previous estimates

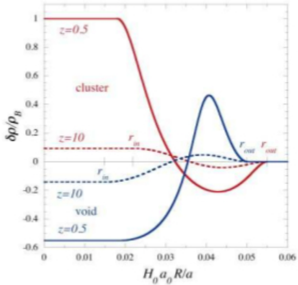
- Hunt & Sarkar, arXiv:0807.4508:
  Assumed a compensated top-hat density profile (asymptotic expectation - Sheth & van de Weygaert 2004) and used density information reported by Granett, Neyrinck & Szapudi (2008).



Obtained $\Delta T \sim 0.1\ \mu$K for given voids - far too small!

ΛCDM prediction: previous estimates

- Inoue, Sakai & Tomita, arXiv:1005.4250:
  Assumed a different (actually not dissimilar) density profile:



Calculated expected temperature shift from abundances:
$\langle \Delta T \rangle \sim 0.5\ \mu$K - still over an order of magnitude too small!

ΛCDM prediction: previous estimates

- Papai, Granett & Szapudi, arXiv:1012.3750:
  Used a radial profile motivated by Gaussian statistics.
  Performed a template fit based on parameter λ:

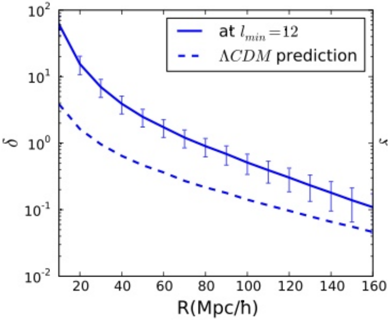
$$\lambda \approx \frac{1}{2}\left(\delta_0^{50c} - \delta_0^{50v}\right).$$

ΛCDM prediction: previous estimates

- Papai, Granett & Szapudi, arXiv:1012.3750:
  Used a radial profile motivated by Gaussian statistics.
  Performed a template fit based on parameter λ:

$$\lambda \approx \frac{1}{2}\left(\delta_0^{50c} - \delta_0^{50v}\right).$$

→ Confirmed discrepancy with ΛCDM but claimed it is only 2σ



ΛCDM prediction: previous estimates

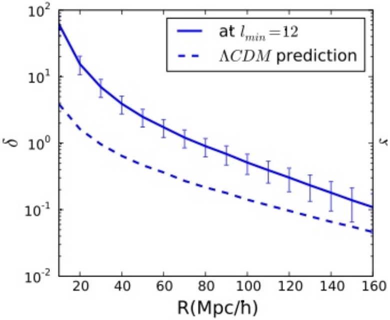
- Papai, Granett & Szapudi, arXiv:1012.3750:
  Used a radial profile motivated by Gaussian statistics.
  Performed a template fit based on parameter λ:

$$\lambda \approx \frac{1}{2}\left(\delta_0^{50c} - \delta_0^{50v}\right).$$

→ Confirmed discrepancy with ΛCDM but claimed it is only 2σ

However their fit requires $\lambda > 1$ and therefore $\delta_0^{50v} < -1$.

... i.e. template was used *outside* range of physical validity (void cannot be emptier than empty!)



ΛCDM prediction: improving the estimate

So what went wrong and what is the correct ΛCDM expectation?

ΛCDM prediction: improving the estimate

So what went wrong and what is the correct ΛCDM expectation?

Assumed profile of structures makes a difference:

Do not use arbitrary profiles - expected profile can be calculated exactly from linear theory.

Template fit doesn't work:

Use linear theory predictions for abundances of superclusters/voids.

ΛCDM prediction: improving the estimate

So what went wrong and what is the correct ΛCDM expectation?

Assumed profile of structures makes a difference:	Do not use arbitrary profiles - expected profile can be calculated exactly from linear theory.
Template fit doesn't work:	Use linear theory predictions for abundances of superclusters/voids.

$\rightarrow$ Model to be tested is ΛCDM + Gaussian primordial perturbations.

ΛCDM prediction: structures

- Bond, Bardeen, Kaiser & Szalay (1986): fully worked out all the linear theory for Gaussian-distributed density perturbations.
- Start with matter power spectrum calculated for ΛCDM: $\Omega_\mathrm{m} = 0.29$, $\Omega_\Lambda = 0.71$, $n_s = 0.96$, $\sigma_8 = 0.83$.
- Smooth this power spectrum using a Gaussian filter with scale R_f.
- Different values of R_f correspond to density perturbations on different scales.

ΛCDM prediction: structures

Define moments of the filtered density field:

$$\sigma_j^2(z) \equiv \int_0^\infty \frac{k^2}{2\pi^2}\mathcal{P}_\mathrm{f}(k,z)k^{2j}\,dk,$$

which depend only on R_f and matter power spectrum. Thus obtain:

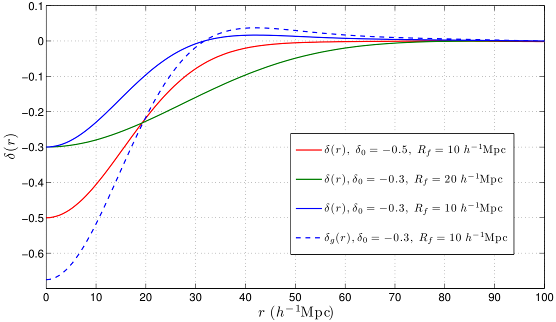
- Comoving number density of points of extrema $\delta = \delta_0 = \nu\sigma_0$.

$$\mathcal{N}_\mathrm{max}(\nu;R_\mathrm{f})\mathrm{d}\nu \equiv \mathcal{N}_\mathrm{min}(-\nu;R_\mathrm{f})\mathrm{d}\nu = \frac{1}{(2\pi)^2 R_*^3}\mathrm{e}^{-\nu^2/2}G(\gamma,\gamma\nu)\mathrm{d}\nu$$

- Mean, spherically averaged, radial profile $\bar{\delta}(r)$ at distance r away from a point of extremum $\delta(r=0)=\delta_0$.

ΛCDM prediction: structures

Example profiles:



These profiles are *different* from those used by Papai *et al* (2010).

ΛCDM prediction: temperature signal

Assume the following:

- Linear treatment of ISW (OK on relevant scales $\sim 100\ h^{-1}$Mpc).

ΛCDM prediction: temperature signal

Assume the following:

- Linear treatment of ISW (OK on relevant scales $\sim 100\ h^{-1}$Mpc).
- Structures centred at $z = 0.52$ (SDSS median redshift).

ΛCDM prediction: temperature signal

Assume the following:

- Linear treatment of ISW (OK on relevant scales $\sim 100\ h^{-1}$Mpc).
- Structures centred at $z = 0.52$ (SDSS median redshift).
- LRGs trace matter density with simple linear bias ($\delta_{\rm g} = b\delta$, $b \approx 2.25$ for SDSS LRGs).

ΛCDM prediction: temperature signal

Assume the following:

- Linear treatment of ISW (OK on relevant scales $\sim 100\ h^{-1}$Mpc).
- Structures centred at $z = 0.52$ (SDSS median redshift).
- LRGs trace matter density with simple linear bias ($\delta_{\mathrm{g}} = b\delta$, $b \approx 2.25$ for SDSS LRGs).
- Number of structures $N \gg 1$ so can use the mean profile to calculate expectation values.

ΛCDM prediction: temperature signal

Assume the following:

- Linear treatment of ISW (OK on relevant scales $\sim 100\ h^{-1}$Mpc).
- Structures centred at $z = 0.52$ (SDSS median redshift).
- LRGs trace matter density with simple linear bias ($\delta_{\rm g} = b\delta$, $b \approx 2.25$ for SDSS LRGs).
- Number of structures $N \gg 1$ so can use the mean profile to calculate expectation values.
- Sample of structures contains only those that would pass the VOBOZ/ZOBOV "significance" test (a condition on δ_0.)

ΛCDM prediction: temperature signal

We find that if $\delta < 1$ (linear regime), there are *no* overdensities satisfying VOBOZ significance cut!

- This means that the Granett *et al* sample of 50 "superclusters" were selected on the basis of small-scale collapsed structures, *not* linear overdensities.
- Hence *cannot* model superclusters.

.... but ZOBOV significance cut on voids is different, so voids in linear regime can still pass it

Therefore compare $\langle \Delta T \rangle$ to observations of voids only.

ΛCDM prediction: temperature signal

$\langle \Delta T \rangle$ = expectation value of signal
= weighted average value of ΔT for voids passing cut

So

$$\langle \Delta T \rangle = \frac{\int_{-1}^{\delta_0^c} \int_0^{\theta_{out}} W(\theta) \Delta T(\theta) \mathcal{N}_{\rm min} \sigma_0^{-1} \, {\rm d}^2\theta d\delta_0}{\pi \theta_{\rm c}^2 \int \mathcal{N}_{\rm min} \sigma_0^{-1} \, {\rm d}\delta_0},$$

where:

- $\mathcal{N}_{\rm min} \sigma_0^{-1}$ is weighting factor,
- δ_0^c is cutoff imposed by significance selection,
- $W(\theta)$ is a compensating top-hat filter, $\theta_c = 4^\circ$ to match observation.

Possible sources of bias

Obviously strong selection effects are limiting size of observed sample.

Bias towards large voids:

- Larger voids have larger ΔT.
- Maybe only voids with radius $R_v > R_v^{\min}$ are found by ZOBOV.

Bias towards deep voids:

- Deeper voids have larger ΔT.
- Maybe only voids with $\delta_0 < \delta_0^{\min}$ are found by ZOBOV.

Possible sources of bias

Obviously strong selection effects are limiting size of observed sample.

Bias towards large voids:

- Larger voids have larger ΔT.
- Maybe only voids with radius $R_v > R_v^{\min}$ are found by ZOBOV.

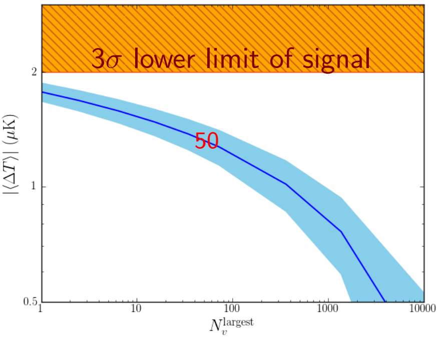
Bias towards deep voids:

- Deeper voids have larger ΔT.
- Maybe only voids with $\delta_0 < \delta_0^{\min}$ are found by ZOBOV.

Can these bias the sample towards larger $\langle \Delta T \rangle$?

Possible sources of bias

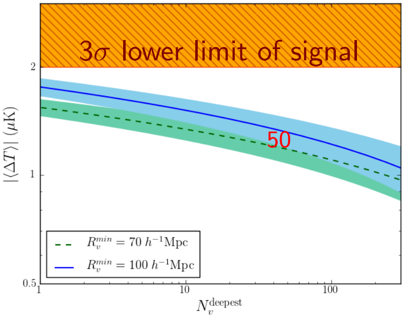
Model bias towards larger voids by increasing R_f (increasing R_v^{min}).



Still cannot explain the observation!

Possible sources of bias

Model bias towards deeper voids by decreasing $\delta_0^{\min}$ (vary $R_v^{\min}$).

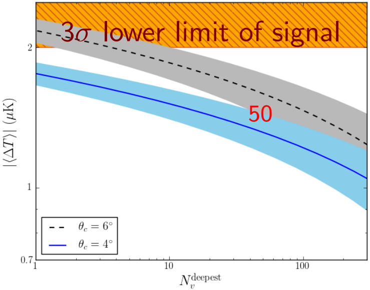


Still cannot explain the observation!

Theoretical errors

Density field is smoothed with filter size R_f so $\Delta T(\theta)$ may be smoothed too … spillover possible because of filter $W(\theta)$.

Check using larger filter size $\theta_c = 6^\circ$ (*generous* estimate).

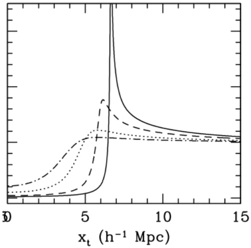


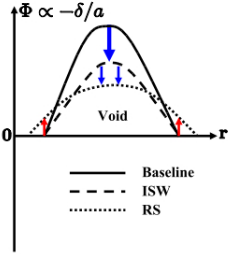
Still cannot explain the observation!

Other theoretical uncertainties

Non-linear effects of gravity:

- evolution leads to colder centre, hotter edges





- Overall correction unclear, but linear treatment may even *overestimate* the signal
- In any case non-linear effects $\lesssim 10\%$ at low z (Cai *et al*, 2010)

Conclusions

- Late ISW signal *discrepant* with linear theory predictions for Gaussian perturbations in ΛCDM at $> 3\sigma$
  $\Rightarrow$ Large voids in matter density far more numerous than expected
- Is the universe not homogeneous even at scales $\gtrsim 100\ h^{-1}$Mpc?

  - Excess clustering at very large scales in MegaZ redshift survey (Thomas, Abdalla & Lahav, arXiv:1012.2272)
  - Absence of self-averaging in SDSS galaxy counts (Sylos Labini, Vasilyev & Baryshev, arXiv:0909.0132) i.e. no statistical homogeneity
  - Excessive bulk flow traced by optical galaxies (Watkins, Feldman & Hudson, arXiv:0809.4041) and Union 2 SN Ia catalogue (Colin, Mohayaee, Sarkar & Shafieloo, arXiv:1011.6292) ... extending out well beyond BAO scale

The *foundations* of the standard cosmological model need testing!

Hints of new physics

Perhaps primordial density perturbations are not perfectly gaussian?

- Extreme structures lie in tail of PDF
- Abundance sensitive to primordial non-Gaussianity ($g_{\rm NL}$ not $f_{\rm NL}$)
- So are profiles (under investigation)

Hints of new physics

Perhaps primordial density perturbations are not perfectly gaussian?

- Extreme structures lie in tail of PDF
- Abundance sensitive to primordial non-Gaussianity ($g_{\rm NL}$ not $f_{\rm NL}$)
- So are profiles (under investigation)

Other possibilities?

- Growth rate of perturbations modified in scalar-tensor gravity
- Large inhomogeneities themselves alter growth rate of structure?
- More speculative ideas (e.g. late-time phase transitions)?

Hints of new physics

Perhaps primordial density perturbations are not perfectly gaussian?

- Extreme structures lie in tail of PDF
- Abundance sensitive to primordial non-Gaussianity ($g_{\rm NL}$ not $f_{\rm NL}$)
- So are profiles (under investigation)

Other possibilities?

- Growth rate of perturbations modified in scalar-tensor gravity
- Large inhomogeneities themselves alter growth rate of structure?
- More speculative ideas (e.g. late-time phase transitions)?

"Cosmologists are often wrong ... but never in doubt" - Lev Landau