The ISW imprint of superstructures
A problem for ΛCDM?

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(arXiv:xxxx.xxxx with Shaun Hotchkiss and Subir Sarkar)

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Outline

Executive summary

- A measurement has been made of the late ISW effect on the CMB from individual structures at redshifts ~ 0.5, finding $\Delta T \sim 10\ \mu$K to $\sim 4\sigma$ significance
- Theoretical predictions in the literature for the expected signal vary by an order of magnitude
- We recalculate the theory and find that the ΛCDM prediction is discrepant with observation at $\sim 3\sigma$ even with the most generous assumptions we can think of
- This might be a sign of new physics ...
- ... or the observation might be wrong - but in this case the real ΛCDM signal should still be observable

The late ISW effect

- If CMB photons traverse decaying large-scale potential fluctuations, secondary anisotropies are introduced $\rightarrow$ the late ISW effect

$$\frac{\Delta T(\hat{n})}{T_0} = \frac{2}{c^3}\int_0^{r_L} \dot{\Phi}(r, z, \hat{n}) a \, dr$$

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- Potentials decay in presence of dark energy ($\Omega_\Lambda > 0$) or in an open universe, but not for $\Omega_m = 1$
- Detecting the late ISW effect is an *independent* test of ΛCDM
- Can measure the dynamical effects of dark energy
- Perhaps also constrain deviations from FLRW metric

The late ISW 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

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

- Assume linear growth of inhomogeneities: $\delta(t) = D(t)\delta(z = 0)$
- Obtain

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

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

The late ISW 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

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- For any given δ we can calculate the temperature signal expected
- The cosmological model will also predict expected δ
- Studies from N-body simulations shows non-linear (Rees-Sciama) effects are at most $\sim 10\%$ at low redshifts $z < 1$ Cai, Cole, Jenkins, Frenk 2010
- Therefore our linear treatment is accurate to at least 10%

Observing the ISW effect

- Full sky detections of ISW signal are tricky because of cosmic variance, but some work has been done in this area
- Very interesting to look at correlations between CMB and individual structures in galaxy surveys such as SDSS
- Such a study has already been done - (Granett, Neyrinck, Szapudi 2008 - with SDSS DR6 LRGs. They report a 4σ detection of the ISW effect; this is "evidence for dark energy"

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- But is the detected signal consistent with ΛCDM?

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- But is the detected signal consistent with ΛCDM?
- No theoretical prediction had been made before the detection (!)

The Granett observation

- The first step was 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)

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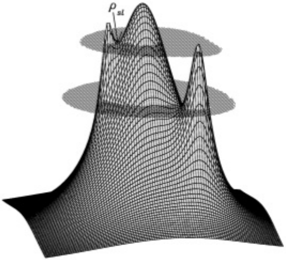
- Select structures based on "significance of detection", which is related to ratio of densities at centre and lip
- Applied cutoff on "significance" to get 50 voids and 50 clusters



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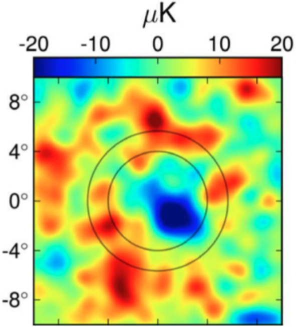

The Granett observation

Results: found

- $\Delta T = -11.3 \pm 3.1$ μK for voids,
- $\Delta T = 7.9 \pm 3.0$ μK for clusters, and
- $\Delta T = 9.6 \pm 2.2$ μK for both together (clusters minus voids)

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- High significance detection of a rather large signal!
- How big is the signal we expect to see?

ΛCDM prediction: previous estimates

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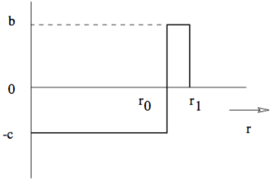
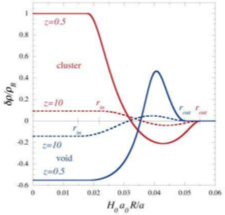
- So what is going on and what is the correct ΛCDM expectation?

ΛCDM prediction: previous estimates

- Hunt and Sarkar used a simplistic compensated top-hat density profile



- Inoue et al use a different, arbitrary, density profile



- Szapudi and collaborators argue profile makes a big difference - they use a Gaussian density profile

ΛCDM prediction: structures

- We can do better than taking arbitrary profiles - what is the expected profile from linear theory predictions?
- Bond, Bardeen, Kaiser, Szalay 1986 (BBKS): all the linear theory for Gaussian-distributed density perturbations nicely worked out
- We use the matter power spectrum calculated for the standard ΛCDM cosmological model: $\Omega_m = 2.29$, $\Omega_\Lambda = 0.71$, $n_s = 0.96$, $\sigma_8 = 0.83$
- This power spectrum is smoothed using a Gaussian filter with scale R_f
- Different values of R_f correspond to density perturbations on different scales - i.e. structures of different sizes

ΛCDM prediction: structures

- Define moments of the filtered density field

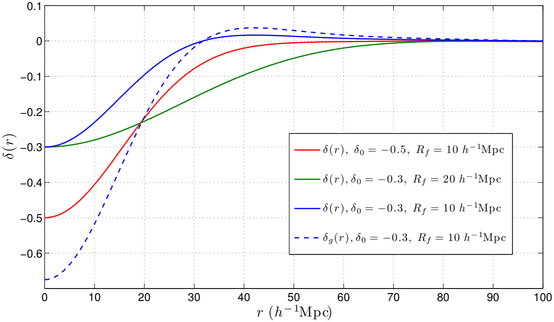
$$\sigma_j^2(z) \equiv \int_0^\infty \frac{k^2}{2\pi^2} \mathcal{P}_f(k,z) k^{2j} \, dk$$

and the quantities $\gamma = \frac{\sigma_1^2}{\sigma_2 \sigma_0}$ and $R_* = \sqrt{3}\frac{\sigma_1}{\sigma_2}$

- Using BBKS, can calculate comoving number density of points of extrema of the δ field where $\delta = \delta_0$, as a function of δ_0, γ, R_* and σ_0
- Can also calculate mean, spherically averaged, radial profile $\delta(r)$ at distance r away from a point of extremum $\delta(r=0) = \delta_0$

ΛCDM prediction: structures

Example profiles:



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To calculate the expected temperature signal from structures, we make the following assumptions:

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- Sample of structures contains only those that would pass the VOBOZ/ZOBOV "significance" test (this is a condition on $\delta(r)$)
- The centres of all structures are at $z = 0.52$, the median redshift of SDSS sample

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- Conclusion: the Granett et al sample of 50 overdensities ("clusters") is tainted. Not the most overdense large-scale linear perturbations, but the large-scale perturbations containing the most overdense, non-linear, collapsed structures - not the same thing!
- So we ignore overdensities and calculate expected signal for voids only

ΛCDM prediction: temperature signal

Calculate a weighted average value of ΔT with weighting factor proportional to number density of voids for given values of δ_0 and R_f

$$\langle \Delta T_{\mathrm{ISW}} \rangle \equiv \frac{\int_0^{\theta_{out}} \int_{-1}^{\delta_{0,c}} \int_{R_{f,min}}^{\infty} 2\pi\theta W(\theta,\theta_c)\Delta T(\theta,\delta_0,R_f)\mathcal{N}(\delta_0,R_f)\, d\theta d\delta_0 dR_f}{\pi\theta_c^2 \int_{-1}^{\delta_{0,c}} \int_{R_{f,min}}^{\infty} \mathcal{N}(\delta_0,R_f)\, d\delta_0 dR_f}$$

where

- $\mathcal{N}(\delta_0, R_f)\, d\delta_0 dR_f$ is differential number density of voids,
- $\delta_{0,c}$ is cutoff imposed by significance selection,
- $W(\theta, \theta_c)$ is a compensating top-hat filter, with $\theta_c = 4^\circ$

ΛCDM prediction: temperature signal

- With $R_{f,min} = 10\ h^{-1}$Mpc, we find

$$\langle \Delta T_{\mathrm{ISW}} \rangle = -0.19 \pm 0.17\ \mu\mathrm{K}$$

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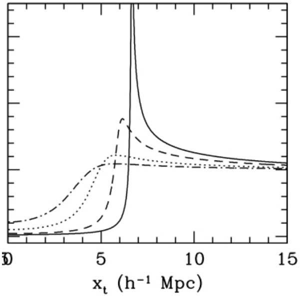
- Consistent with zero
- But compare with detection of $\langle \Delta T \rangle_{\rm obs} = -11.3 \pm 3.1\ \mu{\rm K}$!
- Appears to be a discrepancy, but can we be sure that there is no bias in (a) our theoretical prediction, and (b) in the observation?

Possible sources of bias

Possible sources of bias in theory prediction may be:

- Evolution of voids under gravity: but the asymptotic final state of evolution is a compensated top-hat (Sheth and van der Weygaert 2003), so linear treatment should *overestimate* the signal if anything



Possible sources of bias

Possible sources of bias in theory prediction may be:

- Full redshift-dependent selection function for SDSS: Using single redshift is simplification, but we expect errors introduced to be small (see later); can make this improvement later

Possible sources of bias

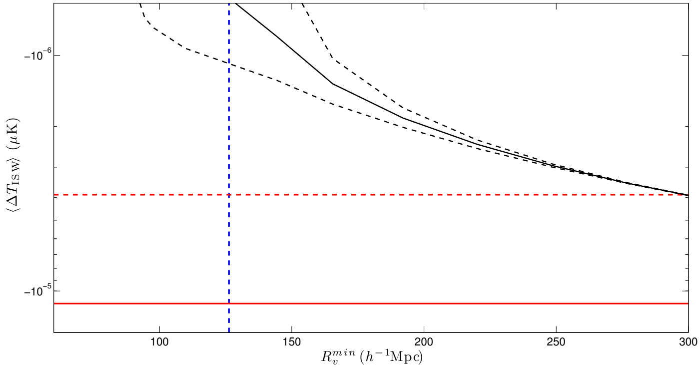
Possible sources of bias in the observation may be:

- Selection bias towards large voids: Stated selection criterion does not depend on void size, but it is plausible that only voids with radius $R_v > R_v^{min}$ are found by ZOBOV $\rightarrow$ sample biased towards larger voids, so larger signal

  Note: $R_{f,min} = 10\ h^{-1}$Mpc corresponds to $\sim 10^5$ voids in SDSS survey volume, whereas Granett et al only see 50

Possible sources of bias

Hmm ...



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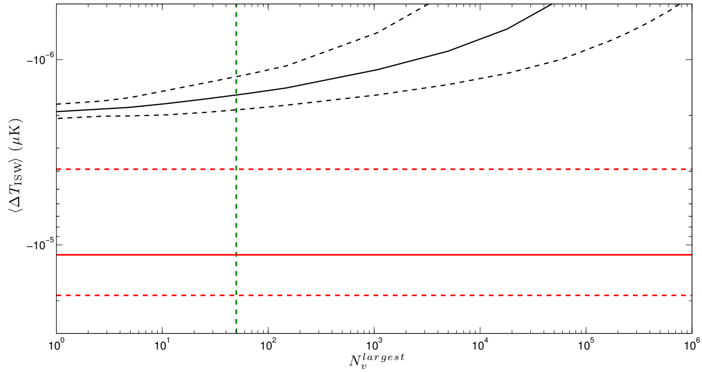

Possible sources of bias

Possible sources of bias in the observation may be:

- Selection bias towards large *and deep* voids: Stated selection criterion already imposes cutoff $\delta_0 < \delta_{0,c} \sim -0.24$, but maybe there is further bias so only very deepest voids are seen

Possible sources of bias

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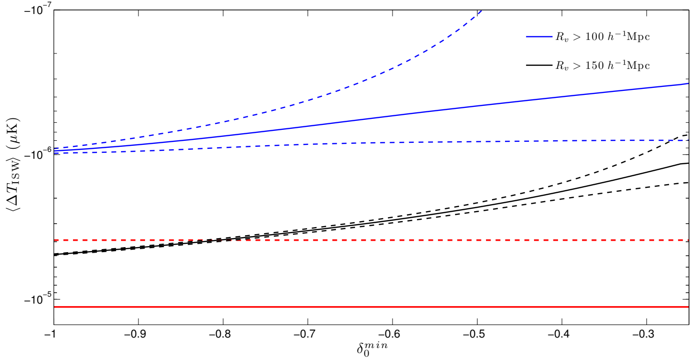

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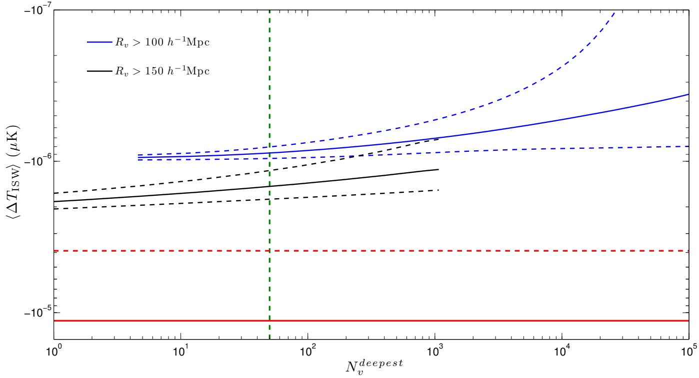

Possible sources of bias: summary

Can we be confident in the theory prediction?

- Study of Millennium Simulation finds "most extreme" regions in similar volume region have $\Delta T \gtrsim -4\ \mu\mathrm{K}$, even at $z = 0$, where signal is larger than at SDSS redshifts: Cai, Cole, Jenkins, Frenk 2010 (includes full non-linear calculation)
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Can we be confident in the observation?

- No obvious faults we can see
- Even benefit of doubt for undetected bias does not improve matters
- Should be reasonably easy to reproduce?

Conclusions

- Observed late ISW signal appears incompatible with linear theory predictions for Gaussian density field in a ΛCDM universe
- Discrepancy is at the level of $\sim 3\sigma$ *even when accounting for unexpected selection bias effects* (error bars are from observation, not theory)
- At any given void radius $R_v \gtrsim 100\ h^{-1}$Mpc, observed density perturbations appear to be larger than expected for standard ΛCDM model
- Alternatively, large, deep voids appear to be more numerous than expected

Hints of new physics

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Or maybe the observation is just wrong ...

- should be tested with larger galaxy surveys and newer SDSS catalogues
- even if discrepancy disappears, the ΛCDM effect should still be detectable