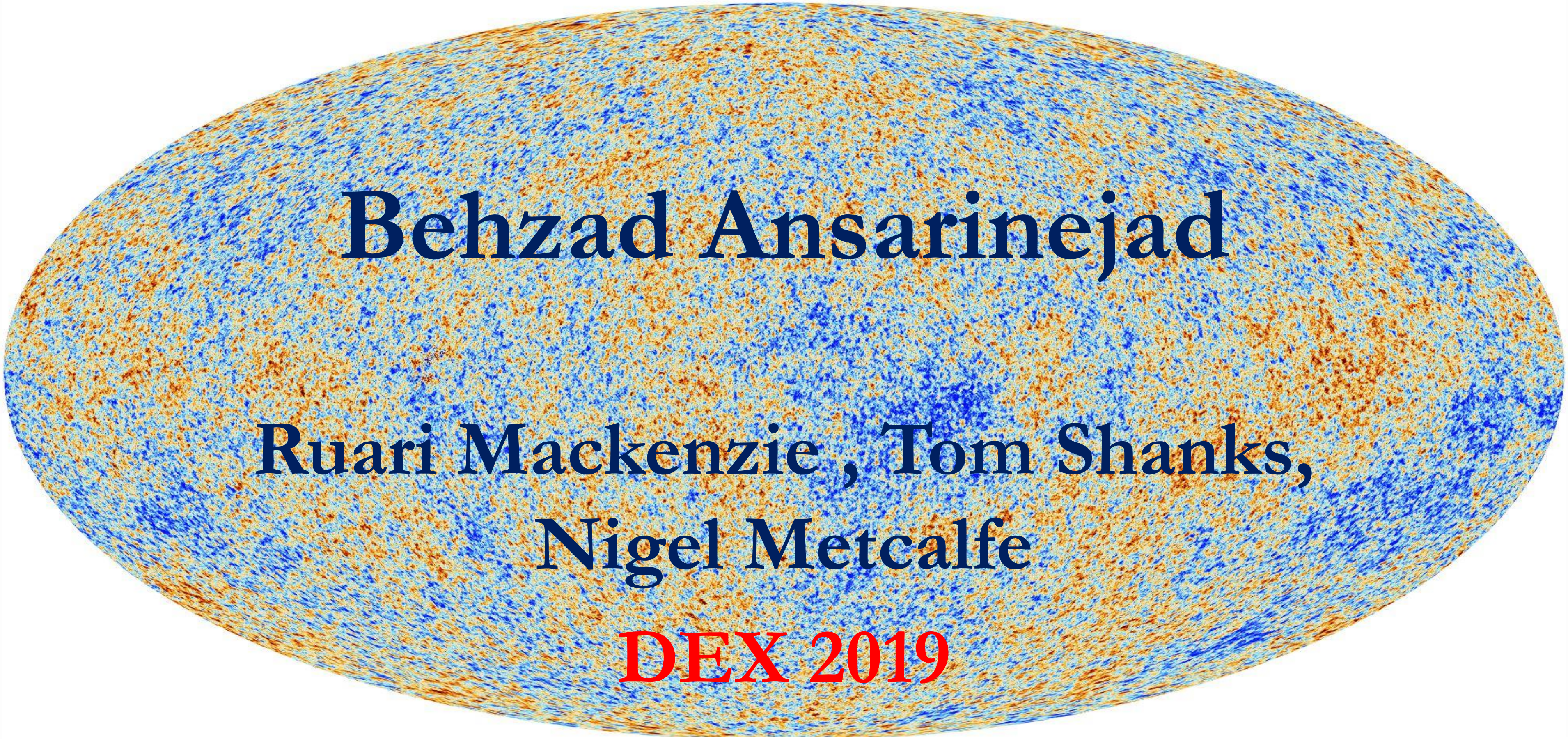
ISW Constraints via CMB-LRG Cross Correlation



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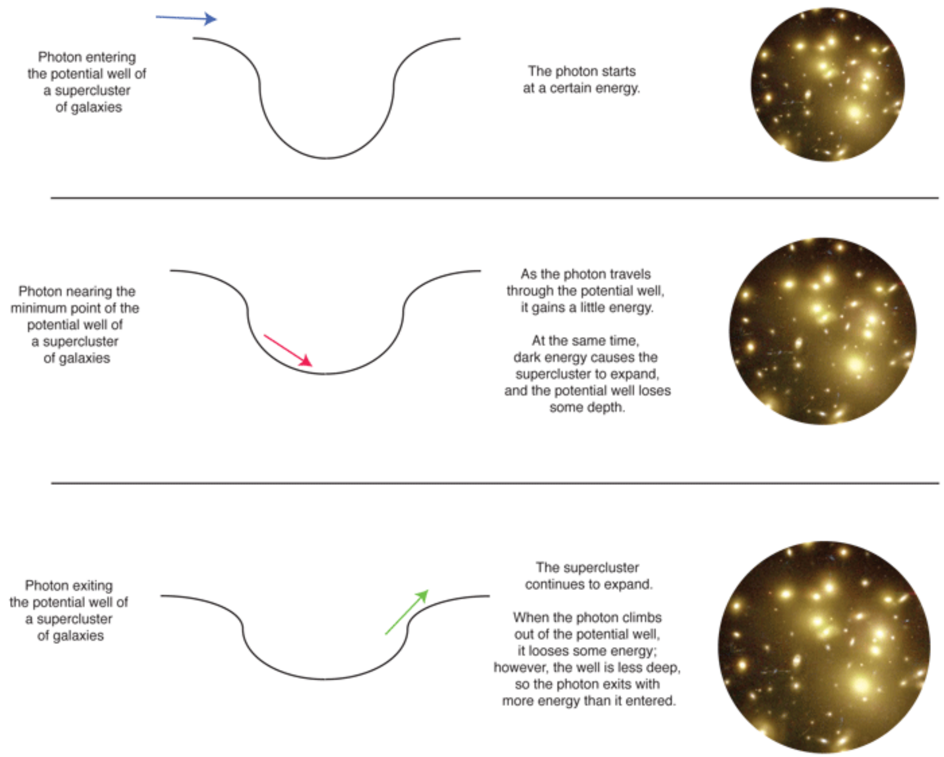
Late-time integrated Sachs–Wolfe effect

- Arises as the universe becomes Dark Energy dominated (below z~1).
- CMB photons left with net gain in energy as they pass through expanding gravitational potential wells of galaxy clusters, (opposite effect for voids).
- Results in secondary anisotropies on CMB temperature map detectable via CMB-LSS cross correlation -> Direct evidence for dark energy.
- Currently low signal to noise & mostly moderate detection significance – most detections <3σ, few detections up to 4σ.



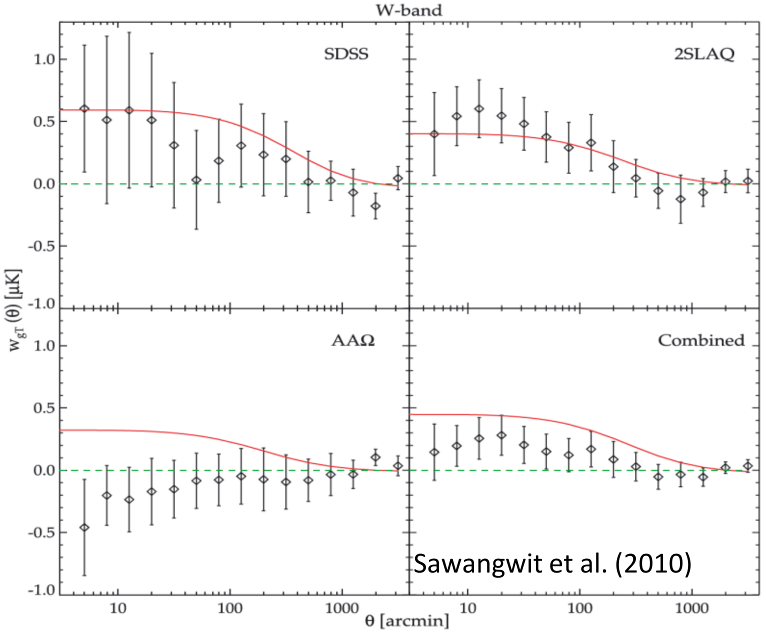
(Image credit: NASA's Cosmic Times)

http://ifa.hawaii.edu/cosmowave/supervoids/the-integrated-sachs-wolfe-effect/

ISW detection methods

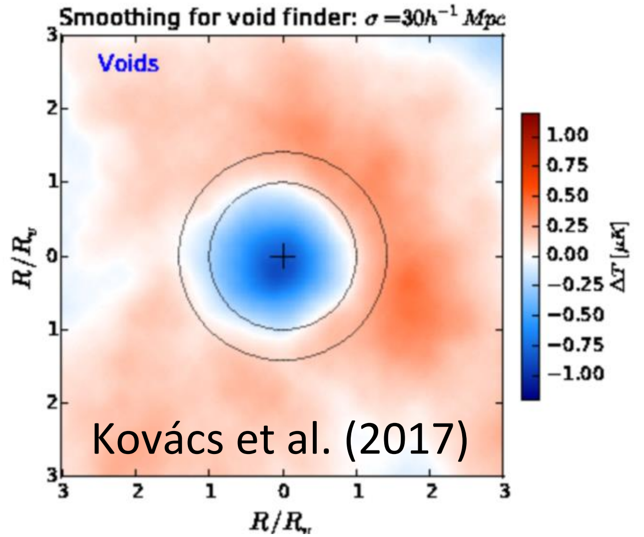
CMB-LSS Cross Correlation

- **<3σ:** WMAP-SDSS (Sawangwit et al. 2010), WMAP-WISE (Kovács et al. 2013)
- **Up to ~4σ:** Planck-NVSS+SDSS+WISE (Planck Collaboration et al. 2016), WMAP-NVSS (Giannantonio et al. 2008)



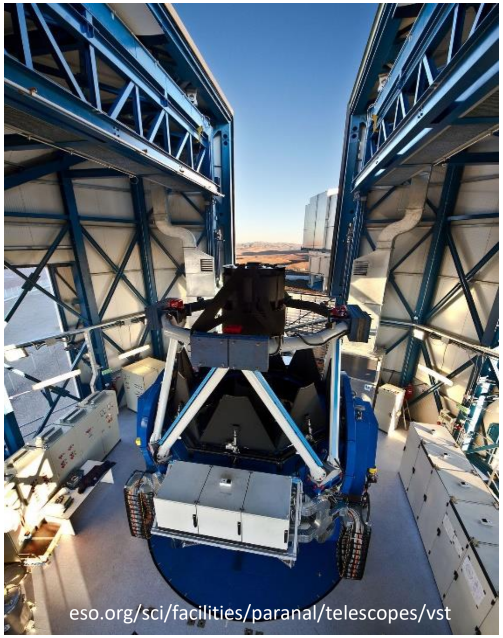
Stacking of voids and superclusters

- **<3σ:** Granett et al. (2017) using Planck & BOSS, Kovács et al. (2017) using Planck & DES Y1.
- **>3σ**: BOSS CMASS sample (Nadathur & Crittenden 2016; Cai et al. 2017).



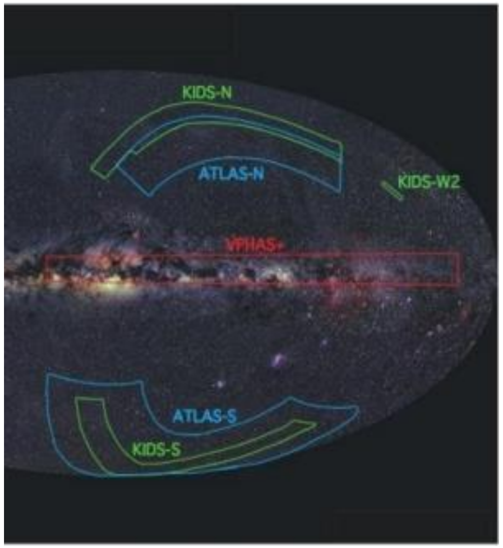
VLT Survey Telescope (VST)

- 2.6-m wide field optical survey telescope located at Paranal. 1°x 1° field of view + OmegaCAM (16k x16k pixels) CCD.



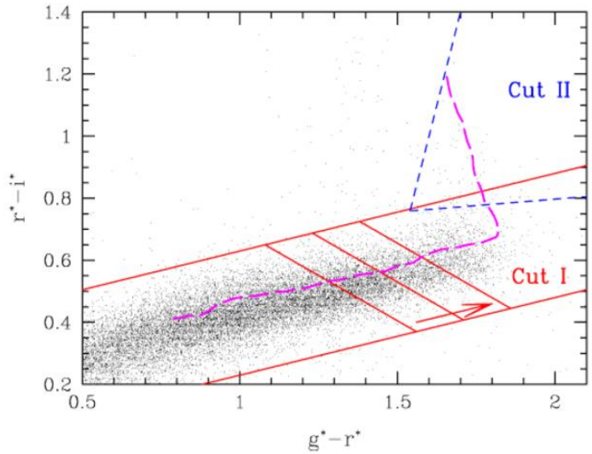
VST ATLAS Survey

- Optical *ugriz* survey covering ≈ 4700 deg^2 of the Southern sky to similar depths as SDSS, but superior seeing (e.g. ~0.''8 in i, compared to 1.''2).
- ½ of SGC & NGC will be overlapped by German section of eROSITA, will be covered by 4MOST. Also overlapped by DES, VHS, KIDS, GAMA G23 & Pan-STARRS.
- Advantage of covering a large area in the southern hemisphere and can further reduce the ISW error bars, combined with SDSS in the North.



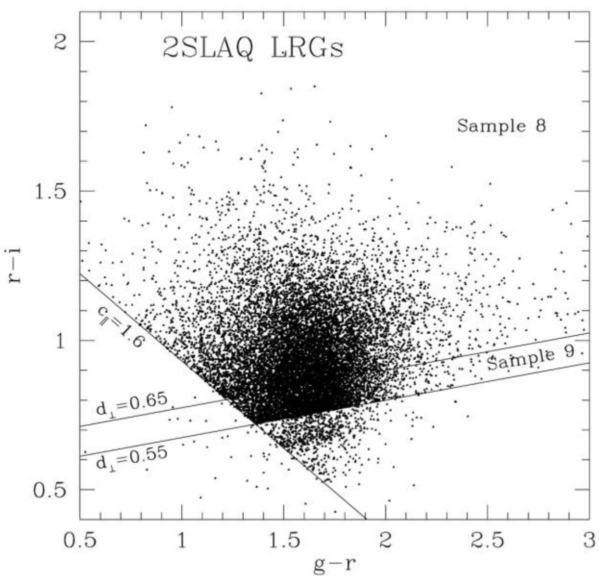
LRG samples photometric selection criteria

$\bar{z} \approx 0.35$ *low redshift LRG sample*



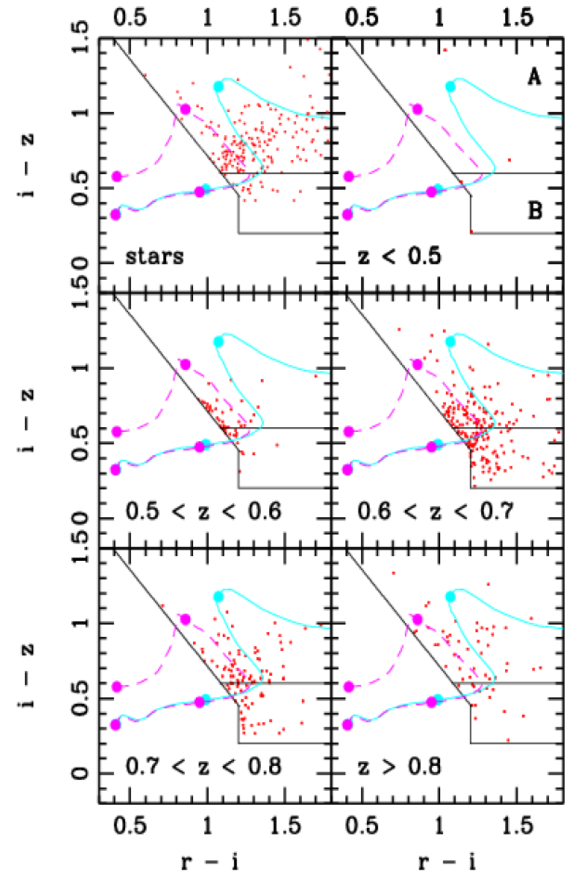
Following SDSS;
Eisenstein et al. (2001)

$\bar{z} \approx 0.55$ *intermediate redshift LRG sample*



Following 2SLAQ;
Canon et al. (2006)

$\bar{z} \approx 0.68$ *high redshift LRG sample*

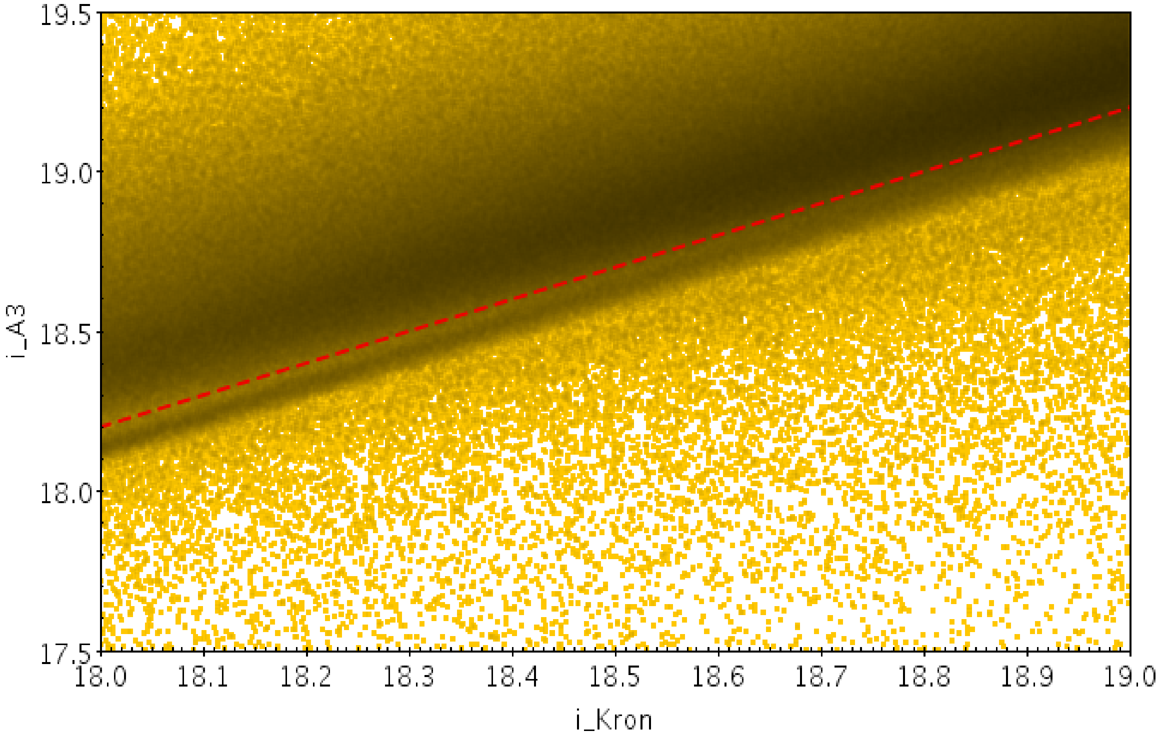


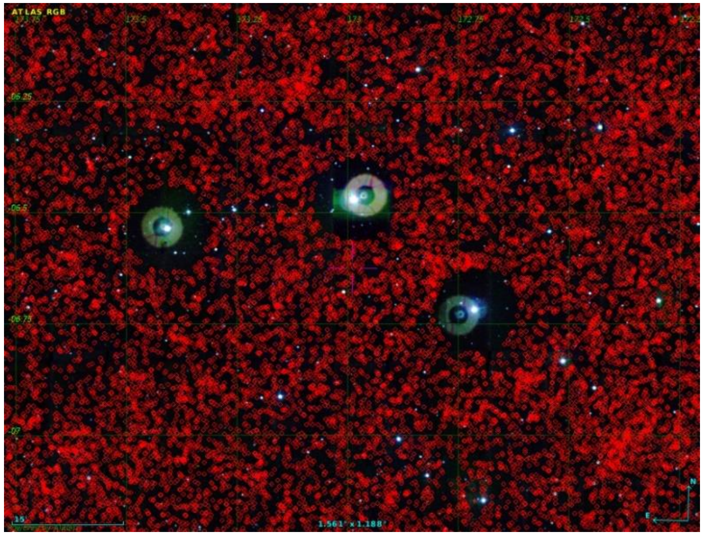
Following AAΩ;
Ross et al. (2008)

- And 3 magnitude limited samples: 18<r<19, 19<r<20, 20<r<21

Stellar Contamination

- We correct for dust extinction (Schlegel et al. 1998), mask for artefacts and stellar contamination is removed by matching to Tycho-2 bright star catalogue (Høg *et al.* 2000) & visually imposing cuts on the i_{A3} vs i_{Kron} diagram.
- Also trying z_A3-z_A5 vs z_kron & r-i vs i-W1 cuts. Seeing / sky brightness dependent S/G separation.





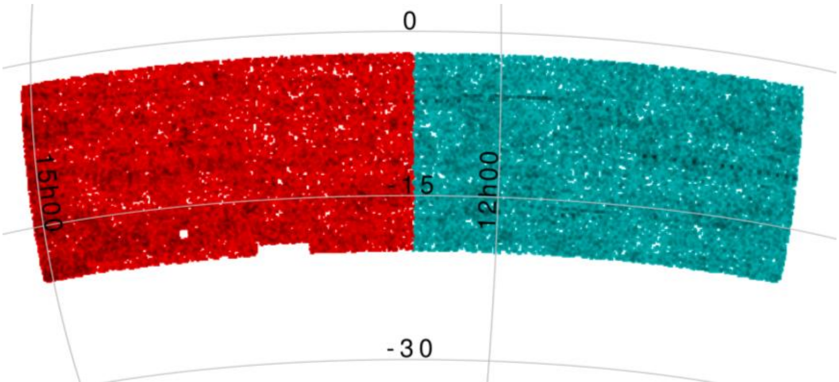
LRG projected angular auto-correlation

Landy-Szalay estimator (Landy & Szalay 1993):

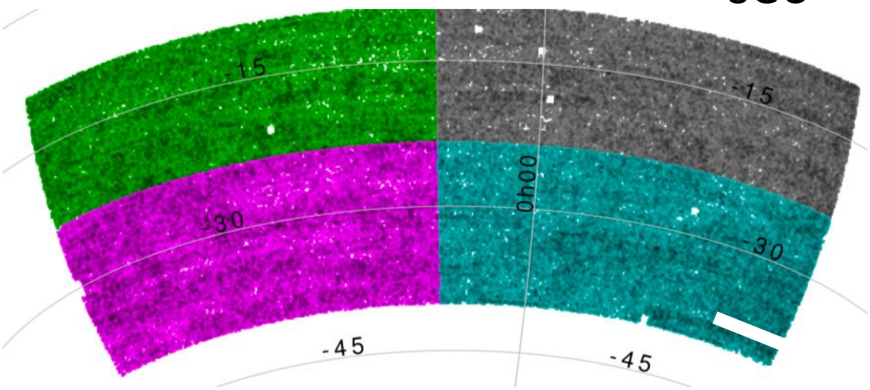
$$\omega(\theta) = 1 + \left(\frac{N_r}{N_d}\right)^2 \frac{DD(\theta)}{RR(\theta)} - 2\left(\frac{N_r}{N_d}\right)\frac{DR(\theta)}{RR(\theta)},$$

$$\sigma_{\bar{\omega}(\theta)} = \frac{\sigma_{N_s - 1}}{\sqrt{N_s}} = \sqrt{\frac{\sum(\omega_i(\theta) - \bar{\omega}(\theta))^2}{N_s^2 - N_s}}.$$

NGC



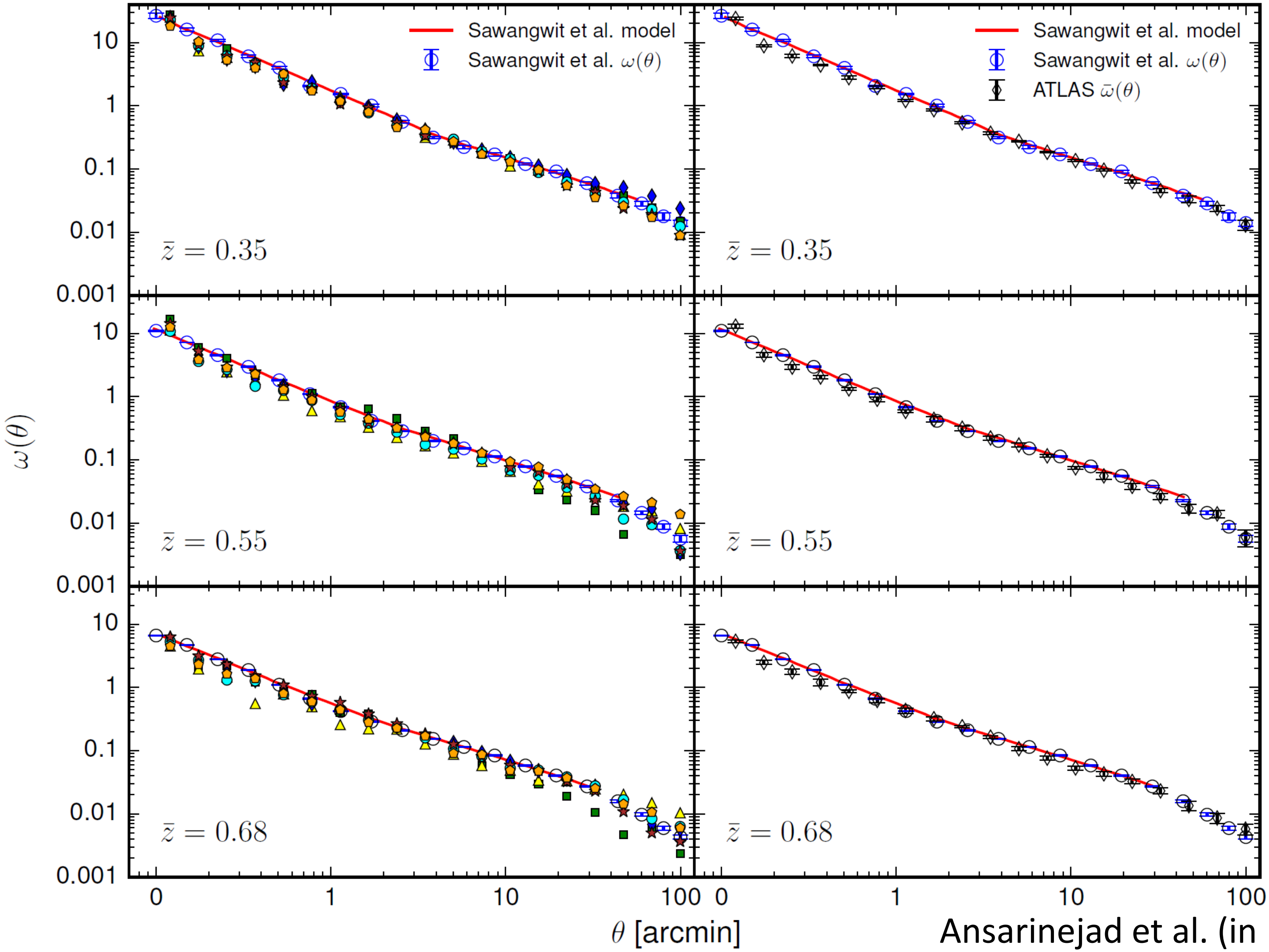
SGC



6 fields: each ~670 deg^2 in area.

Containing ~15,300, ~40,200 and ~32,700 galaxies for the z=0.35, z=0.55 and z=0.68 samples respectively.

LRG auto-correlation- ATLAS vs SDSS



Ansarinejad et al. (in prep)

LRG samples

- Number of LRGS in each sample after applying the colour cuts, masking artefacts and removing stellar contamination.

Sample $\bar{z}$	Number of LRGs	Sky Density (deg^{-2})	Magnitude (AB)
0.35	94,776	≈ 22	$17.5 \leq r < 19.5$
0.55	250,846	≈ 58	$17.5 \leq i < 19.5$
0.68	201,356	≈ 50	$19.8 \leq i < 20.5$

Ansarinejad et al. (in prep)

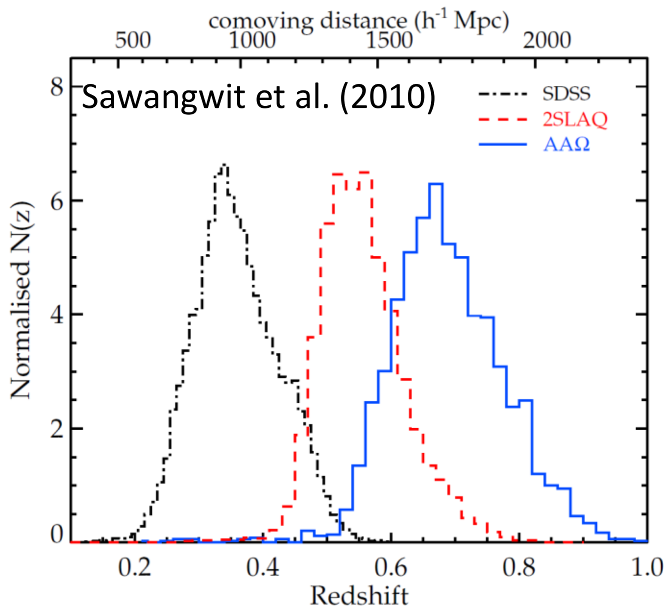


Figure 1. Redshift distribution of the three LRG samples inferred from the redshift surveys used in their selections.

Table 1. Summary of the LRG samples used in the cross-correlation analyses.

Sample	$\bar{z}$	Number	Sky density (deg^{-2})	Magnitude (AB)
SDSS	0.35	106 699	$\approx$13	$17.5 \leqslant r < 19.5$
2SLAQ	0.55	655 775	$\approx$85	$17.5 < i < 19.8$
AAΩ	0.68	800 346	$\approx$105	$19.8 < i \leqslant 20.5$

Sawangwit et al. (2010)

CMB-LRG angular cross-correlation

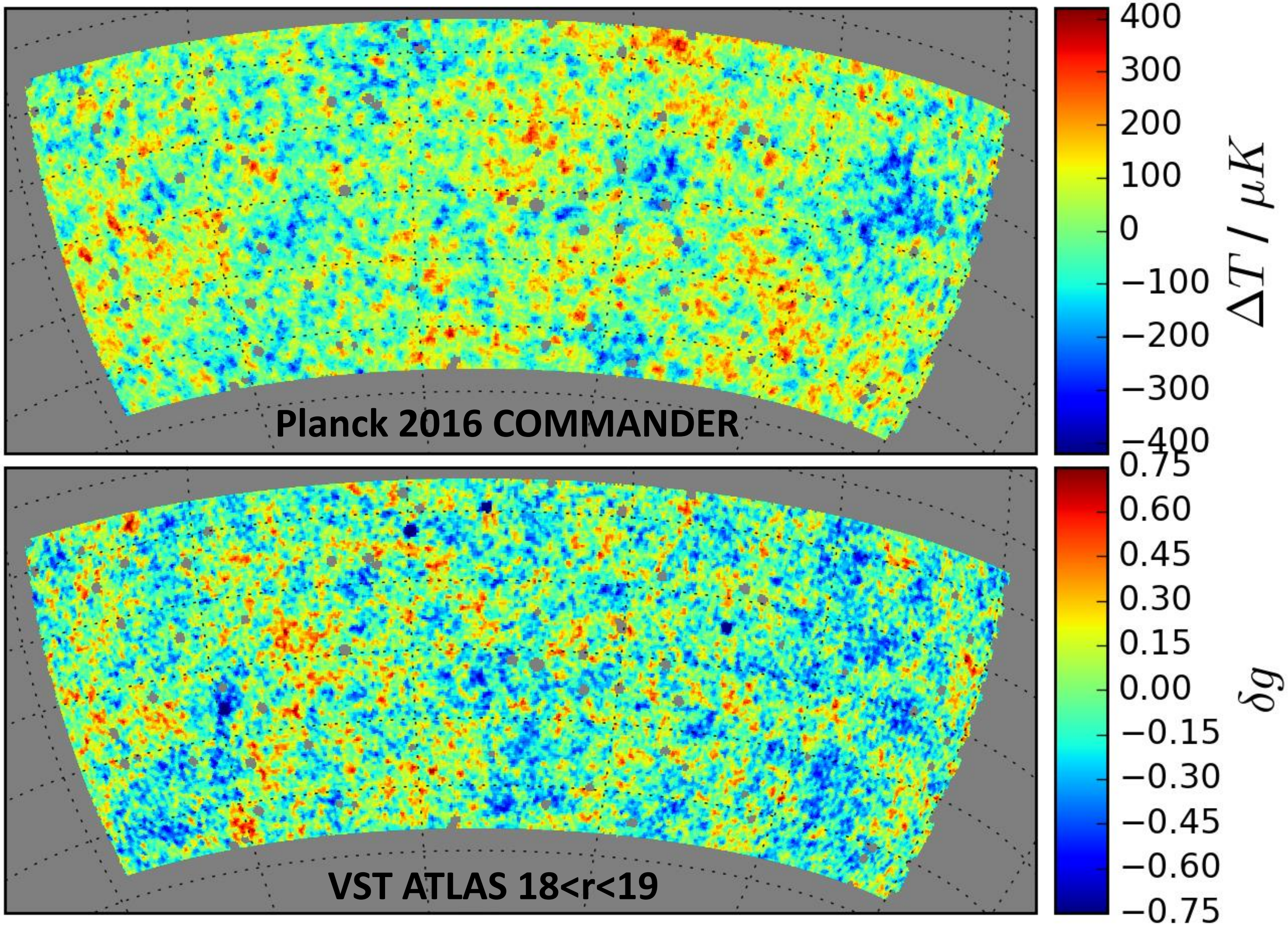
$$\omega_{LC}(\theta) = \frac{\sum_{ij} f_i \delta_L(\bar{n_i}) f_i \Delta_T(\hat{n}_j)}{\sum_{ij} f_i f_j},$$

$$\delta_L(\hat{n}) = \frac{n_L(\hat{n}) - \bar{n}_L}{\bar{n}_L}, \quad \Delta T = T - \bar{T} \qquad \hat{\boldsymbol{n}}_i \cdot \hat{\boldsymbol{n}}_j = \cos\theta$$

$$C_{ij} = \frac{N_{JK}-1}{N_{JK}} \sum_{n=1}^{N_{JK}} [(\omega_{LC,n}(\theta_i) - \bar{\omega}_{LC}(\theta_i))$$
$$((\omega_{LC,n}(\theta_j) - \bar{\omega}_{LC}(\theta_j))],$$

$$\chi^2 = [\hat{\omega}_{LC,obs}(\theta) - \omega_{LC,mod}(\theta)]^T C^{-1}$$
$$[\hat{\omega}_{LC,obs}(\theta) - \omega_{LC,mod}(\theta)],$$

CMB & LRG maps – 0.3 deg smoothing



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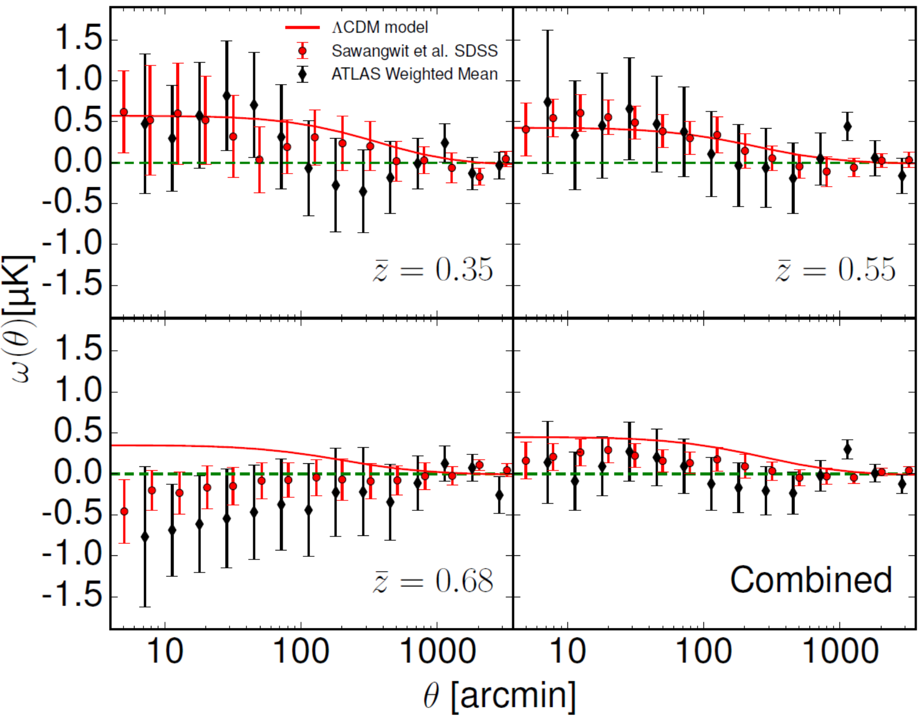
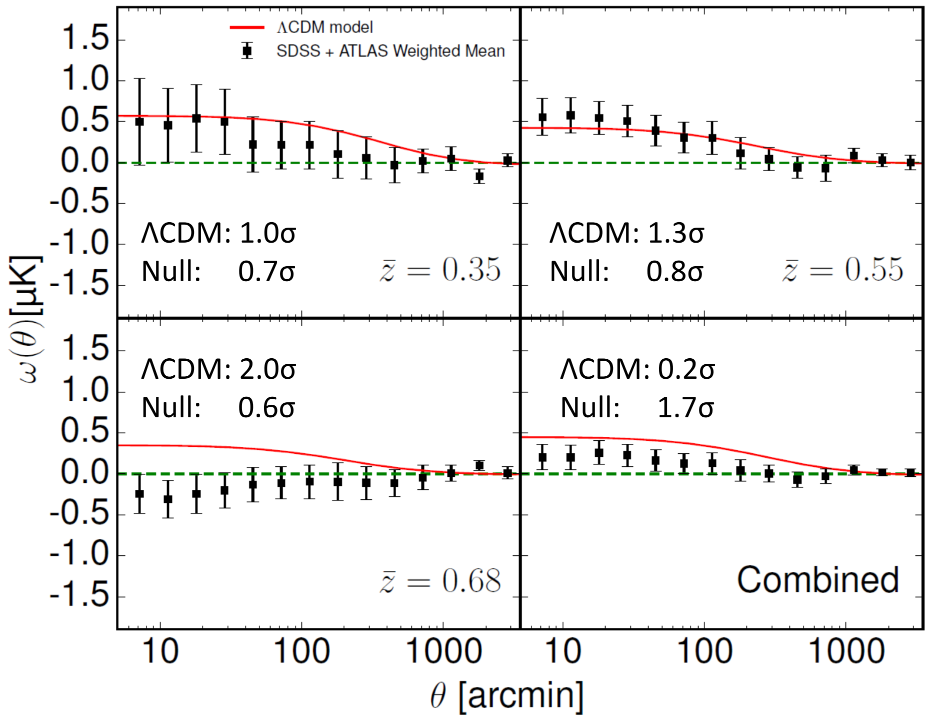
ISW cross correlation

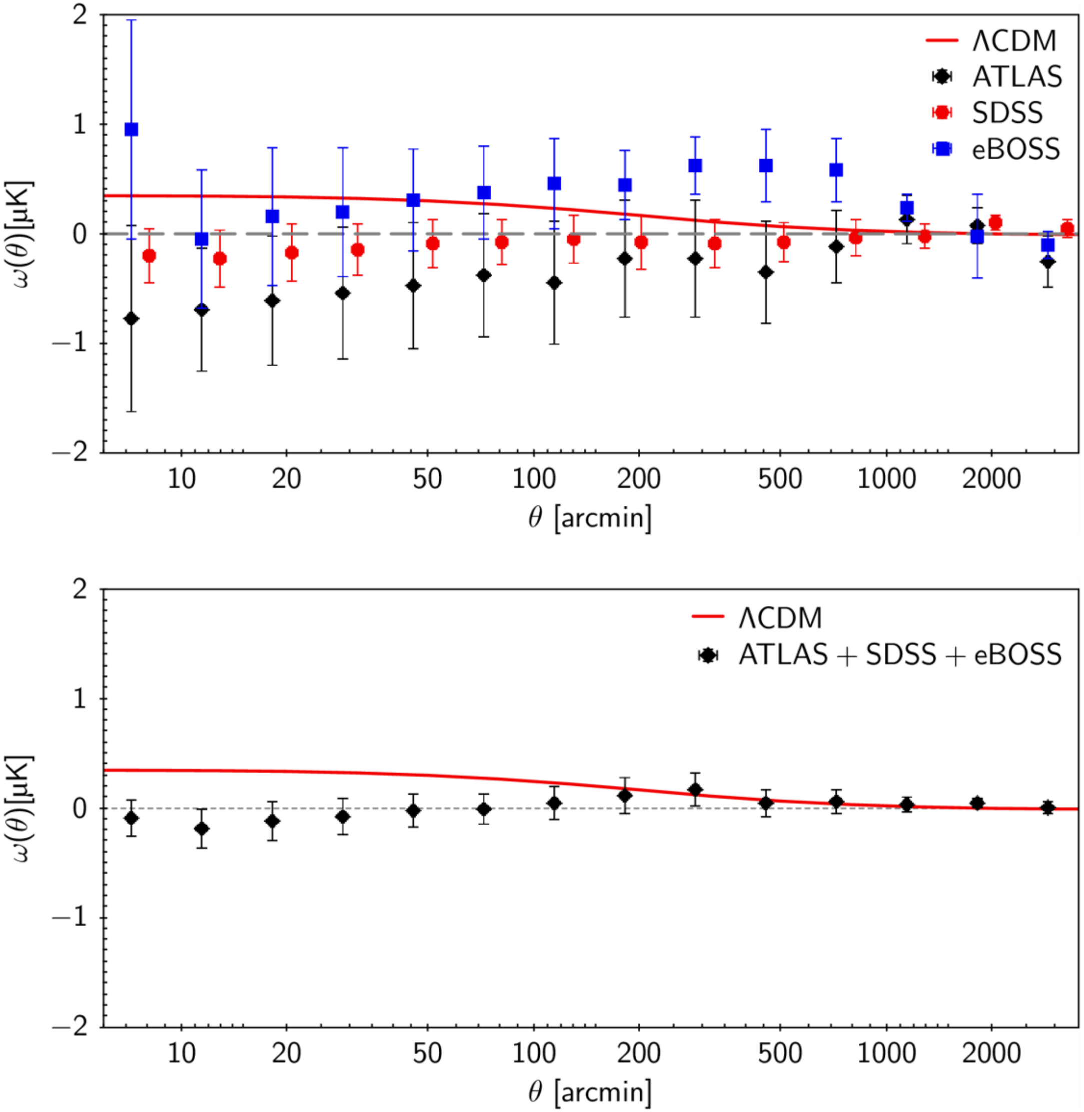




Ansarinejad et al. (in prep)

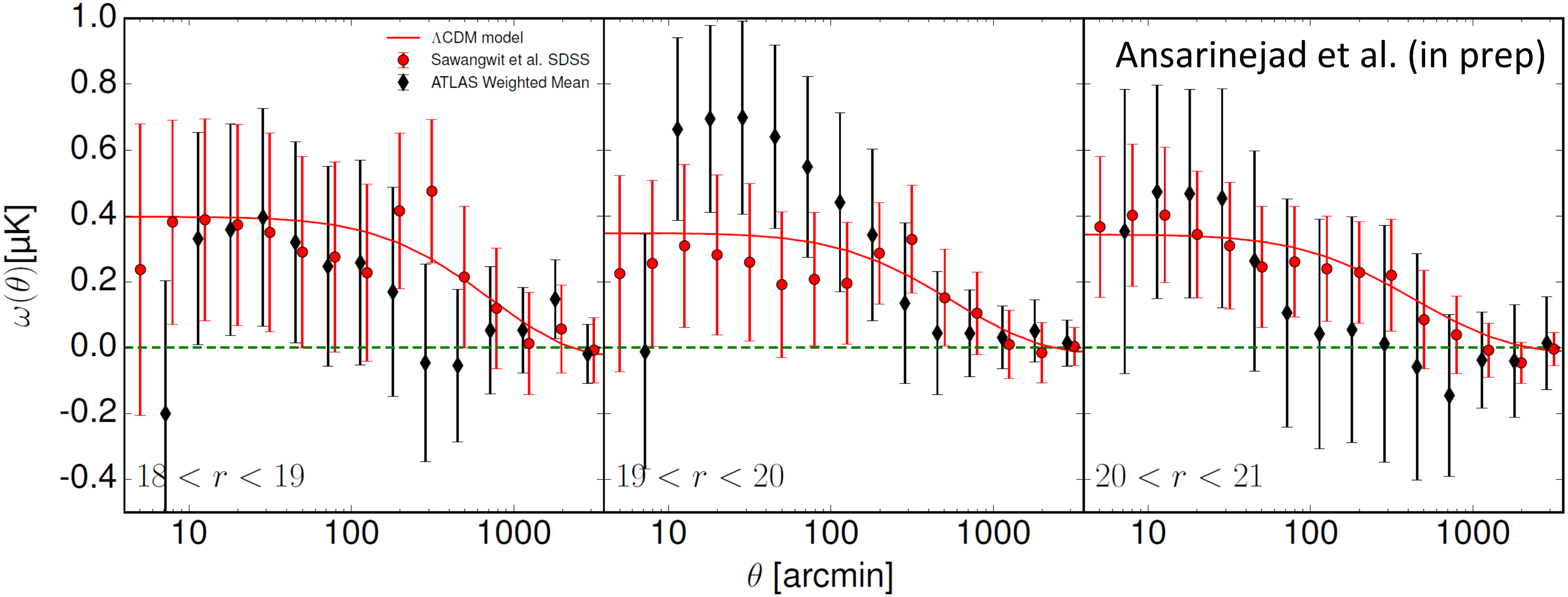
High redshift negative ISW signal?

- Negative signal currently insignificant and likely due to cosmic variance.
- No detection at z~0.68 when combining SDSS, ATLAS and eBOSS LRGs. ΛCDM rejected at up to ~3σ on small scales.
- If ISW shown to be redshift dependent might need alternative cosmological models, e.g. higher Ω_m?, modified gravity? Backreaction (Beck et al. 2018) – negative ISW signal between z~1.5-4.4?
- Test with DES / DECaLS LRGs to further reduce error bars.



Ansarinejad et al. (in prep)

ISW cross correlation – magnitude limited samples



Null rejection: 0.9σ

Null rejection: 1.7σ

Null rejection : 0.2σ

Combined Null rejection: 1.6σ

Summary & ongoing plans

- Measured ISW effect using Planck CMB + VST ATLAS LRGs.
- In agreement with SDSS, up to ~3σ detection at z~0.35, 0.55, consistent with ΛCDM. Supports accelerating expansion rate.
- Also detected in magnitude limited samples (out to z~0.4).
- But no detection at z~0.68 when combining SDSS, ATLAS and eBOSS LRGs. ΛCDM rejected but only at up to ~3σ on small scales.
- If ISW shown to be redshift dependent might need alternative interpretation e.g. higher Ω_m?, modified gravity?, backreaction (Beck et al. 2018)?
- Ongoing:
  -Repeat with new ATLAS calibration + improved S/G separation (improvement in detection significance). Further test high-z signal with DES / DECaLS.
  - Extend the projected LRG auto-correlation measurements to larger scales to check previous claims of non-Gaussianity.
  - Cross-correlate LRGs with CMB lensing map.