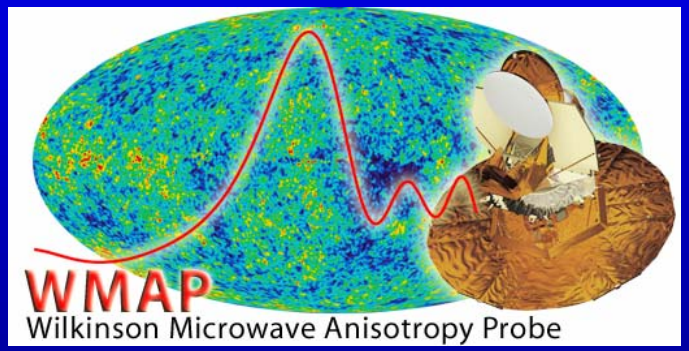

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Looking for Dark Energy with the SDSS & WMAP

Ryan Scranton

13 July 2004

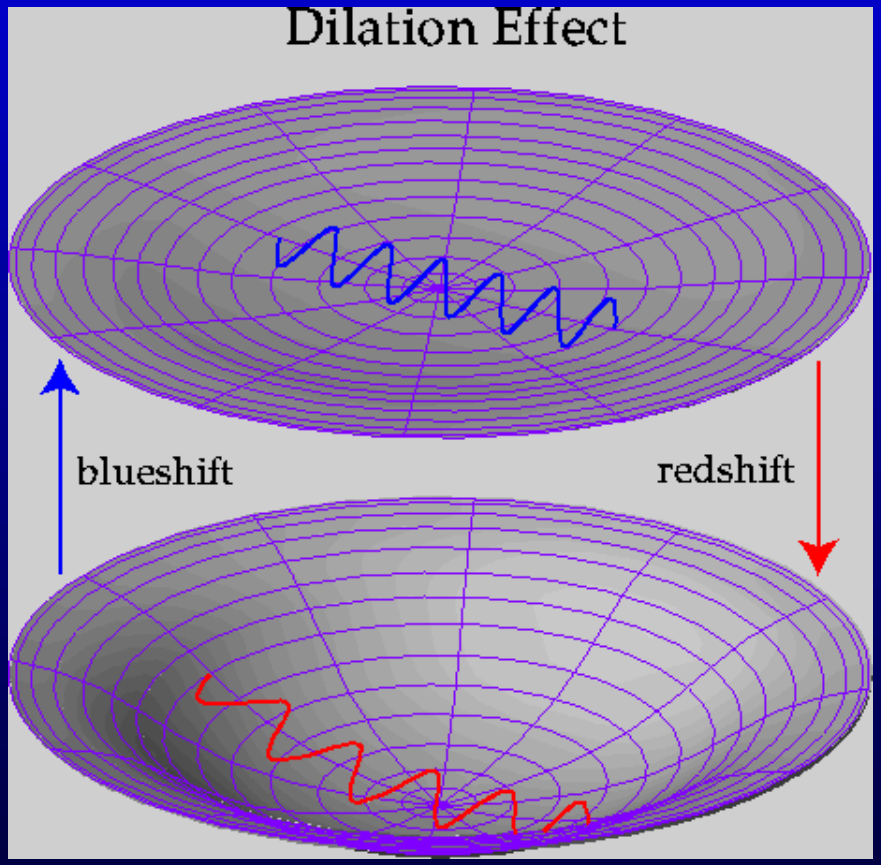
Andy Connolly, Bob Nichol, Albert Stebbins, István Szapudi, Daniel Eisenstein, Max Tegmark, Niayesh Afshordi, Tamas Budavari, István Csabai, Josh Frieman, Jim Gunn, David Johnston, Yeong-Shang Loh, Robert H. Lupton, Chris Miller, Erin Sheldon, Ravi Sheth, Alex Szalay, Yongzhong Xu

The Basic Idea

- CMB photons emitted at surface of last scattering ($z \sim 1000$)
- Pass through foreground LSS to us
- Interaction between CMB photons and LSS leads to cross-correlation bewteen observed CMB temperature and projected galaxy density
- Amplitude and signal of induced cross-correlation function of cosmology (Ω_M, Ω_Λ, w) and astrophysics (b, T_e).

The Details – Late Integrated Sachs-Wolfe Effect

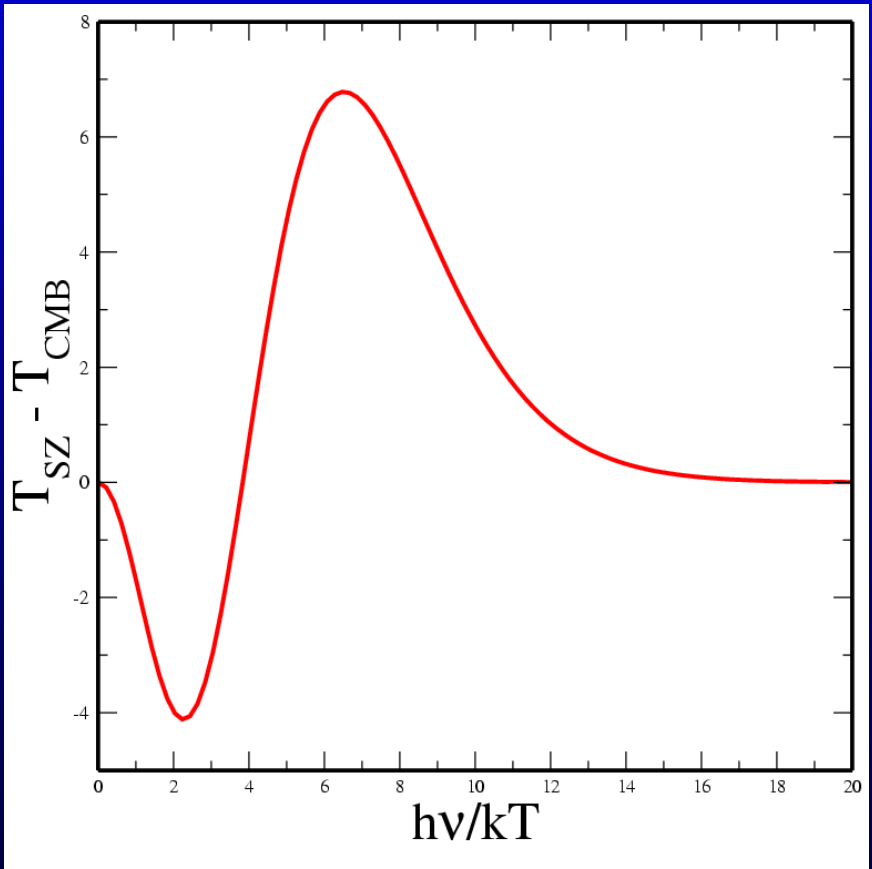
- After matter-radiation equality, dark matter falls into potential wells set up during inflation.
- For open or ΛCDM universes, universe expands faster than potentials, leading to potential decay
- CMB photons passing through potentials see net blue-shift in energy $\Rightarrow$ positive correlation with foreground structure



Wayne Hu, Samuel Laroque

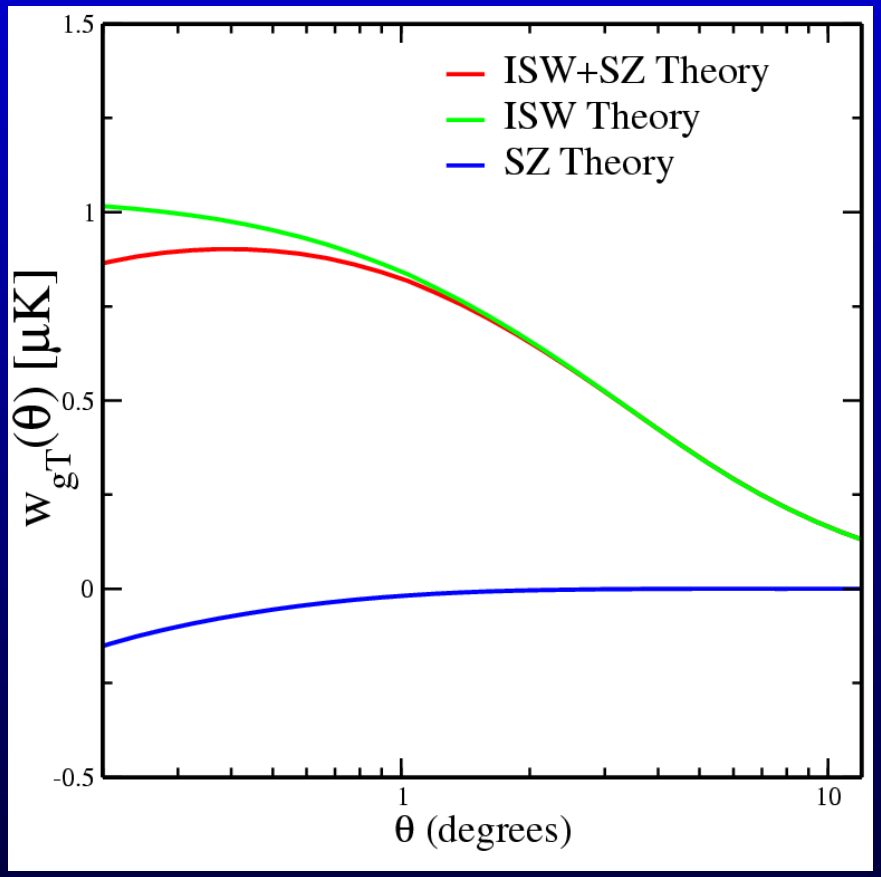
The Details – Thermal Sunyaez-Zel'dovich Effect

- Hot electron gas surrounds galaxy filaments and clusters
- CMB photons inverse Compton scatter off of electrons, shifting photons to higher energies
- CMB in Rayleigh-Jeans region of original spectrum gives observed temperature decrement ⇒ anti-correlation with foreground structure



The Details – Theory Curves

- Expect ISW to dominate on large angles, SZ to become important on smaller angles
- 2 free parameters in linear theory: galaxy bias ($\delta_{gal} = b_{gal}\delta_{DM}$) and electron gas-bias ($T_e b_P$). b_{gal} controls overall amplitude of the signal and $T_e b_P$ determines the relative importance of the SZ effect
- Very important to maximize sky coverage (cosmic variance) and keep Poisson noise low



Other Similar Measurements

- **Boughn & Crittenden** and **Nolta et al**: 1/2 sky with NVSS radio selected galaxies, $z \sim 1$, broad redshift distribution
- **Fosalba & Gaztanaga**: 3300 square degrees with APM digitized optical plate data, $z \sim 0.3$, broad redshift distribution
- **Fosalba, Gaztanaga & Castander**: SDSS DR1 data, $z \sim 0.35$, broad redshift distributions
- **Afshordi et al**: 2MASS full-sky IR selected galaxies, $z \sim 0.1$, some redshift information

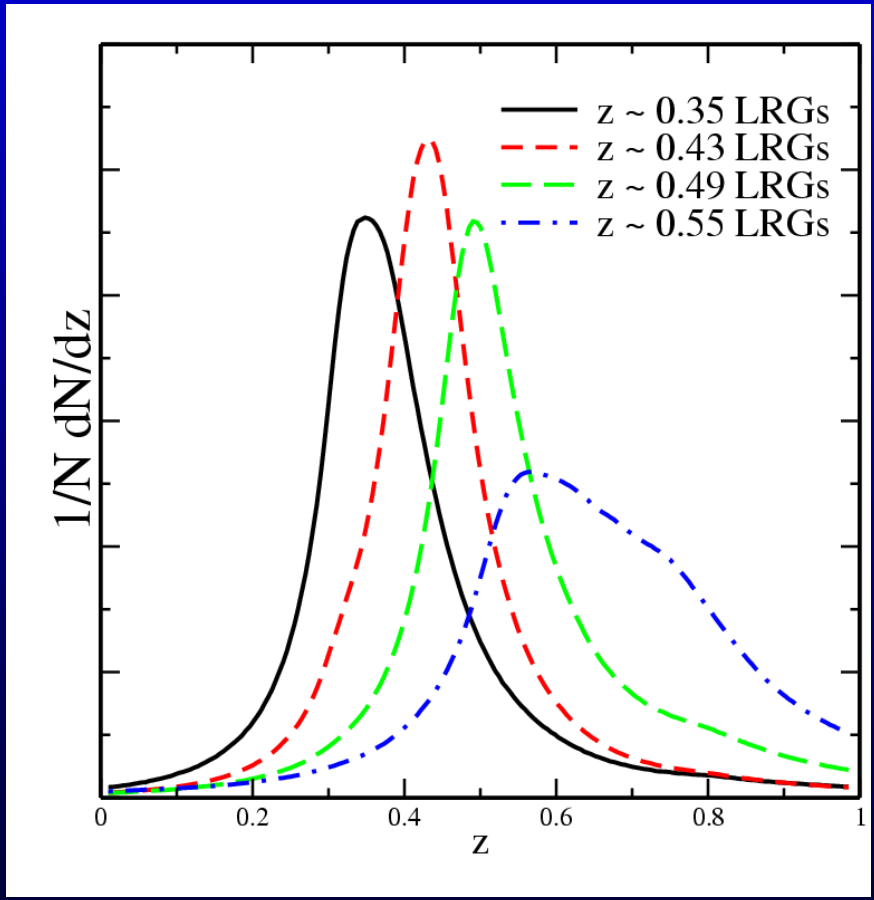
SDSS Basics

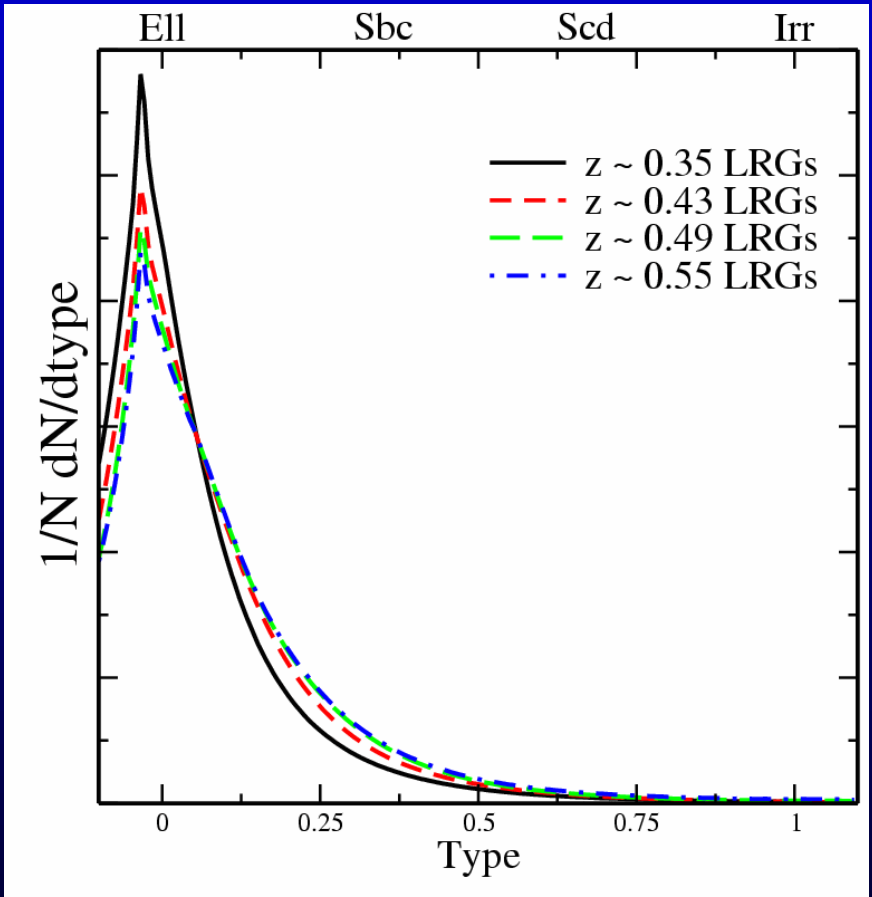
- 5-color photometry and follow-up spectroscopy on 1/4 of the sky
- Reliable galaxy identification down to $r' \sim 22$
- Current catalog consists of approximately 5000 square degrees on the sky & 400,000 spectra.
- Combining five filters gives photometric redshifts with typical $\Delta z \sim 0.05$ for galaxies $r' < 21$

Our Galaxy Data Set

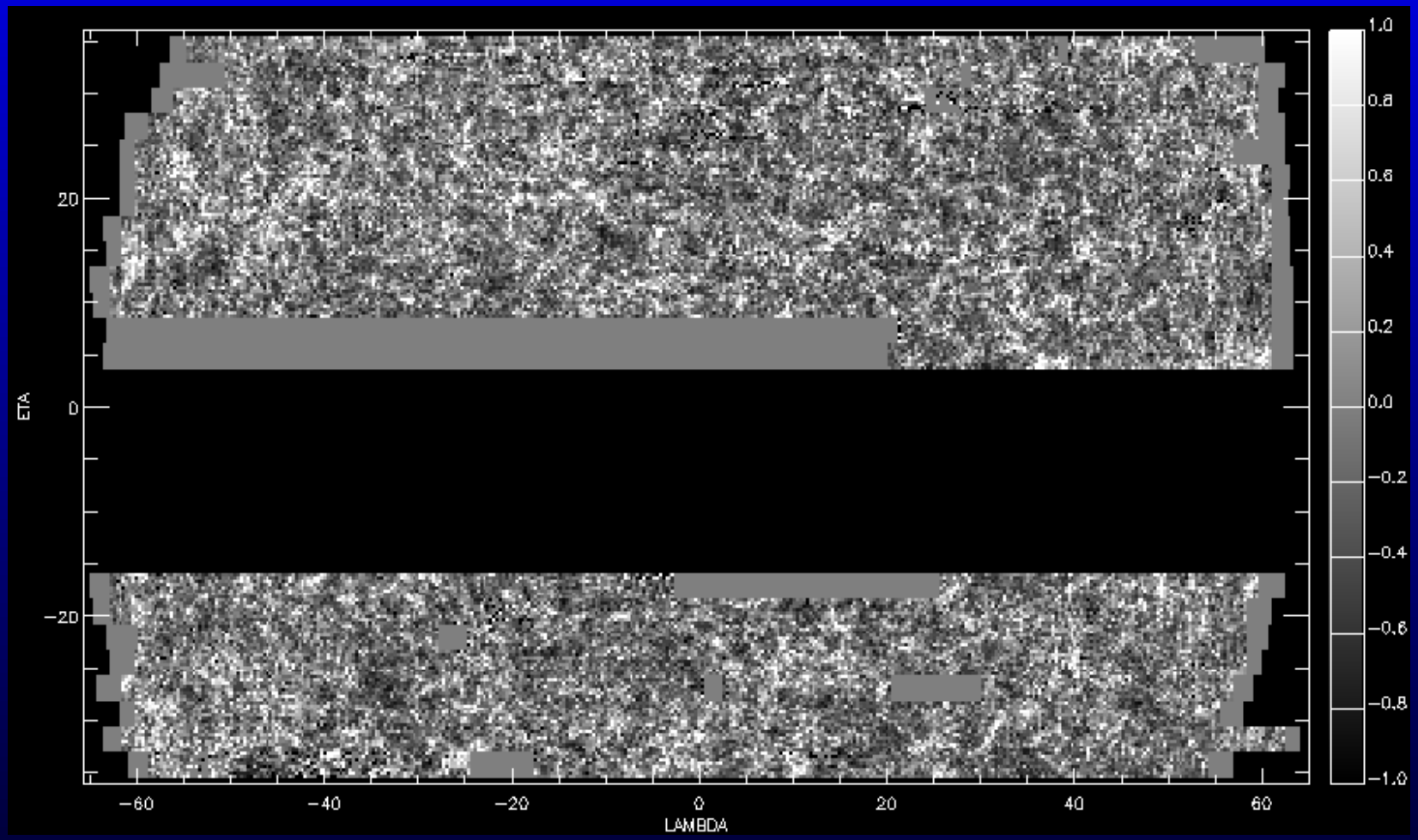
- Begin with 25 million galaxies covering ~ 3900 square degrees
- $i < 21$, seeing $<$ 1".5 (~ 3400 square degrees)
- Use color-based selection to pick out **L**uminous **R**ed **G**alaxies
- 4 photometric redshift bins spanning $0.3 < z < 0.8$ with 0.4, 0.8, 1.0 and 0.7 million galaxies (from lowest to highest mean redshift)
- Well-matched to peak in $(S/N)^2$ for ΛCDM (Afshordi, 2003)

LRG Distributions





LRG Map

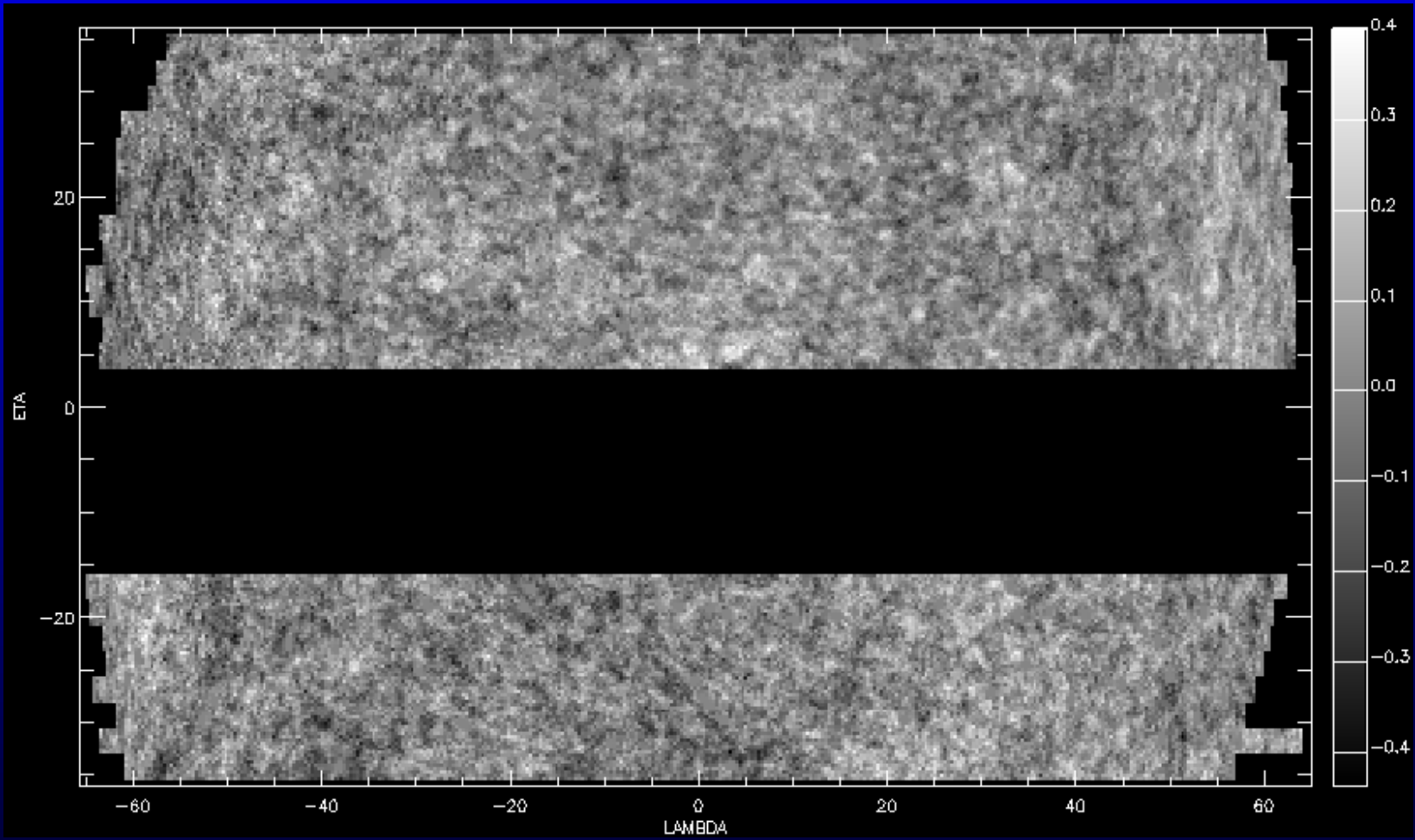


$z \sim 0.43$

The CMB Data Set

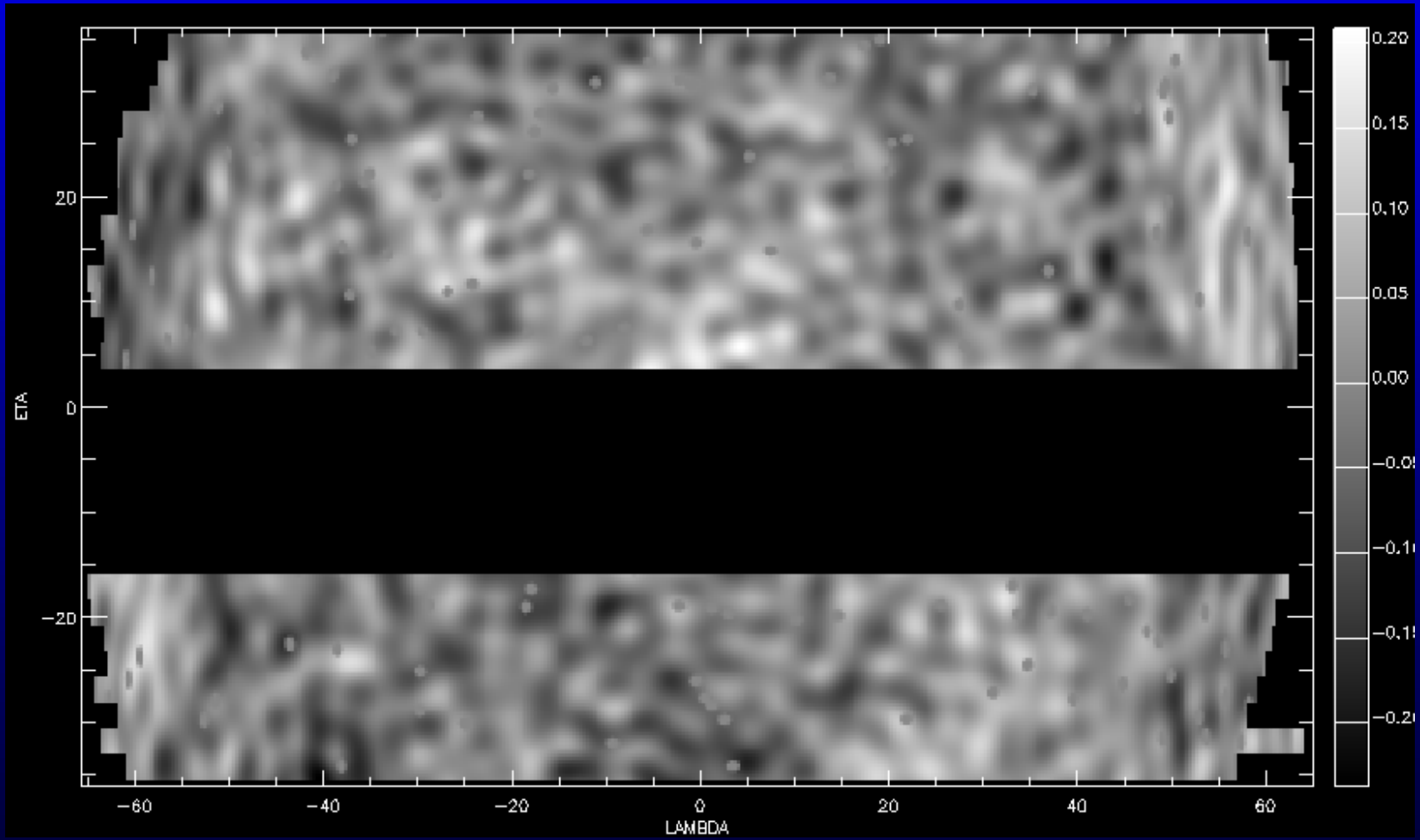
- Three primary CMB bands: Q, V, W
- Max Tegmark's "Clean Map"
- Smoothed Map (convolved "clean" map with 1 degree Gaussian – isolate large scale ISW signal)
- Pixelized with Healpix and SDSSPix

Resampled CMB Map



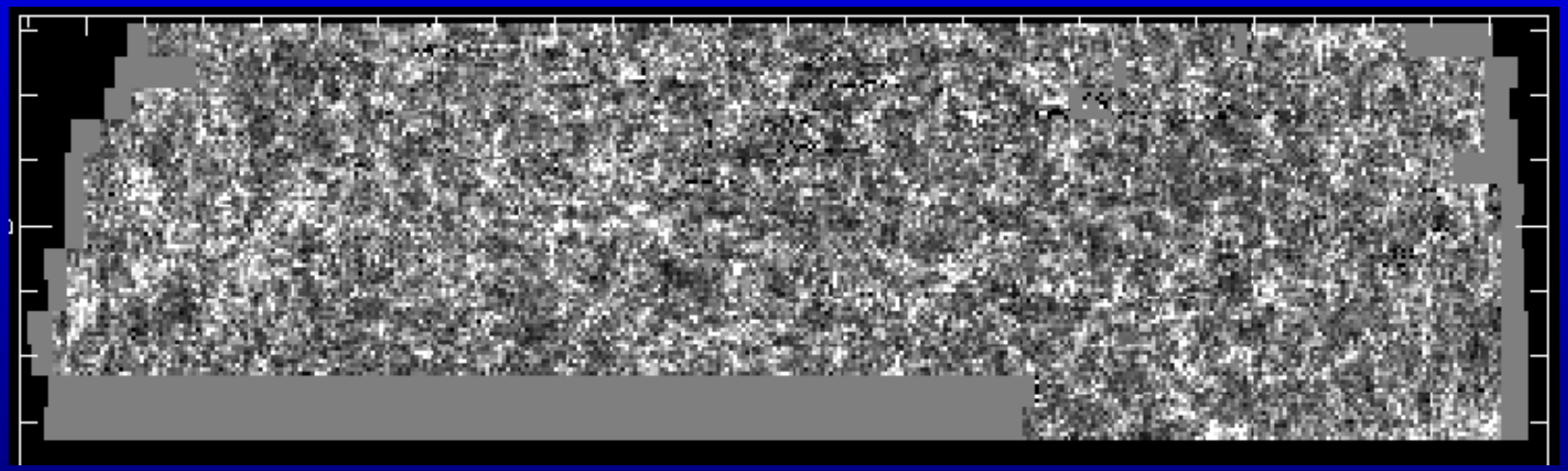
w band with kp12 mask

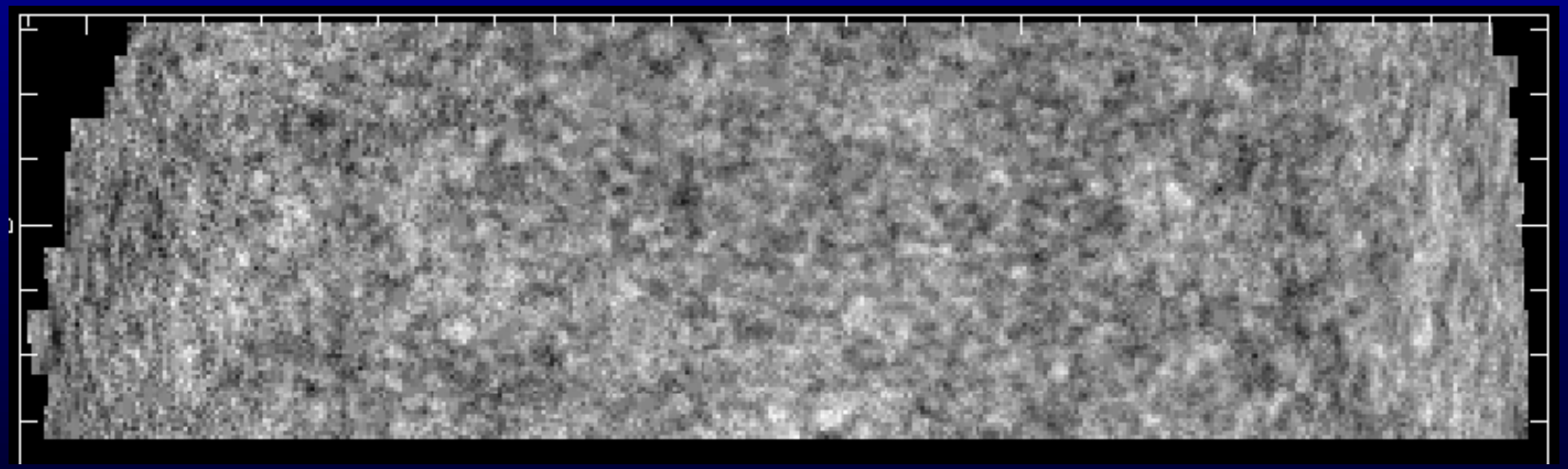
Resampled CMB Map



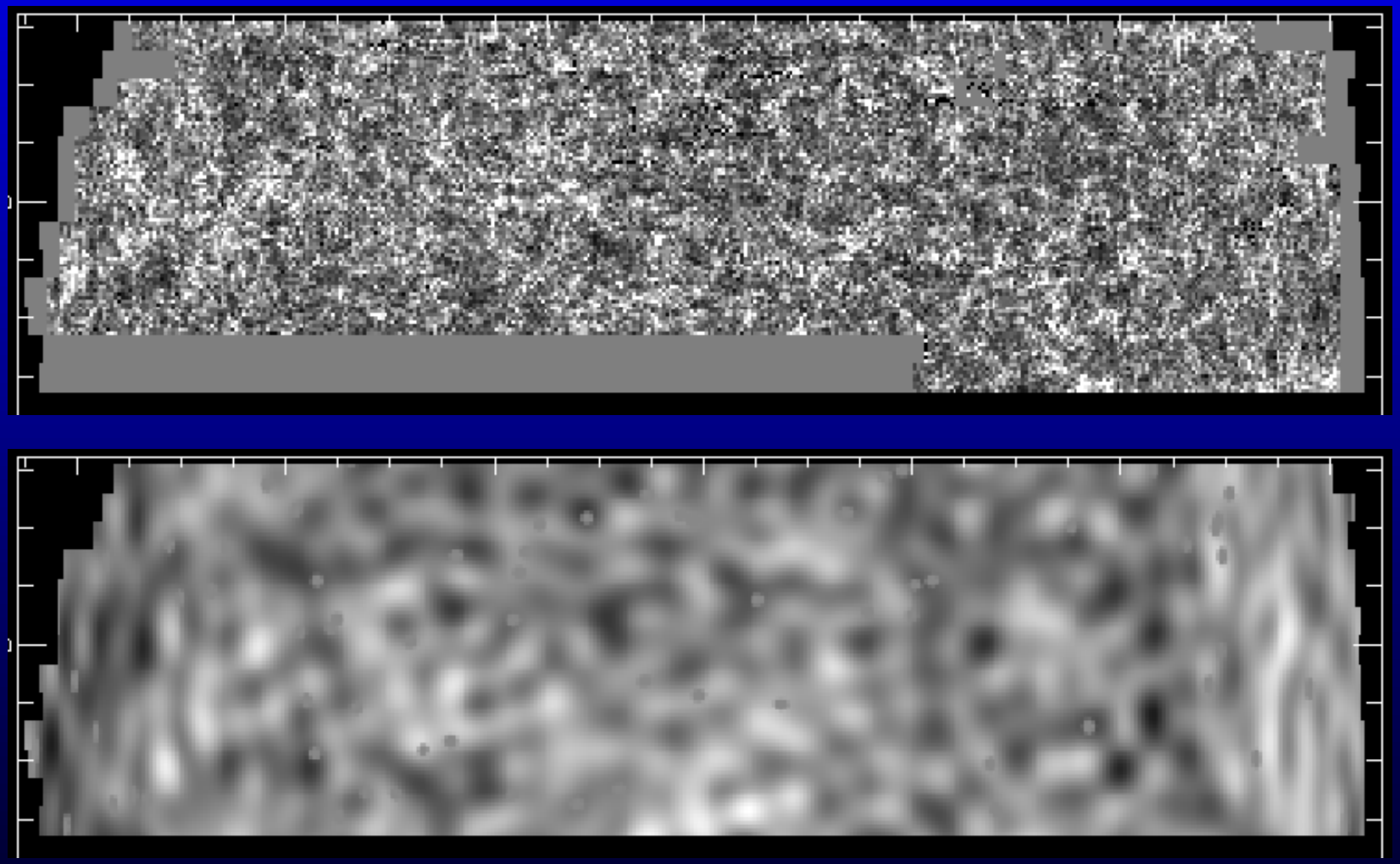
Smoothed clean map with kp12 mask

Map Comparisons I

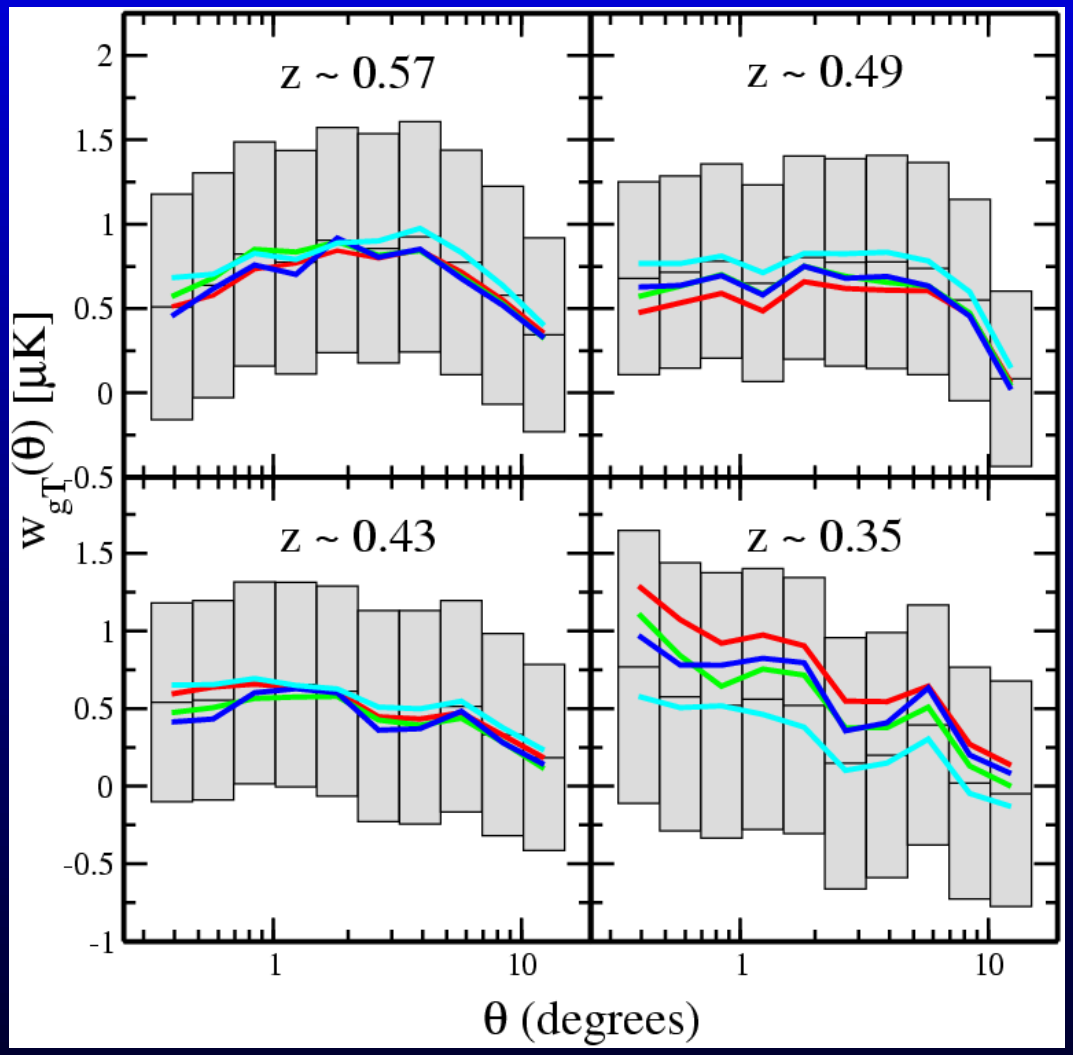




Map Comparisons II



Results



Statistical Tests I

Systematics Tests

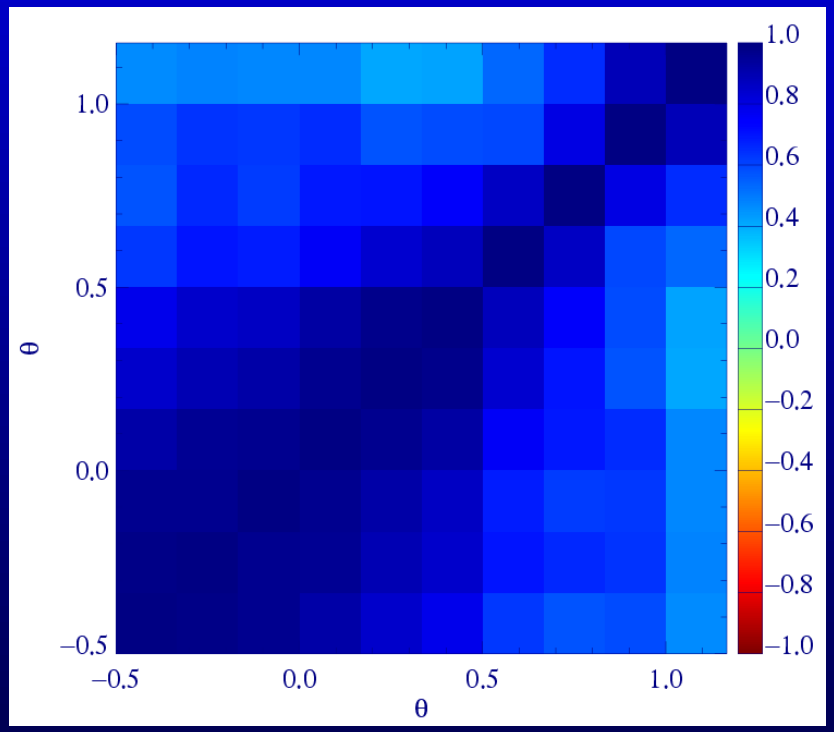
- Star-CMB $\Rightarrow$ No correlation except for the $z \sim 0.35$ bin.
- Cross-correlation with WMAP colors:
  - ⋆ Q-V, V-W
  - ⋆ Synchrotron (9Q-12V+3W), Dust (3Q-12V+9W)
  - ⋆ Null signal consistent with galaxy Poisson errors
- Achromatic Signal

Statistical Tests II

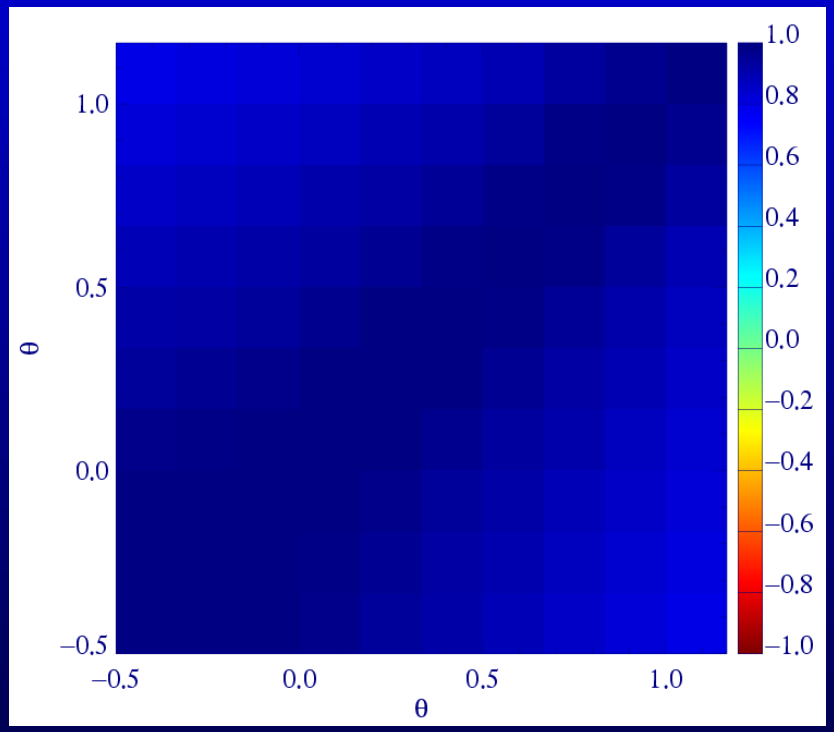
Significance Tests

- Extremely Correlated Angular Bins
- Covariance Matrices: Jack–knife & Random CMB maps.
- χ^2 tests against null hypothesis ($w_{gT}(\theta) = 0$; flat, matter dominated universe):
  - ⋆ Exclude null hypothesis ($\geq 90\%$ confidence) for most combinations of CMB maps and LRG samples using jack–knife covariance except $z \sim 0.35$ LRGs
  - ⋆ Exclude null for highest two redshift bins only using random CMB map covariance

Correlation Matrices



Jackknife Resampling



Mock CMB Maps

Statistical Tests II

Significance Tests

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Statistical Tests III

False Discovery Rate

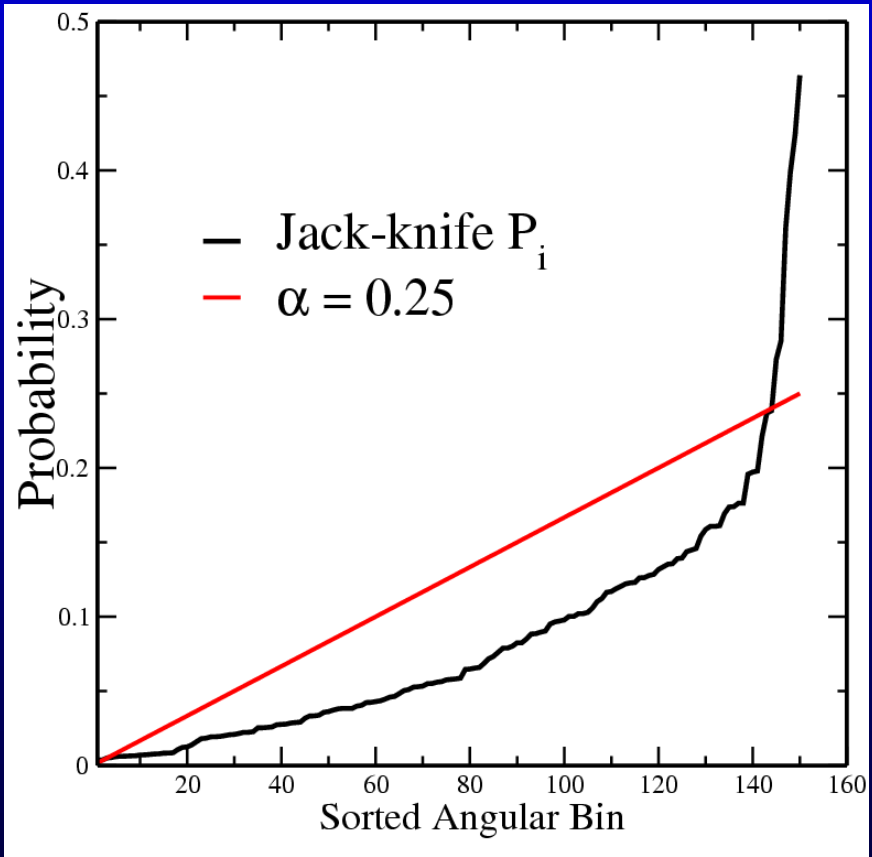
- Frequentist technique for combining correlated data
- Calculate the probability (P) that a given angular bin is consistent with null hypothesis & order bins by P
- For given FDR (α), determine how many bins reject the null hypothesis (n_{reject}):

$$\texttt{max}\ \ i : P_i > \frac{i\alpha}{N_\theta}$$

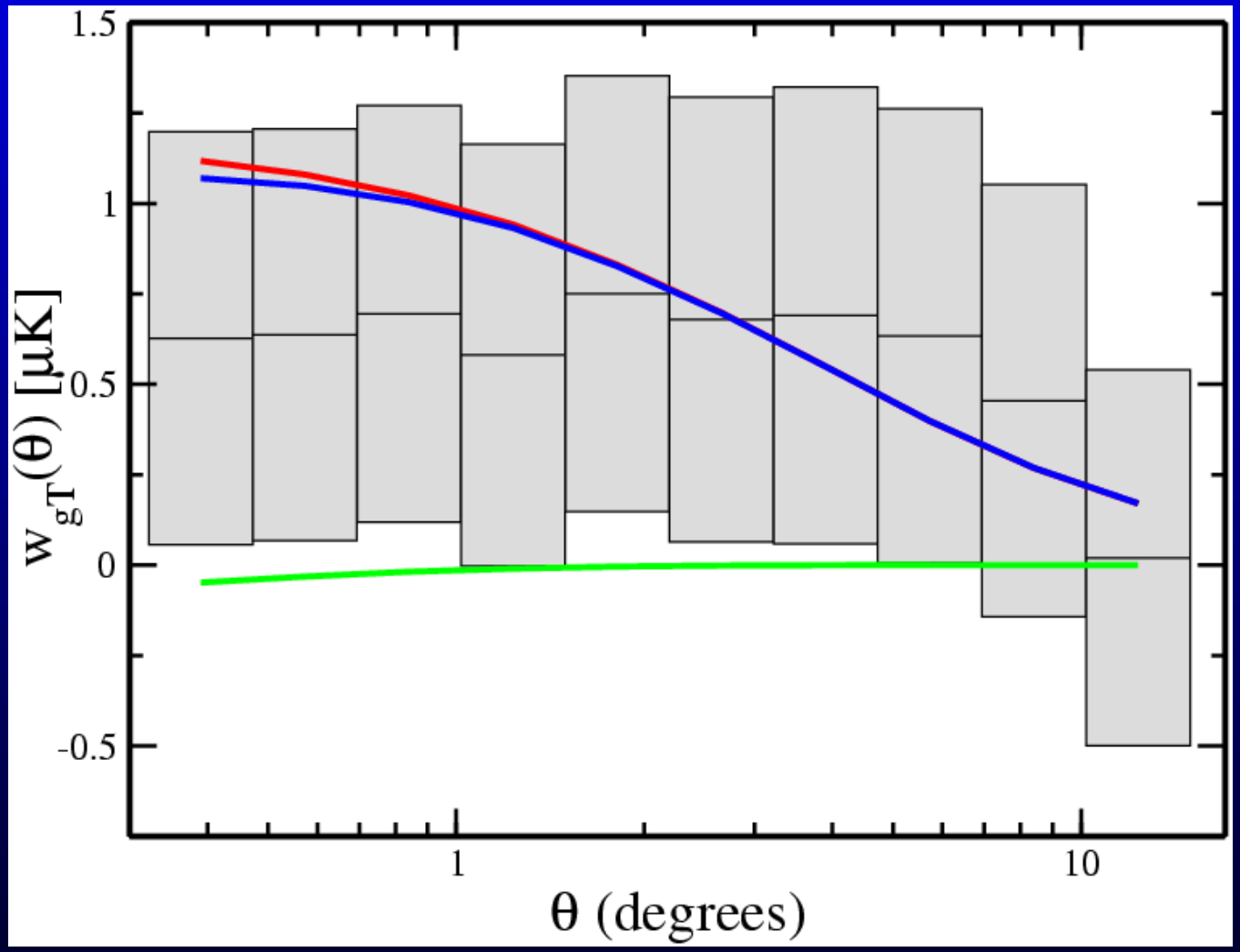
- At most αn_{reject} rejections are false
- Generally, more conservative test than χ^2

Our FDR

- Our results: 144/150 angular bins excluded at $\alpha = 0.25$ for jack-knife and 113/150 for random CMB map errors
- $\Rightarrow$ null hypothesis (flat, matter dominated universe) is rejected

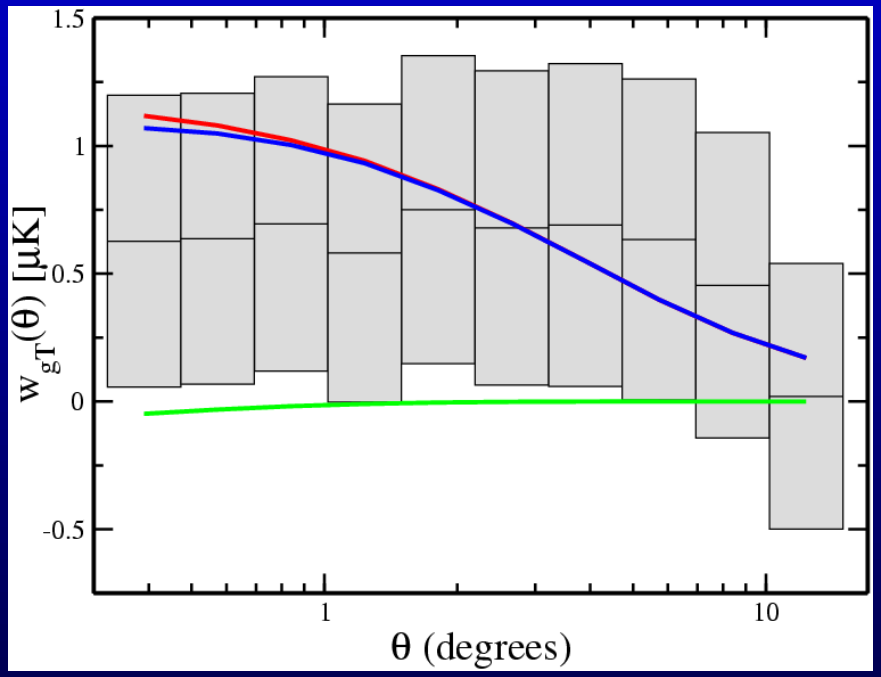


Model Fits



Model Fits – Details

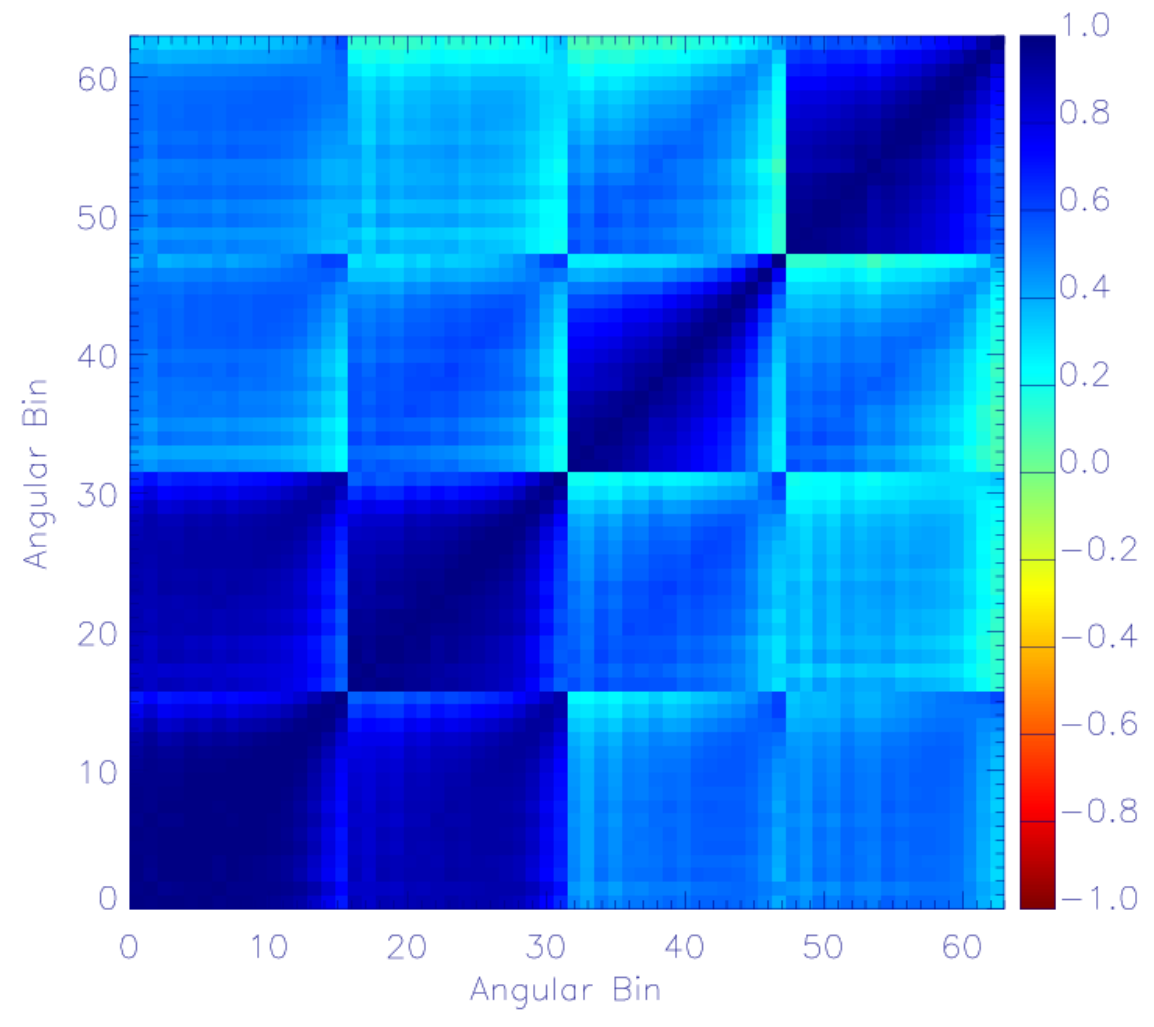
- Two parameter fit: $b_{gal}, T_e b_P$
- Exclude null hypothesis in favor of model fits at $> 95\%$ confidence for 14/15 combinations of LRGs & CMB with jack-knife covariance
- 4/15 combinations at $> 95\%$ confidence with random CMB covariance (8/15 at $> 80\%$ confidence)
- Systematics with photo-z redshift distributions



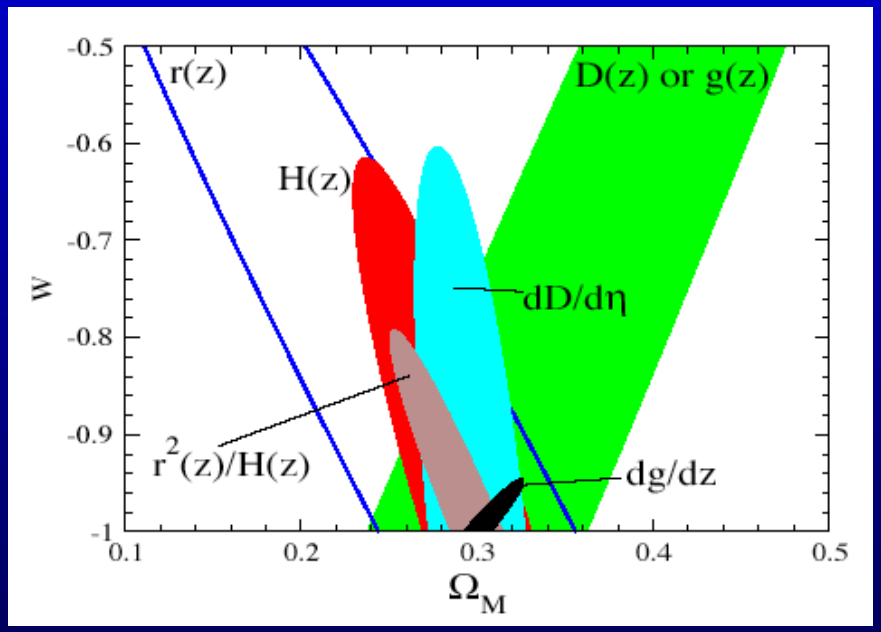
Future Work

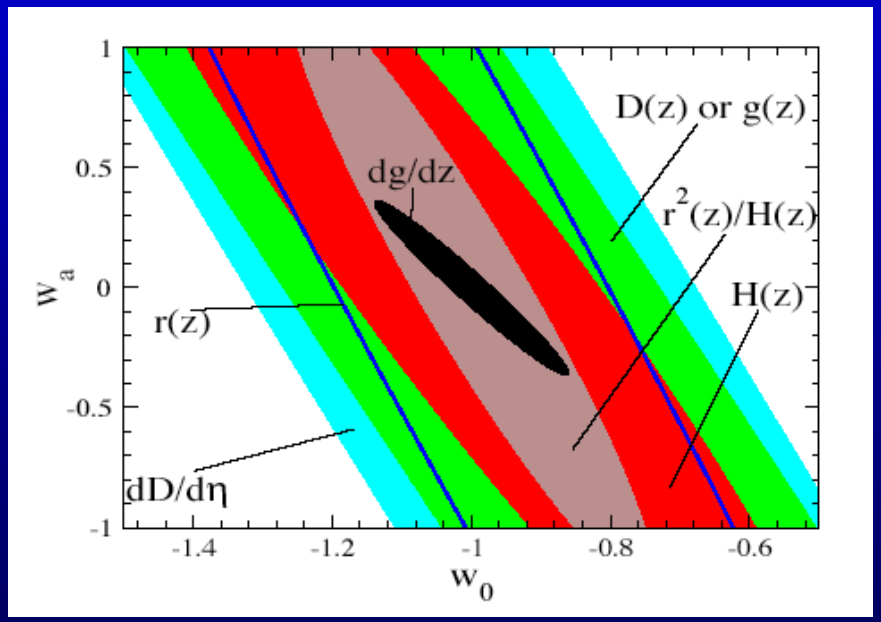
- More precise modelling of individual combinations of CMB and LRG maps:
  - ⋆ Evolution of galaxy bias & electron gas parameters
  - ⋆ Dark Energy parameters
- Improve photo-z calibration
- Further work on covariance matrix calculation (global χ^2)
- Increase area for lower cosmic variance

4 LRG Slice Correlation Matrix



Semi-bridled Optimism





Cooray, Huterer & Baumann (2003)

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