Correlations between the Cosmic Microwave Background and Infrared Galaxies

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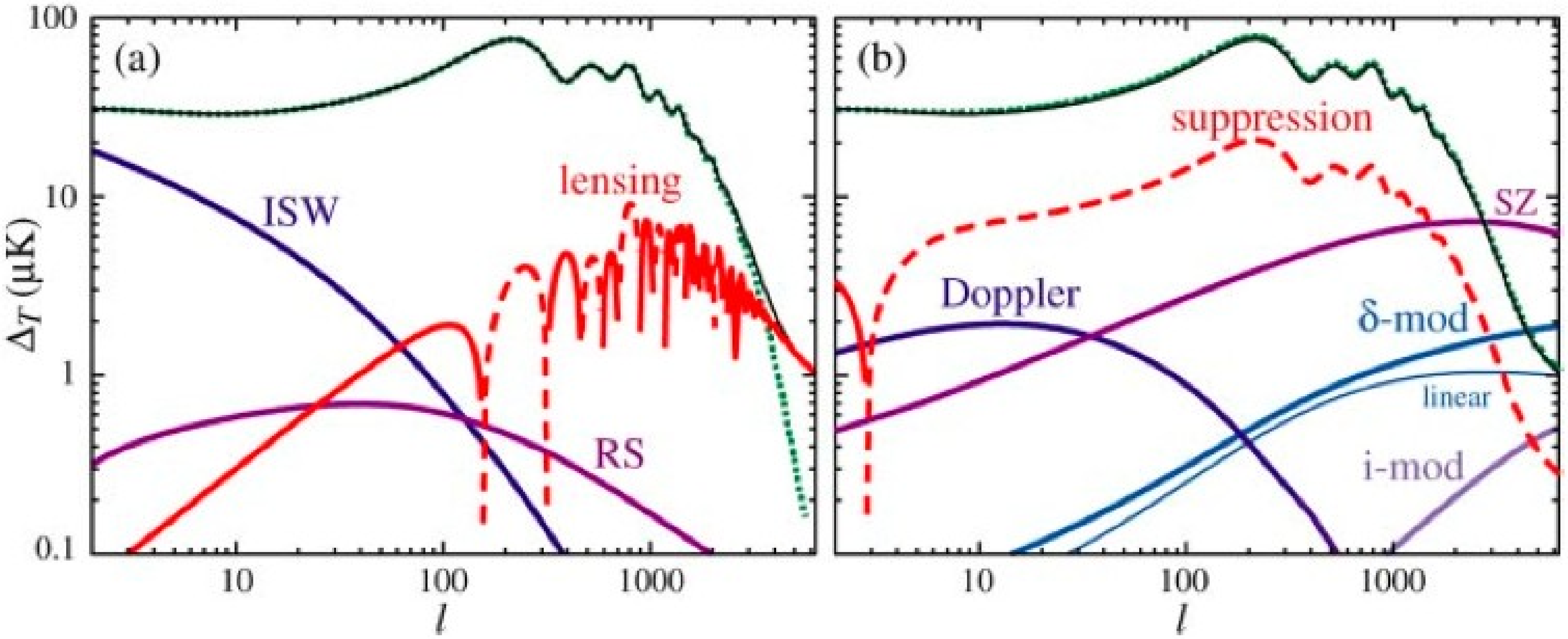
Based on work by Goto, Szapudi and Granett (2012)
http://cdsads.u-strasbg.fr/abs/2012MNRAS.422L..77G

The Cosmic Microwave Background

- Universe is homogeneous & isotropic on very large scales only
  - Galaxy clusters
  - CMB fluctuations
- Size of fluctuations are small (~1°) at z~1100
  - Hubble radius & sound horizon of photon-baryon fluid
- Mass distribution with small irregularities at time of decoupling
  - Gravity takes over – baryonic matter clumps together
  - Larger scale structure formation at later times
- Later processes can distort initial anisotropies
  - Affects the CMB we actually observe
  - The Integrated Sachs-Wolfe Effect

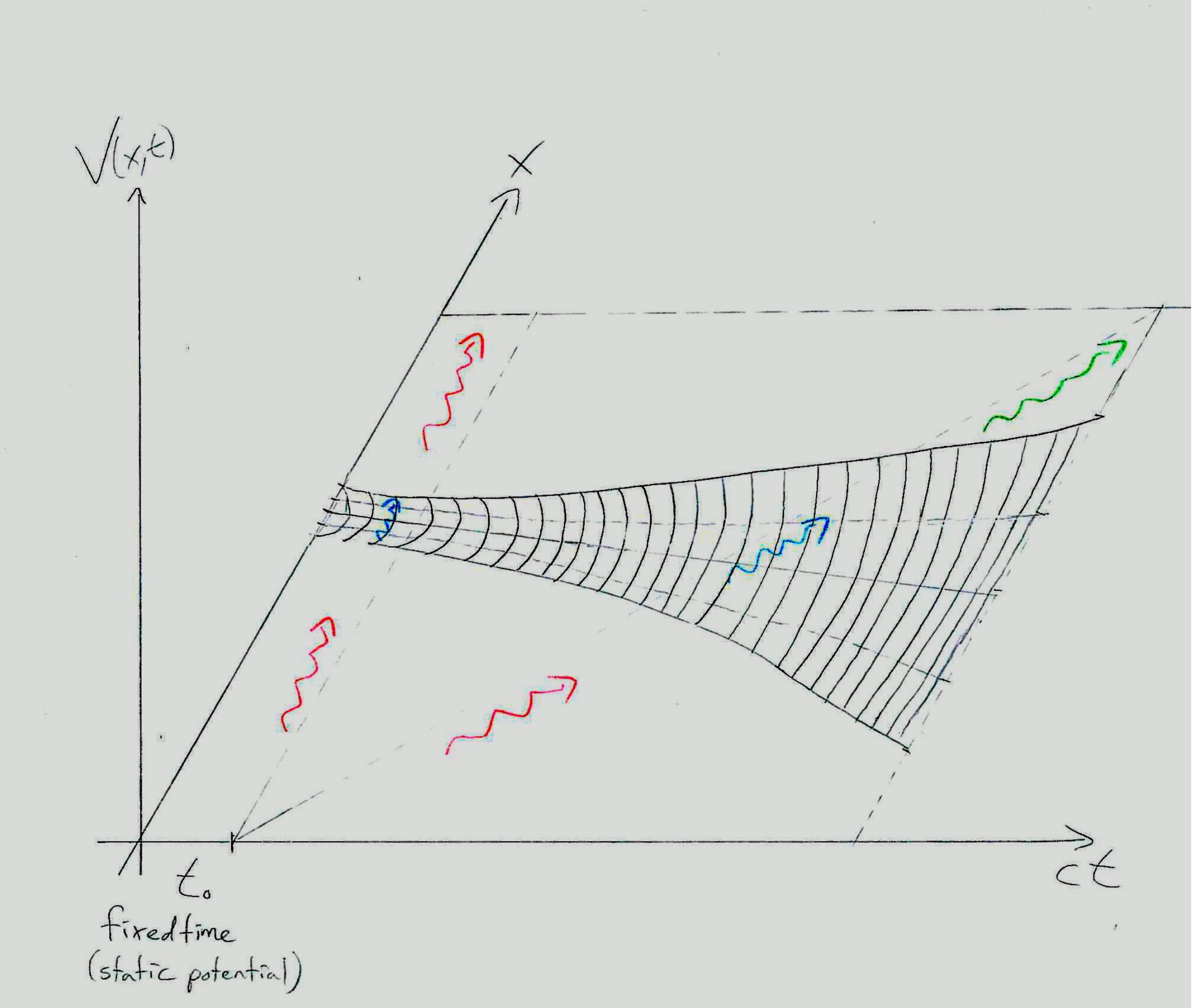
The Cosmic Microwave Background



Hu & Dodelson 2002 ARA&A 40, 171

The Integrated Sachs-Wolfe (ISW) Effect

- Frozen potential wells in flat, Λ-free Universe
- Universe becomes Λ-dominated at z~0.5
- Accelerated expansion causes potential decay



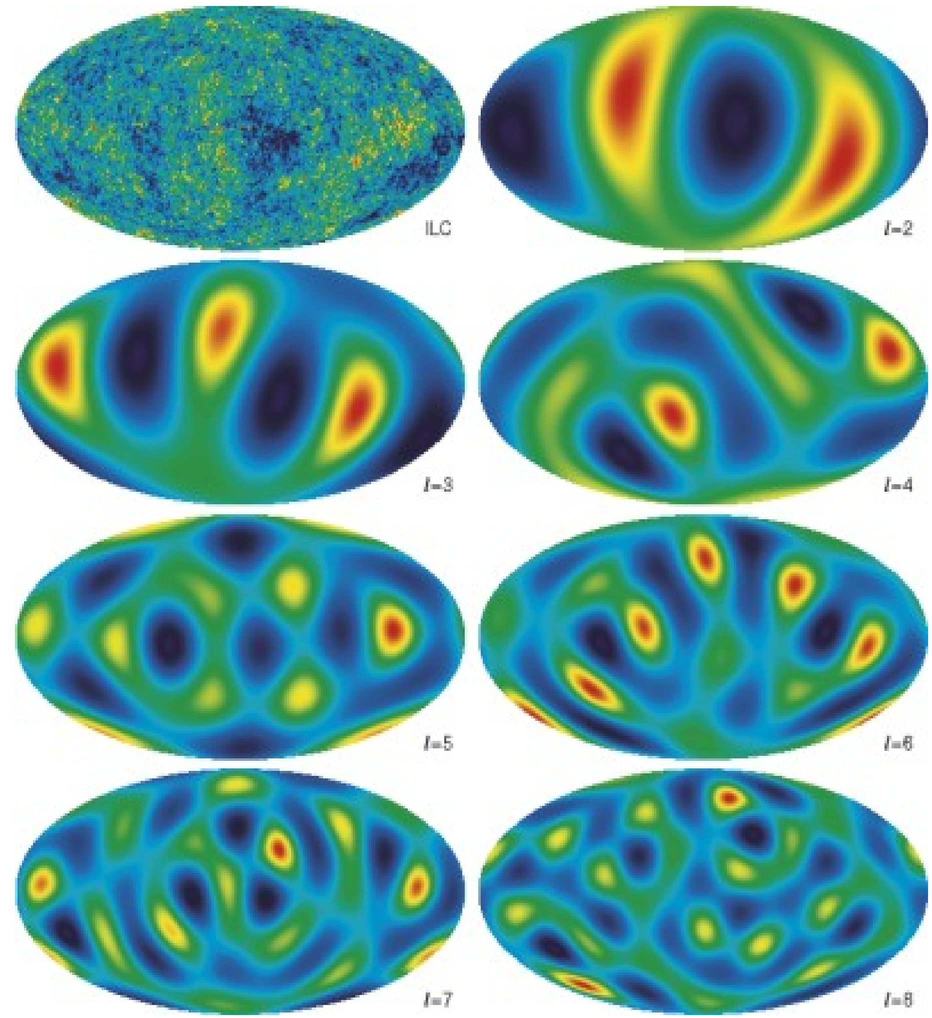
The Integrated Sachs-Wolfe (ISW) Effect

- WISE galaxy counts trace mass distribution
- Probe at different redshifts by studying galaxy distributions seen in different sky surveys
- Also has been done for SDSS, 2MASS, NVSS, HEAO and APM optical galaxies
- Another way to constrain Λ – effect will be more pronounced for lower Λ-dominated redshifts

CMB Temperature Anisotropies

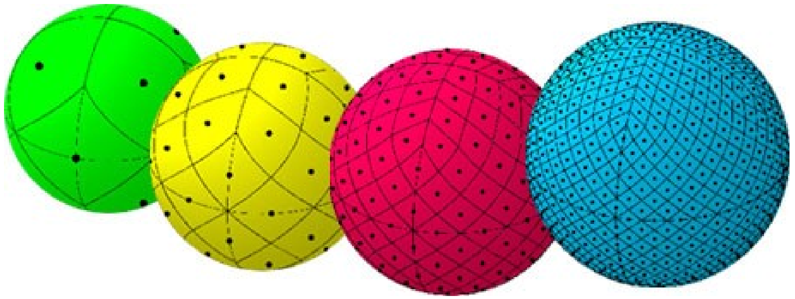
$$\frac{T(\theta,\phi)-\bar{T}}{\bar{T}} = \sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

- How much power in temperature fluctuations is due to large scale structure?
- Decompose into spherical harmonics - both CMB temperature & WISE galaxy number density maps are on a sphere
- Cross-correlate map of WISE relative galaxy number density with CMB temperature anisotropies
- $\ell \sim 180^\circ/\theta$



Hinshaw et al. 2007 ApJ 170, 288-334

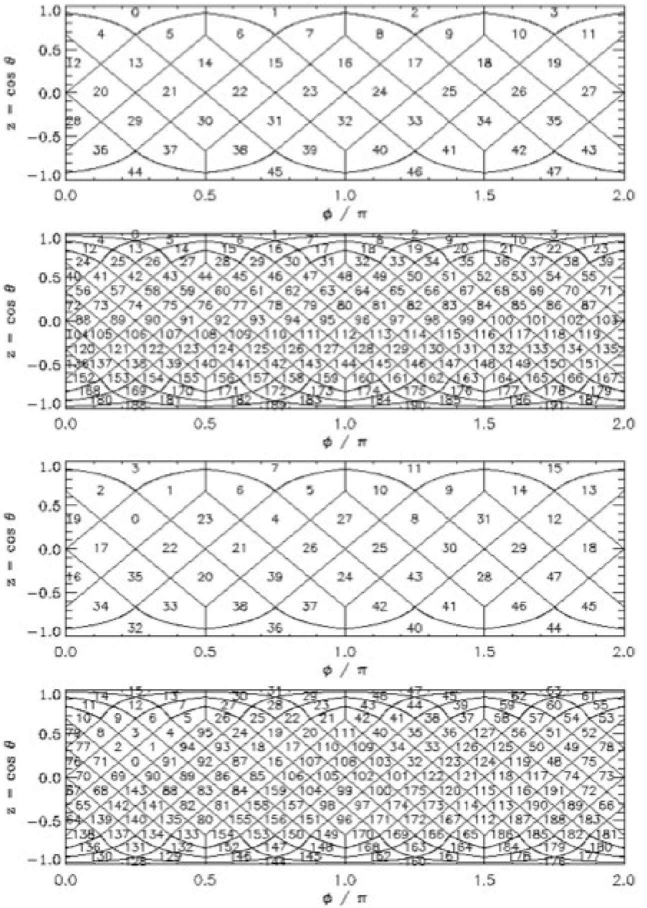
HEALPIX



- Defines pixels as equal area tessellations on sphere
- Number of pixels in terms of resolution parameter Nside.

$$N_{pix} = 12 \times N_{side}^2$$

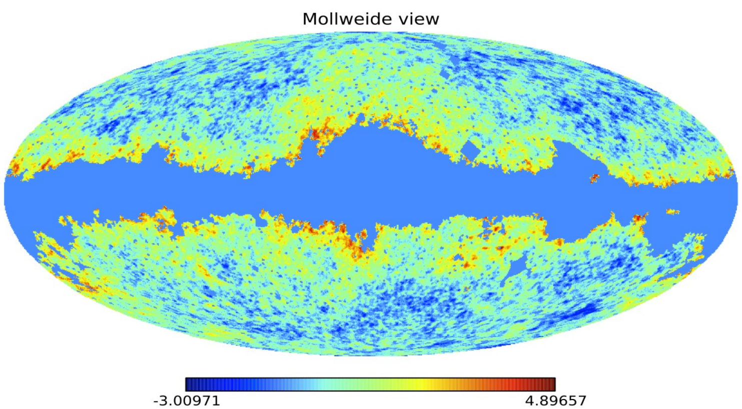
- Pixels placed on 4xNside-1 rings of constant latitude
- Resolution, or angular size, of each pixel can be easily changed from one value of Nside to another.



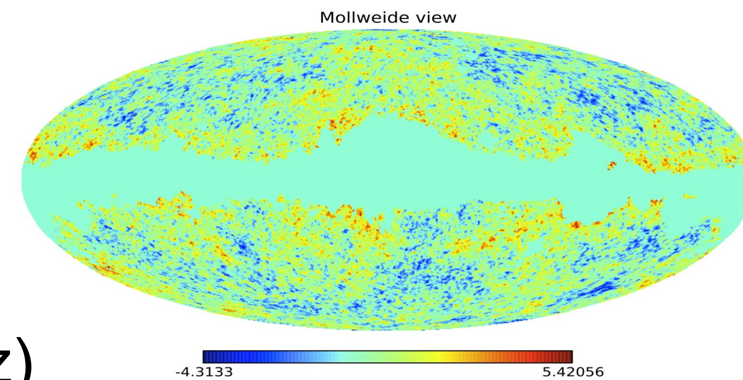
http://healpix.jpl.nasa.gov/

WMAP

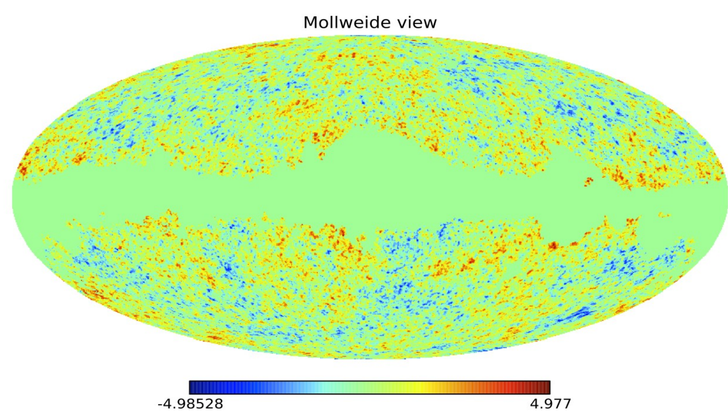
K-band (22 GHz)



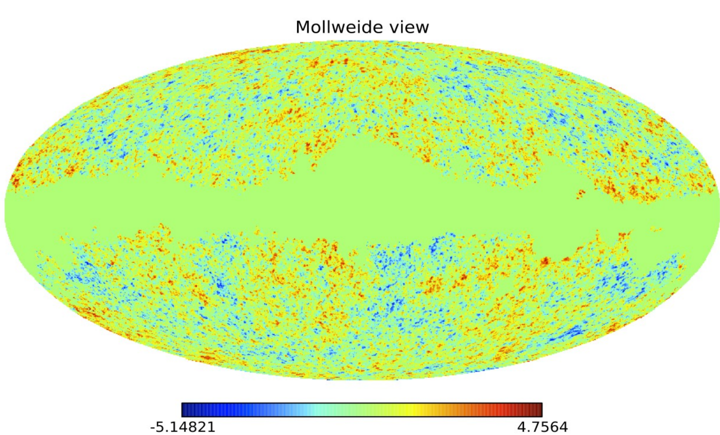
Ka-band (30 GHz)



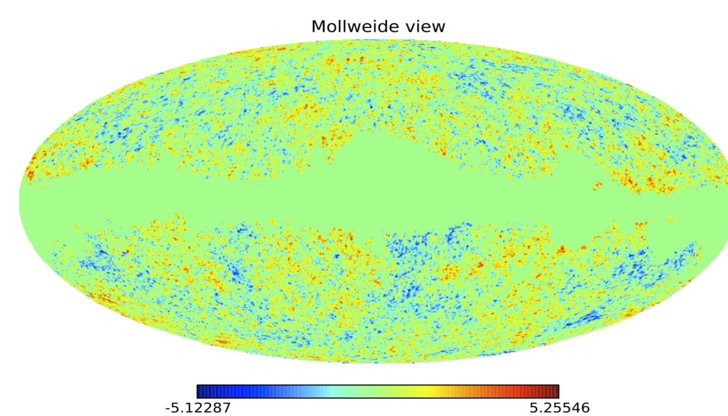
Q-band (40 GHz)



V-band (60 GHz)

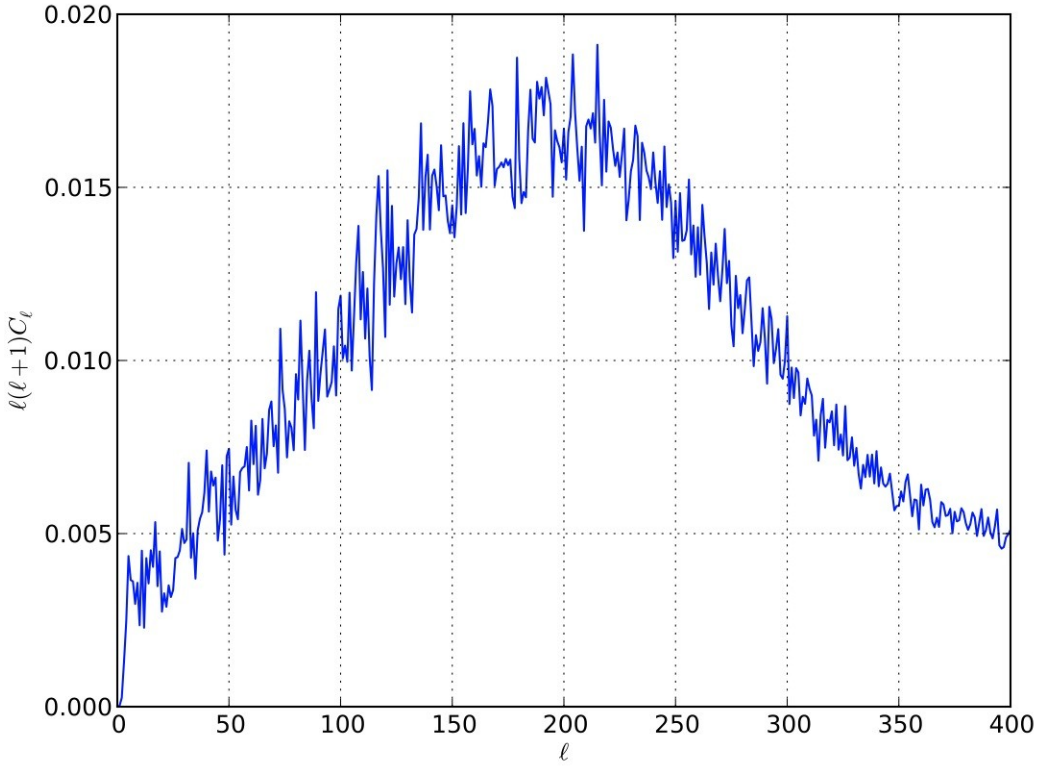


W-band (90 GHz)



CMB Power Spectrum

$$(2\ell+1)C_\ell^{TT} = \sum_{m=-\ell}^{\ell} a_{\ell m} a^*_{\ell m}$$



- Peak l~200 – Hubble radius, sound horizon
- Expect ISW effect contribution for l < 100

WISE Galaxy Selection

- Want to consider only galaxy distribution for cross-correlation
- Foreground stars removed with (3.4-4.6μm)>0.2
- More stars removed at expense of some galaxies with (4.6-12μm)>2.9
- Because WISE is deeper near poles, cutoff 3.4μm<15.2 mag for a more uniform galaxy sample
- ~2.5 million objects from WISE

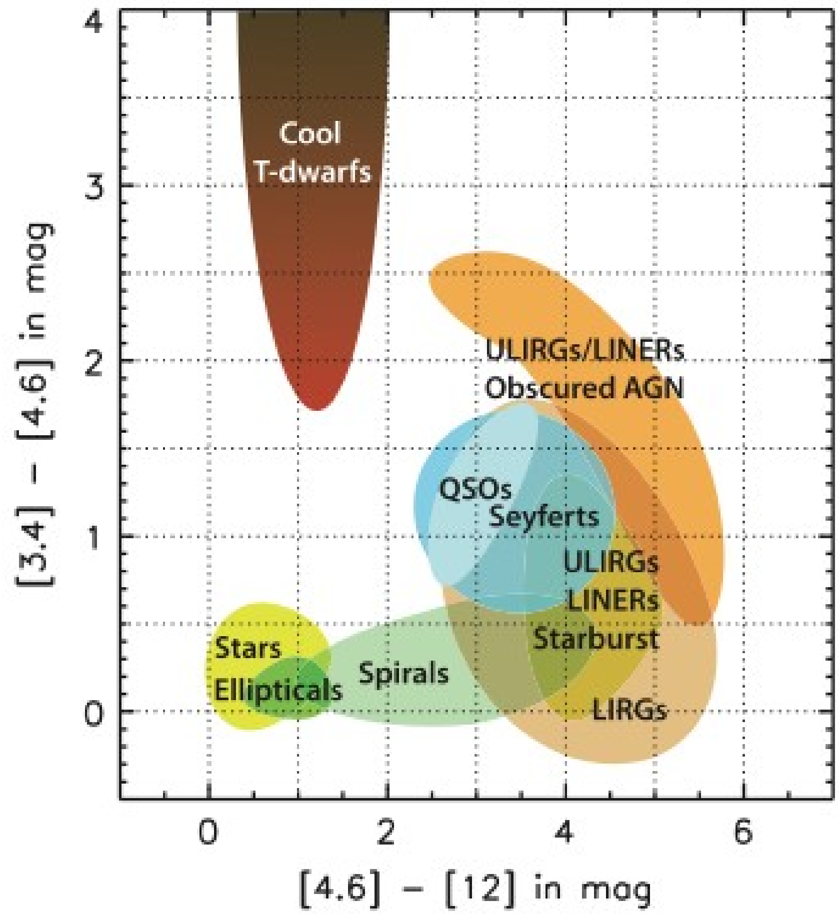
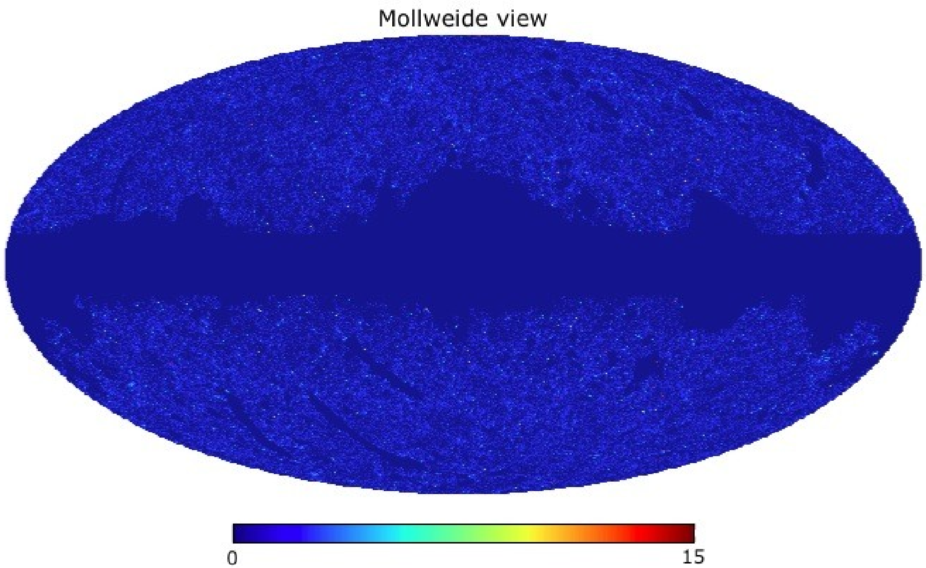


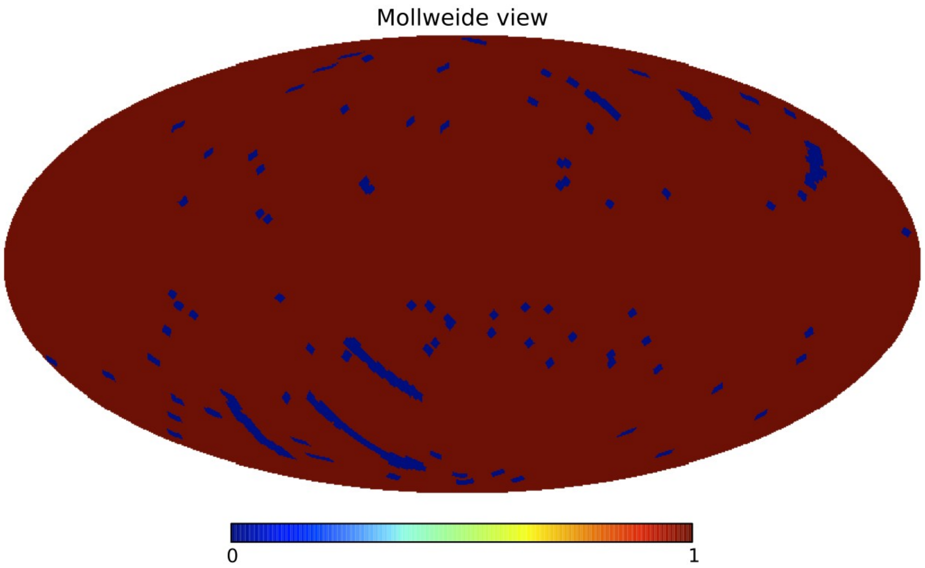
Figure 12. Color–color diagram showing the locations of interesting classes of objects. Stars and early-type galaxies have colors near zero, while brown dwarfs are very red in *W*1–*W*2, spiral galaxies are red in *W*2–*W*3, and ULIRGS tend to be red in both colors.

Wright et al. ApJ 140:1868–1881 (2010)

WISE Galaxy Density

- Binned galaxy counts on sky in equal area pixels on a sphere with HEALPIX
- Zone of avoidance removed, WMAP mask applied
- Non-uniform nearby structure masked manually by retrieving coordinates from DEXTER
- Resolution sensitivity to multipole l~256





Probing the ISW Effect at z=0.148

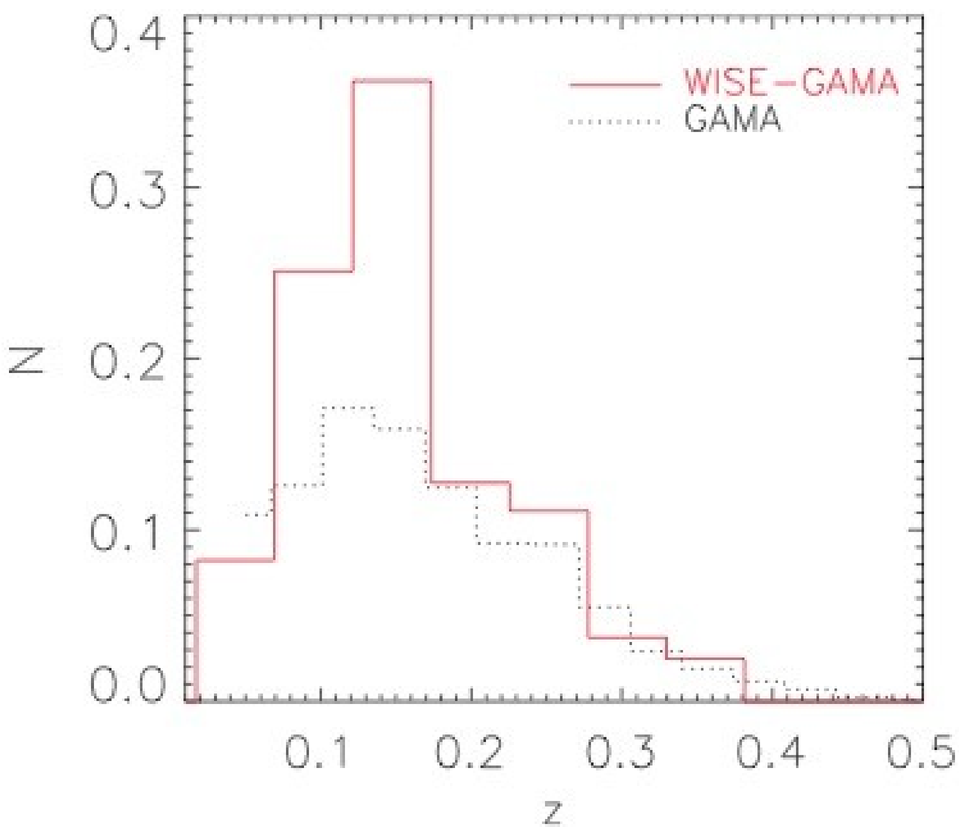
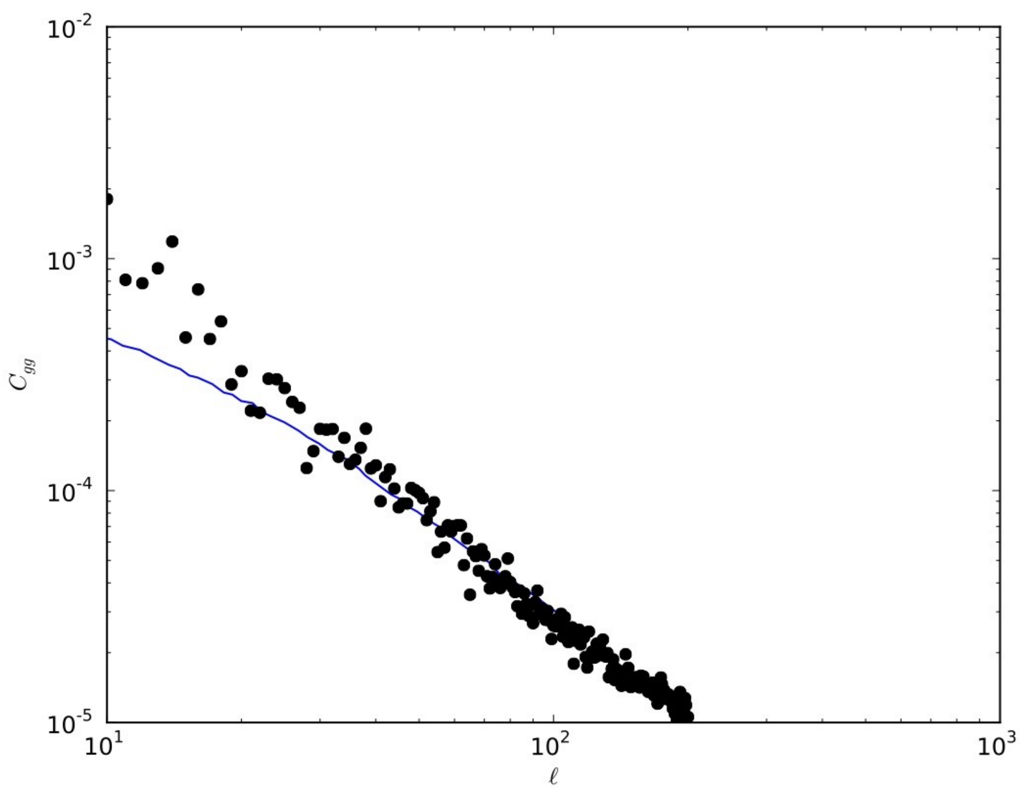


Figure 3. The normalized redshift distributions of the *WISE* galaxy sample (red solid line) and the GAMA spectroscopic sample (black dotted line).

- Universe becomes Λ-dominated at z~0.5
- GAMA: Galaxy And Mass Assembly
- Spectroscopic redshift survey
- Goto et al. 2012 crossed matched WISE & GAMA to find median redshift

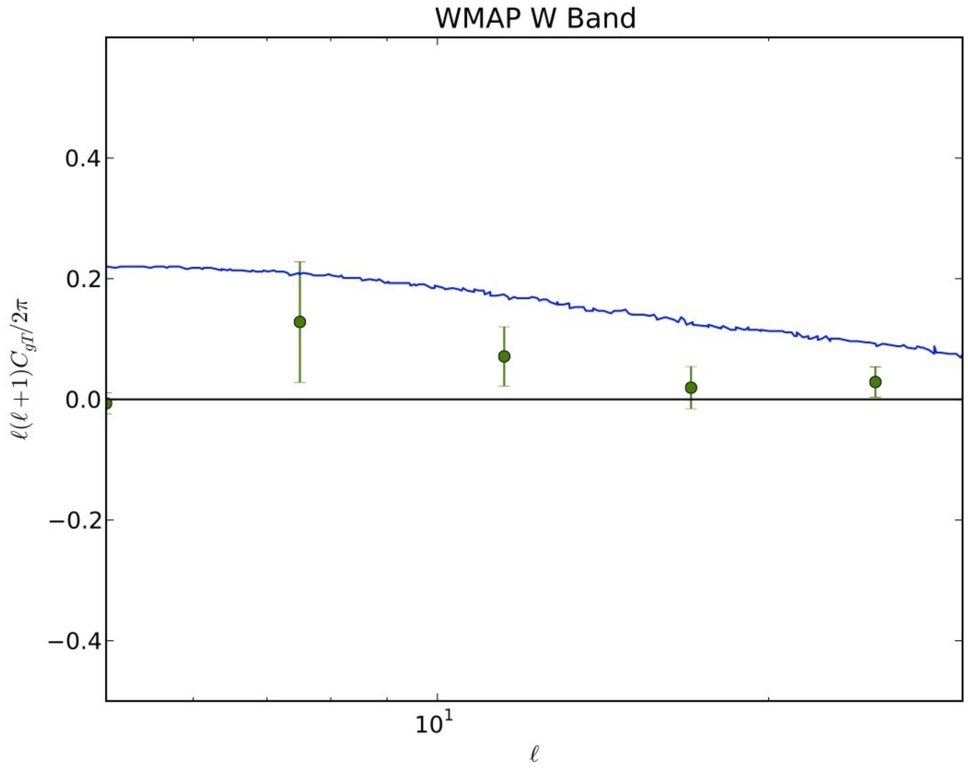
Goto et al. 2012 MNRAS 422, L77-L81

Galaxy Number Density Power Spectrum

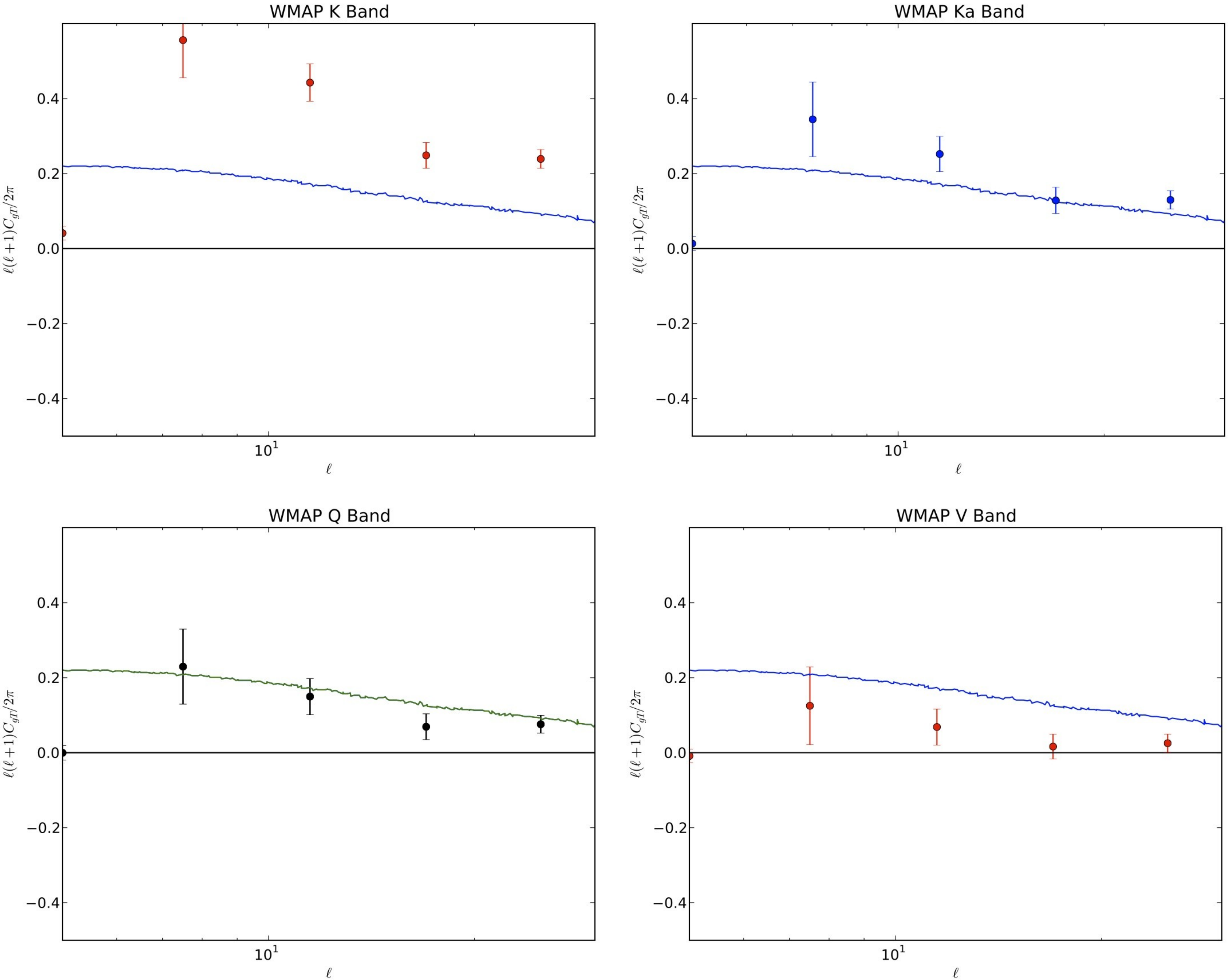


- Theory curve from Goto et. al. was fit to our data to determine the galaxy bias.
- Galaxy bias determines how well galaxies trace dark matter distribution
- We find a galaxy bias of 1.38

CMB-Galaxy Cross-Correlation

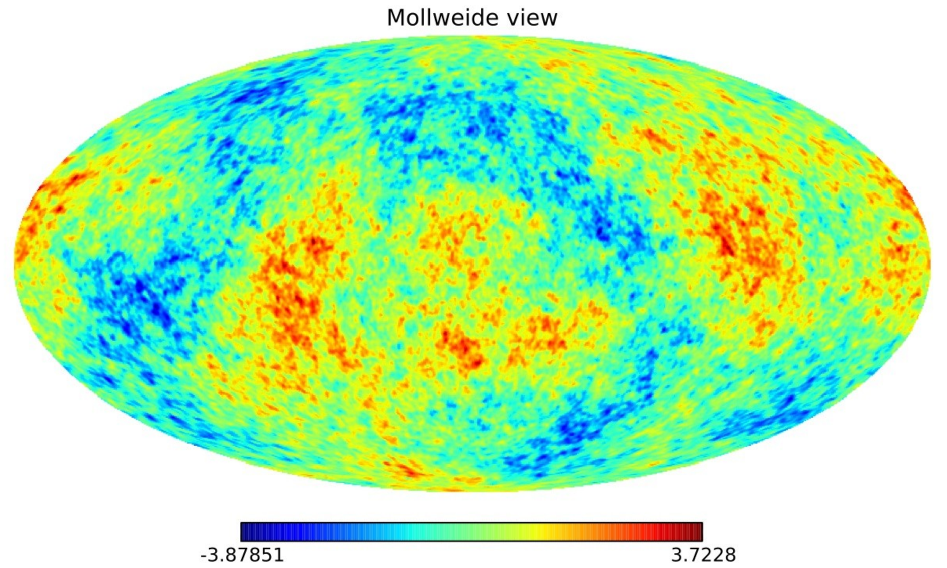


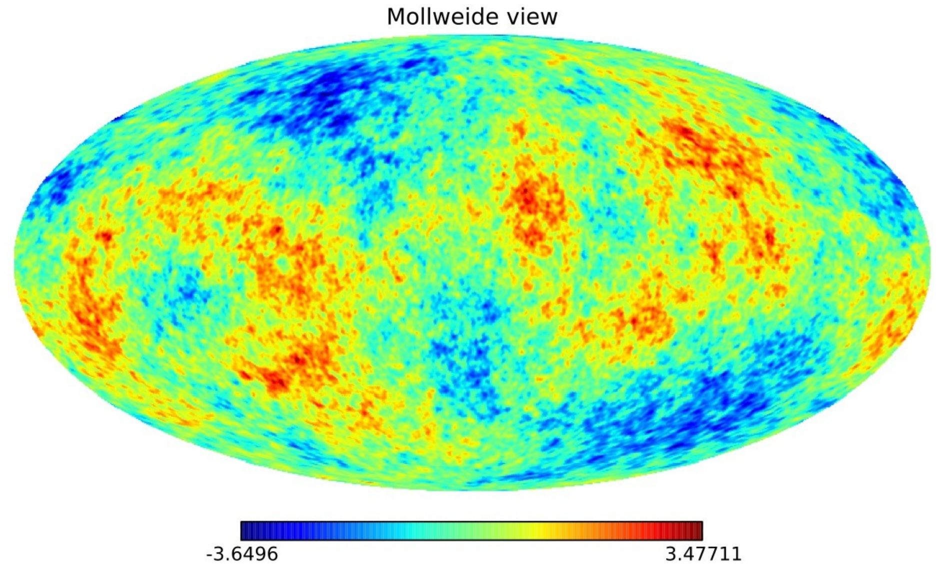
- HEALPIX algorithm
- Logarithmic binning to better see signal
- Start at l=5 – size of WMAP mask affects smaller multipoles
- Used bin boundaries l=5,7,10,15,21,30,43,60 and 86
- ISW effect should contribute to lower multipoles



WMAP K Band
WMAP Ka Band
WMAP Q Band
WMAP V Band
$\ell(\ell+1)C_{gT}/2\pi$
ℓ
10^1
0.4
0.2
0.0
−0.2
−0.4

Error Analysis





- Used SYNFAST to produce 1000 statistically equivalent random CMB maps
- Spatial phase information not preserved in correlations
- Performed cross-correlation with WISE for each
- Error bars given by standard deviation

Conclusions

- ISW effect detected in the range $7<l<15$ at 1.7, 1.8 3.4, 5.5 and 8.9 sigma in the WMAP V, W, Q, Ka, and K bands.
- Considered larger portion of the sky than Goto et al.
- K & Ka bands contaminated by foreground emission – correlation appears stronger.
- V & W bands are consistent with each other, evidence for some source contamination in Q-band.
- Universe must have been dark energy dominated by Z=0.148 in agreement with ΛCDM.
- Another piece of evidence for the accelerated expansion of the Universe.