CMB anisotropies from the late universe

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work with Stephen Boughn
earlier work with Neil Turok

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cross correlation studies

First few talks today discuss what can be learnt from comparing cmb maps with probes at other frequencies, which will tell us about nearby sources of anisotropies:

1) isw fluctuations (linear)
2) weak lensing
3) sunyaev-zeldovich
4) foregrounds

Thanks to all the observers who made these comparisons possible!

isw effect

while most cmb anisotropies arise on the last scattering surface, some may be induced by passing through a time varying gravitational potential:

$$\frac{\Delta T}{T} = -2\int d\eta\, \dot{\Phi}(\eta)$$

linear regime – integrated Sachs-Wolfe (ISW)

non-linear regime – Rees-Sciama effect

when does the linear potential change?

$$\nabla^2\Phi = 4\pi G a^2 \bar{\rho}\,\delta$$

Poisson's equation

- constant during matter domination
- decays after curvature or dark energy come to dominate (z~1)

induces an additional, uncorrelated layer of large scale anisotropies at late times!

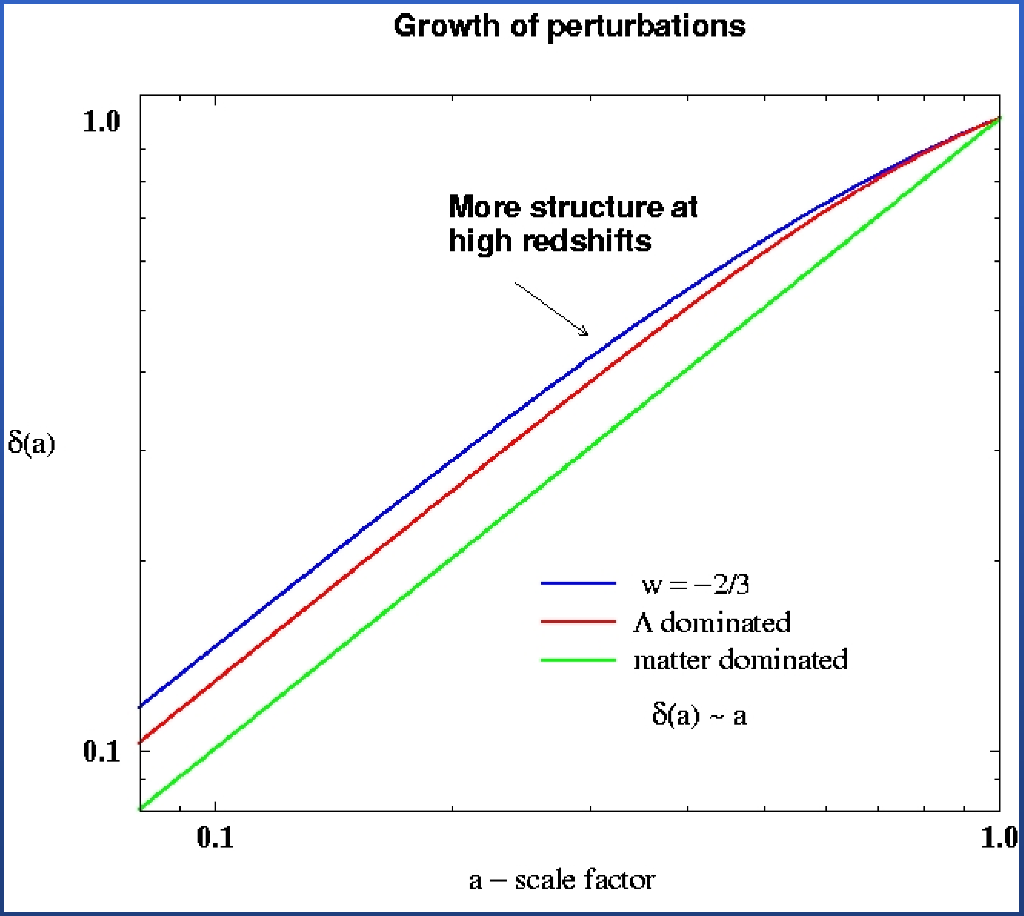
growth of perturbations

Modifying expansion changes the growth rate of perturbations

$$\ddot{\delta}_m + 2H\dot{\delta}_m = \frac{3}{2}H^2\Omega_m\delta_m$$

Dark energy slows down growth of perturbations

Normalized to the present level of fluctuations, dark energy implies <u>more</u> structure at high redshift



large scale correlations

$$\Omega_\Lambda = 0.73 \quad h = 0.72 \quad n = 1.0$$

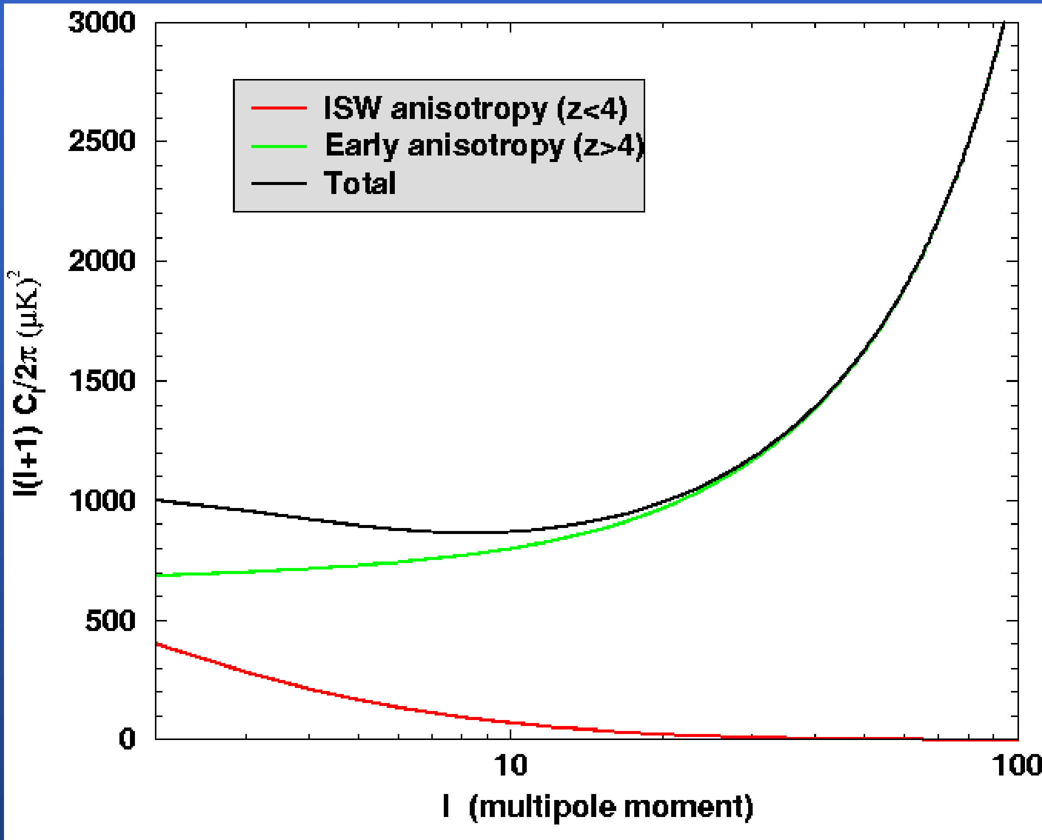
WMAP best fit scale invariant spectrum

These new fluctuations are greatest on the largest scales.

On small scales, positive and negative ISW effects will tend to cancel out.

The early and late power is fairly weakly correlated, so the power spectra add directly:

$$C_l^{total} \cong C_l^{early} + C_l^{isw}$$



Highest correlations are for the quadrupole, but it is still very weak

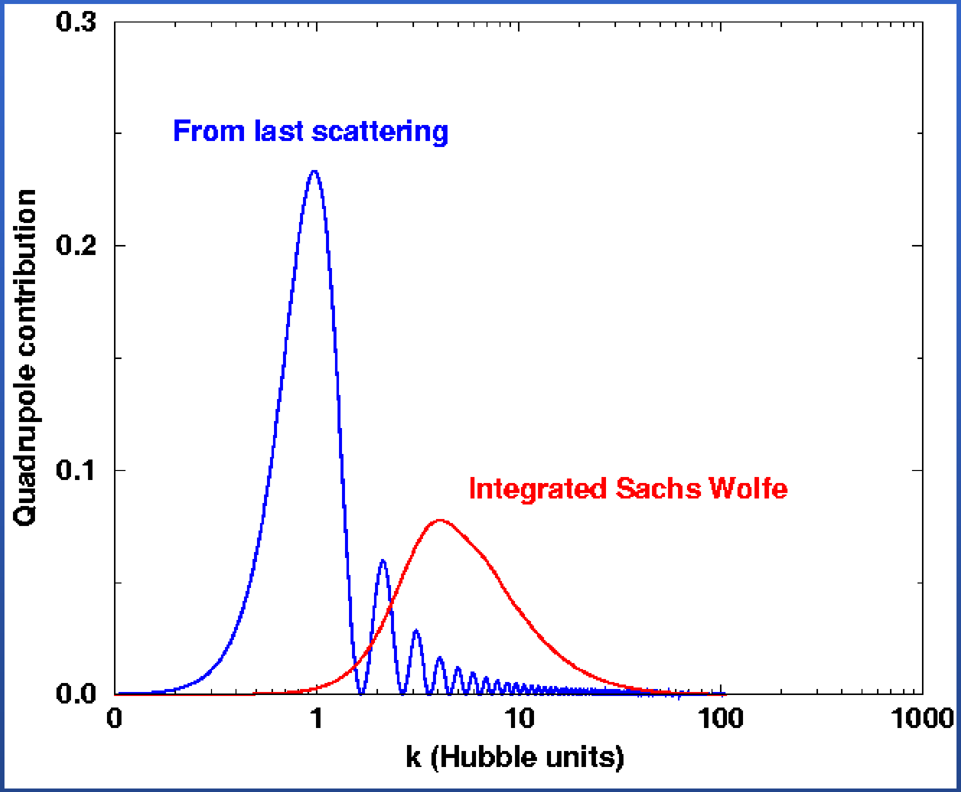
$$C_2^{\times} / \sqrt{C_2^{isw} C_2^{early}} \approx 0.08$$

isw versus anisotropies from last scattering

The quadrupole primarily arises from modes on the scale of the horizon

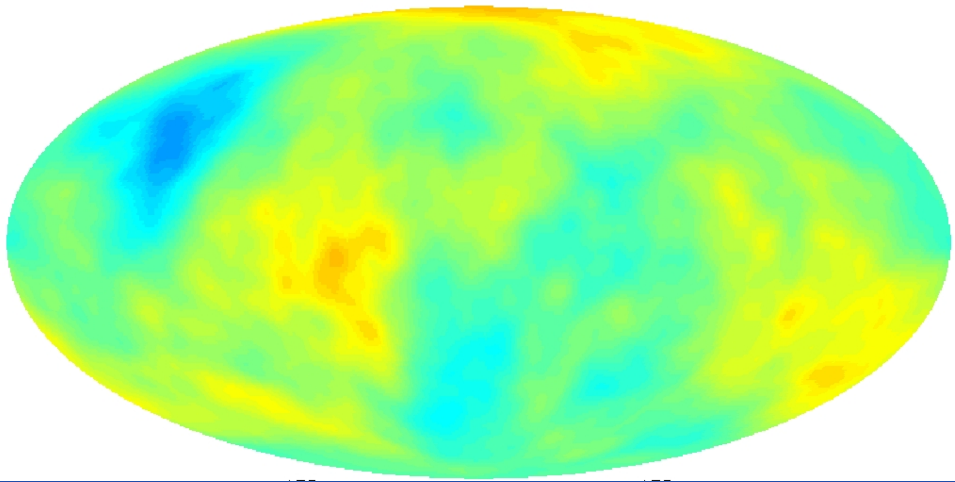
The ISW anisotropies are created nearer to us, and are generated by smaller modes (larger wave number)

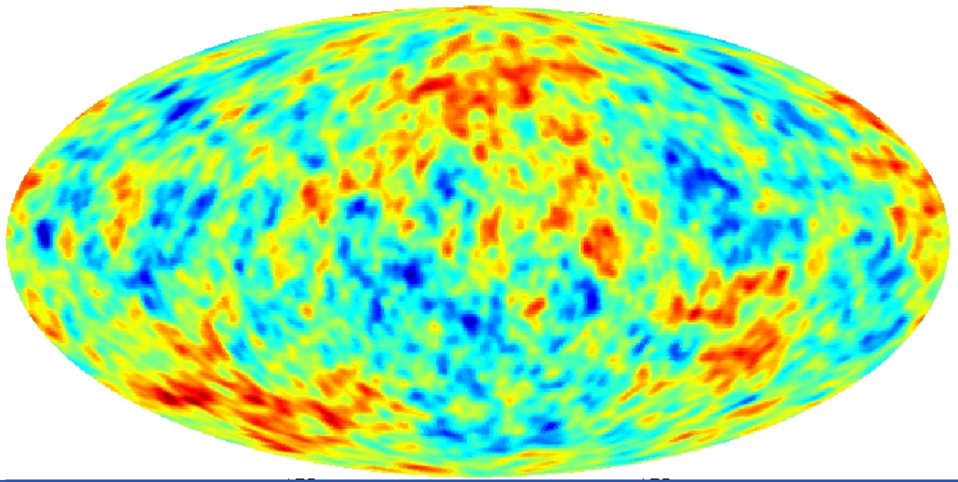
For this reason, the anisotropies produced are not very correlated with each other



Contribution to the quadrupole power as a function of wave number, the oscillations at high k alternatively constructively or destructively interfere, effectively cancelling out

two independent maps

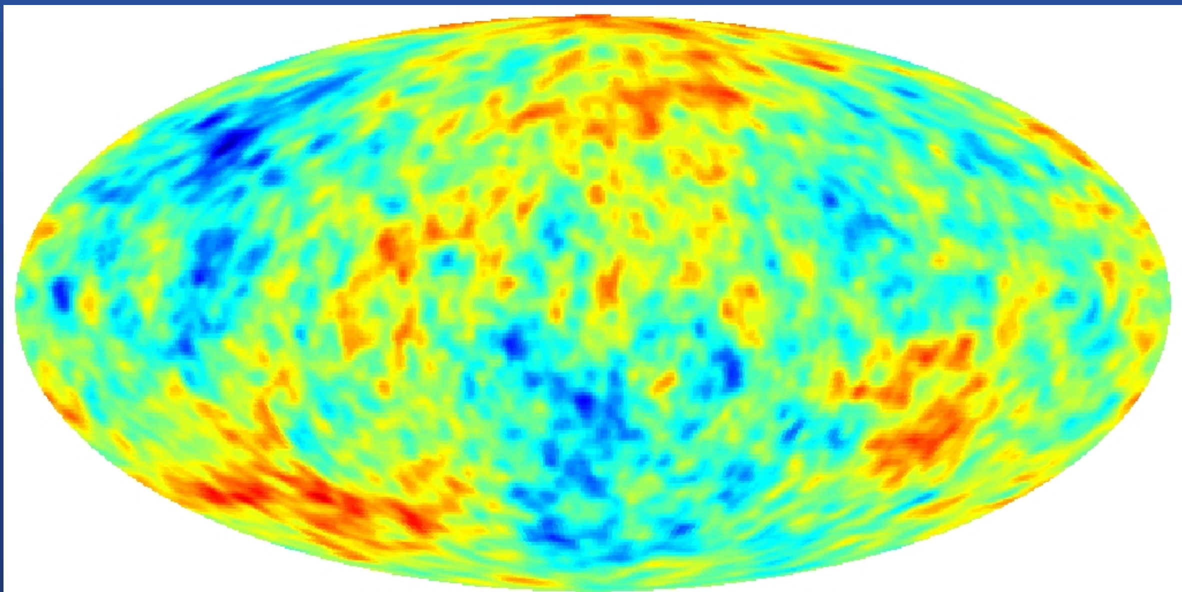




Integrated Sachs-Wolfe map
Mostly large angular features

Early time map ($z > 4$)
Mostly from last scattering surface

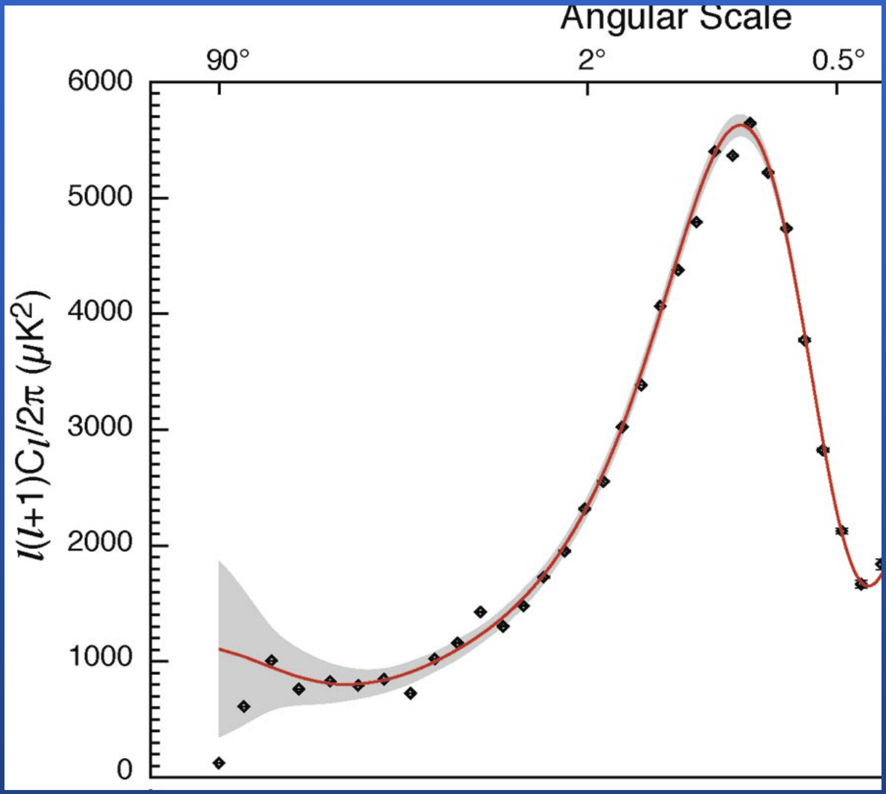
Observed map is total of these, and has features of both (3 degree resolution)



observing the ISW effect

in the cmb map, additional anisotropies should increase large scale power

- Not observed in WMAP data
- In fact, decrease is seen



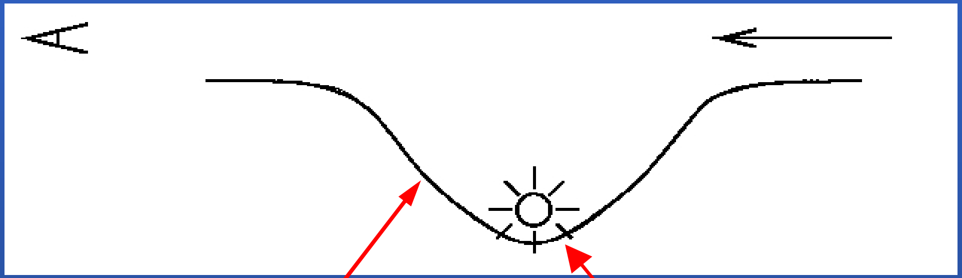
why might this be?

- cosmic variance
- no ISW, still matter dominated
- accidental cancellation
- drop in large scale power
- simple adiabatic scenario wrong

compare with large scale structure

ISW fluctuations are correlated with the galaxy distribution!

observer



potential depth changes as cmb photons pass through

time dependent gravitational potential

density of galaxies traces the potential depth

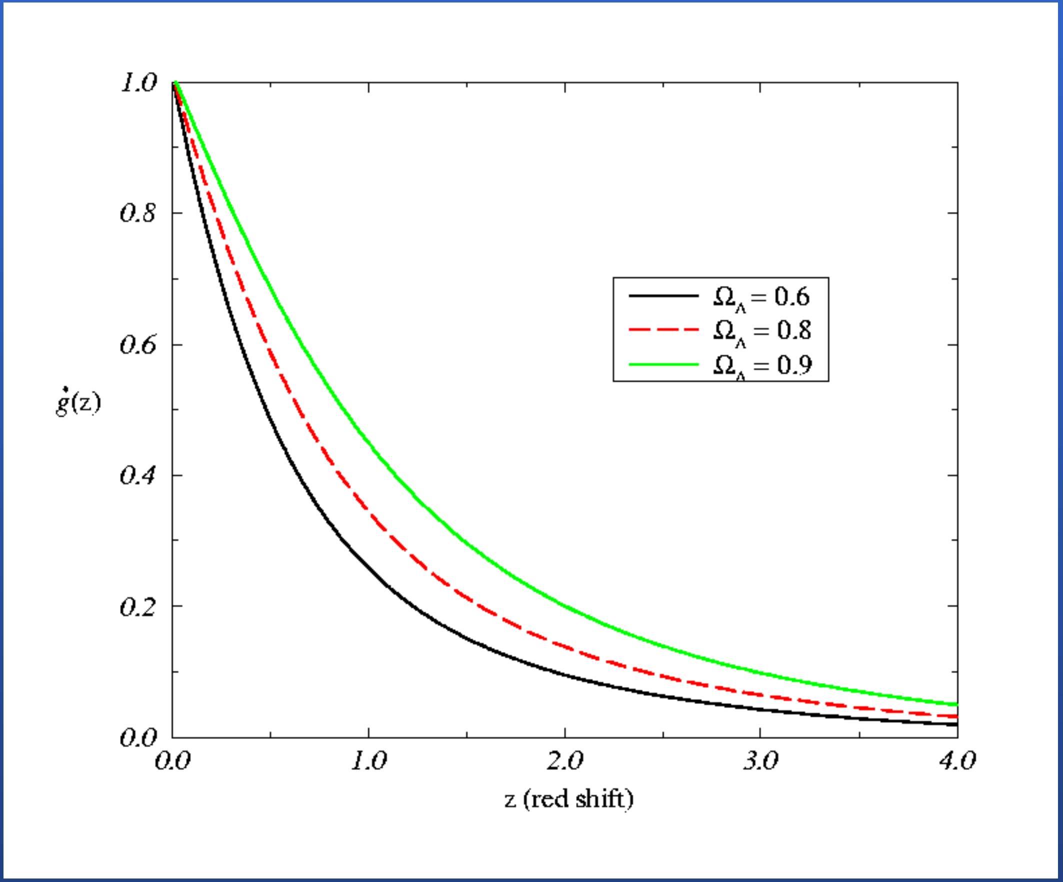
since the decay happens slowly, it helps to see galaxies at high redshifts (z~1)

- active galaxies (quasars, radio, or hard x-ray sources)
- possibility of accidental correlations means full sky needed

where does the isw arise?

Ideally we want a survey which is weighted to match the contribution to the ISW temperature increment as a function of redshift.

(RC & N. Turok, 96)



However, the signal to noise peaks at higher redshift,
z = 0.4 (Afshordi, 04)

calculating the effect

X-ray correlation

$$C_l^{XX} = \frac{2}{\pi}\int k^2 dk\, P(k)\left[f_l^X(k)\right]^2$$

X-ray bias (assumed constant)

Growth of perturbations

$$f_l^X \propto \int dz\; j_l(k\tau)\, b_X(z)\, D(z)\frac{dN}{dz}F(z)$$

Contribution to x-ray flux from a given redshift

Cross correlation

$$C_l^{XT} = \frac{2}{\pi}\int k^2 dk\, P(k)\, f_l^X(k)\, f_l^{isw}(k)$$

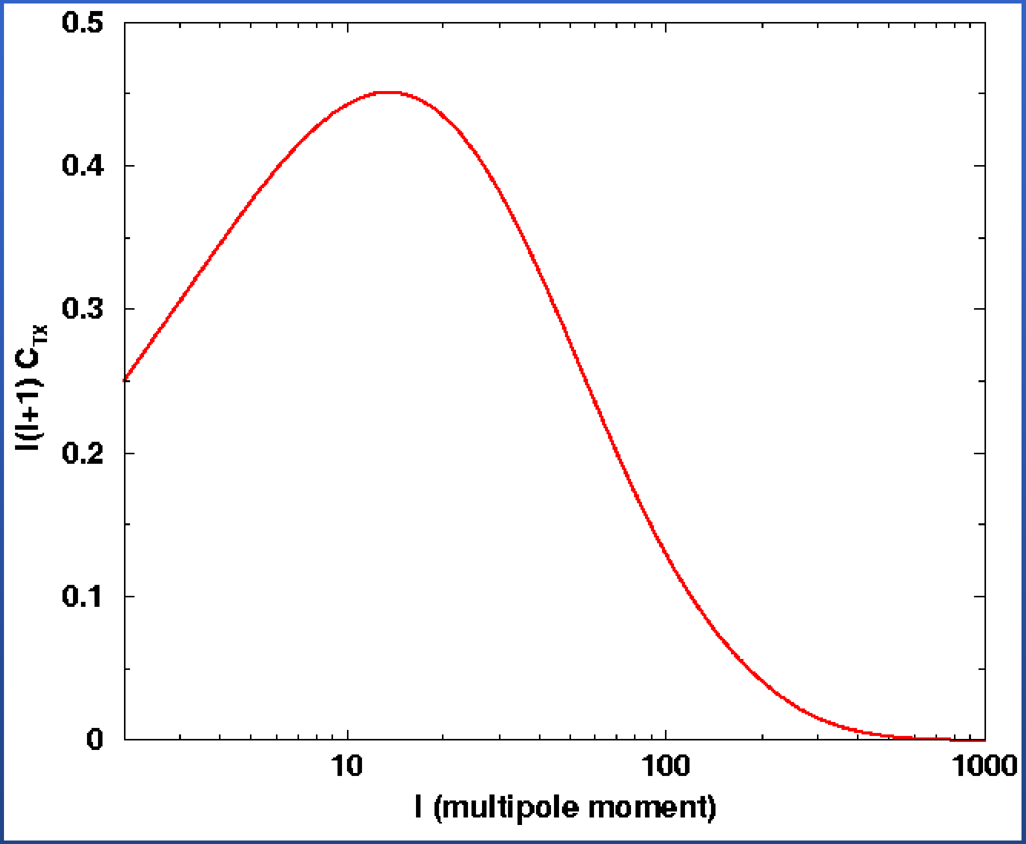
$$f_l^{isw} \propto \frac{1}{k^2}\int d\tau\; j_l(k\tau)\frac{d}{d\tau}\left[D/a\right]$$

ISW ‘filter’

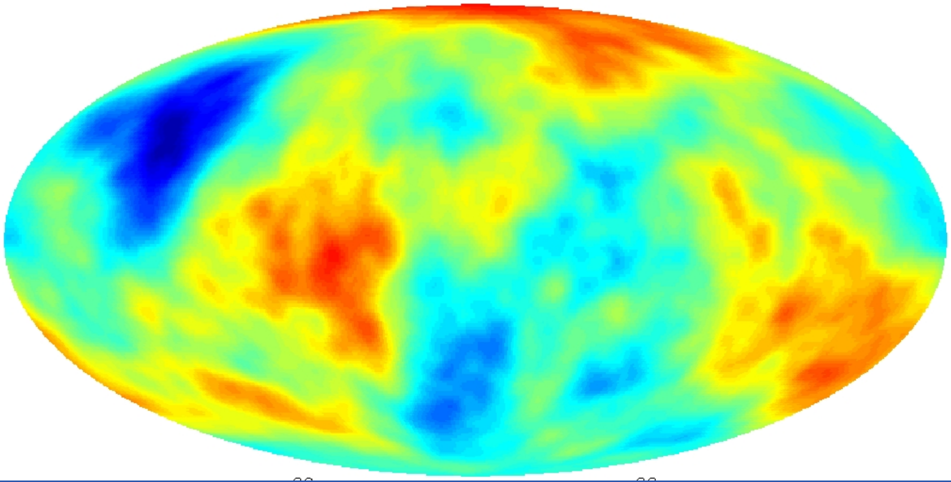
cross correlation spectrum

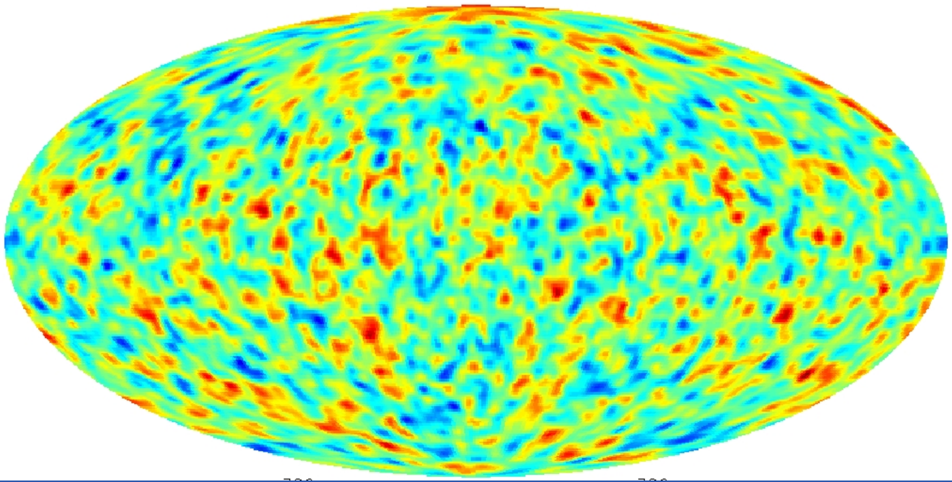
Most of the cross correlation arises on large or intermediate angular scales (>1degree). The CMB is well determined on these scales by WMAP

On small angular scales there is significant ‘noise’ due to the large uncorrelated early CMB signal



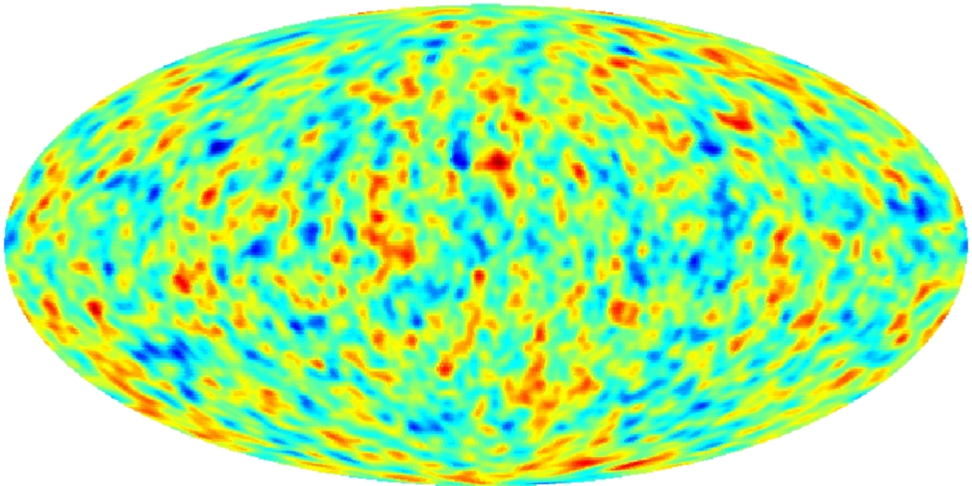
correlated ISW and x-ray maps





ISW part of CMB map

Part of X-ray structure which is correlated with CMB: same phases but much different spectrum



Since the redshift distribution of the X-ray sources is not ideal, only a quarter of the power is correlated

Total X-ray map looks less correlated

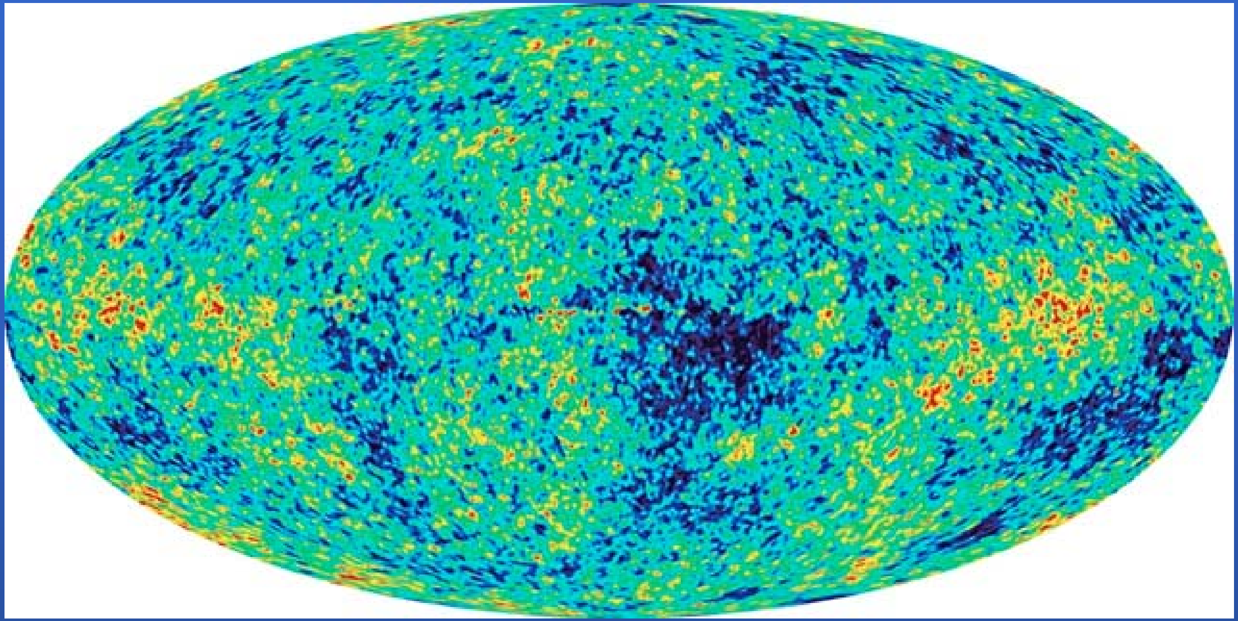
cmb sky

WMAP

Galactic plane,
centre removed

most aggressive
WMAP masking

68% of sky



WMAP internal linear combination map (ilc)

also Tegmark, de Oliveira-Costa & Hamilton map

(no significant differences in resulting correlations)

dominant source of noise to cross correlation is
accidental correlations of cmb map with other maps

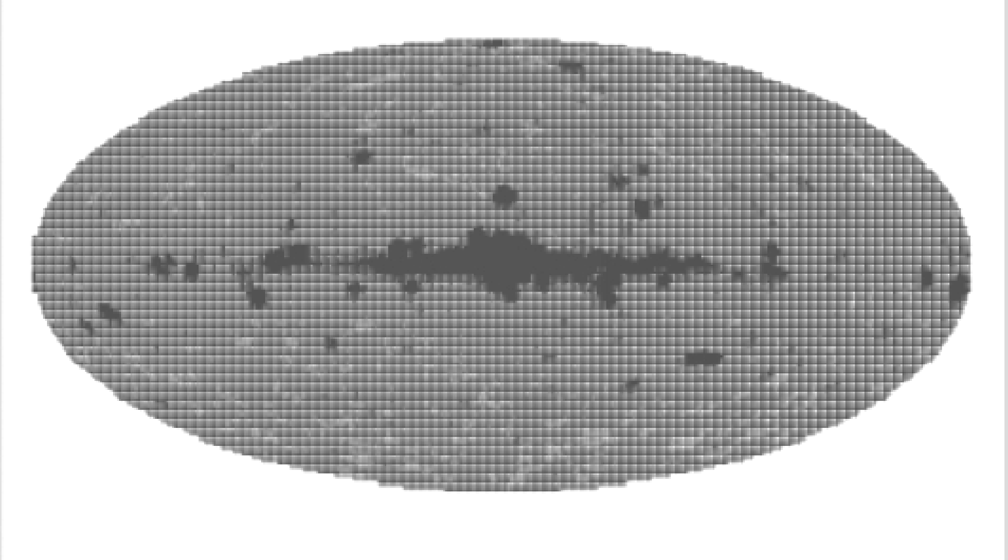
hard x-ray background

HEAO-1 x-ray satellite

3 degree resolution

3-17 keV's

Flown in 1970's



Removed nearby sources:

Cuts (leaving 33% of sky):

- Galactic plane, centre removed
- brightest point sources removed

Fits:

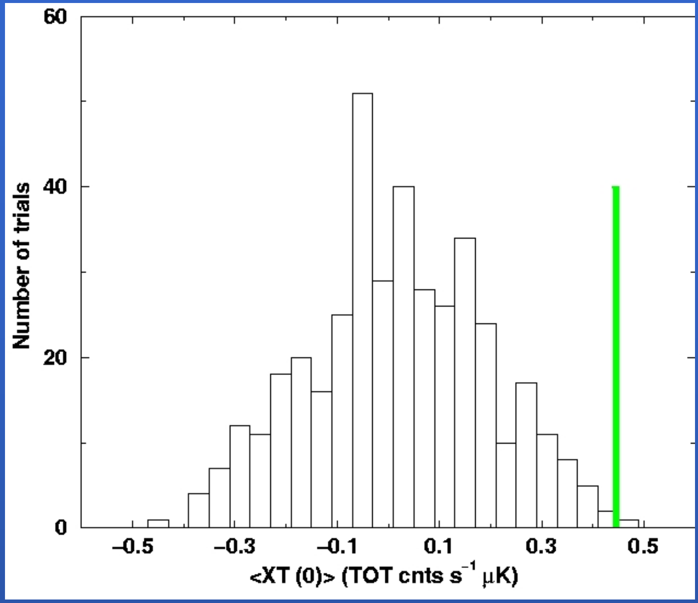
- monopole, dipole
- detector time drift
- Galaxy
- local supercluster

Virtually all visible structures cleaned out

x-ray cmb correlation

compare observed correlation to that with Monte Carlo cmb maps with WMAP power spectrum

correlation detected at 2.5-3 sigma level, comparable to that expected from ISW

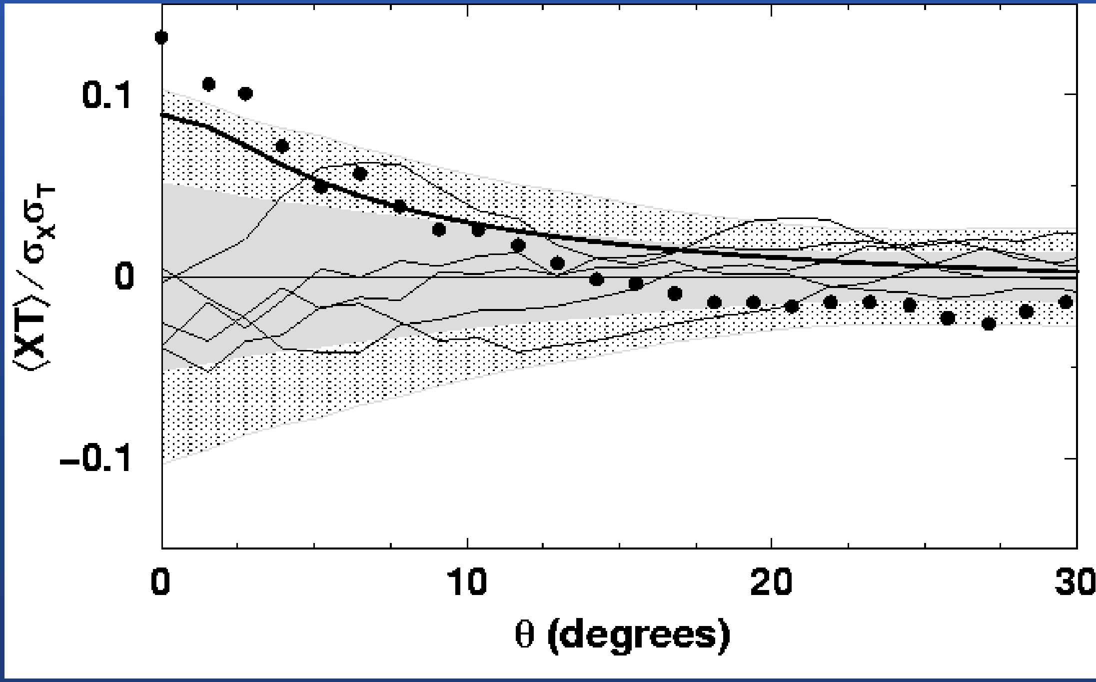


dots: observed

thin: Monte Carlos

thick: ISW prediction (WMAP best fit model)

errors highly correlated



radio galaxies

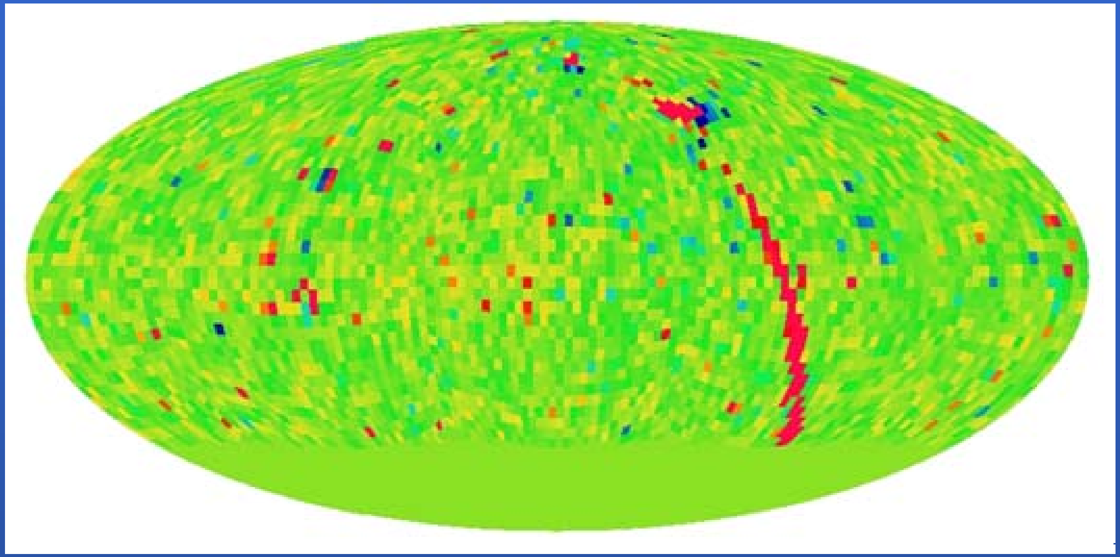
NRAO VLA Sky Survey (NVSS)

flux limited at 1.4 GHz

82% of the sky

1.8 million sources

50 per square degree

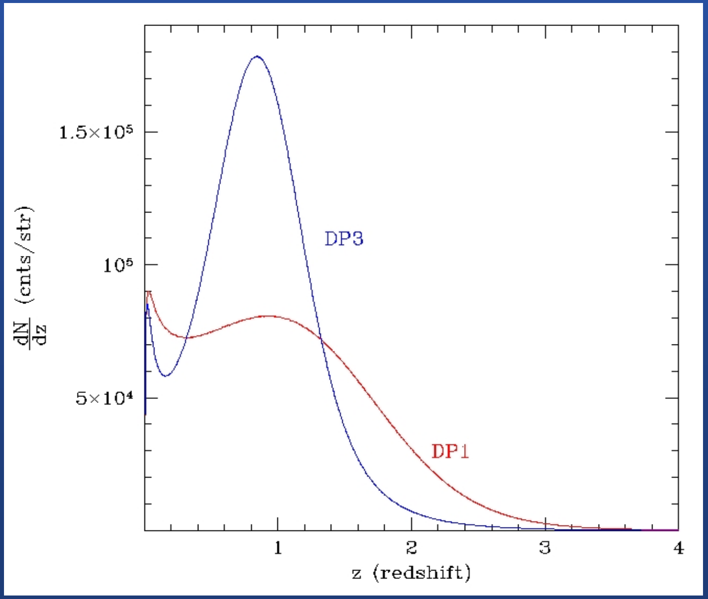


nearby objects and Galaxy removed (leaving 56% of sky)

declination dependent banding corrected

redshift distribution somewhat uncertain

correlated with x-rays!!!



radio cmb correlation

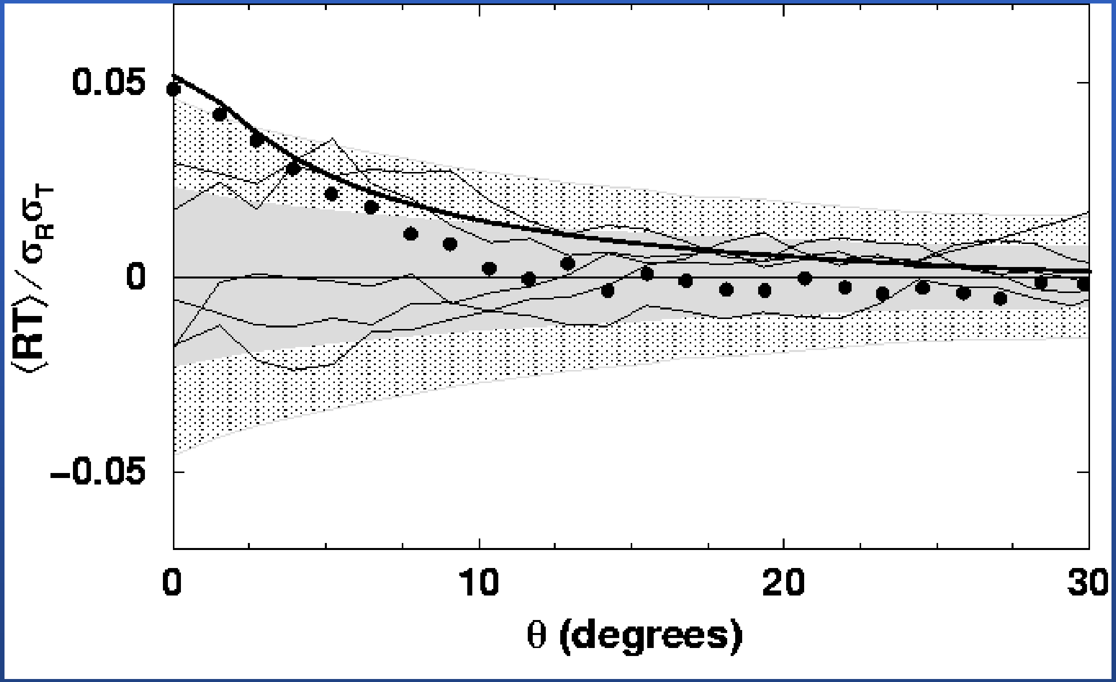
Radio galaxies are also correlated at 2.0-2.5 sigma level, again consistent with ISW origin

dots: observed

thin: Monte Carlos

thick: ISW prediction (WMAP best fit value)

errors highly correlated



Not independent of x-ray signal, but agreement suggests its not due to systematic of maps

Independent WMAP analysis confirmation (Nolta et al.)

could it be a foreground?

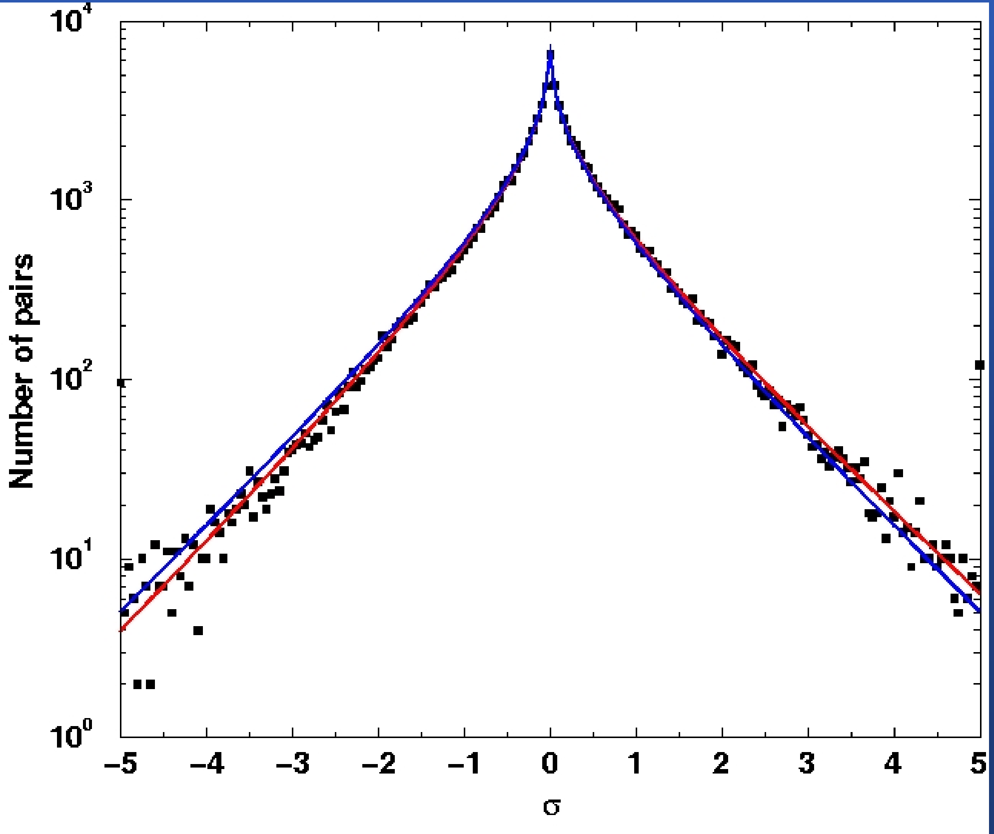
- insensitive to level of galactic cuts
- insensitive to point source cuts
- comparable signal in both hemispheres
- correlation on large angular scales

in addition, the contribution to the correlation from individual pixels is consistent with what is expected for a weak correlation

NOT dominated by a few pixels

blue: product of two Gaussians

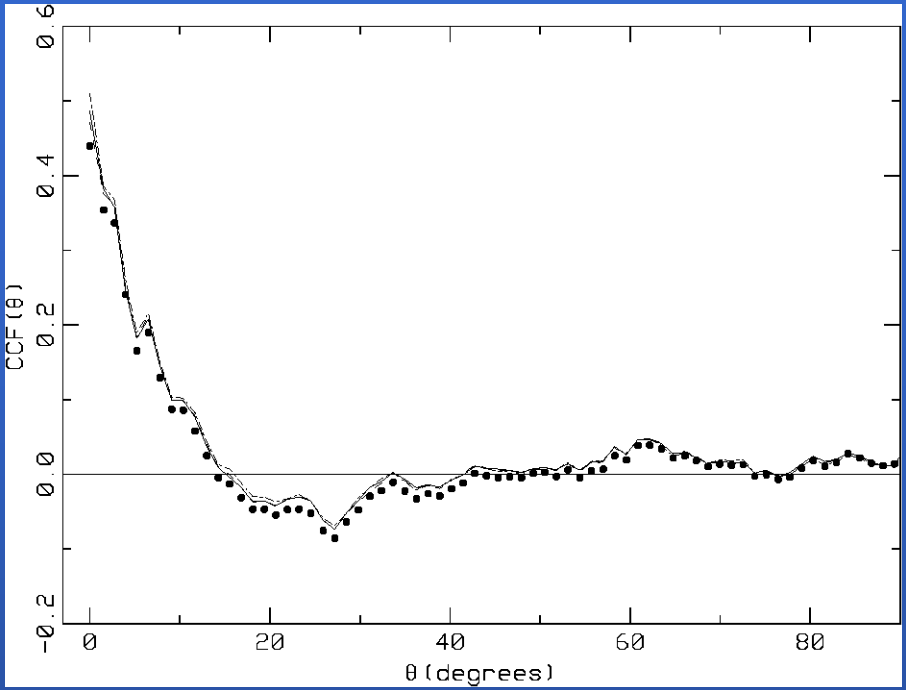
red: product of two weakly correlated Gaussians

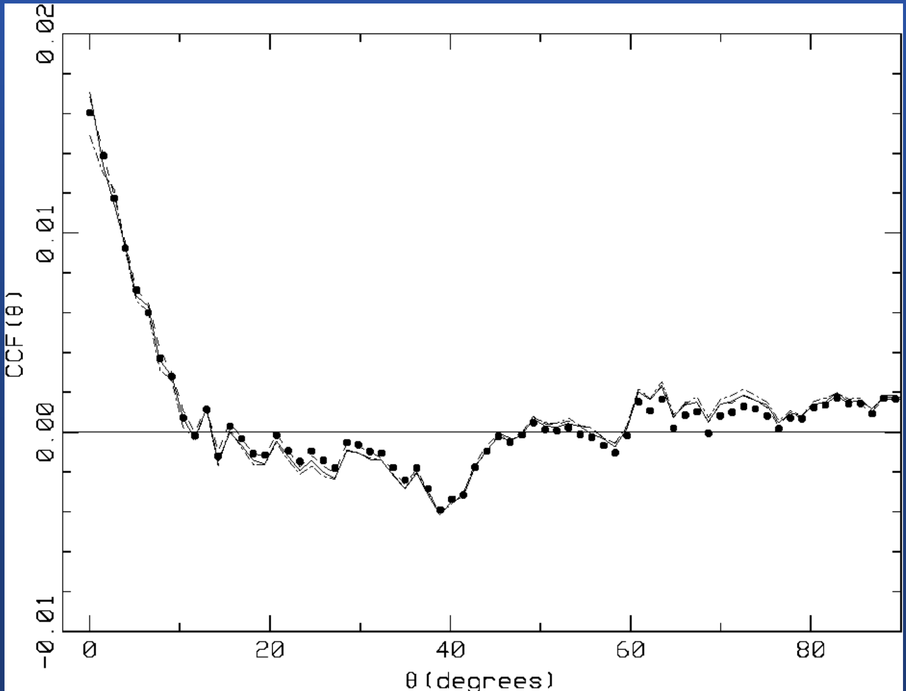


CMB frequency dependence

X-ray and radio cross correlations for ILC and various WMAP bands

There appears to be no strong frequency dependence



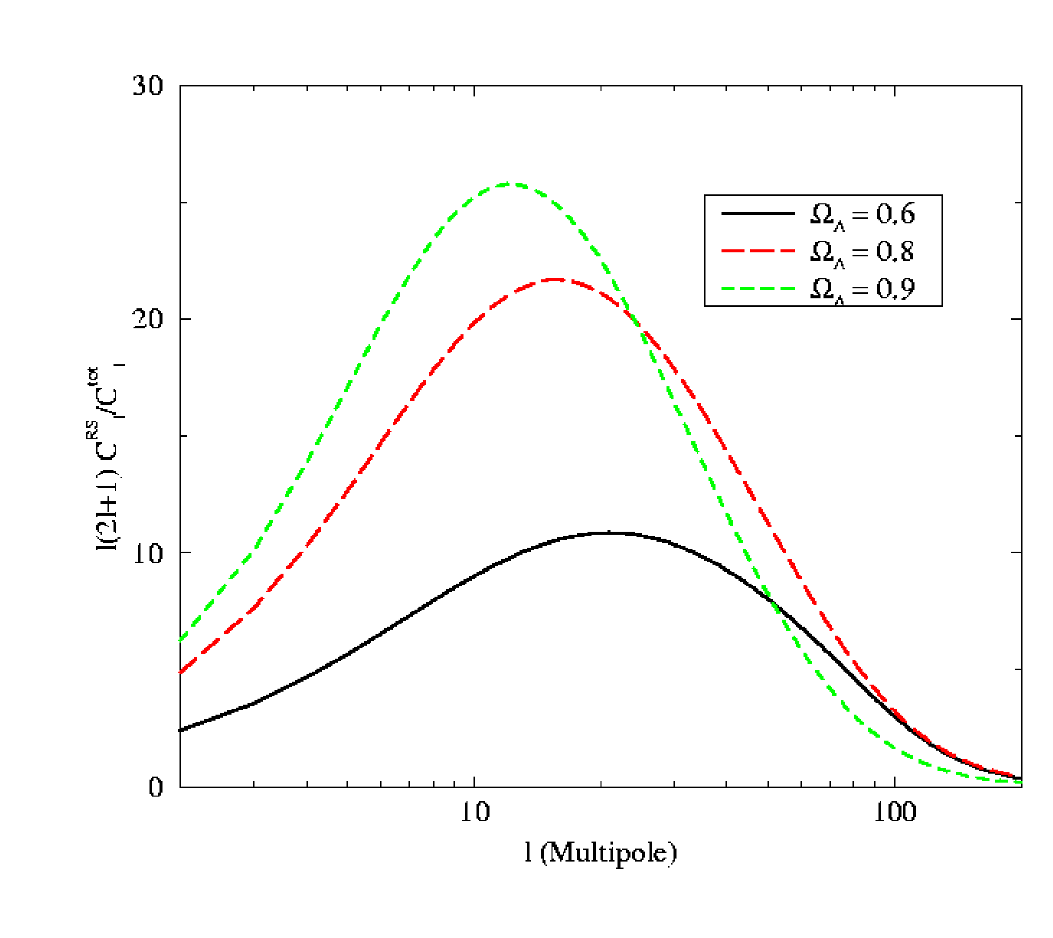


How good will it get?

For the favoured cosmological constant the best signal to noise one can expect is about 7.

The contribution to $(S/N)^2$ as a function of multipole moment.

This is proportional to the number of modes, or the fraction of sky covered, though this does depend on the geometry somewhat.

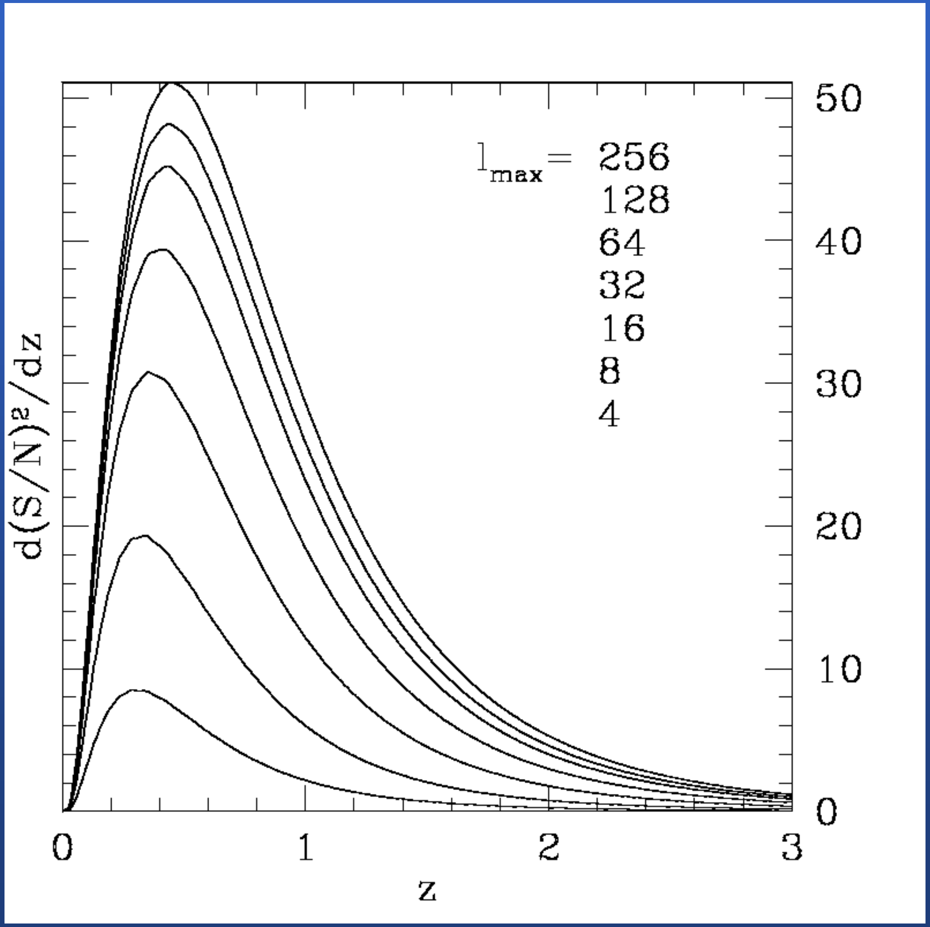


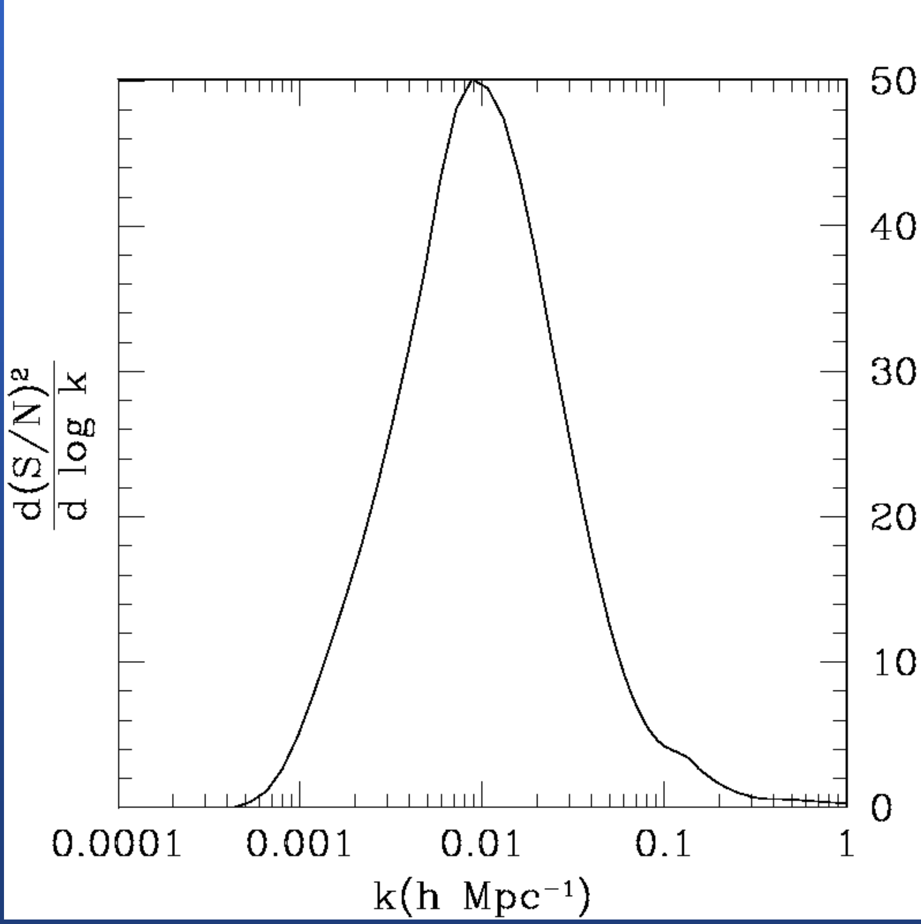
RC, N. Turok 96

Peires & Spergel 2000

Signal to Noise

A good fraction of the signal comes from low redshifts, so a signal is possible with low redshift surveys





$(S/N)^2$ as a function of redshift and wavenumber (Afshordi 04)

related results

NVSS-WMAP correlation confirmed by Nolta et al (WMAP collaboration) at 2.2 sigma level.

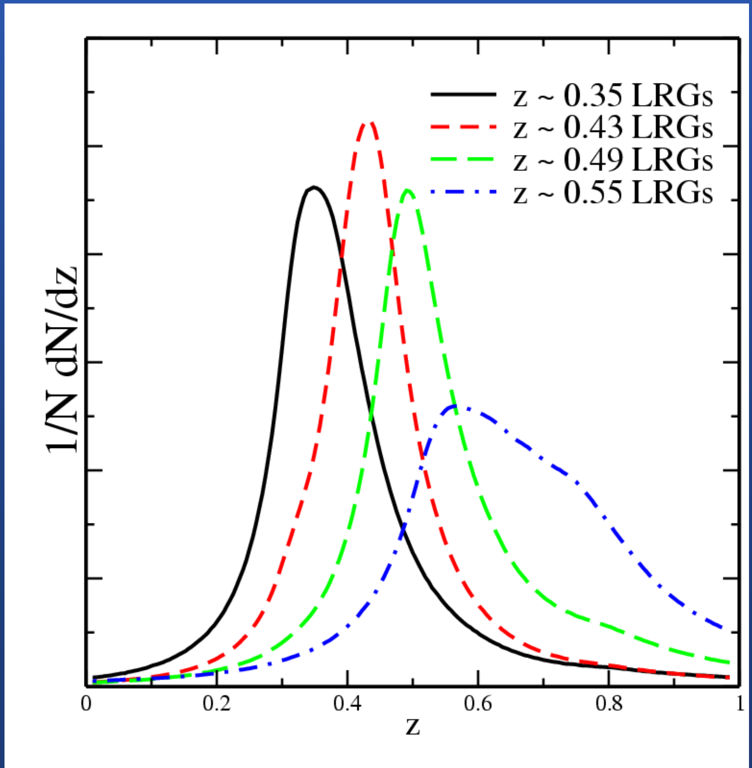
Correlations with other surveys:

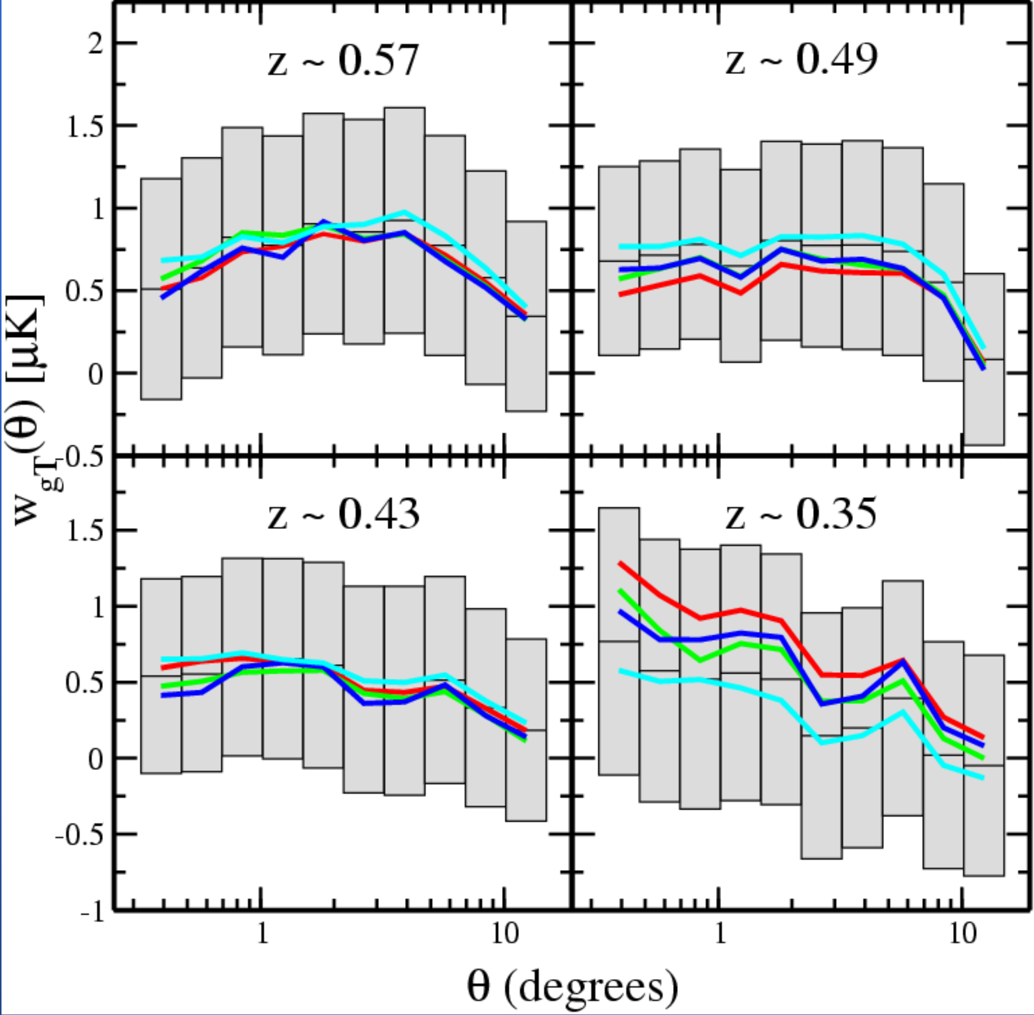
- FIRST radio galaxy survey (Boughn & student)
- 2MASS near infrared survey (Afshordi et al.)
- APM survey (Folsalba and Gaztanaga)
- Sloan Digital Sky Survey (Scranton et al.)

SDSS data
(Scranton et al.)

Luminous red galaxies

3400 square degrees





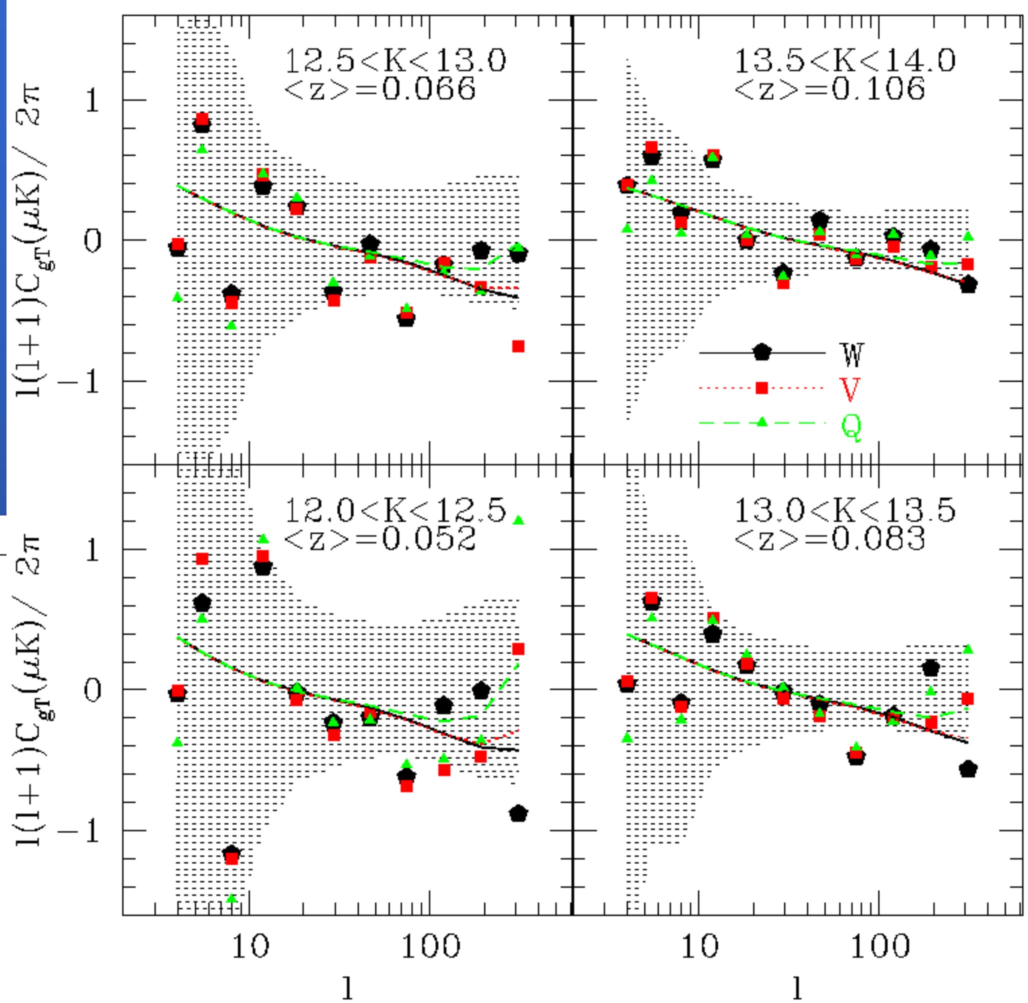
Significant (>90%) detection in all bands

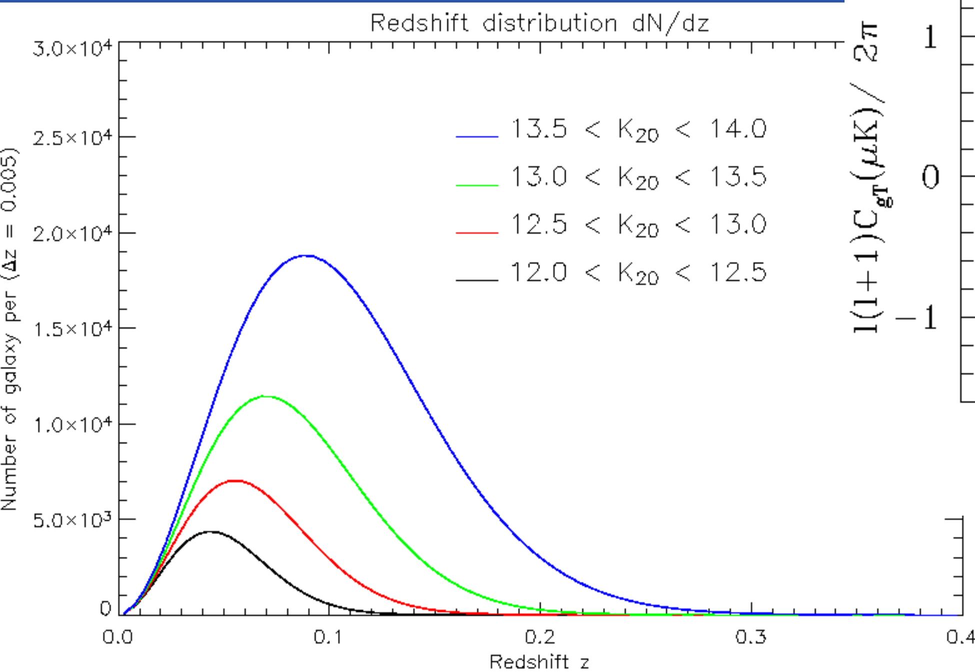
2MASS data

Afshordi, Loh & Strauss

Near infrared

Full sky, but low redshift





2.5 sigma detection of isw

3+ detection of SZ

conclusions

- a significant correlation between the microwave background and large scale structure indicates some of CMB fluctuations produced locally.

- does not appear to be due to the Galaxy or nearby point sources.

- similar in amplitude to that expected from ISW effect in a cosmological constant dominated universe, giving independent confirmation to such models.

- rather than probing how dark energy changes the expansion dynamics, it shows that the modified expansion has affected the growth of structure.

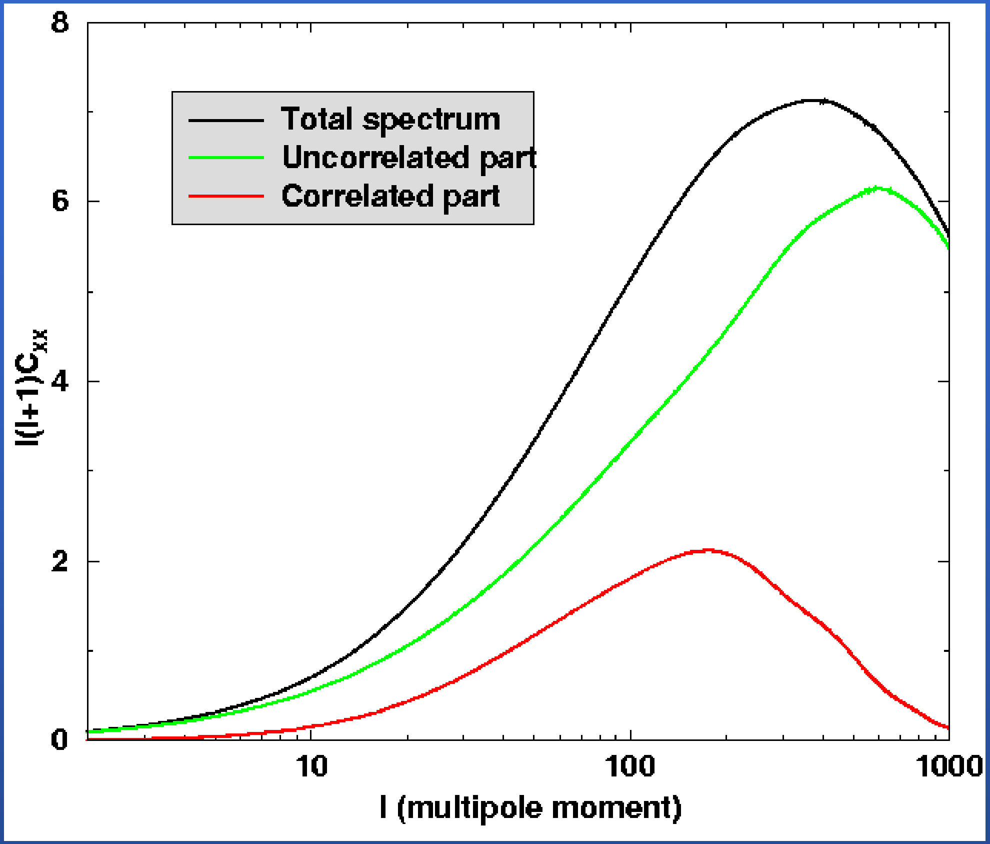
outstanding questions

- can we constrain different dark energy models?
- is there missing large scale power in the nearby ISW map as well? (Power spectrum approach is underway.)
- why didn’t we see this when correlating with COBE?

x-ray power spectra

Typically, the x-ray maps have much more small scale power than CMB maps, the exact form depends on how the sources are distributed in redshift

Some part of the x-ray maps is correlated with the ISW CMB map, but not completely because the distribution of sources differs from how the ISW map arises



$$C_l^{XT} / \sqrt{C_l^{isw} C_l^{XX}} \approx 0.5$$

x-rays correlated with ISW:

$$C_l^{corr} = (C_l^{XT})^2 / C_l^{isw} \approx 0.25 C_l^{XX}$$

Radio correlation comparable

COBE WMAP comparison

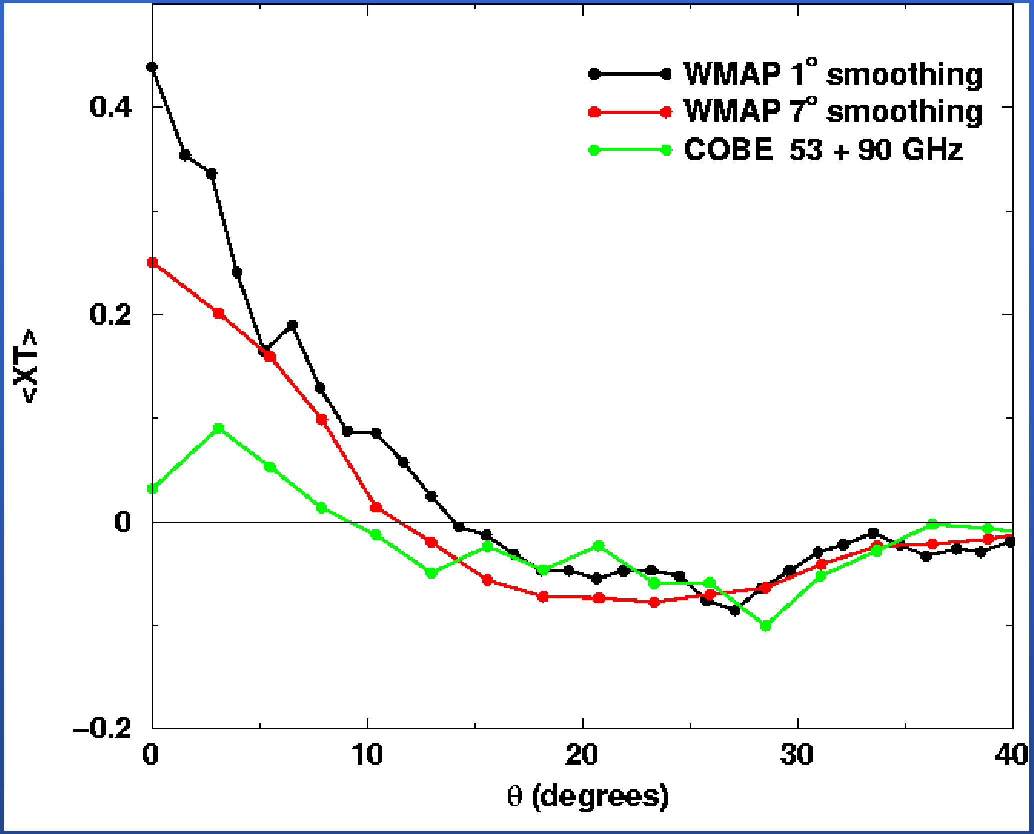
Why wasn't a correlation seen using the COBE map?

This was previously used to put bounds on a cosmological constant

COBE 53 + 90 map was used to minimize detector noise, but still most of the pixel variance was noise

Correlations seem to agree on large scales, but cosmic variance is large there.

Cosmic variance is smallest at small separations, but noise is largest

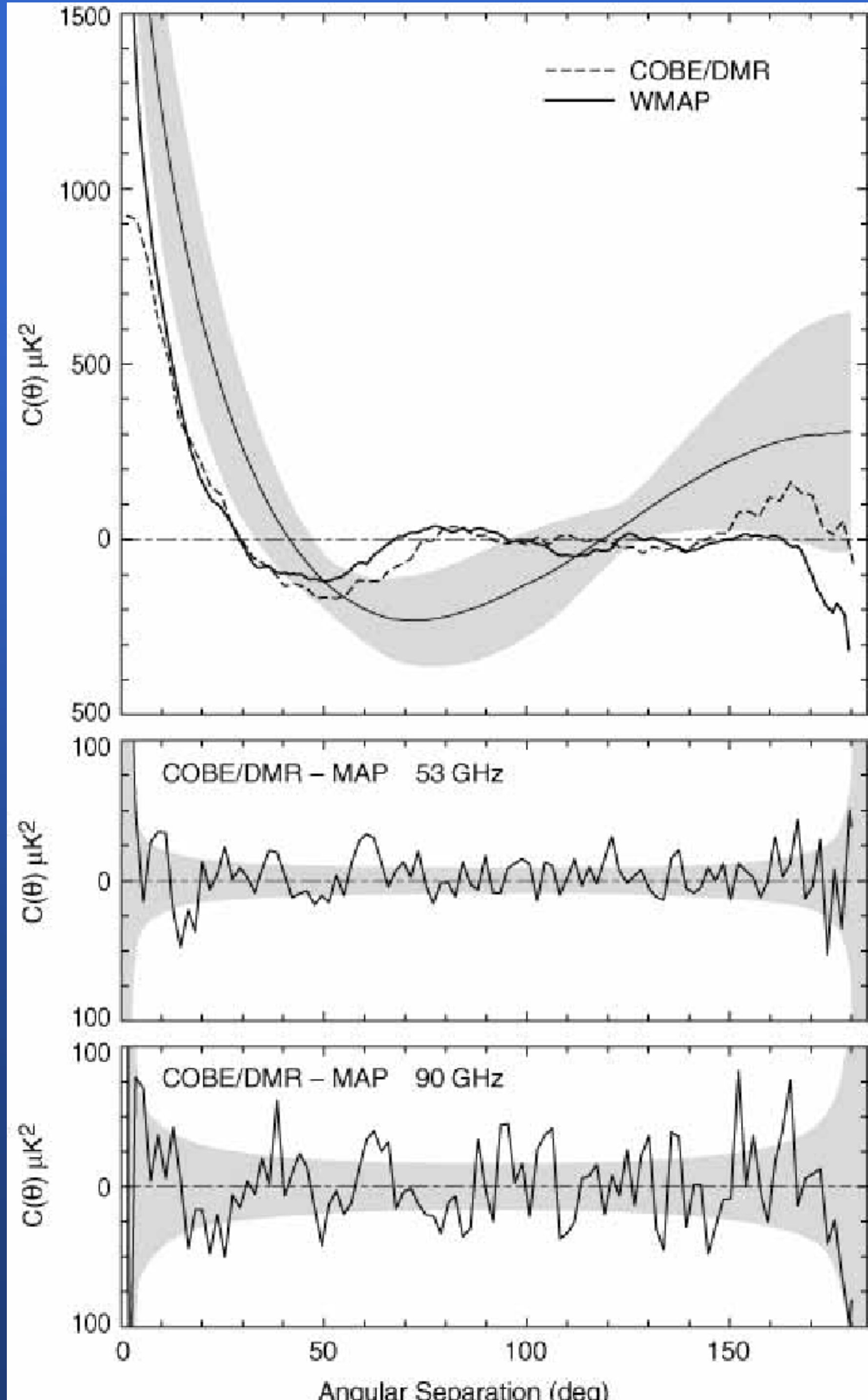


Were we just unlucky that the noise cancelled the correlations?

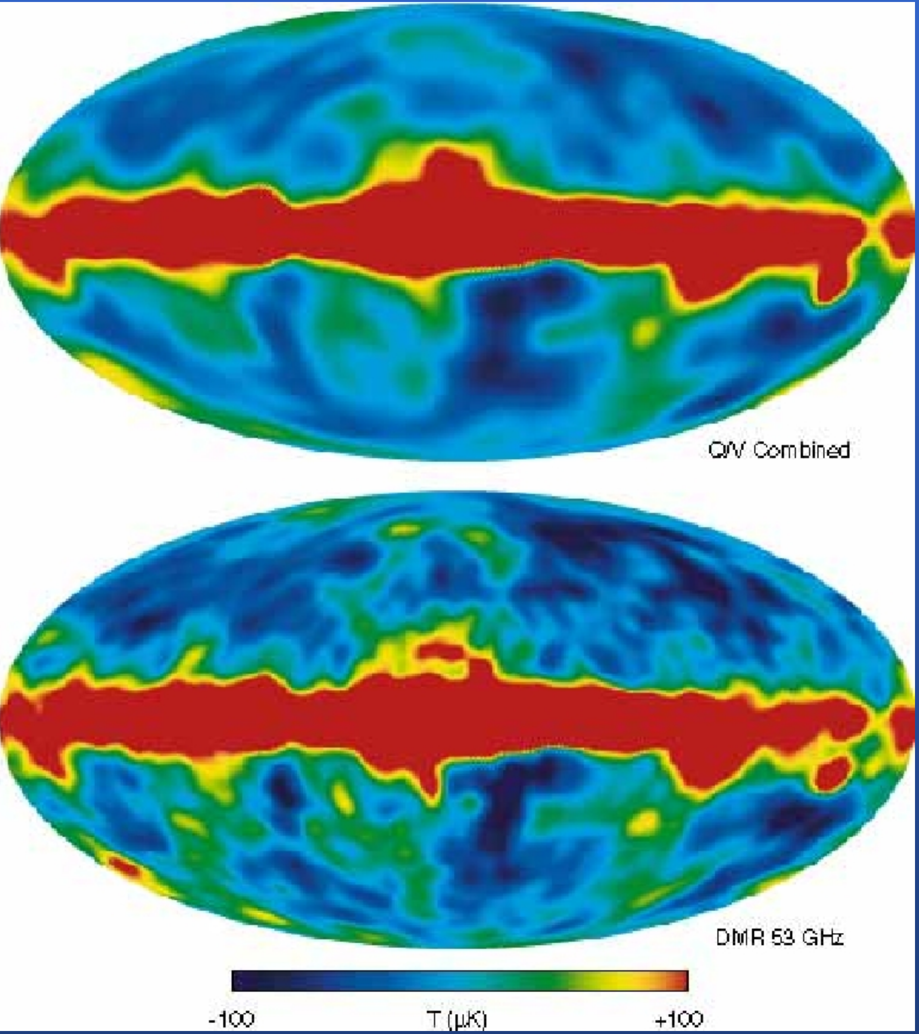
Bennett et al comparison

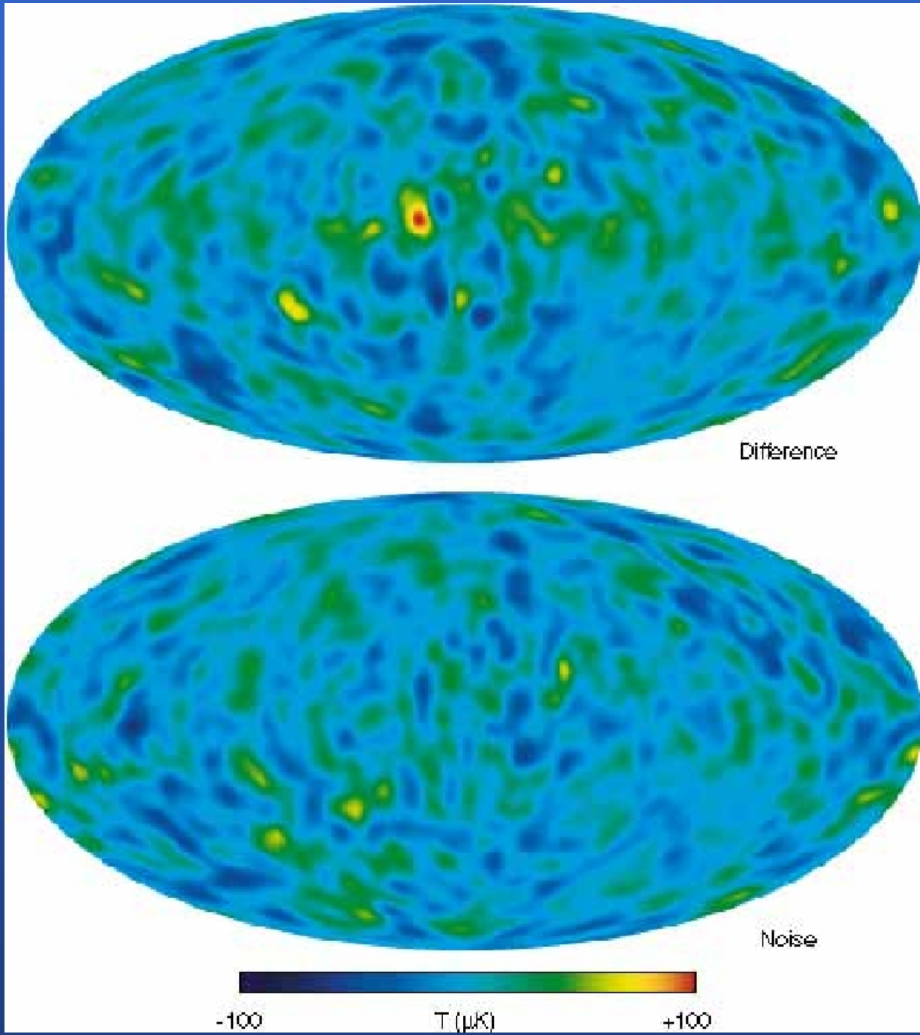
COBE and WMAP are clearly different, but are the differences consistent with the quoted level of COBE noise?

The difference maps at 53 GHz do seem slightly larger than expected– is this due to galactic contamination or how the WMAP analogous map was produced.



Bennett et al comparison





Differences appear fairly consistent with COBE noise level, apart from near galaxy