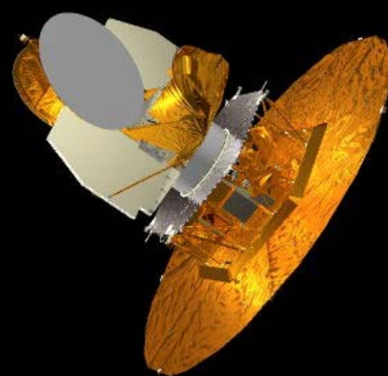
Lessons Learned in WMAP year1

It is (still) all about systematic errors

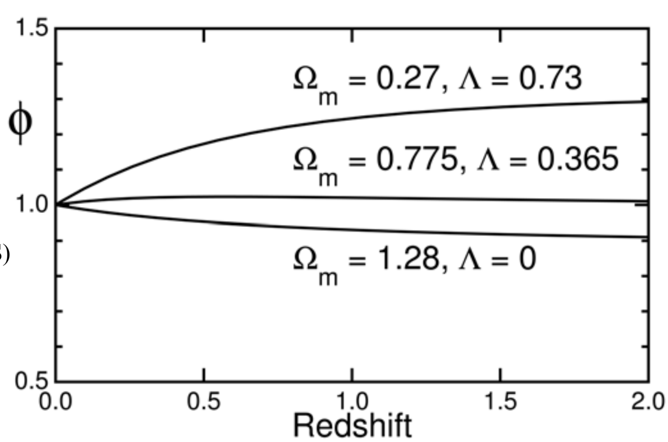
Mark Halpern, UBC



Sun shadow lines

There are effects which we want to measure whose amplitude is a lot smaller than WMAP's noise per pixel. When we average over large parts of the sky we rely on having low spurious correlations in the maps.

We have searched for this effect by cross-correlating WMAP with the NRAO-VLA all sky survey (NVSS) containing 2 million sources.



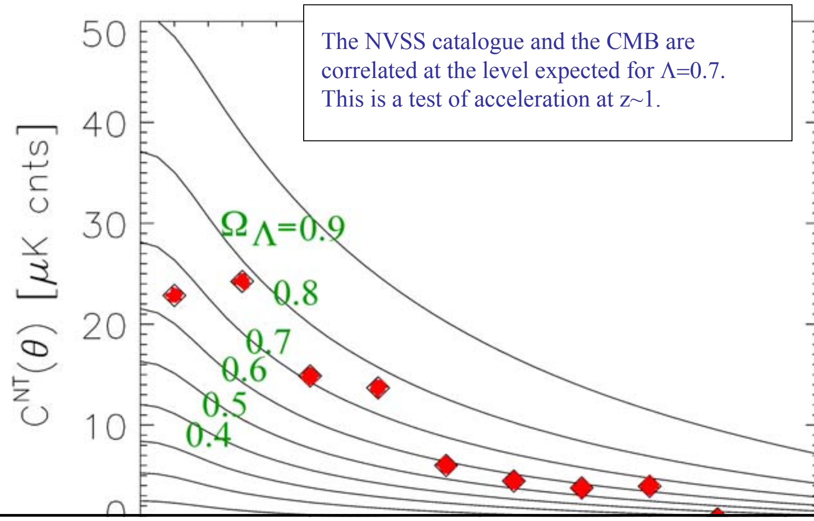
If the gravitational potential of clusters has dropped recently due to acceleration, CMB photons are blue shifted more as they entered the cluster than they are redshifted on exit. Hot spots in the CMB will be correlated with galaxy counts.

‘‘Λ

Nolta et al., 2003

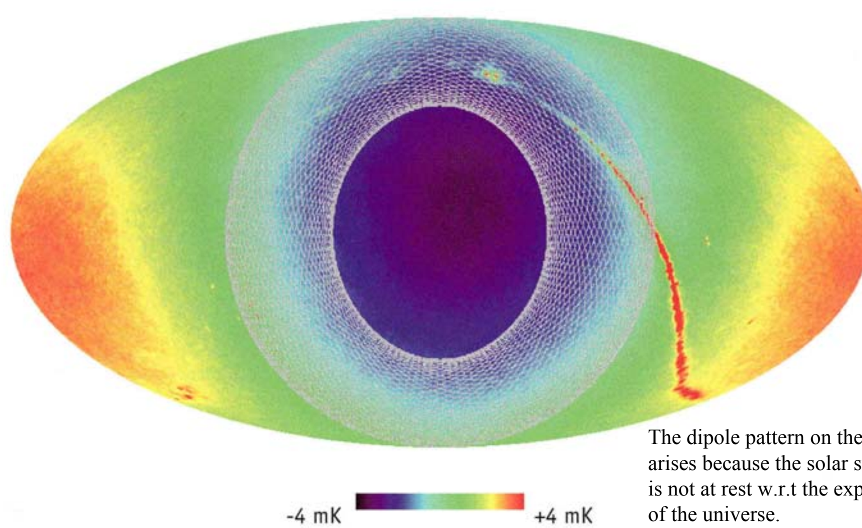
Here the signal is <1/30th of our noise per pixel.

The NVSS catalogue and the CMB are correlated at the level expected for Λ=0.7. This is a test of acceleration at z~1.



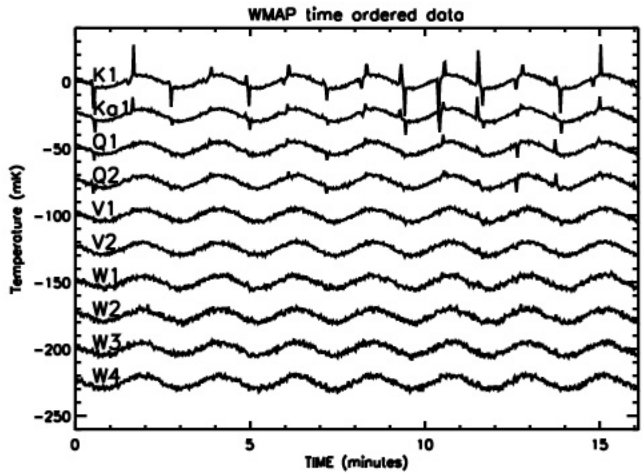
The whole sky is shown in Equatorial coordinates with the WMAP observation pattern in white. The scan pattern covers 30% of the sky every hour, and every circular scan of the sky crosses all the others providing interconnections at many angular scales.

This is achieved with a fixed angle between the spacecraft axis and the sun!

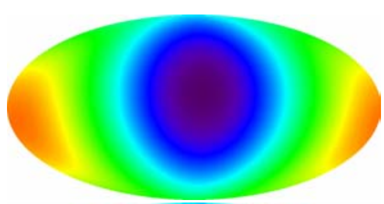


The dipole pattern on the sky arises because the solar system is not at rest w.r.t the expansion of the universe.

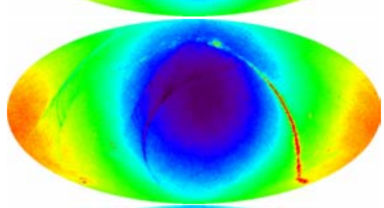
WMAP Time Ordered Data



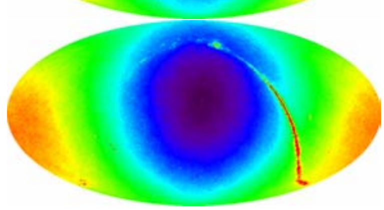
Sky Map Iterations #0, 1, and 10



Initial guess of sky temperature:
$t^{(0)}$ = pure dipole

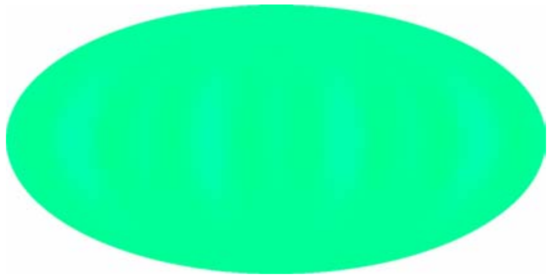


Response after 1 iteration - note spurious "Galaxy echos"



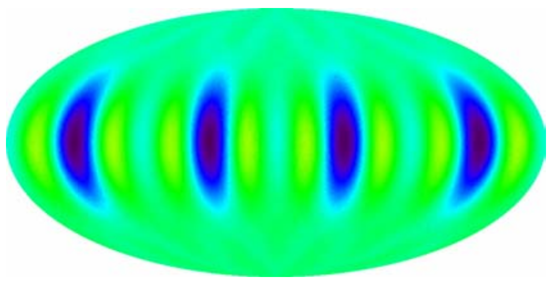
Response after 10 iterations - excellent convergence

Sky Map Residuals - Iteration #40



$\Delta t = t_{out}^{(40)} - t_{in}$

± 5 μK scale

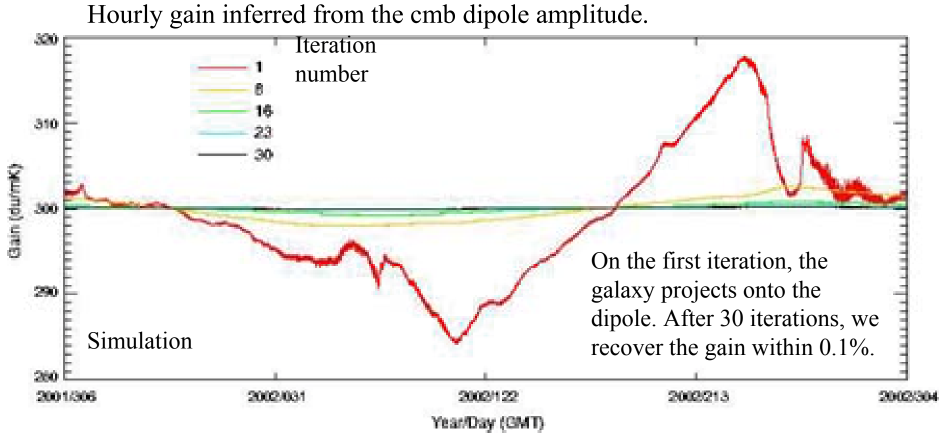


$\Delta t = t_{out}^{(40)} - t_{in}$

± 0.2 μK scale

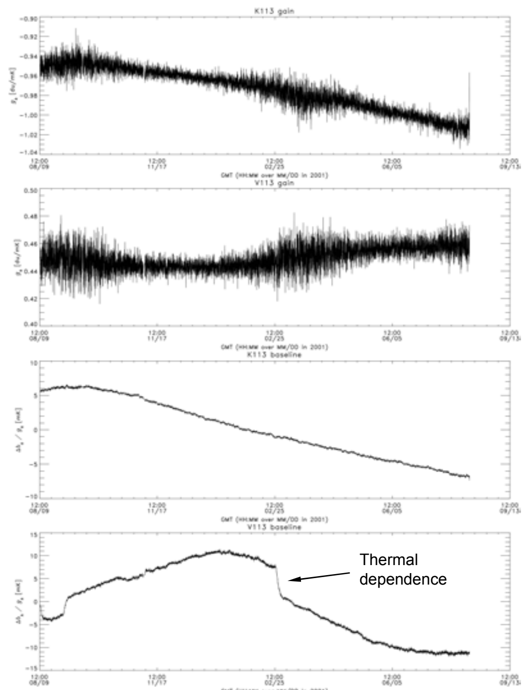
Maps are inferred from the data by iterative deconvolution. The gain is determined from the CMB dipole in the same process.

Hourly gain inferred from the cmb dipole amplitude.



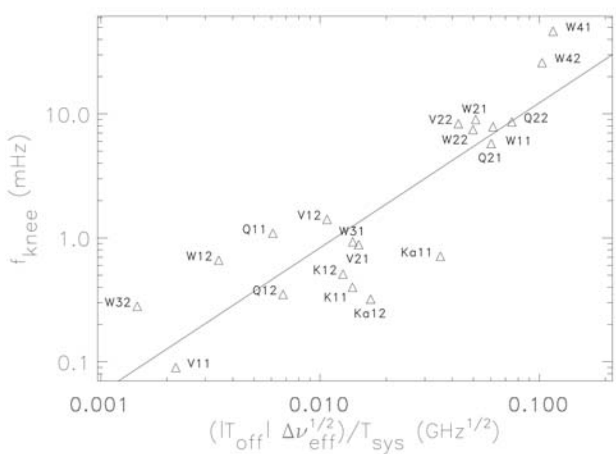
Ultimately, the experiment is calibrated against the *annual change* in the CMB dipole caused by the earth's orbital motion around the sun.

Hourly gain solution,
two typical channels



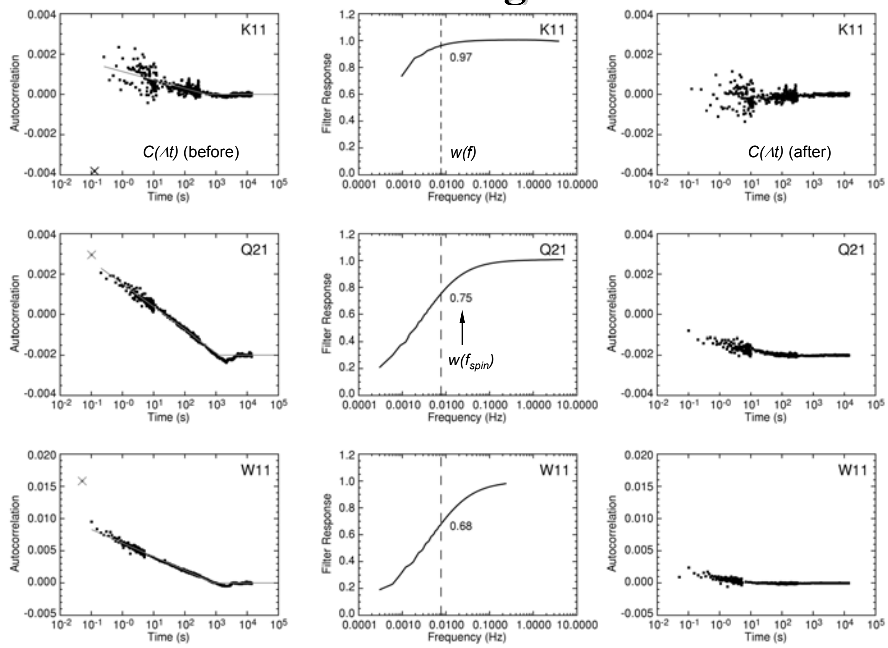
Hourly baseline (offset) solution,
sky map solution to follow

The 1/f knee in the noise in our worst channel is at a higher frequency than our spin rate. Even with our tightly interlocked scan, this is a problem and it has driven the details of our data analysis.



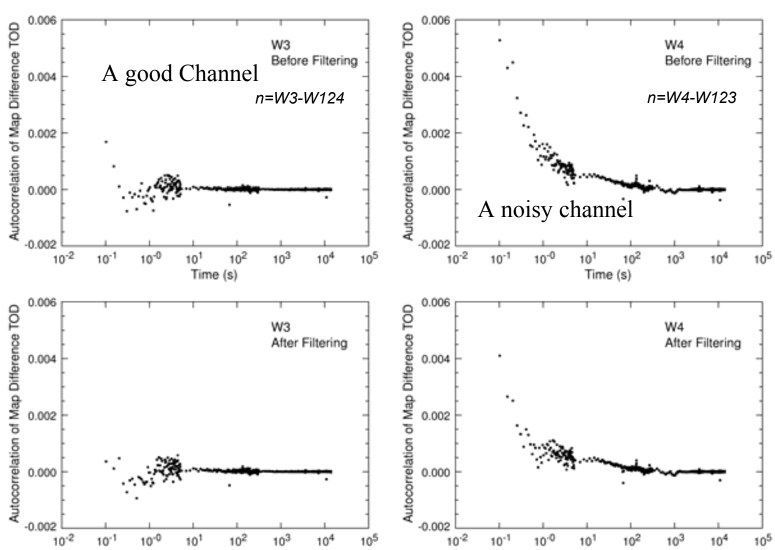
The 1/f knee of our radiometers depends on input offset.

Pre-whitening Filters

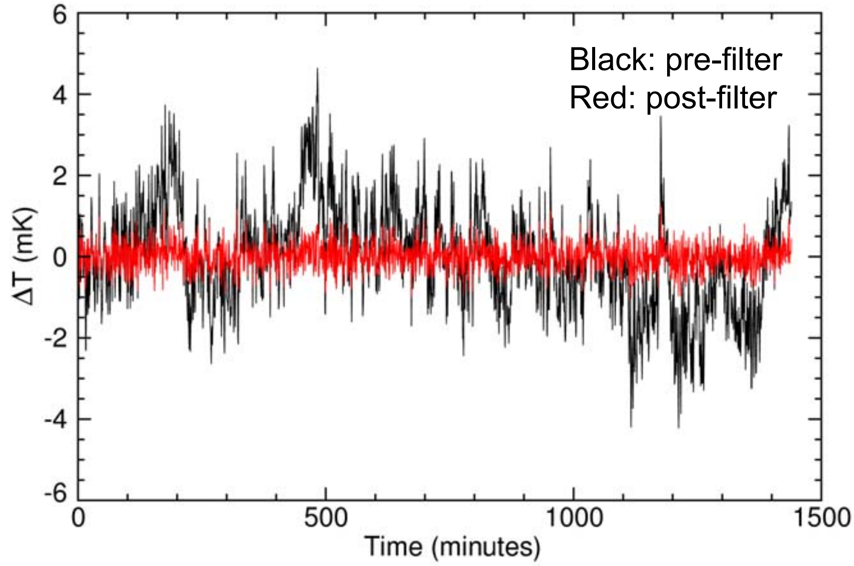


Estimate Pixel-Pixel Covariance

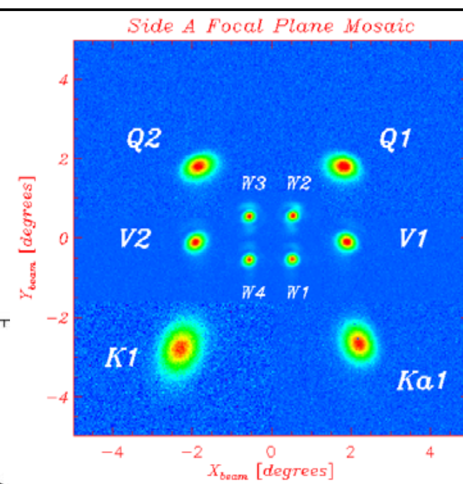
Autocorrelations of one W-band channel minus the mean map of the other three.
There should be very little sky signal in these functions.

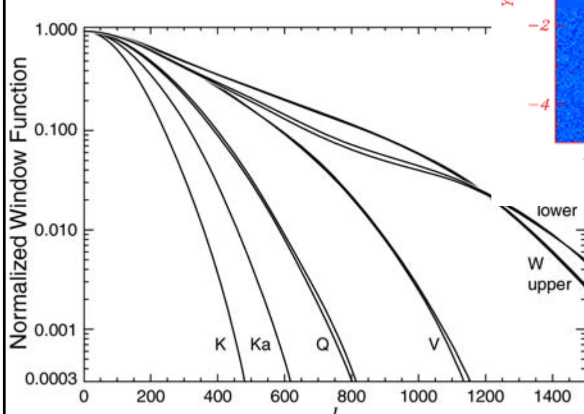


Time-ordered data - W424



Our beam shapes are NOT circular. We can treat the as circular because WMAP scans each point in the sky with several azimuthal orientations. (Year 2 analysis will account slightly for beam shapes.)

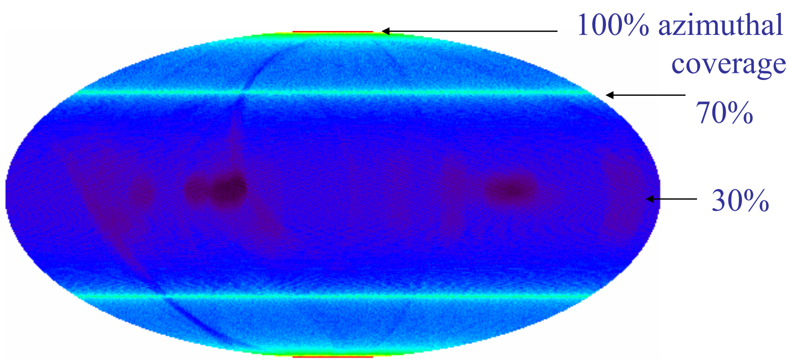




Window functions, the square of the fourier transform of the beam shape, are determined from Jupiter data in flight. We divide by these to infer the power spectrum of the sky.

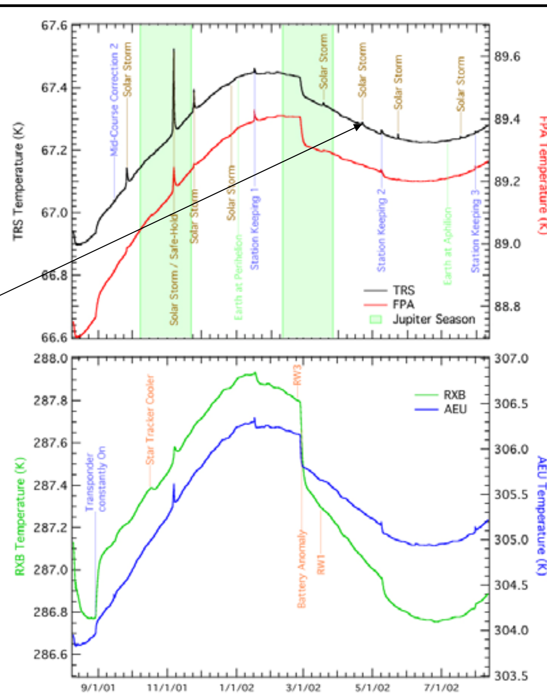
Scan pattern - azimuthal coverage

- Each sky pixel should be scanned with many azimuth angles. This helps produce the following properties:
  - Stable sky map solution,
  - Small pixel-pixel (off-diagonal) covariance:
  - Minimize striping due to 1/f noise,
  - Maximize polarization sensitivity,
  - Maximize azimuthal symmetry of beam response on sky.

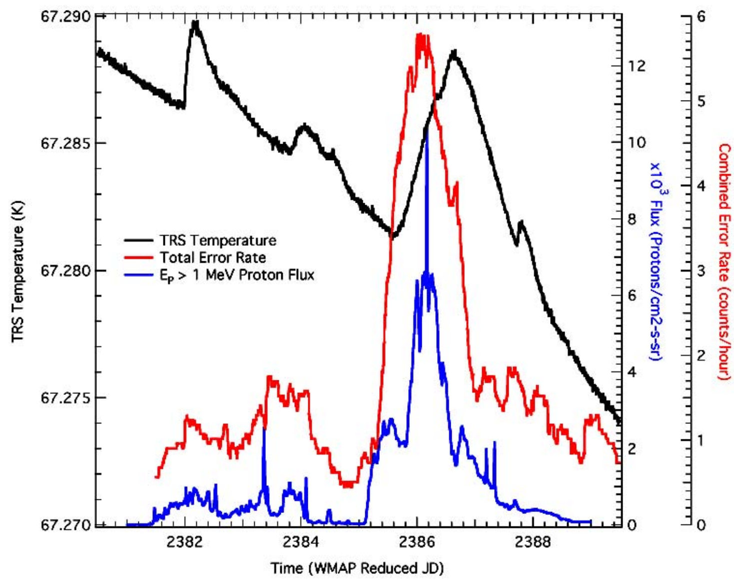


Instrument Temperatures During first Year of Observations

Solar Storm



Thermal Response to Solar Storm



Limits on Spin-Synchronous Environmental Effects[a]

Radiometer/ Band	Gain nK	Thermal nK	Voltage nK
K	6.2	27	4.8
Ka	0.8	2	4.6
Q	15.9	2	7.0
V	0.3	77	37.4
W	0.1	173	9.9

[a] 1σ upper limits derived from measured gain and baseline susceptibilities in Table 8, combined with upper limits on temperature and voltage fluctuations at the spin period. Sign is preserved for each radiometer for roll-up by band.

Spin synchronous systematic errors would accumulate in the maps.

Notice the upper limits for these effects are measured in nano-Kelvin.

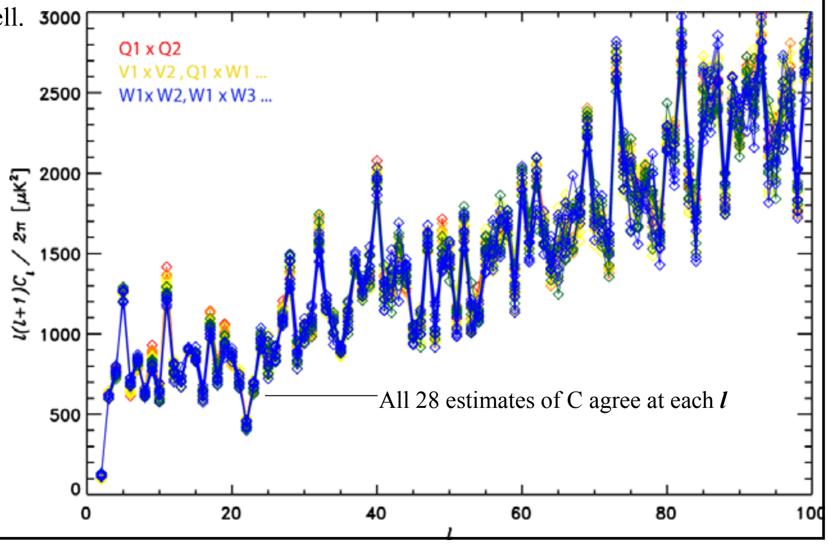
But a warning: You only really can set limits on funny things you know about, not on the ones you do not know to look for.

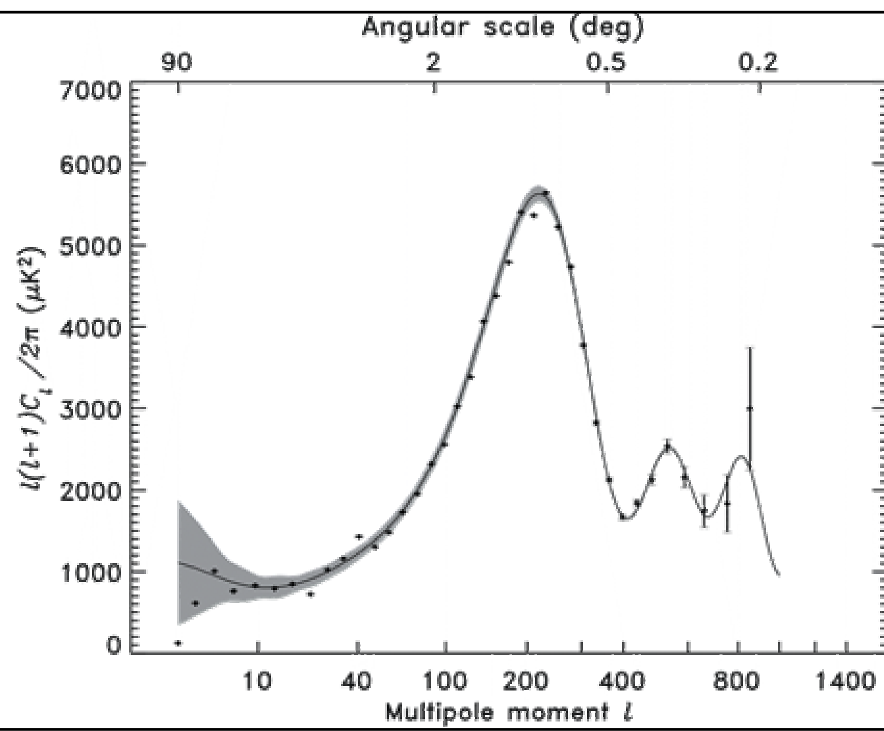
Table 1. Approximate Observational Properties by Band

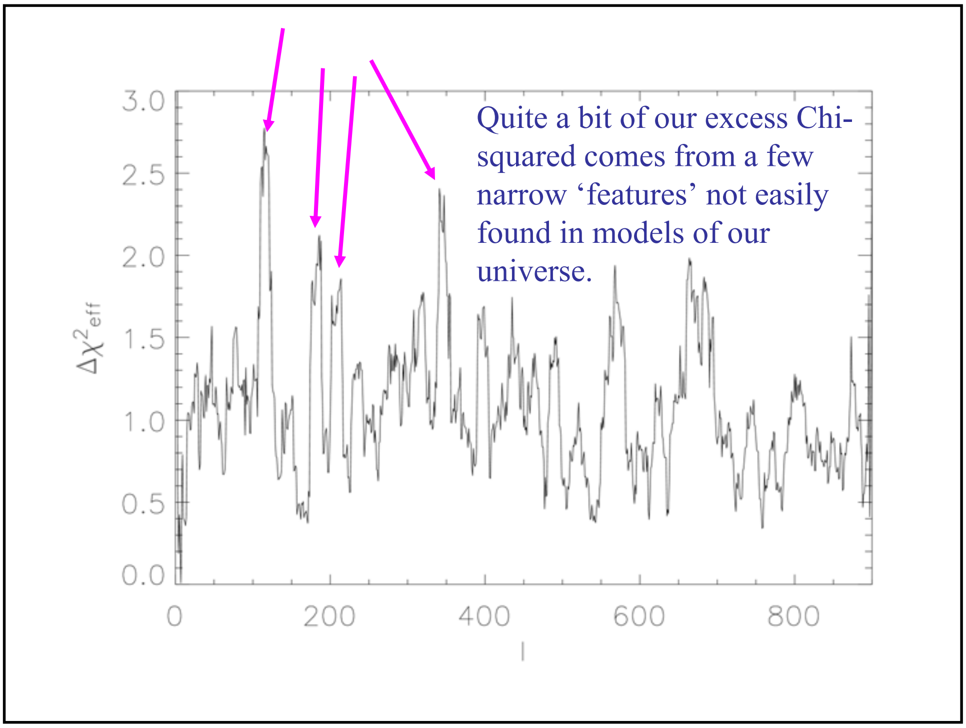
Item	K-Band	Ka-Band	Q-Band	V-Band	W-Band
Wavelength, λ (mm)	13	9.1	7.3	4.9	3.2
Frequency, ν (GHz)	22.8	33.0	40.7	60.8	93.5
Ant./therm. conversion factor, $\Delta T/\Delta T_A$	1.014	1.029	1.044	1.100	1.251
Noise, σ_0 (mK) $\sigma = \sigma_0 N_{obs}^{-1/2}$	1.424	1.449	2.211	3.112	6.498
Beam width θ(°FWHM)	0.82	0.62	0.49	0.33	0.21
No. of Differencing Assemblies	1	1	2	2	4
No. of Radiometers	2	2	4	4	8
No. of Channels	4	4	8	8	16

We calculate 28 Cross-power spectra (Q1xQ2, Q1xV1, etc but never W2xW2). These 28 measurements of the power spectrum agree, indicating very little galactic contamination.

Here they are shown one *l* per bin. The scatter about a smooth spectrum is due to cosmic variance: there are not enough multipoles in our universe to determine their variance well.







Quite a bit of our excess Chi-squared comes from a few narrow ‘features’ not easily found in models of our universe.
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\Delta\chi^2_{eff}$
0
200
400
600
800
l