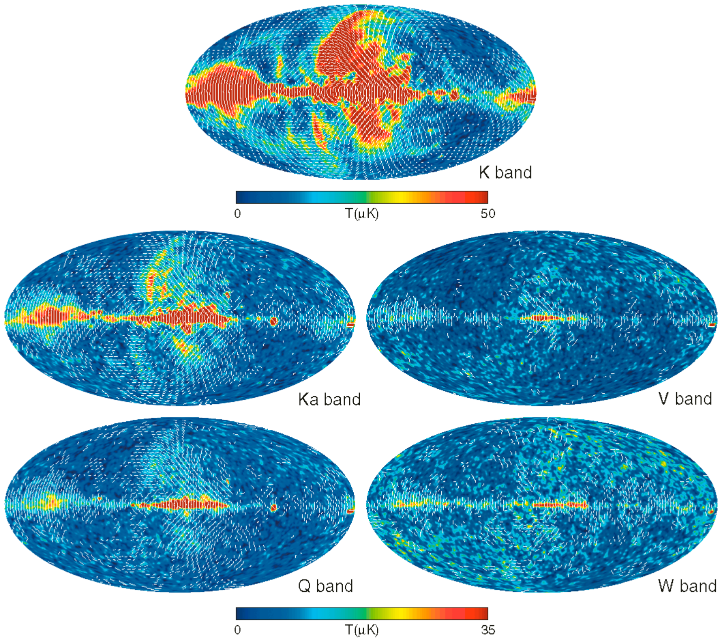
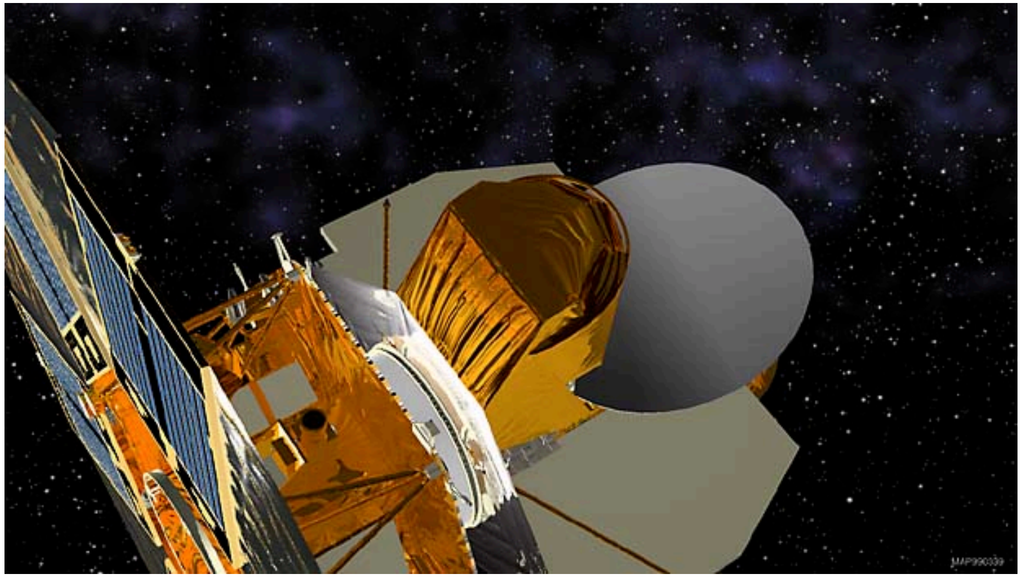
Large-Scale Polarization with WMAP

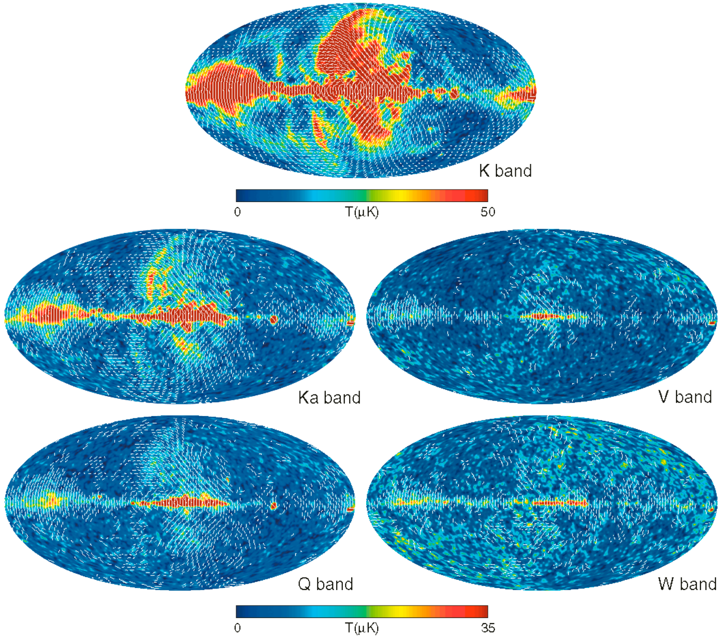


Gary Hinshaw
University of British Columbia

15 February 2012
"Astrophysics from the Radio to the Submillimtre" - Bologna



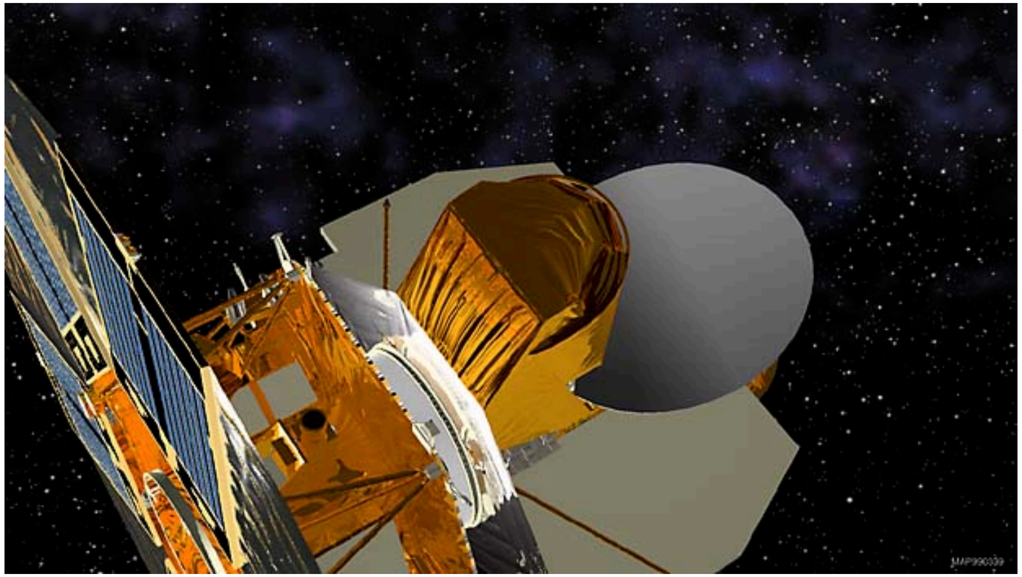
Large-Scale Polarization with WMAP



or –
"Why I Have PTSD"

Gary Hinshaw
University of British Columbia

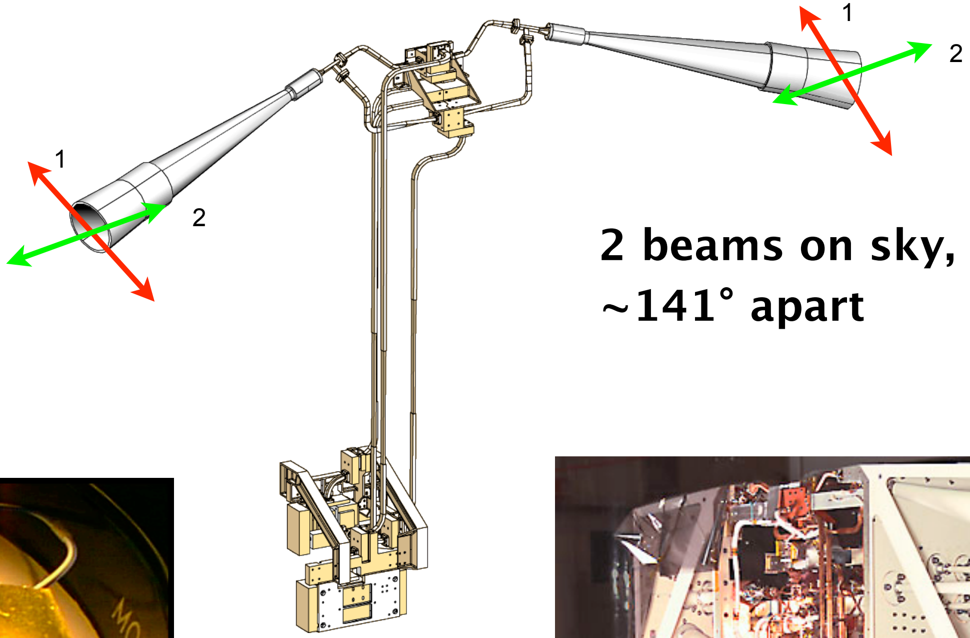
15 February 2012
"Astrophysics from the Radio to the Submillimtre" - Bologna



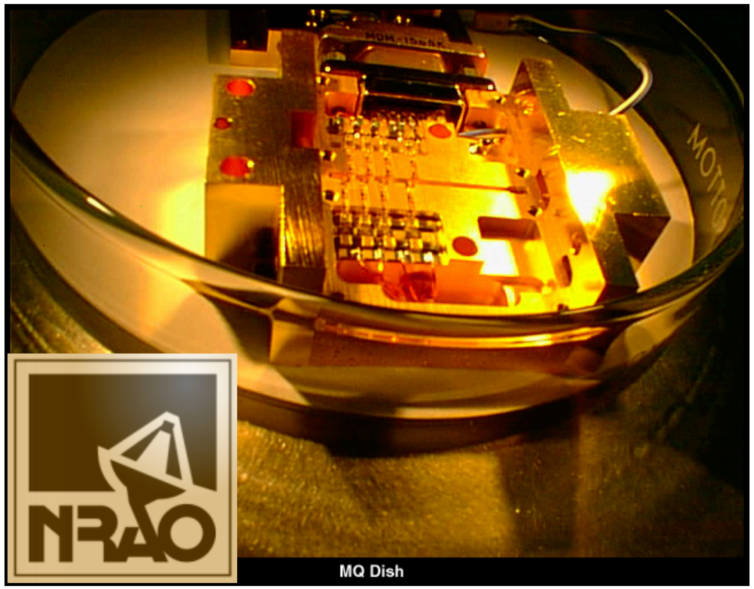
WMAP – Differential Radiometers

5 frequency bands in 10 channels:

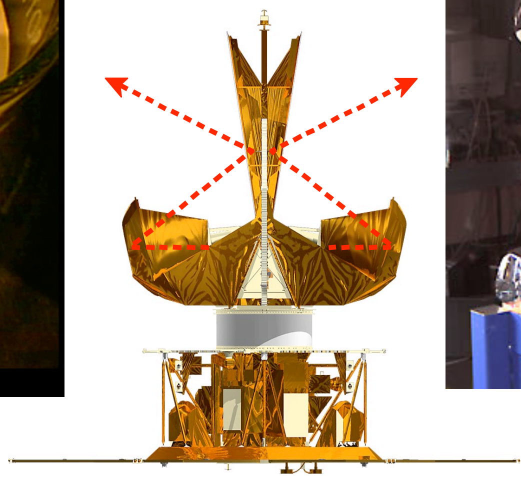
4 @ 94 GHz W-band
2 @ 61 GHz V-band
2 @ 41 GHz Q-band
1 @ 33 GHz Ka-band
1 @ 23 GHz K-band

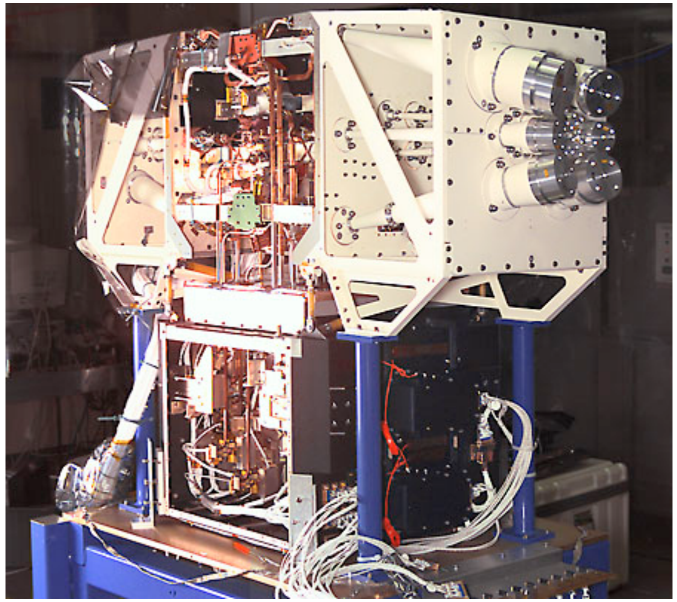


2 beams on sky, ~141° apart

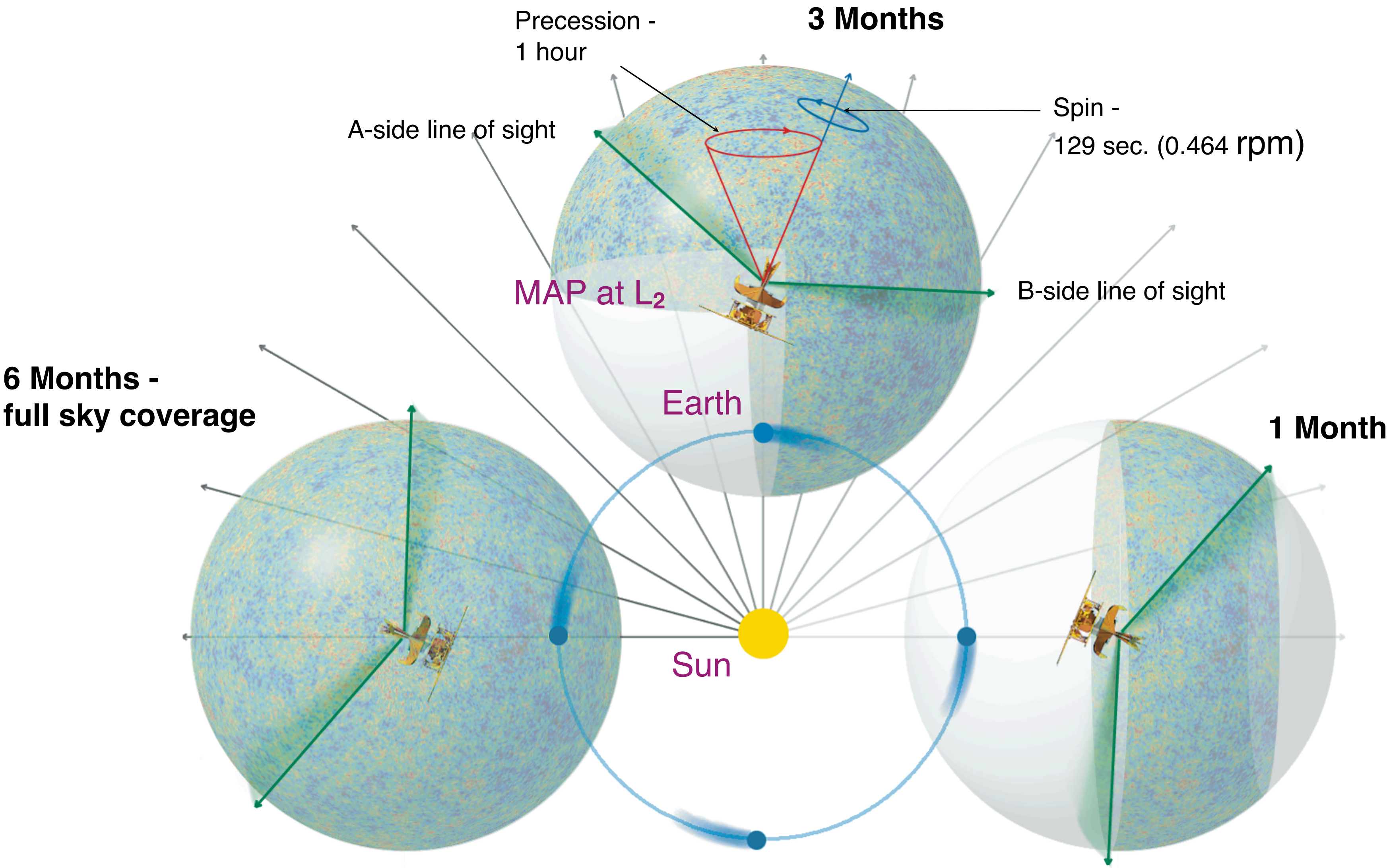


*HEMT design – M. Pospieszalski

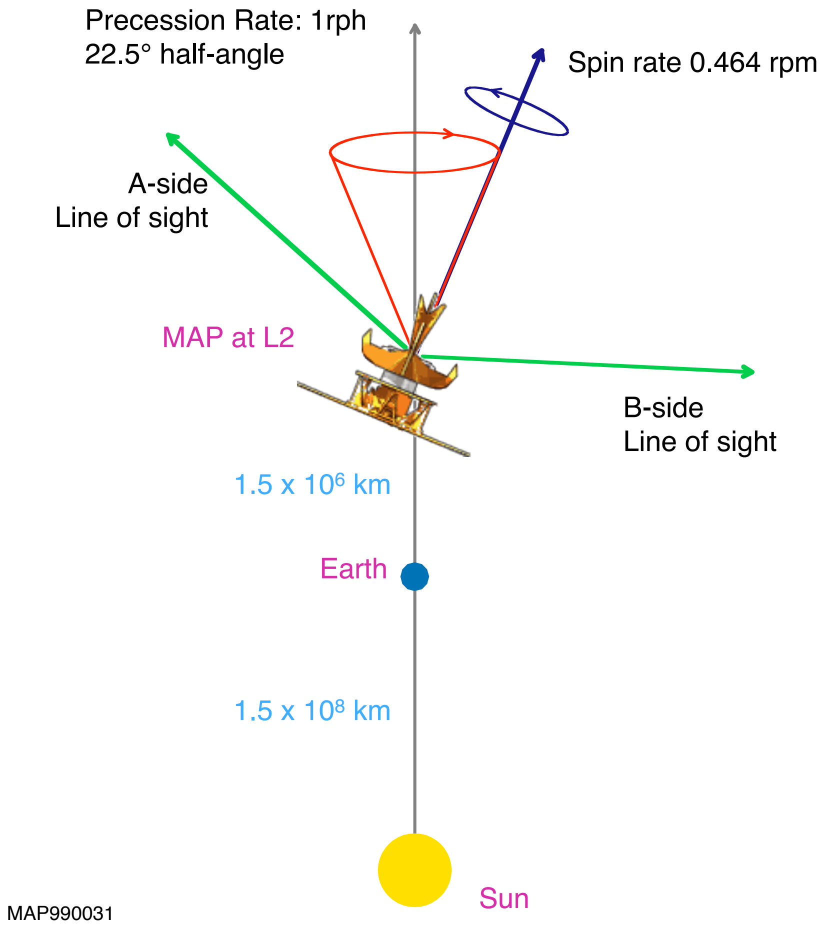


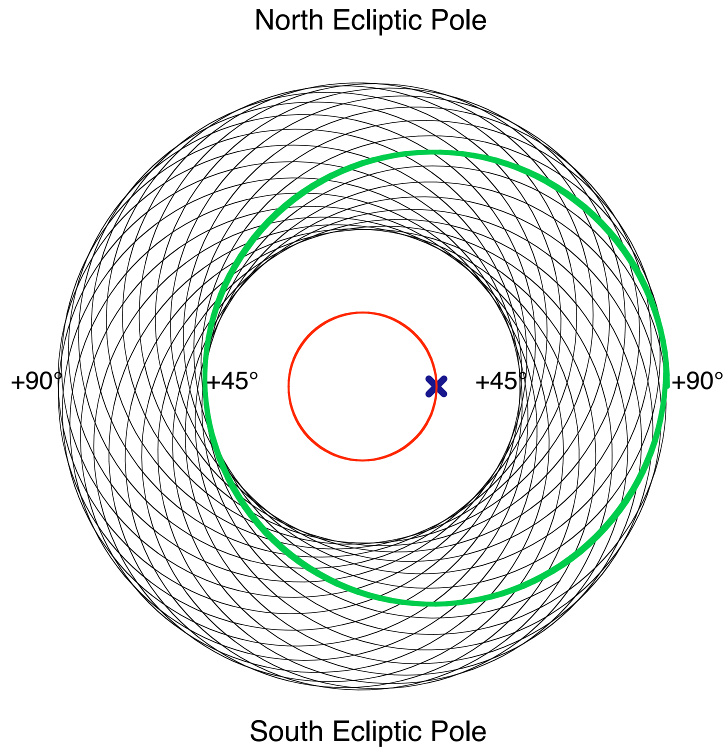


WMAP Scanning From L2 - I

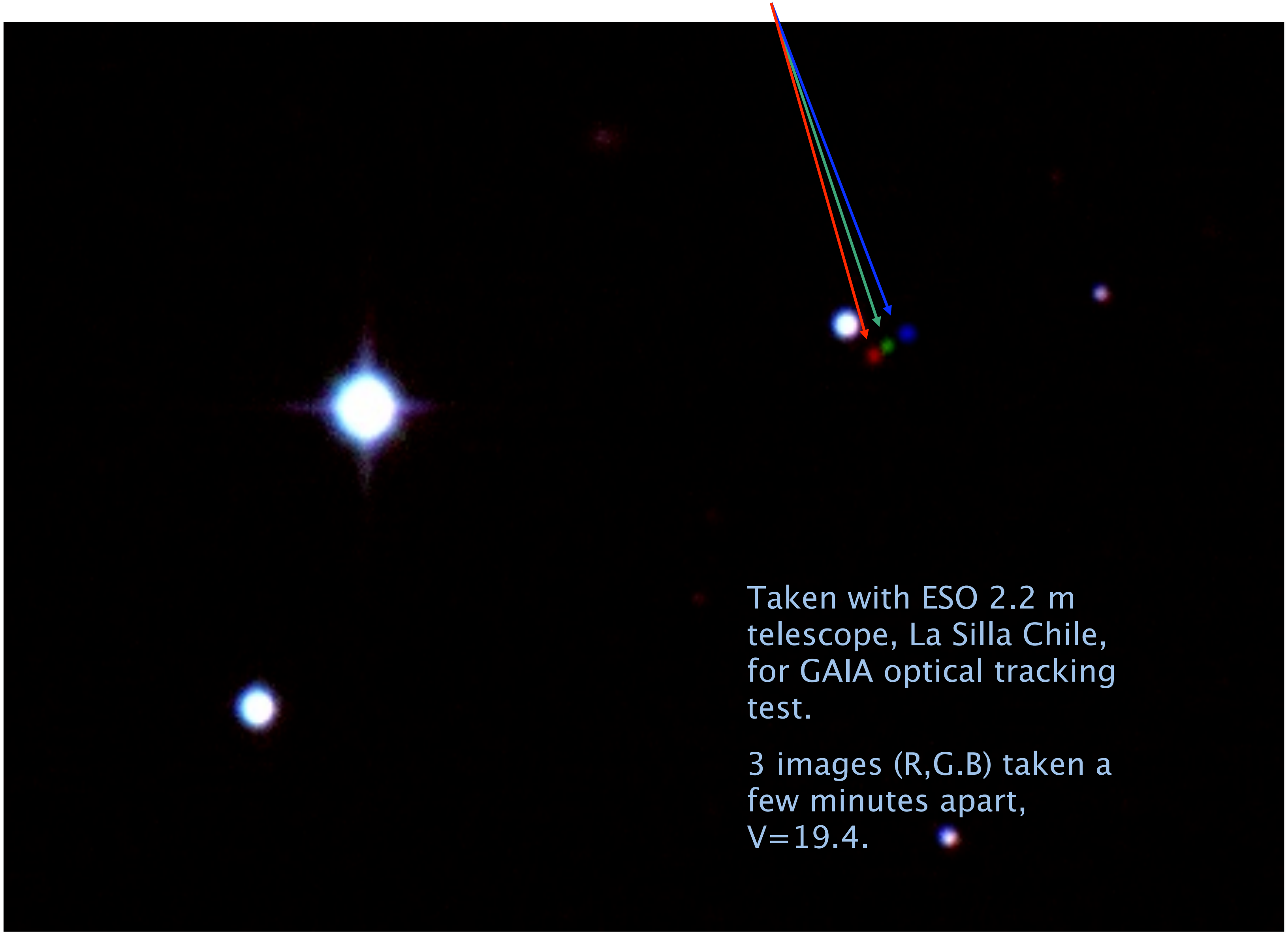


WMAP Scanning From L2 – II

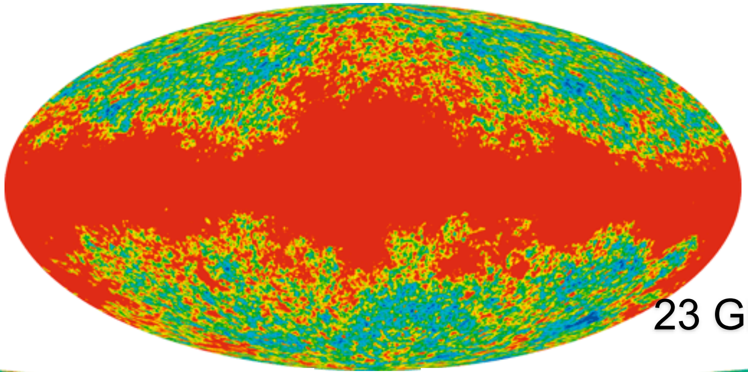




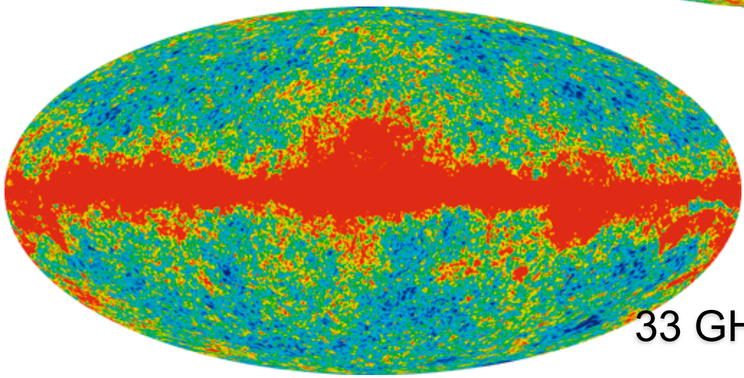
The Last Known Photo of WMAP



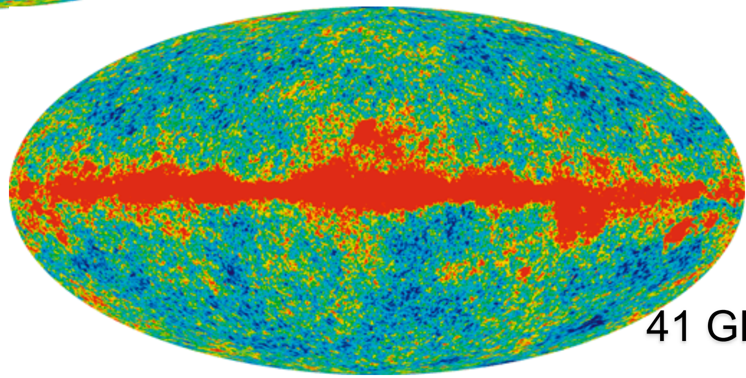
7-year Temperature Maps



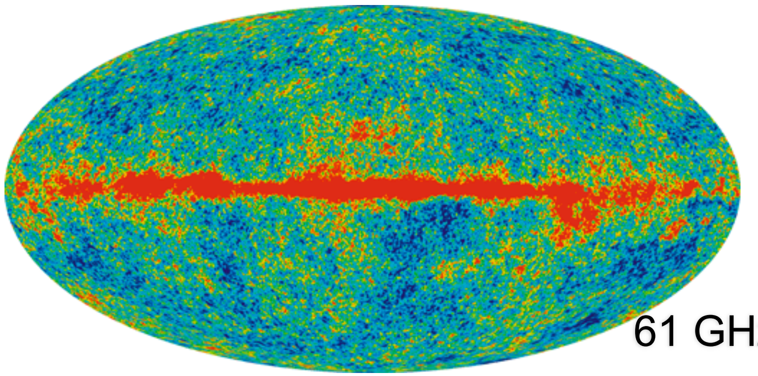
23 GHz



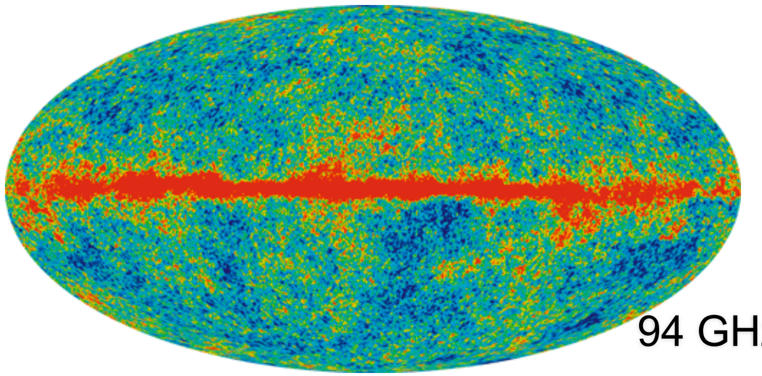
33 GHz



41 GHz

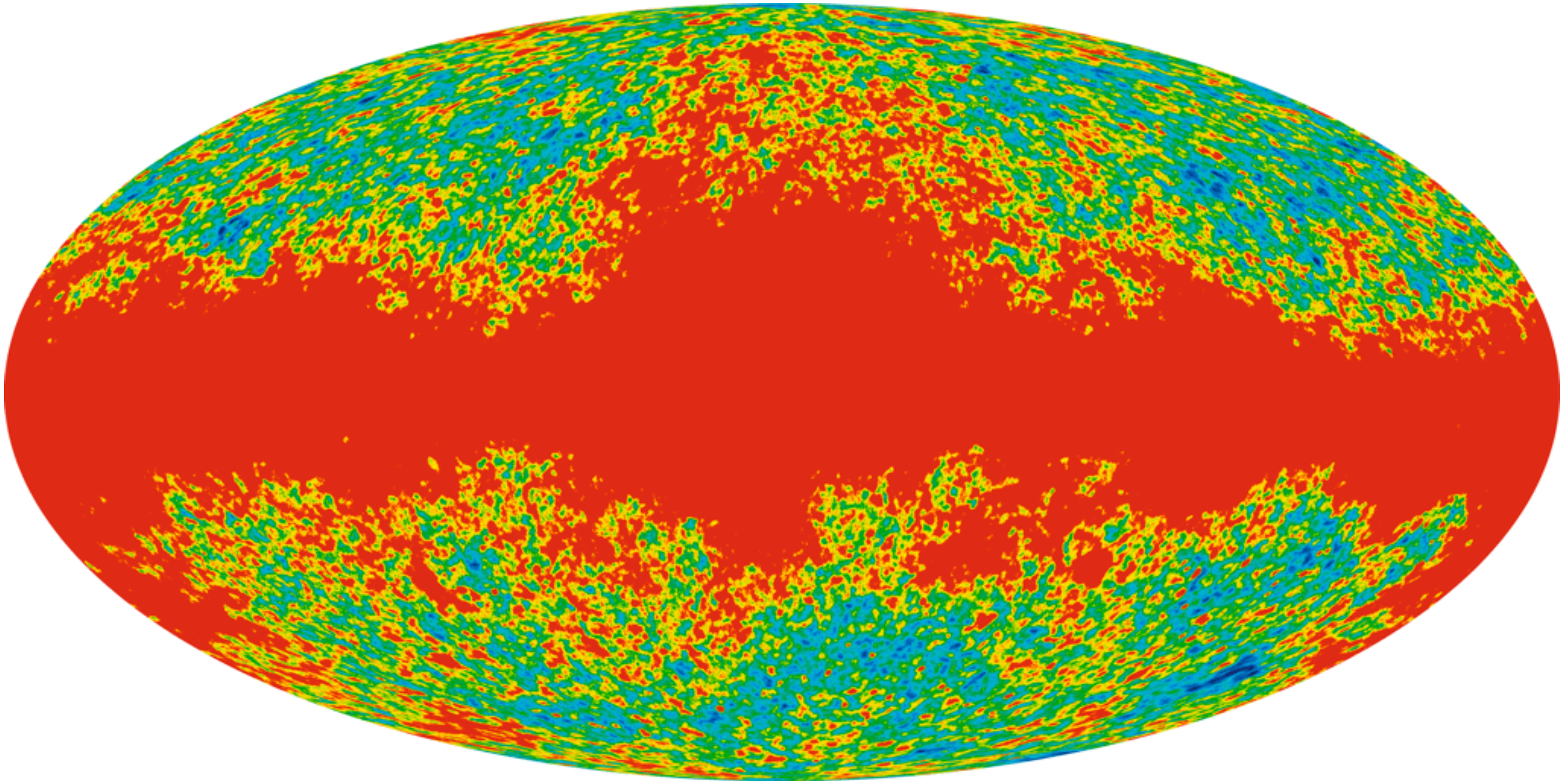


61 GHz

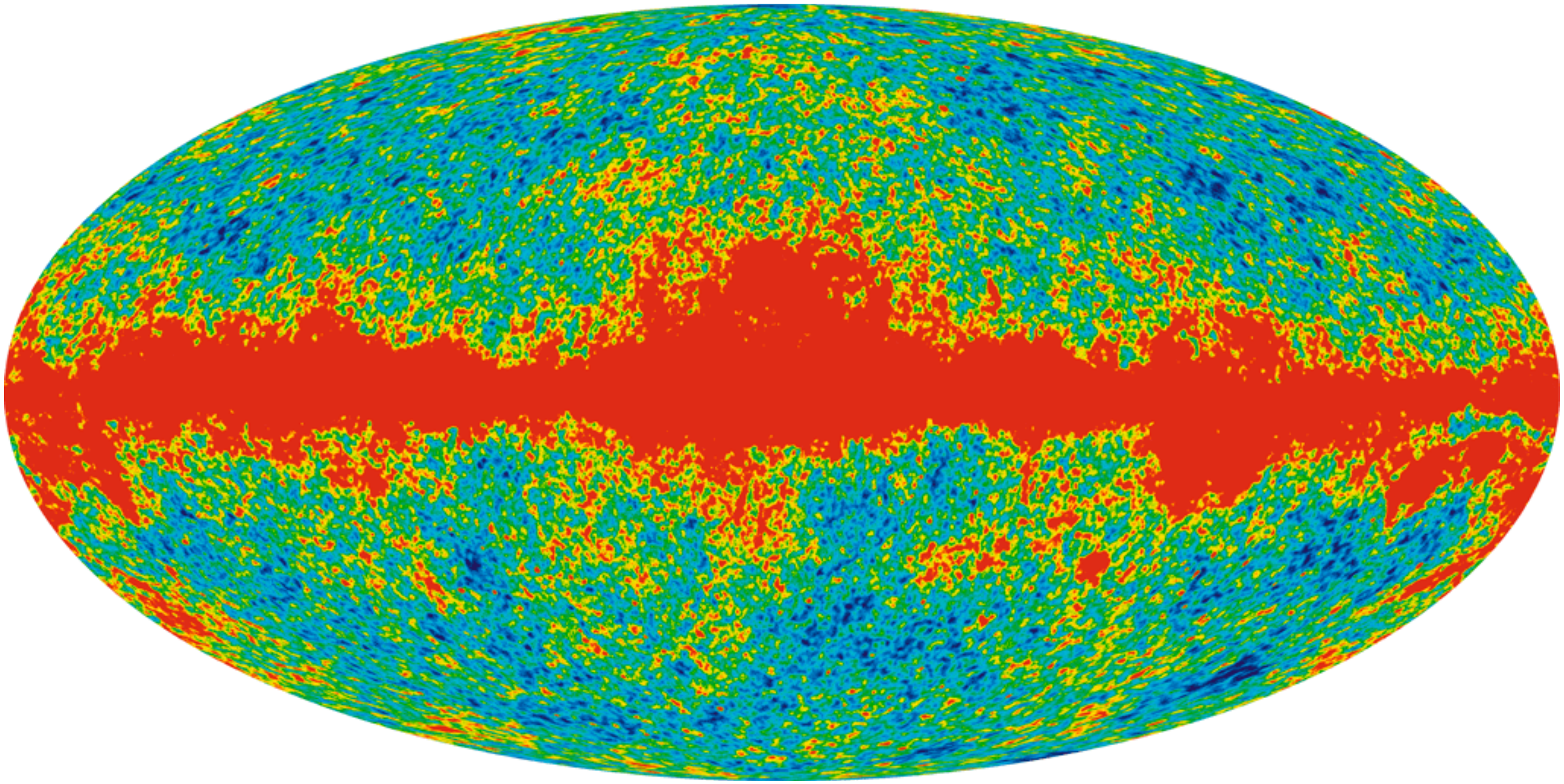


94 GHz

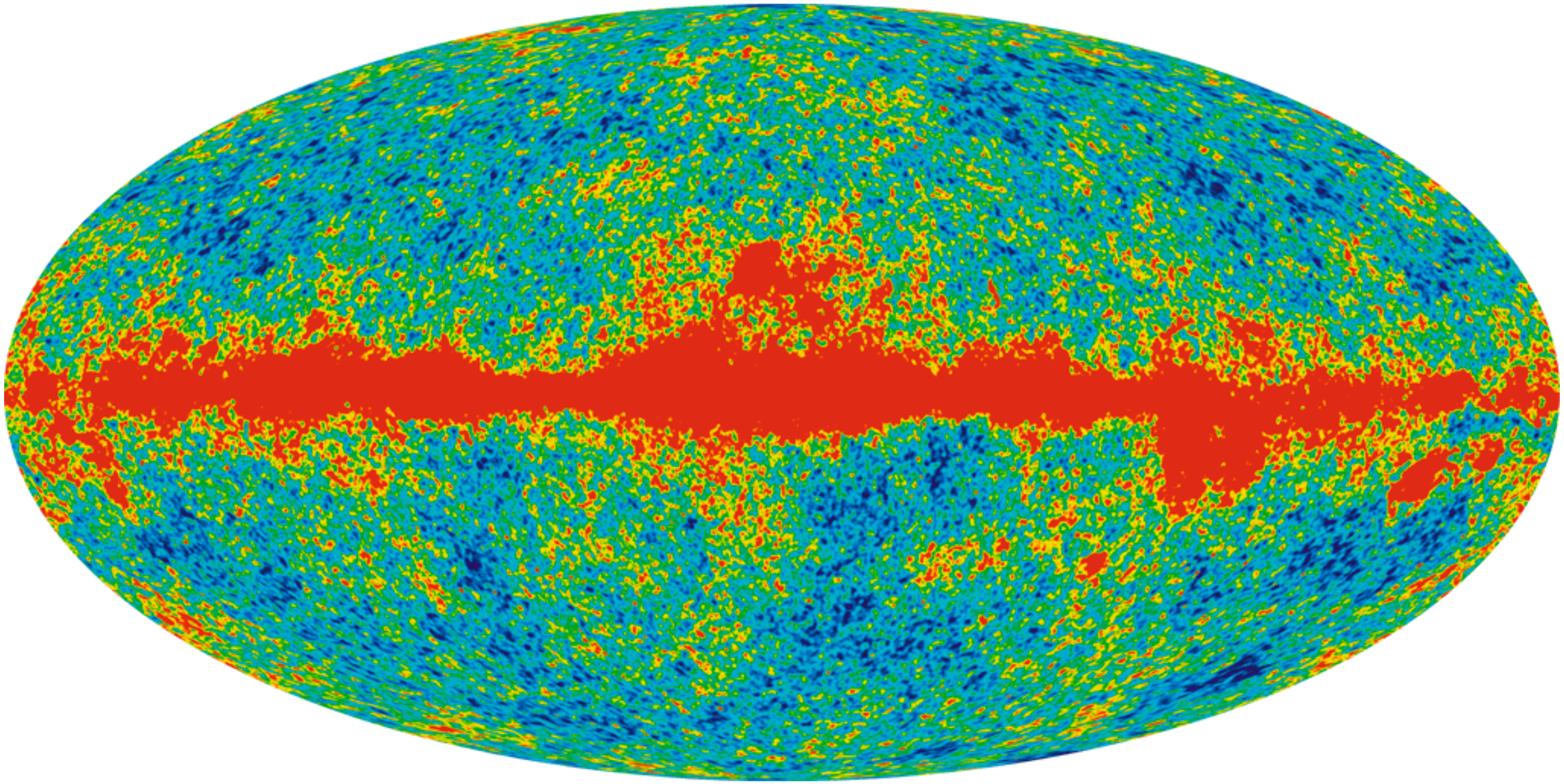
K Band Temperature, 23 GHz



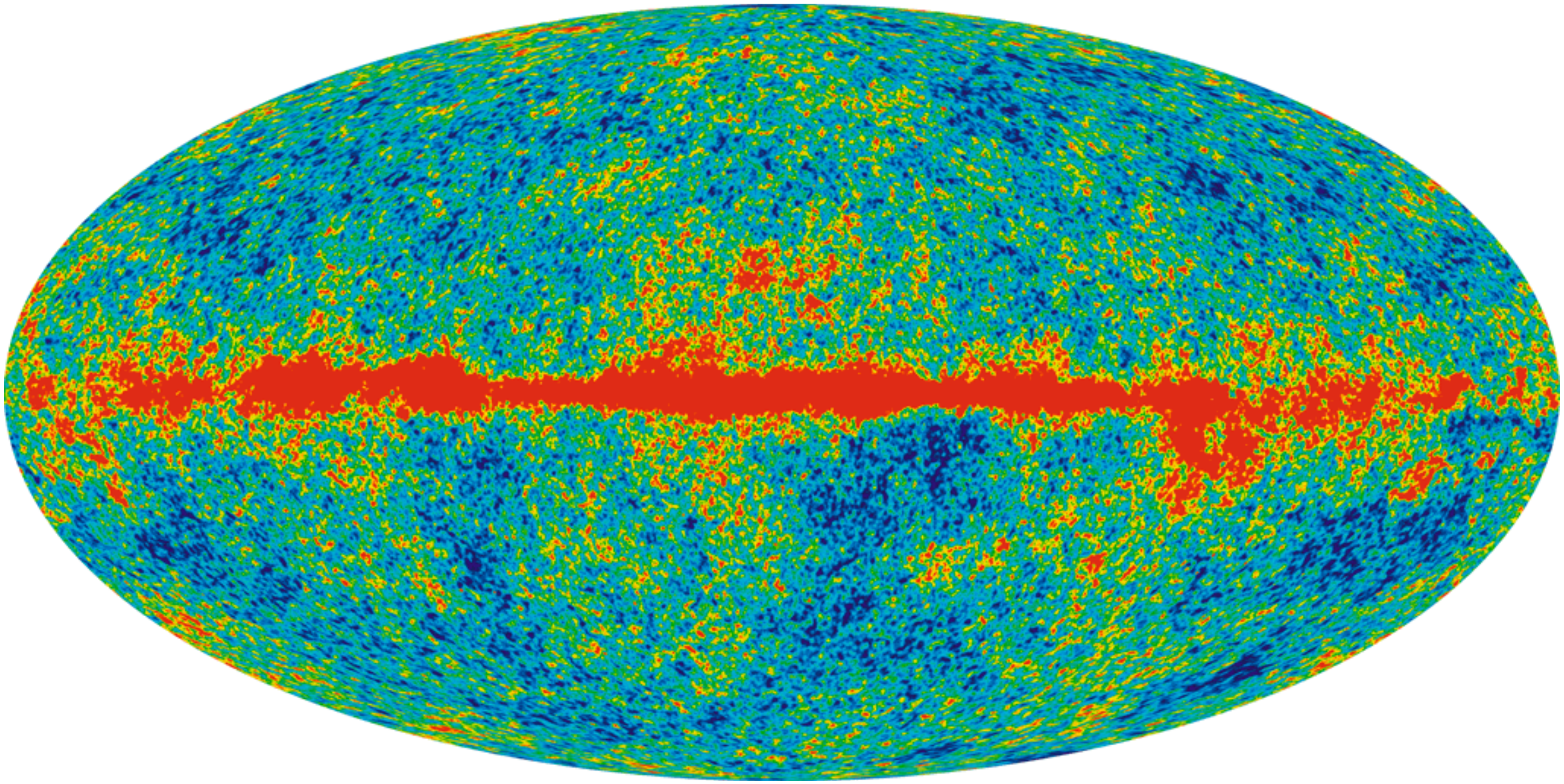
Ka Band Temperature, 33 GHz



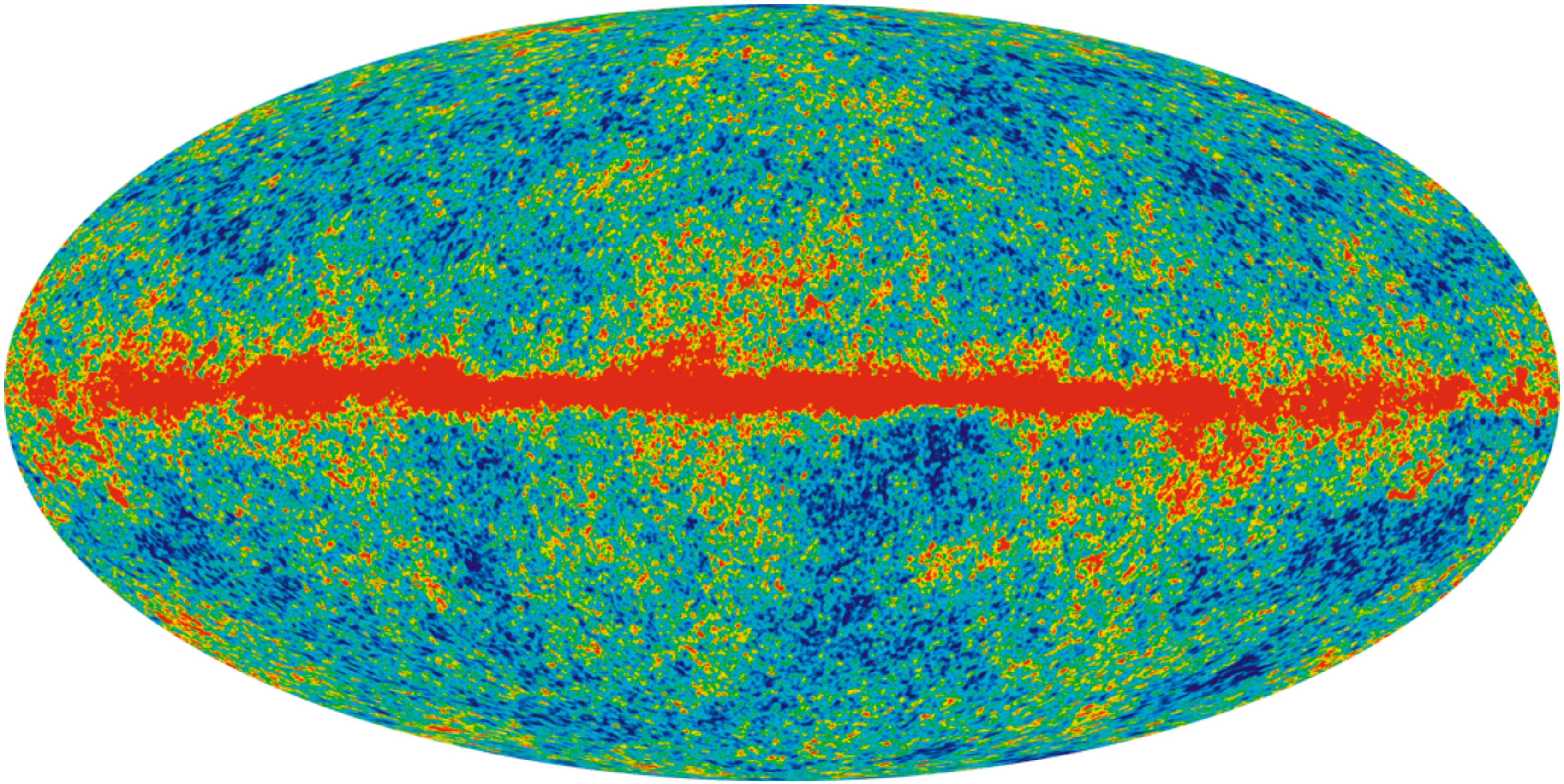
Q Band Temperature, 41 GHz



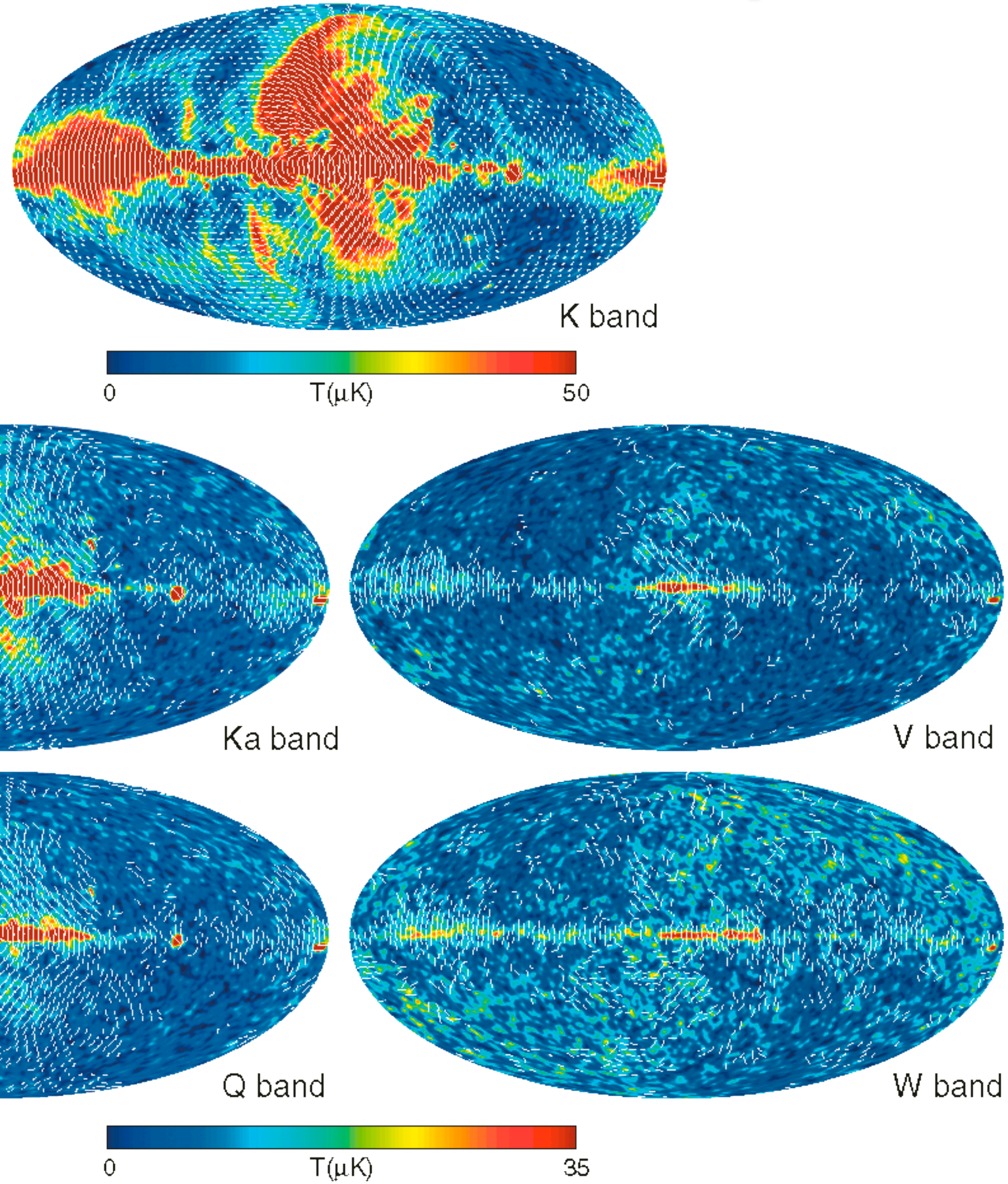
V Band Temperature, 61 GHz



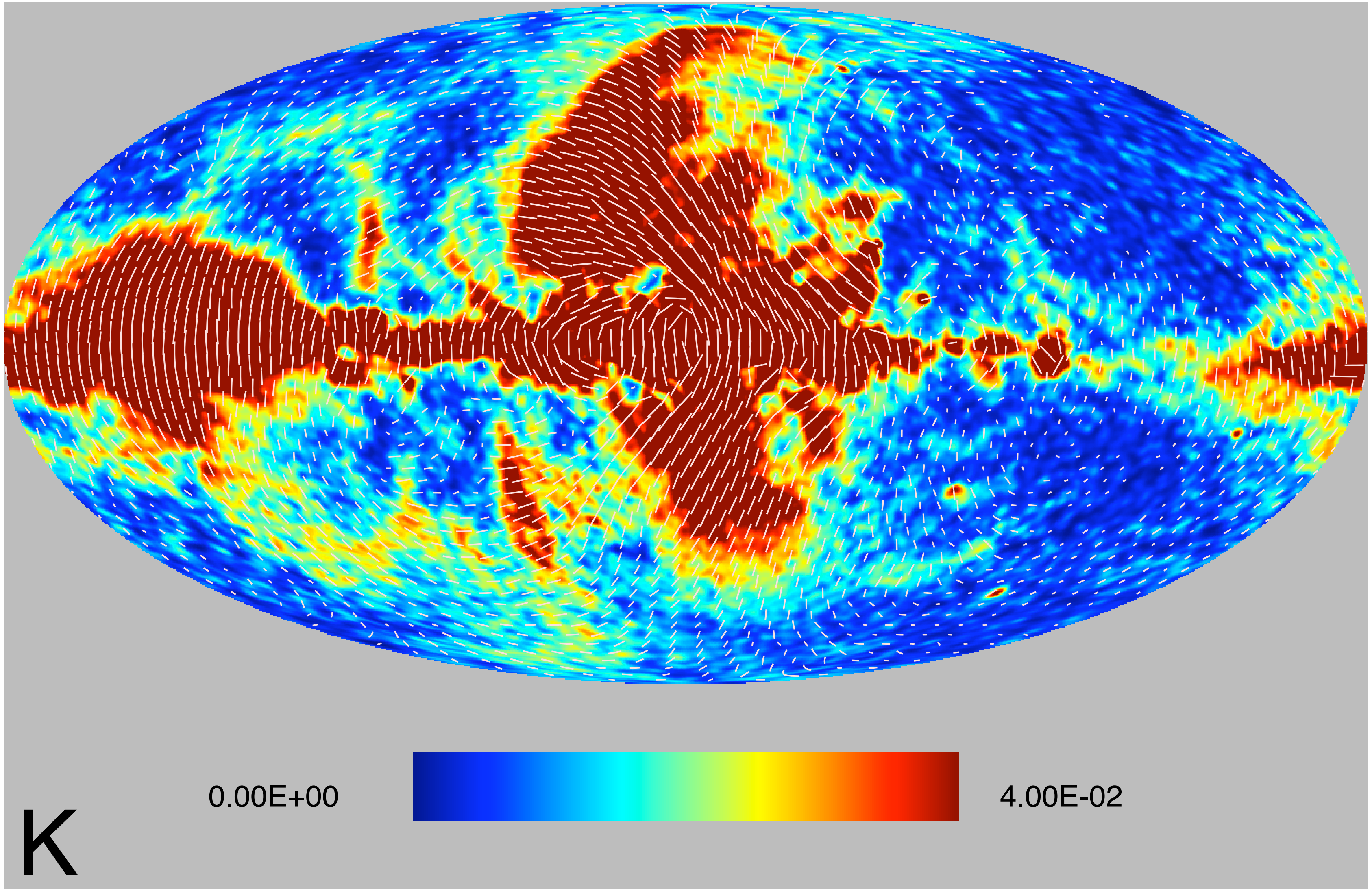
W Band Temperature, 94 GHz



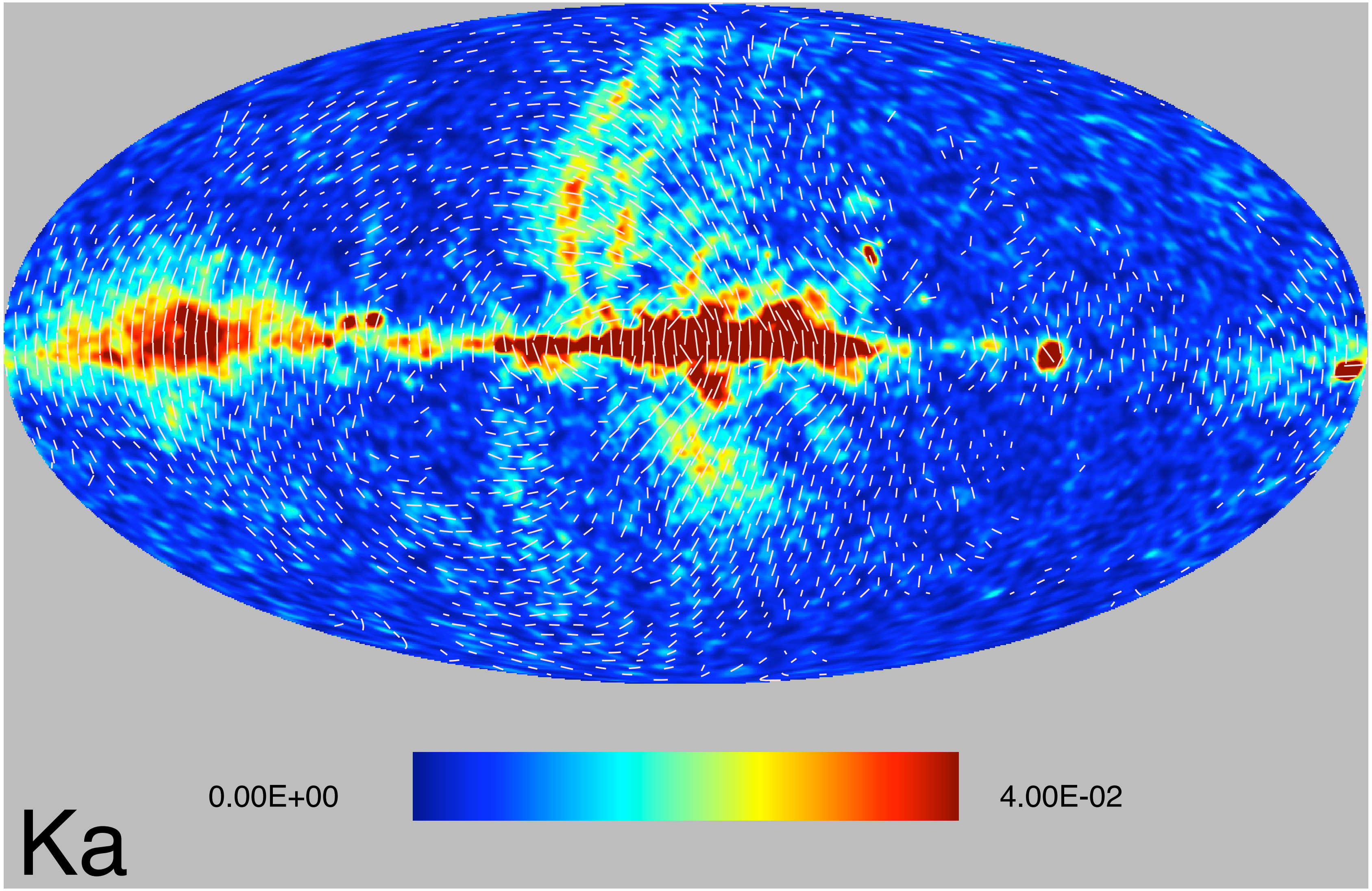
7-year Polarization Maps



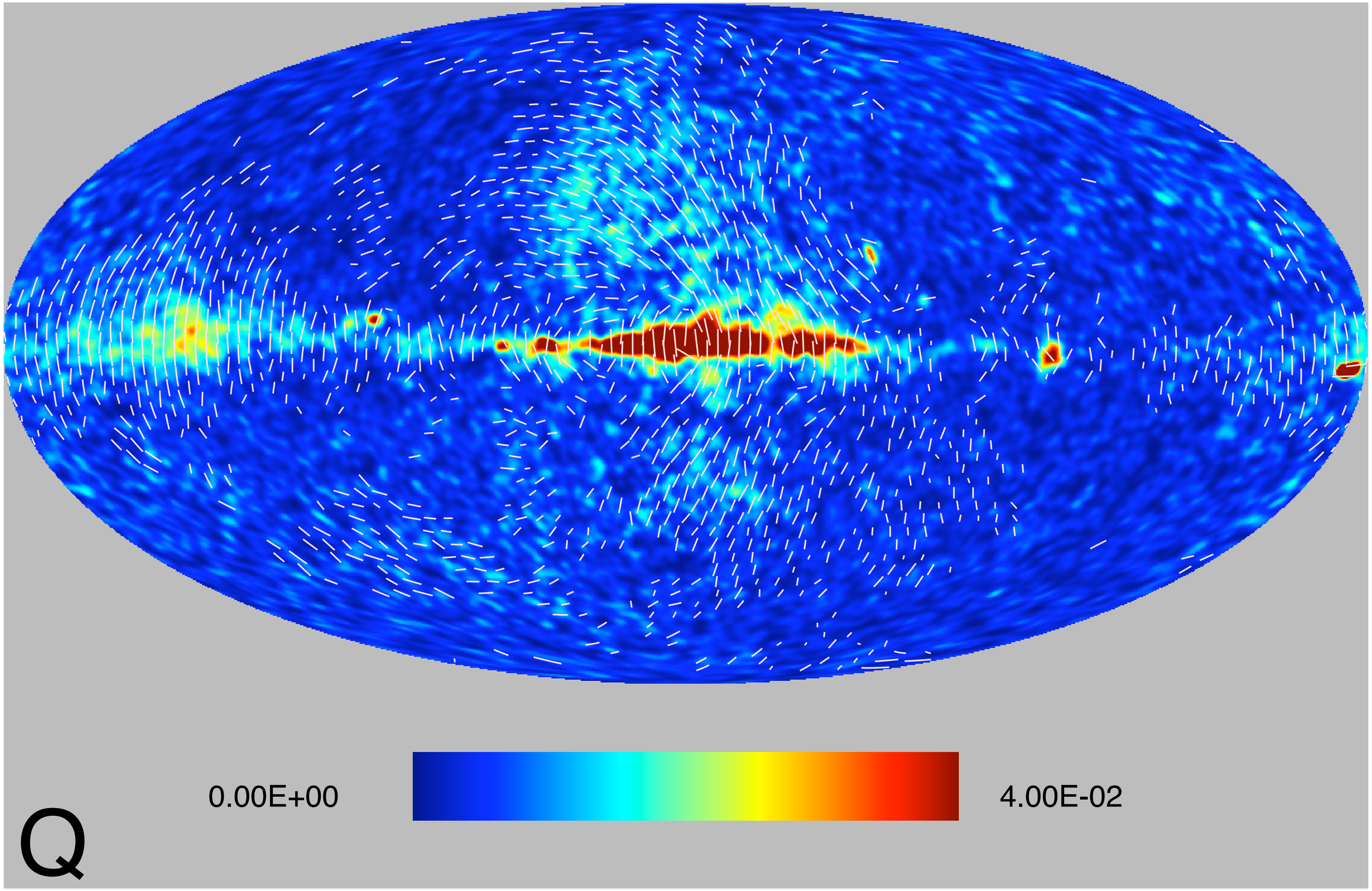
K Band Polarization, 23 GHz



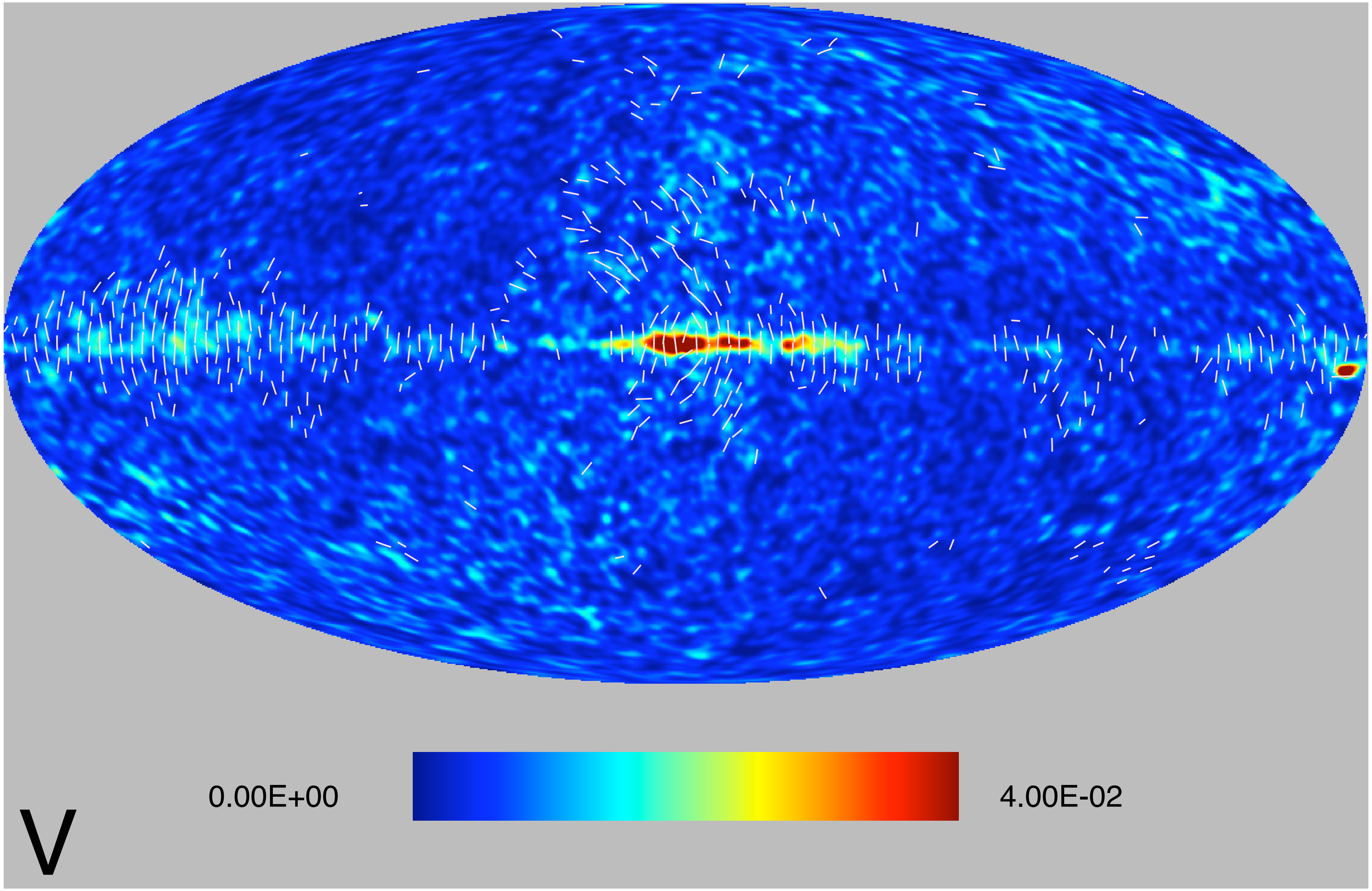
Ka Band Polarization, 33 GHz



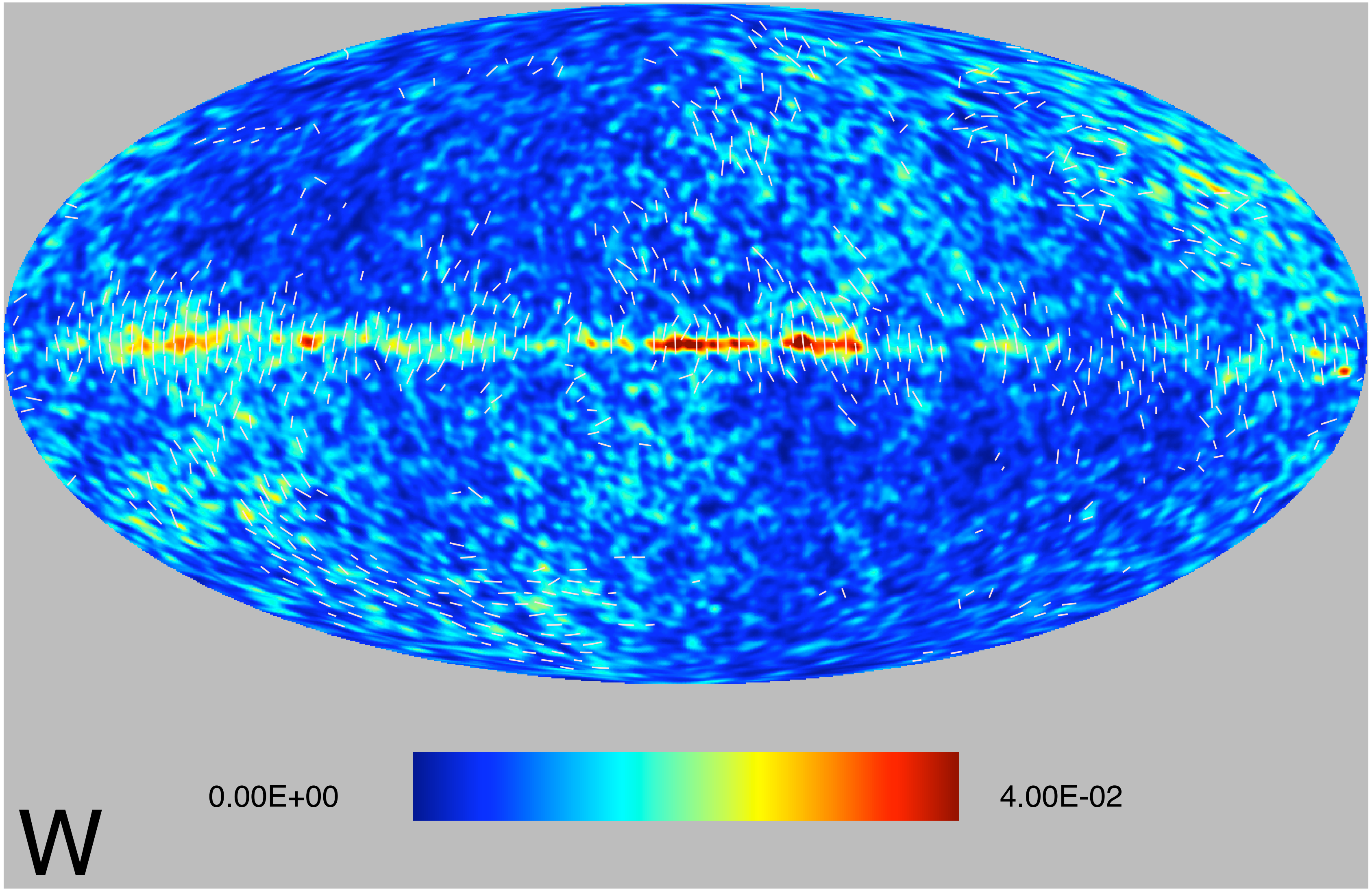
Q Band Polarization, 41 GHz



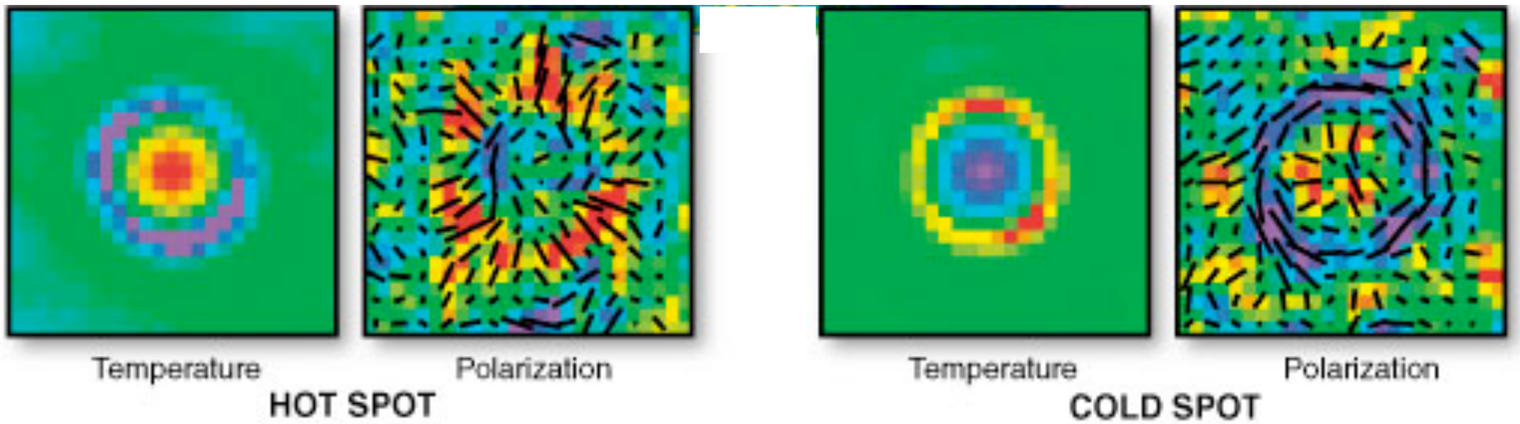
V Band Polarization, 61 GHz



W Band Polarization, 94 GHz



Acoustic Oscillations in T & E



Temperature – the imprint of BAO is visible in the co-added degree-scale hot (left) & cold (right) spots.

Polarization – The expected radial/tangential polarization pattern around these extrema is now clearly seen in the 7-year WMAP data.

This pattern is also imprinted on the baryon gas (baryon acoustic oscillations or BAO) that evolves to form large scale structure.

I look forward to the corresponding plot from Planck!

WMAP Polarization Systematics of Note

A very incomplete survey of polarization systematic effects I will comment on:

- Bandpass mismatch and bandpass drift with time.
- Poorly measured modes
- Other - “anomaly” in l=7 EE @ W band

Bandpass Mismatch

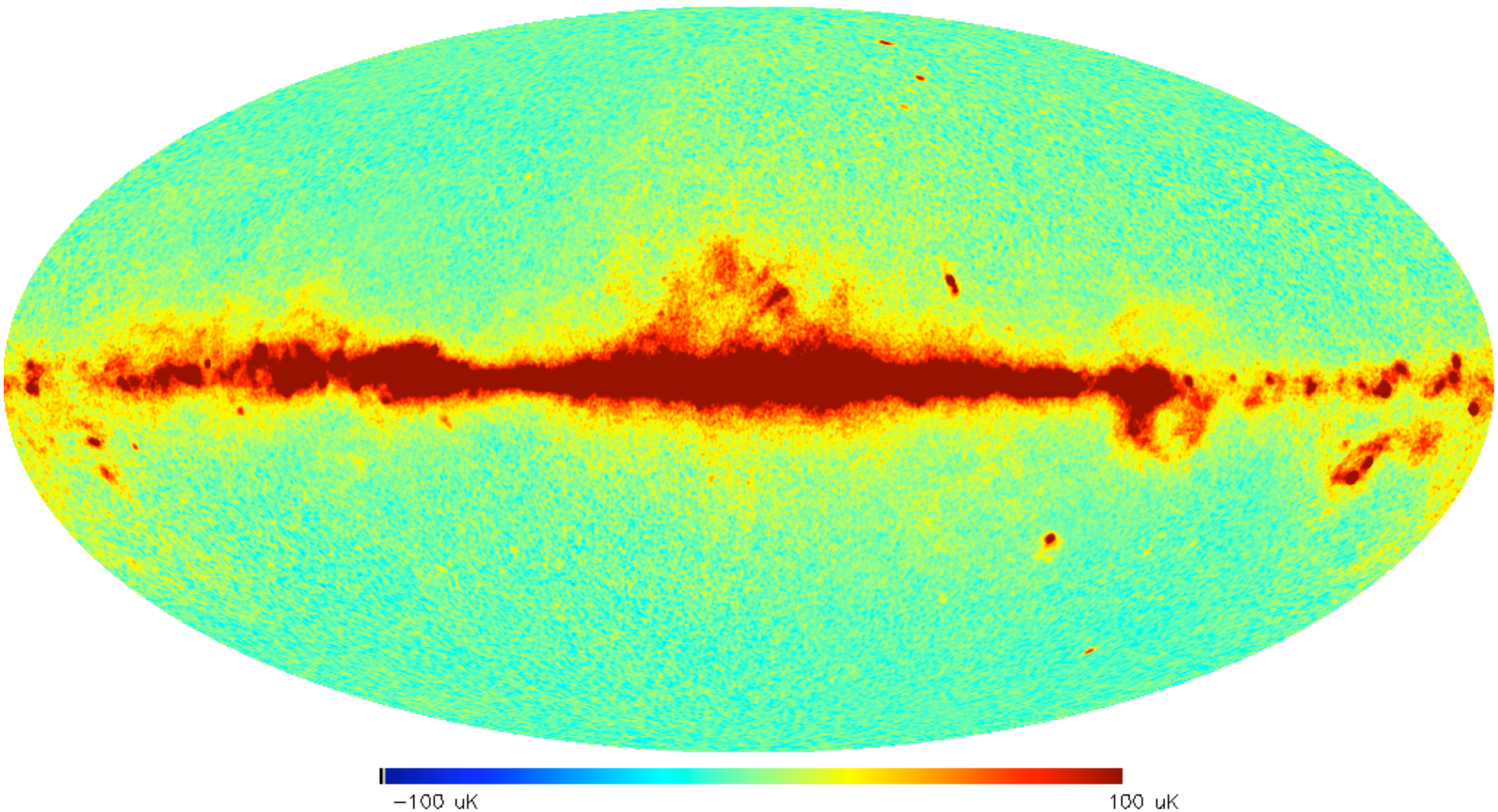
• The two linearly-polarized radiometers that comprise a differencing assembly, in general, have different frequency response. → Unpolarized signals that have a non-CMB-like spectrum (e.g. the Galaxy) will produce a non-zero response in the polarization channel.

• With ideal beams (only m=0 response), this signal does not modulate with polarization angle. We (WMAP) call this effect a "spurious" signal.

• The WMAP scan strategy produces a large-enough range of position angles per pixel that spurious signals can be separated from polarized signals based on the response vs. polarization angle.

• The map-making procedure solves for 4 "Stokes" parameters: I, Q, U, S. The spurious map looks like a scaled version of the foreground map, with a scaling that depends on bandpass difference and source spectrum.

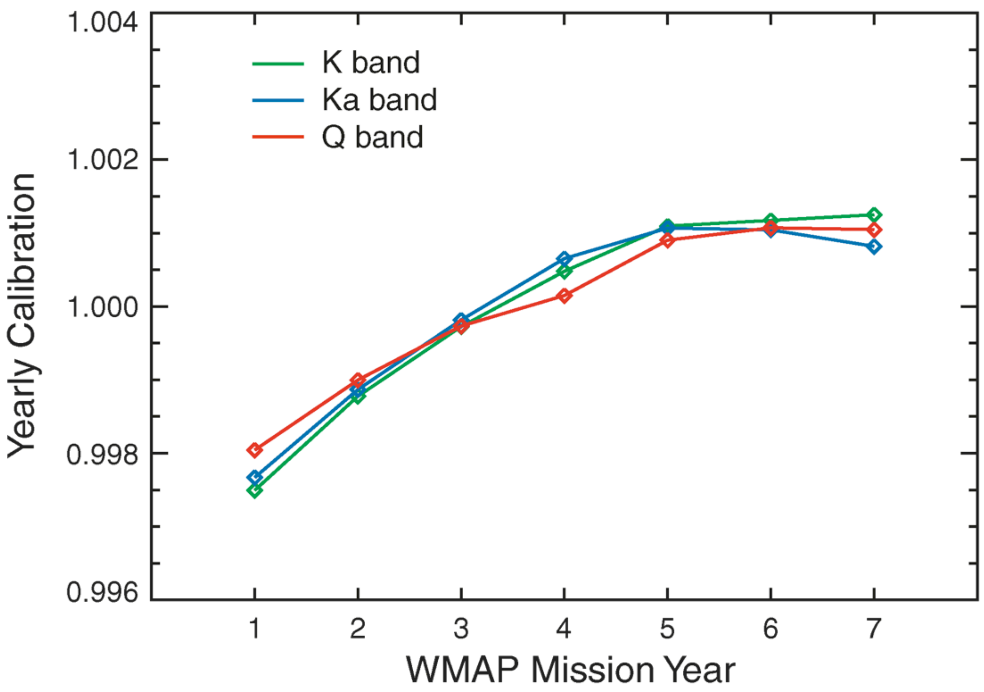
“Spurious” Map – K Band Polarization Data



Notes - If calibration is correct, this map contains only foreground signals,
- K band S map is ~3× brighter than next brightest S map.

Bandpass Drift

Galactic plane brightness vs. time



- WMAP's primary calibration source is the annual modulation of the CMB dipole induced by the Earth's (well-known) motion around the Sun.

- Single-year maps are produced using this calibration.

- The 3.3 mK CMB dipole is stable with time in these maps.

Plot shows the relative brightness of the galactic plane vs. time in K, Ka, and Q band. The V and W band data show a negligible change. Two possible interpretations:

1) The average Galaxy signal is brightening with time. (Implausible!)
2) The frequency response is drifting downward with age. (Our interpretation.)

This could be a small effect for the LFI to consider.

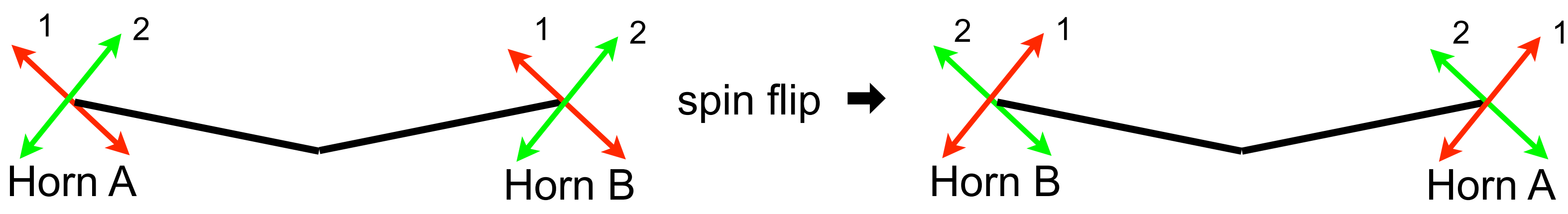
Poorly-Measured Modes

• WMAP polarization data is doubly differential: 1) signal is differenced between two beams, 2) signal is differenced between two linearly polarized radiometers.

• In a single radiometer, the instantaneous response is proportional to the signal difference in the two horns A,B (neglecting loss imbalance):

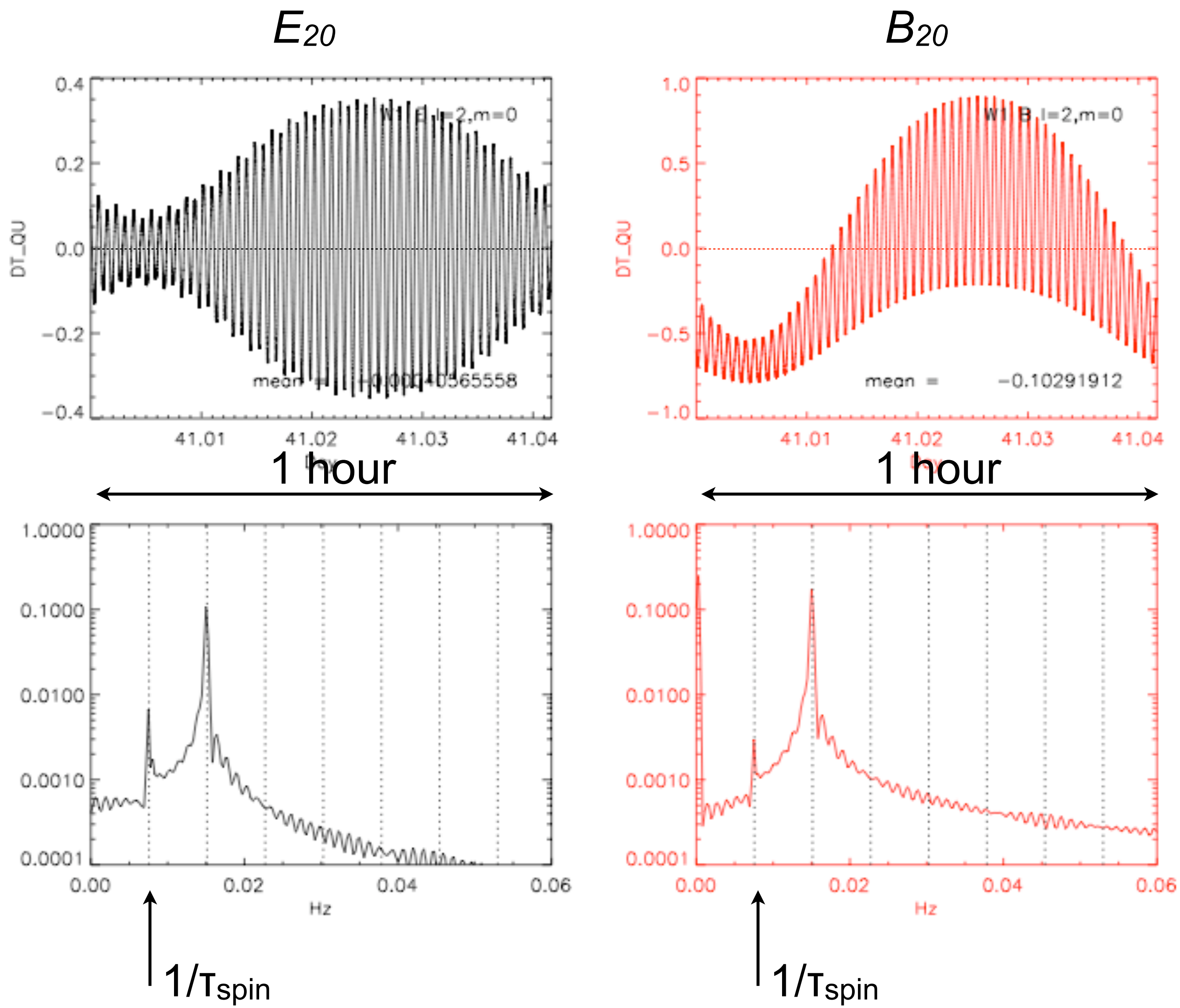
$$DT = I_A - I_B + Q_A \cos 2\alpha_A - Q_B \cos 2\alpha_B + U_A \sin 2\alpha_A - U_B \sin 2\alpha_B$$

• Upon spin flip, A↔B, the *I* term changes sign, but the *Q,U* terms do not, because the polarization directions in the A & B arms, are not invariant to a 180º rotation. (See below) As a result, the differential signal is only approximately spin-modulated, causing a small coupling between radiometer baseline (offset) and polarized signal.

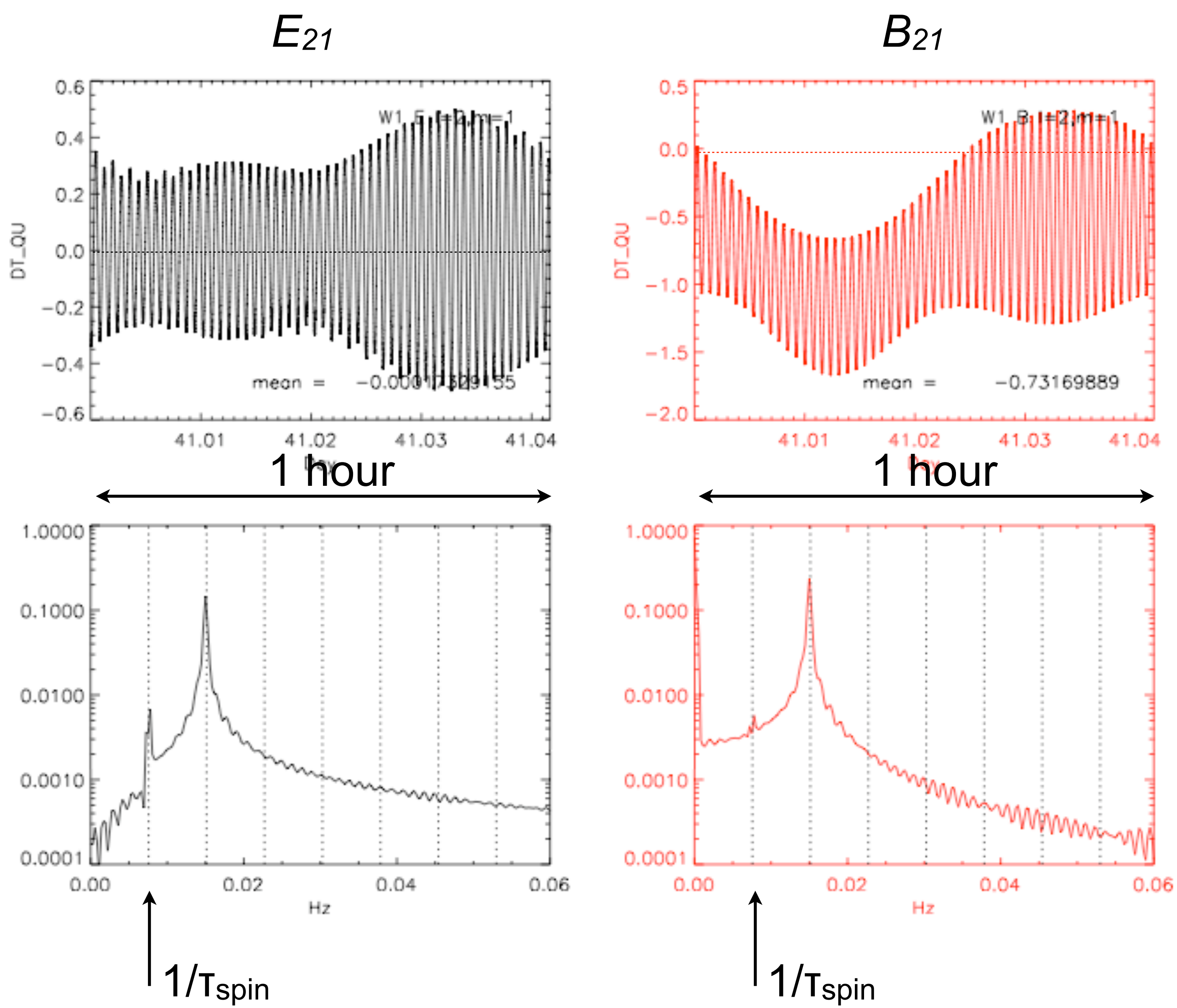


• We can evaluate the time-dependence of any given E,B_{lm} mode given the WMAP radiometer configuration and scan pattern.

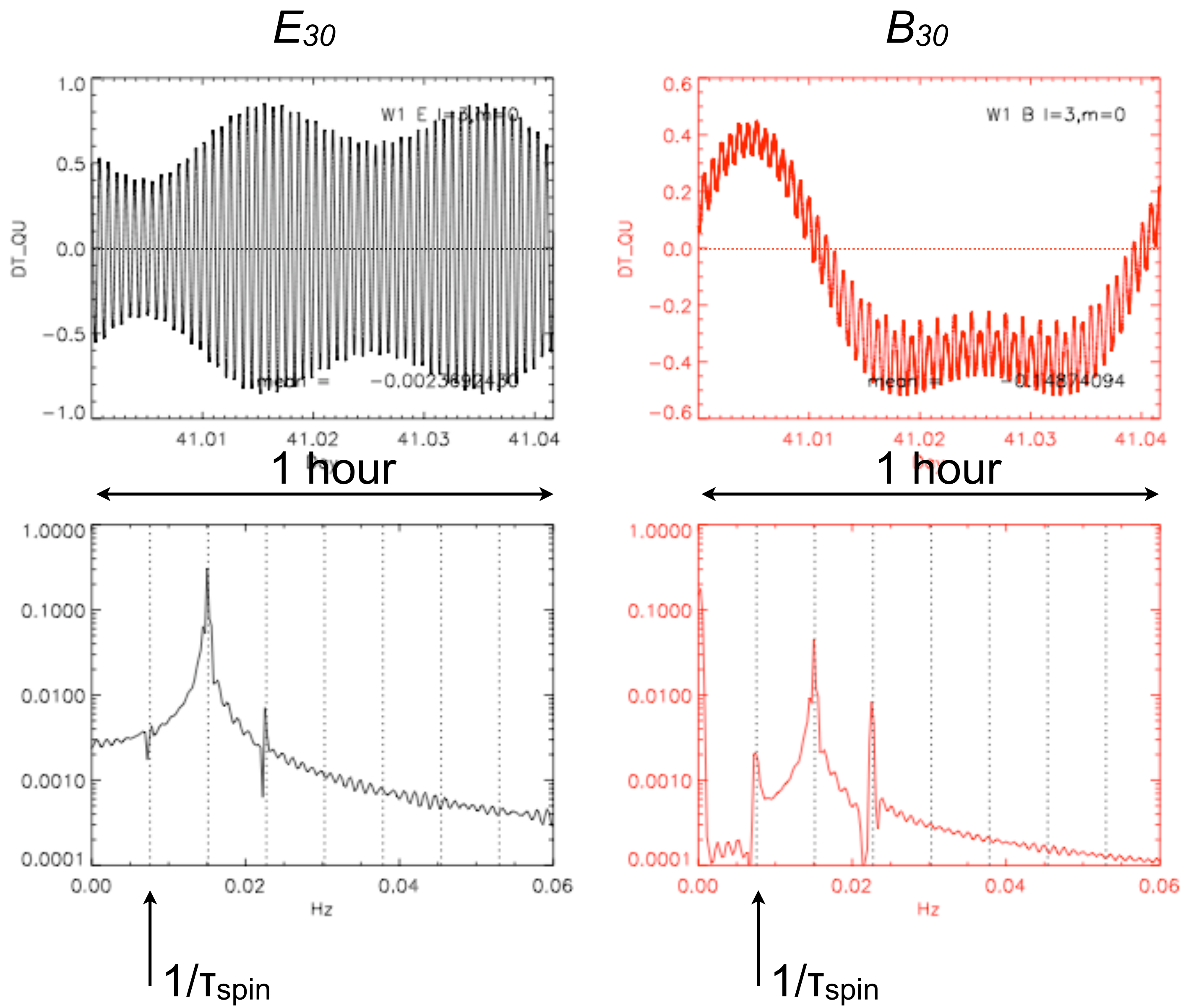
Polarization Modes in Time/Freq Domain



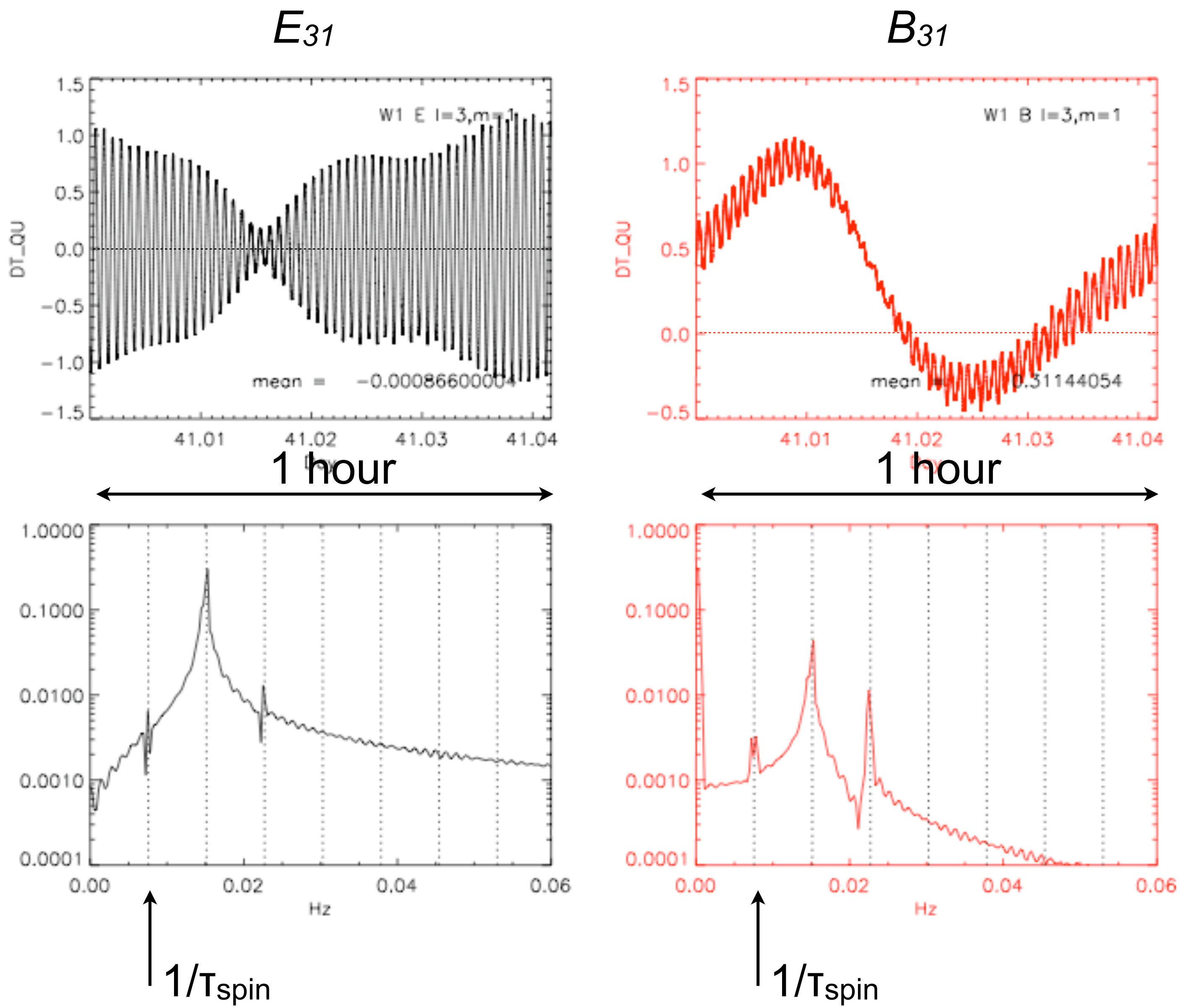
Polarization Modes in Time/Freq Domain



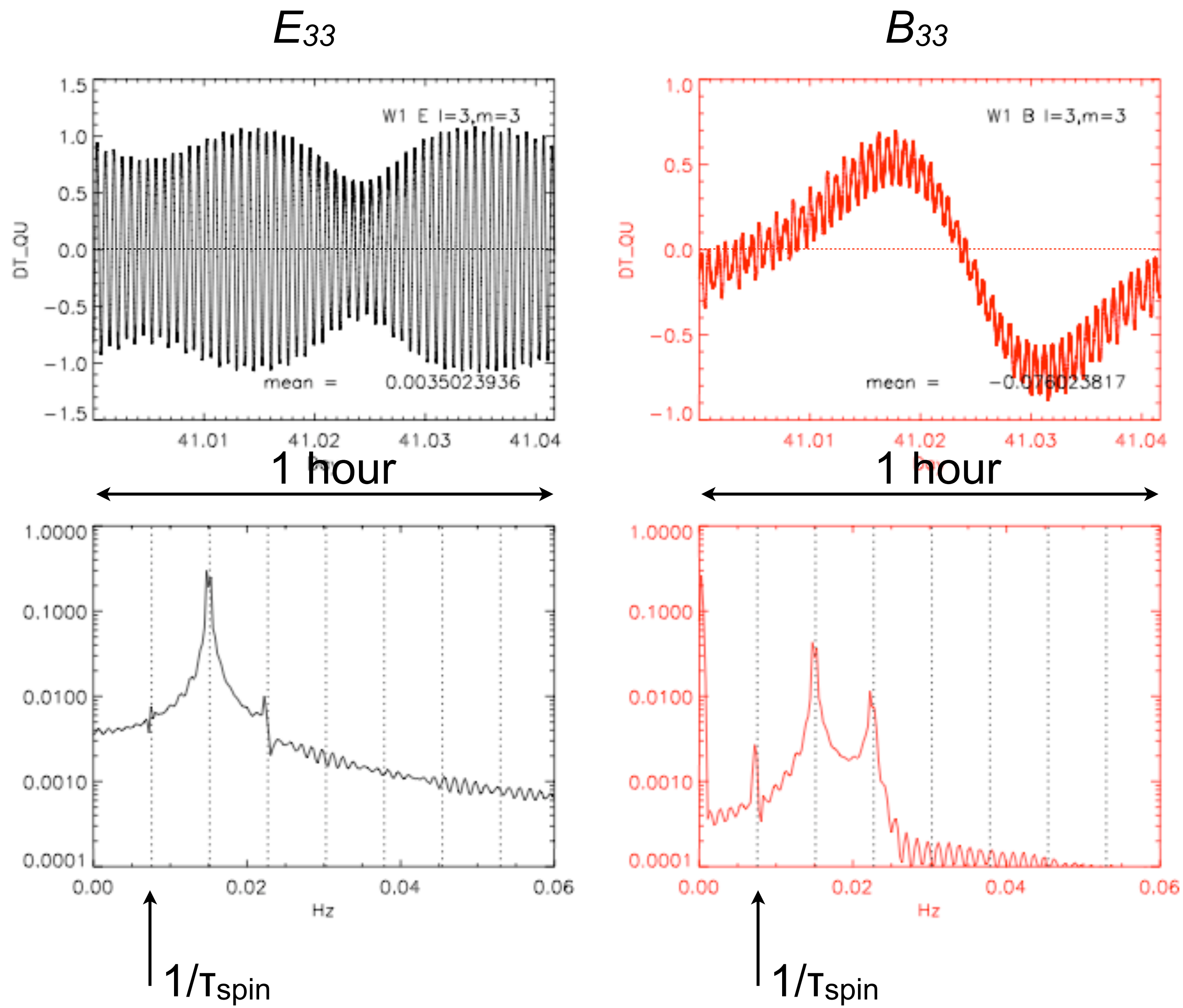
Polarization Modes in Time/Freq Domain



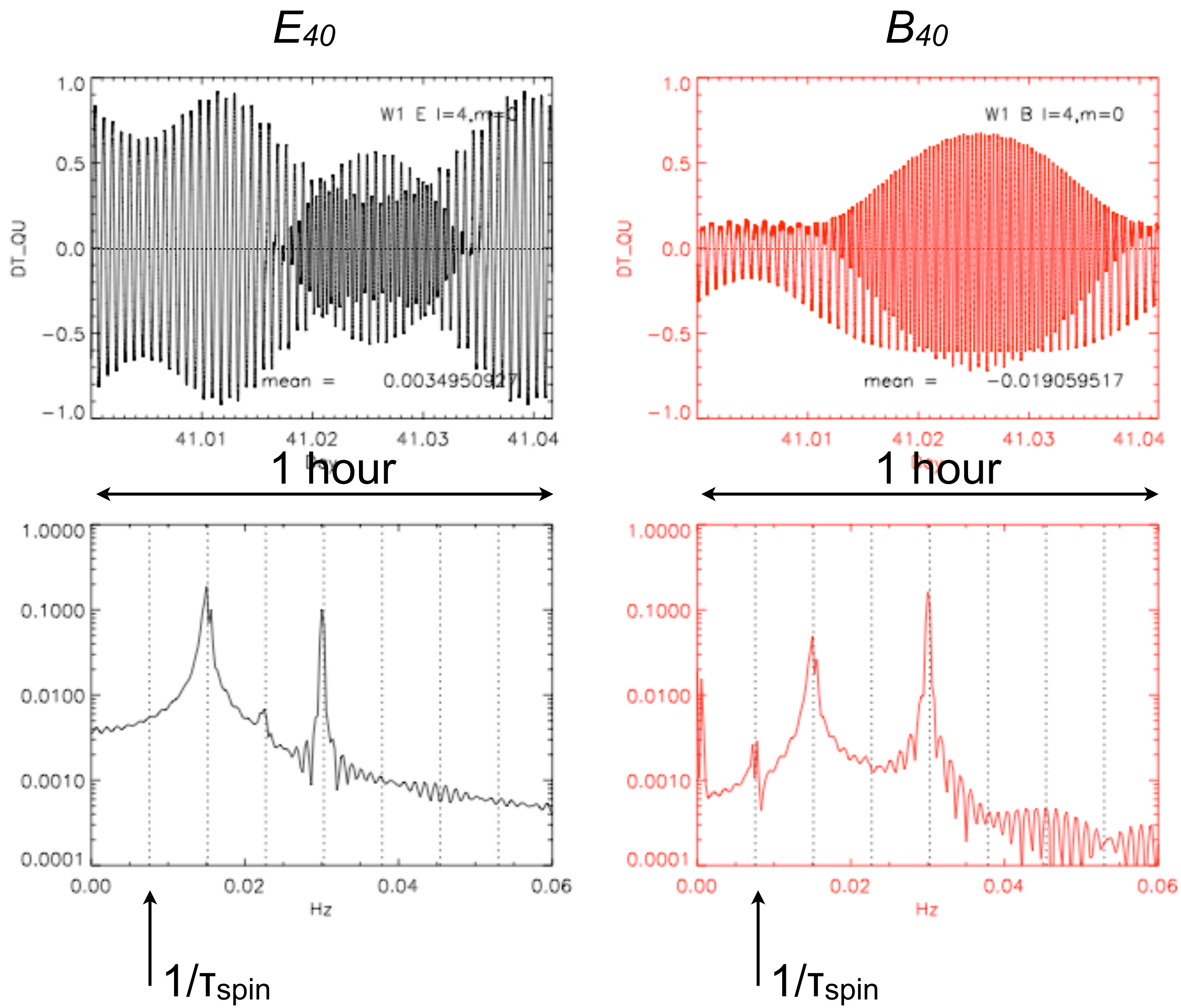
Polarization Modes in Time/Freq Domain



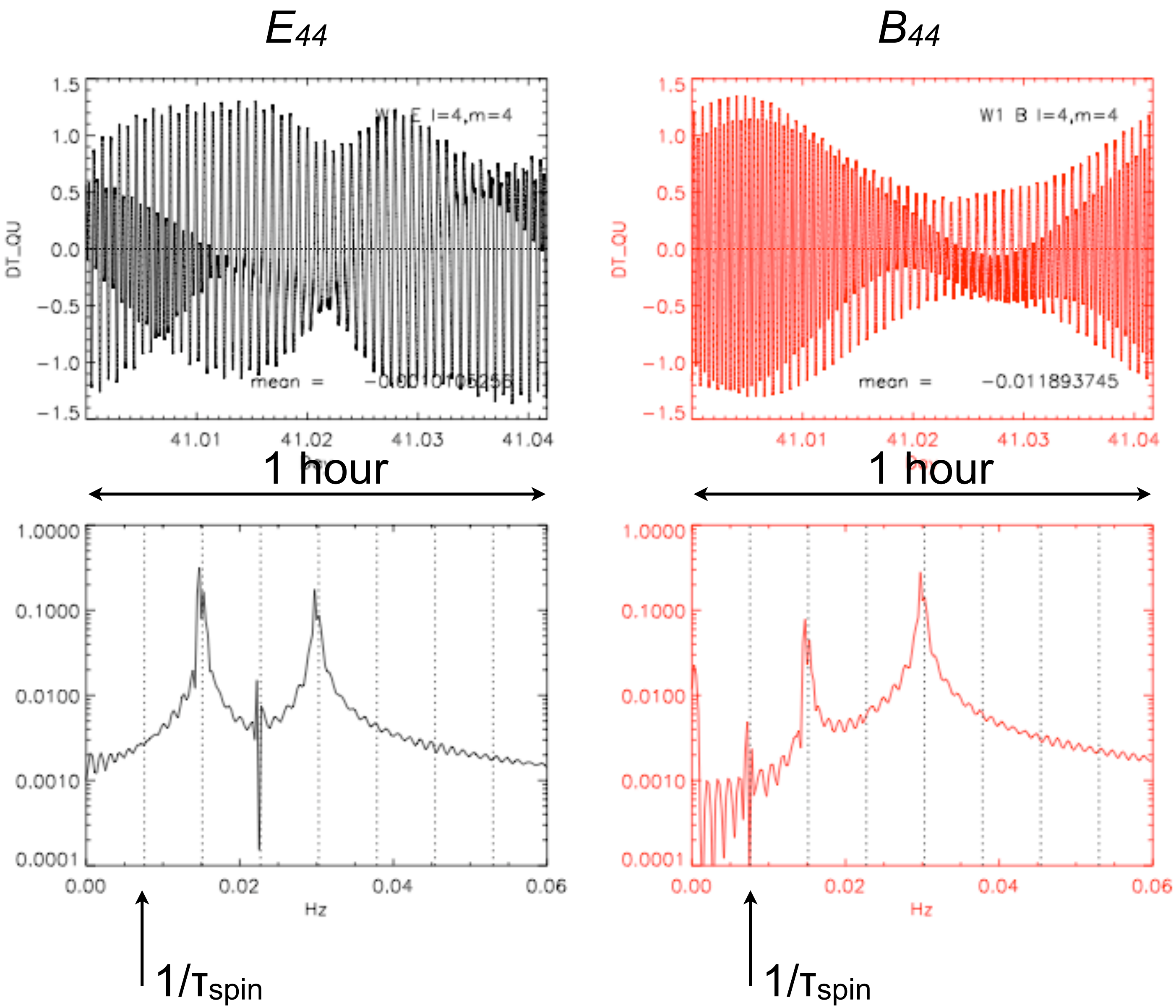
Polarization Modes in Time/Freq Domain



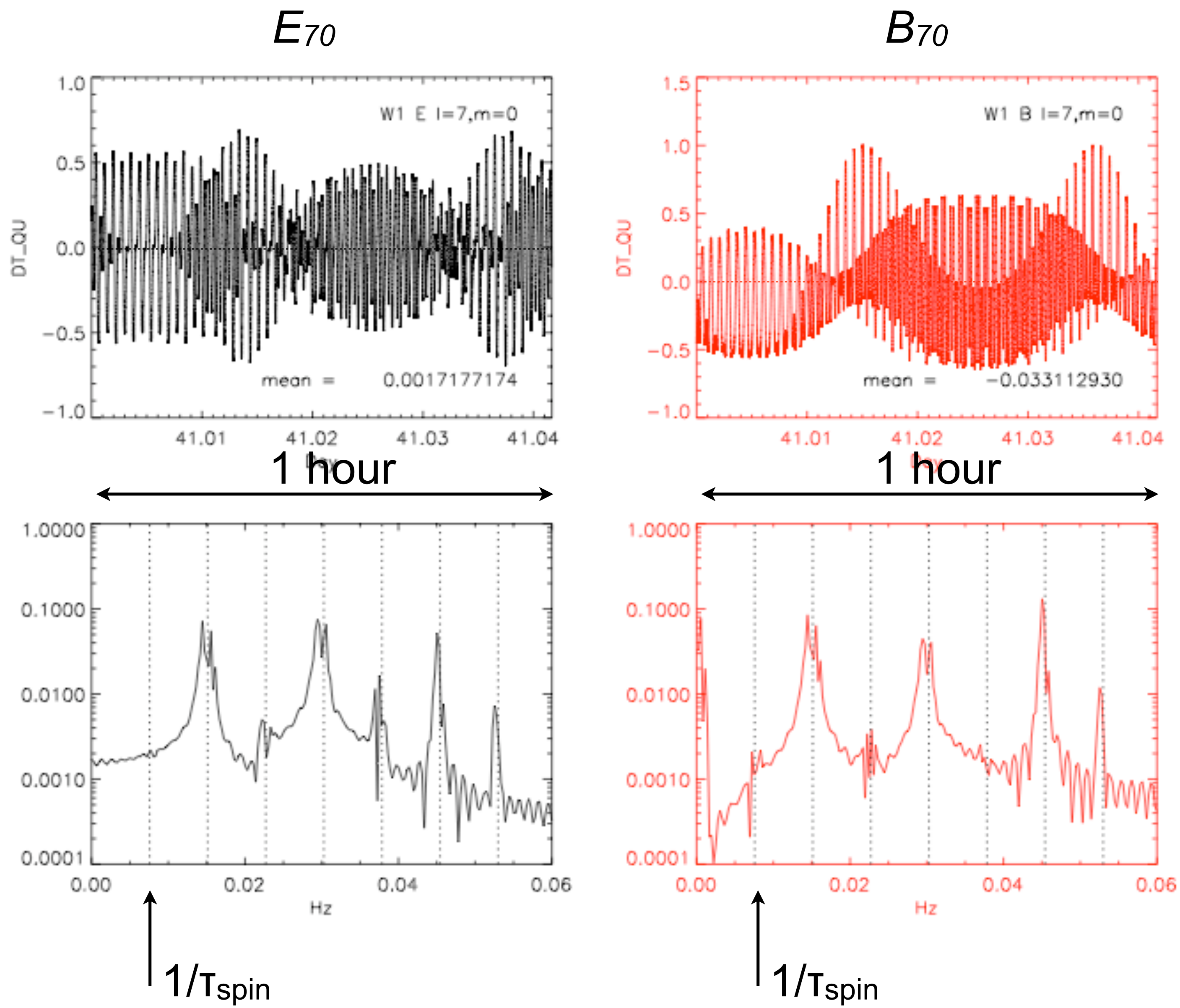
Polarization Modes in Time/Freq Domain



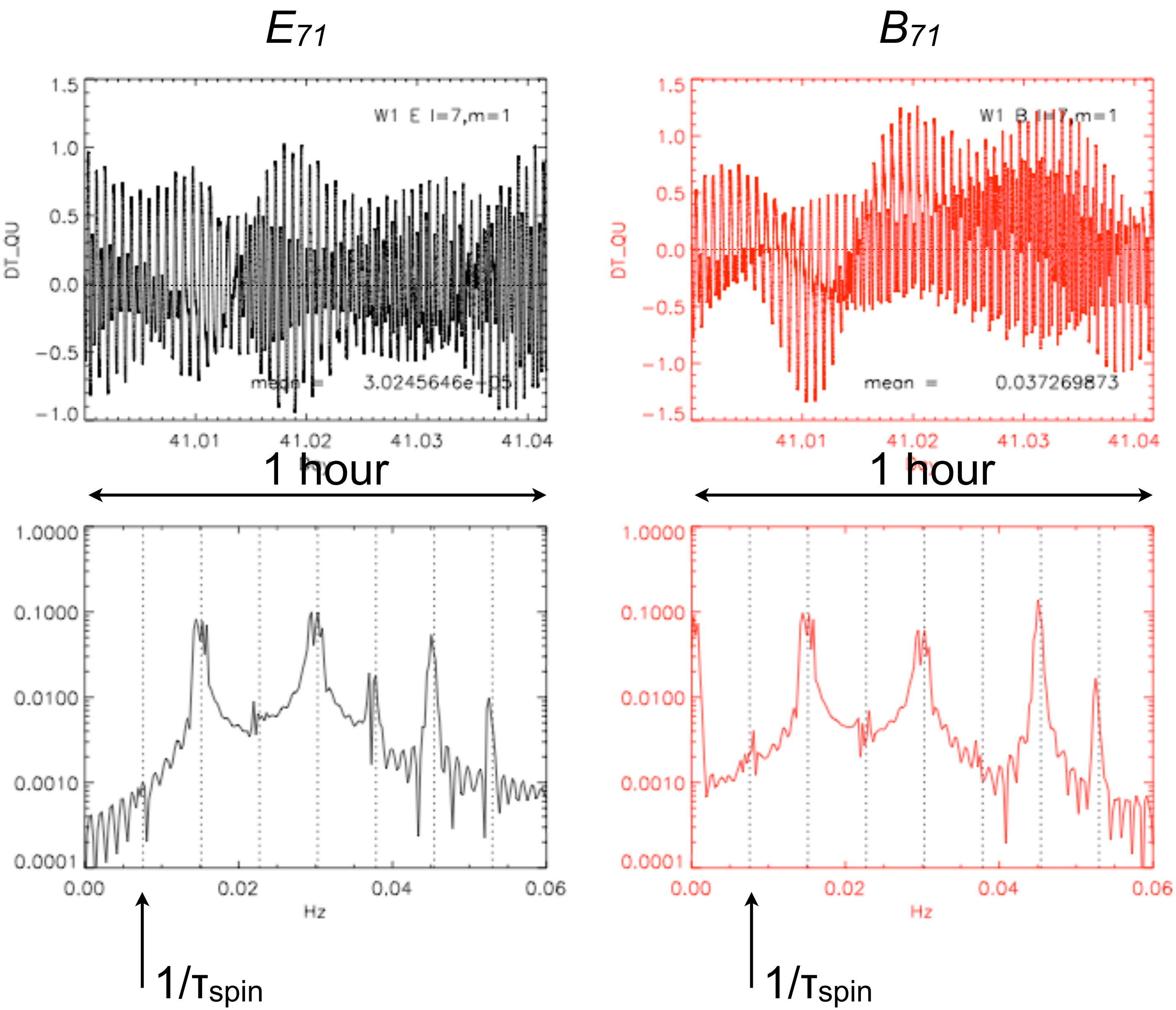
Polarization Modes in Time/Freq Domain



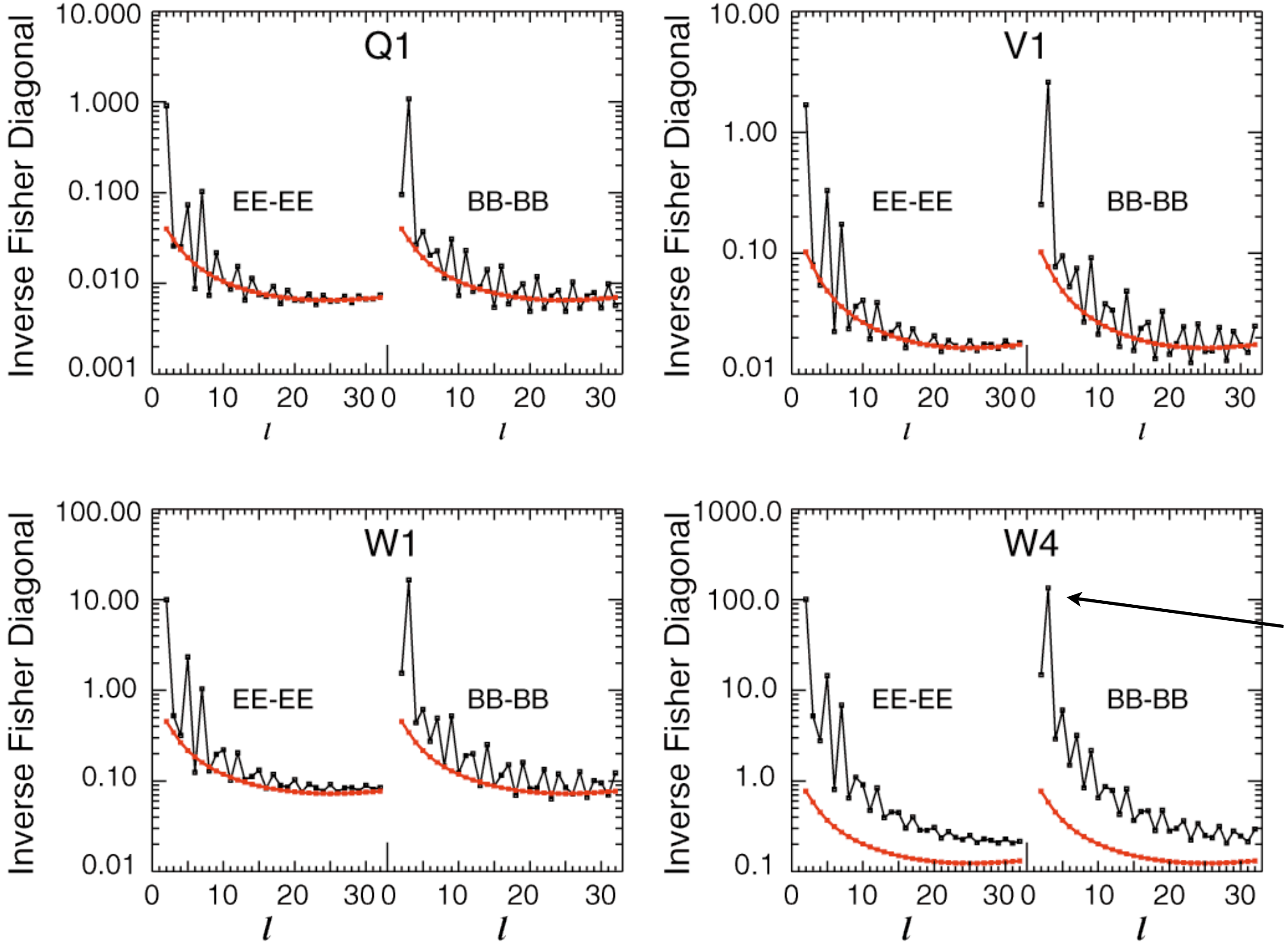
Polarization Modes in Time/Freq Domain



Polarization Modes in Time/Freq Domain



Full EE,BB Errors vs. “Naive” Estimate



Black-

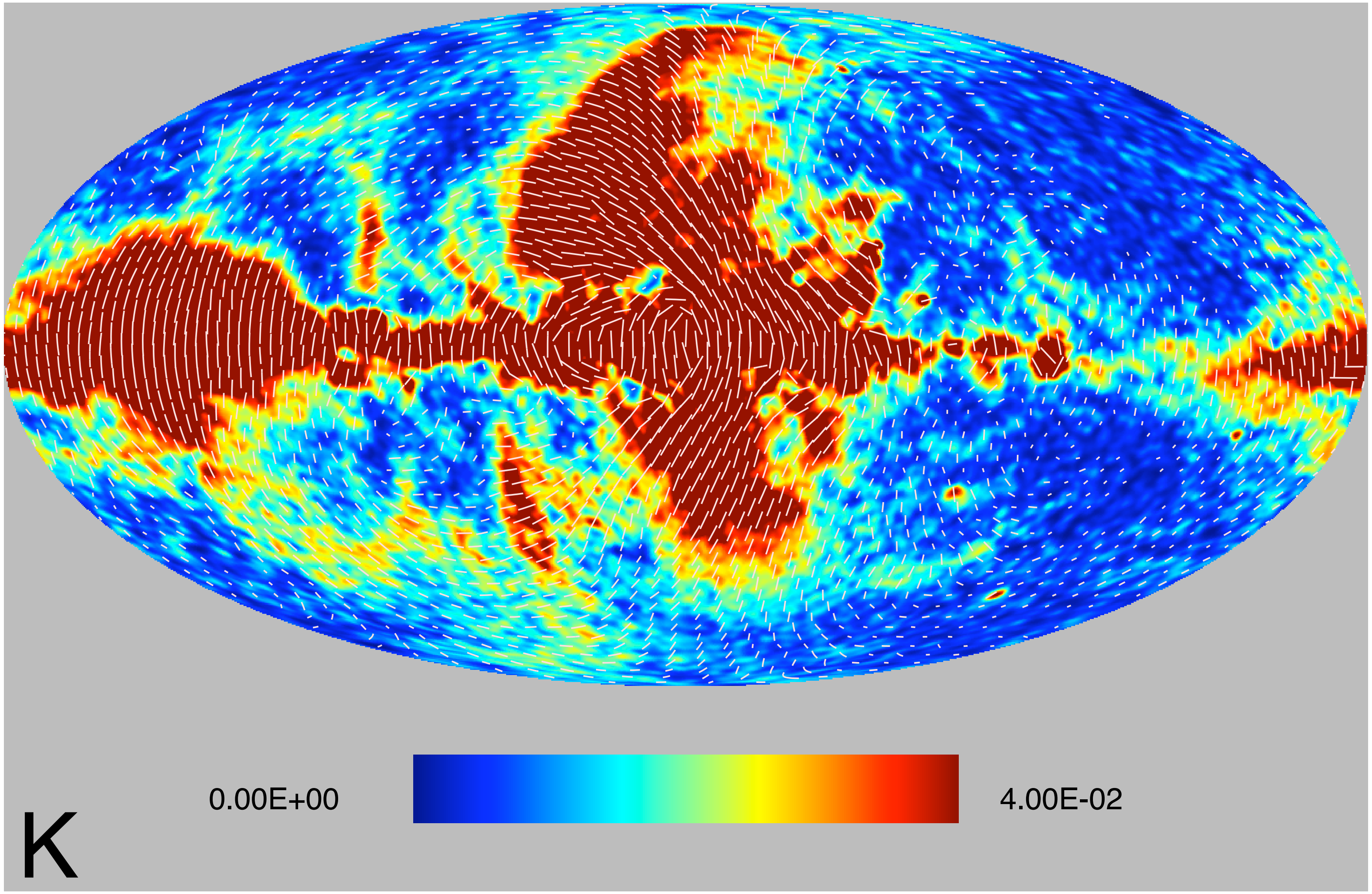
Full propagation of pixel-pixel covariance matrix through to power spectrum errors.

Red -

Naive power spectrum errors assuming only diagonal noise in pixel space.

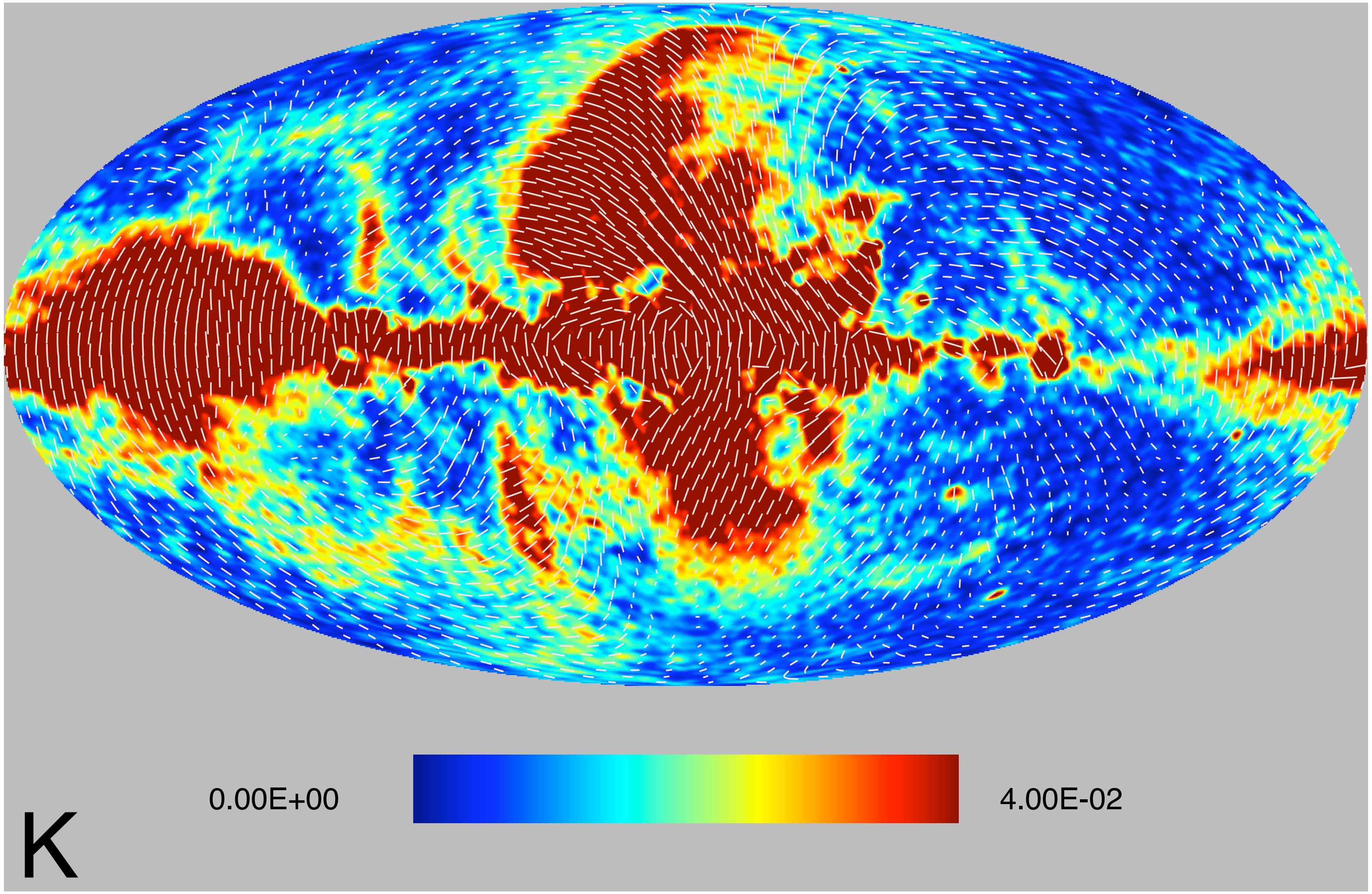
Note factor of ~10 inflation of *the l*=3 BB variance.

K Band Polarization – Case I*



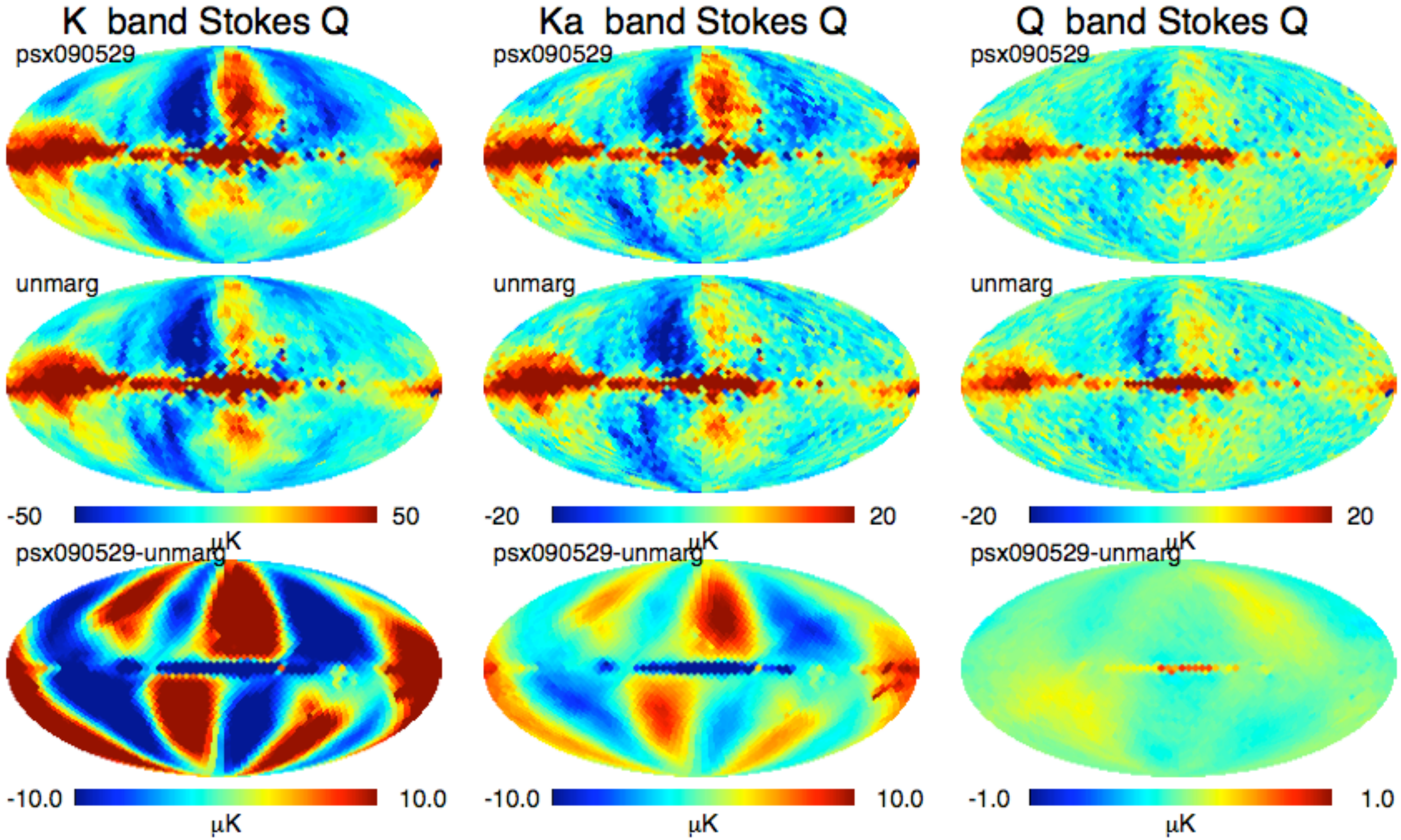
*7-year maps co-added w/o marginalization over loss imbalance uncertainty.
Loss imbalance uncertainty is nominally a small effect.

K Band Polarization – Case II*



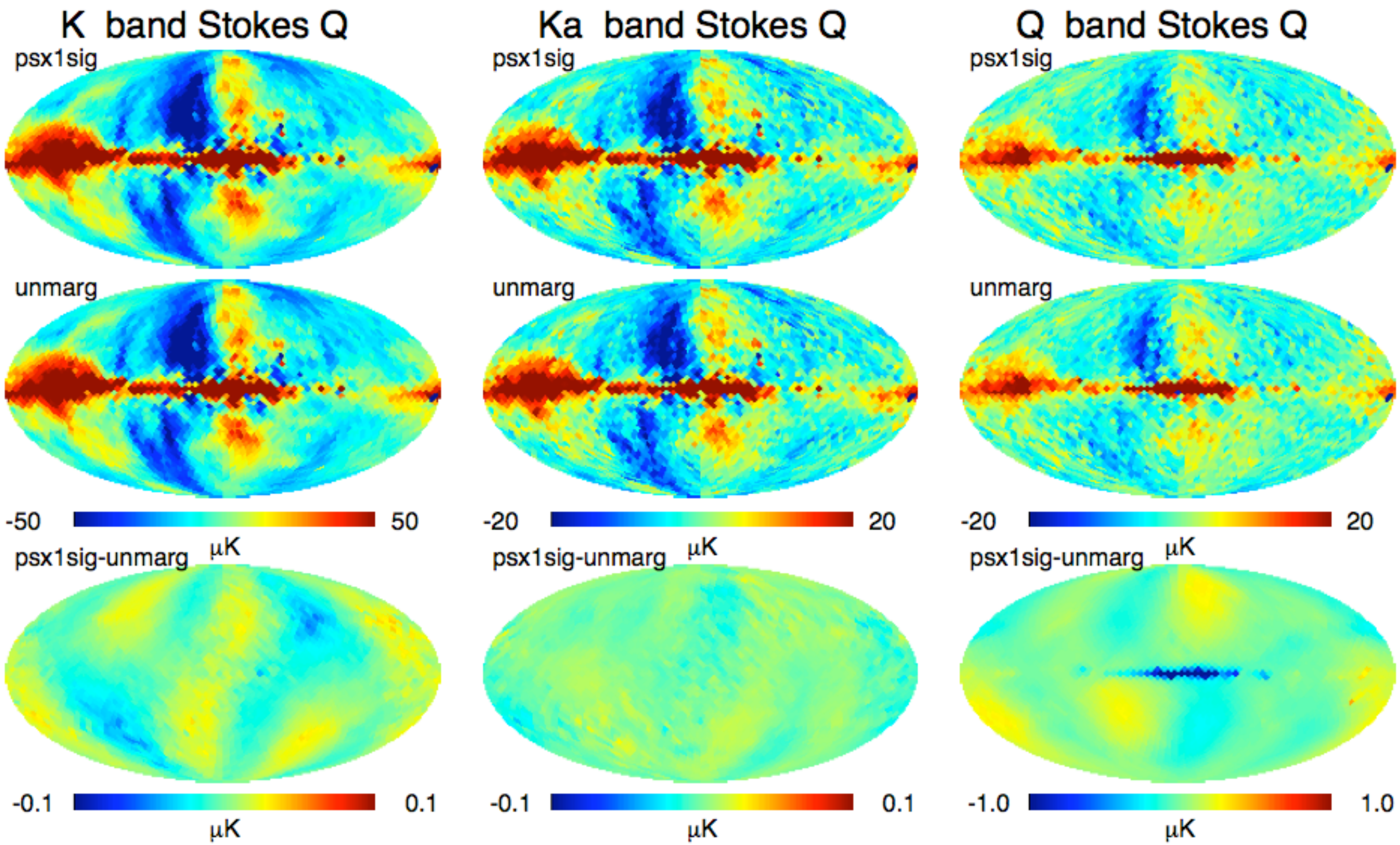
*7-year maps co-added with marginalization over loss imbalance uncertainty.
Loss imbalance uncertainty is nominally a small effect.

Co-added Stokes Q – Case I*



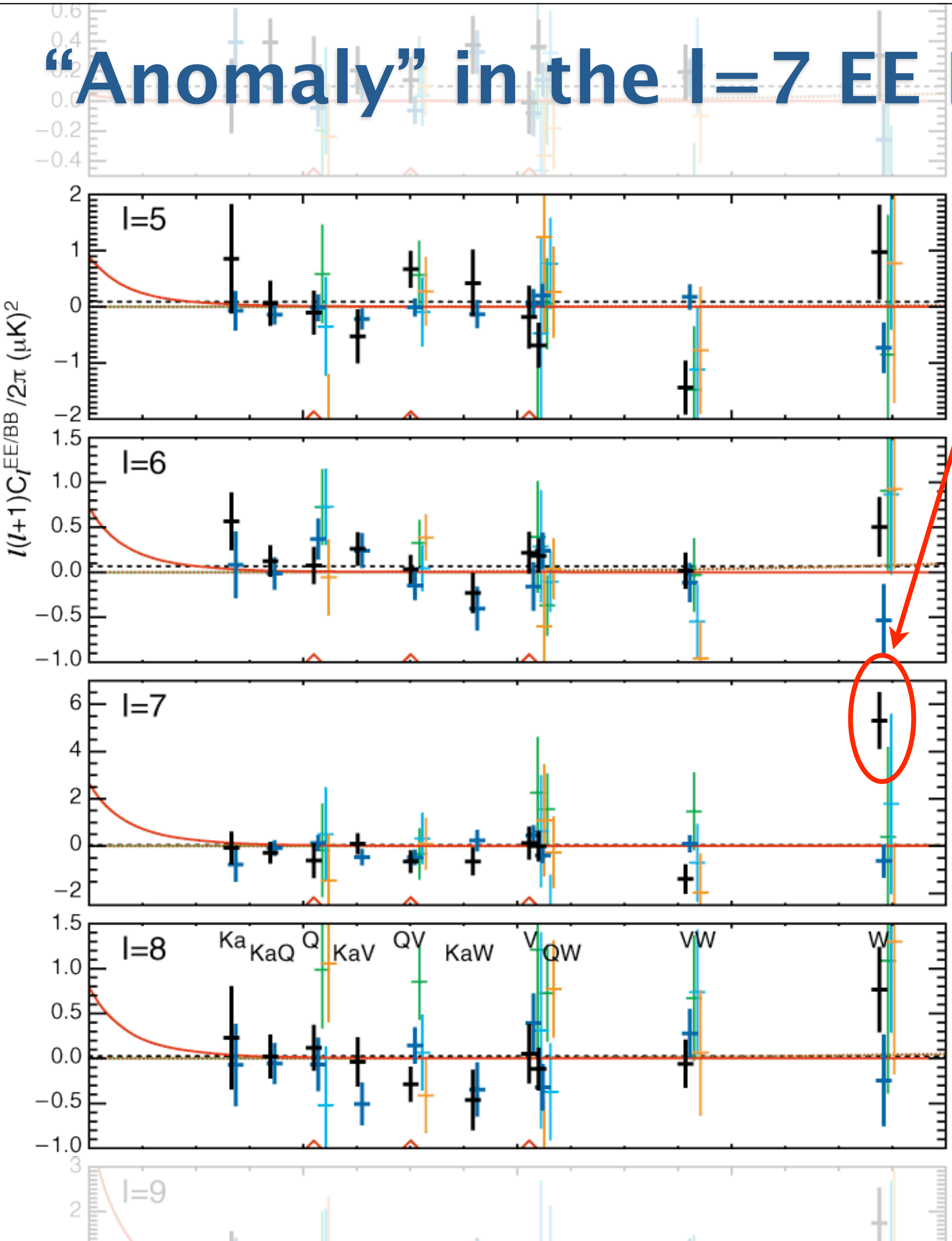
*7-year maps co-added with marginalization over loss imbalance uncertainty assuming complete uncertainty in loss imbalance coefficient (full marginalization - top row).

K Band Polarization with Marginalization



*7-year maps co-added with marginalization over loss imbalance uncertainty assuming 1-sigma uncertainty in loss imbalance coefficient (top row).

“Anomaly” in the l=7 EE Mode @ W Band

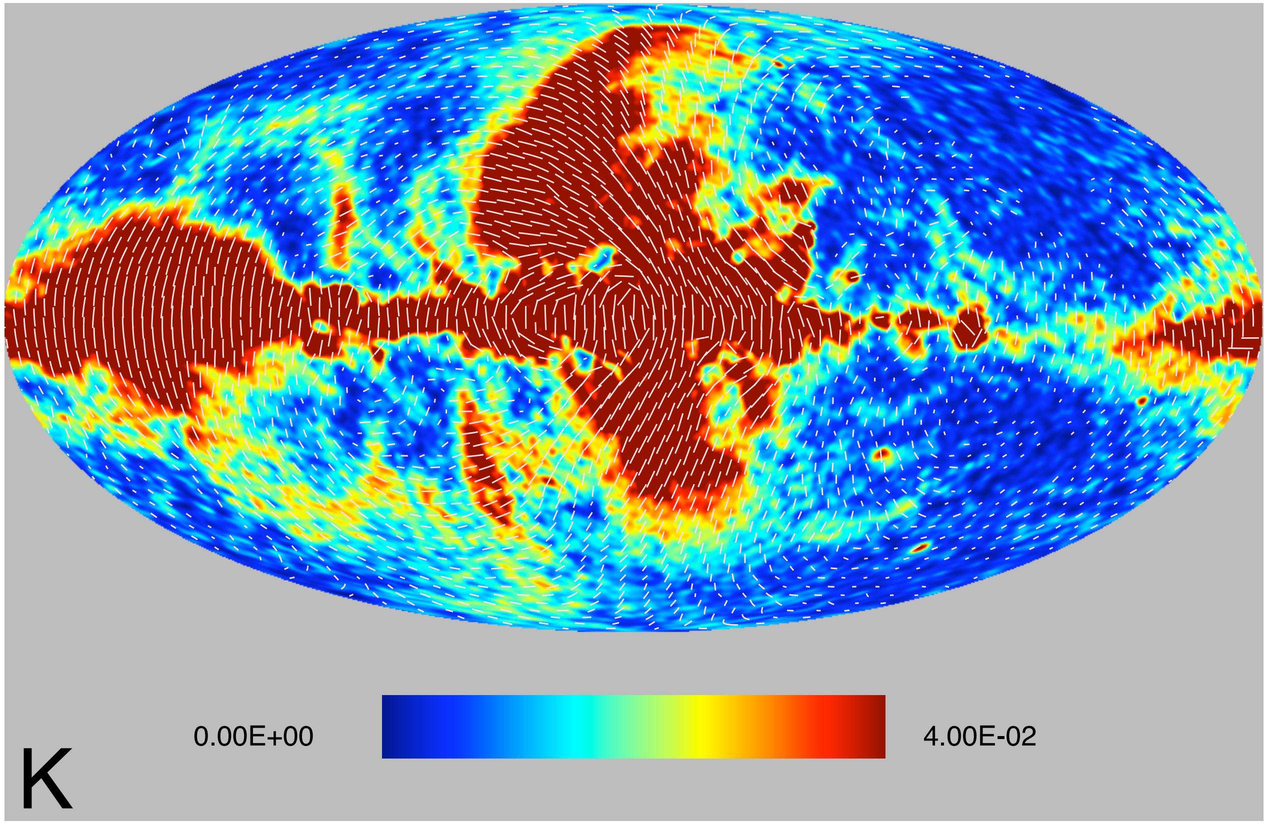


- The power at l=7 in the EE spectrum of W band is was anomalously high (~4 sigma) in the 3-year data.
- The mode passed all jack-knife, null, and consistency tests for a real sky signal.
- If interpreted as a sky signal, the implied V-W spectral index was > +4, and the spatial morphology was very odd. It was not a foreground signal.
- The effect has integrated down to <3 sigma in the 7-year data, so it appears to have been a “glitch” in the early data.

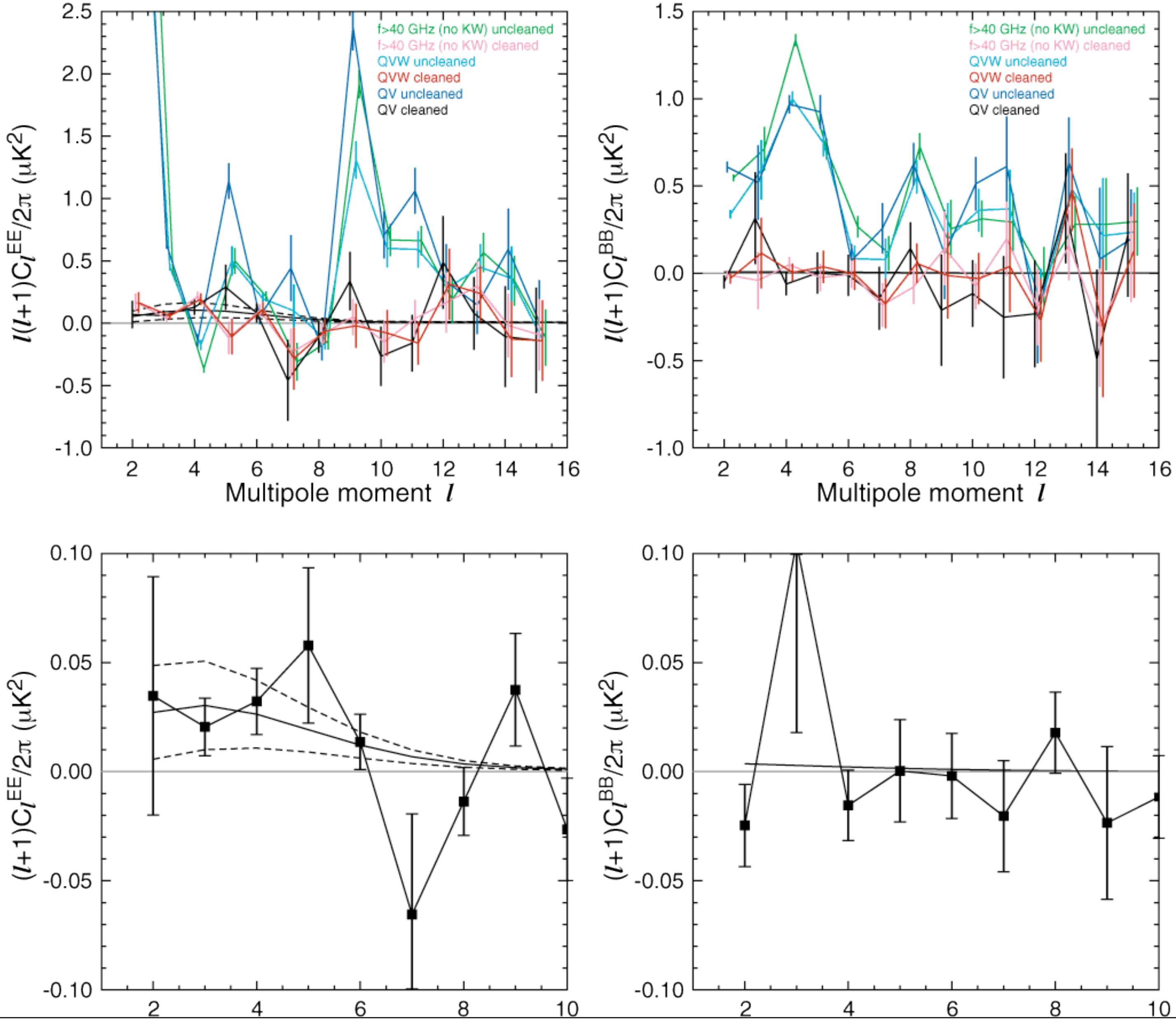
WMAP and Polarized Foregrounds

- Foregrounds are dominant in all bands,

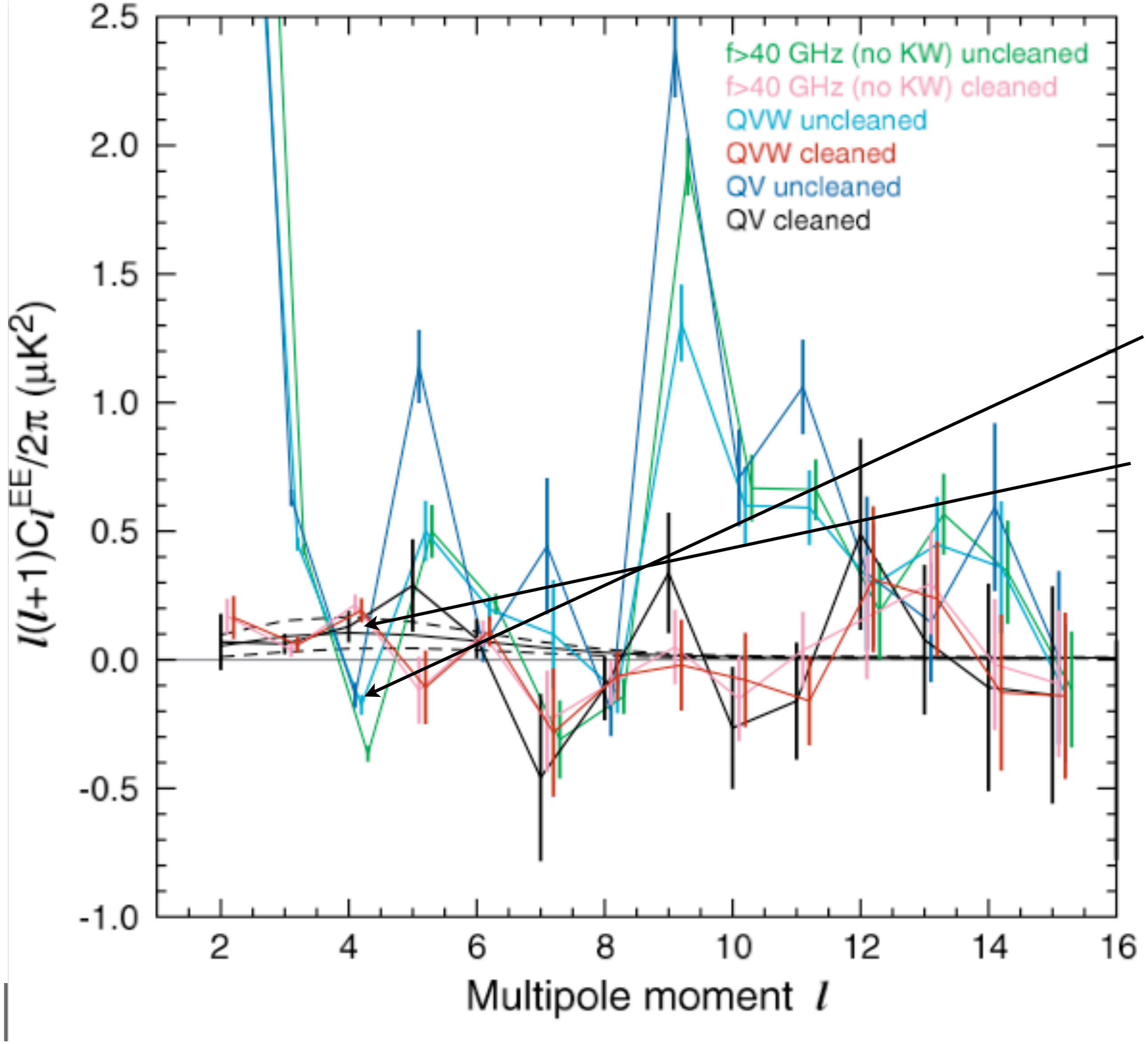
- Despite the warts noted earlier, K band still provides valuable probe of synchrotron morphology in a “clean” frequency range.



Large-Scale EE and BB Spectra



Large-Scale EE Spectra



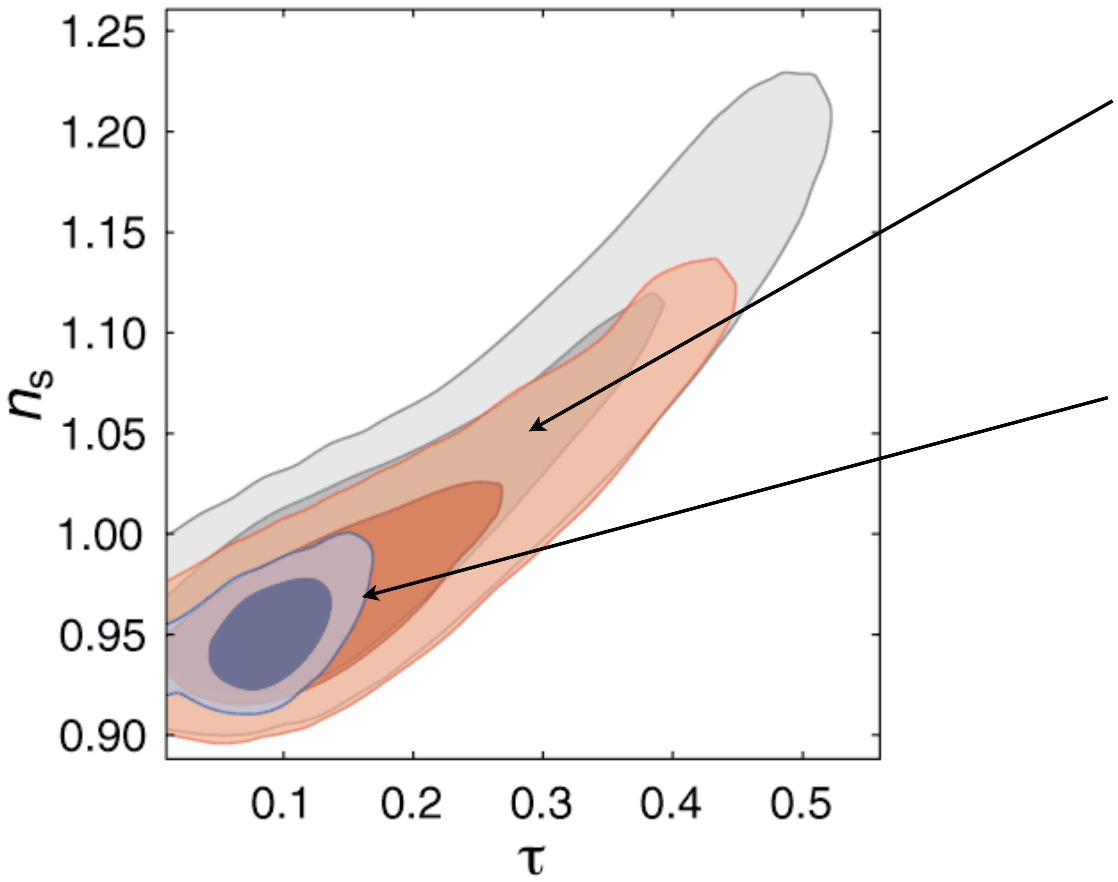
Notes on EE:

- Uncleaned data from various QVW channels shown in green/blue. Note that l=4 is *negative* in these cross-power spectra.

- Most statistical weight for reionization comes from l=4 multipole, which changes sign upon cleaning.

- I want to see an independent measurement of τ!

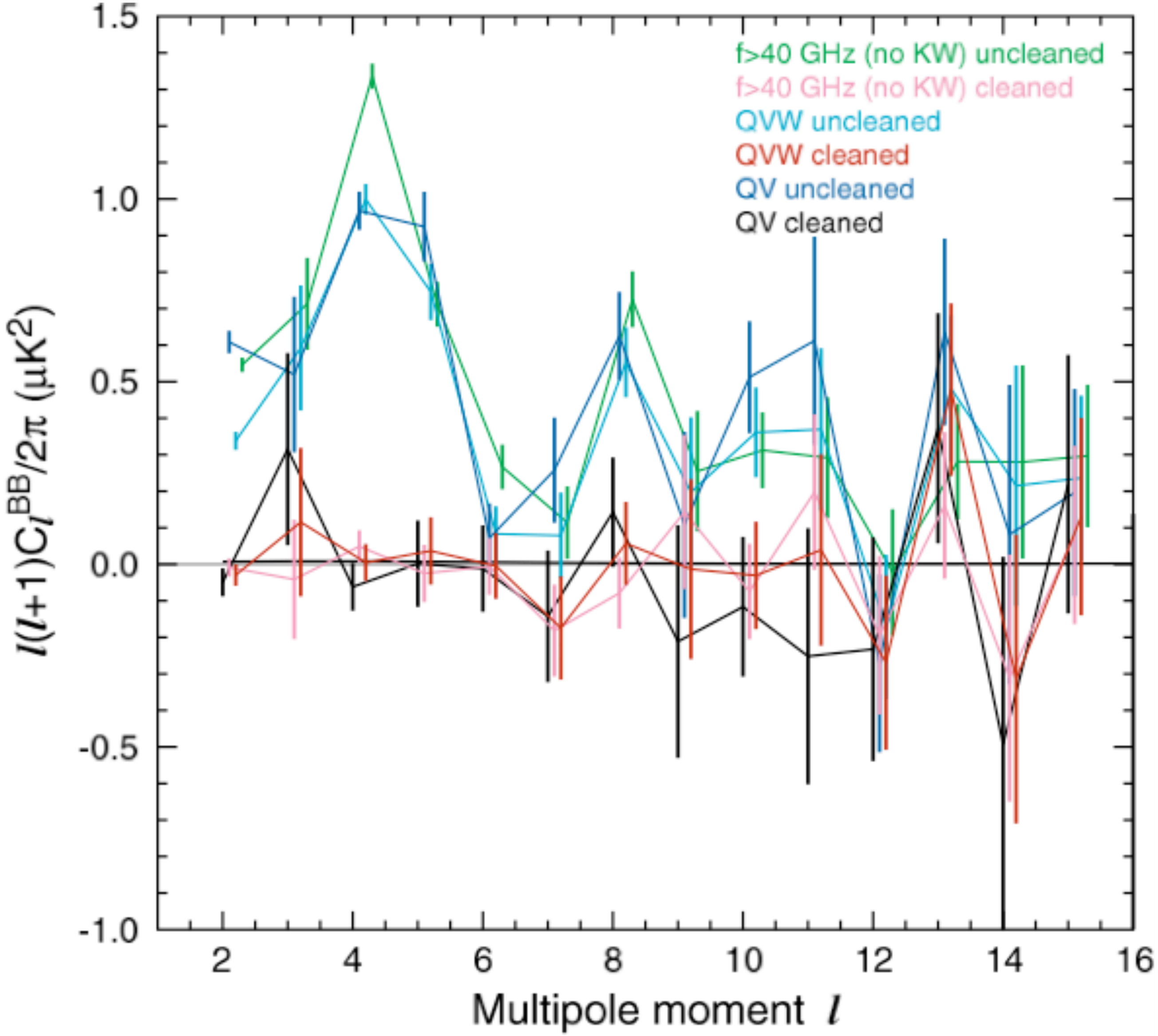
Effects of τ on n_s for WMAP



Notes on τ vs. n_s:

- Analysis of year-1 data w/o EE data places weak constraints on τ. Strong degeneracy with n_s.
- Analysis of 3-year+ data w/ EE cuts off τ, and hence degeneracy.
- This degeneracy may be much less significant for Planck, with larger TT lever arm.

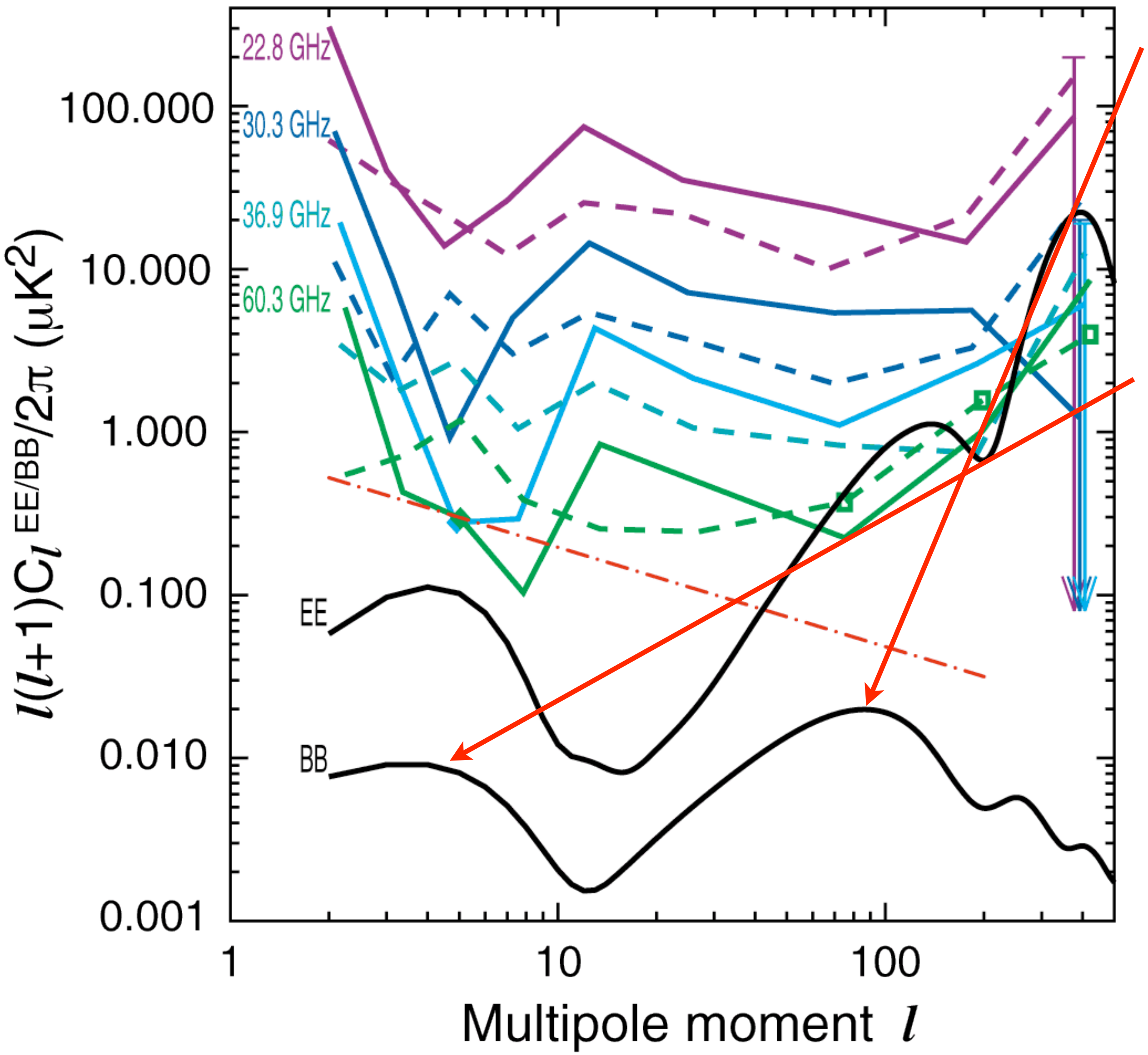
Large-Scale BB Spectra



Notes on BB:

- The l<15 region is already known to be foreground dominated. Probably a factor of >100 in power if r~0.01.
- Not much more to say about that now...

B-modes and Foregrounds



- Planck will give us a good indication of the B-mode foreground environment in the vicinity of the recombination peak.
- We already known the challenge at the reionization peak.
- A robust measurement of gravity waves from inflation likely requires a detection on both angular scales.

WMAP Status – 2012

WMAP completed 9 years of operations at L2: 10 August 2010.

We spent 10 days afterwards increasing WMAP's angle off the sun line from 22.5° to 30° to measure or limit solar interference.

In October 2010, WMAP was given a Viking Funeral*: a final series of thruster burns injected it into a superior solar orbit @1.07 AU. WMAP will enter superior conjunction with the Earth every 14 years.

NASA guidelines provide sufficient funding to complete the analysis of the full 9-year science data set. Processing is nearly complete – we anticipate a final data release around May-June 2012.

Project will officially terminate Sep 2012 with the final archiving of flight data and the storage of mission records.

*The satellite remains in observing mode taking data, but no one is listening.

The End

Sawangwit & Shanks – WMAP Beams are Flawed

S&S (arXiv:0912.0524) try an alternate approach to measuring instrument point spread function (PSF): they stack the sky maps by the location of detected point sources and compare the measured beam profile to the profile measured from Jupiter.

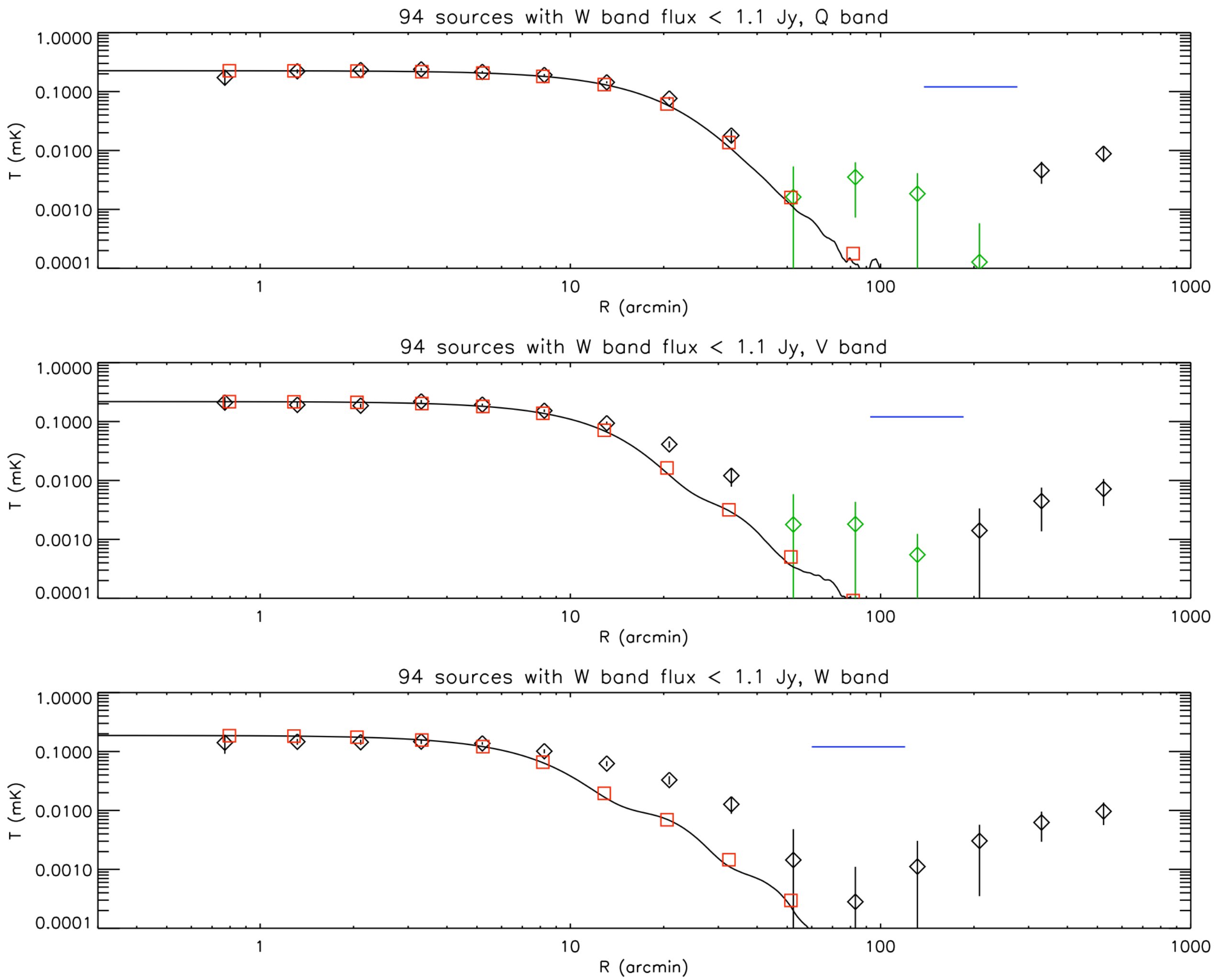
They find the beam response measured from stacked sources to be higher than the beam response measured from Jupiter by a factor of 2-3 in the range of ~1°. They conclude that the CMB power spectrum has been improperly deconvolved and that all cosmological conclusions derived from the CMB power spectrum are suspect.

We have reproduced their analysis and we **do** reproduce their beam response measurement (see following page).

Notes:

- W band (94 GHz) is most important band for beam response (highest resolution).
- Jupiter is about 200 mK in W band.
- There are ~100 detected radio sources at W band, from ~100 μK to ~2 mK.
- The CMB fluctuations are ~100 μK rms, comparable to most radio sources.
- Radio sources must be detected in the data, while the position of Jupiter is known a priori.

Beam Comparison by WMAP Team – Flight Data



Top to bottom:

41 GHz (Q band)

61 GHz (V band)

94 GHz (W band)

Red squares/solid lines:

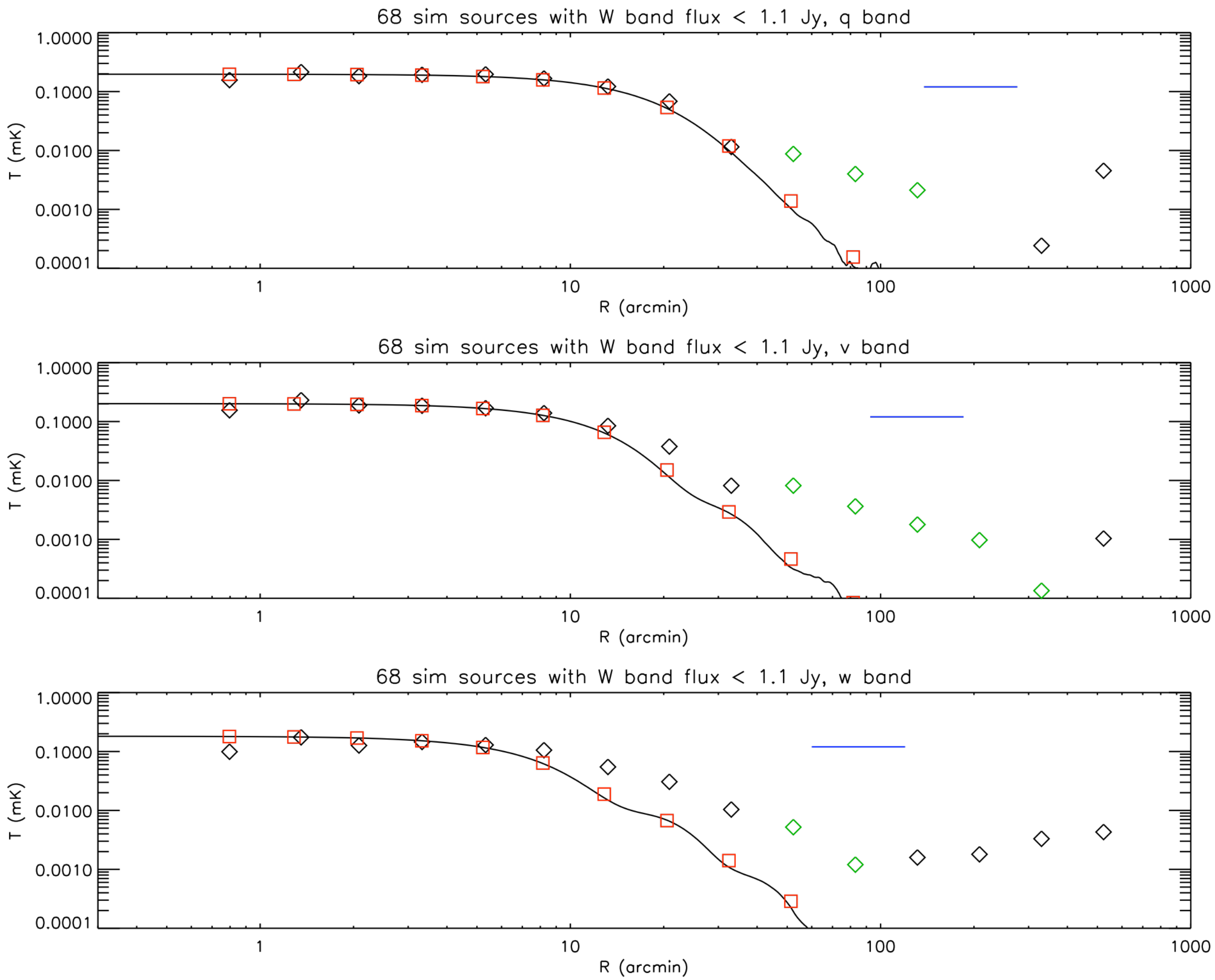
Profile measured from Jupiter

Black diamonds:

Profile measured from stacked sources

Discrepancy increases with decreasing sources brightness – in agreement w/ S&S

Beam Comparison by WMAP Team – Simulated Data



Top to bottom:

41 GHz (Q band)

61 GHz (V band)

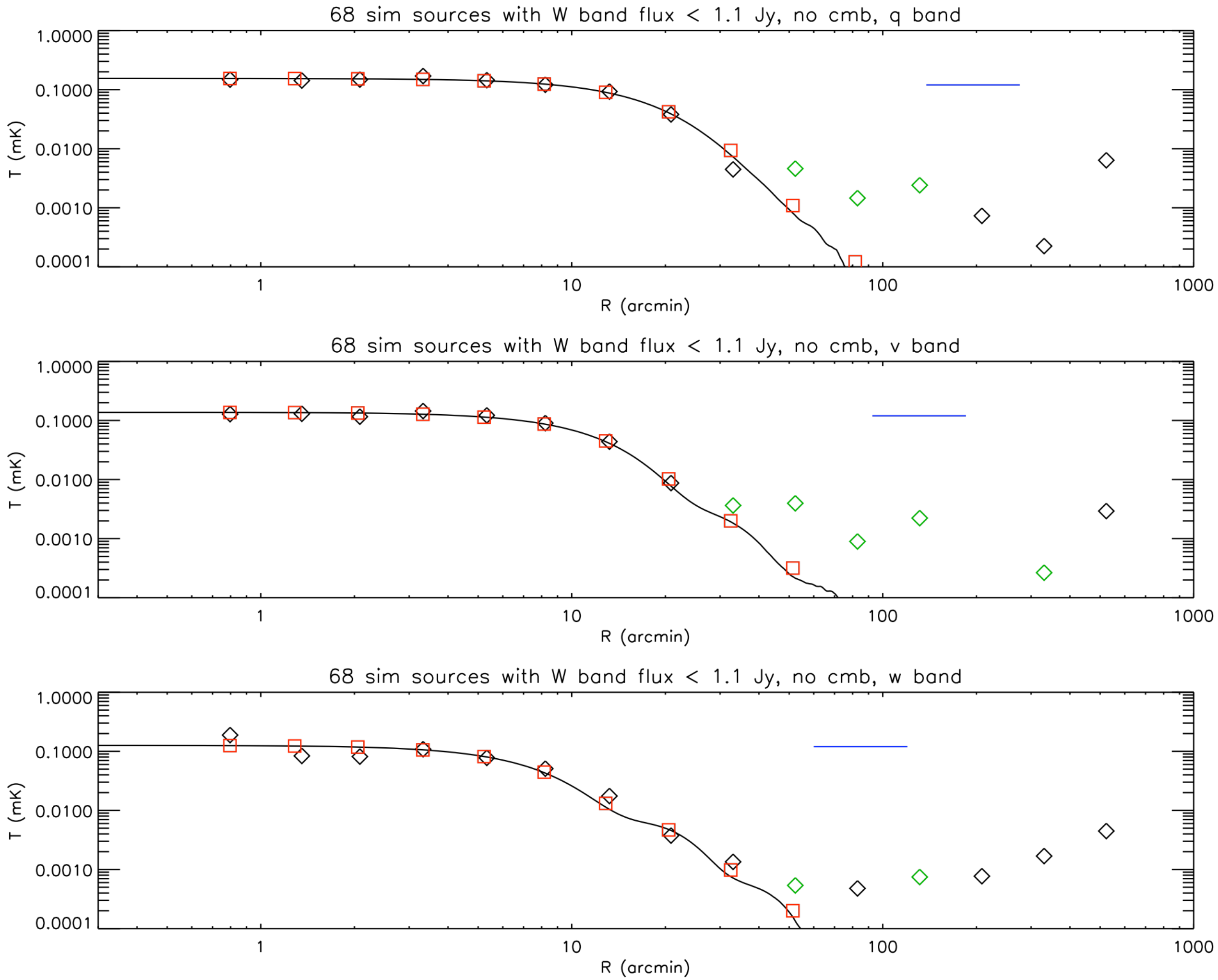
94 GHz (W band)

Same format as flight data. In this case solid lines are input beam model.

Very similar discrepancy between Jupiter and stacked-source profiles.

This suggests a bias in the source stacking.

Beam Comparison –
Simulated Sources w/o CMB



Top to bottom:

41 GHz (Q band)

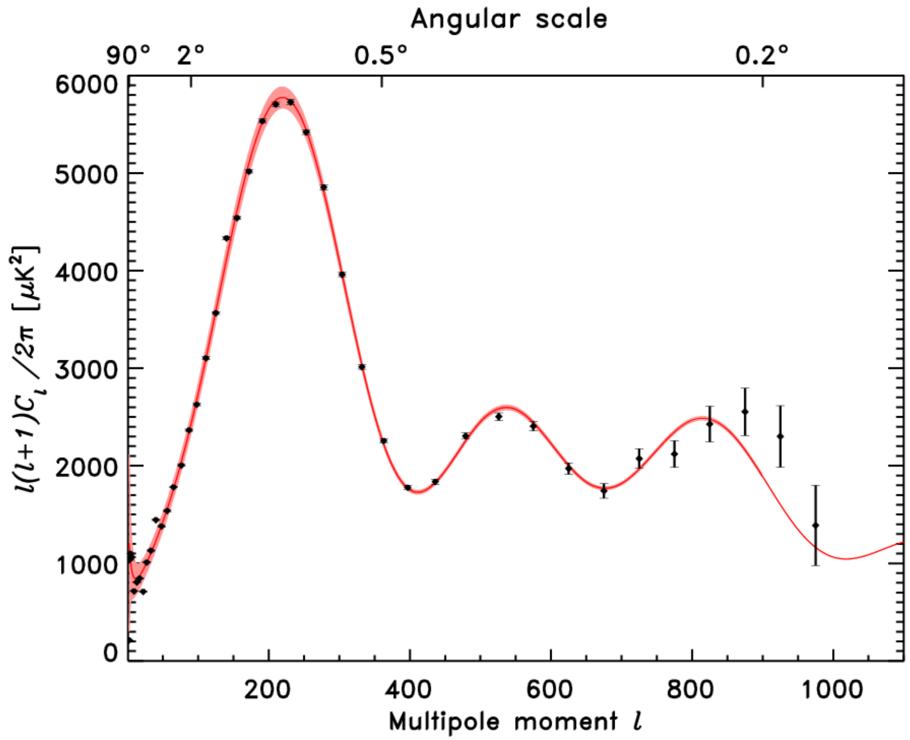
61 GHz (V band)

94 GHz (W band)

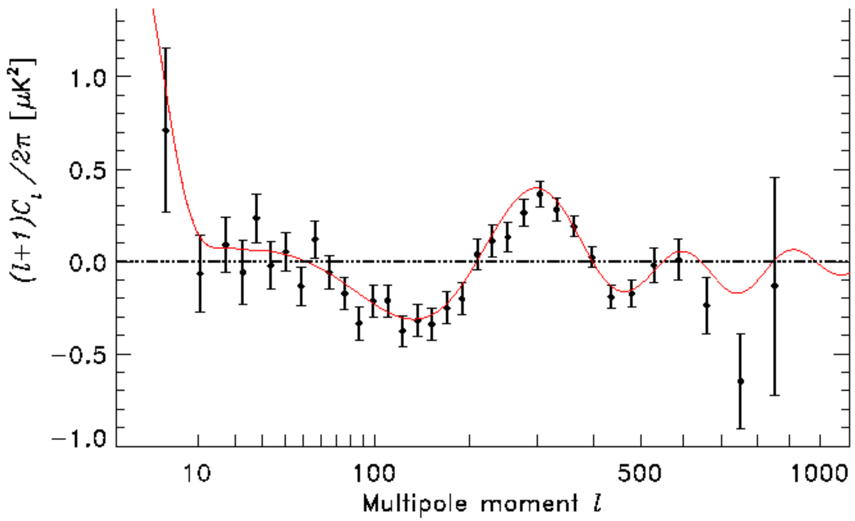
In this case CMB signal is removed from the simulation.

Profiles agree within errors of stacked sources.

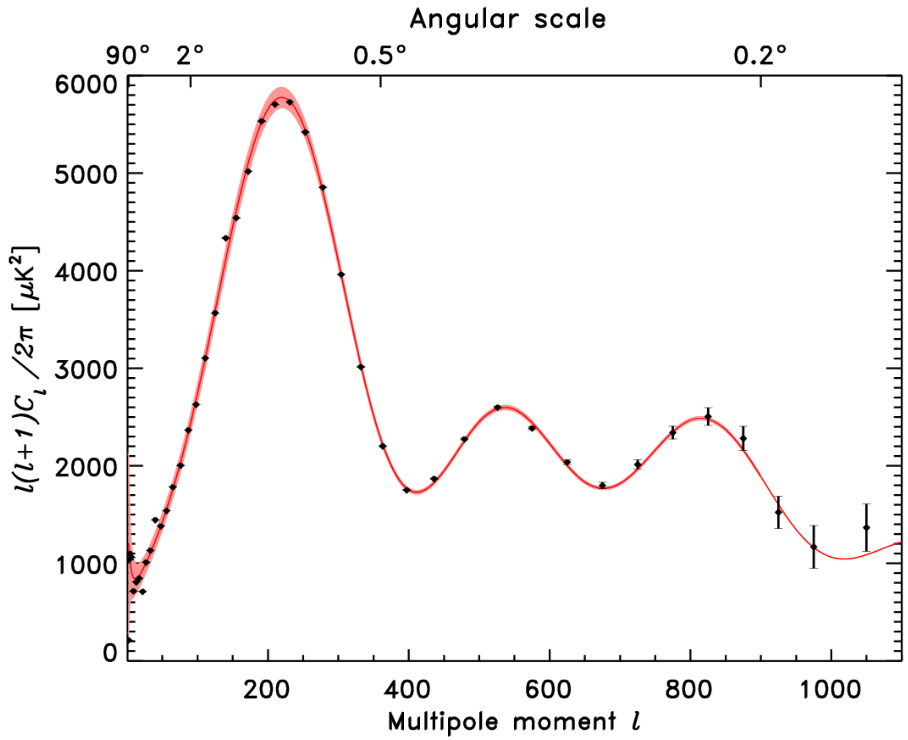
Source sample is not complete – we preferentially detect sources on peaks of CMB, which biases stacked sources


Angular scale
90° 2° 0.5° 0.2°
6000
5000
4000
3000
2000
1000
0
200 400 600 800 1000
Multipole moment l
l(l+1)C_l /2π [μK²]

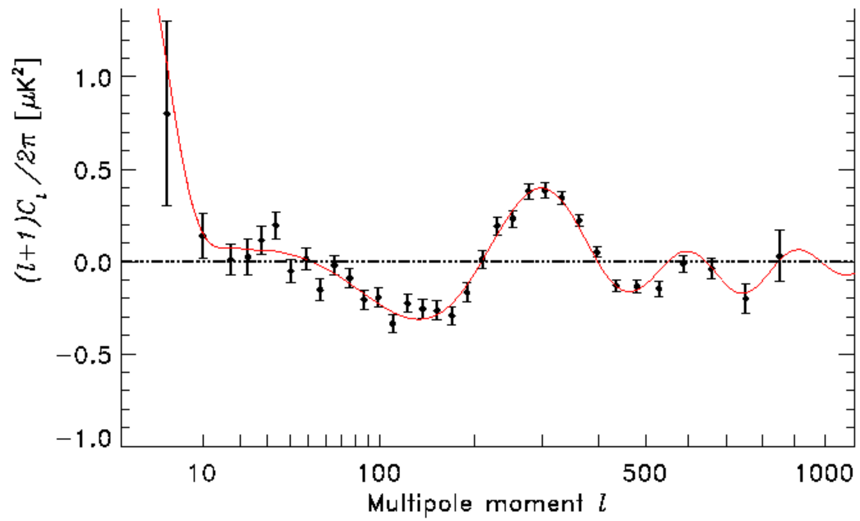
TT 5-Yr


1.0
0.5
0.0
−0.5
−1.0
10 100 500 1000
Multipole moment l
(l+1)C_l /2π [μK²]

TE 5-Yr

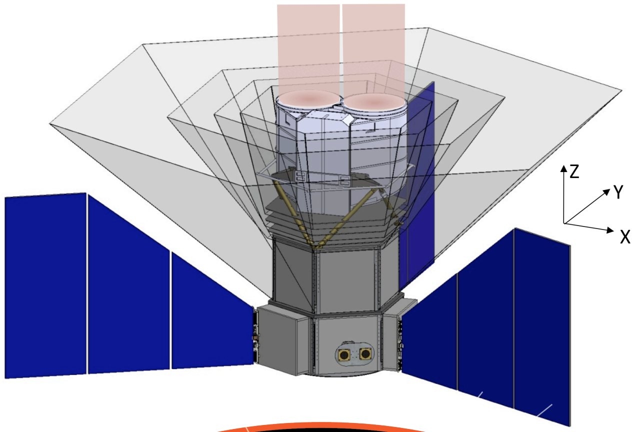


TT 9-Yr (forecast)



TE 9-Yr (forecast)

Primordial Inflation eXplorEr (I?)



Name	Role	Institution
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D. Chuss	Co-I	GSFC
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E. Dwek	Co-I	GSFC
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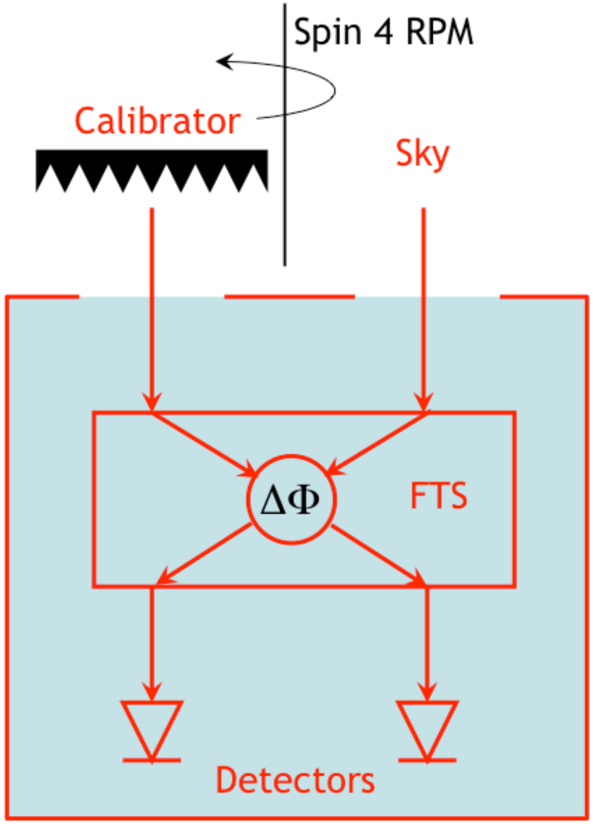
H. Moseley	Co-I	GSFC
M. Seiffert	Co-I	JPL
D. Spergel	Co-I	Princeton
E. Wollack	Co-I	GSFC

Measure B-Mode Polarization To Limits Imposed By Astrophysical and Cosmological Foregrounds.

Midex concept submitted to NASA HQ Feb. 16, 2011

PIXIE Nulling Polarimeter



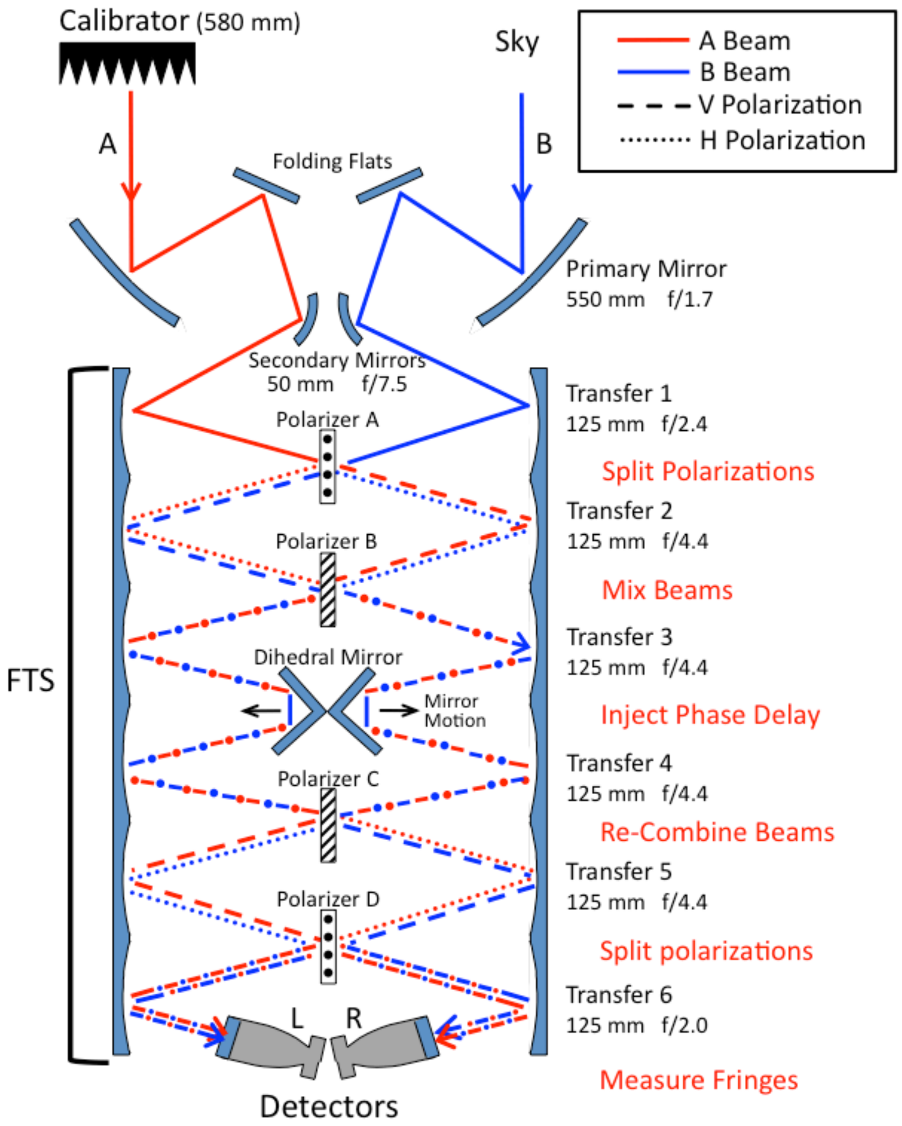
Sensitivity: More photons, not more detectors
- Multi-moded "light bucket"
- Large etendu (4 cm^2 sr)
- Collect 44,000+ modes on just 4 detectors

Frequency Coverage: Fourier Transform Spectroscopy
- Interfere beams and observe fringe pattern
- Synthesize spectrum in 512 bins each 15 GHz wide
- Many more frequency bins than foreground components

Multiple nulls control instrumental signature
- Fringes proportional to Stokes Q between input ports
- Spin S/C to determine QU independently in each pixel
- Blackbody calibrator provides absolute spectrum (Stokes I)
- Symmetric design provides multiple jackknife tests

Measure $r < 10^{-3}$ (5σ) Using Only 4 Detectors

Fourier Transform Spectrometer



Take Observed Fringes ...

$$P_{Lx} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{Ax}^2 - E_{By}^2\right)\cos(z\omega/c)\, d\omega$$

$$P_{Ly} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{Ay}^2 - E_{Bx}^2\right)\cos(z\omega/c)\, d\omega$$

... Fourier Transform ...

$$S_\upsilon = \sum_{k=0}^{N-1} P_k \exp(2\pi i k\upsilon/N)$$

... To get Frequency Spectra

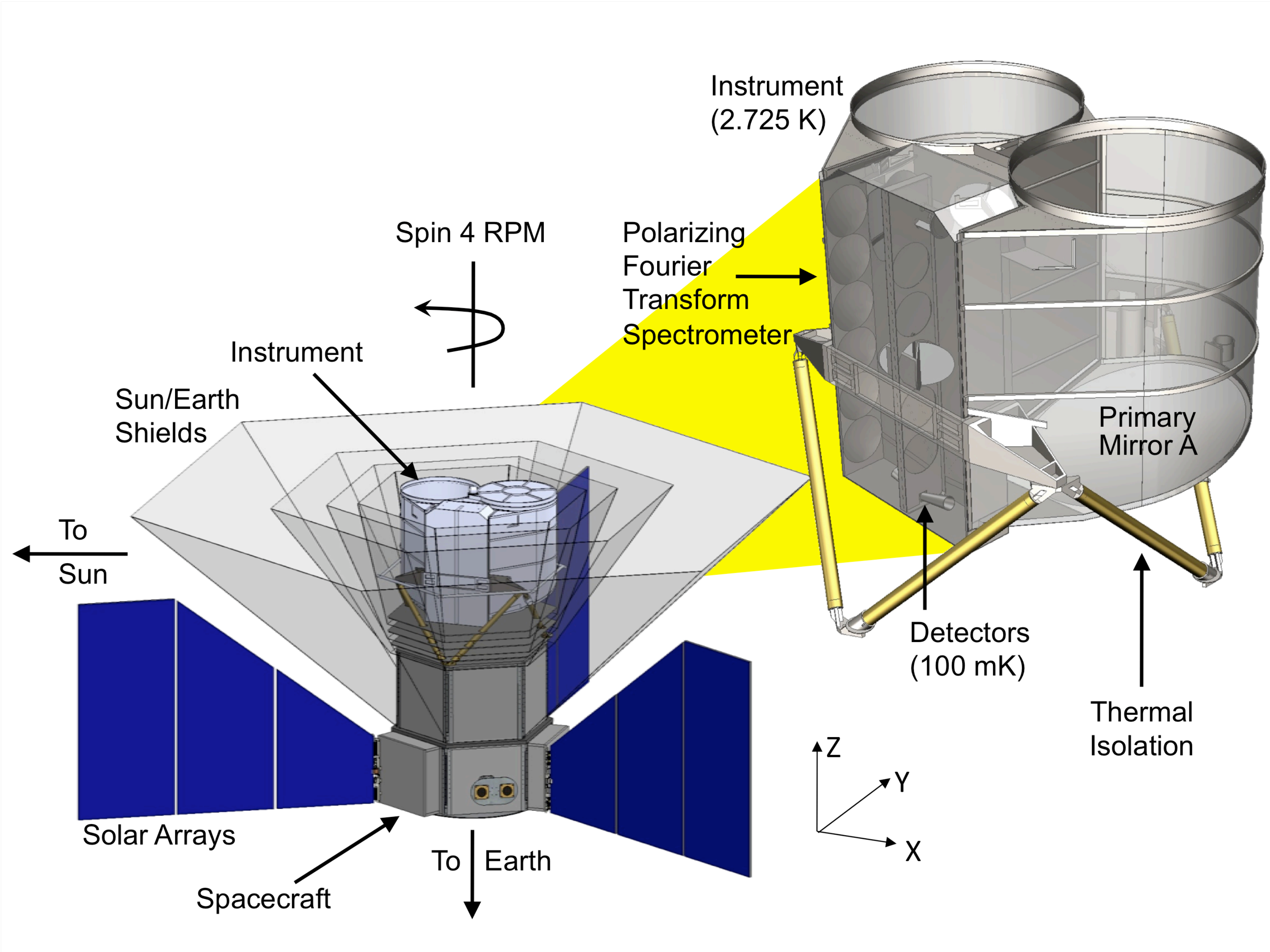
$$S_\upsilon^{Lx} = \frac{1}{4}\left[I_\upsilon^A - I_\upsilon^B + Q_\upsilon \cos(2\gamma) + U_\upsilon \sin(2\gamma)\right]$$

$$S_\upsilon^{Ly} = \frac{1}{4}\left[I_\upsilon^A - I_\upsilon^B - Q_\upsilon \cos(2\gamma) - U_\upsilon \sin(2\gamma)\right]$$

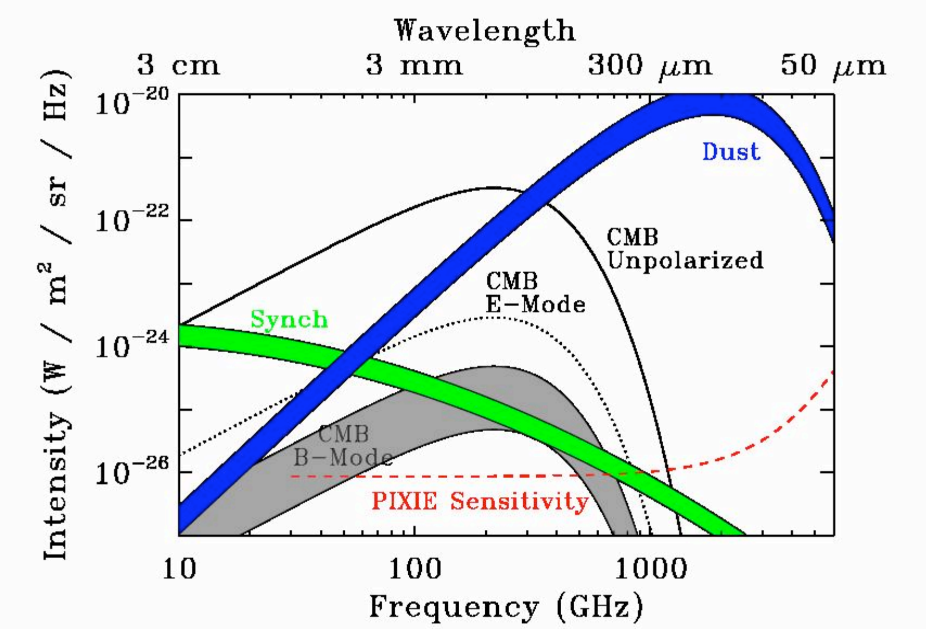
Calibrator in: Fringes measure IQU
Calibrator out: Fringes measure QU only

Nulling Polarimeter: Zero = Zero

PIXIE Instrument & Observatory



Sensitivity & Frequency Coverage



Synthesize 512 channels each 15 GHz wide

Lowest effective channel = 30 GHz (1 cm)

Highest effective channel ~ 6 THz (50 μm)

400 high S/N channels for foregrounds

Foreground "penalty" ~ 2%

Fit multiple foreground parameters

Mirror Scan and Noise Properties

Real part of FFT: Signal + noise

Imaginary part of FFT: Noise only

Background-limited sensitivity

Etendu 4 cm^2 sr, Throughput > 82%

Large detectors: Signal increases faster than noise

Calibrator Position	NET (μK s^1/2)	NEQ (μK s^1/2)
Deployed	13.6	19.2
Stowed	—-	5.6

Measure B modes to cosmological limit

Lensing foreground as "sky noise"

Nearly diagonal noise matrix