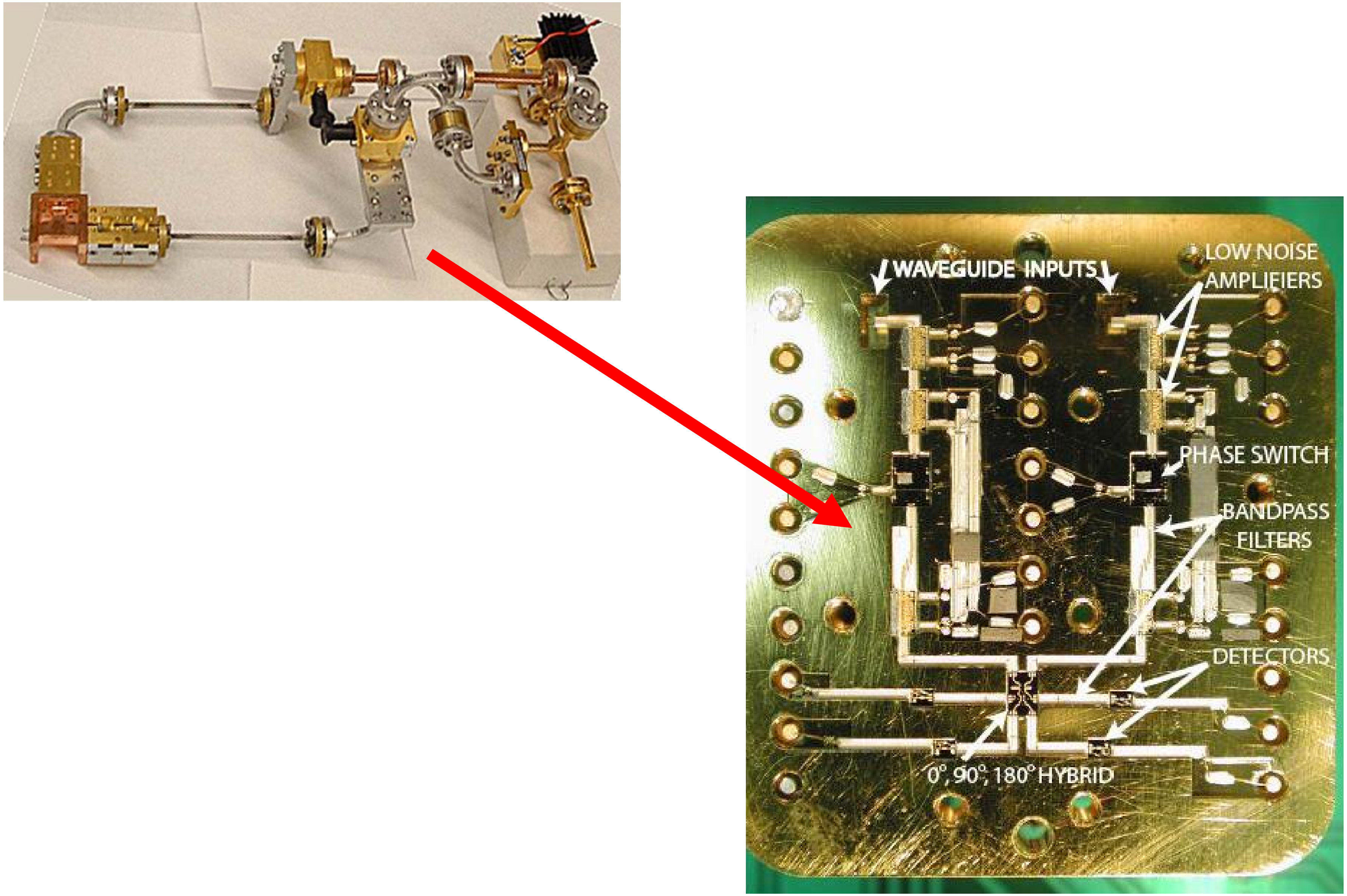
The CMB sky observed at 43 and 95 GHz with QUIET

Hans Kristian Eriksen for the QUIET collaboration

University of Oslo

Munich, November 28th, 2012


WAVEGUIDE INPUTS
LOW NOISE AMPLIFIERS
PHASE SWITCH
BANDPASS FILTERS
DETECTORS
0°, 90°, 180° HYBRID

QUIET (Q/U Imaging ExperimenT)

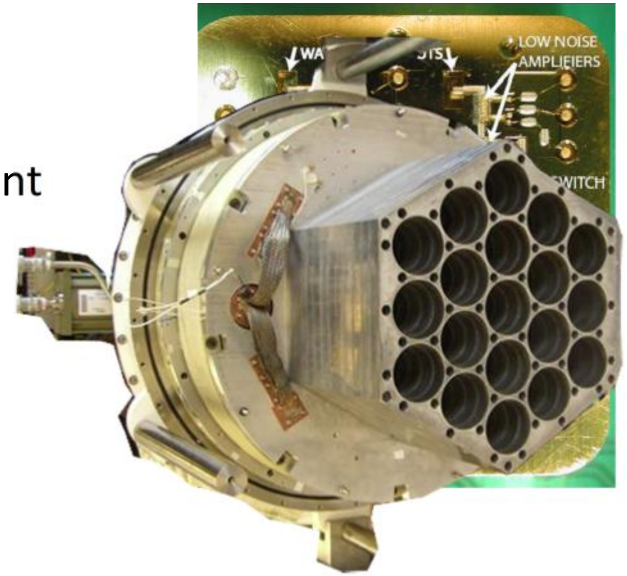
- QUIET is a ground-based experiment measuring CMB polarisation using MMICs

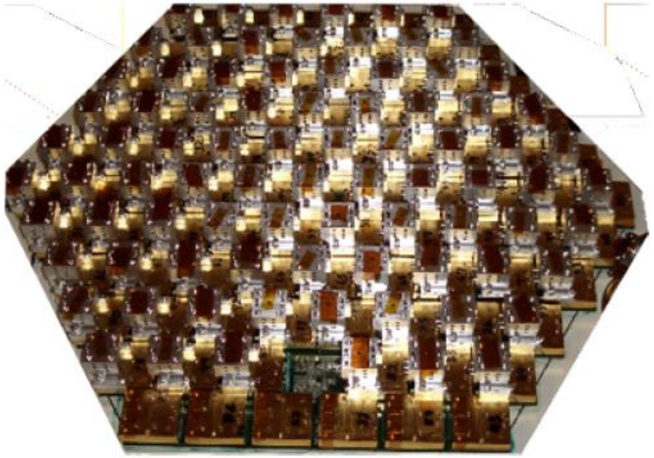
- So far the only B-mode coherent radiometer experiment
  - Different (and I will argue better) systematics
  - Unique *radiometer on a chip* technology

- Phase I (Pathfinder)
  - 19 Q-band detectors (43 GHz) Aug 08 - May 09
  - 90 W-band detectors (95 GHz) Jun 09 - Dec 10

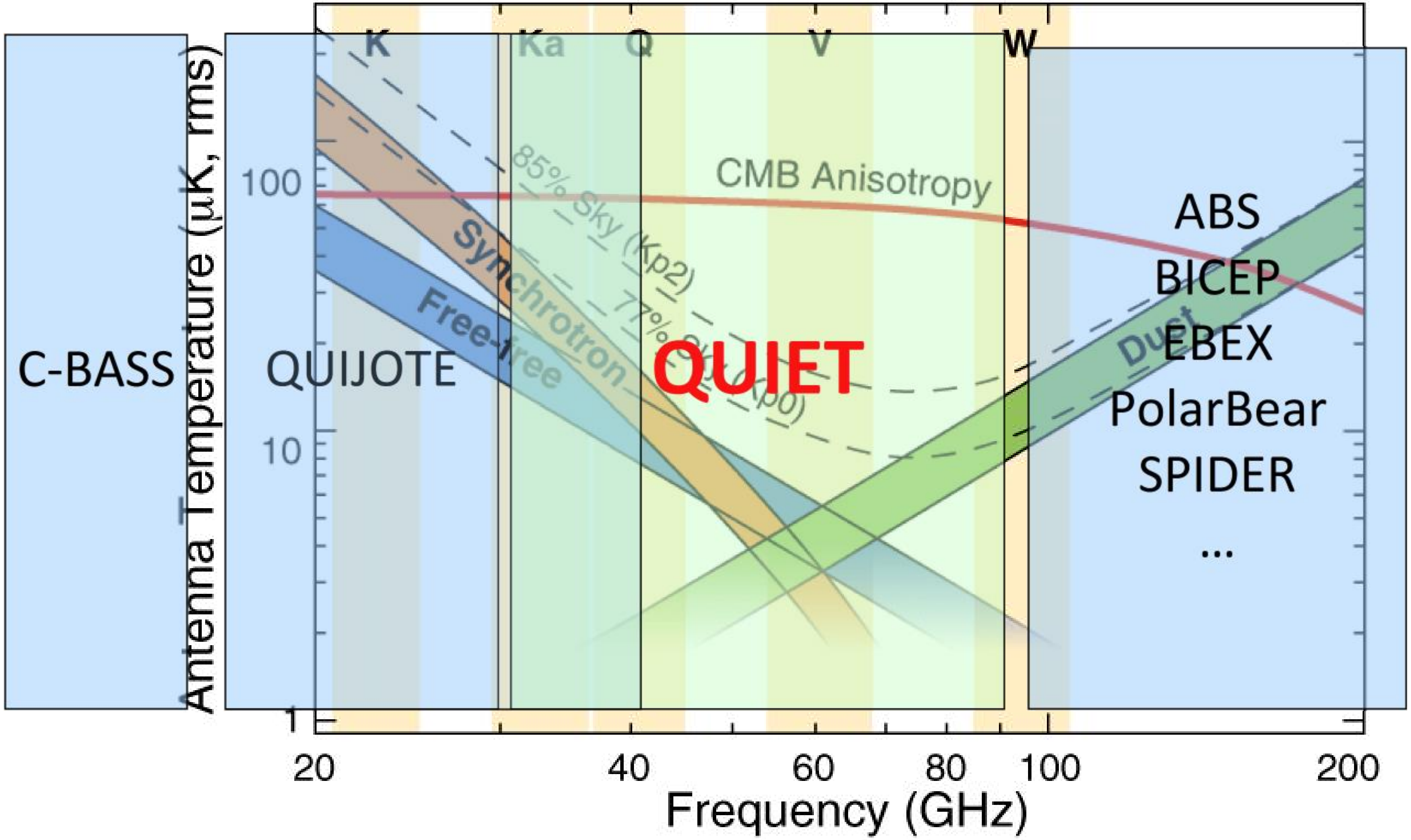
- Phase II (if funded)
  - ~500 detectors in 3 bands (30, 37 and 90 GHz)

- Measure the E- and B-mode spectra between l = 25 and 2500
  - detection of lensing at more than 20σ
  - constraining the tensor-to-scalar ratio *r* down to 0.01





Frequency versus experiment



C-BASS

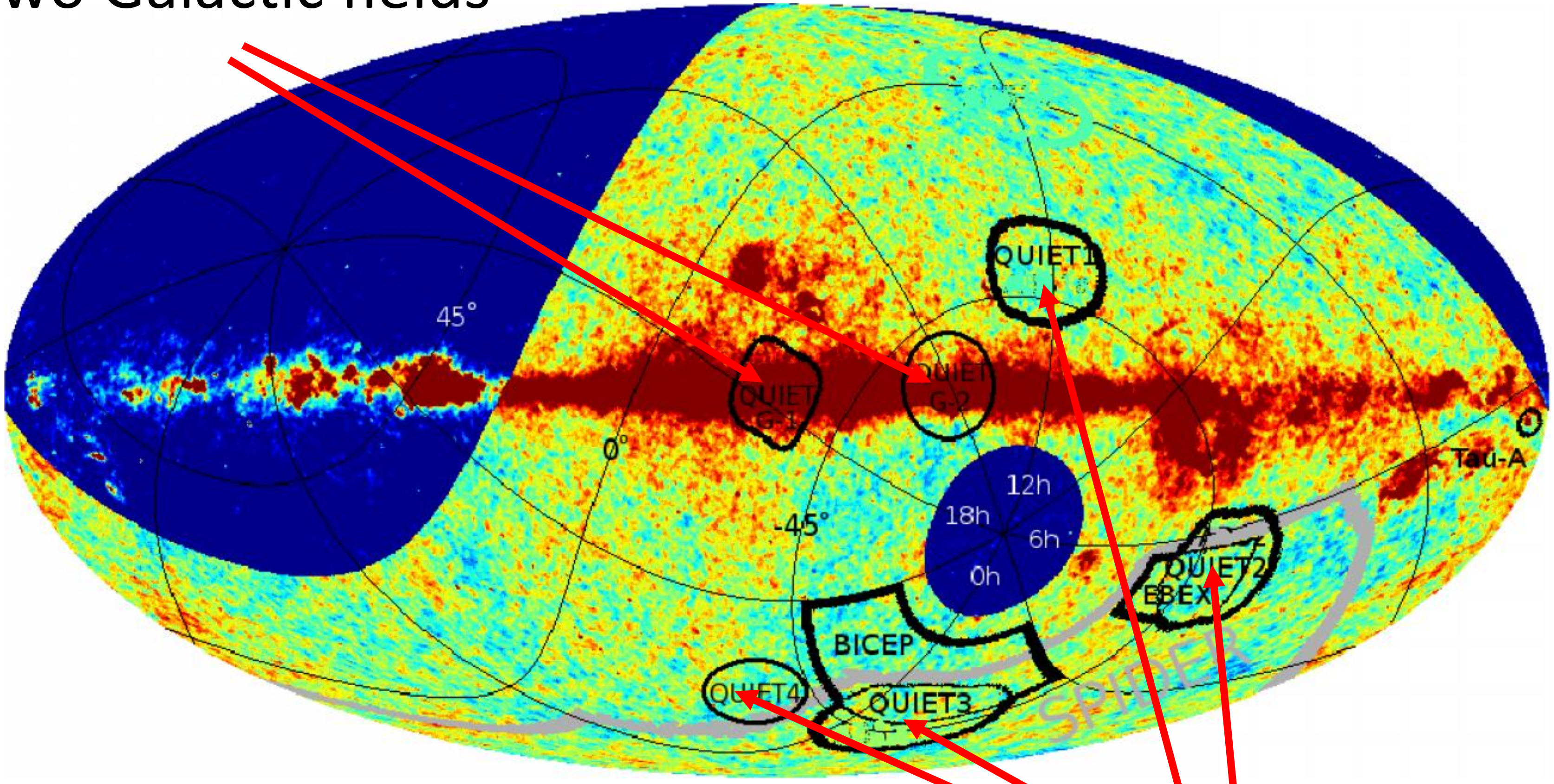
QUIJOTE

QUIET

ABS
BICEP
EBEX
PolarBear
SPIDER
…

The QUIET Fields

Two Galactic fields

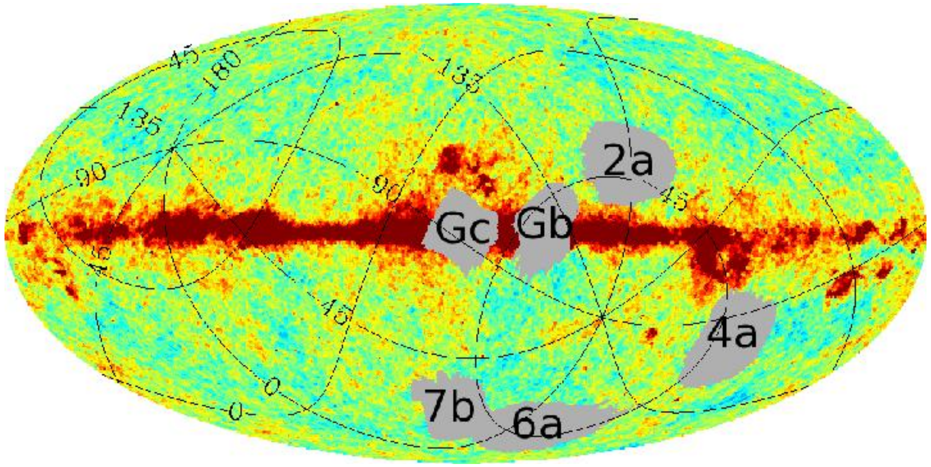


Overlap with BICEP, EBEX and SPIDER,
(and probably with ABS and PolarBear)

Four CMB fields

Observation hours

	Q-band	W-band
Patch 2a	905	1855
Patch 4a	703	1444
Patch 6a	837	1389
Patch 7b	223	650
All CMB	2668	5337
Patch Gb	311	
Patch Gc	92	

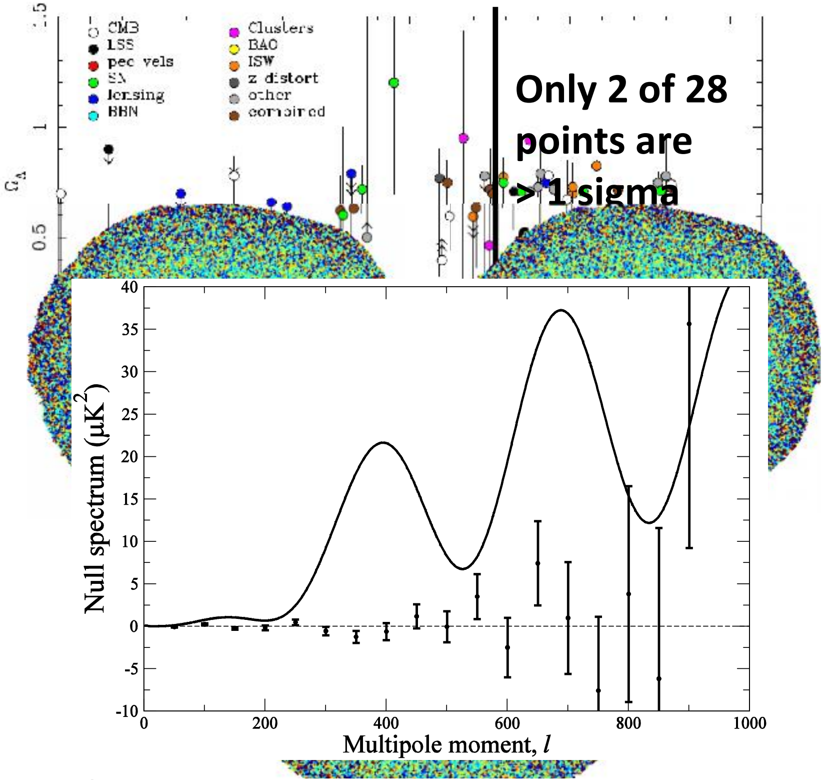


Q-band: 77% CMB, 12% Galactic,
7% calib, 4% cut

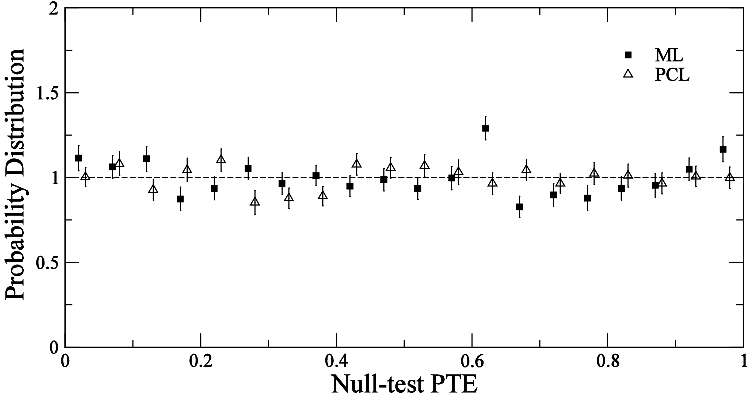
W-band: 72% CMB, 14% Galactic,
13% calib, 1% cut

A fully blind analysis

- QUIET is the first CMB experiment to implement a strict blind analysis policy
    - Never look at a cosmological power spectrum until filters, cuts and calibration are finalized
    - Avoids bias toward ”expected result”
- Main tool: ”The null-test suite”
    - Procedure:
        - Split the full data set into two halves
        - Make separate maps, and difference them
        - Compute the corresponding spectrum, and compare with noise-only simulations
    - Each null-test targets a known potential systematic
- ML (PCL) pipeline implements 23 (32) tests
- The final QUIET null-suite is fully consistent with noisy-only simulations



Only 2 of 28 points are > 1 sigma



FIRST SEASON QUIET OBSERVATIONS: MEASUREMENTS OF CMB POLARIZATION POWER SPECTRA AT 43 GHZ IN THE MULTIPOLE RANGE $25 \leq \ell \leq 475$

QUIET Collaboration—C. Bischoff[1,22], A. Brizius[1,2], I. Buder[1], Y. Chinone[3,4], K. Cleary[5], R. N. Dumoulin[6],
A. Kusaka[1], R. Monsalve[7], S. K. Næss[8], L. B. Newburgh[6,23], R. Reeves[5], K. M. Smith[1,23], I. K. Wehus[9],
J. A. Zuntz[10,11,12], J. T. L. Zwart[6], L. Bronfman[13], R. Bustos[7,13,14], S. E. Church[15], C. Dickinson[16],
H. K. Eriksen[8,17], P. G. Ferreira[10], T. Gaier[18], J. O. Gundersen[7], M. Hasegawa[3], M. Hazumi[3],
K. M. Huffenberger[7], M. E. Jones[10], P. Kangaslahti[18], D. J. Kapner[1,24], C. R. Lawrence[18], M. Limon[6], J. May[13],
J. J. McMahon[19], A. D. Miller[6], H. Nguyen[20], G. W. Nixon[21], T. J. Pearson[5], L. Piccirillo[16], S. J. E. Radford[5],
A. C. S. Readhead[5], J. L. Richards[5], D. Samtleben[2,25], M. Seiffert[18], M. C. Shepherd[5], S. T. Staggs[21],
O. Tajima[1,3], K. L. Thompson[15], K. Vanderlinde[1,26], R. Williamson[6,27], B. Winstein[1]

Submitted to ApJ—This paper should be cited as "QUIET (2010)"

ABSTRACT

The Q/U Imaging ExperimenT (QUIET) employs coherent receivers at 43 GHz and 95 GHz, operating on the Chajnantor plateau in the Atacama Desert in Chile, to measure the anisotropy in the polarization of the CMB. QUIET primarily targets the B modes from primordial gravitational waves. The combination of these frequencies gives sensitivity to foreground contributions from diffuse Galactic synchrotron radiation. Between 2008 October and 2010 December, over 10,000 hours of data were collected, first with the 19-element 43-GHz array (3458 hours) and then with the 90-element 95-GHz array. Each array observes the same four fields, selected for low foregrounds, together covering ≈ 1000 square degrees. This paper reports initial results from the 43-GHz receiver which has an array sensitivity to CMB fluctuations of $69\,\mu\mathrm{K}\sqrt{\mathrm{s}}$. The data were extensively studied with a large suite of null tests before the power spectra, determined with two independent pipelines, were examined. Analysis choices, including data selection, were modified until the null tests passed. Cross correlating maps with different telescope pointings is used to eliminate a bias. This paper reports the EE, BB, and EB power spectra in the multipole range $\ell = 25$–475. With the exception of the lowest multipole bin for one of the fields, where a polarized foreground, consistent with Galactic synchrotron radiation, is detected with 3-σ significance, the E-mode spectrum is consistent with the ΛCDM model, confirming the only previous detection of the first acoustic peak. The B-mode spectrum is consistent with zero, leading to a measurement of the tensor-to-scalar ratio of $r = 0.35^{+1.06}_{-0.87}$. The combination of a new time-stream "double-demodulation" technique, Mizuguchi–Dragone optics, natural sky rotation, and frequent boresight rotation leads to the lowest level of systematic contamination in the B-mode power so far reported, below the level of $r = 0.1$.

Subject headings: cosmic background radiation—Cosmology: observations—Gravitational waves—Inflation—Polarization

SECOND SEASON QUIET OBSERVATIONS:
MEASUREMENTS OF THE CMB POLARIZATION POWER SPECTRUM AT 95 GHZ

QUIET Collaboration — D. Araujo[1], C. Bischoff[2,3], A. Brizius[2,4], I. Buder[2,3], Y. Chinone[5,6], K. Cleary[7],
R. N. Dumoulin[1], A. Kusaka[2,8], R. Monsalve[9], S. K. Næss[10], L. B. Newburgh[1,8], R. Reeves[7], I. K. Wehus[11,12],
J. T. L. Zwart[1,13], L. Bronfman[14], R. Bustos[9,14,15], S. E. Church[16], C. Dickinson[17], H. K. Eriksen[10,18], T. Gaier[19],
J. O. Gundersen[9], M. Hasegawa[5], M. Hazumi[5], K. M. Huffenberger[9], K. Ishidoshiro[5], M. E. Jones[11],
P. Kangaslahti[19], D. J. Kapner[2,20], D. Kubik[21], C. R. Lawrence[19], M. Limon[1], J. J. McMahon[22], A. D. Miller[1],
M. Nagai[5], H. Nguyen[21], G. Nixon[8,23], T. J. Pearson[7], L. Piccirillo[17], S. J. E. Radford[7], A. C. S. Readhead[7],
J. L. Richards[7], D. Samtleben[4,24], M. Seiffert[19], M. C. Shepherd[7], K. M. Smith[2,8], S. T. Staggs[8], O. Tajima[2,5],
K. L. Thompson[16], K. Vanderlinde[2,25], R. Williamson[1,2]

Submitted to ApJ—This paper should be cited as "QUIET Collaboration (2012)"

ABSTRACT

The Q/U Imaging ExperimenT (QUIET) has observed the cosmic microwave background (CMB) at 43 and 95 GHz. The 43-GHz results have been published in QUIET Collaboration et al. (2011), and here we report the measurement of CMB polarization power spectra using the 95-GHz data. This data set comprises 5337 hours of observations recorded by an array of 84 polarized coherent receivers with a total array sensitivity of $87\,\mu\mathrm{K}\sqrt{\mathrm{s}}$. Four low-foreground fields were observed, covering a total of $\sim$ 1000 square degrees with an effective angular resolution of $12\farcm8$, allowing for constraints on primordial gravitational waves and high–signal-to-noise measurements of the E-modes across three acoustic peaks. The data reduction was performed using two independent analysis pipelines, one based on a pseudo-C_ℓ (PCL) cross-correlation approach, and the other on a maximum-likelihood (ML) approach. All data selection criteria and filters were modified until a predefined set of null tests had been satisfied before inspecting any non-null power spectrum. The results derived by the two pipelines are in good agreement. We characterize the EE, EB and BB power spectra between $\ell = 25$ and 975 and find that the EE spectrum is consistent with ΛCDM, while the BB power spectrum is consistent with zero. Based on these measurements, we constrain the tensor-to-scalar ratio to $r = 1.1^{+0.9}_{-0.8}$ ($r < 2.8$ at 95% C.L.) as derived by the ML pipeline, and $r = 1.2^{+0.9}_{-0.8}$ ($r < 2.7$ at 95% C.L.) as derived by the PCL pipeline. In one of the fields, we find a correlation with the dust component of the Planck Sky Model, though the corresponding excess power is small compared to statistical errors. Finally, we derive limits on all known systematic errors, and demonstrate that these correspond to a tensor-to-scalar ratio smaller than $r = 0.01$, the lowest level yet reported in the literature.

Subject headings: cosmic background radiation—Cosmology: observations—Gravitational waves—inflation—Polarization

THE QUIET INSTRUMENT

QUIET COLLABORATION—C. BISCHOFF[1,20], A. BRIZIUS[1,2], I. BUDER[1,20], Y. CHINONE[3,4], K. CLEARY[5], R. N. DUMOULIN[6], A. KUSAKA[1,19], R. MONSALVE[7], S. K. NÆSS[8], L. B. NEWBURGH[6,19], G. NIXON[19], R. REEVES[5], K. M. SMITH[1,19], K. VANDERLINDE[1,23], I. K. WEHUS[9,10], M. BOGDAN[1], R. BUSTOS[7,11,12], S. E. CHURCH[13], R. DAVIS[14], C. DICKINSON[14], H. K. ERIKSEN[8,15], T. GAIER[16], J. O. GUNDERSEN[7], M. HASEGAWA[3], M. HAZUMI[3], C. HOLLER[10], K. M. HUFFENBERGER[7], W. A. IMBRIALE[16], K. ISHIDOSHIRO[3], M. E. JONES[10], P. KANGASLAHTI[16], D. J. KAPNER[1,21], C. R. LAWRENCE[16], E. M. LEITCH[16], M. LIMON[6], J. J. MCMAHON[17], A. D. MILLER[6], M. NAGAI[3], H. NGUYEN[18], T. J. PEARSON[5], L. PICCIRILLO[14], S. J. E. RADFORD[5], A. C. S. READHEAD[5], J. L. RICHARDS[5], D. SAMTLEBEN[2,22], M. SEIFFERT[16], M. C. SHEPHERD[5], S. T. STAGGS[19], O. TAJIMA[1,3], K. L. THOMPSON[13], R. WILLIAMSON[6,1], B. WINSTEIN[1,†], E. J. WOLLACK[24], J. T. L. ZWART[6,25]

Submitted to ApJ—This paper should be cited as "QUIET Collaboration (2012)"

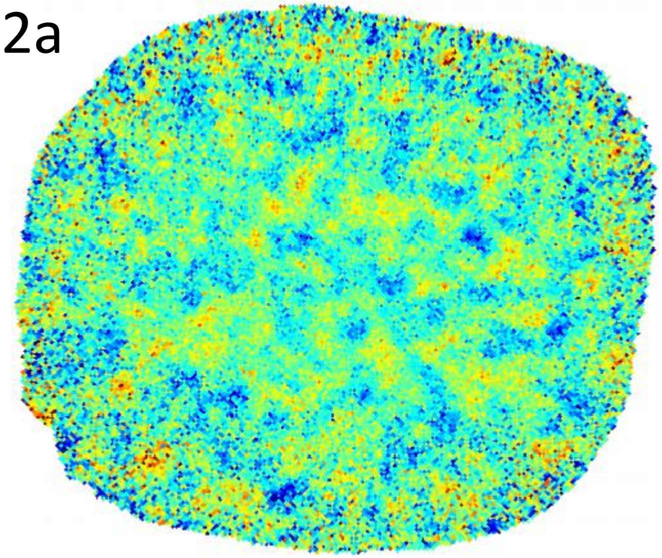
ABSTRACT

The Q/U Imaging ExperimenT (QUIET) is designed to measure polarization in the Cosmic Microwave Background, targeting the imprint of inflationary gravitational waves at large angular scales ($\sim 1°$). Between 2008 October and 2010 December, two independent receiver arrays were deployed sequentially on a 1.4 m side-fed Dragonian telescope. The polarimeters which form the focal planes use a highly compact design based on High Electron Mobility Transistors (HEMTs) that provides simultaneous measurements of the Stokes parameters Q, U, and I in a single module. The 17-element Q-band polarimeter array, with a central frequency of 43.1 GHz, has the best sensitivity ($69\,\mu\mathrm{Ks}^{1/2}$) and the lowest instrumental systematic errors ever achieved in this band, contributing to the tensor-to-scalar ratio at $r < 0.1$. The 84-element W-band polarimeter array has a sensitivity of $87\,\mu\mathrm{Ks}^{1/2}$ at a central frequency of 94.5 GHz. It has the lowest systematic errors to date, contributing at $r < 0.01$ (QUIET Collaboration 2012) The two arrays together cover multipoles in the range $\ell \approx 25-975$. These are the largest HEMT-based arrays deployed to date. This article describes the design, calibration, performance of, and sources of systematic error for the instrument.

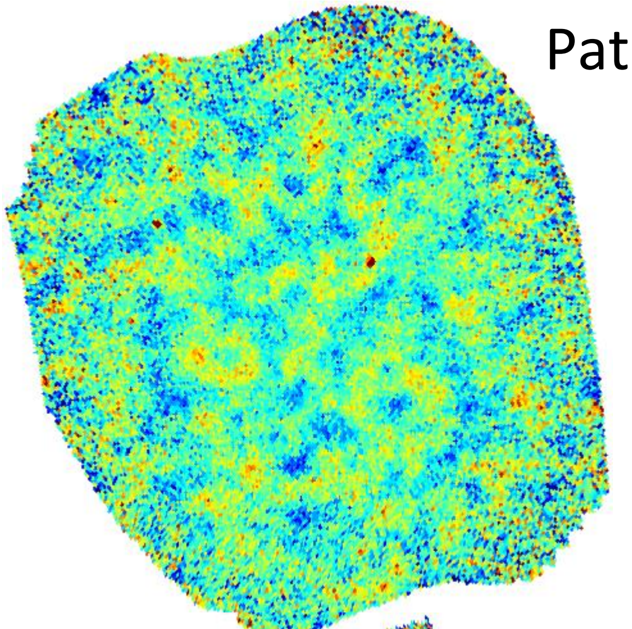
Subject headings: cosmology: cosmic microwave background — cosmology: observations — astronomical instrumentation: polarimeters — astronomical instrumentation: detectors — astronomical instrumentation: telescopes

Temperature maps – QUIET vs WMAP

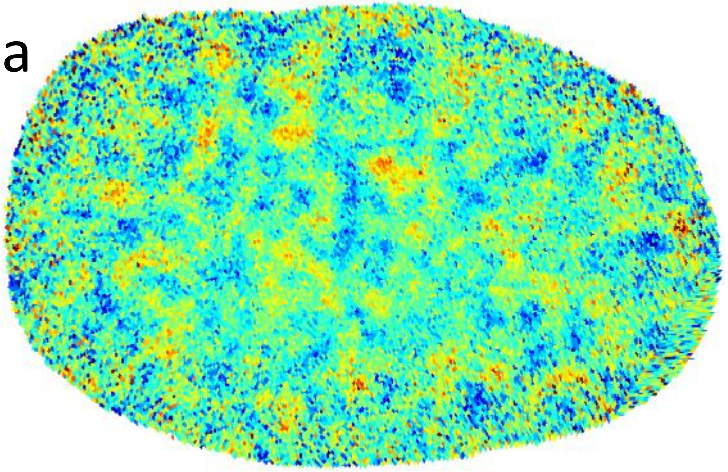
Patch 2a



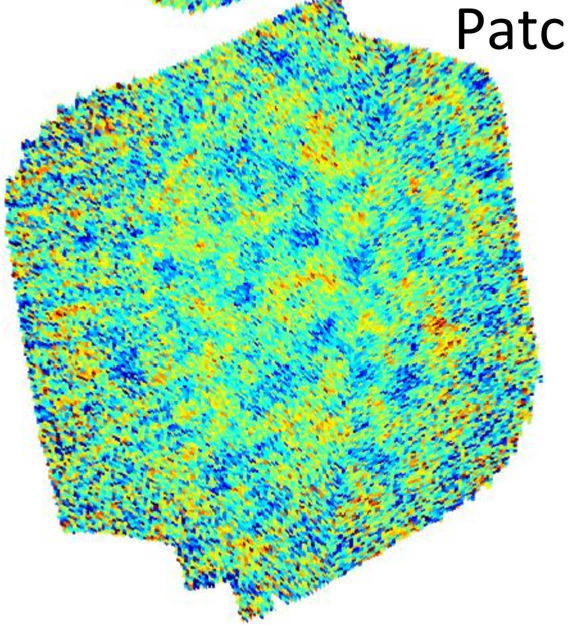
Patch 4a



Patch 6a

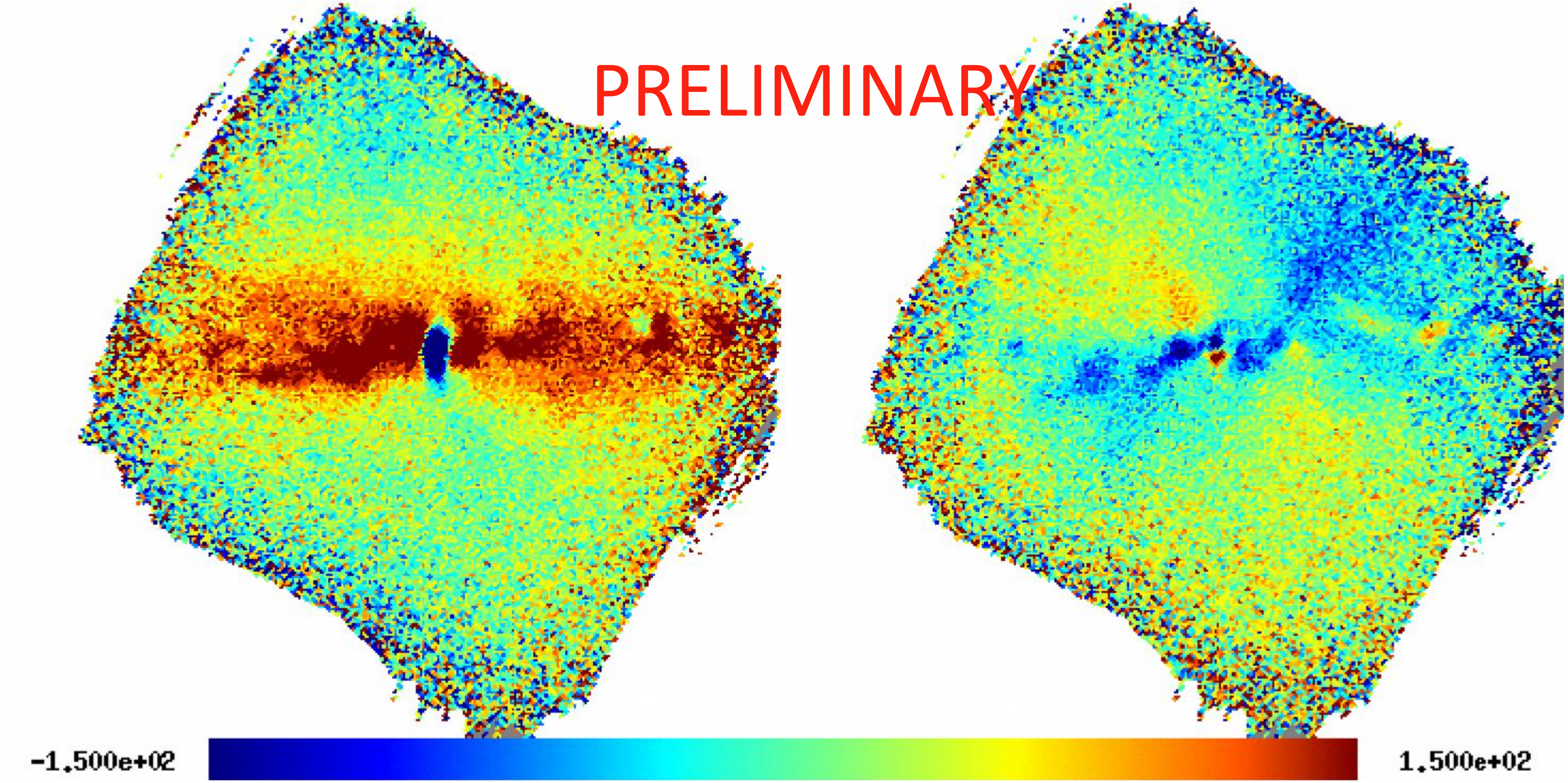


Patch 7b



Note: Slight gain excess, about 10% (Jupiter calibration)

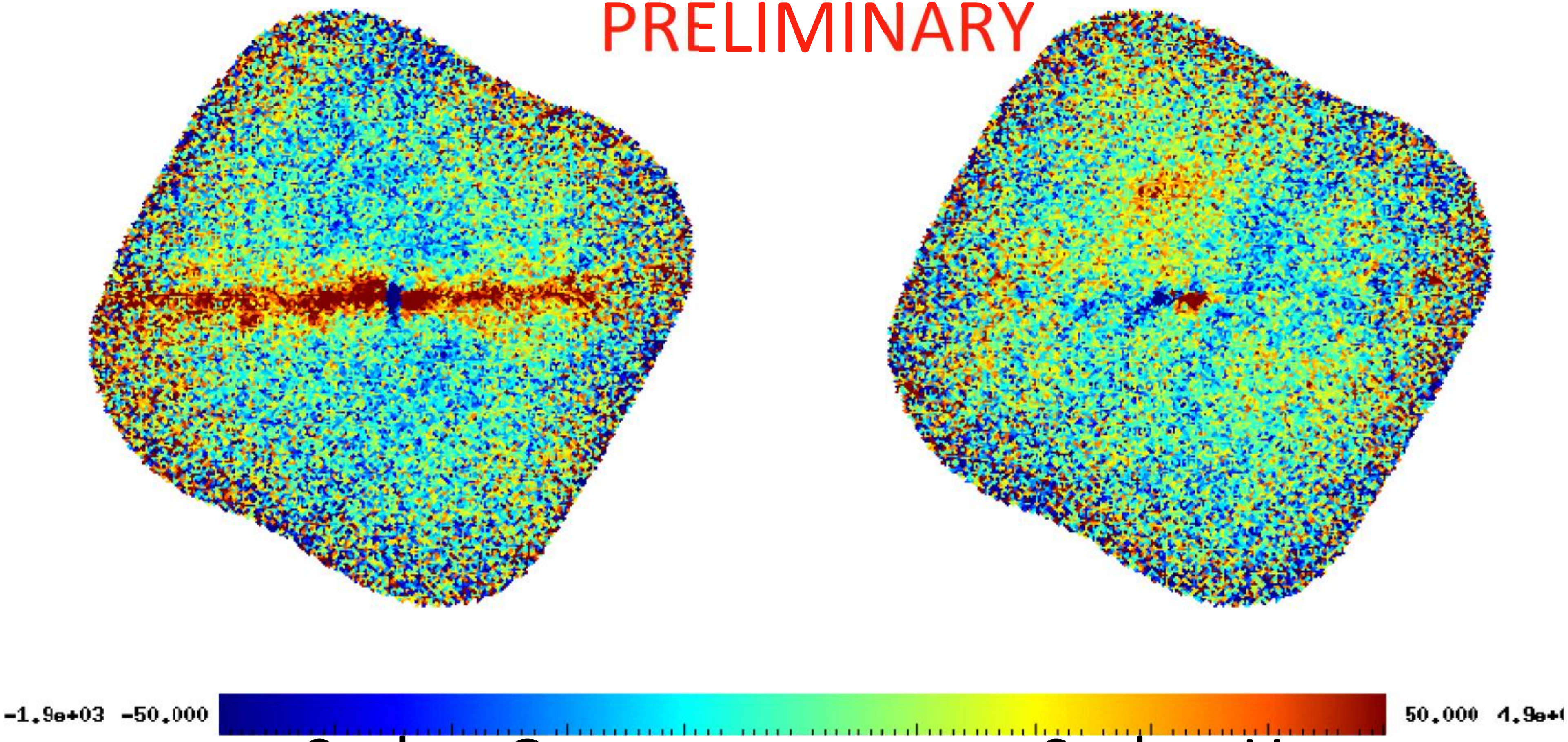
Galactic center observed at 43 GHz



Stokes Q

Stokes U

Galactic center observed 95 GHz



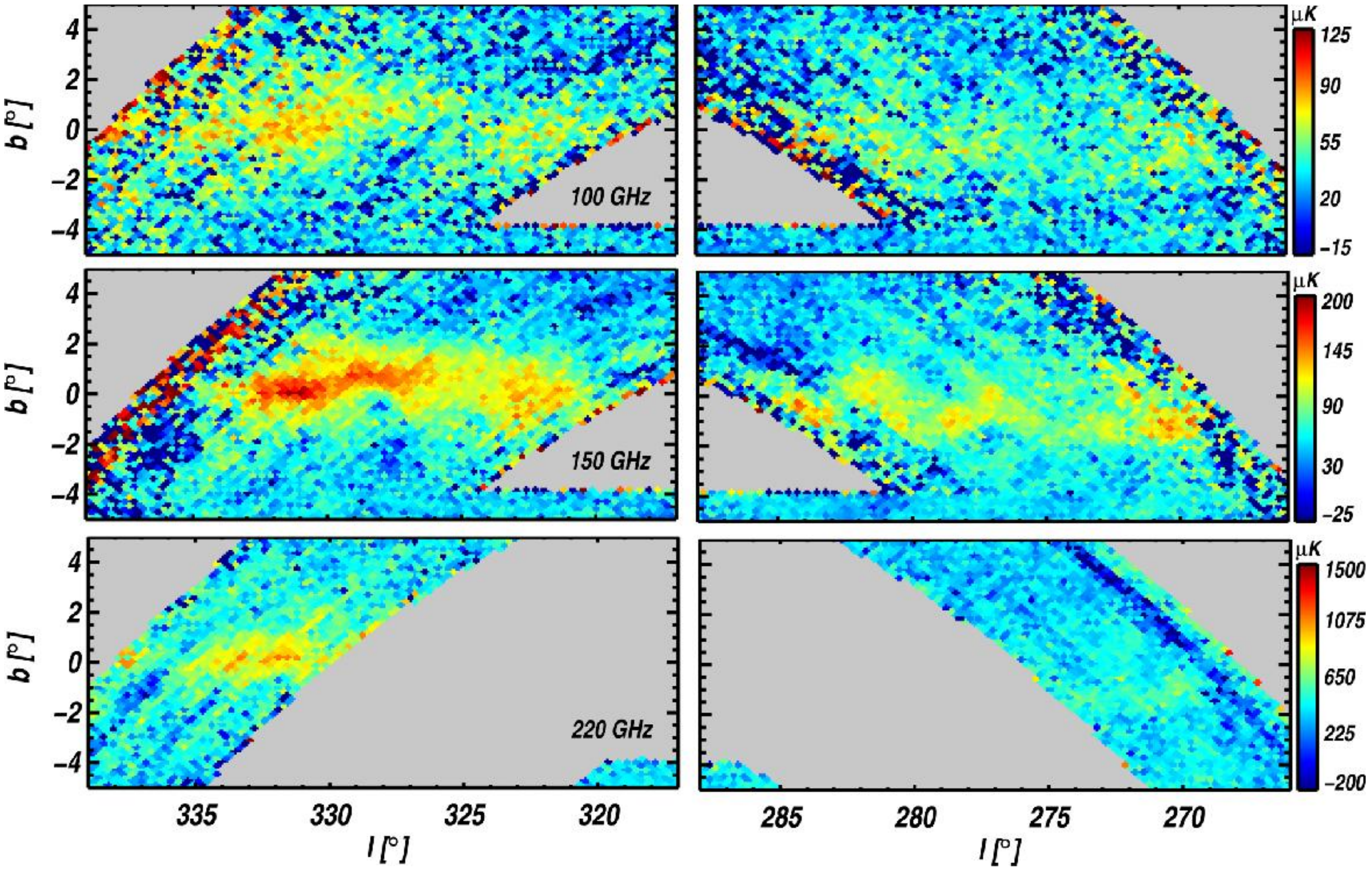
PRELIMINARY

Stokes Q

Stokes U

BICEP

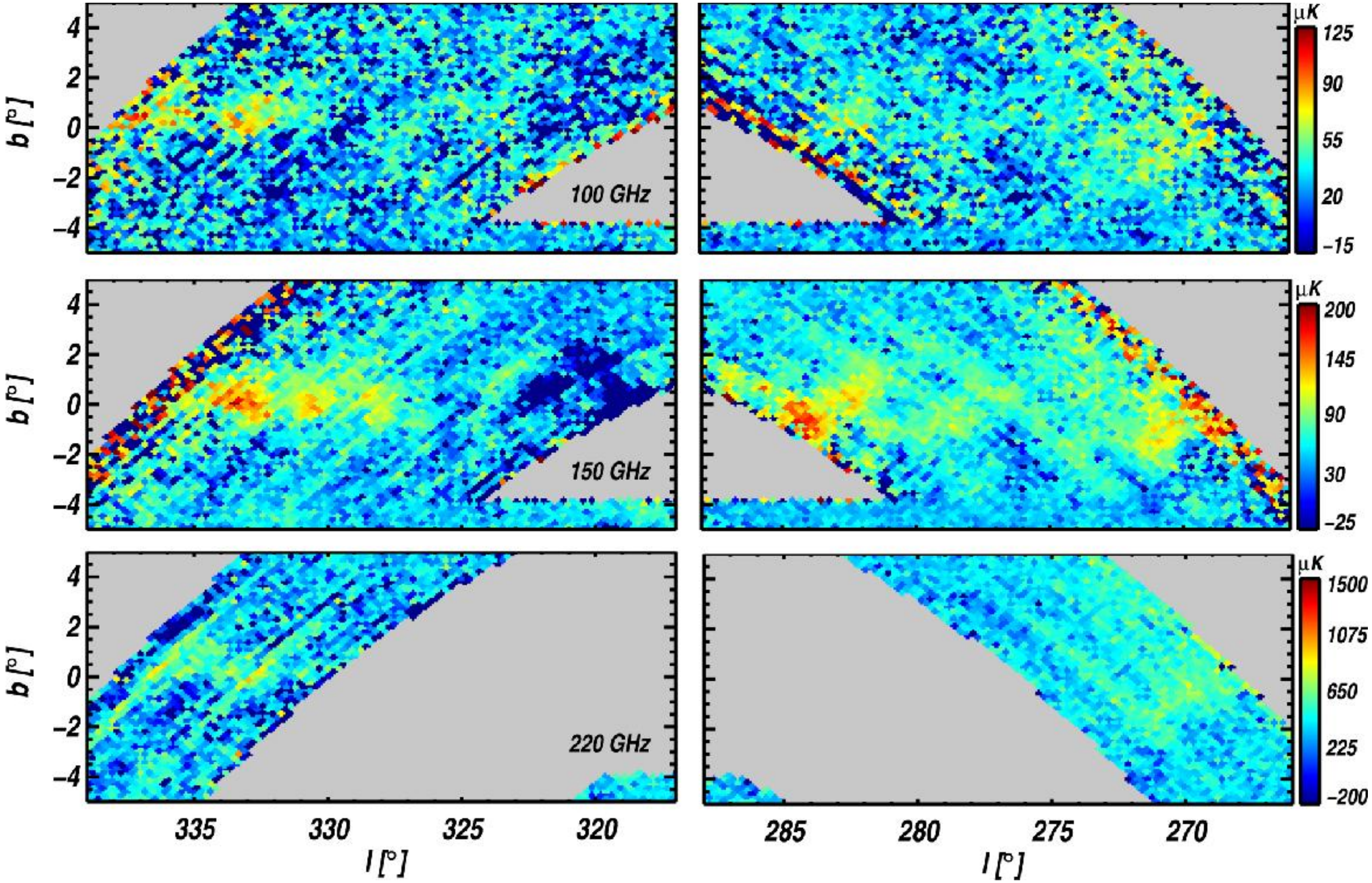
Stokes Q



Observations at 100, 150 and 220 GHz

BICEP

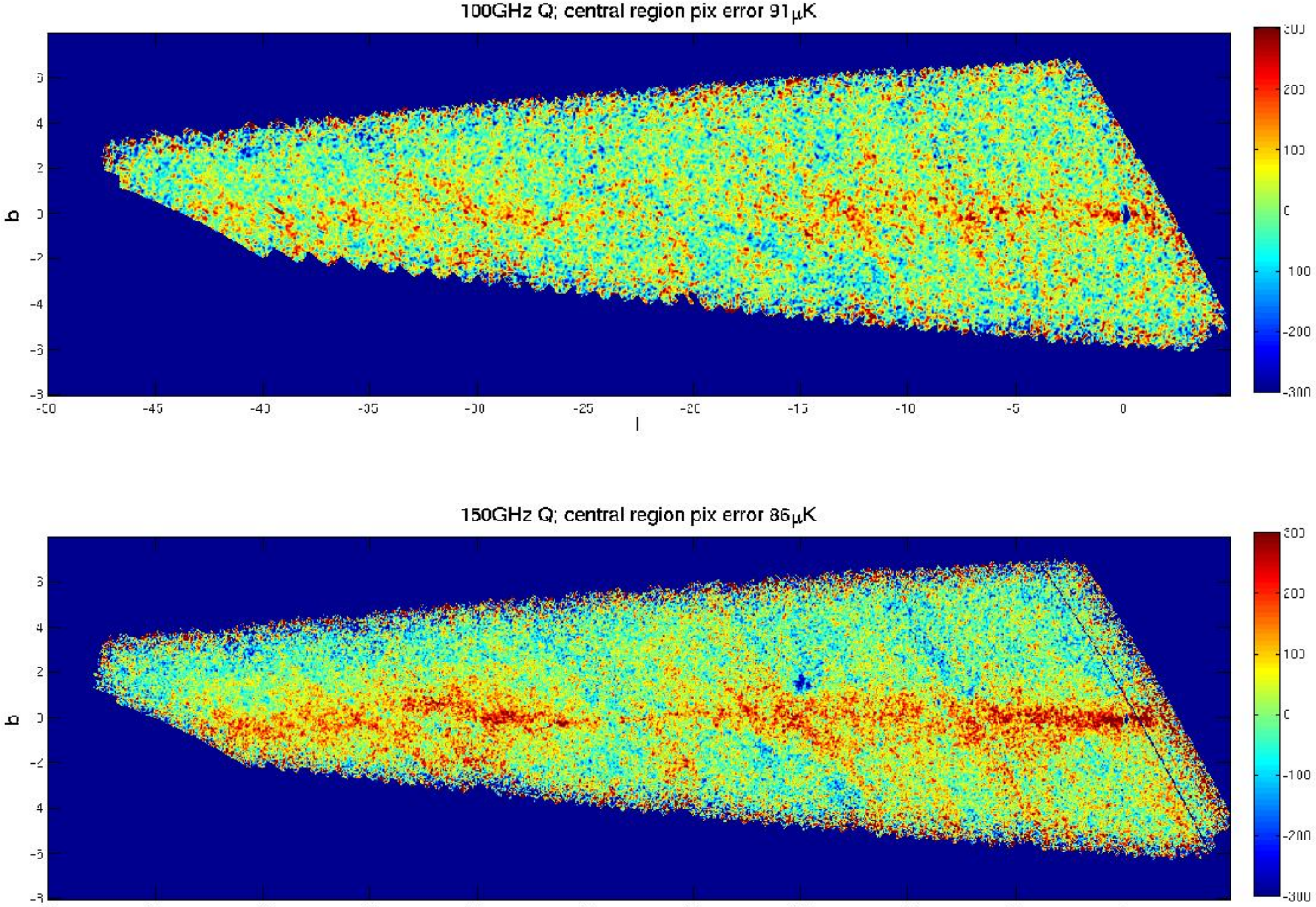
Stokes U



Observations at 100, 150 and 220 GHz

QUAD

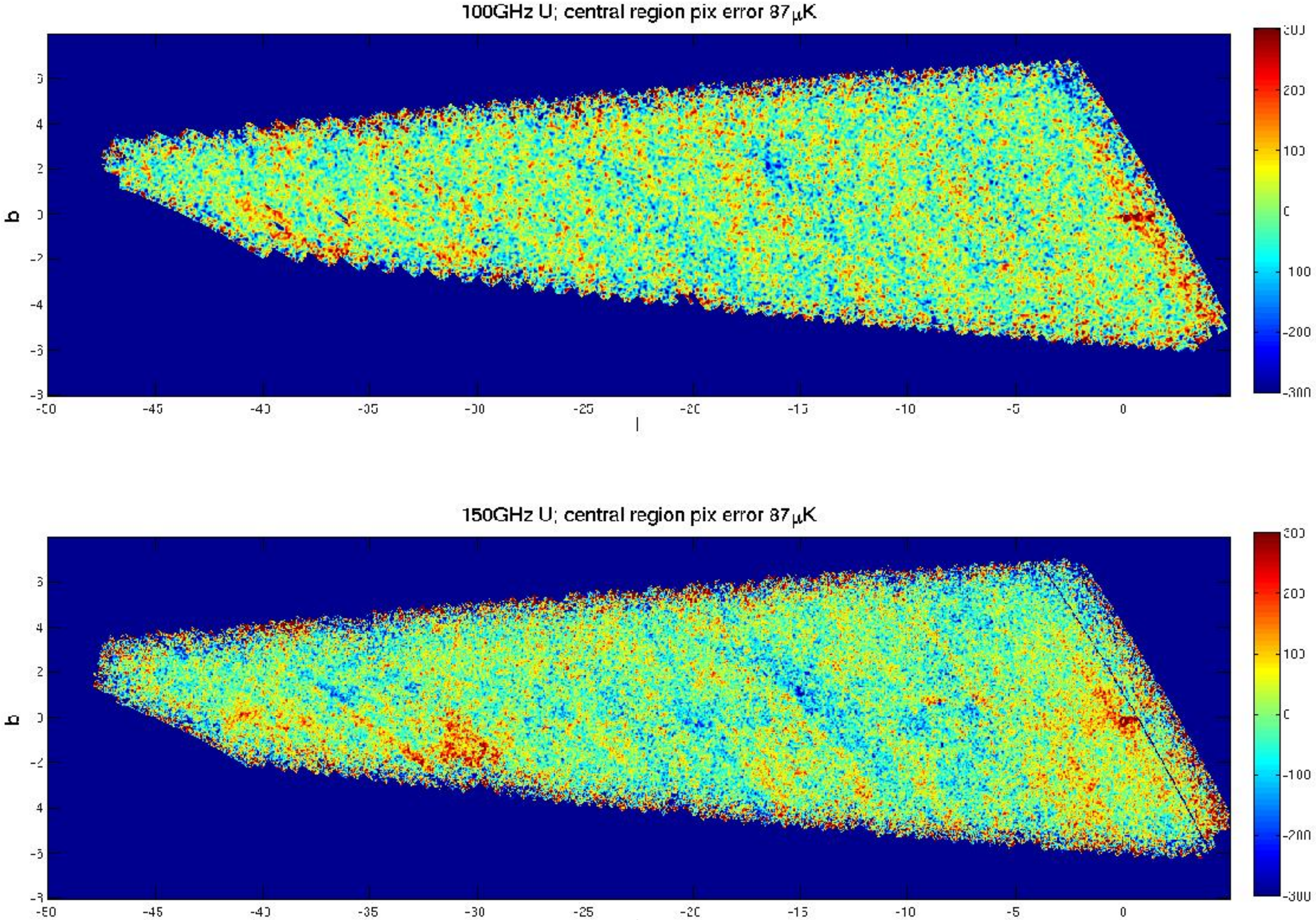
Stokes Q



Observations at 100 and 150 GHz

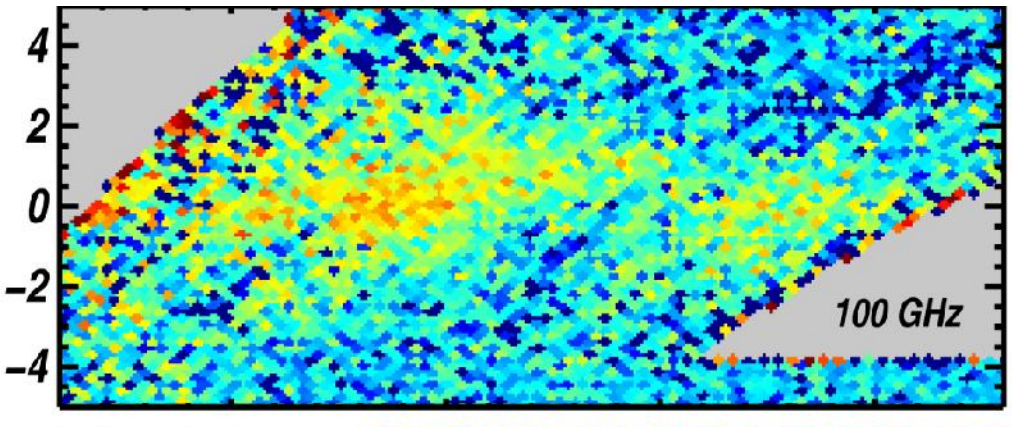
QUAD

Stokes U

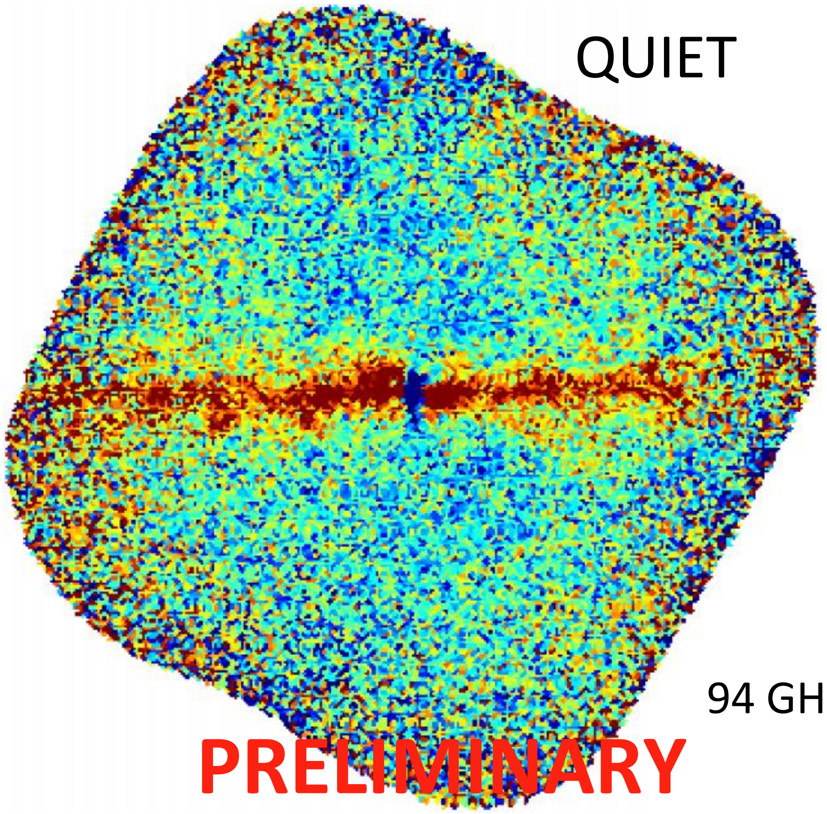


Observations at 100 and 150 GHz

BICEP

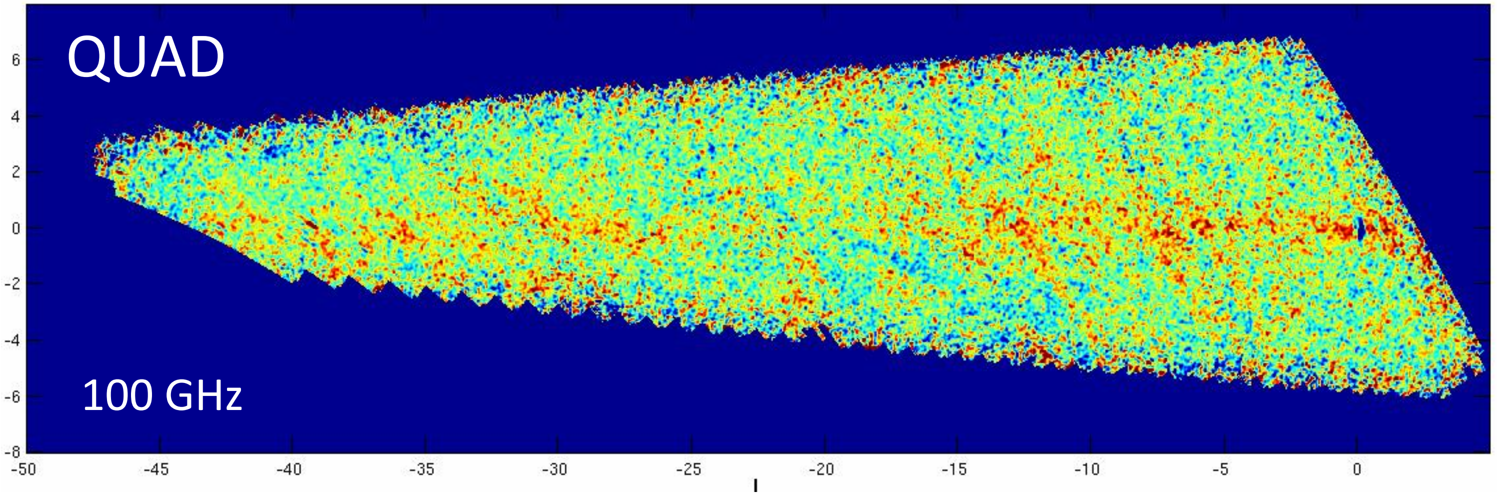


QUIET

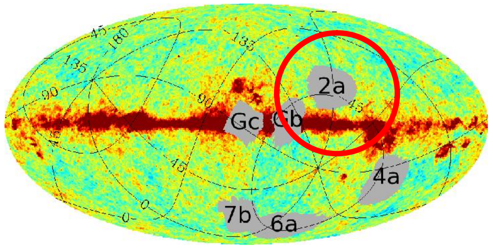

94 GHz

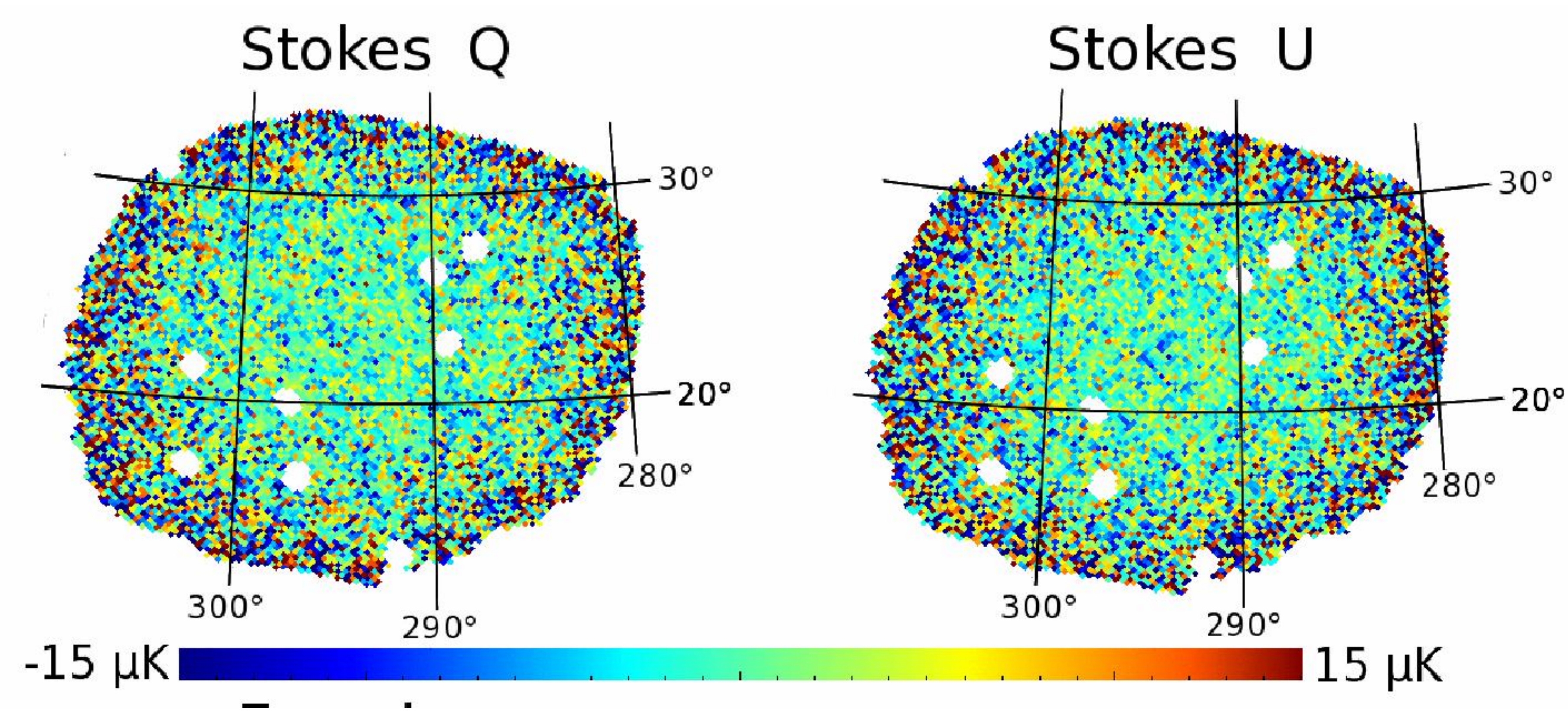
PRELIMINARY

QUAD

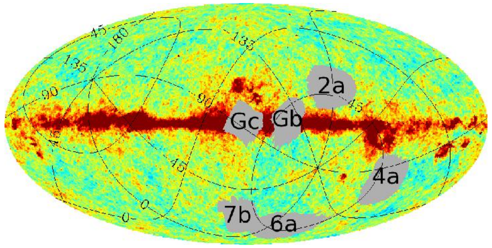

100 GHz

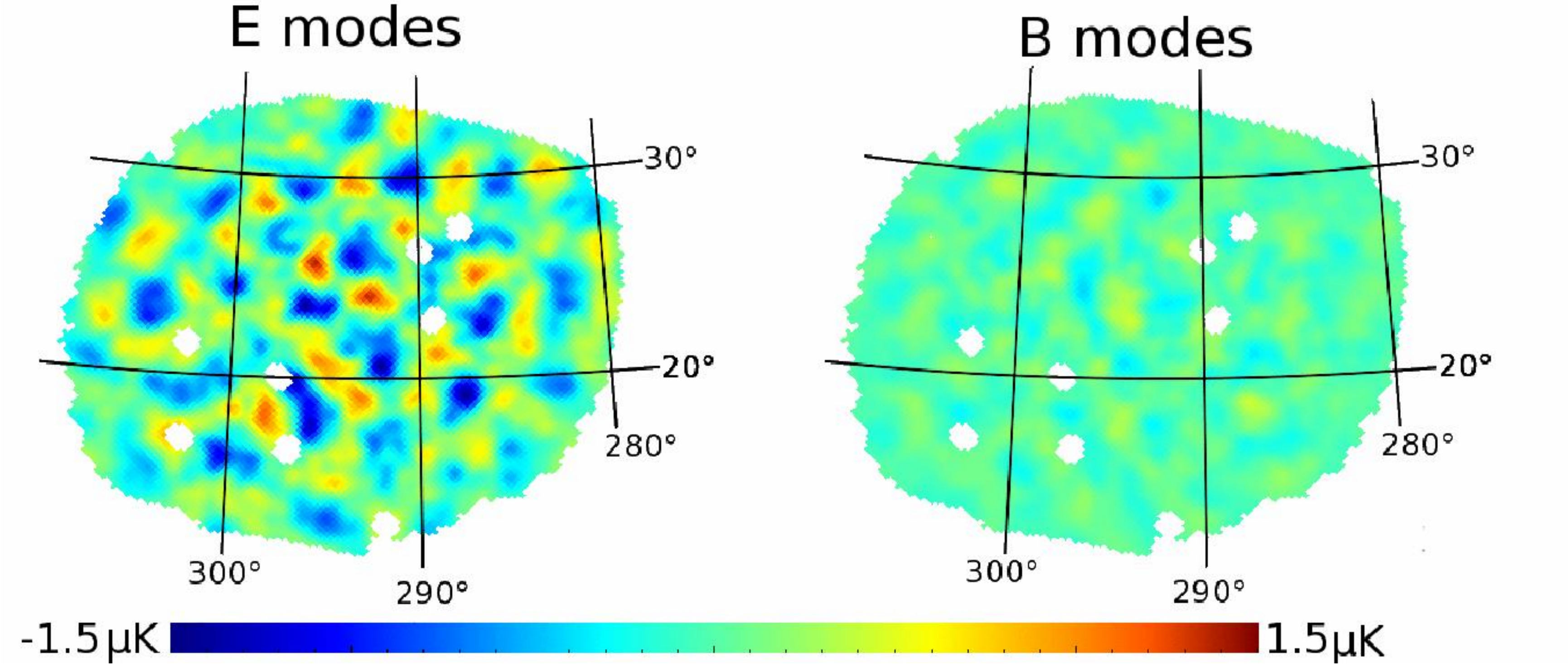
Patch 2a at 43 GHz



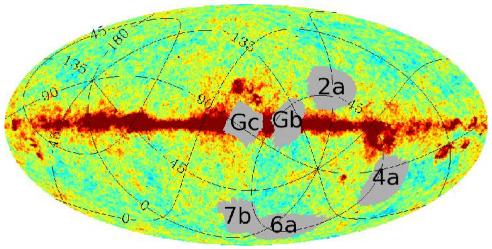


Patch 2a at 43 GHz



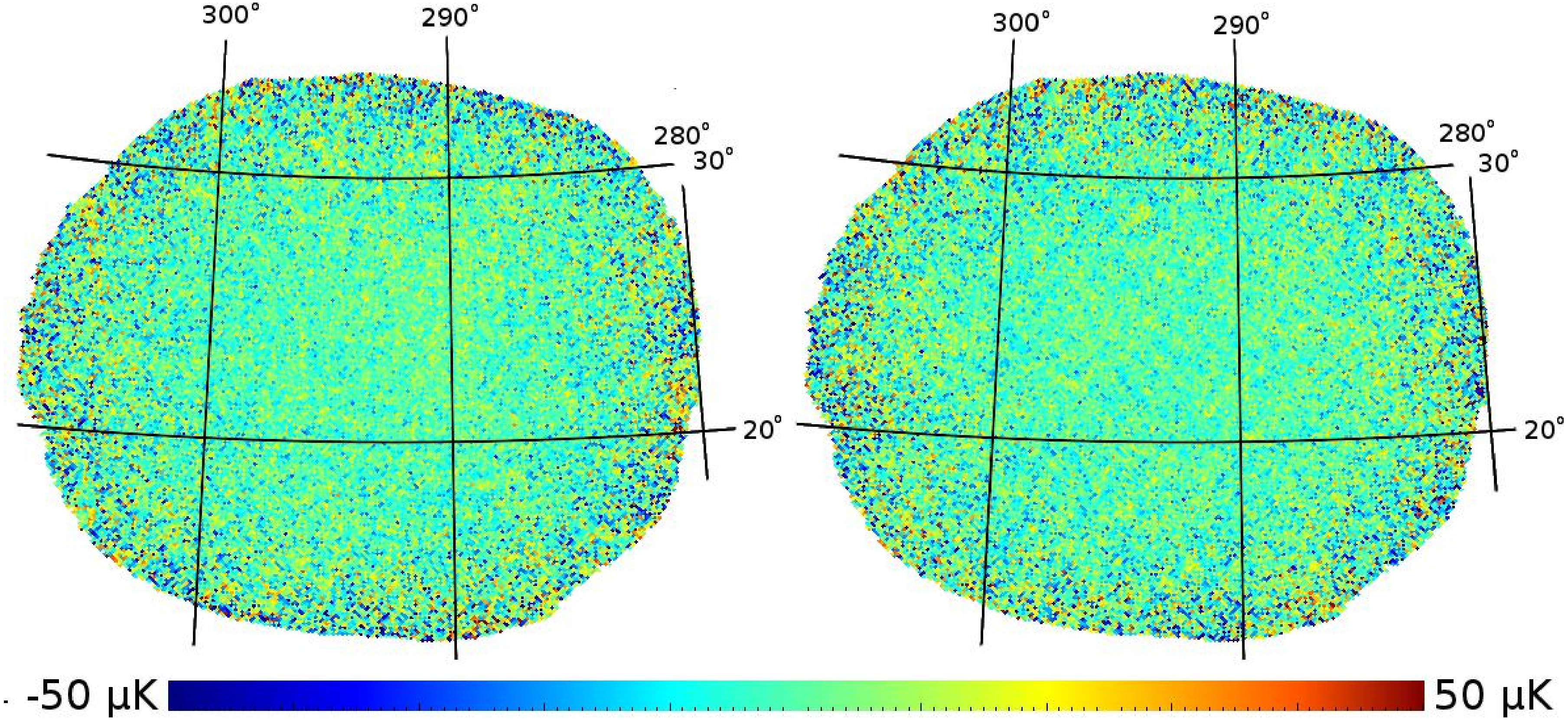


Patch 2a at 95 GHz

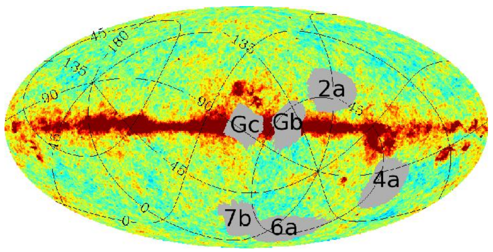


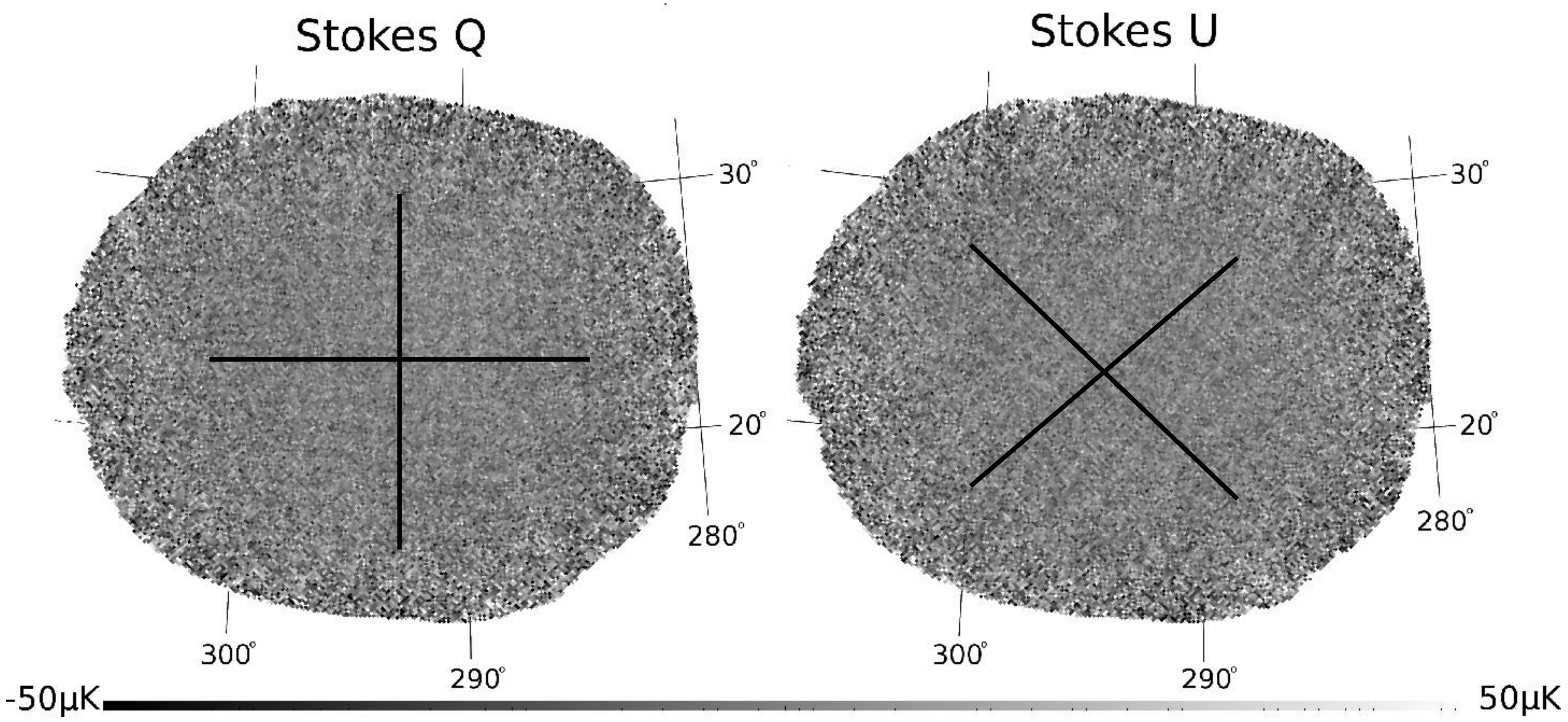
Stokes Q

Stokes U



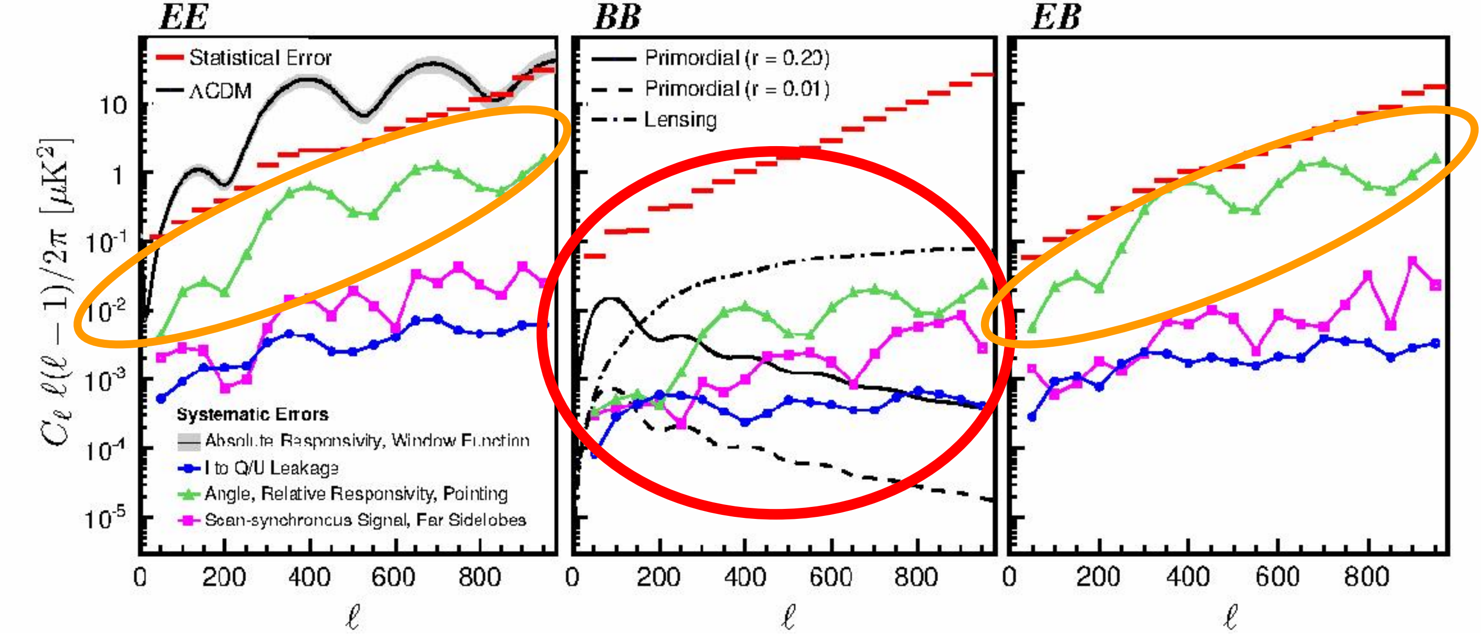
Patch 2a at 95 GHz





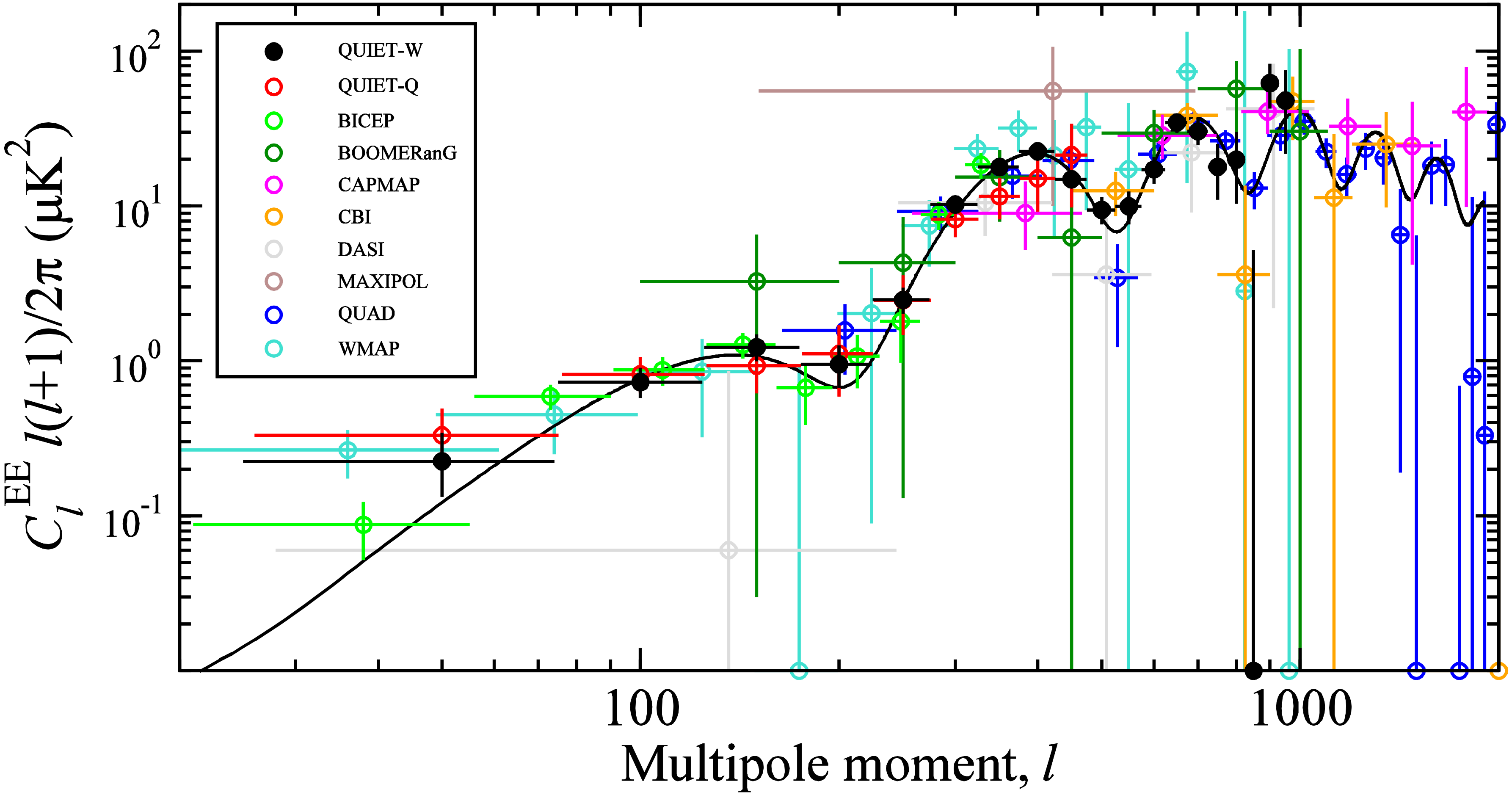
= E-mode signal by eye!

Assessment of systematic errors

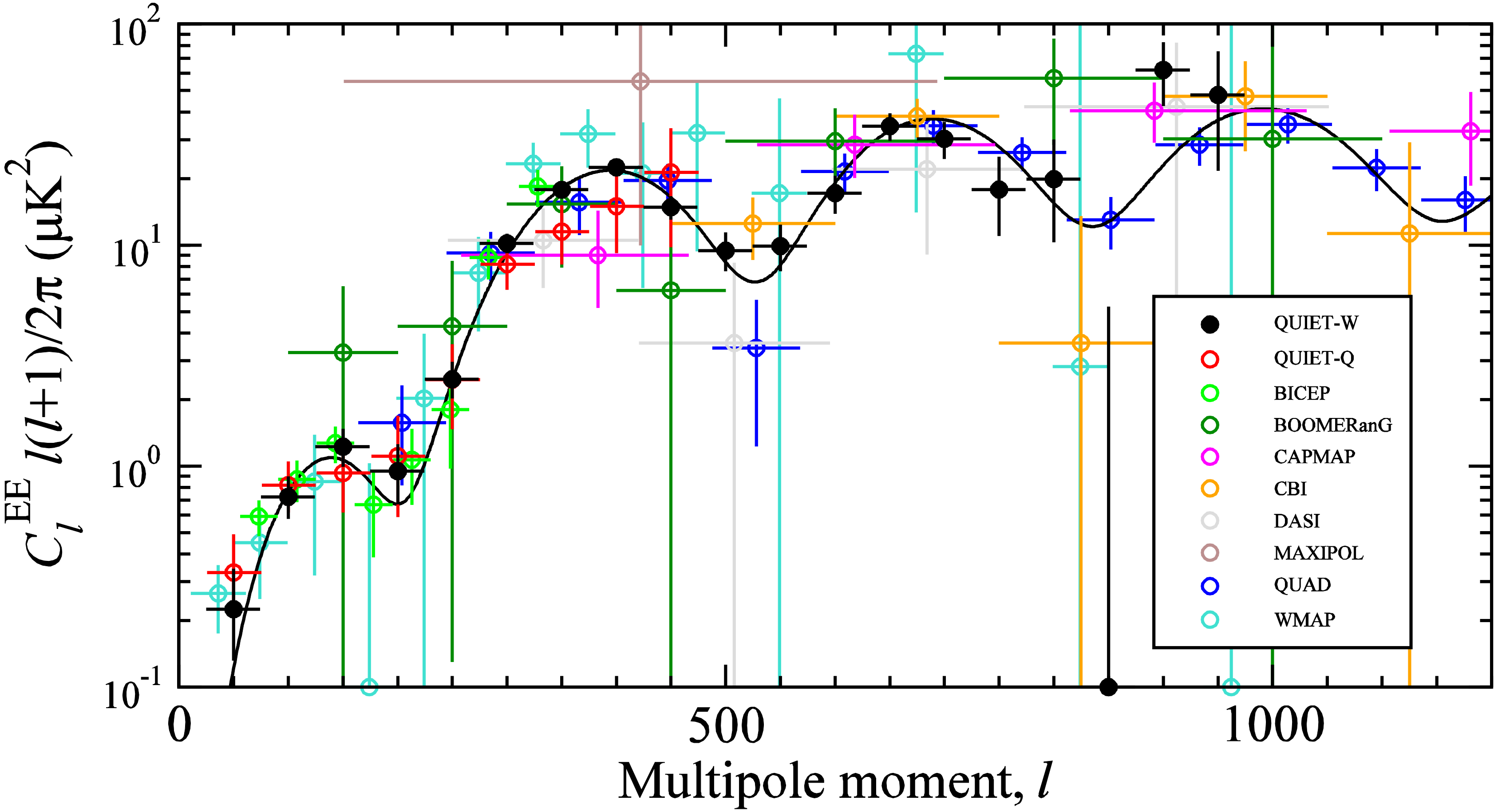


- All known instrumental systematic effects are assessed by processing empirical models through the full pipeline
- The main EE systematic is absolute gain uncertainties
- The main EB systematic is polarization angle uncertainties
- But NO LARGE BB systematics!
  - Corresponds to a tensor-to-scalar ratio of $r < 0.01$ on degree scales
- Lowest levels of B-mode systematics reported so far

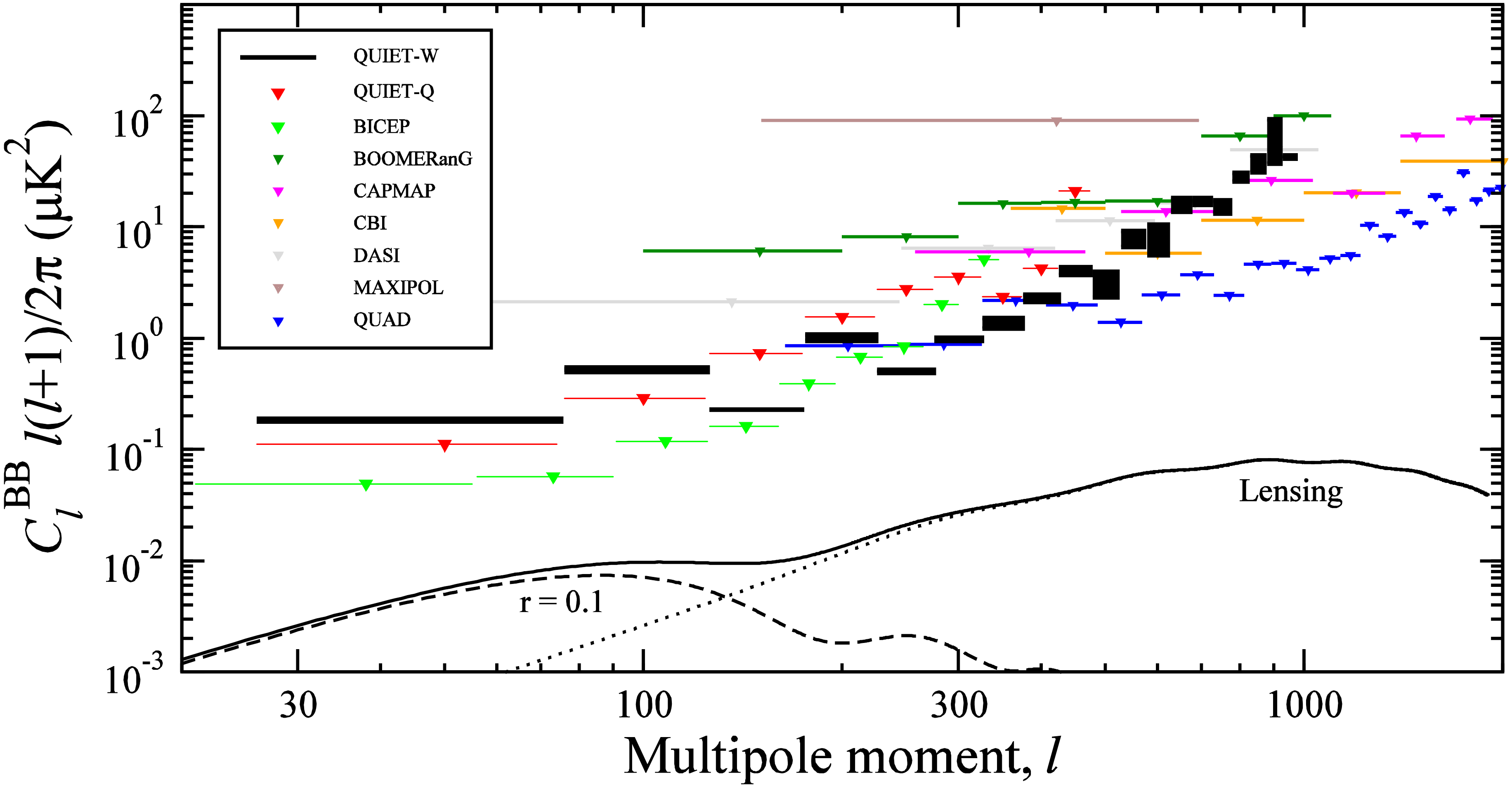
Comparison with ΛCDM



Comparison with ΛCDM



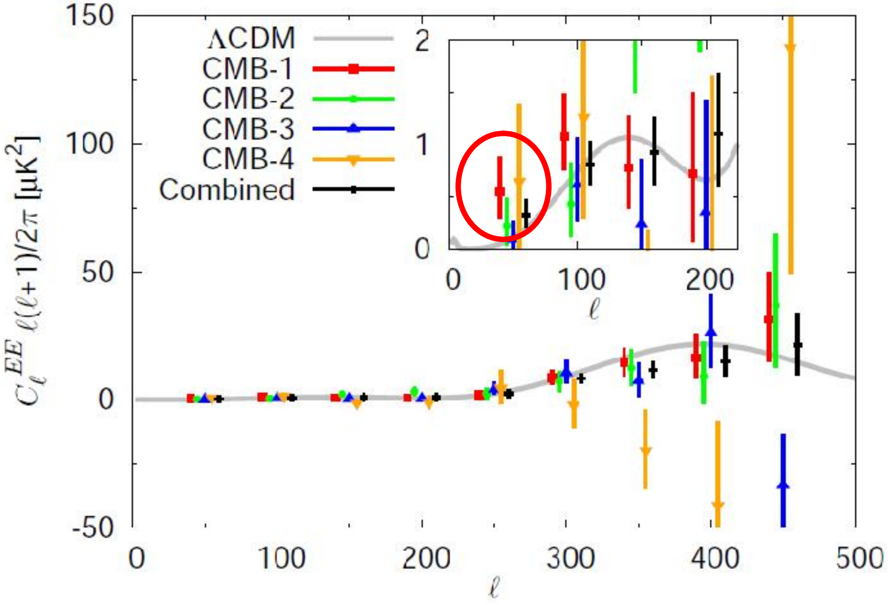
The BB spectrum and tensor-to-scalar ratio



Tensor-to-scalar ratio: $r = 1.1^{+0.9}_{-0.8}$ r < 2.8 @ 95% CL (ML)

$r = 1.2^{+0.9}_{-0.8}$ r < 2.7 @ 95% CL (PCL)

1) Synchrotron contamination at 43 GHz



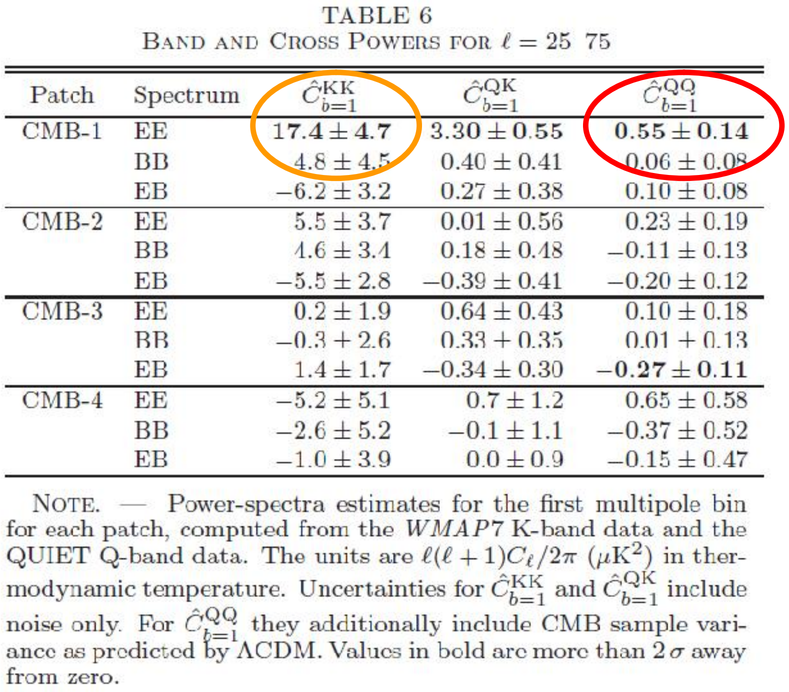


TABLE 6

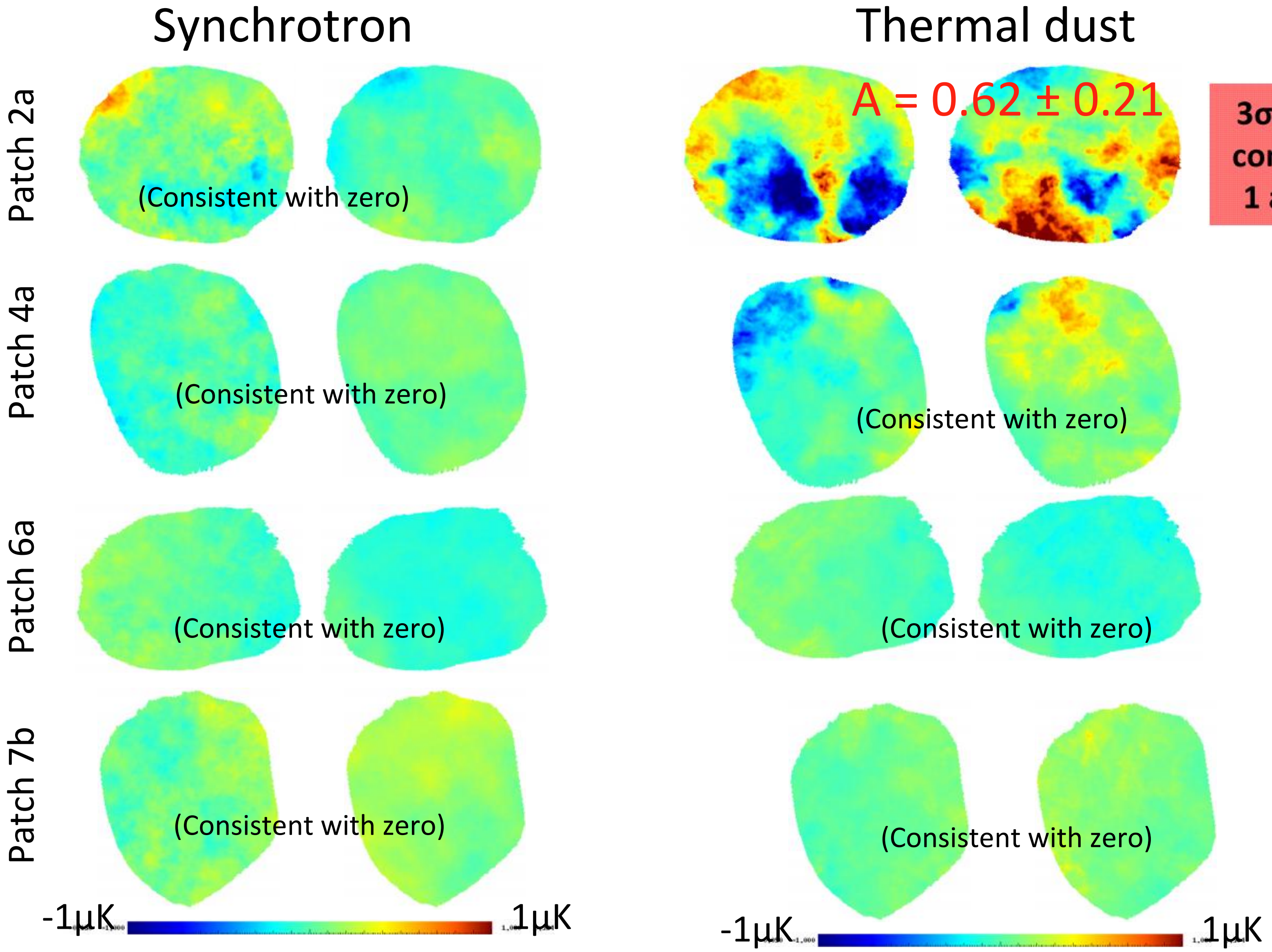
Band and Cross Powers for $\ell = 25$ 75

Patch	Spectrum	$\hat{C}^{\mathrm{KK}}_{b=1}$	$\hat{C}^{\mathrm{QK}}_{b=1}$	$\hat{C}^{\mathrm{QQ}}_{b=1}$
CMB-1	EE	$\mathbf{17.4 \pm 4.7}$	3.30 ± 0.55	$\mathbf{0.55 \pm 0.14}$
	BB	4.8 ± 4.5	0.40 ± 0.41	0.06 ± 0.08
	EB	-6.2 ± 3.2	0.27 ± 0.38	0.10 ± 0.08
CMB-2	EE	5.5 ± 3.7	0.01 ± 0.56	0.23 ± 0.19
	BB	4.6 ± 3.4	0.18 ± 0.48	-0.11 ± 0.13
	EB	-5.5 ± 2.8	-0.39 ± 0.41	-0.20 ± 0.12
CMB-3	EE	0.2 ± 1.9	0.64 ± 0.43	0.10 ± 0.18
	BB	-0.3 ± 2.6	0.33 ± 0.35	0.01 ± 0.13
	EB	1.4 ± 1.7	-0.34 ± 0.30	$\mathbf{-0.27 \pm 0.11}$
CMB-4	EE	-5.2 ± 5.1	0.7 ± 1.2	0.65 ± 0.58
	BB	-2.6 ± 5.2	-0.1 ± 1.1	-0.37 ± 0.52
	EB	-1.0 ± 3.9	0.0 ± 0.9	-0.15 ± 0.47

Note. — Power-spectra estimates for the first multipole bin for each patch, computed from the *WMAP7* K-band data and the QUIET Q-band data. The units are $\ell(\ell+1)C_\ell/2\pi$ (μK^2) in thermodynamic temperature. Uncertainties for $\hat{C}^{\mathrm{KK}}_{b=1}$ and $\hat{C}^{\mathrm{QK}}_{b=1}$ include noise only. For $\hat{C}^{\mathrm{QQ}}_{b=1}$ they additionally include CMB sample variance as predicted by ΛCDM. Values in bold are more than $2\,\sigma$ away from zero.

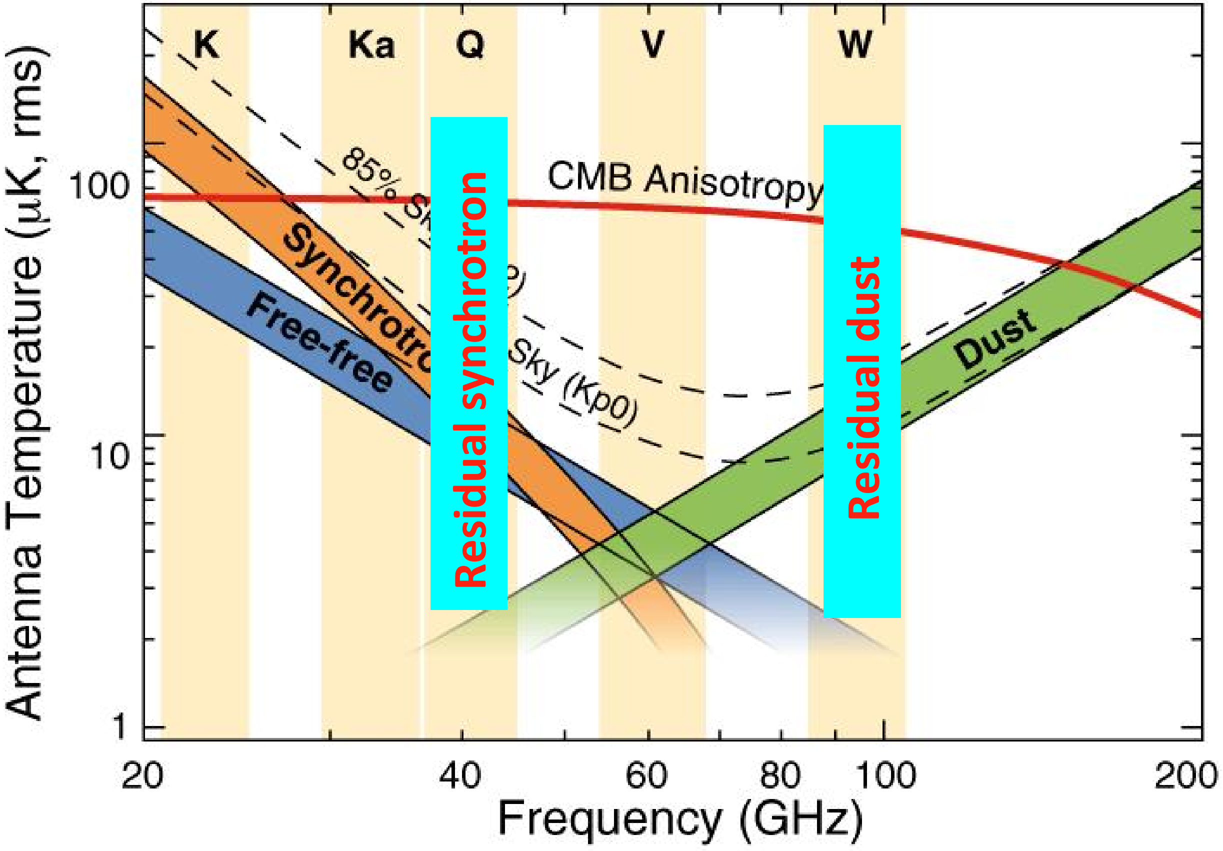
- Observe excess power in patch 2a at 43 GHz
- Fully consistent with WMAP 23 GHz scaled by a spectral index of -3
  - Clear evidence of residual synchrotron contamination at 43 GHz

2) PSM dust correlation at 95 GHz



3σ correlation, consistent with 1 at 1.6 sigma

Where is the foreground minimum in polarization?

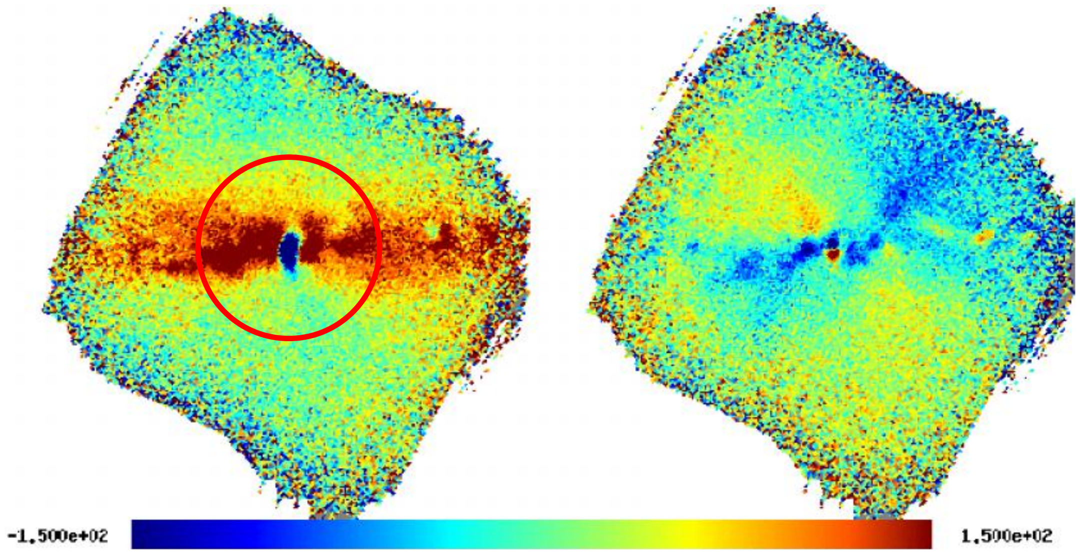


Cartoon based on WMAP temperature observations

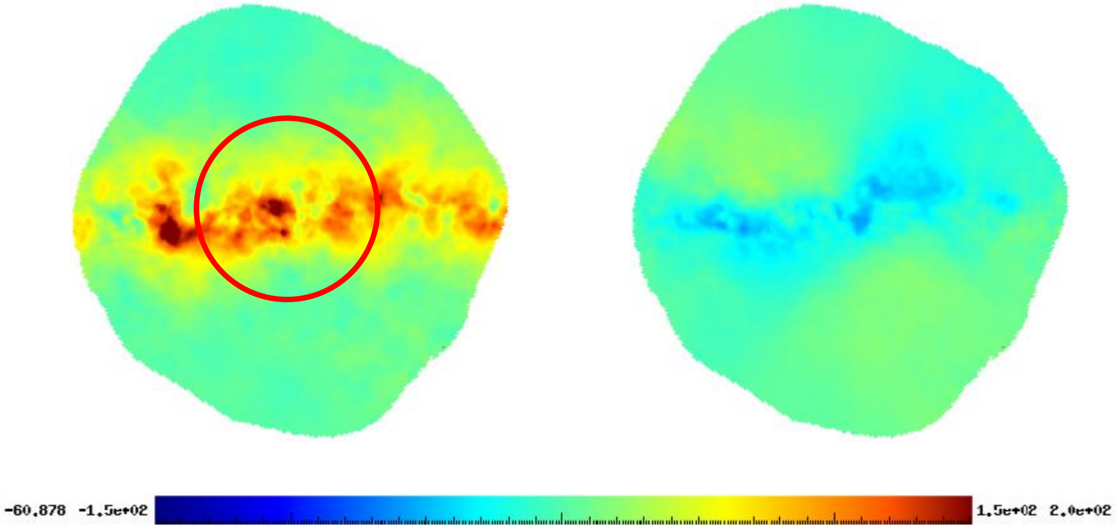
⇒ Polarized foreground minimum is also likely to lie between 60 and 80 GHz

A side comment on the PSM

QUIET/WMAP



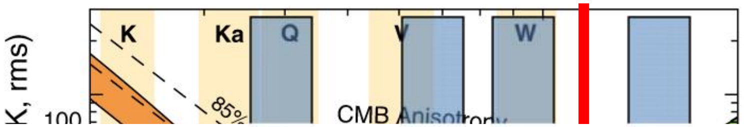
PSM



How would *I* design the next CMB satellite?

1. Following in the proud footsteps of well-known CMB names like CambSpec, Plik, BolPol and ROMAster, I would first of all call the project ***HKEpol***
    - Disclaimer 1: All of the following represent my own personal view, and not necessarily those of the QUIET collaboration as a whole ☺
    - Disclaimer 2: Many of the following statements are controversial by design, to stimulate discussion

2. HKEpol would have *at least four* bands:
    - 35-45 GHz for synchrotron
    - 61-79 GHz as first CMB channel
    - 83-107 GHz as second CMB channel
    - 140-180 GHz as dust channel



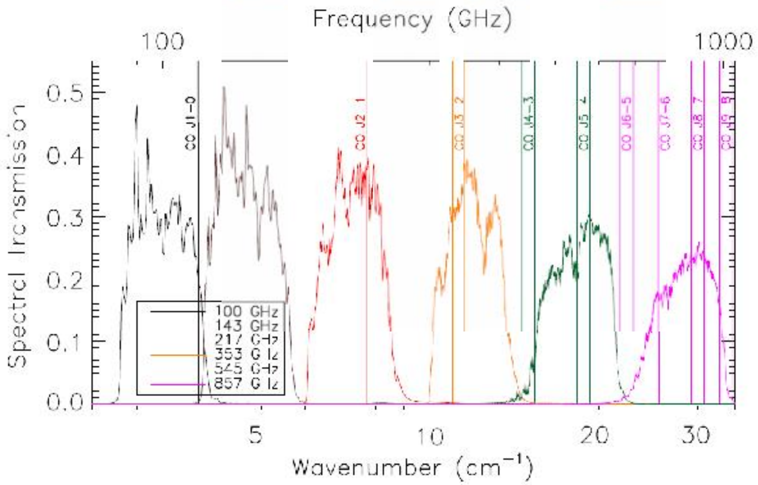


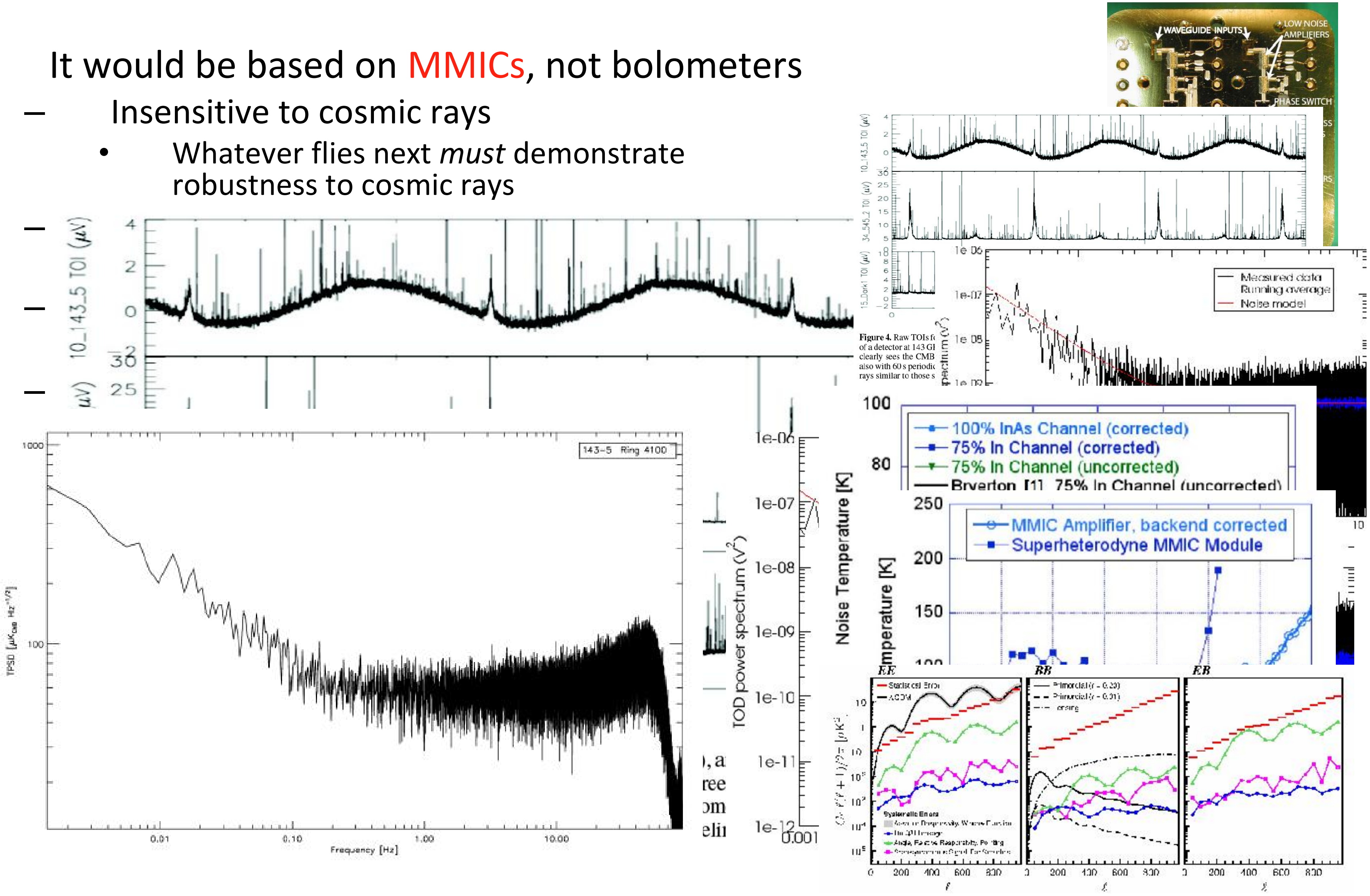
Figure 44. The average spectral response for each of the HFI frequency bands. The vertical bars represent the spectral regions of CO transitions and are interpolated by a factor of ~ 10.

Comments:

- Planck+WMAP will give spectral indices, but I wouldn't trust them for amplitudes
- Stay a *long way away* from CO lines at *N* times 115 GHz
    - Particularly nasty because of bandpass mismatch
    - Also other lines at 110 GHz

How would *I* design the next CMB satellite?

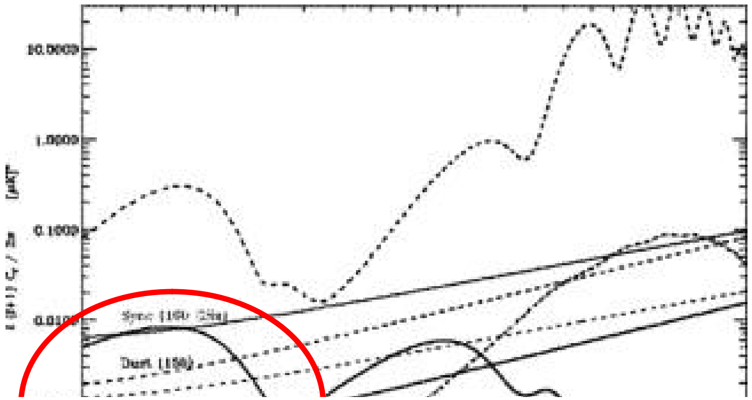
3. It would be based on MMICs, not bolometers
   - Insensitive to cosmic rays
     - Whatever flies next *must* demonstrate robustness to cosmic rays

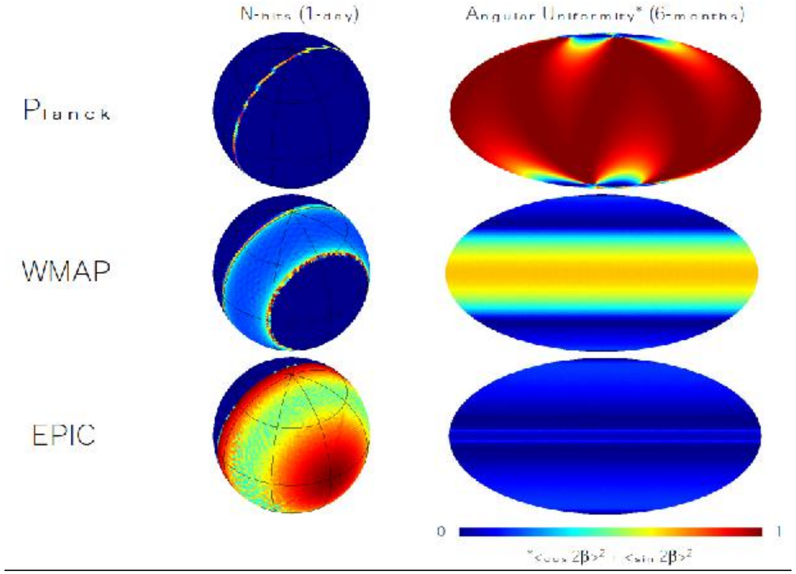


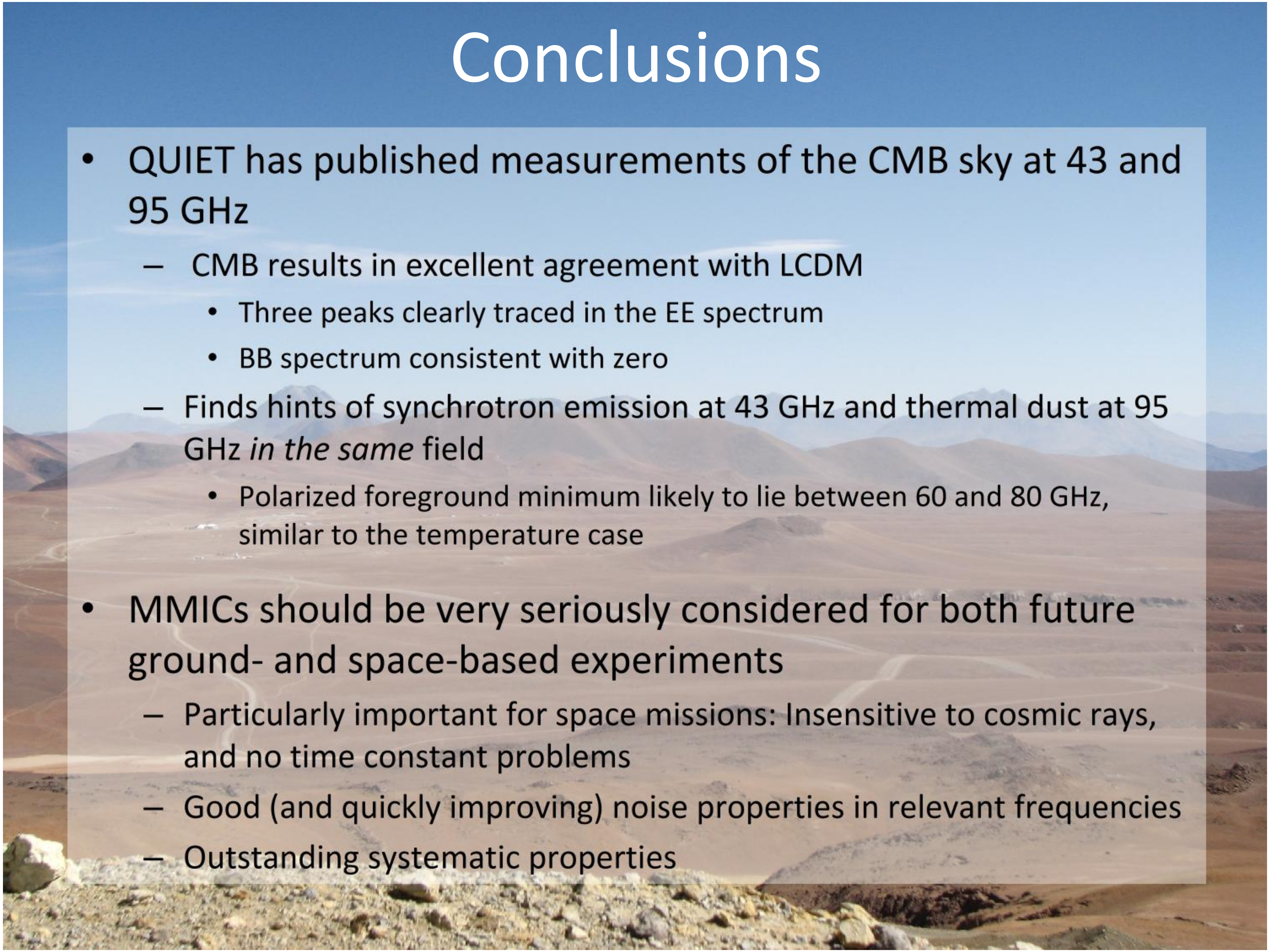
How would *I* design the next CMB satellite?

4. If cost is a driver, I would sacrifice angular resolution before virtually anything that compromises control over large-angle systematics
   - This experiment is really all about l < 200, and mostly even l < 10
   - Lensing will be nailed by ground-based experiments long before we fly

5. The angle between the spin and the bore axis would be 45 degree angle, like EPIC
   - The only experiments for which cross-linking and polarization angle coverage do not matter are those that are noise dominated







Conclusions

- QUIET has published measurements of the CMB sky at 43 and 95 GHz
  - CMB results in excellent agreement with LCDM
    - Three peaks clearly traced in the EE spectrum
    - BB spectrum consistent with zero
  - Finds hints of synchrotron emission at 43 GHz and thermal dust at 95 GHz *in the same* field
    - Polarized foreground minimum likely to lie between 60 and 80 GHz, similar to the temperature case
- MMICs should be very seriously considered for both future ground- and space-based experiments
  - Particularly important for space missions: Insensitive to cosmic rays, and no time constant problems
  - Good (and quickly improving) noise properties in relevant frequencies
  - Outstanding systematic properties

- First-season Q-band results: arXiv:1012.3191
- Second-season W-band results: arXiv:1207.5034
- Instrument paper: arXiv:1207.5562
- See http://quiet.uchicago.edu/ for more information