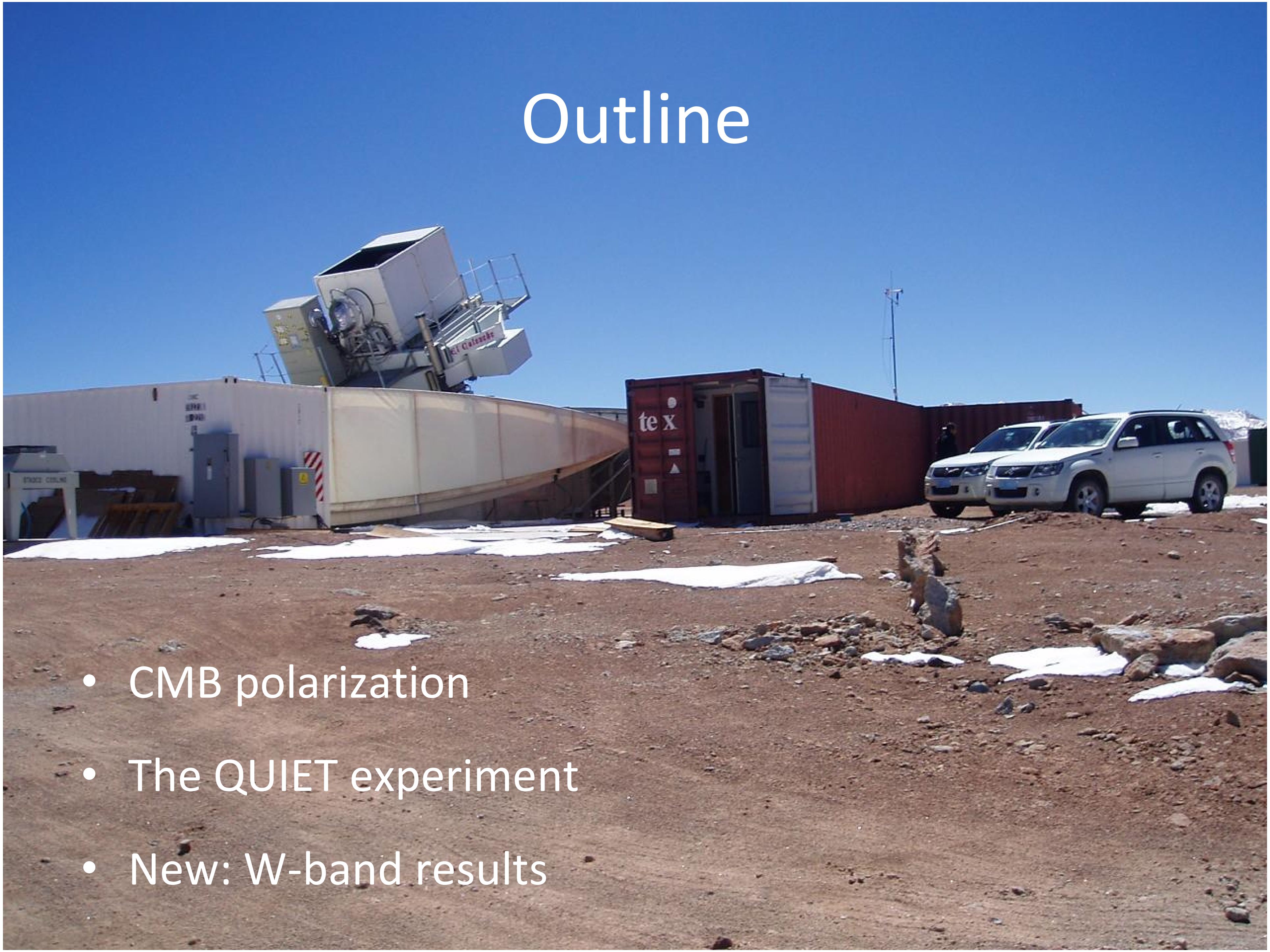
New W-band polarization results from QUIET

Ingunn Kathrine Wehus for the QUIET collaboration
University of Oxford

16th Paris Cosmology Colloquium 26/7-12

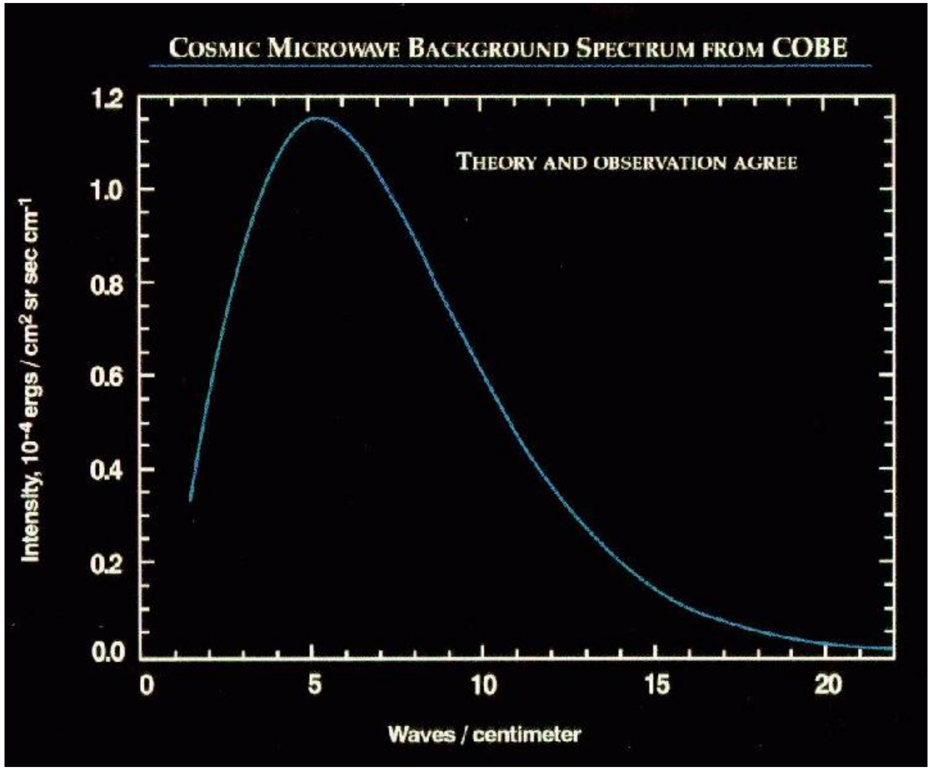


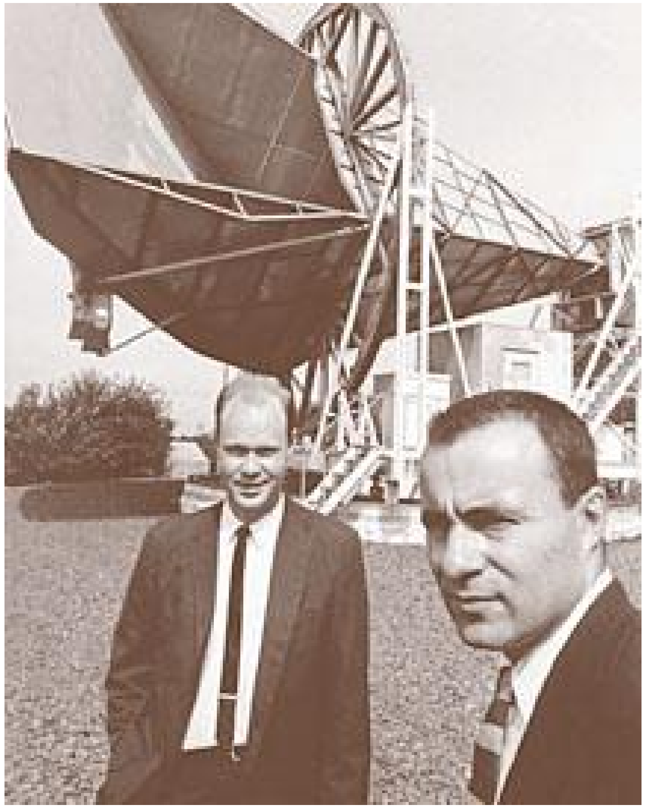
Outline

- CMB polarization
- The QUIET experiment
- New: W-band results

CMB

- First measured by Penzias and Wilson in 1965
- Perfect black-body spectrum of T=2.73K
- Same in all directions
  - big bang only explanation





CMB temperature fluctuations

- Tiny fluctuations around background temperature

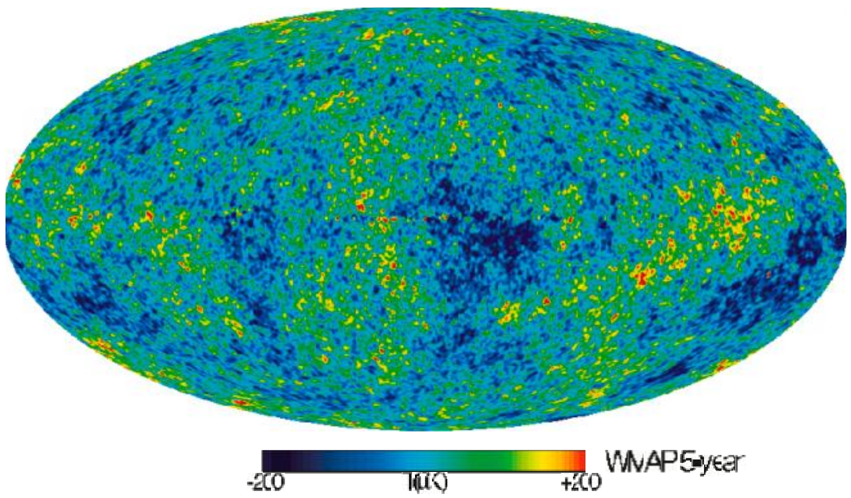
$$\frac{\delta T}{T} \sim 10^{-5}$$

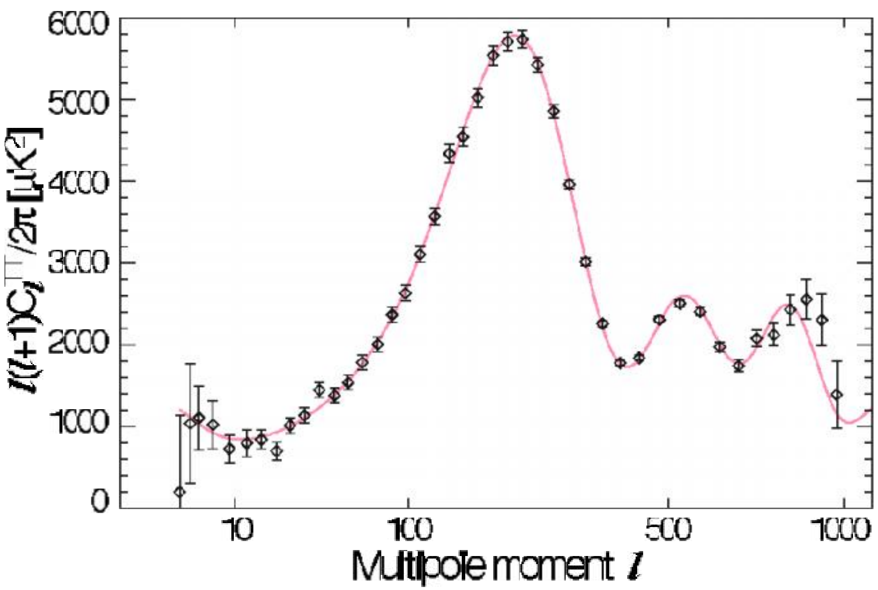
- Temperature field on the sphere decomposed in spherical harmonics

$$T = \sum_{\ell,m} a_{\ell m} Y_{\ell m}$$

- Power spectrum

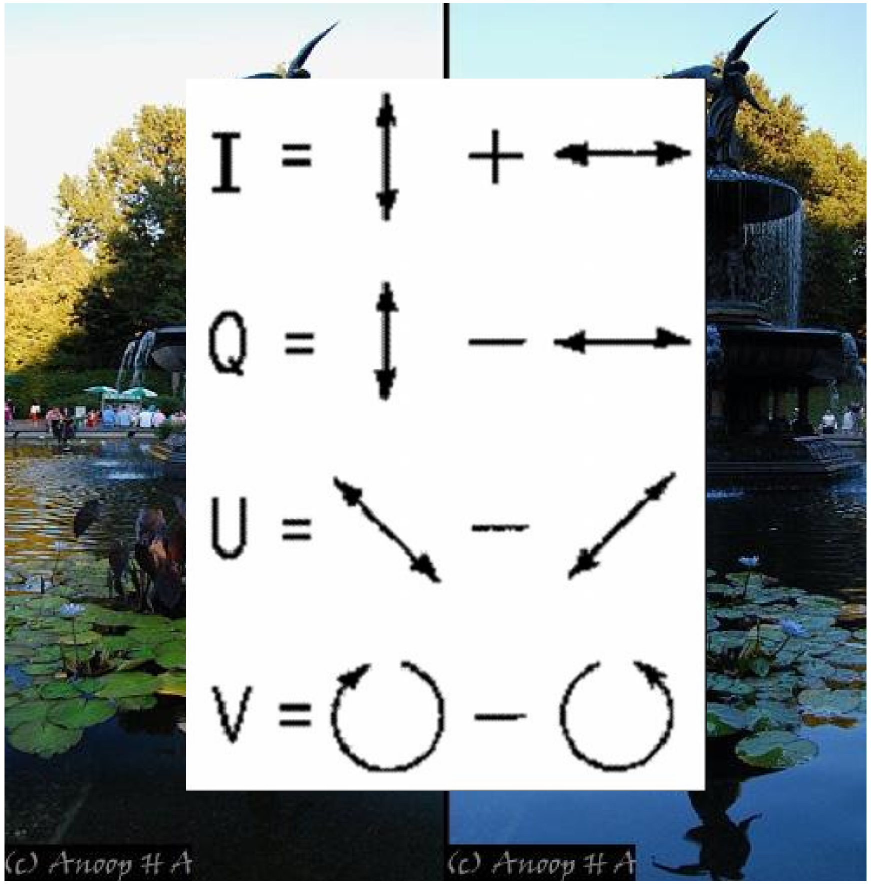
$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$





The CMB fluctuations are polarised

- We can measure the polarisation of the CMB the same way as for light
- The Stokes parameters quantify the polarization properties of a light ray
  - I = no filter at all
  - Q = linear polarizer at 0 and 90°
  - U = linear polarizer at -45 and 45 °
  - V = circular polarizer
- I is just the temperature
- Q and U combine to form E- and B-modes
- No known physical process can generate V-type CMB polarization



The CMB fluctuations are polarised

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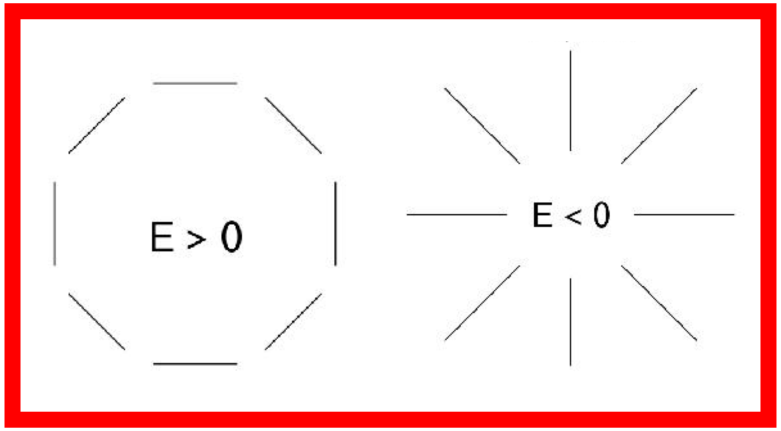
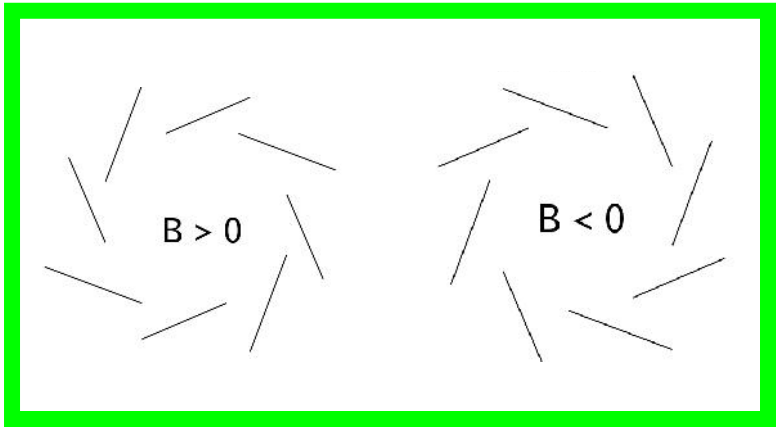
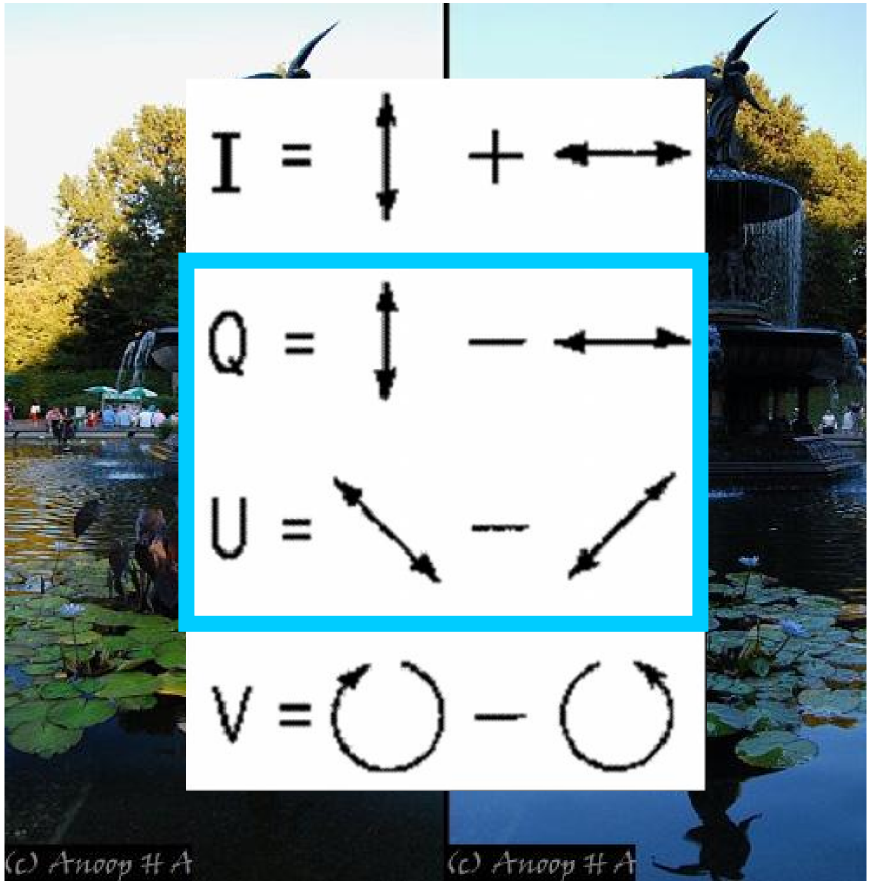
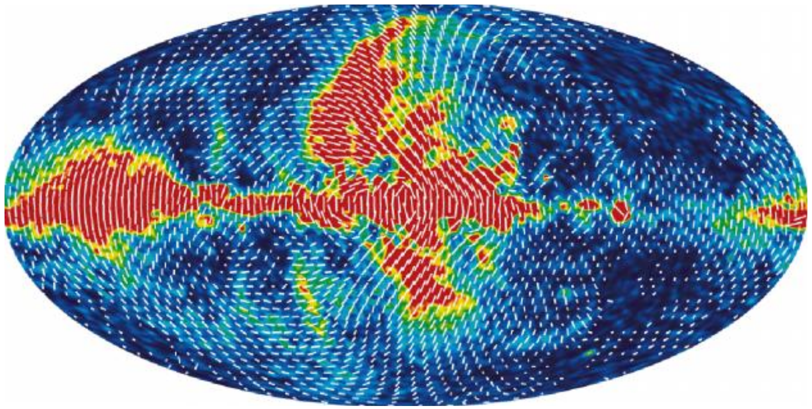






CMB polarisation fluctuations

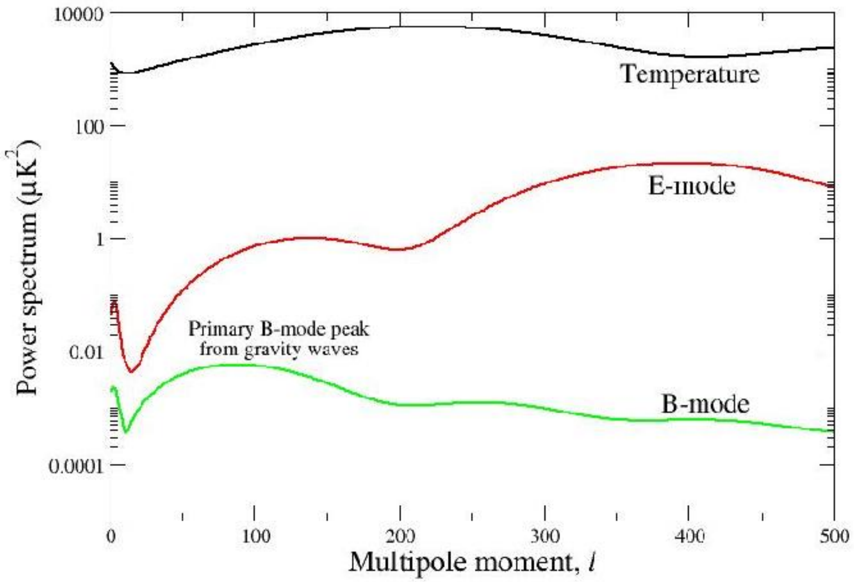
- E and B field on the sphere decomposed in spherical harmonics



$$E = \sum_{\ell,m} a^E_{\ell m} Y_{\ell m}(\mathbf{n})$$

$$B = \sum_{\ell,m} a^B_{\ell m} Y_{\ell m}(\mathbf{n})$$

- Power spectrum



$$C^E_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a^E_{\ell m}|^2$$

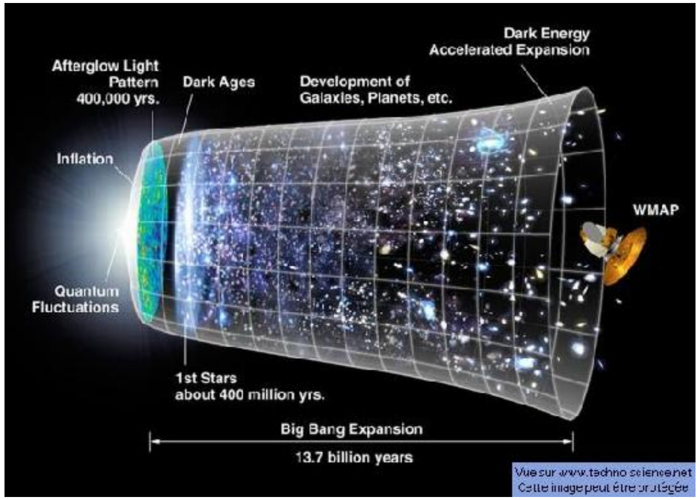
$$C^B_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a^B_{\ell m}|^2$$

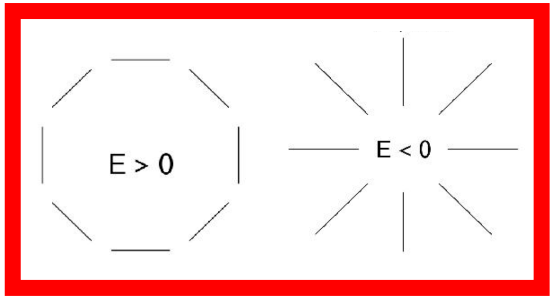
Inflation and the B-mode spectrum

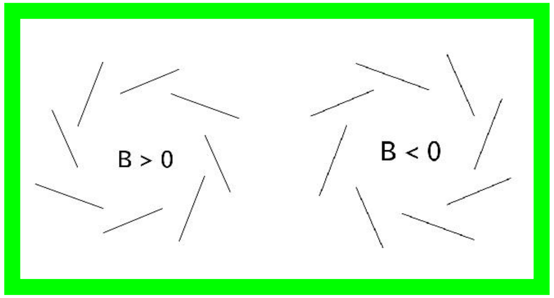
- Some predictions of inflation
  - Flat universe
  - Gaussian fluctuations
  - Nearly scale-invariant spectrum, but $n_s < 1$
  - Gravity waves
- The first three appear to be OK by WMAP
- Primordial gravitational waves produce B-modes in the CMB polarization
- Density fluctuations at last scattering only produce E-modes
- Detection of B-modes will be a strong confirmation of inflation
- The energy scale of inflation is given by the tensor-to-scalar ratio *r*

$$r \sim \frac{C_l^{BB}}{C_l^{EE}}$$

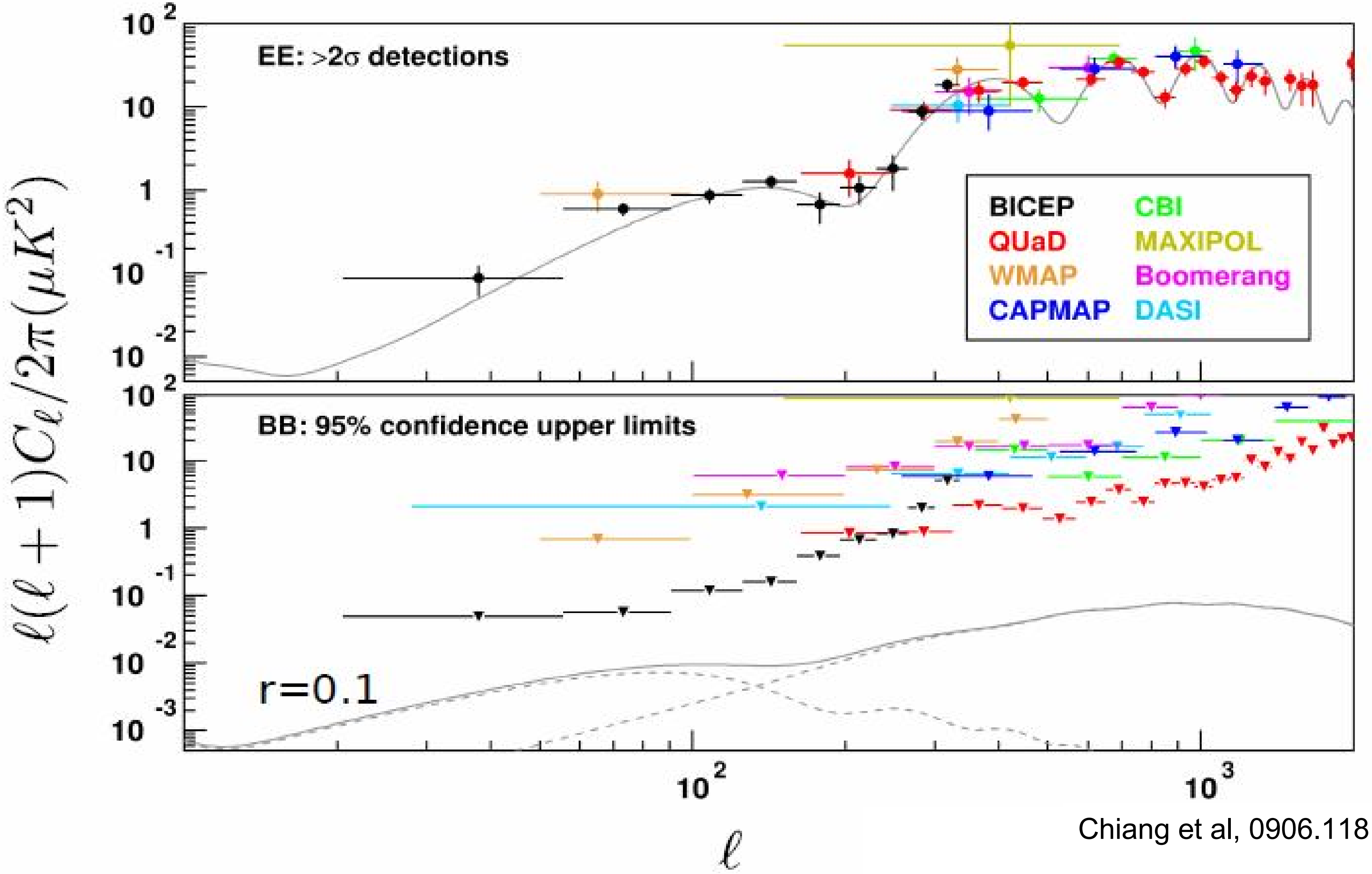
- r=0.01 corresponds to a 0.025 μK signal







Status of the field before QUIET

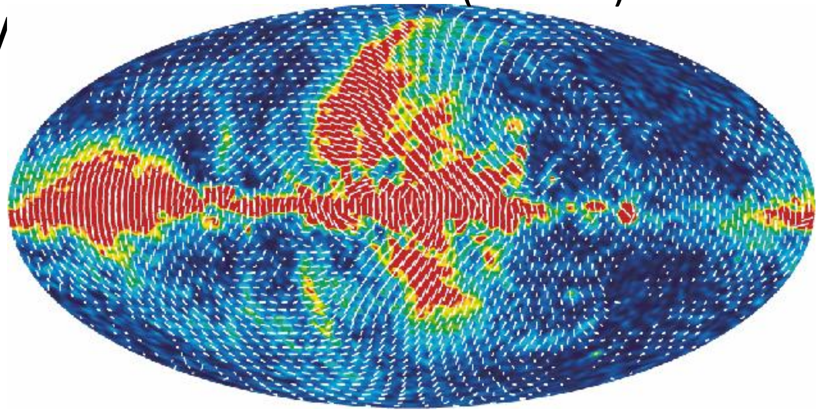


Chiang et al, 0906.1181

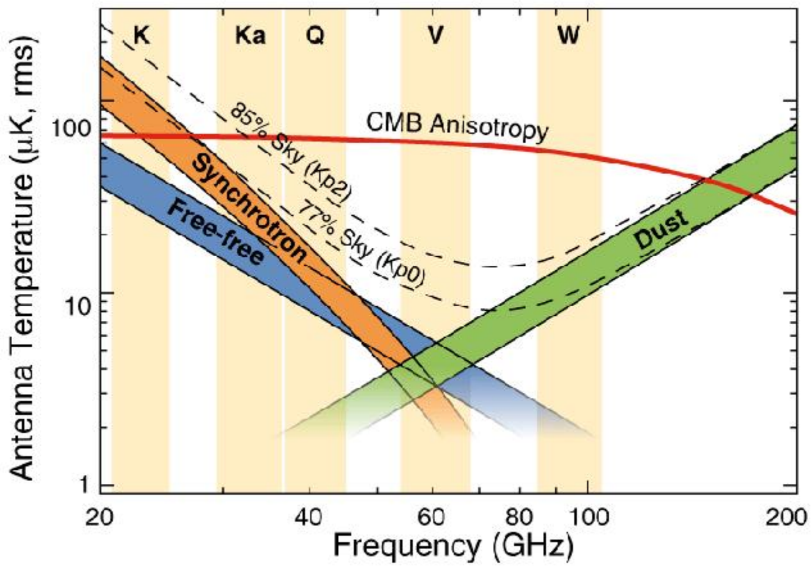
How to get to r=0.01?

- We need maps with sub-μK accuracy per square-degree pixel to constrain inflation through CMB polarization
  - Current detectors perform close to quantum noise limit
    - Impossible to reduce noise dramatically by building better detectors
    - Need many detectors to beat down noise statistics
  - The Milky Way is highly polarized
    - Need to separate ~10 μK galactic radiation from ~1μK CMB signal.
    - Need many frequencies to separate out cosmological signal
- Want small and cheap detectors capable of observing at a wide range of frequencies!

WMAP K-band (23 GHz)

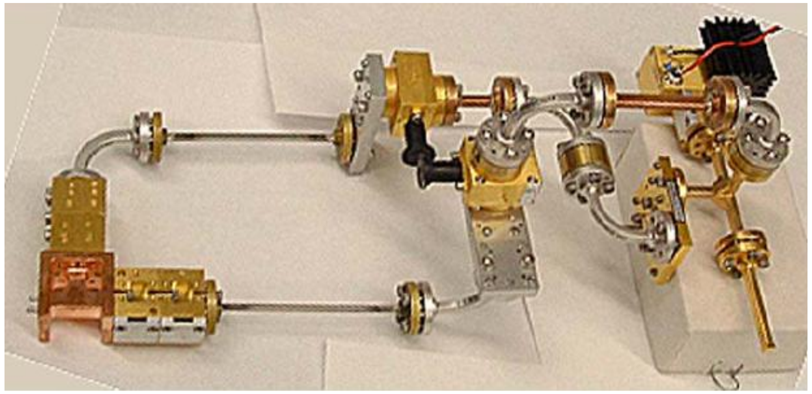


Color range: 0 - 50 μK

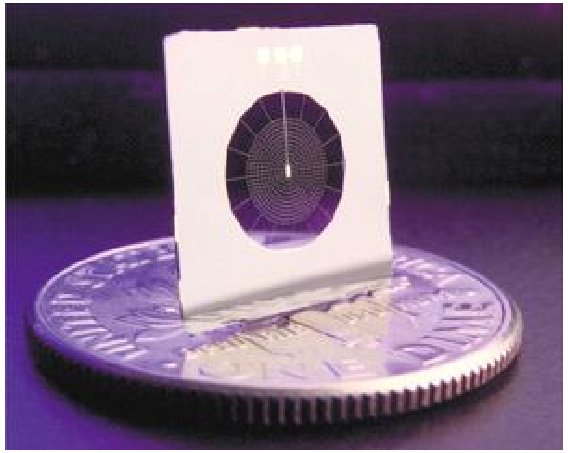


Measuring CMB polarisation

- Radiometers (antenna)
  - Measure electric field
  - Good at low frequencies (< 100 GHz)
  - Good systematic properties due to differencing schemes
  - Traditionally large and expensive
    - Cost ~ $40000
    - Problem fitting many in one focal plane
  - Labour-intensive
    - Each requires ~50 physicist hours for testing and calibration

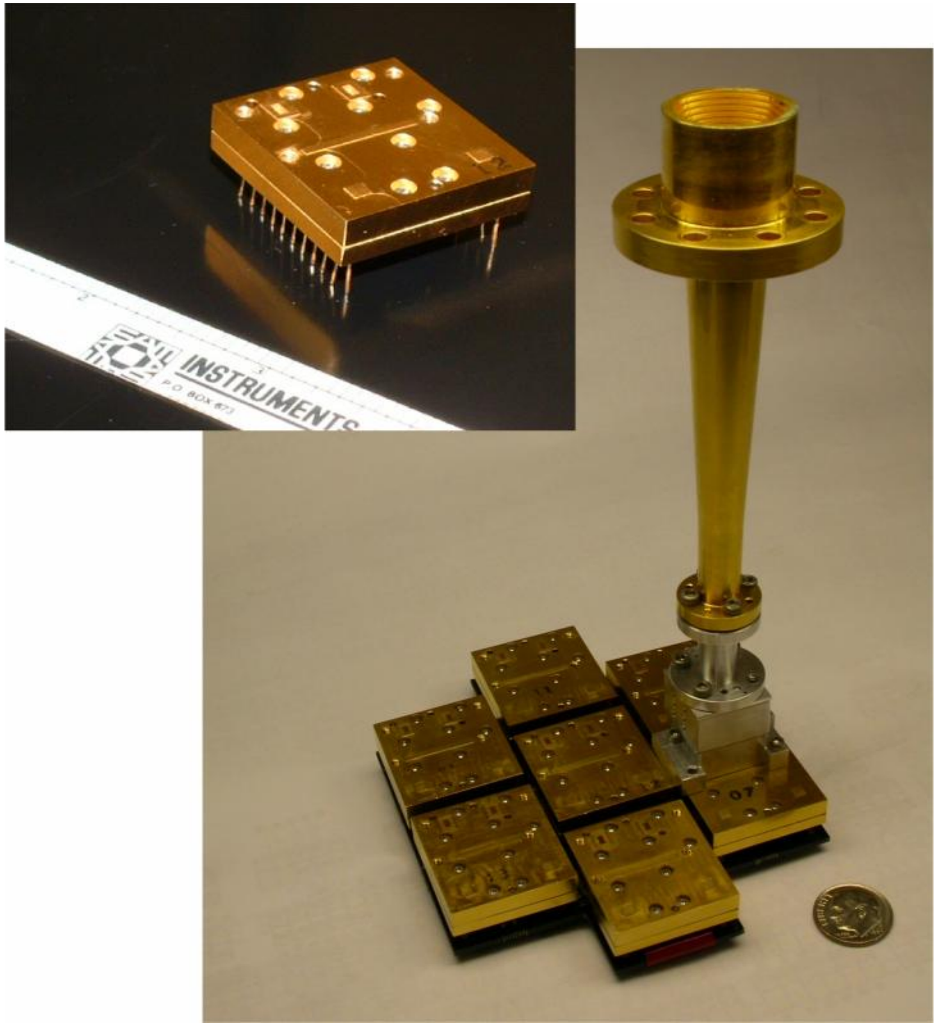


- Bolometers (thermometer)
  - Measure total incident radiation
  - Good at high frequencies (> 100 GHz)
  - Different systematics
    - Measures only one polarisation at a time

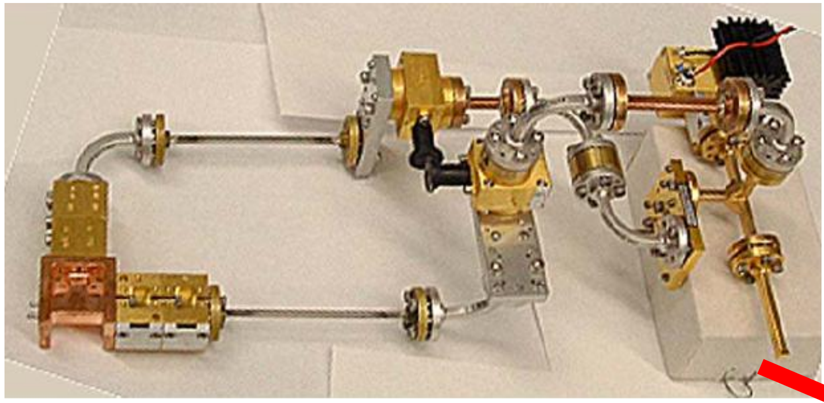


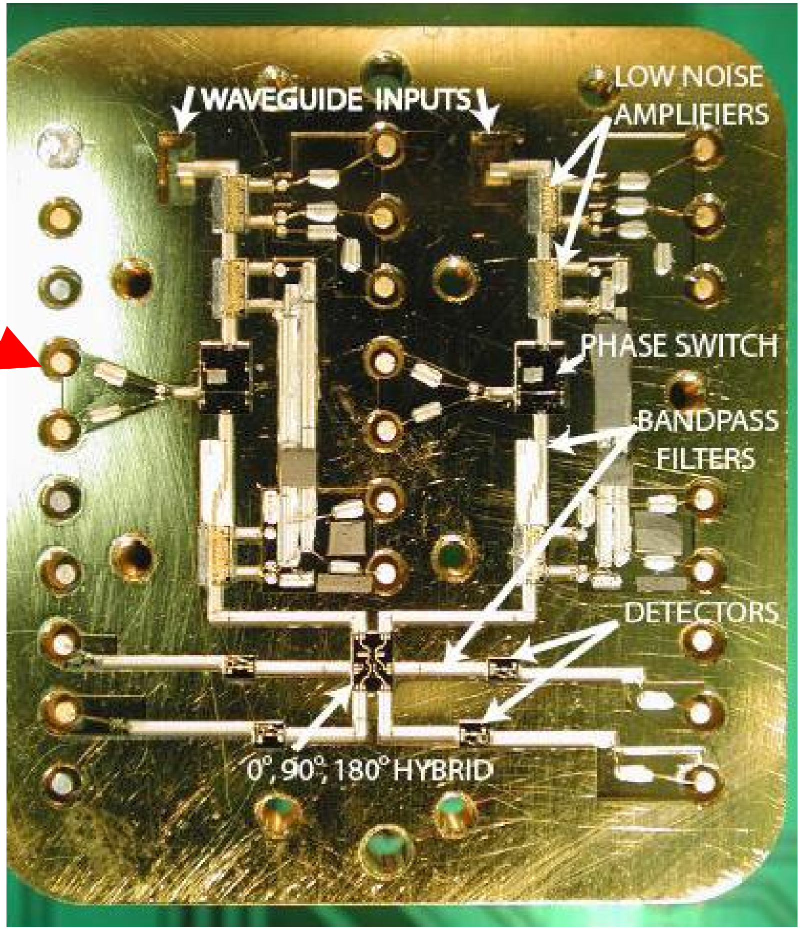
Radiometer on a chip

- Breakthrough at JPL around 2003 by Todd Gaier and Mike Seiffert
- Can be mass produced
- Efficient testing and calibration by computers

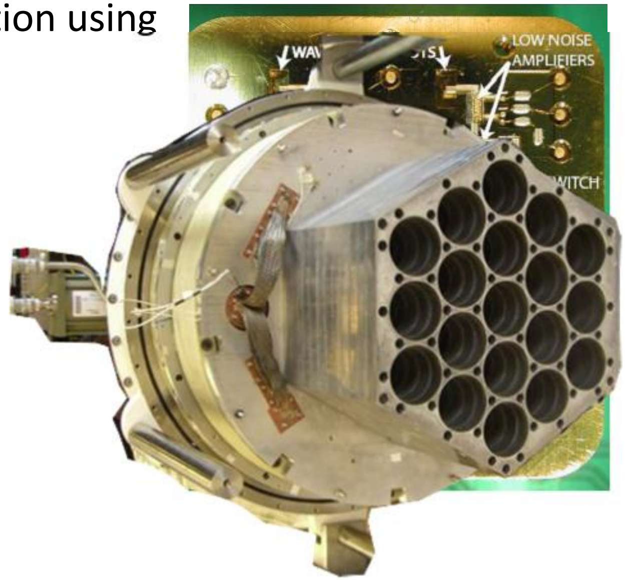


Radiometer on a chip

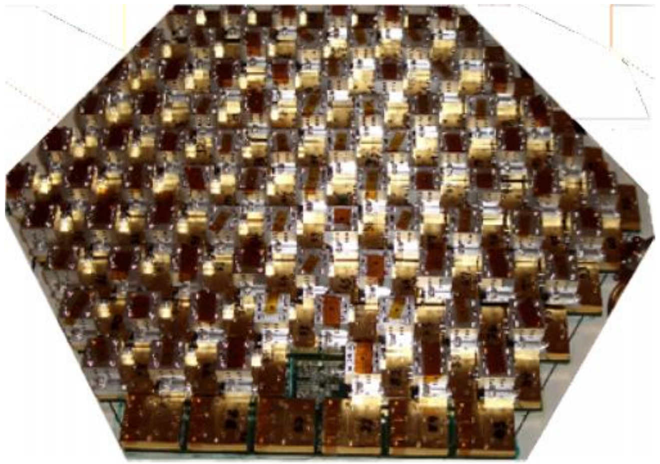




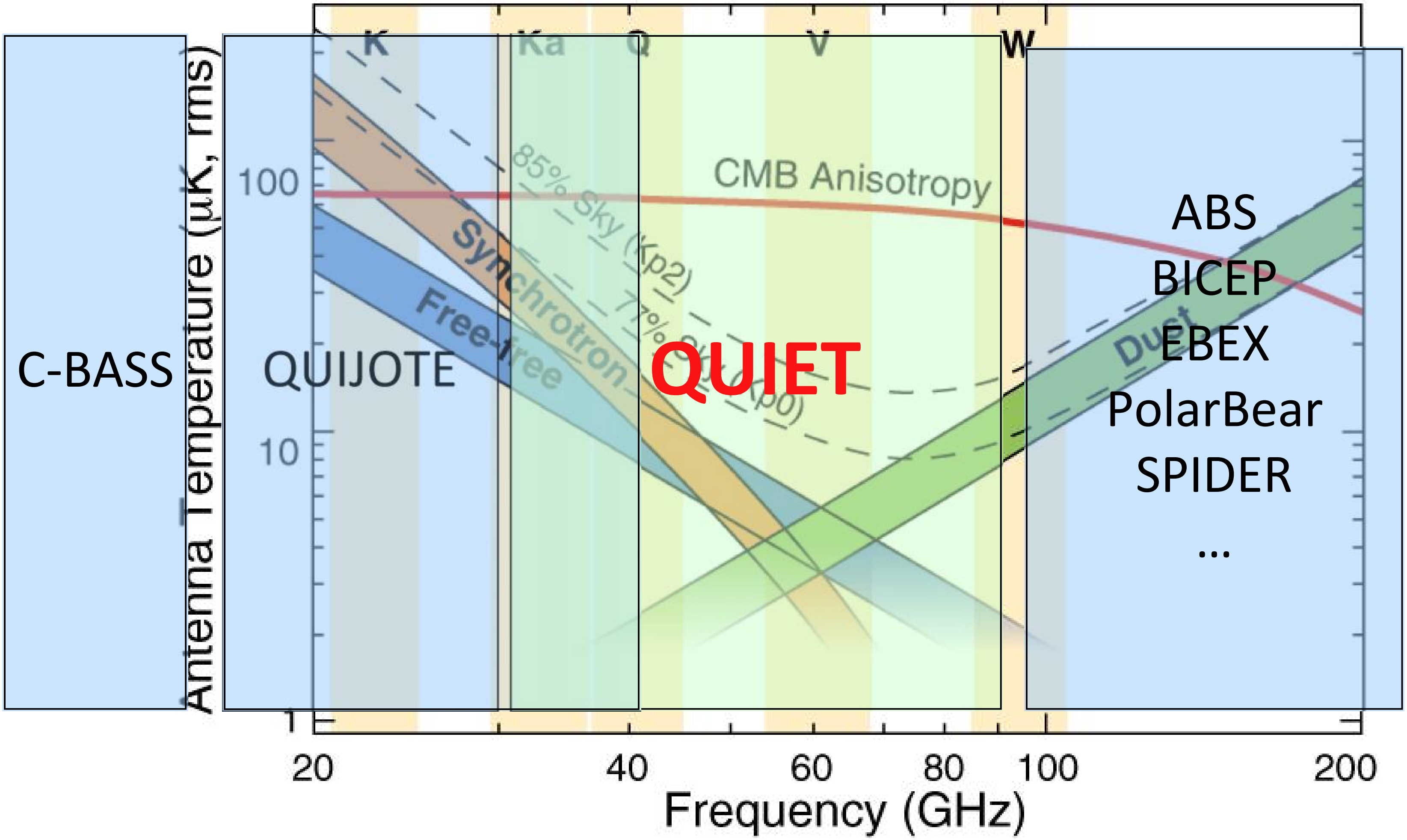
QUIET (Q/U Imaging ExperimenT)



- QUIET is a ground-based experiment measuring CMB polarisation using these new MMIC modules
  - Goal: Learn about inflation by constraining B-mode polarization
- Currently the only B-mode radiometer experiment
  - Different (and possibly better) systematics
  - Unique *radiometer on a chip* technology
  - Input to case studies for the next generation satellite
- Phase I
  - 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

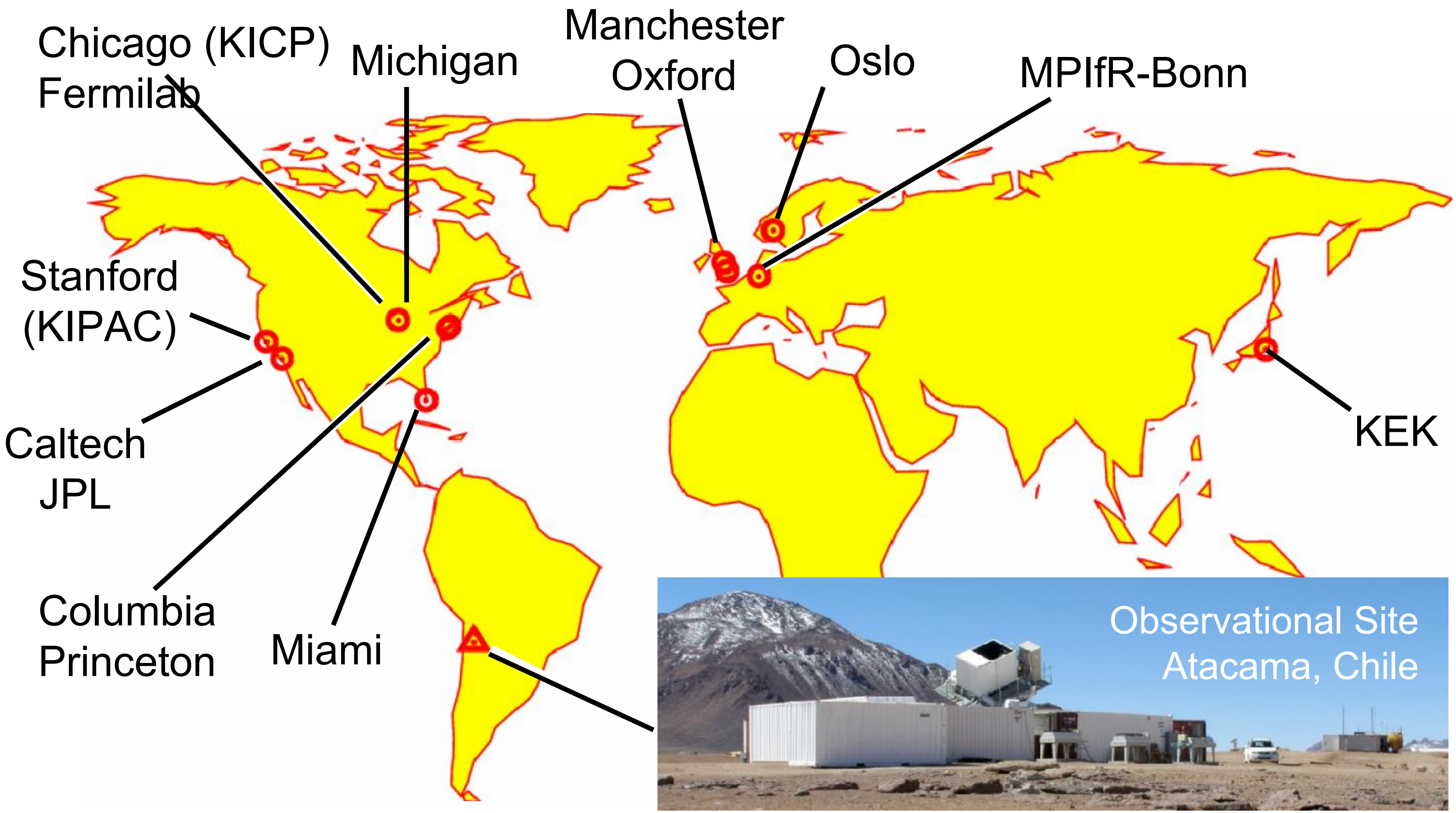


Another look at the frequency spectrum



QUIET collaboration

QUIET collaboration



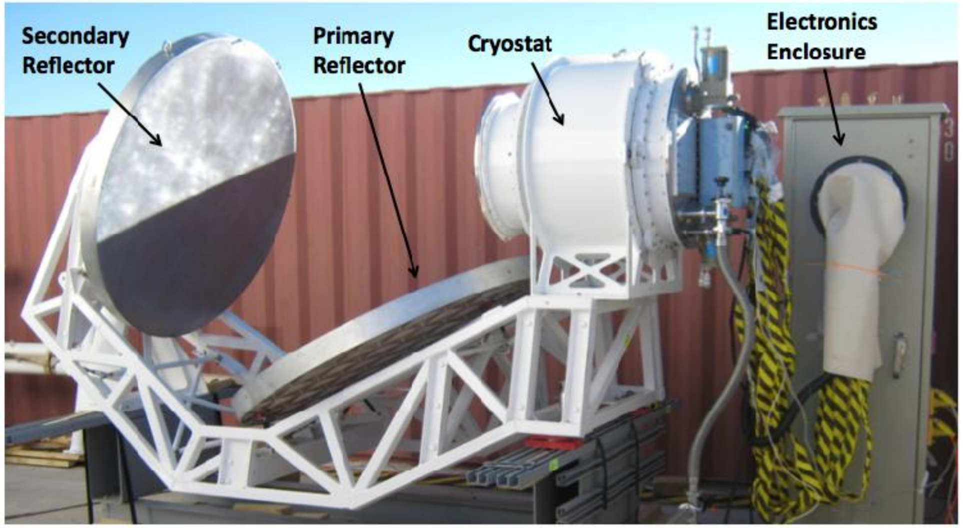
5 countries, 14 institutes, ~40 people

The site

- Located at 5080 m above sea level at the Chajnantor platau in the Atacama desert in Chile
- One of the driest places on earth
  - South pole has 40% lower PWV, but lower temperature results in comparable transmission
  - More of the sky is available than on south pole, and the same patch of sky can be observed from different angles. Good for systematics control
  - Accessible year round, day and night

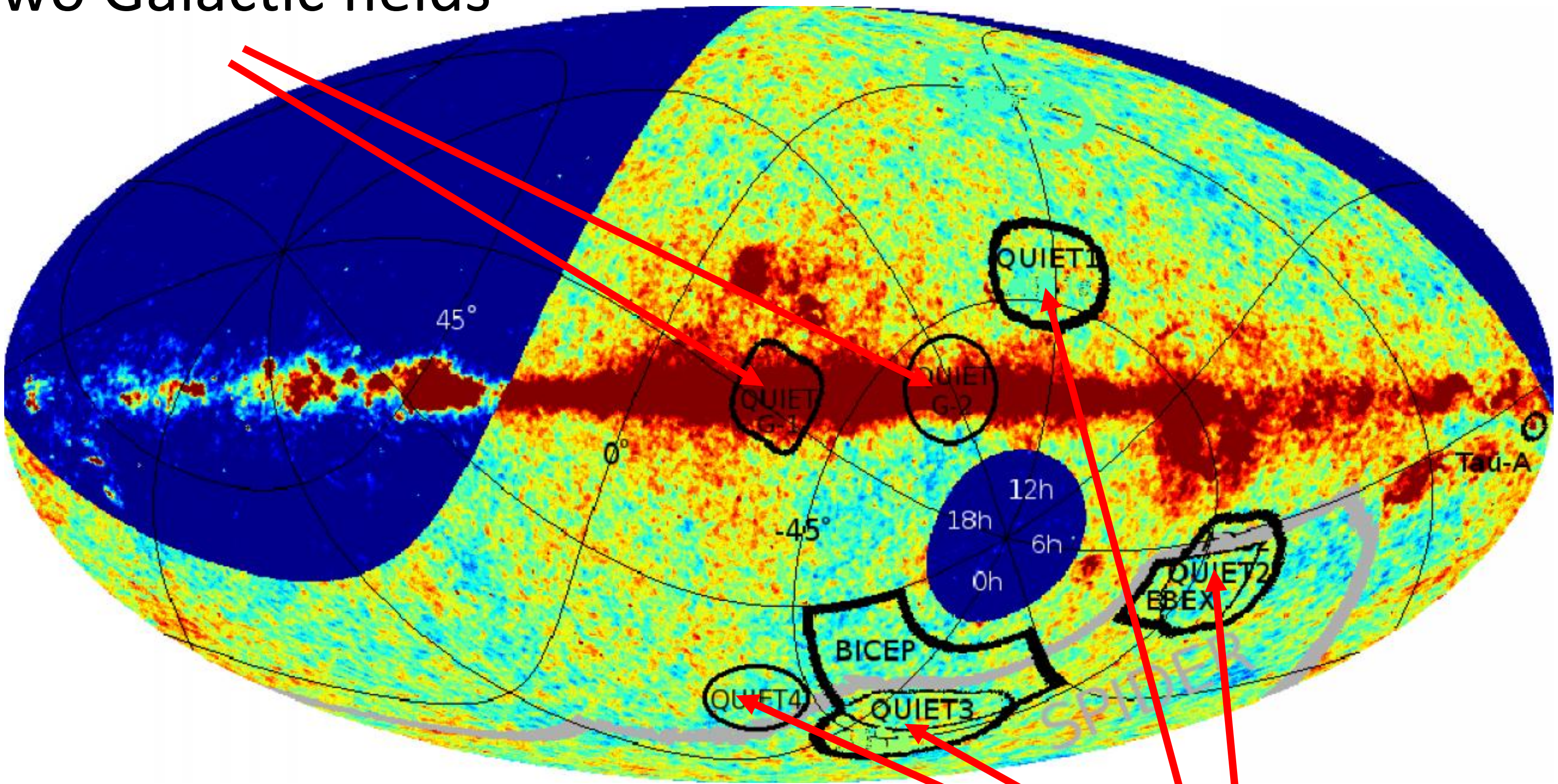
Telescope


Lower Ground
Screen
Upper Ground
Screen
CBI
Mount


Secondary
Reflector
Primary
Reflector
Cryostat
Electronics
Enclosure

The QUIET Fields

Two Galactic fields

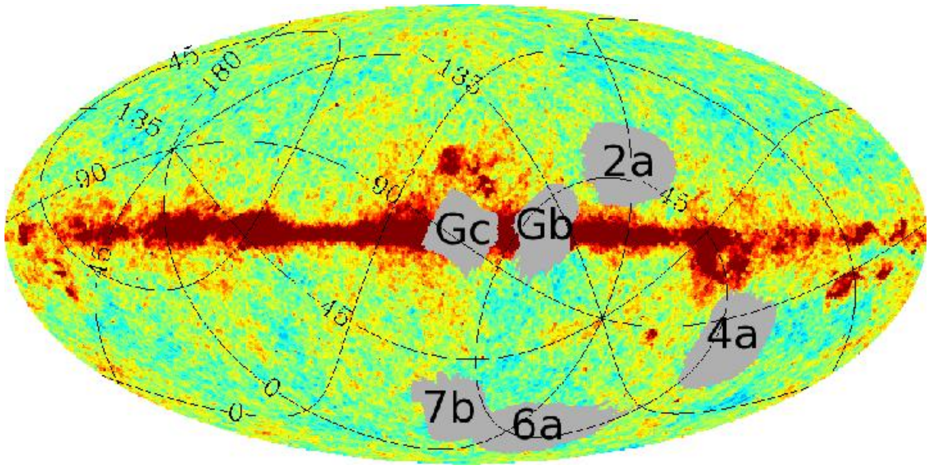


Overlap with BICEP, EBEX and SPIDER,
(and probably with ABS and PolarBear)

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

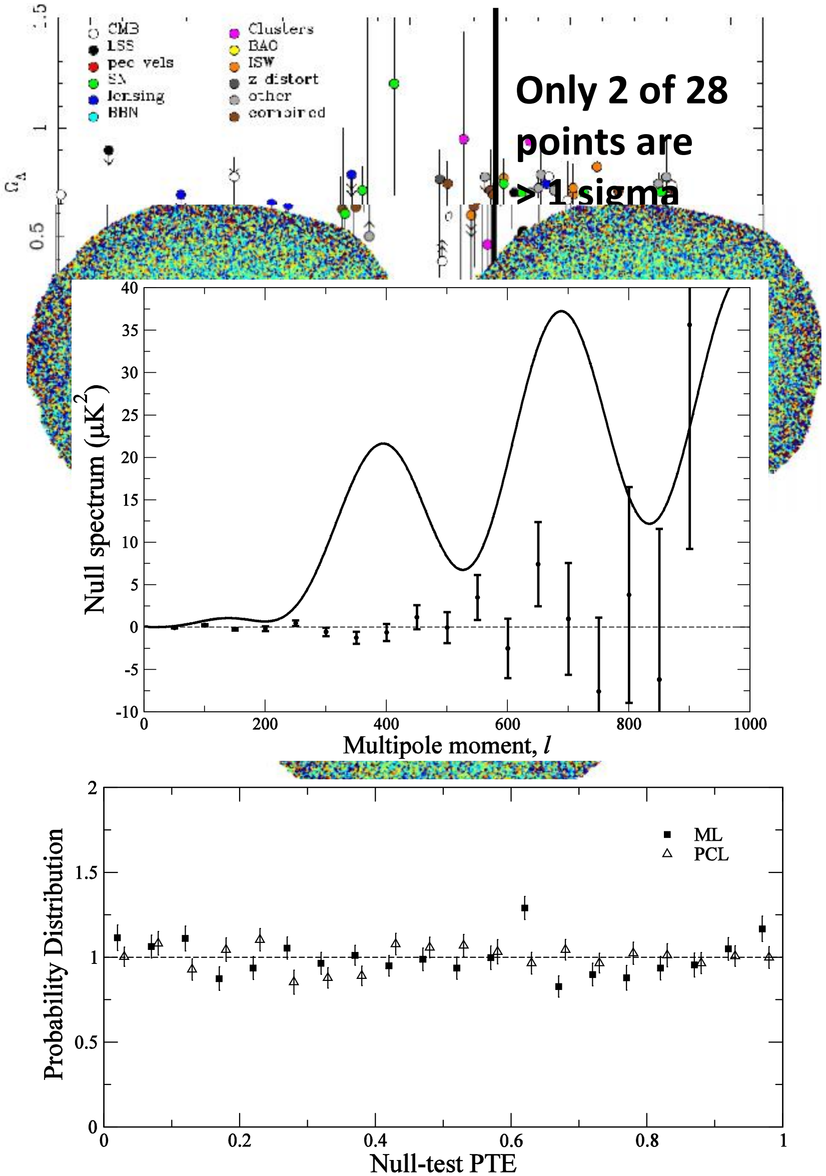
W-band: 72% CMB, 14% Galactic, 13% calib, 1% cut

Data handling and analysis

- 20-100 GB data per day in Phase I
  - Burned to dvd/bluray at site and shipped to Chicago
  - Mirrored from Chicago to Oslo and KEK every night
- ~1TB per day in Phase II
- QUIET has two independent pipelines
- Maximum-likelihood (ML) pipeline
  - Produces unbiased maps
  - Power spectrum calculated from exact likelihood
  - Gives more accurate error bars
  - Needs the full covariance matrix; computatinally heavy
- Pseudo-Cl (PCl) pipeline
  - Computationally less heavy; massive null-testing
  - Easy to simulate systematic errors

Optimization by 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



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 $12'\!.8$, 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)"

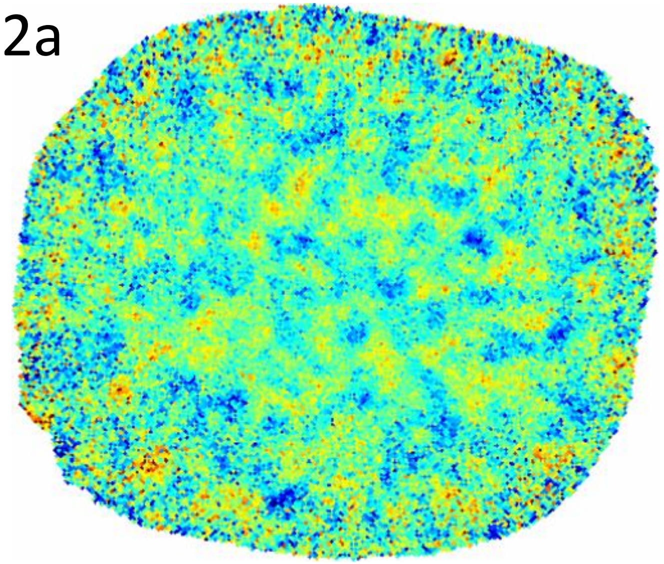
ABSTRACT

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.

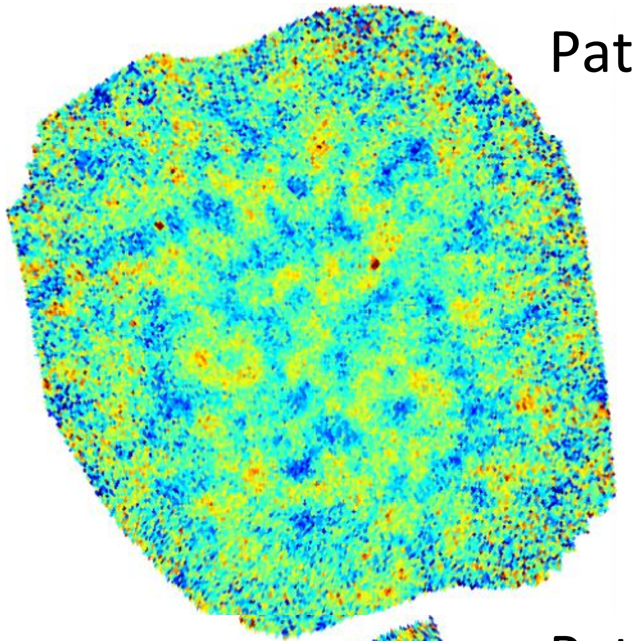
Subject headings: cosmology: cosmic microwave background — cosmology: observations — astronomical instrumentation: polarimeters — astronomical instrumentation: detectors — astronomical instrumentation: telescopes

Temperature maps – QUIET vs WMAP

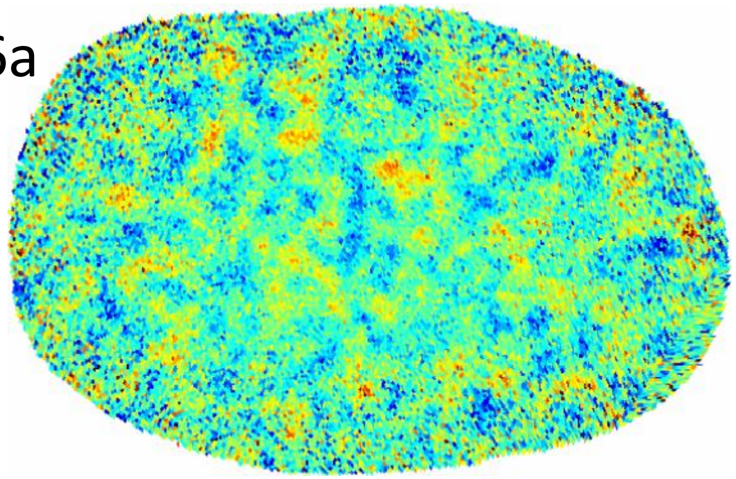
Patch 2a



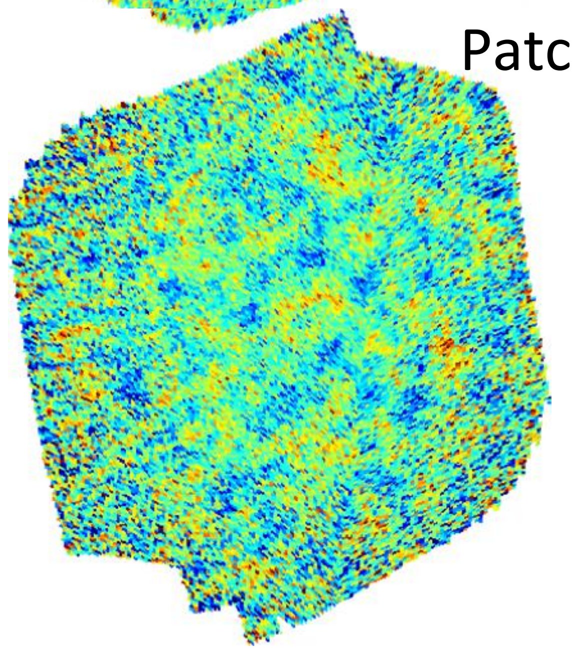
Patch 4a



Patch 6a

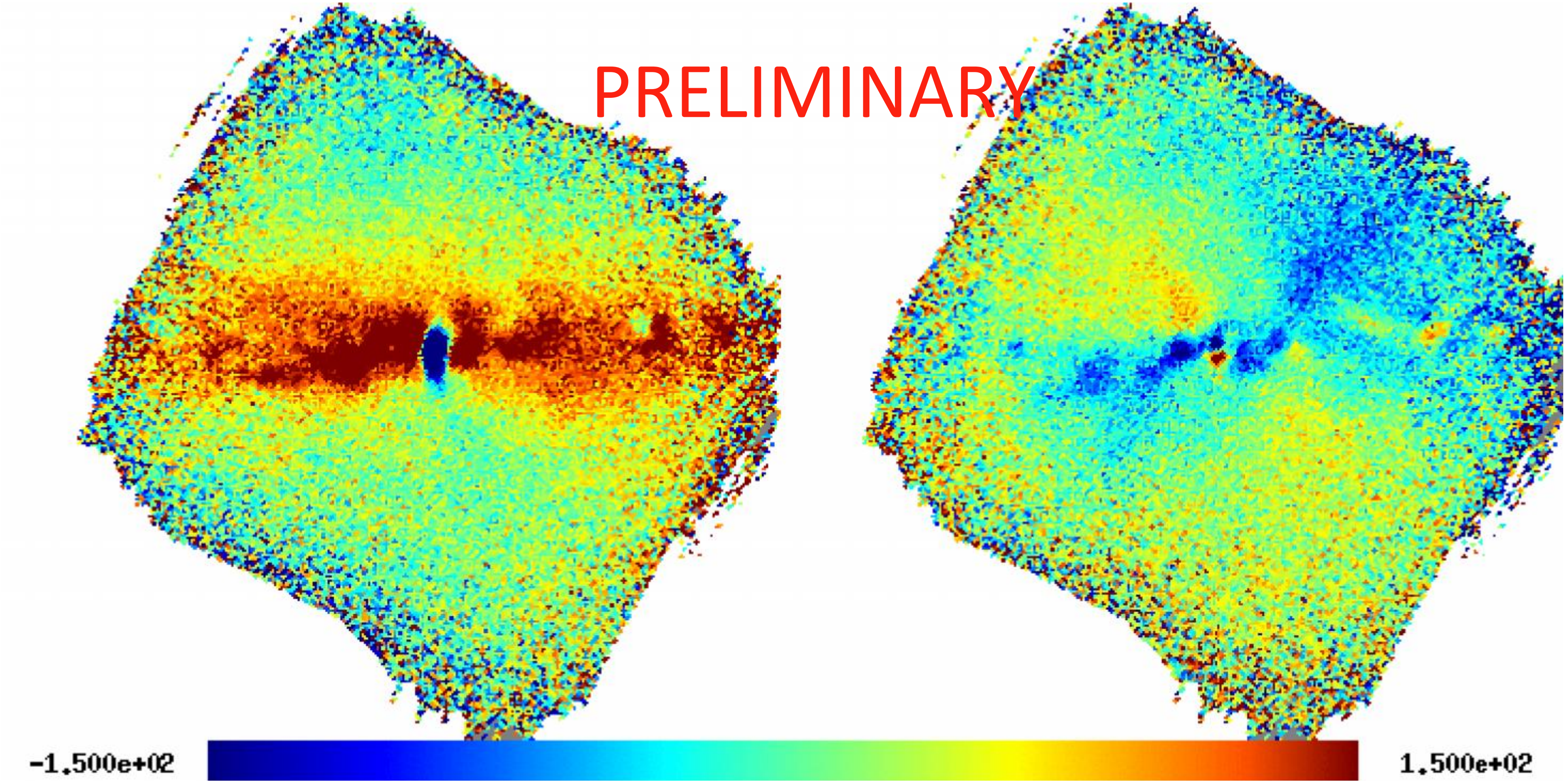


Patch 7b



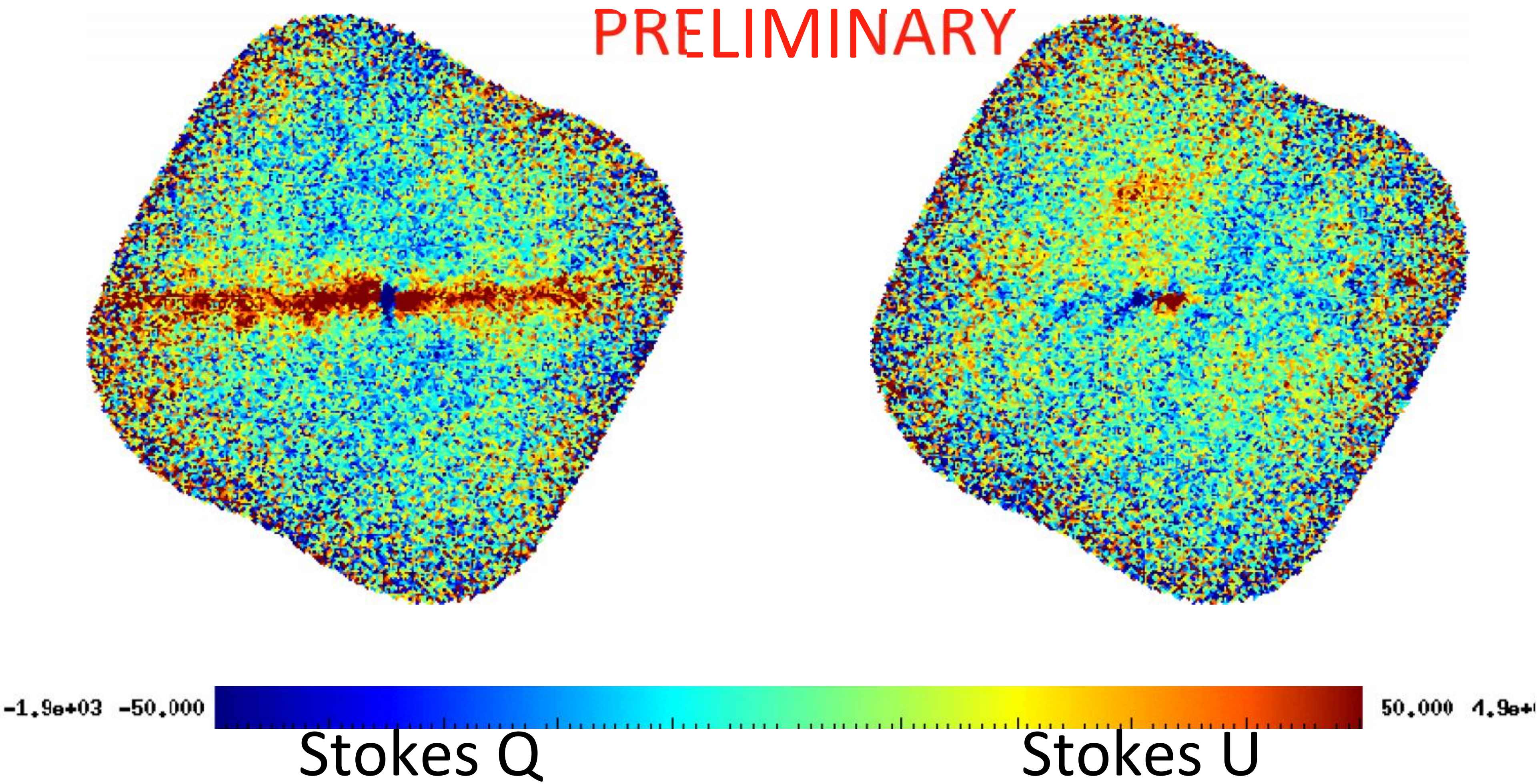
Note: Slight gain excess, about 10% (Jupiter calibration)

Galactic center observed at Q-band



Stokes Q Stokes U

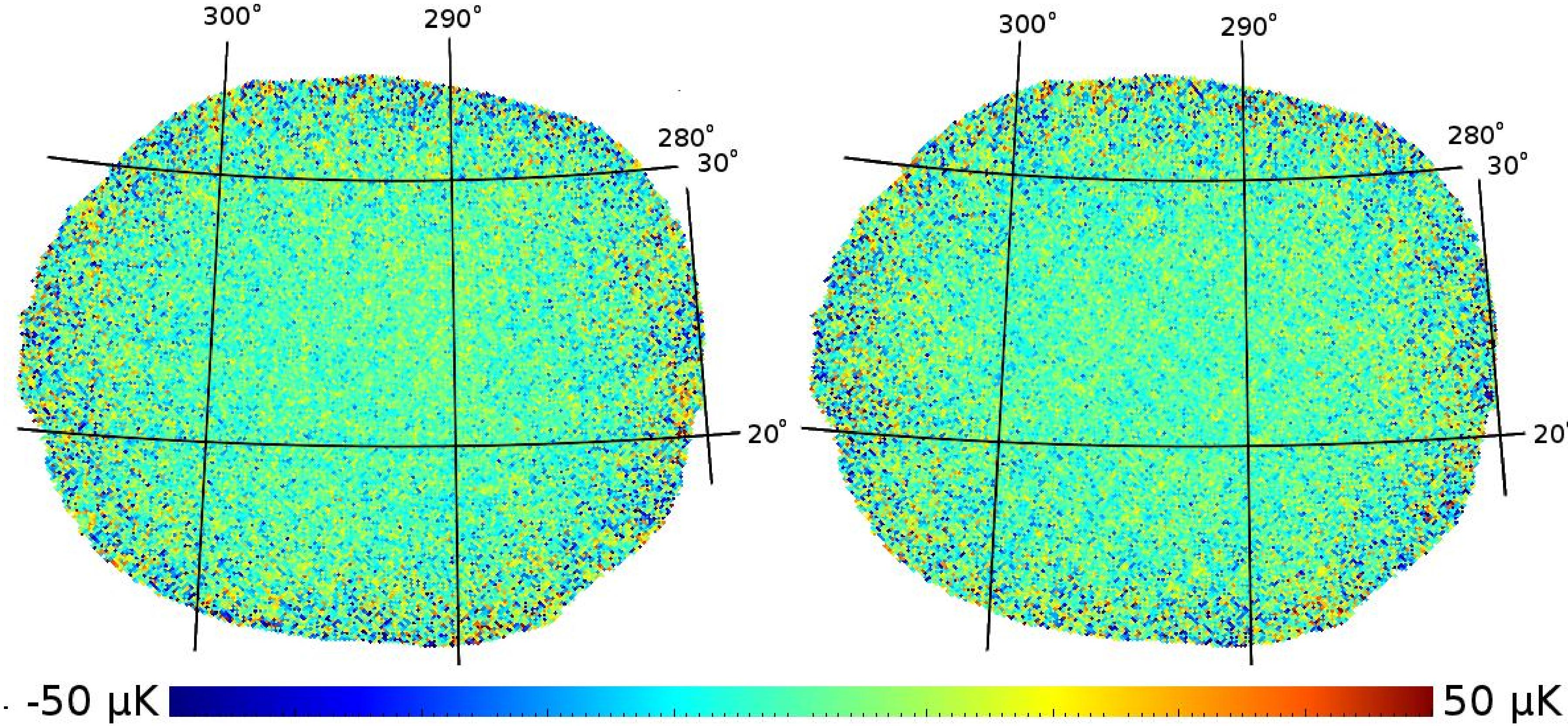
Galactic center observed at W-band



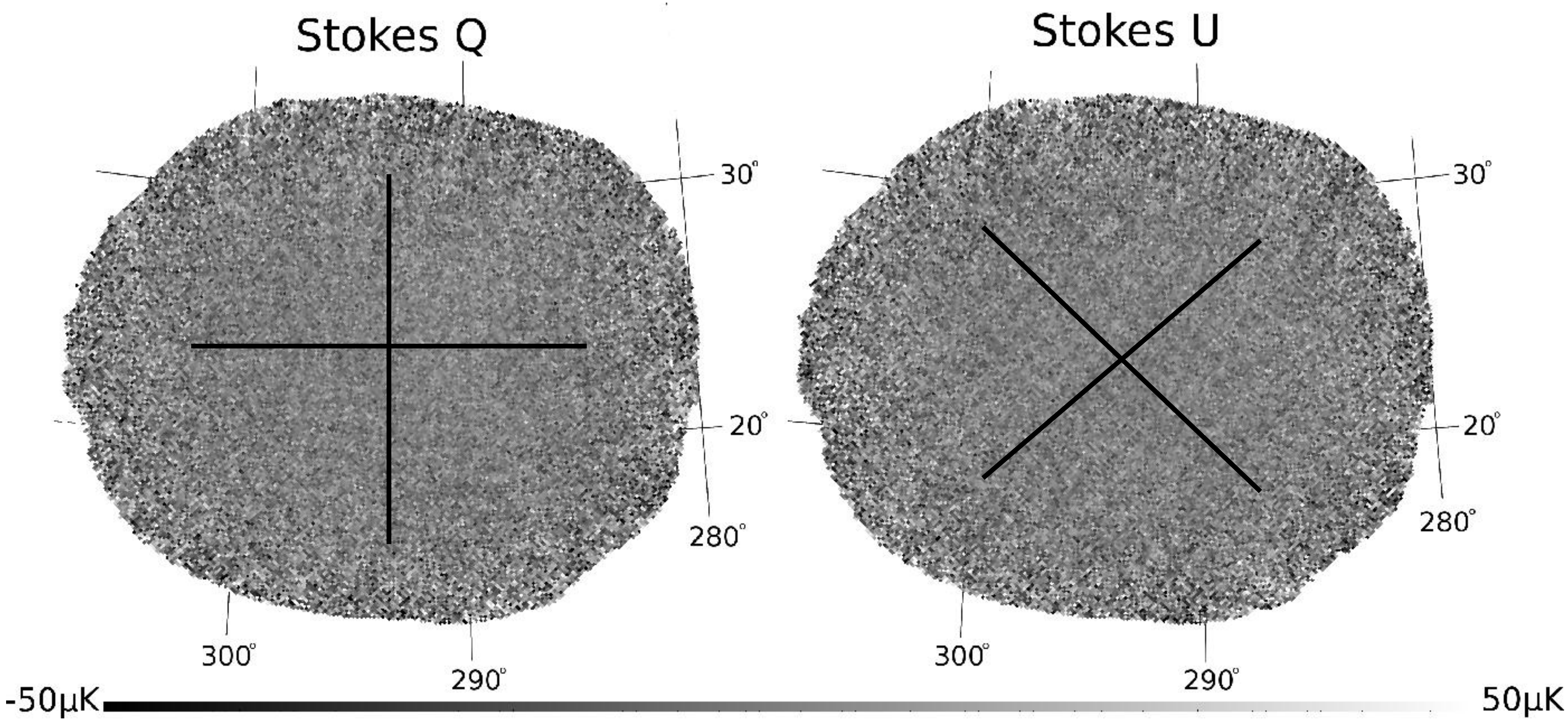
QUIET CMB Field – Patch 2a

Stokes Q

Stokes U

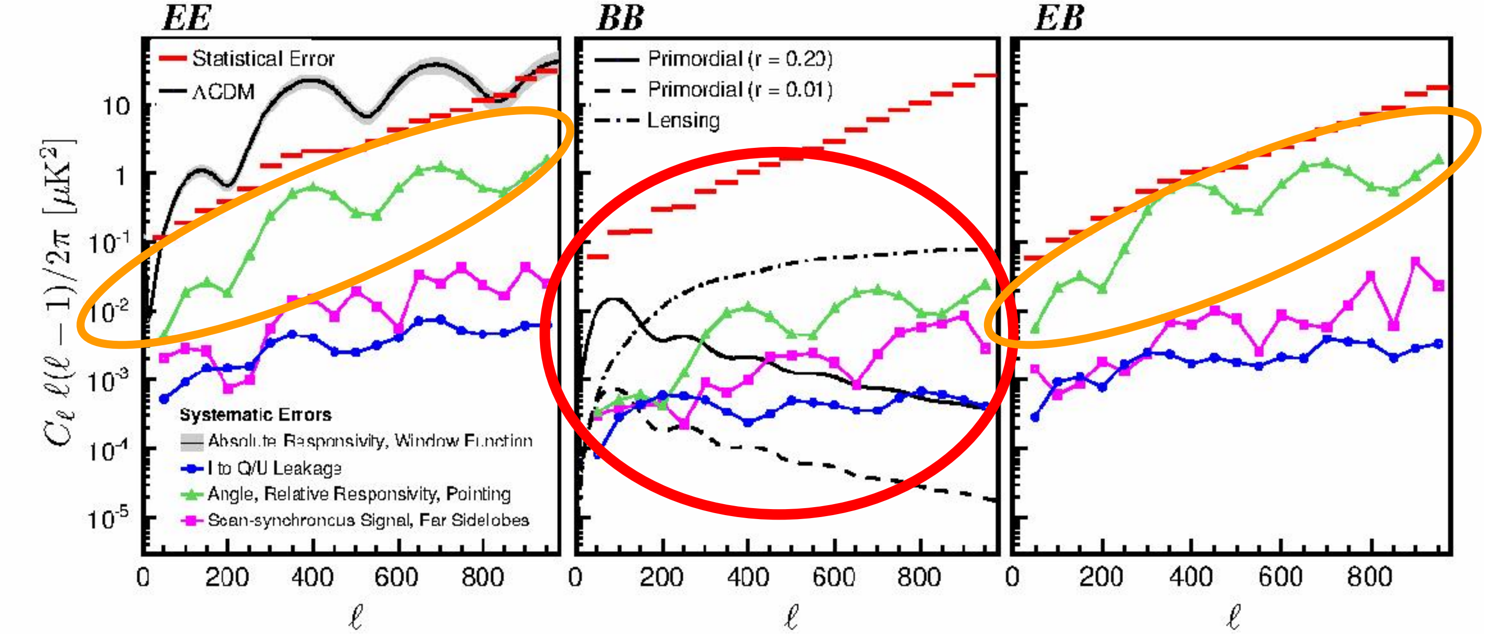


QUIET CMB Field – Patch 2a



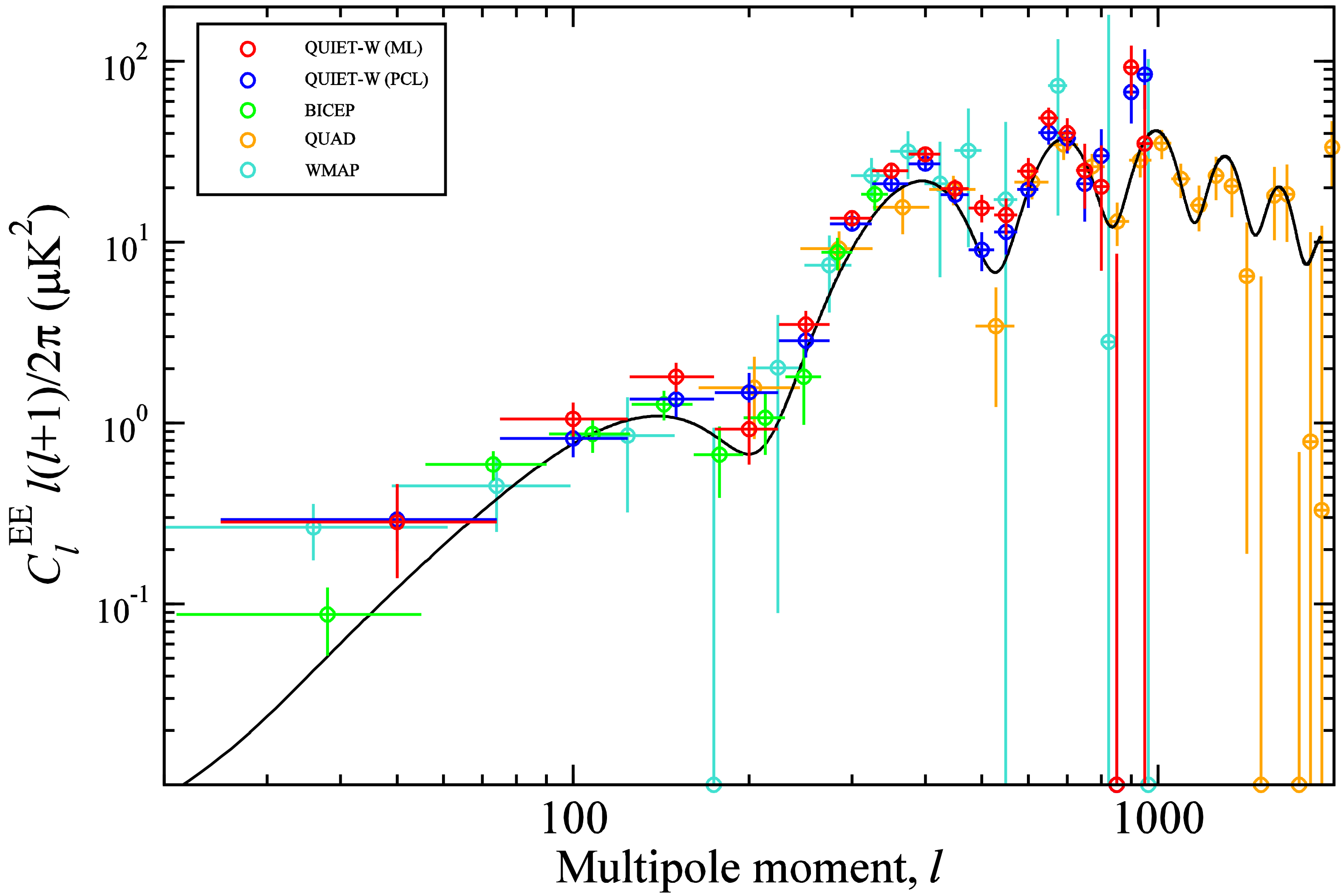
= can see E-mode signal by eye!

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

The EE power spectrum

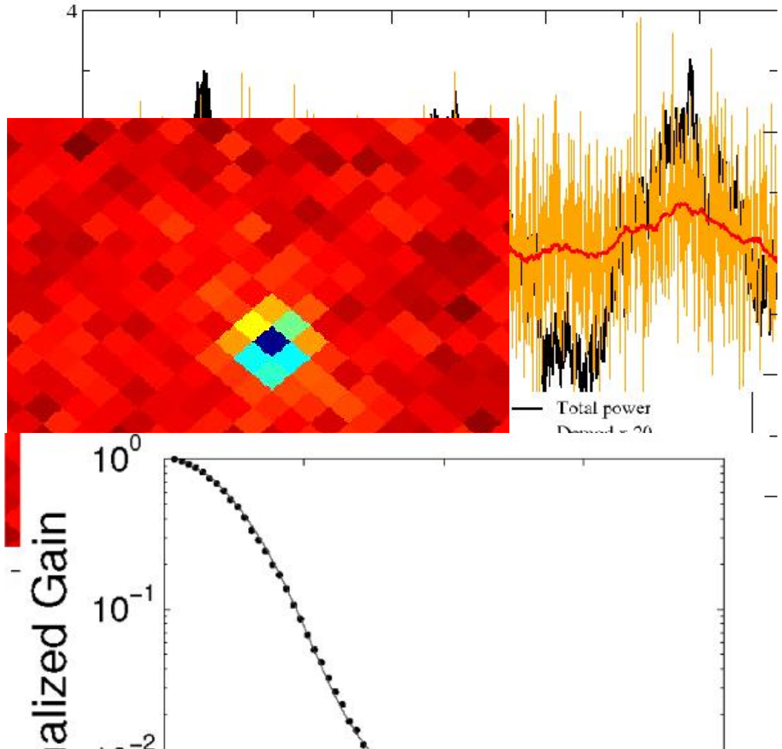


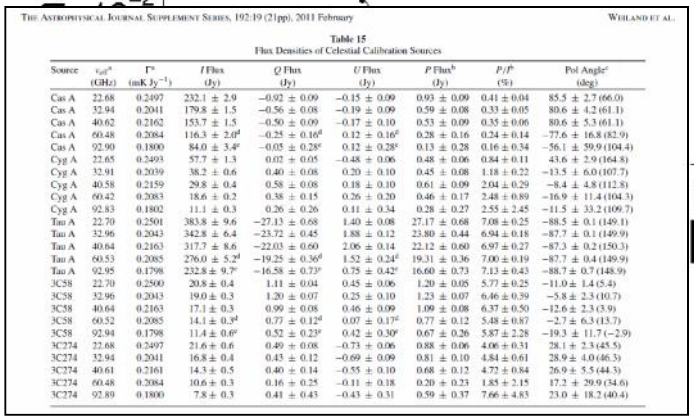
Gain calibration and uncertainties

- QUIET gain model:
  - Relative gains from sky-dips and Tau-A
    - Tau-A values from WMAP7
  - Absolute gain from Tau-A

- Absolute gain uncertainty contributions:
  - Time-dependent modelling = 4%
  - QUIET beam solid angle = 5%
  - WMAP catalog value = 5%
  - **Total = 8%**

- Total systematic gain uncertainty in the power spectrum is 17%
  - Statistical uncertainty is ~4%



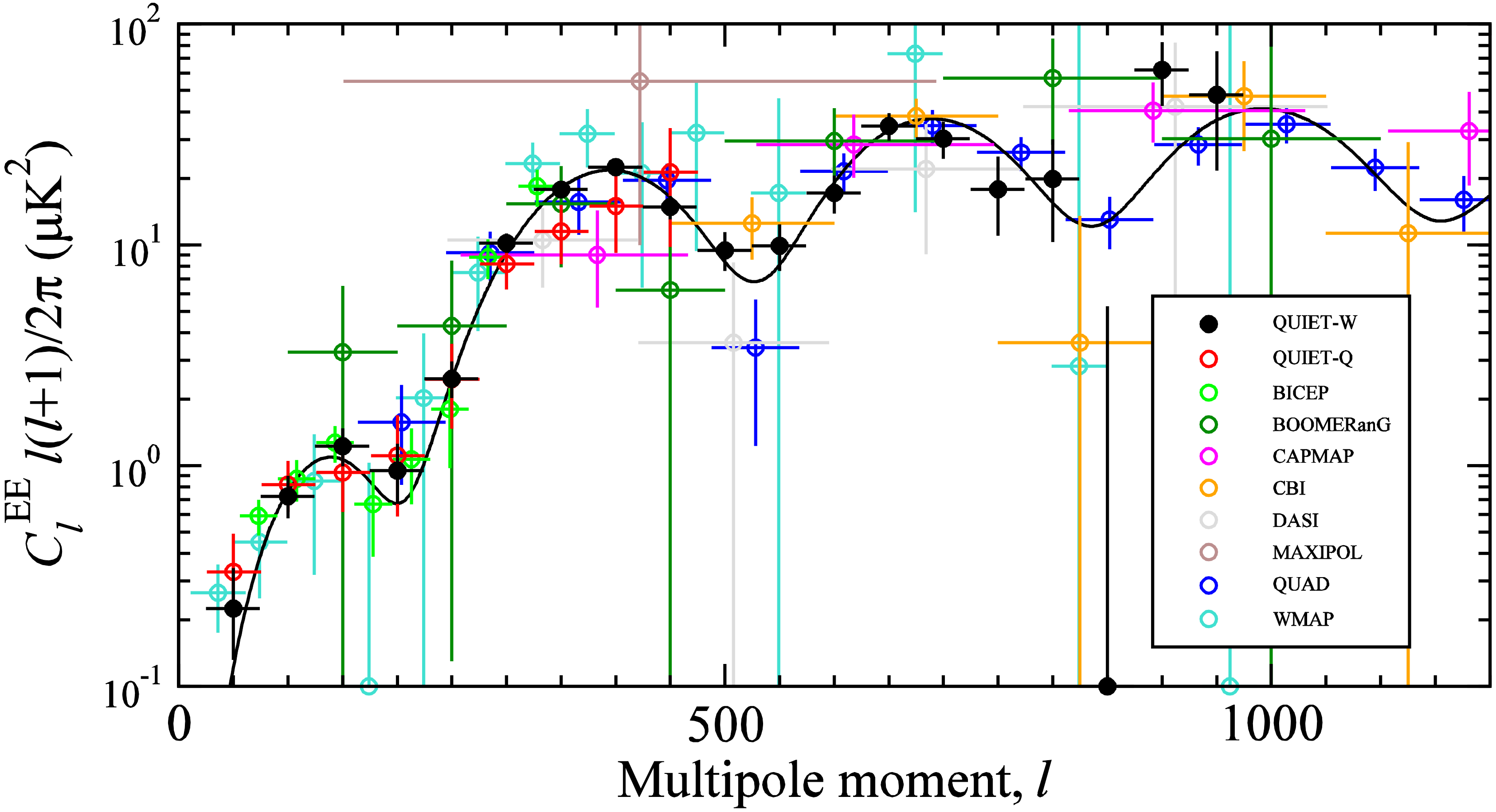


The Astrophysical Journal Supplement Series, 192:19 (21pp), 2011 February Weiland et al.

Table 15
Flux Densities of Celestial Calibration Sources

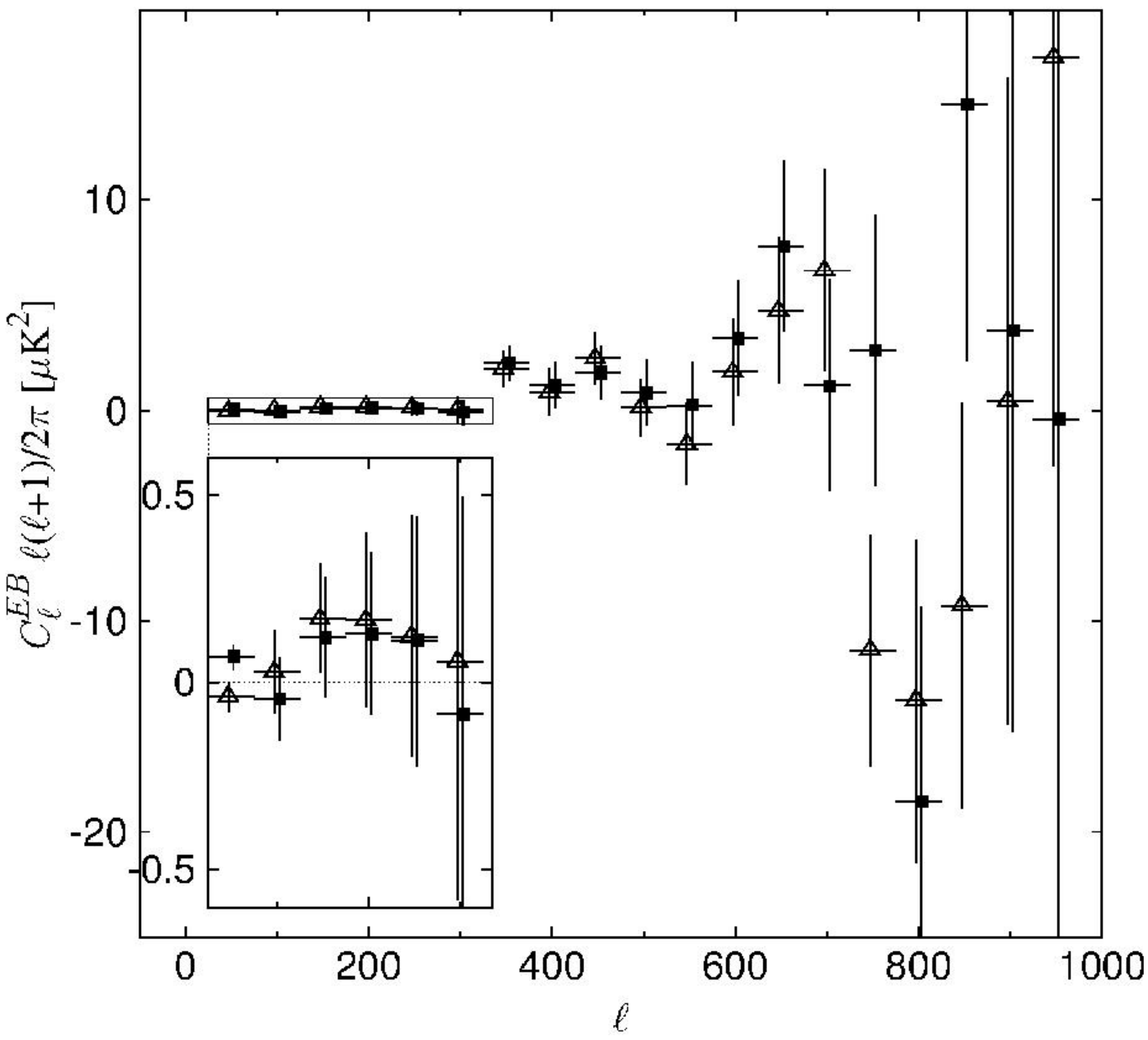
Source	ν_{eff}[a] (GHz)	Γ[a] (mK Jy^{-1})	I Flux (Jy)	Q Flux (Jy)	U Flux (Jy)	P Flux[b] (Jy)	P/I[b] (%)	Pol Angle[c] (deg)
Cas A	22.68	0.2497	232.1 ± 2.9	−0.92 ± 0.09	−0.15 ± 0.09	0.93 ± 0.09	0.41 ± 0.04	85.5 ± 2.7 (66.0)
Cas A	32.94	0.2041	179.8 ± 1.5	−0.56 ± 0.08	−0.19 ± 0.09	0.59 ± 0.08	0.33 ± 0.05	80.6 ± 4.2 (61.1)
Cas A	40.62	0.2162	153.7 ± 1.5	−0.50 ± 0.09	−0.17 ± 0.10	0.53 ± 0.09	0.35 ± 0.06	80.6 ± 5.3 (61.1)
Cas A	60.48	0.2084	116.3 ± 2.0[d]	−0.25 ± 0.16[d]	0.12 ± 0.16[d]	0.28 ± 0.16	0.24 ± 0.14	−77.6 ± 16.8 (82.9)
Cas A	92.90	0.1800	84.0 ± 3.4[e]	−0.05 ± 0.28[e]	0.12 ± 0.28[e]	0.13 ± 0.28	0.16 ± 0.34	−56.1 ± 59.9 (104.4)
Cyg A	22.65	0.2493	57.7 ± 1.3	0.02 ± 0.05	−0.48 ± 0.06	0.48 ± 0.06	0.84 ± 0.11	43.6 ± 2.9 (164.8)
Cyg A	32.91	0.2039	38.2 ± 0.6	0.40 ± 0.08	0.20 ± 0.10	0.45 ± 0.08	1.18 ± 0.22	−13.5 ± 6.0 (107.7)
Cyg A	40.58	0.2159	29.8 ± 0.4	0.58 ± 0.08	0.18 ± 0.10	0.61 ± 0.09	2.04 ± 0.29	−8.4 ± 4.8 (112.8)
Cyg A	60.42	0.2083	18.6 ± 0.2	0.38 ± 0.15	0.26 ± 0.20	0.46 ± 0.17	2.48 ± 0.89	−16.9 ± 11.4 (104.3)
Cyg A	92.83	0.1802	11.1 ± 0.3	0.26 ± 0.26	0.11 ± 0.34	0.28 ± 0.27	2.55 ± 2.45	−11.5 ± 33.2 (109.7)
Tau A	22.70	0.2501	383.8 ± 9.6	−27.13 ± 0.68	1.40 ± 0.08	27.17 ± 0.68	7.08 ± 0.25	−88.5 ± 0.1 (149.1)
Tau A	32.96	0.2043	342.8 ± 6.4	−23.72 ± 0.45	1.88 ± 0.12	23.80 ± 0.44	6.94 ± 0.18	−87.7 ± 0.1 (149.9)
Tau A	40.64	0.2163	317.7 ± 8.6	−22.03 ± 0.60	2.06 ± 0.14	22.12 ± 0.60	6.97 ± 0.27	−87.3 ± 0.2 (150.3)
Tau A	60.53	0.2085	276.0 ± 5.2[d]	−19.25 ± 0.36[d]	1.52 ± 0.24[d]	19.31 ± 0.36	7.00 ± 0.19	−87.7 ± 0.4 (149.9)
Tau A	92.95	0.1798	232.8 ± 9.7[e]	−16.58 ± 0.73[e]	0.75 ± 0.42[e]	16.60 ± 0.73	7.13 ± 0.43	−88.7 ± 0.7 (148.9)
3C58	22.70	0.2500	20.8 ± 0.4	1.11 ± 0.04	0.45 ± 0.06	1.20 ± 0.05	5.77 ± 0.25	−11.0 ± 1.4 (5.4)
3C58	32.96	0.2043	19.0 ± 0.3	1.20 ± 0.07	0.25 ± 0.10	1.23 ± 0.07	6.46 ± 0.39	−5.8 ± 2.3 (10.7)
3C58	40.64	0.2163	17.1 ± 0.3	0.99 ± 0.08	0.46 ± 0.09	1.09 ± 0.08	6.37 ± 0.50	−12.6 ± 2.3 (3.9)
3C58	60.52	0.2085	14.1 ± 0.3[d]	0.77 ± 0.12[d]	0.07 ± 0.17[d]	0.77 ± 0.12	5.48 ± 0.87	−2.7 ± 6.3 (13.7)
3C58	92.94	0.1798	11.4 ± 0.6[e]	0.52 ± 0.23[e]	0.42 ± 0.30[e]	0.67 ± 0.26	5.87 ± 2.28	−19.3 ± 11.7 (−2.9)
3C274	22.68	0.2497	21.6 ± 0.6	0.49 ± 0.08	−0.73 ± 0.06	0.88 ± 0.06	4.06 ± 0.31	28.1 ± 2.3 (45.5)
3C274	32.94	0.2041	16.8 ± 0.4	0.43 ± 0.12	−0.69 ± 0.09	0.81 ± 0.10	4.84 ± 0.61	28.9 ± 4.0 (46.3)
3C274	40.61	0.2161	14.3 ± 0.5	0.40 ± 0.14	−0.55 ± 0.10	0.68 ± 0.12	4.72 ± 0.84	26.9 ± 5.5 (44.3)
3C274	60.48	0.2084	10.6 ± 0.3	0.16 ± 0.25	−0.11 ± 0.18	0.20 ± 0.23	1.85 ± 2.15	17.2 ± 29.9 (34.6)
3C274	92.89	0.1800	7.8 ± 0.3	0.41 ± 0.43	−0.43 ± 0.31	0.59 ± 0.37	7.66 ± 4.83	23.0 ± 18.2 (40.4)

Comparison with ΛCDM

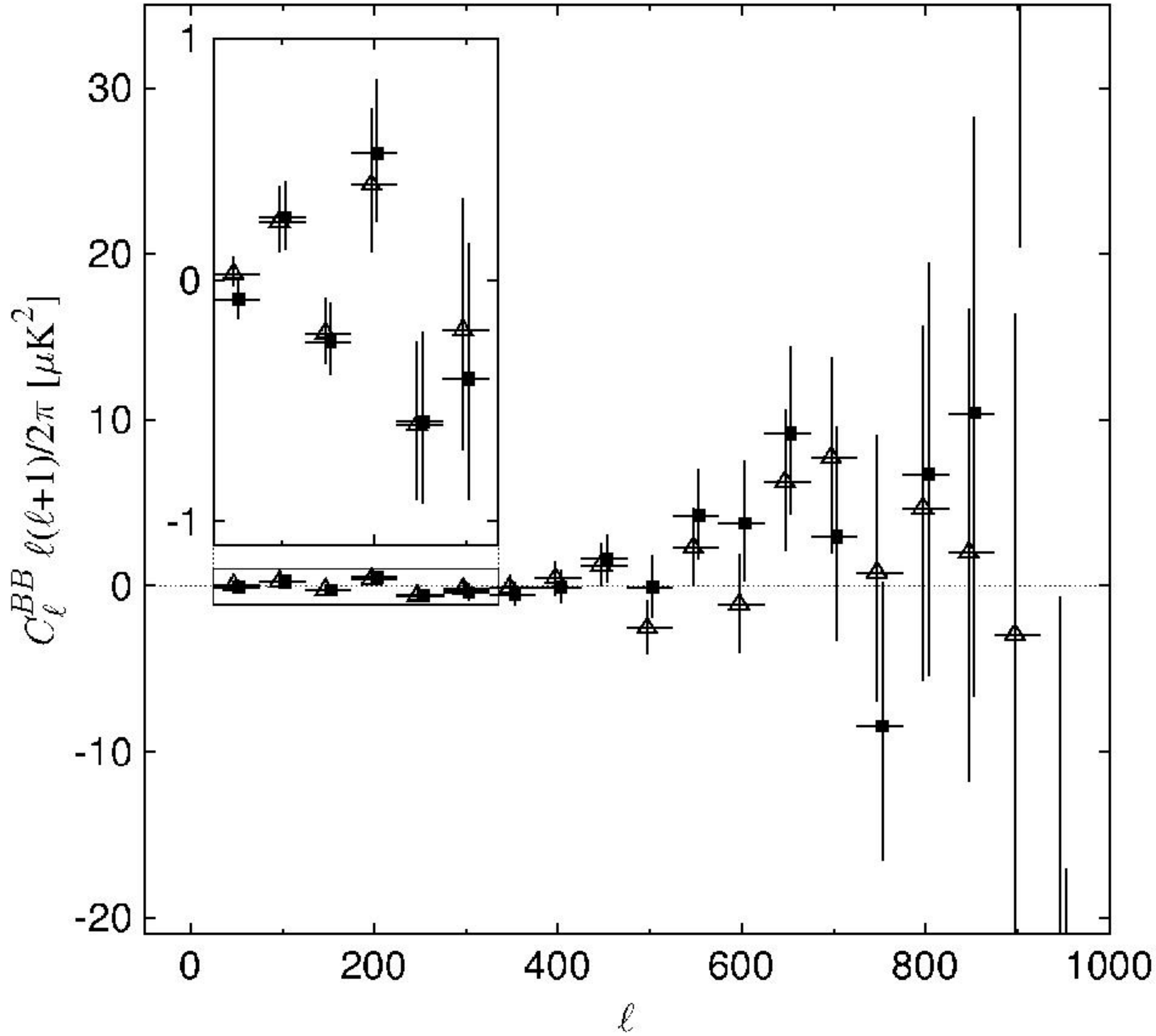


Note: QUIET amplitude is here scaled to q = 1 to highlight the shape of the accoustic peaks

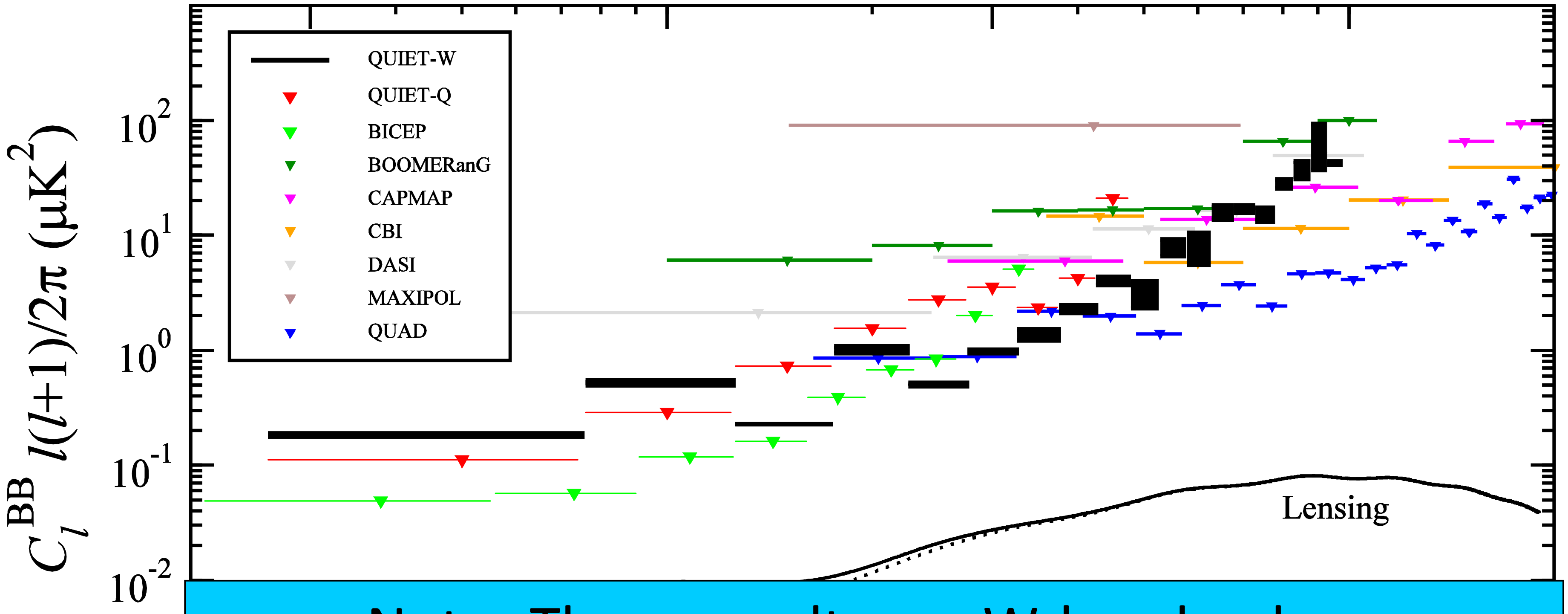
EB power spectrum



BB power spectrum



The BB spectrum and tensor-to-scalar ratio

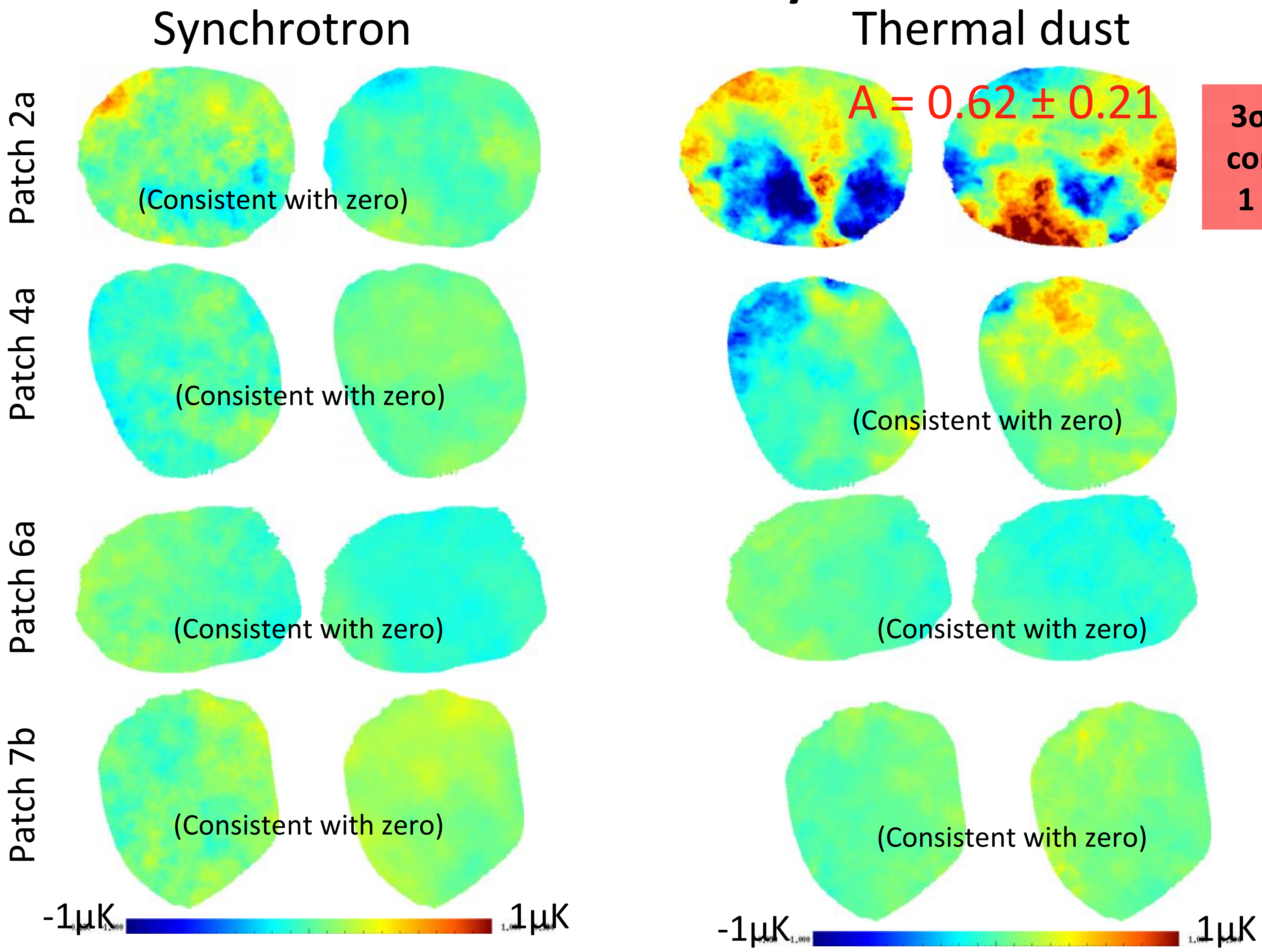


Note: These results are W-band only.
The results from the combined
Q+W analysis are in progress.

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

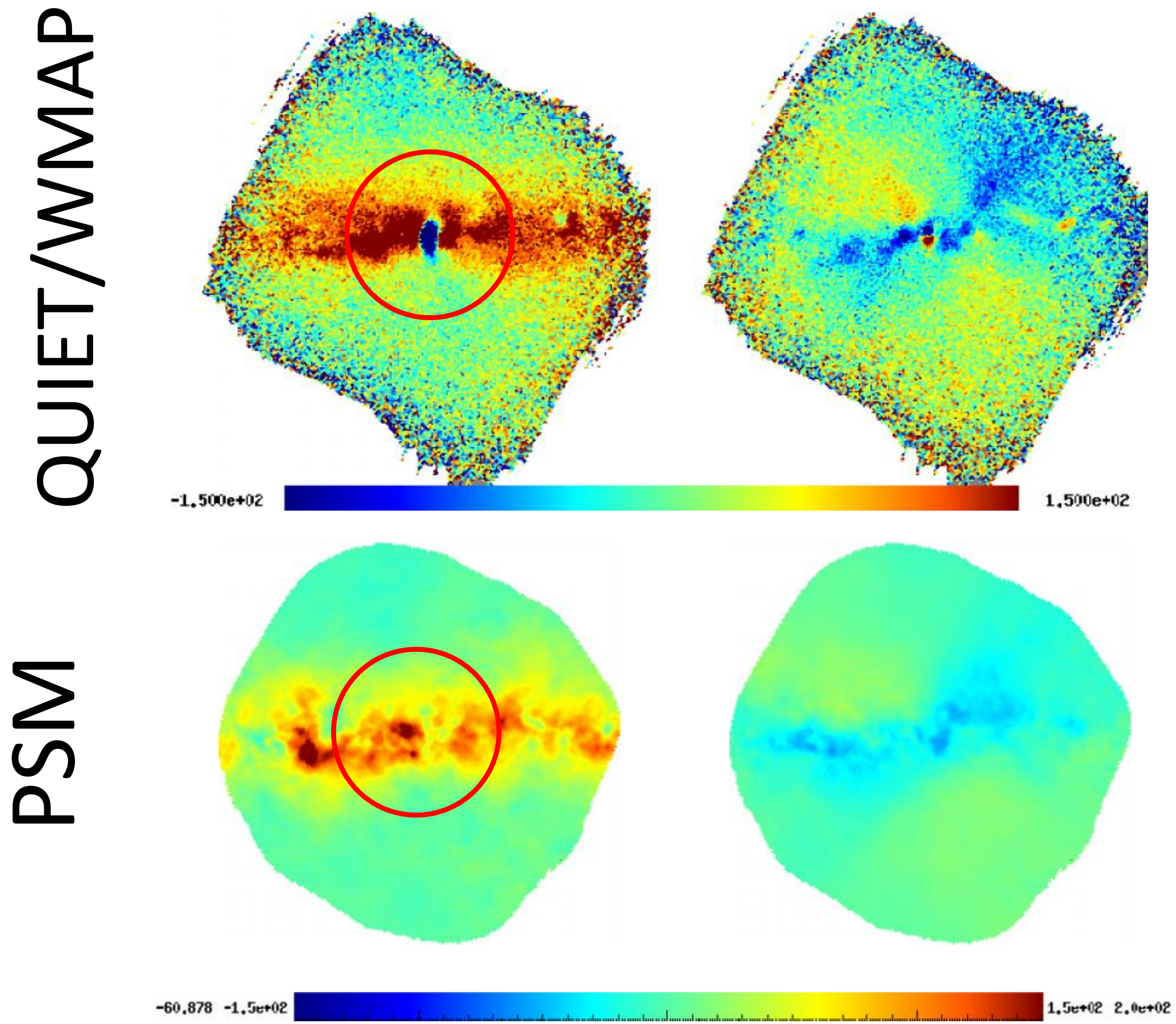
$r = 1.2^{+0.9}_{-0.8}$ r < 2.7 @ 95% CL (PCL)

Foregrounds, QUIET and the Planck Sky Model

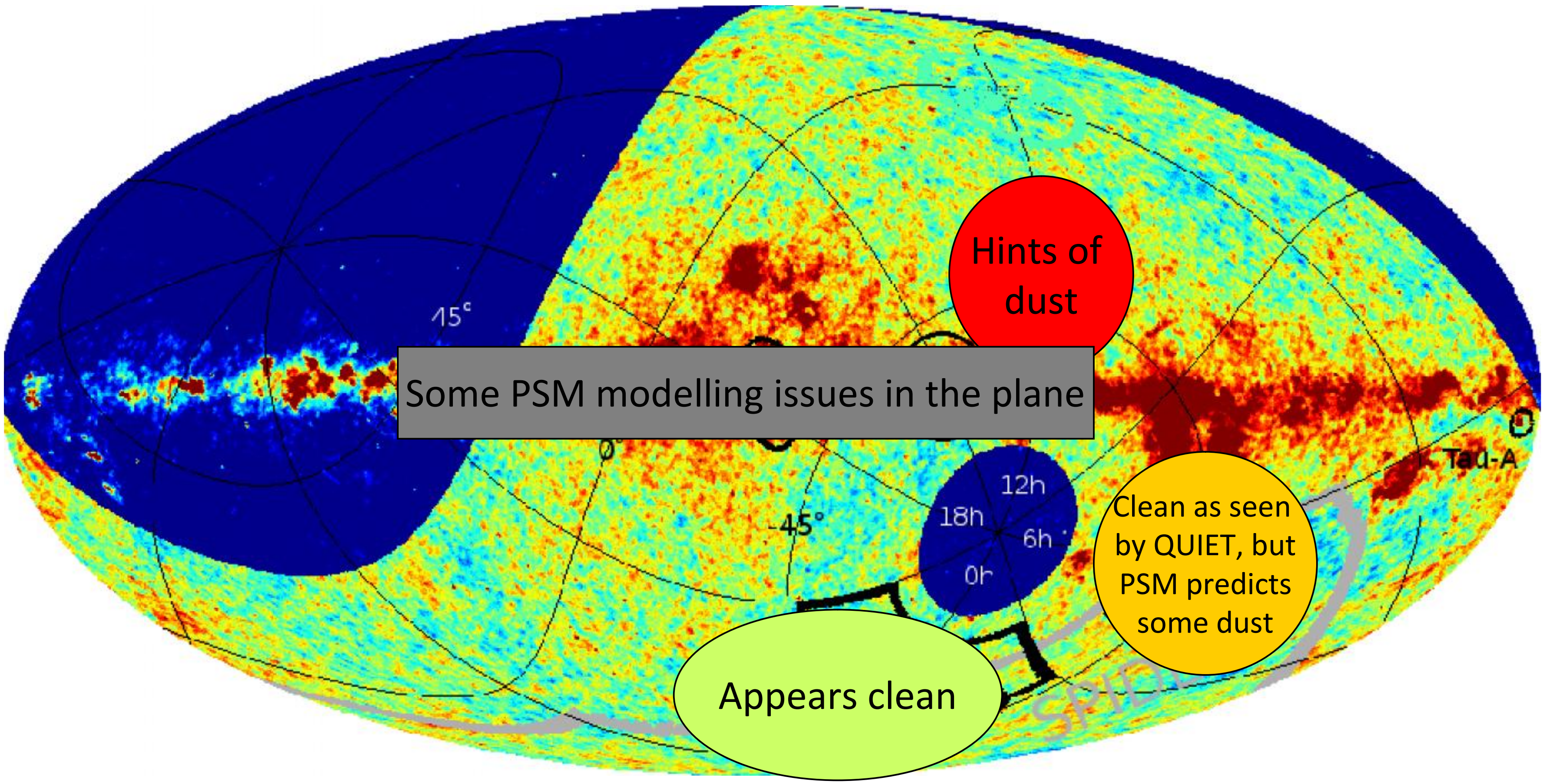


3σ correlation, consistent with 1 at 1.6 sigma

Modelling of the Galactic plane

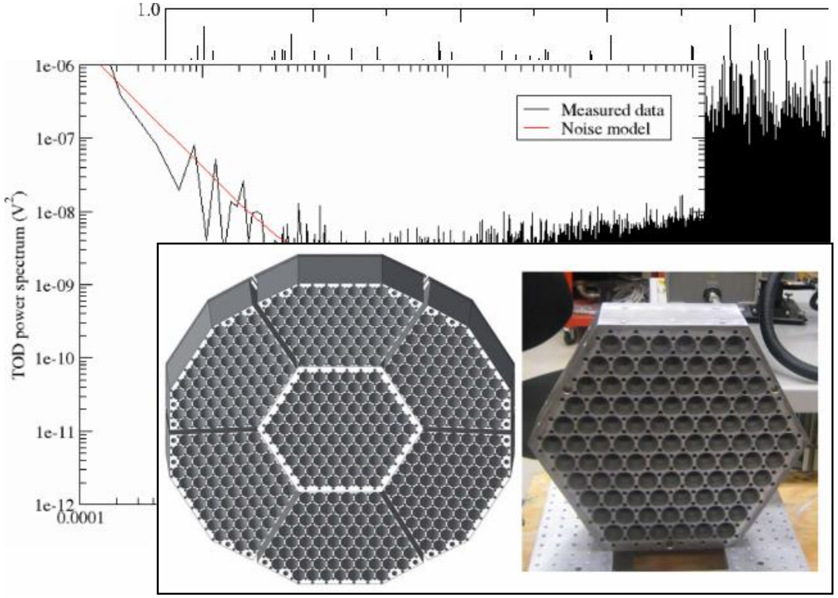


PSM and foreground summary



A few lessons learned from QUIET1

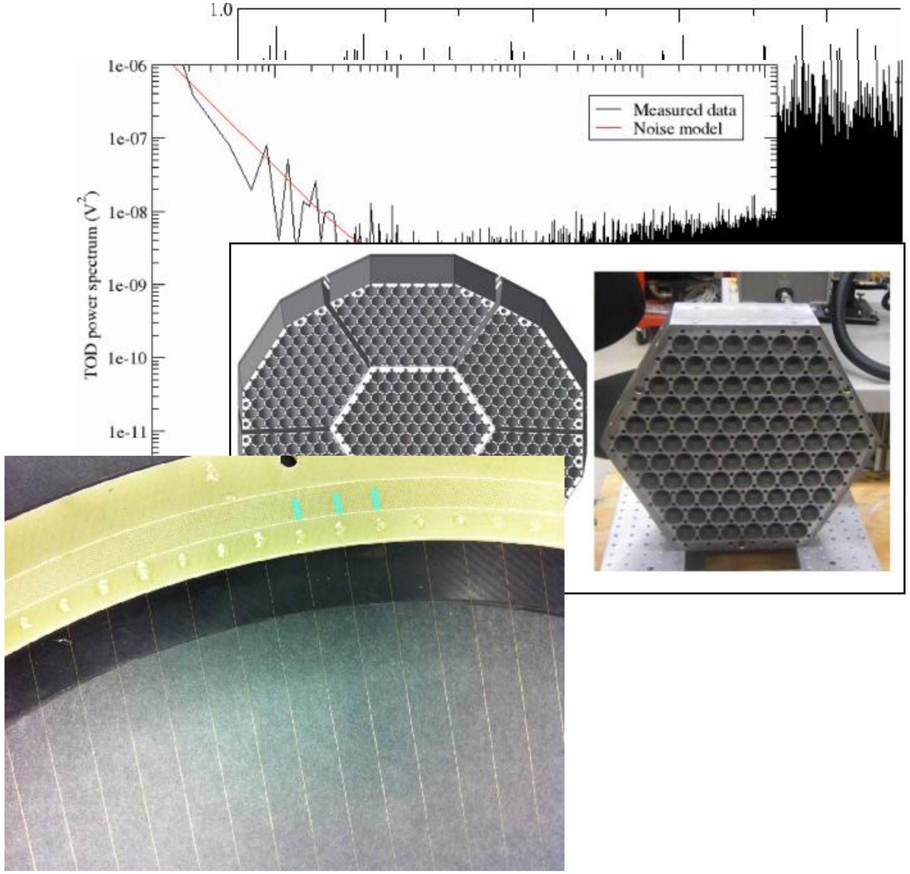
- QUIET1 as a pathfinder experiment
  - What have we learned?
- MMICs perform beautifully!
  - Close to white noise at both low and high frequencies (fknee < 10 mHz; no high-frequency time constant)
  - Extremely low I-to-Q/U leakage
  - The current detector arrays can be scaled up to reach $r < 0.01$ with 3 years of observations



A few lessons learned from QUIET1

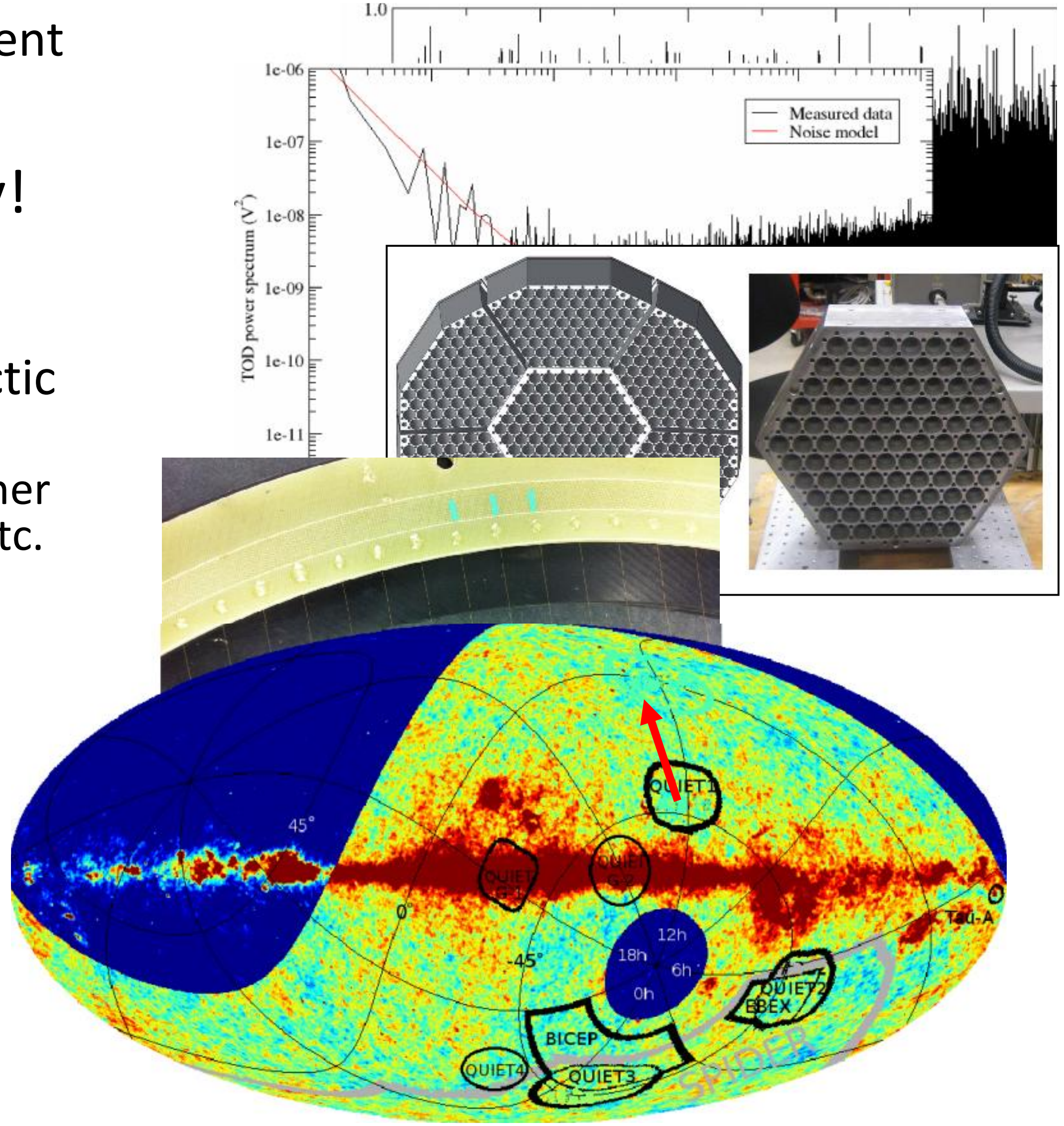
- QUIET1 as a pathfinder experiment
  - What have we learned?
- MMICs perform beautifully!

- Absolute calibration is difficult
  - Plan for several independent calibration sources; hardware calibrators can be very useful



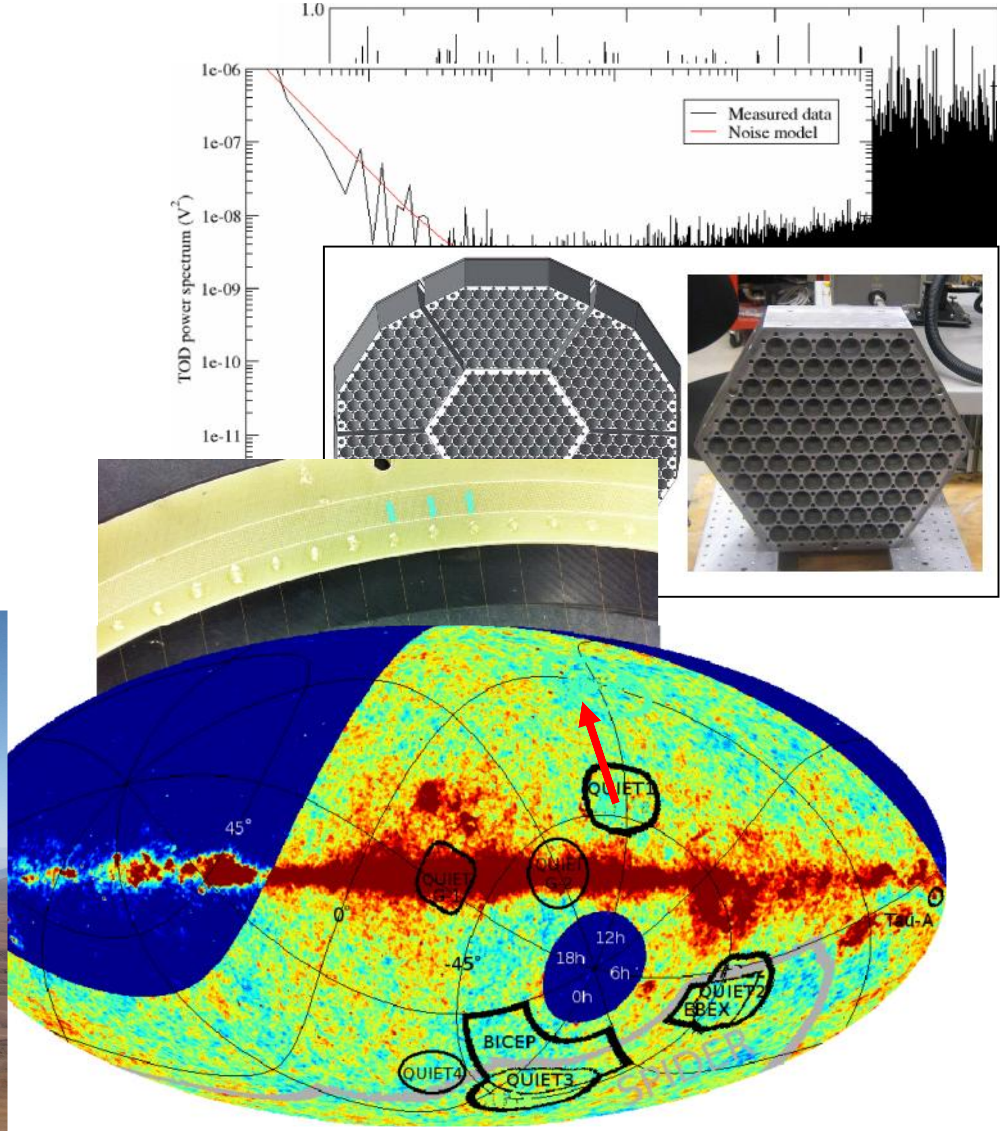
A few lessons learned from QUIET1

- QUIET1 as a pathfinder experiment
  - What have we learned?
- MMICs perform beautifully!
- Absolute calibration is difficult
- Don't observe close to the Galactic plane
  - Patch 2a should be moved further north; note to ABS, PolarBear etc.
  - Will lose time to Sun/Moon/ planets, but worth it



A few lessons learned from QUIET1

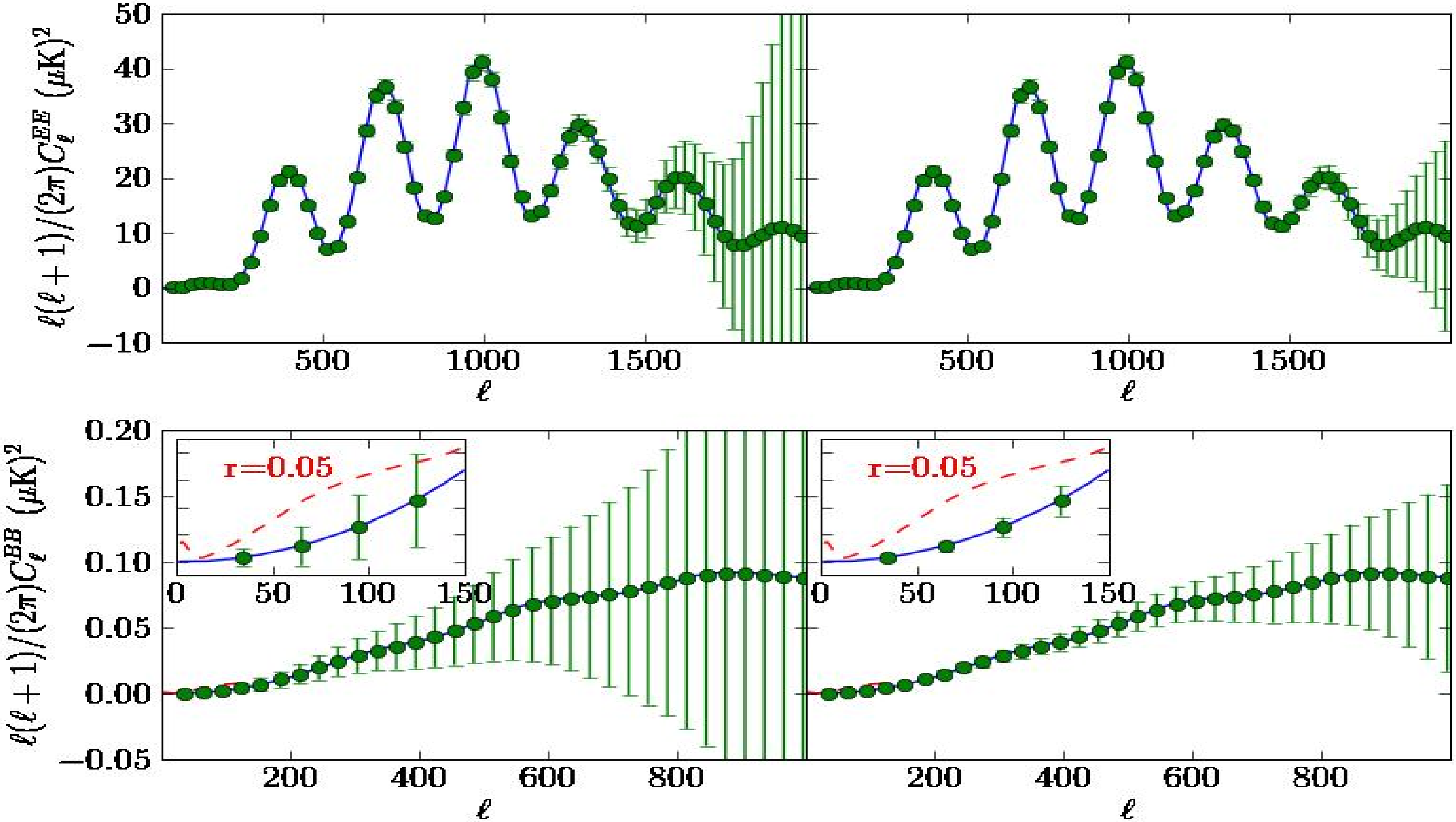
- QUIET1 as a pathfinder experiment
  - What have we learned?
- MMICs perform beautifully!
- Absolute calibration is difficult
- Don't observe close to the Galactic plane
- Chile is a really nice place to work



QUIET2 power spectrum forecasts

Current Performance
(noise, duty cycle, 1/f)

Likely Improvements



0.018	Δr	0.005
10σ	lensing	35σ

Courtesy K. Smith

Conclusions

- QUIET has published measurements of the CMB polarization spectra at 95 GHz
  - Clearly traces three accoustic peaks between l = 25 and 1000
  - EE spectrum consistent with LCDM, BB spectrum consistent with zero
    - Can see E-mode signal by eye in the sky maps
  - Finds hints of thermal dust emission consistent with the Planck Sky Model in one field near the Galactic plane
  - Demonstrate the lowest levels of systematics to date

- **The QUIET pathfinder has convincingly shown that MMICs are capable of probing inflation to r ~ 0.01**

- 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