CMB Polarization Results from the QUIET Experiment

Cosmology on the Beach
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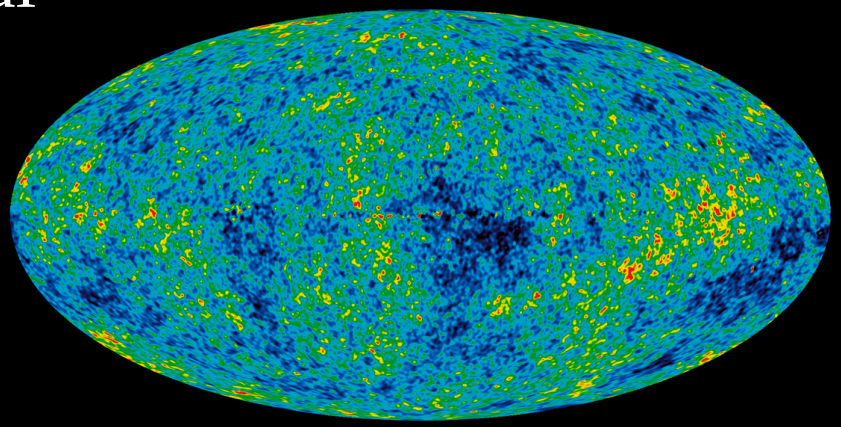
How will we make a B-mode detection convincing?

- Review of Inflationary Cosmology and CMB Polarization
- QUIET Overview and Techniques for controlling systematic error
- 43-GHz (Q-band) Analysis and Results
- Future Prospects: 95-GHz (W-band) Analysis

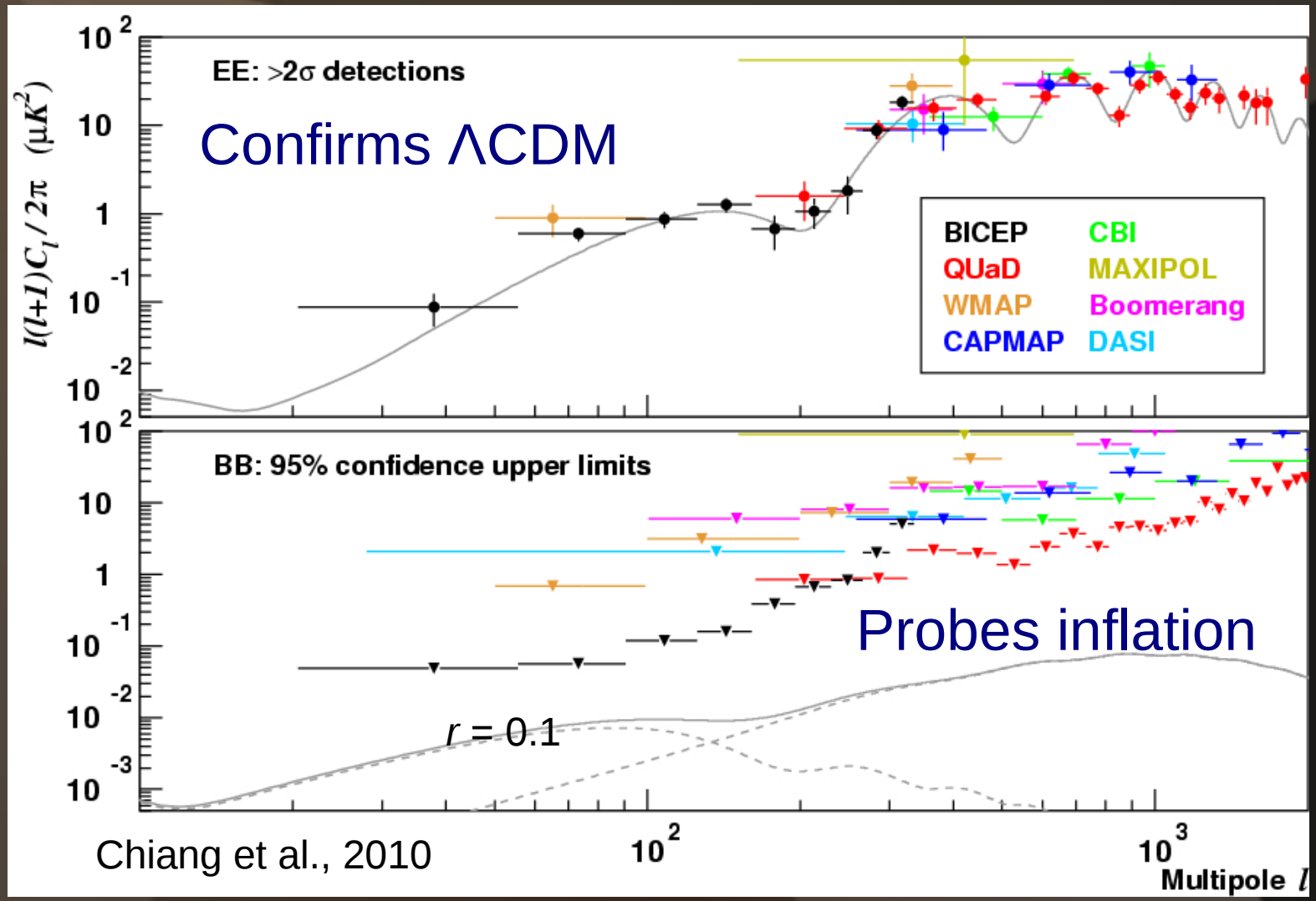
Inflation Explains Puzzles

- Exponential expansion at very early times (high energy)
- An answer to:
  - How were different parts of the observable Universe in causal contact at last scattering?
  - Why is the Universe so flat?
  - What seeded density fluctuations?
- Predicts gravity waves (tensor modes) in the early Universe
  - Causes an observable signal (B mode) in the CMB polarization



NASA/WMAP Science Team

We Need Better Data



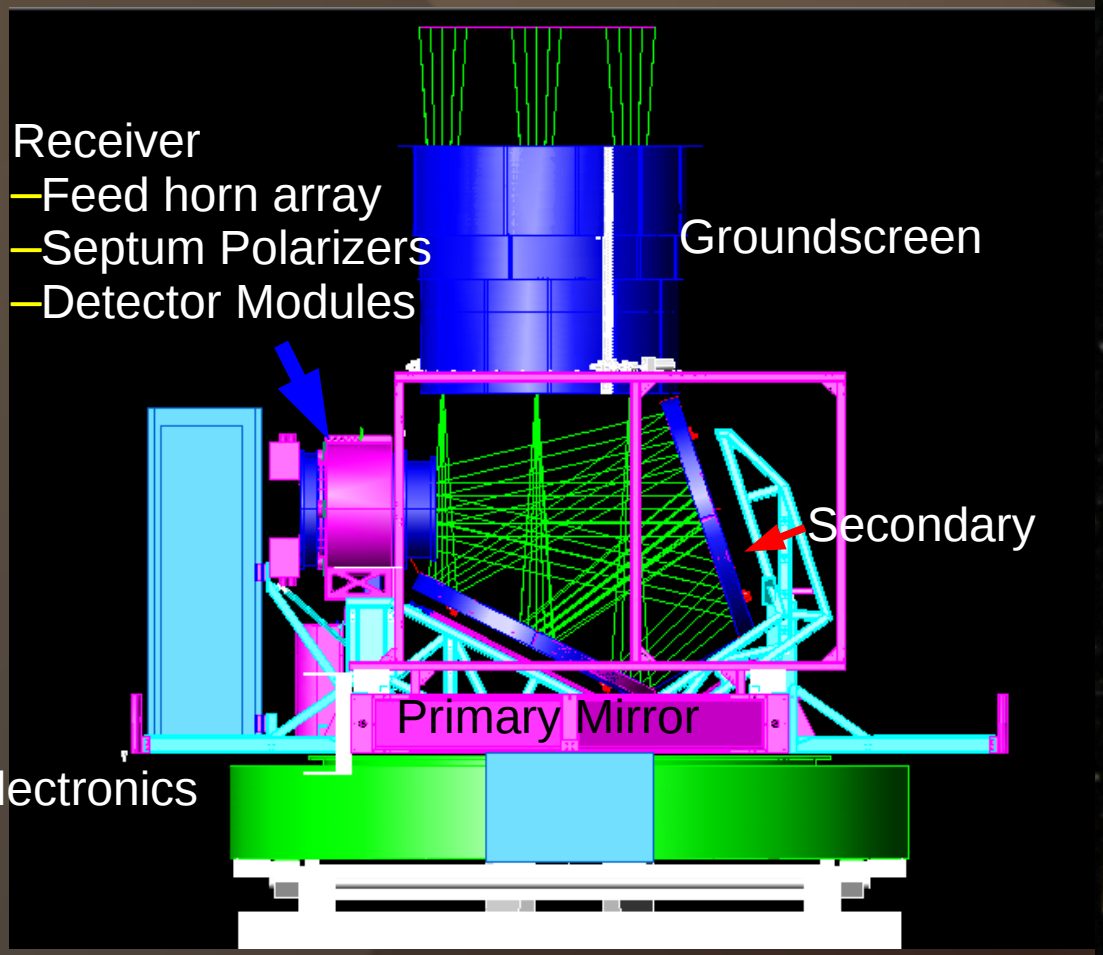
Chiang et al., 2010

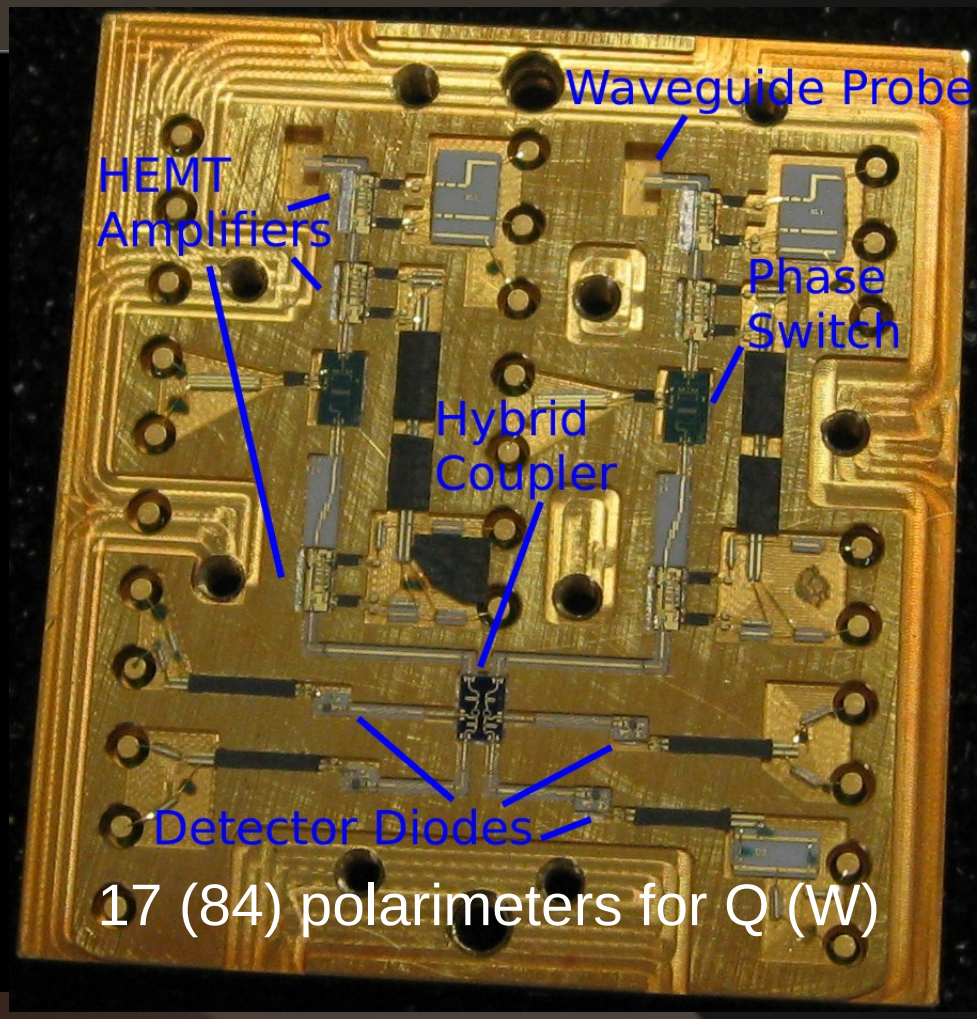
- Best limits: $r < 0.72$ (BICEP) $r < 0.2$ (*WMAP*) with T
- $r \geq 0.01$ in the most natural models (Boyle et al. 2006)

QUIET has completed 2 observing seasons

- 2008—2009 Q-band observing
- 2009—2010 W-band observing
- 2010 December Q-band result released
- Now analyzing W-band data
- Early 2012 W-band result released

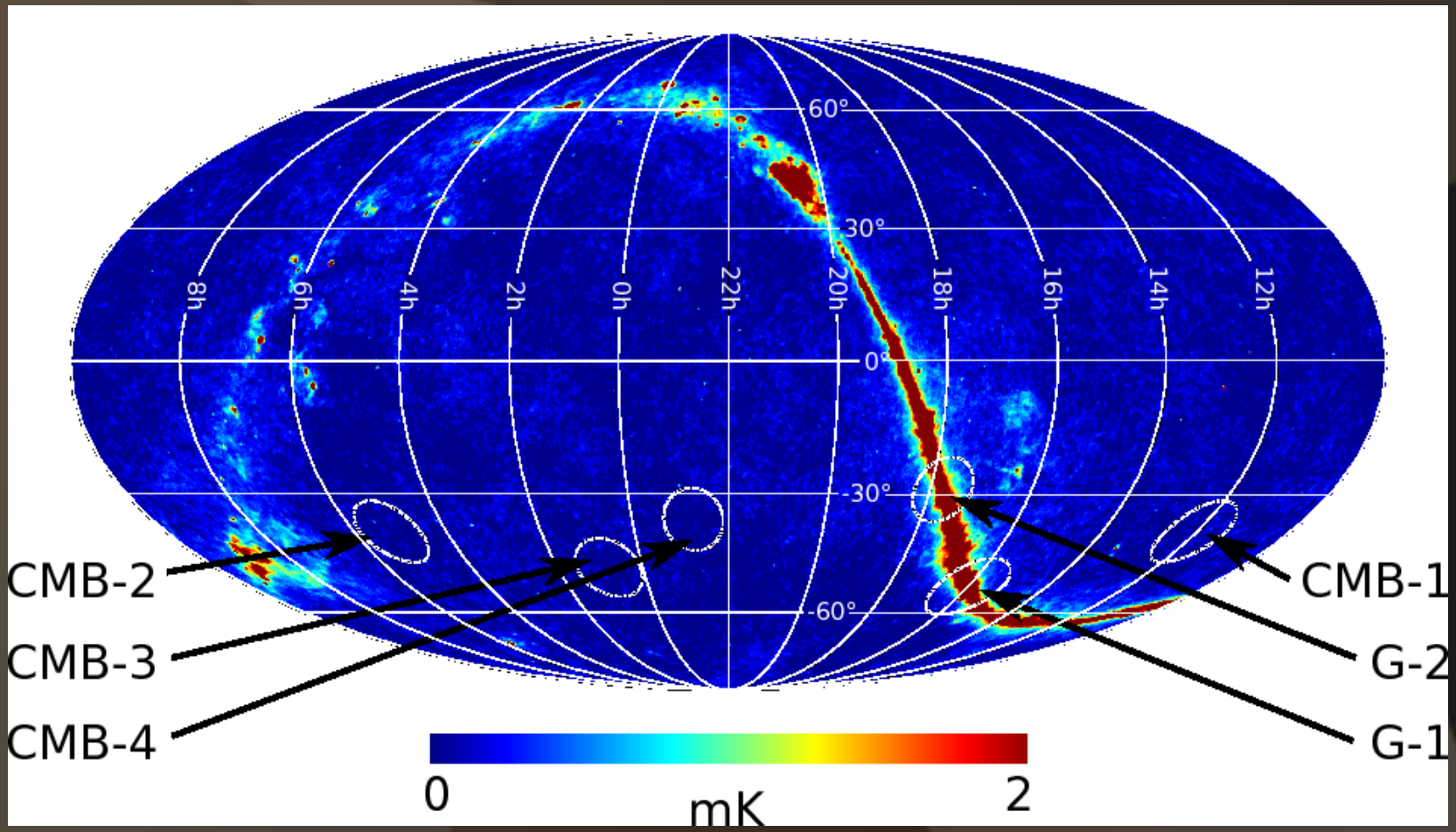
Design for Sensor Density and Low Systematic Error





3-axis Mount (azimuth, elevation, boresight): boresight rotation (about the optical axis) suppresses the effect of instrumental polarization

Optimized Observing Strategy for Atacama



Plus calibration observation

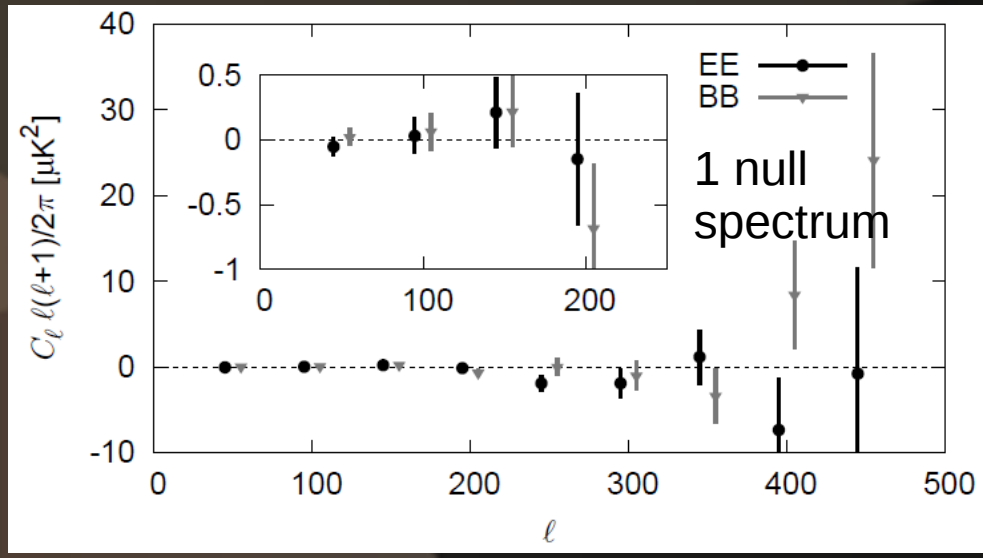
- CMB Patches chosen to minimize foregrounds
- Q-band precision in 1 deg. square pixel:
  - 1.1, 1.4, 1.4, 2.3 μK (CMB 1—4)
  - c.f. Planck Q band: 3.6 μK (15 months)

Robust Check for Systematics

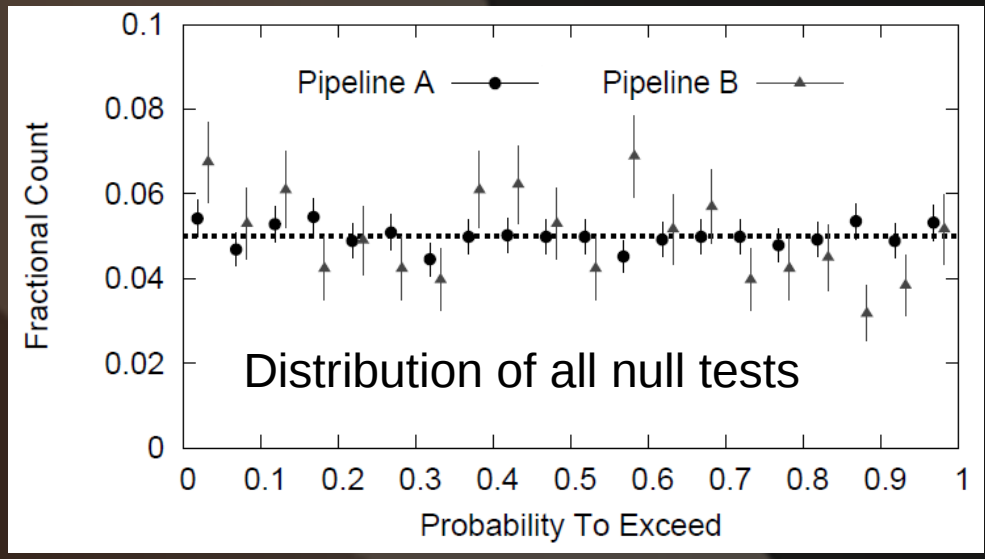
- Two independent and complementary pipelines
  - **Pipeline A**: Pseudo-Cl / MASTER
  - Pipeline B: Maximum likelihood
- Blind analysis
  - Calibration, data selection, filtering choices made without knowledge of result
  - Removes experimenter bias
- Extensive null suite and consistency checks
- Detailed systematic error estimates
  - Much lower than statistical error to show potential of the technology

Innovative Null Suite Evaluation

- Check consistency between two halves of data
- 42 null tests include
  - Q vs. U detectors
  - Spurious polarization
  - Array orientation
- Statistical evaluation
- ~1000 reference MC
  - Correlations and non-Gaussian error taken into account



Q-sensitive vs. U-sensitive diodes



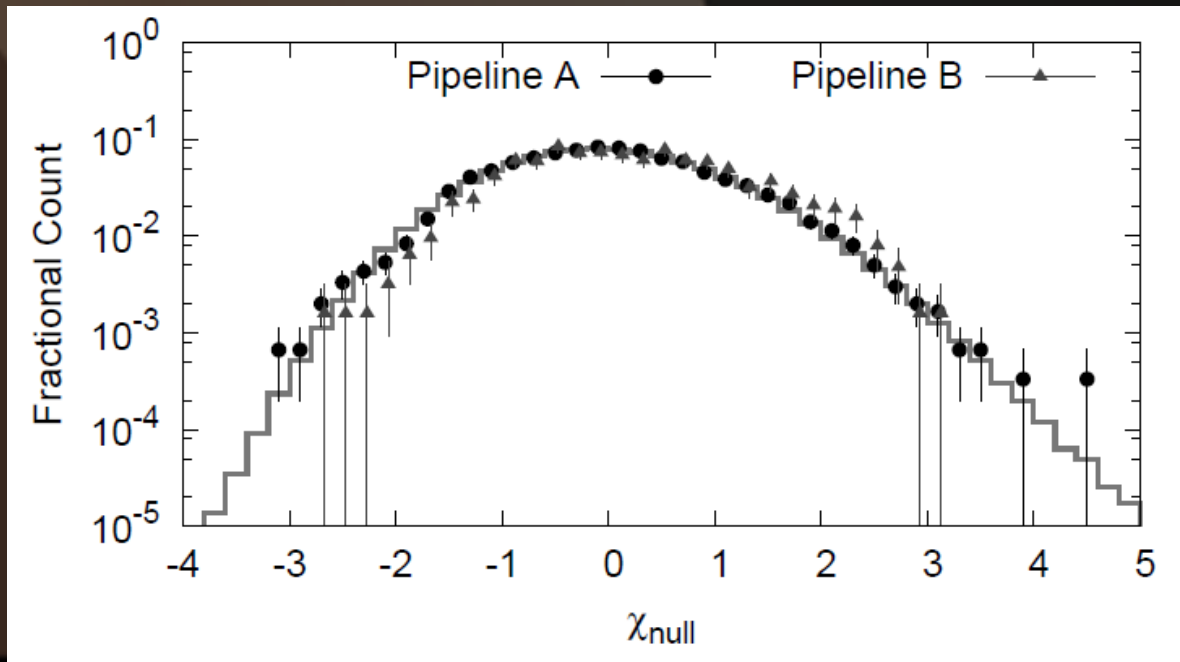
χ^2 PTE distribution

Understand Null Distribution

- Mean of χ is sensitive to overall contamination while χ^2 is sensitive to outliers

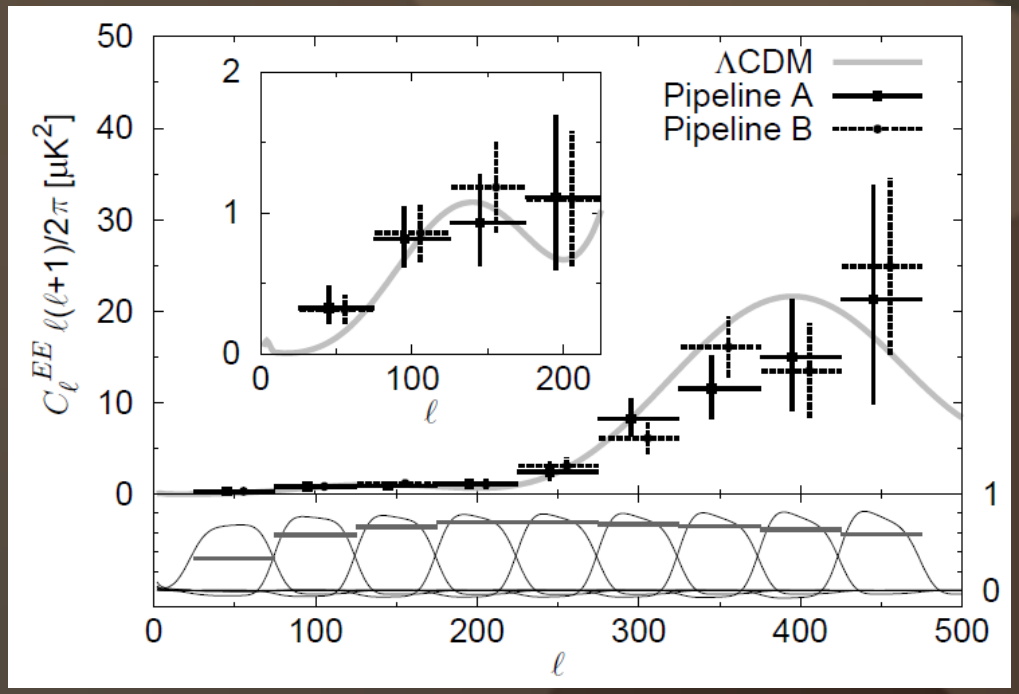
$$\chi_{null} \equiv \frac{C_\ell^{null}}{\sigma_\ell}$$

- Without cross correlation there was a statistically significant χ bias but χ^2 did not show contamination
- With cross correlation the bias in χ distribution is consistent with 0 to the uncertainty of ~2% of statistical error
- Important for future experiments to check the distribution detail

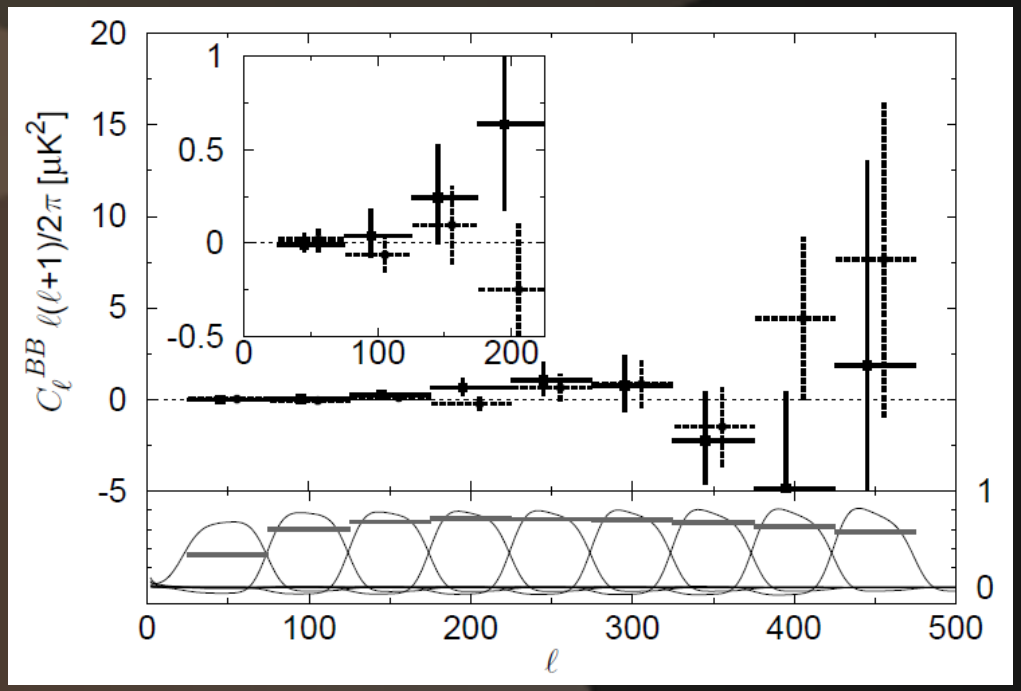


Q-band Results: Power Spectra

EE power

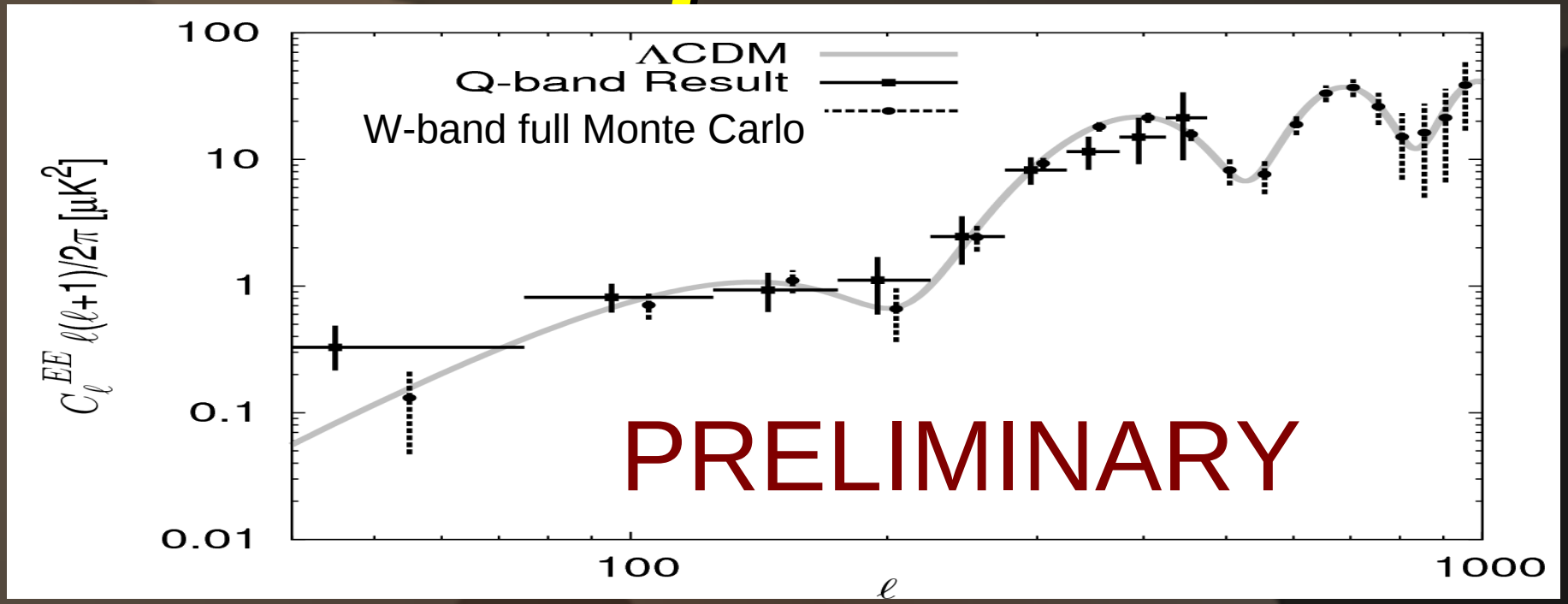


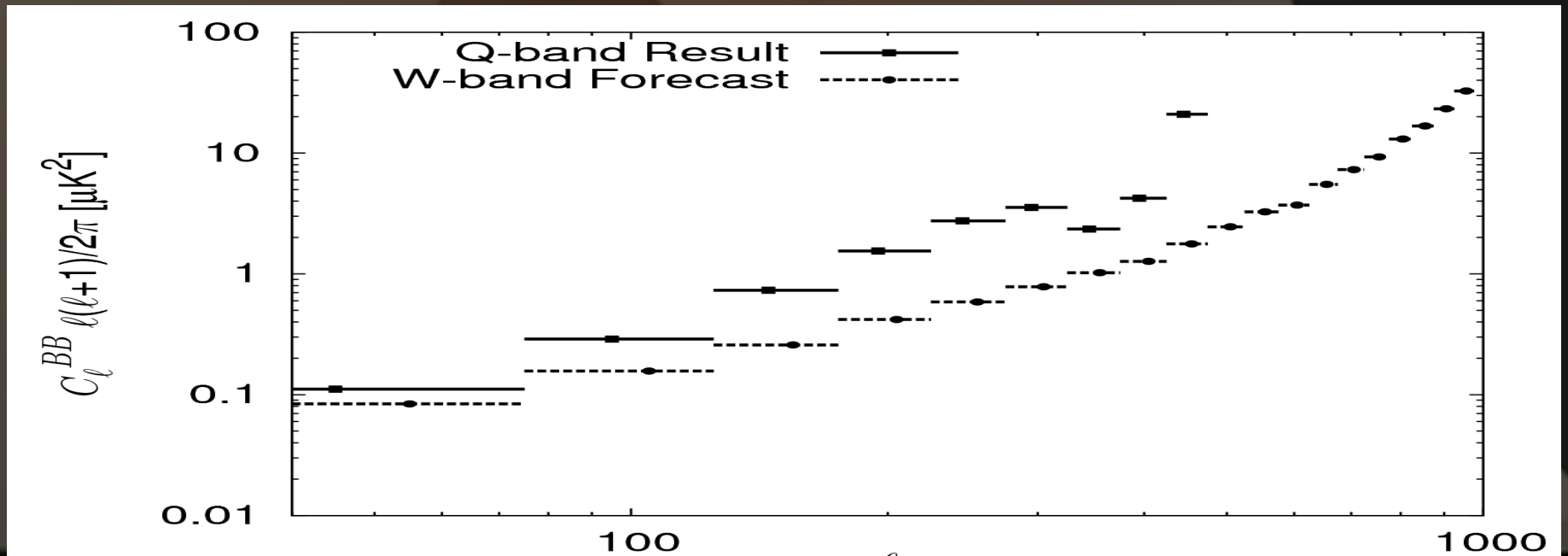
BB power



- Two pipelines show consistent results
- Consistent with concordance cosmology (ΛCDM)
- No detection of B modes (detection not expected at our sensitivity)

Forecast Improved Result





Summary

- QUIET Experiment first phase observing completed successfully
- Q-band Results (arxiv: 1012.3191)
  - Improved analysis techniques to avoid systematic error (include blind analysis)
  - Unique contribution to foreground characterization
- More sensitive W-band result is coming

QUIET Experiment Summary

Frequencies	43 (Q Band) / 95 (W Band)	GHz
Angular resolutions	27 / 12 (FWHM)	arcmin at each freq
Field centers and sizes	181/-39, 78/-39, 12/-48, 341/-36 4x(15× 15) ~ 1000	Ra/Dec (Deg) Size (Deg^2)
Telescope type	crossed Mizuguchi-Dragone	
Polarization Modulations	Phaseswitch (4kHz&50Hz), Boresight, Sky rotation, Fast scan	
Detector type	HEMT	Bolometer, HEMT etc.
Location	Chajnantor(Atacama),Chile	
Instrument NEQ/U	69 / ~70	$\mu K\ s^{1/2}$, combined Q *and* U
Focal plane size	19 / 90	Number of modules
Observing time	3458 / ~7500	hours
Projected limit on *r*	0.5 (?)	No foreground assumed

Extra Slides

QUIET Group at Chicago

- PI: B. Winstein
- Postdoc: A. Kusaka
- Grad Students: A. Brizius, I. Buder
- C. Bischoff, M. Becker, Y. Chinone, E. Curry, M. Hedman, K. Huff, D. Kapner, S. Li, M. Malin, D. Moore, A. Robinson, D. Samtleben, K. Smith, A. Sugarbaker, O. Tajima, K. Vanderlinde, R. Williamson

QUIET is a Worldwide Collaboration

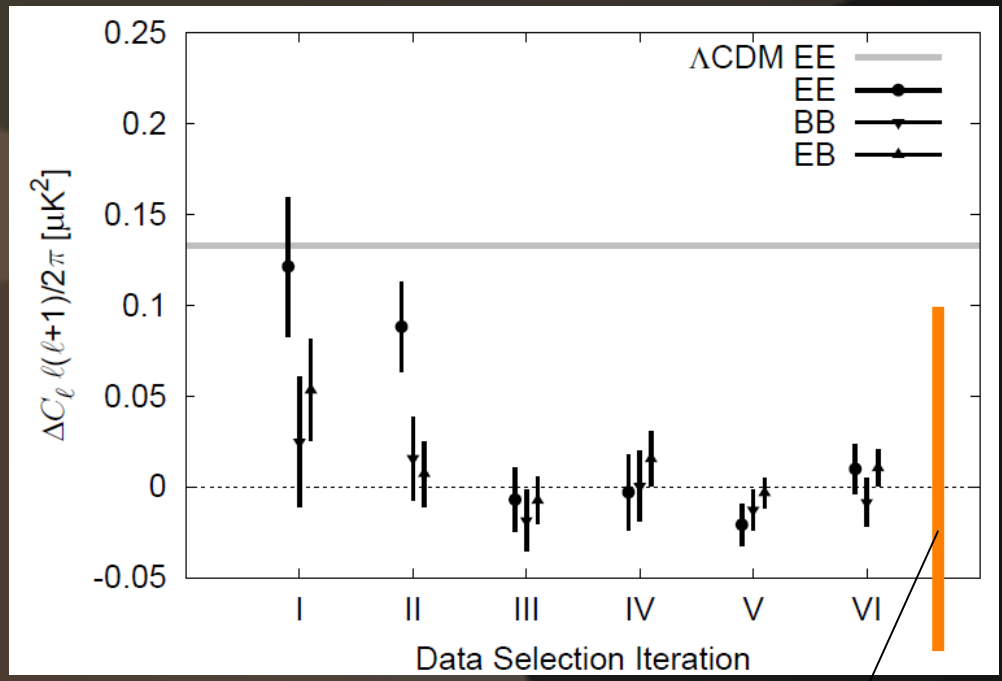
5 countries, 14 institutions, ~50 scientists

Check Consistency

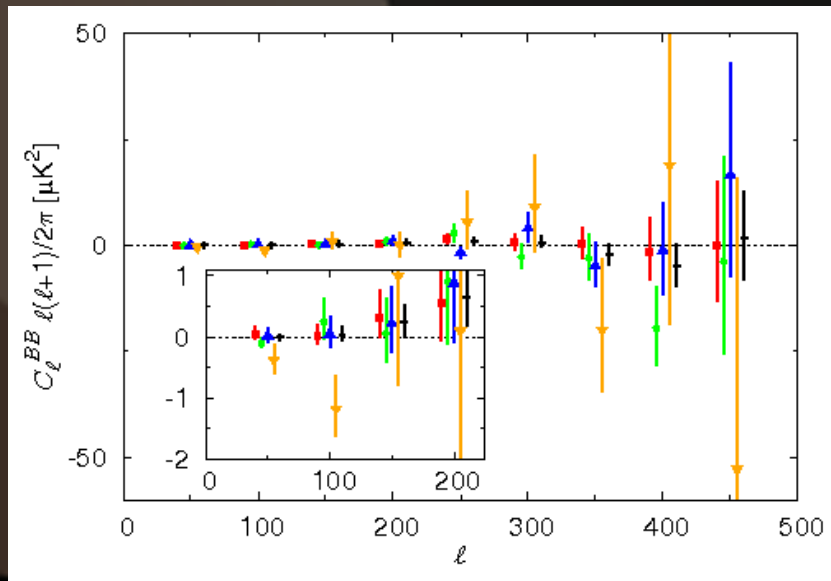
- Many analysis configuration iterations are examined before seeing the result
- Consistency check among iterations
  - Non-statistical change implies residual contamination
- Consistency check among patches

$$\chi_p^2 \equiv \sum_{i=0}^{3} \sum_{b=0}^{8} \left(\frac{C_{ib} - \mu_b}{\sigma_{ib}} \right)^2$$

Consistency among different cuts

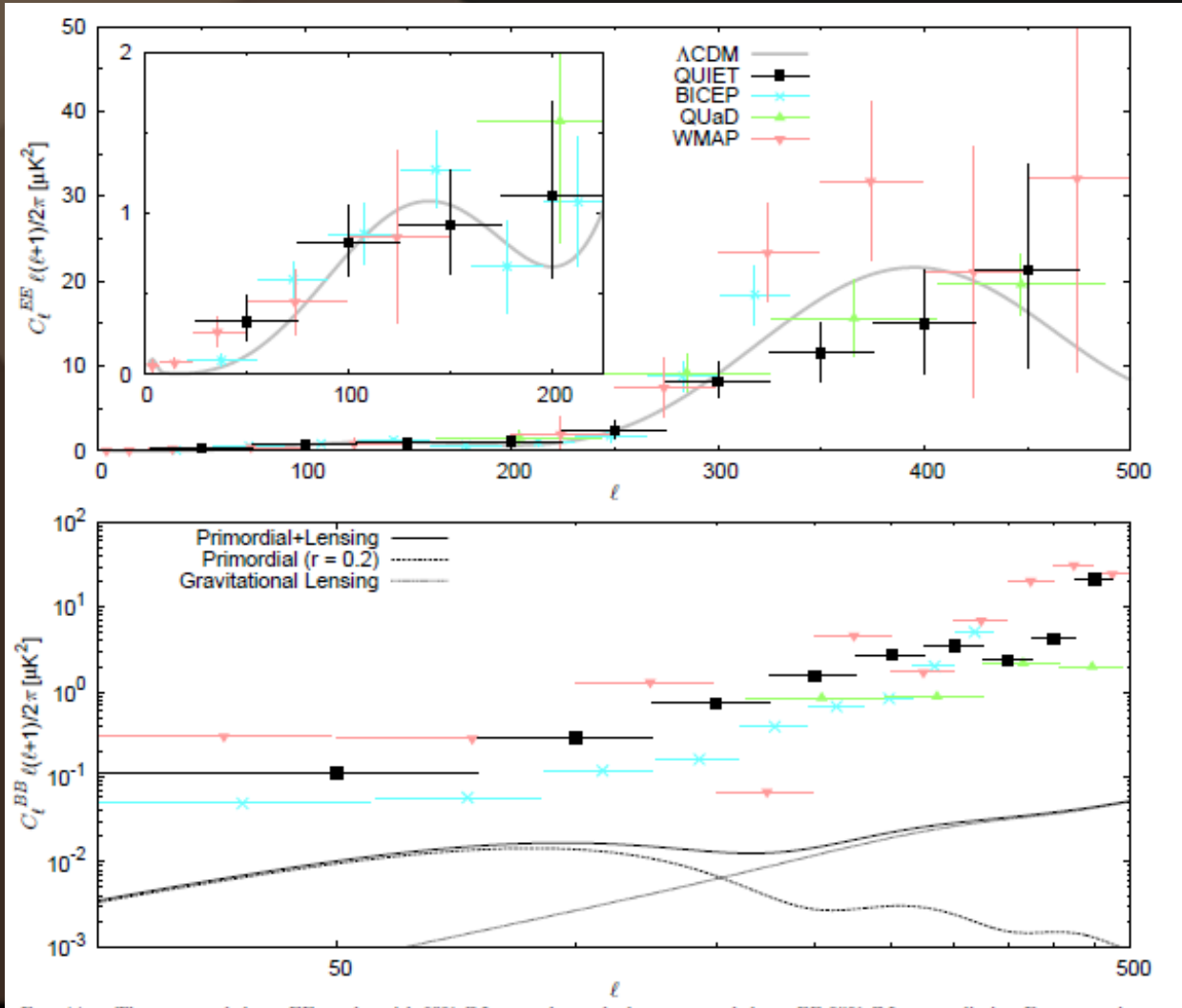


Final error

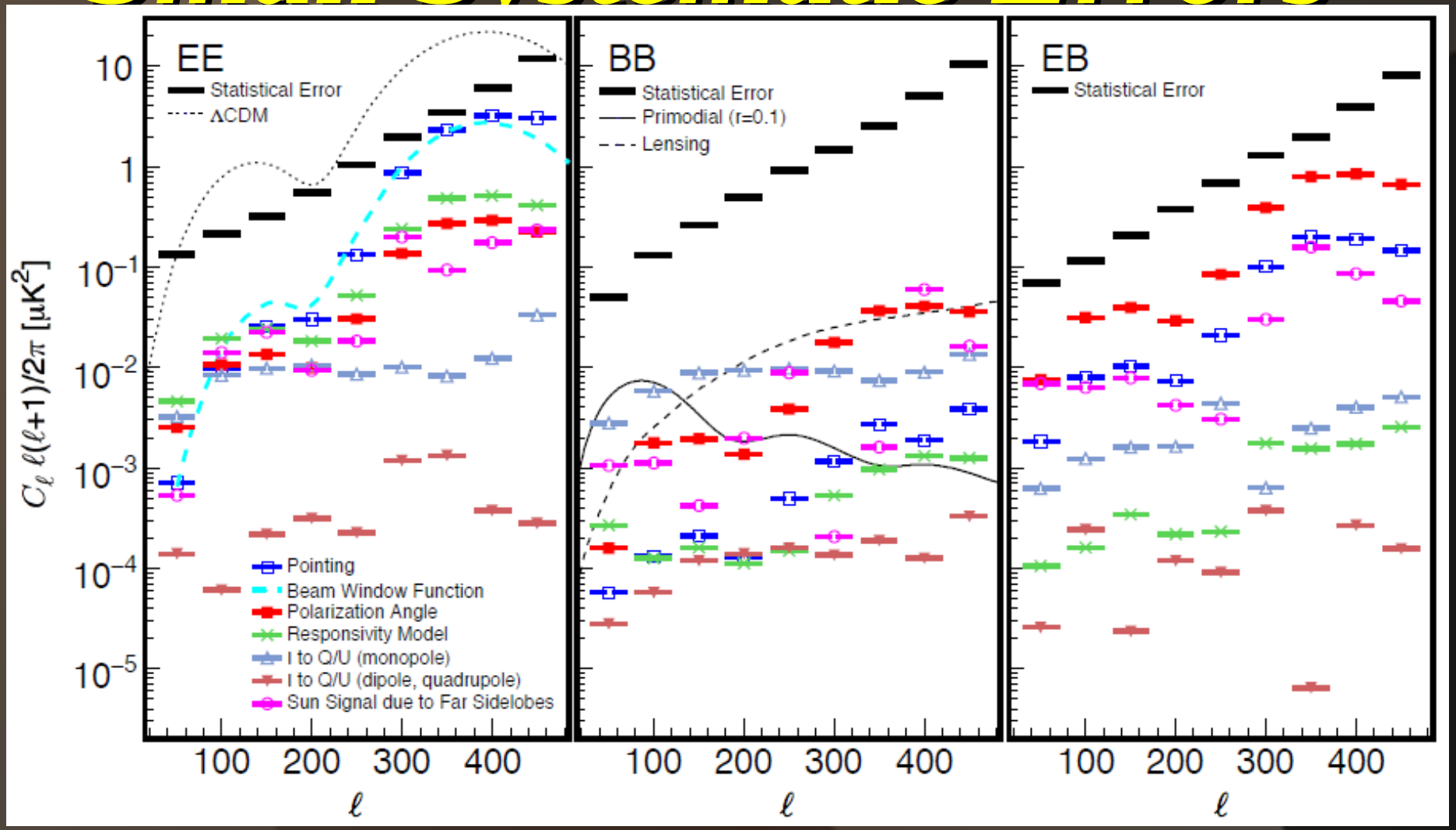


Upper Limit for Inflation

- $r = 0.35^{+1.06}_{-0.87}$ $r < 2.2$ (95% C.L.)
- QUIET's B-mode limit lies between BICEP's and *WMAP*'s
  - This result used < ½ the data compared to BICEP
- We are still far from the limits placed by other probes so the systematics level is essential

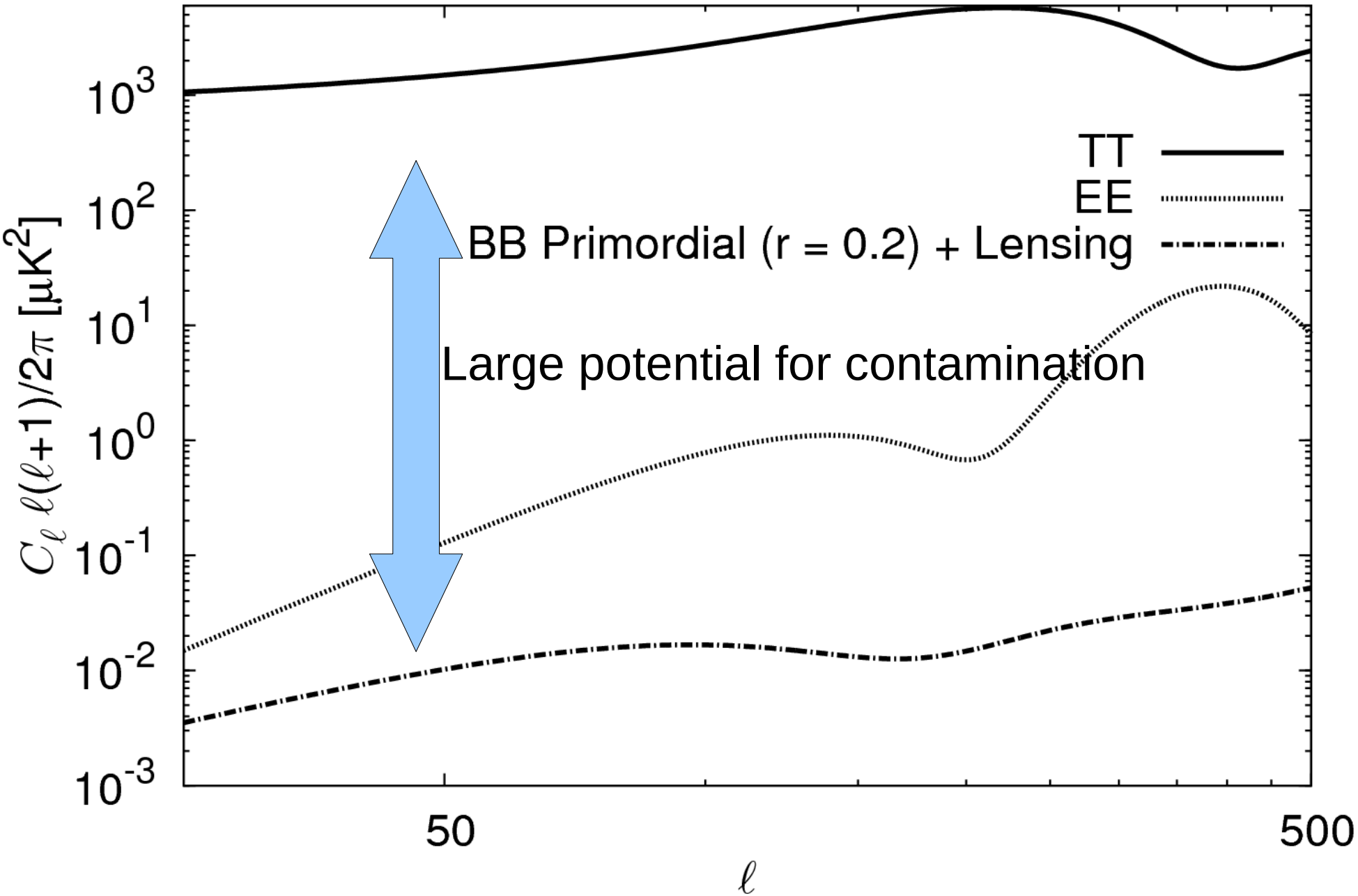


Small Systematic Errors



- Instrumental polarization is dominant (could correct for it in analysis; W is intrinsically better)
- Lowest systematic errors for B modes reported to date

Scale of the Problem



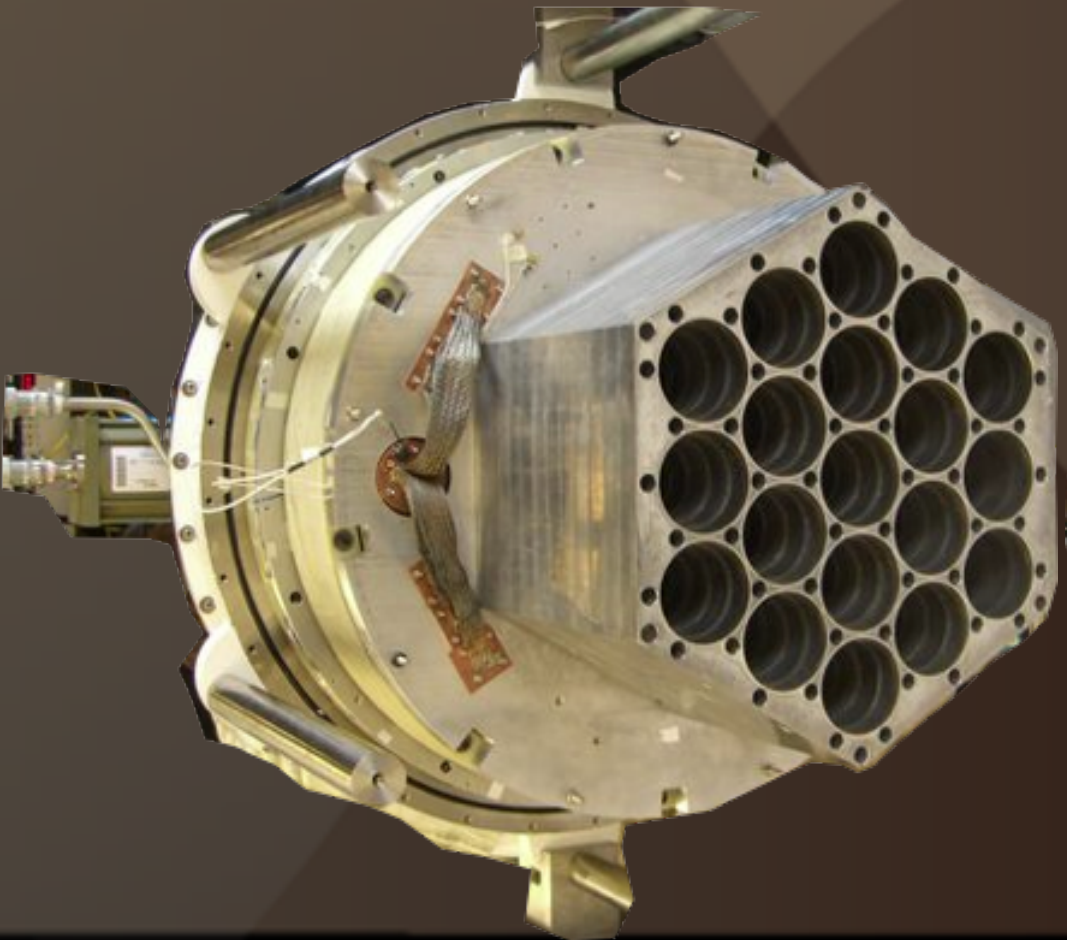
QUIET Arrays

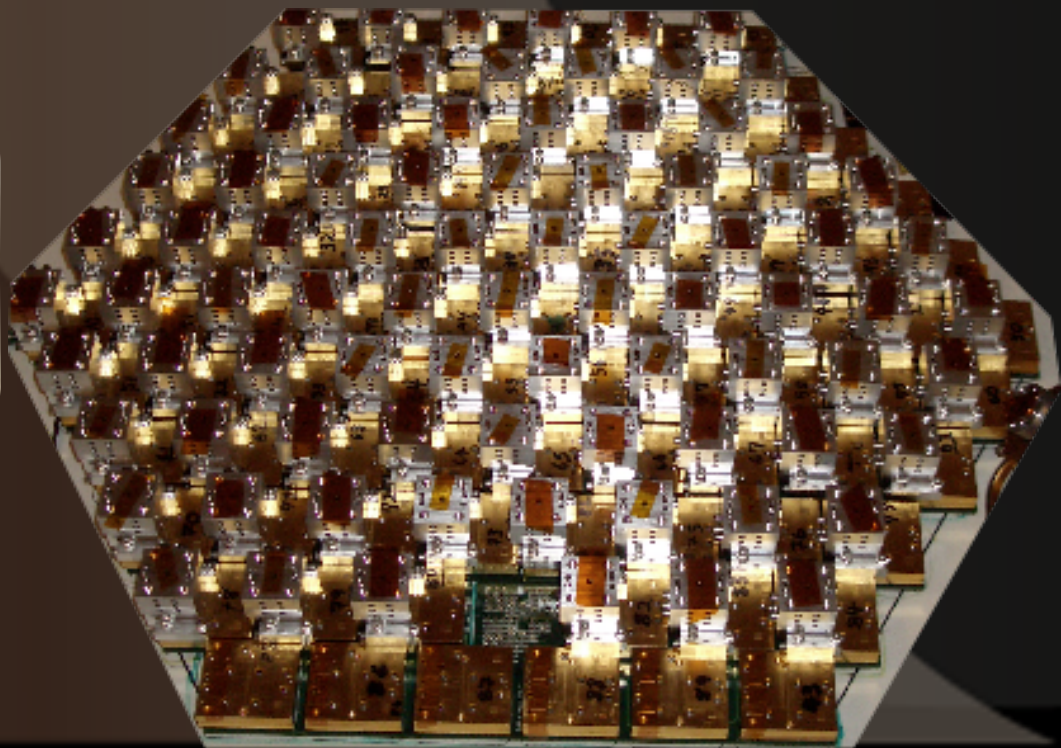
Q band

19 elements @ 43 GHz
17 Polarimeters
2 temperature diff.

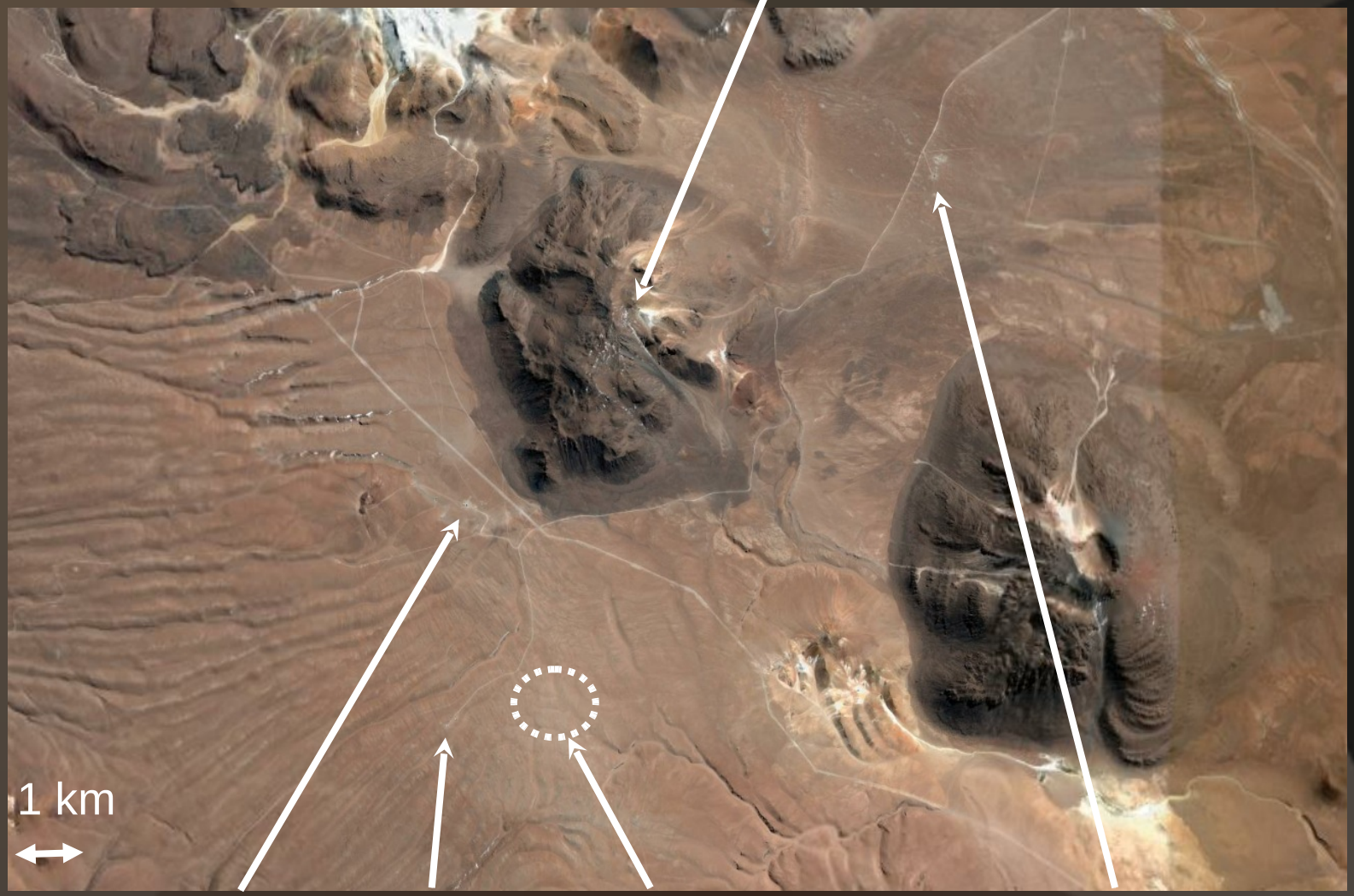
W band

90 elements @ 95 GHz
84 Polarimeters
6 temperature diff.



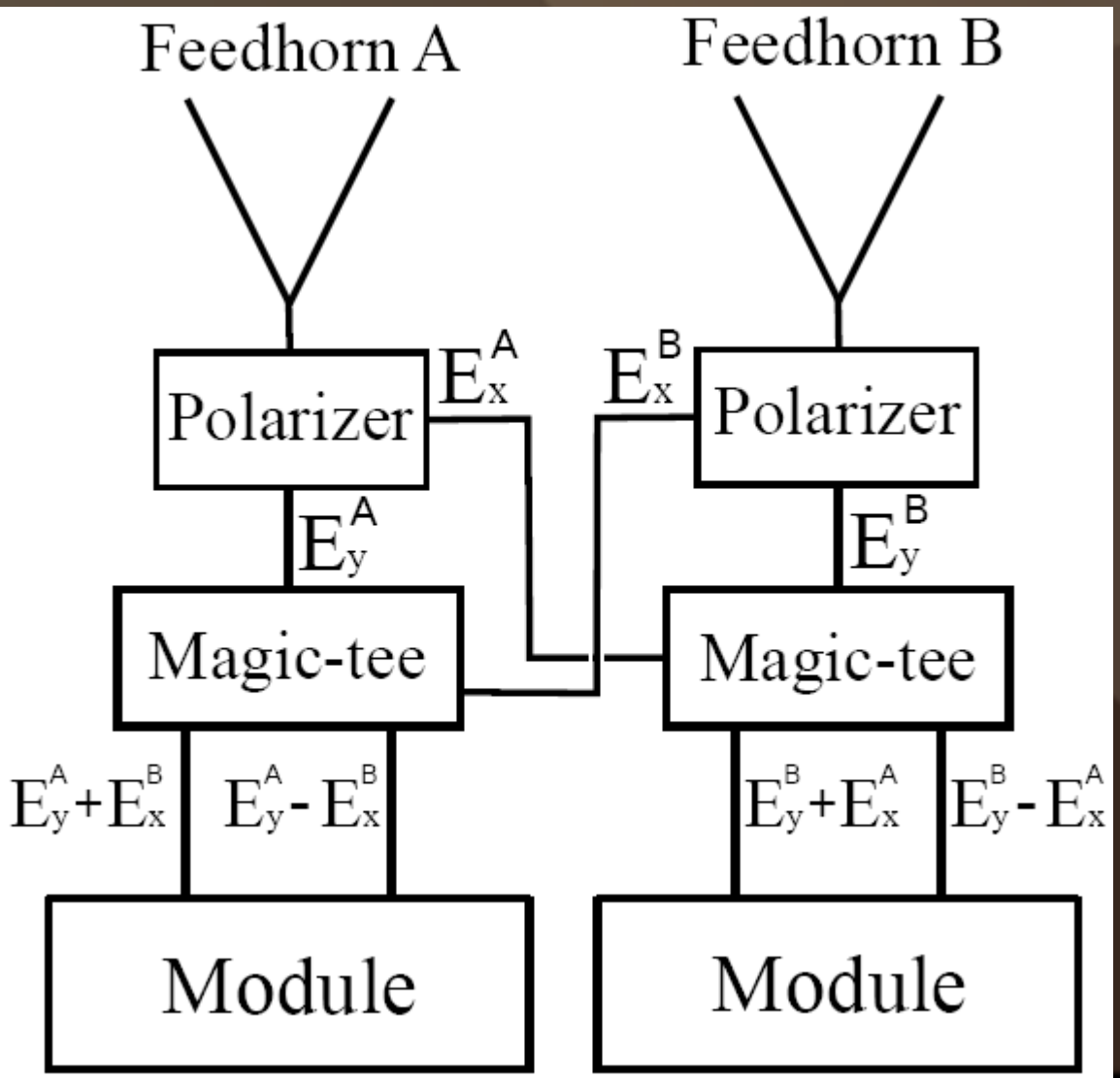


Other Atacama Experiments



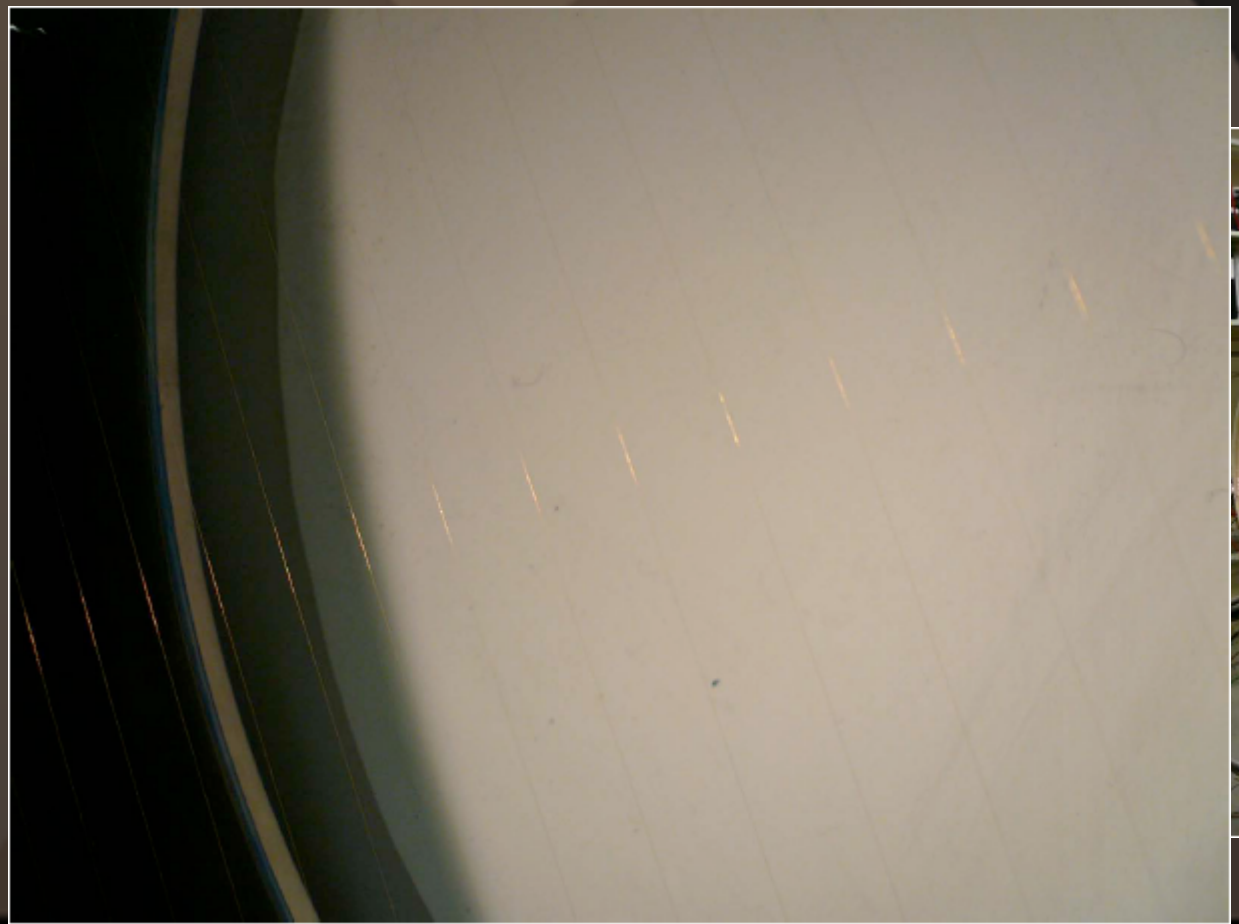
TT Assembly

- Replace Septum Polarizer with OMT+Magic Tee to measure temperature anisotropy

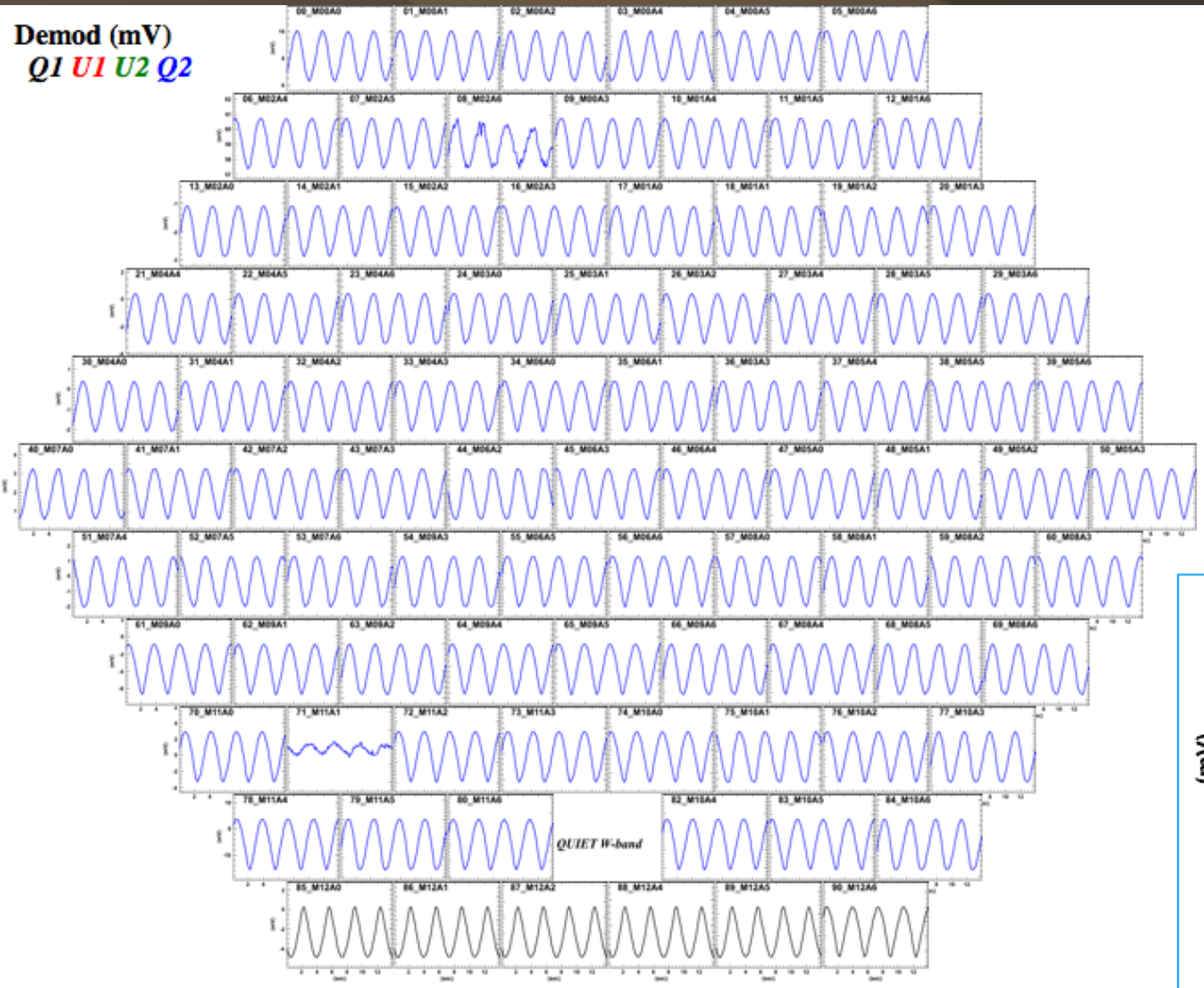


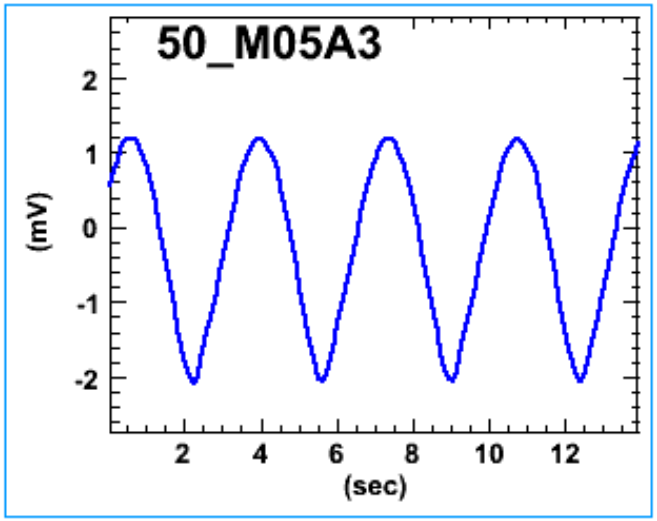
Module Optimization

- Digital control of amplifier biasing (10-bit DAC)
- Maximize S/N with wire-grid polarization source
- 90 modules can be optimized in 24 hours



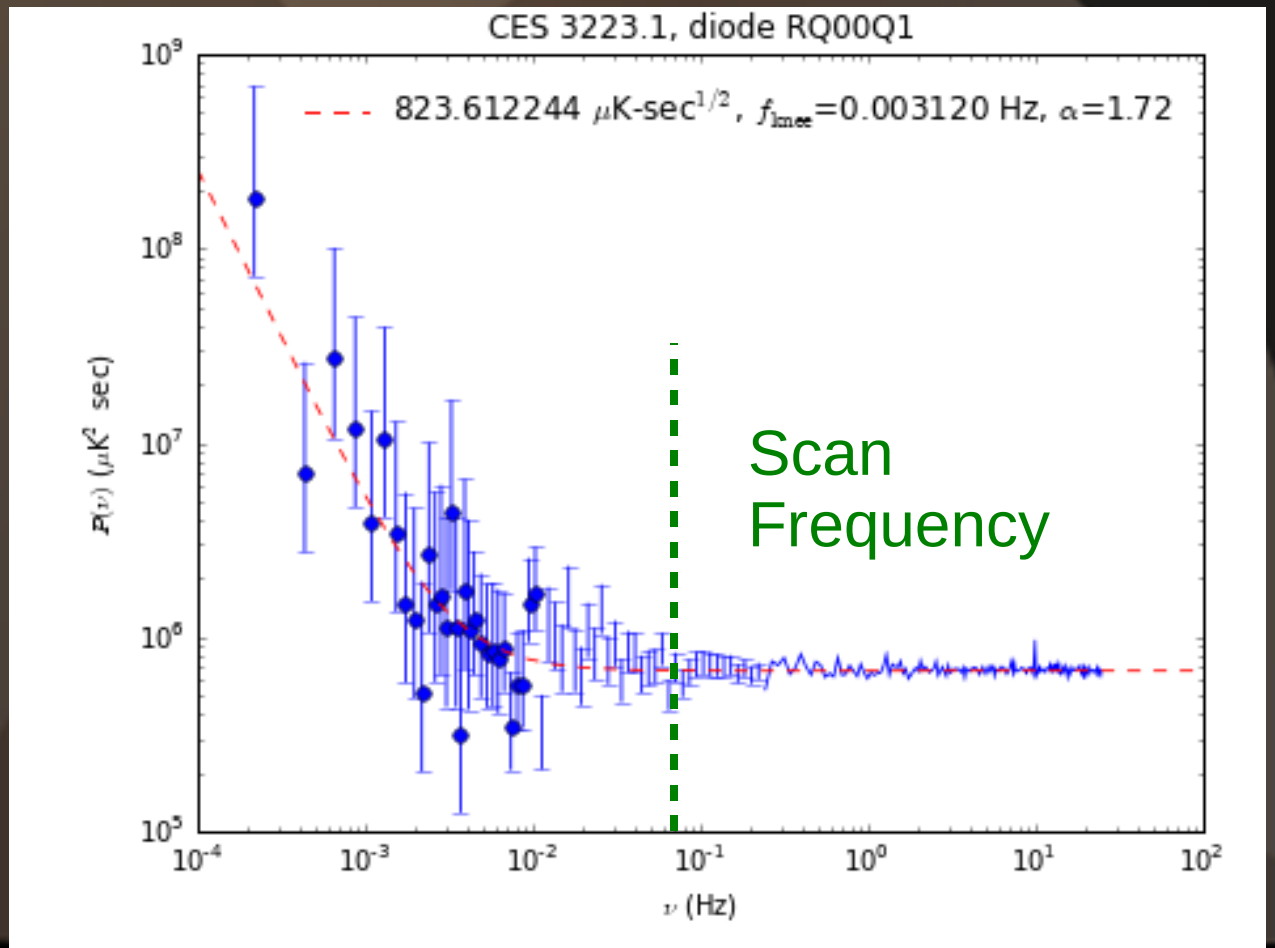
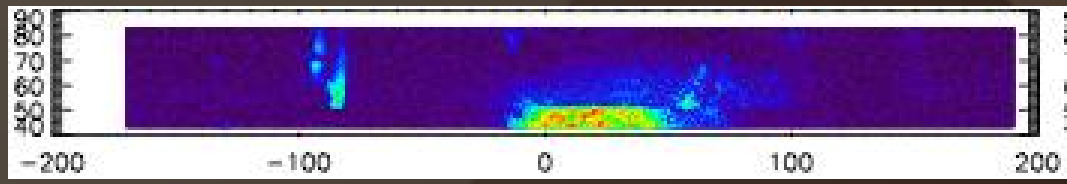
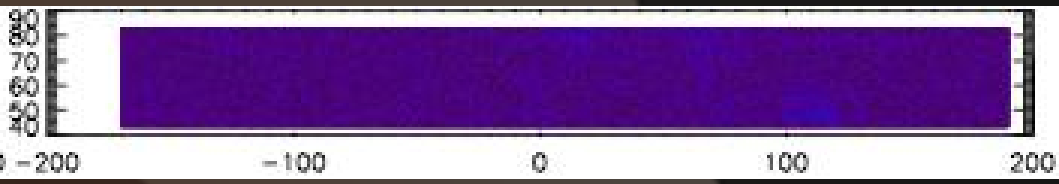
Module Optimization





1/f Performance

- Measured every ~hour from data in the field
- Median knee frequency 5.5 mHz (Q band)
- Modulate at 45--100 mHz by azimuth scan



Upper Groundscreen