CMB Polarization Results from the QUIET Experiment

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QUIET Group at Chicago

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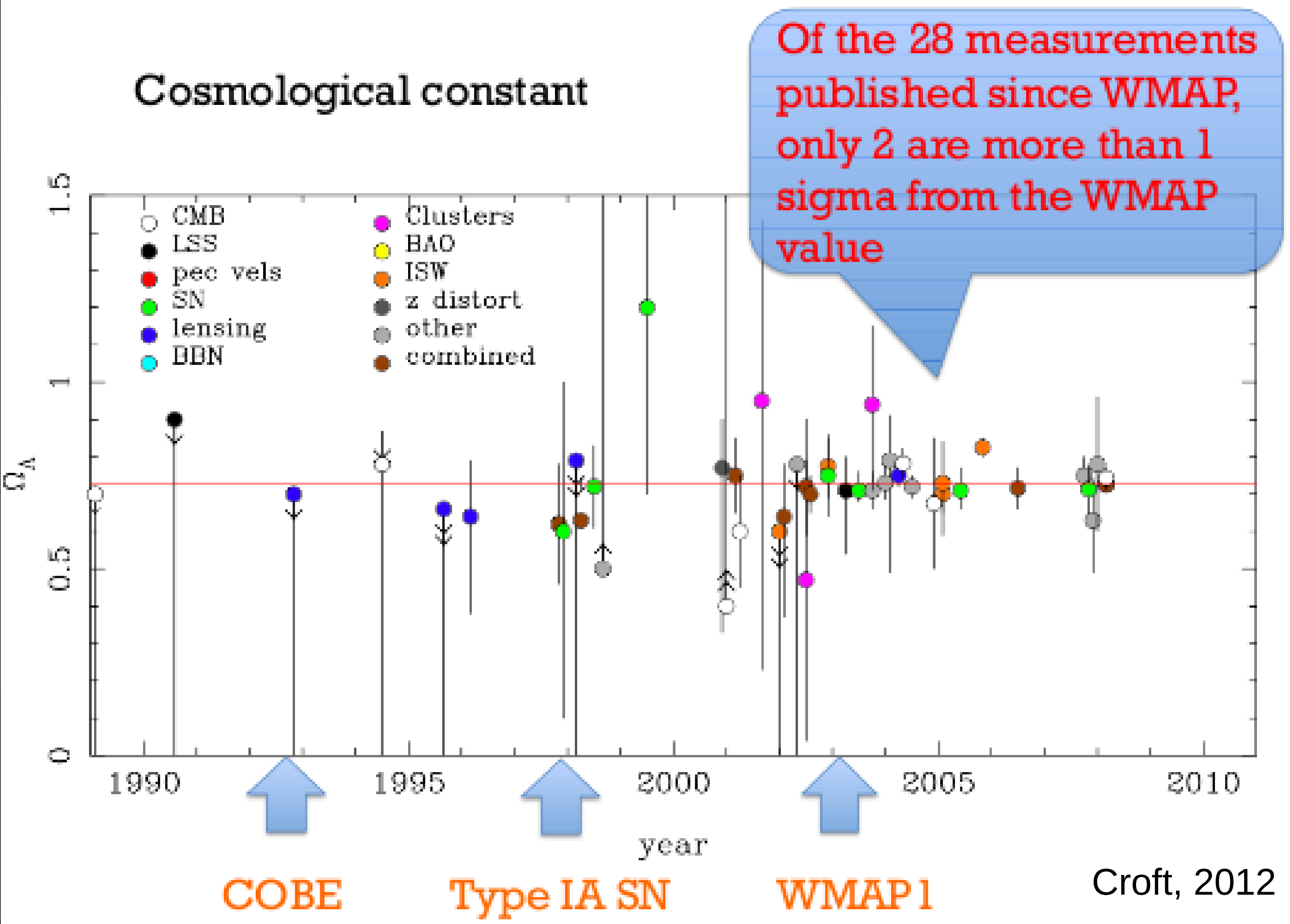
Kavli Institute for Cosmological Physics at the University of Chicago

Is there observer bias in Cosmology?



Croft, 2012

QUIET will make the systematic error small to measure inflationary B modes

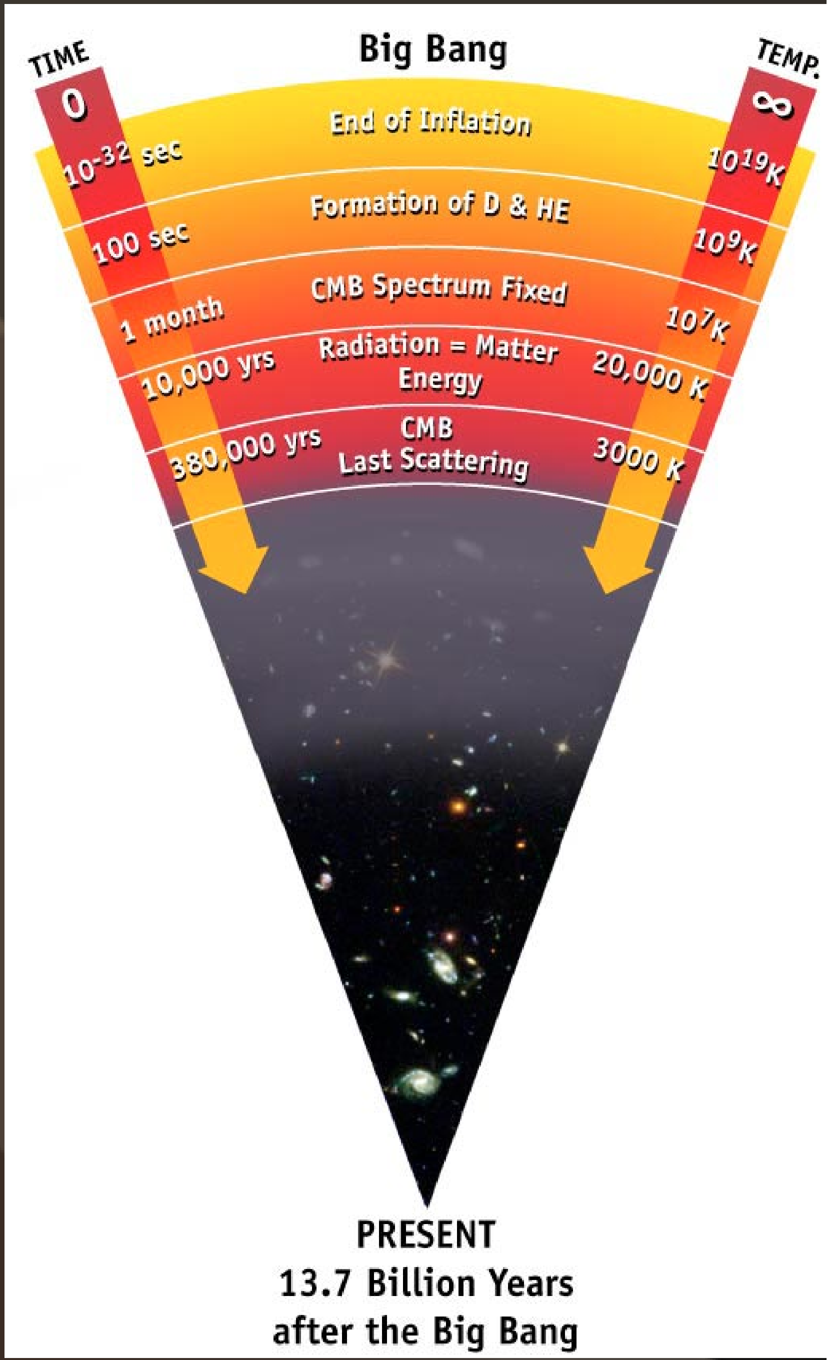
- Current published systematic errors are too large to distinguish the signal from inflation in the CMB polarization
- The QUIET instrument and analysis was designed with low systematic error in mind
- QUIET shows how to reduce systematic errors to the level where a B-mode detection is likely ($r \sim 0.01$)

Outline of this Talk

- Introduction
  - Inflationary Cosmology
  - Why measure CMB Polarization
- QUIET Experiment Overview
- 43-GHz (Q-band) Analysis and Results
- Future Prospects
  - 95-GHz (W-band) Analysis
  - Improved Detectors

CMB gives us information about the early Universe

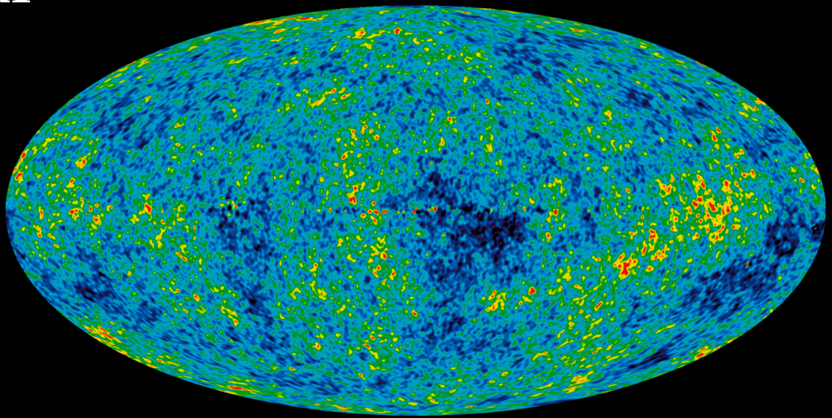
- CMB is created when hydrogen atoms form ("recombination") and the Universe becomes transparent to photons
- Inflation is postulated to explain the initial conditions and several observed puzzles



NASA/WMAP Science Team

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?



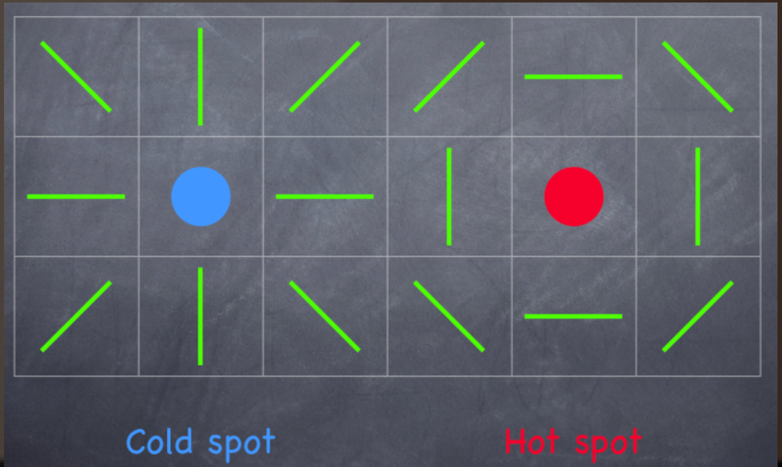
NASA/WMAP Science Team

- Predicts gravity waves (tensor modes) in the early Universe
  - Causes an observable signal (B mode) in the CMB polarization

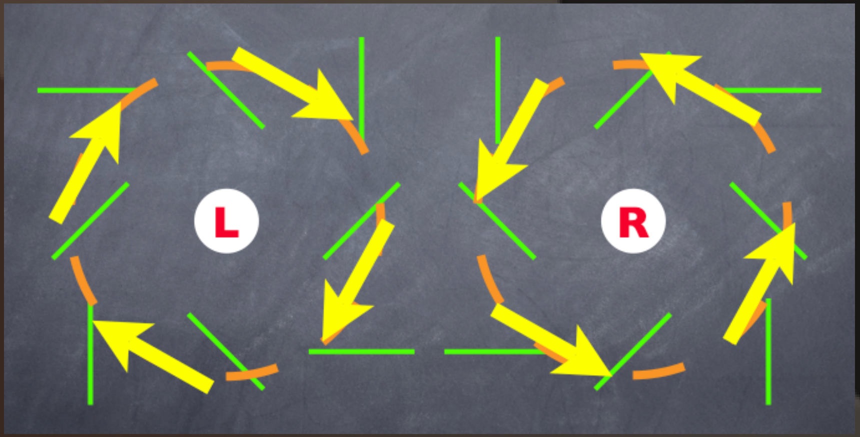
CMB Polarization may contain evidence for inflation

- Thomson scattering partially polarizes the CMB anisotropy
- Scalar perturbation creates only E modes (even parity)
- Inflationary gravity waves can create B modes (odd parity)
  - "Smoking gun" signal of inflation
- Amplitude of B modes, *r*, is proportional to the energy scale of inflation E ~ $r^{1/4}$ 10^{16} GeV   (⇔ GUT scale)

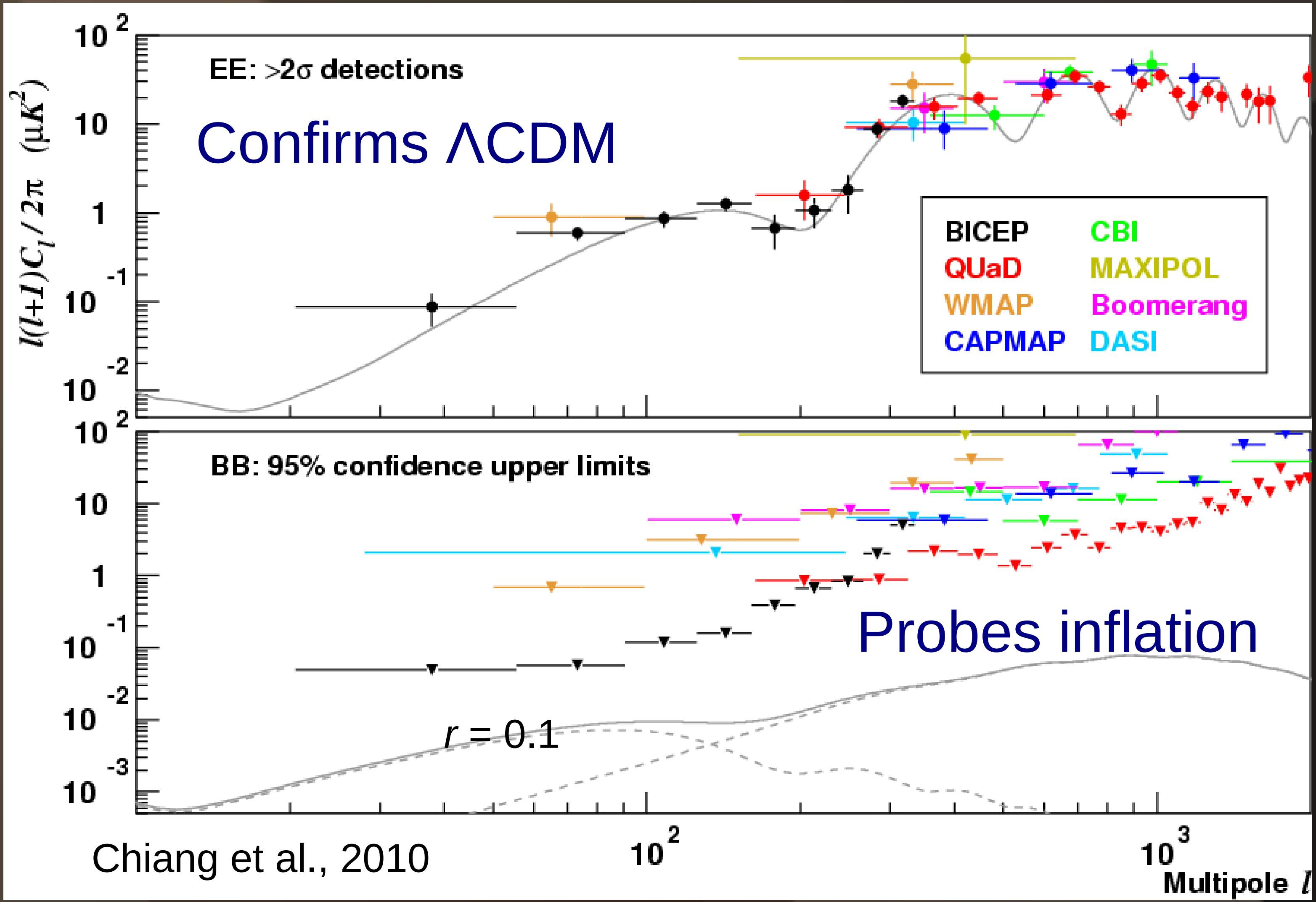
E-mode



B-mode



We Need Better Data



- 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)

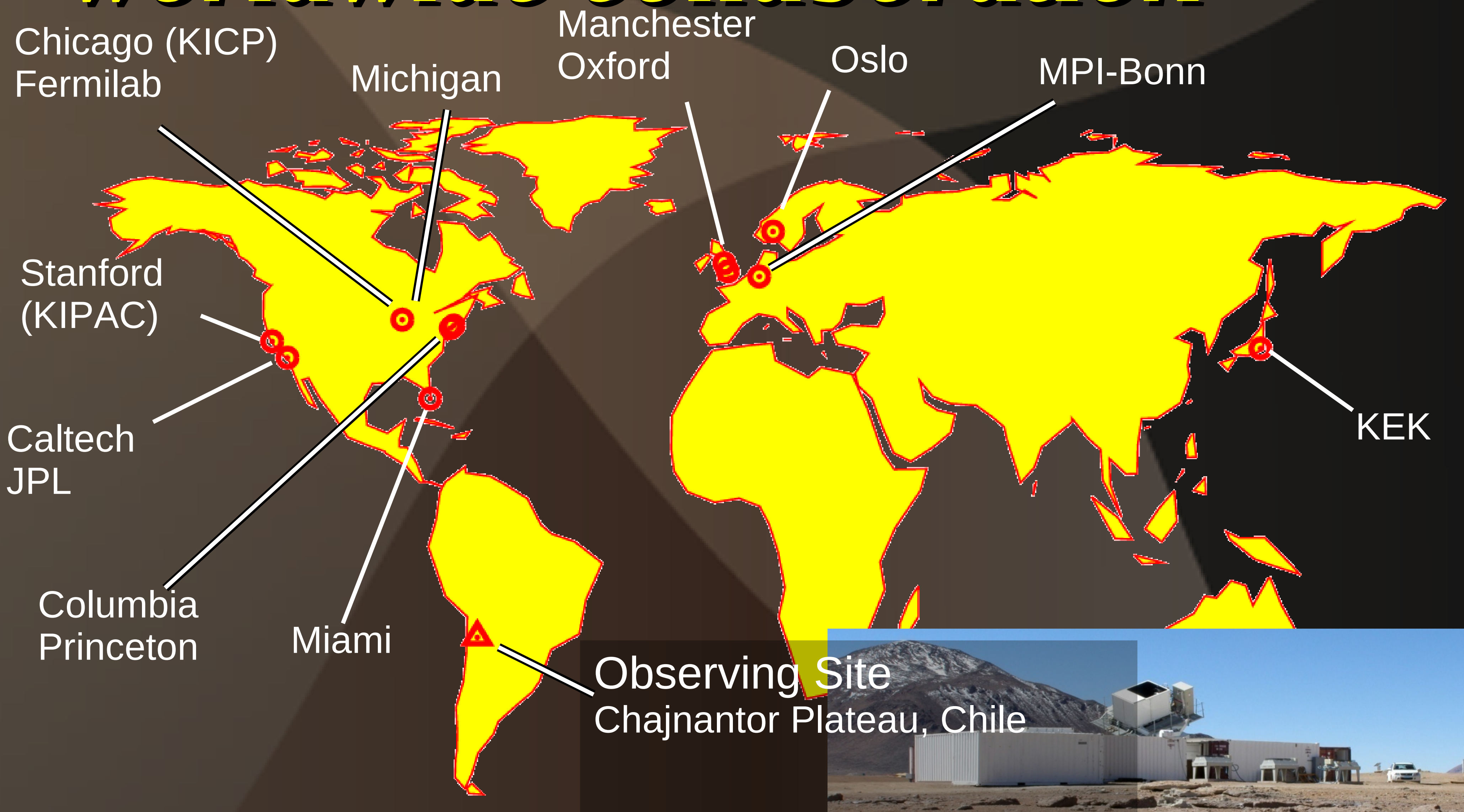
QUIET Experiment

One of many B-mode polarimeters (e.g. BICEP2, Keck, ACTPol, CLASS, POLAR, QUBIC, ABS, EBEX, SPIDER, SPT-POL, PIPER, PolarBear, ...), but QUIET is unique...

QUIET is

- Coherent (HEMT-based)
  - Different (perhaps better) systematics than bolometers
- 43 and 95 GHz
- Ground-based
- Designed to minimize spurious polarization

QUIET is a large, worldwide collaboration



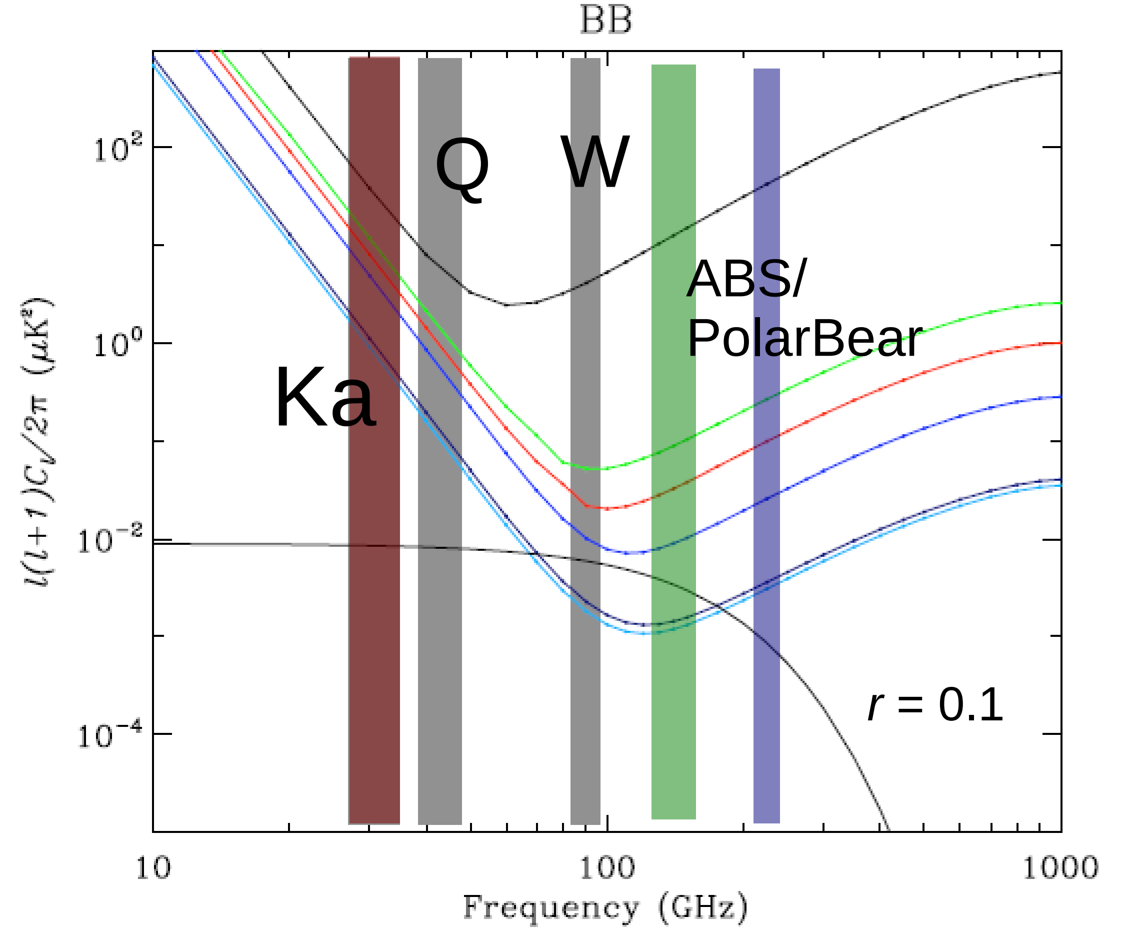
5 countries, 14 institutions, ~50 scientists

QUIET has completed 2 observing seasons

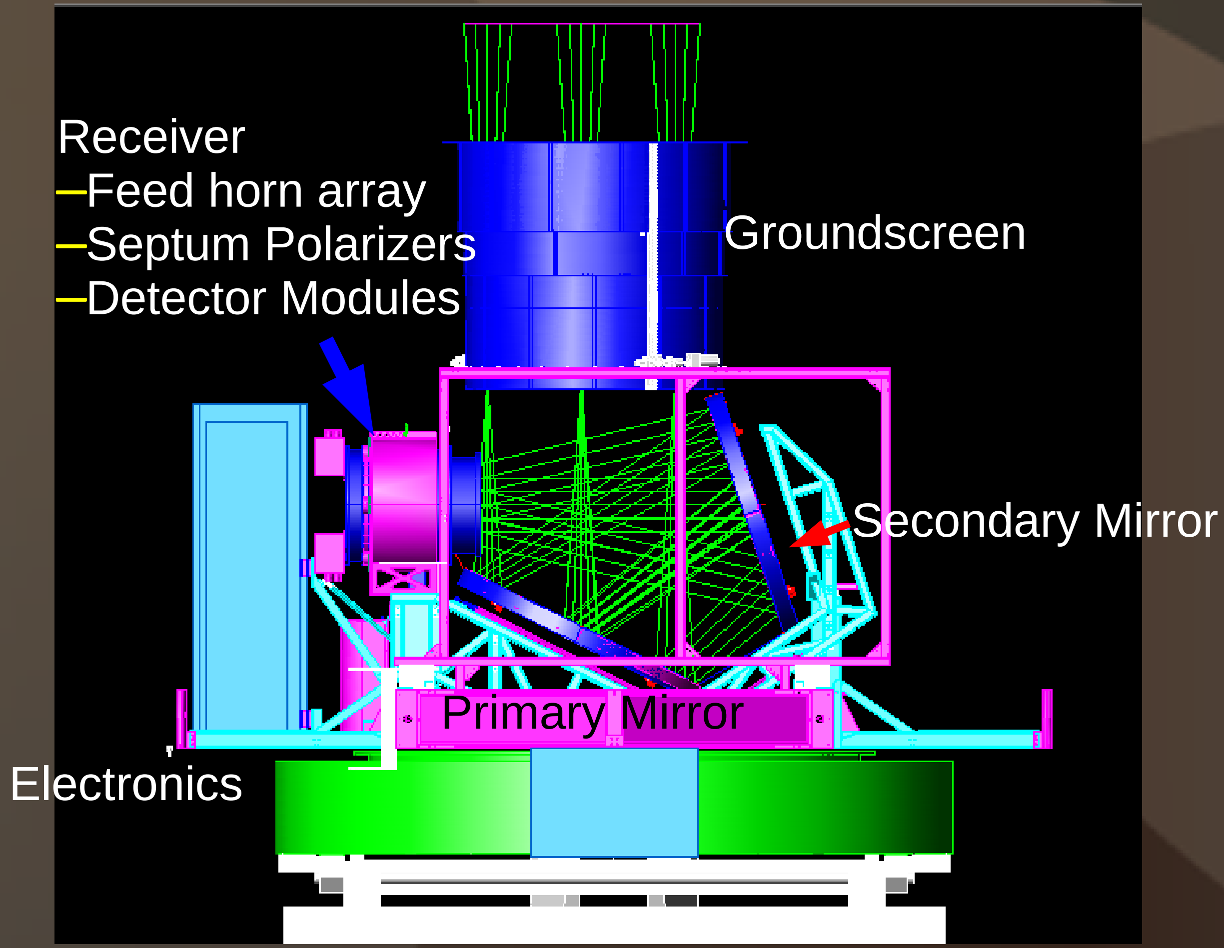
- 2008—2009 Q-band observing
- 2009—2010 W-band observing
- 2010 December Q-band result released
- Now analyzing W-band data
- Early 2012 W-band result released
- Continuing to work on improved detector R&D

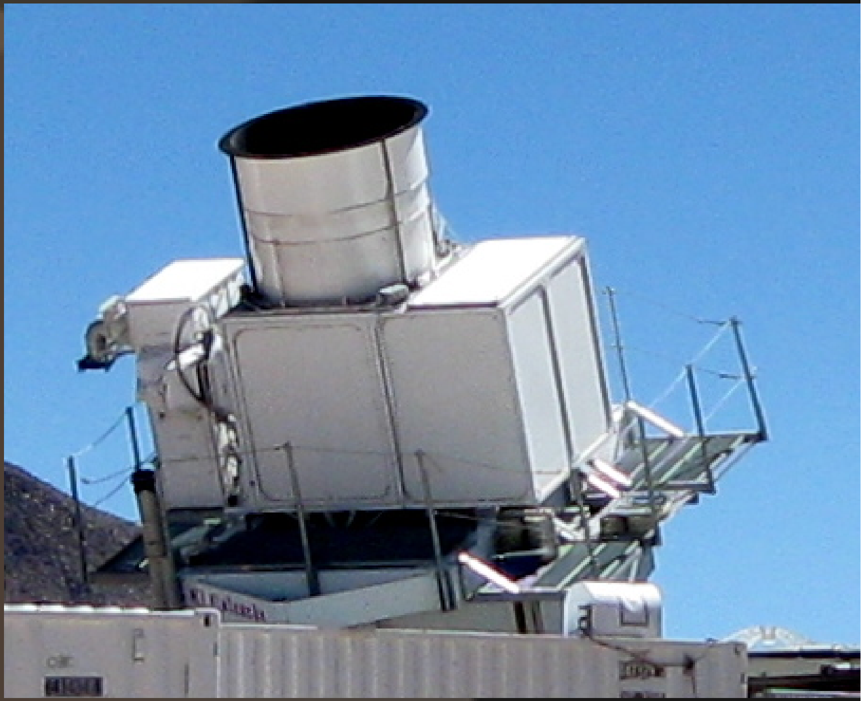
Frequencies Avoid Astrophysical Contamination

- W band is near the expected foreground minimum of synchrotron+dust
- Use Q band to clean synchrotron
- Combine with ABS & PolarBear (higher frequency) data to clean dust



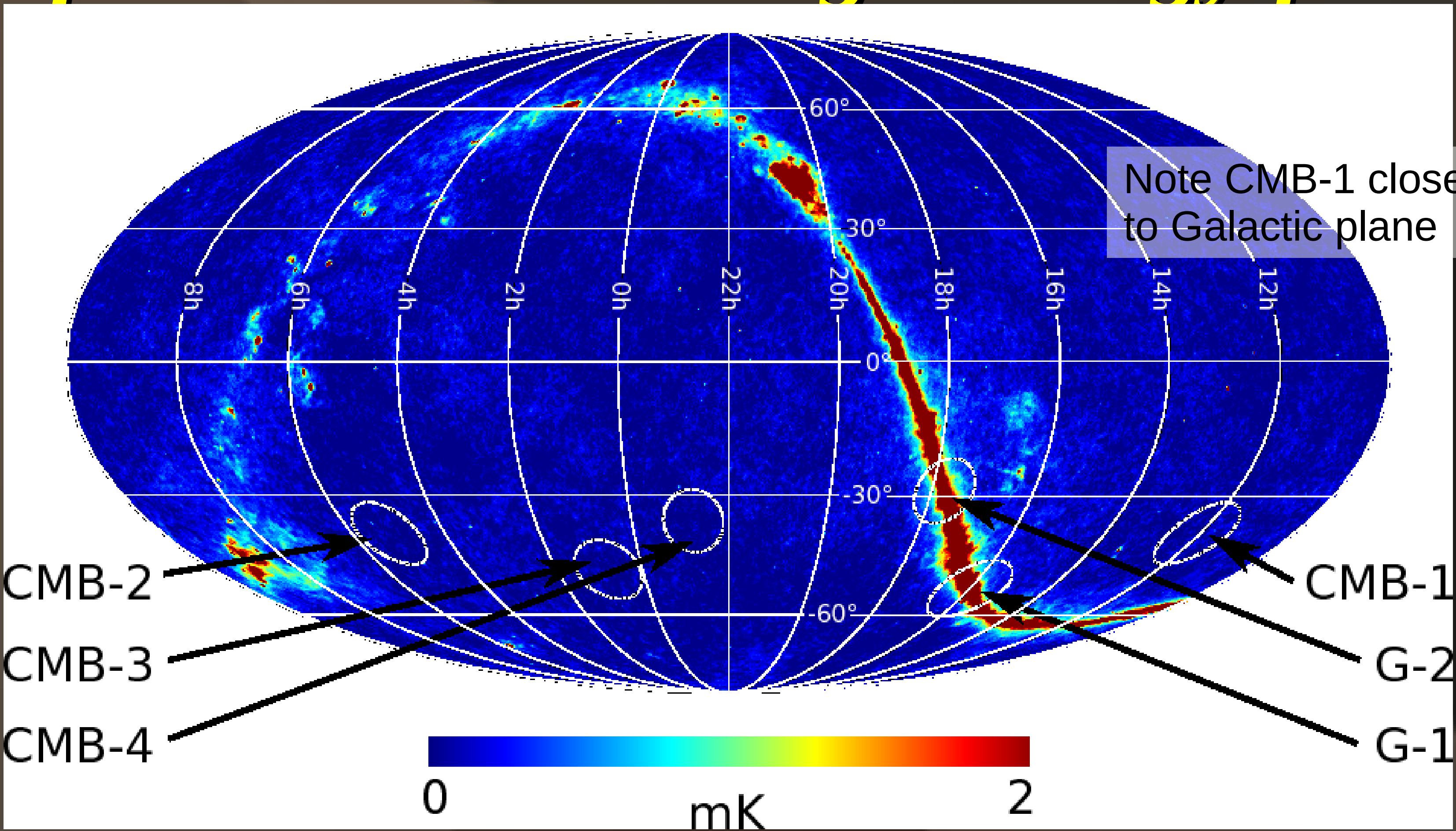
Design for low systematic error





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

Optimized Observing Strategy for Atacama



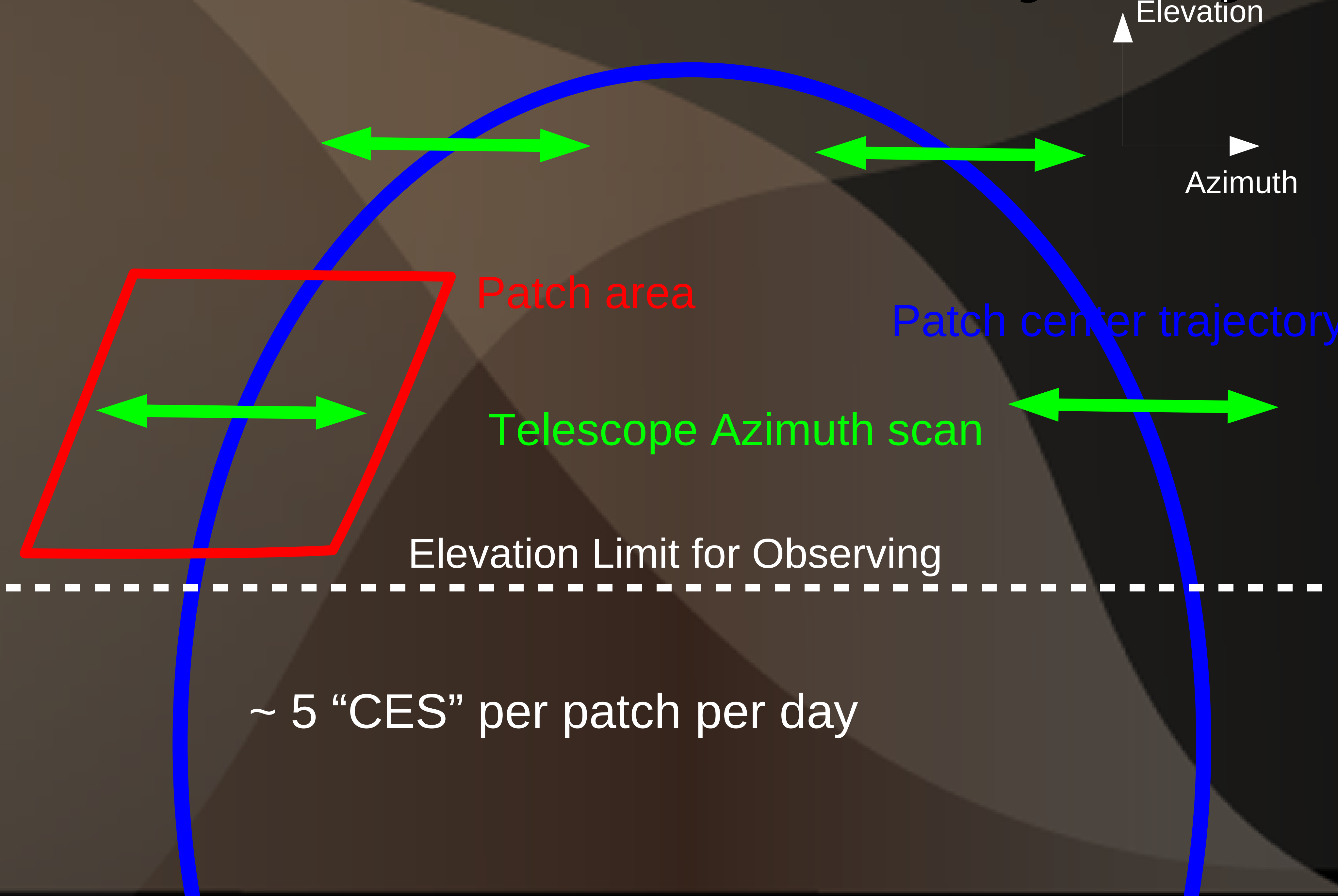
Plus calibration observation

- 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)

Chile is one of the best sites

- Chajnantor Plateau, Atacama, Chile
  - 5 km elevation
  - Very low moisture
  - Year-round observing, day and night
- Sky rotation causes the patches to rise and set
  - Sky rotation modulates polarization each day
  - Follow with constant elevation azimuth scans

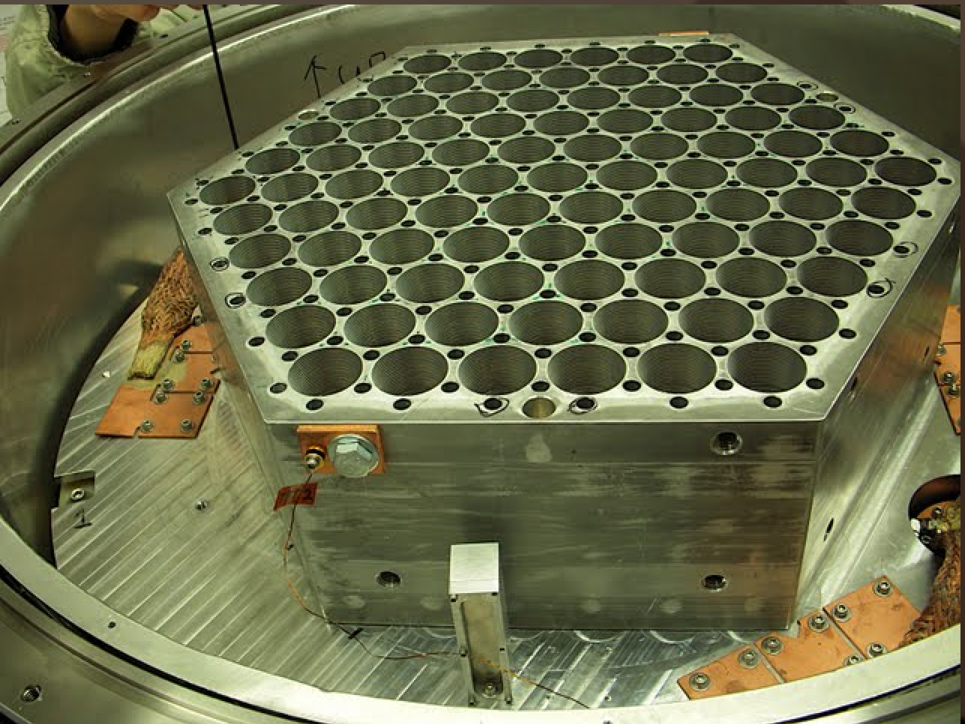
Scan Each Patch Every Day

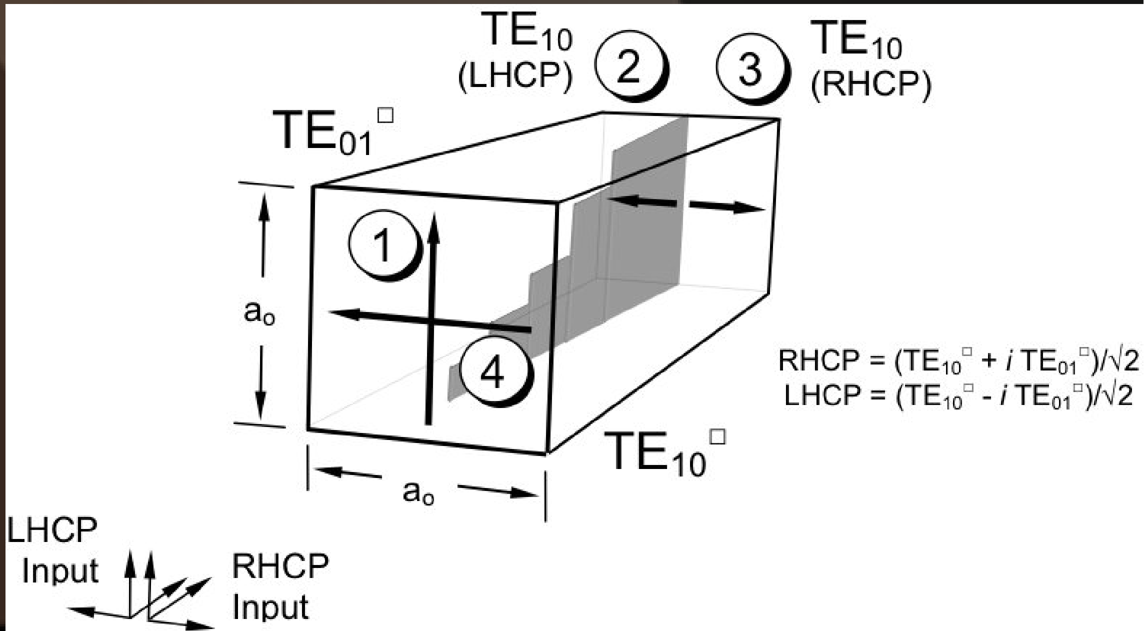


~ 5 “CES” per patch per day

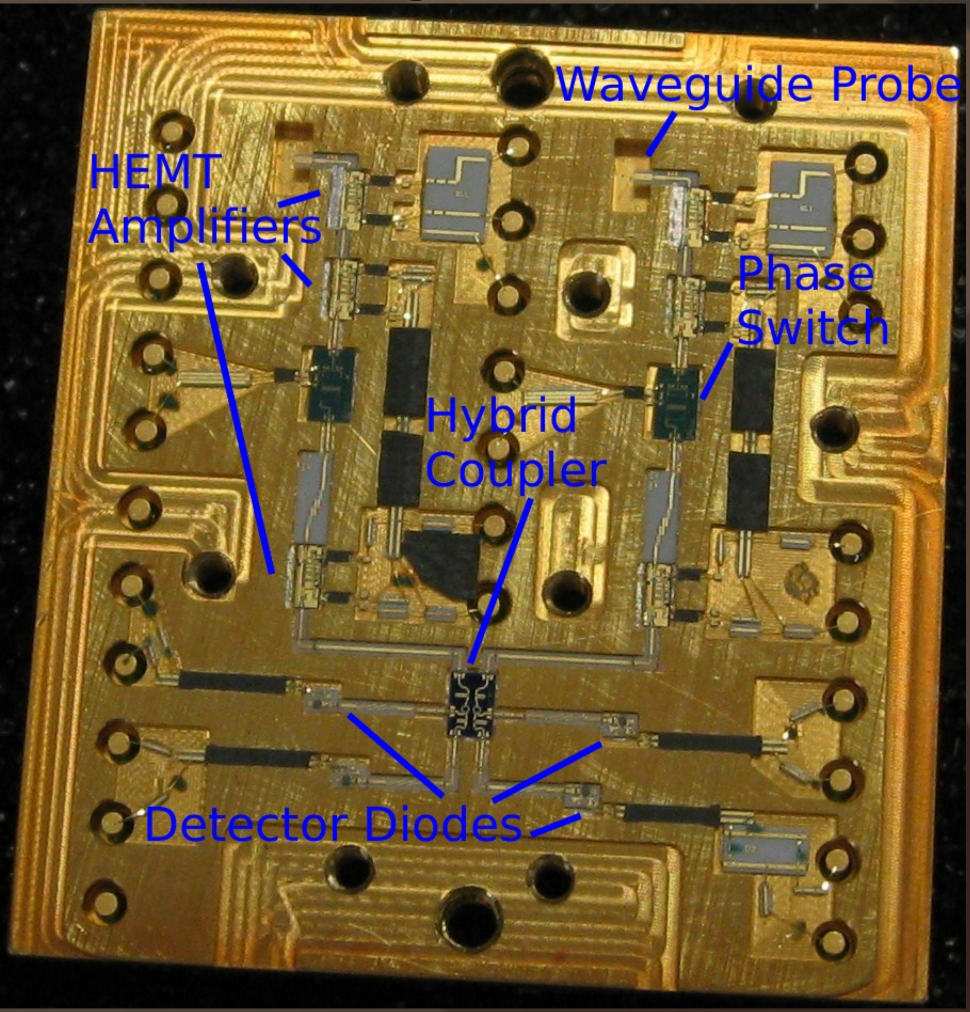
We used innovative optics

- Crossed Mizuguchi--Dragone 1.4-m telescope
  - Compact, low cross polarization, large FOV
  - First use for CMB polarization
- Feed horn platelet array (low cost)
- Stepped-thickness septum polarizer (~1% temperature to polarization leakage in Q)



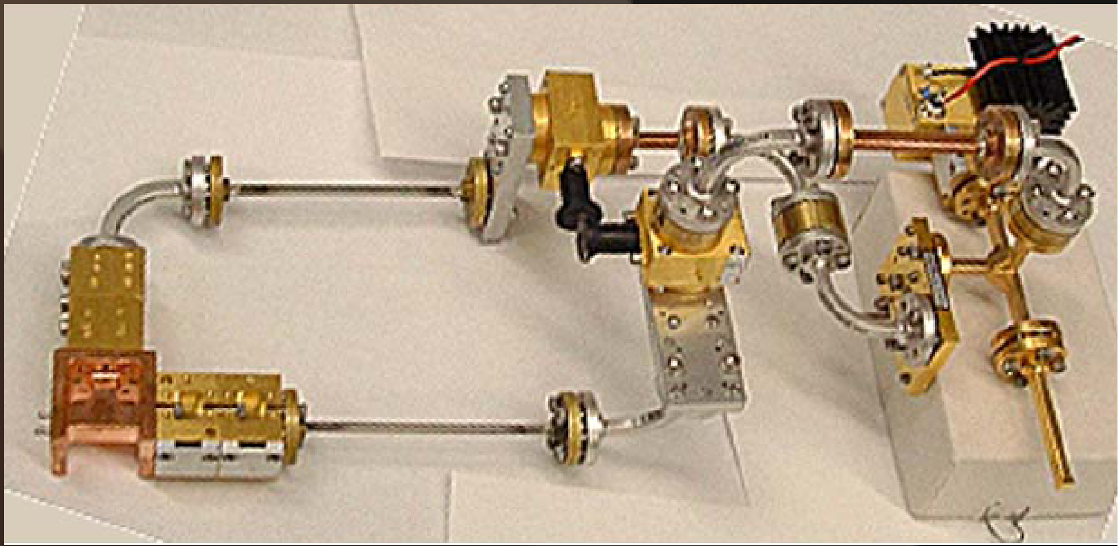


New detectors improve sensor density



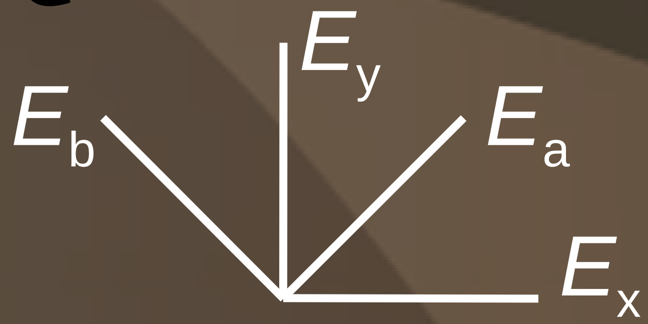
3-cm module
(W-band)

Miniaturized pseudo-correlation polarimeter on a chip, making large arrays (19 & 90) feasible

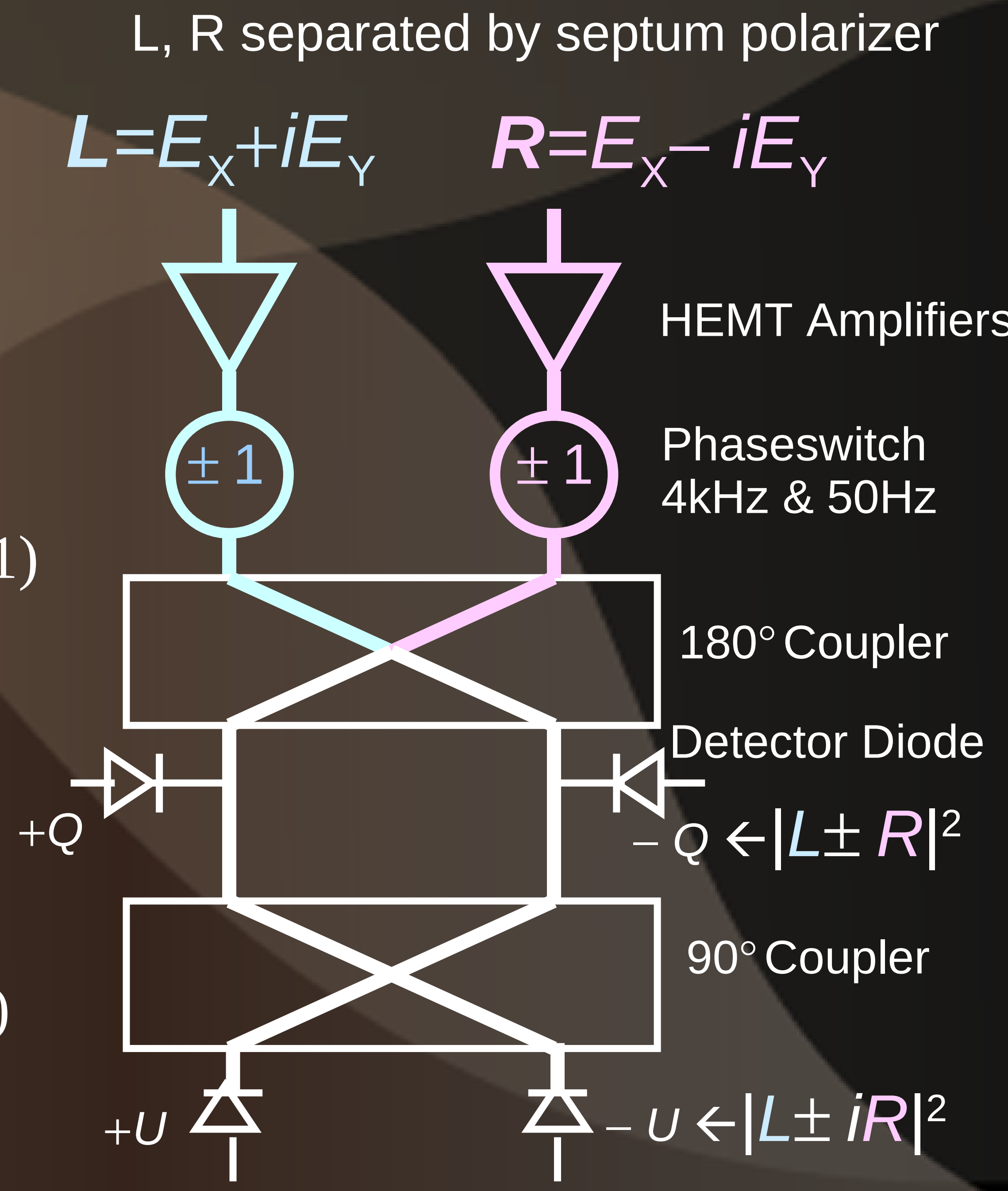


cf. CAPMAP polarimeter, ~30-cm

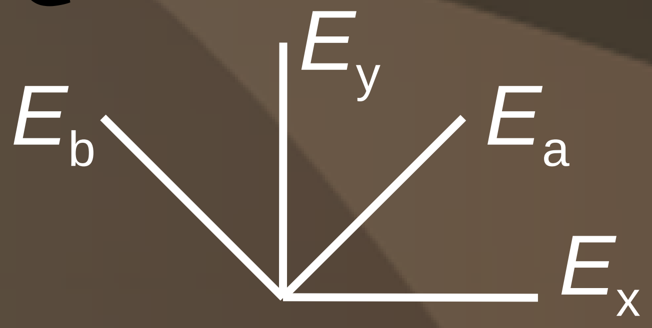
QUIET Module Operation



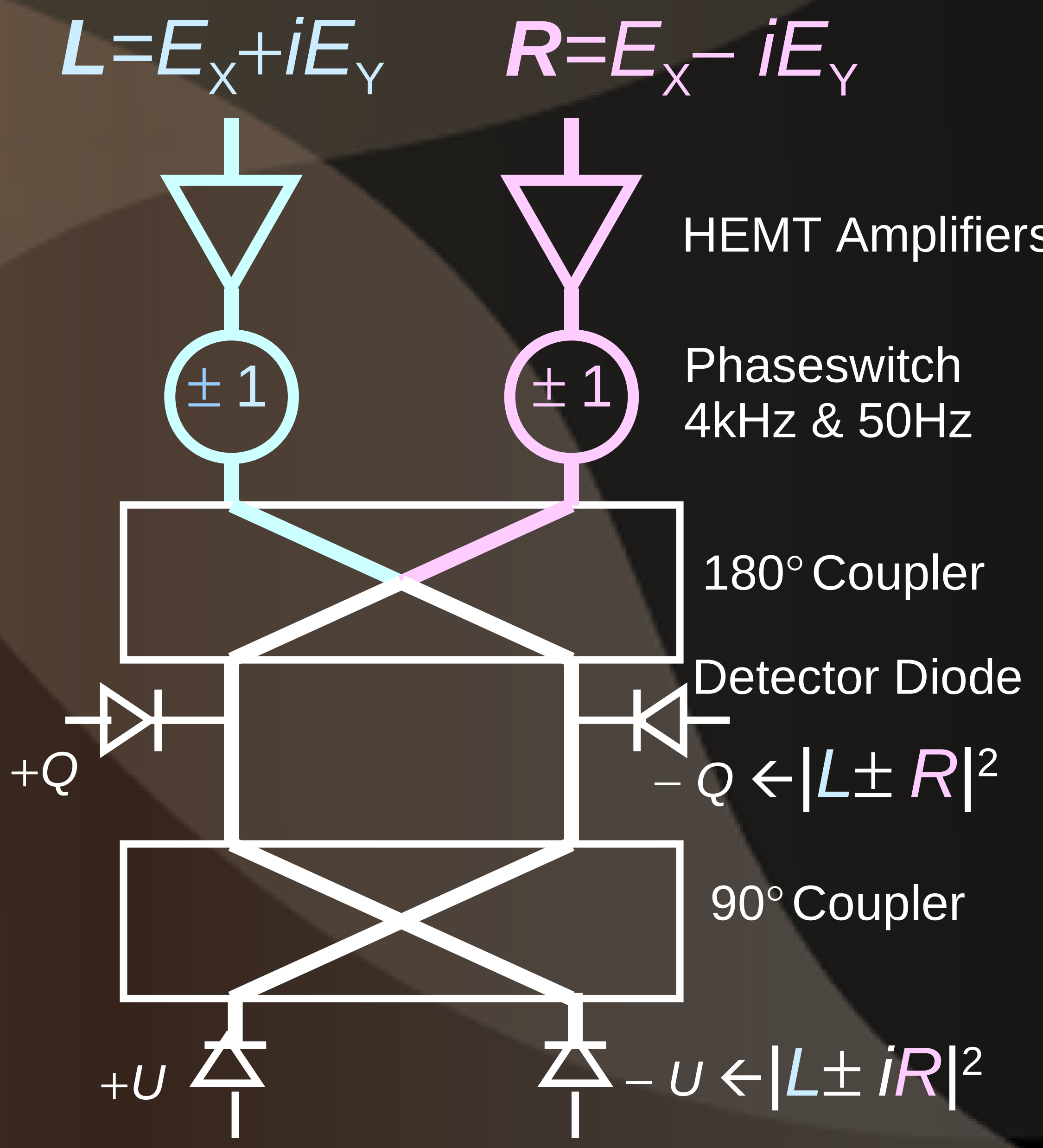
- $Q = E_x^2 - E_y^2$ $U = E_a^2 - E_b^2$
- Two inputs: *L*, *R*
- Modulate by phaseswitch (± 1)
- Combine two signals (*L*± *R*)
- Rectify power at 4 detector diodes $|L \pm R|^2$
- Each diode has a modulated linear polarization (*Q* or *U*)



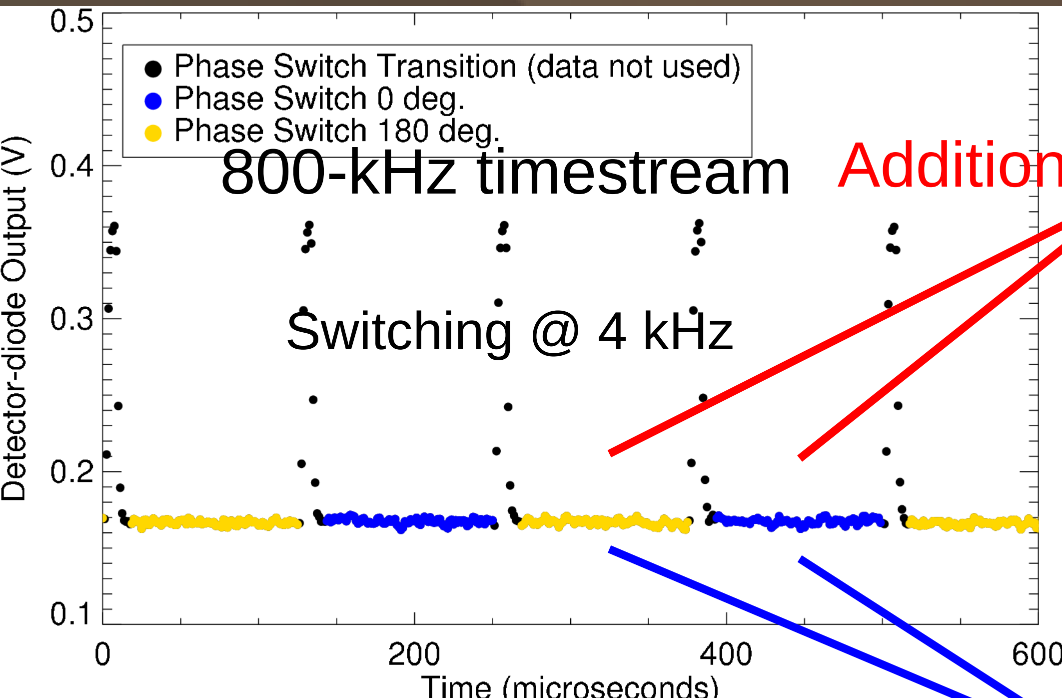
QUIET Module Benefits



- $Q = E_x^2 - E_y^2 \qquad U = E_a^2 - E_b^2$
- Simultaneously Measures *Q* and *U* linear polarization components
- Gain difference between legs does not fake a signal
- Modulation
  - 1/*f* noise reduction
  - Double modulation cancels temperature to polarization leakage in the module



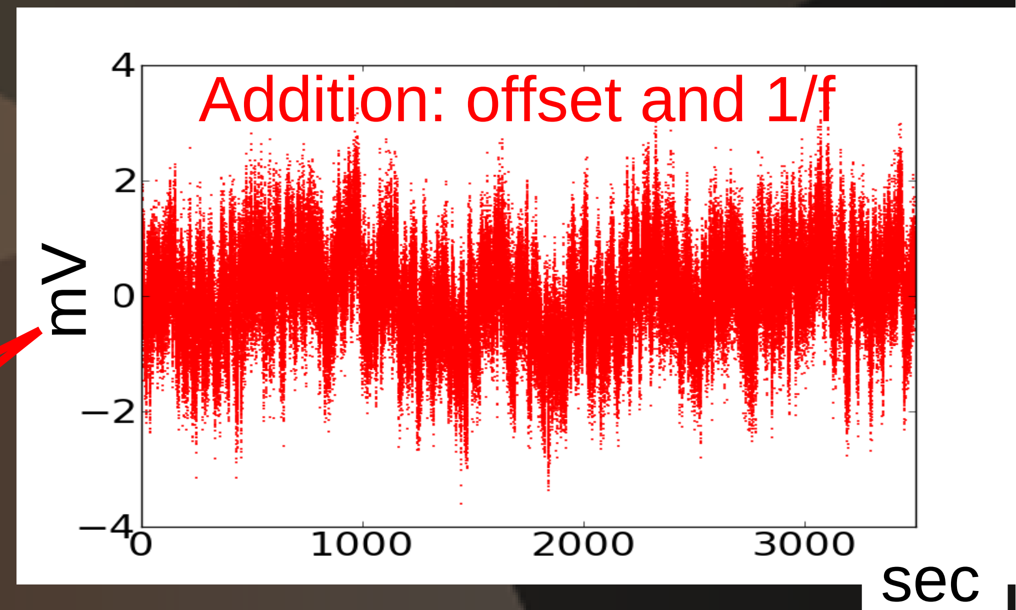
Demodulation Reduces 1/f

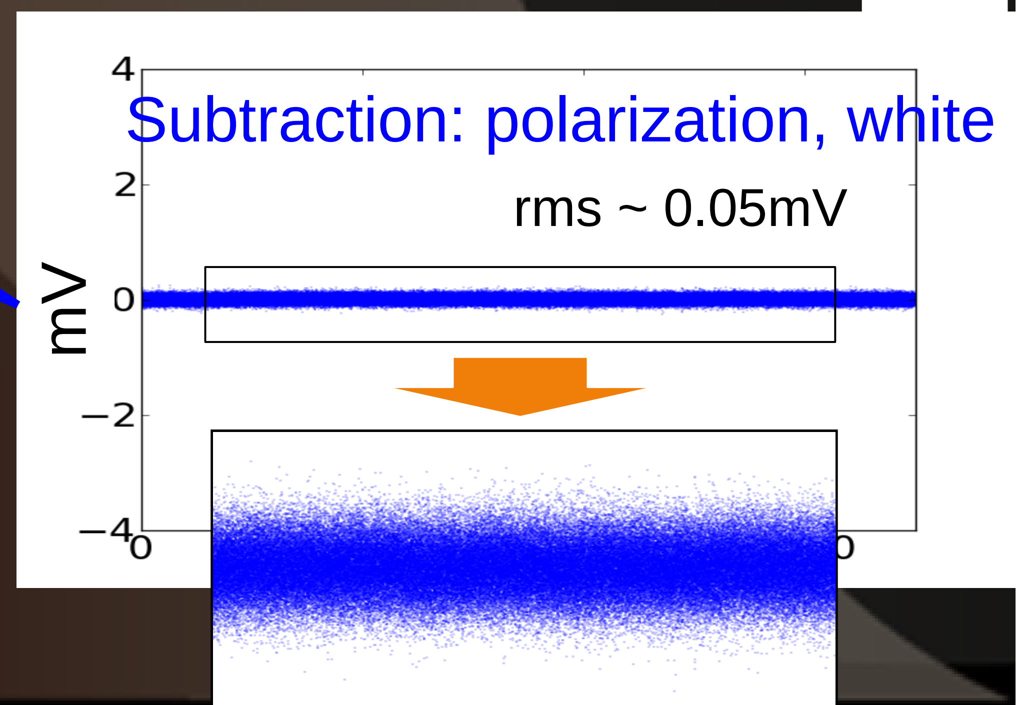


Addition

Subtraction

50-Hz timestream



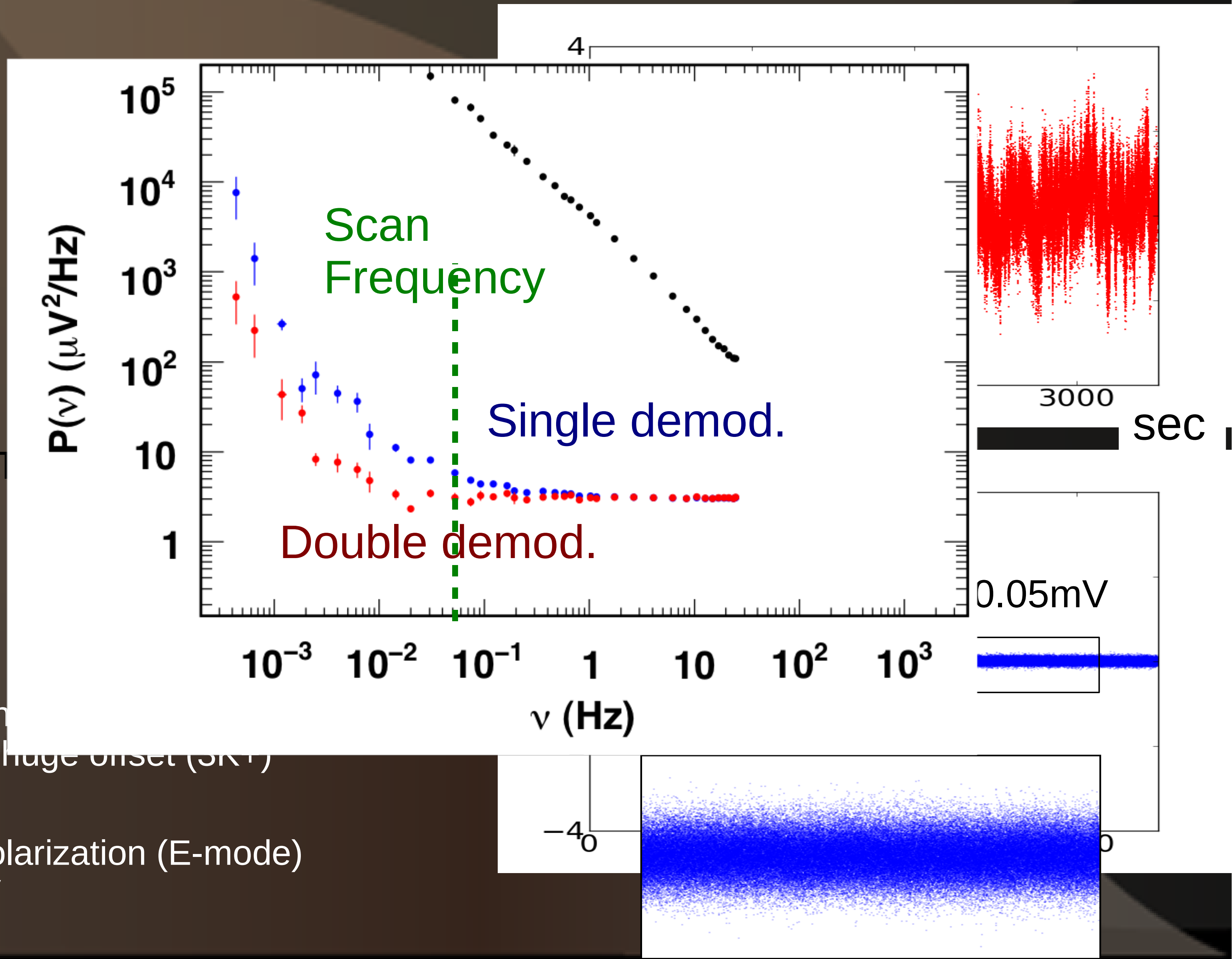


Extraction of small signal
on top of huge offset (3K+)

CMB polarization (E-mode)
~ 20 nV

Demodulation Reduces 1/f

50-Hz timestream



Extraction
on top of huge offset (3K+)

CMB polarization (E-mode)
~ 20 nV

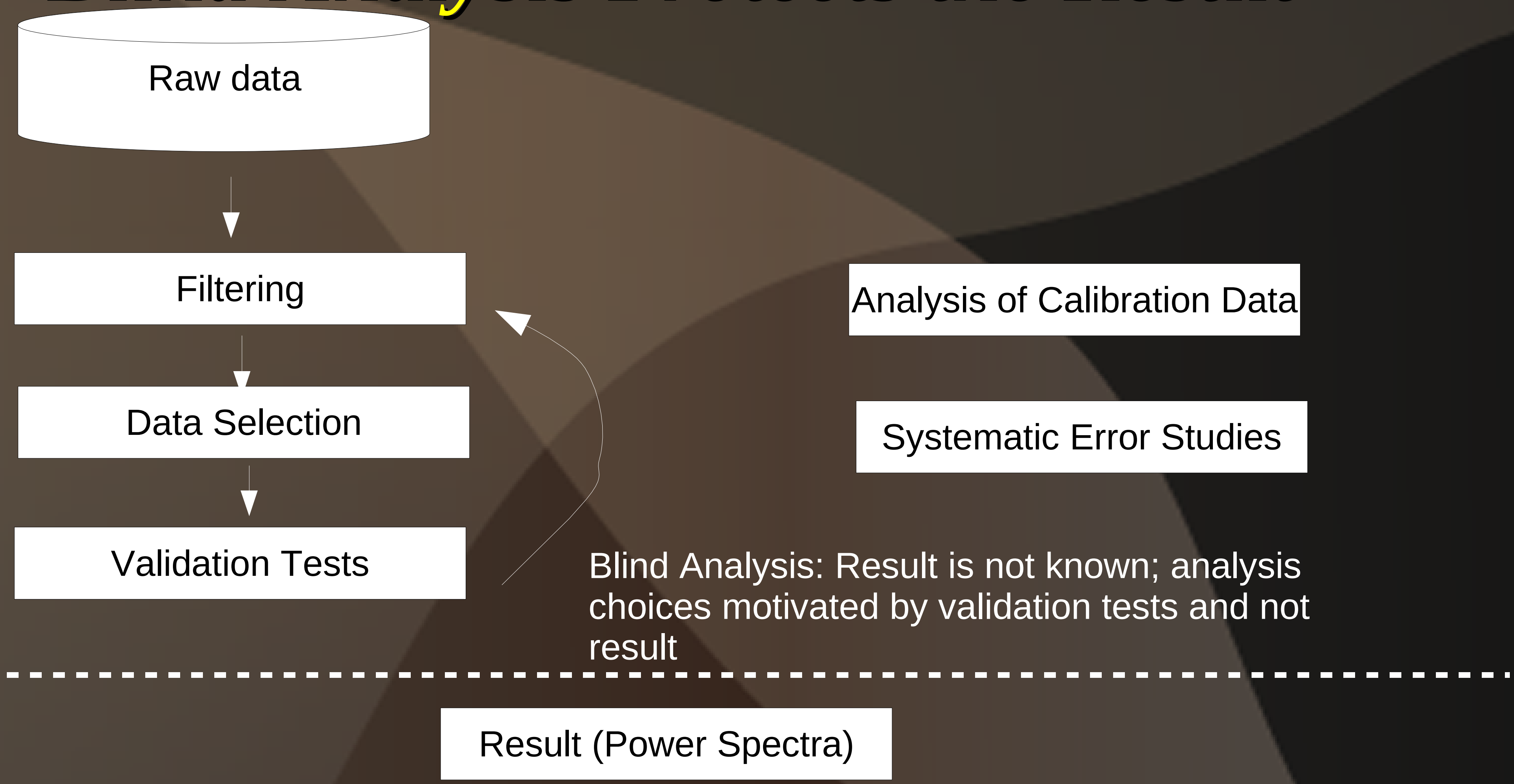
Q-band Analysis and Results

arxiv:1012.3191
ApJ 741, 111

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

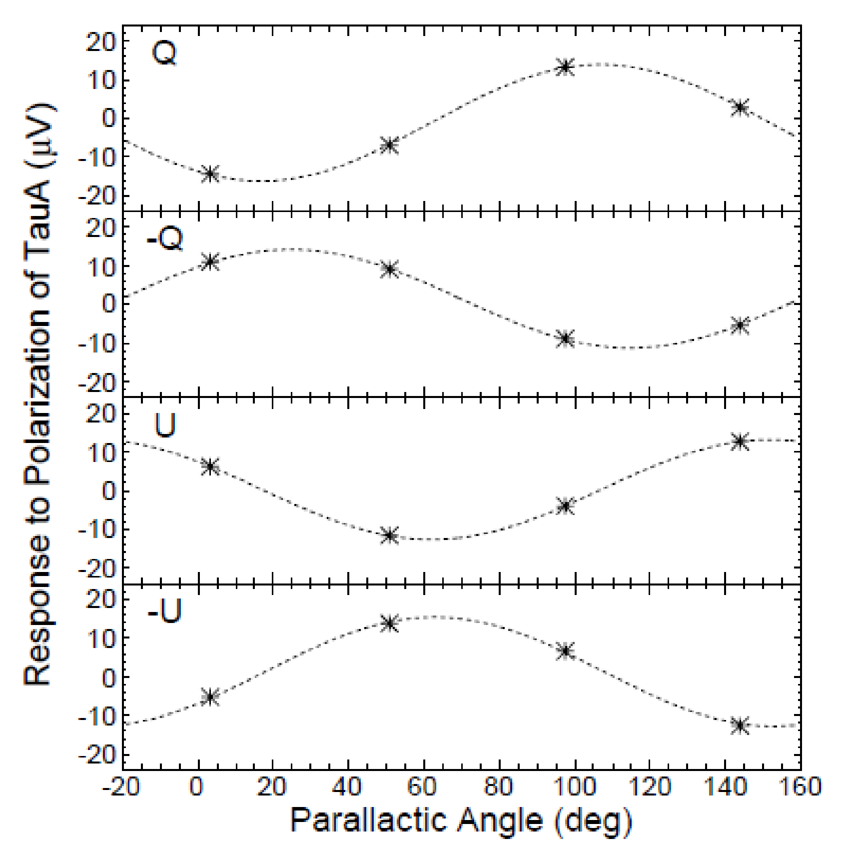
Blind Analysis Protects the Result

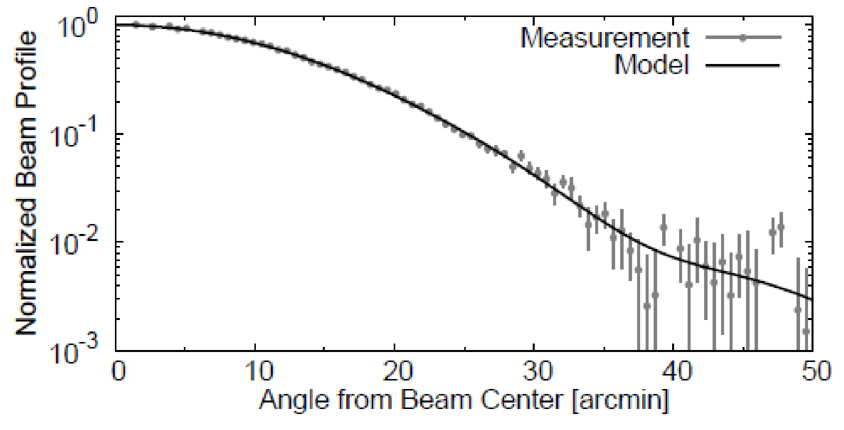


Examine result only after validation tests pass and systematic error is understood and acceptable

We have redundant calibration

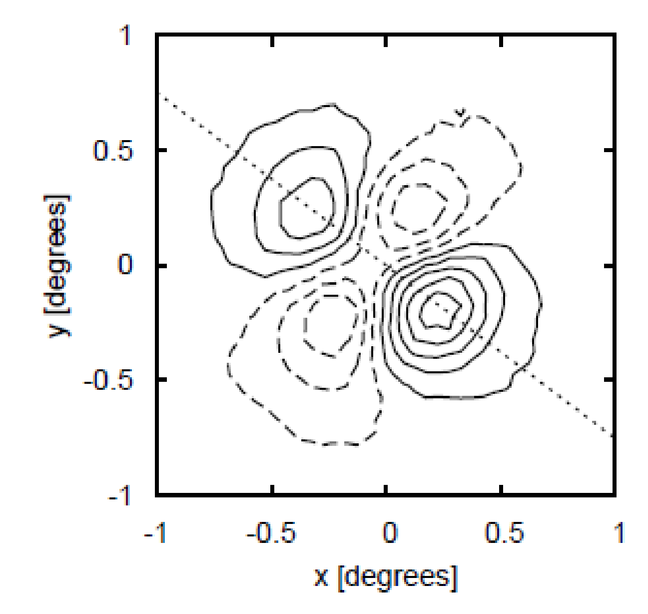
- Responsivity
  - Absolute reference Tau A (6% uncertainty)
  - Stability, relative reference from Moon, sky dip
- Beam shape: Tau A, (Jupiter)
  - Model as Gauss-Hermite profile





We have redundant calibration

- Detector polarization axis
  - Moon radial polarization
  - Systematic check with Tau A (~2 deg. systematic uncertainty)

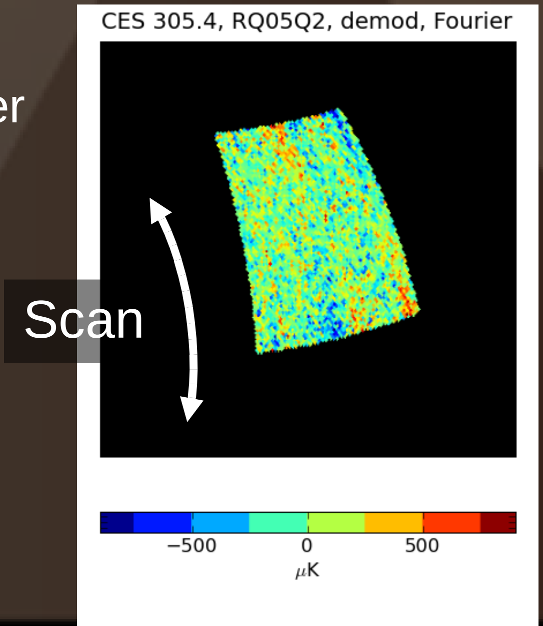


- Additional checks with artificial sources
  - Rotating sparse wire grid (made at FNAL!)
  - Polarized broadband noise source

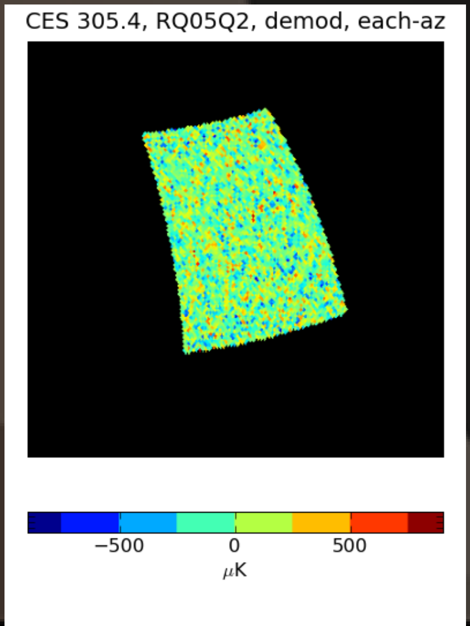
Filter Contaminated Modes

- Highpass filter cutoff near scan frequency
  - Pipeline A: in azimuth domain by slope subtraction
  - Sufficient for both 1/f noise and atmosphere
- Subtract ground structure

Naïve N^{-1} filter

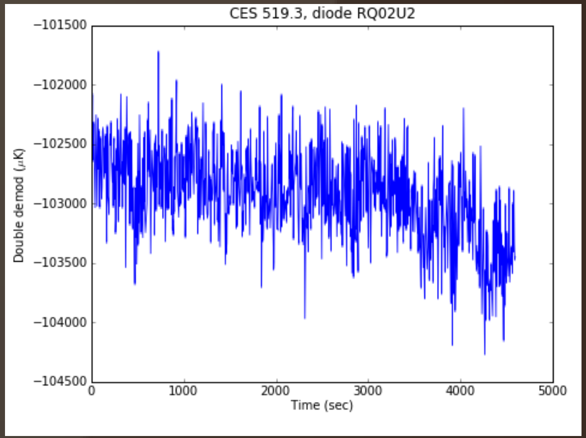


Our filter

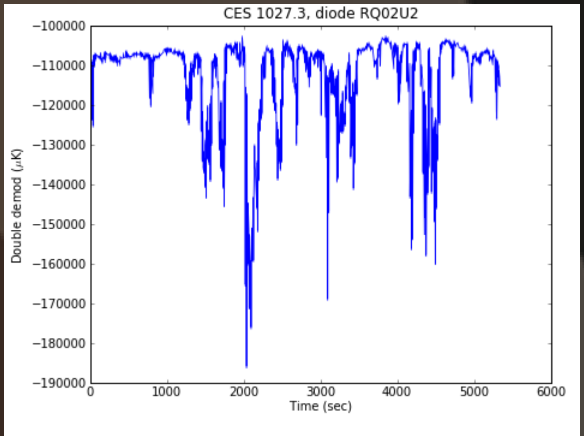


Reject Contaminated Data

- Driven by success of null suite
- Model noise power spectra of each ~hour of data
  - Cut if agreement with model is poor
- Targeted cuts: sidelobe pickup, bad weather (11%)
- Cut if outlier > 6 σ
- Simulate cuts to confirm unbiased result



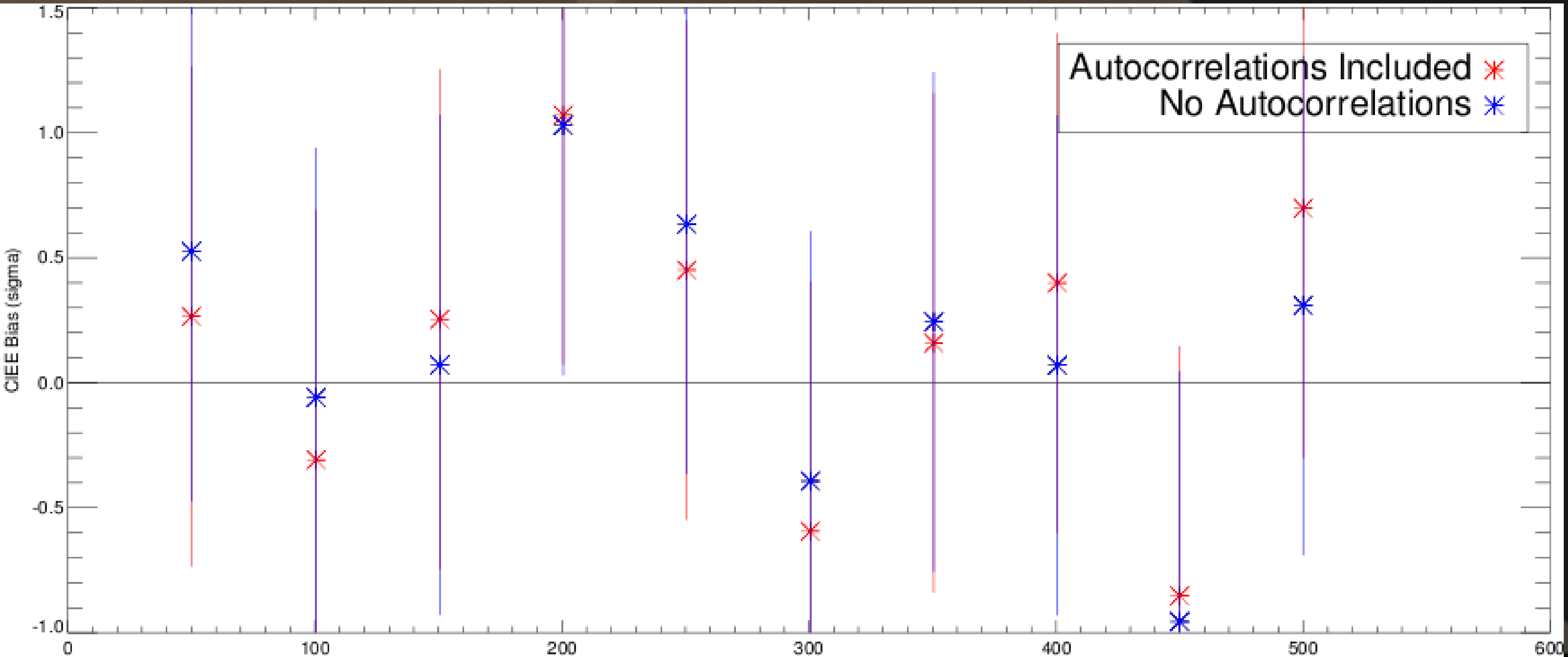
Good weather



Extremely bad weather

Proved data selection does not cause bias

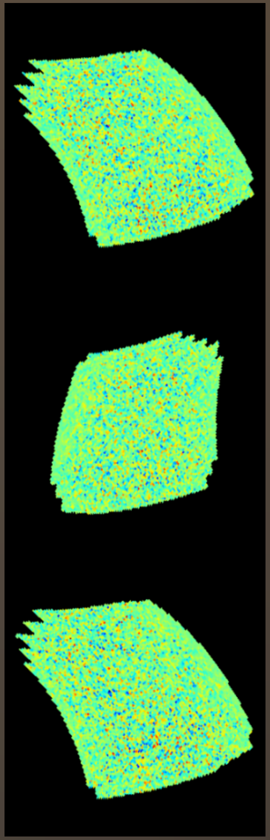
- Simulate 144 realizations of experiment TOD
- Apply data selection to each realization
- Compute power spectrum of each realization and show the data selection does not change it



Map Cross Correlation

- Eliminates noise bias and suppresses contamination
- (unique to Pipeline A)

Map from each telescope pointing



$S_\ell + N^1_\ell$

$S_\ell + N^2_\ell$

$S_\ell + N^3_\ell$

Cross-correlate all combinations

$$<(S_\ell + N^1_\ell)\,(S_\ell + N^2_\ell)> + <(S_\ell + N^1_\ell)\,(S_\ell + N^3_\ell)> + <(S_\ell + N^2_\ell)\,(S_\ell + N^3_\ell)> \ldots$$

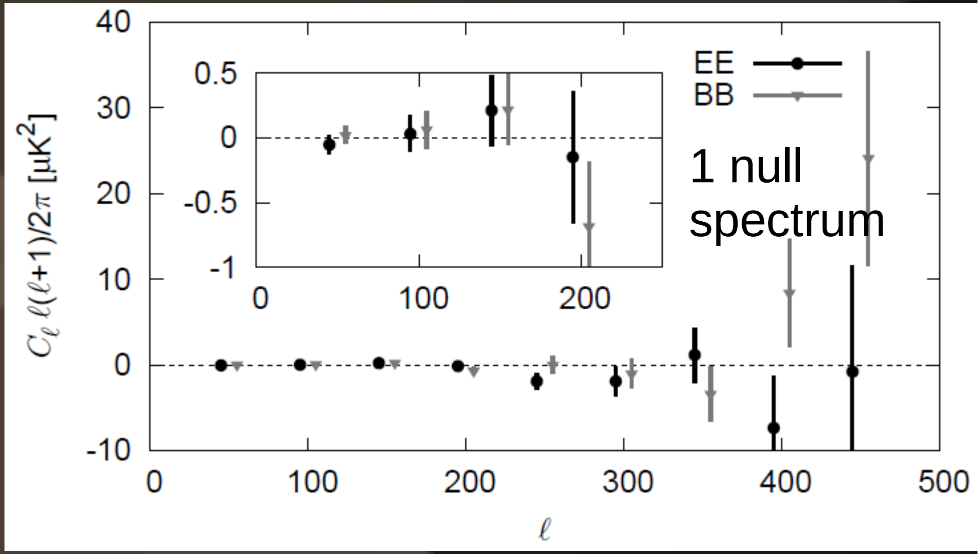
$$\propto <S_\ell^{\,2}>$$

since $<N^i_\ell \; N^j_\ell> = 0$

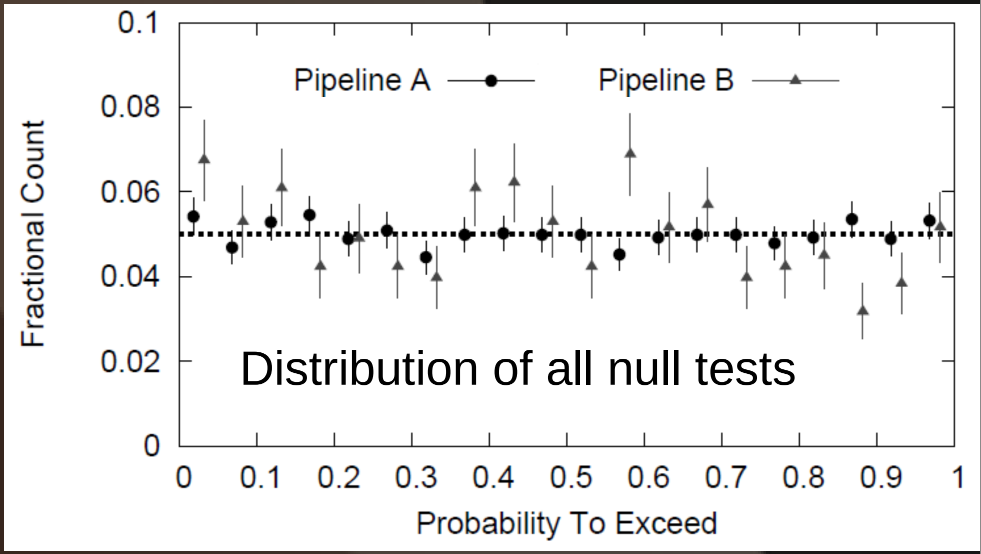
Same sky but different noise/contamination

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



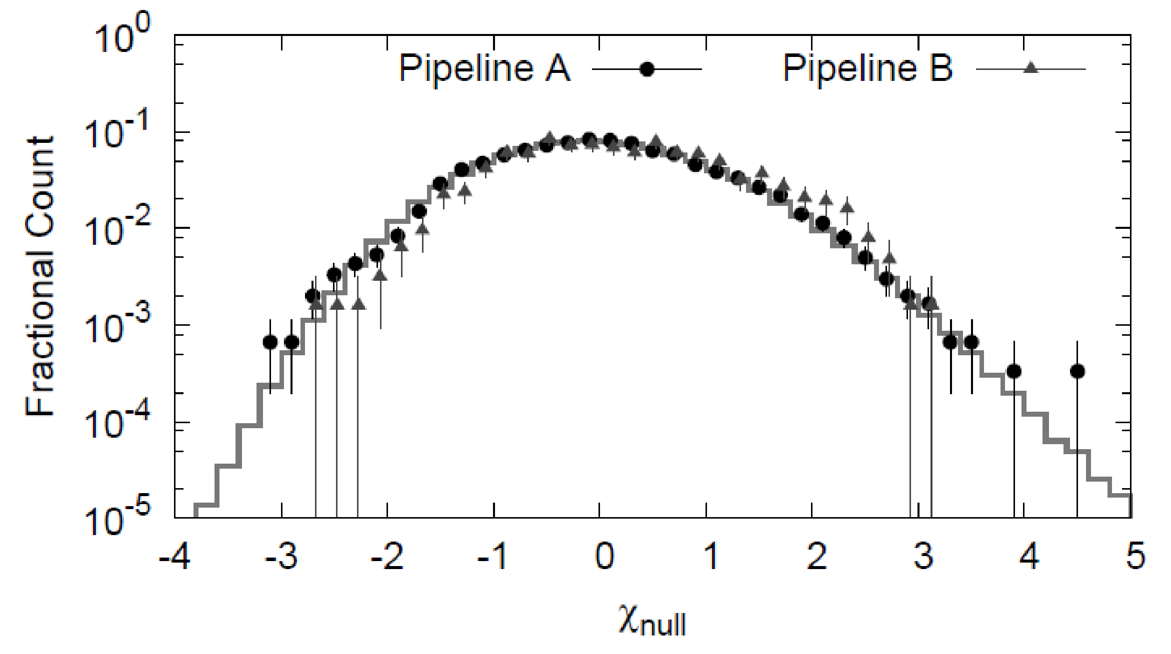
χ^2 PTE distribution

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

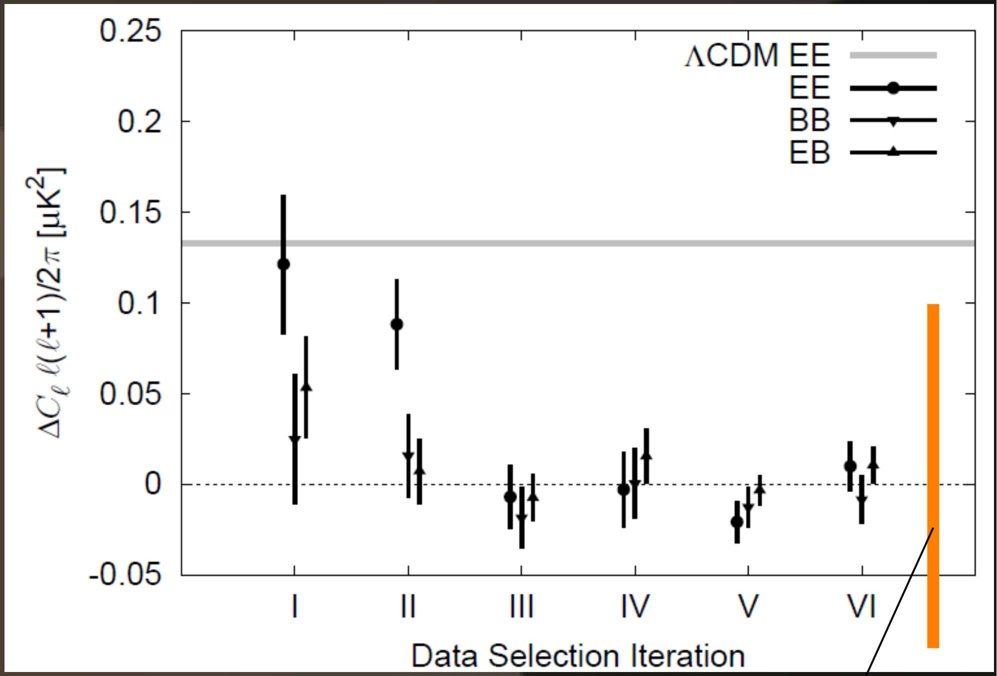


Consistency tests show the result is robust

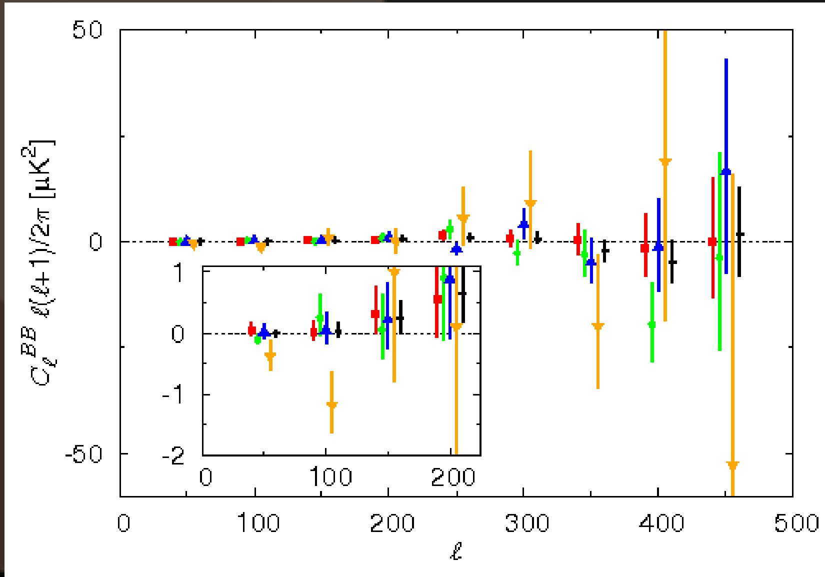
- Many analysis configuration iterations are examined before seeing the result
- Consistency check among iterations
  - Non-statistical change implies residual contamination
- Consistency check among patches

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

Consistency among different cuts

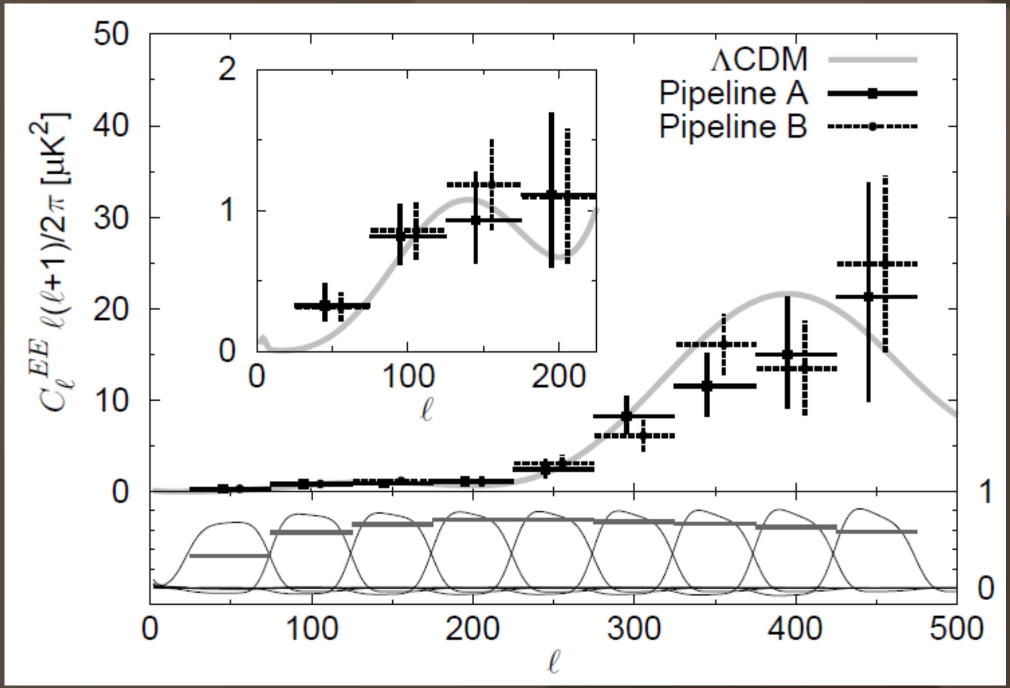


Final error

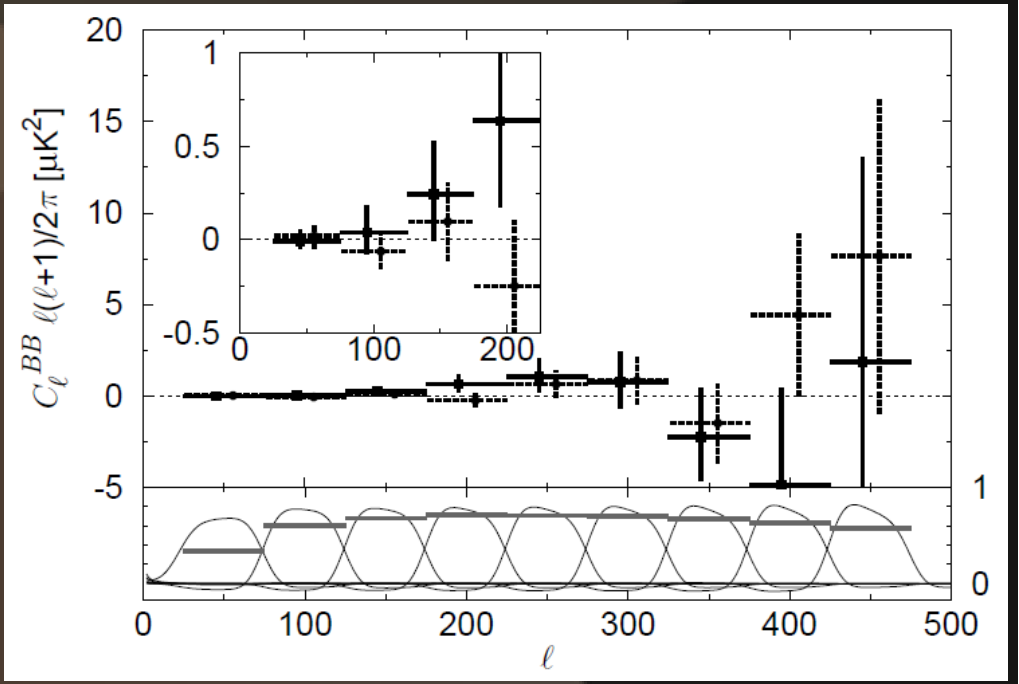


Q-band Results: Power Spectra

EE power



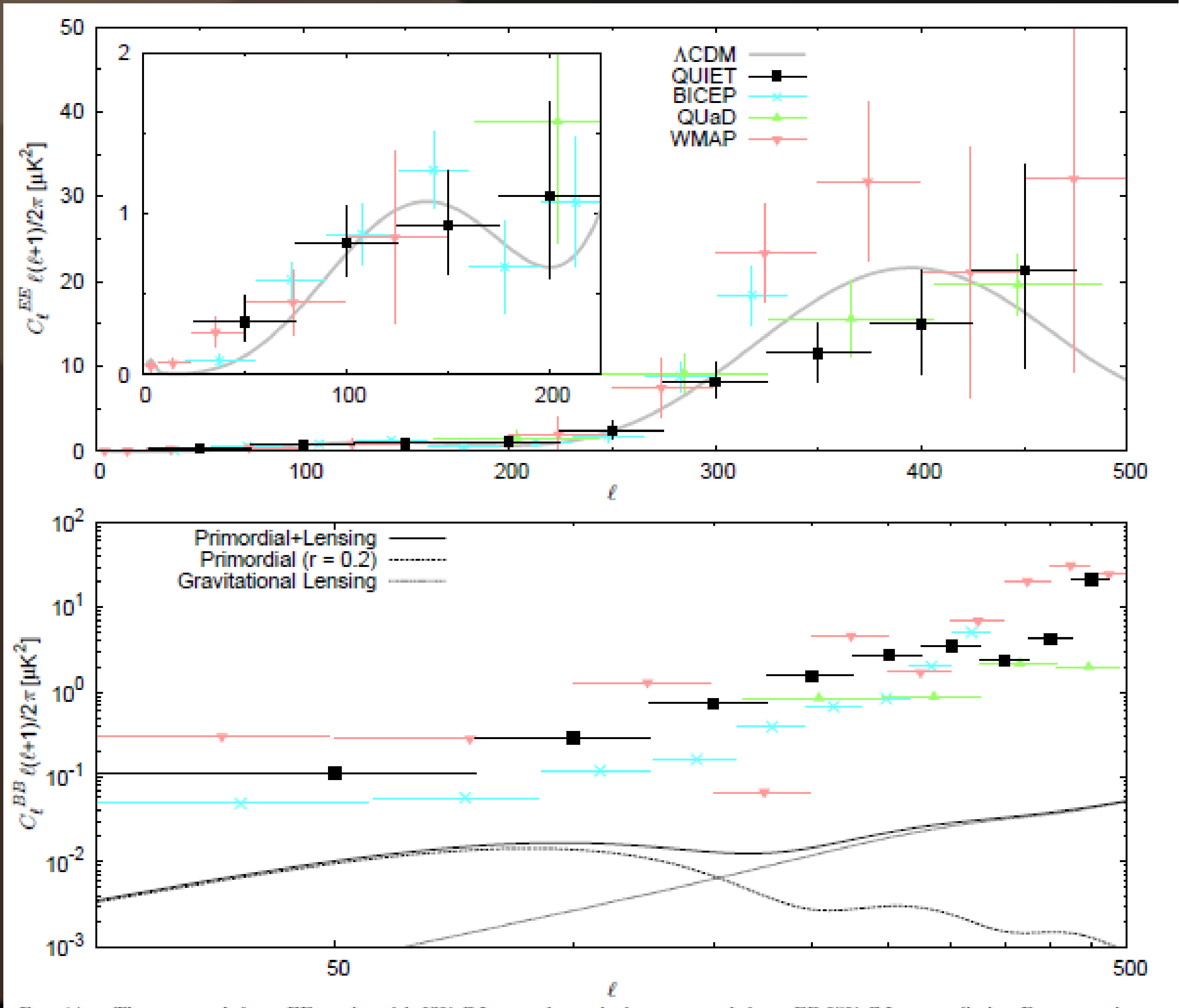
BB power



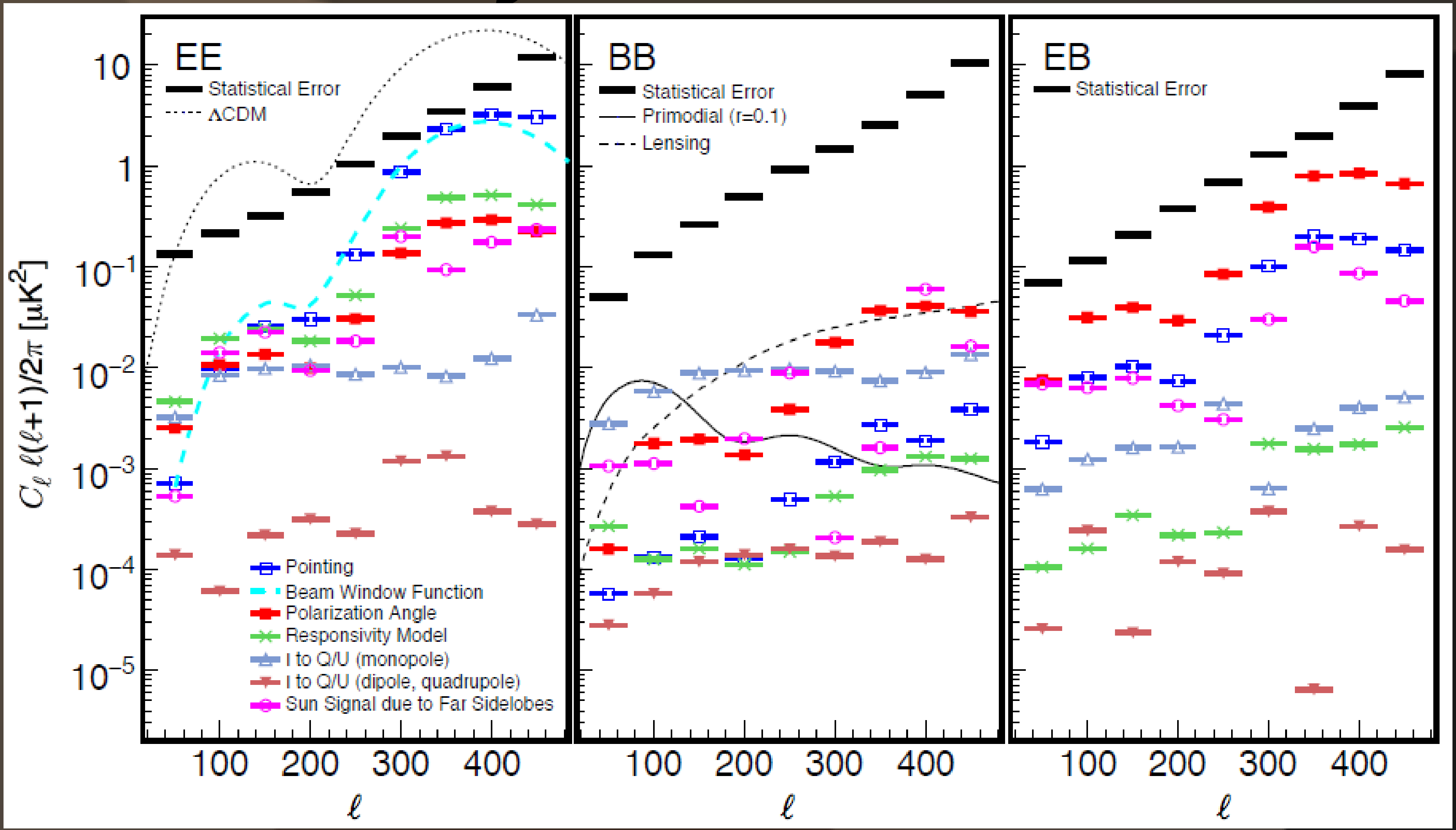
- Two pipelines show consistent results
- Consistent with concordance cosmology (ΛCDM)
- No detection of B modes (detection not expected at our sensitivity)

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



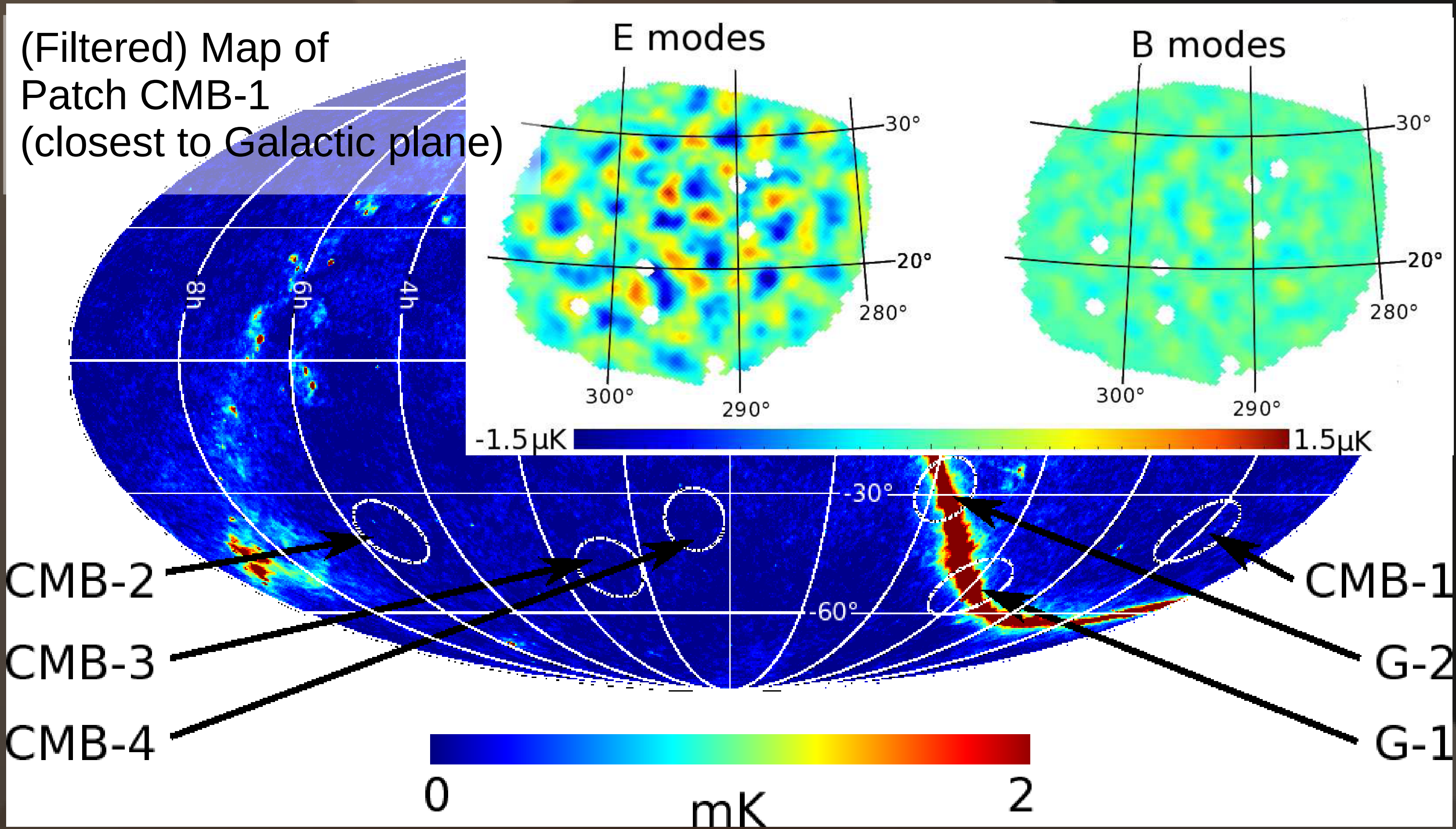
Smallest Systematic Errors



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

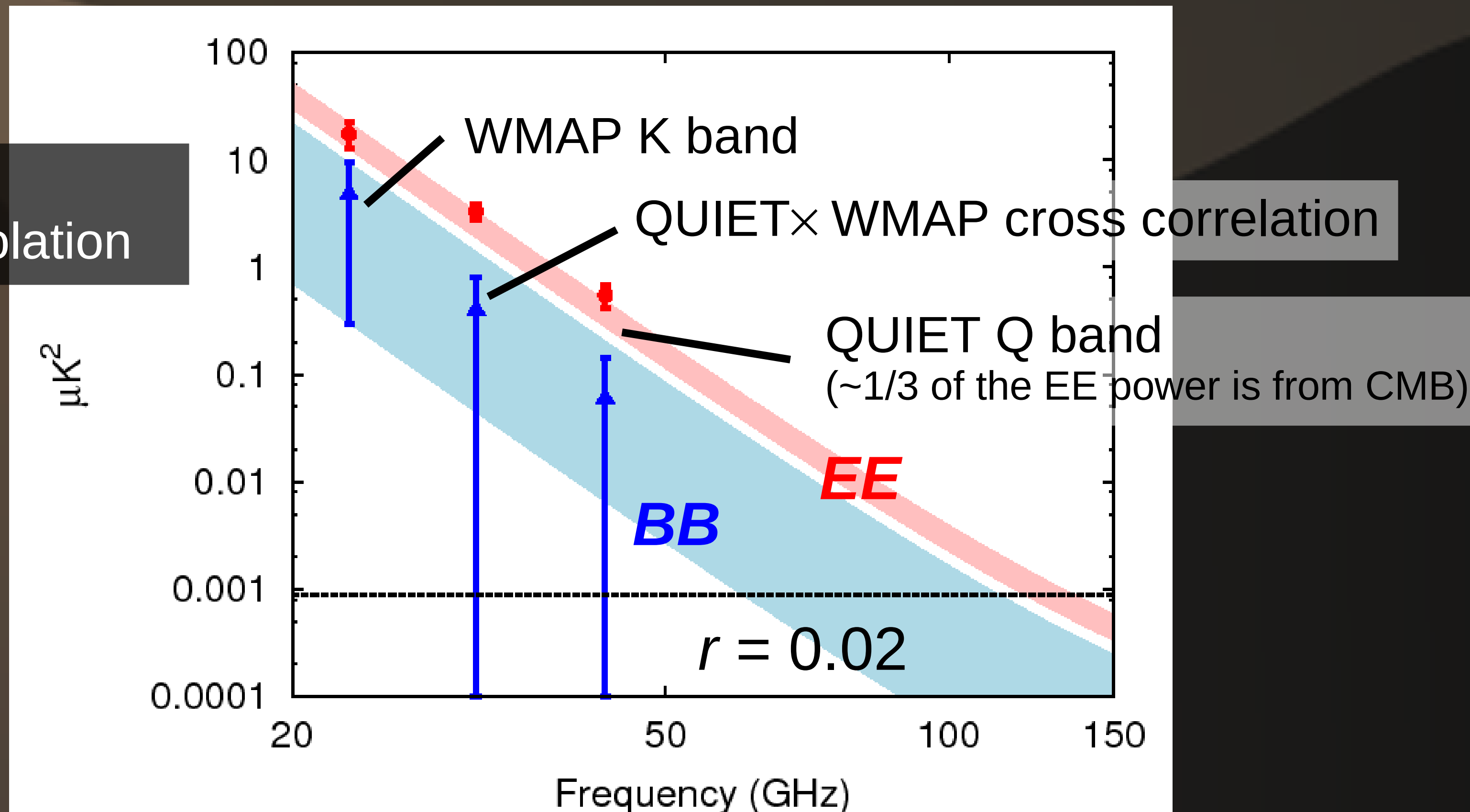
QUIET will help understand foregrounds

- Likely to be the ultimate limit for B-mode measurements
- Patches will be common to Atacama experiments
- QUIET Q-band maps are a unique contribution



Detected foreground in CMB-1

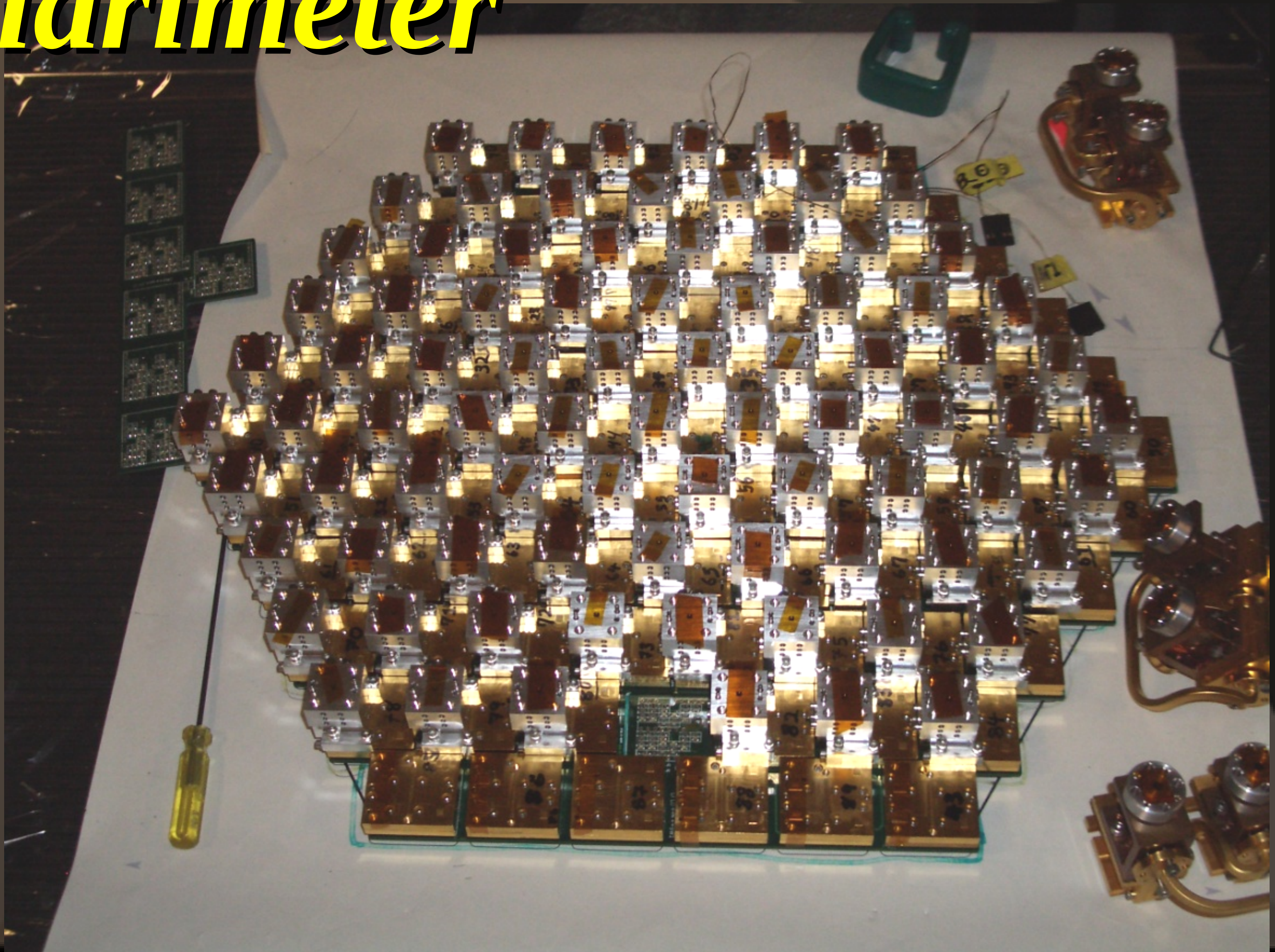
1st bin (l=25–75)
β = –3.1 for extrapolation



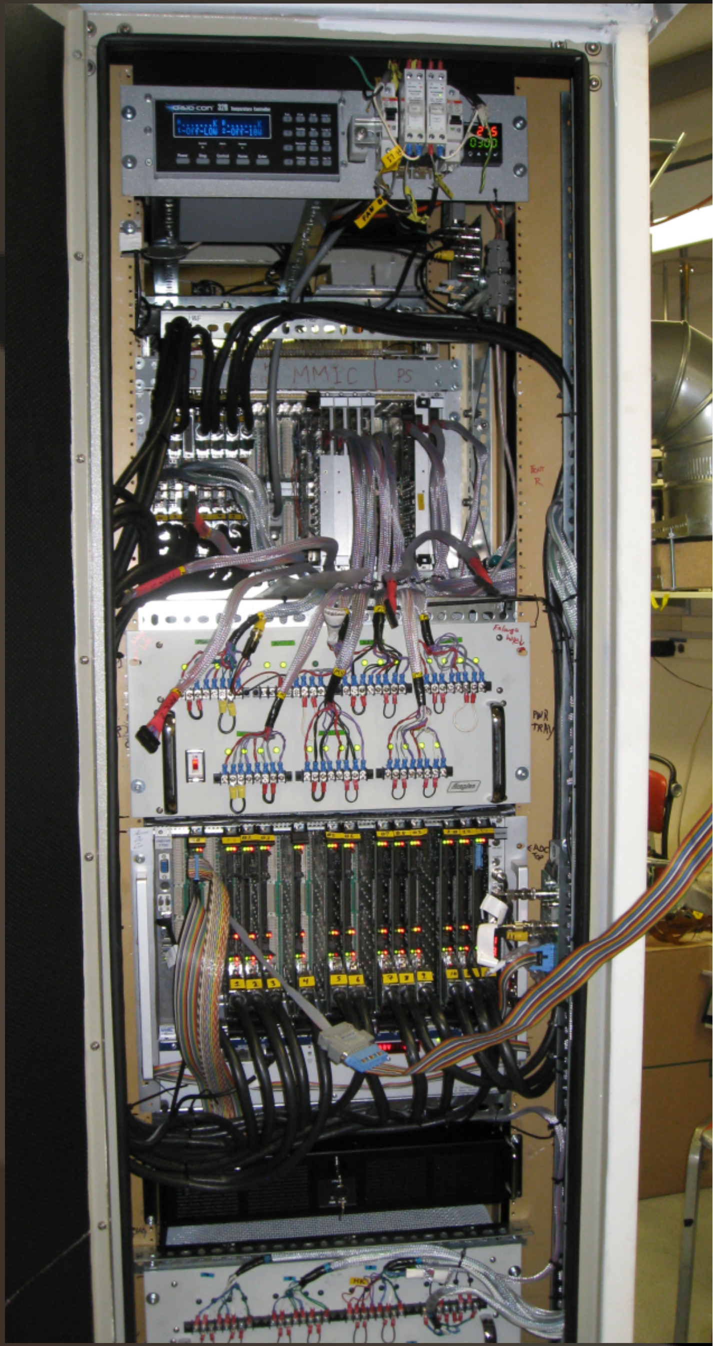
- Foreground detected at 3 σ in first bin of patch CMB-1
- Identified as Galactic synchrotron emission
- B-mode foreground not detected
  - WMAP K band extrapolates to $r \sim 0.02$ at W band

Future Prospects: W band

W-band Array is the world's largest HEMT-based array polarimeter



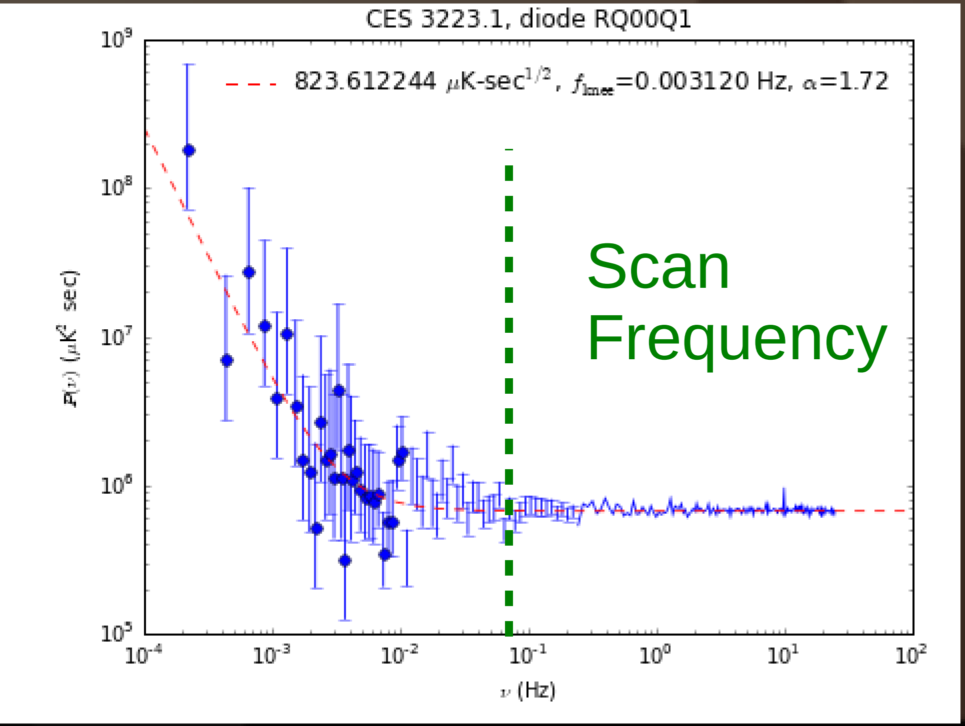
W-band Array integrated at Chicago

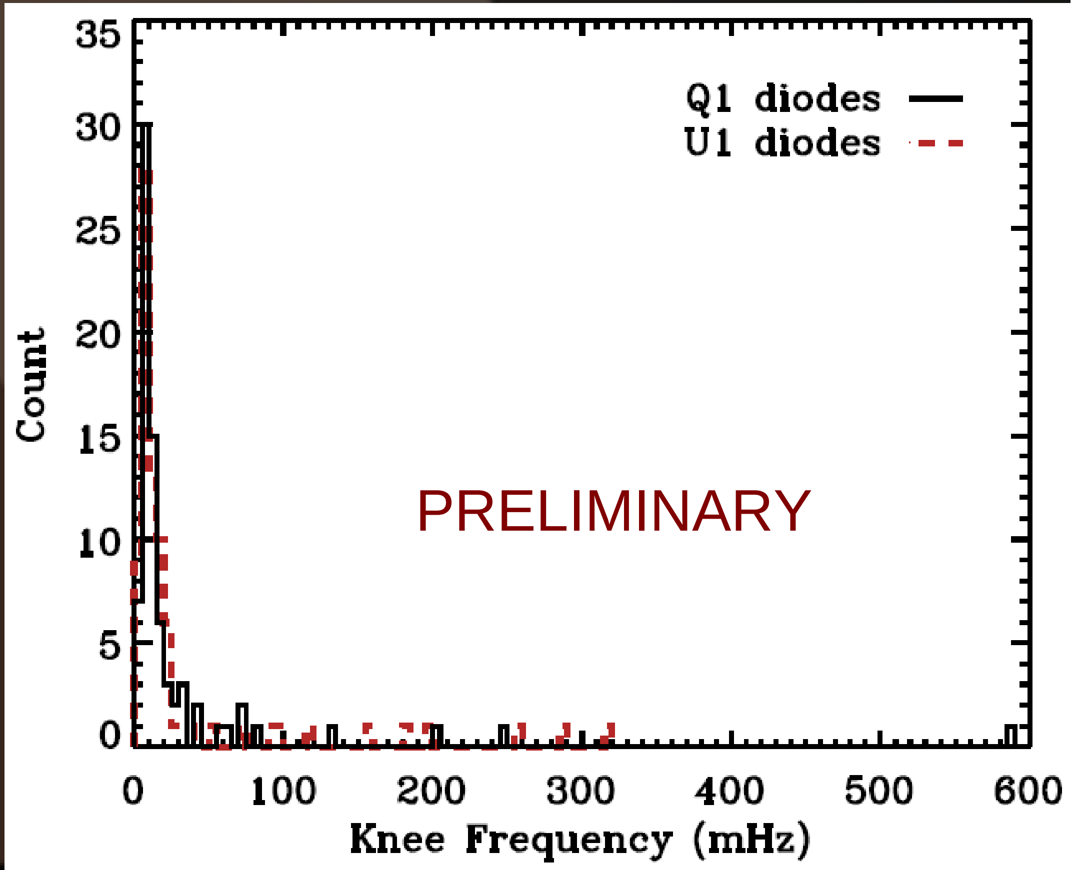


W-band Array shipped!

W-band Analysis is Underway

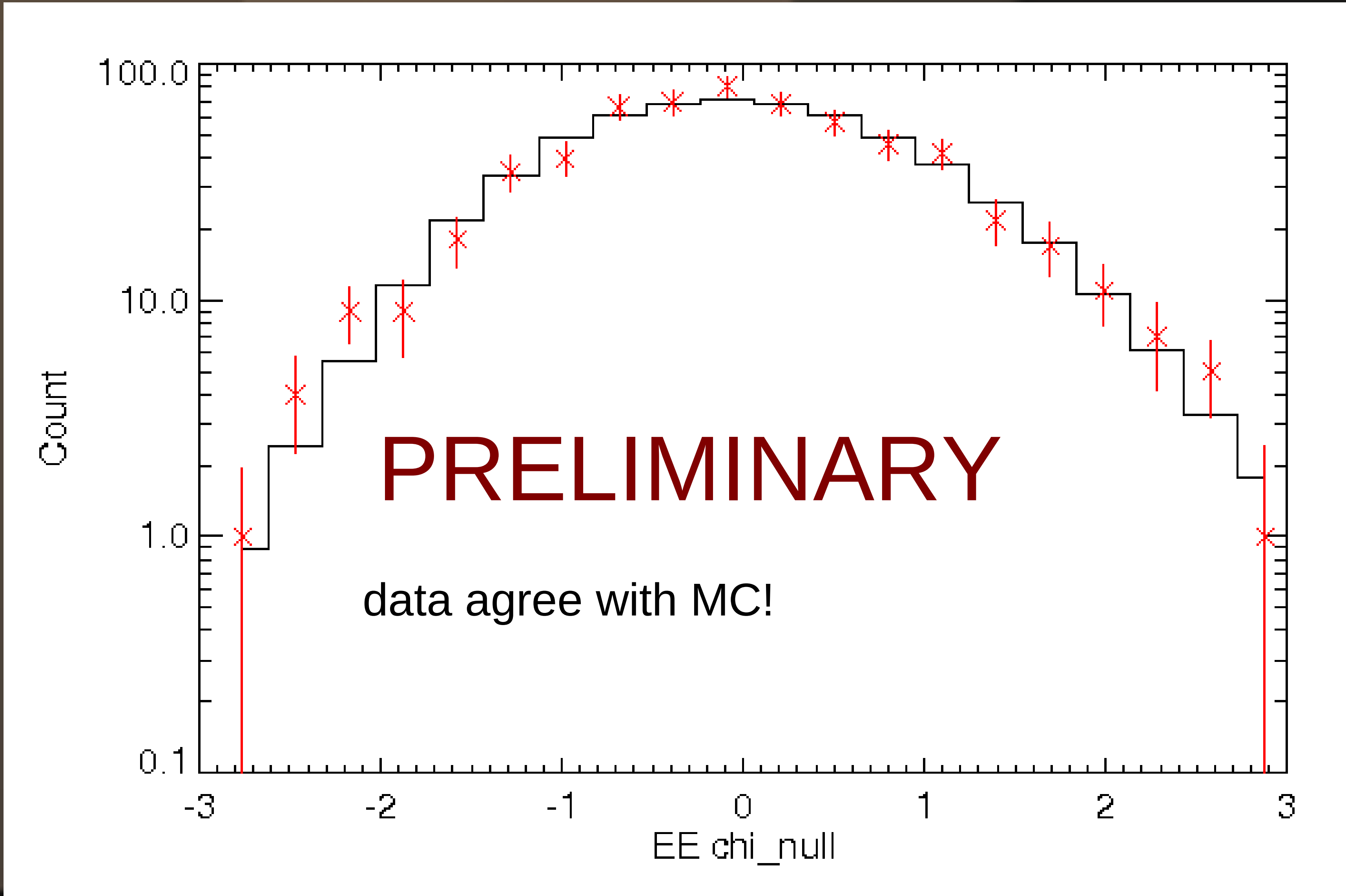
- QUIET has ~twice as much W-band data with similar sensitivity to Q-band



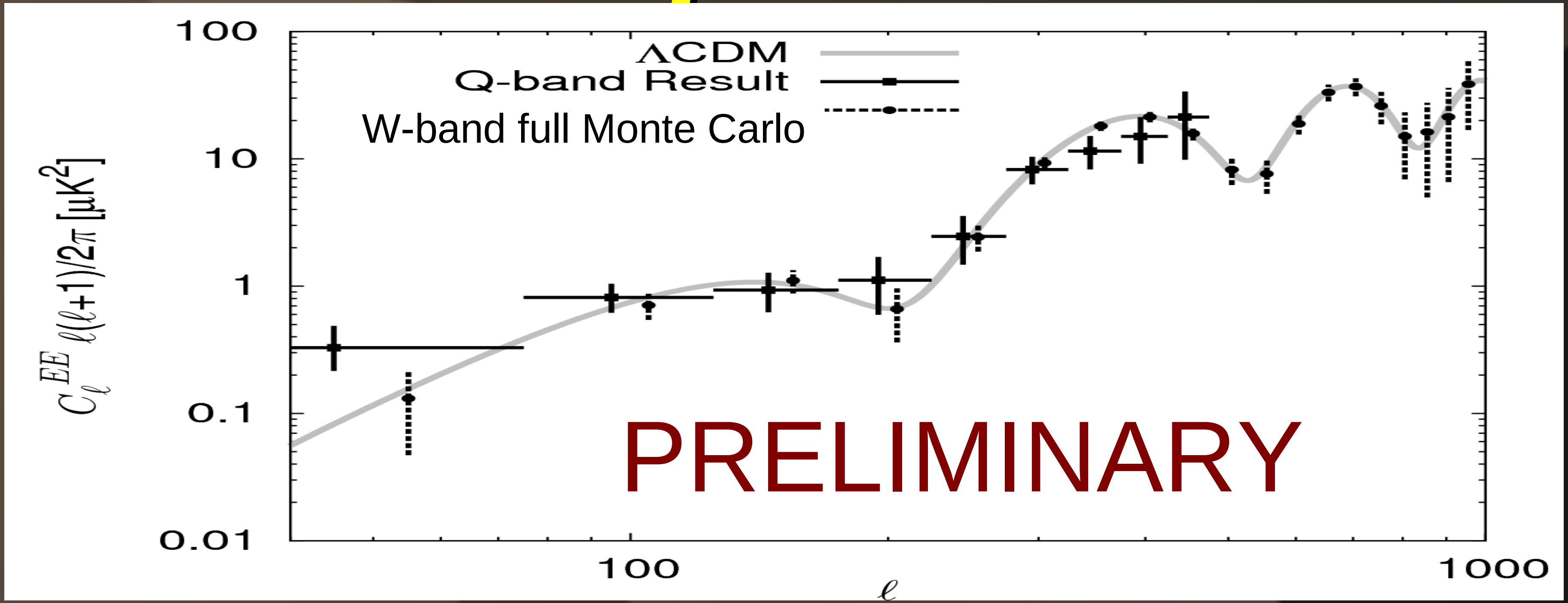


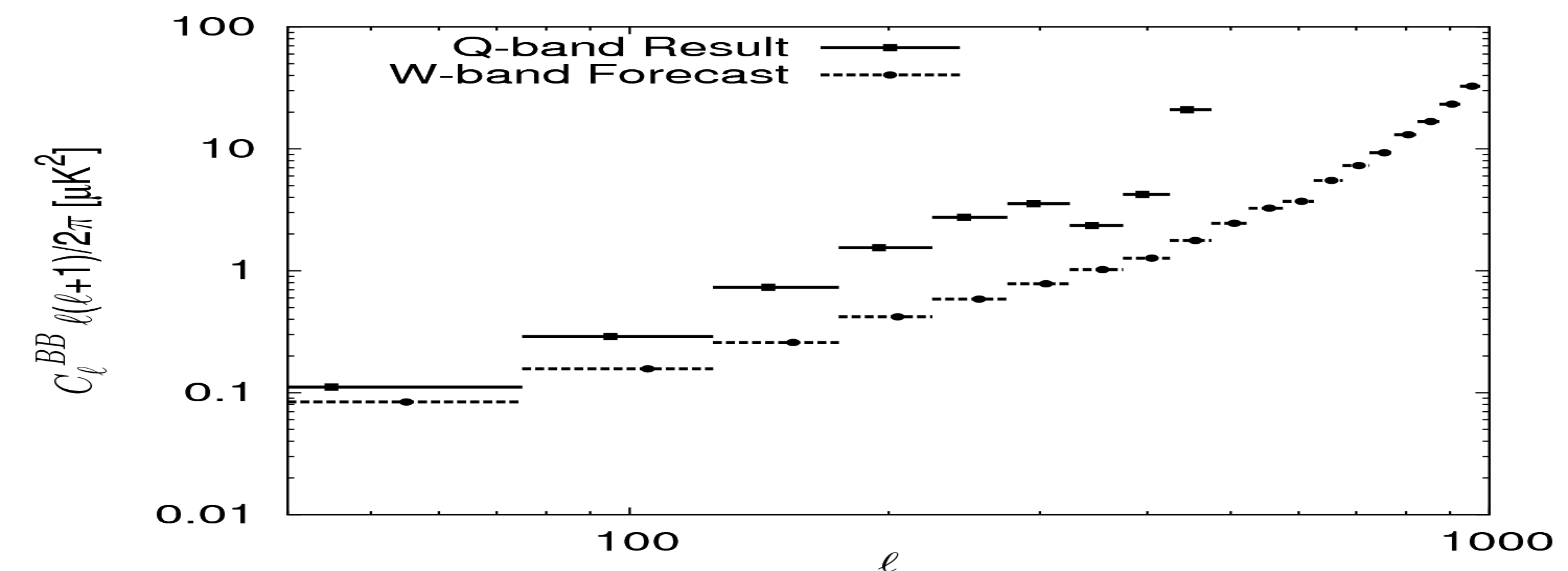
Null Test Going Well

- Same stringent tests as Q band (plus some new ones)



Forecast Improved Result





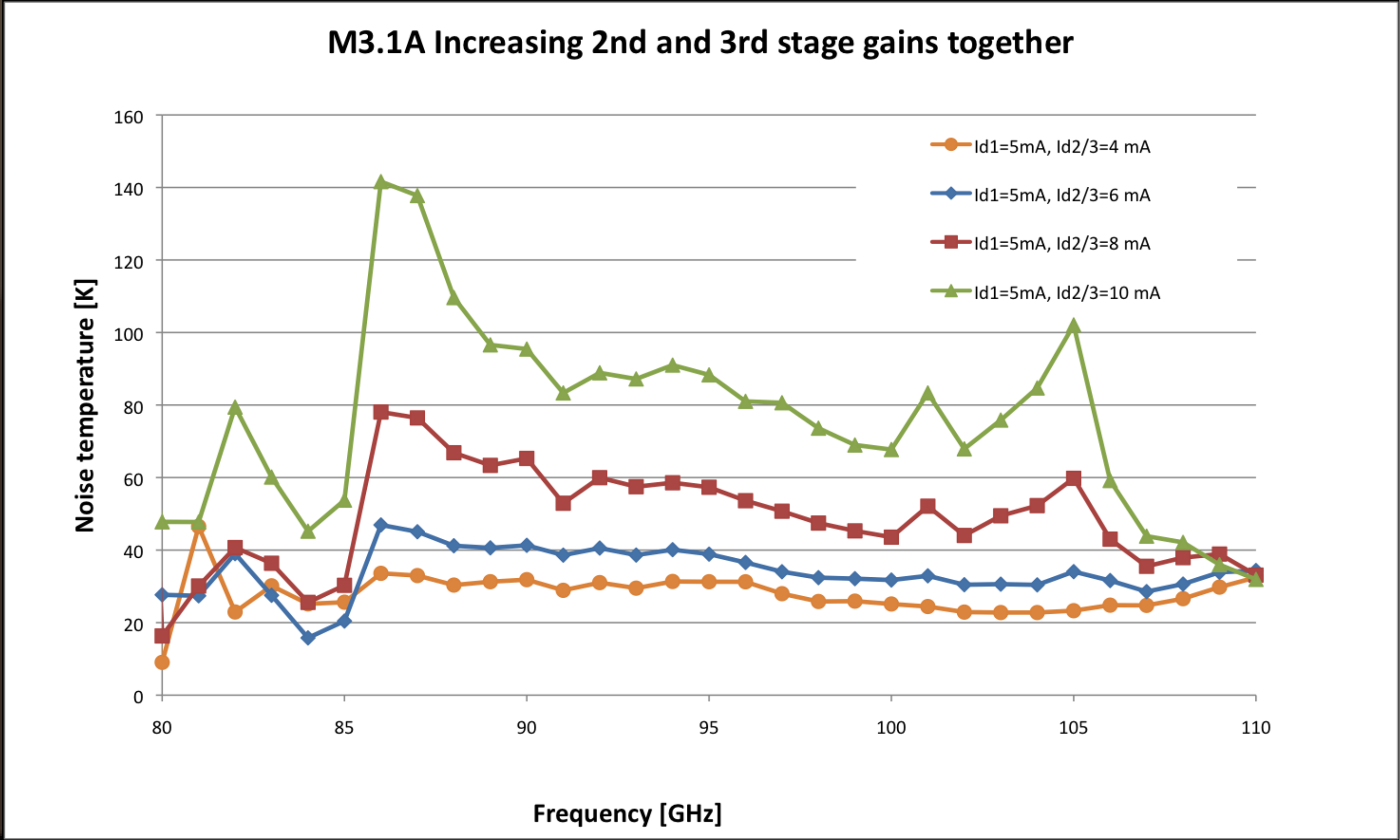
Smaller Systematic Errors (compared to Q band)

- Target is $r = 0.01$
- Intrinsic leakage is ~0.2% (better septum polarizer/ module match)
- More uniform boresight/parallactic angle coverage
- Better polarization axis measurement
  - 0.2 deg systematic uncertainty for Tau A from IRAM reference measurement (Aumont et al. 2010)
  - Relative angle from artificial wire grid source

Sensitivity is being improved

- Target noise temperature < 40 K
- 500-element array with sensitivity < 10 μK s$^{1/2}$
- B-mode measurement with uncertainty on r < 0.01 in 2 years of observation

Improved module prototype test results



Summary and Conclusion

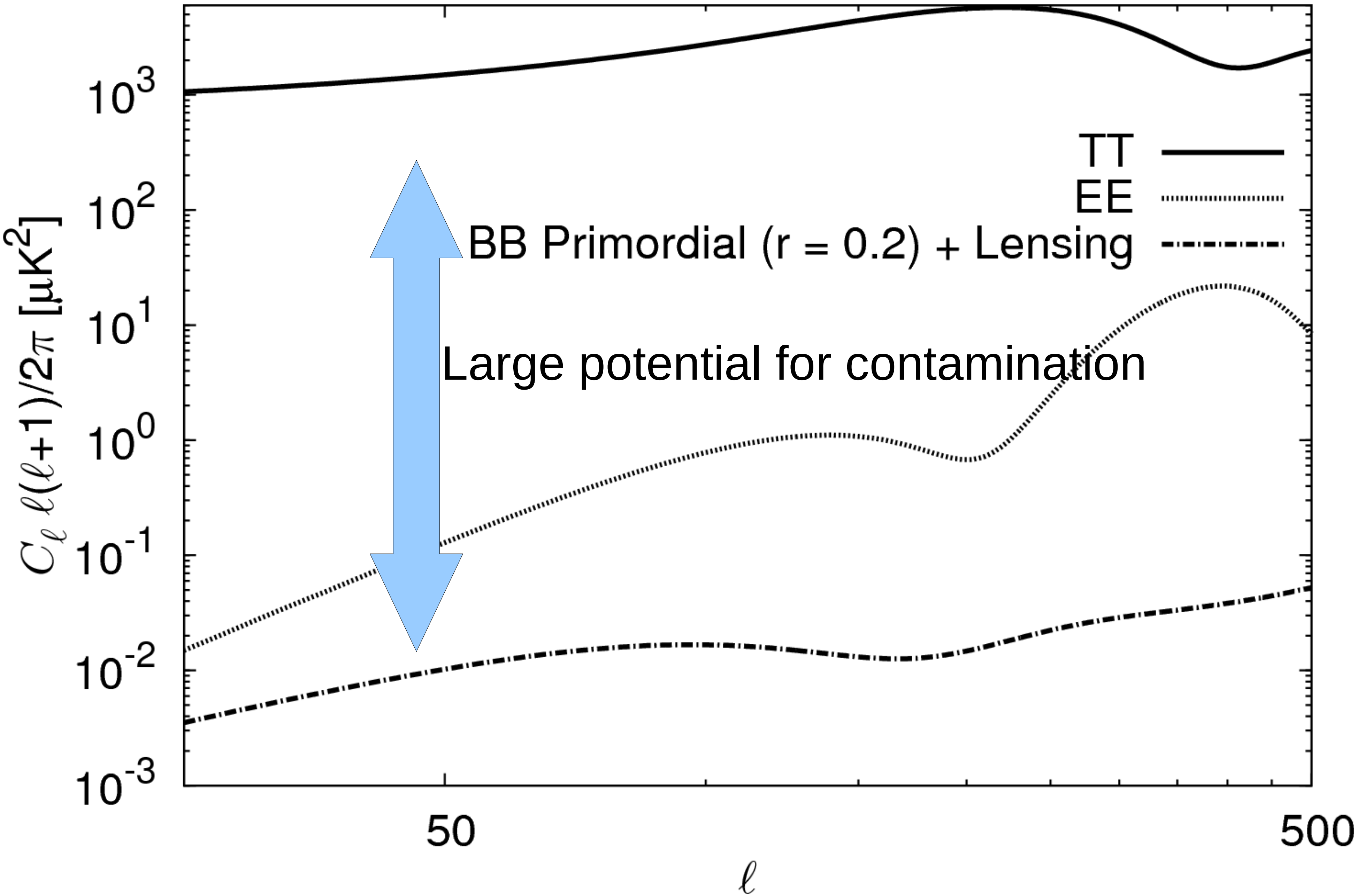
- It's an exciting time for B-mode experiments
- QUIET Experiment
  - Unique detector technology
  - First phase observing completed successfully
- Q-band Results (arxiv: 1012.3191)
  - Competitive B-mode limit
  - Improved analysis techniques (including use of blind analysis) to make the systematic error small enough for future B-mode detection
  - Unique contribution to foreground characterization
- W band: Improved detector in R&D and new result coming in a few months!

QUIET 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$\times$ 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	μK 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

Scale of the Problem



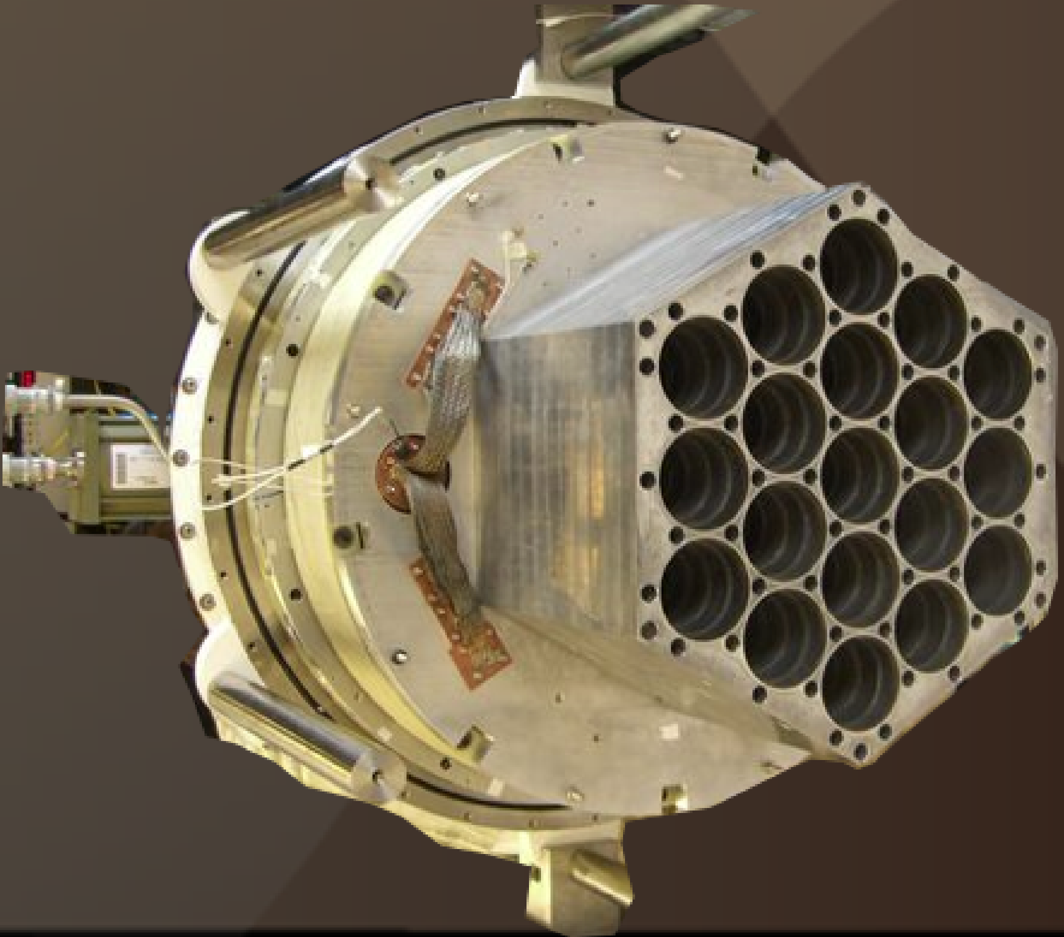
QUIET Arrays

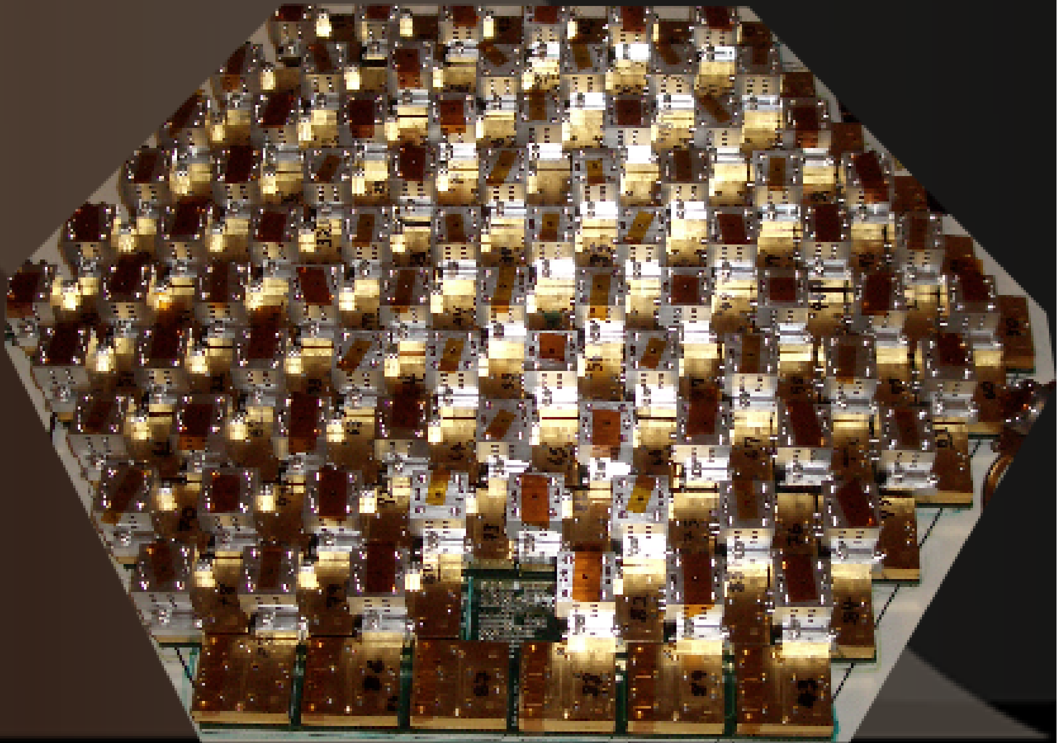
Q band

19 elements @ 43 GHz
17 Polarimeters
2 temperature diff.

W band

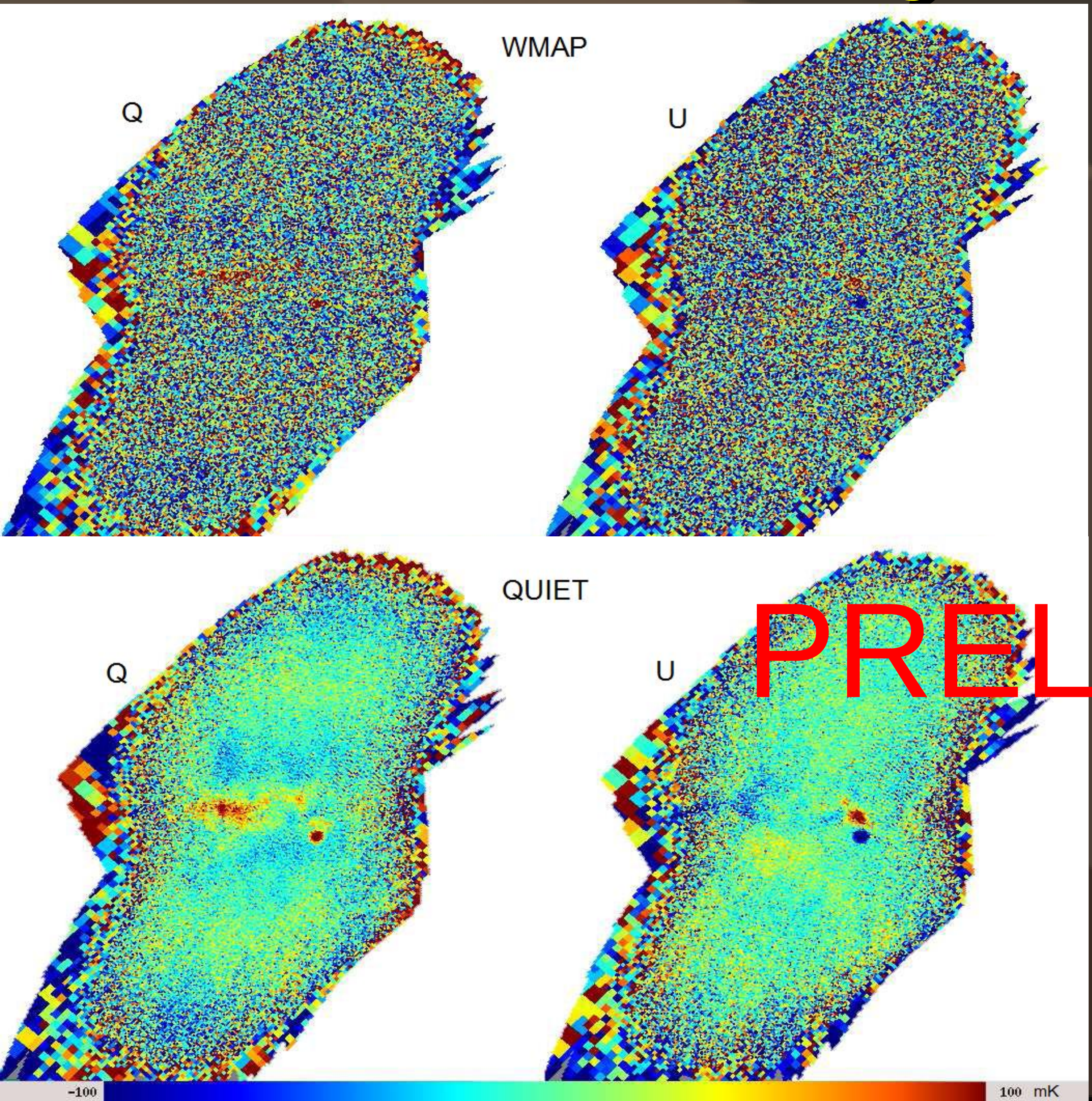
90 elements @ 95 GHz
84 Polarimeters
6 temperature diff.





Other Atacama Experiments

Q-band Analysis: Galaxy

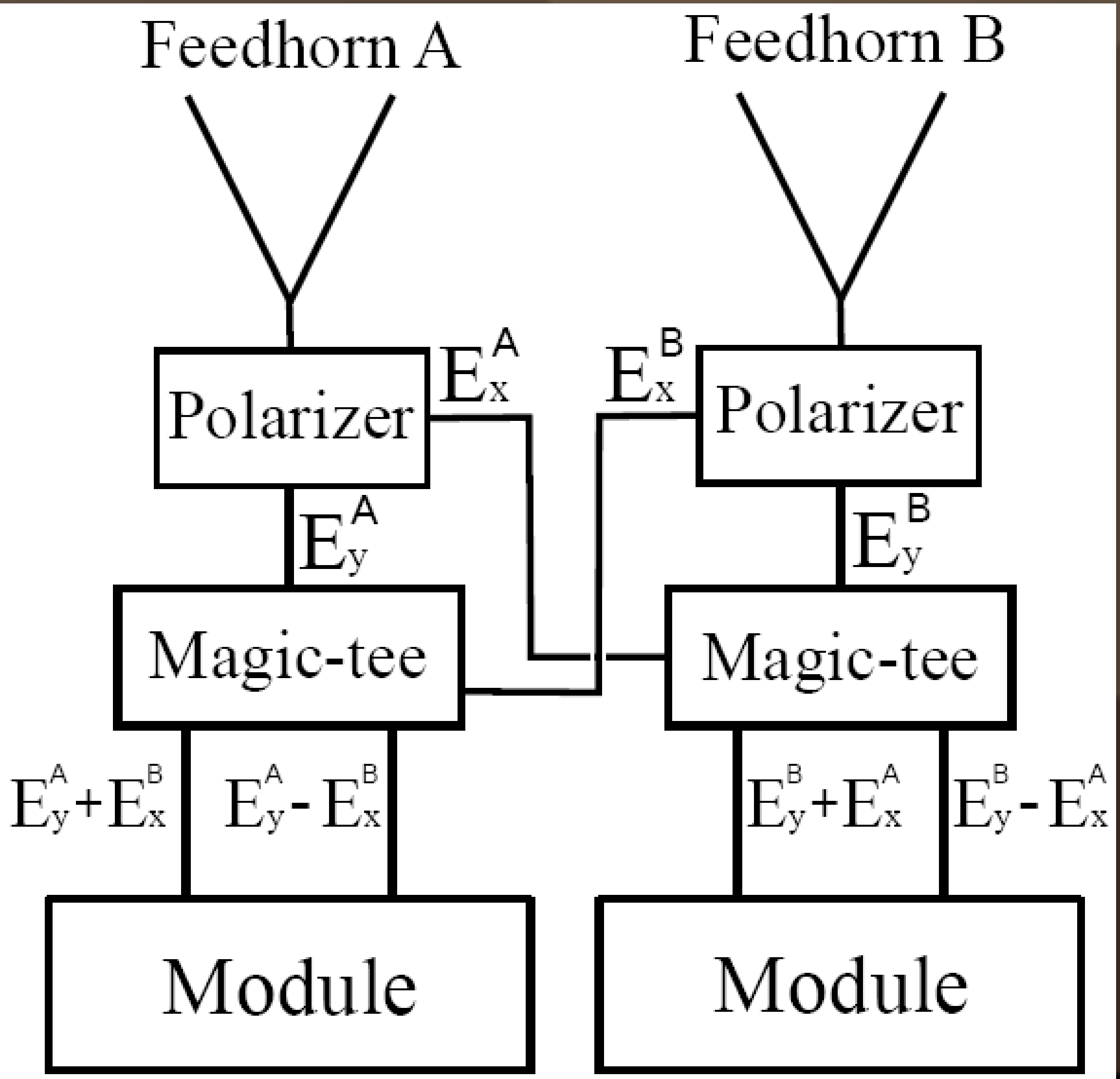


- ~100 hours of data from one Galactic patch (G-1) in Q band
- Top: WMAP
- Bottom: QUIET

PRELIMINARY

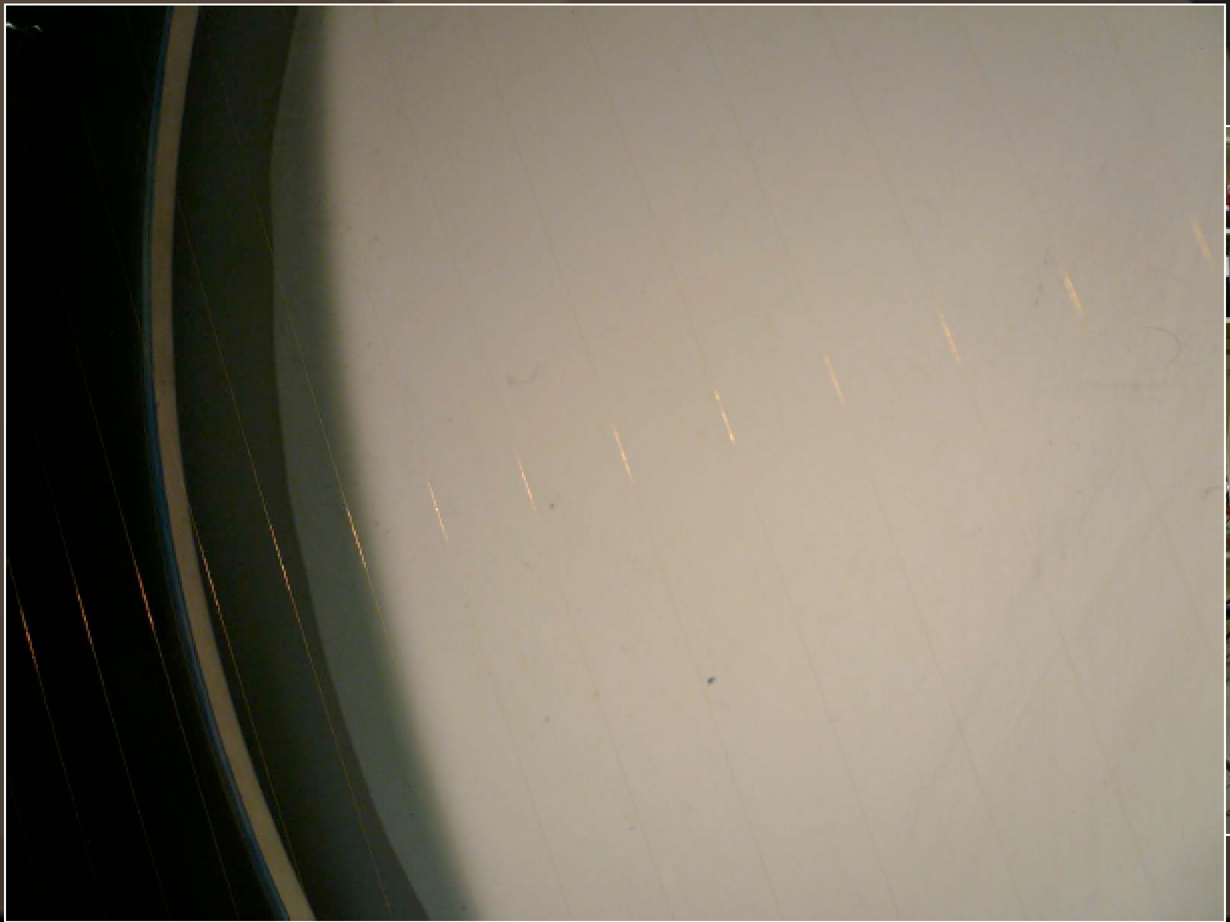
TT Assembly

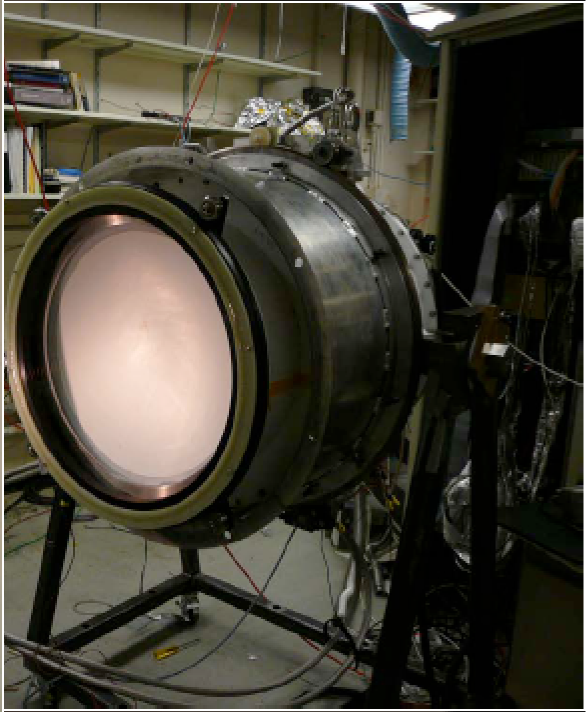
- Replace Septum Polarizer with OMT+Magic Tee to measure temperature anisotropy



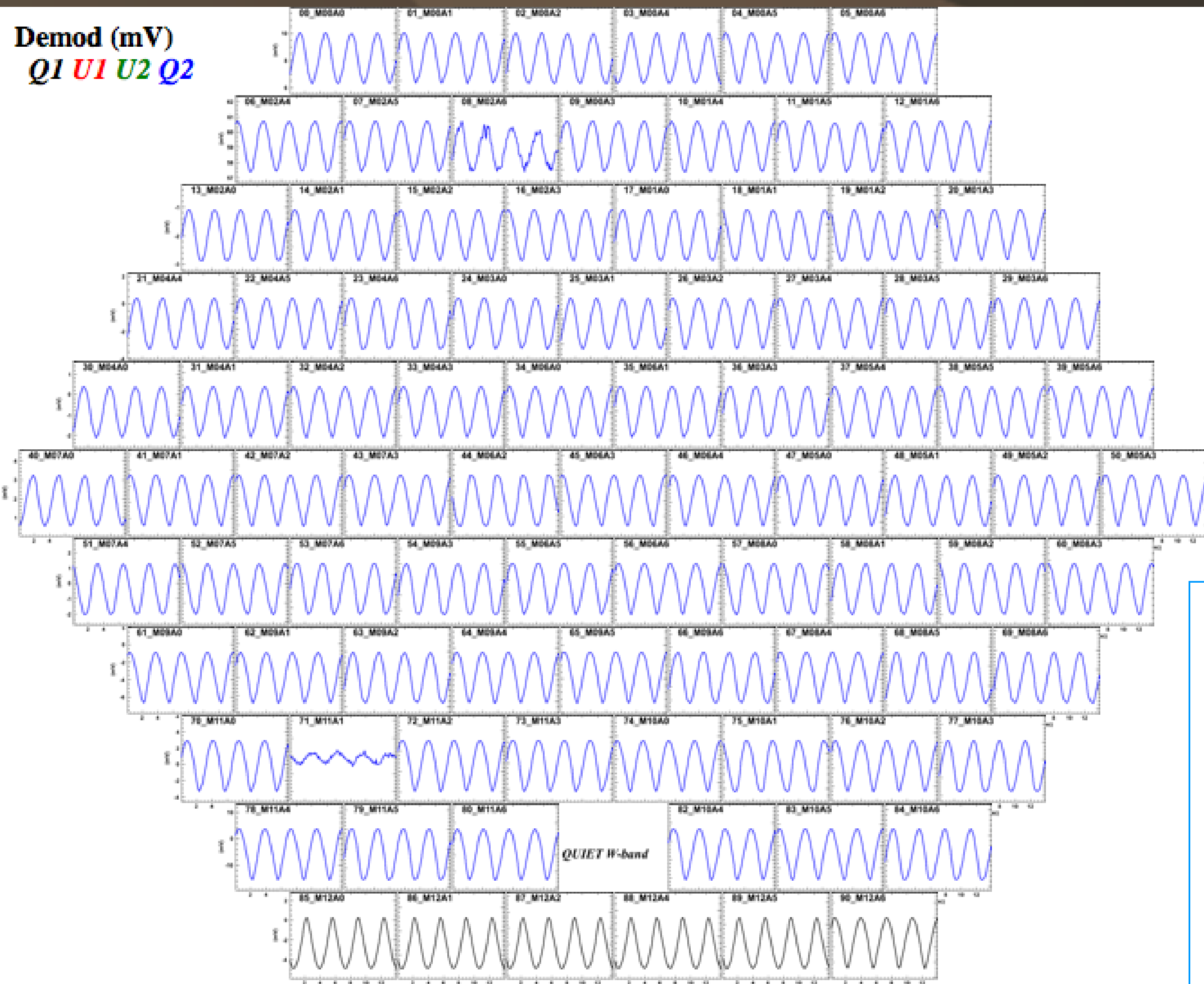
Module Optimization

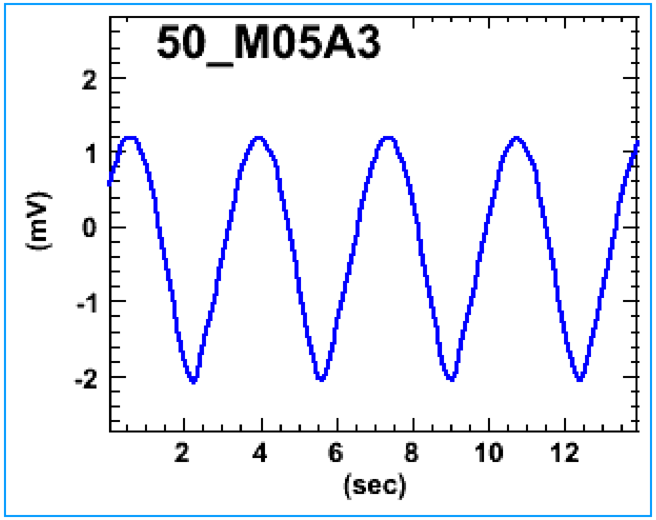
- Digital control of amplifier biasing (10-bit DAC)
- Maximize S/N with wire-grid polarization source
- 90 modules can be optimized in 24 hours





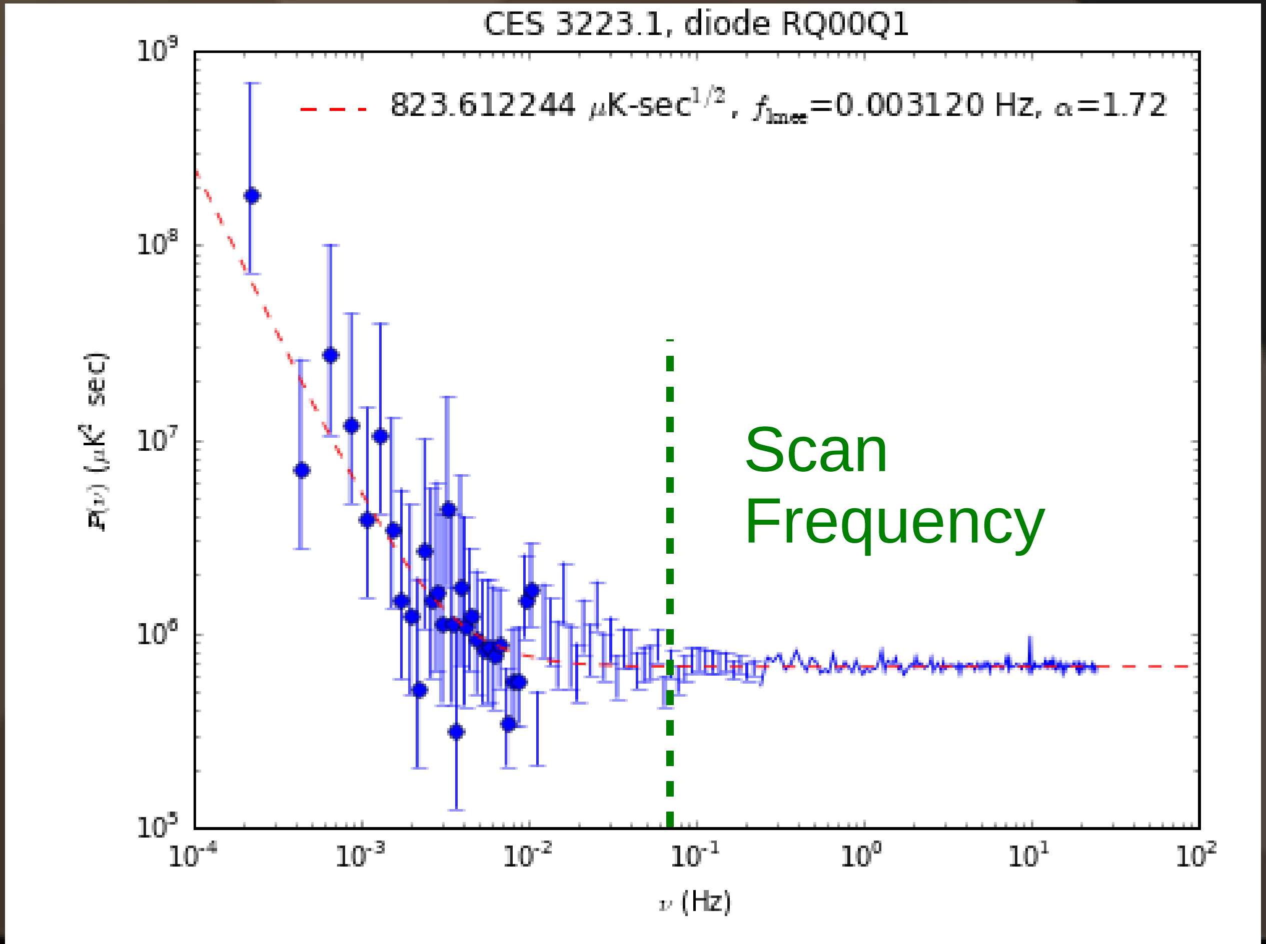
Module Optimization





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