State of the Art CMB Polarization Measurements:

BICEP (2006-2008 seasons)

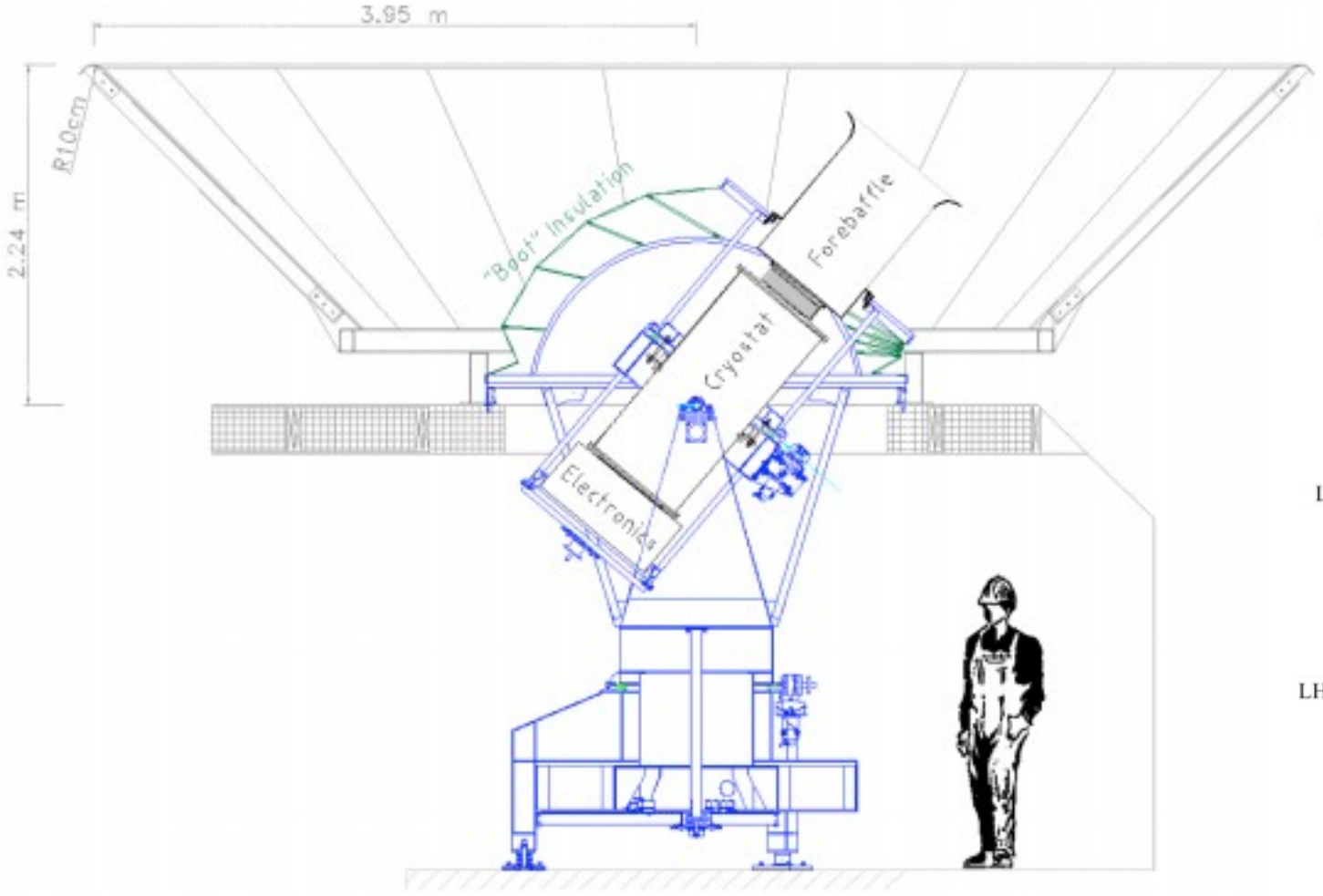
Wendy Everett

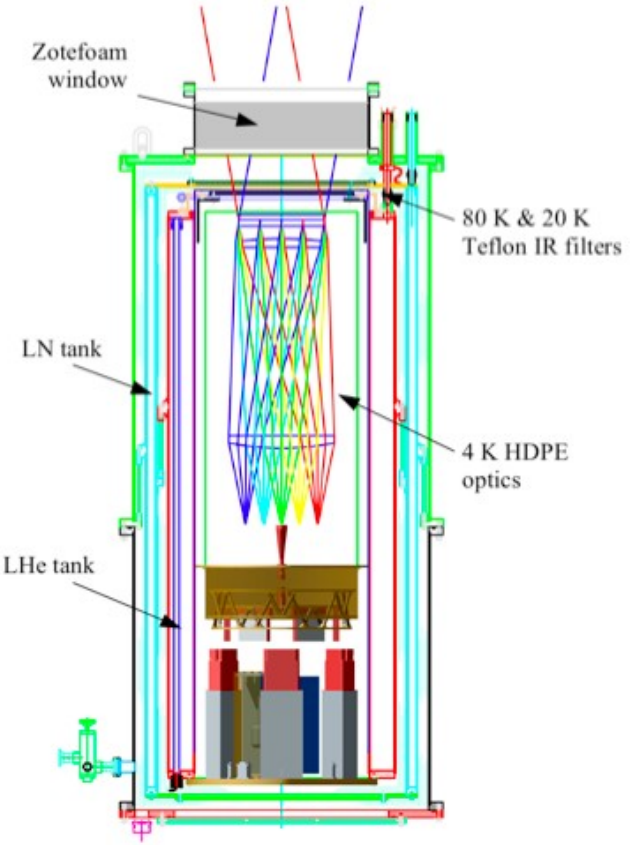
ASTR 6000

3/1/2012

It's **mostly** inside...

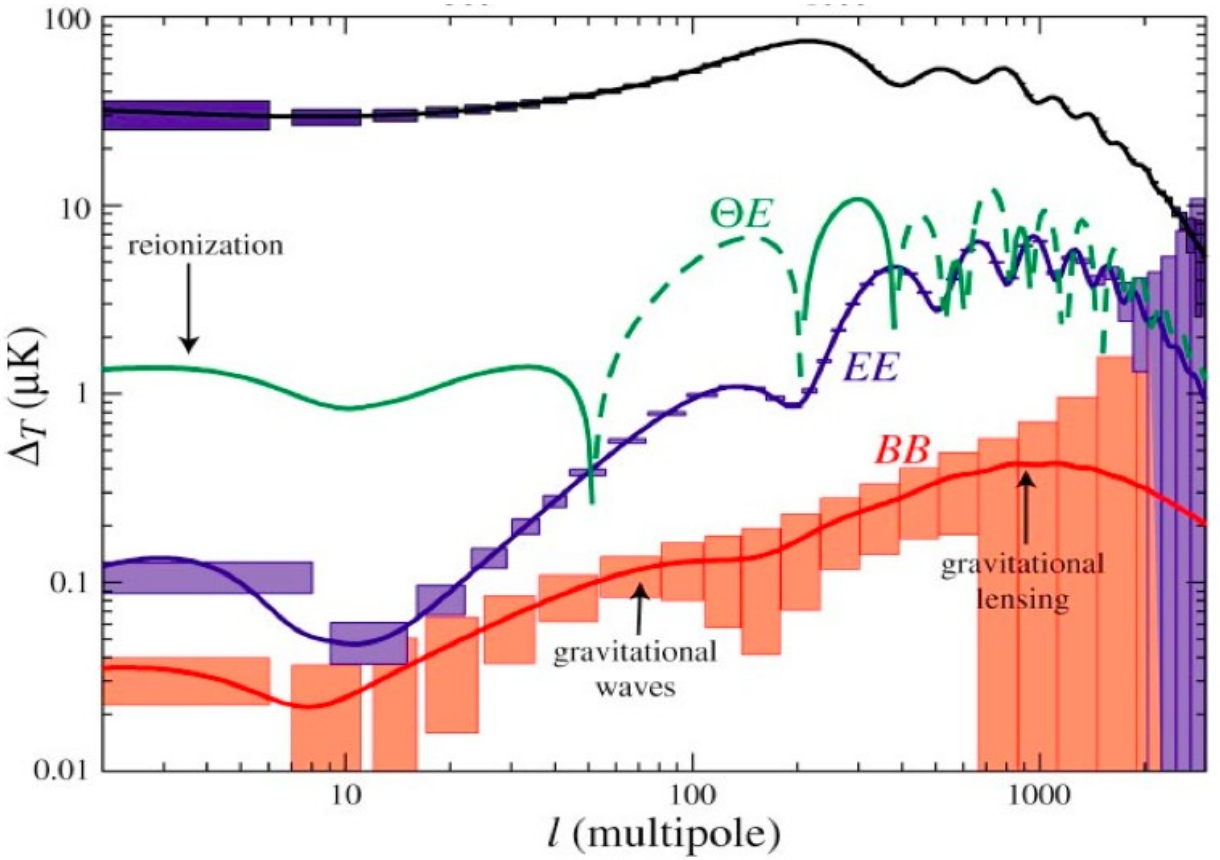
- Refractive optics (why?)
- Why not use a big mirror?





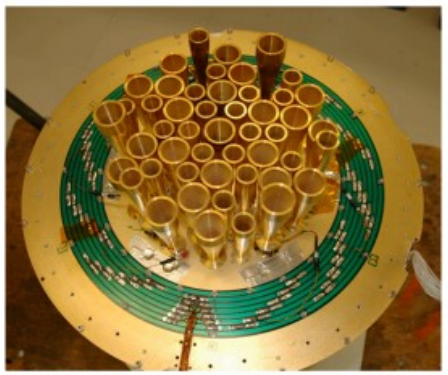
Science goals?

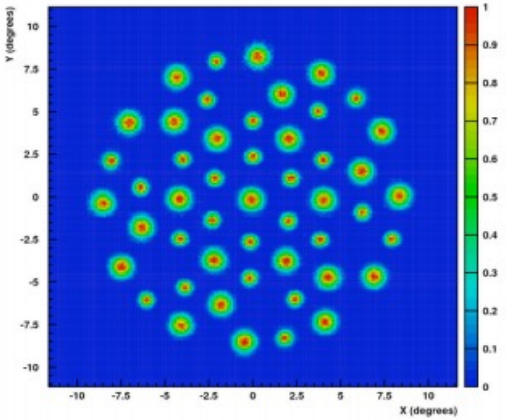
- Targeting degree angular scales for inflationary B modes
- (Remember:
  - Density perturbations at surface of last scattering → E modes
  - Gravitational lensing turns E modes → B modes at small scales
  - AND primordial gravitational waves (inflationary) → B modes at large scales)

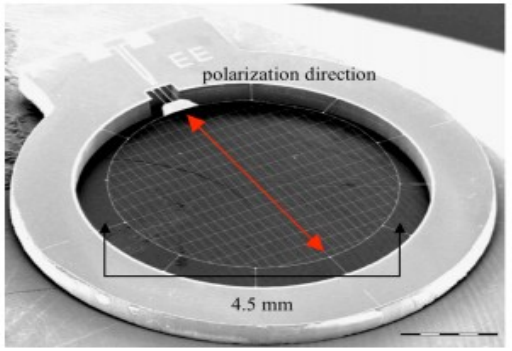


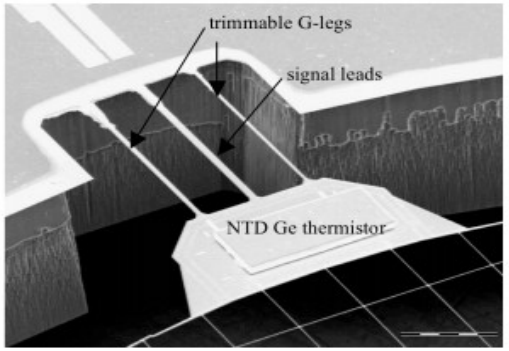
Instrument Characteristics

- 49 pairs of bolometers (PSBs)
- Two frequencies (100GHz, 150GHz)
- 0.93° (100GHz), and 0.60° (150GHz) ang resolution
- 18° instantaneous FOV
- az, el, and boresight degrees of freedom

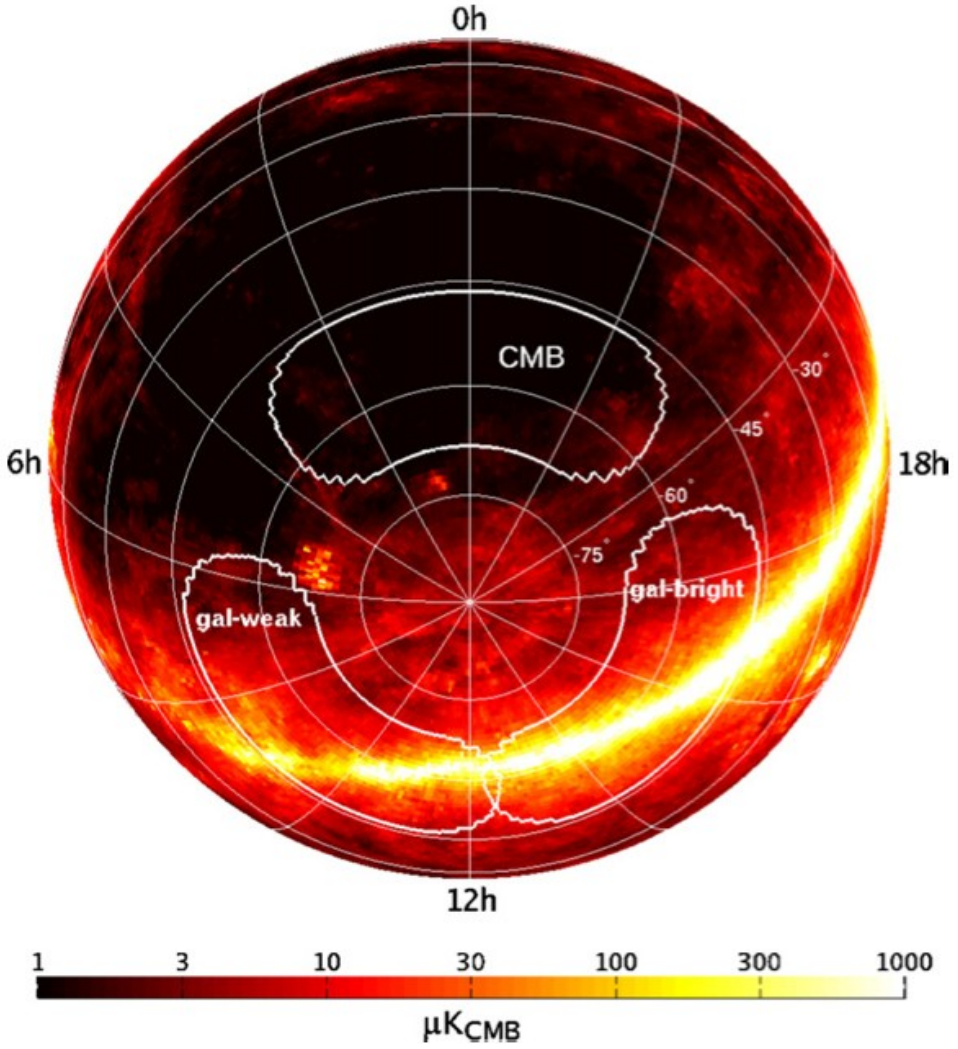








Observing Strategy



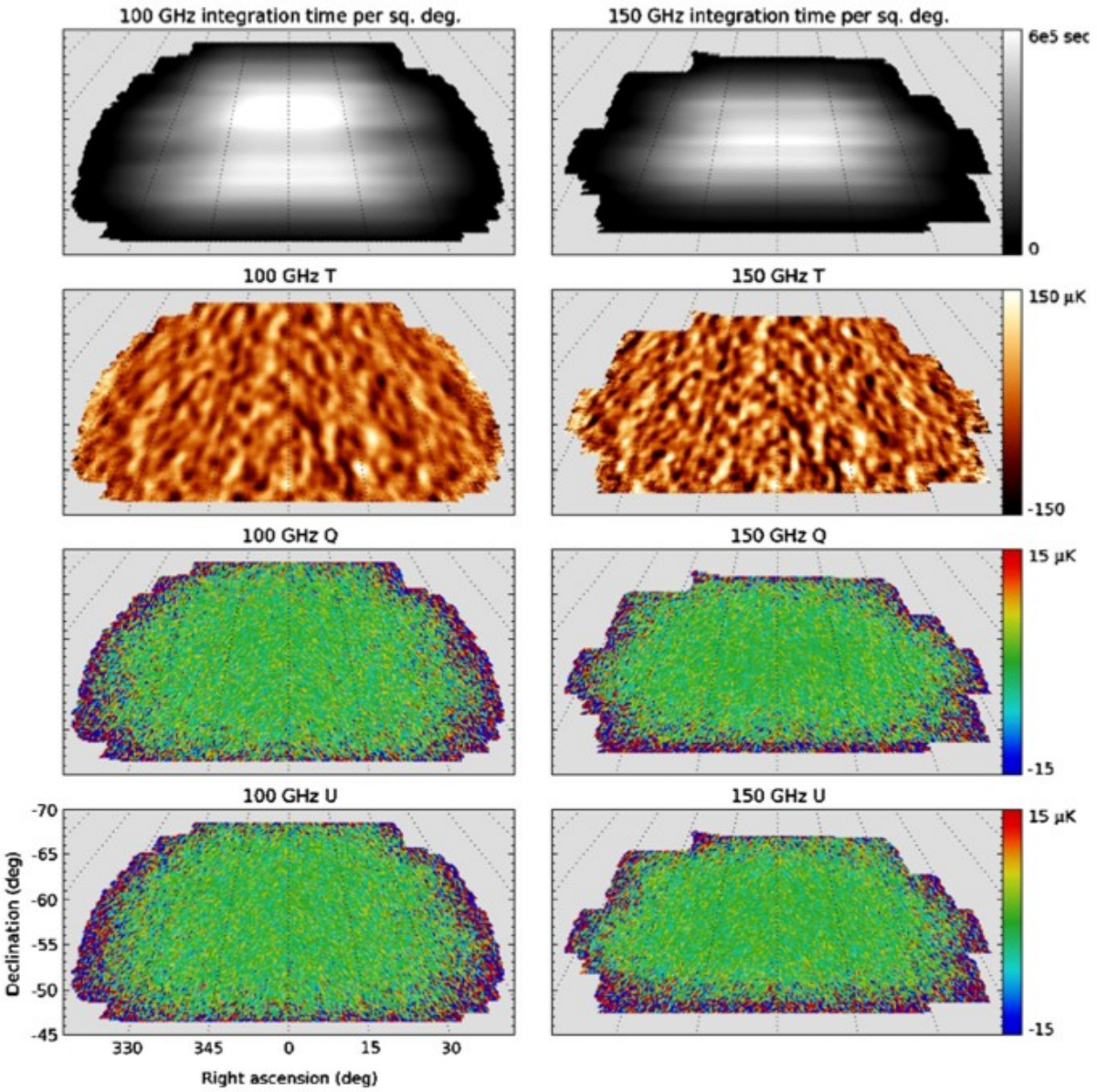
- Image 2% of the sky
- Az-El raster scans
- El nods at end of each scan in constant elevation
- CMB field covered twice per 48 hour cycle

timestream → (maps) → spectra

- 2 mapmaking pipelines

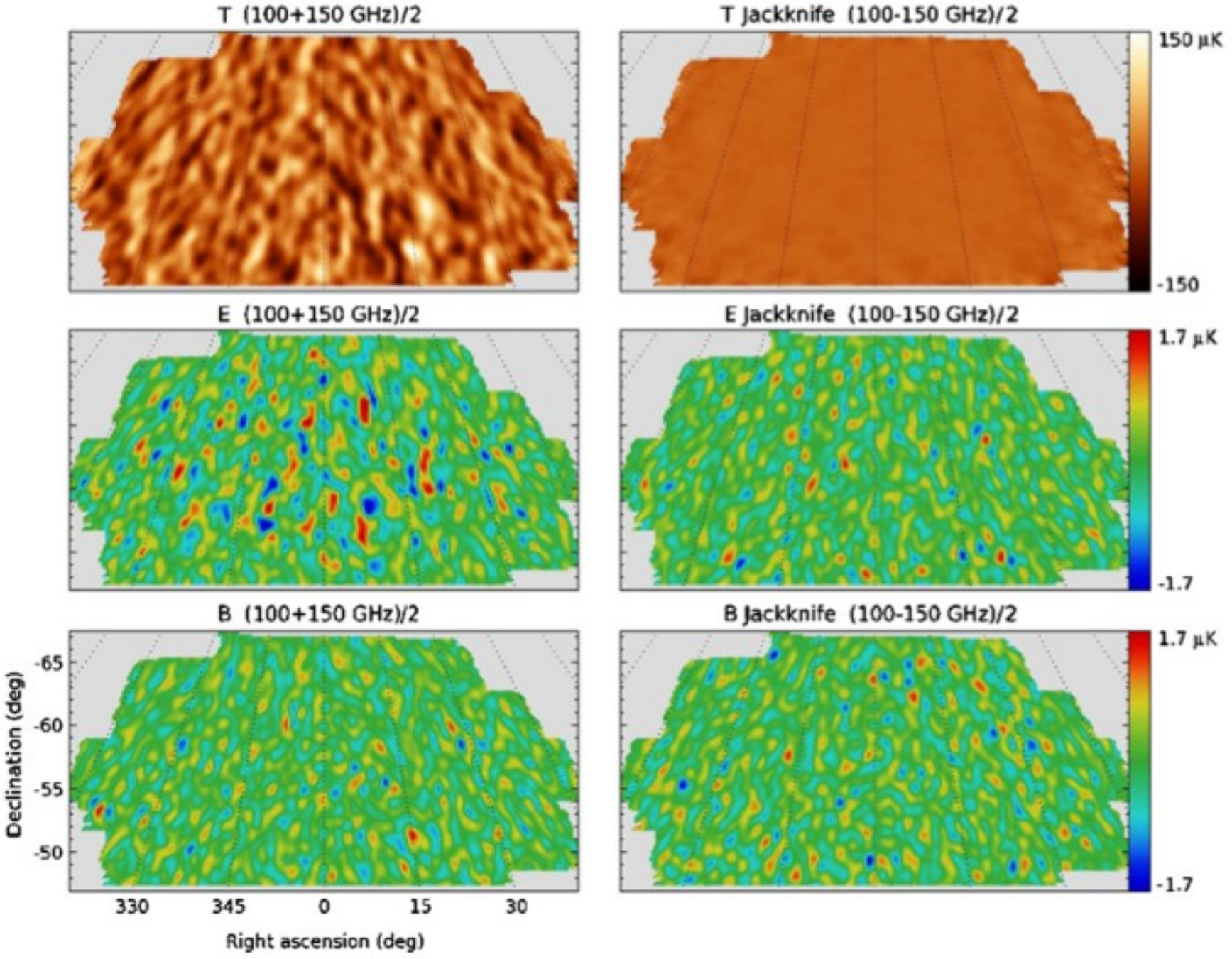
- Relative gains from El nods
- Absolute gains from WMAP

- T(p) = sum timestreams
- Q(p), U(p) = difference timestreams



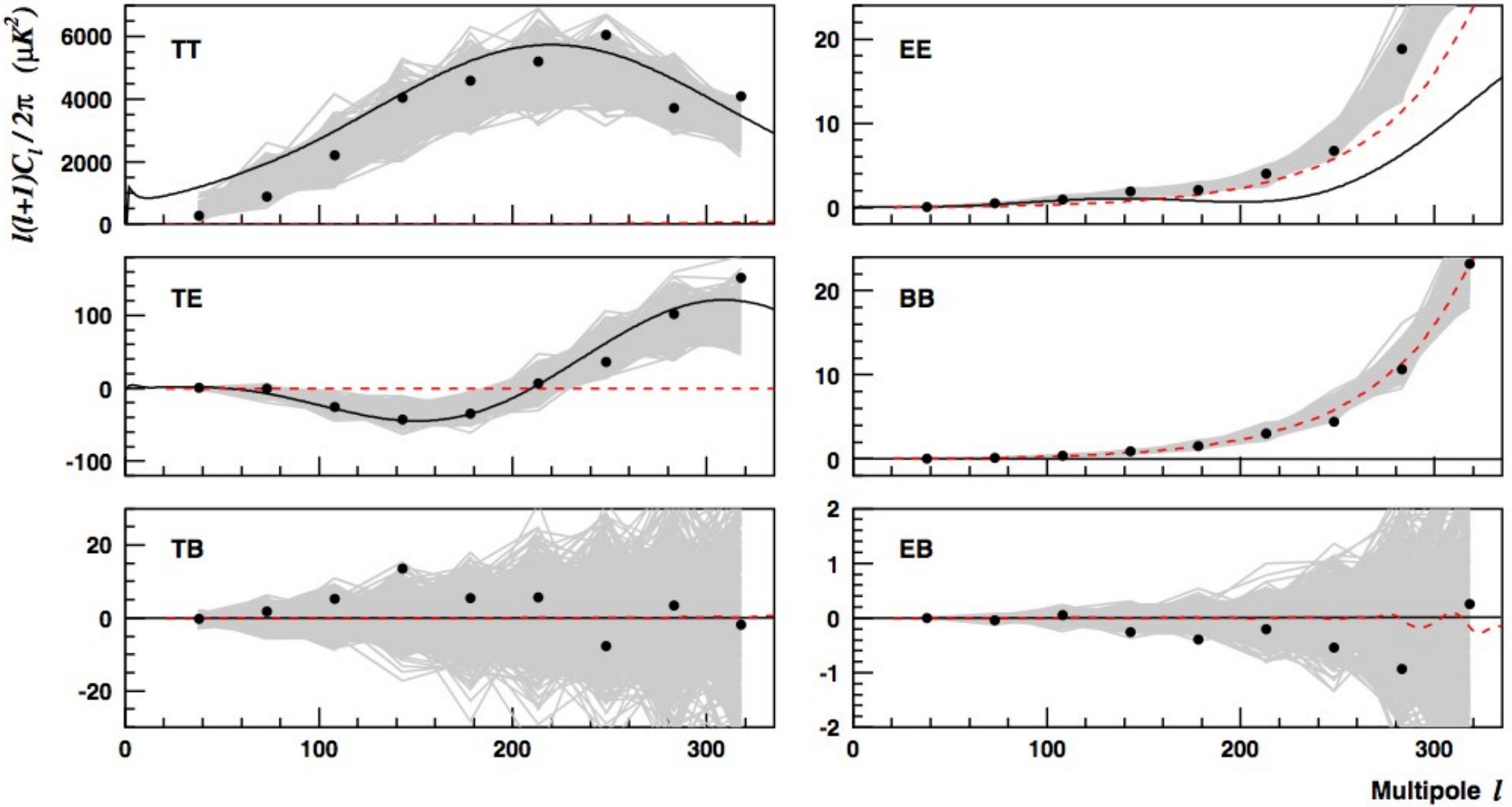
Noise per sq. deg in center of Q and U: 0.81 uK (100GHz) 0.64uK (150GHz)

Sum and Difference Maps: Everything looks good!



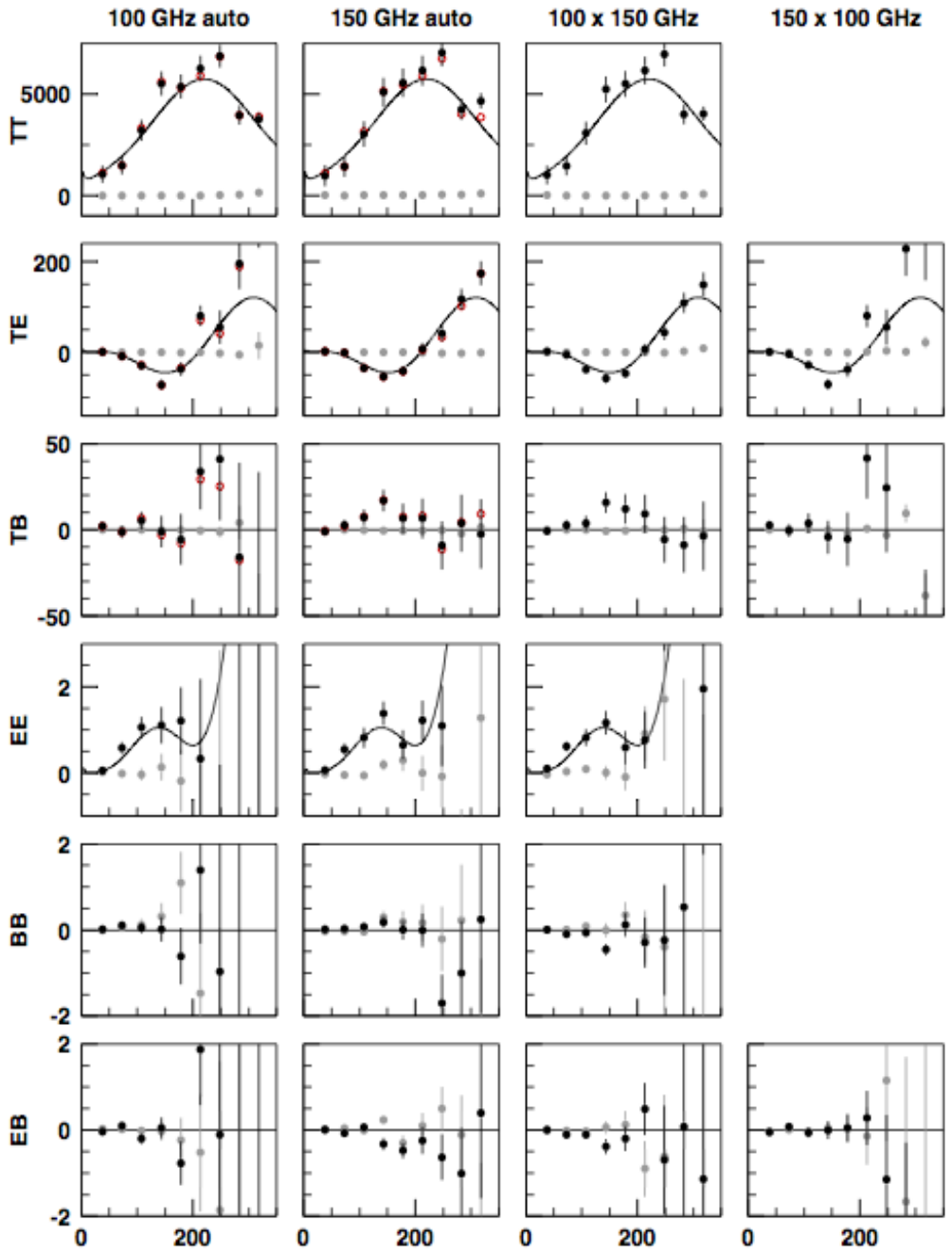
raw power spectra

- 2 pipelines
- Error bar estimates from 500 simulations of noise + signal
- Most of EE and all of BB are noise-dominated



- E → B leakage corrected with signal-only (r = 0) sims fed through analysis pipeline

final power spectra



- 9 band powers
- Width: $\Delta\ell = 35$
- Range: $21 \leqslant \ell \leqslant 335$
- Compare to:
  - ΛCDM model (WMAP 5, with r = 0) (black lines),
  - boresight angle pair jackknife (grey dots),
  - WMAP 5 temperature data, "BICEP-filtered" (open circles)
- TT, TE, EE detected with high significance
- Good agreement with WMAP
- No detection in TB, EB, BB
- What does good agreement with WMAP compared with model indicate?

jackknives

- Jackknives performed at mapmaking stage
- 6 varieties:
  - Scan direction (left and right)
  - Elevation coverage (top and bottom)
  - Boresight orientation angle

    ({-45°, 0°}, {135°, 180°})
  - Temporal (early cycle, late cycle)
  - Season split (first season, second season)
  - Focal plane QU

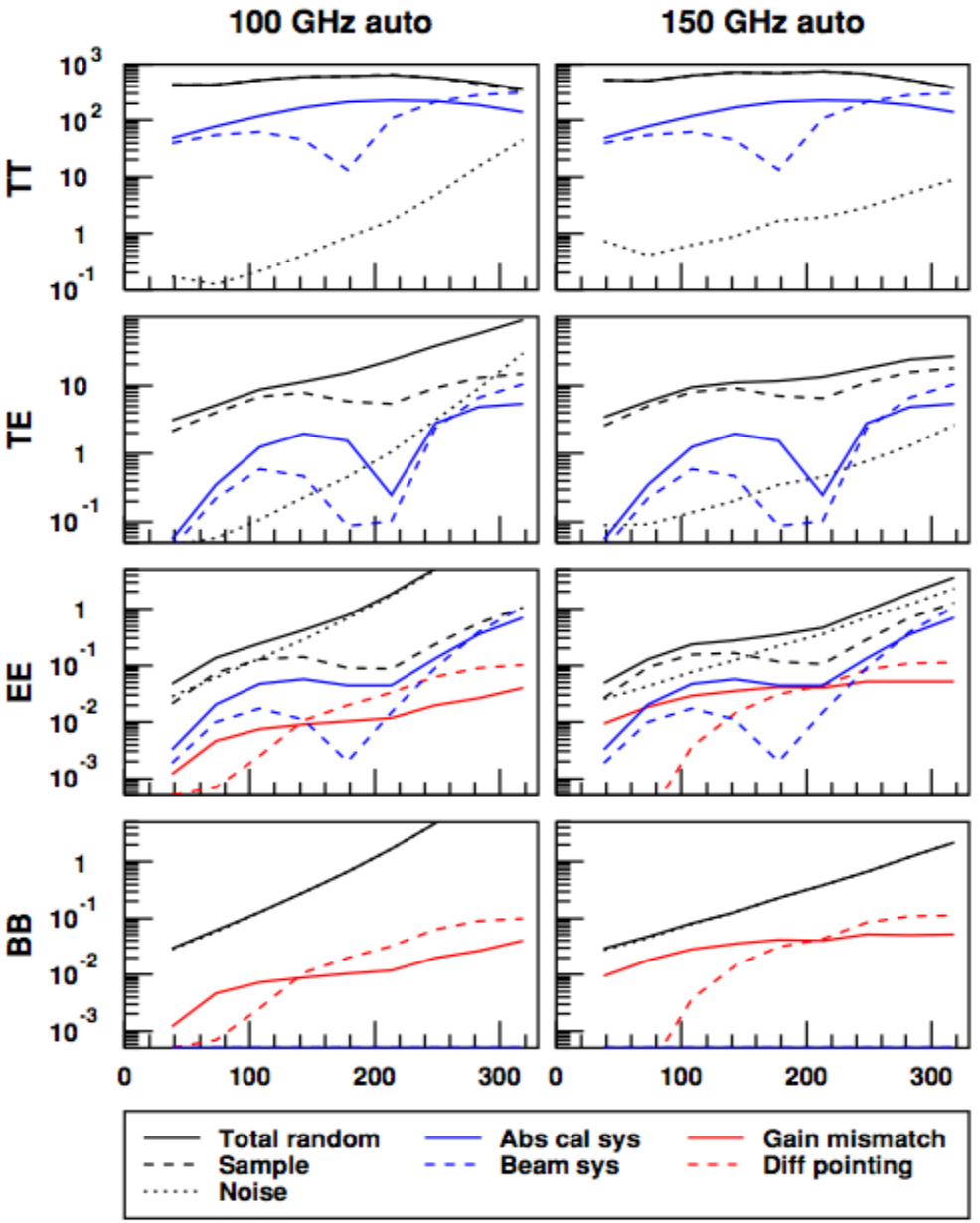
    (Q pol, U pol detector orientation)
- Calculate χ^2 and PTE (from sims)
- Victory = PTEs are not too high nor too low, uniform distribution of PTEs
- Polarization jackknives all pass!
- Temperature jackknives all fail! (so don't publish...)

Table 1
Jackknife PTE Values from χ^2 Tests

Jackknife	100 GHz	150 GHz	100 × 150	150 × 100
Scan direction				
EE	0.532	0.588	0.740	
BB	0.640	0.568	0.212	
EB	0.816	0.962	0.924	0.358
Elevation coverage				
EE	0.576	0.546	0.924	
BB	0.584	0.288	0.618	
EB	0.872	0.728	0.892	0.892
Boresight angle				
EE	0.916	0.448	0.320	
BB	0.242	0.548	0.592	
EB	0.912	0.100	0.392	0.944
Temporal split				
EE	0.378	0.208	0.796	
BB	0.788	0.020	0.852	
EB	0.370	0.580	0.476	0.232
Season split				
EE	0.564	0.716	0.216	
BB	0.790	0.992	0.056	
EB	0.806	0.514	0.456	0.986
Focal plane *QU*				
EE	0.670	0.014	0.994	
BB	0.896	0.804	0.576	
EB	0.236	0.806	0.234	0.560

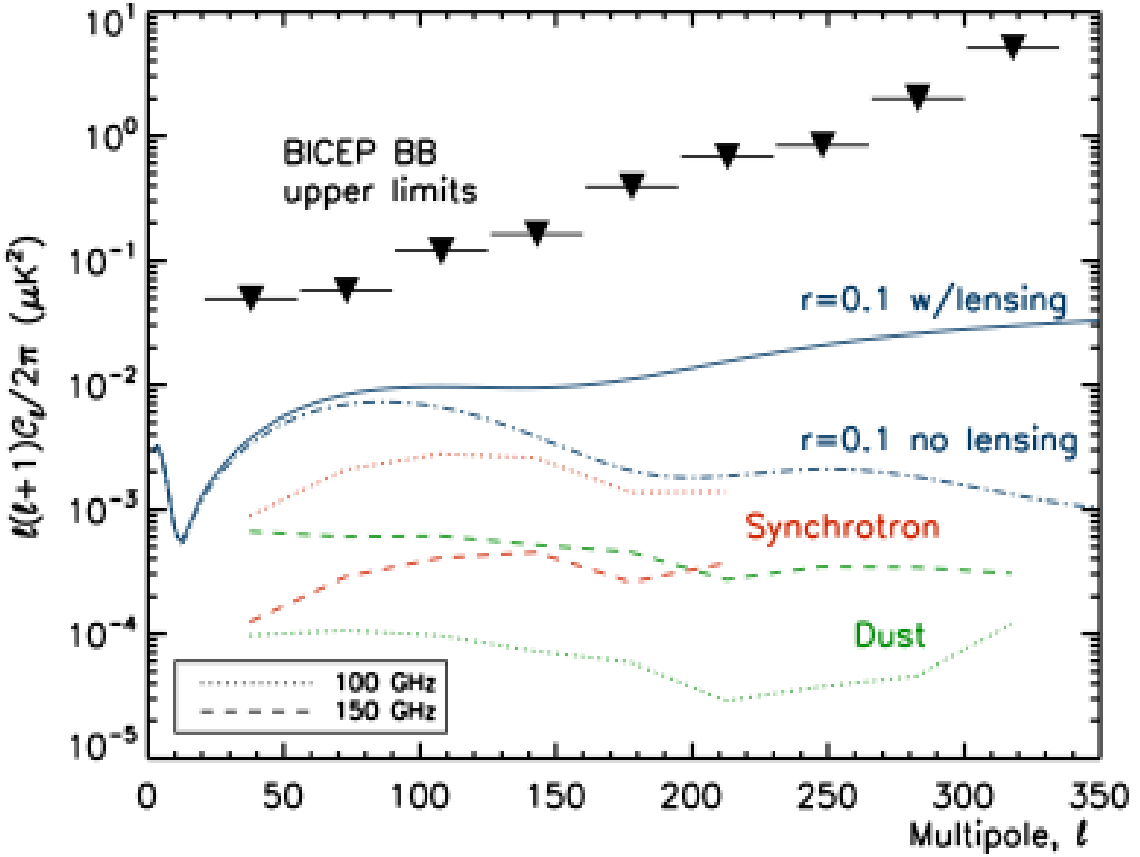
systematic uncertainties

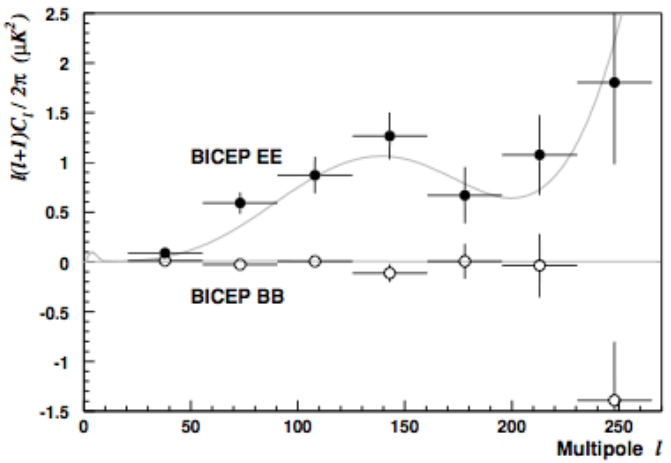
- Two types:
  - Temp-polarization mixing
  - Calibration errors
- TT dominated by sample noise
- EE mostly dominated by instrument noise
- BB dominated by instrument noise... where is sample variance?)



Wait... why are there multiple frequencies?

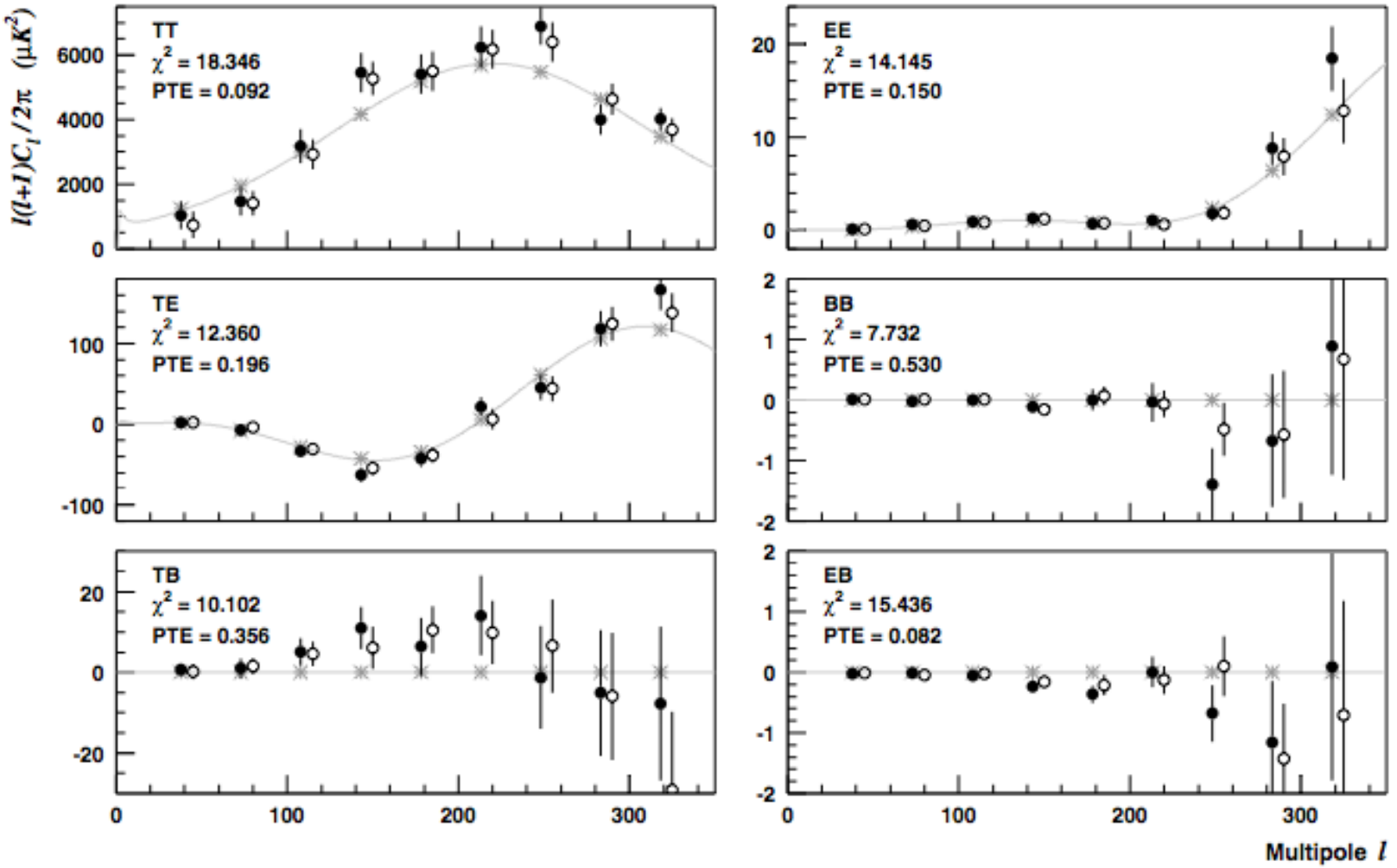
- Normally multiple frequencies are used to constrain foregrounds...



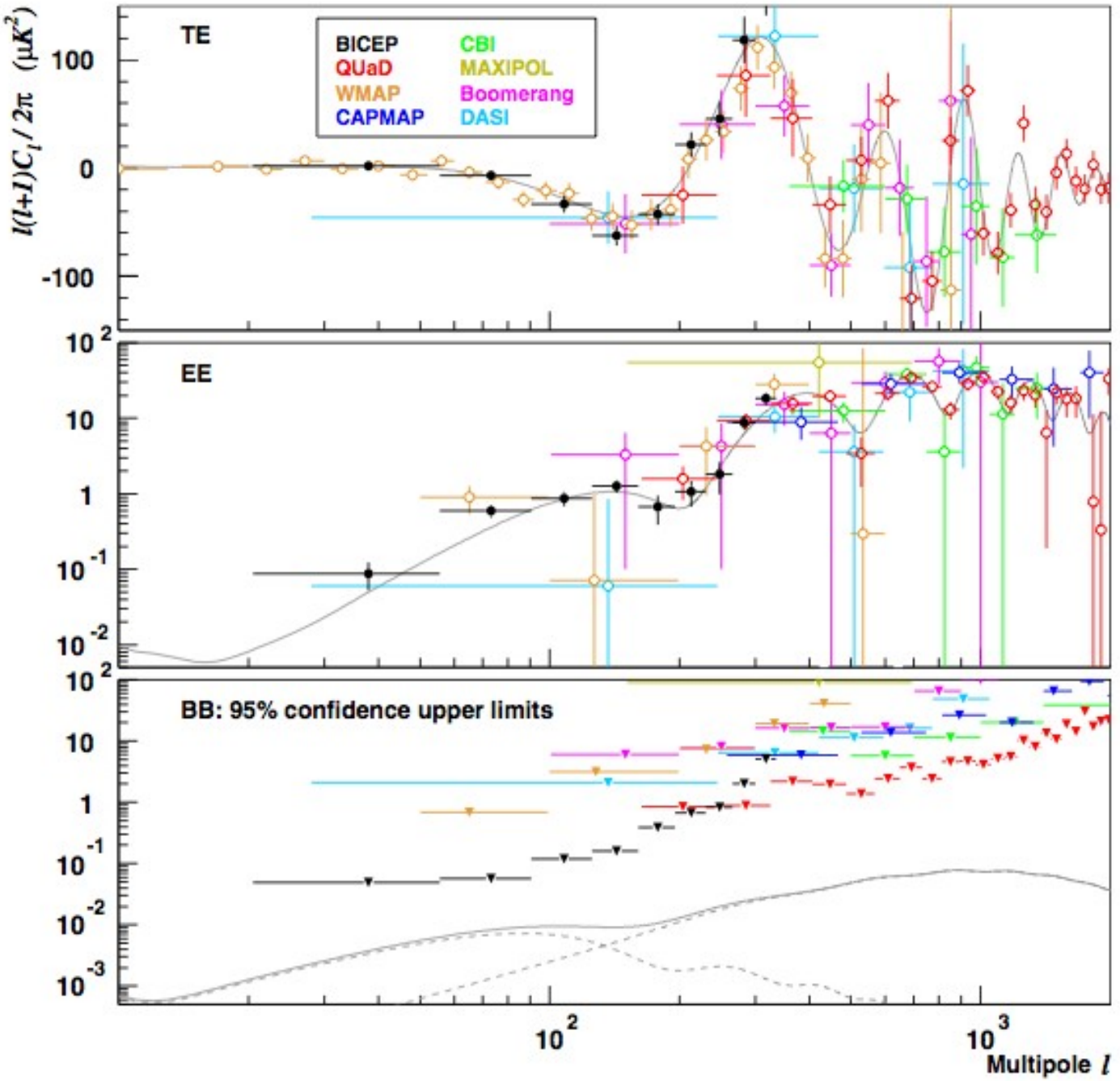


combine all the spectra!

- Multiple pipelines
- Comparison with 6-param ΛCDM



comparison to other projects



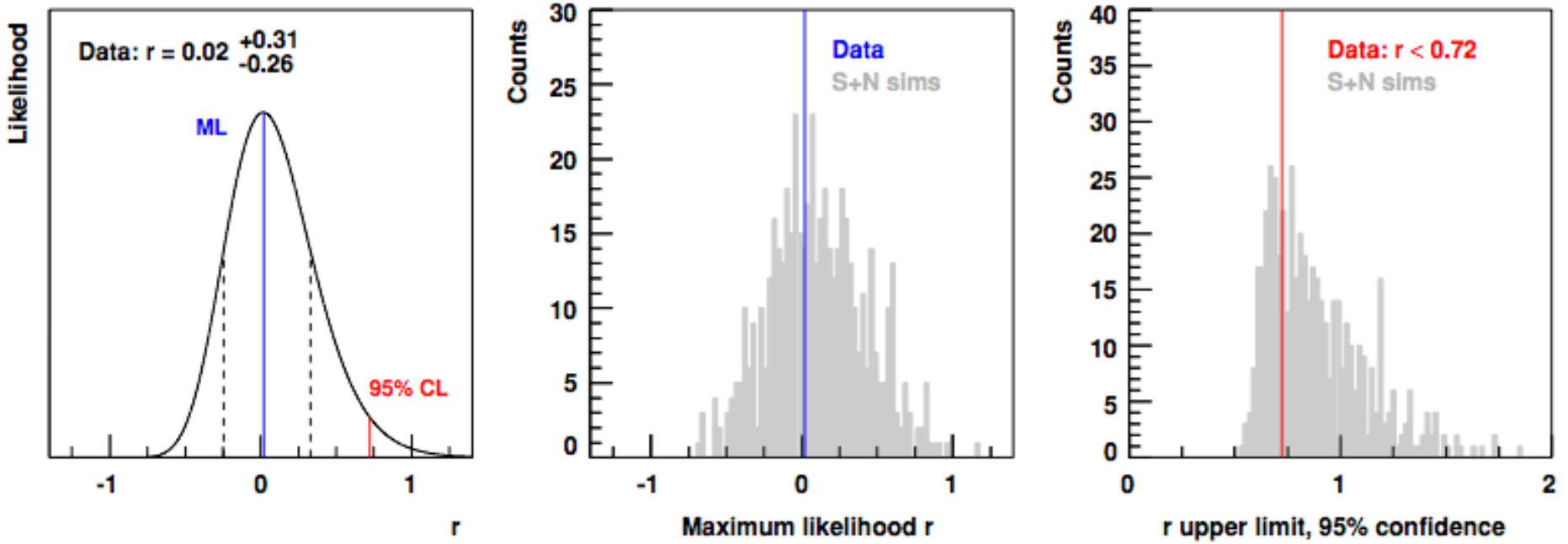
quantifying B modes vs E modes: r

- Tensor-to-scalar ratio: $r = \frac{\text{amplitude of gravitational waves}}{\text{amplitude of curvature perturbations}}$

- Max likelihood value from BICEP: $r = 0.02\ ^{+0.31}_{-0.26}$
- Integrating positive likelihood to 95%: $r < 0.72$

- Current tightest constraint from WMAP 5-year TT (+ SN Ia + BAO):

  $r < 0.22$ at 95% confidence (but using only BB data: $r < 6$)



How to improve in the future?

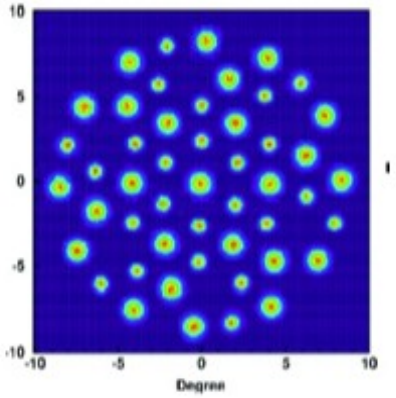
- More pixels?
- More sky area?
- More frequencies? Fewer frequencies?

Future?

Exponential increase in sensitivity

BICEP1

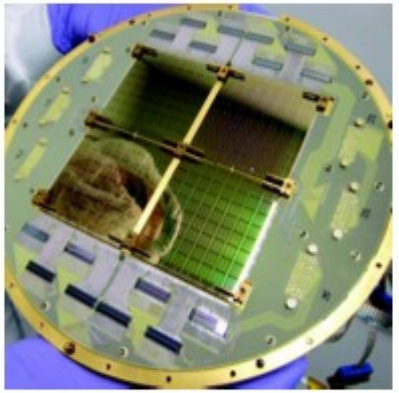
Completed 3 yrs. of observation in Nov. 2008

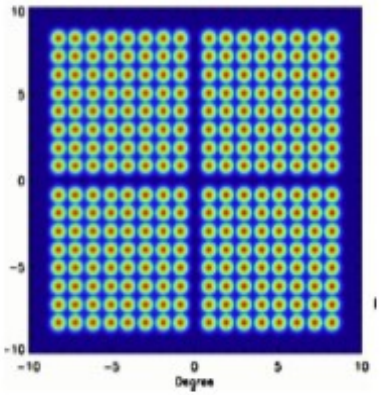


48 detectors @ 150 GHz

BICEP2

Deployed Nov. 2009, currently observing!

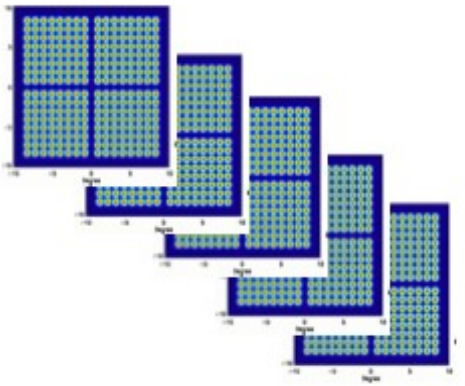




512 detectors @ 150 GHz
JPL antenna-coupled TES arrays

Keck array

Deploying x3 in Nov. 2010, with 2 more in Nov. 2011

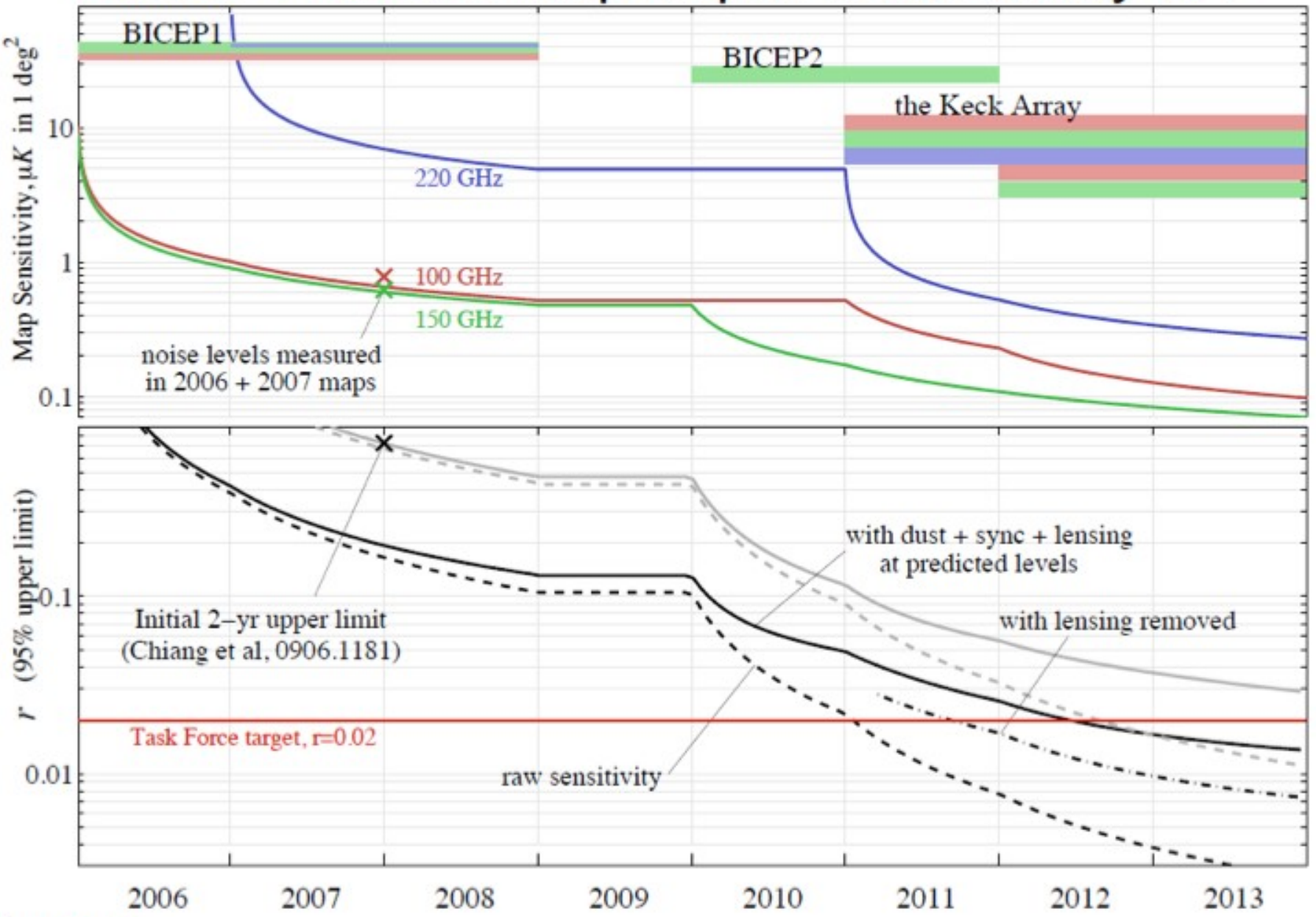


3 x 512 detectors @ 150 GHz
2 x 512 @ 100/220 GHz

Chris Sheehy, 2010

Expectations for BICEP2 and Keck

BICEP / Keck : map depth & sensitivity to *r*



John Kovac