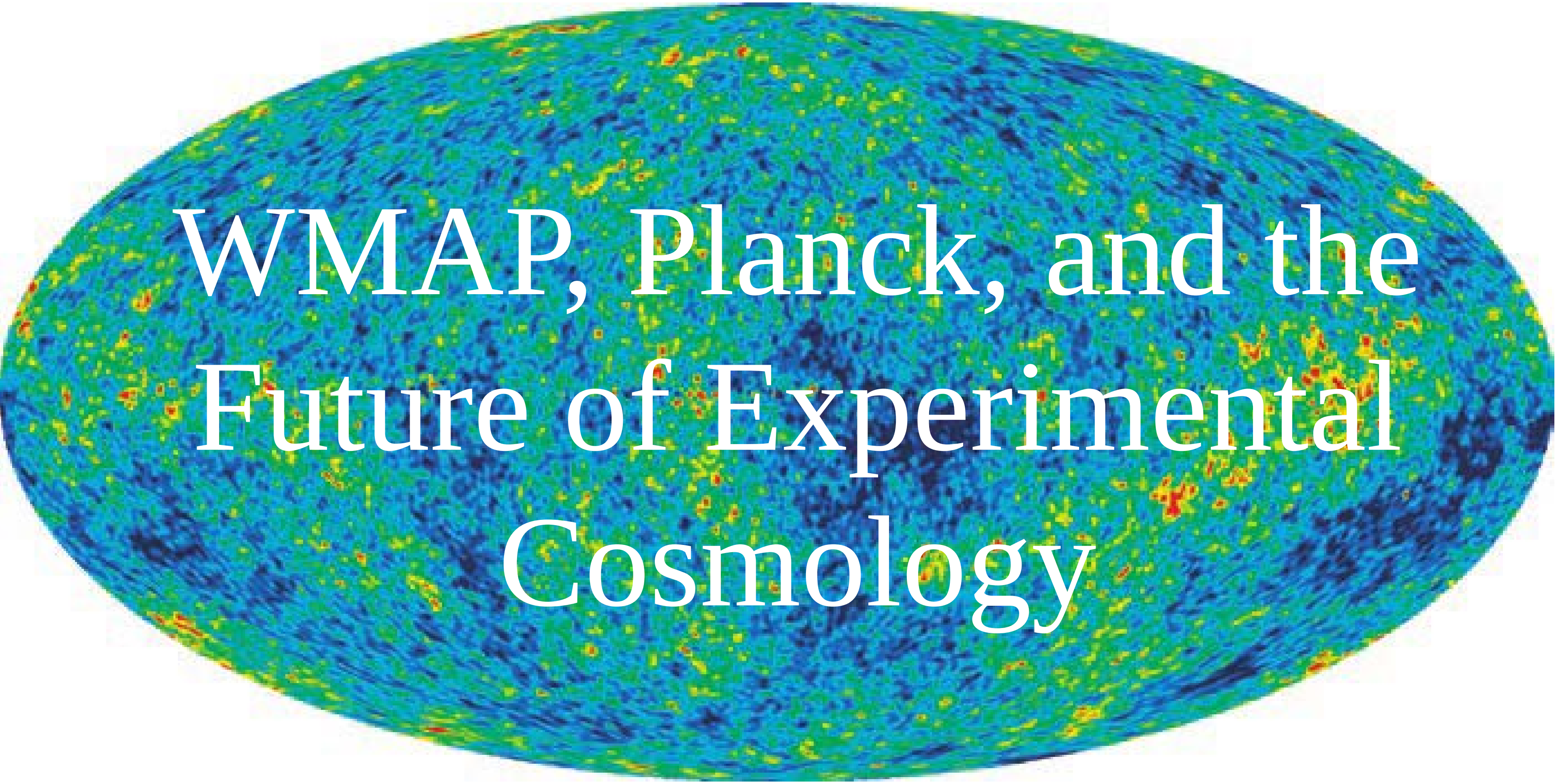
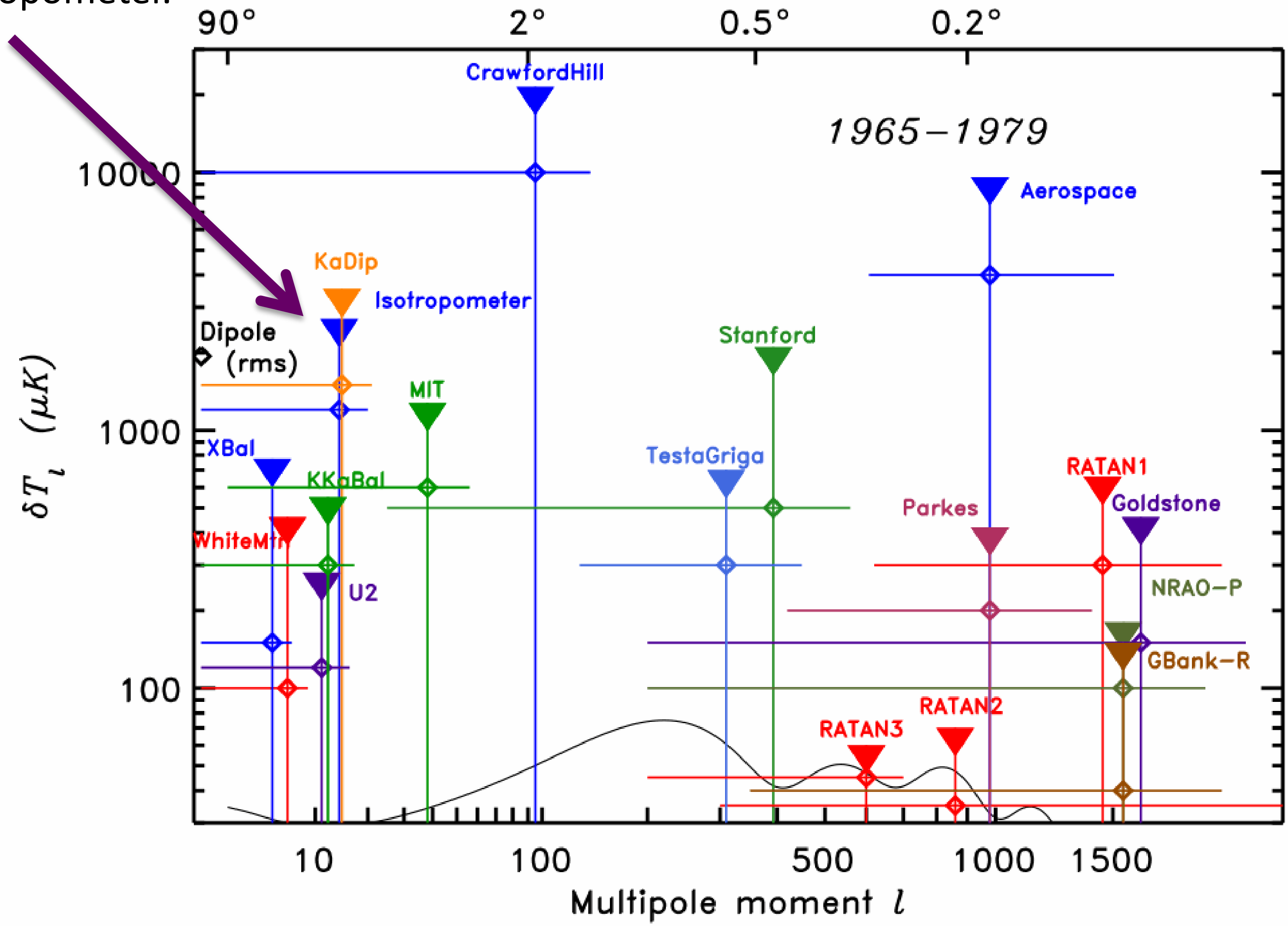
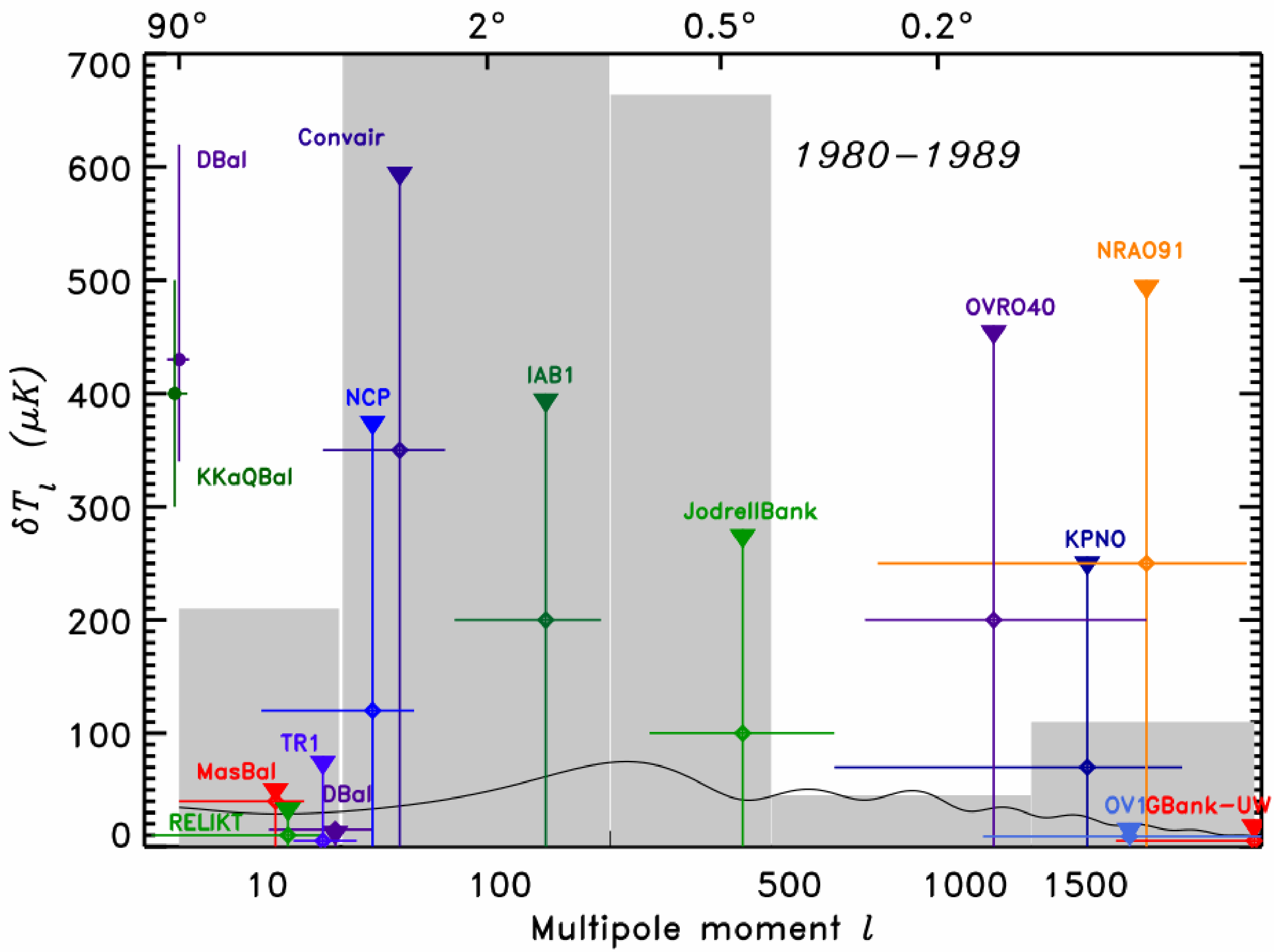


WMAP, Planck, and the Future of Experimental Cosmology

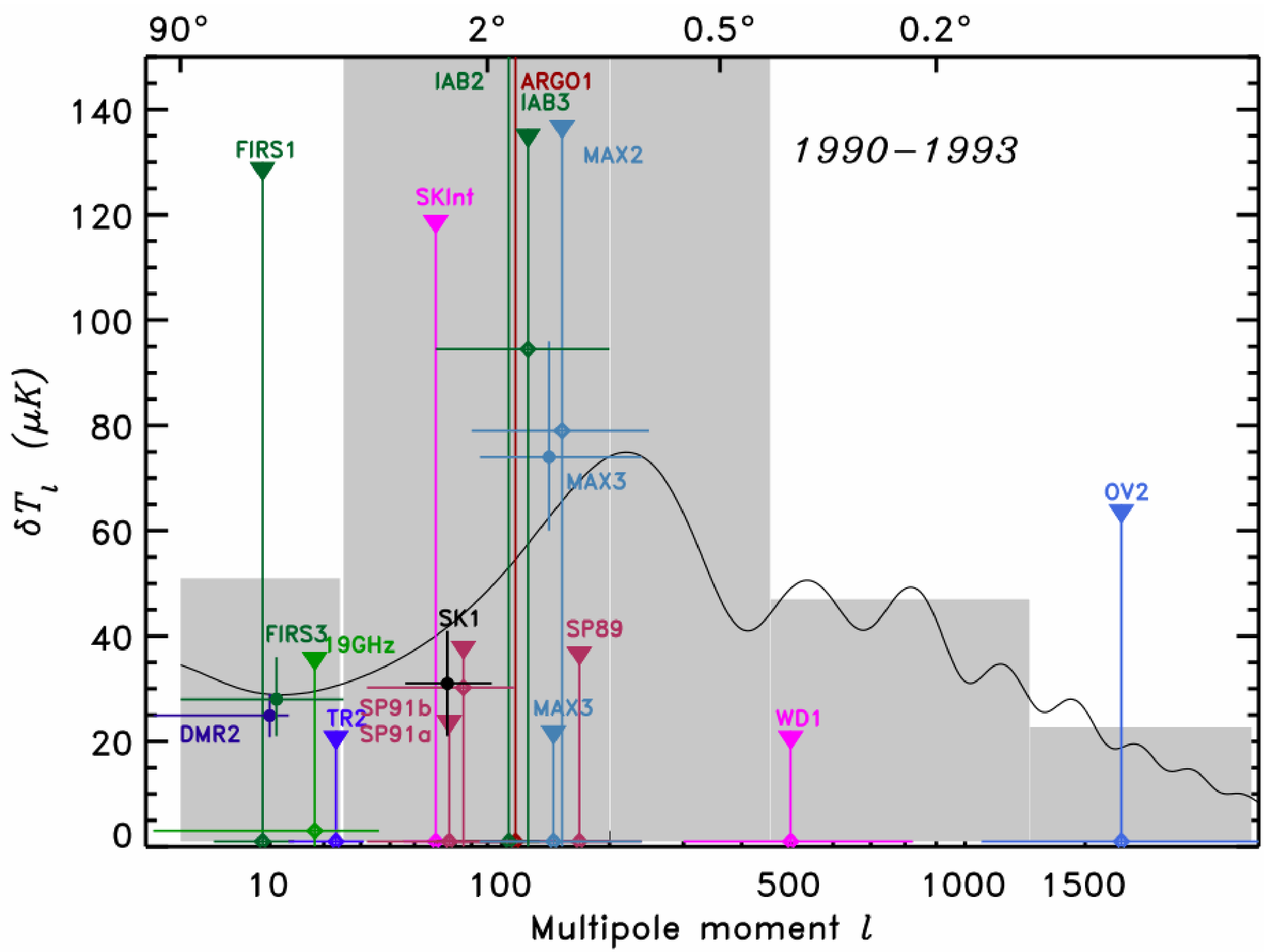
L. Page ESLAB April 2013

The beginning: Partridge and Wilkinson, dedicated "Isotropometer."

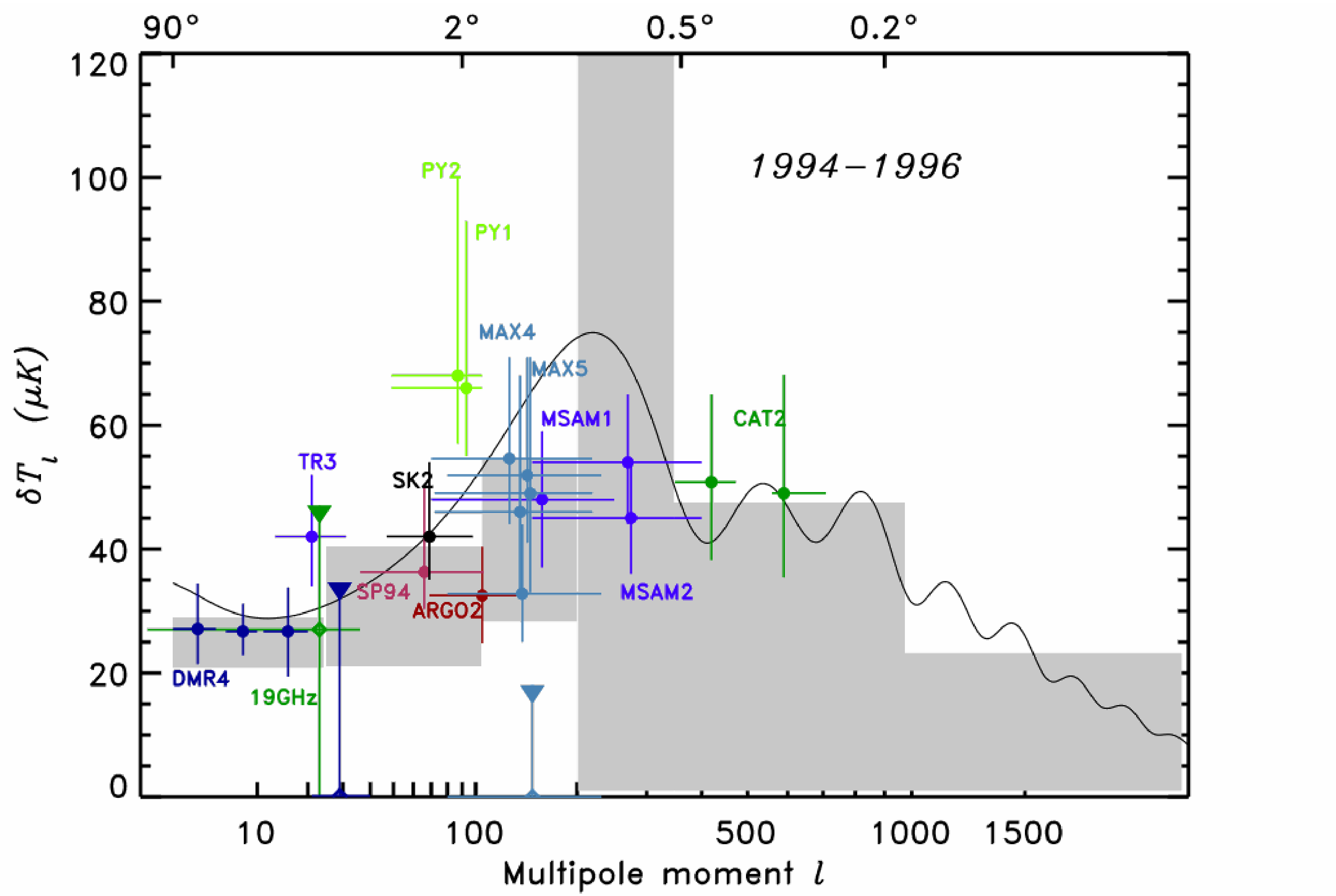




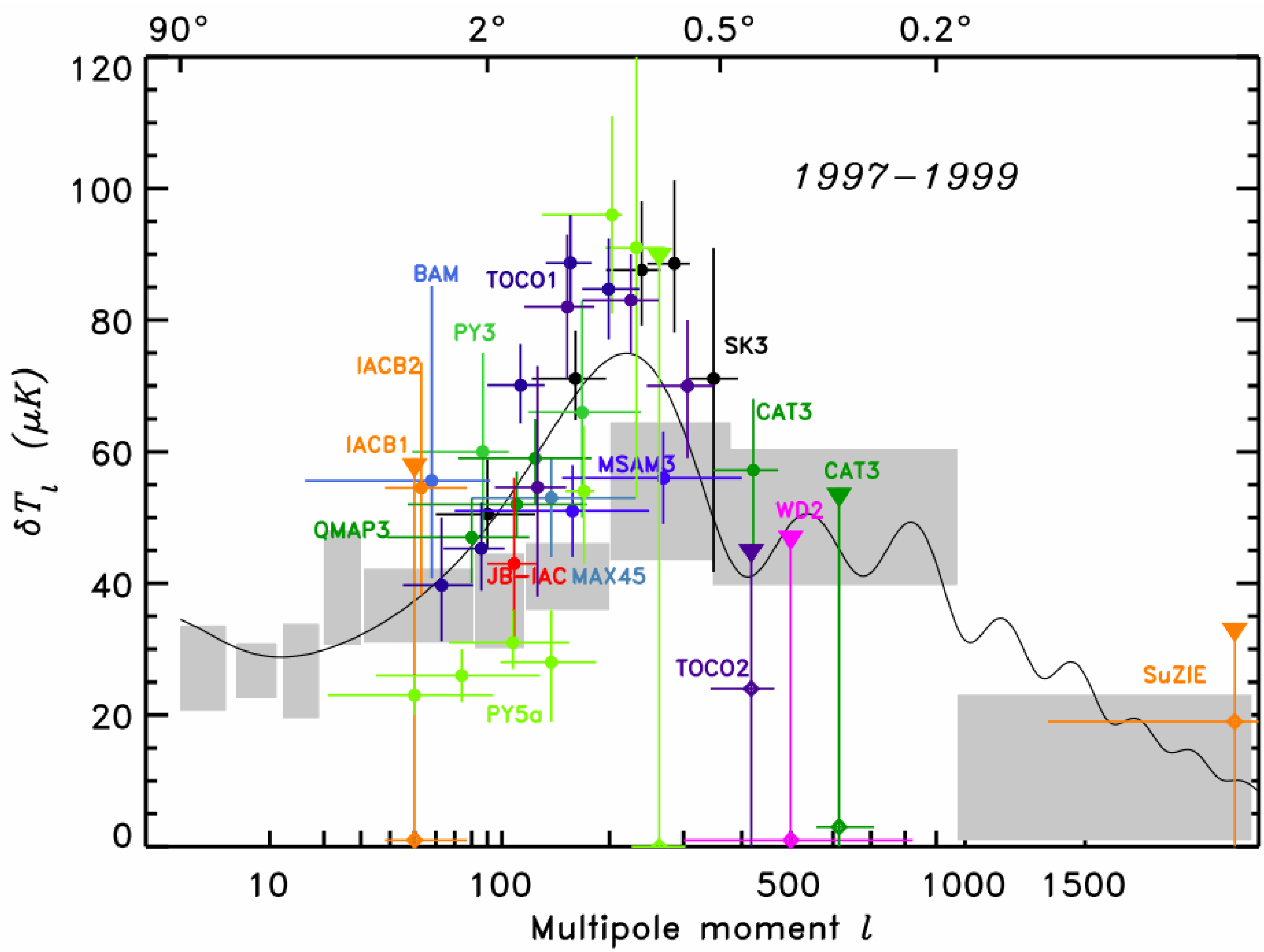
90°
2°
0.5°
0.2°
1980–1989
DBal
Convair
NCP
IAB1
KKaQBal
JodrellBank
OVRO40
NRAO91
KPNO
TR1
MasBal
DBal
RELIKT
OV1
GBank-UW
δT_l (μK)
Multipole moment l
0
100
200
300
400
500
600
700
10
100
500
1000
1500



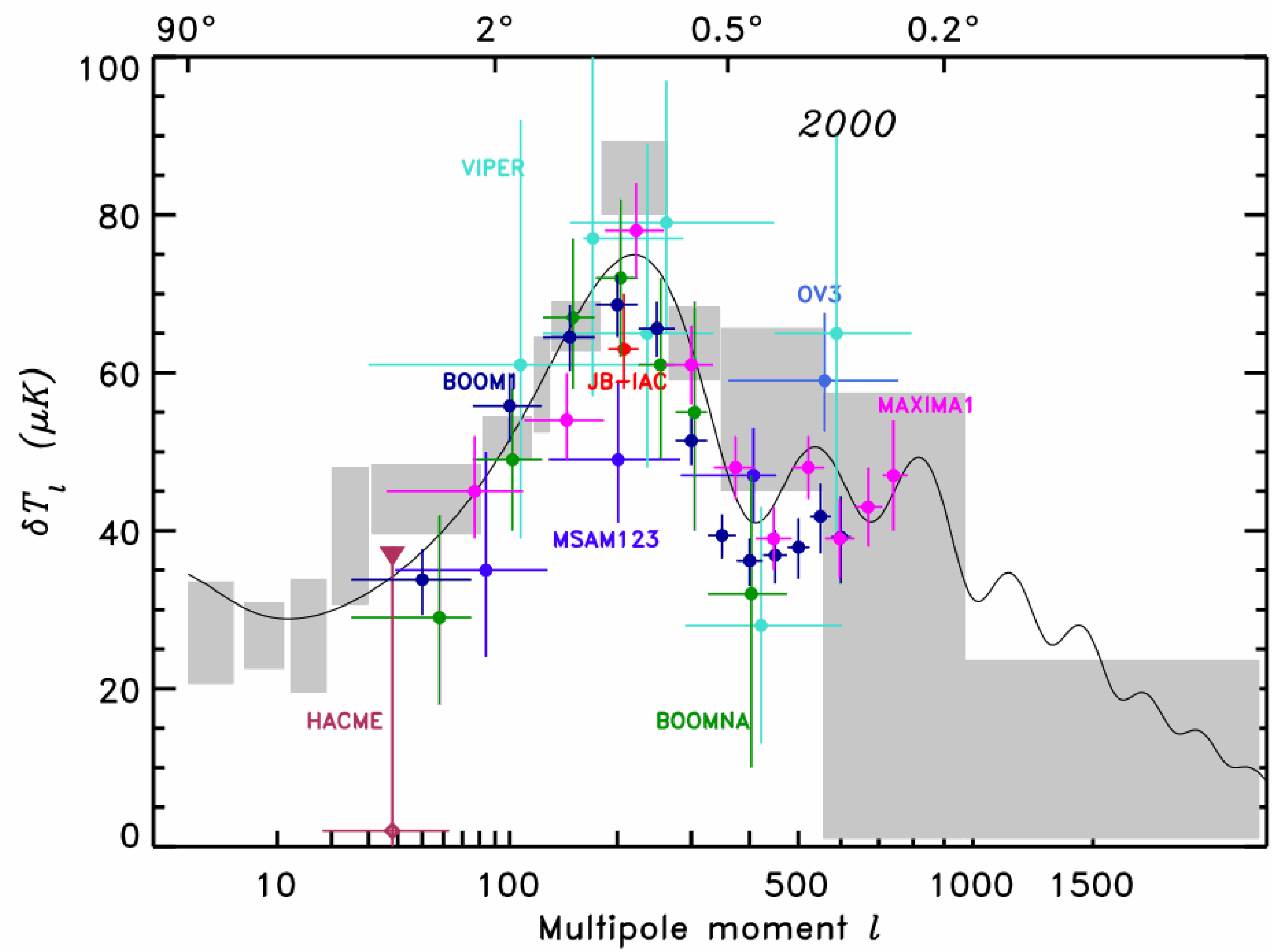
90°
2°
0.5°
0.2°
1990–1993
IAB2
ARGO1
IAB3
MAX2
FIRS1
SKInt
MAX3
OV2
SK1
SP89
FIRS3
19GHz
SP91b
SP91a
MAX3
TR2
DMR2
WD1
140
120
100
80
60
40
20
0
δT_l (μK)
10
100
500
1000
1500
Multipole moment l



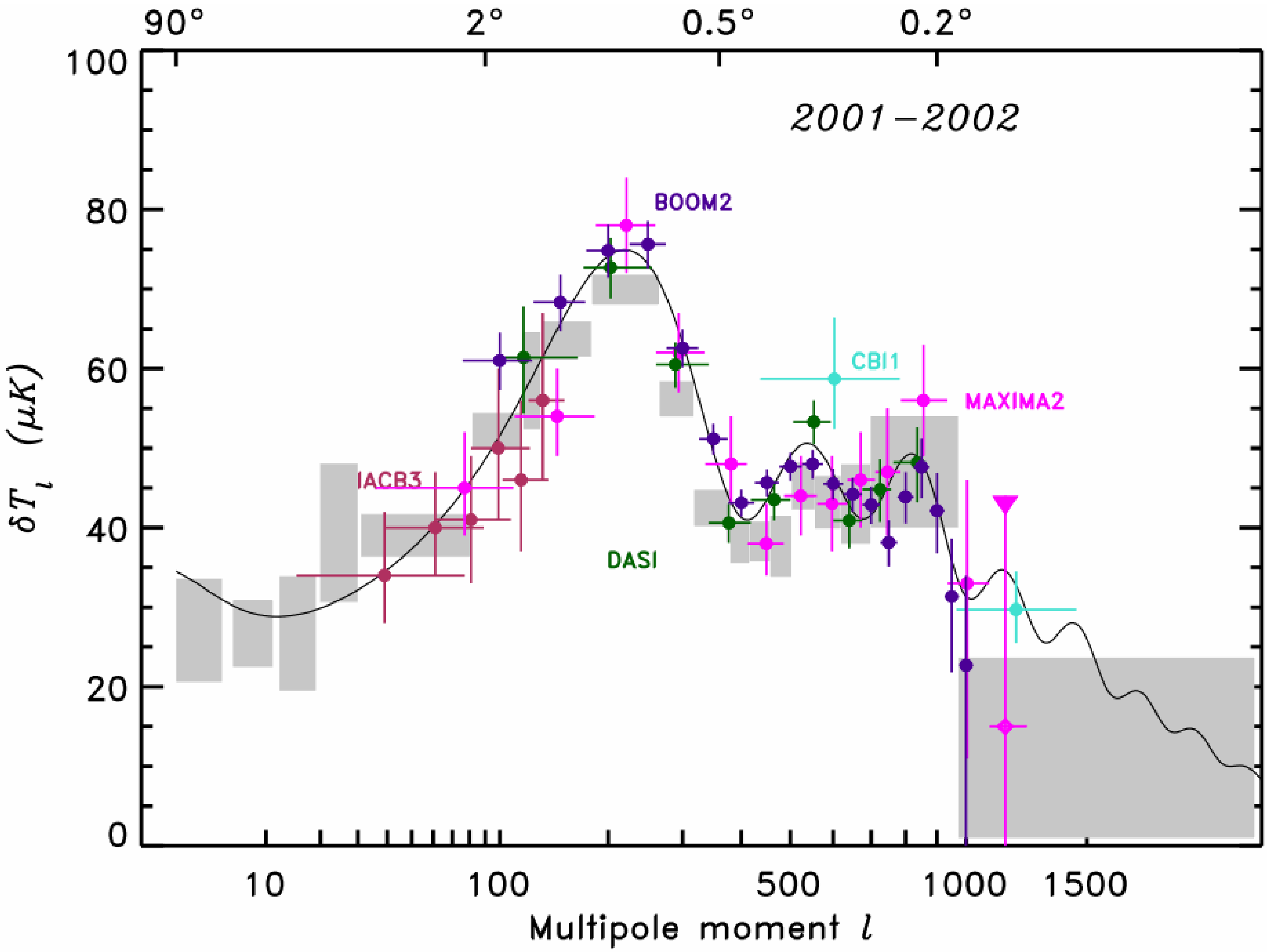
90°
2°
0.5°
0.2°
1994–1996
PY2
PY1
MAX4
MAX5
MSAM1
CAT2
TR3
SK2
SP94
ARGO2
MSAM2
DMR4
19GHz
δT_l (μK)
120
100
80
60
40
20
0
10
100
500
1000
1500
Multipole moment l



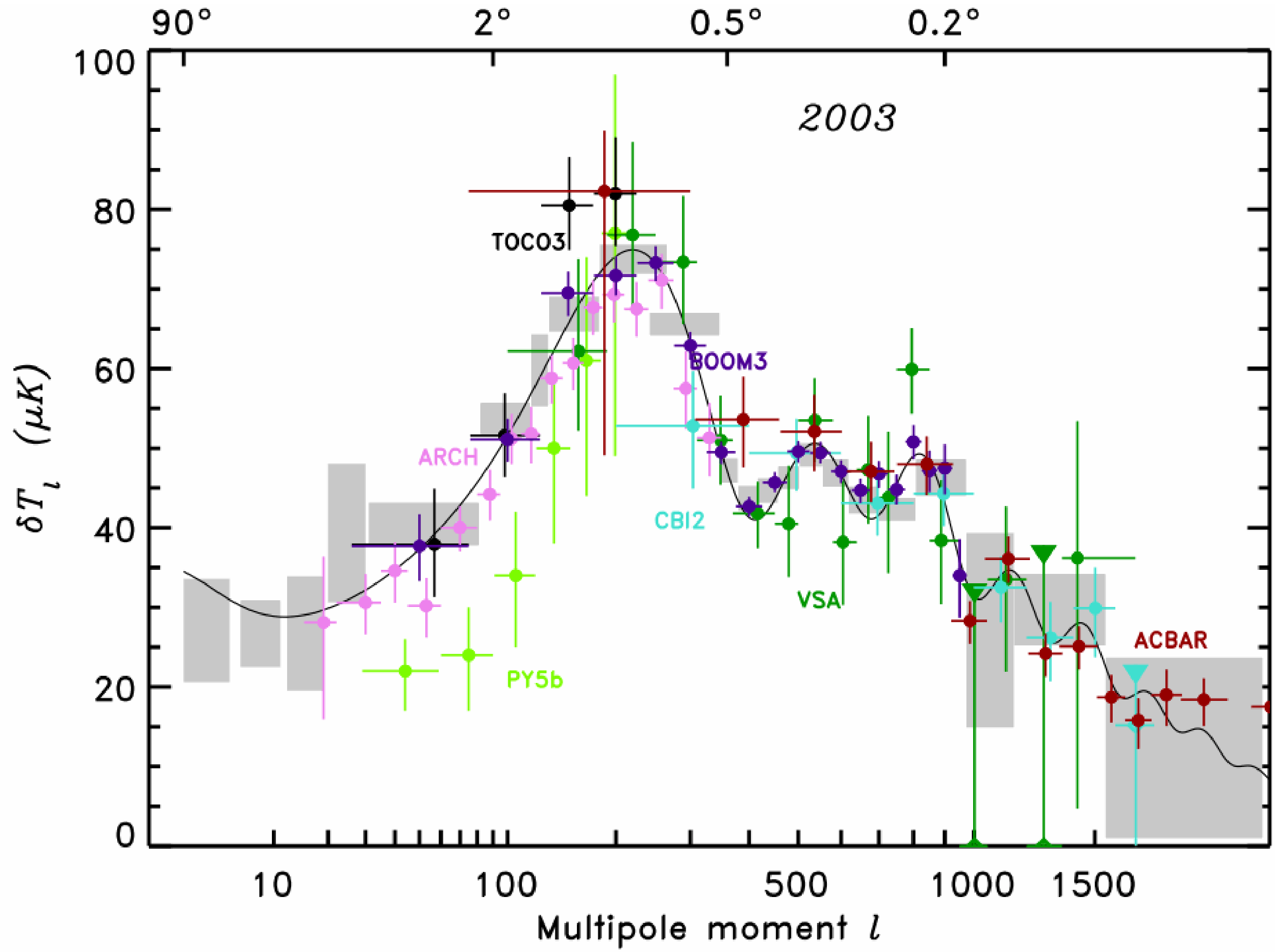
90°
2°
0.5°
0.2°
1997–1999
BAM
TOCO1
PY3
IACB2
SK3
CAT3
IACB1
MSAM3
CAT3
WD2
QMAP3
JB–IAC
MAX45
TOCO2
SuZIE
PY5a
δT_l (μK)
Multipole moment l
120
100
80
60
40
20
0
10
100
500
1000
1500



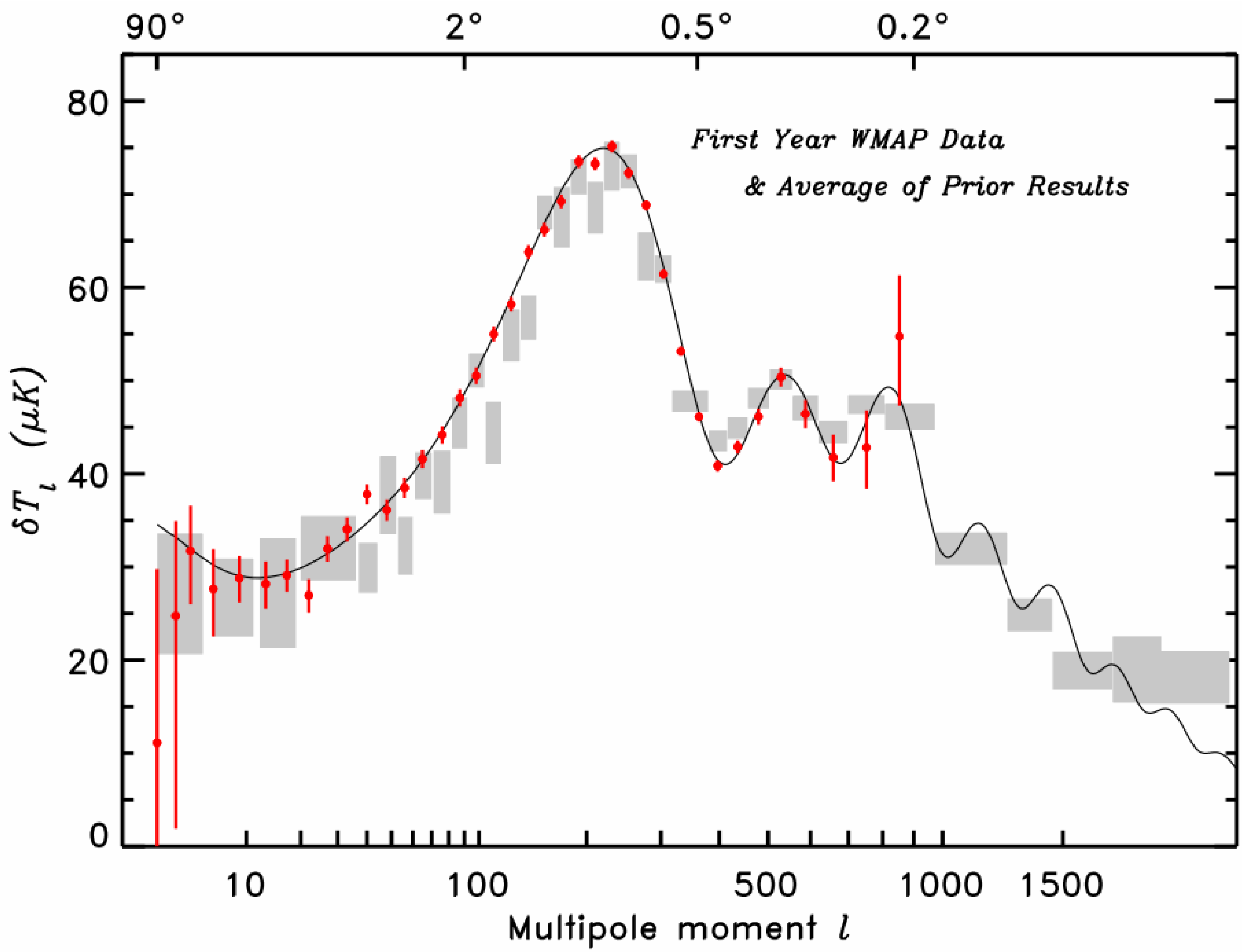
90°
2°
0.5°
0.2°
100
80
60
40
20
0
2000
VIPER
OV3
BOOM1
JB+IAC
MAXIMA1
MSAM123
HACME
BOOMNA
δT_l (μK)
10
100
500
1000
1500
Multipole moment l



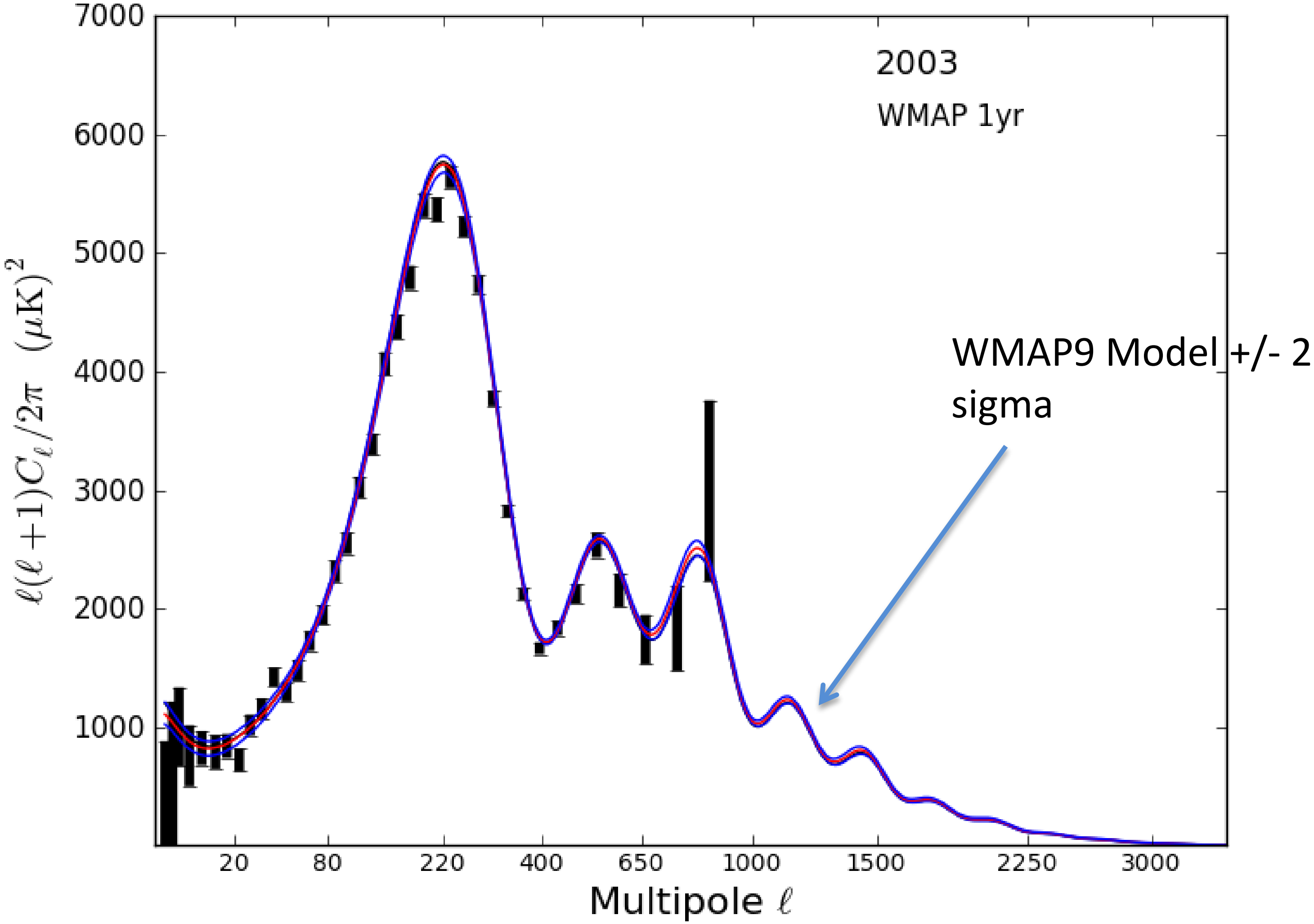
90°
2°
0.5°
0.2°
2001–2002
BOOM2
CBI1
MAXIMA2
IACB3
DASI
δT_l (μK)
Multipole moment l
0
20
40
60
80
100
10
100
500
1000
1500



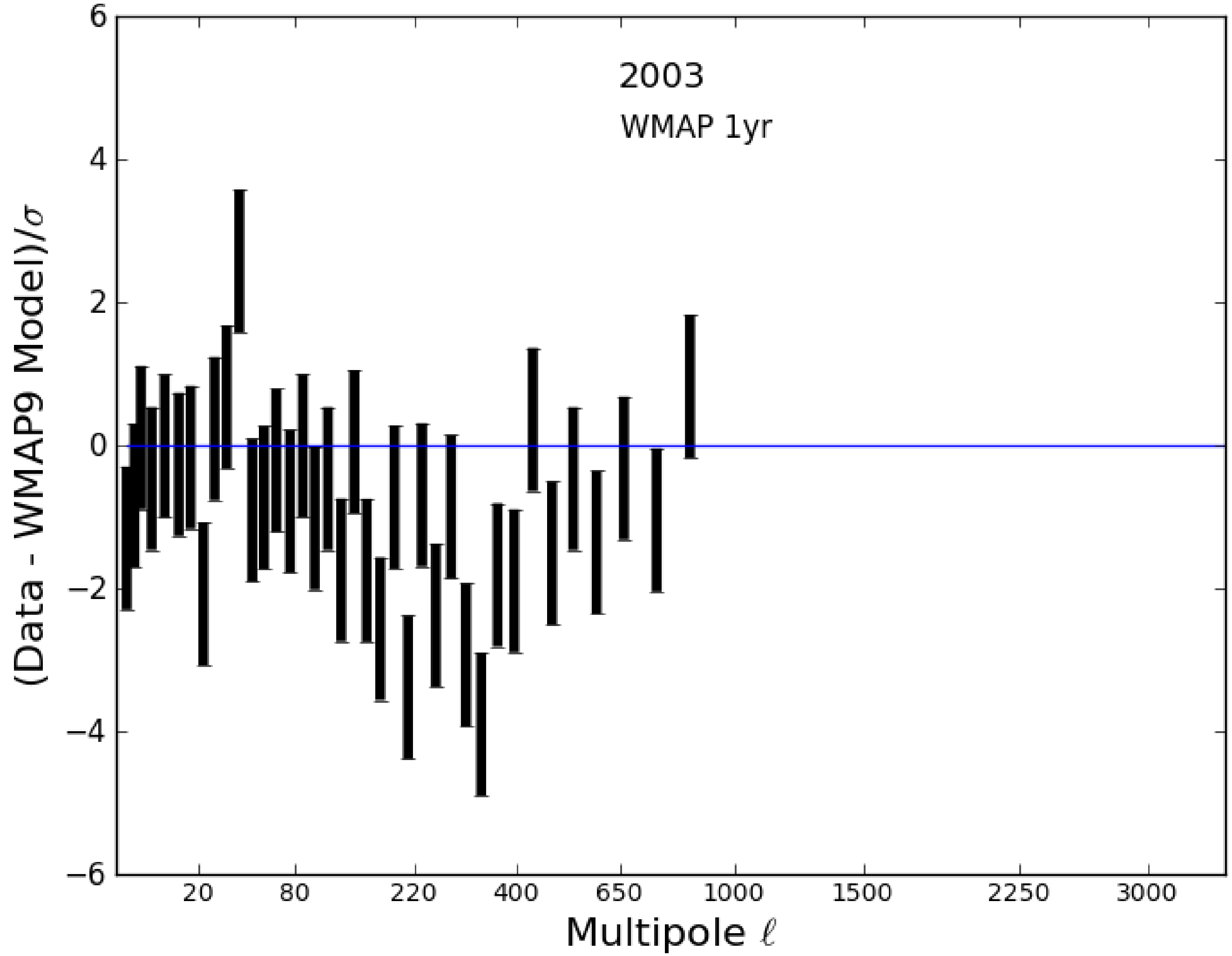
90°
2°
0.5°
0.2°
2003
TOCO3
BOOM3
ARCH
CBI2
VSA
ACBAR
PY5b
δT_l (μK)
Multipole moment l
0
20
40
60
80
100
10
100
500
1000
1500



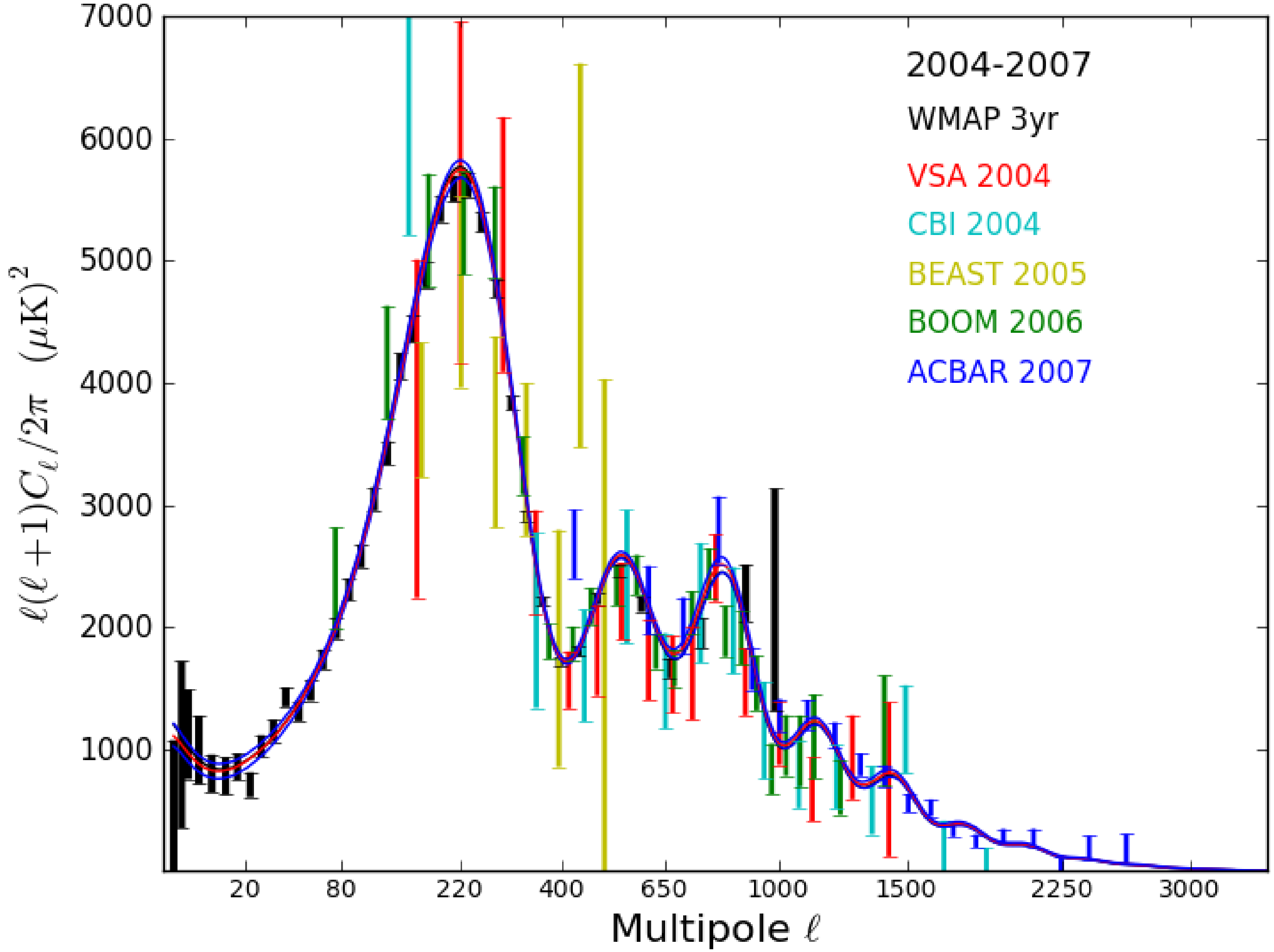
90°
2°
0.5°
0.2°
First Year WMAP Data
& Average of Prior Results
δT_l (μK)
80
60
40
20
0
10
100
500
1000
1500
Multipole moment l



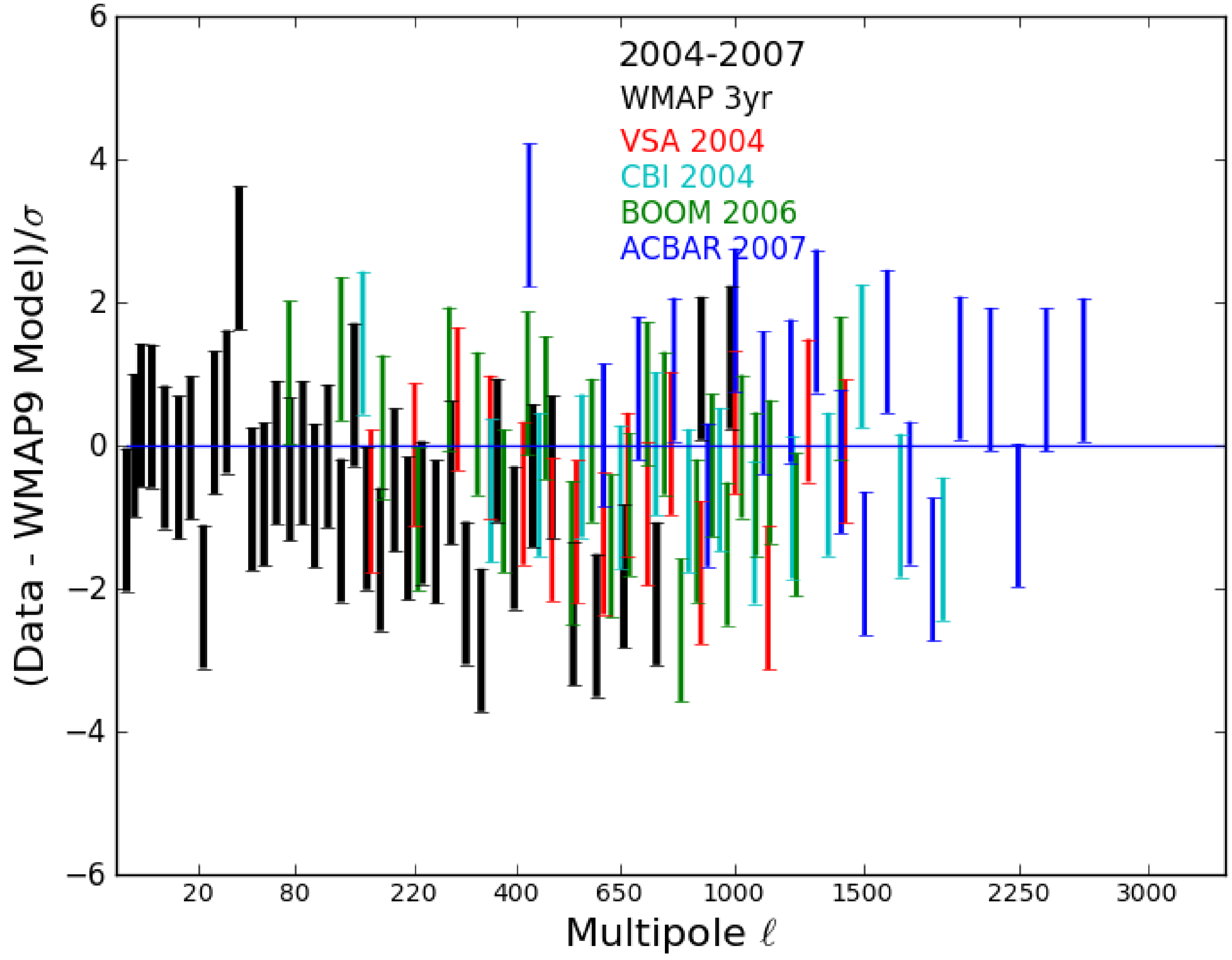
2003
WMAP 1yr
WMAP9 Model +/- 2 sigma
7000
6000
5000
4000
3000
2000
1000
$\ell(\ell+1)C_\ell/2\pi \quad (\mu K)^2$
20
80
220
400
650
1000
1500
2250
3000
Multipole ℓ

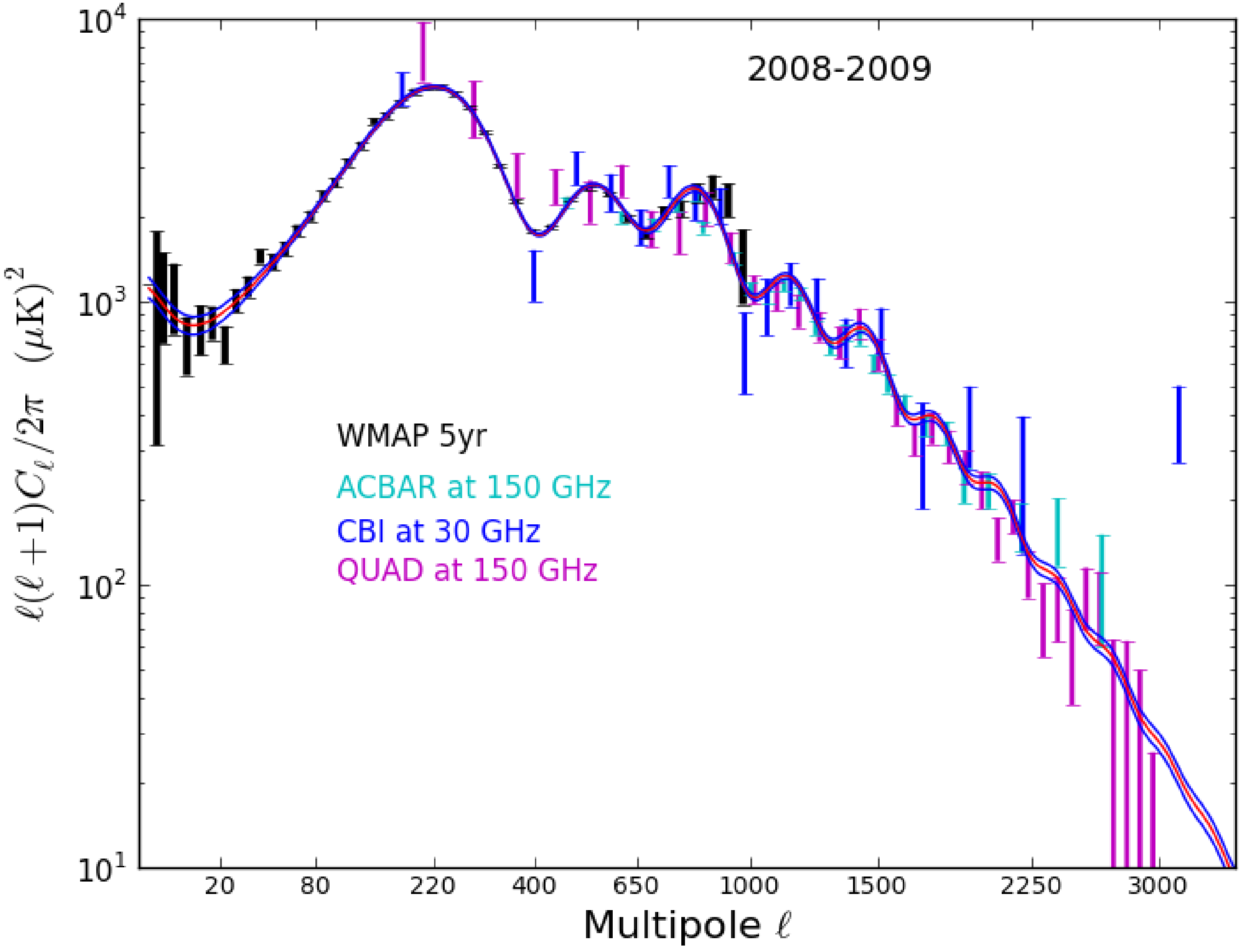


2003
WMAP 1yr
(Data - WMAP9 Model)/σ
6
4
2
0
−2
−4
−6
20
80
220
400
650
1000
1500
2250
3000
Multipole ℓ

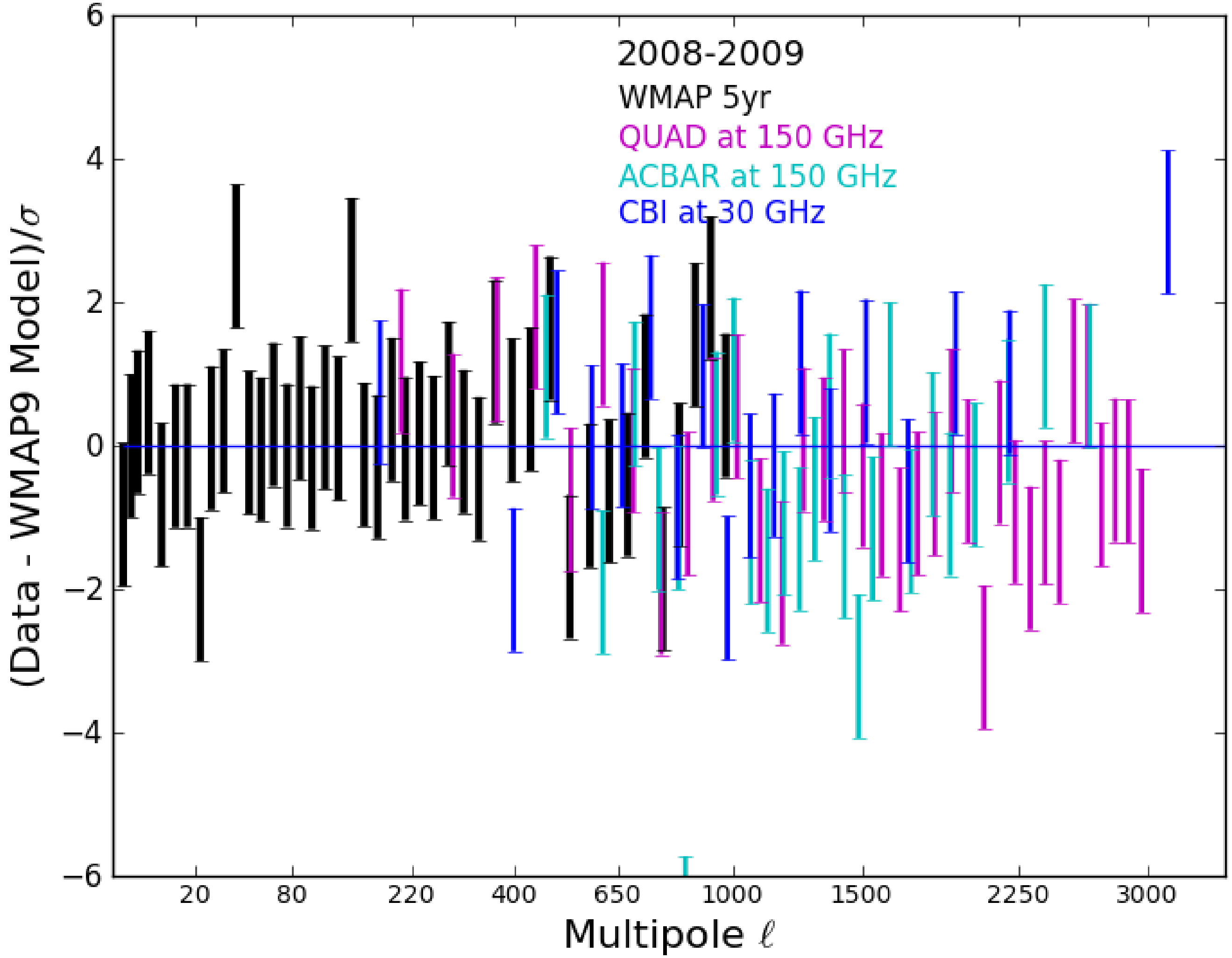


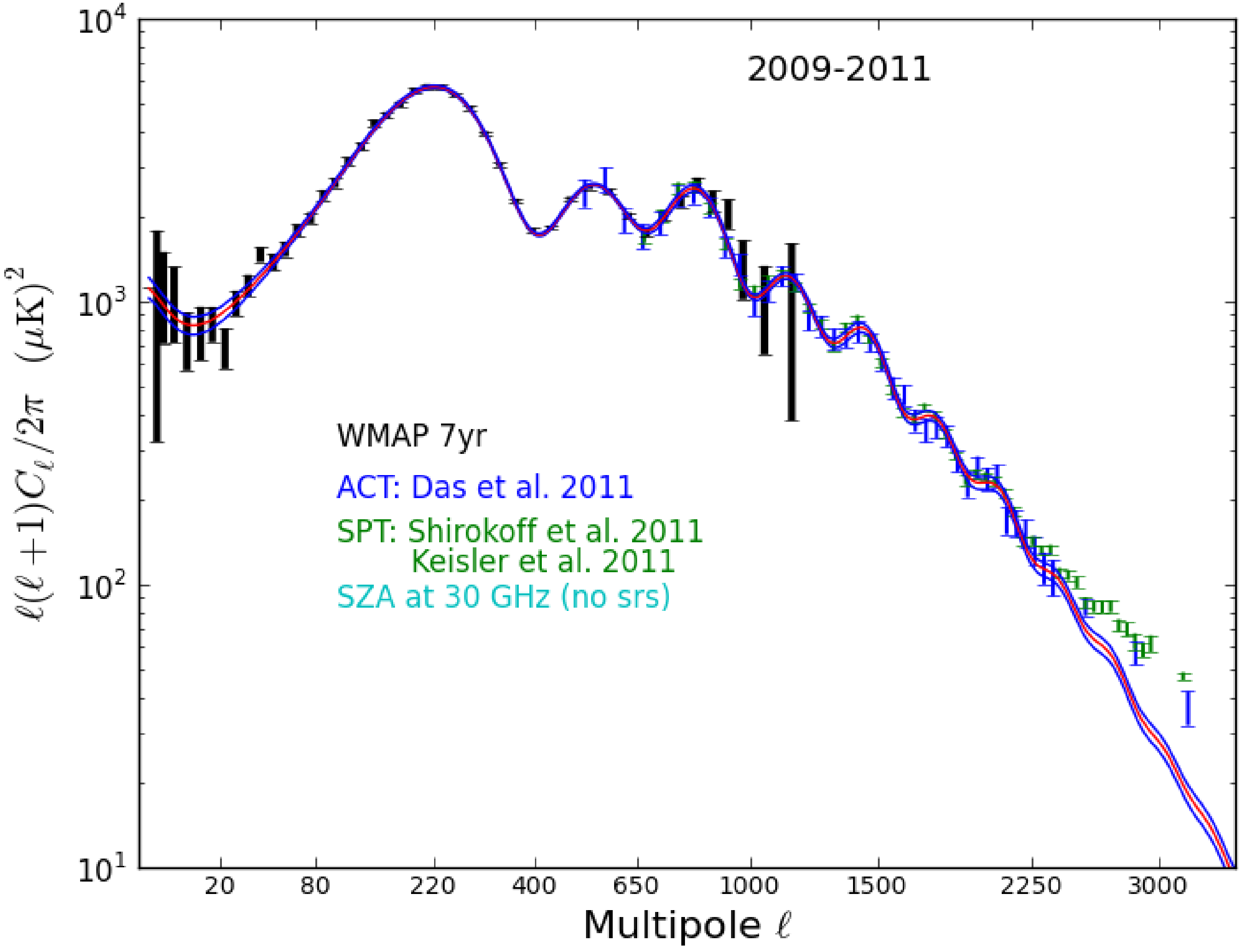
2004-2007
WMAP 3yr
VSA 2004
CBI 2004
BEAST 2005
BOOM 2006
ACBAR 2007
$\ell(\ell+1)C_\ell/2\pi \quad (\mu\mathrm{K})^2$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
20
80
220
400
650
1000
1500
2250
3000

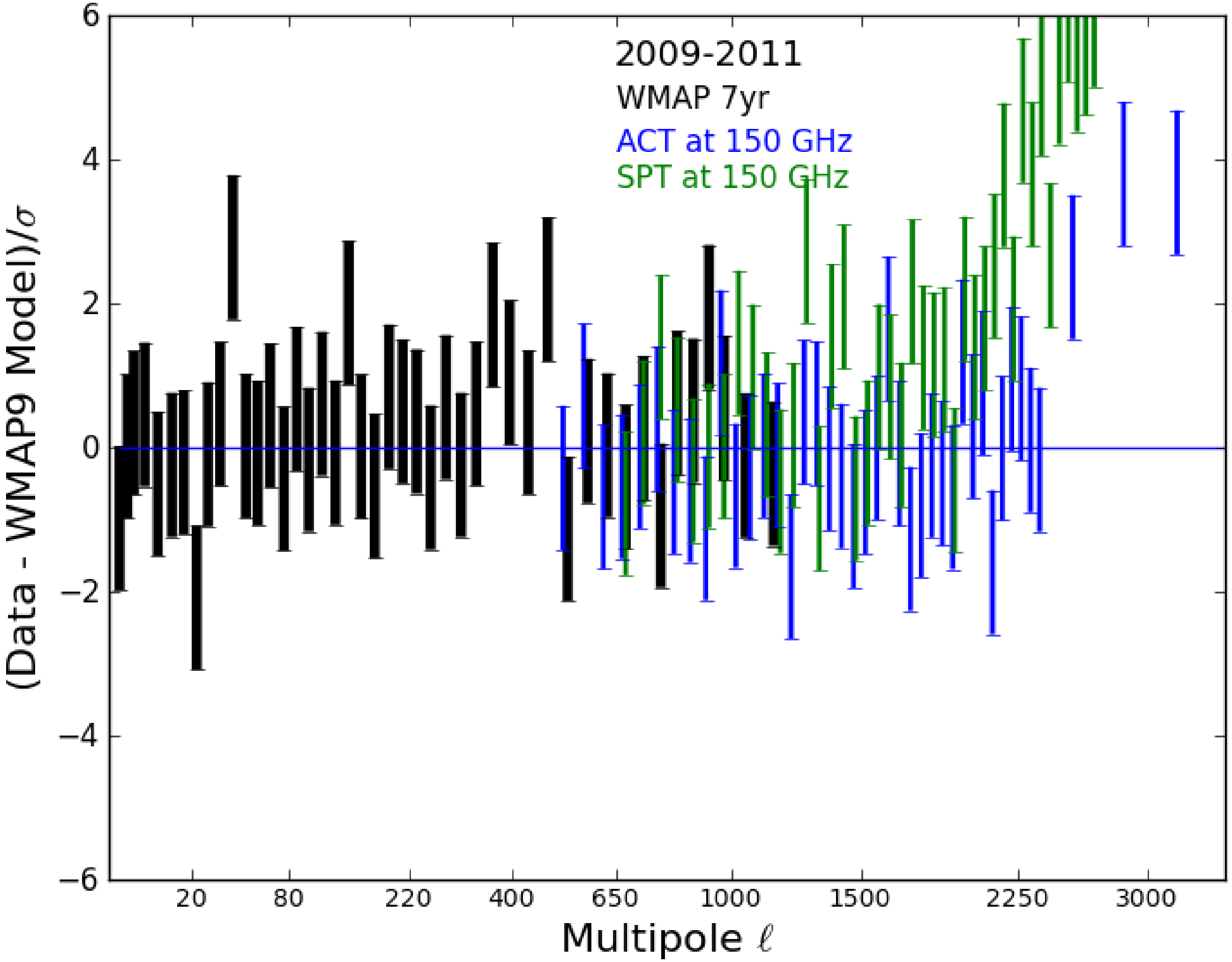

2004-2007
WMAP 3yr
VSA 2004
CBI 2004
BOOM 2006
ACBAR 2007
(Data - WMAP9 Model)/σ
Multipole ℓ
6
4
2
0
−2
−4
−6
20
80
220
400
650
1000
1500
2250
3000

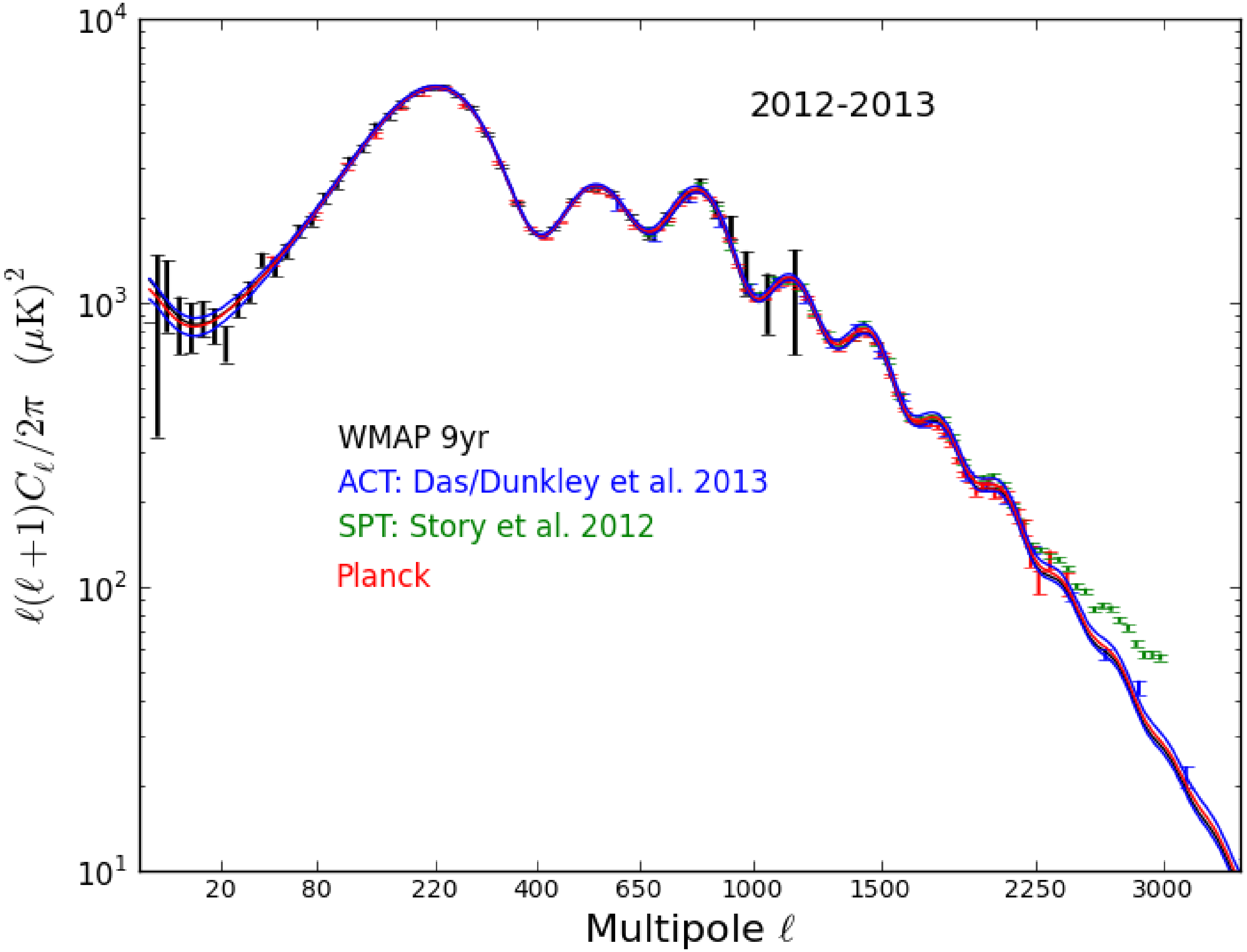


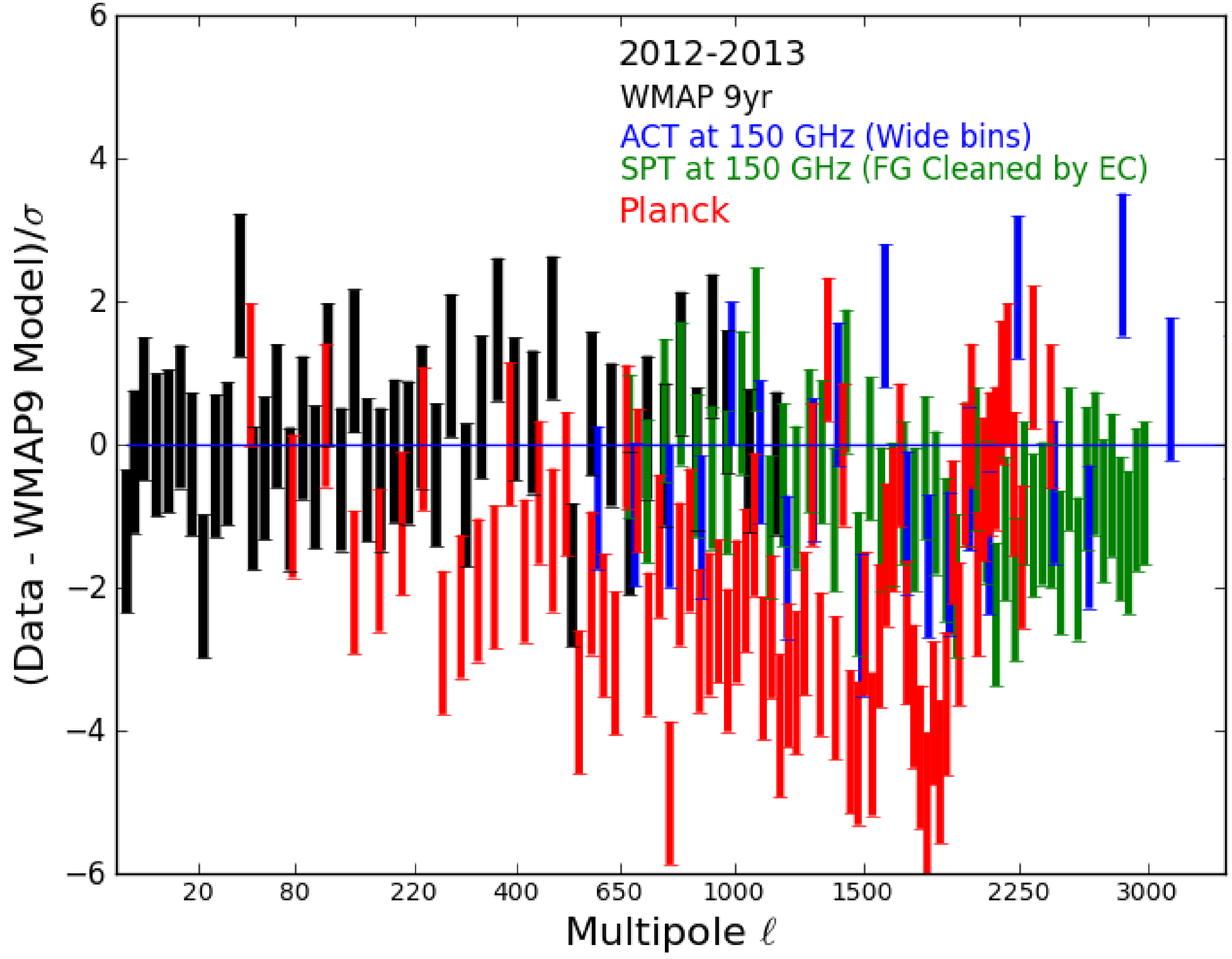
2008-2009
WMAP 5yr
ACBAR at 150 GHz
CBI at 30 GHz
QUAD at 150 GHz
$\ell(\ell+1)C_\ell/2\pi \quad (\mu K)^2$
10^4
10^3
10^2
10^1
20
80
220
400
650
1000
1500
2250
3000
Multipole ℓ


2008-2009
WMAP 5yr
QUAD at 150 GHz
ACBAR at 150 GHz
CBI at 30 GHz
(Data - WMAP9 Model)/σ
Multipole ℓ
6
4
2
0
−2
−4
−6
20
80
220
400
650
1000
1500
2250
3000


2009-2011
WMAP 7yr
ACT: Das et al. 2011
SPT: Shirokoff et al. 2011
Keisler et al. 2011
SZA at 30 GHz (no srs)
$\ell(\ell+1)C_\ell/2\pi \quad (\mu K)^2$
10^4
10^3
10^2
10^1
20
80
220
400
650
1000
1500
2250
3000
Multipole ℓ


2009-2011
WMAP 7yr
ACT at 150 GHz
SPT at 150 GHz
(Data - WMAP9 Model)/σ
Multipole ℓ
6
4
2
0
−2
−4
−6
20
80
220
400
650
1000
1500
2250
3000

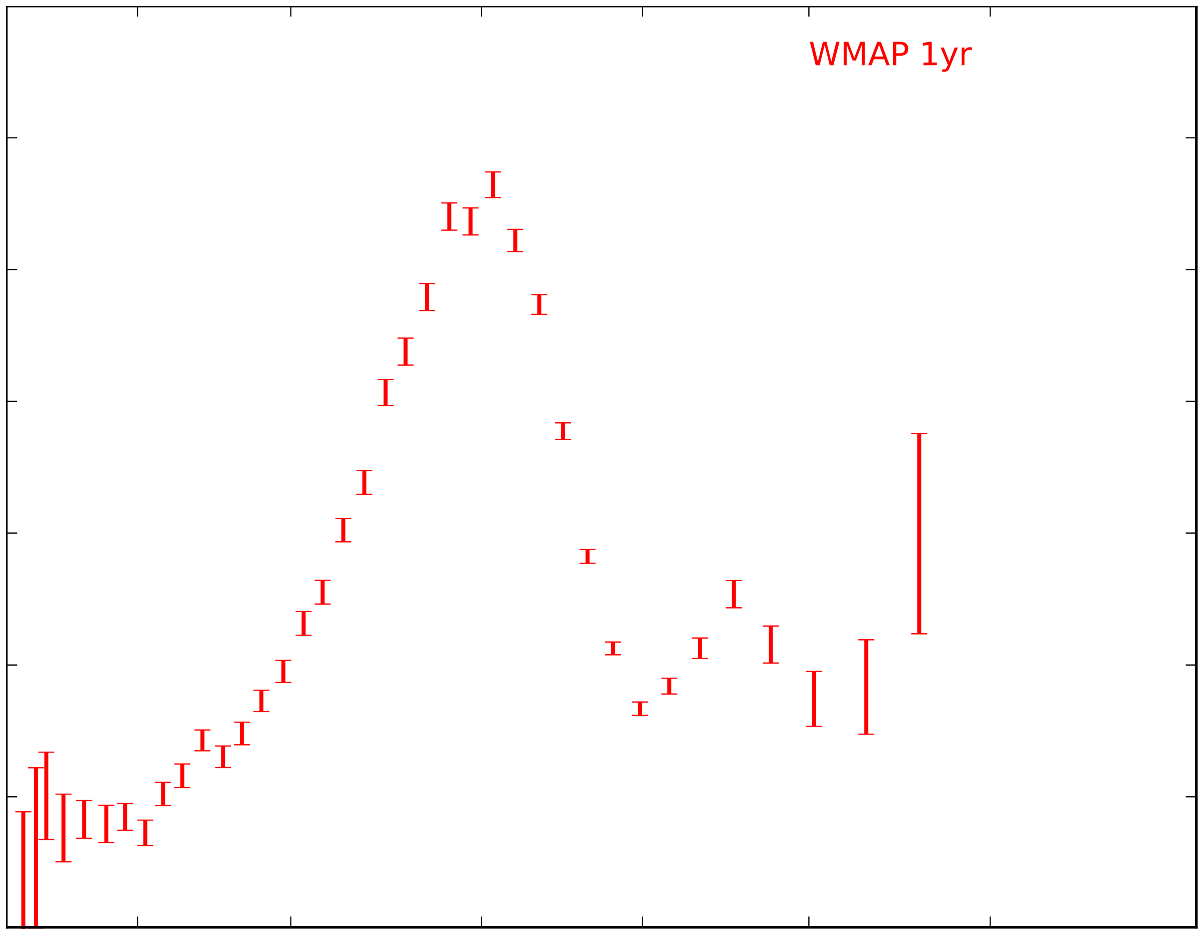

2012-2013
WMAP 9yr
ACT: Das/Dunkley et al. 2013
SPT: Story et al. 2012
Planck
$\ell(\ell+1)C_\ell/2\pi \quad (\mu\mathrm{K})^2$
10^4
10^3
10^2
10^1
20
80
220
400
650
1000
1500
2250
3000
Multipole ℓ



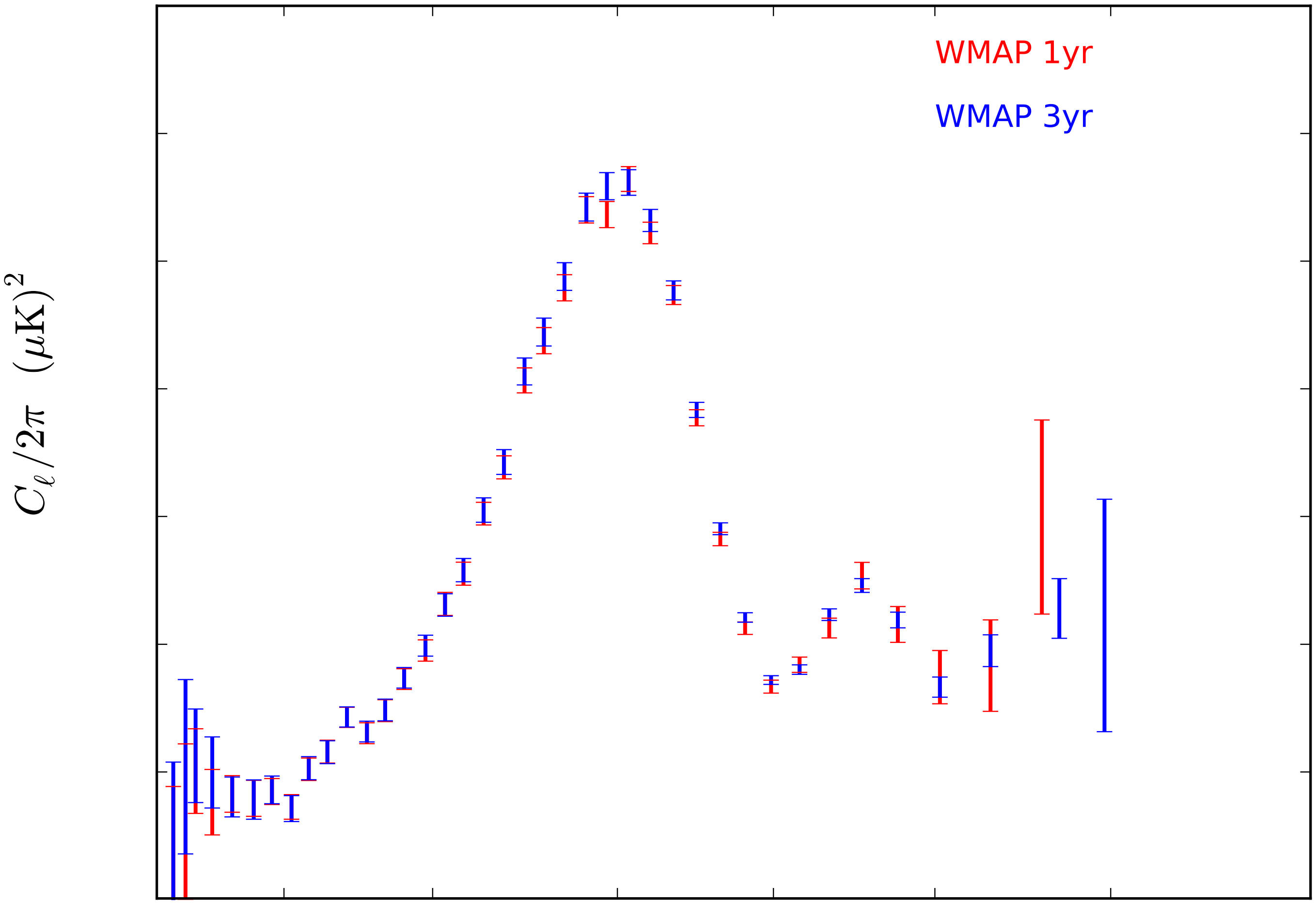
2012-2013
WMAP 9yr
ACT at 150 GHz (Wide bins)
SPT at 150 GHz (FG Cleaned by EC)
Planck
(Data - WMAP9 Model)/σ
Multipole ℓ
6
4
2
0
−2
−4
−6
20
80
220
400
650
1000
1500
2250
3000

WMAP Observations

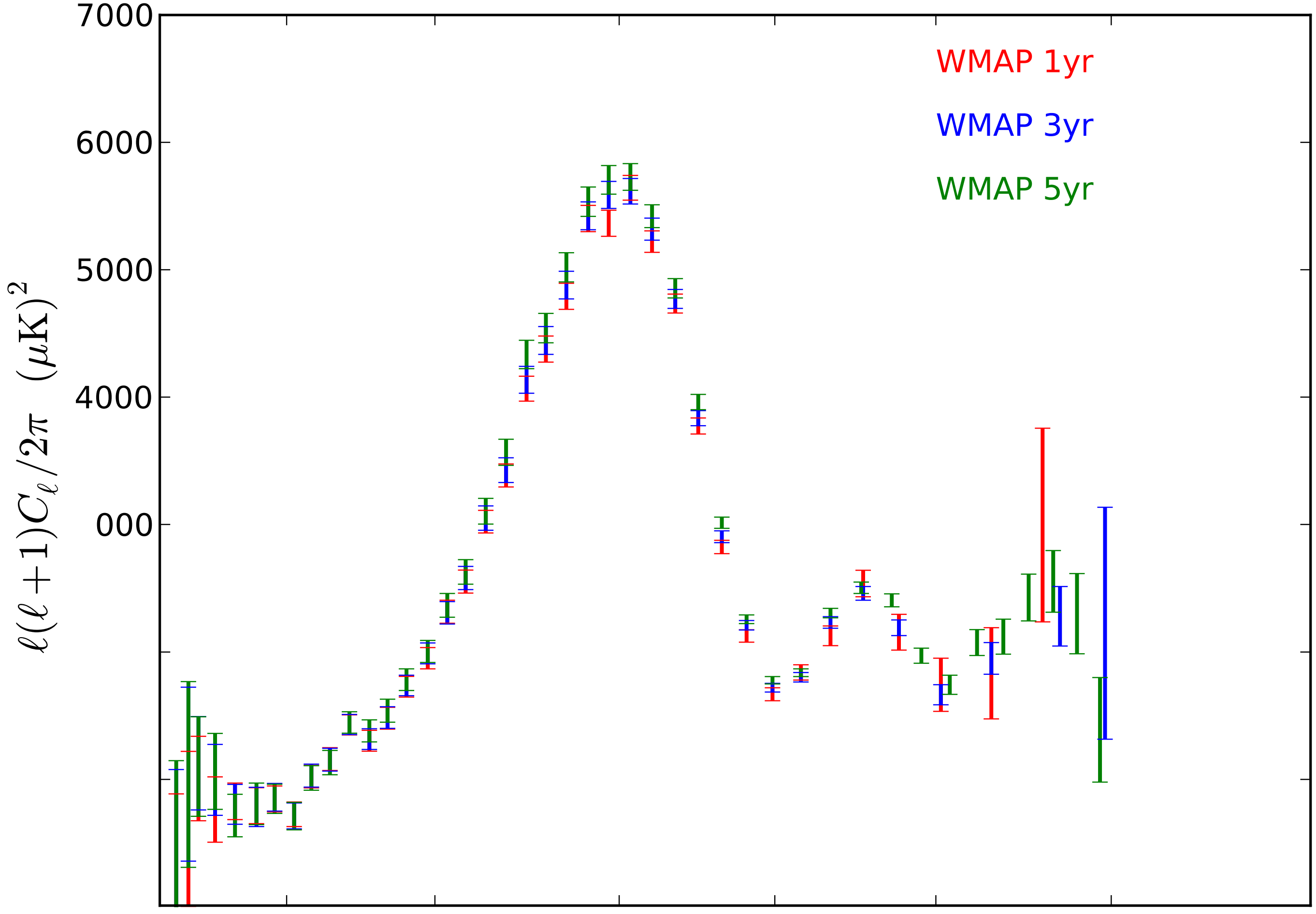
- 30% of the sky in 1 hour. Heavy cross linking.
- Just a few parameters for gain model for 9 years.
- 17 seasons of Nyquist-sampled Jupiter mapping to determine beams.
- Noise model independent of cosmology. Depends only on N_{obs}.
- Unity transfer function & low 1/f.
- Sidelobe mapping on the ground and in flight.


WMAP 1yr

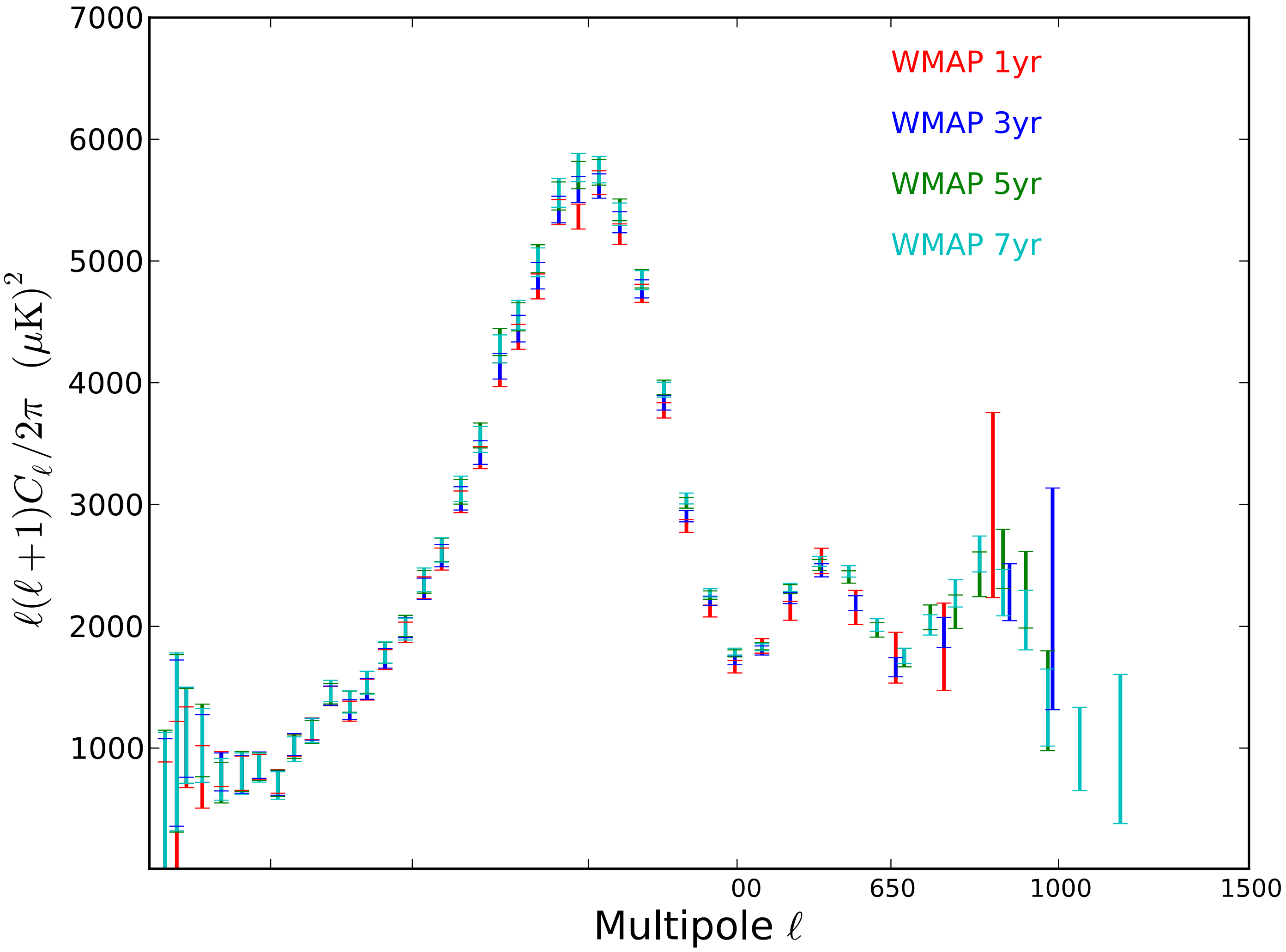
New dipole and gain model. ** Small pointing error corrected.
Physical optics model the beams on A side. Use K and Ka bands for foreground cleaning.
Maximum likelihood for l<30, pseudo C $_l$ for l>30



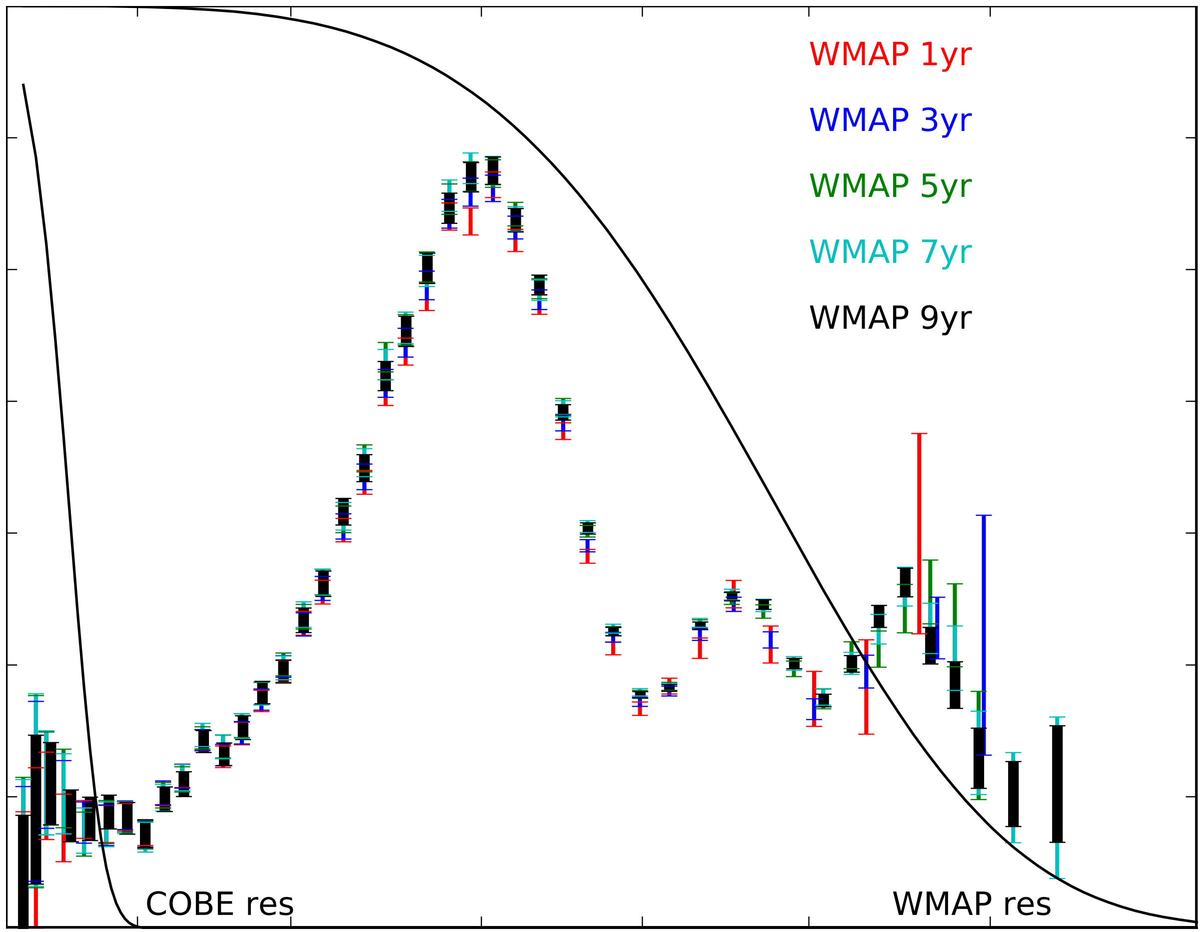
Reassess gain model, 0.2% ** 10 seasons for beam. Measure at -44dB, 0.5% Omega beyond that. ** Full physical optics model. ** Reassess far sidelobes, enlarge transition radius, mode sidelobe accounting into time line. ** Improved likelihood at l<32



Continued improved improvement in beams. A and B separately



Reassess ILC and move to optimal C_l estimator.



WMAP

1 Established and tested the standard model of cosmology: Flat, adiabatic & Gaussian ptb., 6 parameters.

τ=0.089 +/- 0.014

	WMAP9	WMAP9+ACT	Planck	Planck+WP
$100\ \Omega_b h^2$	2.264± 0.050	2.260± 0.041	2.217± 0.033	2.205± 0.028
$100\ \Omega_c h^2$	11.38± 0.45	11.46± 0.43	11.86± 0.31	11.99± 0.27
n_s	0.972± 0.013	0.973± 0.011	0.9635± 0.0094	0.9603± 0.0073
σ_8	0.821± 0.023	0.83± 0.021	0.823± 0.018	0.829± 0.012
H_0	70.0± 2.2	69.7± 2.0	67.9± 1.5	67.3± 1.2

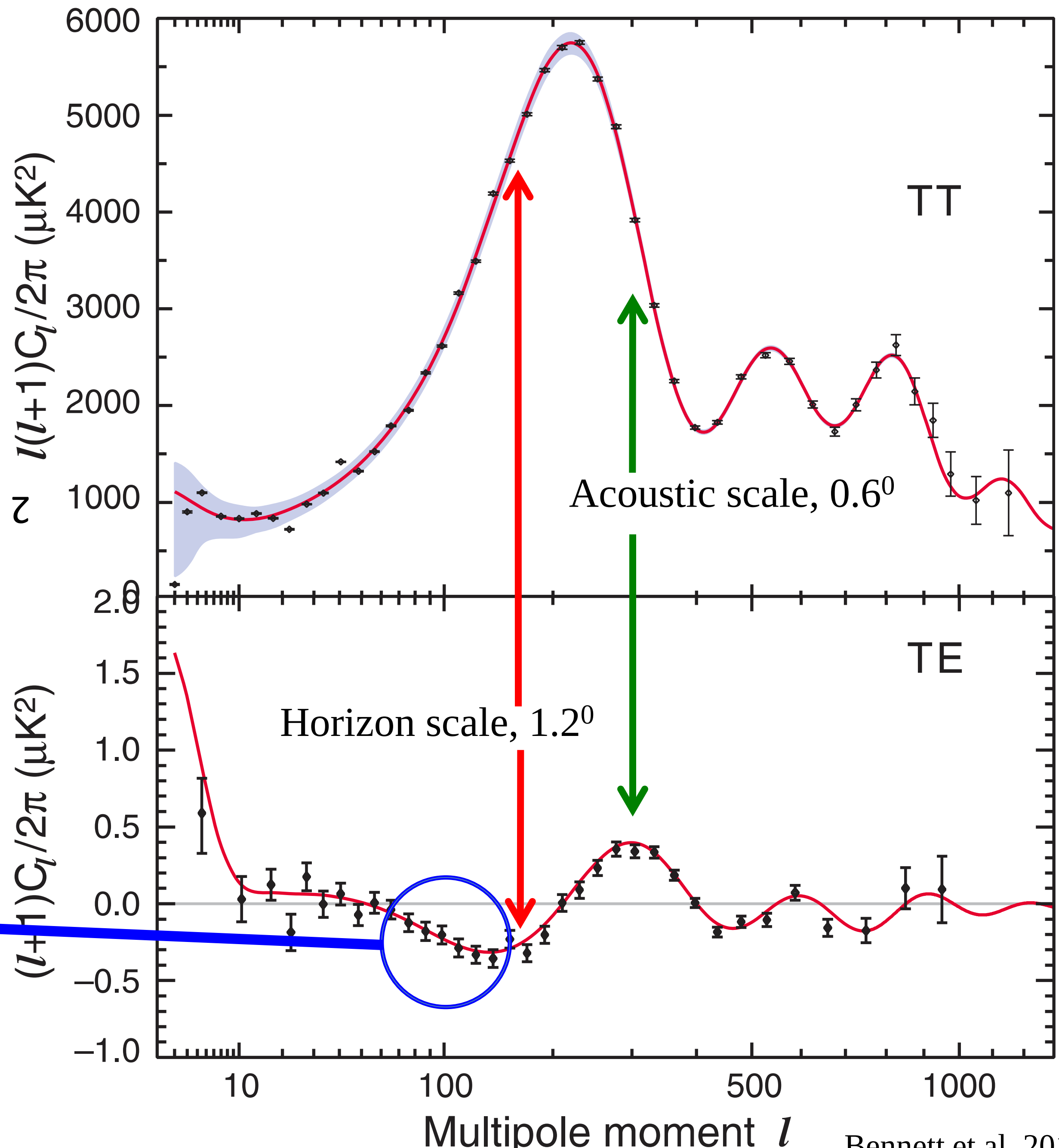
WMAP: χ^2=3336/3115 (PTE =0.003) Driven by low l polarization.

② WMAP

Demonstrated superhorizon fluctuations.

This TE anti-correlation is the best evidence for the existence of super horizon fluctuations, a key element of the standard model.

Spergel & Zaldarriaga (1997)
Peiris et al. (2003)

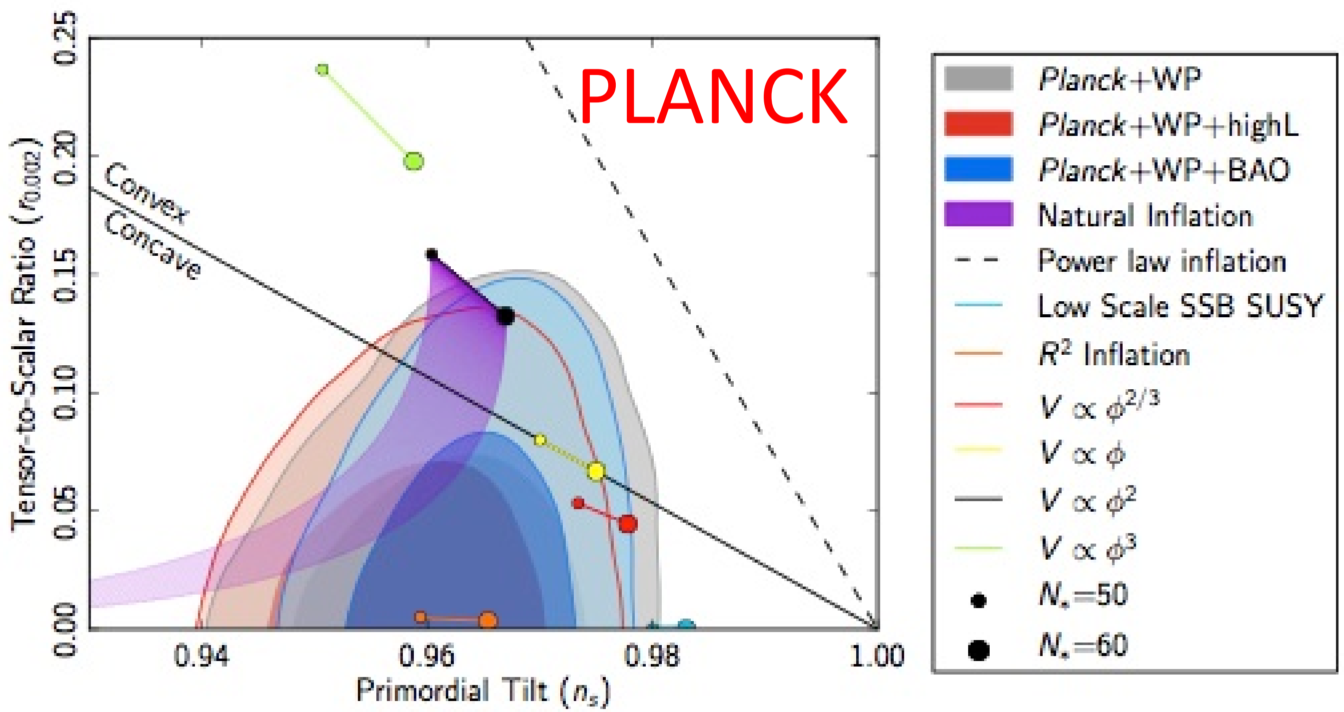


Bennett et al, 2013

3

WMAP

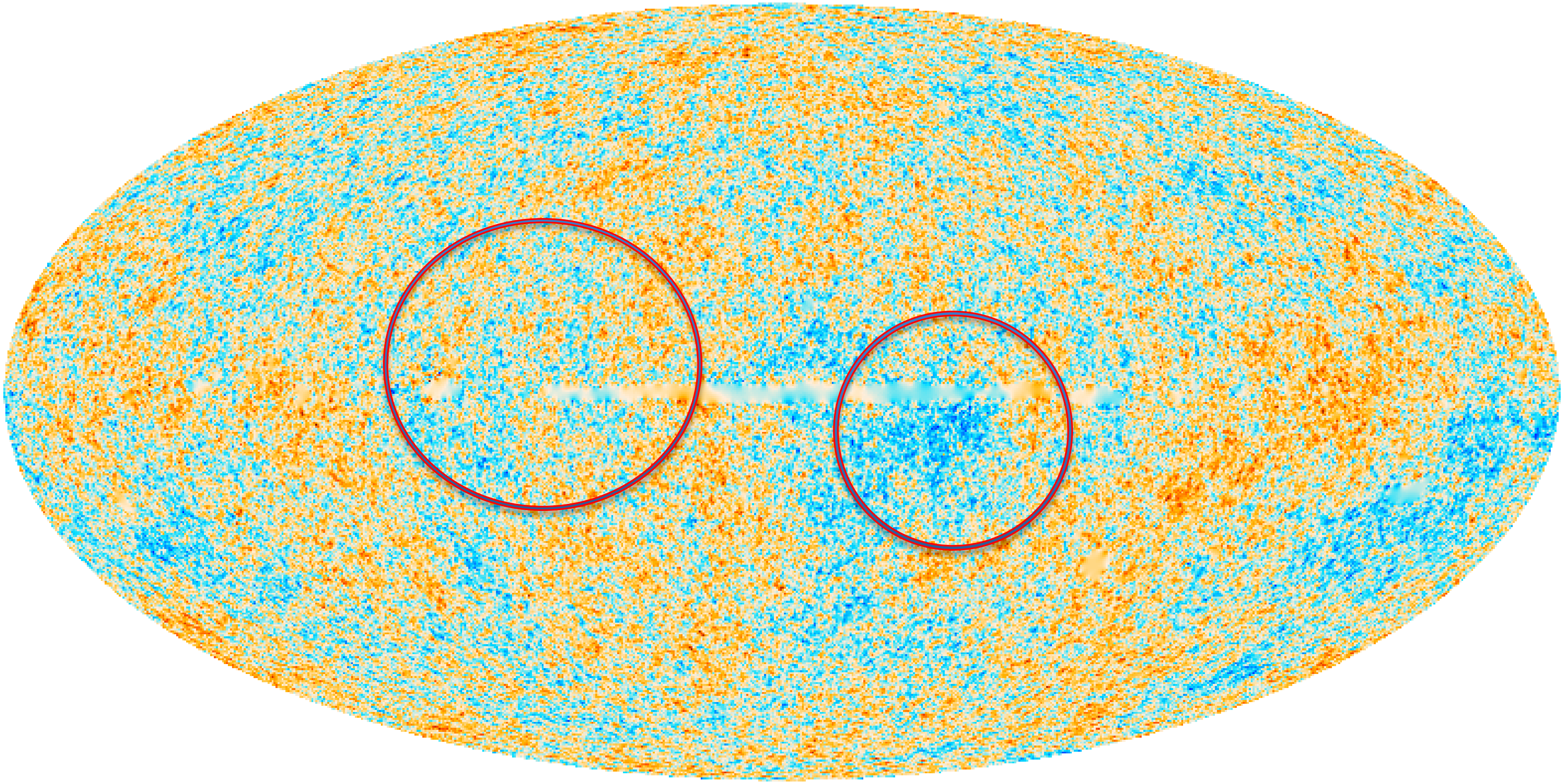
Got a good start on the early universe or "Inflation parameters": r, n_s, dn_s/dk, f_{nl}



Current best B-mode limit, r<0.74 (BICEP/Chiang et al.)

More to r than inflation

“Anomalies”?



What's Next. Low-l Polarization

Space/balloon

EBEX

SPIDER

Planck

LSPE

PIPER

SKIP ?

DELITE ?

2013 2014 2015 2016

QUIJOTE

ABS

CLASS

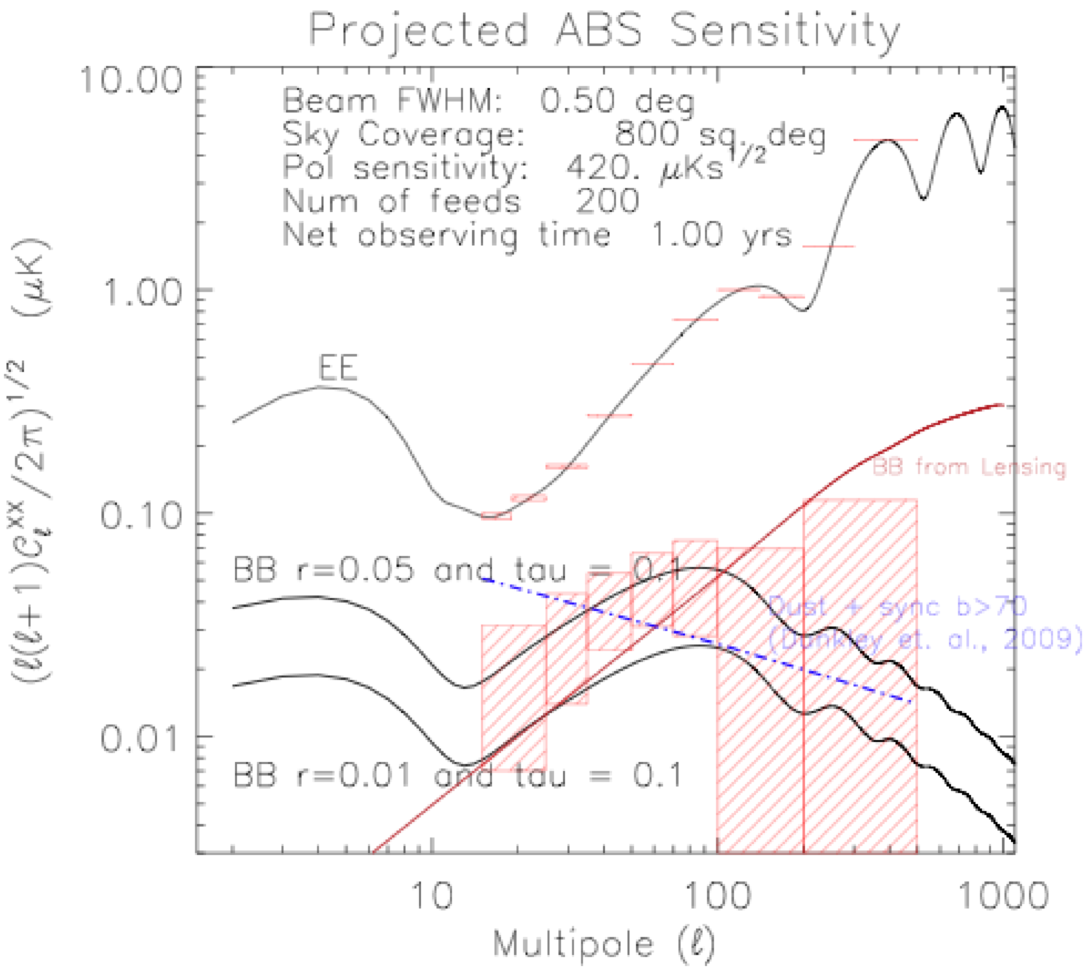
Ground

QUBIC
(Antarctic interferometer)

SPUD

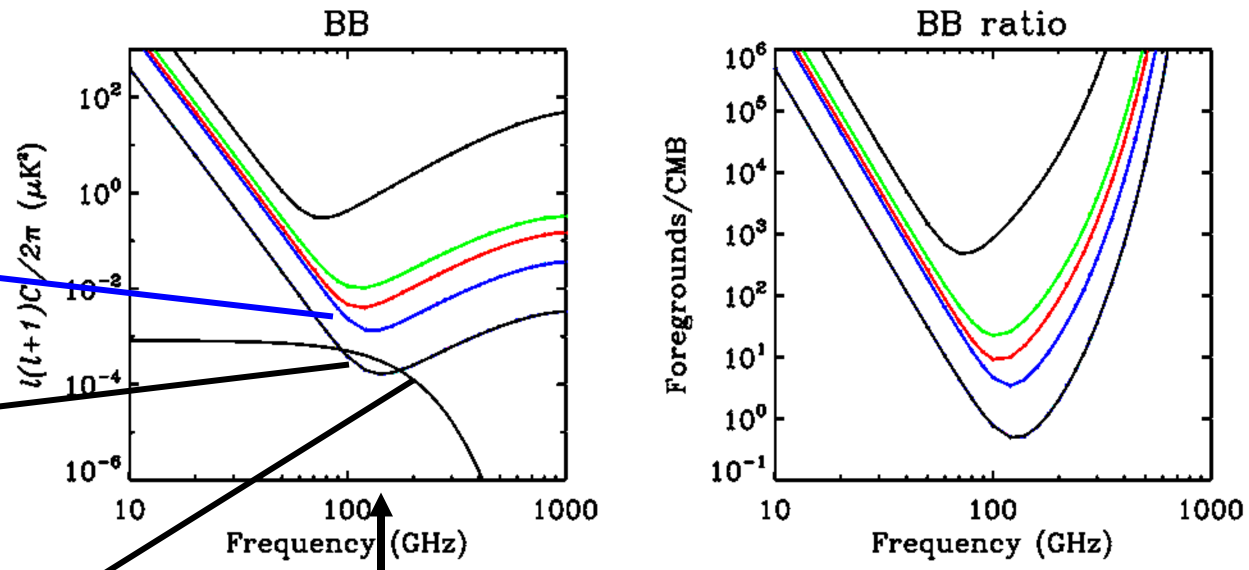
BICEP3

ABS



Staggs et al.

Foreground emission.



|b|>50, 9000 deg sq., one hemisphere.

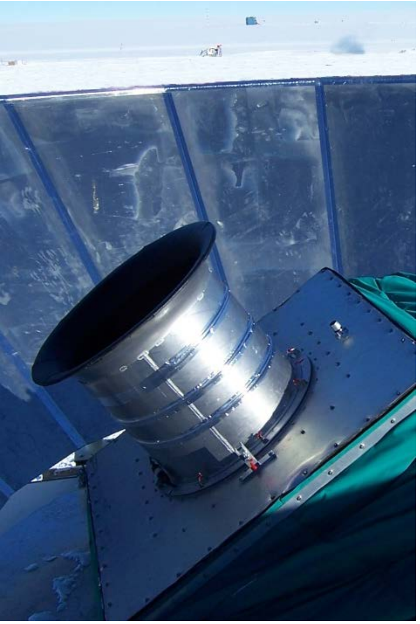
300 deg sq., at coldest spot.

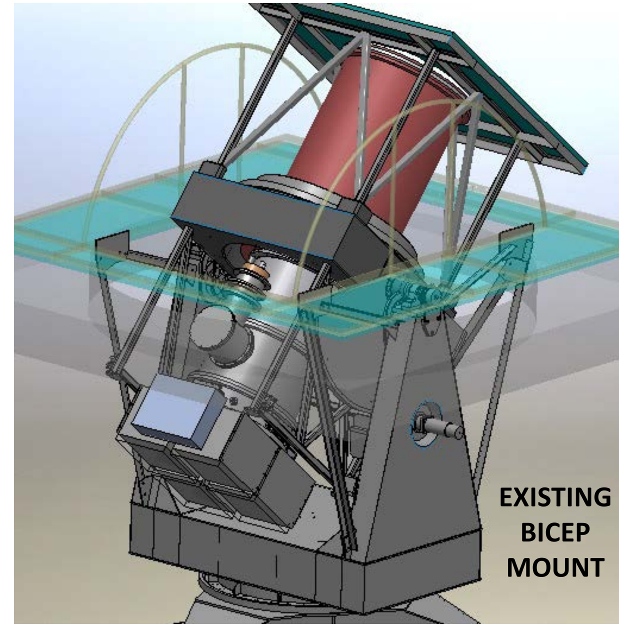
145 GHz

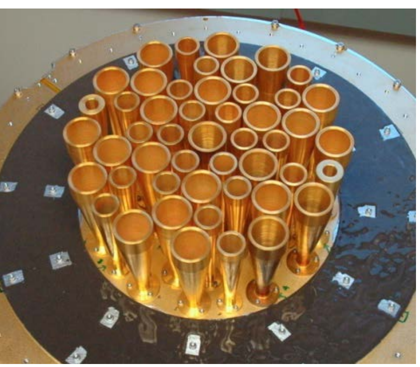
BB for r=0.01 for 80<l<120.

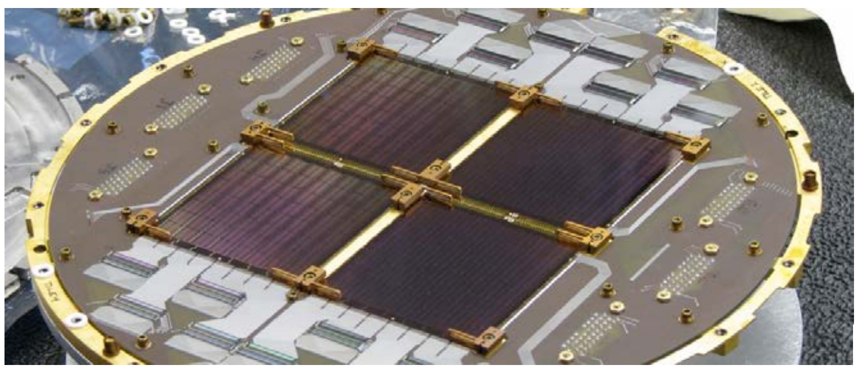
From Dunkley et al. 2008, calculation by Clive Dickinson

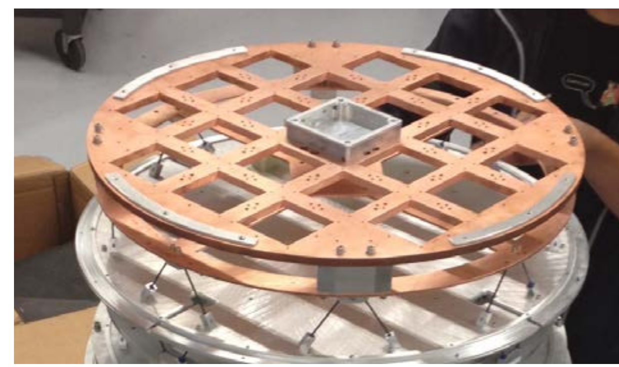
Model: WMAP synchrotron plus FDS dust with 2% polarization.





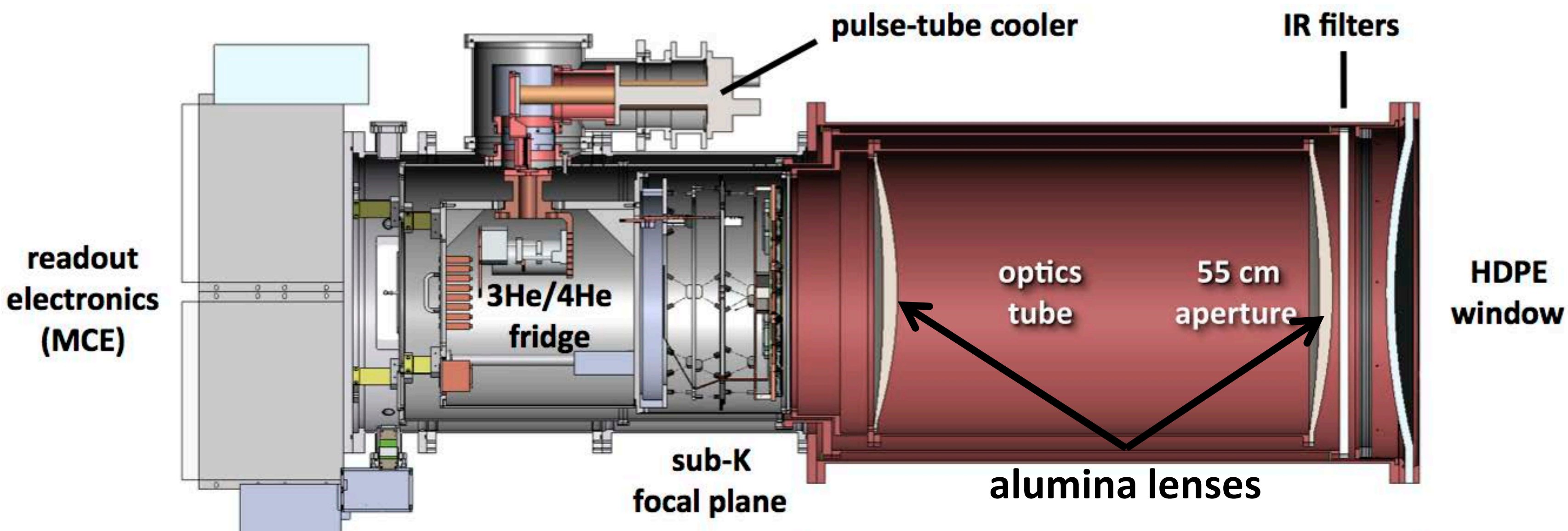


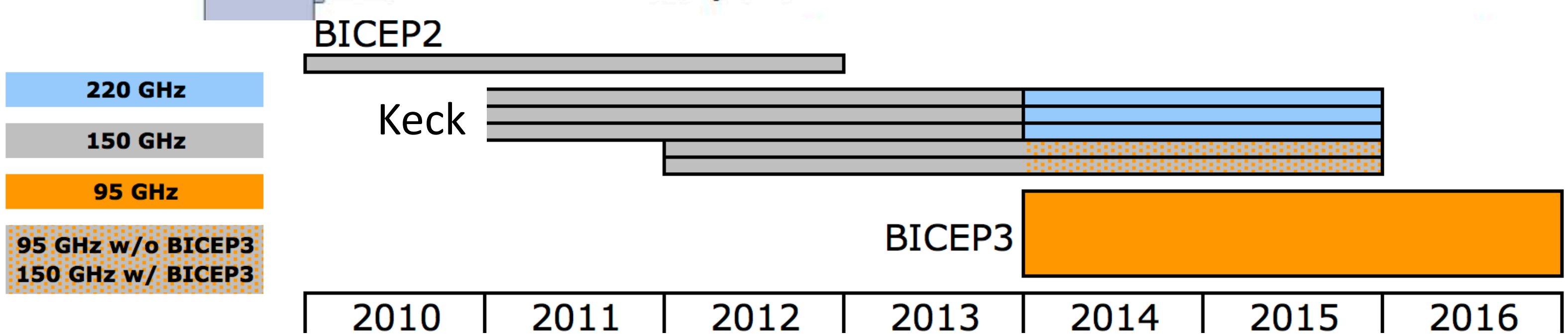




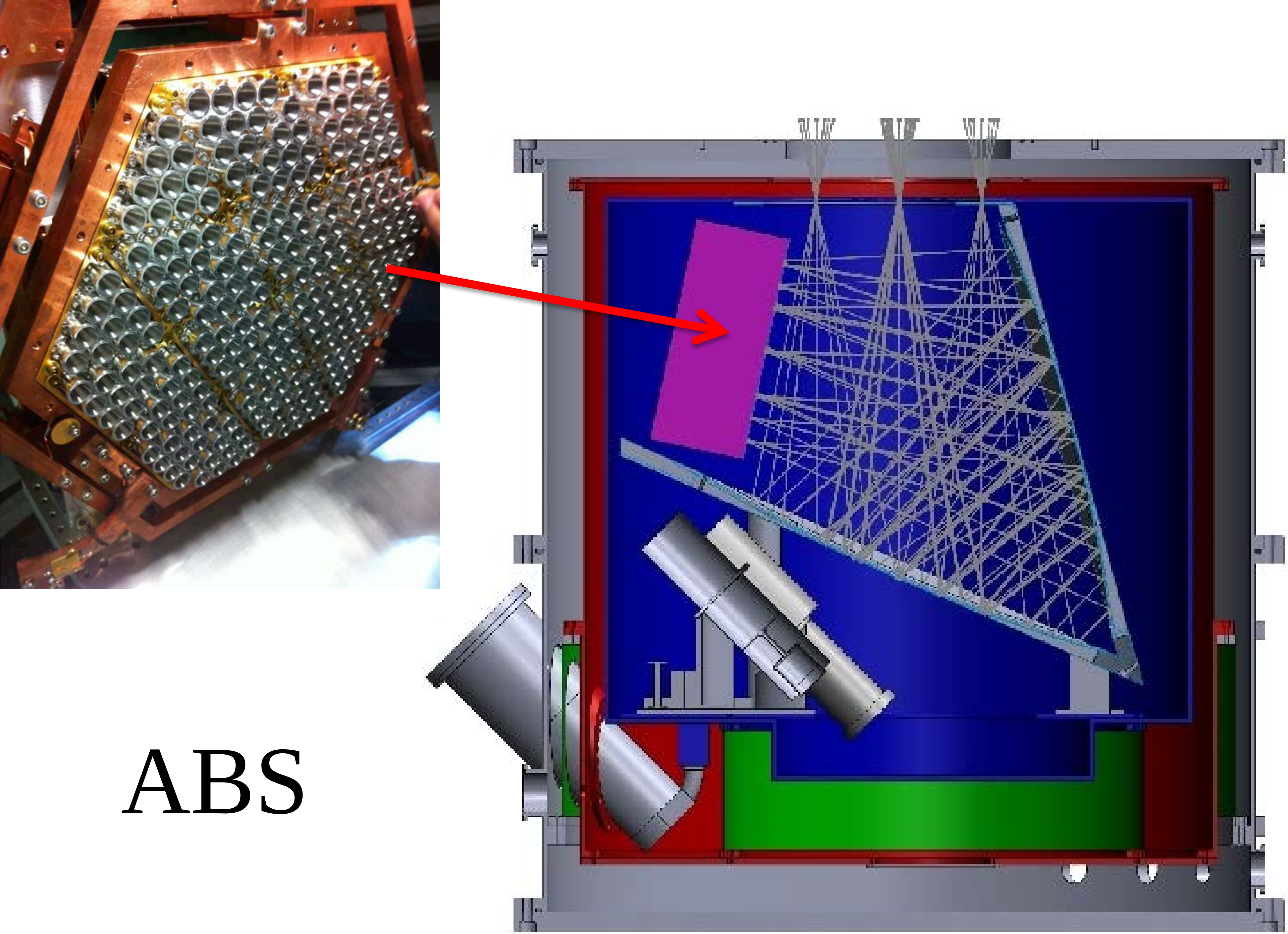
BICEP (2006–2008)	BICEP2 (2010–2012)	Keck (2011–)	**BICEP3 (2014-)**
98 NTDs (95/150 GHz)	512 TESs (150 GHz)	2560 TESs (150 GHz)	**2560 TESs (95 GHz)**
0.93°/0.60° FWHM	0.52° FWHM		**0.37° FWHM**
18° FOV	17° FOV		**26° FOV**
44 m^2 deg^2 AΩ	44 m^2 deg^2 AΩ	222 m^2 deg^2 AΩ	**502 m^2 deg^2 AΩ optical throughput**

BICEP3 has more than x2 larger throughput than *5* Keck receivers

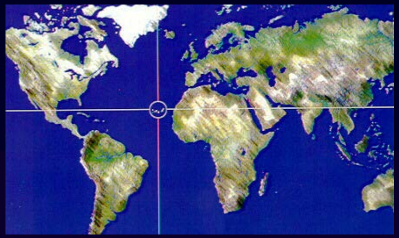


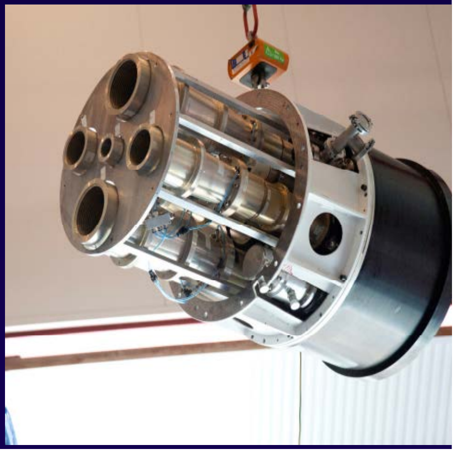


*** The increased throughput will enable BICEP/Keck program to go deep at 95GHz**



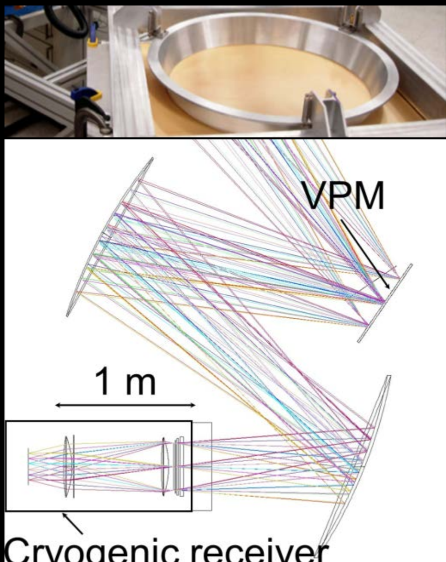
ABS





Cosmology Large Angular Scale Surveyor

Modulator & Optics



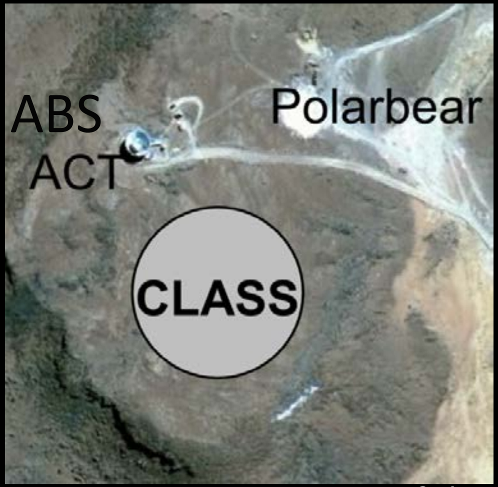
Search for B-mode inflation signature from primordial gravitational radiation at >2^{o} scales with projected sensitivity to detect tensor-to-scalar ratios below 0.01, even when including foreground and systematic errors.

Use demonstrated front-end wire grid polarization modulator (VPM) at 10 Hz to isolate cosmic signal.

Take advantage of enhanced signal of reionization "bump" and avoid lensing B-mode signal.

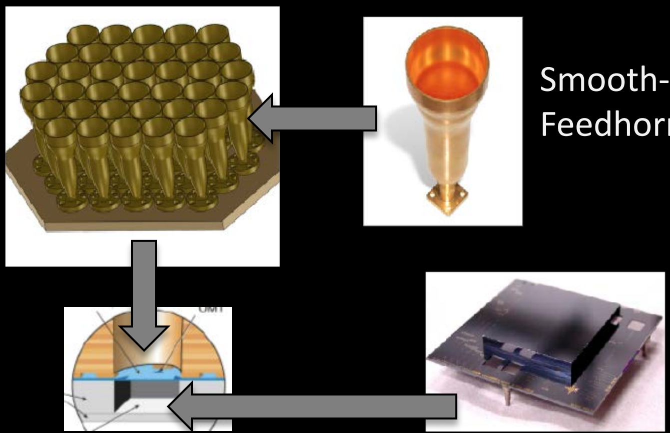
Survey large fraction (65%) of sky observable from Atacama Desert at frequencies (40, 90, 150 GHz) where the full-sky CMB-to-foreground ratio is maximized.

Atacama Site



Cerro Toco, 5200 m, 65% of sky observable above elev 45^{o}

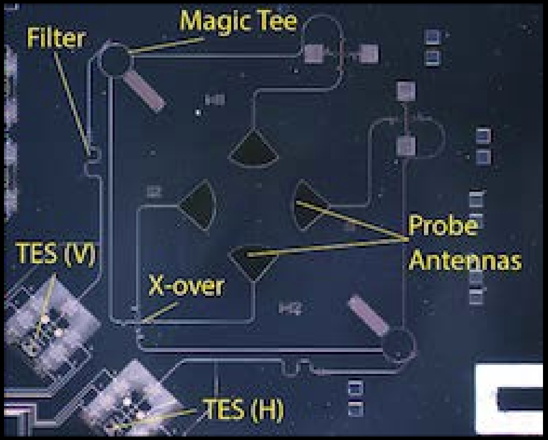
Focal Plane



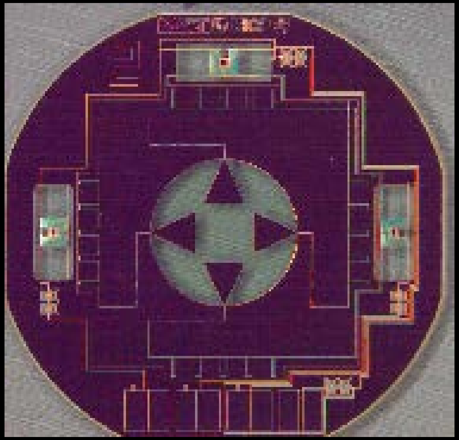
Horn Coupled Detectors

Integrated Backshort

Polarization Sensitive Bolometric Detectors



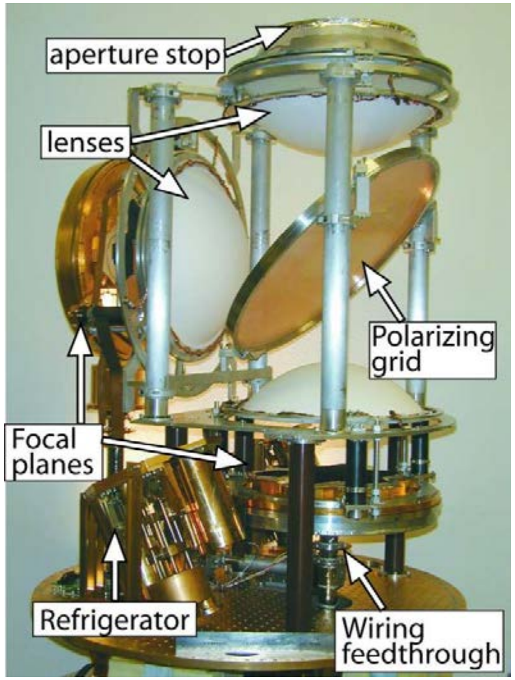
NASA/GSFC 40 & 90 GHz

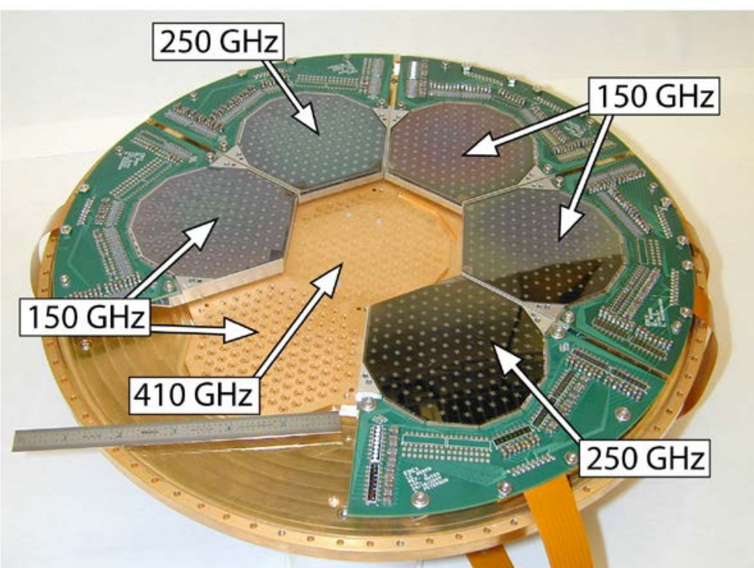


NIST 150 GHz

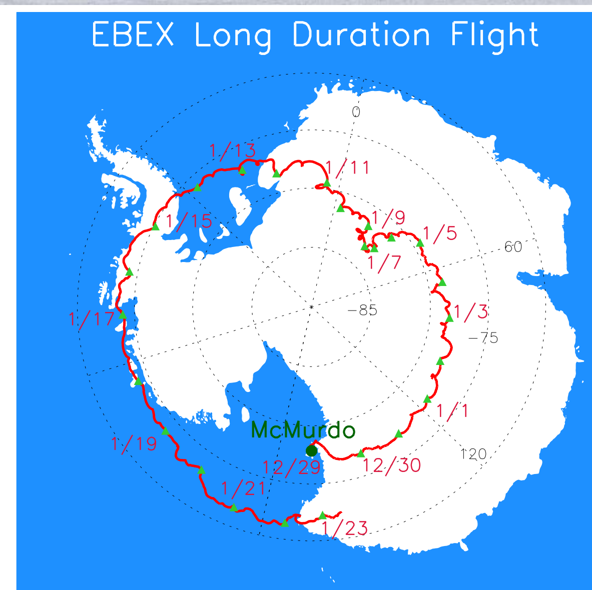
EBEX

EBEX 1 K optics, 0.3 K focal planes and refrigerator





One of two focal planes with 5 of 7 detector wafers



SPIDER

Primordial Inflation Polarization Explorer (PIPER)

Sensitivity

- 5120 Detectors (TES bolometers)
- 1.5 K optics with no windows
- Background-limited performance

Systematics

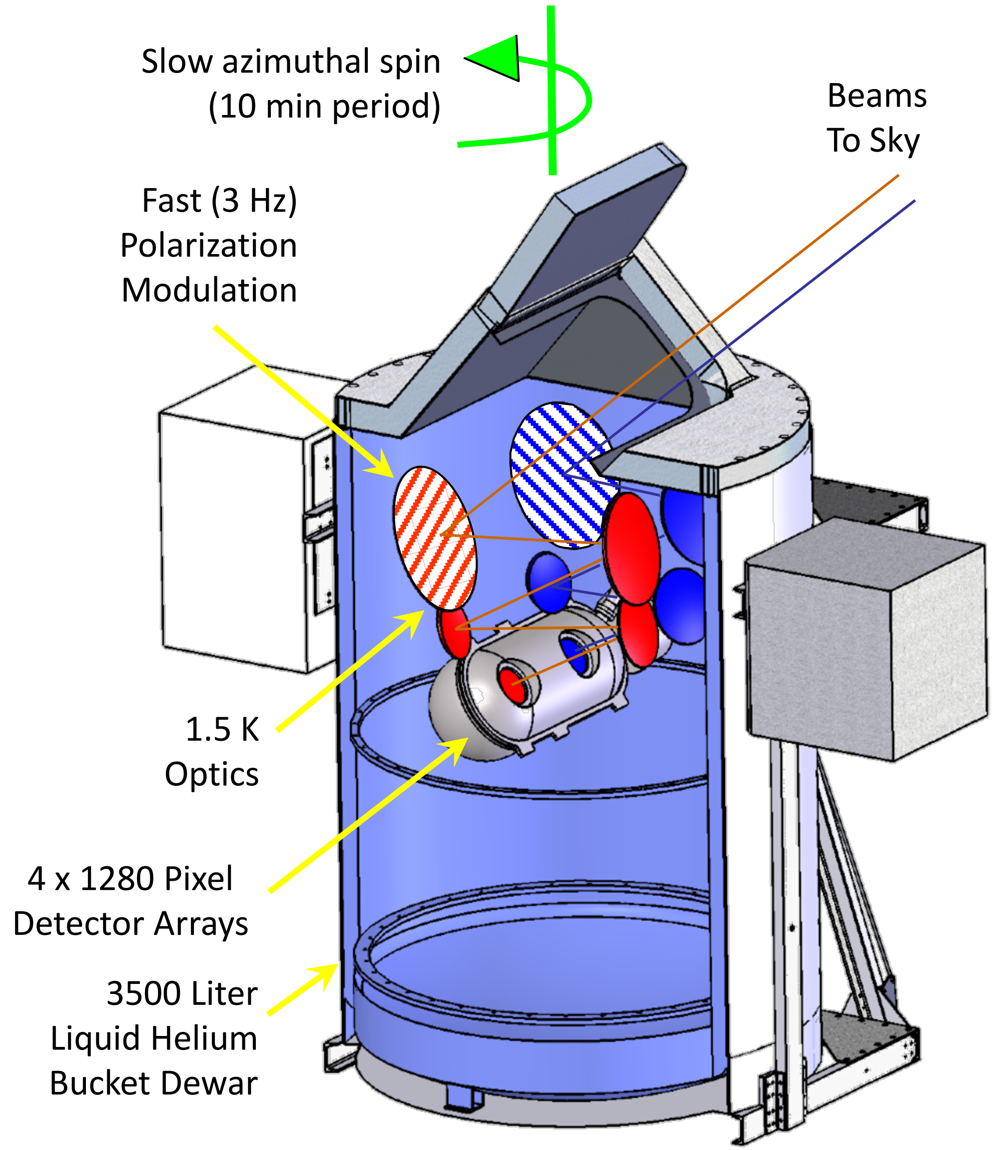
- Front-End polarization modulator
- Twin telescopes in bucket dewar

Foregrounds

- 1500, 1100, 850, and 500 μm
- Clearly separate dust from CMB

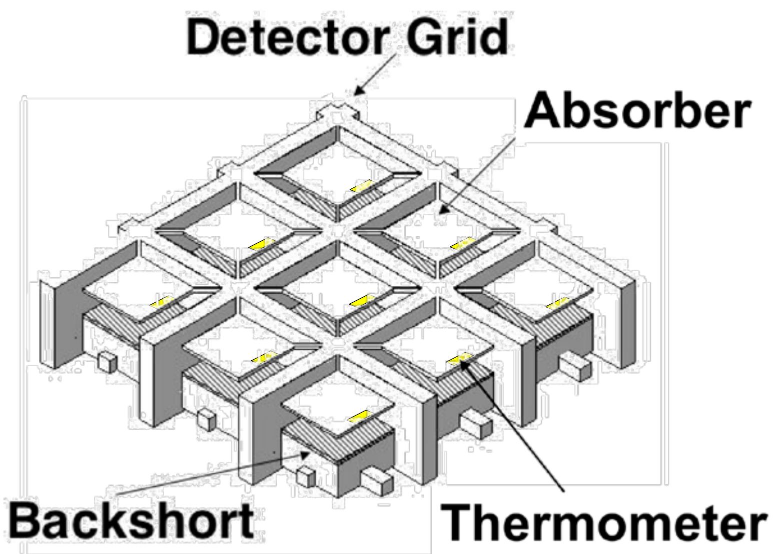
Sky Coverage

- Balloon payload, conventional flight
- 8 flights; half the sky each night



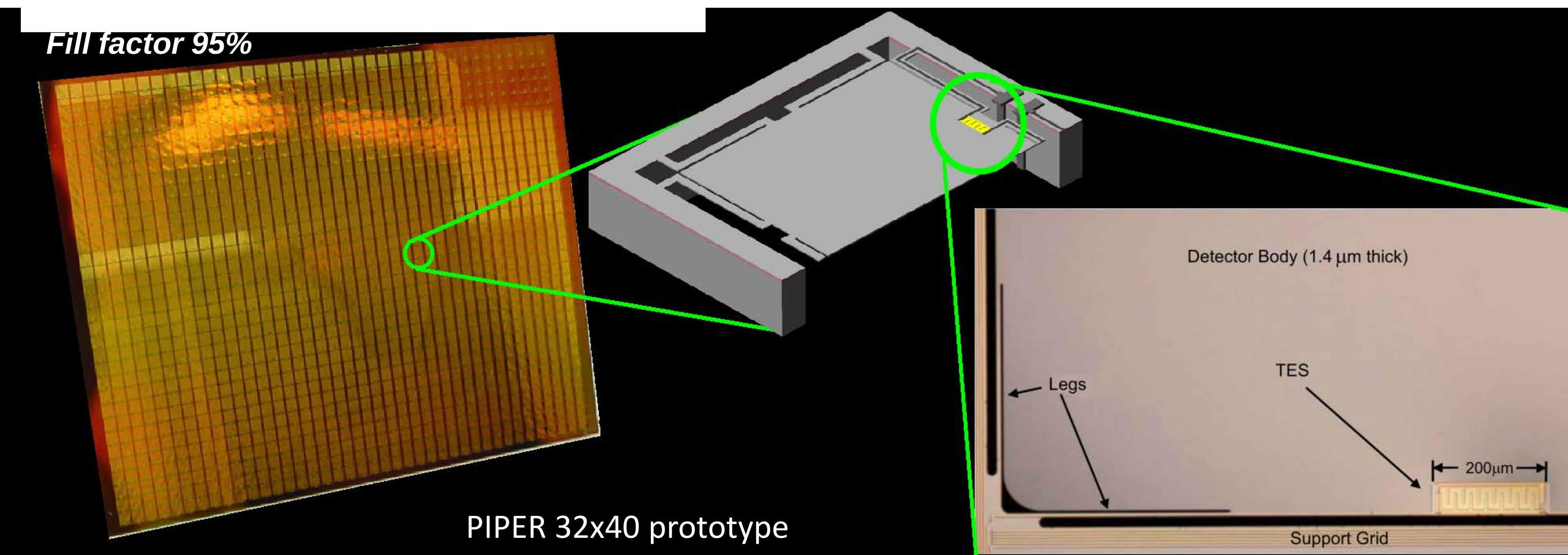
Goal: Detect Primordial B-Modes with r < 0.01

PIPER Detector Arrays



- Absorber-coupled TES bolometers at 100 mK
- 4 arrays each 32 x 40 pixels (5120 total)
- Backshort-Under-Grid (BUG) architecture
- Through-wafer vias put wiring UNDER array
- Bump-bond to NIST 32x40 tMUX chip

5120 detectors in each frequency band!



An open question

- Will large telescopes e.g. ACT/Polarbear/SPT be able to get l=20-100 well enough to get primordial B-modes?
- It depends on the modes one has to throw away in the analysis. South Pole has better atmosphere, Atacama has 90^0 cross linking.
- For T, l_{min} ~500 for ACT & SPT

What's Next at l>1000

HTT/Polarbear-I
(640 feeds
1280 dets)

Simons Array/PB3
(~20,000 dets 3 telescopes)

ACTPol
(1300 feeds)
3000 dets)

Advanced ACTPol
(~3800 feeds
16,000 dets)

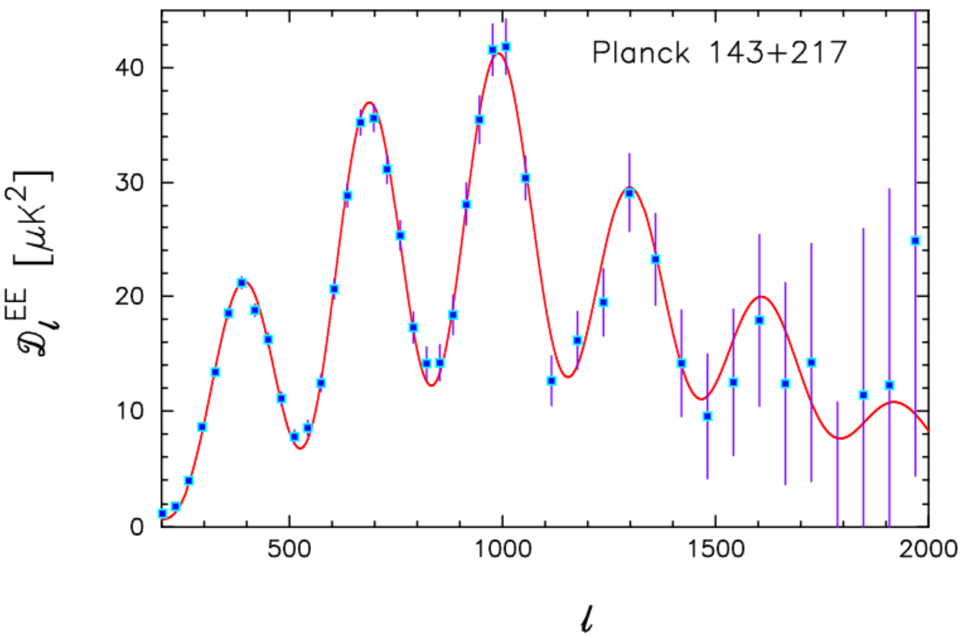
2013 2014 2015 2016

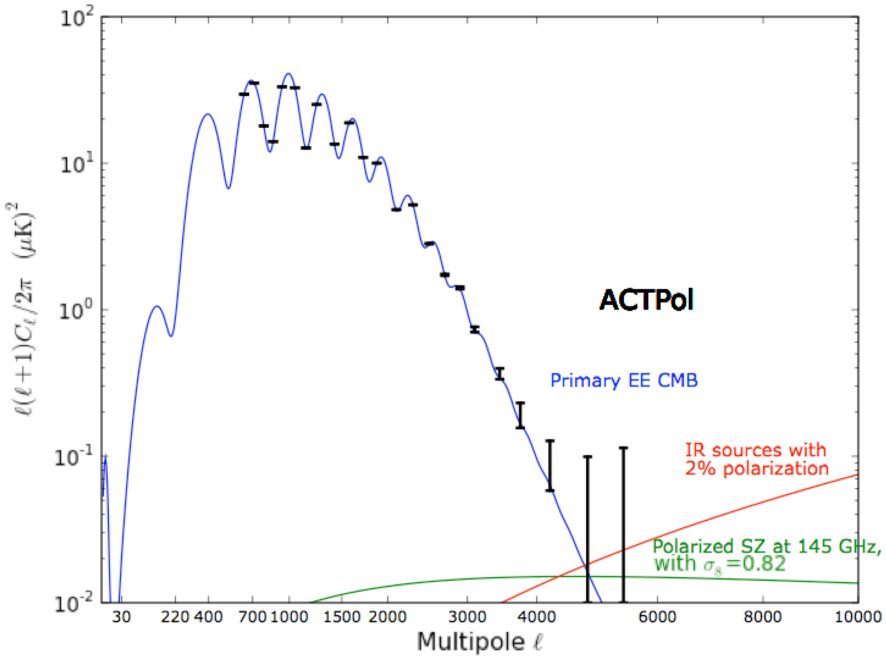
SPTPol
(~1000 feeds)
South Pole

SPT 3G
(~2500 feeds
15,000 dets)

ACTPol/SPTPol

Planck





Can look through foregrounds in EE at l>2000 to get at n_s

Science from l>1000+ Planck

- Early universe parameters… is there running?
- Sum of neutrino masses to ~0.06 eV.
- Early dark energy.
- Curvature.
- Structure formation through the ages—biases of various populations.
- Etc.

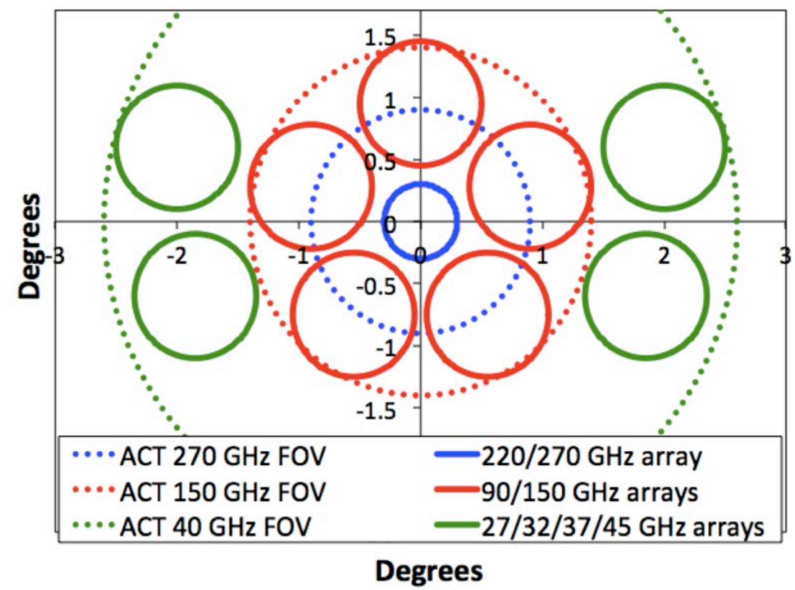
Advanced ACTPol

(Baseline design led by Michigan and Cornell)

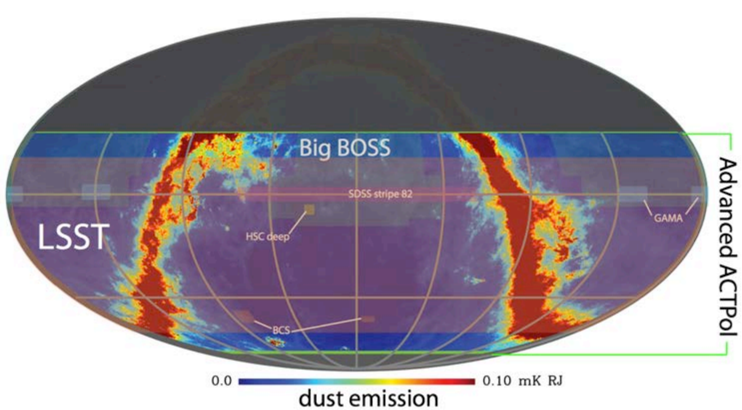
Unique Instrument Capabilities:

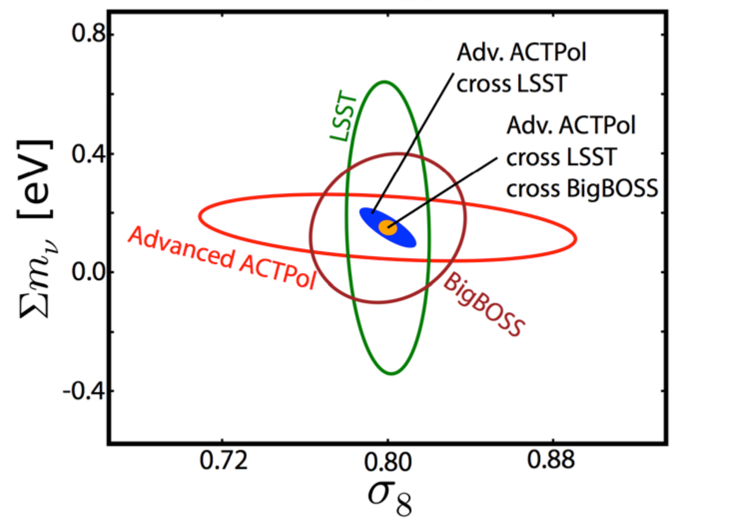
- Arcmin resolution across ~3/4 sky
- 4x optical throughput of ACTPol
- 30 – 300 GHz coverage
- ~ 16,000 multichroic detectors
- Polarization modulation

Baseline optics layout on ACT



Sky Coverage

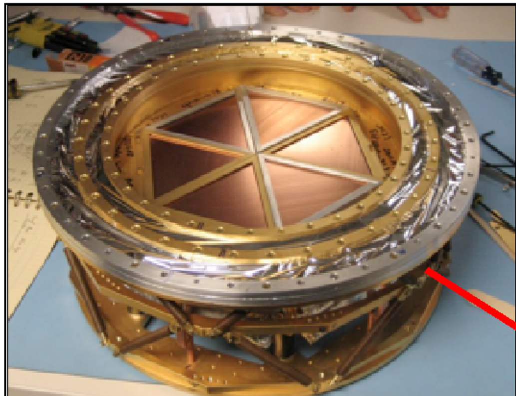




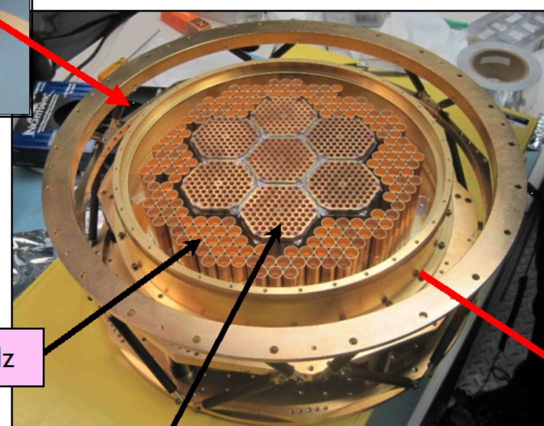
SPT future plans

	Area (deg^2)	Beamsize (arcmin)	Map Noise (uK-arcmin)
WMAP	40,000	**13**	**300**
Planck	40,000	**5**	**45**
SPT	2500	**1**	**18**
SPTpol	600	**1**	**5**
SPT-3G	2500	**1**	**2**

SPT-SZ (done)
960 TES detectors



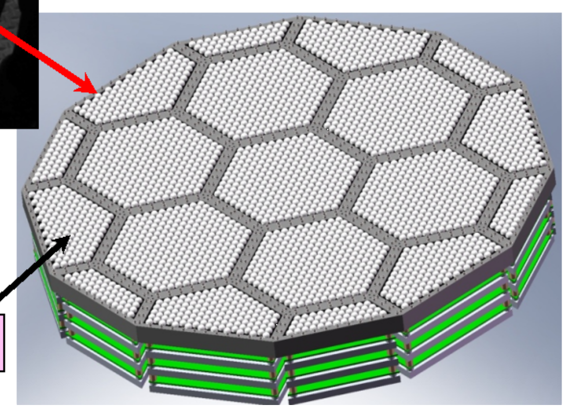
SPTpol (ongoing)
1600 detectors



360 detectors at 100 GHz

1176 detectors at 150 GHz

SPT-3G (planned for 2016)
15,234 detectors

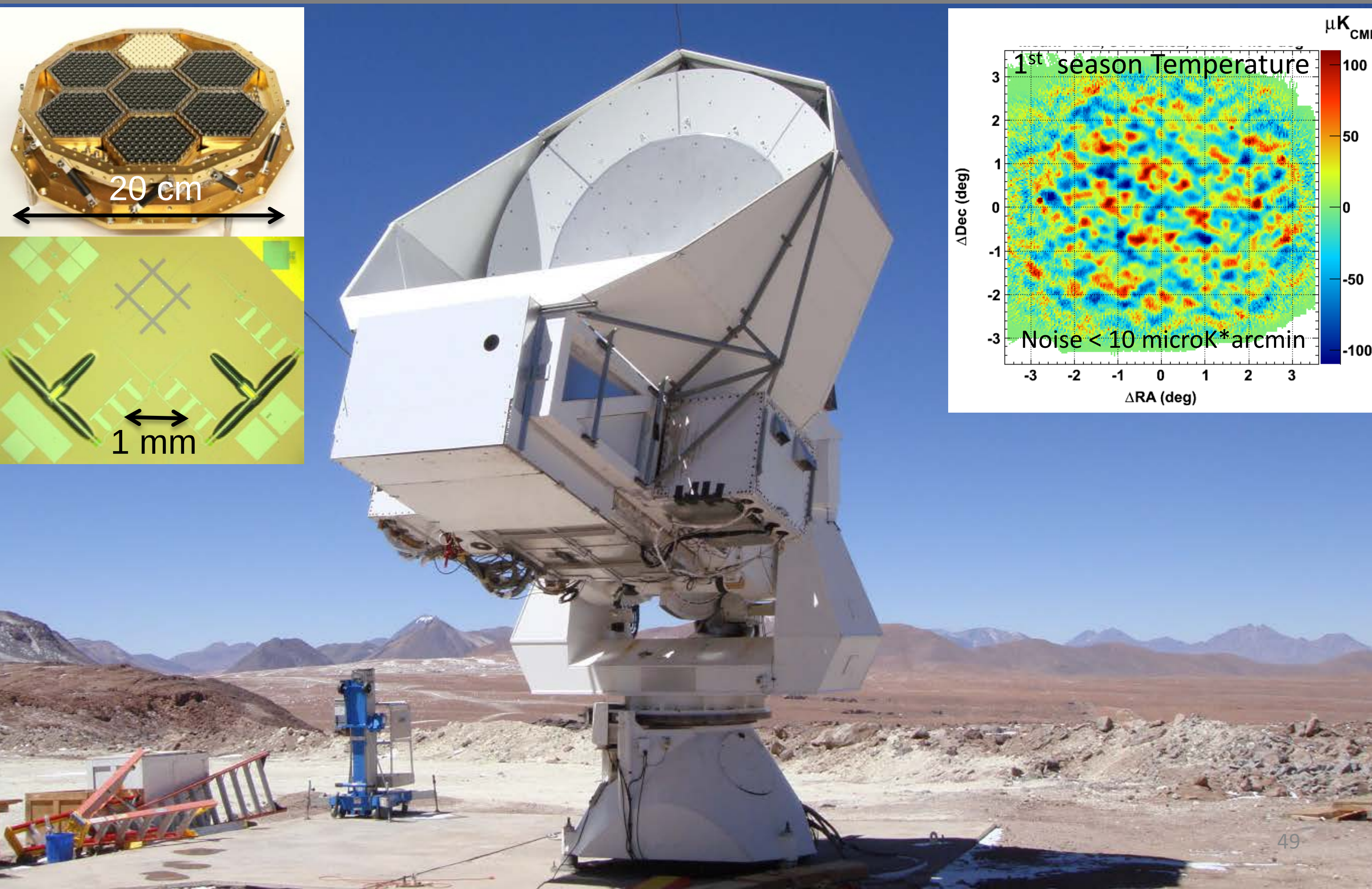


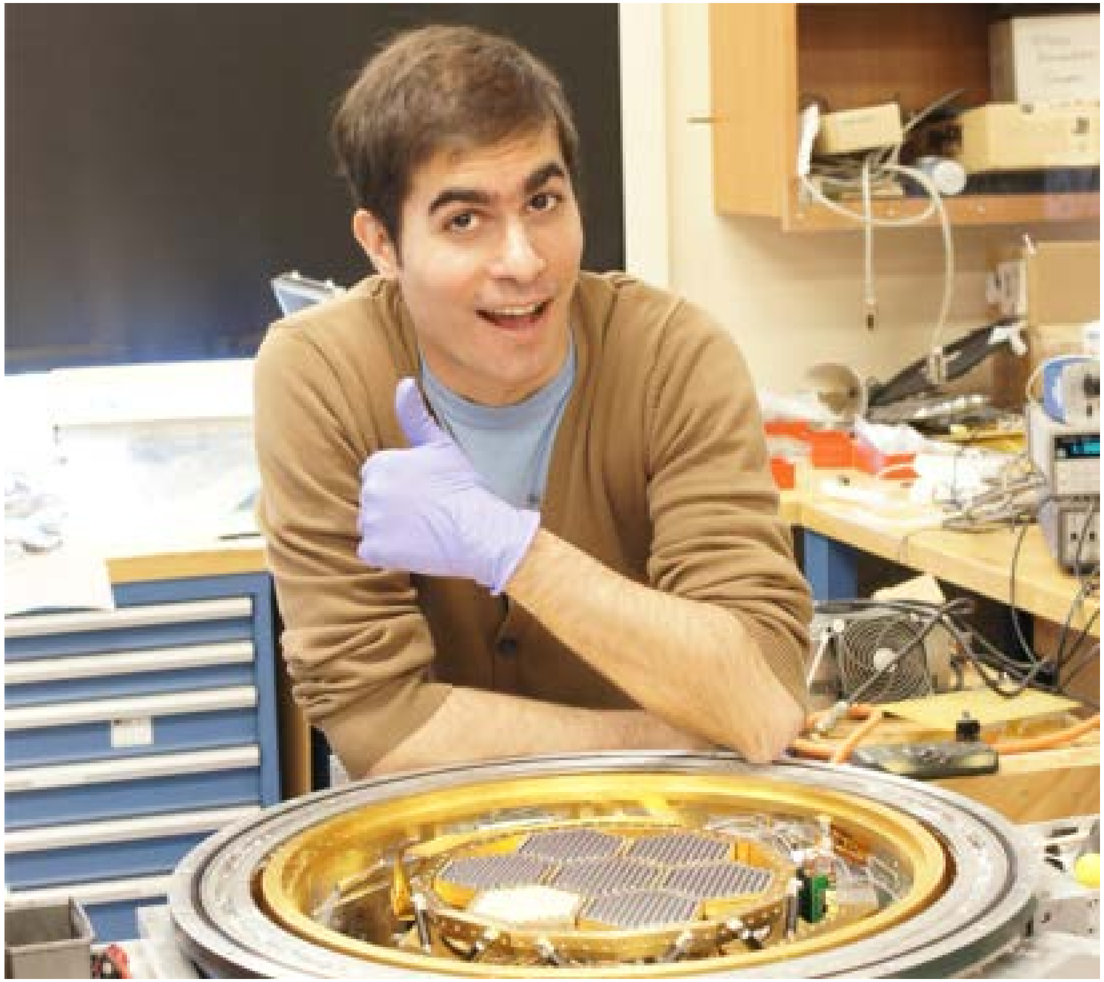
3-band pixels at 90/150/220 GHz

U.S. DEPARTMENT OF ENERGY
Office of Science

POLARBEAR – CMB Polarization

APC, Berkeley, Cardiff , C.U. Boulder, Dalhousie, Imperial, IPMU, KEK, McGill, UCSD





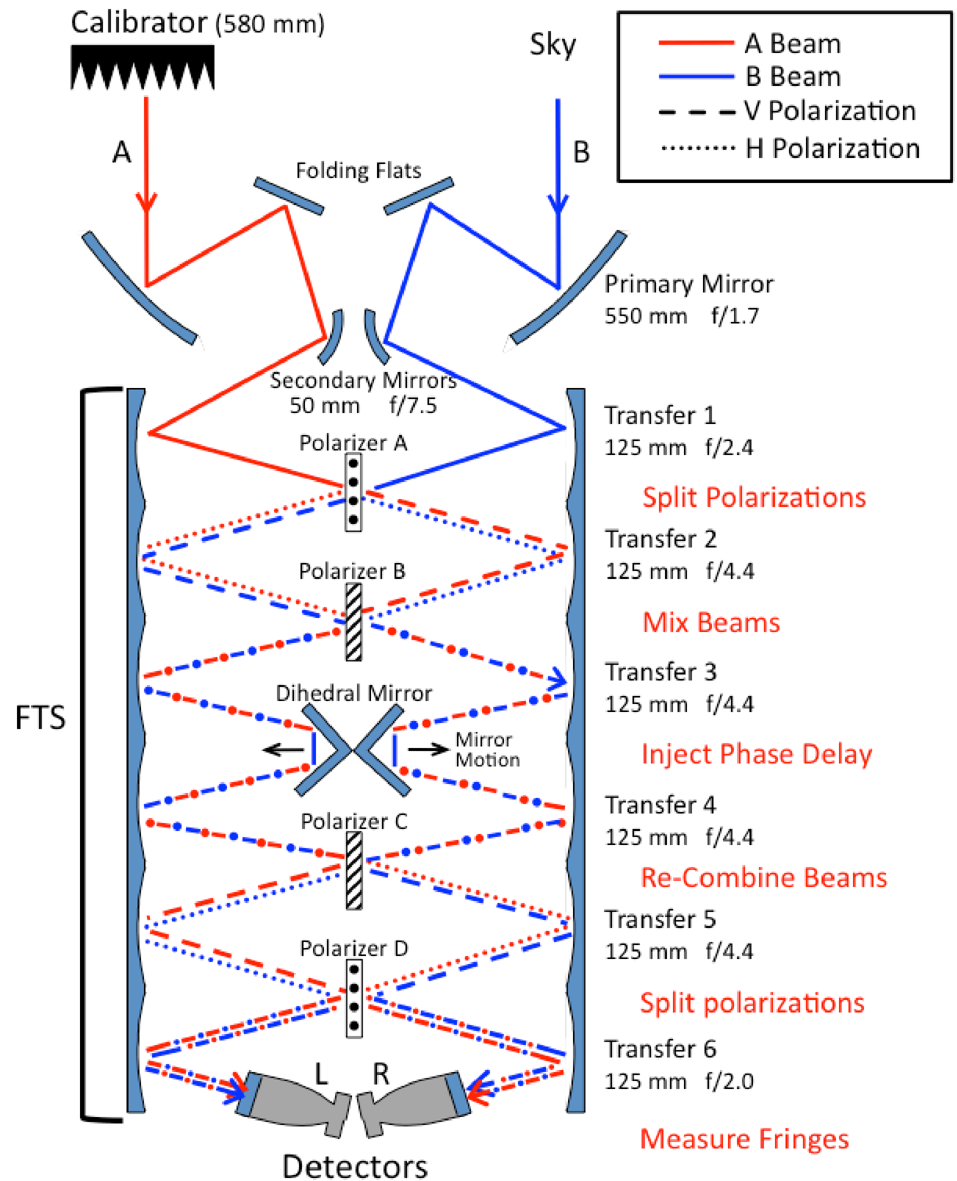
Another CMB Satellite? Yes!

PIXIE (NASA/GSFC)

EPIC (NASA/JPL)

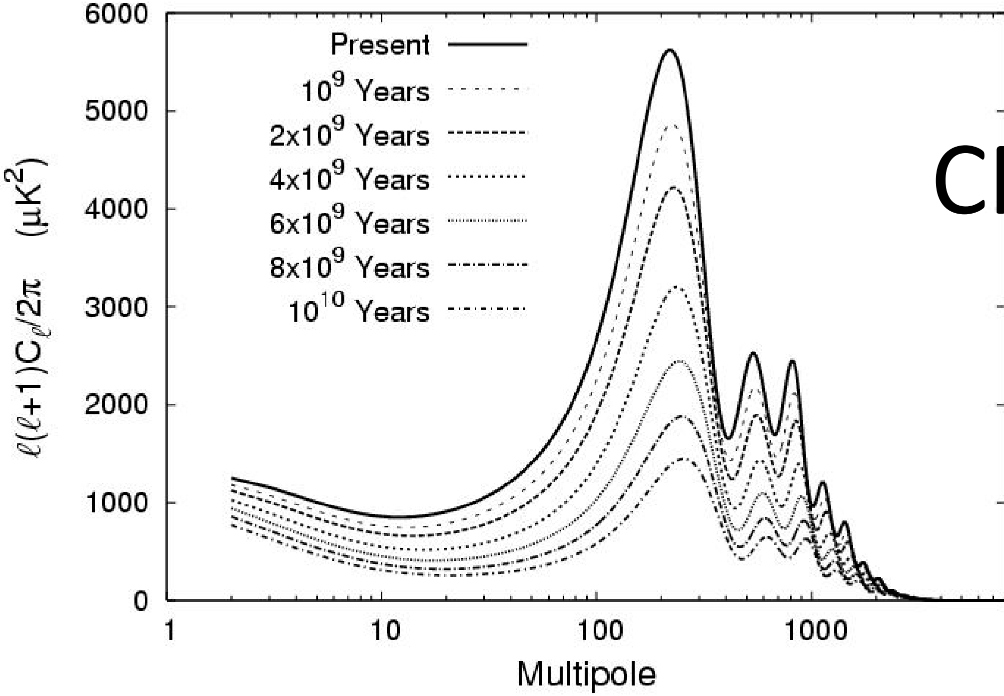
LiteBIRD (KEK)

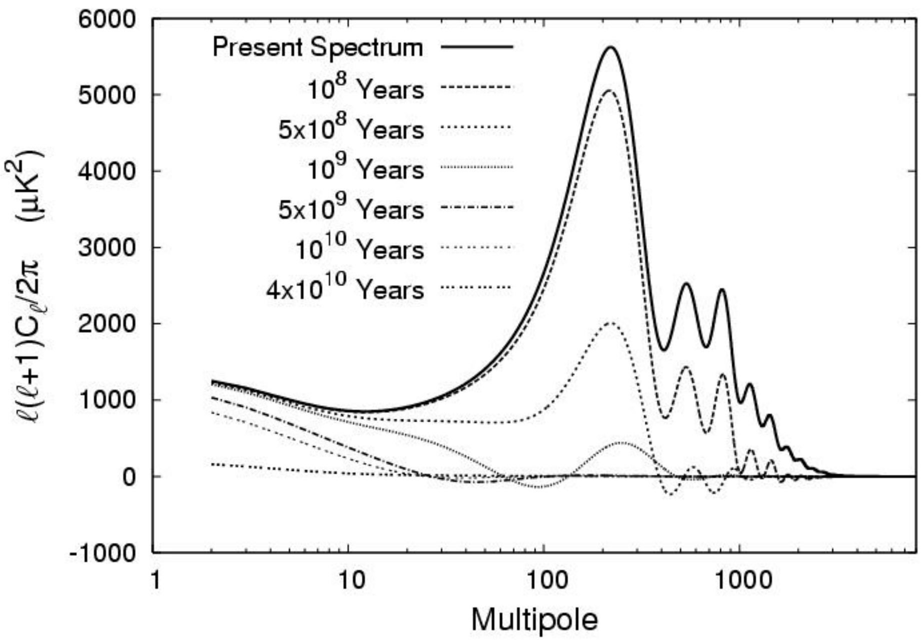
CoRE (ESA)



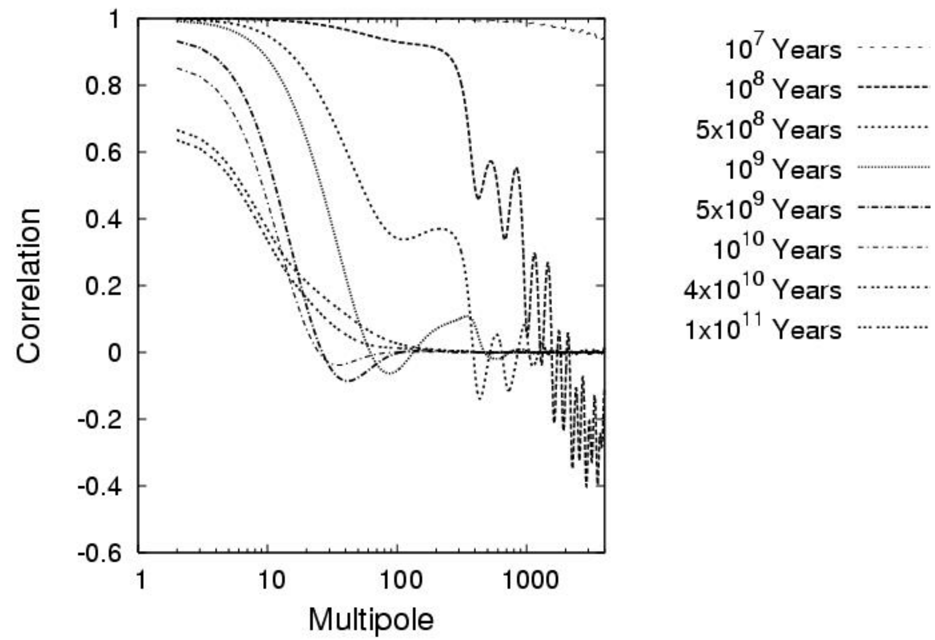
CMB in the Expanding Universe

Stuart Lange,
Senior Thesis, 2007





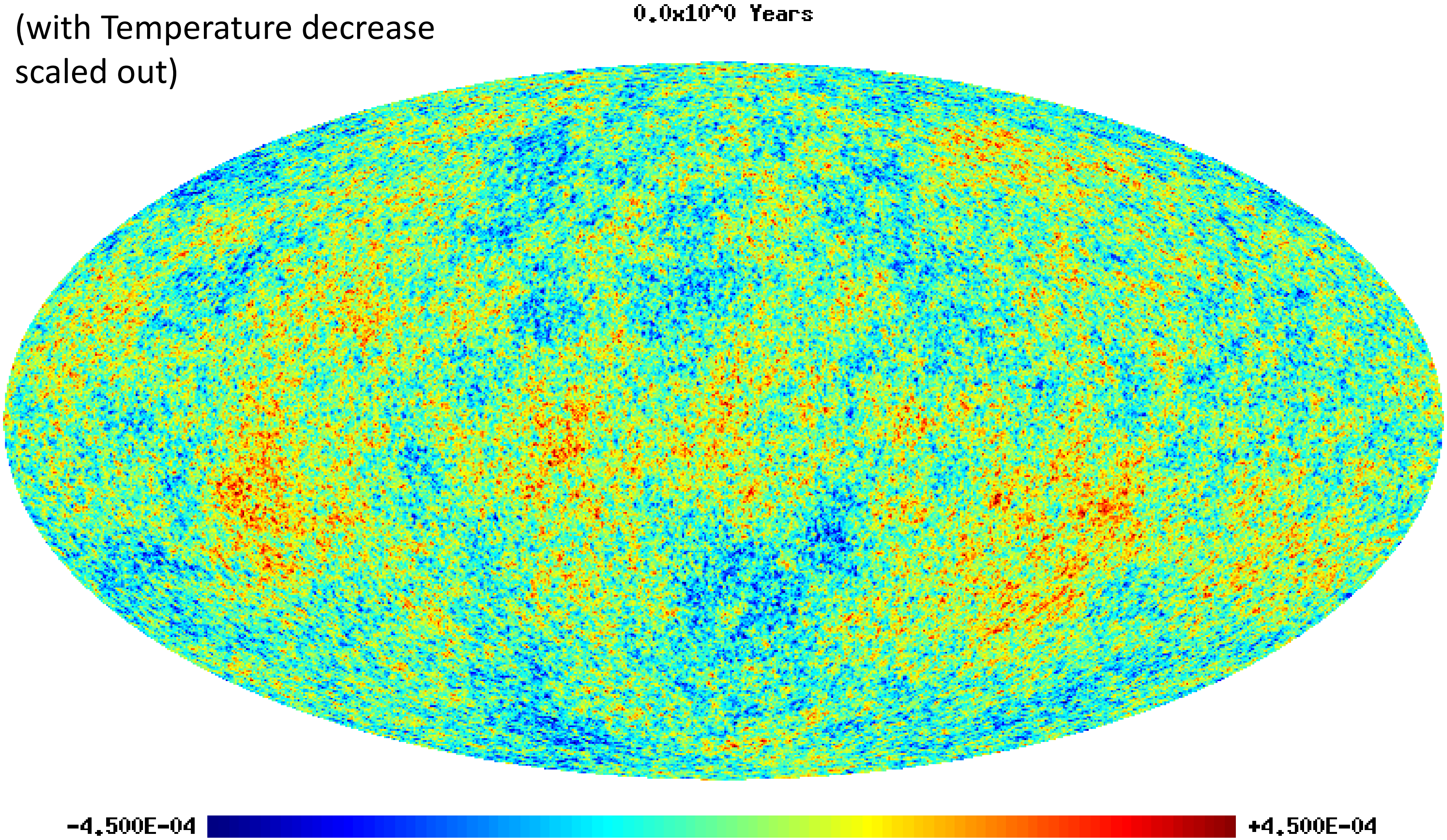
Temp decrease scaled out.



Correlation with current CMB.

Expanding CMB Photosphere

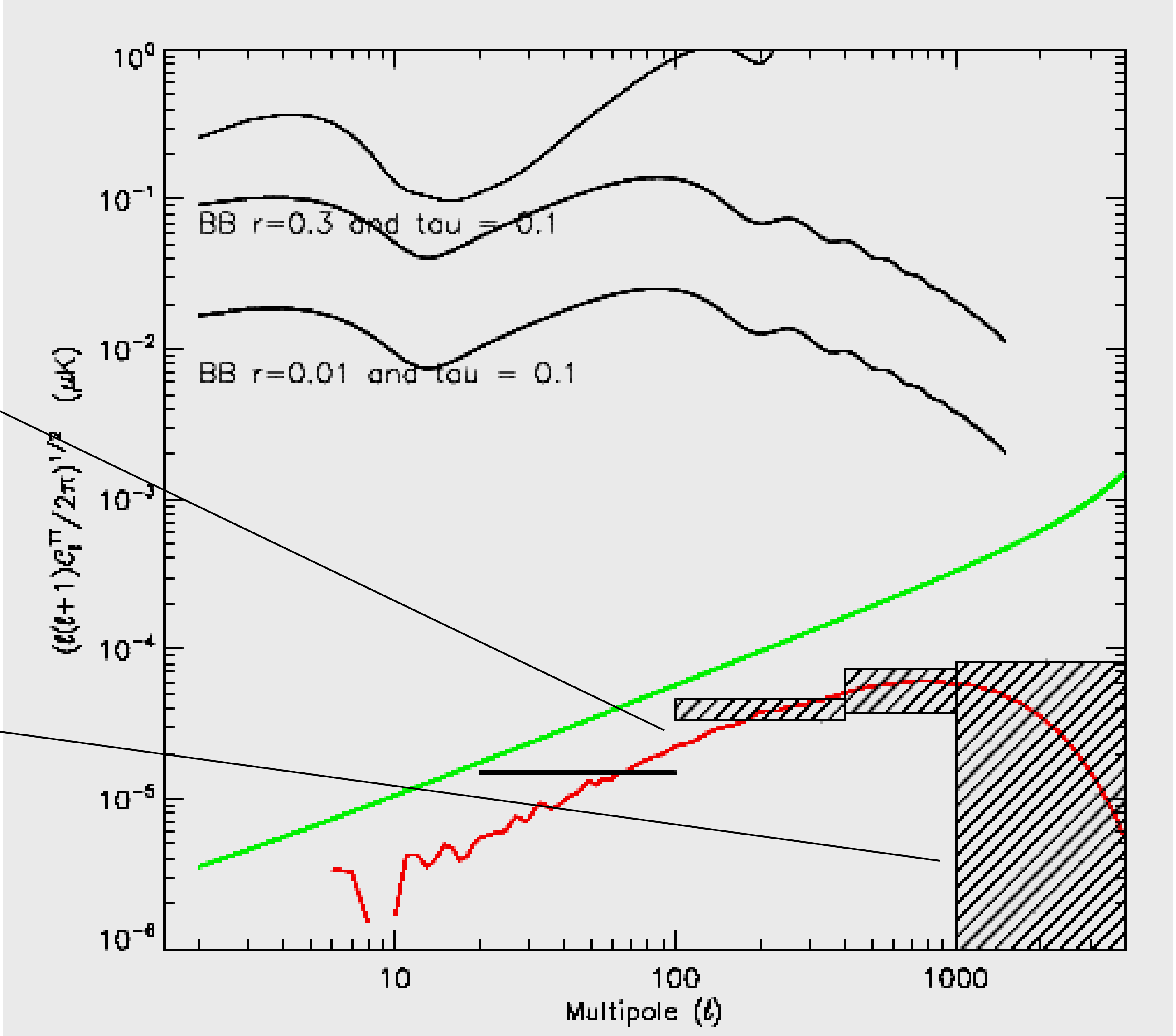
(with Temperature decrease scaled out)

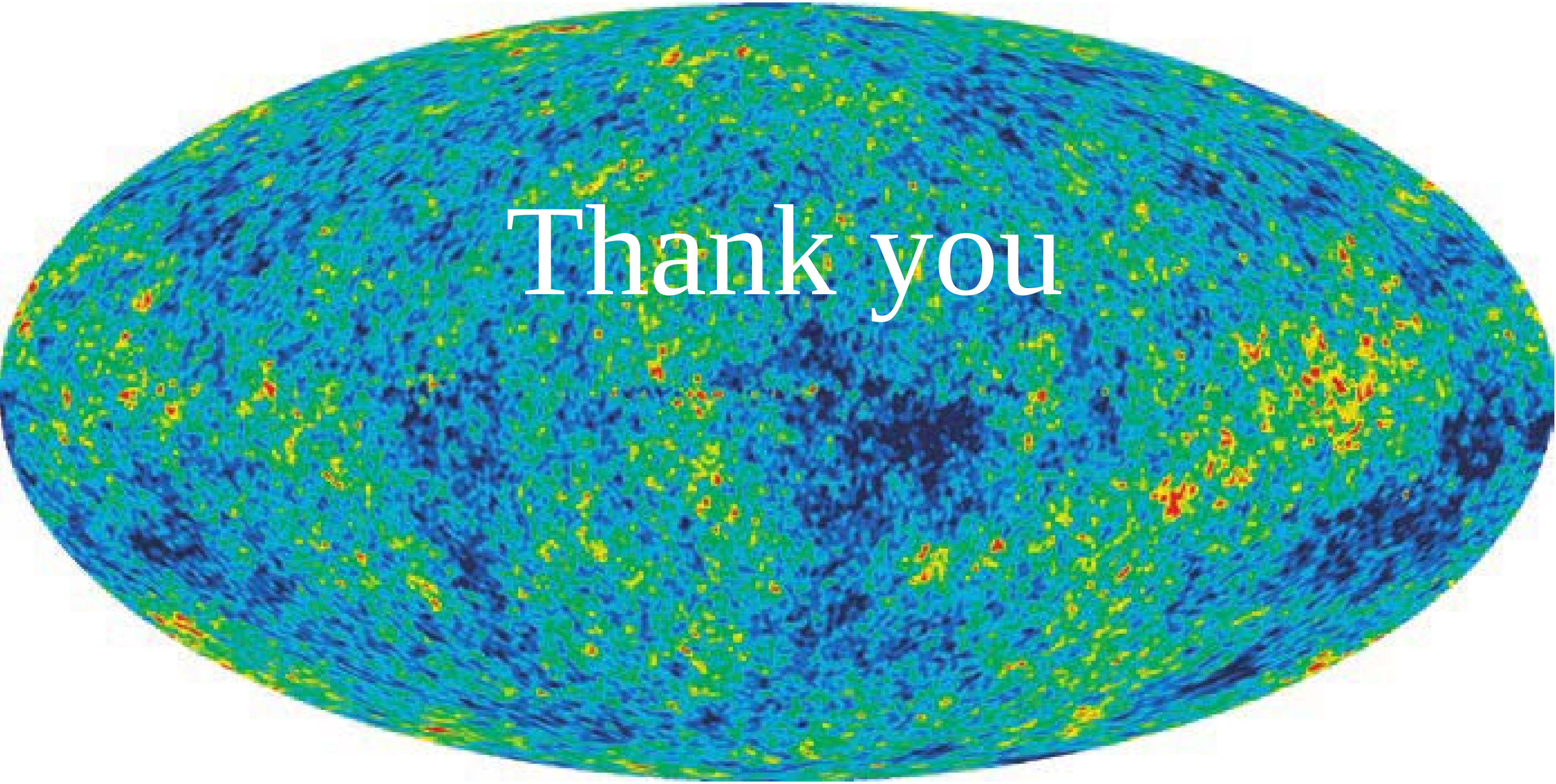


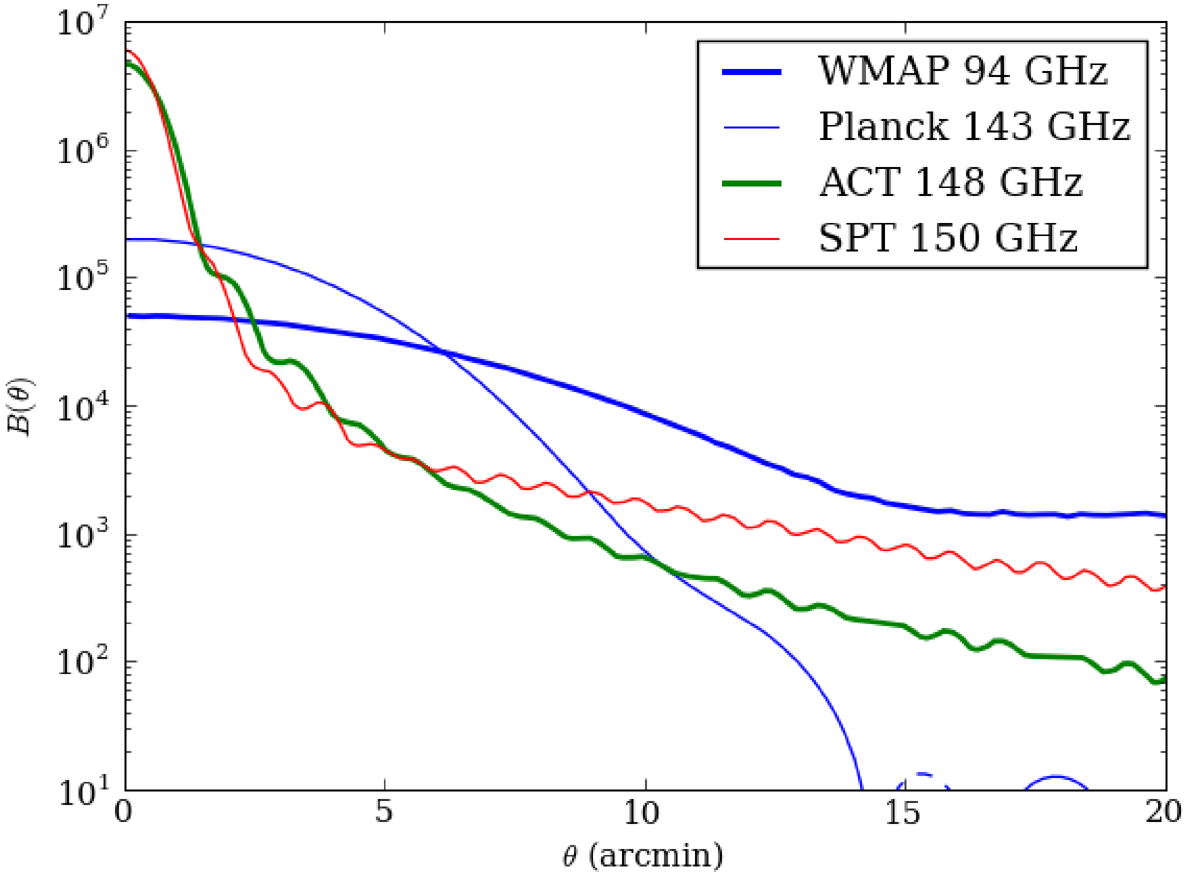
An Experiment for the Century

Power spectrum of difference between two maps made 100 years apart.

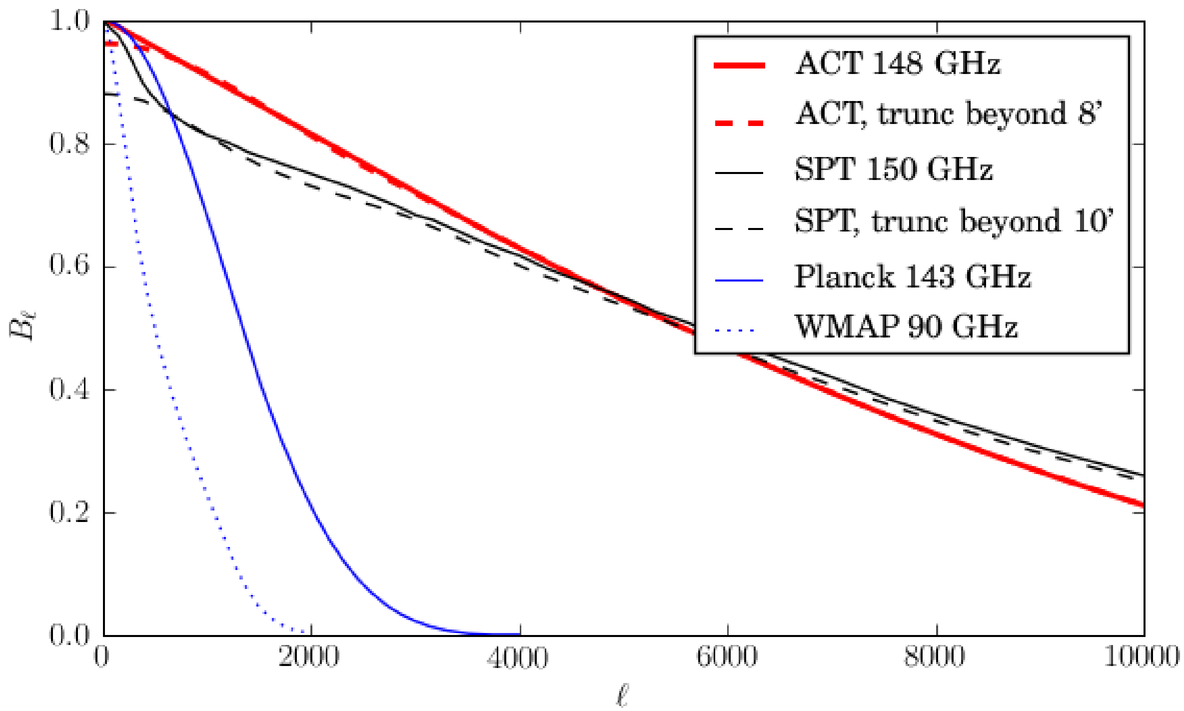
Error bars with a 3000x3000 array of detectors.




Thank you



WMAP 94 GHz
Planck 143 GHz
ACT 148 GHz
SPT 150 GHz
$B(\theta)$
θ (arcmin)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0
5
10
15
20


ACT 148 GHz
ACT, trunc beyond 8'
SPT 150 GHz
SPT, trunc beyond 10'
Planck 143 GHz
WMAP 90 GHz
B_ℓ
ℓ
0.0
0.2
0.4
0.6
0.8
1.0
0
2000
4000
6000
8000
10000