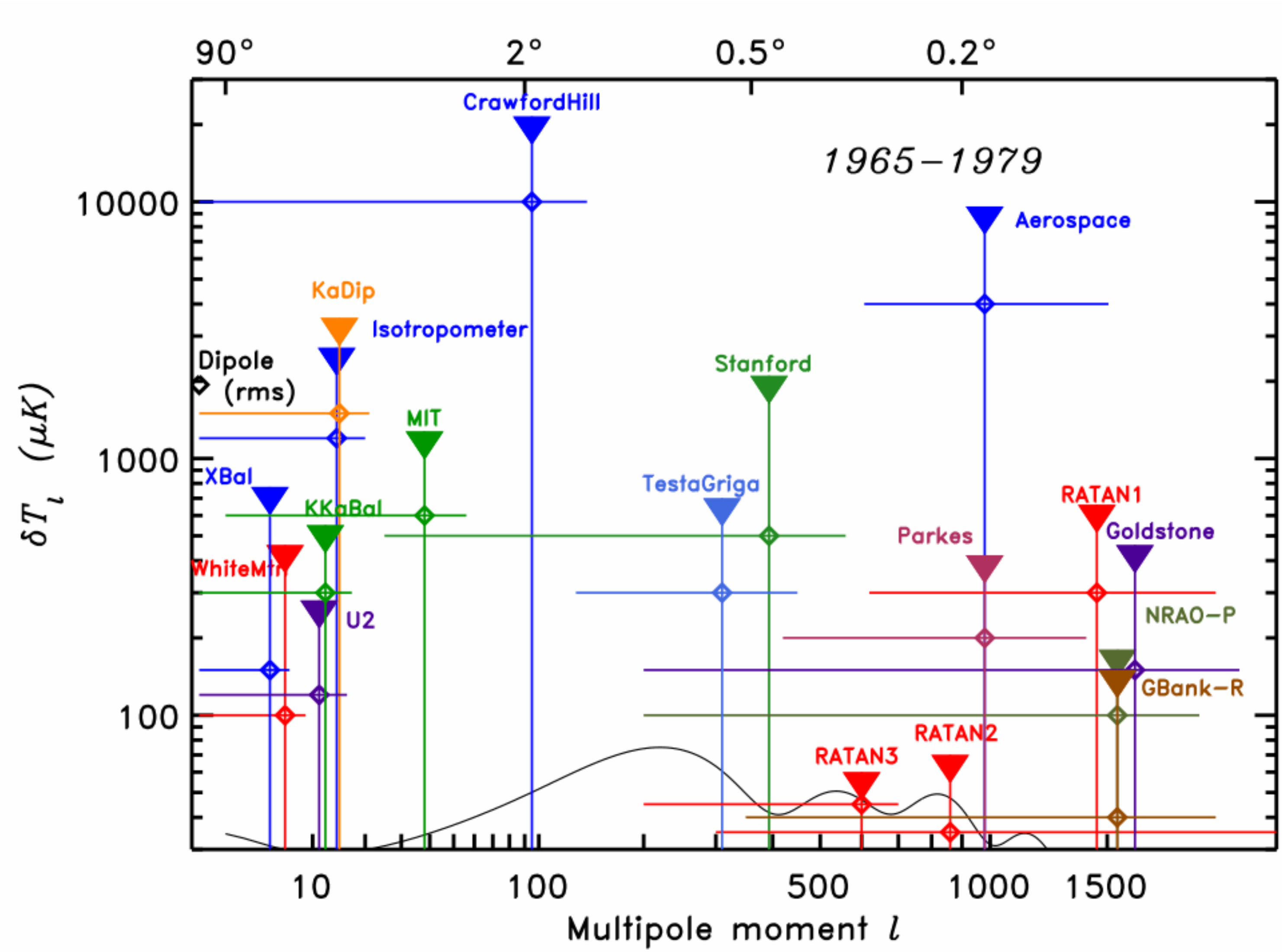
Astro215hf
CMB Experiments, Surveys and Analysis
Lecture 3

Clem Pryke

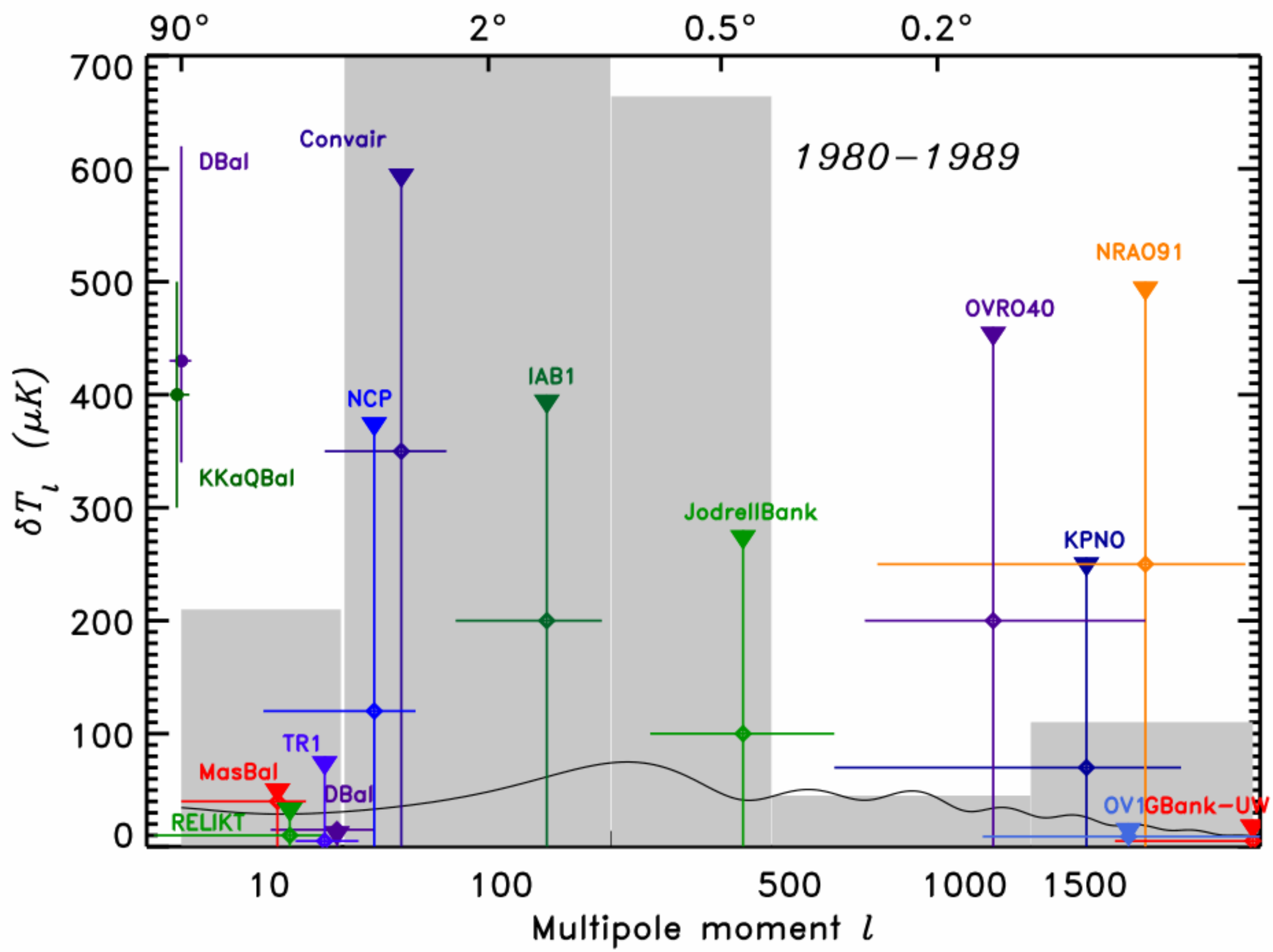
Feb 16 2016

History of CMB Anisotropy Results

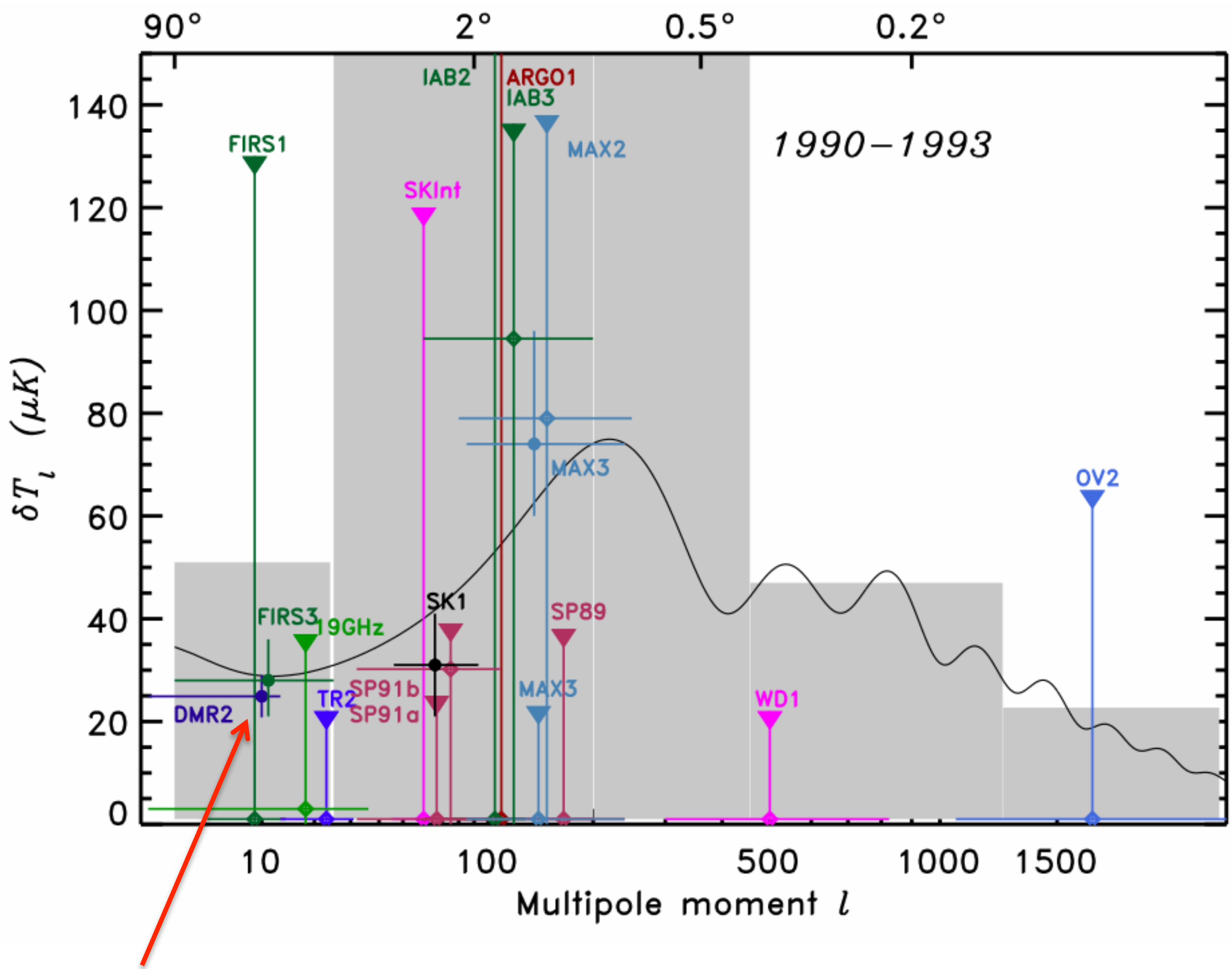
- As soon as it was established that there is a CMB it was realized that there ought to be CMB anisotropy – the "seeds of large scale structure"
- The following is a very cool sequence of plot from Lyman Page (Princeton) showing the build up sensitivity to the temperature anisotropy over time.
- Gray boxes show the average of all available data at each epoch



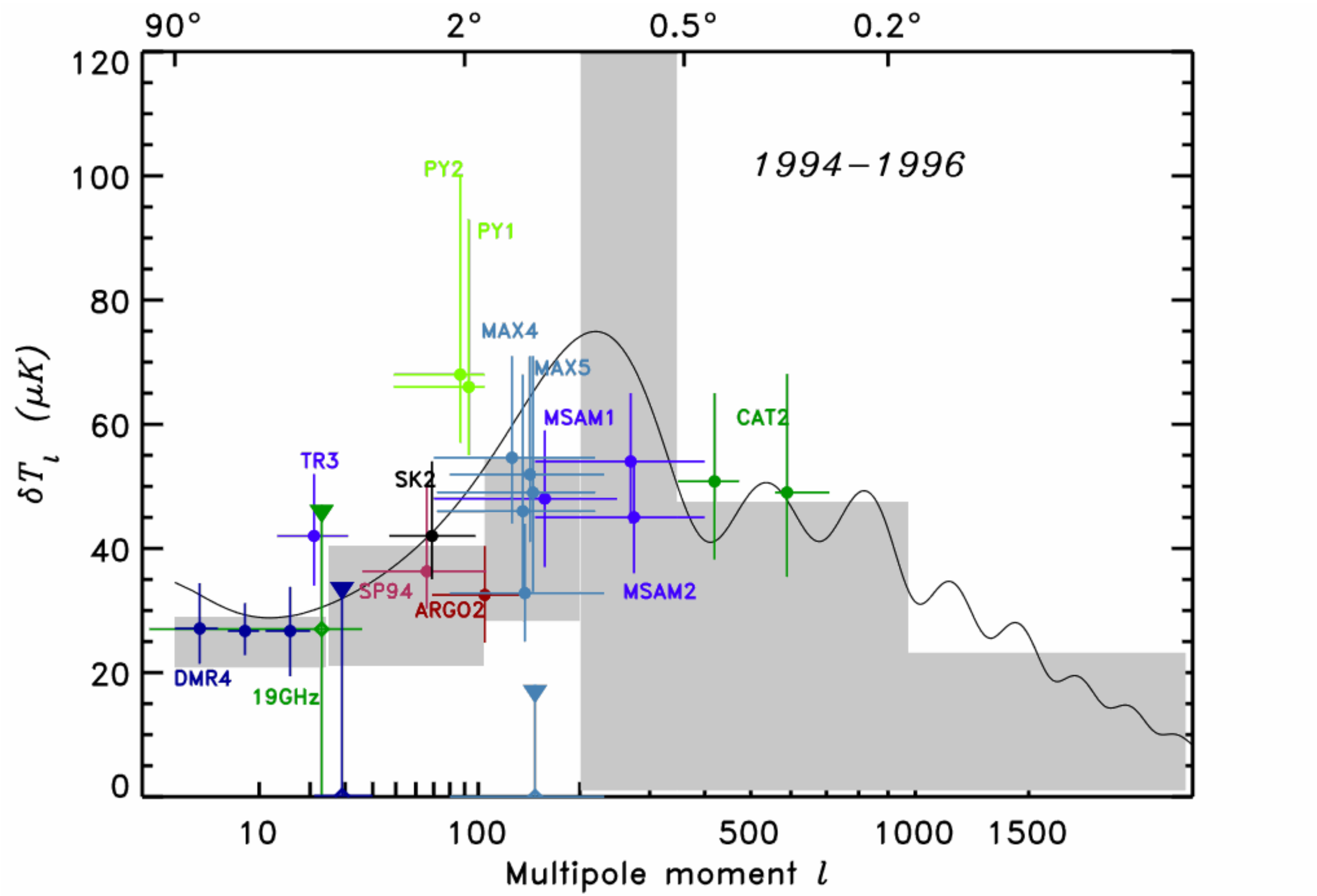
90°
2°
0.5°
0.2°
1965–1979
CrawfordHill
Aerospace
KaDip
Isotropometer
Dipole
(rms)
Stanford
MIT
XBal
KKaBal
TestaGriga
RATAN1
Parkes
Goldstone
WhiteMtn
U2
NRAO-P
GBank-R
RATAN3
RATAN2
10000
1000
100
δT_l (μK)
10
100
500
1000
1500
Multipole moment l



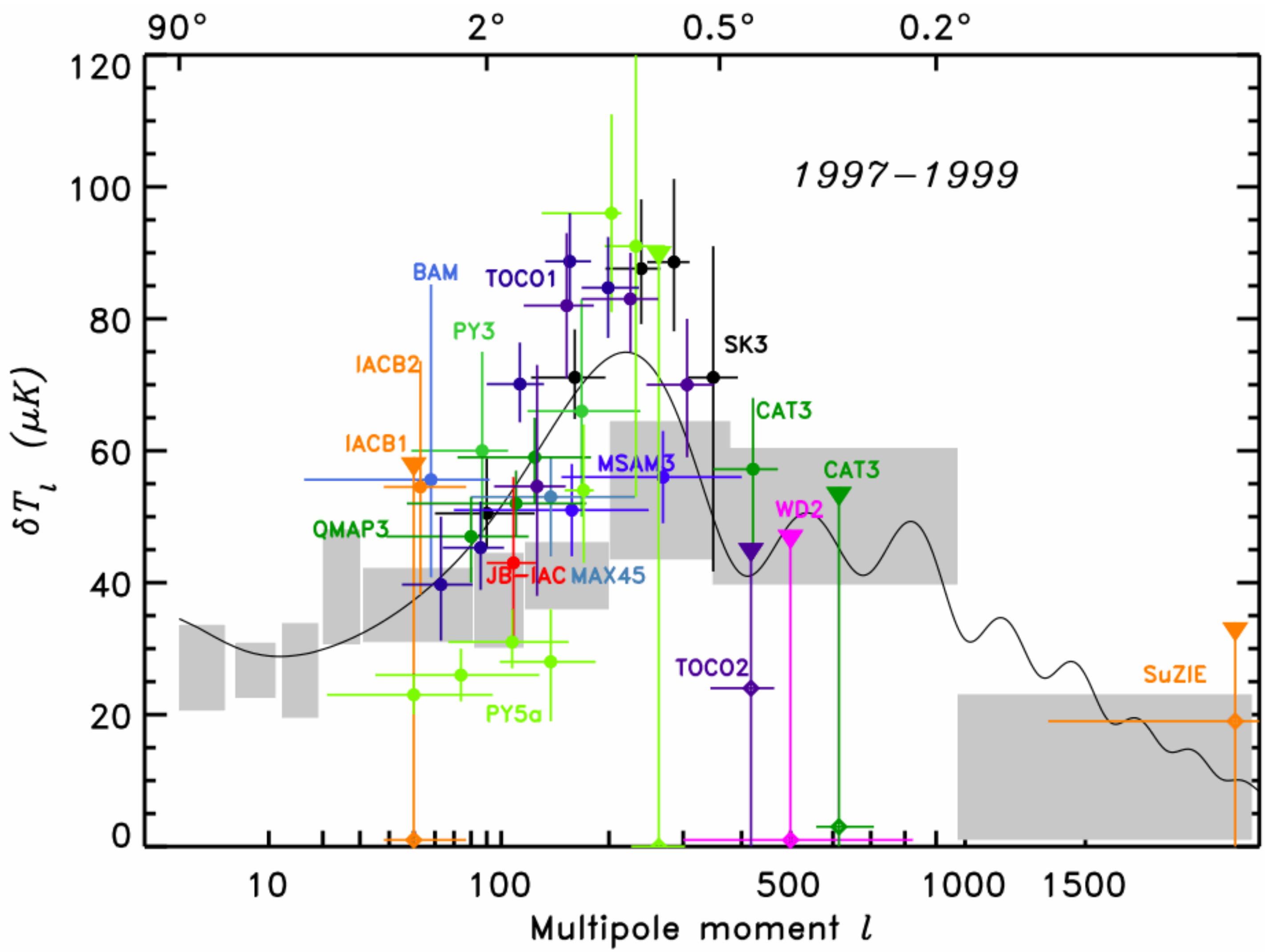
90°
2°
0.5°
0.2°
700
600
500
400
300
200
100
0
δT_l (μK)
1980−1989
DBal
Convair
KKaQBal
NCP
IAB1
JodrellBank
OVRO40
NRAO91
KPNO
TR1
MasBal
DBal
RELIKT
OV1
GBank-UW
10
100
500
1000
1500
Multipole moment l



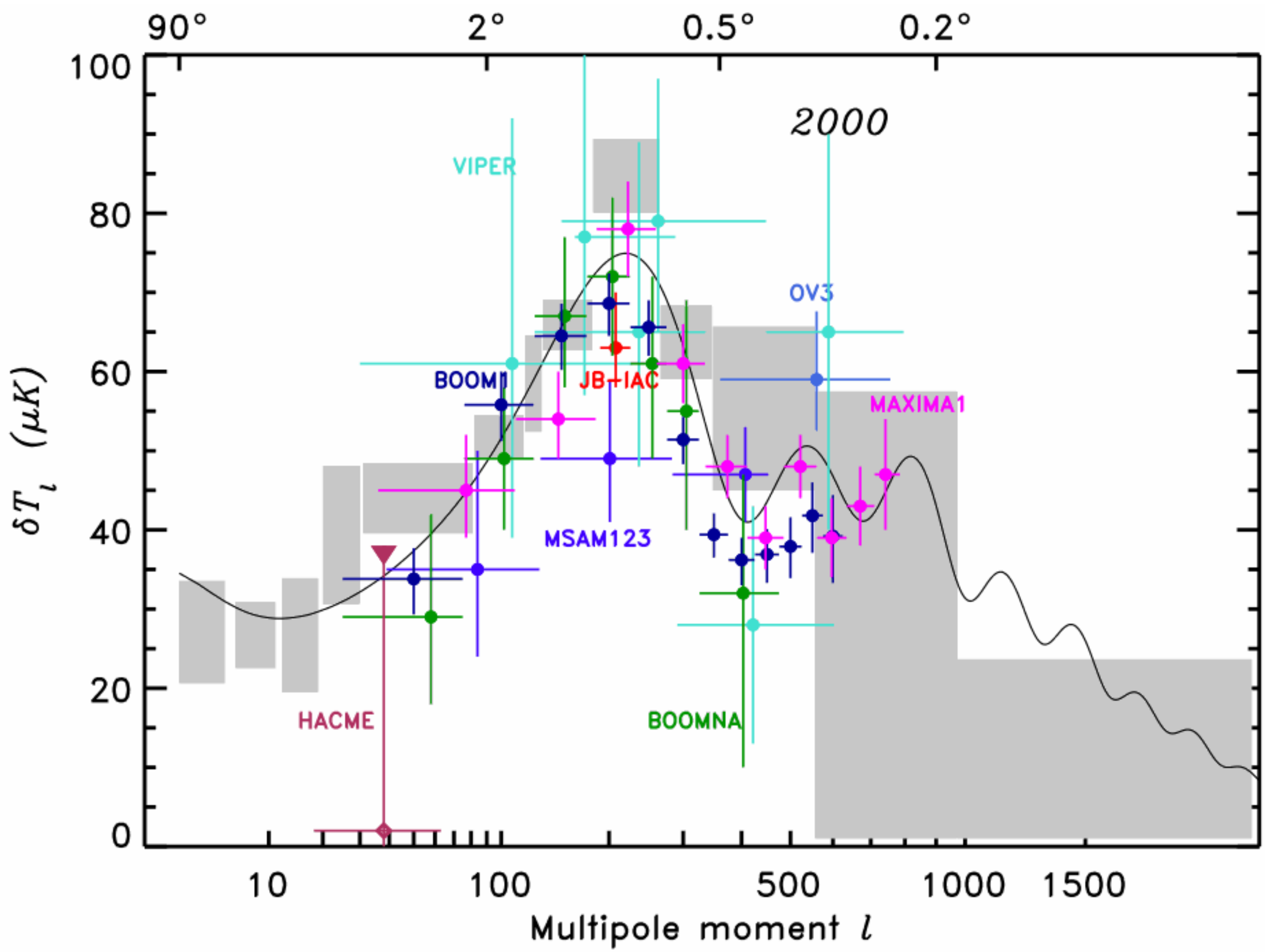
First detection by COBE DMR in 1992 at large angular scales



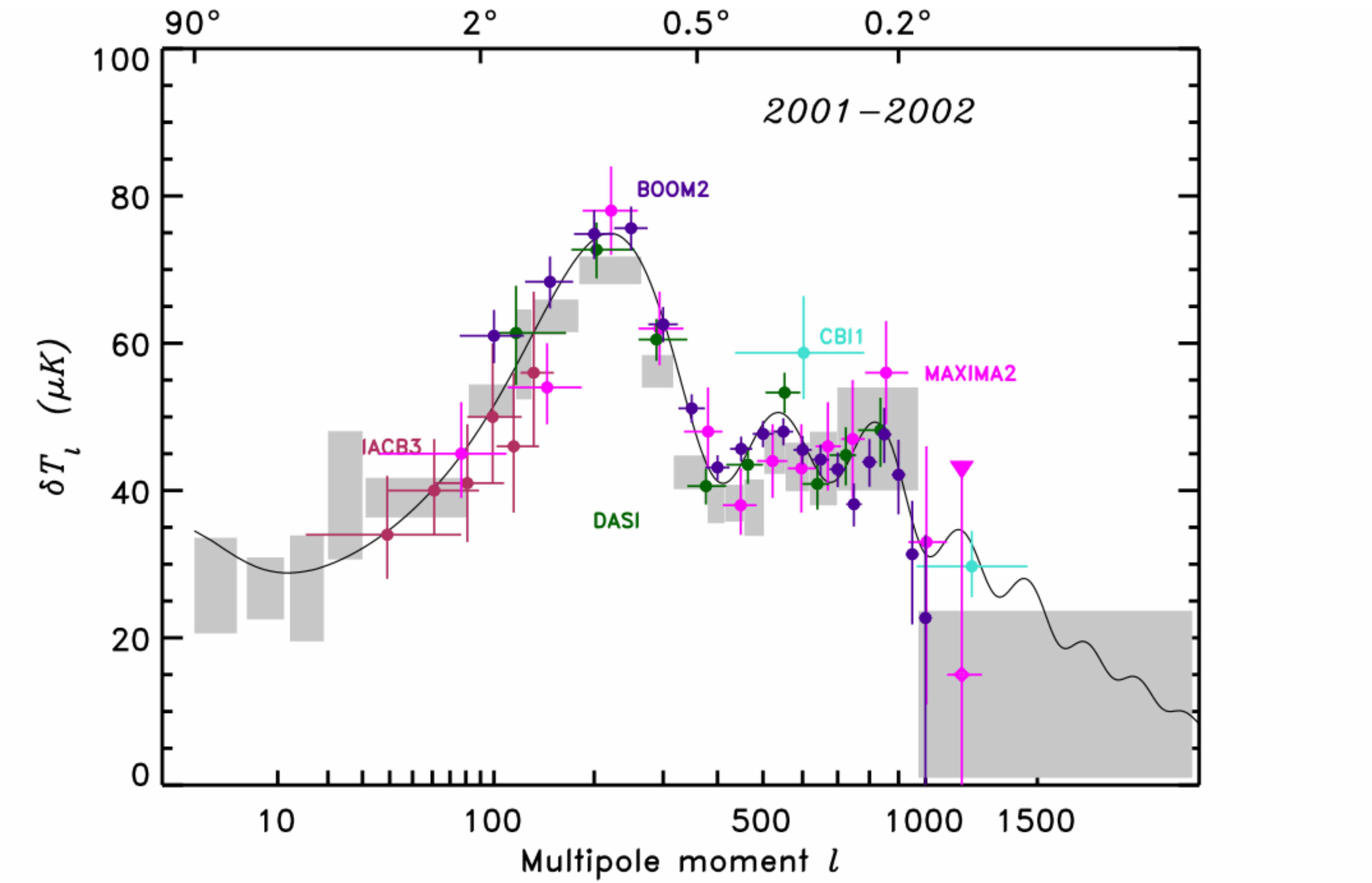
90°
2°
0.5°
0.2°
1994–1996
PY2
PY1
MAX4
MAX5
MSAM1
CAT2
TR3
SK2
SP94
ARGO2
MSAM2
DMR4
19GHz
δT_l (μK)
Multipole moment l
0
20
40
60
80
100
120
10
100
500
1000
1500



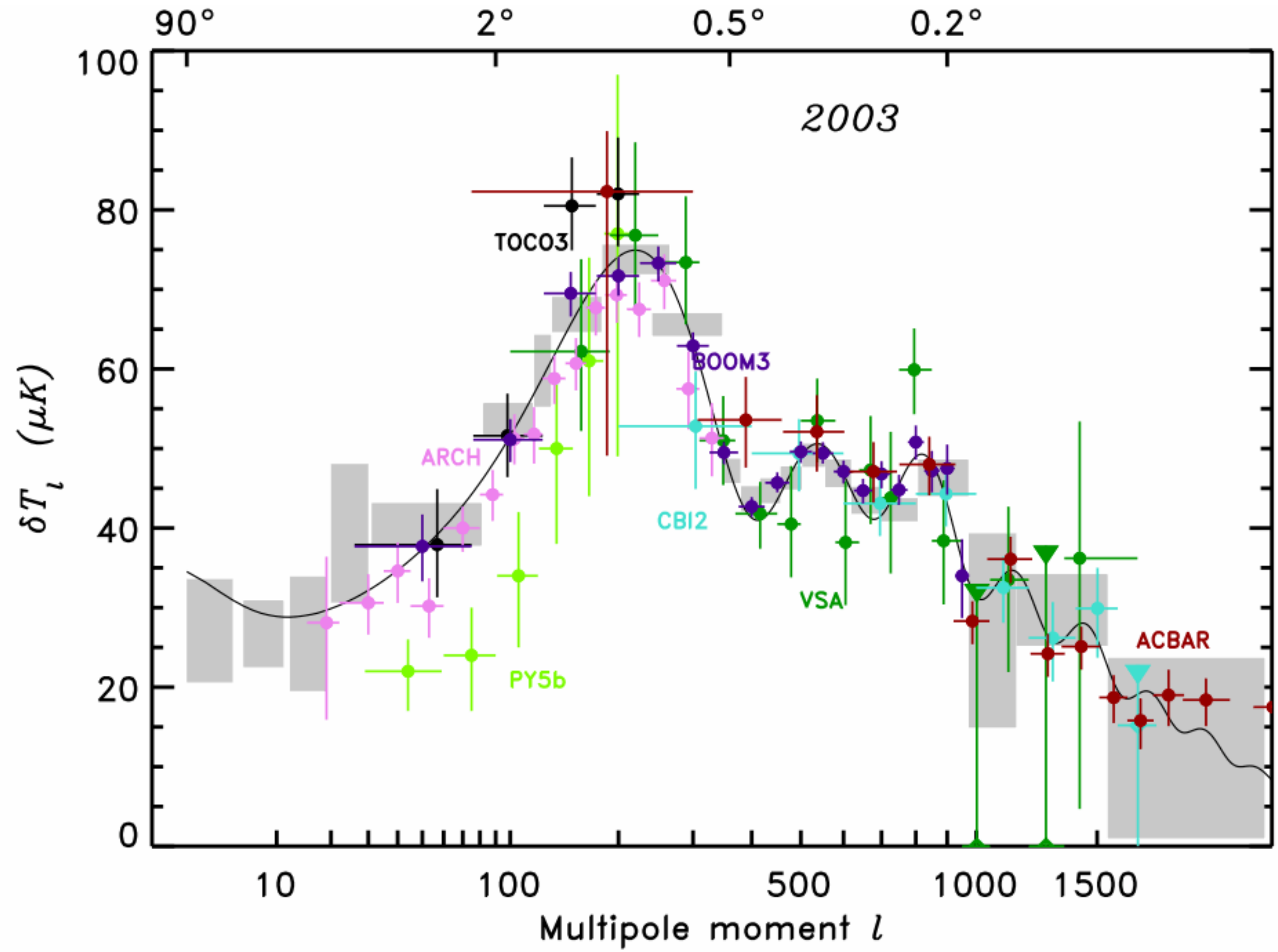
90°
2°
0.5°
0.2°
120
100
80
60
40
20
0
1997–1999
δT_l (μK)
BAM
TOCO1
PY3
IACB2
SK3
CAT3
IACB1
MSAM3
CAT3
WD2
QMAP3
JB–IAC
MAX45
TOCO2
SuZIE
PY5a
10
100
500
1000
1500
Multipole moment l



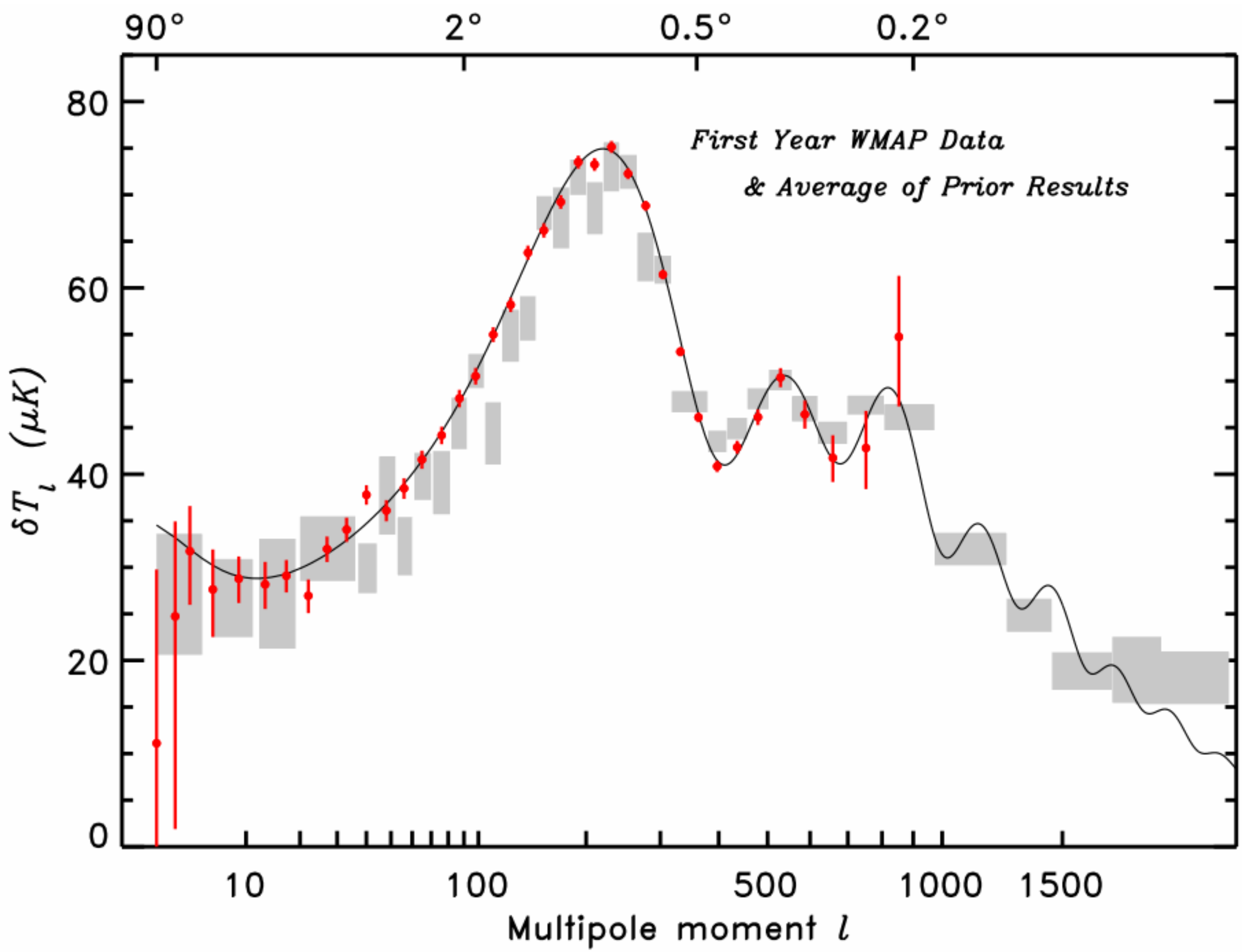
90°
2°
0.5°
0.2°
2000
100
80
60
40
20
0
δT_l (μK)
VIPER
OV3
BOOM1
JB+IAC
MAXIMA1
MSAM123
HACME
BOOMNA
10
100
500
1000
1500
Multipole moment l



Boomerang and Maxima were balloon based experiments

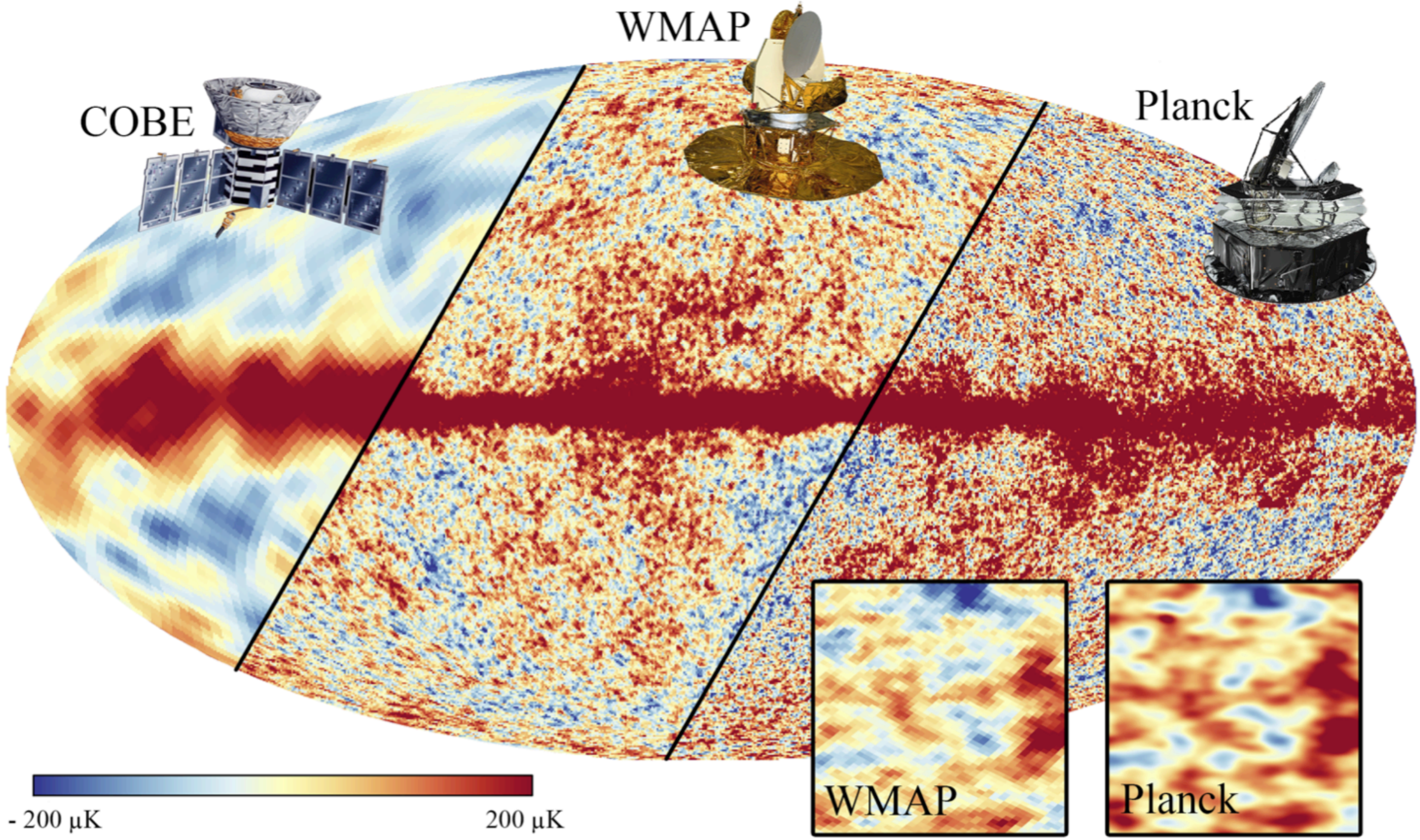


90°
2°
0.5°
0.2°
2003
TOCO3
BOOM3
ARCH
CBI2
VSA
ACBAR
PY5b
δT_l (μK)
100
80
60
40
20
0
10
100
500
1000
1500
Multipole moment l



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

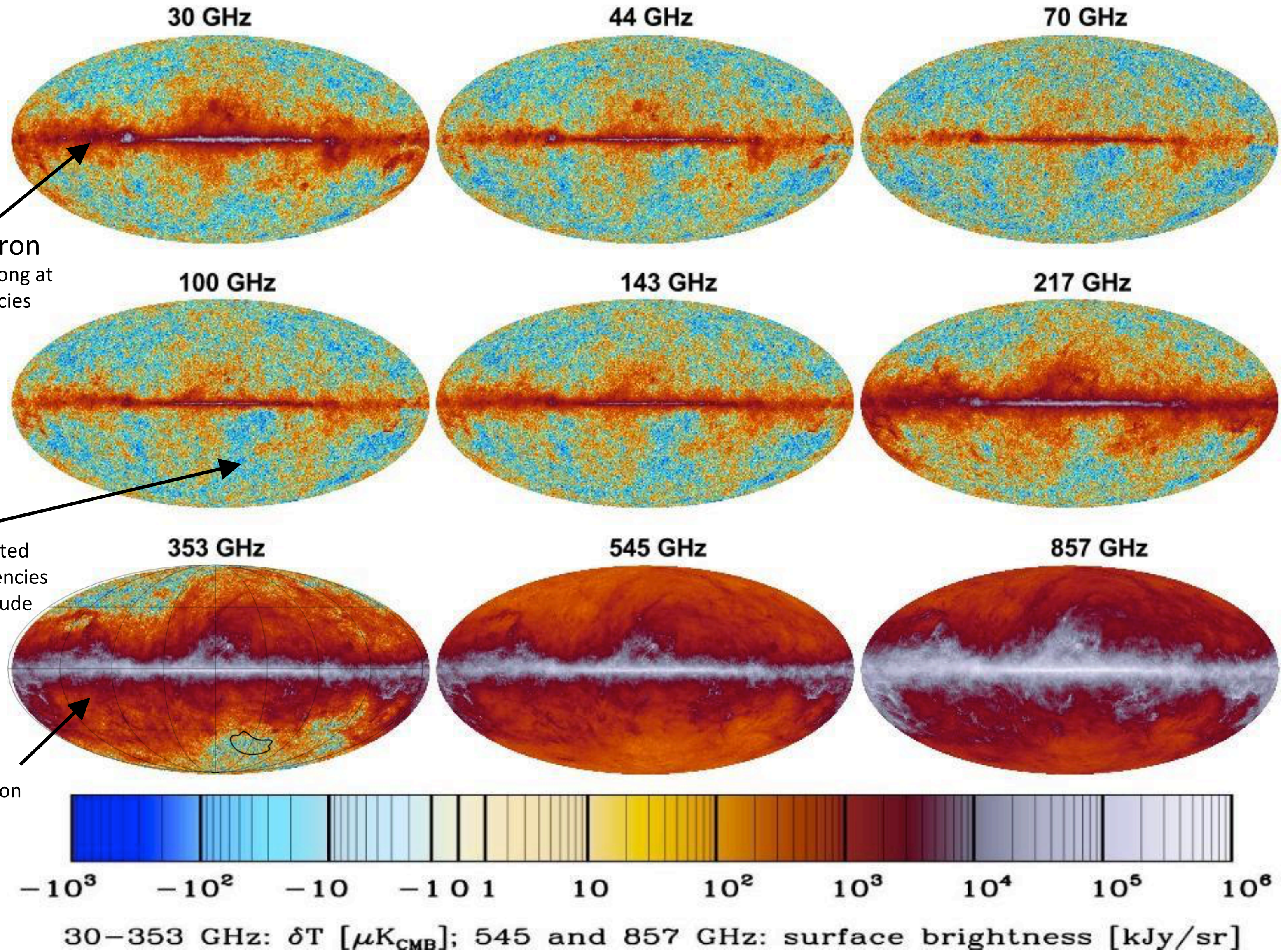
CMB Space Missions



graphic: J. Gudmundsson

- Planck is the third space mission to observe the CMB: An ESA-led mission Launched 14 May 2009, mission completed Oct 2013
- Full sky maps produced in seven polarization-sensitive bands centered at 30,44,70,100,143,217,353 GHz to be released in 2015. Also intensity maps at 545 and 857 GHz

Planck full sky maps at 9 frequencies



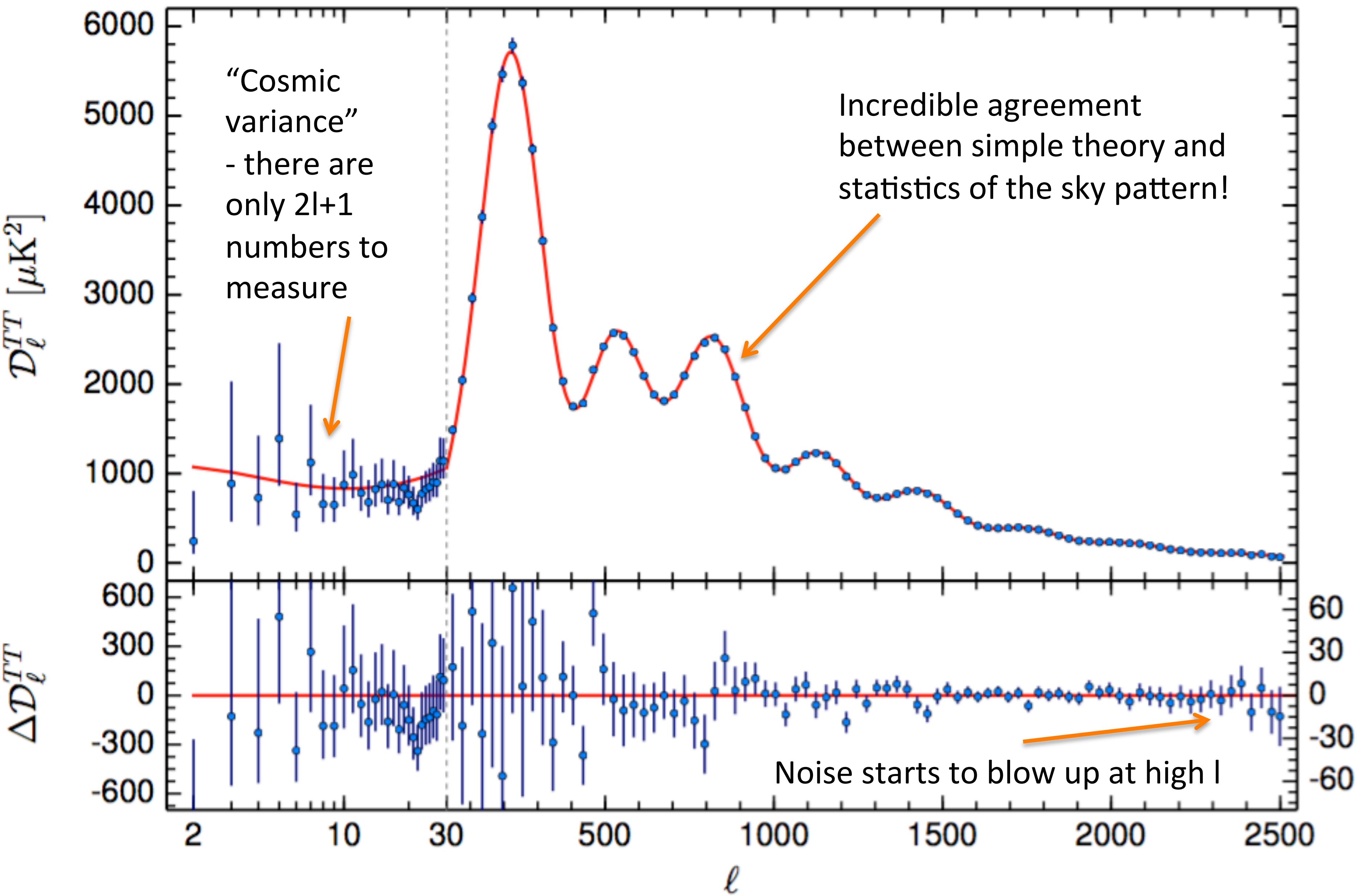
synchrotron emission strong at low frequencies

CMB most uncontaminated at mid frequencies and high latitude

Dust emission strong at high frequencies

Full sky coverage and 9 frequencies - but not as deep as BICEP2/Keck in any given region of the sky

Planck Temperature Spectrum

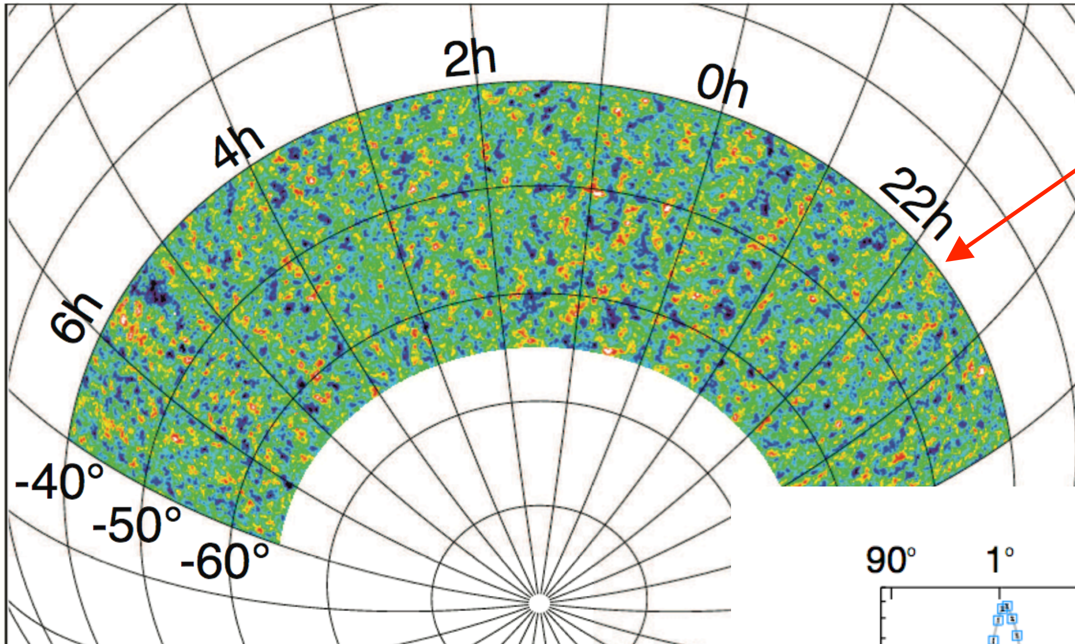


High Angular Resolution Experiments

South Pole
Telescope (SPT)
10 meter diameter

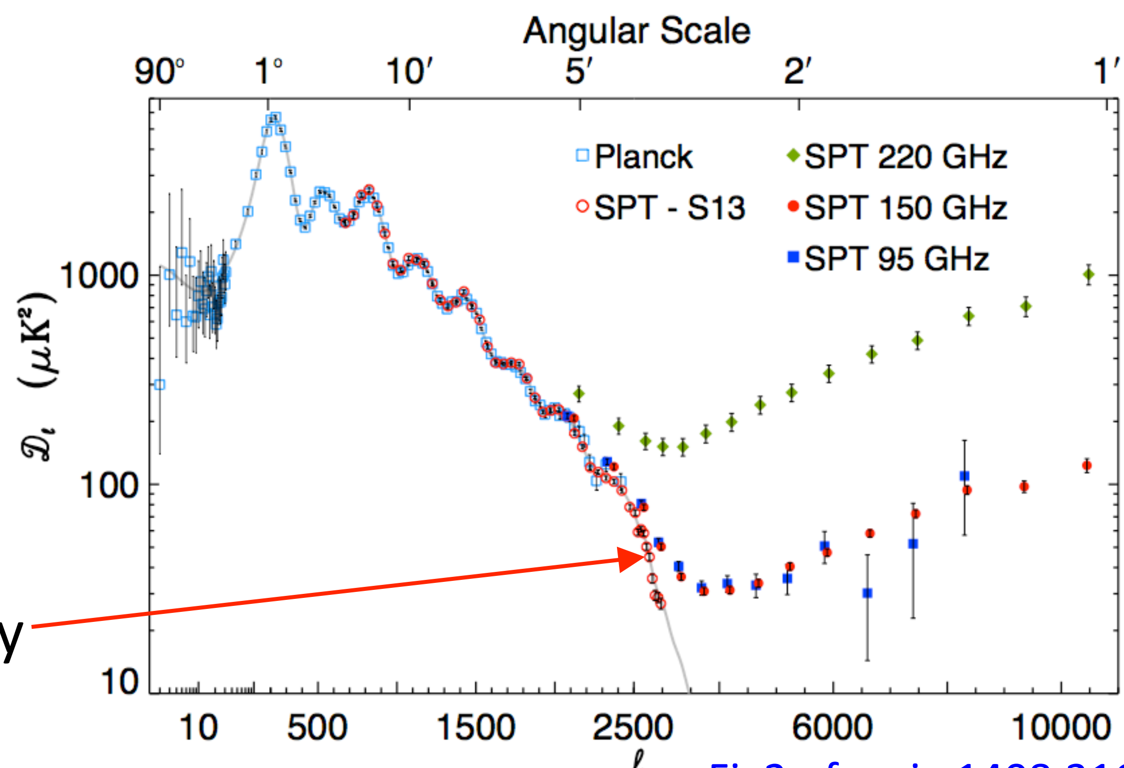
Atacama Cosmology
Telescope (ACT)
6 meter diameter

SPT Temperature Results



Beautiful contiguous 2500 sq deg high resolution survey

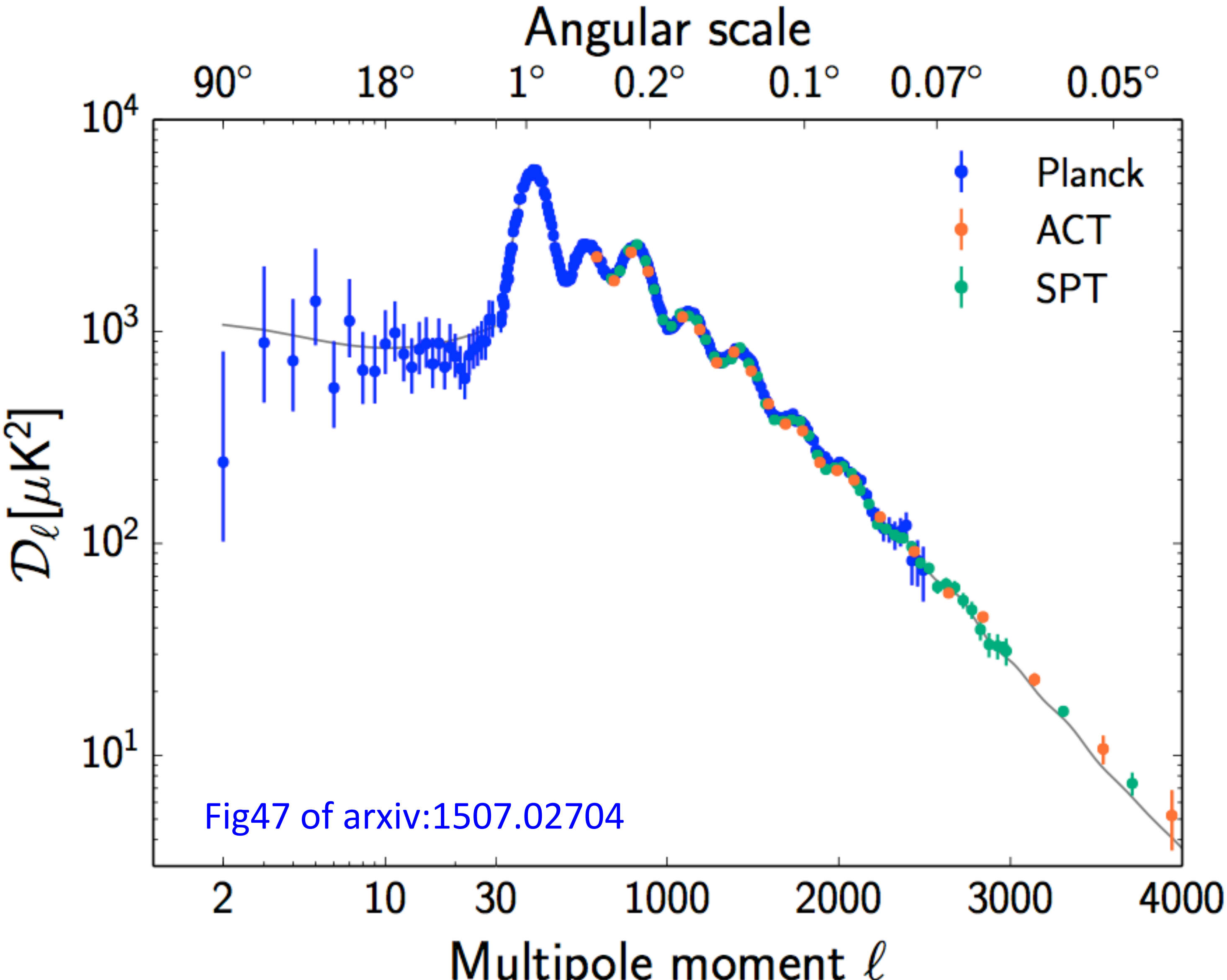
Fig1 of arxiv:1210.7231



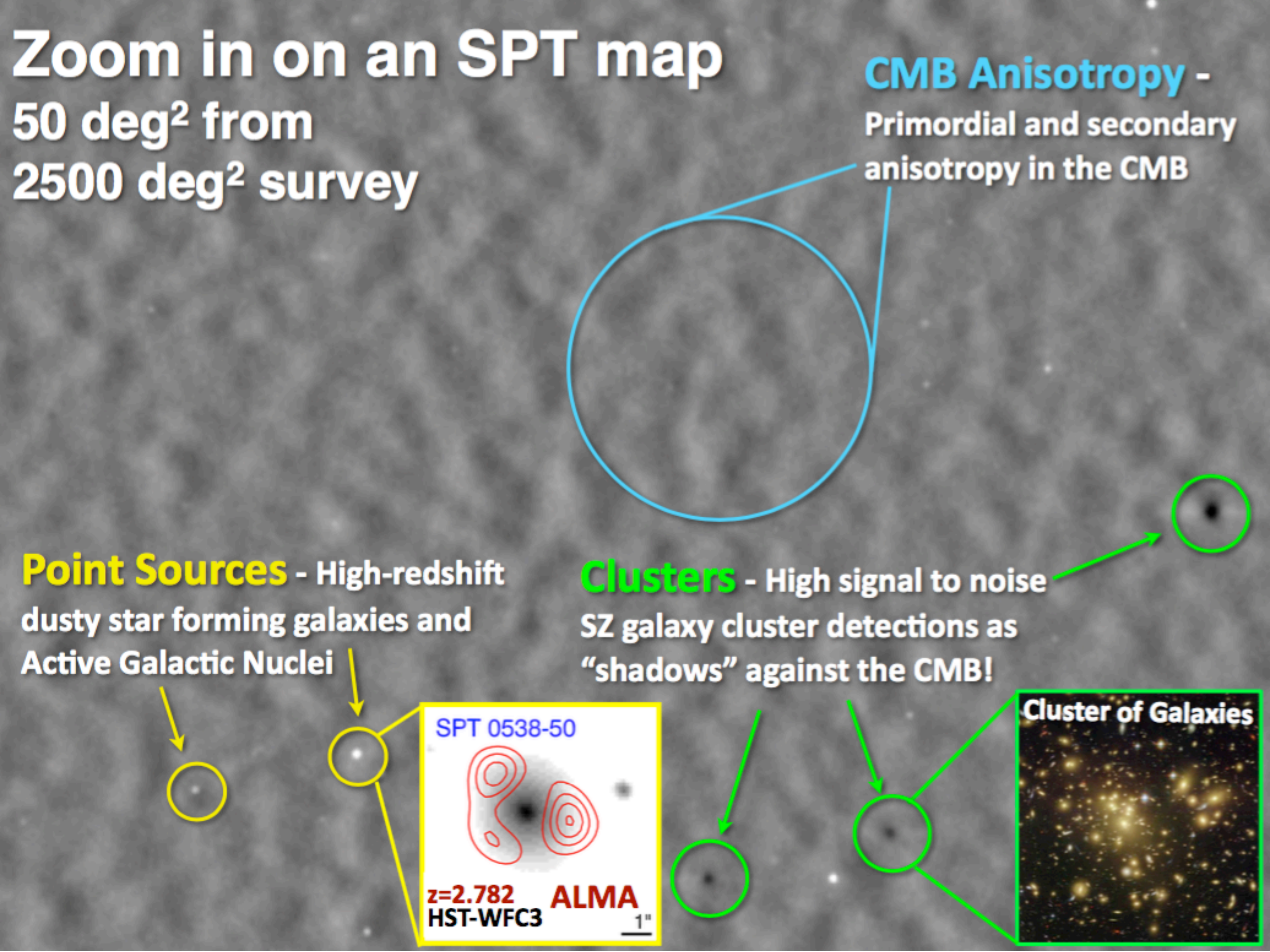
Measurements of TT damping tail hampered by foregrounds

Fig2 of arxiv:1408.3161

High ell TT in conjunction with Planck



At the moment doesn't add much in basic LCDM fits



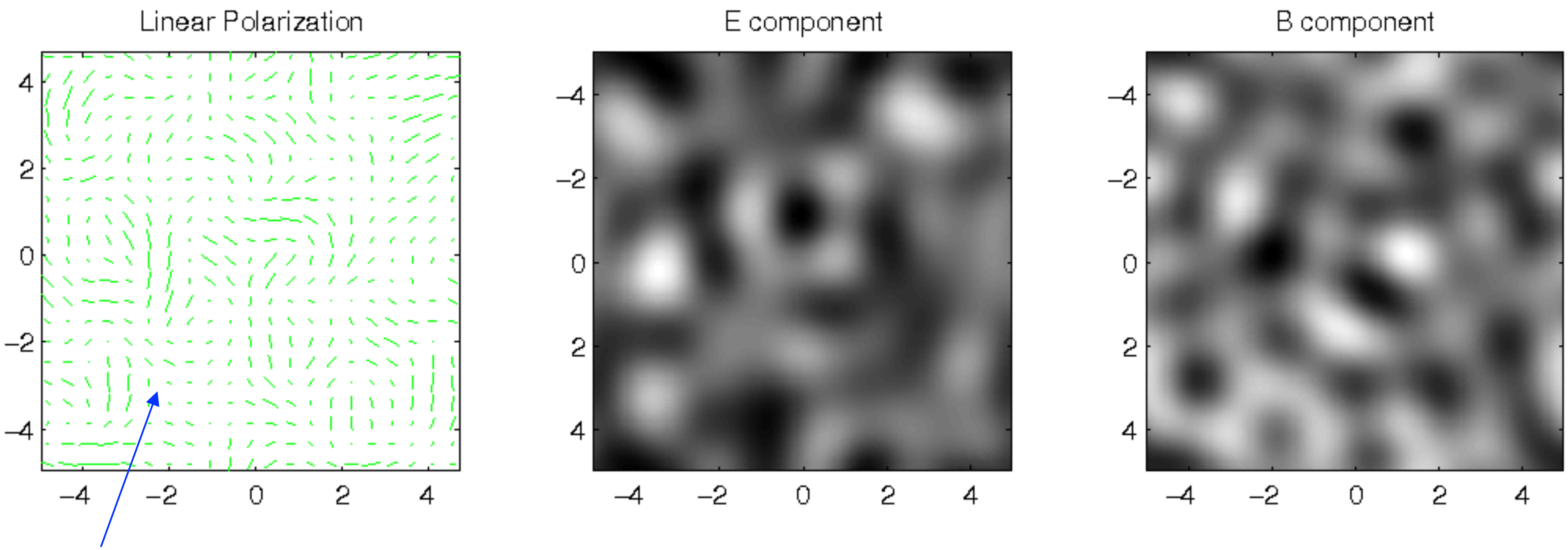
Zoom in on an SPT map
50 deg² from
2500 deg² survey
CMB Anisotropy -
Primordial and secondary
anisotropy in the CMB
Point Sources - High-redshift
dusty star forming galaxies and
Active Galactic Nuclei
Clusters - High signal to noise
SZ galaxy cluster detections as
"shadows" against the CMB!
SPT 0538-50
z=2.782
HST-WFC3
ALMA
1"
Cluster of Galaxies

“First Order” Polarization of the CMB

- Density perturbations at last scattering produce anisotropy of the Total Intensity - T spectrum
- Material flowing (accelerating) along gradients in the density field
  - In local ref. frame see Doppler shift along flow direction versus across flow direction - quadrupole
    - Hence polarization aligned with gradient - zero curl.
  - Since density perturbations produce the motion there is TE cross correlation.
- Given measurements of T spectrum, and standard cosmological model, can predict expected E and TE spectra
  - …measuring E and TE is mainly a paradigm test

Characterizing the Sky Pattern

- Polarization is a (pseudo) vector pattern on the sky
  - Decompose into 2 scalar patterns which measure the "gradient" (E-mode) and "curl" (B-mode) of the pattern



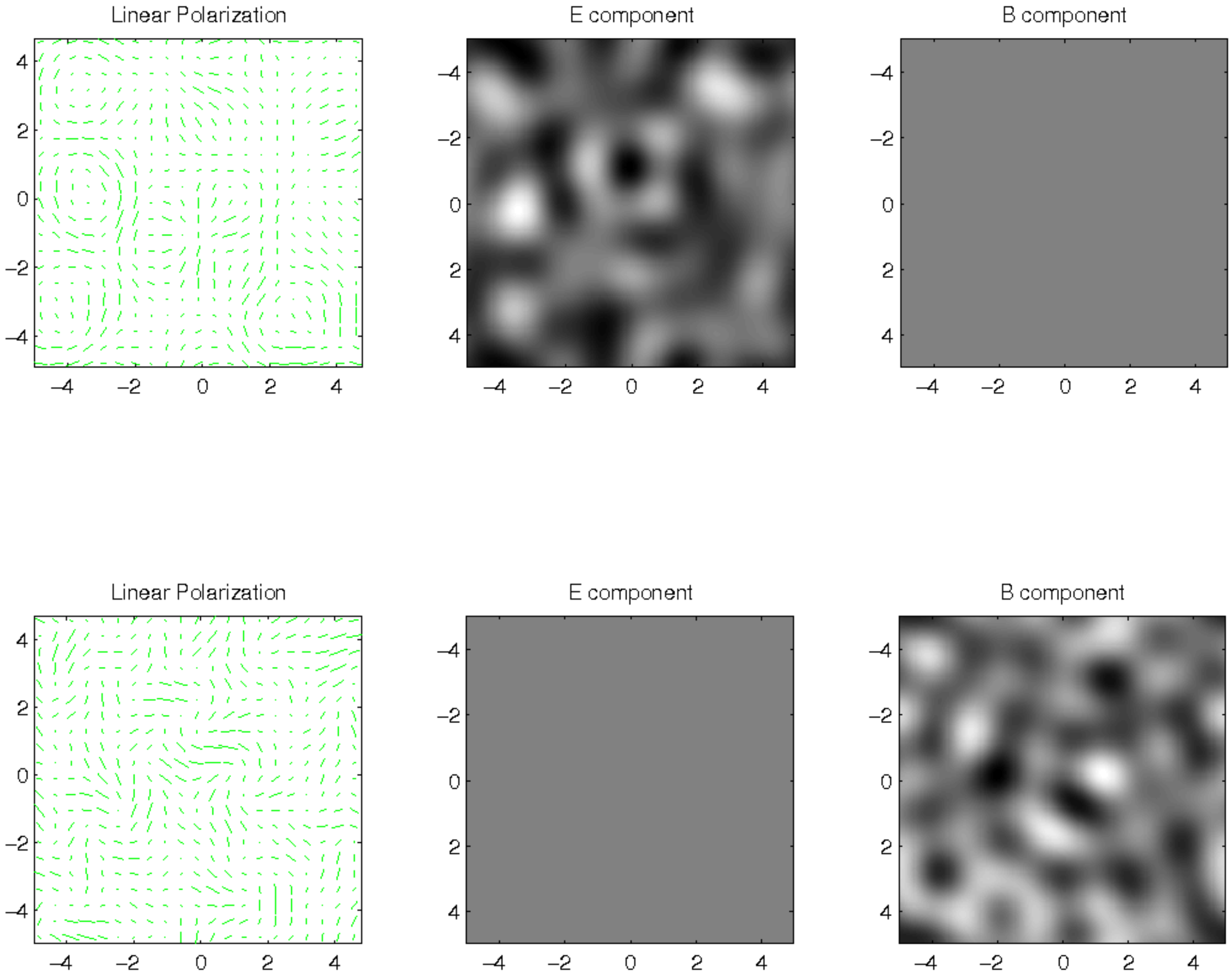
Q/U are "vector" components →

$$\begin{aligned} \chi &= \arctan 2(v,u) - \pi/2 \\ E &= +Q\cos 2\chi + U\sin 2\chi \\ B &= -Q\sin 2\chi + U\cos 2\chi \end{aligned}$$

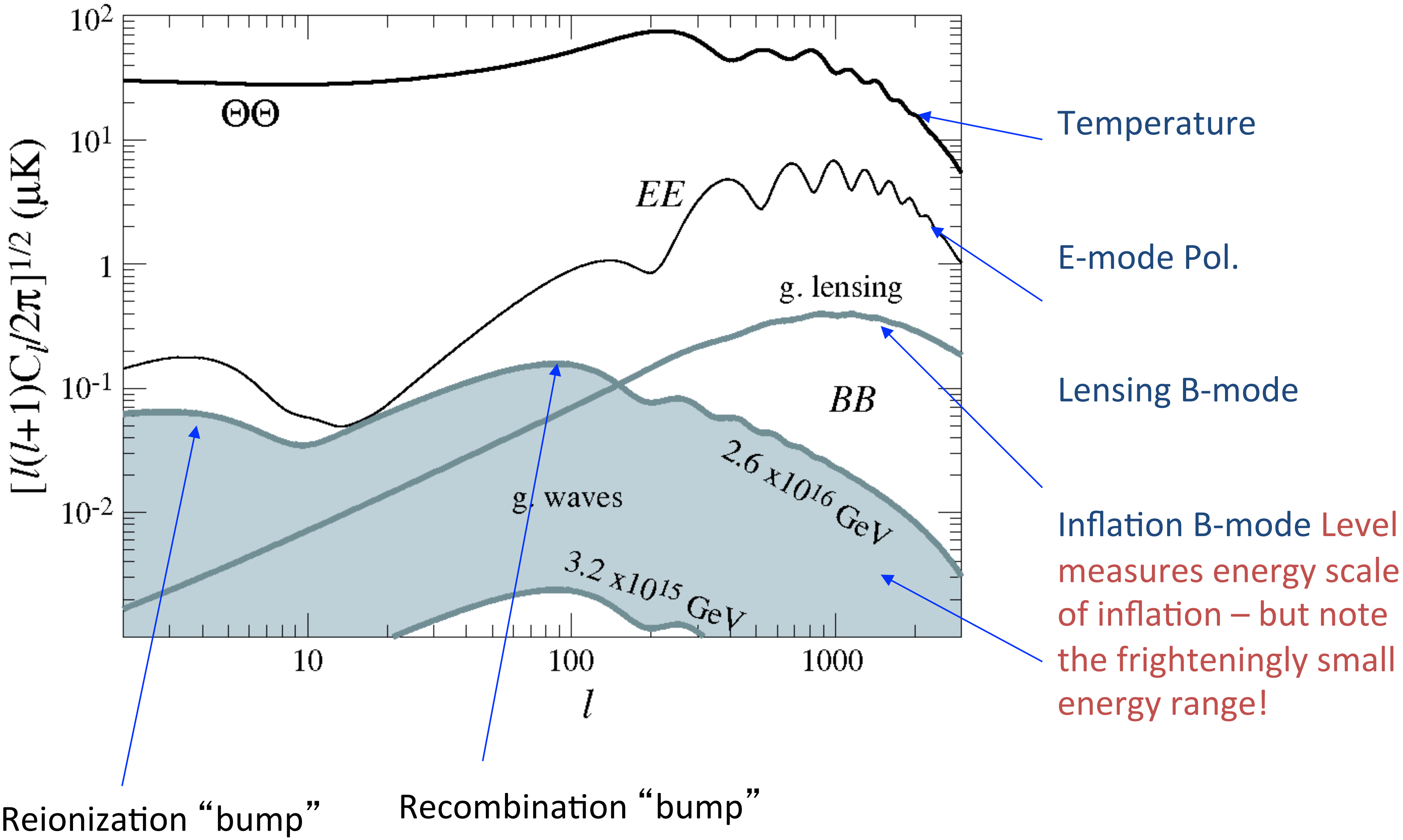
← Local transform in Fourier space
Non-local in map space

Why Use E/B Basis?

- Flow induced pattern all E-mode
- …with zero B-mode



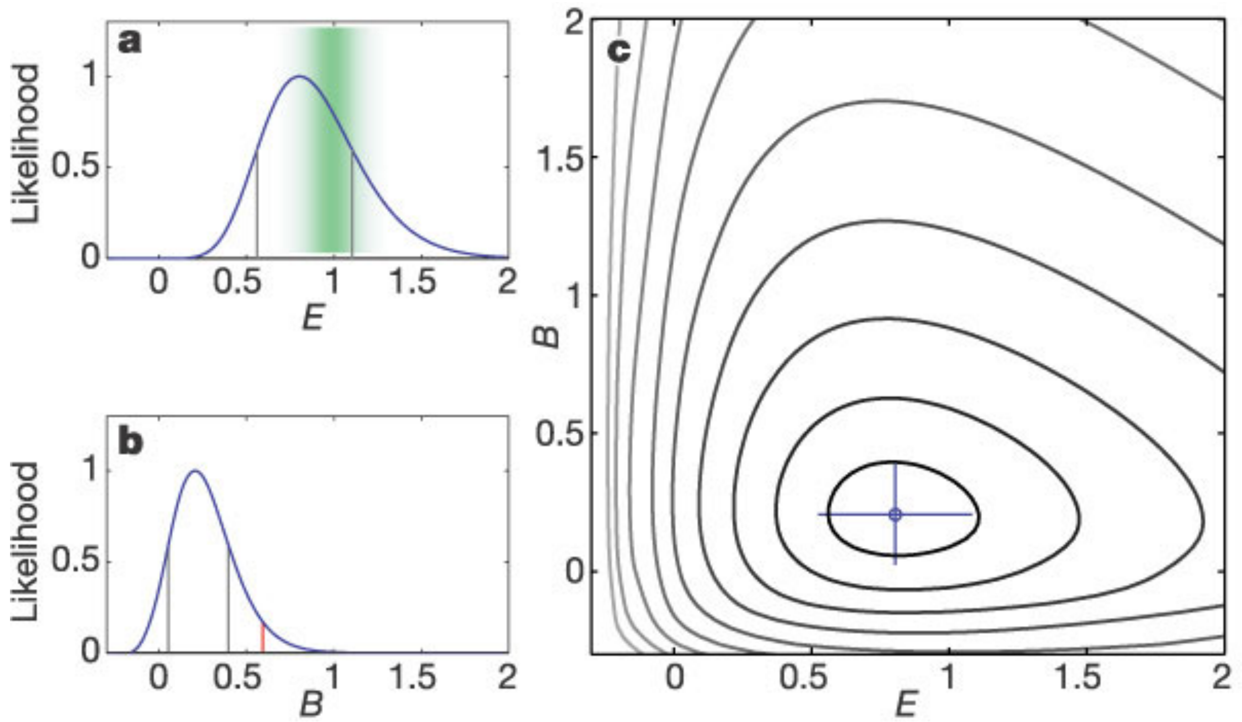
Theoretical Polarization Spectra



Hu et al astro-ph/0210096

Log Scale! Enormous experimental challenge!

DASI First Detection of CMB Polarization In 2002



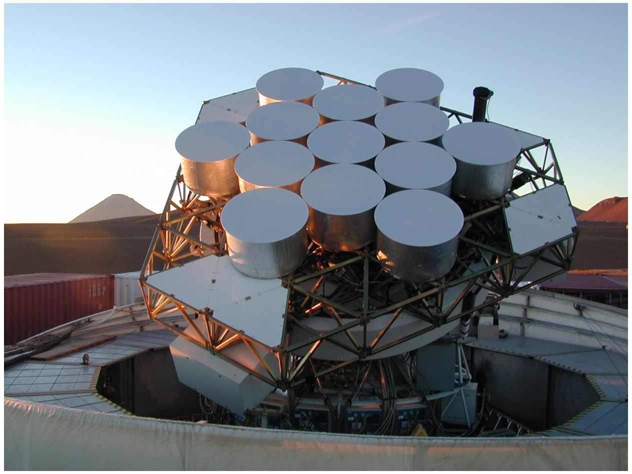
Kovac et al Nature 12/19/02

DASI showed CMB *has* E-mode pol.

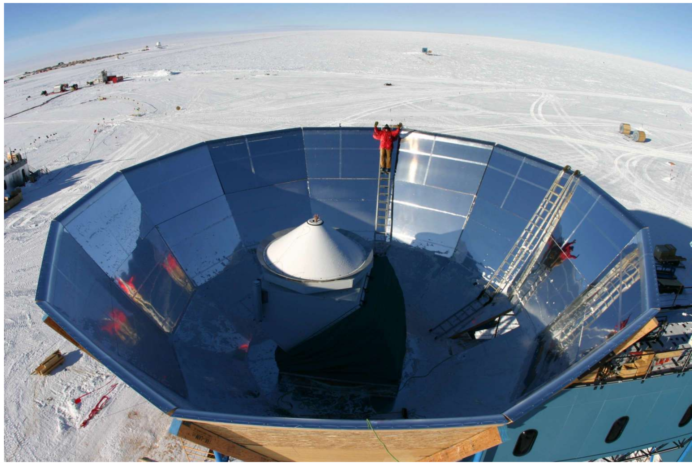
- B-mode was consistent with zero

Older Experiments which made CMB Pol Detections

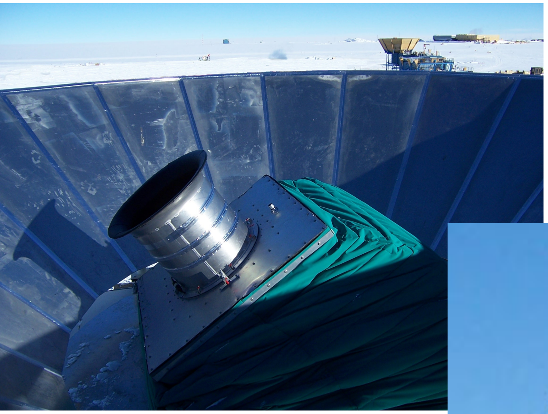
CAPMAP



CBI

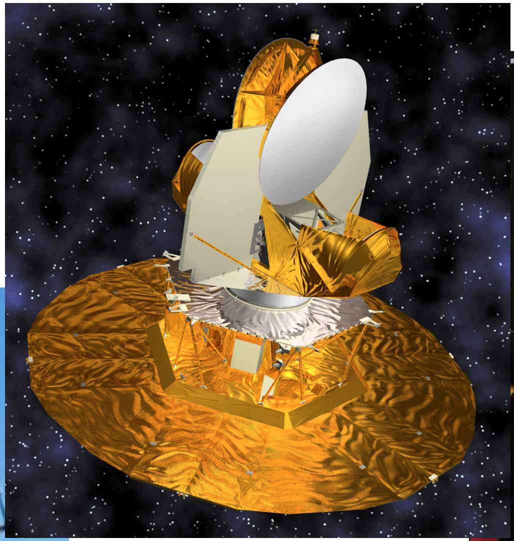


QUaD

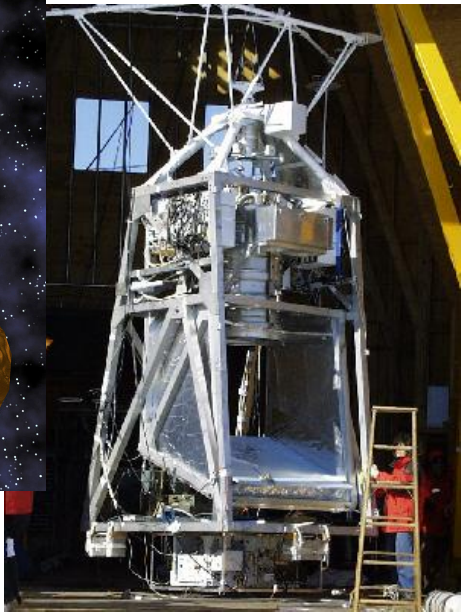


BICEP1

QUIET

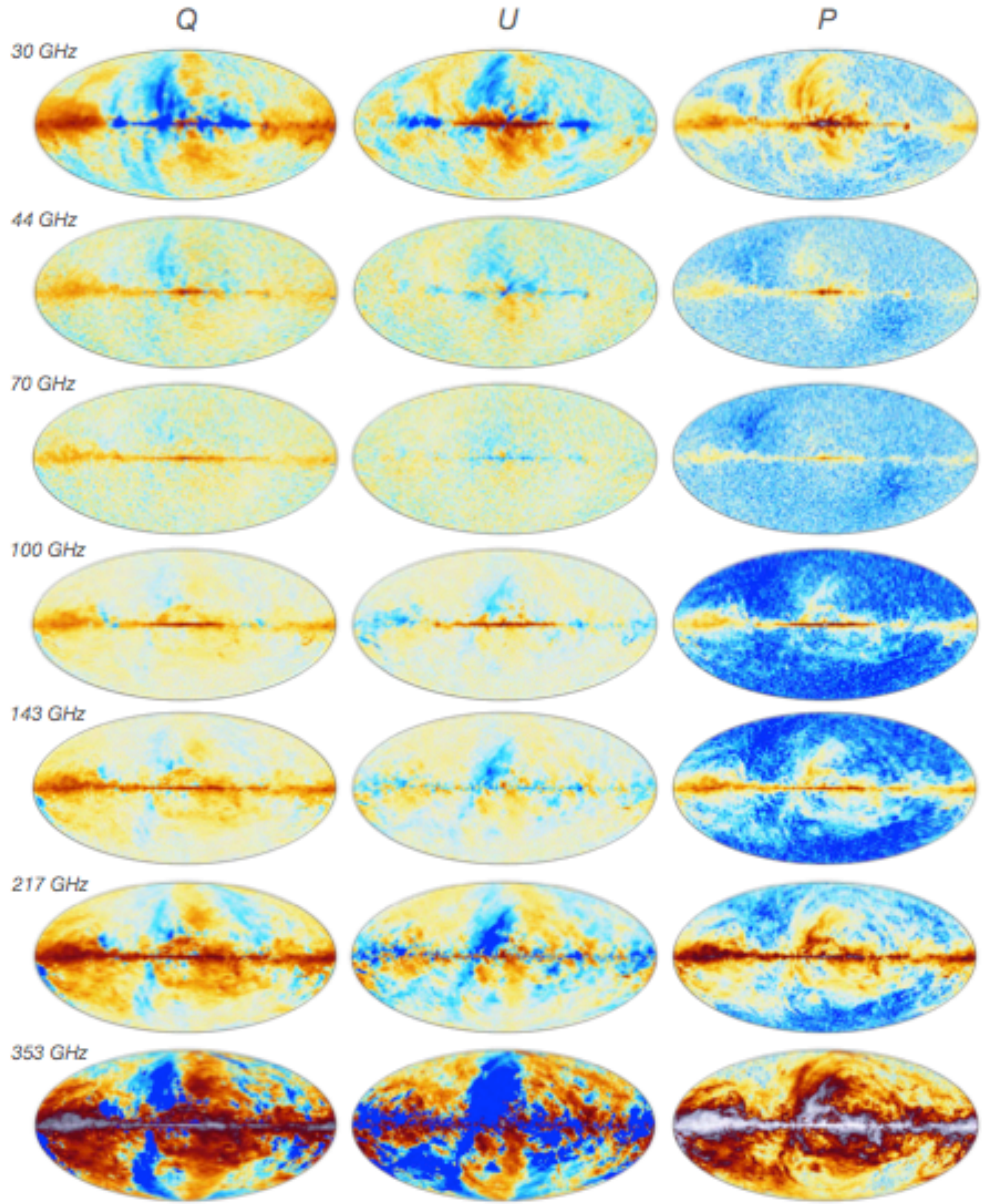


WMAP



BOOMERANG

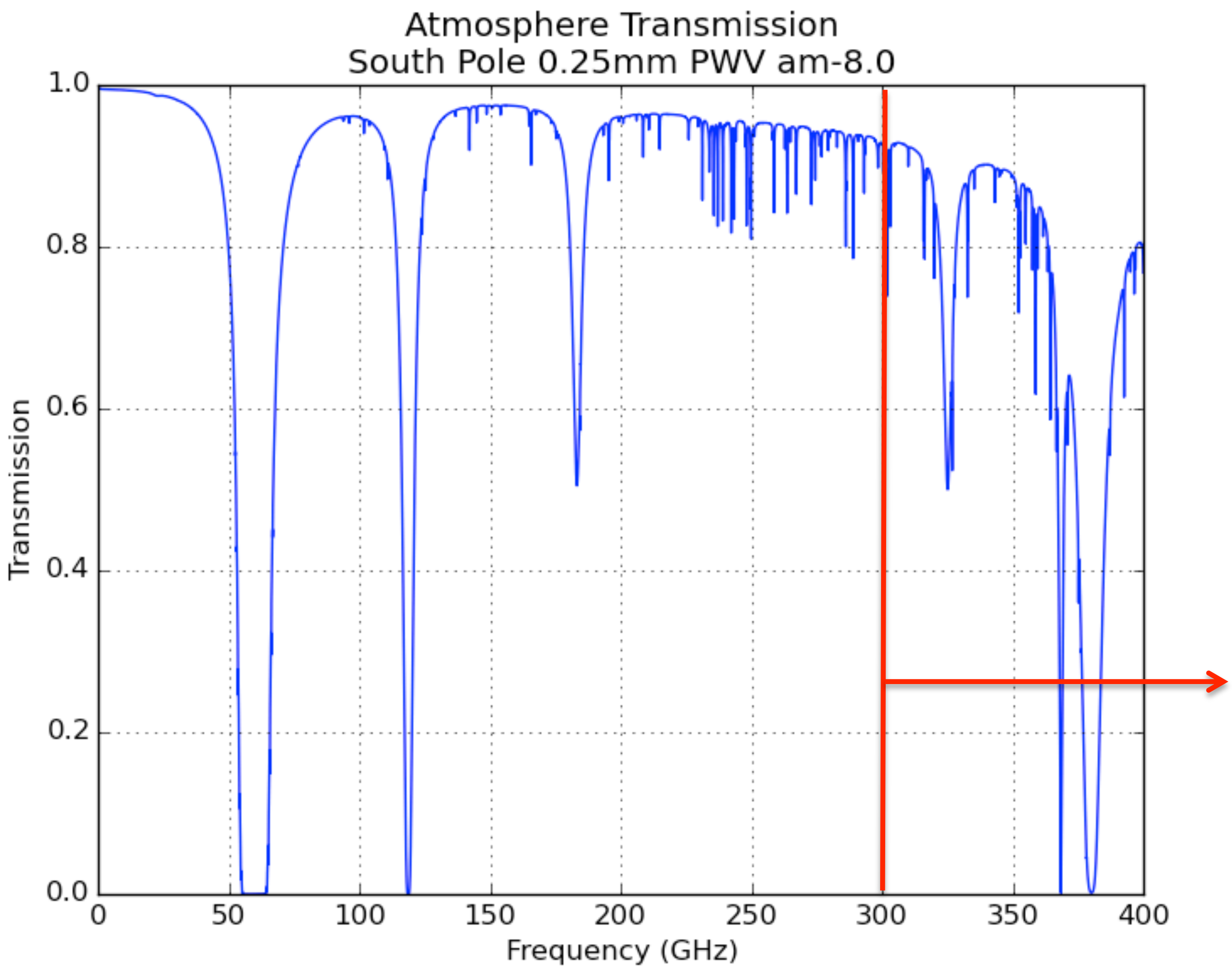
Planck has now provided full sky polarized maps at 7 frequencies



Given that Planck maps exist why make further suborbital measurements?

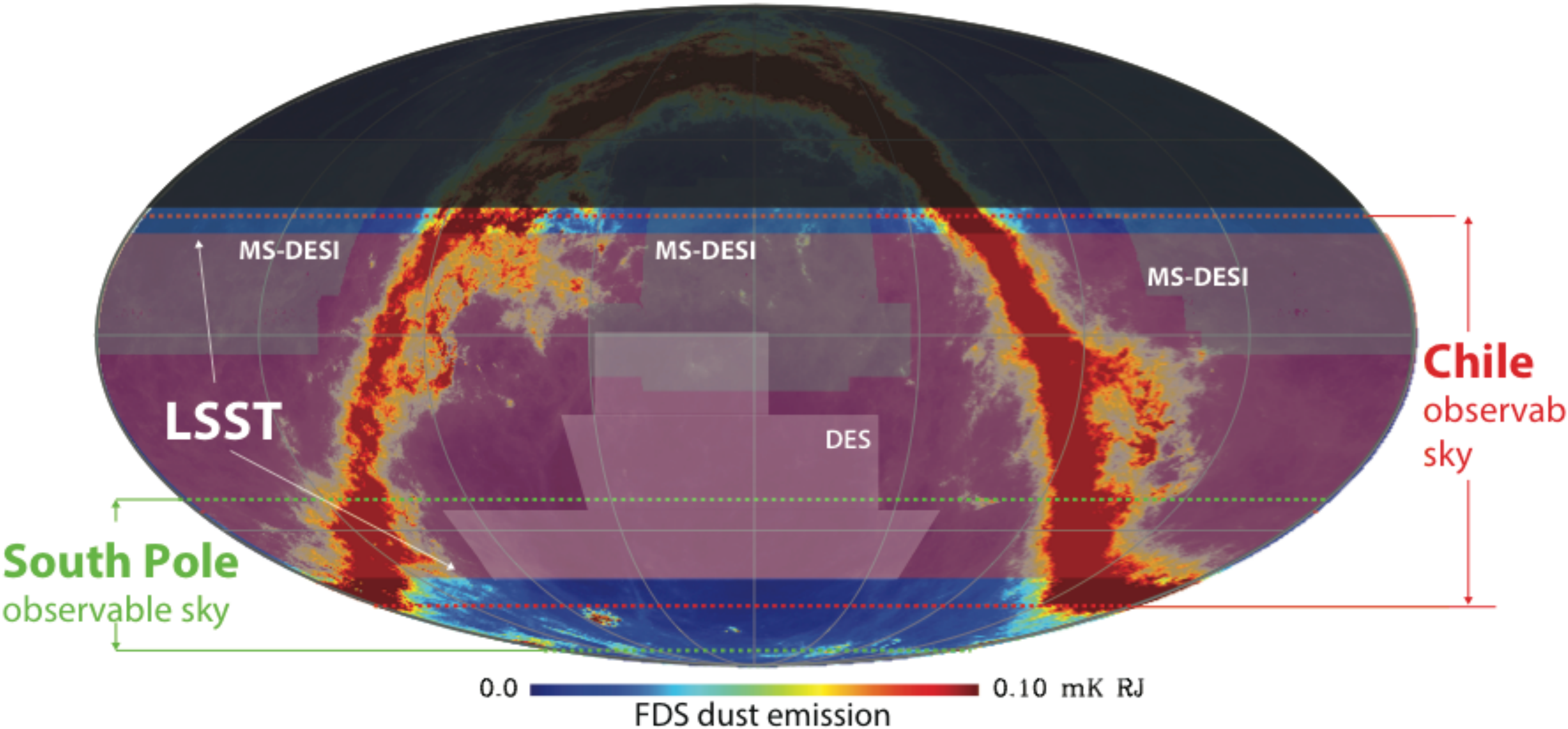
- Can achieve higher sensitivity – quite easily on small patches of the full sky
- Can have higher angular resolution – particularly with ground based experiments

Ground based limitation: Can't do high frequencies



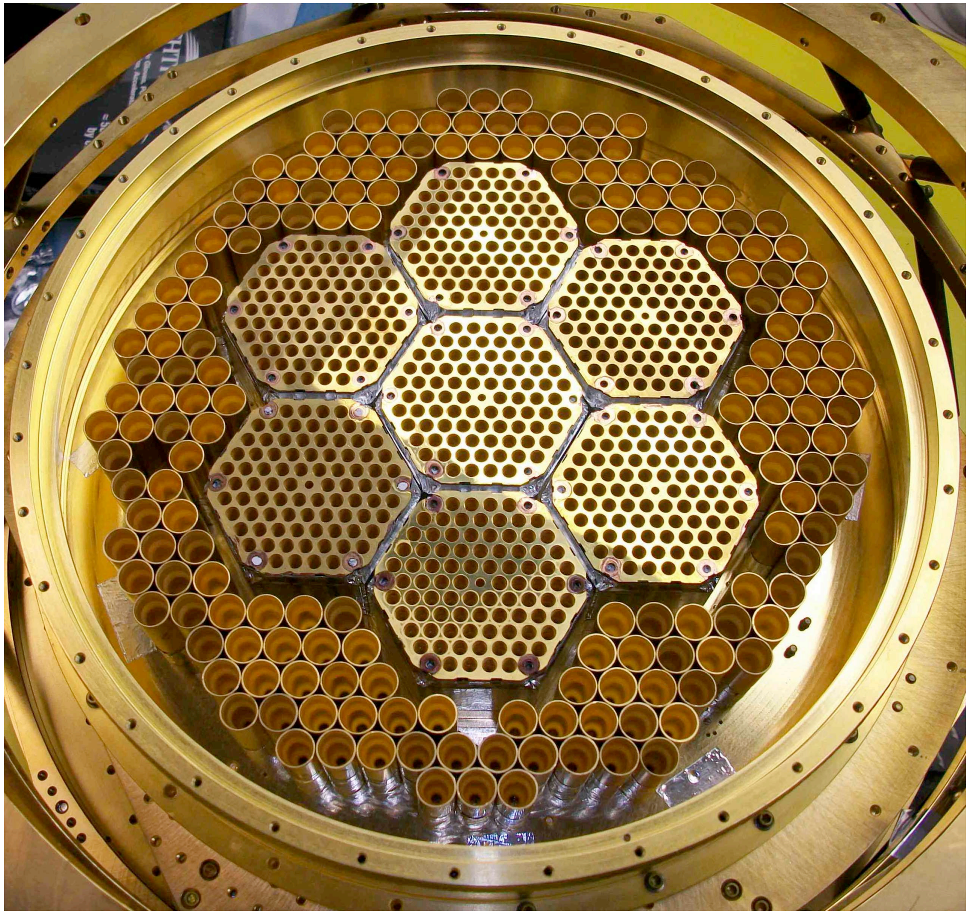
Even from the best sites can't go above 300GHz

Suborbital Limitation: Can't do full sky from a single site (or flight)



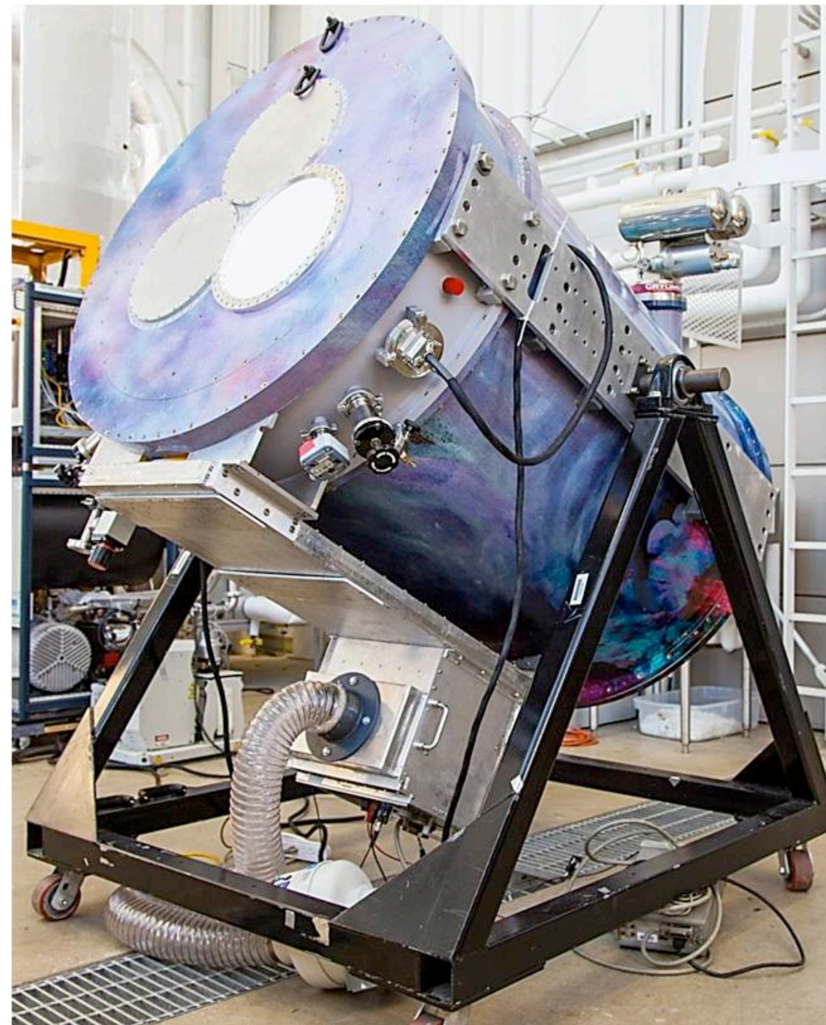
But full sky maps have been made from the ground (e.g. Haslam 408MHz using 2 sites)

High Angular Res Pol Experiments (2G)

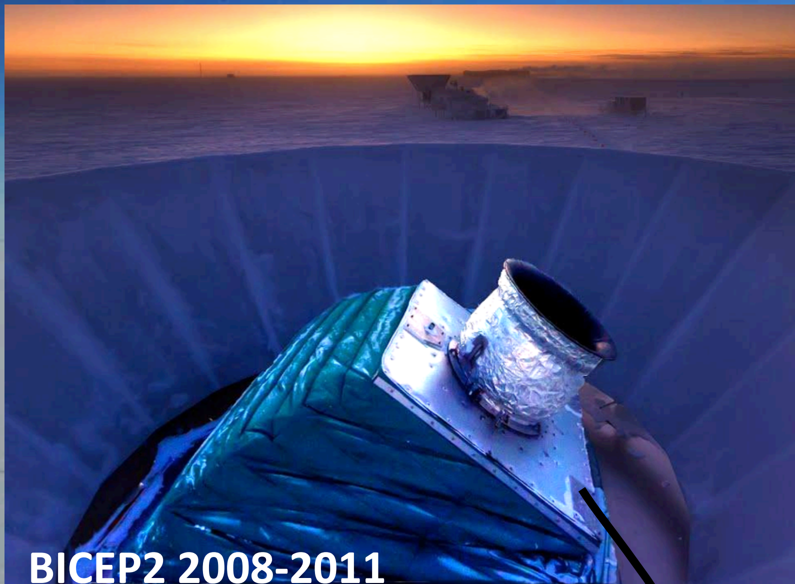


The SPTpol camera

The ACTpol receiver



Low Res Pol Experiments - BICEP2 and Keck Array



Keck Array 2011-present

x5

Relentless observation of the CMB polarization from NSF's station at the geographic South Pole

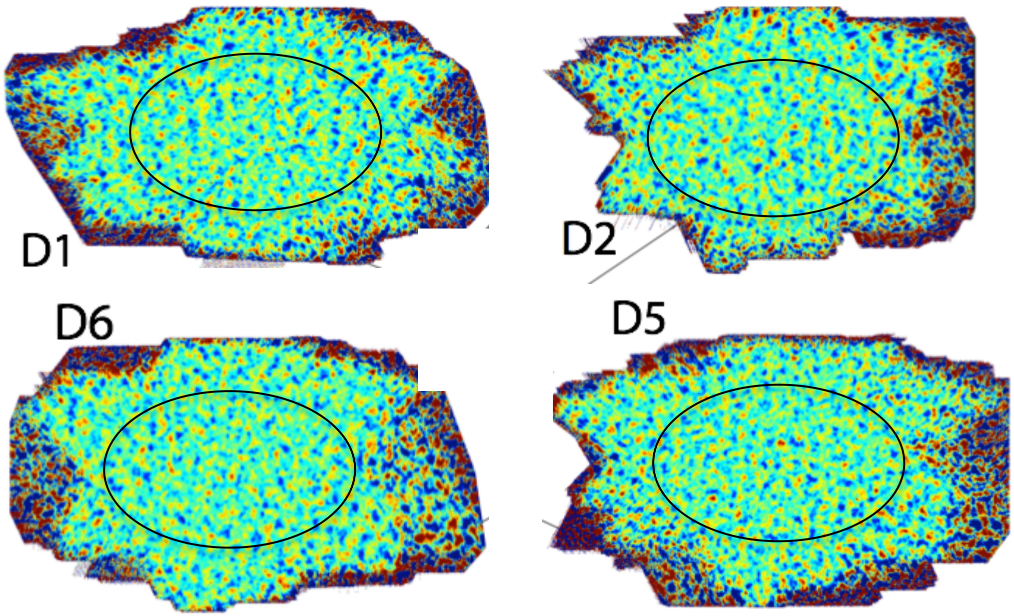
Dry, stable atmosphere, high altitude + 24h coverage of the Southern Sky

Compact cold refractive optics optimized for the angu scales of the potential inflationary signal

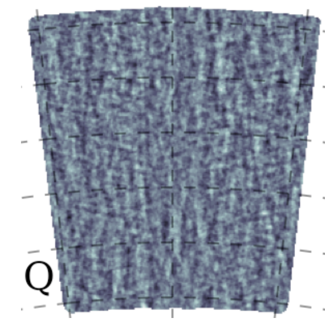
Superconducting phased antenna arrays

Focus on ~**400 deg²** patch = 1% of the sky

Published Deep Suborbital Polarization Maps To Date

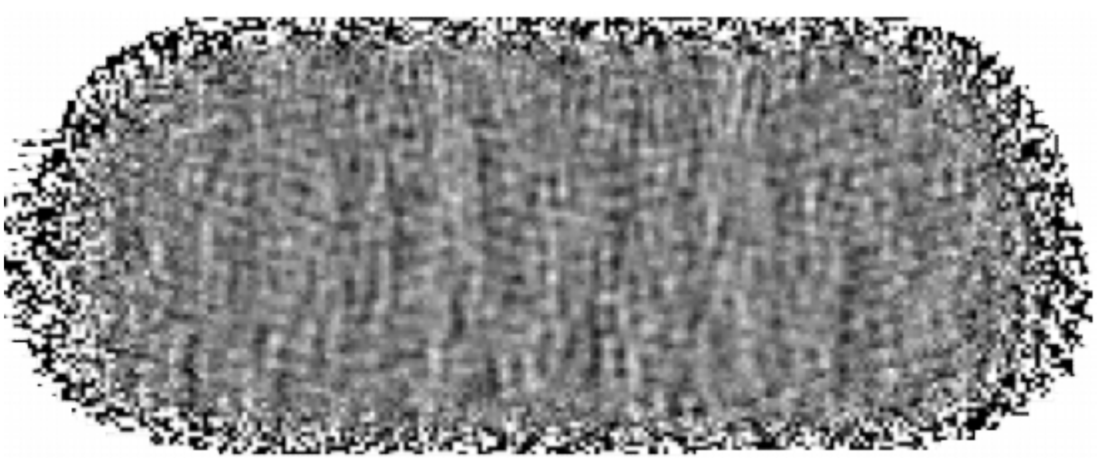


ACTpol 275 sq deg arxiv:1405.5524

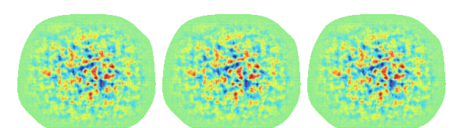


SPTpol 100 sq deg arxiv: 1411.1042 and 1503.02315

Roughly scaled to indicate relative map sky coverage



BICEP2/Keck 400 sq deg arxiv:1403.3985 and 1502.00643



POLARBEAR 25 sq deg arxiv:1403.2369

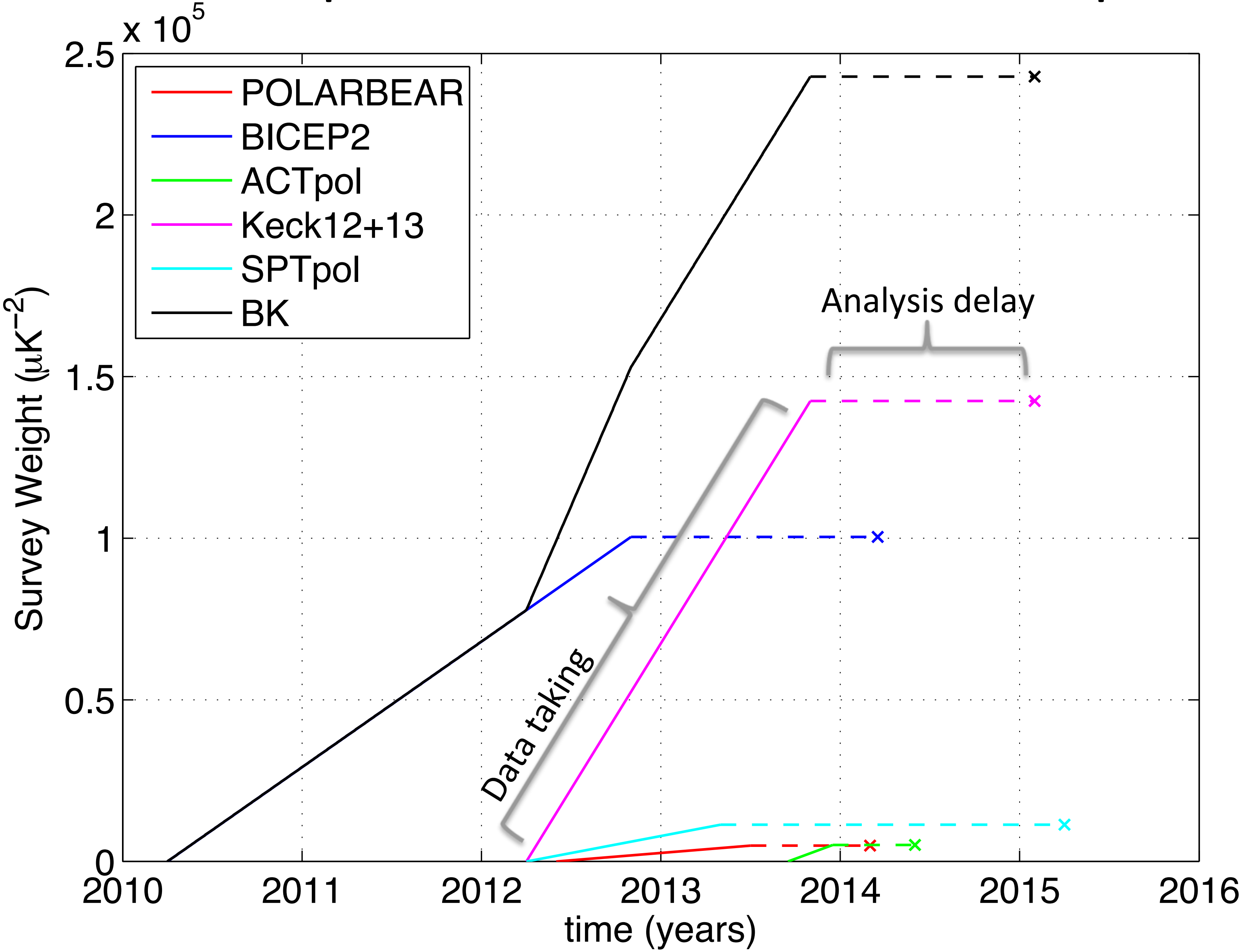
Published Deep Suborbital Polarization Maps To Date

	Q,U Map rms noise N [uK-arcmin]	Survey effective area A [deg^2]	**Total** Q+U **Survey Weight** $W=2A/N^2$ [uK^{-2}]	Reference
POLARBEAR	6	24.5	**5,000**	arxiv:1403.2369
BICEP2	5.2	380	**100,000**	arxiv:1403.3985
ACTpol	15.8 to 24	276	**5,000**	arxiv:1405.5524
SPTpol	17@95 & 9@150	100	**11,000**	arxiv:1503.02315
BICEP2+Keck	3.4	400	**360,000**	arxiv:1510.09217
Planck 143 GHz (for reference)	70	41,000	**60,000**	

Caution: gauging relative performance of experiments using nominal detector counts can be misleading – also projections are often optimistic!

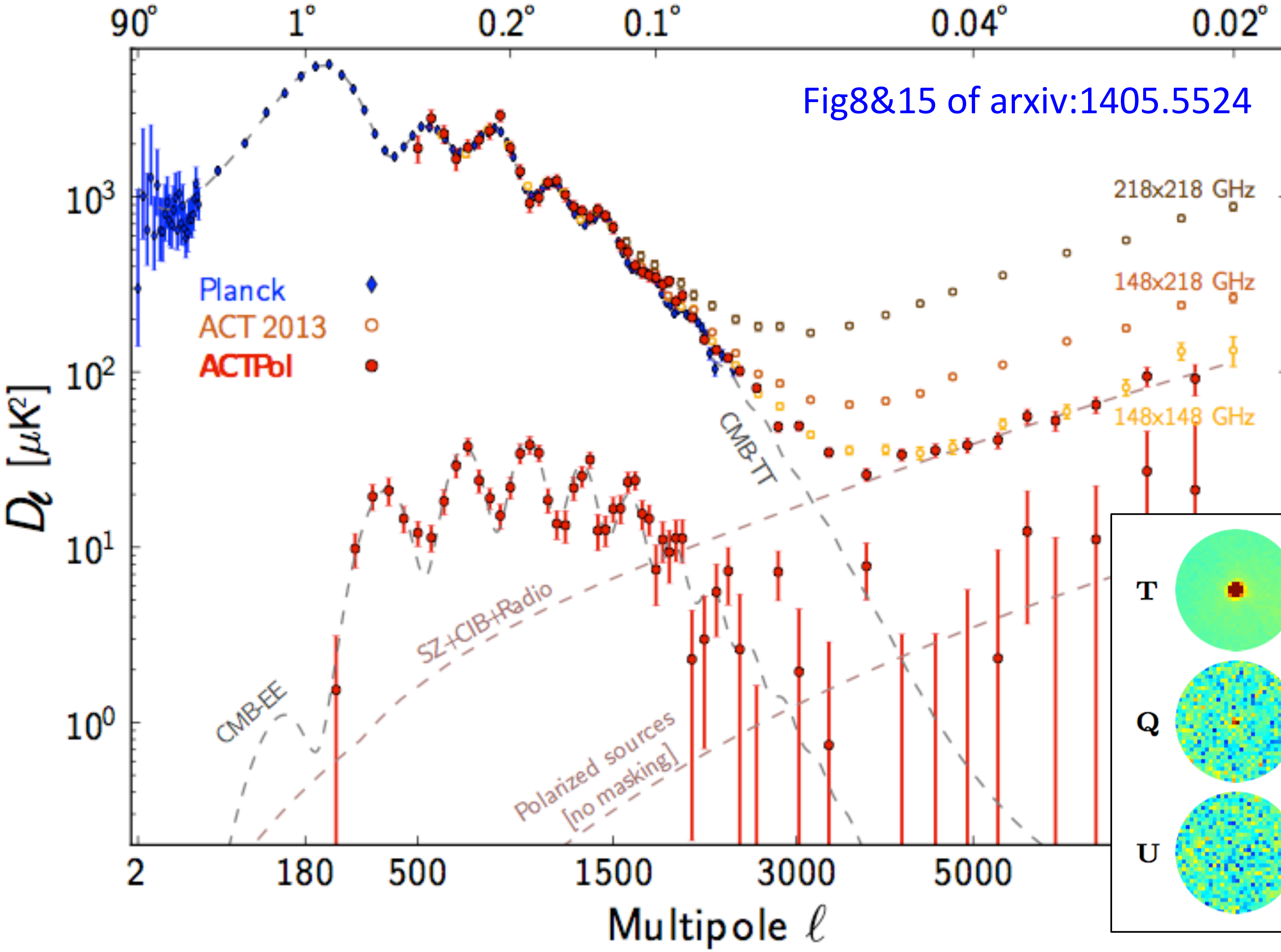
Survey weight: A quantity which is linear in number of detectors and integration time – i.e. difficulty of achieving
Also linear in power spectrum noise error bar size

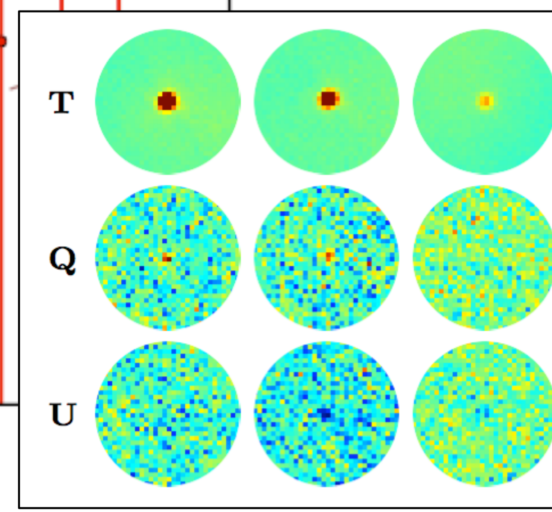
Published Deep Suborbital Polarization Maps To Date



NB: Published results only – no projections!

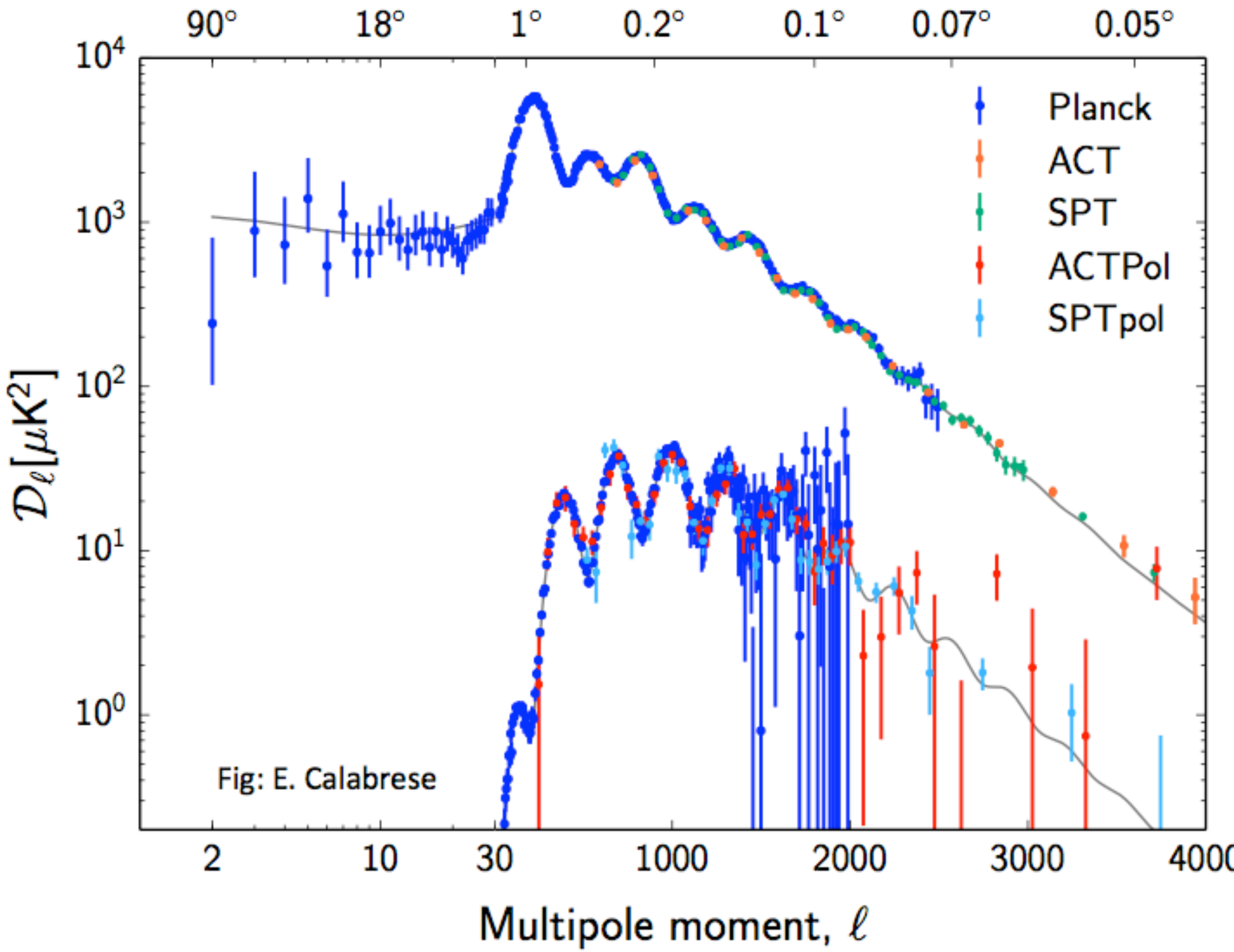
High Res Experiments can measure EE damping tail





CMB has higher fractional polarization than point source foregrounds – can push further down the damping tail in EE

High Res Experiments can measure EE damping tail

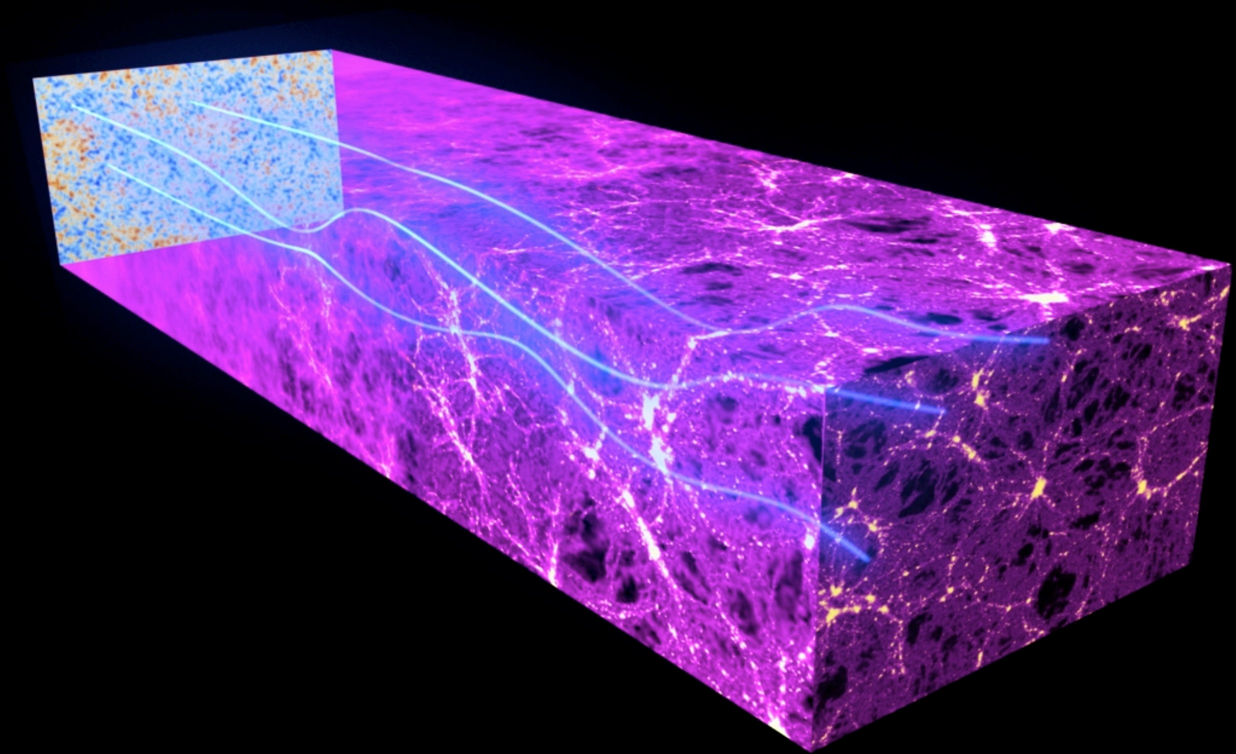


Note that SPT/ACTpol already better than Planck EE for ell>1500

"Second Order" Polarization of the CMB

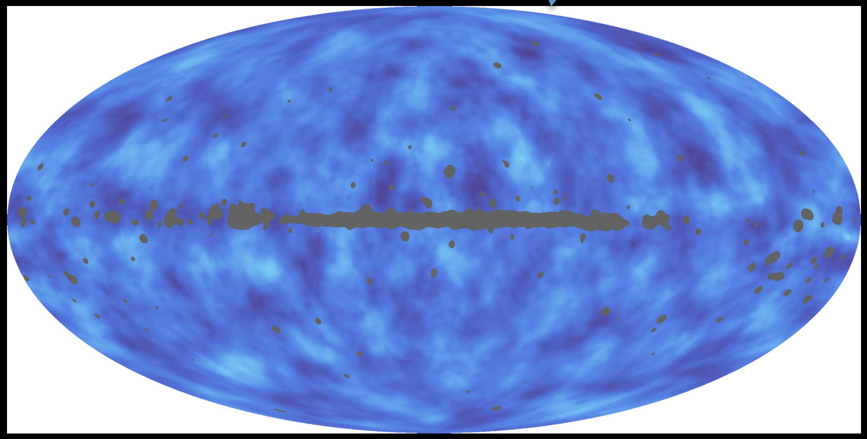
- Lensing by large scale structure between last scattering and us distorts the polarization pattern...
  - Mixes E into B to a small extent.
  - Called "Lensing B-modes" – small angular scales
  - By measuring can constrain sum of neutrino masses and potentially reconstruct projected mass map...
- Gravity waves propagating through the primordial plasma at last scattering potentially add to all spectra...
  - Based on existing T data we know contribution small.
  - Called "Gravity Wave B-modes" – large angular scales
  - Characterize amount using tensor/scalar ratio "r"

CMB Lensing

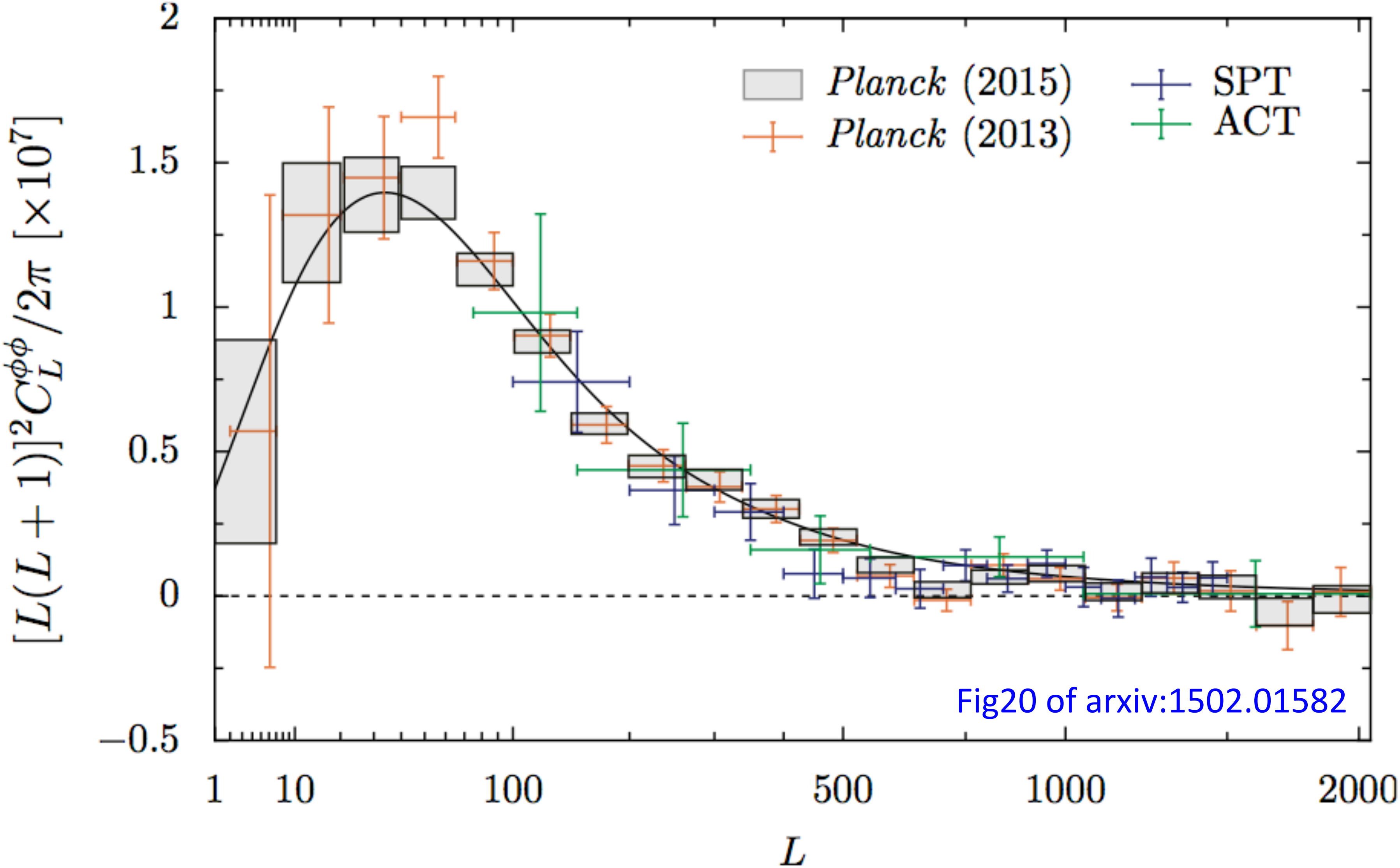


Planck mass map
(mostly from
temperture)

Lensing re-maps the CMB patterns introducing non-Gaussianity which can allows to reconstruct the projected mass map

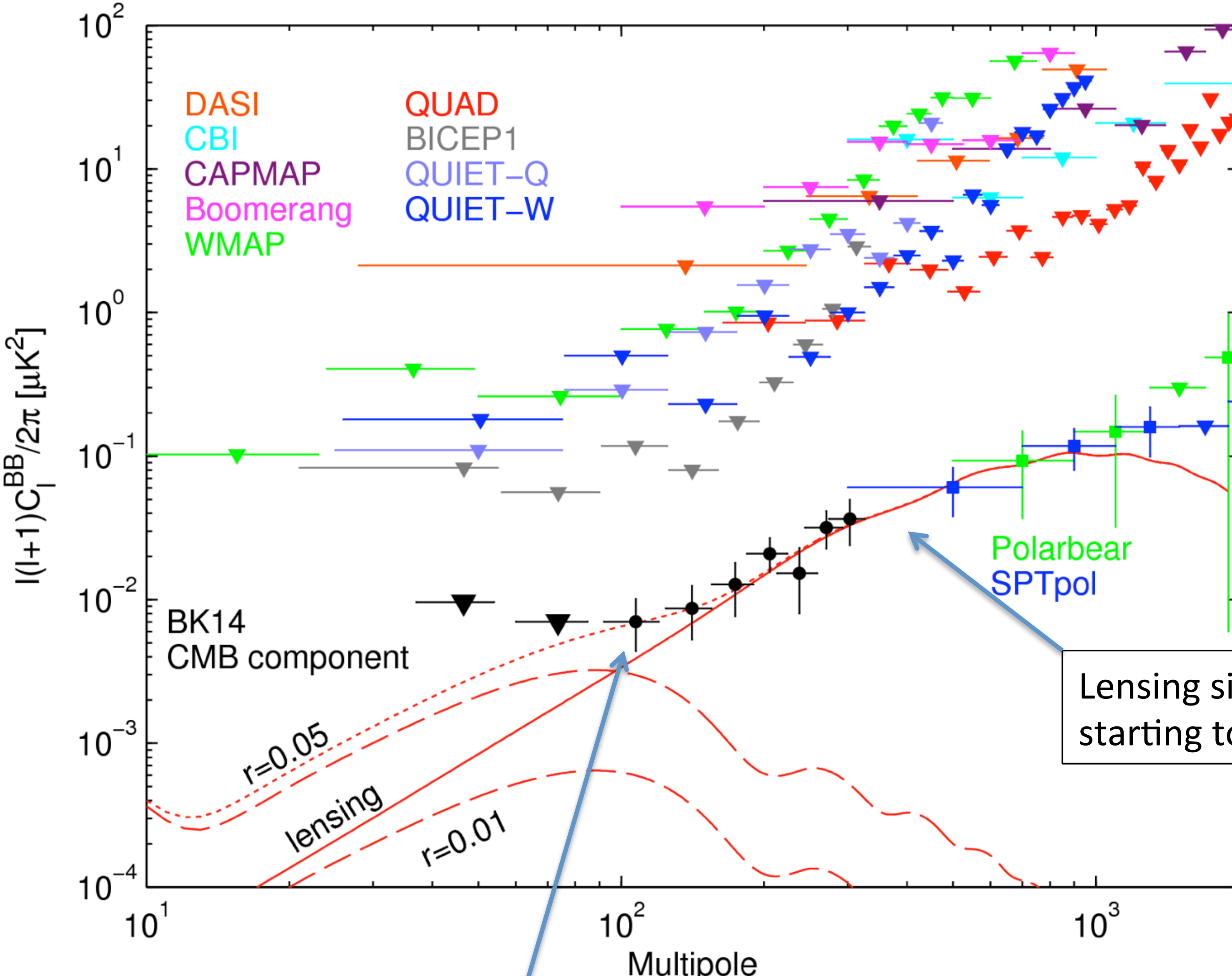


High Res Experiments Can Do Lensing Reconstruction



Planck currently best – High res ground based can eventually do much better

Current BB Results



Lensing signal starting to be seen

No evidence for gravity wave signal yet…