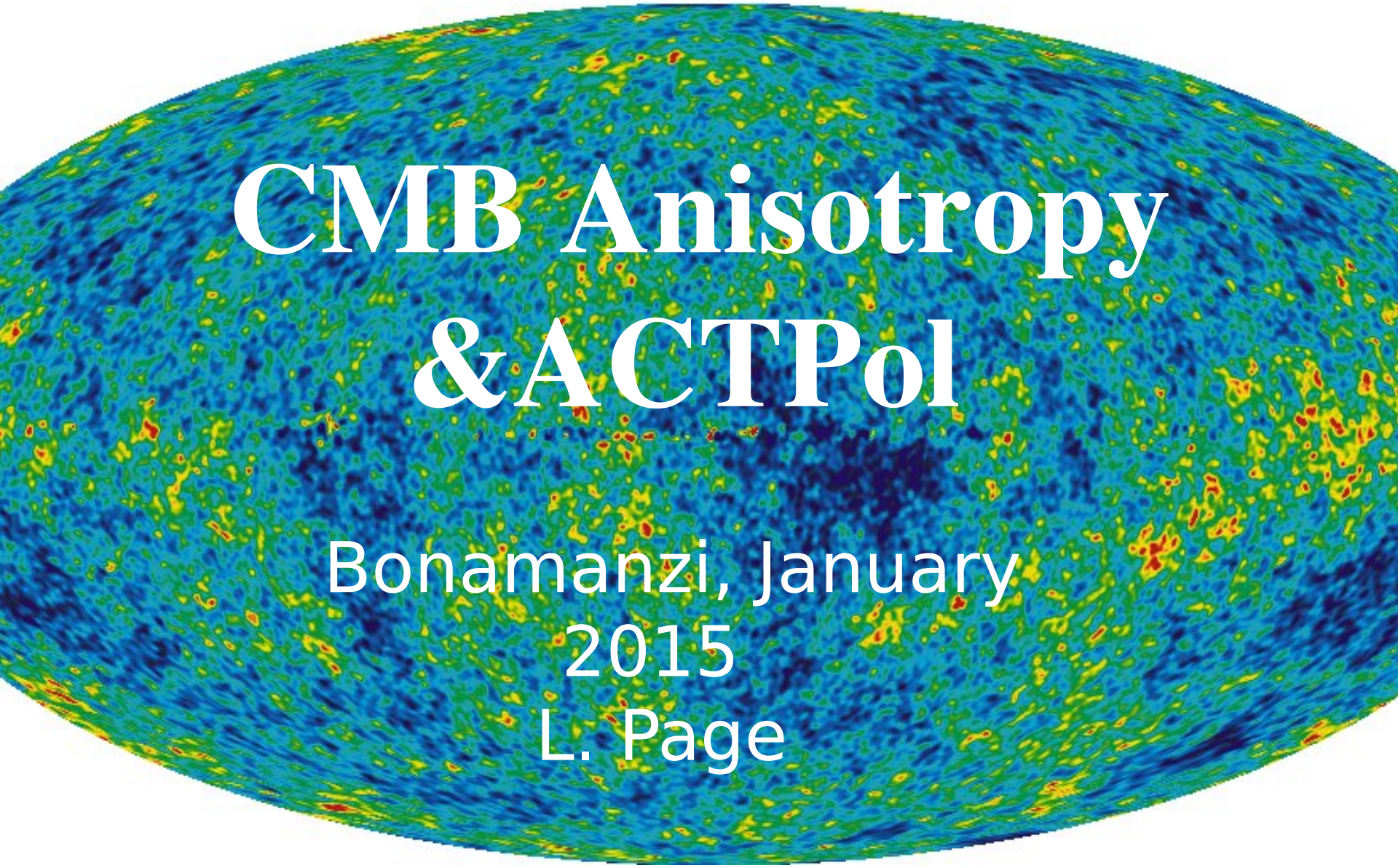
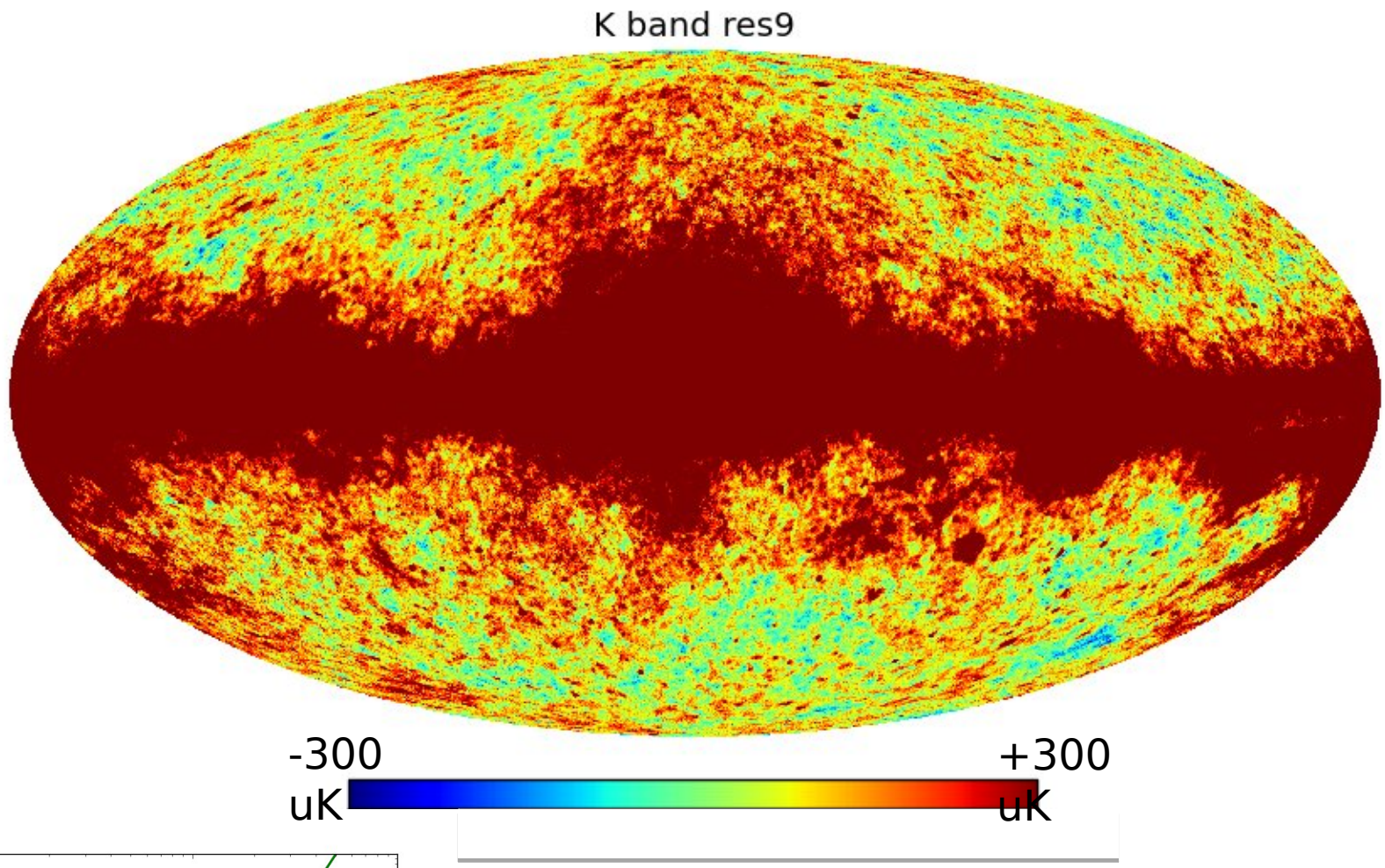
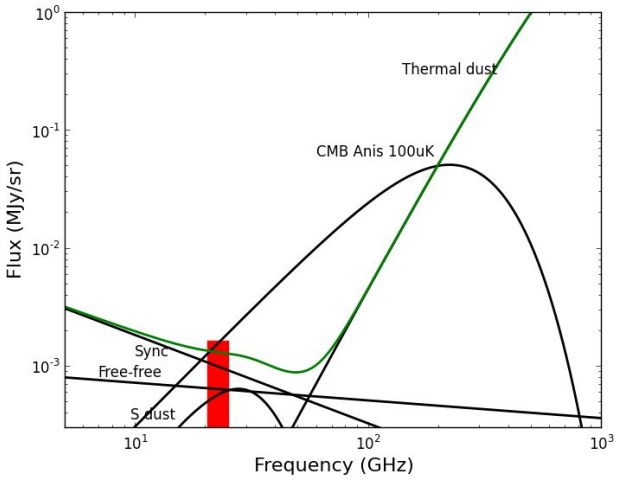


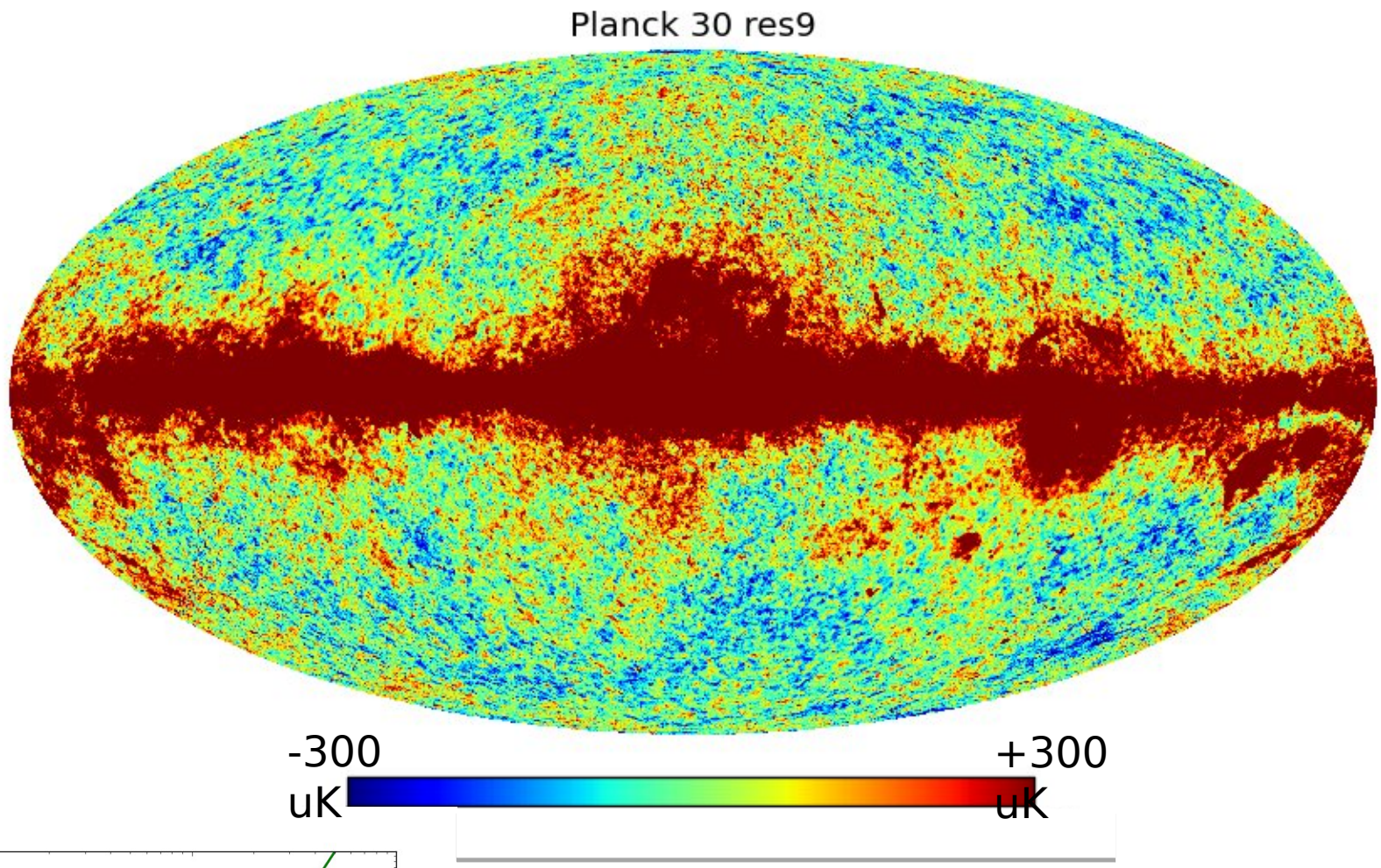
CMB Anisotropy &ACTPol

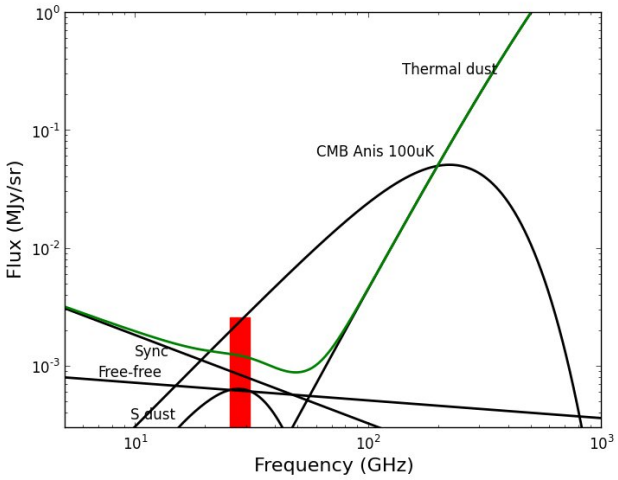
Bonamanzi, January 2015

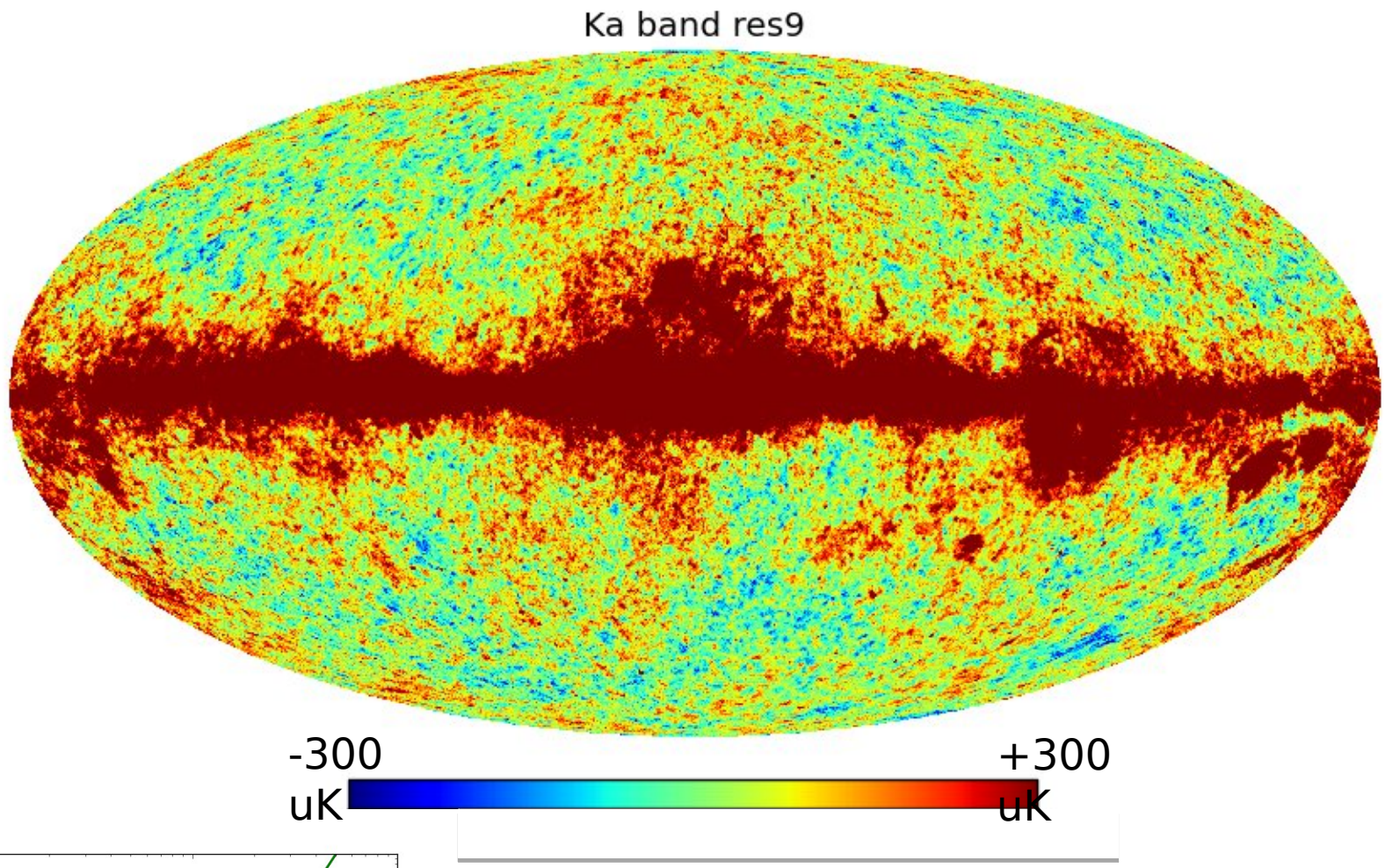
L. Page

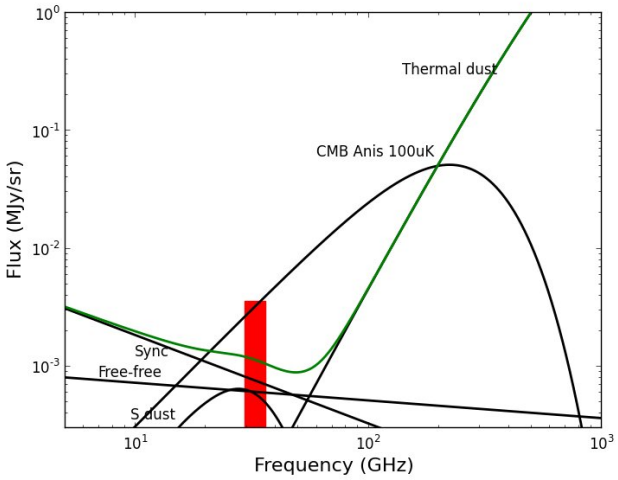

K band res9
-300
uK
+300
uk


Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)

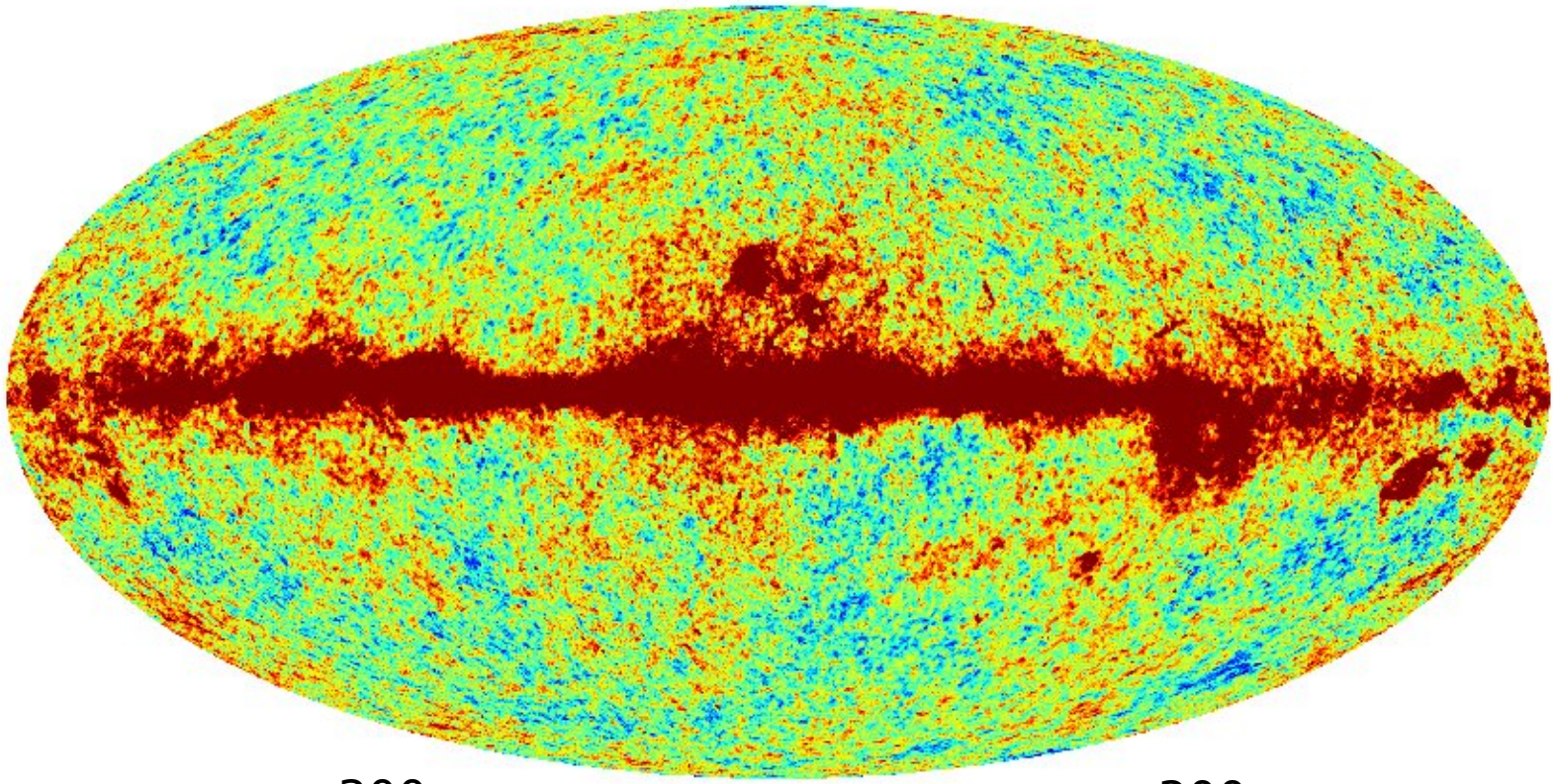

Planck 30 res9
-300
uK
+300
uK


Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)


Ka band res9
-300
uK
+300
uK

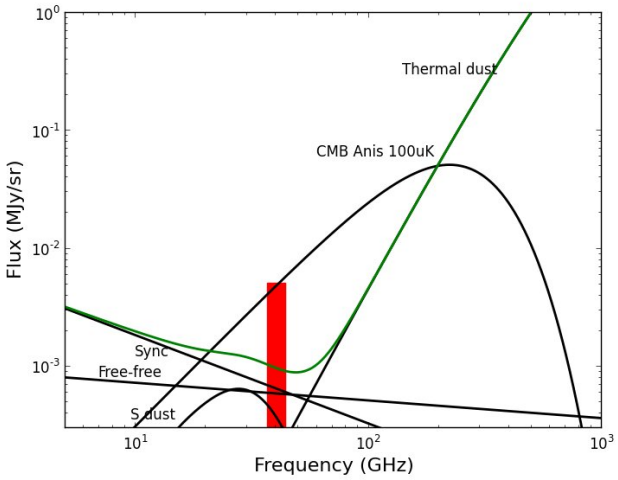

Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)

Q band res9

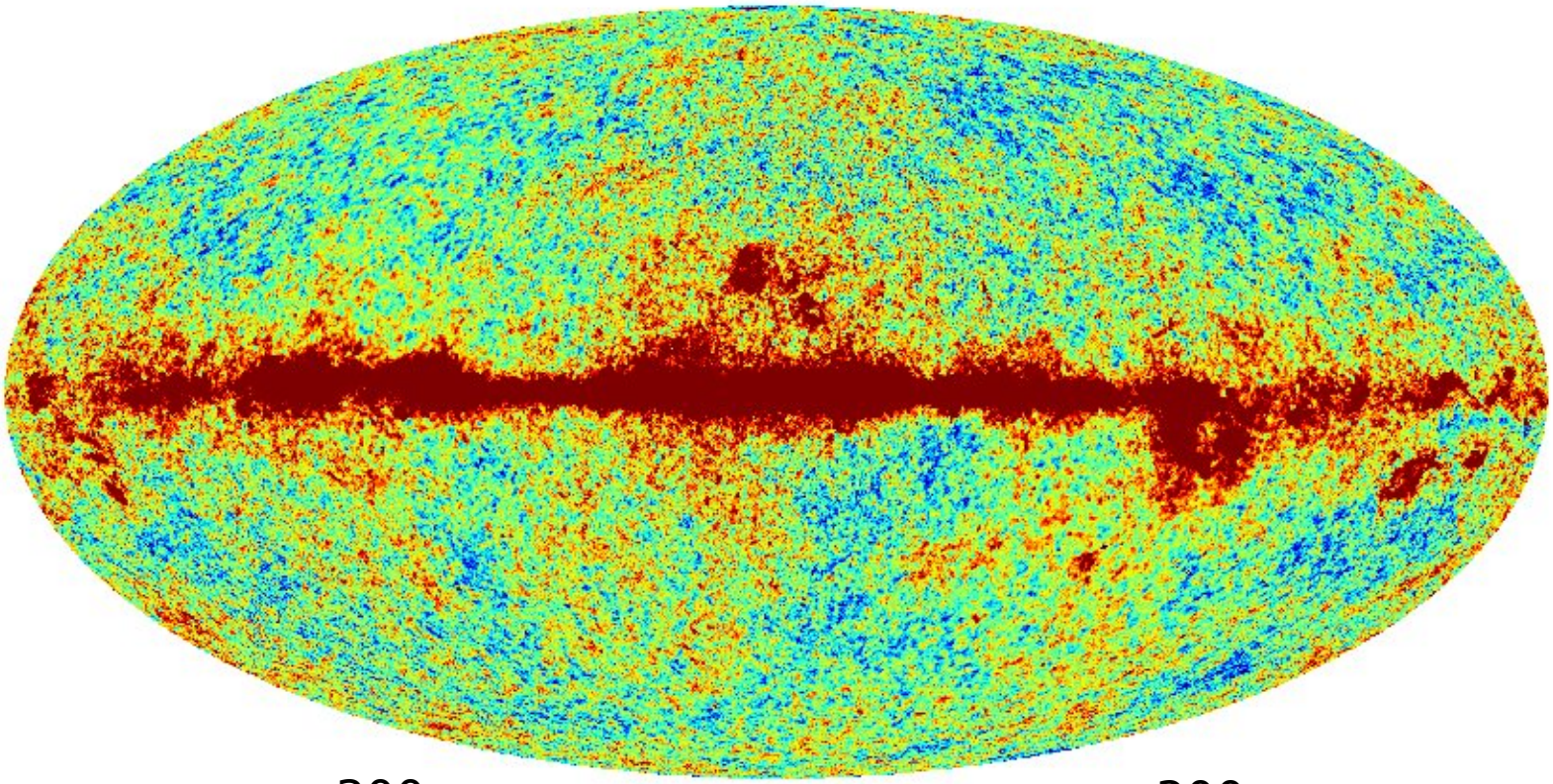


-300 uK

+300 uk

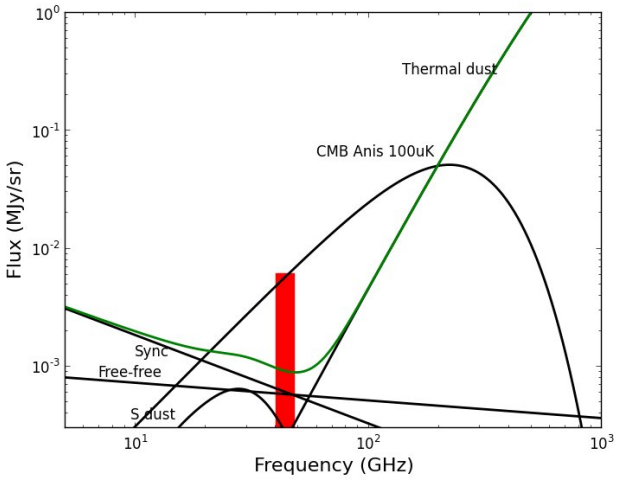


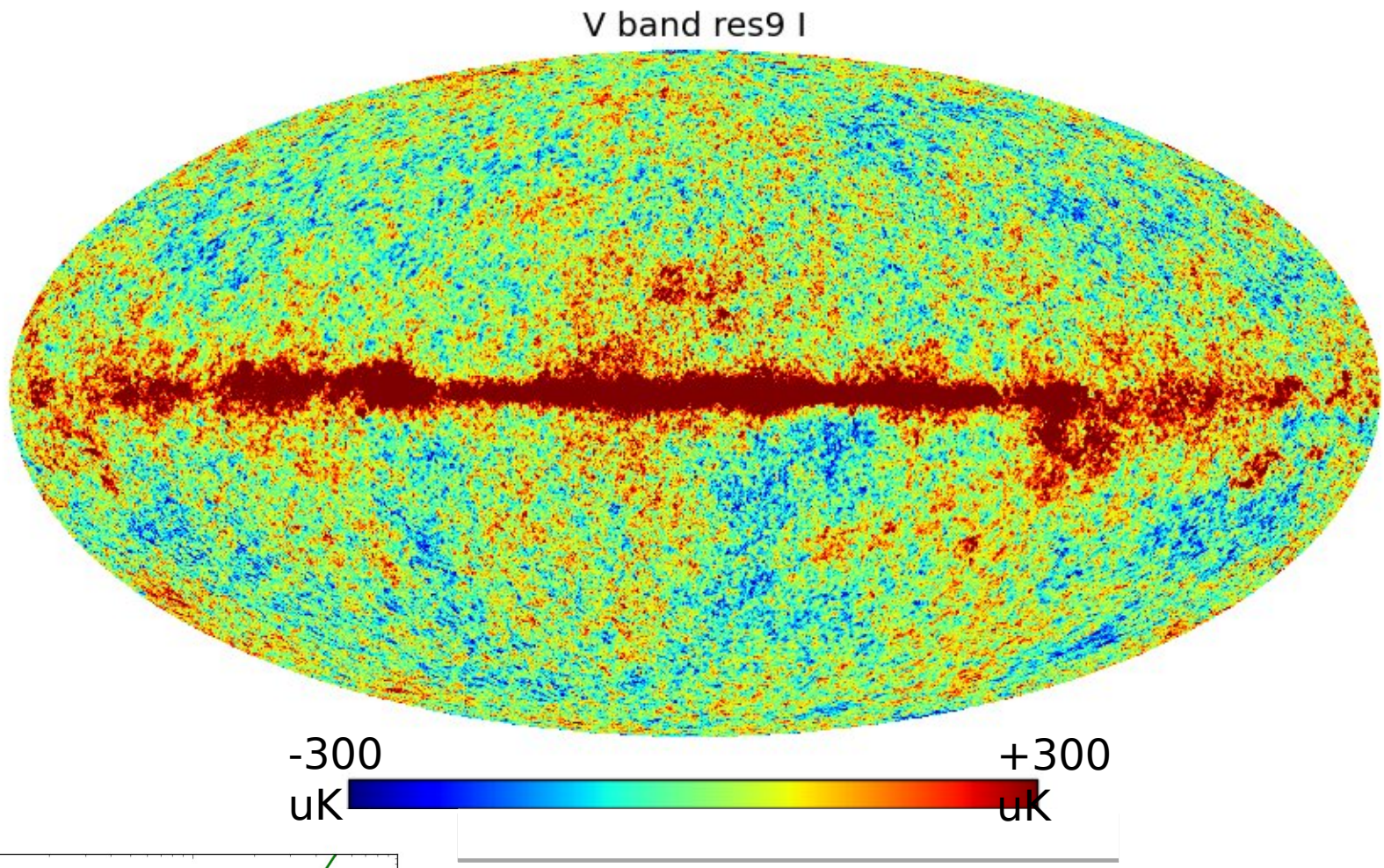
Planck 44 res9

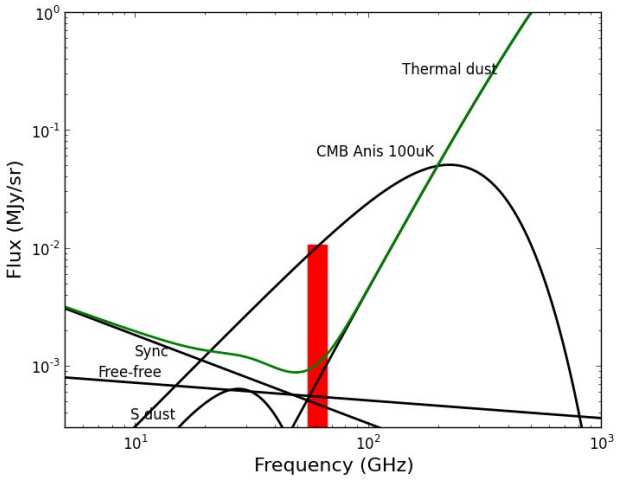


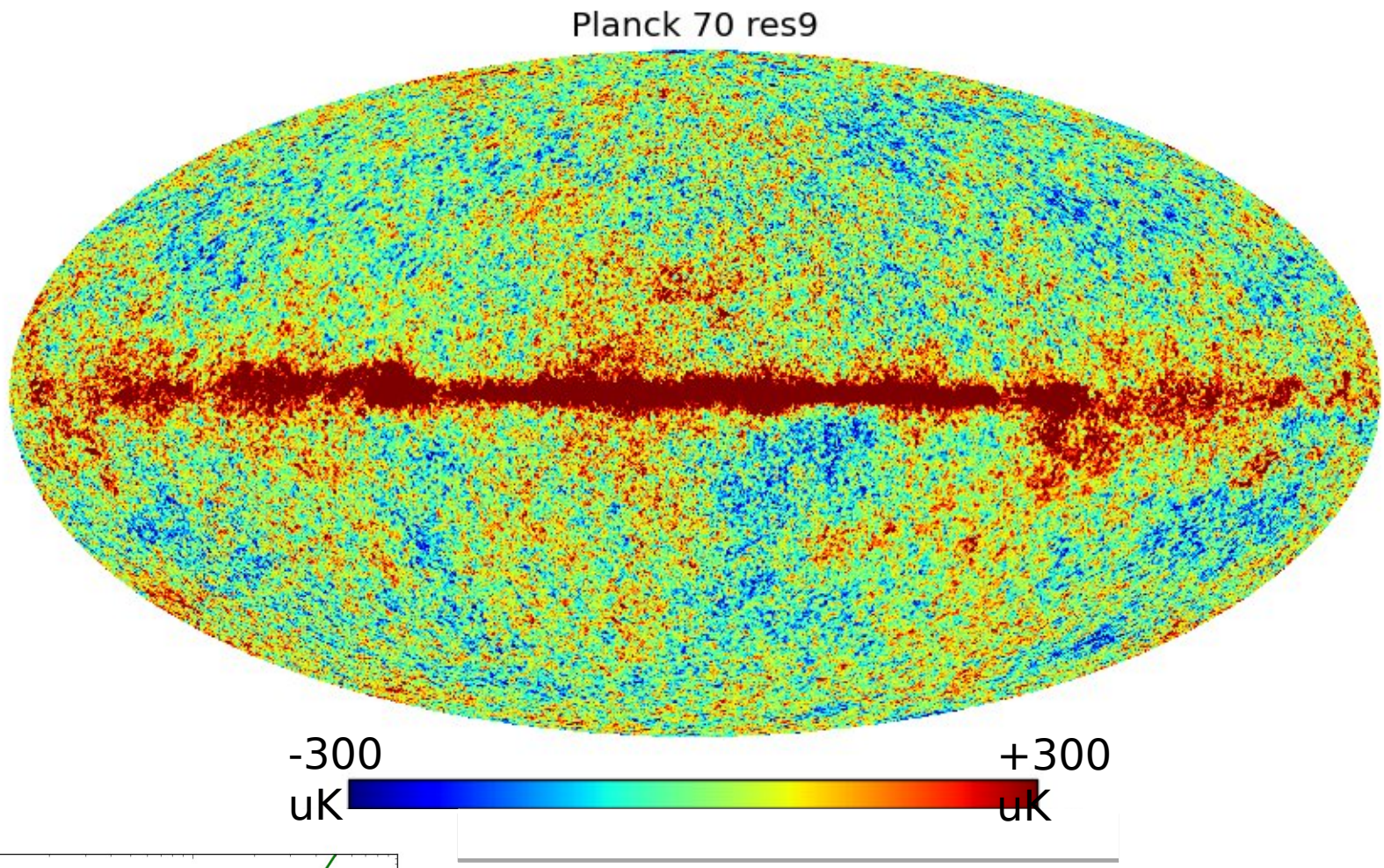
-300 uK

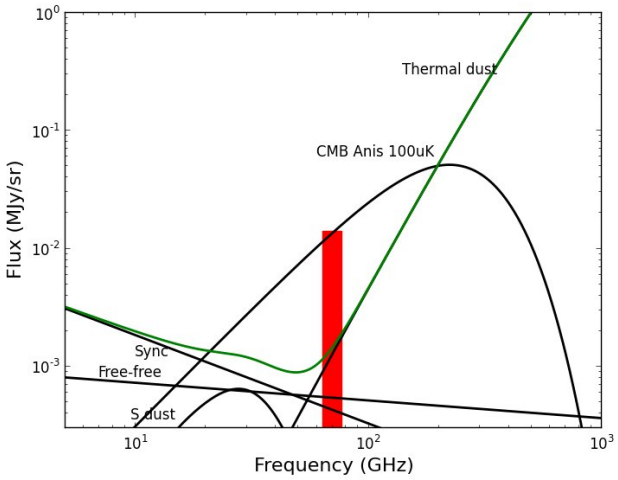
+300 uK

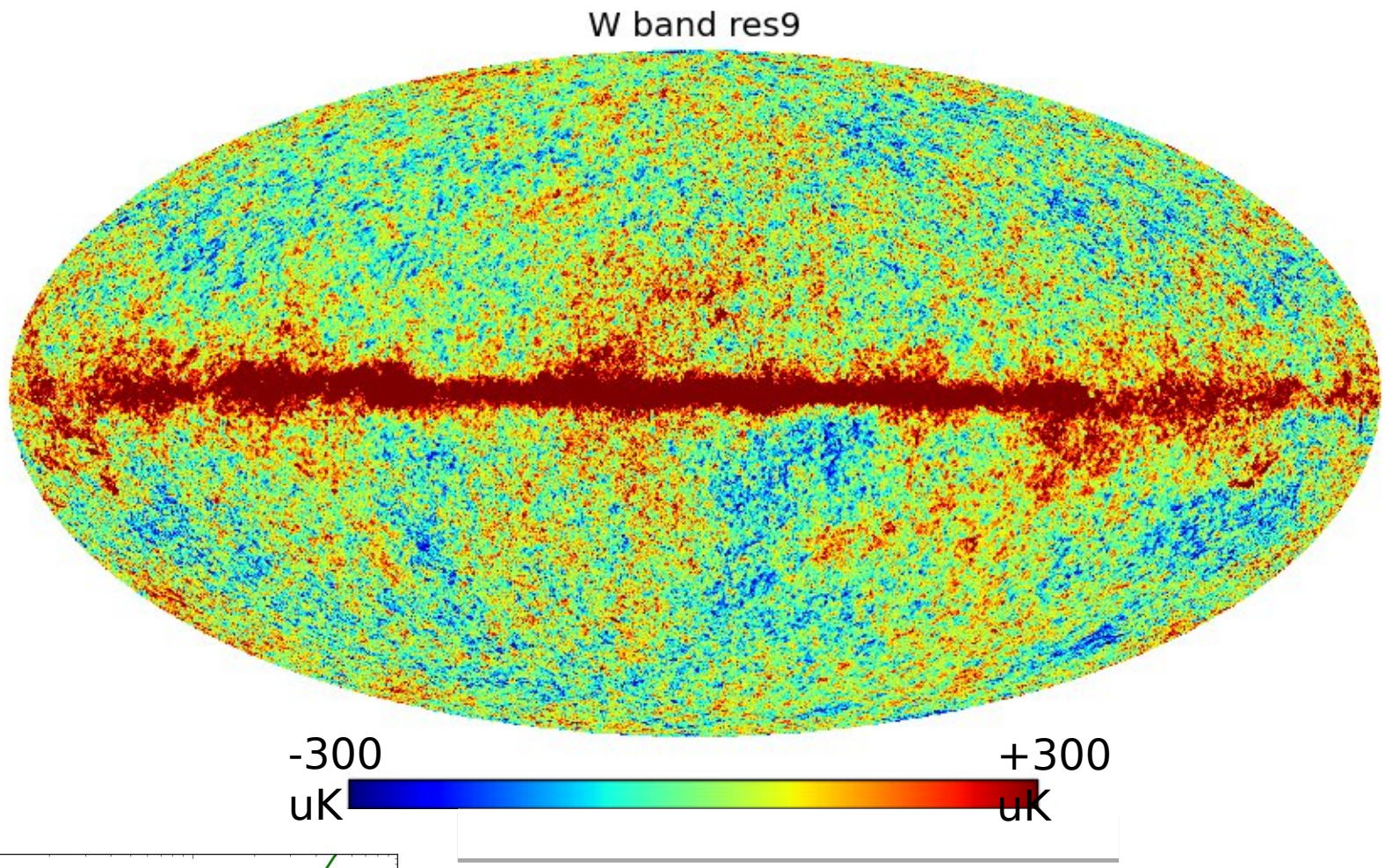


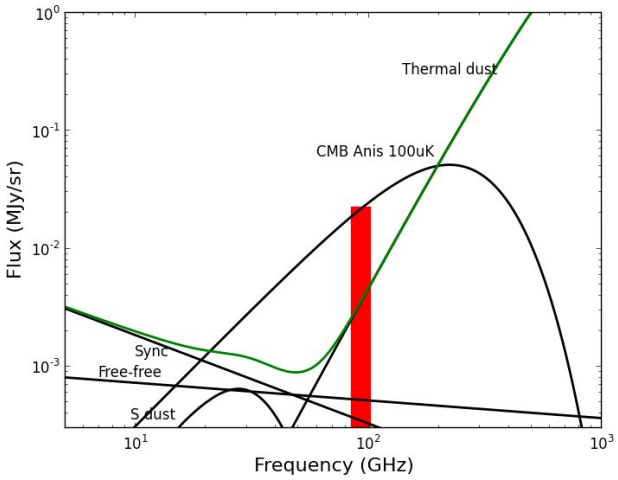

V band res9 I
-300
uK
+300
uK


Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)

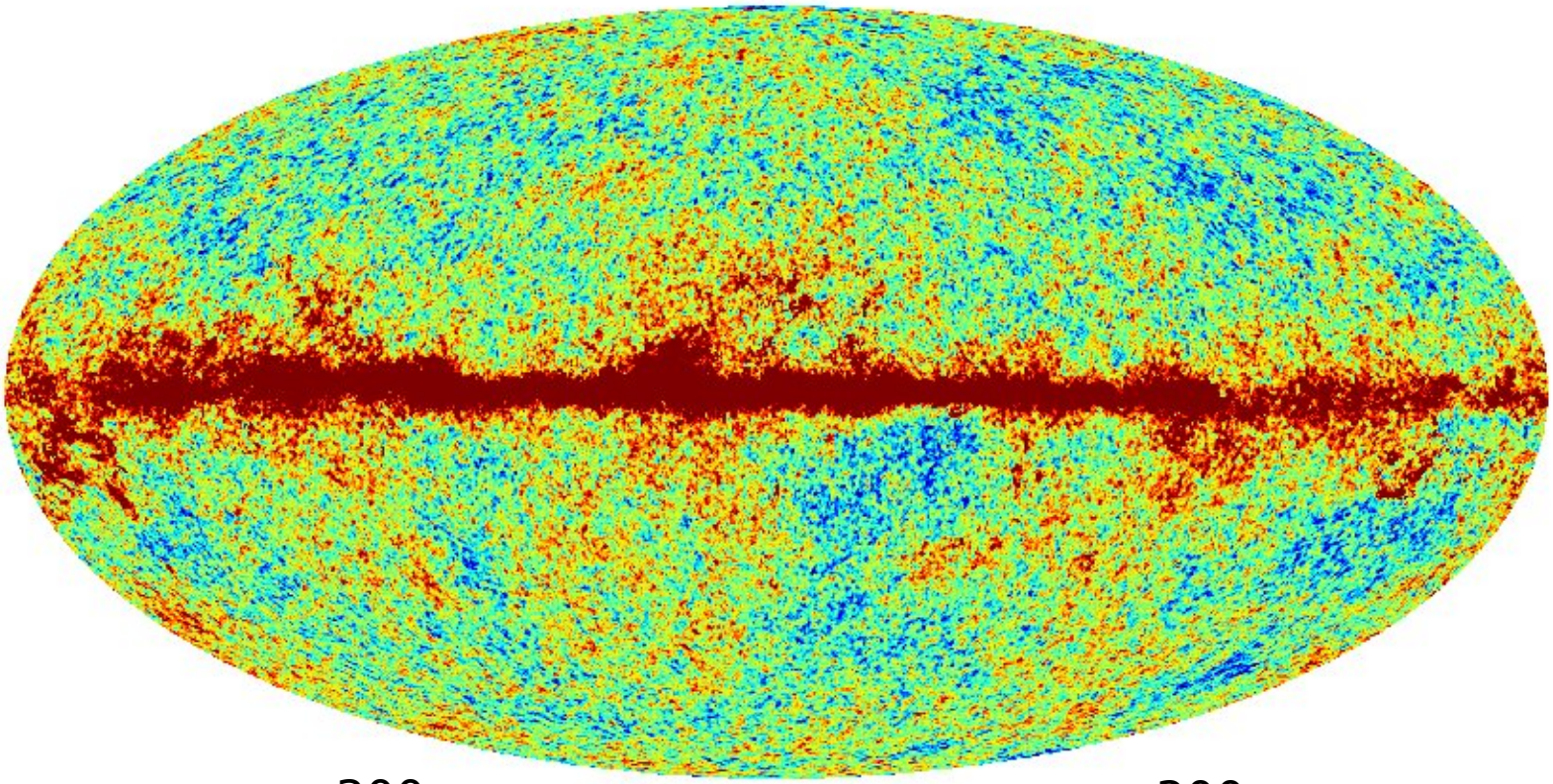

Planck 70 res9
-300
uK
+300
uK


Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)


W band res9
-300
uK
+300
uK

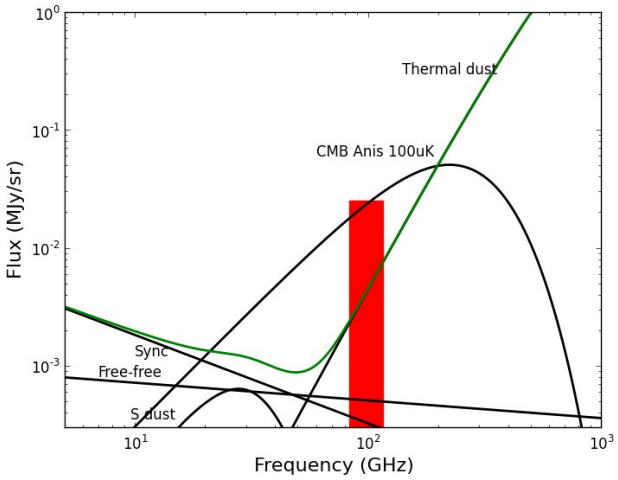

Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)

Planck 100 res9

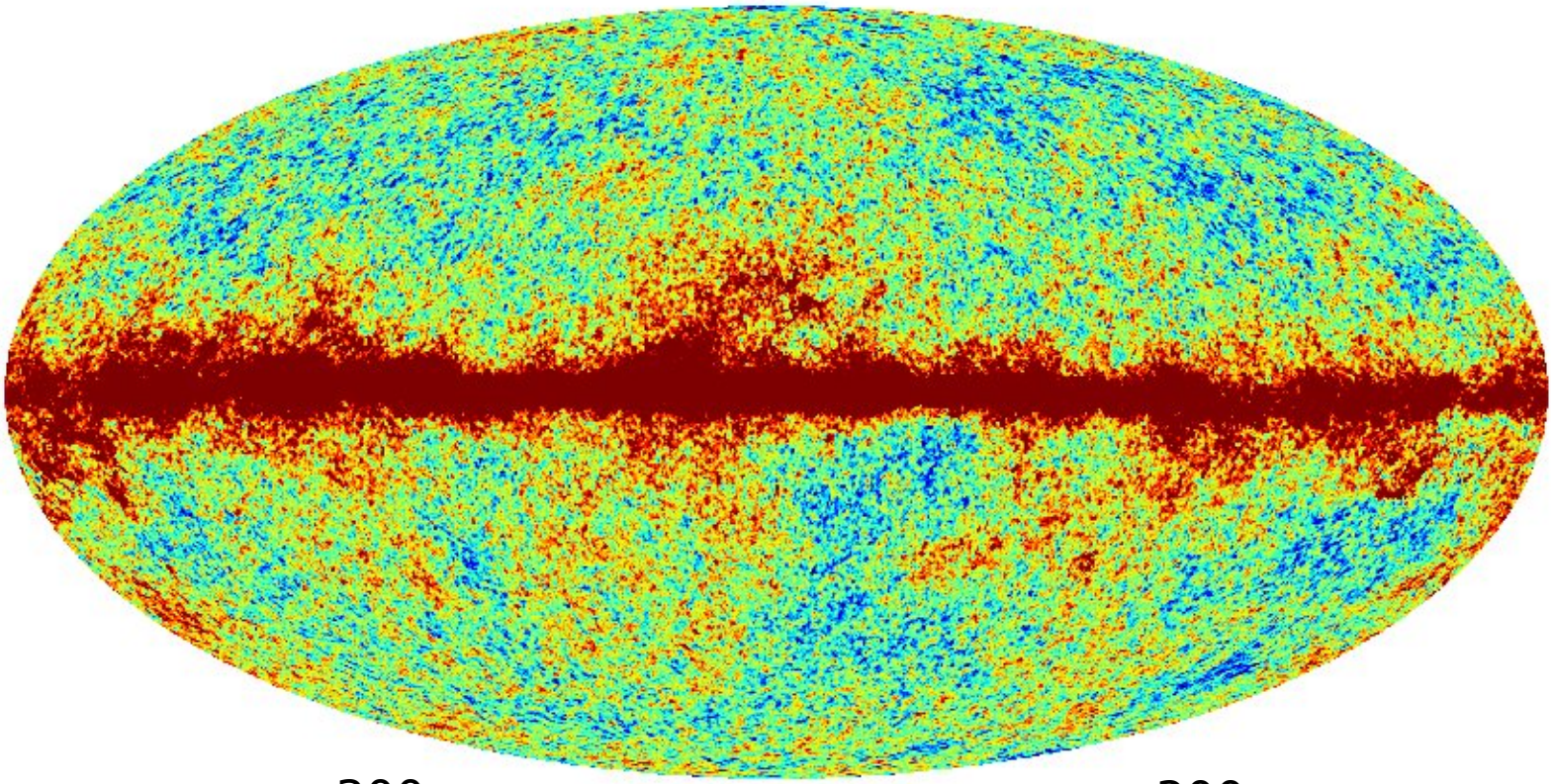


-300 uK

+300 uK

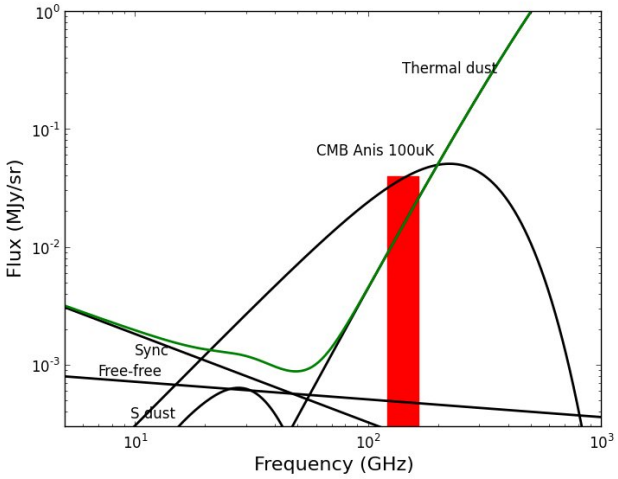


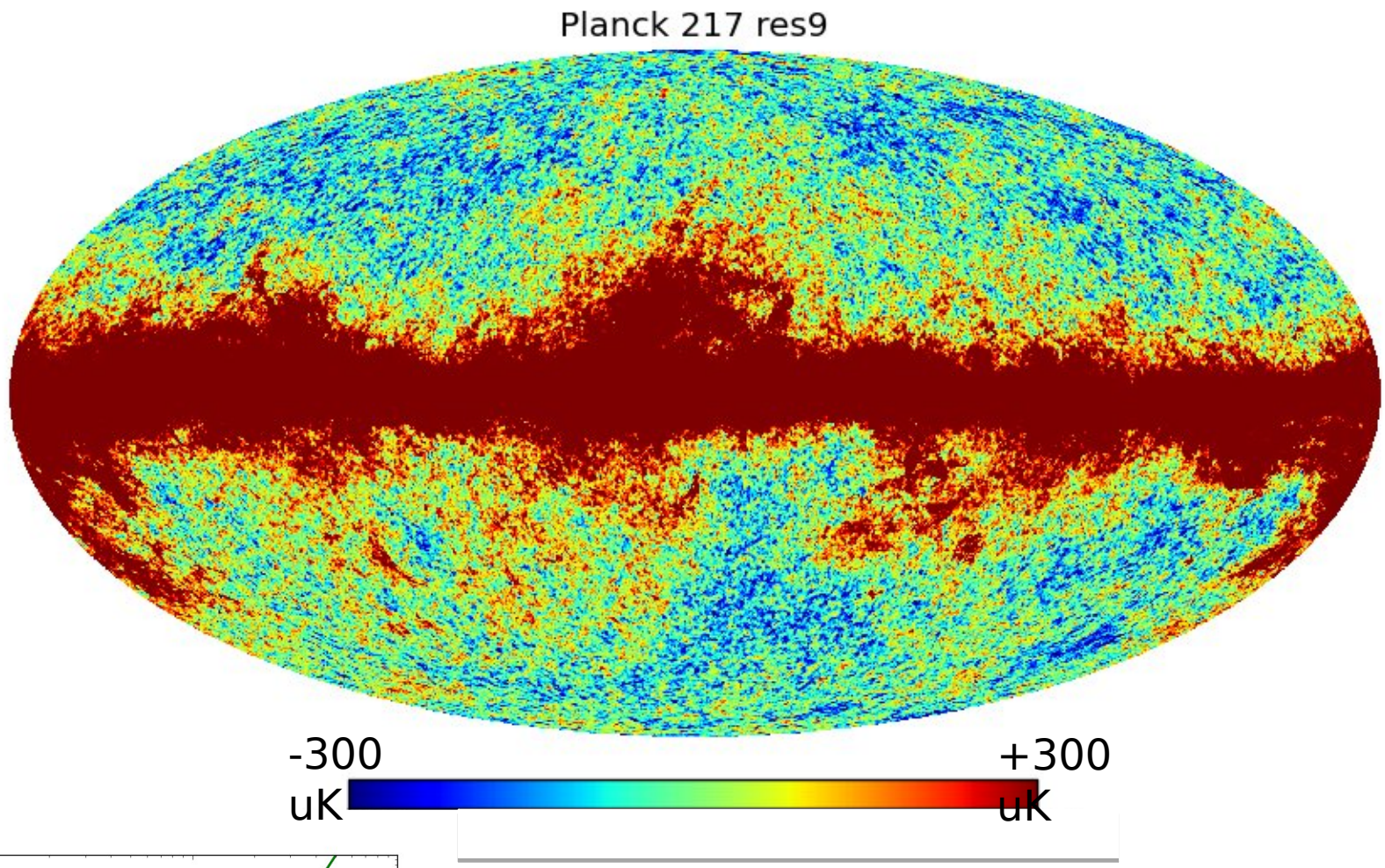
Planck 143 res9

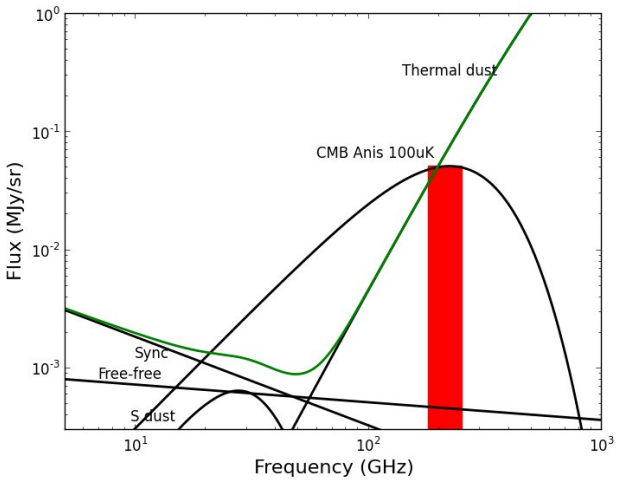


-300 uK

+300 uK



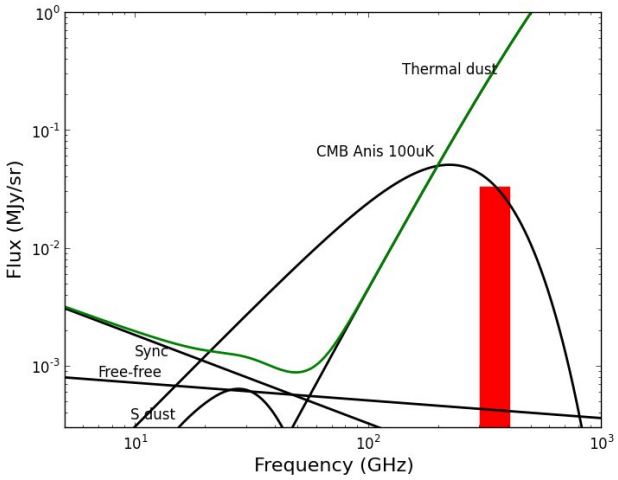

Planck 217 res9
-300
uK
+300
uK


Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)

Planck 353 res9

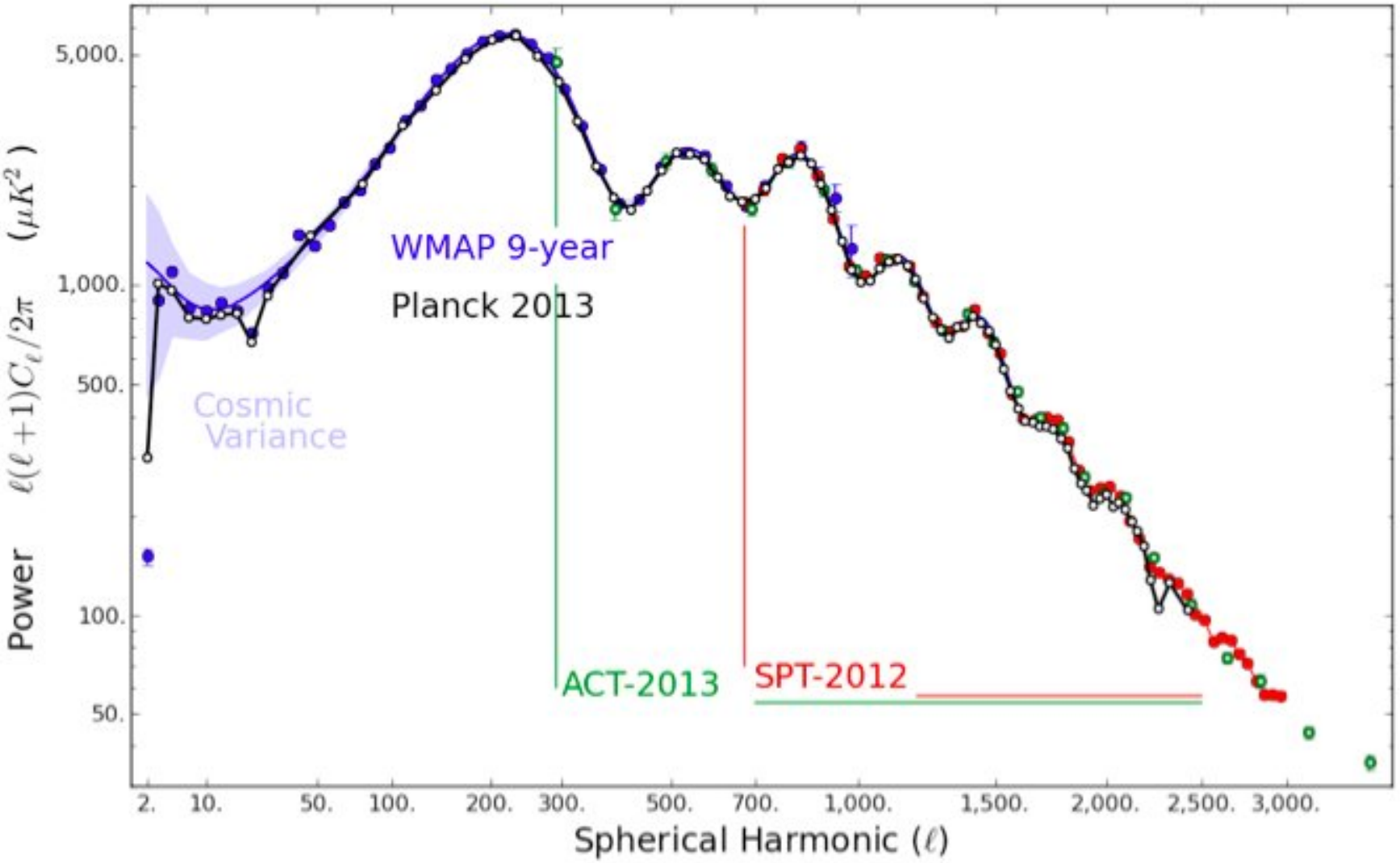
-300 uK

+300 uK



The ACT Neighborhood

temperature anisotropy has been measured very w



From these data plus the WMAP measurement of the polarization, we have a well-established standard model of cosmology.

- Universe is flat and described by six cosmological parameters: $\Omega_b h^2$, $\Omega_c h^2$, Ω_Λ, τ, n_s, Δ_R^2
- **Fluctuations are super-horizon, nearly scale invariant, Gaussian, and adiabatic.**
- Theory of **General Relativity** describes gravity.
- The model is so good we can observe departures from it to determine the **sum of neutrino masses** and test GR among other things.

Why measure the CMB polarization?

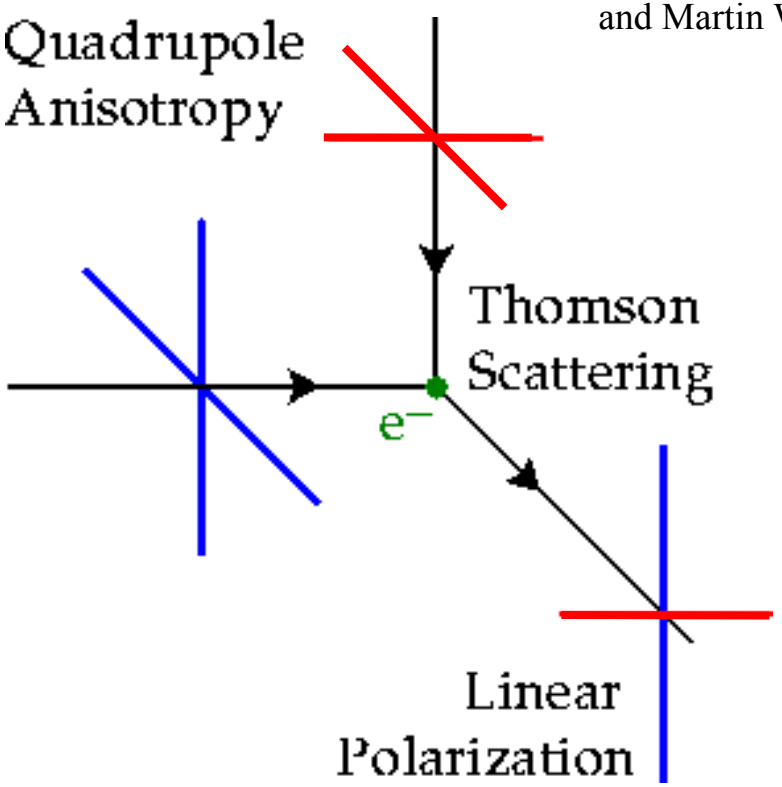
- Independent check of cosmological parameters based on primordial plasma momentum.
- Search for primordial gravitational waves.
- Lensing of E-modes turns out to be especially sensitive to the sum of neutrino masses.
- Search for isocurvature (i.e. not

Polarization is produced by free electrons in a quadrupolar radiation field

Different physical conditions produce the quadrupole.

1) At decoupling (z~1100) it is plasma velocity gradients or the local CMB temperature distribution for G-waves.
2) For reionizaion (z~10) it is the local CMB temperature distribution.

From Wayne Hu and Martin White

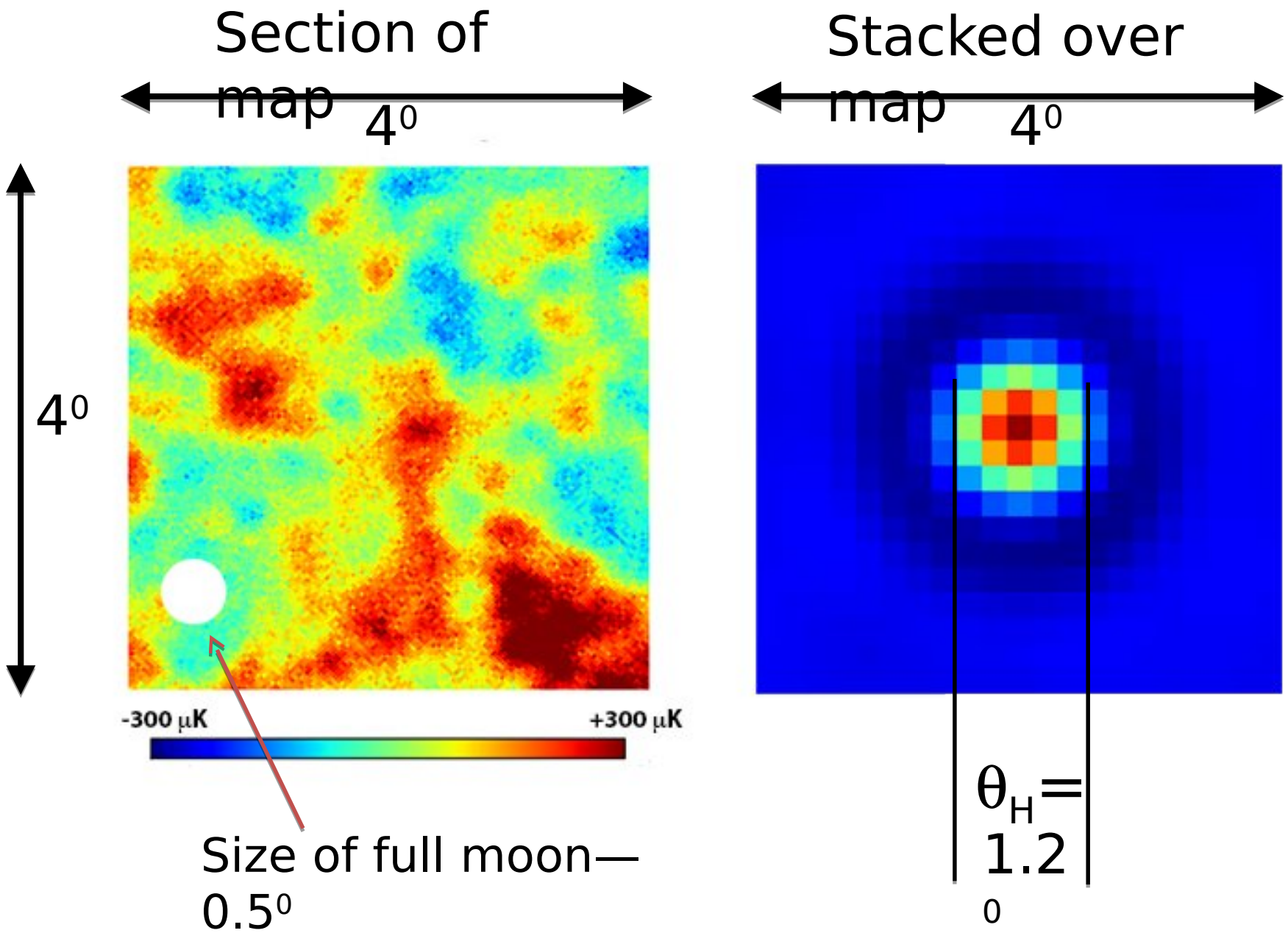


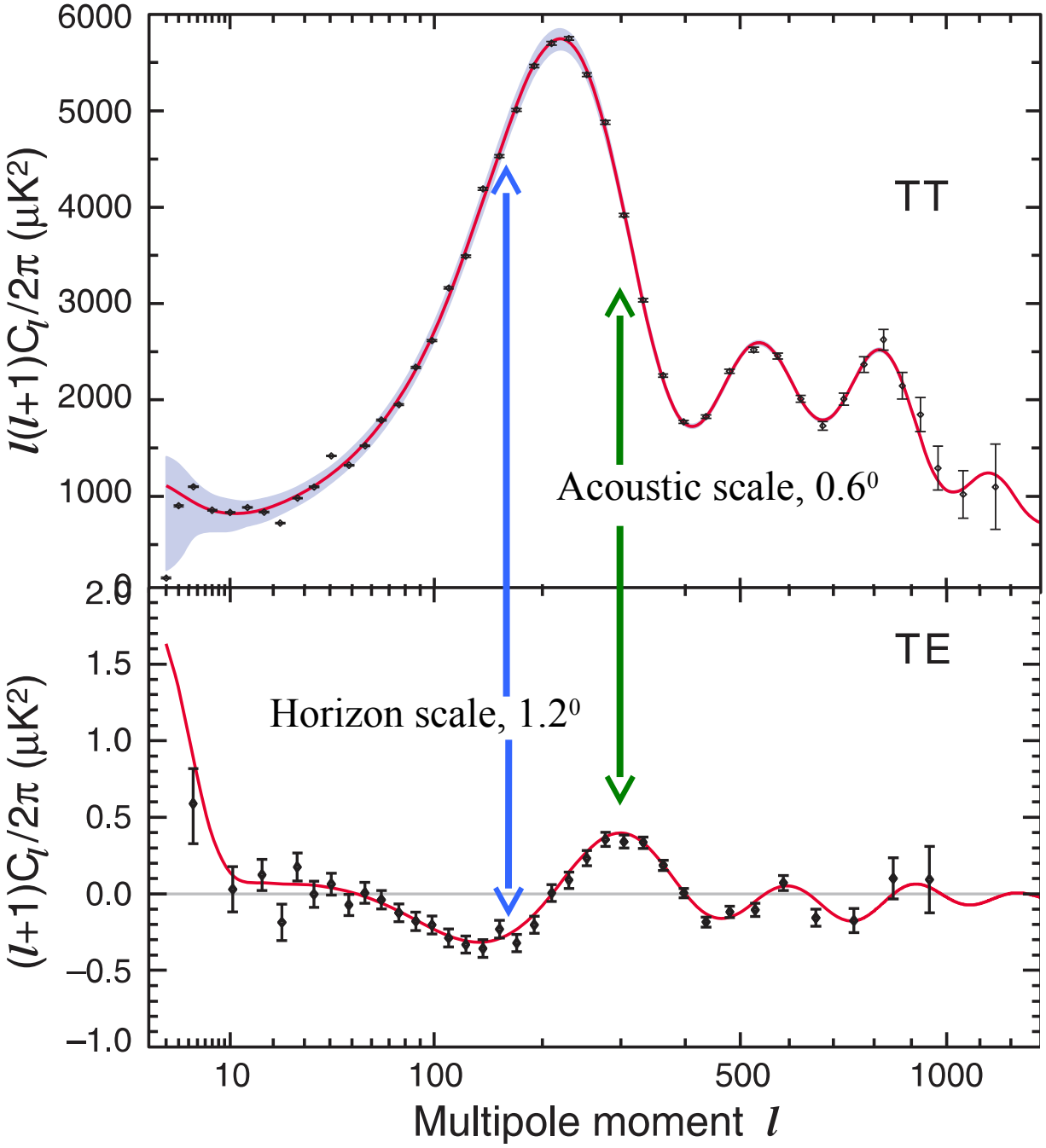
There are two “patterns” of polarization.

E modes: The pattern does not change when observed in a mirror, that is it does not change under a parity transformation.

B modes: The pattern changes when observed in a mirror, that is it **does** change under a parity transformation. There are “lensing” B modes and “primordial” B modes.

Planck's stacked hot spots

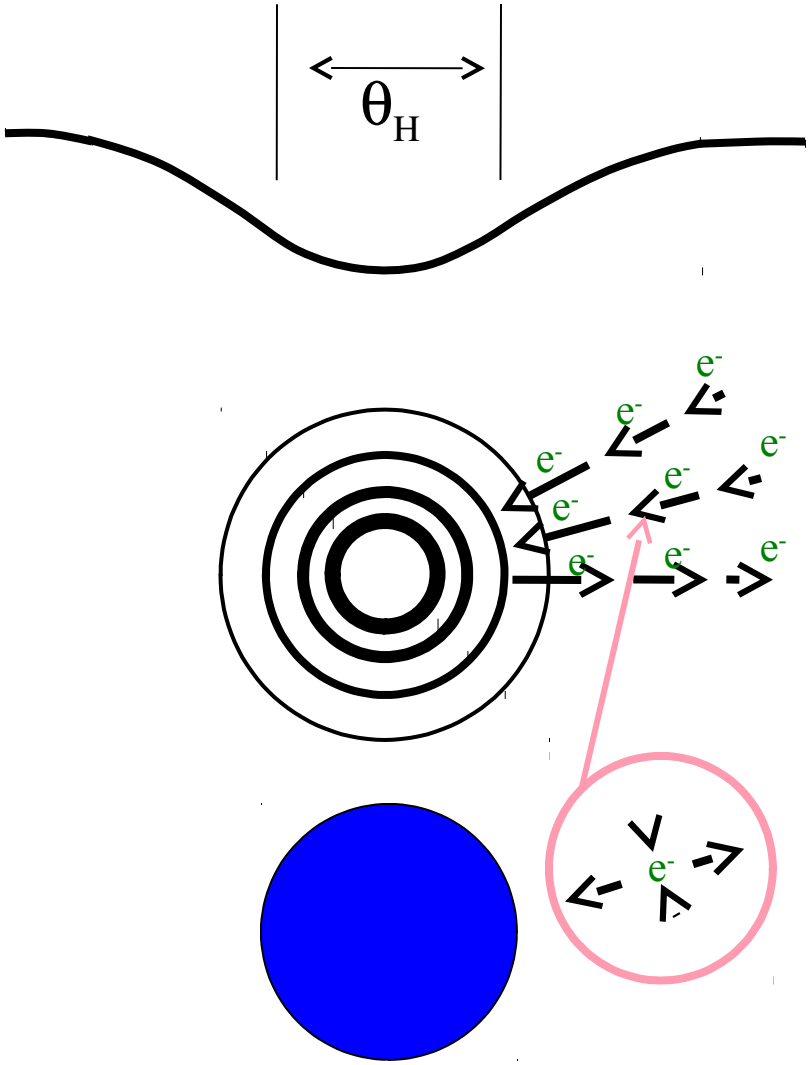




*Super-horizon fluctuations

Spergel & Zaldarriaga (1997)
Peiris et al. (2003)
Bennett et al, 2013

Consider a fluctuation in potential at **large** angular scales.

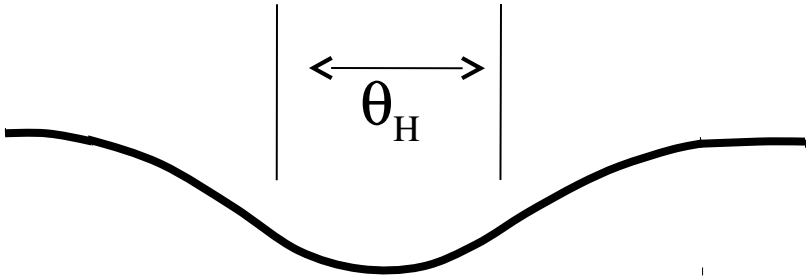


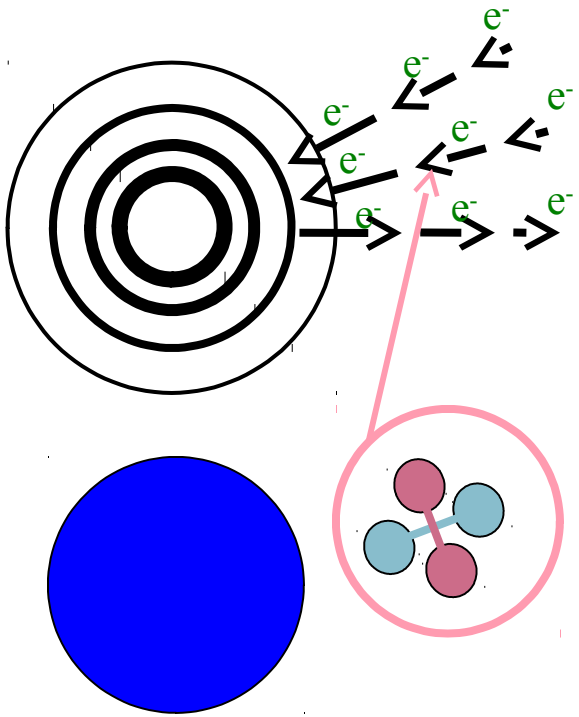
Photons climb out of well so this appears as a cold splotch on large angular scales.

The primordial plasma flows into the well.

An electron sees a local quadrupole and thus scatters polarized light towards us.

Consider a fluctuation in potential at **large** angular scales.





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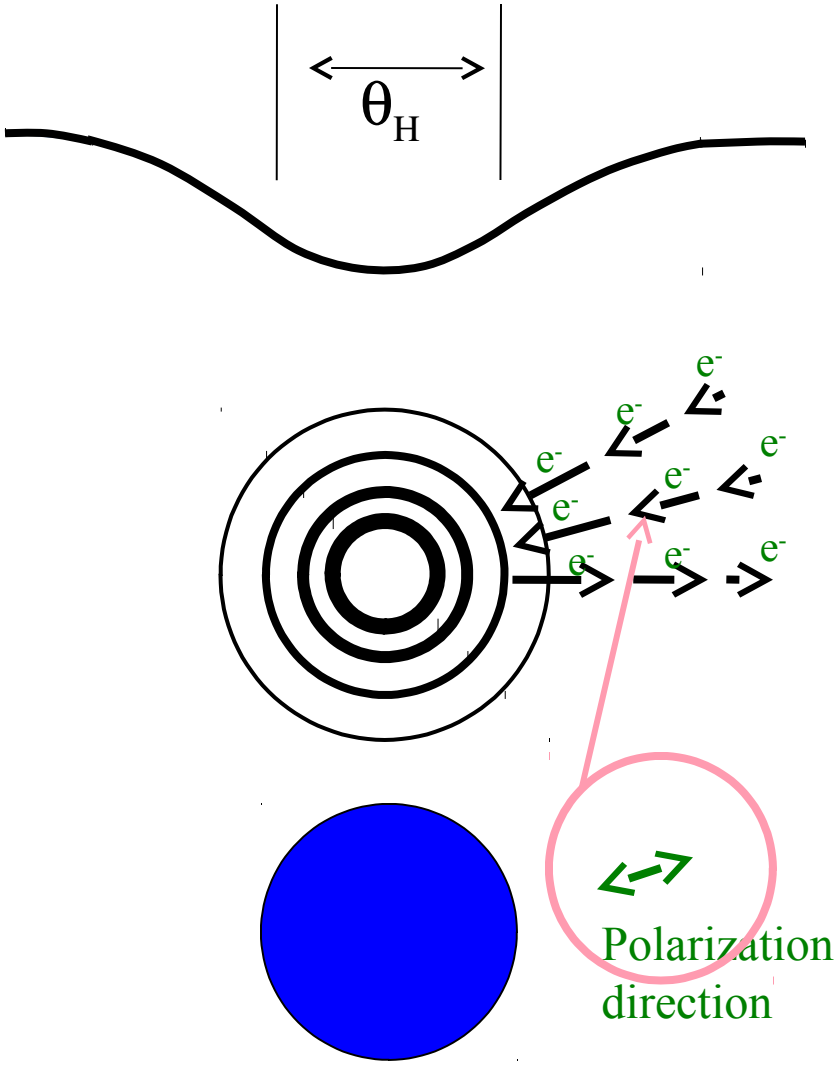

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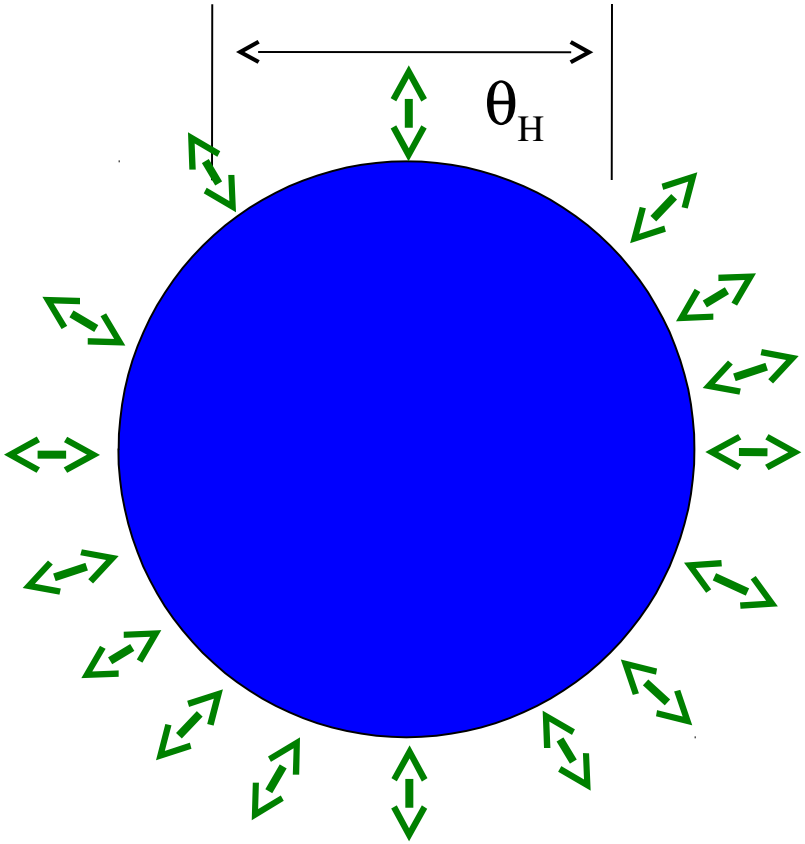
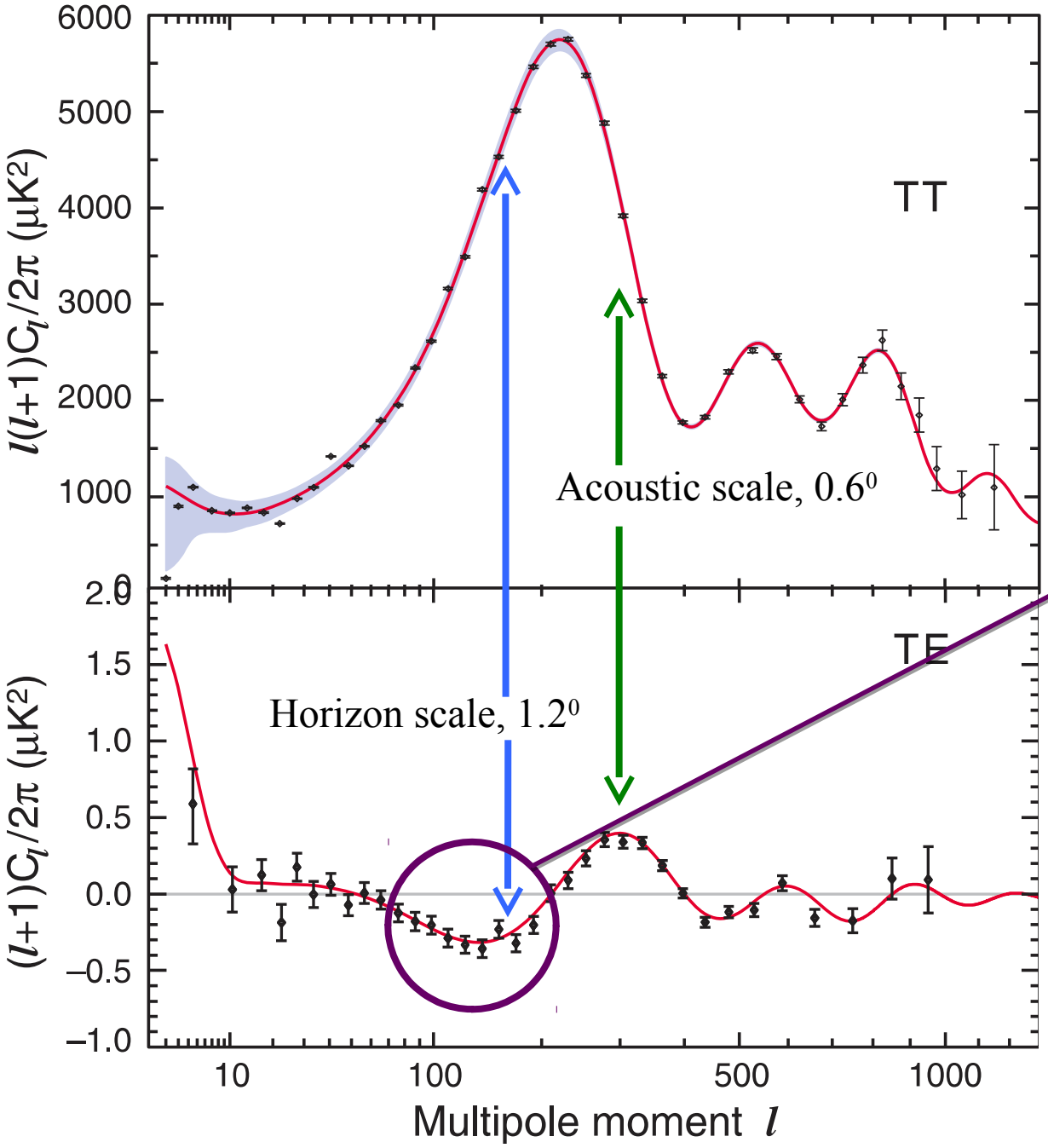


At **large** angular scales we expect the direction of the correlated component of the polarization to be **radial** around cold spots (or potential minima or over dense regions).

T here is negative, and the E polarization "positive" and so TE is negative.

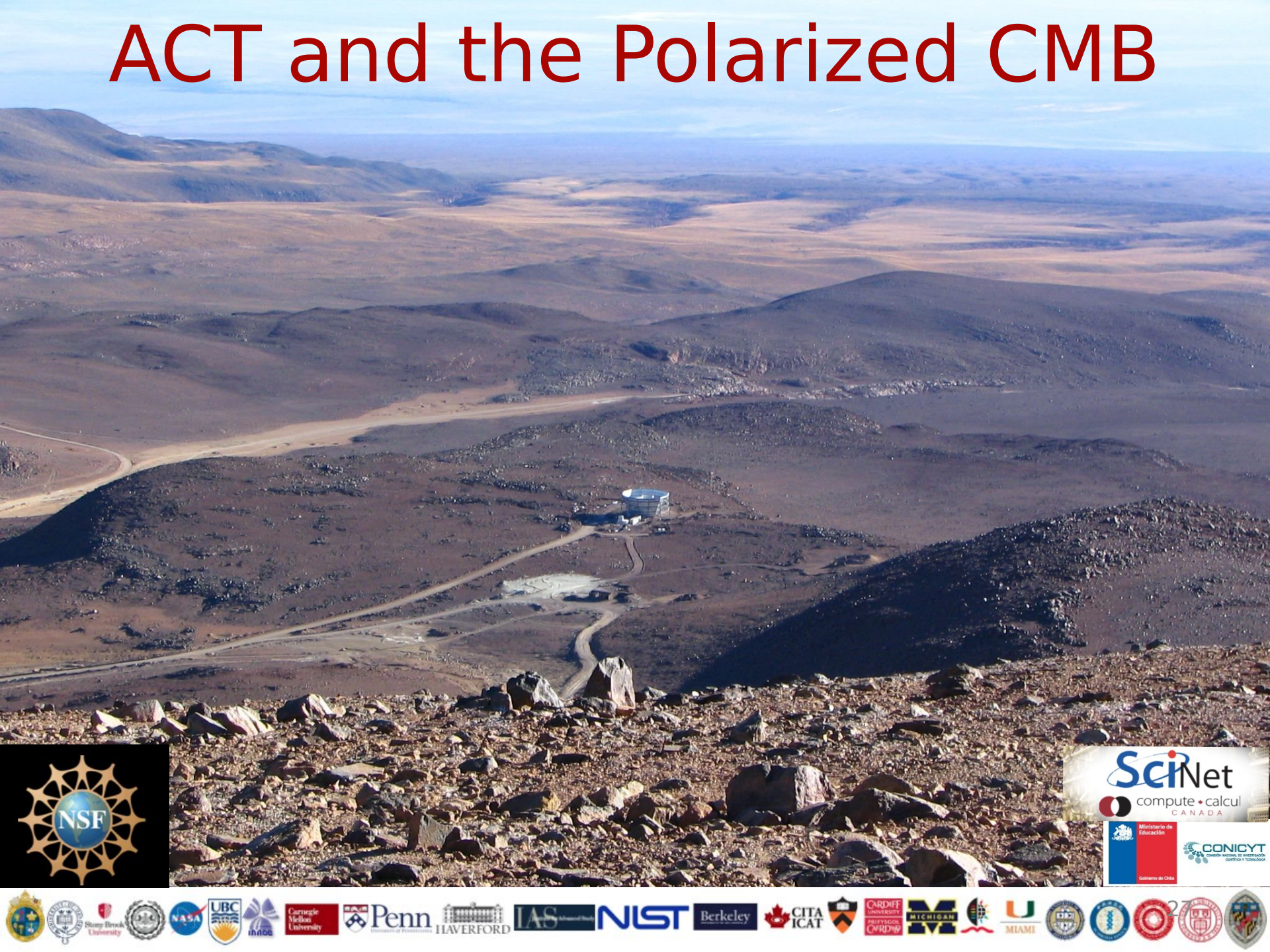
If fluctuations are superhorizon there should be an anti-correlation for $\theta > 1.2^0$



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

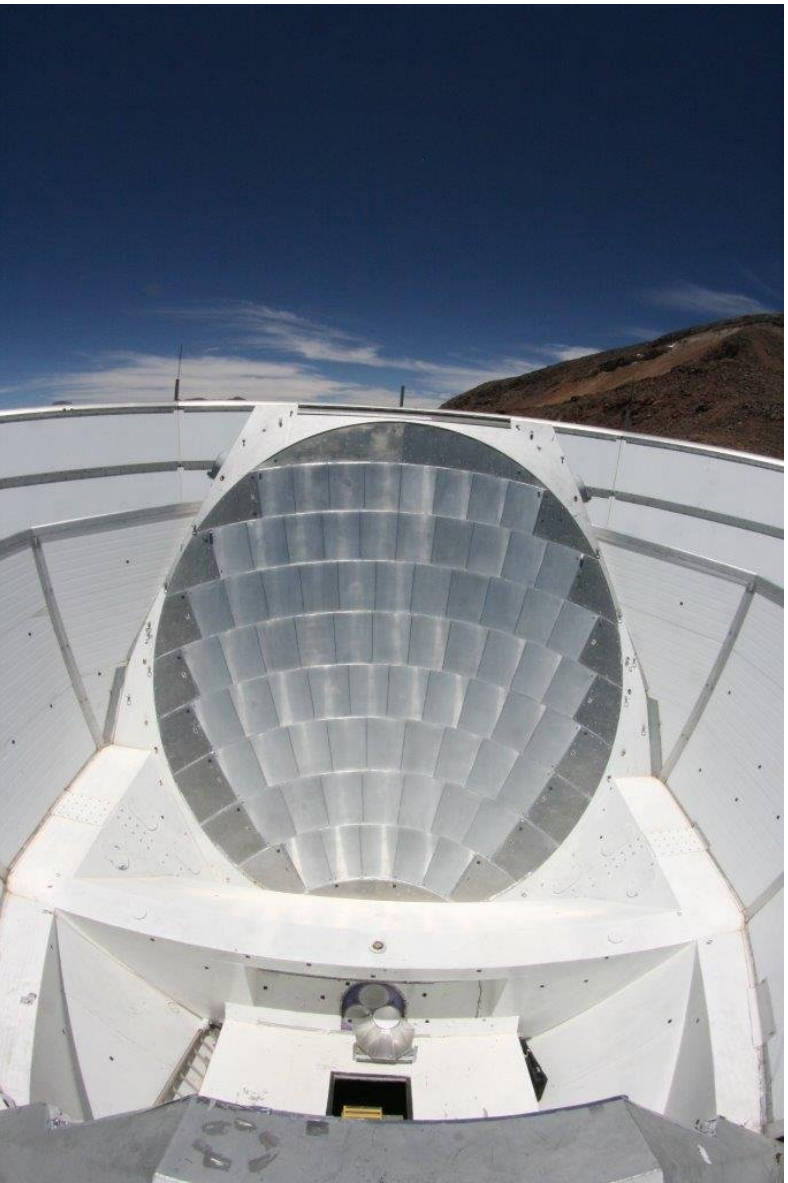
Spergel & Zaldarriaga (1997)
Peiris et al. (2003)
Bennett et al, 2013

ACT and the Polarized CMB

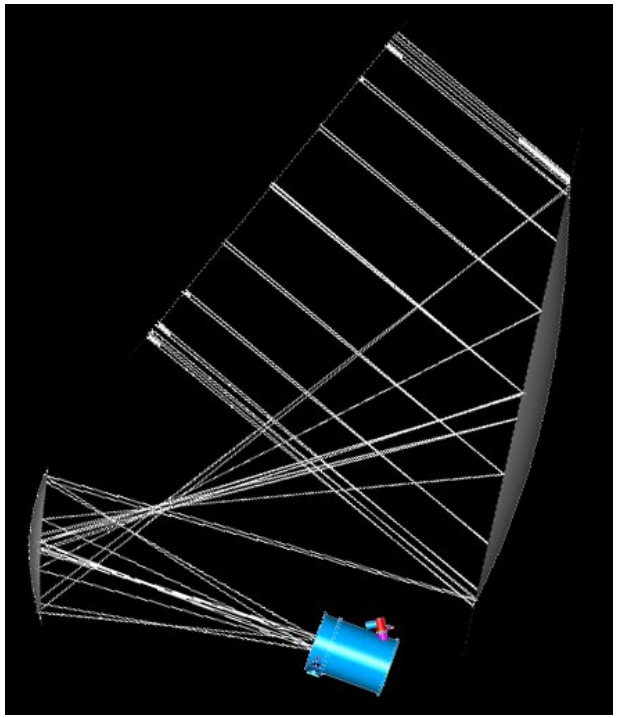


ACTPol

(Atacama Cosmology Telescope Polarimeter)

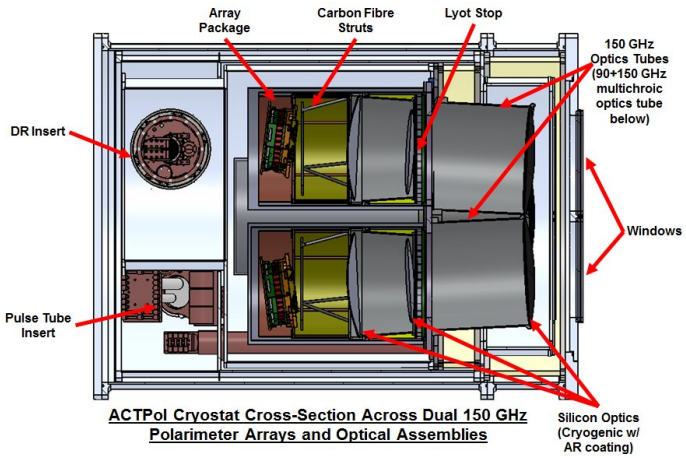


- **6m off-axis telescope**
- **Arcminute resolution**
- **5200 m (0.5 mm PWV)**
- **Latitude -23^{o}**



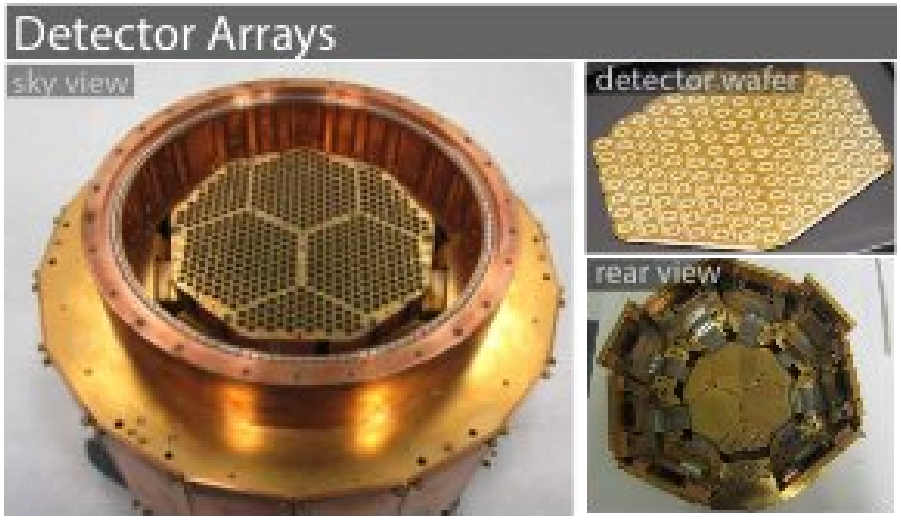
ACT's Polarimeter

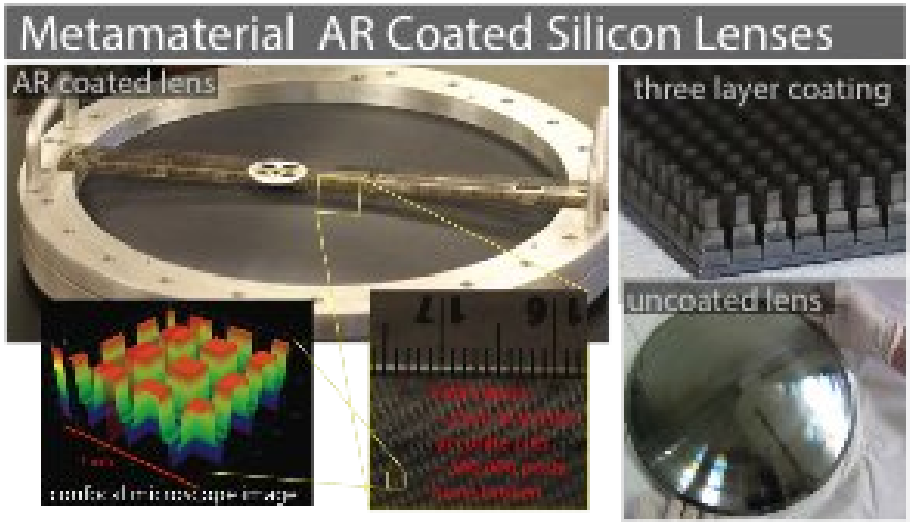
Present:
2013-2015
ACTPol



ACTPol Cryostat Cross-Section Across Dual 150 GHz Polarimeter Arrays and Optical Assemblies

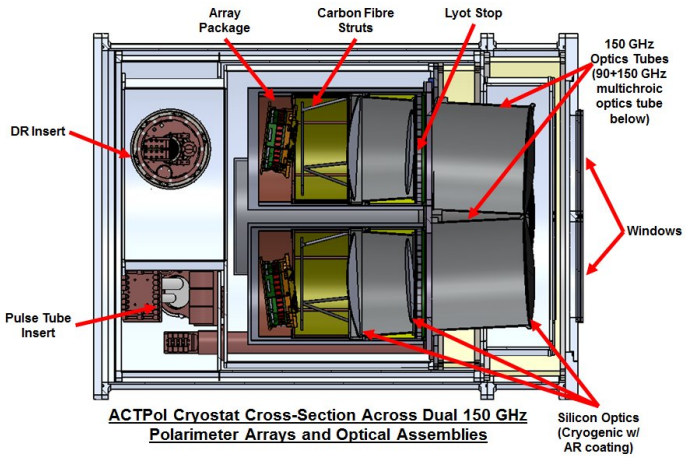
Temperature & Polarization
Two bands: 90 & 146 GHz
90 mK dilution fridge





ACT's Polarimeter

Present:
2013-2015
ACTPol



ACTPol Cryostat Cross-Section Across Dual 150 GHz Polarimeter Arrays and Optical Assemblies

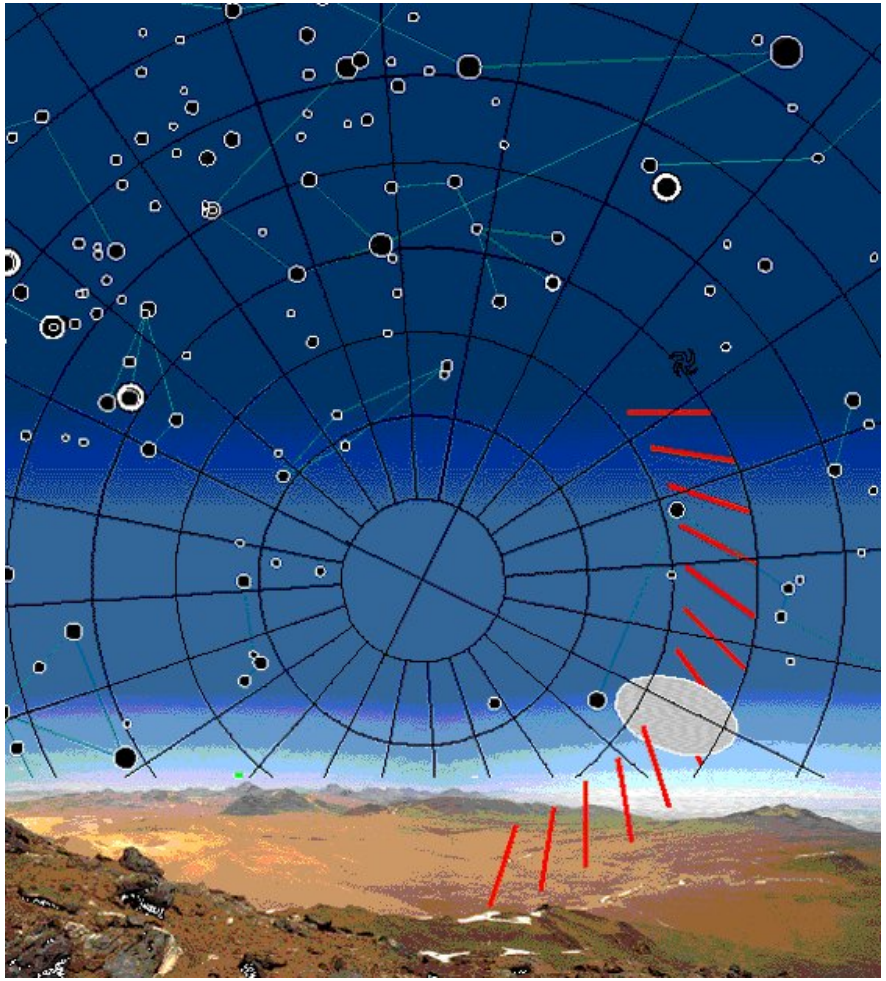
Temperature & Polarization
Two bands: 90 & 146 GHz
90 mK dilution fridge

ACTPOL STATUS

2013: First array (all 146 GHz) – 19 uK $s^{1/2}$ -- first results published
2014: Two arrays (all 146 GHz) – analysis underway
2015: Third **multichroic** array with **simultaneous** 90/146 GHz just installed.

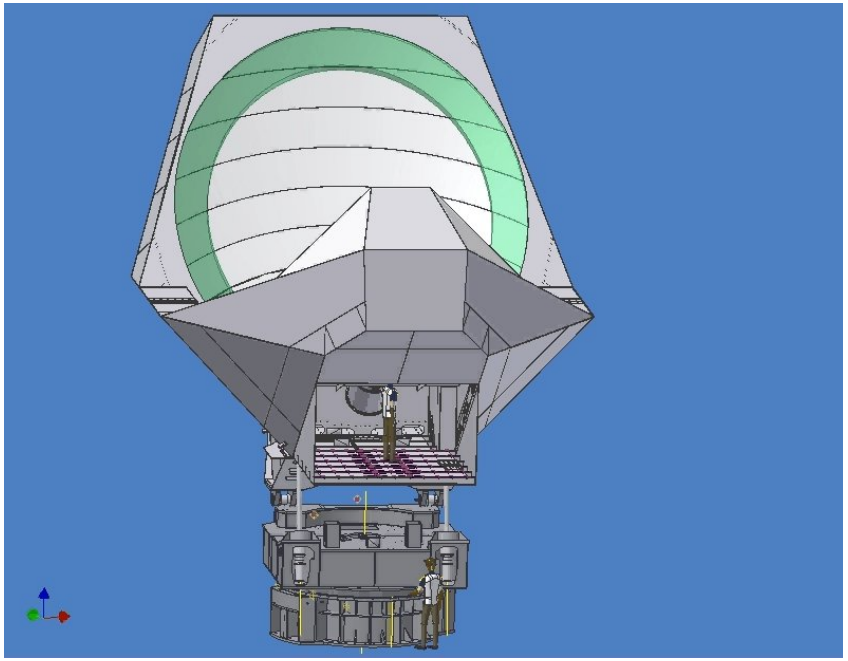
Looking ahead

Compare: Planck – 17 uK $s^{1/2}$. Soon, multiple systems (ground and balloon) will be ~ 5 uK $s^{1/2}$ and thus the mapping speed will be 10X Planck.



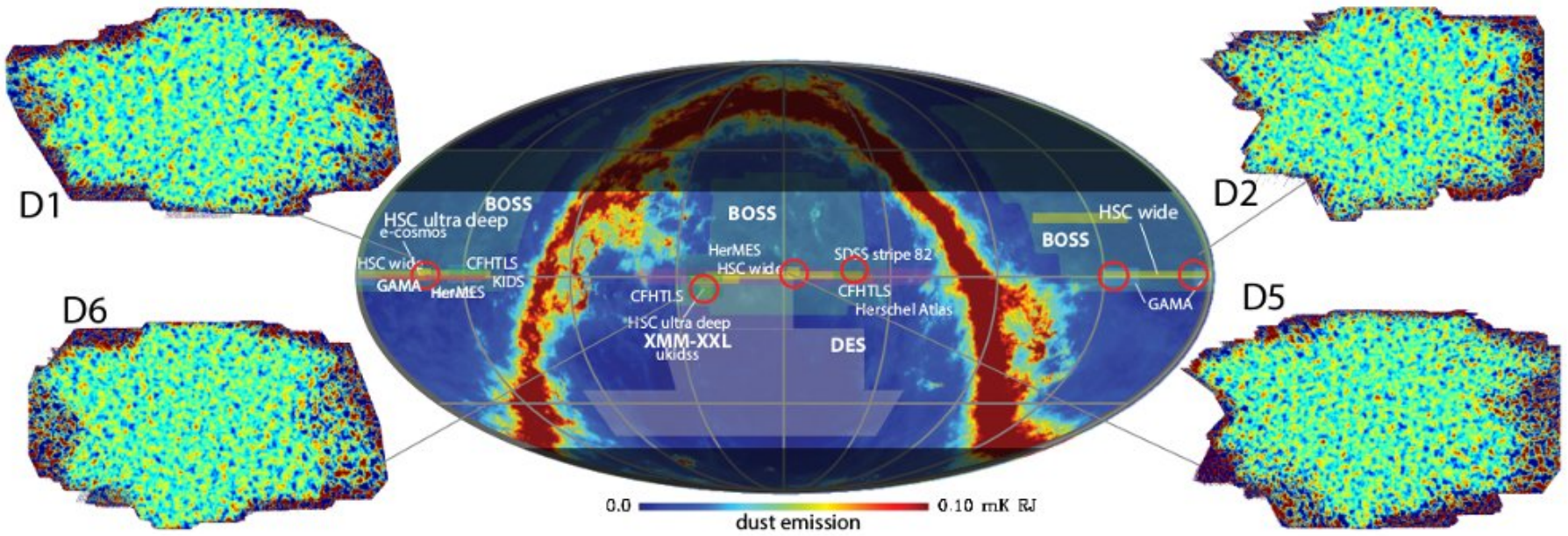
Telescope scans 7 deg at 1 deg/sec

Cross-linked observations:



ACTPol First Season Observations

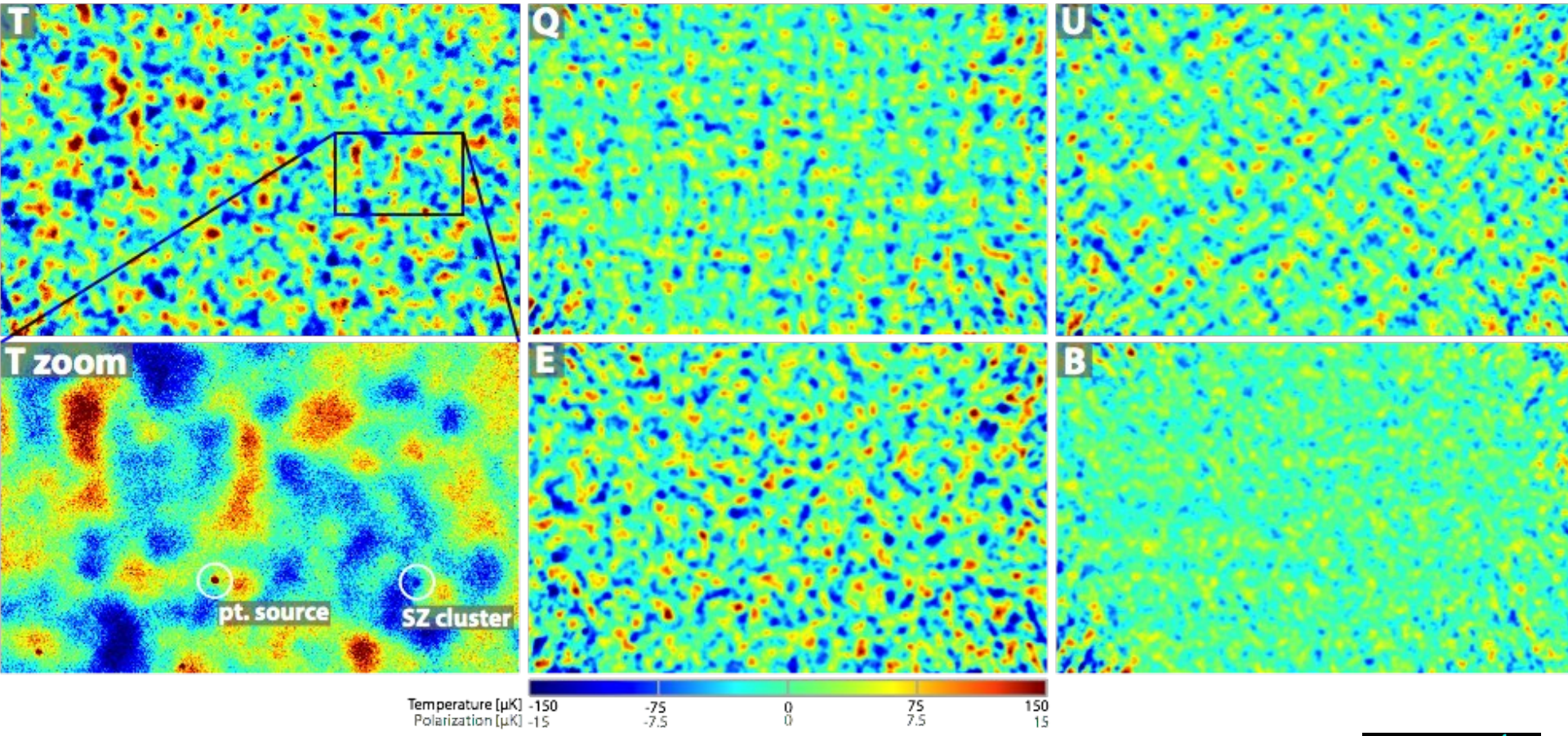
(Naess et al, JCAP10(2014)007)



- 11 Sept 2013 – 24 Dec 2013 (650 hrs)
- Only one 150 GHz array installed then
- Four ~ 70 deg^2 patches
- Overlap with other surveys for xcorr

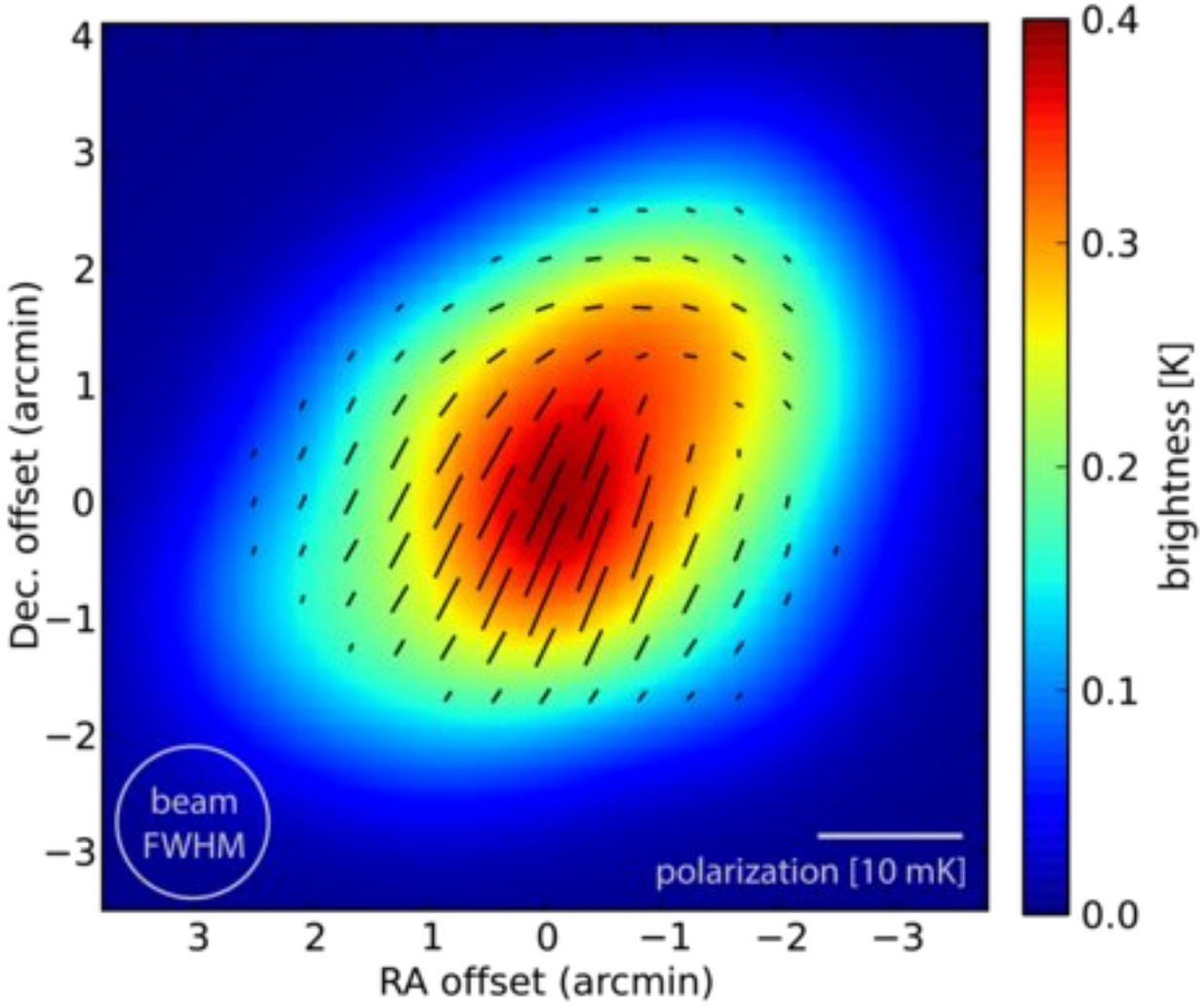
ACTPol First Season Observations

(Naess et al, JCAP10(2014)007)

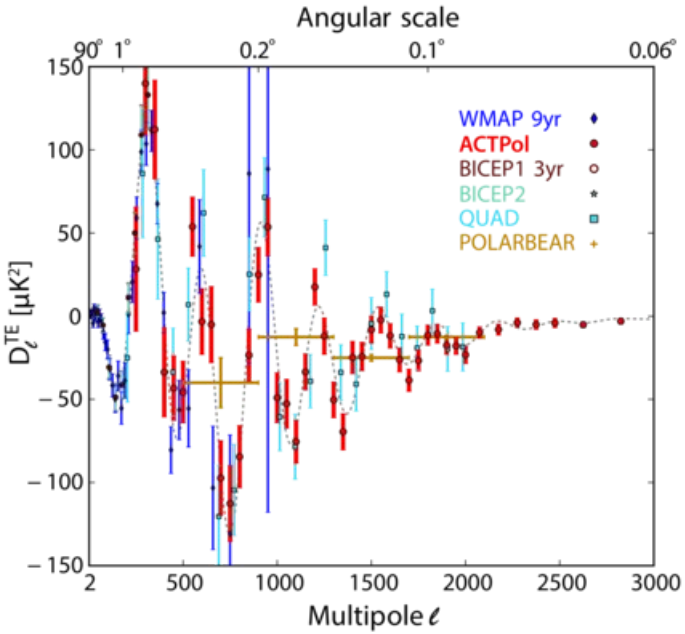


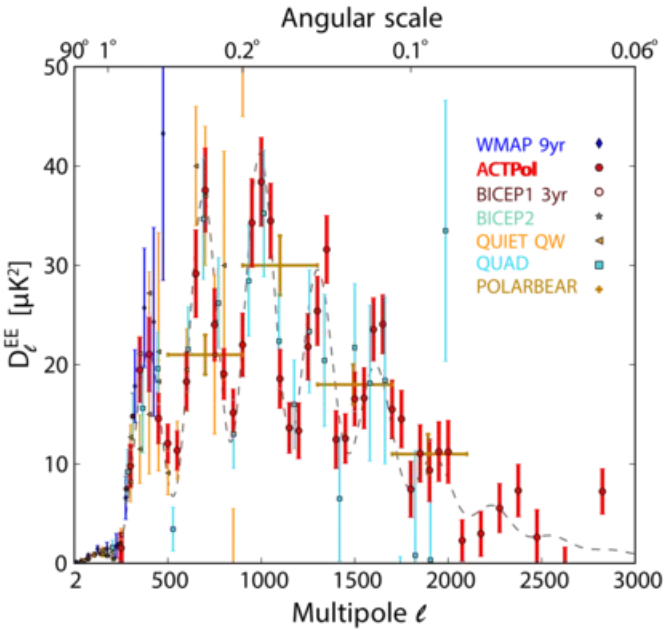
- Bandpassed images: 260 < l < 1370)
- High resolution: find clusters & point sources
- Q & U have E-style patterns; B ~ noise

Tau A


Dec. offset (arcmin)
RA offset (arcmin)
brightness [K]
beam
FWHM
polarization [10 mK]
4
3
2
1
0
−1
−2
−3
0.4
0.3
0.2
0.1
0.0

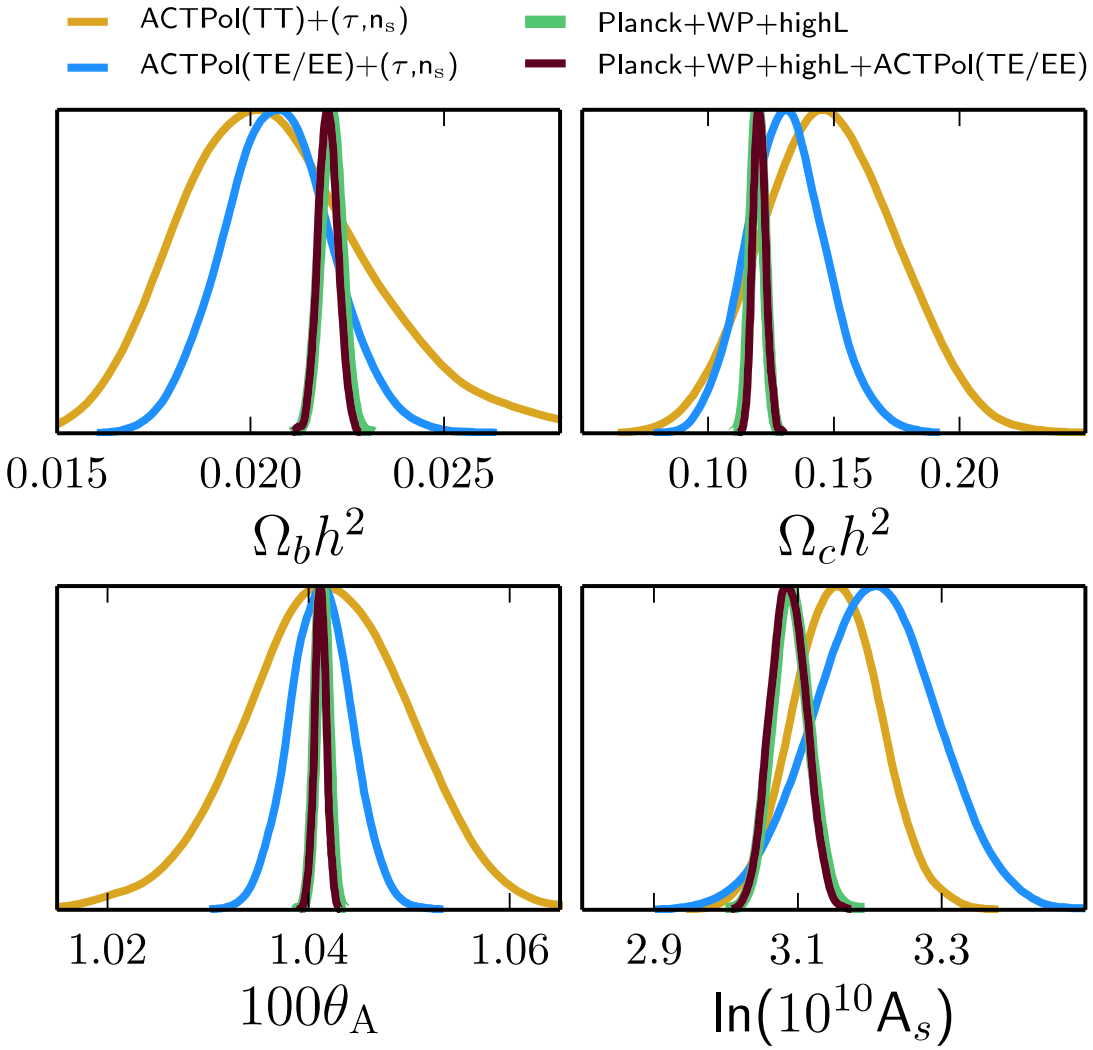
ACTPol Polarization Spectra





The x-axis is scaled as $\ell^{0.45}$ to emphasize the mid-ℓ range.

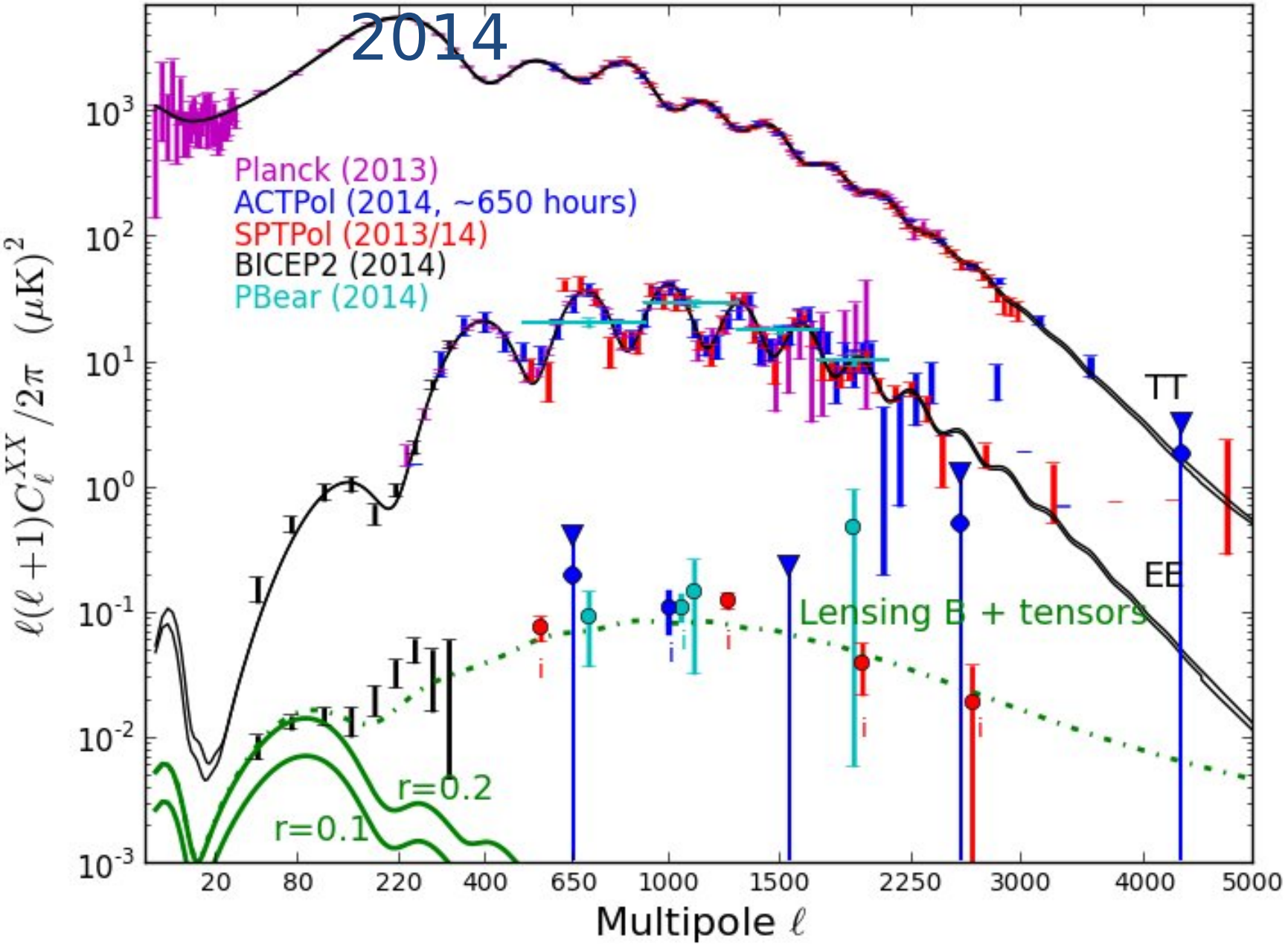
LCDM Parameters from polarization

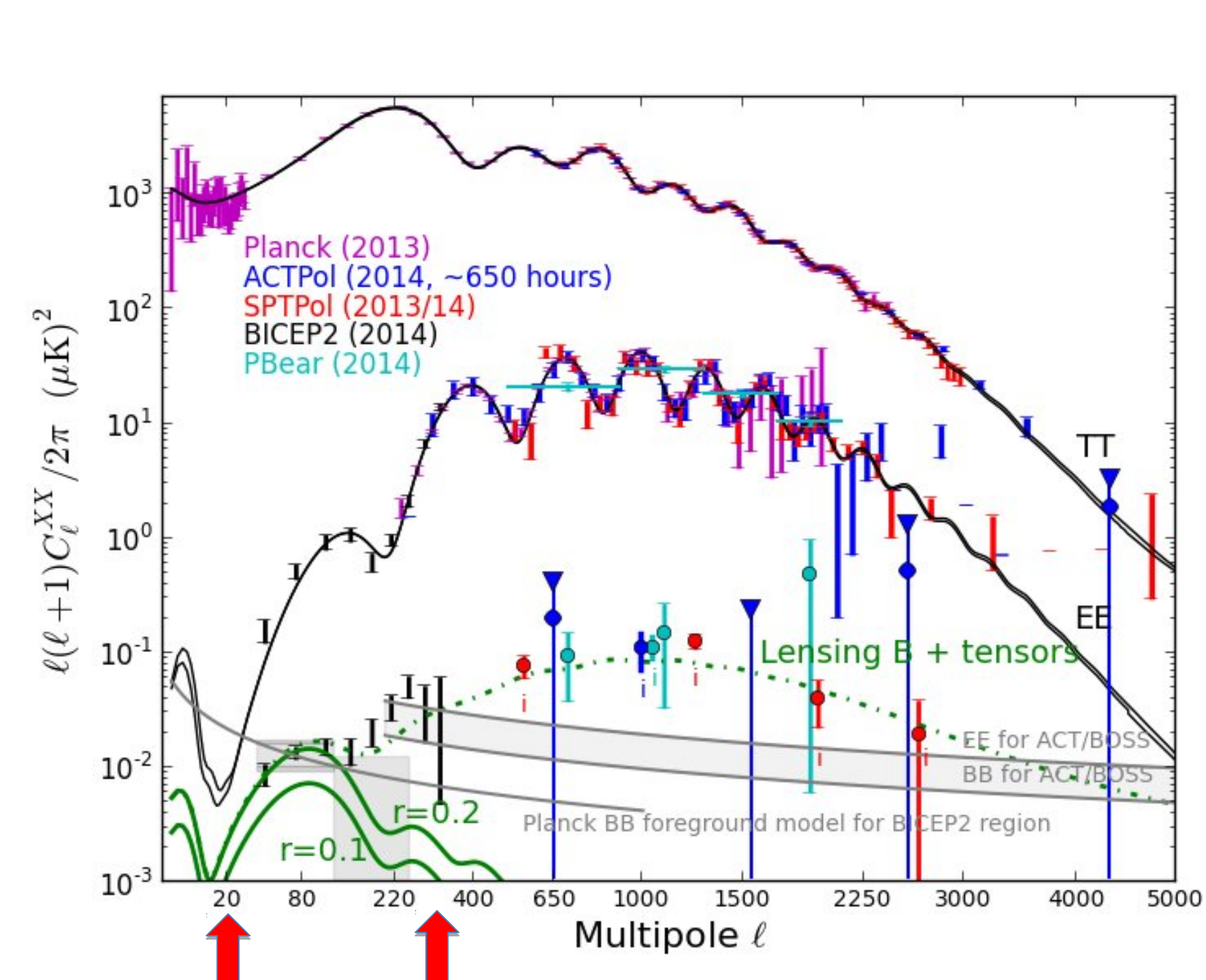


- ACTPol TE + EE spectra constrain parameters somewhat better than ACTPol TT.
- However, Planck+WP+highL is considerably better (so far!)

(Planck 2013 XVI)

State of TT, EE, BB Nov 2014

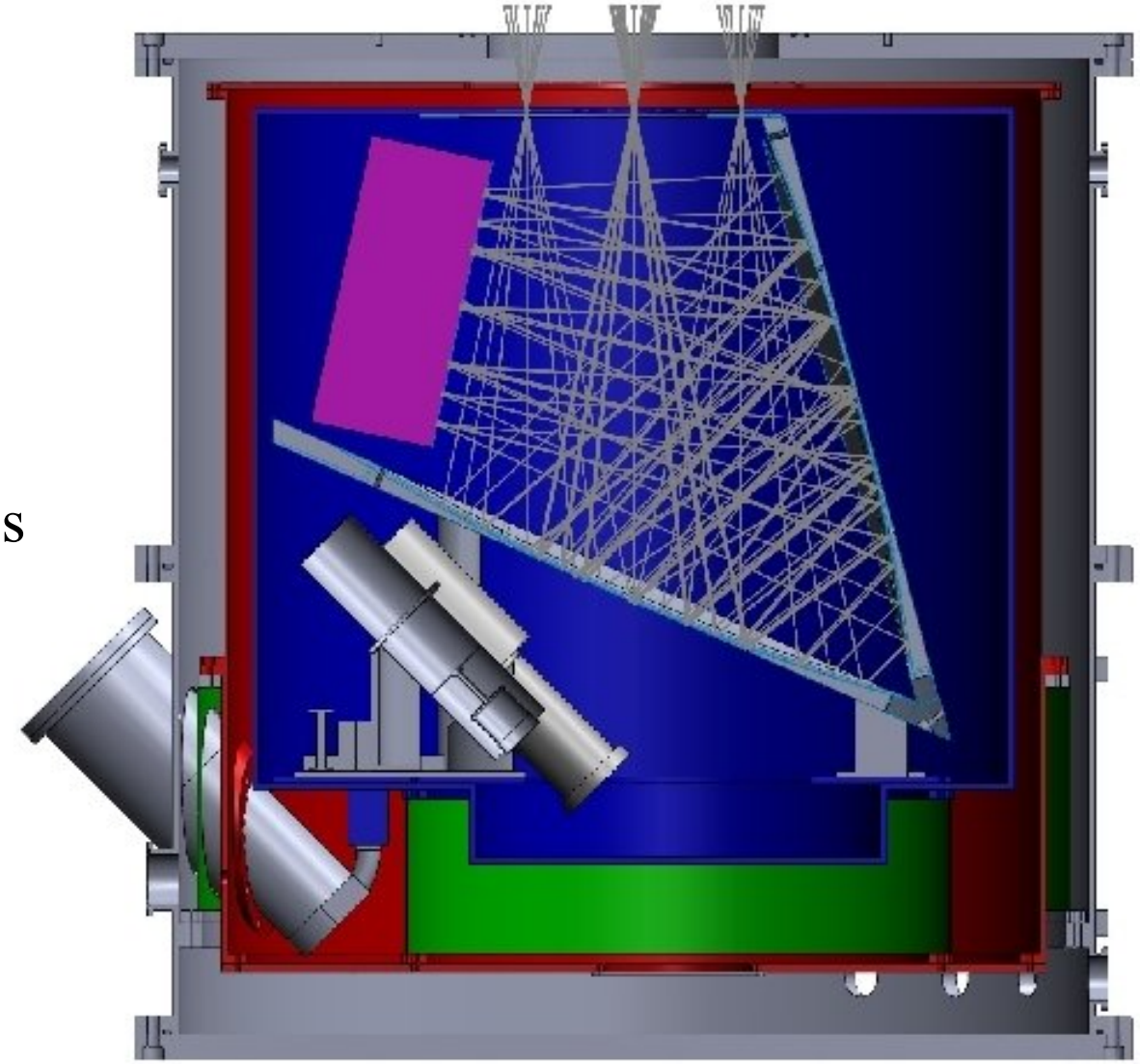



Planck (2013)
ACTPol (2014, ~650 hours)
SPTPol (2013/14)
BICEP2 (2014)
PBear (2014)
TT
EE
Lensing B + tensors
EE for ACT/BOSS
BB for ACT/BOSS
Planck BB foreground model for BICEP2 region
r=0.2
r=0.1
$\ell(\ell+1)C_\ell^{XX}/2\pi \ \ (\mu\mathrm{K})^2$
Multipole ℓ
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
20
80
220
400
650
1000
1500
2250
3000
4000
5000

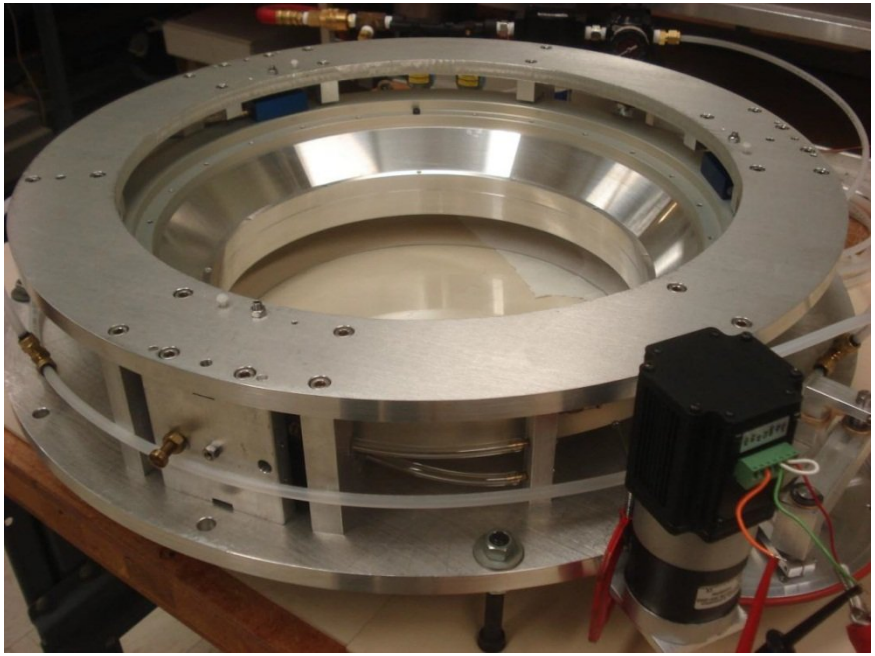
Dealing with the atmosphere

Lessons from ABS

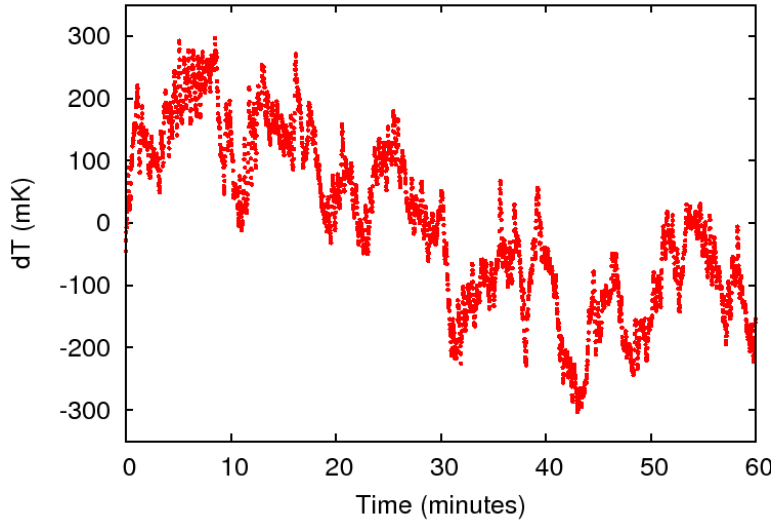
- 240 feeds
- 0.3 K detectors
- 4 K all reflective optics
- 1 cubic meter
- Cryoperm/mu metal
- **270 K HWP**
- 145 GHz.



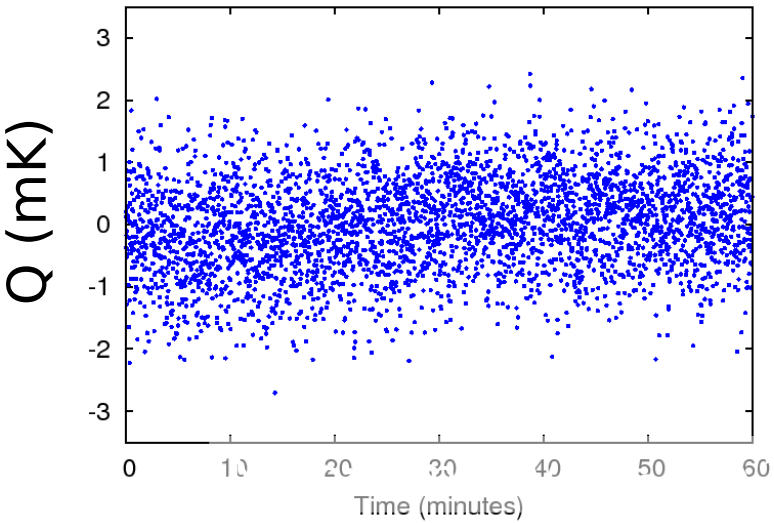
Continuously 2.5 Hz rotating warm half-wave plate with ABS



Kusaka, Essinger-Hileman , et al 2014

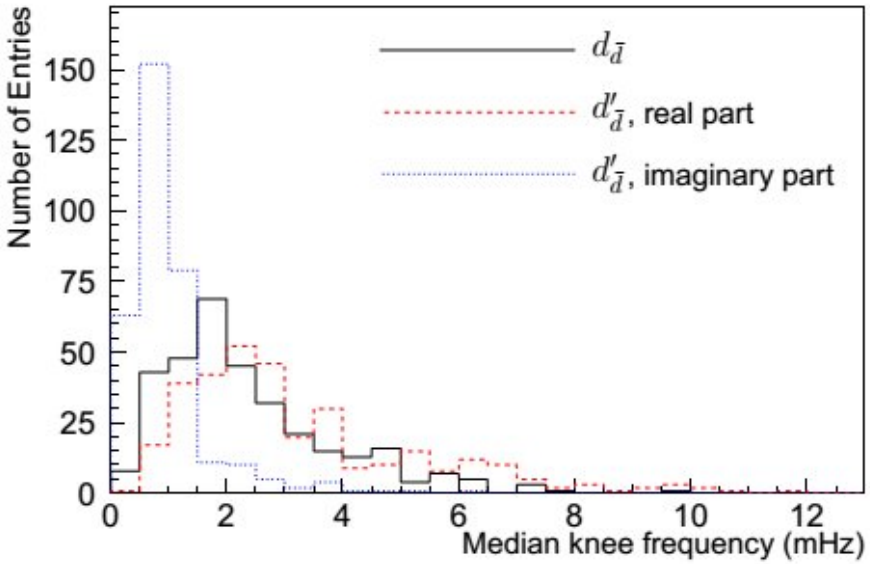


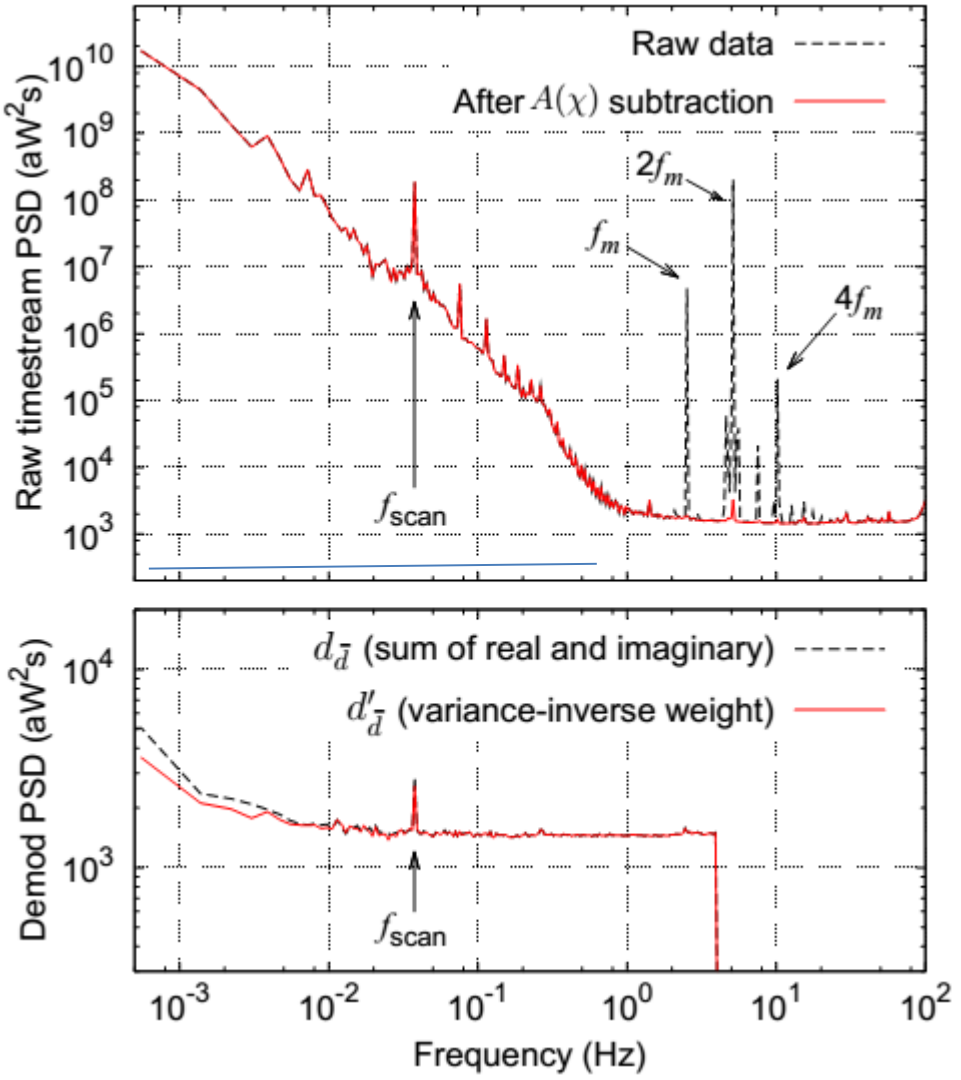
Demodulation



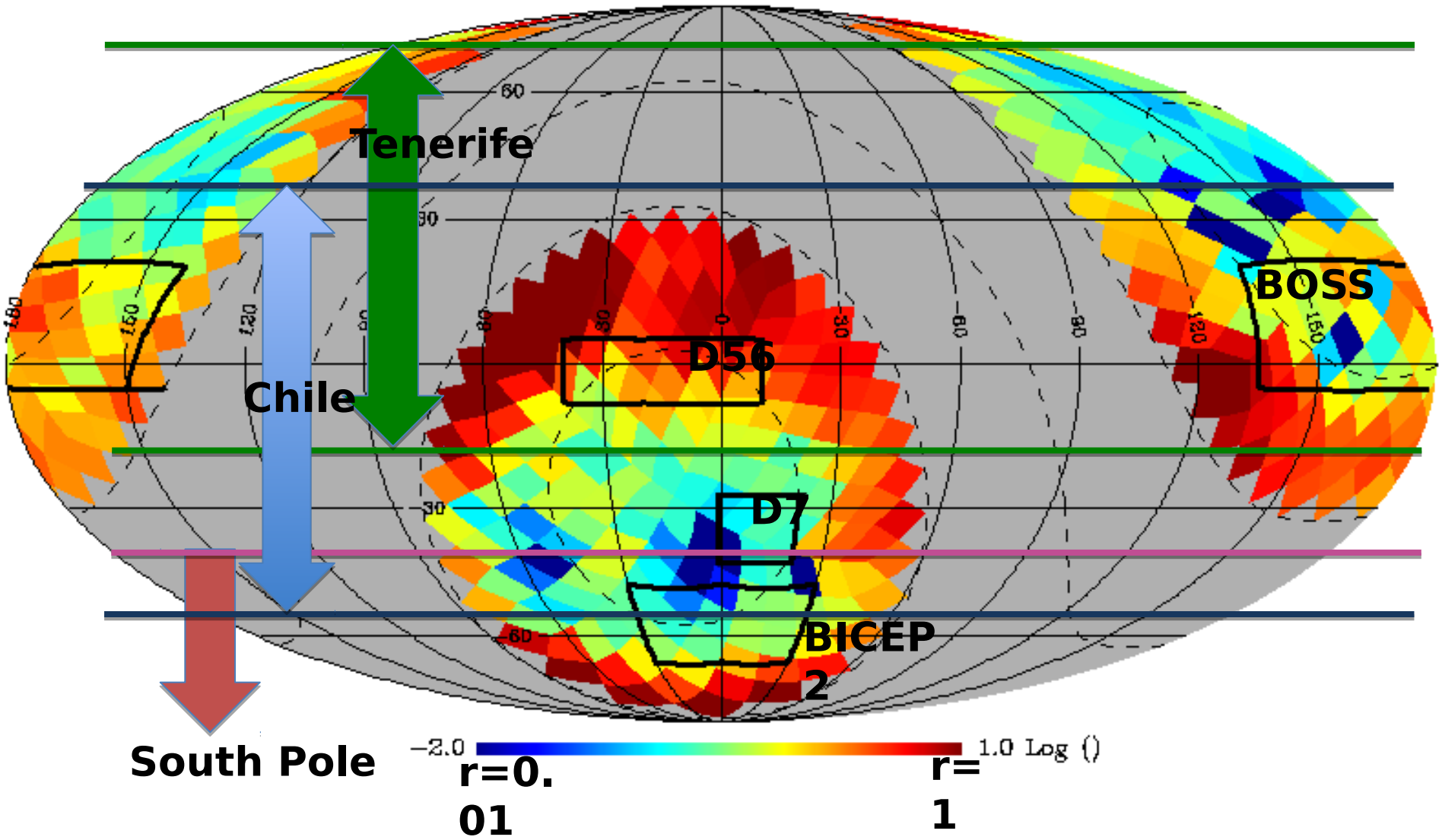
Demodulated timestream

f_{knee}~ 1mHz
~1000 sec
~3^0 sky rotation
=>/~60





Planck guide to low dust polarization level in effective r

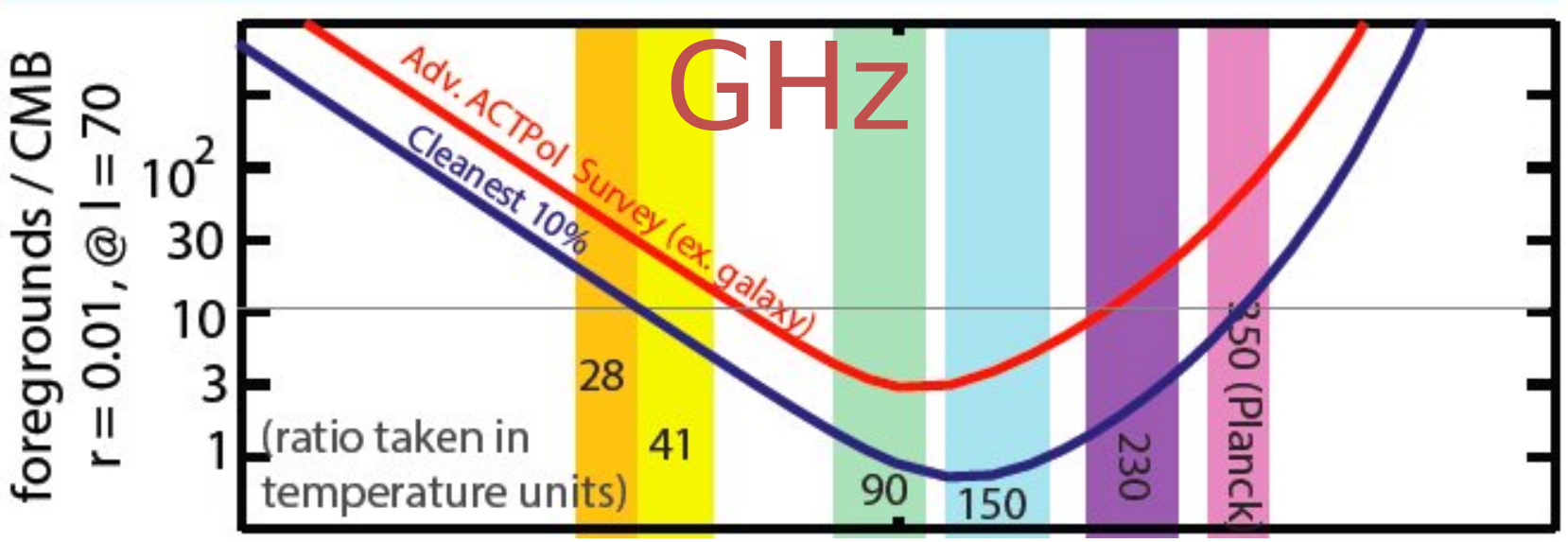


Advanced ACTPol

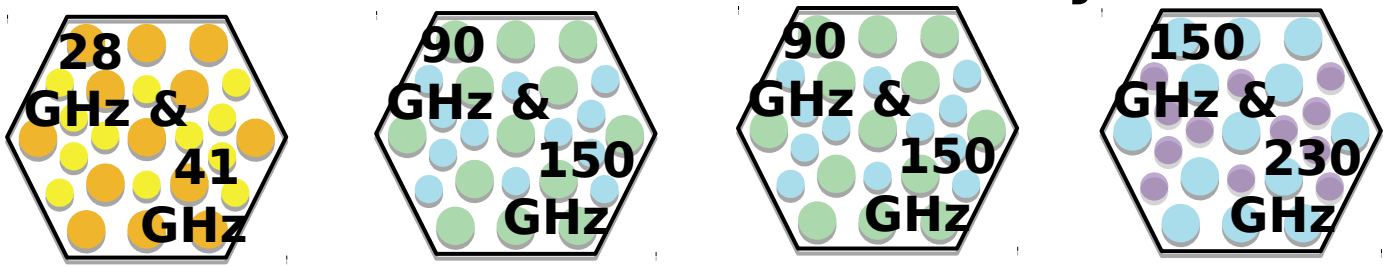
PI: Suzanne Staggs

Co-Director: Mark Devlin

Five bands from 30 to 230 GHz



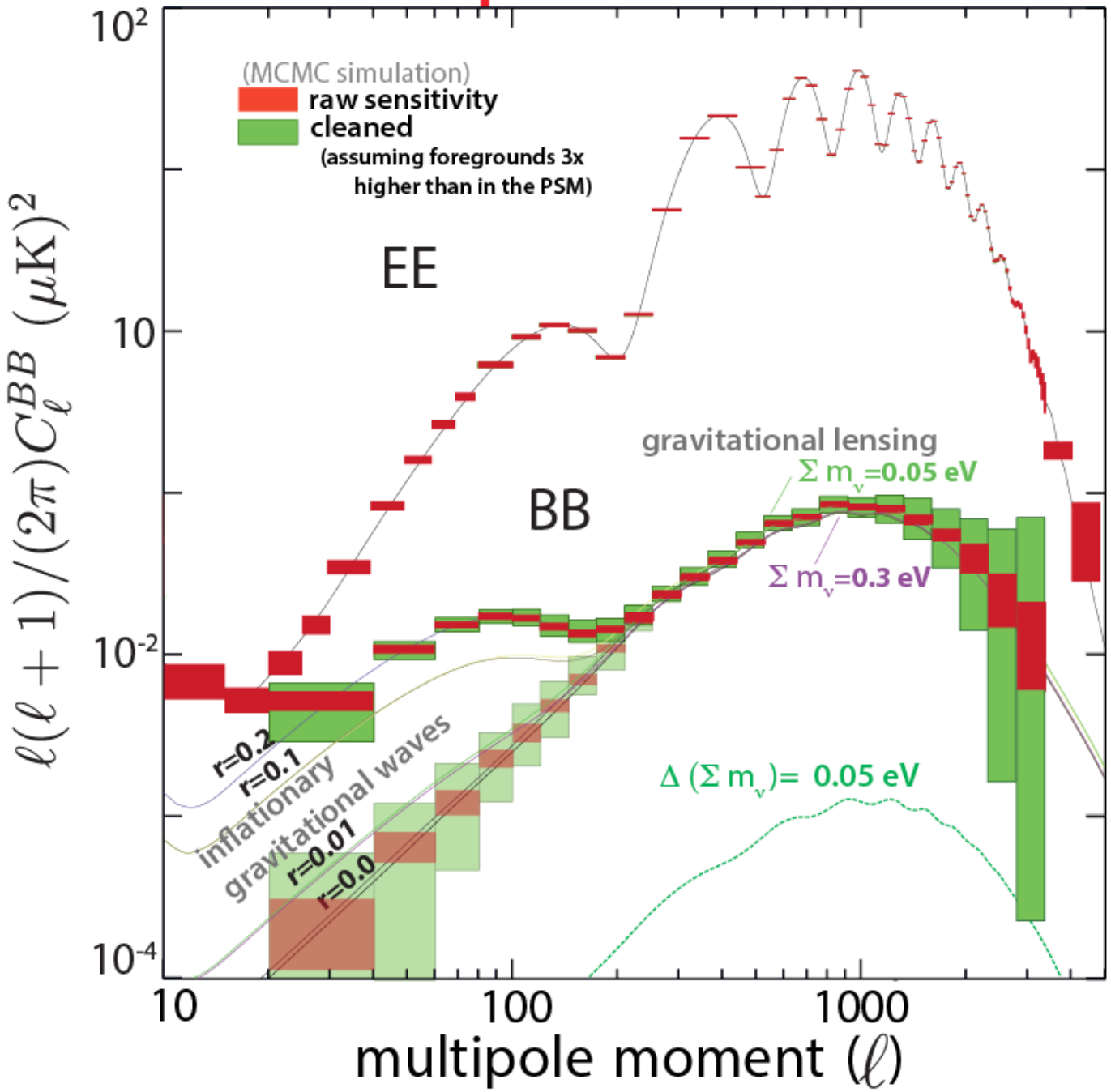
Four multichroic arrays



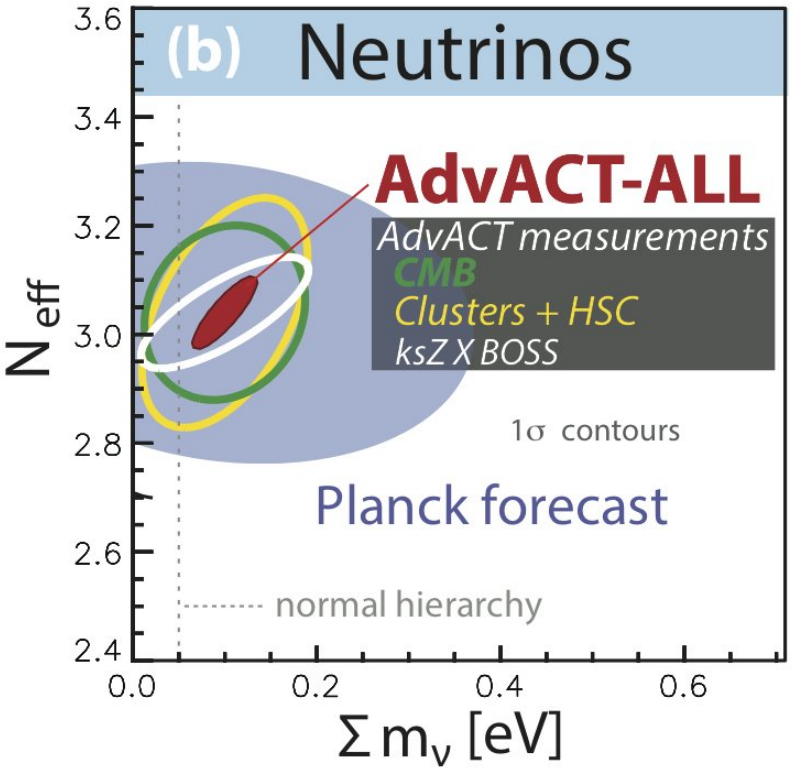
ACTPol just fielded the first multichroic

Low (28 & 41 GHz) and high (230 GHz + Planck 353 GHz) frequency channels allow detection and subtraction of synchrotron and dust foregrounds.

AdvACT polarization forecast

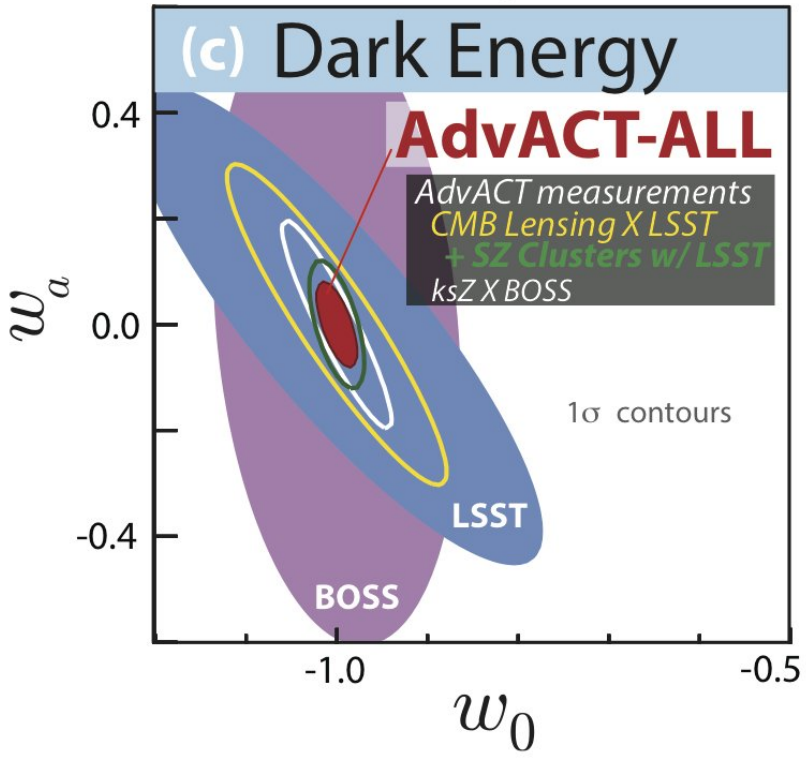


AdvACT Projections (based on combining many analyses & cross-correlations)

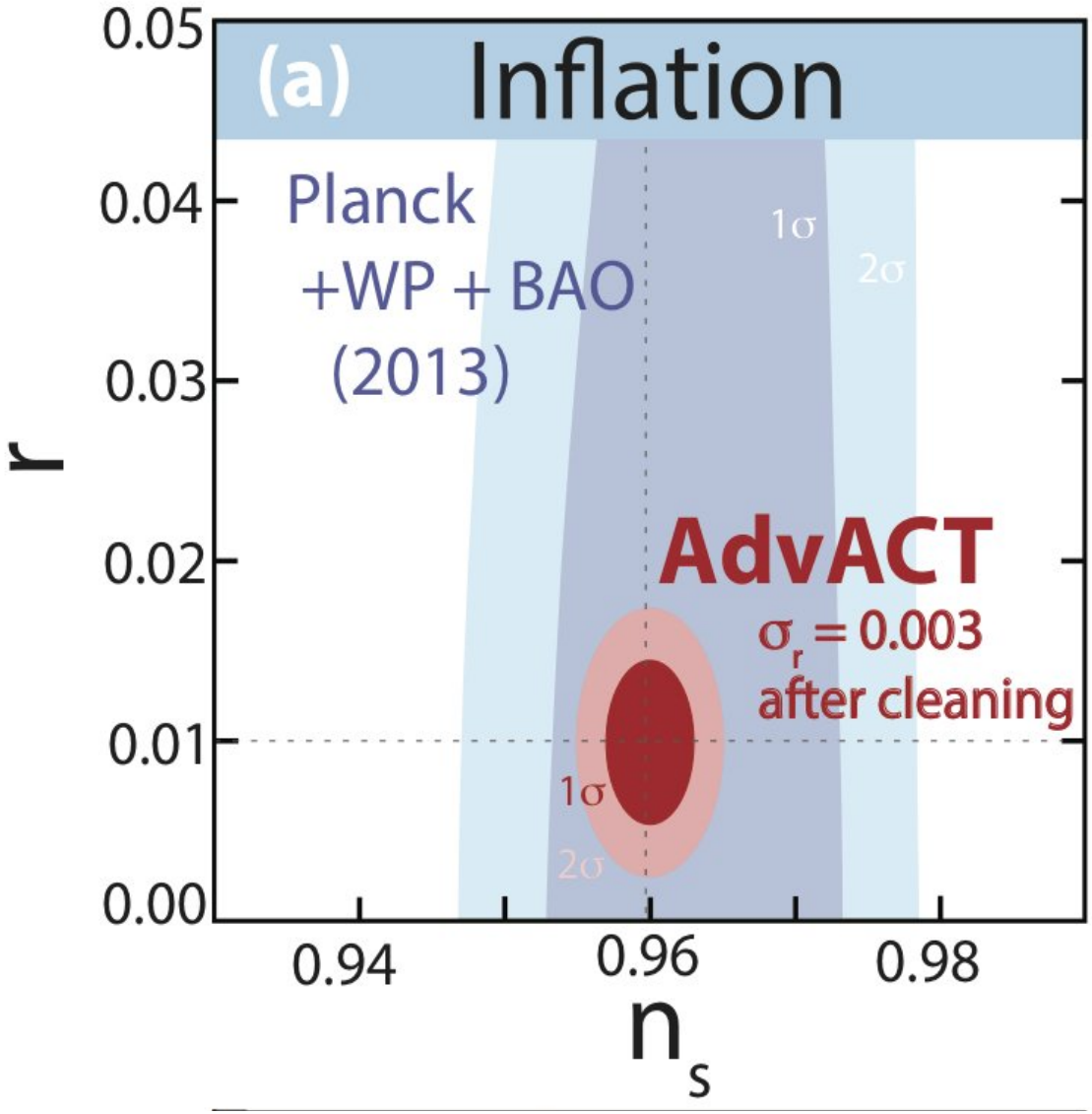


Projected to improve Planck limit on Σm_ν by 10x!

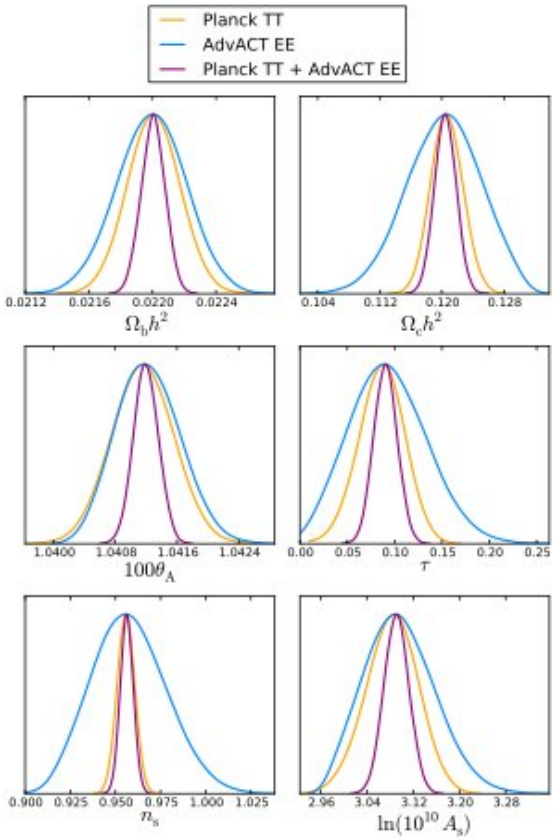
Projected to improve LSST's DE FOM by 20x!

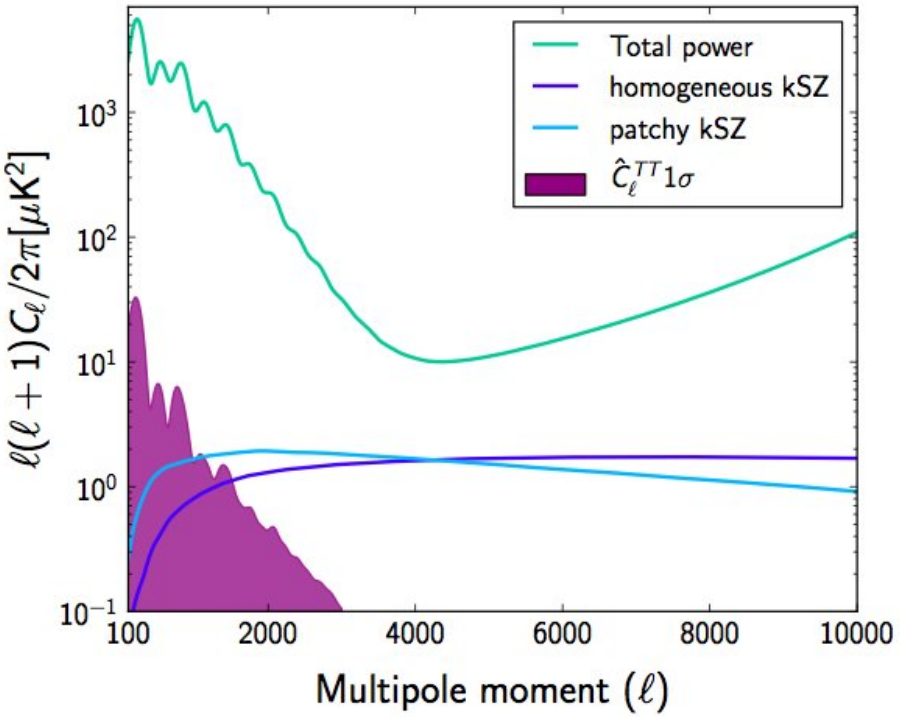


Early Universe



AdvACT Projections
(Calabrese et al., 2014)





Big sensitive maps can improve on Planck LCDM parameters.

Getting at the kSZ by removing the CMB TT: fix the cosmology with AdvACT high-res EE combined with Planck TT (small beam matters!)

“Sure bets” from the ground and balloons with ***experiments in progress***

r<0.01 (or detection) l<200

Sum of neutrino masses to 0.06 eV 200<l<4000

New tests of GR and the standard model through multiple cross correlations and the growth of structure. X-Corr

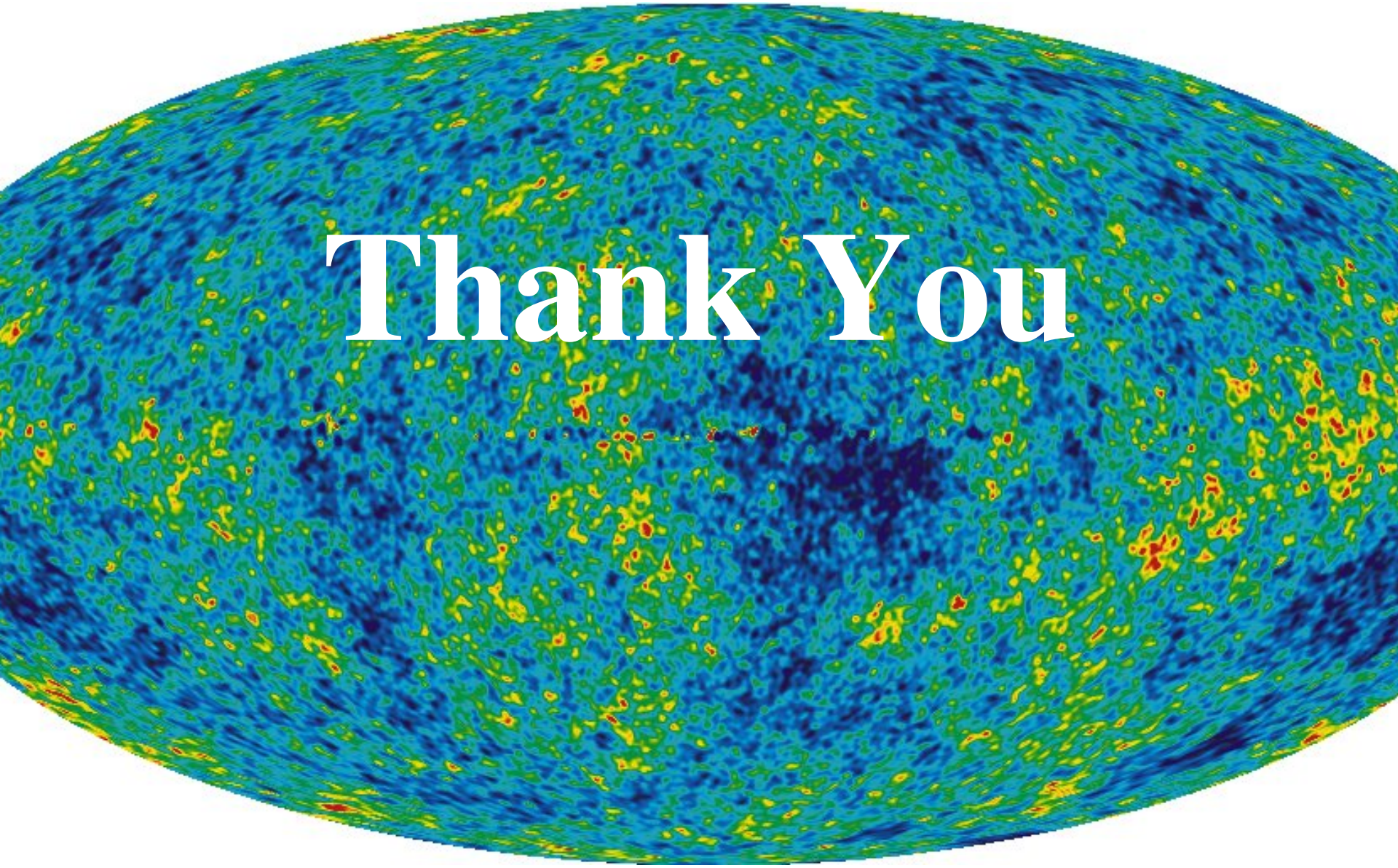
Technology: near term 1000s of bolometers, then to 10,000. Currently single frequency pixels, multichroic in 2015.

Ground Based

Chile	Have data	Current or planned fre
ABS		145 GHz
ACTPol/AdvACt		30, 40, 90, 150, 230
POLARBEAR		90, 150 GHz
CLASS		40, 90, 150 GHz
Antarctica		
BICEP/KECK		90, 150, 220 GHz
SPTPol		90, 150 GHz
QUBIC-Bolo int. 2016		90, 150, 220 GHz
Elsewhere (for now)		
B-Machine –WMRS		40 GHz
GroundBIRD, LiteBIRD		150 GHz
2016		150, 210, 270 GHz
GLP – Greenland		44, 95, 145, 225, 275
TBD		11-20, 30 GHz

Balloons

	Have data	Current or planned freqs
EBEX		150, 250, 210 GHz
LPSE	TBD	5 chan 40-250 GHz
PIPER	2015	200, 270, 350, 600 GHz
SPIDER		90, 150, 280 GHz


Thank You