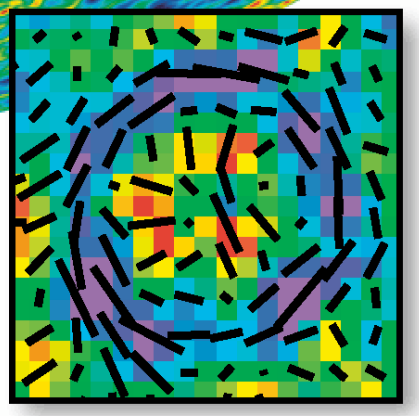
The polarization of the CMB and the mm-wave sky.

Stacked Temperature

TIFR, April 2010
L. Page



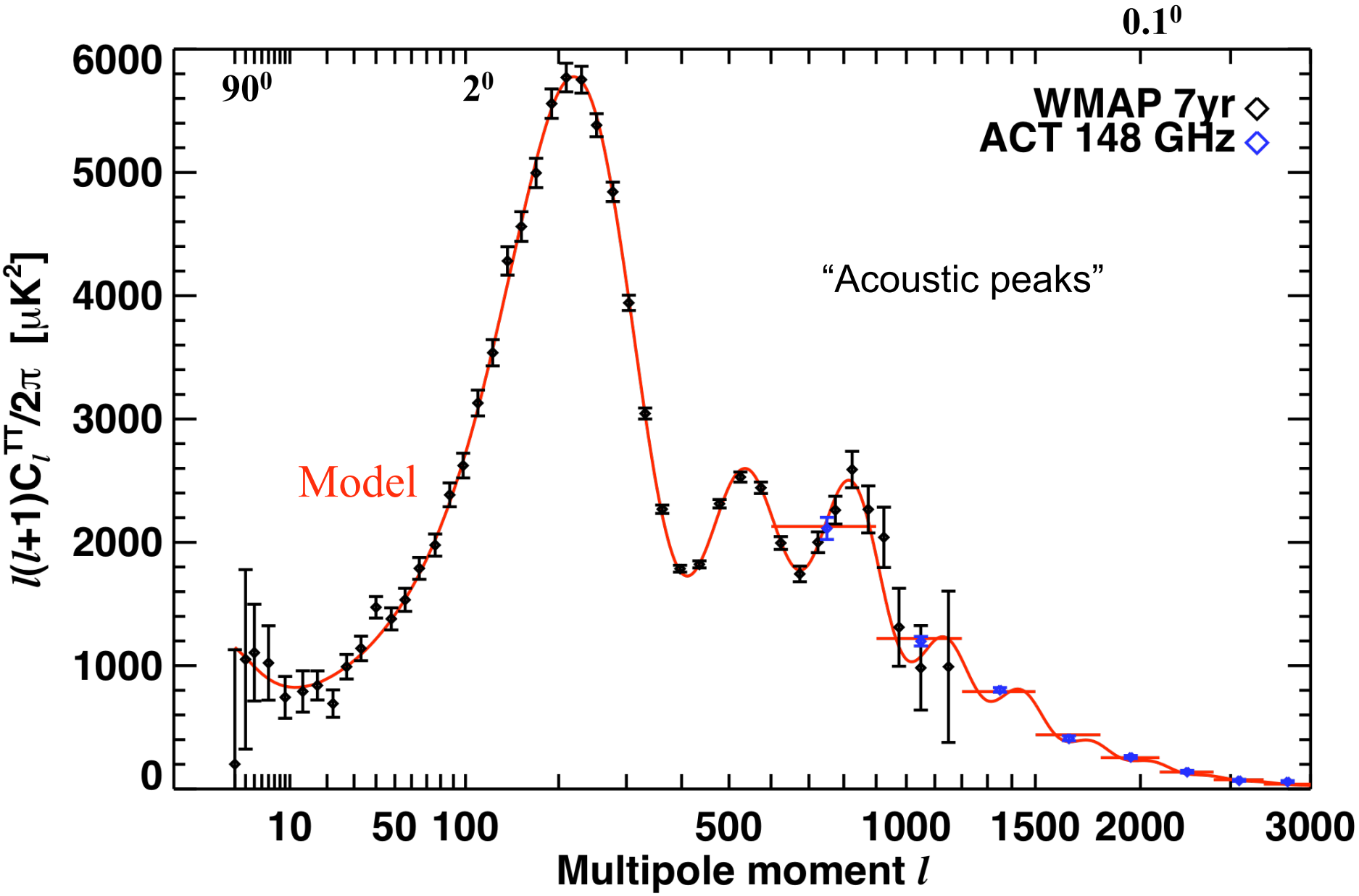
Stacked Polarization

What's new for WMAP7?

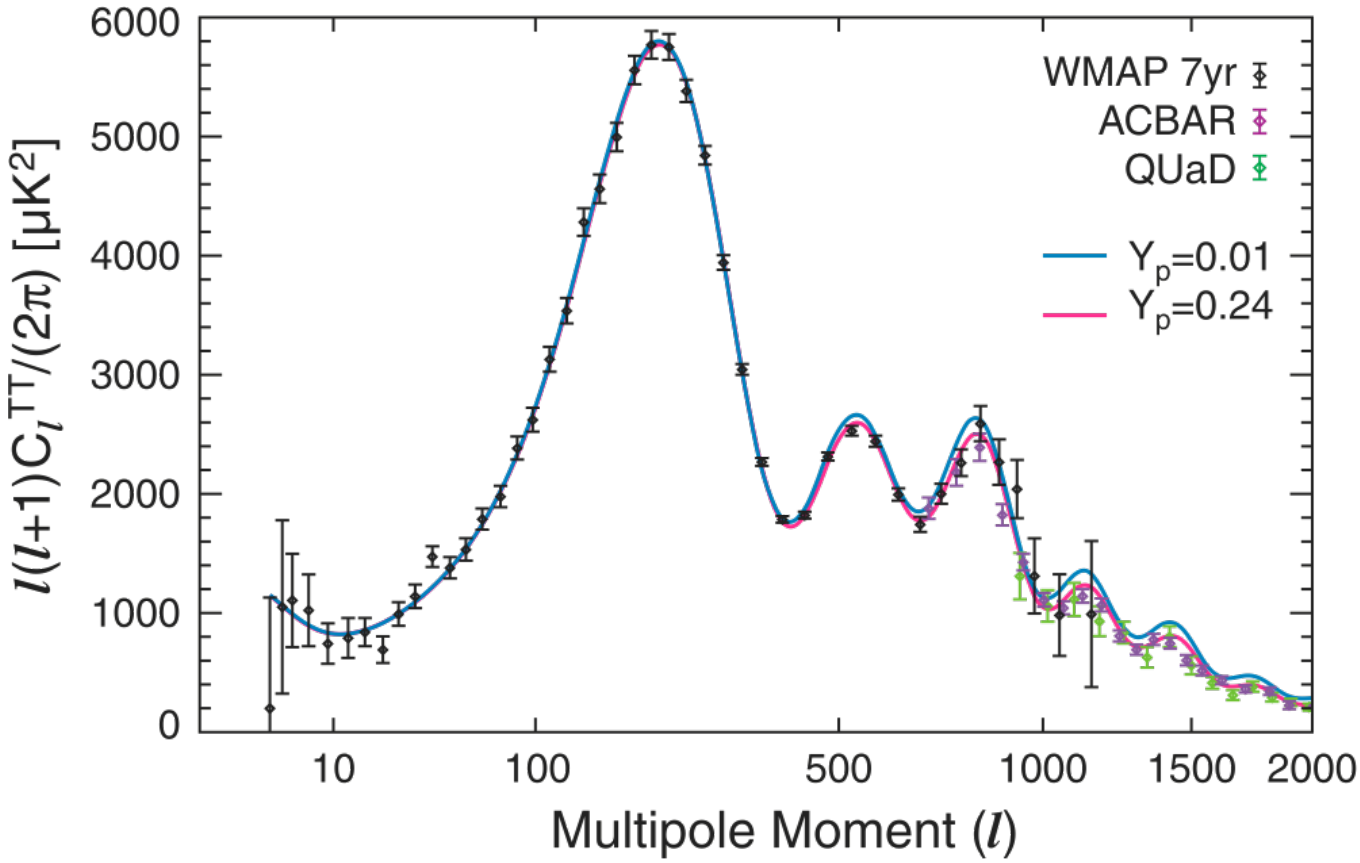
Selected highlights:

- New mapmaking technique for full sky (Jarosik et al. 2010).
- No evidence of foreground contamination in TT (Gold et al. 2010)
- Clearly see 3rd peak in TT and calibrate it to 0.2% to rest of spectrum.
- With ACBAR and QUaD (and soon ACT), see evidence for primordial He in TT power spectrum, Y_p=0.33+/-0.08.
- Calibrate planets and see evidence for a feature in Uranus, and see effects of Saturn's rings (Weiland et al 2010).
- WMAP+H_0+BAO give n_s=0.963+/- 0.012 with r=0.
- Through SZ effect, see some evidence for low gas pressure in low mass clusters.
- Sum of neutrino masses <0.58eV (95% cl).

WMAP7


0.1^0
90^0
2^0
WMAP 7yr
ACT 148 GHz
"Acoustic peaks"
Model
l(l+1)C_l^TT/2π [μK^2]
6000
5000
4000
3000
2000
1000
0
10
50
100
500
1000
1500
2000
3000
Multipole moment l

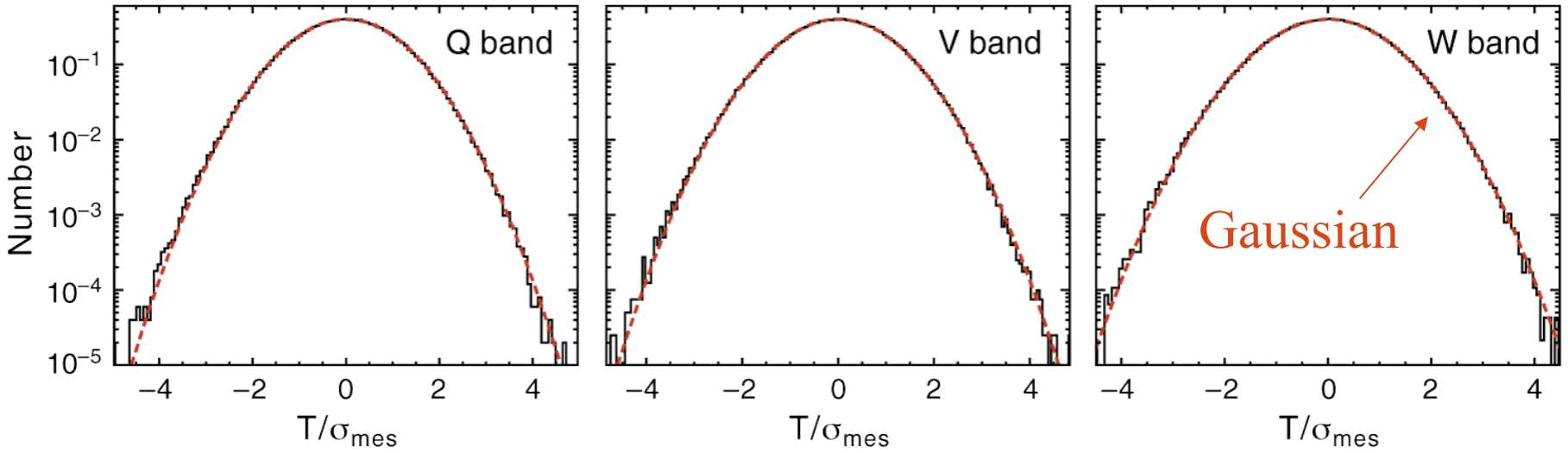
Primordial Helium



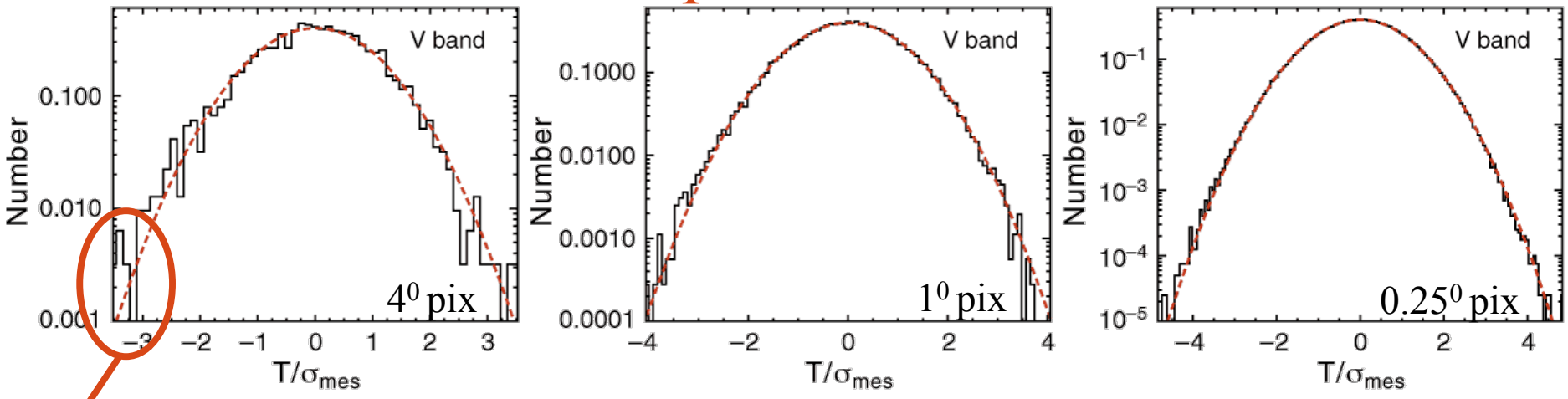
Y_p=0.33+/-0.08

If there is more helium (decouples at z~1800) then there are fewer free electrons ($n_e=(1-Y_p)n_b$), and a longer photon mean free path ($\sim 1/\sigma_T n_e$), and enhanced Silk damping.

Distribution by map temp. by frequency (accounting for uneven weighting)



Data are an excellent representation of a Gaussian!



Cold spot

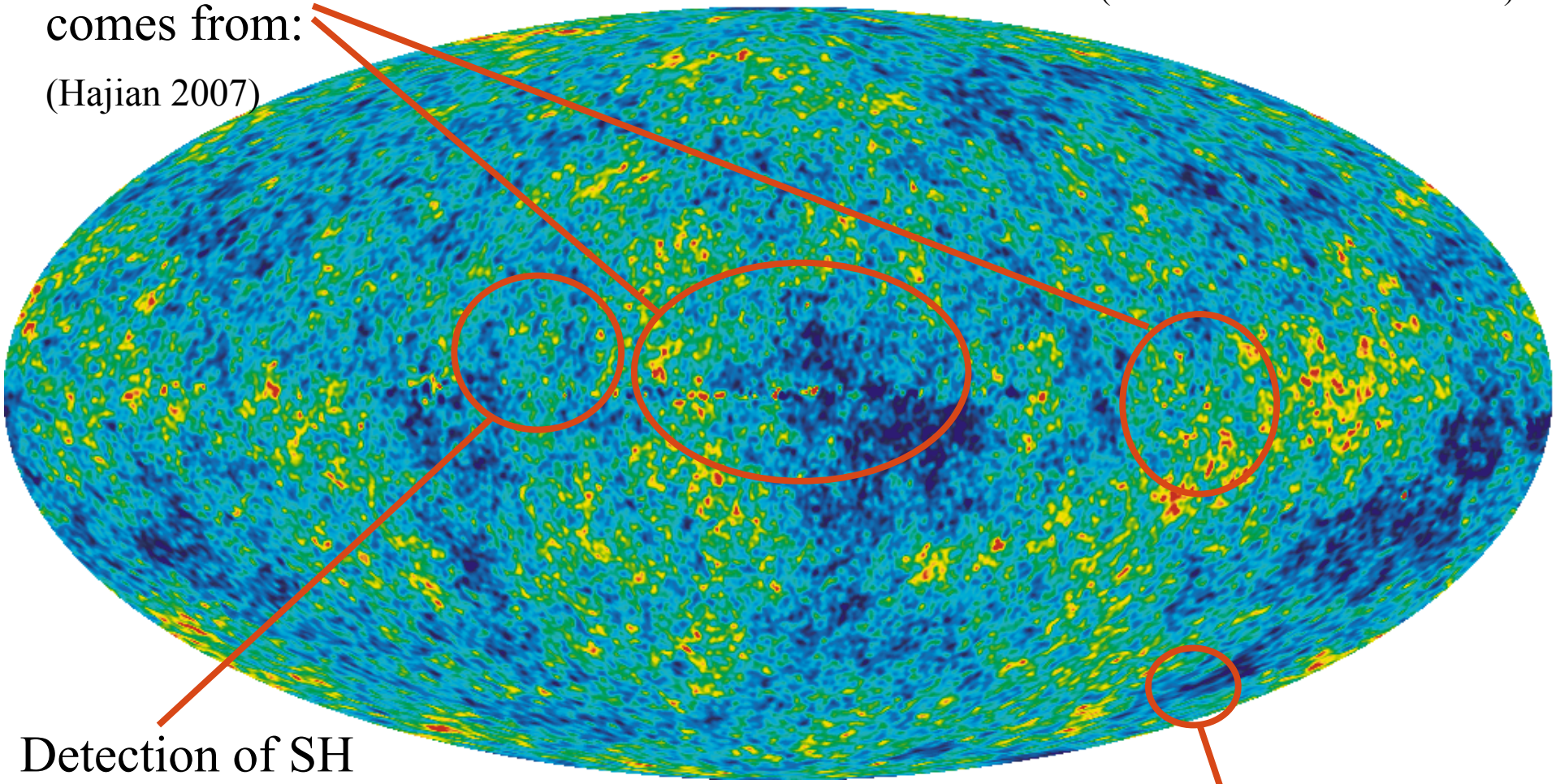
Distribution by resolution.

A significant fraction of the full-sky quadrupole comes from:

(Hajian 2007)

Alignment?

(de Oliveira-Costs et al. 2004)



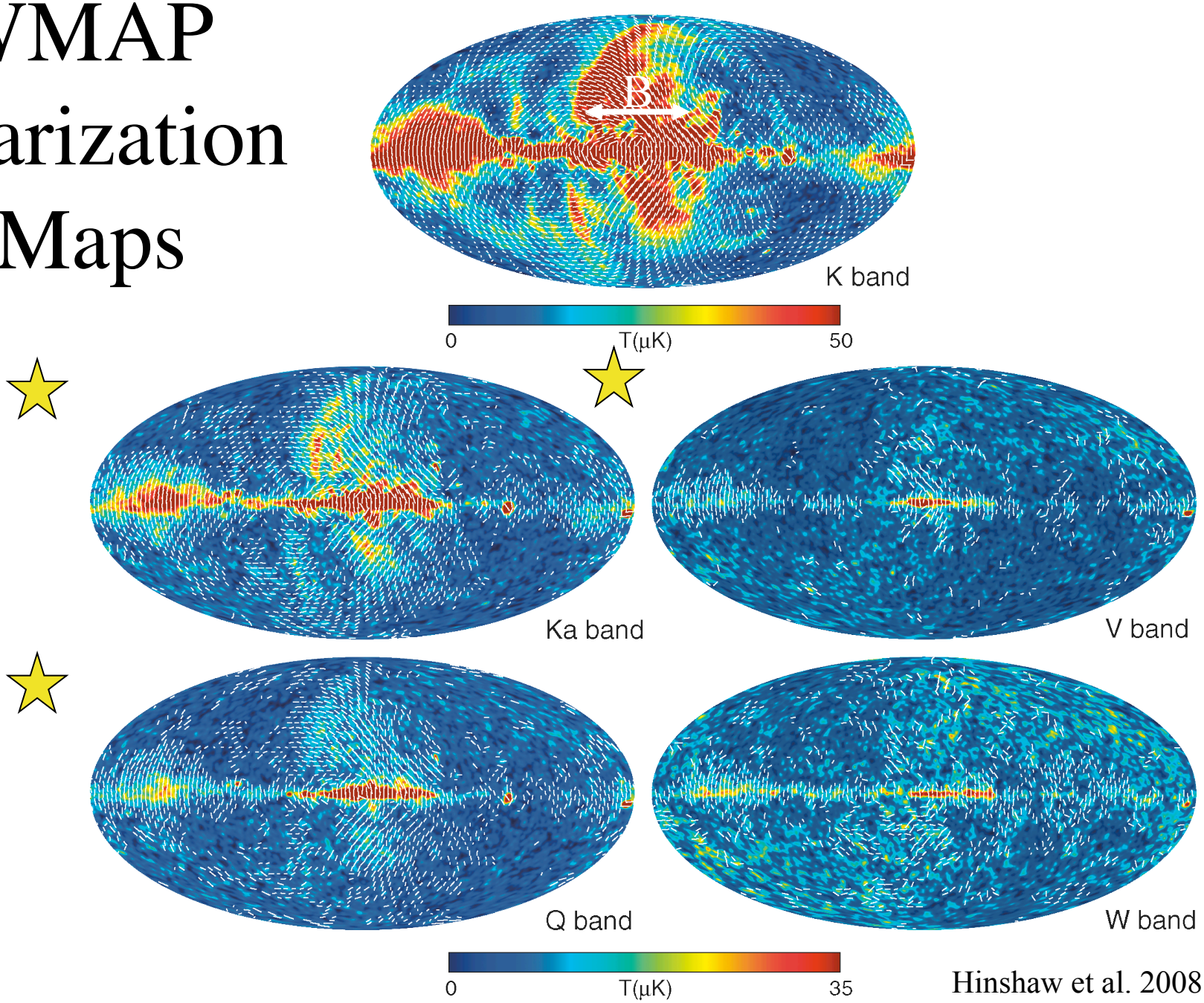
Detection of SH persists!

Note “fingers” present in the southern Galactic hemisphere. Largest effect in almost ecliptic coord.

Extra cold spot:

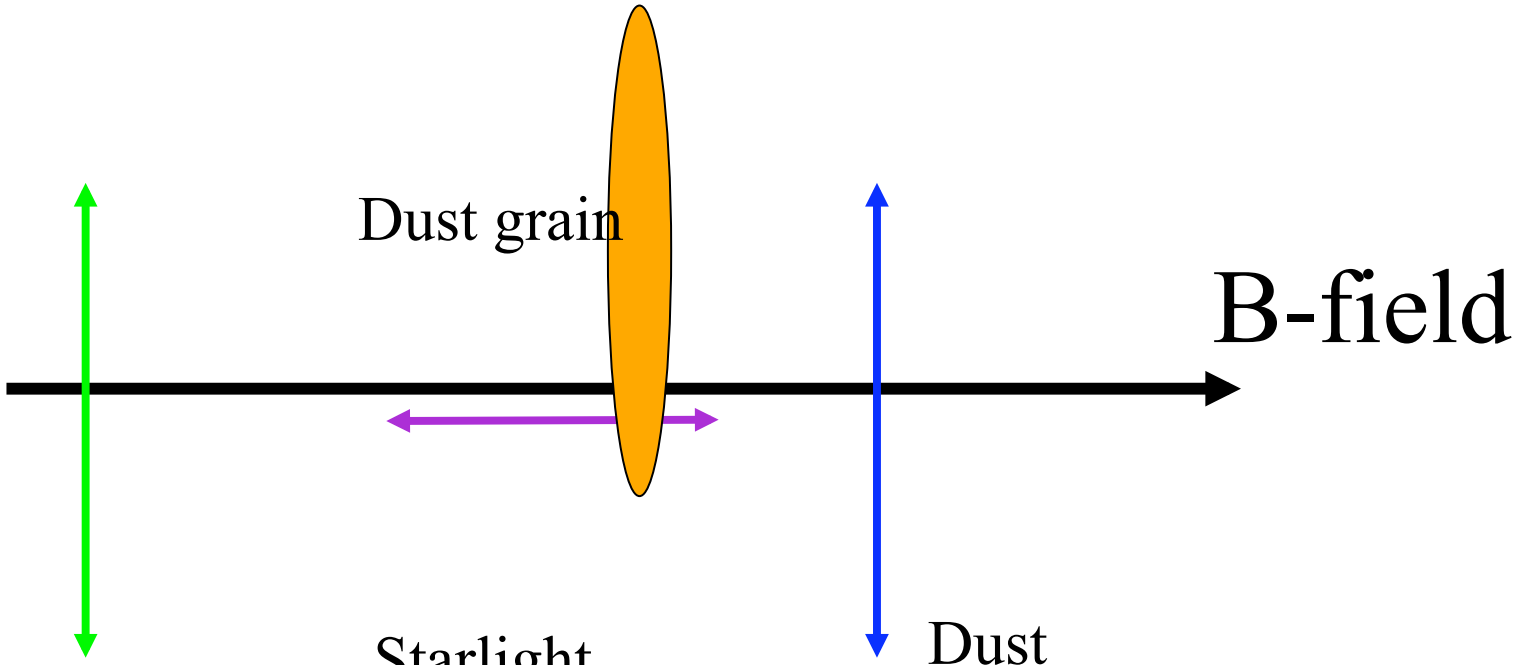
(Vielva et al. 2004, Cruz et al. gave 1.8% prob. 2005)

WMAP Polarization Maps



Hinshaw et al. 2008

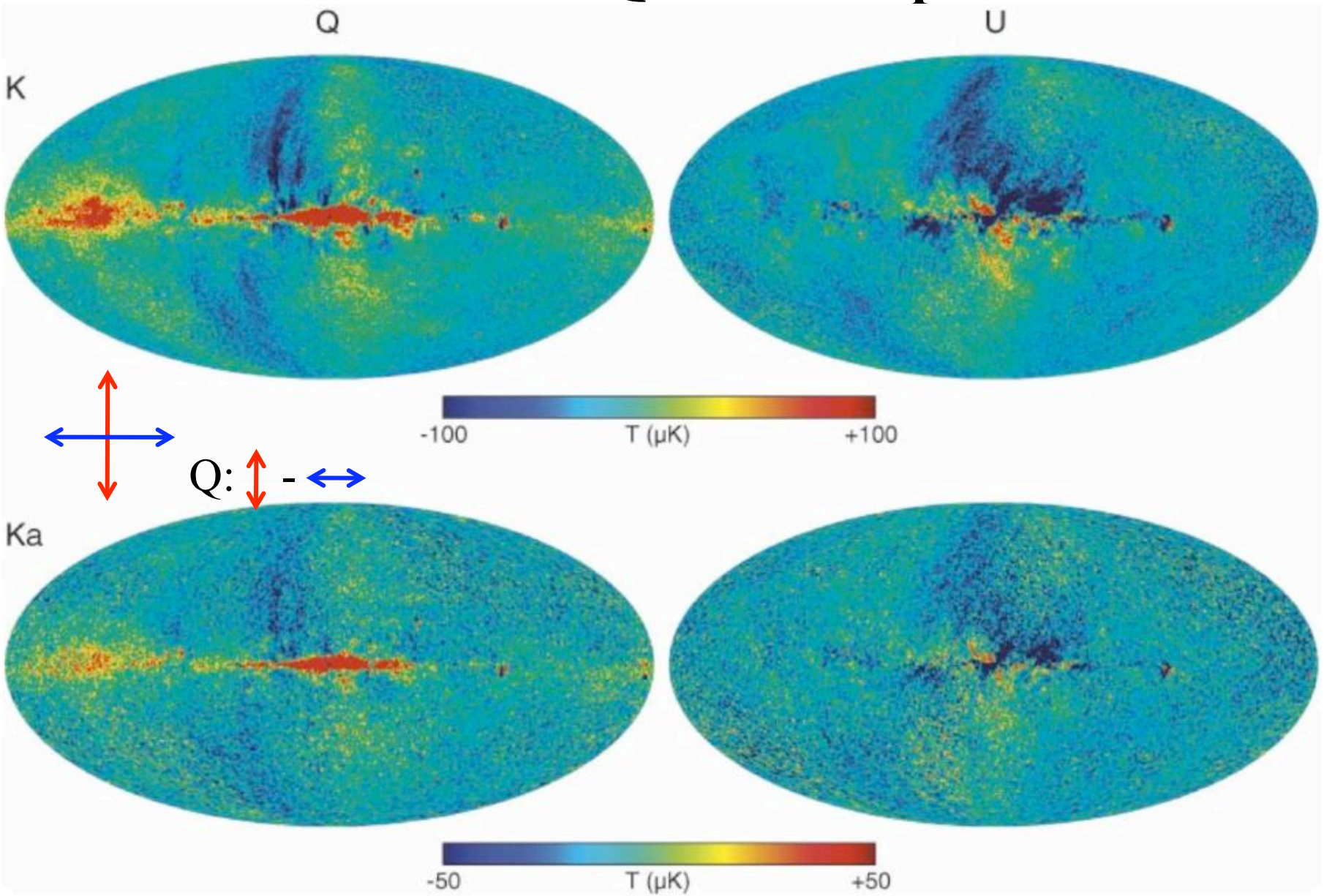
Polarized Foreground Emission



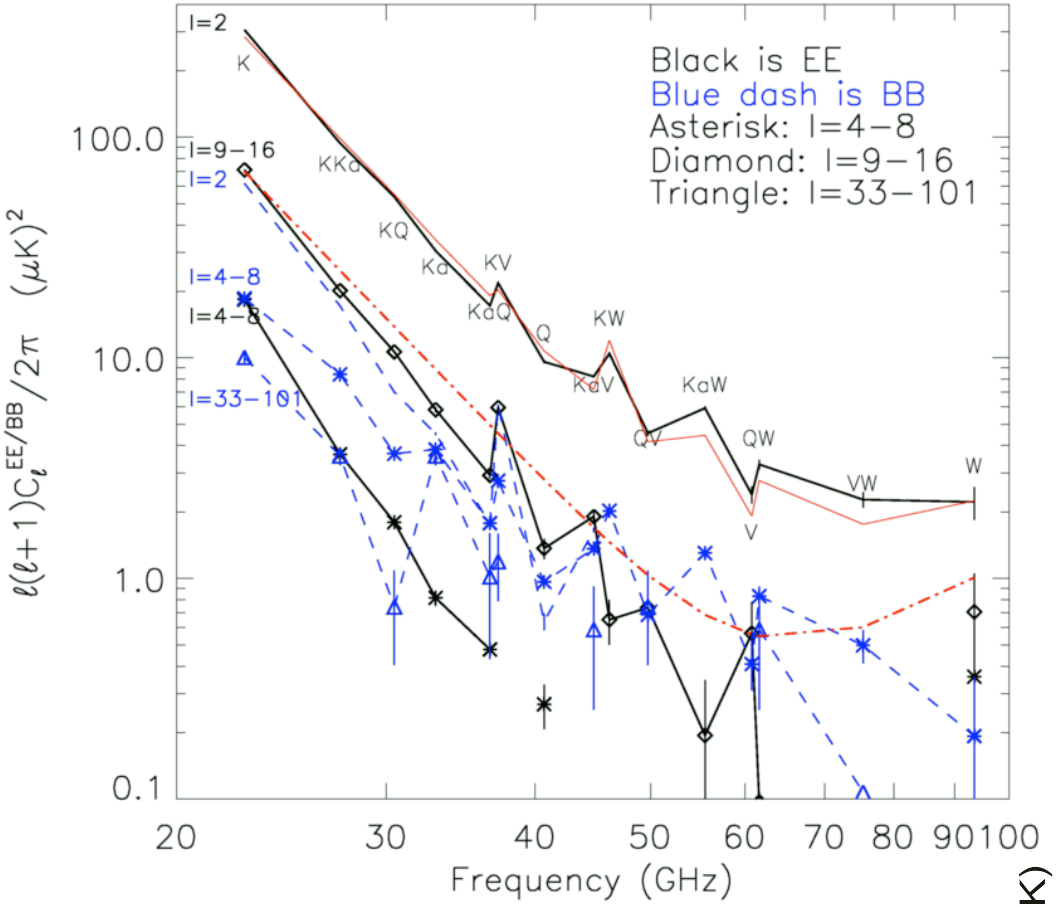
Max pol about 75%

Max pol about 15% but low pol for spinning dust.

Stokes Q&U Maps

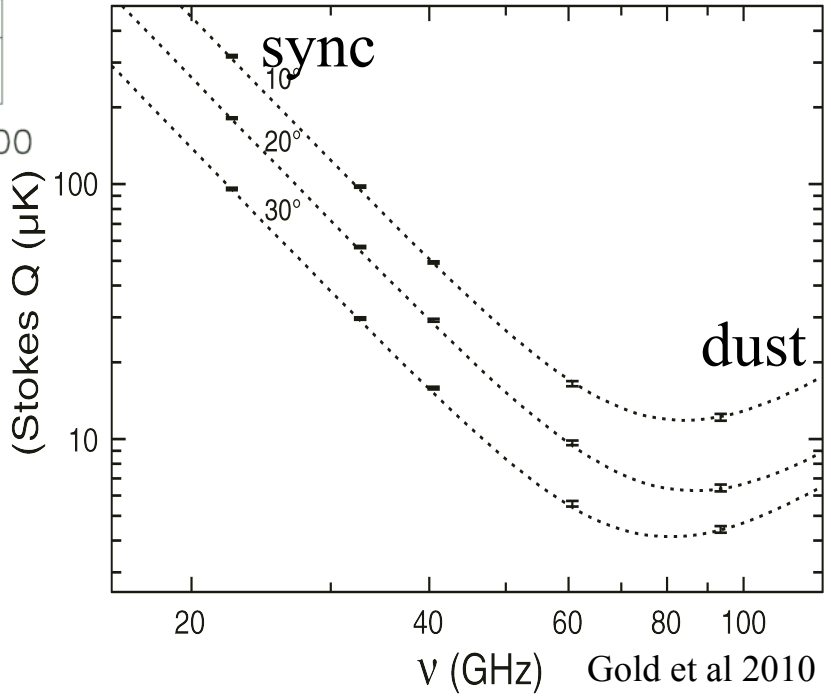


Frequency spectrum



Averaged over
75% of the sky.

Near galactic center.

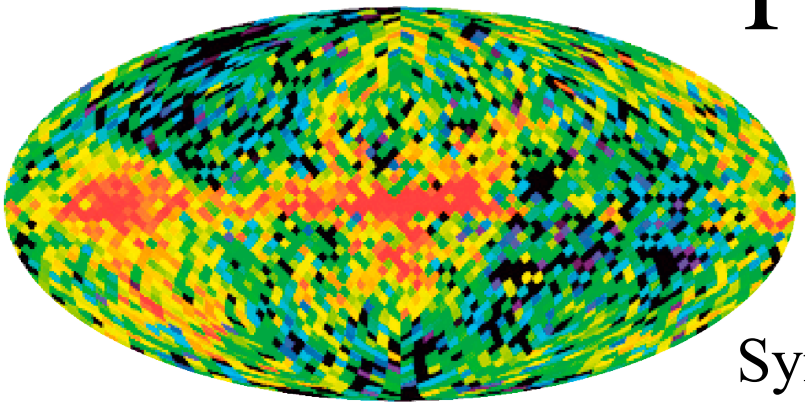


Gold et al 2010

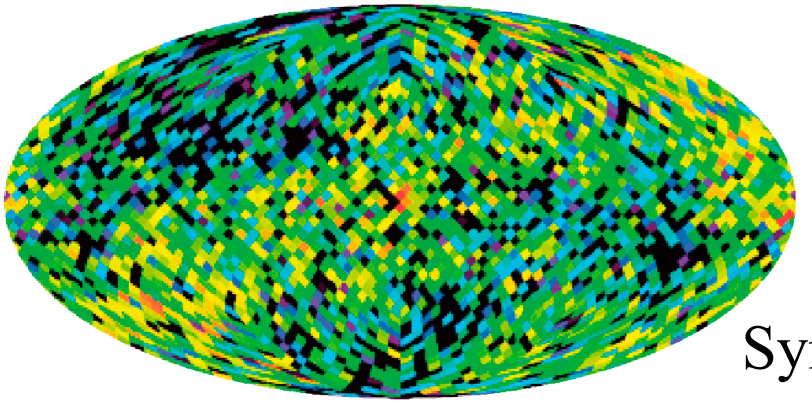
"Spikes" from correlated polarized sync and dust.

Minimum near 90 GHz,
but could easily be higher.

Polarized foreground components

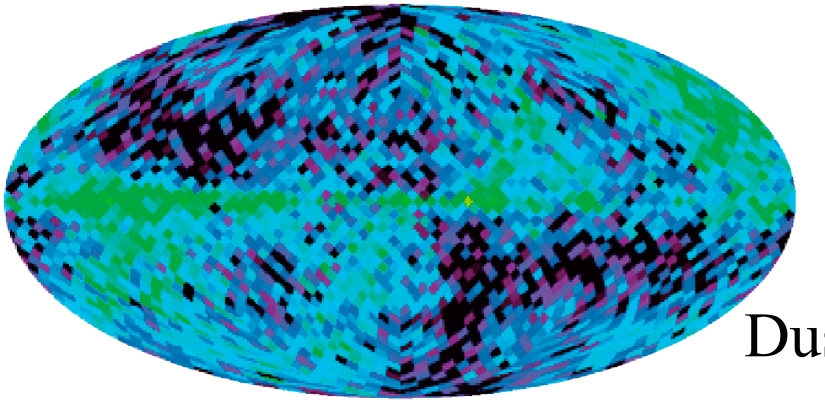


Synchrotron with index $\nu^{-3.1}$



(consistent with no signal)

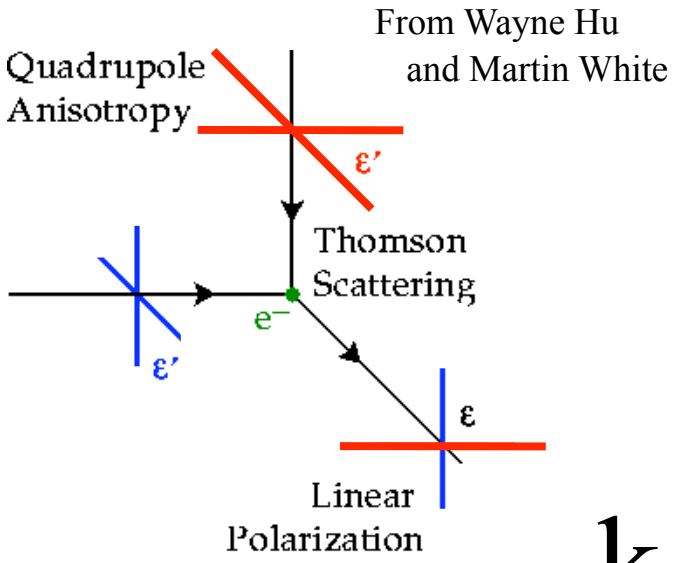
Synchrotron with index $\nu^{-2.4}$



Dust with index ν^{2}

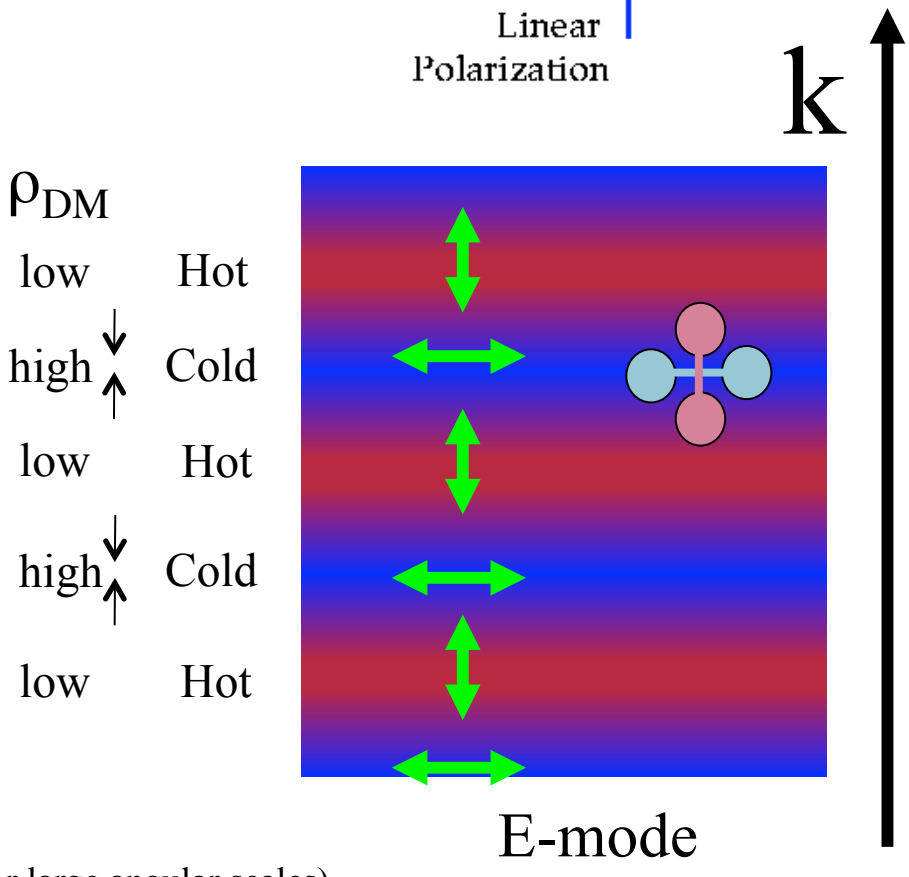
Gold et al. 2010

Polarization comes from free electrons in a quadrupolar electric field.



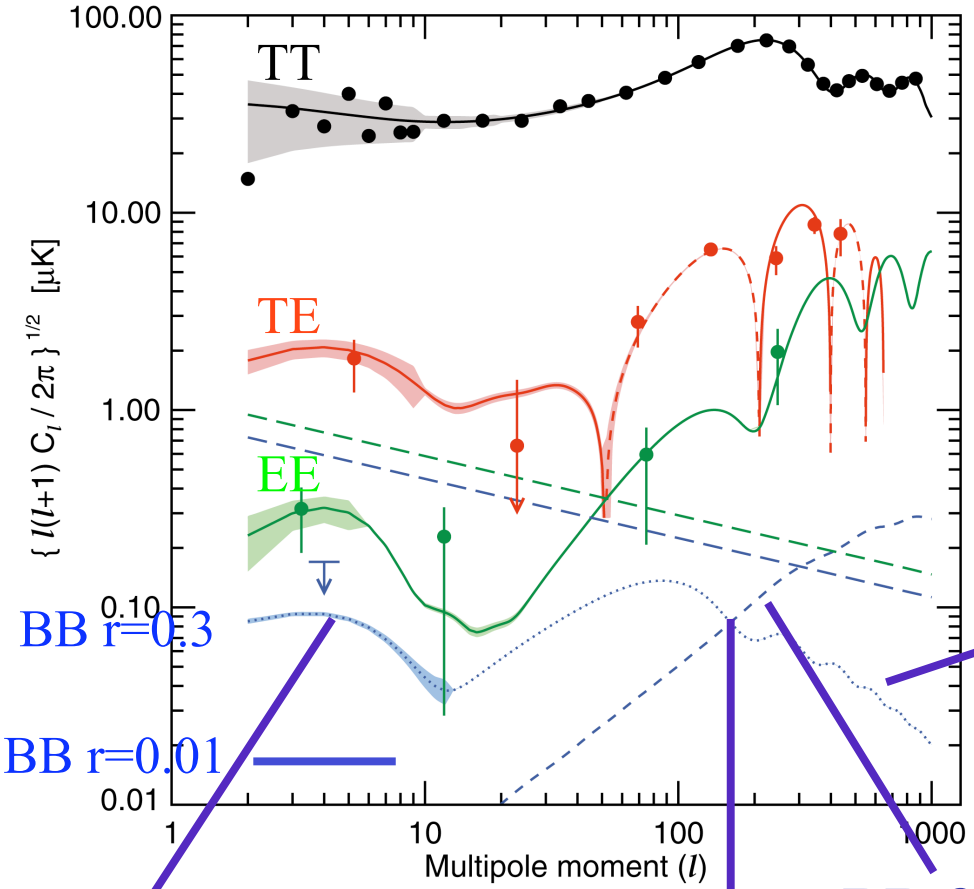
At decoupling (z~1100) and reionization (z~10), conditions are right to produce polarization.

B-modes have polarization vectors at +/- 45 deg to **k**.



(for large angular scales)

Polarization Landscape



EE from reionization

EE from decoupling

Approx EE/BB foreground averaged over 75% of the sky.

BB from GWs

G-waves decay once inside the horizon.

BB from lensing of E-modes (not primordial)

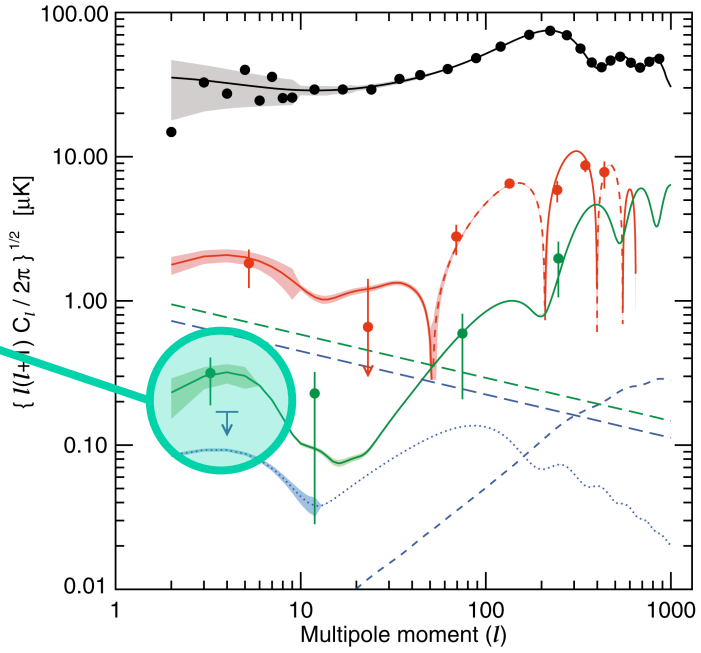
Reionization peak (z_r=10)

Horizon size at decoupling ($\theta_H \sim 1.2^0$)

EE at large angular scales

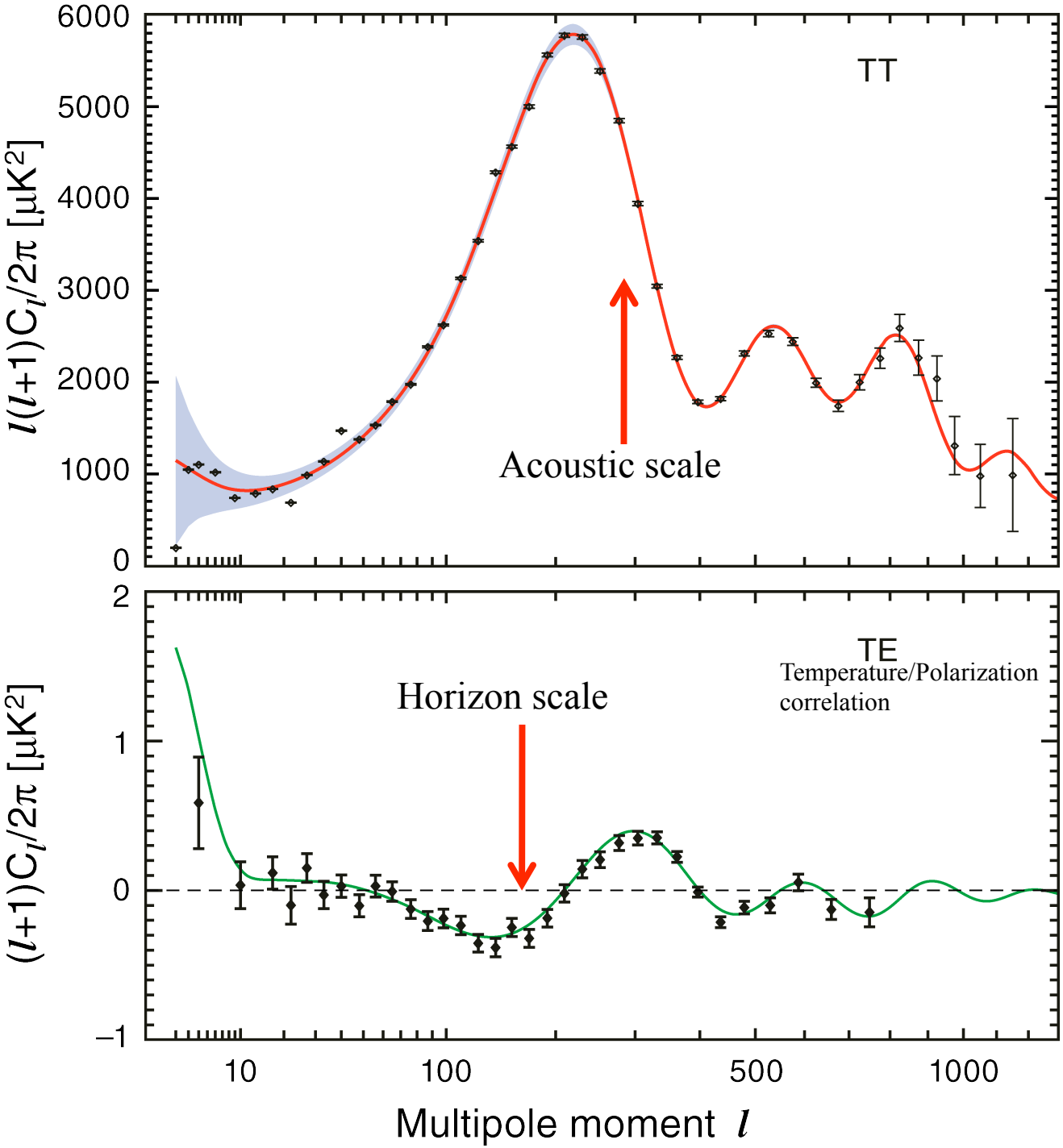
The most challenging aspect of measuring the polarization *at large angular* scales is subtracting foreground emission. We do this a few ways but base results on the Dunkley et al pixel-based maximum-likelihood method.

WMAP's polarization measurements tell us the optical depth, τ, to the surface of last scattering.



$$< l(l+1)C_l^{EE}/2\pi >_{l=2\text{-}7} = 0.074^{+0.034}_{-0.025}\ \mu K^2$$

$$< l(l+1)C_l^{BB}/2\pi >_{l=2\text{-}7} < 0.055\ \mu K^2\ (95\%\ cl)$$

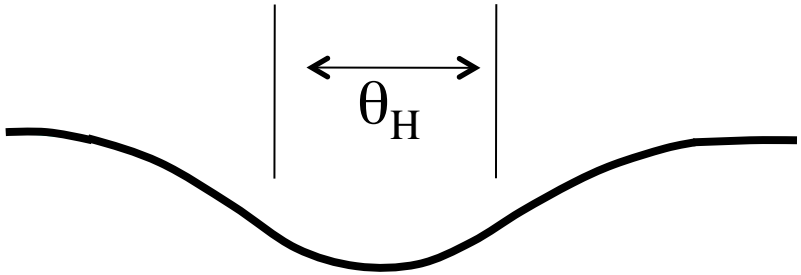


WMAP7 TT&TE Spectra

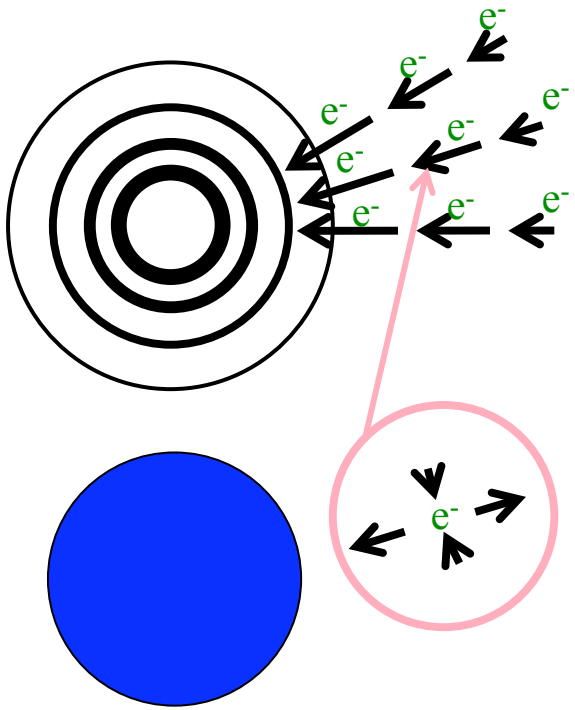
Q, V, and W bands, now 21 sigma

Jarosik et al. 2010

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



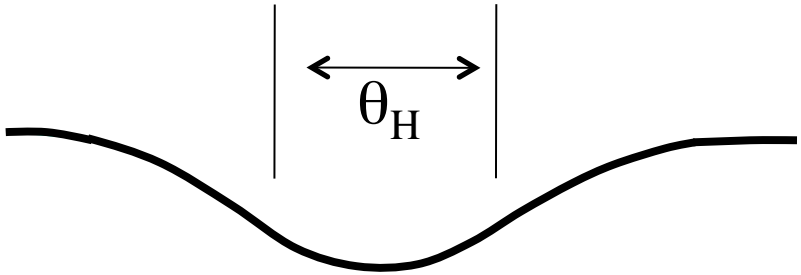
Photons climb out of well so this appears as a cold splotch on large angular scales.



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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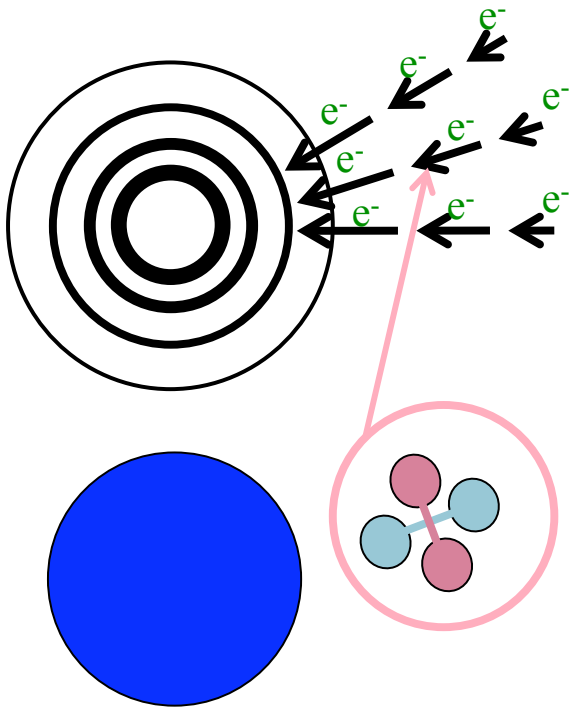

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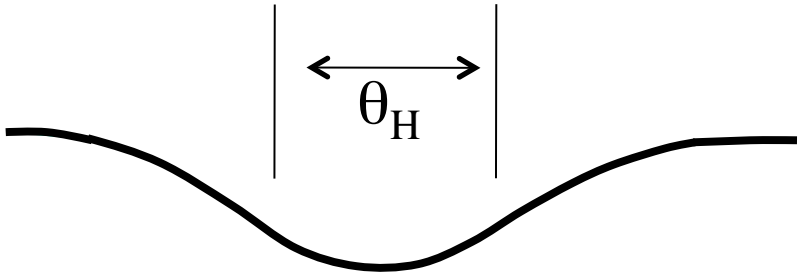

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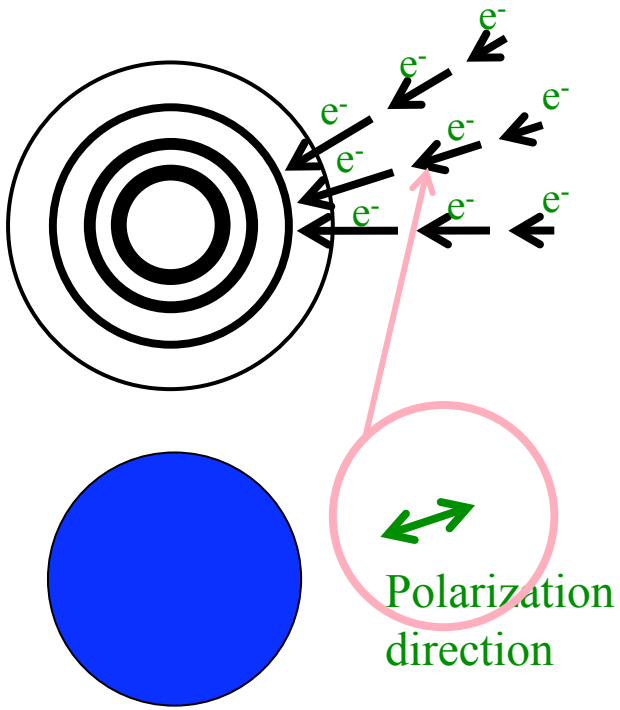

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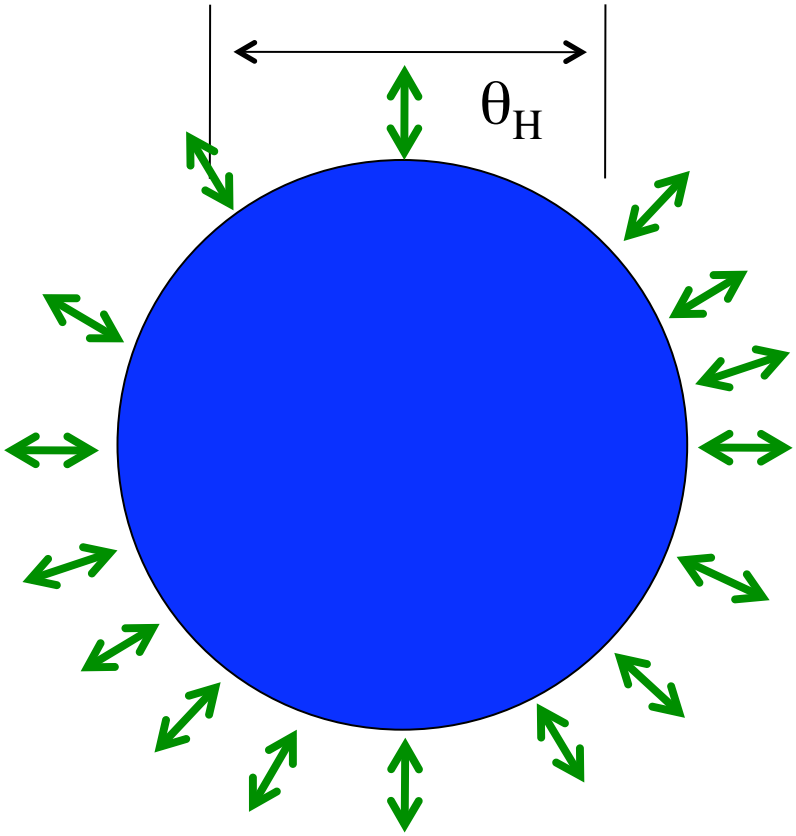
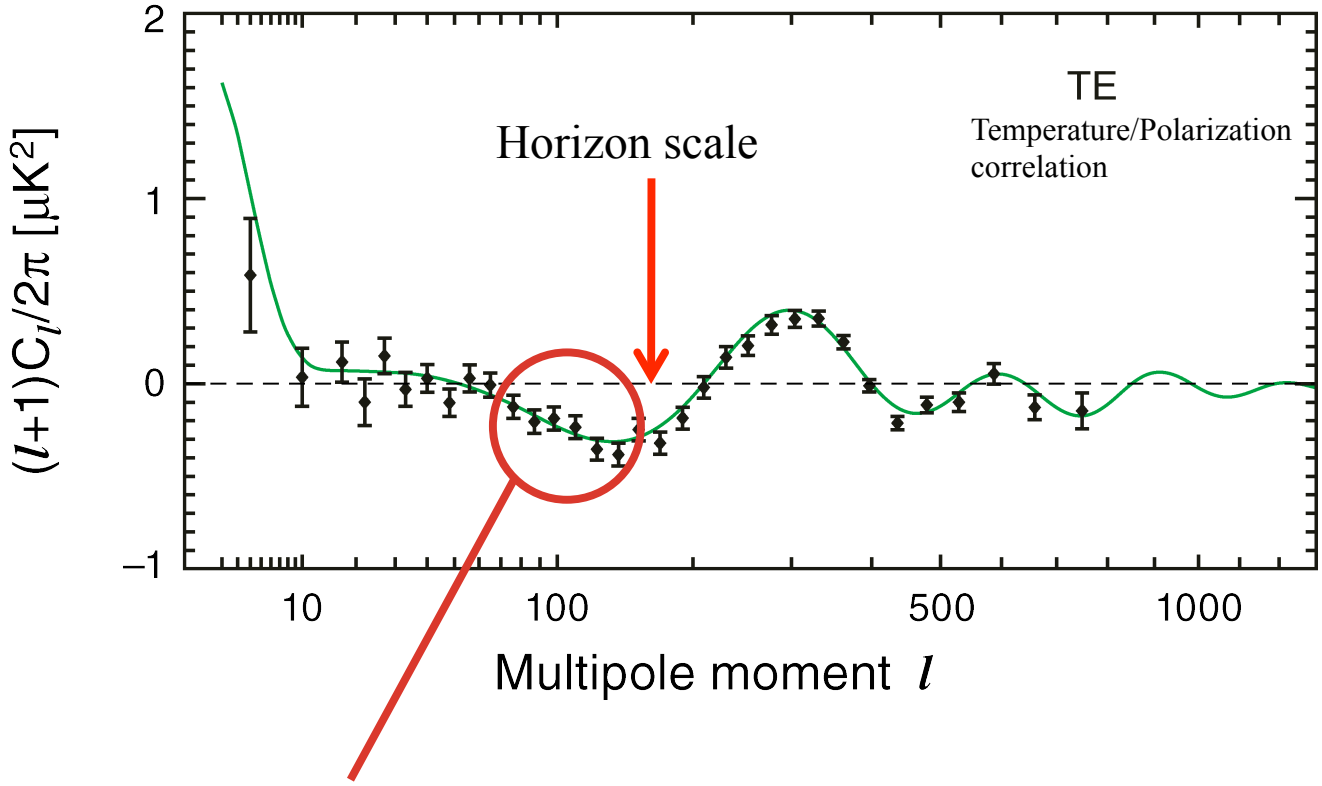


At **large** angular scales we expect the direction of the correlated component of the polarization to be **radial** around cold spots (or potential minima or over dense regions).

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 is a picture of it.

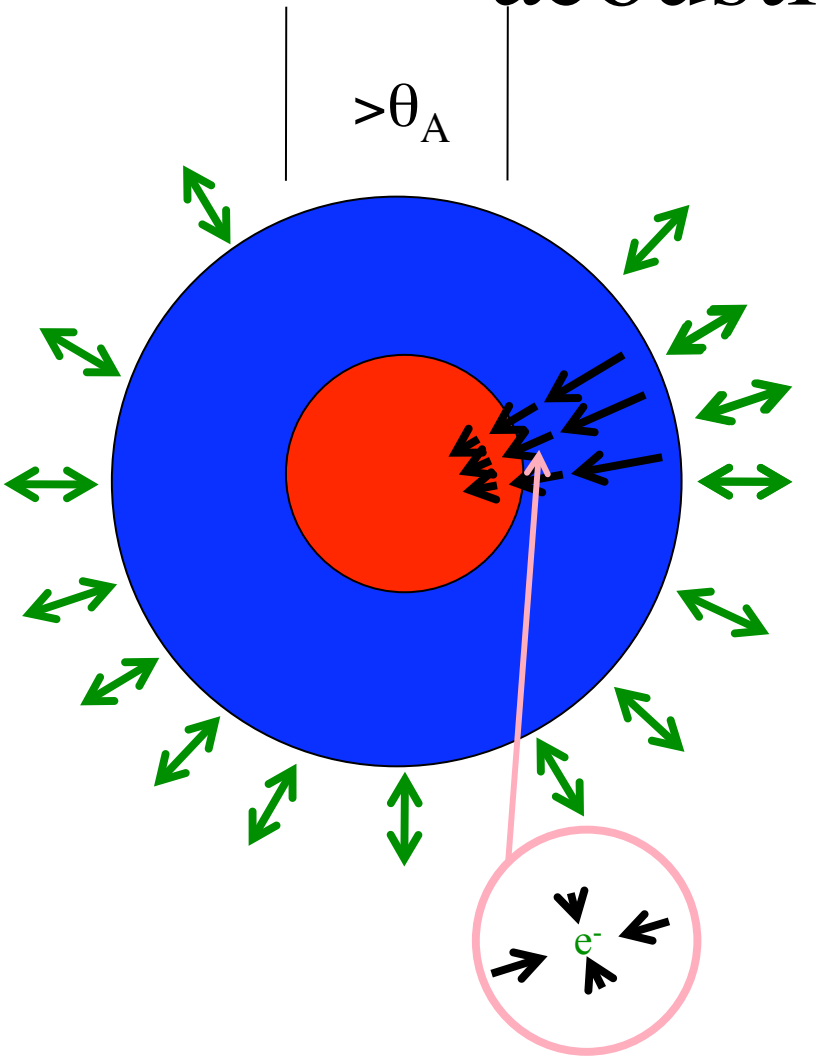


WMAP7 TE Spectrum

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)

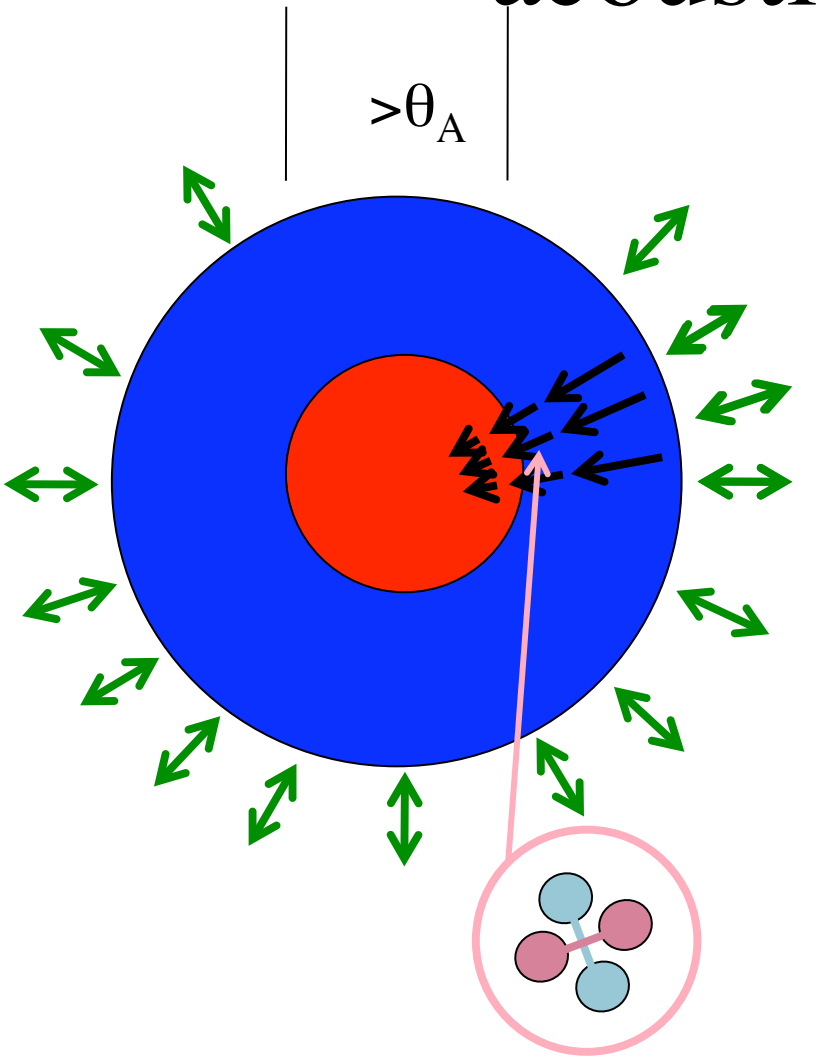
Consider compression at the acoustic scale.



As the plasma flows in it compresses and slows down near the acoustic scale, θ_A

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

Consider compression at the acoustic scale.



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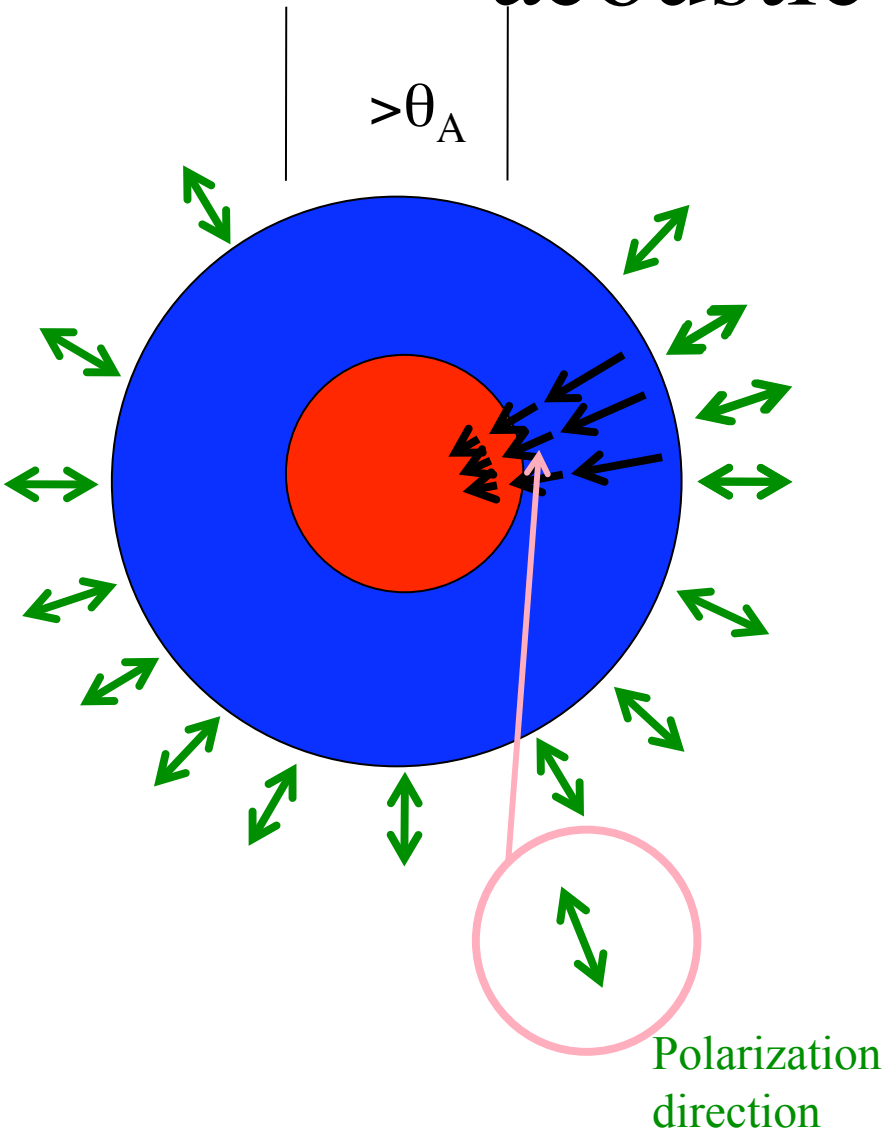

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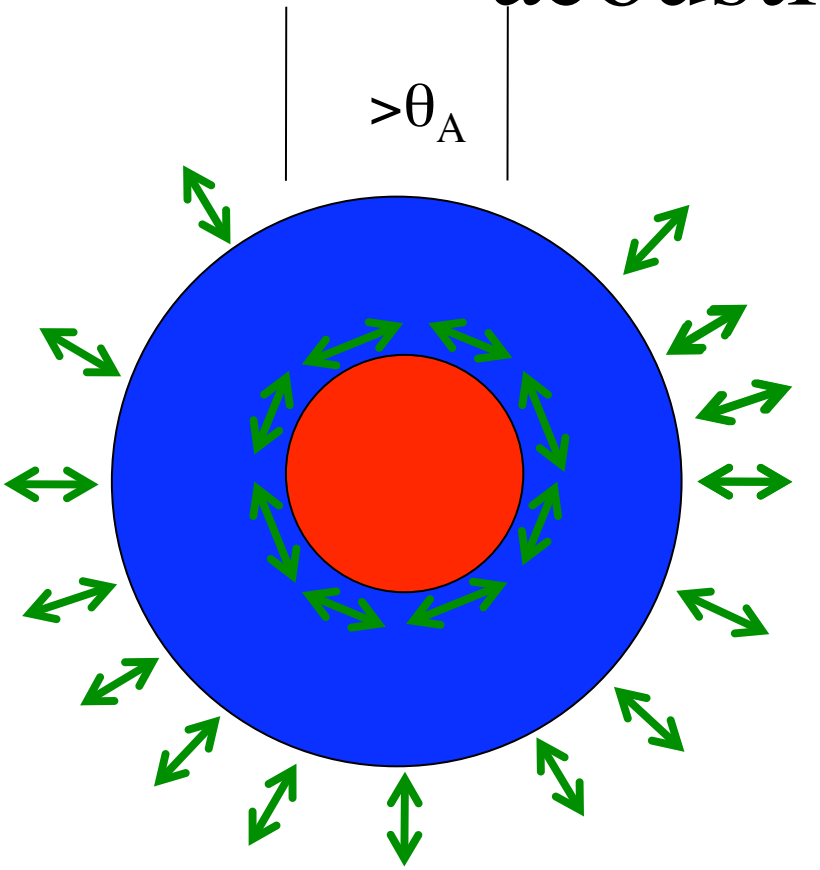
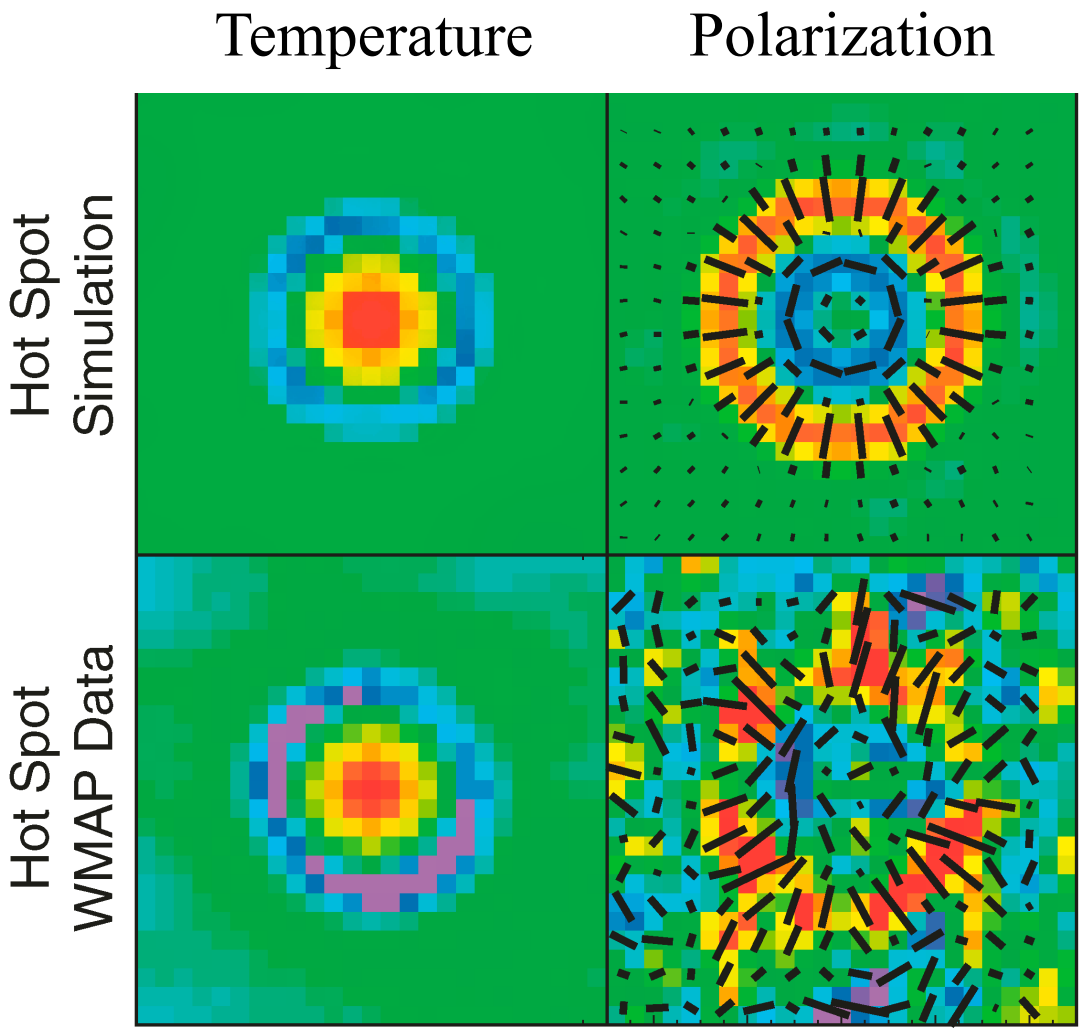


Expected polarization pattern is radial around hot spots but becomes tangential as you move in.

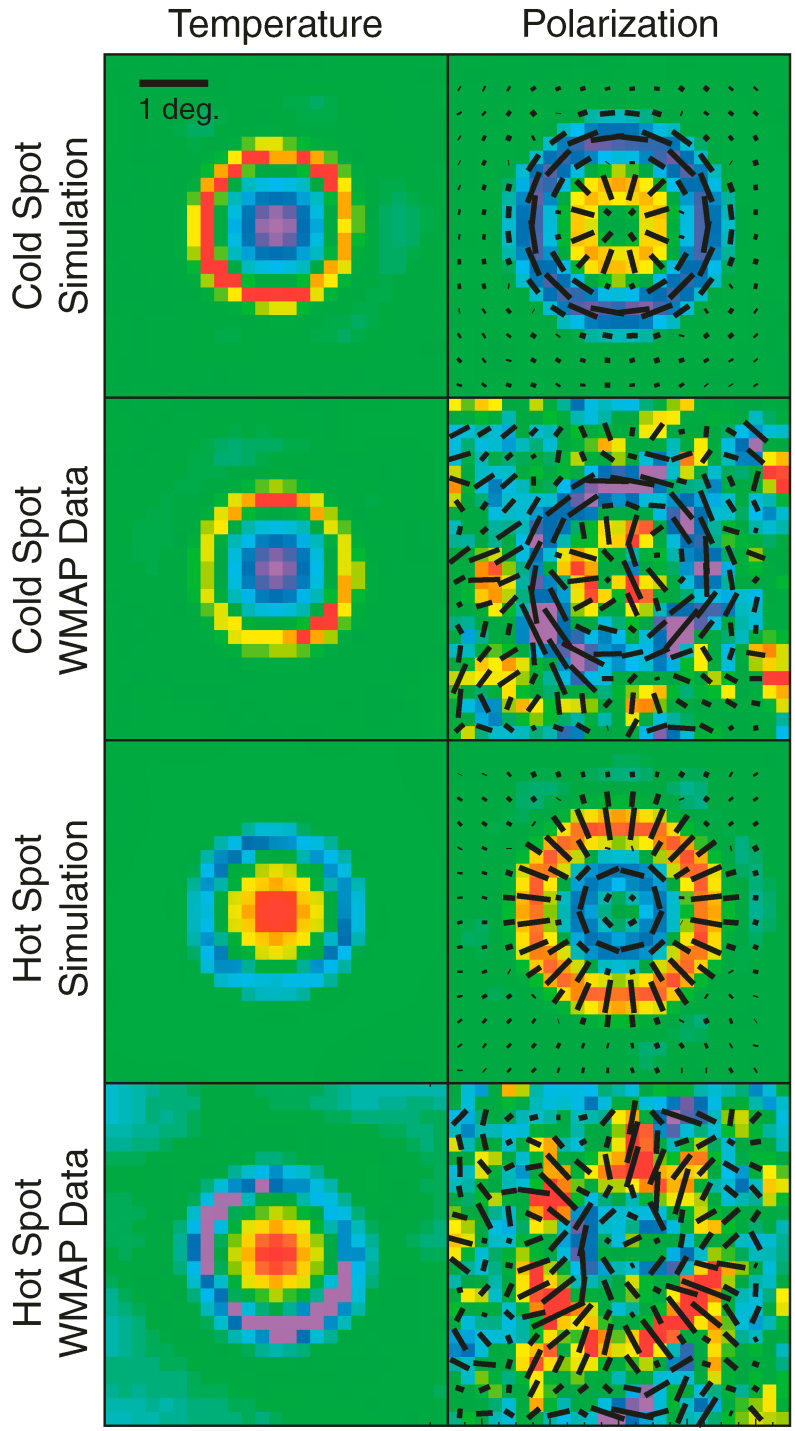
The effect was first predicted in 1994 by Coulson, Crittenden, and Turok.

WMAP sees the effect



~12,000 stacked hot spots

Komatsu et al, 2010



…around cold spots as well.

But with all the signs flipped.

Komatsu et al. 2010

Tensor perturbations

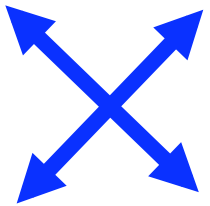
Tensors: h (GW strain) → Temperature

Tensors: h (GW strain) → E-mode polarization

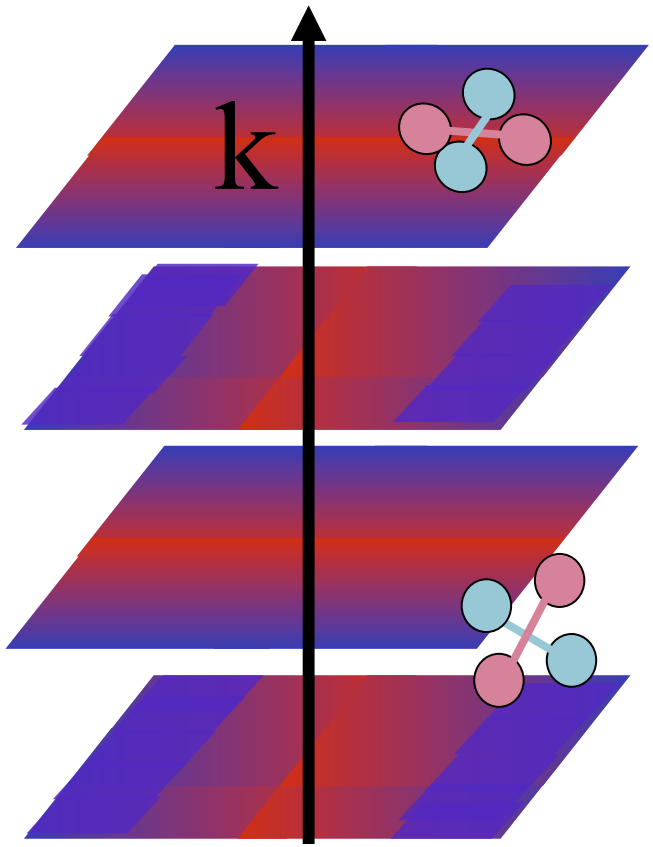
Tensors: h (GW strain) → B-mode polarization

$$r = \frac{\mathrm{Var(Tensors)}}{\mathrm{Var(Scalars)}}$$

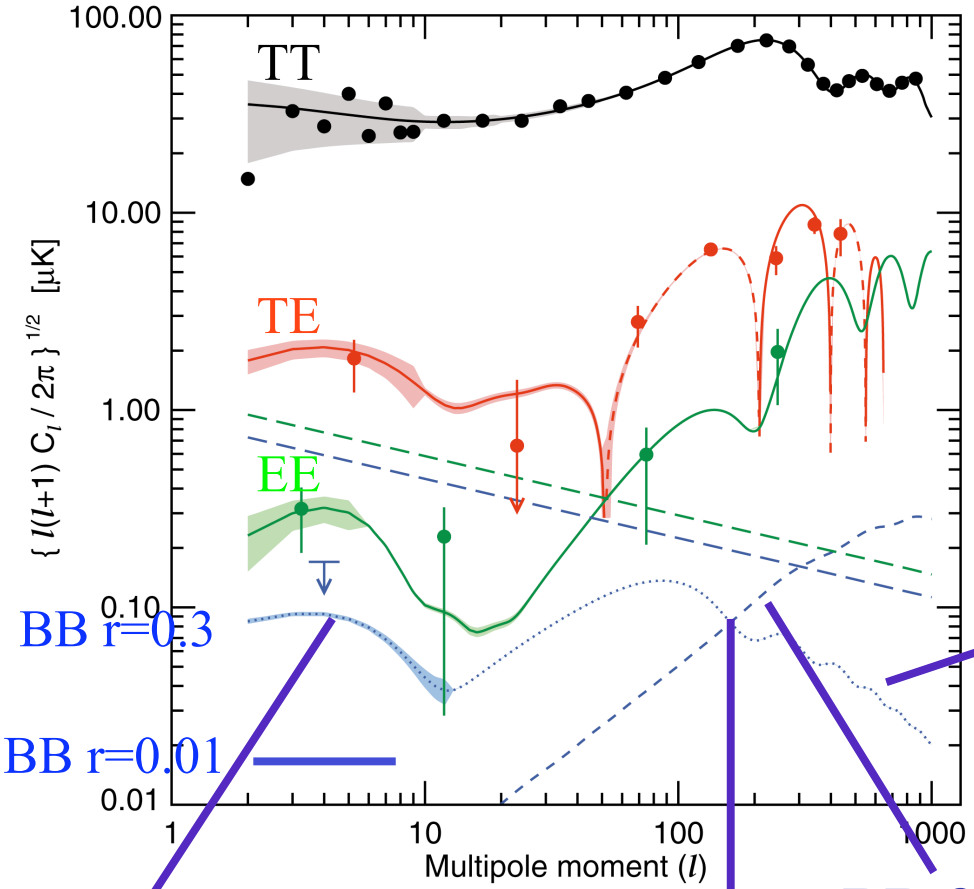
"Generic" (1980's) predicts r~0.2-0.3, but could be much less.



B-modes



Polarization Landscape



EE from reionization

EE from decoupling

Approx EE/BB foreground averaged over 75% of the sky.

BB from GWs

G-waves decay once inside the horizon.

BB from lensing of E-modes (not primordial)

Reionization peak (z_r=10)

Horizon size at decoupling ($\theta_H \sim 1.2^0$)

Limits on tensor perturbations

WMAP polarization (EE, BB, TE) alone r<0.93 (95% cl.)

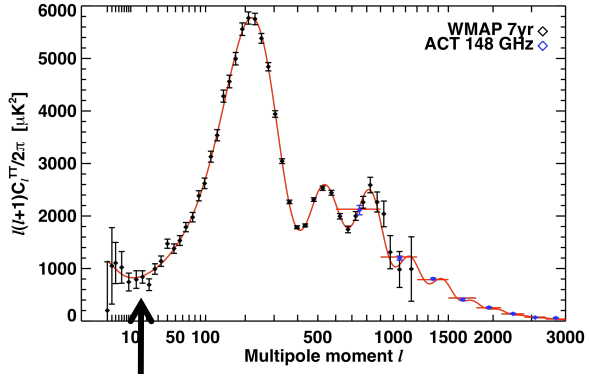
WMAP alone r<0.36 (95% cl.)

WMAP +H_0+BAO r<0.24 (95% cl.)

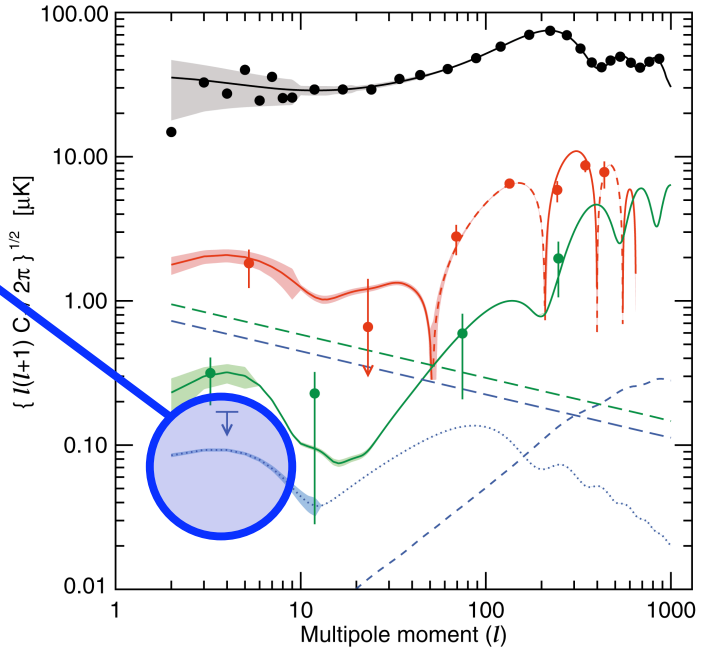
BiCEP r<0.72 (95% cl.)

Based just on B-modes

Chiang et al. (2010)

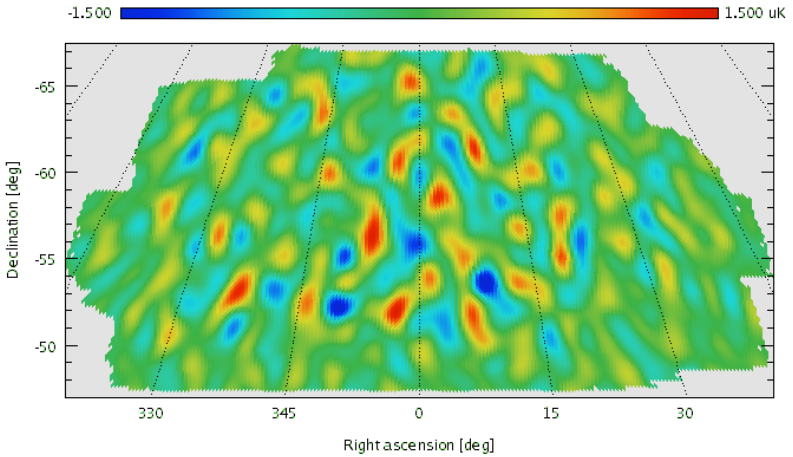


Tensors add here.

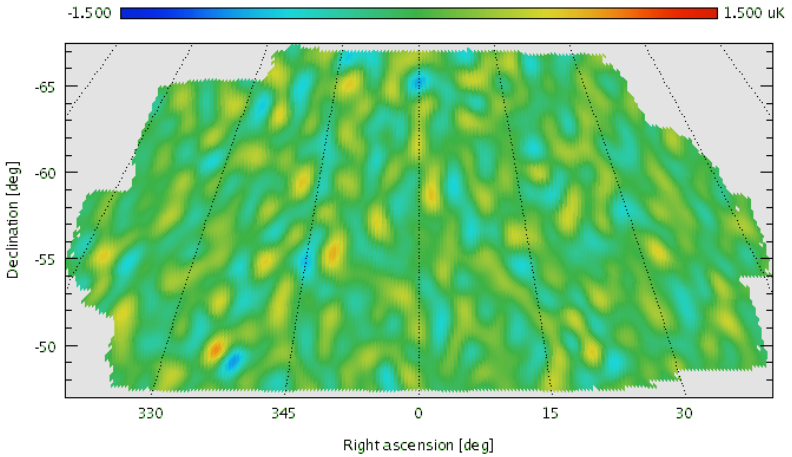


E and B polarization maps

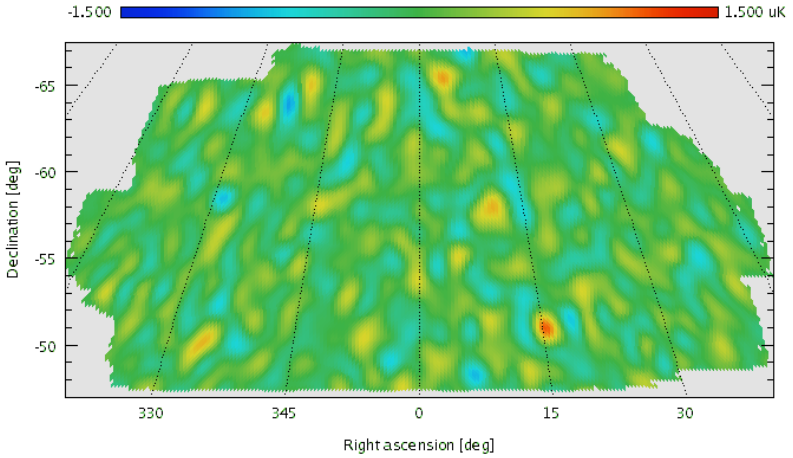
100 + 150 GHz E



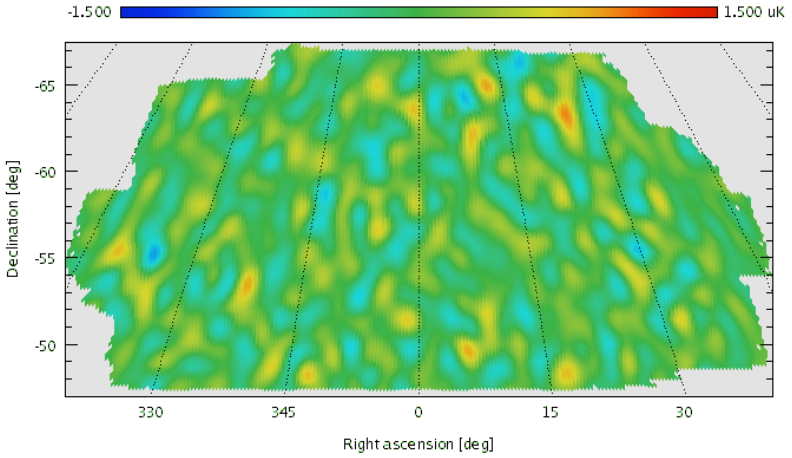
100 - 150 GHz E



100 + 150 GHz B

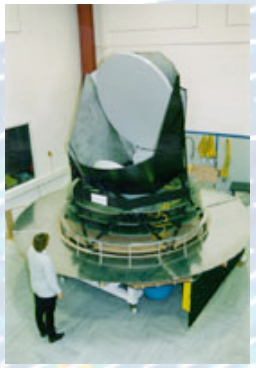


100 - 150 GHz B



BiCEP, Chiang et al. 2010

What's Next in Polarization ?



Planck

BiCEP 2

(50 bolometers)

ACTPol
(1920 feeds)
Chile

PIPER

BRAIN

SPIDER

2011 2012 2013 2014

QUIET

ABS

HTT/Polarbear-I
(640 feeds)
California

SPTPol
(~1000 feeds)
South Pole

EBEX

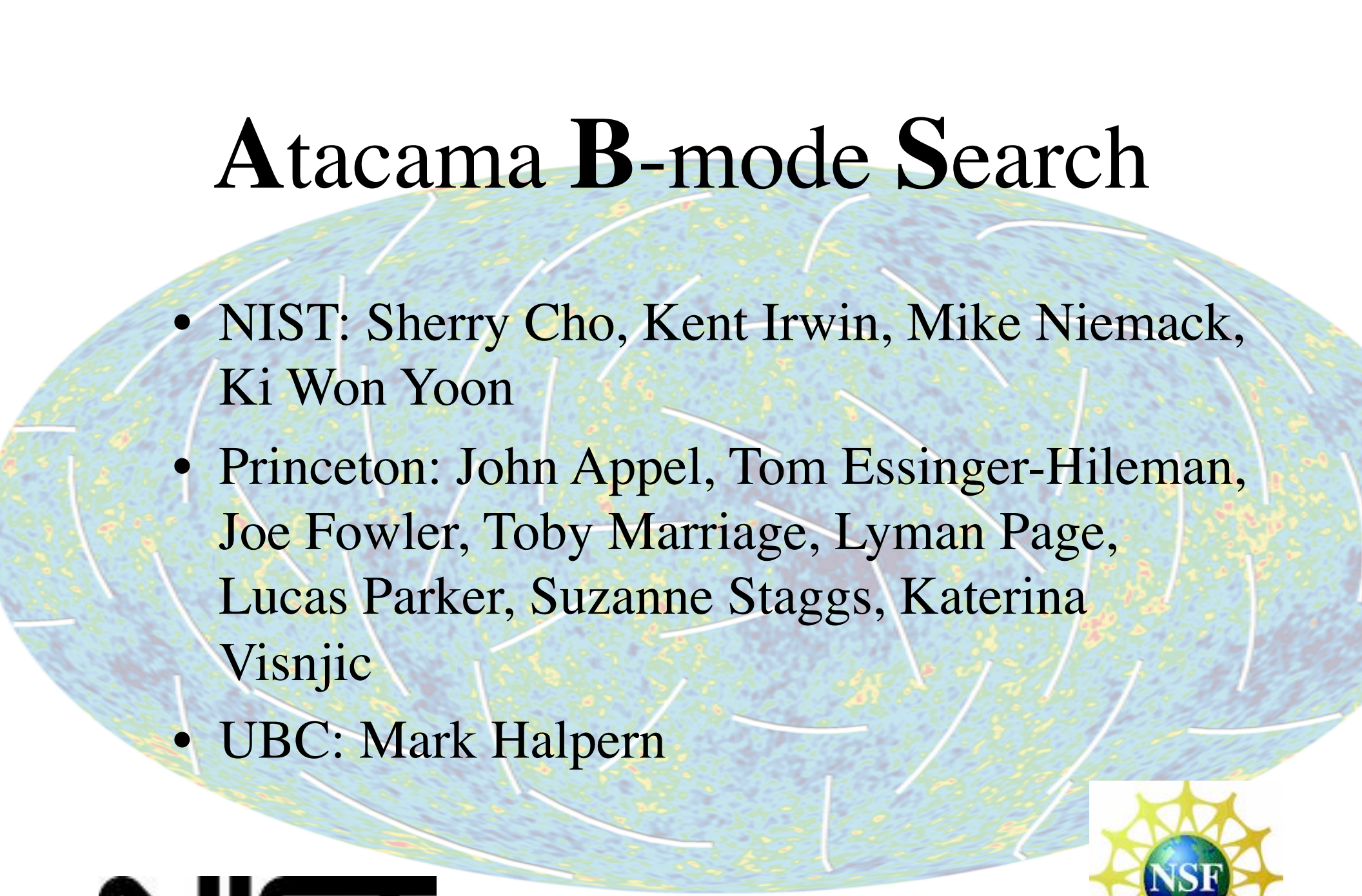
POLAR-1

POINCARE

CLASS

POLARBEAR

Atacama **B**-mode **S**earch



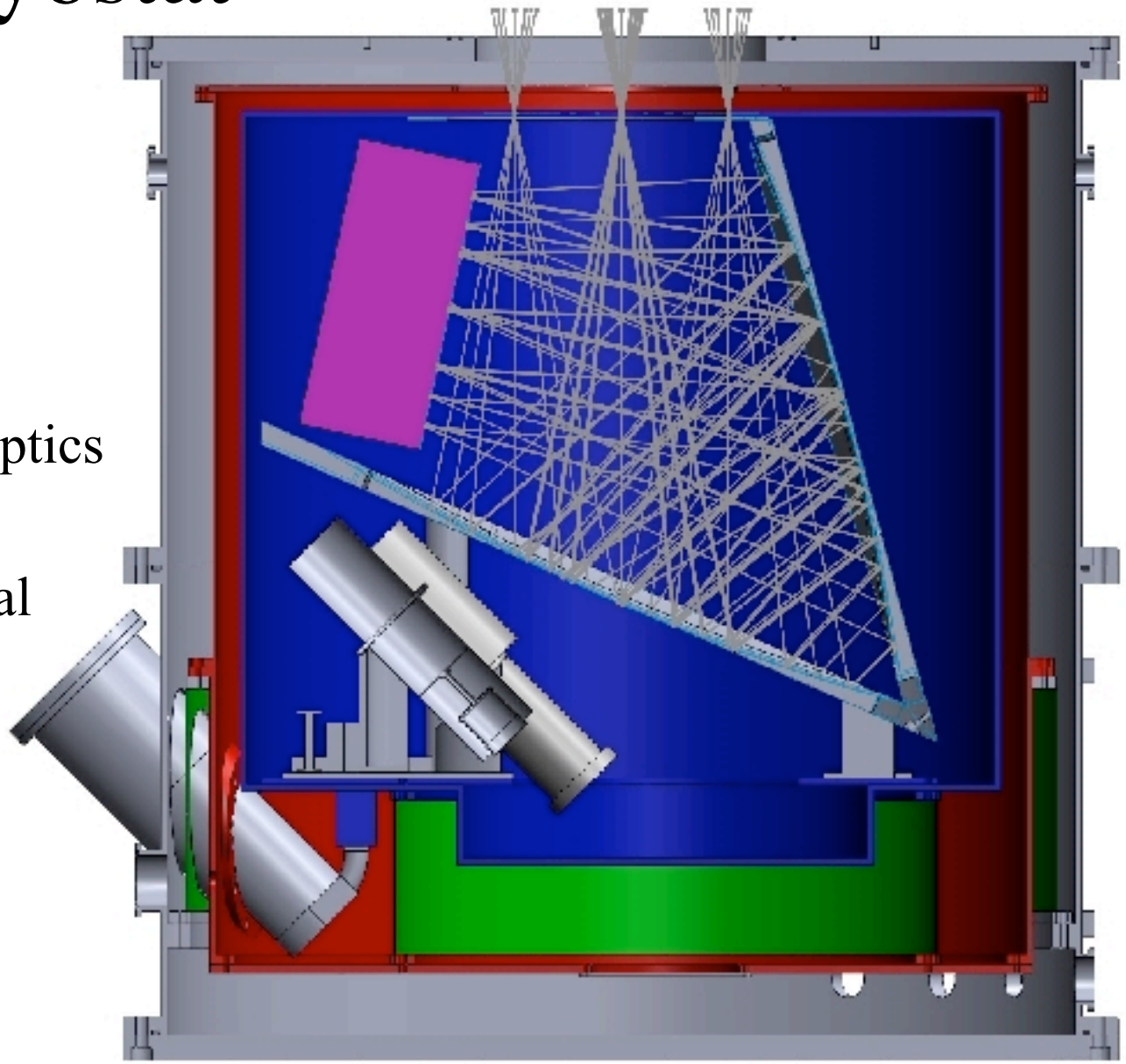
- NIST: Sherry Cho, Kent Irwin, Mike Niemack, Ki Won Yoon
- Princeton: John Appel, Tom Essinger-Hileman, Joe Fowler, Toby Marriage, Lyman Page, Lucas Parker, Suzanne Staggs, Katerina Visnjic
- UBC: Mark Halpern

NIST

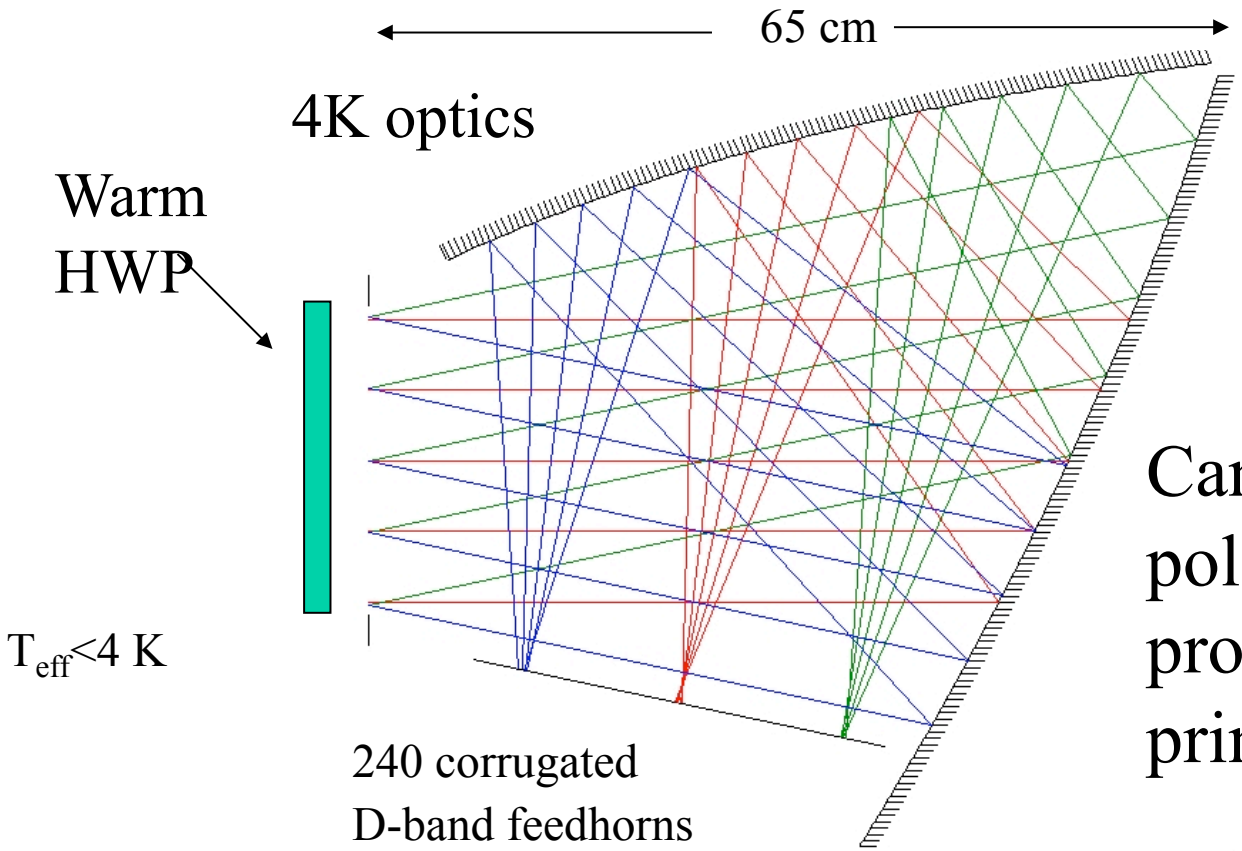
NSF

ABS Cryostat

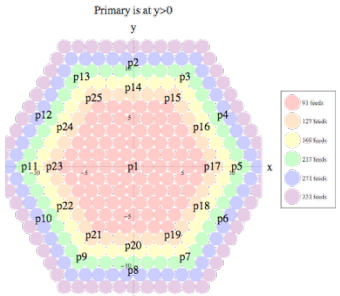
- 240 feeds
- 0.3 K detectors
- 4 K all reflective optics
- 270 K HWP
- Cryoperm/mu metal
- 1 cubic meter
- 145 GHz.



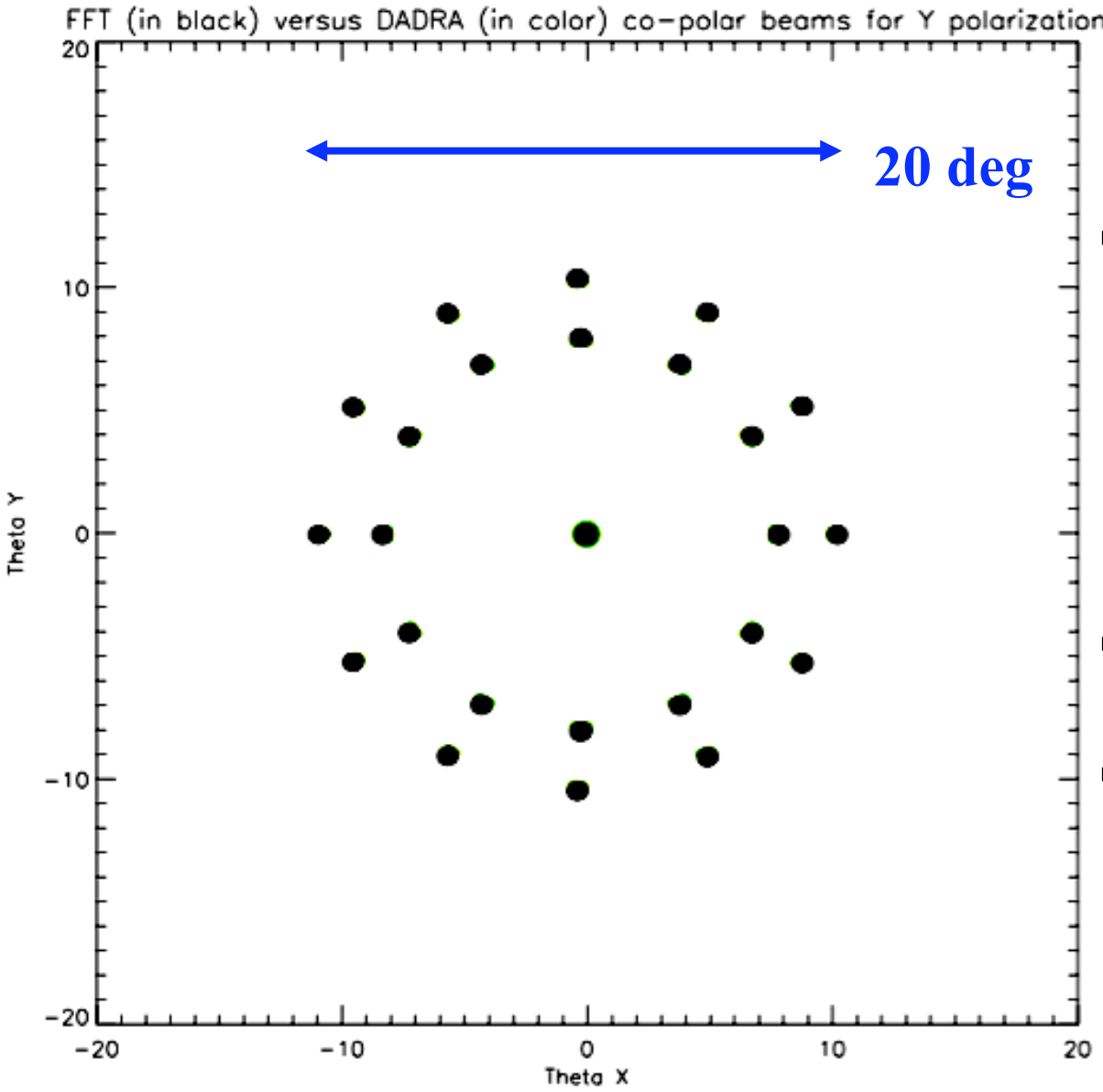
Optics



Can compute full polarized beam profile from “first principles”



Optical Modeling

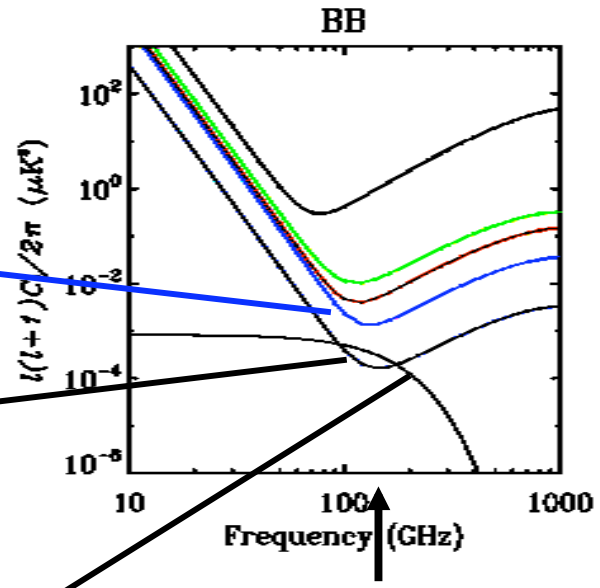


- Full diffractive optics calculations to tune the angles and compute systematic error.
- FWHM 0.5 deg
- Only 25 of 240 beams shown.

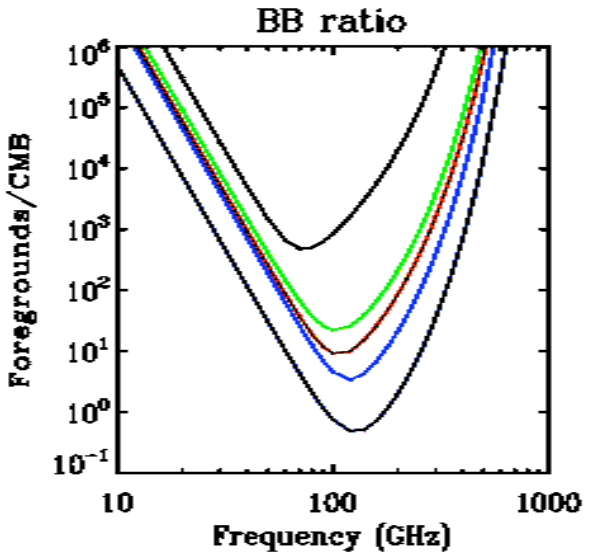
Foreground emission.

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

300 deg sq., at coldest spot.



145 GHz

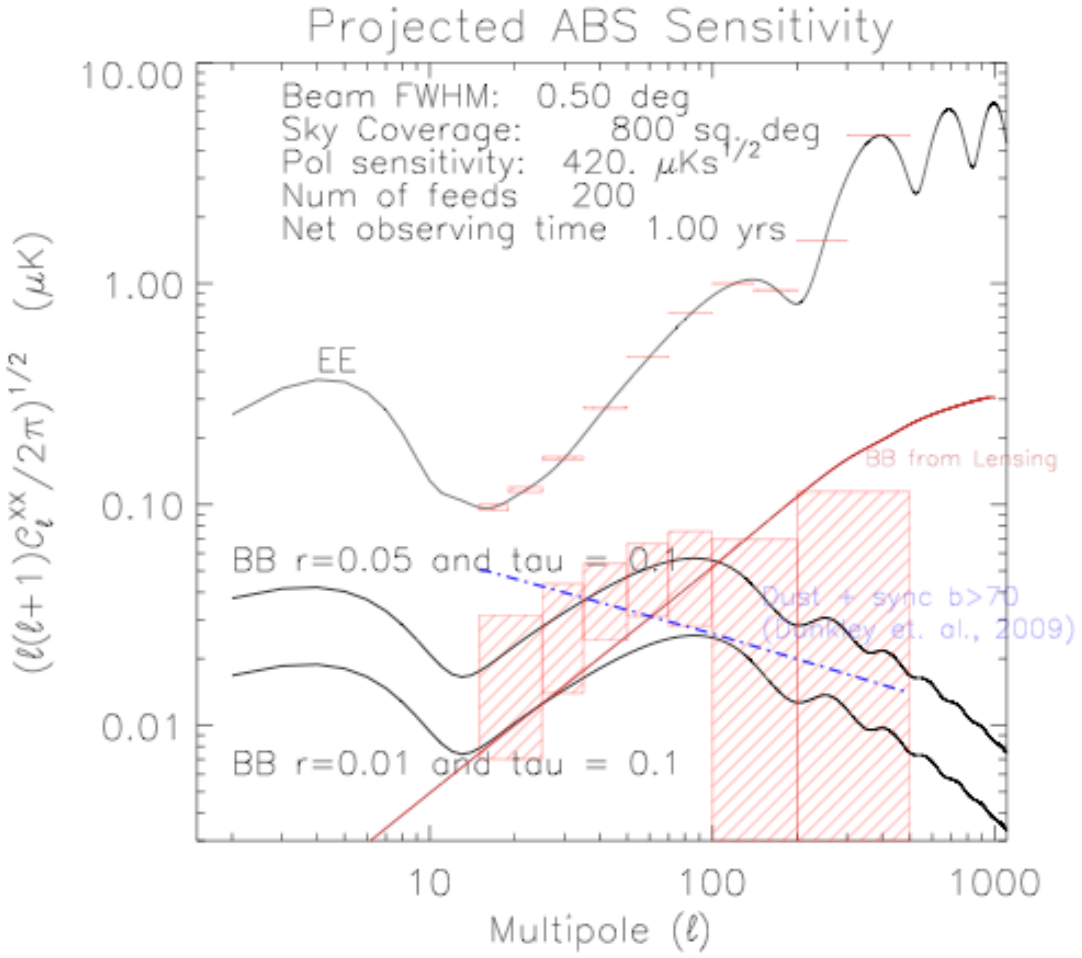


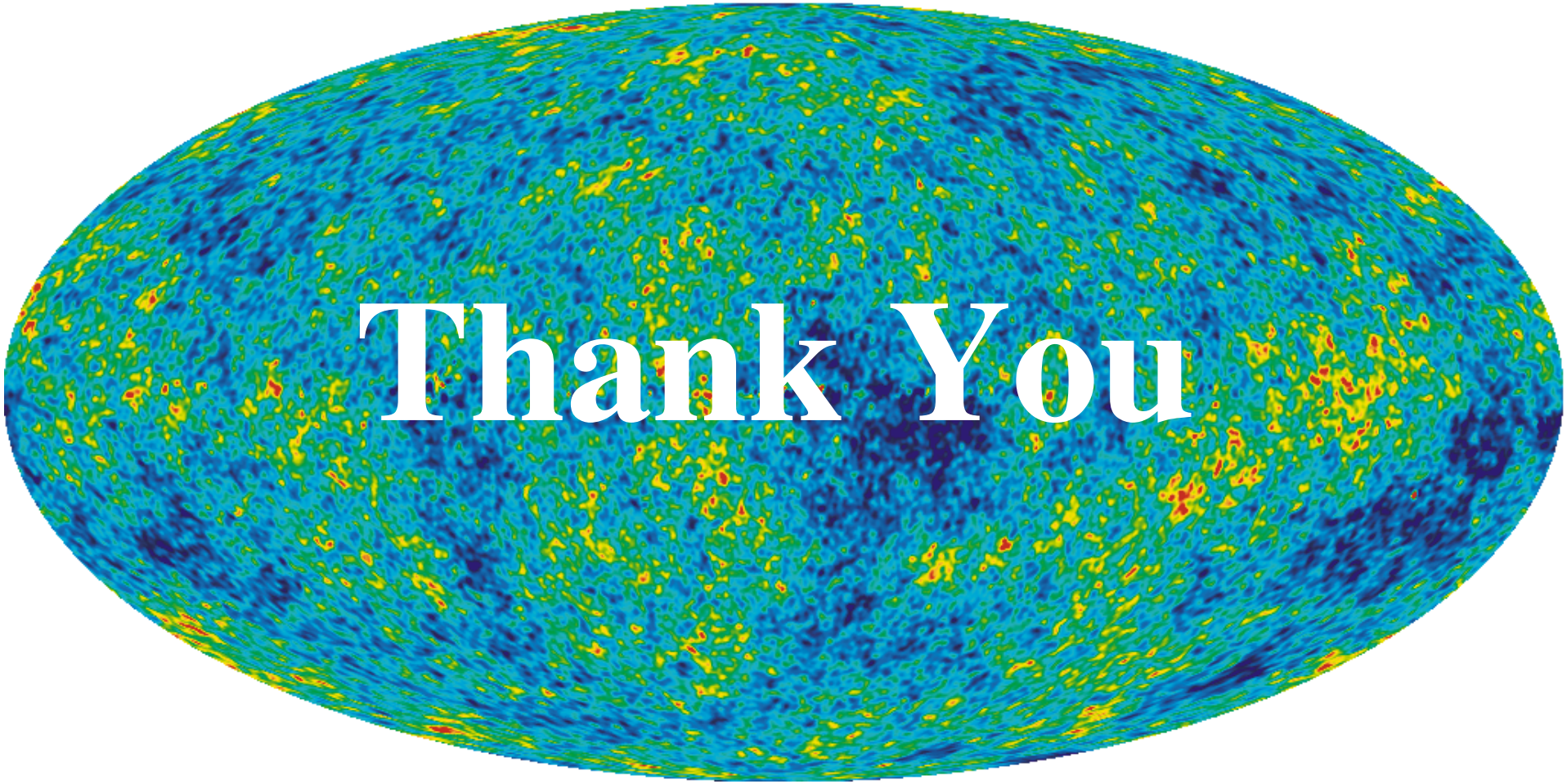
From Dunkley et al. 2008, calculation by Clive Dickinson

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

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

Sensitivity




Thank You