The **7**-Year *WMAP* Observations: Cosmological Interpretation

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TCC/Astrophysics Theory Seminar, UT Austin, February 22, 2010

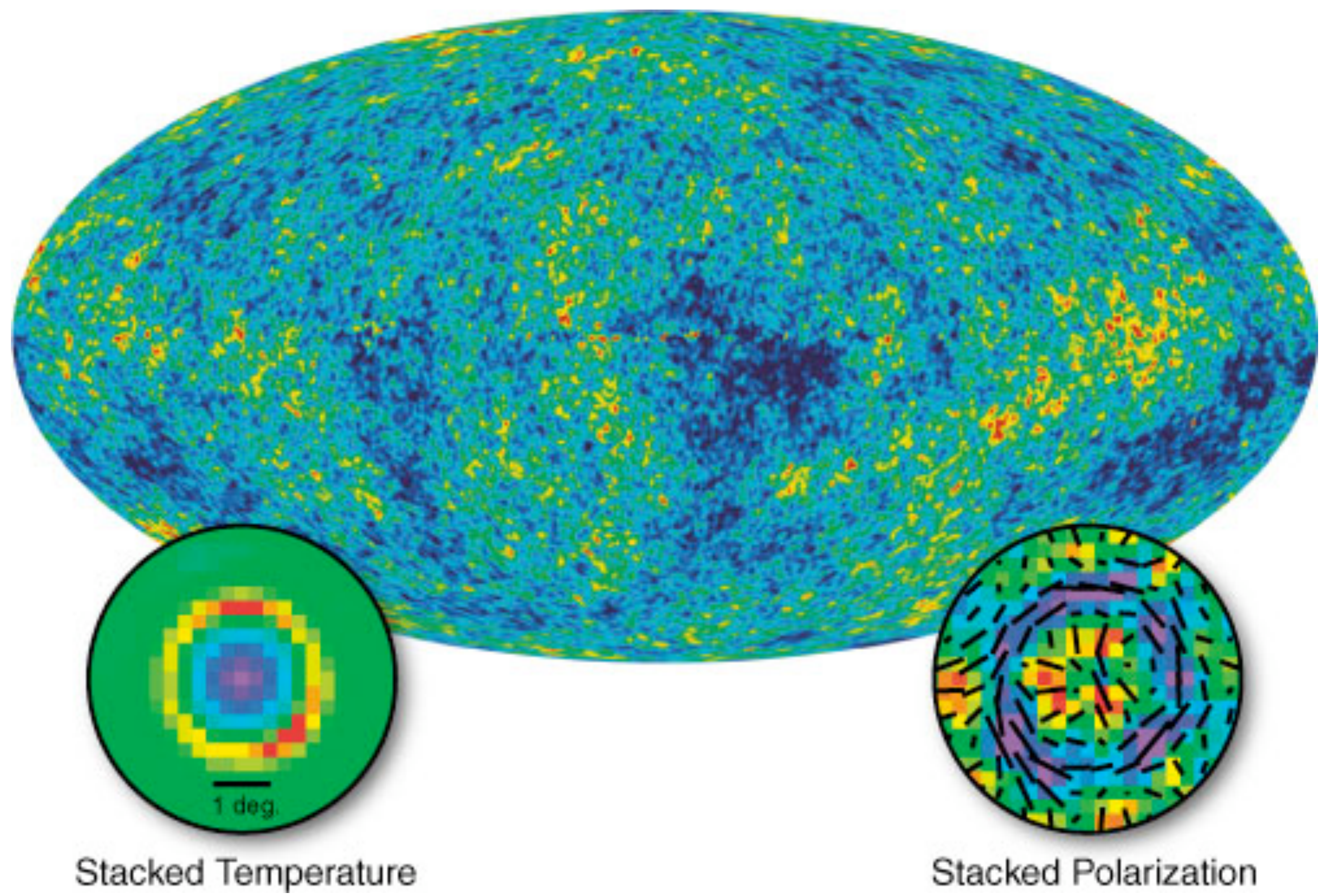
WMAP will have collected 9 years of data by August

June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release



- **January 2010: The seven-year data release**

WMAP 7-Year Papers

- **Jarosik et al.**, "*Sky Maps, Systematic Errors, and Basic Results*" arXiv:1001.4744
- **Gold et al.**, "*Galactic Foreground Emission*" arXiv:1001.4555
- **Weiland et al.**, "*Planets and Celestial Calibration Sources*" arXiv:1001.4731
- **Bennett et al.**, "*Are There CMB Anomalies?*" arXiv:1001.4758
- **Larson et al.**, "*Power Spectra and WMAP-Derived Parameters*" arXiv:1001.4635
- **Komatsu et al**., "*Cosmological Interpretation*" arXiv:1001.4538

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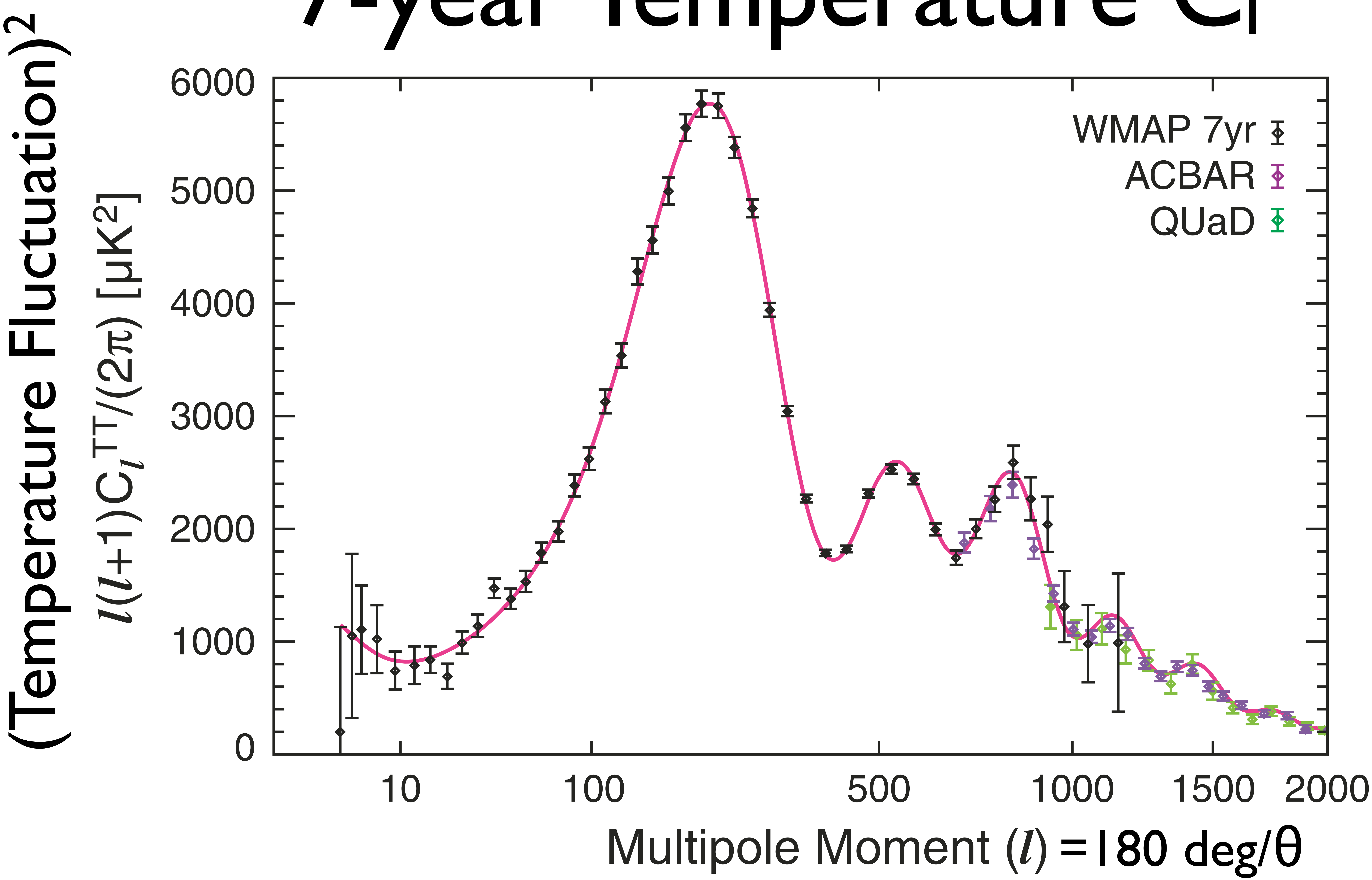
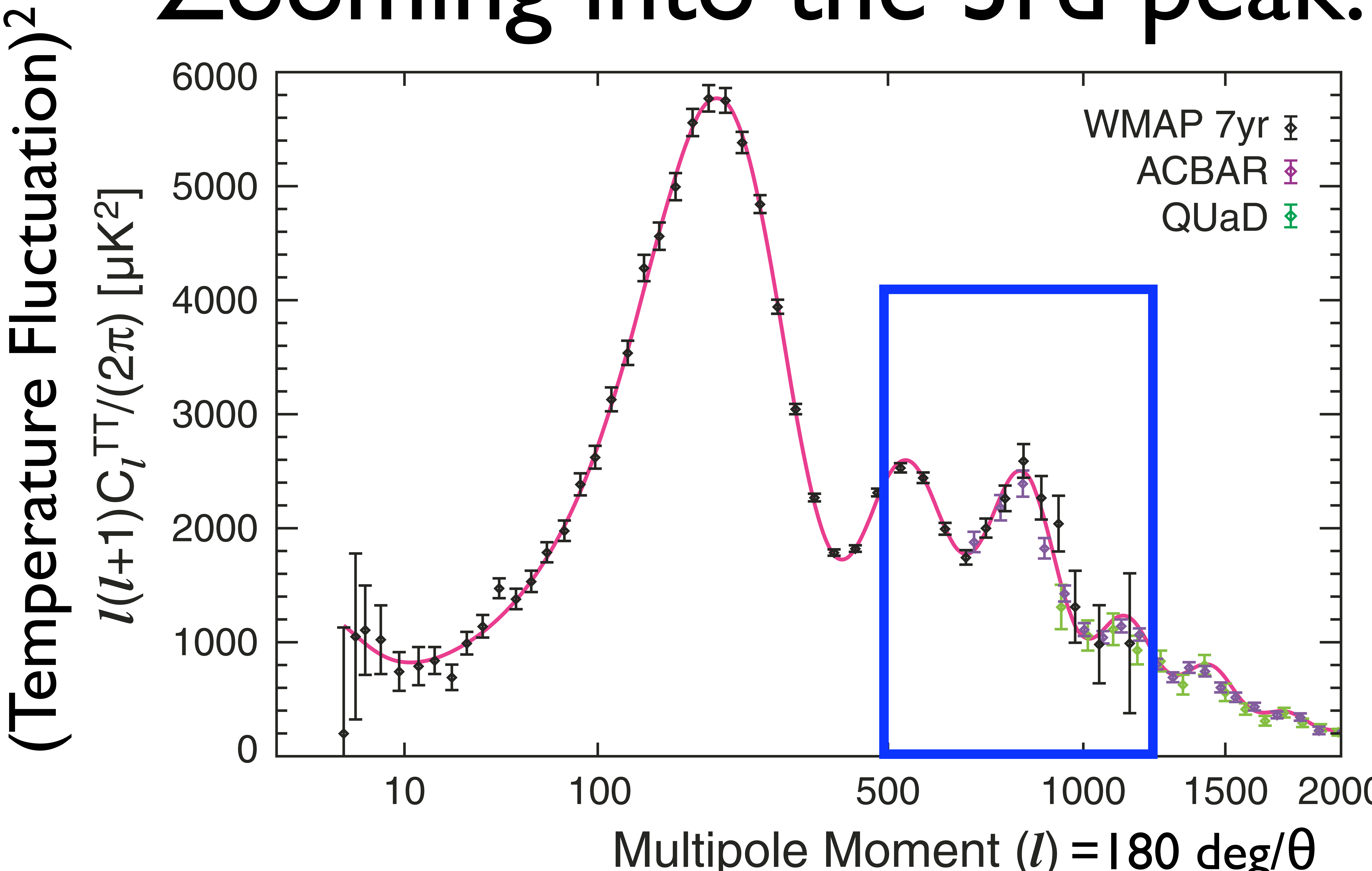
7-year Science Highlights

- First detection (>3σ) of the effect of primordial **helium** on the temperature power spectrum.
- The primordial **tilt** is less than one at >3σ:
  - n_s=0.96±0.01 (68%CL)
- Improved limits on **neutrino** parameters:
  - $\sum m_\nu$<0.58eV (95%CL); N_{eff}=4.3±0.9 (68%CL)
- First direct confirmation of the predicted **polarization** pattern around temperature spots.
- Measurement of the SZ effect: *missing* ***pressure***?

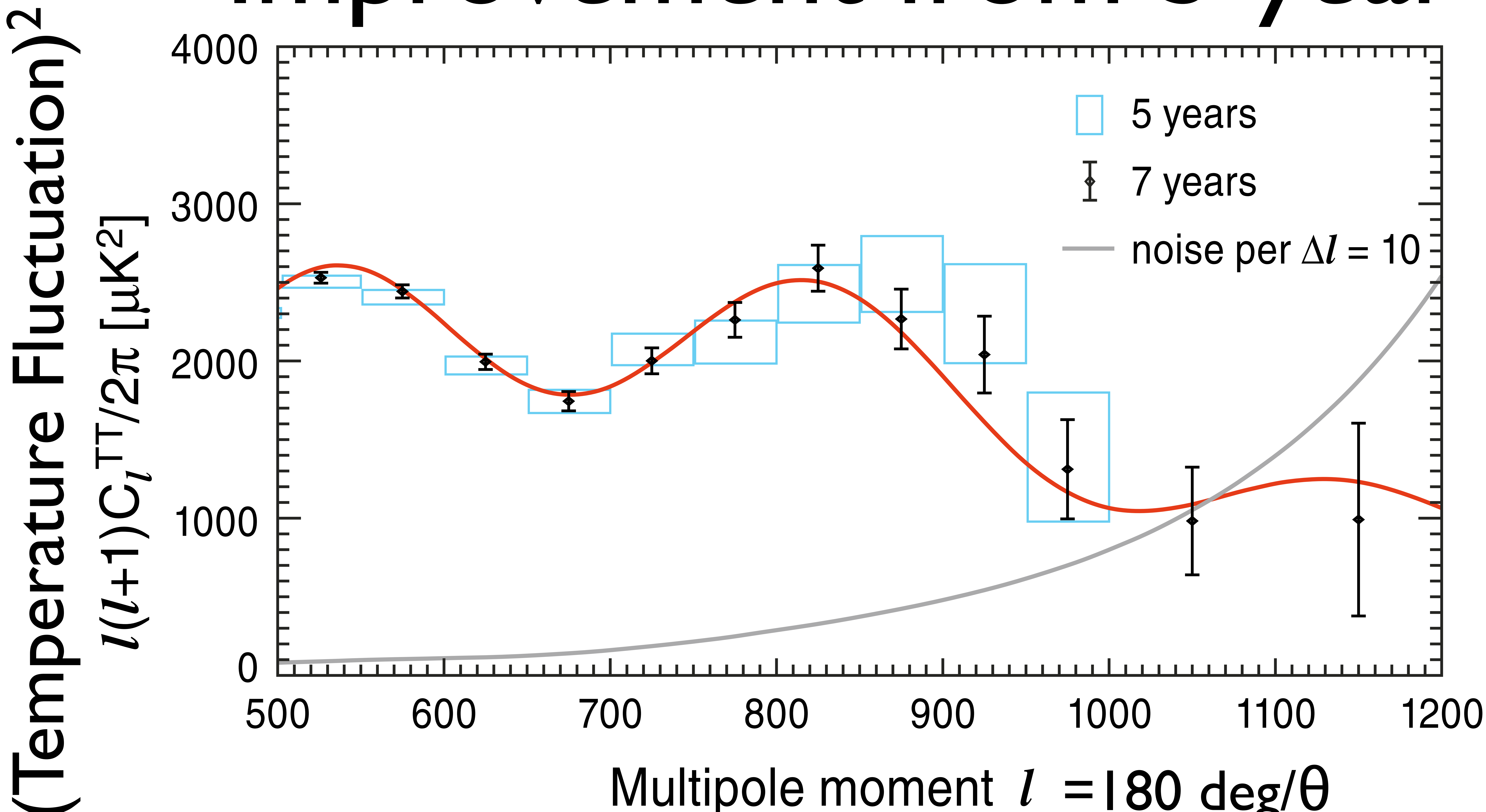
7-year Temperature C_l



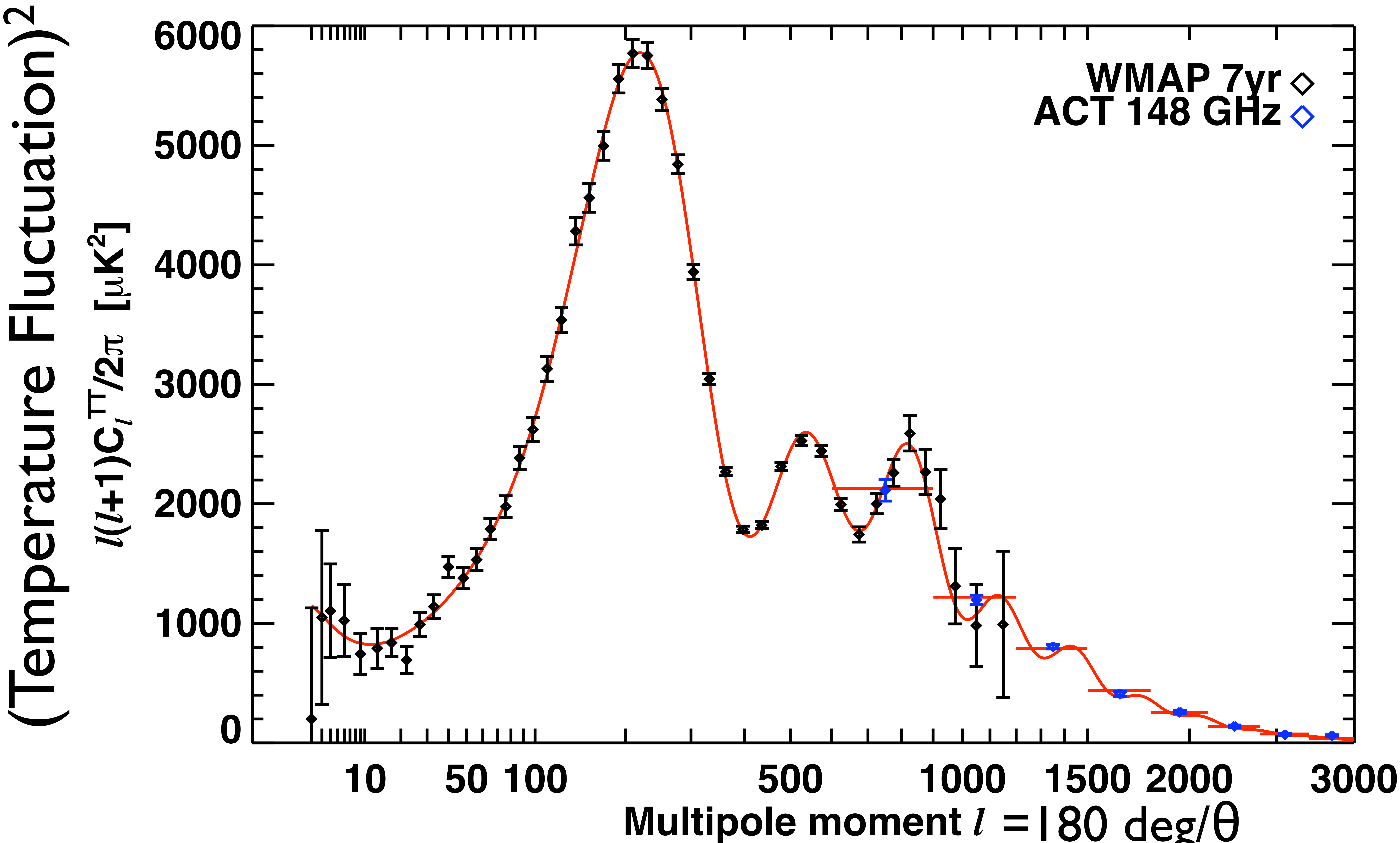
Zooming into the 3rd peak...



High-l Temperature C_l: Improvement from 5-year

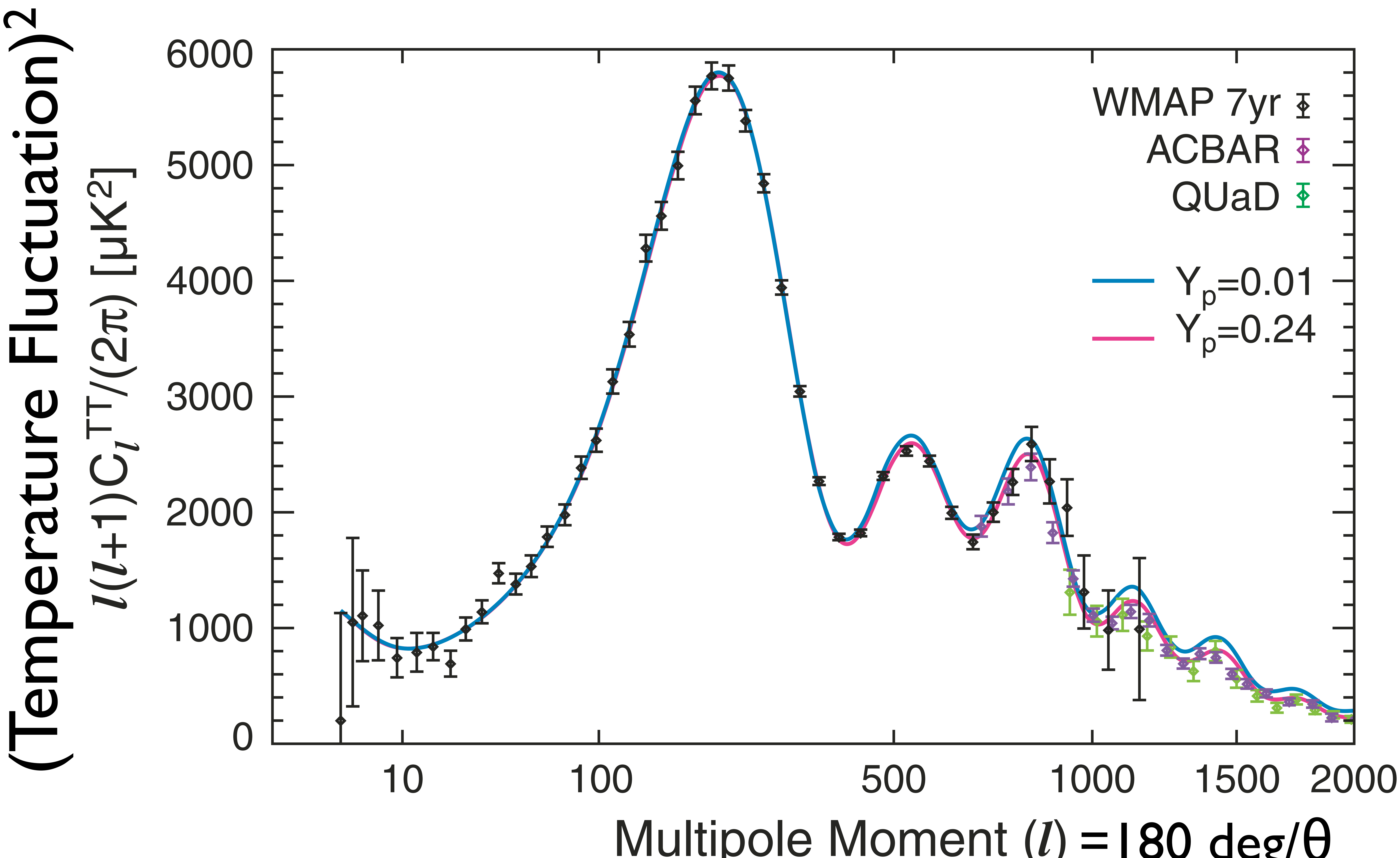


WMAP and ACT



(Temperature Fluctuation)^2
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
6000
5000
4000
3000
2000
1000
0
WMAP 7yr
ACT 148 GHz
10
50
100
500
1000
1500
2000
3000
Multipole moment l = 180 deg/θ

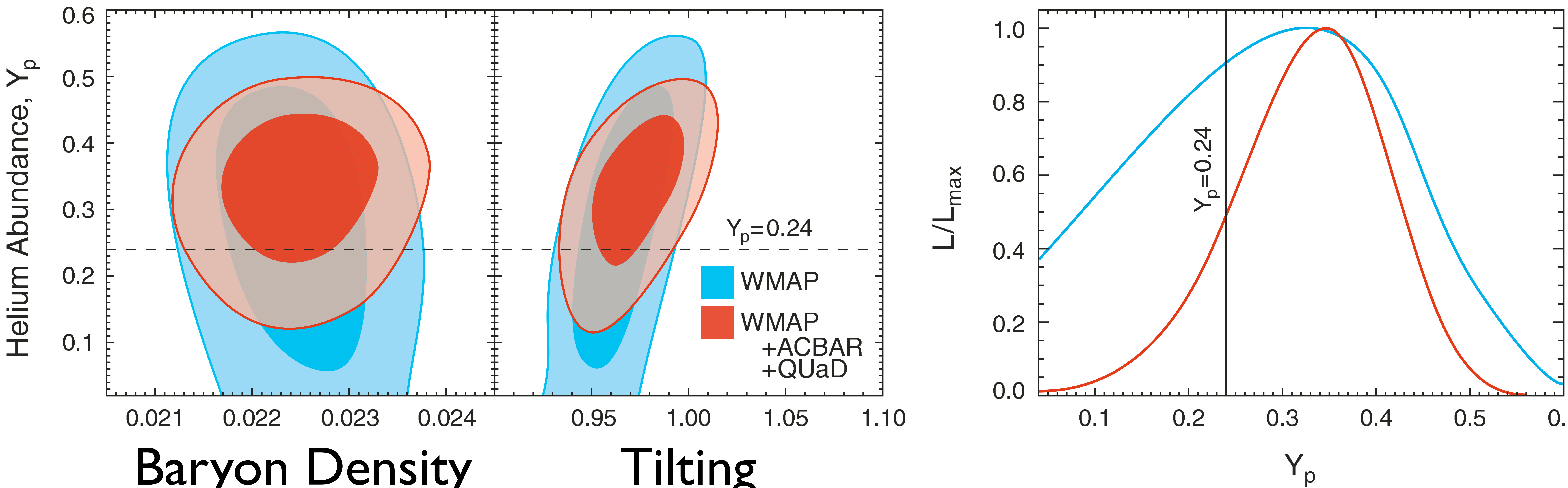
Detection of Primordial Helium



Effect of helium on C_l^{TT}

- We measure the baryon number density, n_b, from the 1st-to-2nd peak ratio.
- As helium recombined at z~1800, there were fewer electrons at the decoupling epoch (z=1090): $n_e=(1-Y_p)n_b$.
- **More helium** = Fewer electrons = Longer photon mean free path $1/(\sigma_T n_e)$ = **Enhanced Silk damping**
- This effect might be degenerate with $\Omega_b h^2$ or n_s...

WMAP + higher-l CMB = Detection of Helium

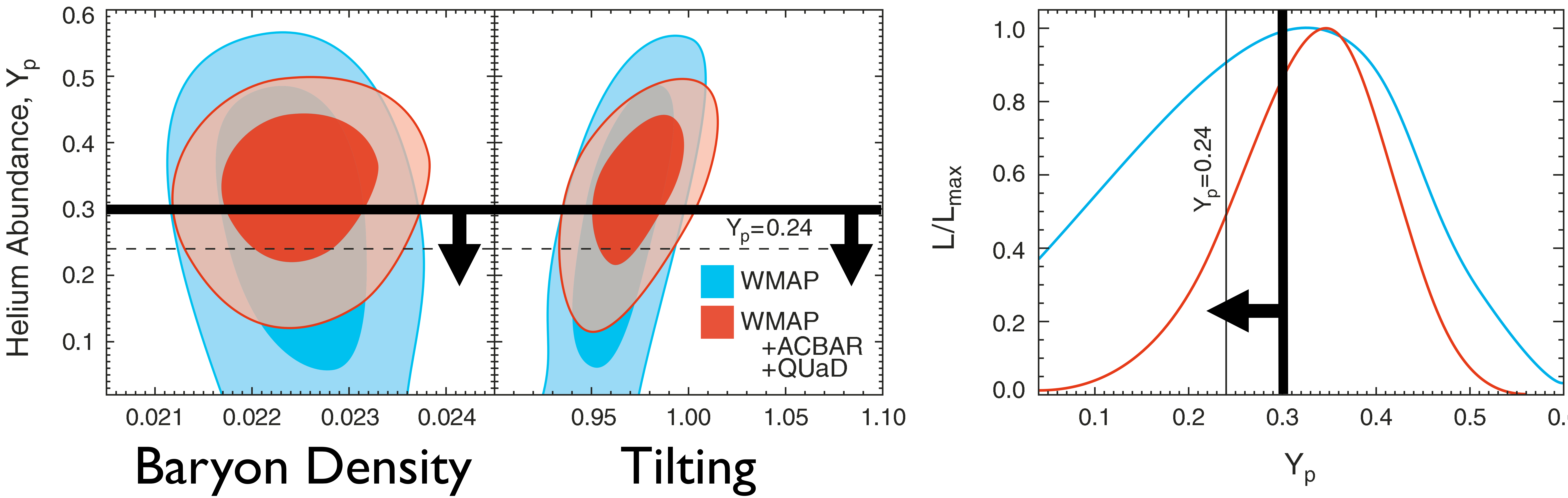


- The combination of WMAP and high-l CMB data (ACBAR and QUaD) is powerful enough to isolate the effect of helium: **$Y_p = 0.33 \pm 0.08$** (68%CL)

Why this can be useful

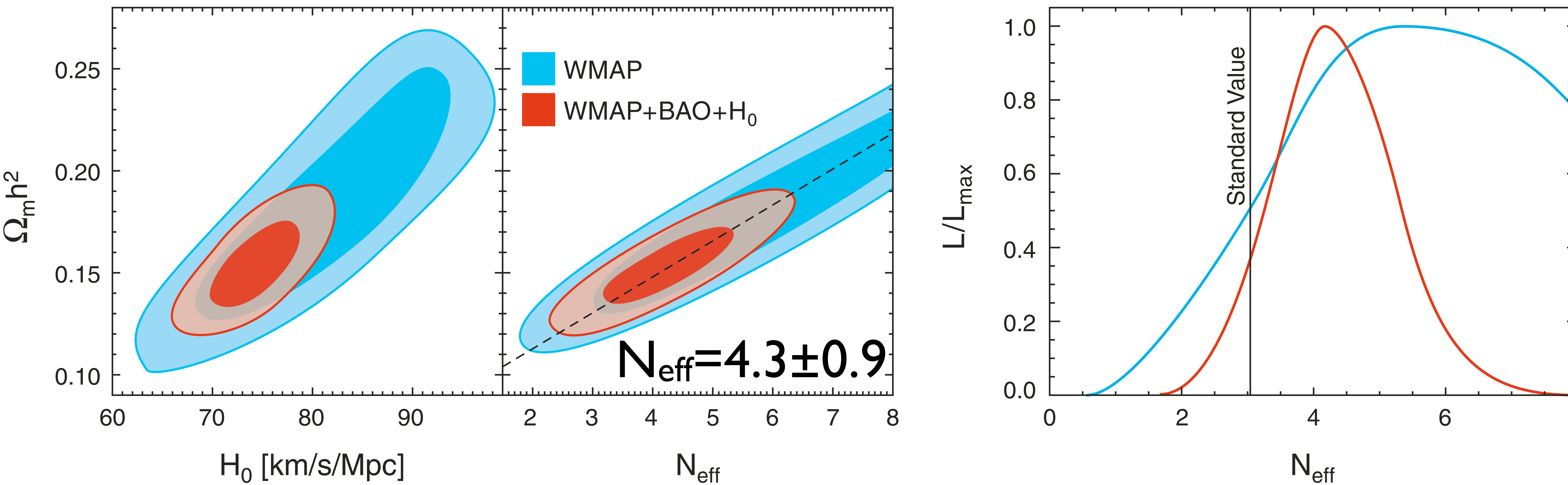
- The helium abundance has been measured from Sun and ionized regions (HII regions); however, as helium can be produced in the stellar core, one has to extrapolate the measured Y_P to the zero-metallicity values.
- In other words, the traditional methods give a robust **upper limit** on Y_P: $Y_P<0.3$.
- The CMB data give us a robust **lower limit** on Y_P.

$0.23<Y_p<0.3$ (68%CL)



- Planck is expected to yield ΔY_p~0.01 (68%CL; Ichikawa et al. 2008).

Another "3rd peak science": Number of Relativistic Species

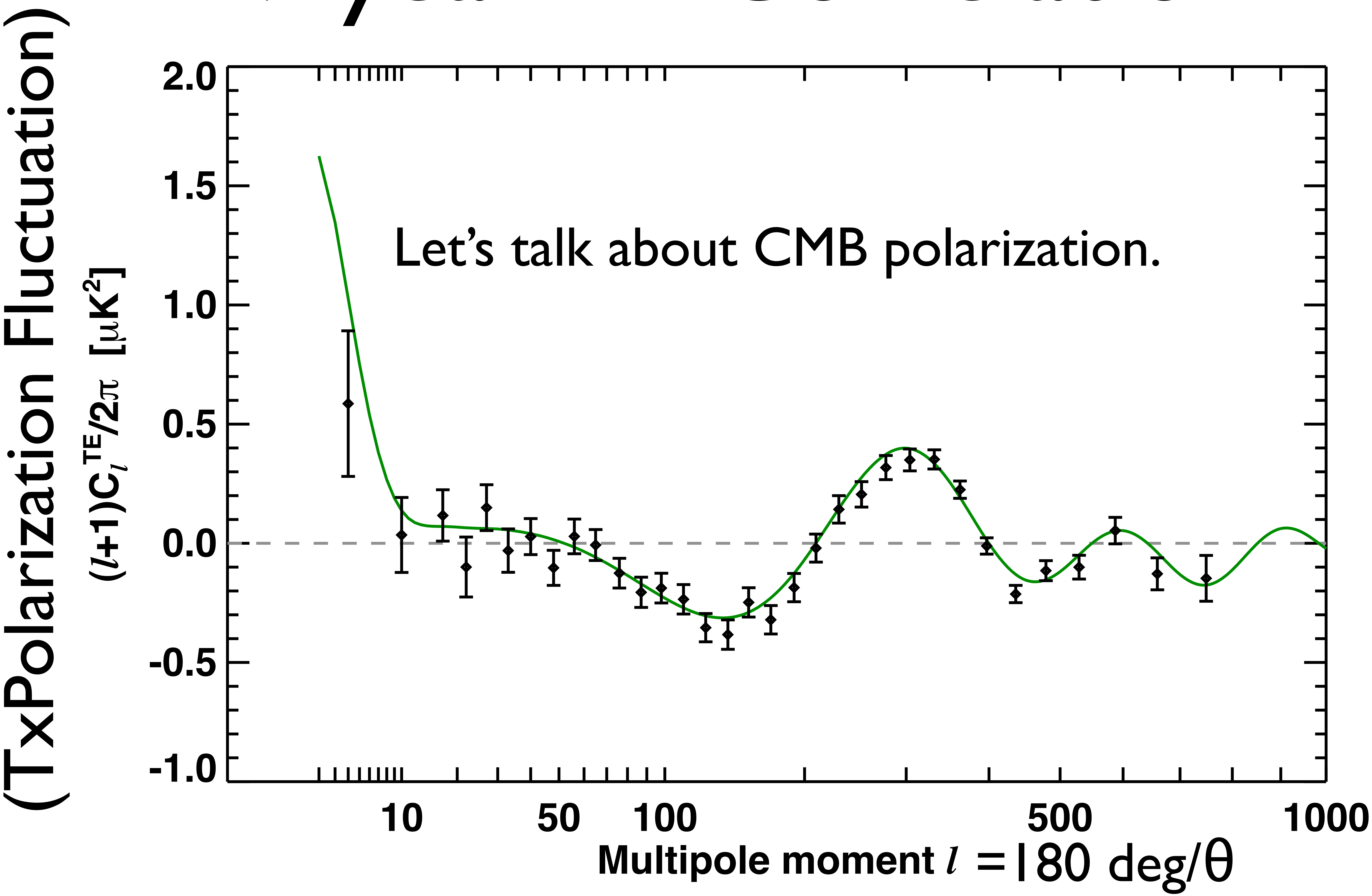


from external data

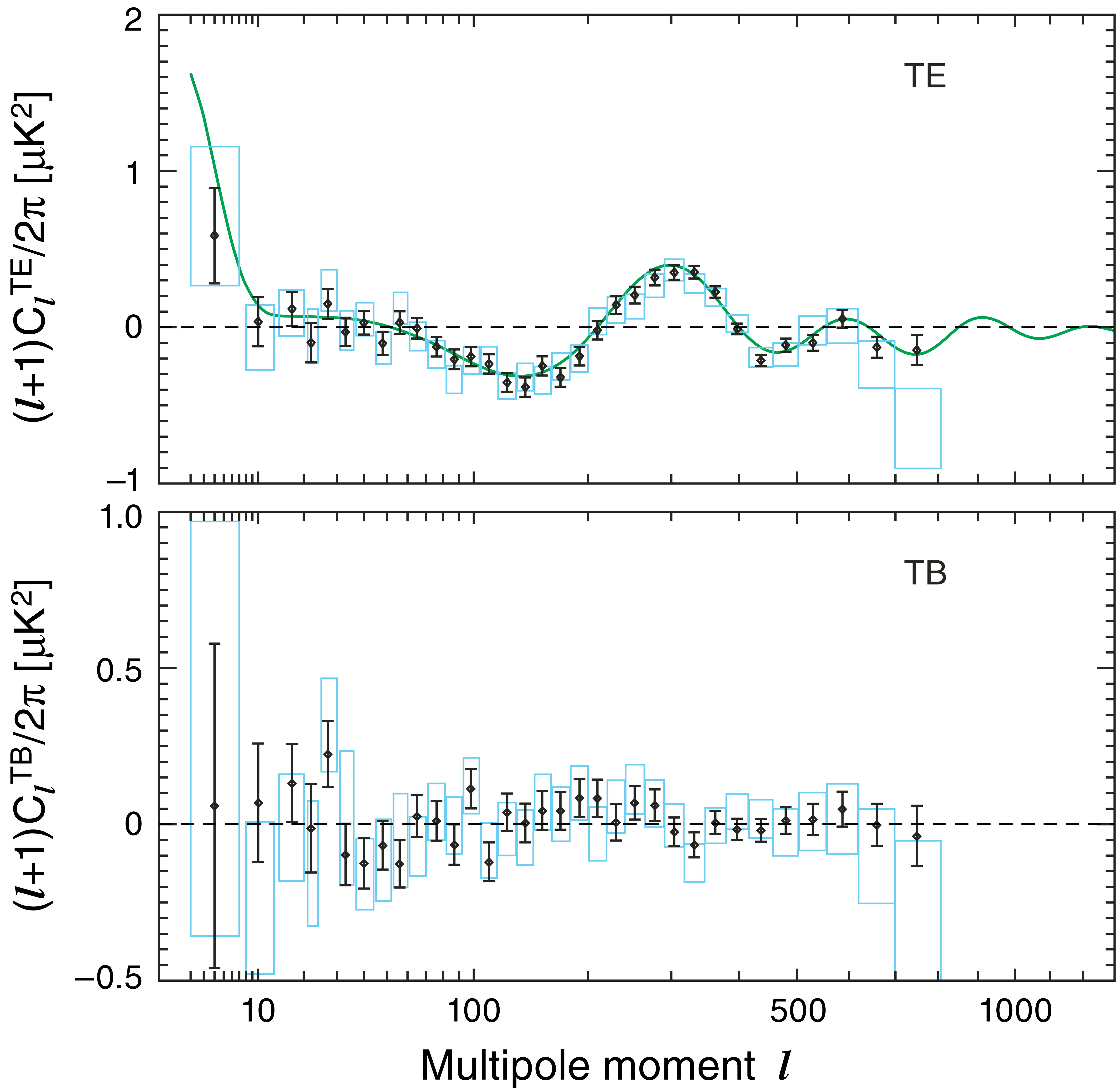
$$N_{\mathrm{eff}} = 3.04 + 7.44\left(\frac{\Omega_m h^2}{0.1308}\frac{3139}{1+z_{\mathrm{eq}}} - 1\right)$$

from 3rd peak

7-year TE Correlation

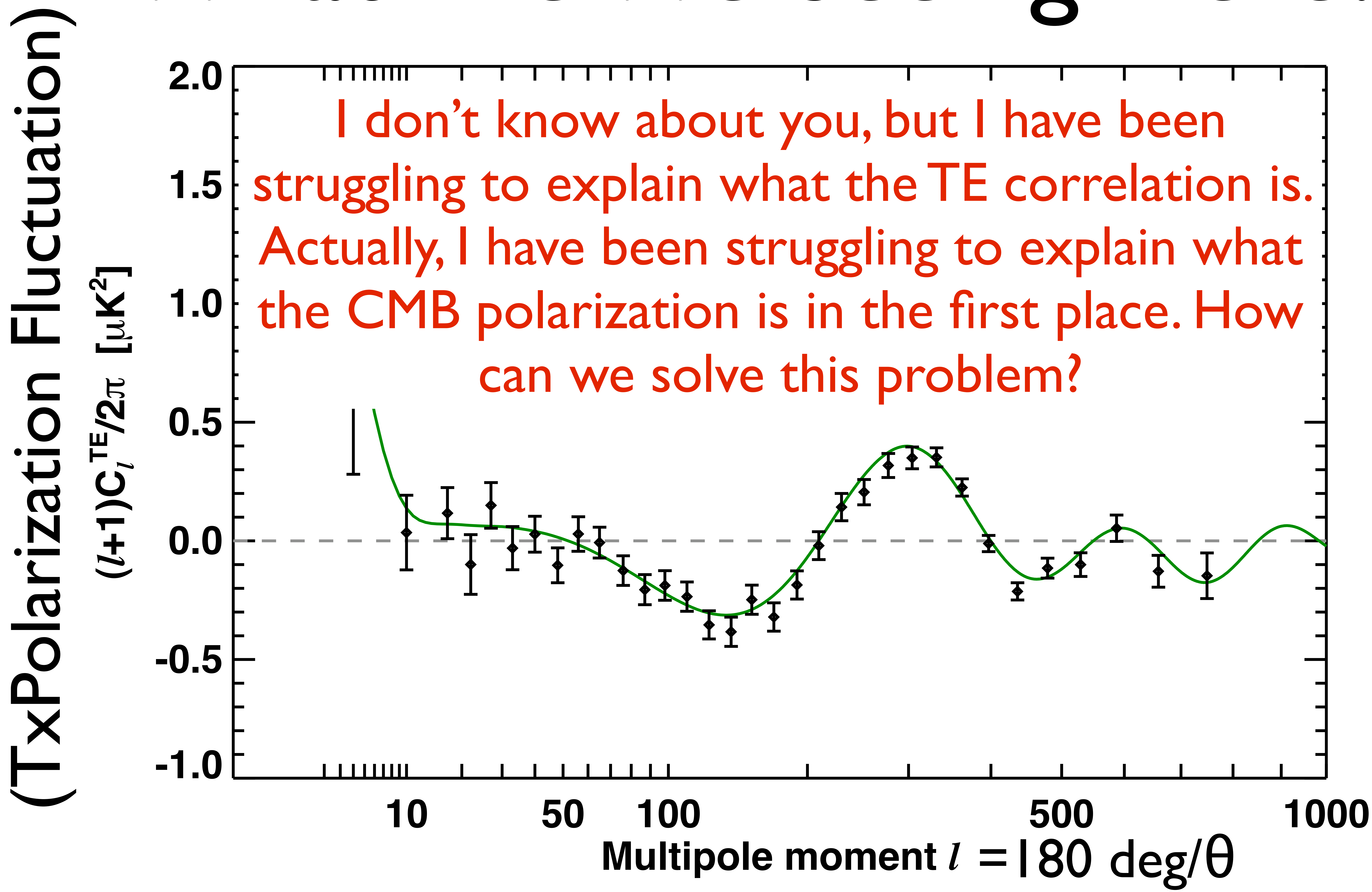


Improvements from 5-year



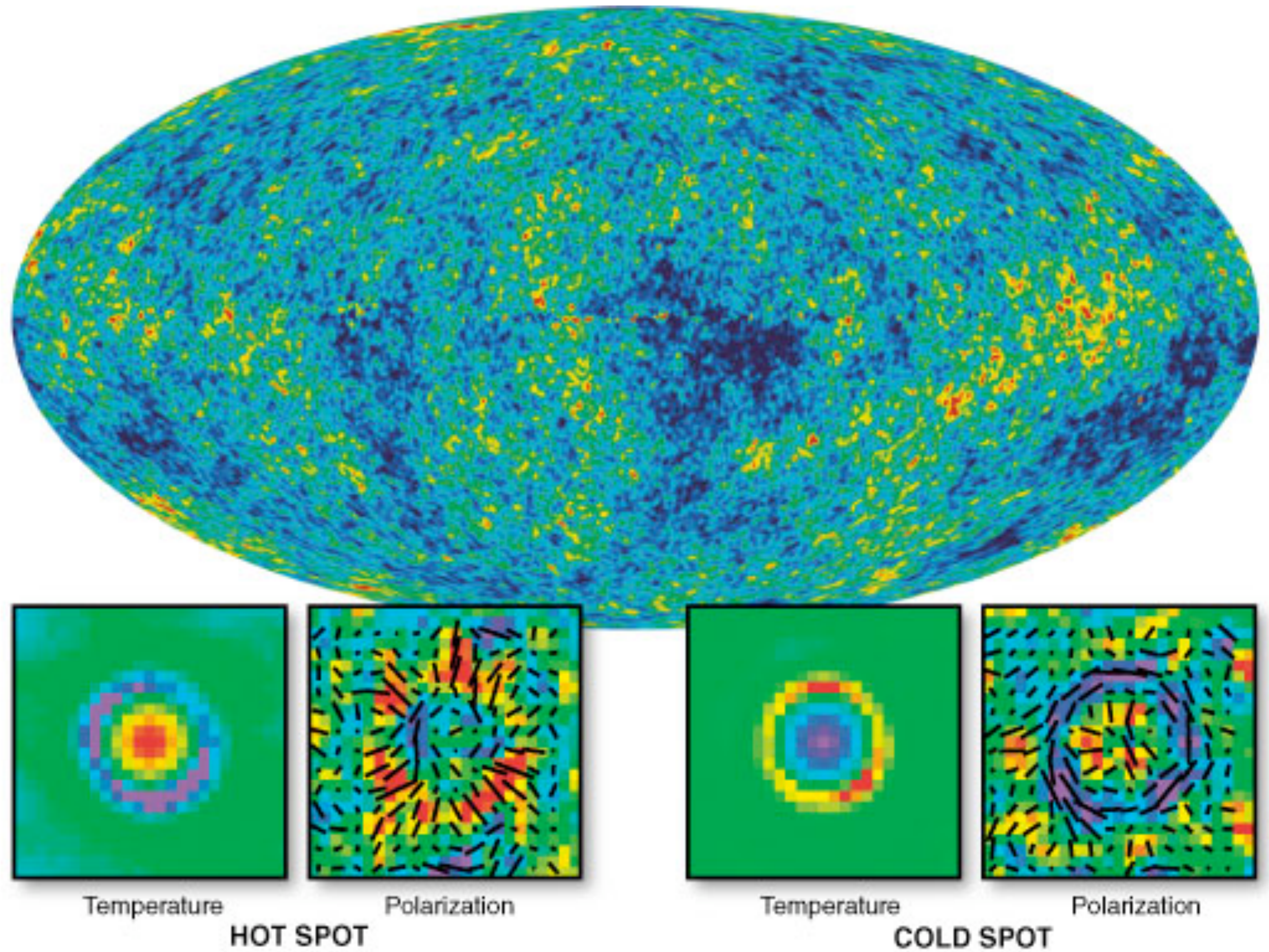
- For 5-year, we used Q and V bands to measure the high-l TE and TB. For 7-year, we also include the W-band data.
- **TE: 21σ detection!** (It was 13σ in 5 year.)
- TB is expected to vanish in a parity-conserving universe, and it is consistent with zero.

What Are We Seeing Here?



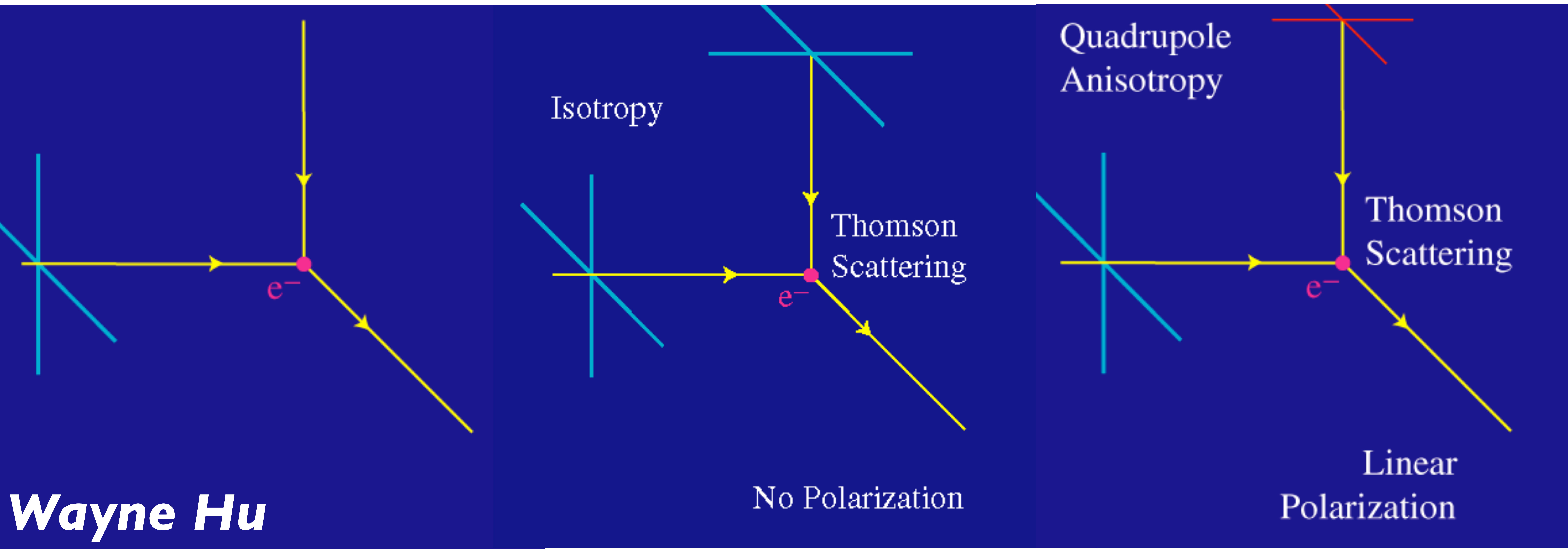
I don't know about you, but I have been struggling to explain what the TE correlation is. Actually, I have been struggling to explain what the CMB polarization is in the first place. How can we solve this problem?

CMB Polarization On the Sky



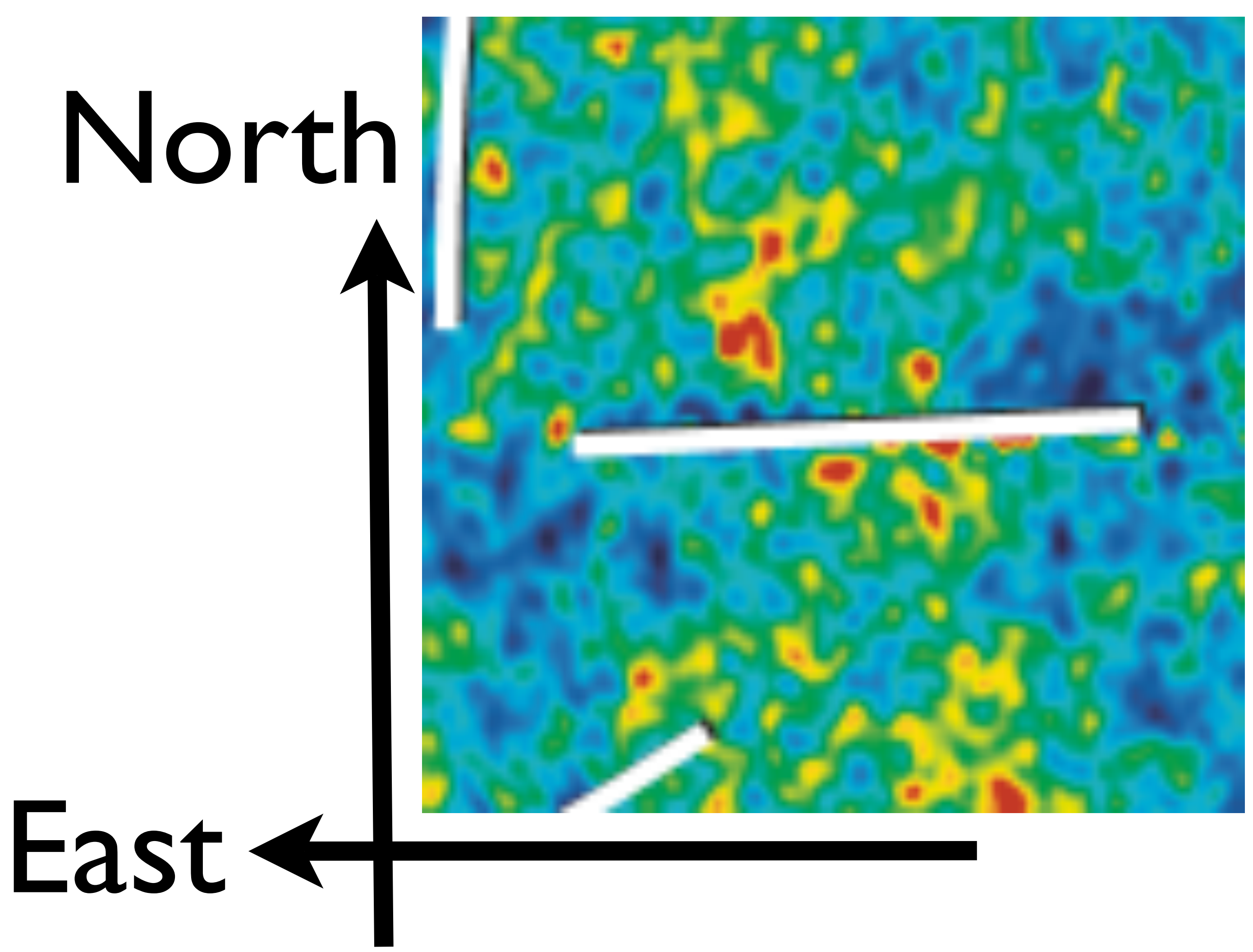
- *Solution*: Leave Fourier space.
  Go back to real space.

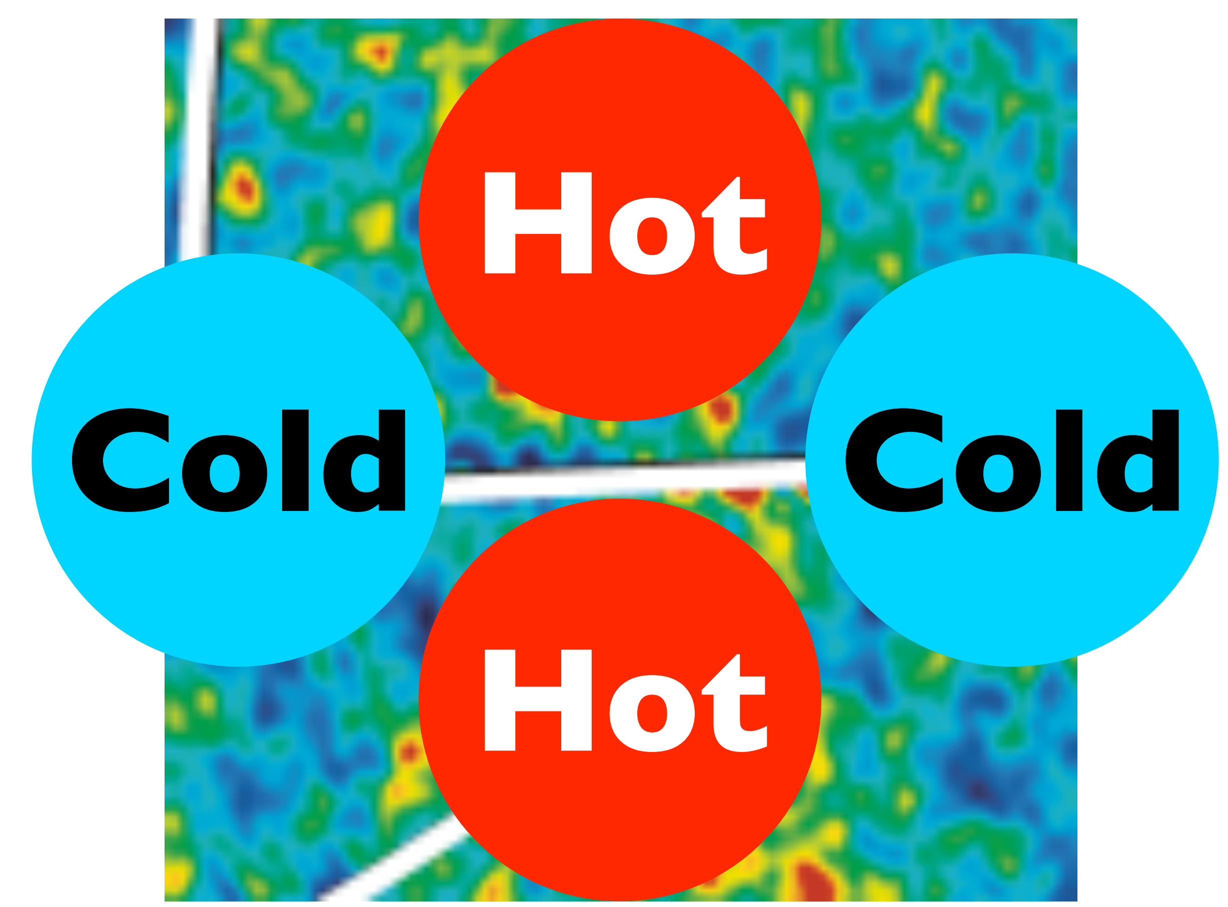
CMB Polarization is a Real-space Stuff



- CMB Polarization is created by a local temperature **quadrupole** anisotropy.

Principle



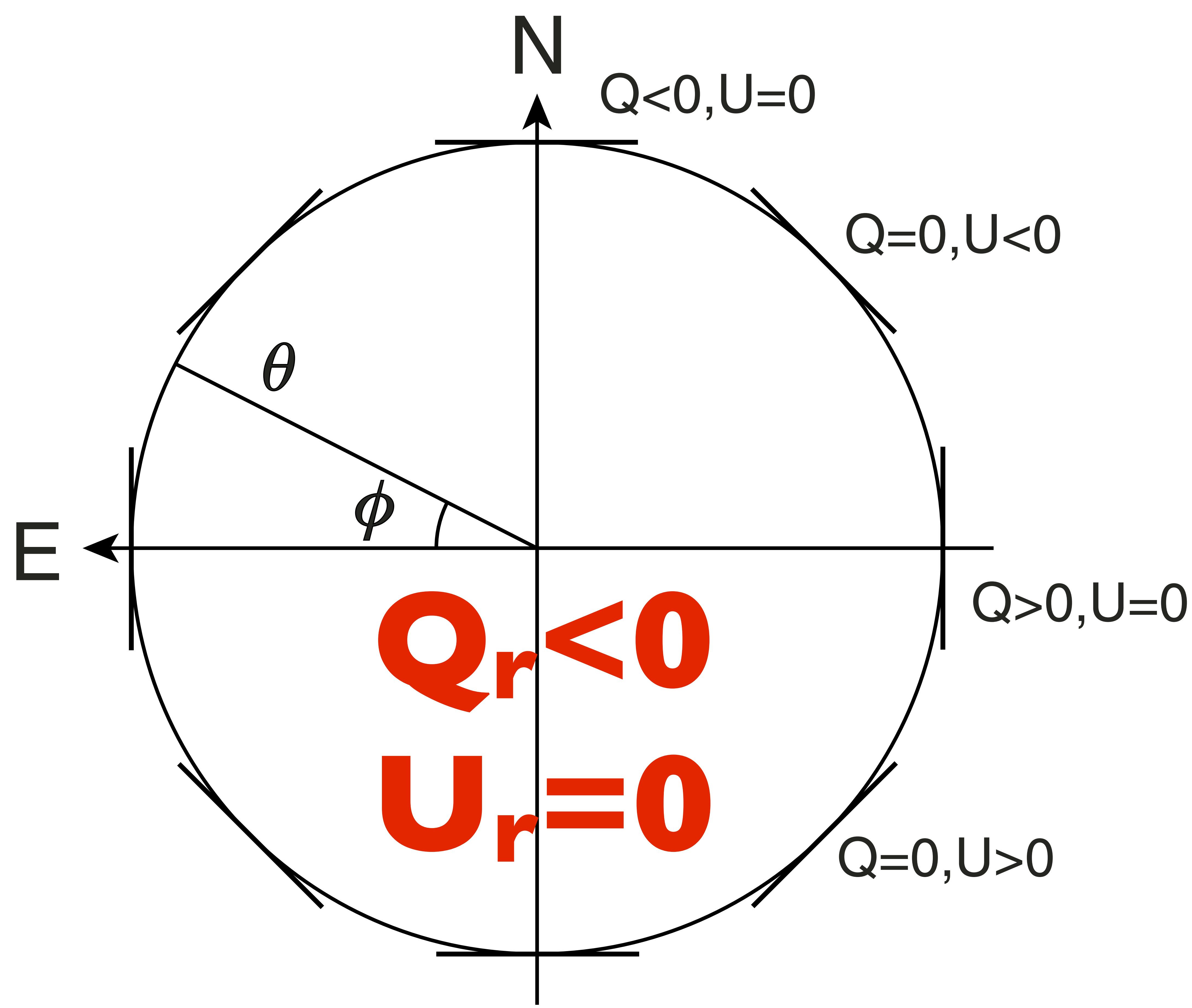


$Q<0$; $U=0$

- **Polarization direction is parallel to “hot.”**
- This is the so-called “E-mode” polarization.

Kamionkowski, Kosowsky and Stebbins (1997)

Stokes Q and U (and KKS's Q_r and U_r)



- As (E-mode) polarization is either radial or tangential around temperature spots, it is convenient to define Q_r and U_r as:

$$Q_r(\boldsymbol{\theta}) = -Q(\boldsymbol{\theta})\cos(2\phi) - U(\boldsymbol{\theta})\sin(2\phi),$$
$$U_r(\boldsymbol{\theta}) = Q(\boldsymbol{\theta})\sin(2\phi) - U(\boldsymbol{\theta})\cos(2\phi).$$

CMB Polarization on Large Angular Scales (>2 deg)

Matter Density

Potential

$\Delta T/T$ = (Newton's Gravitation Potential)/3

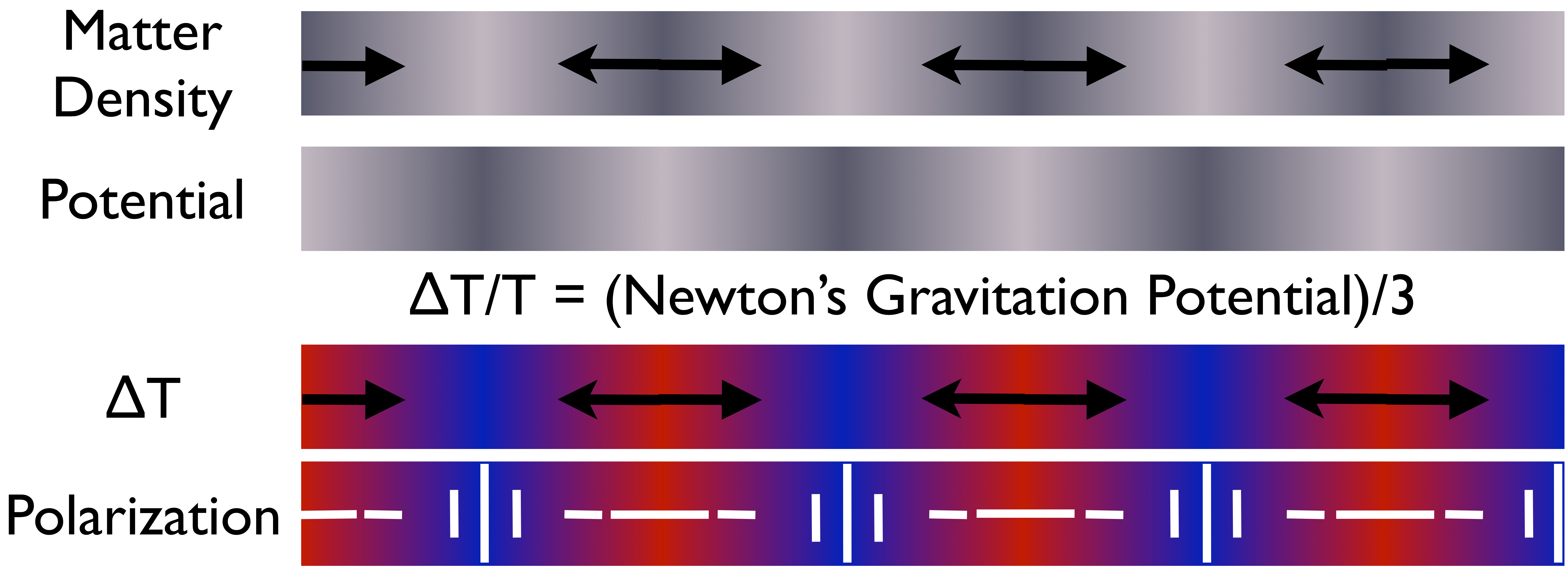
ΔT

Polarization

- How does the photon-baryon plasma move?

CMB Polarization Tells Us How Plasma Moves at z=1090

Zaldarriaga & Harari (1995)



- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern

Quadrupole From Velocity Gradient (Large Scale)

ΔT — Sachs-Wolfe: $\Delta T/T = \Phi/3$

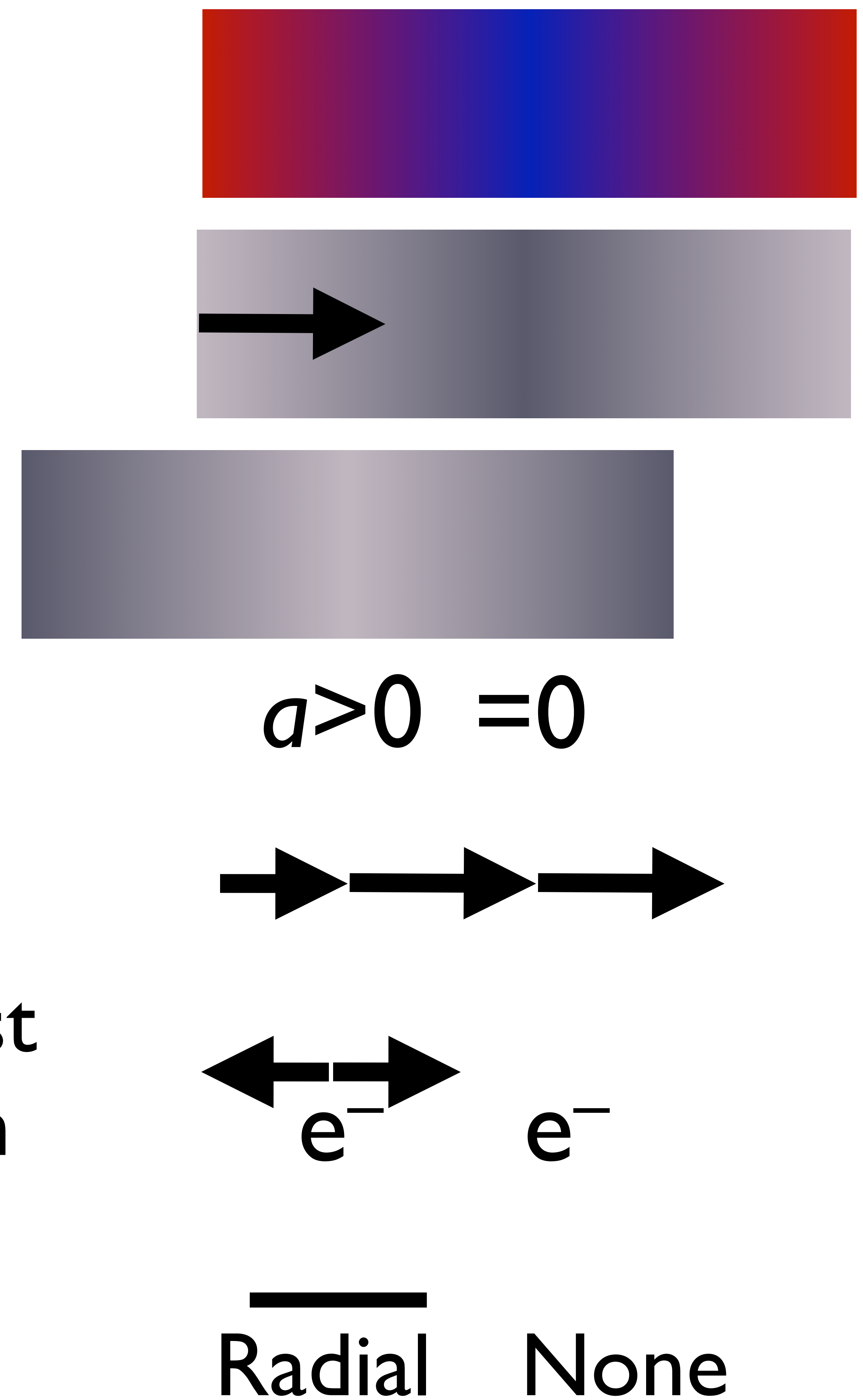
Potential Φ — Stuff flowing *in*

Acceleration $a = -\partial\Phi$

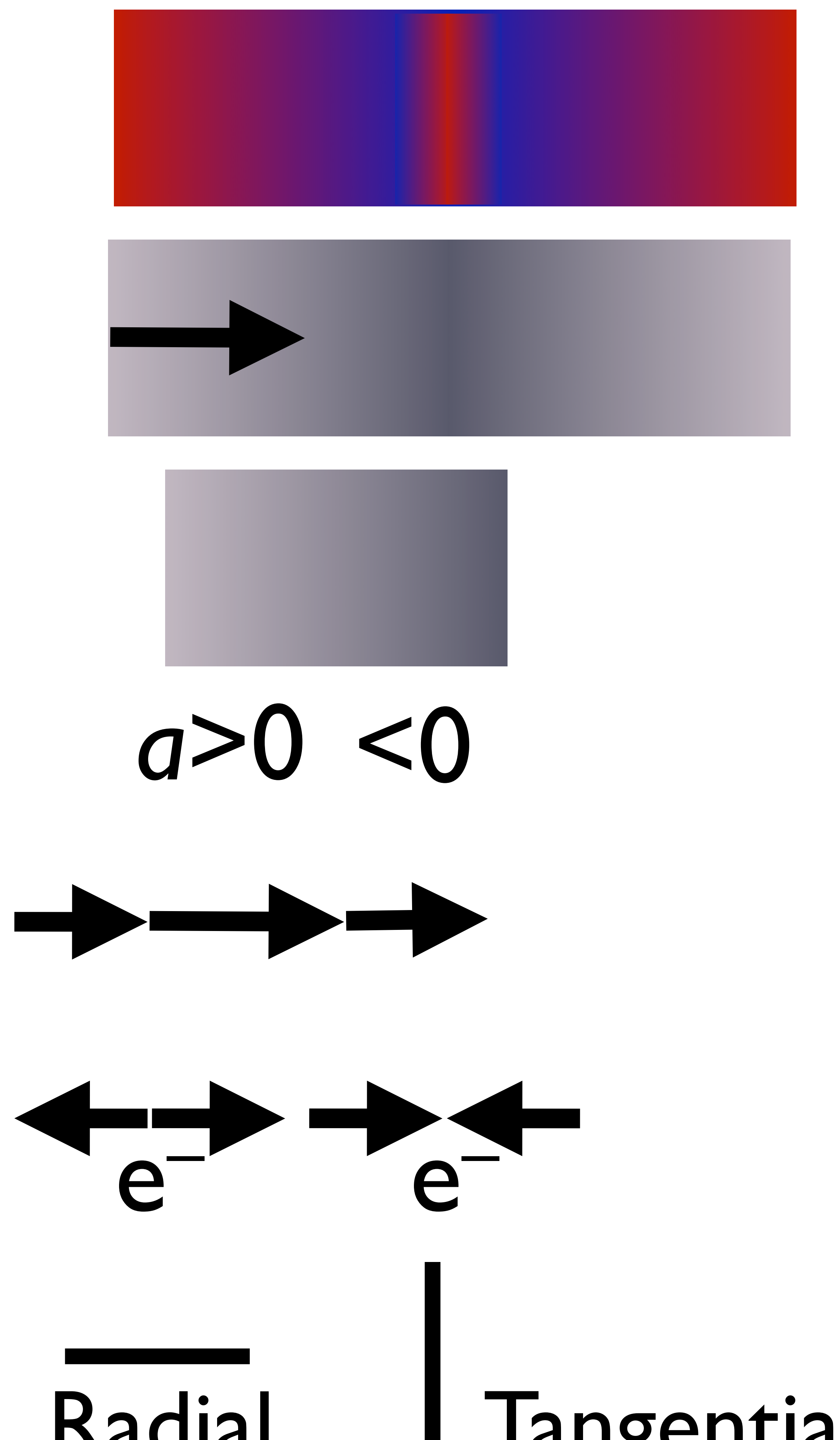
Velocity — Velocity gradient

Velocity in the rest frame of electron — The left electron sees colder photons along the plane wave

Polarization

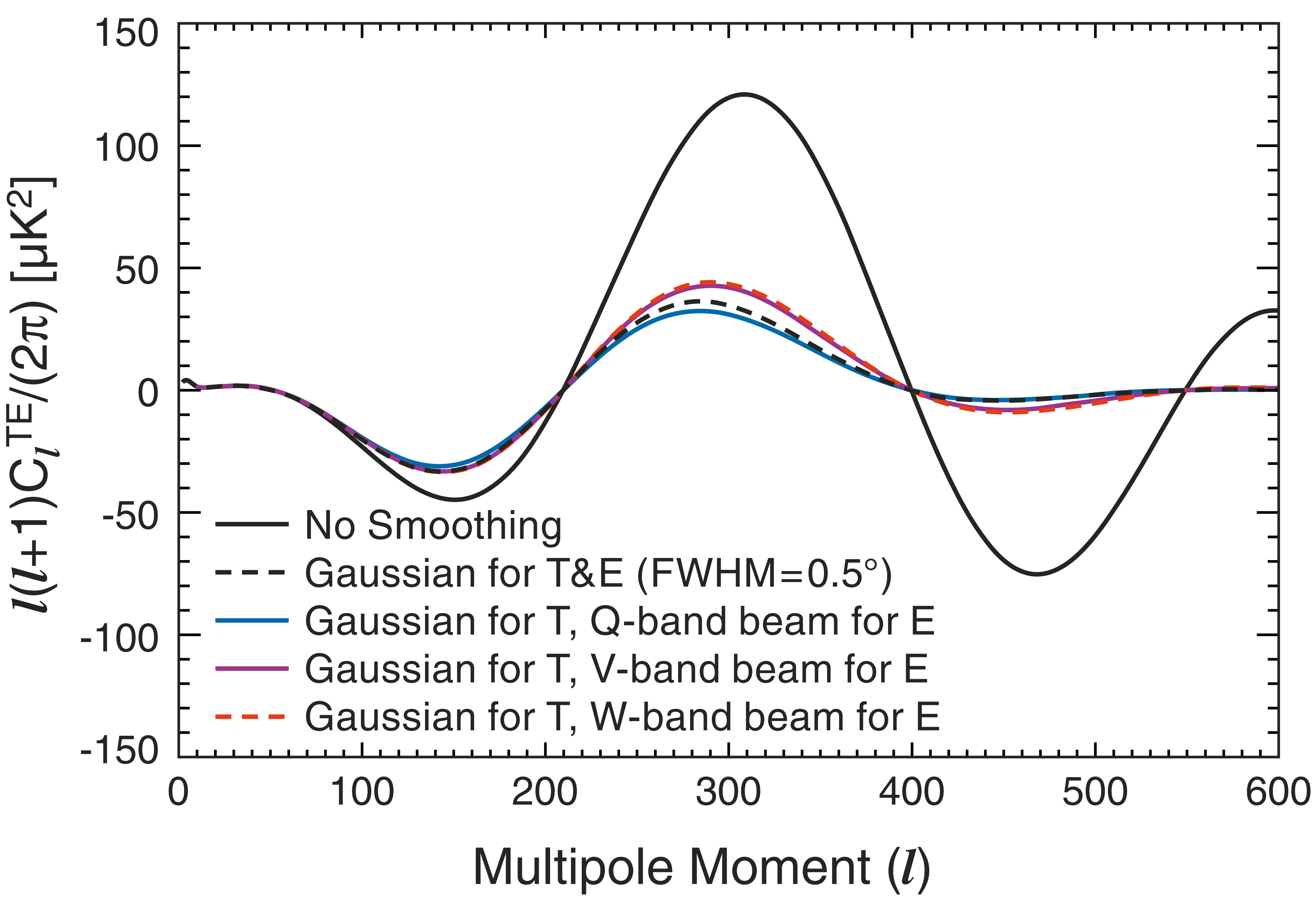


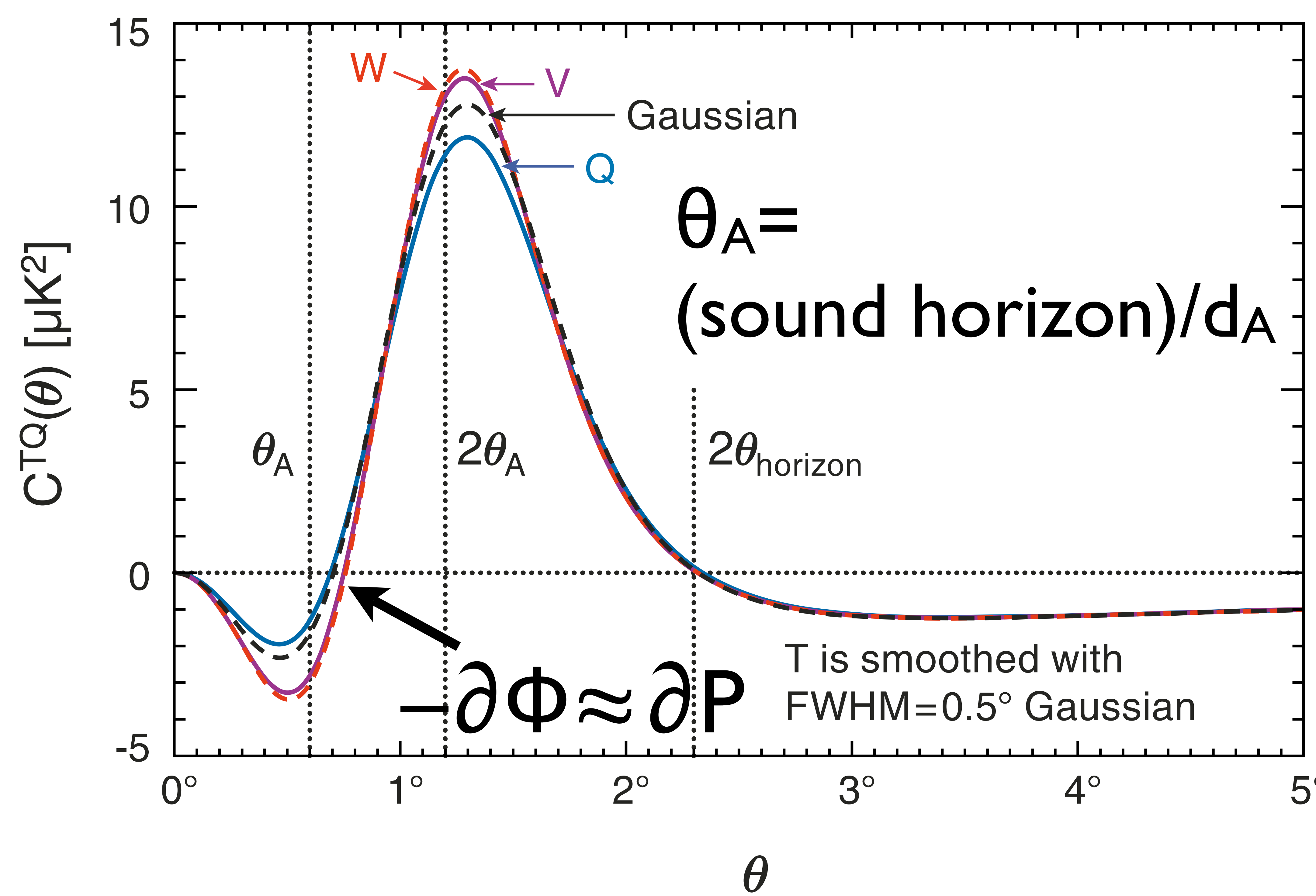
Quadrupole From Velocity Gradient (Small Scale)



ΔT		Compression increases temperature
Potential Φ		Stuff flowing *in*
Acceleration $a = -\partial\Phi - \partial P$	$a>0$ <0	Pressure gradient slows down the flow
Velocity		Velocity gradient
Velocity in the rest frame of electron		
Polarization	Radial / Tangential	

Hence, TE Correlation (Coulson et al. 1994)



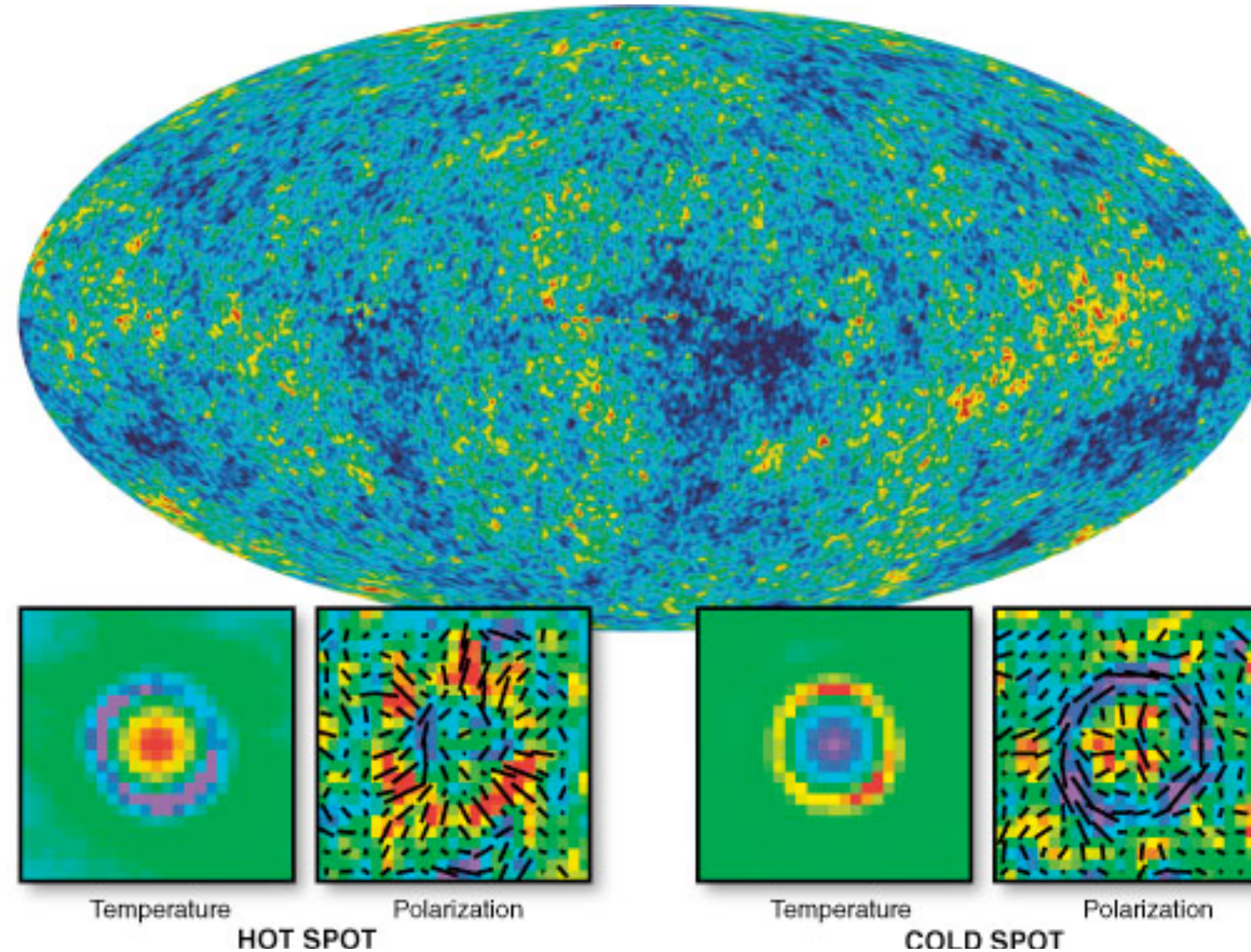


- $C^{TQr}(\theta) = -\int d\ln l\ [l^2 C_l^{TE}/(2\pi)]\ J_2(l\theta)$

Peak Theory and Stacking Analysis

- Stack polarization images around temperature hot and cold spots.

- Outside of the Galaxy mask (not shown), there are **12387 hot spots** and **12628 cold spots**.



- Peak theory gives:

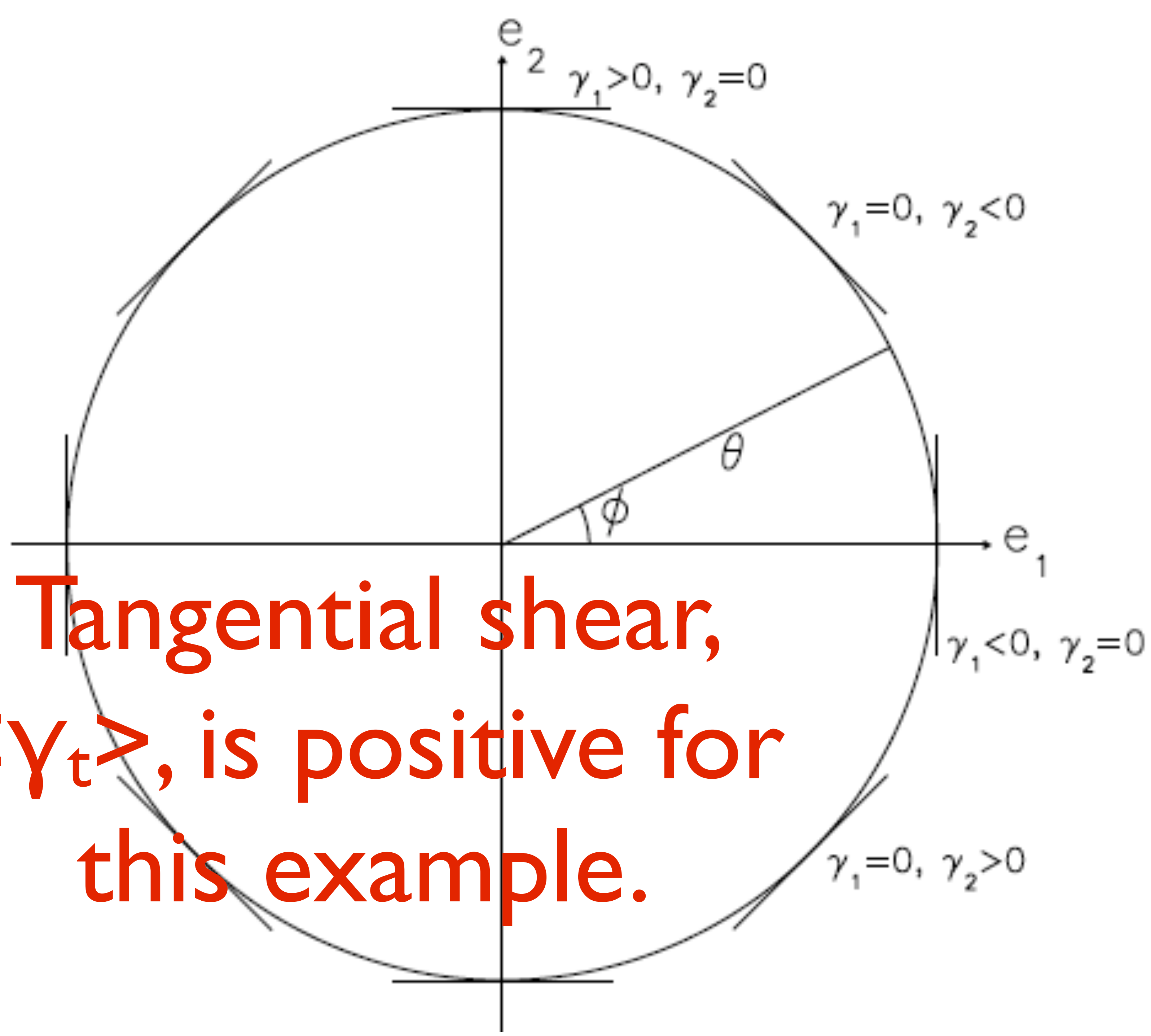
  [Note the l^2 term! (Desjacques 2008)]

$$\langle Q_r\rangle(\theta) = -\int \frac{l\,dl}{2\pi} W_l^T W_l^P (\bar{b}_\nu + \bar{b}_\zeta l^2) C_l^{\mathrm{TE}} J_2(l\theta),$$

$$\langle U_r\rangle(\theta) = -\int \frac{l\,dl}{2\pi} W_l^T W_l^P (\bar{b}_\nu + \bar{b}_\zeta l^2) C_l^{\mathrm{TB}} J_2(l\theta),$$

Analogy to Weak Lensing

- If you are familiar with weak lensing, this statistic is equivalent to the *tangential shear*: $\langle \overline{\gamma}_t^h \rangle (R, z_L) = \frac{\Delta\Sigma(R, z_L)}{\Sigma_c(z_L)}$



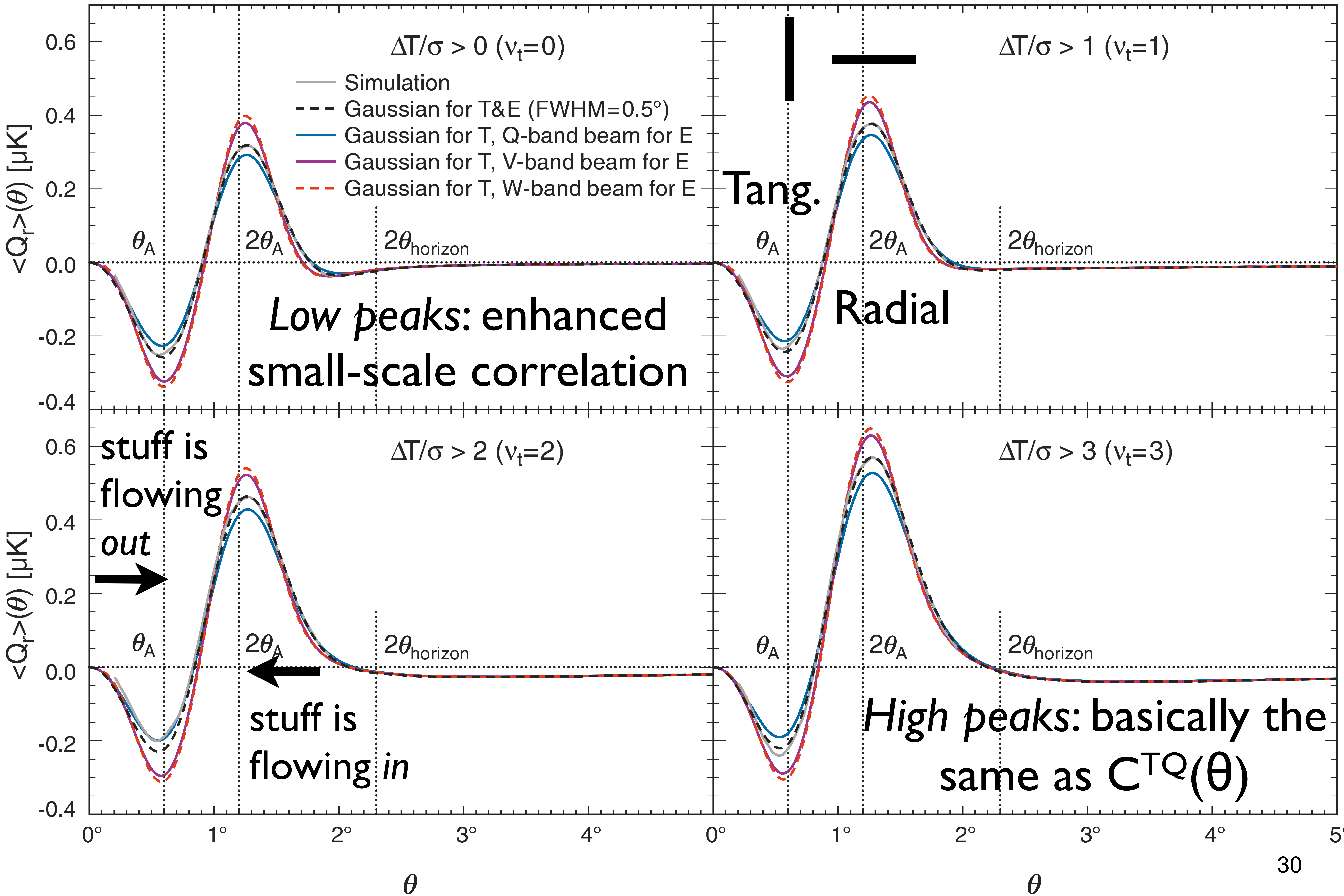
Tangential shear, $\langle \gamma_t \rangle$, is positive for this example.

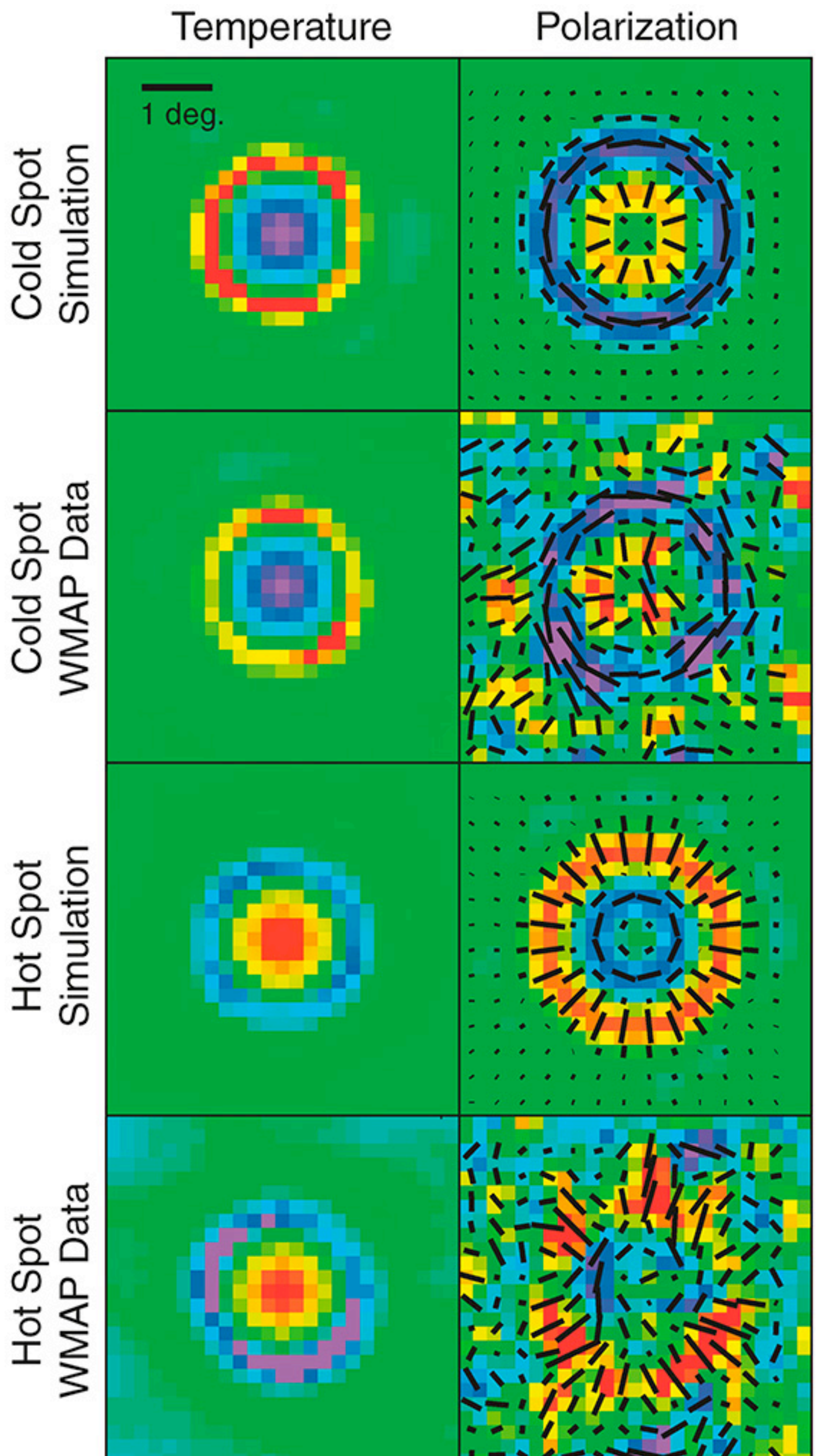
$$\Delta\Sigma(R, z_L) = \rho_0 b_1 \int \frac{k dk}{2\pi} P_m(k, z_L) J_2(kR)$$

However, all the formulae given in the literature use a scale-independent bias, b_1. This formula must be modified to include the k^2 term.

$$\gamma_t(\boldsymbol{\theta}) = -\gamma_1(\boldsymbol{\theta}) \cos(2\phi) - \gamma_2(\boldsymbol{\theta}) \sin(2\phi)$$

Temperature hot spots are stacked



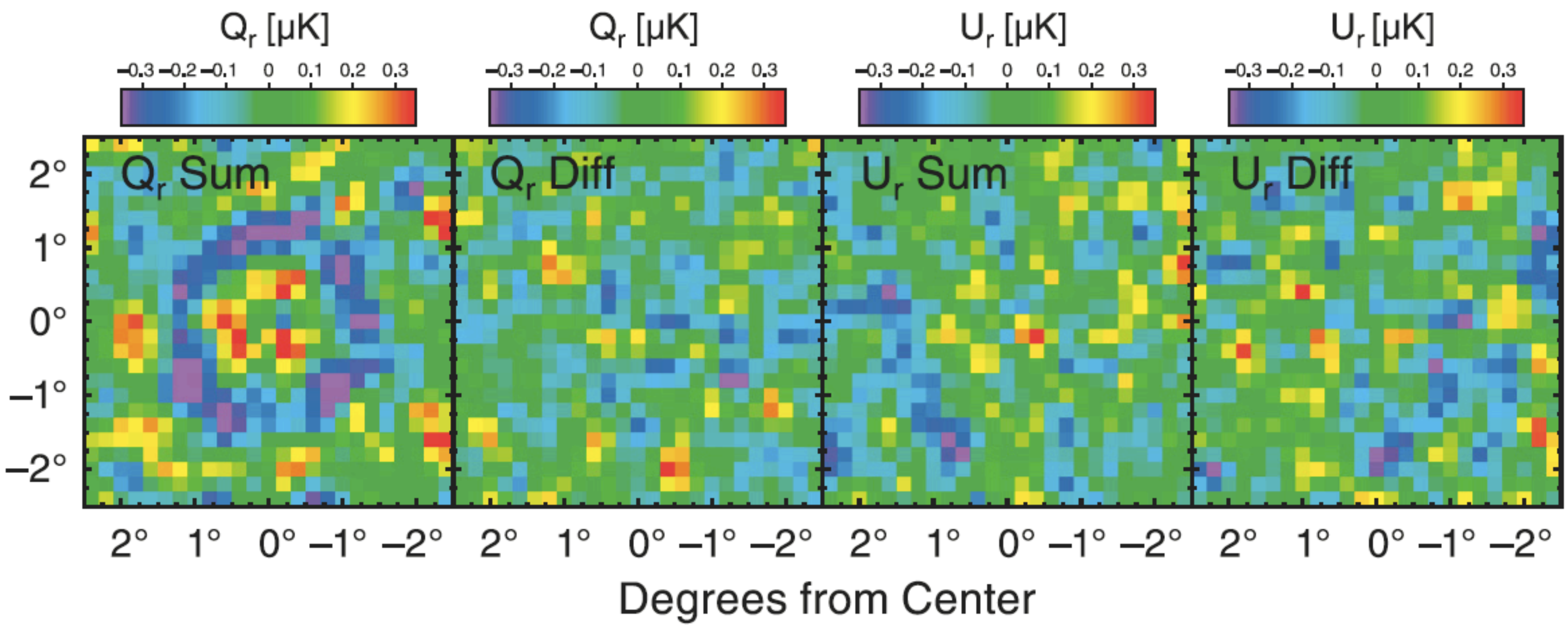


Two-dimensional View

- All hot and cold spots are stacked (the threshold peak height, $\Delta T/\sigma$, is zero)
- "Compression phase" at θ=1.2 deg and "reversal phase" at θ=0.6 deg are predicted to be there and we observe them!
  - The overall significance level: 8σ
- Striking confirmation of the physics of CMB and the dominance of **adiabatic** & **scalar** perturbation.

How About U_r?

- U_r is produced by the TB correlation, which is expected to vanish in a parity-conserving universe.



- The U_r map is consistent with noise.

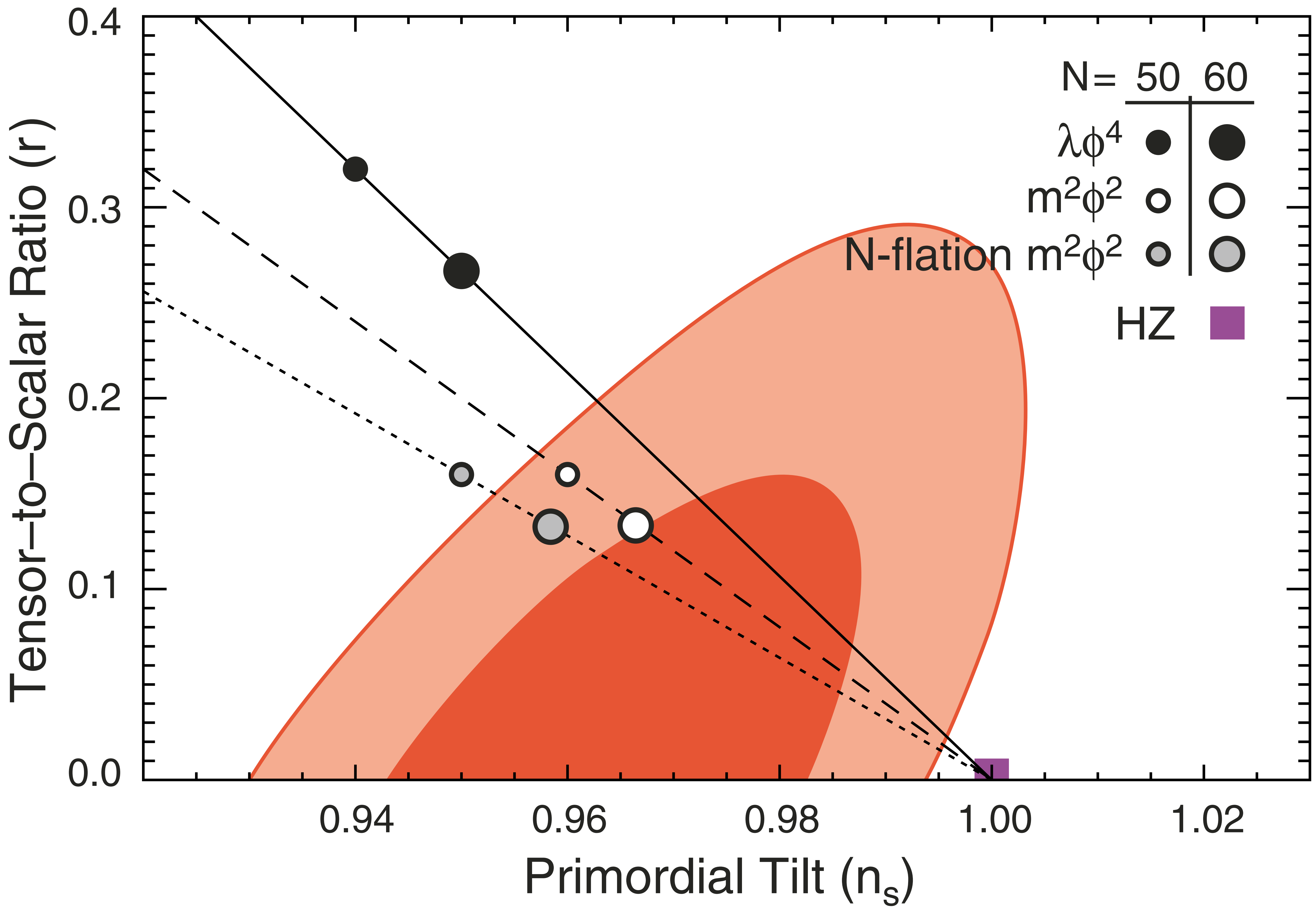
Probing Parity Violation

- Cosmological parity violation ("birefringence," Carroll 1998; Lue et al. 1999) may rotate the polarization plane by an angle $\Delta\alpha$, and convert E modes to B modes:

$$C_l^{\mathrm{TB,obs}} = C_l^{\mathrm{TE}} \sin(2\Delta\alpha)$$

- Non-detection of U_r gives $\Delta\alpha=1\pm3$ deg (68%CL)
- The full analysis using C_l^{TB} (as well as C_l^{EB}) gives
  - $\Delta\alpha = -1.1 \pm 1.3$(statistical) $\pm$ 1.5(systematic) deg.

Probing Inflation (Power Spectrum)



- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL; w/o SN)
  - $r < 0.20$ (95%CL; w/ SN)

Probing Inflation (Bispectrum)

- No detection of 3-point functions of primordial curvature perturbations. The 95% CL limits are:
  - $-10 < f_{NL}^{local} < 74$
  - $-214 < f_{NL}^{equilateral} < 266$
  - $-410 < f_{NL}^{orthogonal} < 6$
- The WMAP data are consistent with the prediction of **simple single-inflation inflation** models:
  - $1-n_s \approx r \approx f_{NL}^{local}$, $f_{NL}^{equilateral} = 0 = f_{NL}^{orthogonal}$.

If this means anything to you...

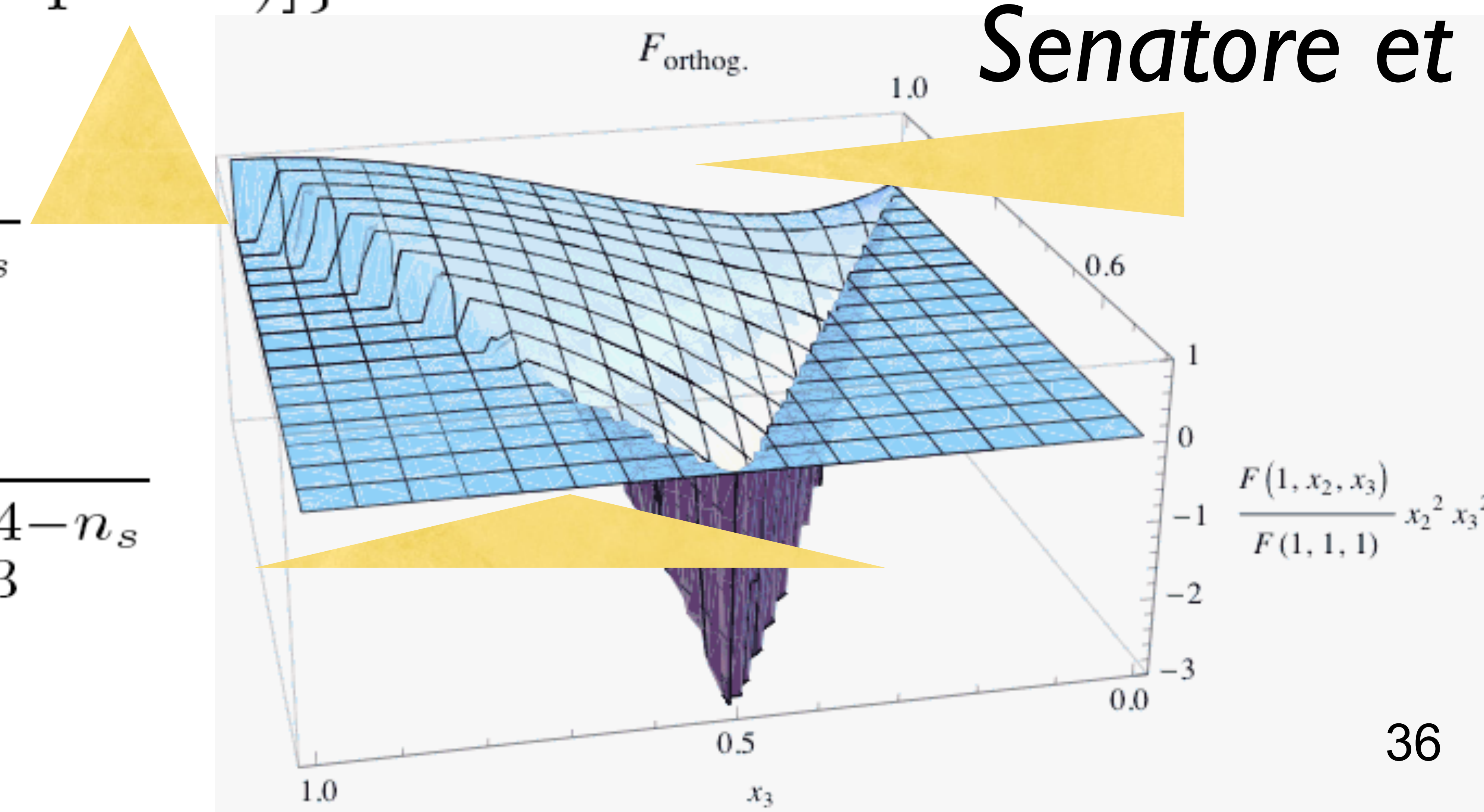
$$\langle \Phi_{\mathbf{k}_1} \Phi_{\mathbf{k}_2} \Phi_{\mathbf{k}_3} \rangle = (2\pi)^3 \delta^D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) F(k_1, k_2, k_3)$$

$$F_{\rm local}(k_1, k_2, k_3) = 2 f_{NL}^{\rm local} [P_\Phi(k_1) P_\Phi(k_2) + P_\Phi(k_2) P_\Phi(k_3) + P_\Phi(k_3) P_\Phi(k_1)] = 2 A f_{NL}^{\rm local} \left[\frac{1}{k_1^{4-n_s} k_2^{4-n_s}} + (2 \text{ perm.}) \right],$$

$$F_{\rm equil}(k_1, k_2, k_3) = 6 A f_{NL}^{\rm equil} \times \left\{ -\frac{1}{k_1^{4-n_s} k_2^{4-n_s}} - \frac{1}{k_2^{4-n_s} k_3^{4-n_s}} - \frac{1}{k_3^{4-n_s} k_1^{4-n_s}} - \frac{2}{(k_1 k_2 k_3)^{2(4-n_s)/3}} + \left[\frac{1}{k_1^{(4-n_s)/3} k_2^{2(4-n_s)/3} k_3^{4-n_s}} + (5 \text{ perm.}) \right] \right\}.$$

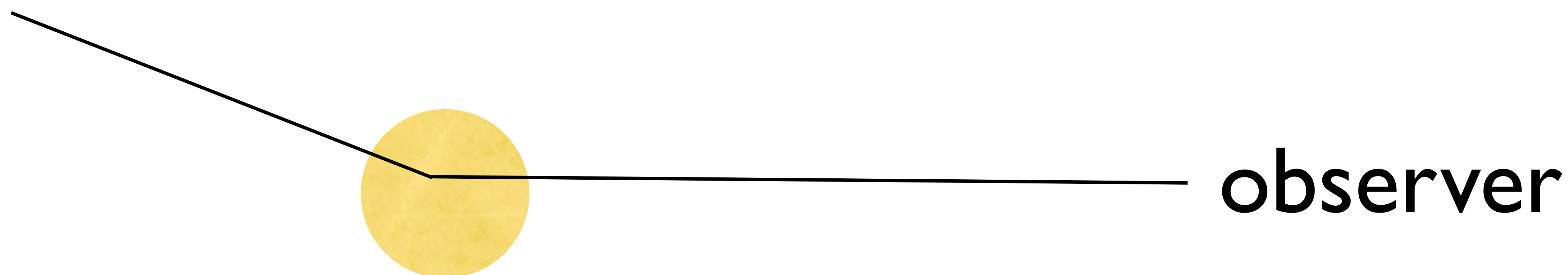
$$F_{\rm orthog}(k_1, k_2, k_3) = 6 A f_{NL}^{\rm orthog} \times \left\{ -\frac{3}{k_1^{4-n_s} k_2^{4-n_s}} - \frac{3}{k_2^{4-n_s} k_3^{4-n_s}} - \frac{3}{k_3^{4-n_s} k_1^{4-n_s}} - \frac{8}{(k_1 k_2 k_3)^{2(4-n_s)/3}} + \left[\frac{3}{k_1^{(4-n_s)/3} k_2^{2(4-n_s)/3} k_3^{4-n_s}} + (5 \text{ perm.}) \right] \right\}.$$

Senatore et al.



Zel'dovich & Sunyaev (1969); Sunyaev & Zel'dovich (1972)

Sunyaev–Zel'dovich Effect



Hot gas with the electron temperature of $T_e >> T_{cmb}$

- $\Delta T/T_{cmb} = g_\nu$ **y**

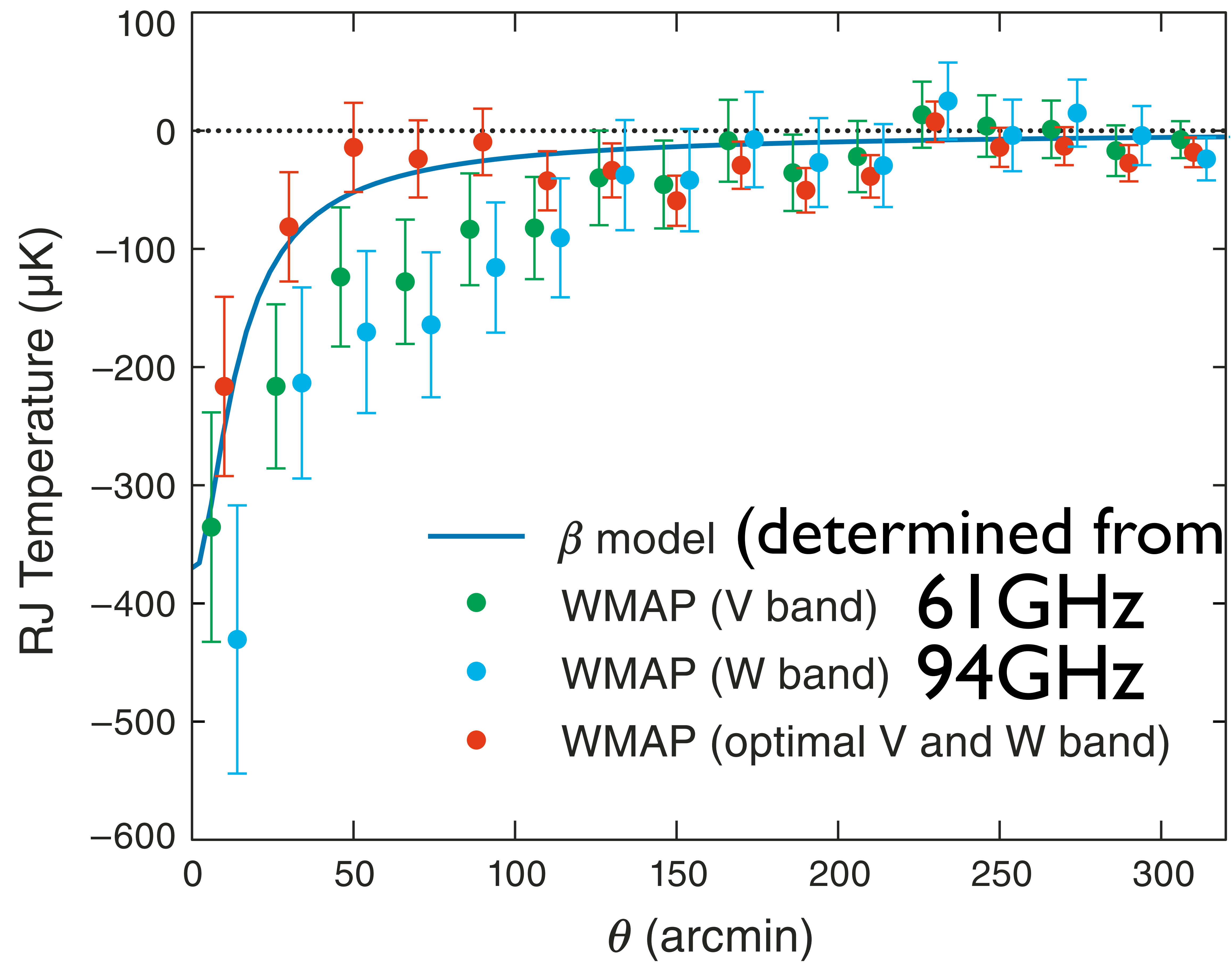
$$y = (\text{optical depth of gas})\, k_B T_e/(m_e c^2)$$
$$= [\sigma_T/(m_e c^2)] \int n_e k_B T_e \, d(\text{los})$$
$$= [\sigma_T/(m_e c^2)] \int (\text{electron pressure}) d(\text{los})$$

$g_\nu = -2$ ($\nu = 0$); -1.91, -1.81 and -1.56 at $\nu = 41$, 61 and 94 GHz

Coma Cluster (z=0.023)

We find that the CMB fluctuation in the direction of Coma is ≈ −100uK. (This is a new result!)

$y_{coma}(0)=(7\pm2)\times10^{-5}$ (68%CL)



(determined from X-ray)

61GHz $g_\nu=-1.81$

94GHz $g_\nu=-1.56$

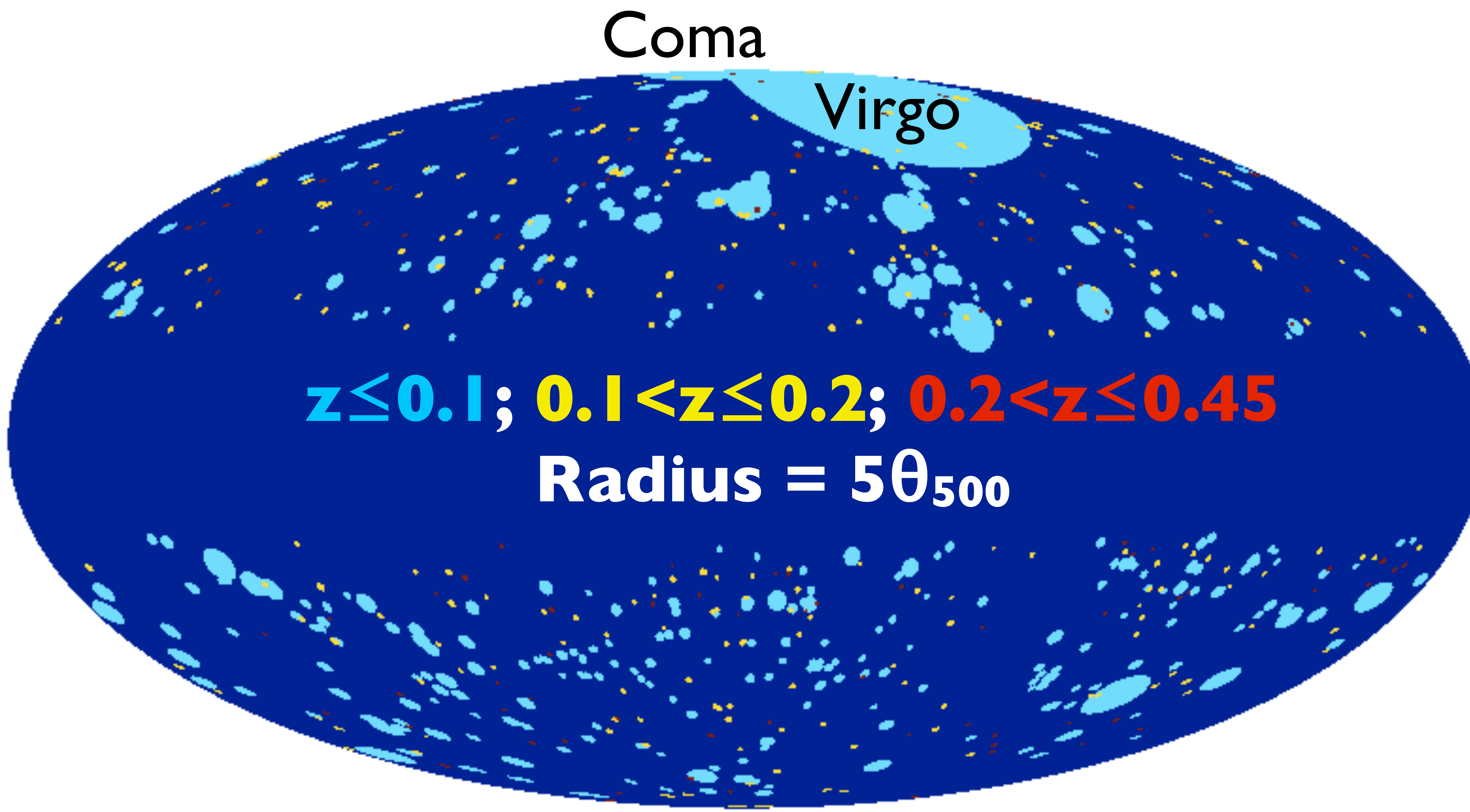
- "Optimal V and W band" analysis can separate SZ and CMB. The SZ effect toward Coma is detected at **3.6σ**.

Statistical Detection of SZ

- Coma is bright enough to be detected by WMAP.
- The other clusters are not bright enough to be detected individually by WMAP.
- By stacking the pixels at the locations of known clusters of galaxies (detected in X-ray), we detected the SZ effect at 8σ.
  - Many statistical detections reported in the literature:

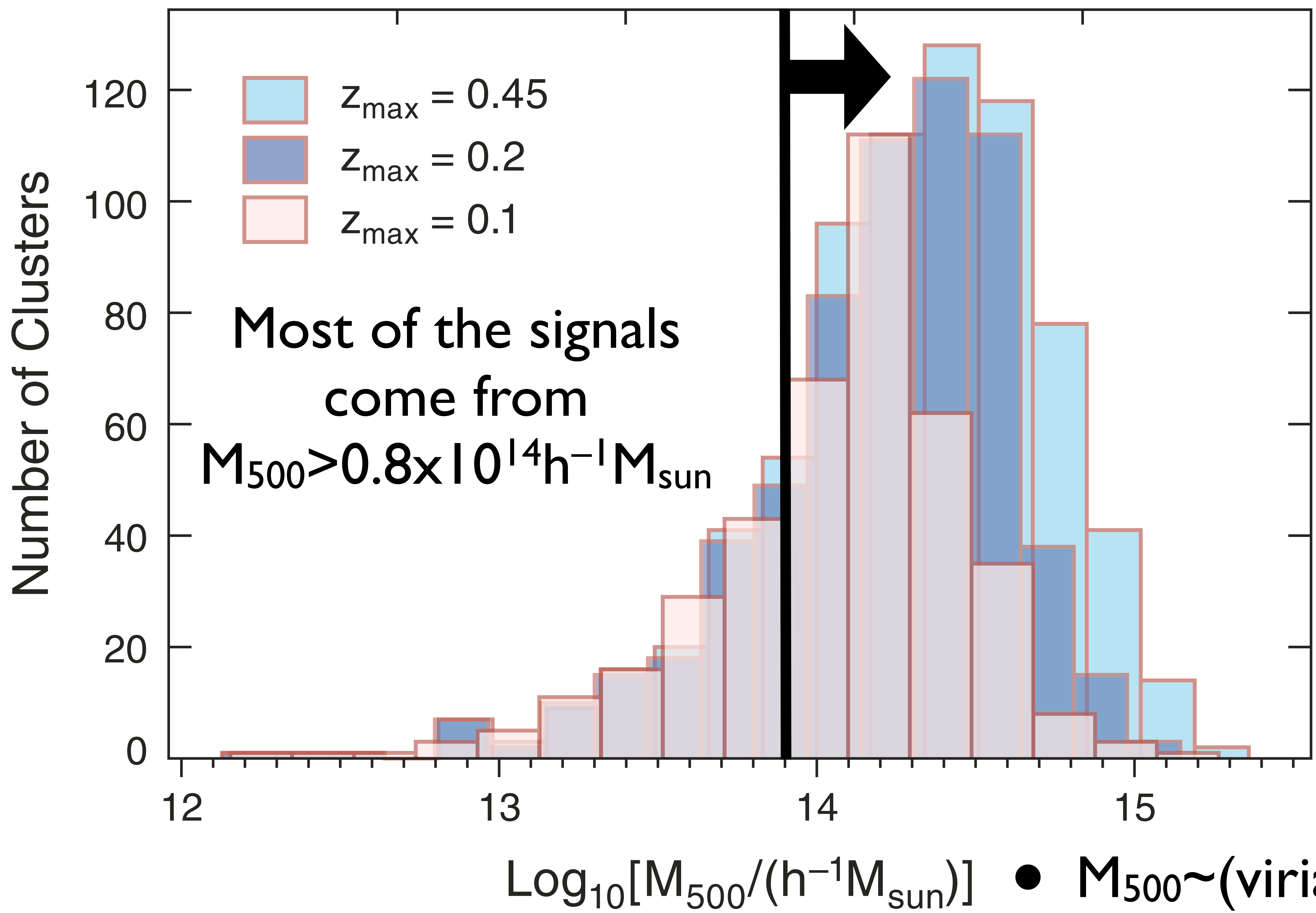
    (Fosalba et al. 2003; Hernández-Monteagudo & Rubiño-Martín 2004; Hernández-Monteagudo et al. 2004; Myers et al. 2004; Afshordi et al. 2005; Lieu et al. 2006; Bielby & Shanks 2007; Afshordi et al. 2007; Atrio-Barandela et al. 2008; Kashlinsky et al. 2008; Diego & Partridge 2009; Melin et al. 2010).

ROSAT Cluster Catalog

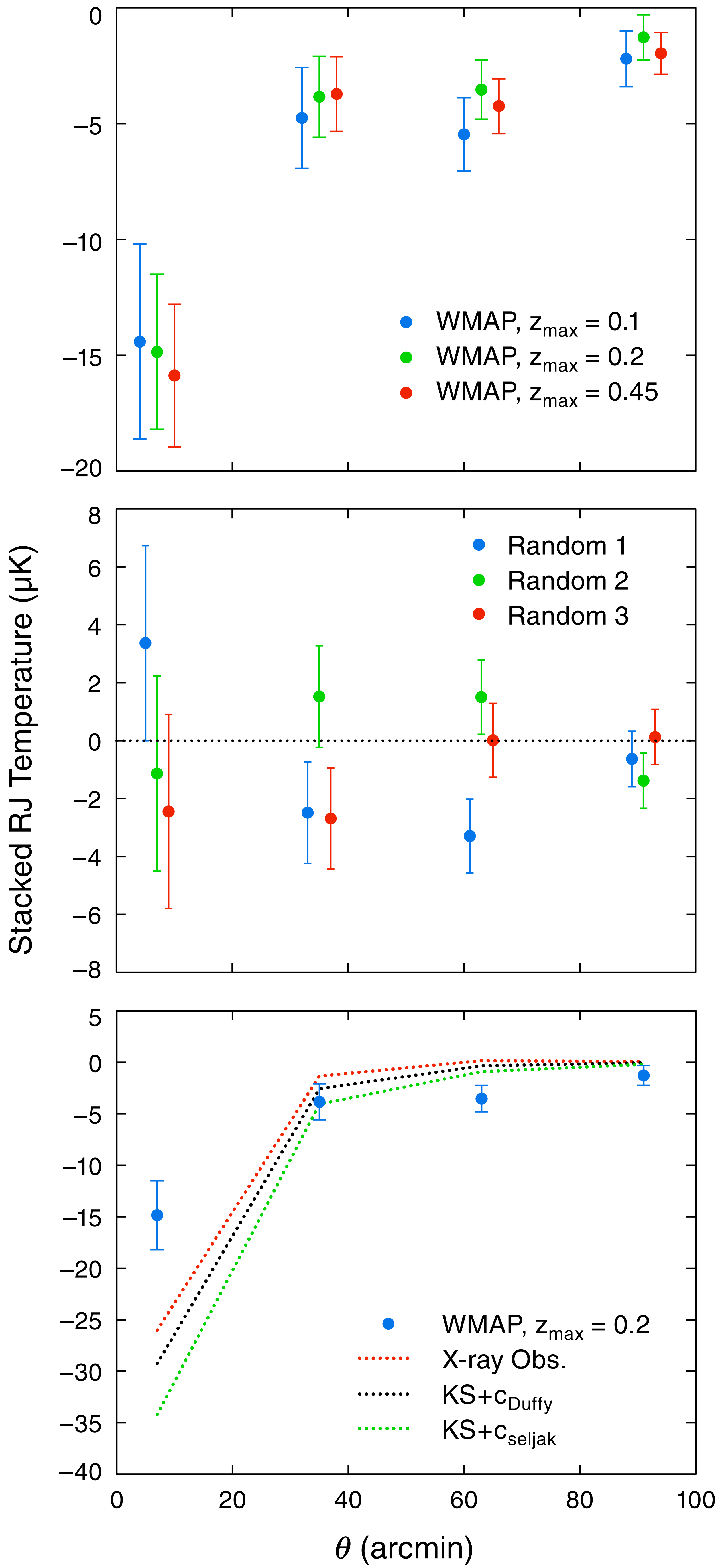


- 742 clusters in |b|>20 deg (before Galaxy mask)
- 400, 228 & 114 clusters in $z \leq 0.1$, $0.1 < z \leq 0.2$ & $0.2 < z \leq 0.45$.

Mass Distribution



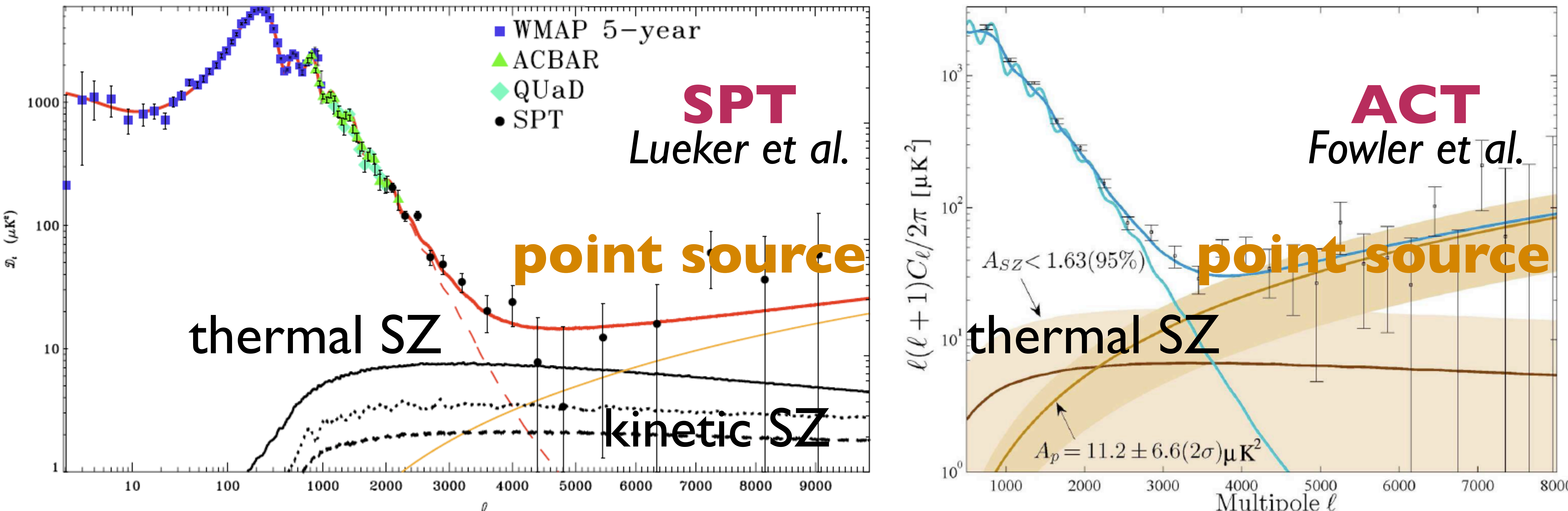
- M_{500}~(virial mass)/1.6



Angular Profiles

- (Top) Significant detection of the SZ effect.
- (Middle) Repeating the same analysis on the random locations on the sky does not reveal any noticeable bias.
- (Bottom) Comparison to the expectations. **The observed SZ ~ 0.5–0.7 times the expectations.** Why?

Small-scale CMB Data



- The SPT measured the secondary anisotropy from (possibly) SZ. **The power spectrum amplitude is A_{SZ}=0.4–0.6 times the expectations.** Why?

Lower A_{SZ}: Two Possibilities

$$C_l = g_\nu^2 \int_0^{z_{\rm max}} dz \frac{dV}{dz} \int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_l(M,z)|^2$$

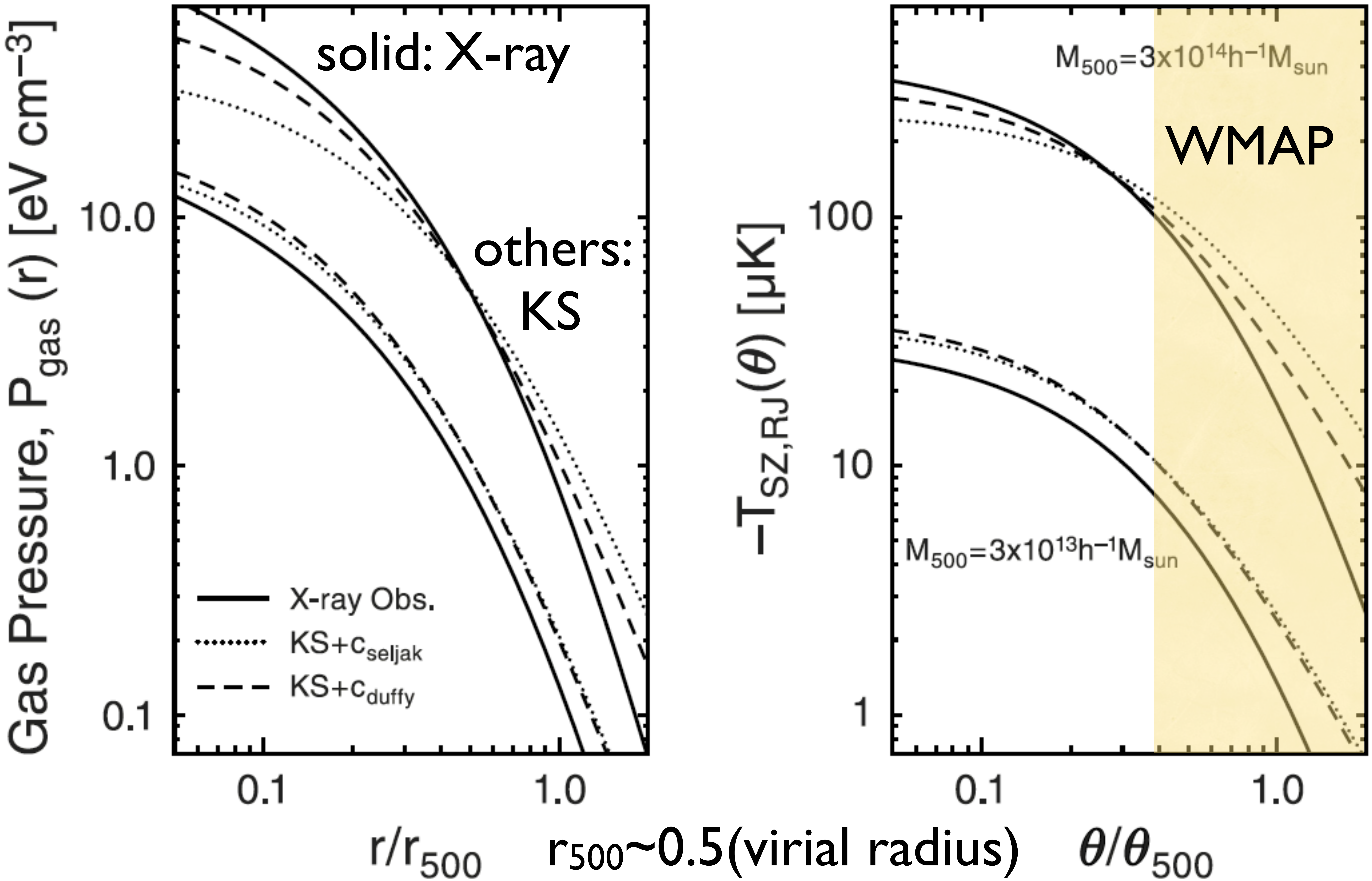
$$\frac{l(l+1)C_l}{2\pi} \simeq 330\,\mu{\rm K}^2\,\sigma_8^7 \left(\frac{\Omega_{\rm b} h}{0.035}\right)^2 \text{x [gas pressure]}$$

- The SZ power spectrum is sensitive to the number of clusters (i.e., σ_8) and the pressure of individual clusters.
- Lower SZ power spectrum can imply:
  - σ_8 is 0.77 (rather than 0.8): $\sum m_\nu \sim 0.2$eV?
  - Gas pressure per cluster is lower than expected

WMAP measurement favors this possibility.

Gory Details and Systematic Error Checks

- What are the "expectations"?
  - Empirical pressure profiles derived from X-ray observations (Arnaud et al. 2009)
  - Theoretical pressure profiles derived from hydrodynamical simulations (Nagai et al. 2007)
  - Theoretical pressure profiles derived from simple analytical modeling of the intracluster medium (Komatsu & Seljak 2001; 2002)
- All of these agree with each other reasonably well.



- The central part of the clusters cannot be resolved by WMAP's beam.

Size-Luminosity Relations

- To calculate the expected pressure profile for each cluster, we need to know the size of the cluster, r_{500}.
- This needs to be derived from the observed properties of X-ray clusters.
  - The best quantity is the gas mass times temperature, but this is available only for a small subset of clusters.
  - We use r_{500}–L_X relation (Boehringer et al.):

$$r_{500} = \frac{(0.753 \pm 0.063)\ h^{-1}\ \mathrm{Mpc}}{E(z)} \times \left(\frac{L_X}{10^{44}\ h^{-2}\ \mathrm{erg\ s^{-1}}} \right)^{0.228 \pm 0.015}$$

Uncertainty in this relation is the major source of sys. error.

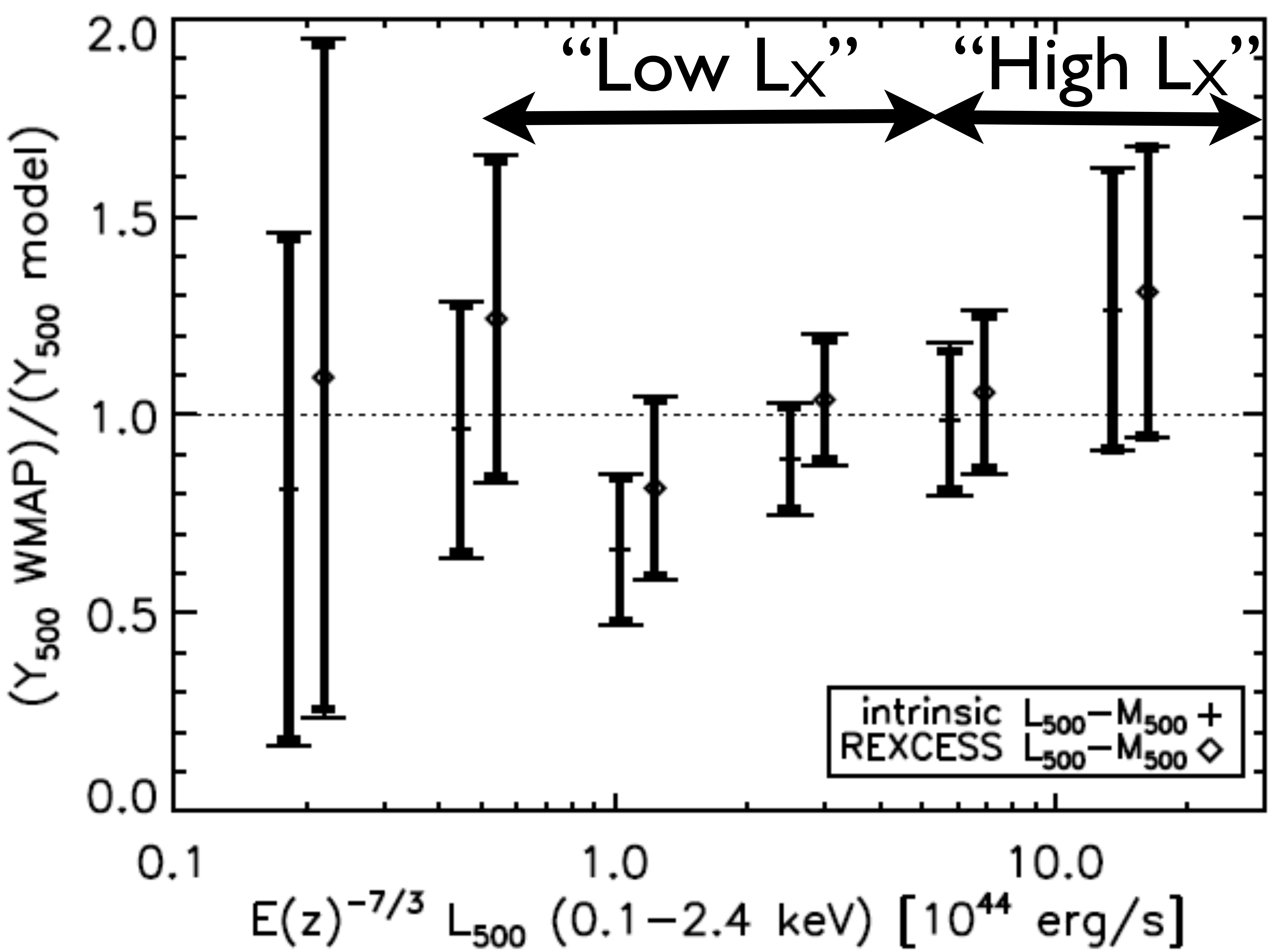
$$E(z) \equiv H(z)/H_0 = \left[\Omega_m(1+z)^3 + \Omega_\Lambda\right]^{1/2}$$

Missing P in Low Mass Clusters?

Gas Pressure Profile	Type	$z_{max} = 0.1$	$z_{max} = 0.2$	High L_X[b]	Low L_X[c]
Arnaud et al. (2009)	X-ray Obs. (Fid.)[d]	0.64 ± 0.09	$0.59 \pm 0.07^{+0.38}_{-0.23}$	0.67 ± 0.09	0.43 ± 0.12
Arnaud et al. (2009)	REXCESS scaling[e]	N/A	0.78 ± 0.09	0.90 ± 0.12	0.55 ± 0.16
Arnaud et al. (2009)	intrinsic scaling[f]	N/A	0.69 ± 0.08	0.84 ± 0.11	0.46 ± 0.13
Arnaud et al. (2009)	$r_{out} = 2r_{500}$[g]	N/A	0.59 ± 0.07	0.67 ± 0.09	0.43 ± 0.12
Arnaud et al. (2009)	$r_{out} = r_{500}$[h]	N/A	0.65 ± 0.08	0.74 ± 0.09	0.44 ± 0.14
Komatsu & Seljak (2001)	equation (C16)	0.59 ± 0.09	$0.46 \pm 0.06^{+0.31}_{-0.18}$	0.49 ± 0.08	0.40 ± 0.11
Komatsu & Seljak (2001)	equation (C17)	0.67 ± 0.09	$0.58 \pm 0.07^{+0.33}_{-0.20}$	0.66 ± 0.09	0.43 ± 0.12
Nagai et al. (2007)	Non-radiative	N/A	$0.50 \pm 0.06^{+0.28}_{-0.18}$	0.60 ± 0.08	0.33 ± 0.10
Nagai et al. (2007)	Cooling+SF	N/A	$0.67 \pm 0.08^{+0.37}_{-0.23}$	0.79 ± 0.10	0.45 ± 0.14

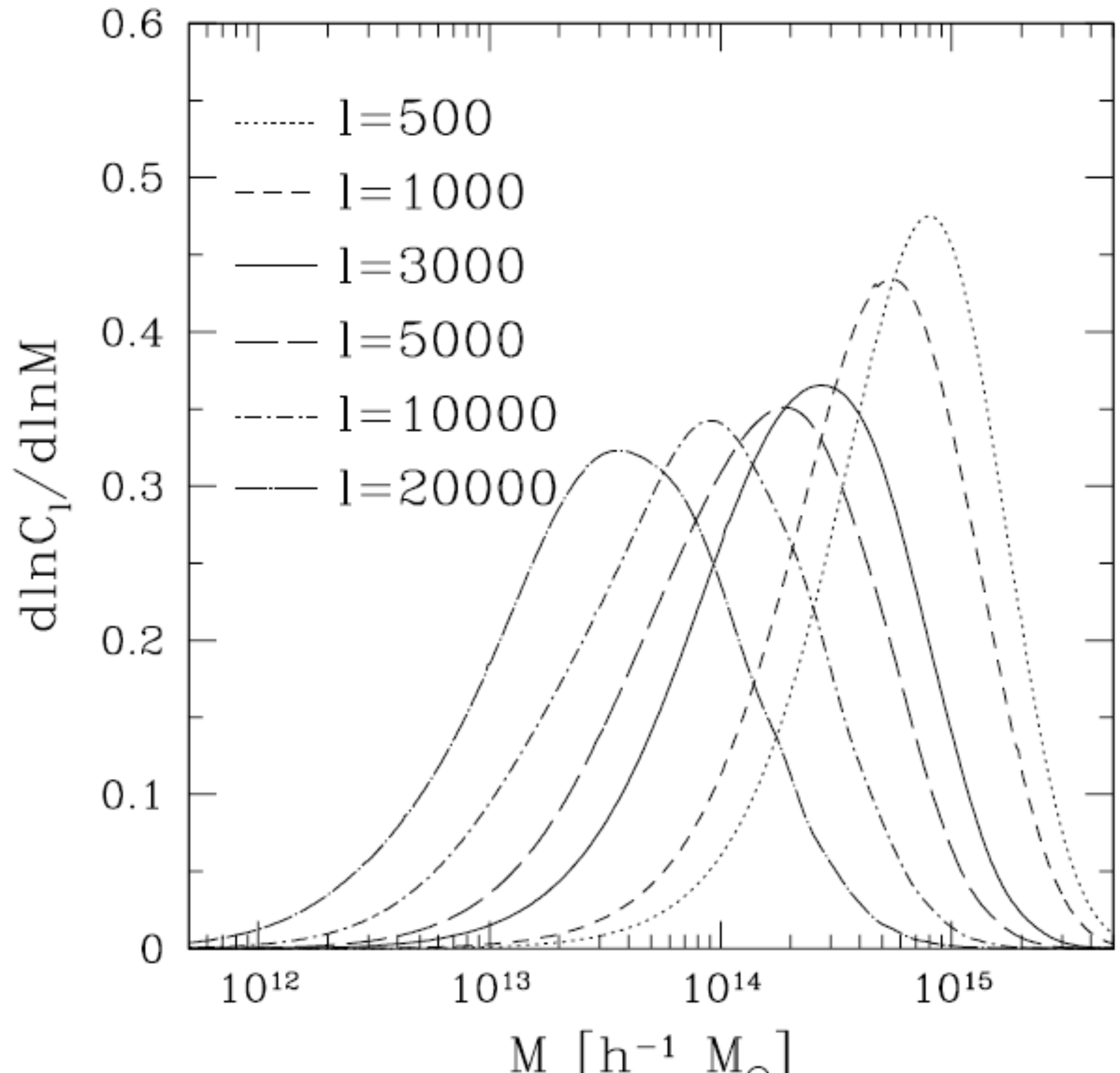
- One picture has emerged:
  - "High L_X" clusters [$M_{500} > 4\times10^{14}\ h^{-1} M_{sun}$] can be brought into agreement with the expectations by playing with the r_{500}–L_X relation.
  - "Low L_X" clusters reveal a significant *missing pressure*.

Comparison with Melin et al.



- That low-mass clusters have lower normalization than high-mass clusters is also seen by a different group using a different method.
- While our overall normalization is much lower than theirs, the *relative* normalization is in an agreement.

This is consistent with the lower-than-expected C_l^{SZ}



- At l>3000, the dominant contributions to the SZ power spectrum come from low-mass clusters ($M_{500}<4\times10^{14}h^{-1}M_{sun}$).

Summary

- Significant improvements in the **high-l temperature** data, and the **polarization data at all multipoles**.
  - High-l temperature: $n_s<1$, detection of helium, improved limits on neutrino properties.
  - Polarization: polarization on the sky!
    - Polarization-only limit on r: $r<0.93$ (95%CL).
    - All data included: $r<0.24$ (95%CL; w/o SN)
    - $\Delta\alpha = -1.1 \pm 1.3$(statistical) $\pm$ 1.5(systematic) deg.

Puzzle?

- SZ effect: Coma's radial profile is measured, and the statistical detection reaches 8σ.
    - Evidence for lower-than-expected gas pressure in low mass clusters.