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

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Astrophysics Seminar, IAS, February 16, 2010

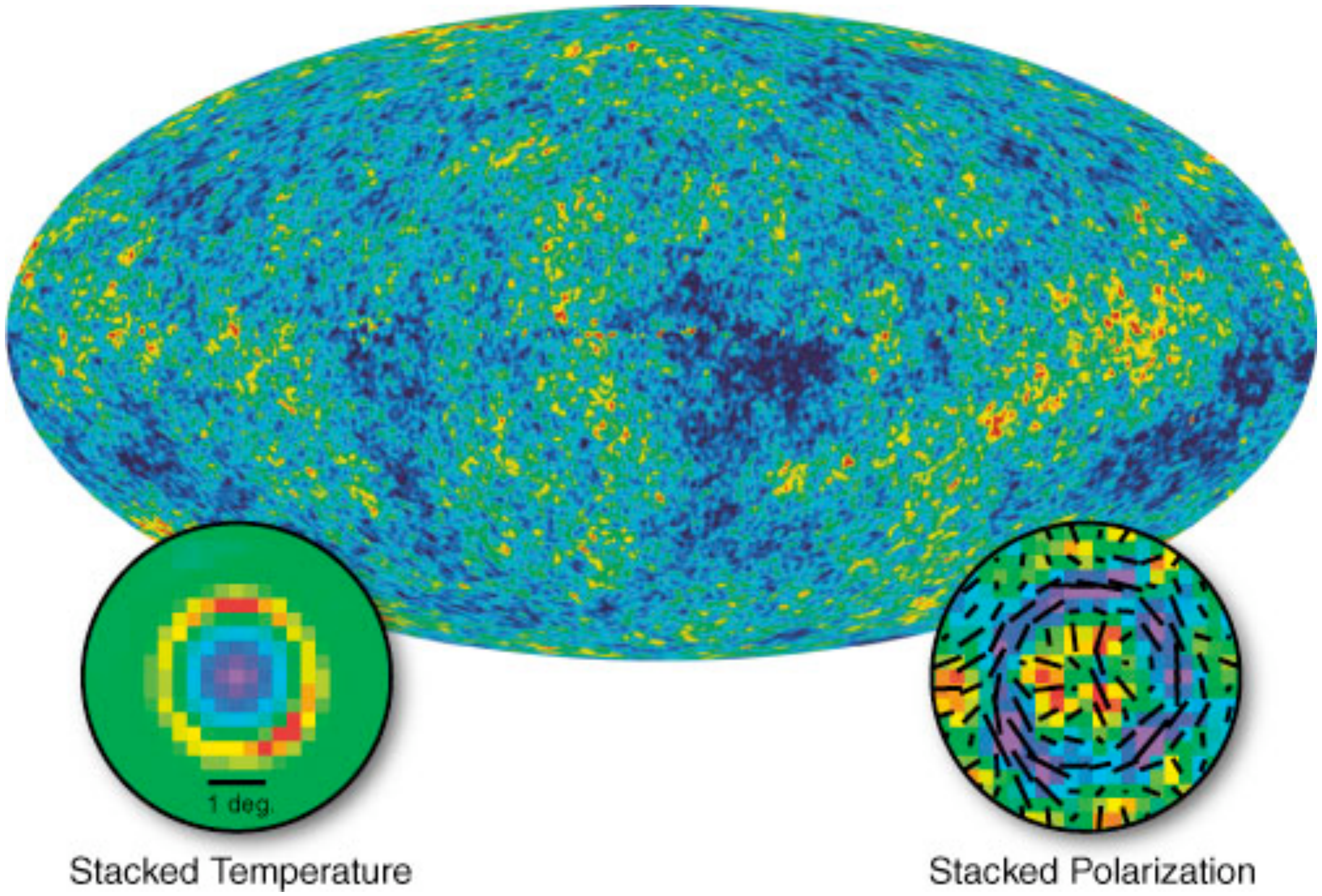
WMAP will have collected 9 years of data by August

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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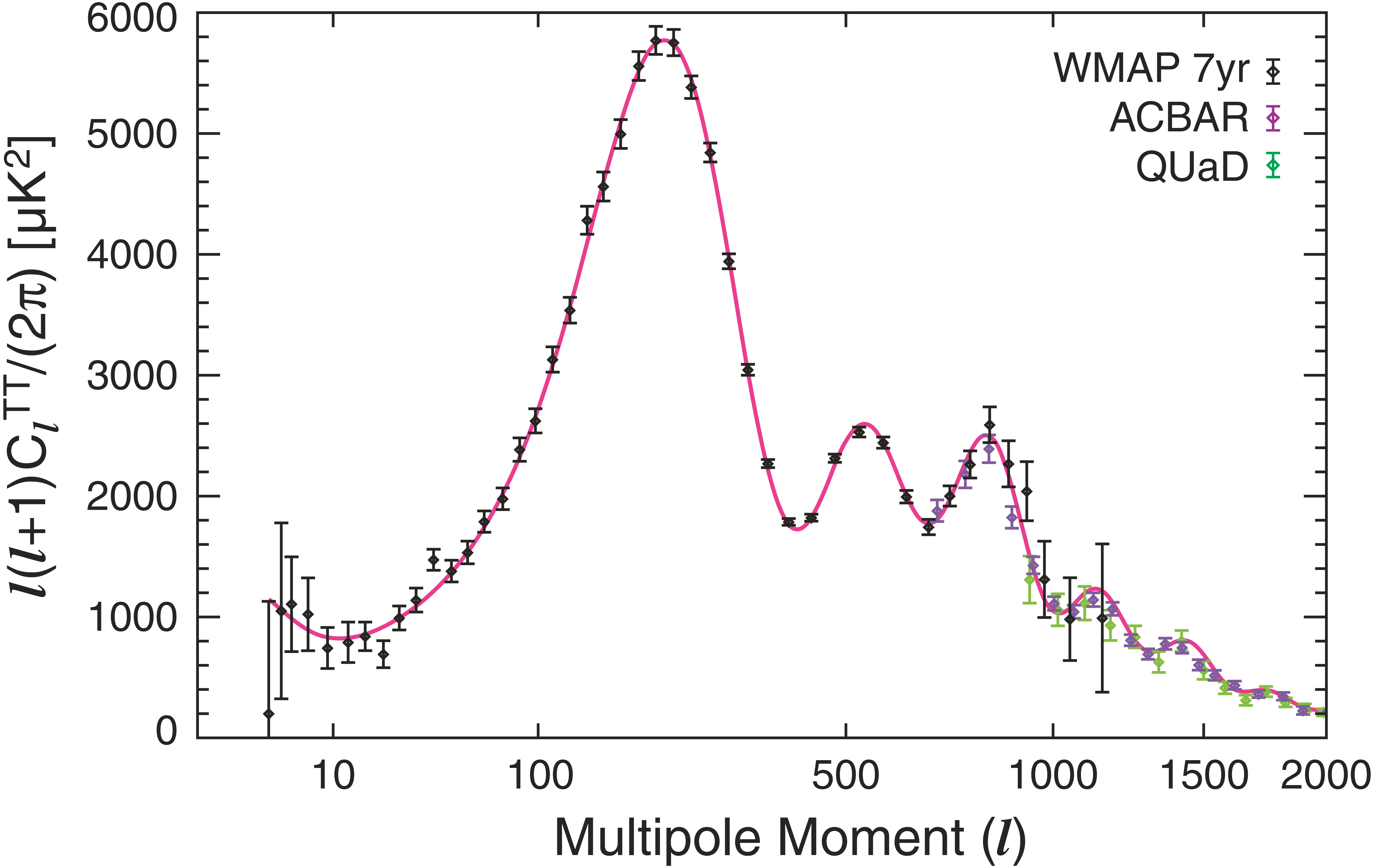
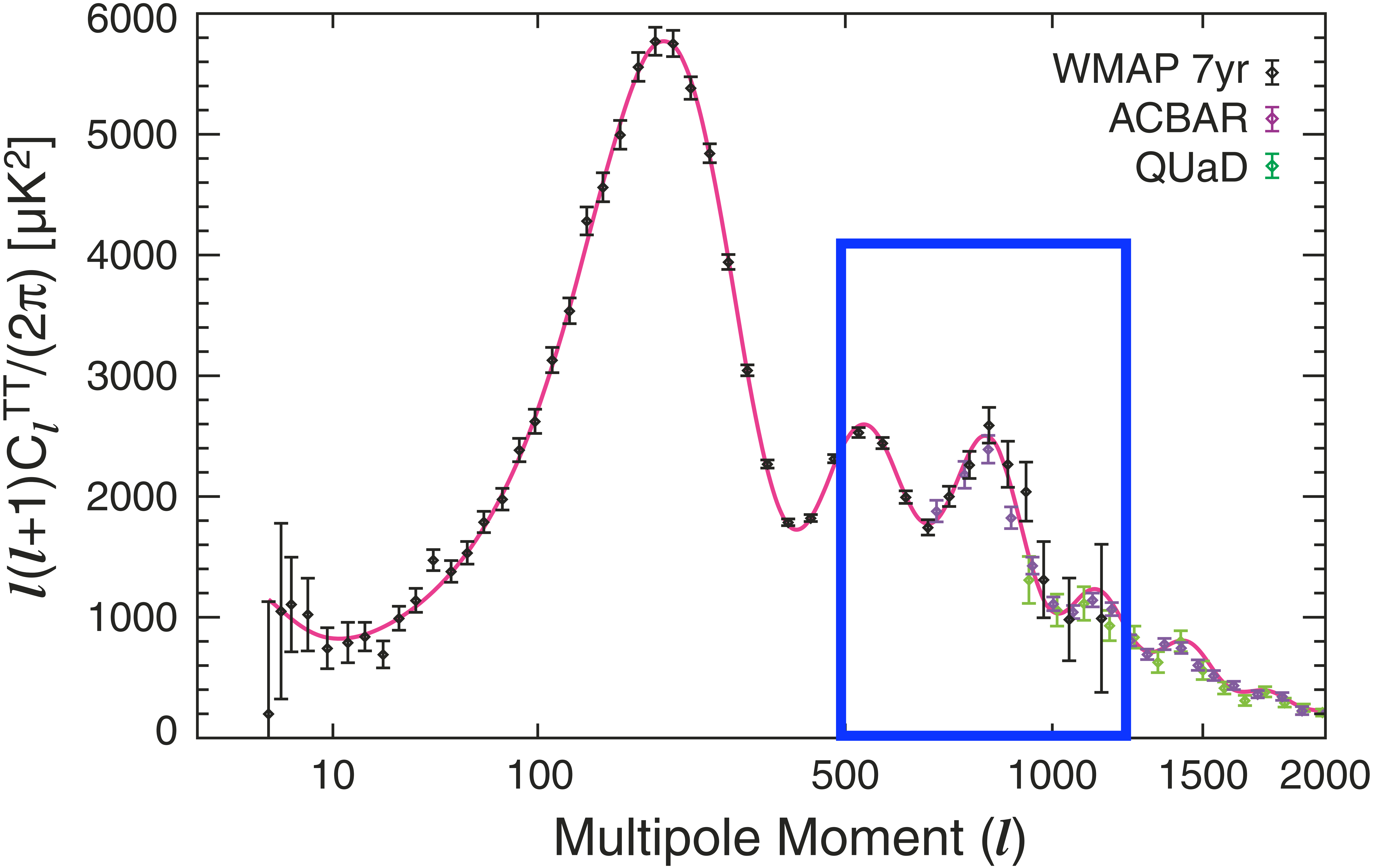
7-year Science Highlights

- First detection (>3σ) of the effect of primordial **helium** on the temperature power spectrum.
- The primordial **tilt** is less than one at >3σ:
  - $n_s=0.96\pm0.01$ (68%CL)
- Improved limits on **neutrino** parameters:
  - $\sum m_\nu<0.58$eV (95%CL); $N_{eff}=4.3\pm0.9$ (68%CL)
- First direct confirmation of the predicted **polarization** pattern around temperature spots.
- Measurement of the SZ effect: *missing* ***pressure****?*

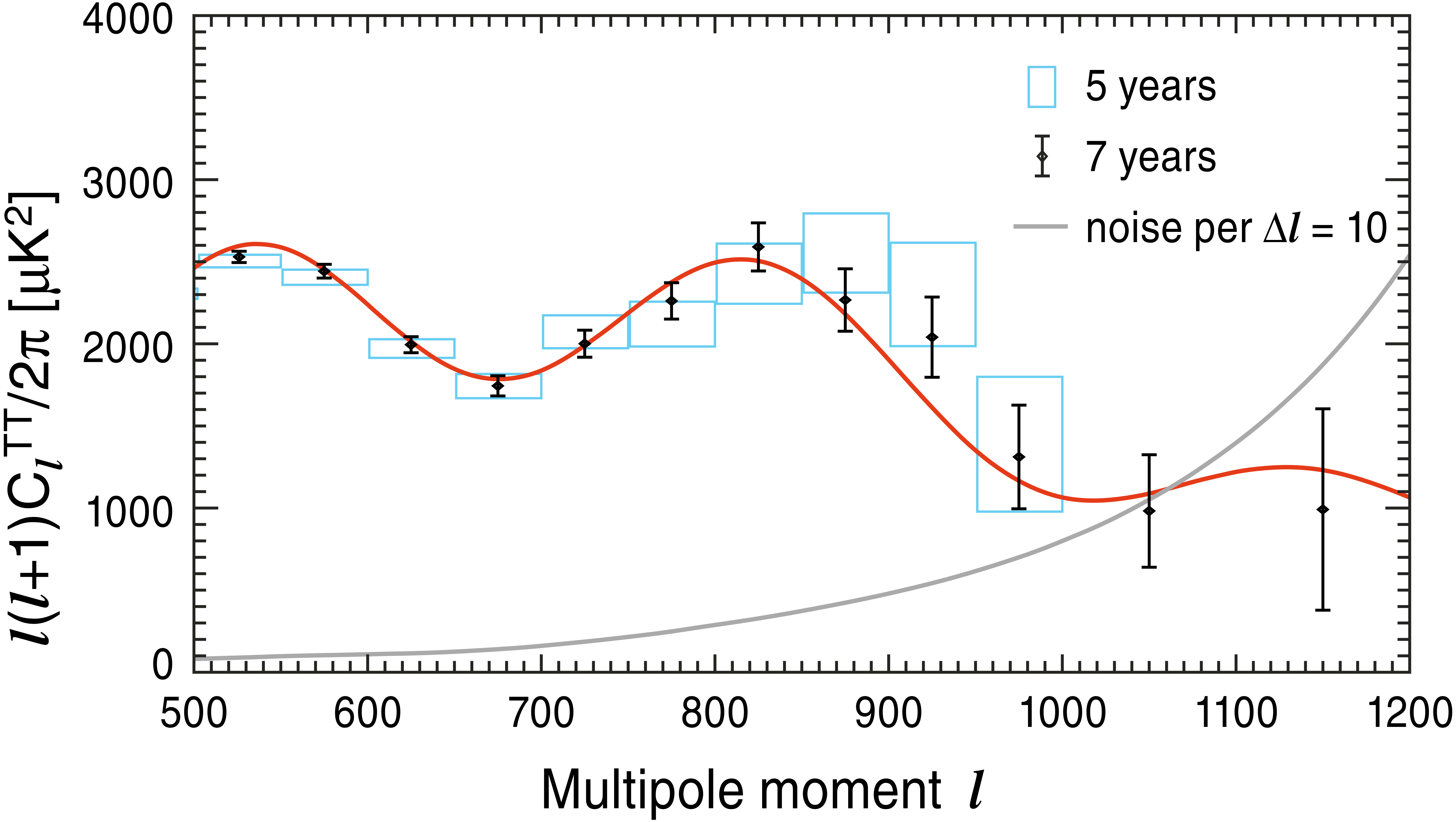
7-year Temperature C_l



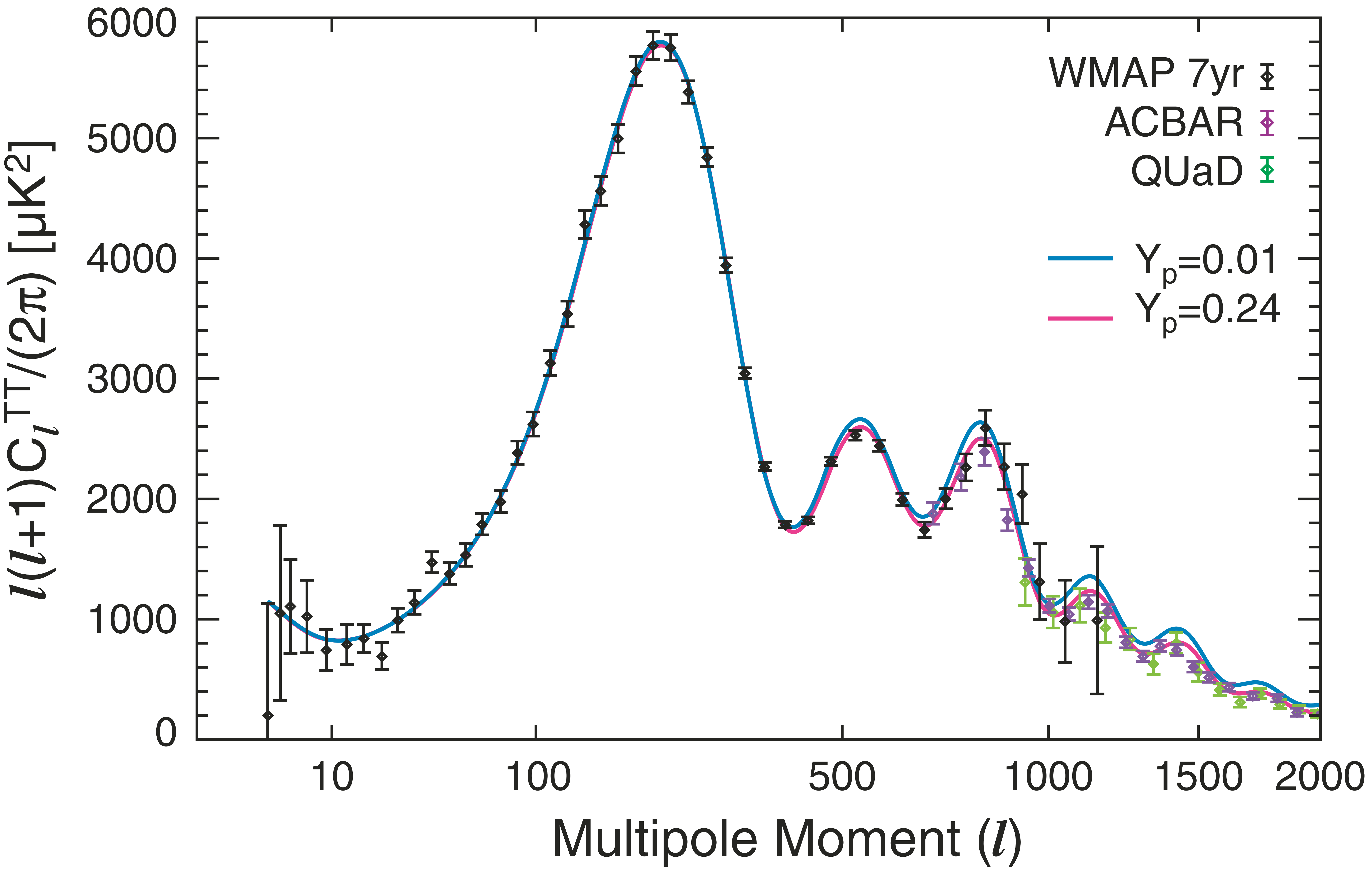
Zooming into the 3rd peak...



High-l Temperature C_l: Improvement from 5-year



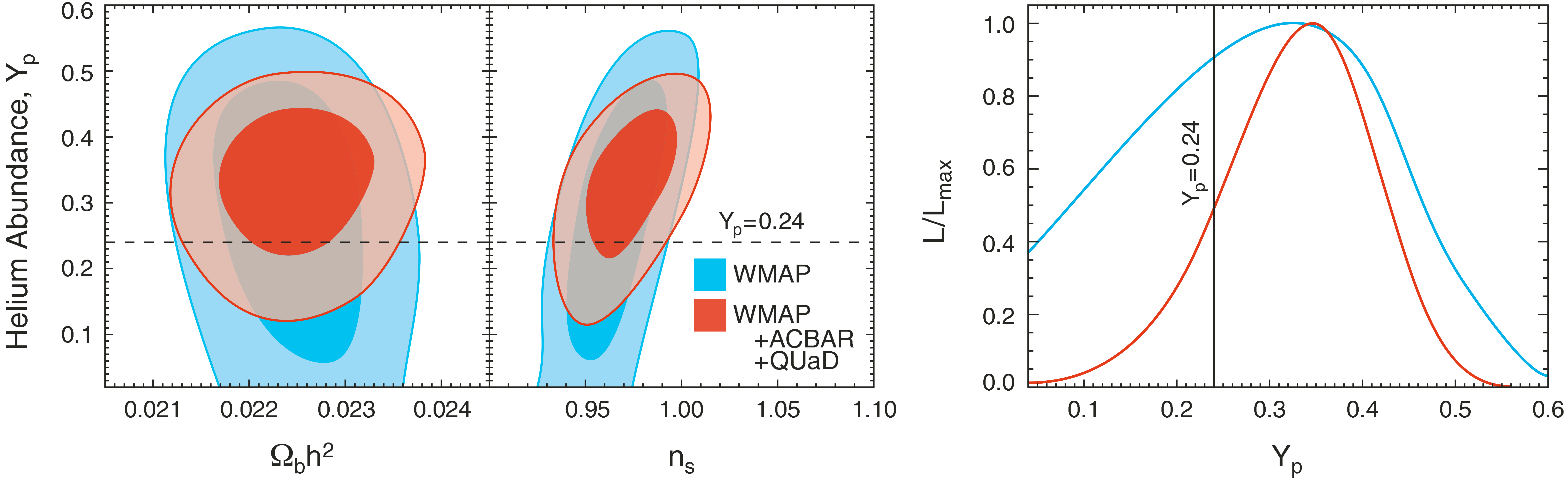
Detection of Primordial Helium



Effect of helium on C_l^{TT}

- We measure the baryon number density, n_b, from the 1st-to-2nd peak ratio.
- For a given n_b, we can calculate the number density of electrons: $n_e=(1-Y_p/2)n_b$.
- As helium recombined at z~1800, there were even 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

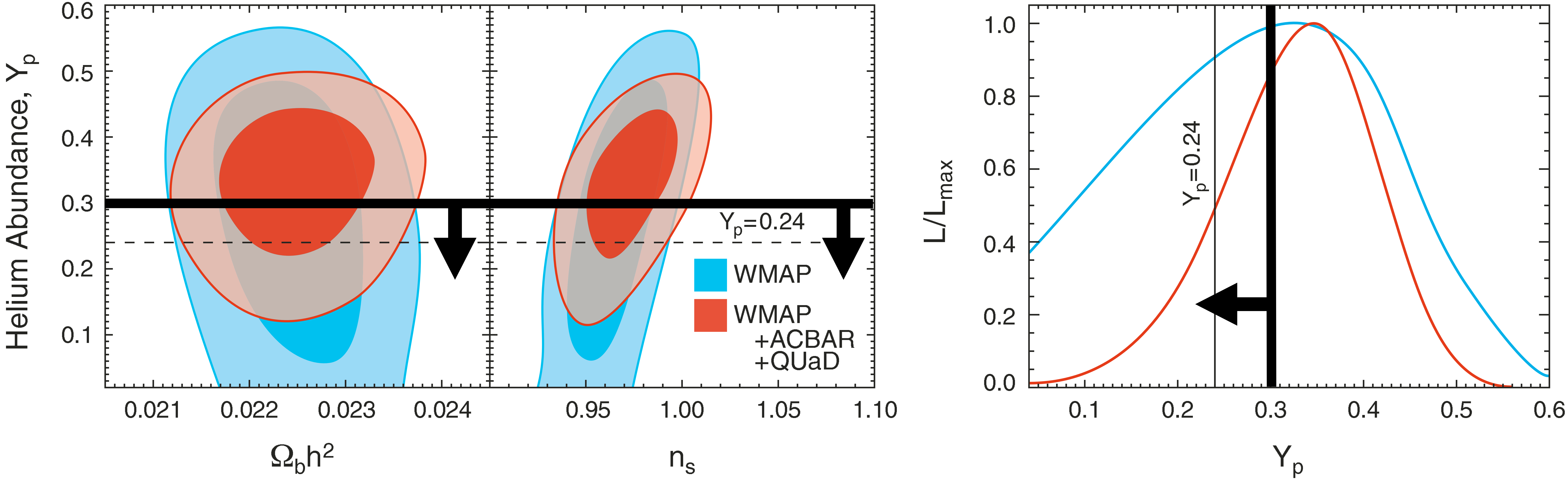


- The combination of WMAP and high-l CMB data (ACBAR and QUaD) is powerful enough to isolate the effect of helium: **Y_p = 0.33 ± 0.08** (68%CL)

Why this can be useful

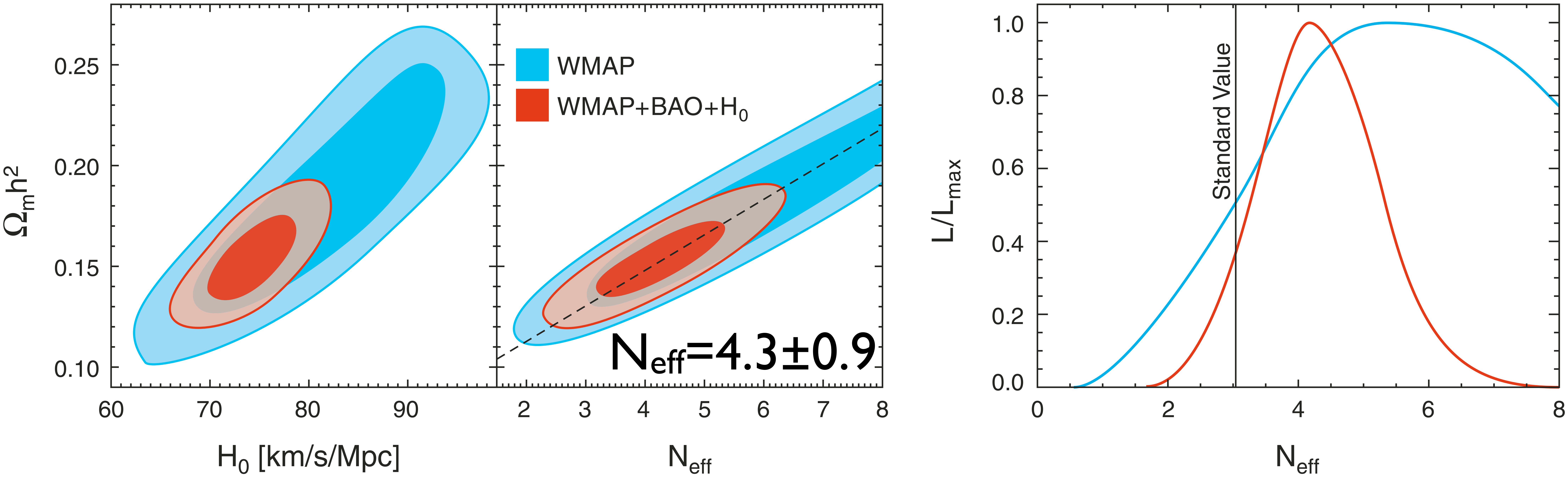
- The helium abundance has been measured from Sun and ionized regions (HII regions); however, as helium can be produced in the stellar core, one has to extrapolate the measured Y_P to the zero-metallicity values.
- In other words, the traditional methods give a robust **upper limit** on Y_P: $Y_P<0.3$.
- 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 $\Delta Y_p \sim 0.01$ (68%CL; Ichikawa et al. 2008).

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

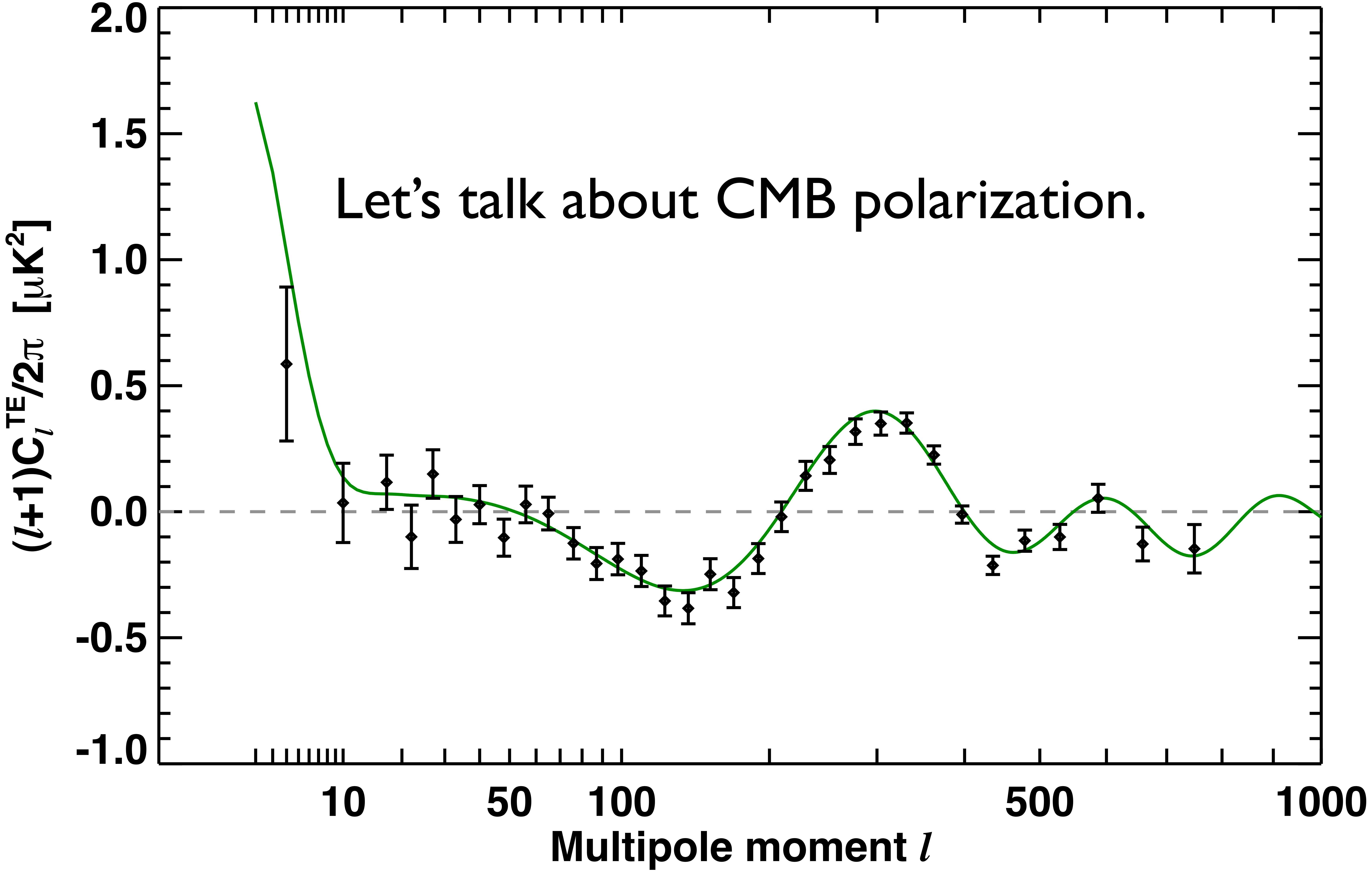


from external data

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

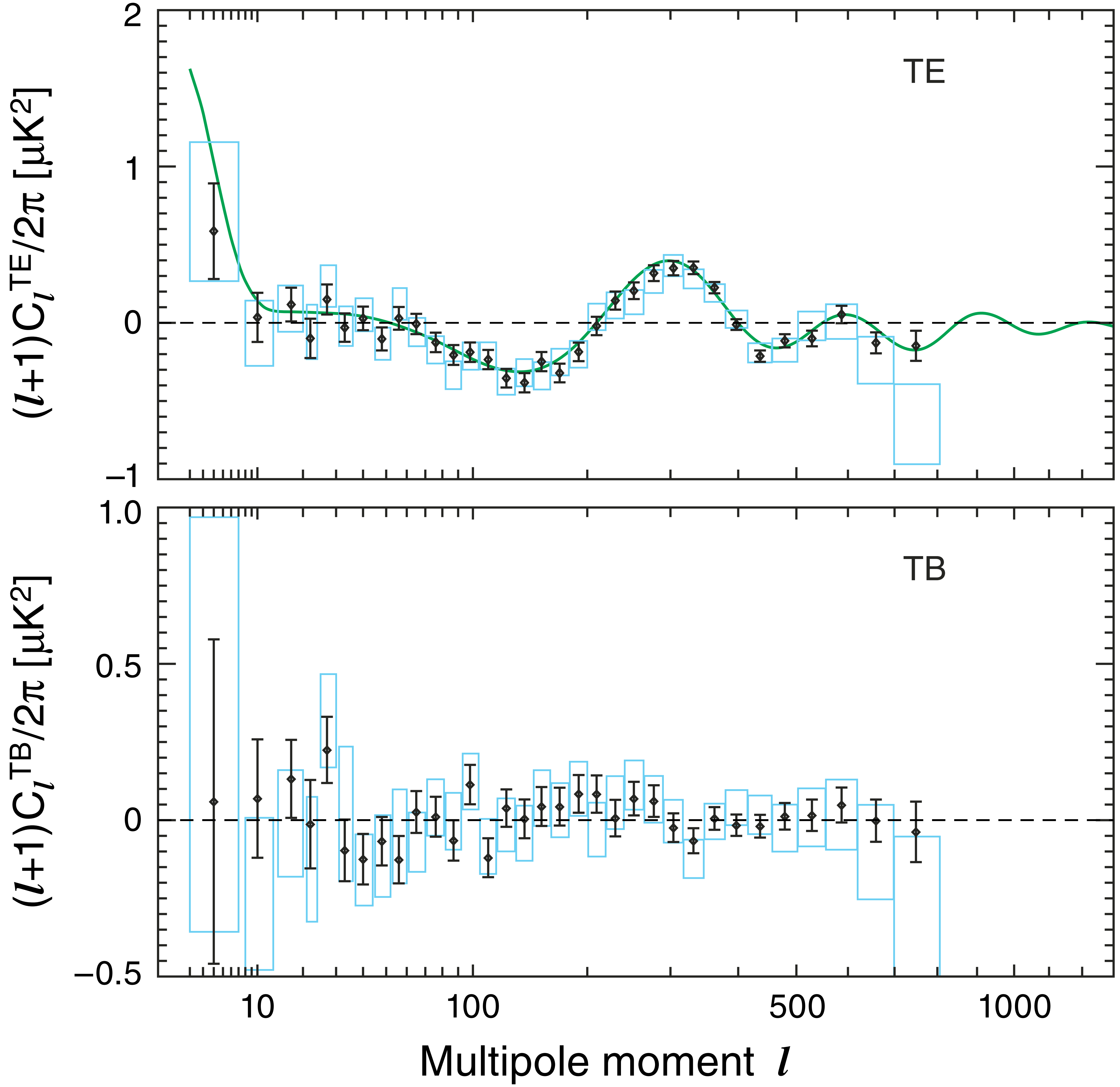
from 3rd peak

7-year TE Correlation



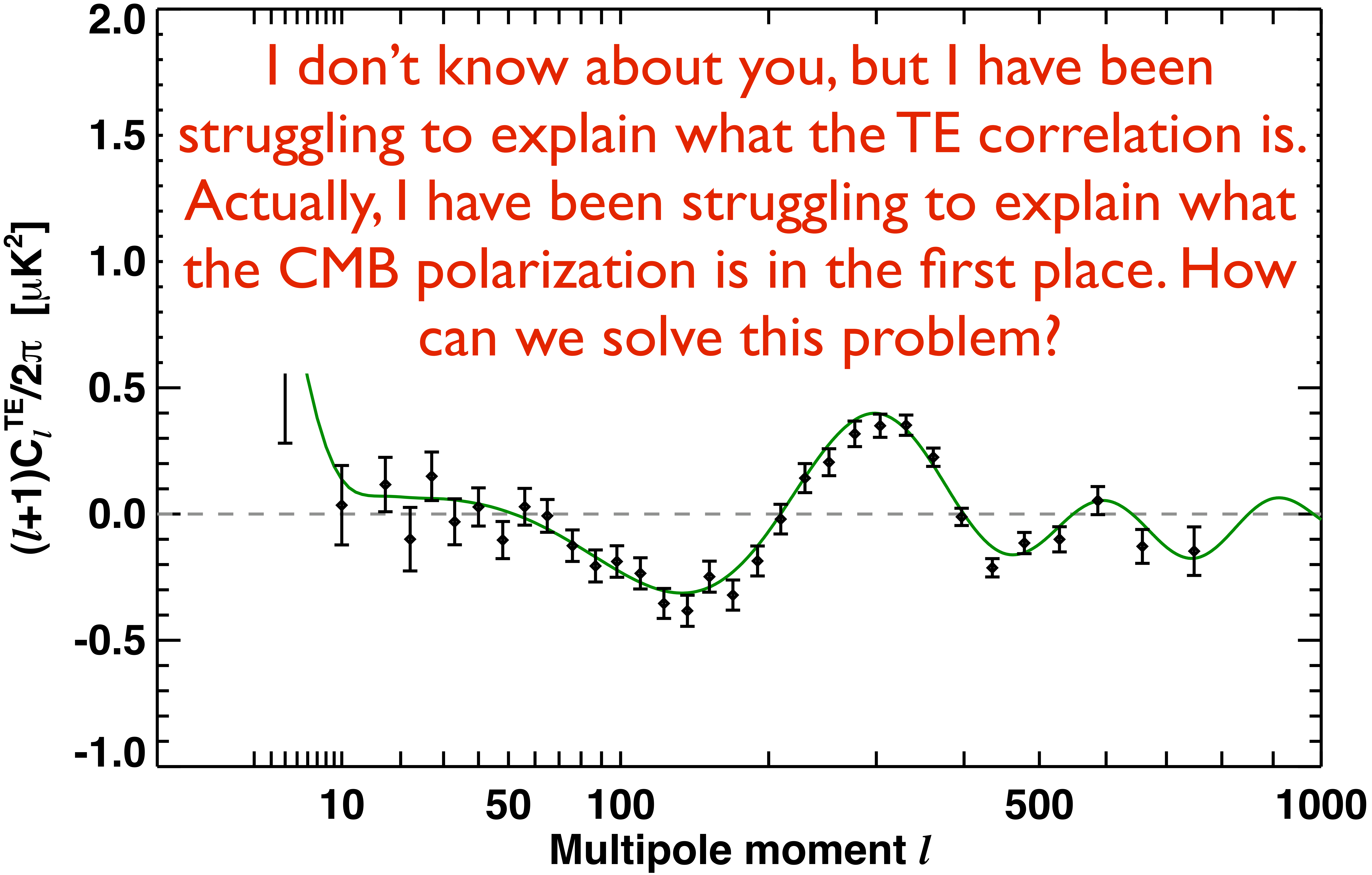
Let’s talk about CMB polarization.

Improvements from 5-year



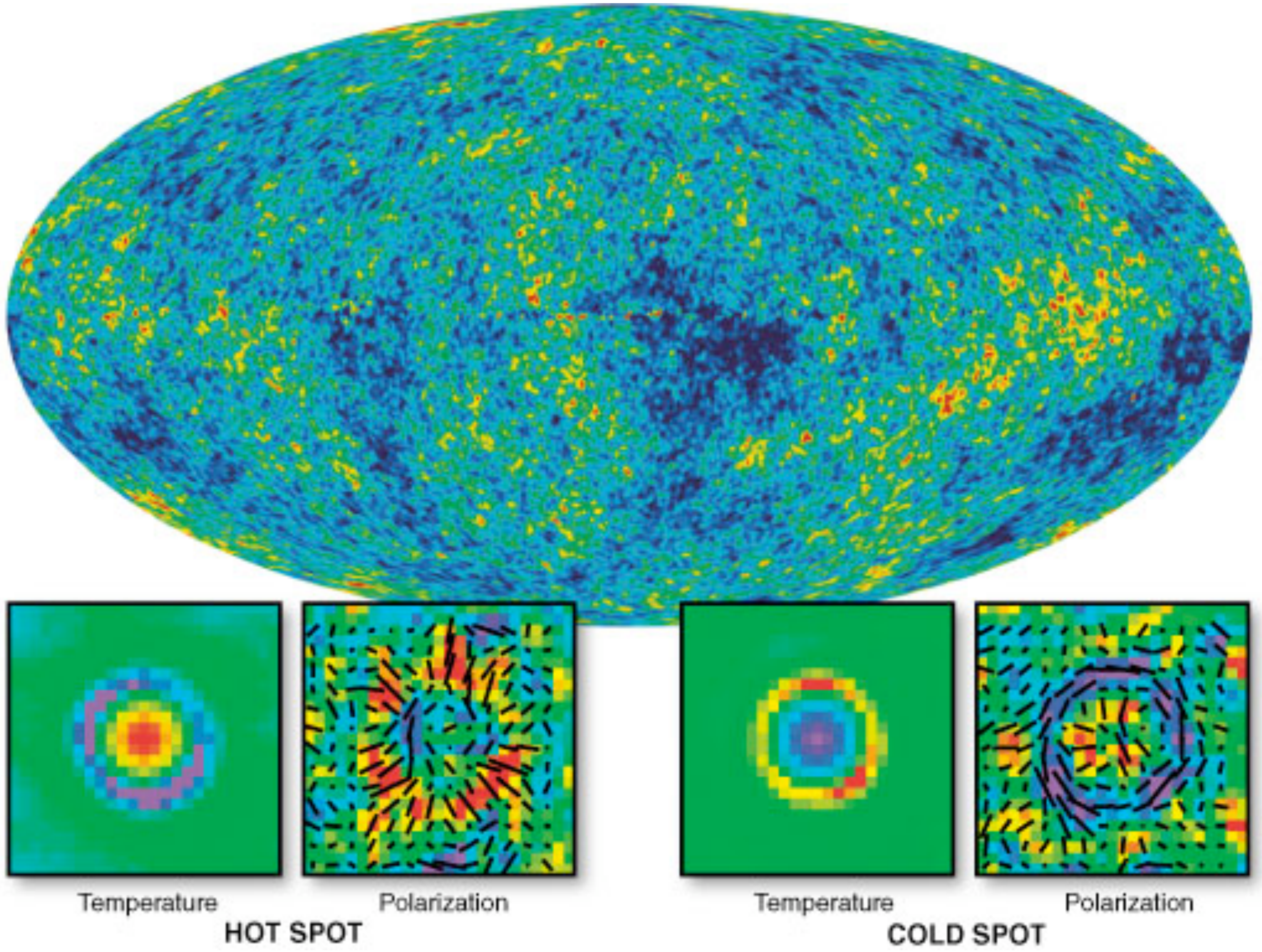
- For 5-year, we used Q and V bands to measure the high-l TE and TB. For 7-year, we also include the W-band data.
- **TE: 21σ detection!** (It was 13σ in 5 year.)
- TB is expected to vanish in a parity-conserving universe, and it is consistent with zero.

What Are We Seeing Here?



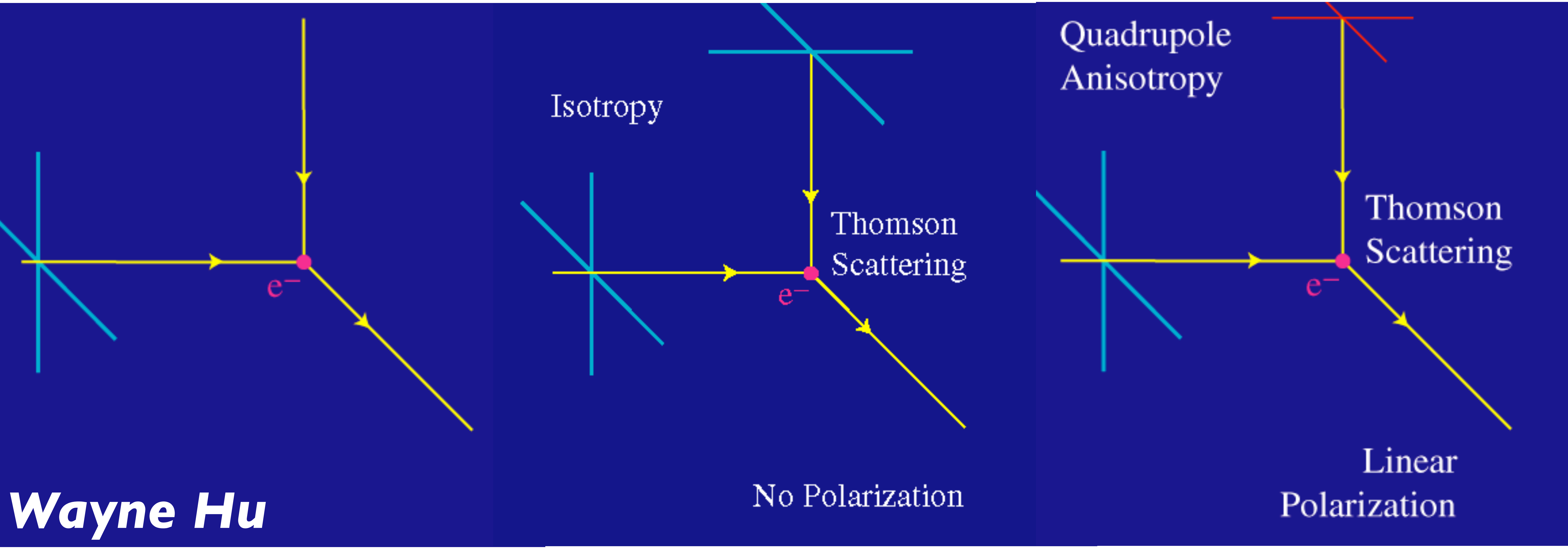
I don't know about you, but I have been struggling to explain what the TE correlation is. Actually, I have been struggling to explain what the CMB polarization is in the first place. How can we solve this problem?

CMB Polarization On the Sky



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

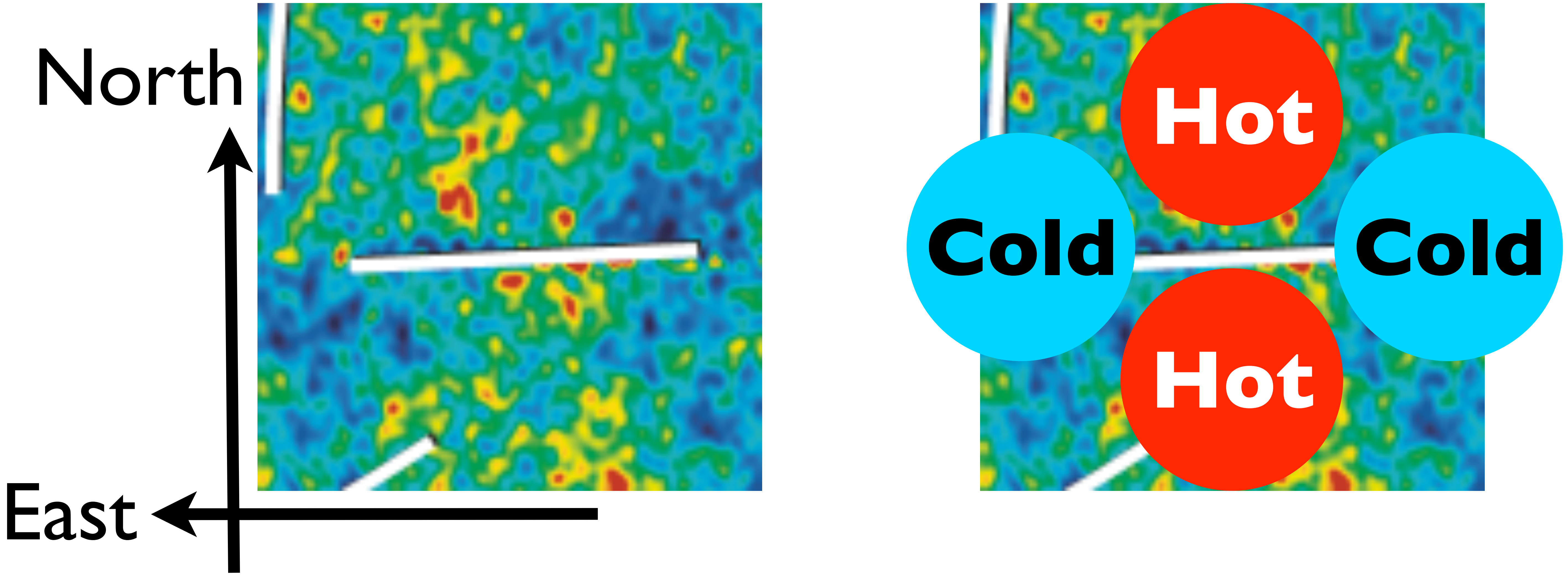
CMB Polarization is a Real-space Stuff



Wayne Hu

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

Principle

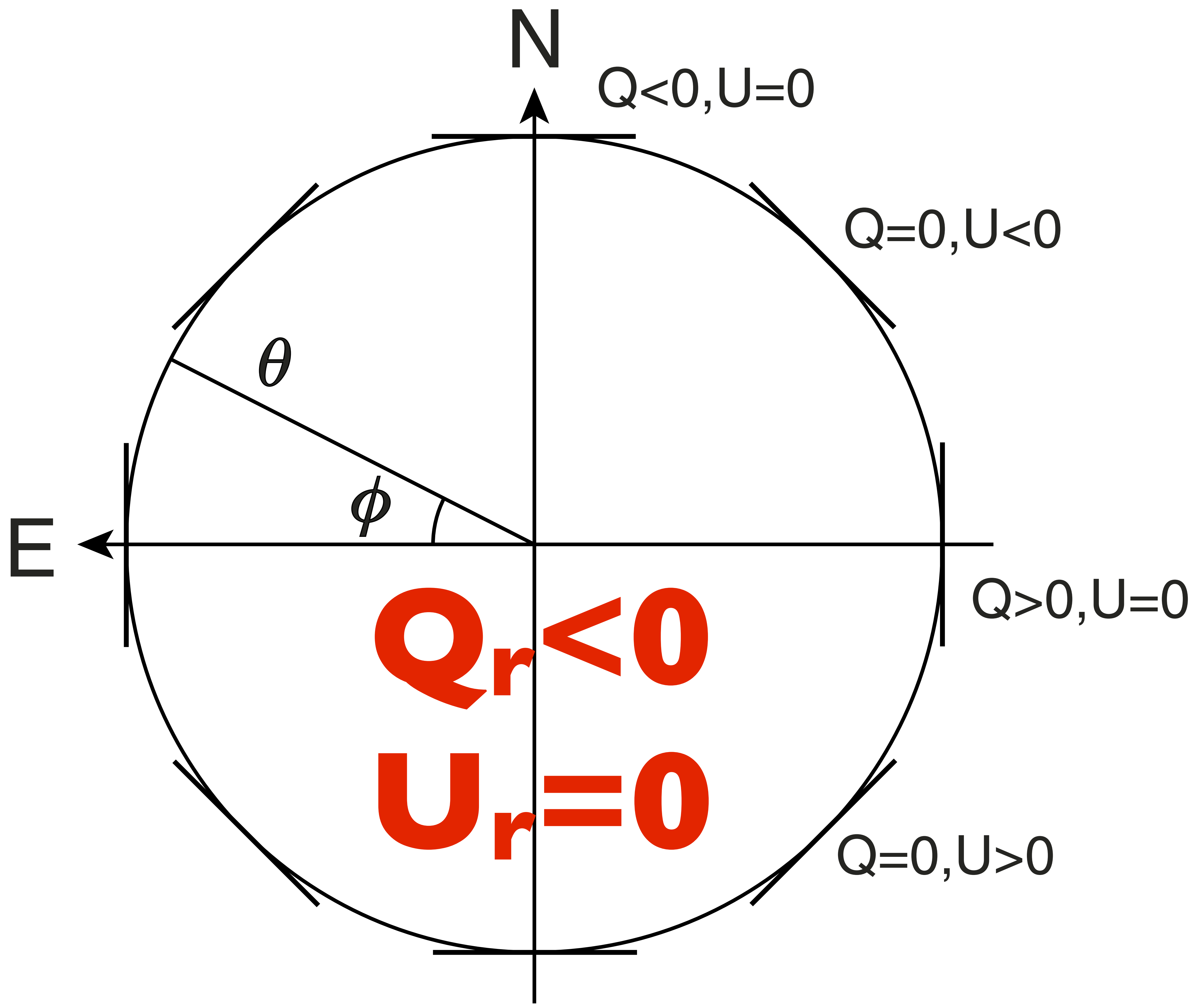


Q<0; U=0

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

Kamionkowski et al. (1997)

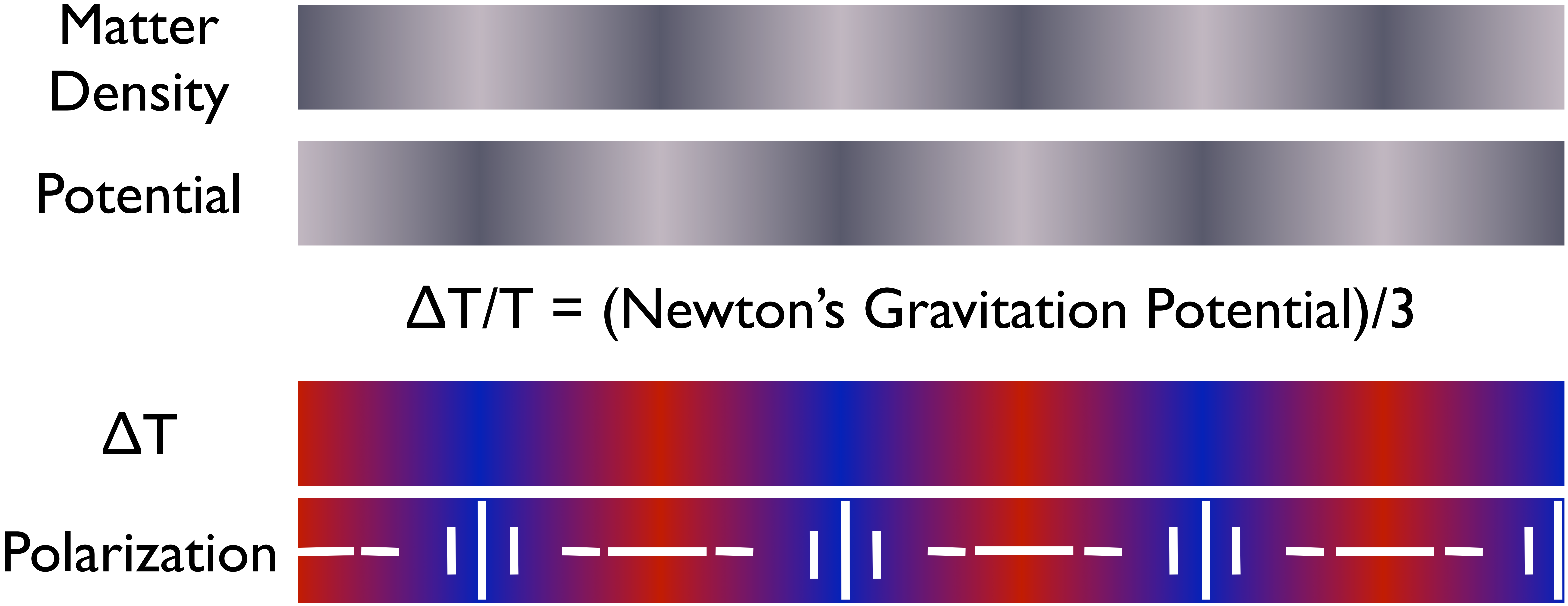
Stokes Q and U (and KKS's Q_r and U_r)



- 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)

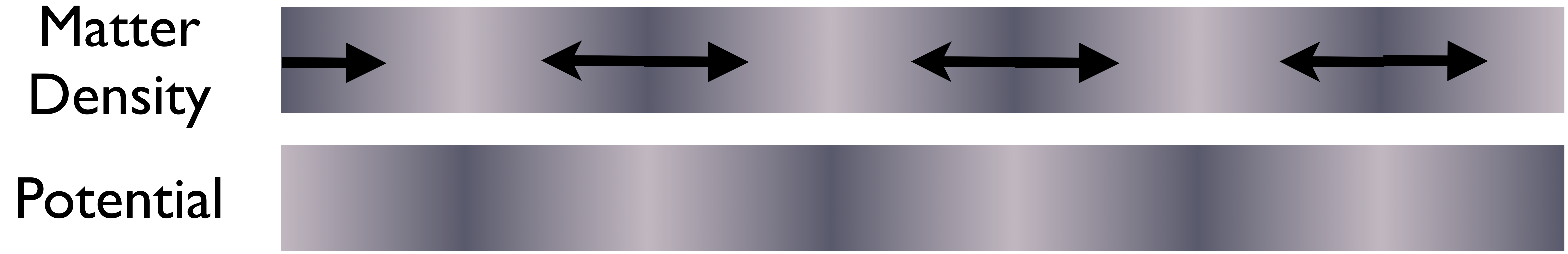


$\Delta T/T$ = (Newton's Gravitation Potential)/3

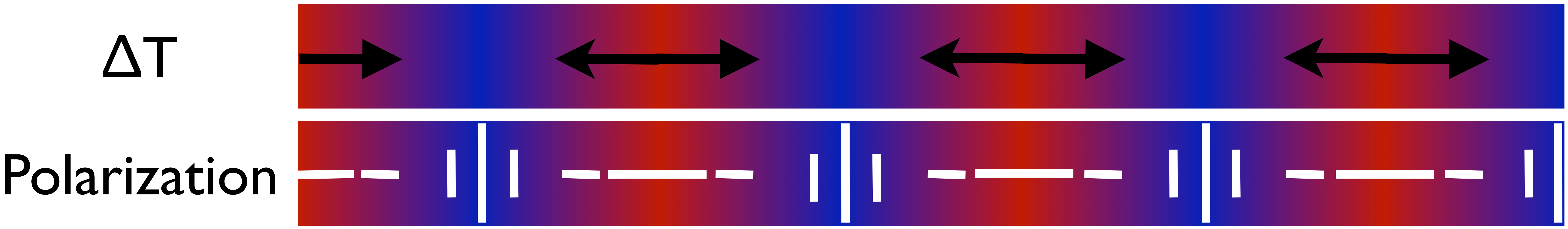
- How does the photon-baryon plasma move?

CMB Polarization Tells Us How Plasma Moves at z=1090

Zaldarriaga & Harari (1995)

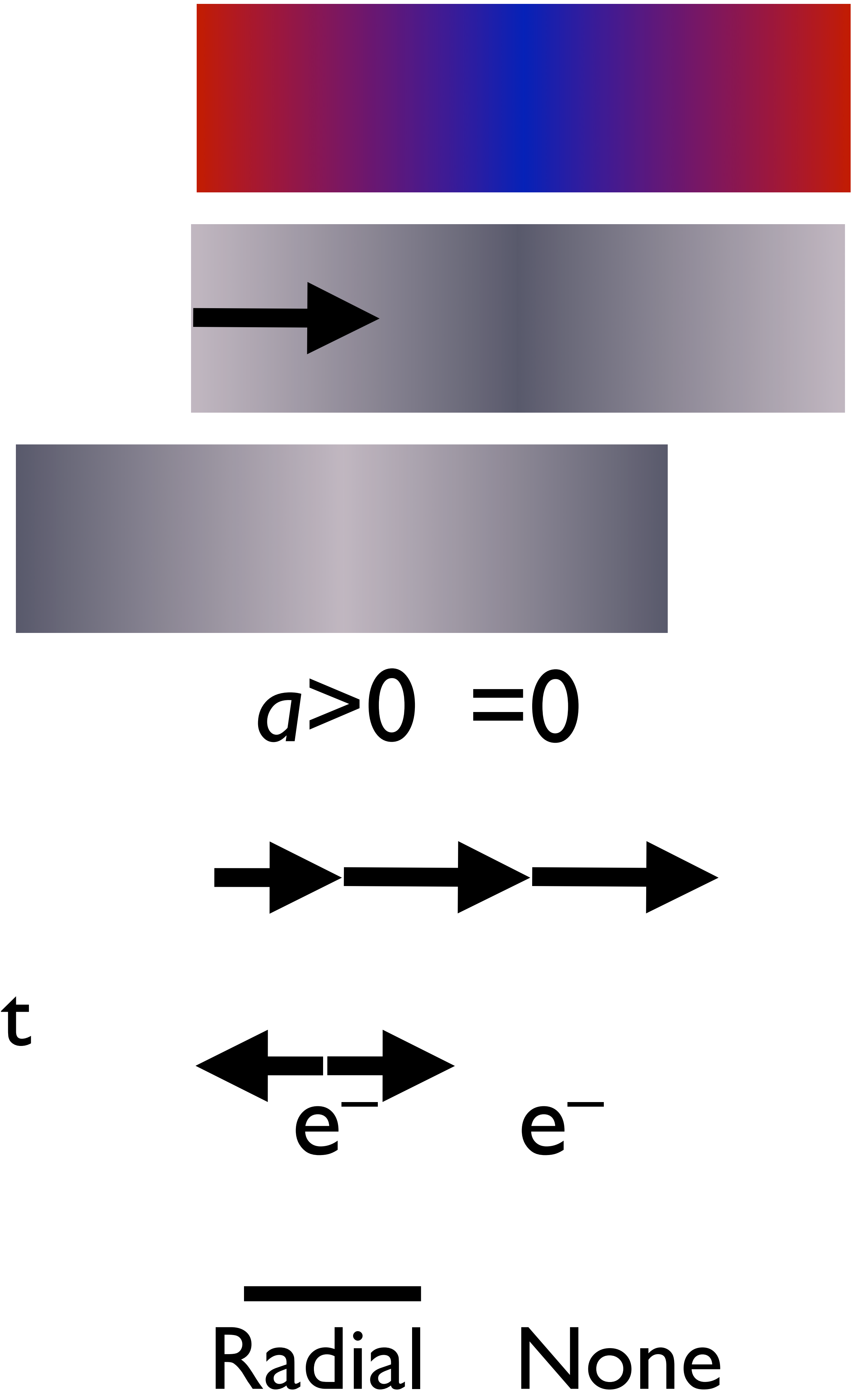


ΔT/T = (Newton's Gravitation Potential)/3



- 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

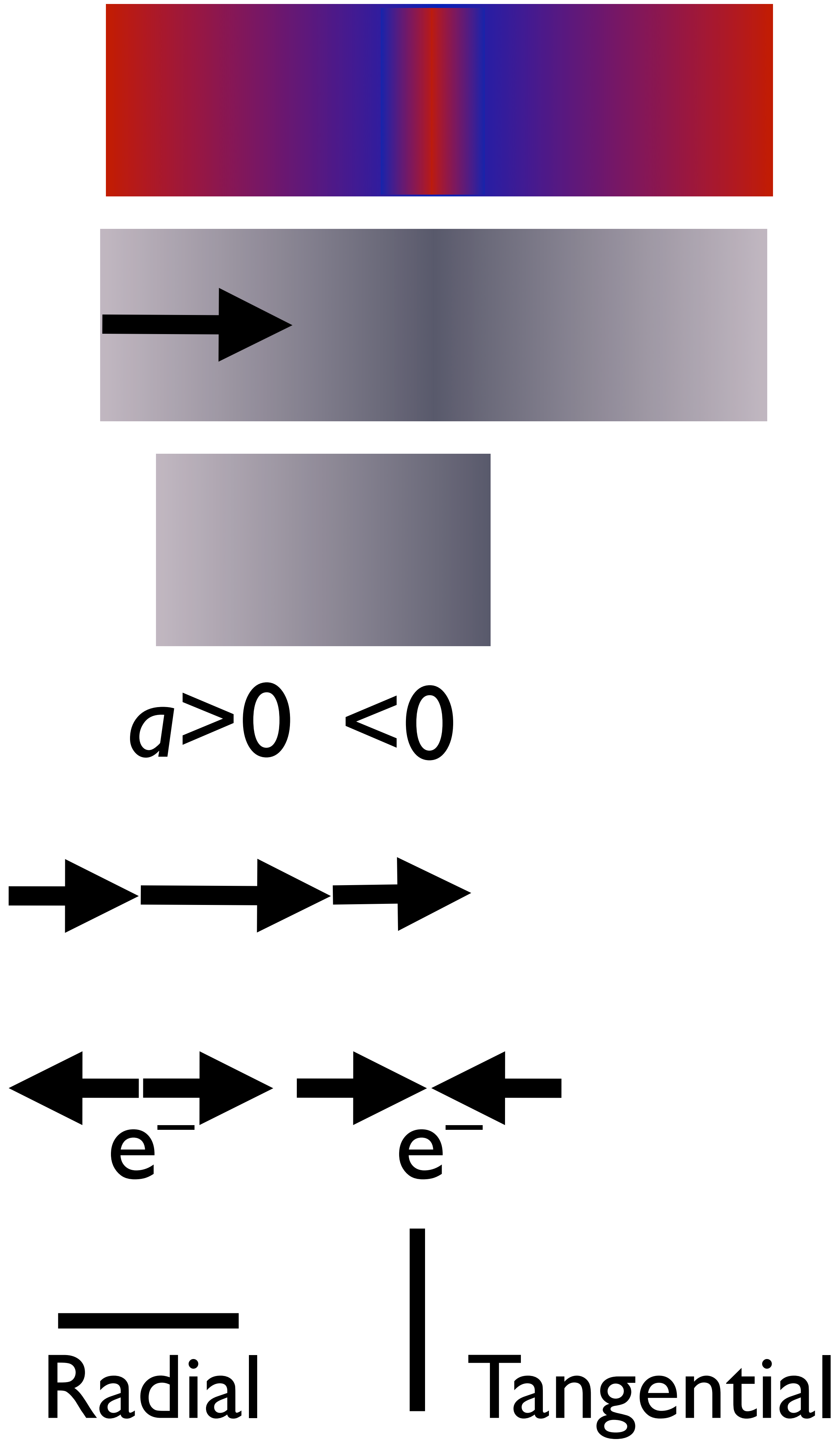
Velocity gradient

Velocity in the rest frame of electron

The left electron sees colder photons along the plane wave

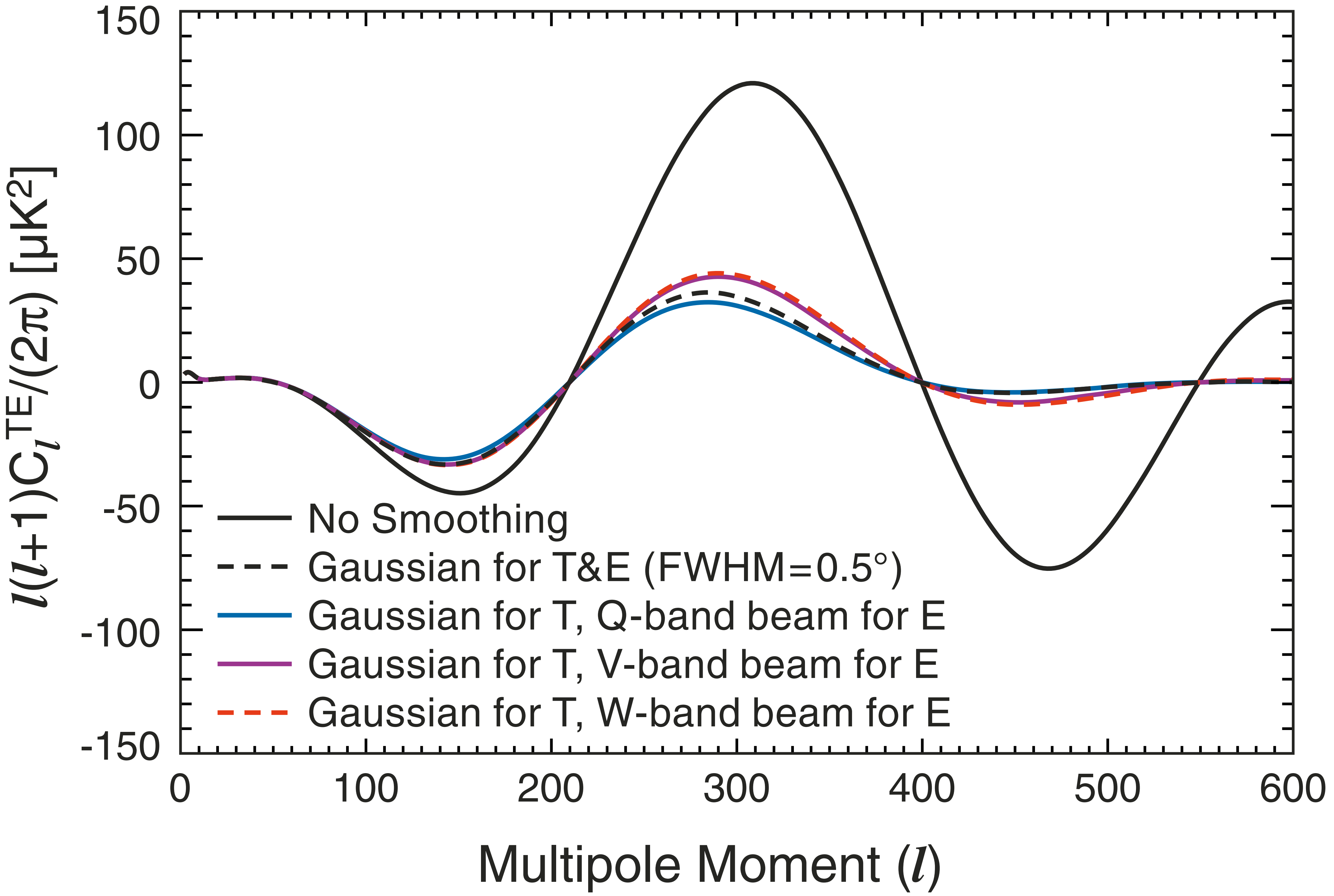
Polarization

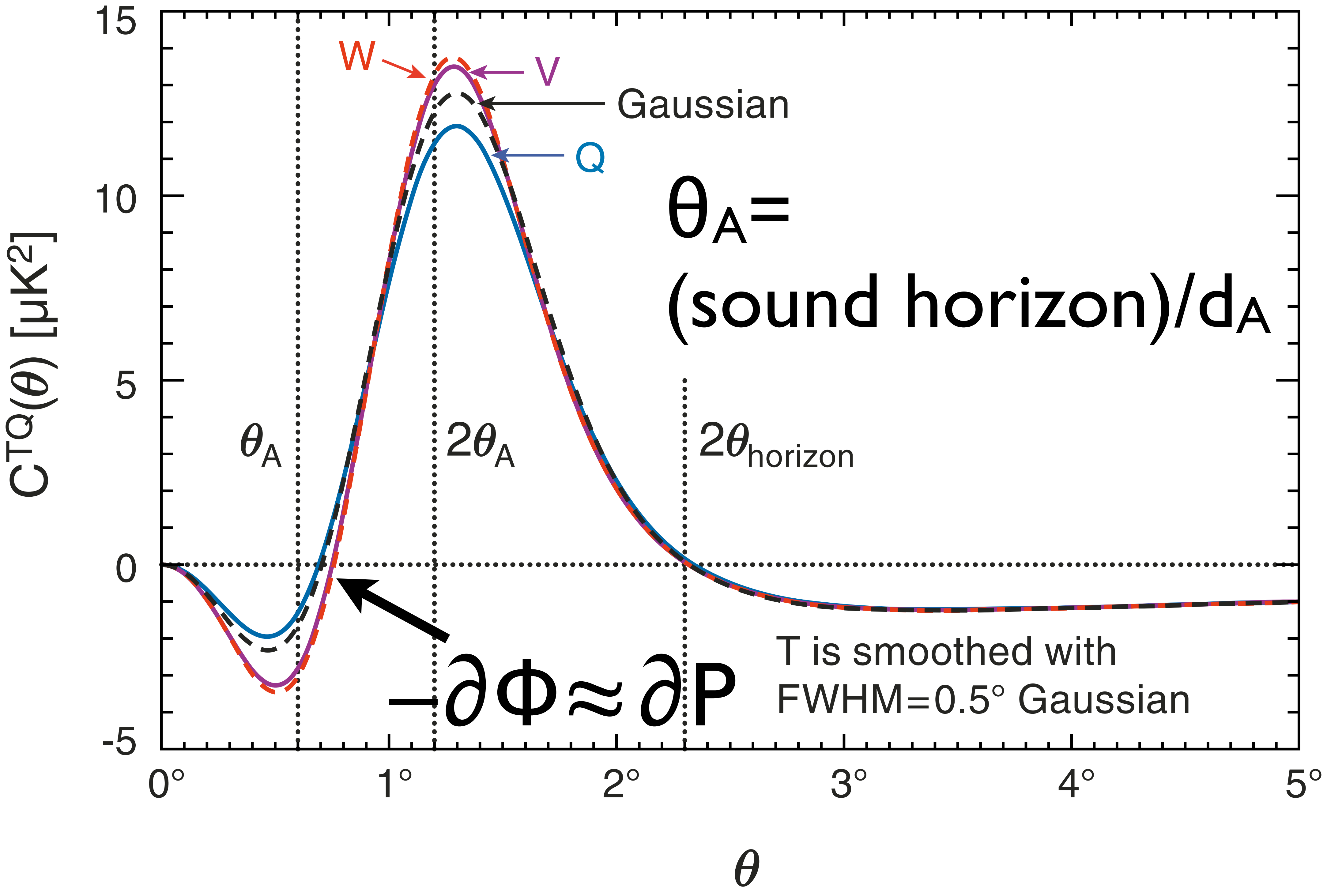
Quadrupole From Velocity Gradient (Small Scale)



ΔT	Compression heats photons
Potential Φ	Stuff flowing *in*
Acceleration $a=-\partial\Phi-\partial P$	Pressure gradient slows down the flow
Velocity	Velocity gradient
Velocity in the rest frame of electron	
Polarization	

Hence, TE Correlation (Coulson et al. 1994)





θ_A= (sound horizon)/d_A

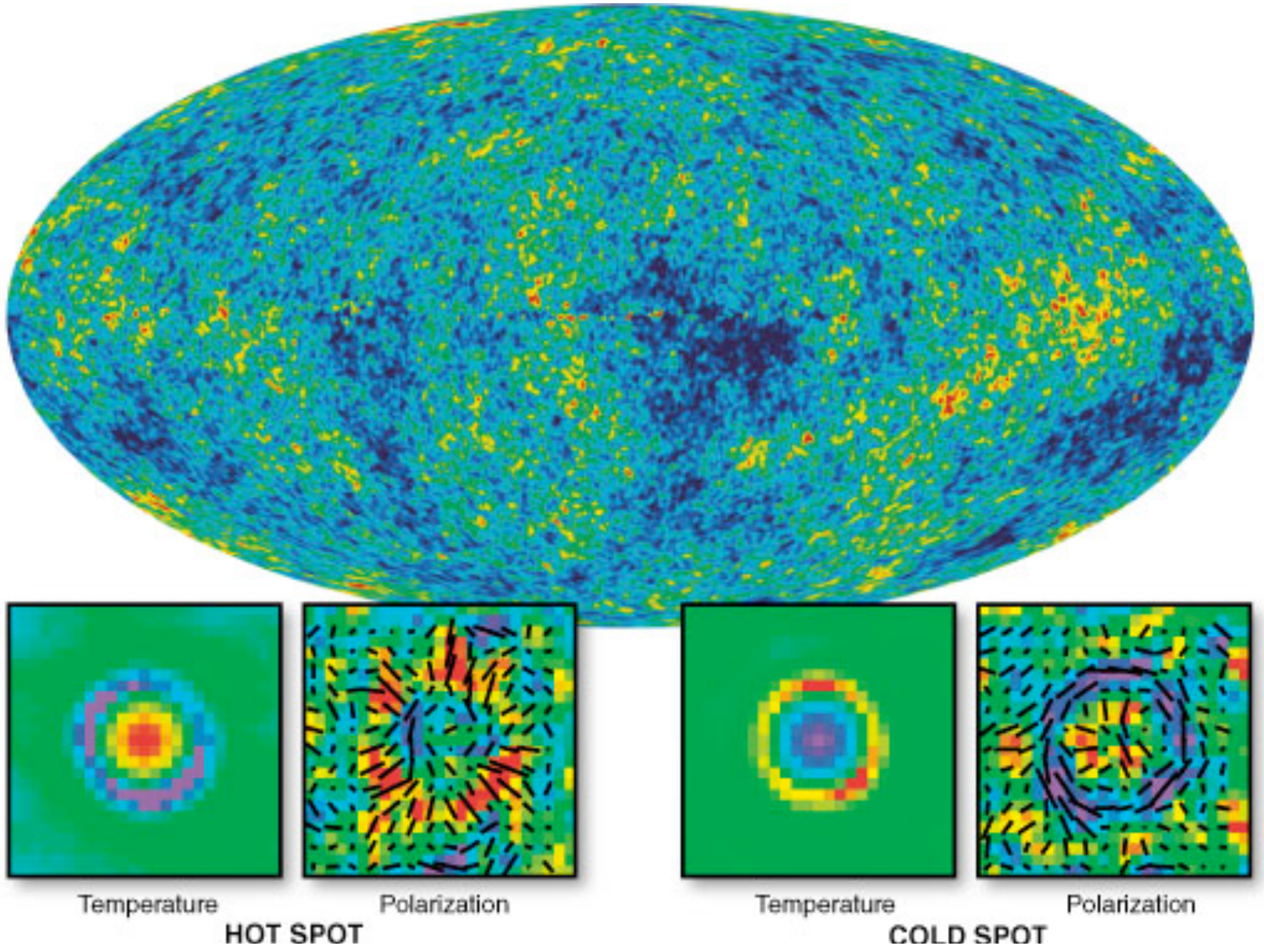
$-\partial\Phi \approx \partial P$

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

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:

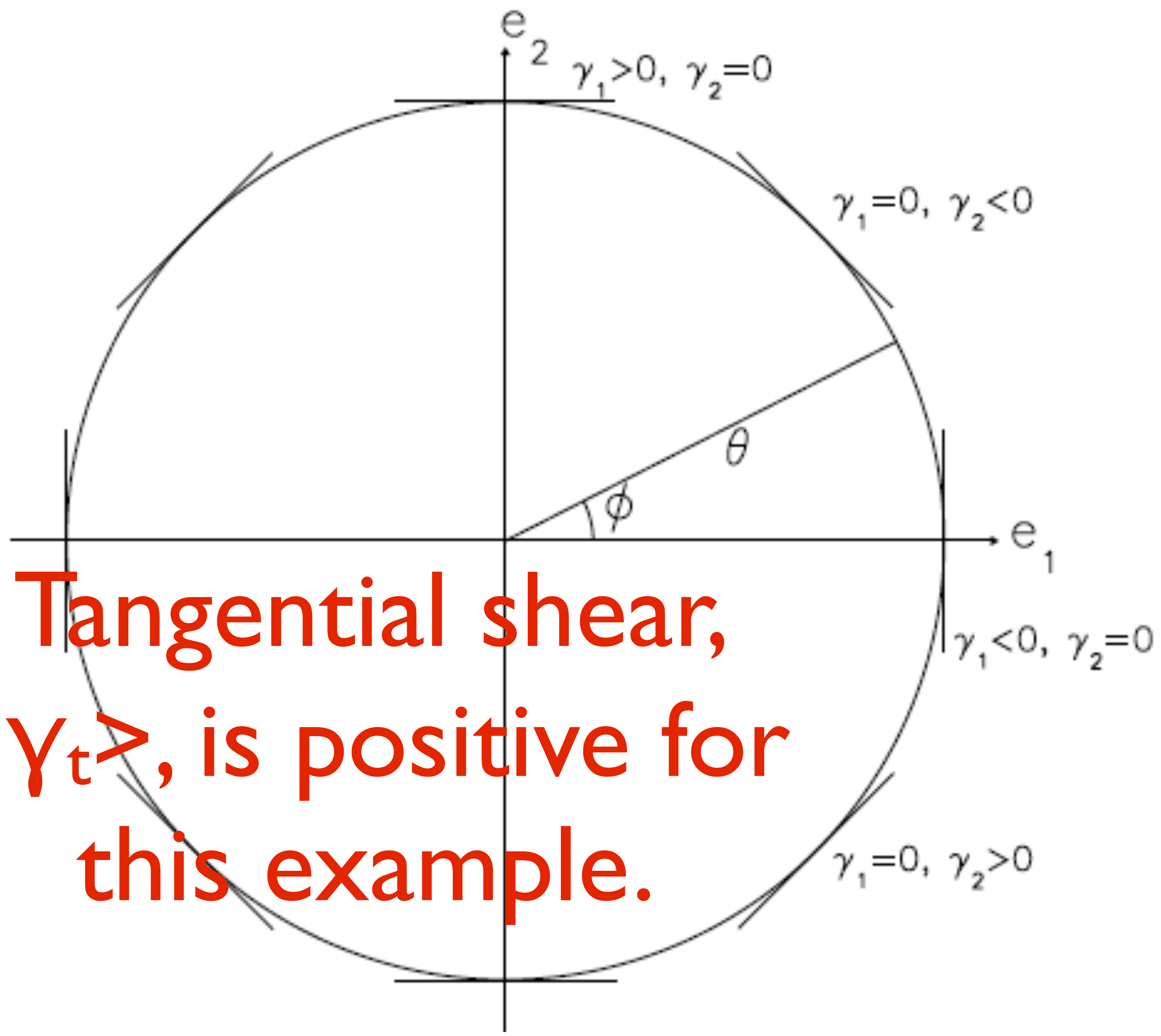
[Note the l^2 term!
(Desjacques 2008)]

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

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

Analogy to Weak Lensing

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



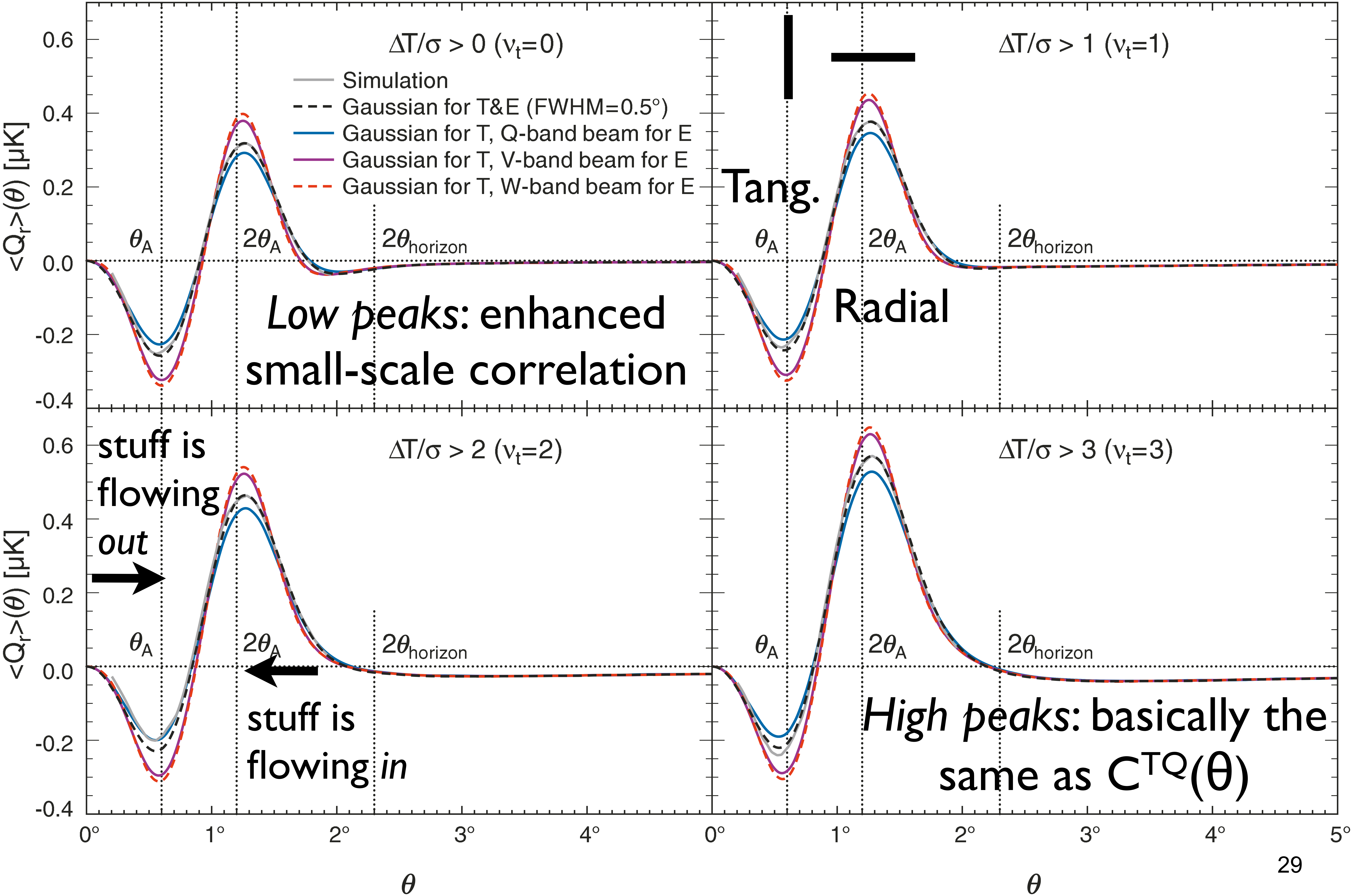
Tangential shear, $\langle\gamma_t\rangle$, is positive for this example.

$$\begin{aligned}&\Delta\Sigma(R, z_L)\\ =\ &\rho_0 b_1 \int \frac{kdk}{2\pi} P_m(k, z_L) J_2(kR)\end{aligned}$$

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



Tang.

Radial

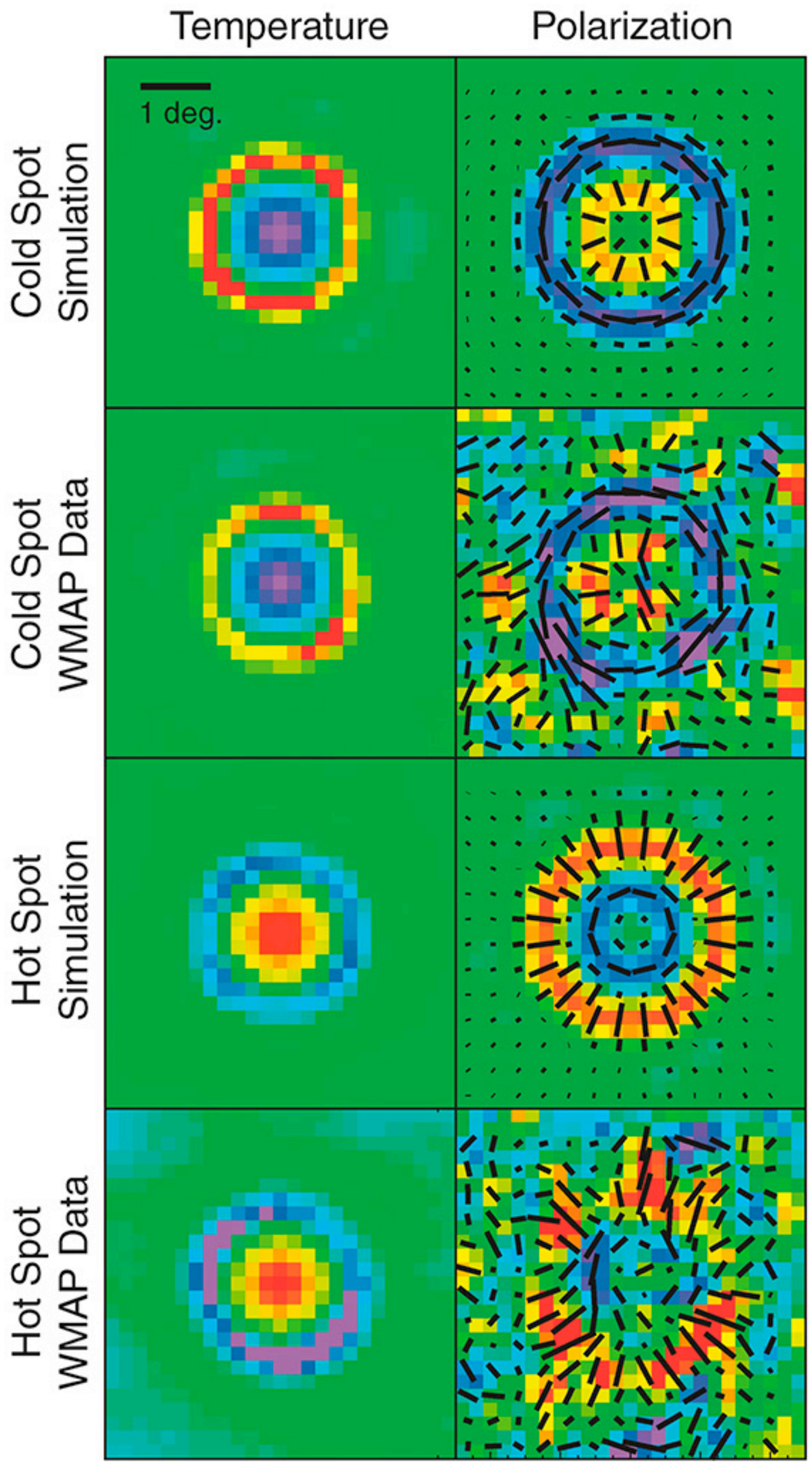
Low peaks: enhanced small-scale correlation

stuff is flowing *out*

stuff is flowing *in*

High peaks: basically the same as $C^{TQ}(\theta)$

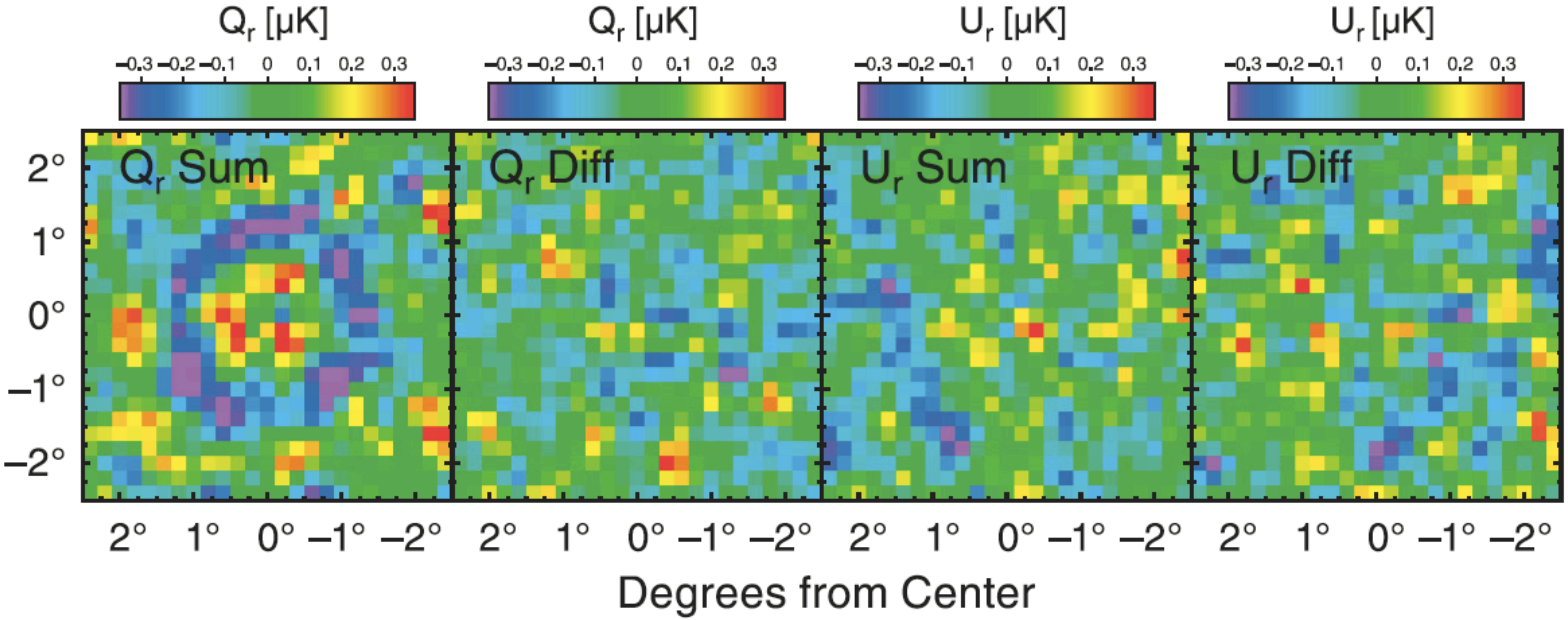
Two-dimensional View



- All hot and cold spots are stacked (the threshold peak height, ΔT/σ, 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.

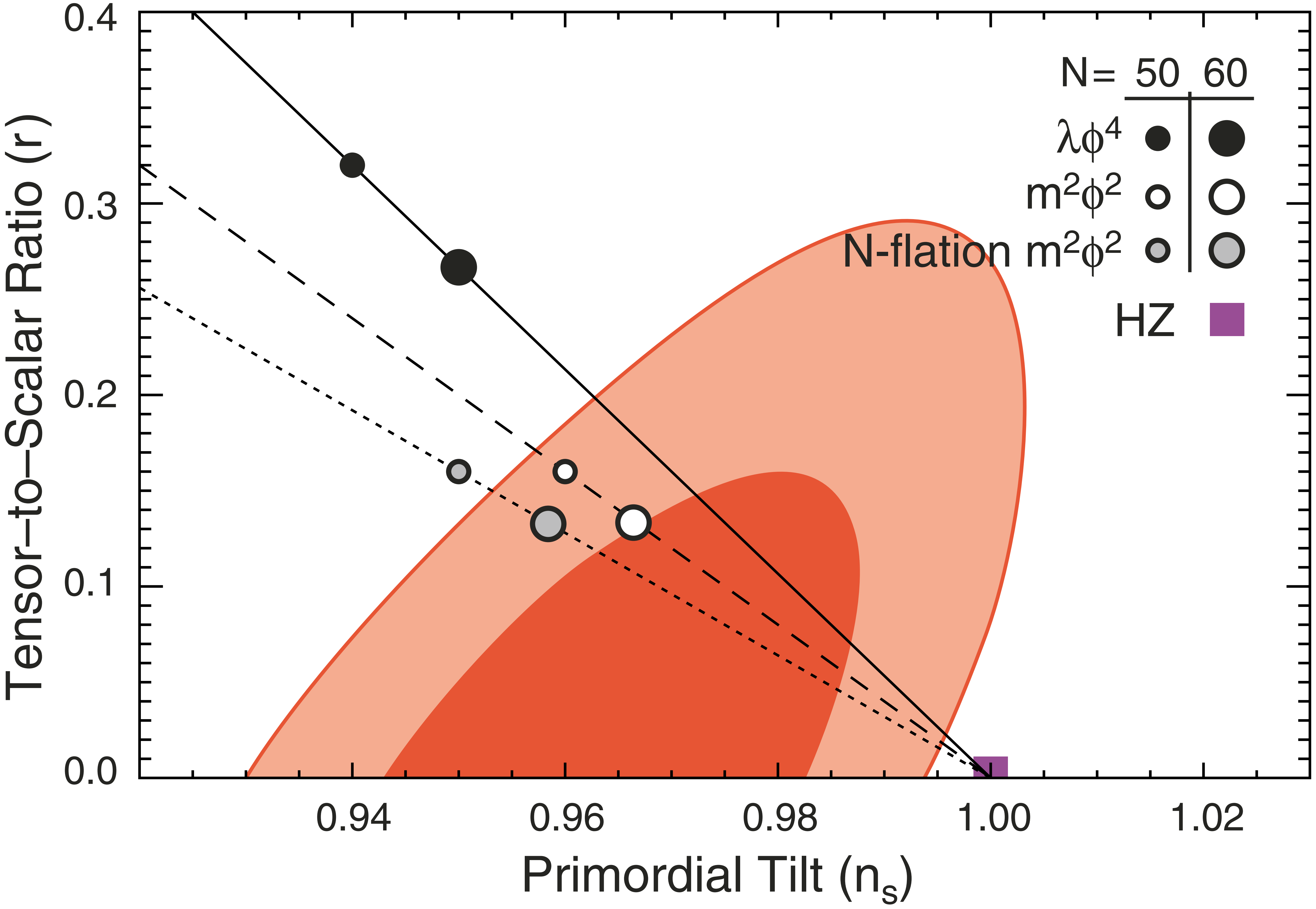
Probing Parity Violation

- 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) ± 1.5(systematic) deg.

Probing Inflation (Power Spectrum)



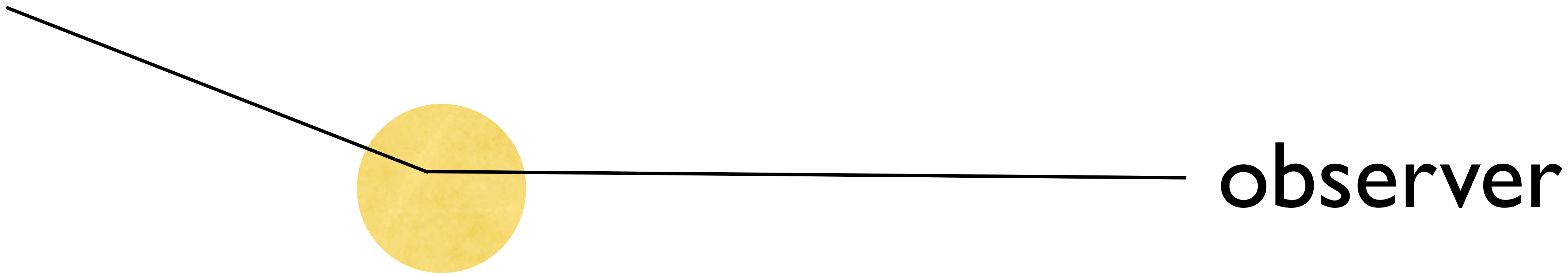
- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL; w/o SN)
  - $r < 0.20$ (95%CL; w/ SN)

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:
    - $1-n_s \approx r \approx f_{NL}^{local}$, $f_{NL}^{equilateral} = 0 = f_{NL}^{orthogonal}$.

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**

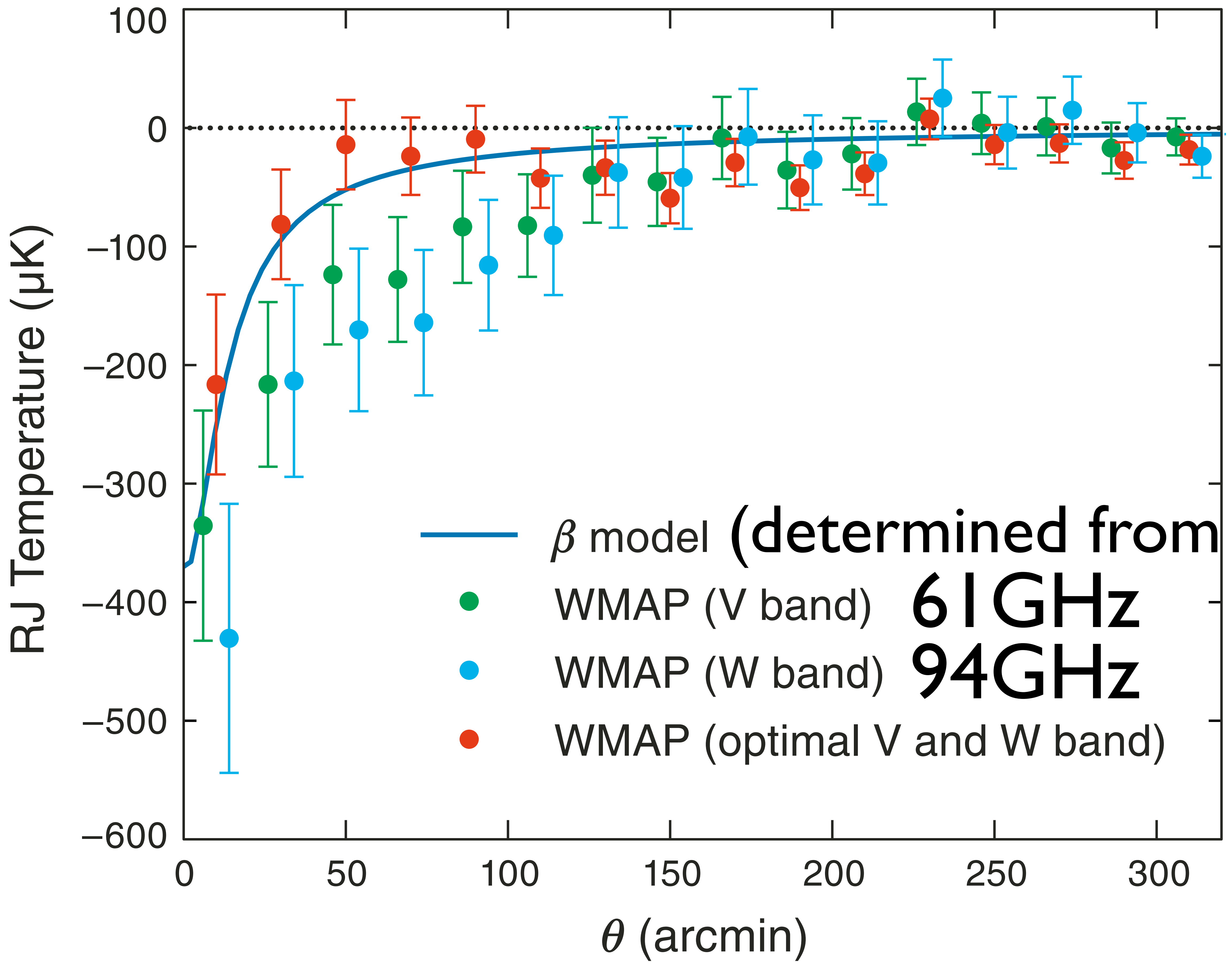
$$y = (\text{optical depth of gas})\, k_BT_e/(m_ec^2)$$
$$= [\sigma_T/(m_ec^2)] \int n_ek_BT_e\, d(\text{los})$$
$$= [\sigma_T/(m_ec^2)] \int (\text{electron pressure}) d(\text{los})$$

$g_\nu=-2$ $(\nu=0)$; -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!)

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



(determined from X-ray)

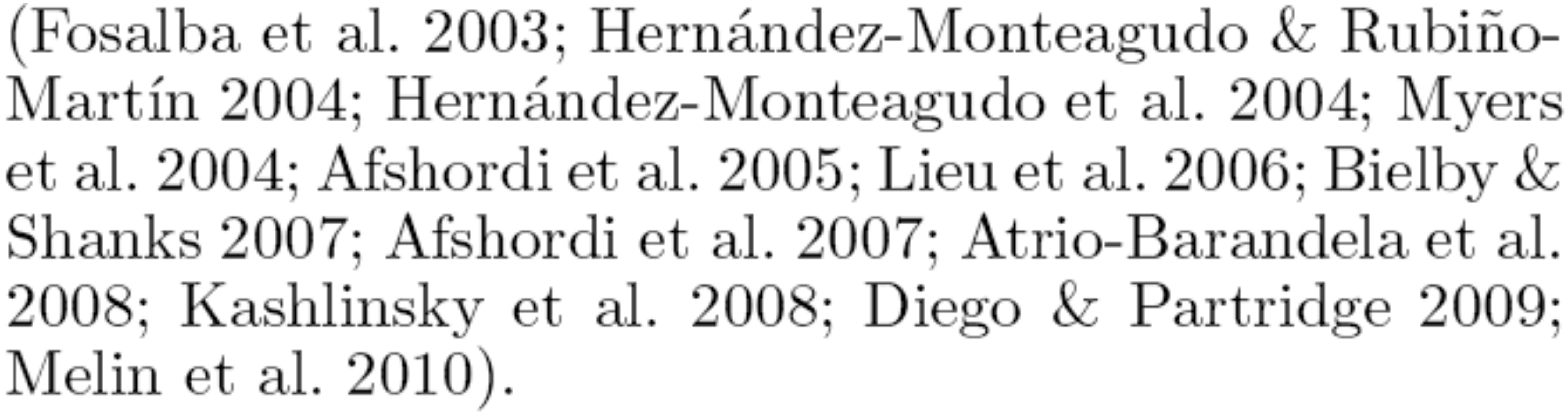
61GHz $g_\nu=-1.81$

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**.

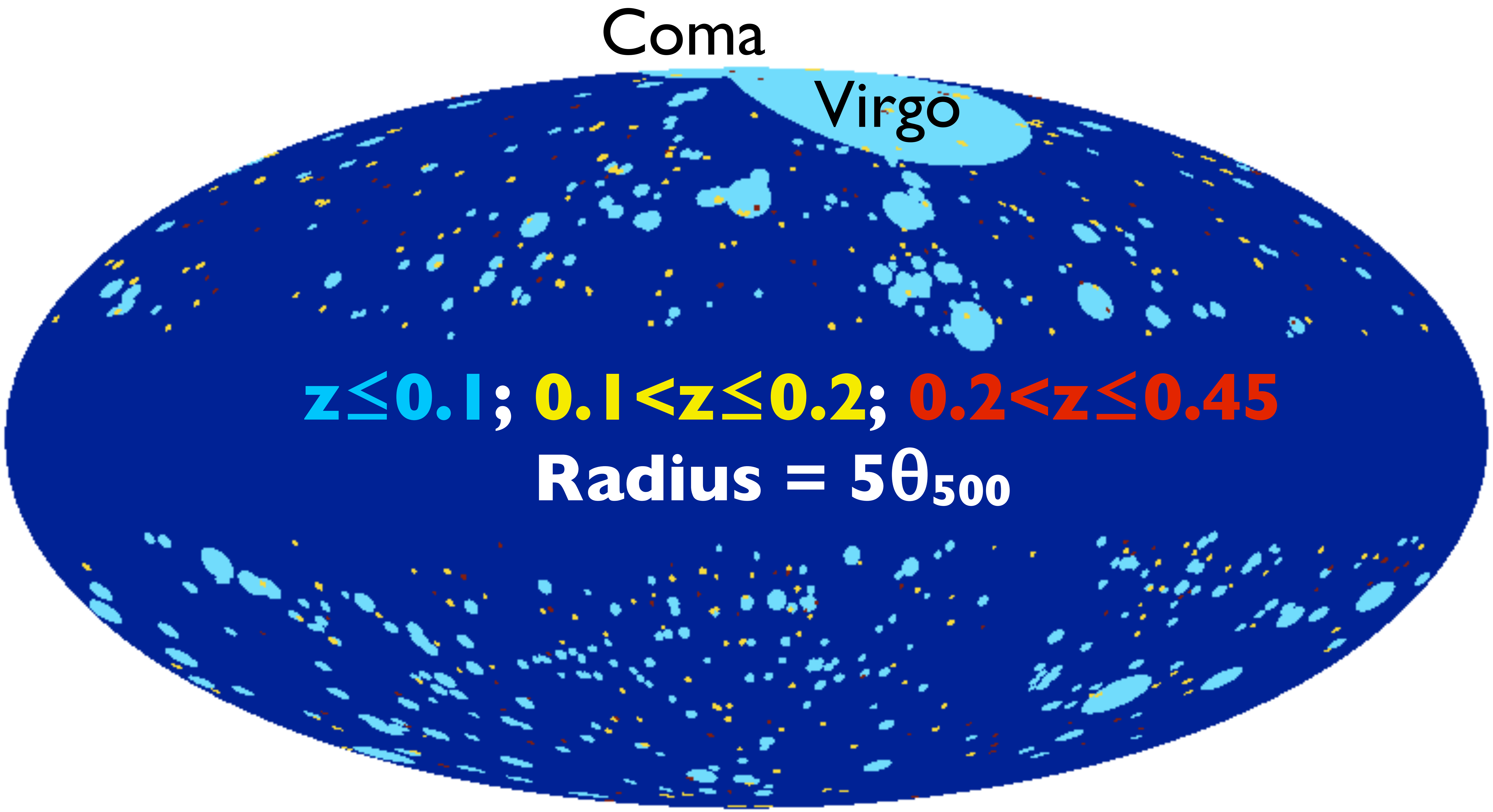
Statistical Detection of SZ

- 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:



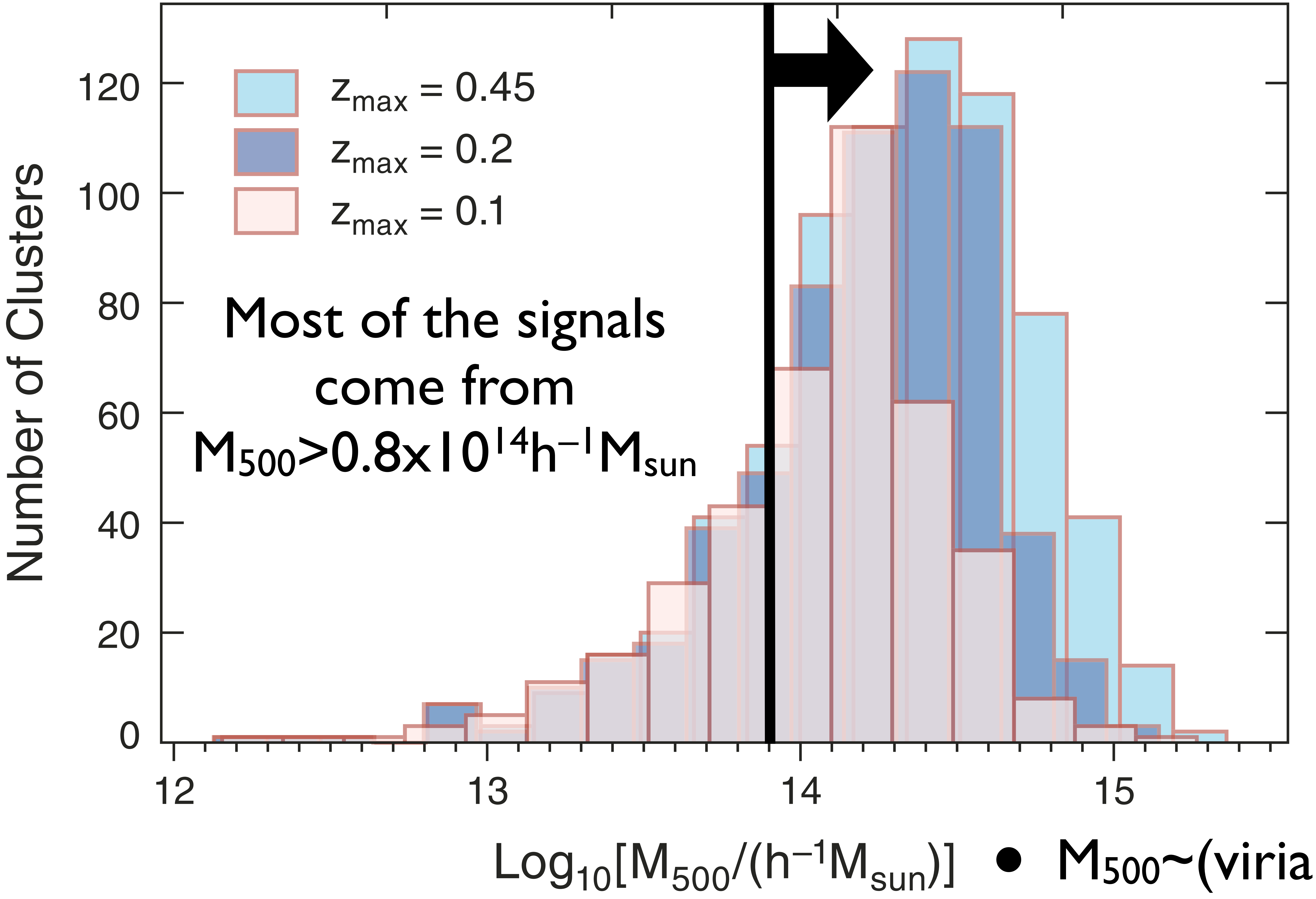
(Fosalba et al. 2003; Hernández-Monteagudo & Rubiño-Martín 2004; Hernández-Monteagudo et al. 2004; Myers et al. 2004; Afshordi et al. 2005; Lieu et al. 2006; Bielby & Shanks 2007; Afshordi et al. 2007; Atrio-Barandela et al. 2008; Kashlinsky et al. 2008; Diego & Partridge 2009; Melin et al. 2010).

ROSAT Cluster Catalog



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

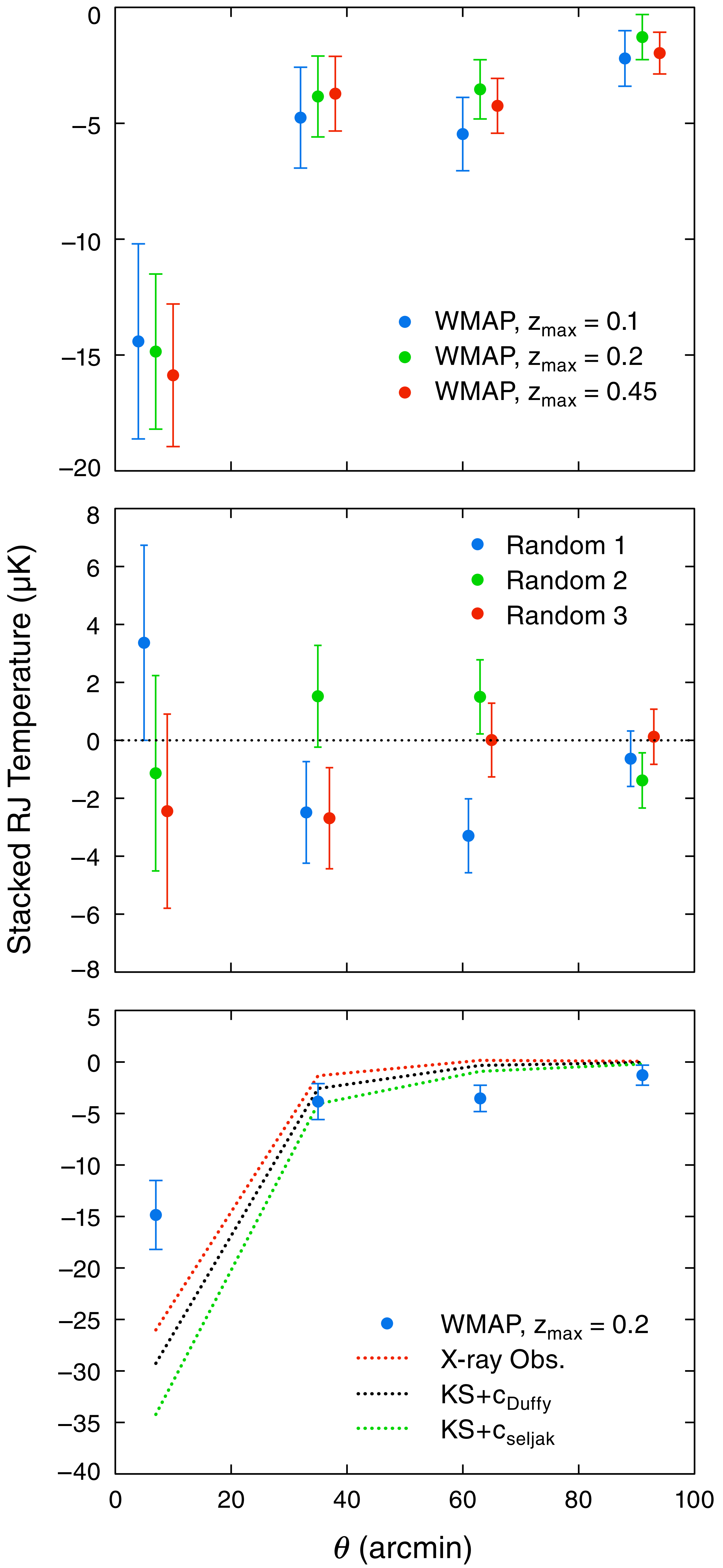
Mass Distribution



Most of the signals come from $M_{500}>0.8\times10^{14}h^{-1}M_{sun}$

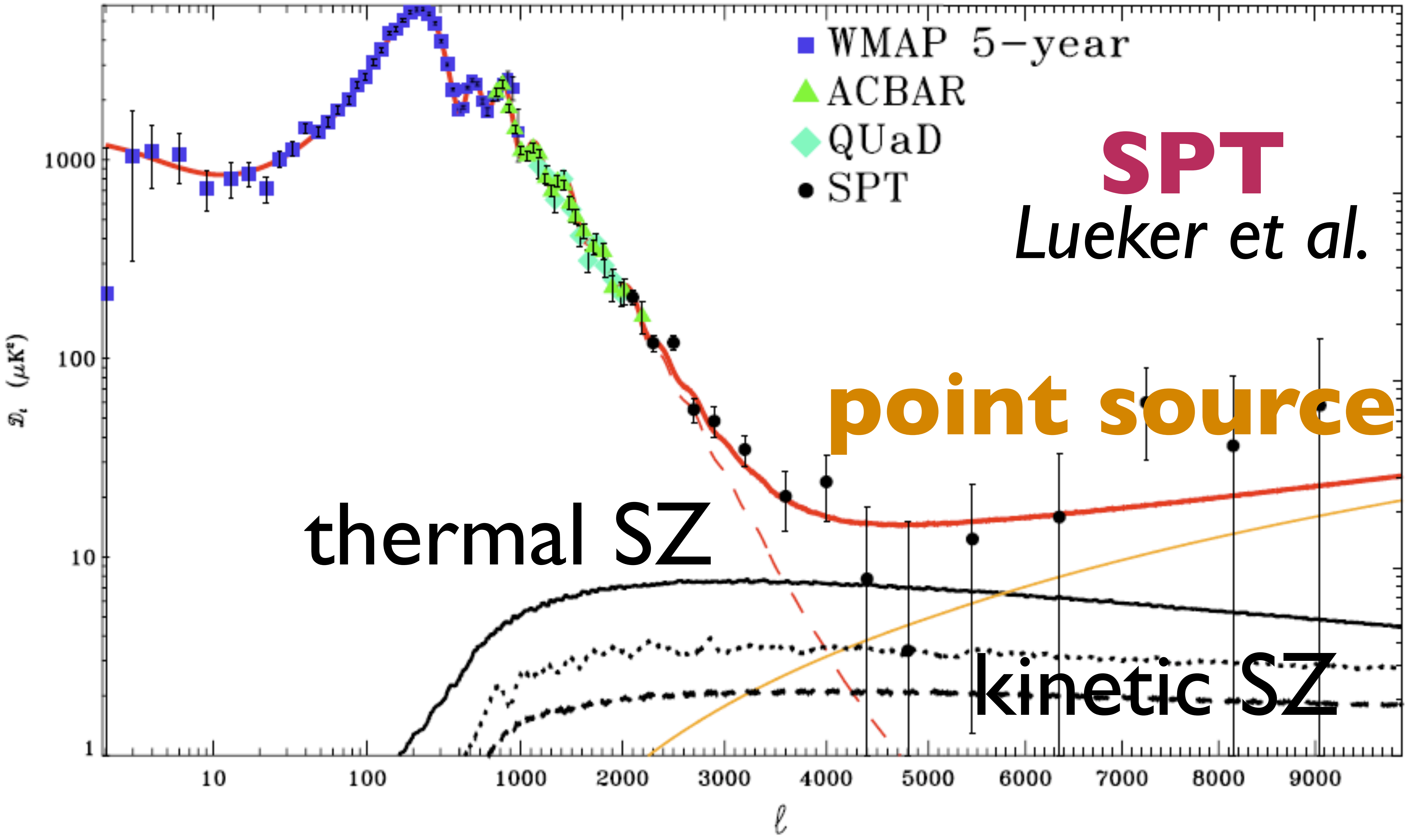
- M_{500}~(virial mass)/1.6

Angular Profiles

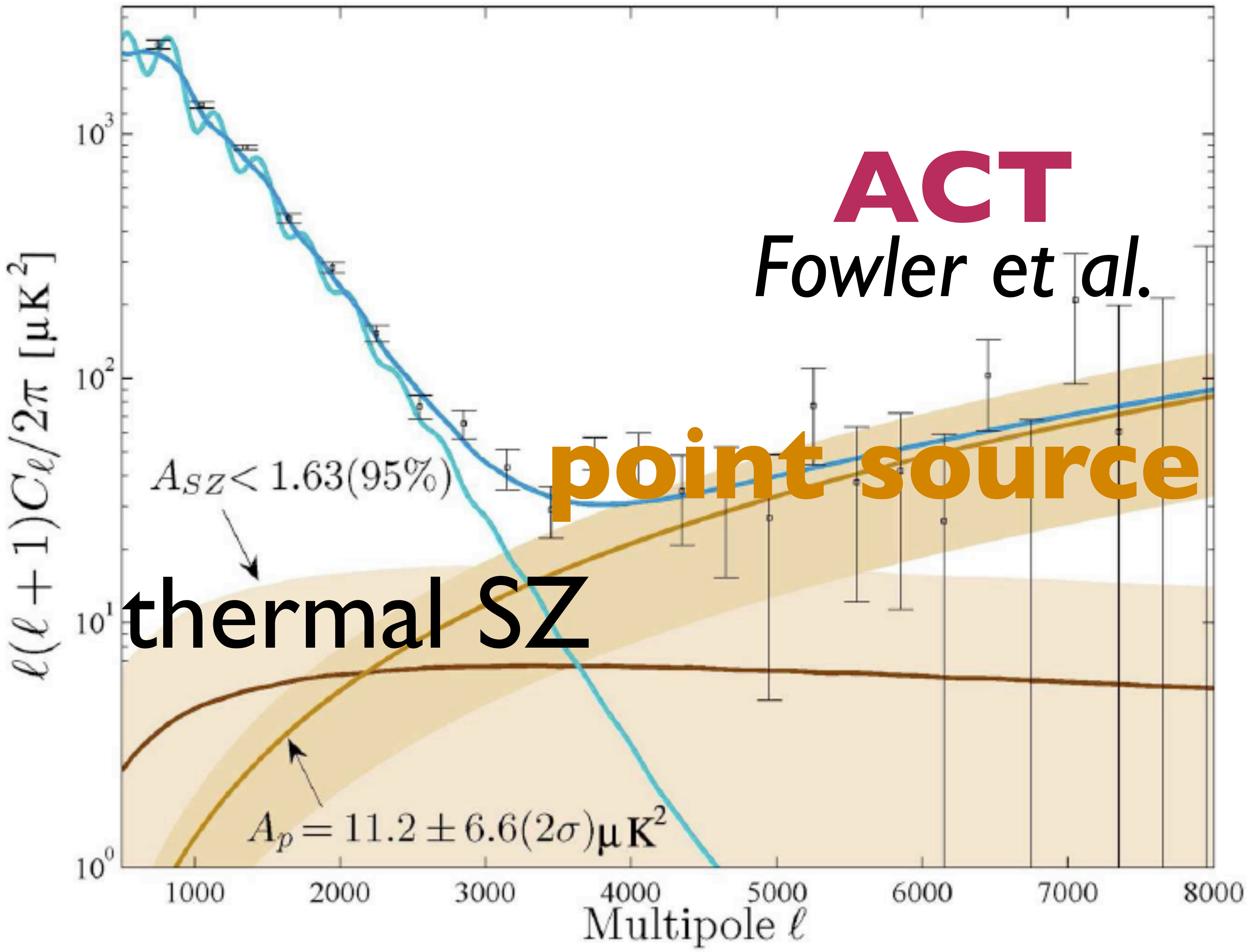


- (Top) Significant detection of the SZ effect.
- (Middle) Repeating the same analysis on the random locations on the sky does not reveal any noticeable bias.
- (Bottom) Comparison to the expectations. **The observed SZ ~ 0.5–0.7 times the expectations.** Why?

Small-scale CMB Data



SPT
Lueker et al.
point source
thermal SZ
kinetic SZ



ACT
Fowler et al.
point source
thermal SZ

- 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

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

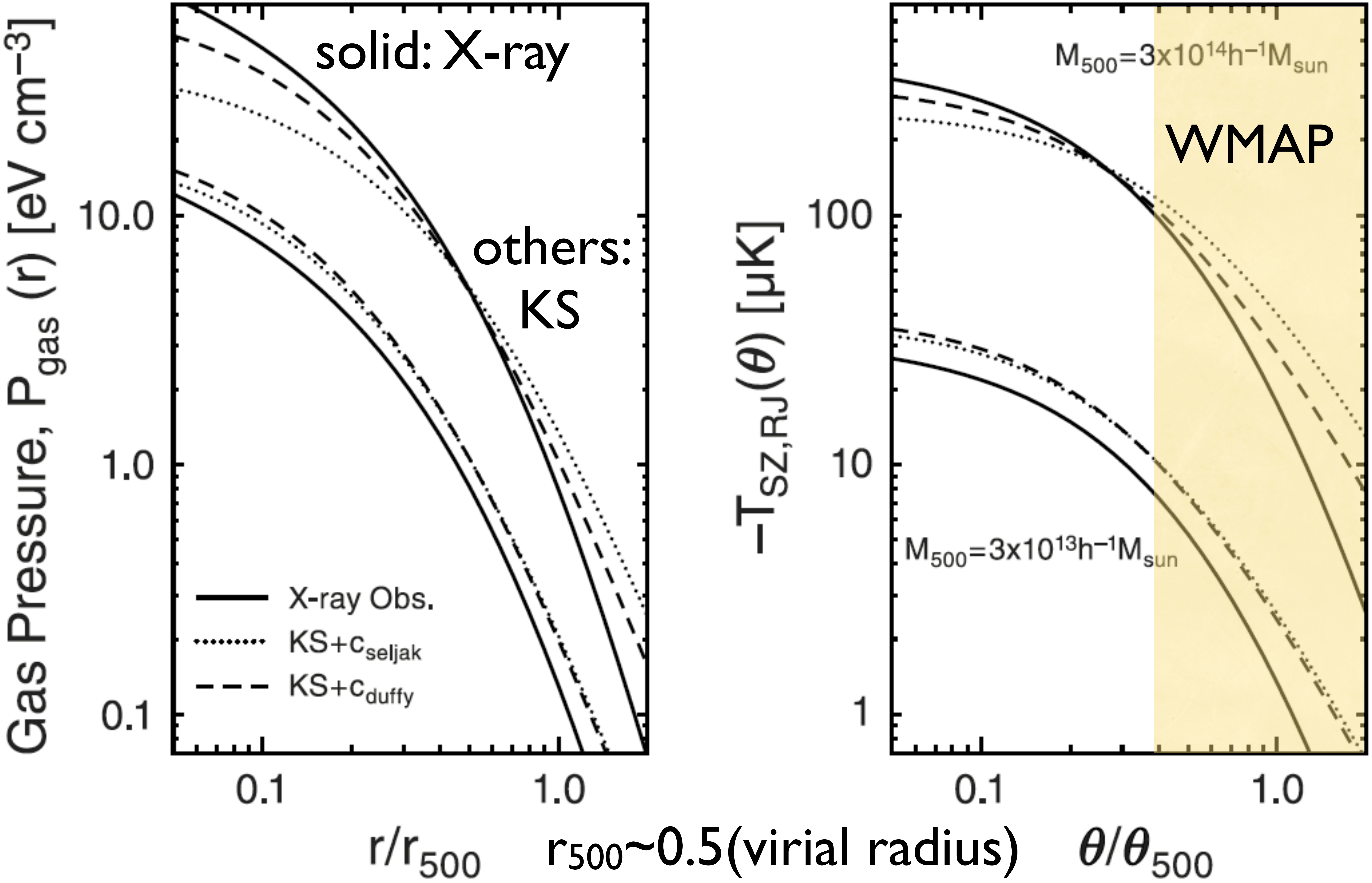
$$\frac{l(l+1)C_l}{2\pi} \simeq 330\,\mu\mathrm{K}^2\,\sigma_8^7 \left(\frac{\Omega_\mathrm{b} h}{0.035}\right)^2 \text{x [gas pressure]}$$

- 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.



solid: X-ray

others: KS

WMAP

r_{500}~0.5(virial radius)

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

Size-Luminosity Relations

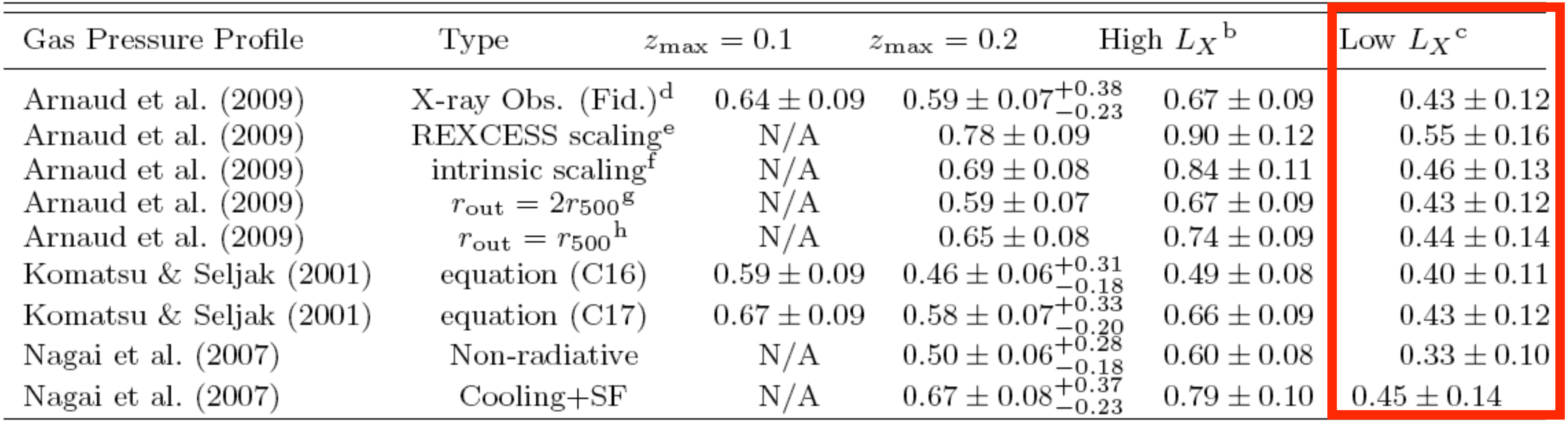
- To calculate the expected pressure profile for each cluster, we need to know the size of the cluster, r_{500}.
- This needs to be derived from the observed properties of X-ray clusters.
  - The best quantity is the gas mass times temperature, but this is available only for a small subset of clusters.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

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

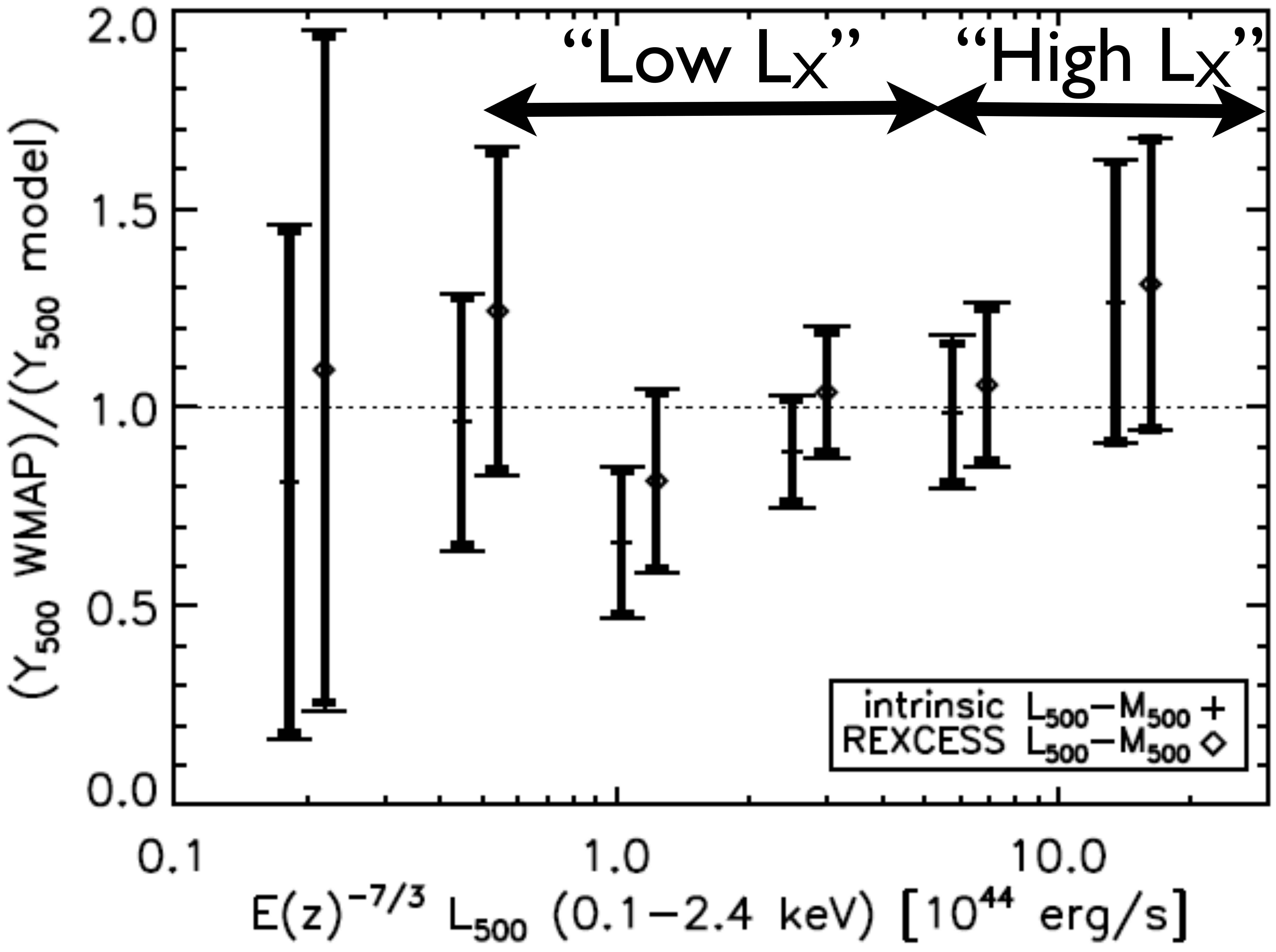
Missing P in Low Mass Clusters?



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)	$r_{\rm out} = 2r_{500}$[g]	N/A	0.59 ± 0.07	0.67 ± 0.09	0.43 ± 0.12
Arnaud et al. (2009)	$r_{\rm out} = r_{500}$[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

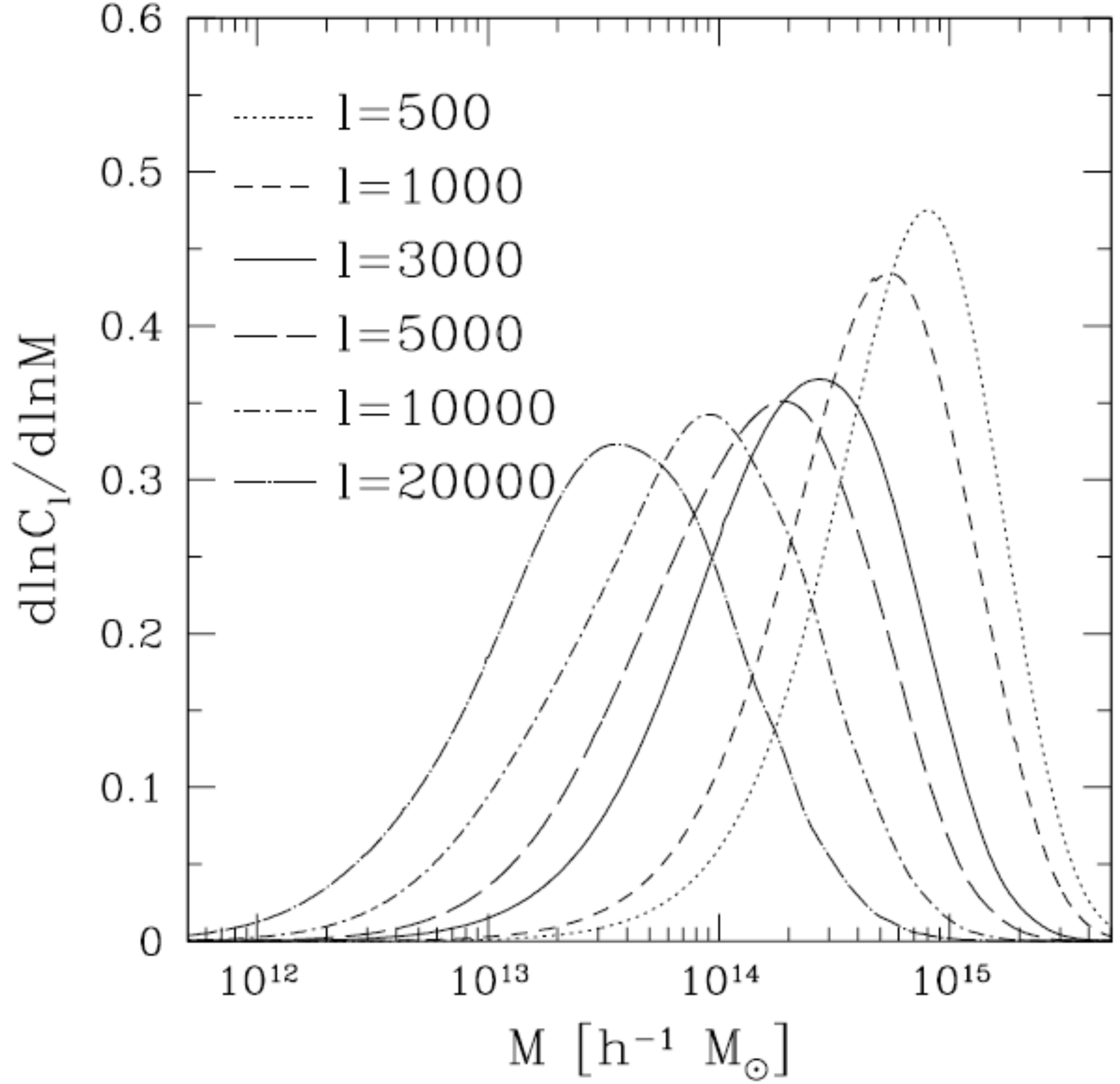
- One picture has emerged:
  - "High L_X" clusters [$M_{500} > 4 \times 10^{14}\ h^{-1} M_{\rm sun}$] can be brought into agreement with the expectations by playing with the r_{500}–L_X relation.
  - "Low L_X" clusters reveal a significant *missing pressure.*

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) ± 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.