

The 7-Year WMAP Observations: Cosmological Interpretation

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Cosmology Seminar, Perimeter Institute, April 27, 2010

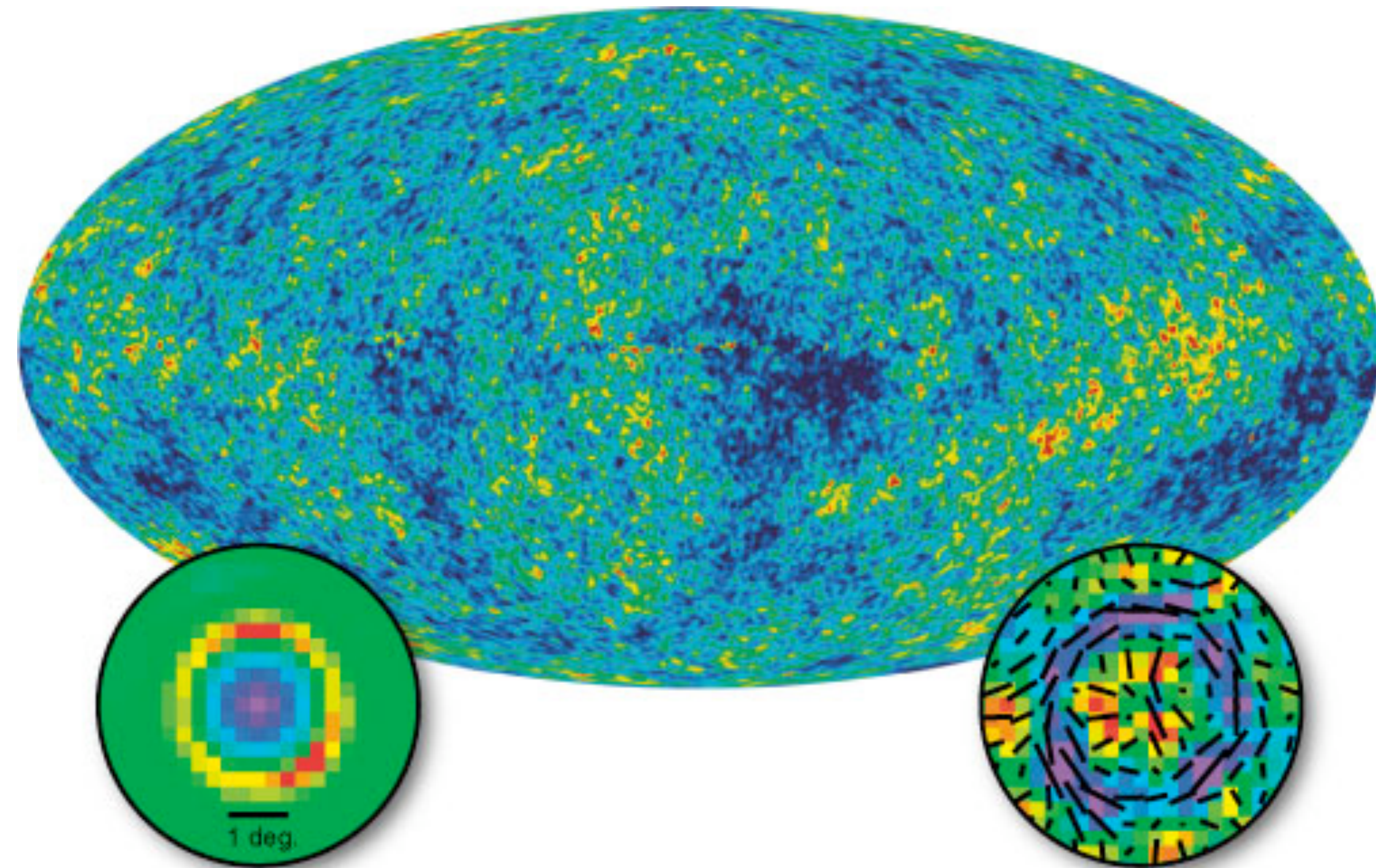
WMAP will have collected 9 years of data by August

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



Stacked Temperature

Stacked Polarization

● **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](#)

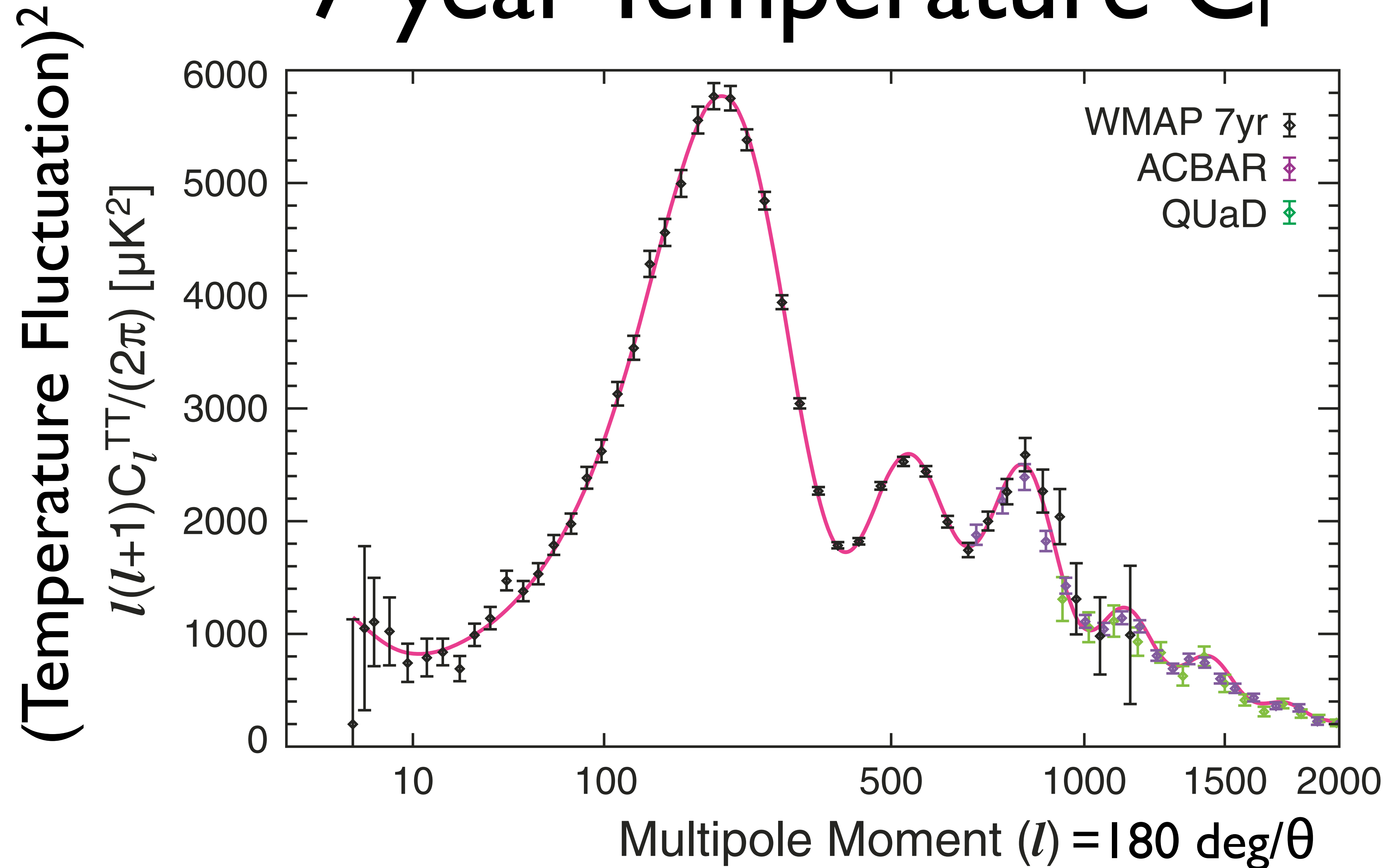
WMAP 7-Year Science Team

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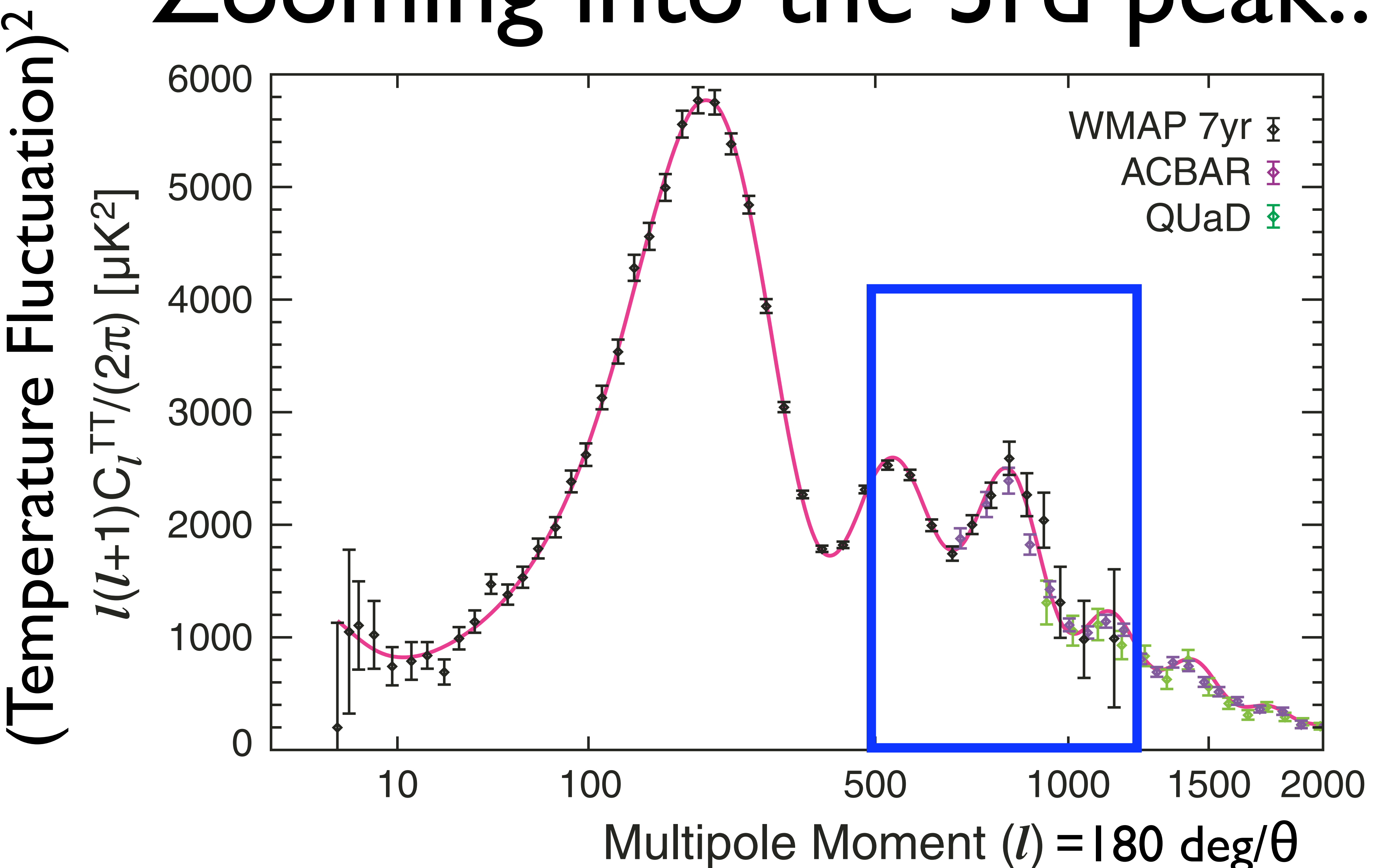
7-year Science Highlights

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

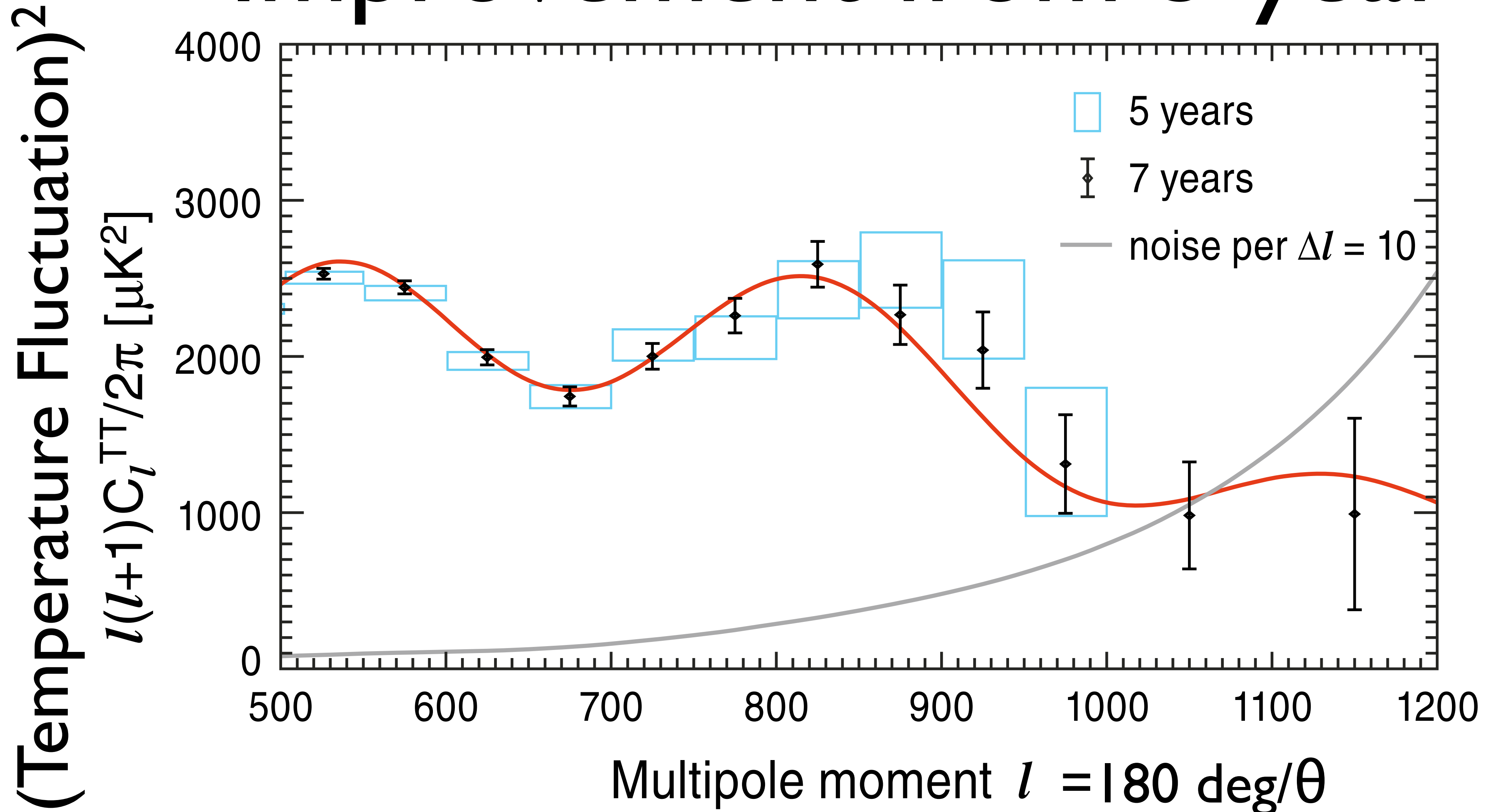
7-year Temperature C_l



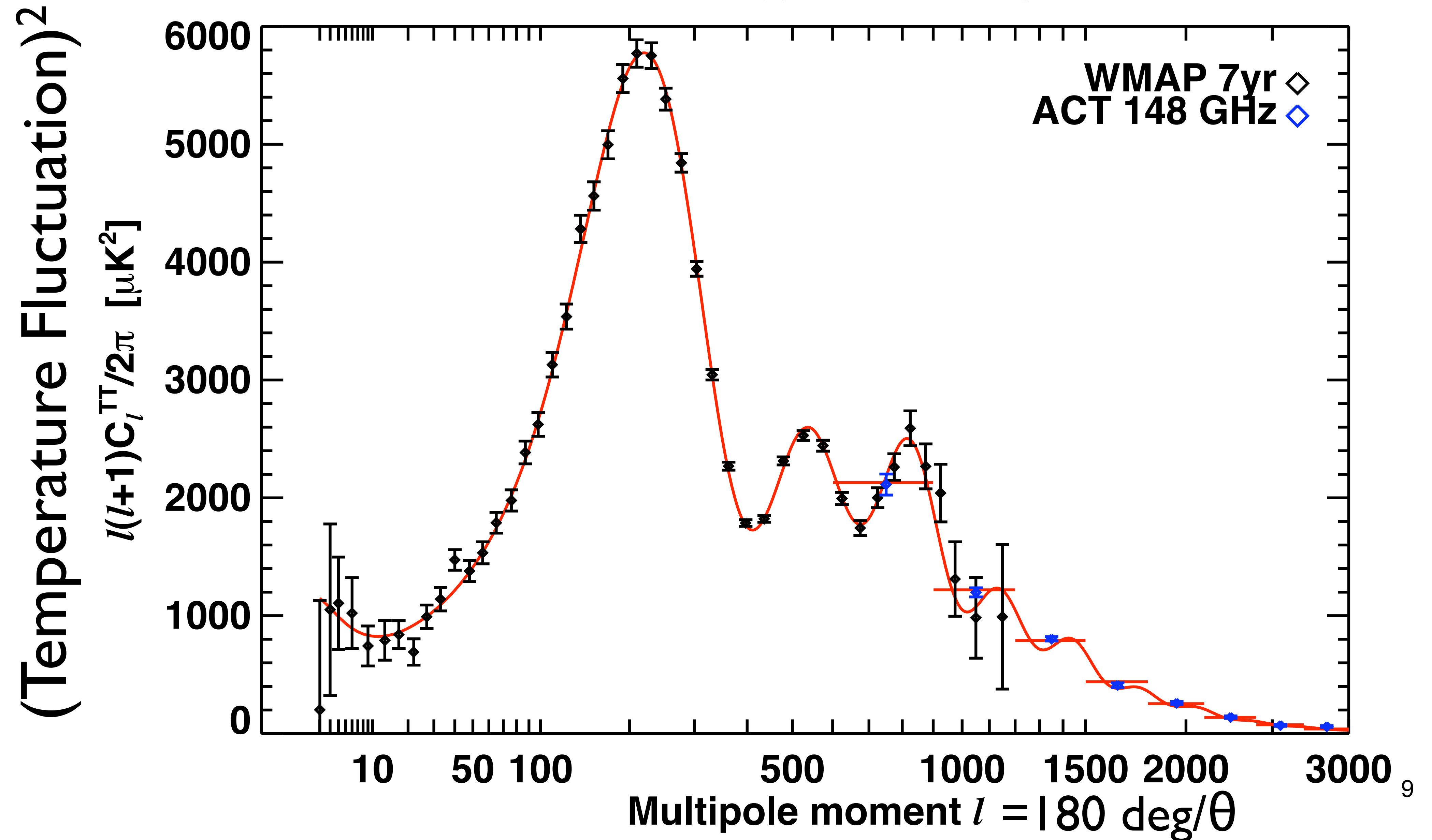
Zooming into the 3rd peak...



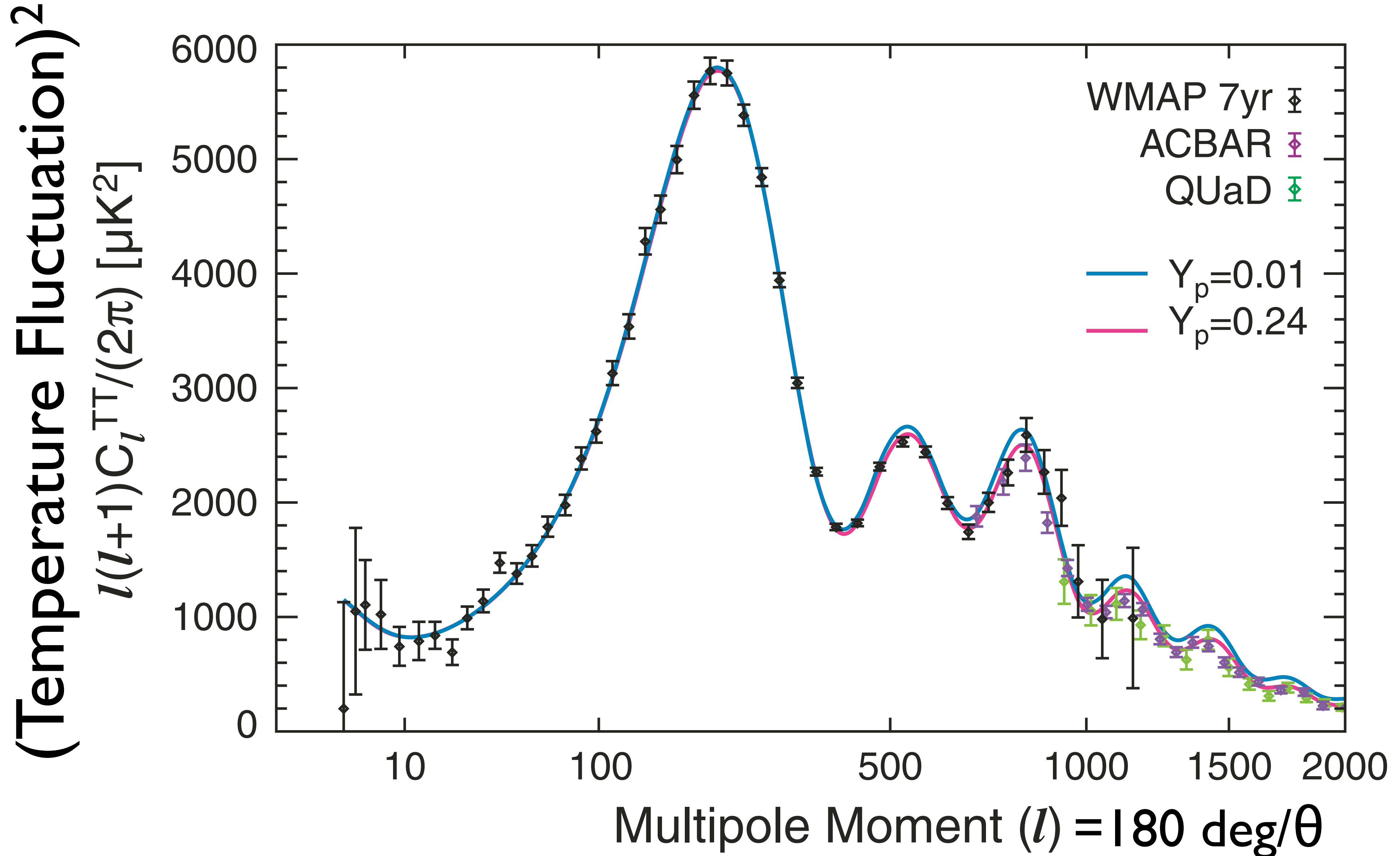
High- l Temperature C_l : Improvement from 5-year



WMAP and ACT



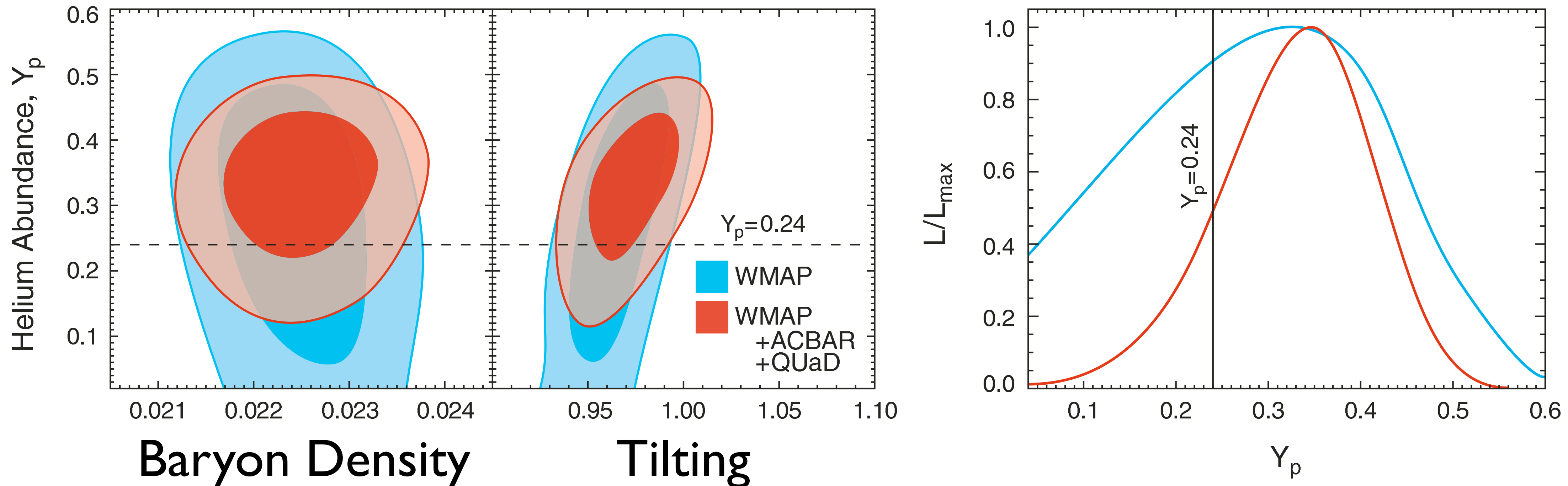
Detection of Primordial Helium



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 $z \sim 1800$, 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 $n_s \dots$

WMAP + higher- l CMB = Detection of Helium

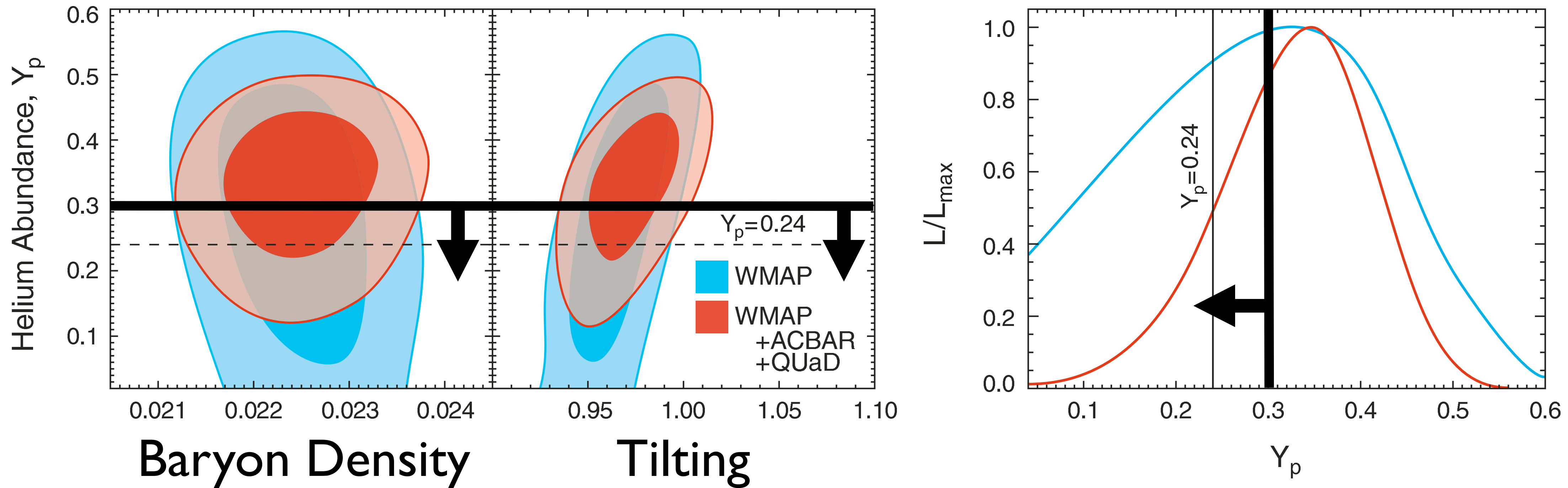


- The combination of WMAP and high- l CMB data (ACBAR and QUaD) is powerful enough to isolate the effect of helium: **$Y_p = 0.33 \pm 0.08$** (68%CL)

Why this can be useful

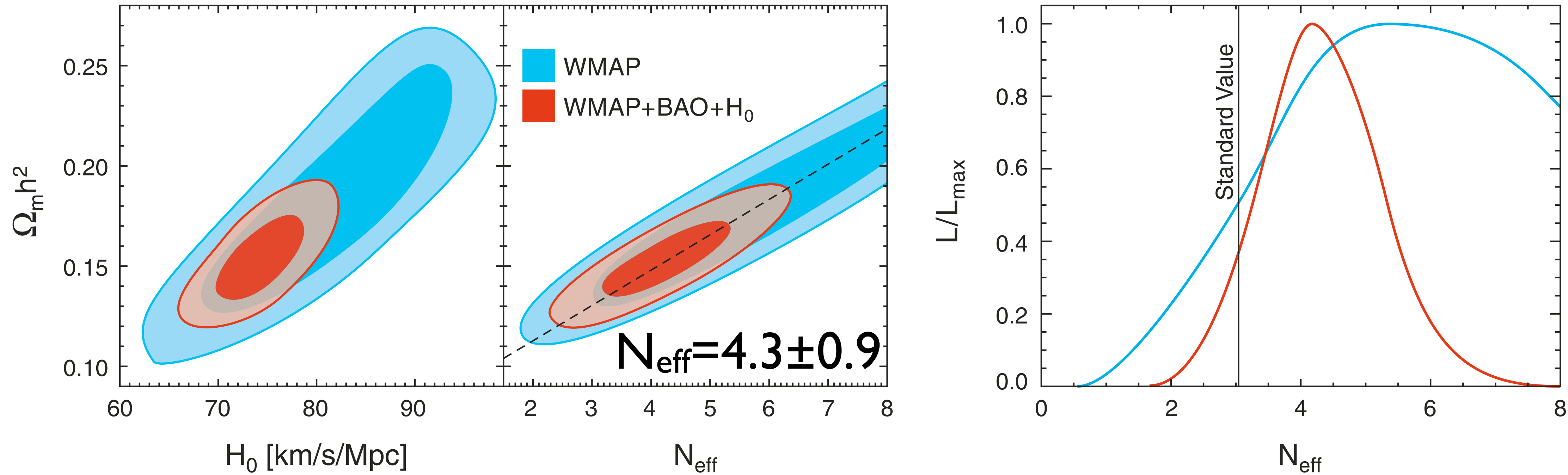
- The helium abundance has been measured from Sun and ionized regions (HII regions); however, as helium can be produced in the stellar core, one has to extrapolate the measured Y_p to the zero-metallicity values.
- In other words, the traditional methods give a robust **upper limit** on Y_p : $Y_p <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

$$0.23 < Y_p < 0.3 \quad (68\% \text{CL})$$



- 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

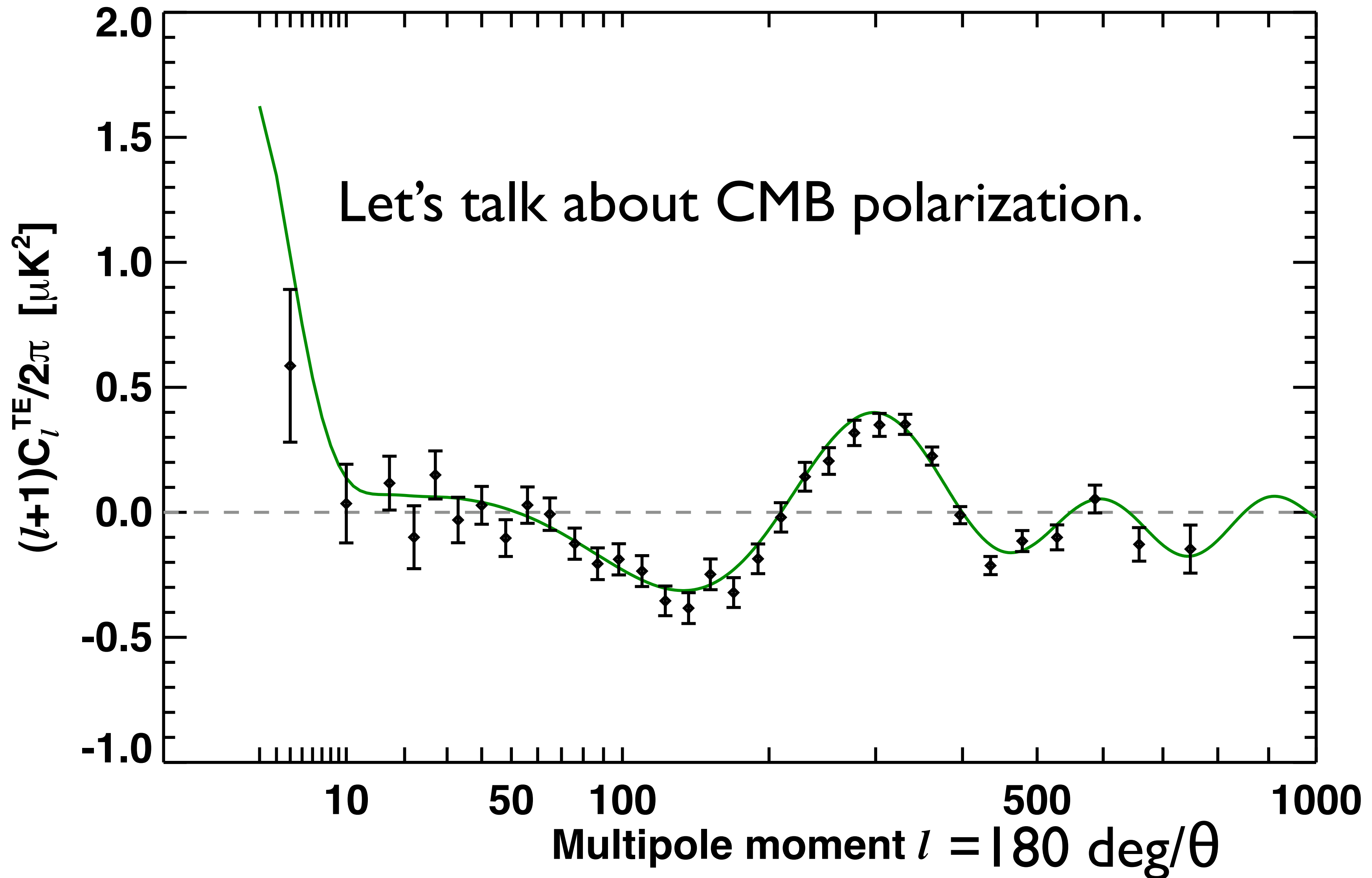


$$N_{\text{eff}} = 3.04 + 7.44 \left(\frac{\Omega_m h^2}{0.1308} \frac{3139}{1 + z_{\text{eq}}} - 1 \right)$$

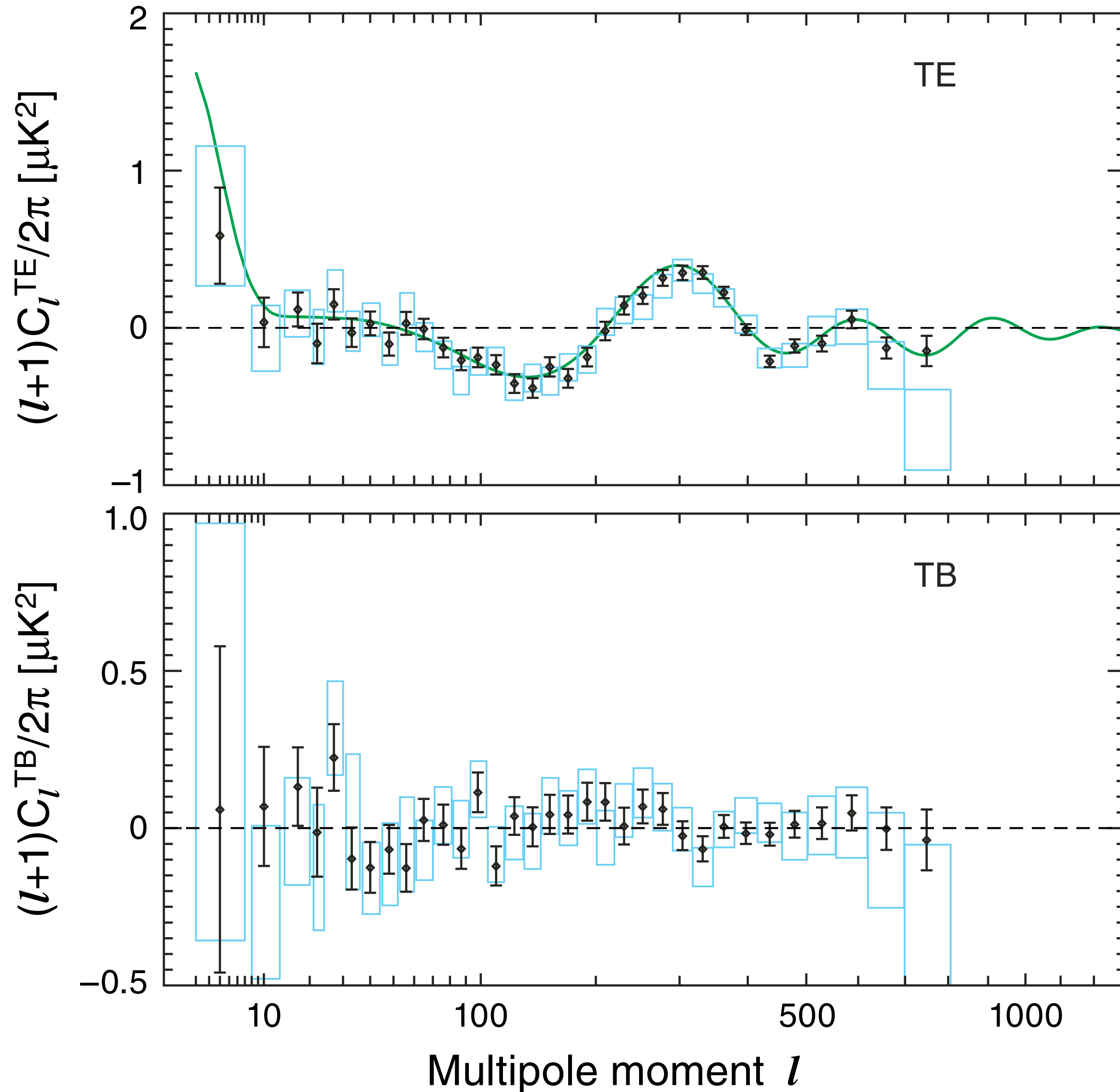
← from external data
← from 3rd peak

7-year TE Correlation

(TxPolarization Fluctuation)



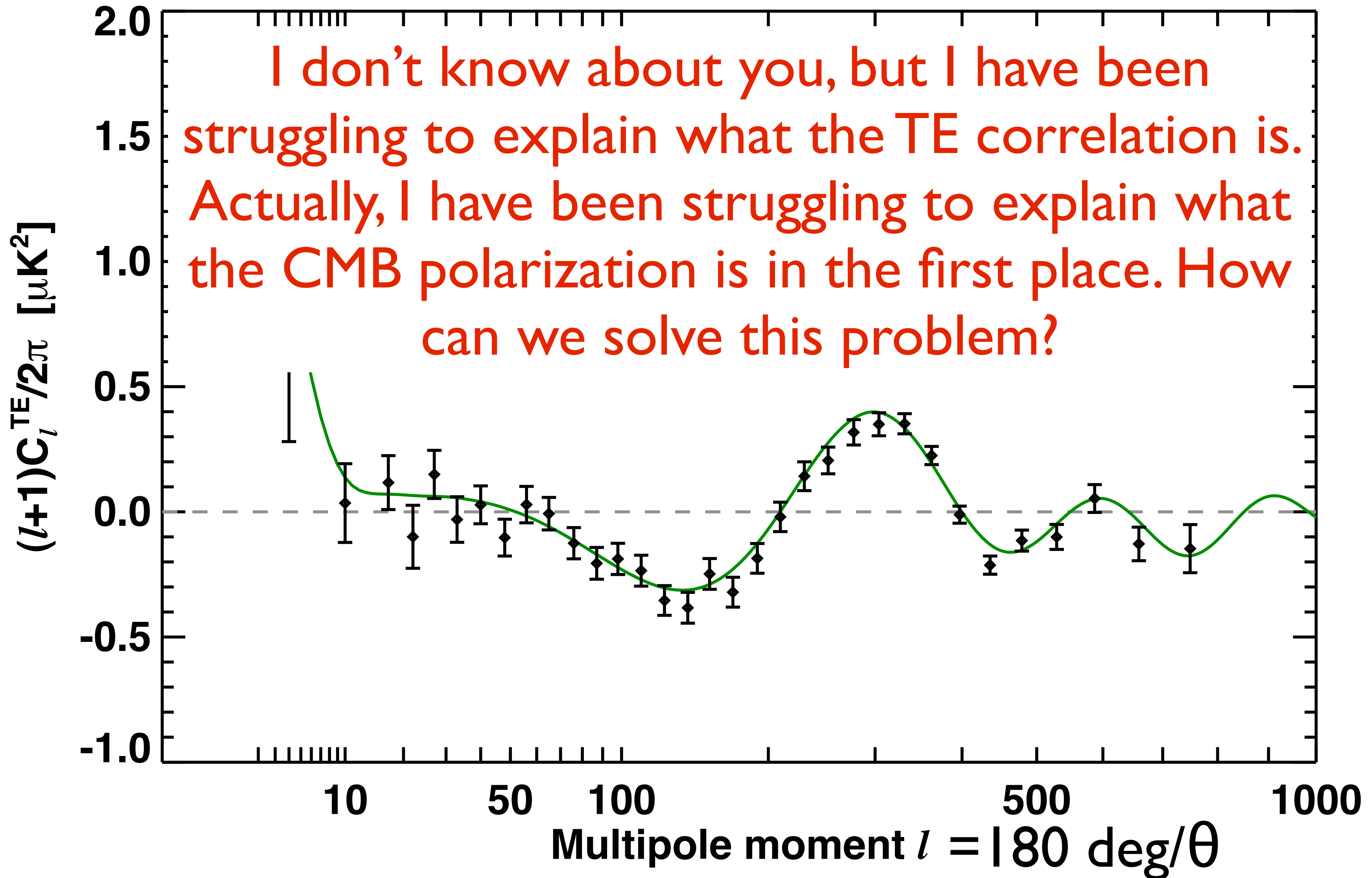
Improvements from 5-year



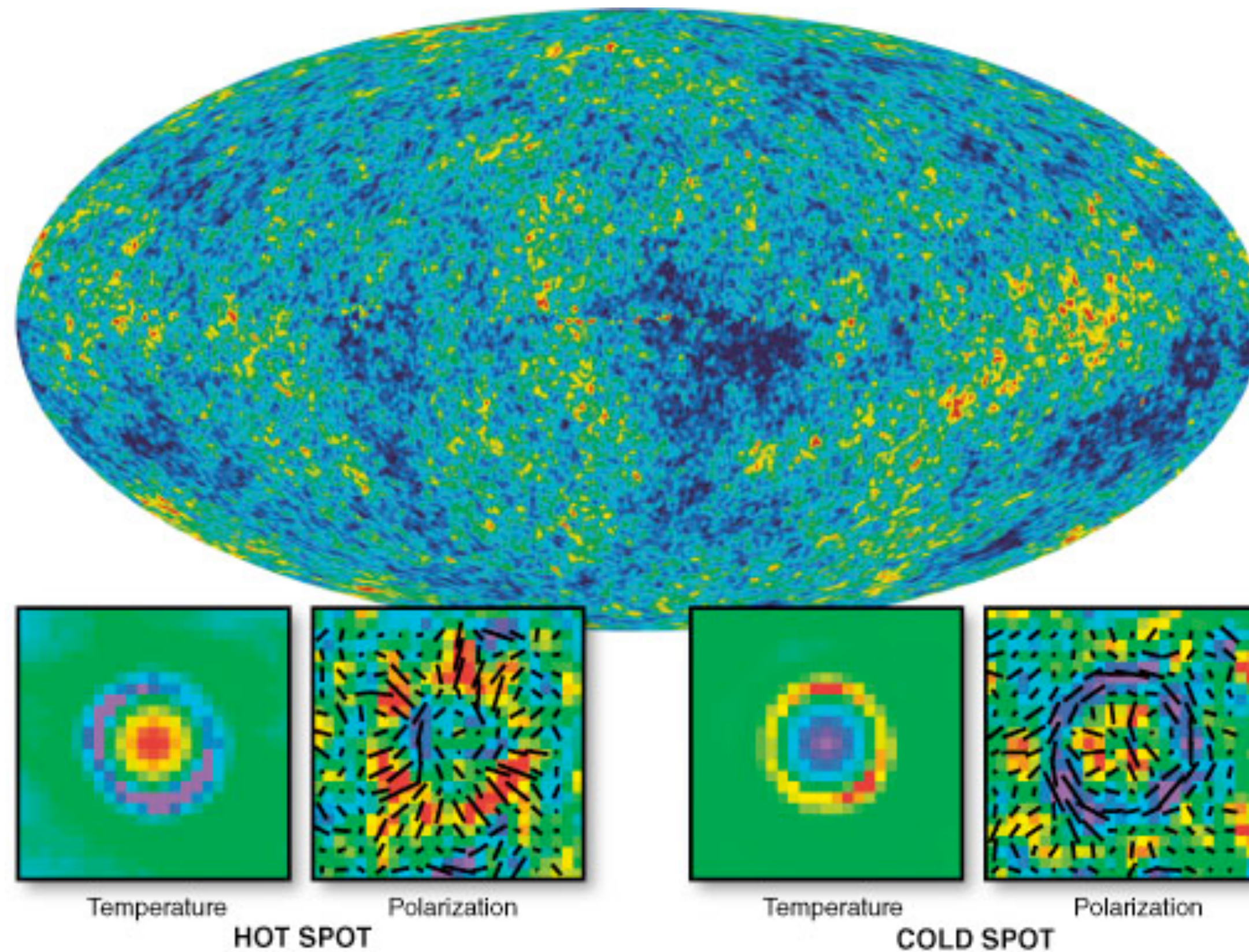
- For 5-year, we used Q and V bands to measure the high- l TE and TB. For 7-year, we also include the W-band data.
- **TE: 21σ detection!**
(It was 13σ in 5 year.)
- TB is expected to vanish in a parity-conserving universe, and it is consistent with zero.

What Are We Seeing Here?

(TxPolarization Fluctuation)

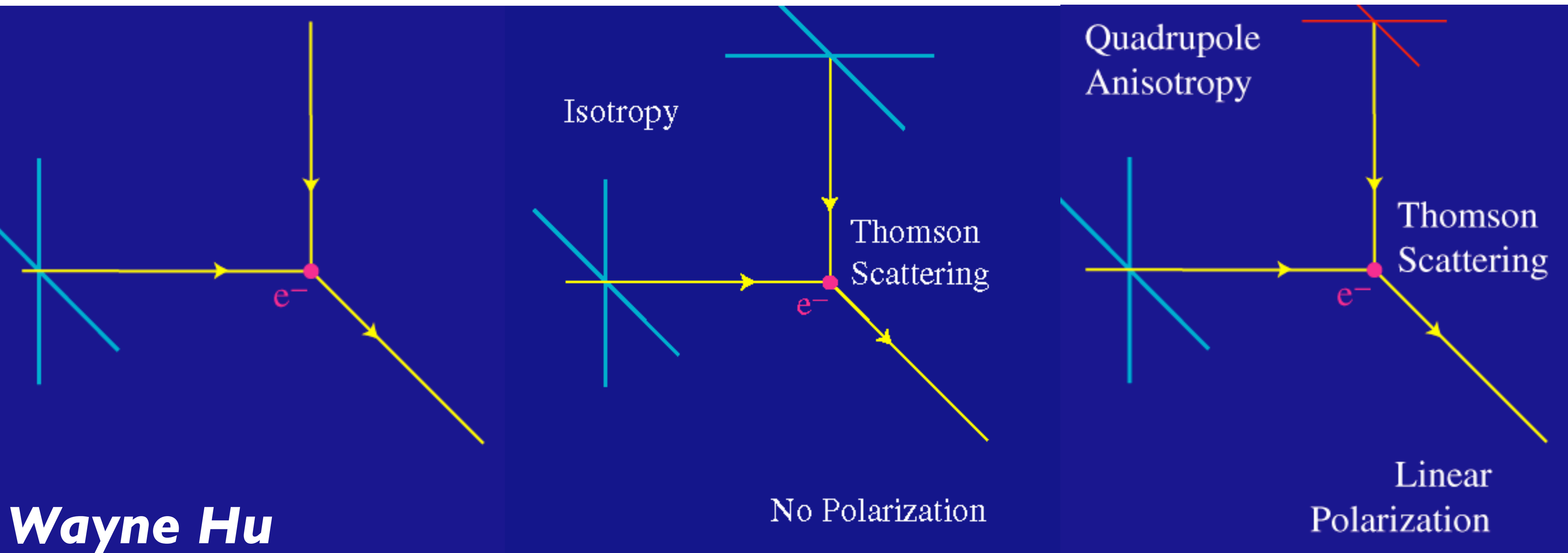


CMB Polarization On the Sky



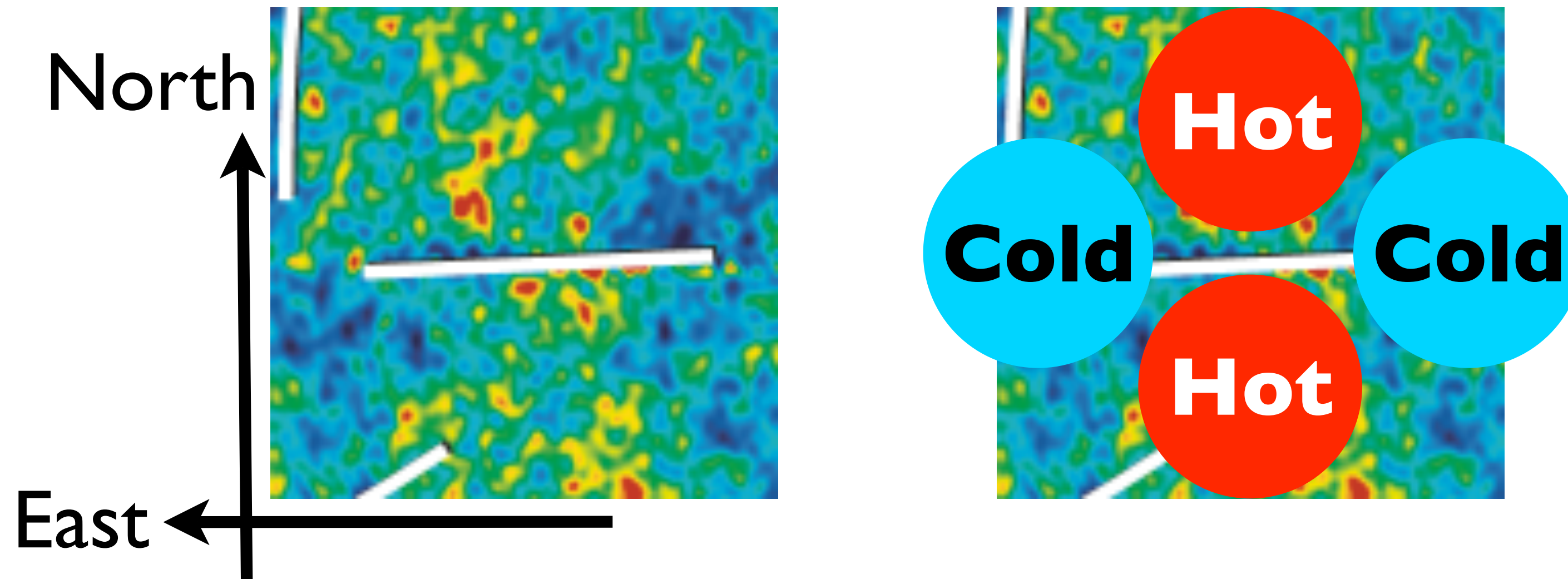
- ***Solution:* Leave Fourier space.
Go back to real space.**

CMB Polarization is a Real-space Stuff



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

Principle

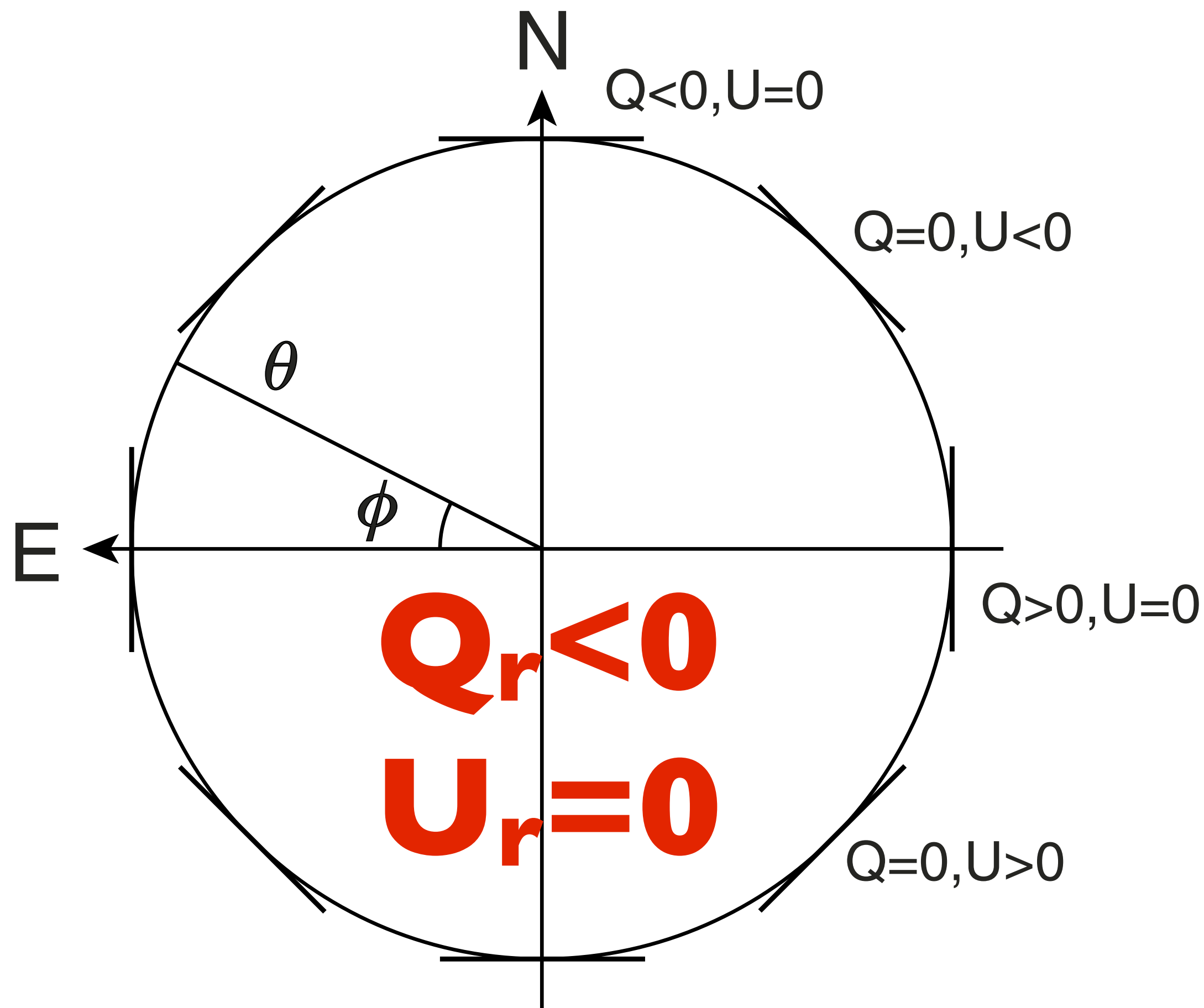


$$Q < 0; U = 0$$

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

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:

$$Q_r(\theta) = -Q(\theta) \cos(2\phi) - U(\theta) \sin(2\phi),$$

$$U_r(\theta) = Q(\theta) \sin(2\phi) - U(\theta) \cos(2\phi).$$

CMB Polarization on Large Angular Scales (>2 deg)

Matter Density



Potential

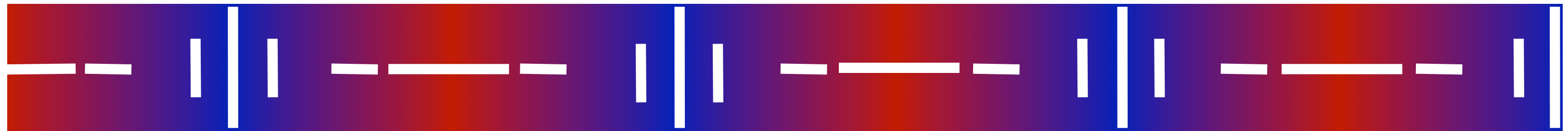


$$\Delta T/T = (\text{Newton's Gravitation Potential})/3$$

ΔT



Polarization

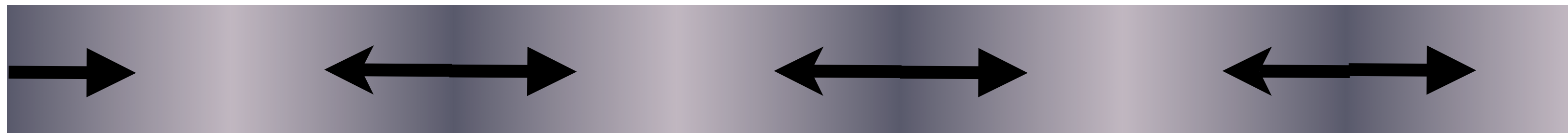


- How does the photon-baryon plasma move?

CMB Polarization Tells Us How Plasma Moves at $z=1090$

Zaldarriaga & Harari (1995)

Matter Density

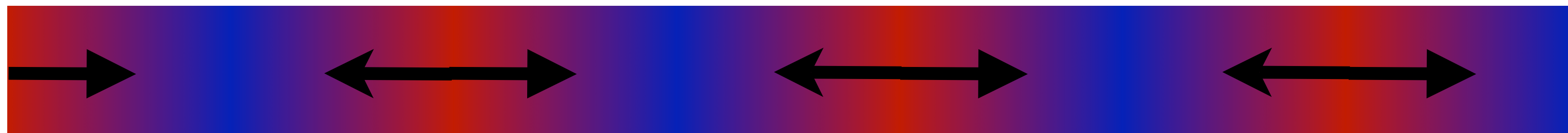


Potential

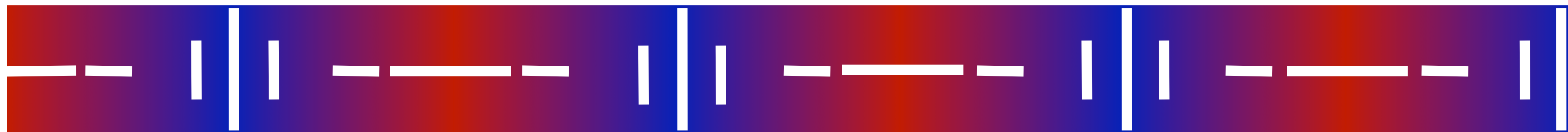


$$\Delta T/T = (\text{Newton's Gravitation Potential})/3$$

ΔT

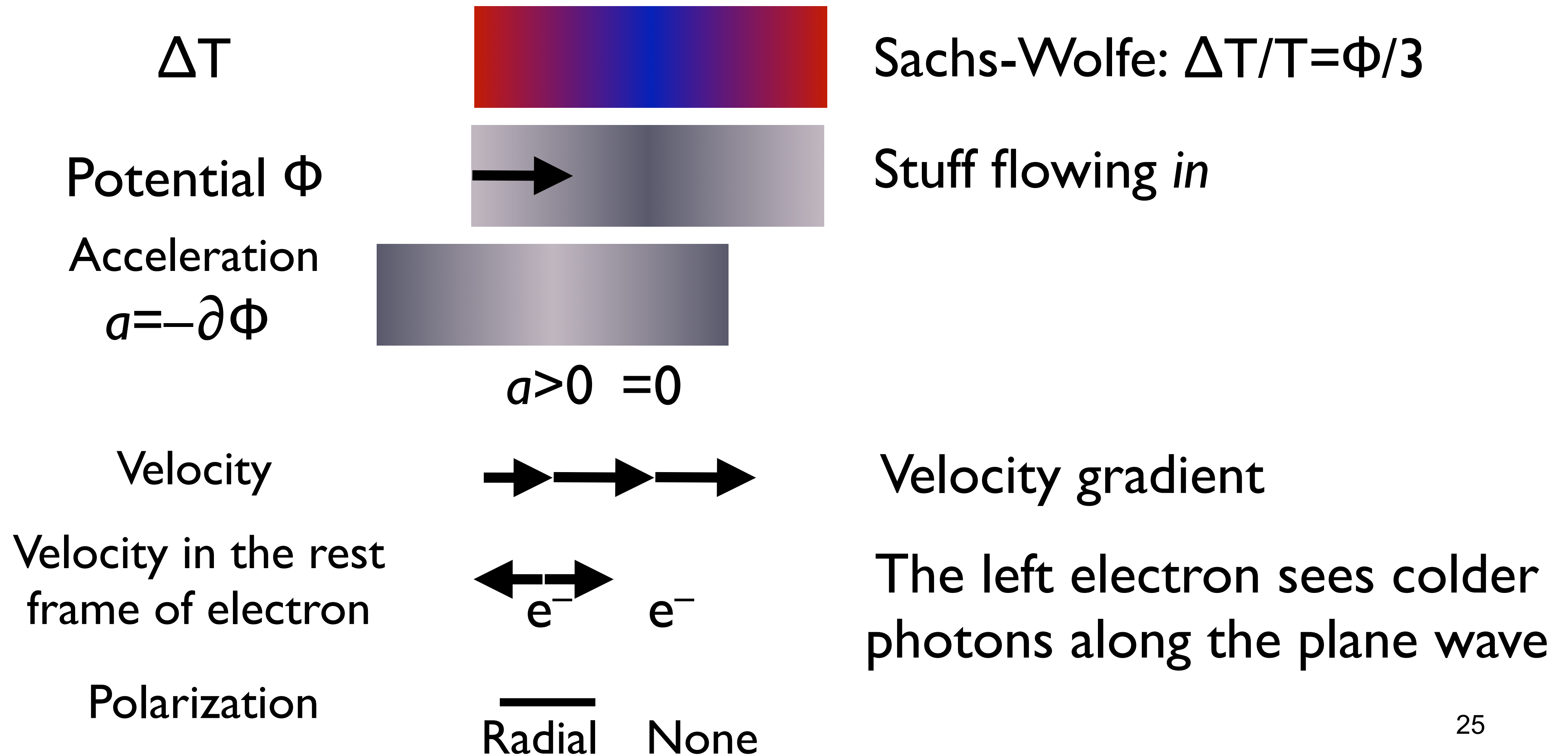


Polarization

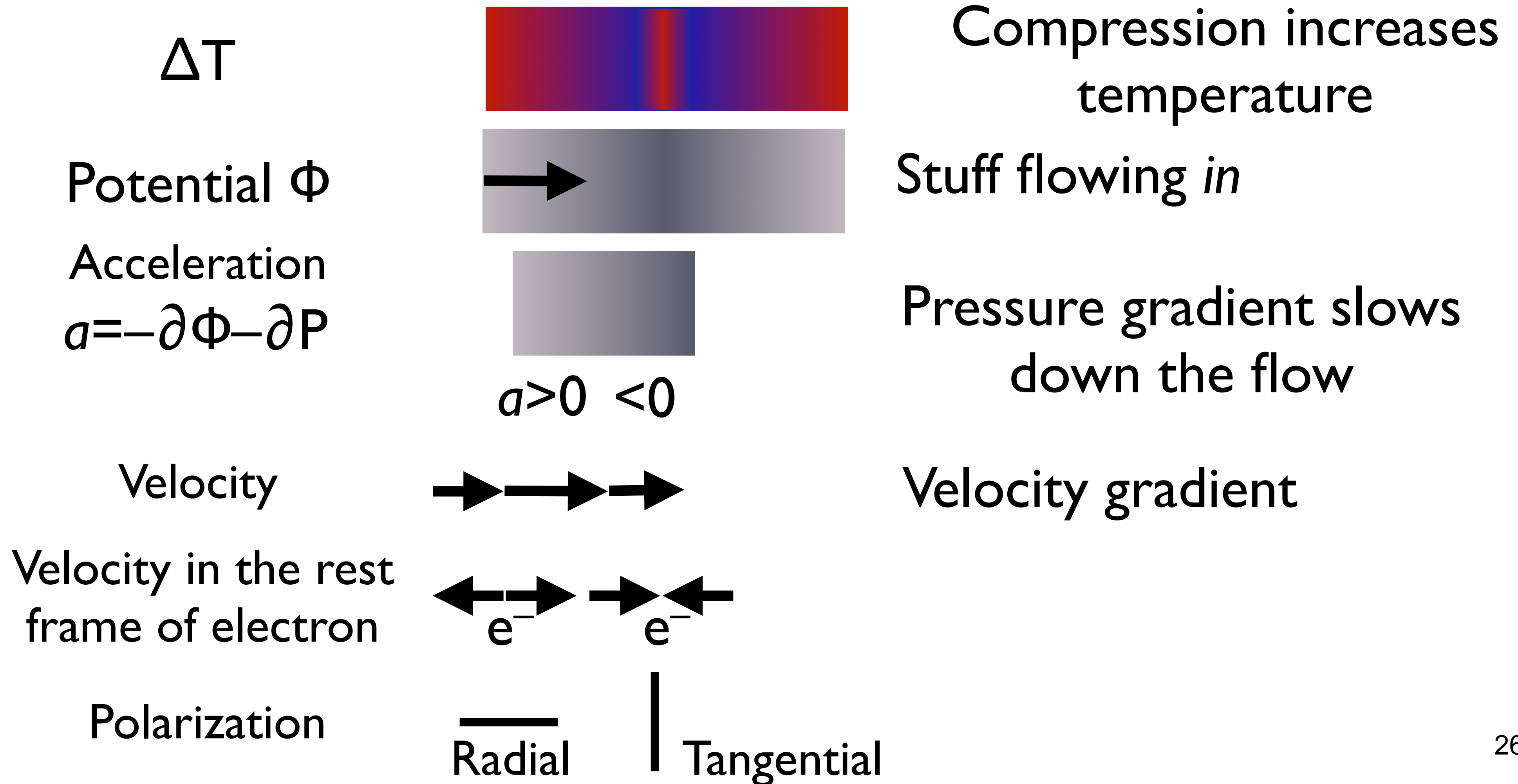


- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern

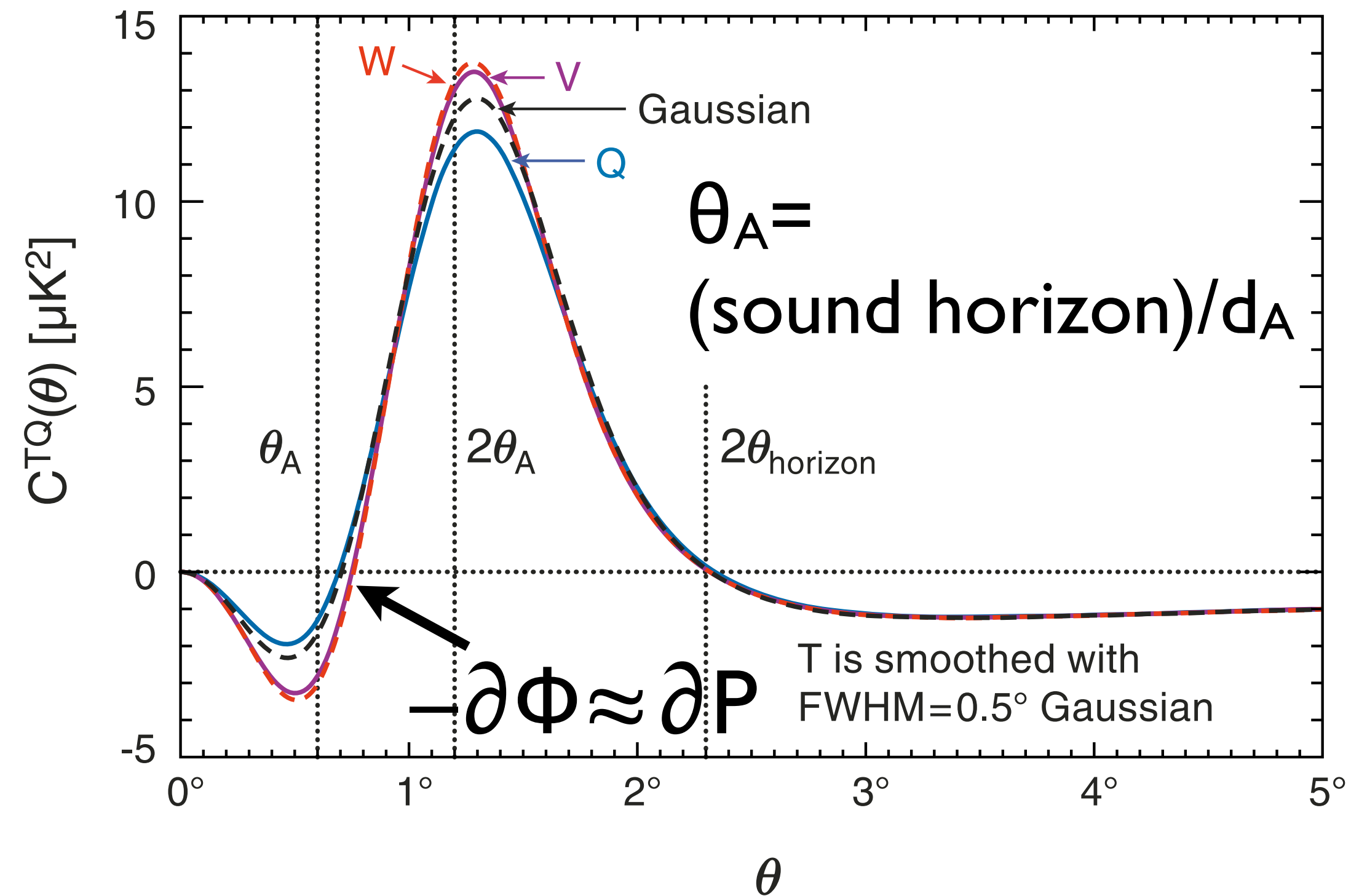
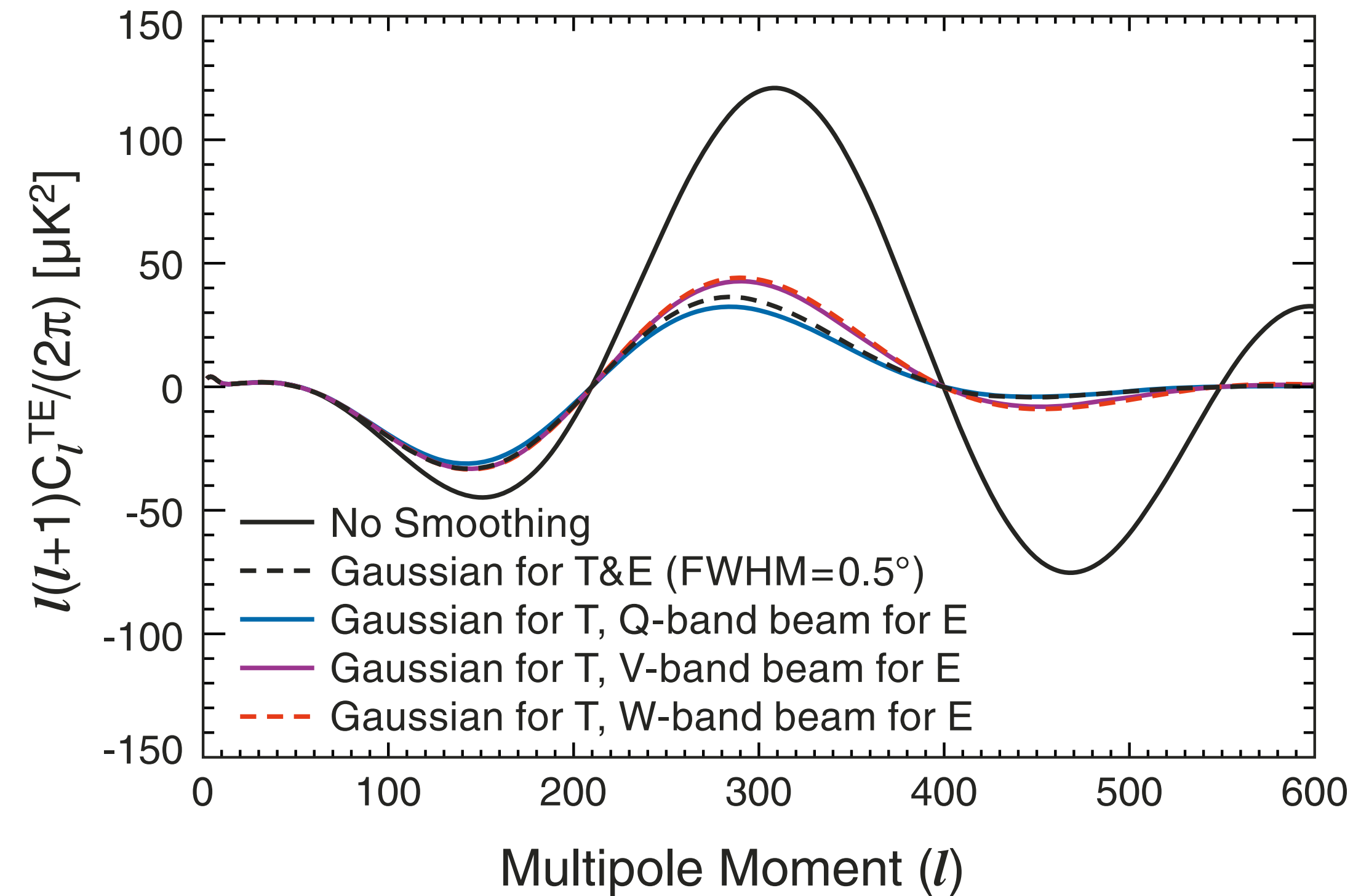
Quadrupole From Velocity Gradient (Large Scale)



Quadrupole From Velocity Gradient (Small Scale)



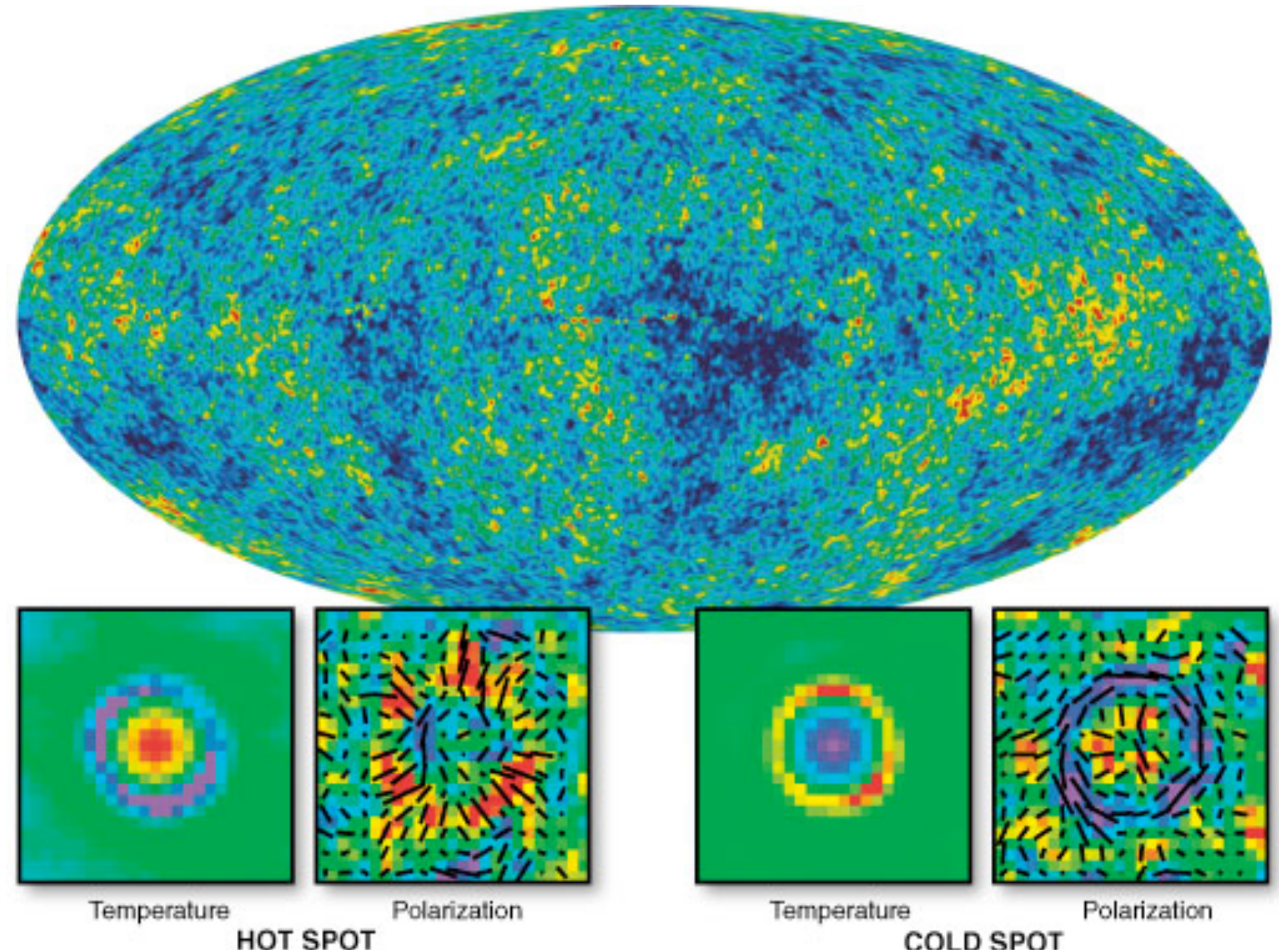
Hence, TE Correlation (Coulson et al. 1994)



● $C^{TQr}(\theta) = -\int dl \ln l / [l^2 C_l^{TE}/(2\pi)] J_2(l\theta)$ 27

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**.



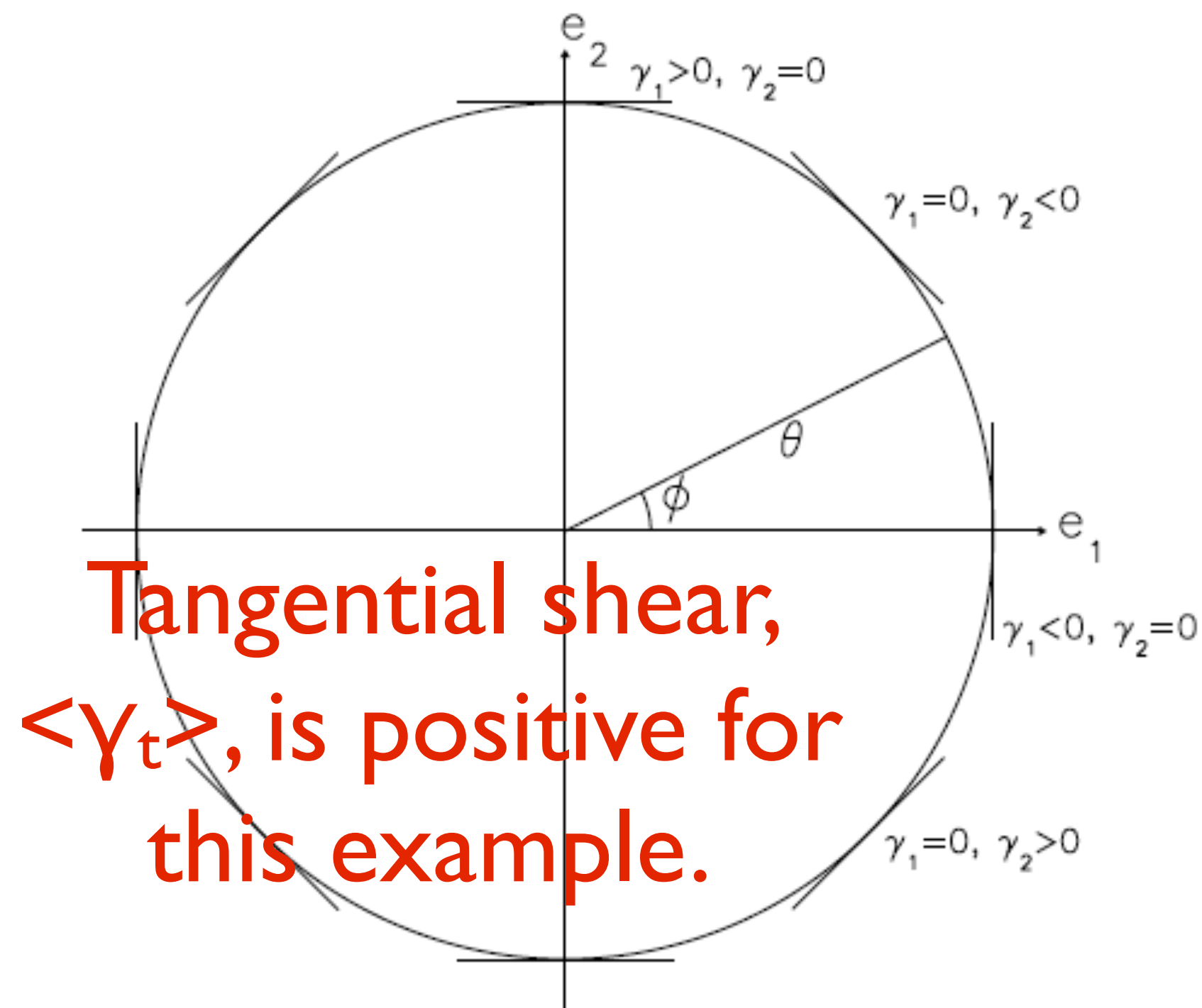
- Peak theory gives:
 [Note the l^2 term!
 (Desjacques 2008)]

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

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

Analogy to Weak Lensing

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

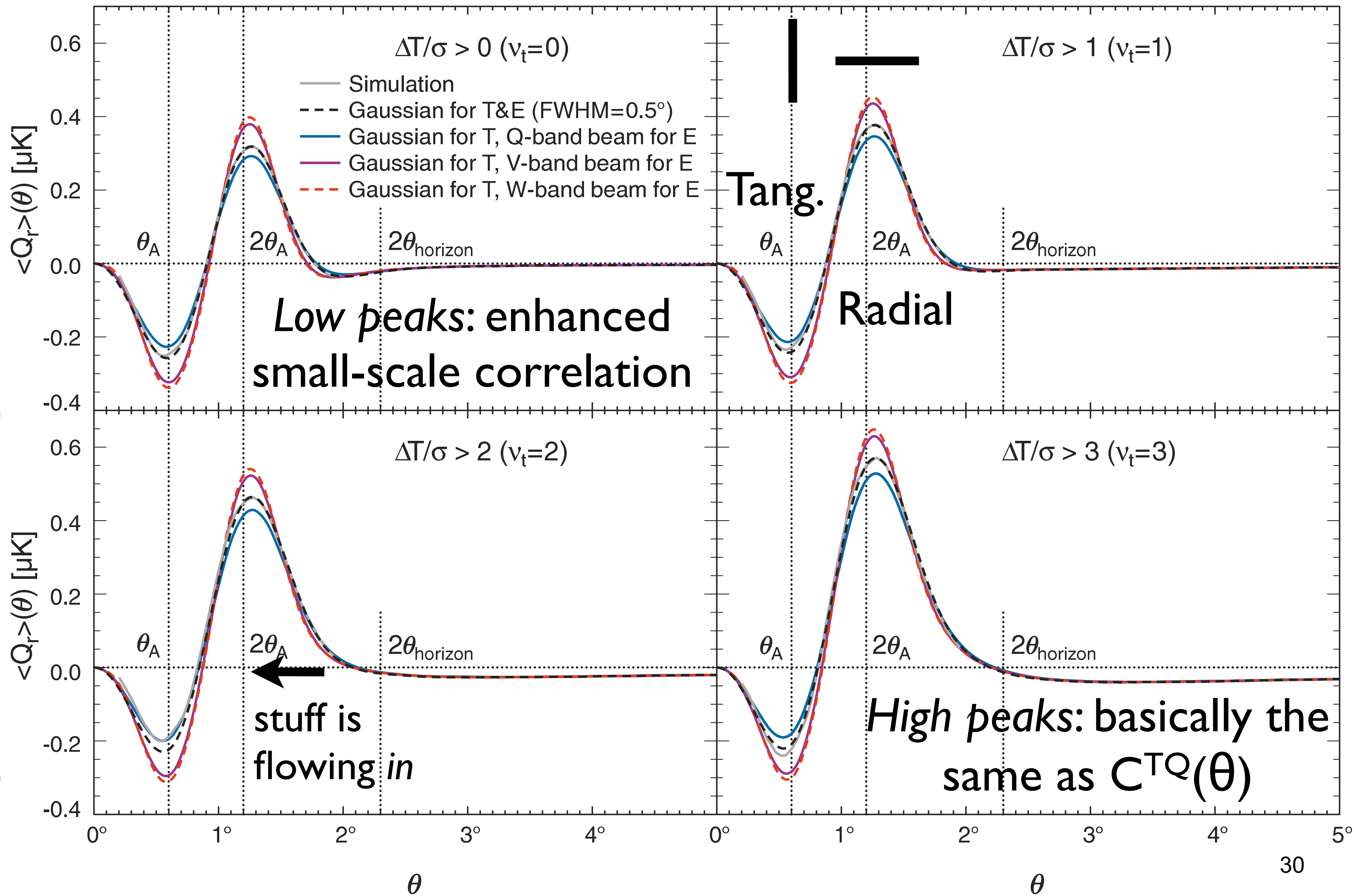


$$\Delta\Sigma(R, z_L) = \rho_0 b_1 \int \frac{k dk}{2\pi} P_m(k, z_L) J_2(kR)$$

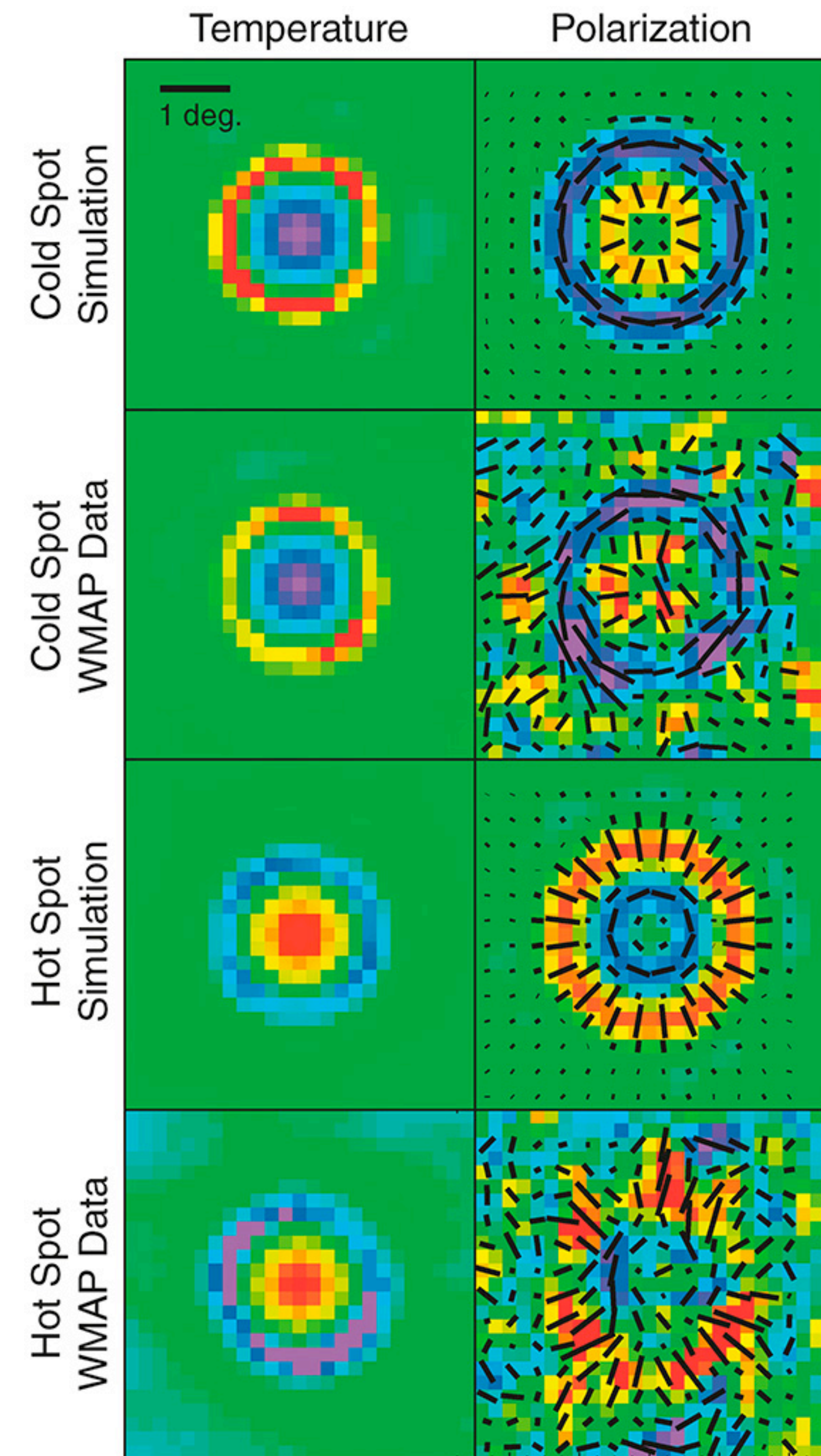
However, all the formulae given in the literature use a scale-independent bias, b_1 . This formula must be modified to include the k^2 term.

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

Temperature hot spots are stacked



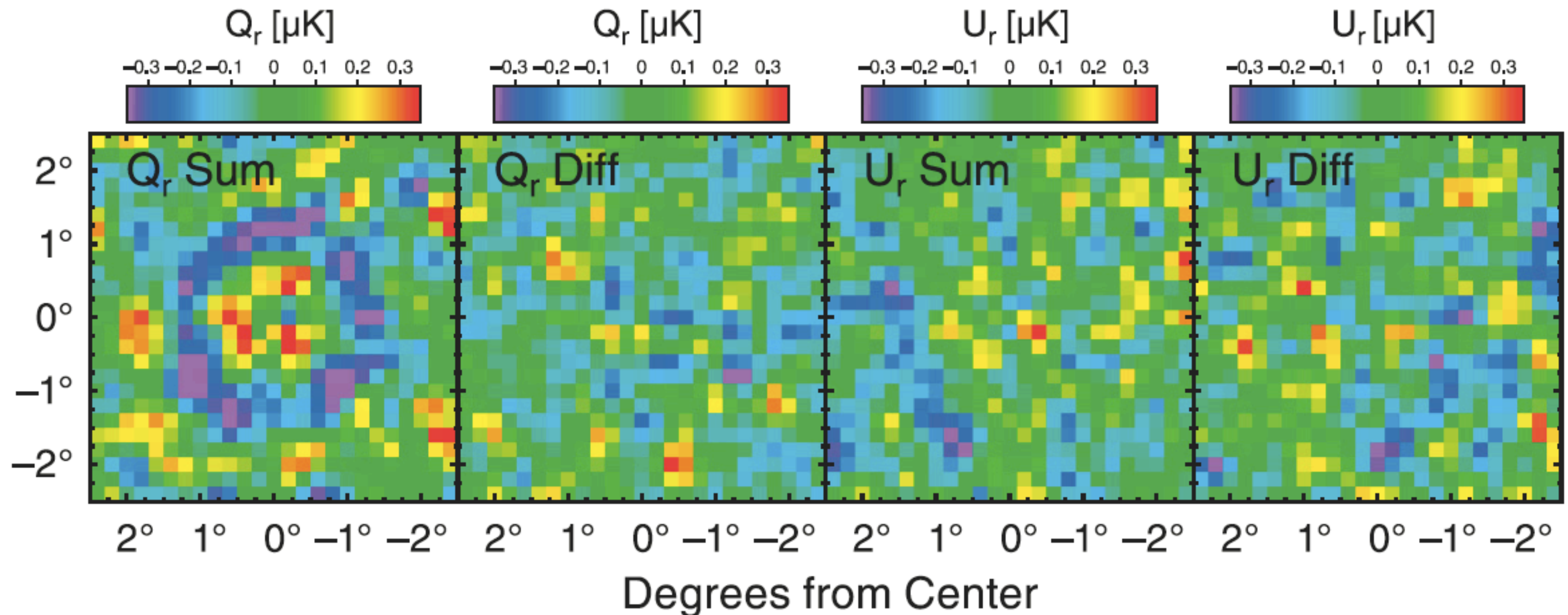
Two-dimensional View



- All hot and cold spots are stacked (the threshold peak height, $\Delta T/\sigma$, is zero)
- “Compression phase” at $\theta=1.2$ deg and “slow-down phase” at $\theta=0.6$ 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.

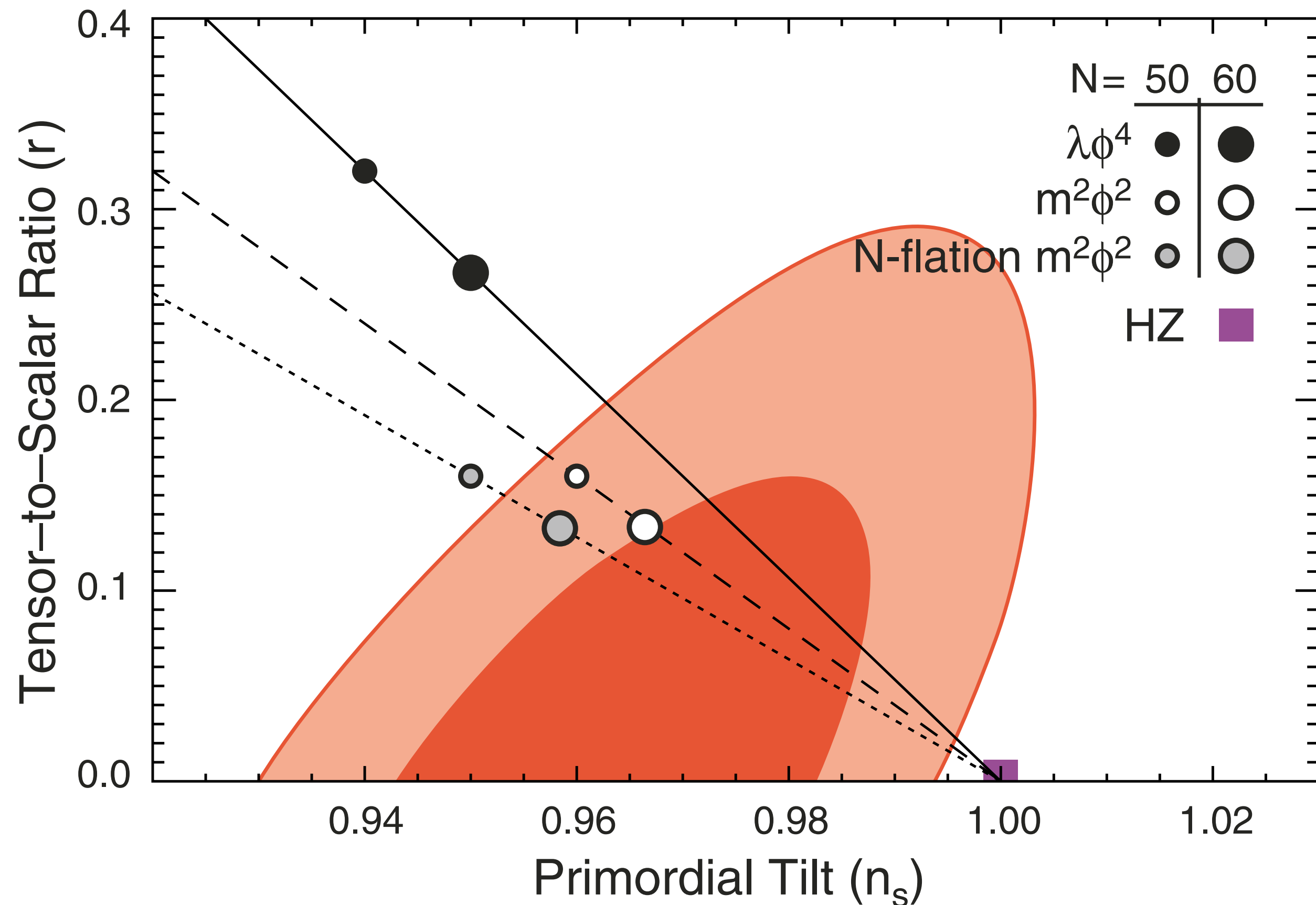
Probing Parity Violation

- 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:

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

- Non-detection of U_r gives $\Delta\alpha = 1 \pm 3$ deg (68%CL)
- The full analysis using C_l^{TB} (as well as C_l^{EB}) gives
 - $\Delta\alpha = -1.1 \pm 1.3(\text{statistical}) \pm 1.5(\text{systematic})$ 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:
 - $-10 < f_{\text{NL}}^{\text{local}} < 74$
 - $-214 < f_{\text{NL}}^{\text{equilateral}} < 266$
 - $-410 < f_{\text{NL}}^{\text{orthogonal}} < 6$
- The WMAP data are consistent with the prediction of **simple single-inflation inflation** models:
 - $1 - n_s \approx r \approx f_{\text{NL}}^{\text{local}}, f_{\text{NL}}^{\text{equilateral}} = 0 = f_{\text{NL}}^{\text{orthogonal}}$.

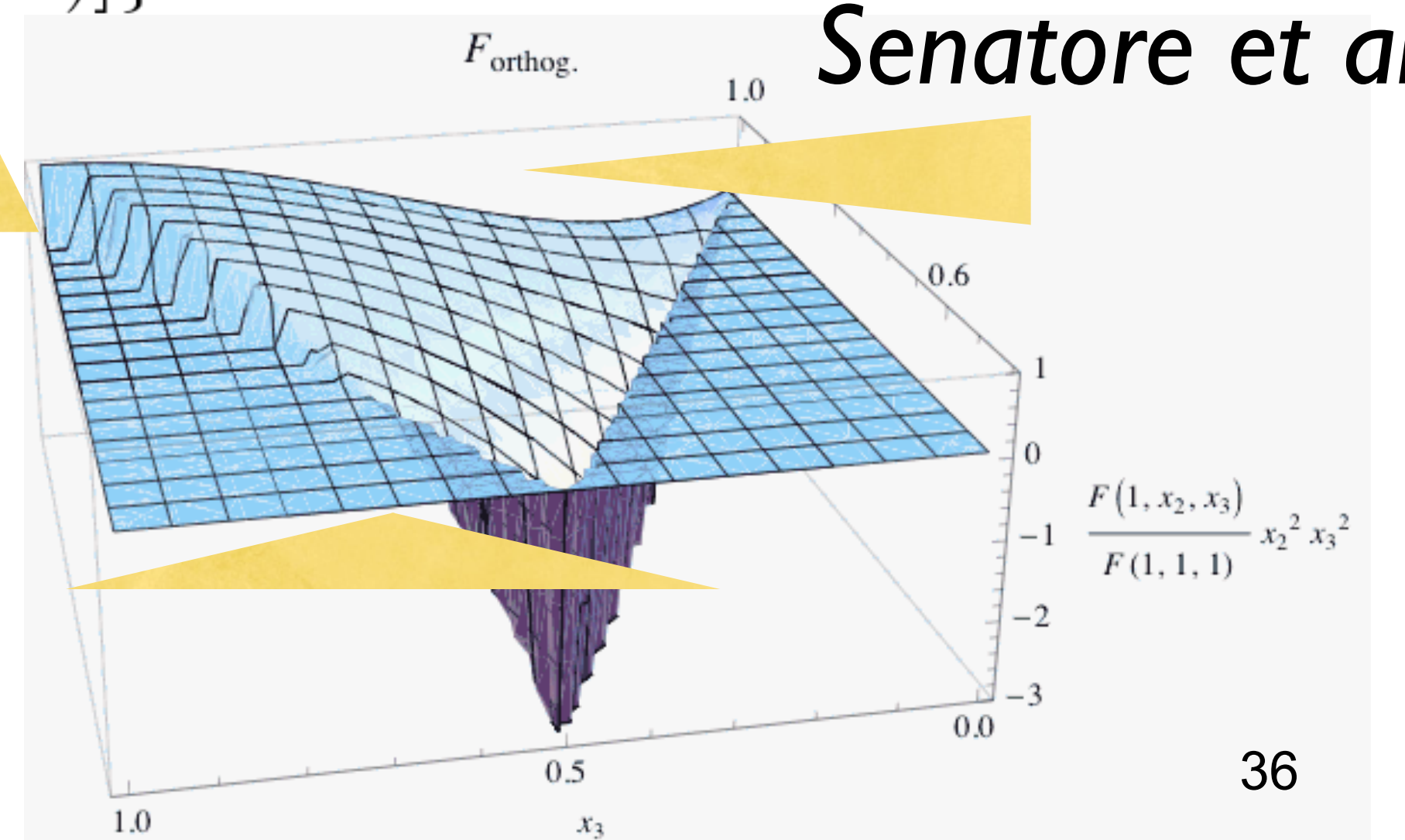
If this means anything to you...

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

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

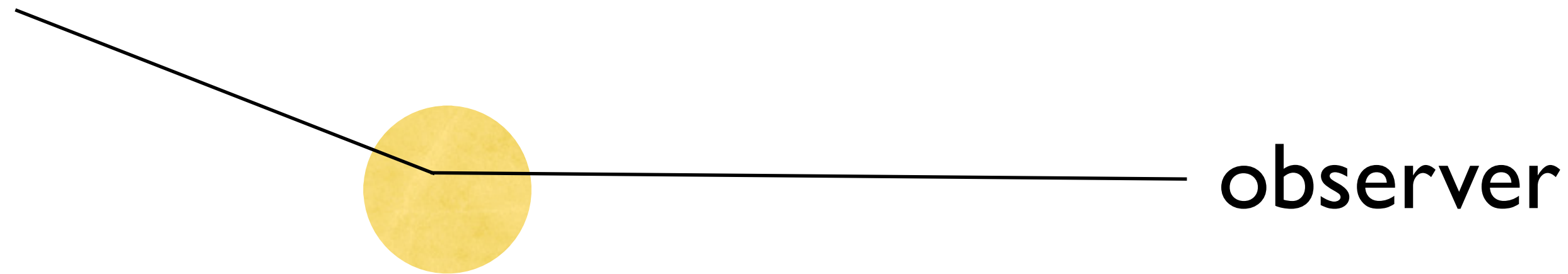
$$\begin{aligned} & F_{\text{equil}}(k_1, k_2, k_3) = 6Af_{NL}^{\text{equil}} \\ & \times \left\{ \frac{1}{k_1^{4-n_s} k_2^{4-n_s}} - \frac{1}{k_2^{4-n_s} k_3^{4-n_s}} - \frac{1}{k_3^{4-n_s} k_1^{4-n_s}} \right. \\ & \quad - \frac{2}{(k_1 k_2 k_3)^{2(4-n_s)/3}} + \left[\frac{1}{k_1^{(4-n_s)/3} k_2^{2(4-n_s)/3} k_3^{4-n_s}} \right. \\ & \quad \left. \left. + (5 \text{ perm.}) \right] \right\}. \end{aligned}$$

$$\begin{aligned} & F_{\text{orthog}}(k_1, k_2, k_3) = 6Af_{NL}^{\text{orthog}} \\ & \times \left\{ \frac{3}{k_1^{4-n_s} k_2^{4-n_s}} - \frac{3}{k_2^{4-n_s} k_3^{4-n_s}} - \frac{3}{k_3^{4-n_s} k_1^{4-n_s}} \right. \\ & \quad - \frac{8}{(k_1 k_2 k_3)^{2(4-n_s)/3}} + \left[\frac{3}{k_1^{(4-n_s)/3} k_2^{2(4-n_s)/3} k_3^{4-n_s}} \right. \\ & \quad \left. \left. + (5 \text{ perm.}) \right] \right\}. \end{aligned}$$



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

Sunyaev–Zel'dovich Effect



Hot gas with the
electron temperature of $T_e \gg T_{\text{cmb}}$

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

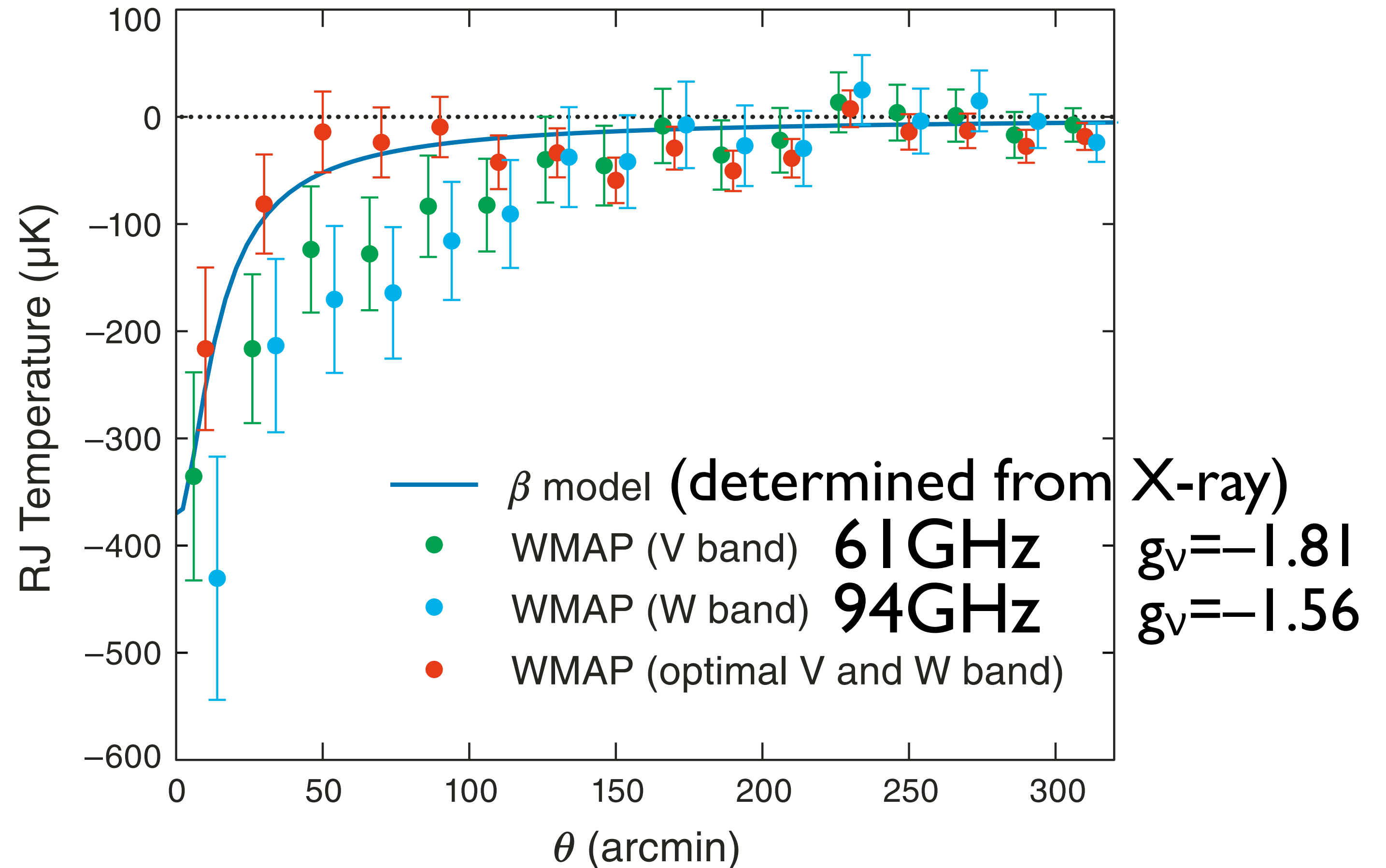
$$\begin{aligned} y &= (\text{optical depth of gas}) k_B T_e / (m_e c^2) \\ &= [\sigma_T / (m_e c^2)] \int n_e k_B T_e d(\text{los}) \\ &= [\sigma_T / (m_e c^2)] \int (\text{electron pressure}) d(\text{los}) \end{aligned}$$

$g_\nu = -2$ ($\nu=0$); -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 $\approx -100\mu\text{K}$. (This is a new result!)

$$y_{\text{coma}}(0) = (7 \pm 2) \times 10^{-5} \quad (68\% \text{CL})$$



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

A Question

- Are we detecting the **expected** amount of electron pressure, P_e , in the SZ effect?
- Expected from X-ray observations.
- Expected from theory.

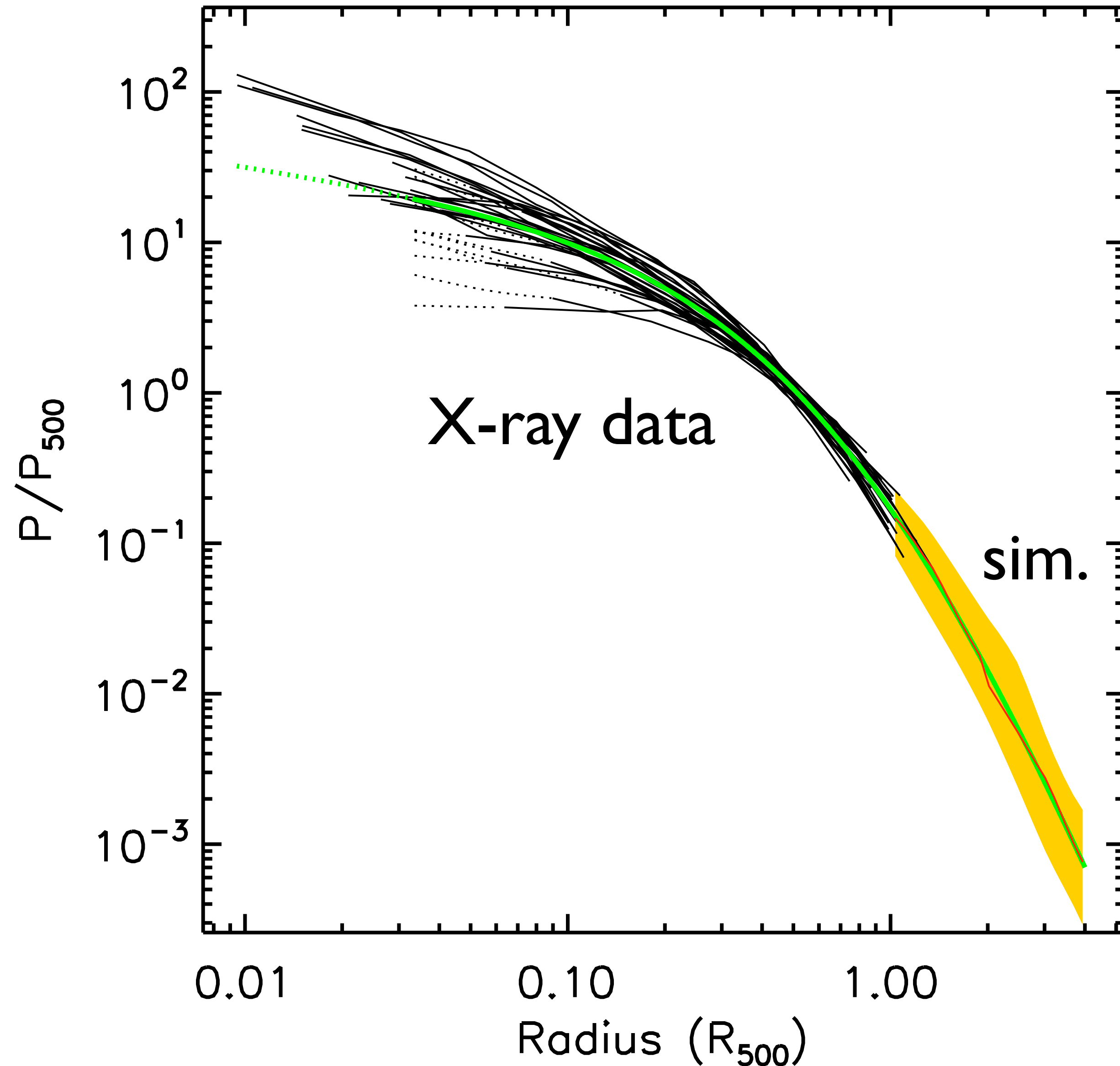
Three approaches

- 1. Compare the WMAP data and X-ray data on individual clusters individually.
- But, not all clusters are detected individually by the WMAP data...
- 2. Compare the stacked WMAP data and the expected average X-ray profiles.
- Systematic effects in the stacking analysis must be carefully studied.
- 3. Compare the stacked WMAP data and the expected profiles from theory (hydro simulation etc).

Arnaud et al. Profile

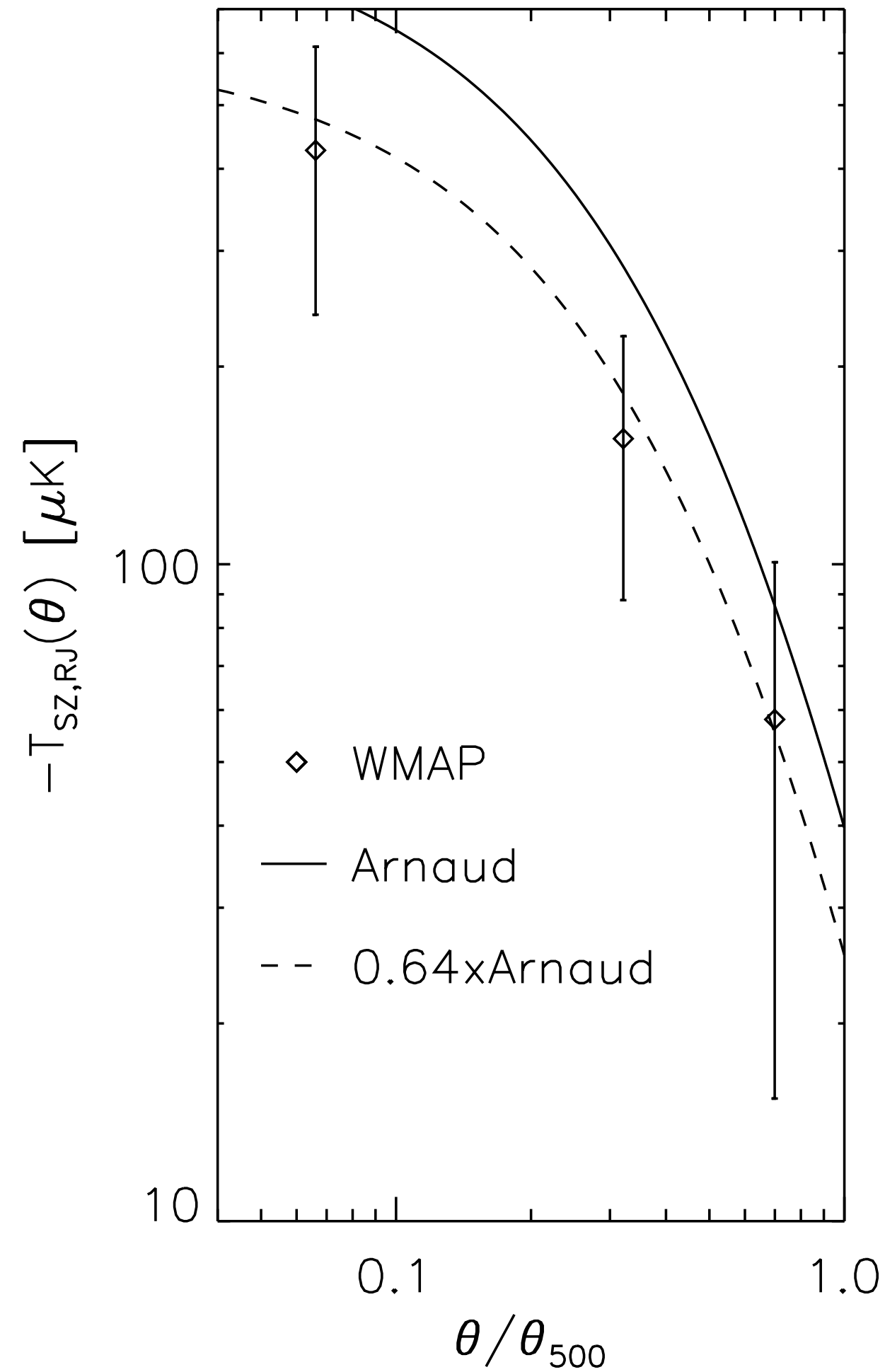
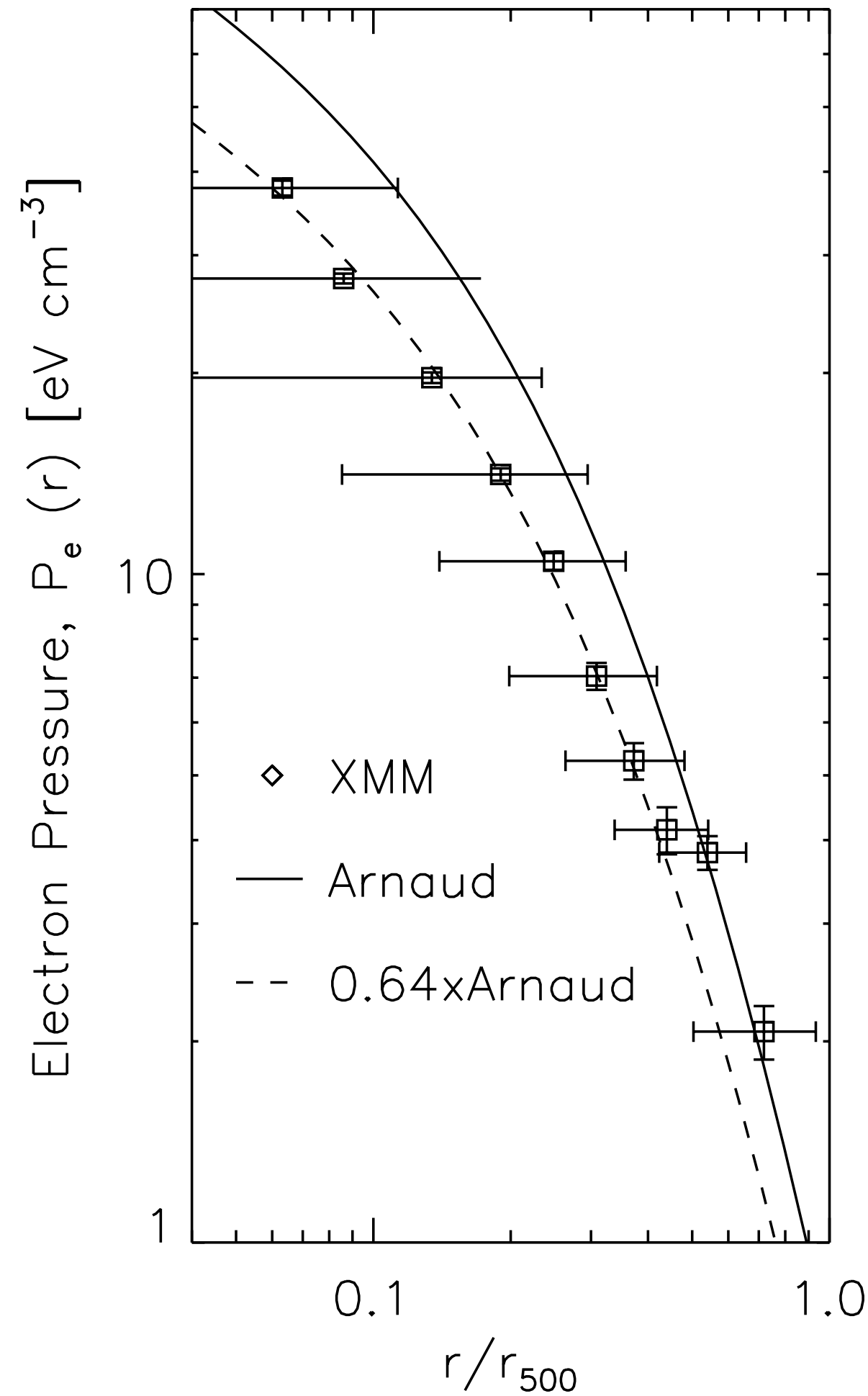
- A fitting formula for the average electron pressure profile as a function of the cluster mass (M_{500}), derived from 33 nearby ($z < 0.2$) clusters.

Arnaud et al. Profile



- A significant scatter exists at $R < 0.2 R_{500}$, but a good convergence in the outer part.

Coma Data vs Arnaud



- $M_{500} = 6.6 \times 10^{14} h^{-1} M_{\text{sun}}$ is estimated from the mass-temperature relation (Vikhlinin et al.)

- $T_X^{\text{coma}} = 8.4 \text{ keV}$.

- Arnaud et al.'s profile overestimates both the direct X-ray data and WMAP data by the same factor (0.64)!

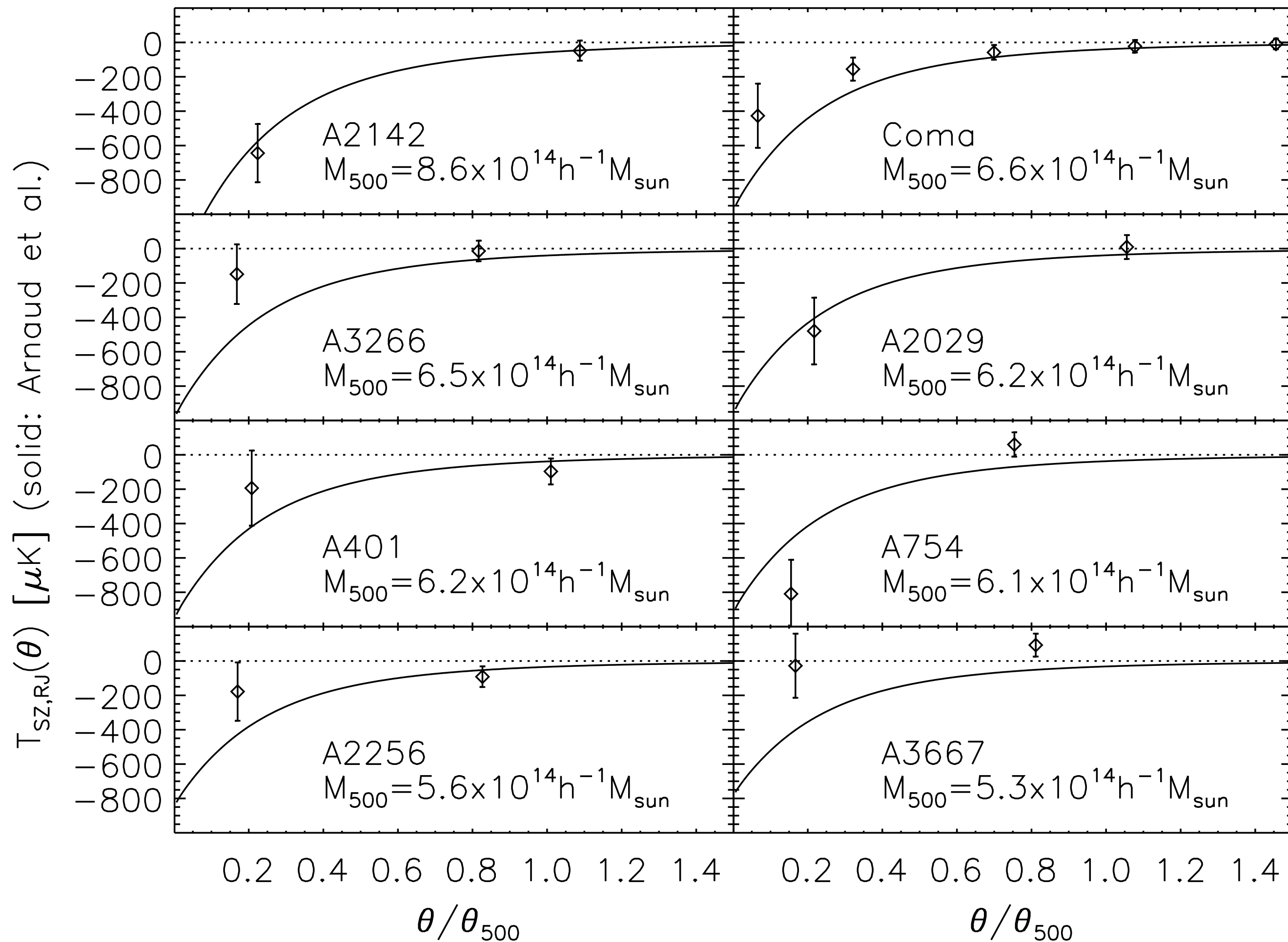
- To reconcile them, $T_X^{\text{coma}} = 6.5 \text{ keV}$ is required, but that is way too low.

The X-ray data (XMM) are provided by A. Finoguenov.

Well...

- That's just one cluster. What about the other clusters?
- We measure the SZ effect of a very nice sample of well-studied nearby clusters compiled by Vikhlinin et al.

New results! (Prelim.)



- Normalization for the 5 very high-mass clusters ($M_{500} > 6 \times 10^{14} h^{-1} M_{\text{sun}}$) is 0.72 ± 0.13 .
- Normalization for the 12 high-mass clusters ($M_{500} > 4 \times 10^{14} h^{-1} M_{\text{sun}}$) is 0.68 ± 0.11 .
- Arnaud et al. profile systematically overestimates the electron pressure!

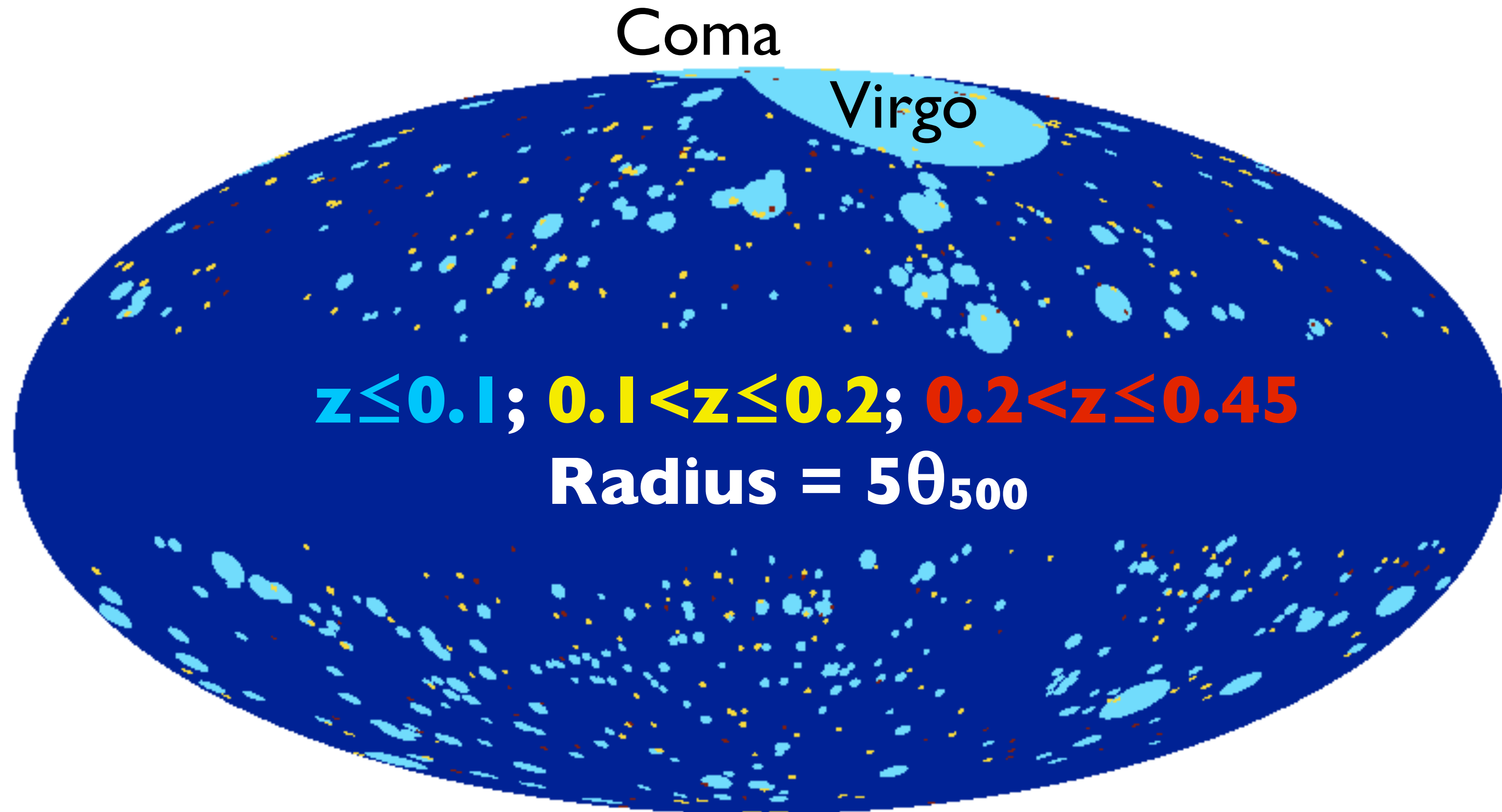
How about the X-ray data?

- The apple-to-apple comparison, i.e., the direct comparison between the WMAP data and the X-ray data (Vikhlinin et al.) is underway. Stay tuned!

Statistical Detection of SZ

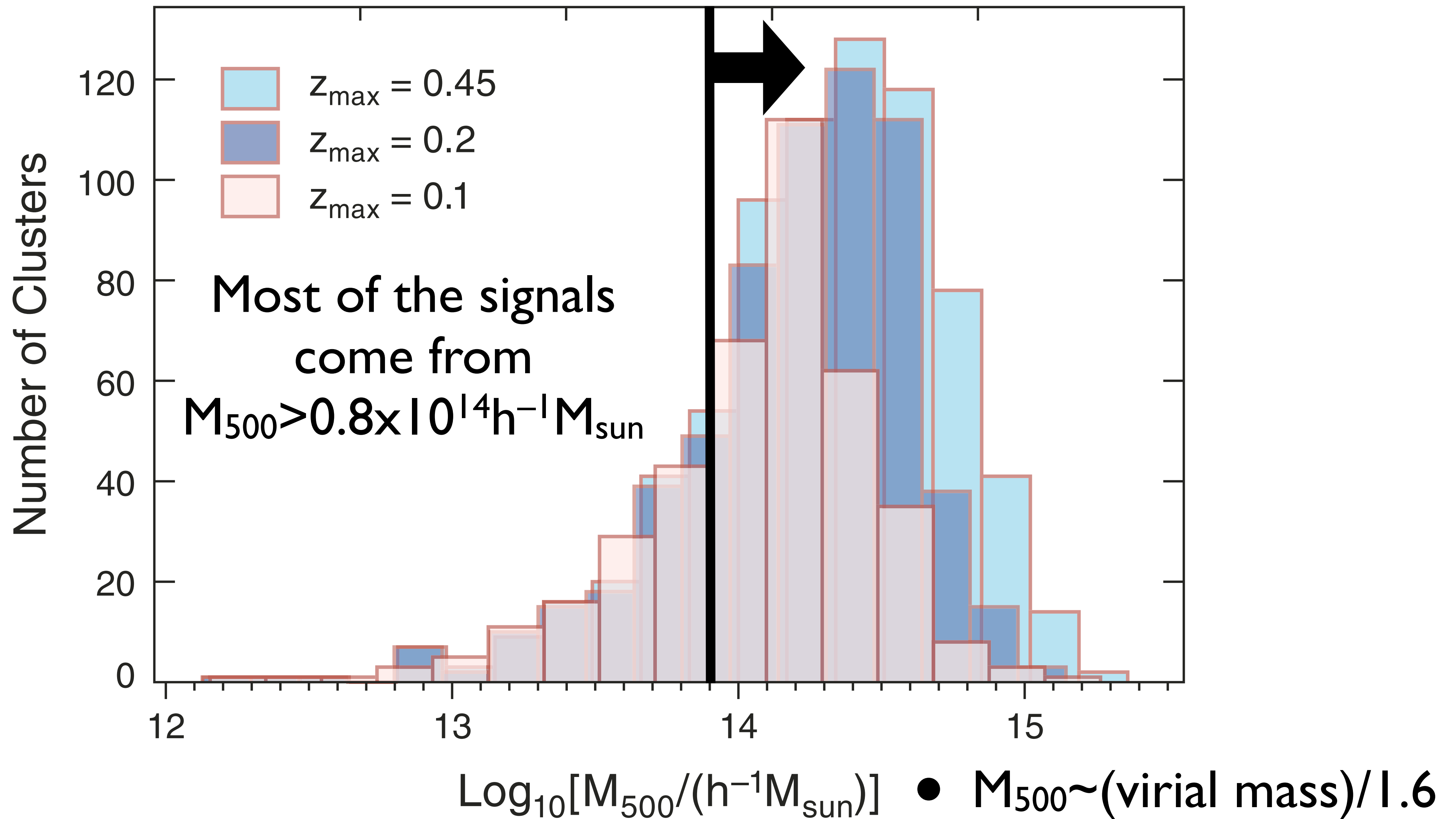
- Coma is bright enough to be detected by WMAP.
- Some clusters are bright enough to be detected individually by WMAP, but the number is still limited.
- By stacking the pixels at the locations of known clusters of galaxies (detected in X-ray), we detected the SZ effect at 8σ .
- Many statistical detections 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



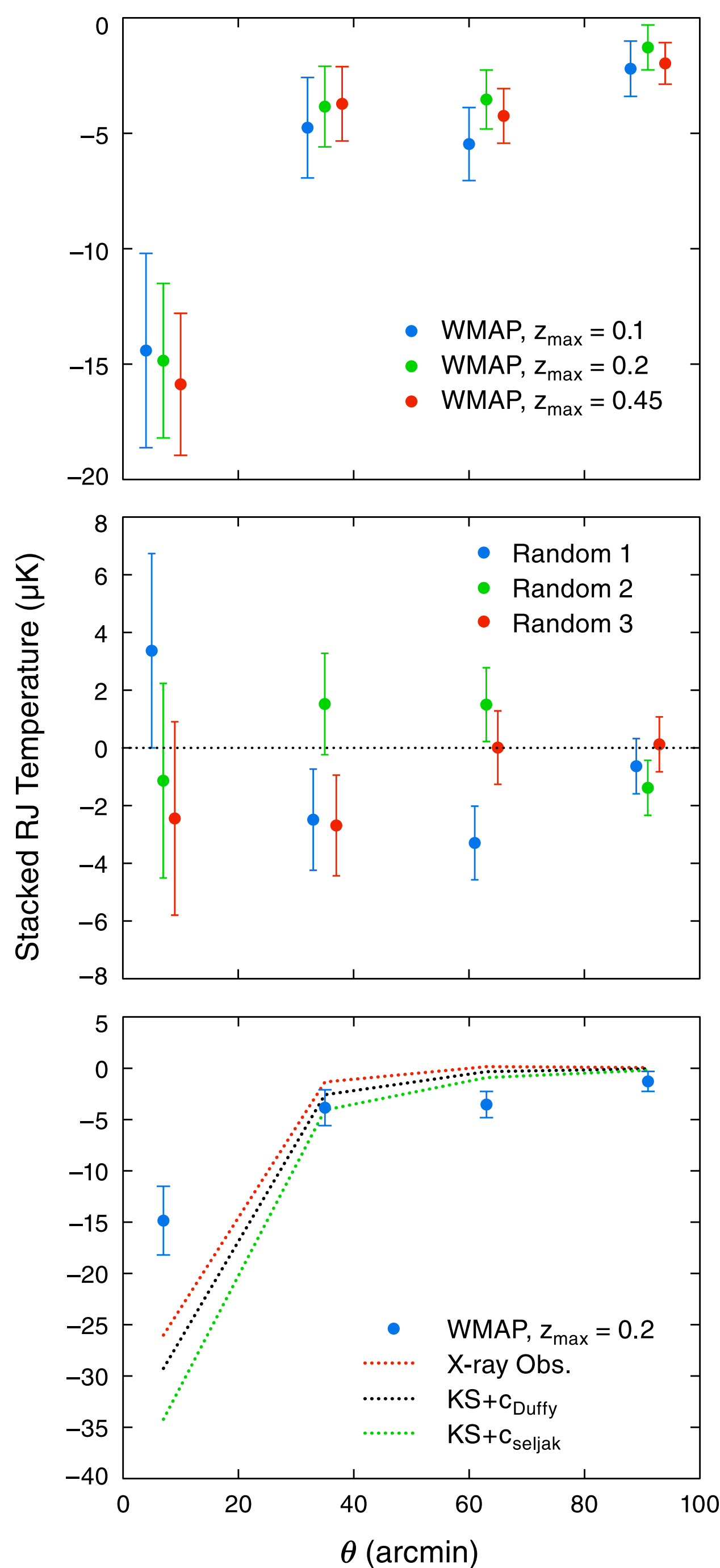
- 742 clusters in $|b| > 20$ deg (before Galaxy mask)
- 400, 228 & 114 clusters in $z \leq 0.1$, $0.1 < z \leq 0.2$ & $0.2 < z \leq 0.45$.⁴⁸

Mass Distribution

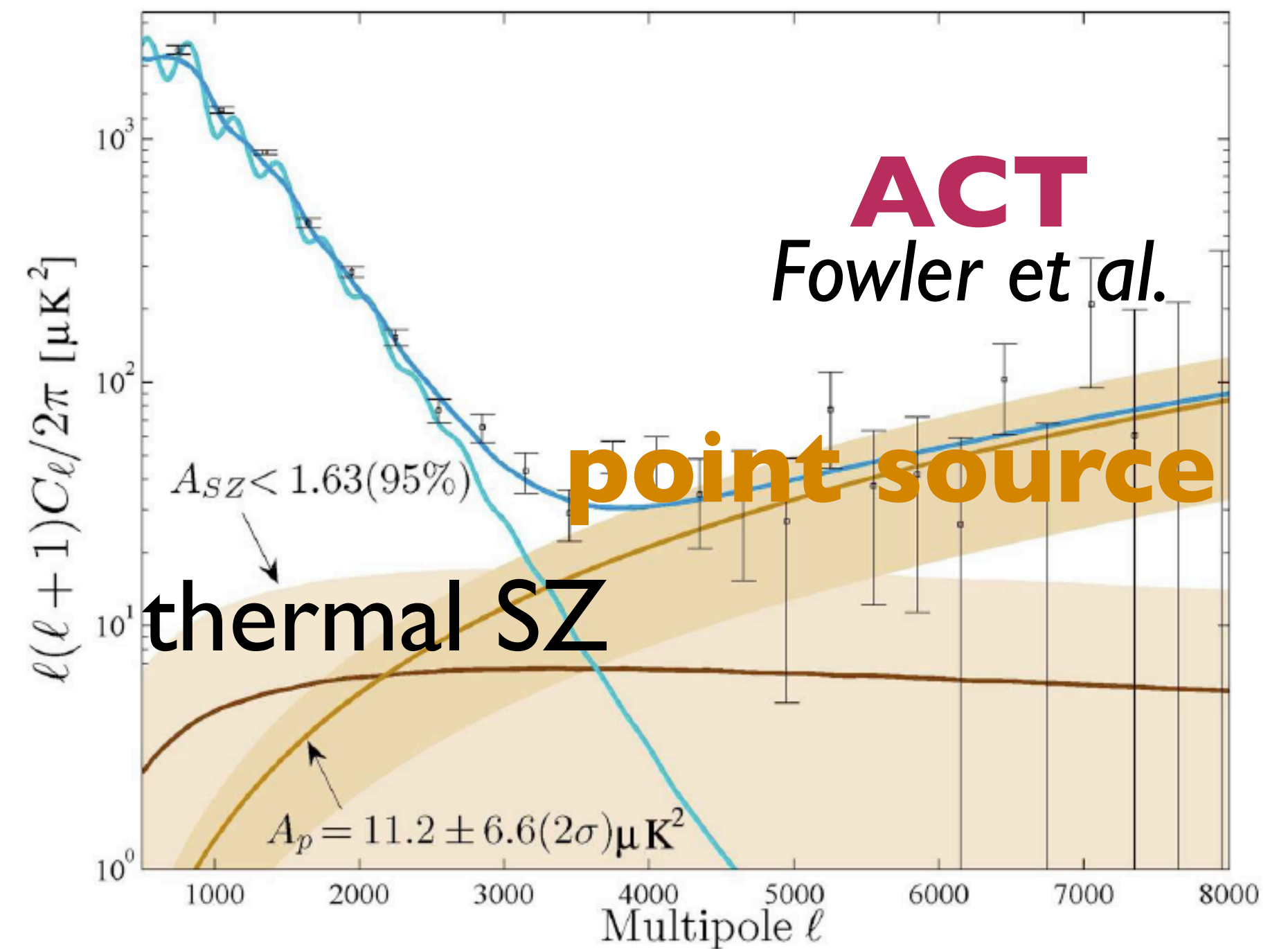
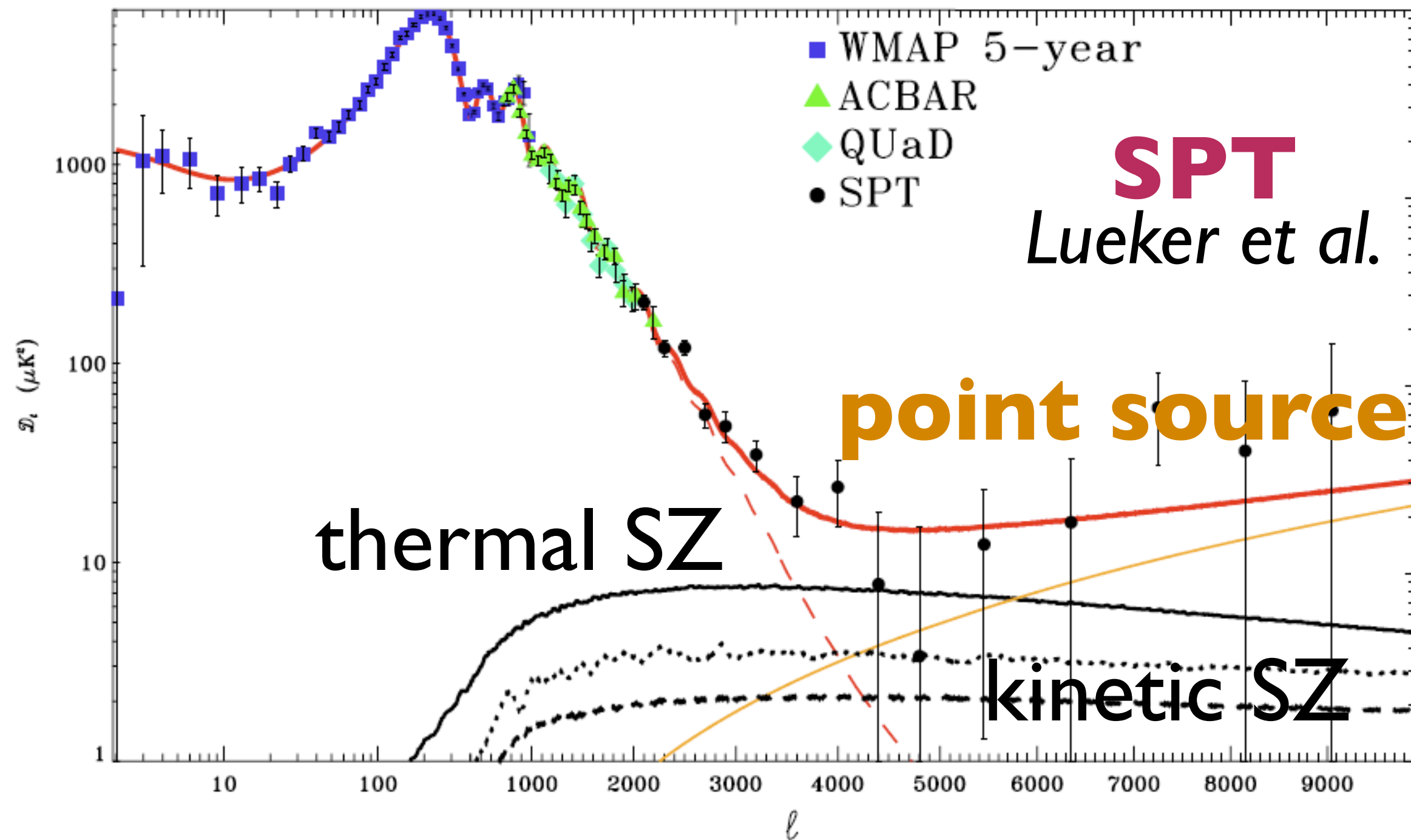


Angular Profiles

- (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 \sim 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

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

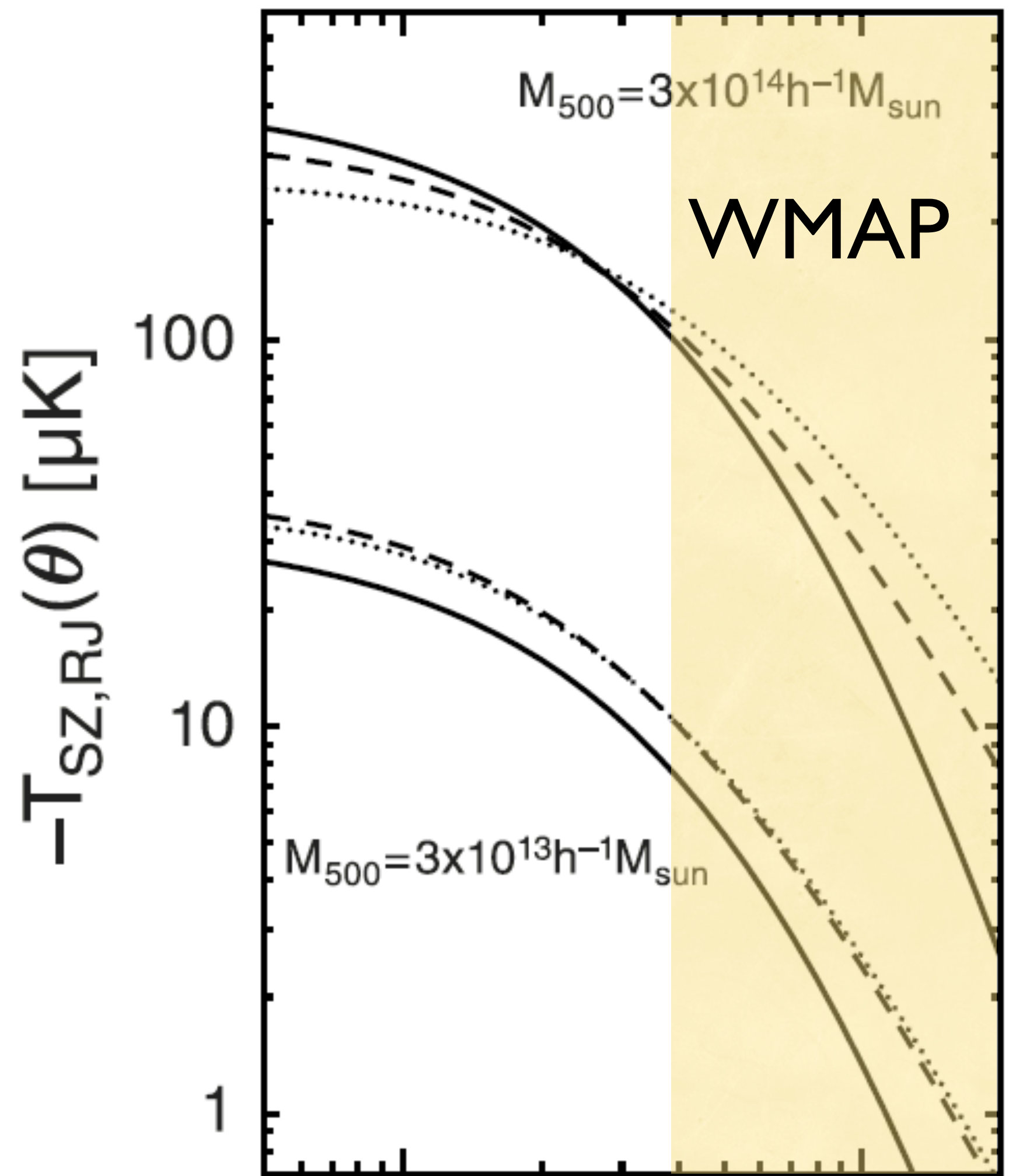
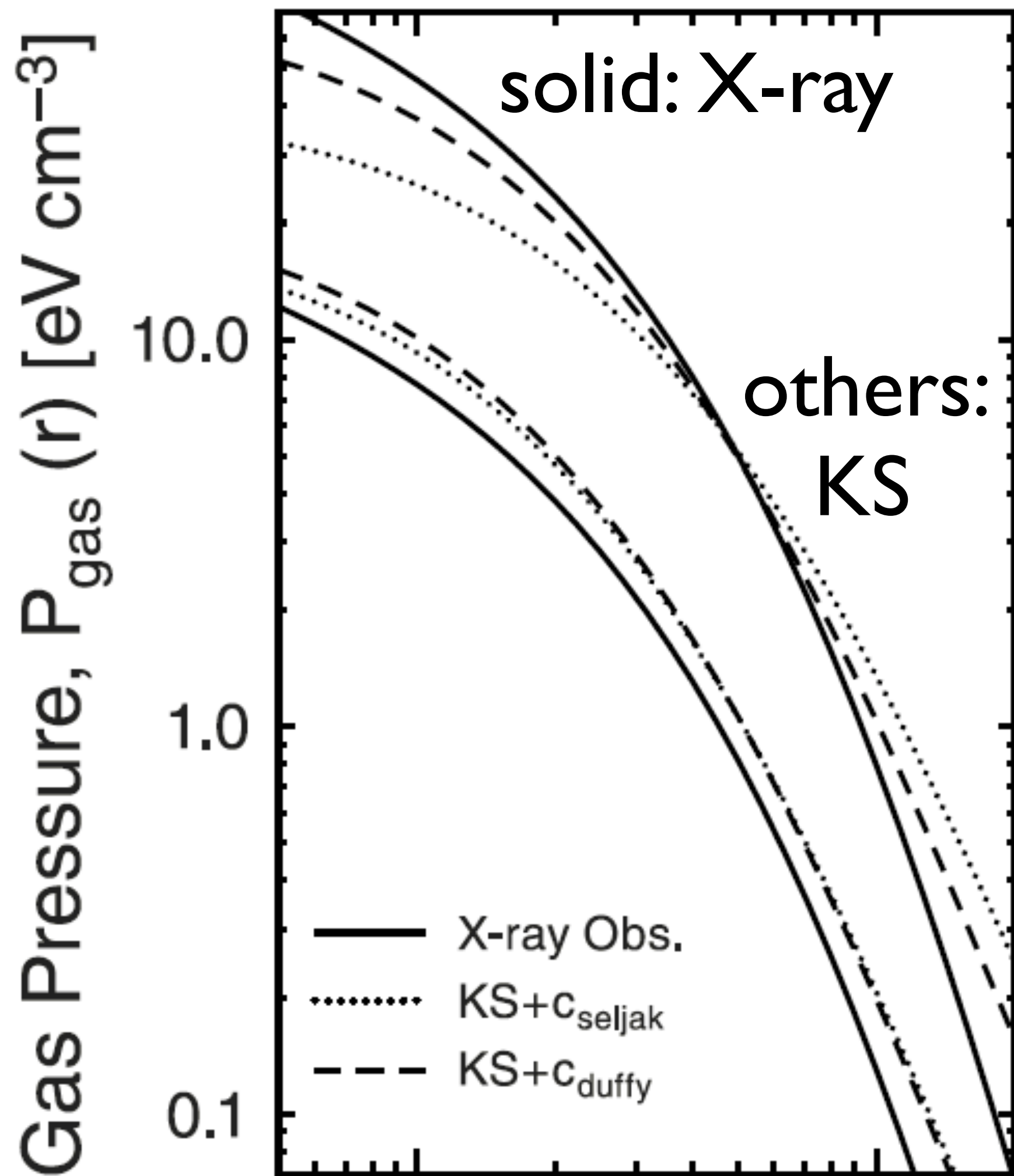
→ $\frac{l(l+1)C_l}{2\pi} \simeq 330 \mu\text{K}^2 \sigma_8^7 \left(\frac{\Omega_b h}{0.035}\right)^2 \times [\text{gas pressure}]$

- 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): $\sum m_\nu \sim 0.2\text{eV}$?
 - 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.



r/r_{500} $r_{500} \sim 0.5$ (virial radius) θ/θ_{500}

- 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.):

$$r_{500} = \frac{(0.753 \pm 0.063) h^{-1} \text{ Mpc}}{E(z)}$$

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

$$\times \left(\frac{L_X}{10^{44} h^{-2} \text{ erg s}^{-1}} \right)^{0.228 \pm 0.015}$$

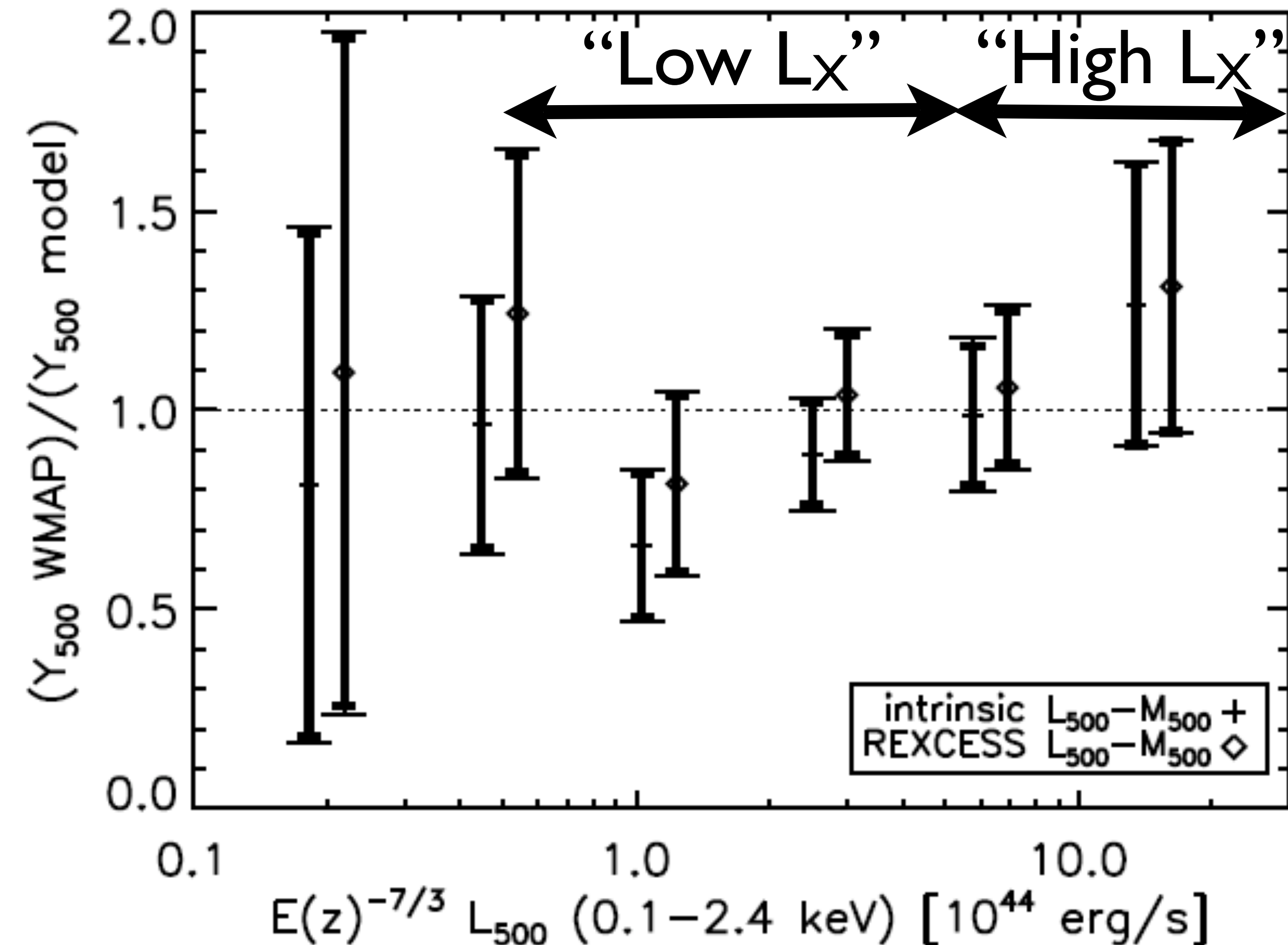
$$E(z) \equiv H(z)/H_0 = [\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$$

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

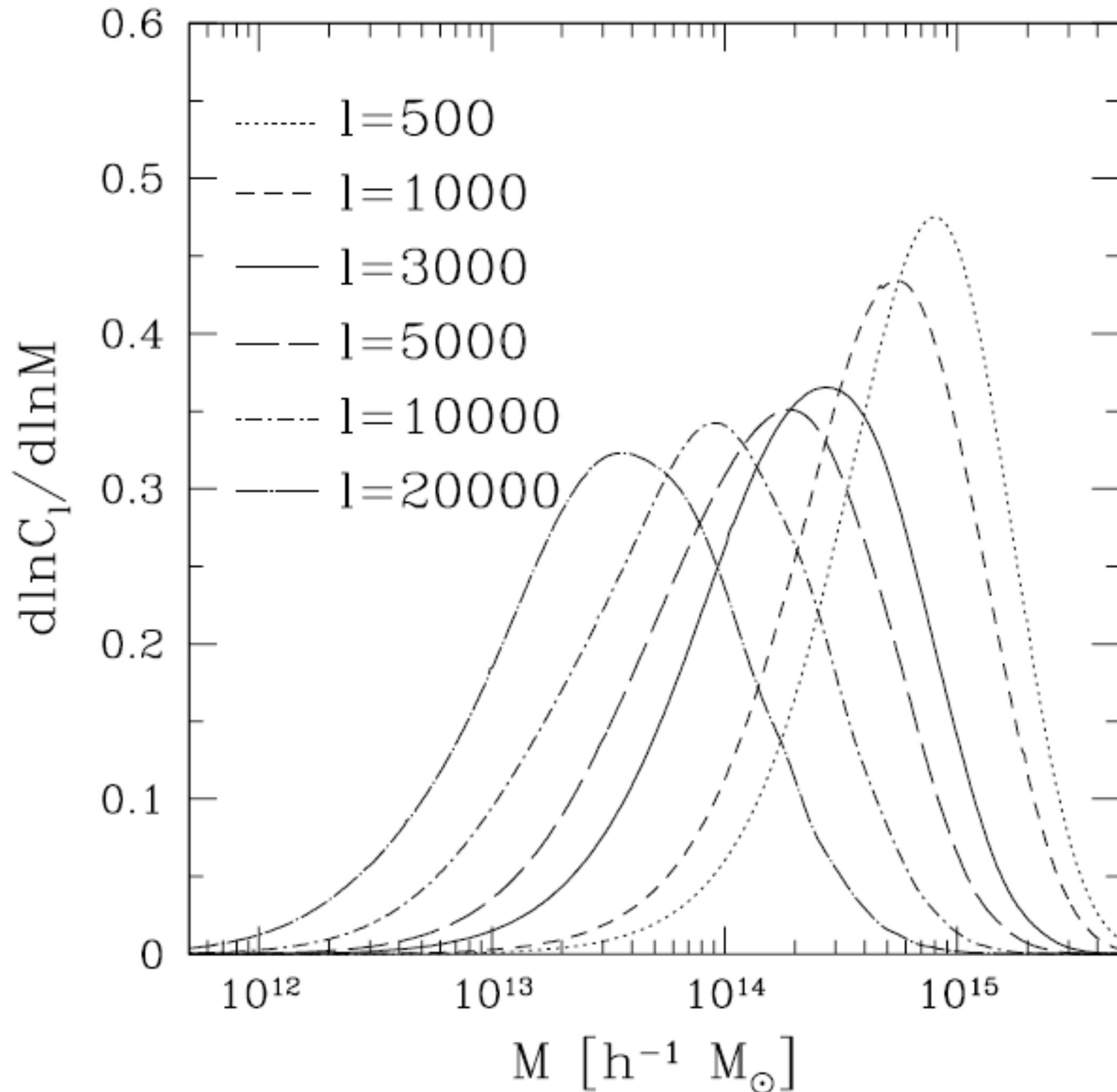
- One picture has emerged:
 - “High L_X ” clusters [$M_{500} > 4 \times 10^{14} h^{-1} M_{\text{sun}}$] can be brought into agreement with the expectations by playing with the r_{500} – L_X relation.
 - “Low L_X ” clusters reveal a significant *missing pressure*.⁵⁶

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 ($M_{500} < 4 \times 10^{14} h^{-1} M_{\text{sun}}$).

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, several massive clusters are detected, and the statistical detection reaches 8σ .
- Evidence for lower-than-expected gas pressure.
- The X-ray data are fine? We just need to revise the existing models.