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

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14th Paris Cosmology Colloquium, July 22, 2010

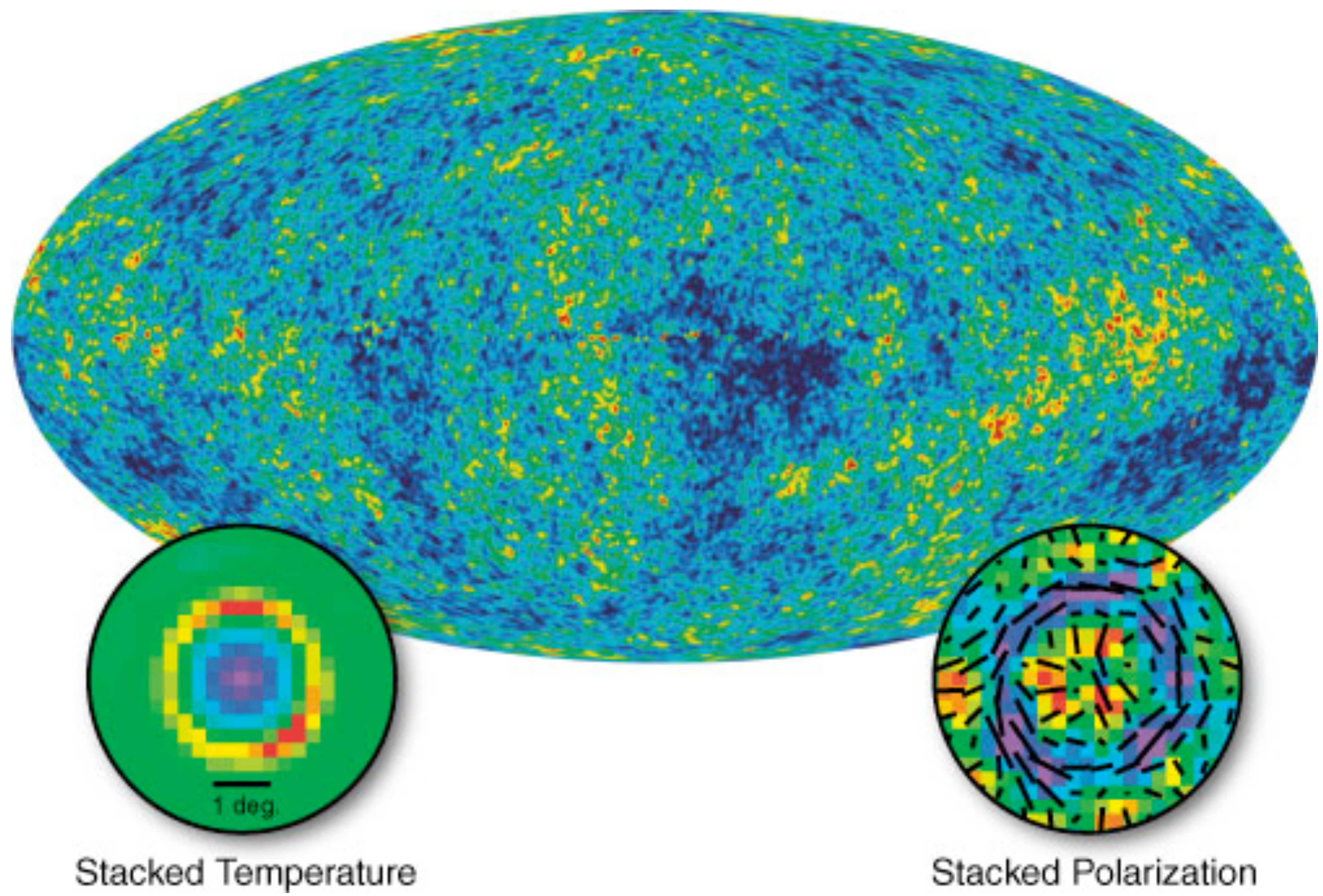
# WMAP will have collected 9 years of data by August

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**

# 7-year Science Highlights

- First detection (>3σ) of the effect of primordial **helium** on the temperature power spectrum.
- The primordial **tilt** is less than 1 at 99.5%CL:
  - $n_s$=0.968±0.012 (68%CL; with new RECFAST)
- 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***?

# 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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# WMAP at Lagrange 2 (L2) Point

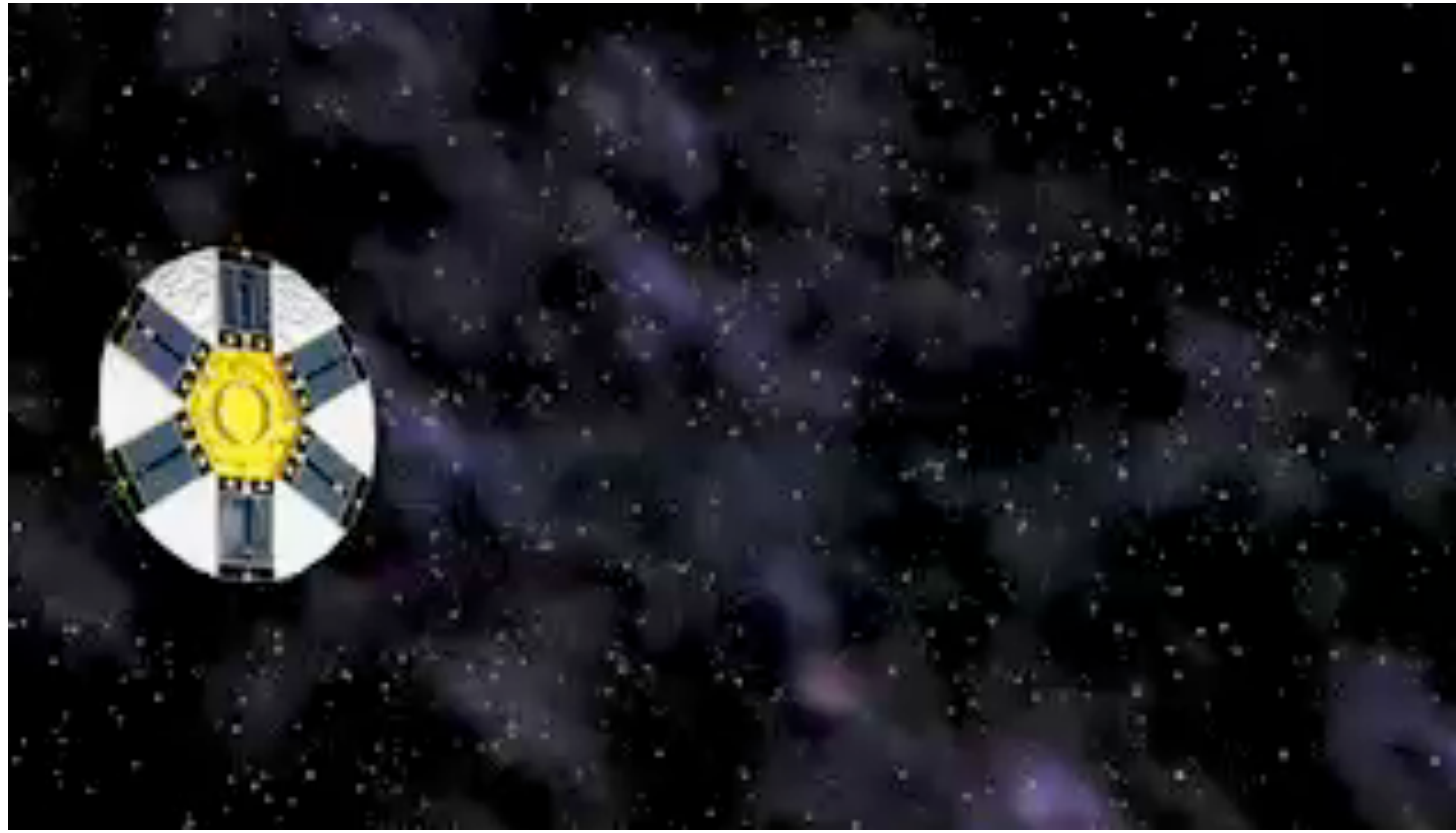
June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release

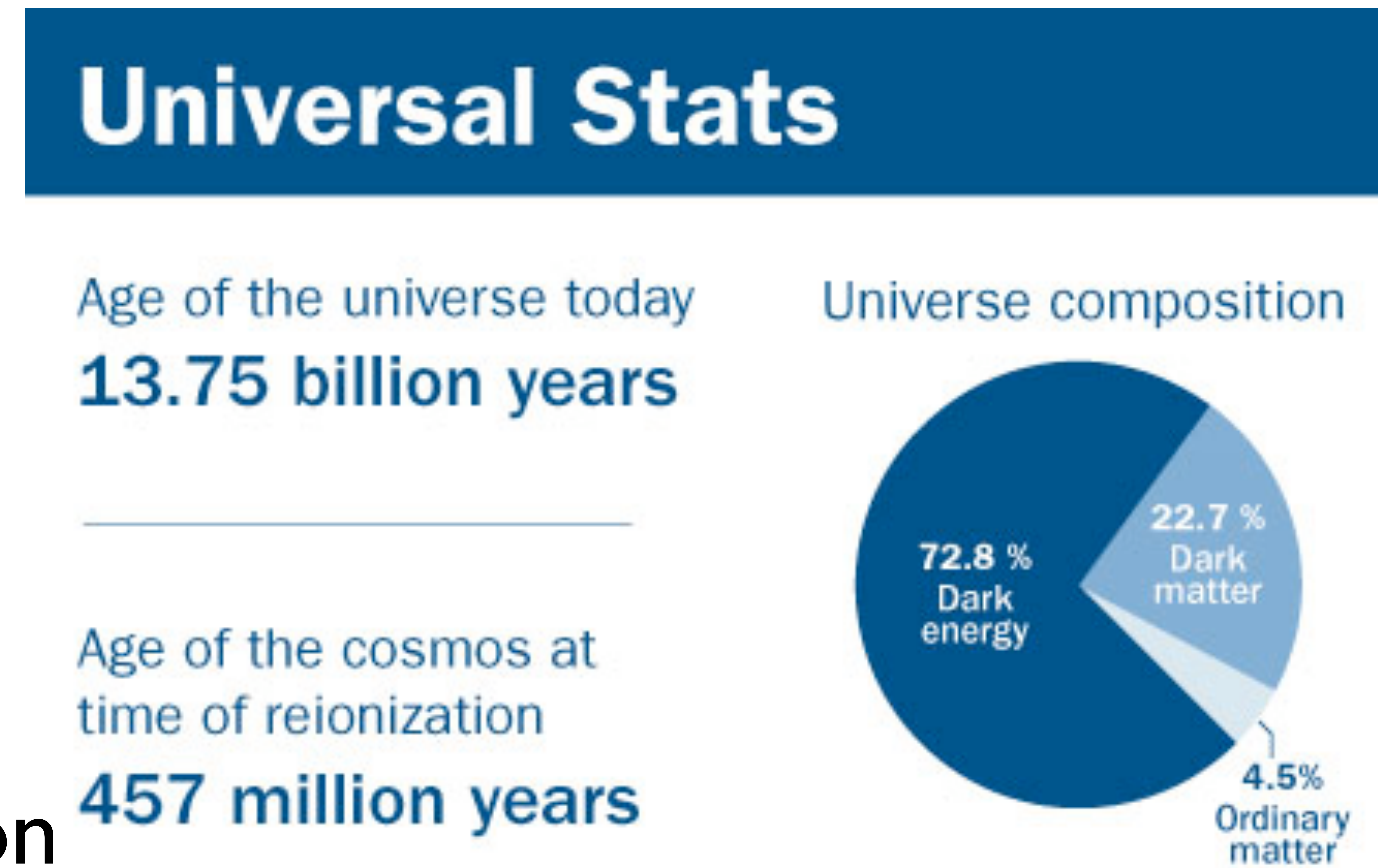
**January 2010:
The seven-year data release**



- L2 is 1.6 million kilometers from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

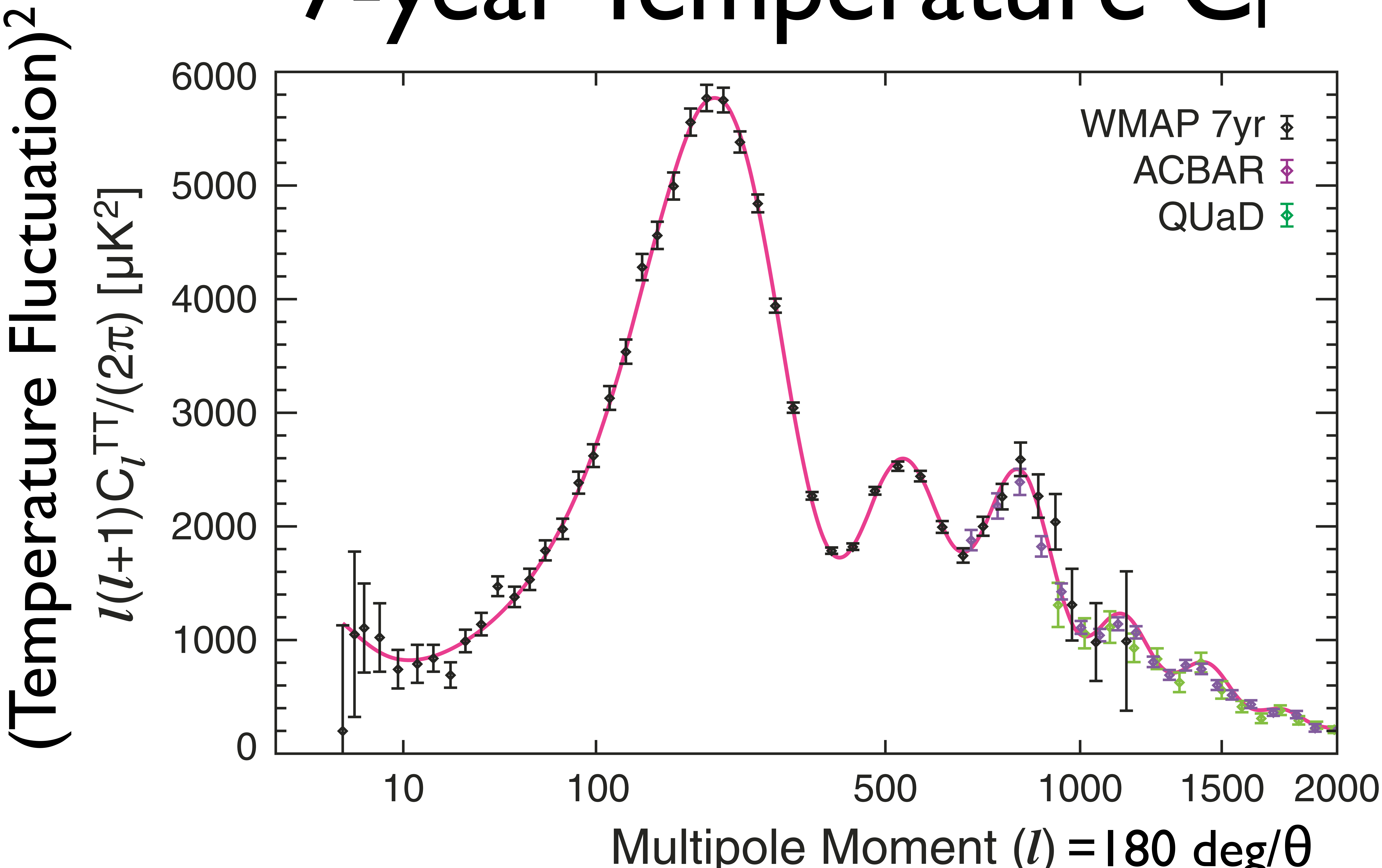
# Cosmology Update: 7-year

- **Standard Model**
  - H&He = 4.56% (±0.16%)
  - Dark Matter = 22.7% (±1.6%)
  - Dark Energy = 72.8% (±1.6%)
  - $H_0$=70.4±1.4 km/s/Mpc
  - Age of the Universe = 13.75 billion years (±0.11 billion years)

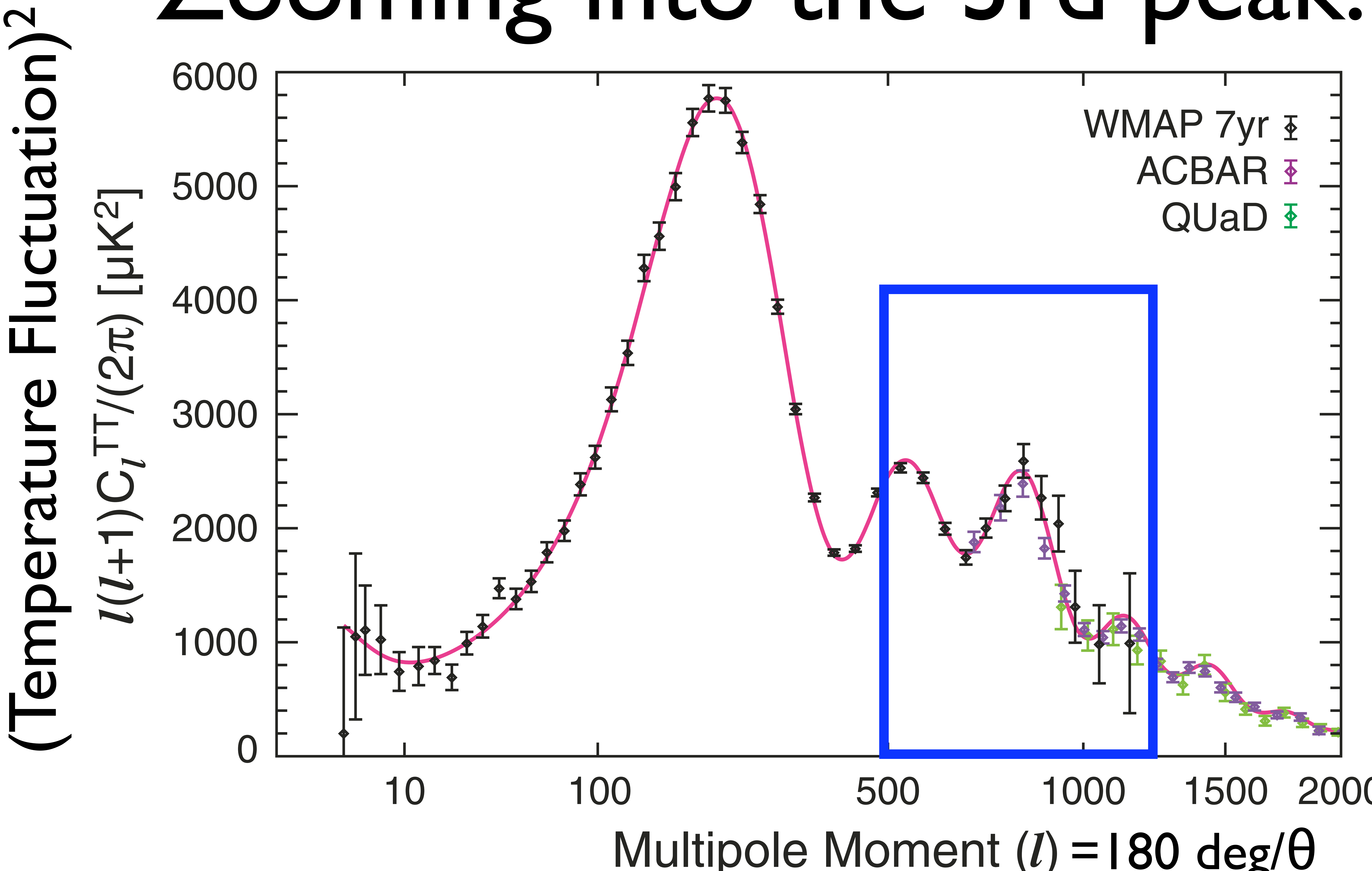



*"ScienceNews" article on the WMAP 7-year results*

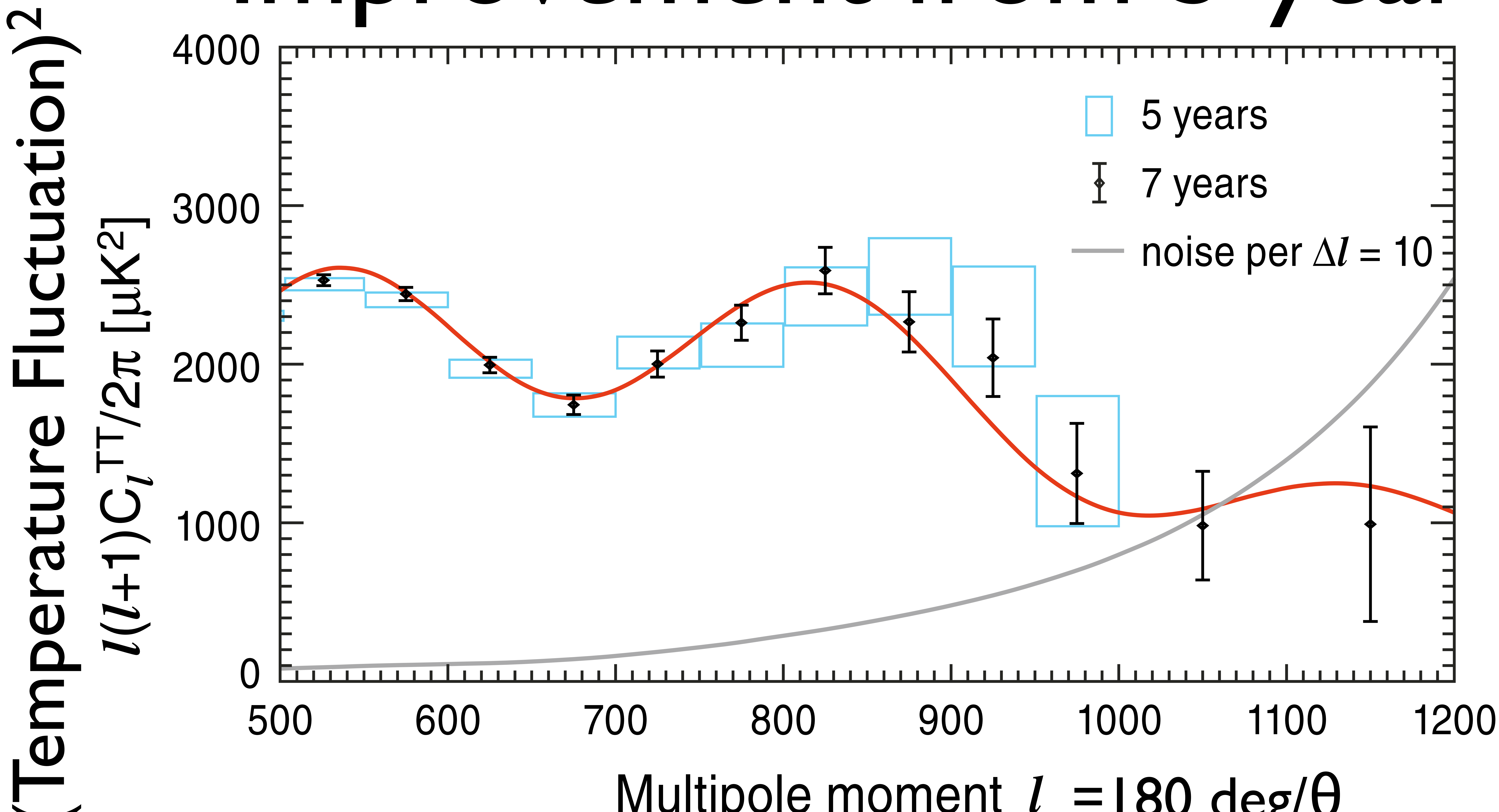
# 7-year Temperature $C_l$



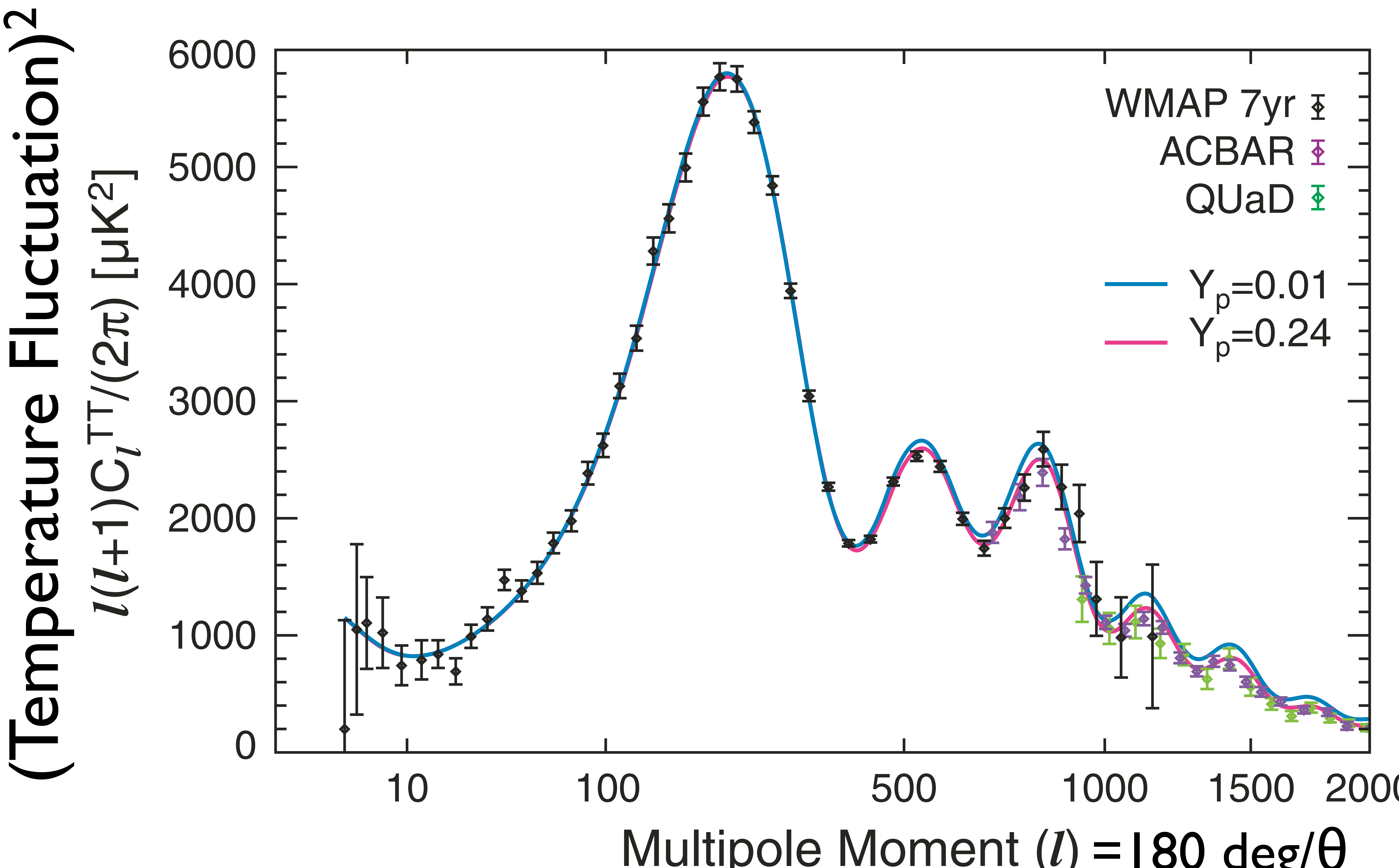
# Zooming into the 3rd peak...



# High-l Temperature $C_l$: Improvement from 5-year



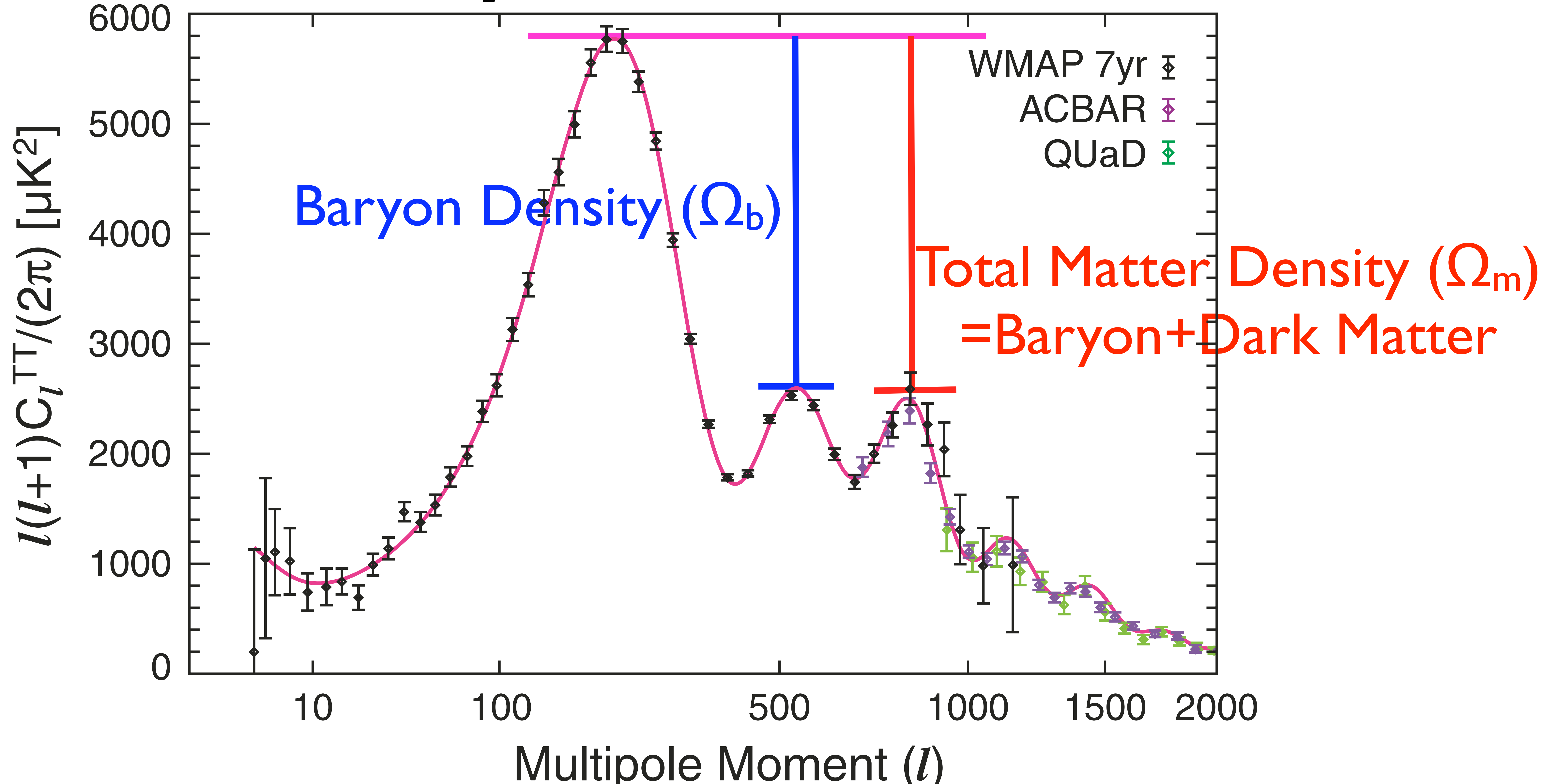
# Detection of Primordial Helium



# Effect of helium on $C_l^{TT}$

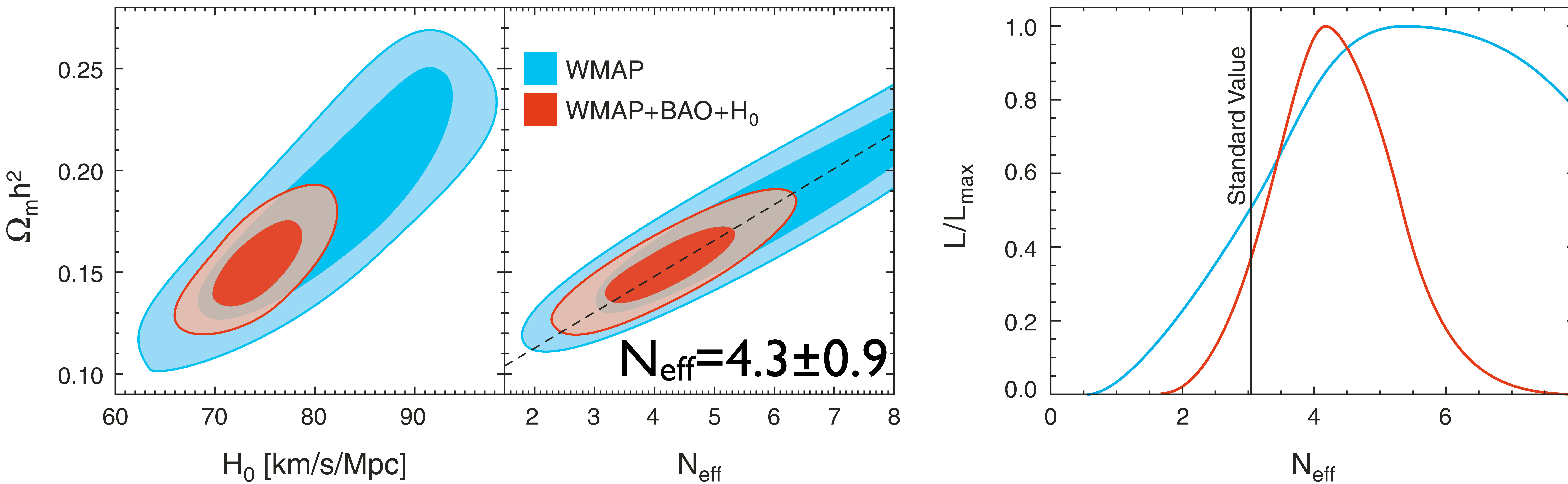
- We measure the baryon number density, $n_b$, from the 1st-to-2nd peak ratio.
- As helium recombined at z~1800, there were fewer electrons at the decoupling epoch (z=1090): $n_e=(1-Y_p)n_b$.
- **More helium** = Fewer electrons = Longer photon mean free path $1/(\sigma_T n_e)$ = **Enhanced damping**
- **$Y_p$ = 0.33 ± 0.08** (68%CL)
  - Consistent with the standard value from the Big Bang nucleosynthesis theory: $Y_P$=0.24.
- Planck should be able to reduce the error bar to **0.01**.

# CMB to Baryon & Dark Matter




- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio ($z_{EQ}$: equality redshift)

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

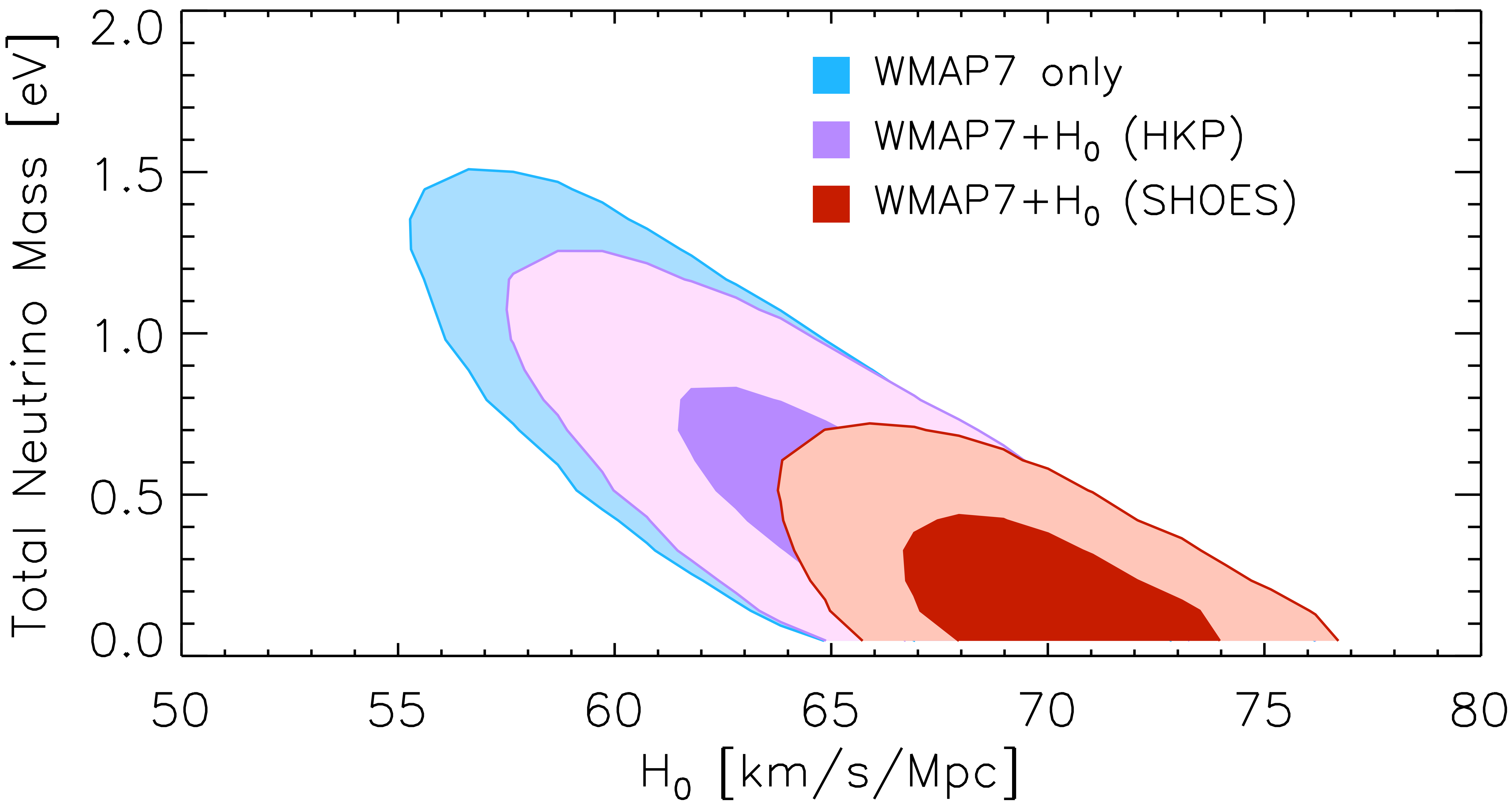



from external data

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

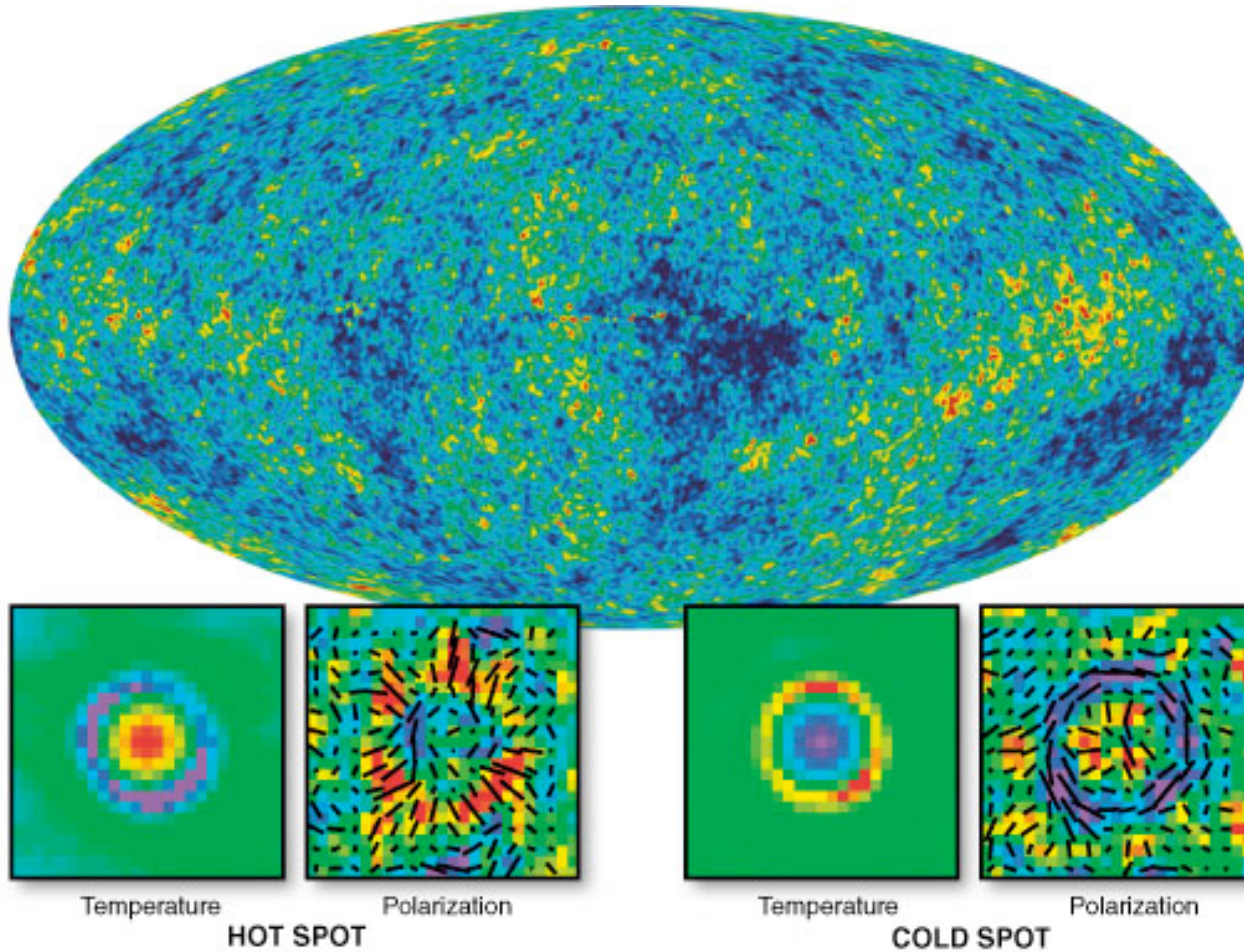
from 3rd peak

# And, the mass of neutrinos



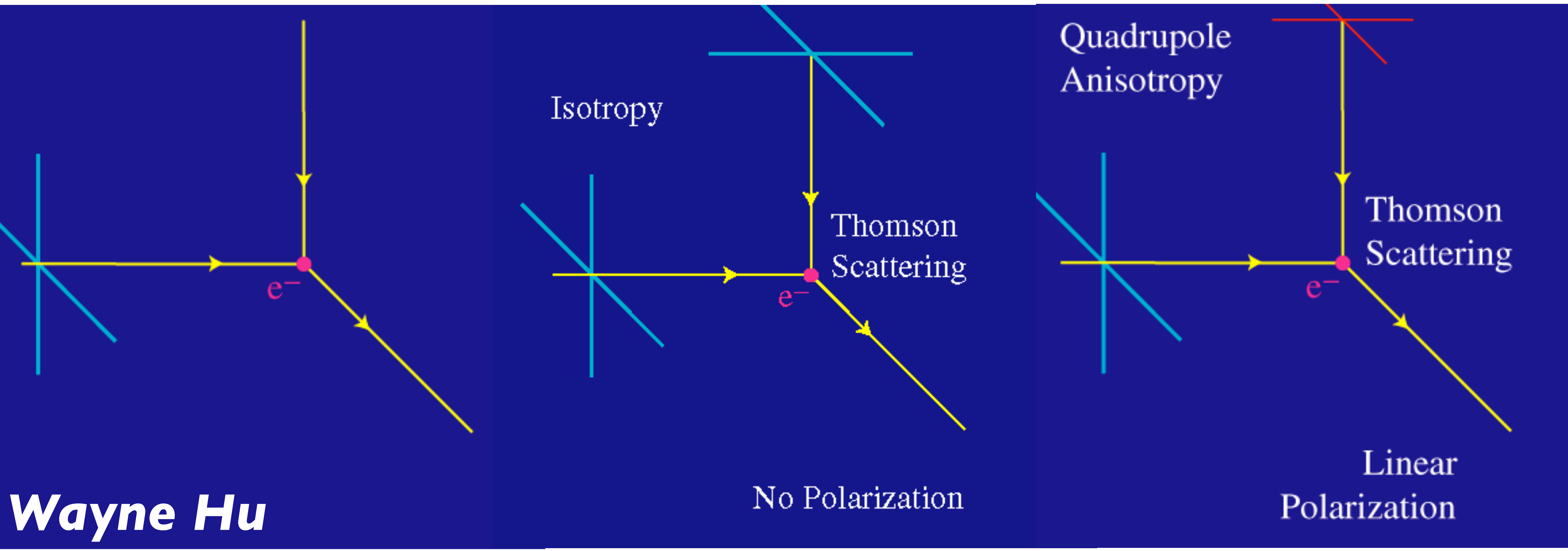

- WMAP data combined with the local measurement of the expansion rate ($H_0$), we get $\sum m_\nu < 0.6$ eV (95%CL)

# CMB Polarization



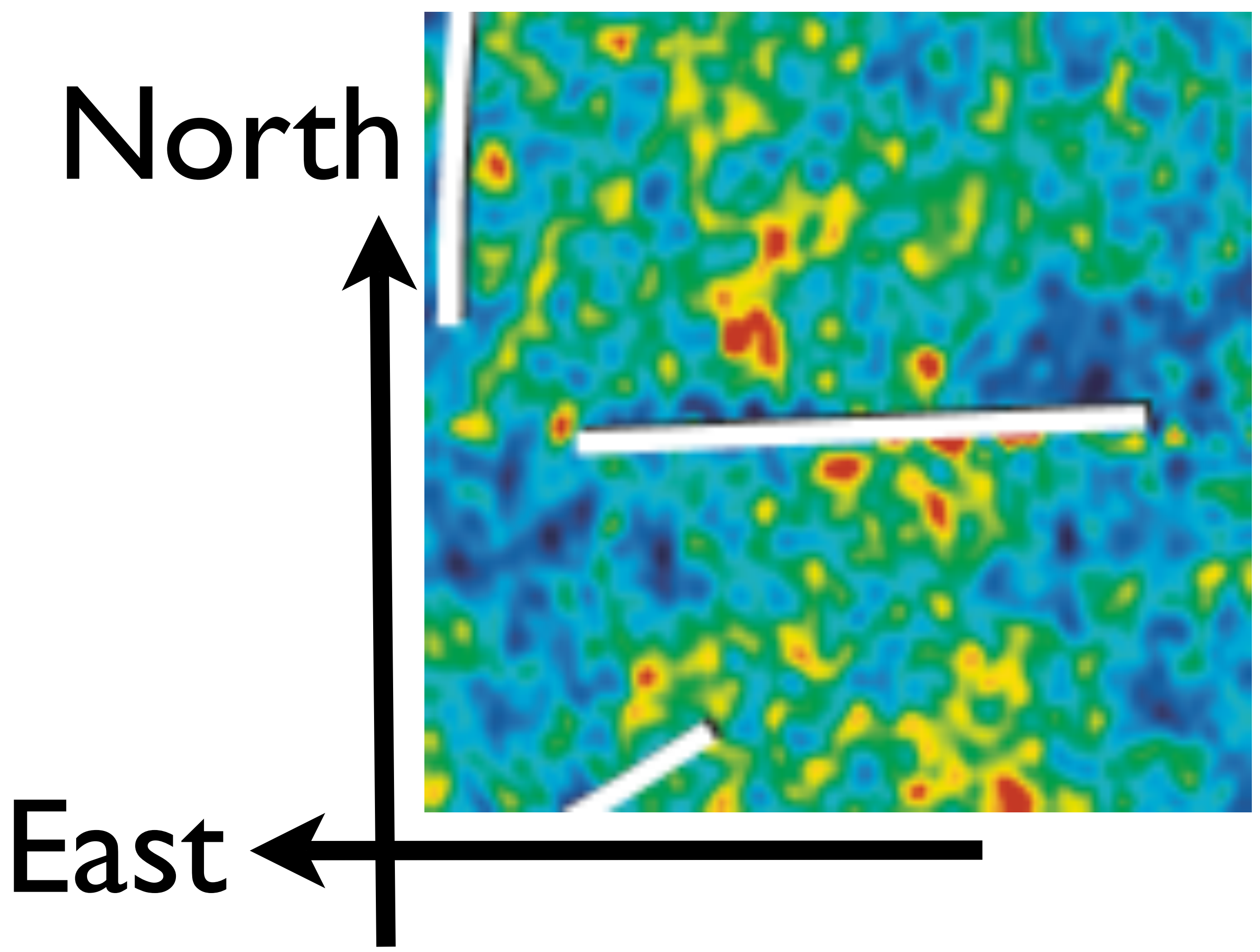

- *CMB is (very weakly) polarized!*

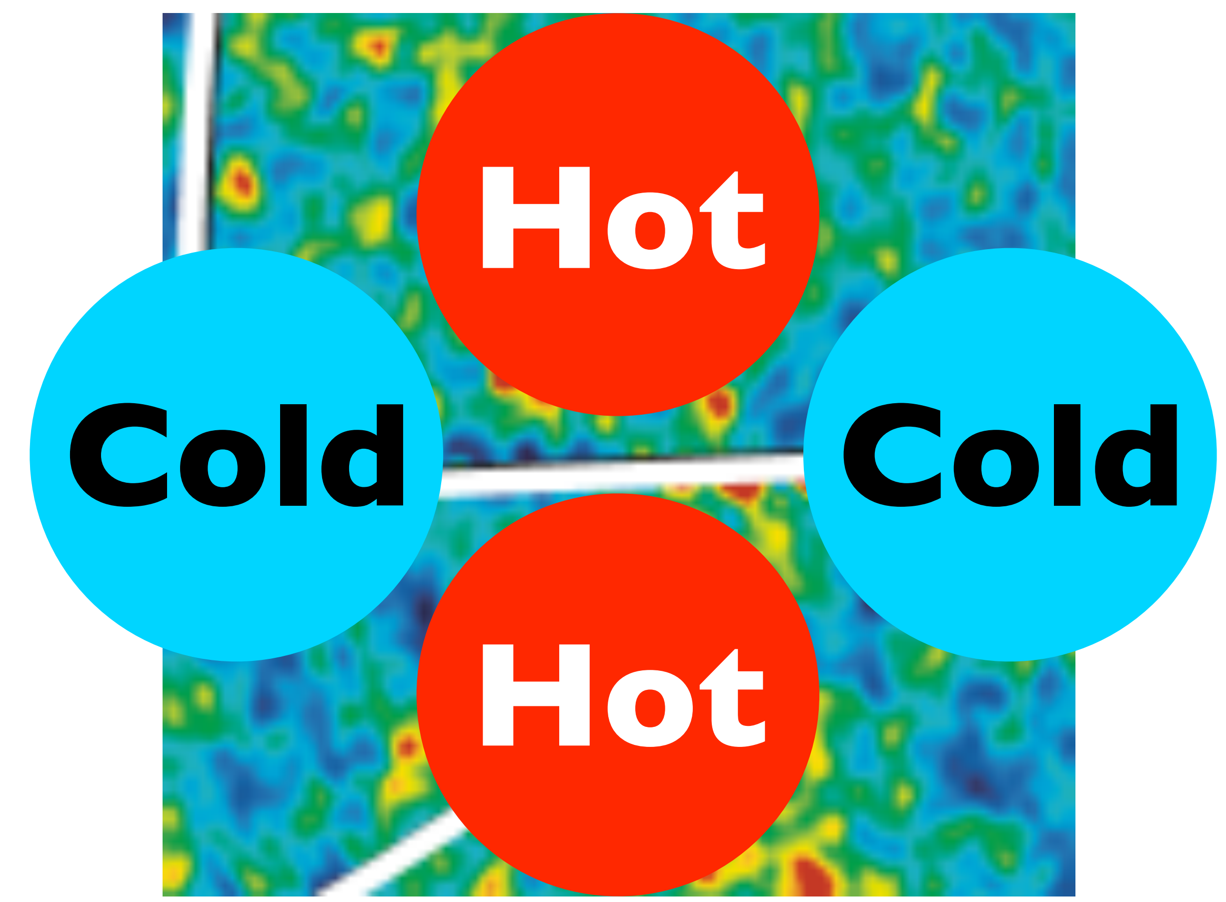
# Physics of CMB Polarization




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

# Principle




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

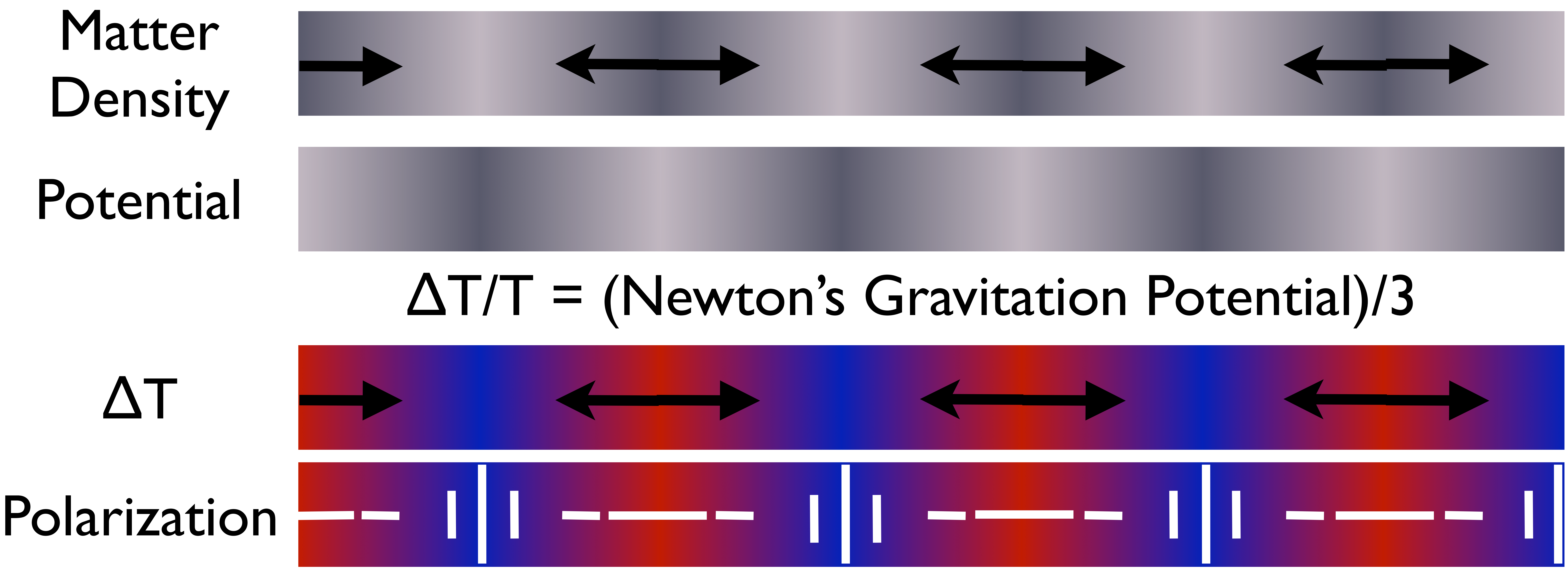
# CMB Polarization on Large Angular Scales (>2 deg)


$\Delta T/T$ = (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)*




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

# Quadrupole From Velocity Gradient (Large Scale)

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

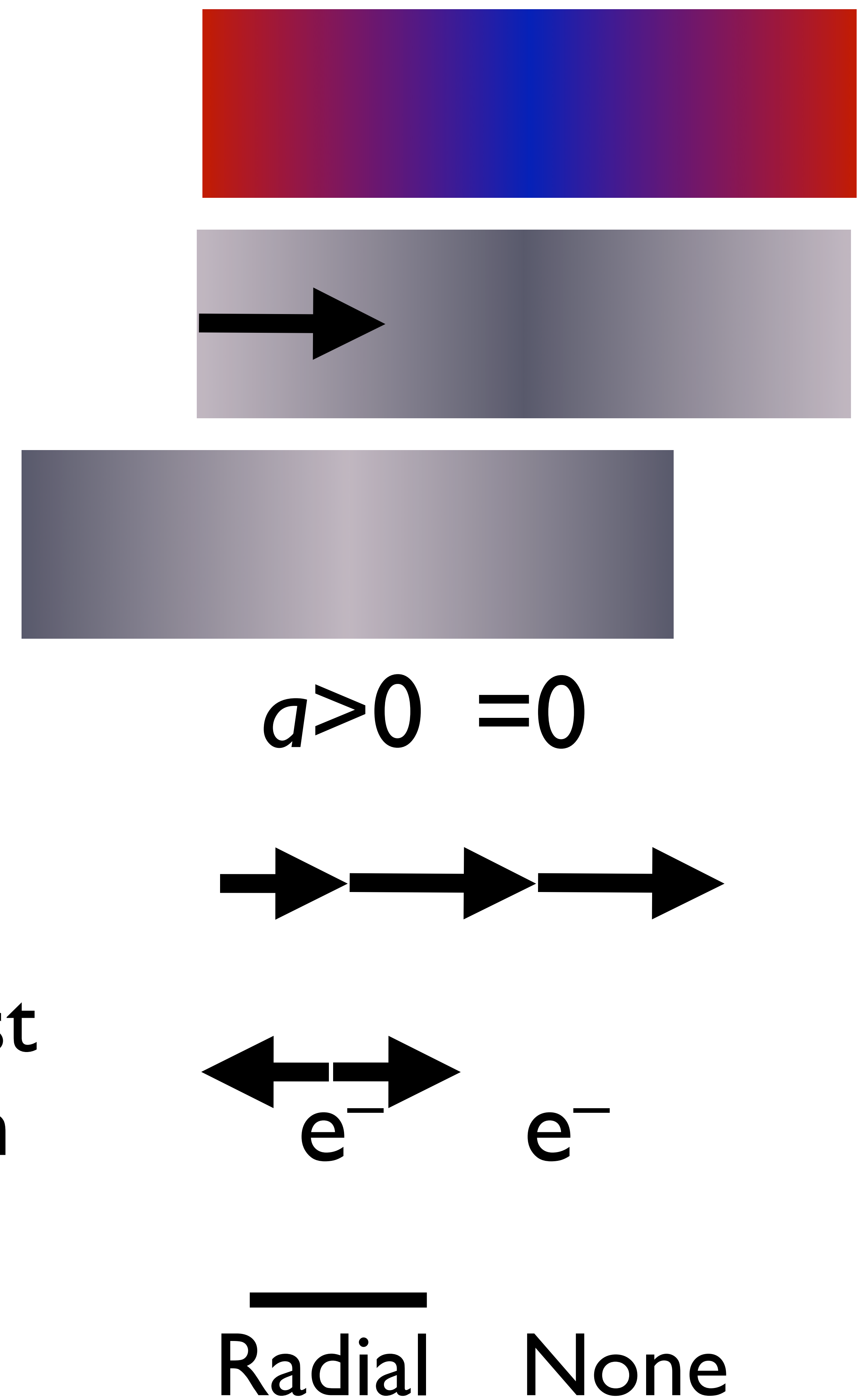
Potential $\Phi$ — Stuff flowing *in*

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)

$\Delta T$ — Compression increases temperature

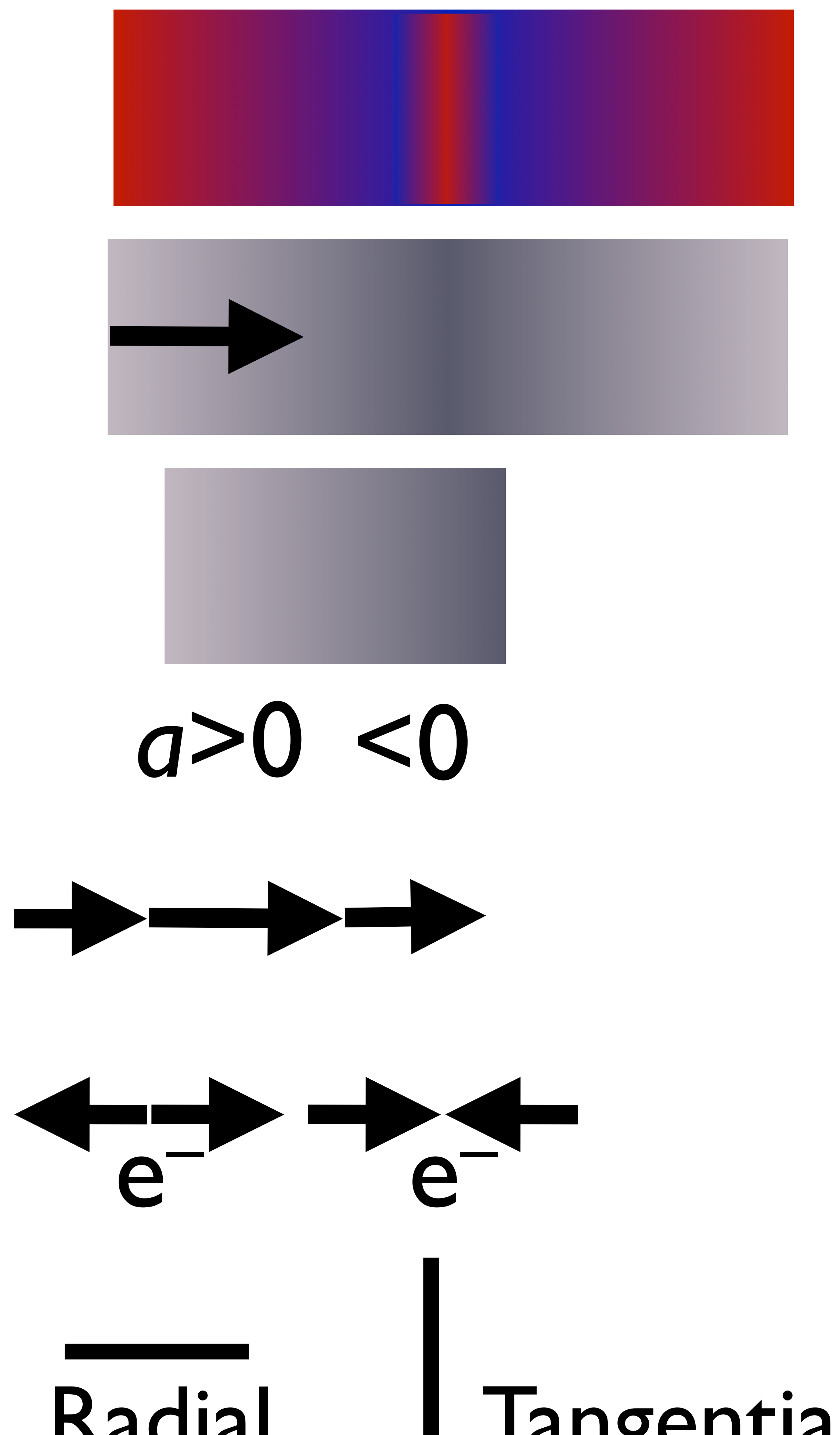
Potential $\Phi$ — Stuff flowing *in*

Acceleration $a = -\partial\Phi - \partial P$ — Pressure gradient slows down the flow

Velocity — Velocity gradient

Velocity in the rest frame of electron

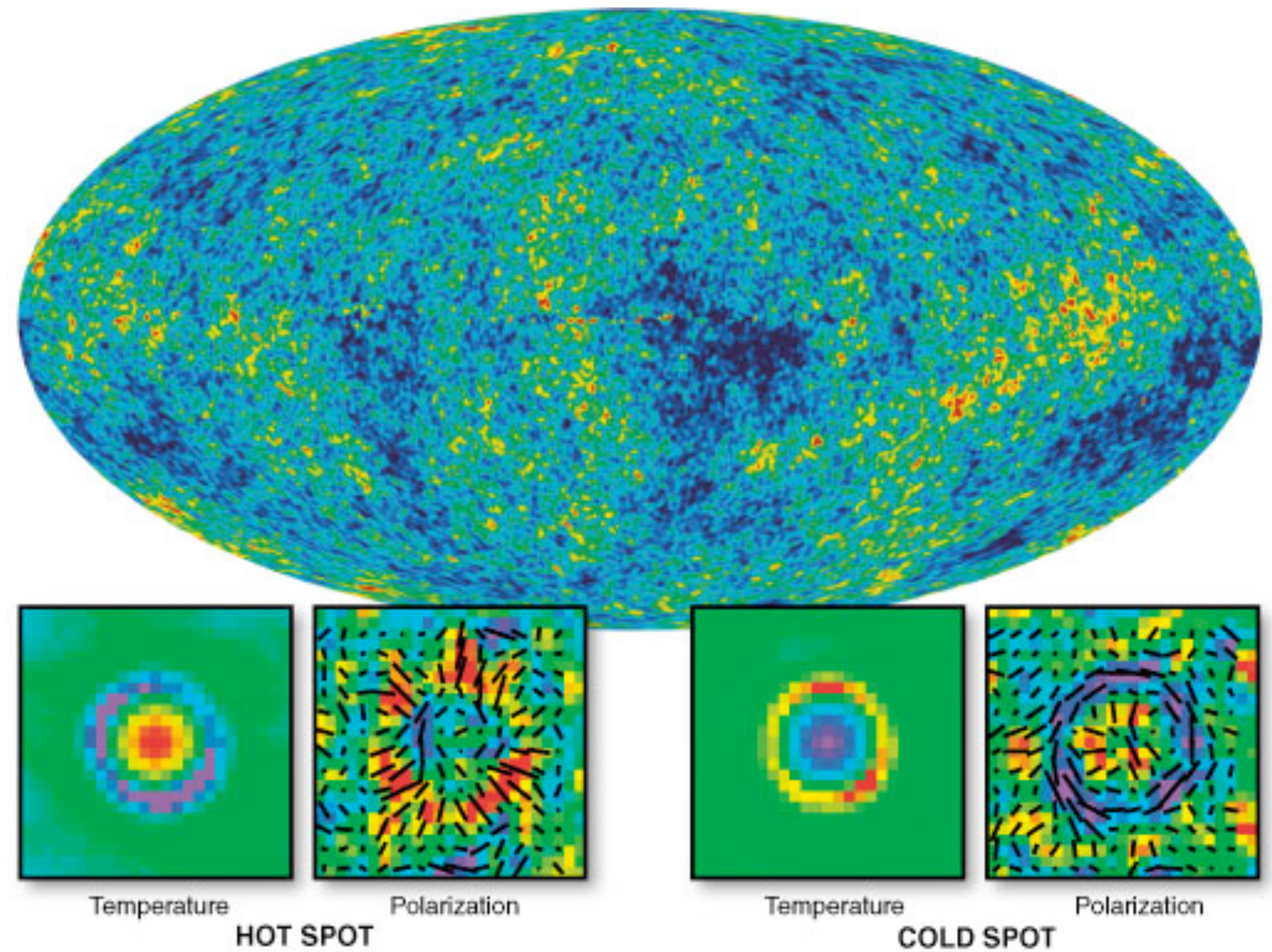
Polarization

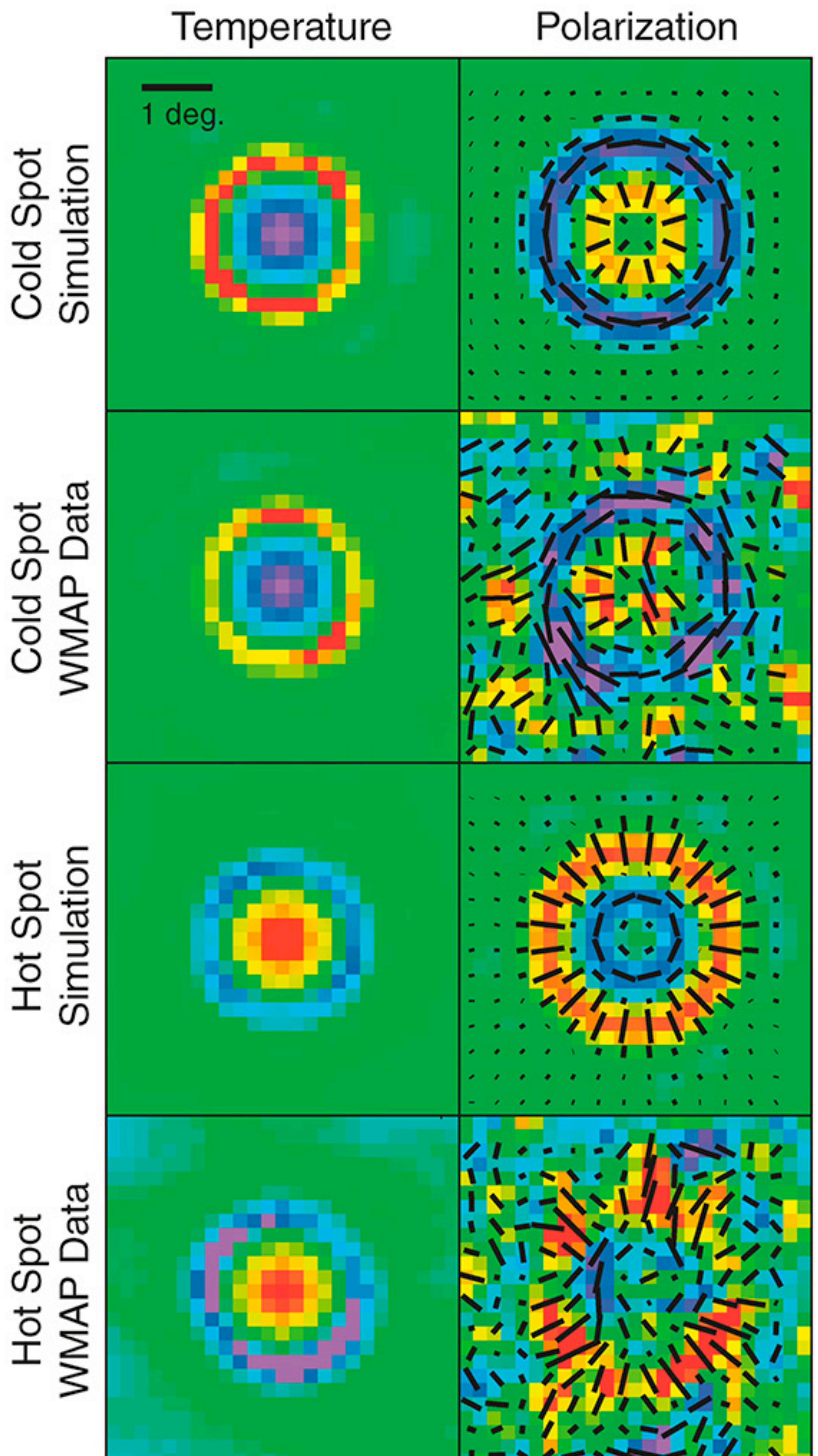


# Stacking Analysis

- 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**.

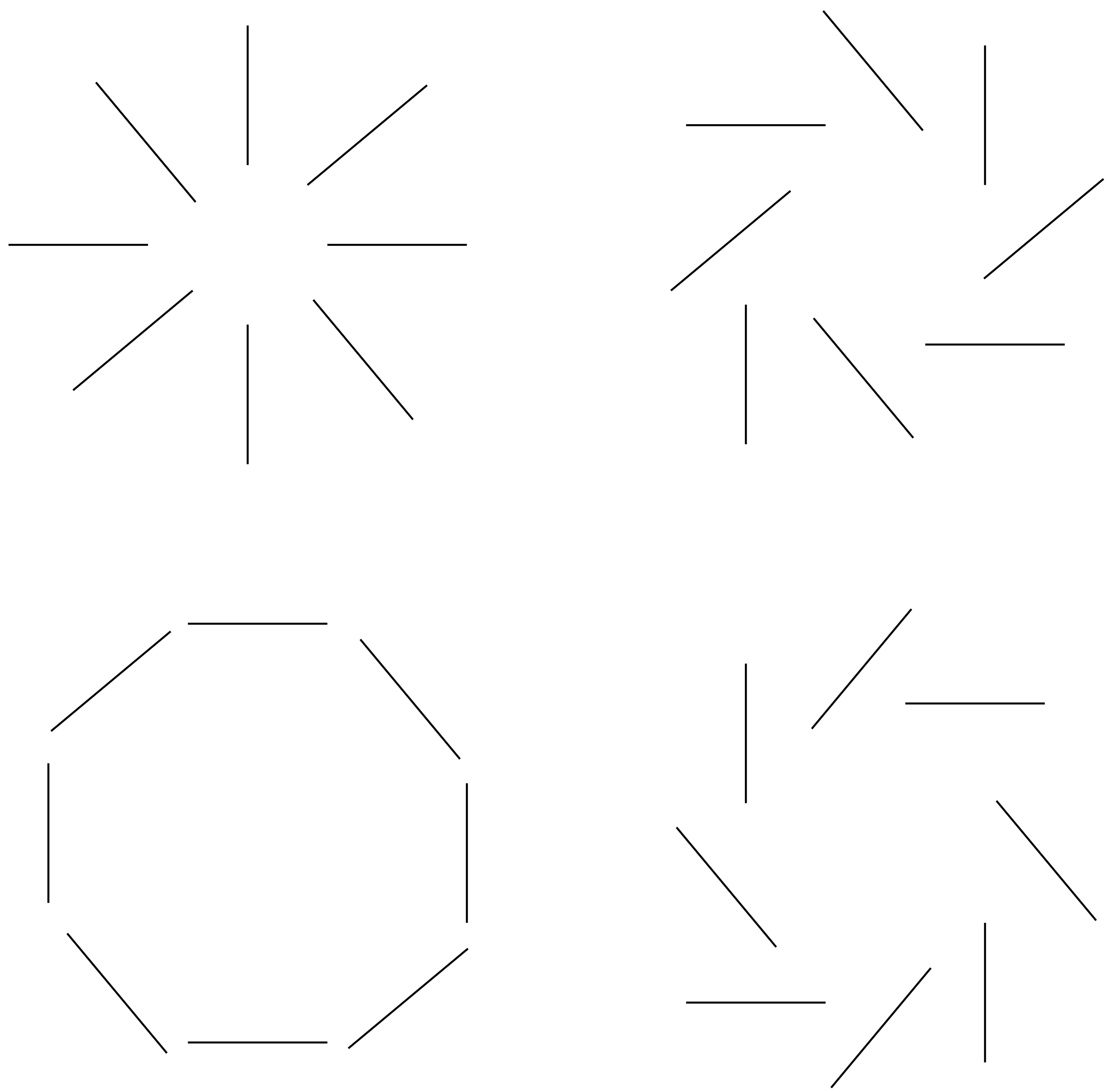





# Two-dimensional View

- 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: $8\sigma$

# E-mode and B-mode



E mode B mode

- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

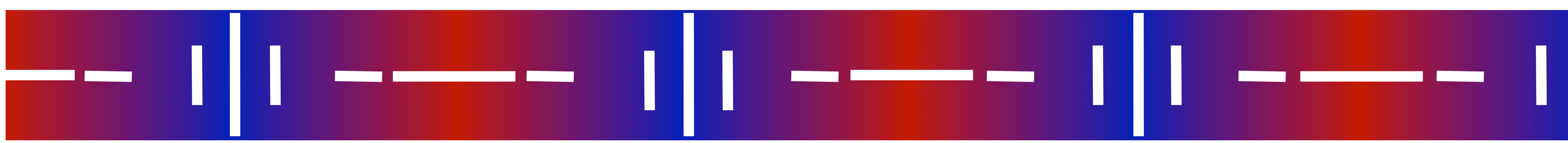
# E-mode

Potential

$\Phi(\boldsymbol{k},\boldsymbol{x})=\cos(\boldsymbol{kx})$

Direction of a plane wave

Polarization Direction



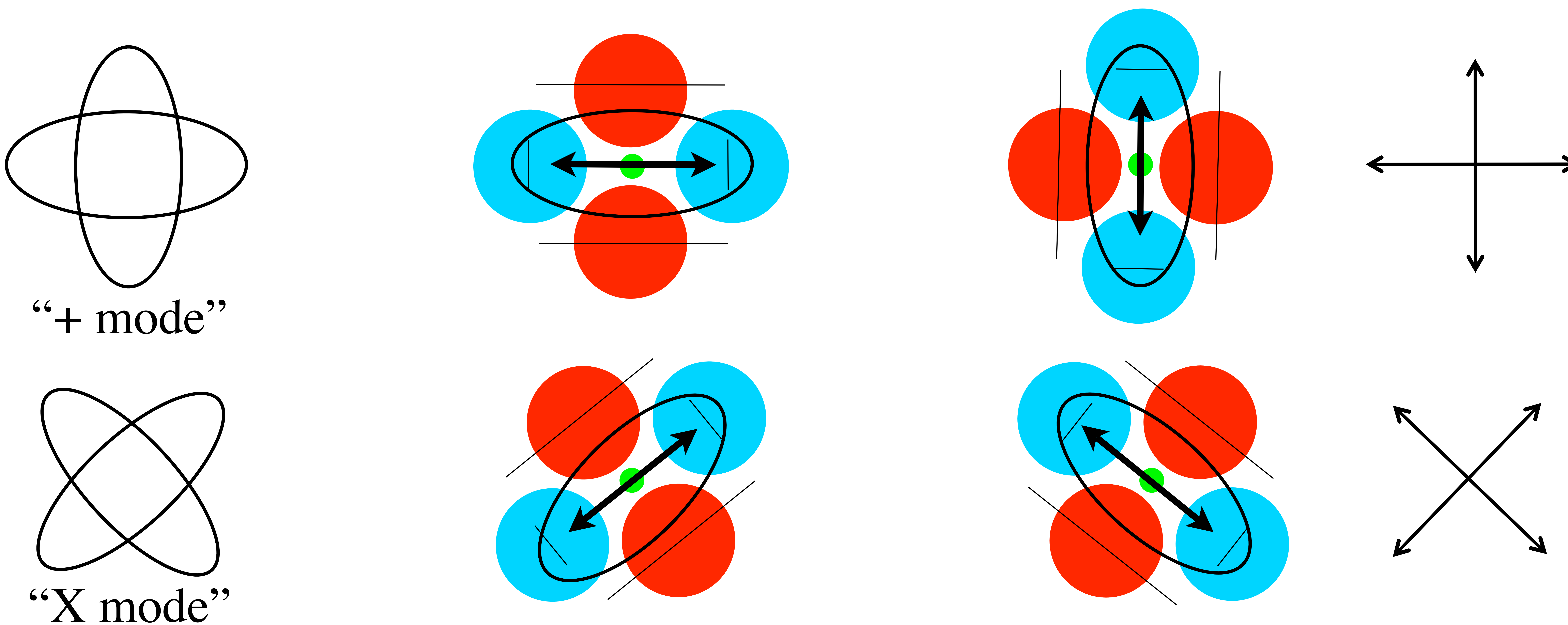
- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

# B-mode

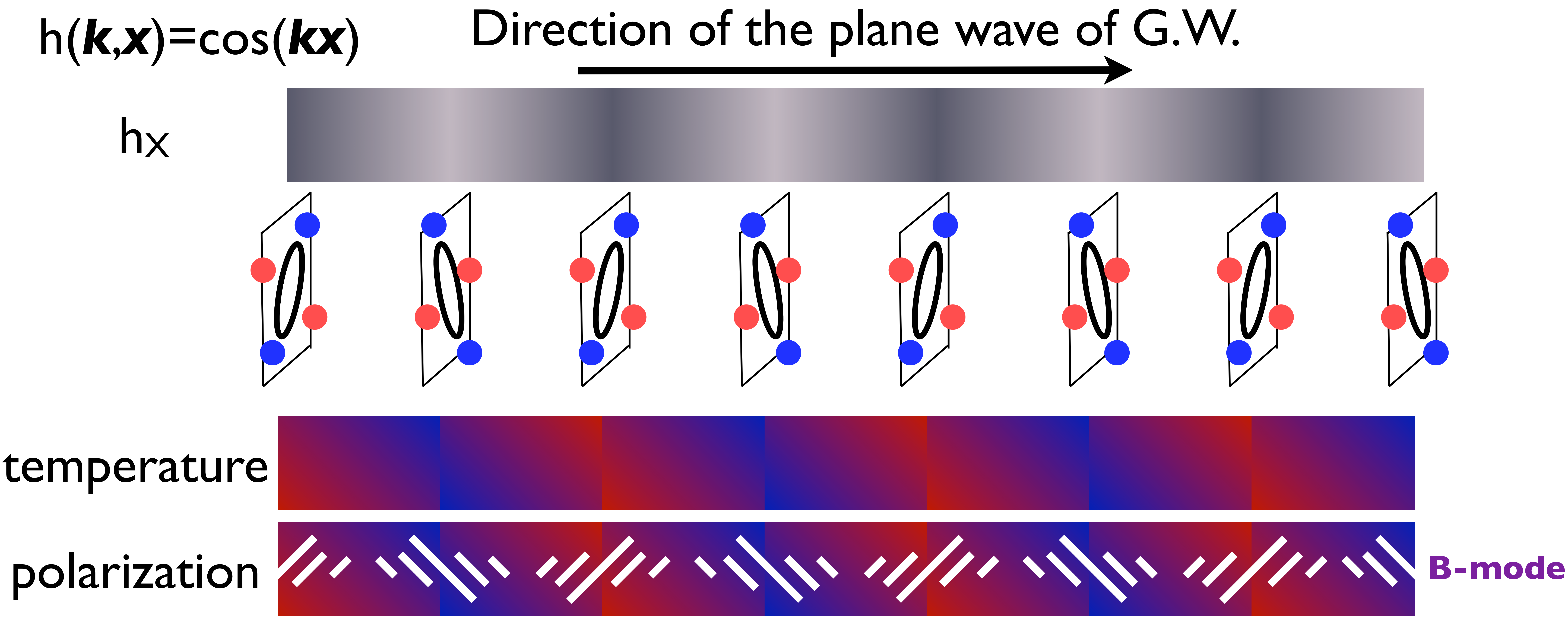

- **B-mode**: the polarization directions are tilted by 45 degrees relative to the direction of the plane wave perturbation.

# Gravitational Waves and Quadrupole

- Gravitational waves stretch space with a quadrupole pattern.



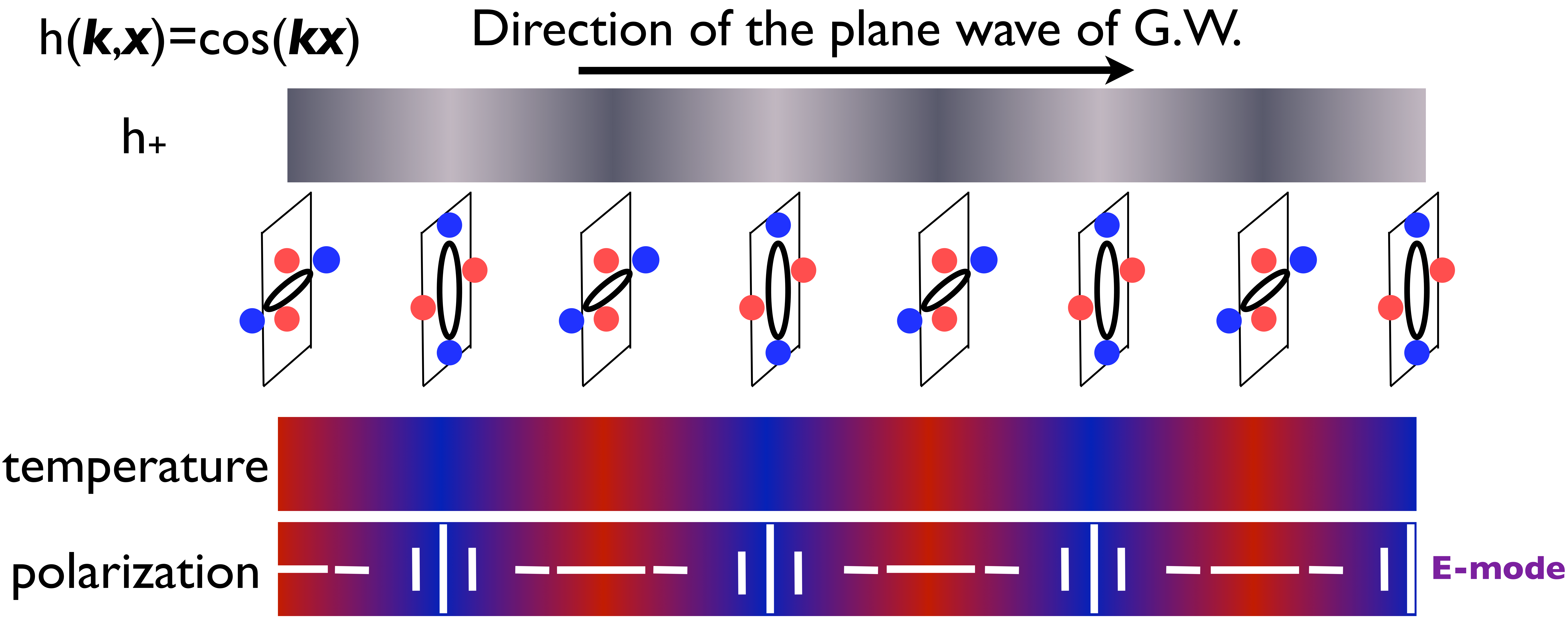
# Quadrupole from G.W.



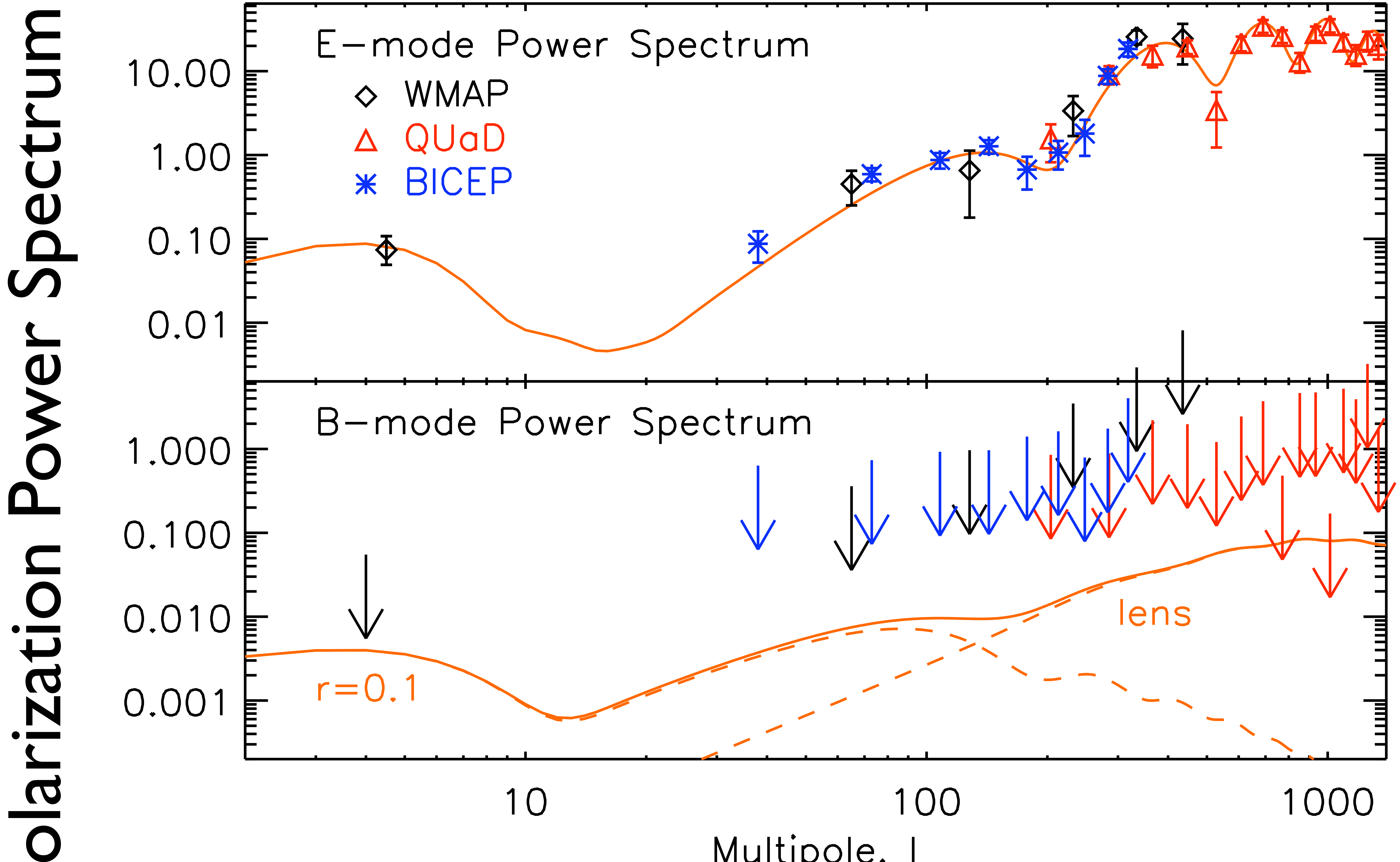

- B-mode polarization generated by $h_\times$

# Quadrupole from G.W.

$h(\boldsymbol{k},\boldsymbol{x})=\cos(\boldsymbol{kx})$

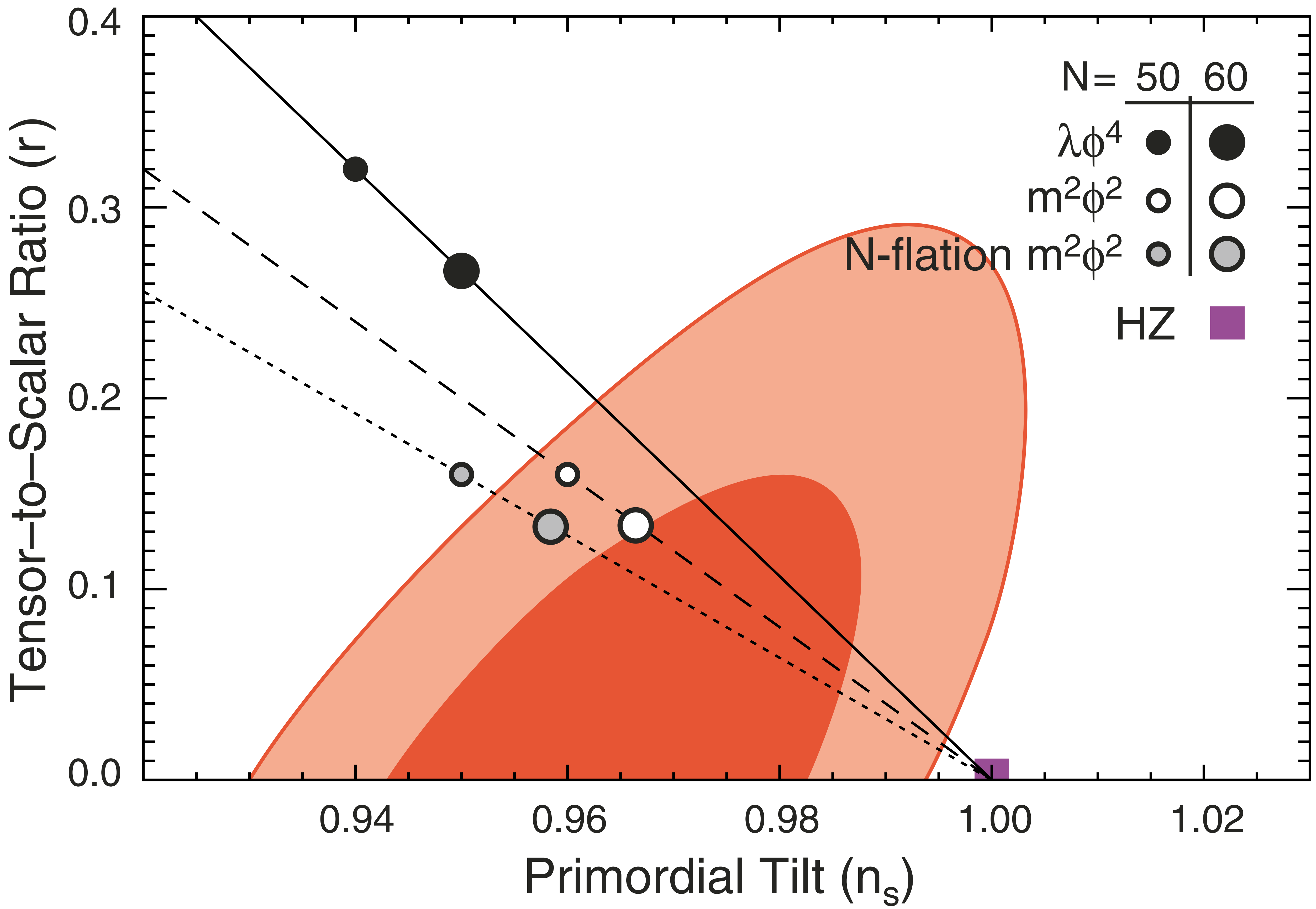



- E-mode polarization generated by $h_+$




- No detection of B-mode polarization yet. **B-mode is the next holy grail!**

# 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)

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

# If this means anything to you...

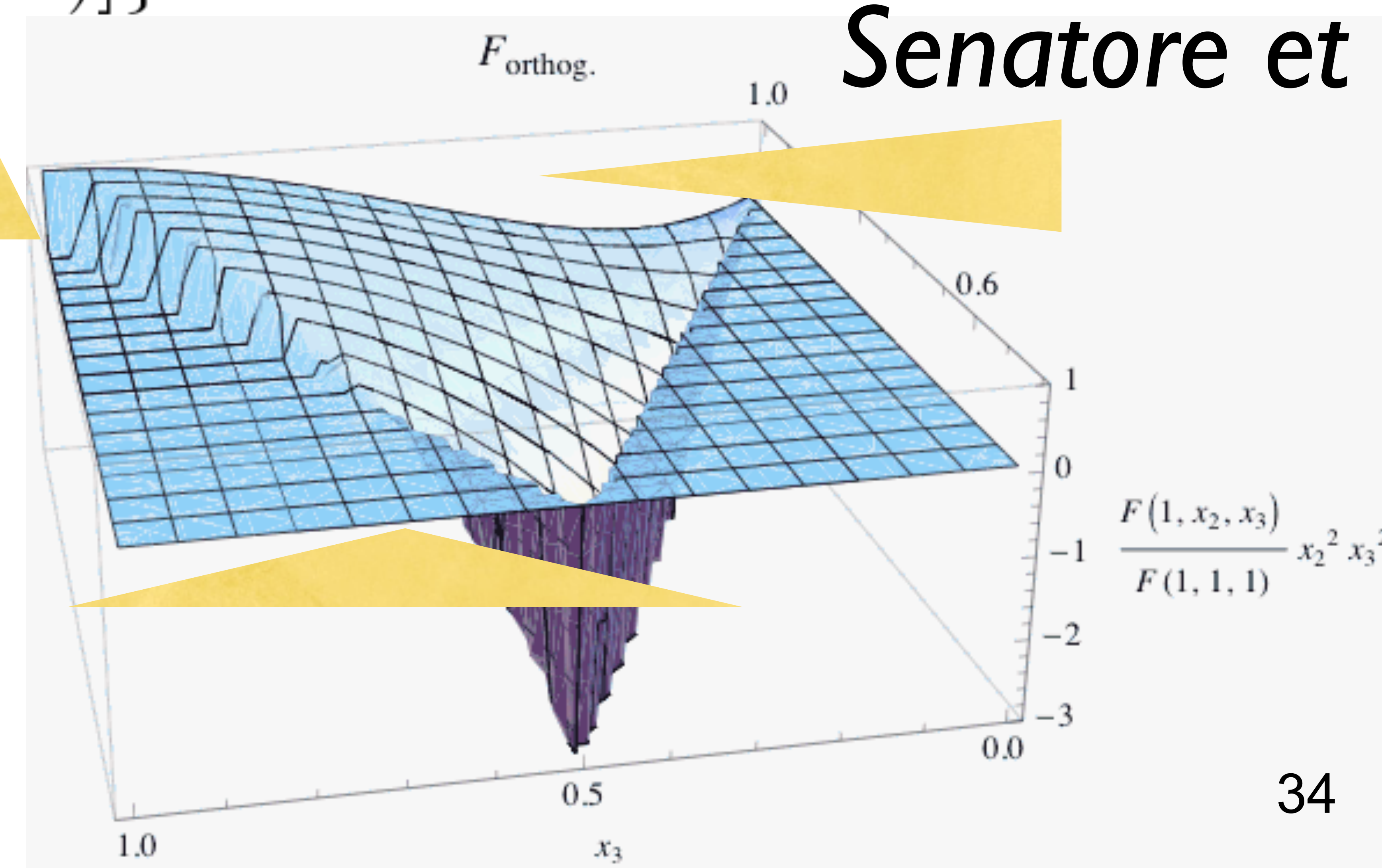
$$\langle \Phi_{\mathbf{k}_1} \Phi_{\mathbf{k}_2} \Phi_{\mathbf{k}_3} \rangle = (2\pi)^3 \delta^D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) F(k_1, k_2, k_3)$$

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

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

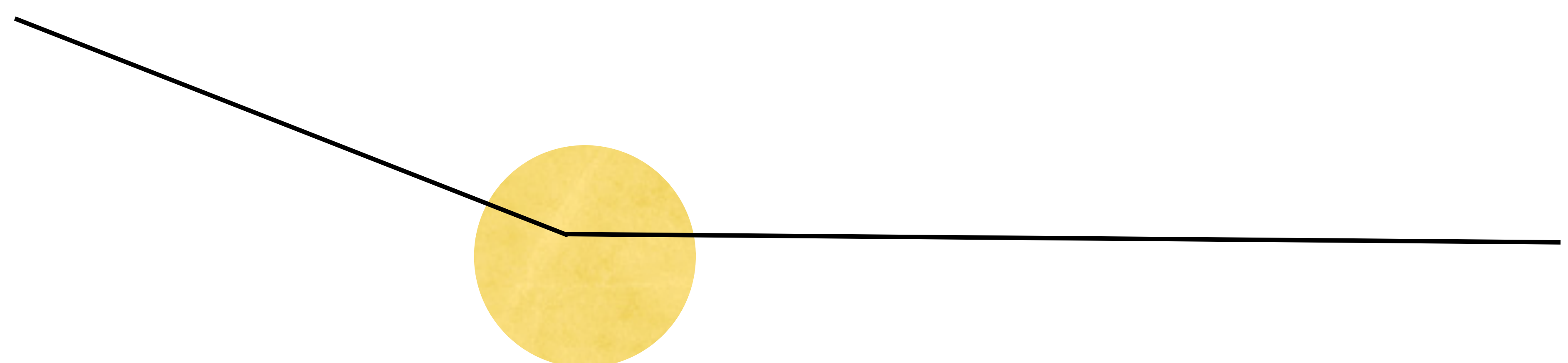
$$\begin{aligned} F_{\rm orthog}(k_1, k_2, k_3) &= 6 A f_{NL}^{\rm orthog} \\ \times \Bigg\{ &-\frac{3}{k_1^{4-n_s} k_2^{4-n_s}} - \frac{3}{k_2^{4-n_s} k_3^{4-n_s}} - \frac{3}{k_3^{4-n_s} k_1^{4-n_s}} \\ &- \frac{8}{(k_1 k_2 k_3)^{2(4-n_s)/3}} + \left[ \frac{3}{k_1^{(4-n_s)/3} k_2^{2(4-n_s)/3} k_3^{4-n_s}}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

*Senatore et al.*



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

# Sunyaev–Zel'dovich Effect



observer

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

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

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

- Decrement: **$\Delta T<0$** ($\nu$<217 GHz)
- Increment: **$\Delta T>0$** ($\nu$>217 GHz)

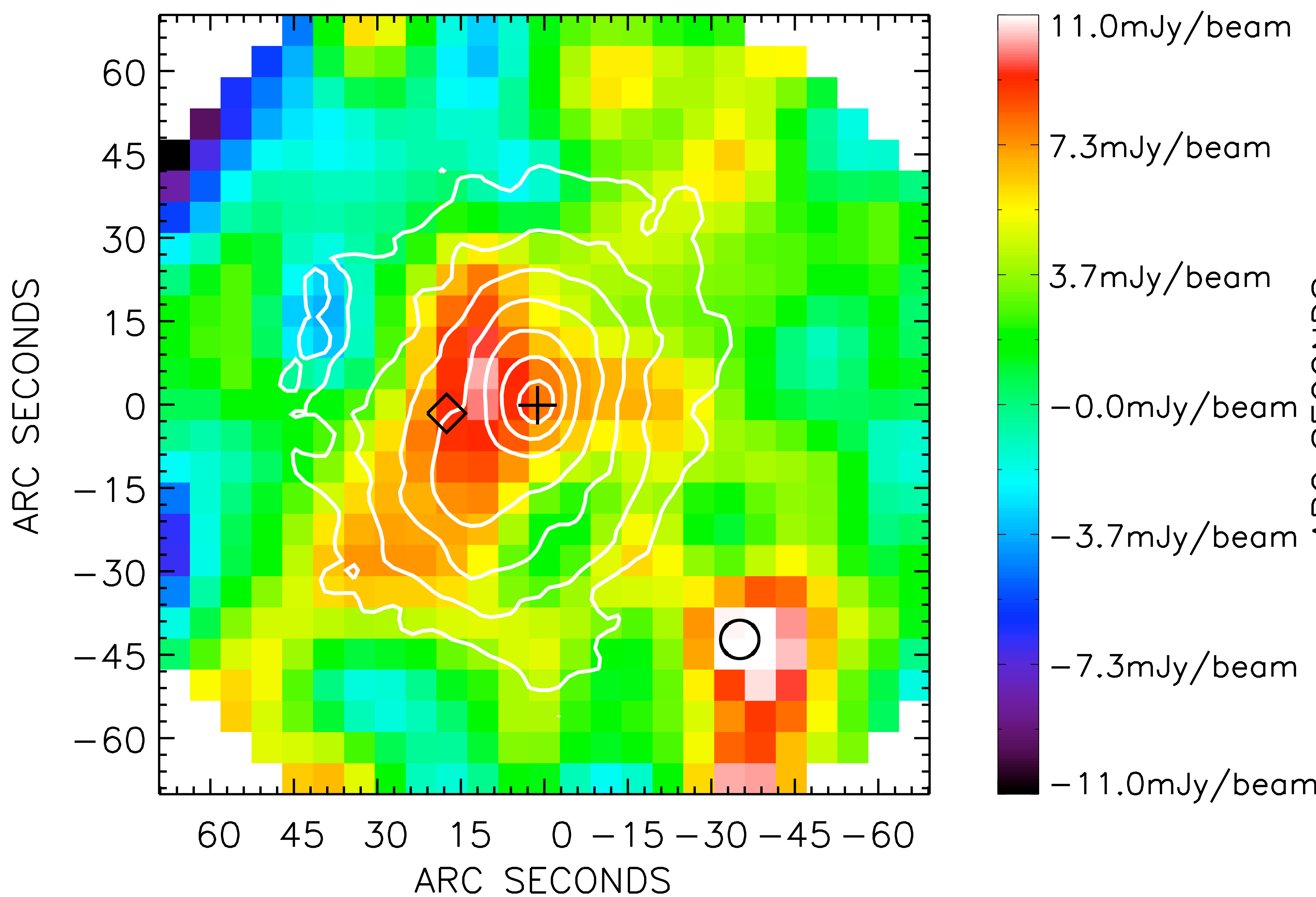
$g_\nu$=–2 ($\nu$=0); –1.91, –1.81 and –1.56 at $\nu$=41, 61 and 94 GHz

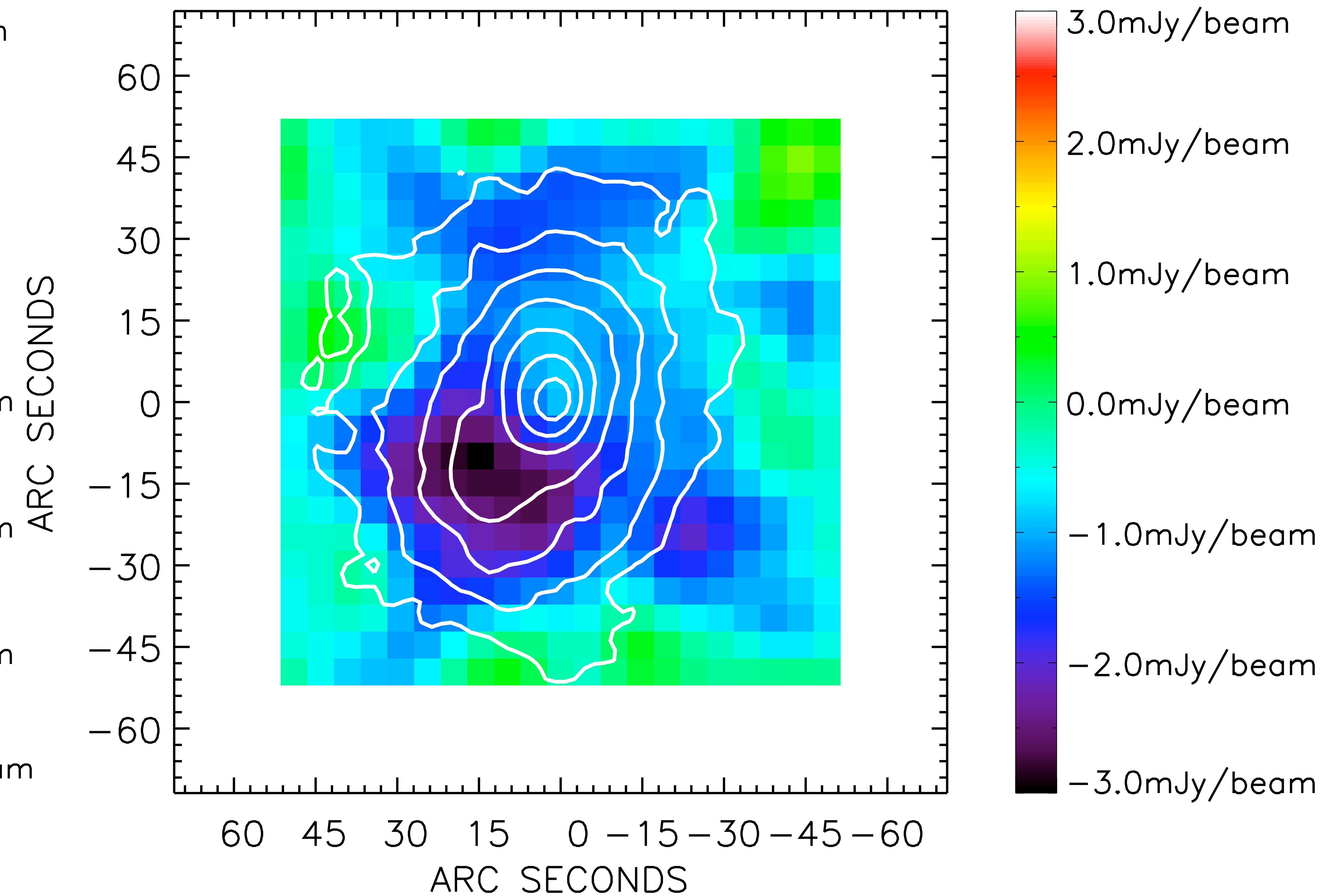
# A New Result!

We find, *for the first time in the Sunyaev-Zel'dovich (SZ) effect*, a significant difference between relaxed and non-relaxed clusters.

- Important when using the SZ effect of clusters of galaxies as a cosmological probe.

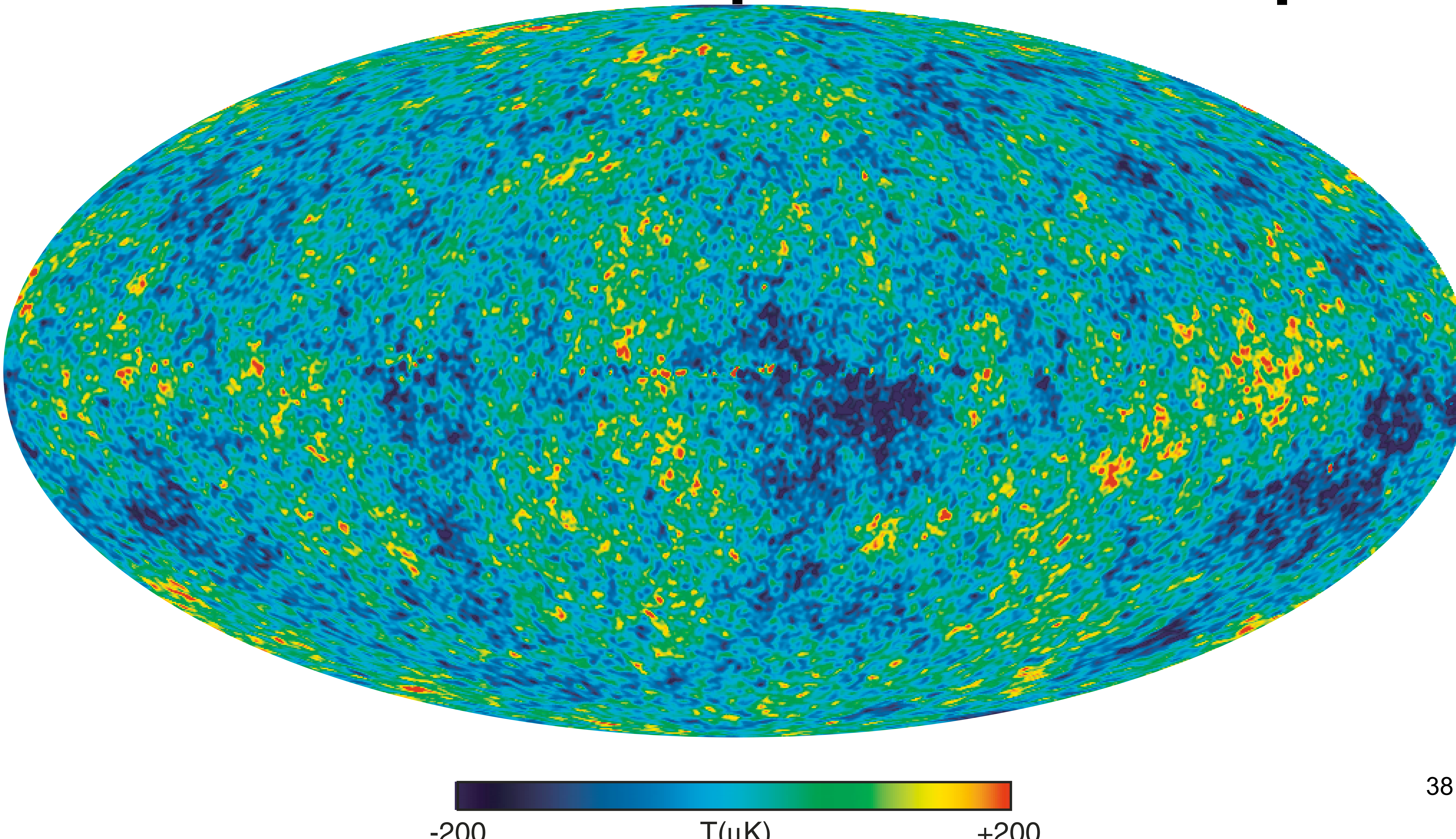
# The SZ Effect: Decrement and Increment



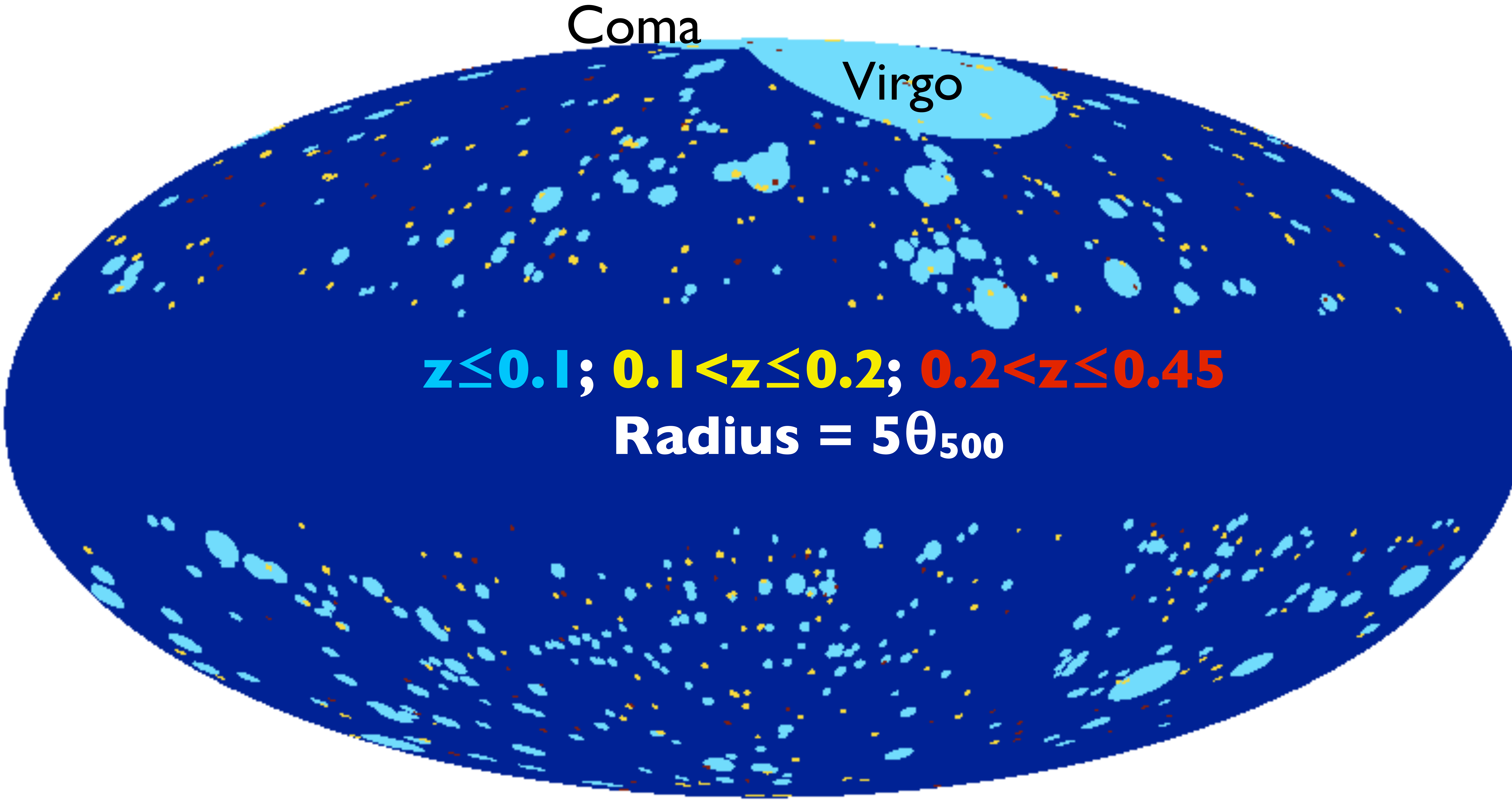




- RXJ1347-1145
  - –Left, SZ increment (350GHz, Komatsu et al. 1999)
  - –Right, SZ decrement (150GHz, Komatsu et al. 2001)

# WMAP Temperature Map



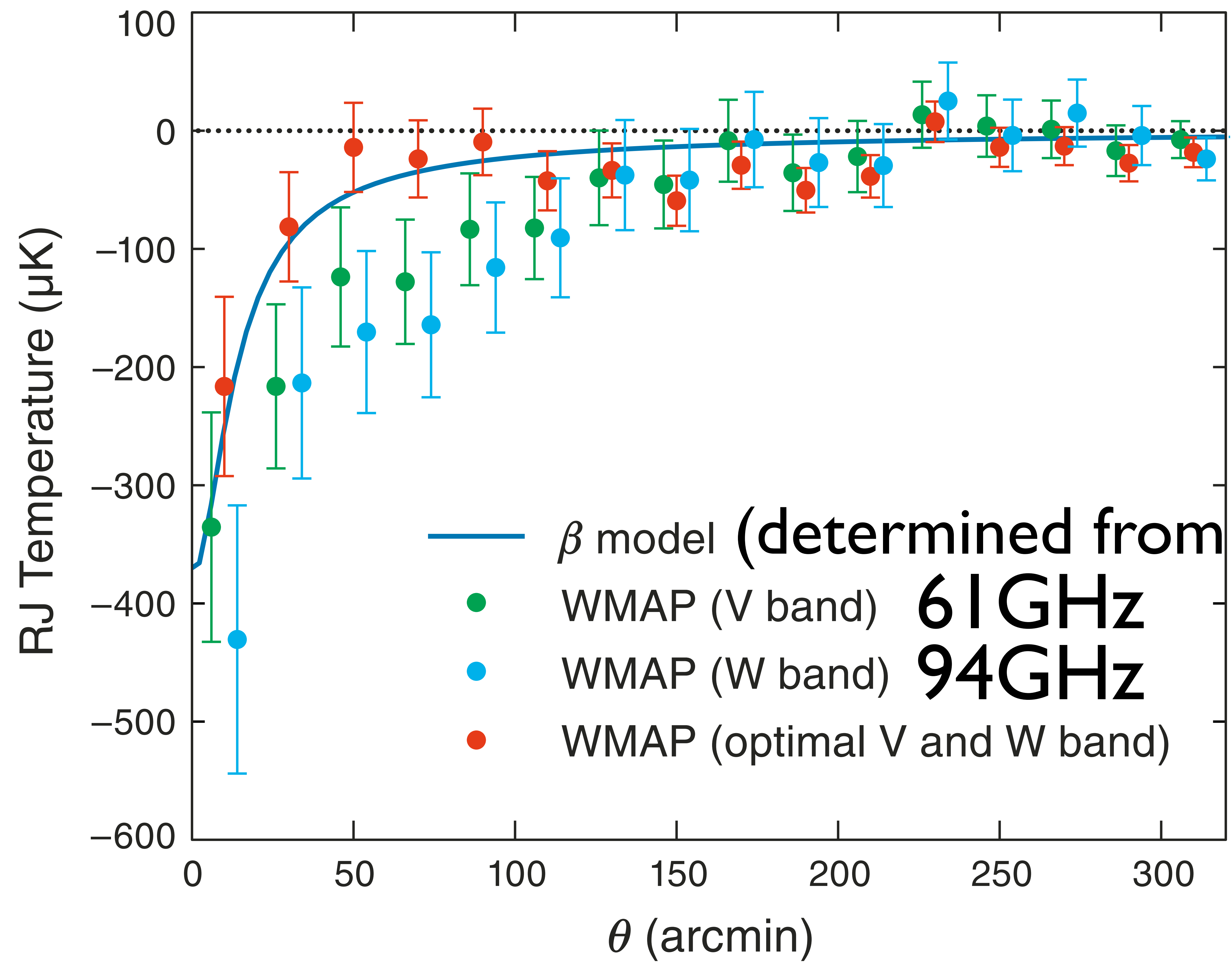
# Where are clusters?



# 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)




$g_\nu=-1.81$

$g_\nu=-1.56$

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

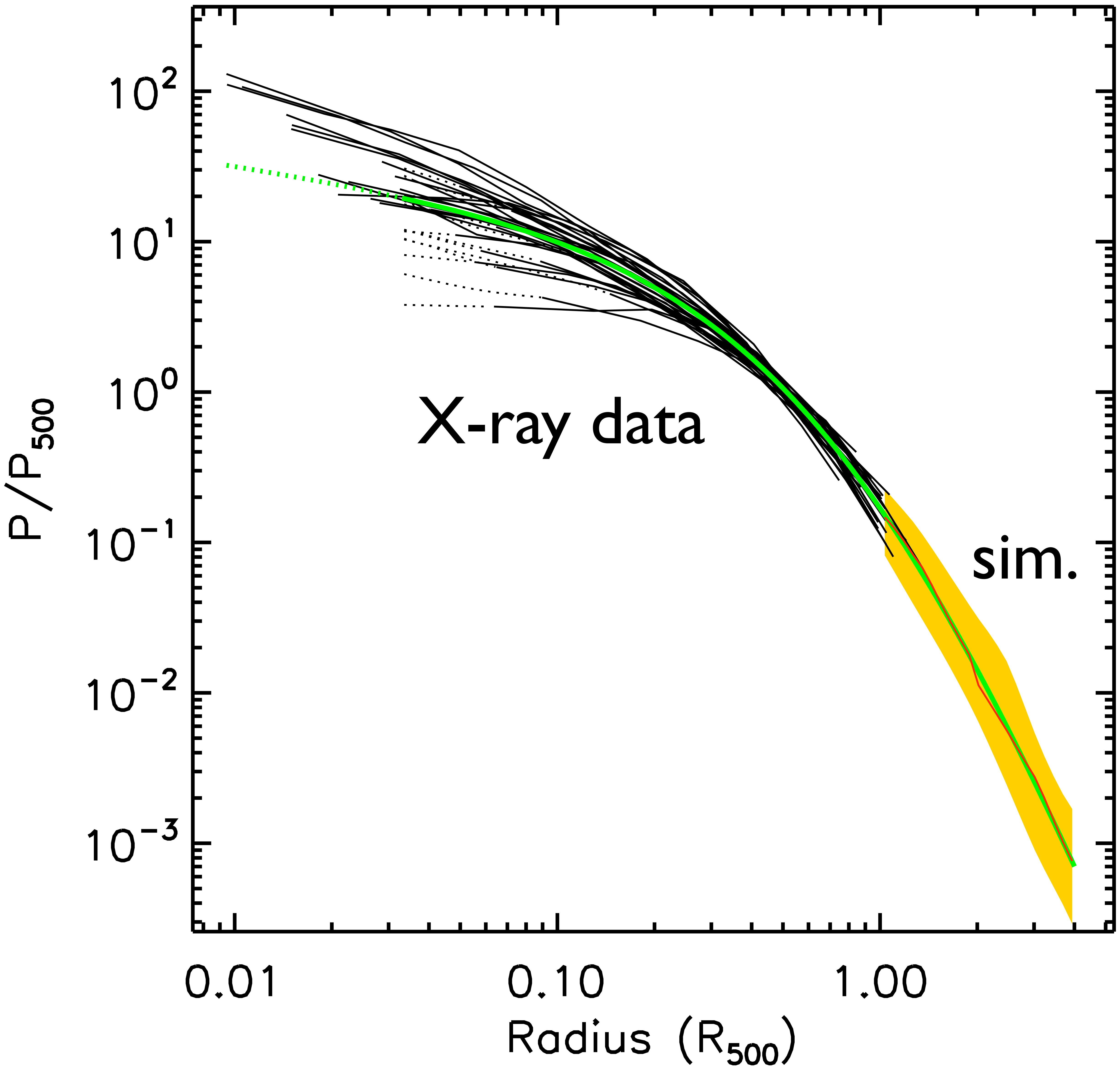
# A Question

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

# Arnaud et al. Profile

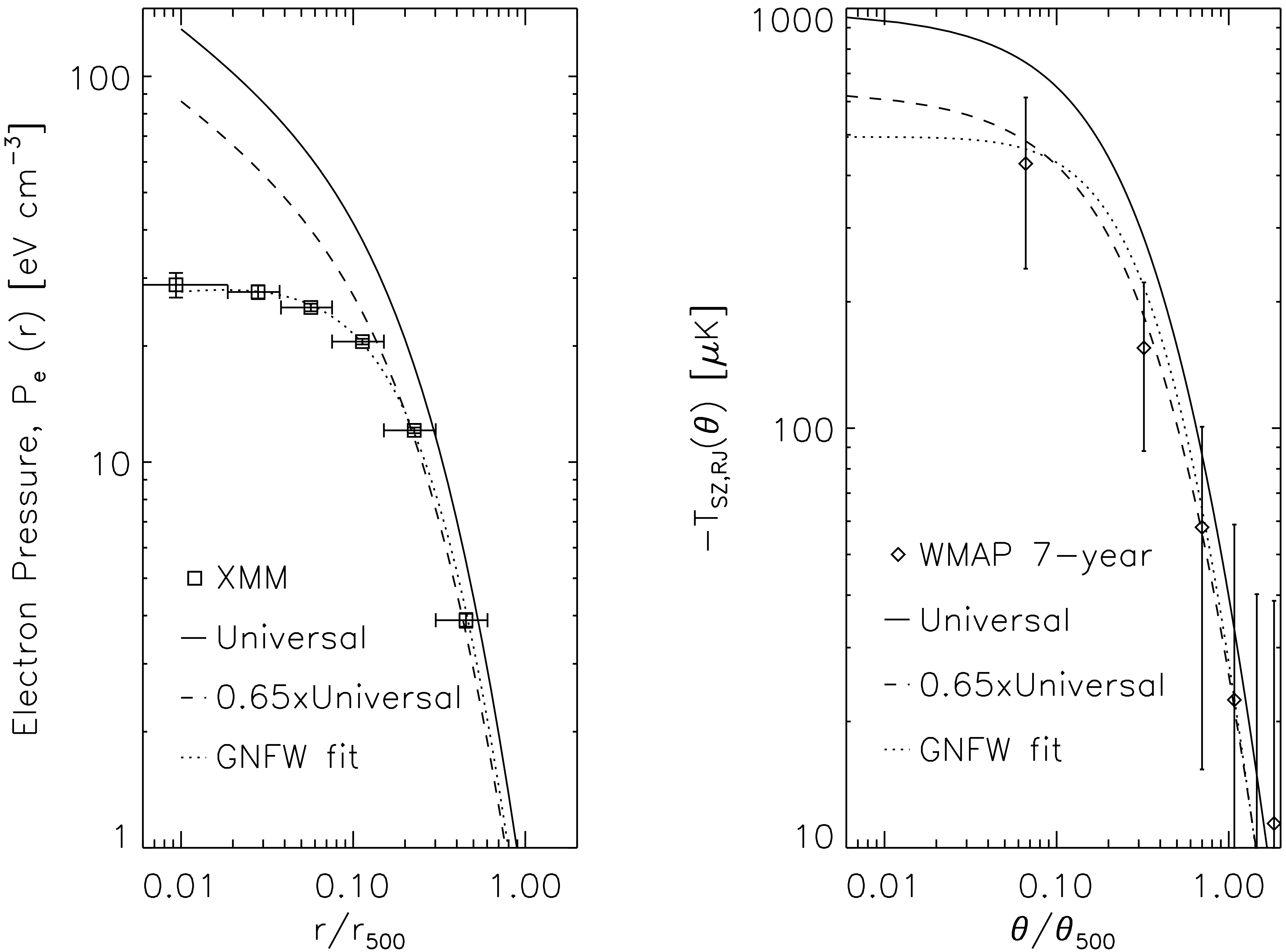
- A fitting formula for the average electron pressure profile as a function of the cluster mass ($M_{500}$), derived from 33 nearby ($z<0.2$) clusters (REXCESS sample).

# Arnaud et al. Profile




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

# Coma Data vs Arnaud

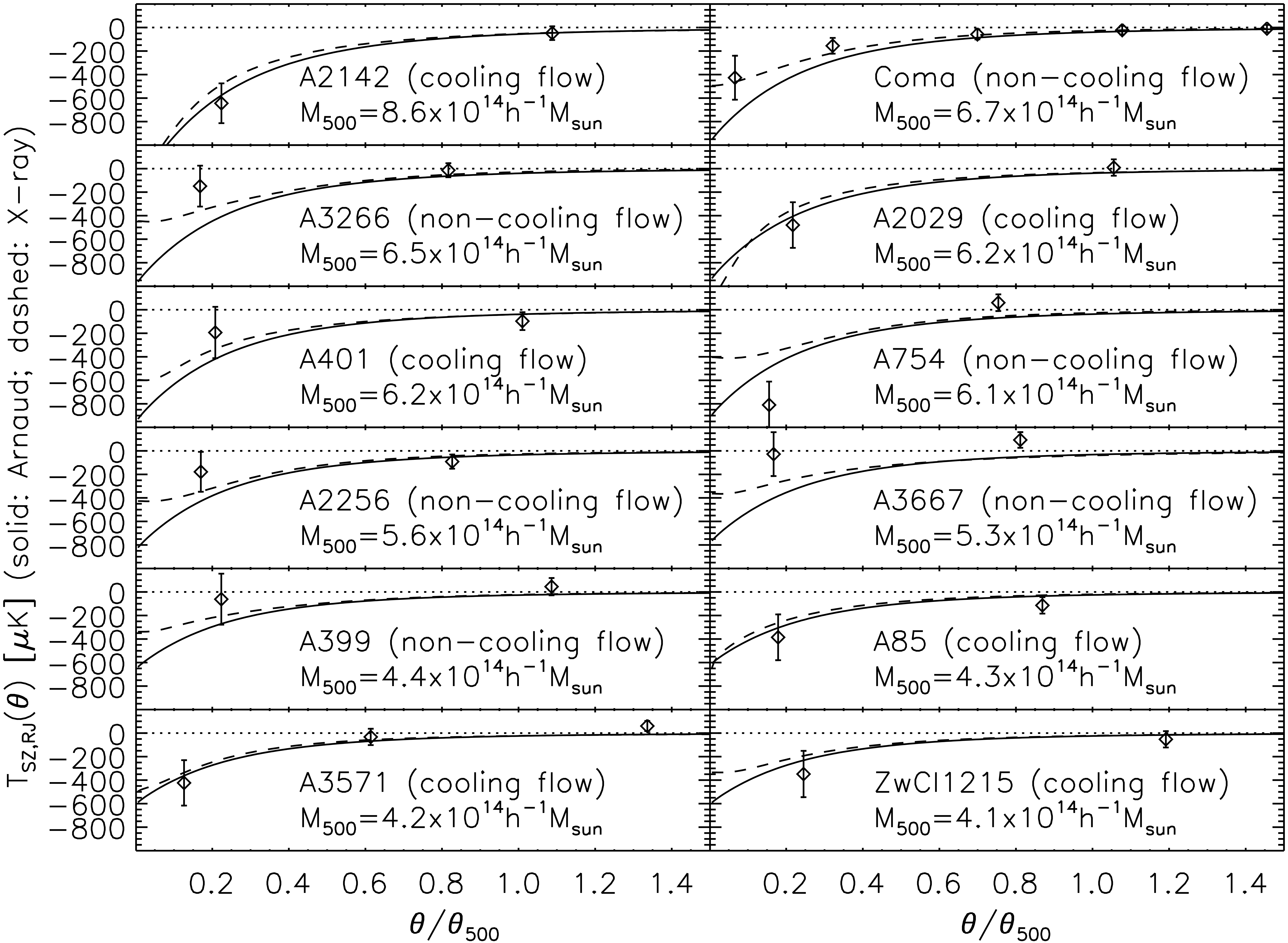



The X-ray data (XMM) are provided by A. Finoguenov.

- $M_{500}=6.6\times10^{14}h^{-1}M_{sun}$ is estimated from the mass-temperature relation (Vikhlinin et al.)
  - $T_X^{coma}$ =8.4keV.
- Arnaud et al.'s profile overestimates both the direct X-ray data and WMAP data by the same factor (0.65)!
  - To reconcile them, $Tx^{coma}$=6.5keV is required, but that is way too low.

# Well...

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




# WMAP 7-year Measurements!

(Komatsu et al. 2010)

# Low-SZ is seen in the WMAP

| Mass Range[a] | # of clusters | X-ray Data | Model |
|---|---|---|---|
| $6 \le M_{500} < 9$ | 5 | $0.90 \pm 0.16$ | $0.73 \pm 0.13$ |
| $4 \le M_{500} < 6$ | 6 | $0.73 \pm 0.21$ | $0.60 \pm 0.17$ |
| $2 \le M_{500} < 4$ | 9 | $0.71 \pm 0.31$ | $0.53 \pm 0.25$ |
| $1 \le M_{500} < 2$ | 9 | $-0.15 \pm 0.55$ | $-0.12 \pm 0.47$ |
| $4 \le M_{500} < 9$ | 11 | $0.84 \pm 0.13$ | $0.68 \pm 0.10$ |
| $1 \le M_{500} < 4$ | 18 | $0.50 \pm 0.27$ | $0.39 \pm 0.22$ |
| $4 \le M_{500} < 9$ | | | |
| cooling flow[d] | 5 | $1.06 \pm 0.18$ | $0.89 \pm 0.15$ |
| non-cooling flow[e] | 6 | $0.61 \pm 0.18$ | $0.48 \pm 0.15$ |
| $2 \le M_{500} < 9$ | 20 | $0.82 \pm 0.12$ | $0.660 \pm 0.095$ |
| $1 \le M_{500} < 9$ | 29 | $0.78 \pm 0.12$ | $0.629 \pm 0.094$ |

[a] In units of $10^{14}\ h^{-1}\ M_\odot$. Coma is not included.

d: ALL of "cooling flow clusters" are relaxed clusters.

e: ALL of "non-cooling flow clusters" are non-relaxed clusters.

# Low-SZ: Signature of mergers?

| Mass Range[a] | # of clusters | X-ray Data | Model |
|---|---|---|---|
| $6 \leq M_{500} < 9$ | 5 | $0.90 \pm 0.16$ | $0.73 \pm 0.13$ |
| $4 \leq M_{500} < 6$ | 6 | $0.73 \pm 0.21$ | $0.60 \pm 0.17$ |
| $2 \leq M_{500} < 4$ | 9 | $0.71 \pm 0.31$ | $0.53 \pm 0.25$ |
| $1 \leq M_{500} < 2$ | 9 | $-0.15 \pm 0.55$ | $-0.12 \pm 0.47$ |
| $4 \leq M_{500} < 9$ | 11 | $0.84 \pm 0.13$ | $0.68 \pm 0.10$ |
| $1 \leq M_{500} < 4$ | 18 | $0.50 \pm 0.27$ | $0.39 \pm 0.22$ |
| $4 \leq M_{500} < 9$ | | | |
| cooling flow[d] | 5 | $1.06 \pm 0.18$ | $0.89 \pm 0.15$ |
| non-cooling flow[e] | 6 | $0.61 \pm 0.18$ | $0.48 \pm 0.15$ |
| $2 \leq M_{500} < 9$ | 20 | $0.82 \pm 0.12$ | $0.660 \pm 0.095$ |
| $1 \leq M_{500} < 9$ | 29 | $0.78 \pm 0.12$ | $0.629 \pm 0.094$ |

[a] In units of $10^{14}\ h^{-1}\ M_{\odot}$. Coma is not included.

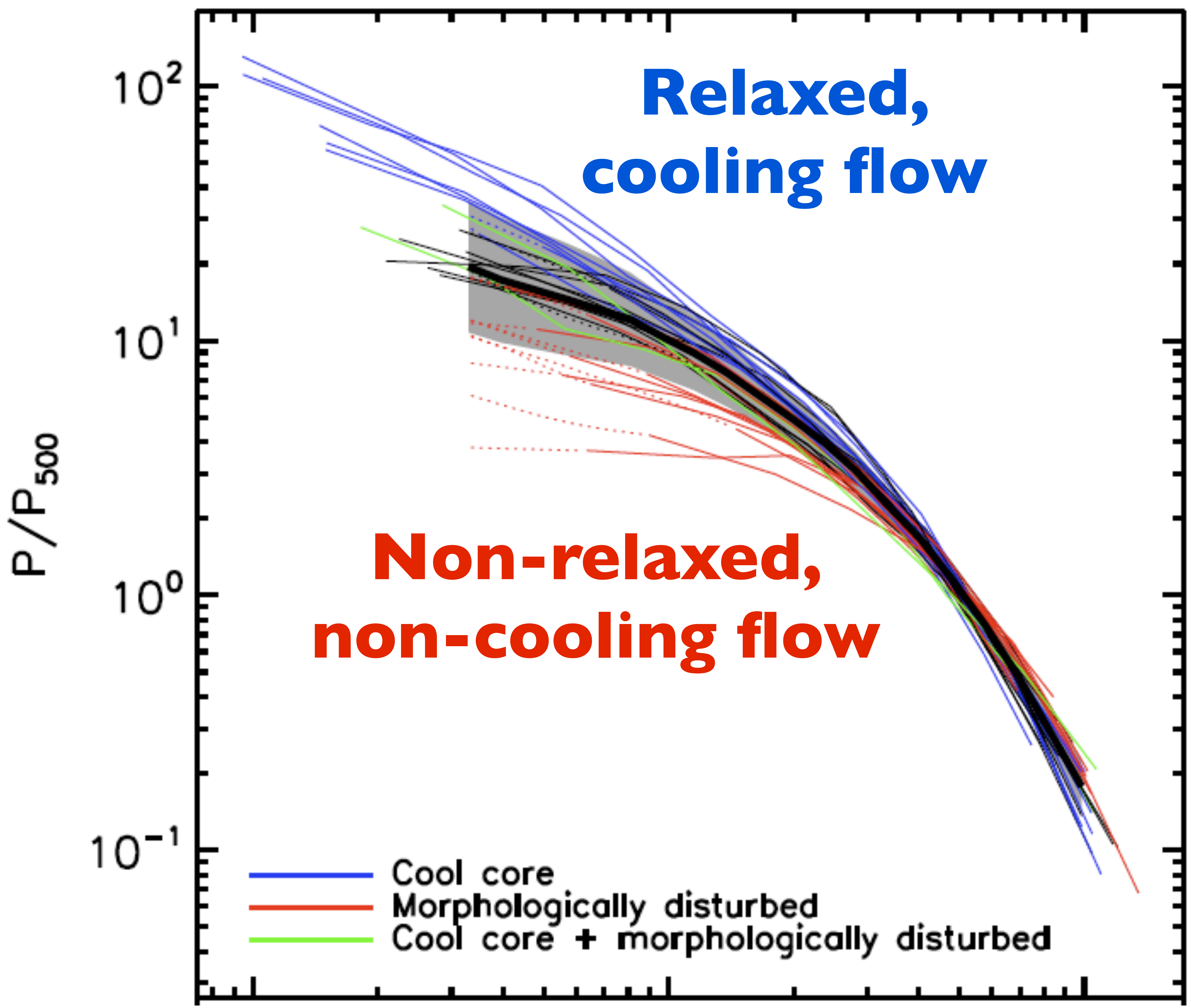
d: ALL of "cooling flow clusters" are relaxed clusters.

e: ALL of "non-cooling flow clusters" are non-relaxed clusters.

# SZ: Main Results

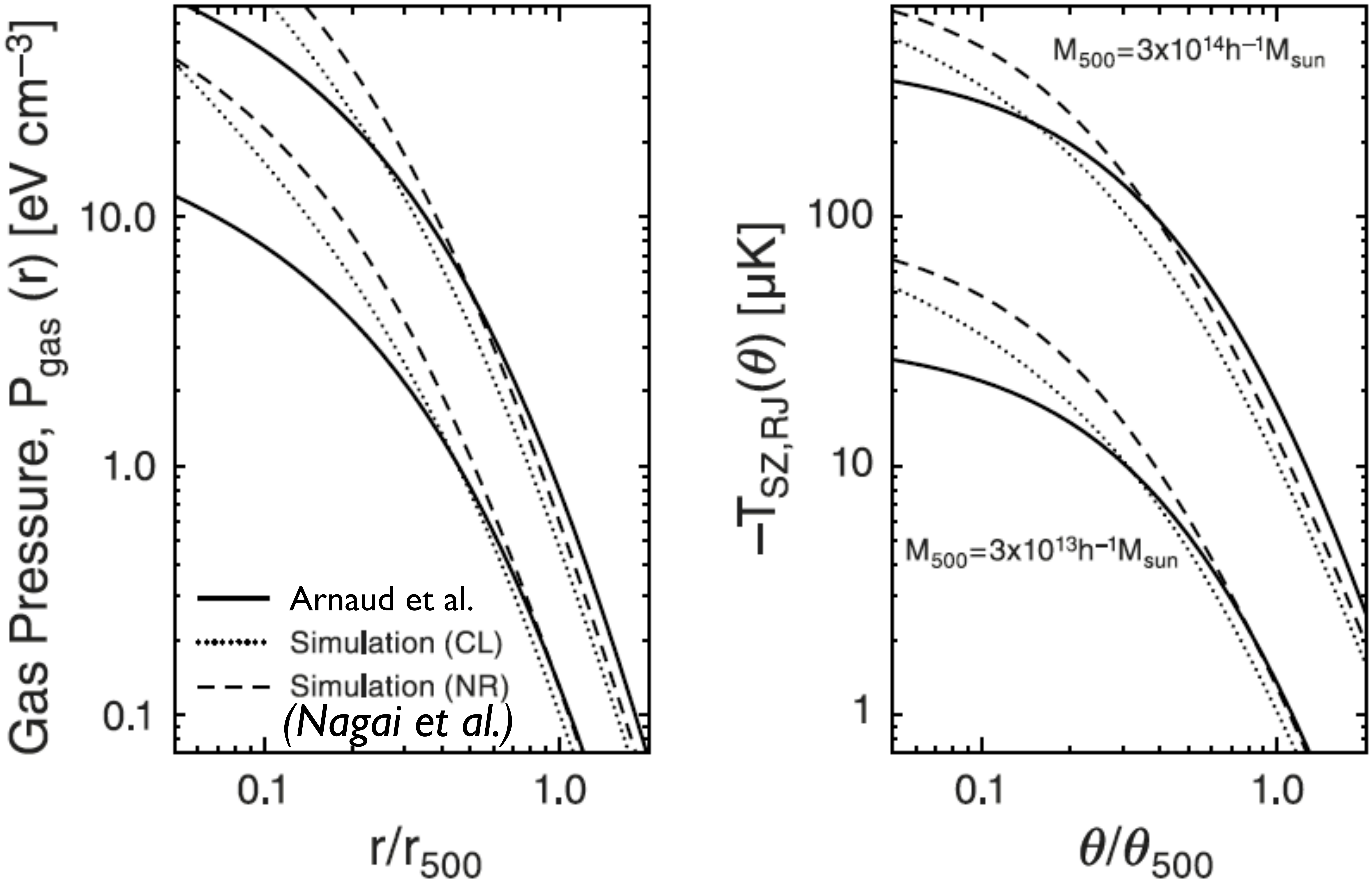
- Arnaud et al. profile systematically overestimates the electron pressure! (Arnaud et al. profile is **ruled out** at 3.2$\sigma$).
- But, the X-ray data on the *individual* clusters agree well with the SZ measured by WMAP.
- Reason: Arnaud et al. did not distinguish between relaxed (CF) and non-relaxed (non-CF) clusters.
  - This will be important for the proper interpretation of the SZ effect when doing cosmology with it.

# Cooling Flow vs Non-CF

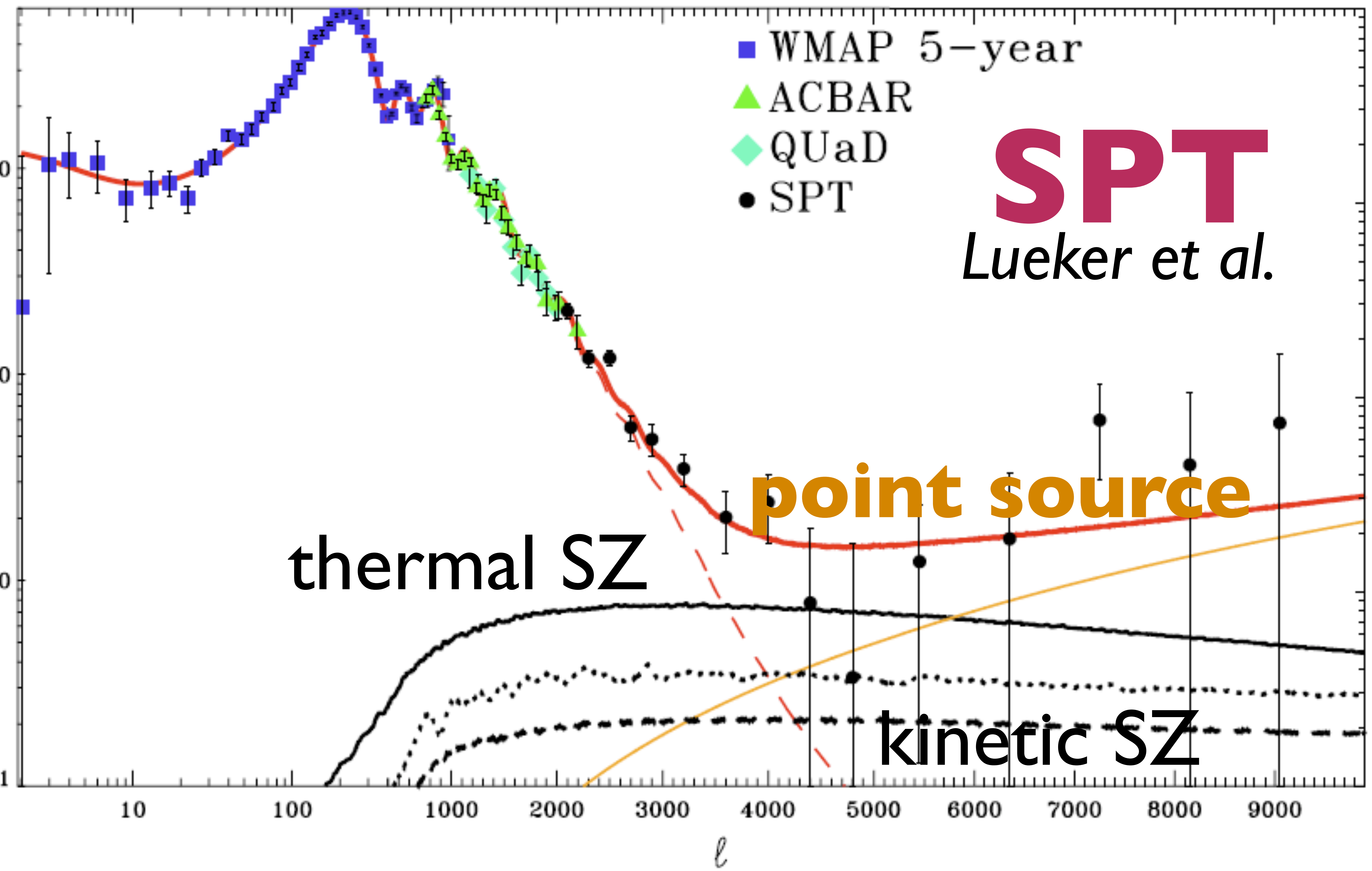


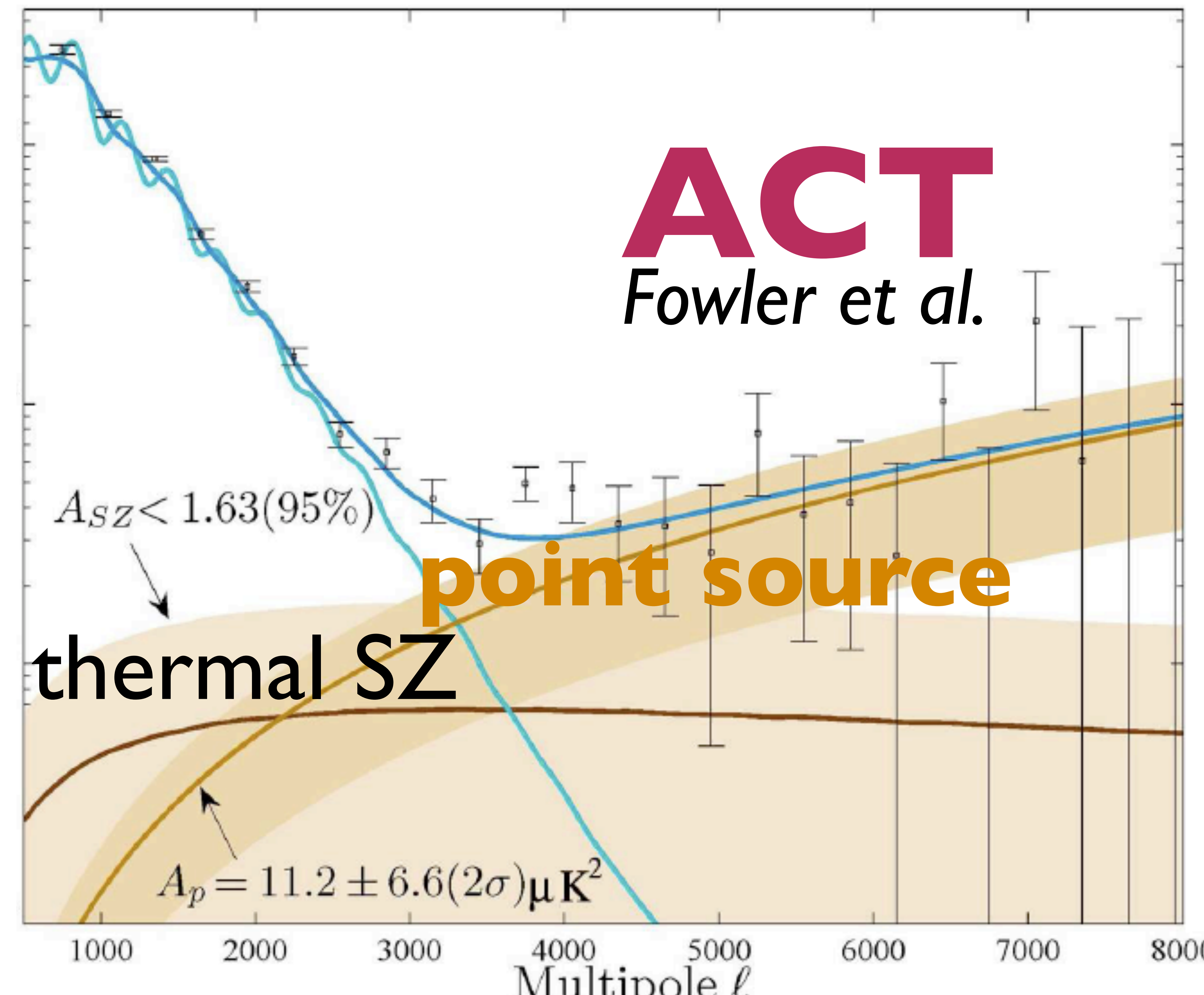

- In Arnaud et al., they reported that the cooling flow clusters have much steeper pressure profiles in the inner part.
- Taking a simple median gave a biased "universal" profile.

# Theoretical Models



# "World" Power Spectrum




- 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

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

- **[1] The number of clusters is less than expected.**
  - In cosmology, this is parameterized by the so-called "$\sigma_8$" parameter.

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

- $\sigma_8$ is 0.77 (rather than 0.81): $\sum m_\nu \sim 0.2\mathrm{eV}$?

# Lower $A_{SZ}$: **Two** Possibilities

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

- **[2] Gas pressure per cluster is less than expected.**
  - The power spectrum is [gas pressure]$^2$.
  - $A_{SZ}$=0.4–0.6 means that the gas pressure is less than expected by ~0.6–0.7.
- *And, our measurement shows that this is what is going on!*

# Conclusion

- SZ effect: Coma's radial profile is measured, several massive clusters are detected, and the statistical detection reaches 6.5σ.
  - Evidence for lower-than-theoretically-expected gas pressure.
- The X-ray data are fine: we need to revise the existing models of the intracluster medium.
  - ***Distinguishing relaxed and non-relaxed clusters is very important!***

# 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)

# A Puzzle

- SZ effect: Coma's radial profile is measured, several massive clusters are detected, and the statistical detection reaches 6.5$\sigma$.
  - Evidence for lower-than-theoretically-expected gas pressure.
  - First detection, in the SZ effect, of the difference between relaxed and non-relaxed clusters.
  - The X-ray data are fine: we need to revise the existing models of the intracluster medium.