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

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Cosmo Seminar, UC Davis, January 6, 2011

# WMAP at Lagrange 2 (L2) Point

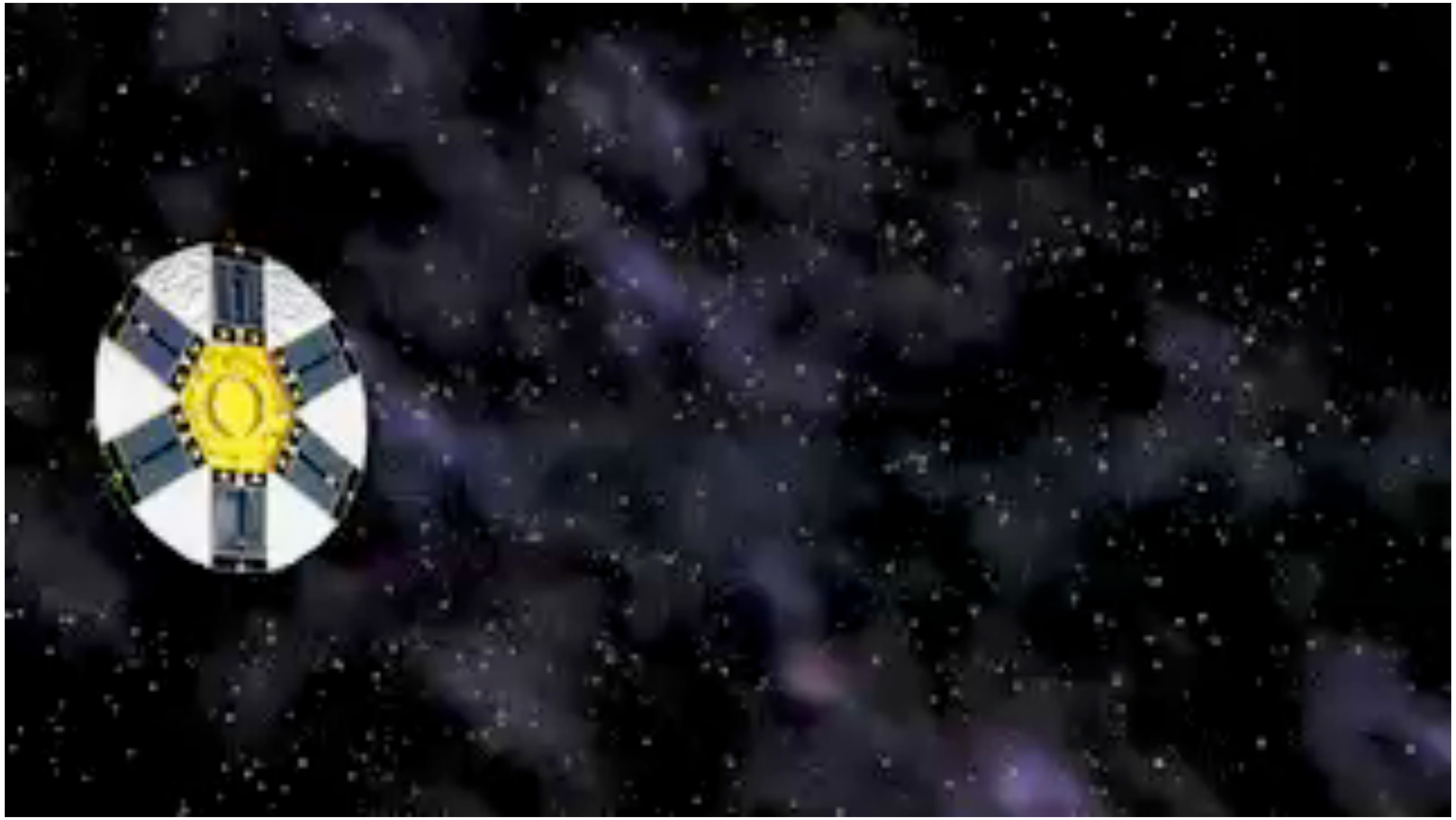
June 2001:
WMAP launched!

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 a million miles from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

# WMAP 7-Year Science Team

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- G. Hinshaw
- N. Jarosik
- S.S. Meyer
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- K.M. Smith
- C. Barnes
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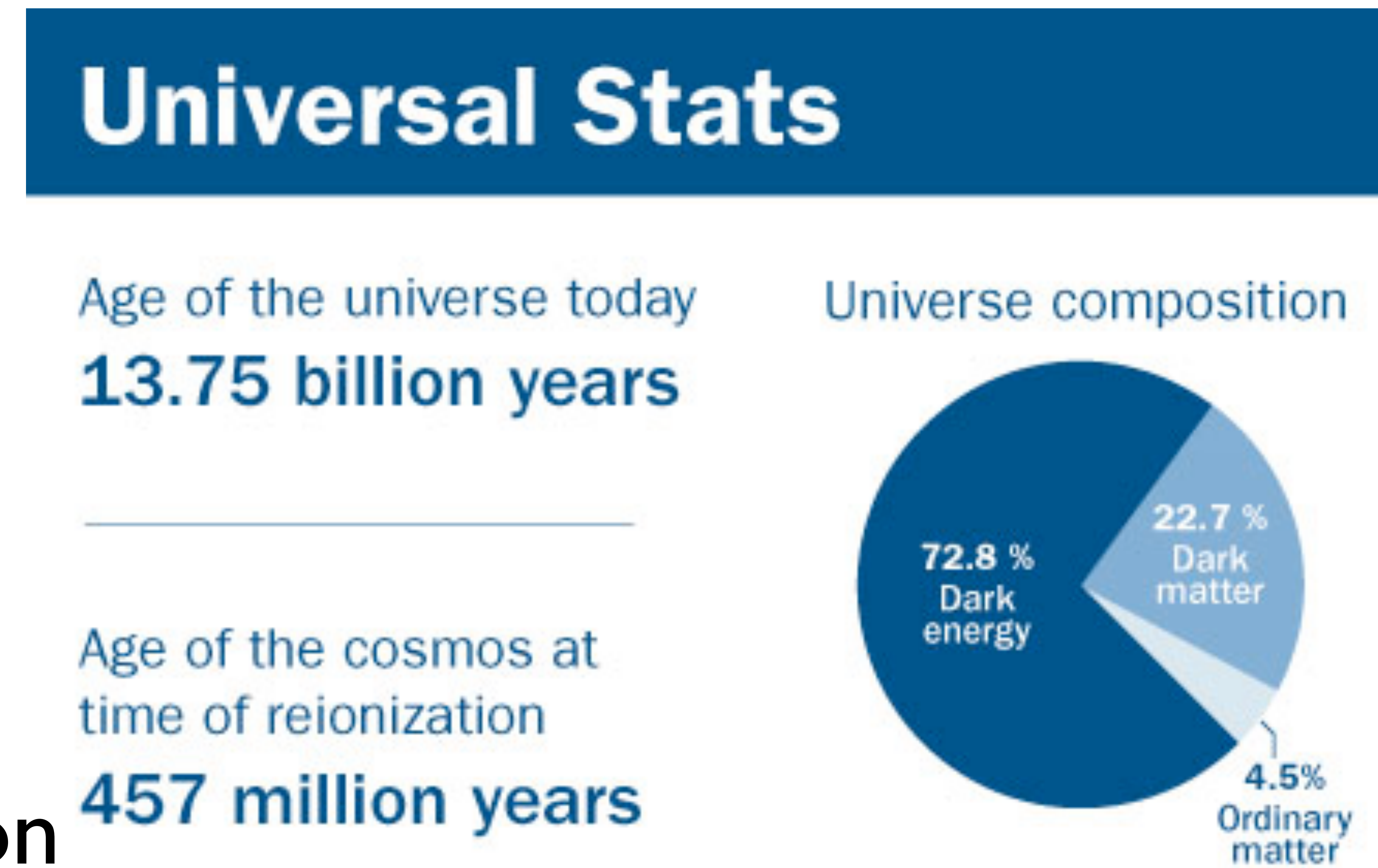
- L. Verde

# 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

# Cosmology Update: 7-year

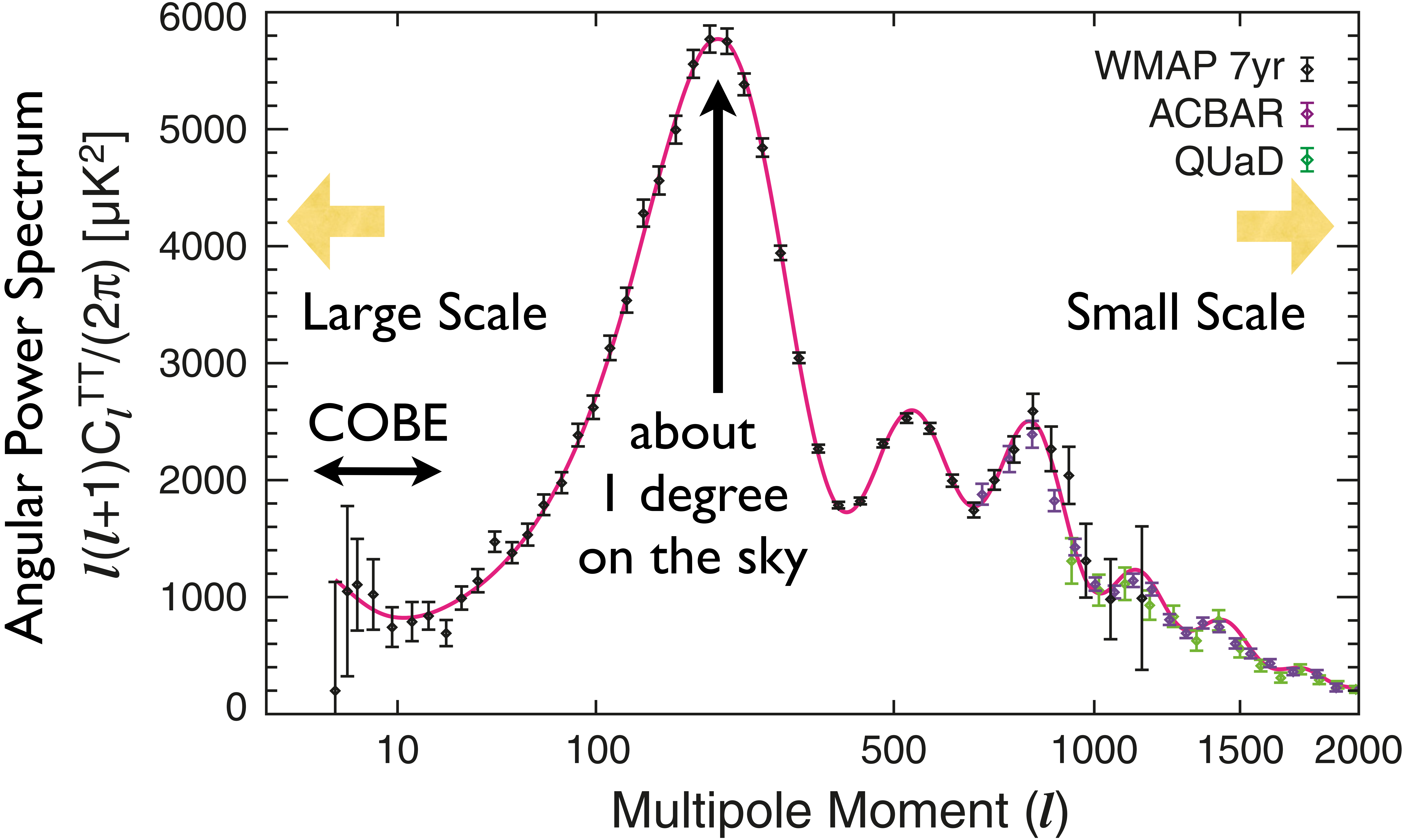
- **Standard Model**
  - H&He = 4.58% (±0.16%)
  - Dark Matter = 22.9% (±1.5%)
  - Dark Energy = 72.5% (±1.6%)
  - $H_0$=70.2±1.4 km/s/Mpc
  - Age of the Universe = 13.76 billion years (±0.11 billion years)



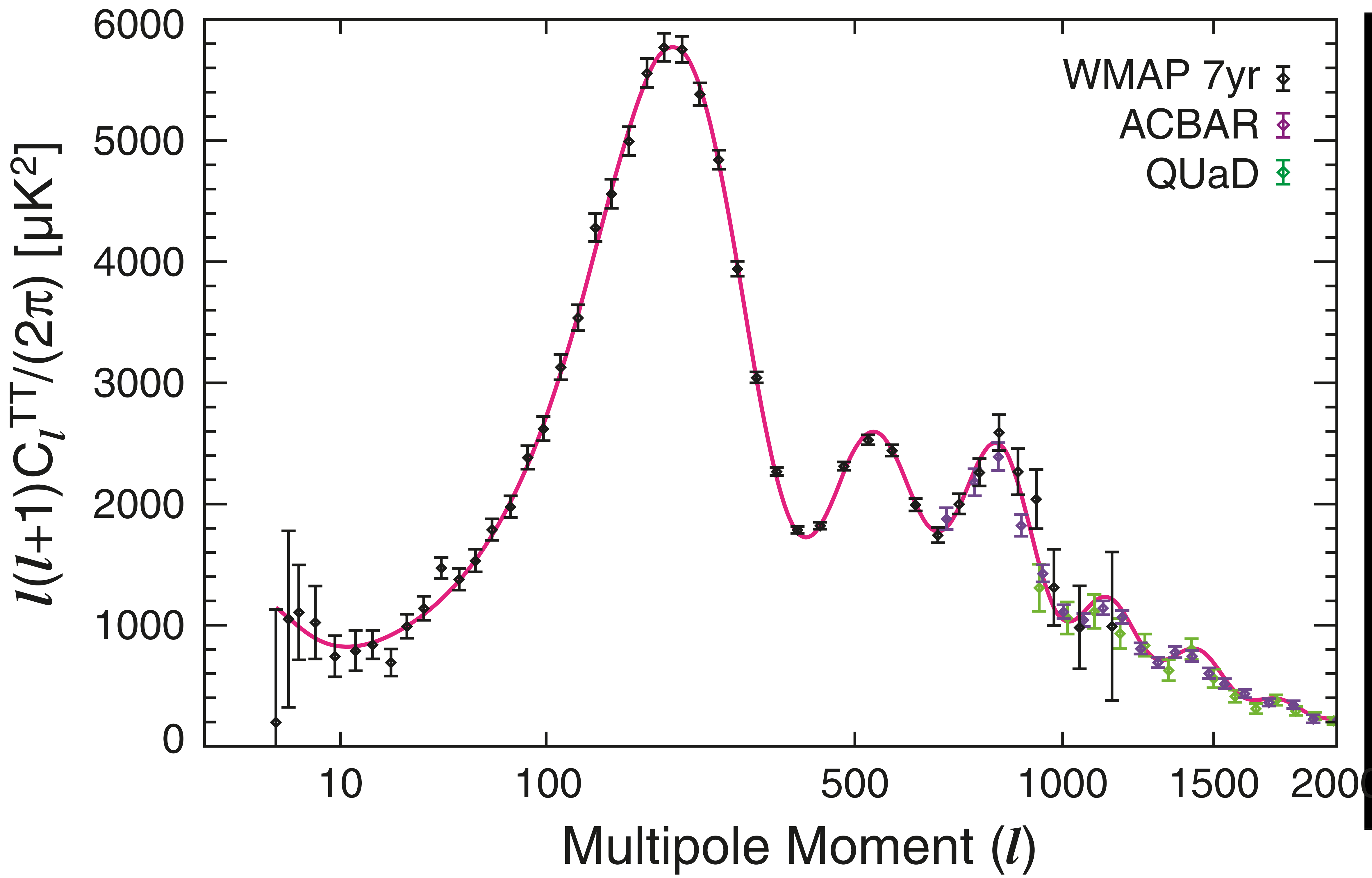

*"ScienceNews" article on the WMAP 7-year results*

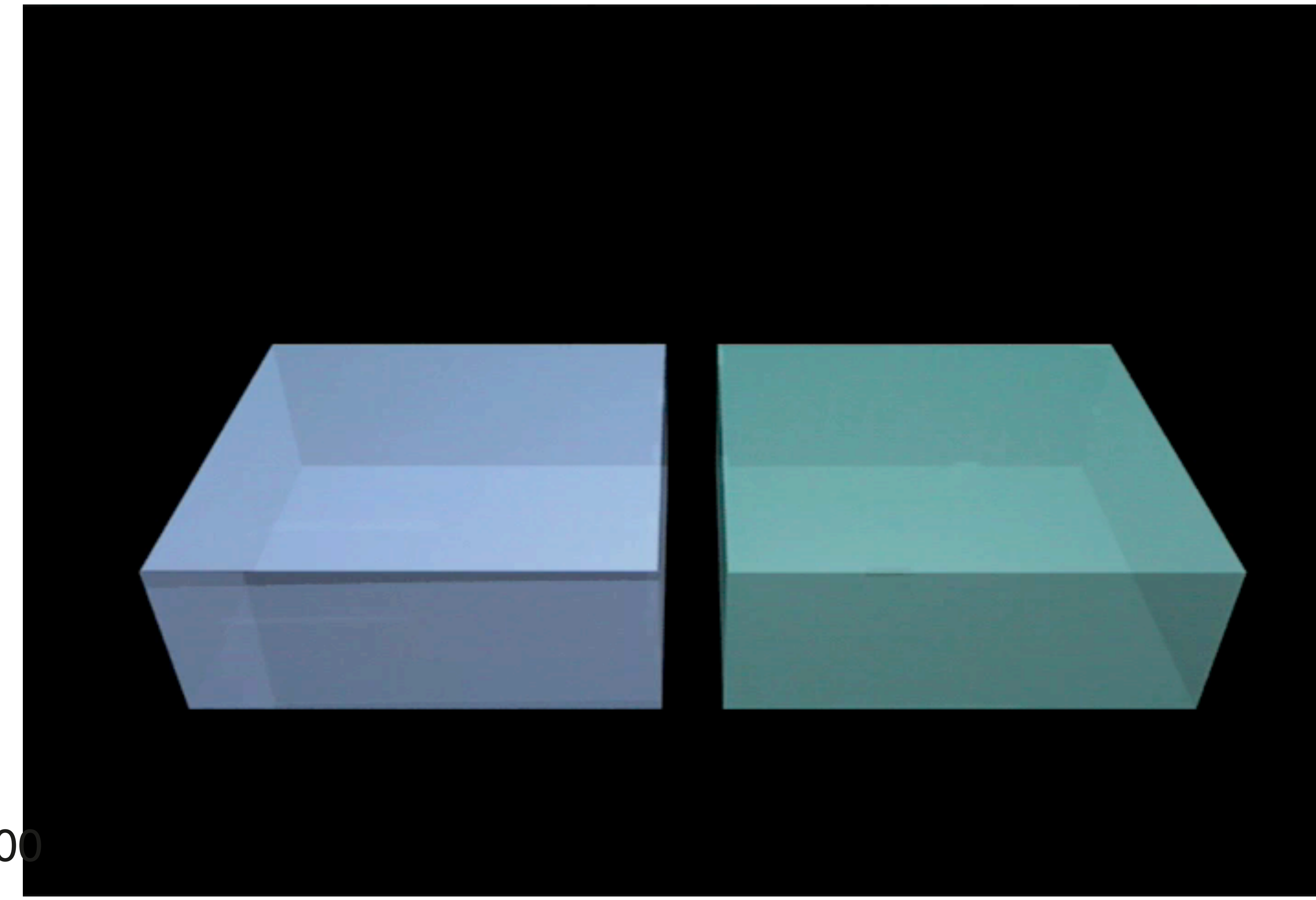
***How did we obtain these numbers?***

# WMAP Power Spectrum



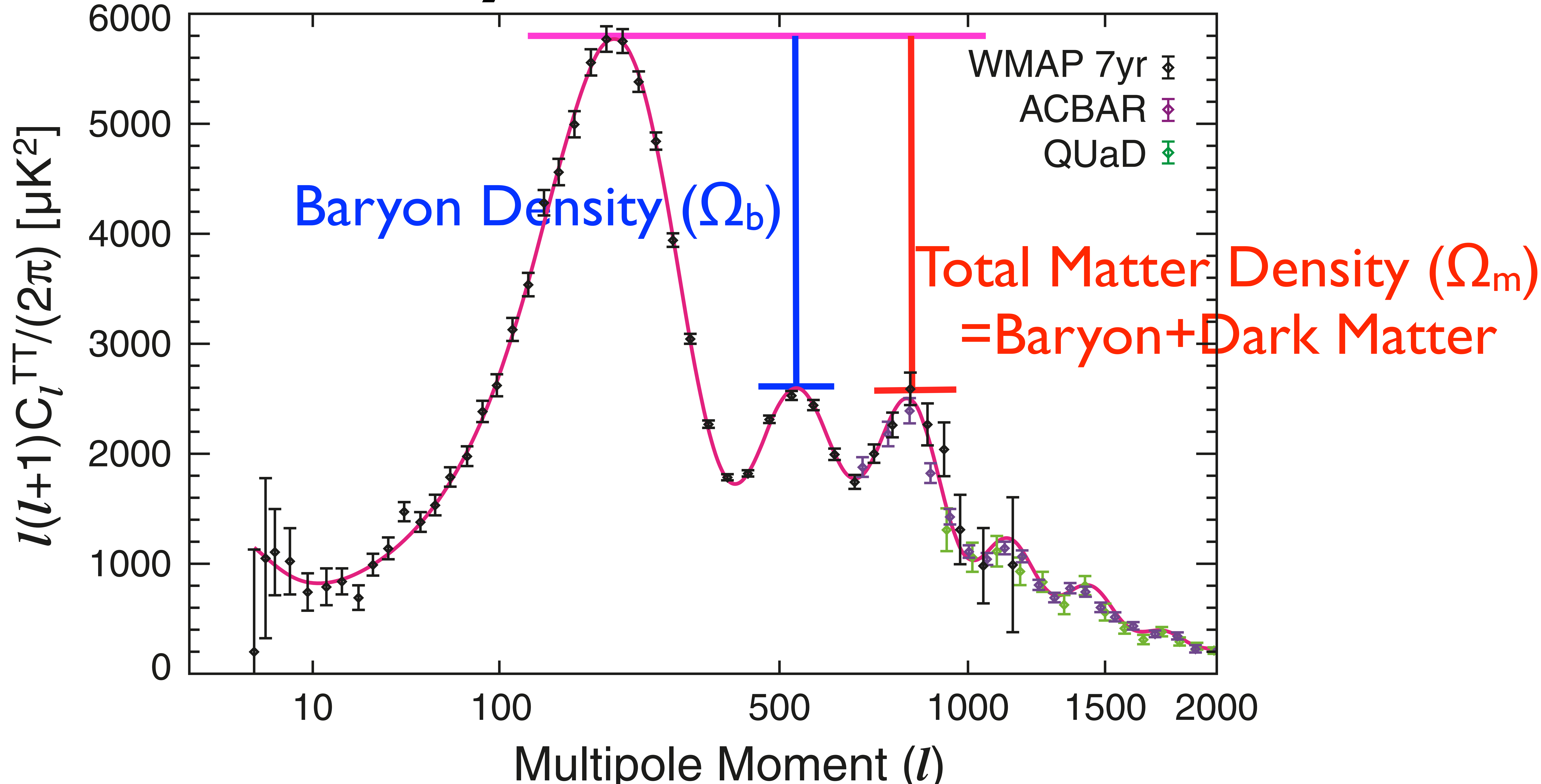
# The Cosmic Sound Wave



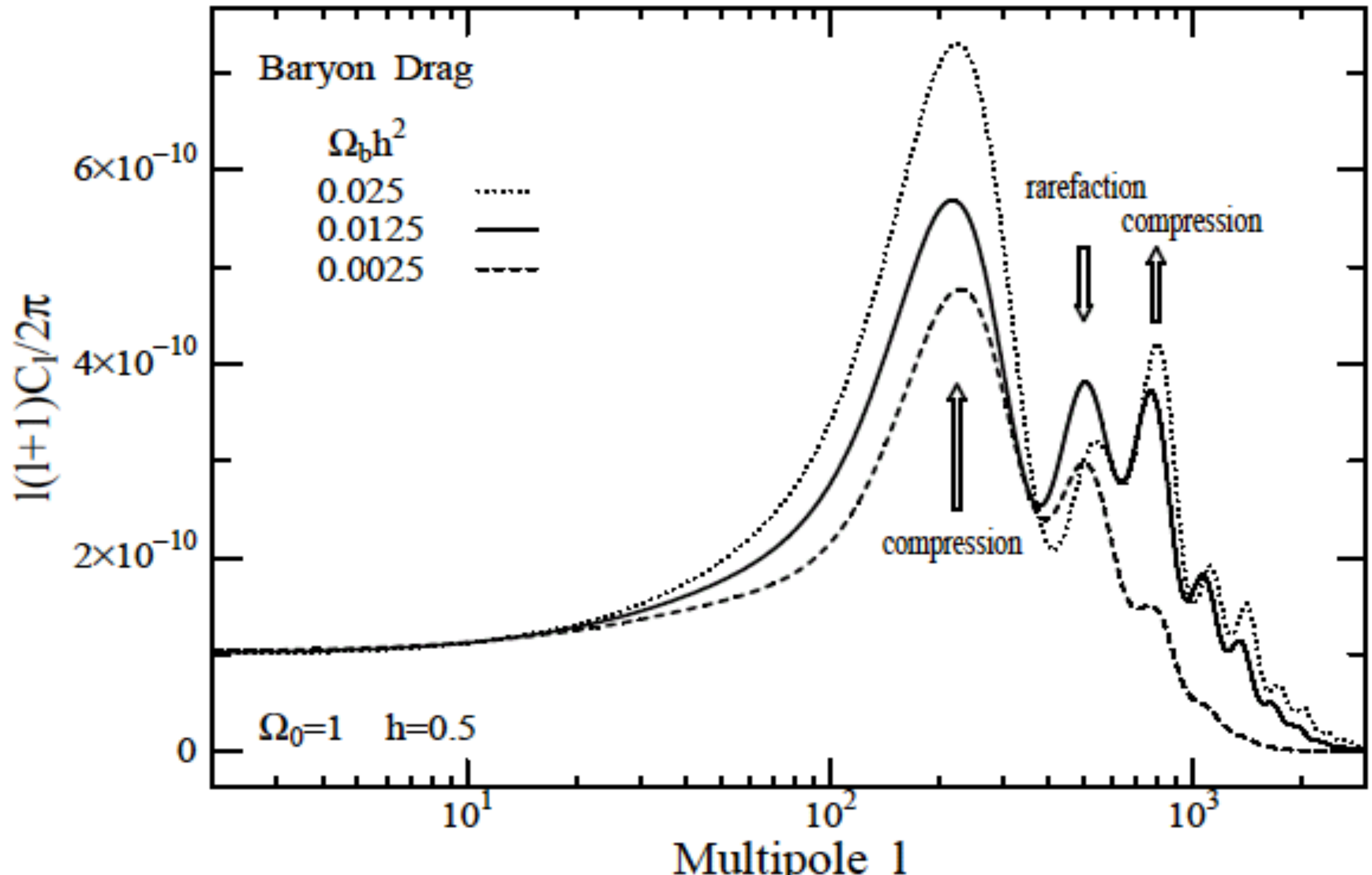
- *"The Universe as a Miso soup"*
  - *Main Ingredients: protons, helium nuclei, electrons, photons*
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

# CMB to Baryon & Dark Matter

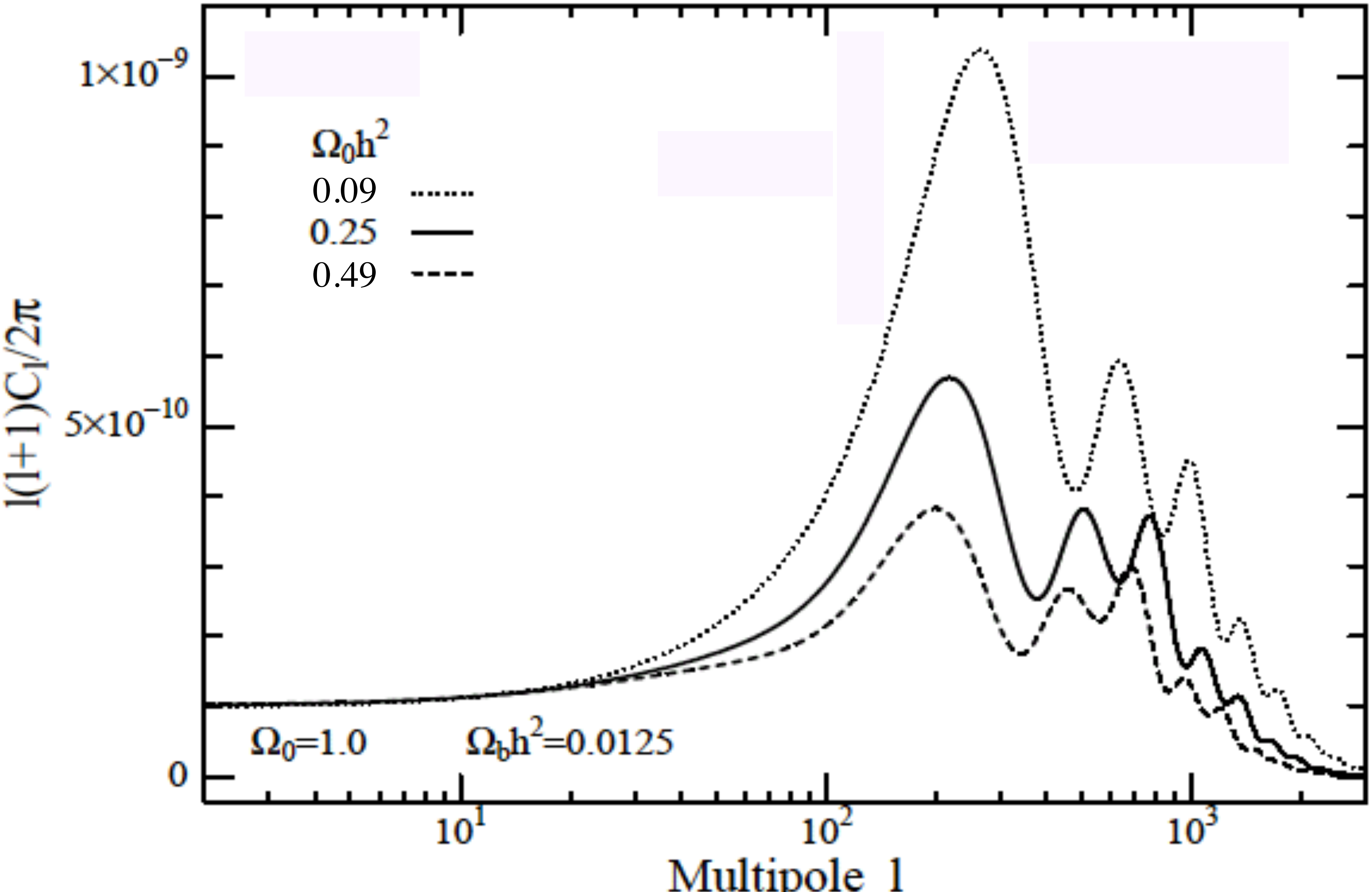



- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio ($z_{EQ}$: equality redshift)

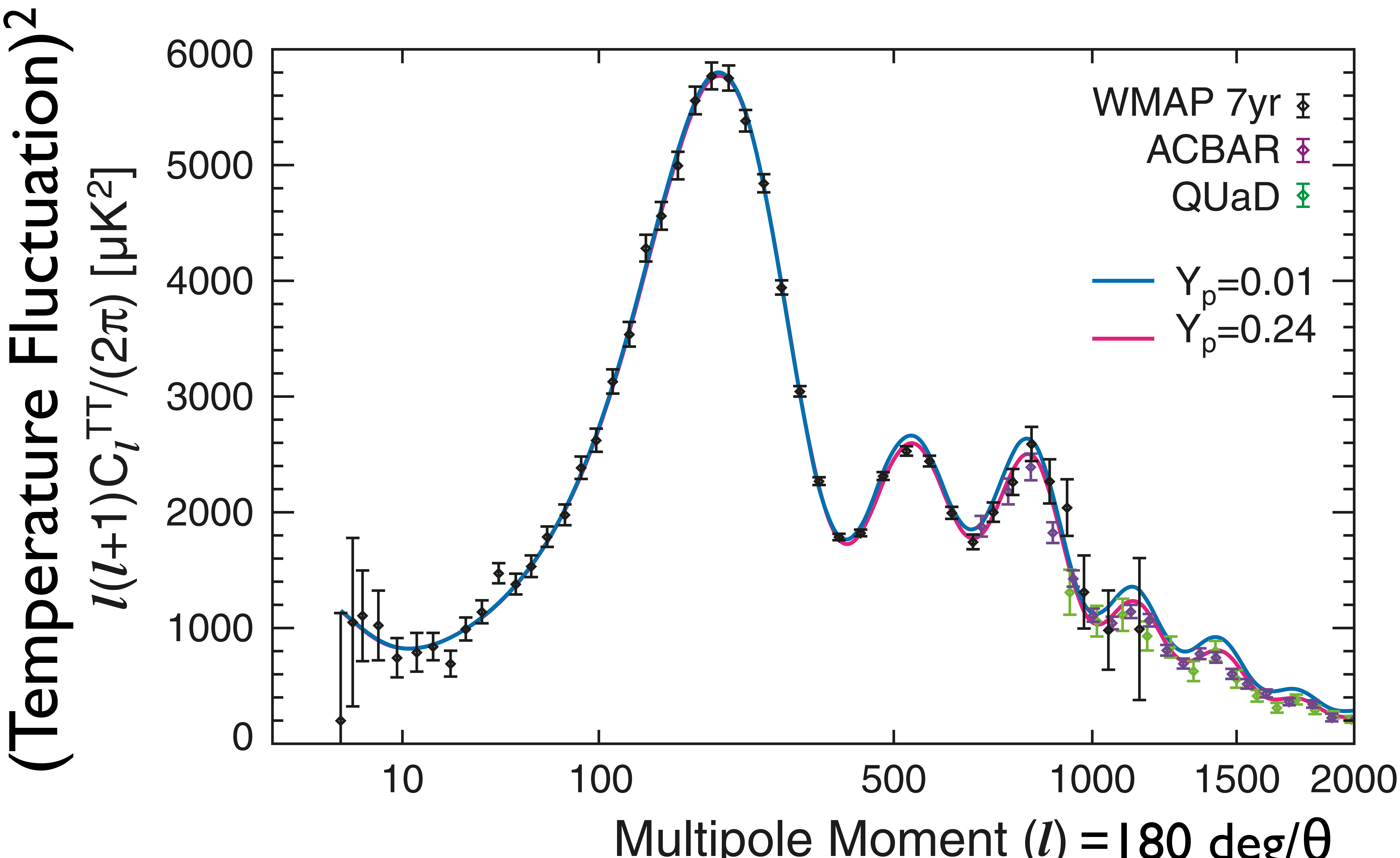
# Determining Baryon Density From $C_l$



# Determining Dark Matter Density From $C_l$



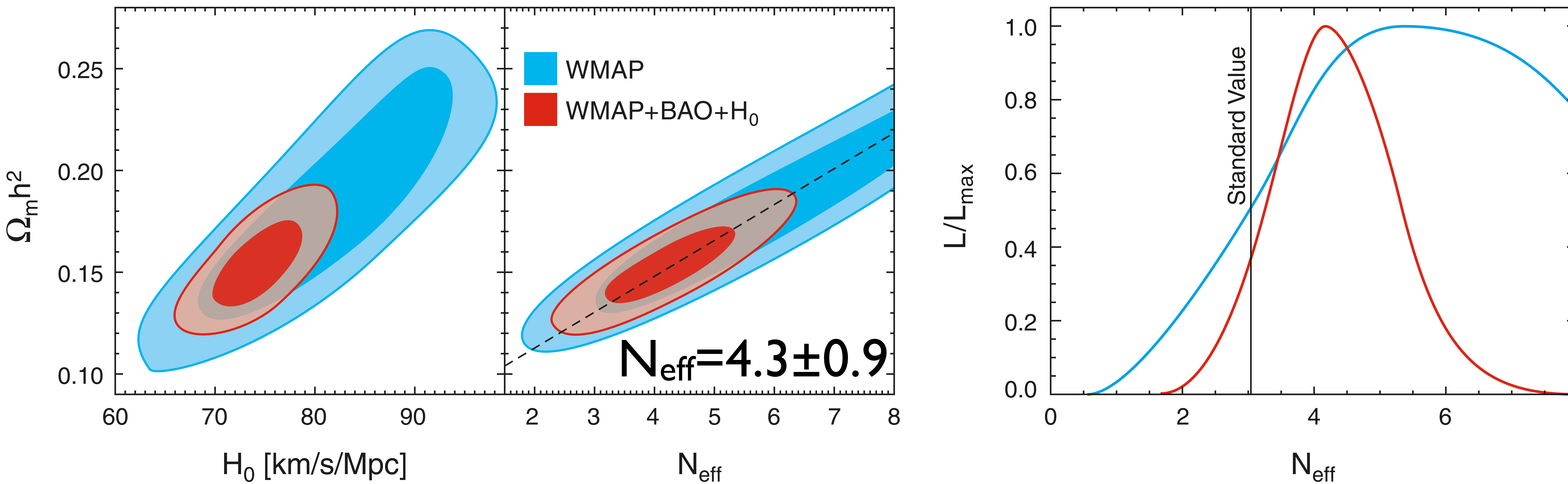
# Detection of Primordial Helium



# 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.

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

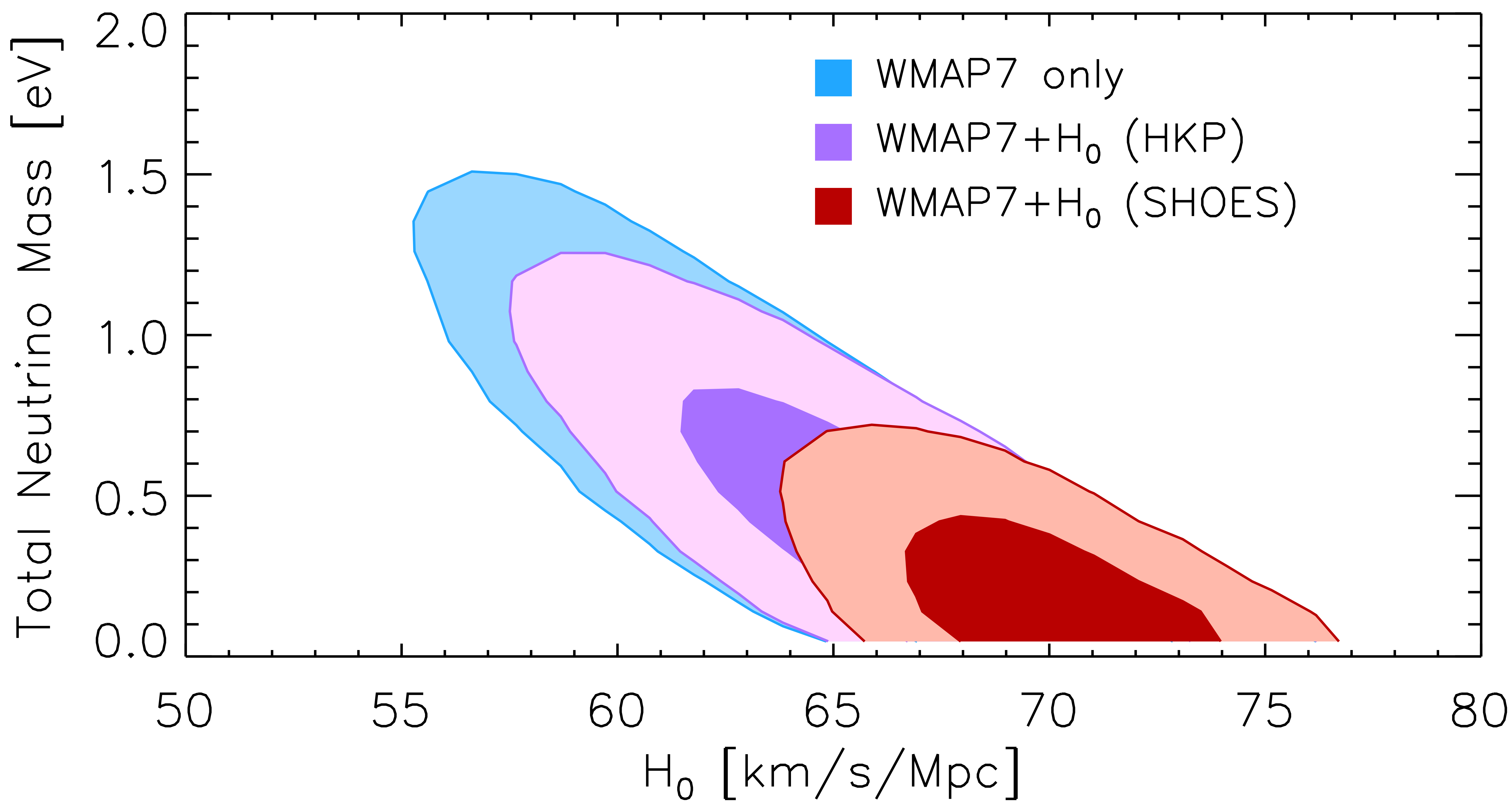



*from external data*

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

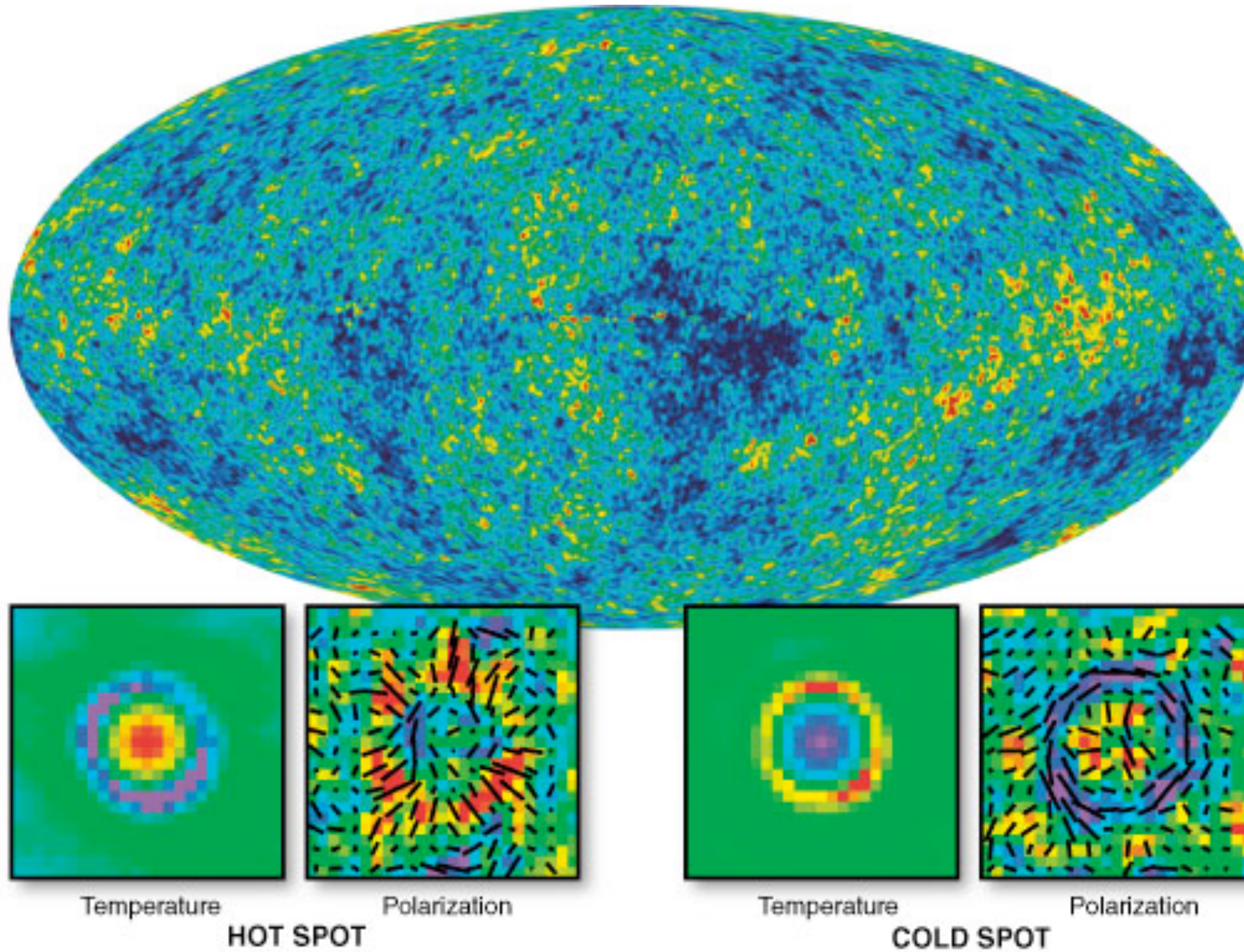
*from 3rd peak*

# And, the mass of neutrinos



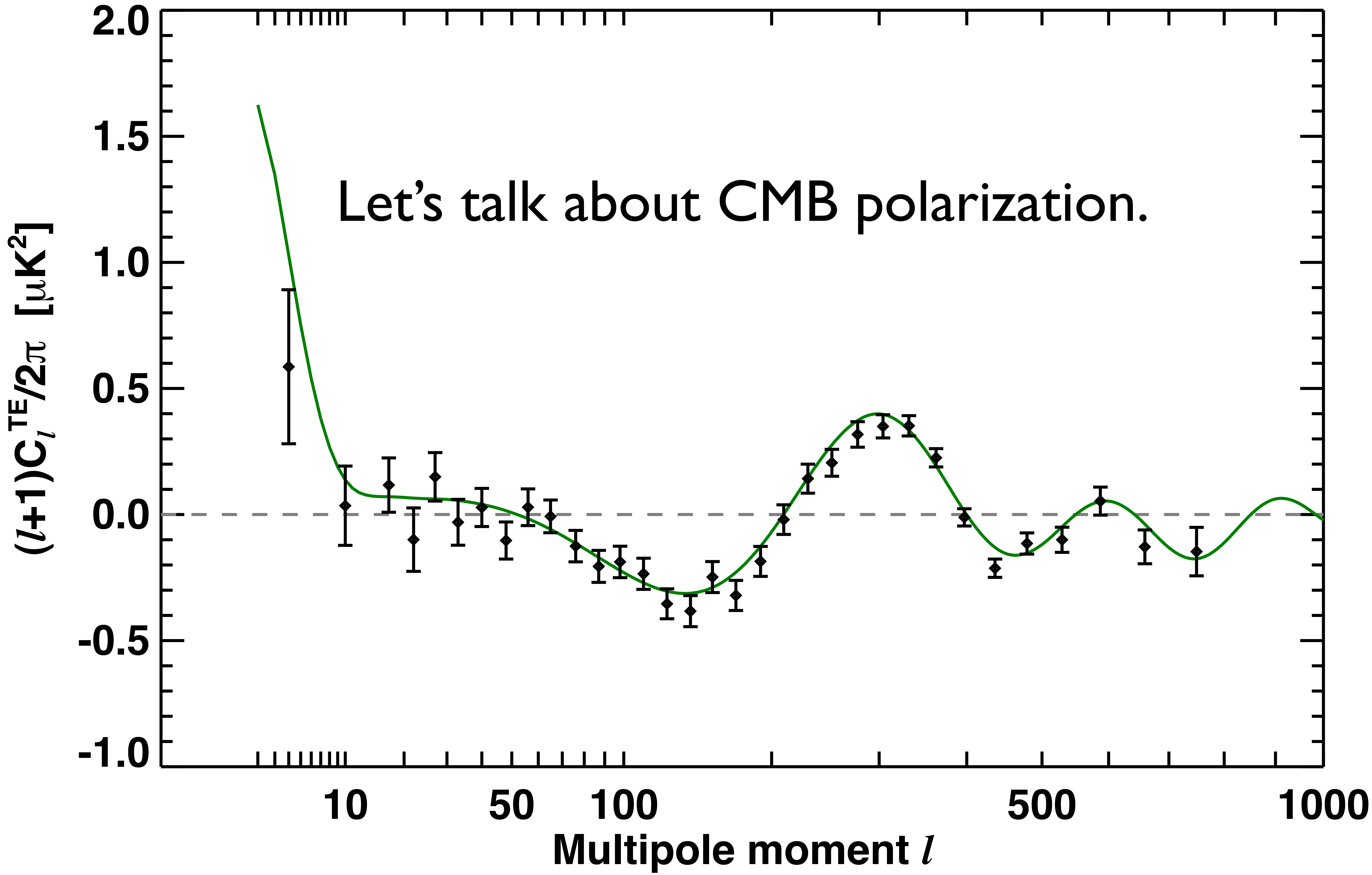

- WMAP data combined with the local measurement of the expansion rate ($H_0$), we get $\sum m_\nu < 0.6$ eV (95%CL)

# CMB Polarization

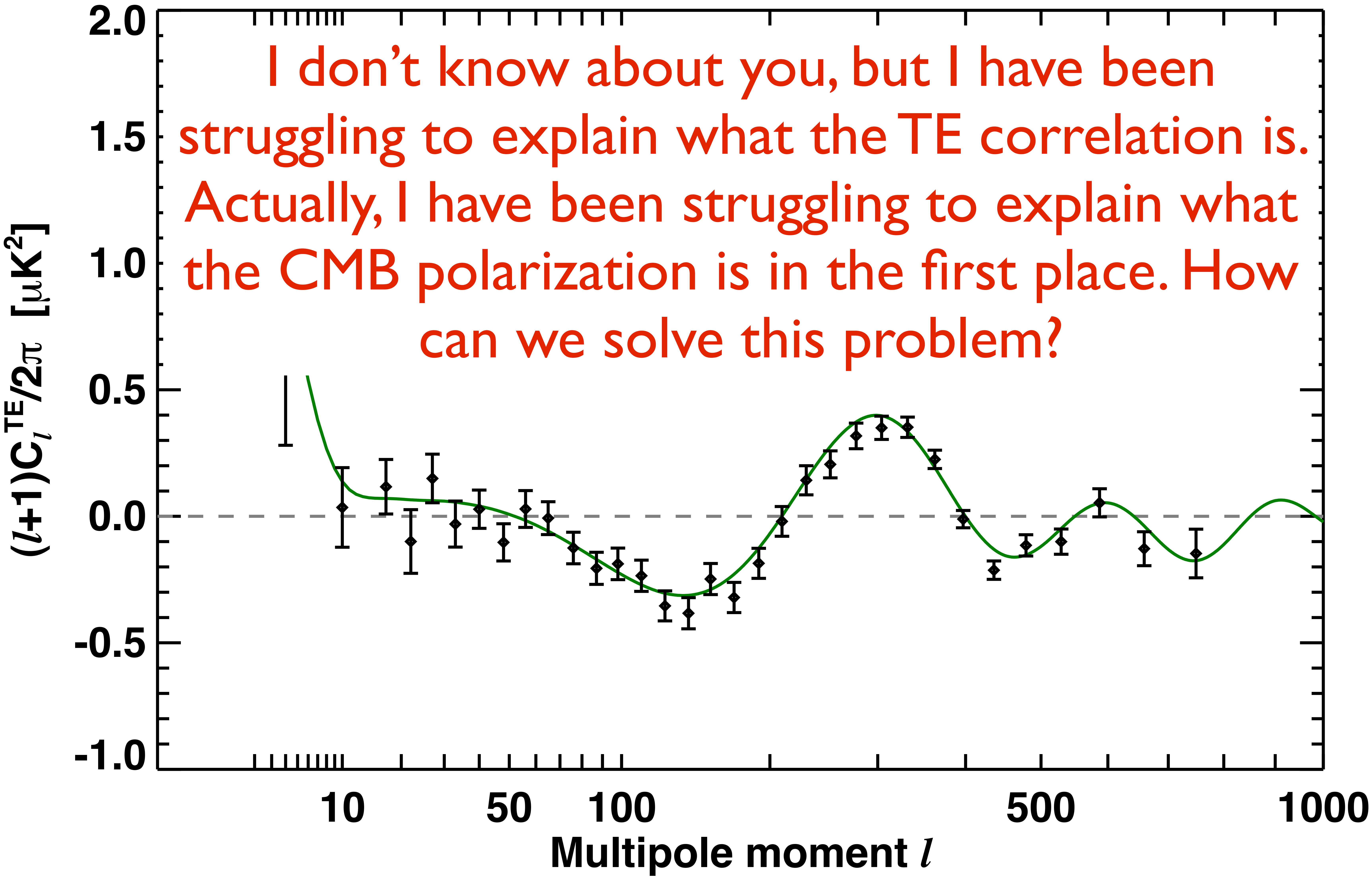



- *CMB is (very weakly) polarized!*

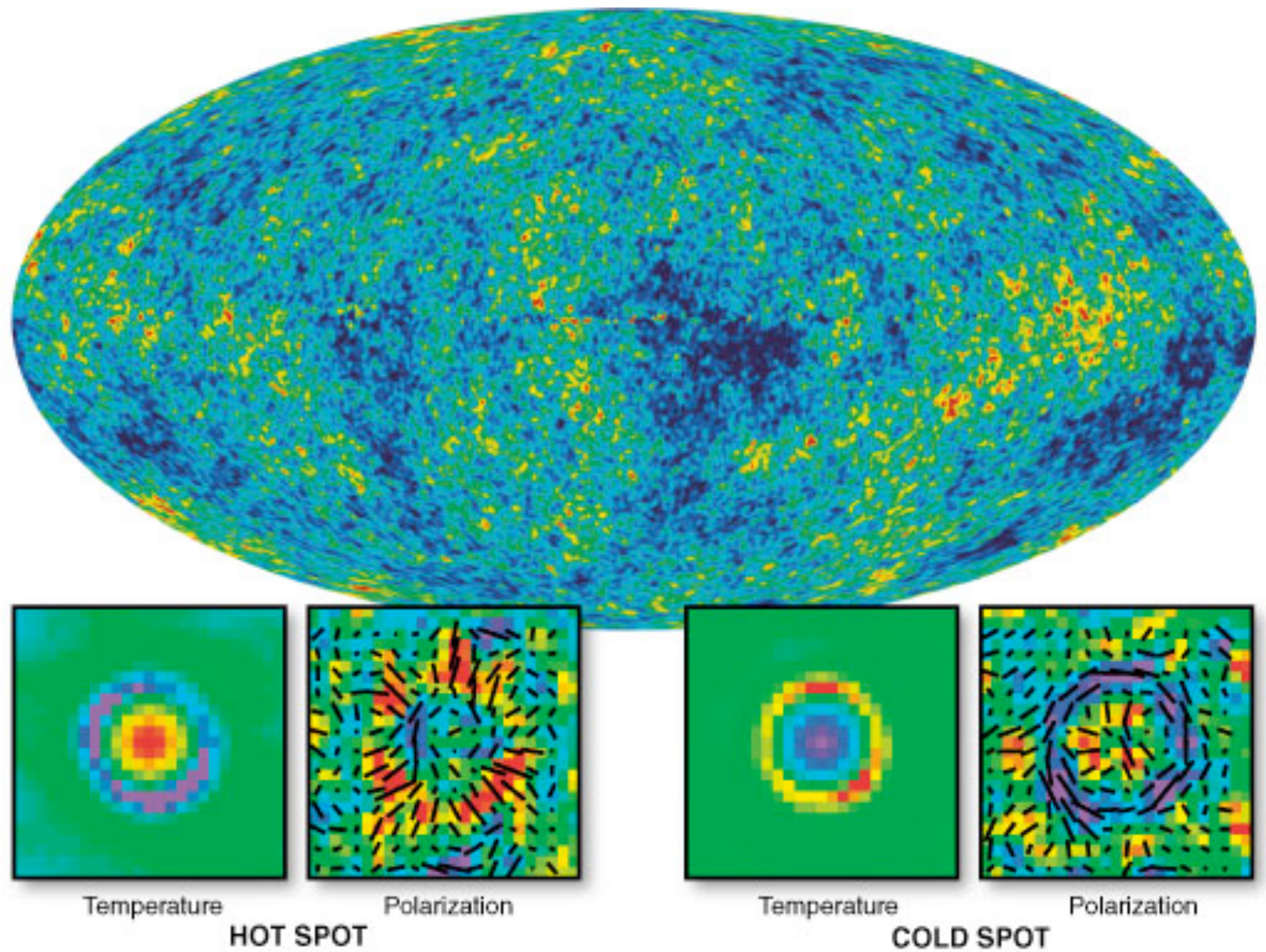
# 7-year TE Correlation



# What Are We Seeing Here?

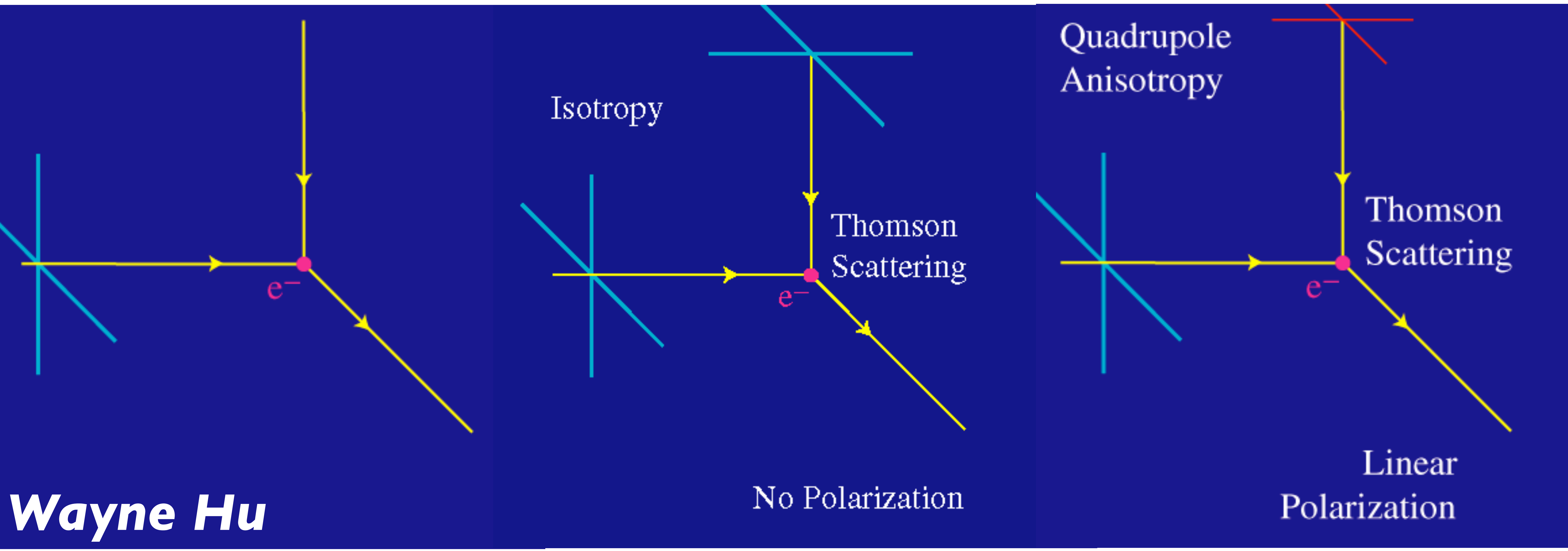


# CMB Polarization On the Sky



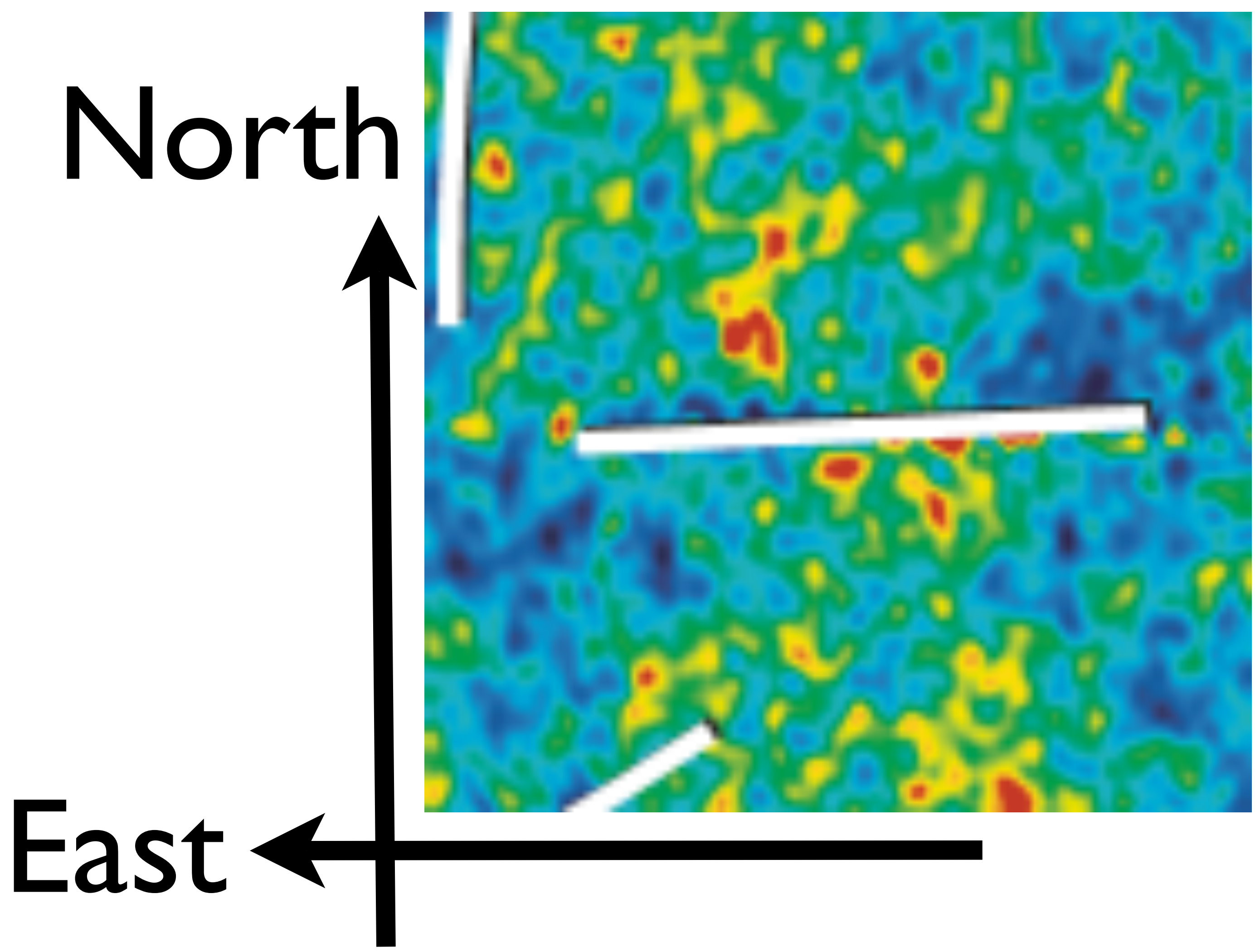

- *Solution*: Leave Fourier space.
  Go back to real space.

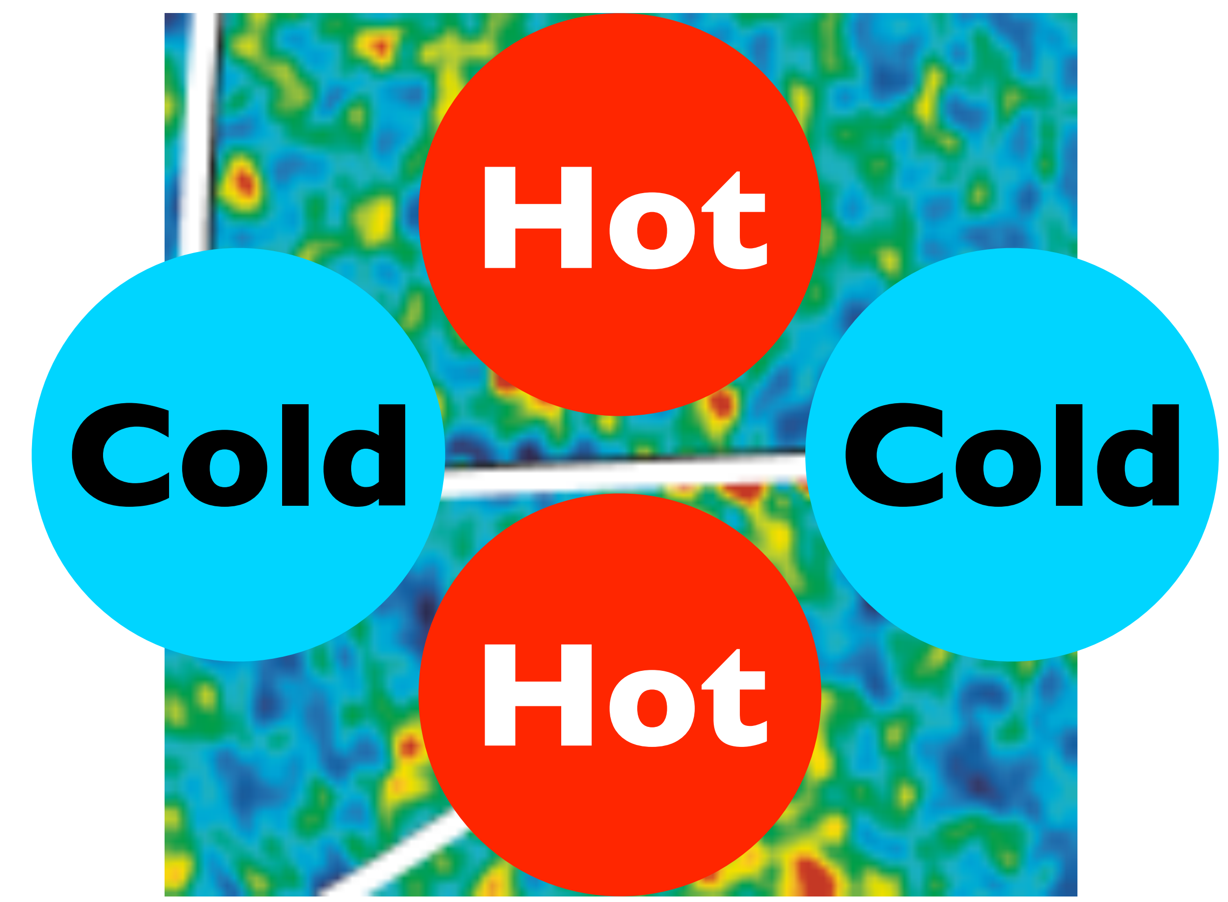
# Physics of CMB Polarization




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

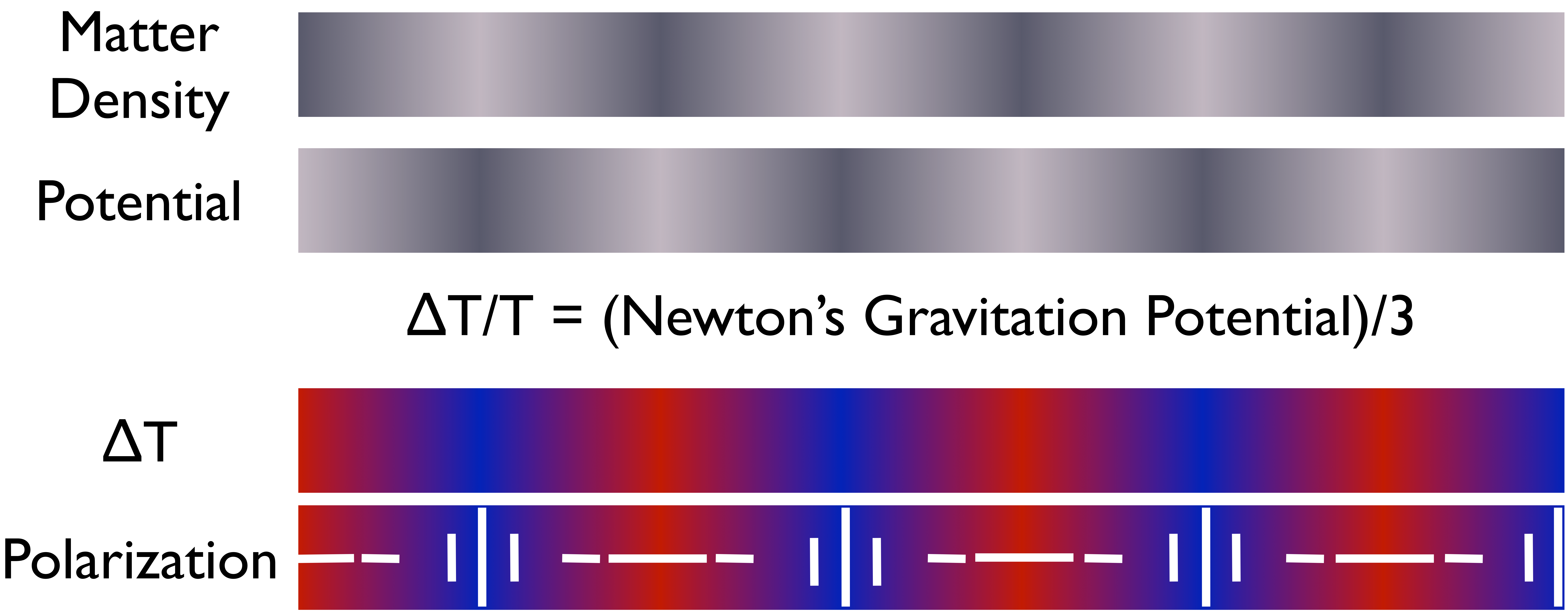
# Principle




- **Polarization direction is parallel to "hot."**

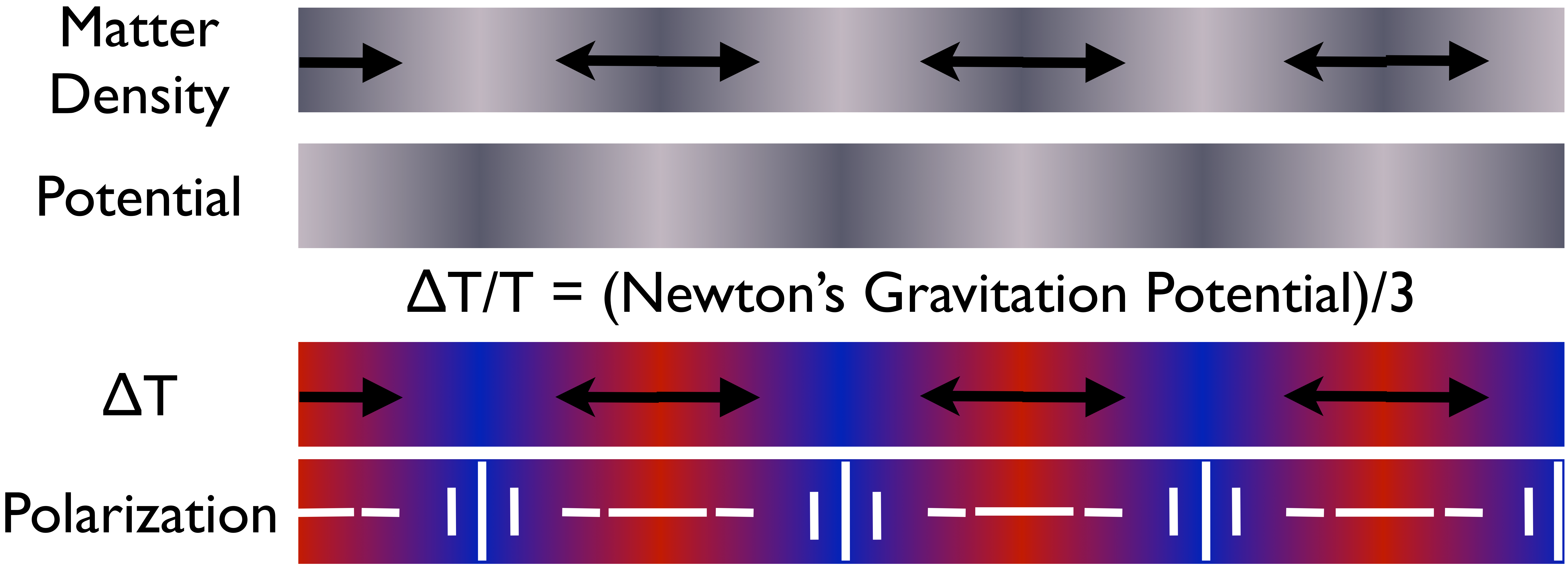
# CMB Polarization on Large Angular Scales (>2 deg)




- 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

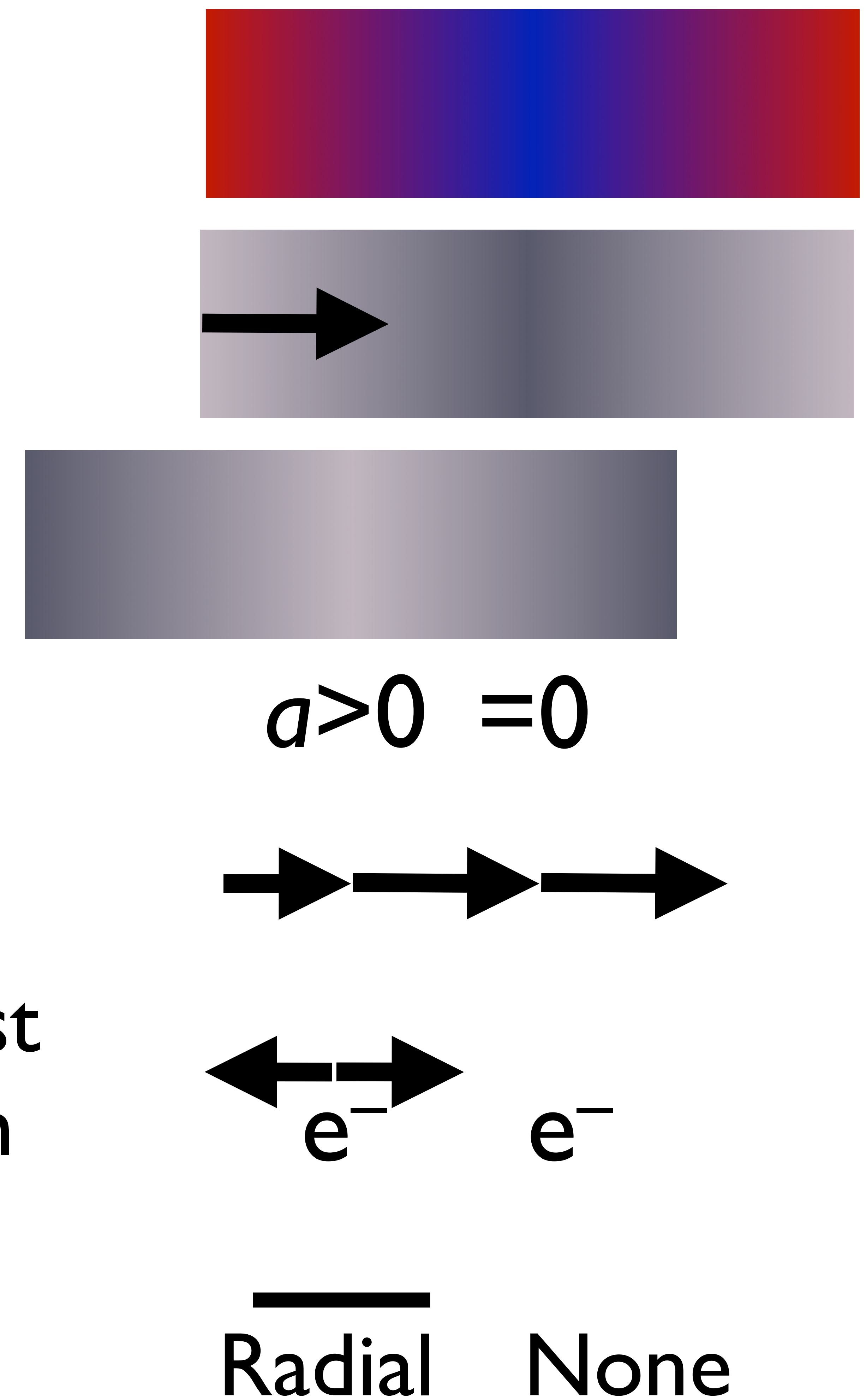
Potential Φ

Acceleration $a=-\partial\Phi$

Velocity

Velocity in the rest frame of electron

Polarization



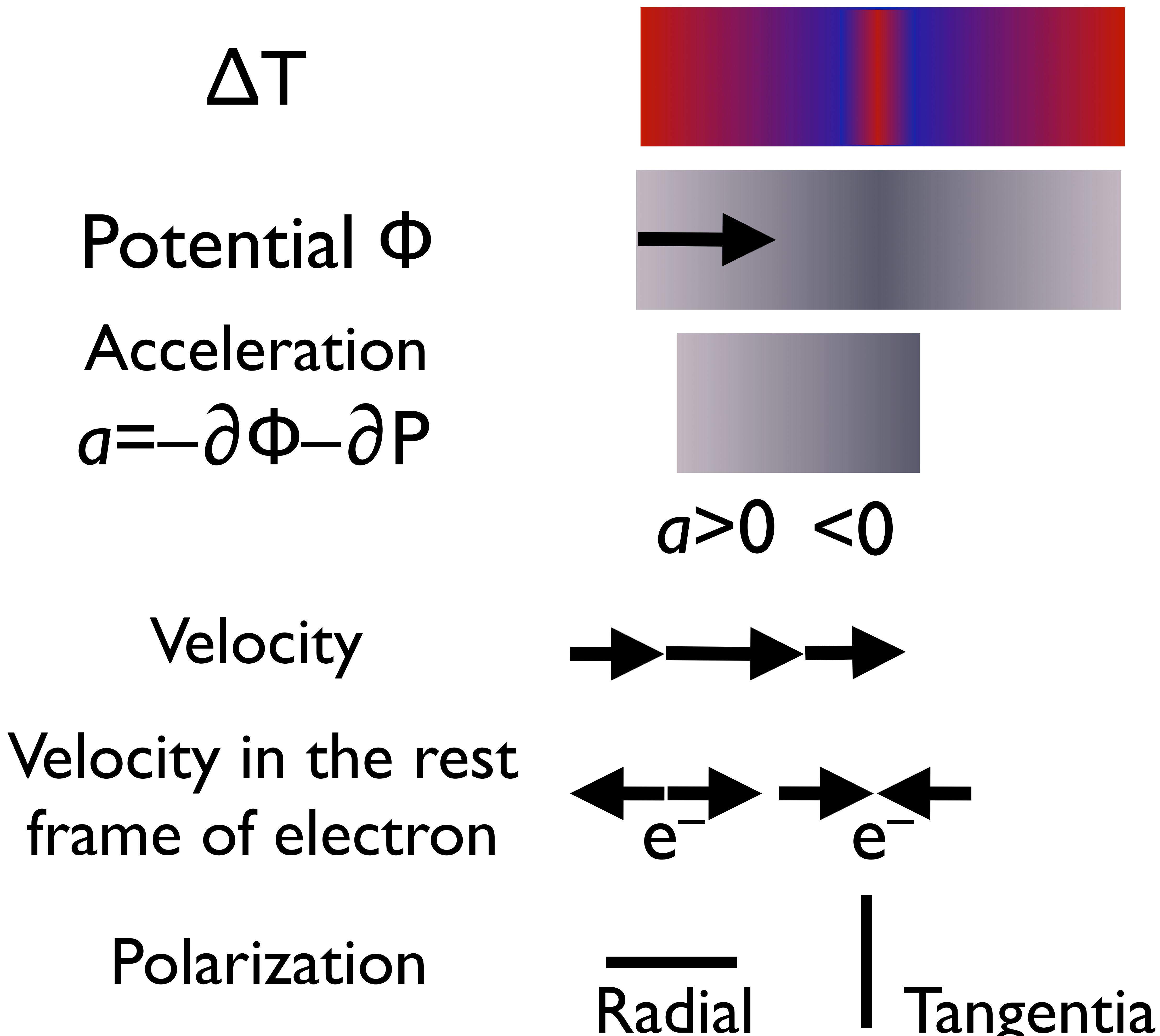

Sachs-Wolfe: $\Delta T/T=\Phi/3$

Stuff flowing *in*

Velocity gradient

The left electron sees colder photons along the plane wave

# Quadrupole From Velocity Gradient (Small Scale)



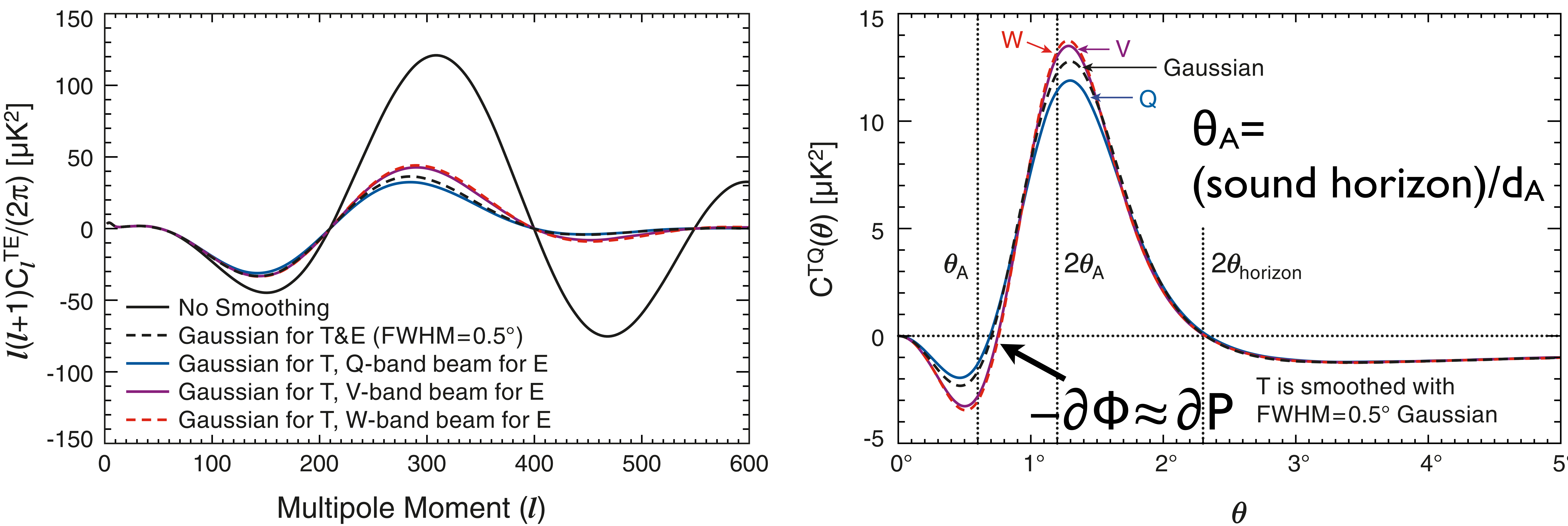

Compression increases temperature

Stuff flowing *in*

Pressure gradient slows down the flow

Velocity gradient

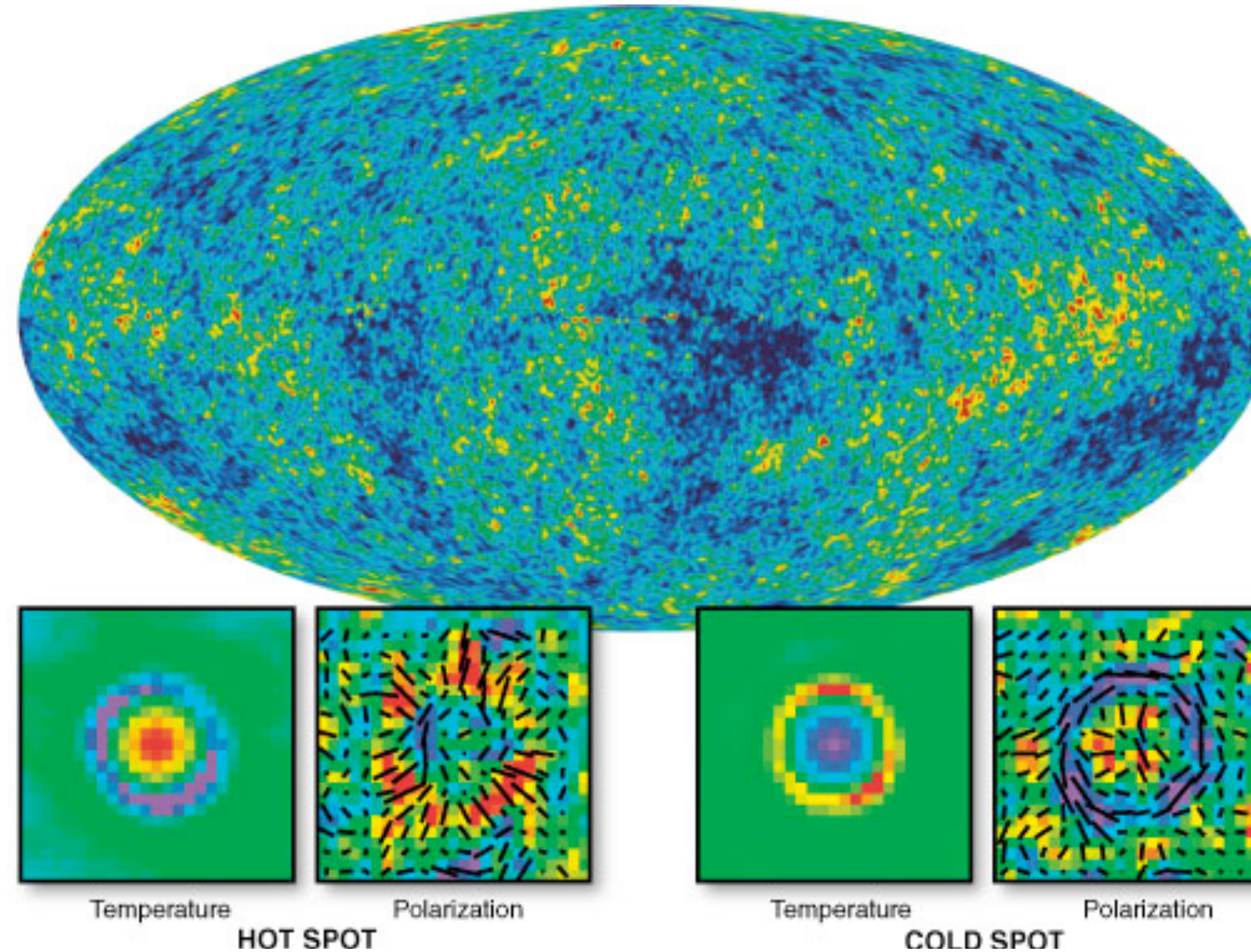
# Hence, T-polarization Correlation (Coulson et al. 1994)




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

# 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:

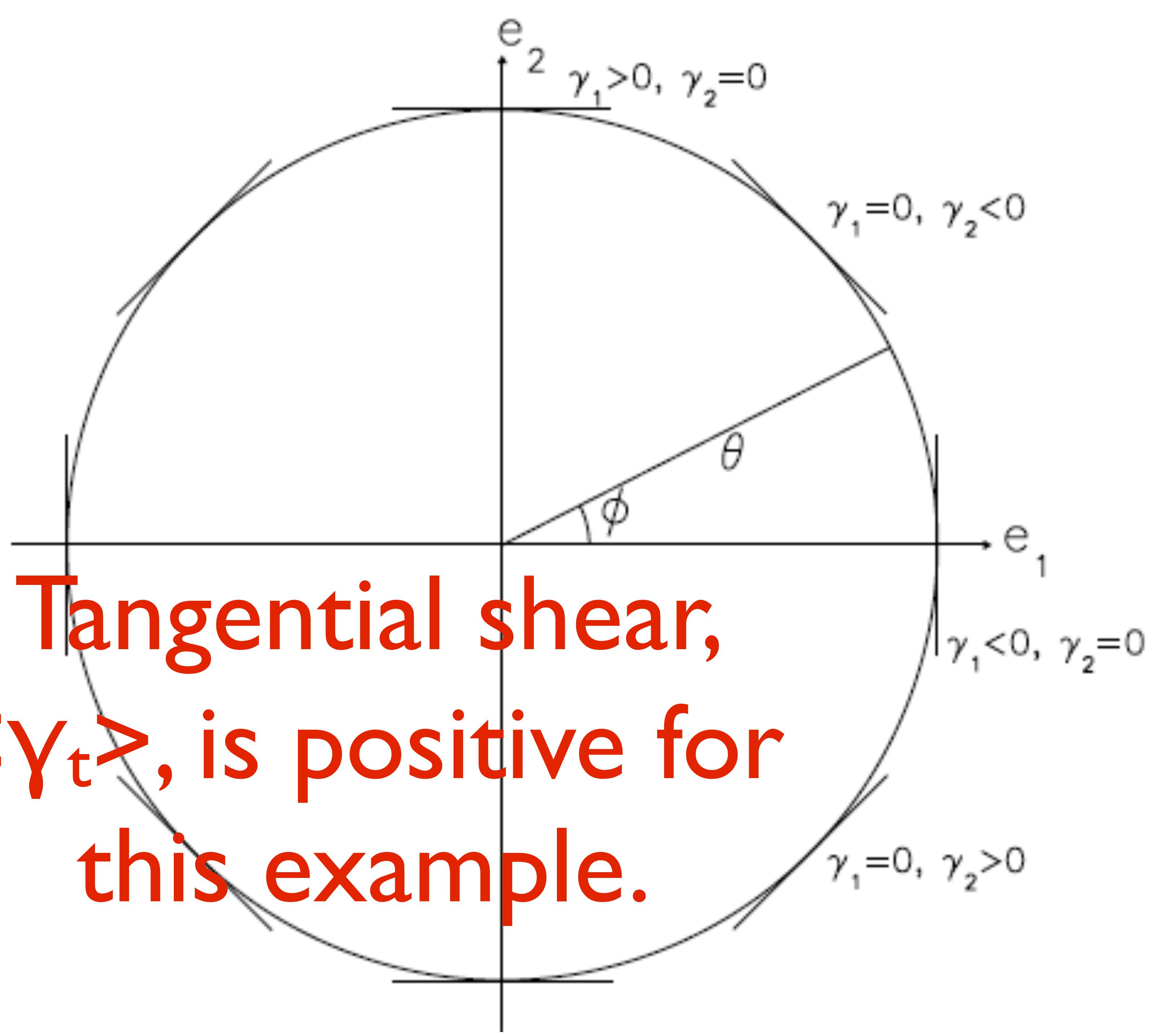
$$\langle Q_r\rangle(\theta) = -\int \frac{l dl}{2\pi} W_l^T W_l^P (\bar{b}_\nu + \bar{b}_\zeta l^2) C_l^{\rm TE} J_2(l\theta),$$

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

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

# Analogy to Weak Lensing

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



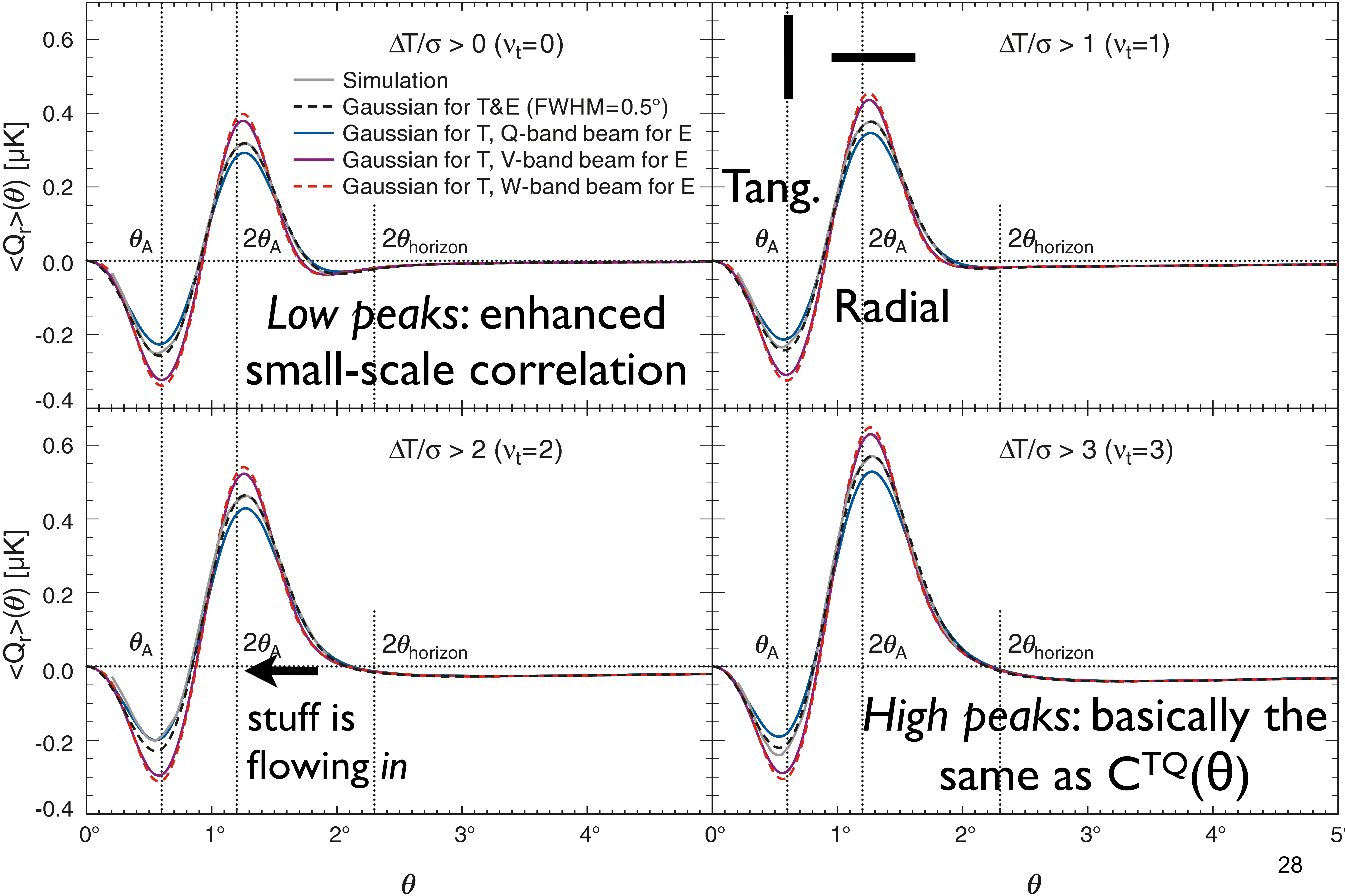

Tangential shear, $\langle\gamma_t\rangle$, is positive for this example.

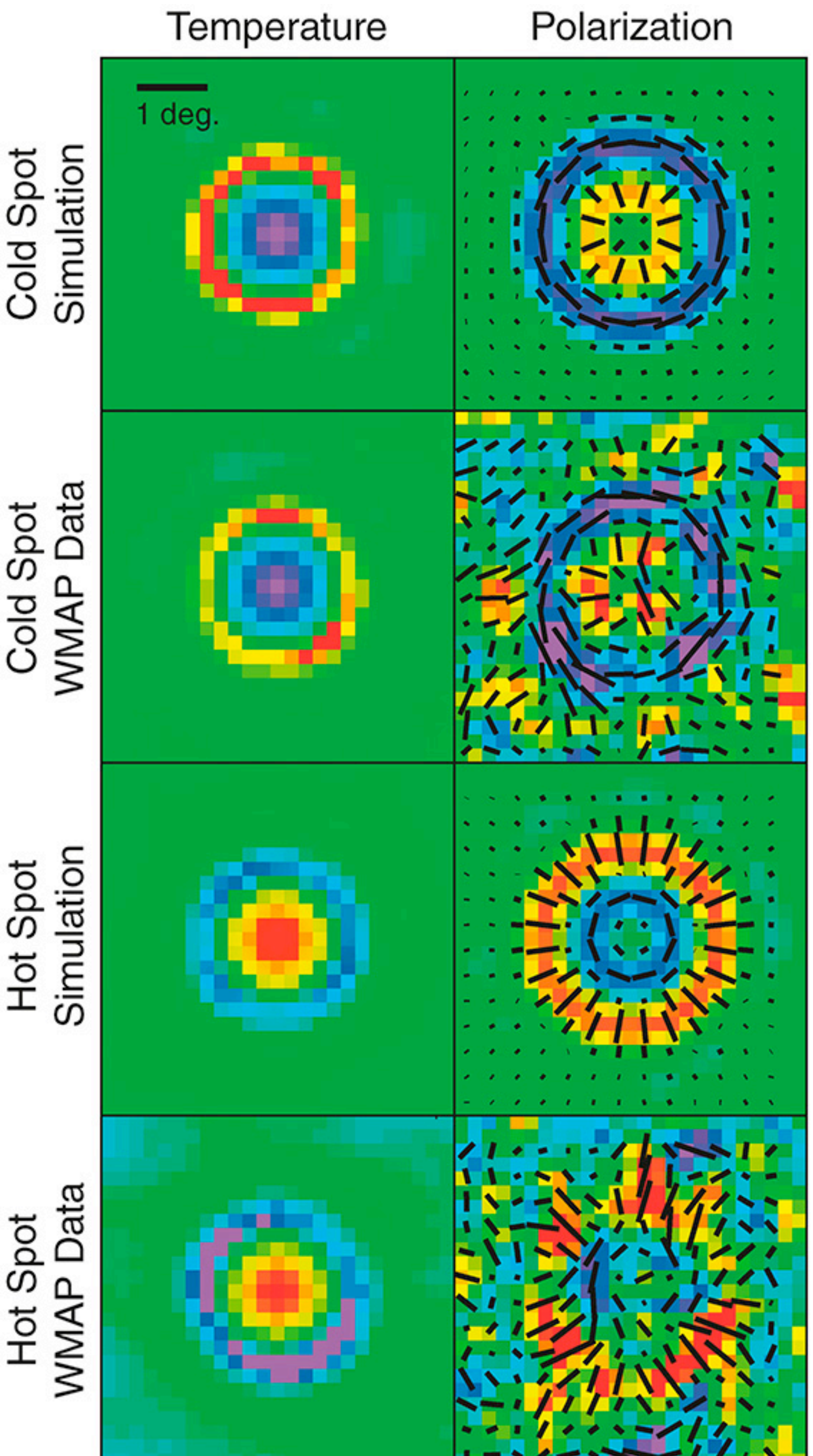
$$\Delta\Sigma(R, z_L) = \rho_0 b_1 \int \frac{kdk}{2\pi} P_m(k, z_L) J_2(kR)$$

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

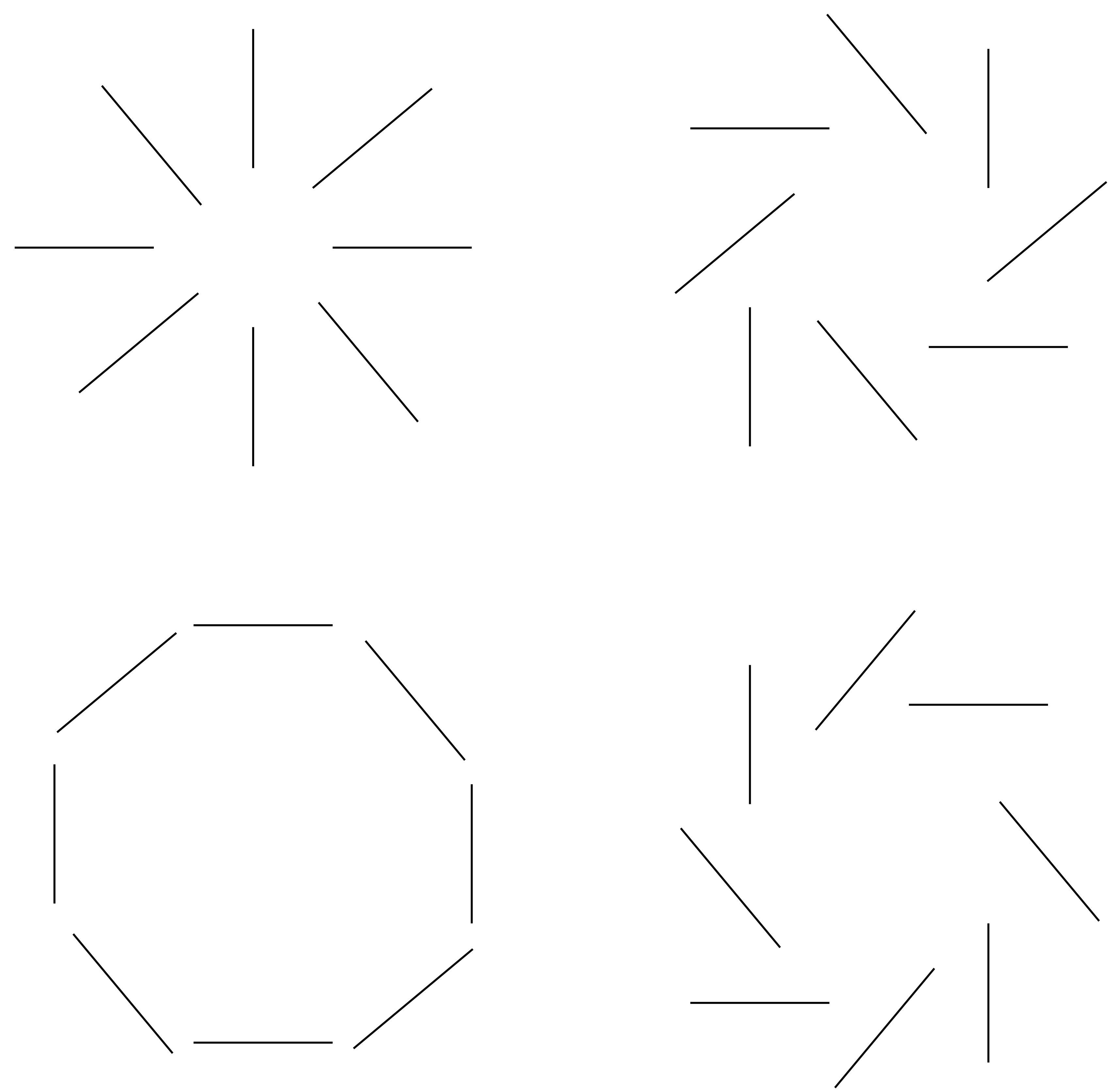





# Two-dimensional View

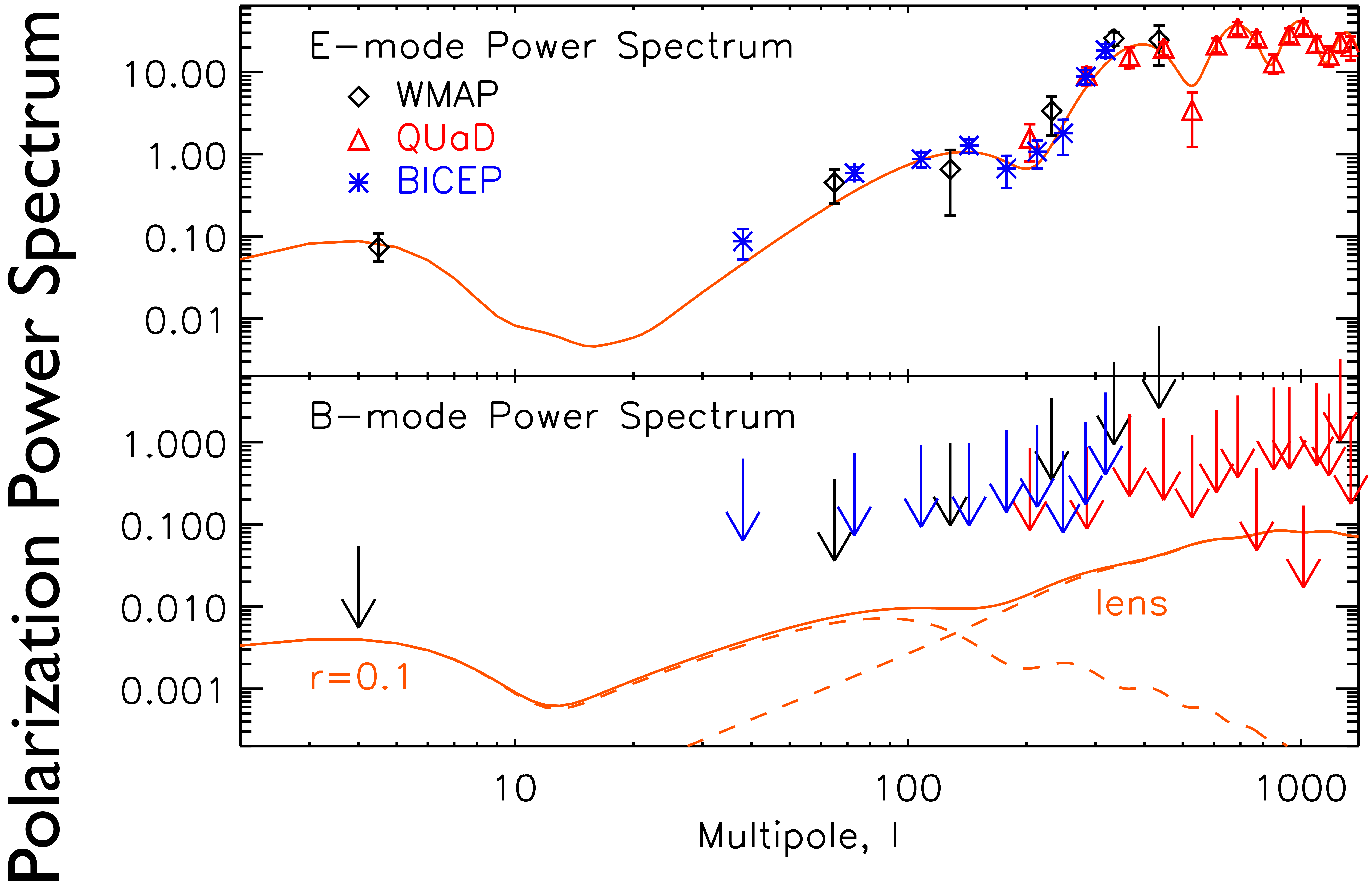
- All hot and cold spots are stacked (the threshold peak height, $\Delta T/\sigma$, is zero)
- "Compression phase" at $\theta$=1.2 deg and "slow-down phase" at $\theta$=0.6 deg are predicted to be there and we observe them!
    - The overall significance level: $8\sigma$

# E-mode and B-mode



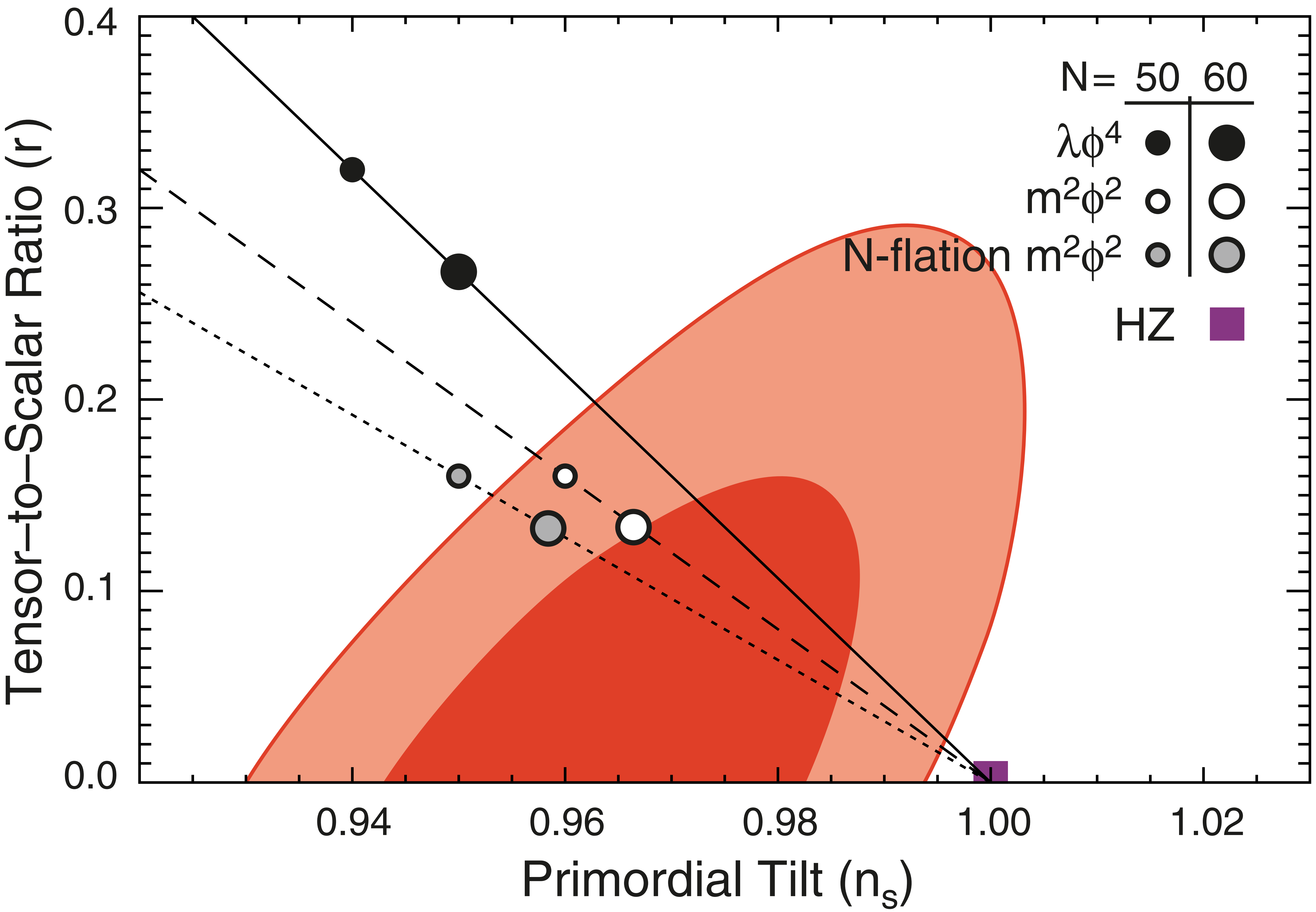
E mode B mode

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




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

# Probing Inflation (2-point Function)

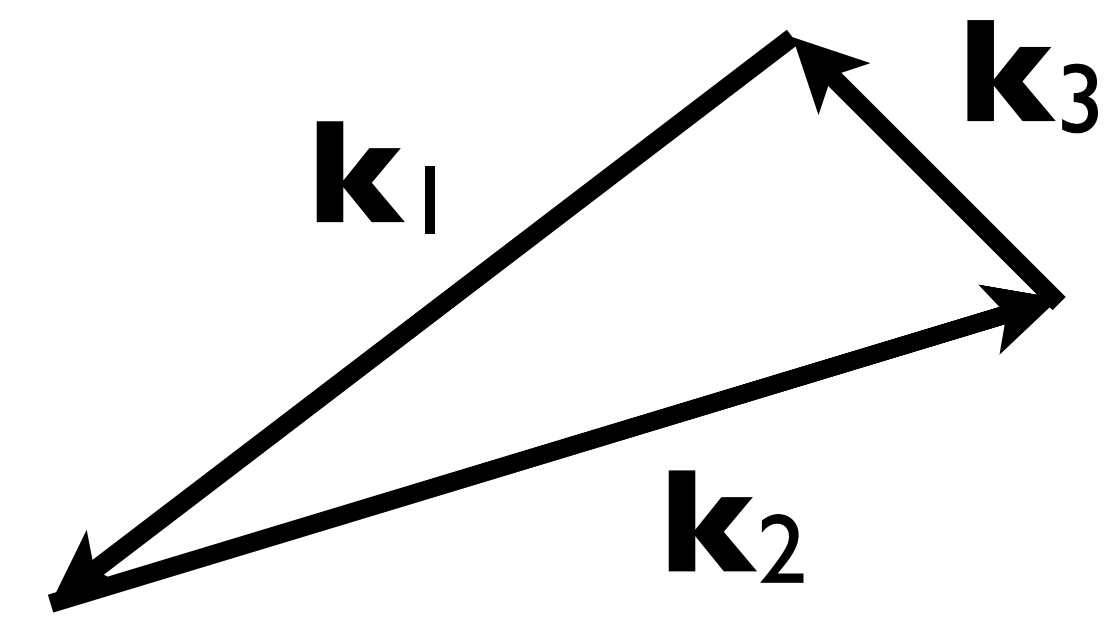



- Joint constraint on the primordial tilt, $n_s$, and the tensor-to-scalar ratio, r.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL)
- Limit on the tilt of the power spectrum: $n_s=0.968\pm0.012$ (68%CL)

# Probing Inflation (3-point Function)

- Inflation models predict that primordial fluctuations are very close to Gaussian.
  - In fact, ALL SINGLE-FIELD models predict a particular form of **3-point function** to have the amplitude of $f_{NL}=0.02$.
  - Detection of $f_{NL}>1$ would rule out ALL single-field models!

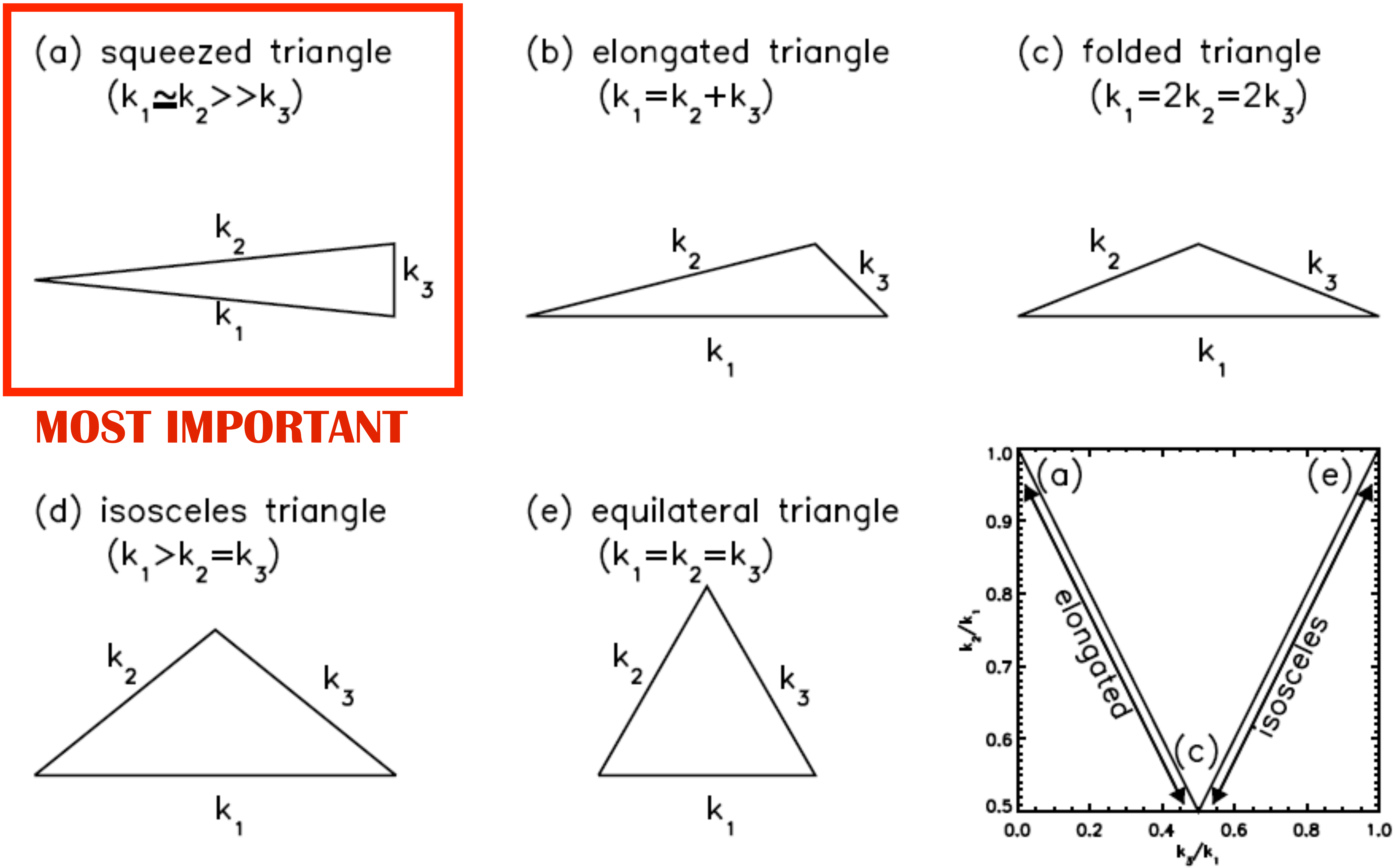
# Bispectrum




- Three-point function!
- $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$
  $= \langle \zeta_{\mathbf{k}1}\zeta_{\mathbf{k}2}\zeta_{\mathbf{k}3} \rangle$ = (amplitude) x $(2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)F(k_1,k_2,k_3)$

model-dependent function

Primordial fluctuation


(a) squeezed triangle
($k_1 \simeq k_2 >> k_3$)
$k_2$
$k_3$
$k_1$
MOST IMPORTANT
(b) elongated triangle
($k_1 = k_2 + k_3$)
$k_2$
$k_3$
$k_1$
(c) folded triangle
($k_1 = 2k_2 = 2k_3$)
$k_2$
$k_3$
$k_1$
(d) isosceles triangle
($k_1 > k_2 = k_3$)
$k_2$
$k_3$
$k_1$
(e) equilateral triangle
($k_1 = k_2 = k_3$)
$k_2$
$k_3$
$k_1$
(a)
(e)
(c)
elongated
isosceles
$k_2/k_1$
$k_3/k_1$
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0

*Maldacena (2003); Seery & Lidsey (2005); Creminelli & Zaldarriaga (2004)*

# Single-field Theorem (Consistency Relation)

- For **ANY** single-field models*, the bispectrum in the squeezed limit is given by
  - $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) \approx (1-n_s) \times (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) \times P_\zeta(k_1)P_\zeta(k_3)$
  - Therefore, all single-field models predict $f_{NL} \approx (5/12)(1-n_s)$.
  - With the current limit $n_s=0.963$, $f_{NL}$ is predicted to be 0.015.

* for which the single field is solely responsible for driving inflation and generating observed fluctuations.

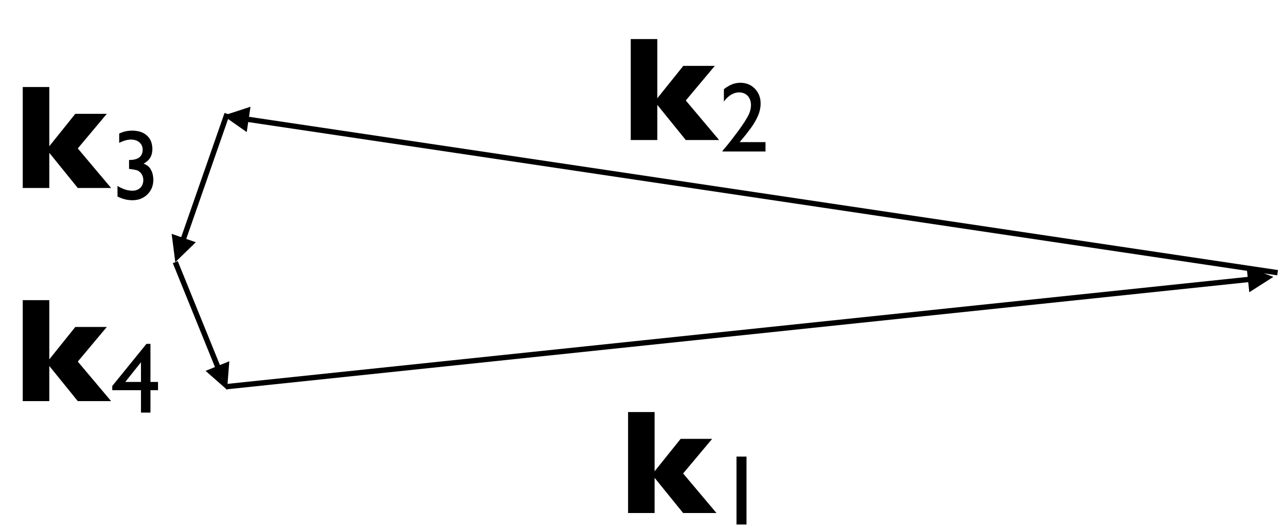
# Probing Inflation (3-point Function)

- No detection of 3-point functions of primordial curvature perturbations. The 95% CL limit is:
  - $-10 < f_{NL} < 74$
- The 68% CL limit: $f_{NL} = 32 \pm 21$
  - The WMAP data are consistent with the prediction of **simple single-field inflation** models: $1-n_s \approx r \approx f_{NL}$
- The Planck's expected 68% CL uncertainty: $\Delta f_{NL} = 5$

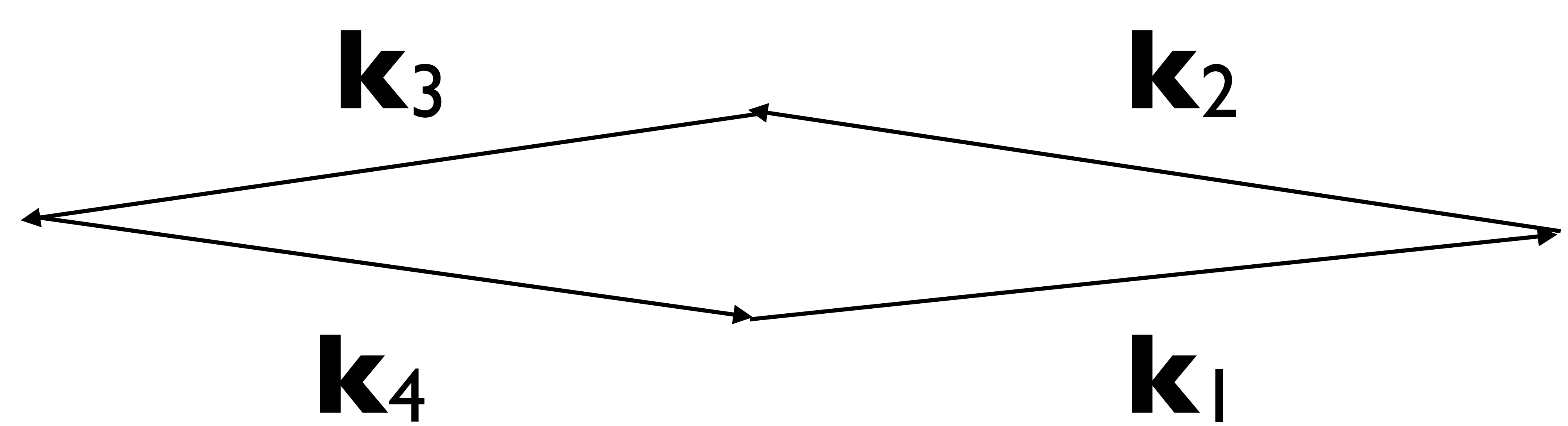
# Trispectrum

- $T_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)=(2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\mathbf{k}_4)$ $\{g_{NL}[(54/25) P_\zeta(k_1)P_\zeta(k_2)P_\zeta(k_3)+\text{cyc.}] + \tau_{NL}[P_\zeta(k_1)P_\zeta(k_2)(P_\zeta(|\mathbf{k}_1+\mathbf{k}_3|)+P_\zeta(|\mathbf{k}_1+\mathbf{k}_4|))+\text{cyc.}]\}$

*The local form consistency relation, $\tau_{NL}=(6/5)(f_{NL})^2$, may not be respected – additional test of multi-field inflation!*

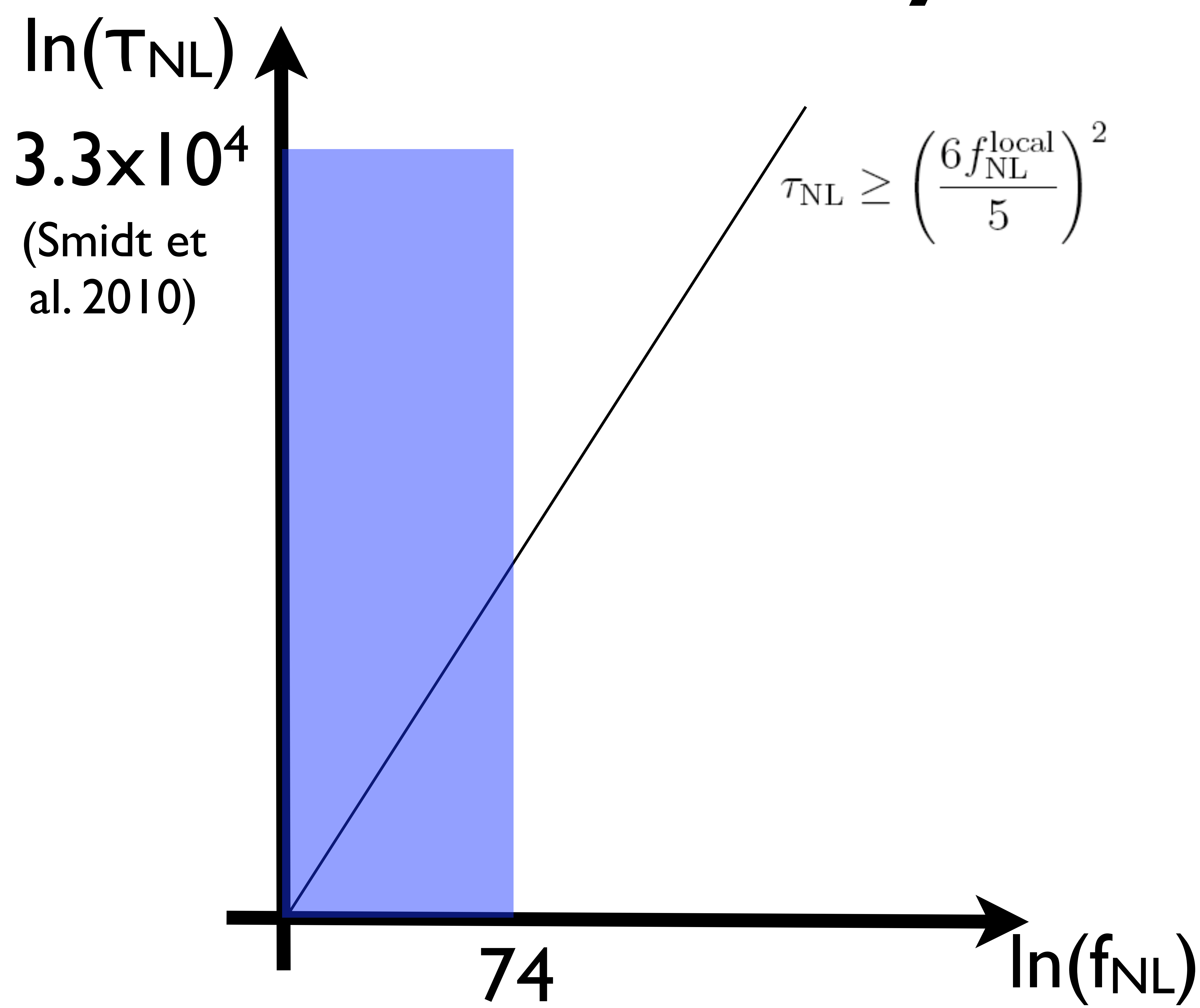



$g_{NL}$



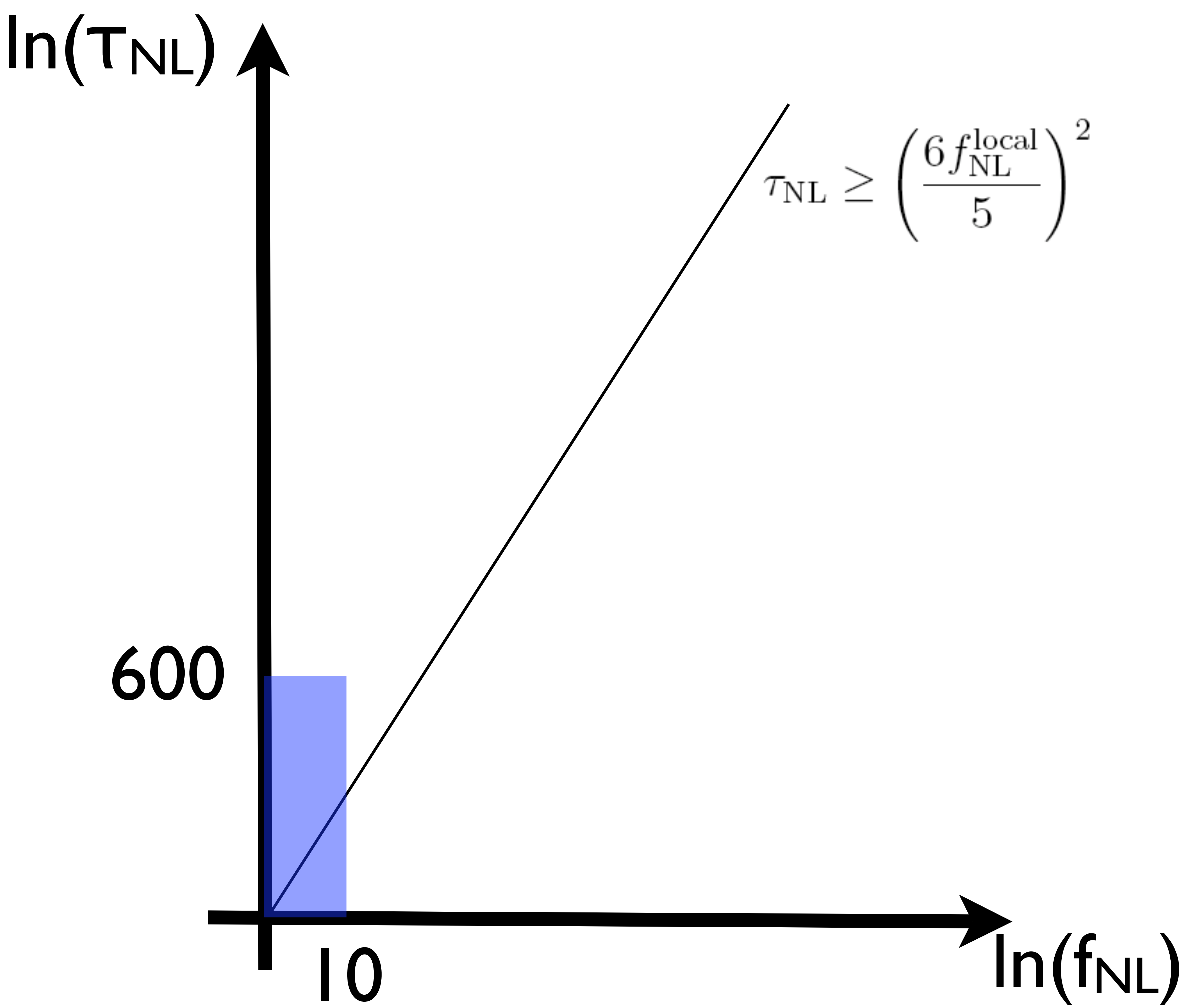

$\tau_{NL}$

# The diagram that you should take away from this talk.



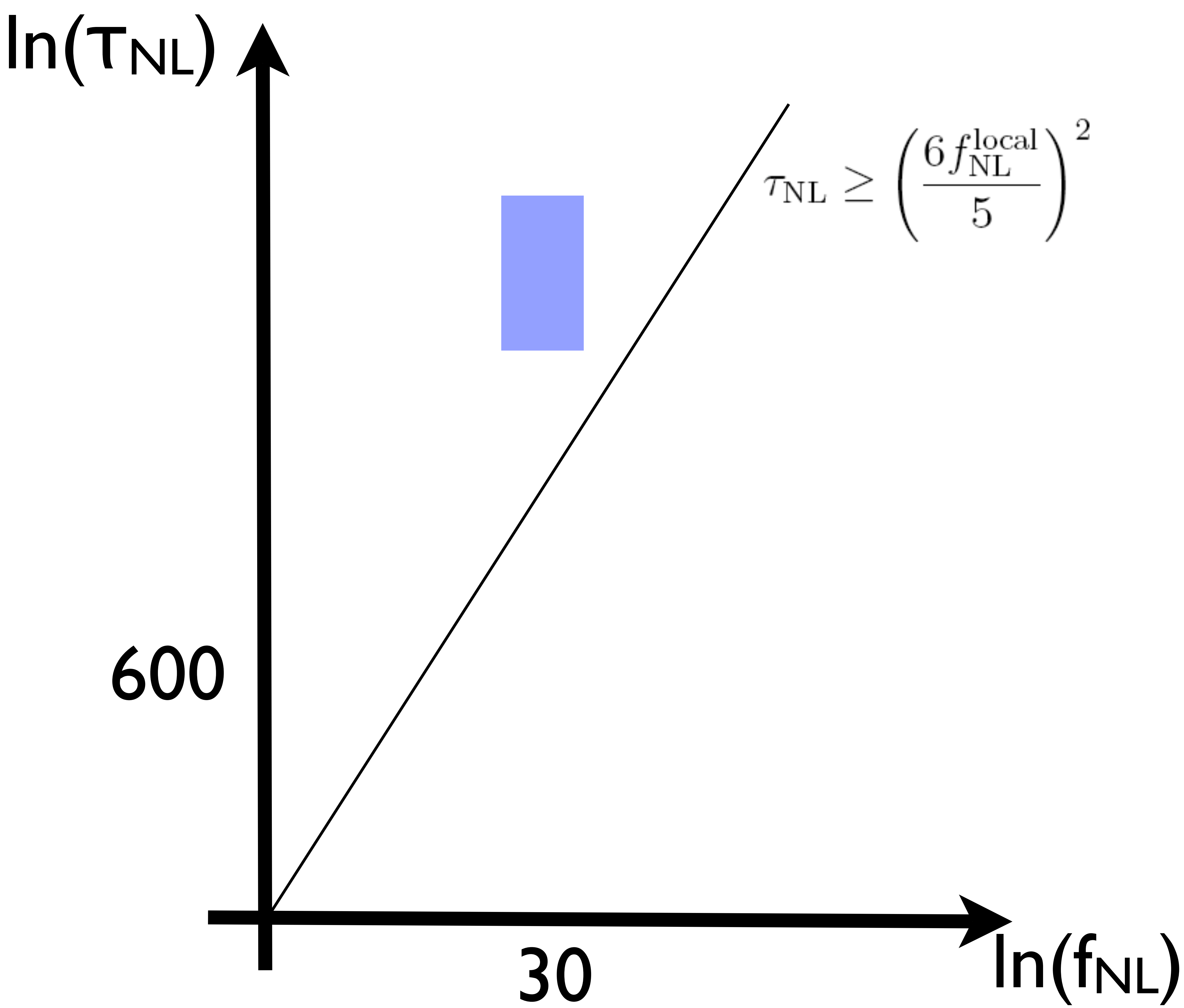

- The current limits from WMAP 7-year are consistent with single-field or multi-field models.
- So, let's play around with the future.

# Case A: Single-field Happiness



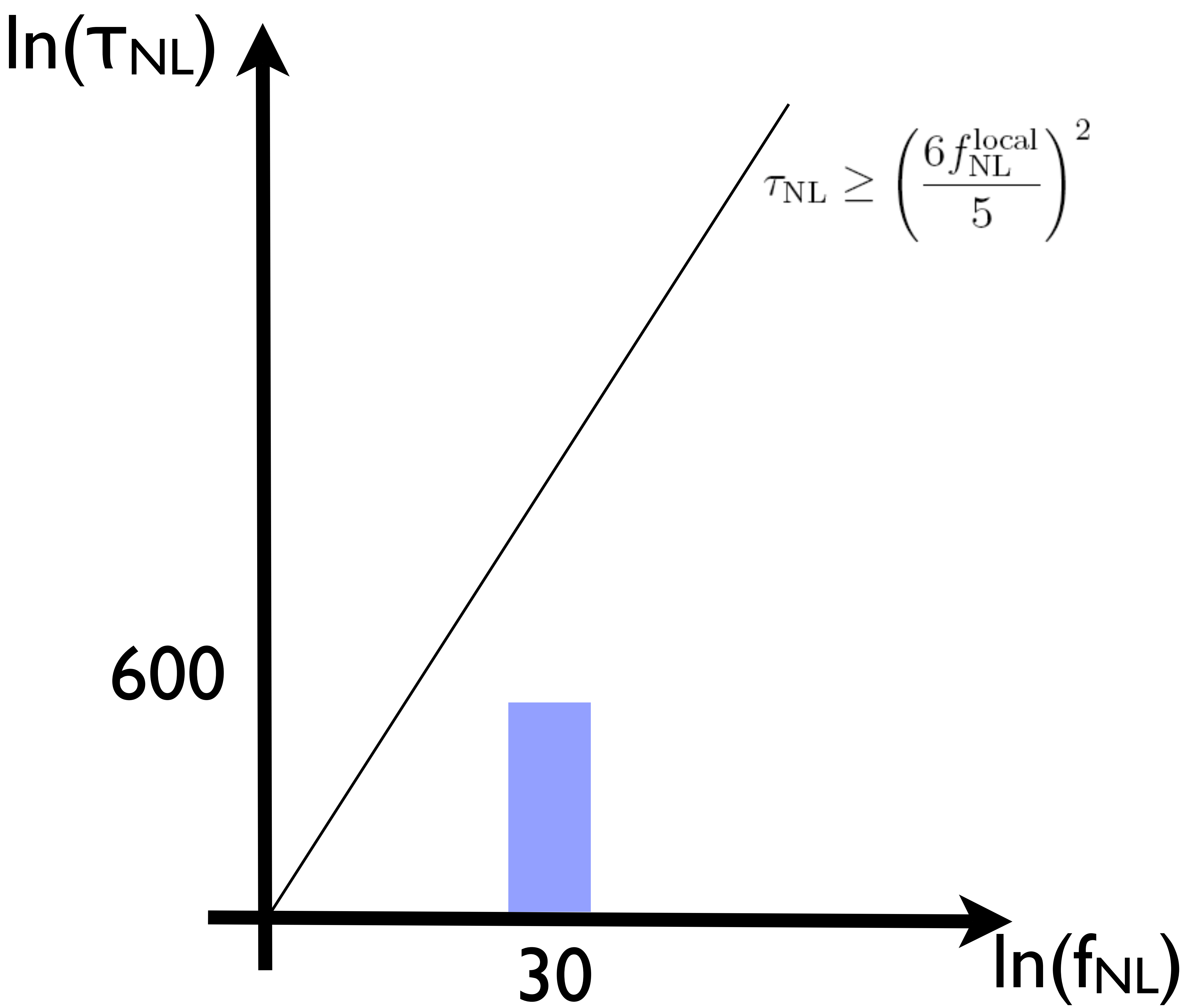

- No detection of anything after Planck. Single-field survived the test (for the moment: the future galaxy surveys can improve the limits by a factor of ten).

# Case B: Multi-field Happiness




- $f_{NL}$ is detected. Single-field is dead.
- But, $\tau_{NL}$ is also detected, in accordance with the Suyama-Yamaguchi inequality, as expected from most (if not all - left unproven) of multi-field models.

# Case C: Madness

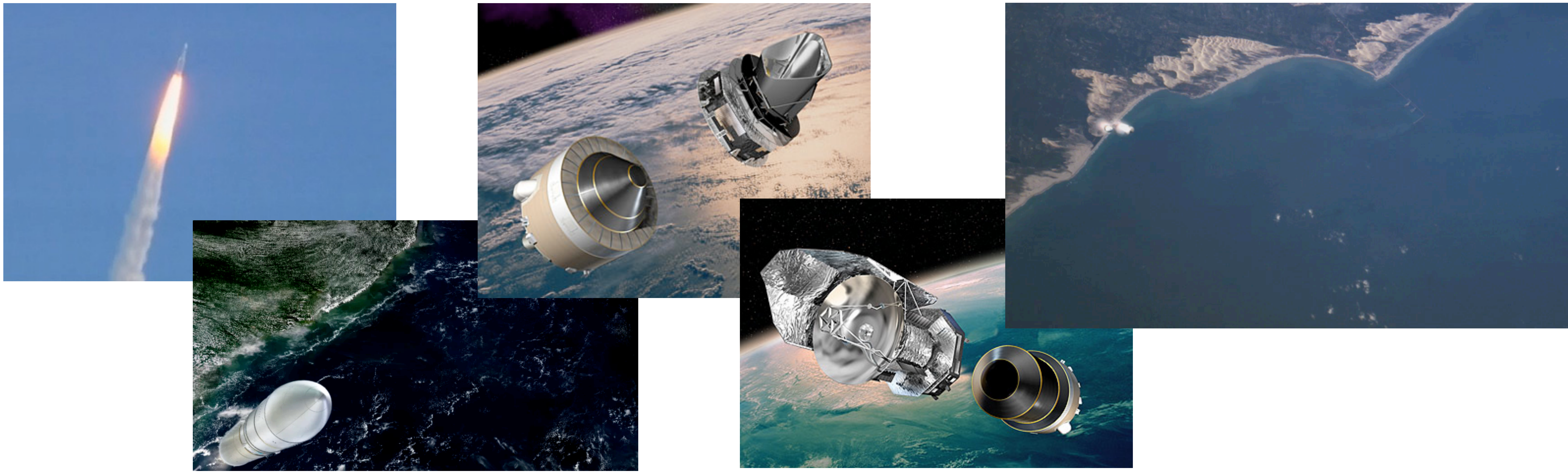



- $f_{NL}$ is detected. Single-field is dead.
- But, $\tau_{NL}$ is **not** detected, inconsistent with the Suyama-Yamaguchi inequality.
- (With the caveat that this may not be completely general) BOTH the single-field and multi-field are gone.

# CMB: Summary

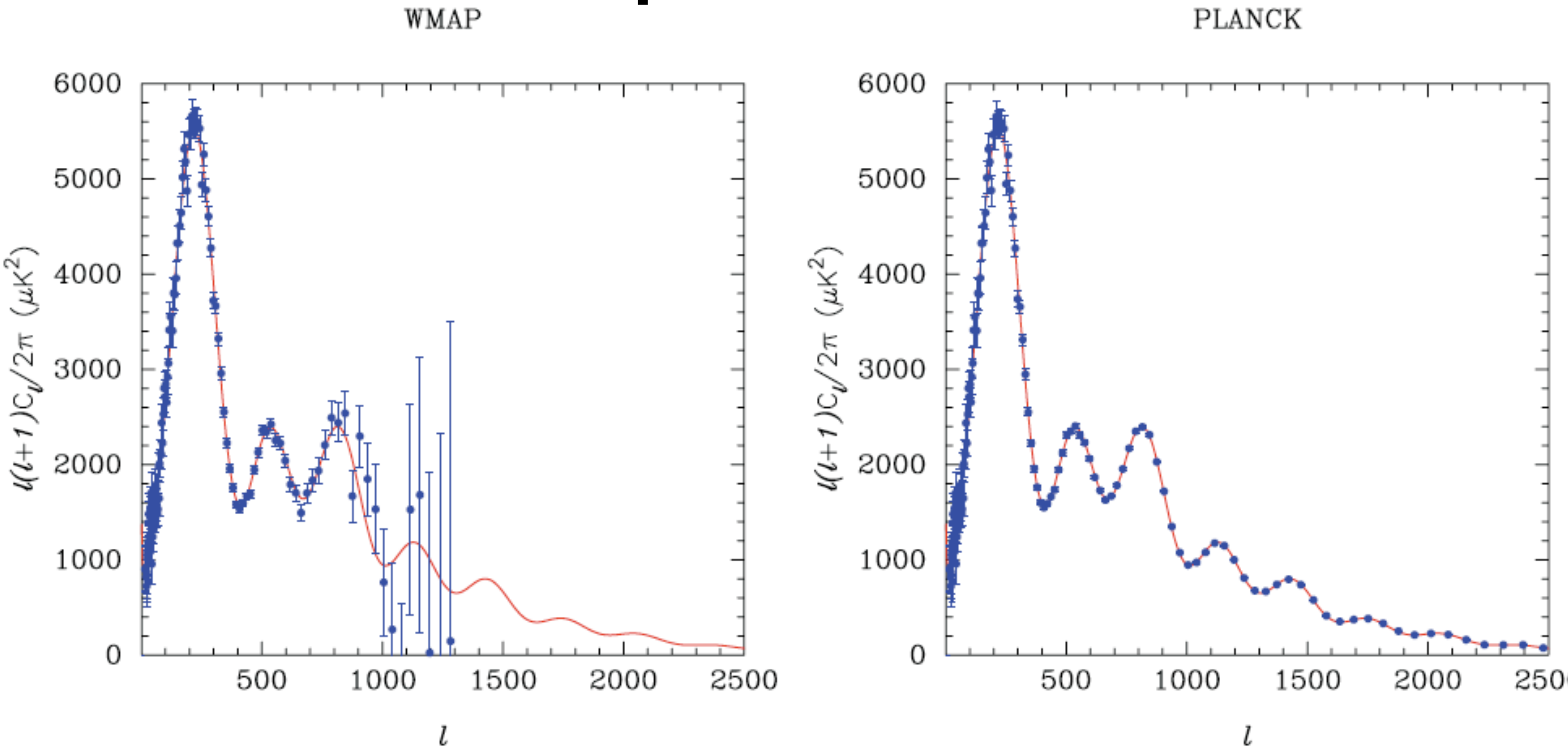
- Primordial helium is detected by CMB alone, for the first time (combining WMAP+ACBAR+QUAD).
- $N_{eff}$~4? Planck will tell...
- Polarizaion map! Confirmation of the basic paradigm.
- $n_s$=0.968±0.012 (68%CL); r<0.24 (95%CL)
- Next Big Thing: **Primordial gravitational waves**
- My favorite: **Detection of $f_{NL}$ to rule out single-field inflation!**

# Planck Launched!



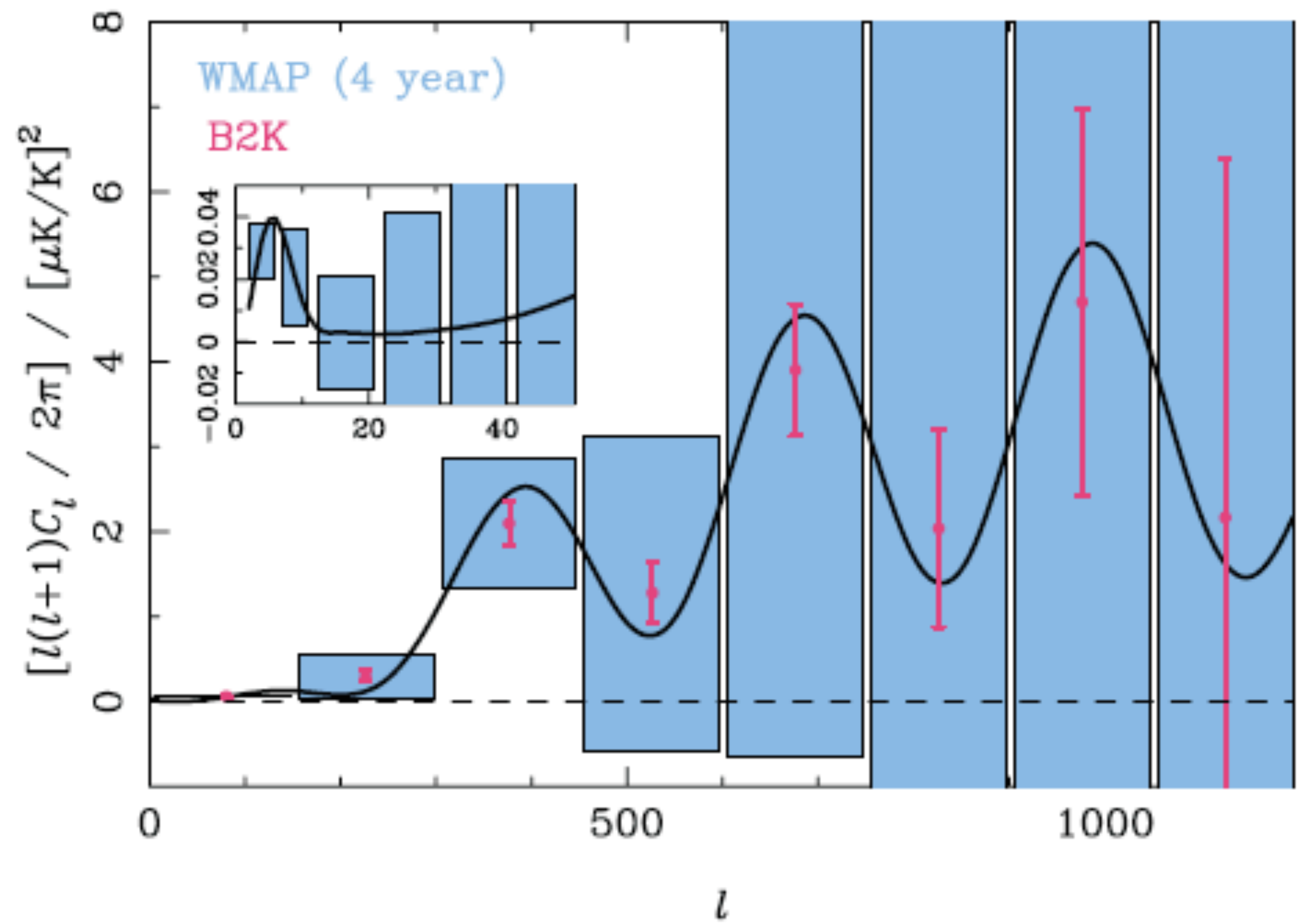
- The Planck satellite was successfully launched from French Guiana on May 14.
- Separation from the Herschell satellite was also successful.
- Planck has mapped the full sky already - results expected to be released in December, 2012.

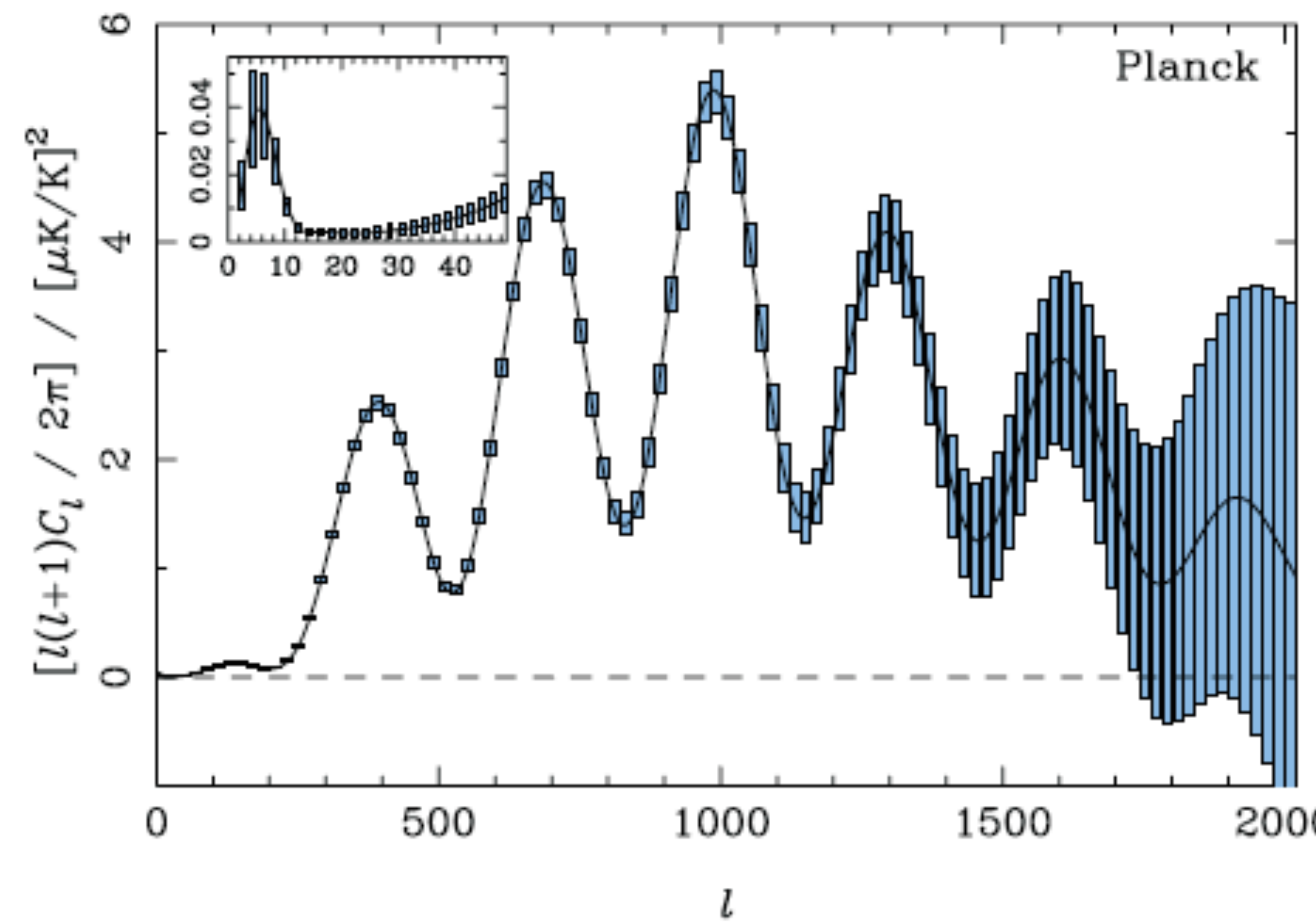
# Planck: Expected $C_l^{Temperature}$

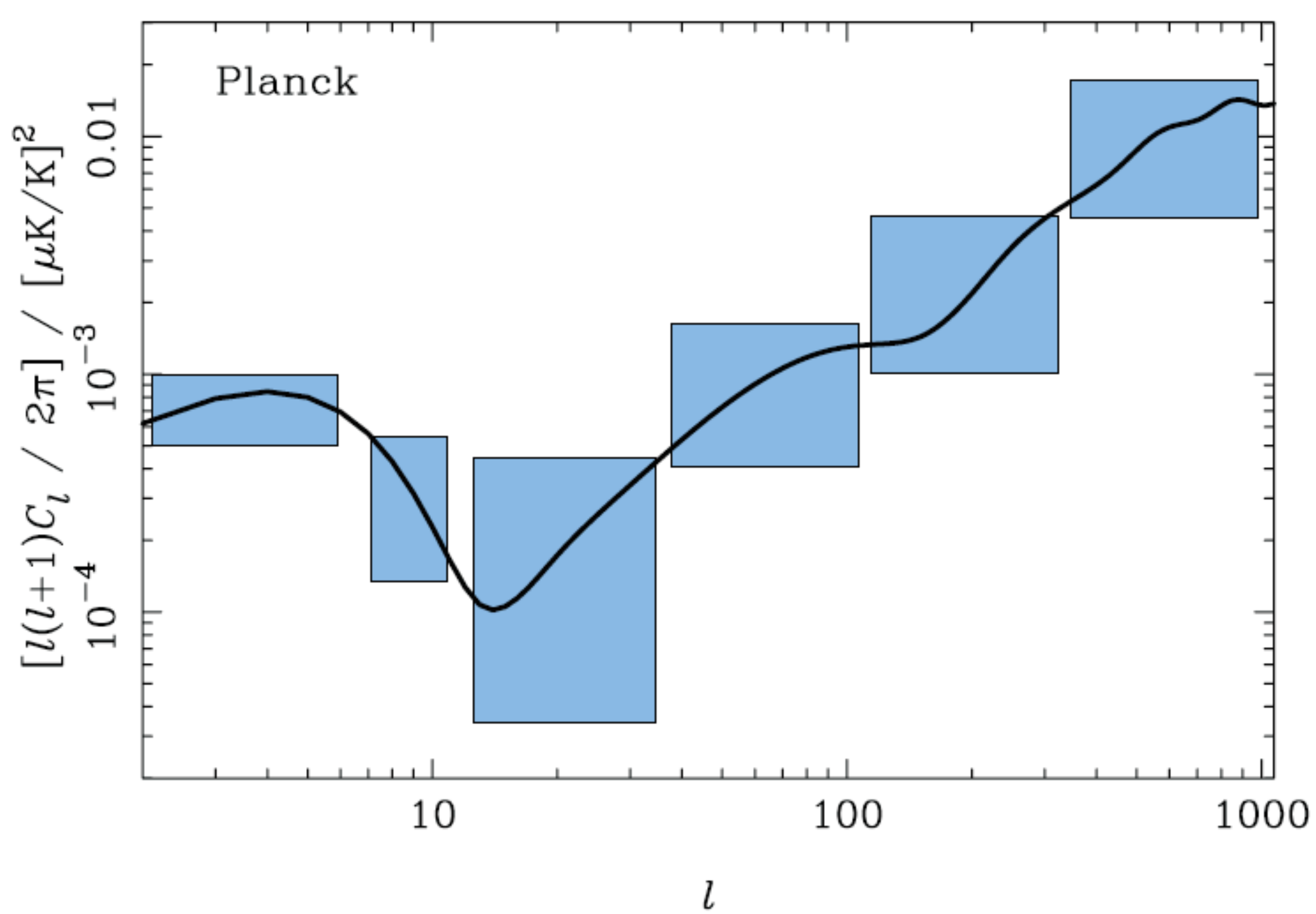



- WMAP: l~1000 => Planck: l~3000

# Planck: Expected $C_l^{Polarization}$



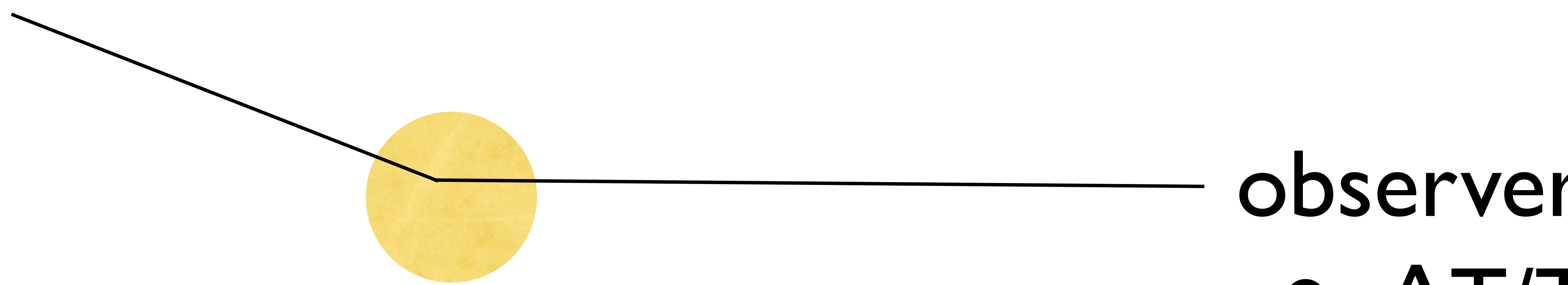




- (Above) E-modes
- (Left) B-modes (r=0.3)

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

# Sunyaev–Zel'dovich Effect




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

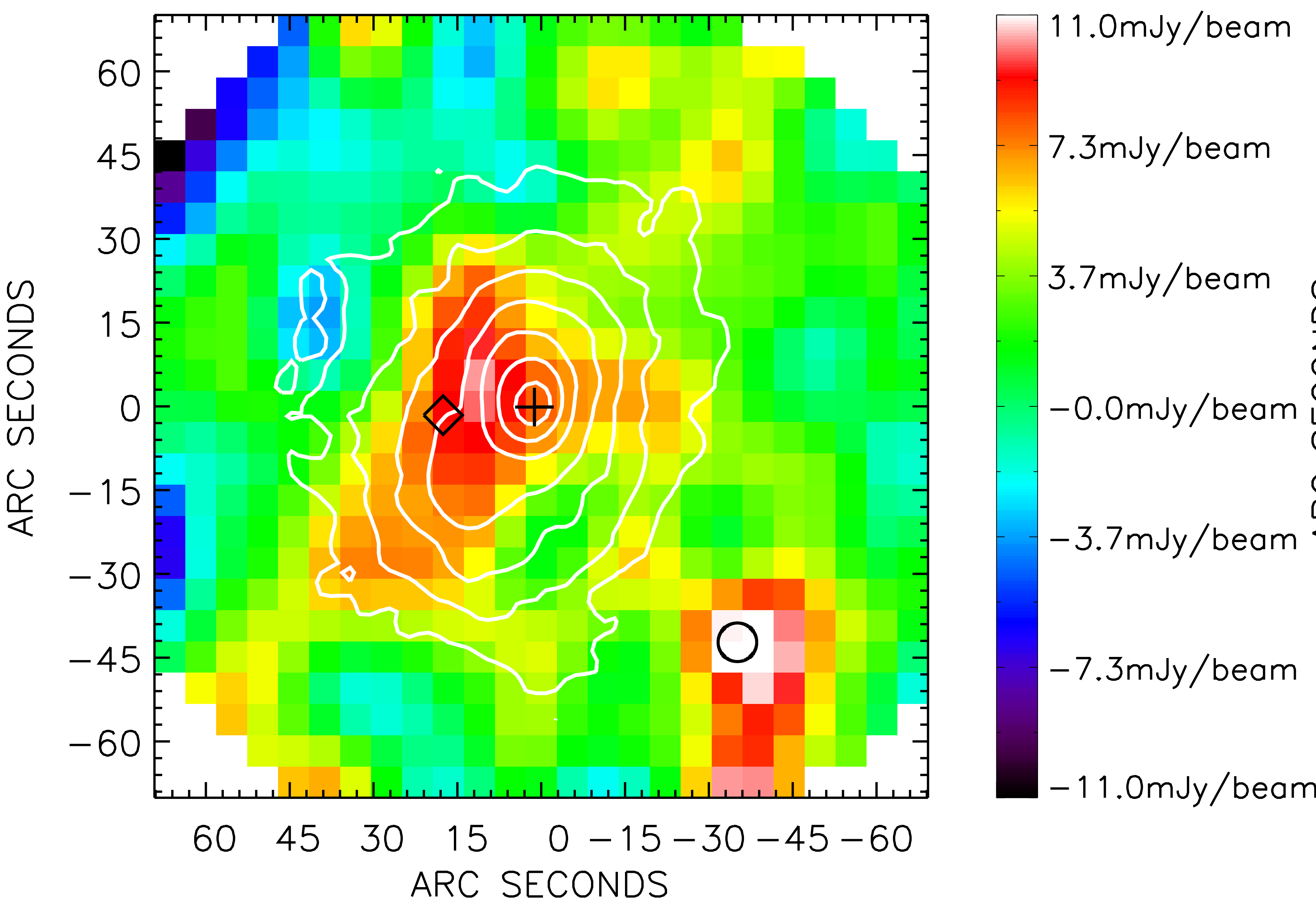
$g_\nu = -2$ ($\nu=0$); $-1.91$, $-1.81$ and $-1.56$ at $\nu=41$, 61 and 94 GHz

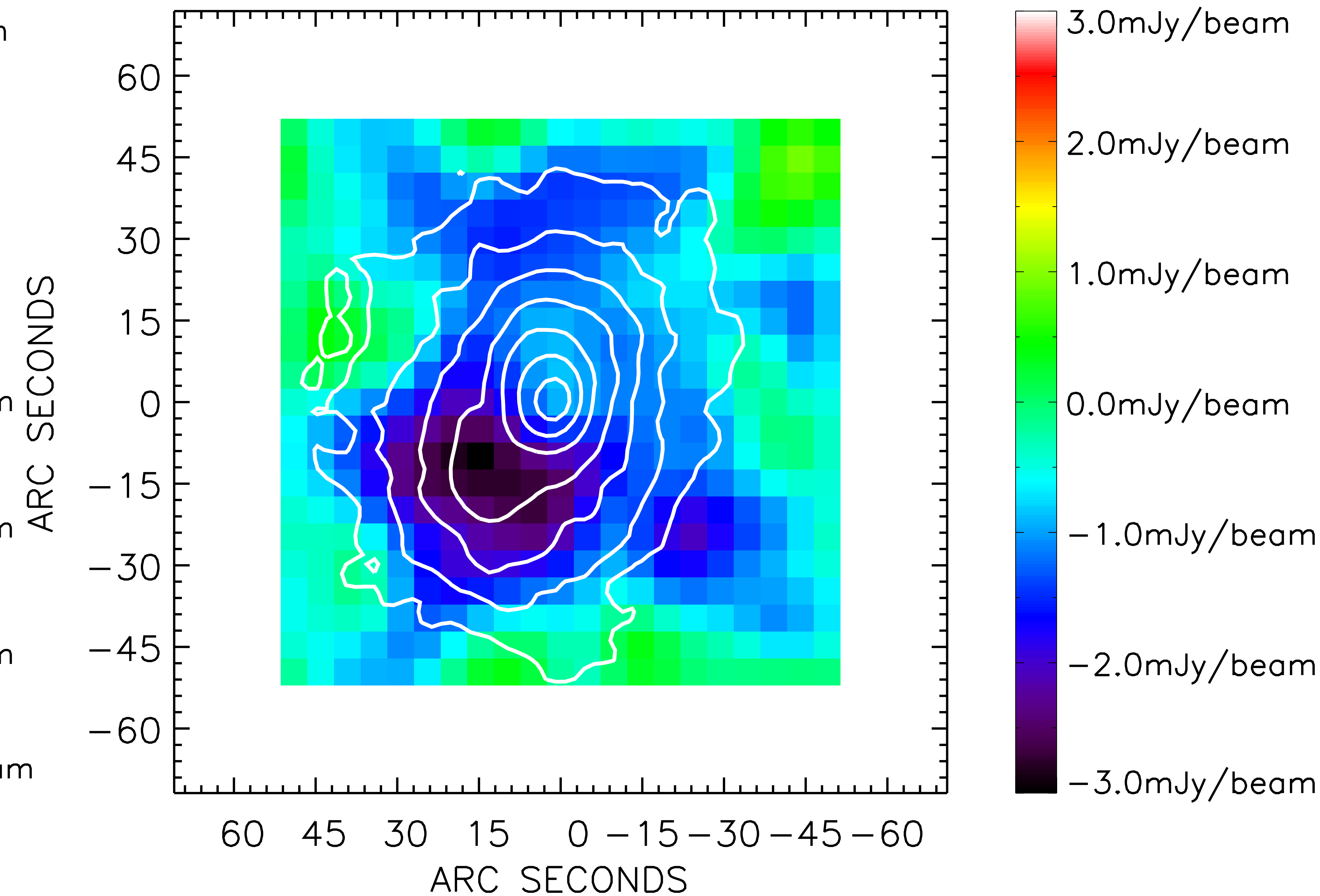
# A New Result!

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.

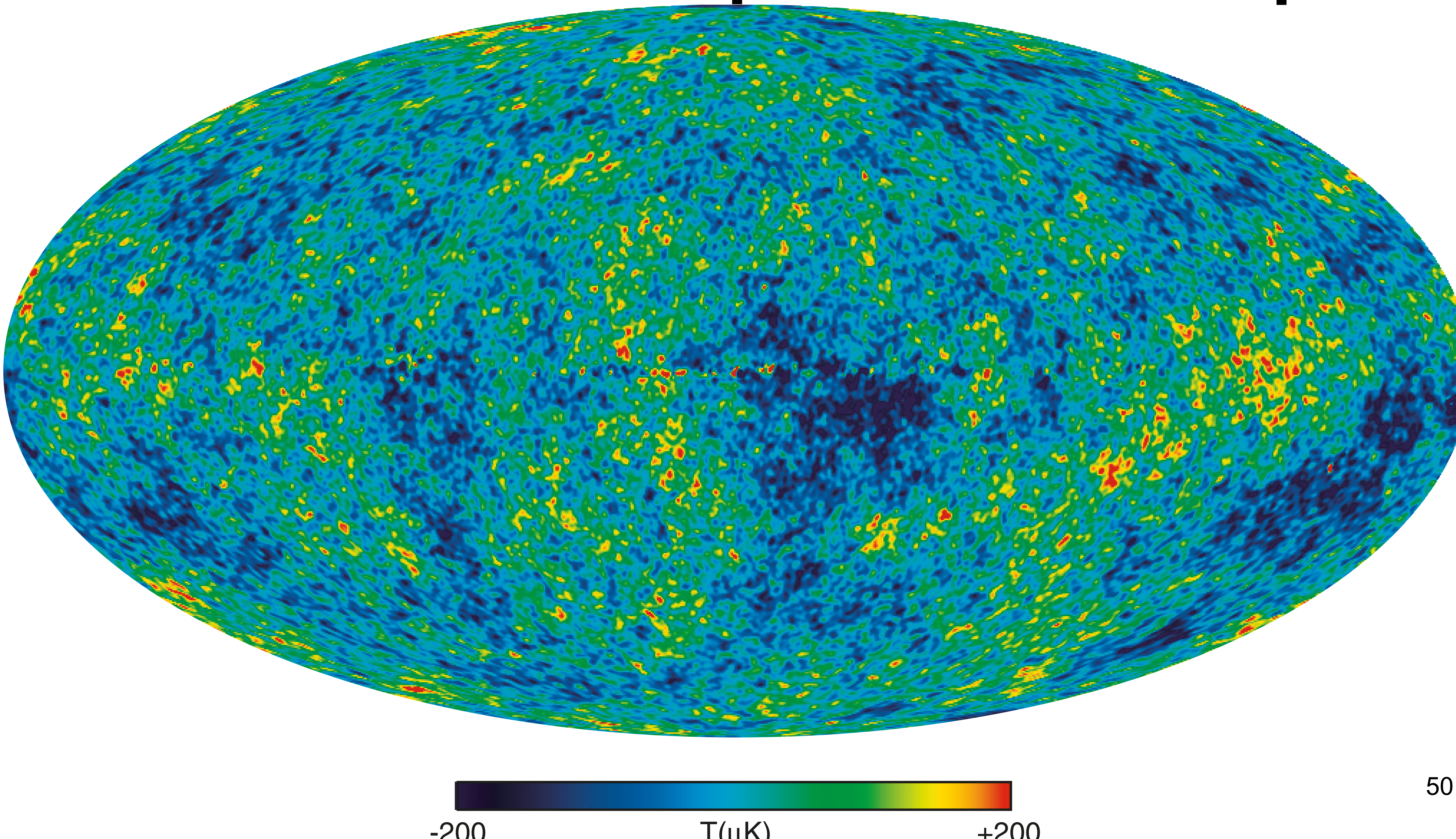
# The SZ Effect: Decrement and Increment



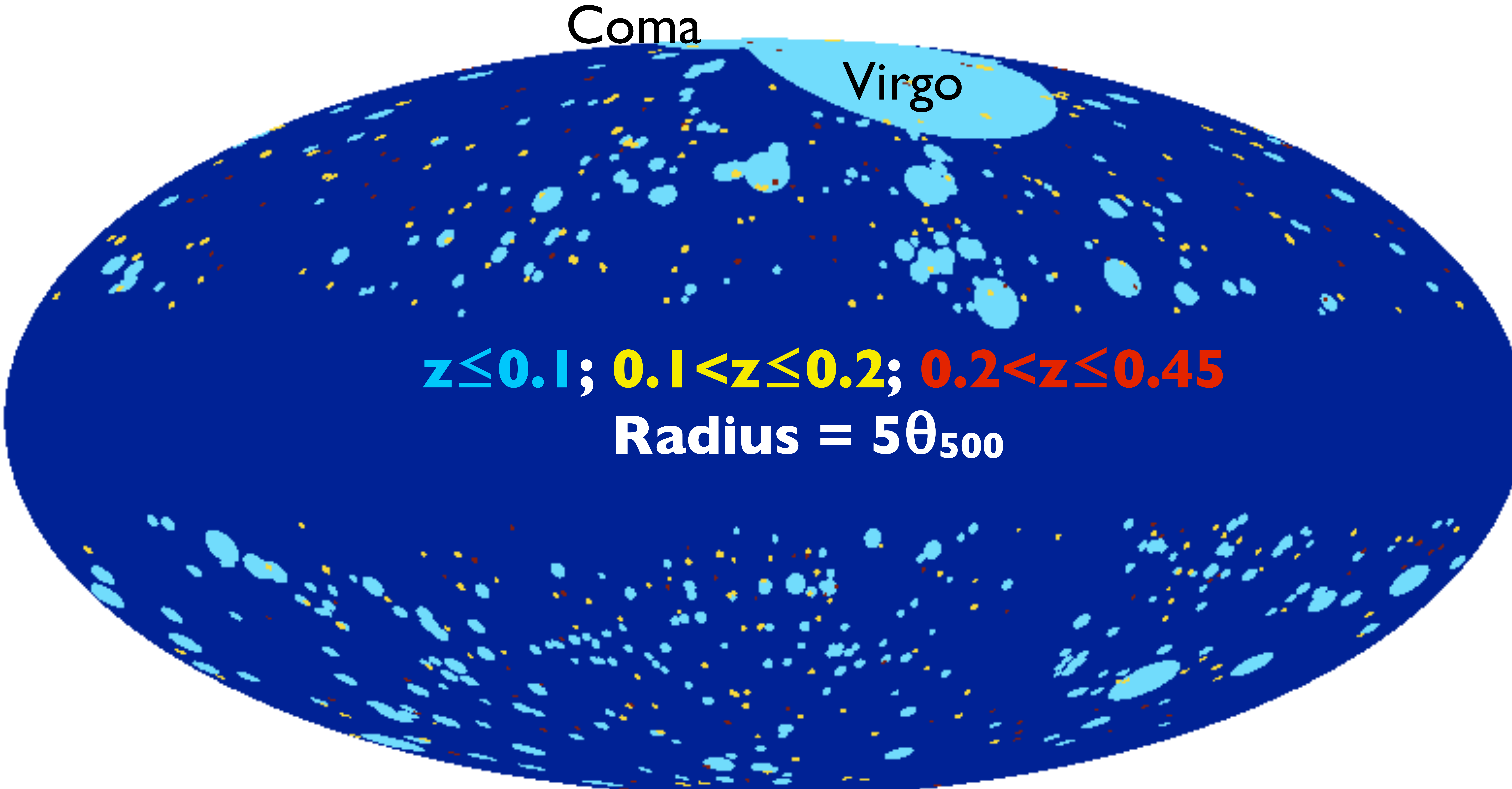




- RXJ1347-1145
  - –Left, SZ increment (350GHz, Komatsu et al. 1999)
  - –Right, SZ decrement (150GHz, Komatsu et al. 2001)

# WMAP Temperature Map



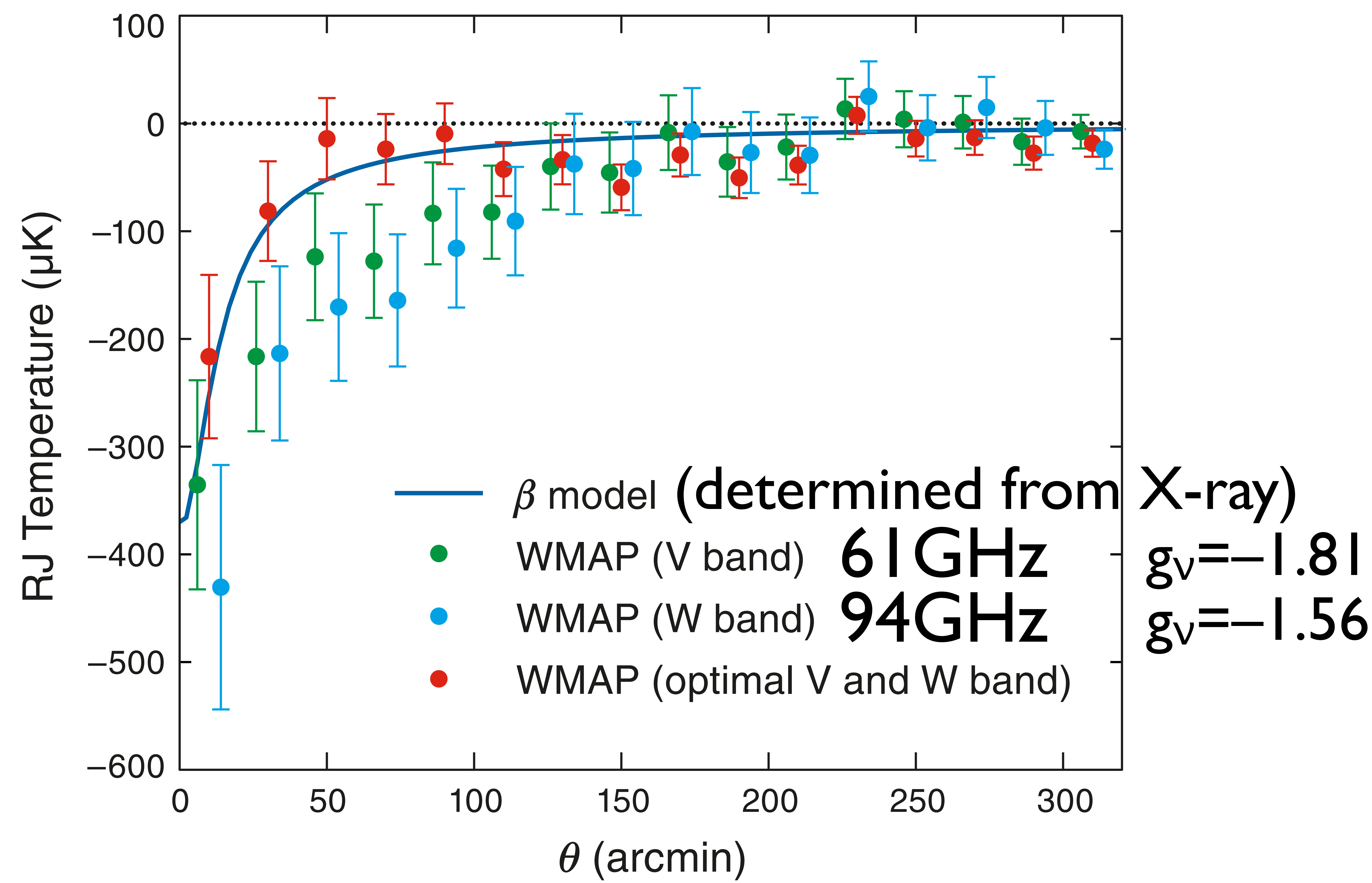
# Where are clusters?



# 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)




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

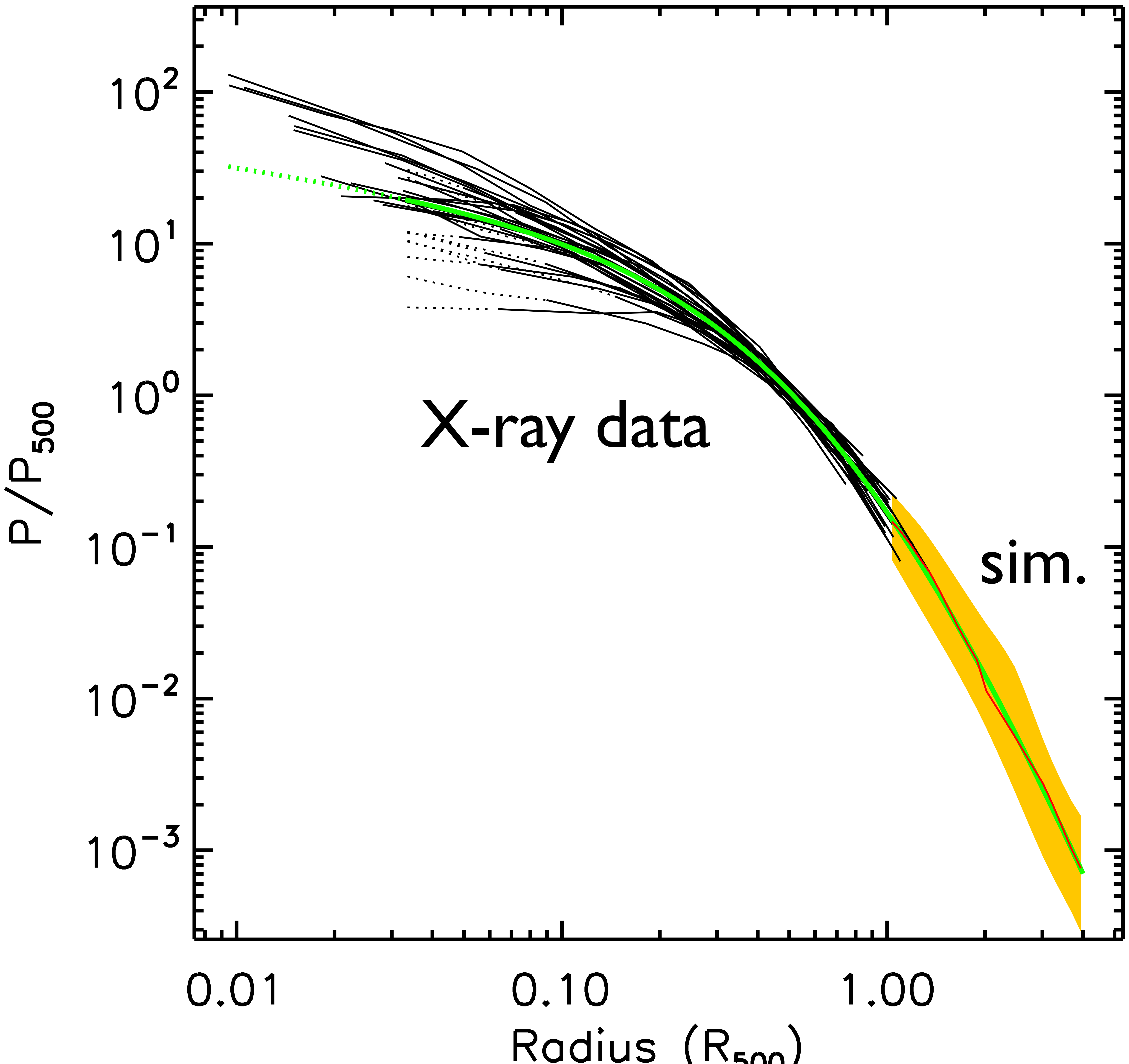
# A Question

- 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

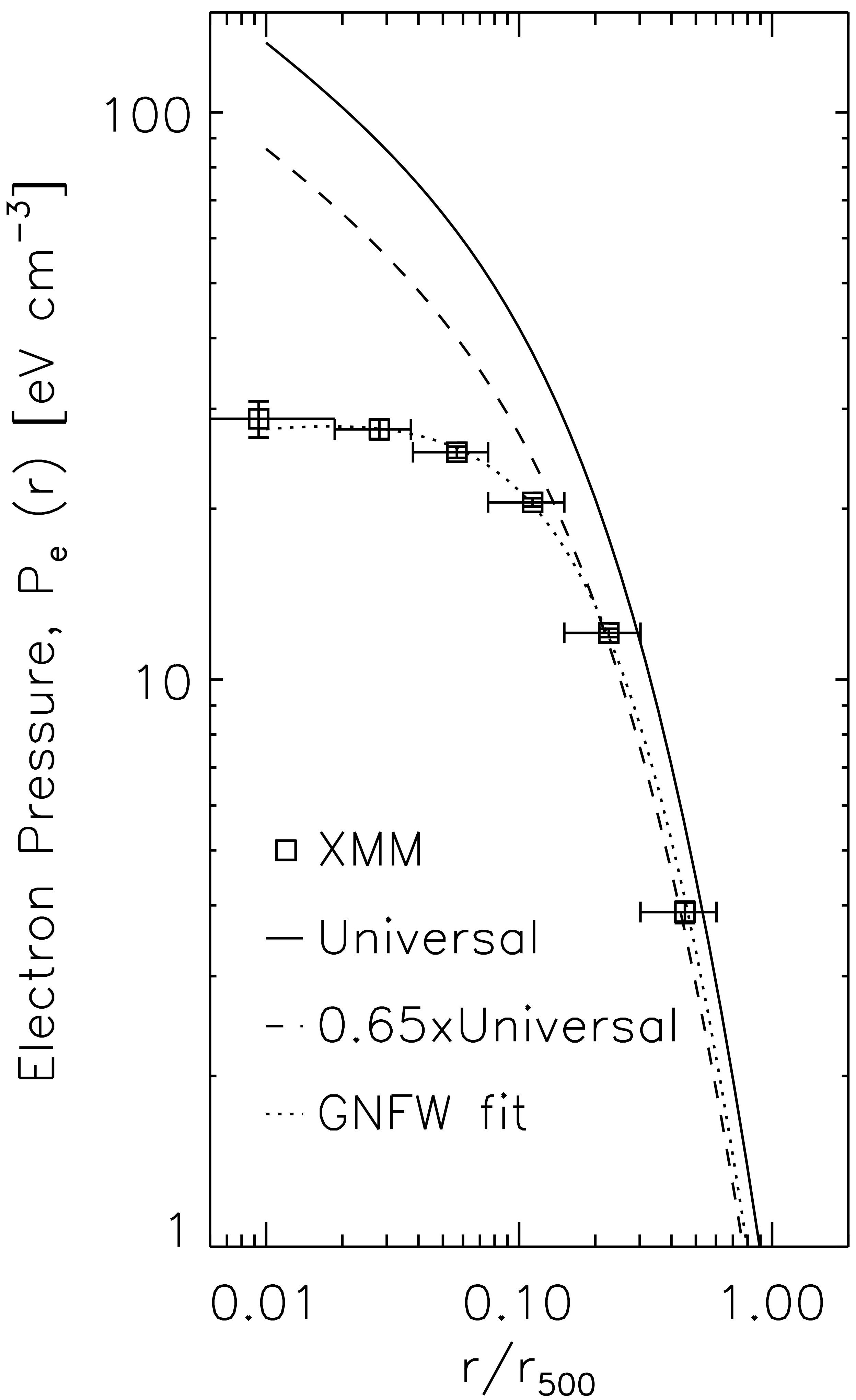
- A fitting formula (*motivated by hydrodynamical simulations*) for the average electron pressure profile as a function of the cluster mass ($M_{500}$), derived from 33 nearby ($z<0.2$) clusters (REXCESS sample).

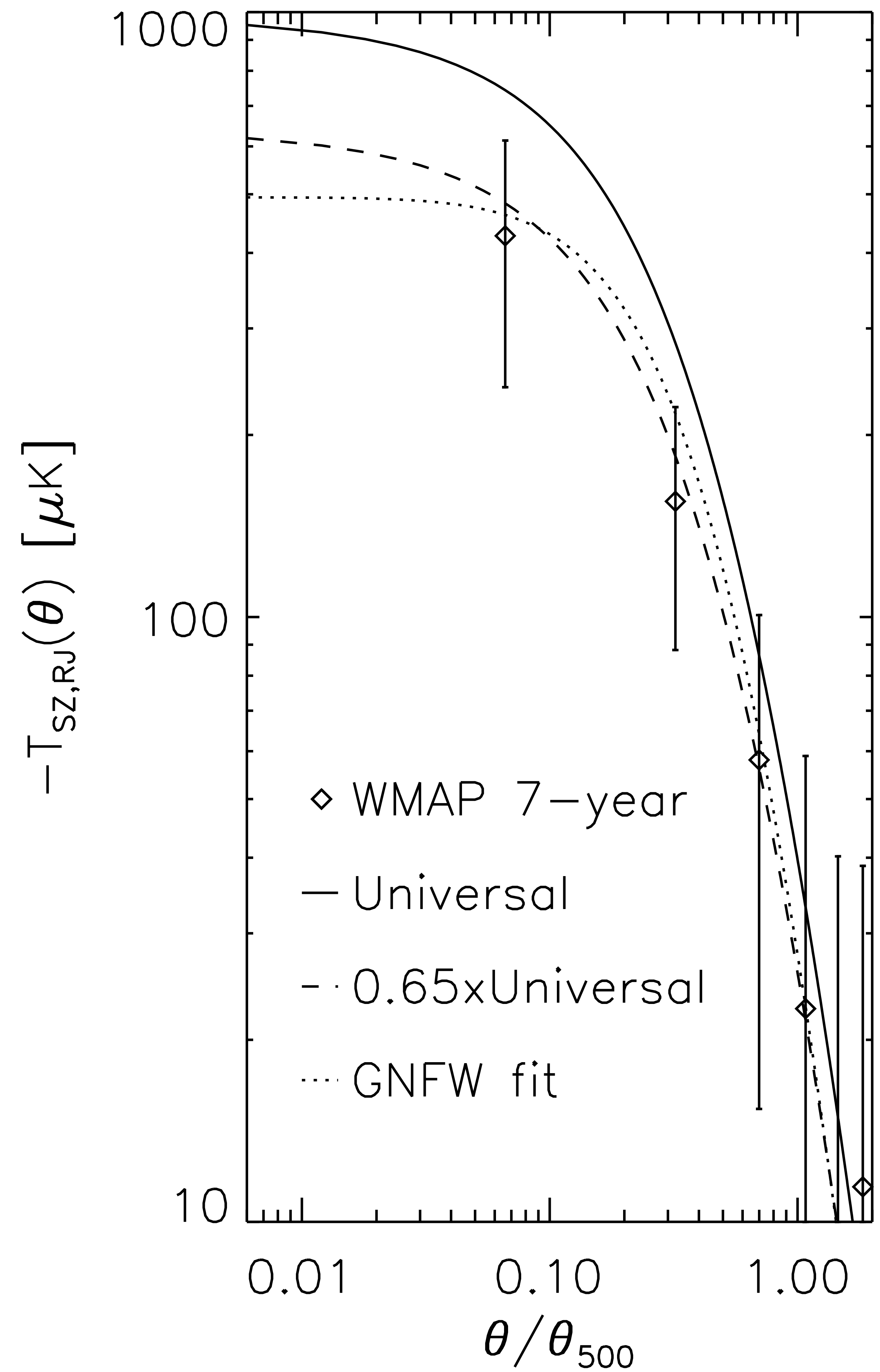
# Arnaud et al. Profile




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

# Coma Data vs Arnaud



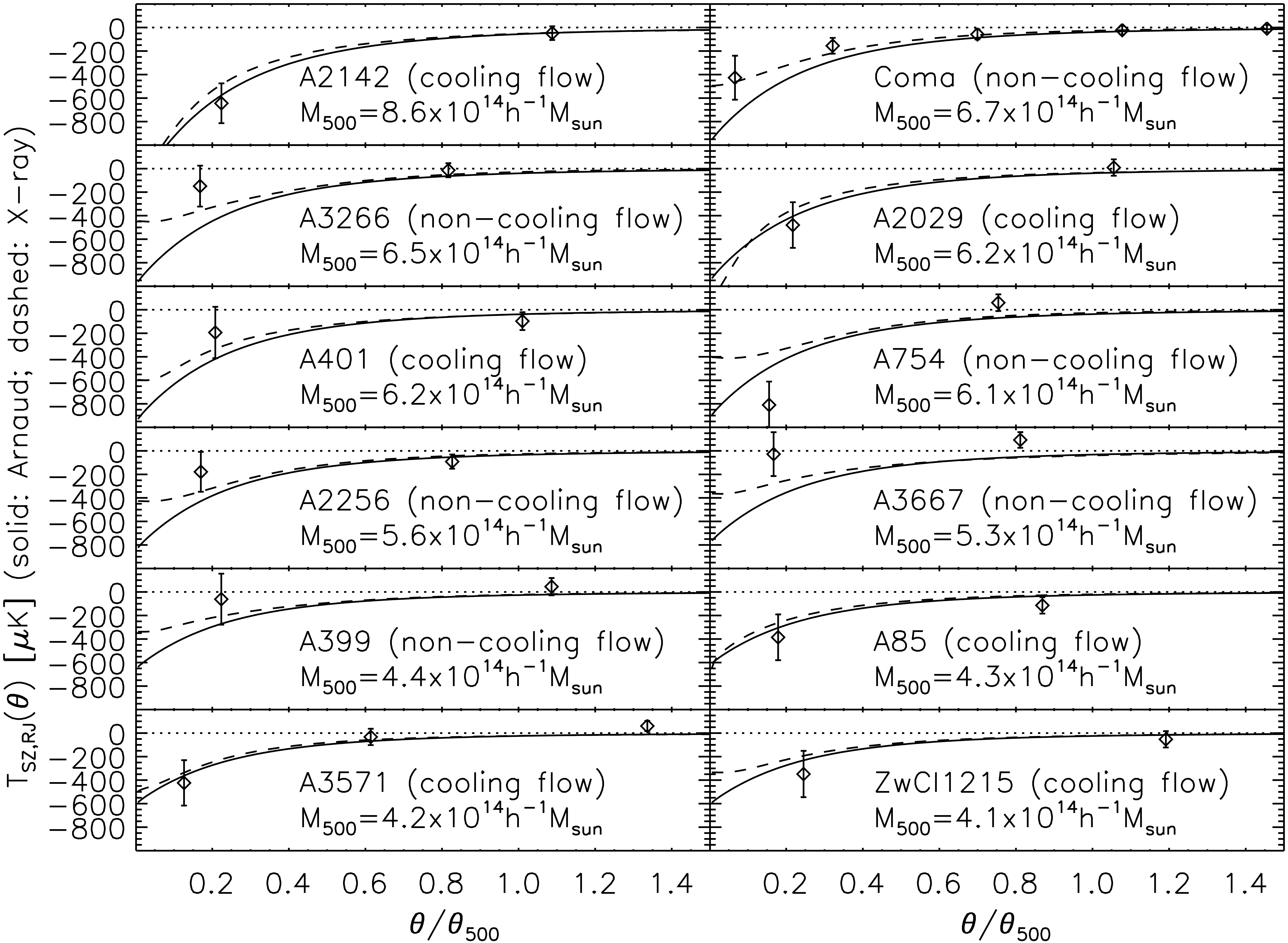

The X-ray data (XMM) are provided by A. Finoguenov.

- $M_{500}=6.6\times10^{14}h^{-1}M_{sun}$ 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 |
|---|---|---|---|
| $6 \leq M_{500} < 9$ | 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.

# Low-SZ: Signature of mergers?

| Mass Range[a] | # of clusters | X-ray Data | Model |
|---|---|---|---|
| $6 \leq M_{500} < 9$ | 5 | $0.90 \pm 0.16$ | $0.73 \pm 0.13$ |
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[a] In units of $10^{14}\ h^{-1}\ M_{\odot}$. Coma is not included.

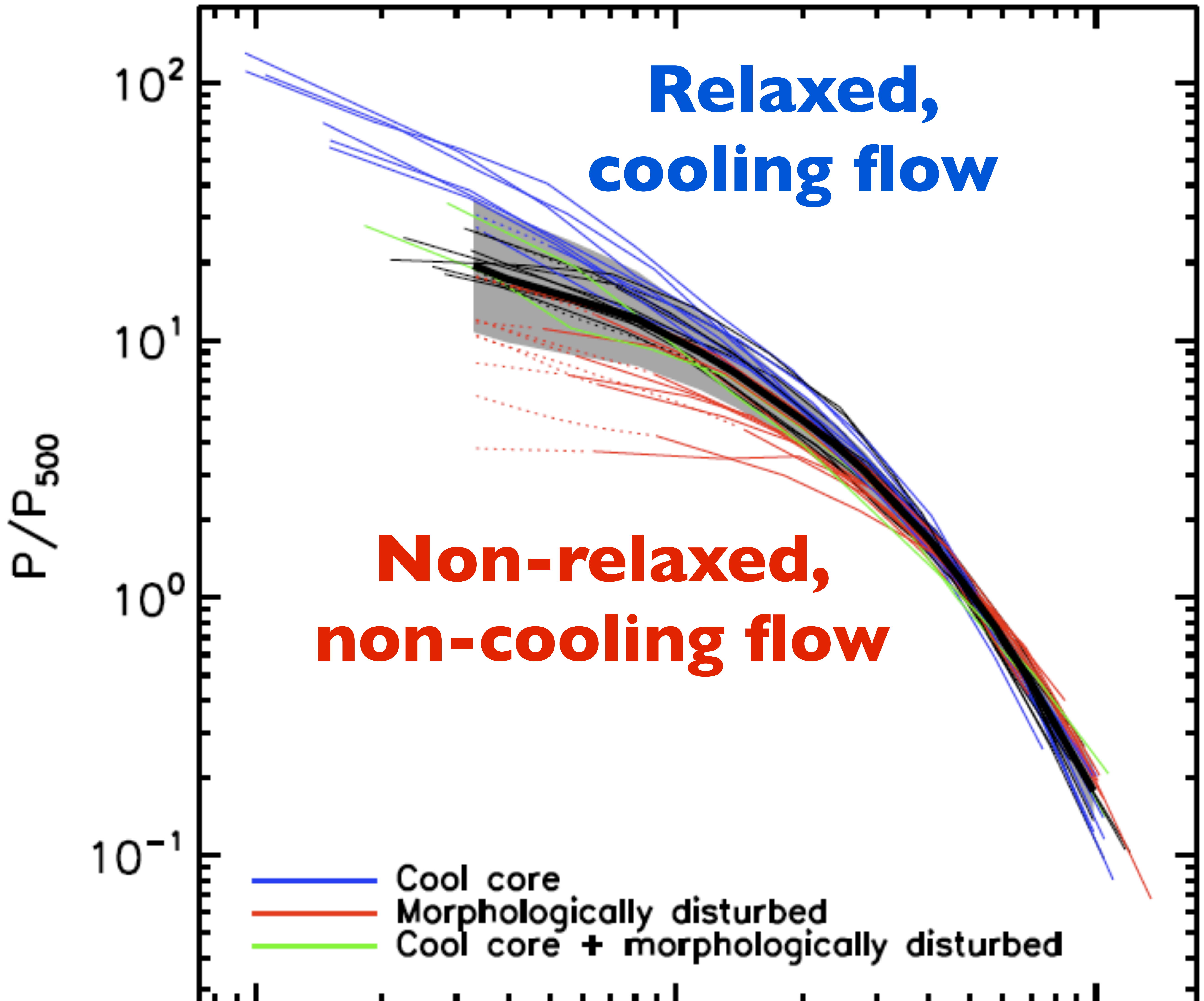
d: ALL of "cooling flow clusters" are relaxed clusters.

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

# SZ: Main Results

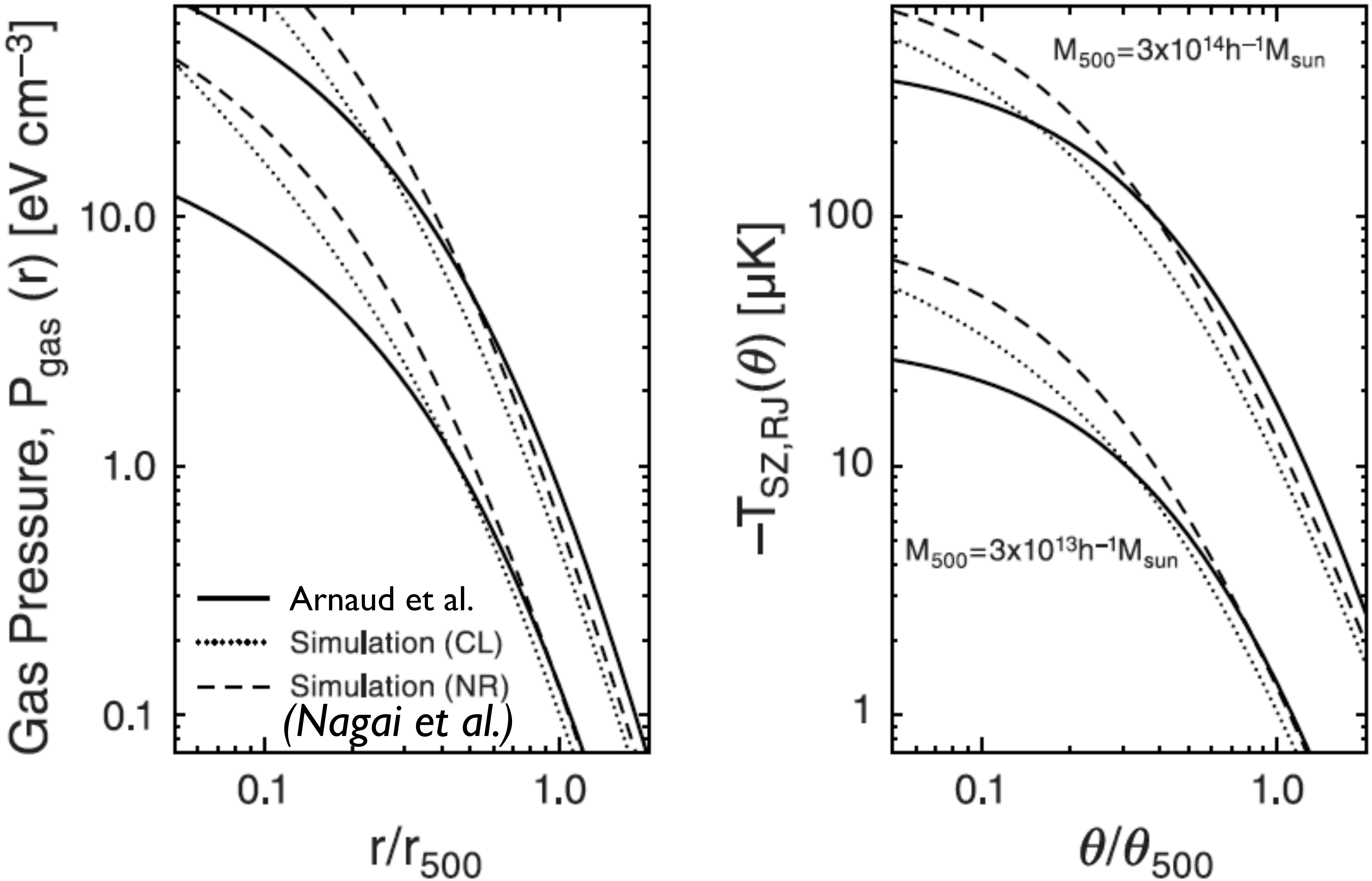
- Arnaud et al. profile systematically overestimates the electron pressure! (Arnaud et al. profile is **ruled out** at 3.2$\sigma$).
- But, the X-ray data on the *individual* clusters agree well with the SZ measured by WMAP.
- Reason: Arnaud et al. did not distinguish between relaxed (CF) and non-relaxed (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.

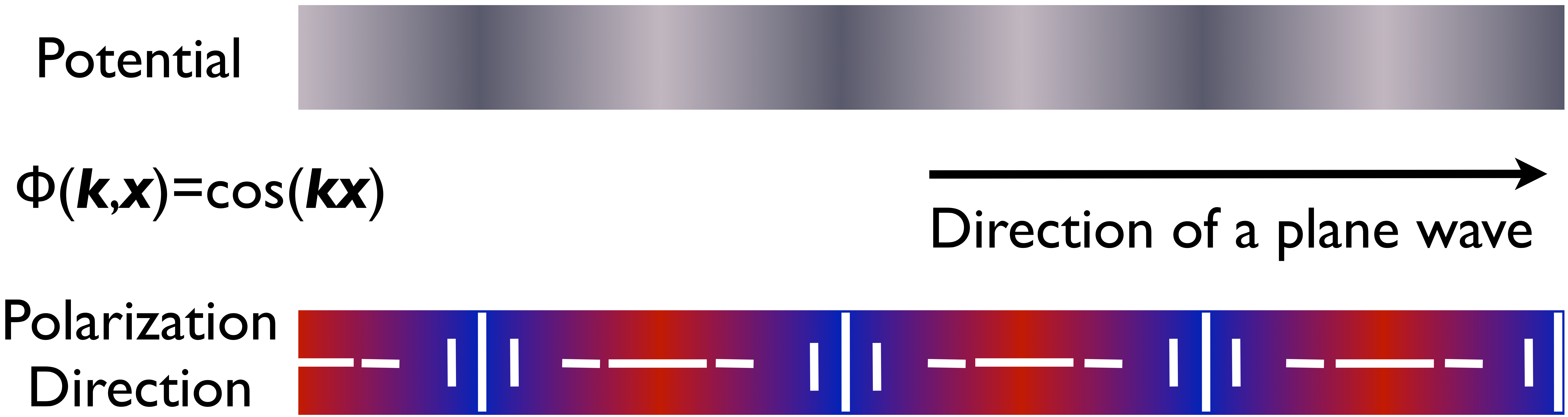
# Theoretical Models



# Summary on Cluster Results

- 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.
  - 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.
  - ***Distinguishing relaxed and non-relaxed clusters is important!***

# E-mode



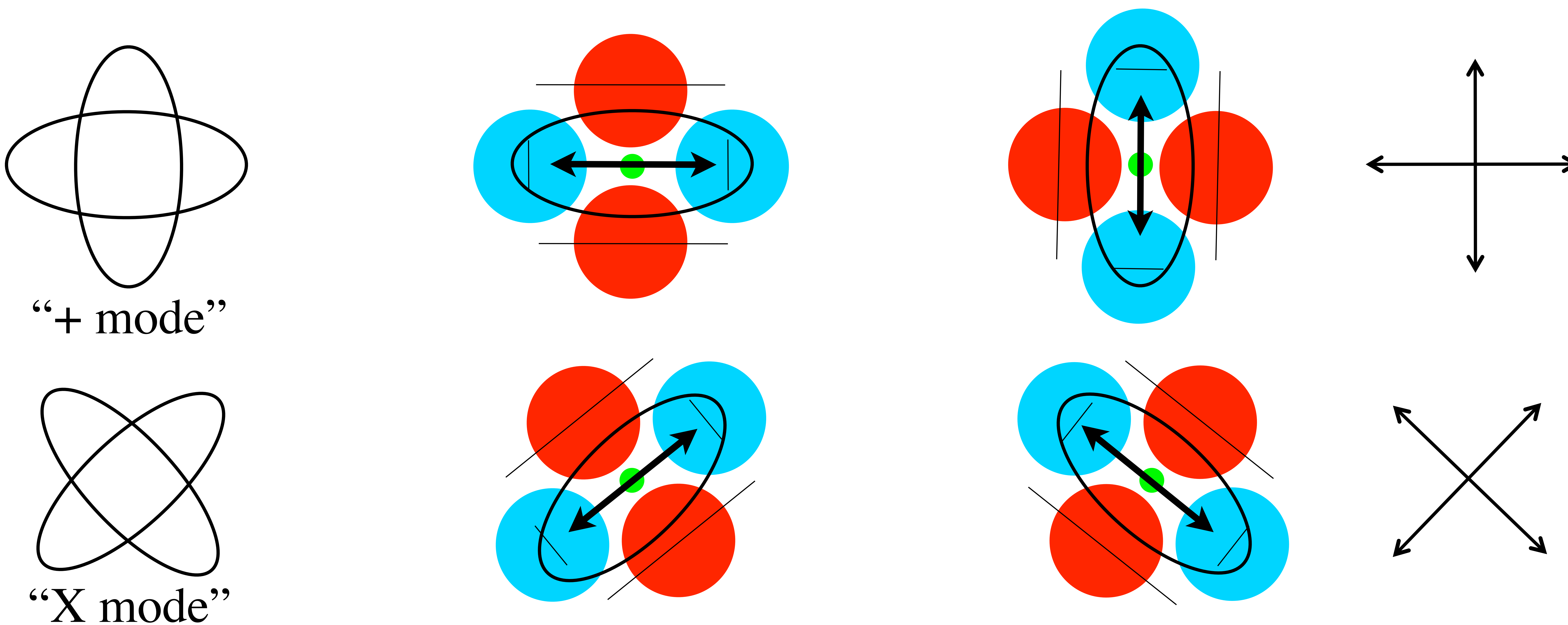

- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

# B-mode


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

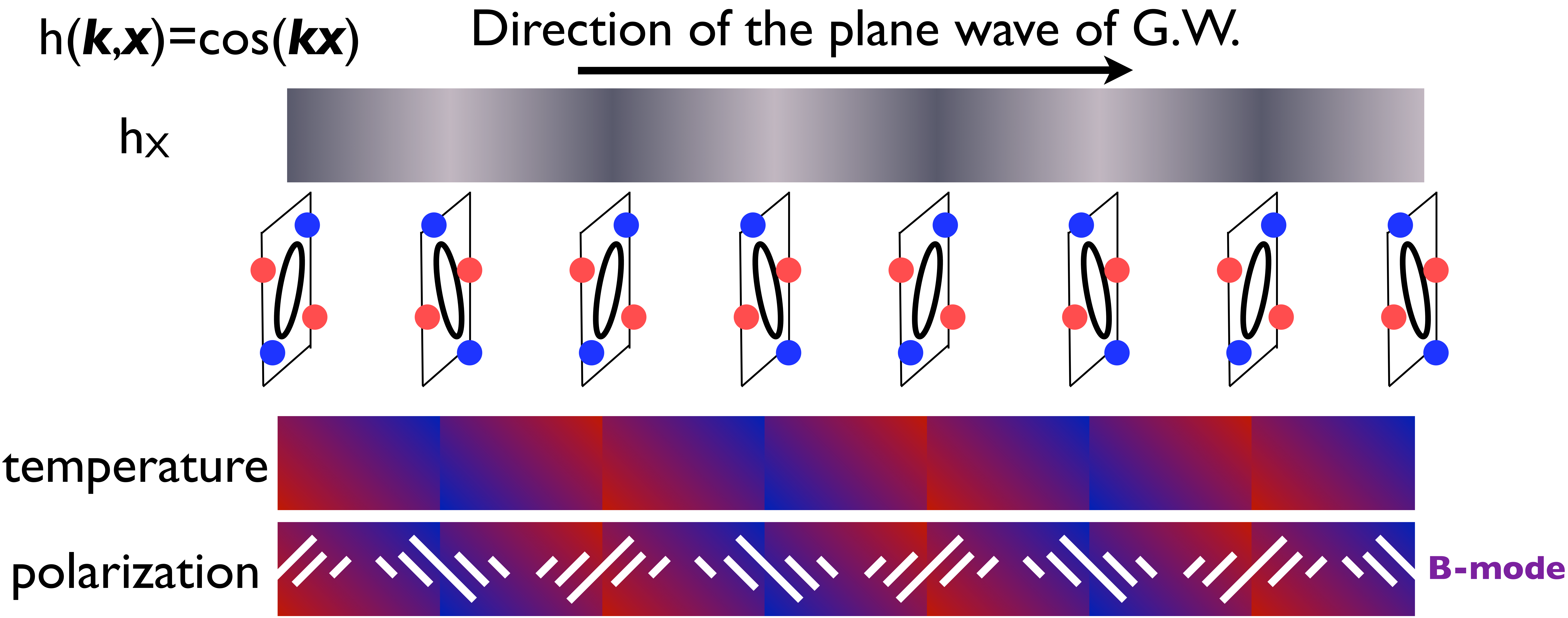
# Gravitational Waves and Quadrupole

- Gravitational waves stretch space with a quadrupole pattern.



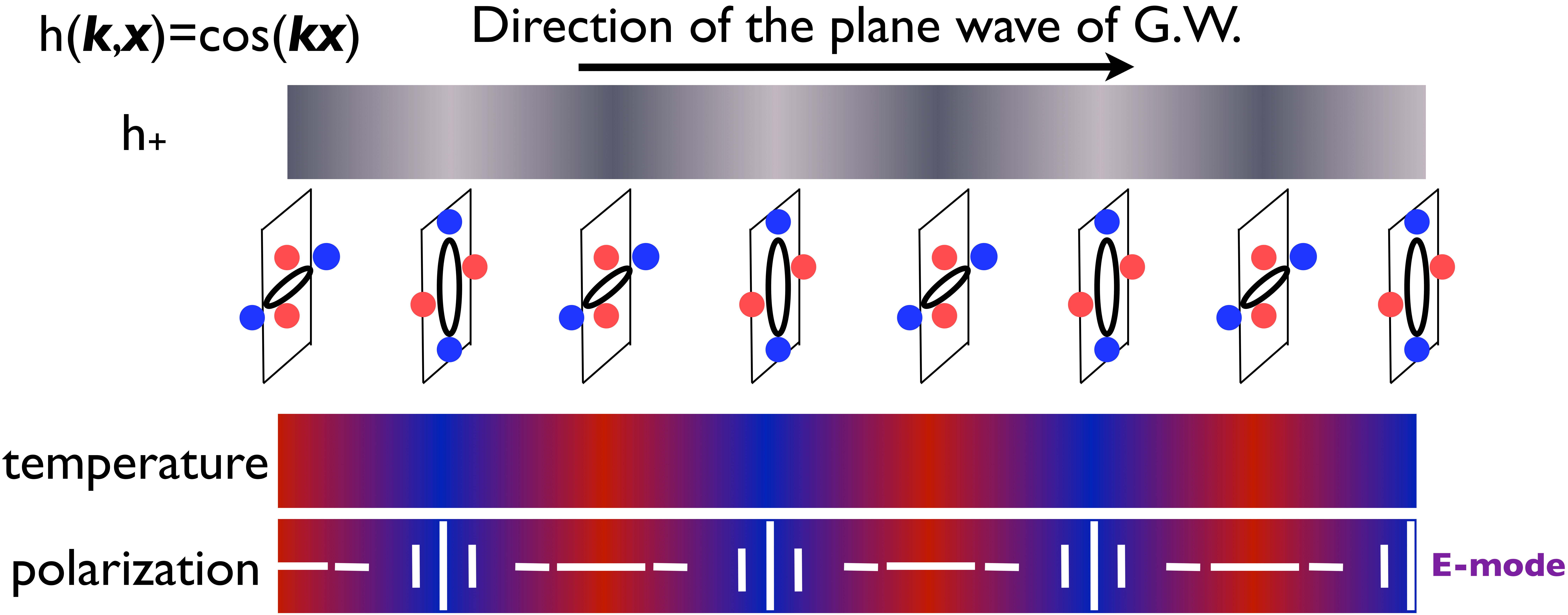
# Quadrupole from G.W.

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




- B-mode polarization generated by $h_X$

# Quadrupole from G.W.




- E-mode polarization generated by $h_+$