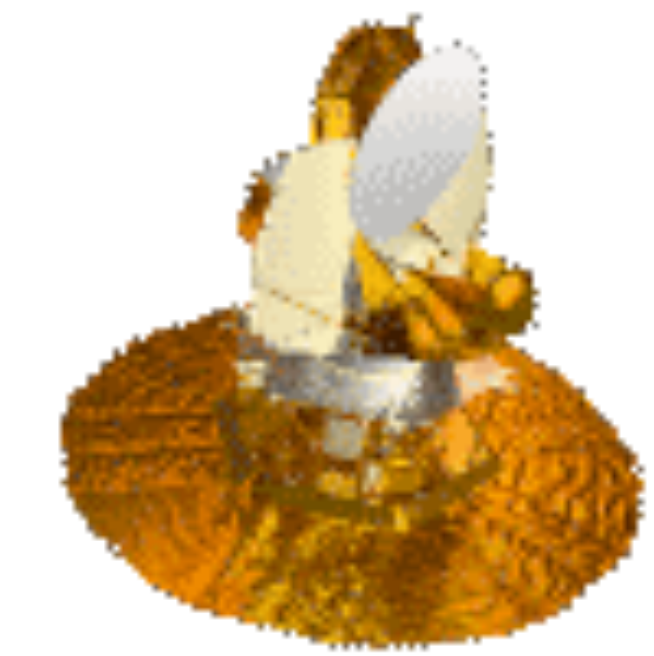


The **7**-Year *WMAP* Observations: Cosmological Interpretation

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)
Astronomy Seminar, University of Pennsylvania, October 20, 2010

WMAP at Lagrange 2 (L2) Point

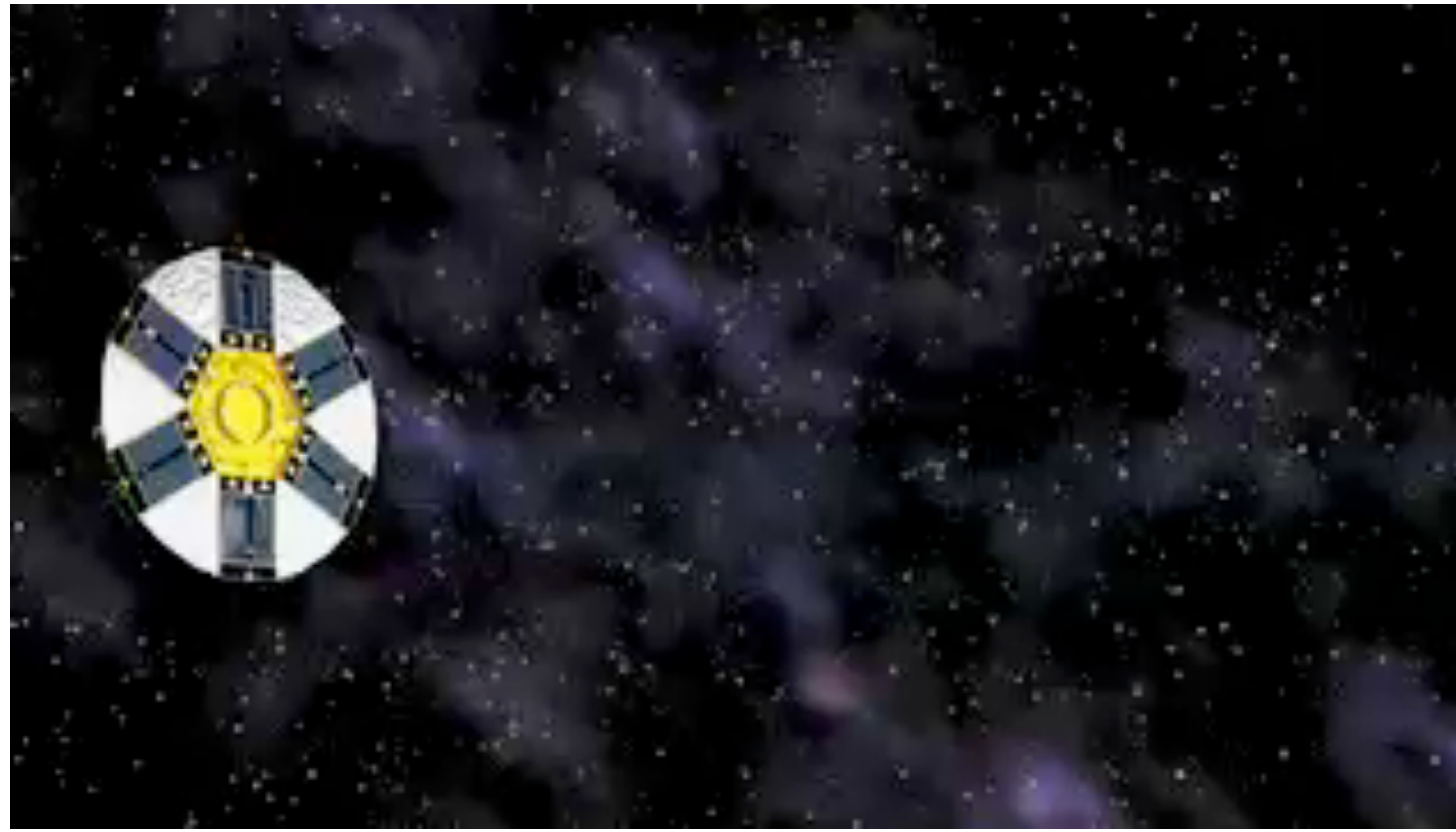
June 2001:
WMAP launched!

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

- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright
- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
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- N. Odegard
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- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta
- K.M. Smith
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- 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

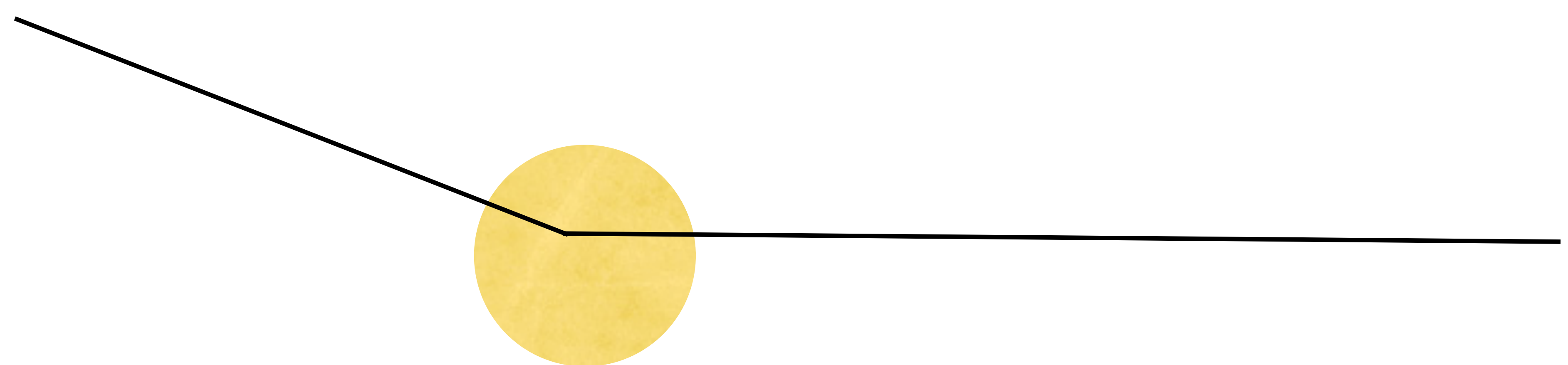
Talk Plan

- Since I was informed that some of you are interested in our results on clusters of galaxies, I will change the order of slides, and first talk about the cluster results, and then talk about the new cosmology results from the WMAP 7-year data.

- I will touch on my new thoughts on non-Gaussianity (four-point function) at the end of the talk (because some of you may be interested in this topic), but I may not have time. Either we can talk about it later, or please see **arXiv:1003.6097**.

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)

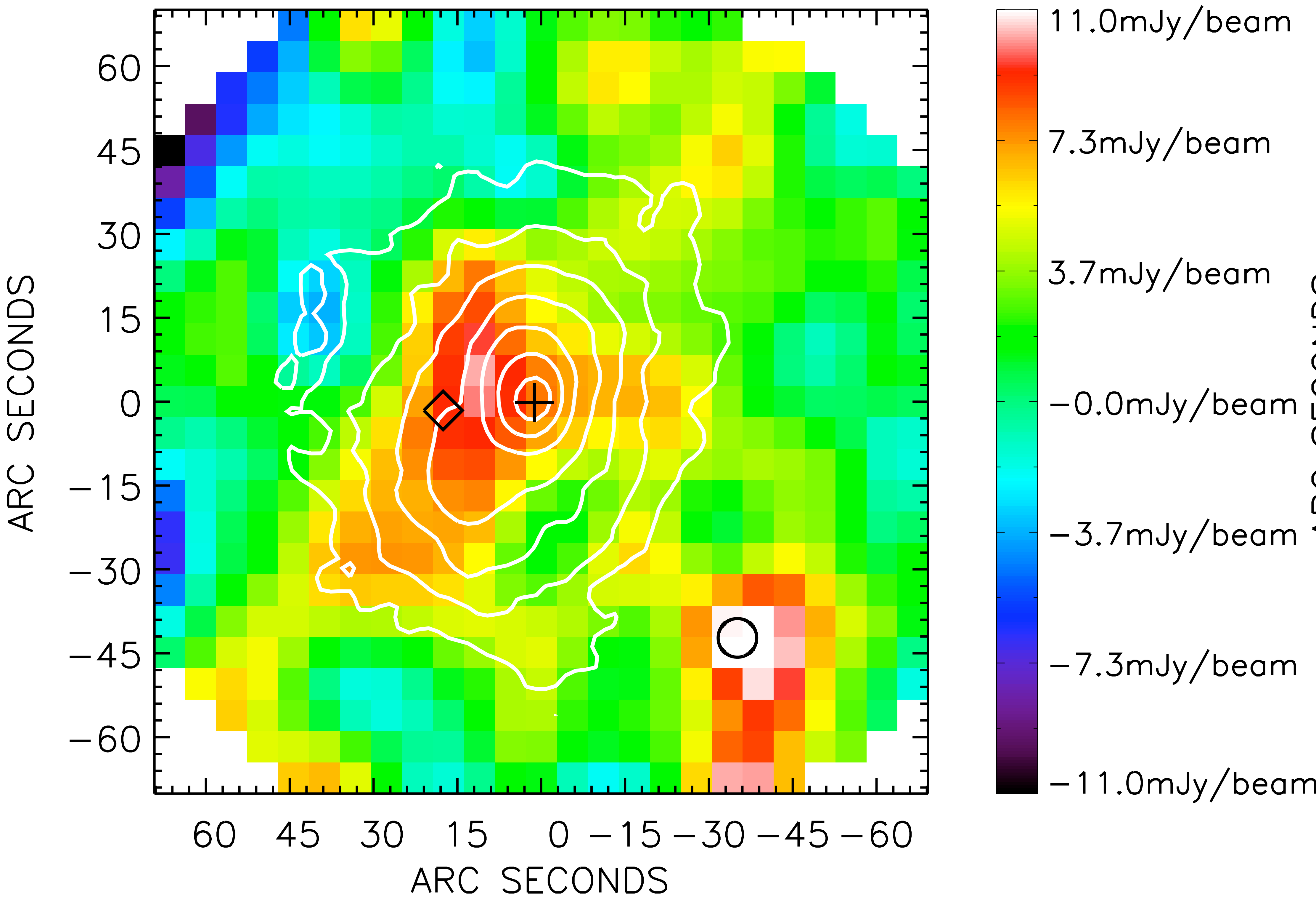
$g_\nu = -2$ ($\nu=0$); -1.91, -1.81 and -1.56 at $\nu=41$, 61 and 94 GHz

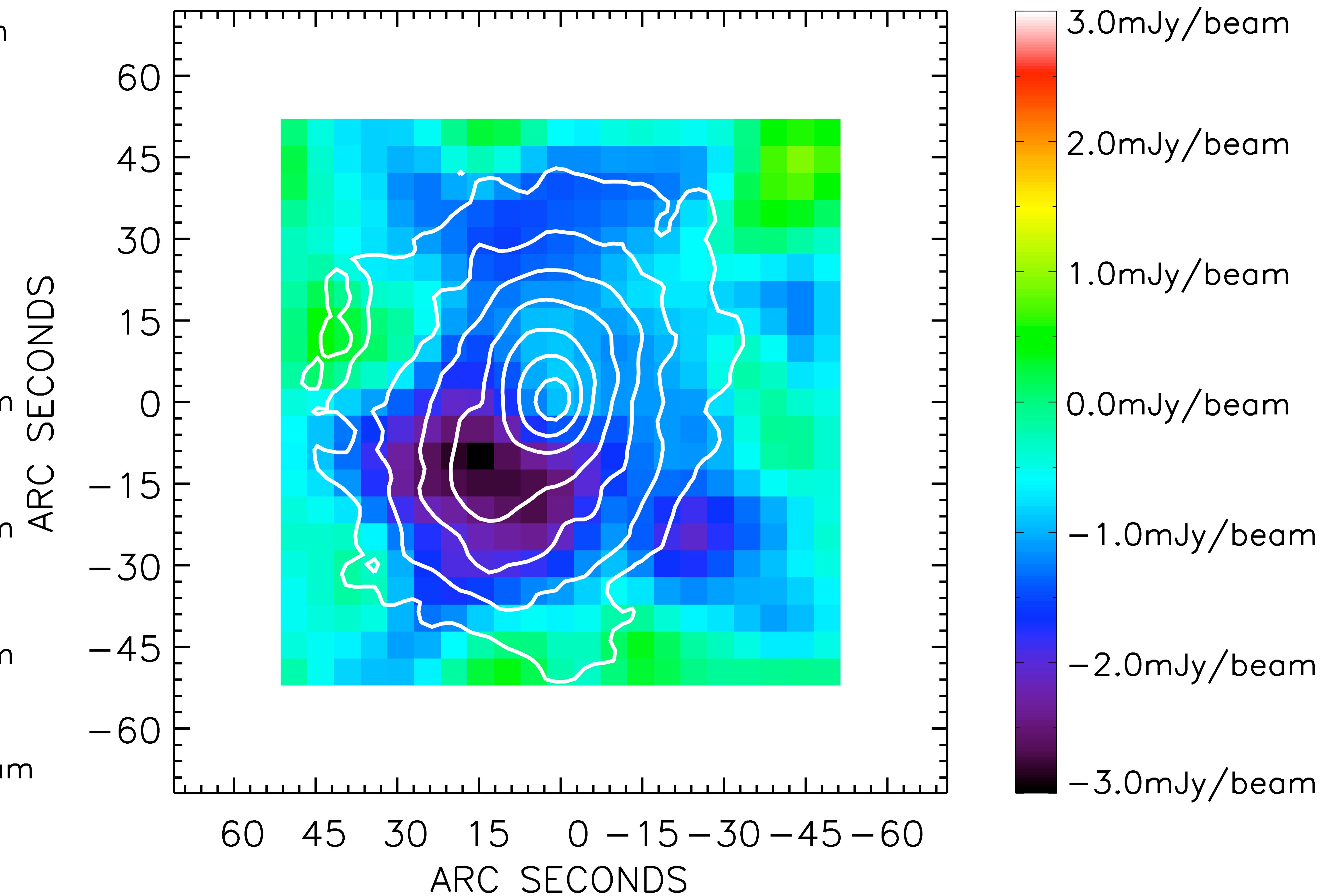
A New Result!

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.

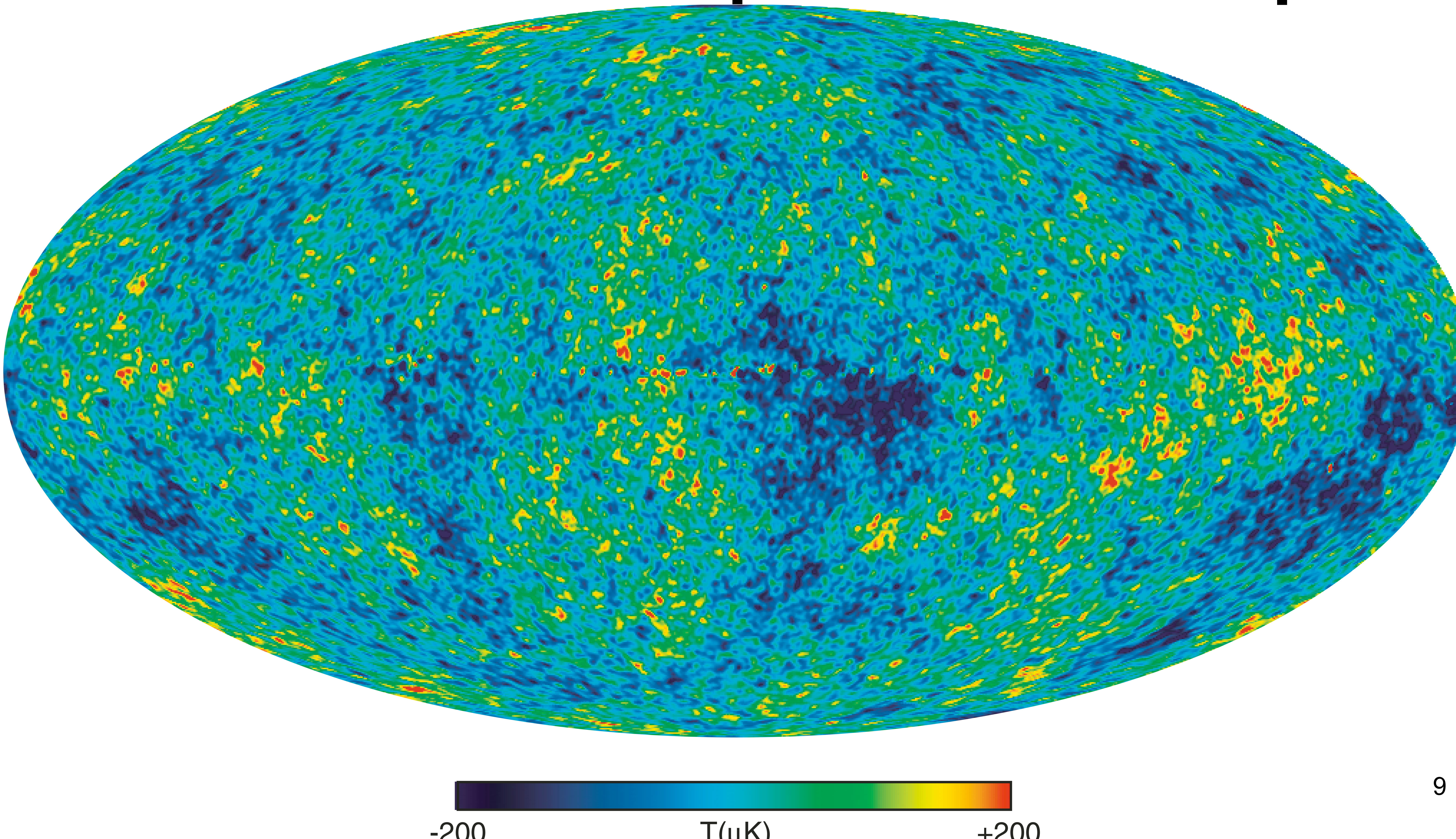
The SZ Effect: Decrement and Increment



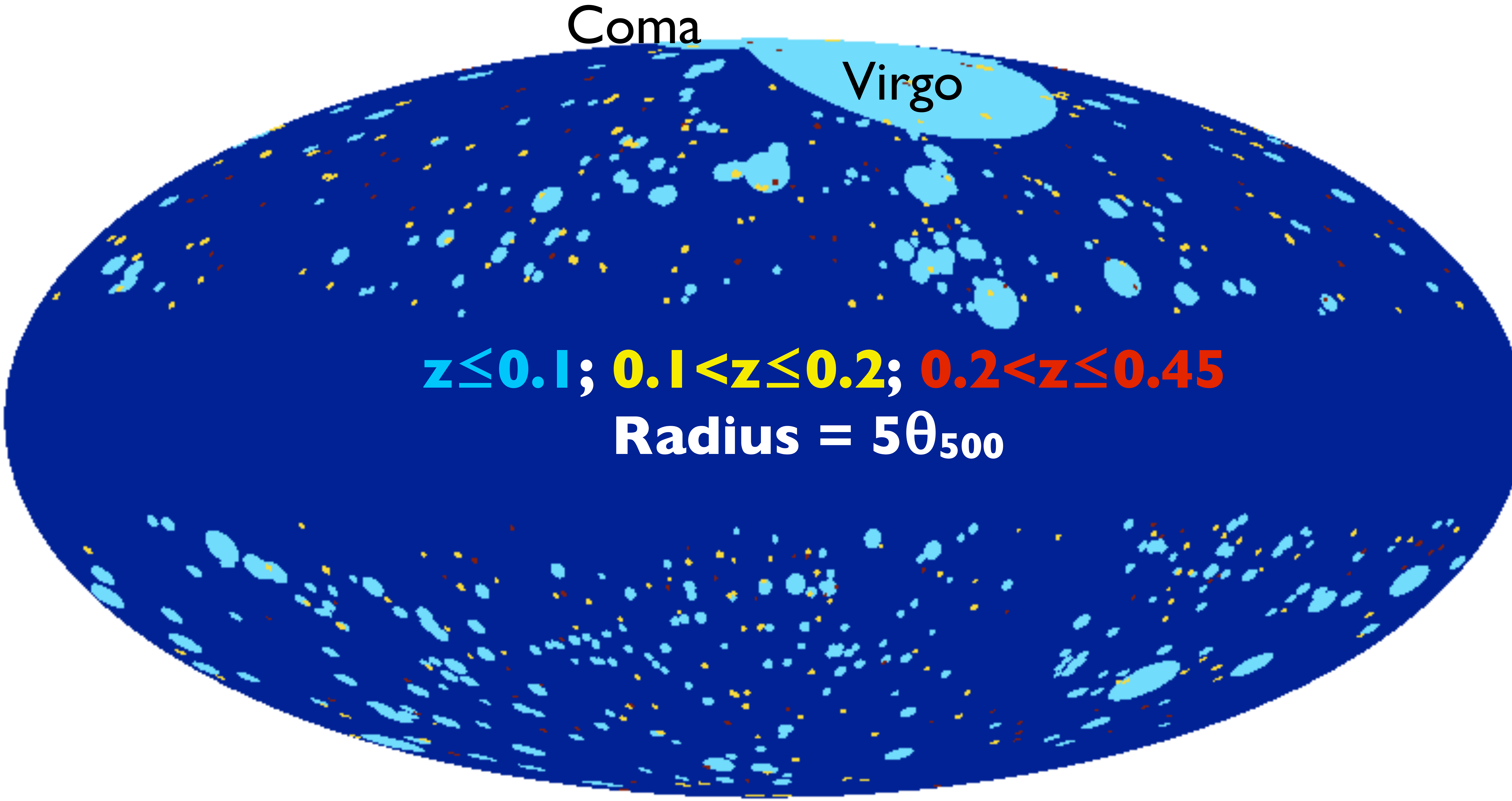


- RXJ1347-1145
  - –Left, SZ increment (350GHz, Komatsu et al. 1999)
  - –Right, SZ decrement (150GHz, Komatsu et al. 2001)

WMAP Temperature Map



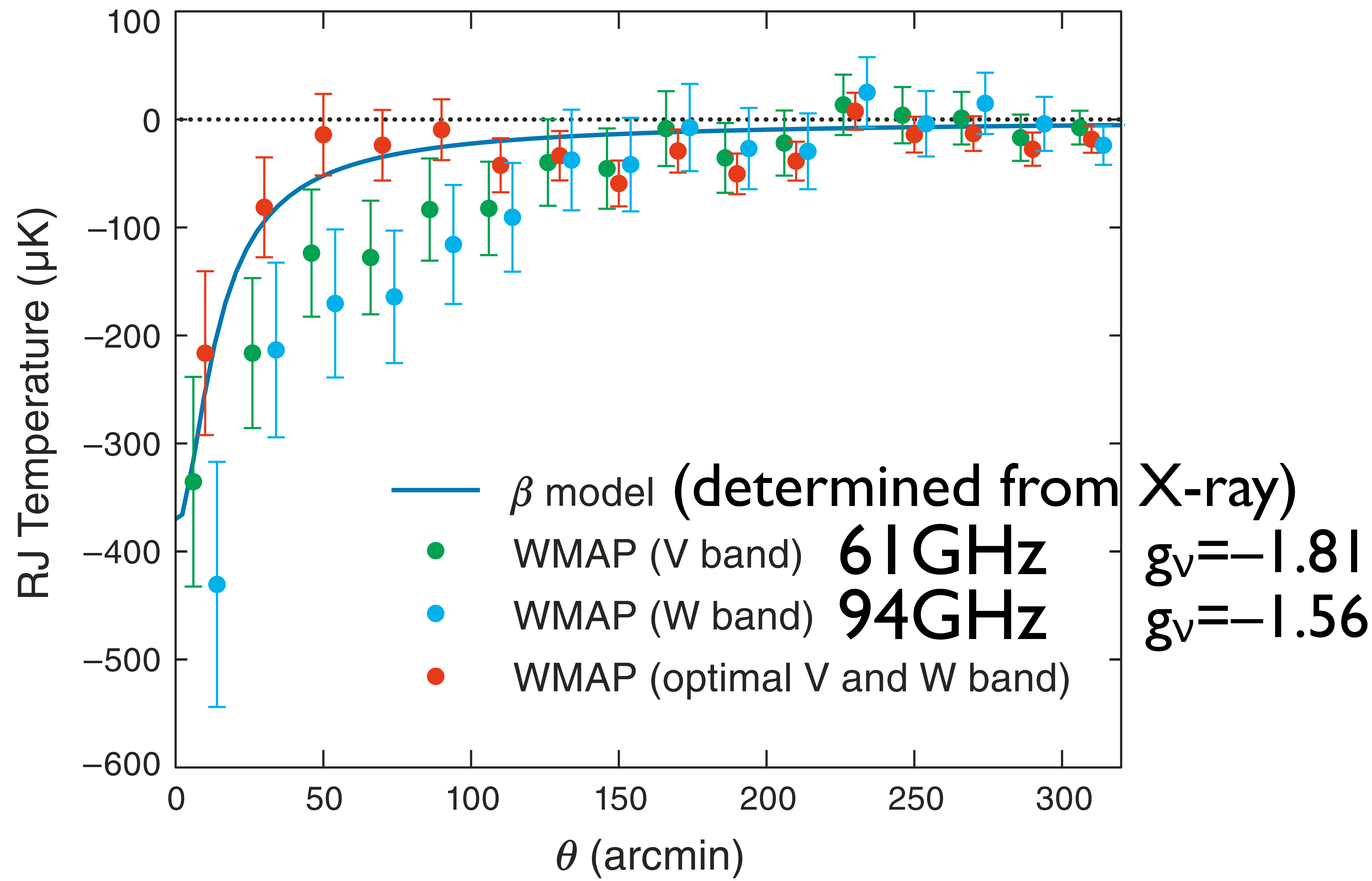
Where are clusters?



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)



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

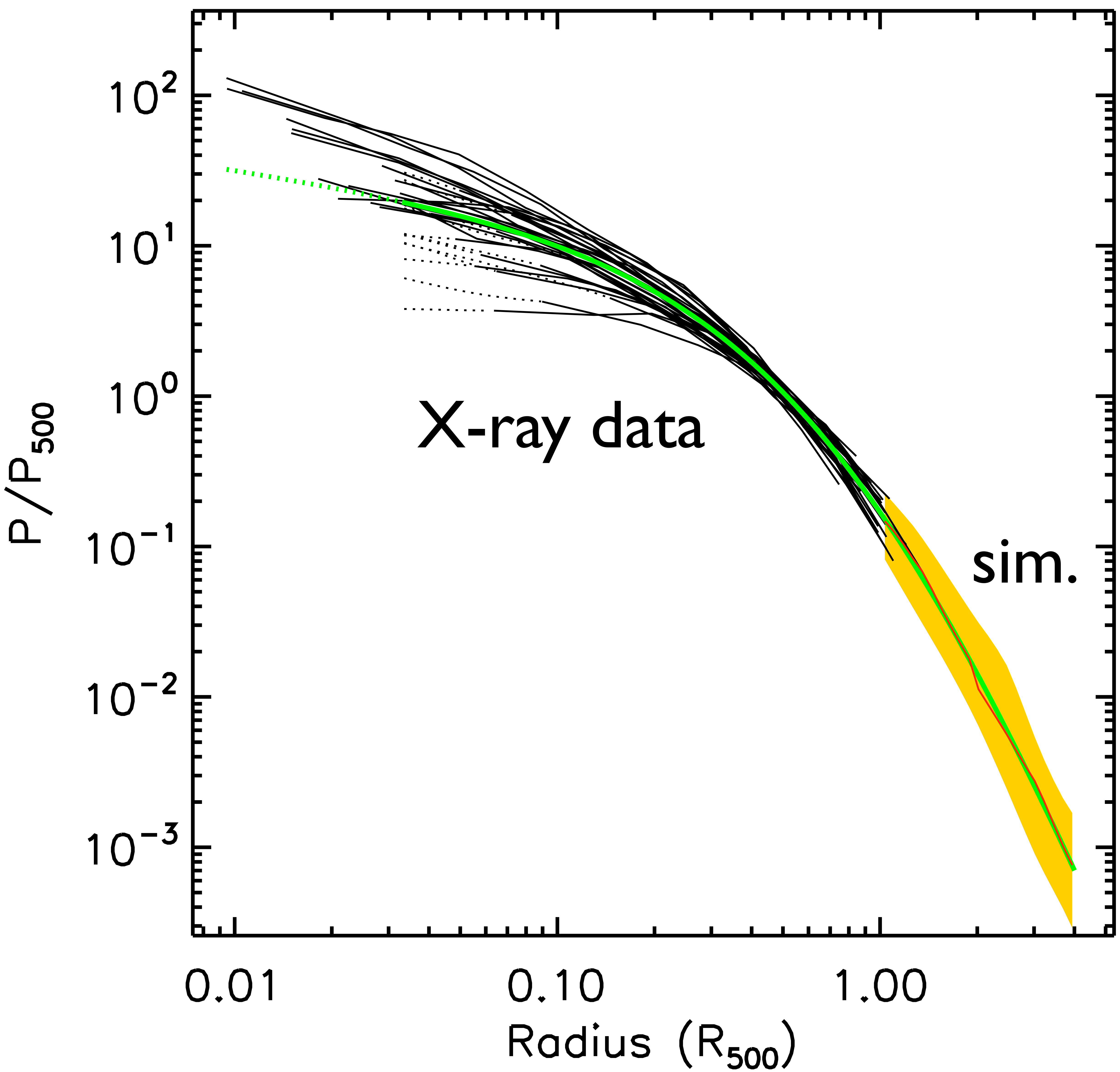
A Question

- 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

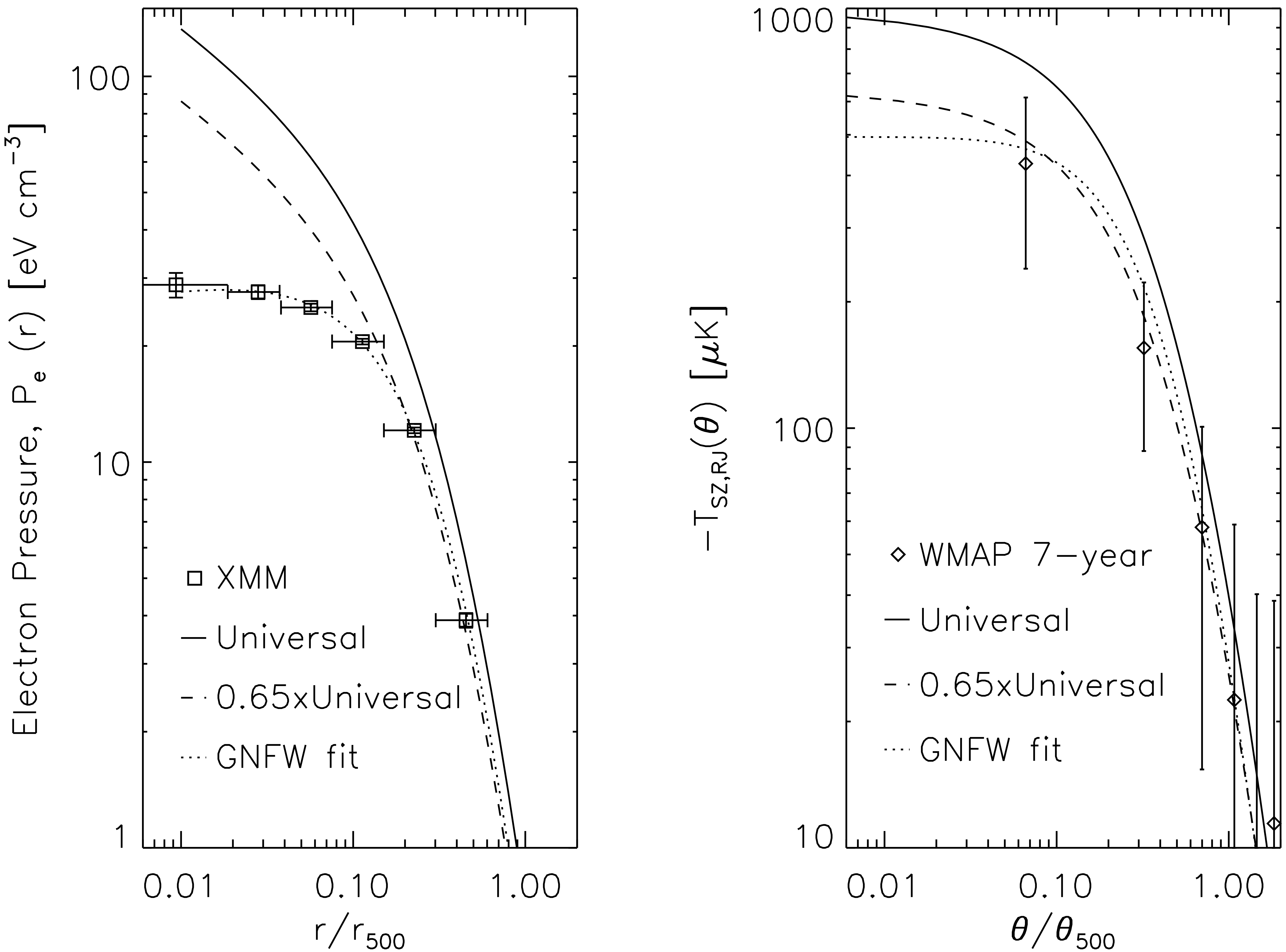
- A fitting formula (*motivated by hydrodynamical simulations*) for the average electron pressure profile as a function of the cluster mass (M_{500}), derived from 33 nearby ($z<0.2$) clusters (REXCESS sample).

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



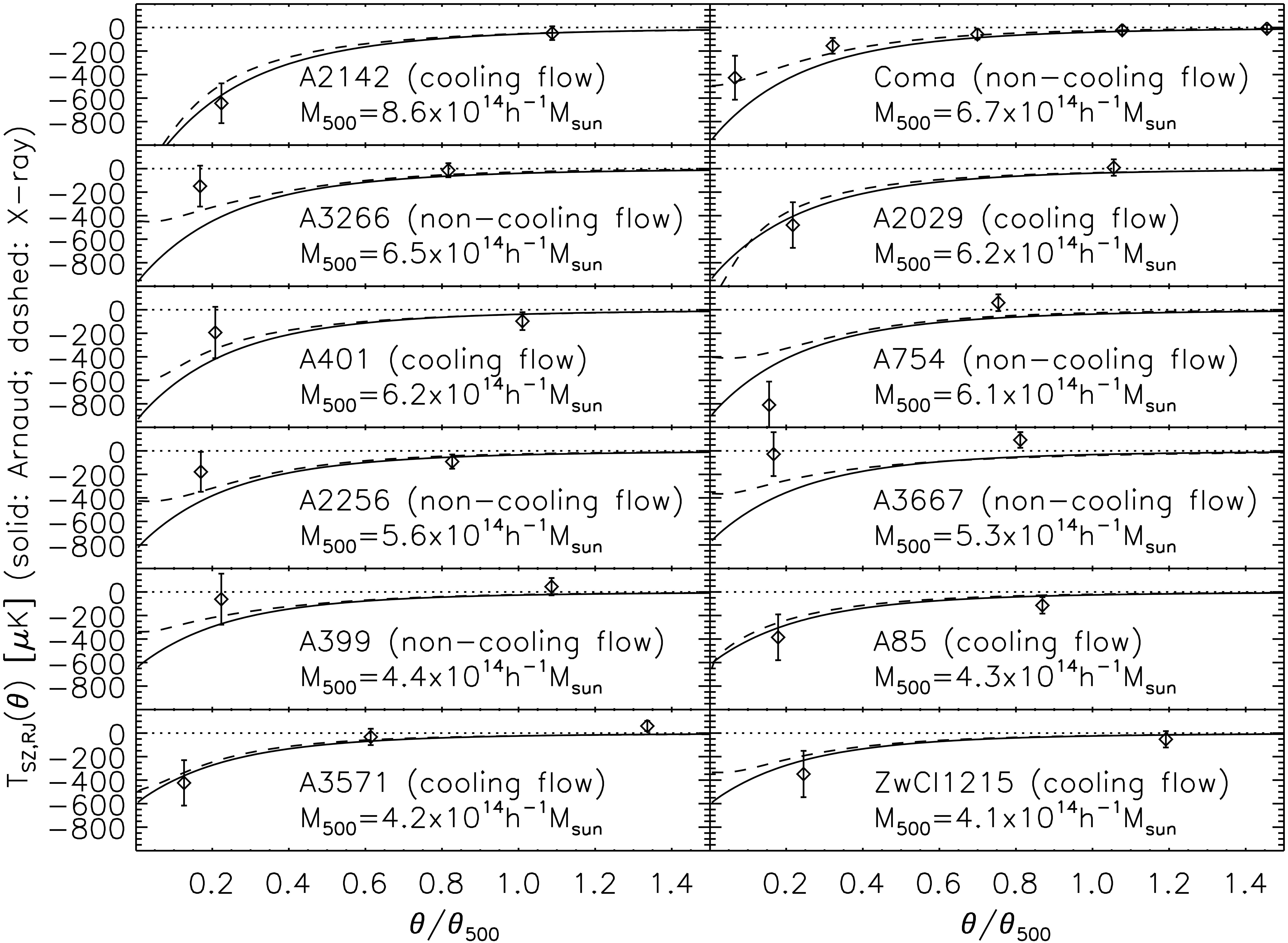
The X-ray data (XMM) are provided by A. Finoguenov.

- $M_{500}=6.6\times10^{14}h^{-1}M_{sun}$ 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 ± 0.16	0.73 ± 0.13
$4 \leq M_{500} < 6$	6	0.73 ± 0.21	0.60 ± 0.17
$2 \leq M_{500} < 4$	9	0.71 ± 0.31	0.53 ± 0.25
$1 \leq M_{500} < 2$	9	-0.15 ± 0.55	-0.12 ± 0.47
$4 \leq M_{500} < 9$	11	0.84 ± 0.13	0.68 ± 0.10
$1 \leq M_{500} < 4$	18	0.50 ± 0.27	0.39 ± 0.22
$4 \leq M_{500} < 9$			
cooling flow[d]	5	1.06 ± 0.18	0.89 ± 0.15
non-cooling flow[e]	6	0.61 ± 0.18	0.48 ± 0.15
$2 \leq M_{500} < 9$	20	0.82 ± 0.12	0.660 ± 0.095
$1 \leq M_{500} < 9$	29	0.78 ± 0.12	0.629 ± 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
$6 \le M_{500} < 9$	5	0.90 ± 0.16	0.73 ± 0.13
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[a] In units of $10^{14}\ h^{-1}\ M_{\odot}$. Coma is not included.

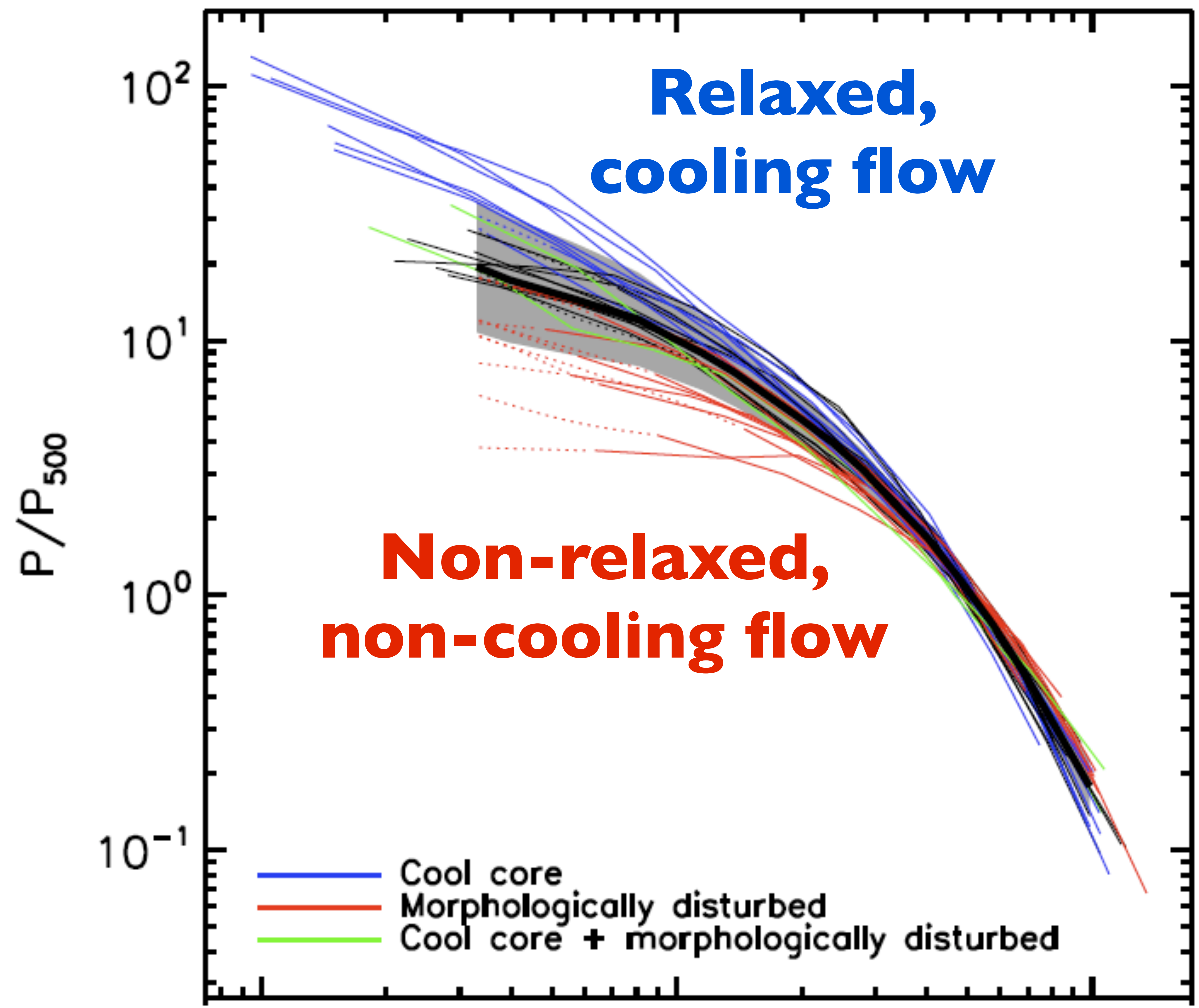
d: ALL of "cooling flow clusters" are relaxed clusters.

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

SZ: Main Results

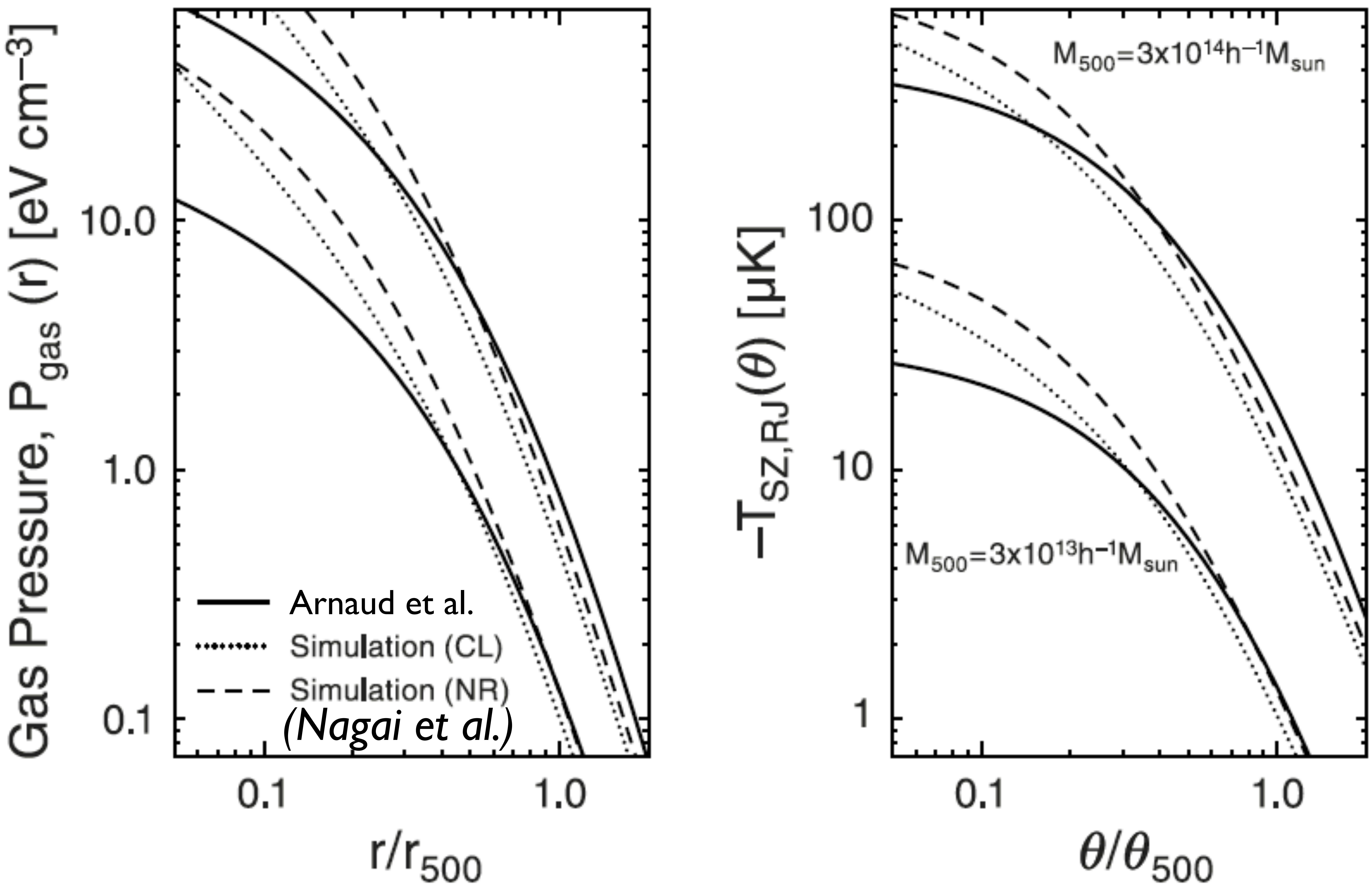
- Arnaud et al. profile systematically overestimates the electron pressure! (Arnaud et al. profile is **ruled out** at 3.2σ).
- But, the X-ray data on the *individual* clusters agree well with the SZ measured by WMAP.
- Reason: Arnaud et al. did not distinguish between relaxed (CF) and non-relaxed (non-CF)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

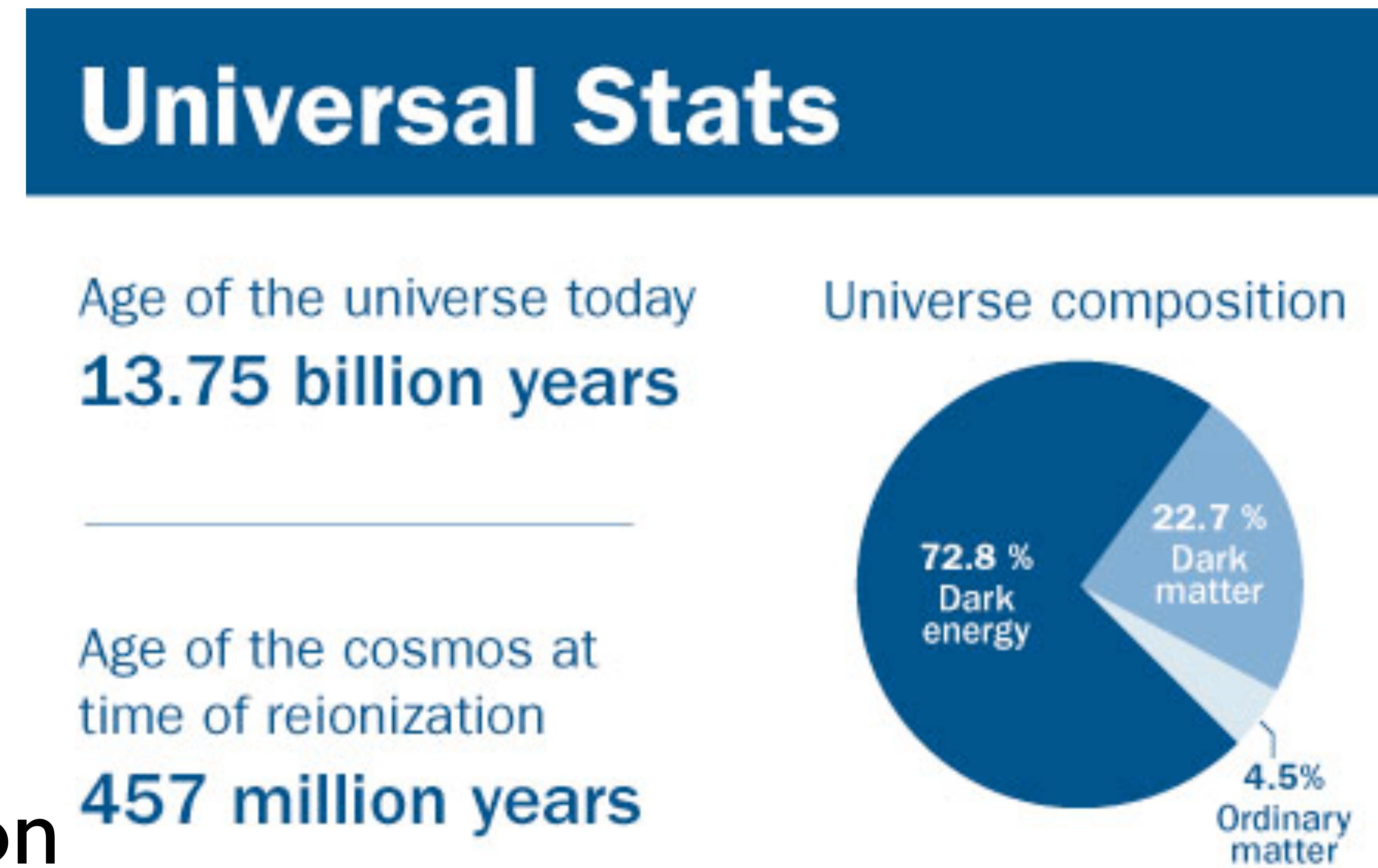


Summary on Cluster Results

- 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!***

Cosmology Update: 7-year

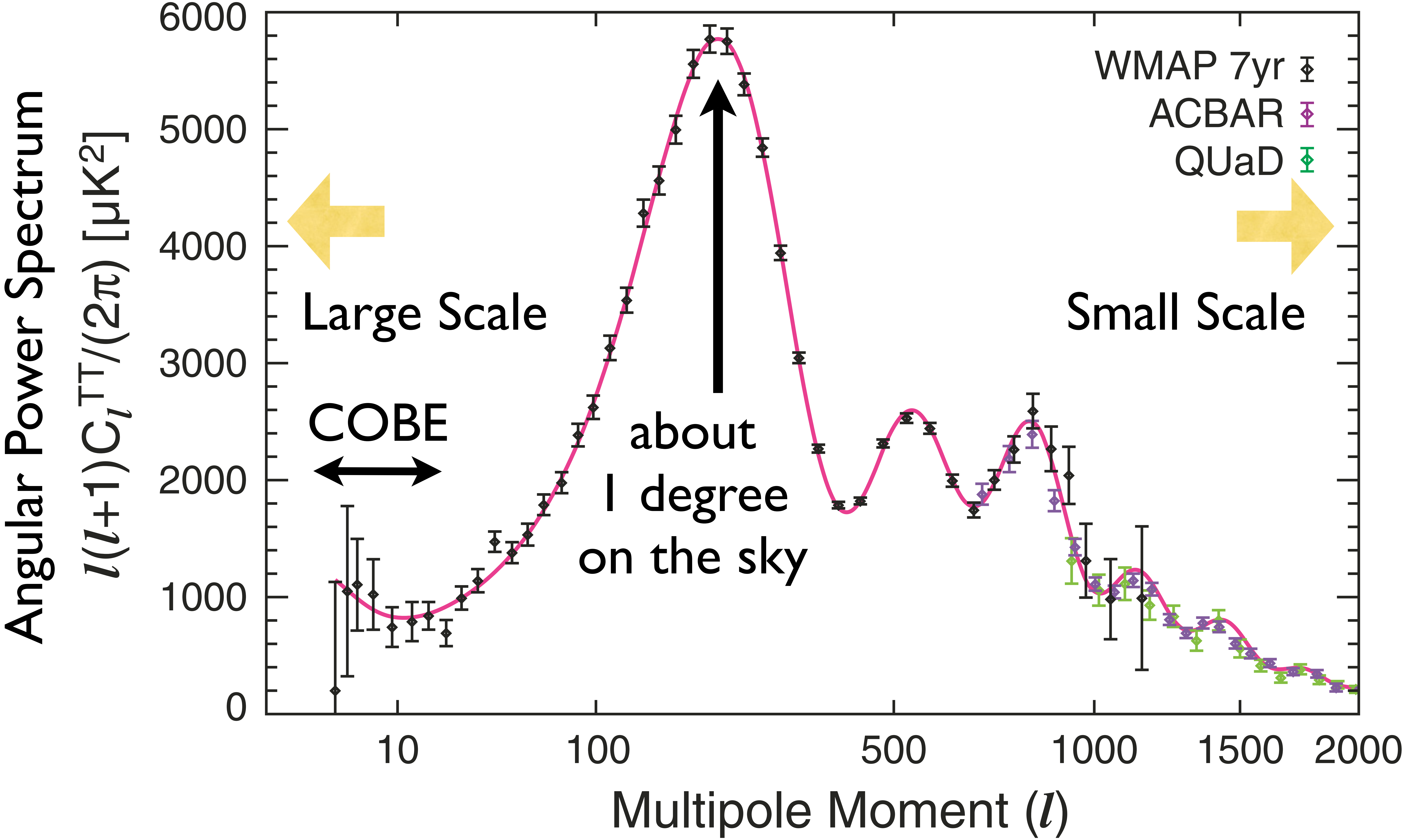
- **Standard Model**
  - H&He = 4.58% (±0.16%)
  - Dark Matter = 22.9% (±1.5%)
  - Dark Energy = 72.5% (±1.6%)
  - H_0=70.2±1.4 km/s/Mpc
  - Age of the Universe = 13.76 billion years (±0.11 billion years)



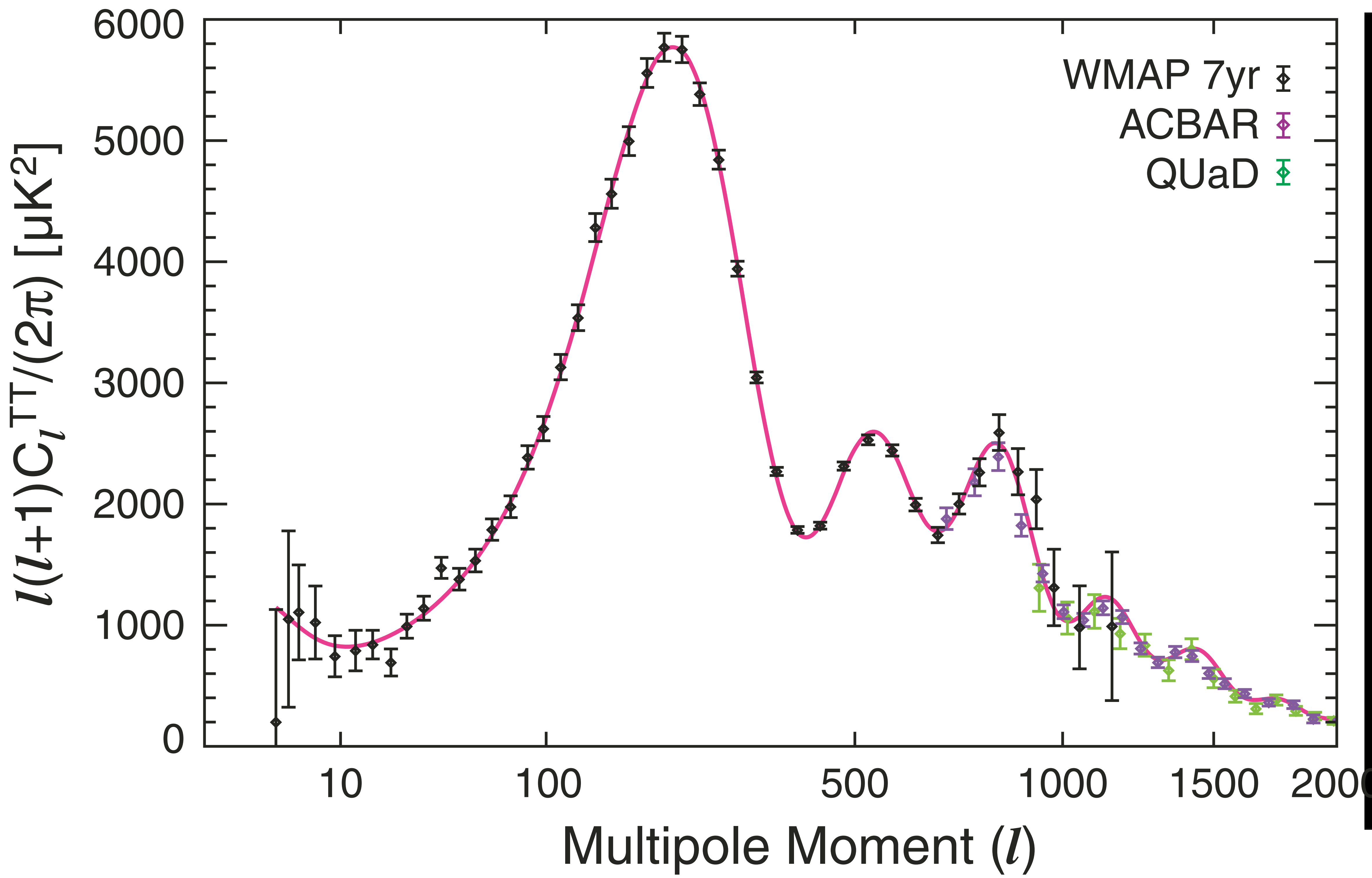
"ScienceNews" article on the WMAP 7-year results

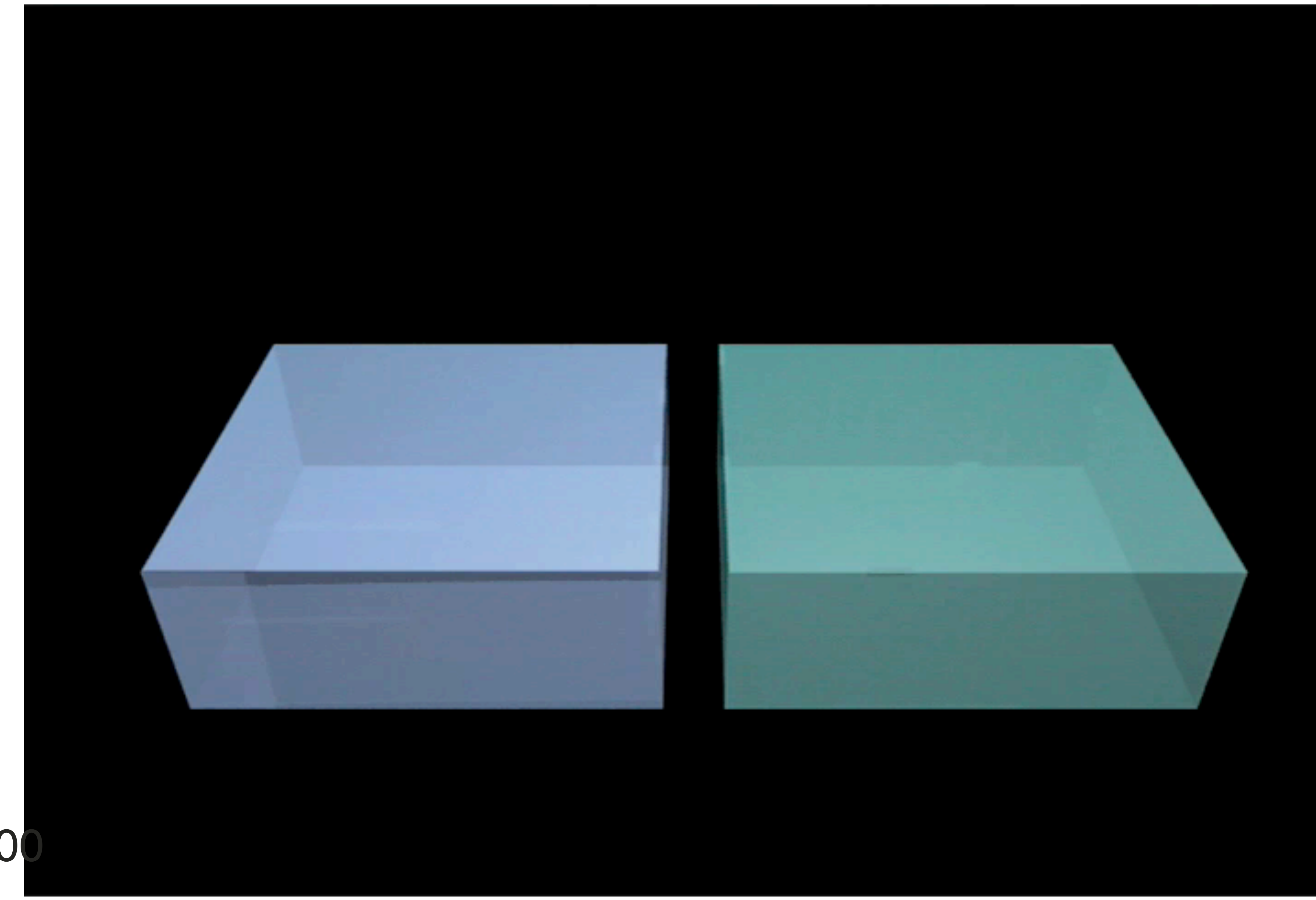
How did we obtain these numbers?

WMAP Power Spectrum



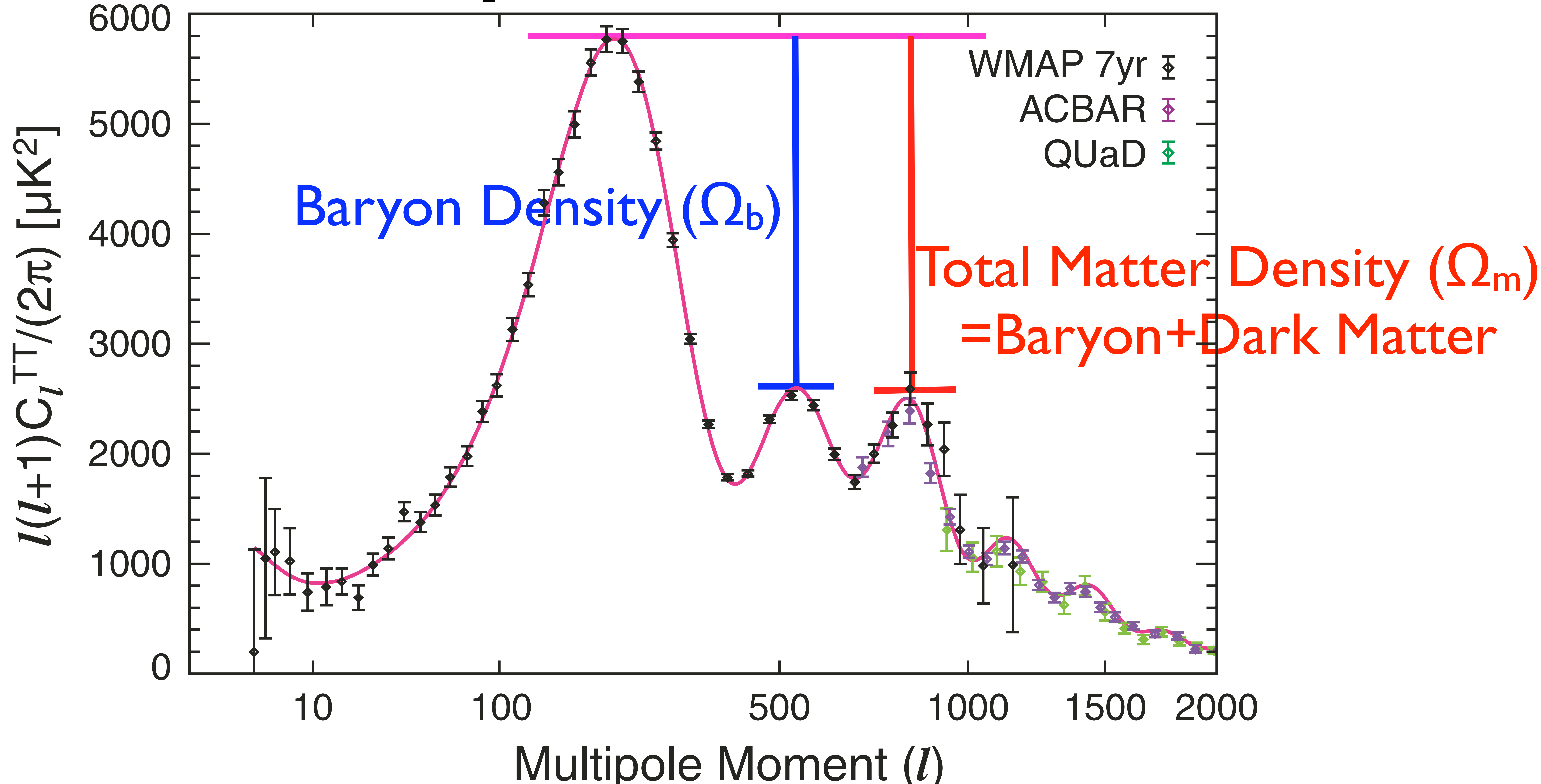
The Cosmic Sound Wave





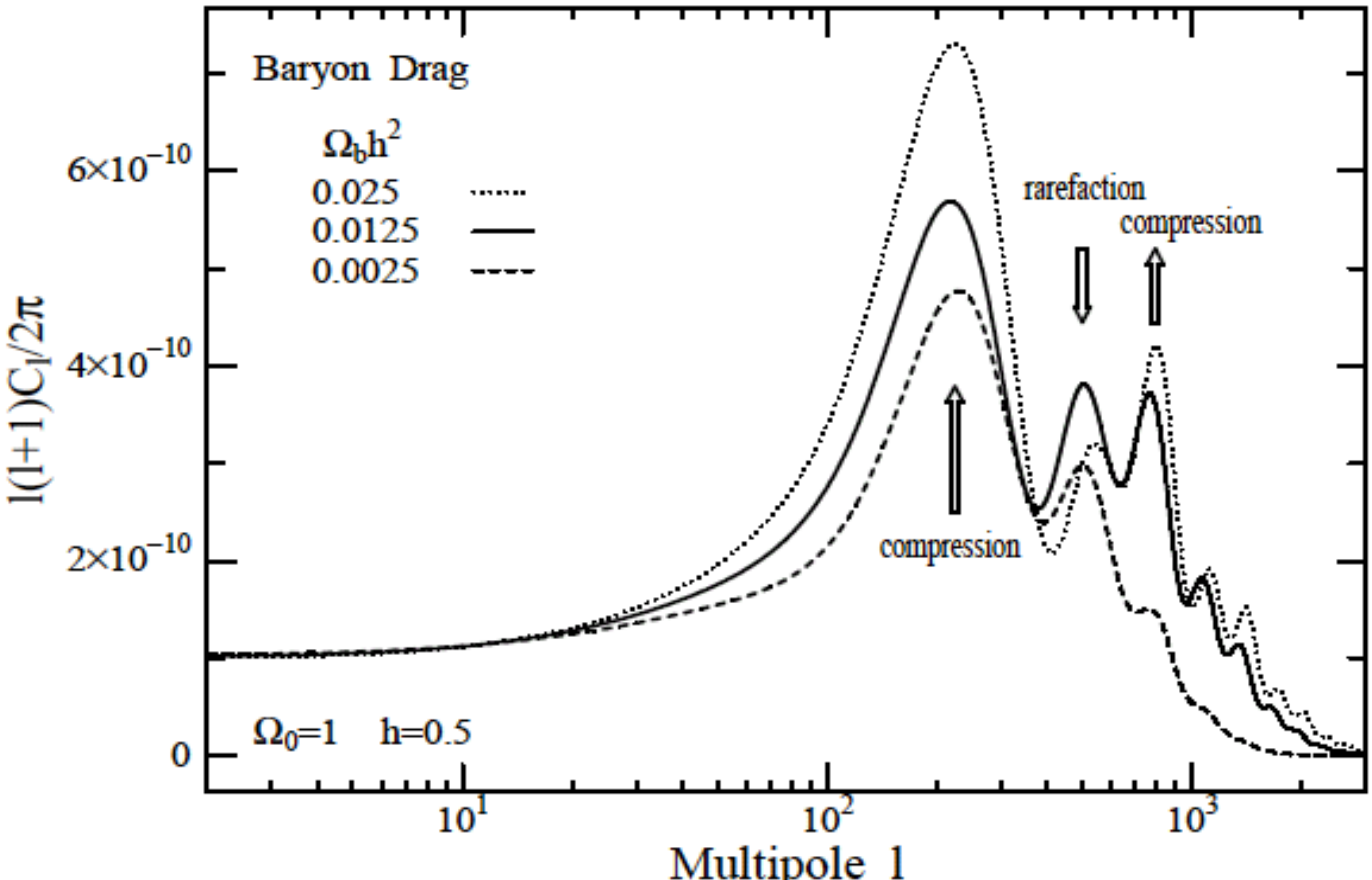
- *"The Universe as a Miso soup"*
  - *Main Ingredients: protons, helium nuclei, electrons, photons*
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

CMB to Baryon & Dark Matter

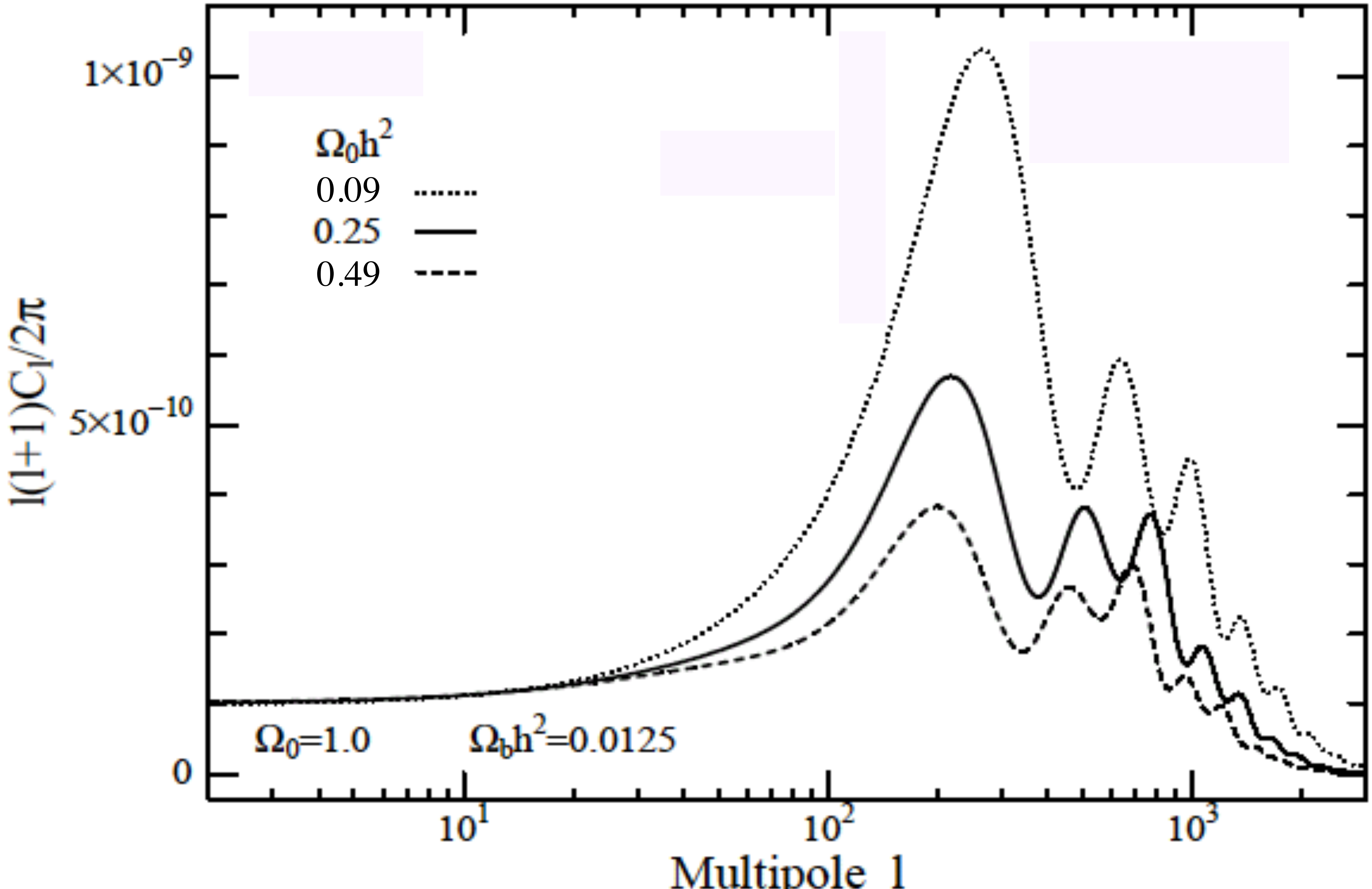


- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio (z_{EQ}: equality redshift)

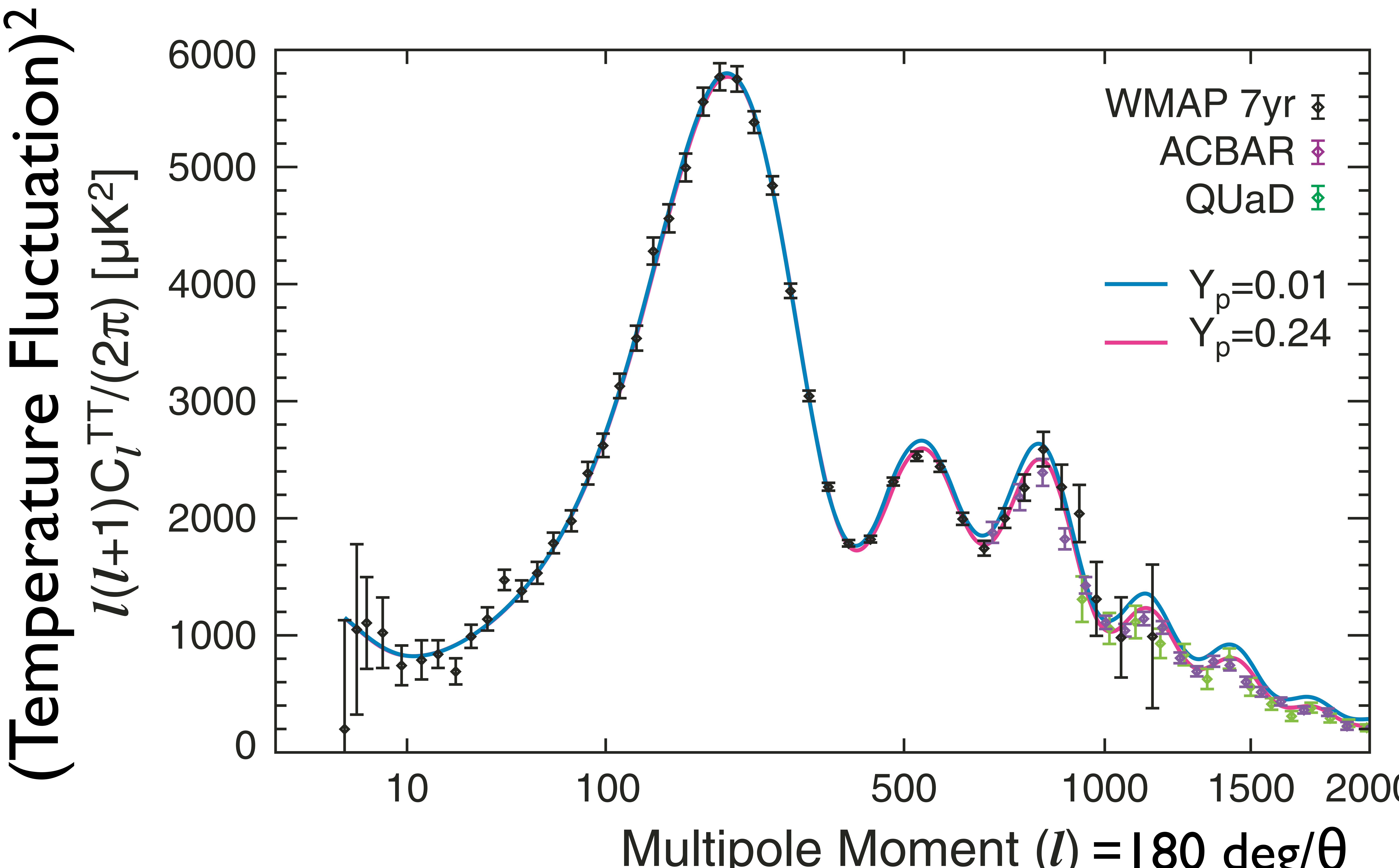
Determining Baryon Density From C_l



Determining Dark Matter Density From C_l



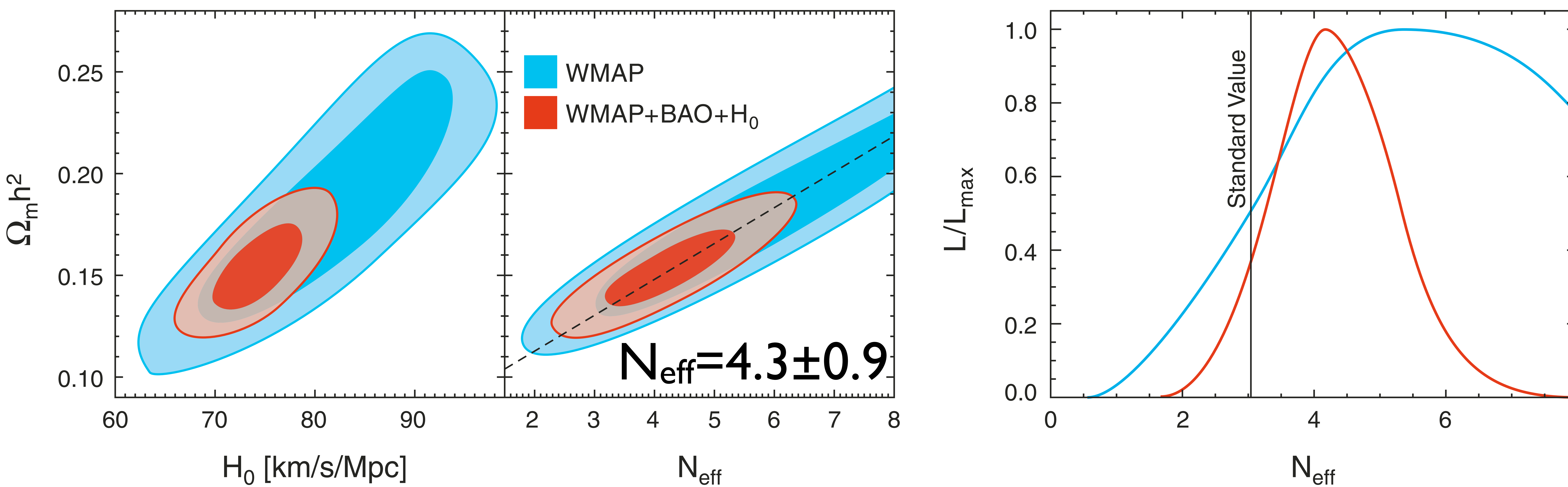
Detection of Primordial Helium



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**
- **$Y_p = 0.33 \pm 0.08$** (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

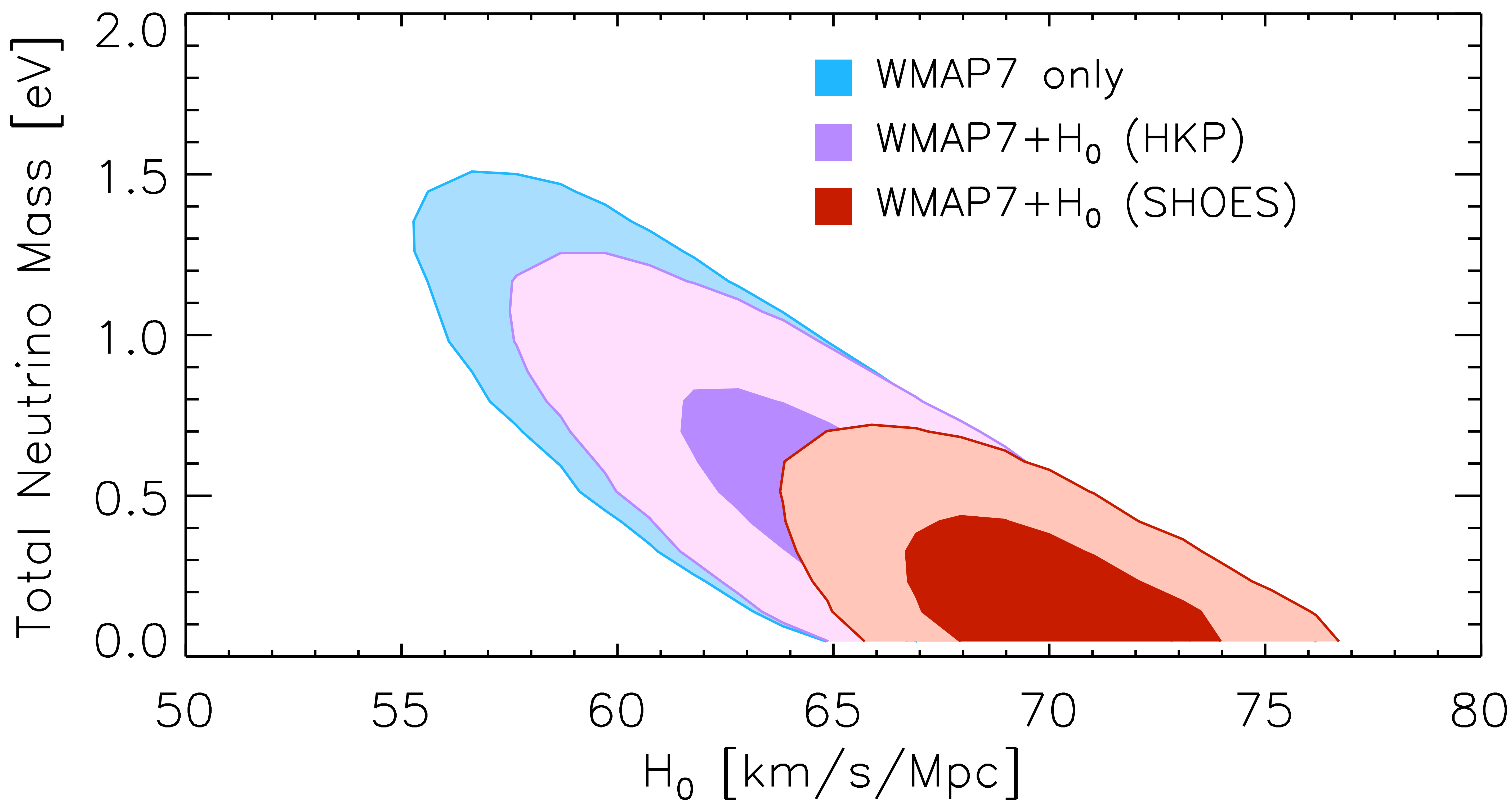


from external data

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

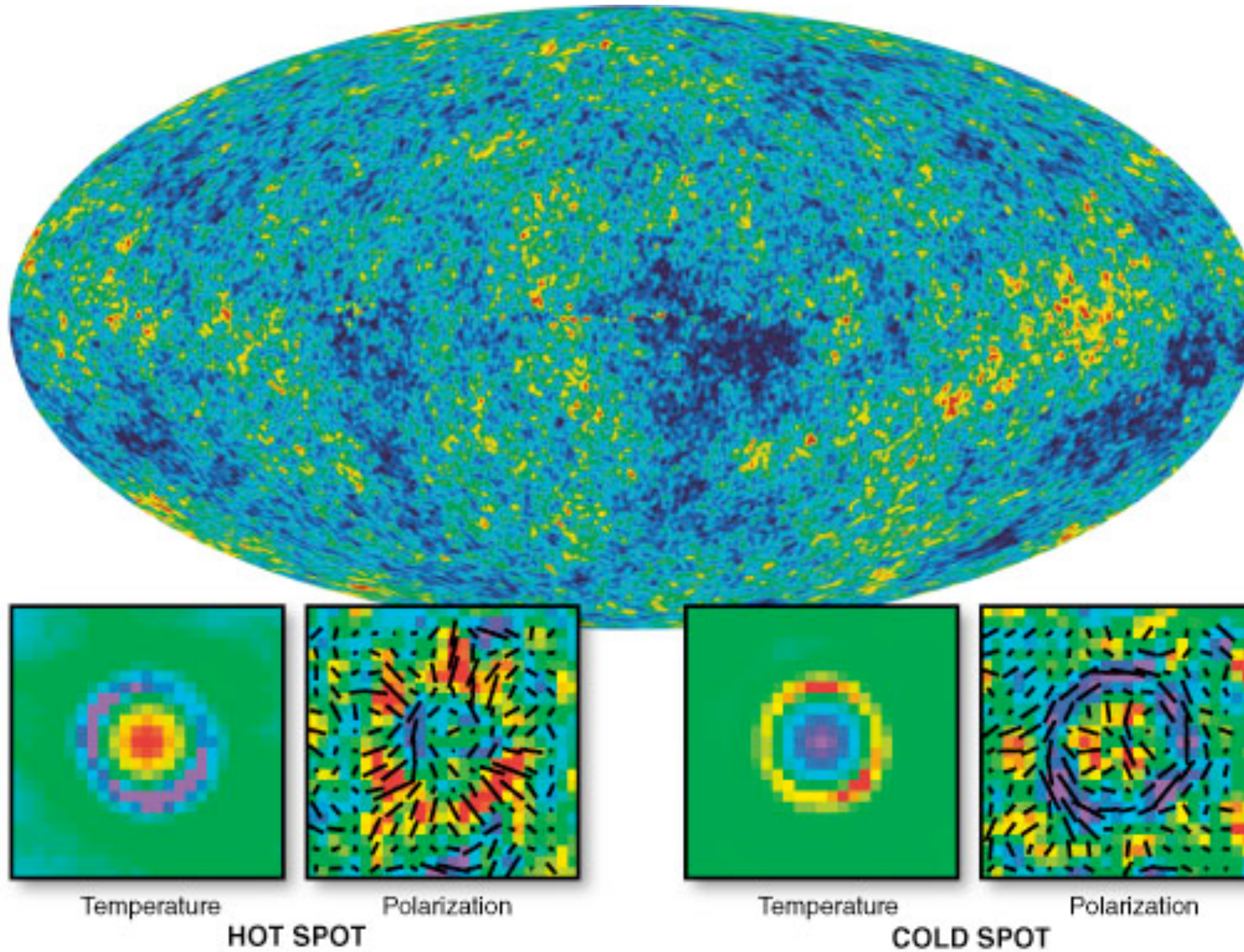
from 3rd peak

And, the mass of neutrinos



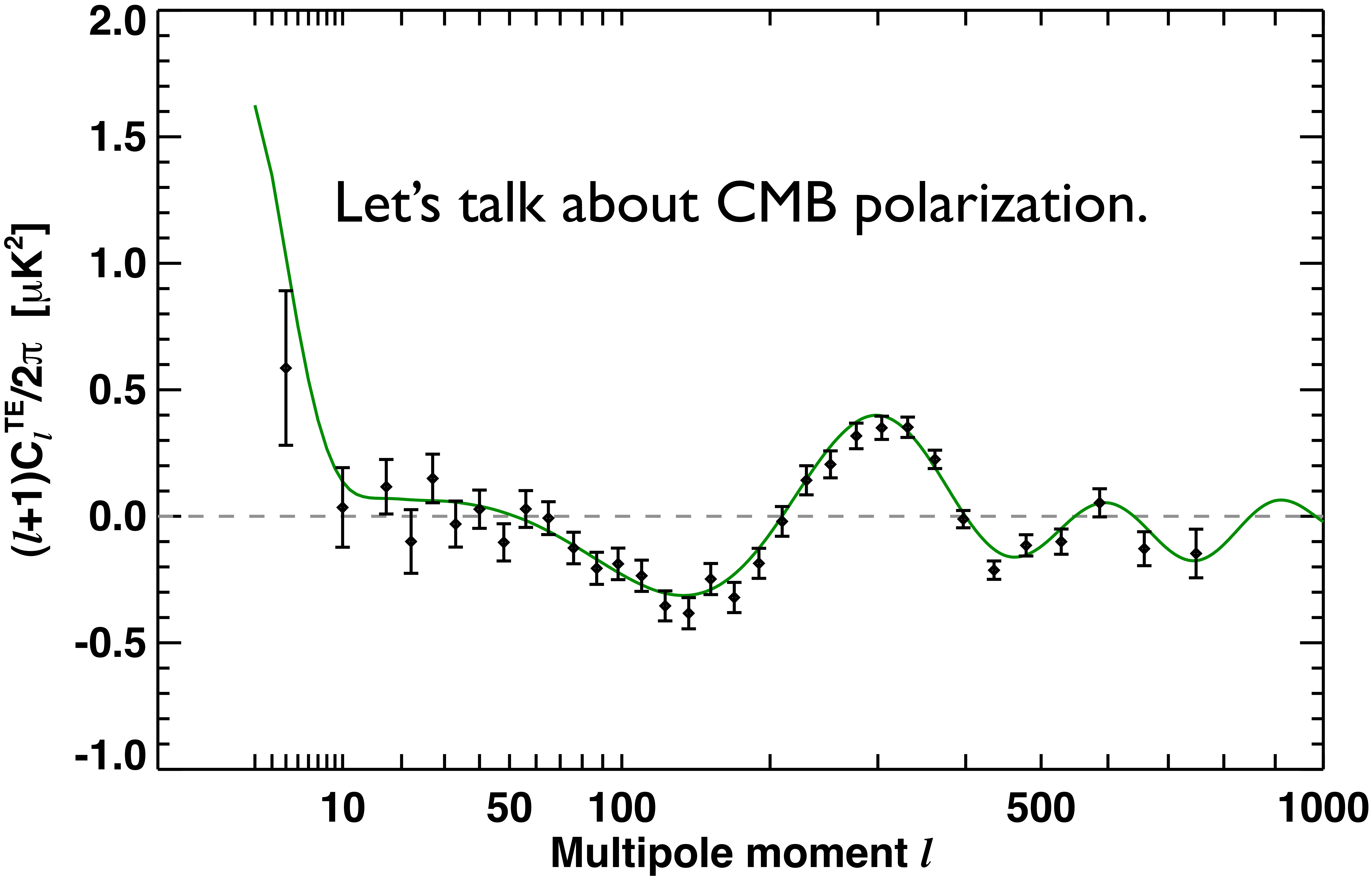
- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

CMB Polarization

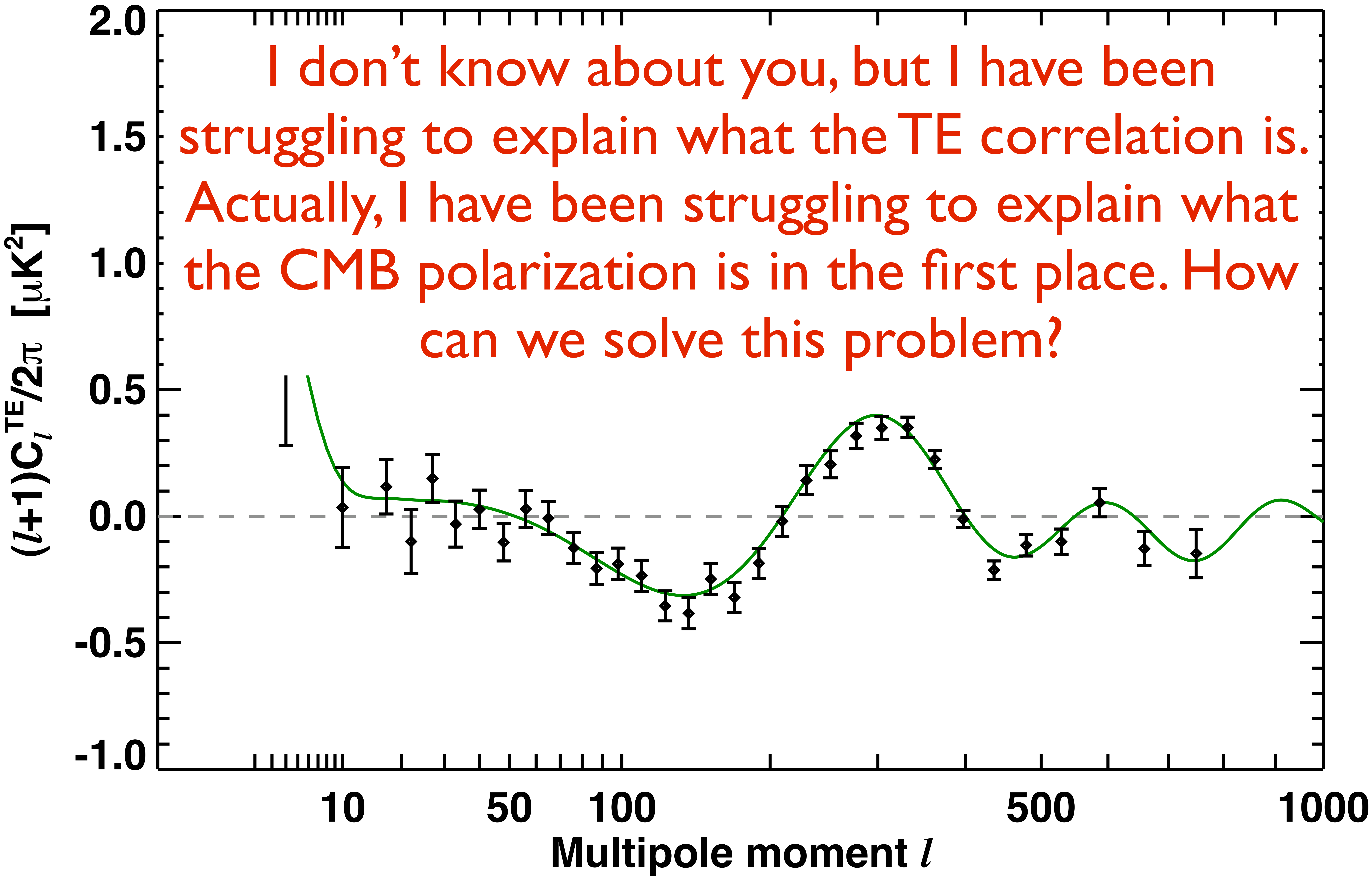


- *CMB is (very weakly) polarized!*

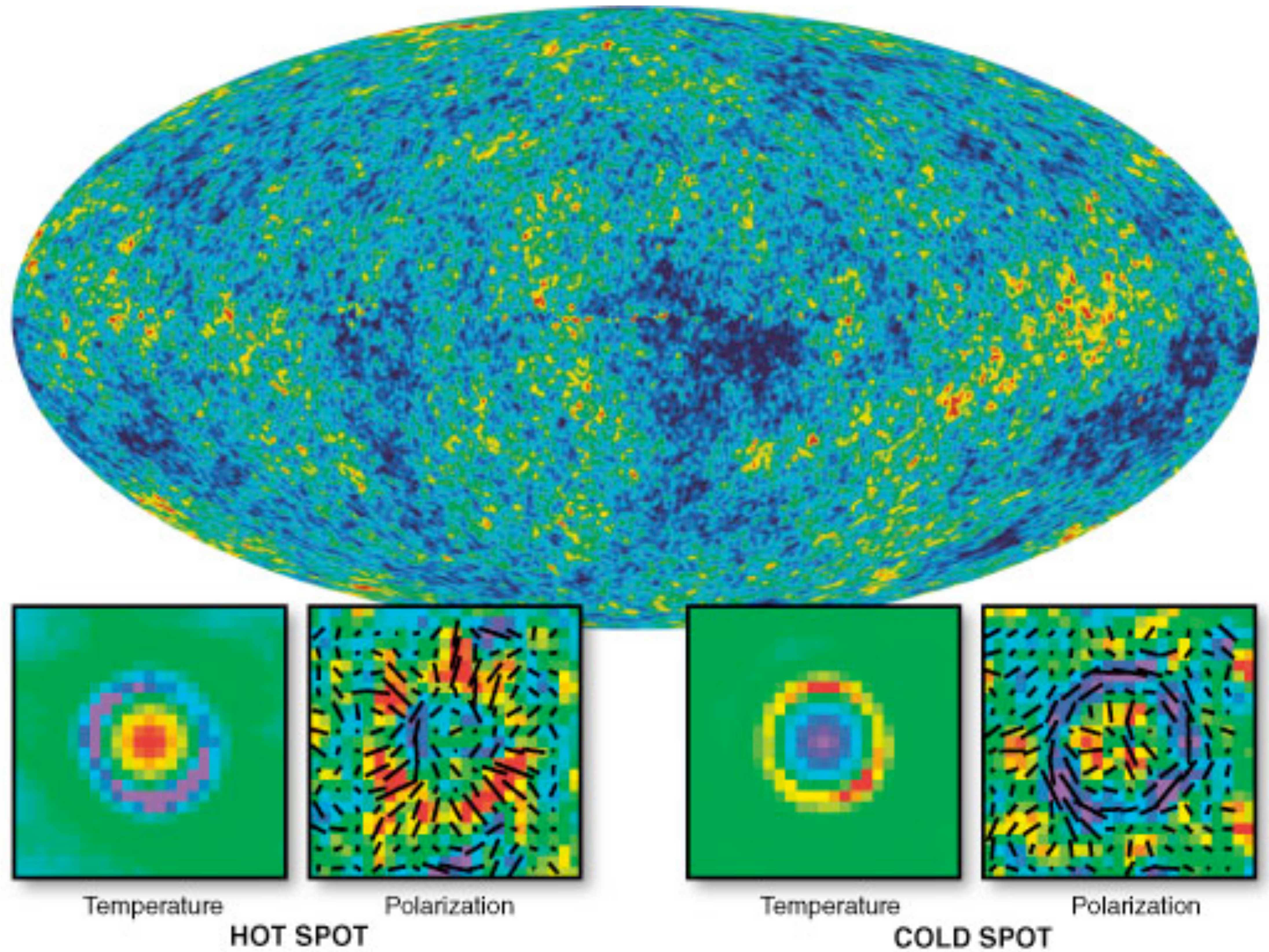
7-year TE Correlation



What Are We Seeing Here?

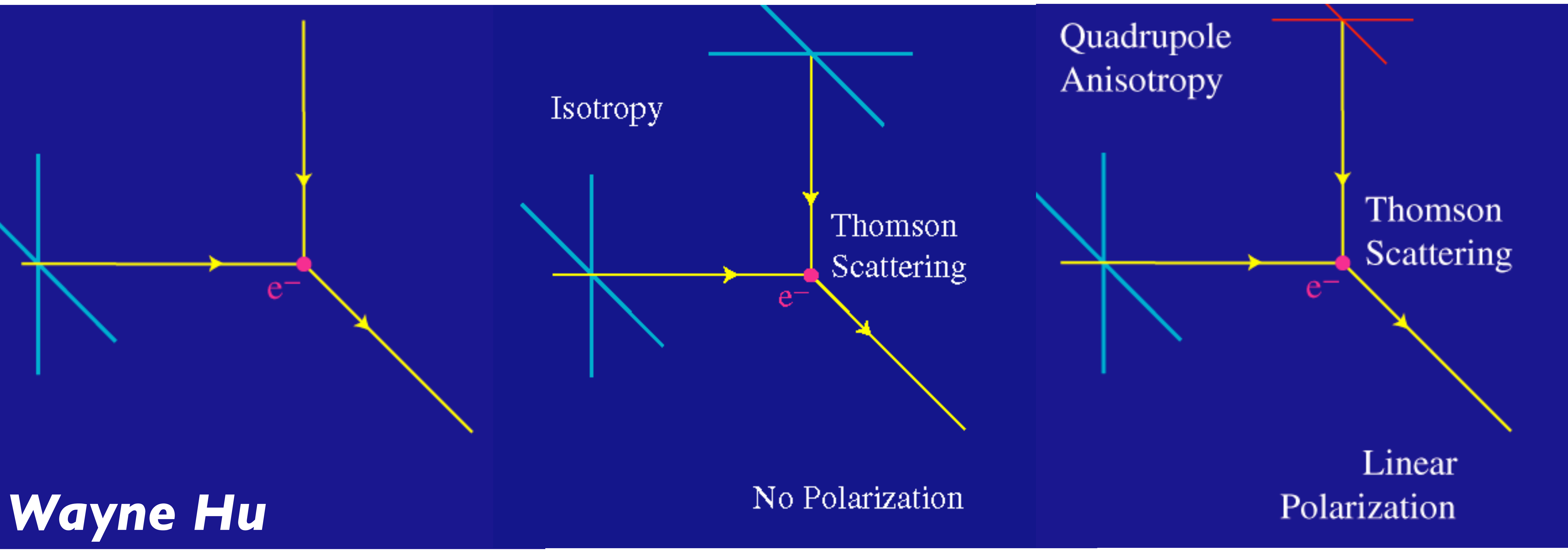


CMB Polarization On the Sky



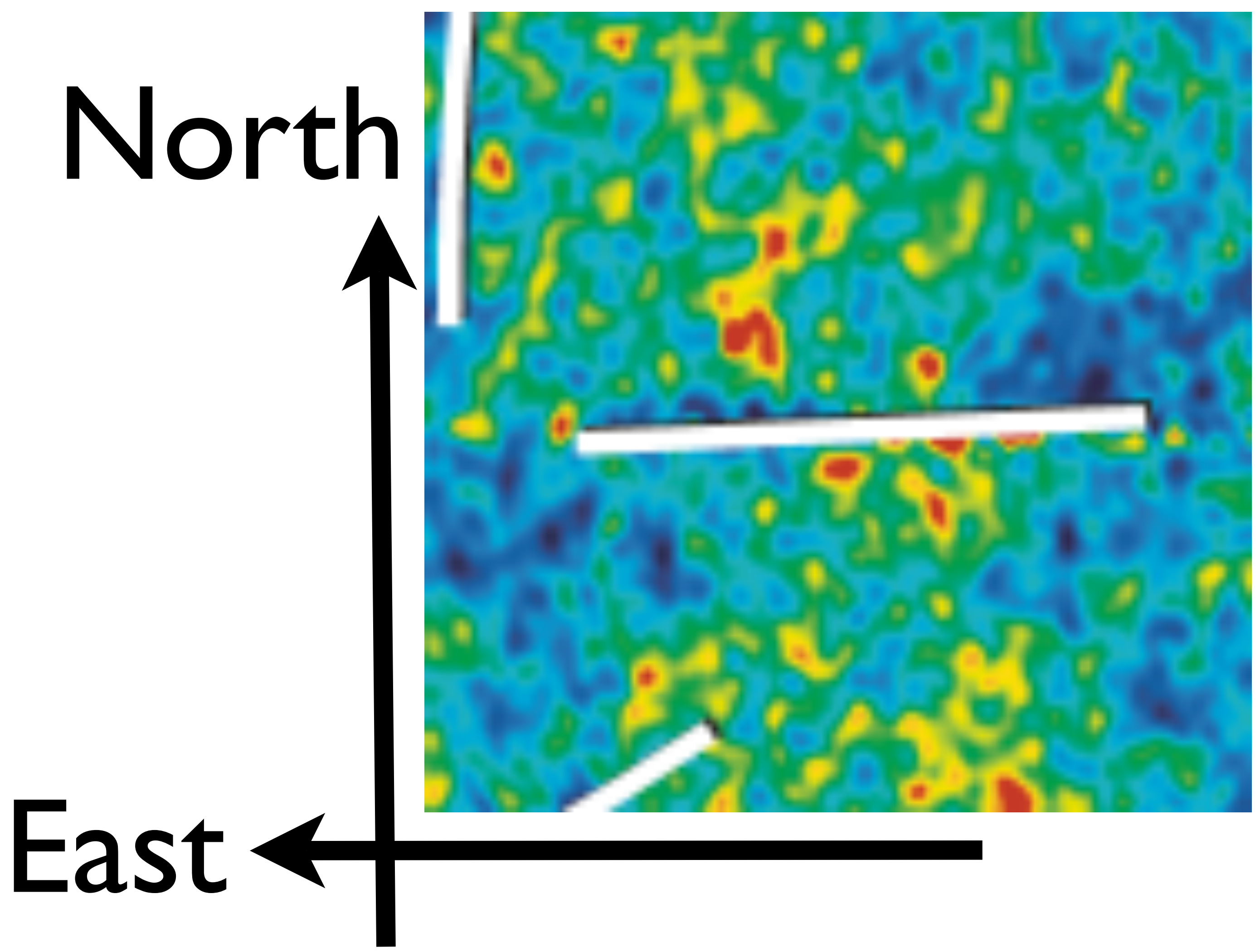
- *Solution*: Leave Fourier space.
  Go back to real space.

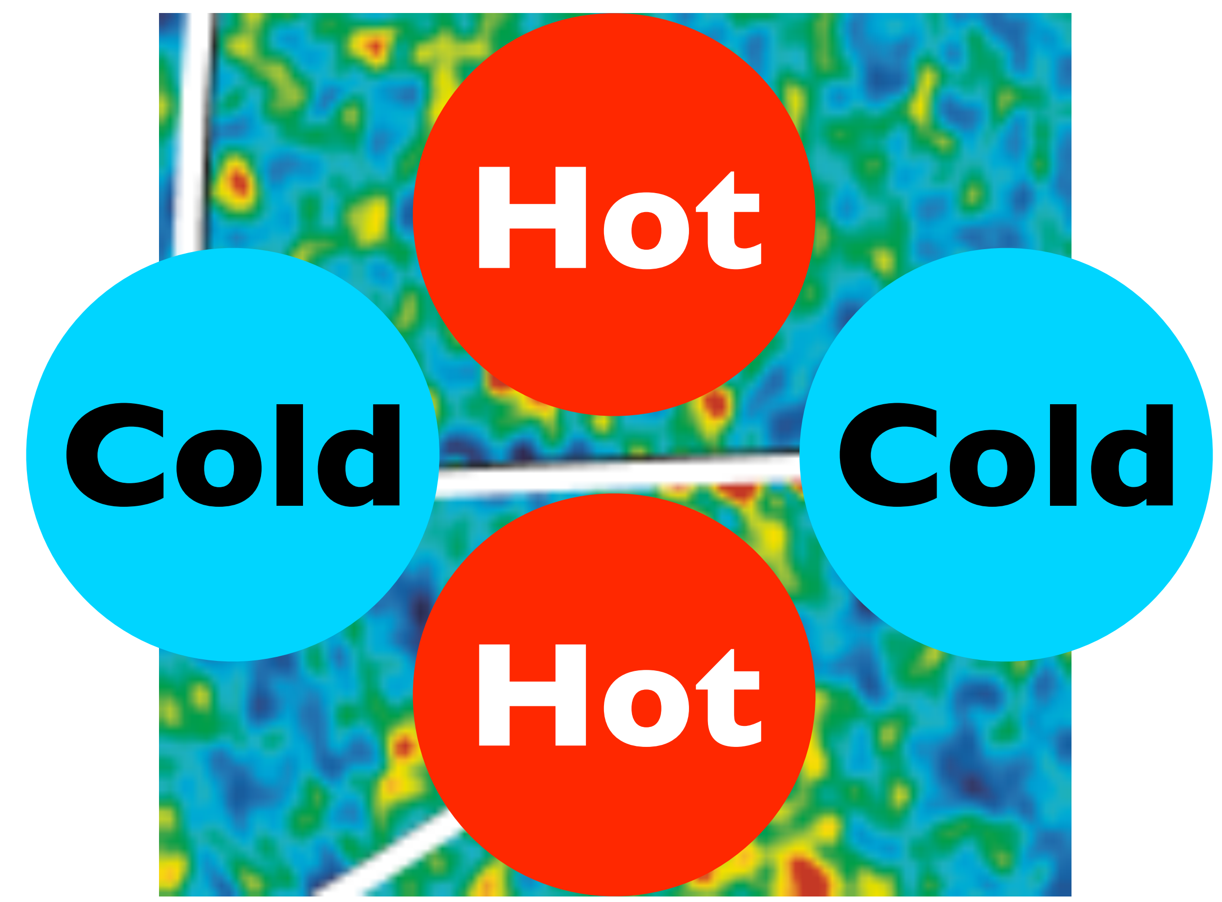
Physics of CMB Polarization



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

Principle





- **Polarization direction is parallel to “hot.”**

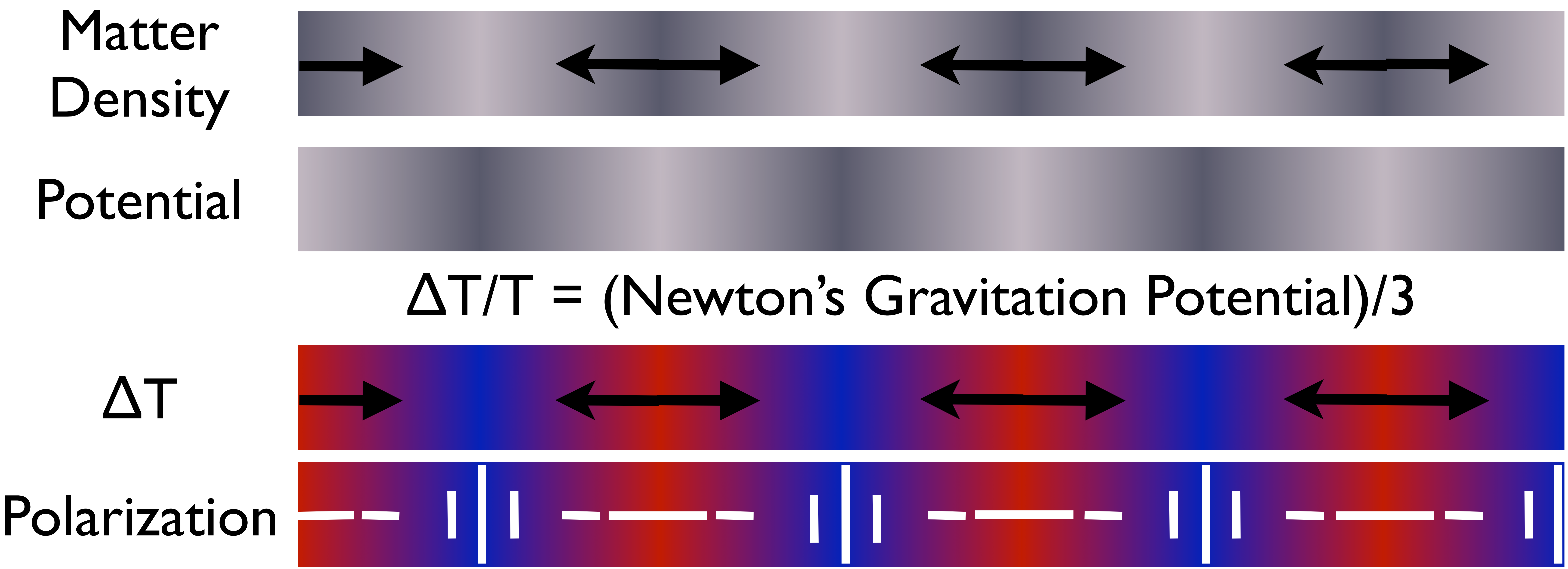
CMB Polarization on Large Angular Scales (>2 deg)

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

- How does the photon-baryon plasma move?

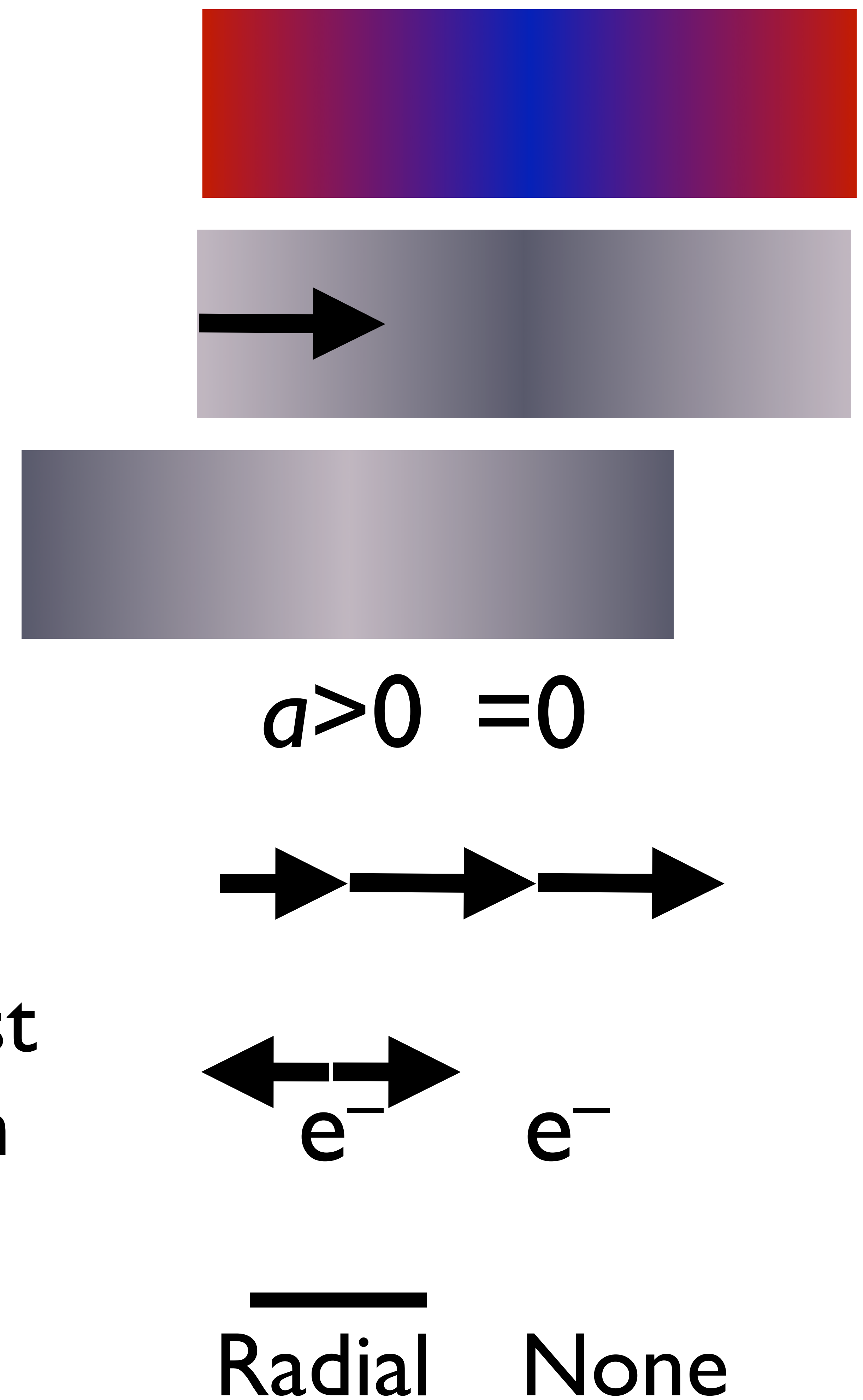
CMB Polarization Tells Us How Plasma Moves at z=1090

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 Φ — Stuff flowing *in*

Acceleration $a=-\partial\Phi$

Velocity — Velocity gradient

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

Polarization

Quadrupole From Velocity Gradient (Small Scale)

ΔT — Compression increases temperature

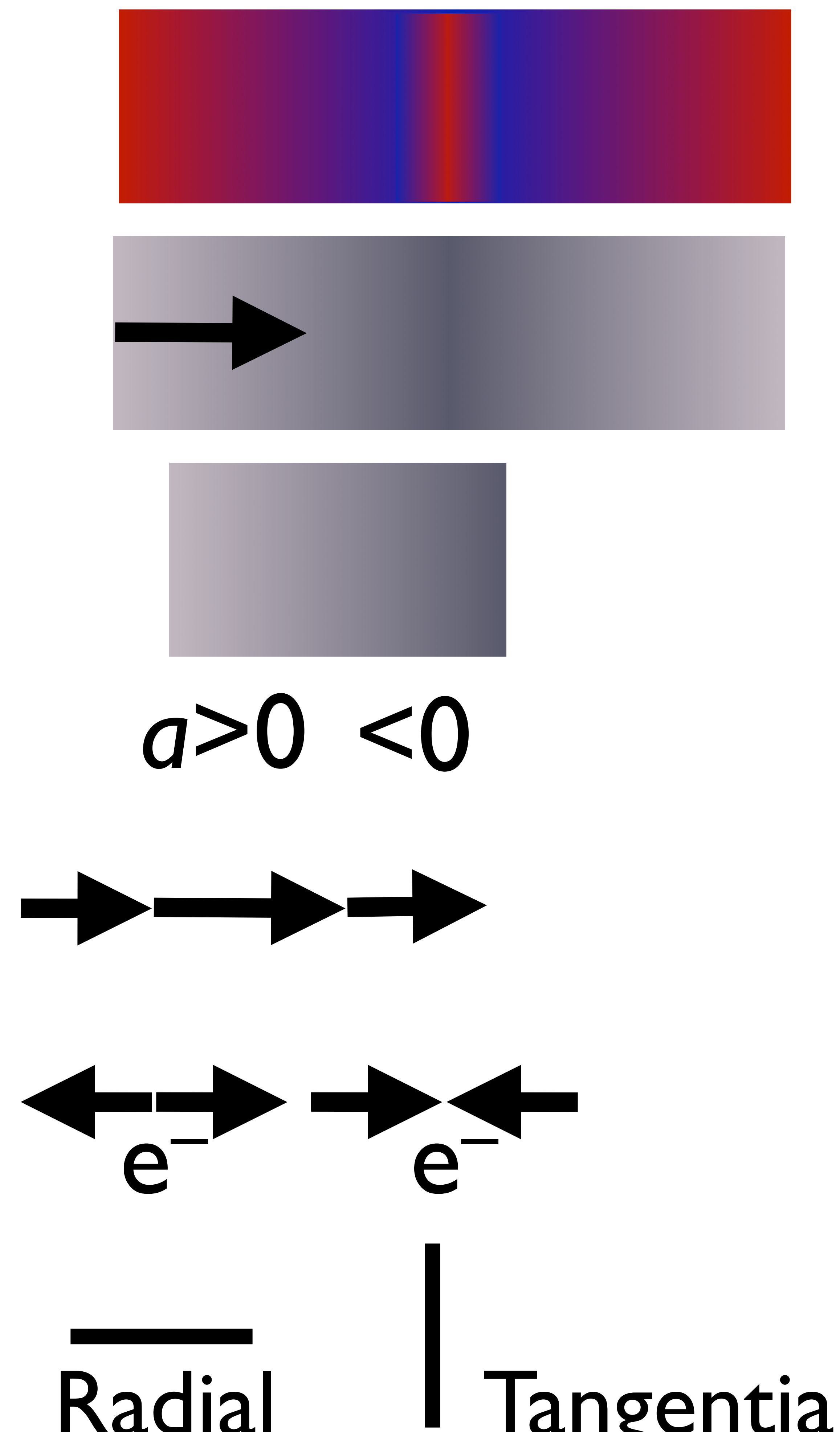
Potential Φ — Stuff flowing *in*

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

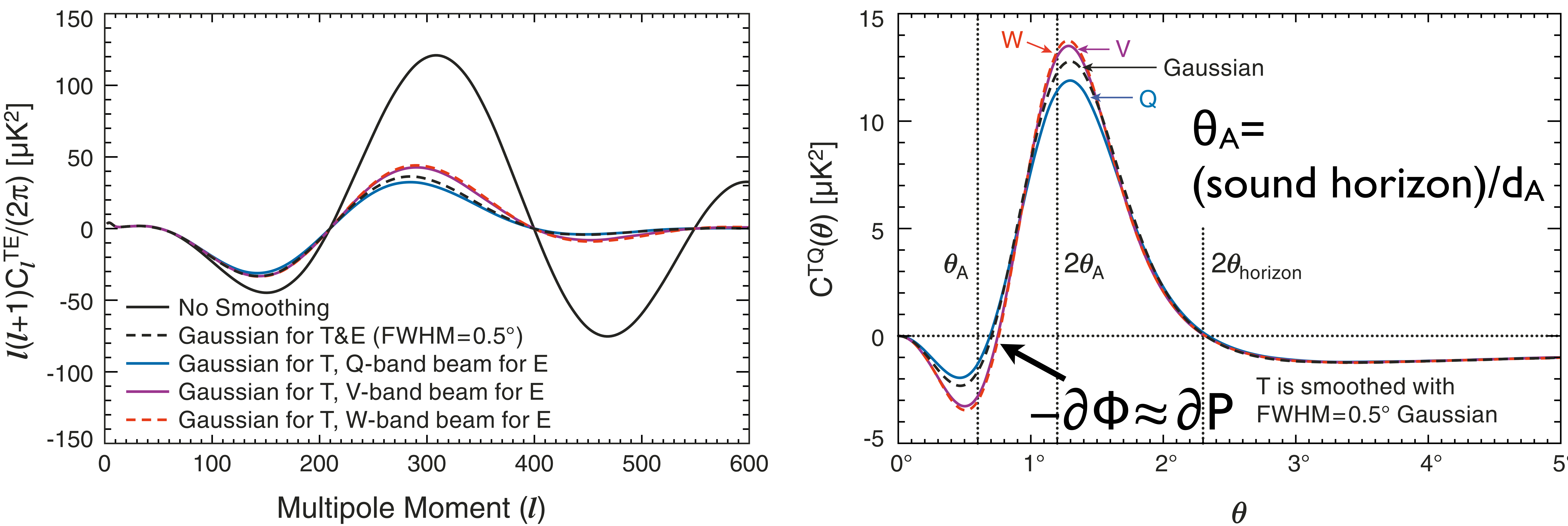
Velocity — Velocity gradient

Velocity in the rest frame of electron

Polarization



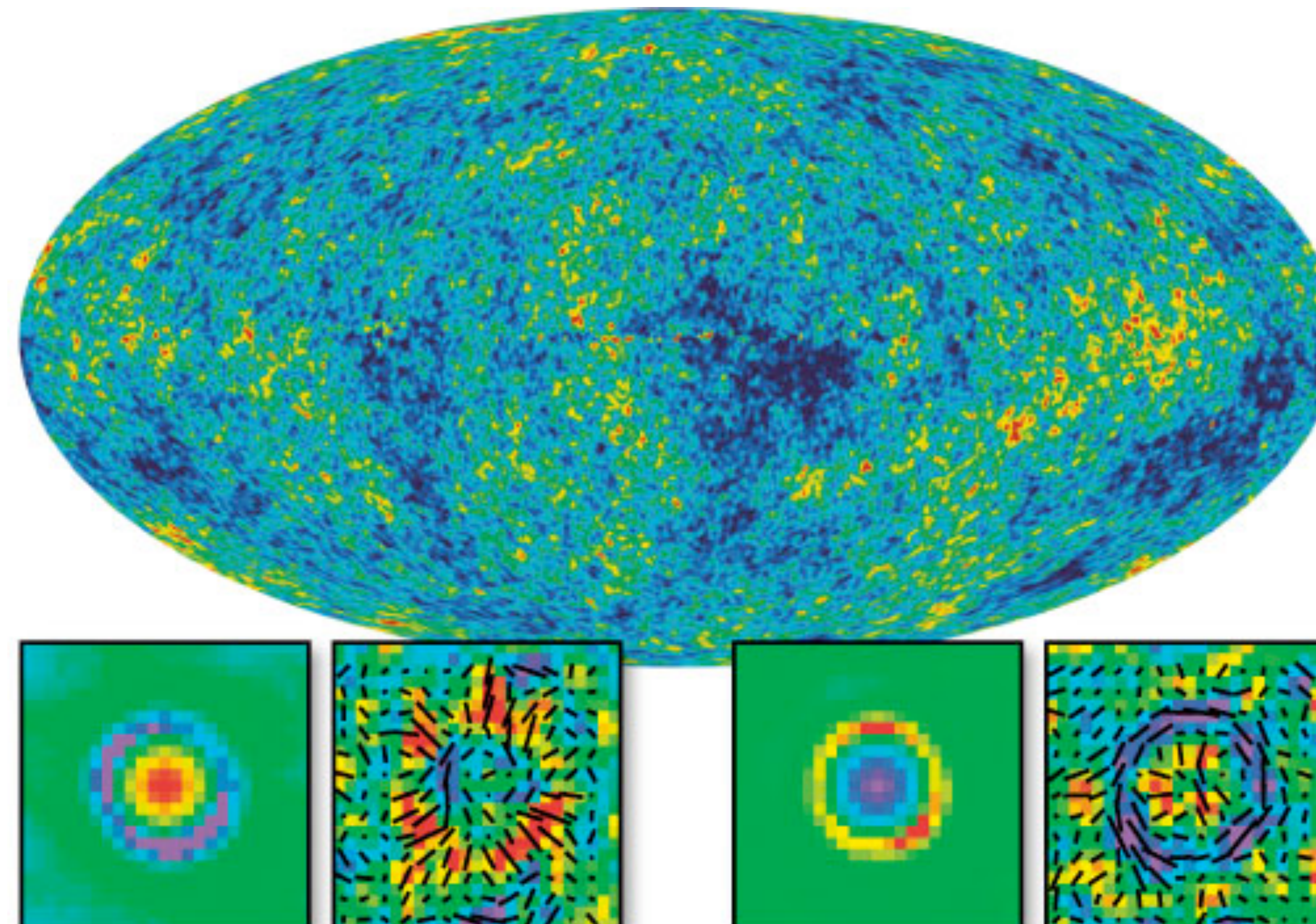
Hence, T-polarization Correlation (Coulson et al. 1994)



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

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:

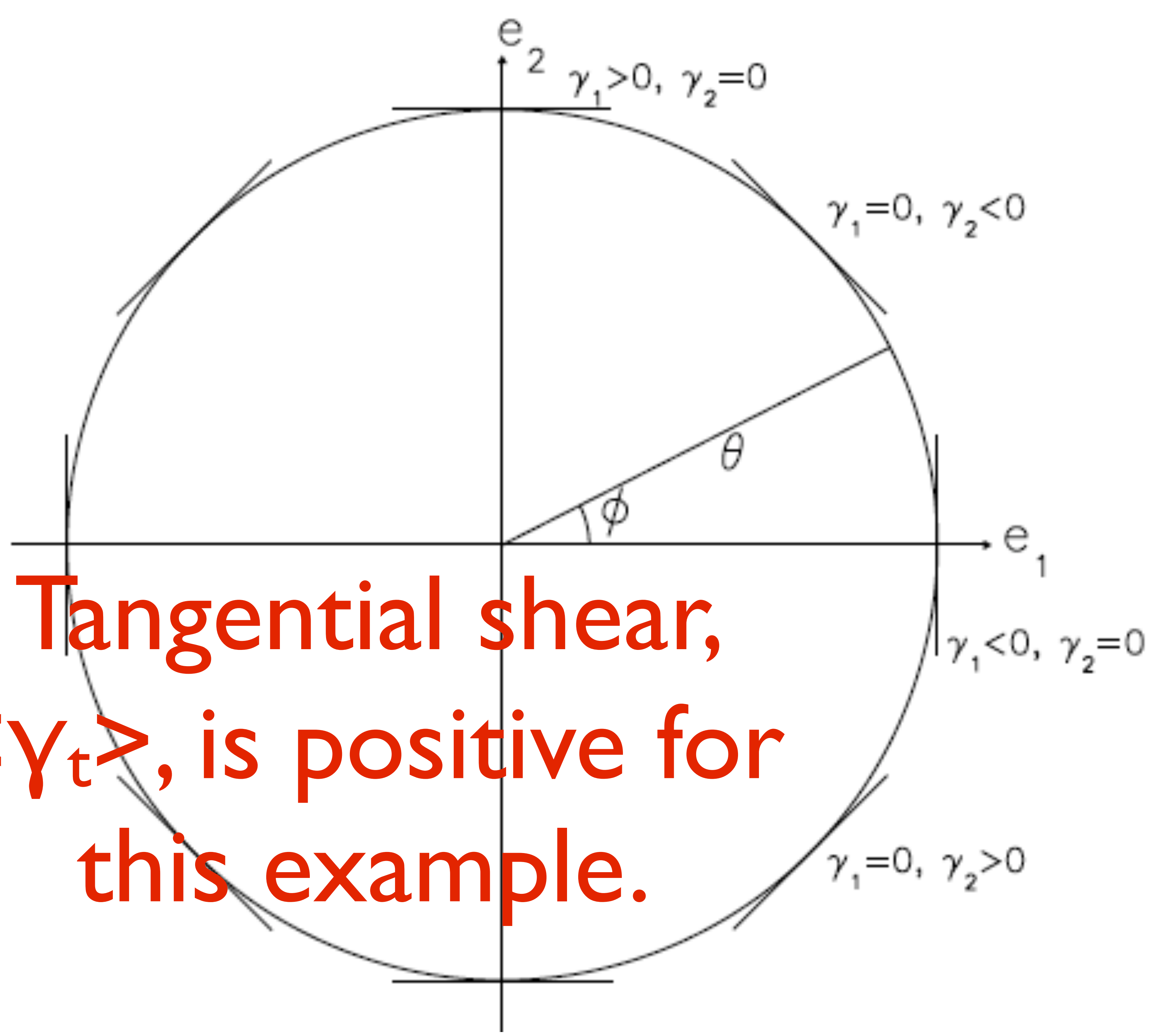
[Note the l^2 term! (Desjacques 2008)]

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

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

Analogy to Weak Lensing

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



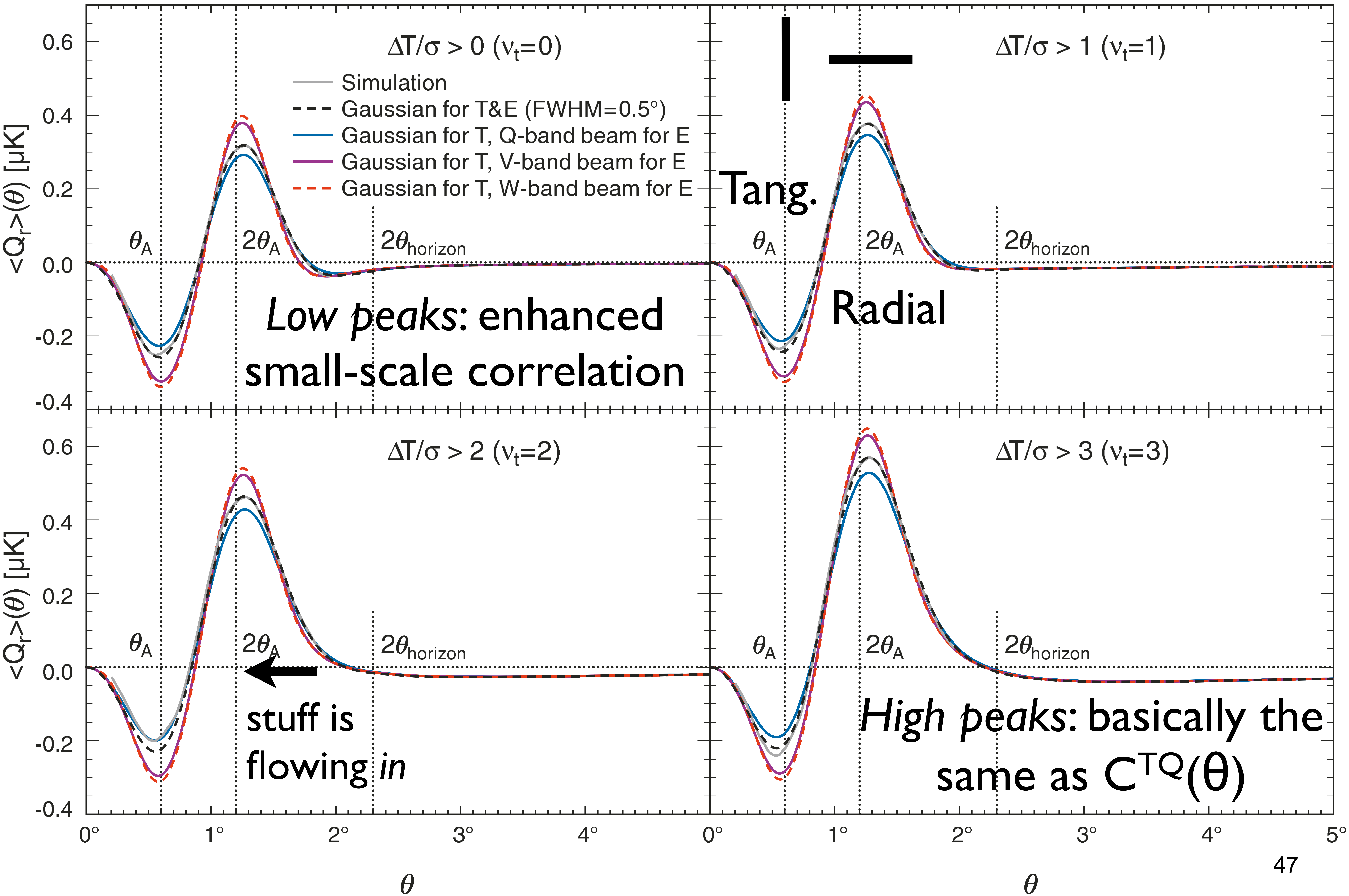
Tangential shear, <γt>, is positive for this example.

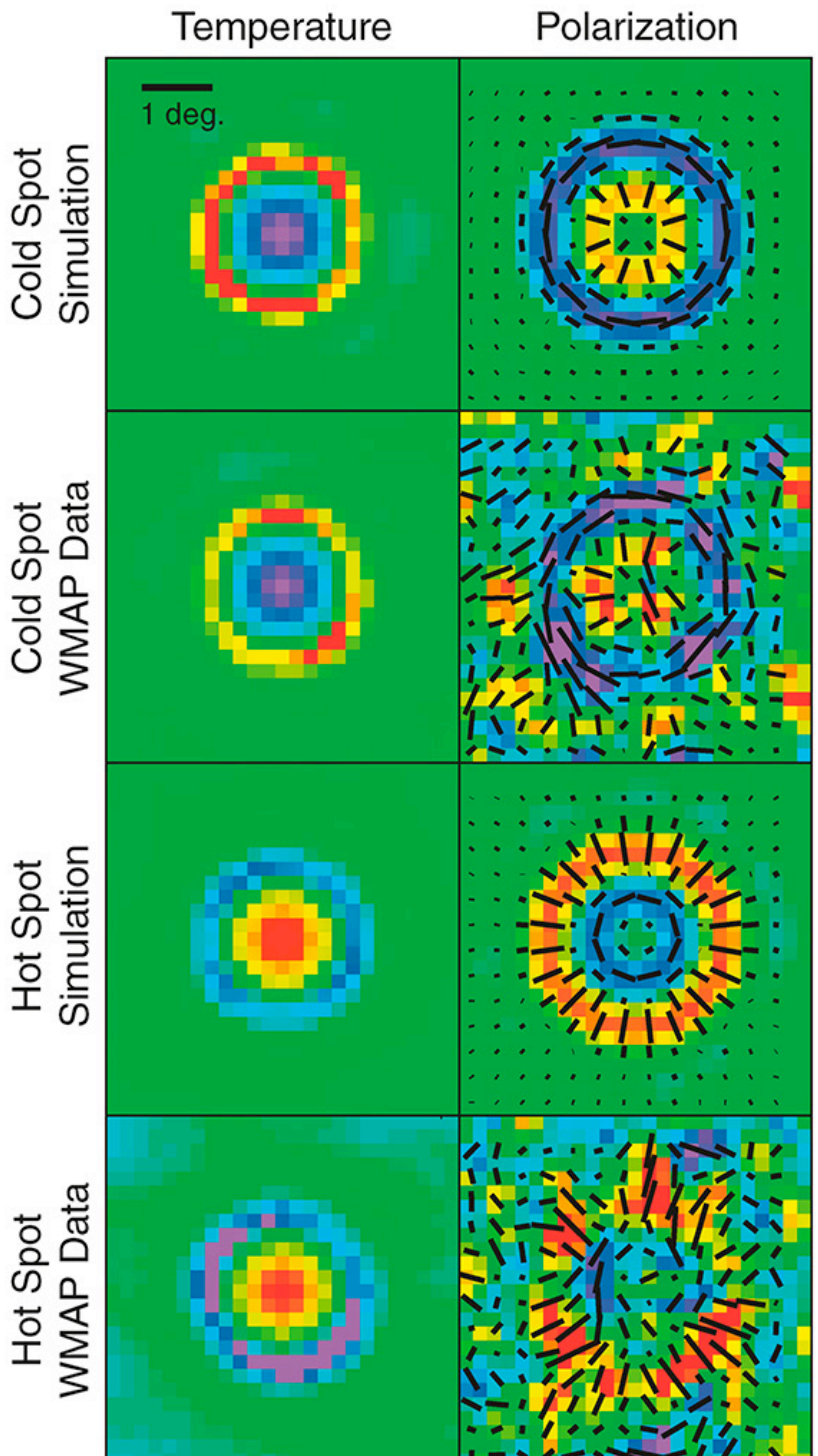
$$\Delta\Sigma(R, z_L)$$
$$= \rho_0 b_1 \int \frac{kdk}{2\pi} P_m(k, z_L) J_2(kR)$$

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

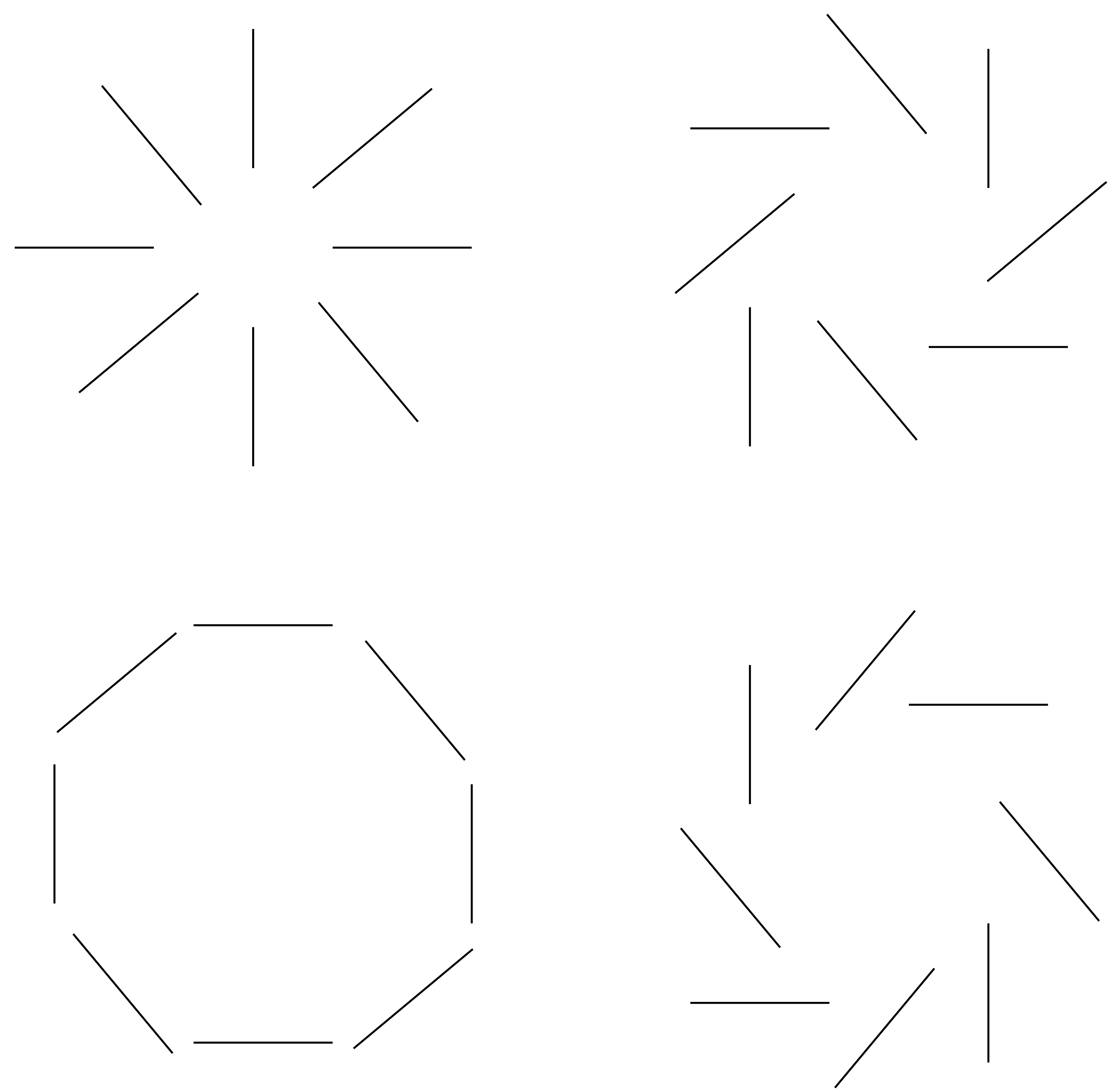




Two-dimensional View

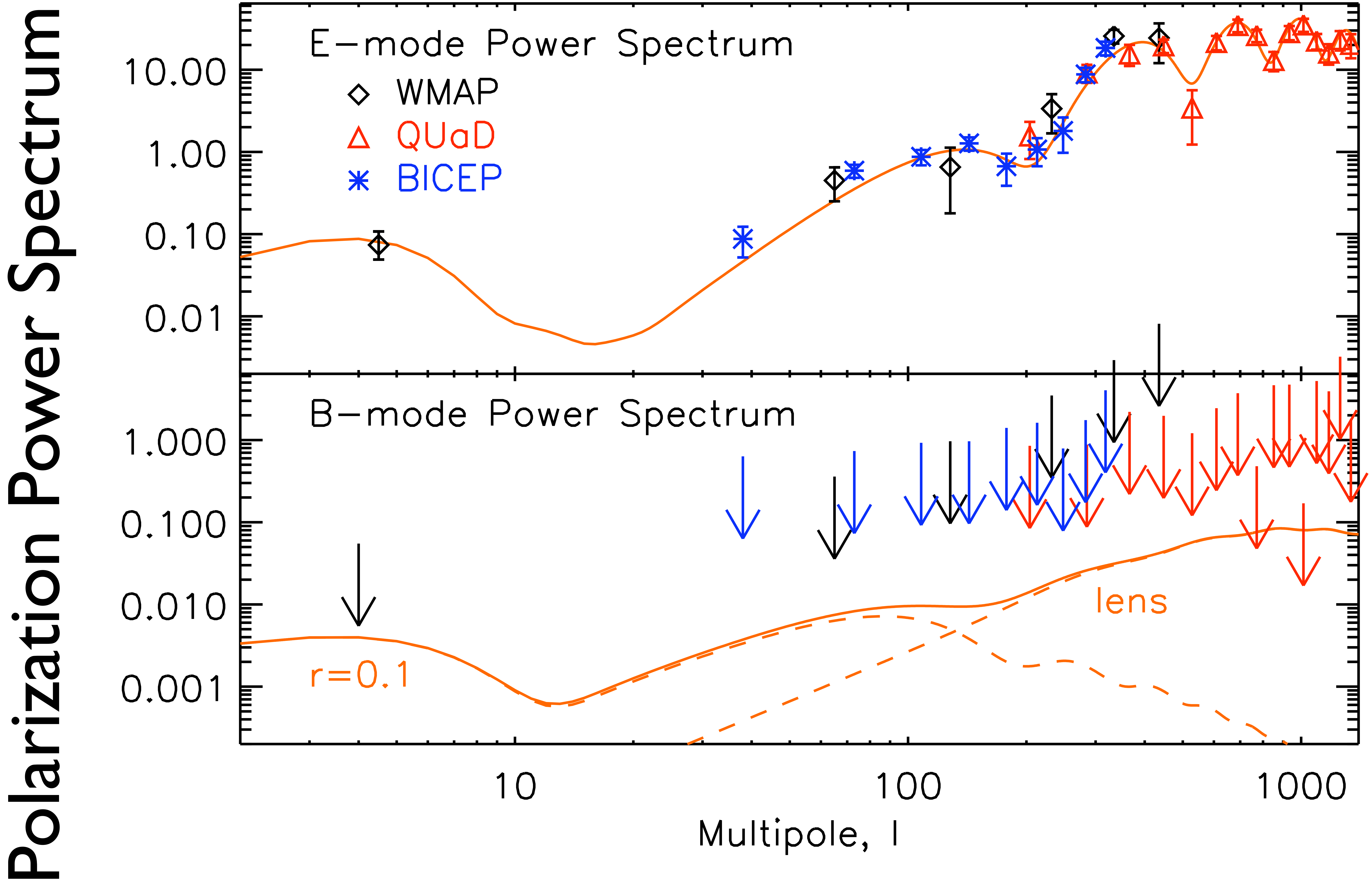
- All hot and cold spots are stacked (the threshold peak height, $\Delta T/\sigma$, is zero)
- "Compression phase" at θ=1.2 deg and "slow-down phase" at θ=0.6 deg are predicted to be there and we observe them!
    - The overall significance level: 8σ

E-mode and B-mode



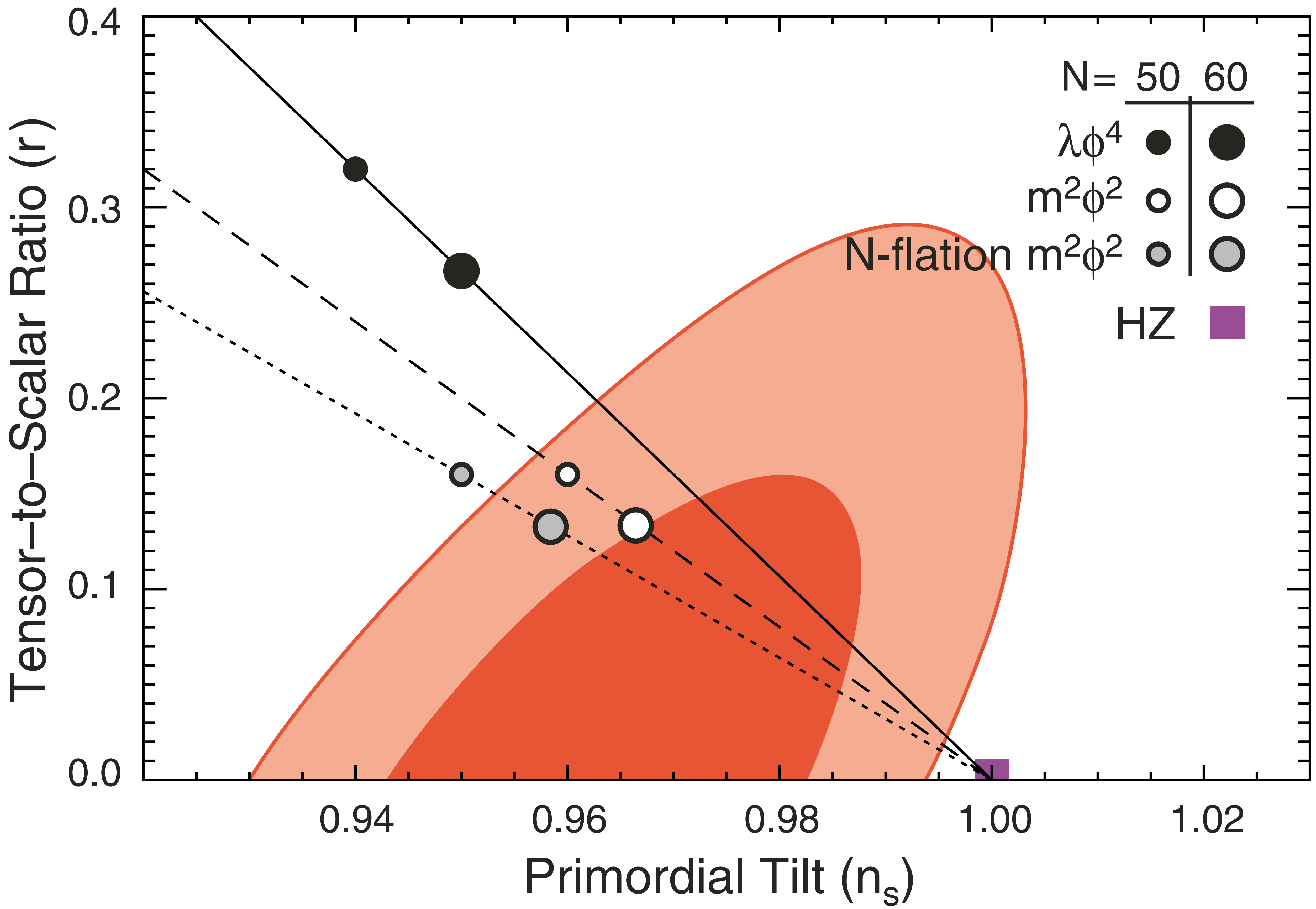
E mode B mode

- 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)

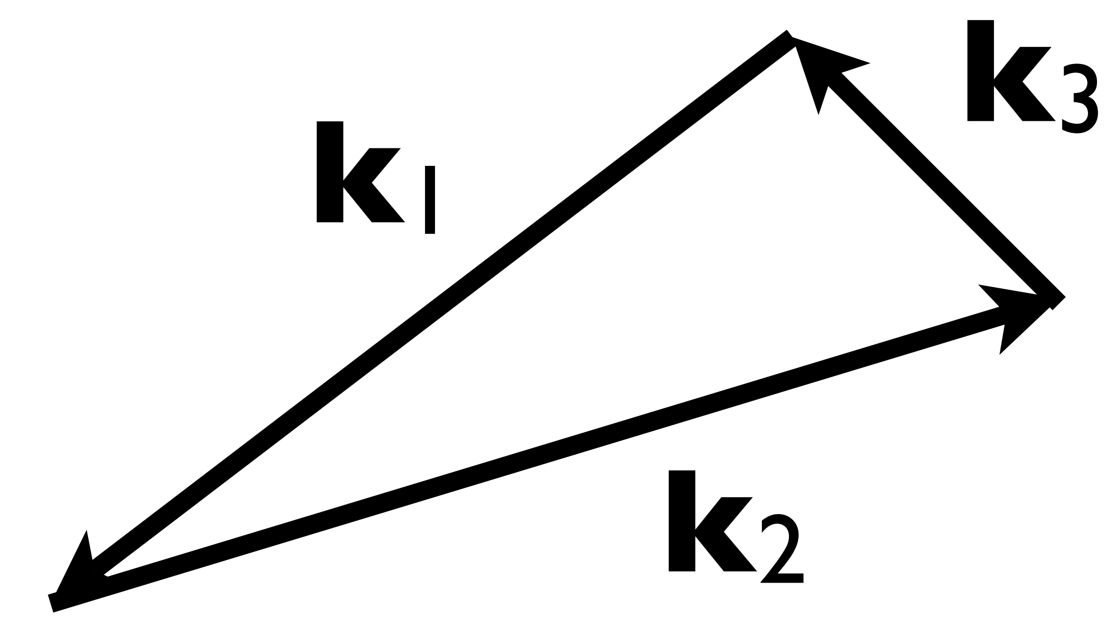


- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL)
- Limit on the tilt of the power spectrum: $n_s=0.968\pm0.012$ (68%CL)

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!

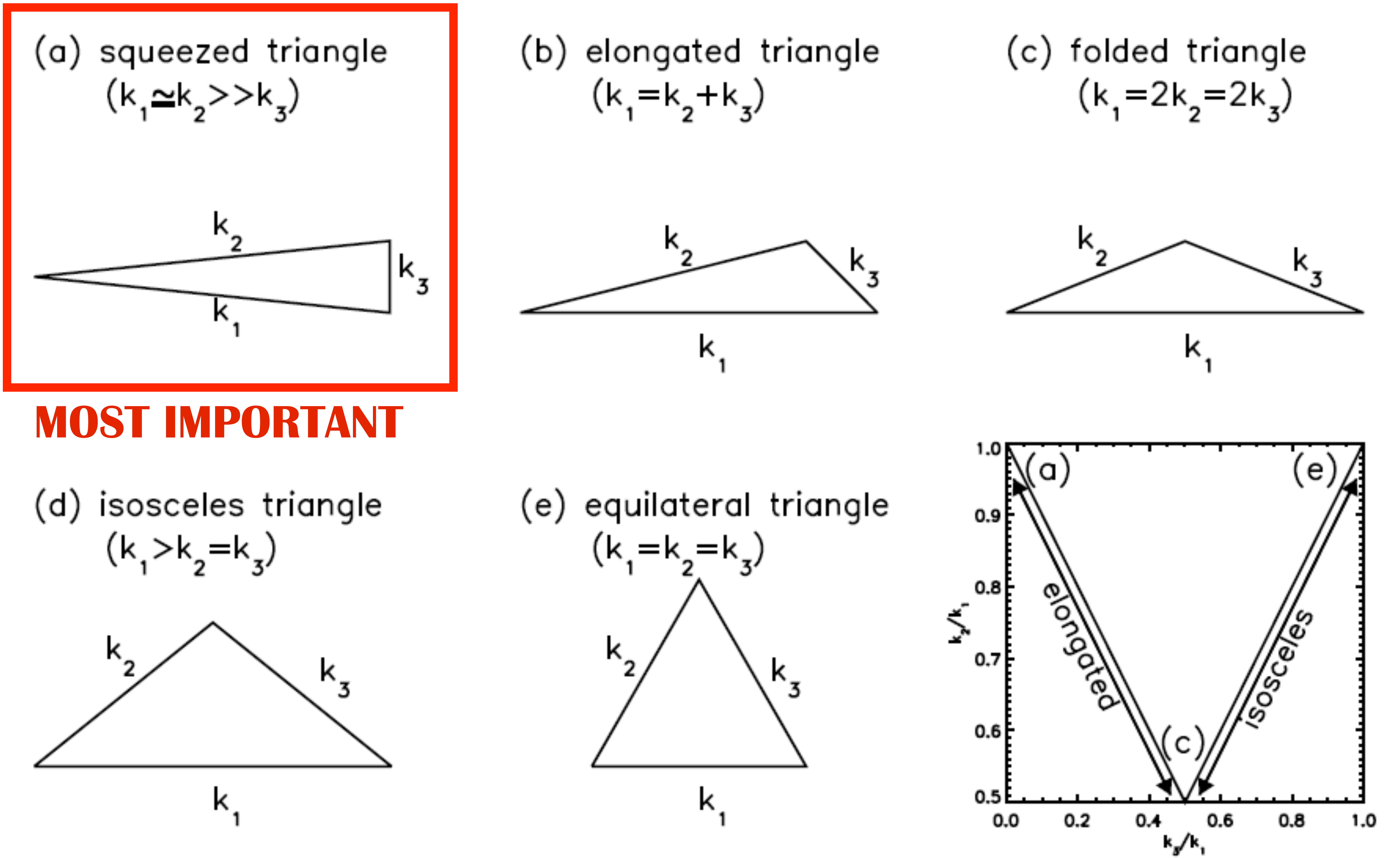
Bispectrum



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

model-dependent function

Primordial fluctuation



(a) squeezed triangle
(k1≃k2>>k3)
MOST IMPORTANT
(b) elongated triangle
(k1=k2+k3)
(c) folded triangle
(k1=2k2=2k3)
(d) isosceles triangle
(k1>k2=k3)
(e) equilateral triangle
(k1=k2=k3)
elongated
isosceles
k2/k1
k3/k1

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.

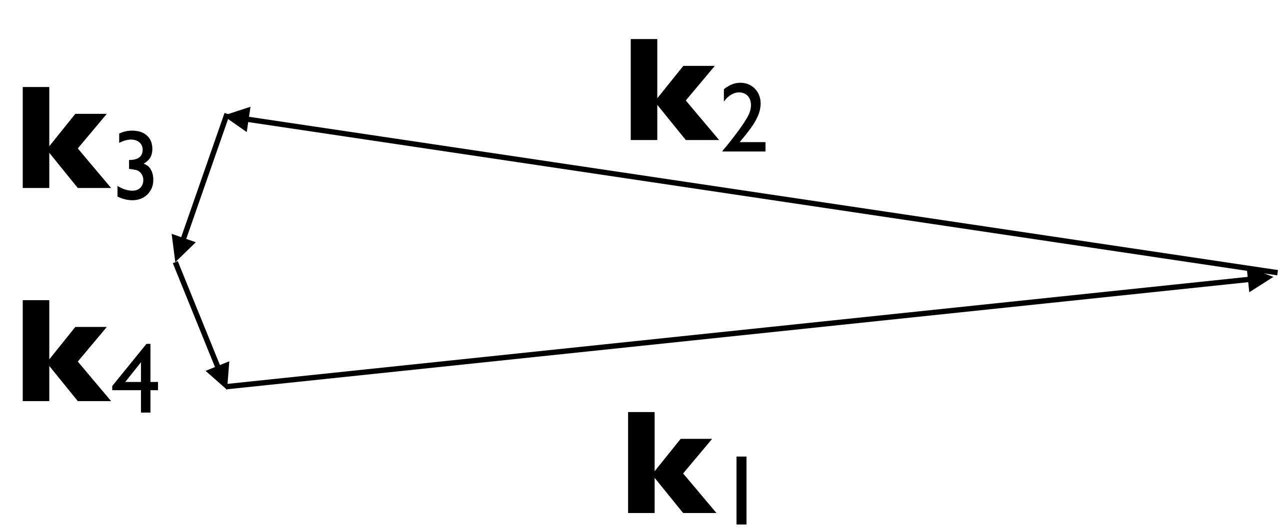
Probing Inflation (3-point Function)

- 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: $\Delta f_{NL} = 5$

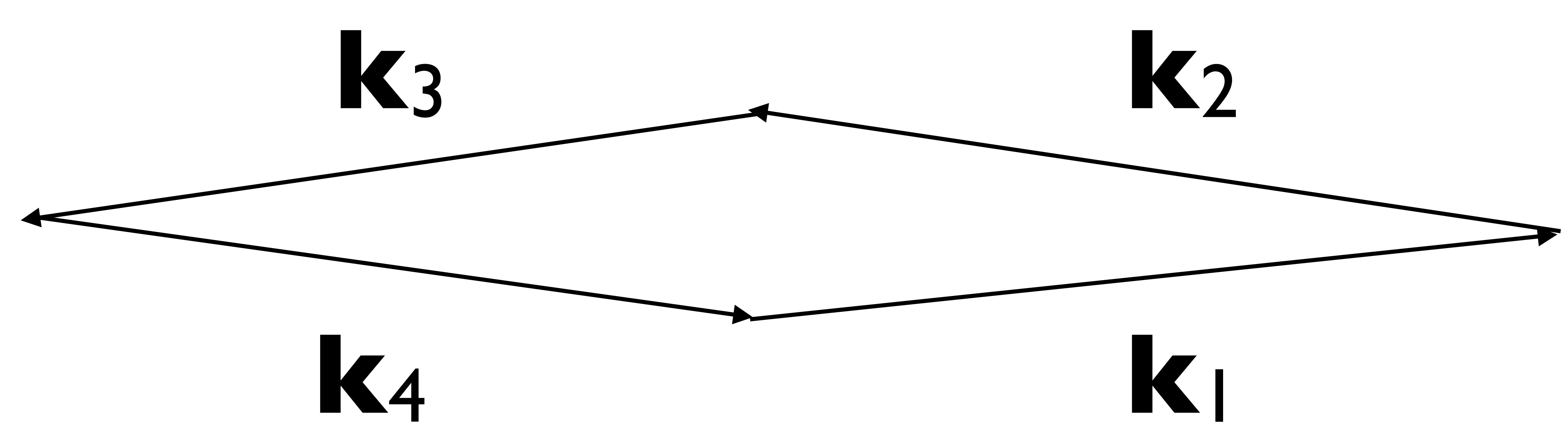
Trispectrum

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

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

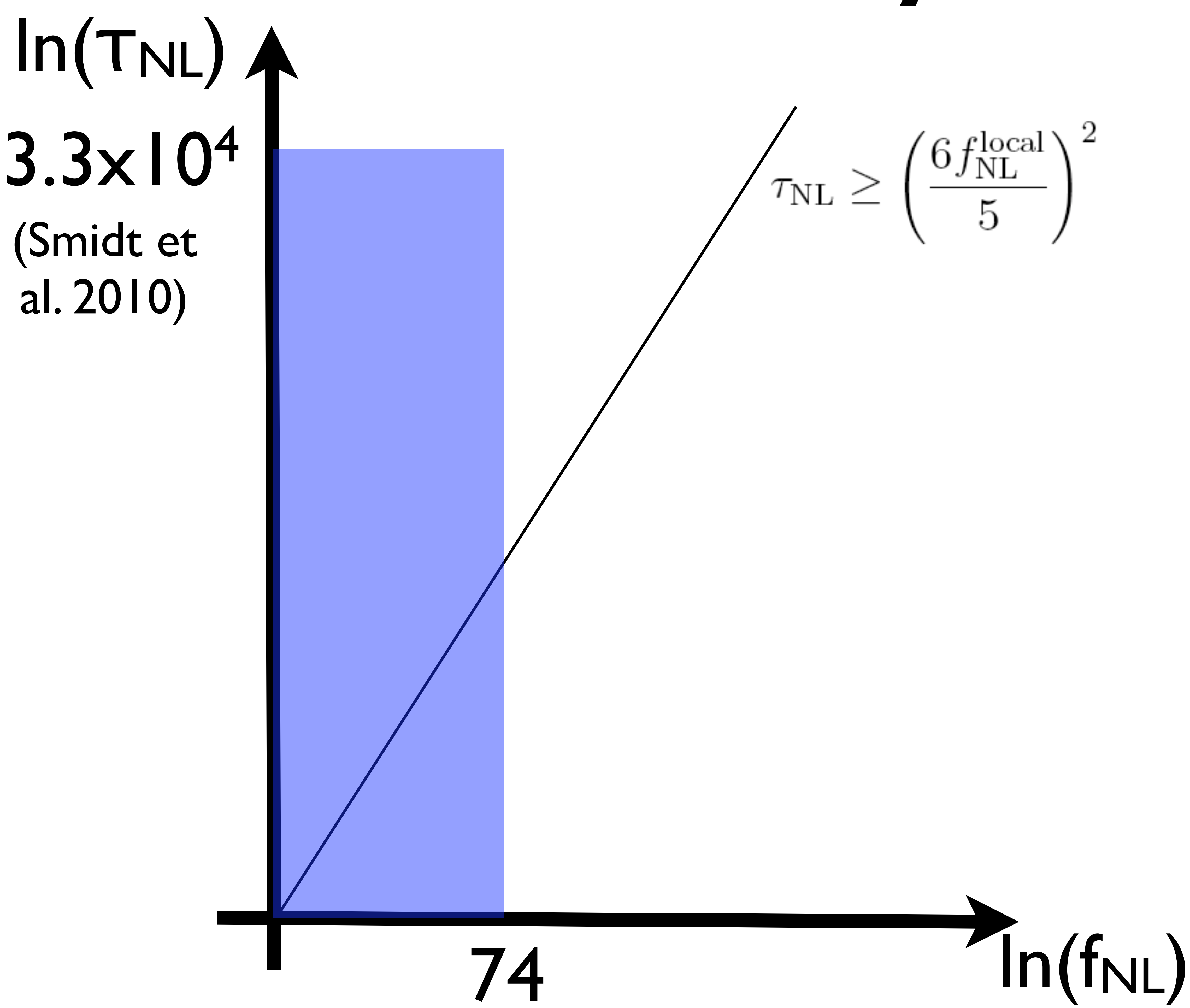


g_{NL}



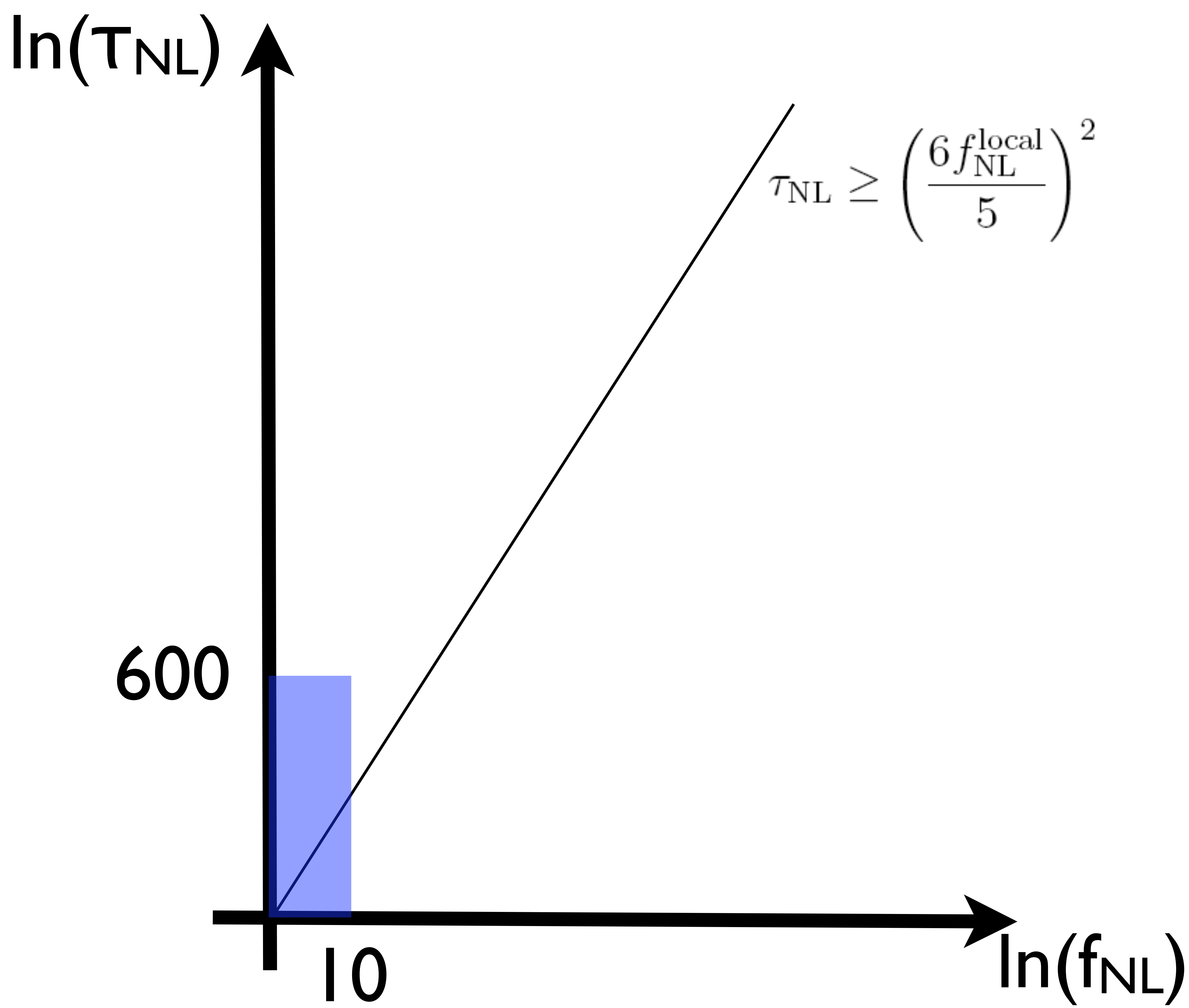
τ_{NL}

The diagram that you should take away from this talk.



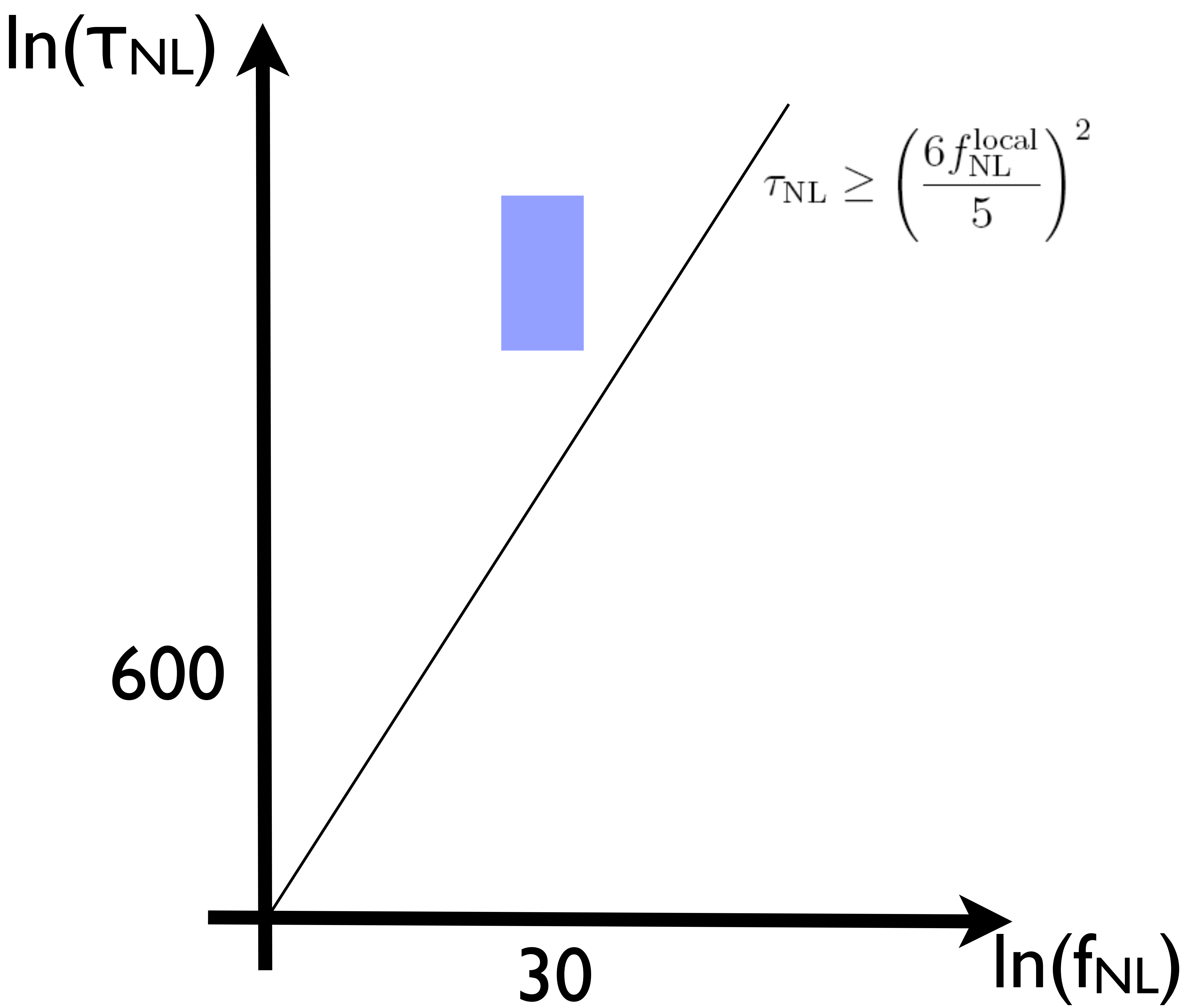
- The current limits from WMAP 7-year are consistent with single-field or multi-field models.
- So, let's play around with the future.

Case A: Single-field Happiness



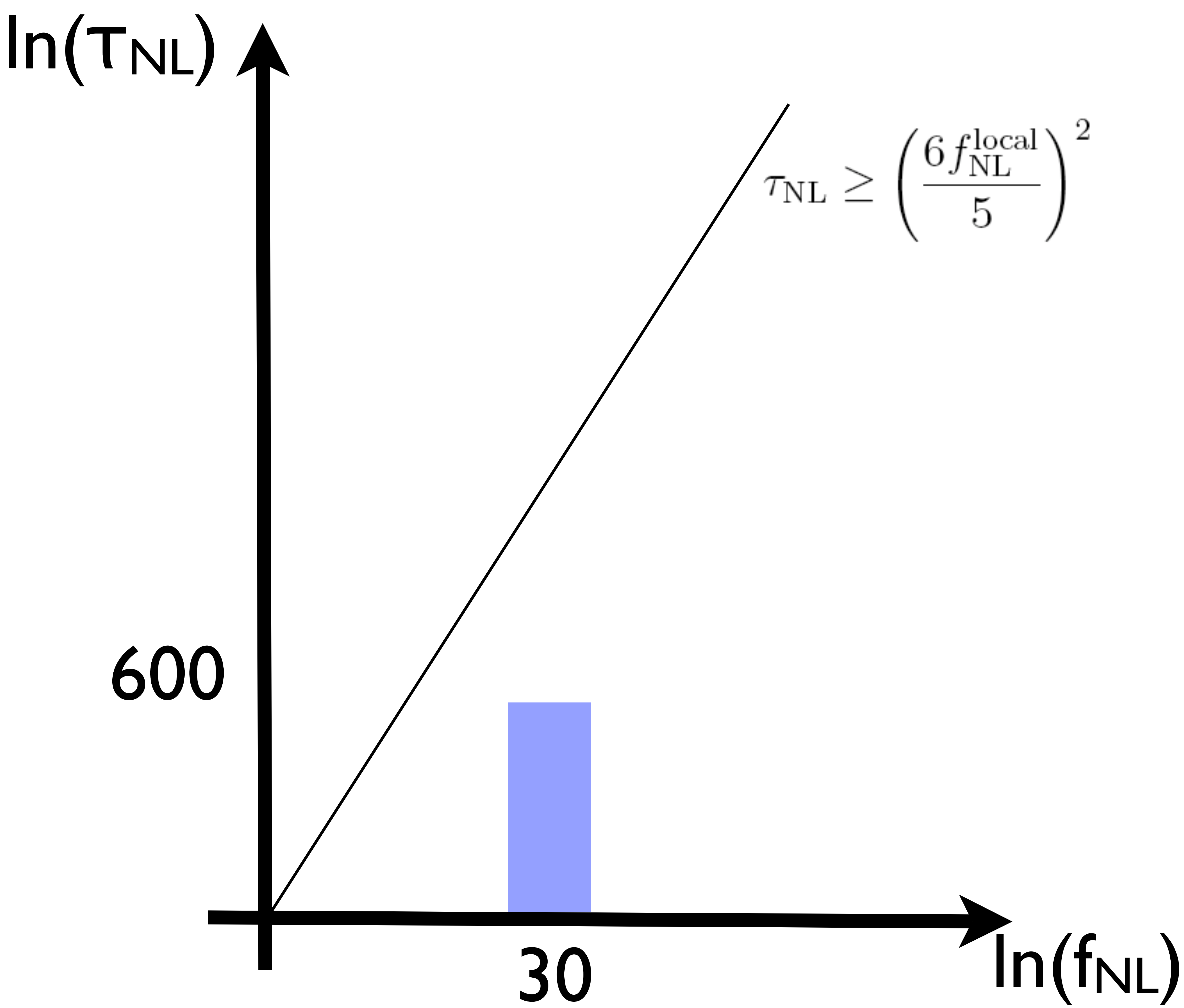
- No detection of anything after Planck. Single-field survived the test (for the moment: the future galaxy surveys can improve the limits by a factor of ten).

Case B: Multi-field Happiness



- f_{NL} is detected. Single-field is dead.
- But, τ_{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

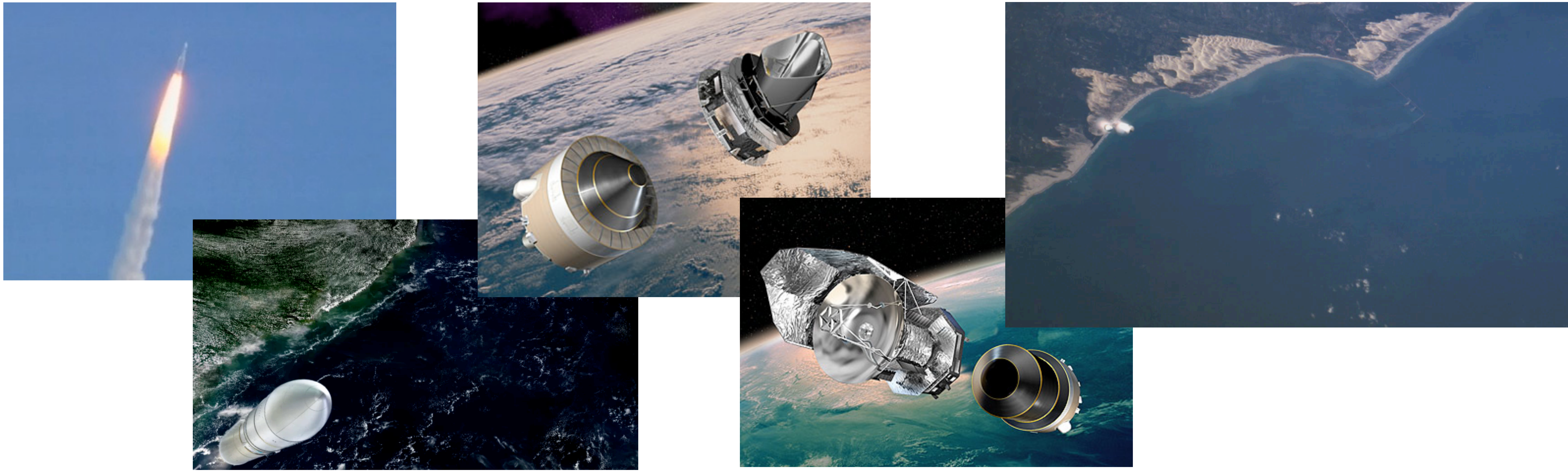


- f_{NL} is detected. Single-field is dead.
- But, τ_{NL} is **not** detected, inconsistent with the Suyama-Yamaguchi inequality.
- (With the caveat that this may not be completely general) BOTH the single-field and multi-field are gone.

CMB: Summary

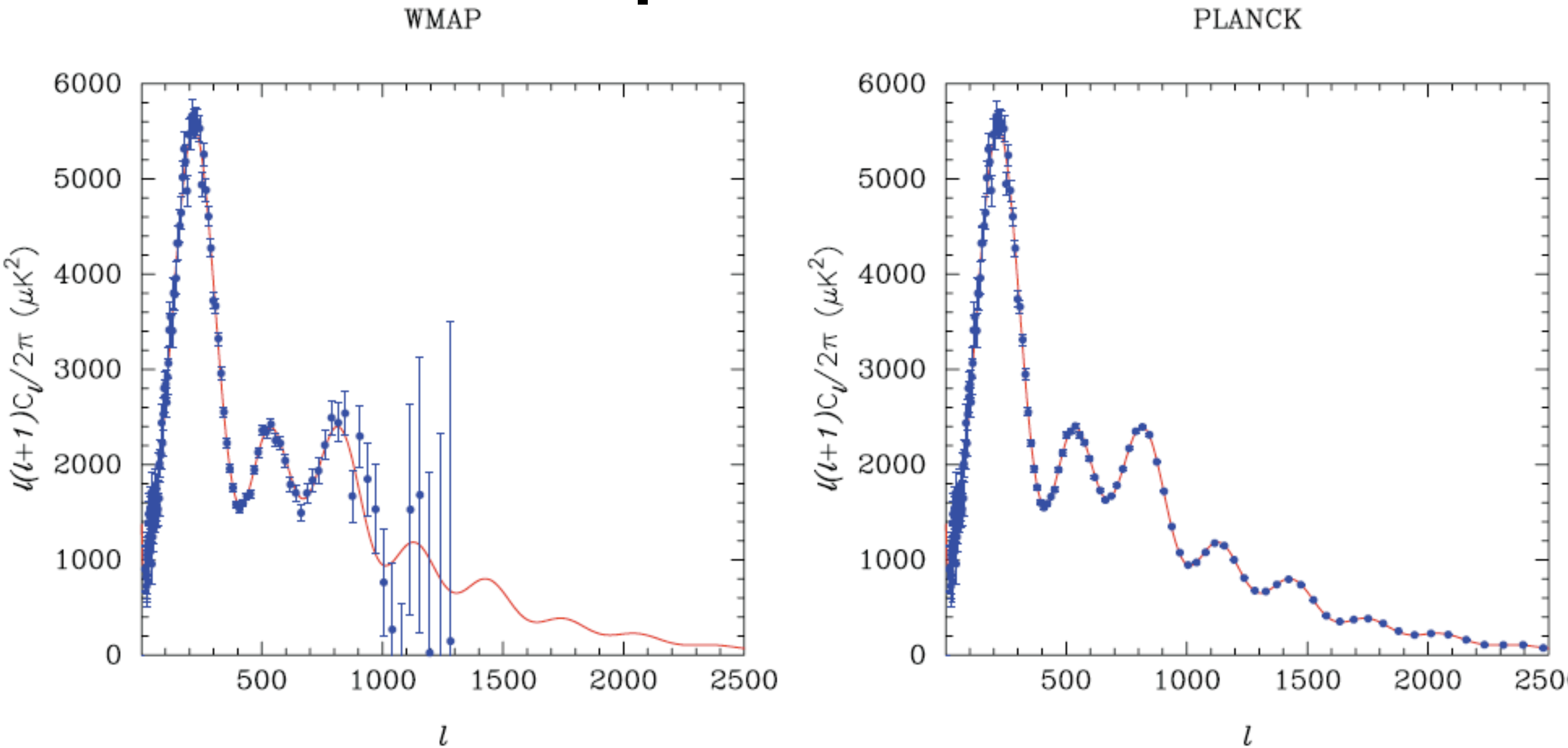
- Primordial helium is detected by CMB alone, for the first time (combining WMAP+ACBAR+QUAD).
- N_{eff}~4? Planck will tell...
- Polarizaion map! Confirmation of the basic paradigm.
- n_s=0.968±0.012 (68%CL); r<0.24 (95%CL)
- Next Big Thing: **Primordial gravitational waves**
- My favorite: **Detection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

Planck Launched!



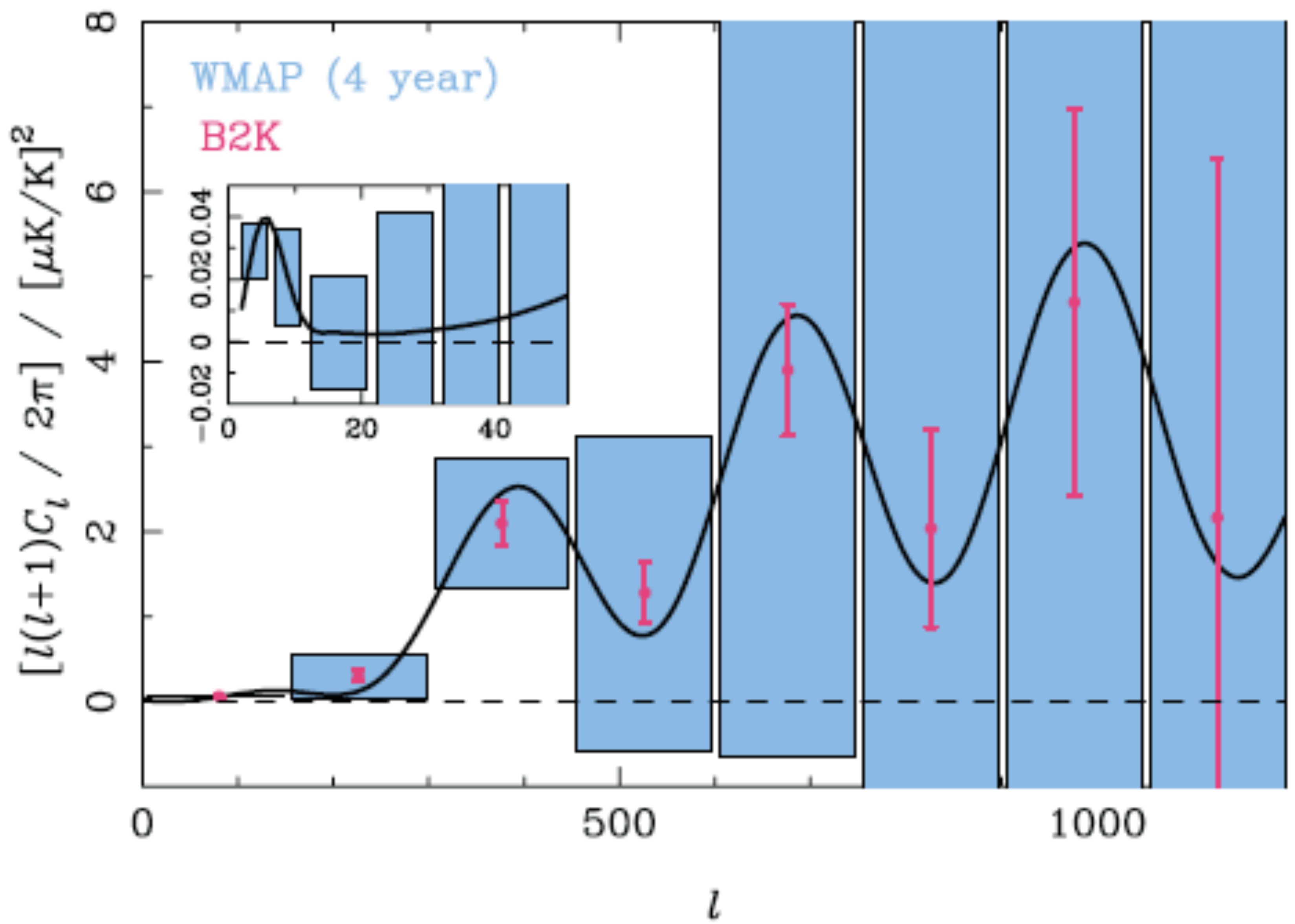
- The Planck satellite was successfully launched from French Guiana on May 14.
- Separation from the Herschell satellite was also successful.
- Planck has mapped the full sky already - results expected to be released in December, 2012.

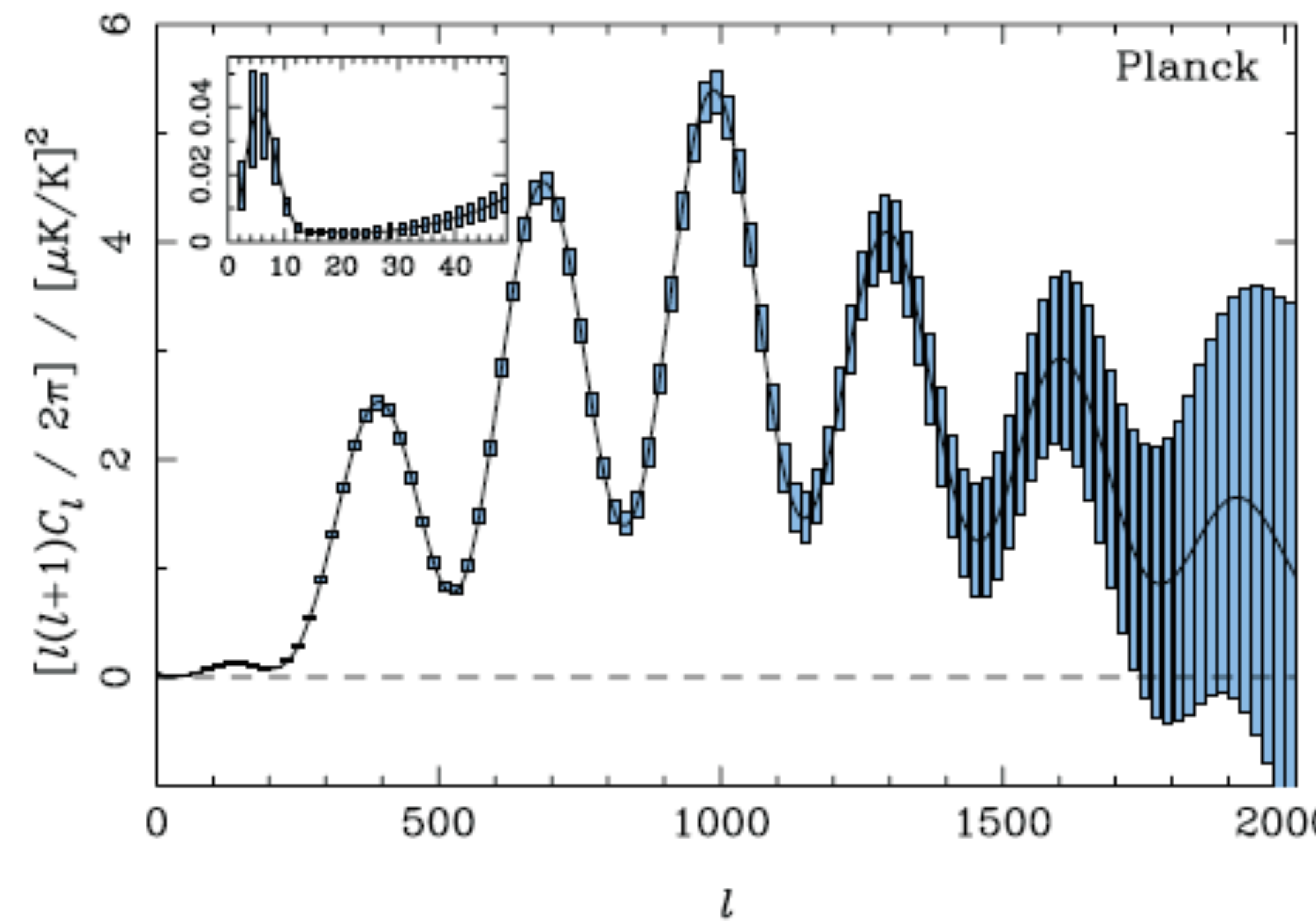
Planck: Expected $C_l^{Temperature}$

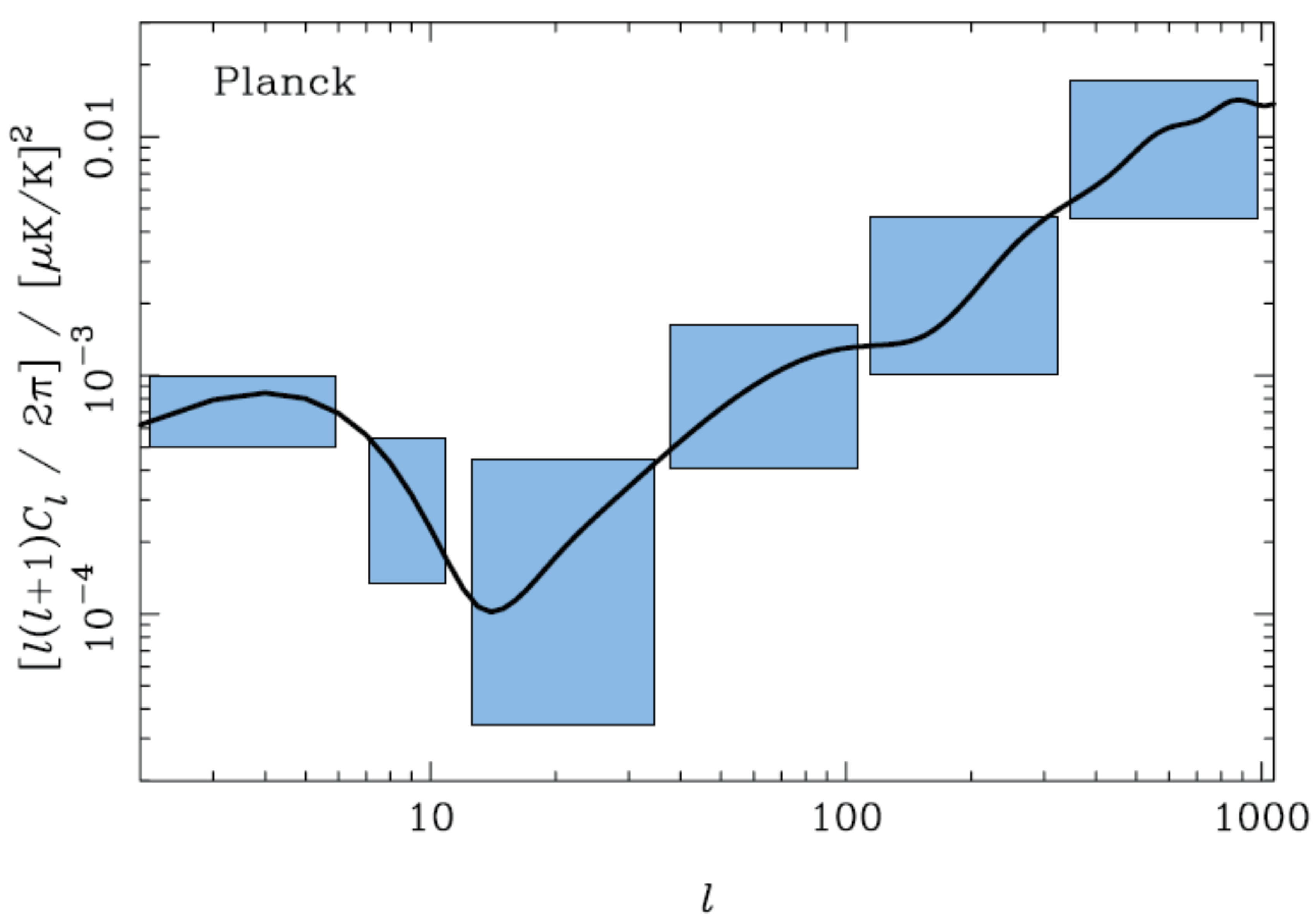


- WMAP: l~1000 => Planck: l~3000

Planck: Expected $C_l^{Polarization}$

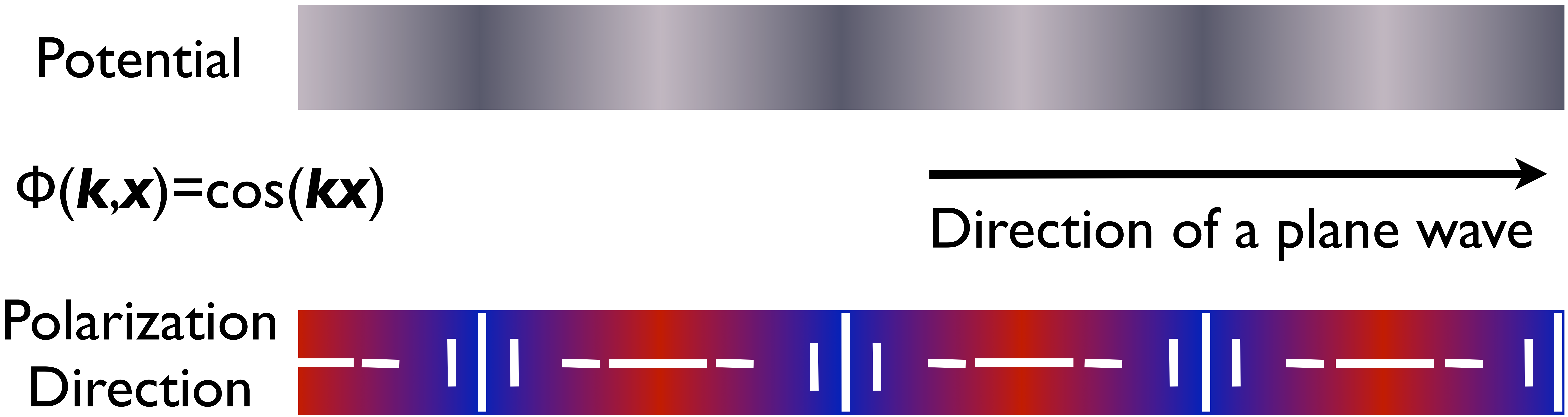






- (Above) E-modes
- (Left) B-modes (r=0.3)

E-mode



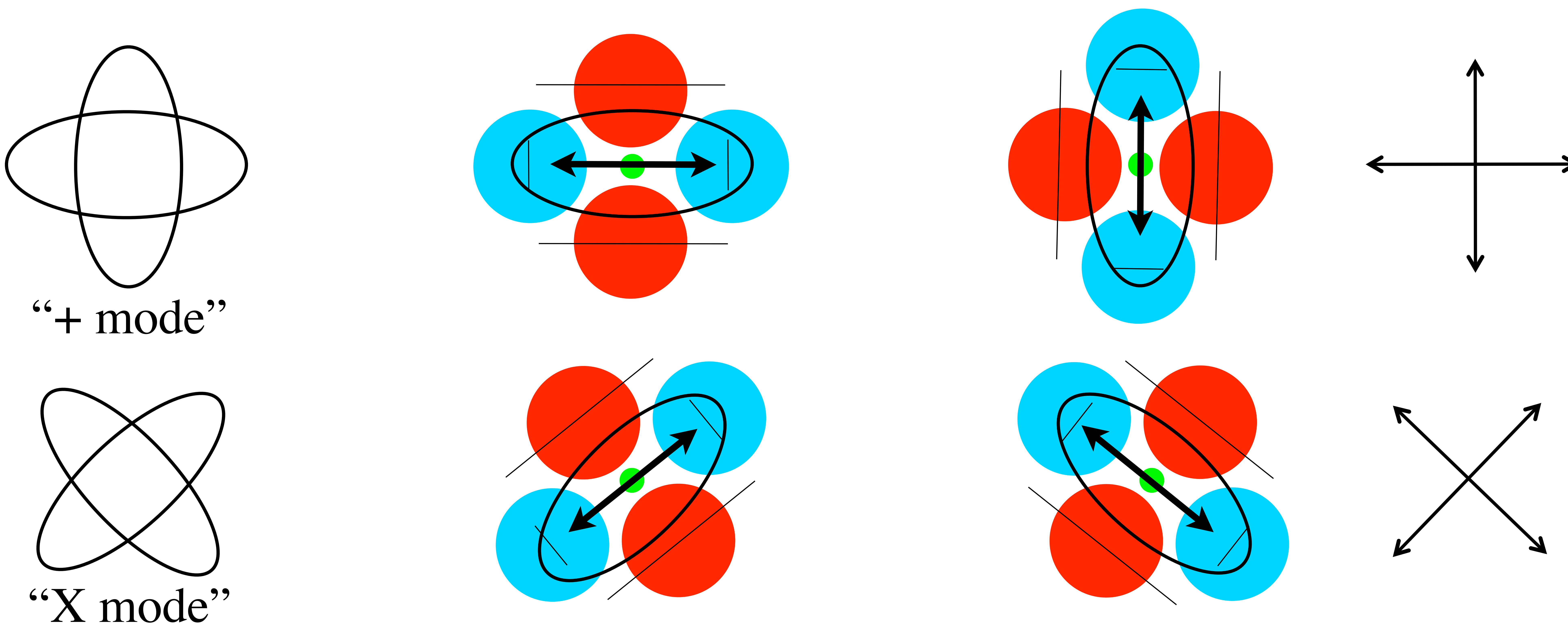
- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

B-mode

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

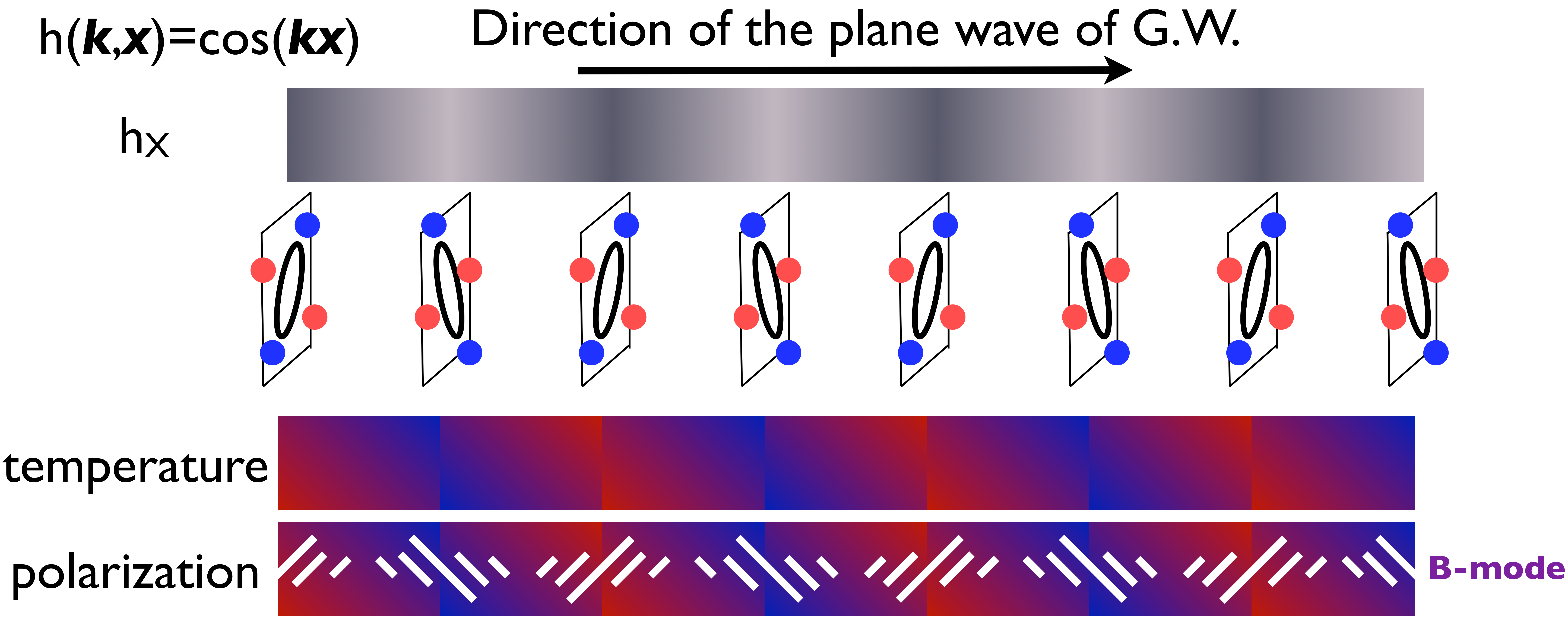
Gravitational Waves and Quadrupole

- Gravitational waves stretch space with a quadrupole pattern.



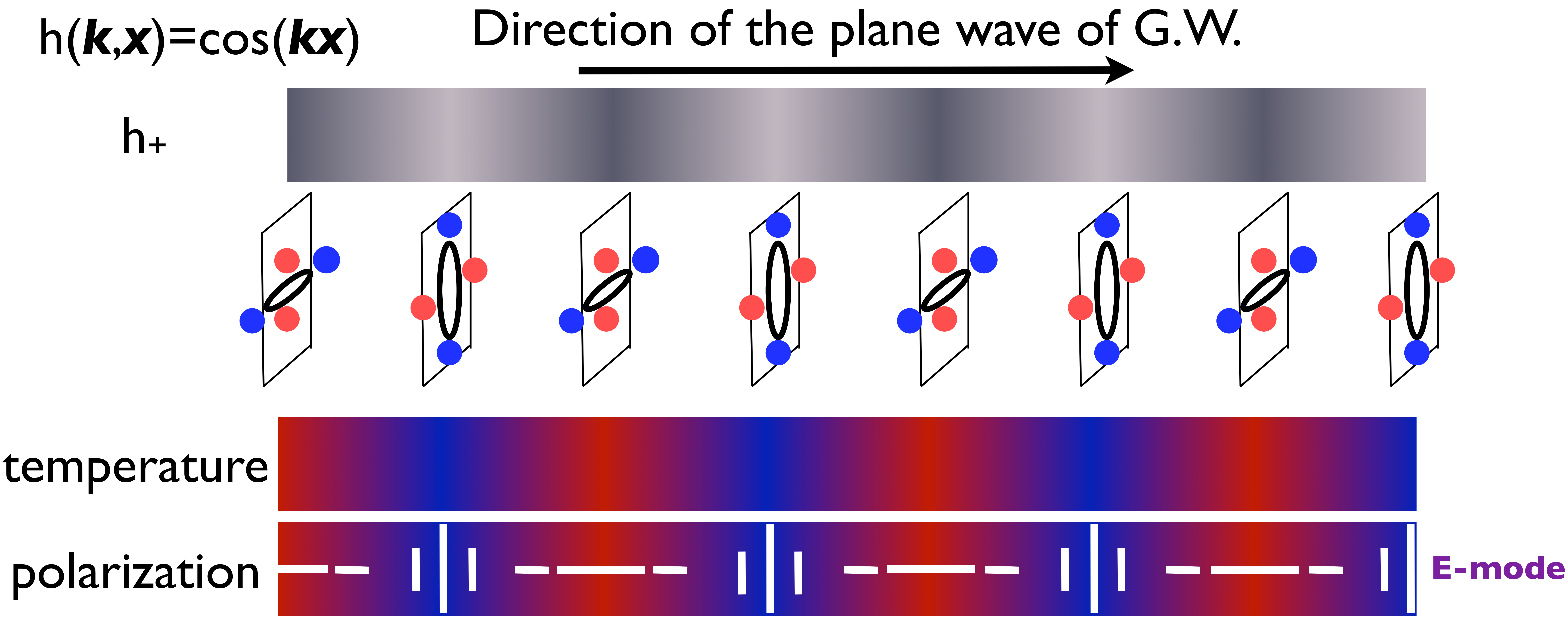
Quadrupole from G.W.

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



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

Quadrupole from G.W.



- E-mode polarization generated by h_+