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

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Seminar, Dark Cosmology Center, Univ. of Copenhagen, May 20, 2010

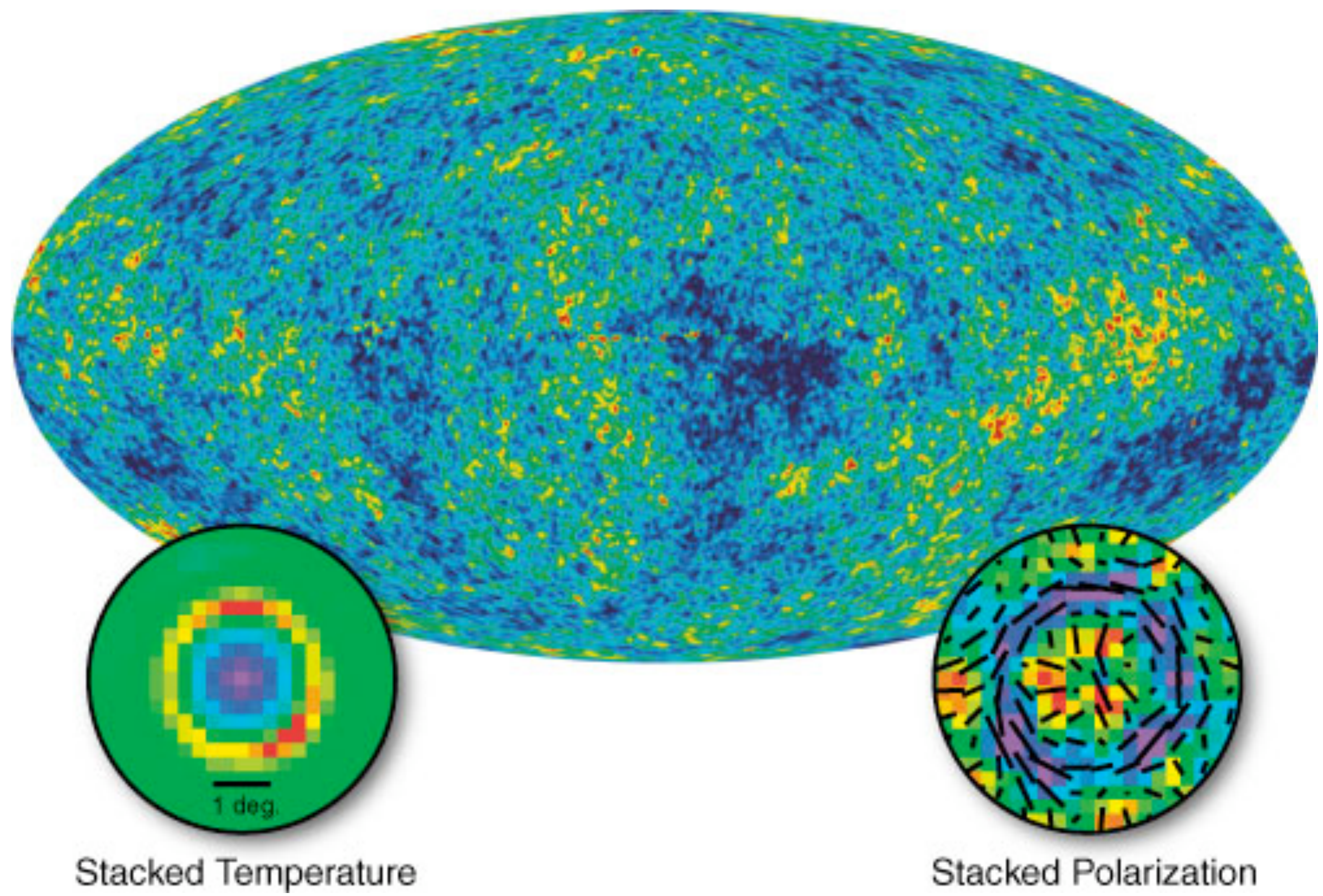
WMAP will have collected 9 years of data by August

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 one at >3σ:
  - n_s=0.96±0.01 (68%CL)
- 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

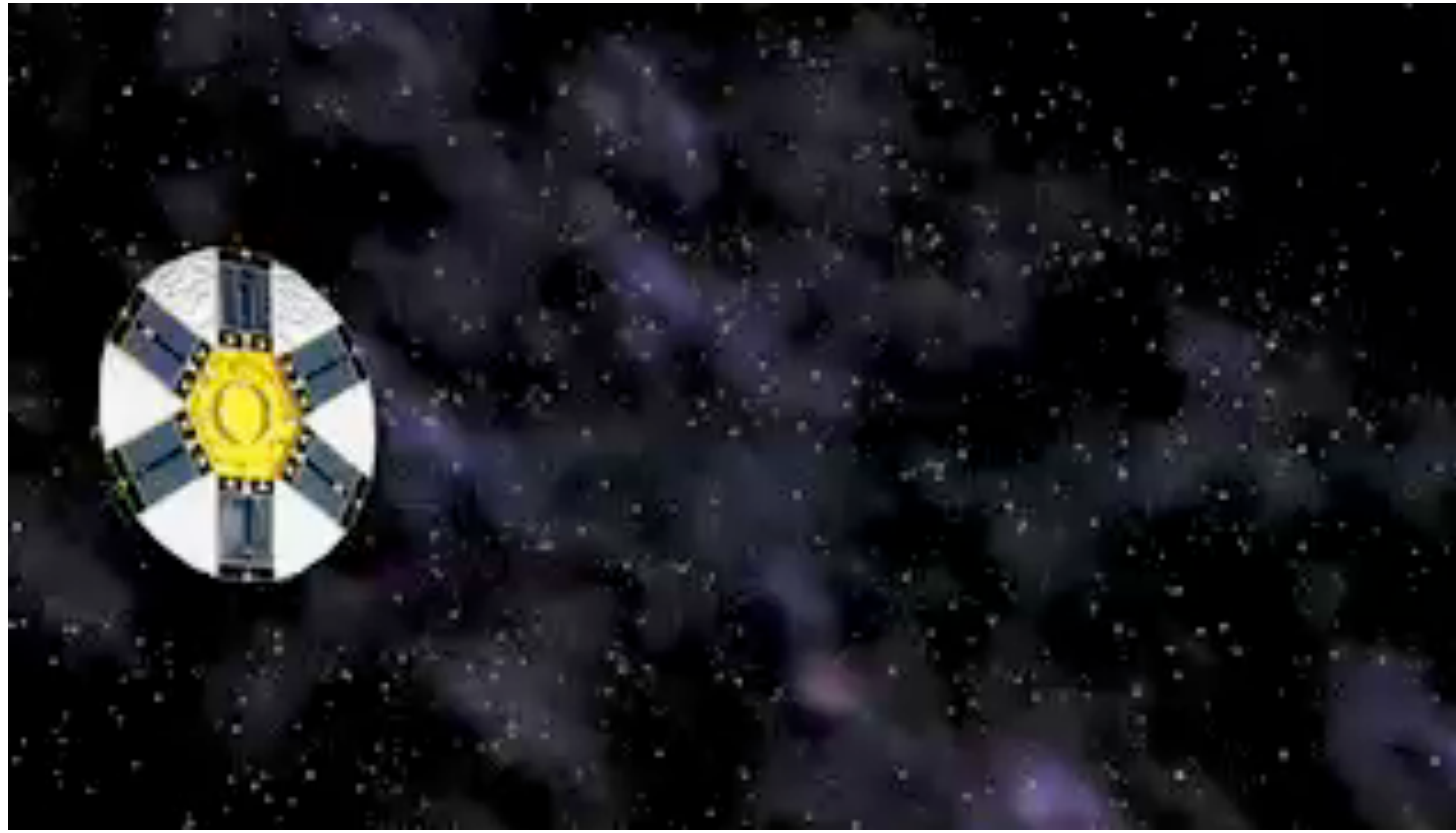
June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release

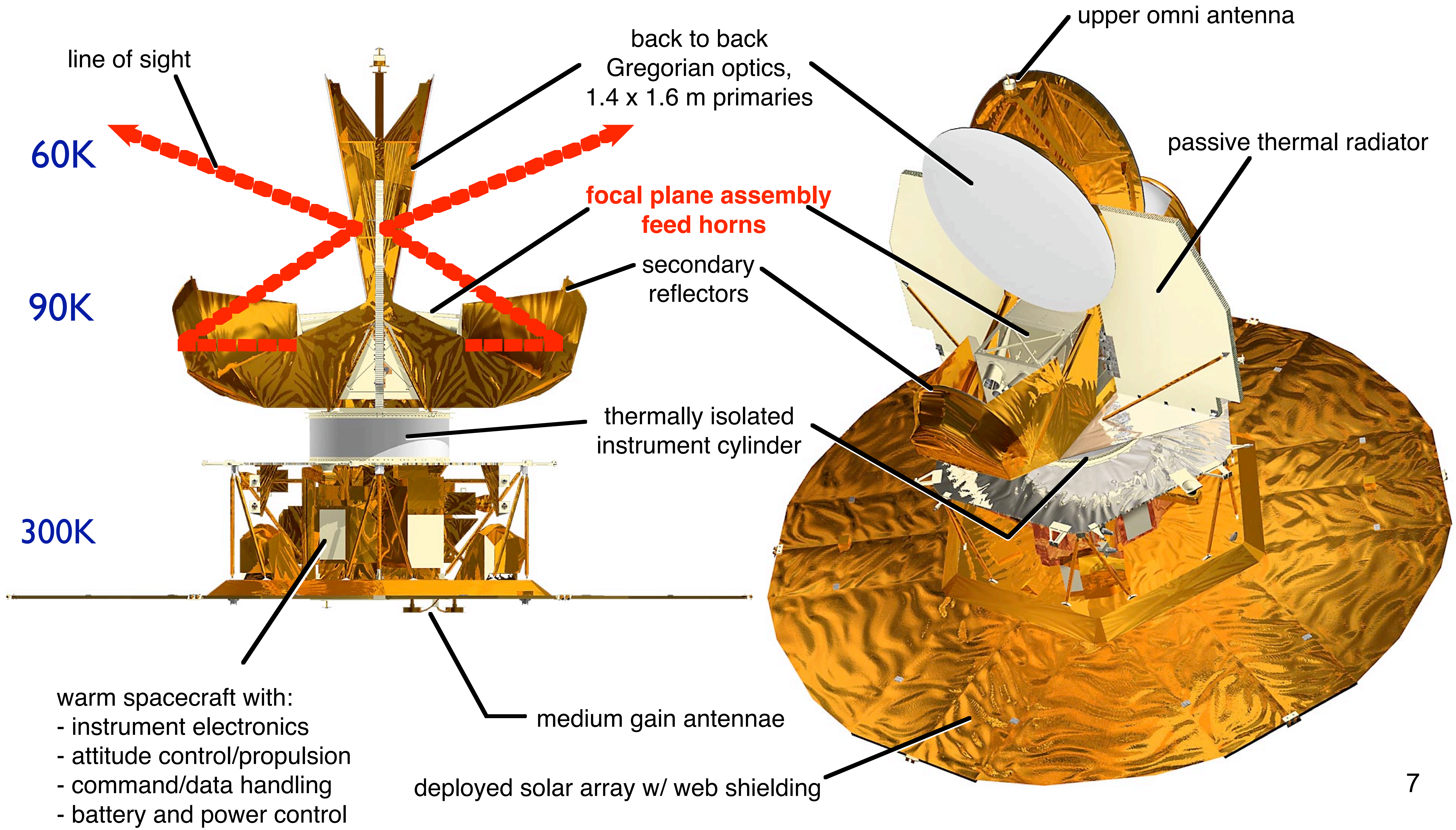
January 2010:
The seven-year data release



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

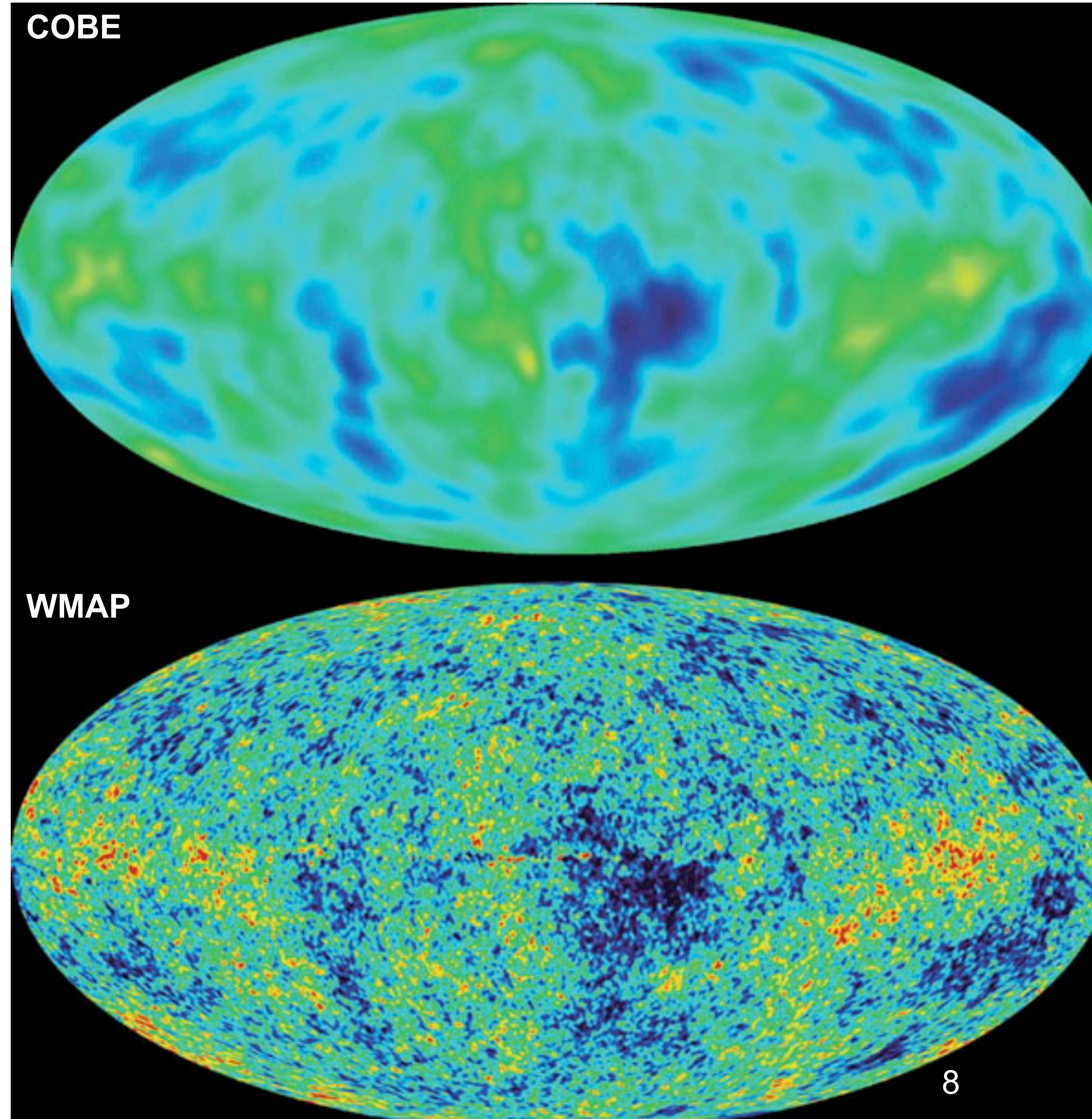
WMAP Spacecraft

Radiative Cooling: No Cryogenic System

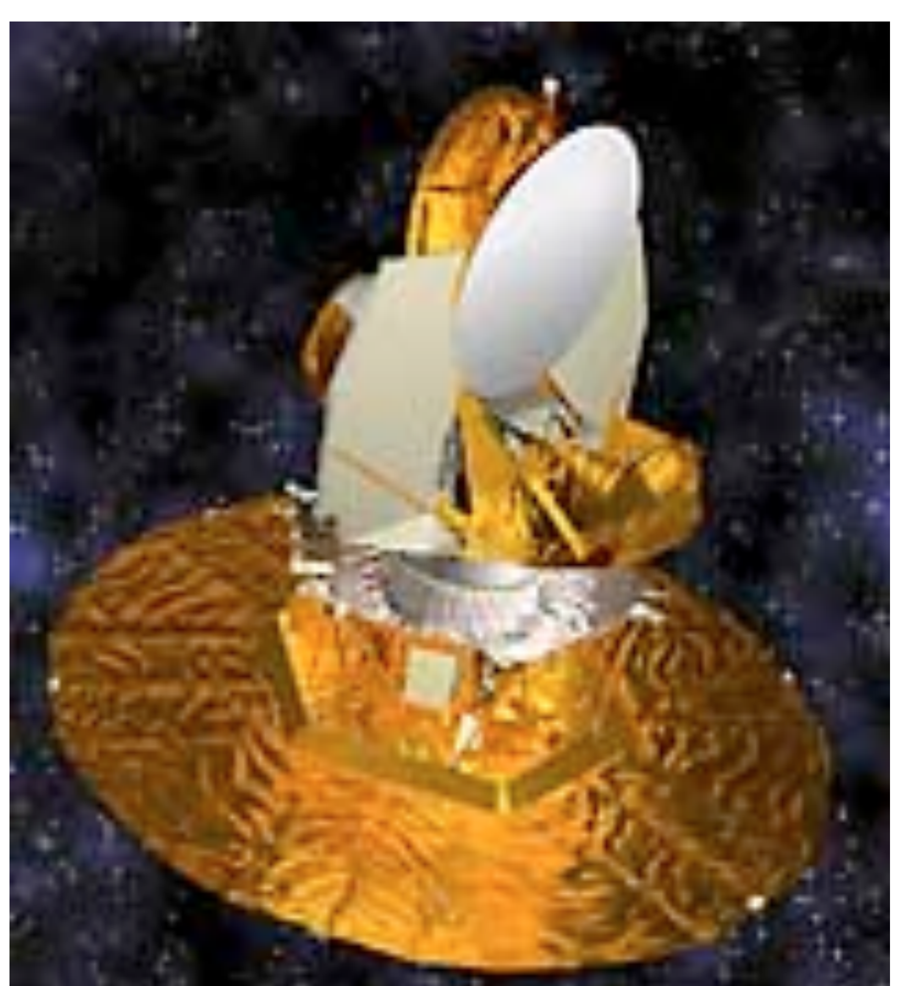


COBE to WMAP (x35 better resolution)

COBE
1989

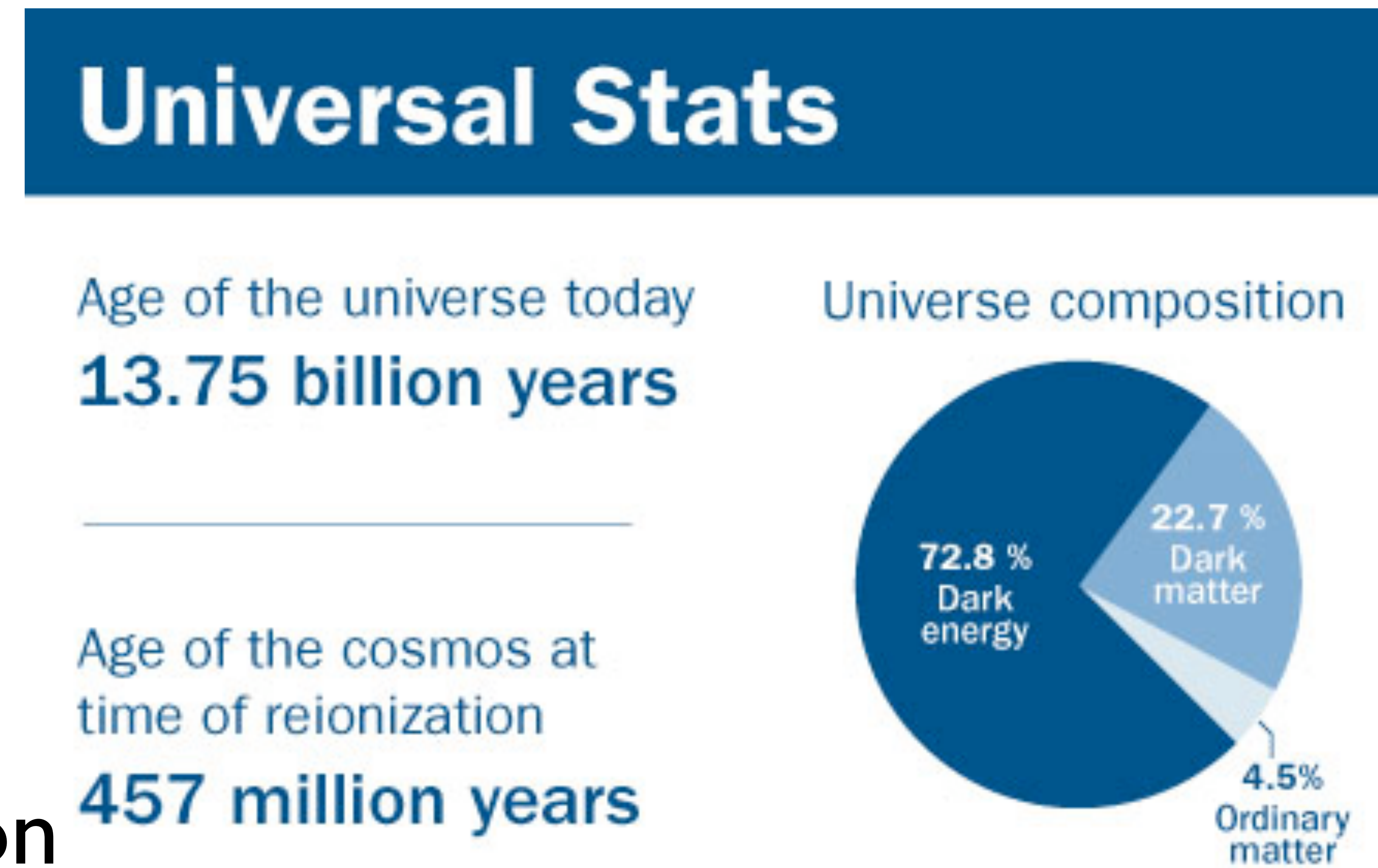


WMAP
2001

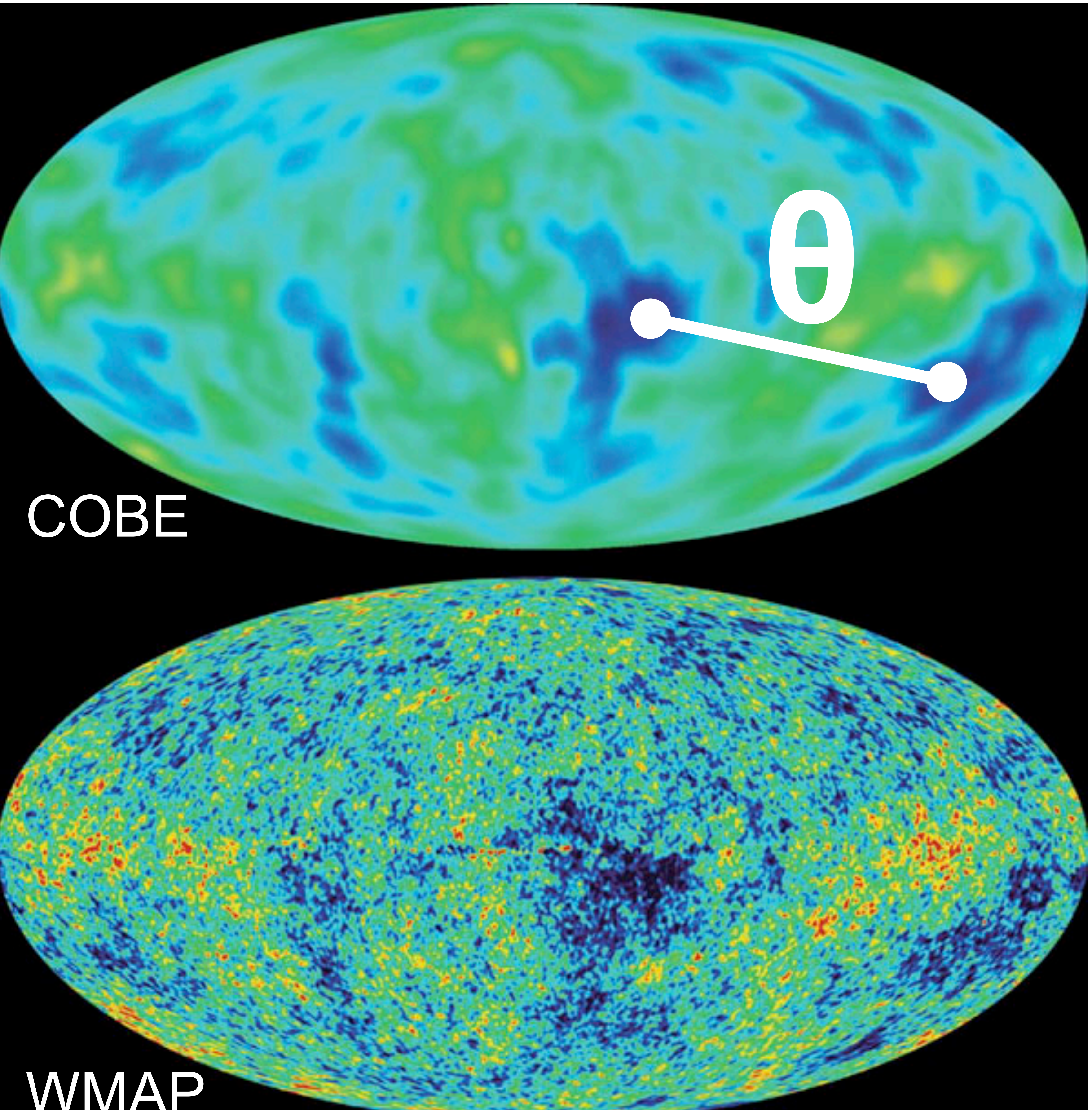


Cosmology Update: 7-year

- **Standard Model**
  - H&He = 4.56% (±0.16%)
  - Dark Matter = 27.2% (±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)

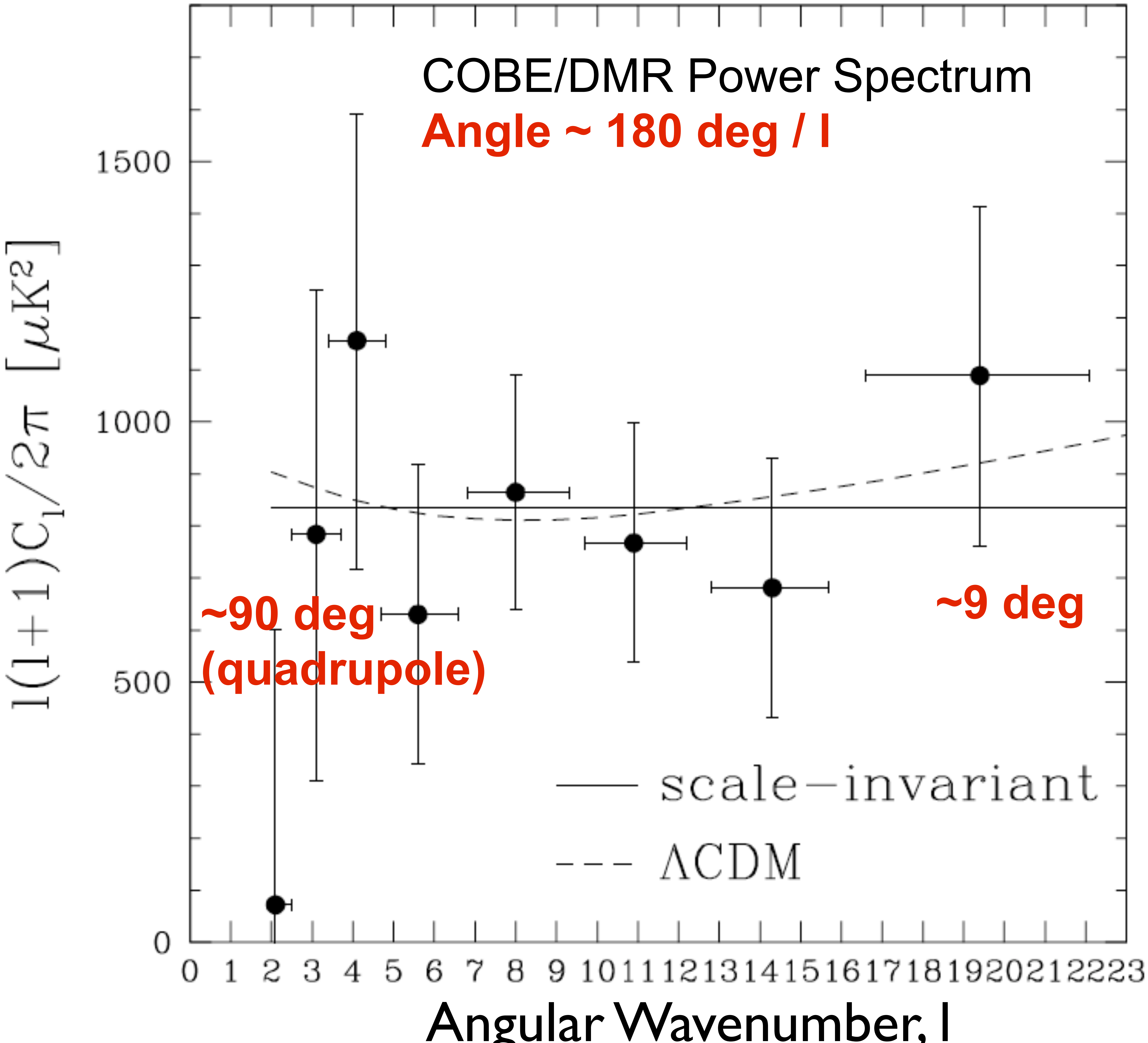


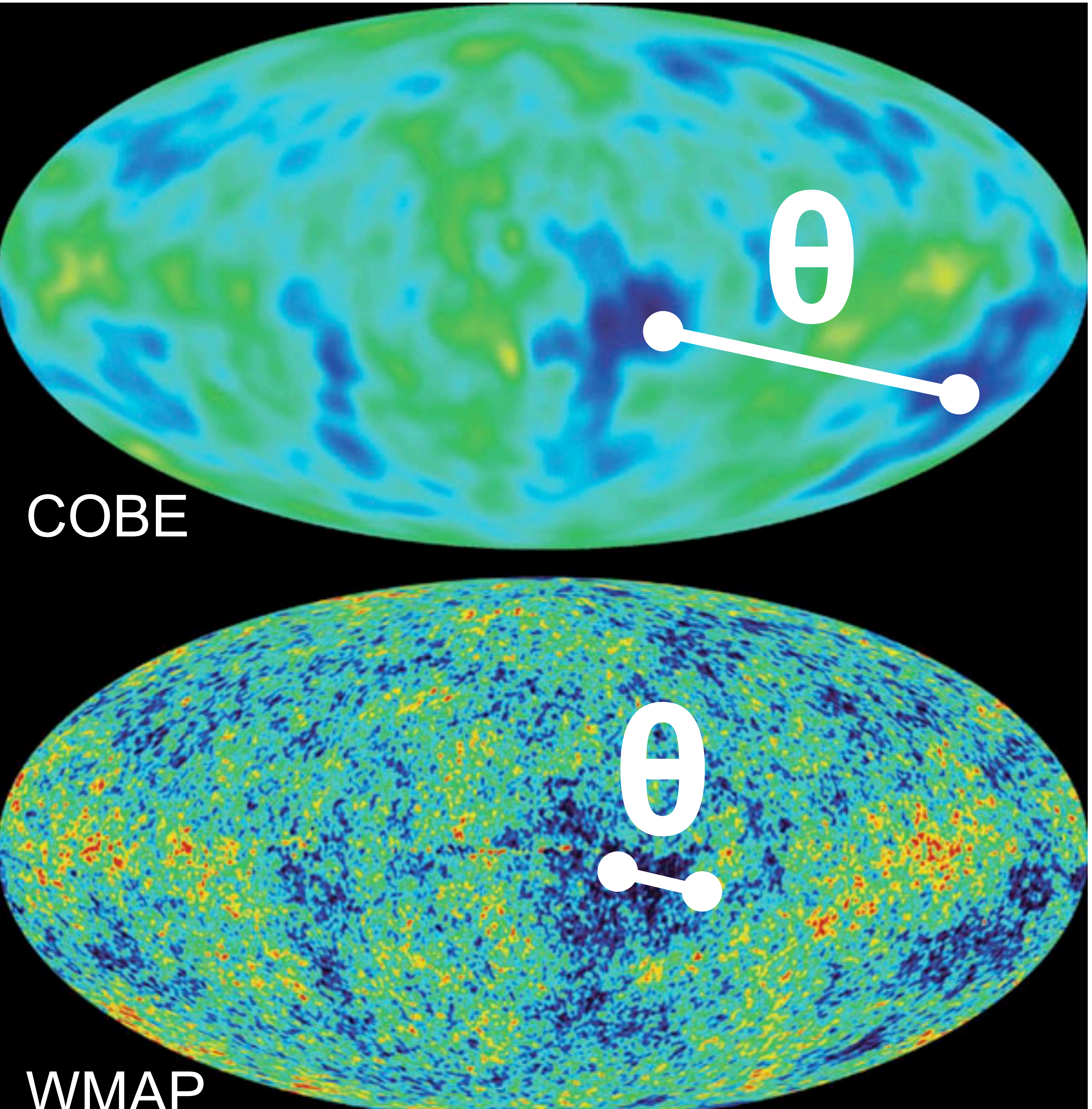
"ScienceNews" article on the WMAP 7-year results



Analysis: 2-point Correlation

- $C(\theta)=(1/4\pi)\sum(2l+1)C_l P_l(\cos\theta)$
- How are temperatures on two points on the sky, separated by θ, are correlated?
- **"Power Spectrum," C_l**
  - How much fluctuation power do we have at a given angular scale?
  - **l~180 degrees / θ**

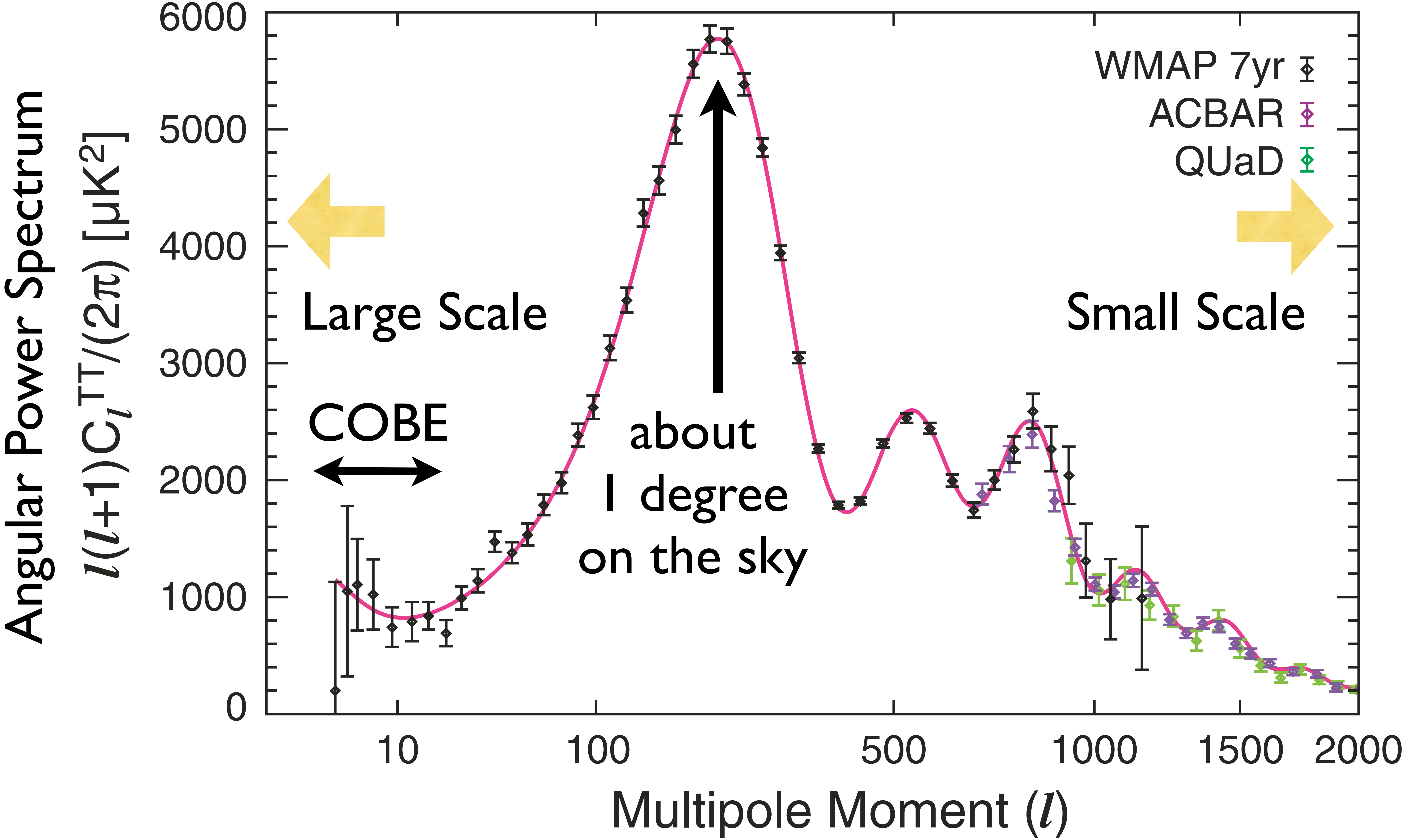

COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
l(l+1)C_l/2π [μK^2]
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Angular Wavenumber, l



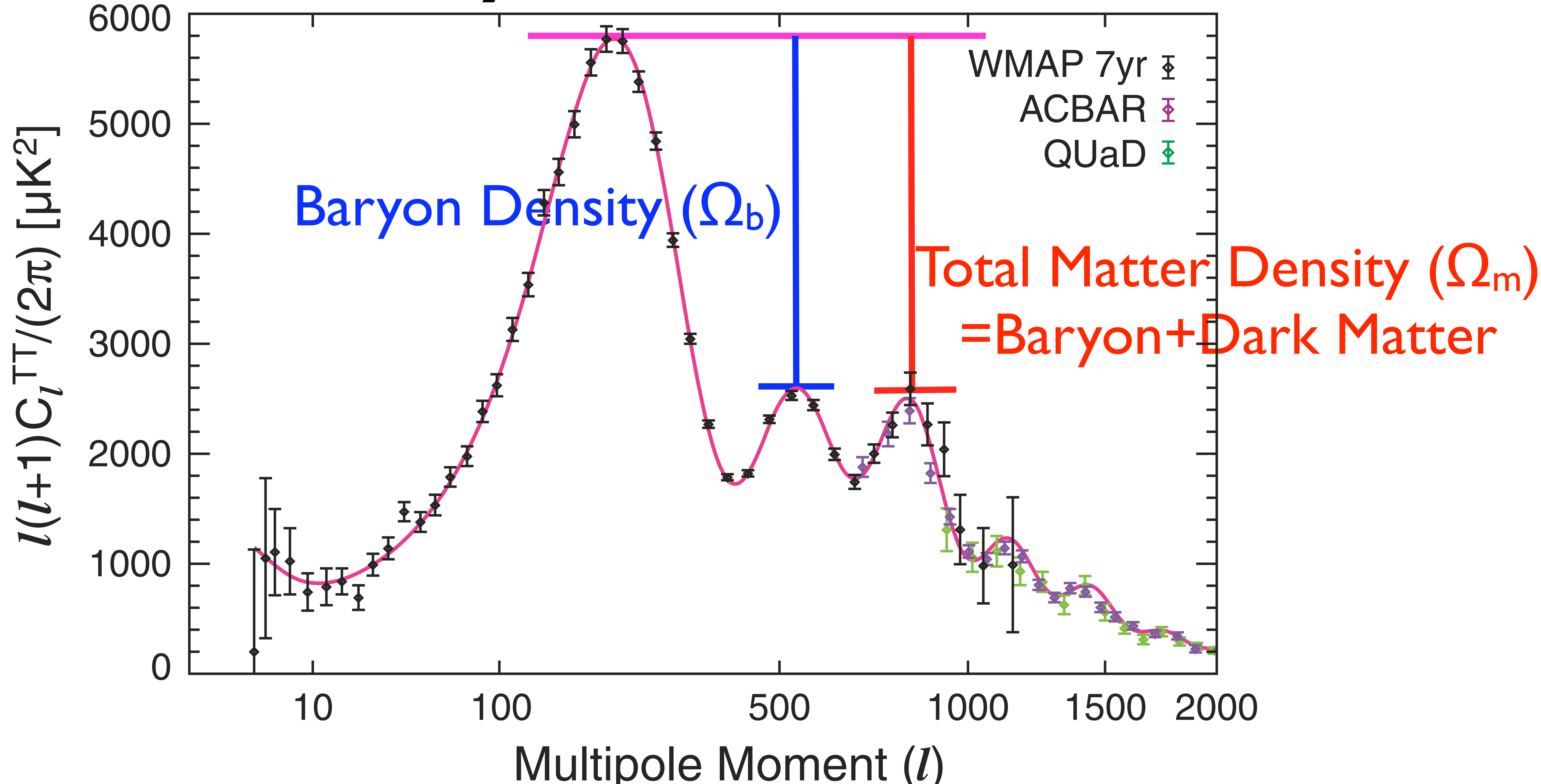
COBE To WMAP

- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP Power Spectrum

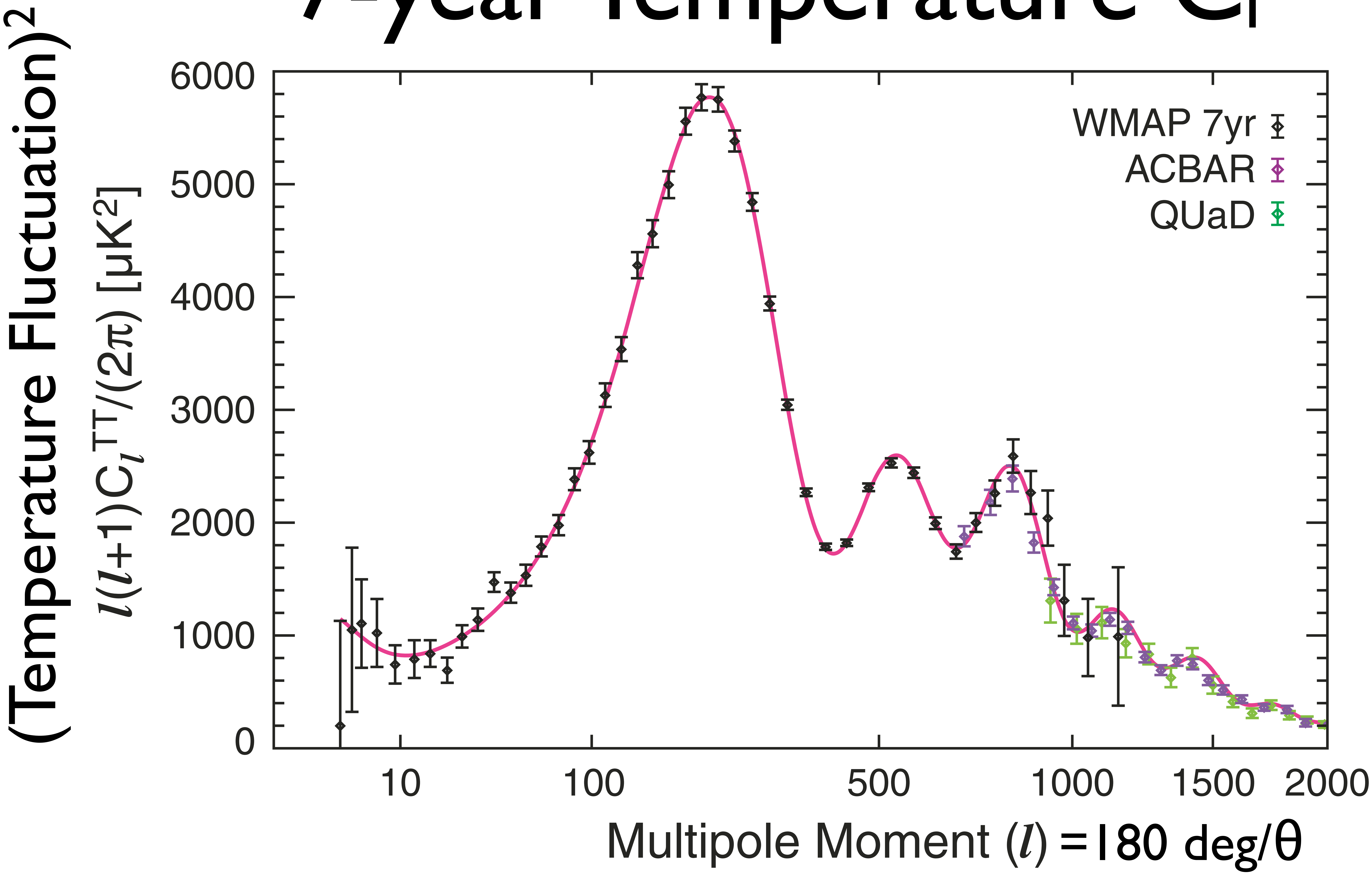


CMB to Baryon & Dark Matter

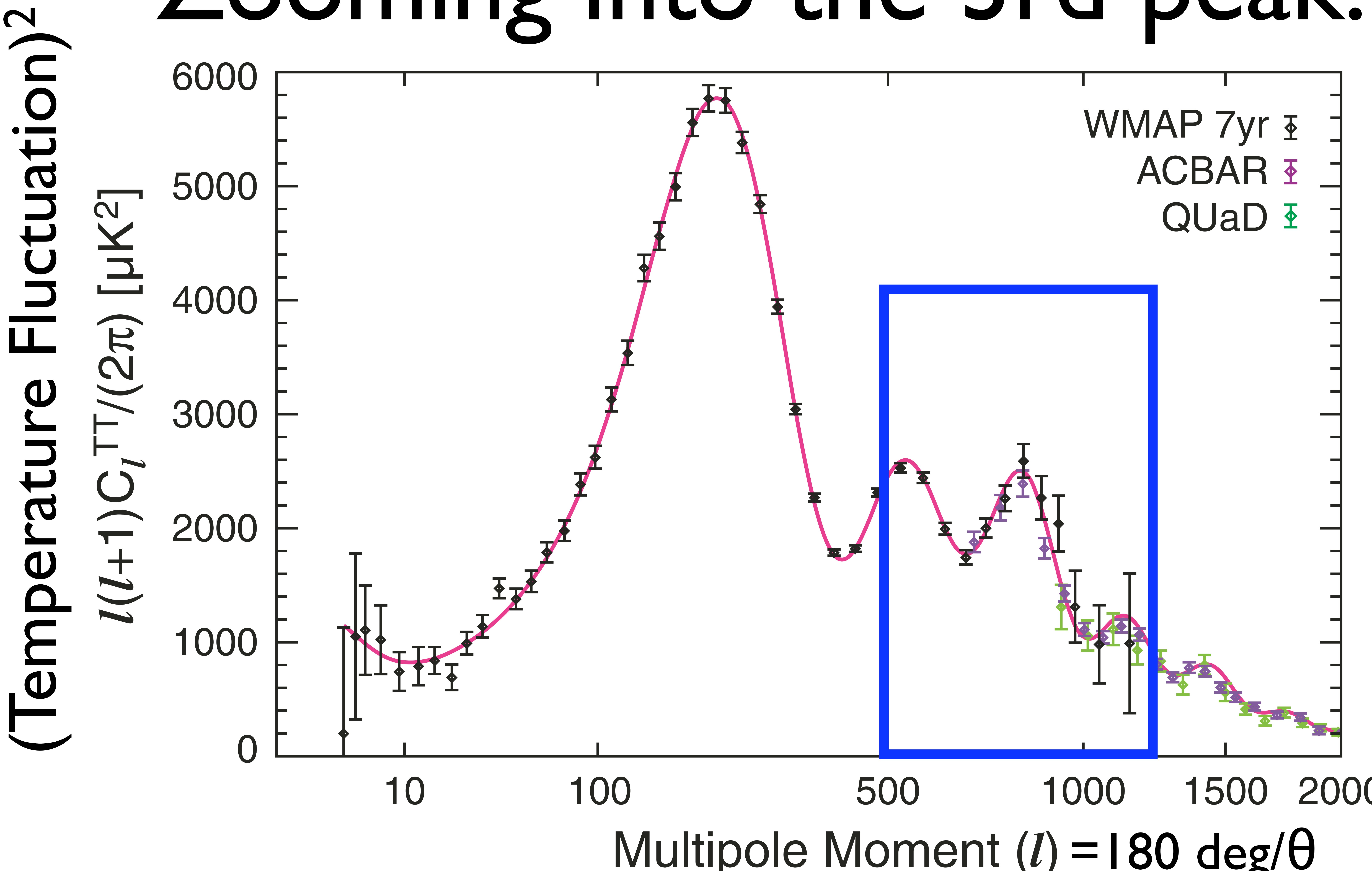


- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio (z_{EQ}: equality redshift)

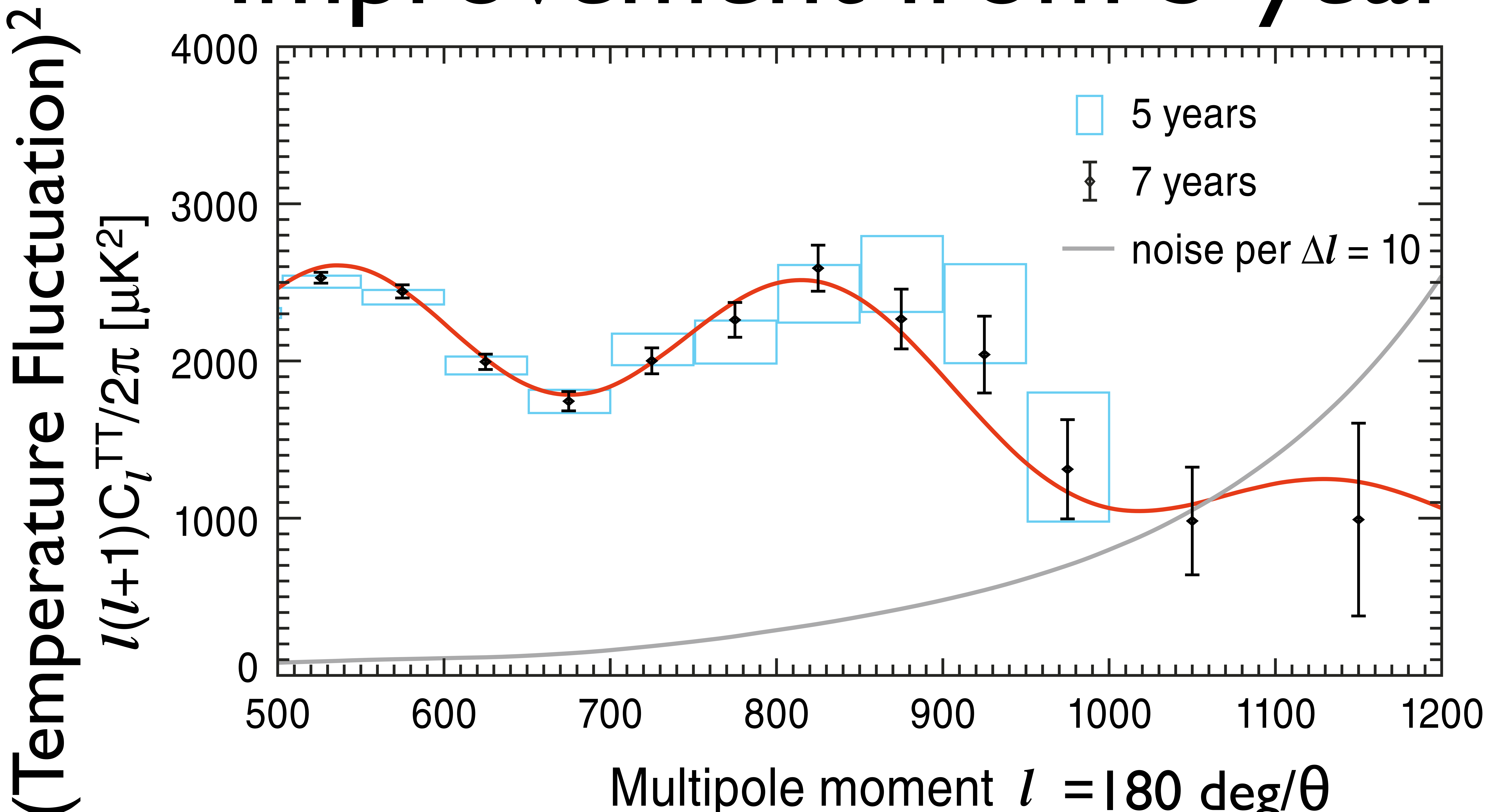
7-year Temperature C_l



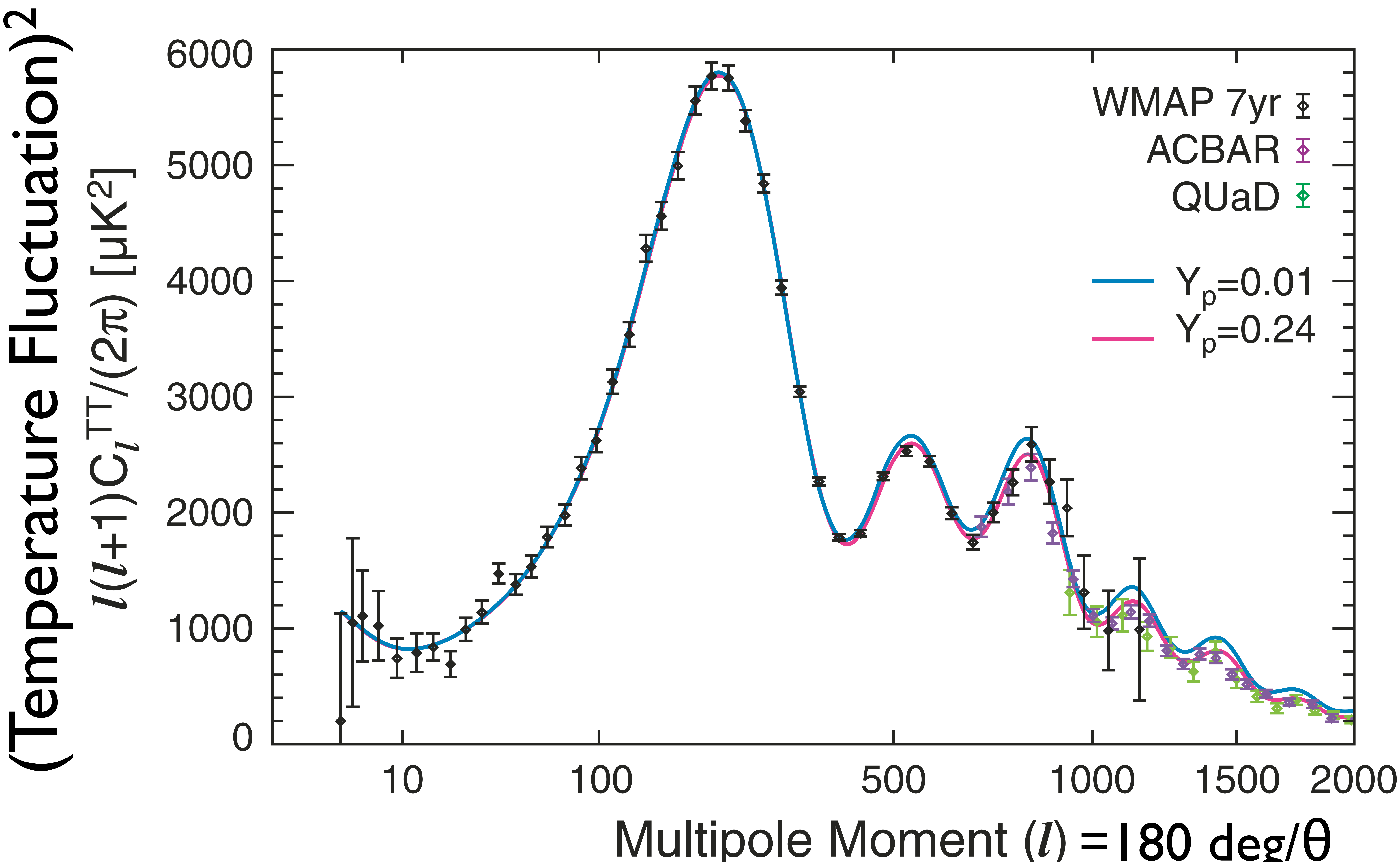
Zooming into the 3rd peak...



High-l Temperature C$_l$: Improvement from 5-year



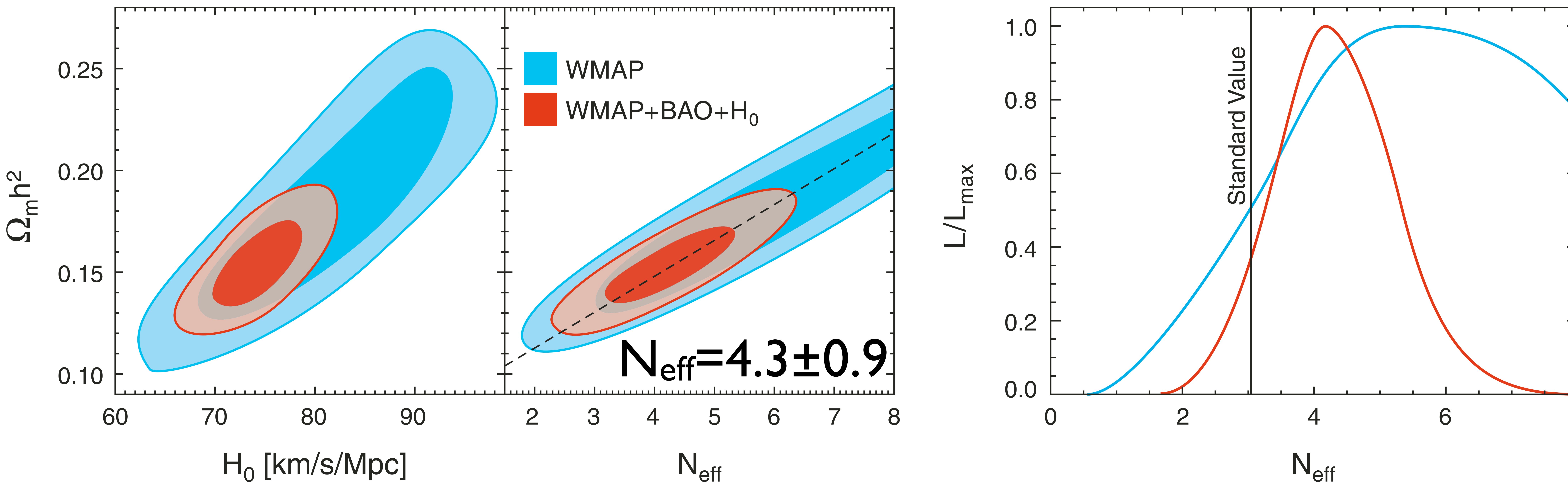
Detection of Primordial Helium



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**.

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

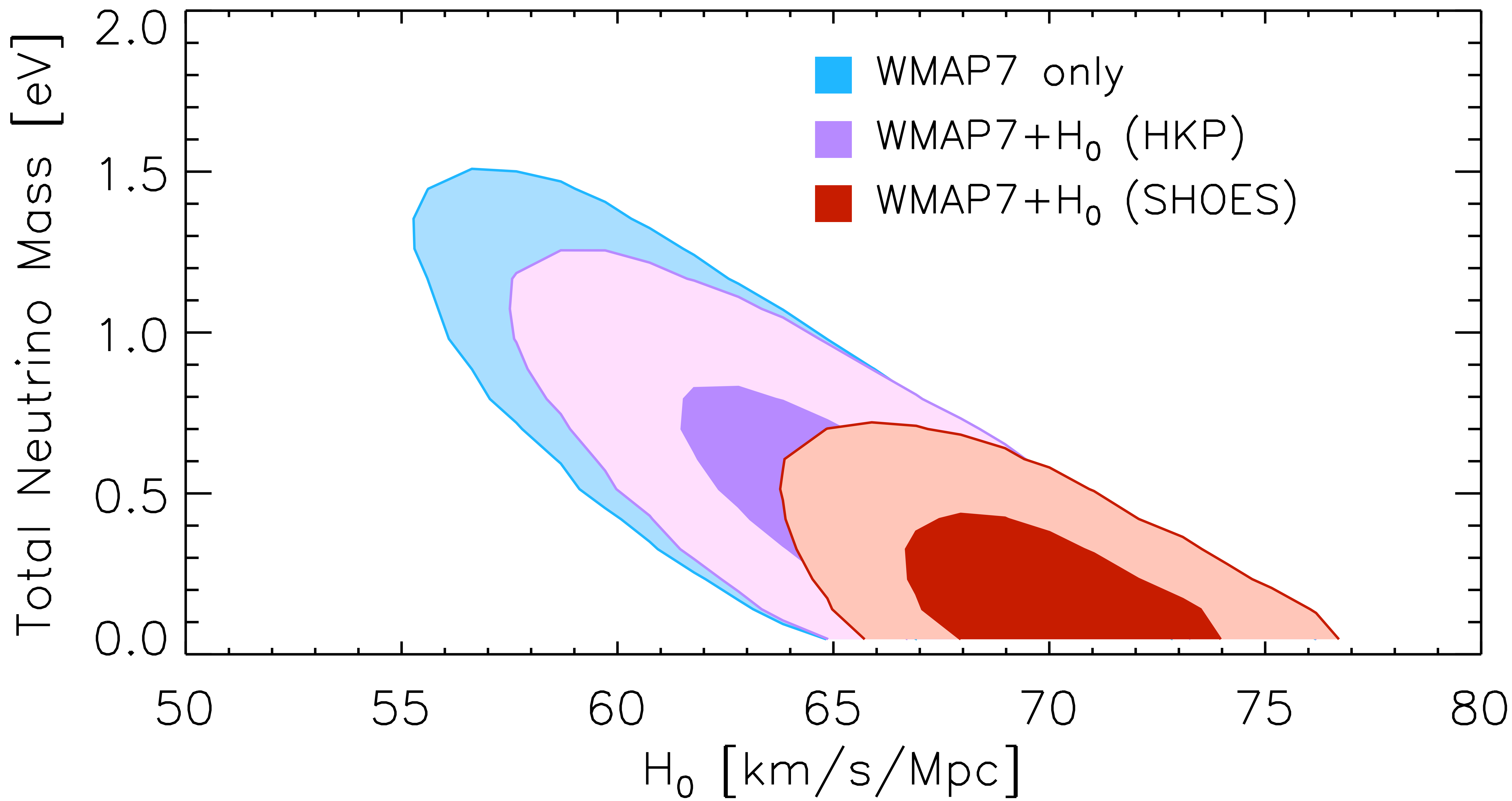


from external data

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

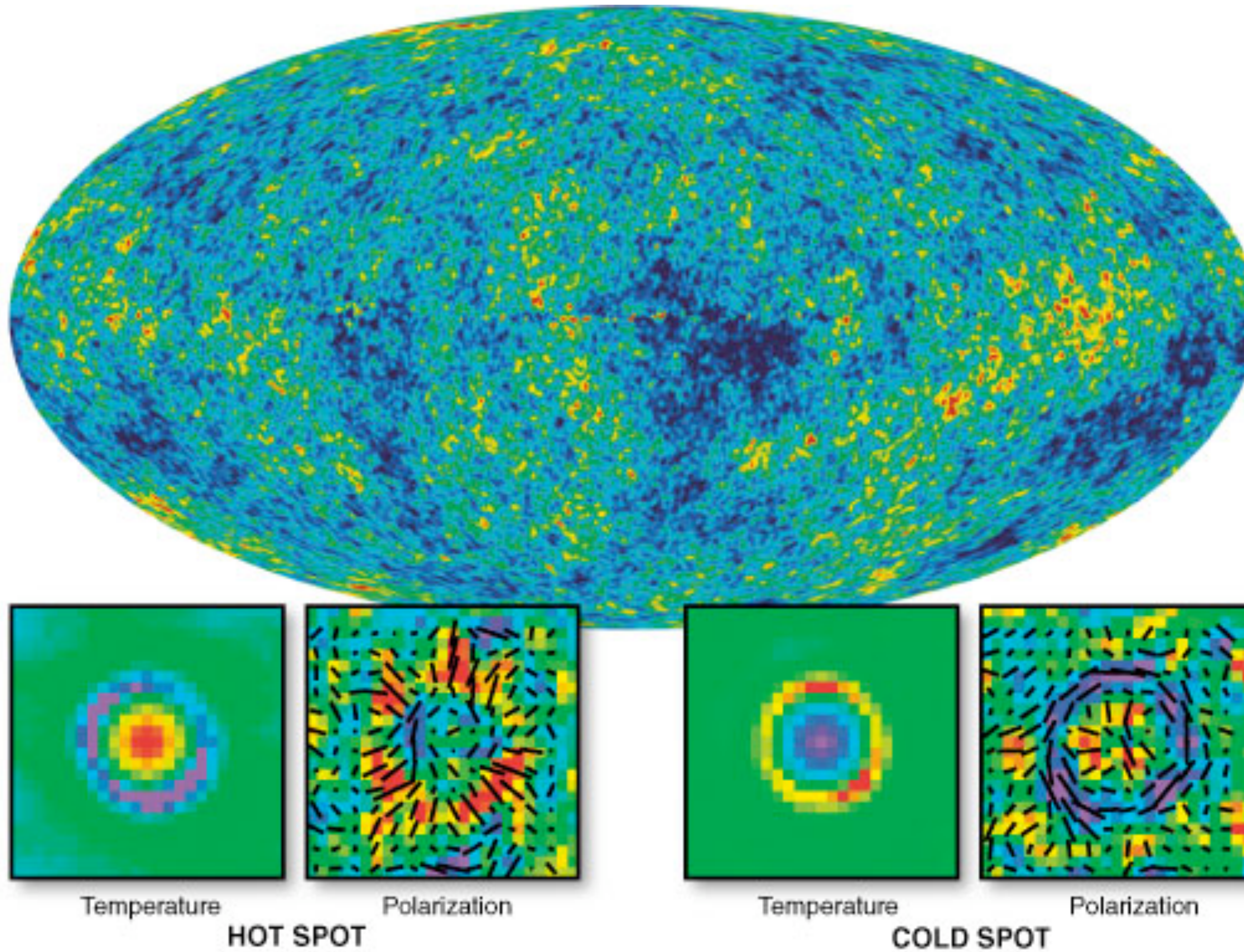
from 3rd peak

And, the mass of neutrinos



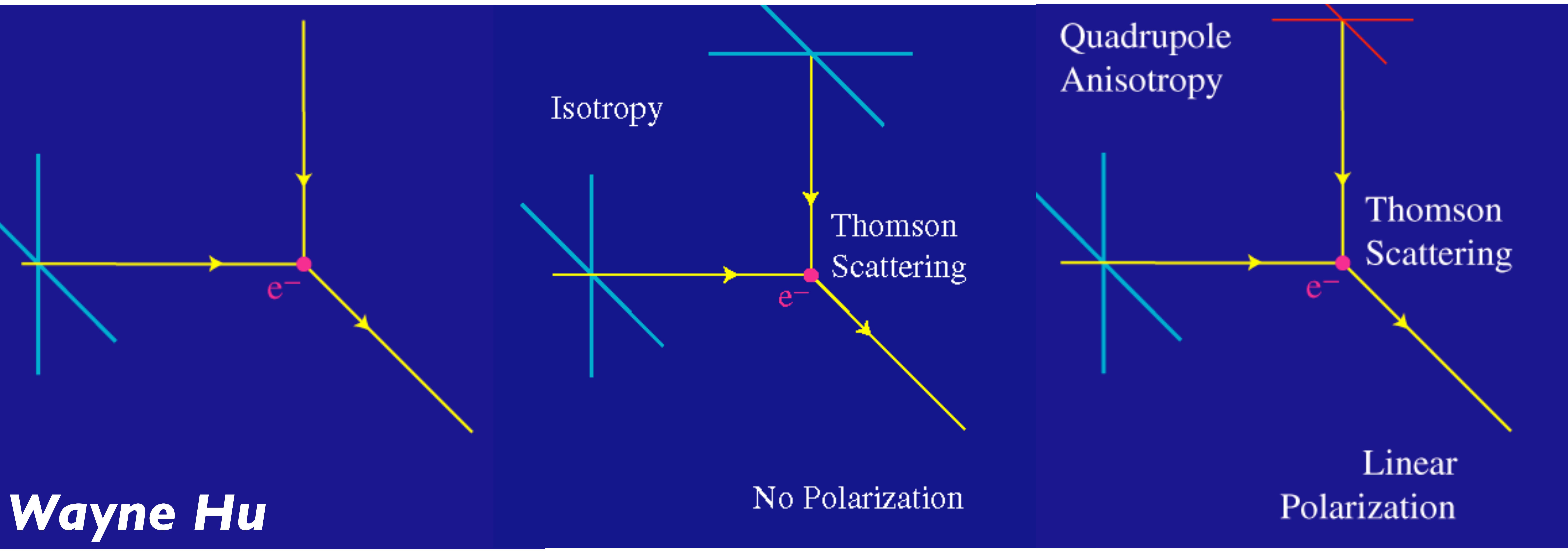
- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

CMB Polarization



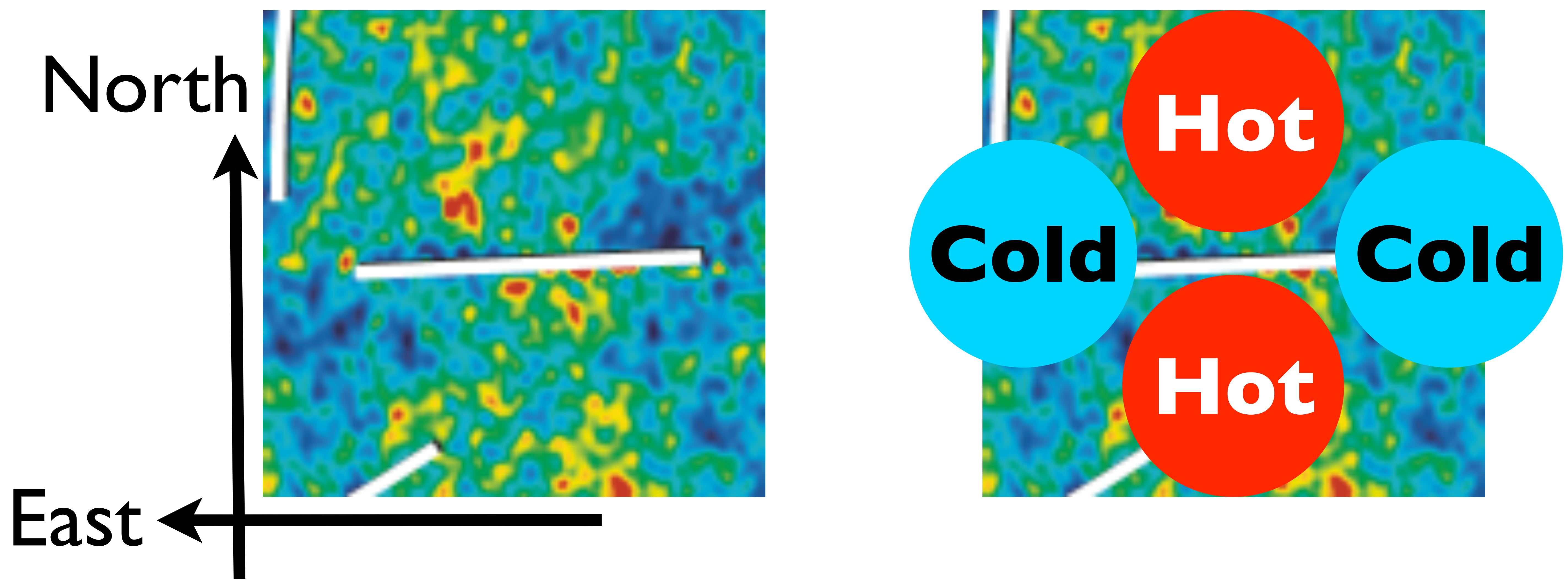
- *CMB is (very weakly) polarized!*

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.

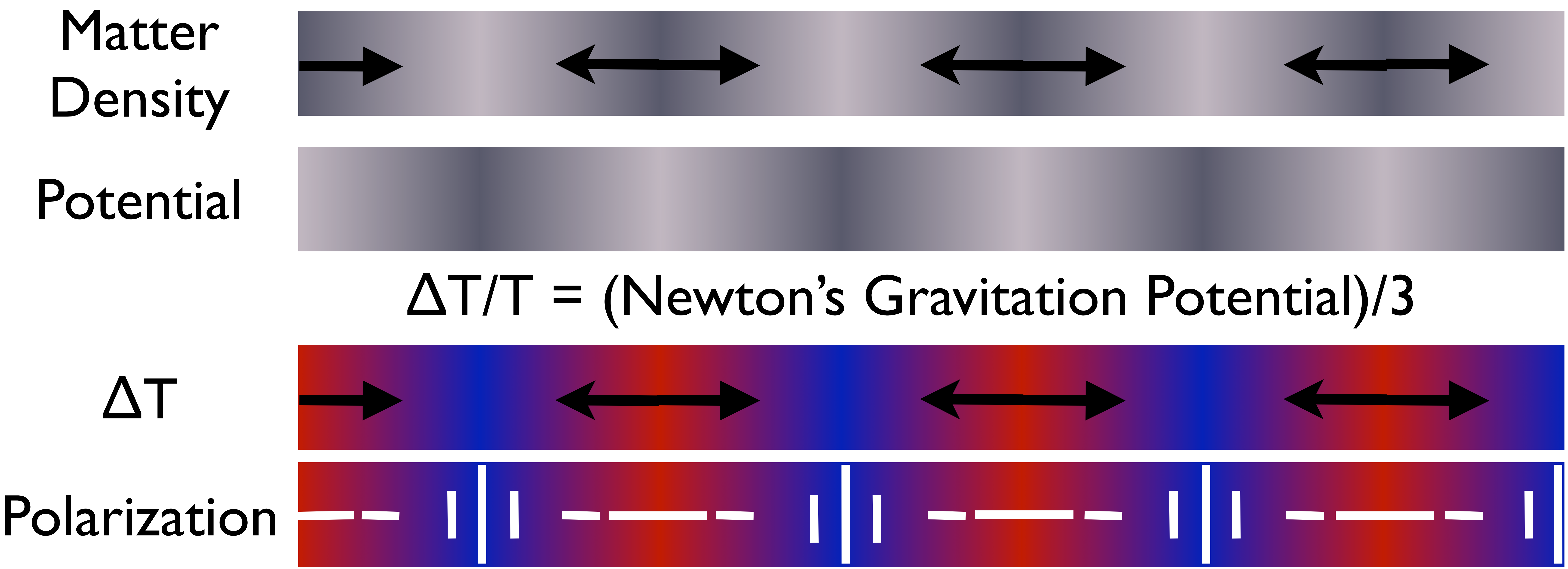
CMB Polarization on Large Angular Scales (>2 deg)

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

- How does the photon-baryon plasma move?

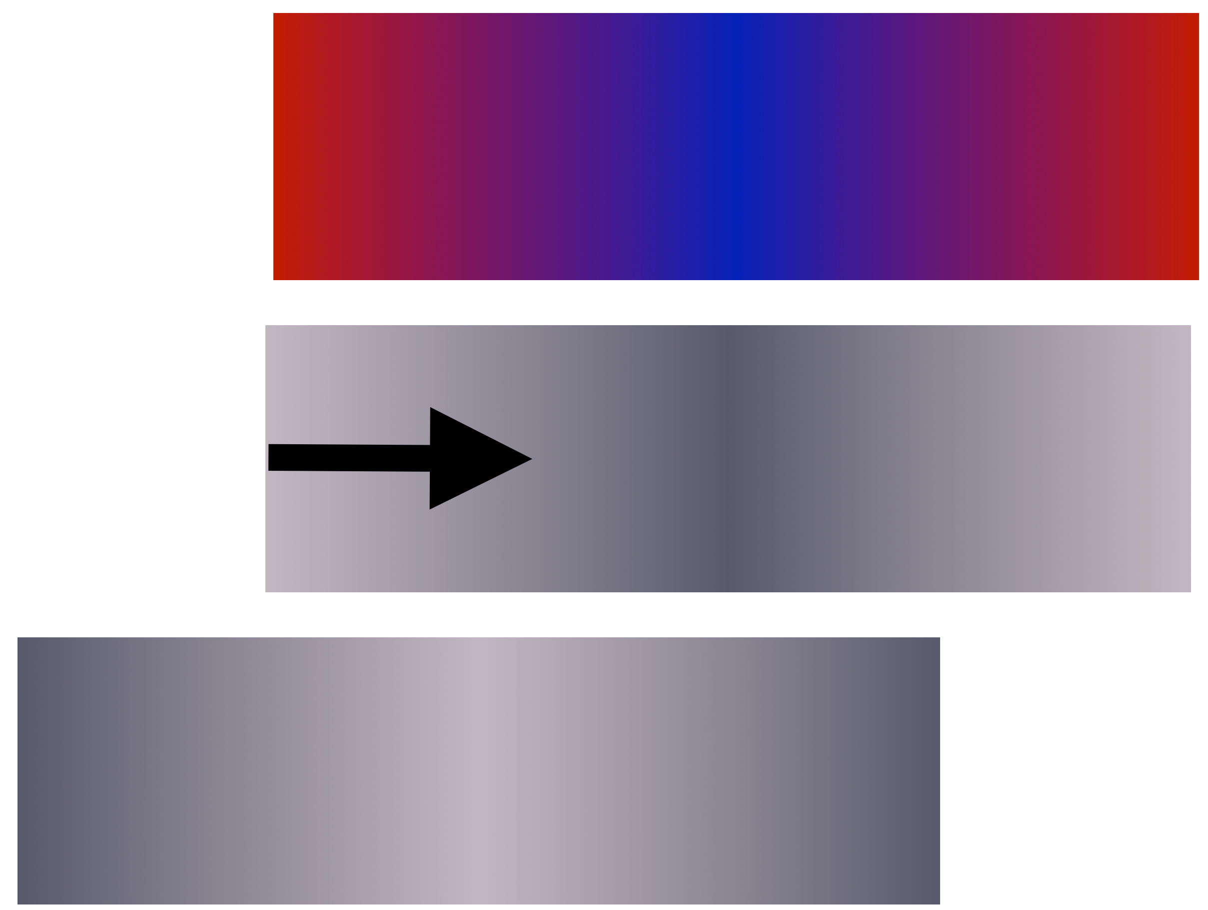
CMB Polarization Tells Us How Plasma Moves at z=1090

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 Φ — Stuff flowing *in*

Acceleration $a=-\partial\Phi$

$a>0$ $=0$

Velocity — Velocity gradient

Velocity in the rest frame of electron — e^- e^-

The left electron sees colder photons along the plane wave

Polarization — Radial None

Quadrupole From Velocity Gradient (Small Scale)

ΔT — Compression increases temperature

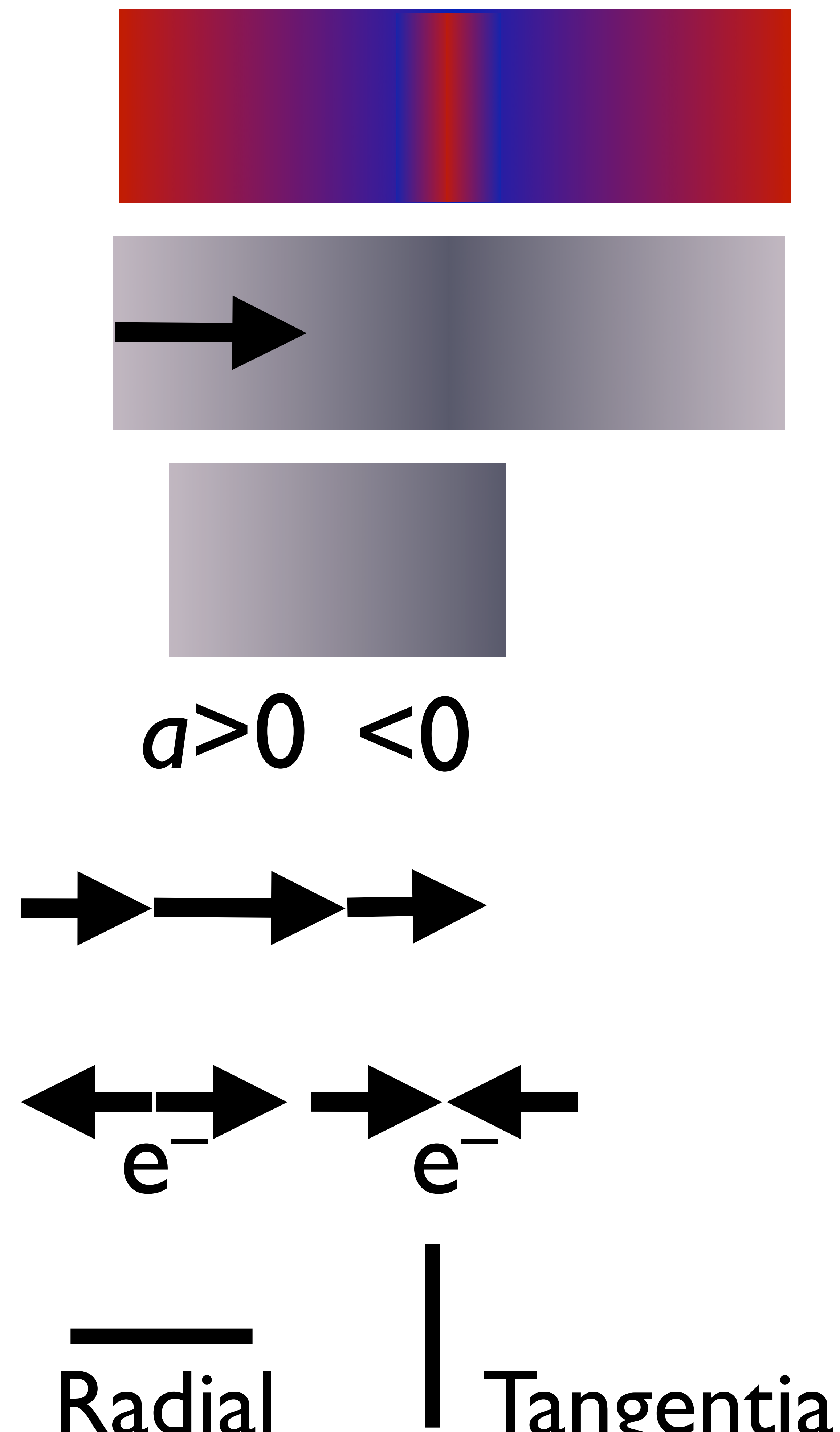
Potential Φ — Stuff flowing *in*

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

Velocity — Velocity gradient

Velocity in the rest frame of electron

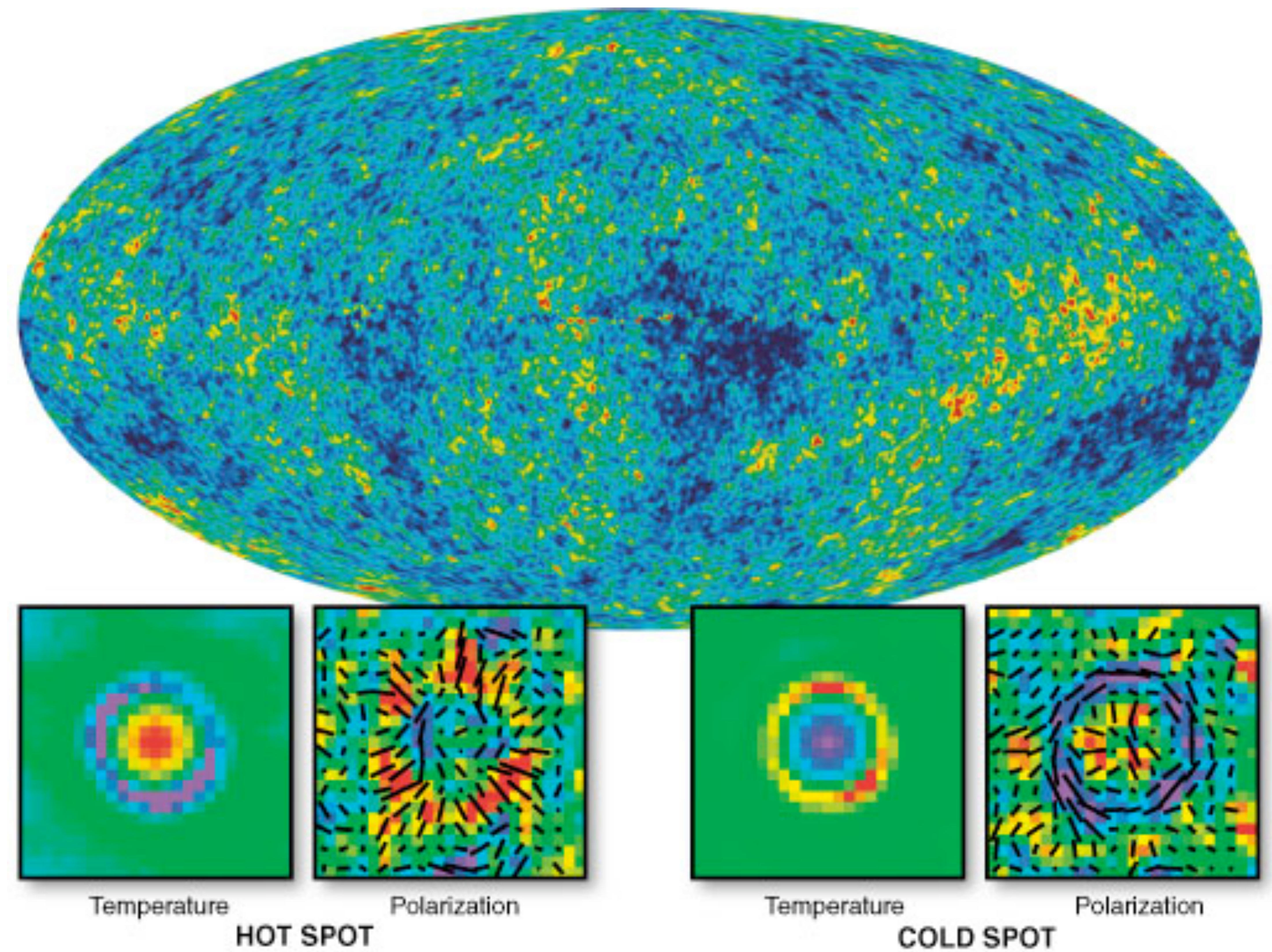
Polarization

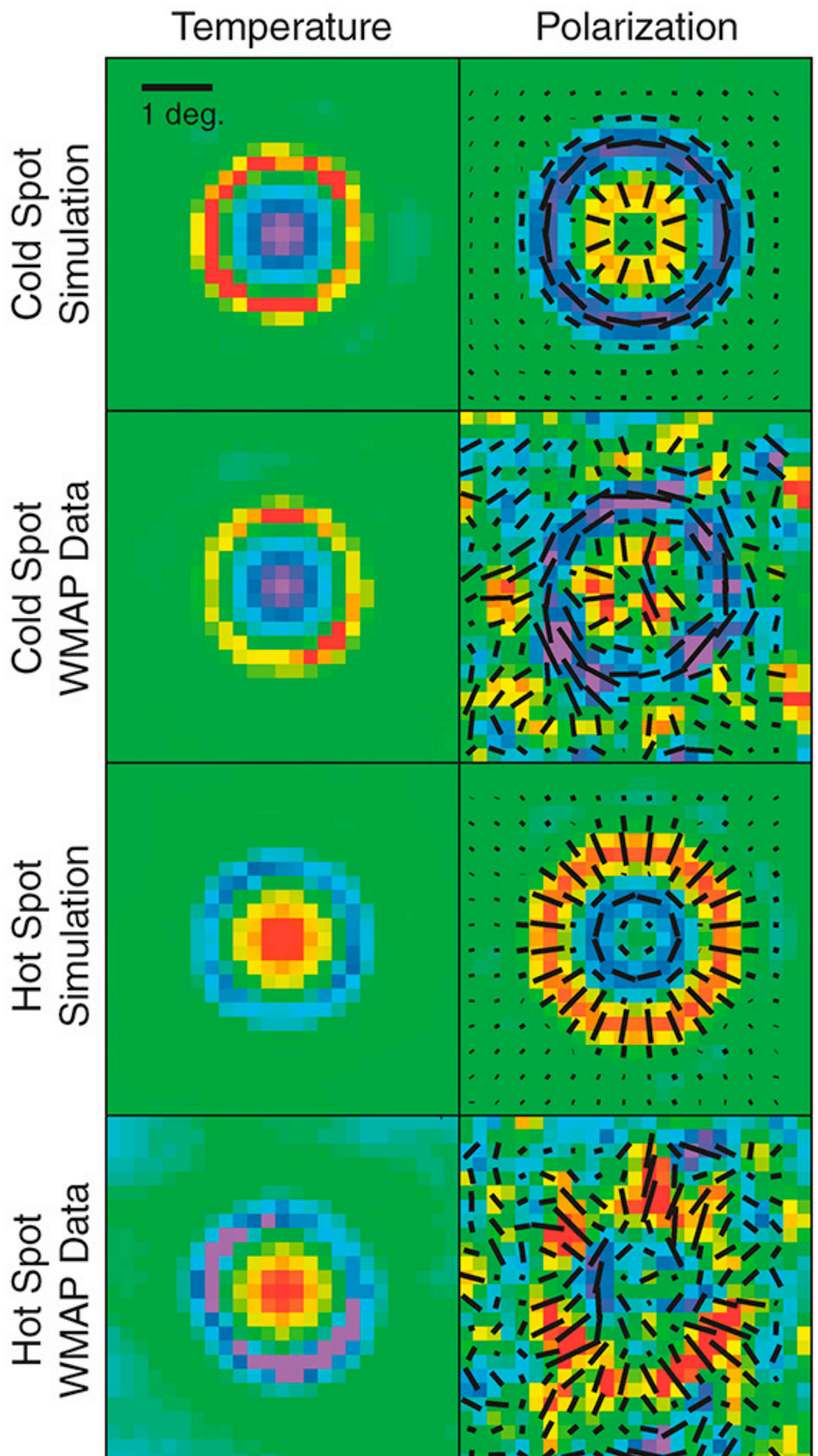


Stacking Analysis

- 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**.

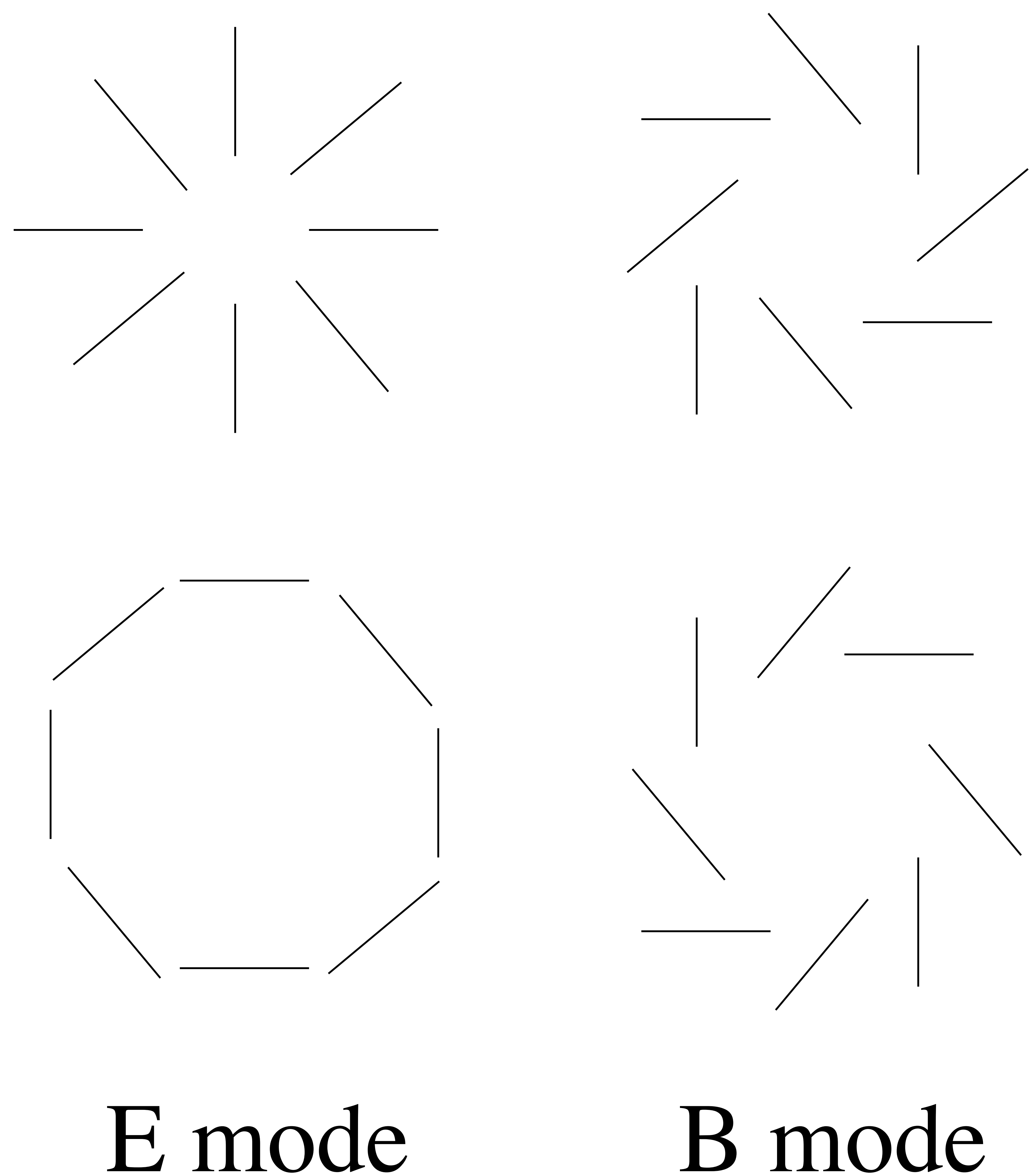




Two-dimensional View

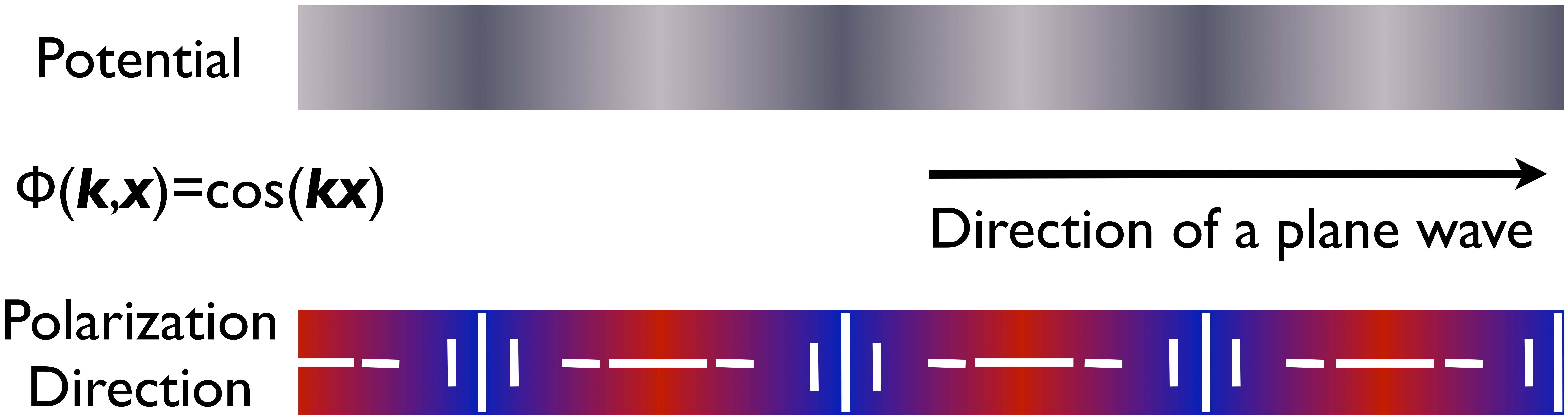
- All hot and cold spots are stacked (the threshold peak height, $\Delta T/\sigma$, is zero)
- "Compression phase" at θ=1.2 deg and "slow-down phase" at θ=0.6 deg are predicted to be there and we observe them!
  - The overall significance level: 8σ

E-mode and B-mode



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

E-mode



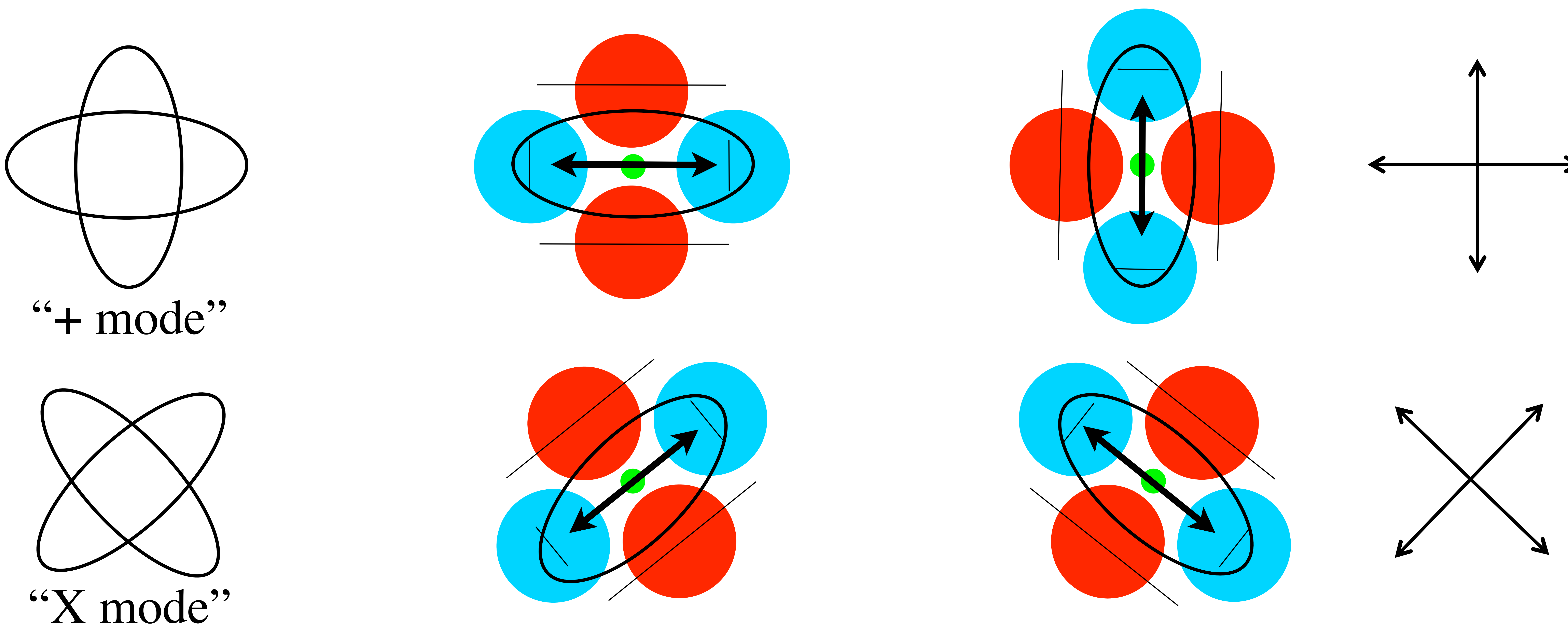
- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

B-mode

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

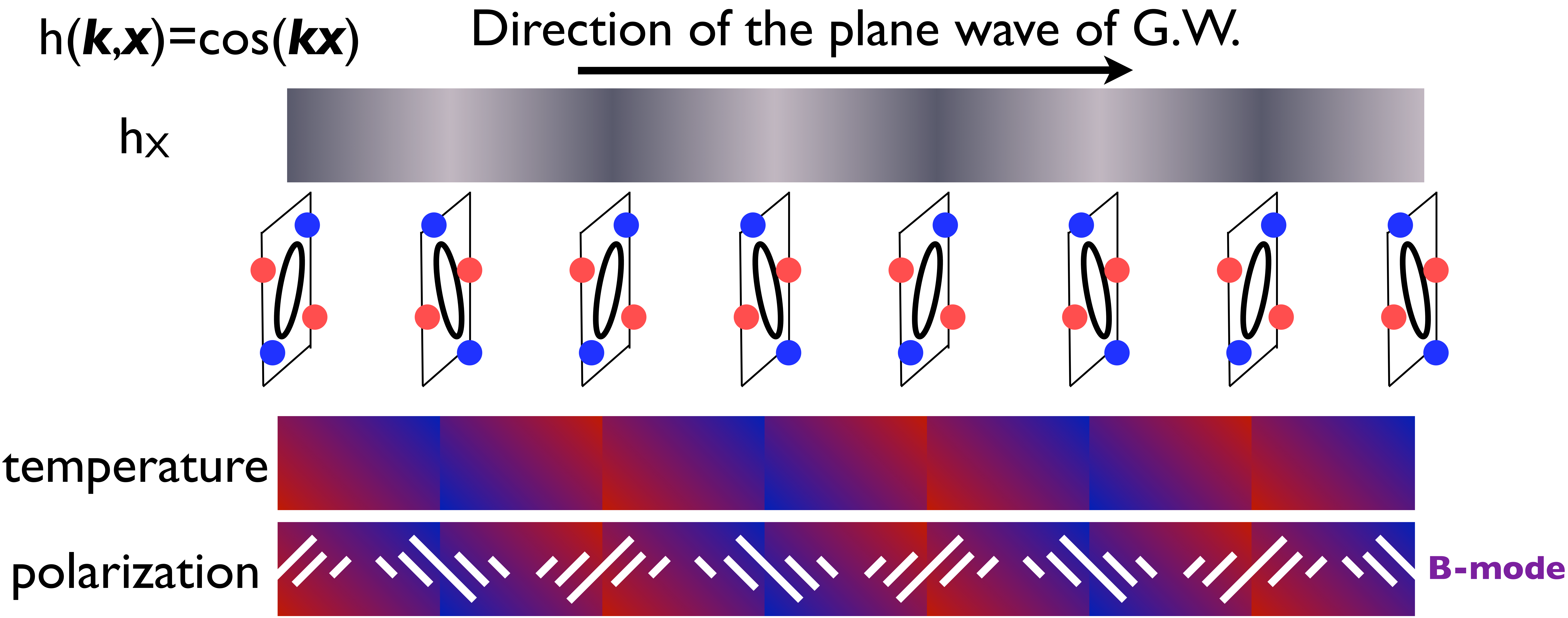
Gravitational Waves and Quadrupole

- Gravitational waves stretch space with a quadrupole pattern.



Quadrupole from G.W.

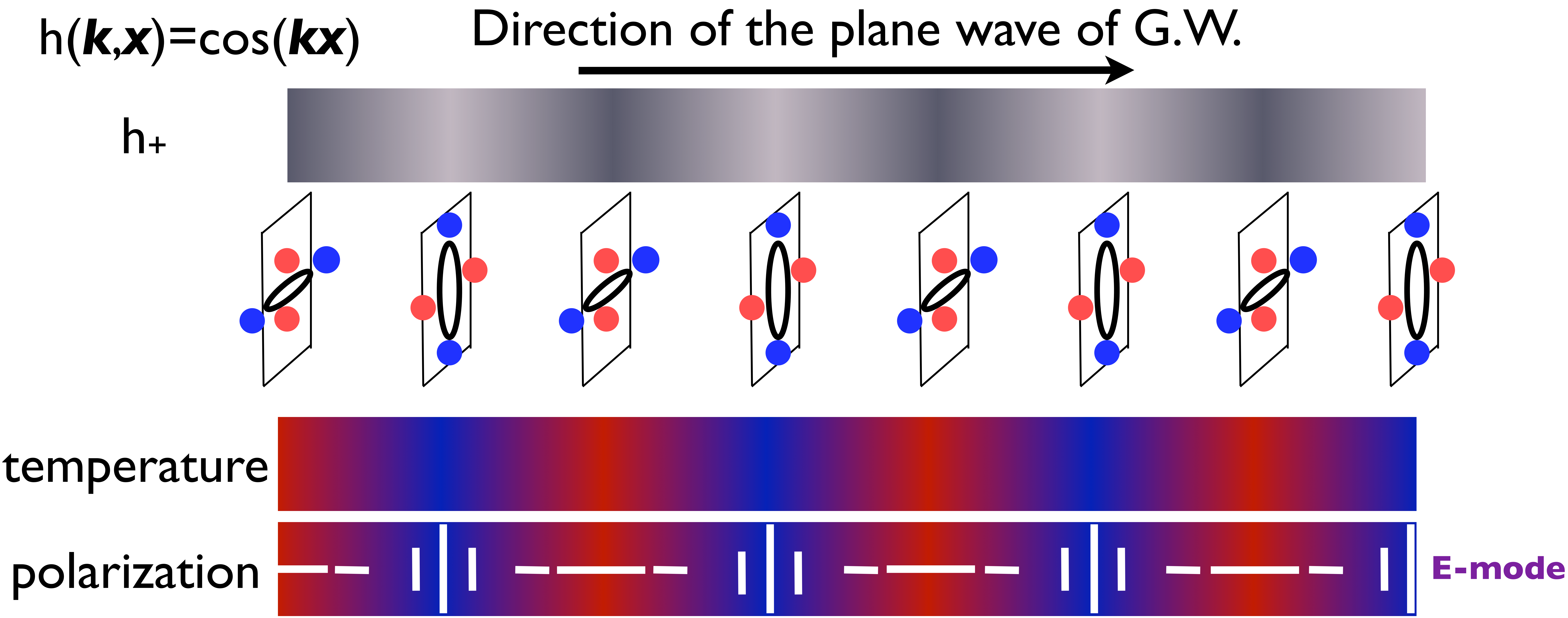
$h(\boldsymbol{k},\boldsymbol{x})=\cos(\boldsymbol{kx})$



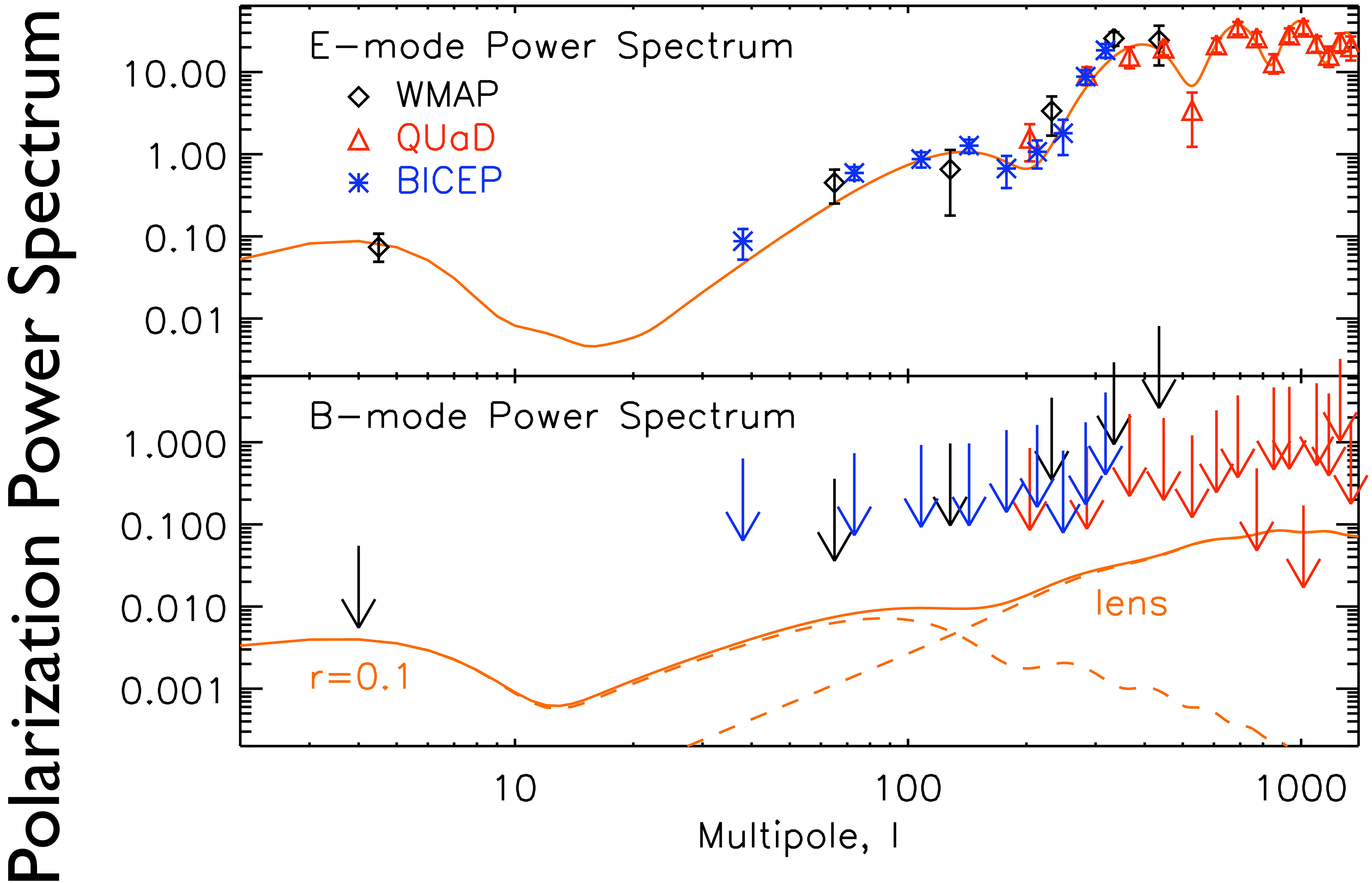
- B-mode polarization generated by $h_\times$

Quadrupole from G.W.

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



- E-mode polarization generated by h_+



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

Mukhanov & Chibisov (1981); Guth & Pi (1982); Starobinsky (1982); Hawking (1982); Bardeen, Turner & Steinhardt (1983)

(Scalar) Quantum Fluctuations

$\delta\varphi$ = (Expansion Rate)/(2π) [in natural units]

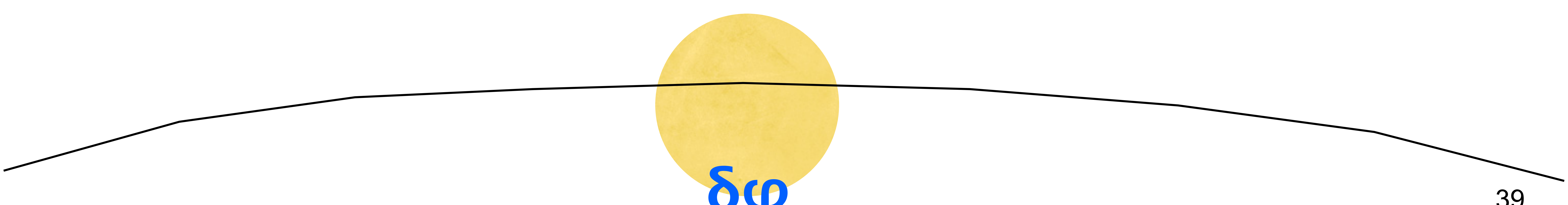
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-34} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

Stretching Micro to Macro

Macroscopic size at which gravity becomes important

Quantum fluctuations on microscopic scales

INFLATION!



Quantum fluctuations cease to be quantum, and become observable!

Inflation Offers a Magnifier for Microscopic World

- Using the *power spectrum of primordial fluctuations* imprinted in CMB, we can observe the quantum phenomena at the ultra high-energy scales that would never be reached by the particle accelerator.

Starobinsky (1979)

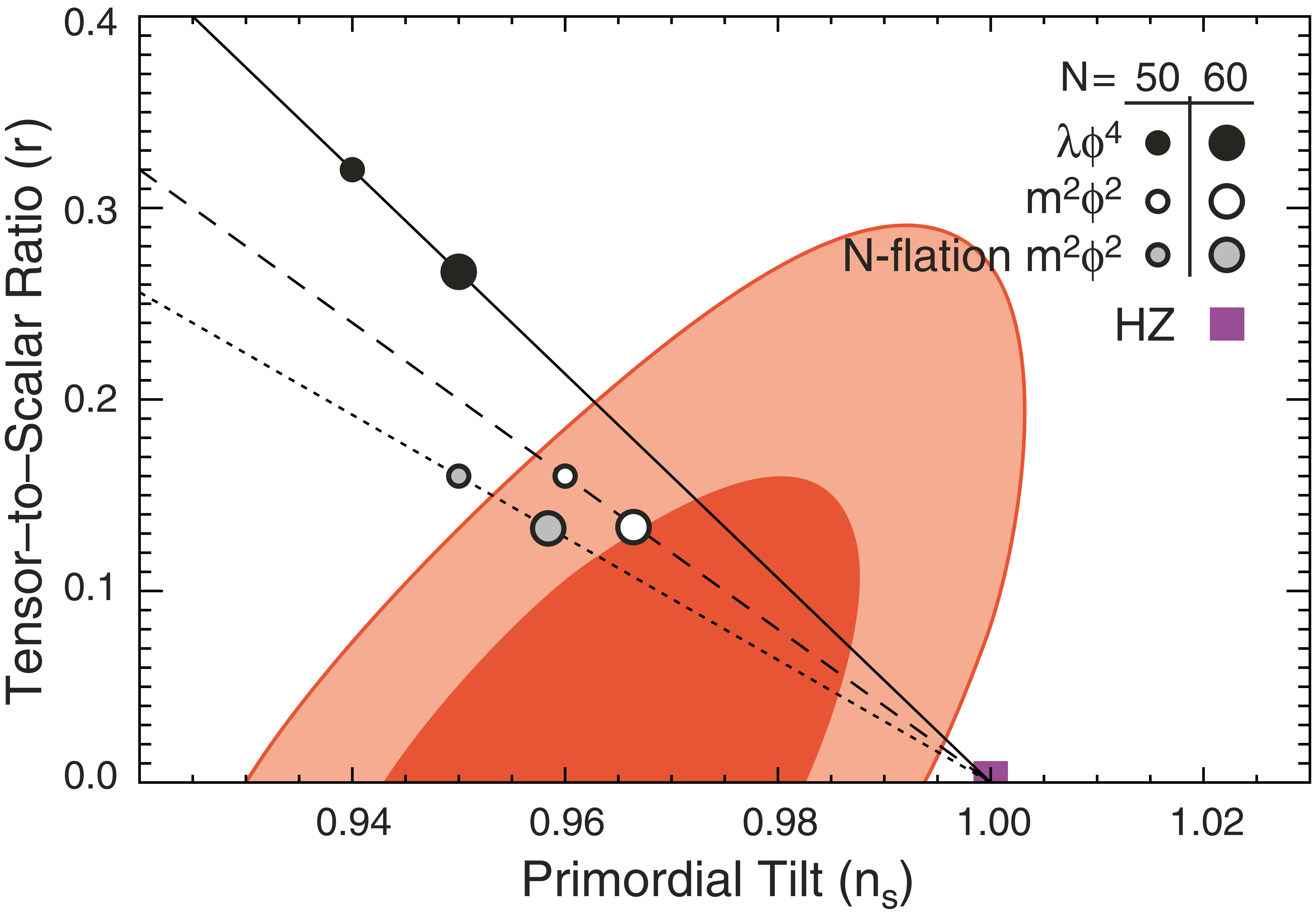
(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

h = (Expansion Rate)/($2^{1/2}\pi M_{planck}$) [in natural units]

[h = "strain"]

- Quantum fluctuations also generate ripples in space-time, i.e., gravitational waves, by the same mechanism.
- Primordial gravitational waves generate temperature anisotropy in CMB, as well as polarization in CMB with a distinct pattern called "**B-mode polarization**."

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

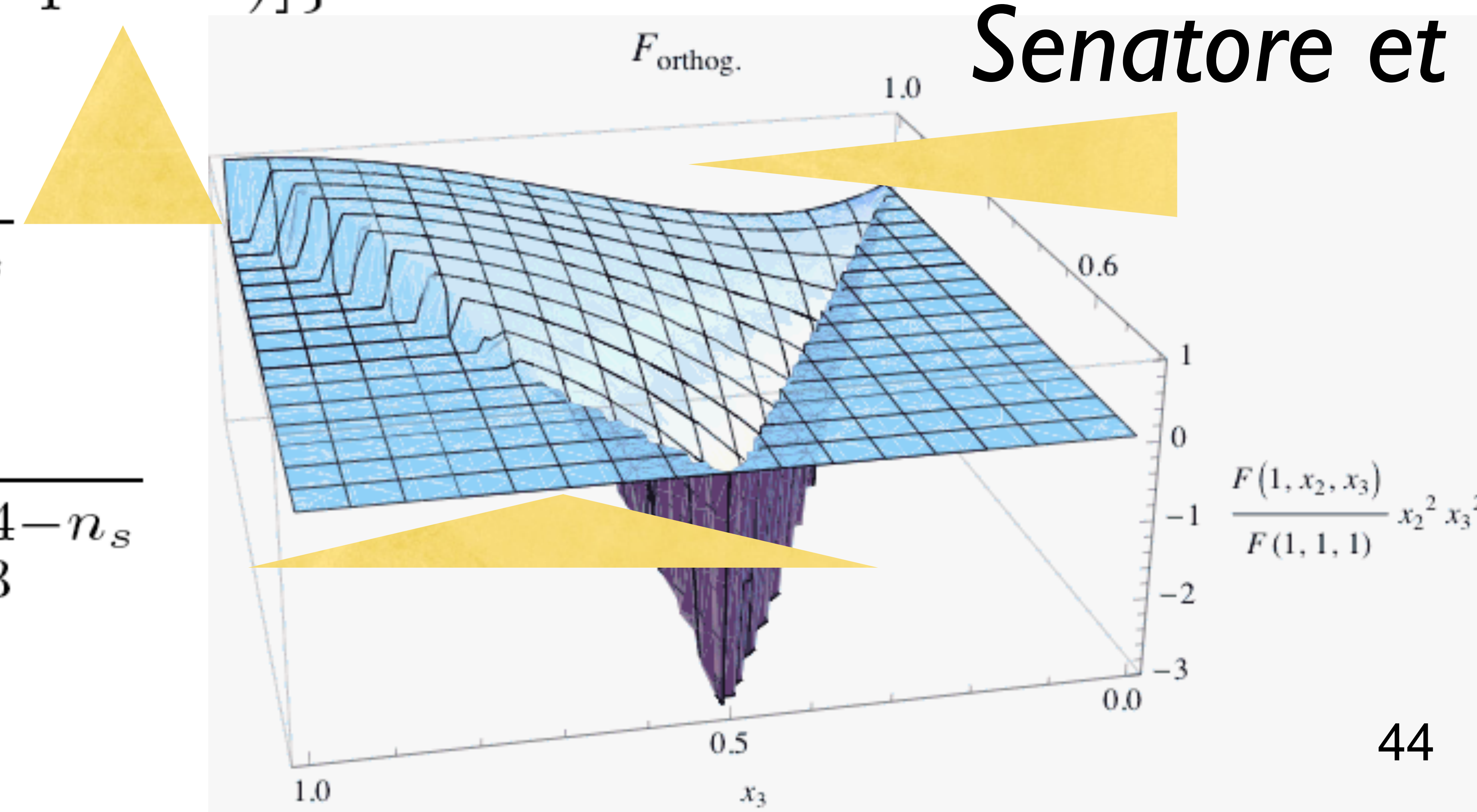
If this means anything to you...

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

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

$$\begin{aligned} F_{\rm equil}(k_1,k_2,k_3) &= 6Af_{NL}^{\rm equil}\\ \times\Bigg\{&-\frac{1}{k_1^{4-n_s}k_2^{4-n_s}}-\frac{1}{k_2^{4-n_s}k_3^{4-n_s}}-\frac{1}{k_3^{4-n_s}k_1^{4-n_s}}\\ &-\frac{2}{(k_1k_2k_3)^{2(4-n_s)/3}}+\Bigg[\frac{1}{k_1^{(4-n_s)/3}k_2^{2(4-n_s)/3}k_3^{4-n_s}}\\ &+(5\ \text{perm.})\Bigg]\Bigg\}. \end{aligned}$$

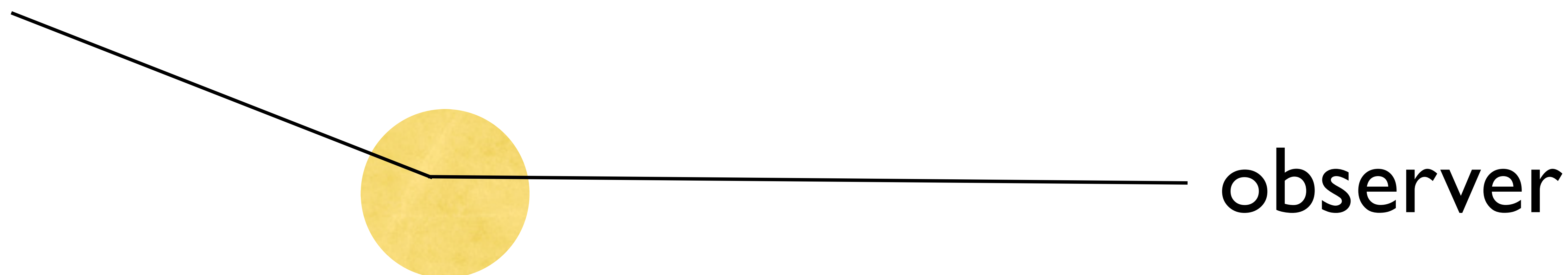
$$\begin{aligned} F_{\rm orthog}(k_1,k_2,k_3) &= 6Af_{NL}^{\rm orthog}\\ \times\Bigg\{&-\frac{3}{k_1^{4-n_s}k_2^{4-n_s}}-\frac{3}{k_2^{4-n_s}k_3^{4-n_s}}-\frac{3}{k_3^{4-n_s}k_1^{4-n_s}}\\ &-\frac{8}{(k_1k_2k_3)^{2(4-n_s)/3}}+\Bigg[\frac{3}{k_1^{(4-n_s)/3}k_2^{2(4-n_s)/3}k_3^{4-n_s}}\\ &+(5\ \text{perm.})\Bigg]\Bigg\}. \end{aligned}$$



Senatore et al.

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

Sunyaev–Zel'dovich Effect



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

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

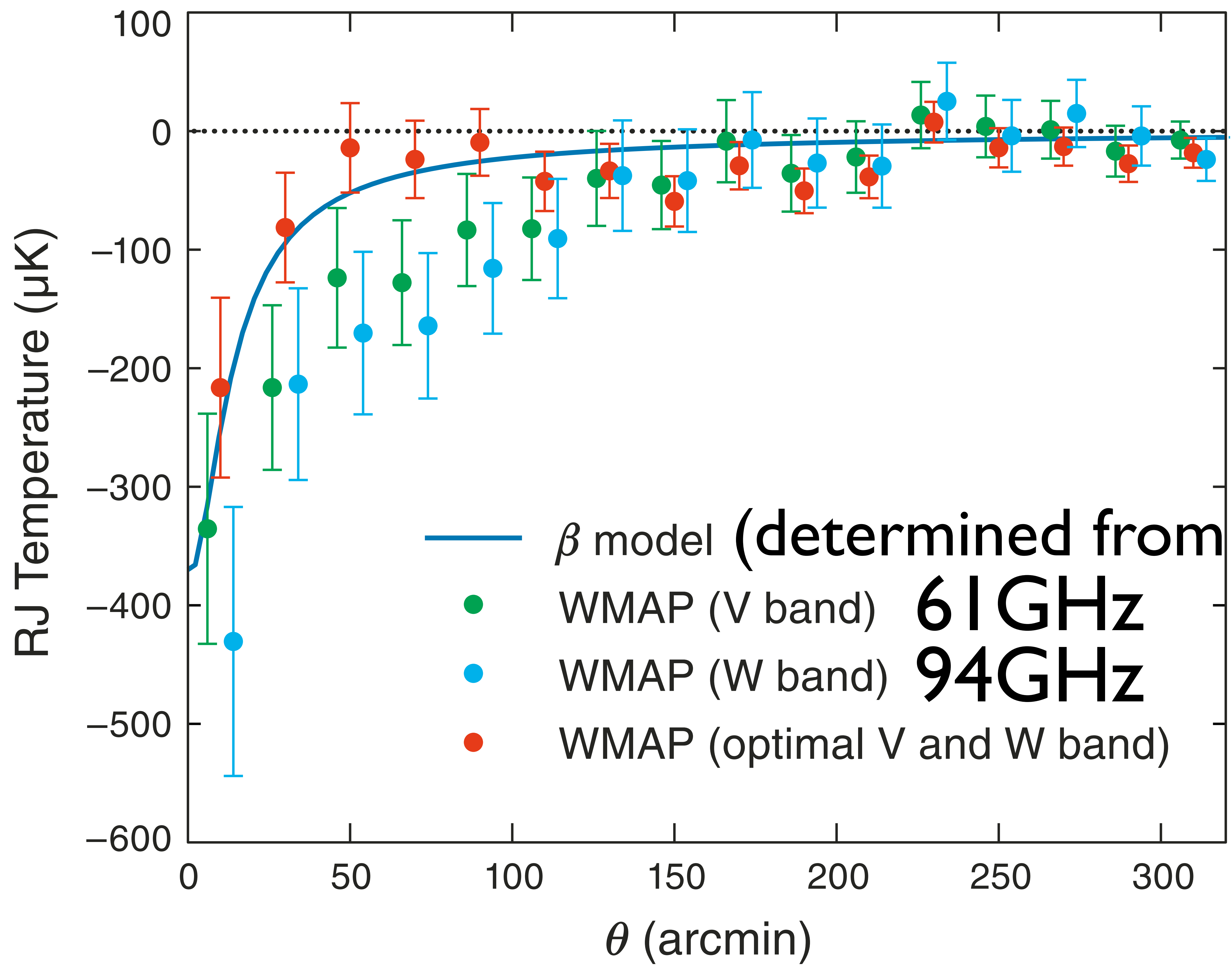
$$y = (\text{optical depth of gas})\, k_B T_e/(m_e c^2)$$
$$= [\sigma_T/(m_e c^2)] \int n_e k_B T_e \, d(\text{los})$$
$$= [\sigma_T/(m_e c^2)] \int (\text{electron pressure}) d(\text{los})$$

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

Coma Cluster (z=0.023)

We find that the CMB fluctuation in the direction of Coma is ≈ –100uK. (This is a new result!)

$y_{coma}(0)=(7\pm2)\times10^{-5}$ (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**.

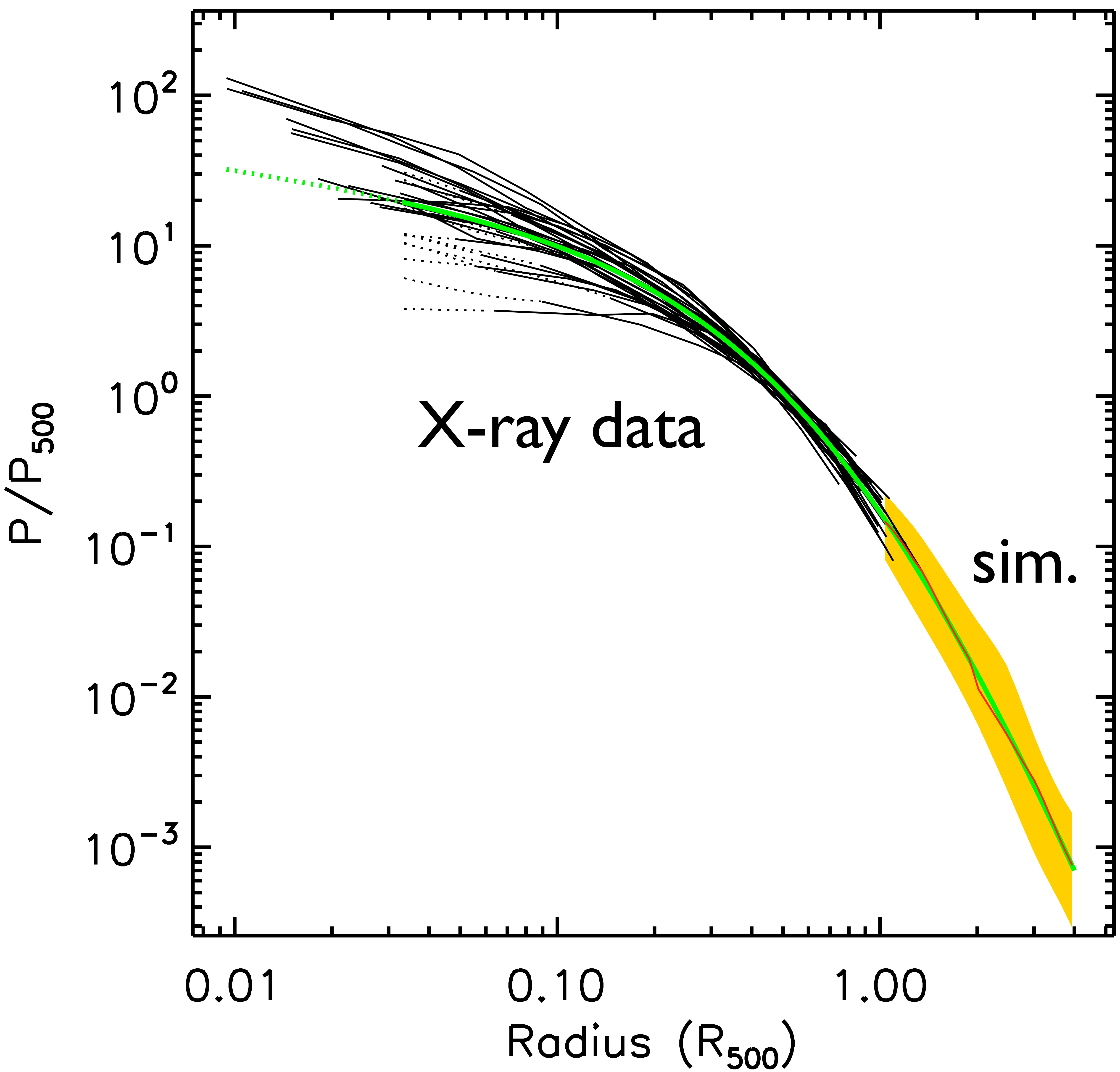
A Question

- 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

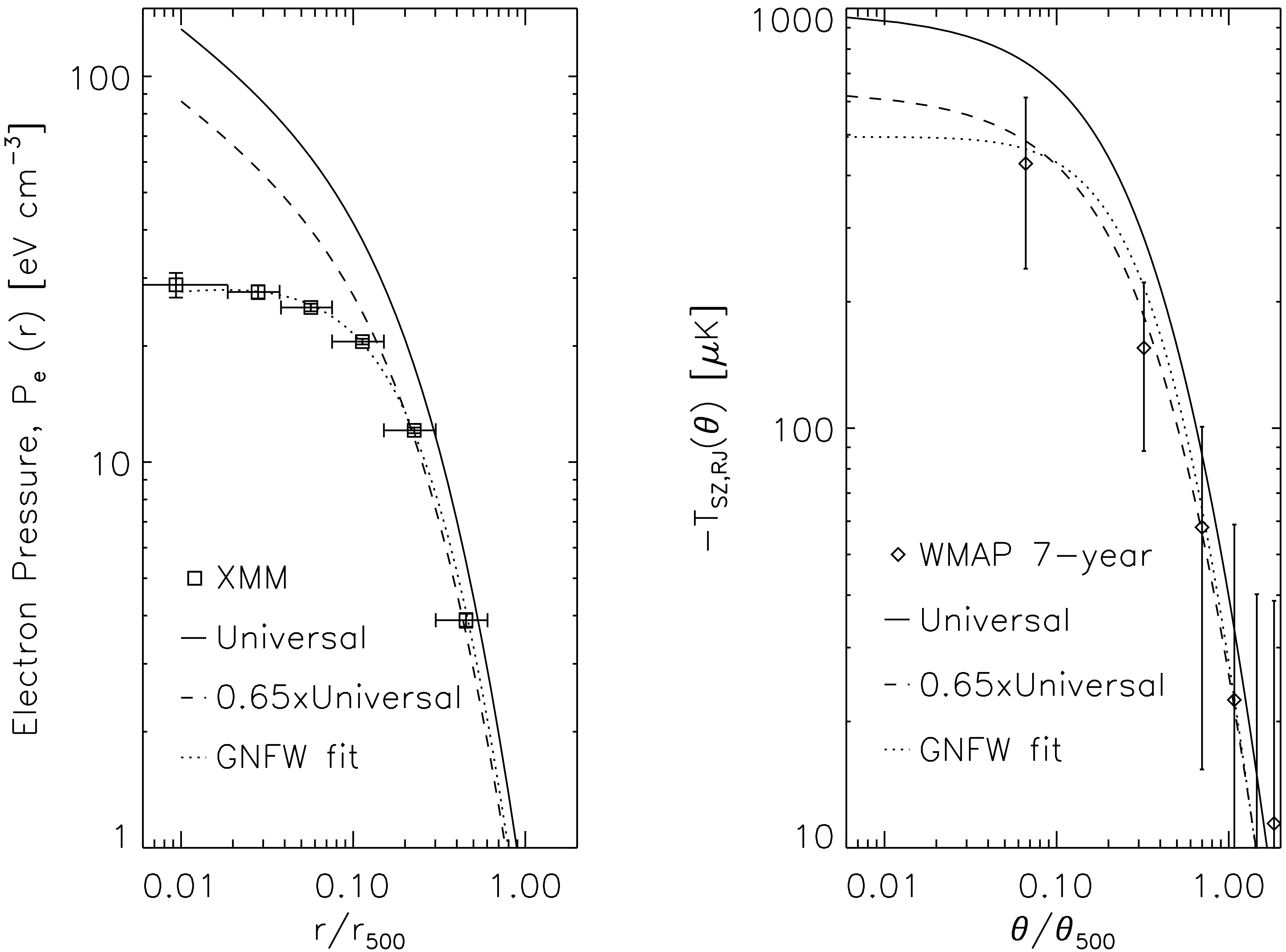
- A fitting formula for the average electron pressure profile as a function of the cluster mass (M_{500}), derived from 33 nearby ($z<0.2$) clusters.

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

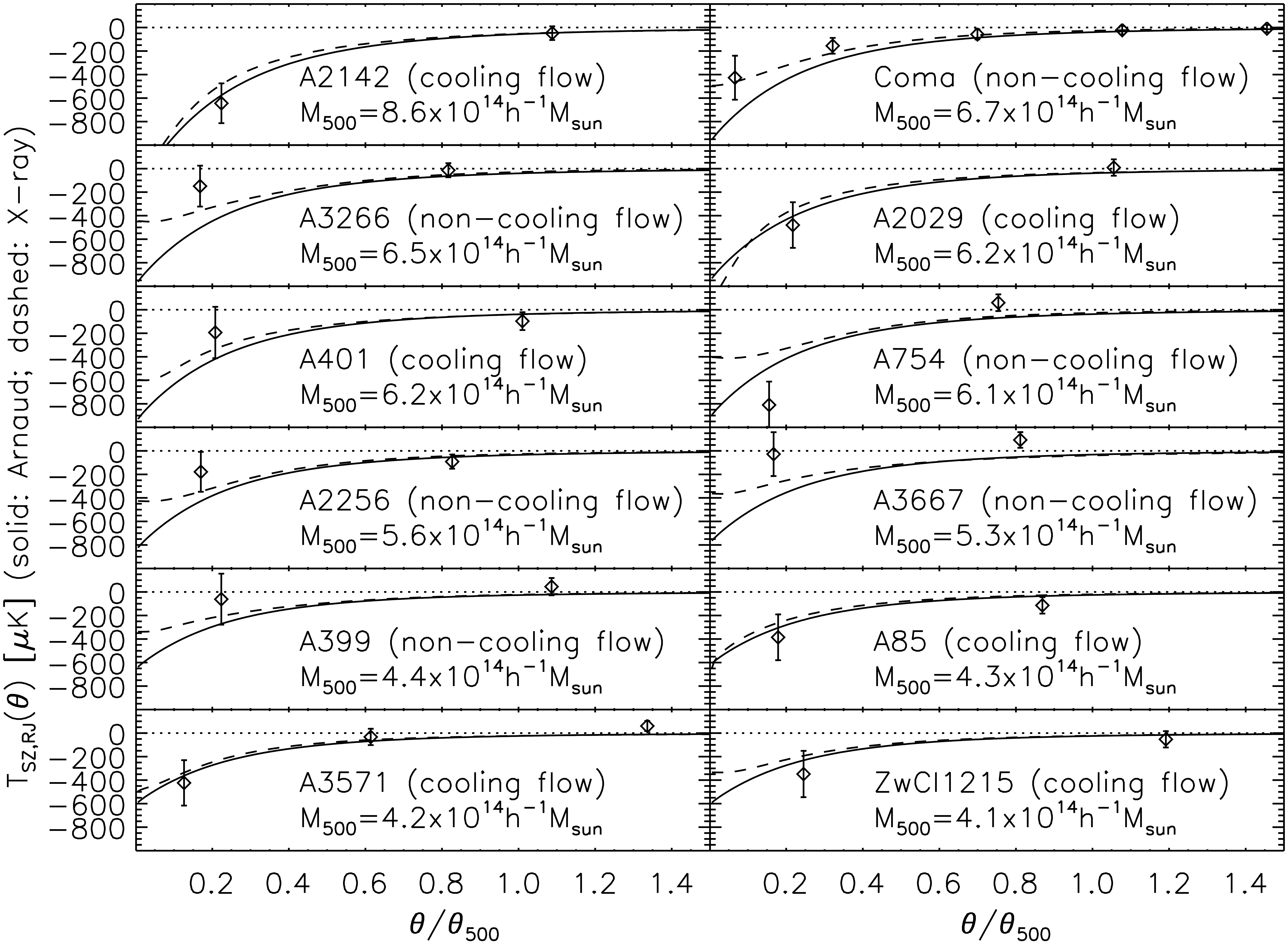


The X-ray data (XMM) are provided by A. Finoguenov.

- $M_{500}=6.6\times10^{14}h^{-1}M_{sun}$ 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...

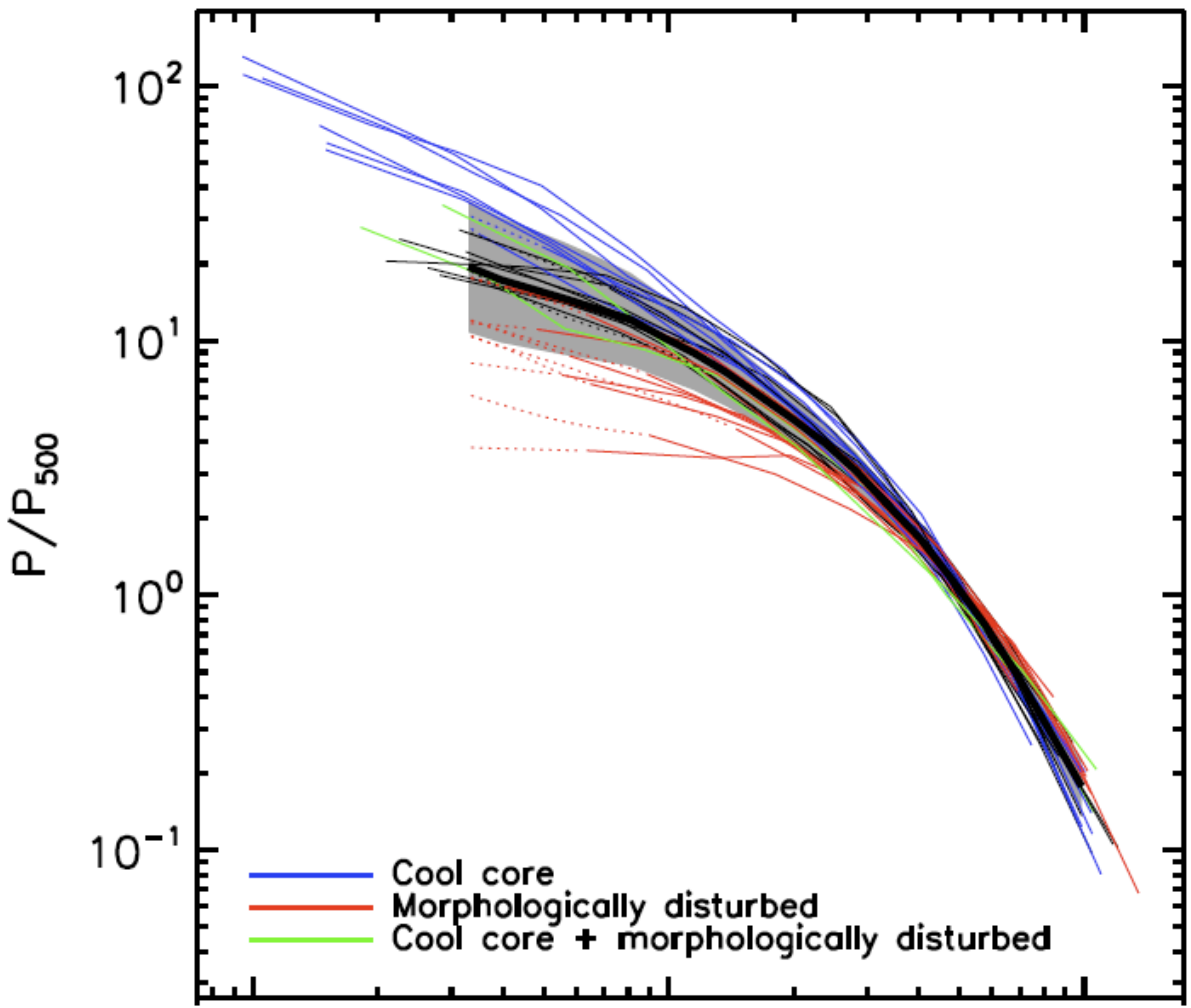
- That's just one cluster. What about the other clusters?
  - We measure the SZ effect of a sample of well-studied nearby clusters compiled by Vikhlinin et al.


A2142 (cooling flow)
$M_{500}=8.6\times10^{14}h^{-1}M_{sun}$
Coma (non-cooling flow)
$M_{500}=6.7\times10^{14}h^{-1}M_{sun}$
A3266 (non-cooling flow)
$M_{500}=6.5\times10^{14}h^{-1}M_{sun}$
A2029 (cooling flow)
$M_{500}=6.2\times10^{14}h^{-1}M_{sun}$
A401 (cooling flow)
$M_{500}=6.2\times10^{14}h^{-1}M_{sun}$
A754 (non-cooling flow)
$M_{500}=6.1\times10^{14}h^{-1}M_{sun}$
A2256 (non-cooling flow)
$M_{500}=5.6\times10^{14}h^{-1}M_{sun}$
A3667 (non-cooling flow)
$M_{500}=5.3\times10^{14}h^{-1}M_{sun}$
A399 (non-cooling flow)
$M_{500}=4.4\times10^{14}h^{-1}M_{sun}$
A85 (cooling flow)
$M_{500}=4.3\times10^{14}h^{-1}M_{sun}$
A3571 (cooling flow)
$M_{500}=4.2\times10^{14}h^{-1}M_{sun}$
ZwCl1215 (cooling flow)
$M_{500}=4.1\times10^{14}h^{-1}M_{sun}$
$T_{SZ,RJ}(\theta)$ [μK] (solid: Arnaud; dashed: X-ray)
θ/θ_{500}

SZ: Main Results

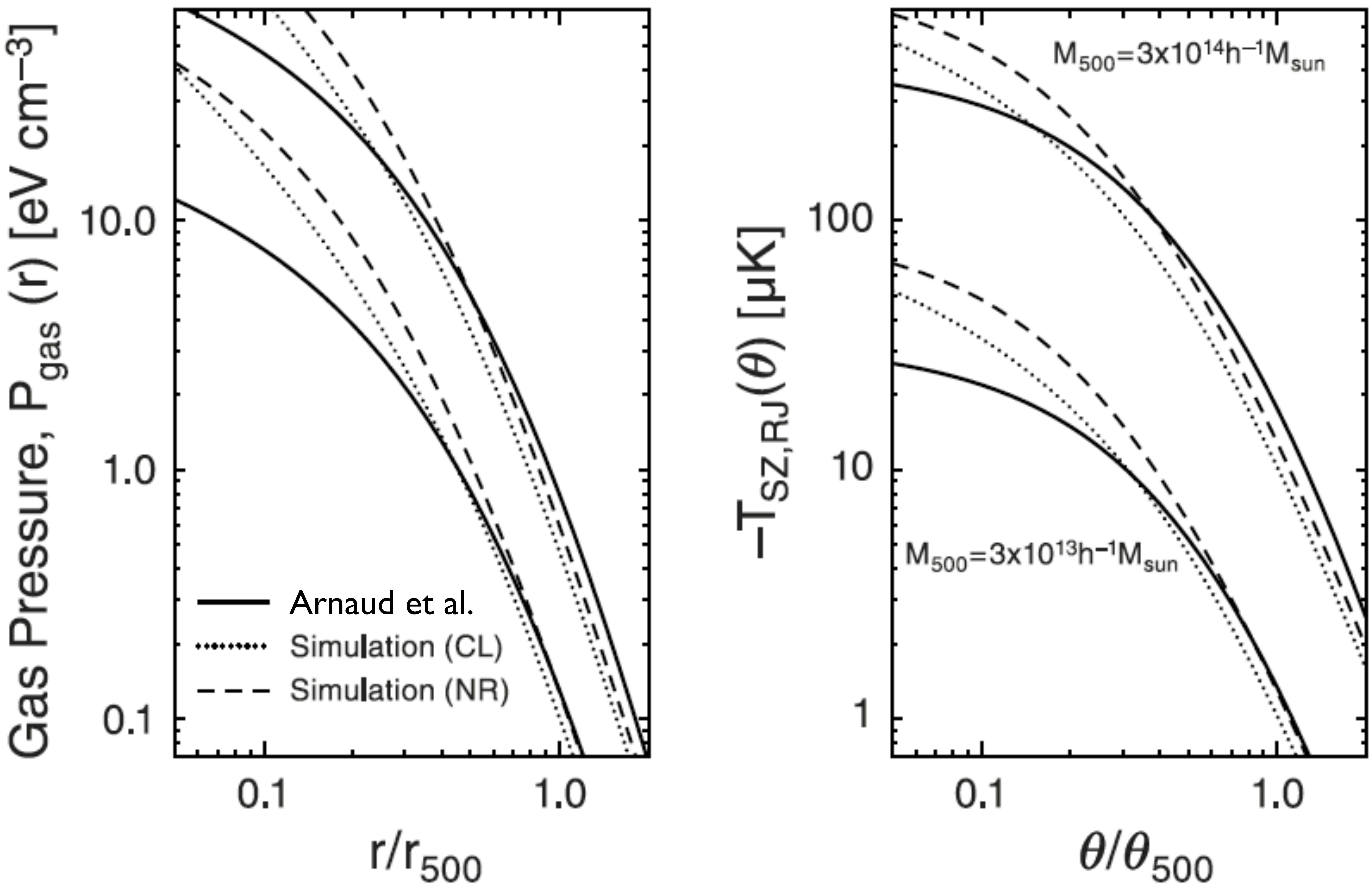
- Arnaud et al. profile systematically overestimates the electron pressure!
- But, the X-ray data on the *individual* clusters agree well with the SZ measured by WMAP.
- Reason: Arnaud et al. did not distinguish between cooling flow and non-cooling flow clusters.
  - This will be important for the proper interpretation of the SZ effect when doing cosmology with it.

Cooling Flow vs Non-CF

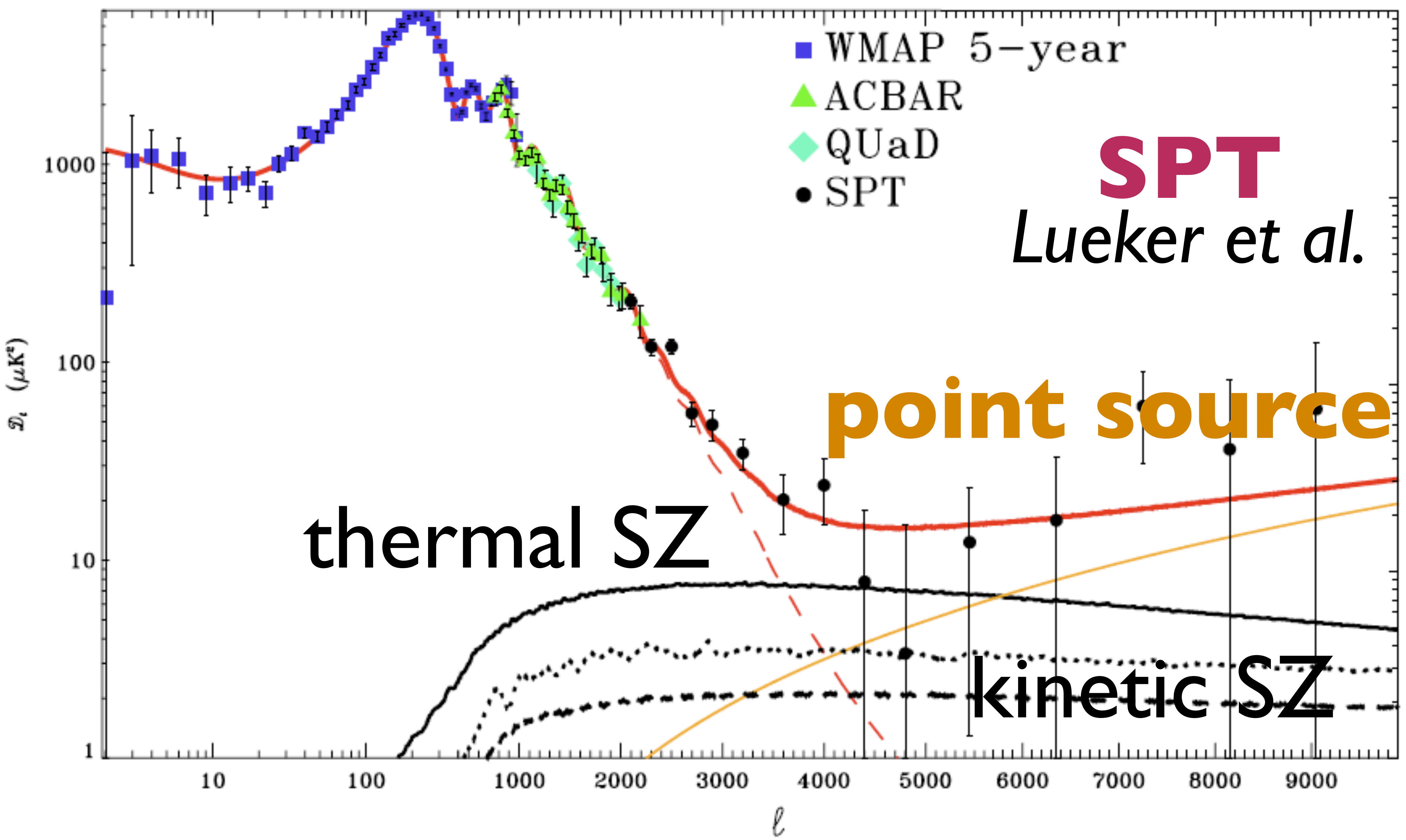


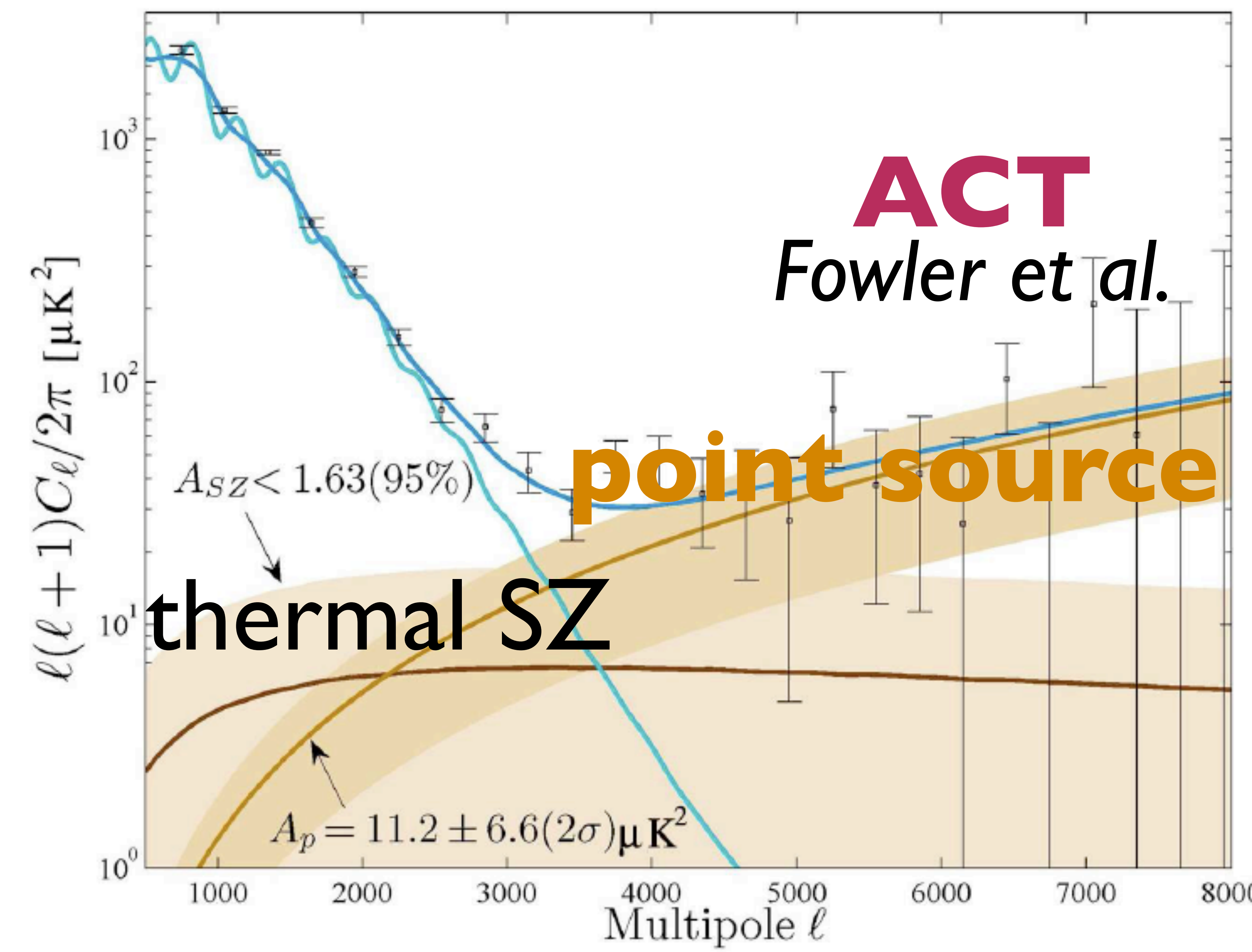
- In Arnaud et al., they reported that the cooling flow clusters have much steeper pressure profiles in the inner part.
- Taking a simple median gave a biased "universal" profile.

Theoretical Models



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

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

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

- 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 0.81): $\sum m_\nu \sim 0.2$eV?
  - Gas pressure per cluster is lower than expected

→ WMAP measurement favors this possibility.

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 6.5σ.
  - 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.