



The *WMAP* 7-Year Results

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)
2nd Kitano Workshop, Maskawa Institute, June 4, 2010

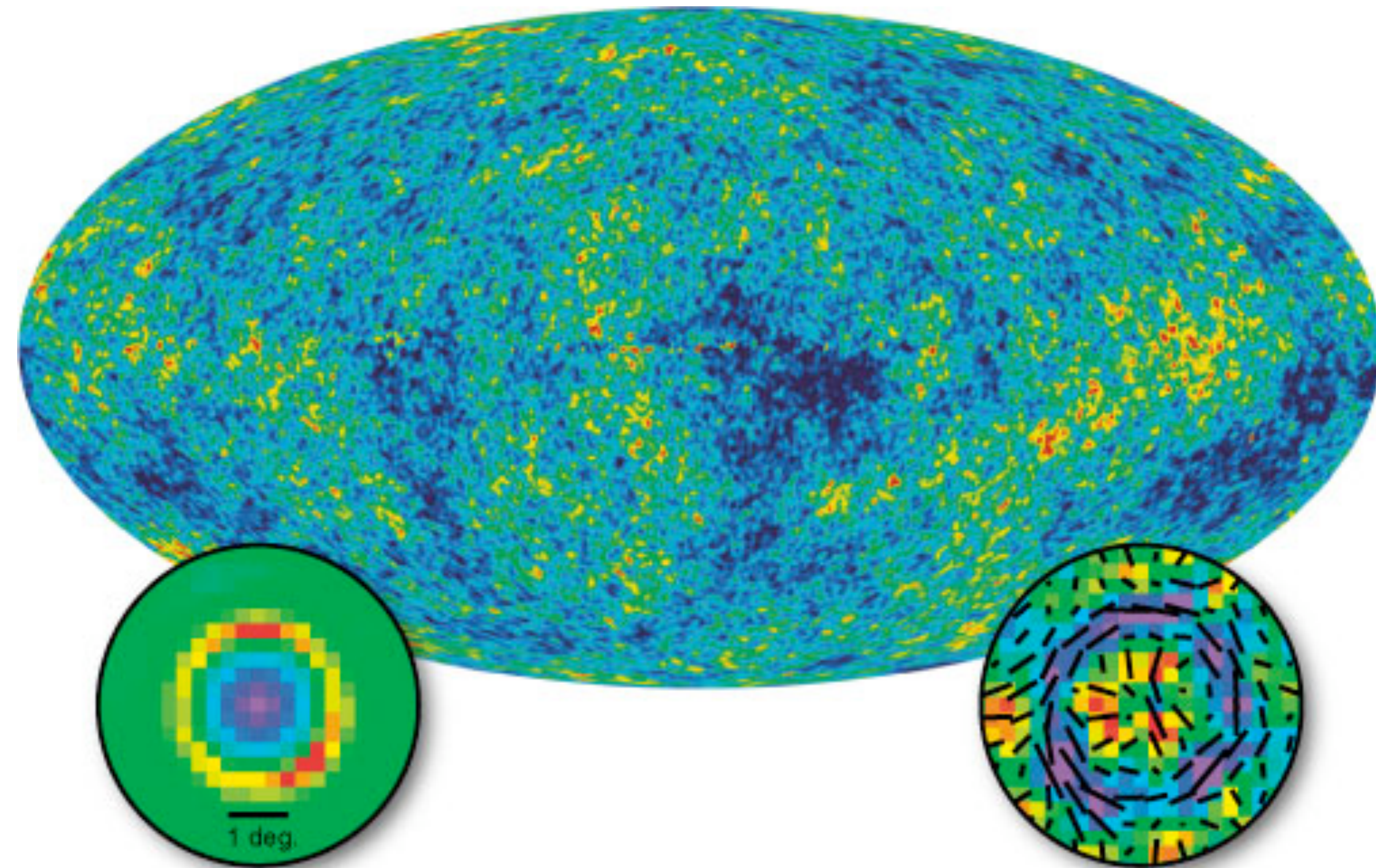
WMAP will have collected 9 years of data by August

June 2001:
WMAP launched!

February 2003:
The first-year data
release

March 2006:
The three-year data
release

March 2008:
The five-year data
release



Stacked Temperature

Stacked Polarization

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

7-year Science Highlights

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

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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- L. Verde

WMAP at Lagrange 2 (L2) Point

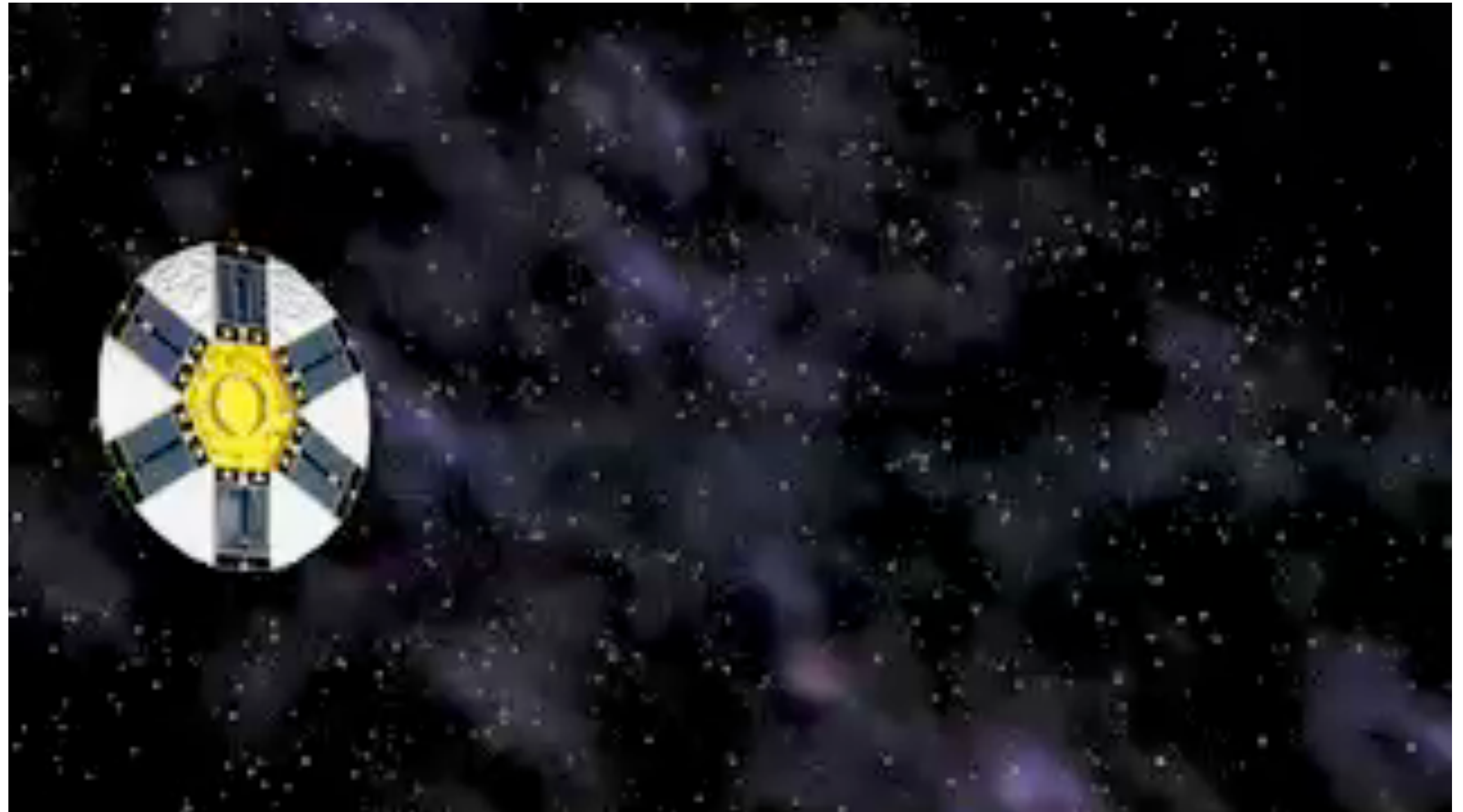
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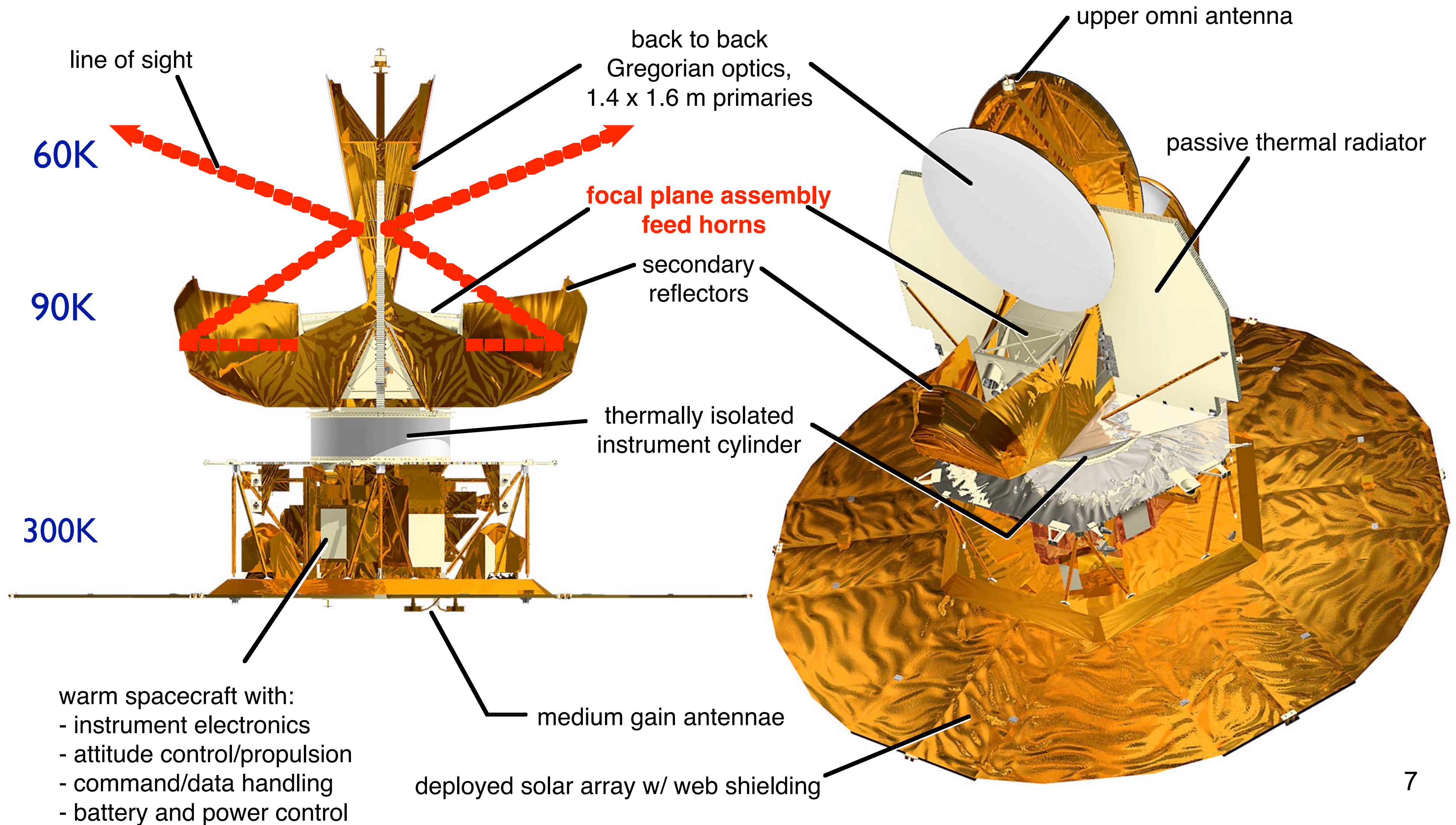
**January 2010:
The seven-year
data release**



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

WMAP Spacecraft

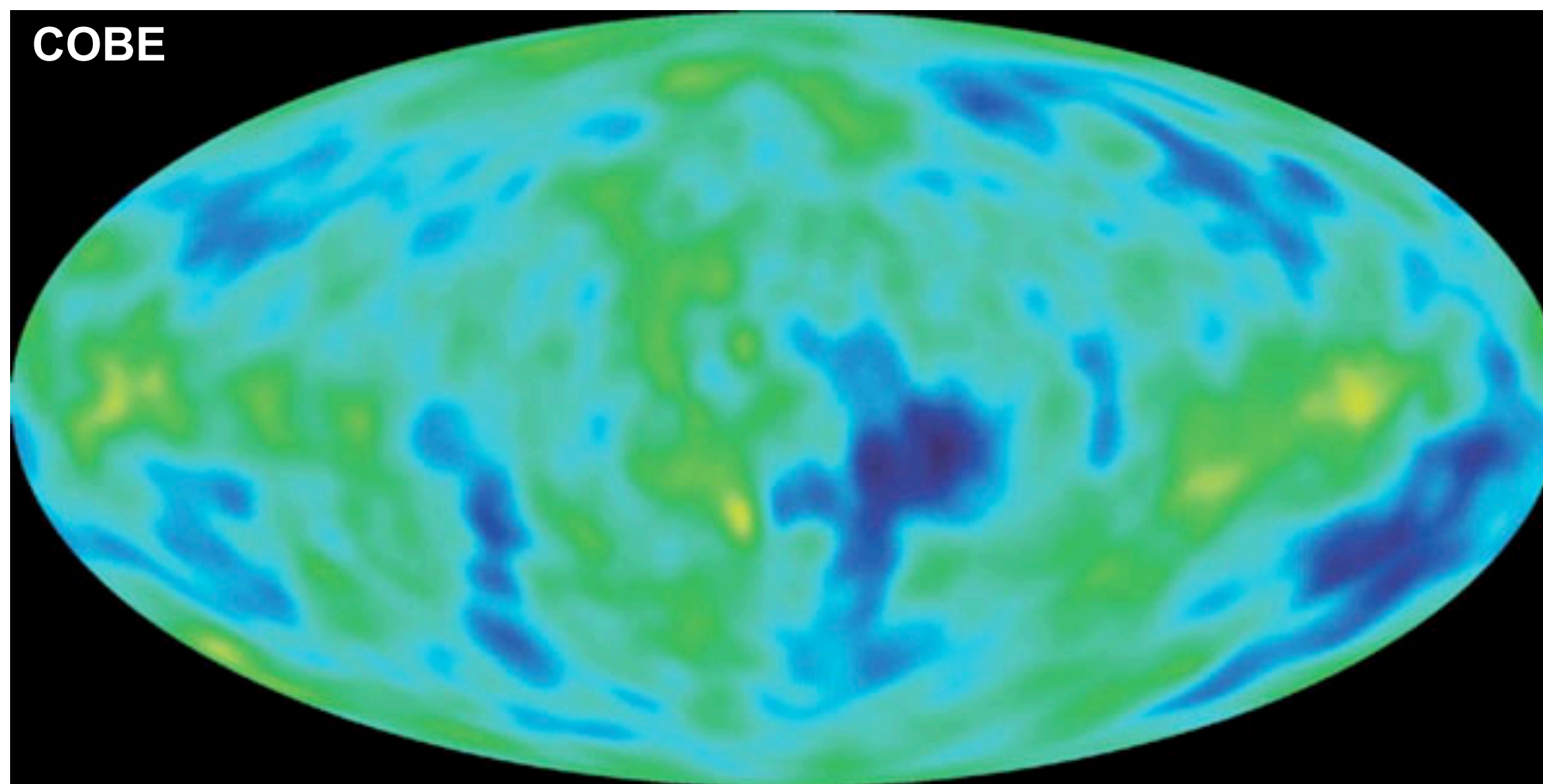
Radiative Cooling: No Cryogenic System



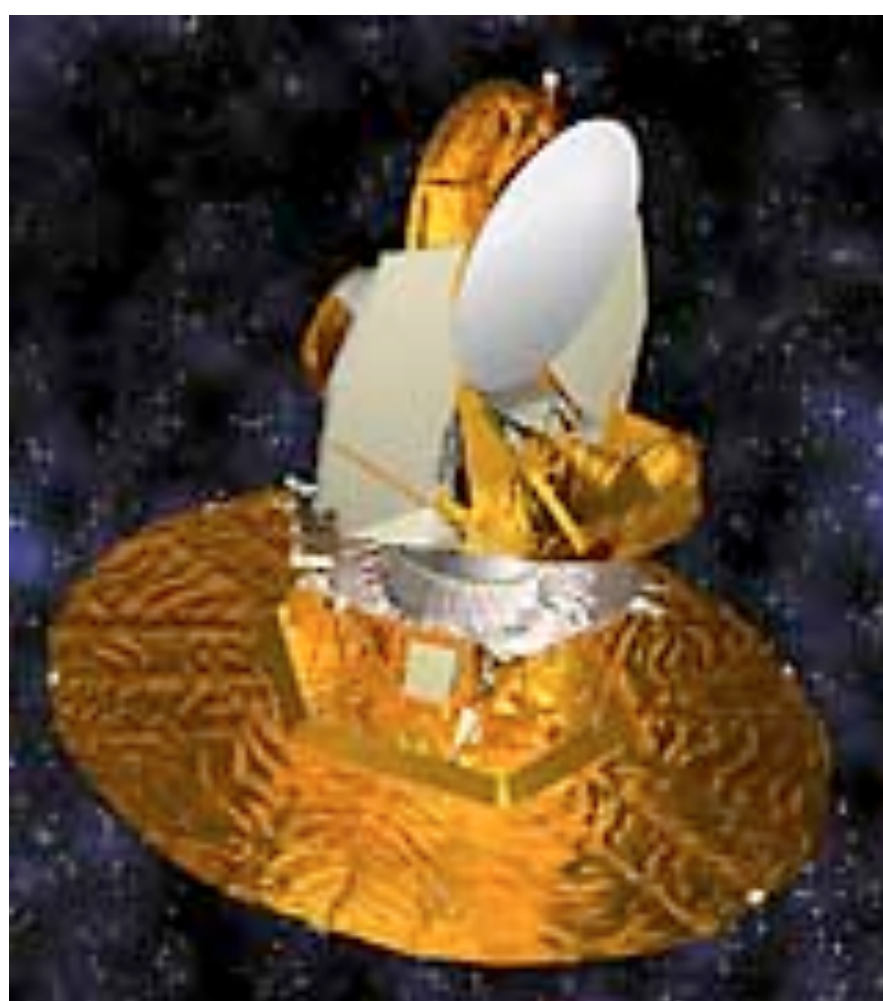
COBE to WMAP (x35 better resolution)



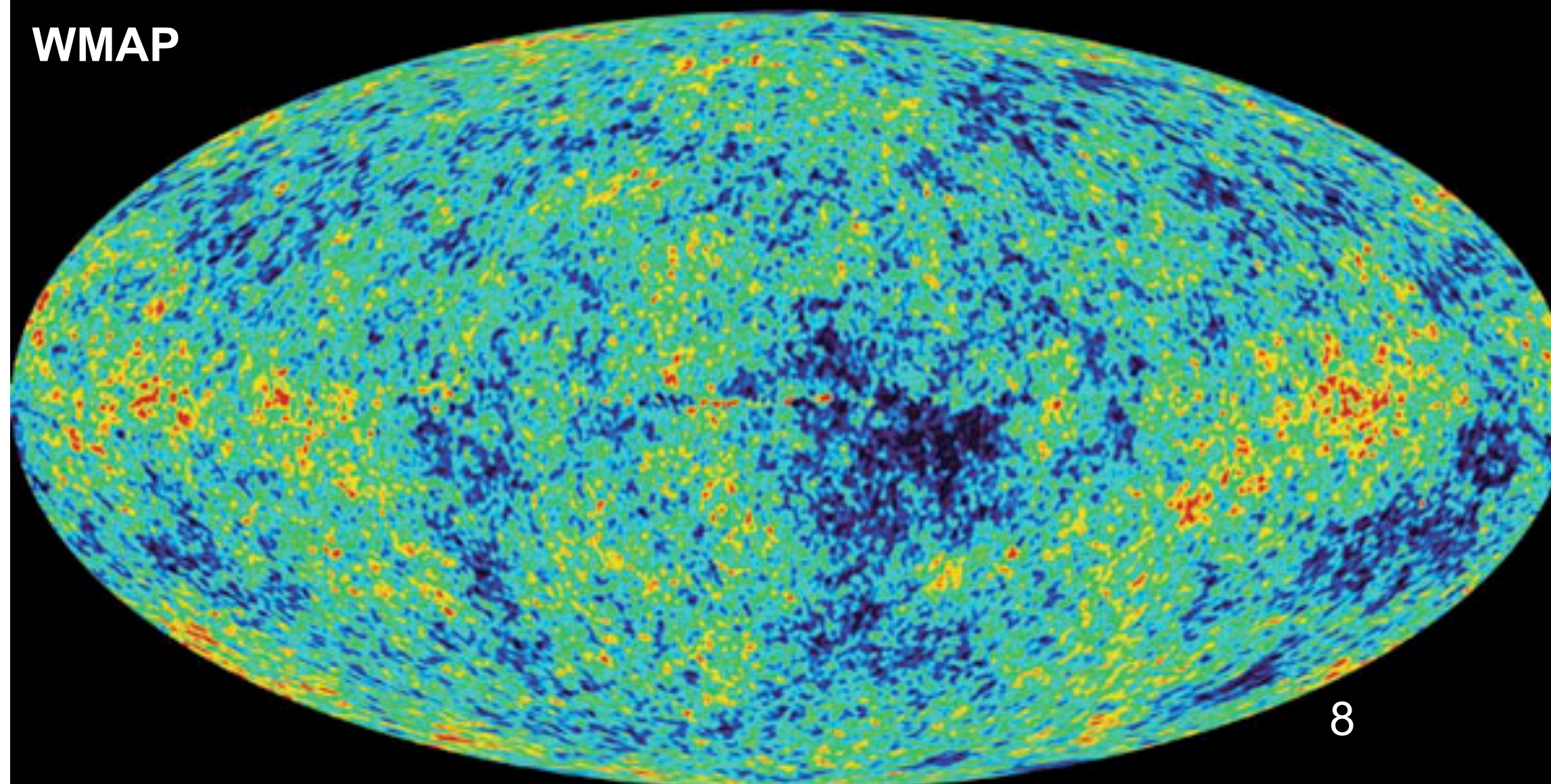
COBE
1989



COBE



WMAP
2001



WMAP

Cosmology Update: 7-year

● Standard Model

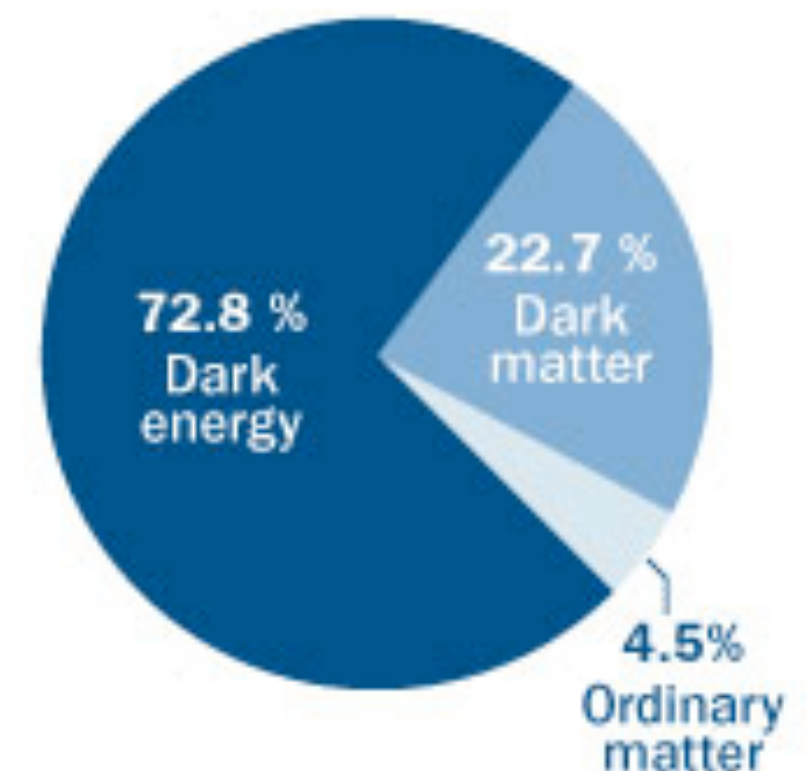
- H&He = 4.56% ($\pm 0.16\%$)
- Dark Matter = 27.2% ($\pm 1.6\%$)
- Dark Energy = 72.8% ($\pm 1.6\%$)
- $H_0 = 70.4 \pm 1.4$ km/s/Mpc
- Age of the Universe = 13.75 billion years (± 0.11 billion years)

Universal Stats

Age of the universe today
13.75 billion years

Age of the cosmos at
time of reionization
457 million years

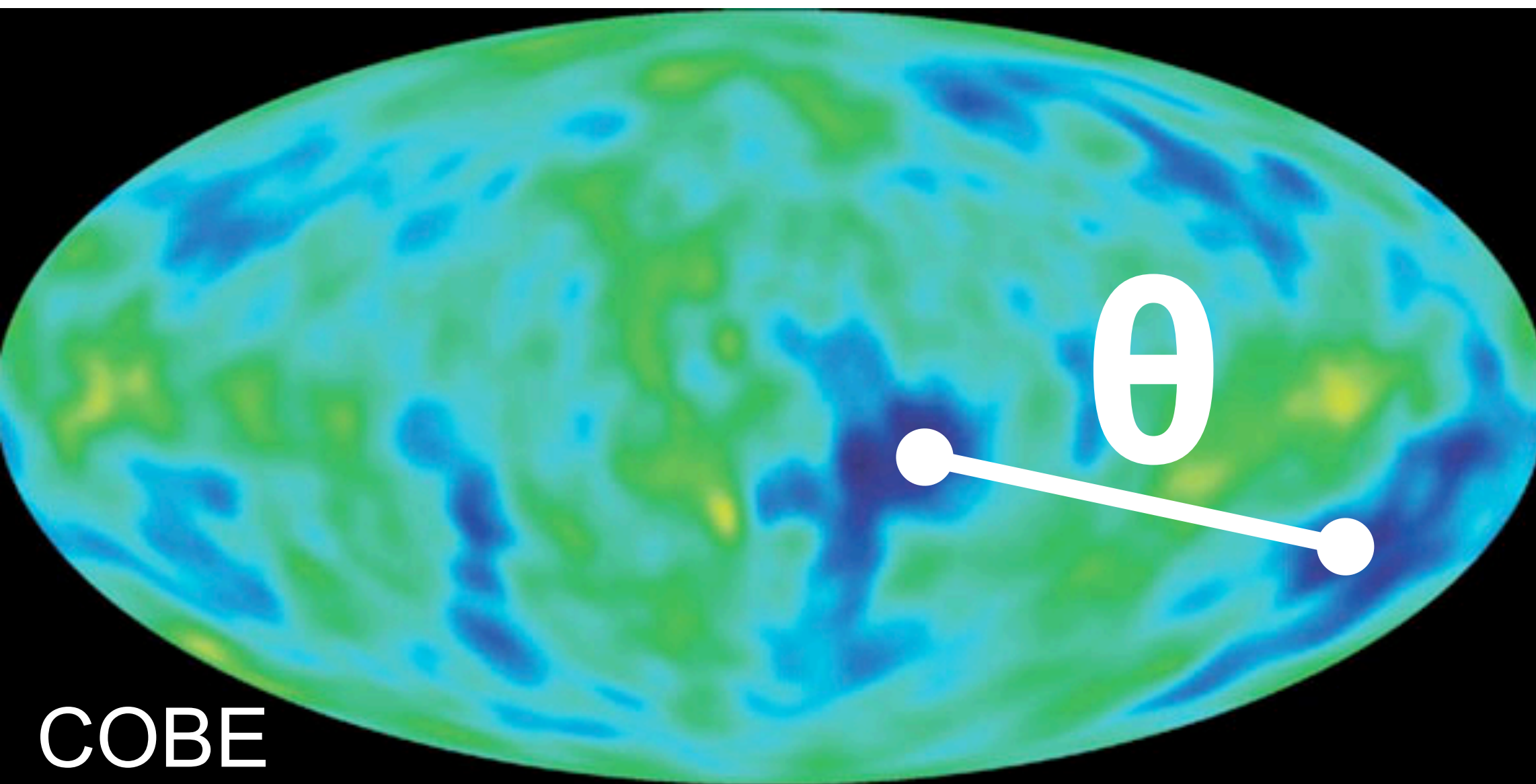
Universe composition



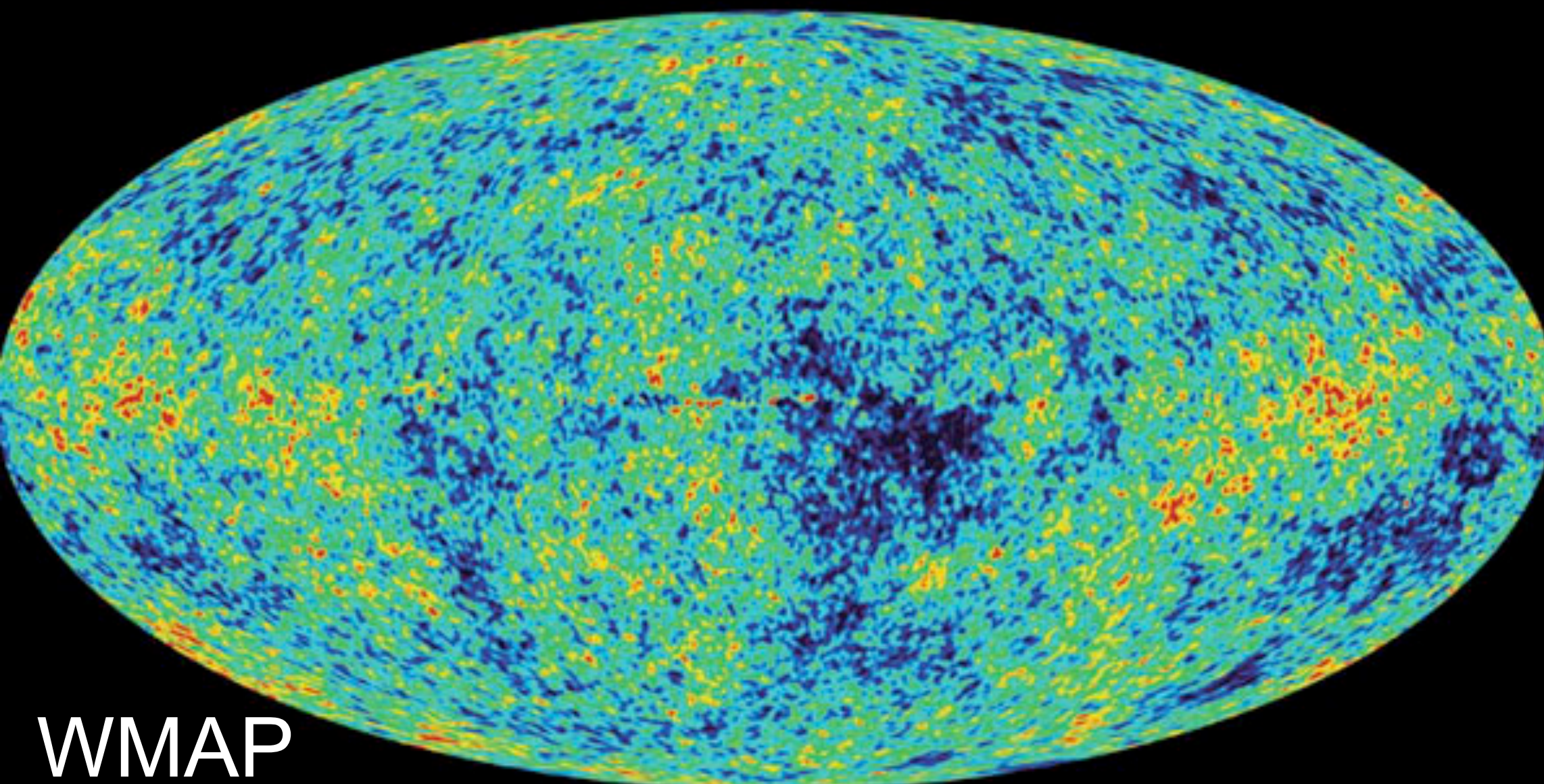
*“ScienceNews” article on
the WMAP 7-year results*

Analysis: 2-point Correlation

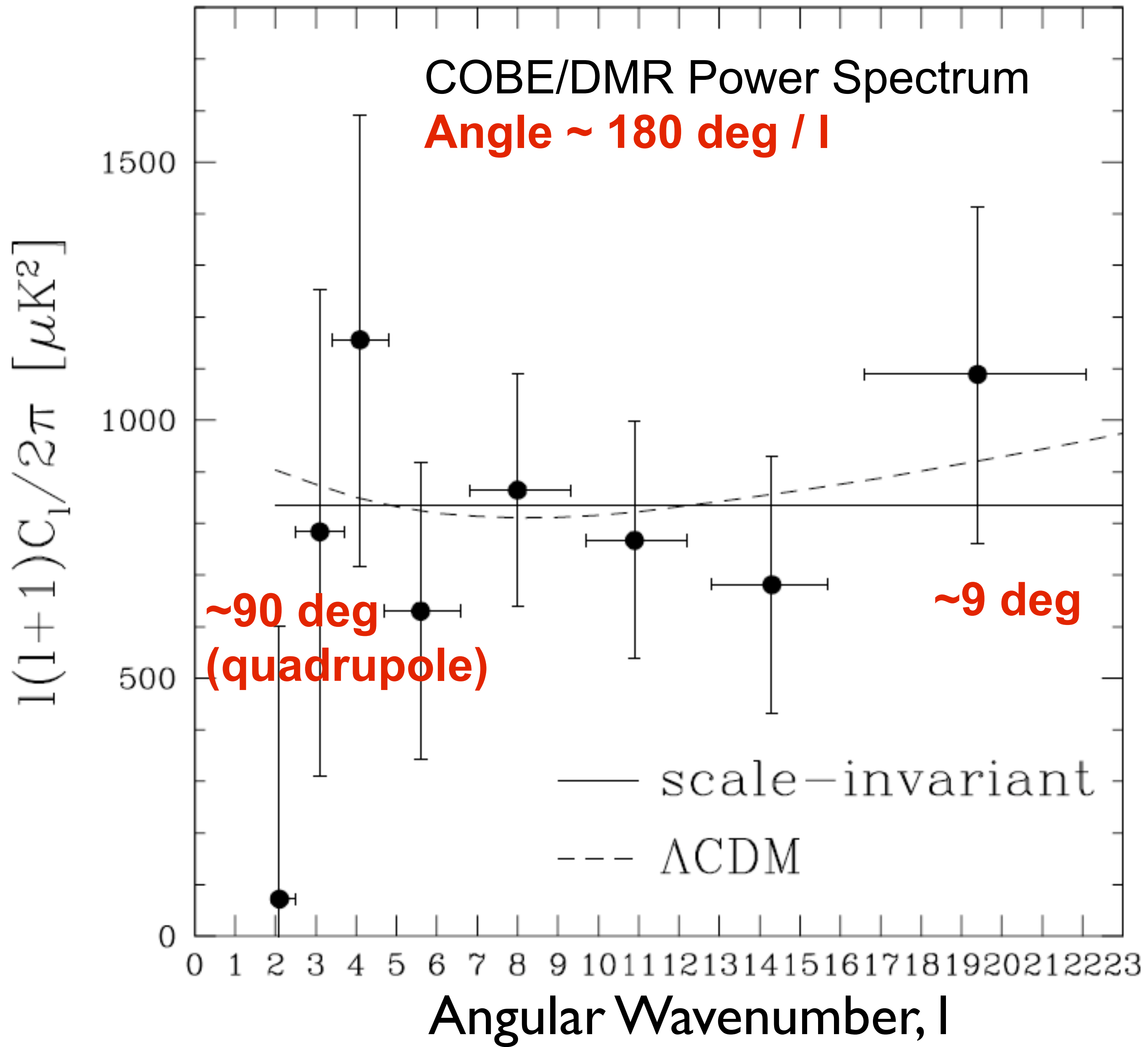
- $C(\theta) = (1/4\pi) \sum (2l+1) C_l P_l(\cos\theta)$
- How are temperatures on two points on the sky, separated by θ , are correlated?
- “Power Spectrum,” C_l
 - How much fluctuation power do we have at a given angular scale?
 - $l \sim 180 \text{ degrees} / \theta$



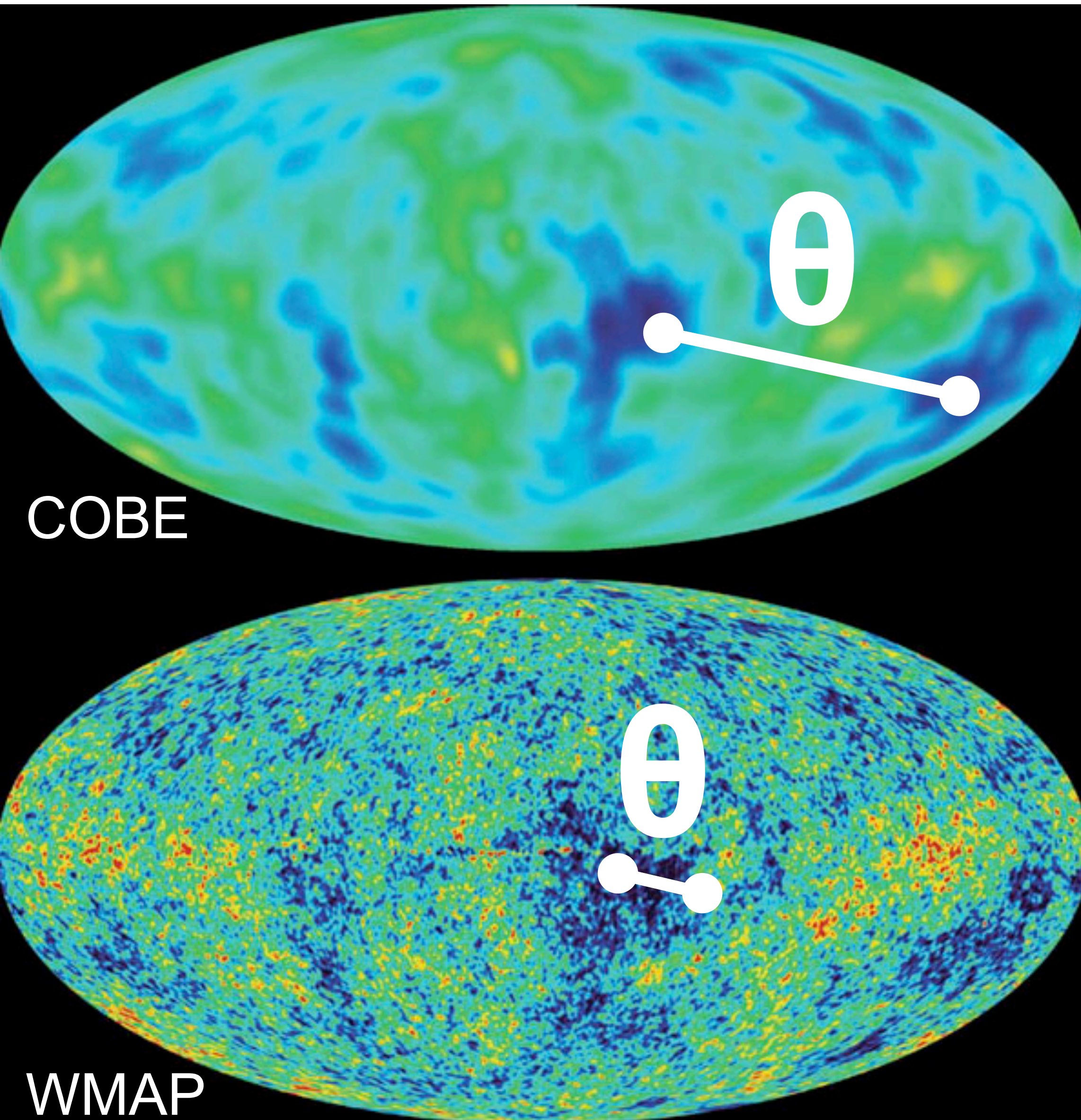
COBE



WMAP

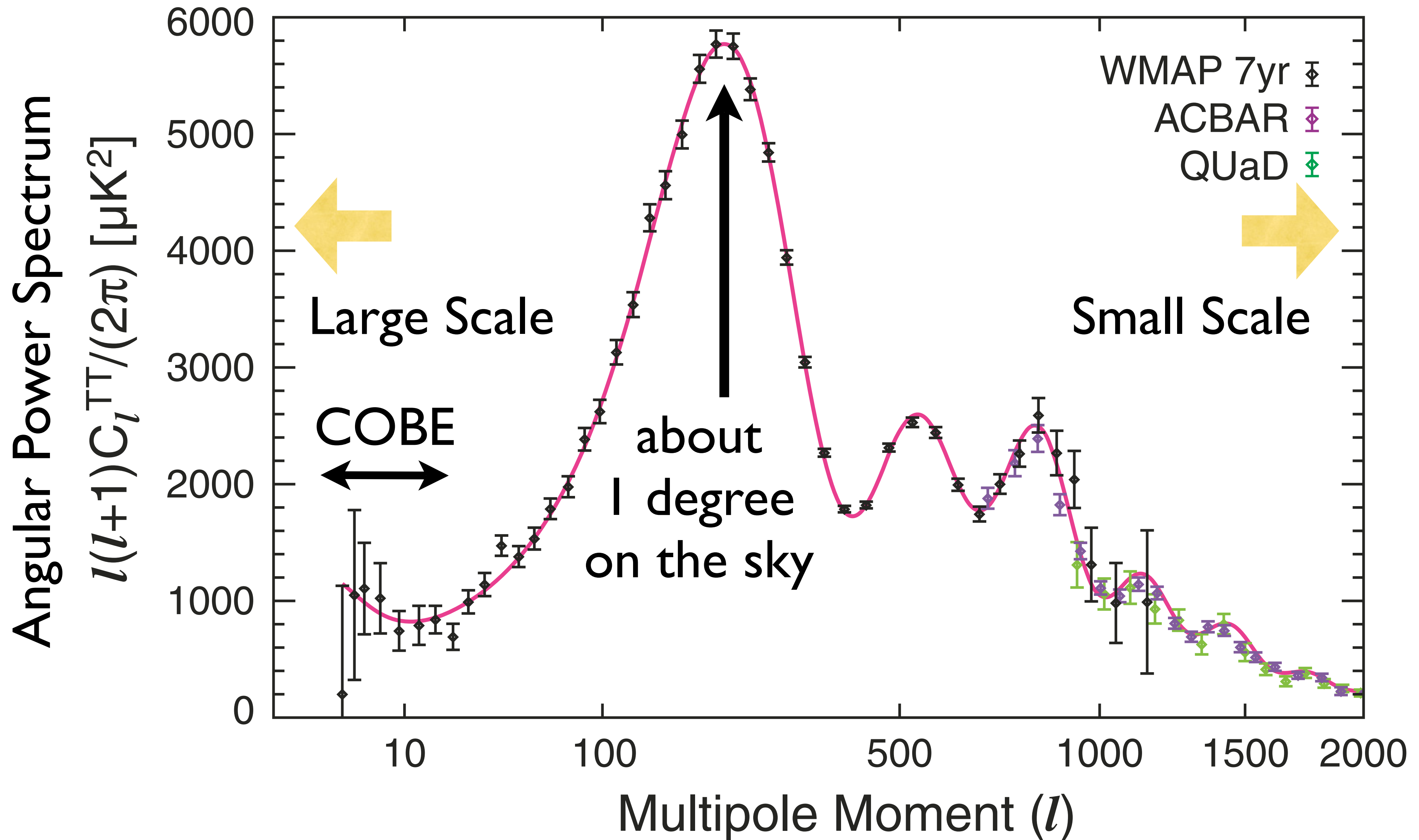


COBE To WMAP

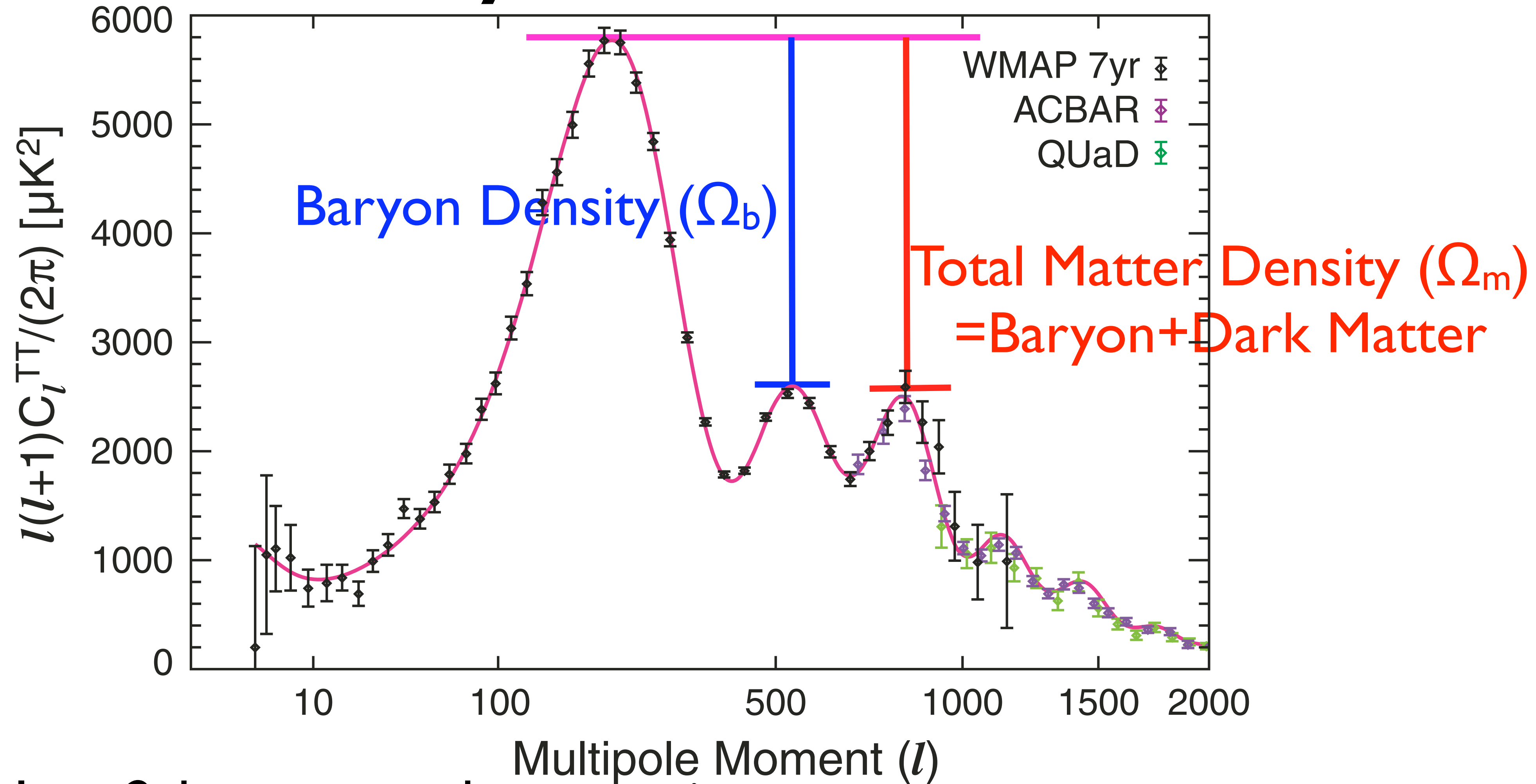


- COBE is unable to resolve the structures below ~ 7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP Power Spectrum

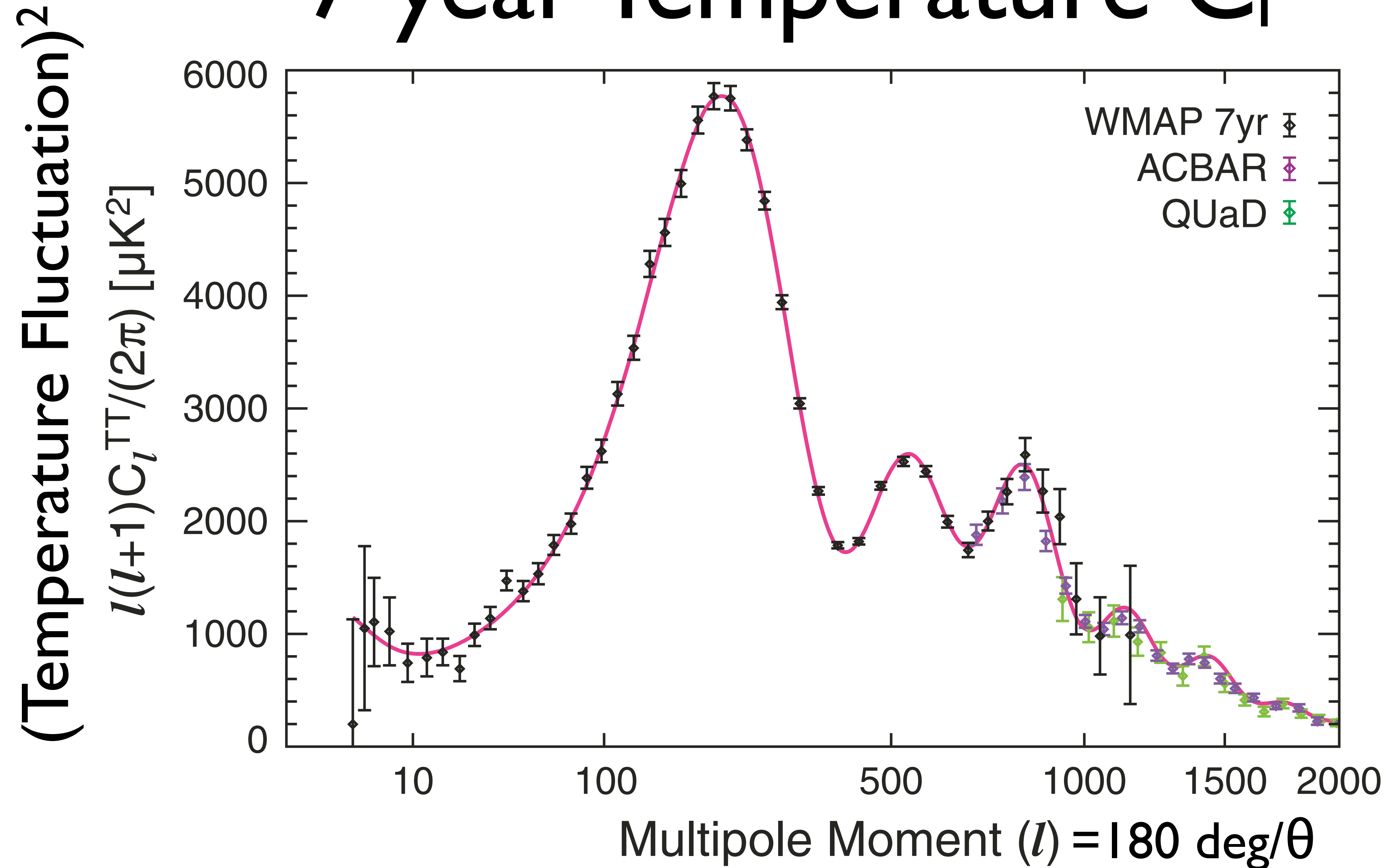


CMB to Baryon & Dark Matter

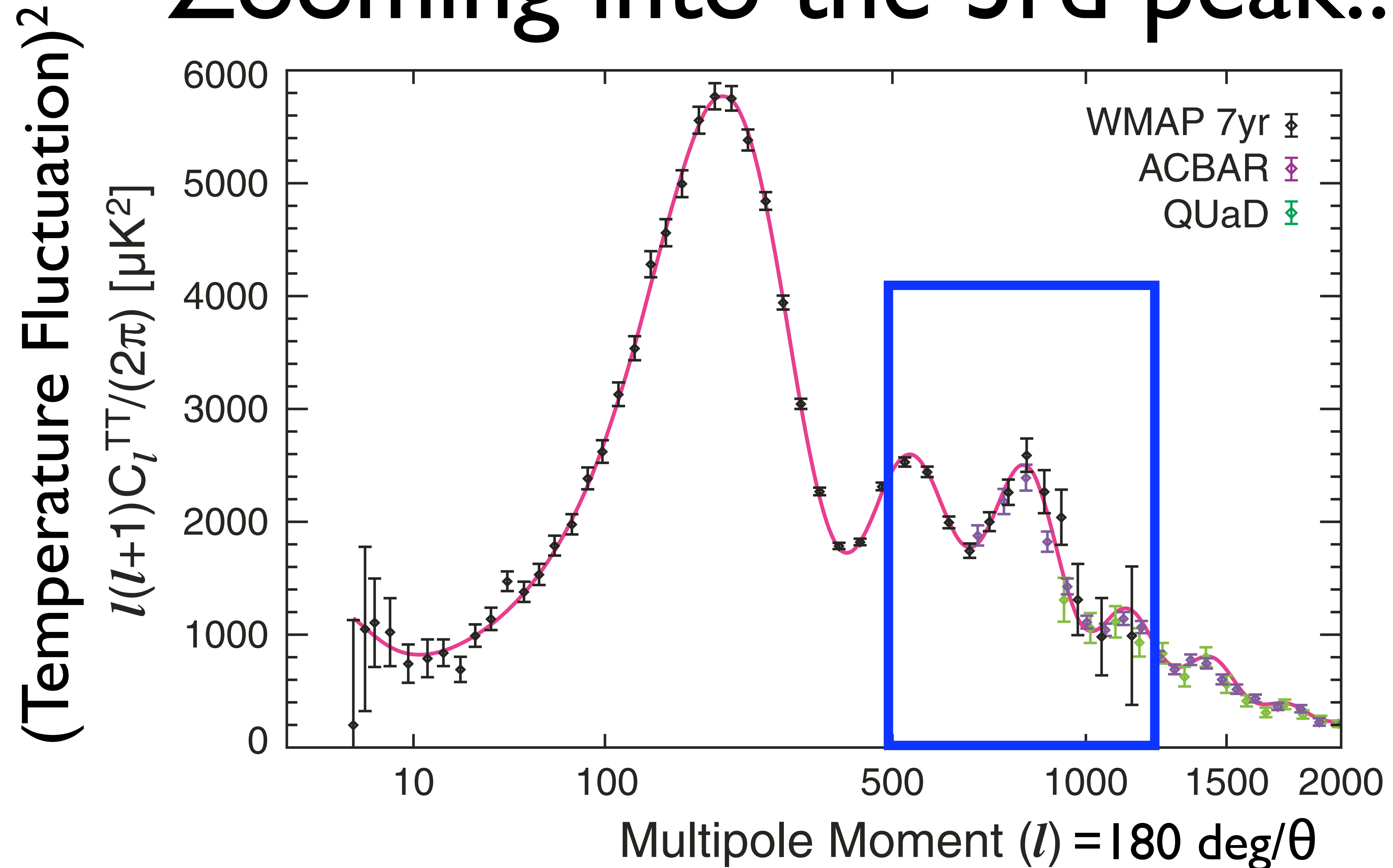


- l -to- 2 : baryon-to-photon ratio
- l -to- 3 : matter-to-radiation ratio (z_{EQ} : equality redshift)

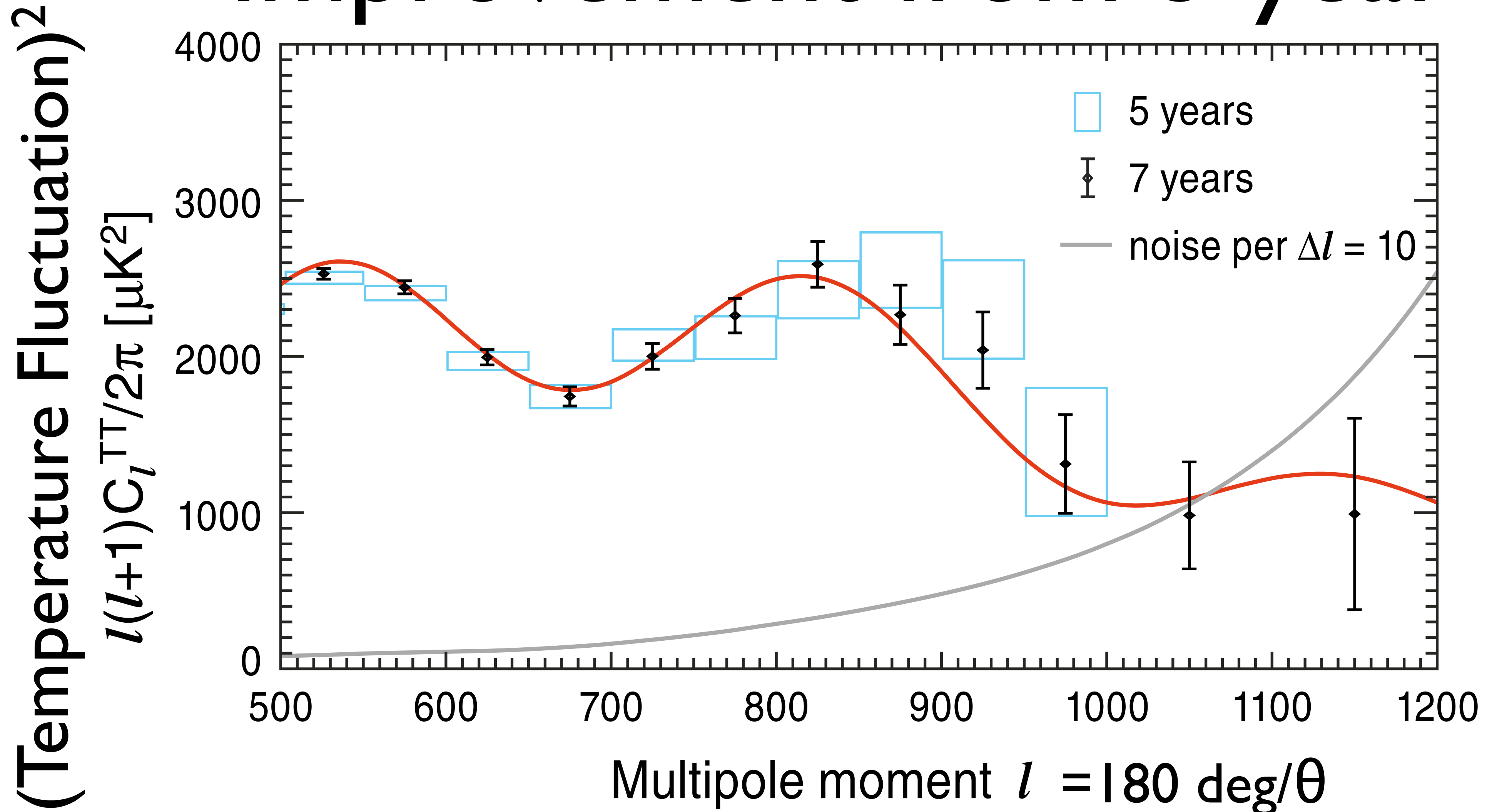
7-year Temperature C_l



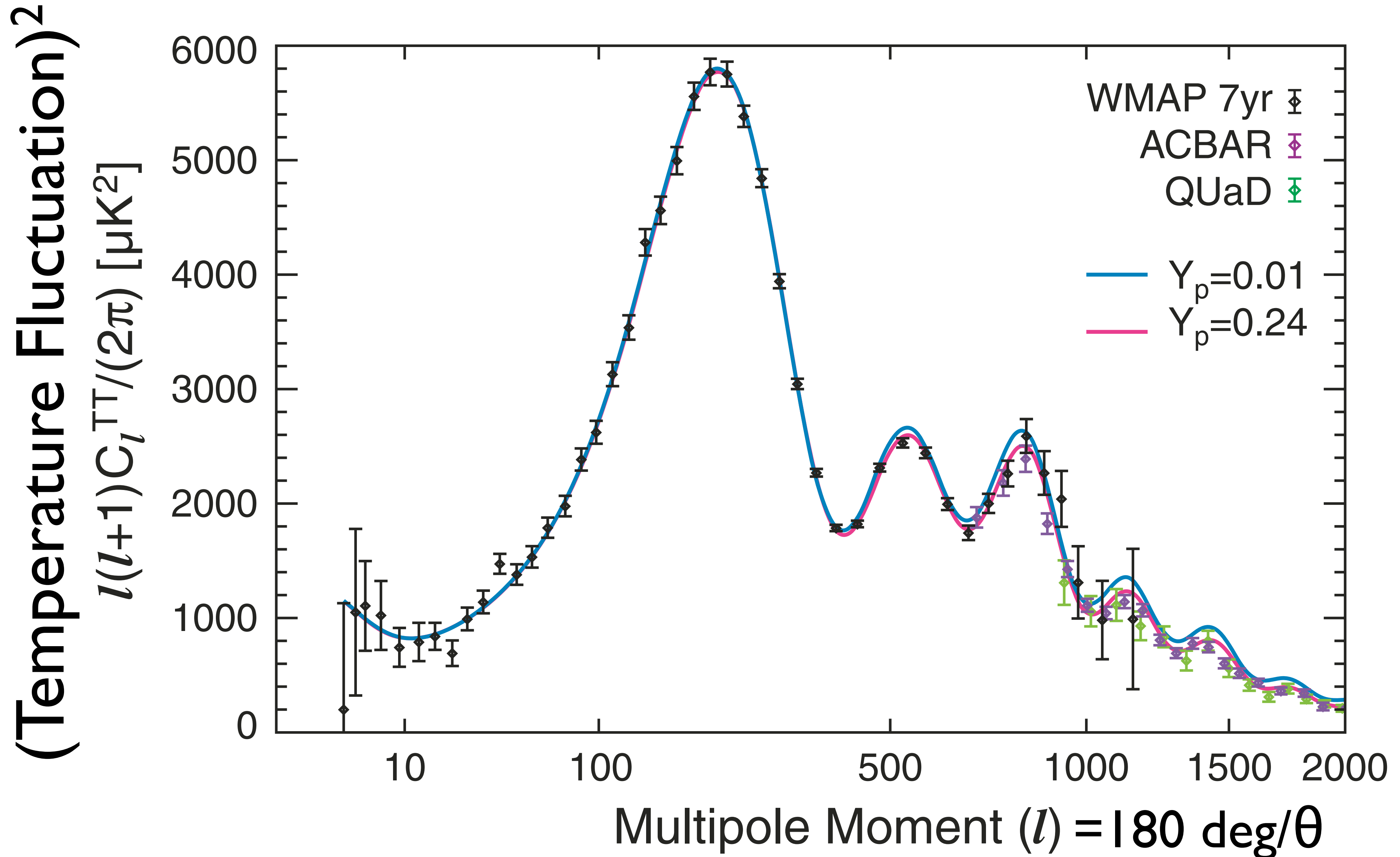
Zooming into the 3rd peak...



High- l Temperature C_l : Improvement from 5-year



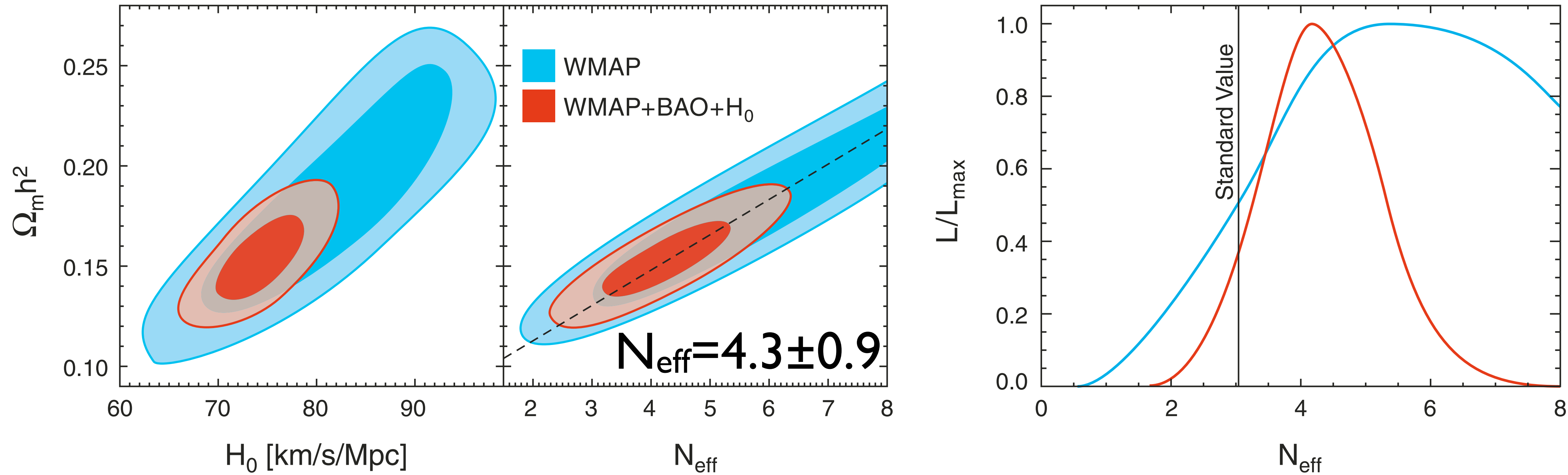
Detection of Primordial Helium



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 $z \sim 1800$, there were fewer electrons at the decoupling epoch ($z = 1090$): $n_e = (1 - Y_p)n_b$.
- **More helium** = Fewer electrons = Longer photon mean free path $1/(\sigma_T n_e) =$ **Enhanced damping**
- **$Y_p = 0.33 \pm 0.08$** (68%CL)
 - Consistent with the standard value from the Big Bang nucleosynthesis theory: $Y_p = 0.24$.
- Planck should be able to reduce the error bar to **0.01**.

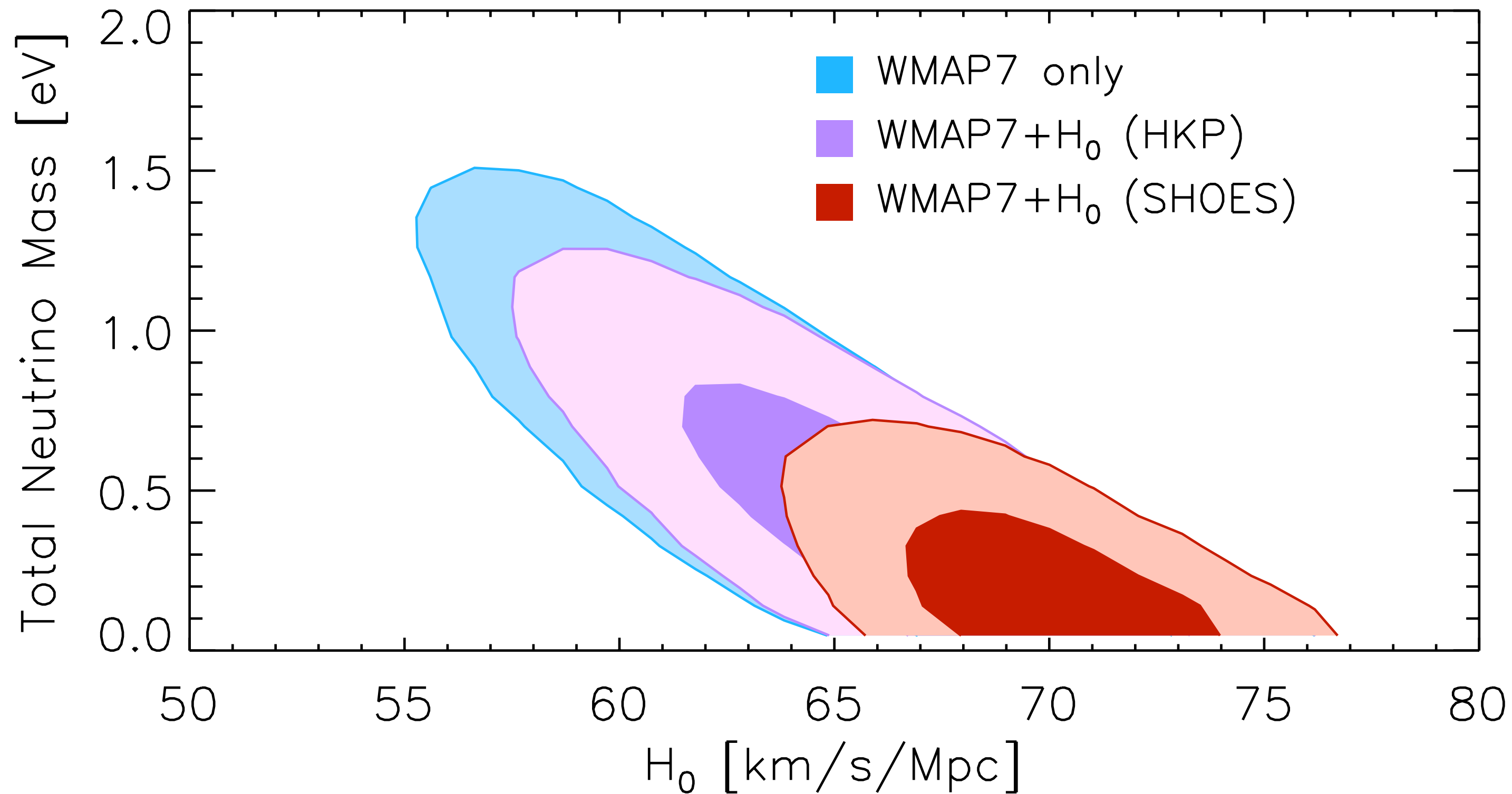
Another “3rd peak science”: Number of Relativistic Species



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

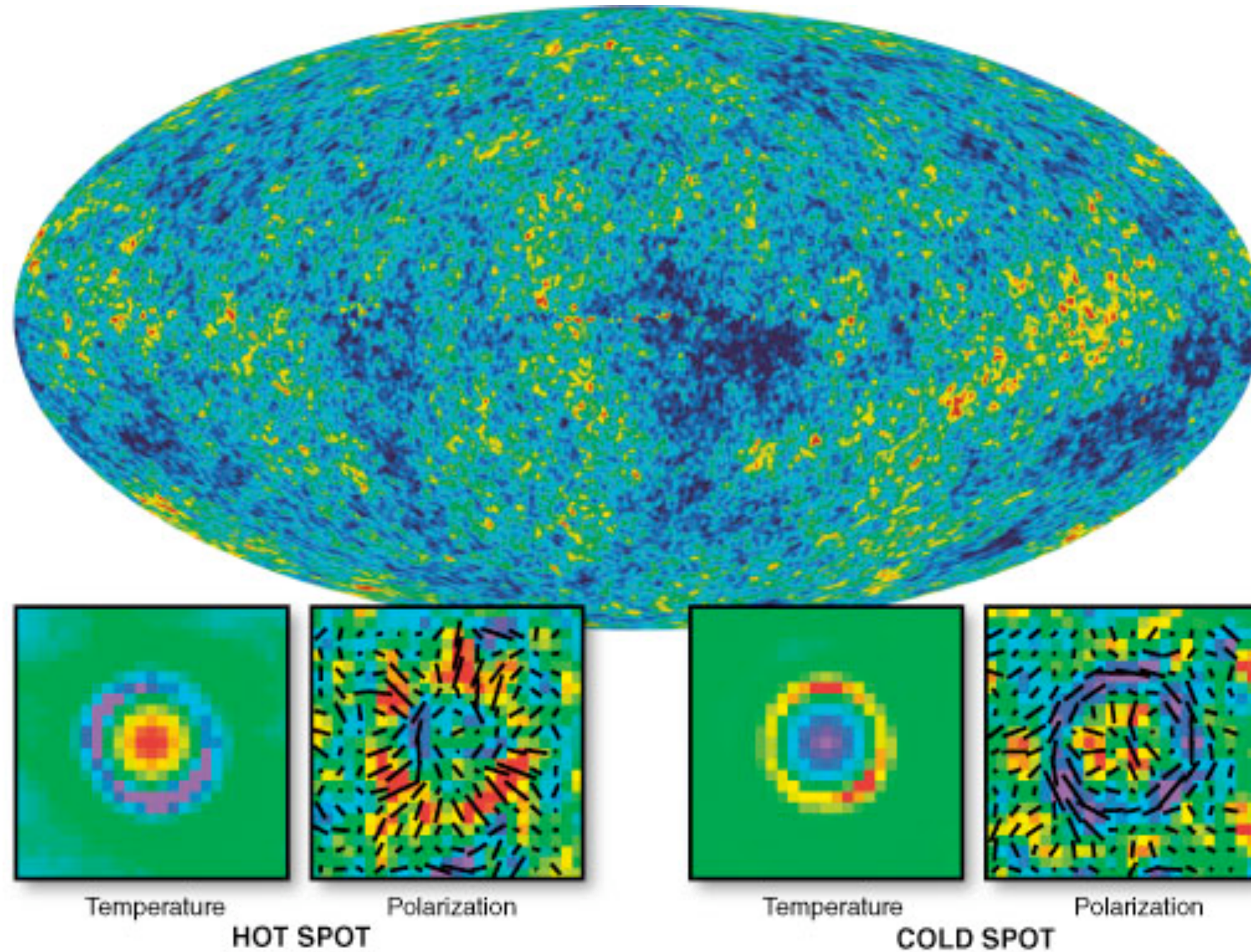
← from external data
← from 3rd peak

And, the mass of neutrinos



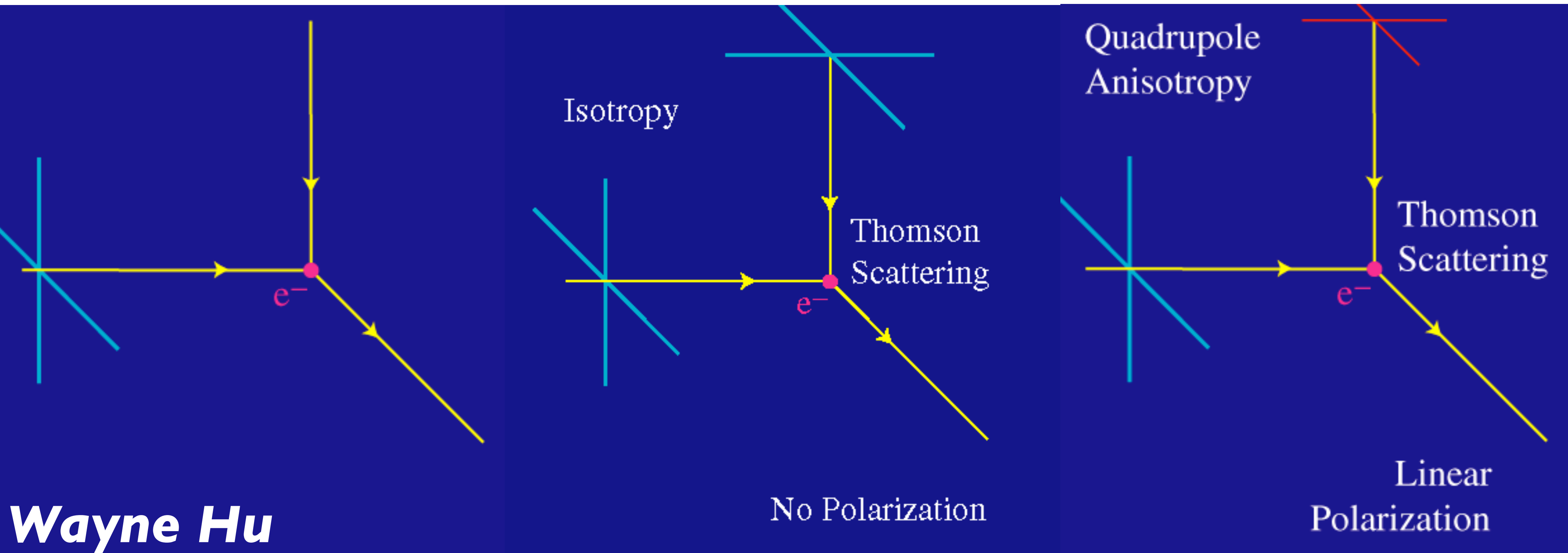
- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

CMB Polarization



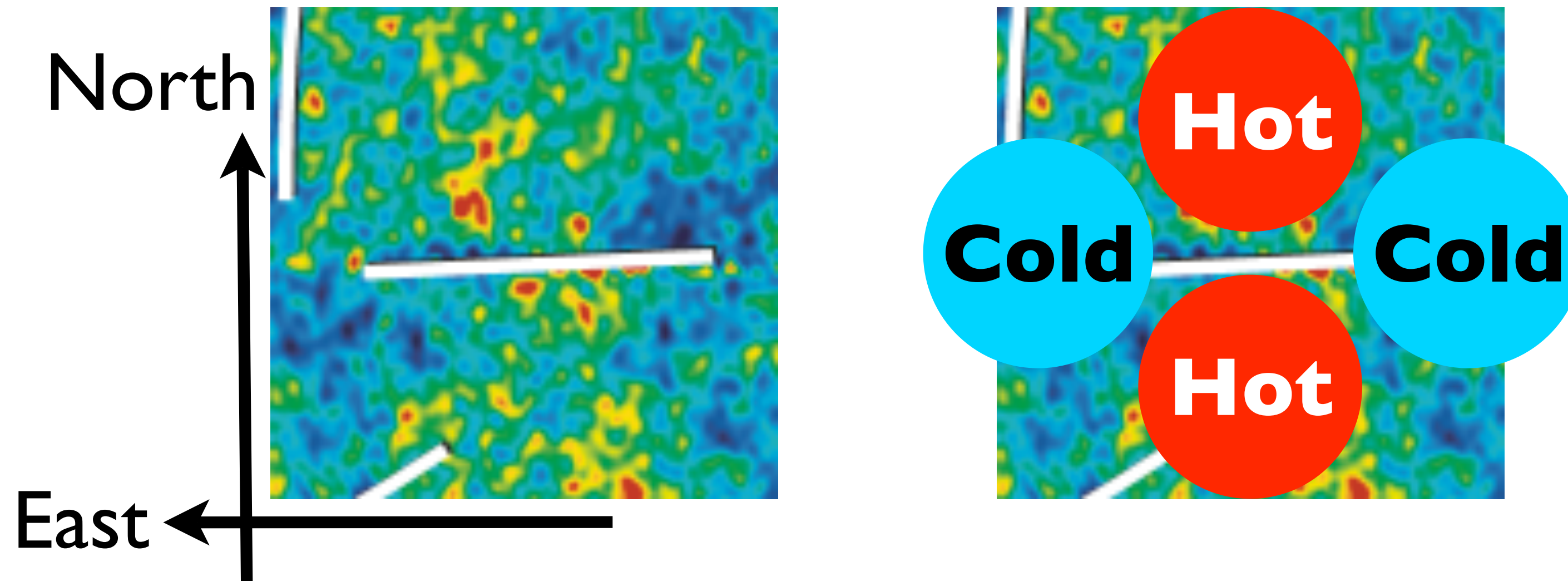
- *CMB is (very weakly) polarized!*

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)

Matter Density



Potential

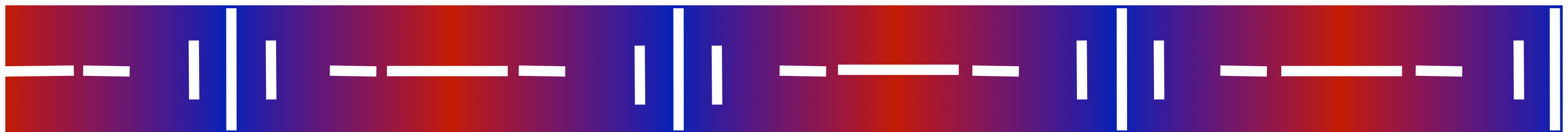


$$\Delta T/T = (\text{Newton's Gravitation Potential})/3$$

ΔT



Polarization

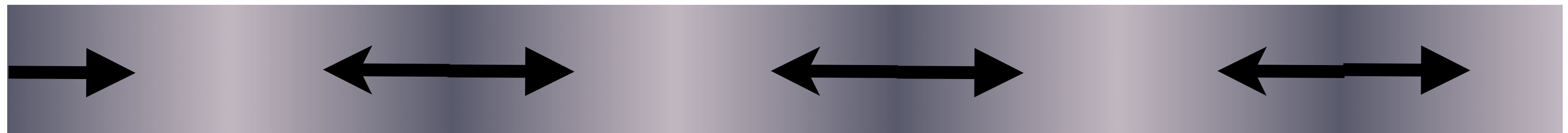


- How does the photon-baryon plasma move?

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

Zaldarriaga & Harari (1995)

Matter Density

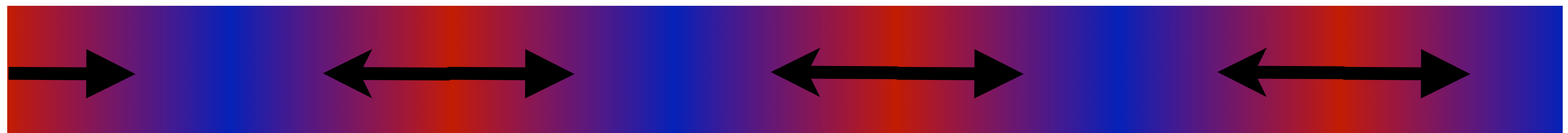


Potential

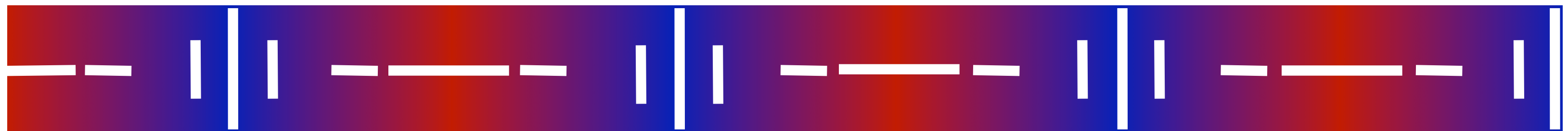


$$\Delta T/T = (\text{Newton's Gravitation Potential})/3$$

ΔT

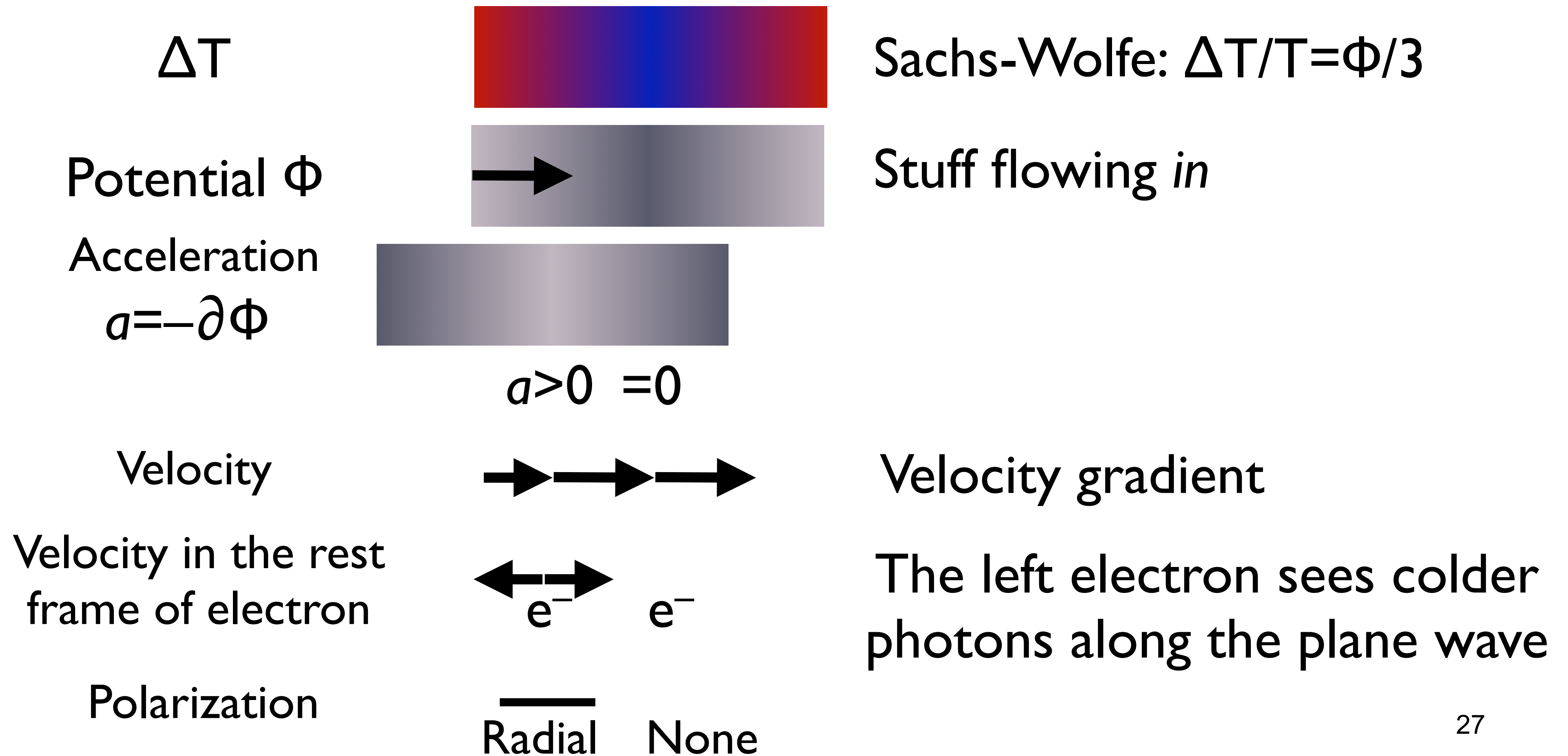


Polarization

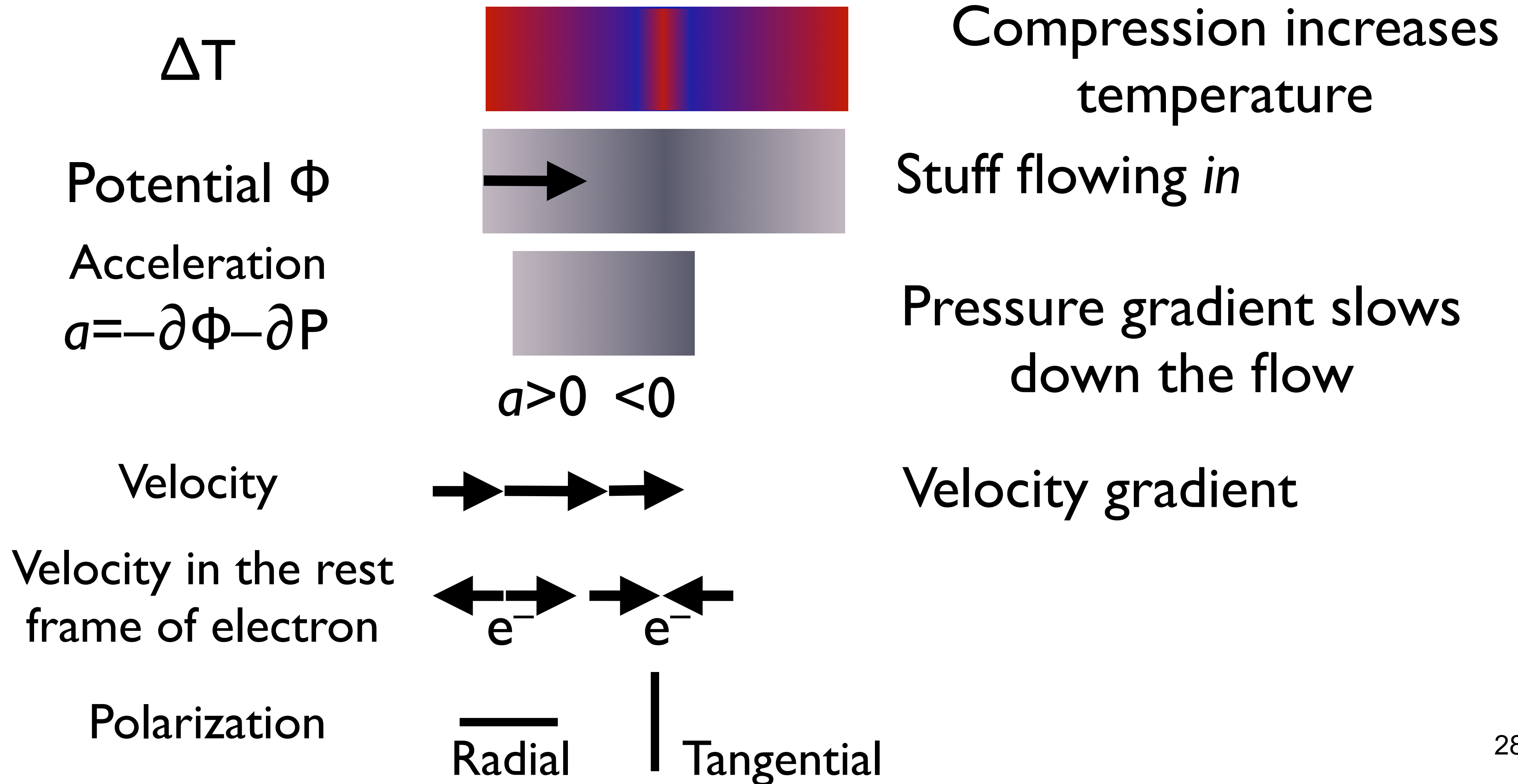


- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern

Quadrupole From Velocity Gradient (Large Scale)

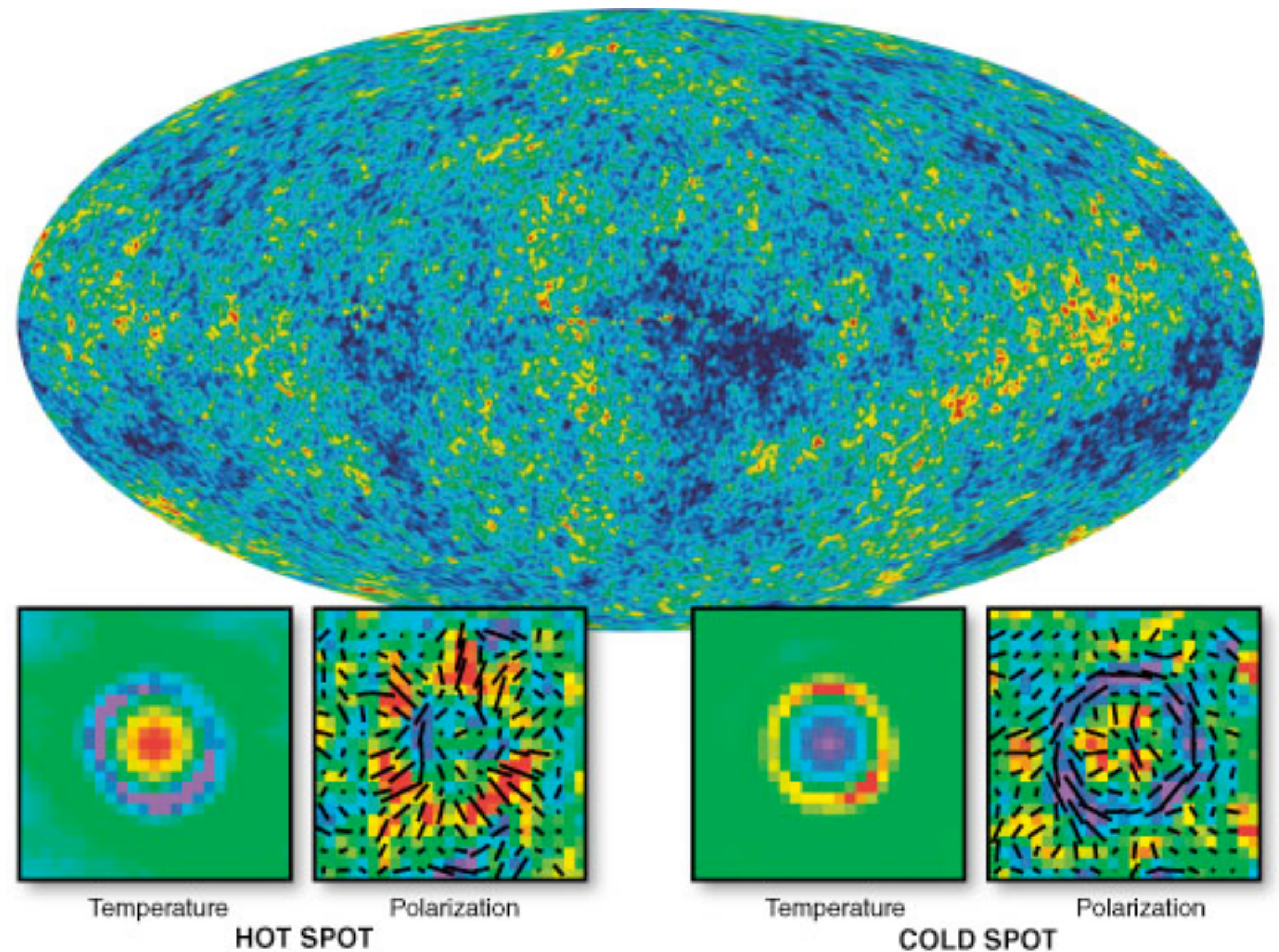


Quadrupole From Velocity Gradient (Small Scale)

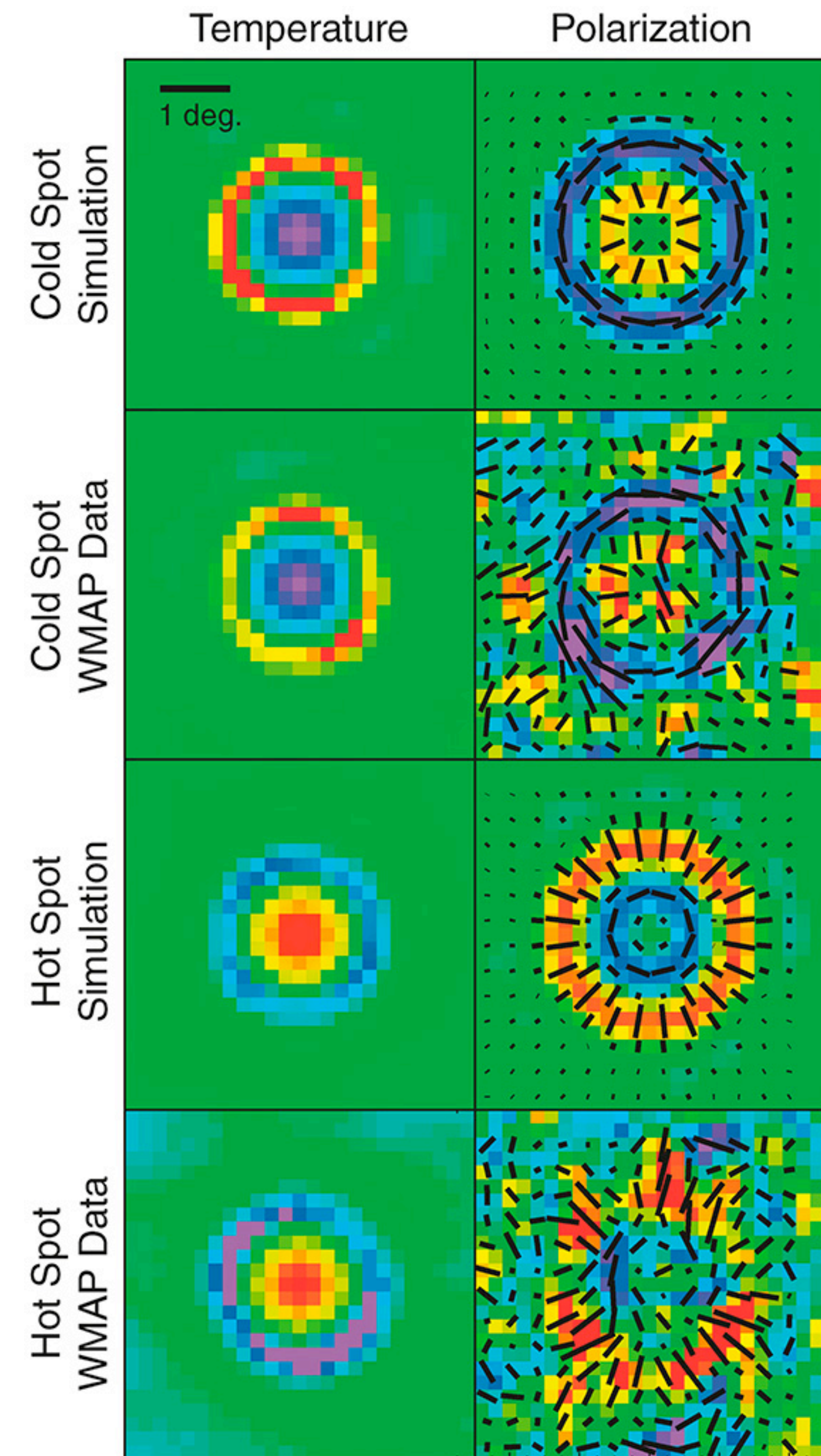


Stacking Analysis

- 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**.

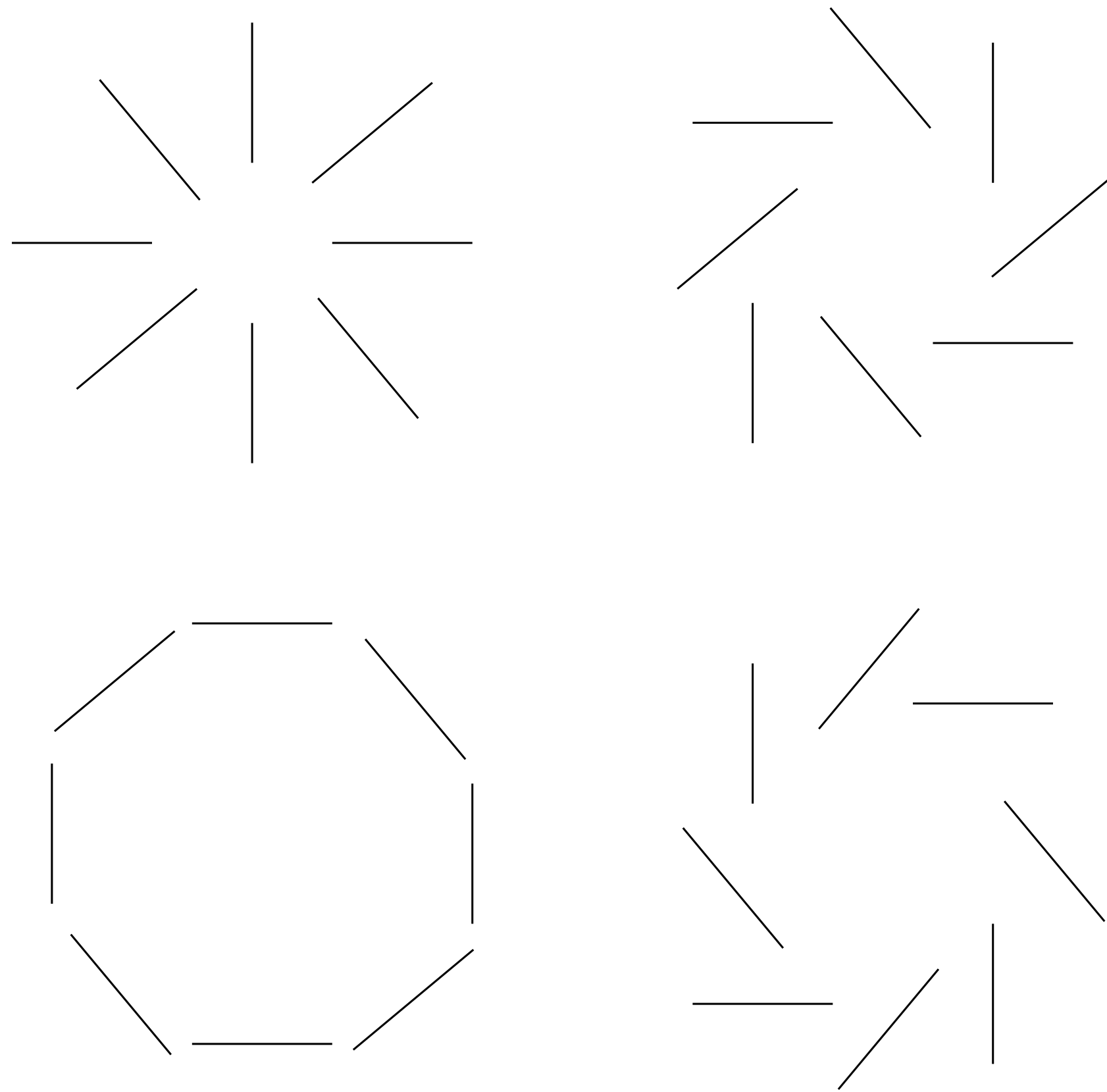


Two-dimensional View



- 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: 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!

E-mode

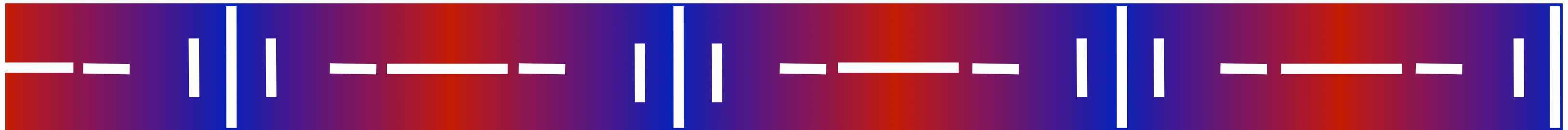
Potential



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

→
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

G.W.



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

→
Direction of a plane wave

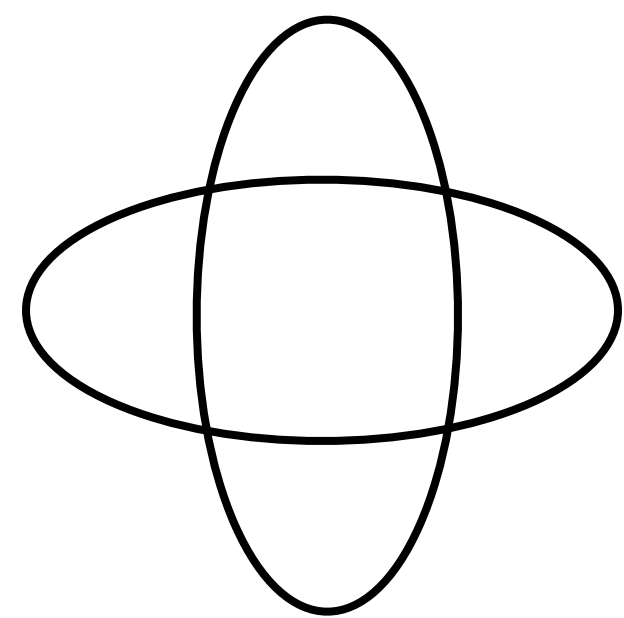
Polarization
Direction



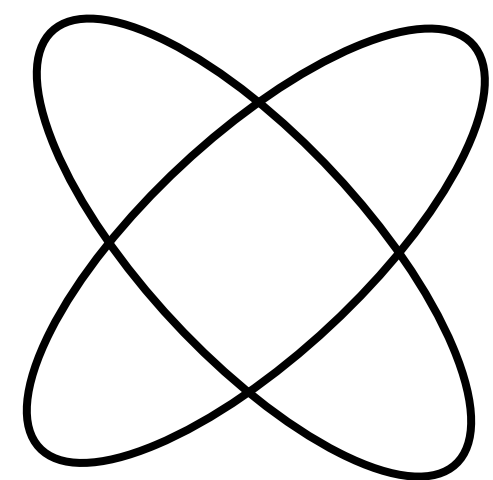
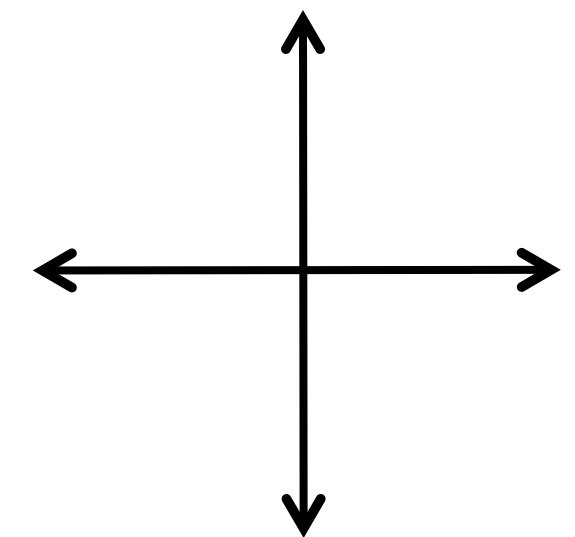
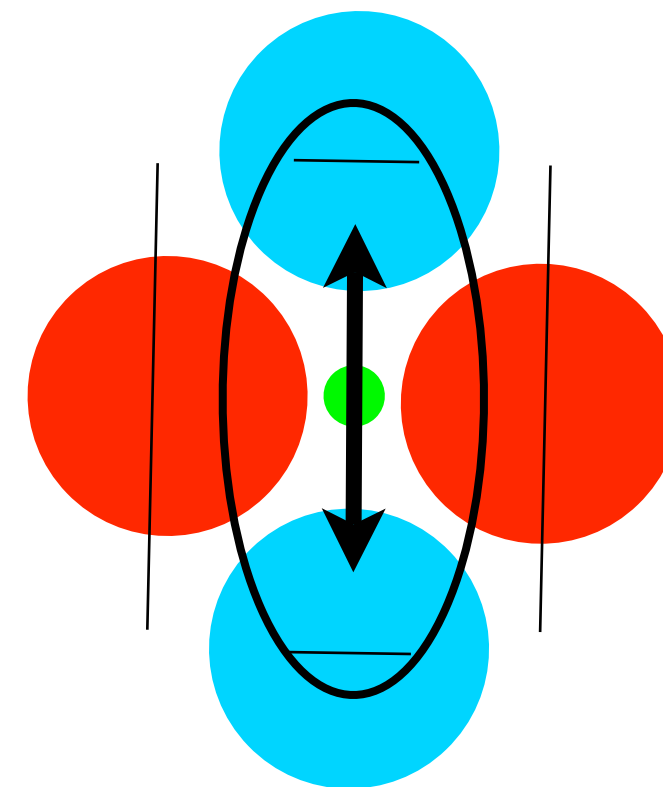
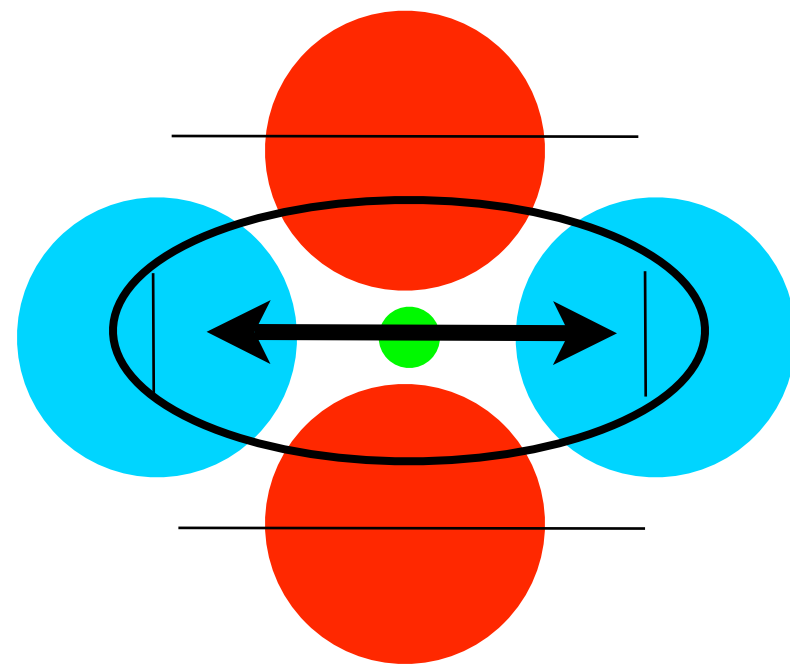
- **B-mode**: the polarization directions are tilted by 45 degrees relative to the direction of the plane wave perturbation.

Gravitational Waves and Quadrupole

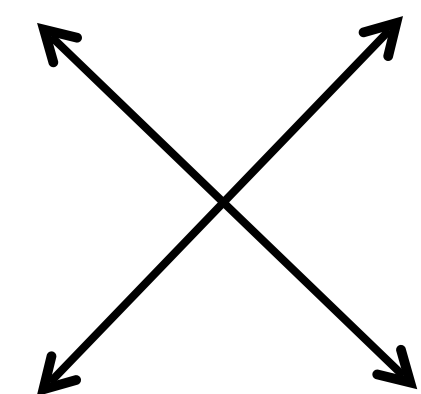
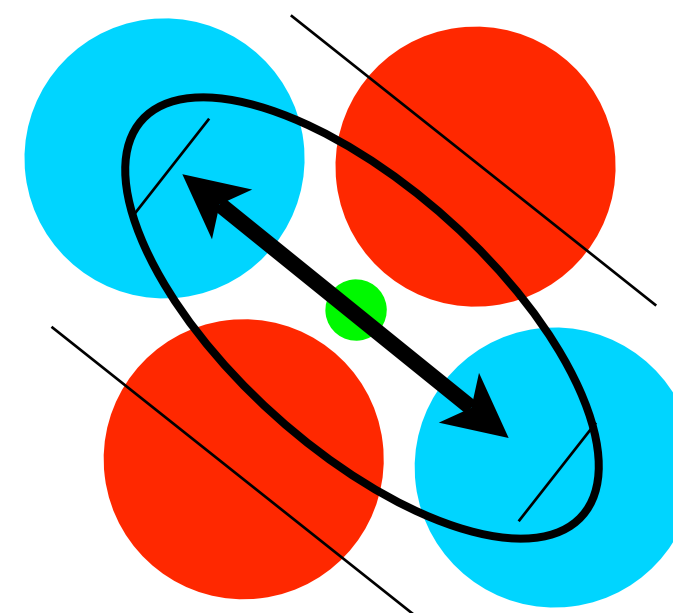
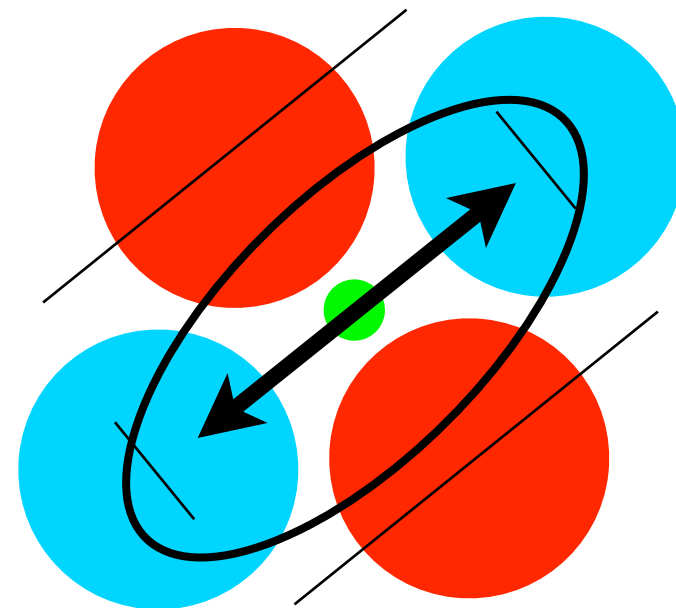
- Gravitational waves stretch space with a quadrupole pattern.



“+ mode”



“X mode”



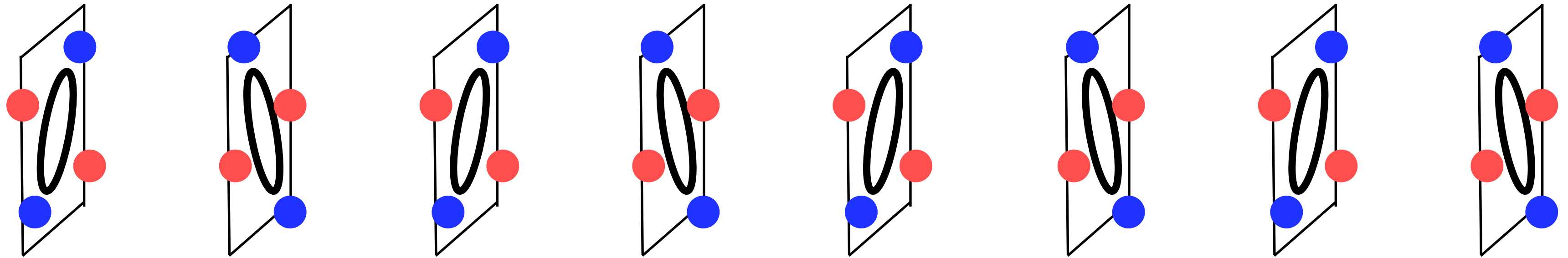
Quadrupole from G.W.

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

Direction of the plane wave of G.W.



h_x



temperature



polarization



B-mode

- B-mode polarization generated by h_x

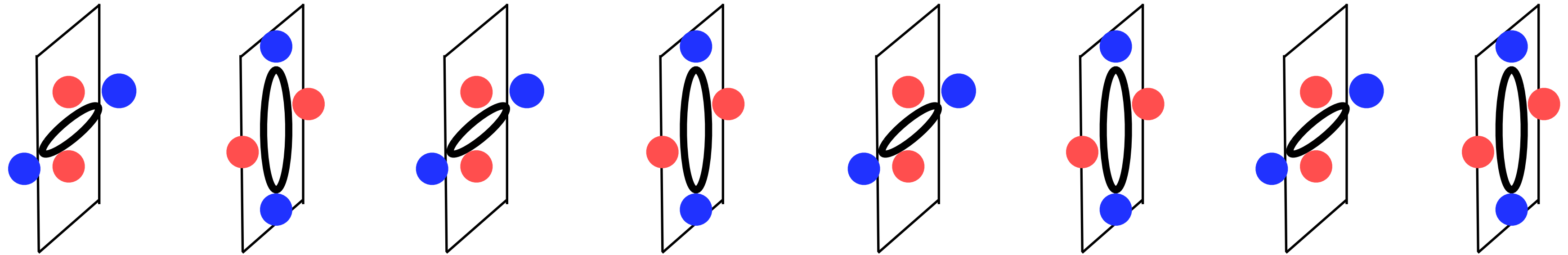
Quadrupole from G.W.

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

Direction of the plane wave of G.W.



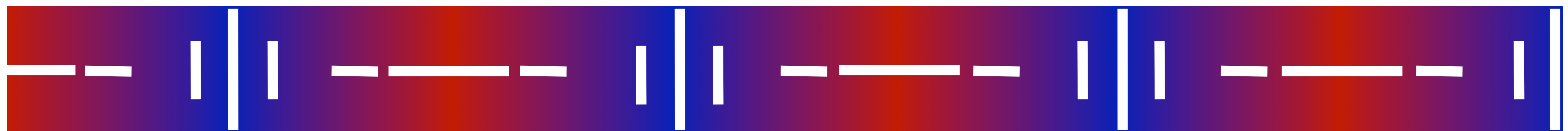
h_+



temperature



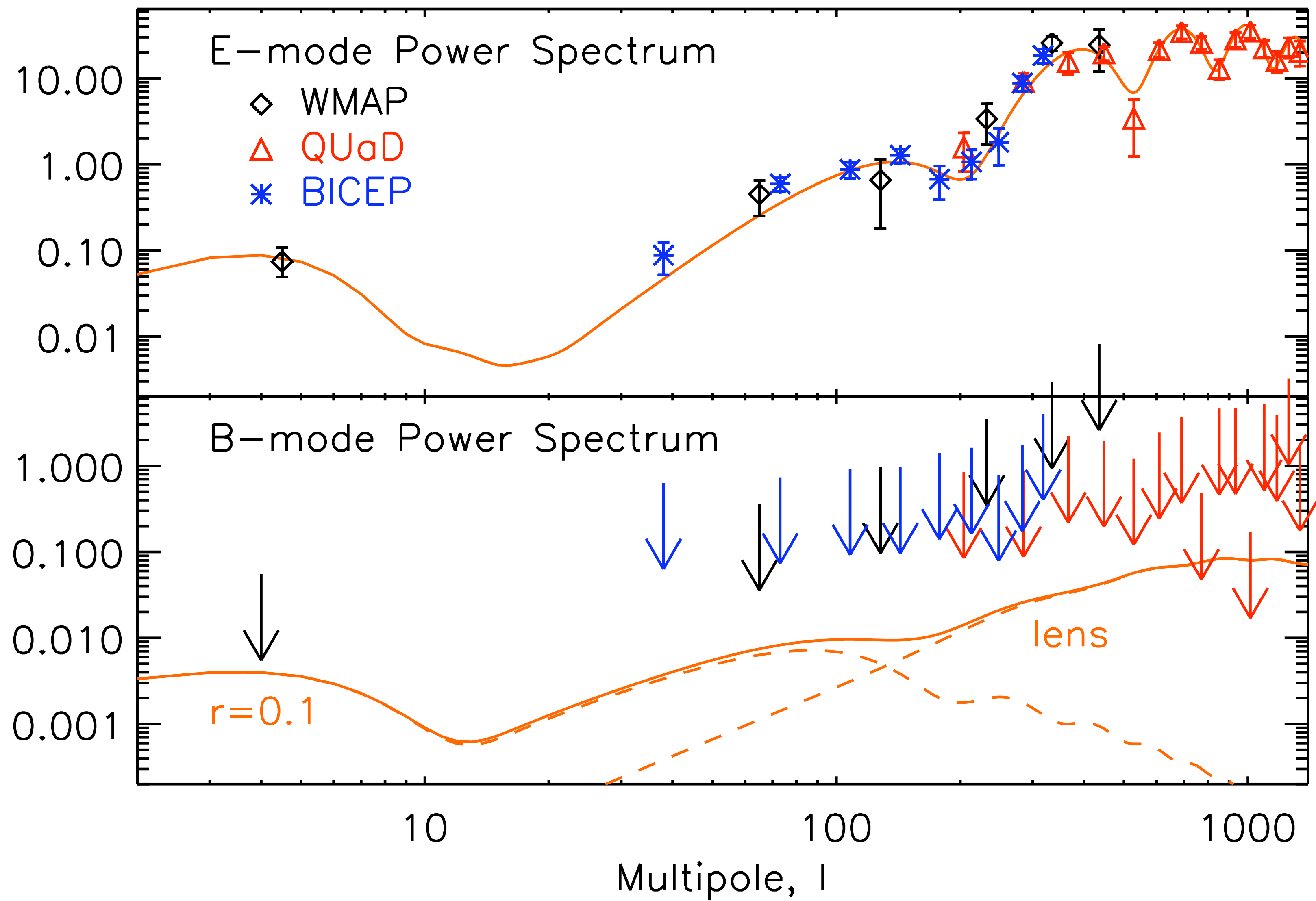
polarization



E-mode

- E-mode polarization generated by h_+

Polarization Power Spectrum



- 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

$$\delta\varphi = (\text{Expansion Rate})/(2\pi) \text{ [in natural units]}$$

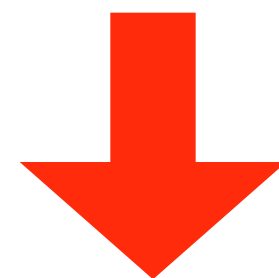
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
 - Something like 10^{-34} second old
 - (Expansion Rate) $\sim 1/(\text{Time})$
 - which is a big number! ($\sim 10^{12}\text{GeV}$)
- *Quantum fluctuations were important during inflation!*

Stretching Micro to Macro

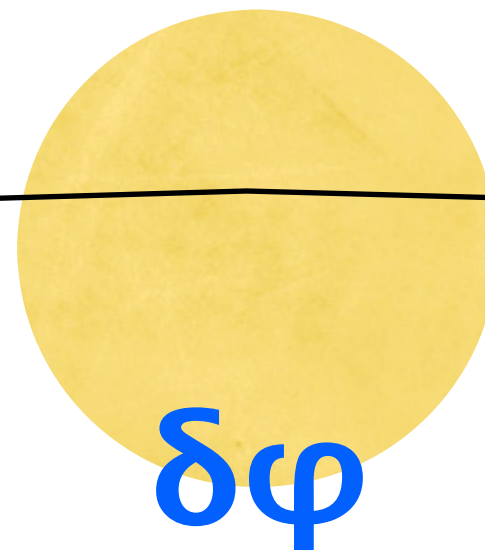
Macroscopic size at which gravity becomes important



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.

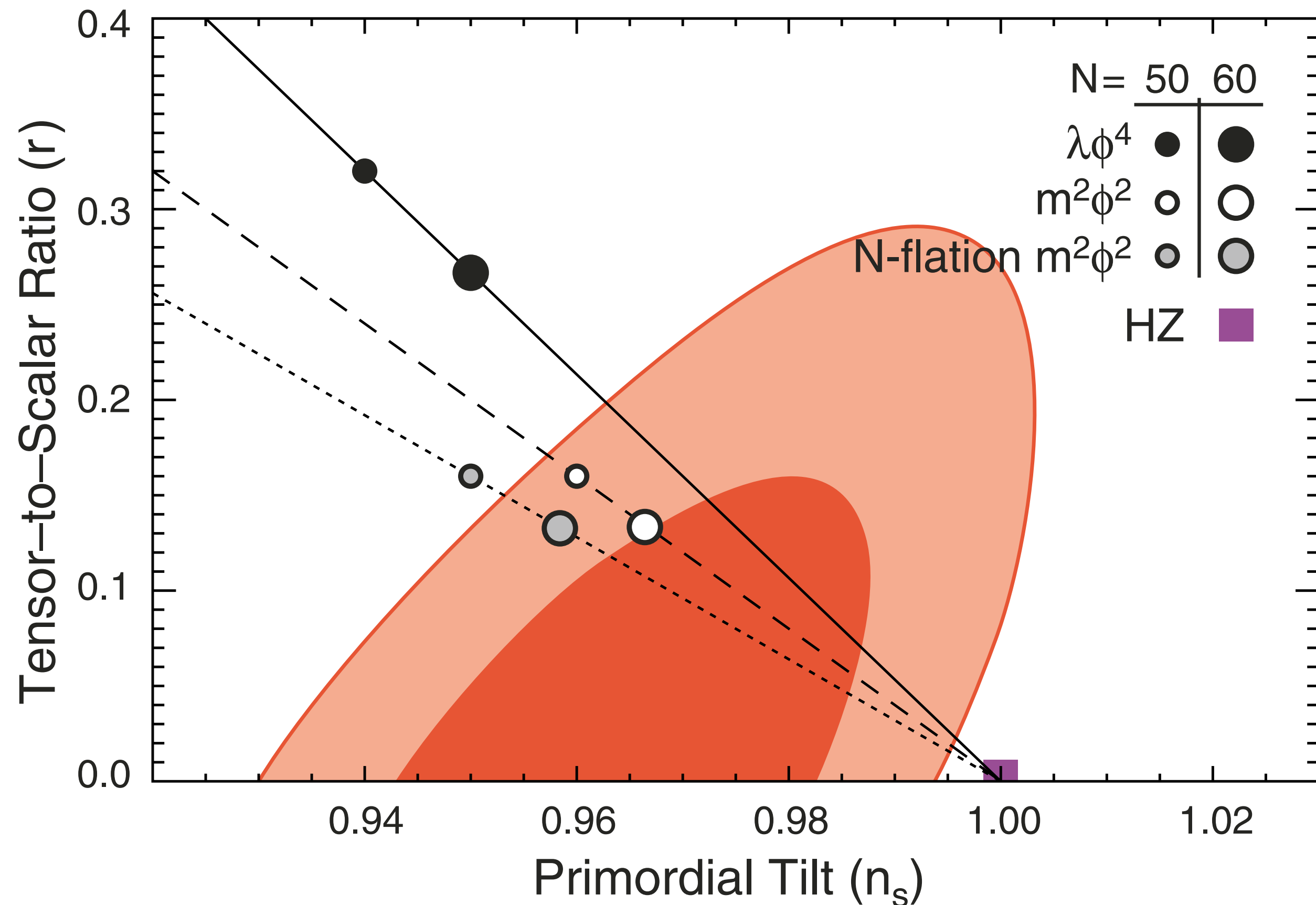
(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

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

[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:
 - $-10 < f_{\text{NL}}^{\text{local}} < 74$
 - $-214 < f_{\text{NL}}^{\text{equilateral}} < 266$
 - $-410 < f_{\text{NL}}^{\text{orthogonal}} < 6$
- The WMAP data are consistent with the prediction of **simple single-inflation inflation** models:
 - $1 - n_s \approx r \approx f_{\text{NL}}^{\text{local}}, f_{\text{NL}}^{\text{equilateral}} = 0 = f_{\text{NL}}^{\text{orthogonal}}$.

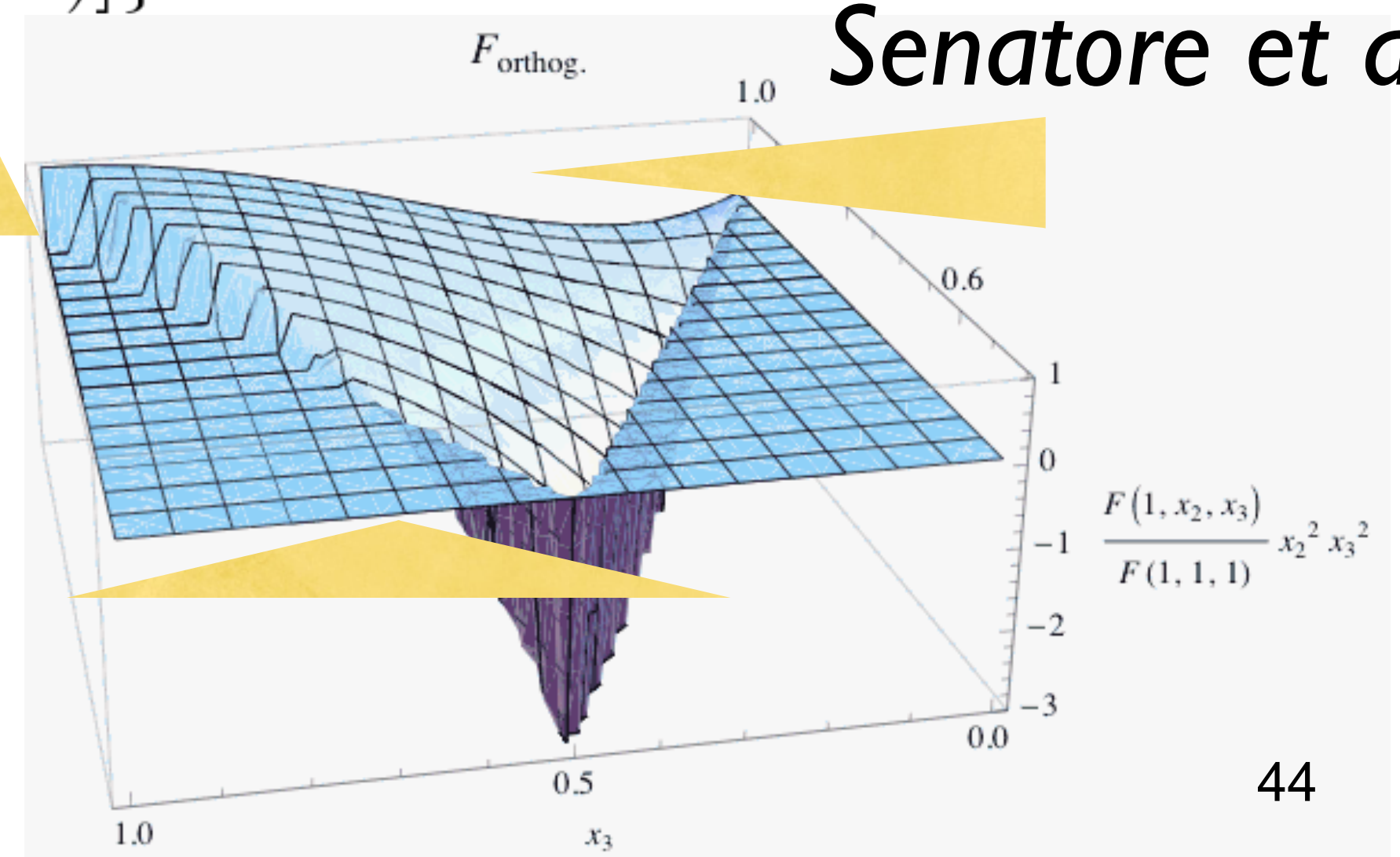
If this means anything to you...

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

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

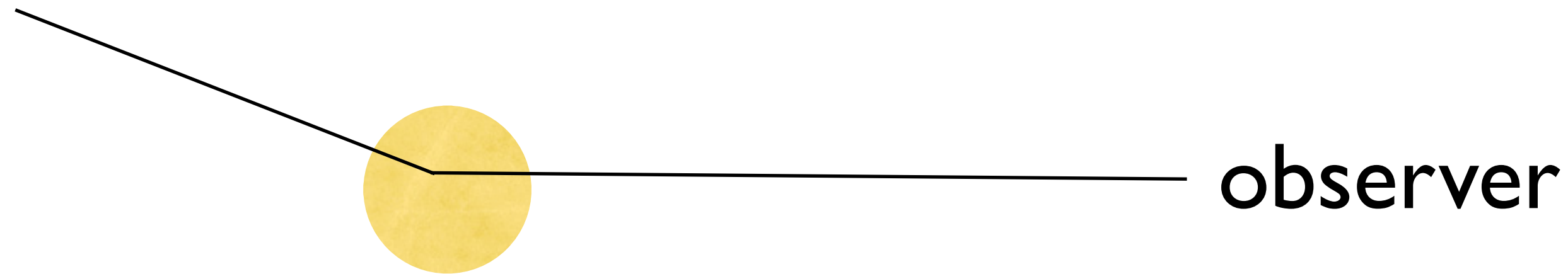
$$\begin{aligned} & F_{\text{equil}}(k_1, k_2, k_3) = 6Af_{NL}^{\text{equil}} \\ & \times \left\{ \frac{1}{k_1^{4-n_s} k_2^{4-n_s}} - \frac{1}{k_2^{4-n_s} k_3^{4-n_s}} - \frac{1}{k_3^{4-n_s} k_1^{4-n_s}} \right. \\ & \quad - \frac{2}{(k_1 k_2 k_3)^{2(4-n_s)/3}} + \left[\frac{1}{k_1^{(4-n_s)/3} k_2^{2(4-n_s)/3}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

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



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

Sunyaev–Zel'dovich Effect



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

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

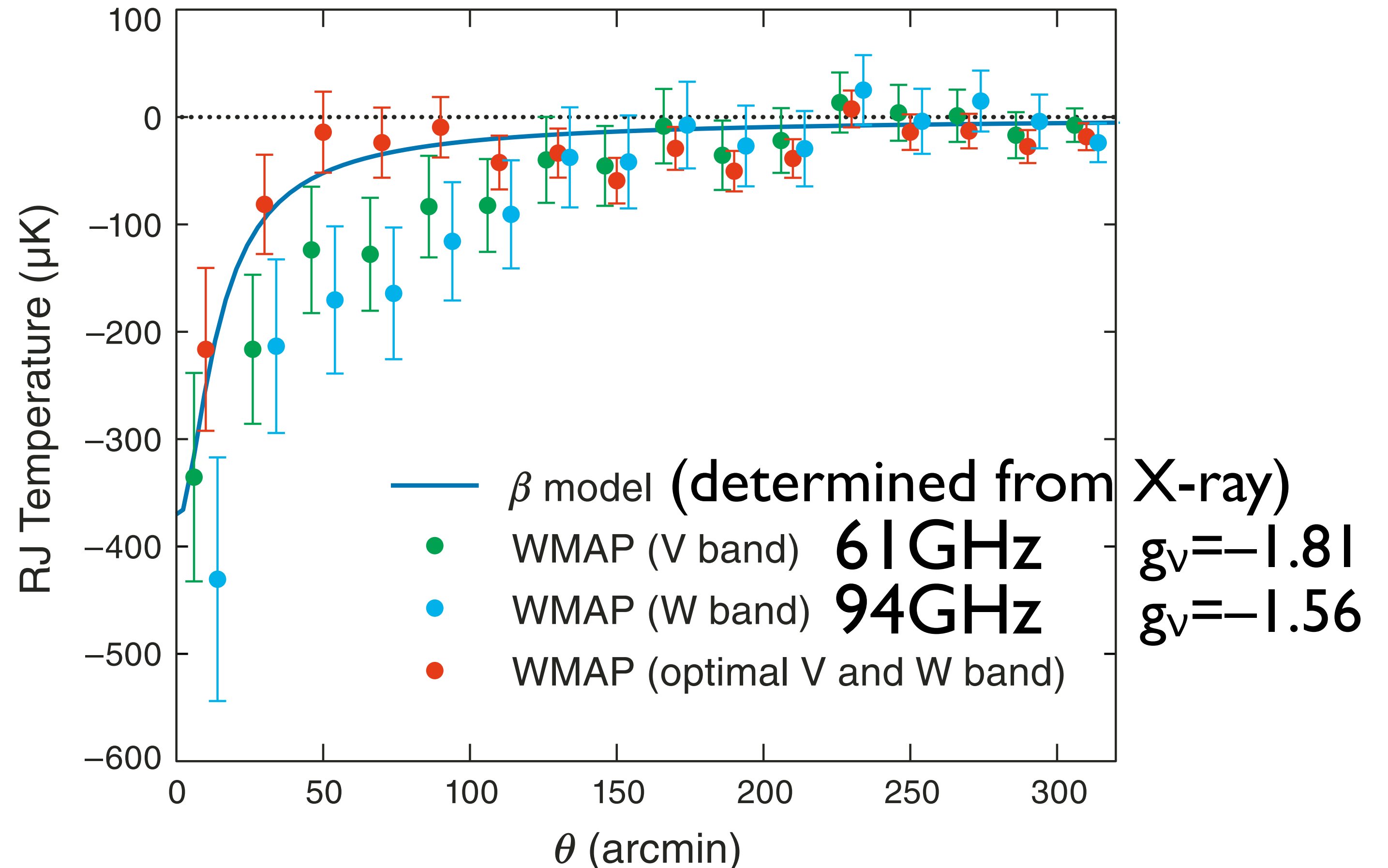
$$\begin{aligned} y &= (\text{optical depth of gas}) k_B T_e / (m_e c^2) \\ &= [\sigma_T / (m_e c^2)] \int n_e k_B T_e d(\text{los}) \\ &= [\sigma_T / (m_e c^2)] \int (\text{electron pressure}) d(\text{los}) \end{aligned}$$

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

Coma Cluster ($z=0.023$)

We find that the CMB fluctuation in the direction of Coma is $\approx -100\mu\text{K}$. (This is a new result!)

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



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

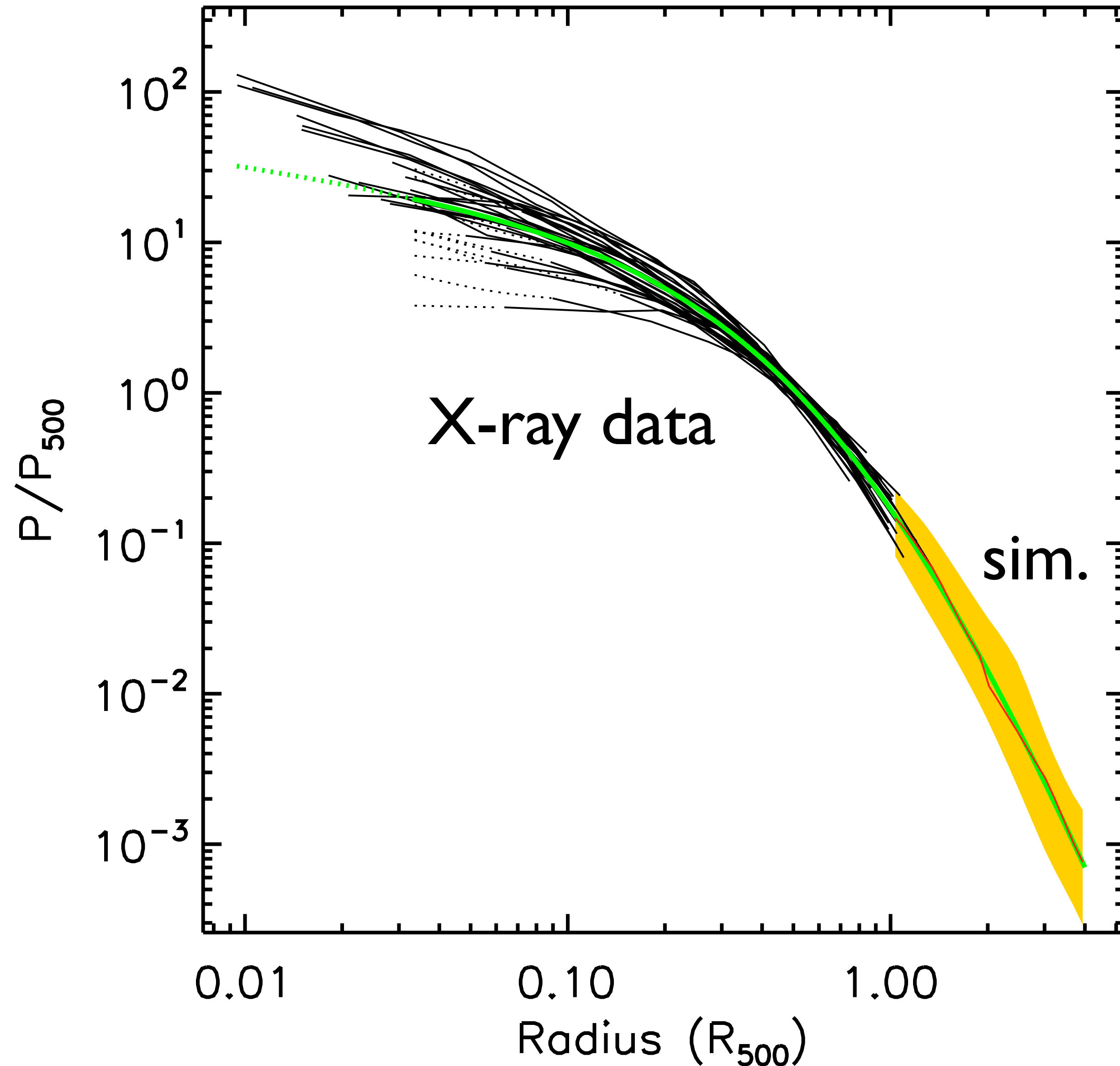
A Question

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

Arnaud et al. Profile

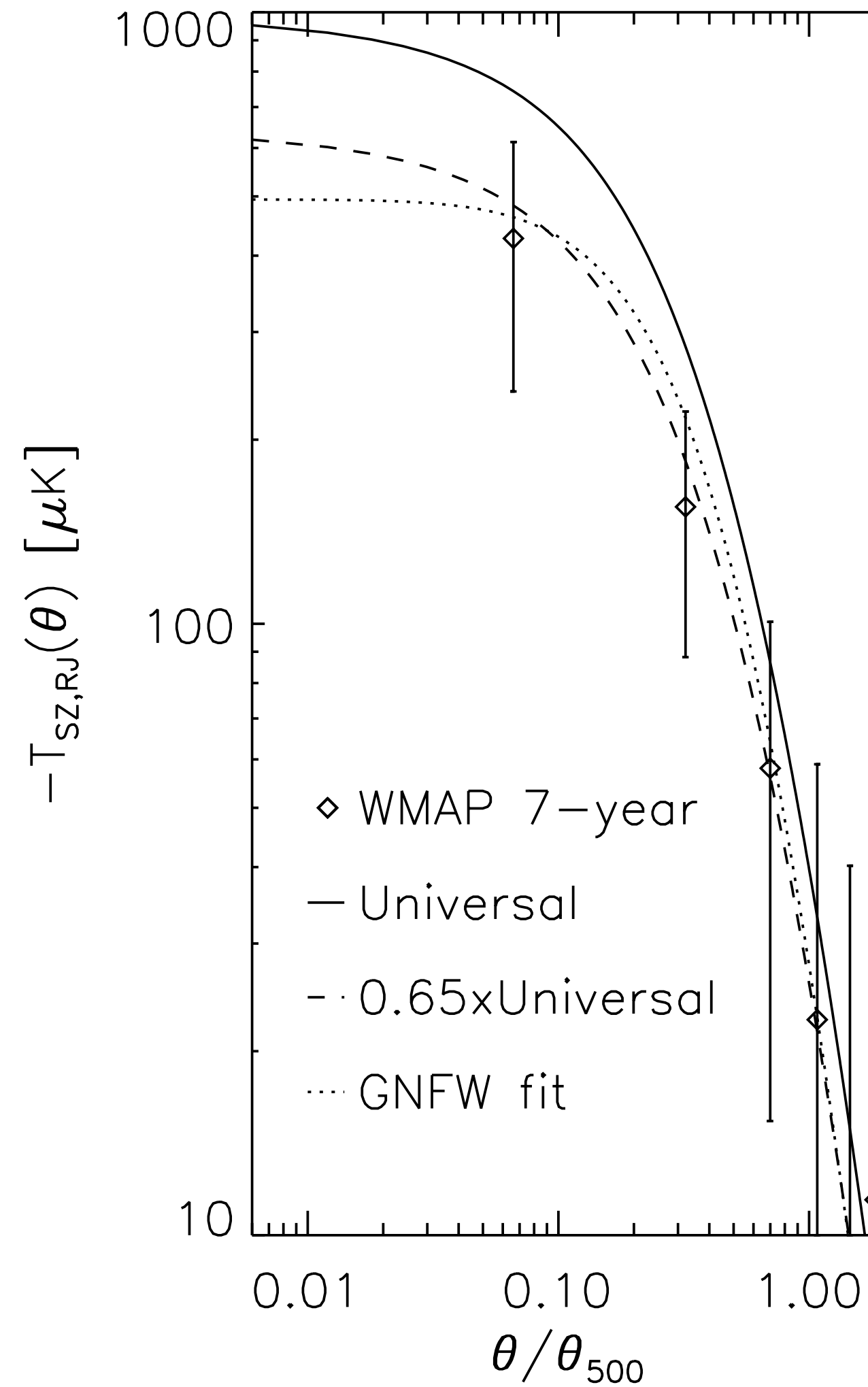
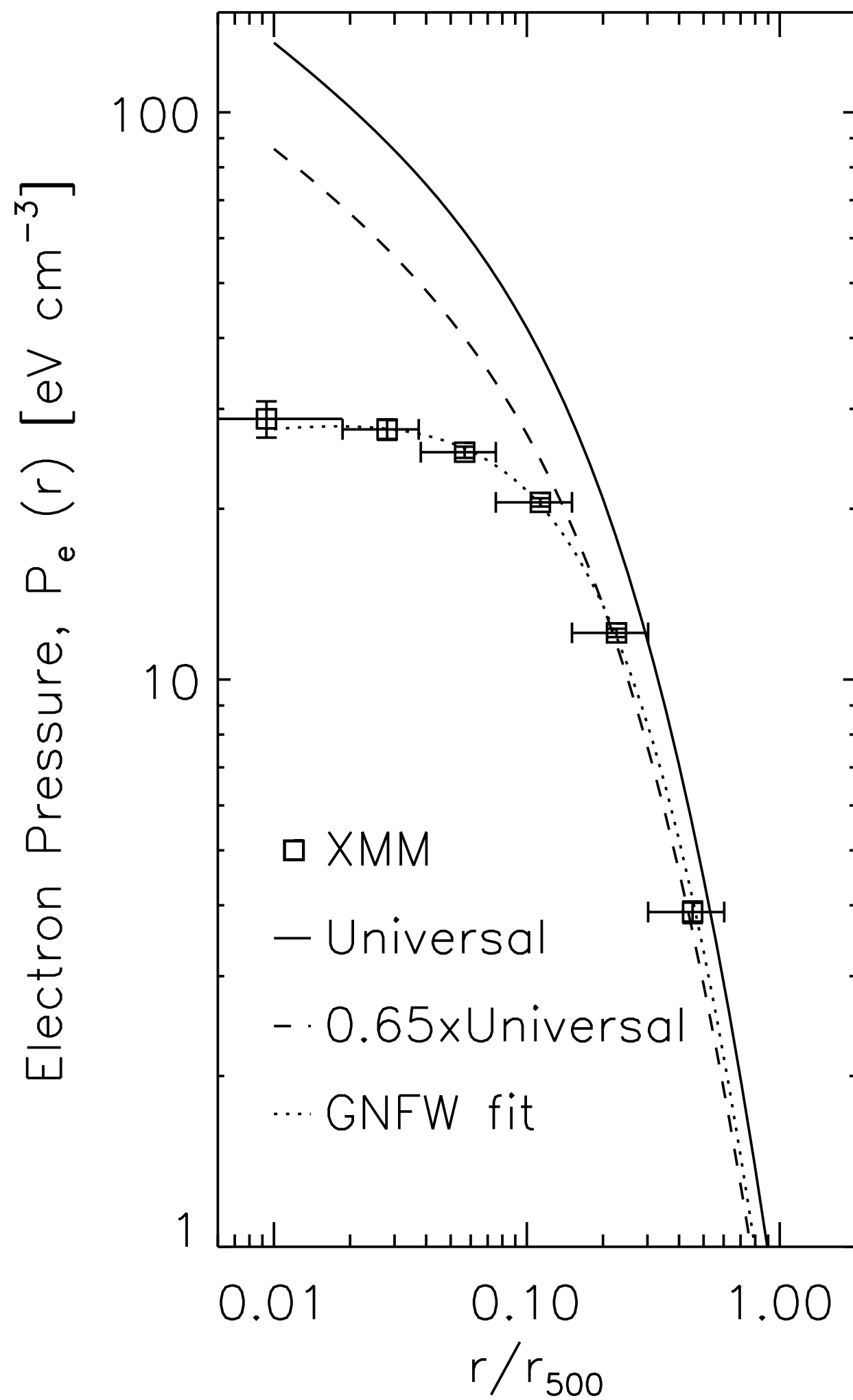
- A fitting formula for the average electron pressure profile as a function of the cluster mass (M_{500}), derived from 33 nearby ($z < 0.2$) clusters.

Arnaud et al. Profile



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

Coma Data vs Arnaud

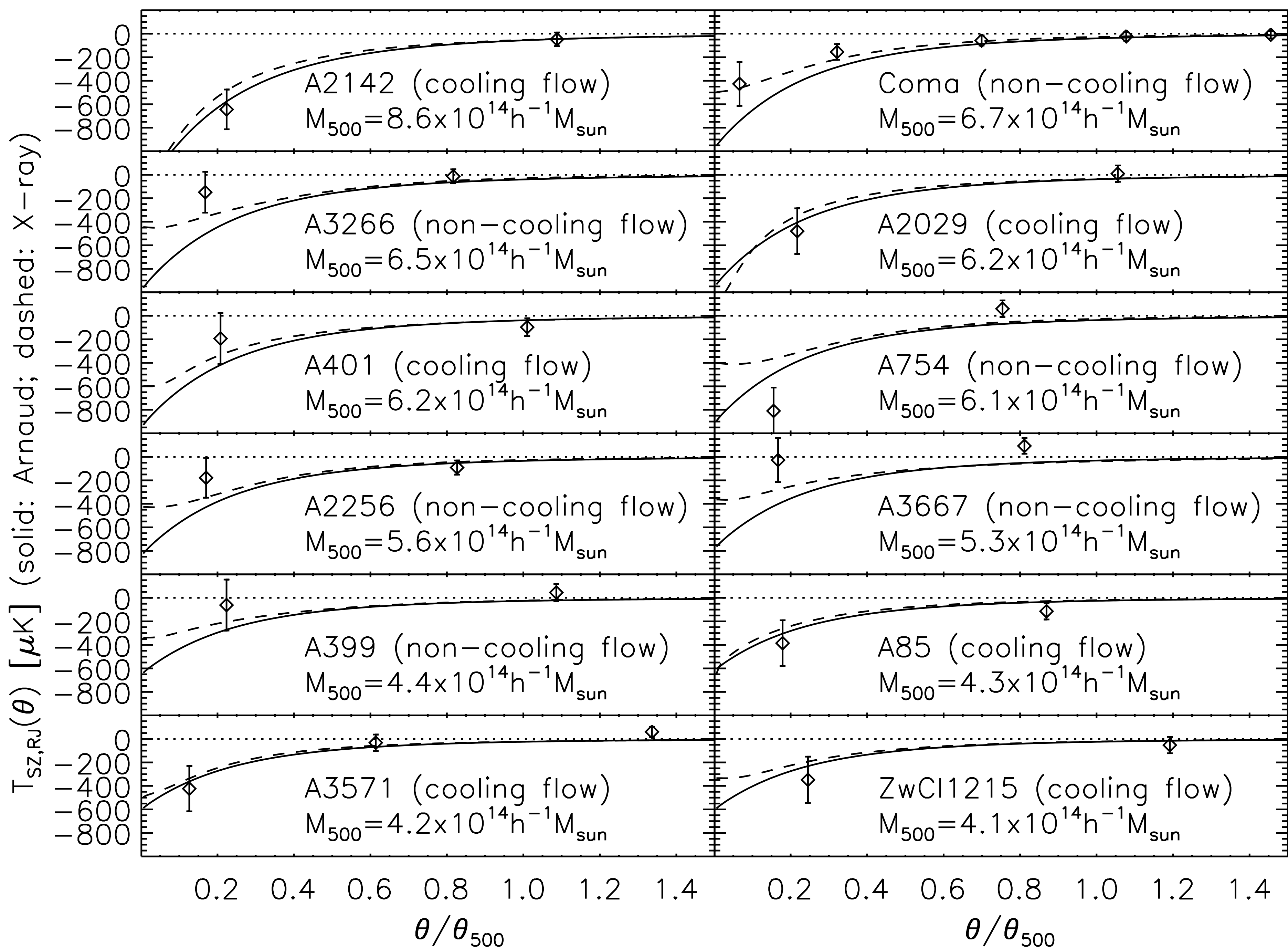


- $M_{500} = 6.6 \times 10^{14} h^{-1} M_{\text{sun}}$ is estimated from the mass-temperature relation (Vikhlinin et al.)
- $T_X^{\text{coma}} = 8.4 \text{ keV}$.
- Arnaud et al.'s profile overestimates both the direct X-ray data and WMAP data by the same factor (0.65)!
- To reconcile them, $T_X^{\text{coma}} = 6.5 \text{ keV}$ is required, but that is way too low.

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

Well...

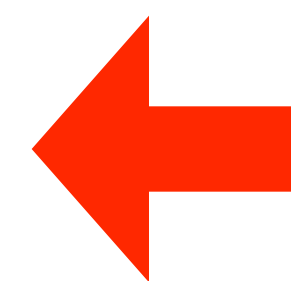
- That's just one cluster. What about the other clusters?
- We measure the SZ effect of a sample of well-studied nearby clusters compiled by Vikhlinin et al.



Some Numbers

Mass Range ^a	# of clusters	Vikhlinin et al. ^b	Arnaud et al. ^c
$6 \leq M_{500} < 9$	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.



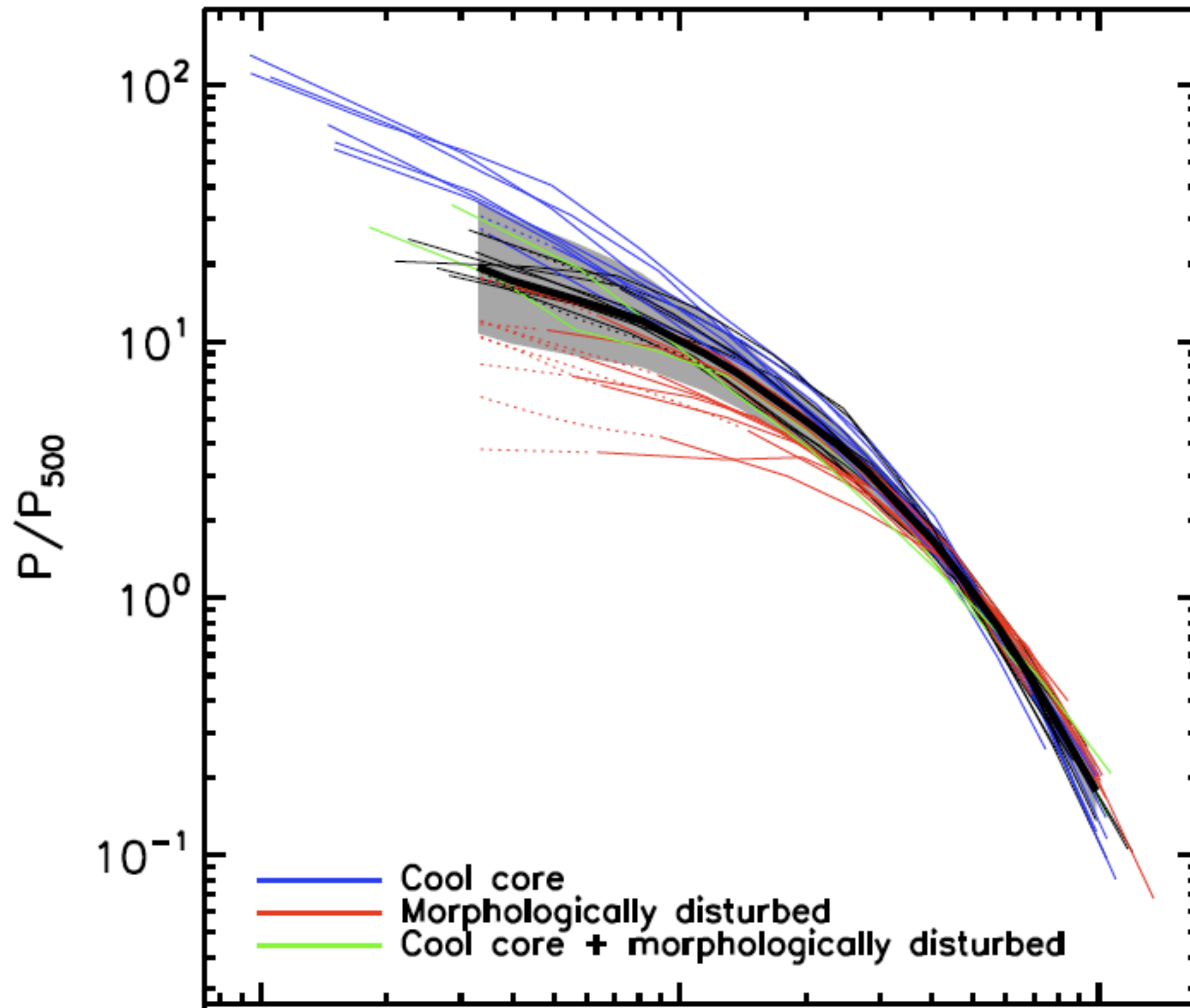
SZ: Main Results

- 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 cooling flow and non-cooling flow clusters.
- This will be important for the proper interpretation of the SZ effect when doing cosmology with it.

Interpretation

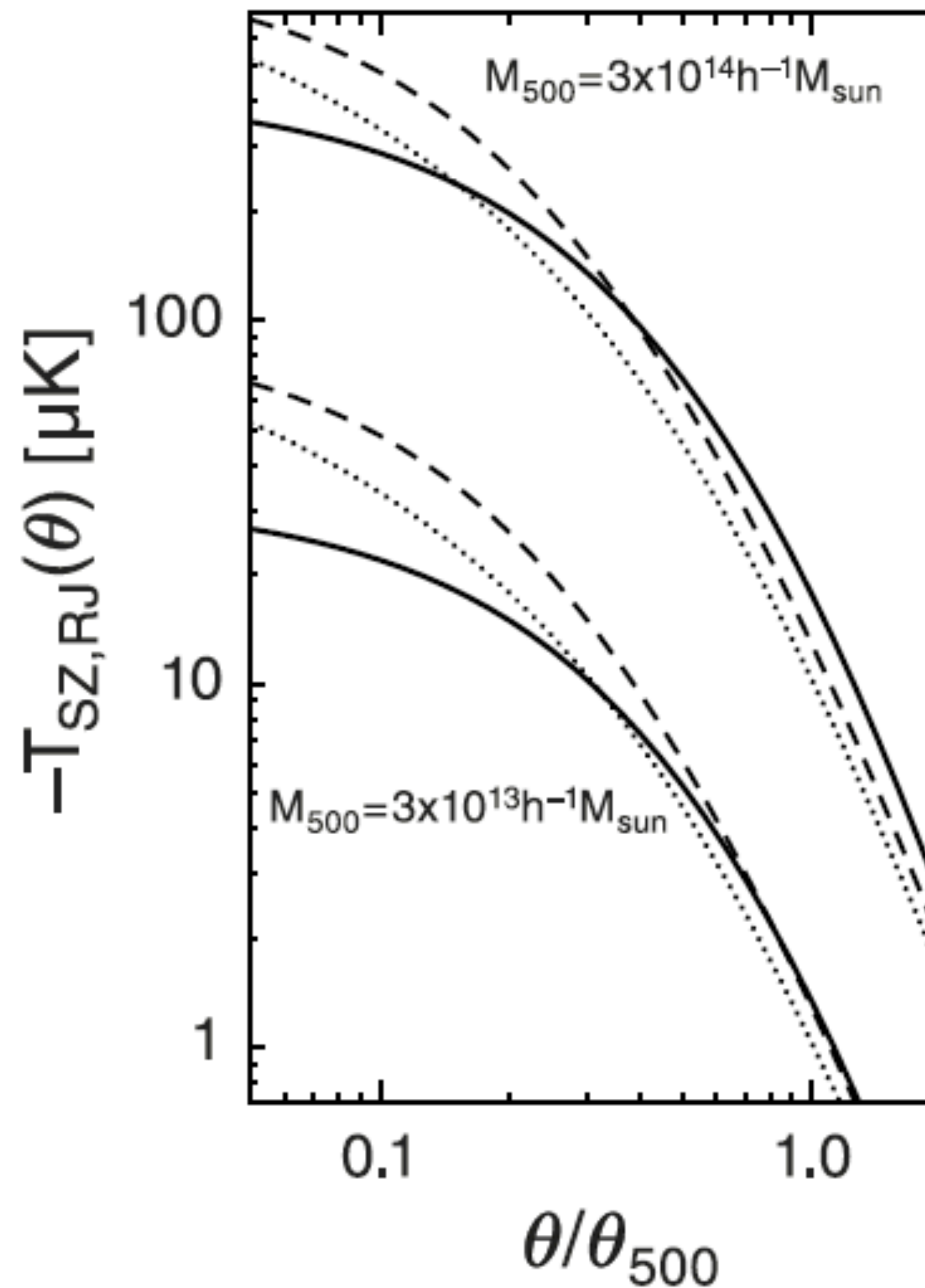
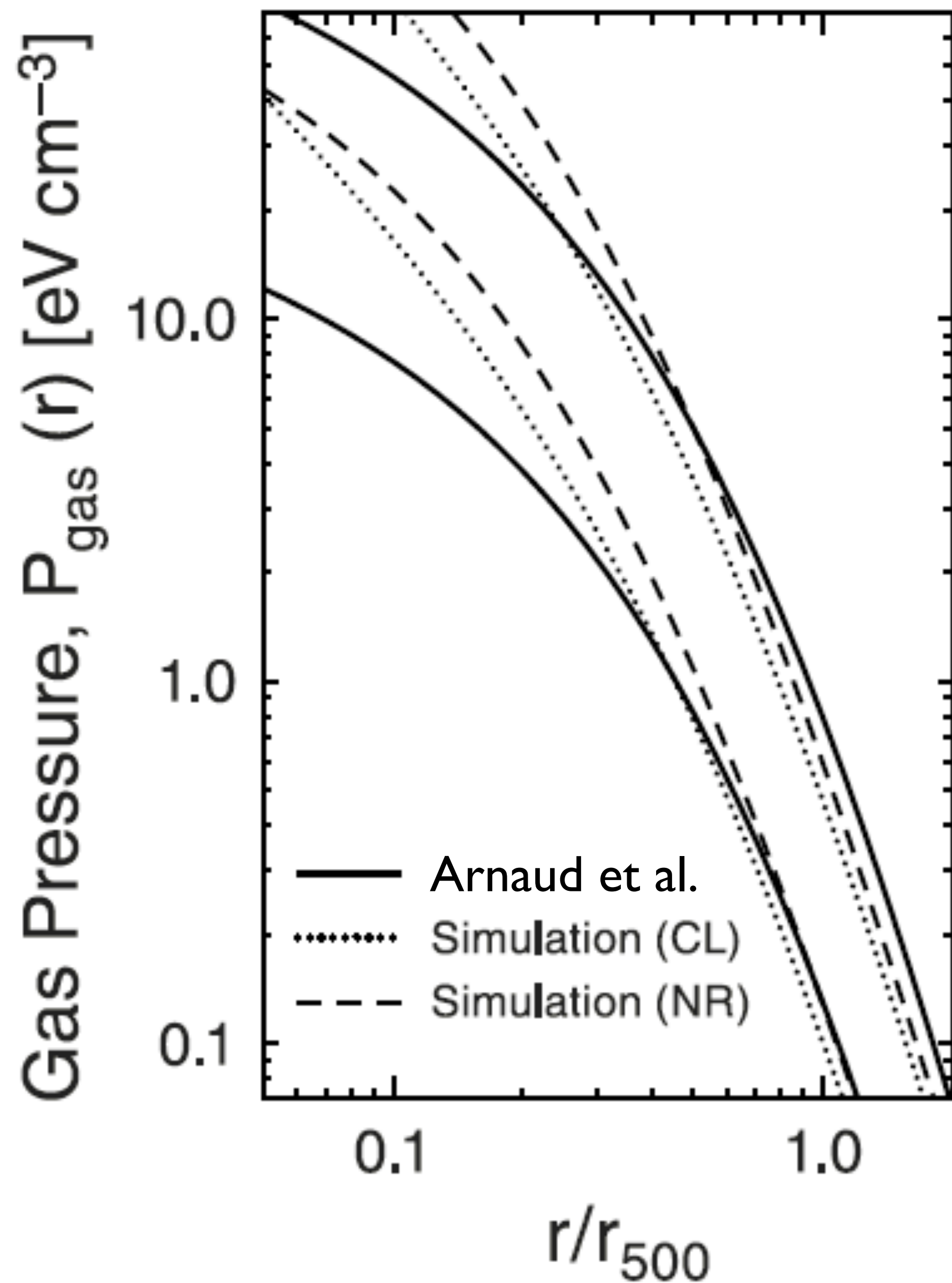
- ALL of cooling-flow clusters in our sample are “relaxed” clusters.
- ALL of non-cooling-flow clusters in our sample are “non-relaxed” (i.e., morphologically disturbed) clusters.
- **We are probably detecting the effect of recent mergers on the SZ effect, for the first time!**

Cooling Flow vs Non-CF

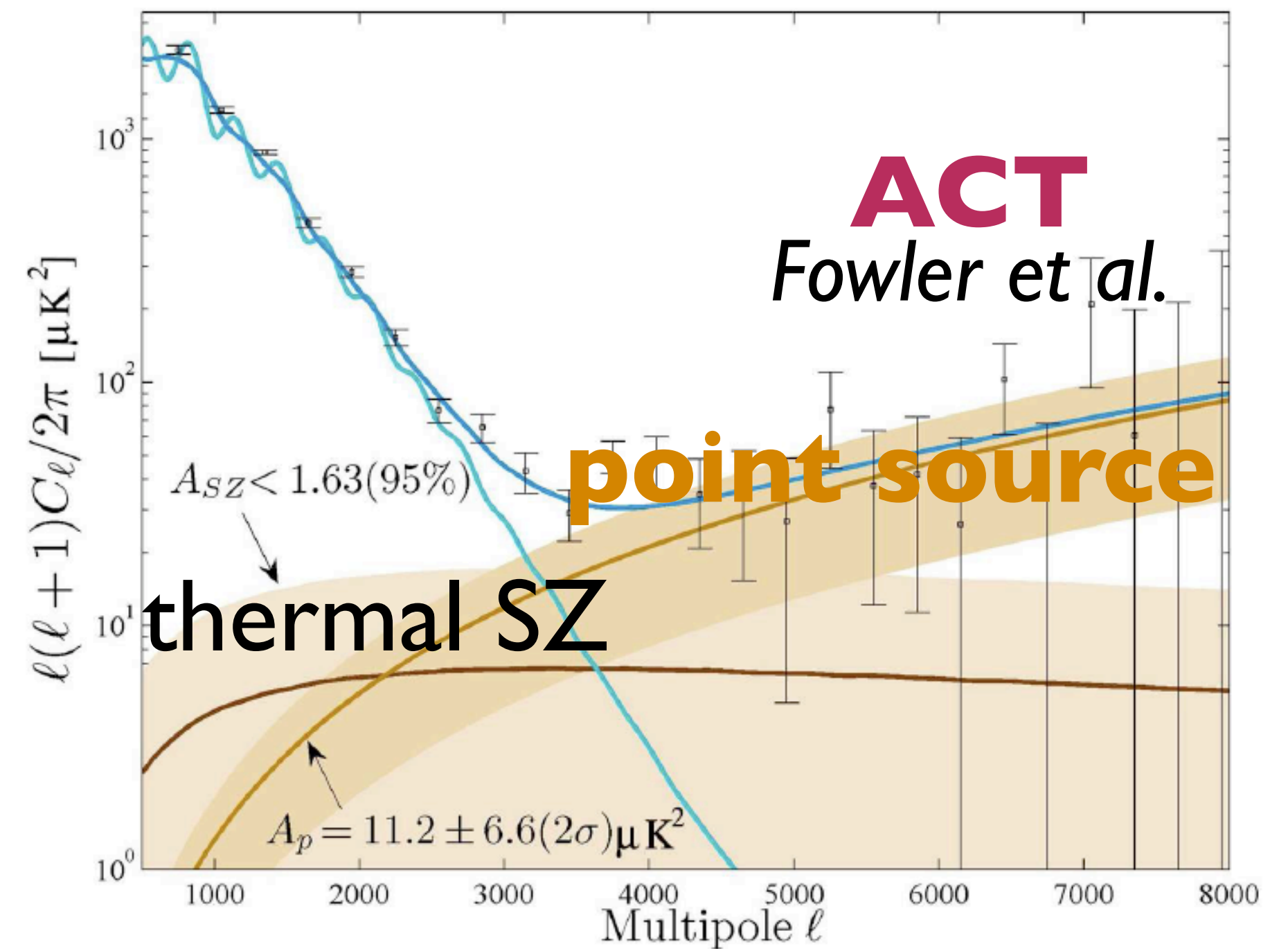
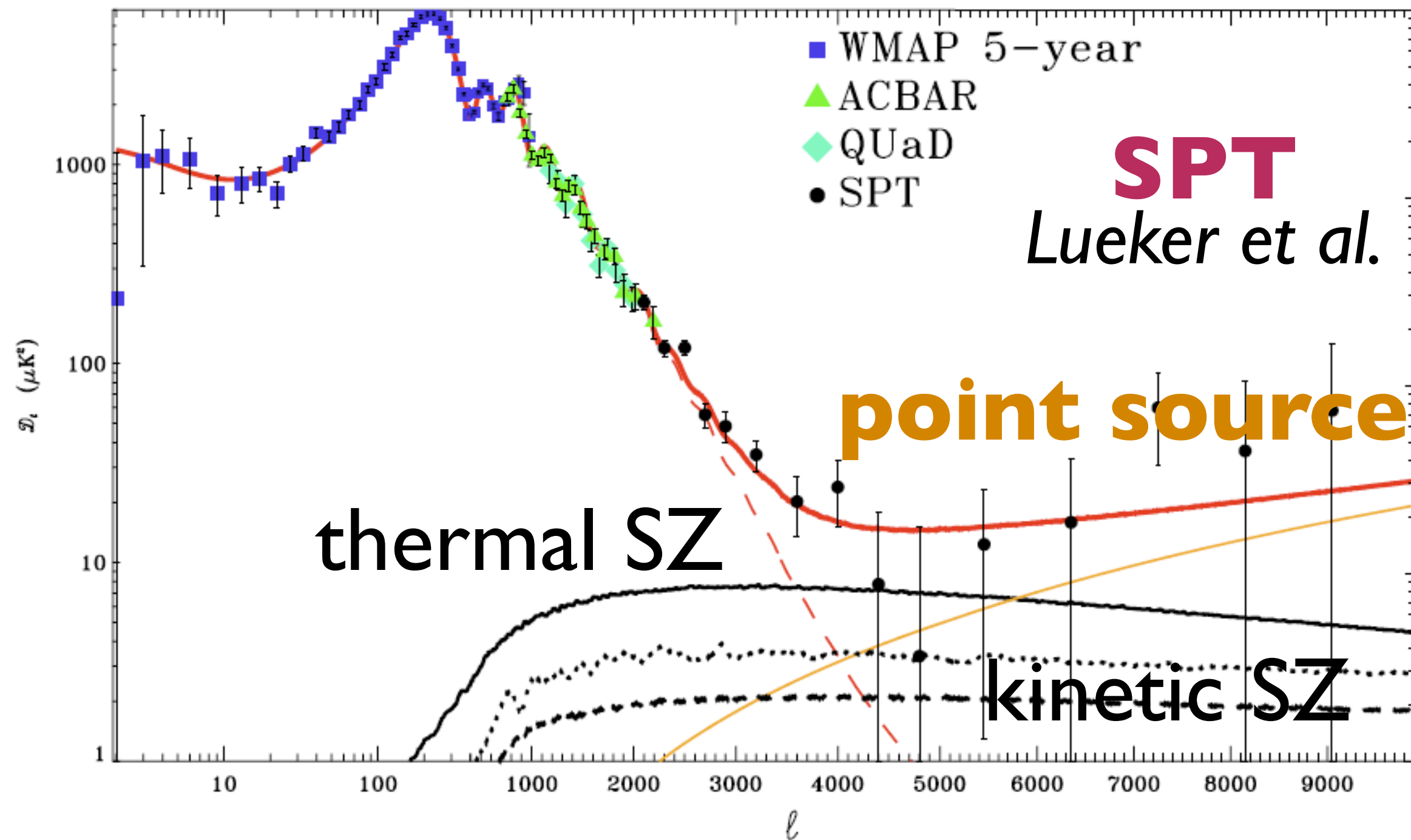


- In Arnaud et al., they reported that the cooling flow clusters have much steeper pressure profiles in the inner part.
- Taking a simple median gave a biased “universal” profile.

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

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

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

- The SZ power spectrum is sensitive to the number of clusters (i.e., σ_8) and the pressure of individual clusters.
- Lower SZ power spectrum can imply:
 - σ_8 is 0.77 (rather than 0.81): $\sum m_\nu \sim 0.2\text{eV}$?
 - 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.
- 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.