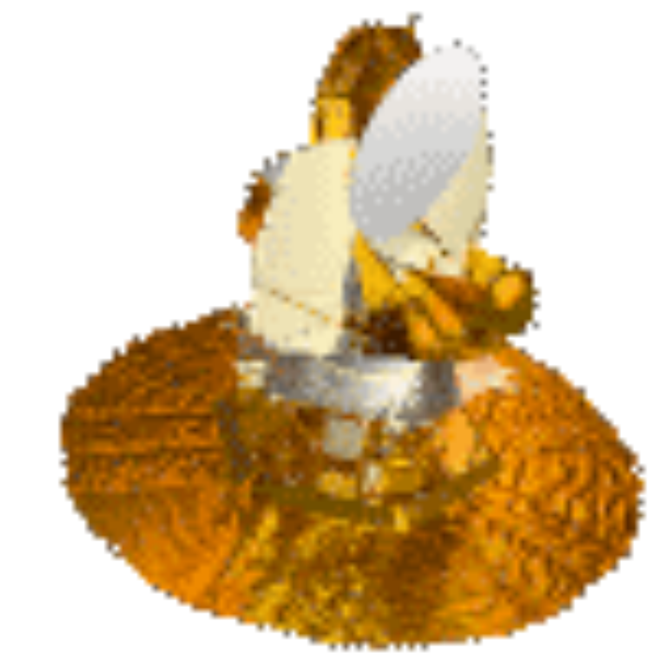


The **7**-Year *WMAP* Observations: Cosmological Interpretation

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)
Physics Club, Yale University, September 13, 2010

Cosmology: The Questions

- How much do we understand our Universe?
  - How old is it?
  - How big is it?
  - What shape does it take?
  - What is it made of?
  - How did it begin?

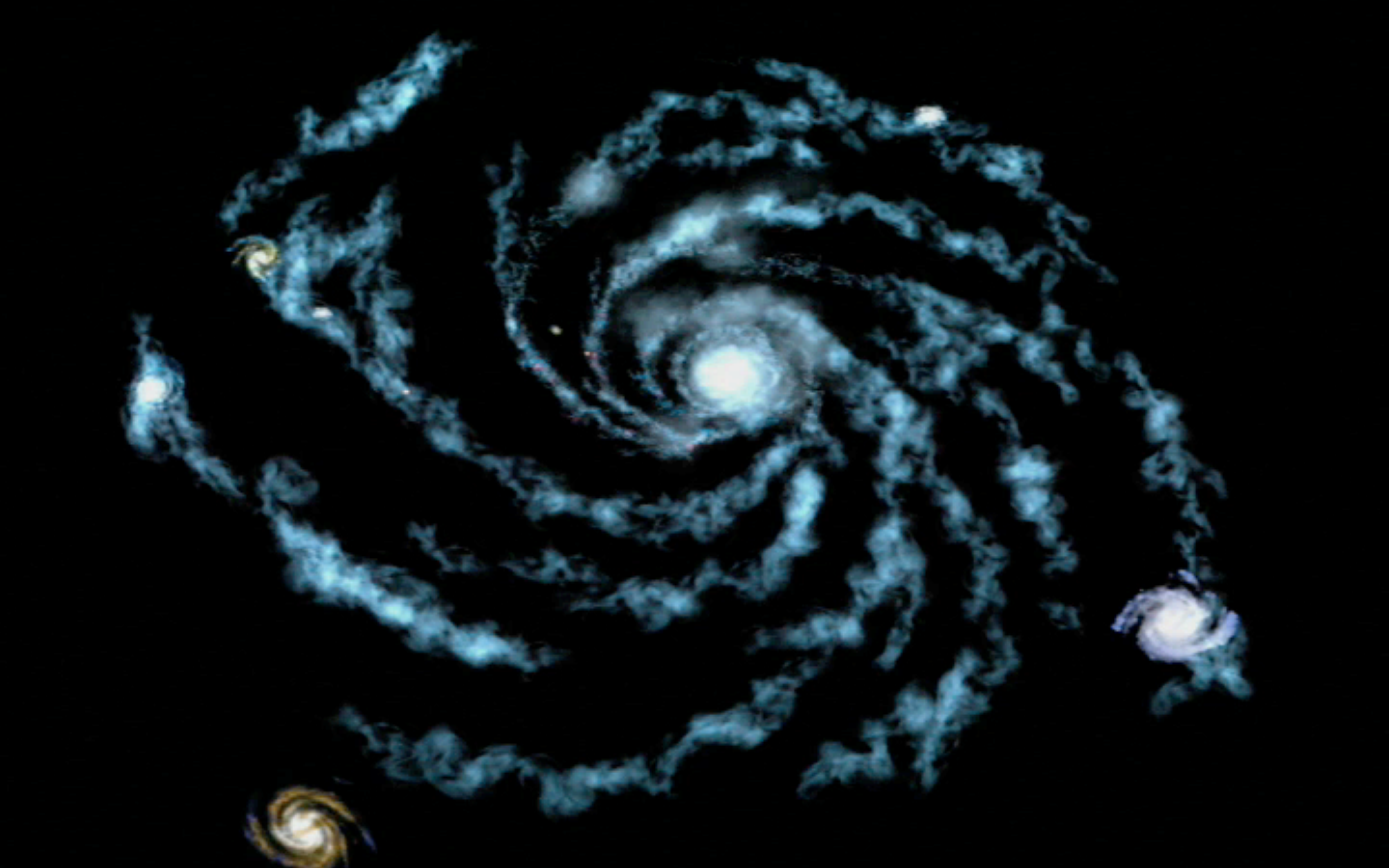
The Breakthrough

- Now we can **observe** the physical condition of the Universe when it was very young.

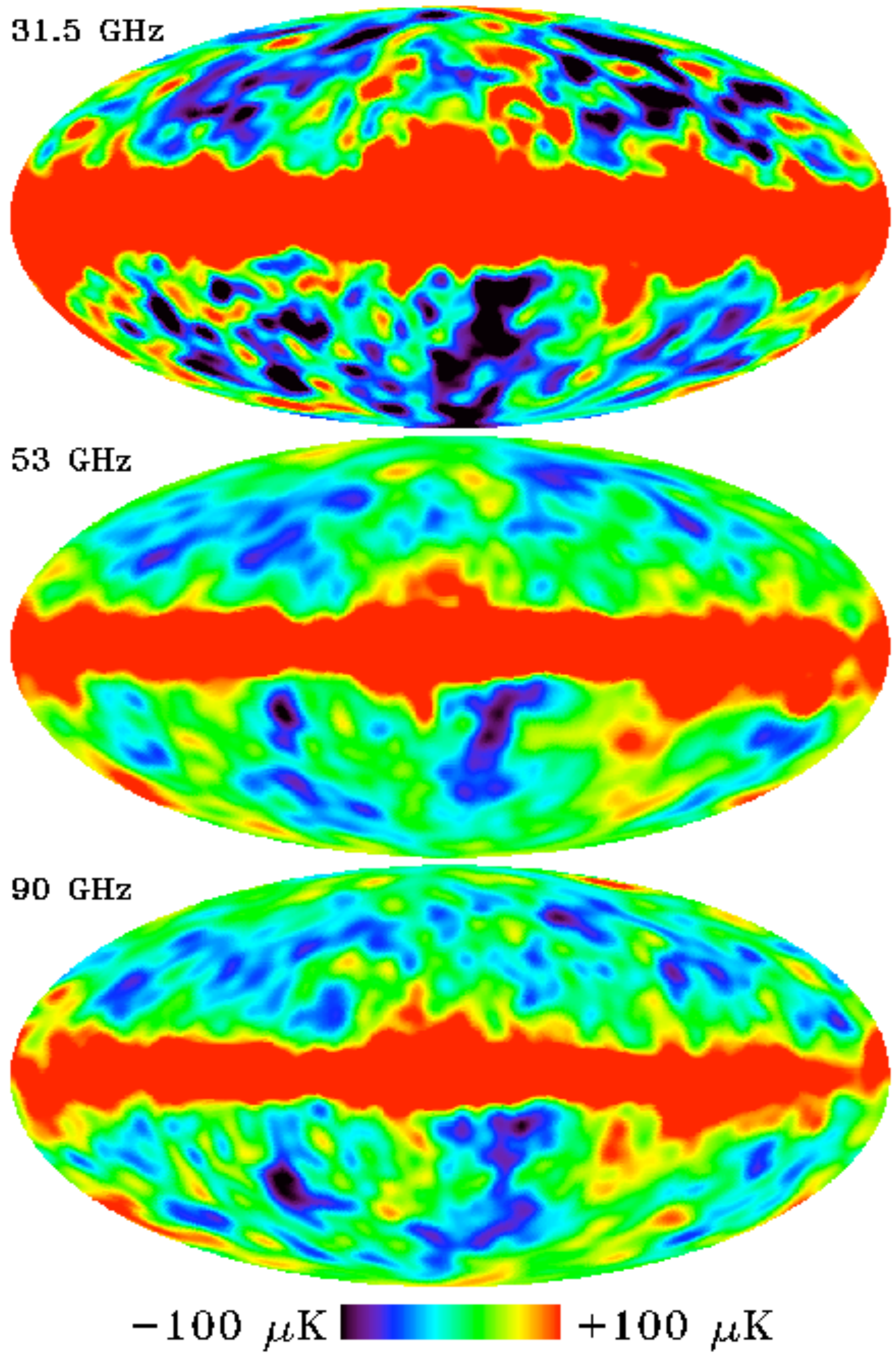
Cosmic Microwave Background (CMB)

- Fossil light of the Big Bang!

From "Cosmic Voyage"

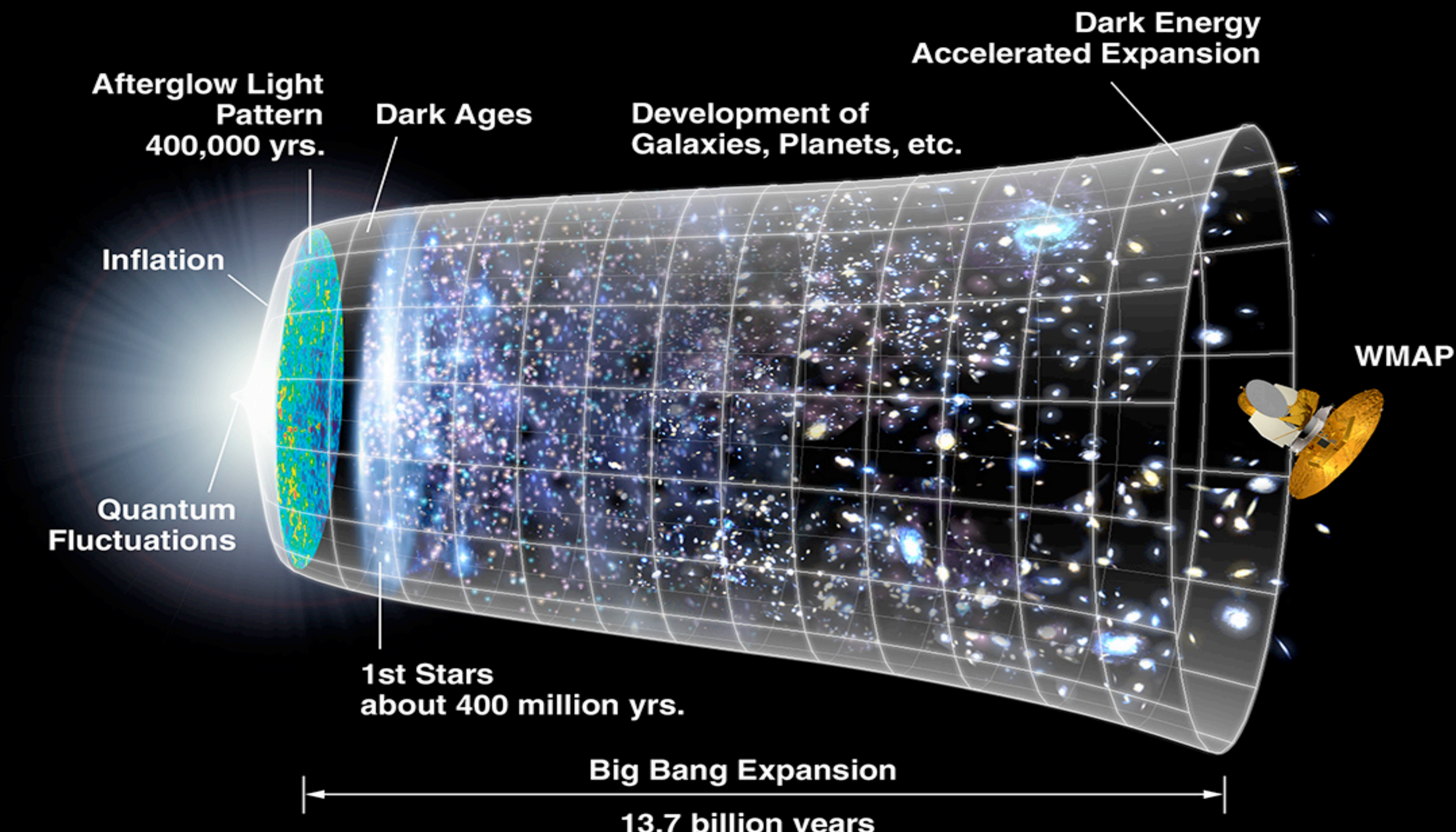


COBE/DMR, 1992



- **Isotropic?**
- **CMB is anisotropic! (at the 1/100,000 level)**

CMB: The Farthest and Oldest Light That We Can Ever Hope To Observe Directly



- When the Universe was 3000K (~380,000 years after the Big Bang), electrons and protons were combined to form neutral hydrogen.

NASA/WMAP Science Team

WMAP at Lagrange 2 (L2) Point

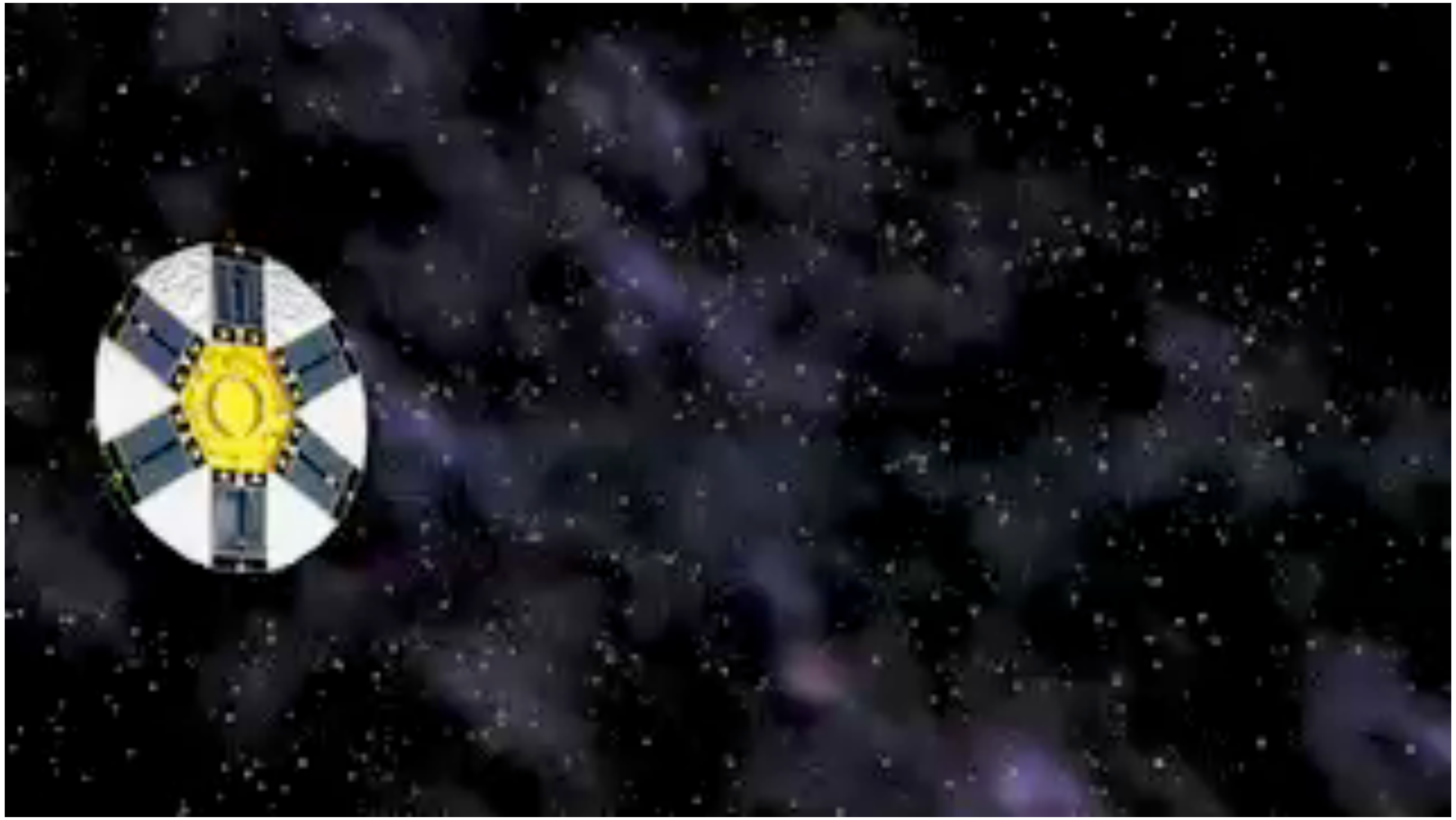
June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release

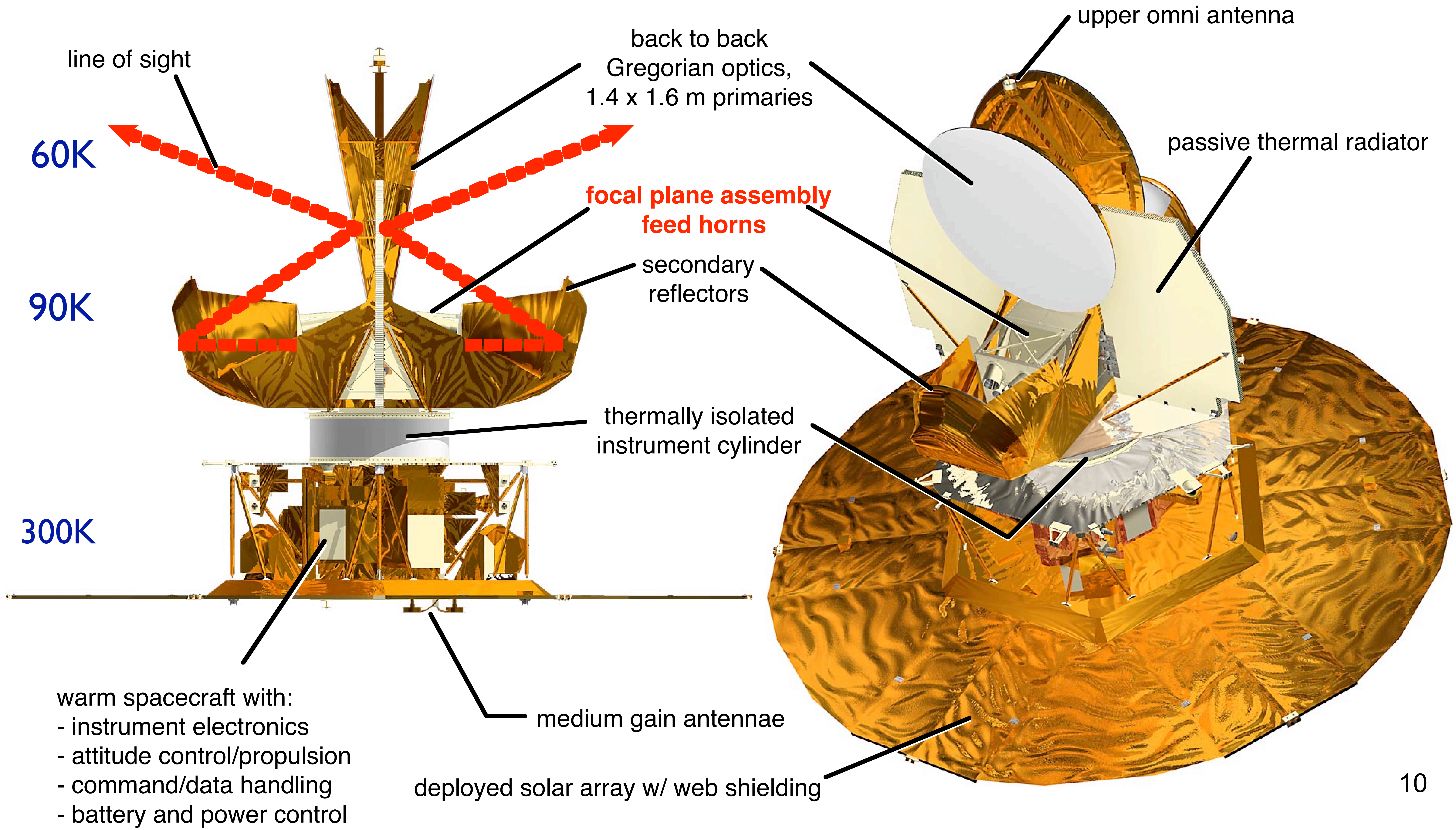
January 2010:
The seven-year data release



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

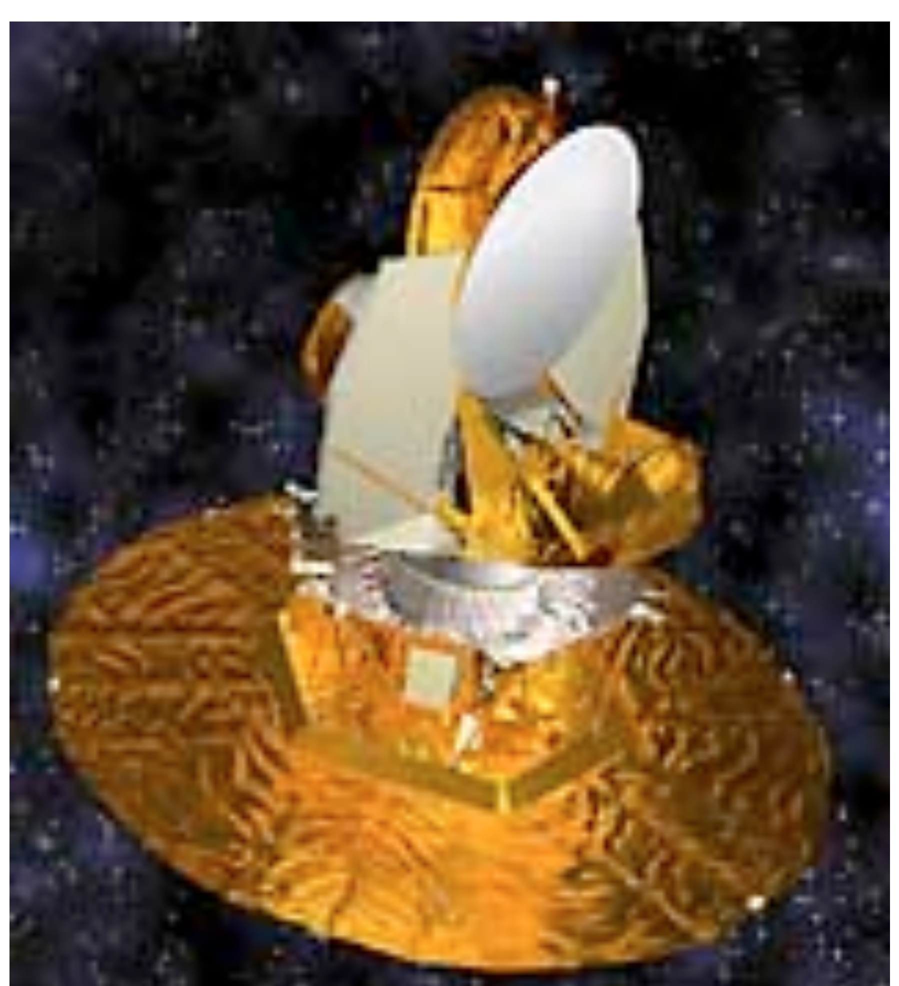
WMAP Spacecraft

Radiative Cooling: No Cryogenic System

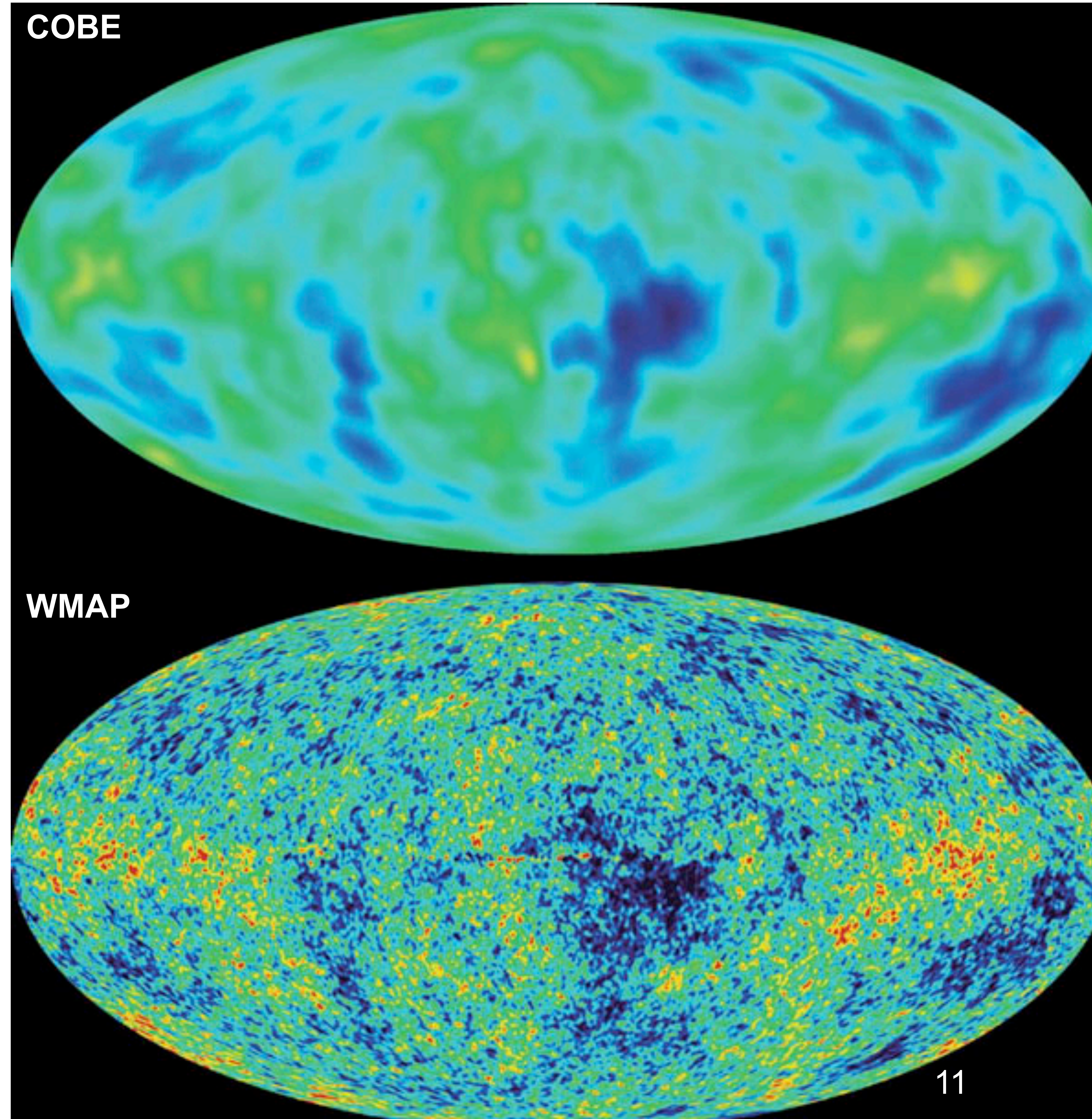


COBE to WMAP (x35 better resolution)

COBE
1989



WMAP
2001



WMAP 7-Year Science Team

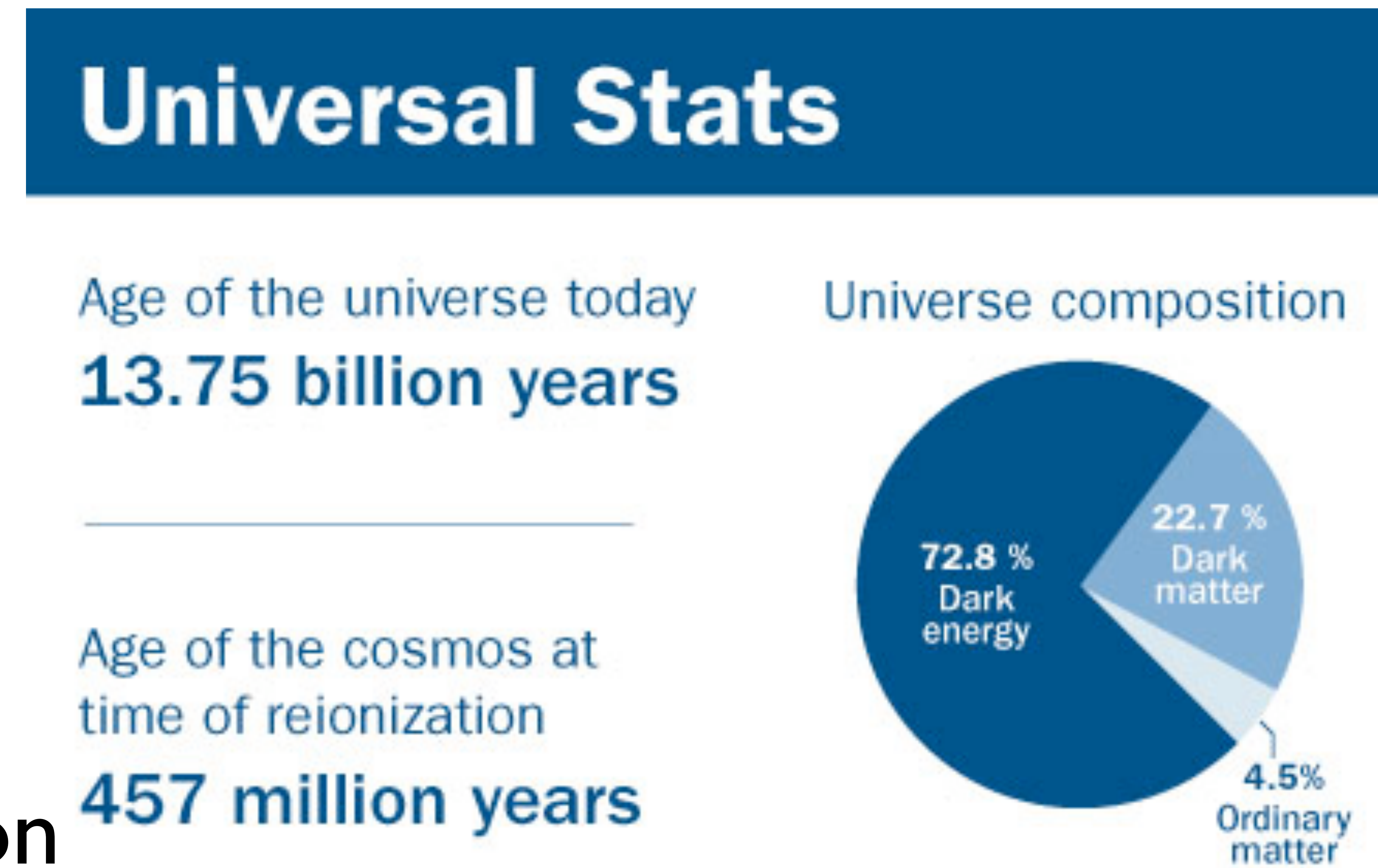
- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright
- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta
- K.M. Smith
- C. Barnes
- R.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

Cosmology Update: 7-year

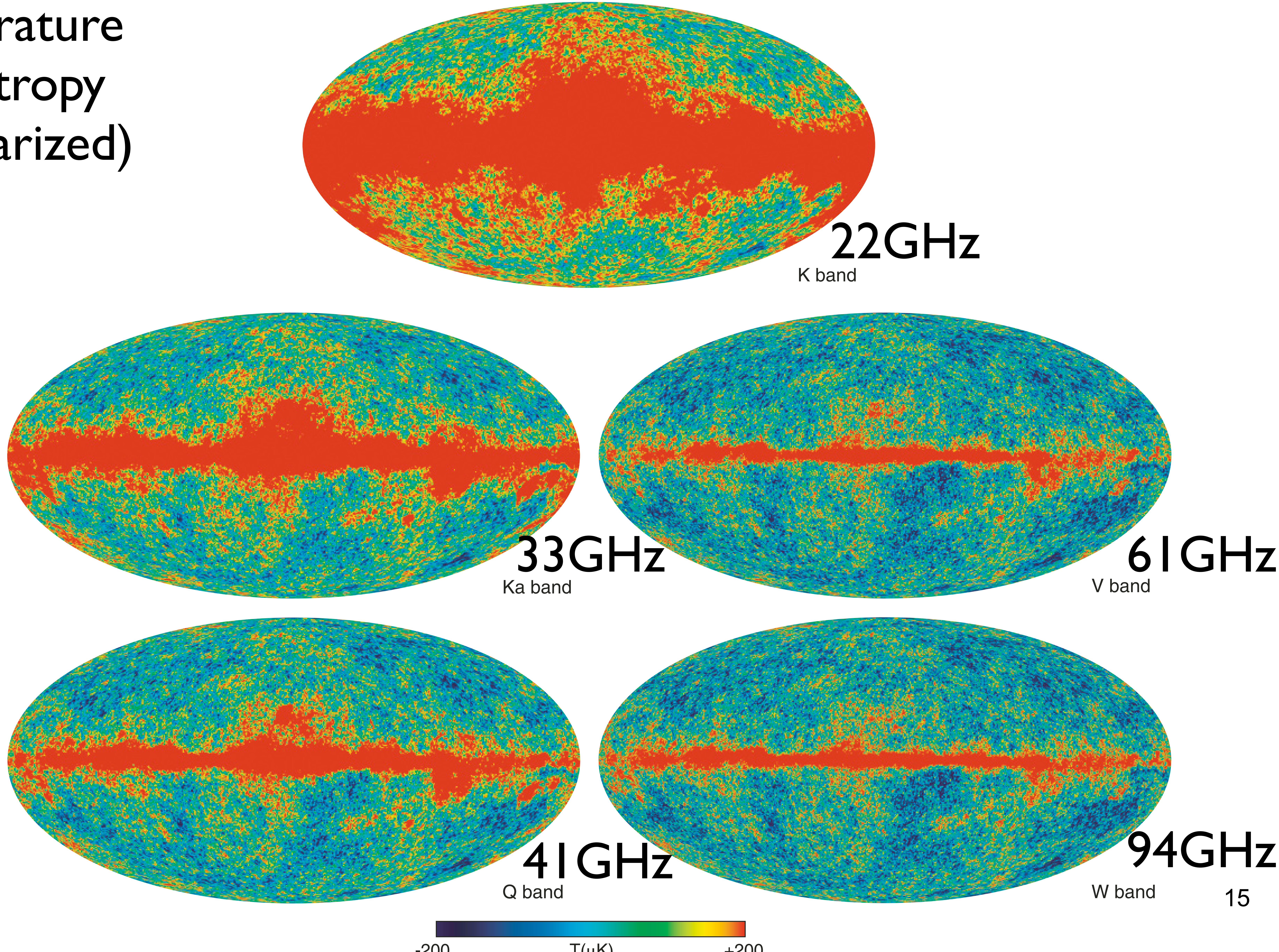
- **Standard Model**
  - H&He = 4.58% (±0.16%)
  - Dark Matter = 22.9% (±1.5%)
  - Dark Energy = 72.5% (±1.6%)
  - H_0=70.2±1.4 km/s/Mpc
  - Age of the Universe = 13.76 billion years (±0.11 billion years)



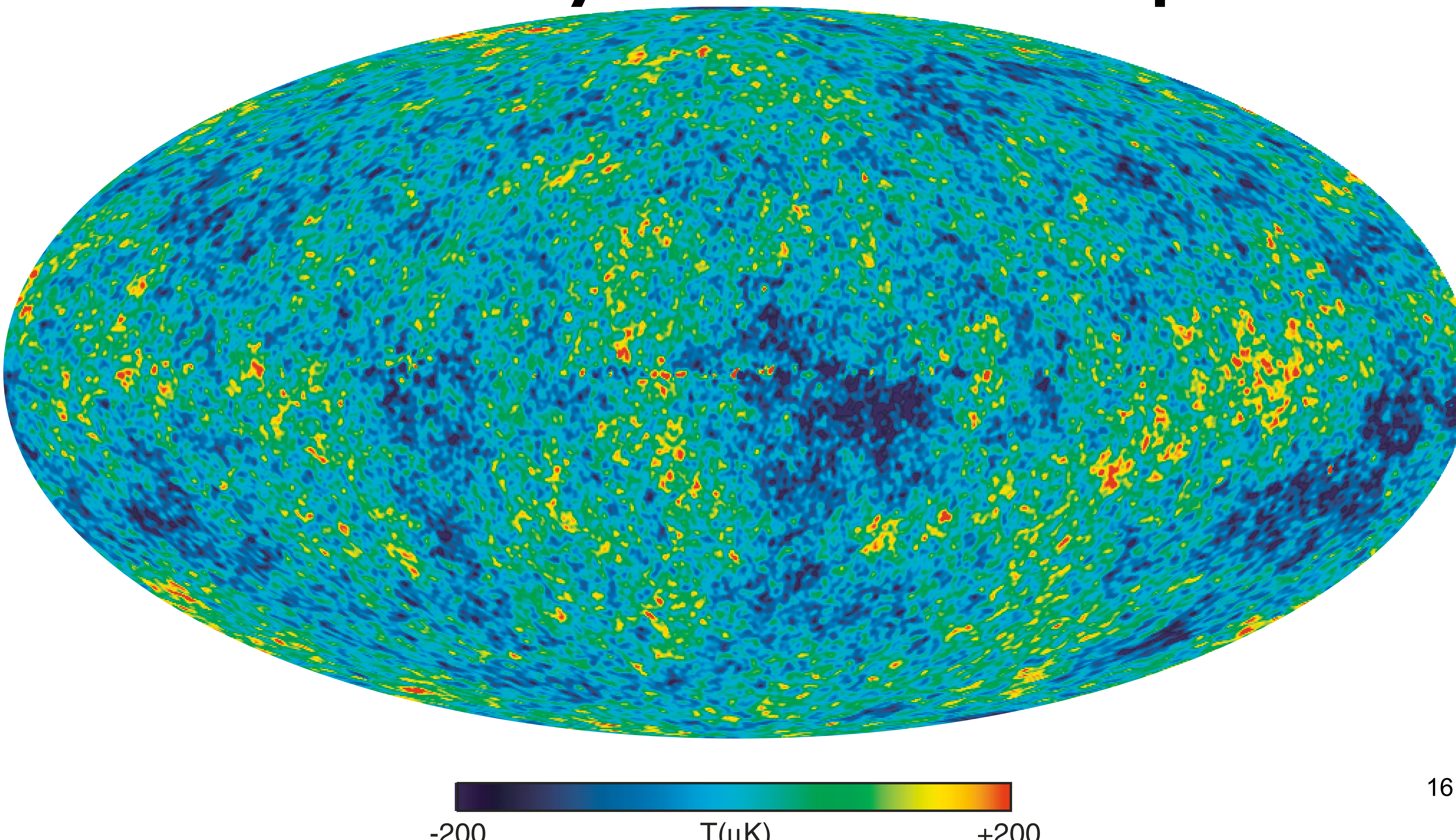
"ScienceNews" article on the WMAP 7-year results

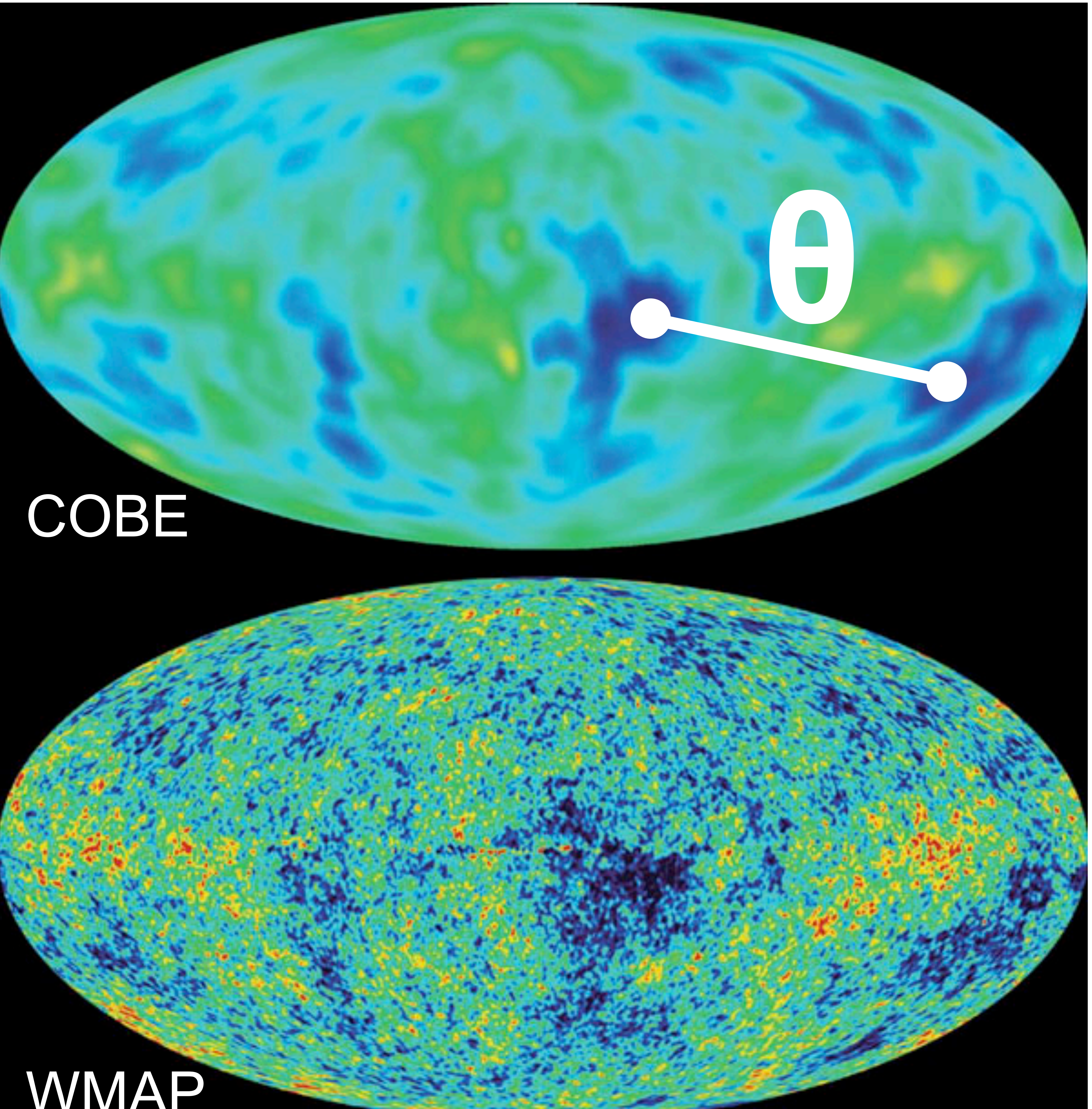
How did we obtain these numbers?

Temperature Anisotropy (Unpolarized)



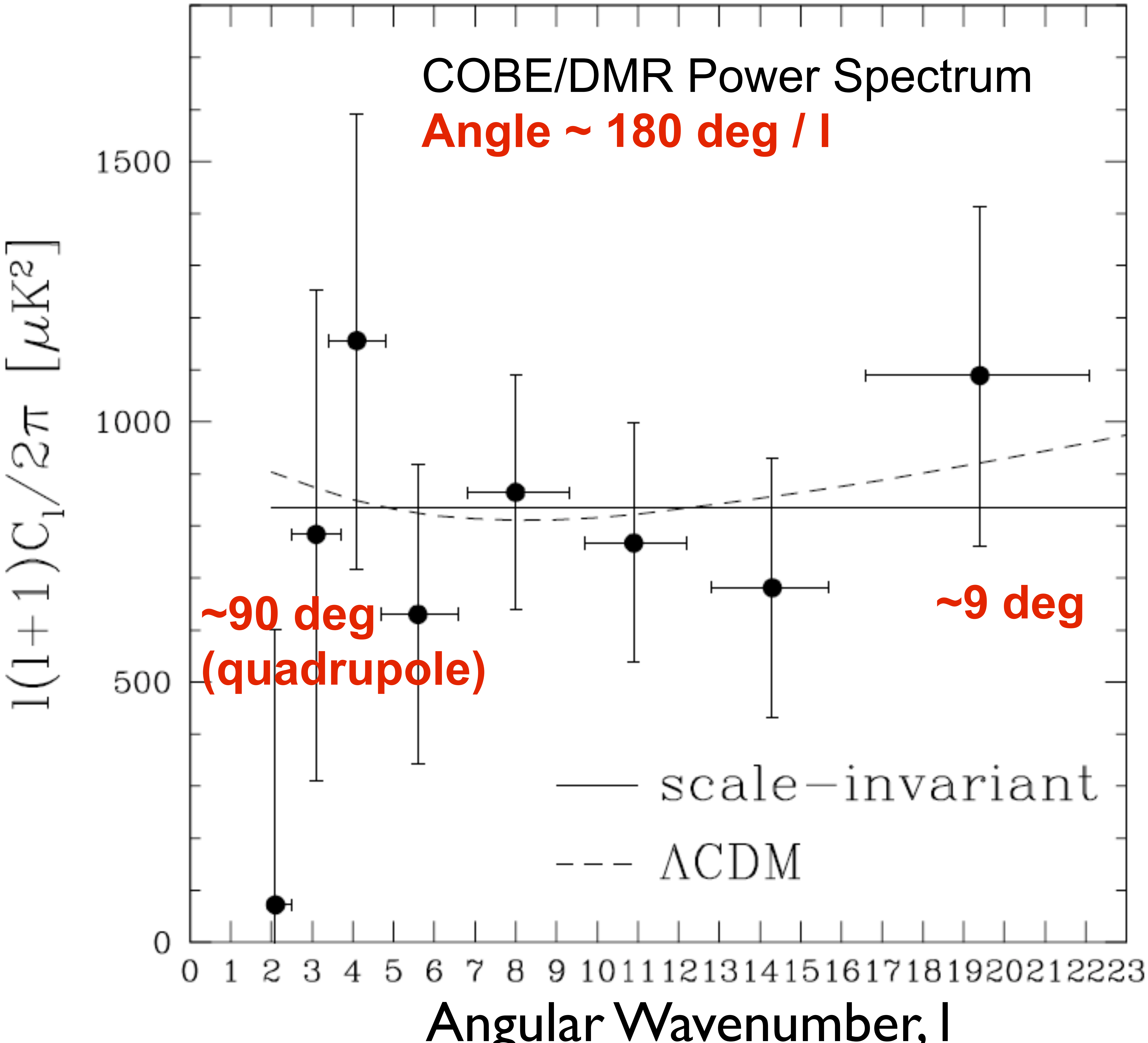
Galaxy-cleaned Map

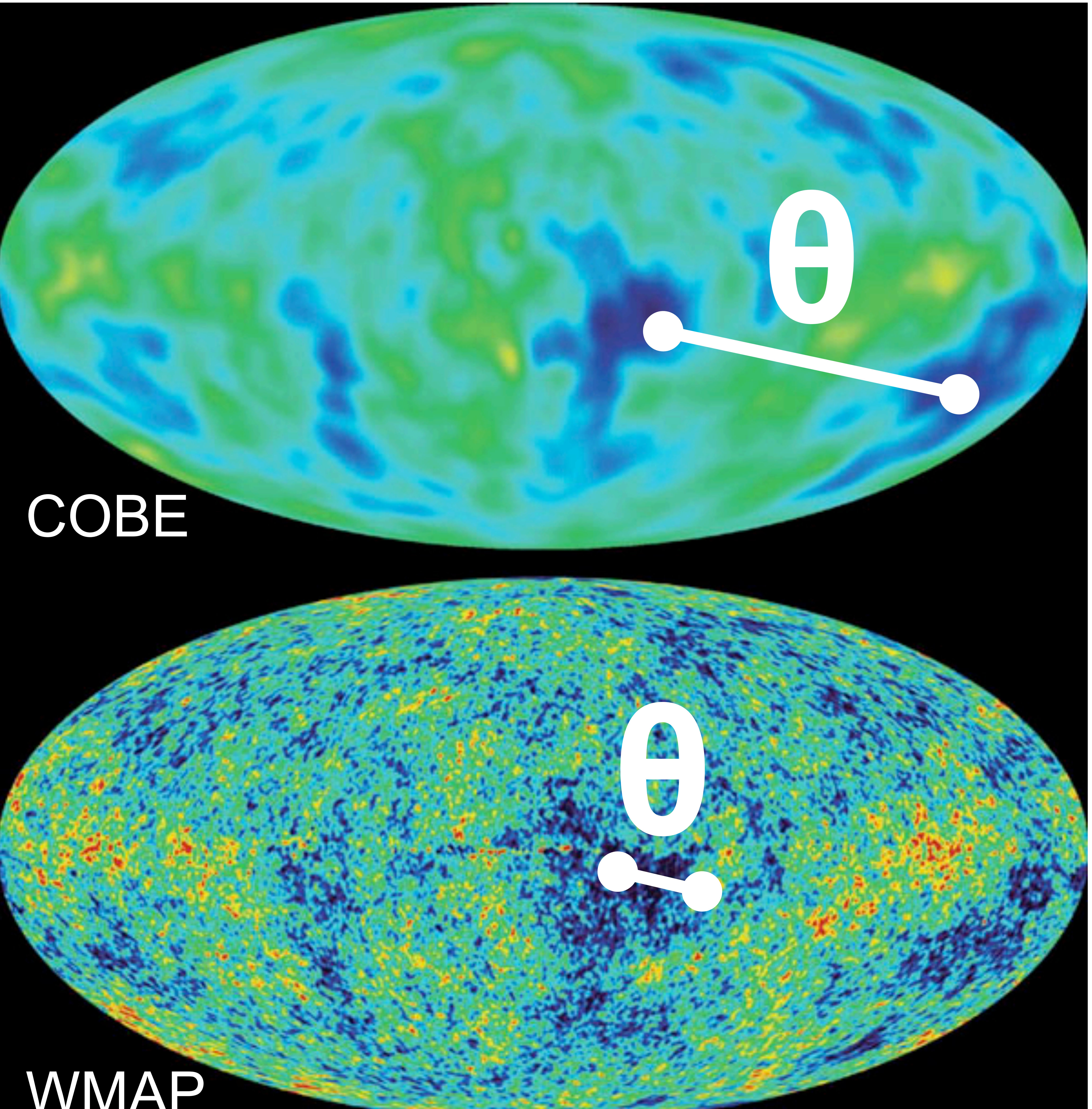




Analysis: 2-point Correlation

- $C(\theta)=(1/4\pi)\sum(2l+1)C_l P_l(\cos\theta)$
- 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**

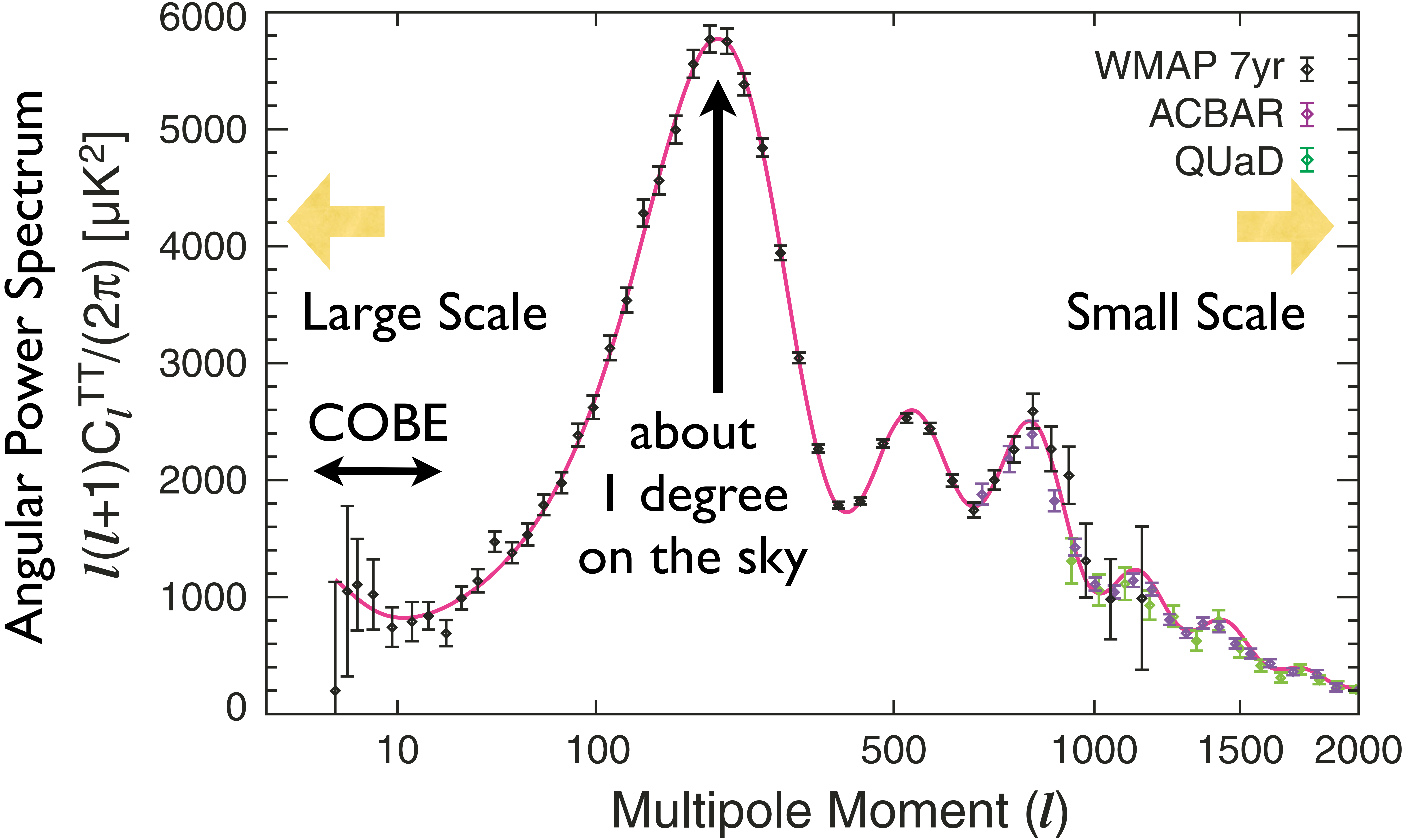

COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
l(l+1)C_l/2π [μK²]
Angular Wavenumber, l



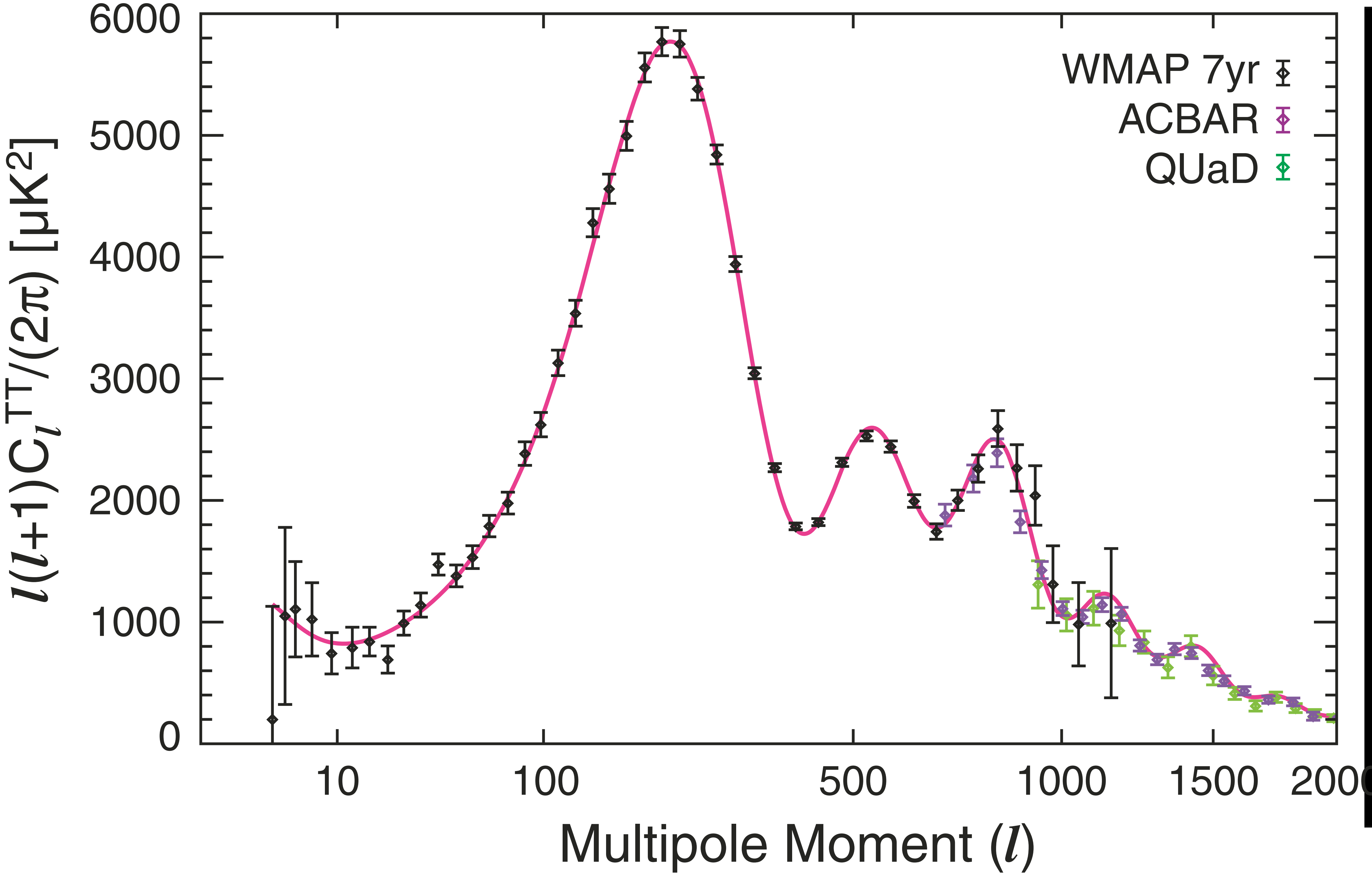
COBE To WMAP

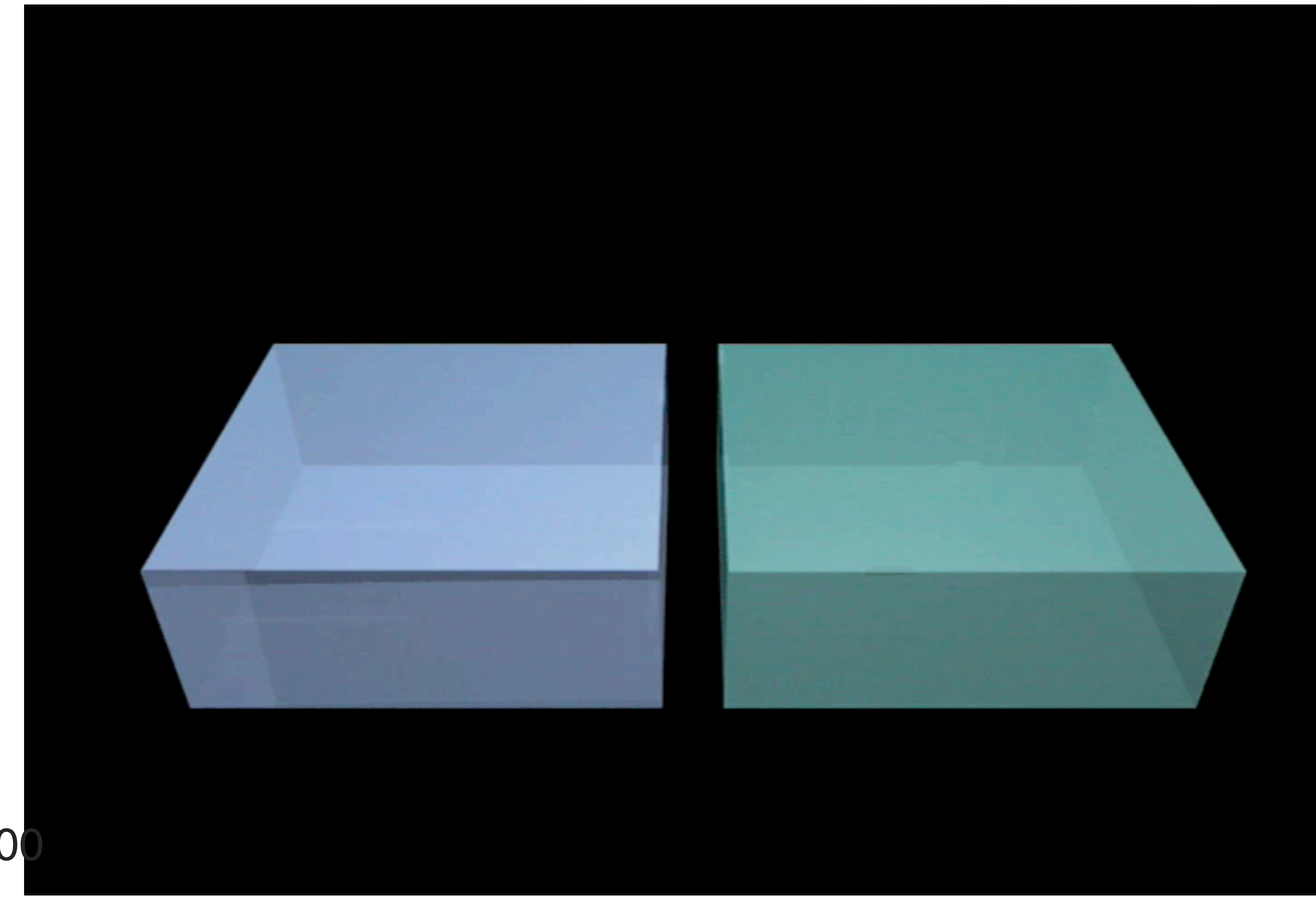
- COBE is unable to resolve the structures below ~7 degrees
- WMAP’s resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP Power Spectrum



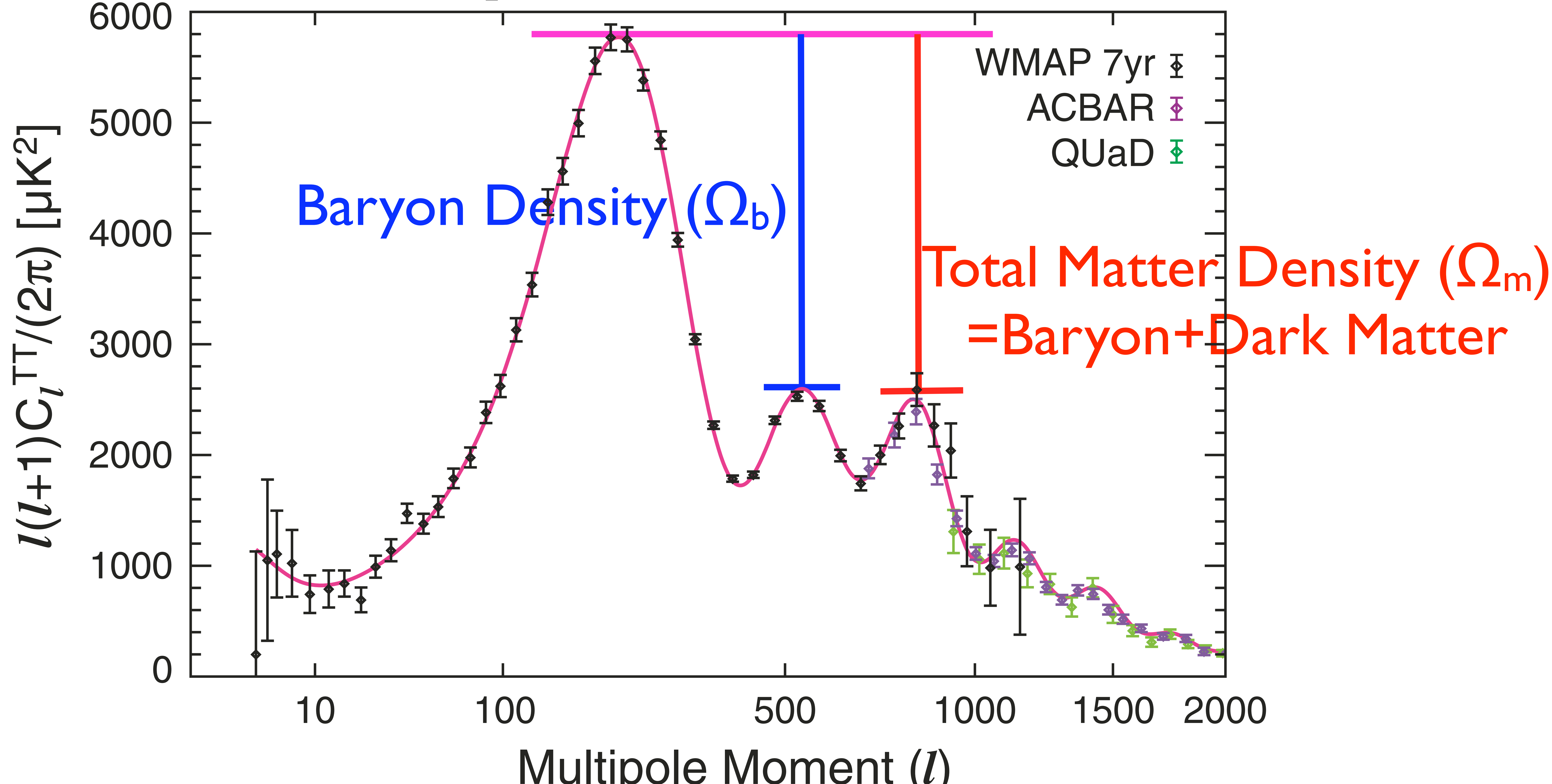
The Cosmic Sound Wave





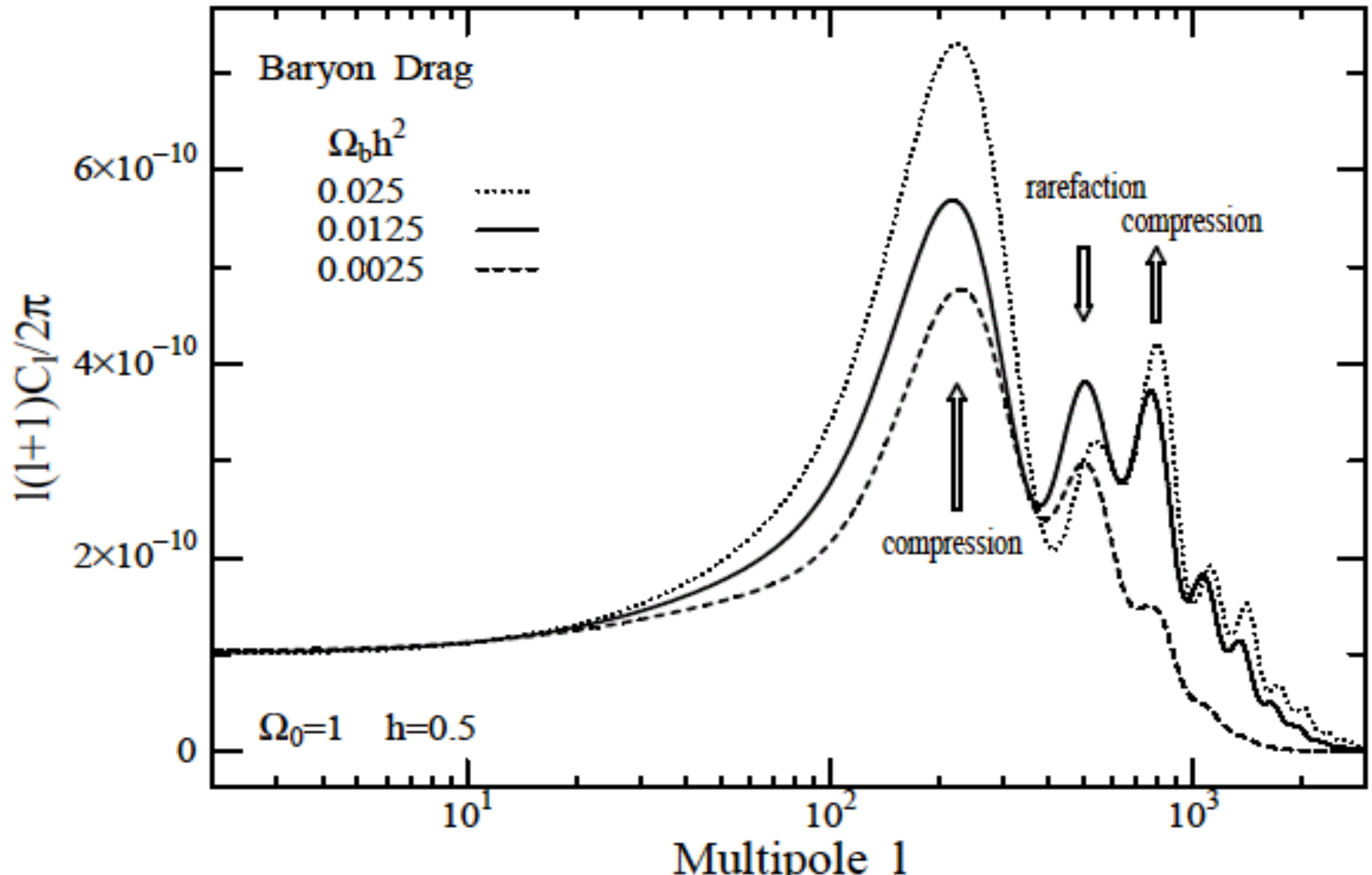
- *"The Universe as a Miso soup"*
  - *Main Ingredients: protons, helium nuclei, electrons, photons*
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

CMB to Baryon & Dark Matter

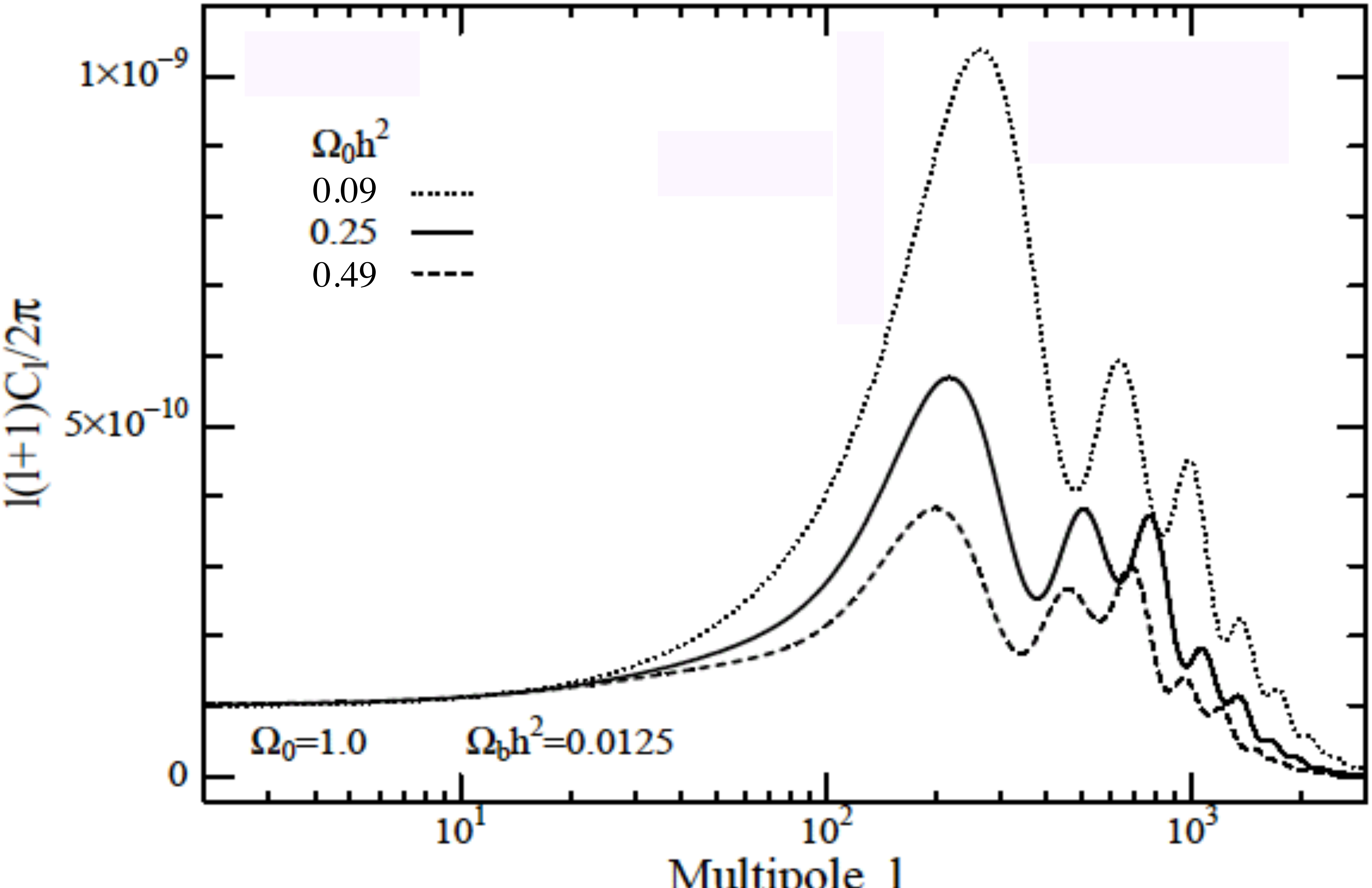


- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio (z_{EQ}: equality redshift)

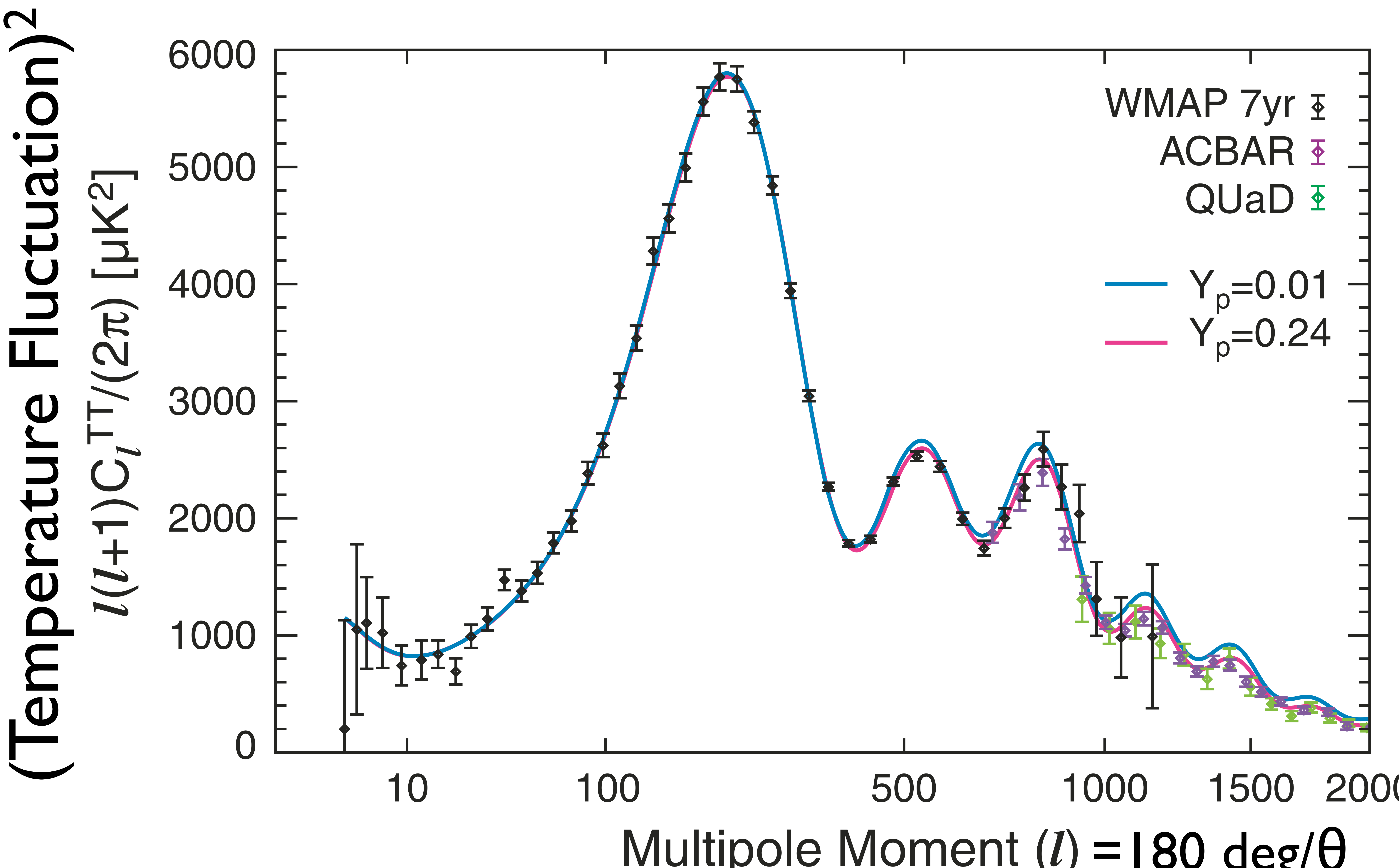
Determining Baryon Density From C_l



Determining Dark Matter Density From C_l



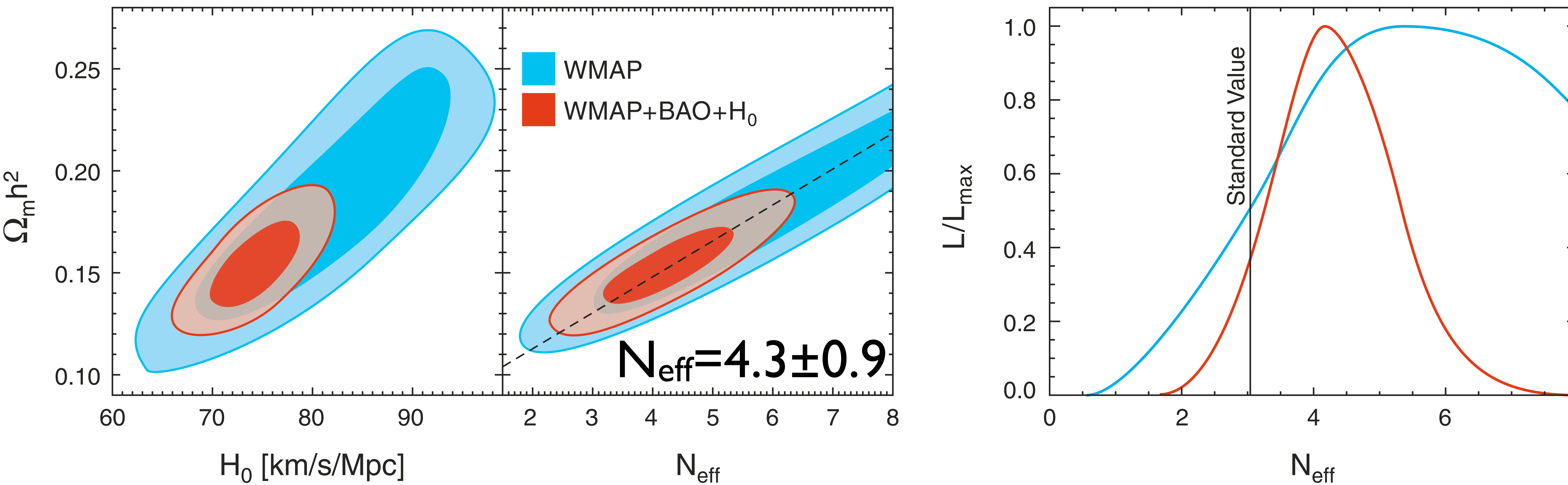
Detection of Primordial Helium



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

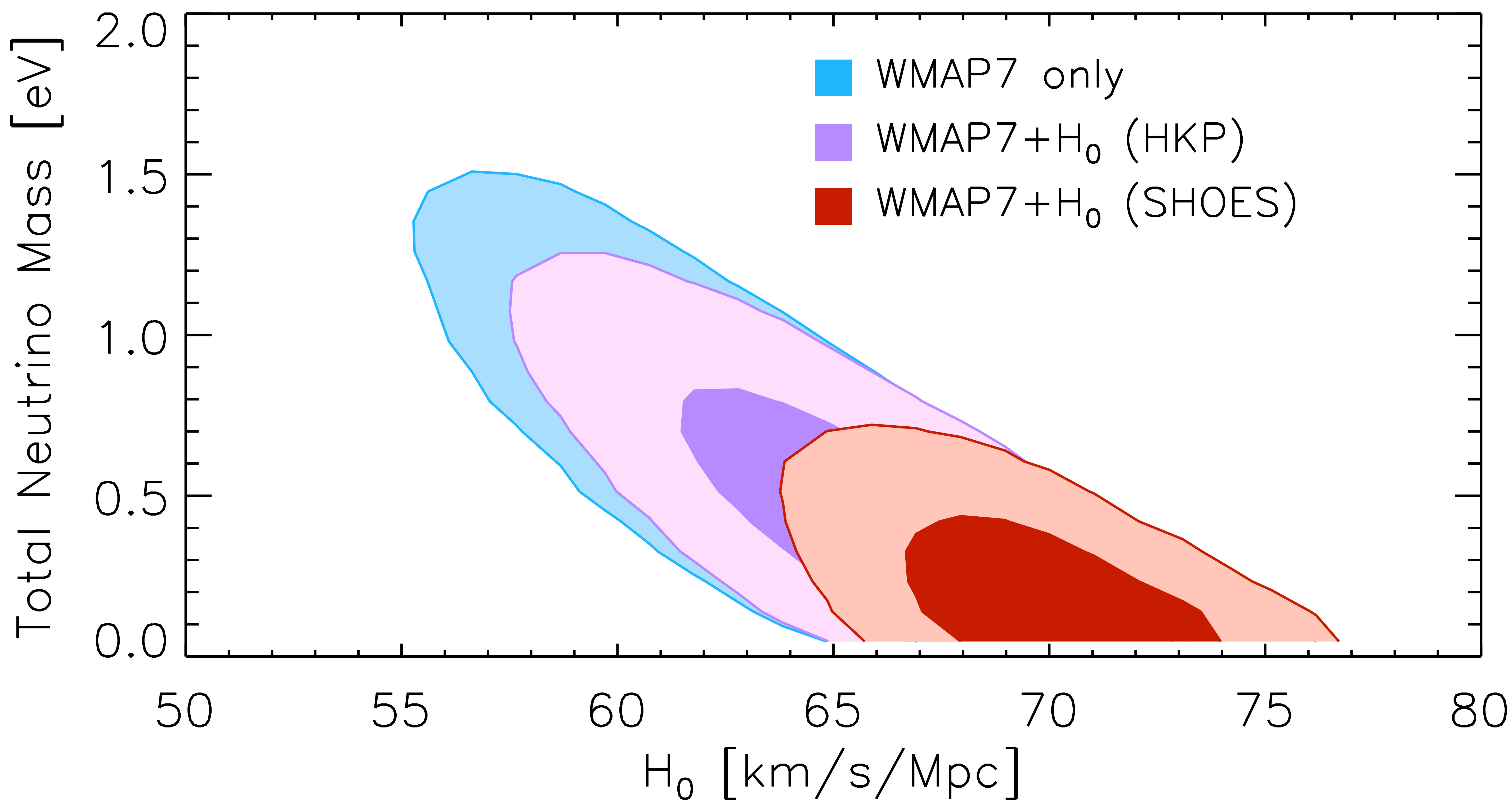


from external data

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

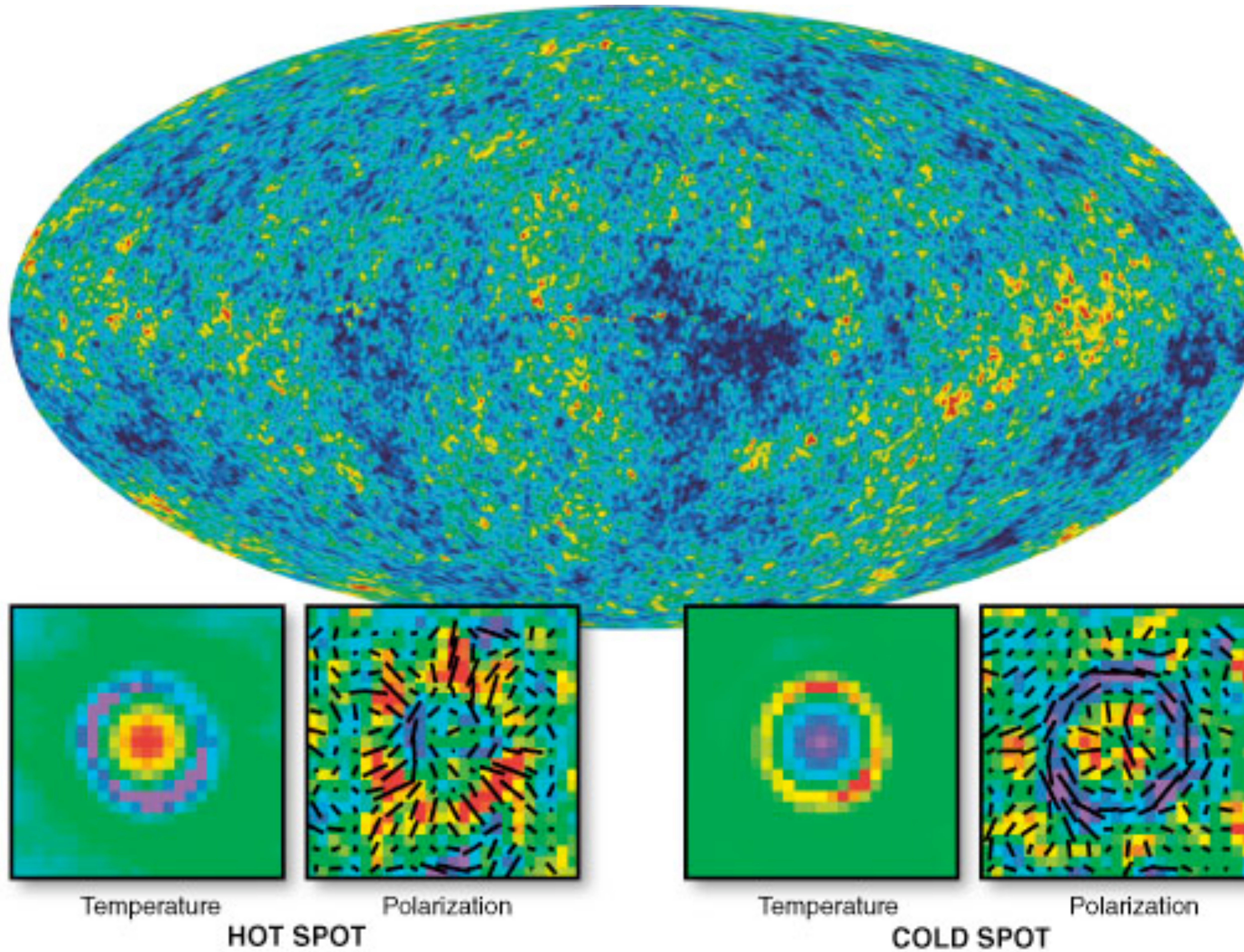
from 3rd peak

And, the mass of neutrinos



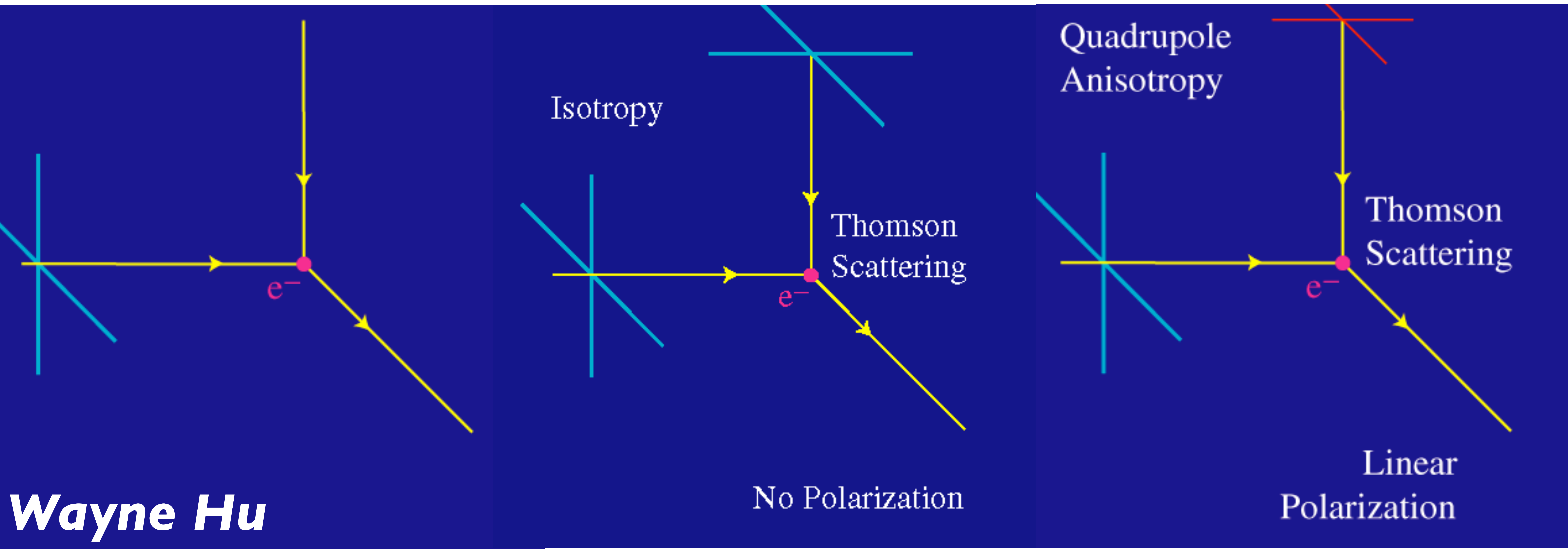
- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

CMB Polarization



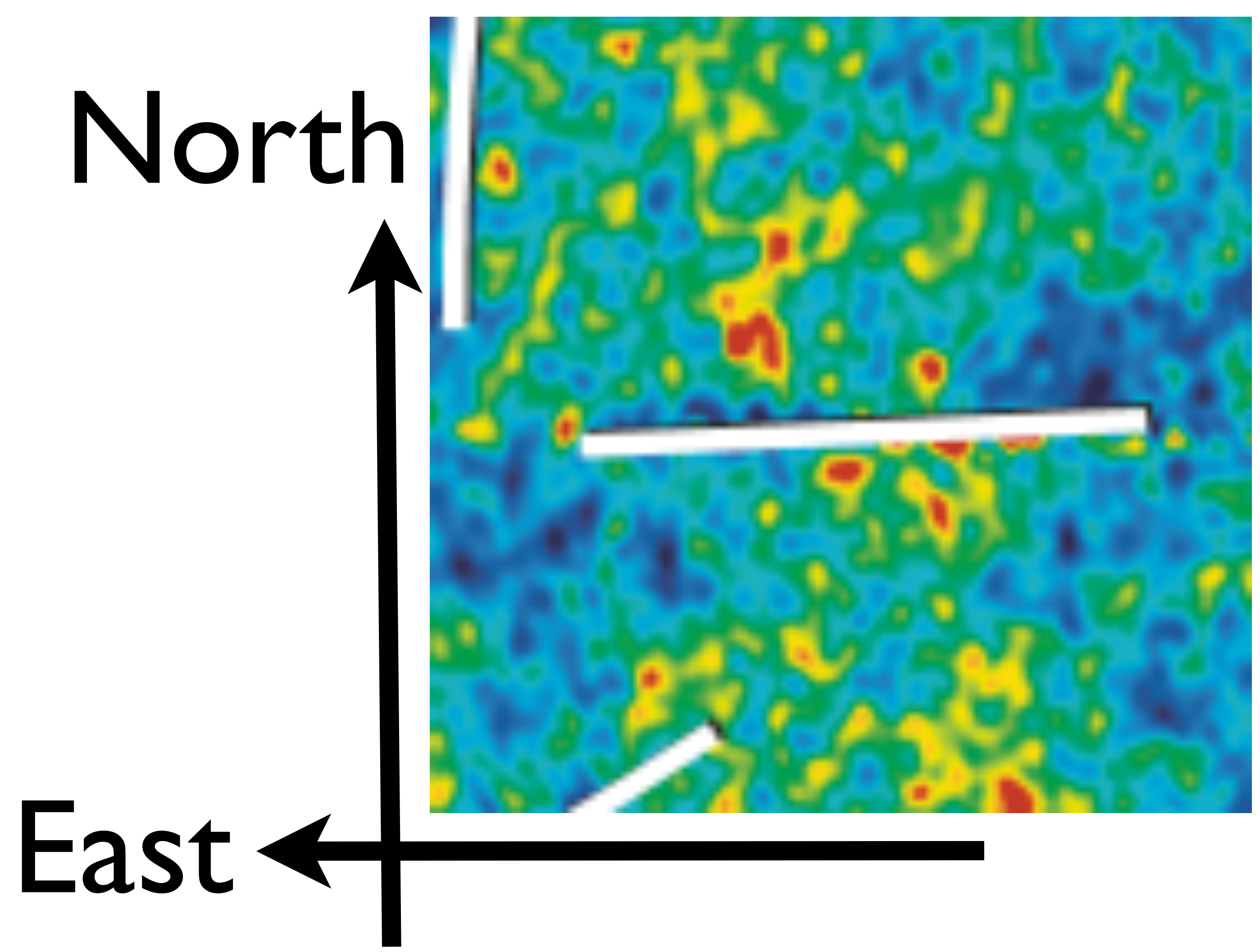
- *CMB is (very weakly) polarized!*

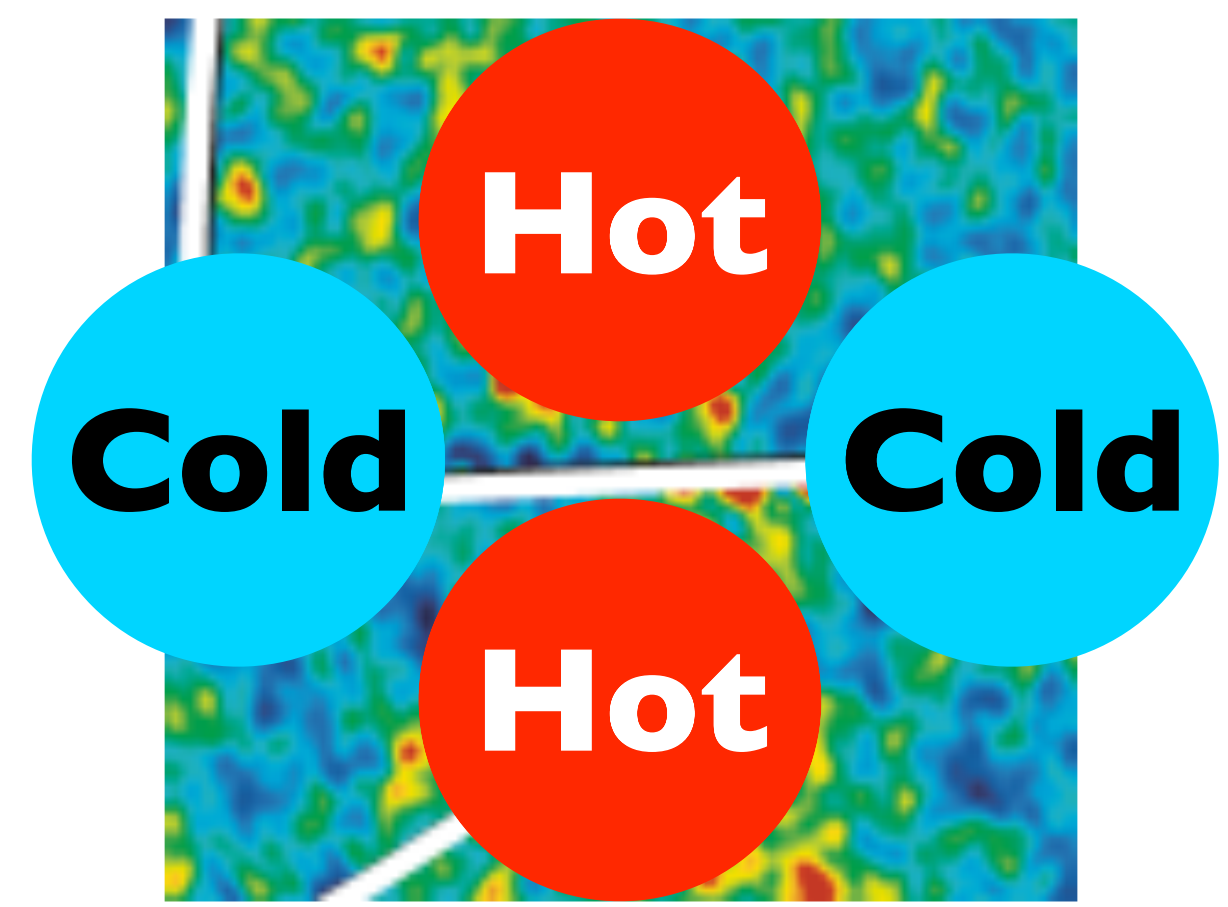
Physics of CMB Polarization



- 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)

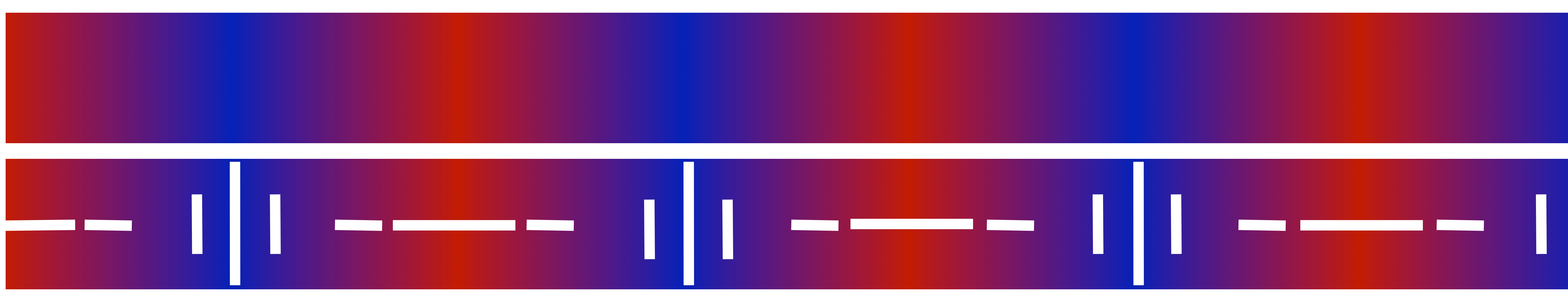
Matter Density

Potential

ΔT/T = (Newton's Gravitation Potential)/3

ΔT

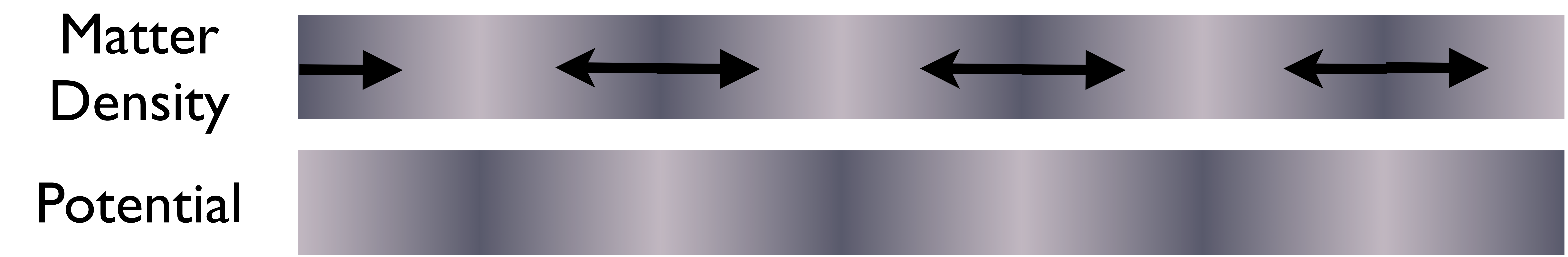
Polarization



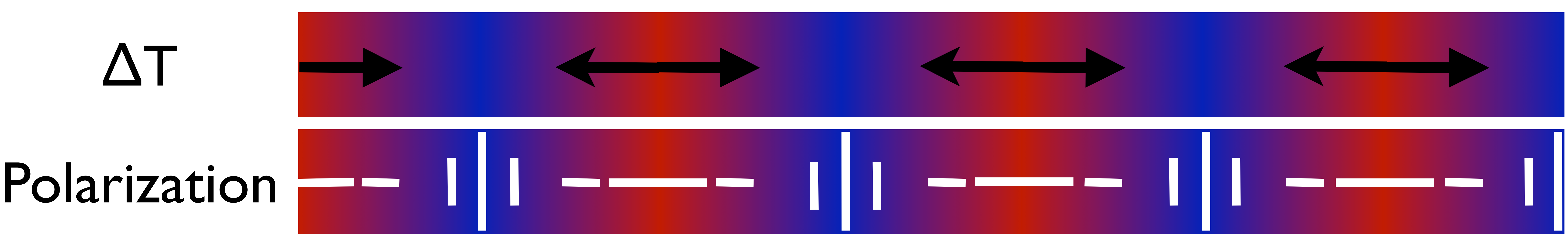
- How does the photon-baryon plasma move?

CMB Polarization Tells Us How Plasma Moves at z=1090

Zaldarriaga & Harari (1995)



ΔT/T = (Newton's Gravitation Potential)/3



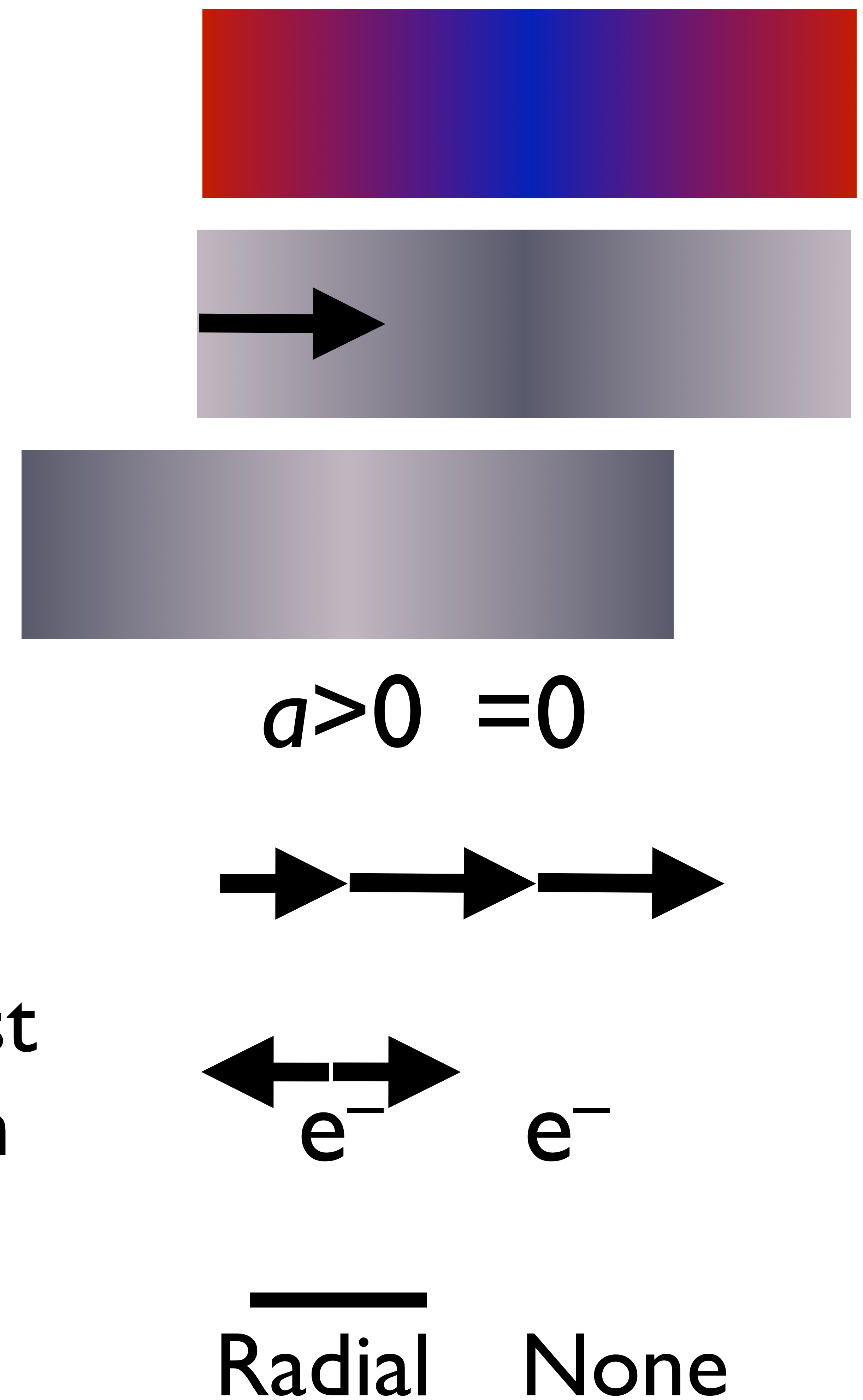
- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern

Quadrupole From Velocity Gradient (Large Scale)

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

Potential Φ — Stuff flowing *in*

Acceleration $a = -\partial\Phi$

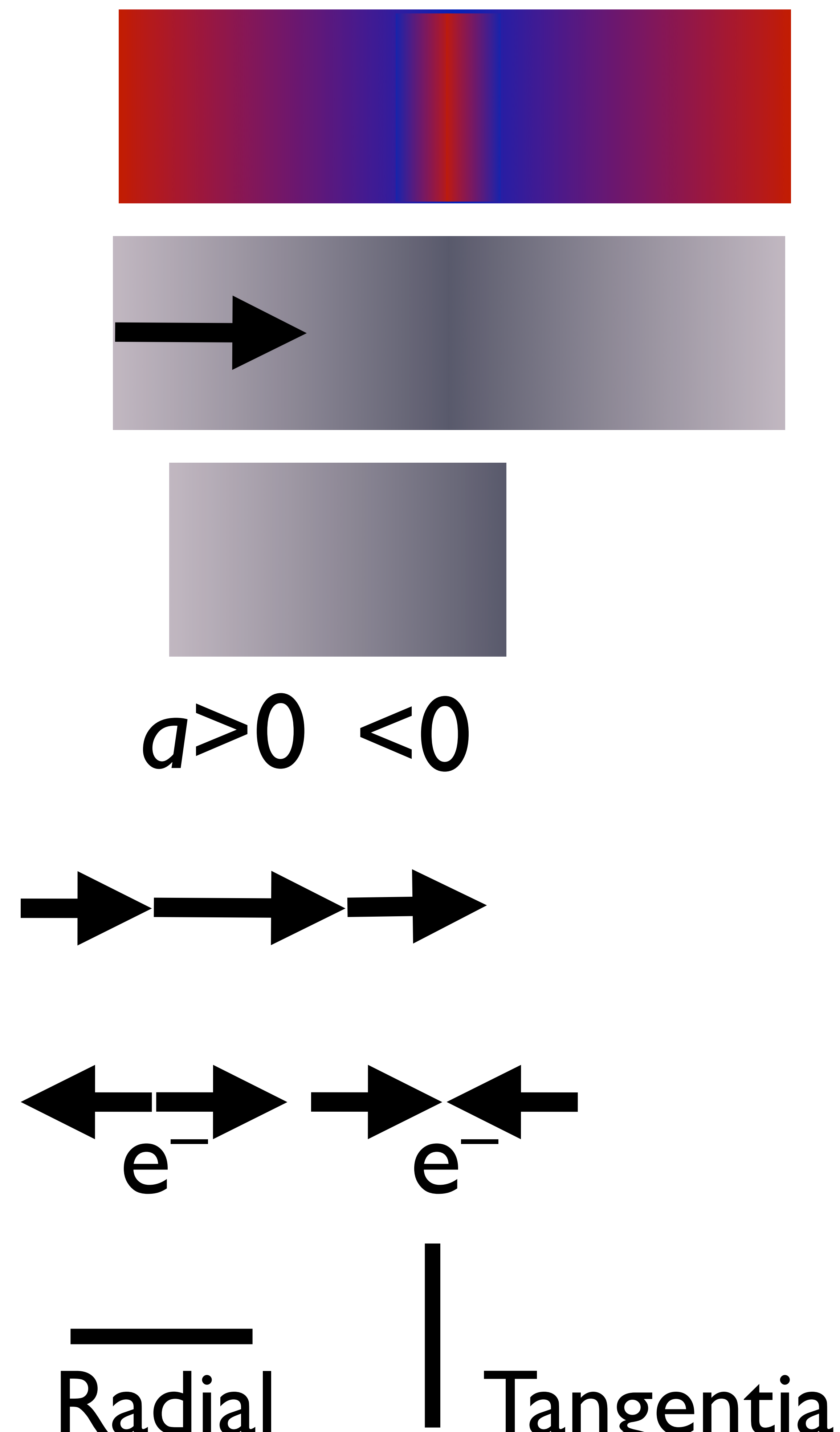


Velocity — Velocity gradient

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

Polarization

Quadrupole From Velocity Gradient (Small Scale)

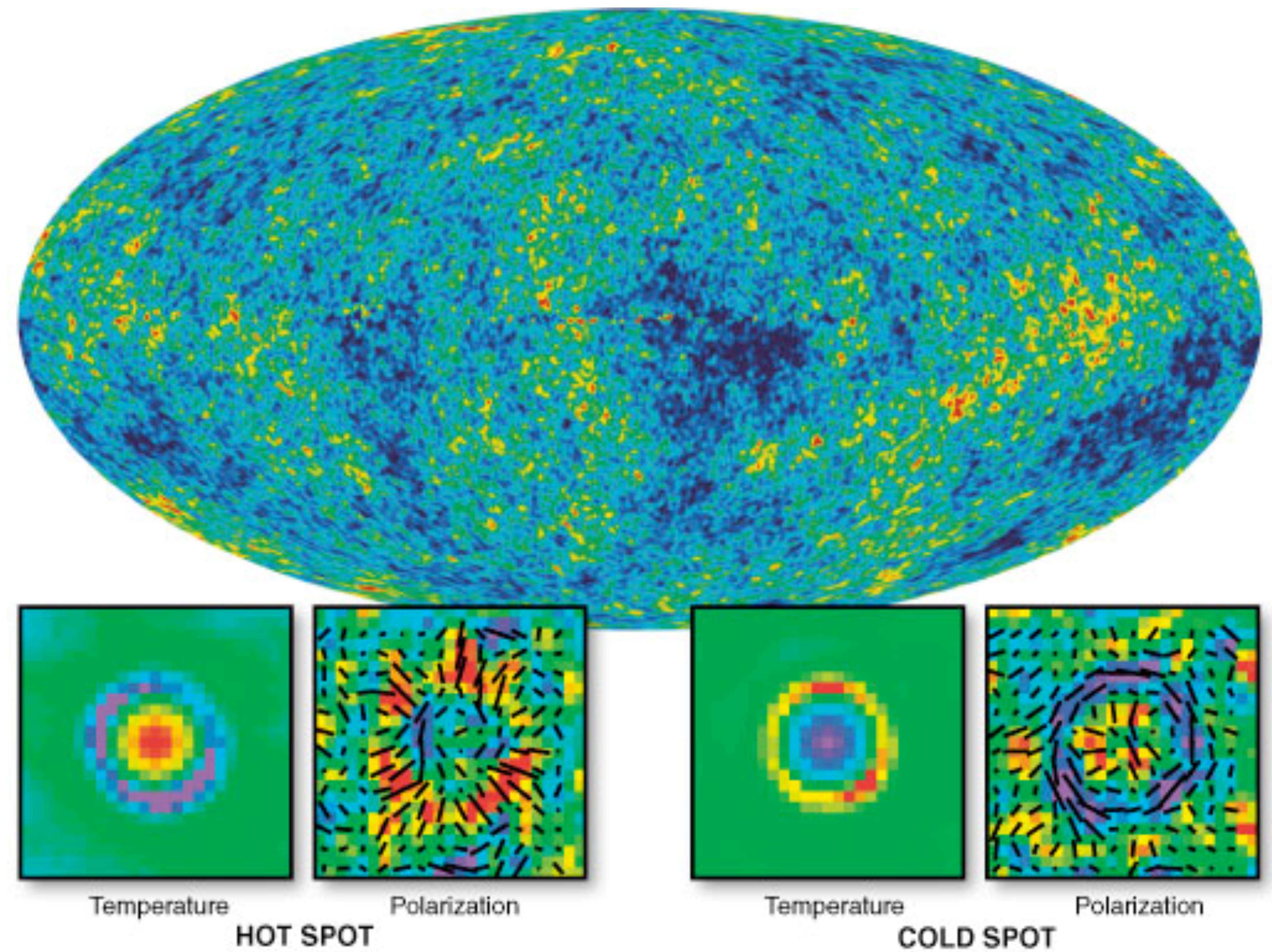


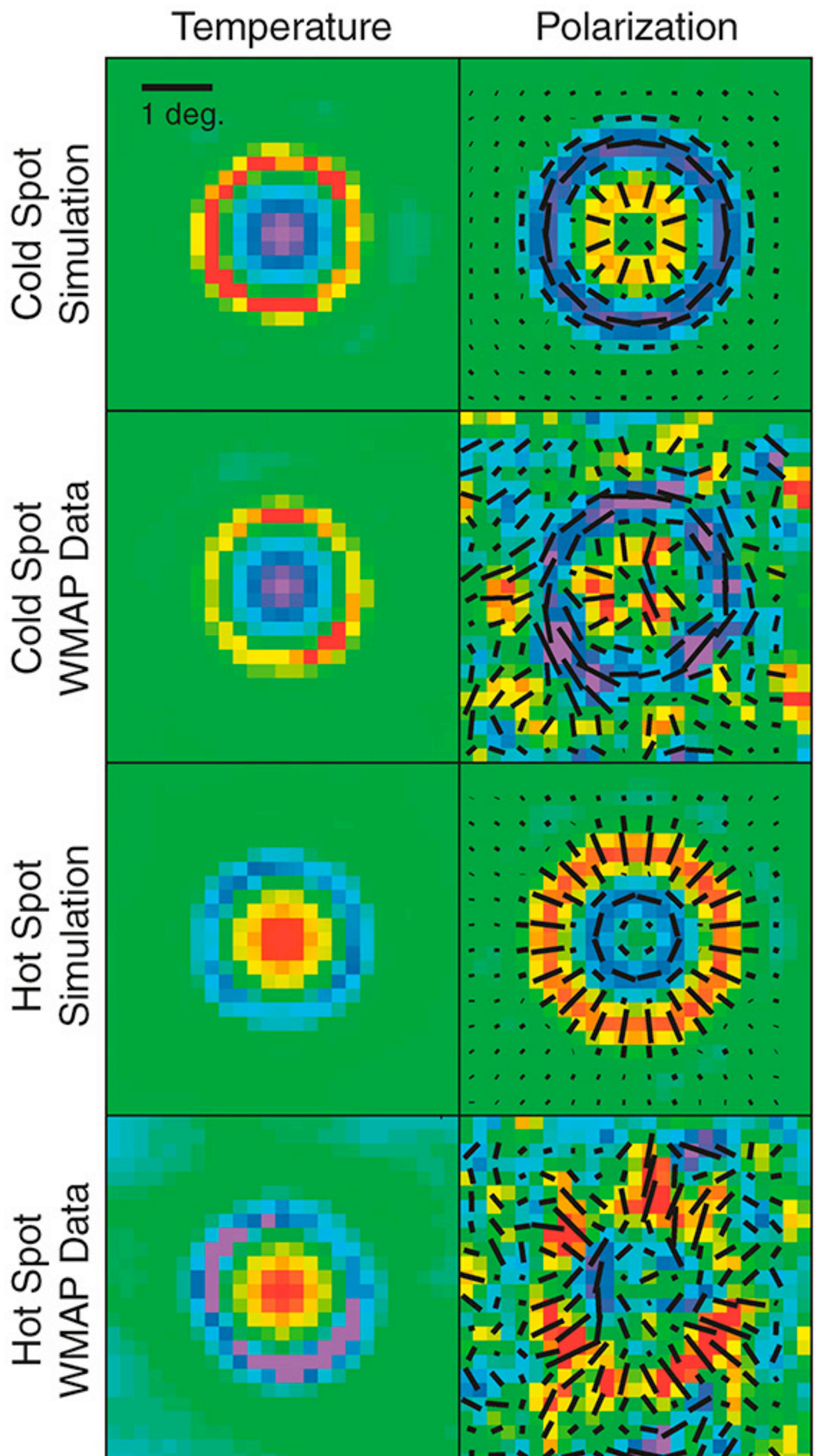
ΔT	Compression increases temperature
Potential Φ	Stuff flowing *in*
Acceleration $a = -\partial\Phi - \partial P$	Pressure gradient slows down the flow
Velocity	Velocity gradient
Velocity in the rest frame of electron	
Polarization	

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**.

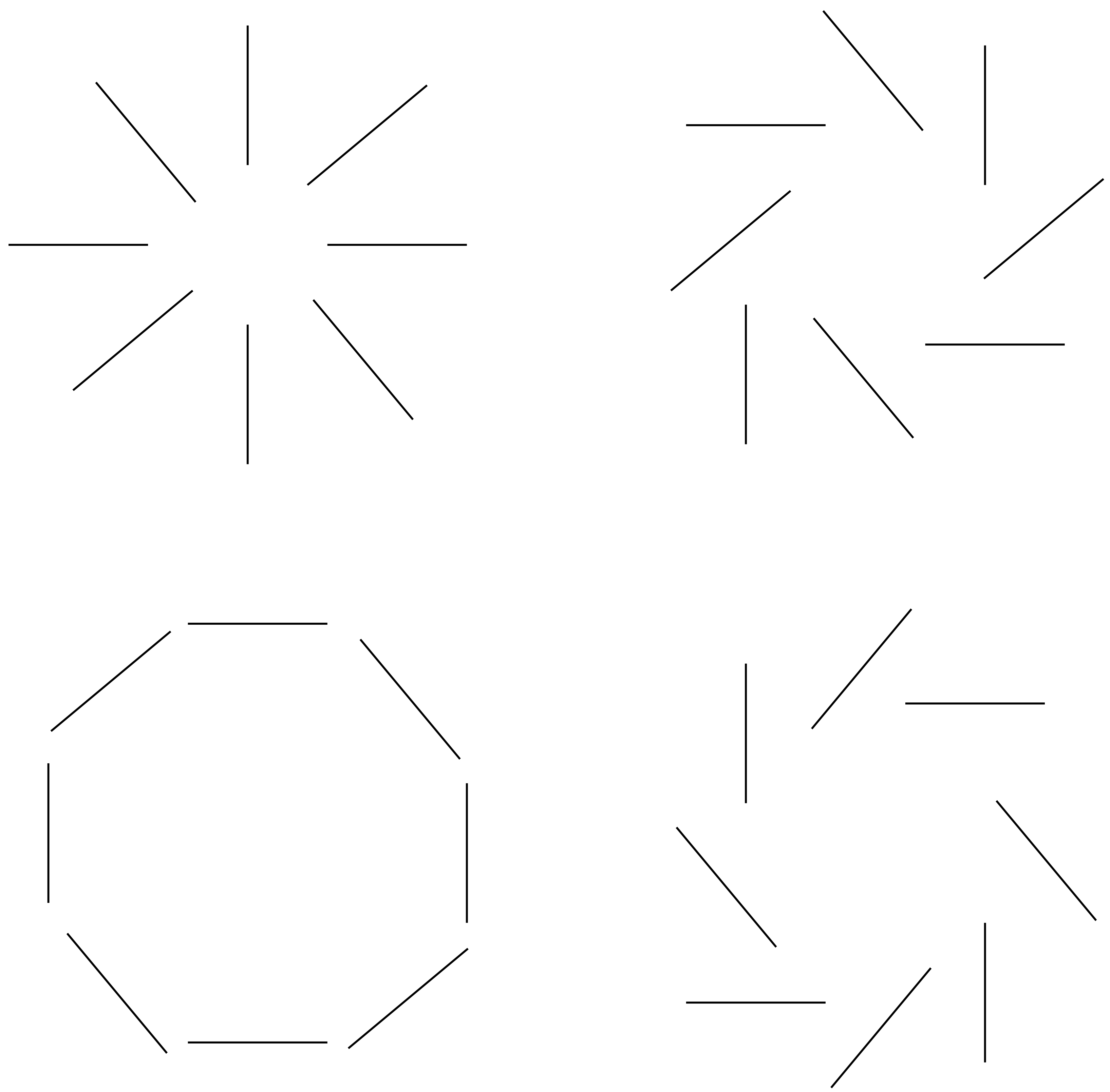




Two-dimensional View

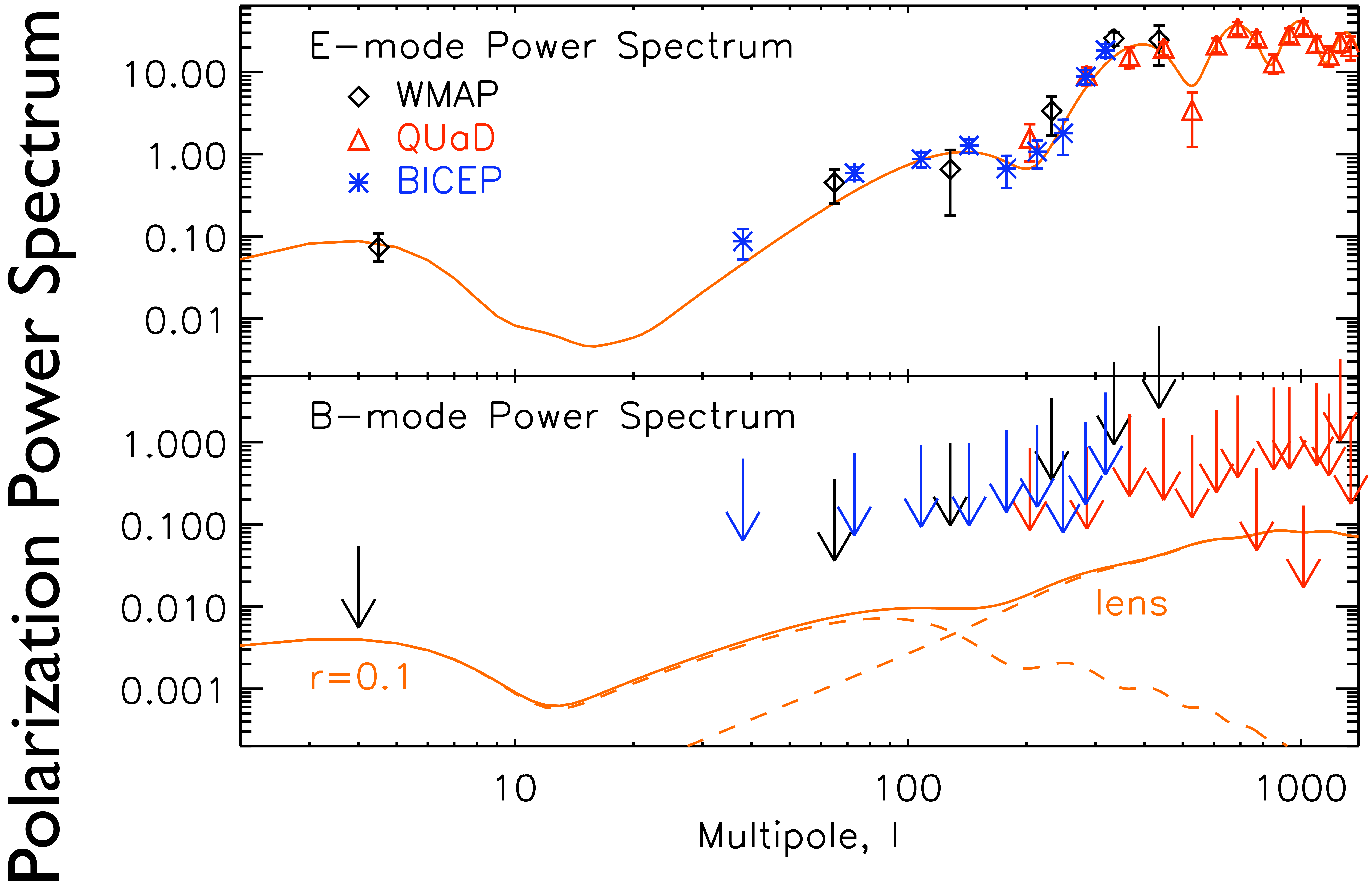
- All hot and cold spots are stacked (the threshold peak height, $\Delta T/\sigma$, is zero)
- "Compression phase" at θ=1.2 deg and "slow-down phase" at θ=0.6 deg are predicted to be there and we observe them!
  - The overall significance level: 8σ

E-mode and B-mode



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!

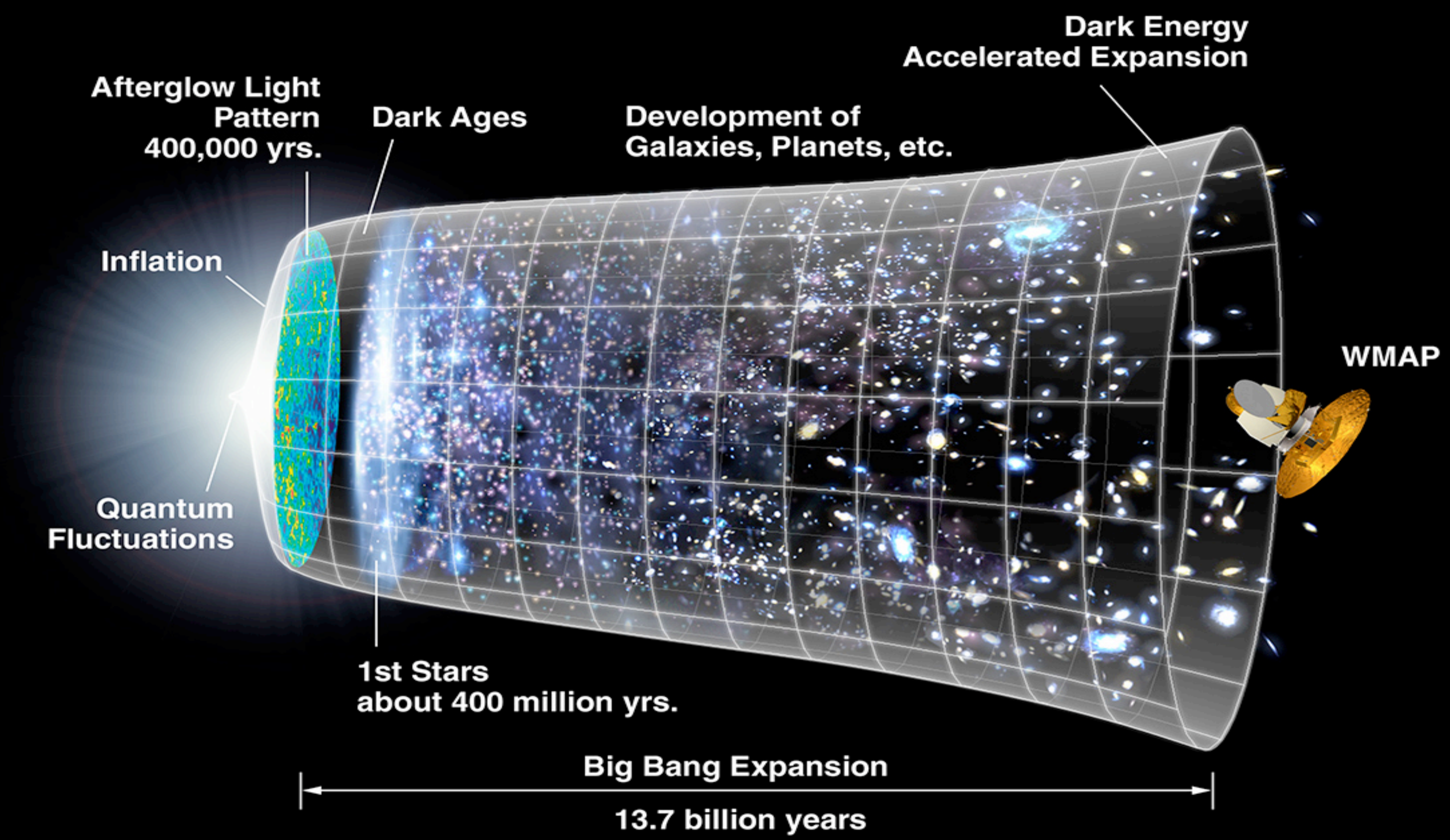


- No detection of B-mode polarization yet. **B-mode is the next holy grail!**

Theory of the Very Early Universe

- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  (Guth 1981; Linde 1982; Albrecht & Steinhardt 1982; Starobinsky 1980)
  - The expansion of our Universe ***accelerated*** in a tiny fraction of a second after its birth.
  - Just like Dark Energy accelerating today's expansion: the acceleration also happened at very, very early times!
- **Inflation stretches "*micro to macro*"**
  - In a tiny fraction of a second, the size of an atomic nucleus (~10^{-15}m) would be stretched to 1 A.U. (~10^{11}m), at least.

Cosmic Inflation = Very Early Dark Energy



NASA/WMAP Science Team

Theory Says...

- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  - The expansion of our Universe ***accelerated*** in a tiny fraction of a second after its birth.
  - the primordial ripples were created by ***quantum fluctuations*** during inflation, and
  - how the power is distributed over the scales is determined by the **expansion history during cosmic inflation**.
- Detailed observations give us **this** remarkable information!

Quantum Fluctuations

- You may borrow a lot of **energy** from vacuum if you promise to return it to the vacuum immediately.
- The amount of **energy** you can borrow is inversely proportional to the time for which you borrow the **energy** from the vacuum.
- Just (a version of) Heisenberg's Uncertainty Principle, the foundation of Quantum Mechanics.

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]

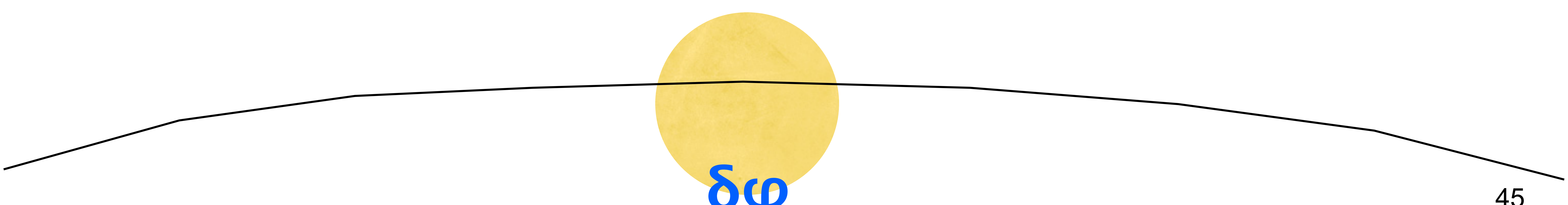
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-36} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

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)

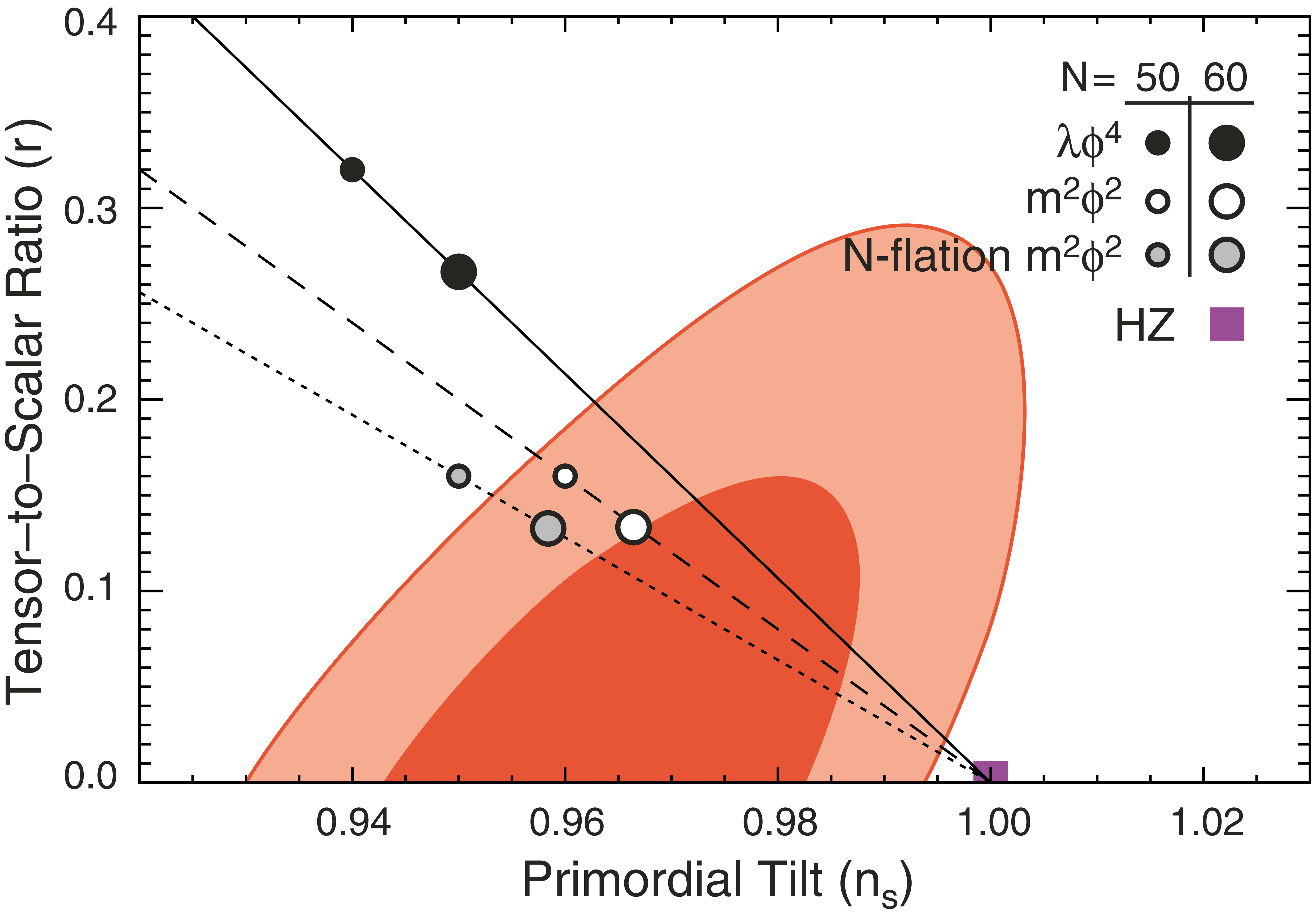
(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

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 (2-point Function)



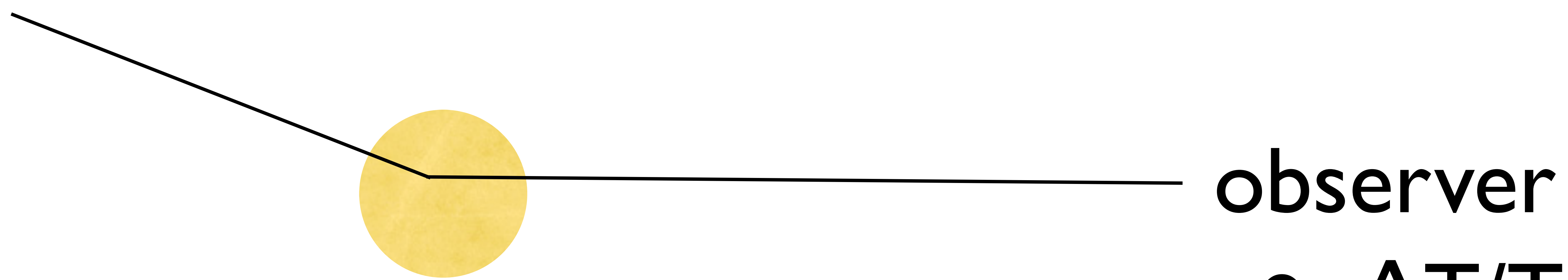
- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL)

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!
- No detection of 3-point functions of primordial curvature perturbations. The 95% CL limits are:
  - $-10 < f_{NL} < 74$
  - The WMAP data are consistent with the prediction of **simple single-field inflation** models: $1-n_s \approx r \approx f_{NL}$

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

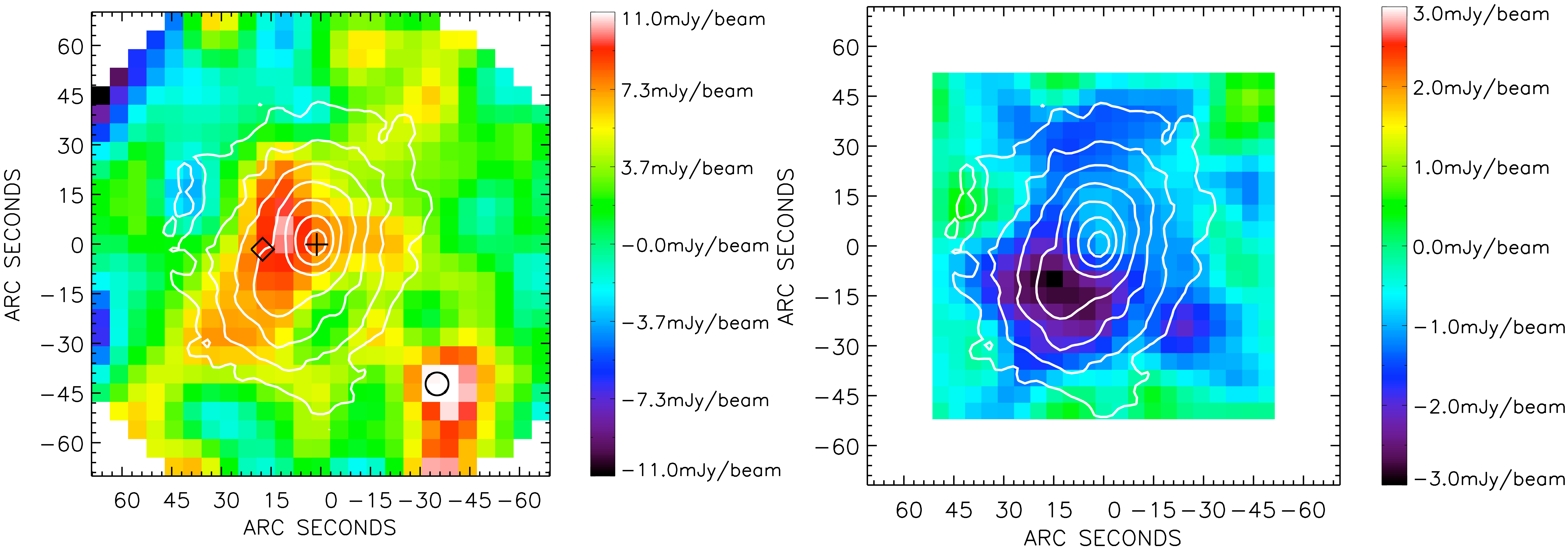
g_ν=–2 (ν=0); –1.91, –1.81 and –1.56 at ν=41, 61 and 94 GHz

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.

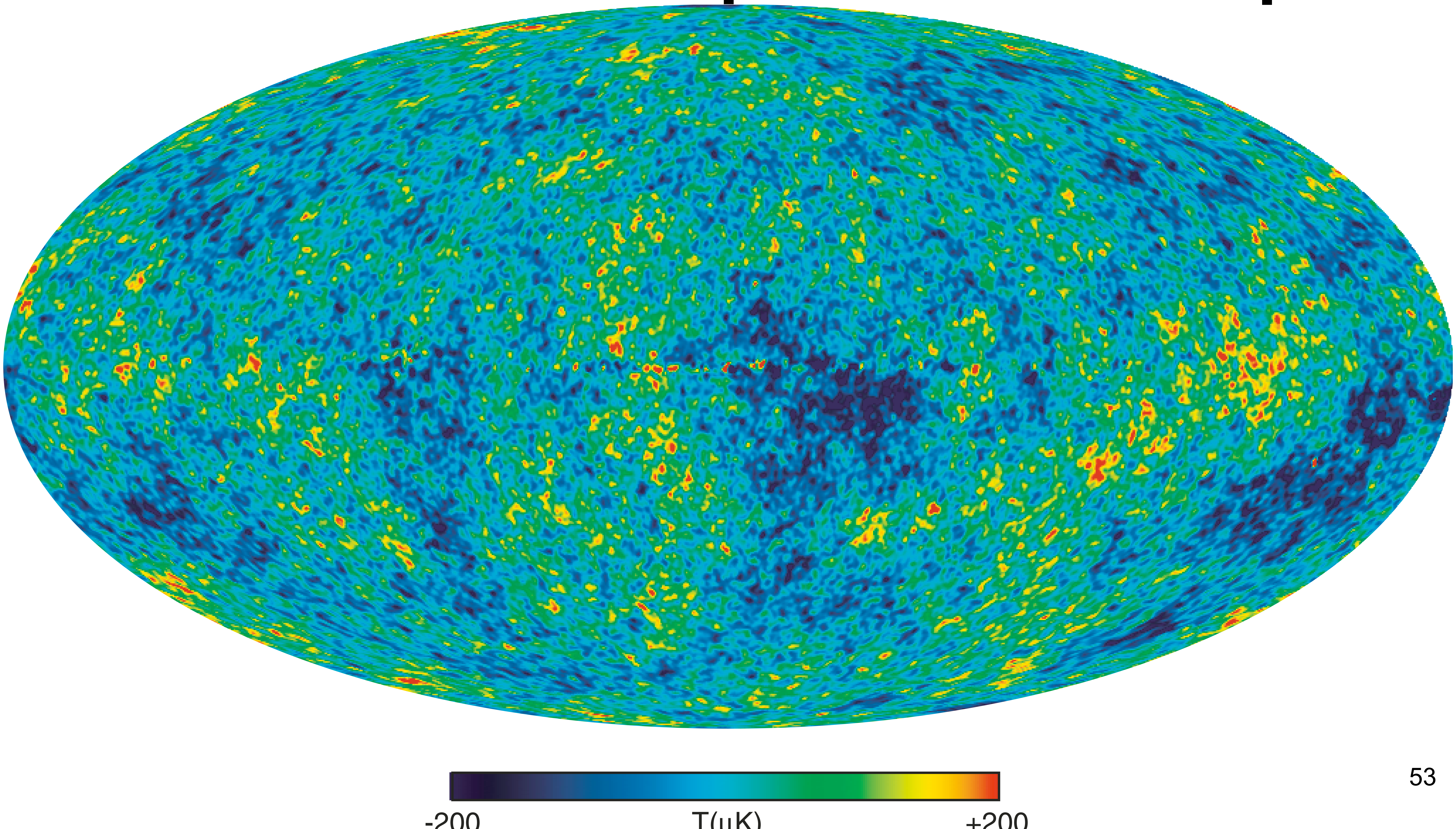
- Important when using the SZ effect of clusters of galaxies as a cosmological probe.

The SZ Effect: Decrement and Increment

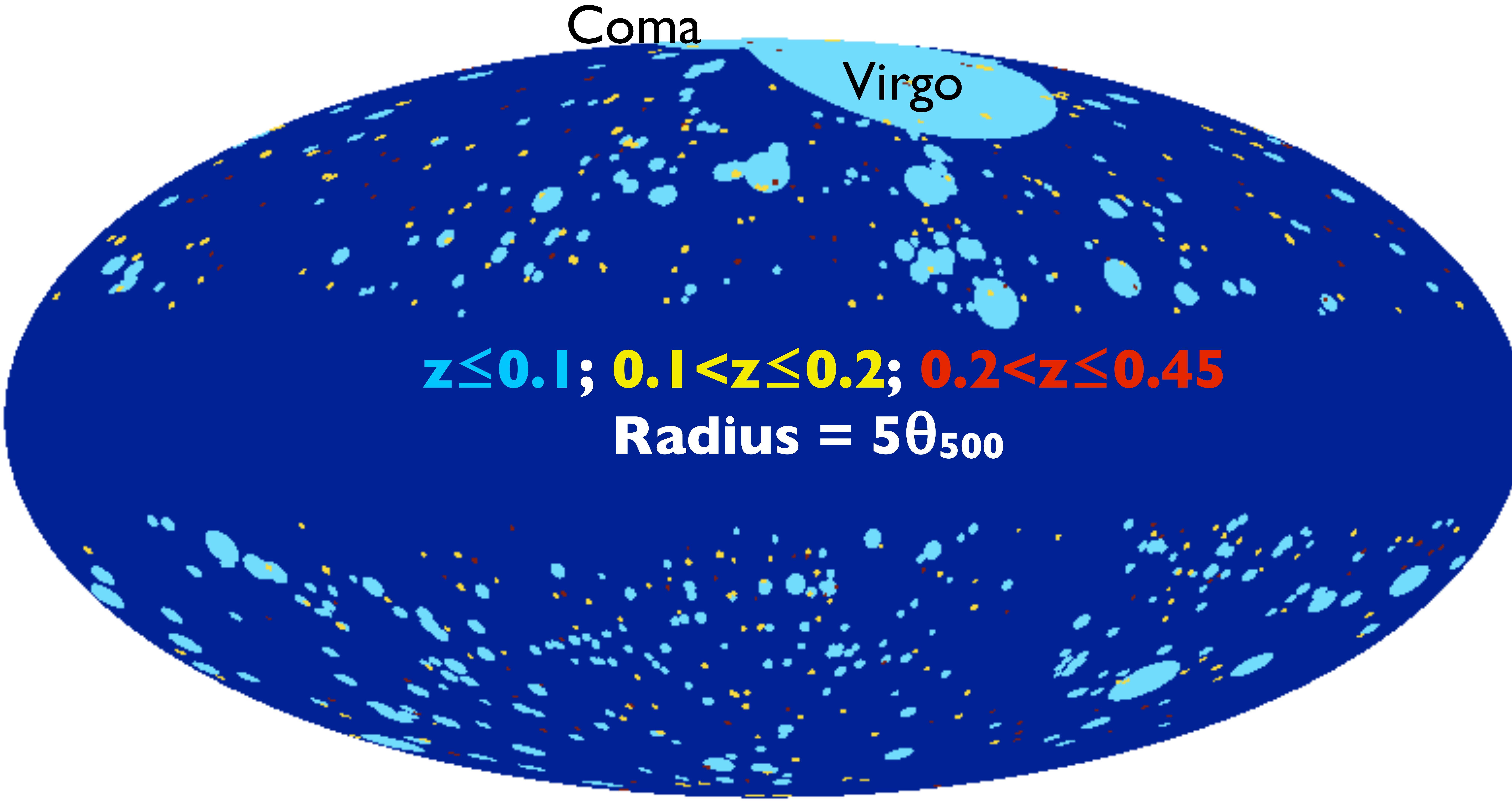


- RXJ1347-1145
  - –Left, SZ increment (350GHz, Komatsu et al. 1999)
  - –Right, SZ decrement (150GHz, Komatsu et al. 2001)

WMAP Temperature Map



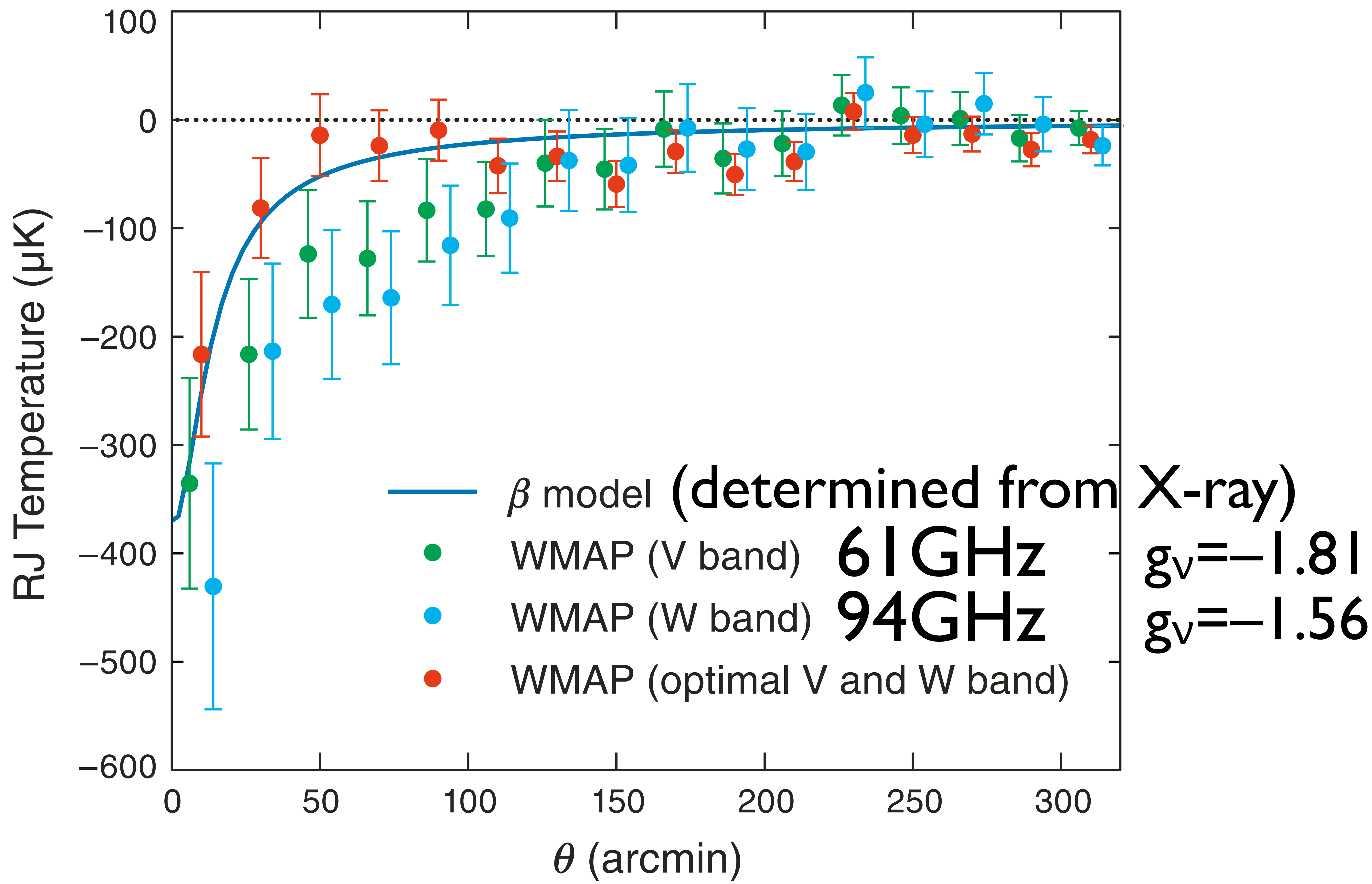
Where are clusters?



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**.

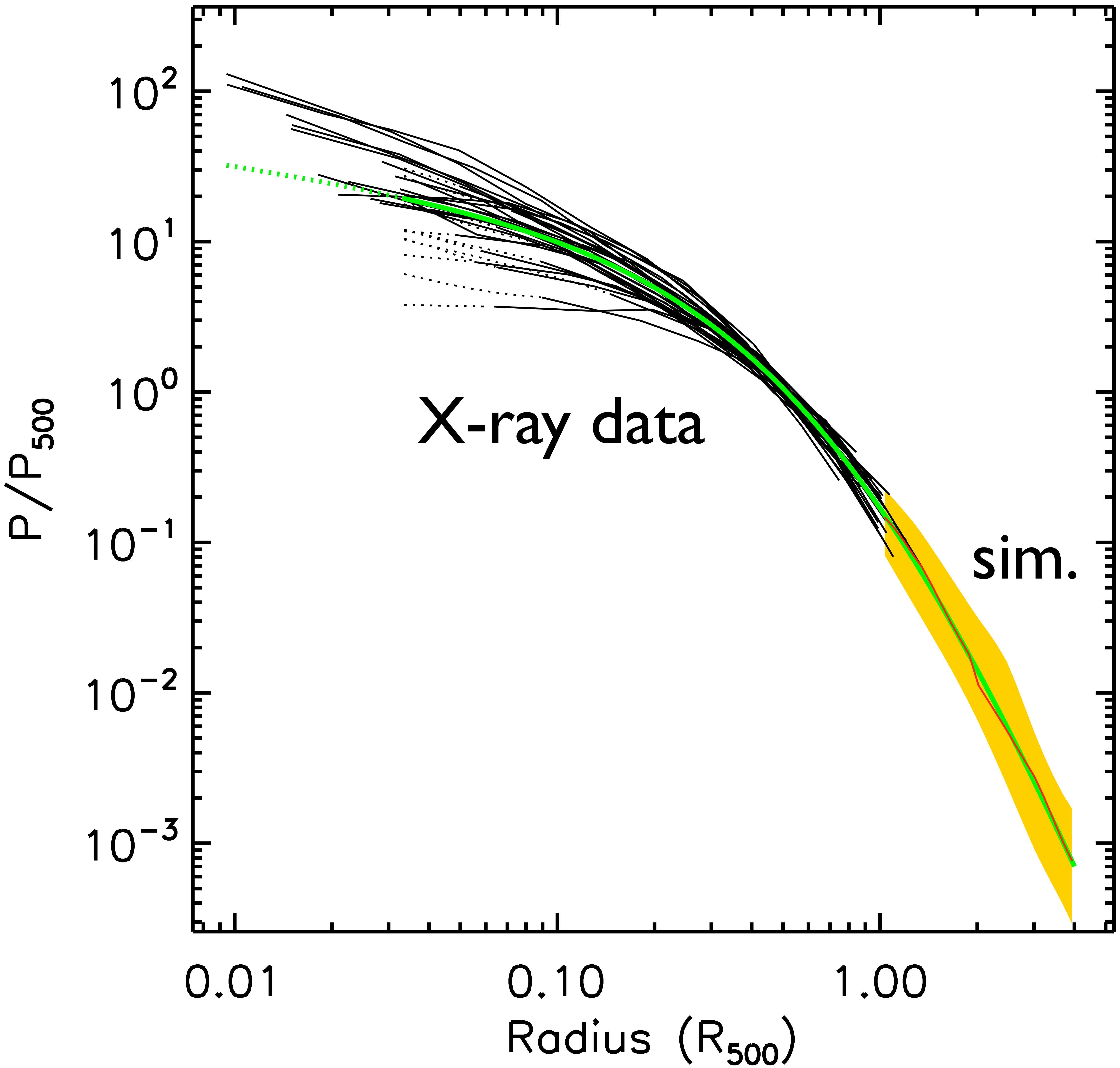
A Question

- 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

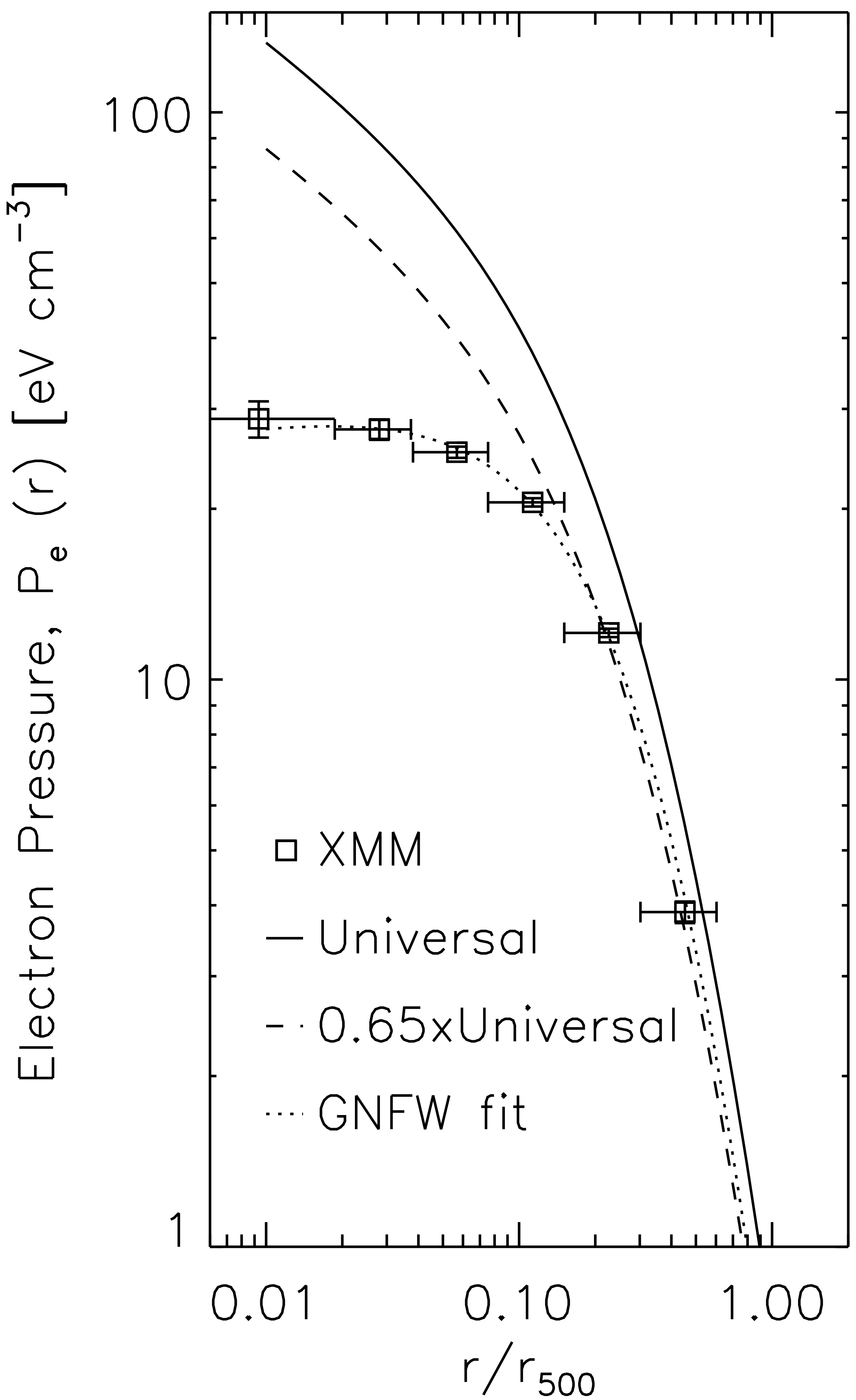
- A fitting formula for the average electron pressure profile as a function of the cluster mass (M_{500}), derived from 33 nearby ($z<0.2$) clusters (REXCESS sample).

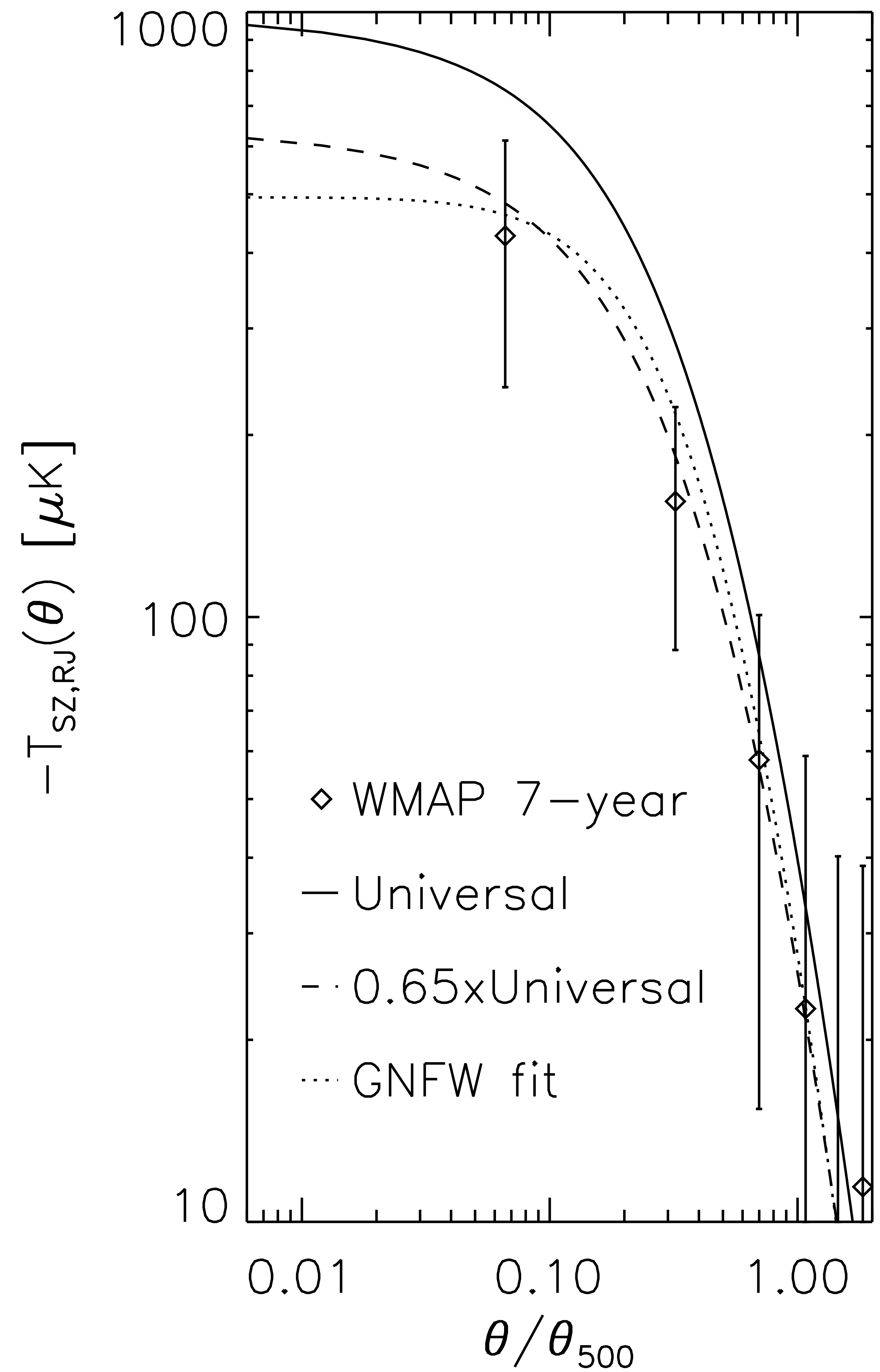
Arnaud et al. Profile



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

Coma Data vs Arnaud





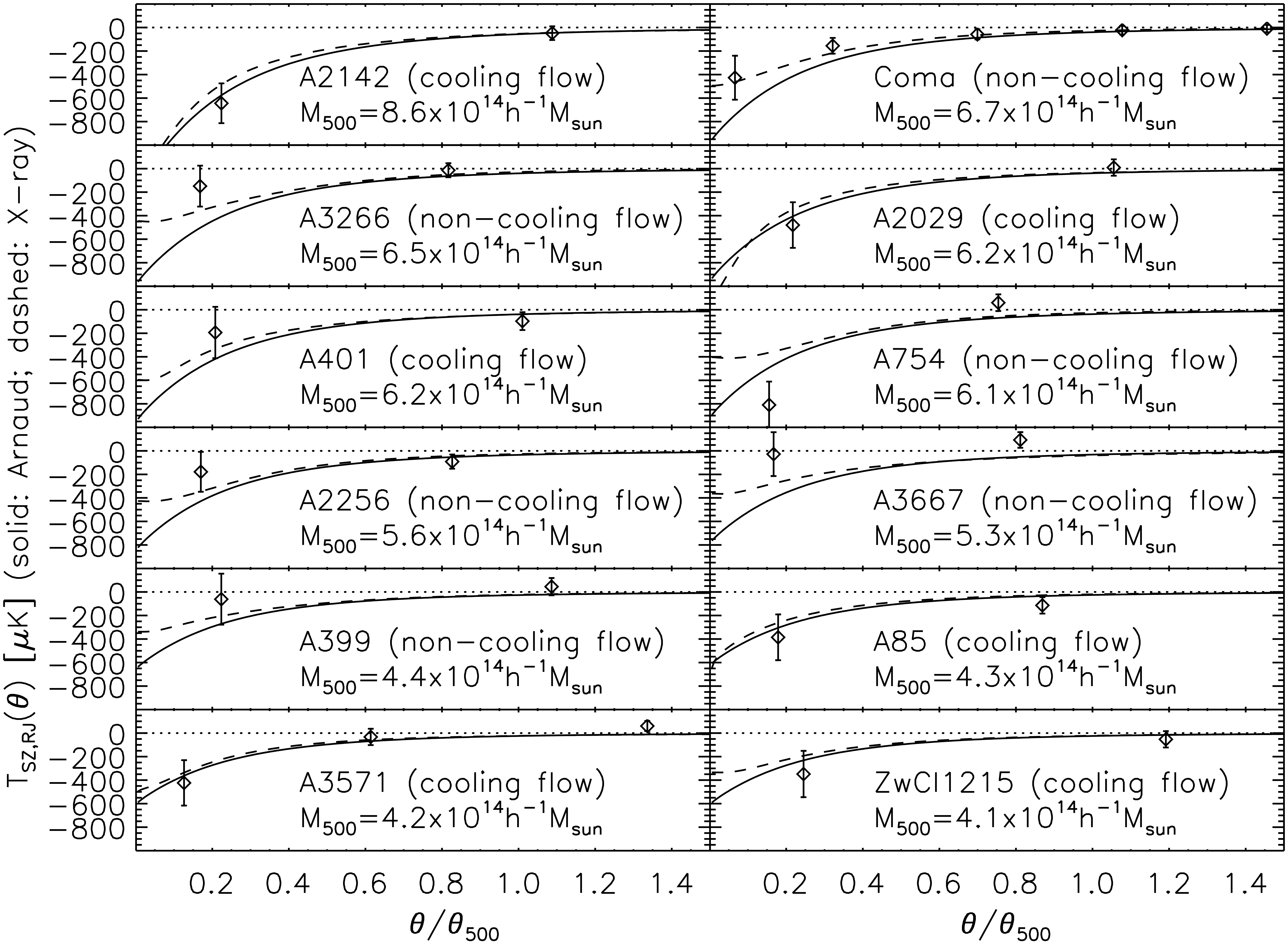
The X-ray data (XMM) are provided by A. Finoguenov.

- $M_{500}=6.6\times10^{14}h^{-1}M_{sun}$ 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
$4 \le M_{500} < 6$	6	0.73 ± 0.21	0.60 ± 0.17
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[a] In units of $10^{14}\ h^{-1}\ M_{\odot}$. Coma is not included.

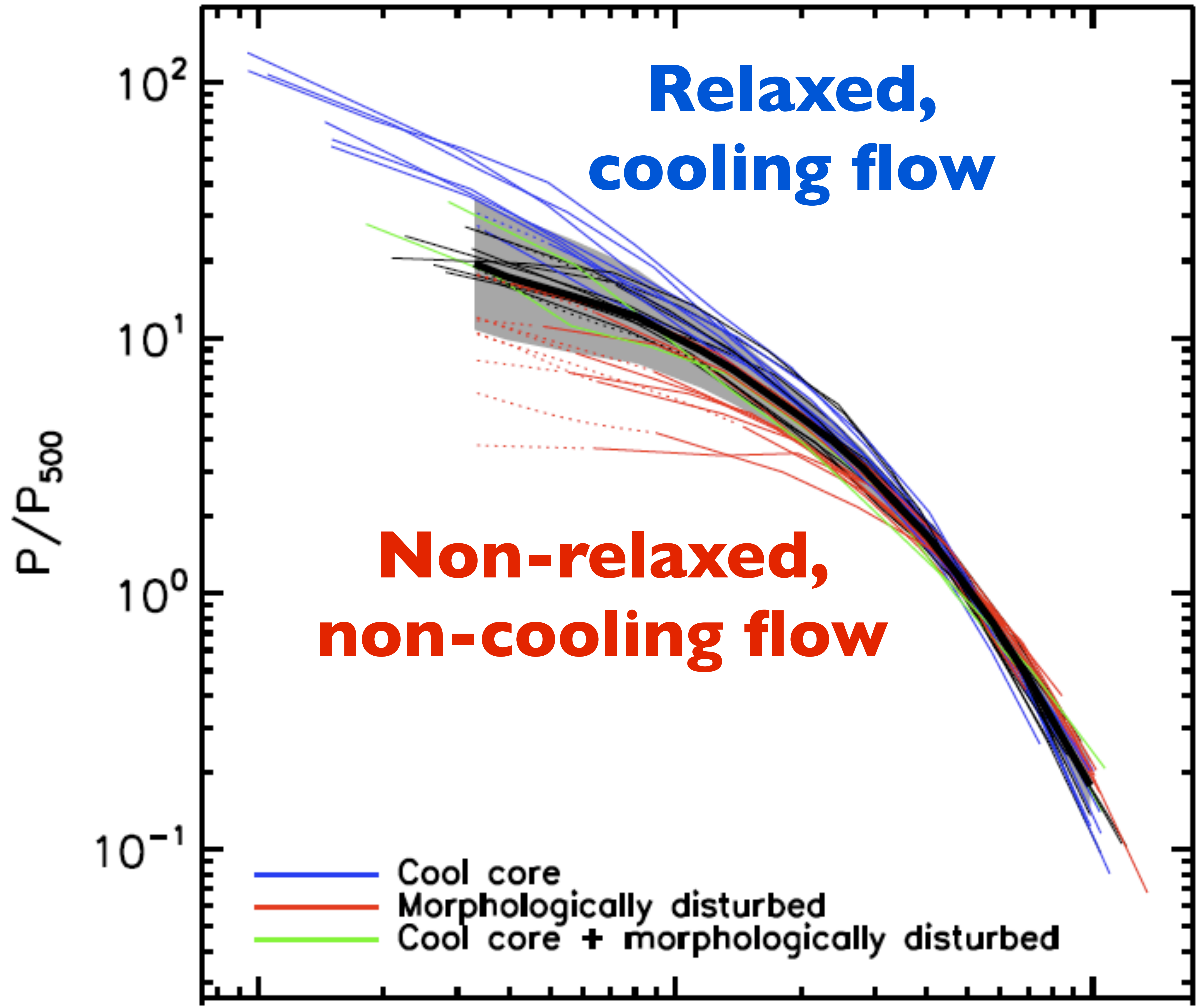
d: ALL of "cooling flow clusters" are relaxed clusters.

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

SZ: Main Results

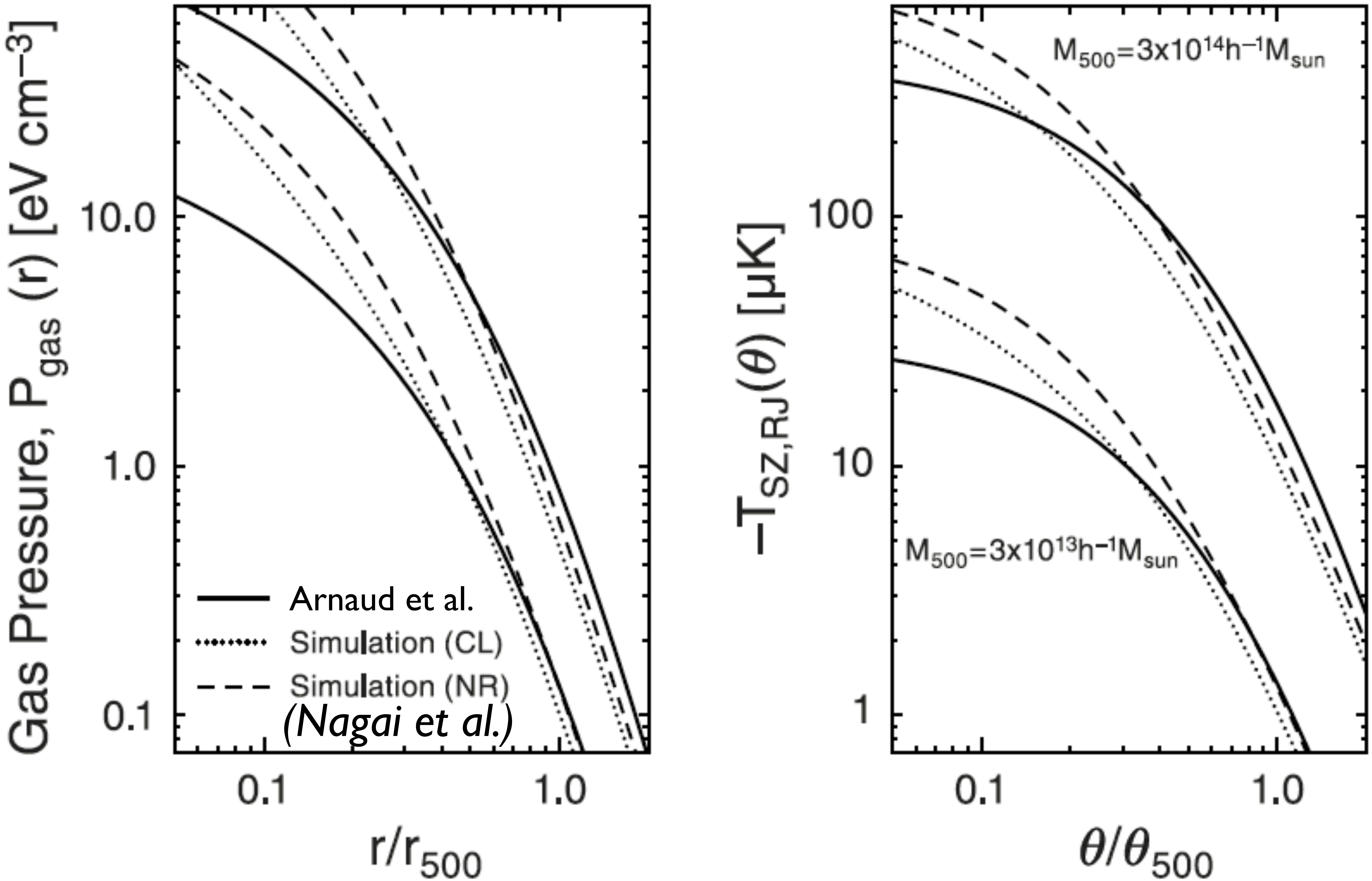
- Arnaud et al. profile systematically overestimates the electron pressure! (Arnaud et al. profile is **ruled out** at 3.2σ).
- But, the X-ray data on the *individual* clusters agree well with the SZ measured by WMAP.
- Reason: Arnaud et al. did not distinguish between relaxed (CF) and non-relaxed (non-CF)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



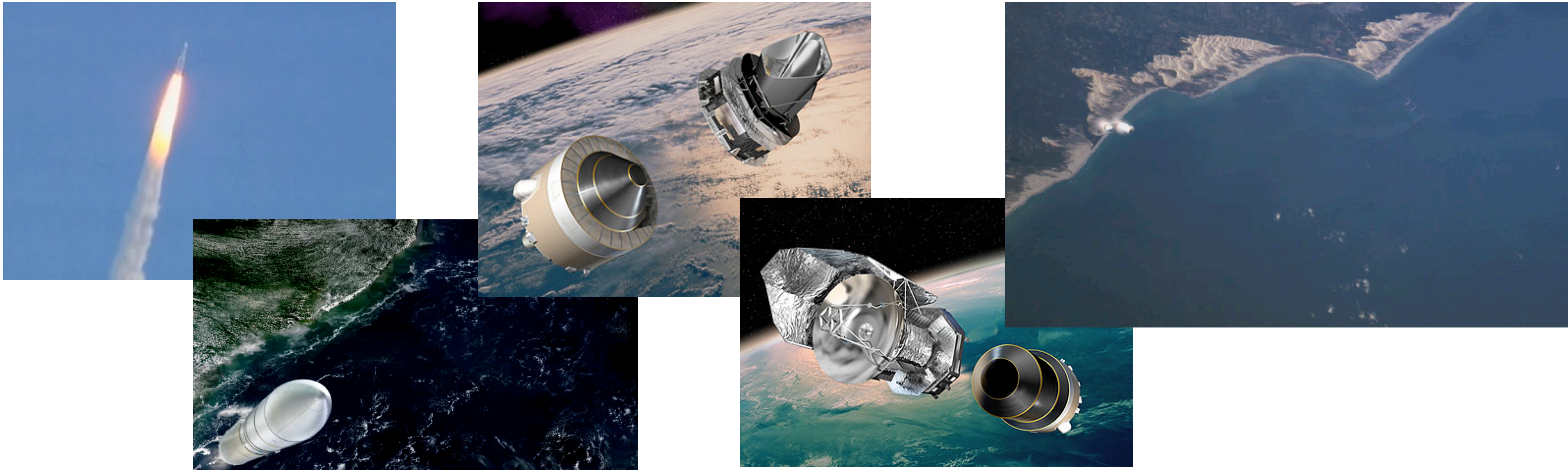
Summary

- CMB is the fossil light of the Big Bang.
- We could determine the age, composition, expansion rate, etc., from CMB.
- We could even push the boundary farther back in time, probing the origin of fluctuations in the very early Universe: inflationary epoch at ultra-high energies.
- Next Big Thing: **Primordial gravitational waves**
- My favorite: **Detection of f_{NL} to rule out single-field inflation!**

A Puzzle

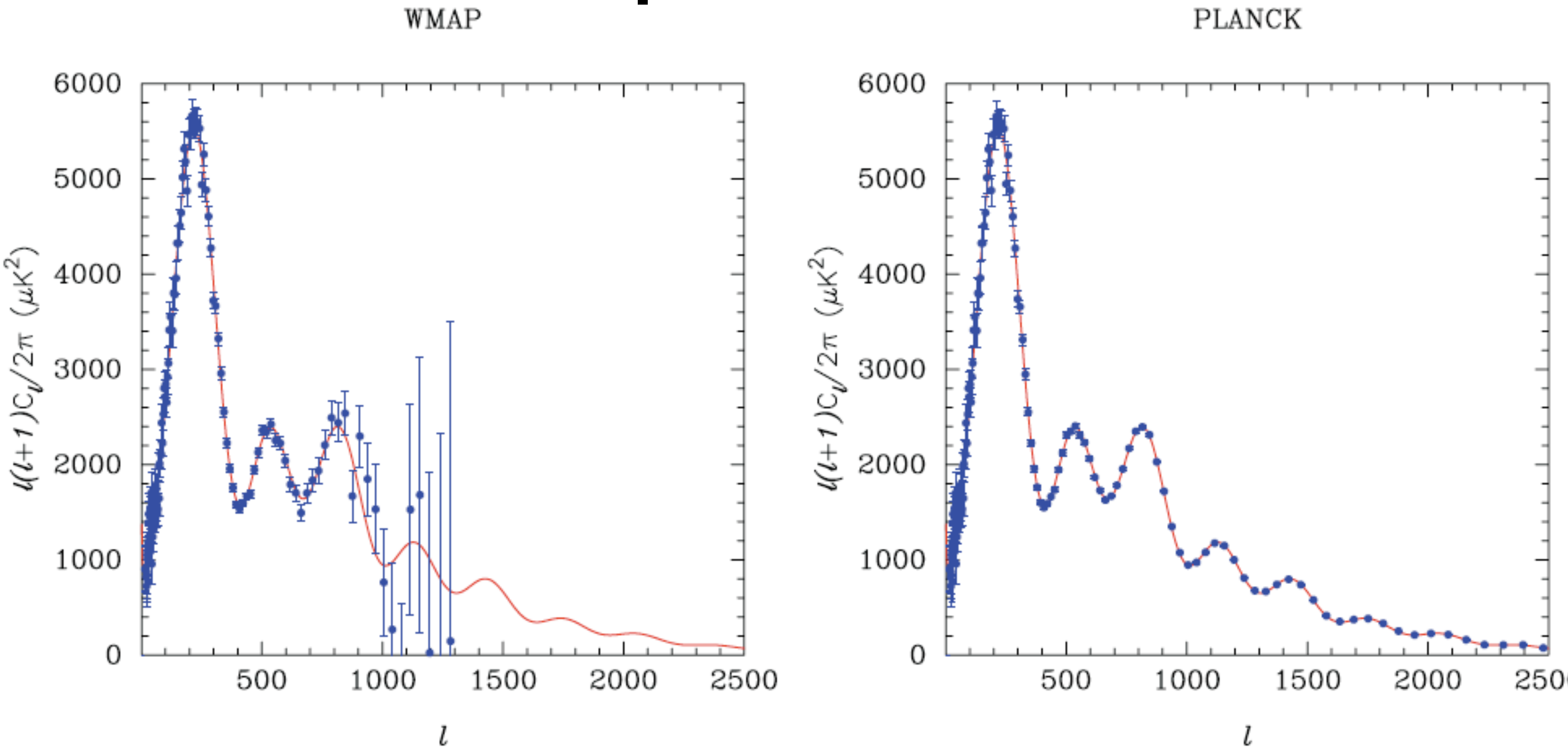
- SZ effect: Coma's radial profile is measured, several massive clusters are detected, and the statistical detection reaches 6.5σ.
  - Evidence for lower-than-theoretically-expected gas pressure.
  - First detection, in the SZ effect, of the difference between relaxed and non-relaxed clusters.
  - The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

Planck Launched!



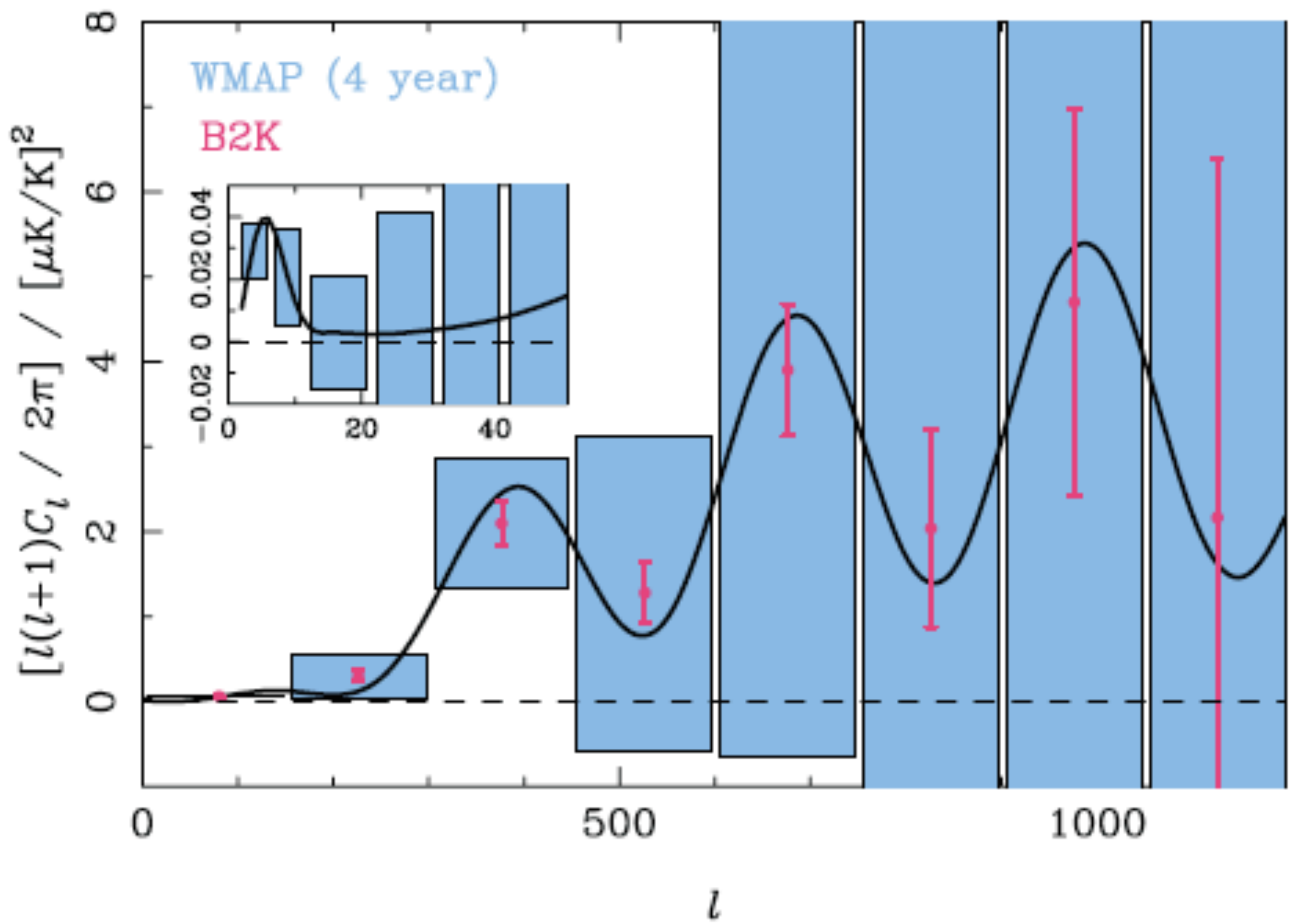
- The Planck satellite was successfully launched from French Guiana on May 14.
- Separation from the Herschell satellite was also successful.
- Planck has mapped the full sky already - results expected to be released in December, 2012.

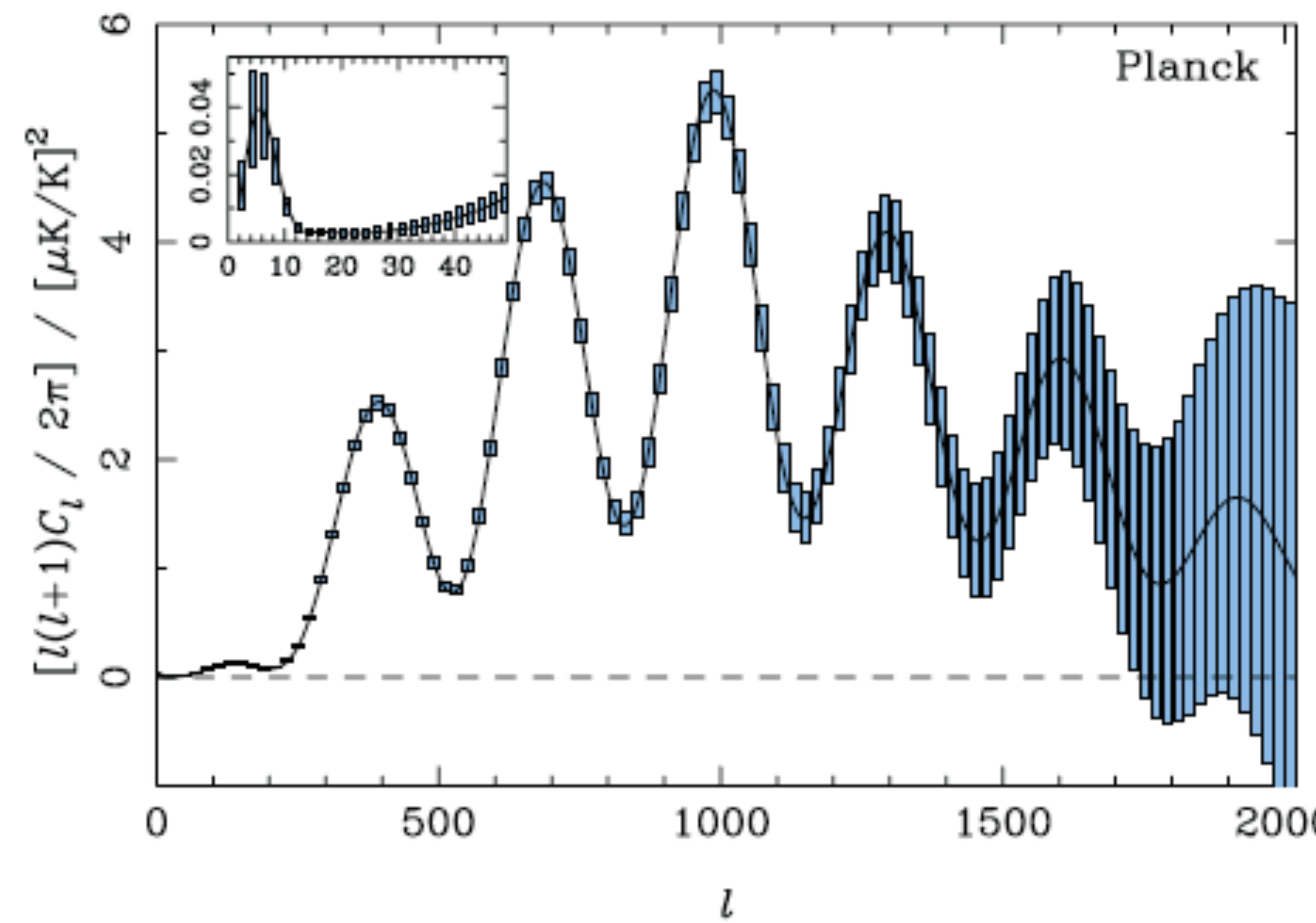
Planck: Expected $C_l^{Temperature}$

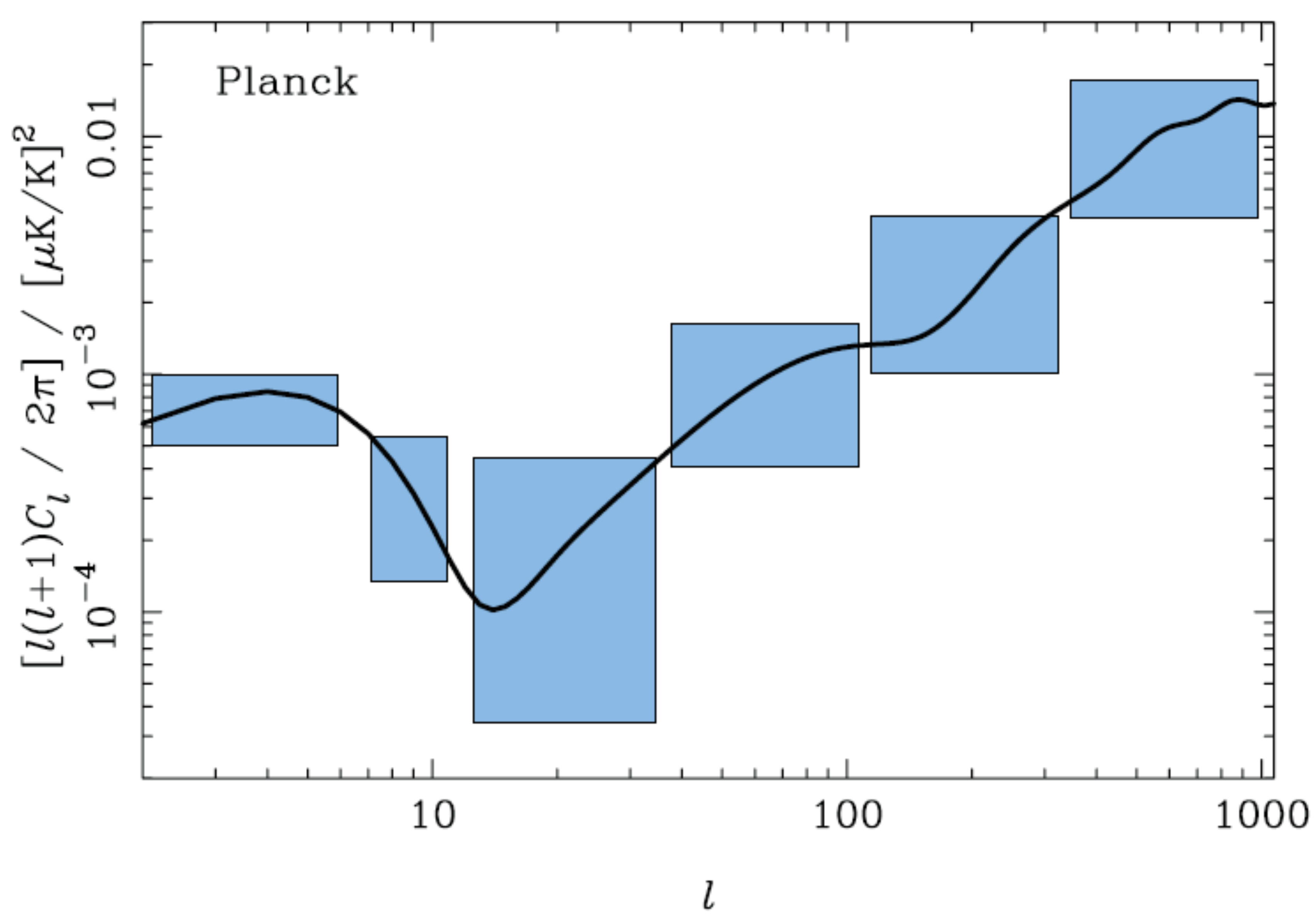


- WMAP: l~1000 => Planck: l~3000

Planck: Expected $C_l^{\mathrm{Polarization}}$

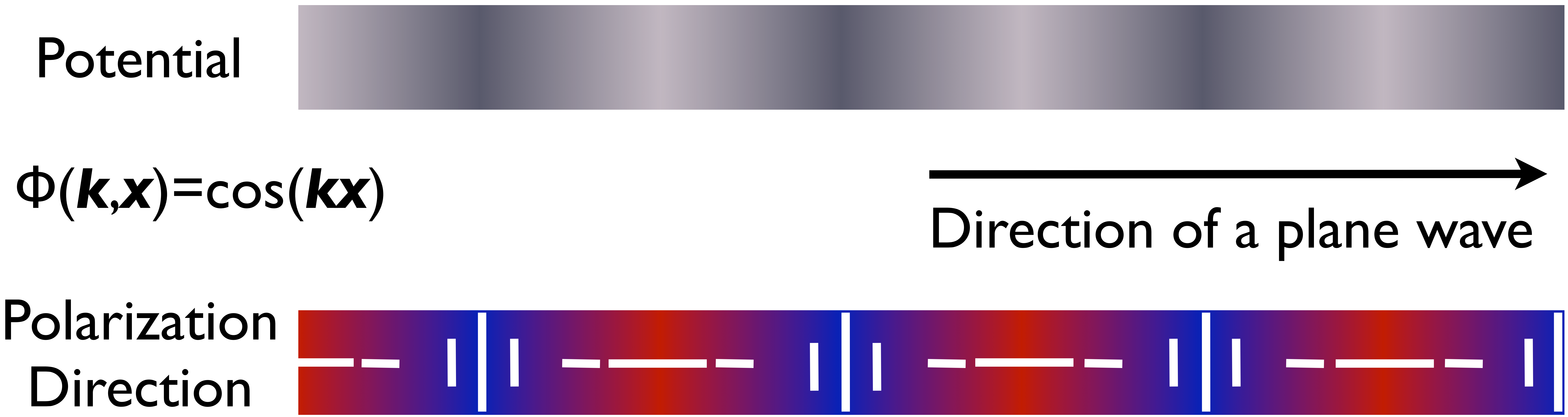






- (Above) E-modes
- (Left) B-modes (r=0.3)

E-mode



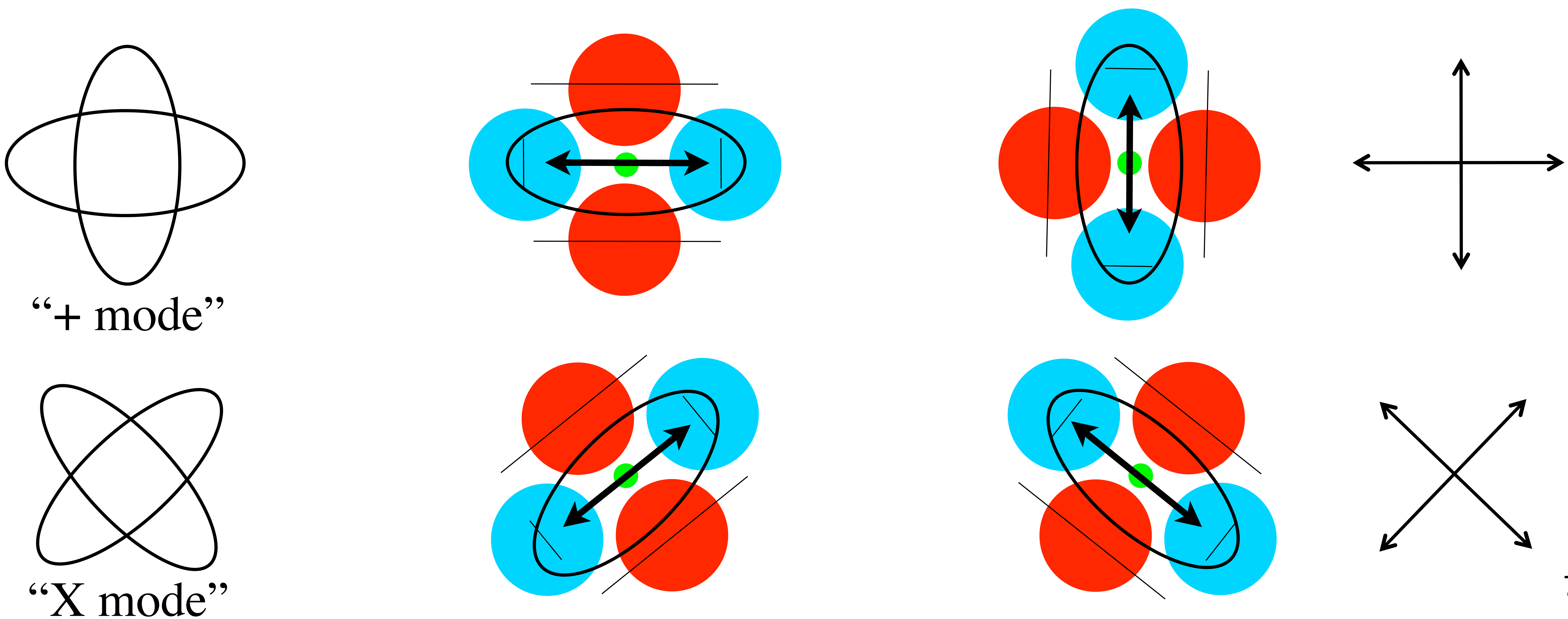
- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

B-mode

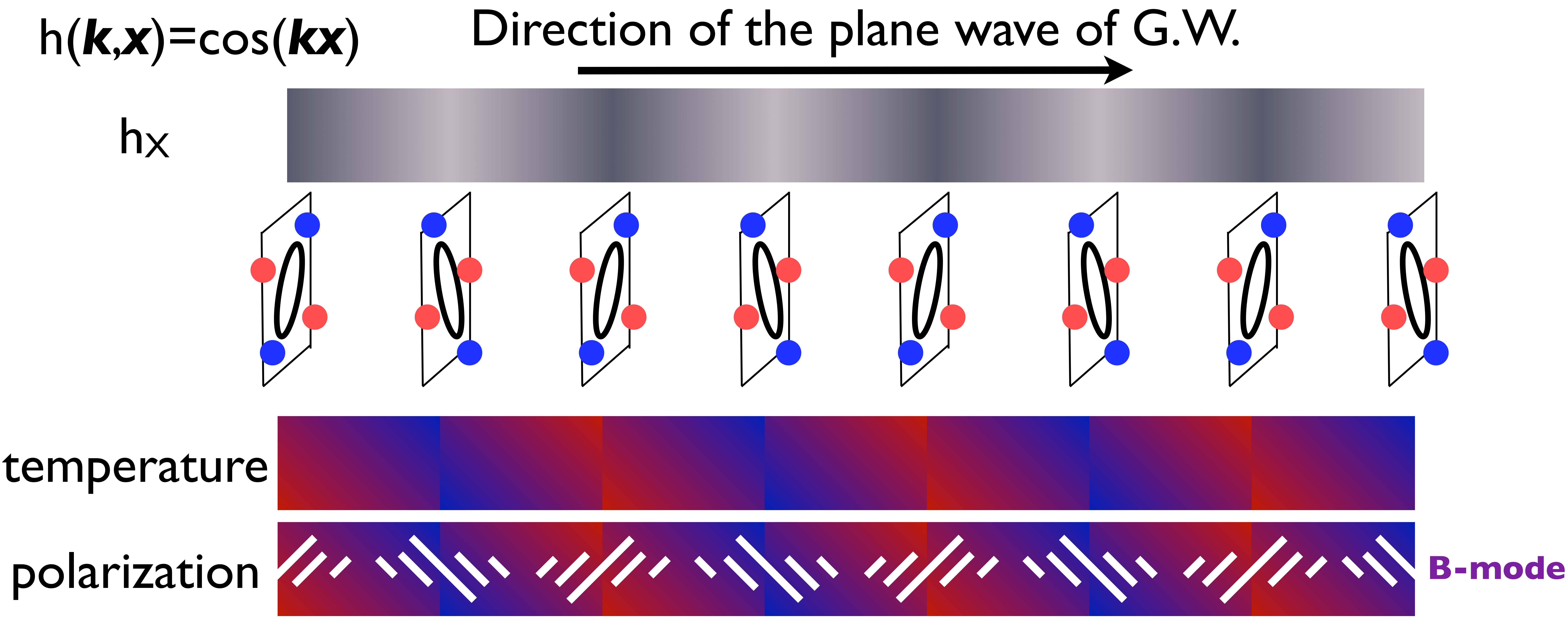
- **B-mode**: the polarization directions are tilted by 45 degrees relative to the direction of the plane wave perturbation.

Gravitational Waves and Quadrupole

- Gravitational waves stretch space with a quadrupole pattern.



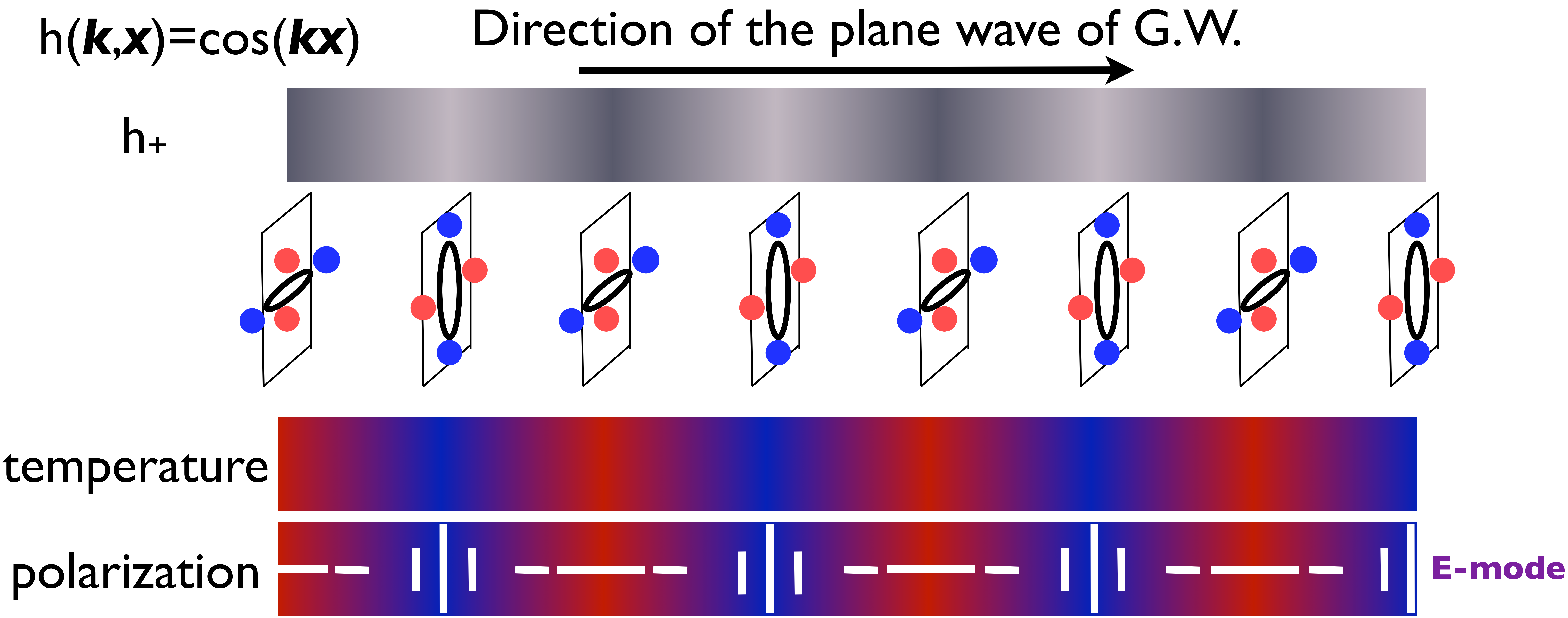
Quadrupole from G.W.



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

Quadrupole from G.W.

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



- E-mode polarization generated by h_+