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

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)

Physics Colloquium, Texas Tech University, April 22, 2010

Cosmology: The Questions

- How much do we understand our Universe?

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  - How old is it?

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  - What shape does it take?

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  - What shape does it take?
  - What is it made of?

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"

Night Sky in Optical (~0.5μm)

courtesy University of Arizona

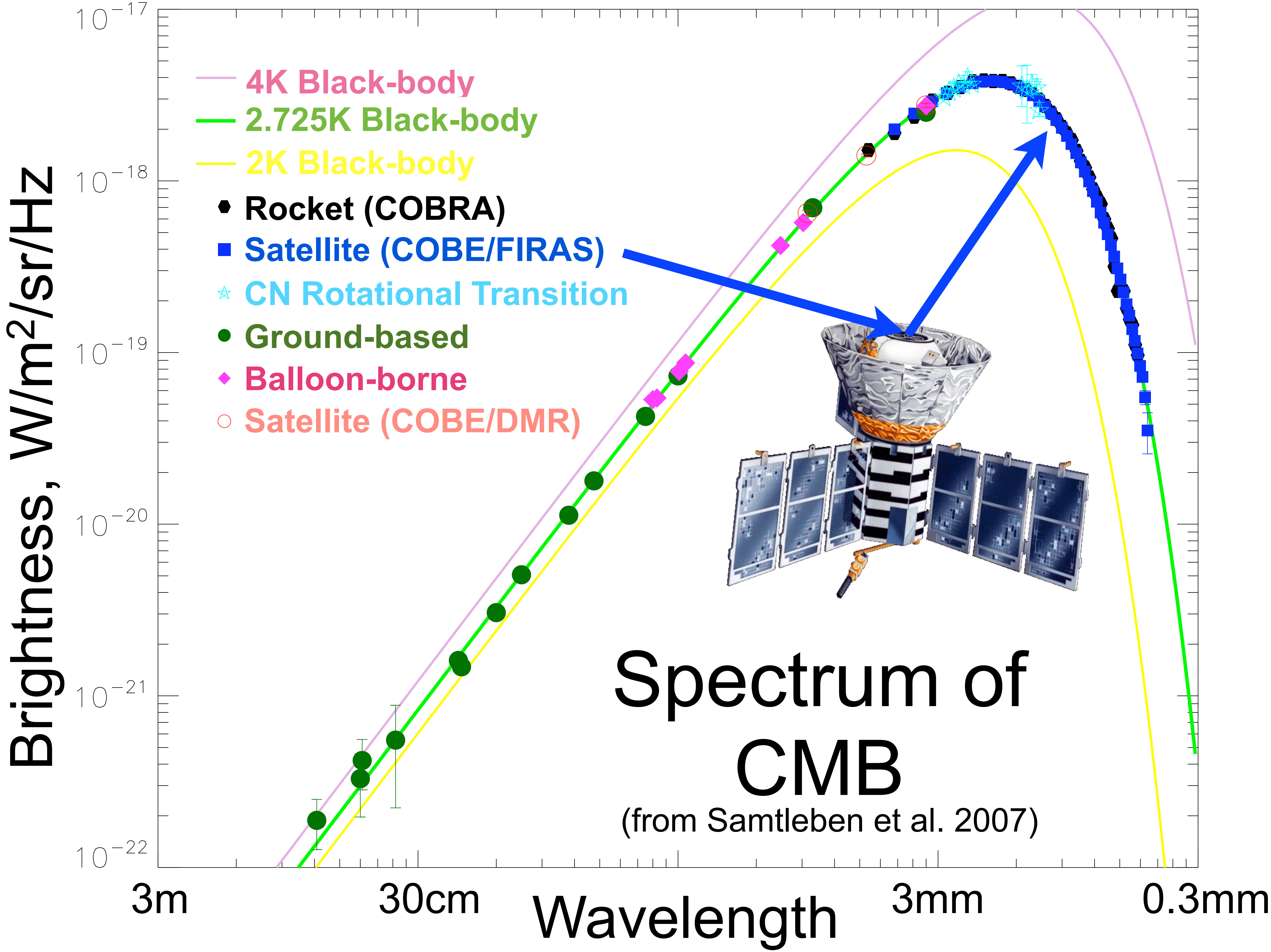
Night Sky in Microwave (~1mm)

courtesy University of Arizona

Night Sky in Microwave (~1mm)

T_{today}=2.725K

COBE Satellite, 1989-1993



4K Black-body
2.725K Black-body
2K Black-body
Rocket (COBRA)
Satellite (COBE/FIRAS)
CN Rotational Transition
Ground-based
Balloon-borne
Satellite (COBE/DMR)
Brightness, W/m²/sr/Hz
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
10⁻²¹
10⁻²²
3m
30cm
3mm
0.3mm
Wavelength
Spectrum of CMB
(from Samtleben et al. 2007)

Arno Penzias & Robert Wilson, 1965

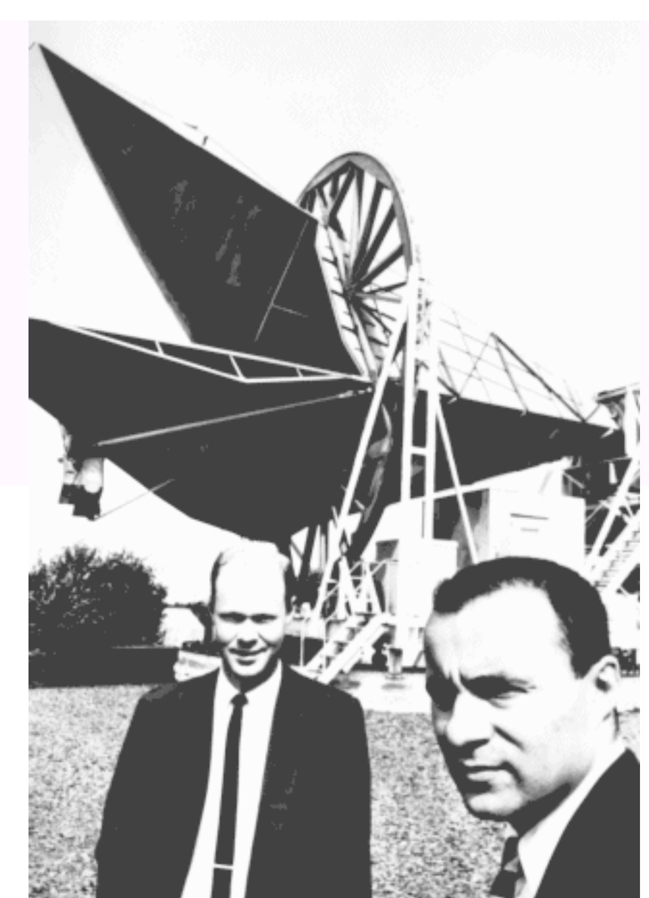
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

- **Isotropic**
- **Unpolarized**

A. A. PENZIAS
R. W. WILSON

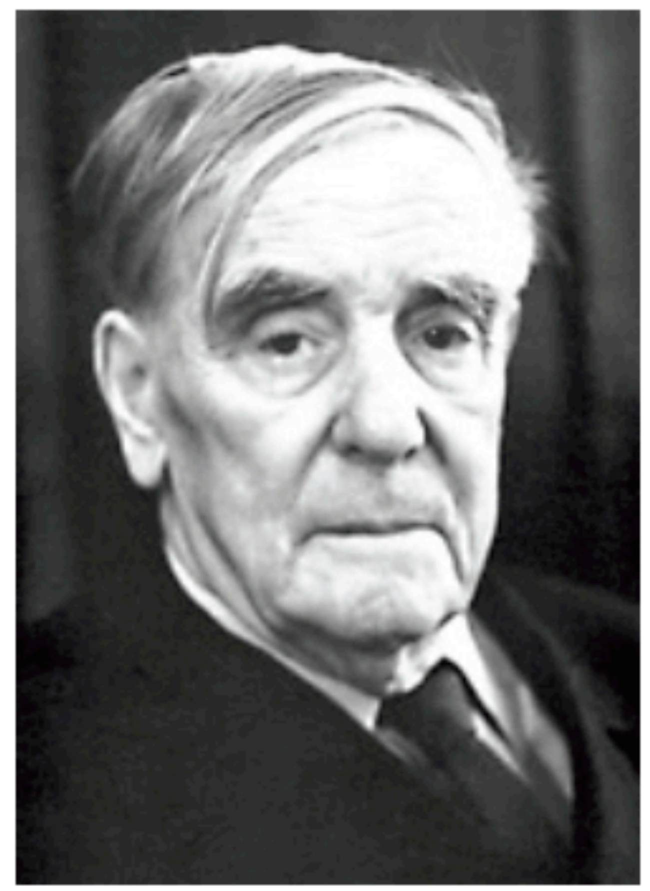
May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

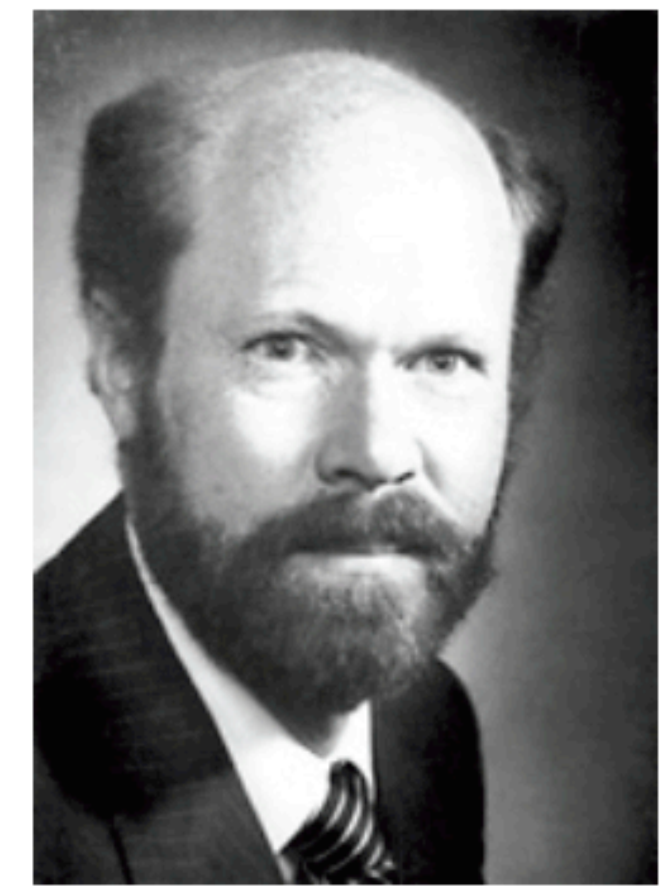


The Nobel Prize in Physics 1978

"for his basic inventions and discoveries in the area of low-temperature physics"

"For their discovery of cosmic microwave background radition"





Pyotr Leonidovich Kapitsa

1/2 of the prize

USSR

Academy of Sciences
Moscow, USSR

b. 1894
d. 1984

Arno Allan Penzias

1/4 of the prize

USA

Bell Laboratories
Holmdel, NJ, USA

b. 1933
(in Munich, Germany)

Robert Woodrow Wilson

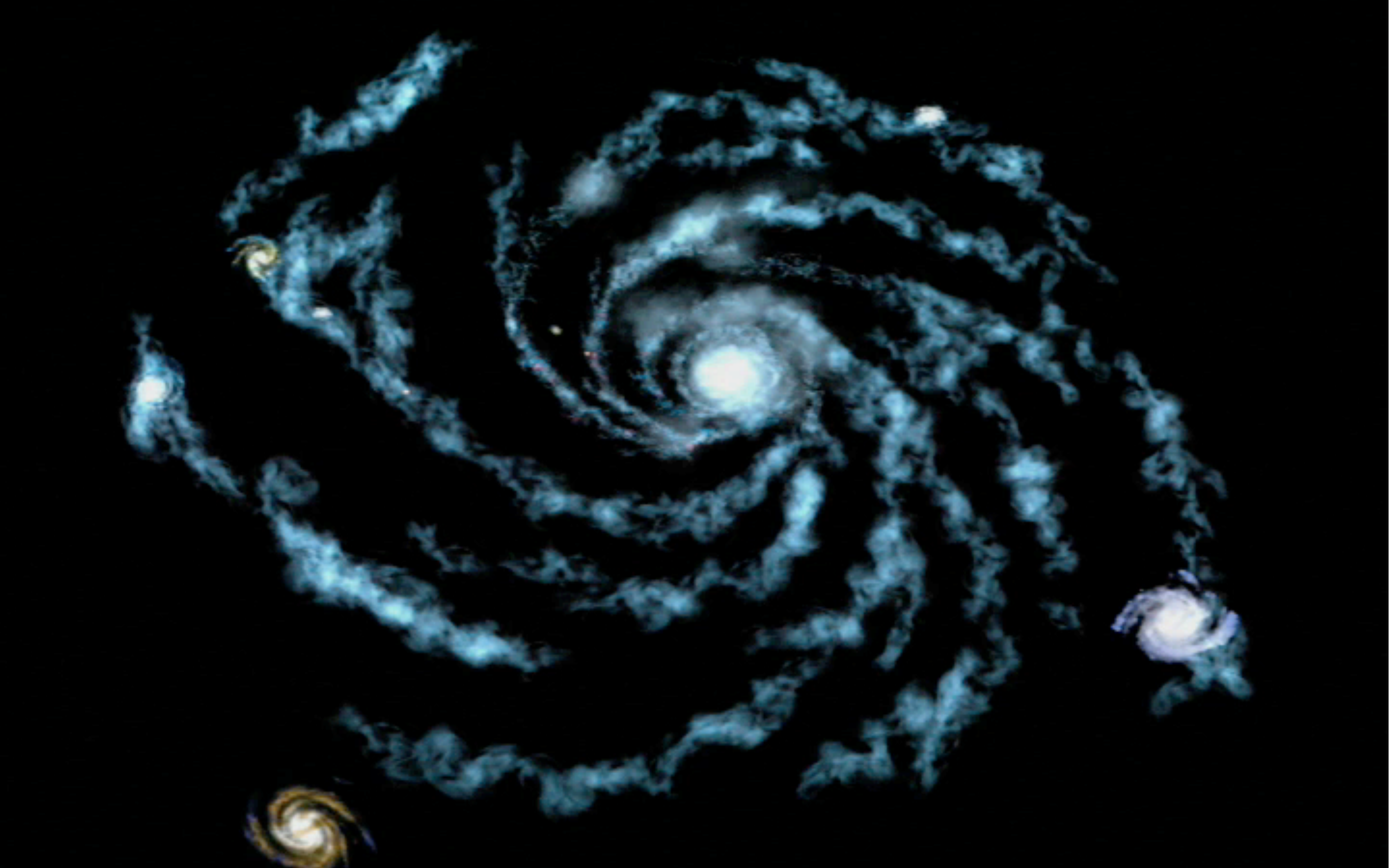
1/4 of the prize

USA

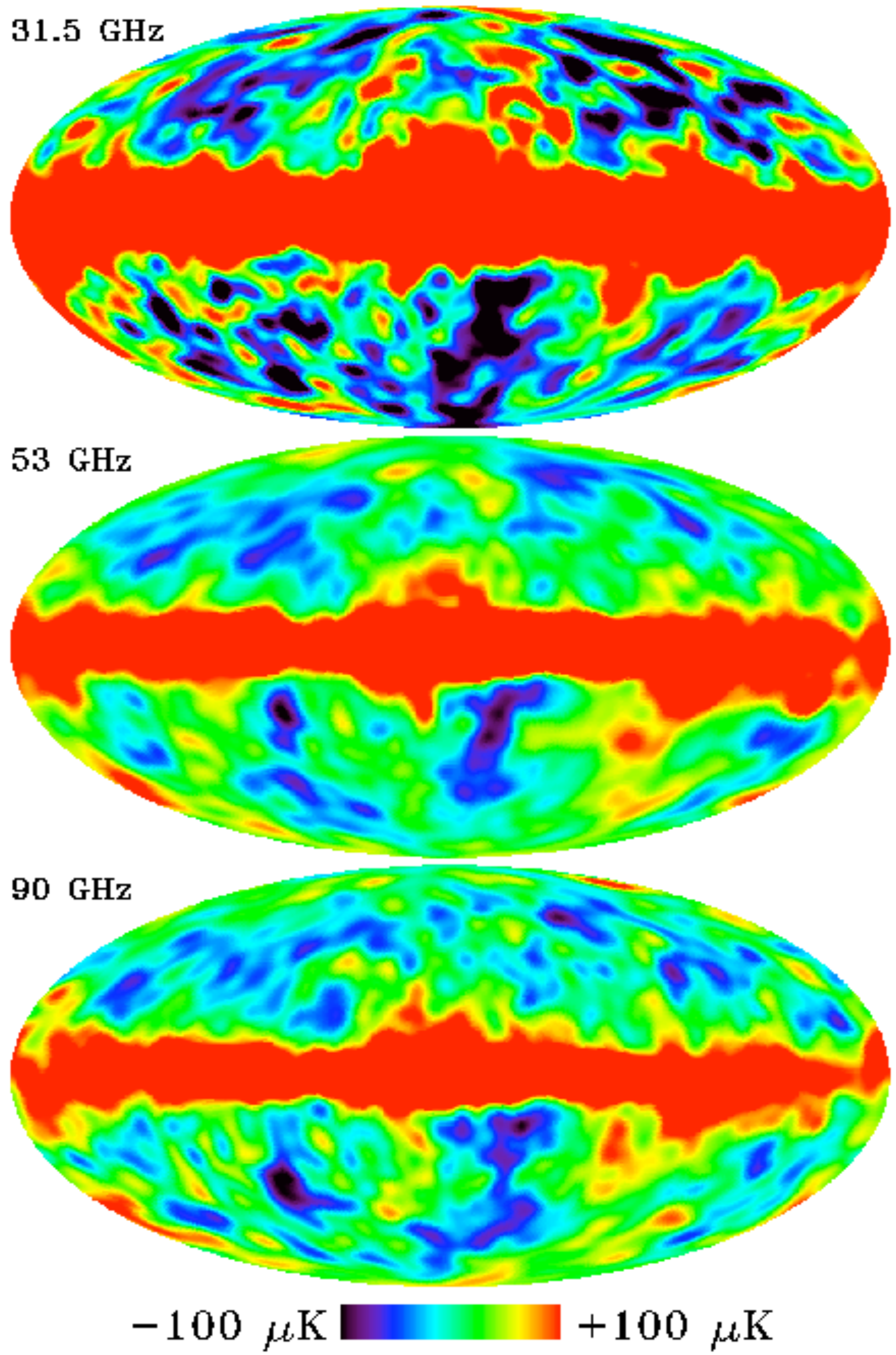
Bell Laboratories
Holmdel, NJ, USA

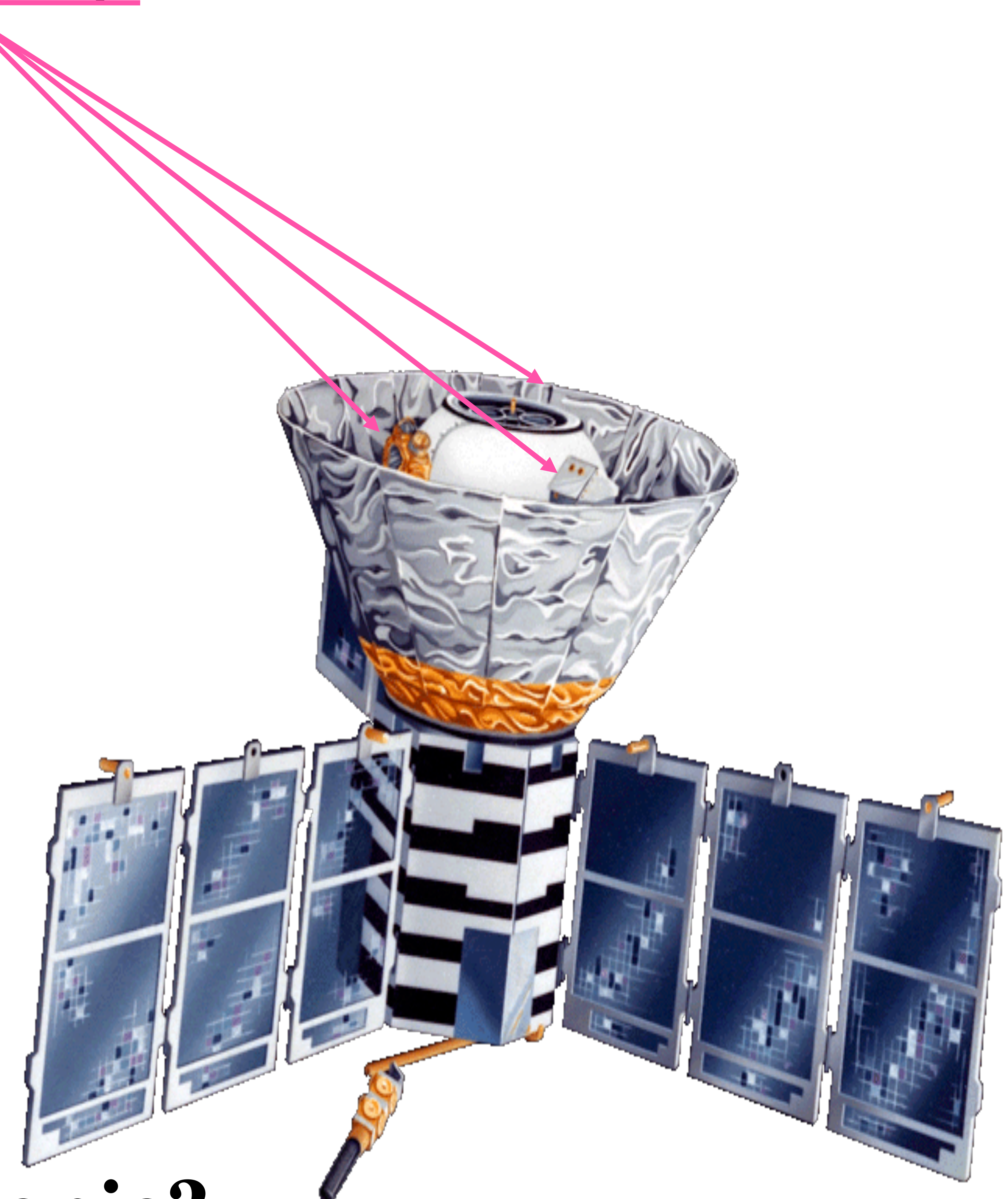
b. 1936

Titles, data and places given above refer to the time of the award.



COBE/DMR, 1992





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

The Nobel Prize in Physics 2006

"For their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"


Photo: NASA

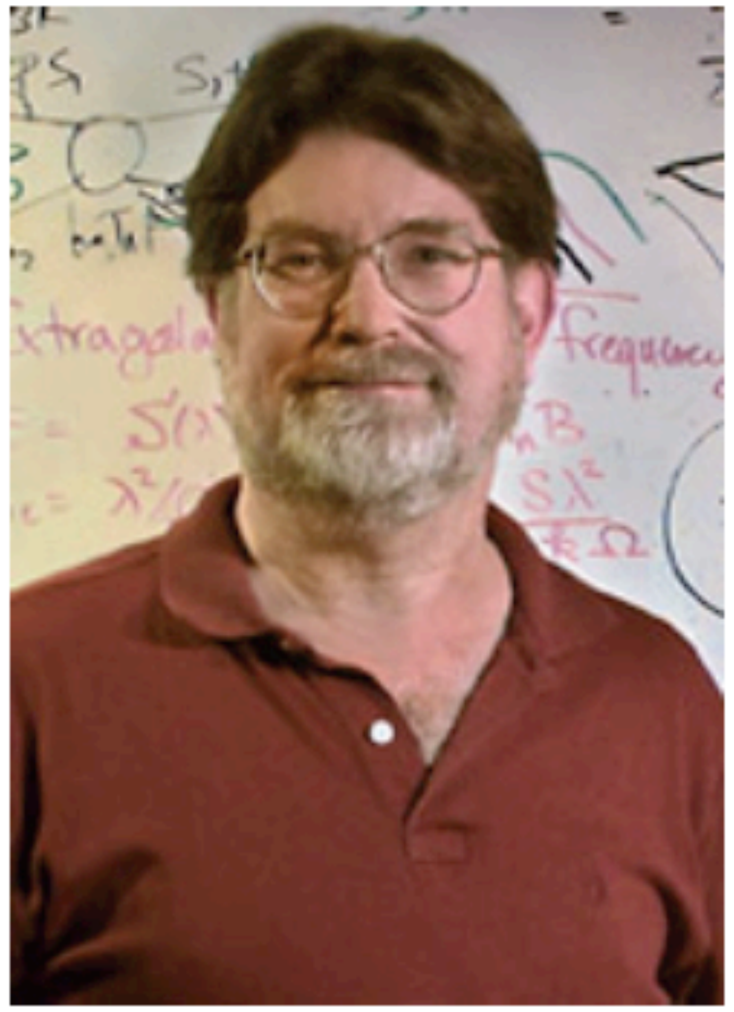
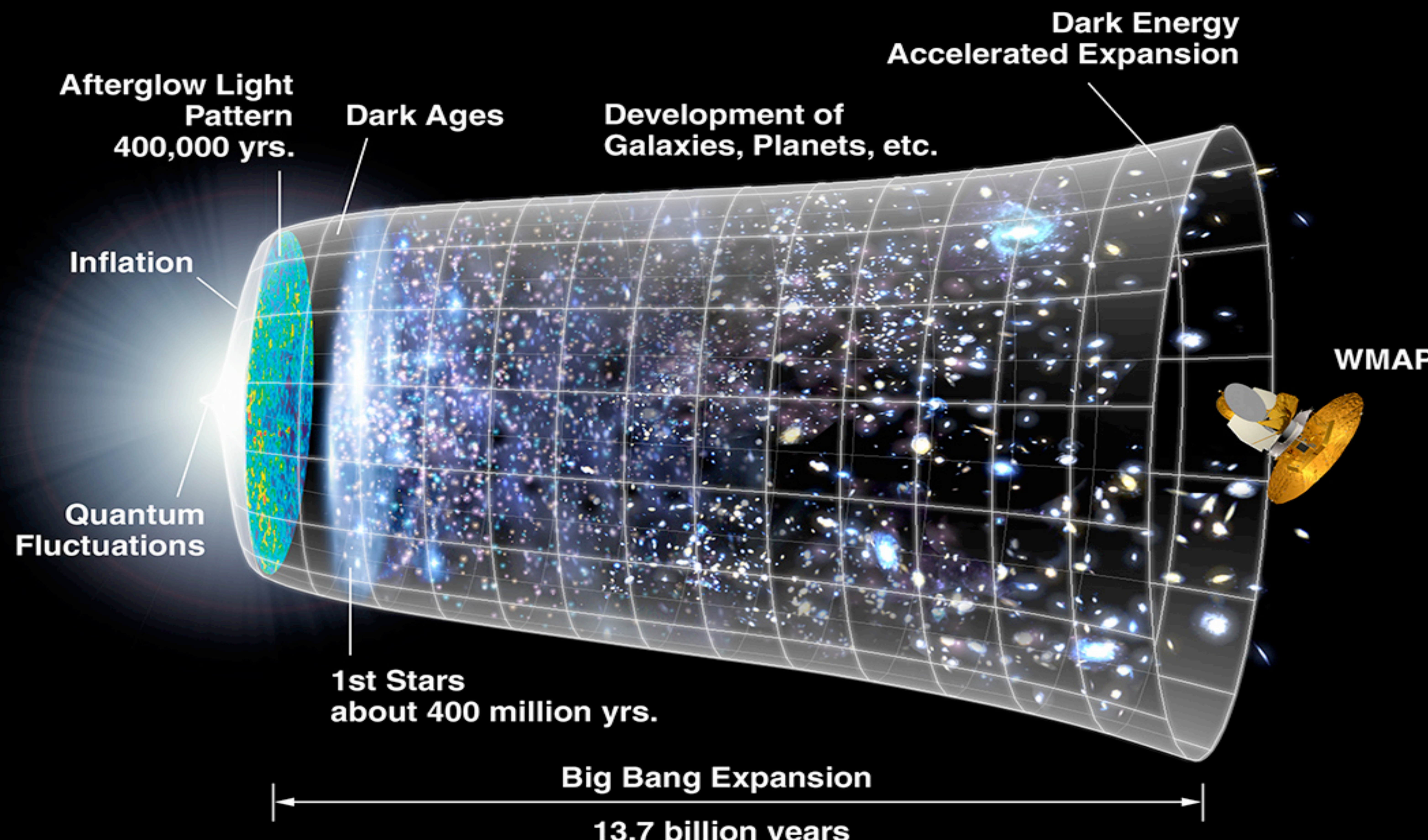


Photo: R. Kaltschmidt/LBNL

John C. Mather	**George F. Smoot**
1/2 of the prize	1/2 of the prize
USA	USA
NASA Goddard Space Flight Center Greenbelt, MD, USA	University of California Berkeley, CA, USA
b. 1946	b. 1945

Titles, data and places given above refer to the time of the award.

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

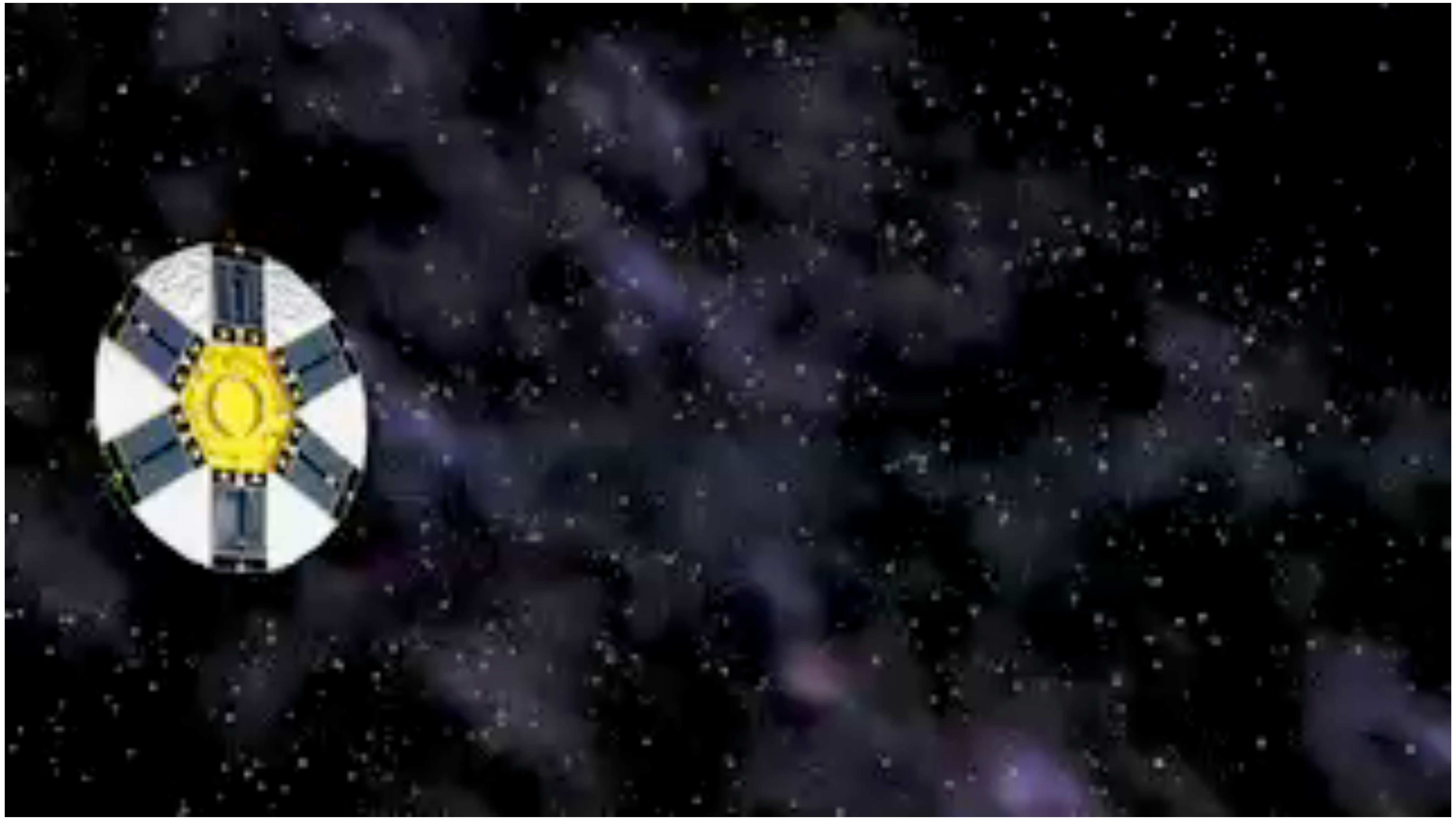
June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release

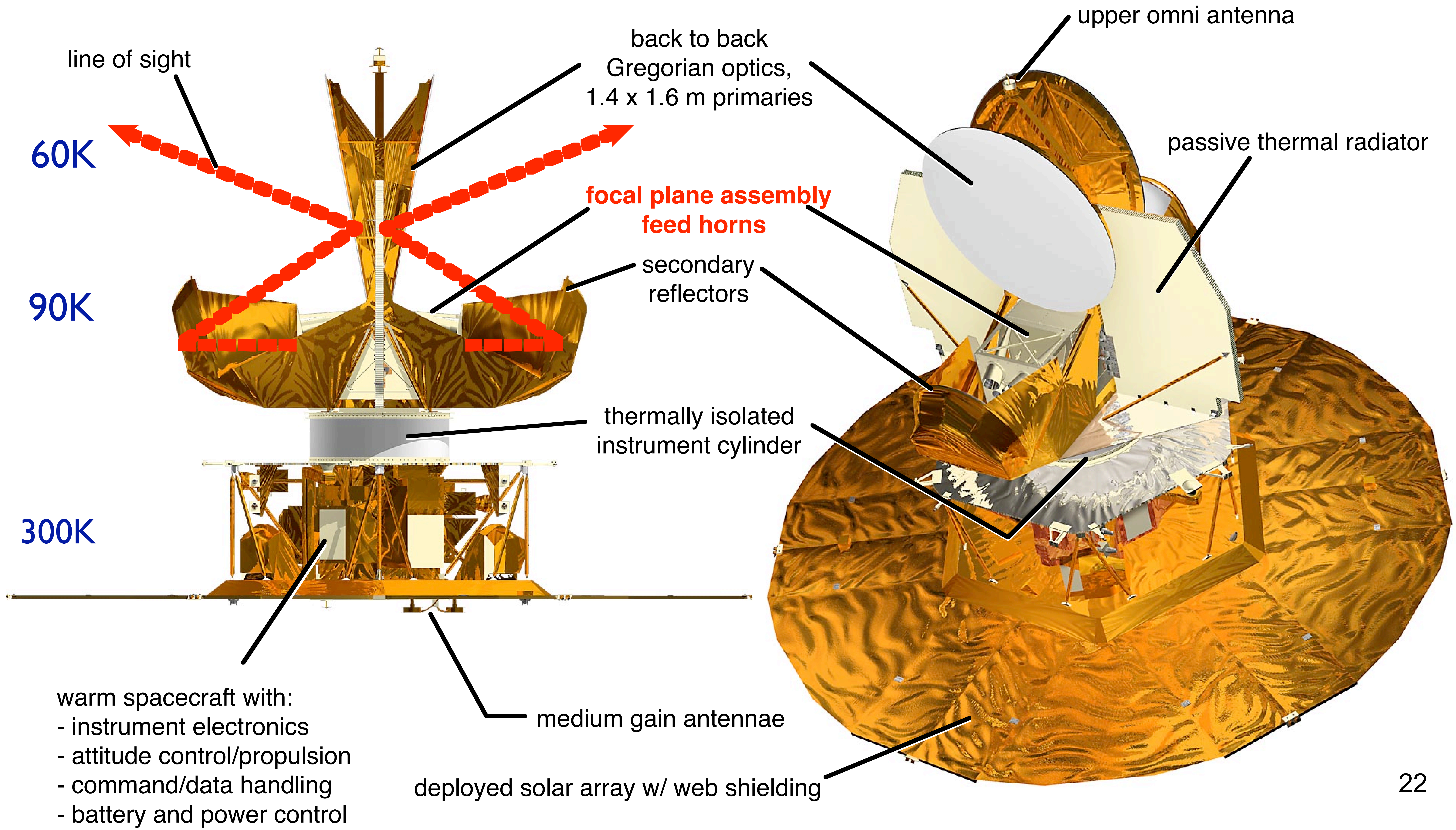
**January 2010:
The seven-year data release**



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

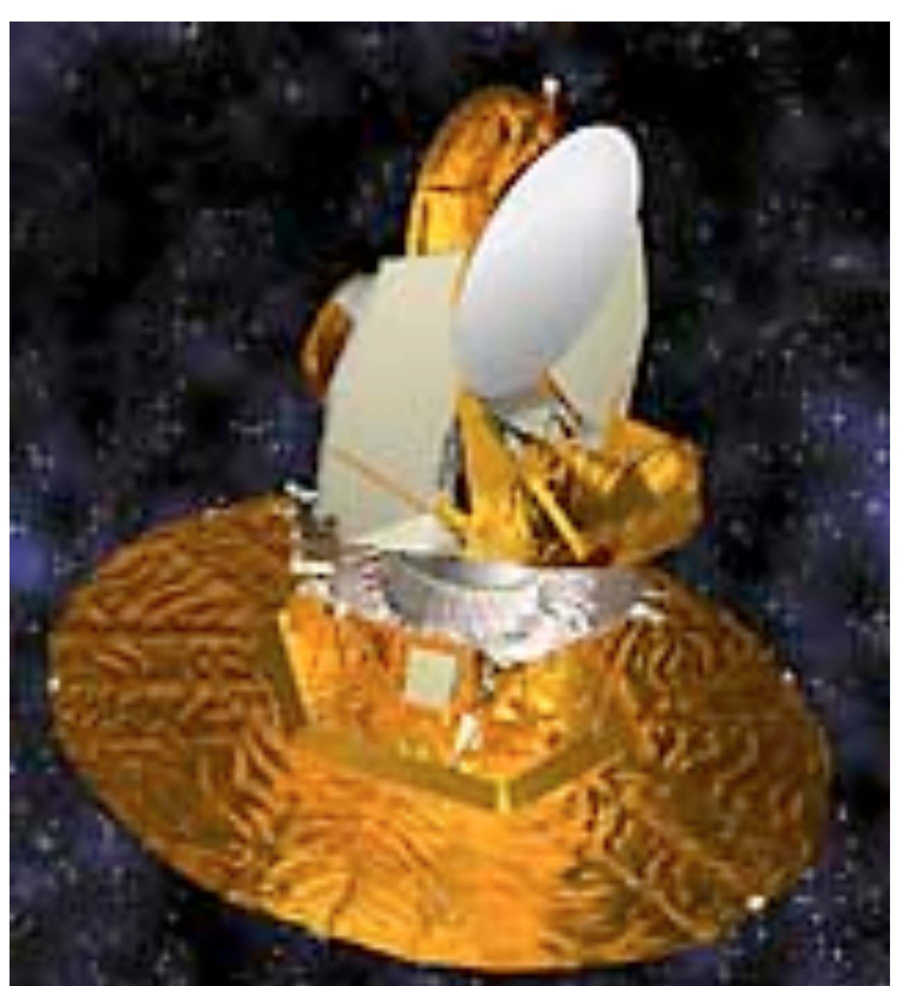
WMAP Spacecraft

Radiative Cooling: No Cryogenic System

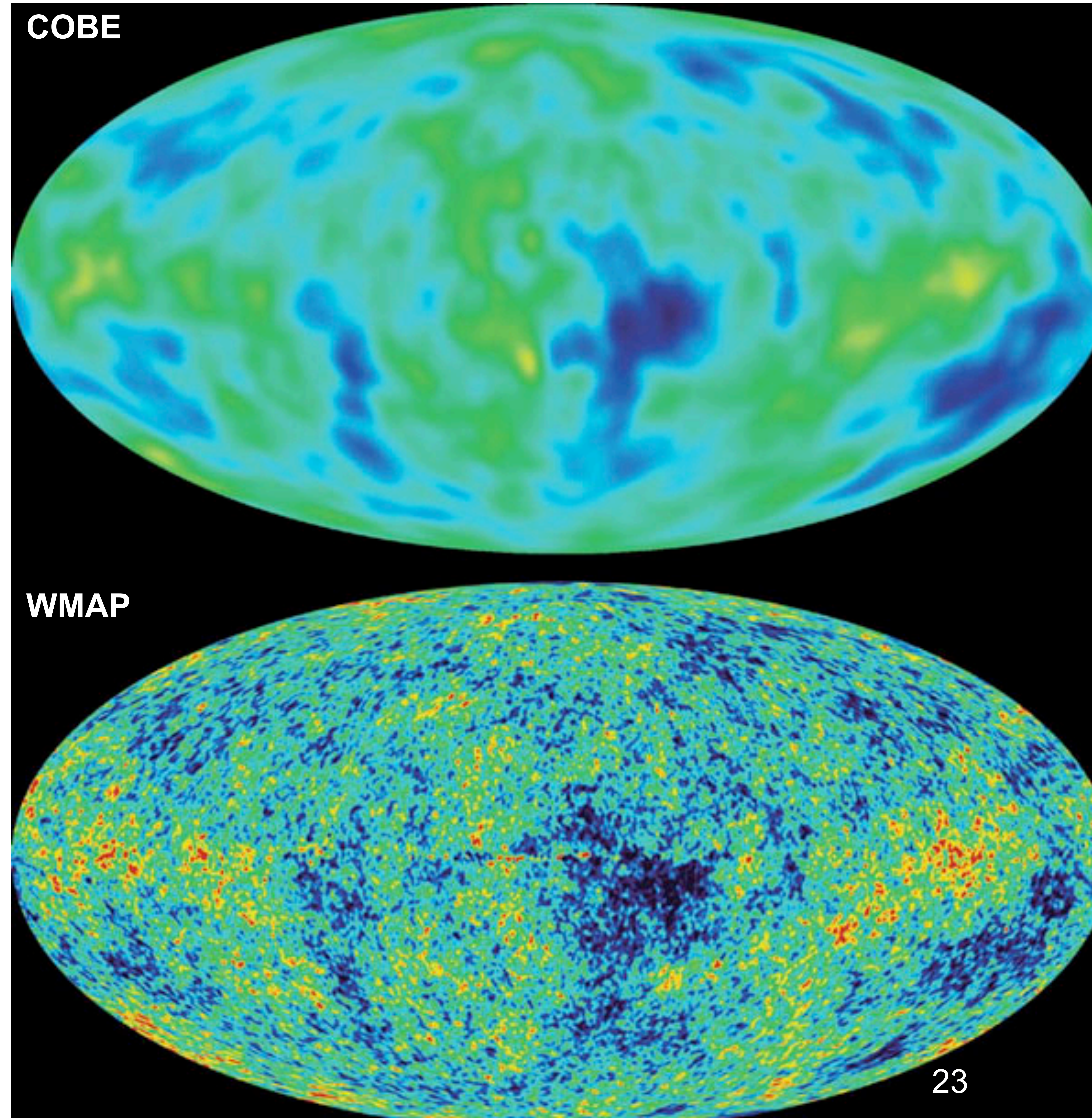


COBE to WMAP (x35 better resolution)

COBE
1989



WMAP
2001



WMAP First Year Science Team

Principal Investigator: ***Charles L. Bennett***

Father of the CMB experiment, ***David Wilkinson***

- WMAP is currently planned to complete 9 years of full-sky survey, ending its mission in ~2010–2011.

WMAP 7-Year Science Team

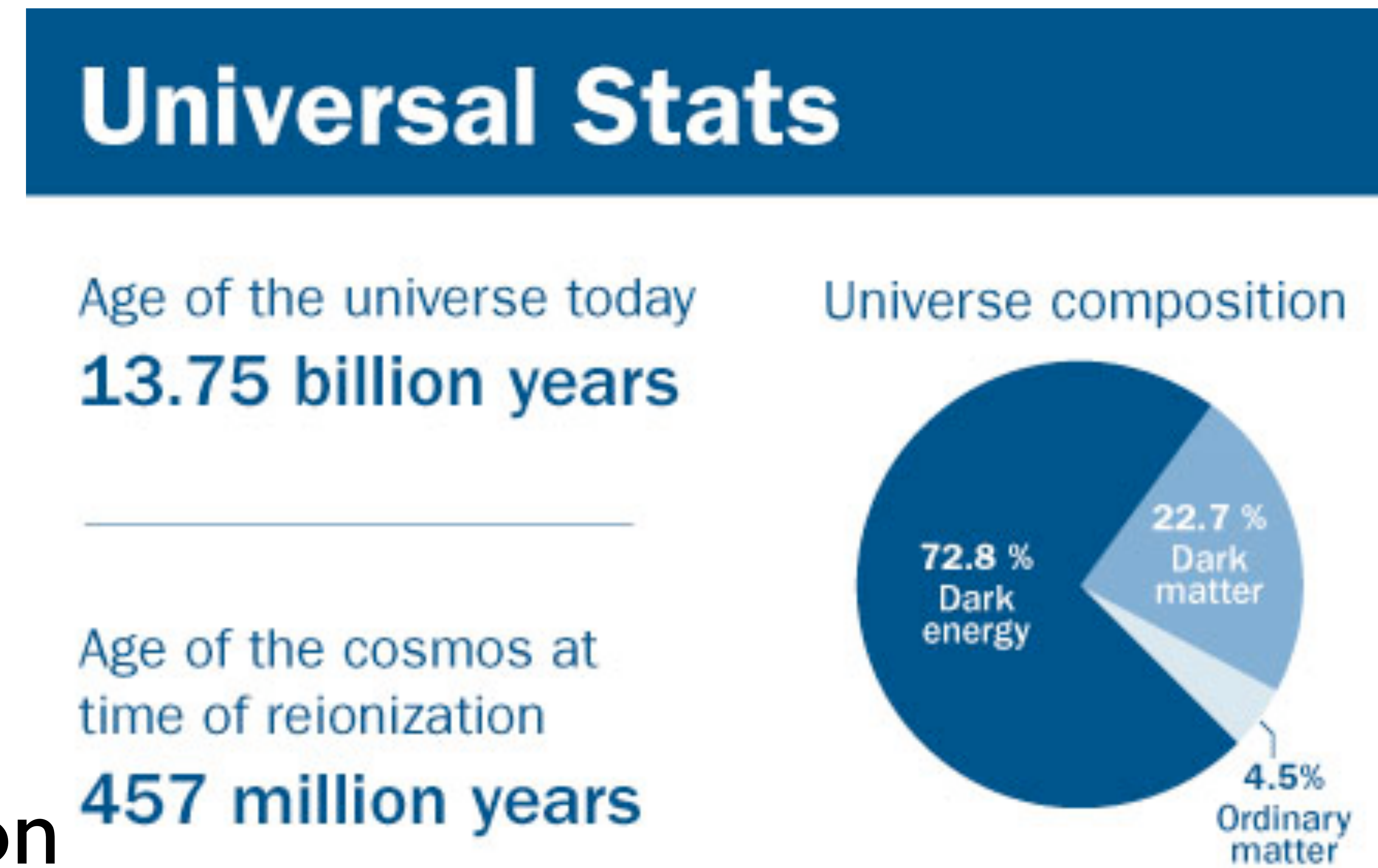
- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright
- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta
- K.M. Smith
- C. Barnes
- R.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

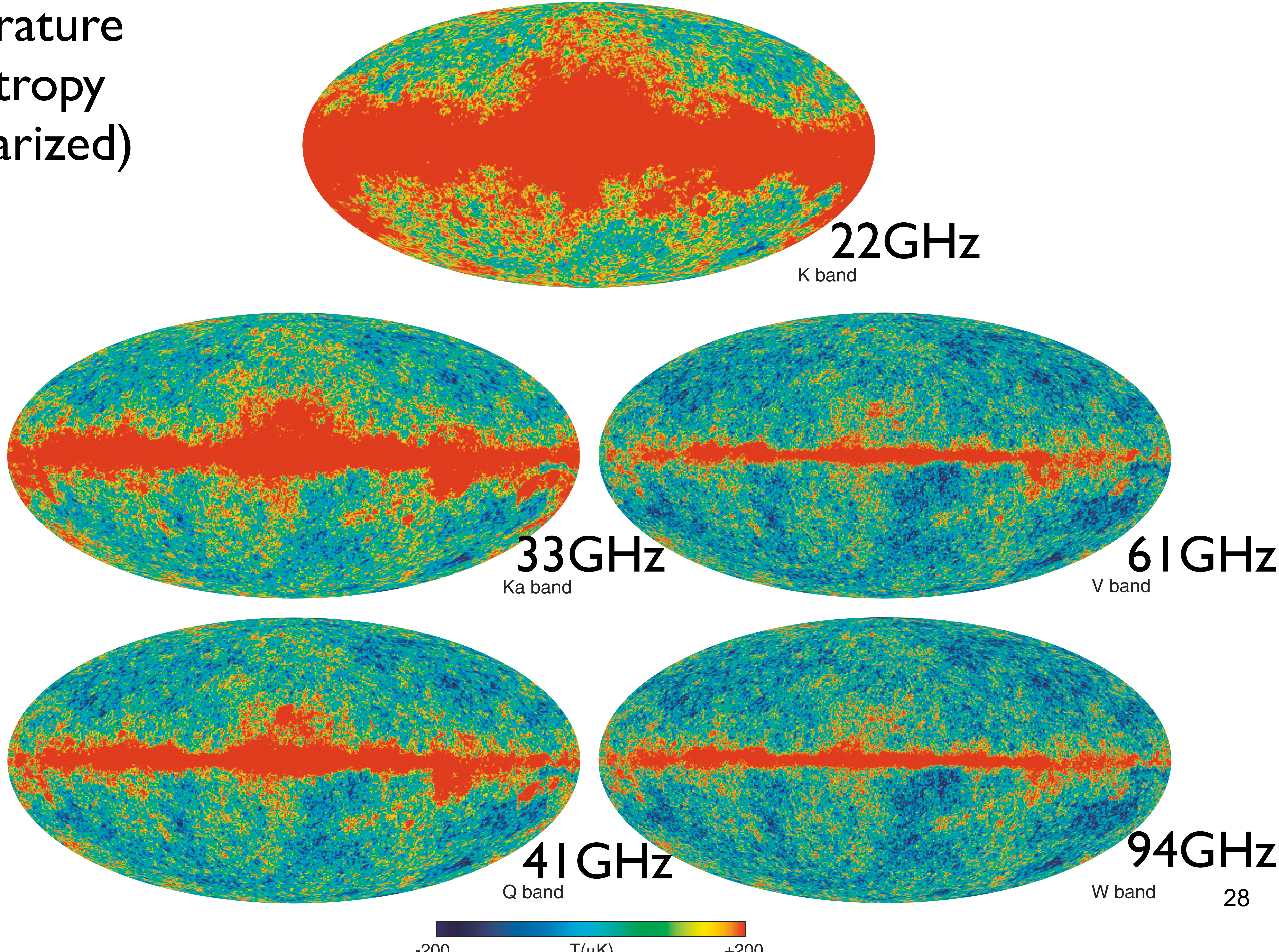
- **Standard Model**
  - H&He = 4.56% (±0.16%)
  - Dark Matter = 27.2% (±1.6%)
  - Dark Energy = 72.8% (±1.6%)
  - H_0=70.4±1.4 km/s/Mpc
  - Age of the Universe = 13.75 billion years (±0.11 billion years)



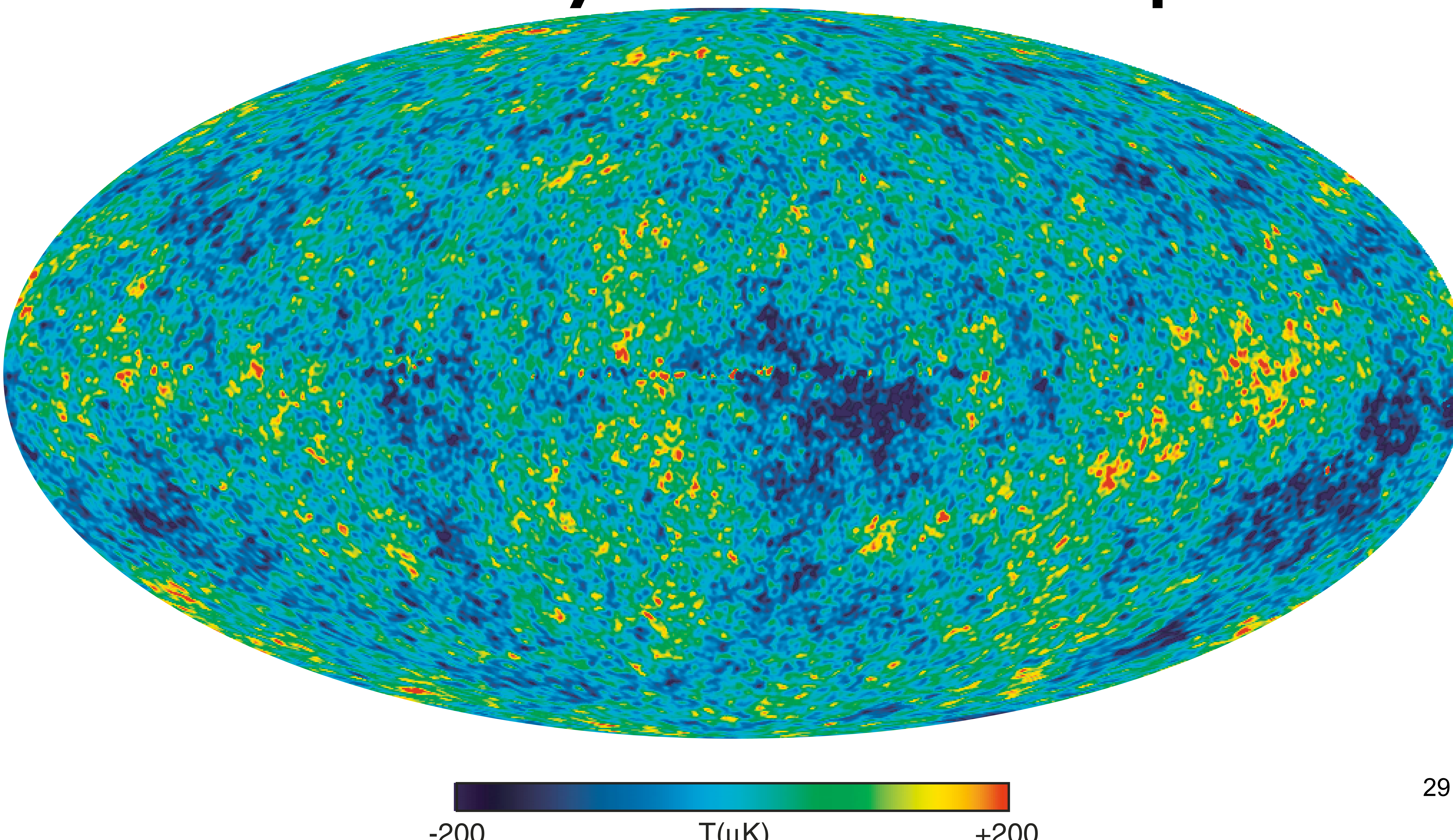
"ScienceNews" article on the WMAP 7-year results

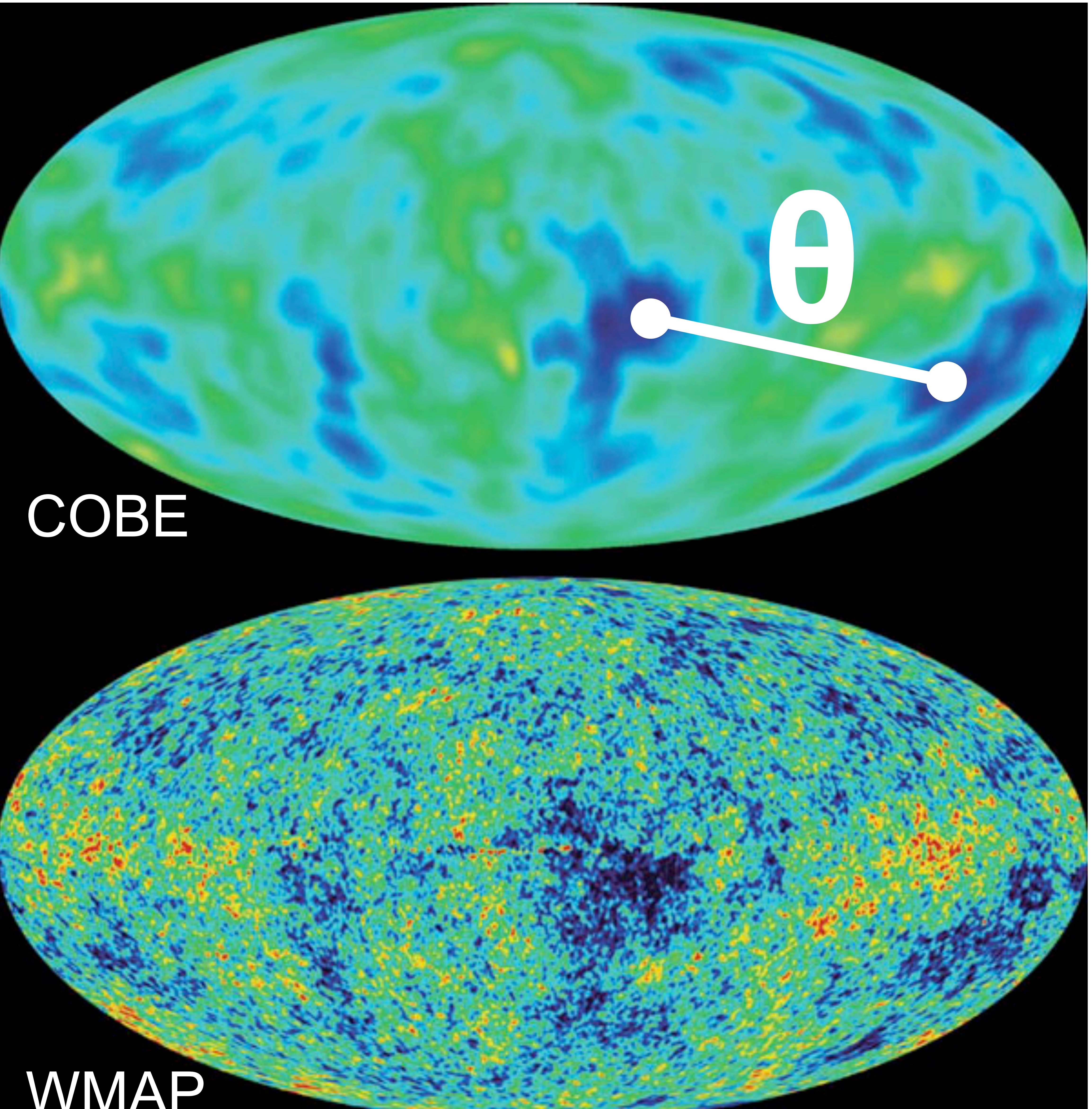
How did we obtain these numbers?

Temperature Anisotropy (Unpolarized)



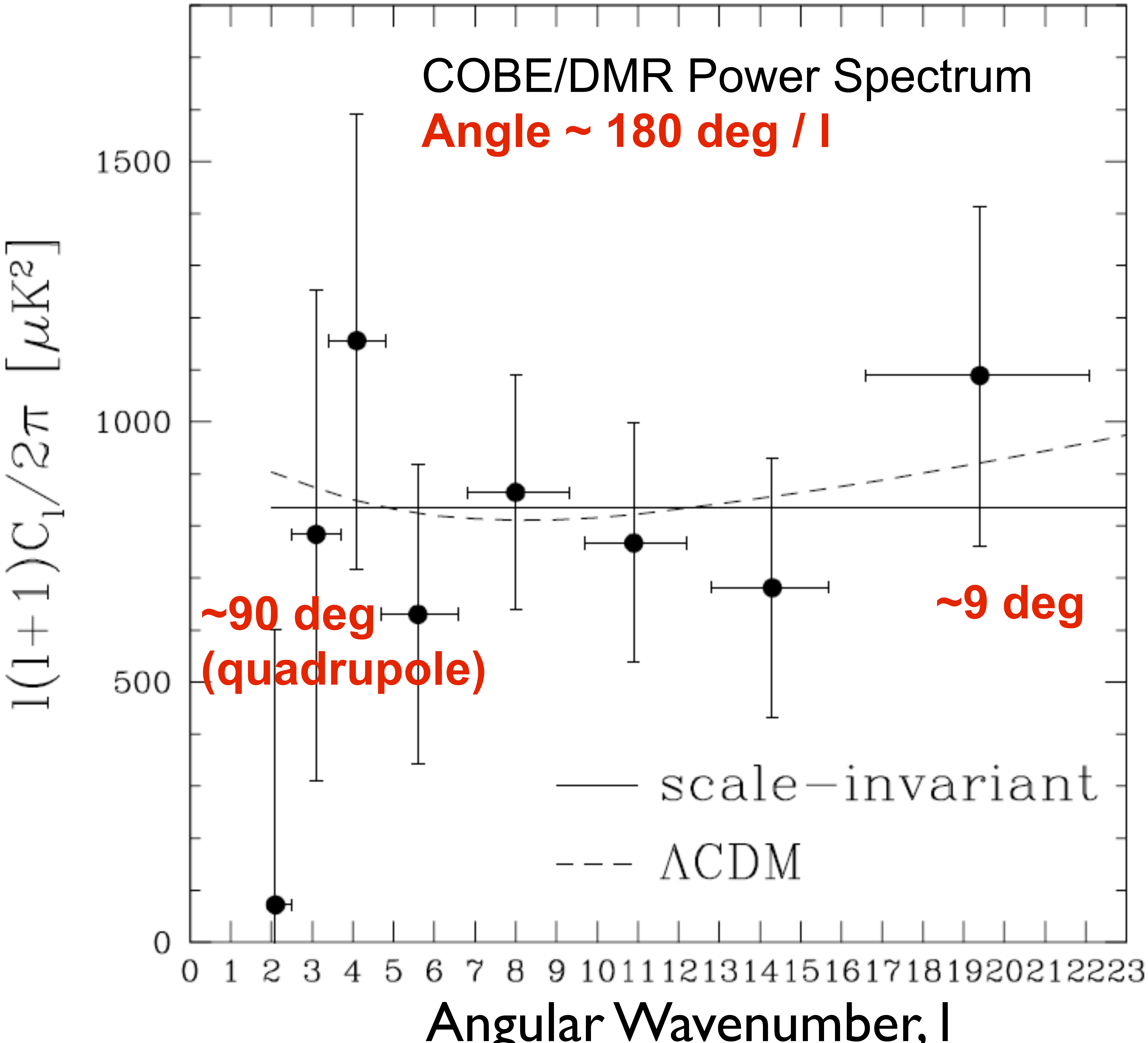
Galaxy-cleaned Map



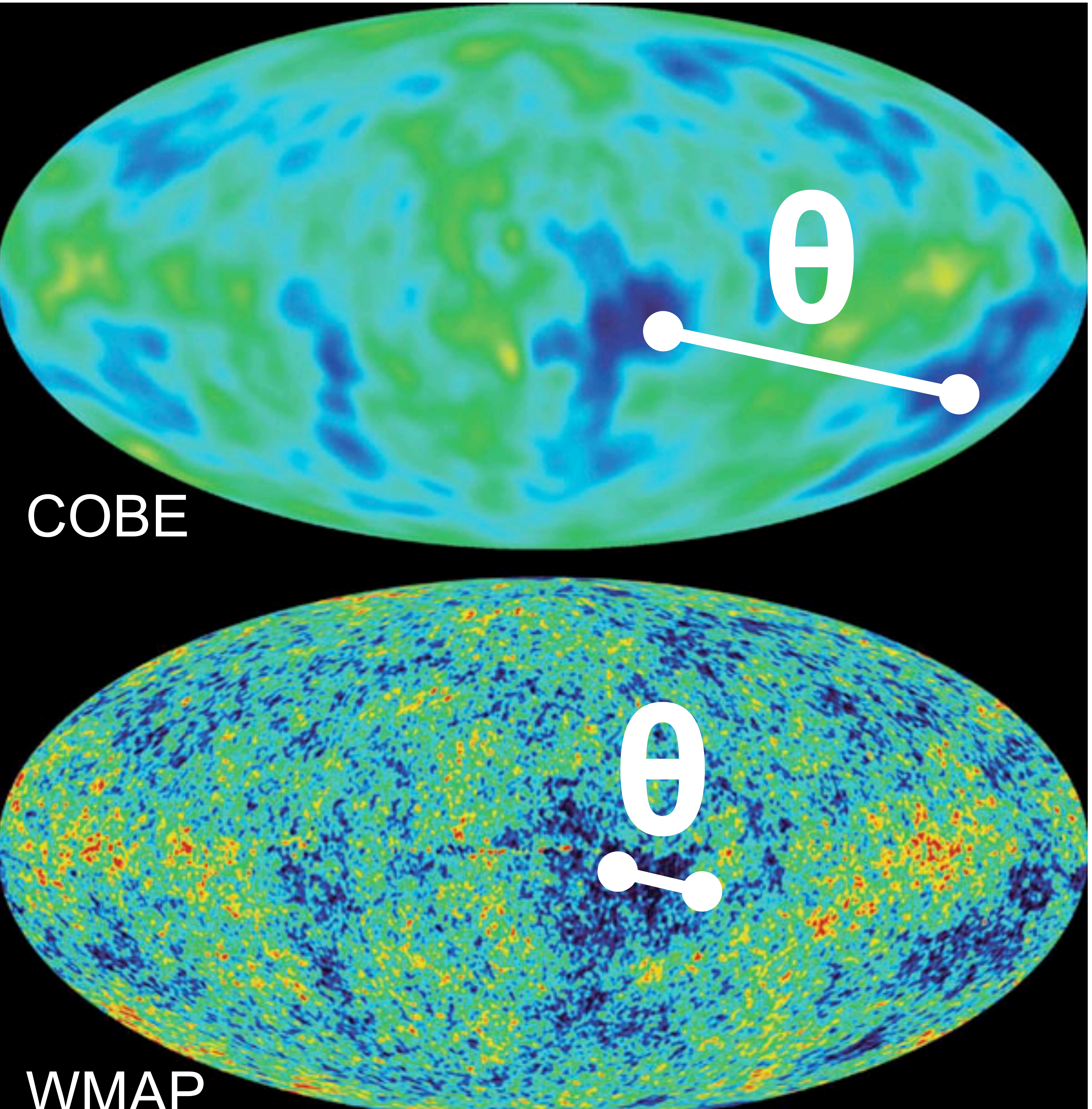


Analysis: 2-point Correlation

- $C(\theta)=(1/4\pi)\sum(2l+1)C_l P_l(\cos\theta)$
- 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?
  - **$l \sim 180$ degrees / θ**



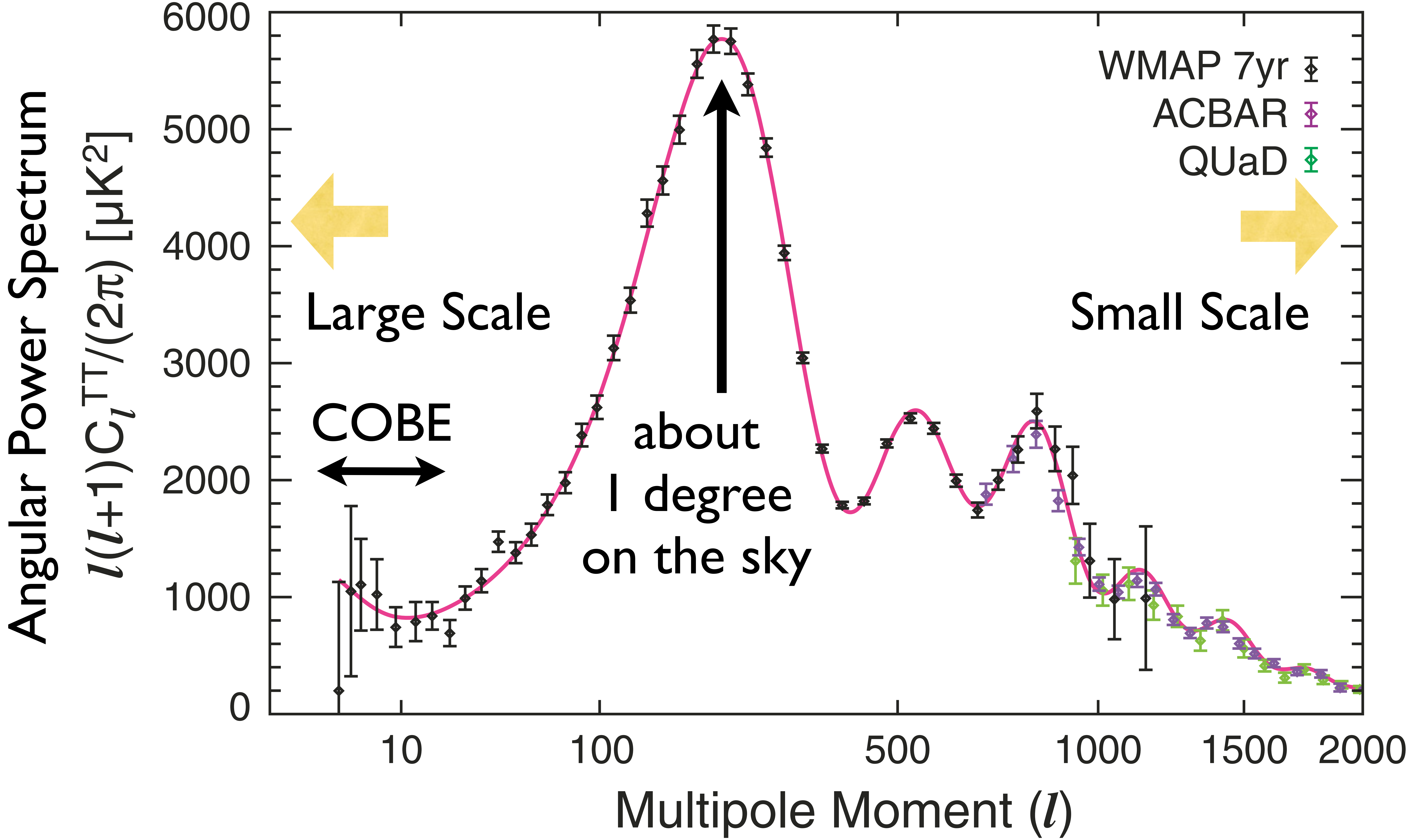
COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
l(l+1)C_l/2π [μK²]
Angular Wavenumber, l
0
500
1000
1500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23



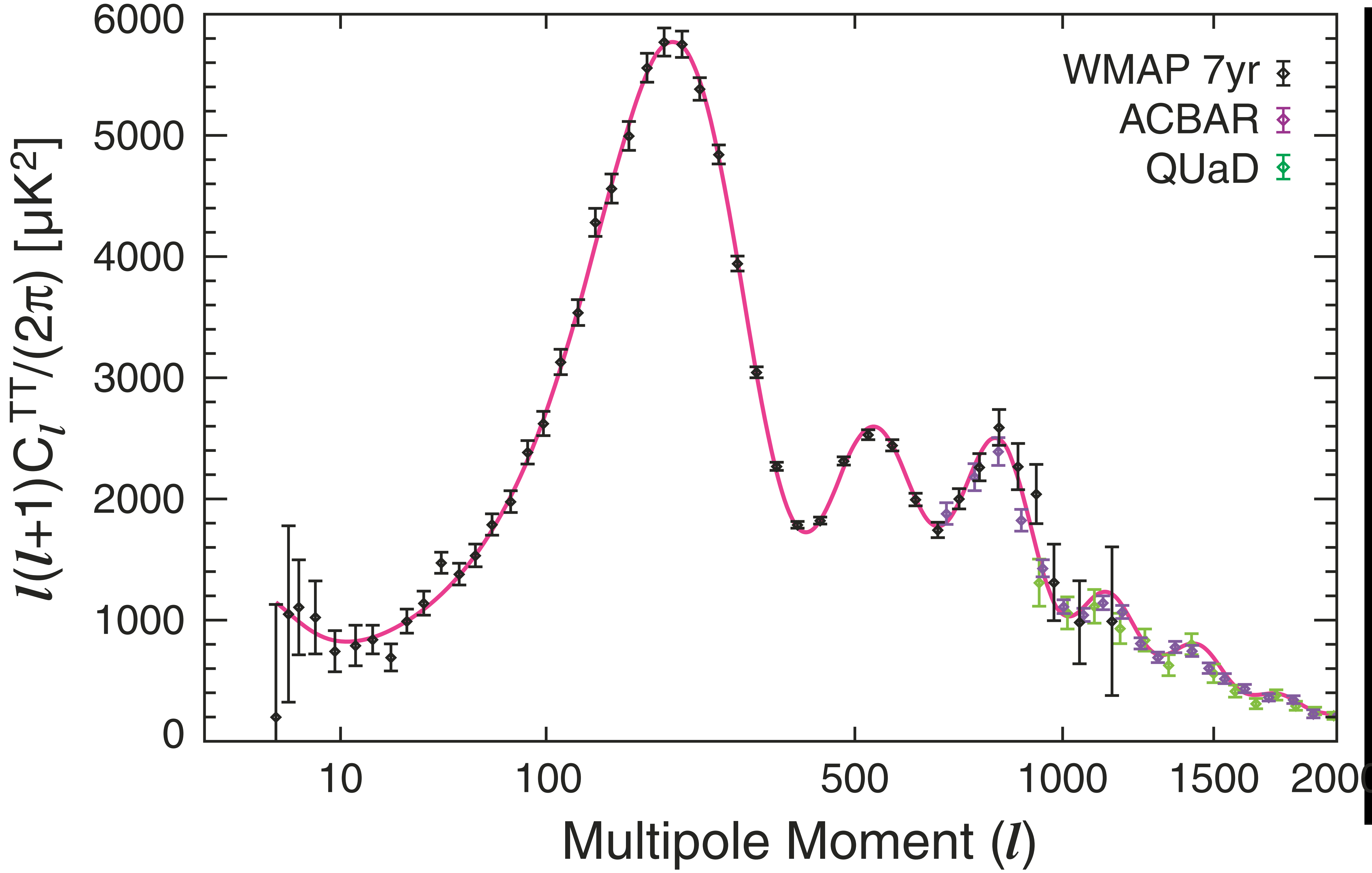
COBE To WMAP

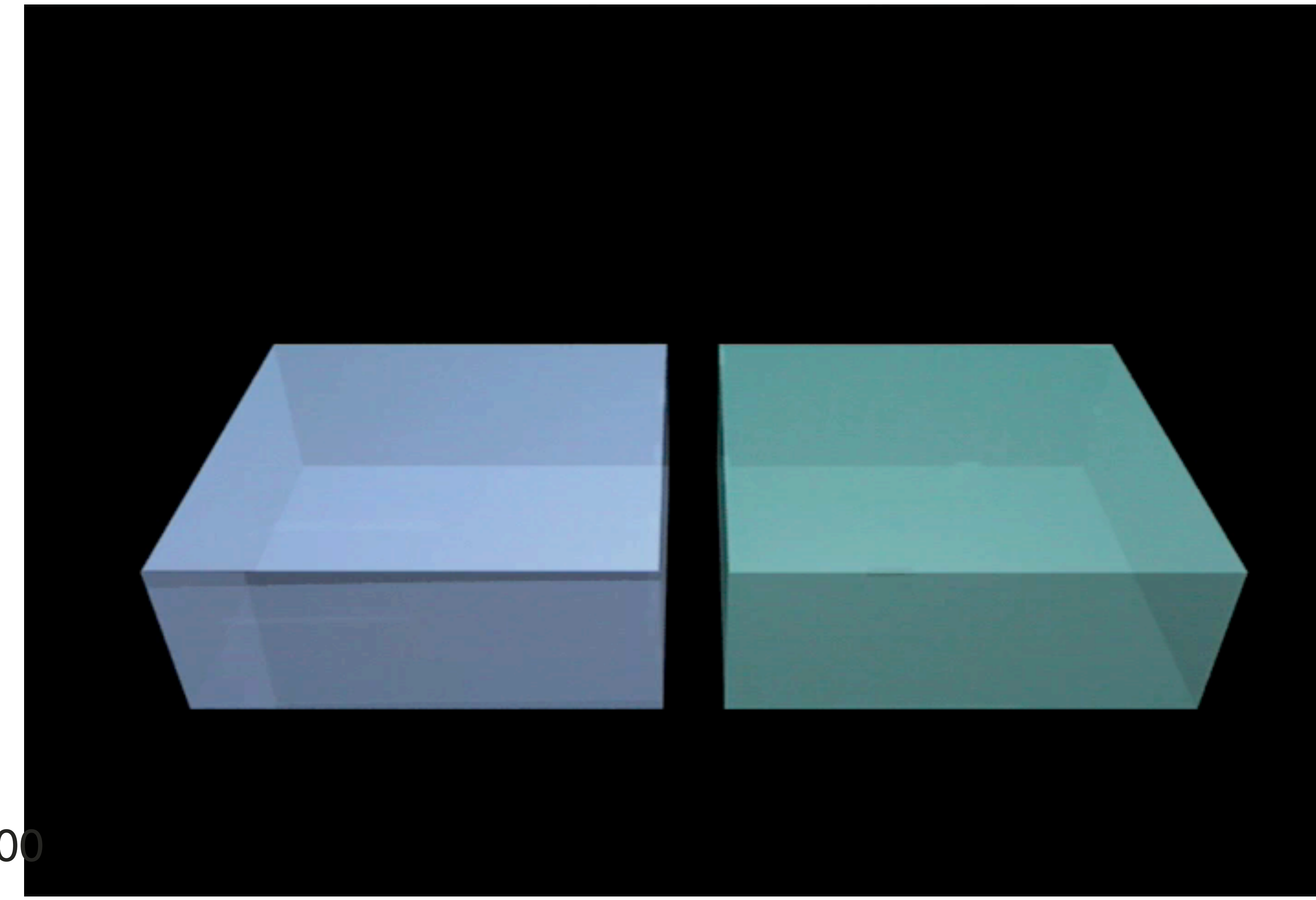
- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP Power Spectrum



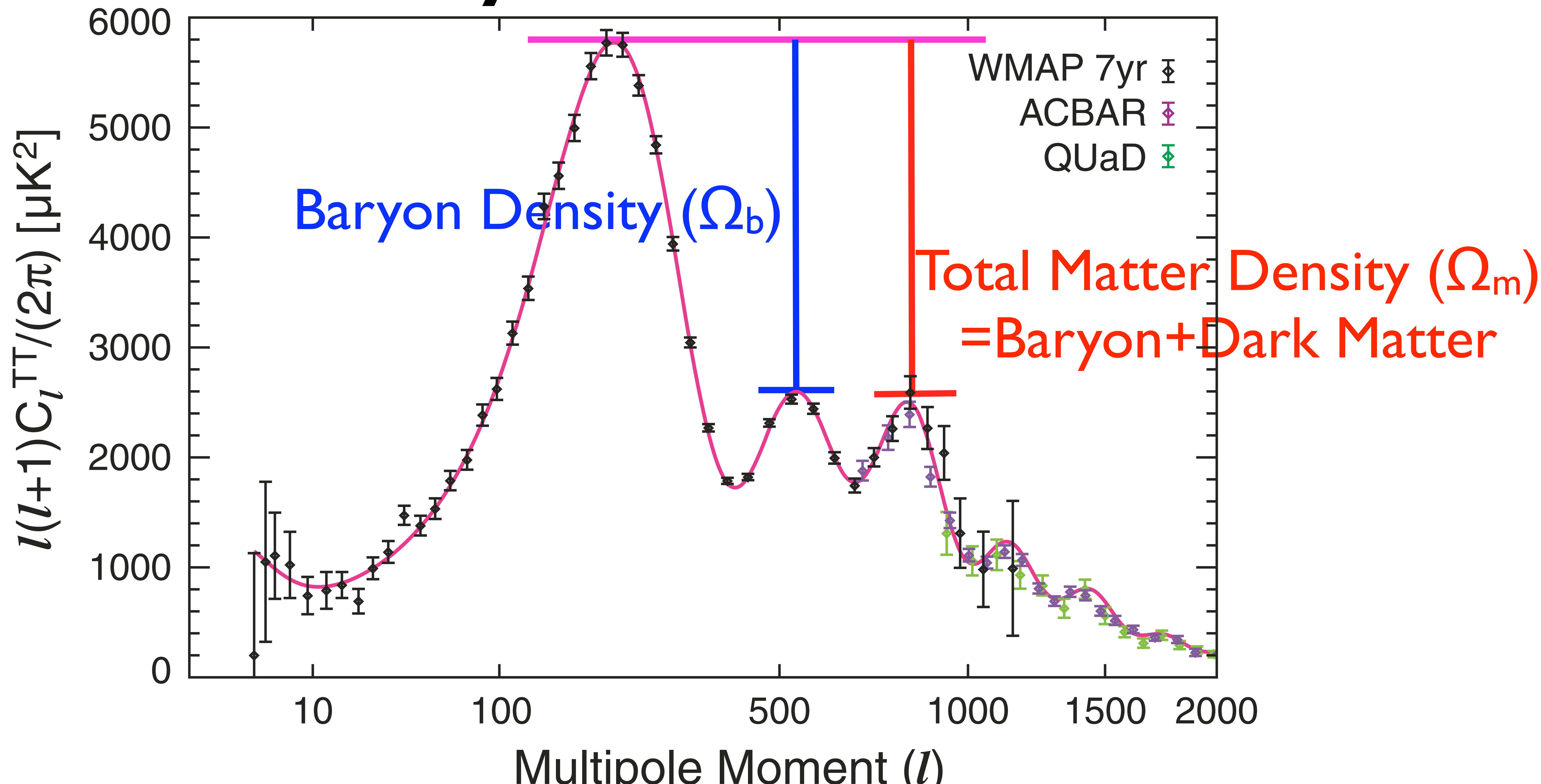
The Cosmic Sound Wave





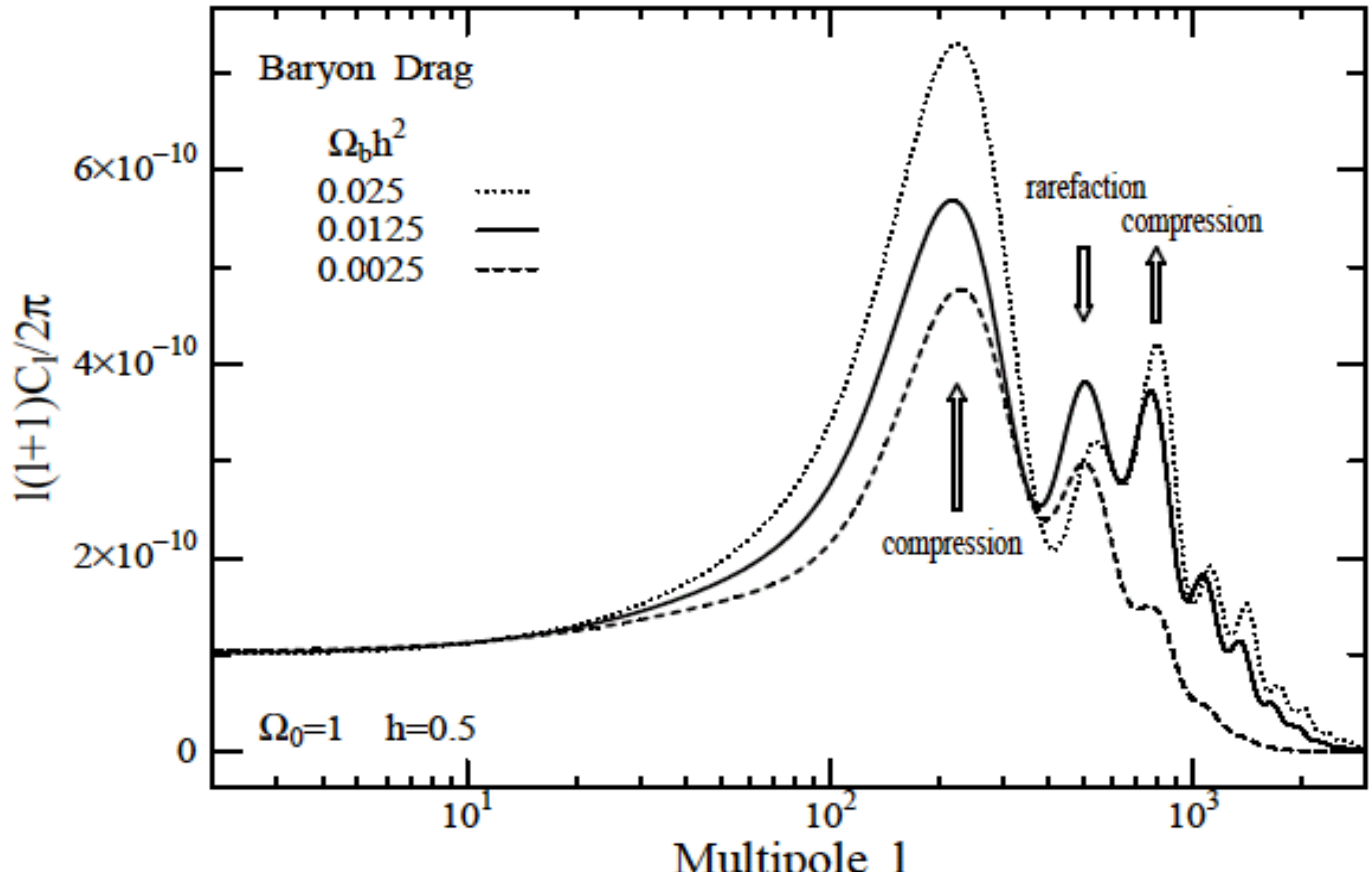
- *"The Universe as a Miso soup"*
  - *Main Ingredients: protons, helium nuclei, electrons, photons*
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

CMB to Baryon & Dark Matter

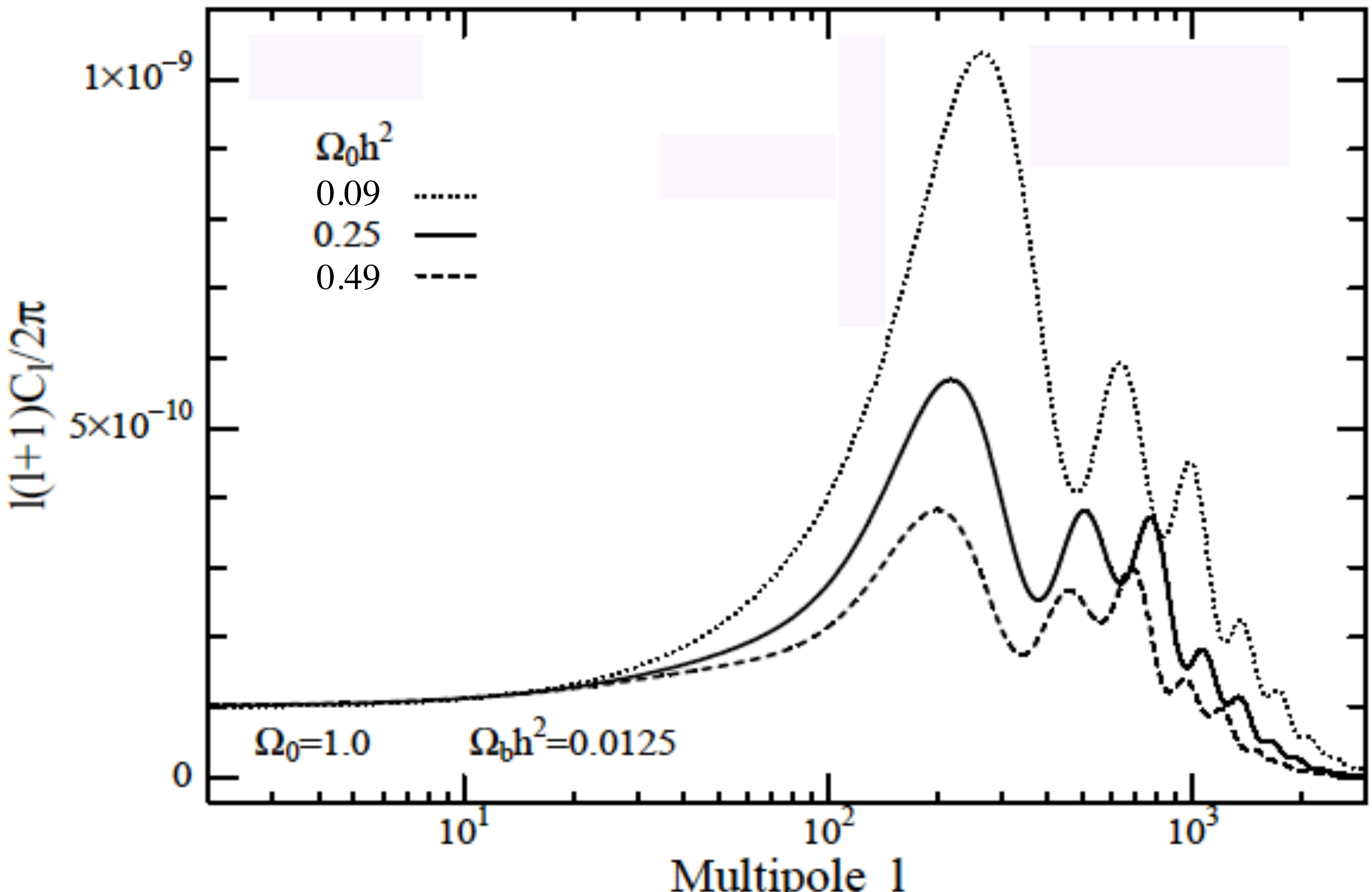


- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio (z_{EQ}: equality redshift)

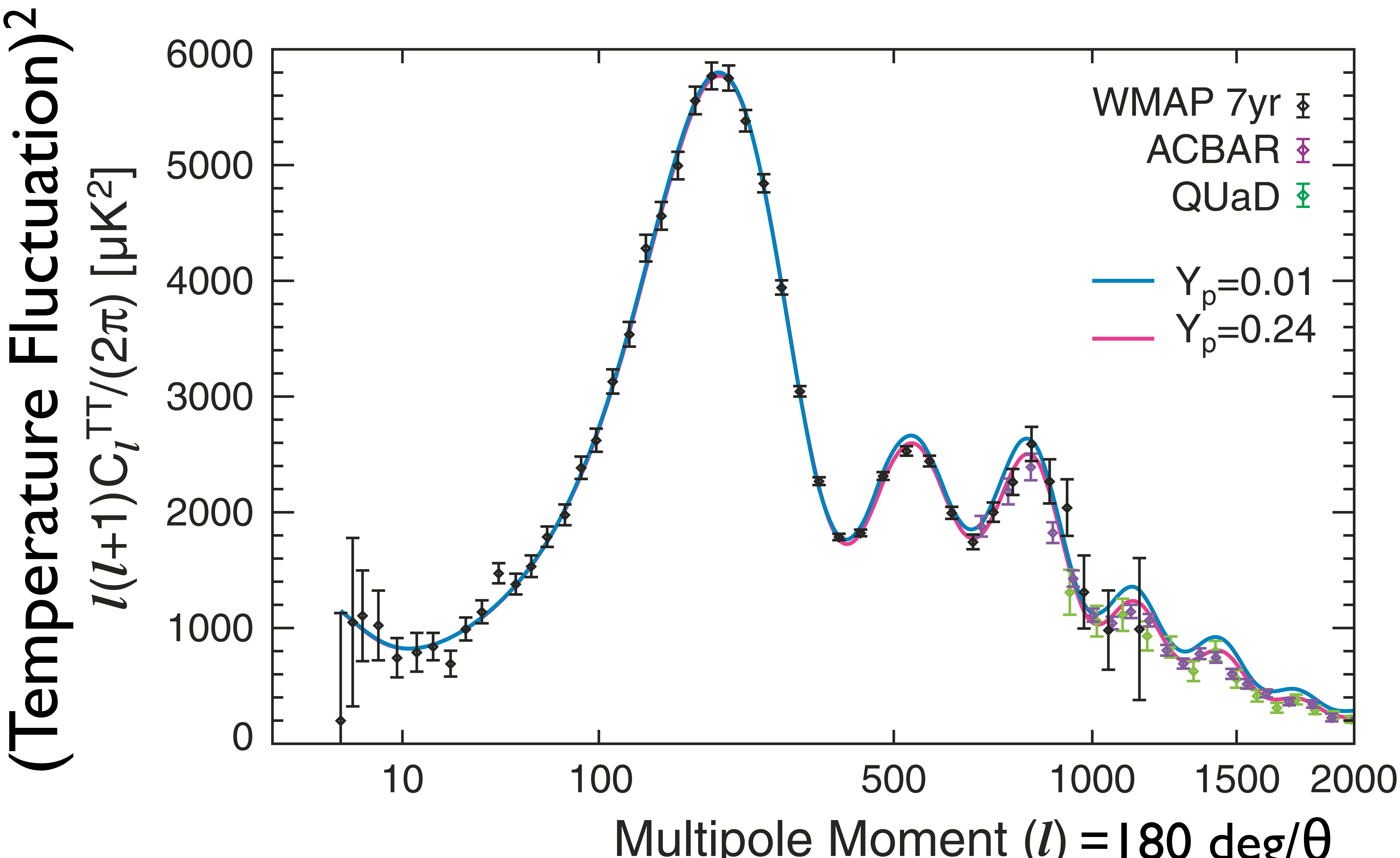
Determining Baryon Density From C_l



Determining Dark Matter Density From C_l



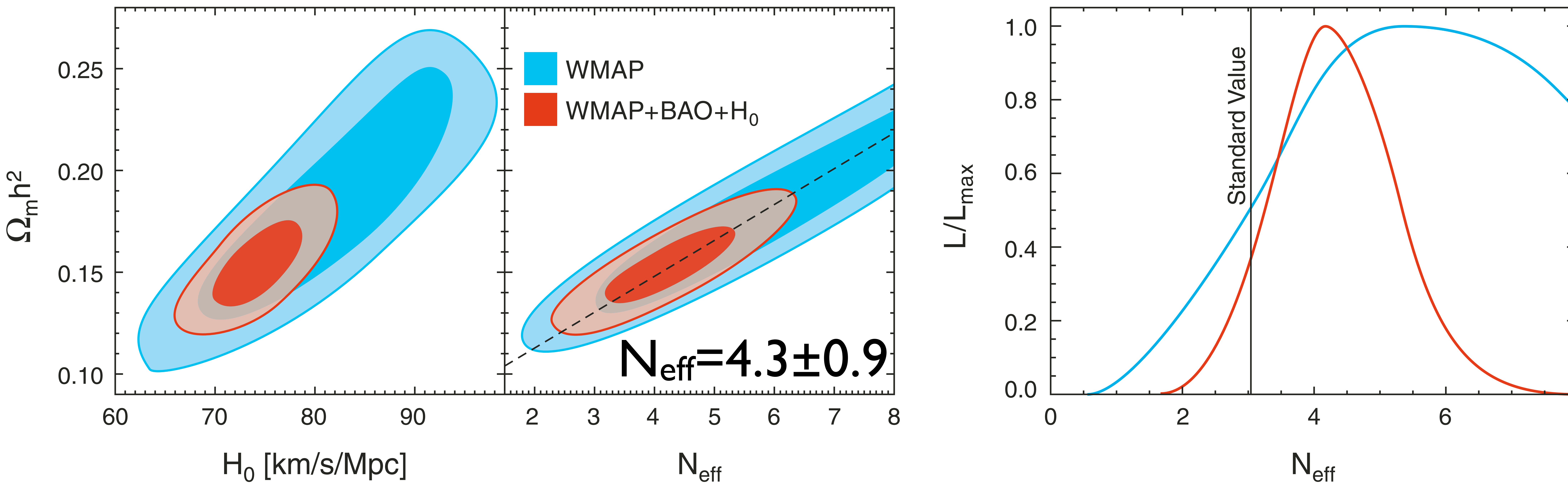
Detection of Primordial Helium



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

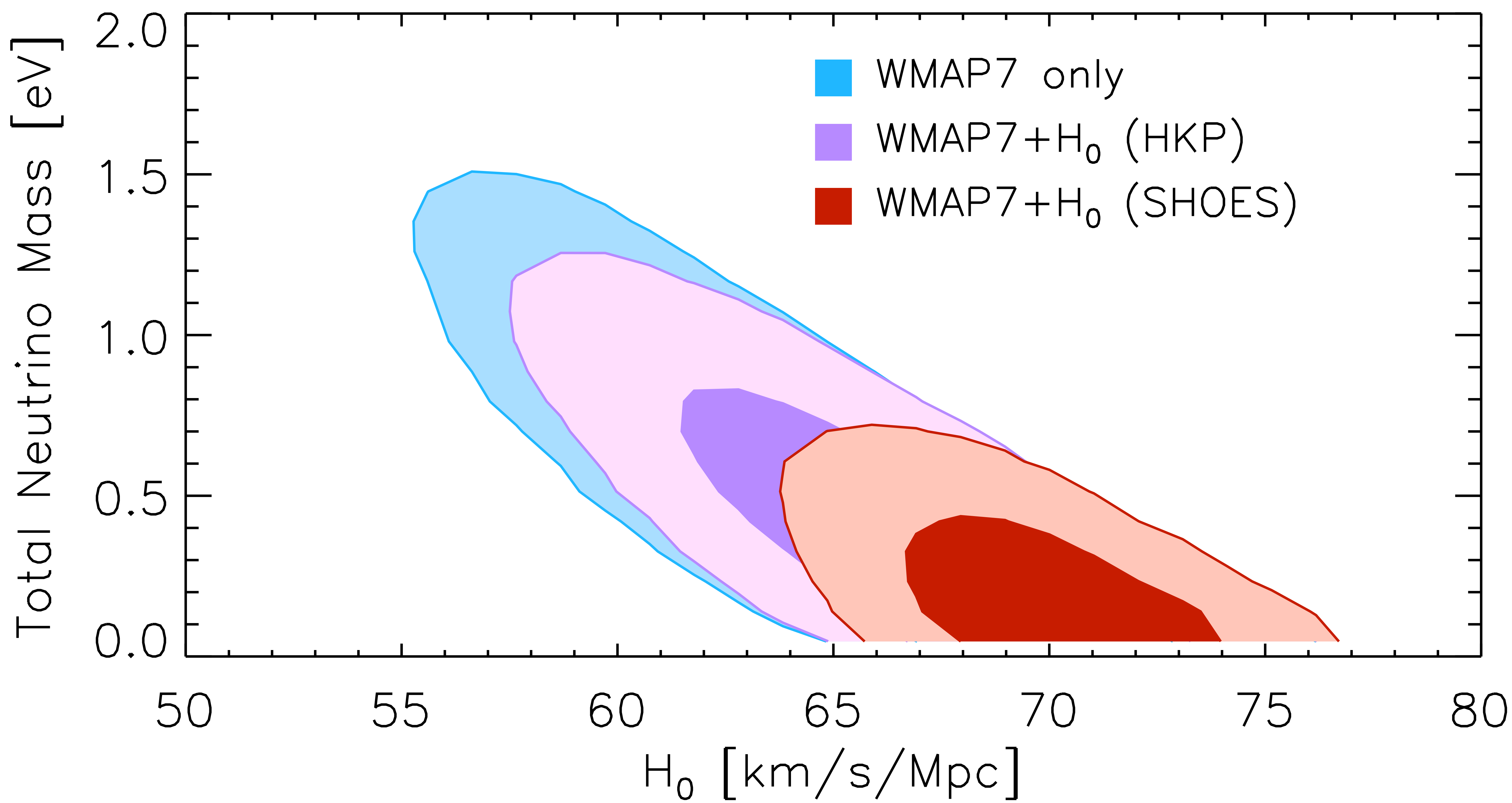


from external data

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

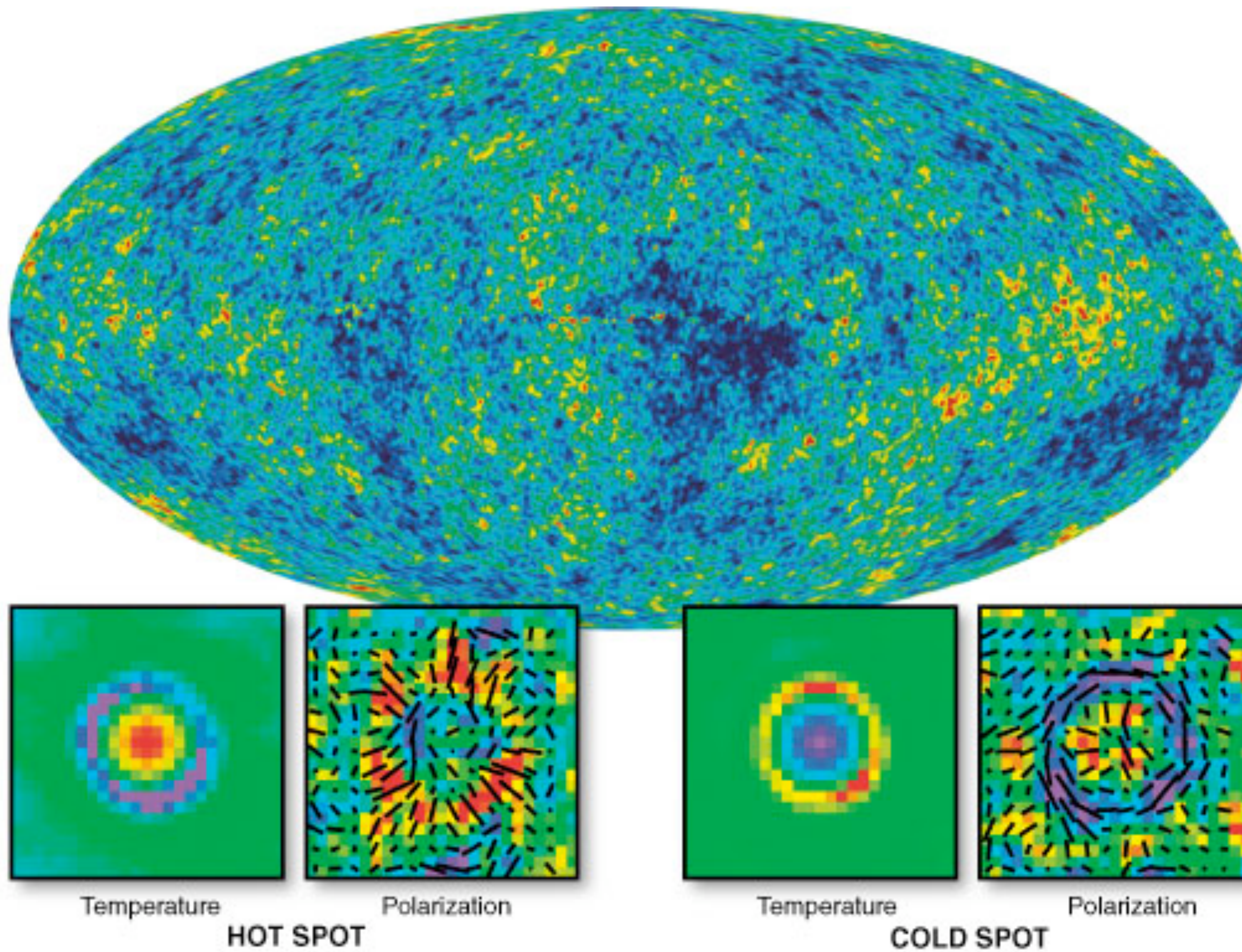
from 3rd peak

And, the mass of neutrinos



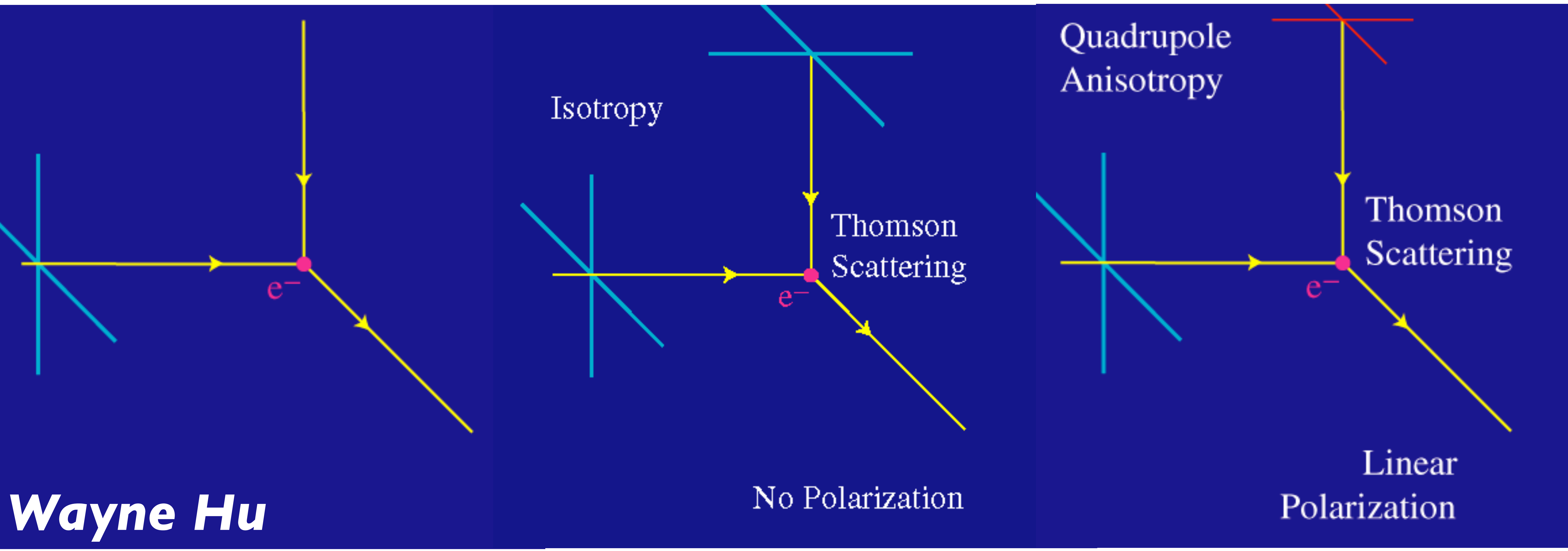
- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

CMB Polarization



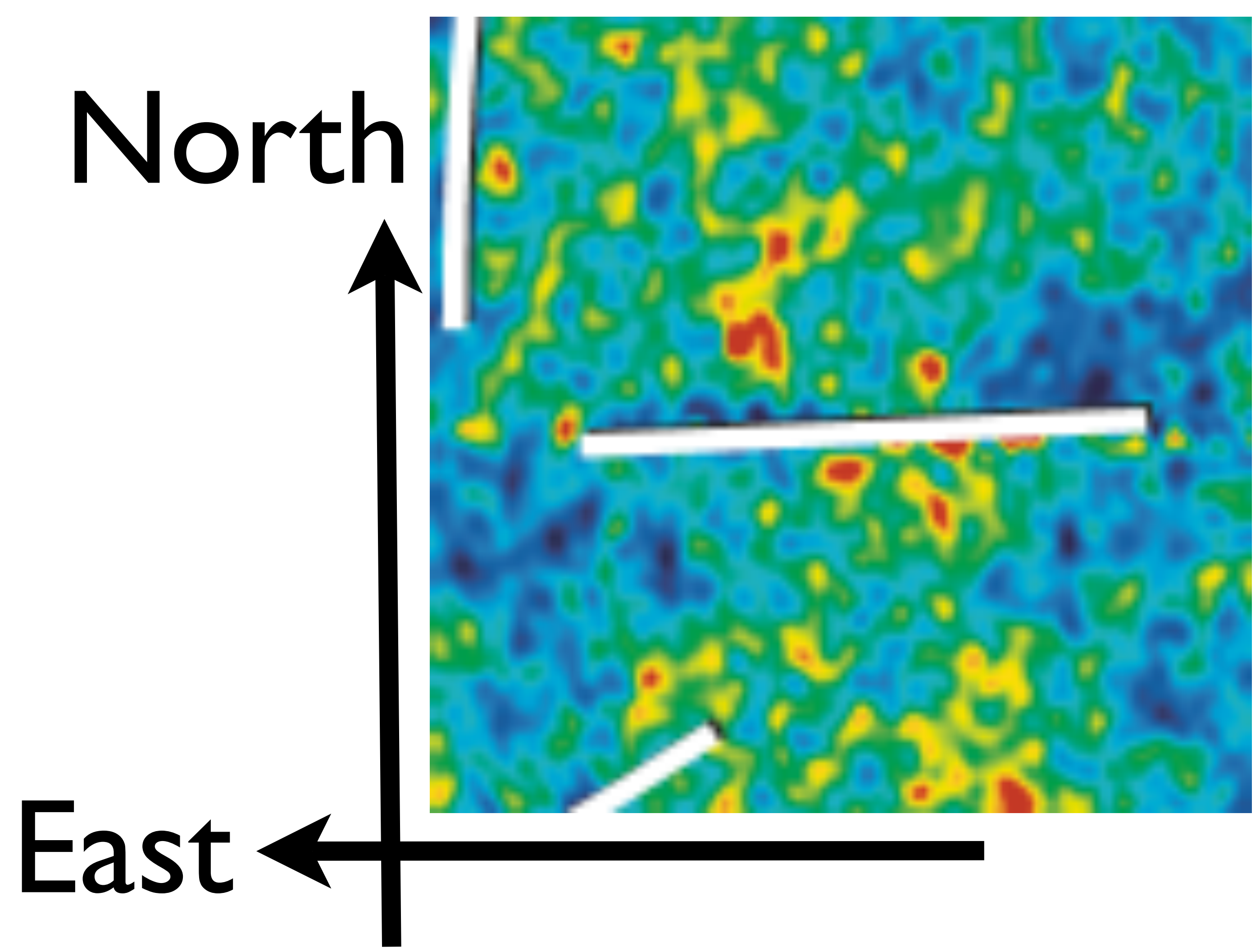
- *CMB is (very weakly) polarized!*

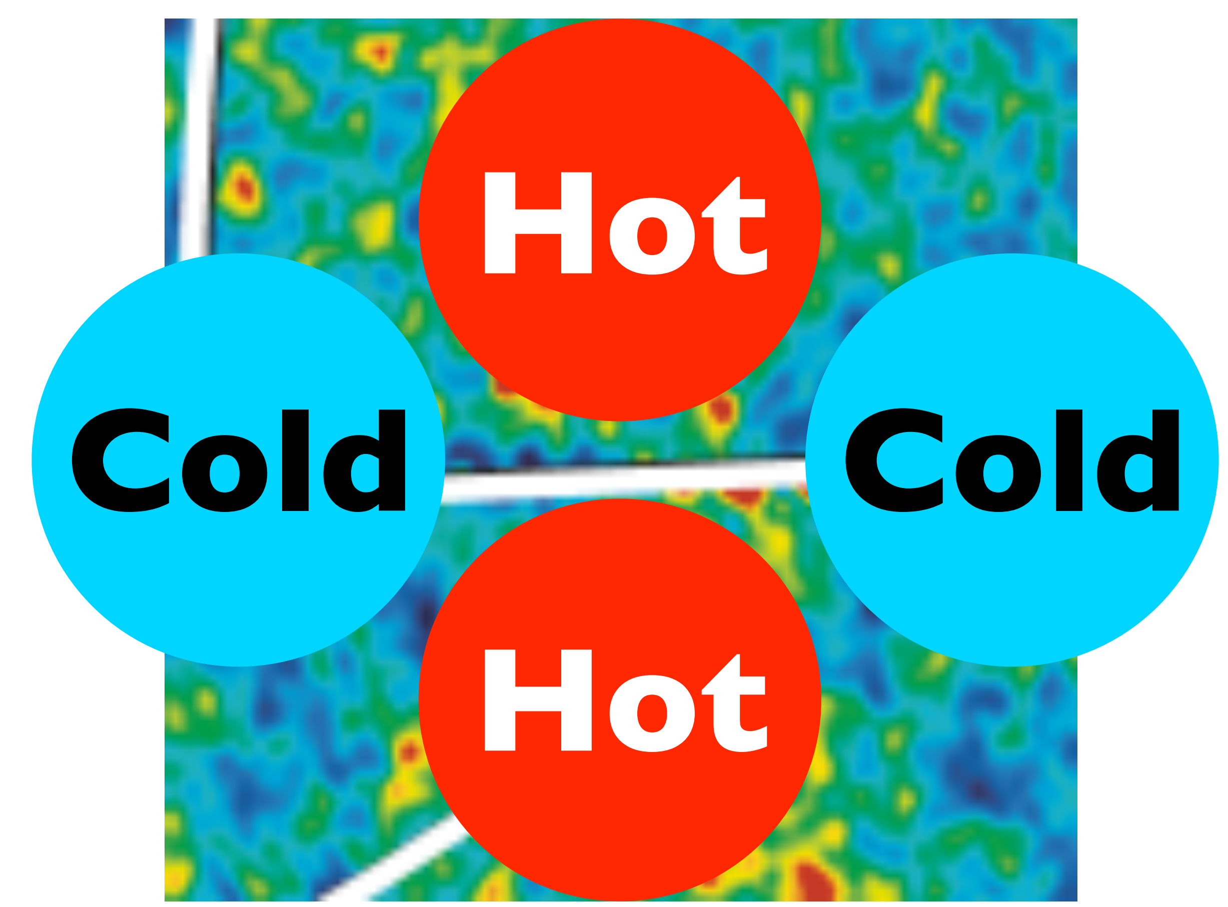
Physics of CMB Polarization



- 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.

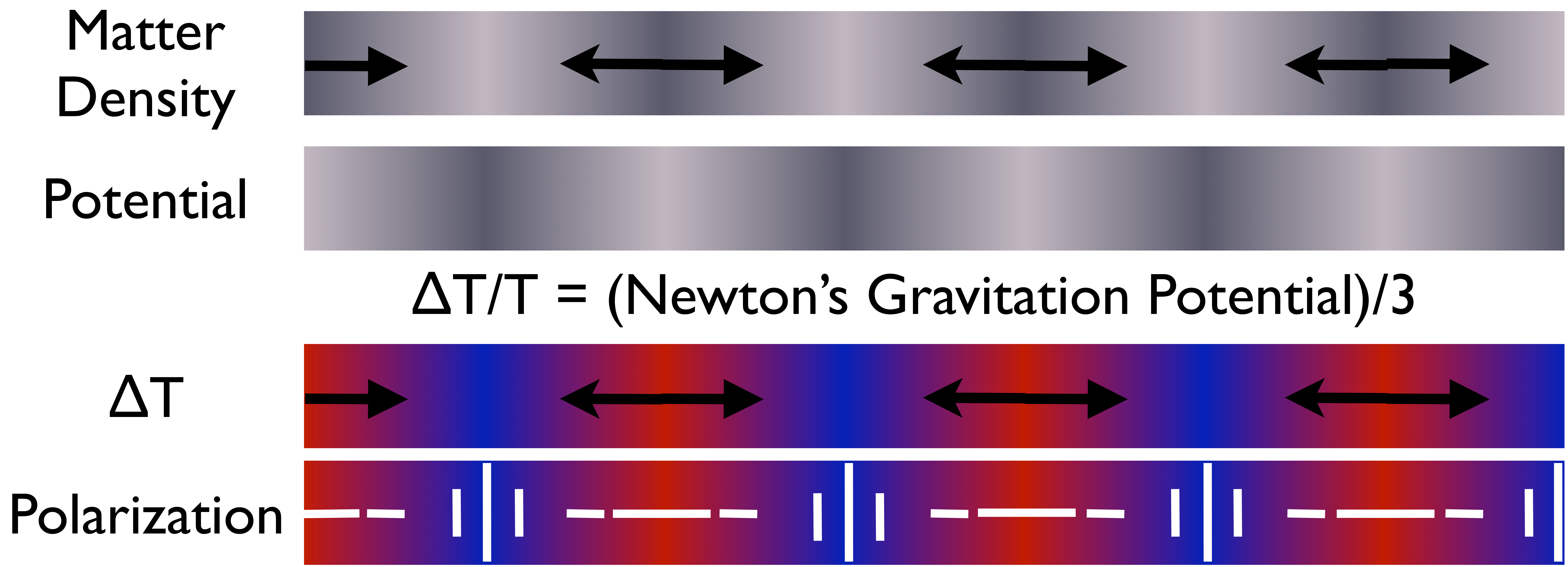
CMB Polarization on Large Angular Scales (>2 deg)

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

- How does the photon-baryon plasma move?

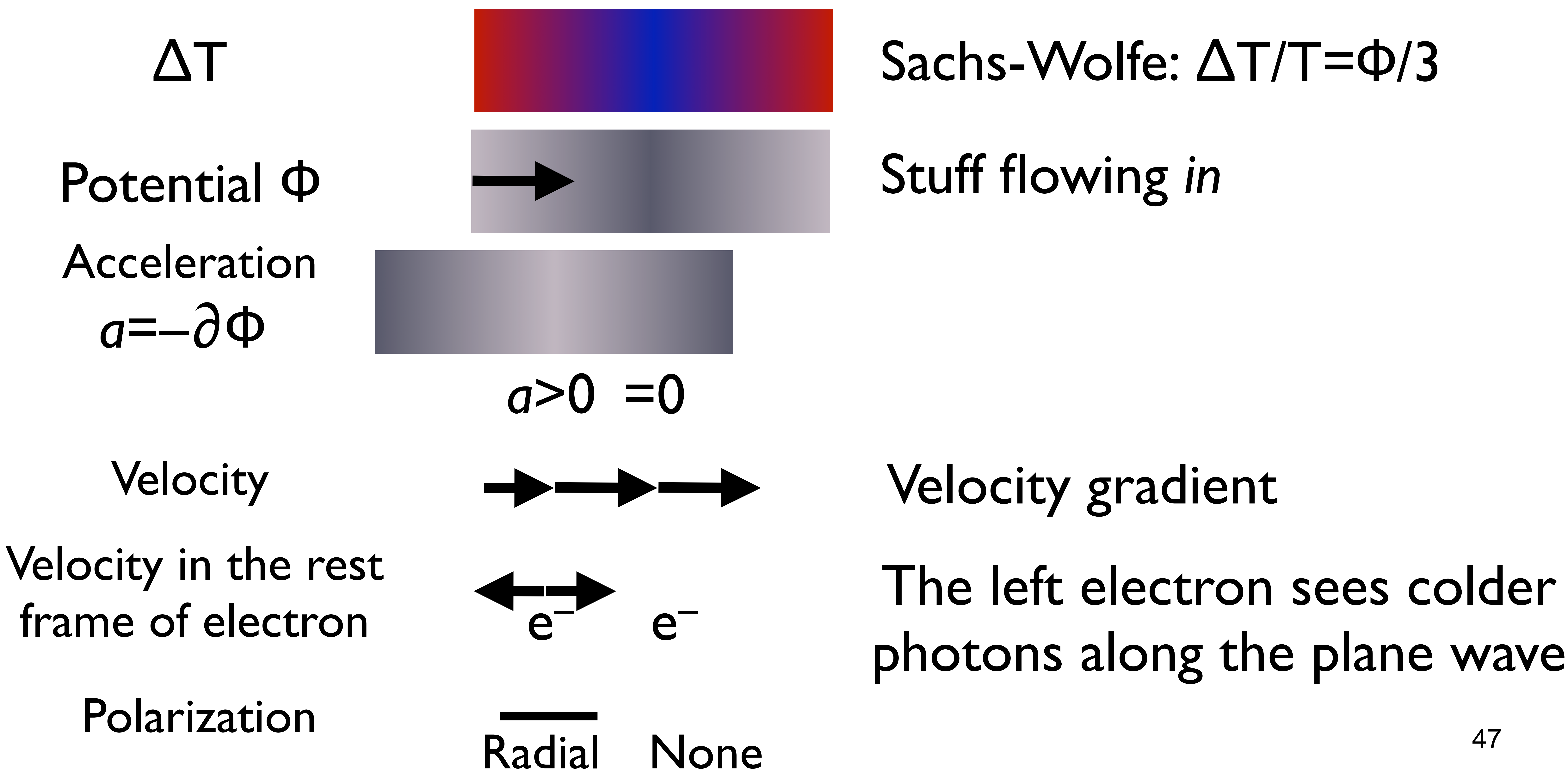
CMB Polarization Tells Us How Plasma Moves at z=1090

Zaldarriaga & Harari (1995)



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

Quadrupole From Velocity Gradient (Large Scale)



Quadrupole From Velocity Gradient (Small Scale)

ΔT — Compression increases temperature

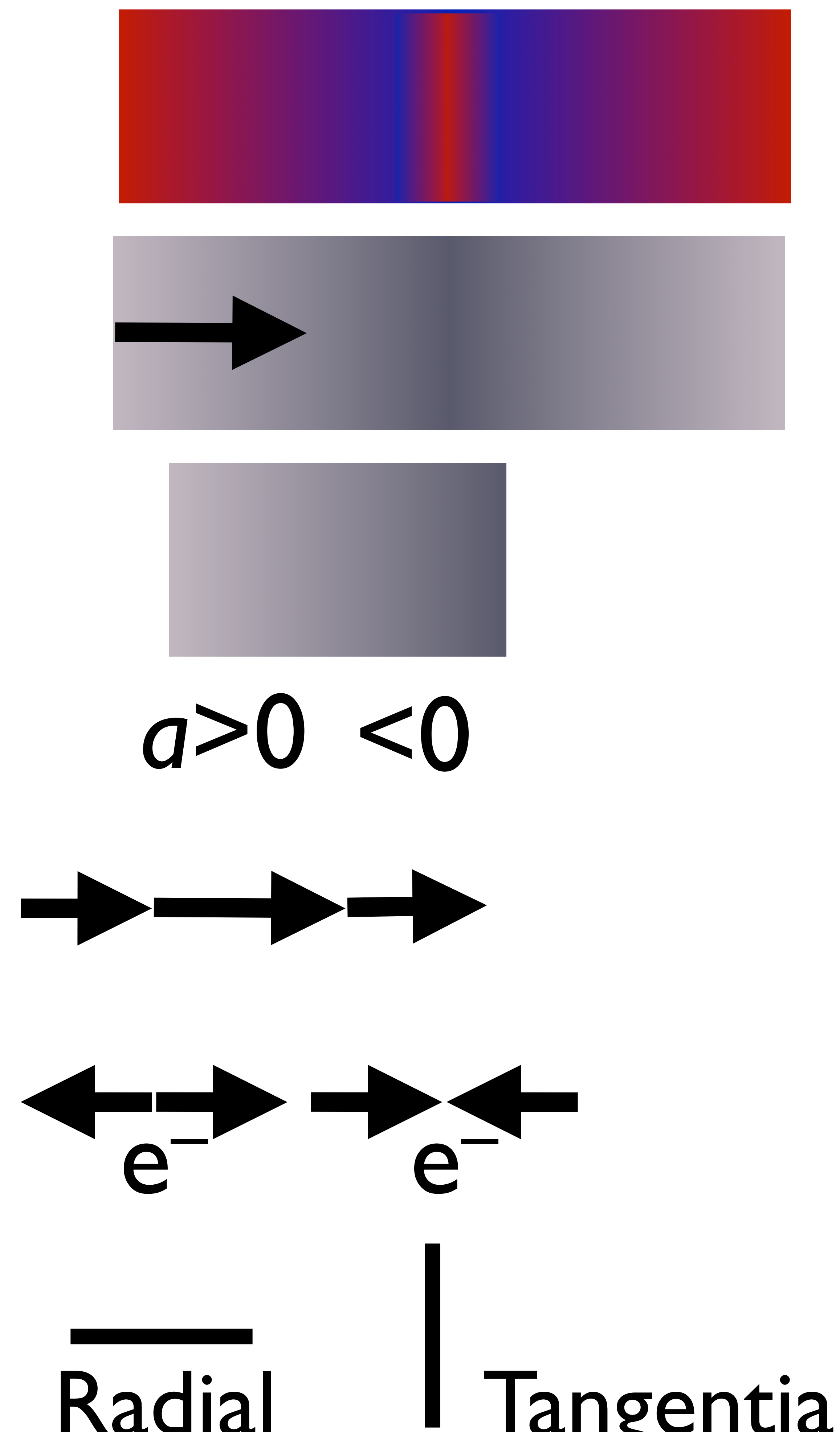
Potential Φ — Stuff flowing *in*

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

Velocity — Velocity gradient

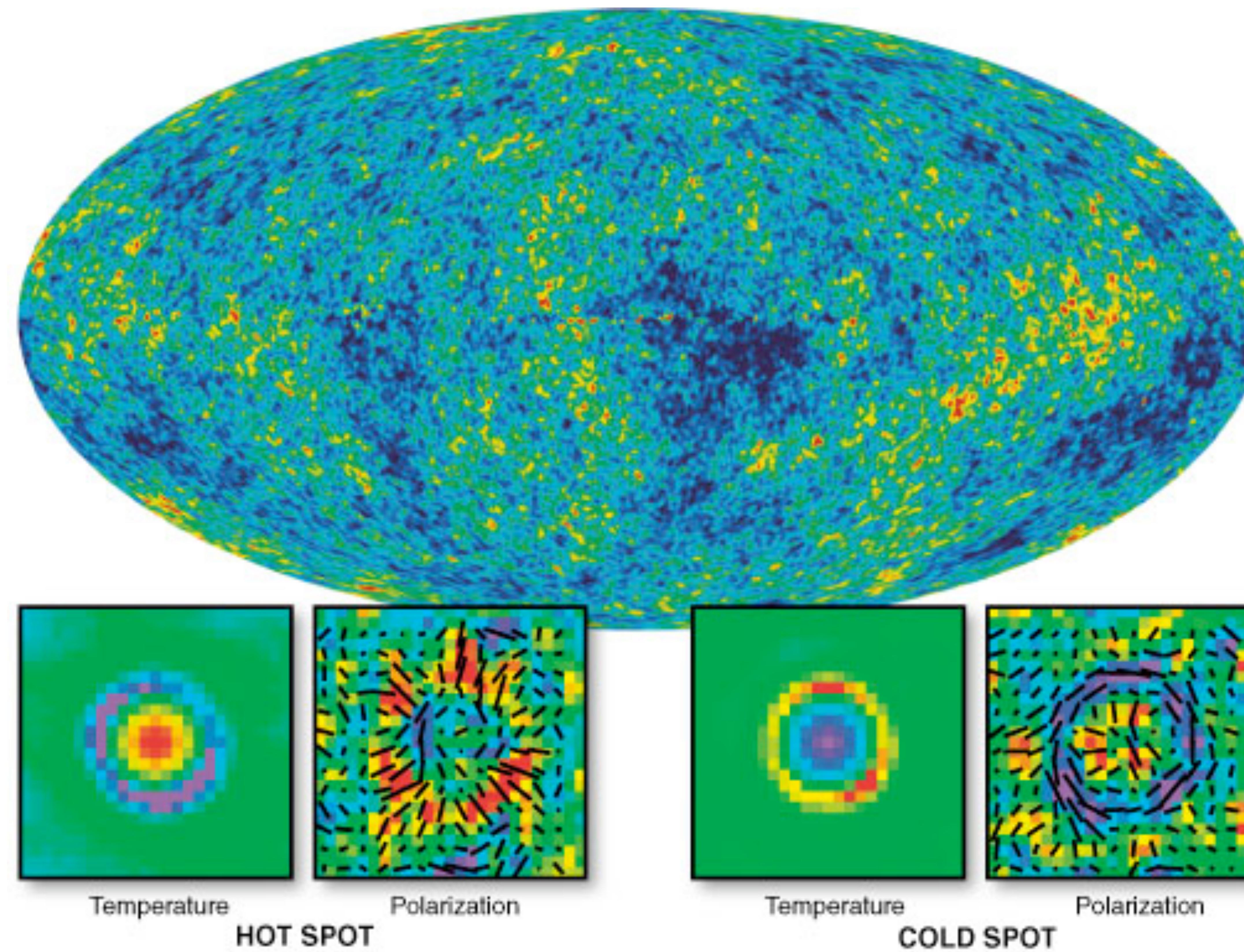
Velocity in the rest frame of electron

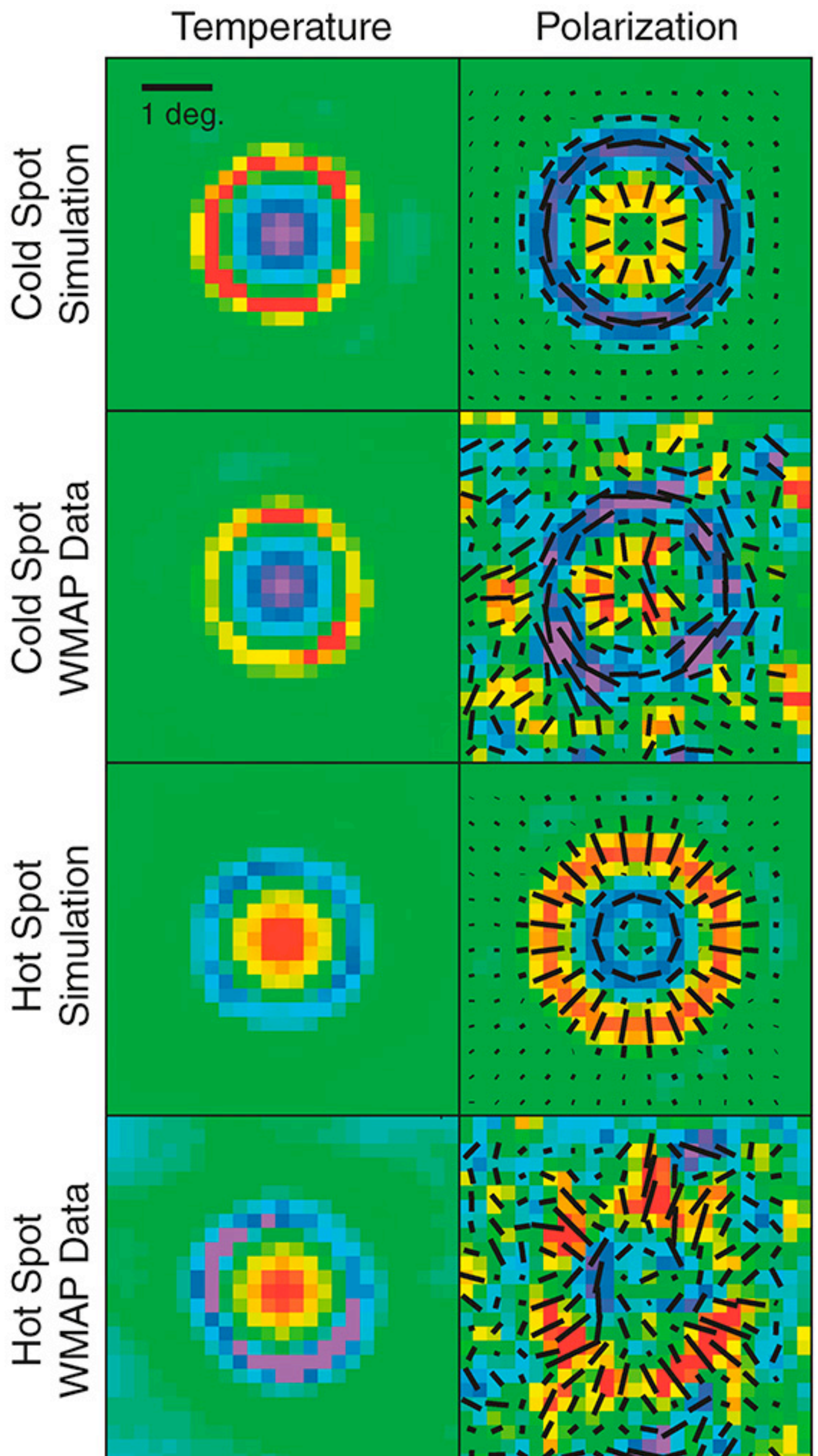
Polarization



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**.

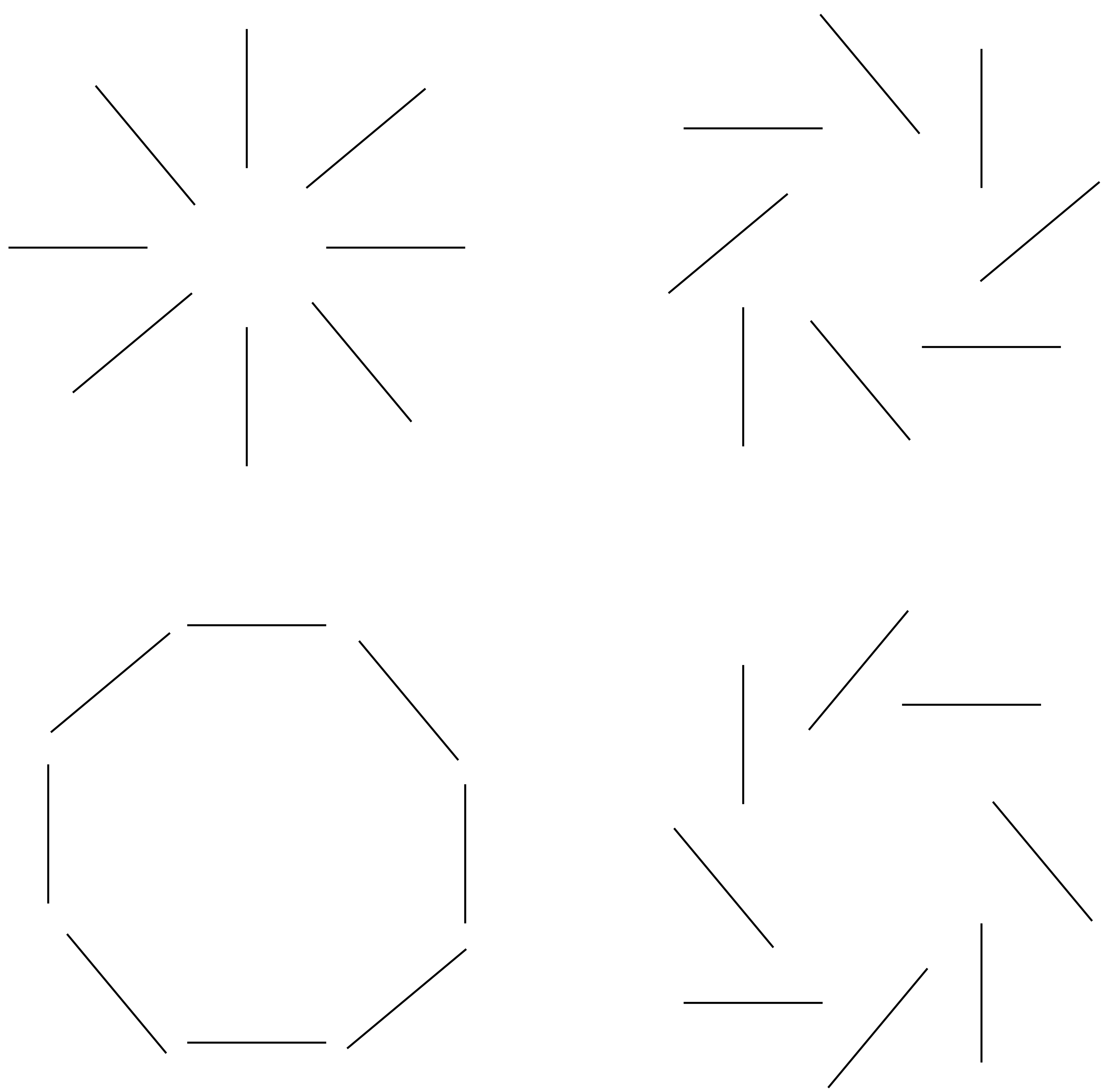




Two-dimensional View

- 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

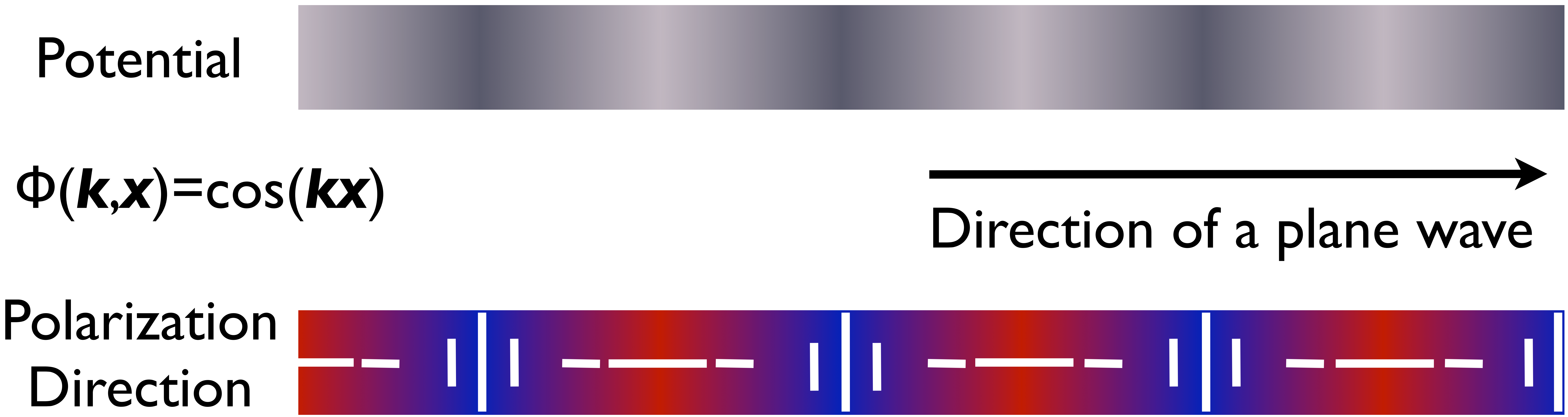
E-mode and B-mode



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!

E-mode



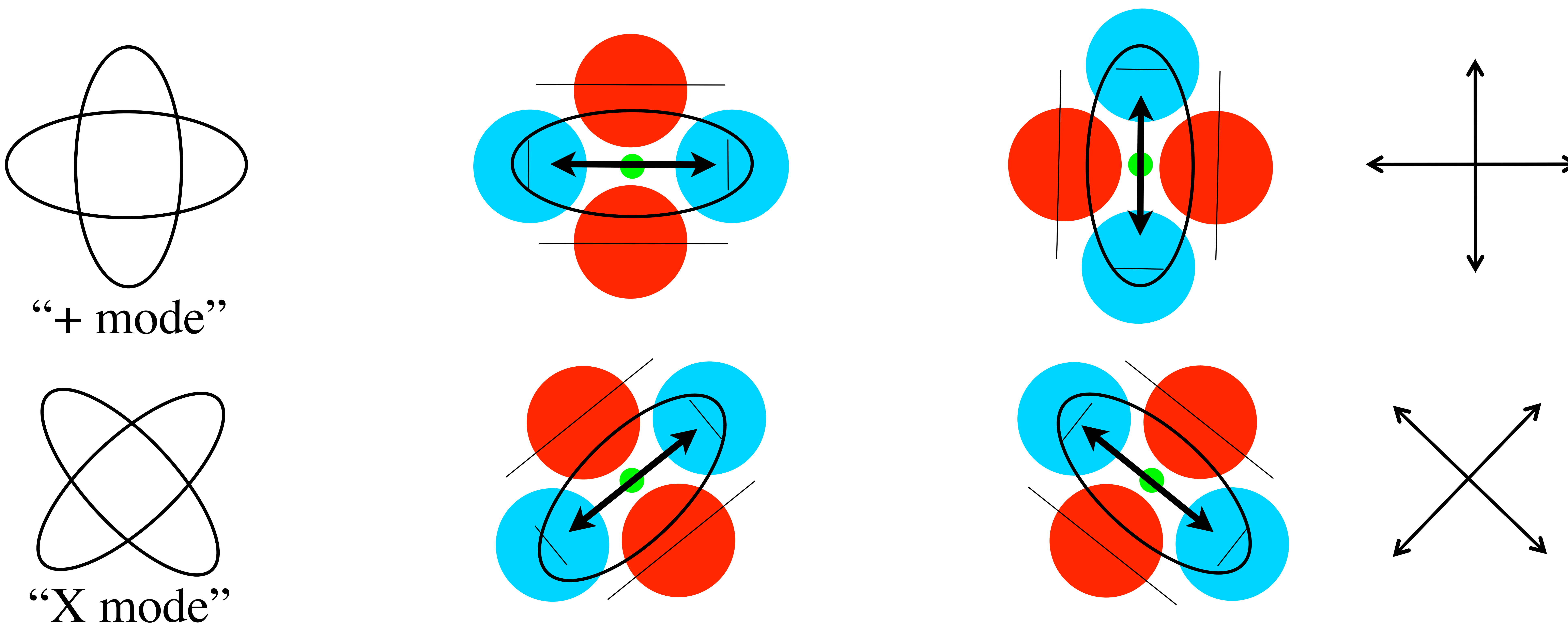
- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

B-mode

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

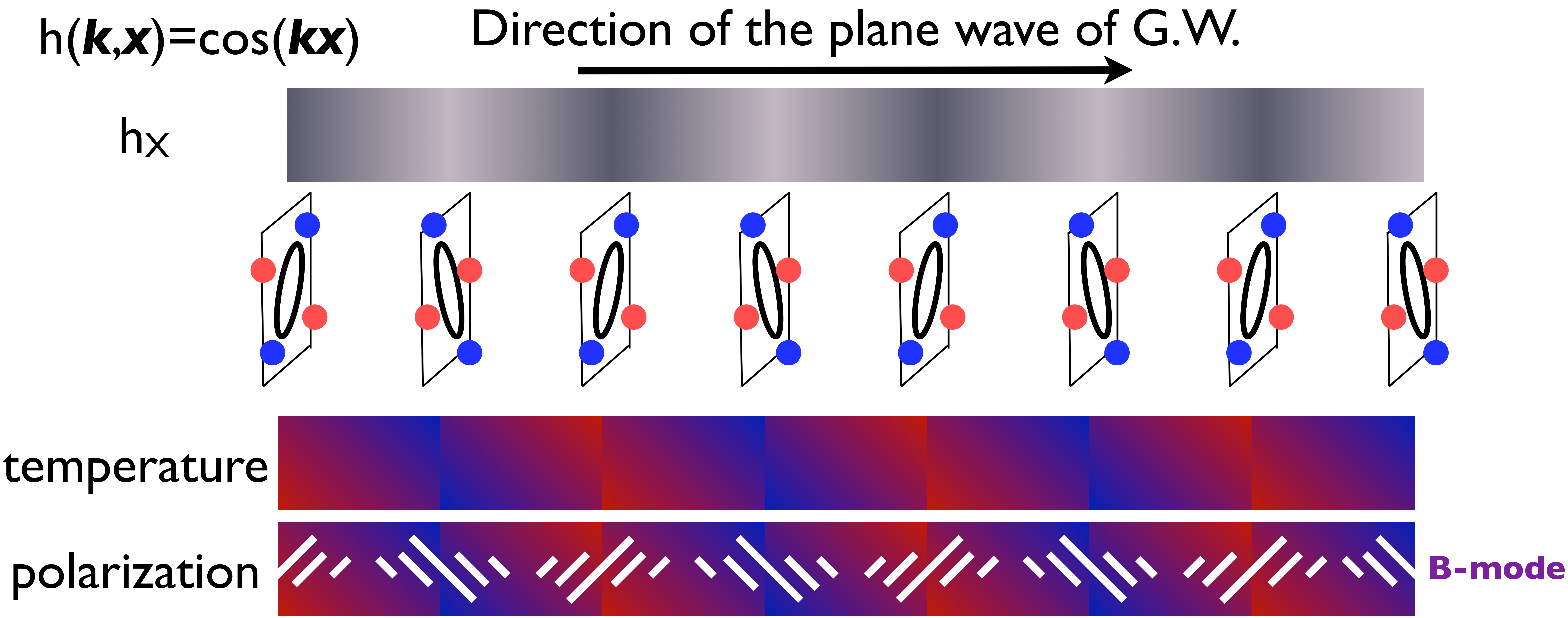
Gravitational Waves and Quadrupole

- Gravitational waves stretch space with a quadrupole pattern.



Quadrupole from G.W.

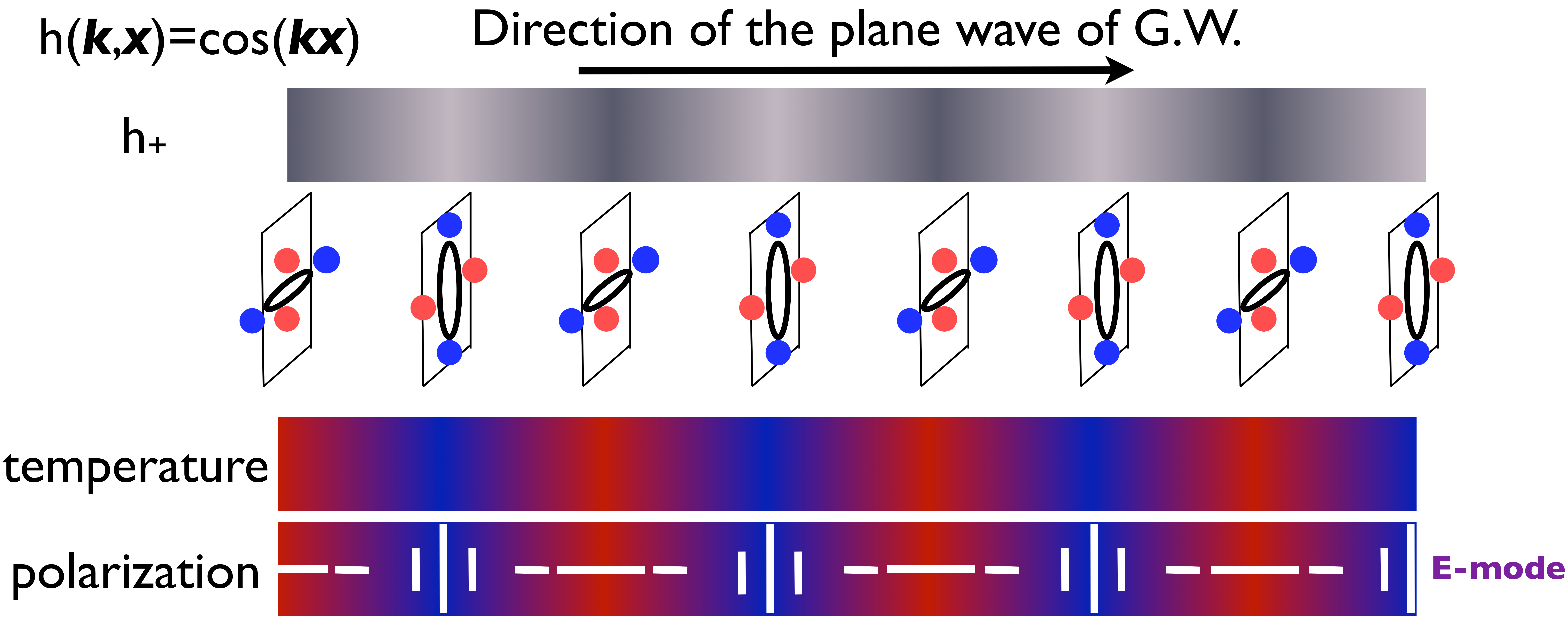
$h(\boldsymbol{k},\boldsymbol{x})=\cos(\boldsymbol{kx})$



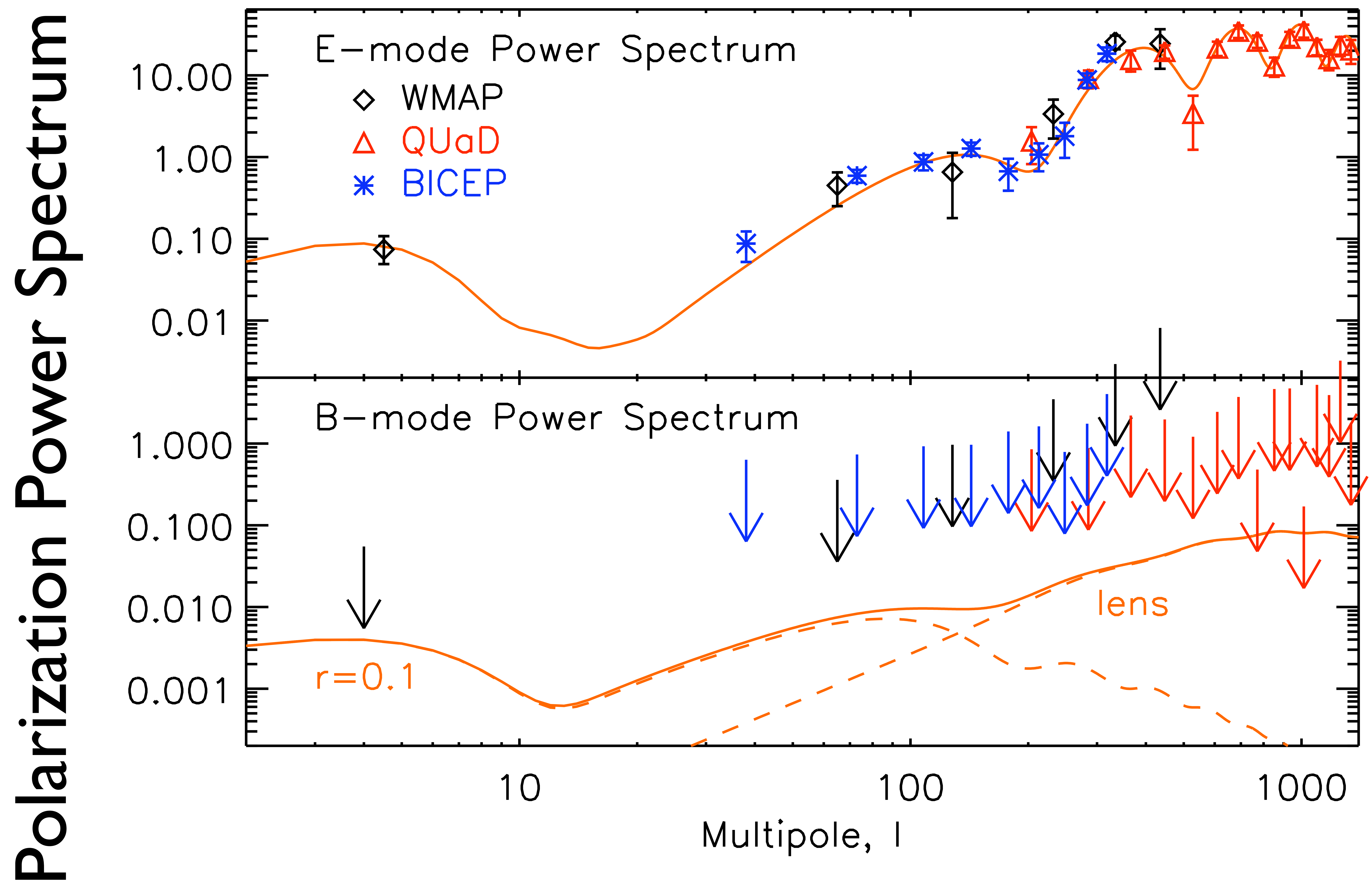
- B-mode polarization generated by $h_\times$

Quadrupole from G.W.

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



- E-mode polarization generated by h_+



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

Theory of the Very Early Universe

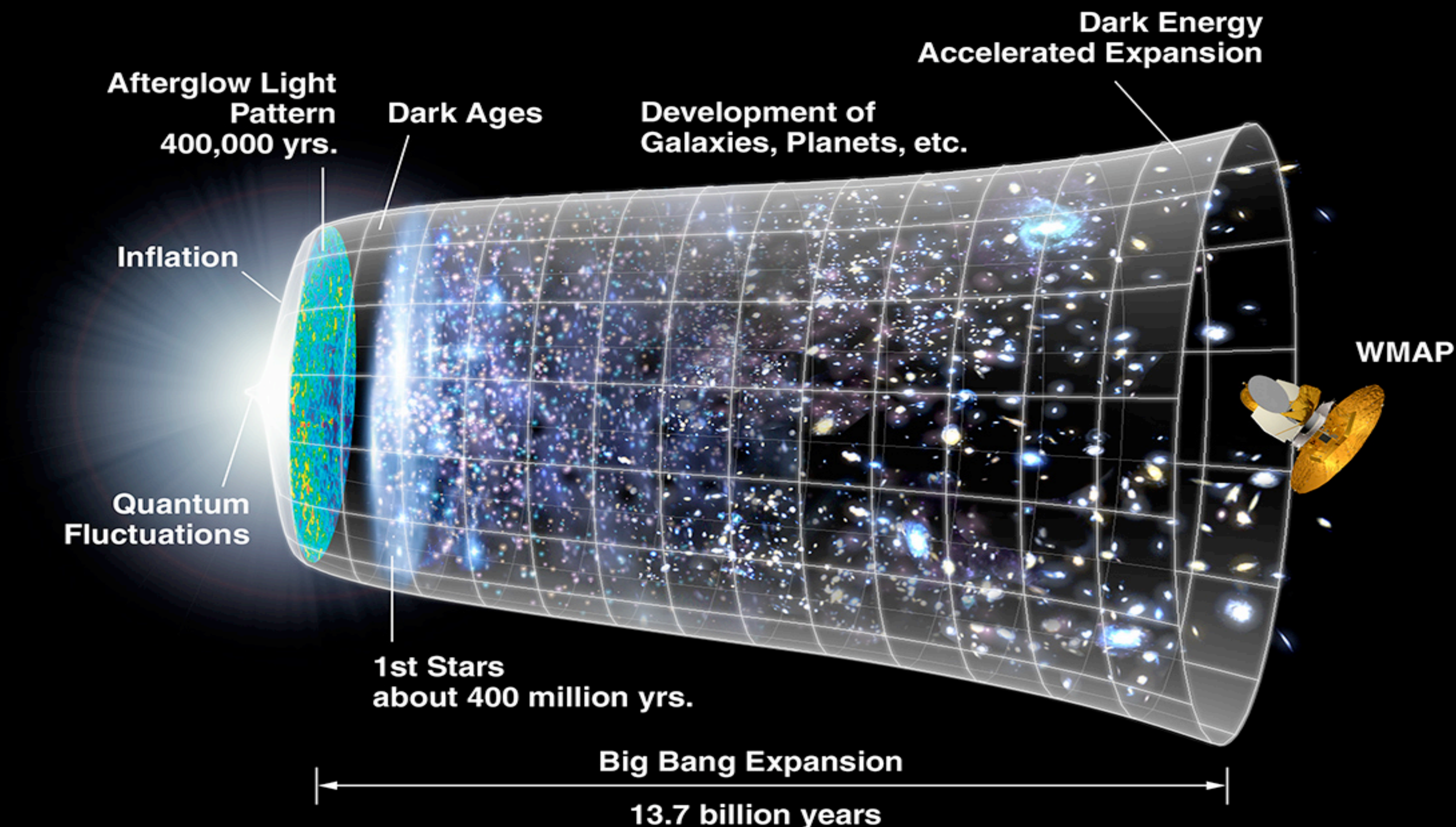
- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  (Guth 1981; Linde 1982; Albrecht & Steinhardt 1982; Starobinsky 1980)

  - 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***," <u>predicts</u>:
  - 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 <u>**expansion history during cosmic inflation**</u>.
- 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.
- This is the so-called Heisenberg's Uncertainty Principle, which is 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]

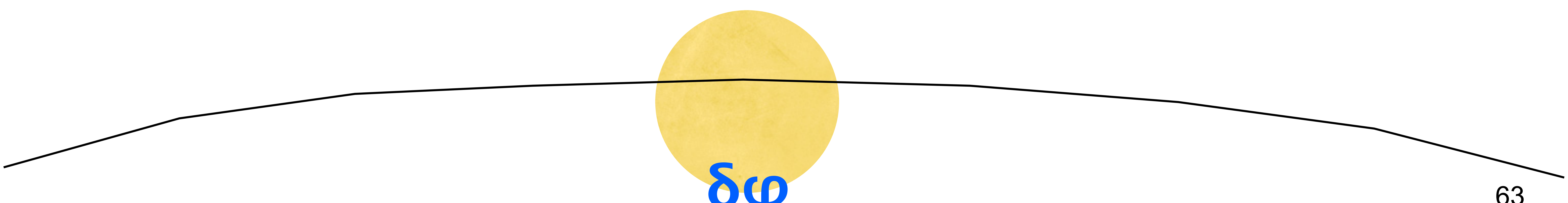
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-36} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

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

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

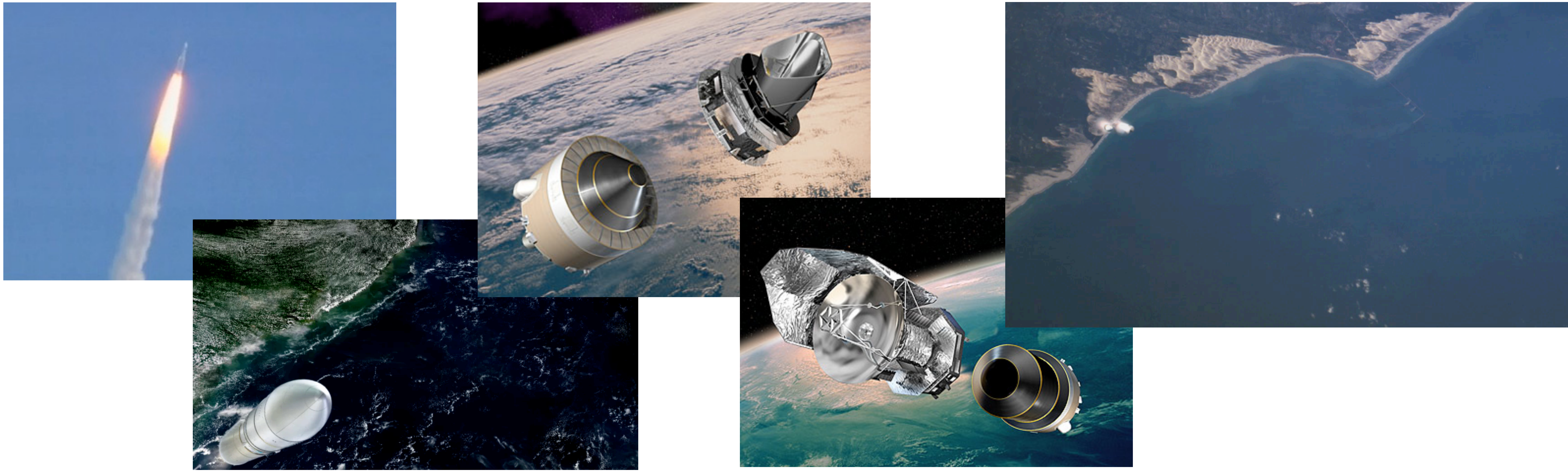
[h = "strain"]

- 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**."

Summary

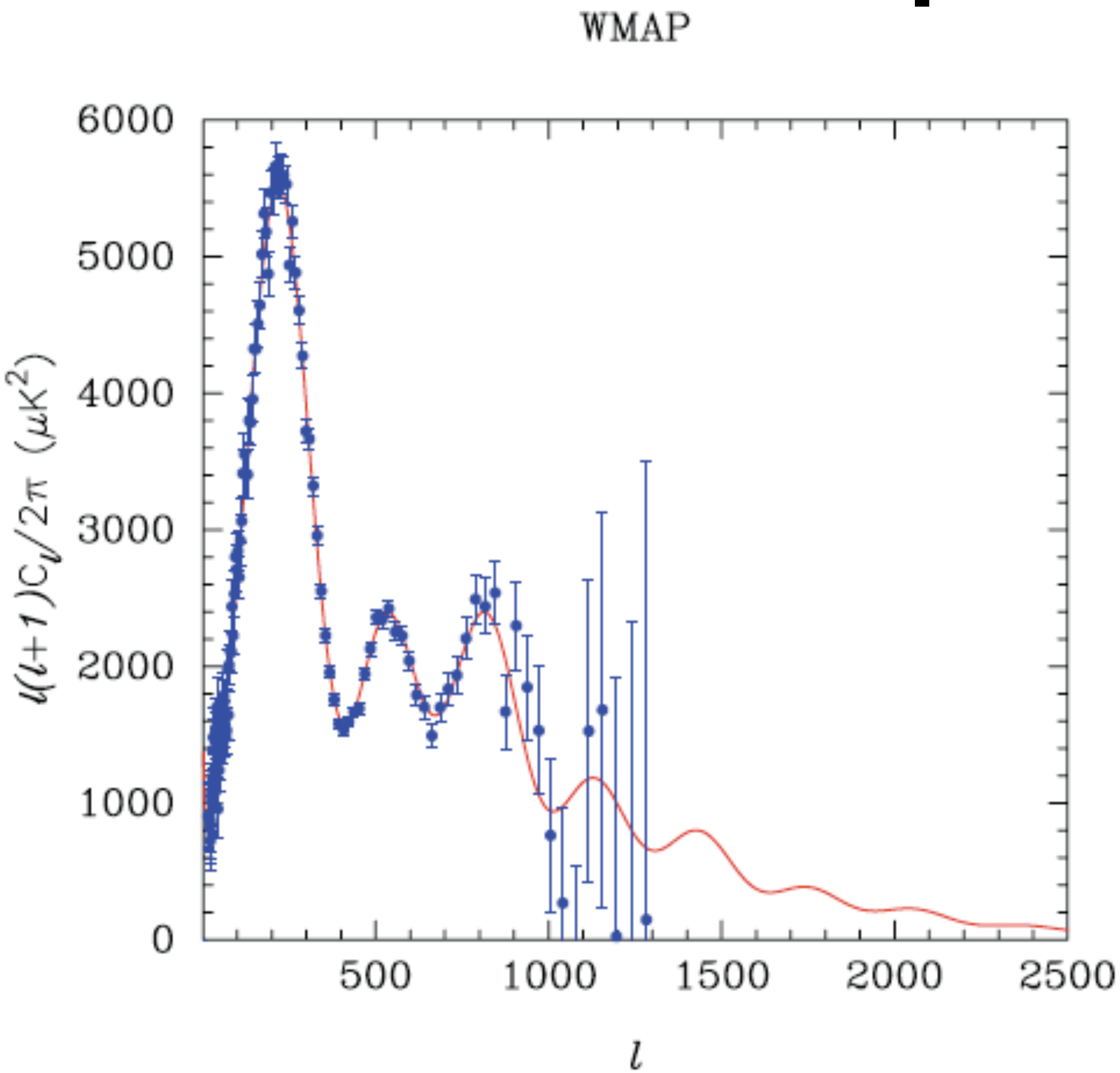
- CMB is the fossil light of the Big Bang.
- We could determine the age, composition, expansion rate, etc., from CMB.
- We could even push the boundary farther back in time, probing the origin of fluctuations in the very early Universe: inflationary epoch at ultra-high energies.
- Next Big Thing: **Primordial gravitational waves**.

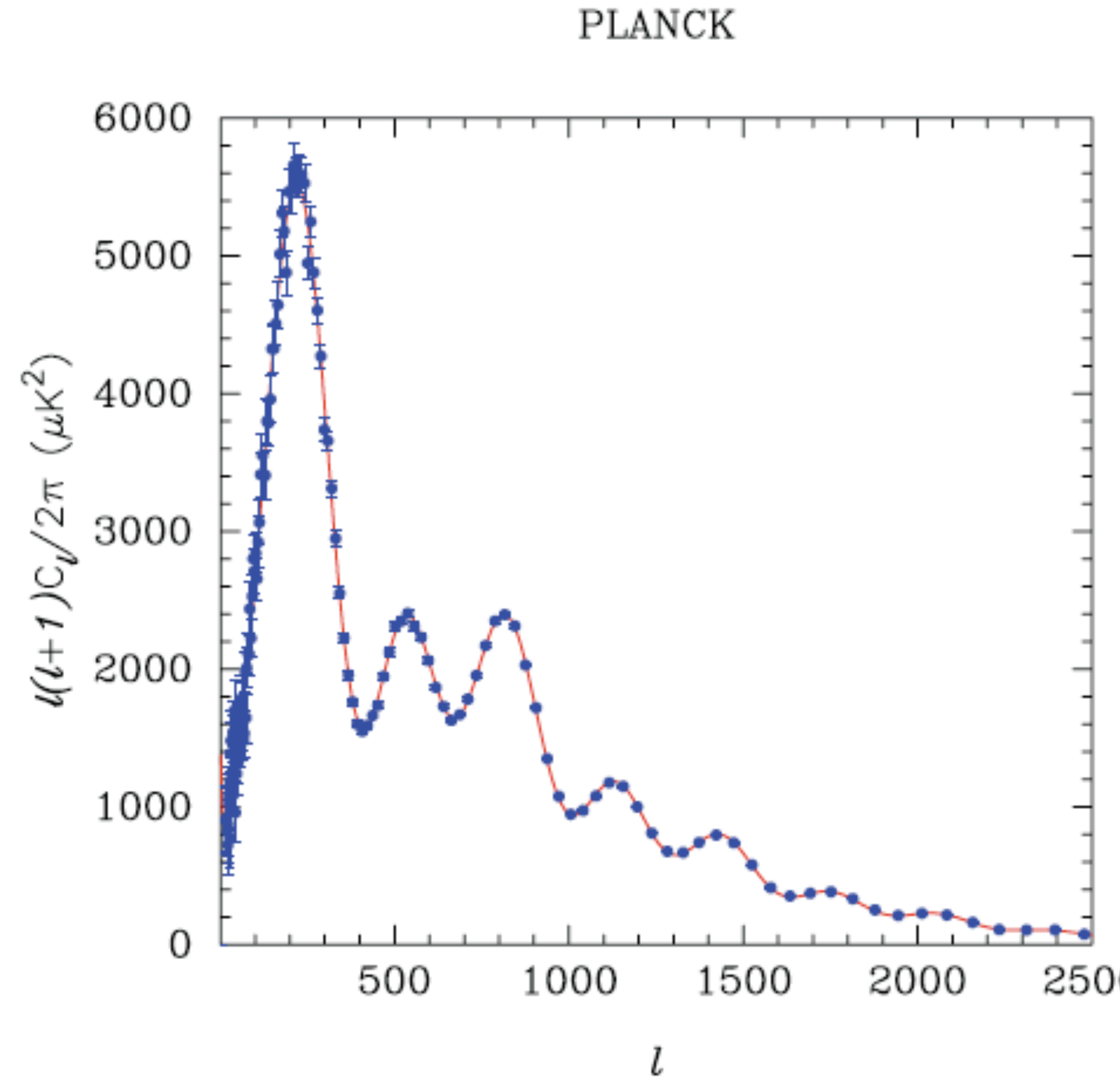
Planck Launched!



- 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 ~2012.

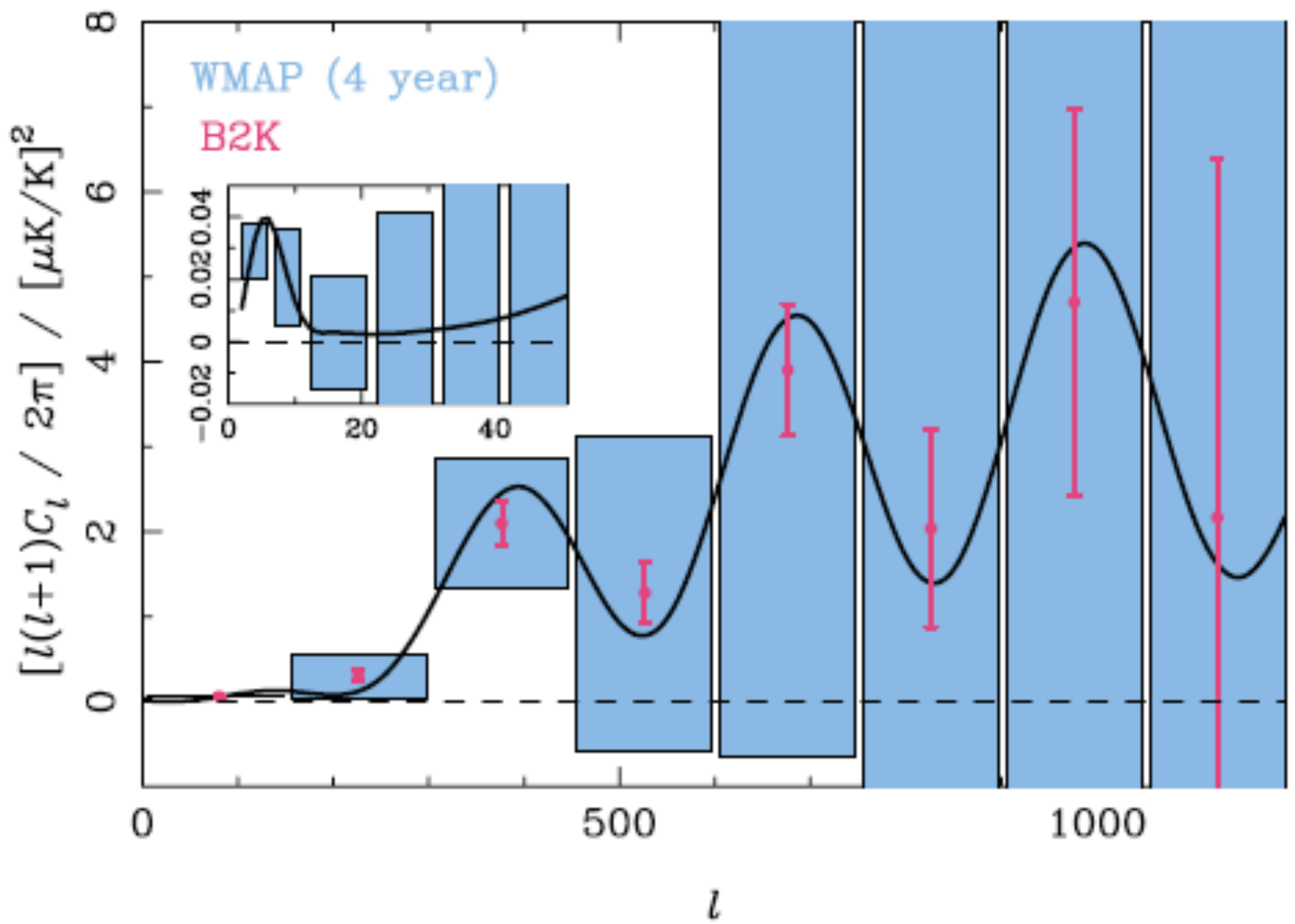
Planck: Expected $C_l^{Temperature}$

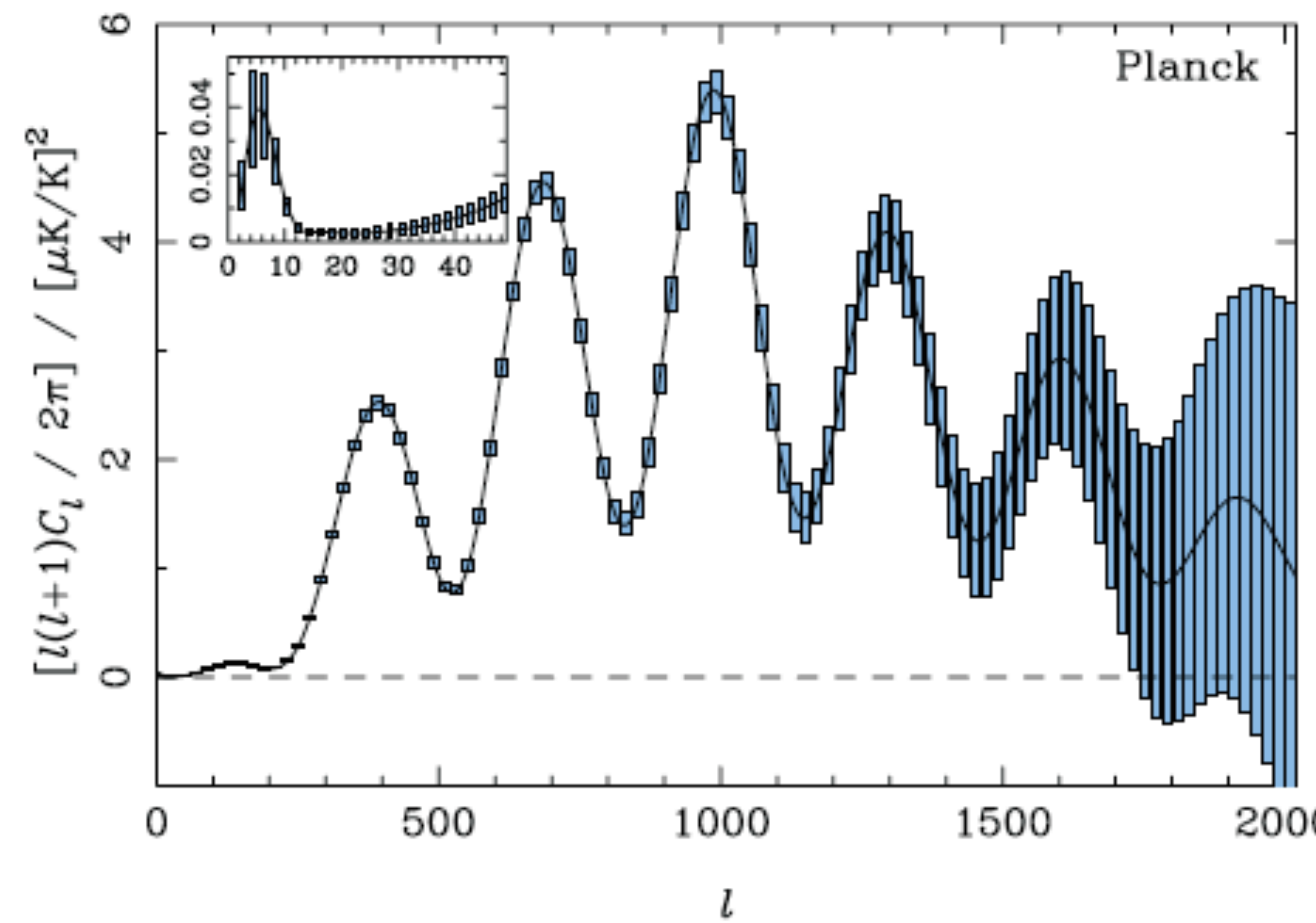


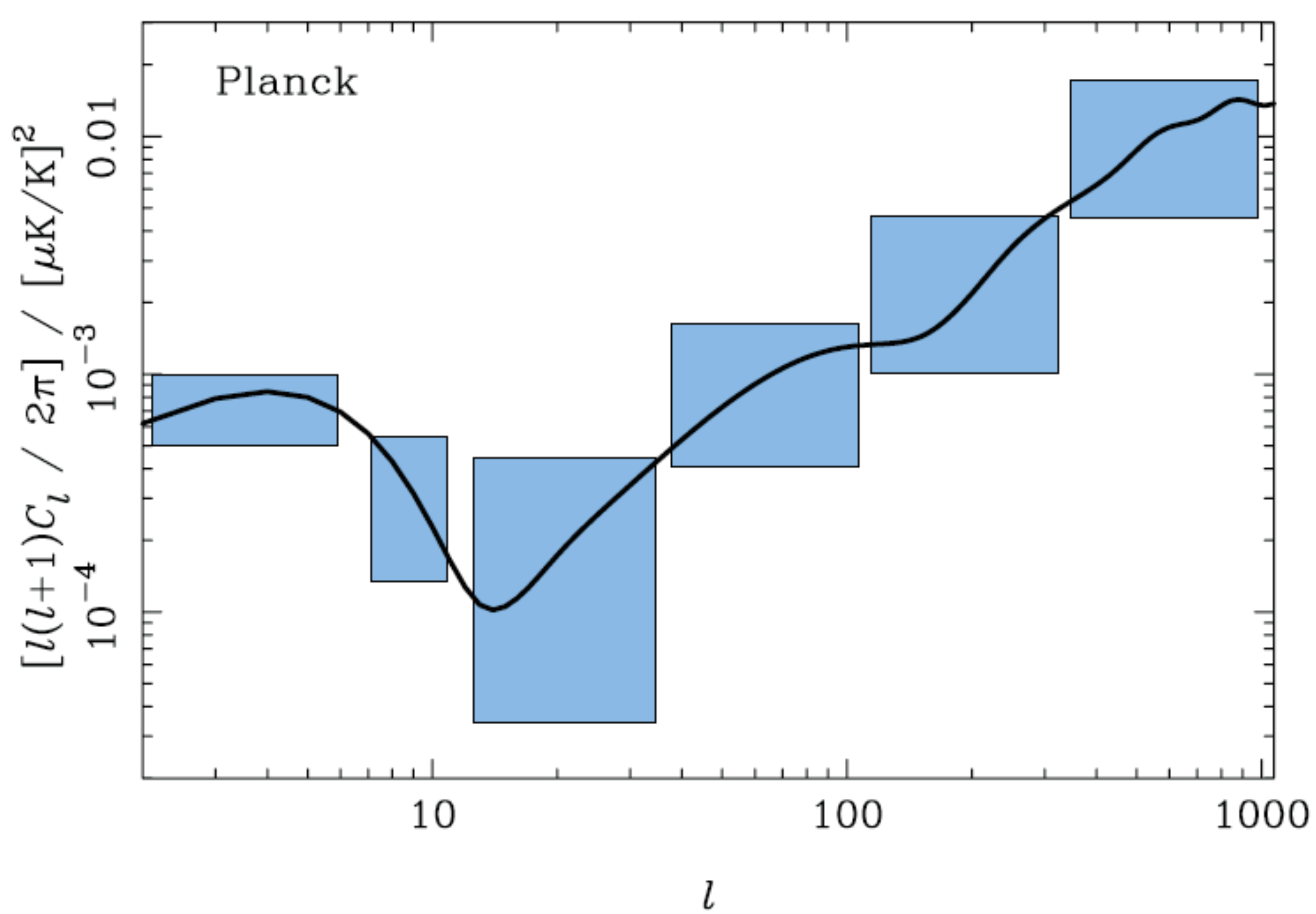


- WMAP: l~1000 => Planck: l~3000

Planck: Expected $C_l^{Polarization}$







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