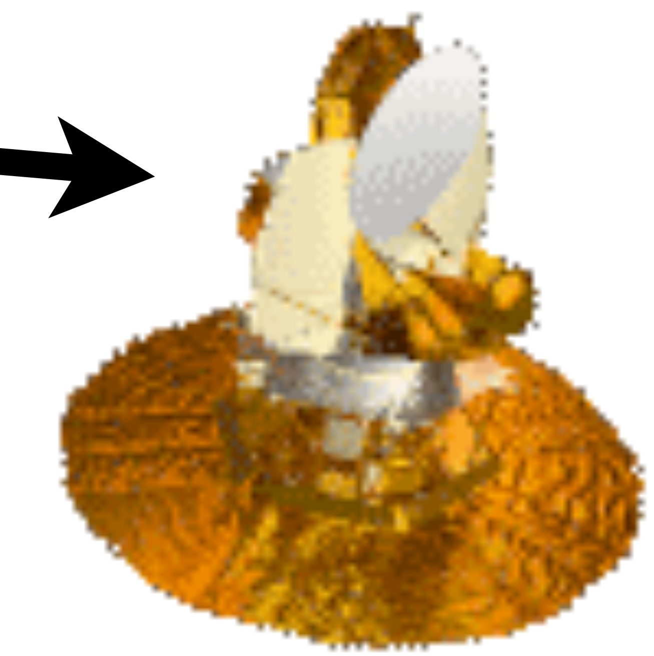
WMAP



Critical Tests of Theory of the Early Universe using the CMB

Eiichiro Komatsu (MPA)

Colloquium, Leibniz-Institut für Astrophysik Potsdam
March 15, 2014

Cosmology: The Questions

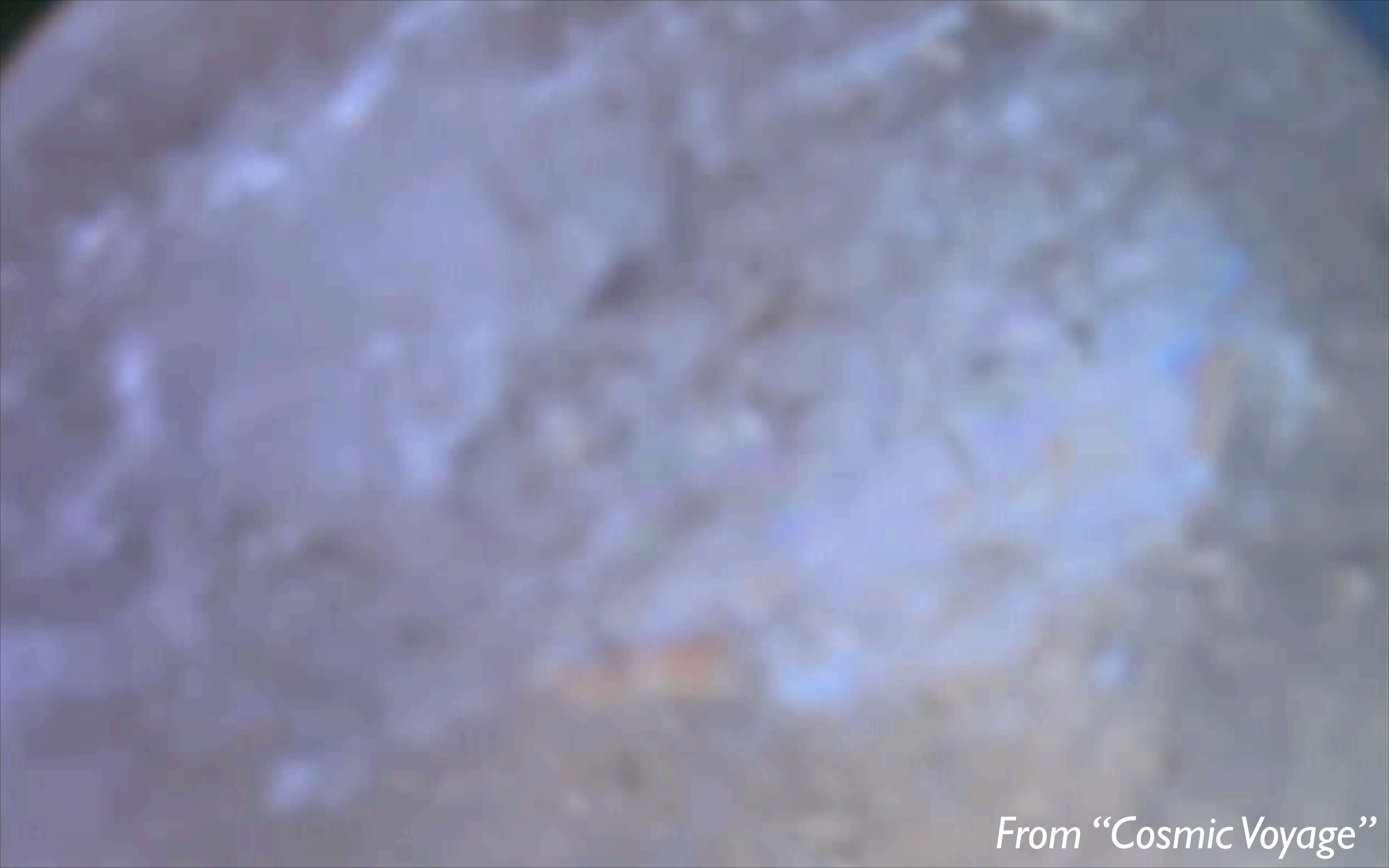
- How much do we understand our Universe?
  - How old is it?
  - How big is it?
  - What shape does it take?
  - What is it made of?
  - How did it begin?

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!

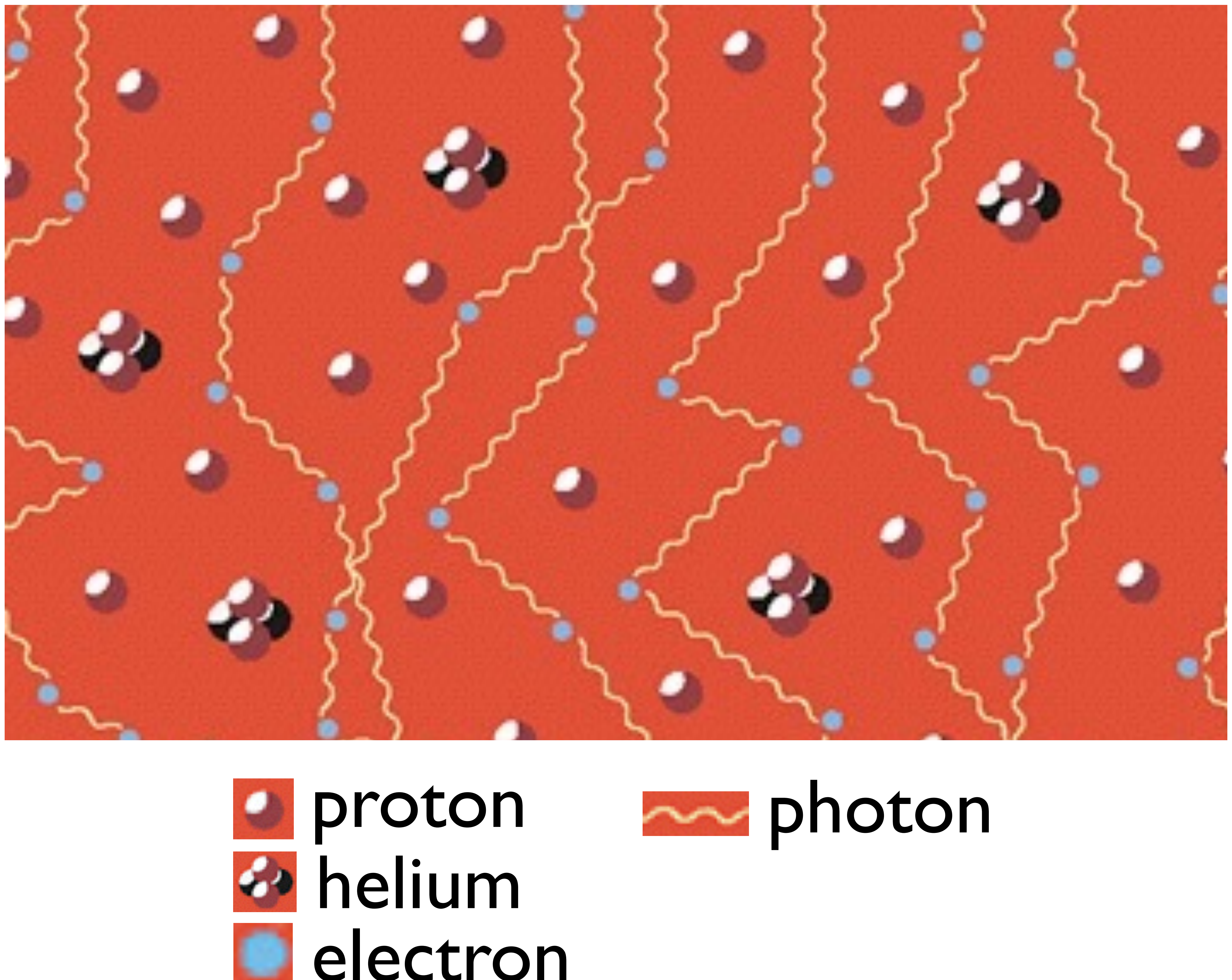


From “Cosmic Voyage”

How was CMB created?

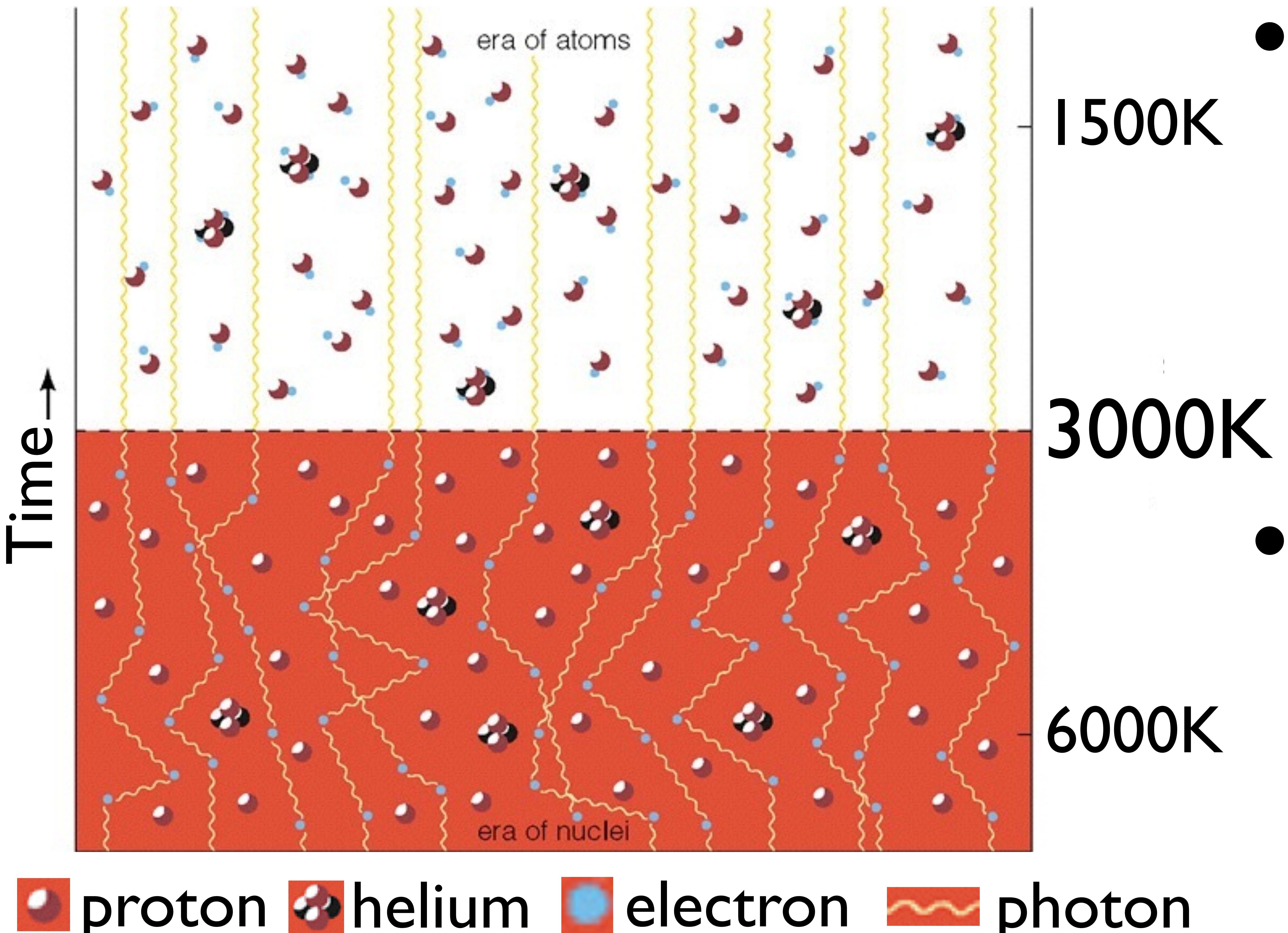
- When the Universe was hot, it was a hot soup made of:
  - Protons, electrons, and helium nuclei
  - Photons and neutrinos
  - Dark matter (DM)
    - DM does not do much, except for providing a a gravitational potential because $\rho_{DM}/\rho_{H,He}$~5

Universe as a hot soup



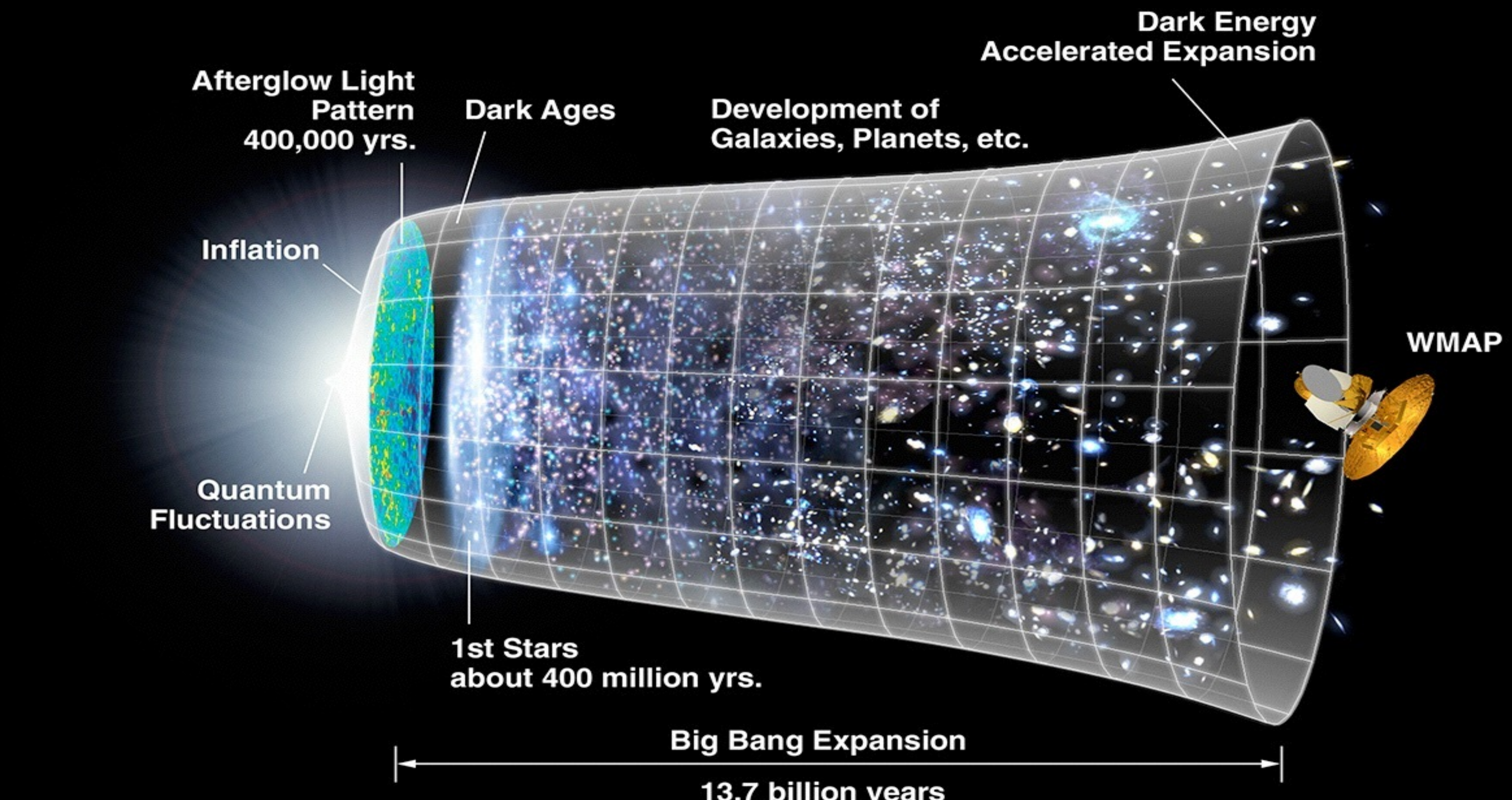
- Free electrons can scatter photons efficiently.
- Photons cannot go very far.

Recombination and Decoupling



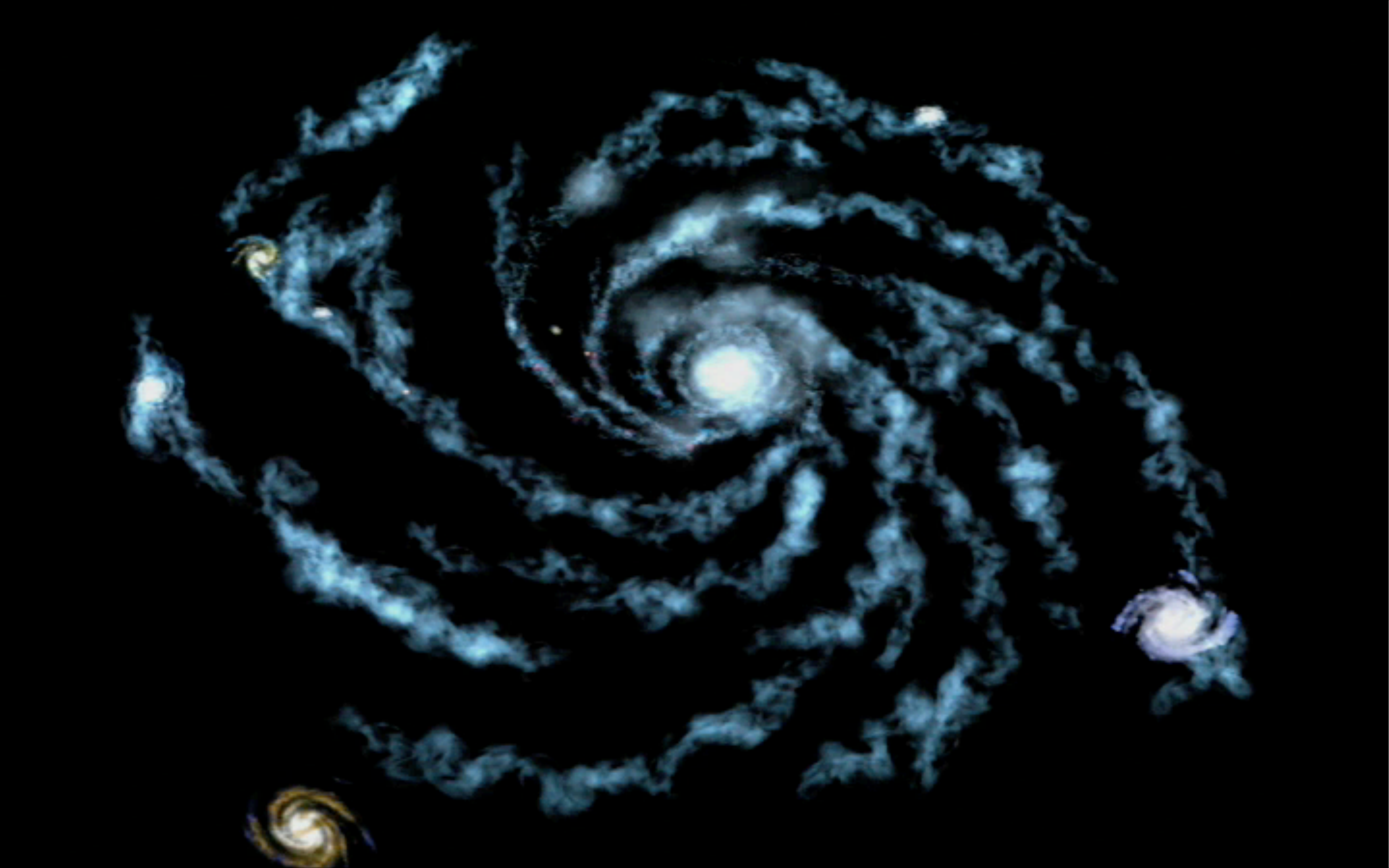
- [*recombination*] When the temperature falls below 3000 K, almost all electrons are captured by protons and helium nuclei.
- [*decoupling*] Photons are no longer scattered. I.e., photons and electrons are no longer coupled.

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



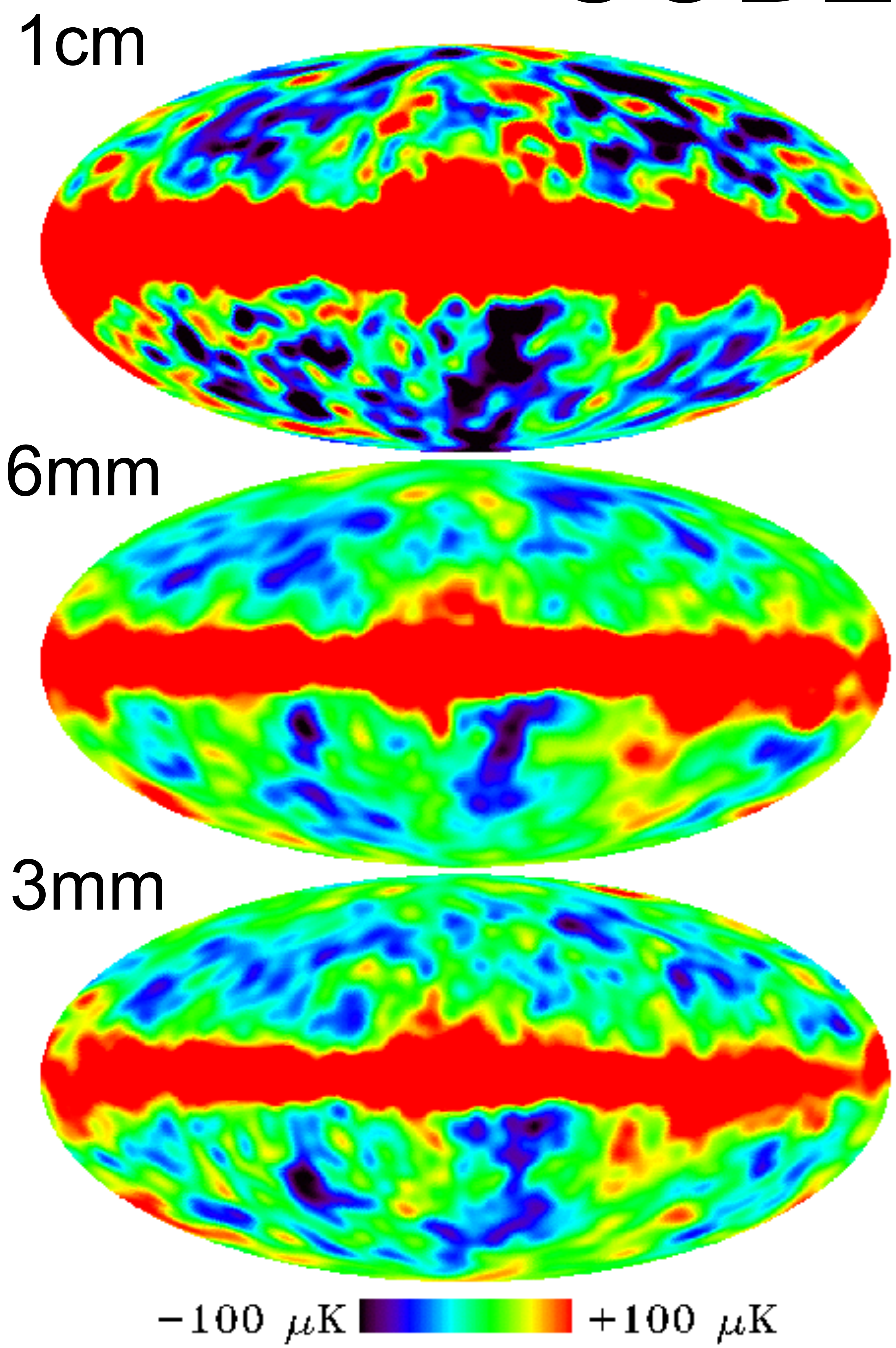
- When the Universe was 3000K (~380,000 years after the Big Bang), electrons and protons were combined to form neutral hydrogen.

NASA/WMAP Science Team



Smoot et al. (1992)

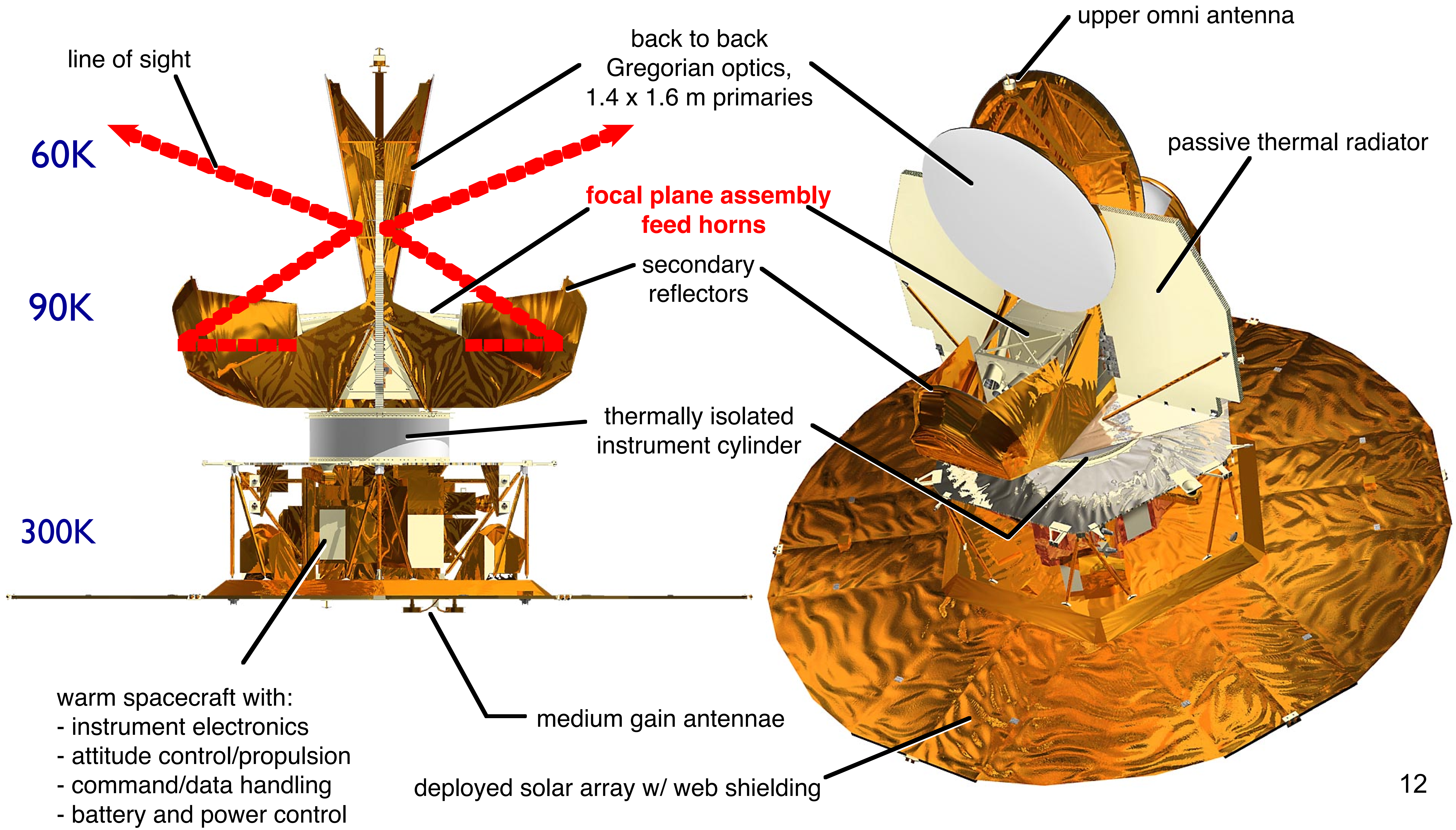
COBE/DMR, 1992



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

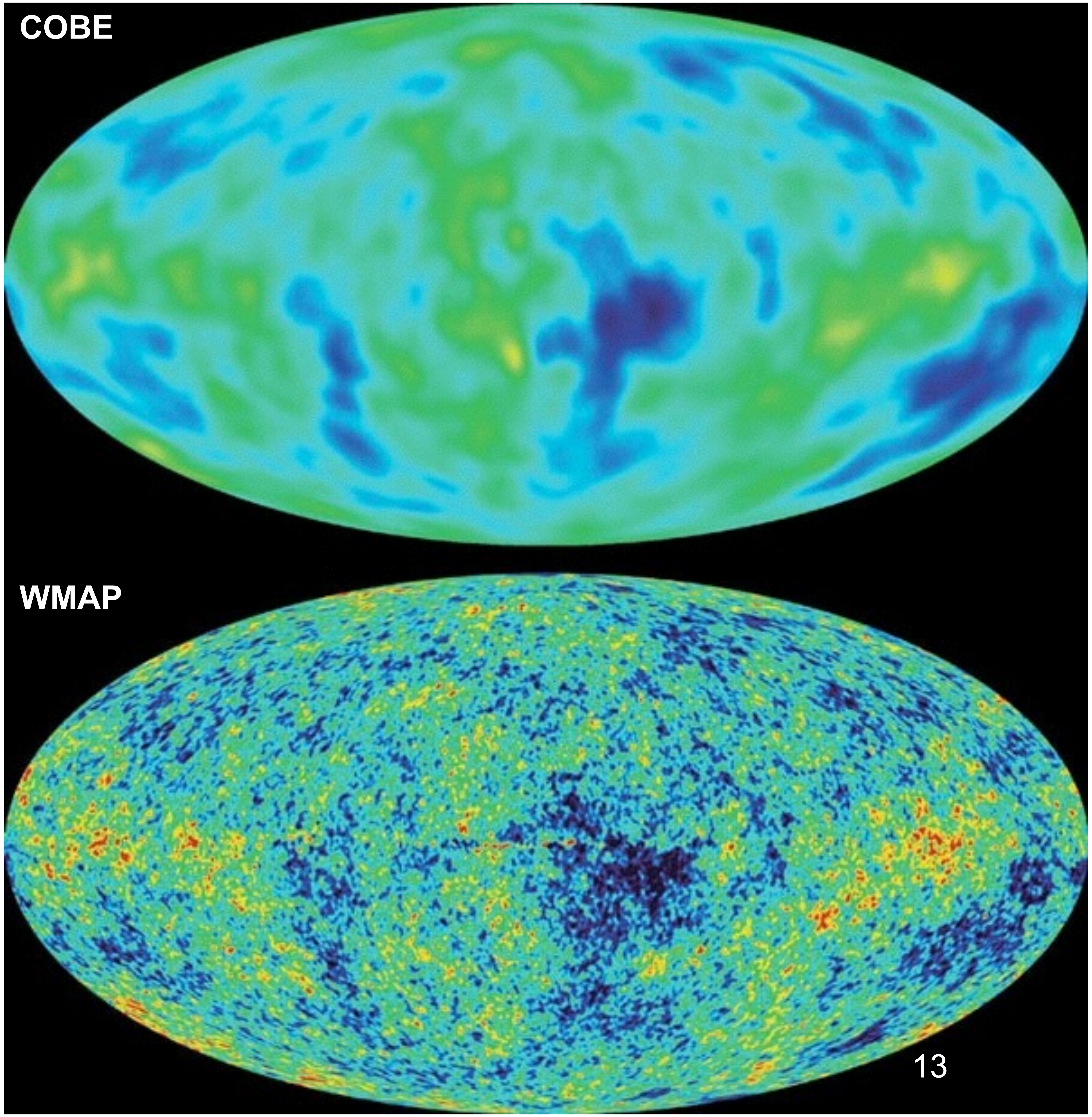
WMAP Spacecraft

Radiative Cooling: No Cryogenic System



COBE to WMAP (x35 better resolution)

COBE
1989



WMAP
2001

used to be

WMAP at Lagrange 2 (L2) Point

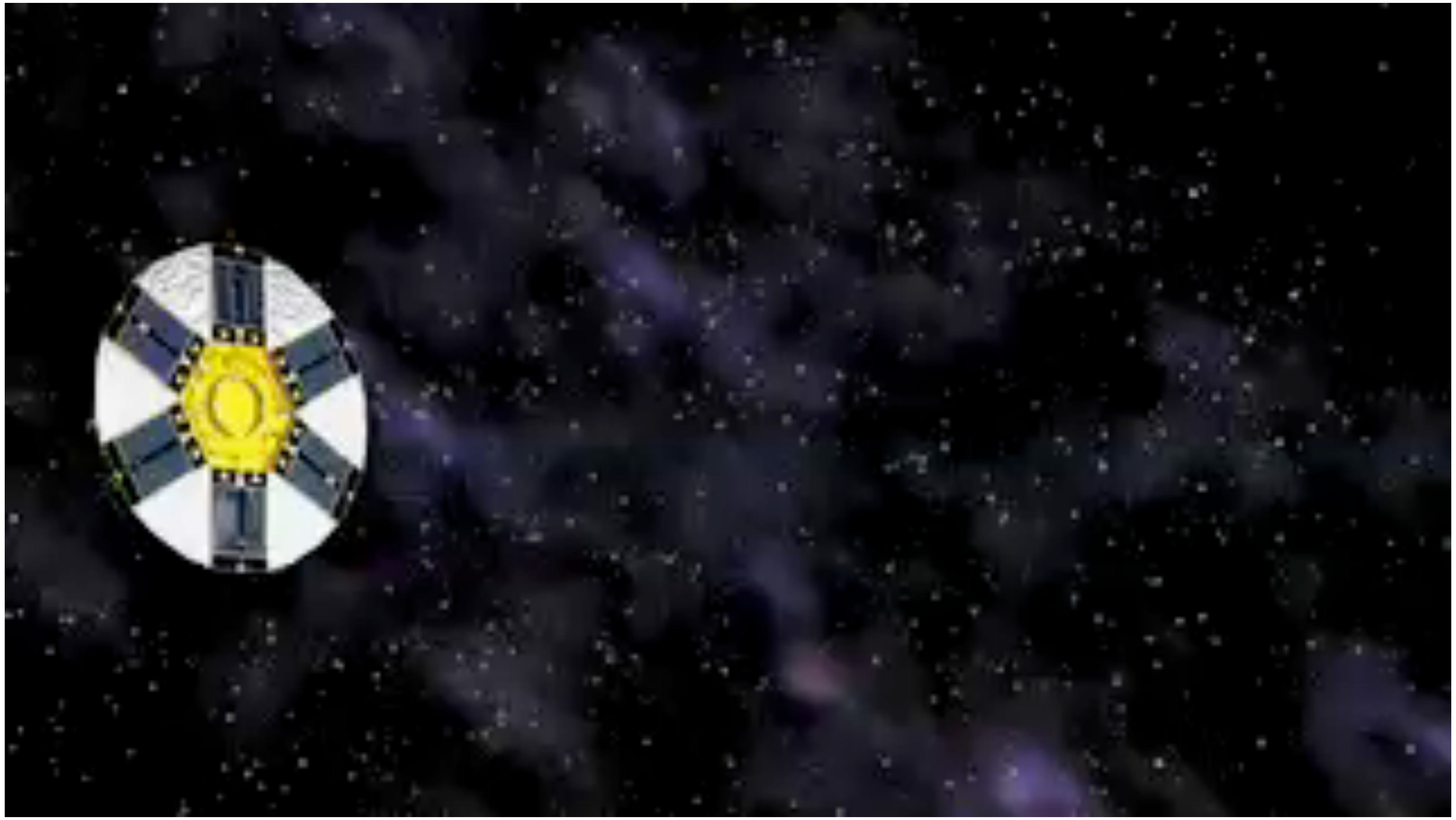
June 2001:
WMAP launched!

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



September 8, 2010:
WMAP left L2

December 21, 2012:
The final, nine-year data release

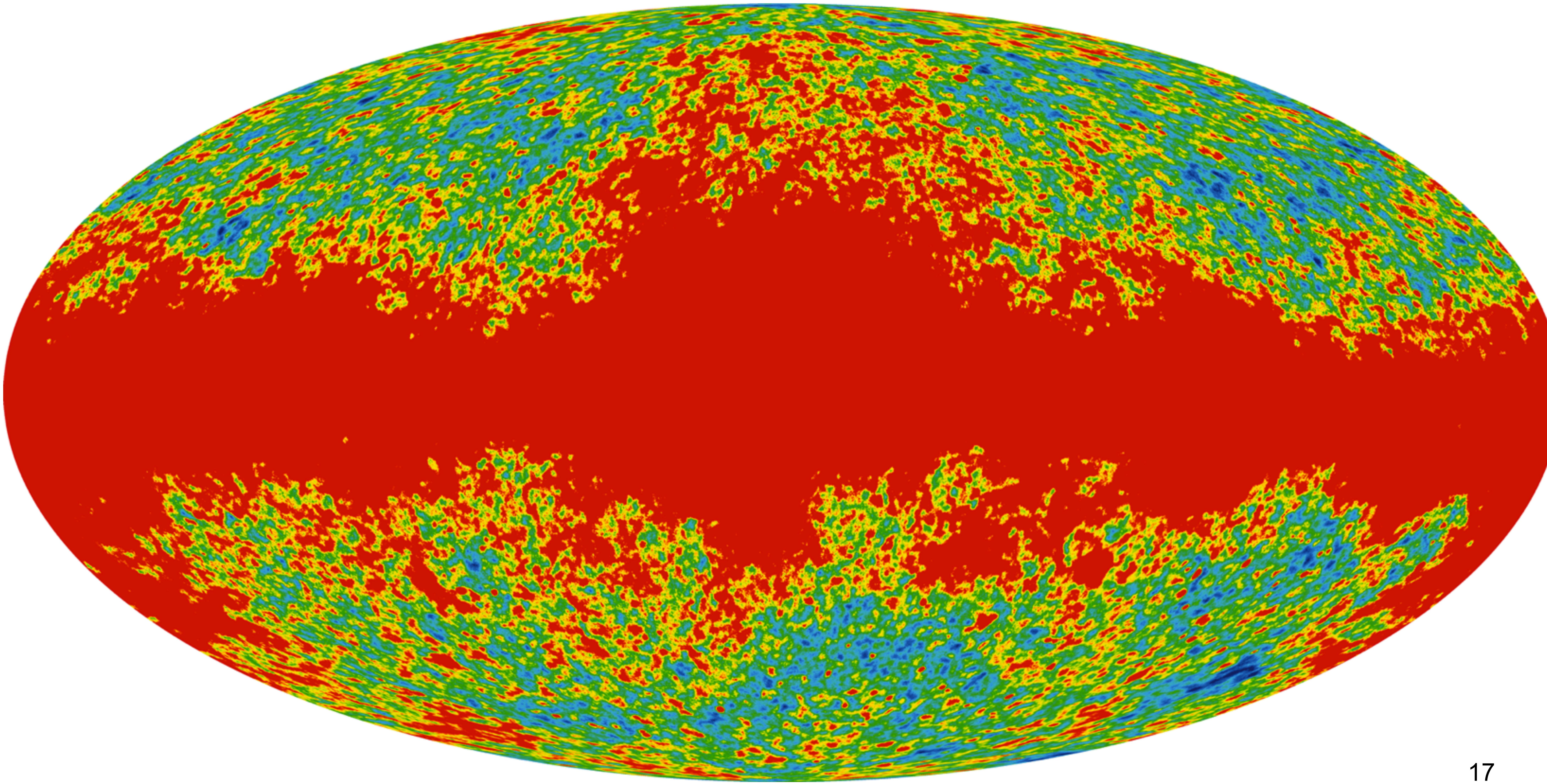
WMAP Science Team

- 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

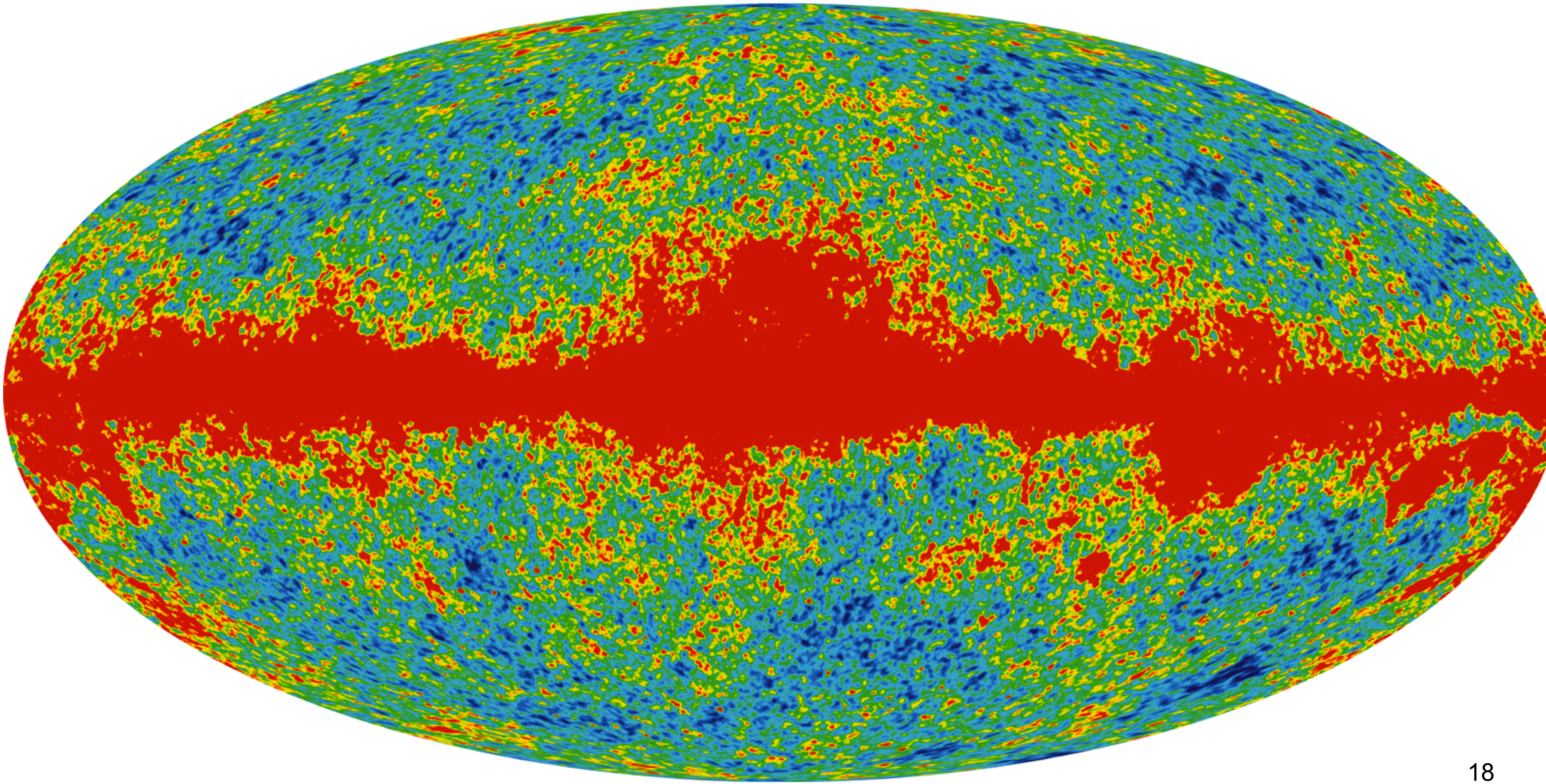
WMAP 9-Year Papers

- **Bennett et al.**, "*Final Maps and Results*," ApJS, 208, 20
- **Hinshaw et al.**, "*Cosmological Parameter Results*," ApJS, 208, 19

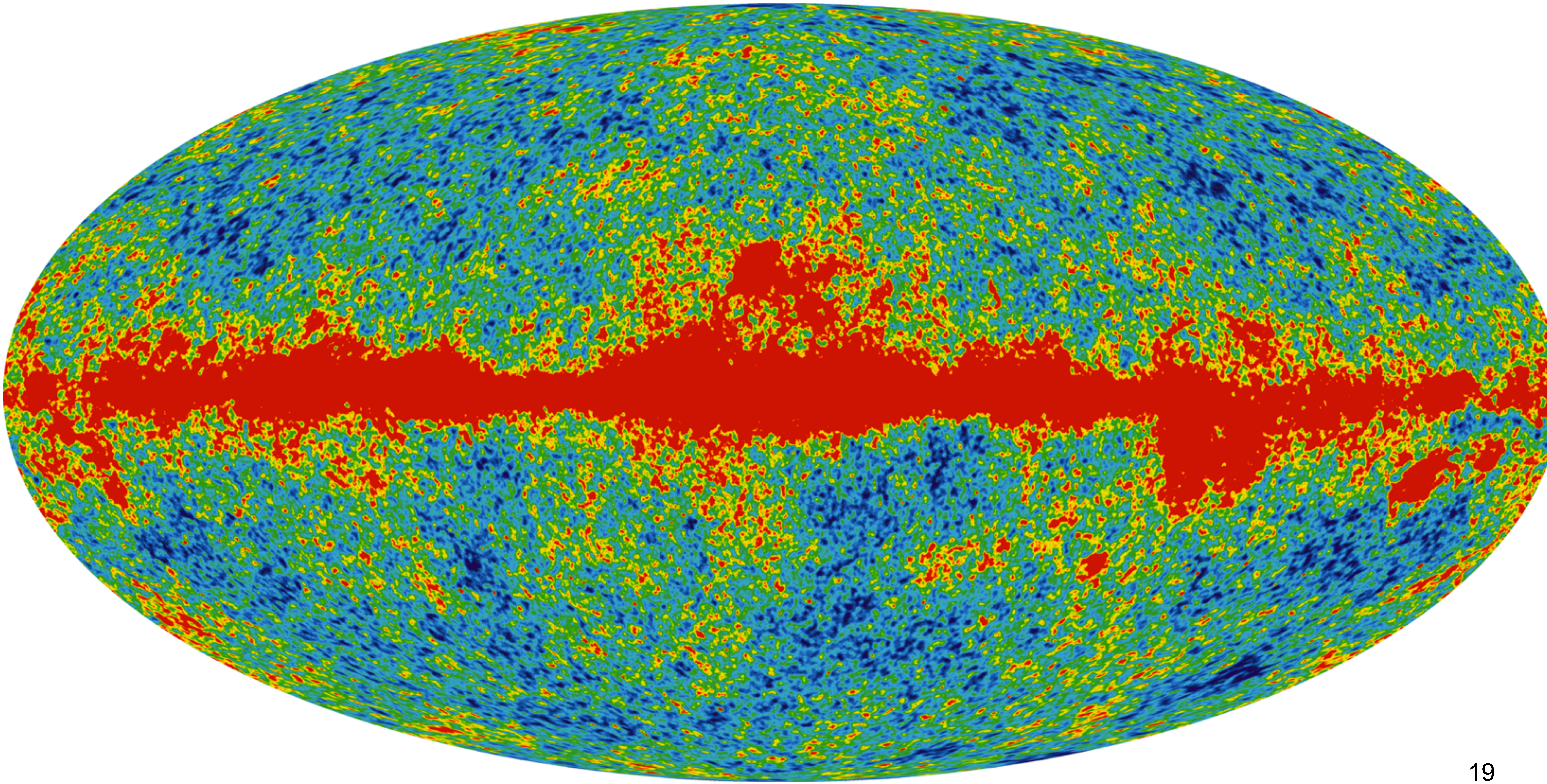
23 GHz [unpolarized]



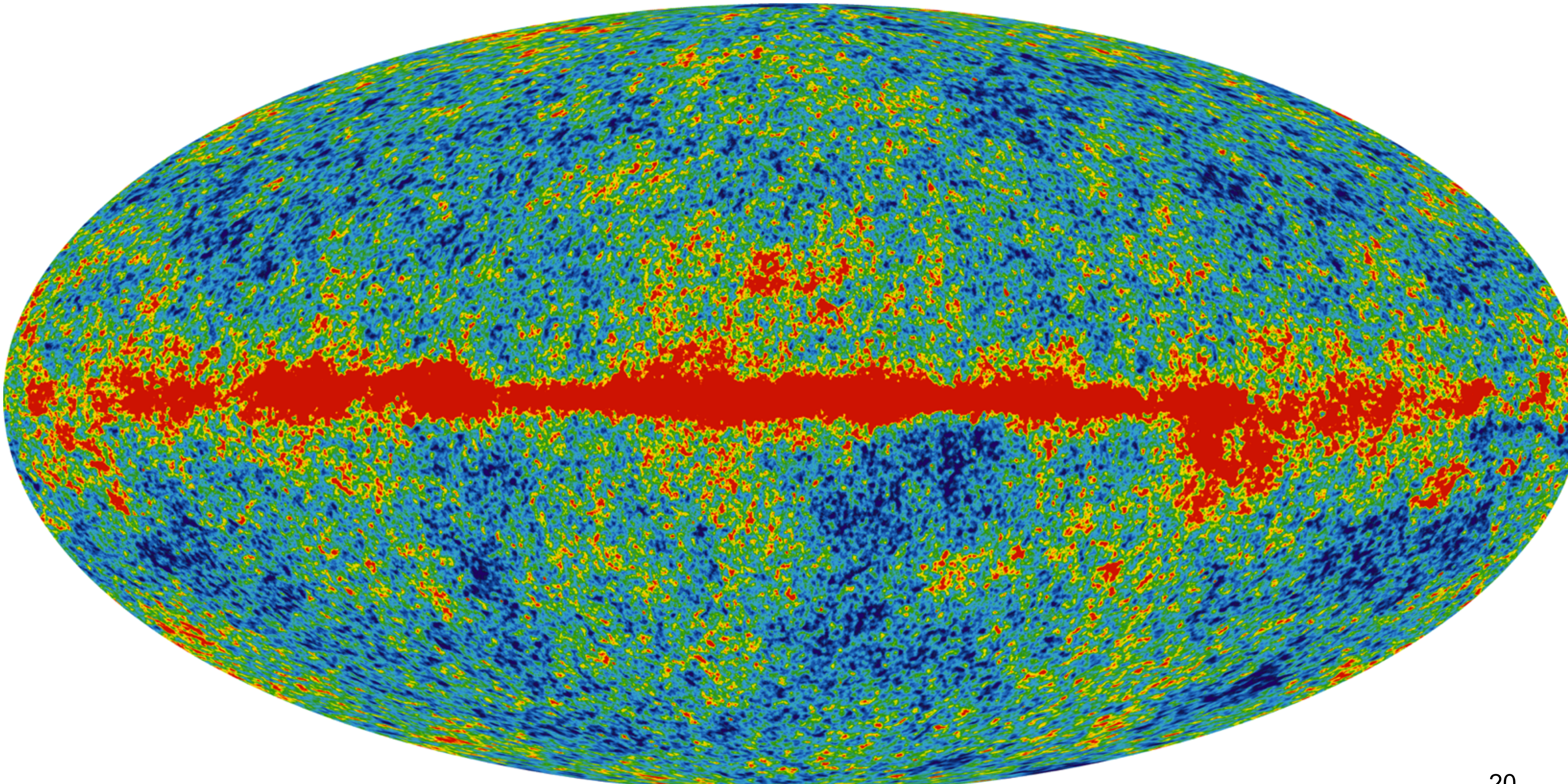
33 GHz [unpolarized]



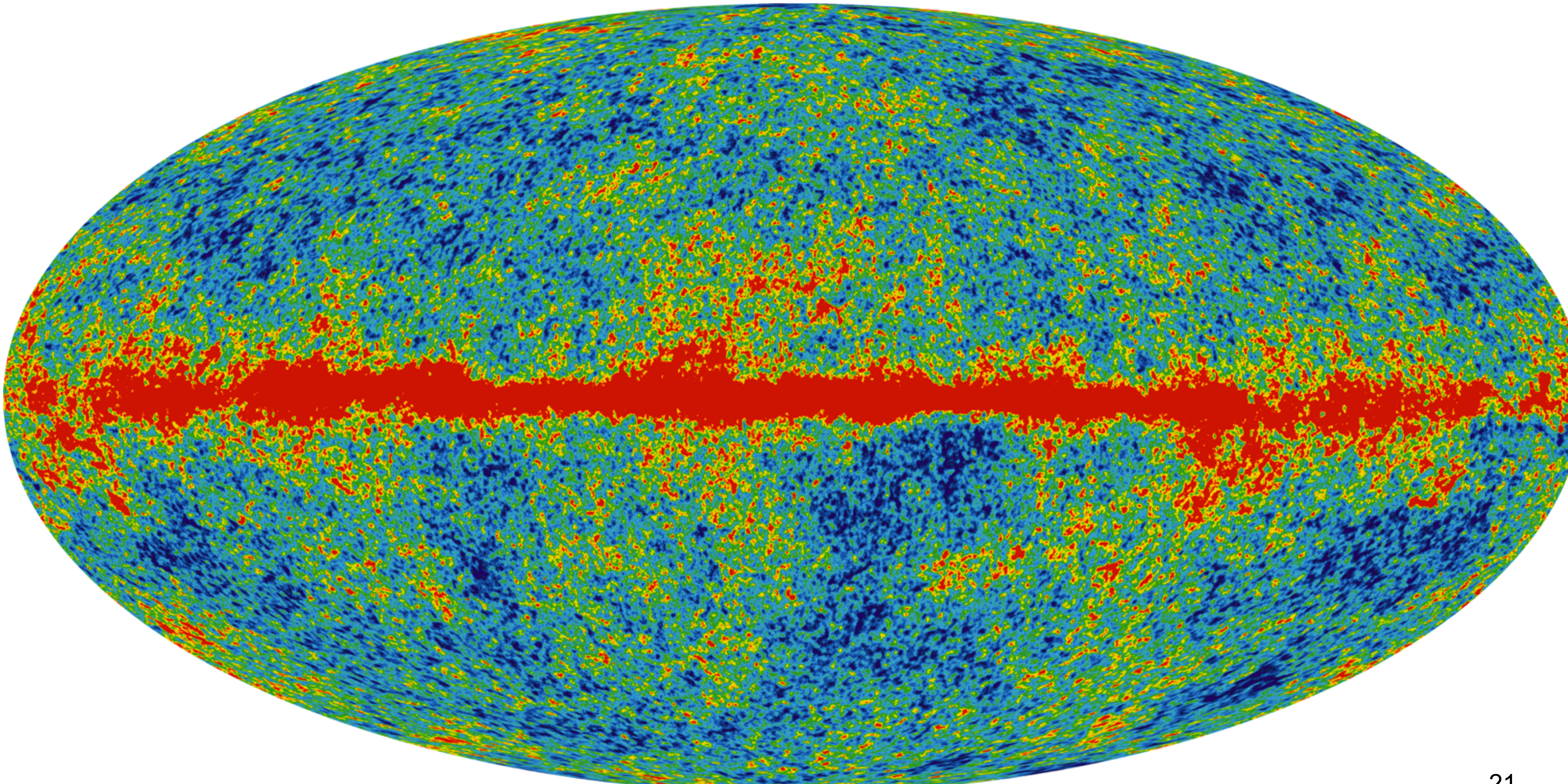
41 GHz [unpolarized]



61 GHz [unpolarized]



94 GHz [unpolarized]

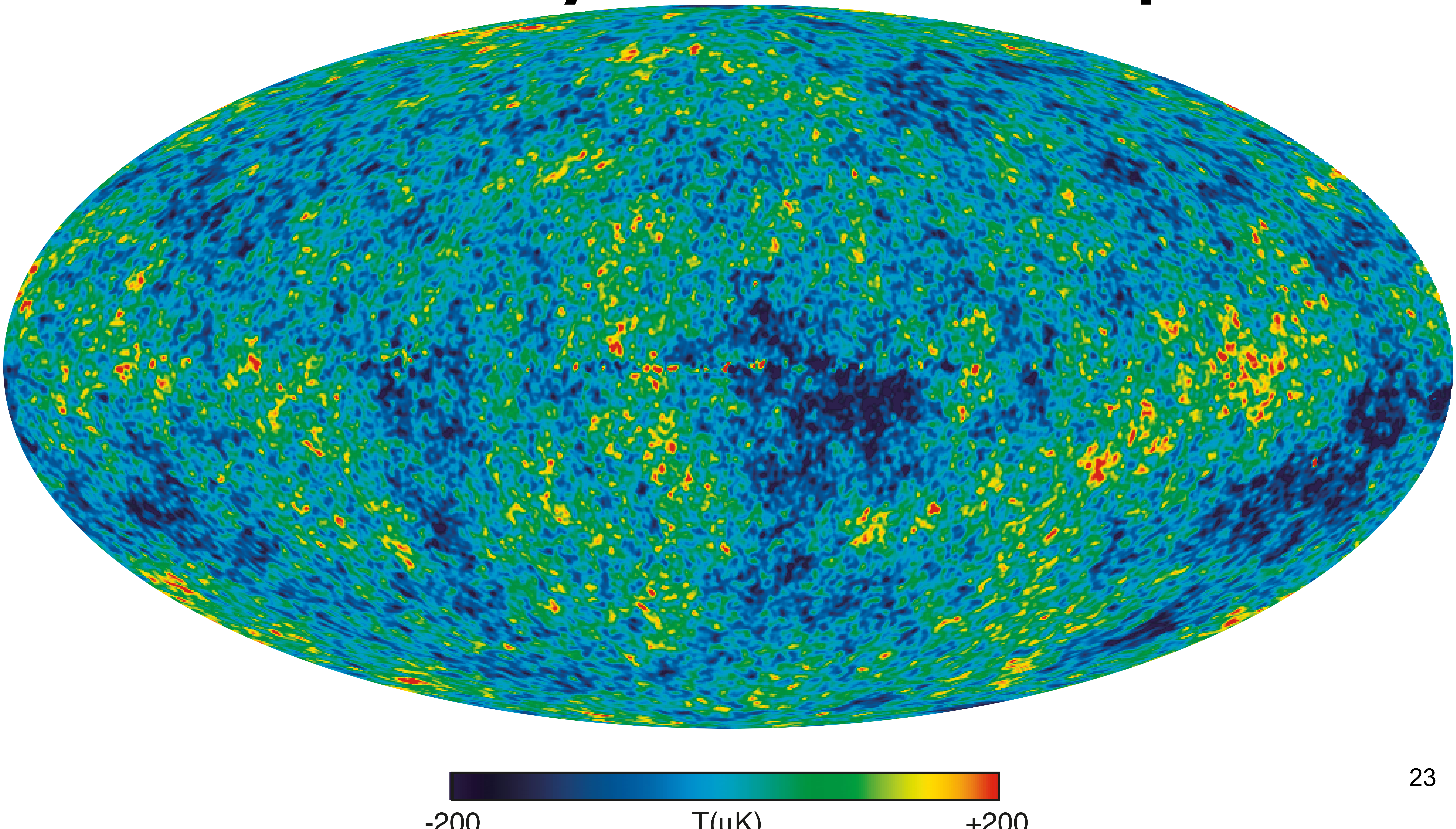


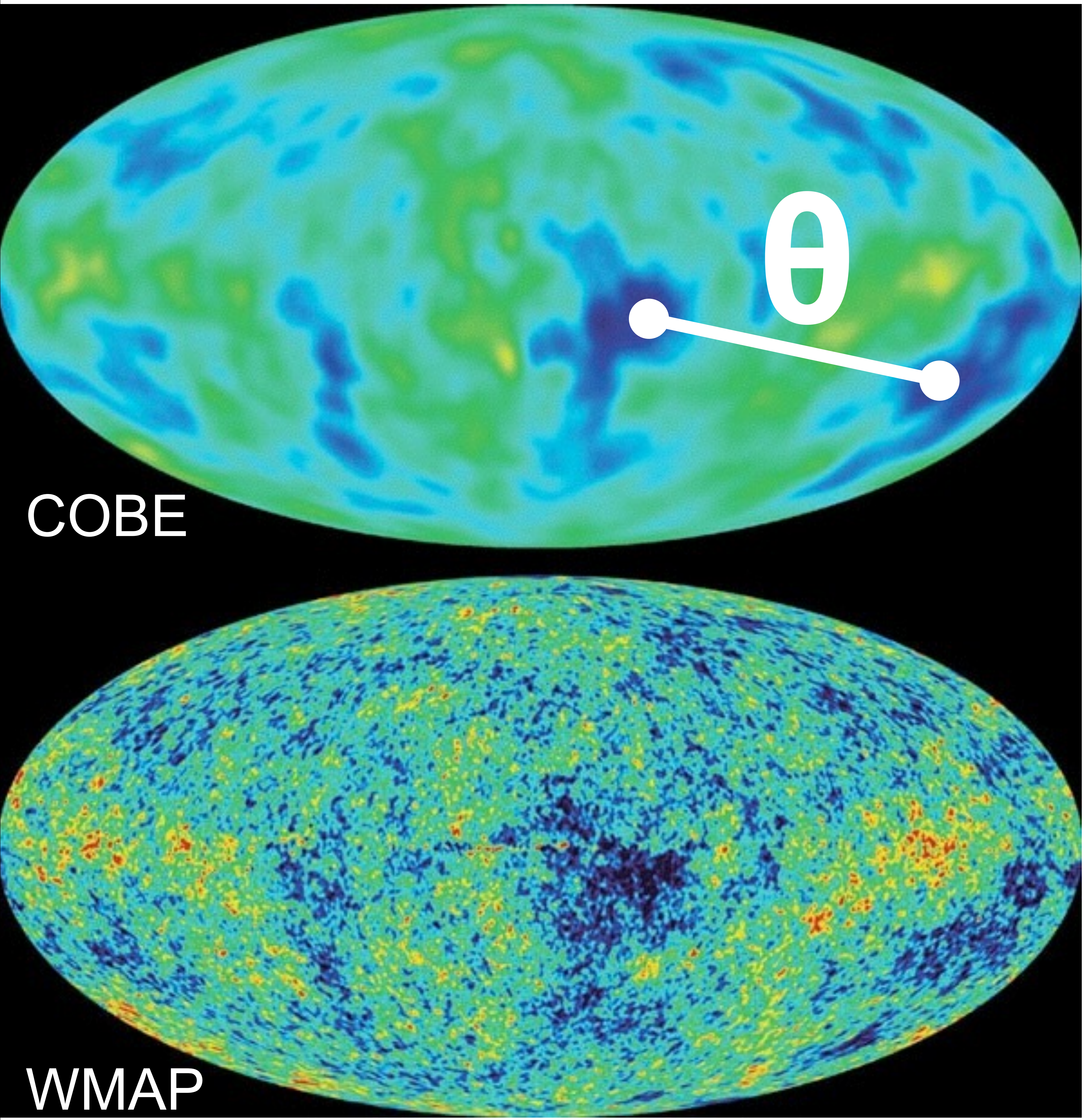
How many components?

1. **CMB**: $T_\nu \sim \nu^0$
2. **Synchrotron** (electrons going around magnetic fields): $T_\nu \sim \nu^{-3}$
3. **Free-free** (electrons colliding with protons): $T_\nu \sim \nu^{-2}$
4. **Dust** (heated dust emitting thermal emission): $T_\nu \sim \nu^2$
5. **Spinning dust** (rapidly rotating tiny dust grains): $T_\nu \sim$complicated

You need at least five frequencies to separate them!

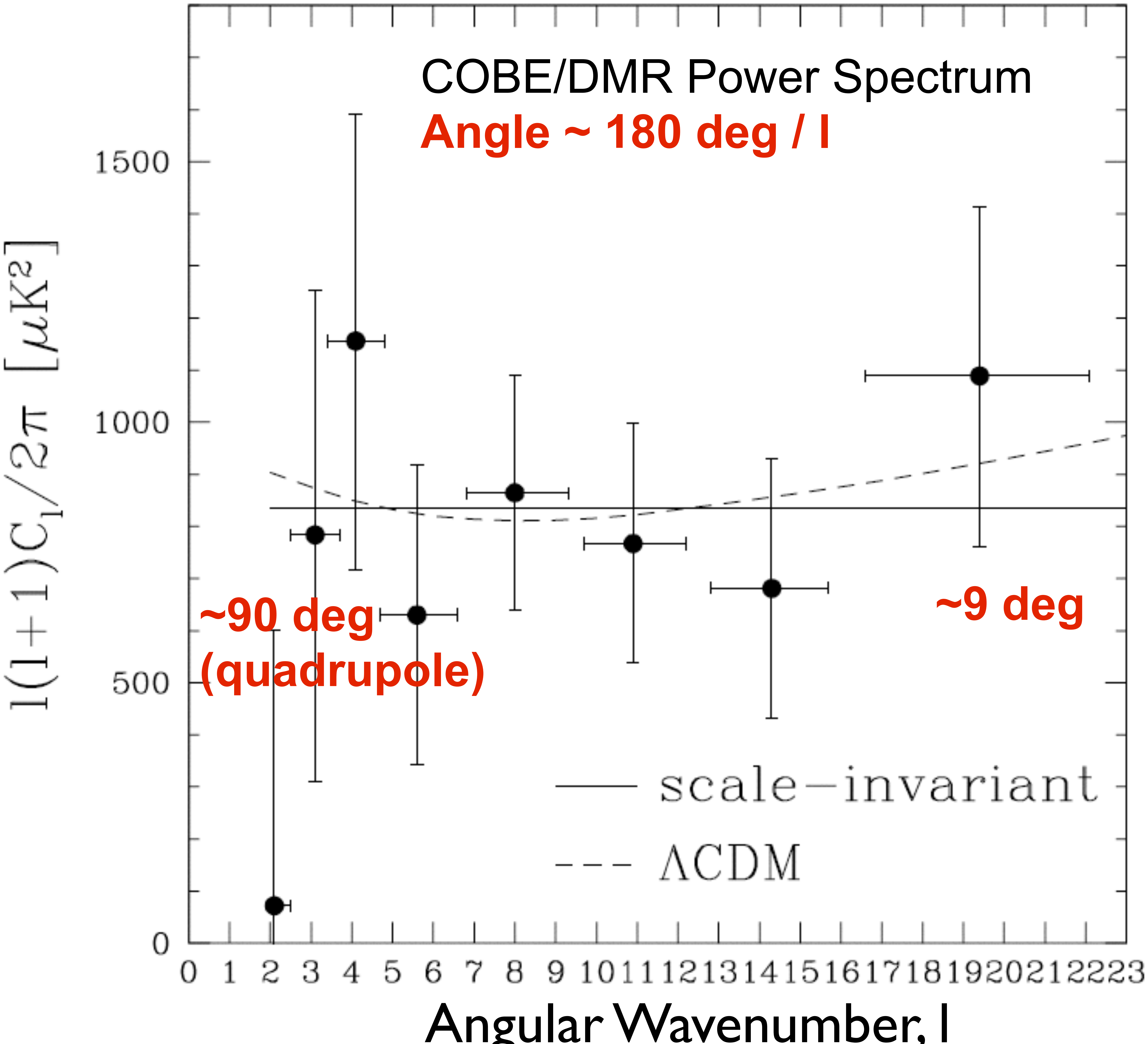
Galaxy-cleaned Map



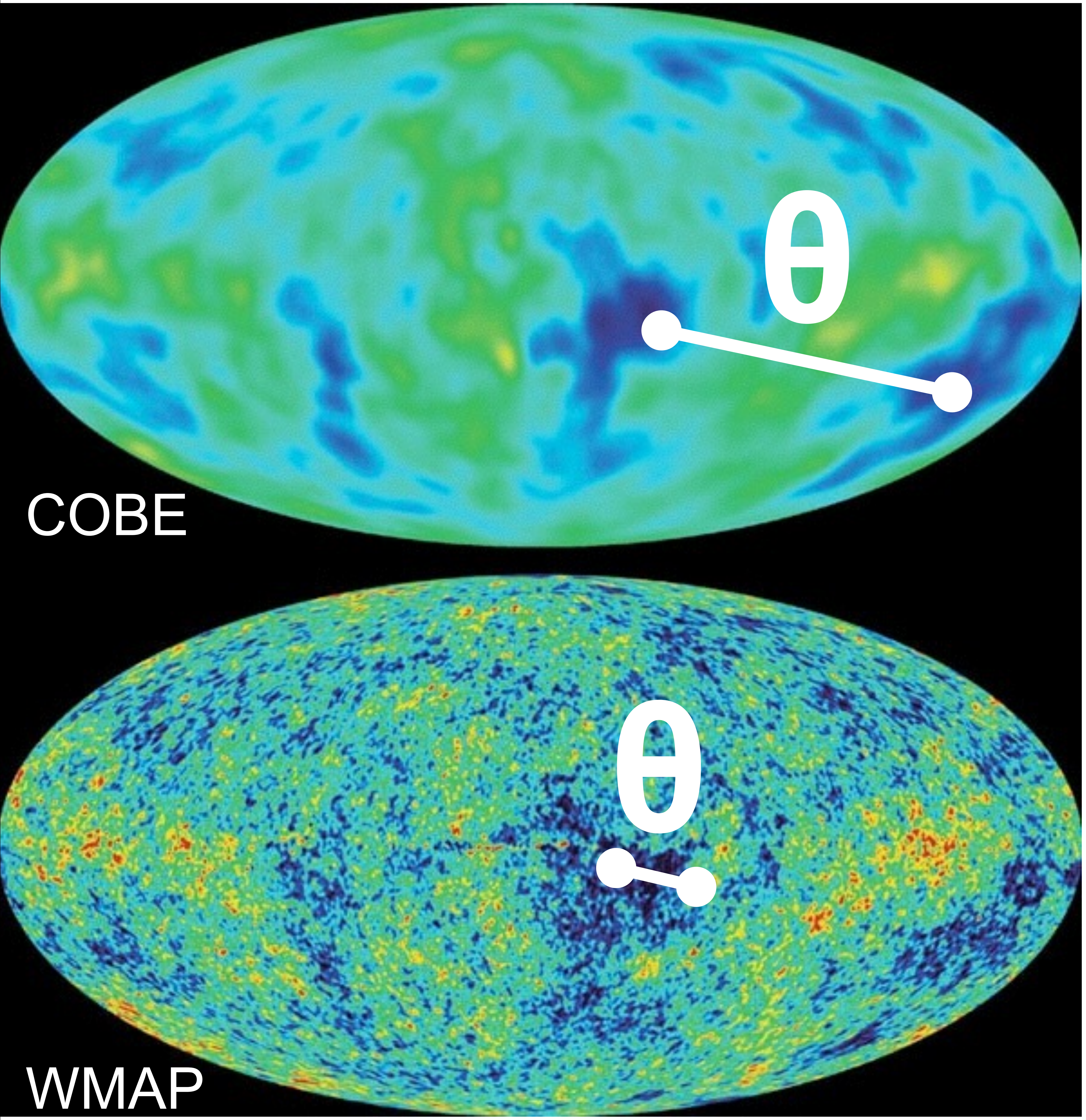


Analysis: 2-point Correlation

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



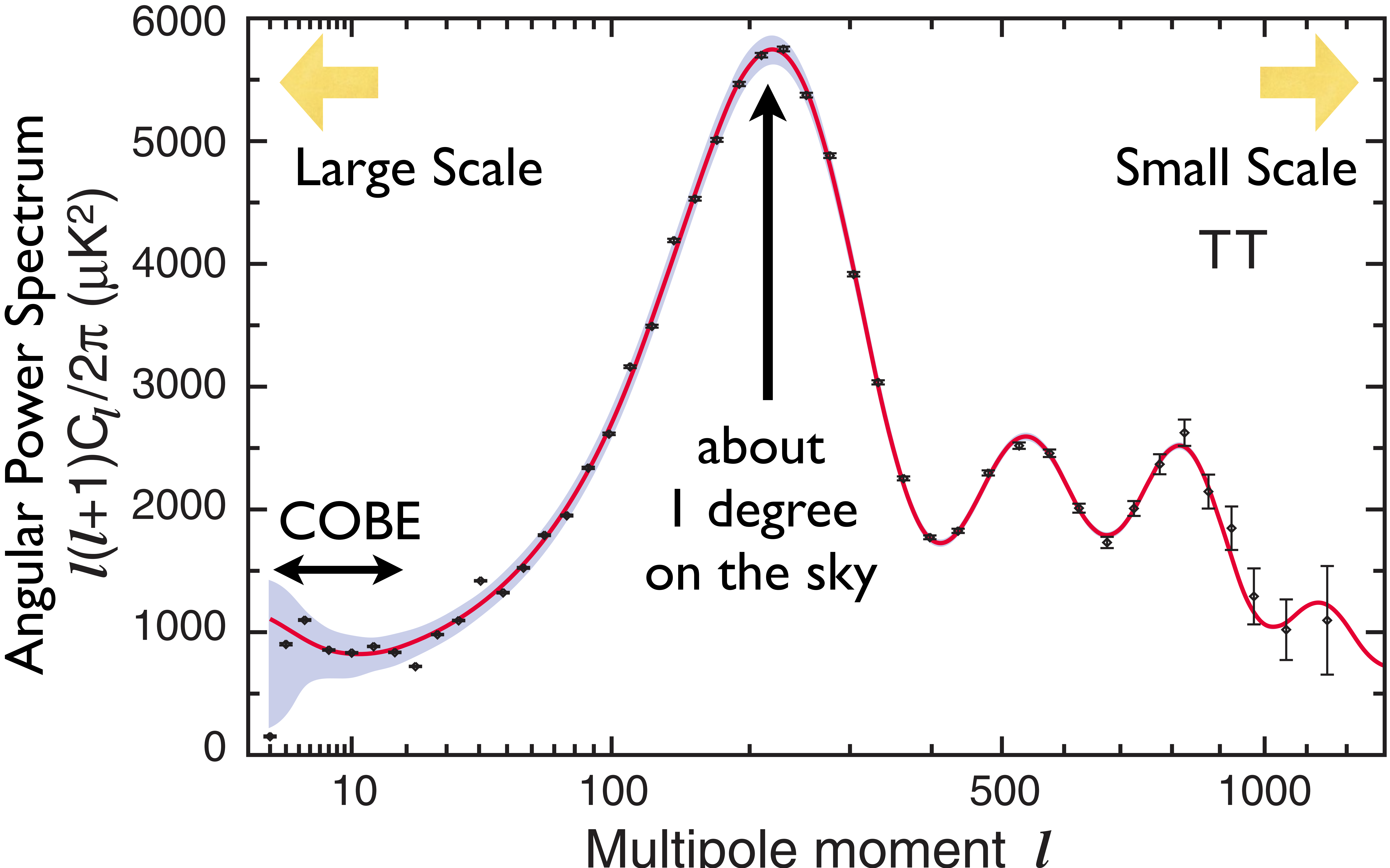
COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
$l(l+1)C_l/2\pi\ [\mu K^2]$
0
500
1000
1500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Angular Wavenumber, l



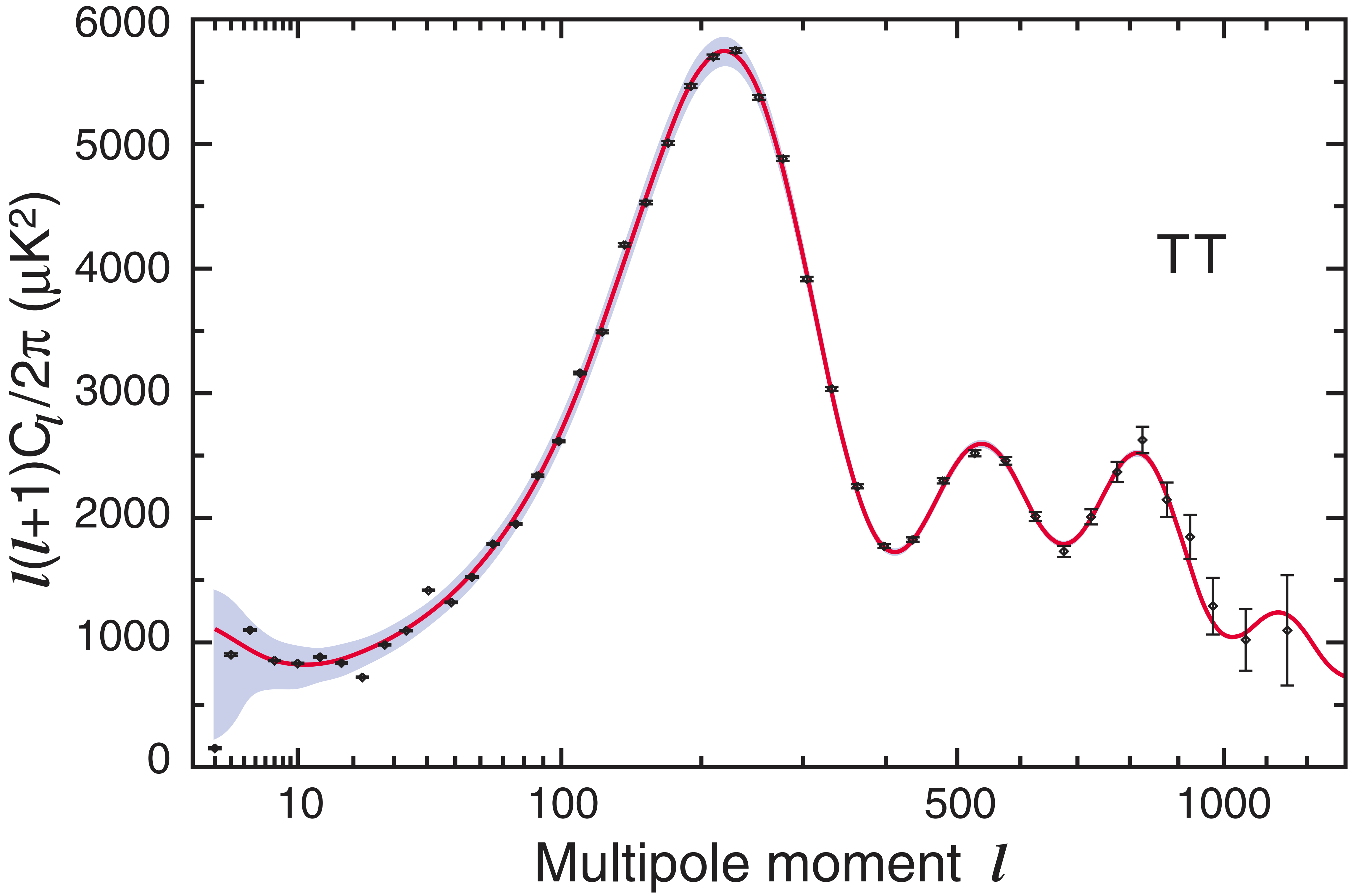
COBE To WMAP

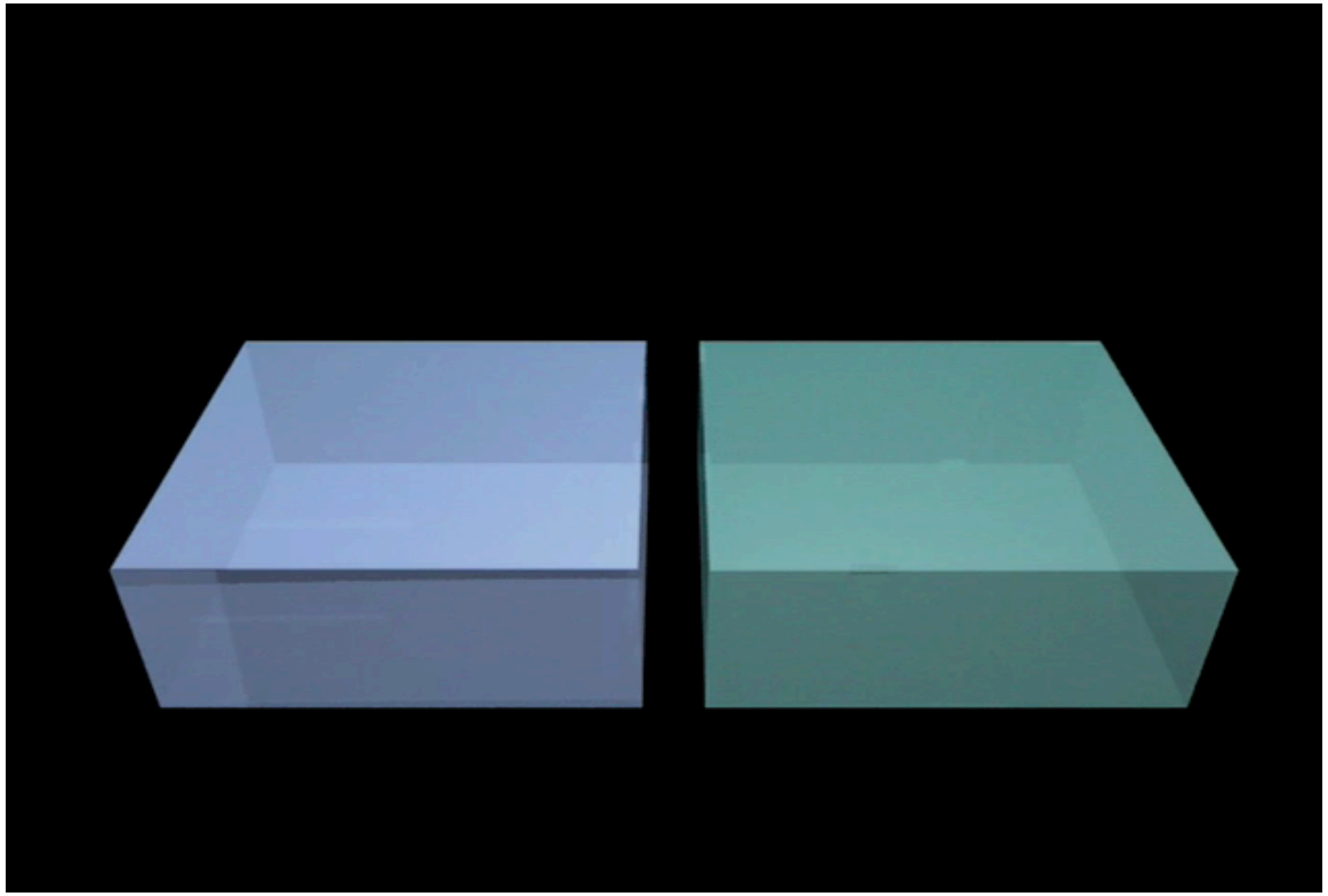
- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP 9-year Power Spectrum



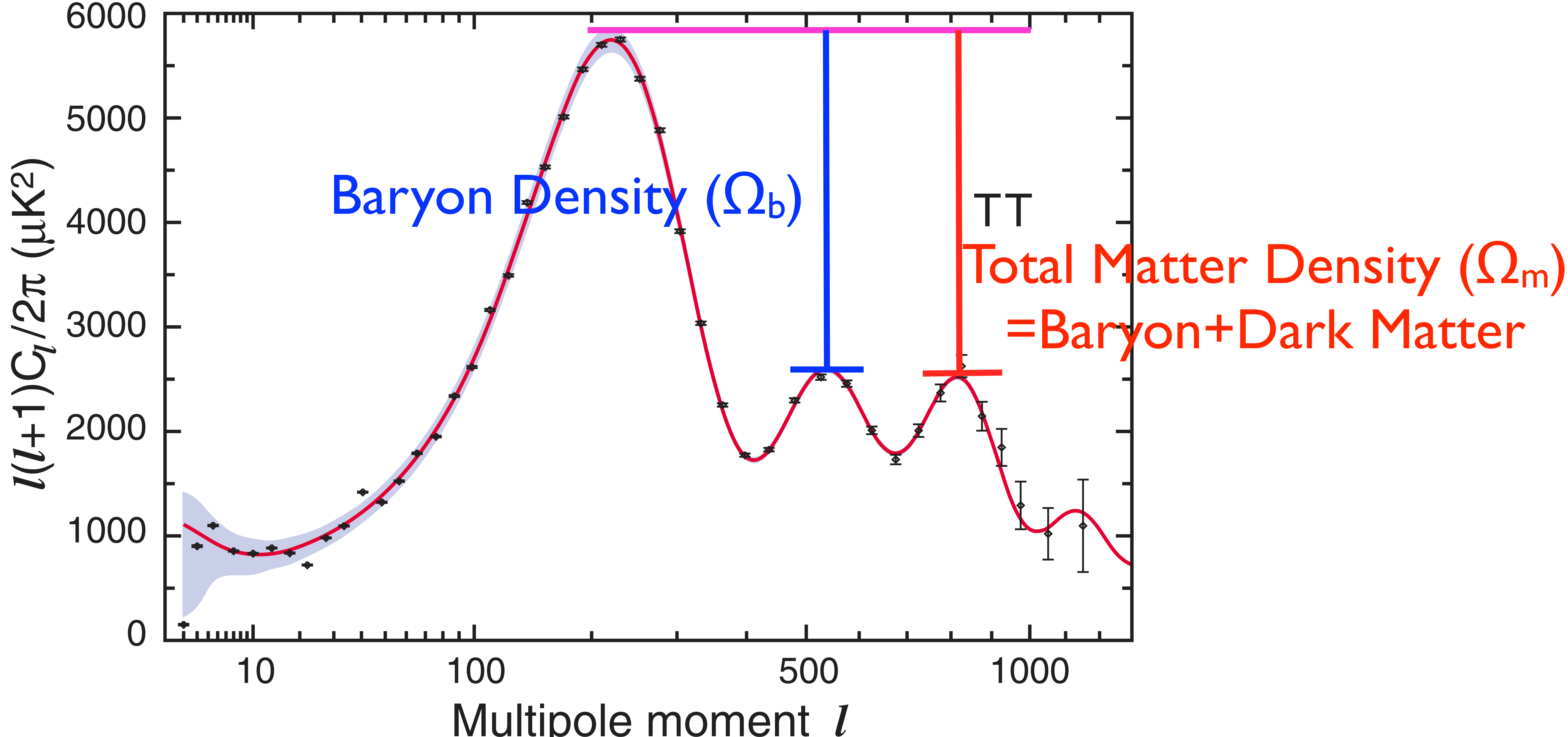
The Cosmic Sound Wave





- *"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

With CMB, we can measure:

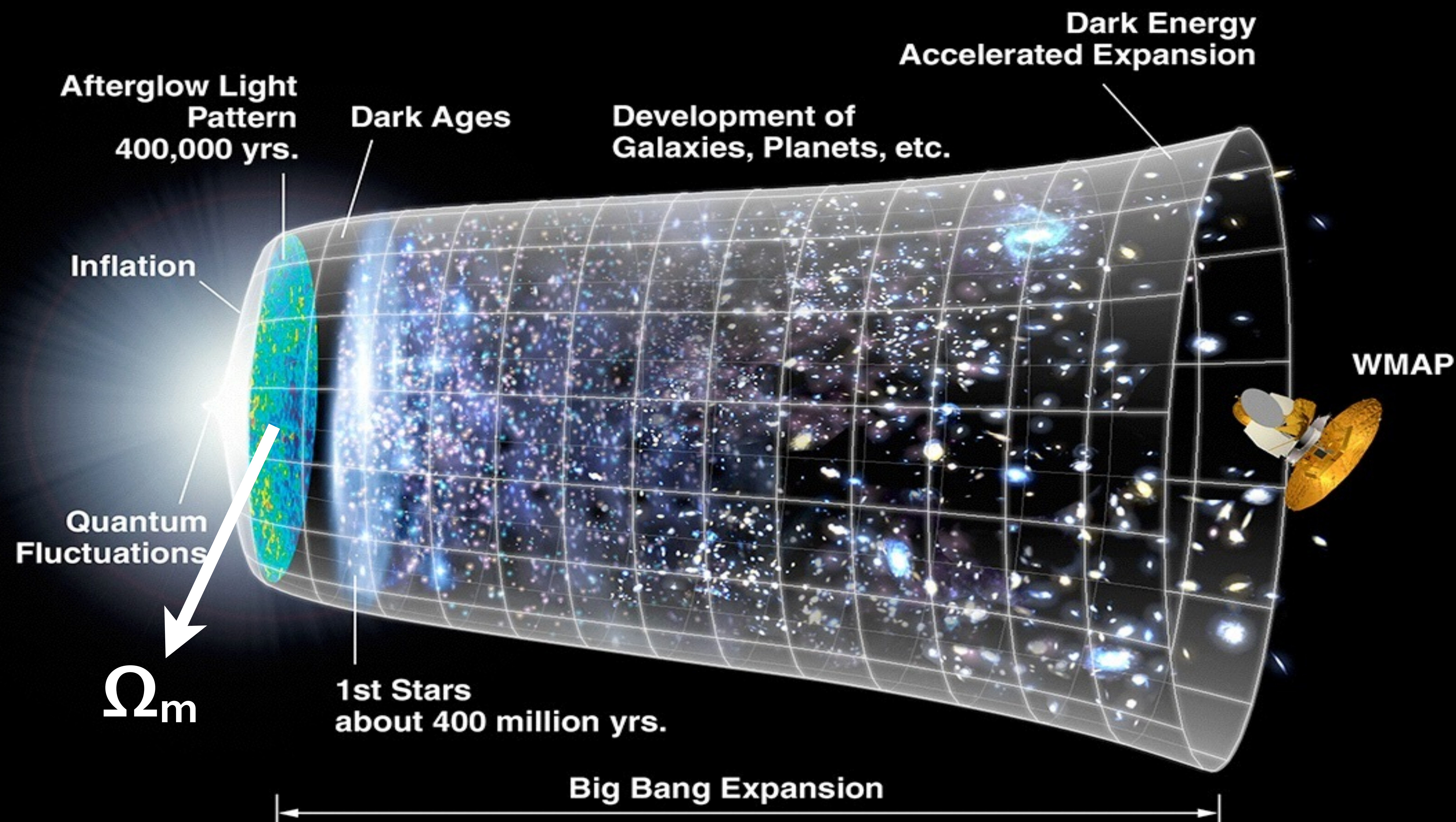
- Amount of protons and helium nuclei; or **anything that can interact with photons**

- Amount of dark matter; **or anything that can contribute to gravitational potential**

...at the time when the universe was at 3000 K.

No matter is left behind!

Total Matter Density from z=1090
Total Energy Density from the Distance to z=1090



- Angular Diameter Distance to z=1090

$$=H_0^{-1} \int dz / [\Omega_m(1+z)^3+\Omega_\Lambda]^{1/2}$$

dark energy

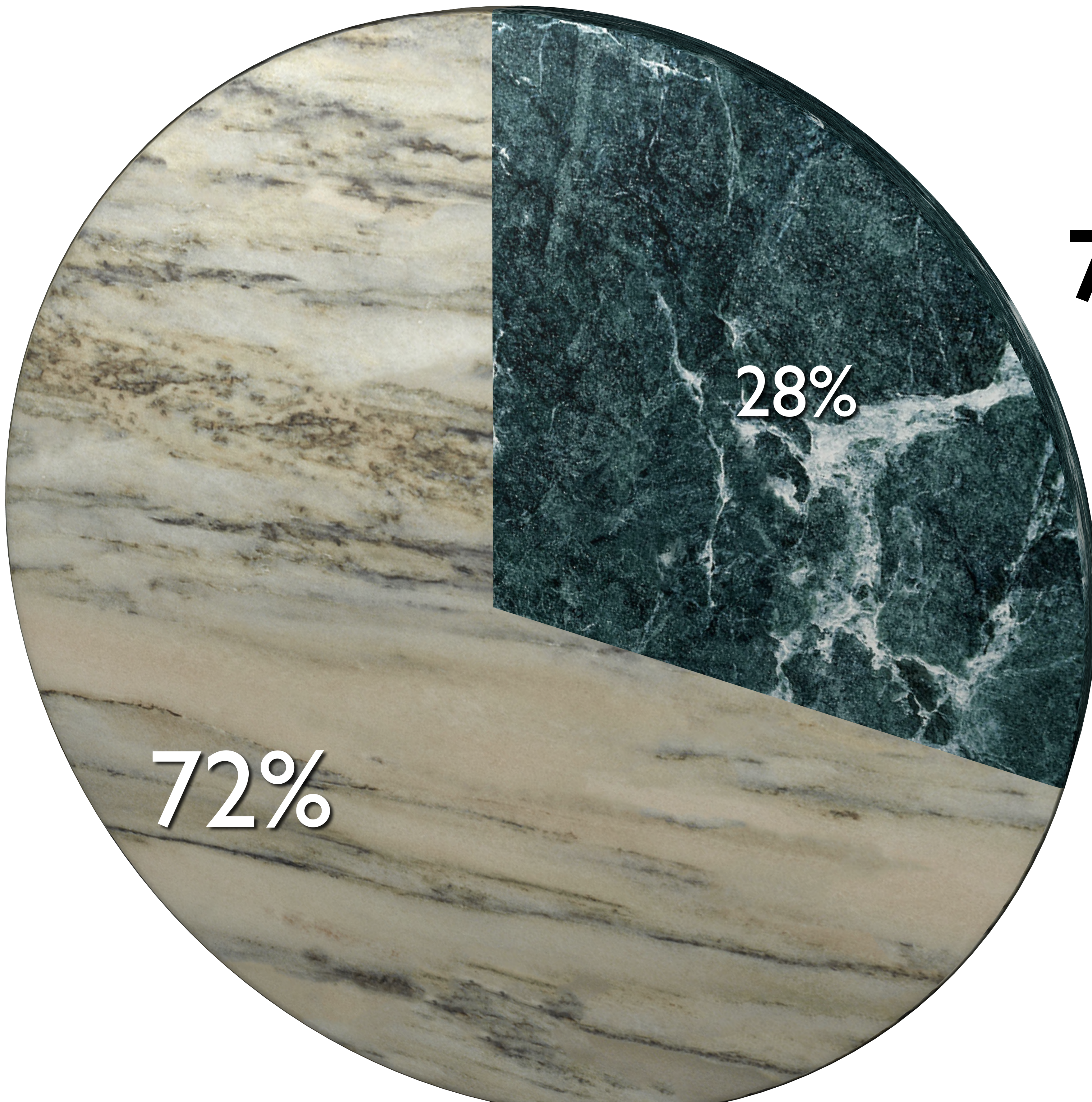
NASA/WMAP Science Team

Parameter	Nine-year
Fit parameters	
$\Omega_b h^2$	0.02264 ± 0.00050
$\Omega_c h^2$	0.1138 ± 0.0045
Ω_Λ	0.721 ± 0.025
$10^9 \Delta^2_{\mathcal{R}}$	2.41 ± 0.10
n_s	0.972 ± 0.013
τ	0.089 ± 0.014
Derived parameters	
t_0 (Gyr)	13.74 ± 0.11
H_0 (km/s/Mpc)	70.0 ± 2.2
σ_8	0.821 ± 0.023
Ω_b	0.0463 ± 0.0024
Ω_c	0.233 ± 0.023
z_{reion}	10.6 ± 1.1

H&He: 4.6%
Dark Matter: 23.3%
Dark Energy: 72.1%

Age: 13.7 billion years
H_0: 70 km/s/Mpc

Composition of the Univ.



72% of the present-day energy density in our Universe is NOT EVEN MATTER!

Matter

Dark Energy


ZERO


ZERO
暗黒エネルギーが支配する場合

Origin of Fluctuations

- OK, back to the cosmic hot soup.
- The sound waves were created when we perturbed it.
- “We”? **Who?**
- Who actually perturbed the cosmic soup?
- **Who generated the original (seed) ripples?**

Theory of the Very Early Universe

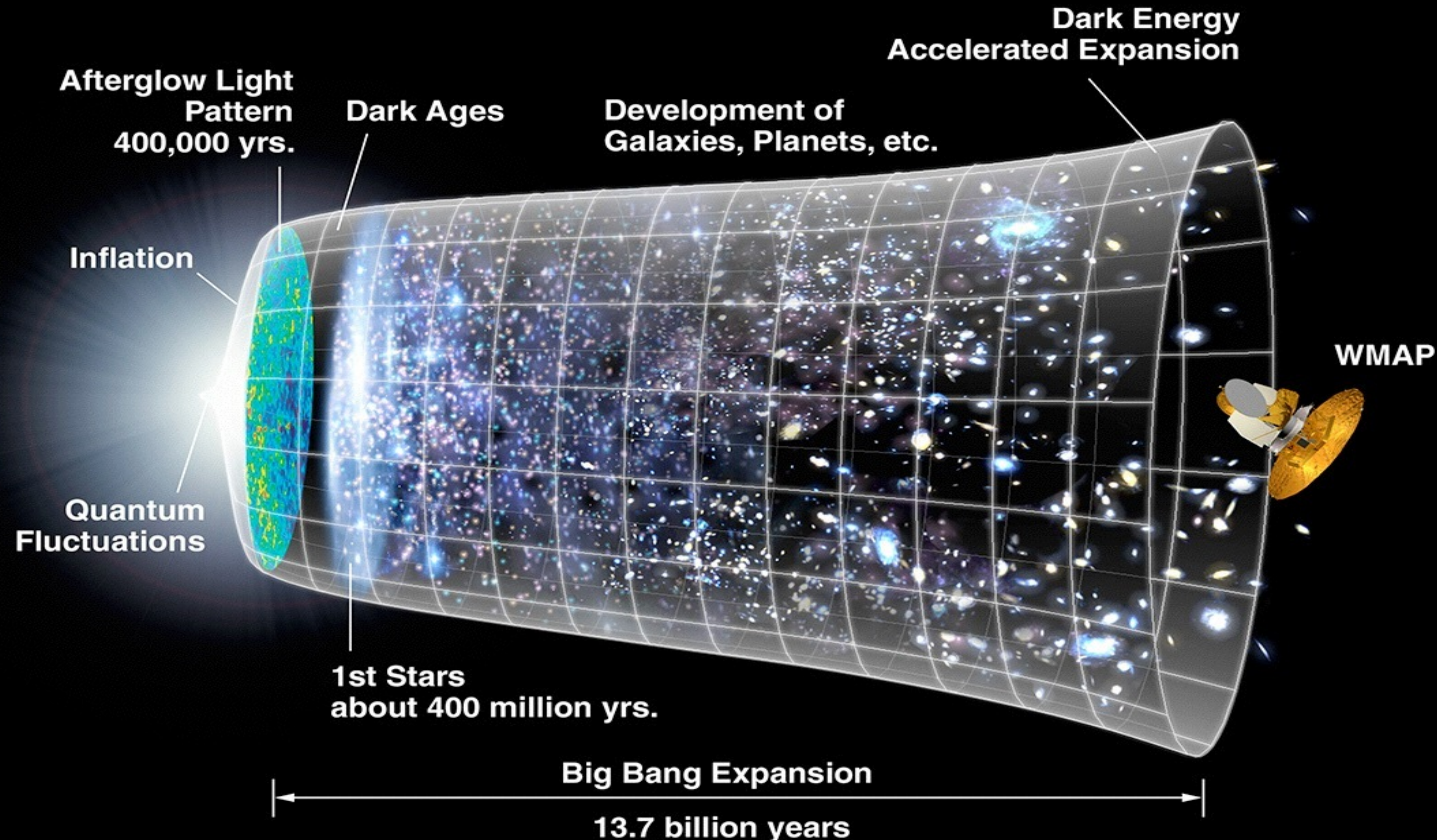
- The leading theoretical idea about the primordial Universe, called "*Cosmic Inflation*," predicts:

(Starobinsky 1980; Sato 1981; 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 ($\sim 10^{-15}$m) would be stretched to 1 A.U. ($\sim 10^{11}$m), at least.

Cosmic Inflation = Very Early Dark Energy



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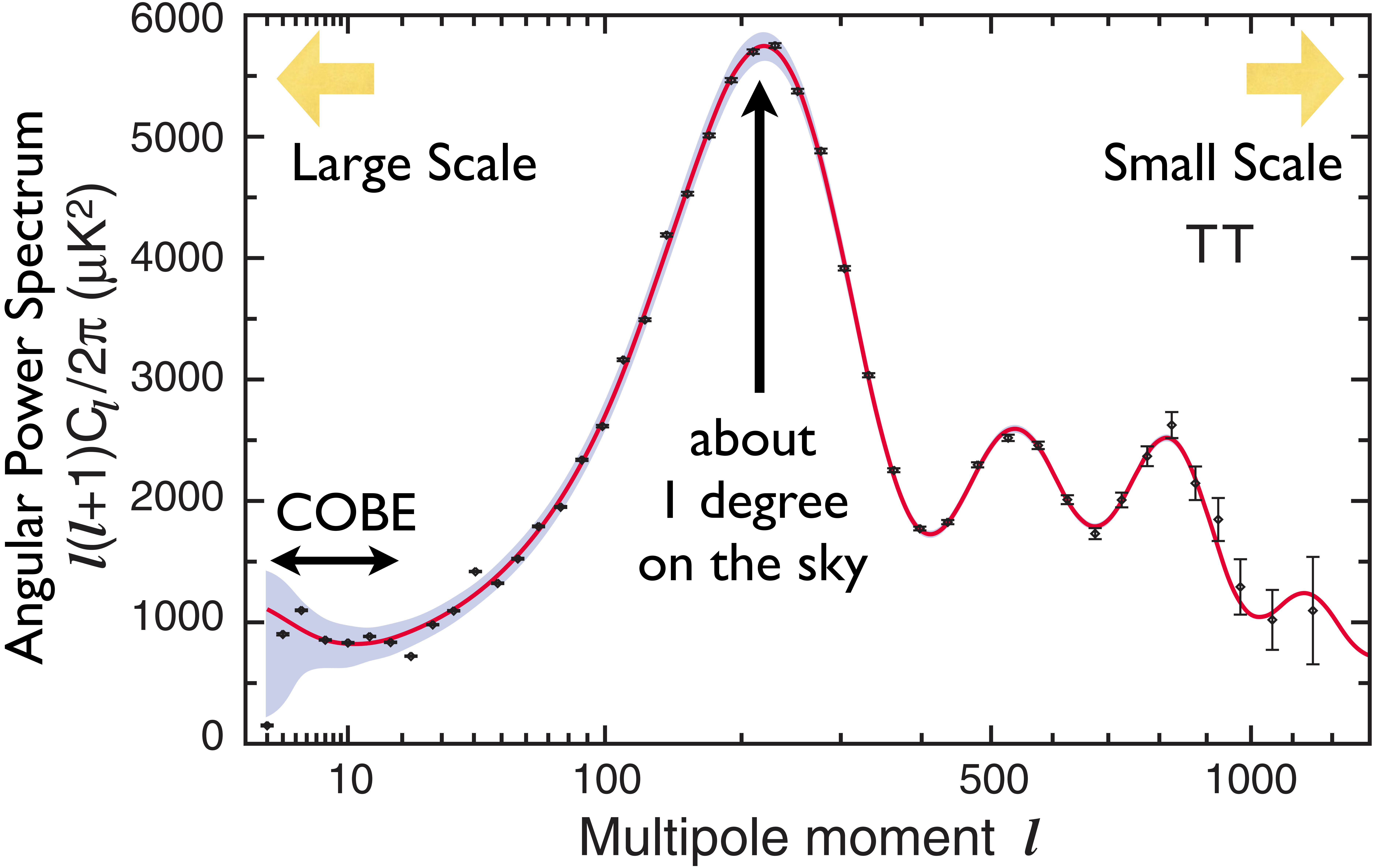
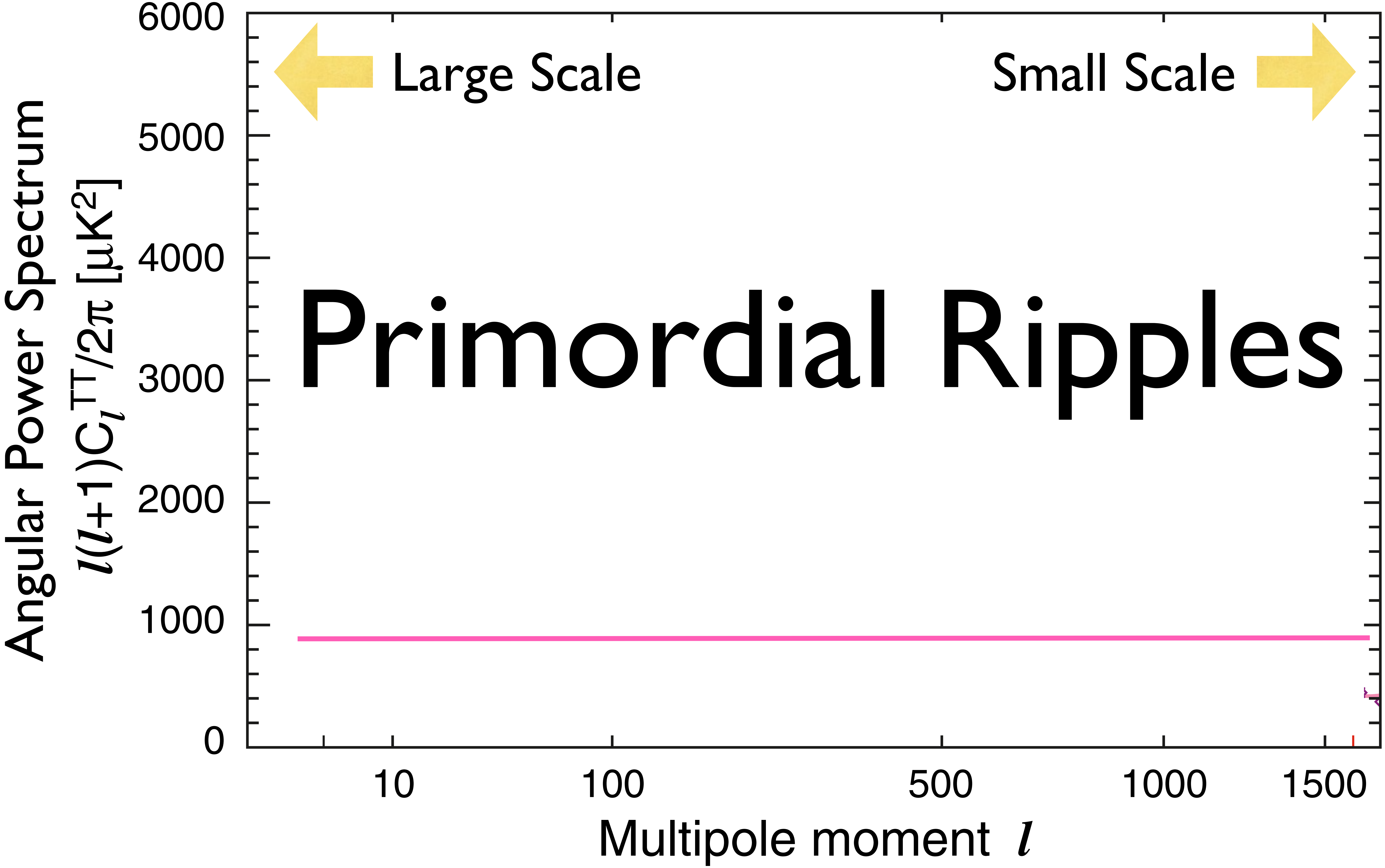
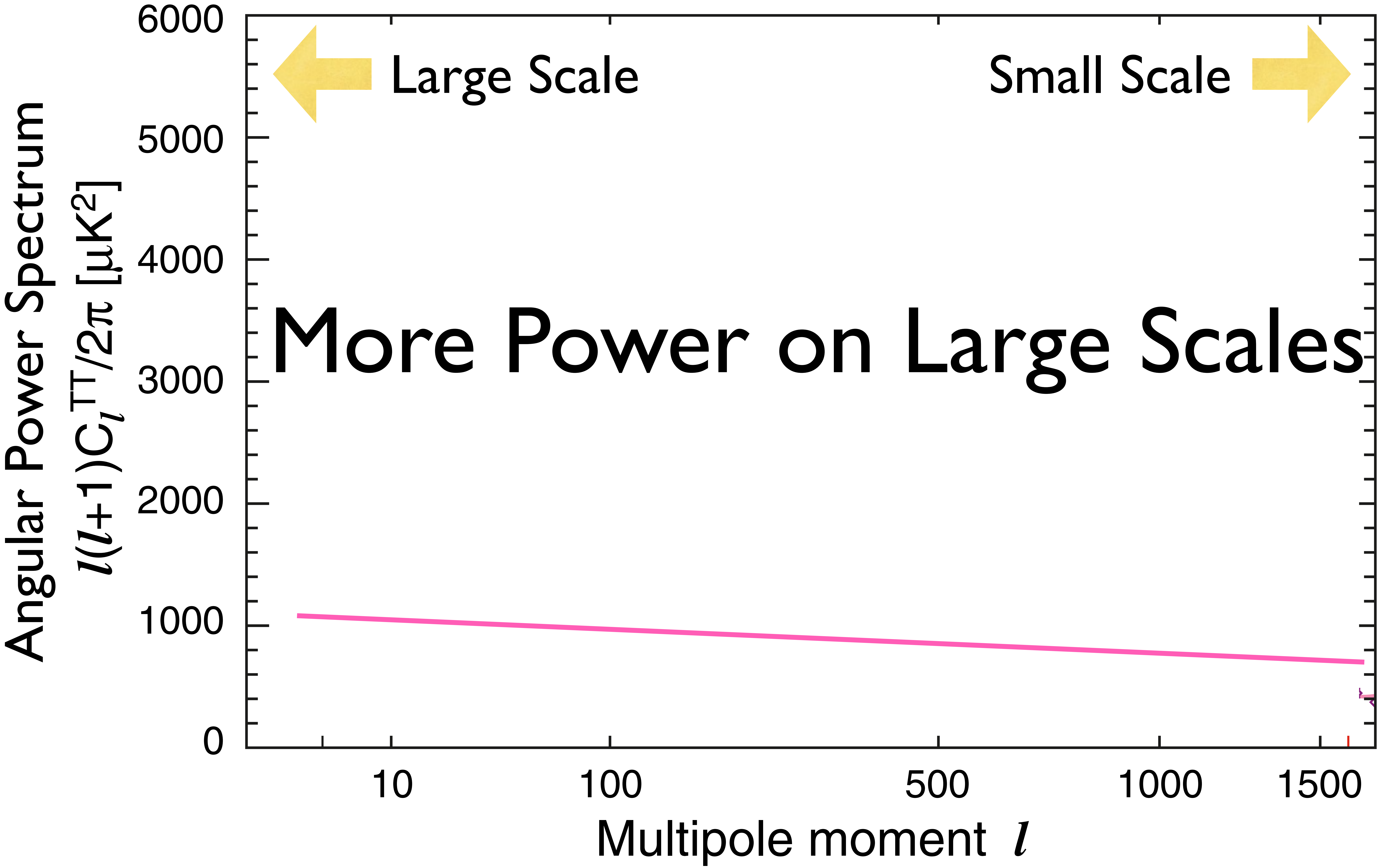
WMAP 9-year Power Spectrum



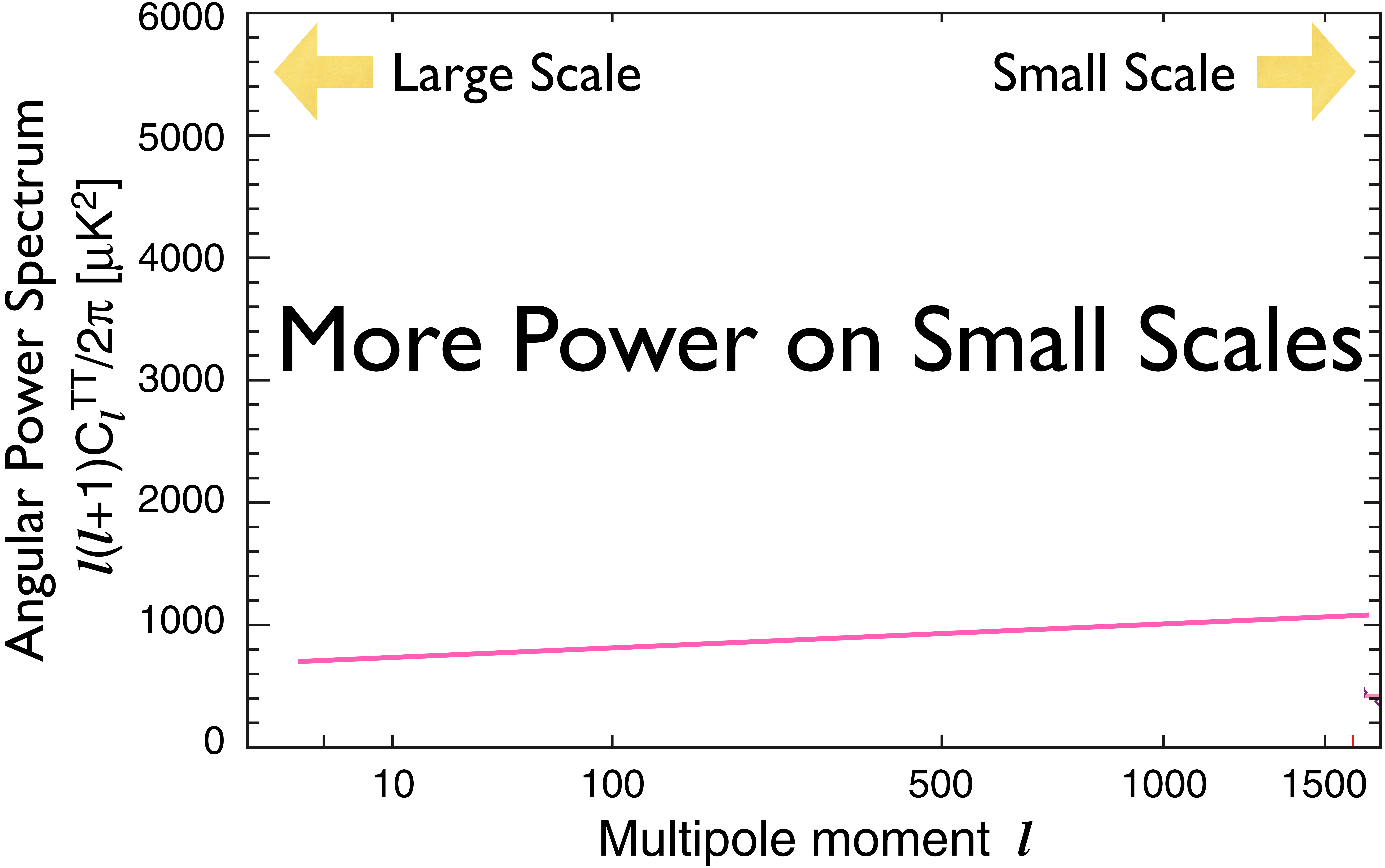
Getting rid of the Sound Waves



The Early Universe Could Have Done This Instead

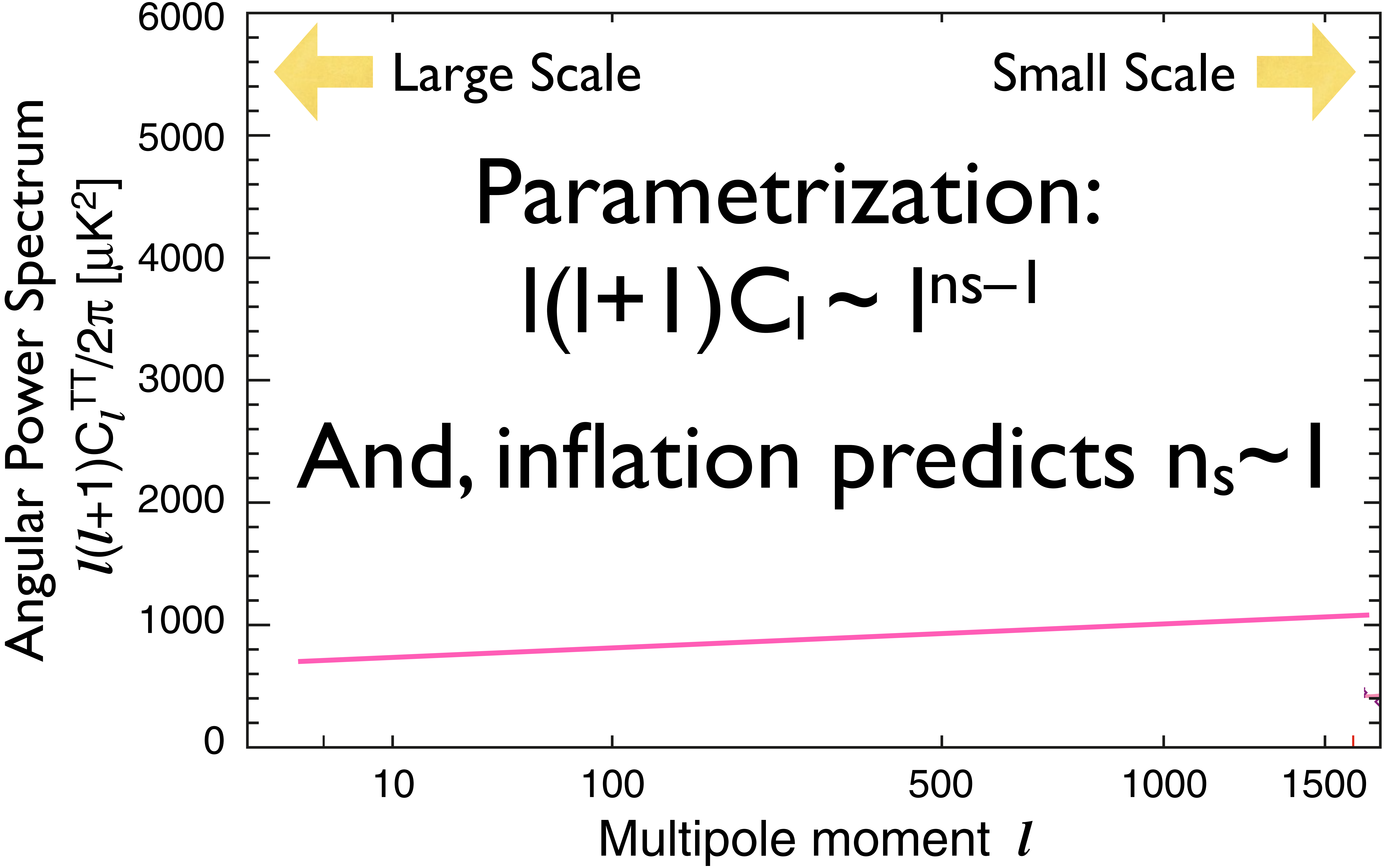


...or, This.



Large Scale
Small Scale
More Power on Small Scales
Angular Power Spectrum
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l

...or, This.



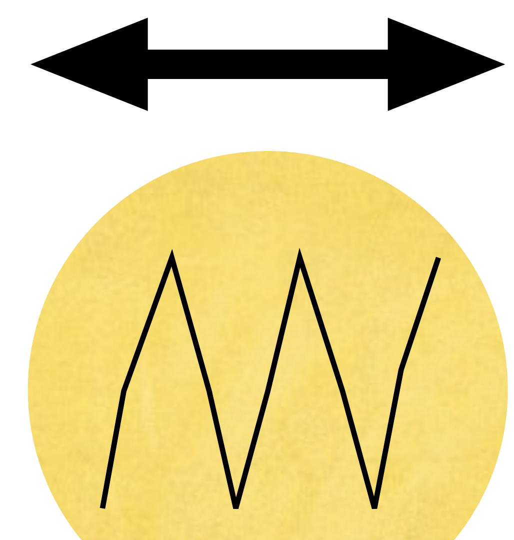
Large Scale
Small Scale
Parametrization:
$l(l+1)C_l \sim l^{ns-1}$
And, inflation predicts $n_s \sim 1$
Angular Power Spectrum
$l(l+1)C_l^{TT}/2\pi$ [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l

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**.
- Measurement of n_s gives us **this** remarkable information!

Stretching Micro to Macro

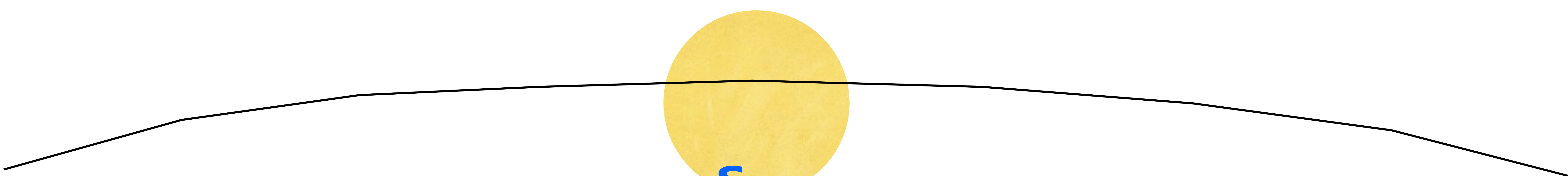
Macroscopic size at which gravity becomes important



$\delta\varphi$

Quantum fluctuations on microscopic scales

INFLATION!



$\delta\varphi$

Quantum fluctuations cease to be quantum, and become observable!

Quantum Fluctuations

Heisenberg's Uncertainty Principle

- 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.

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]

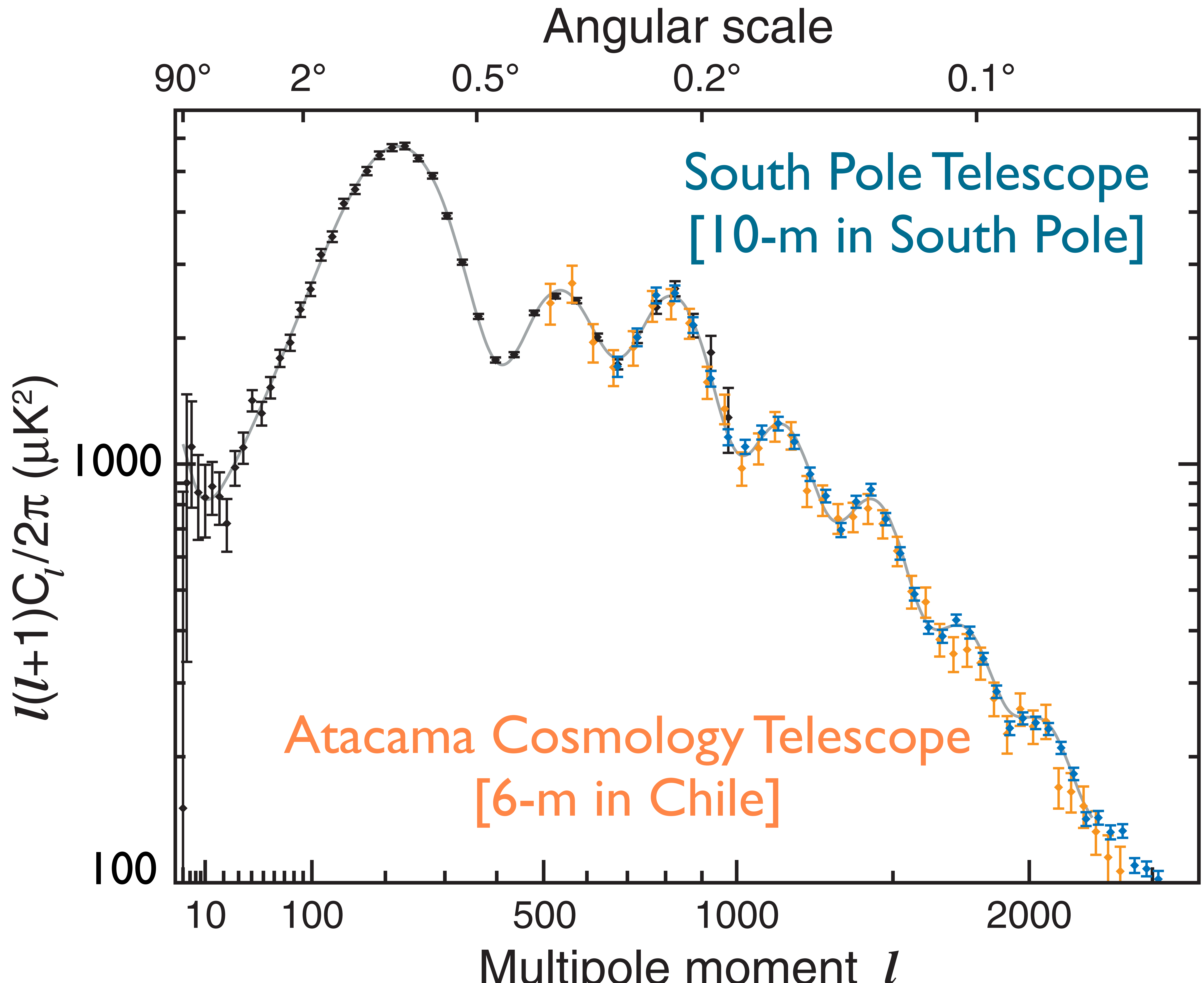
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-36} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

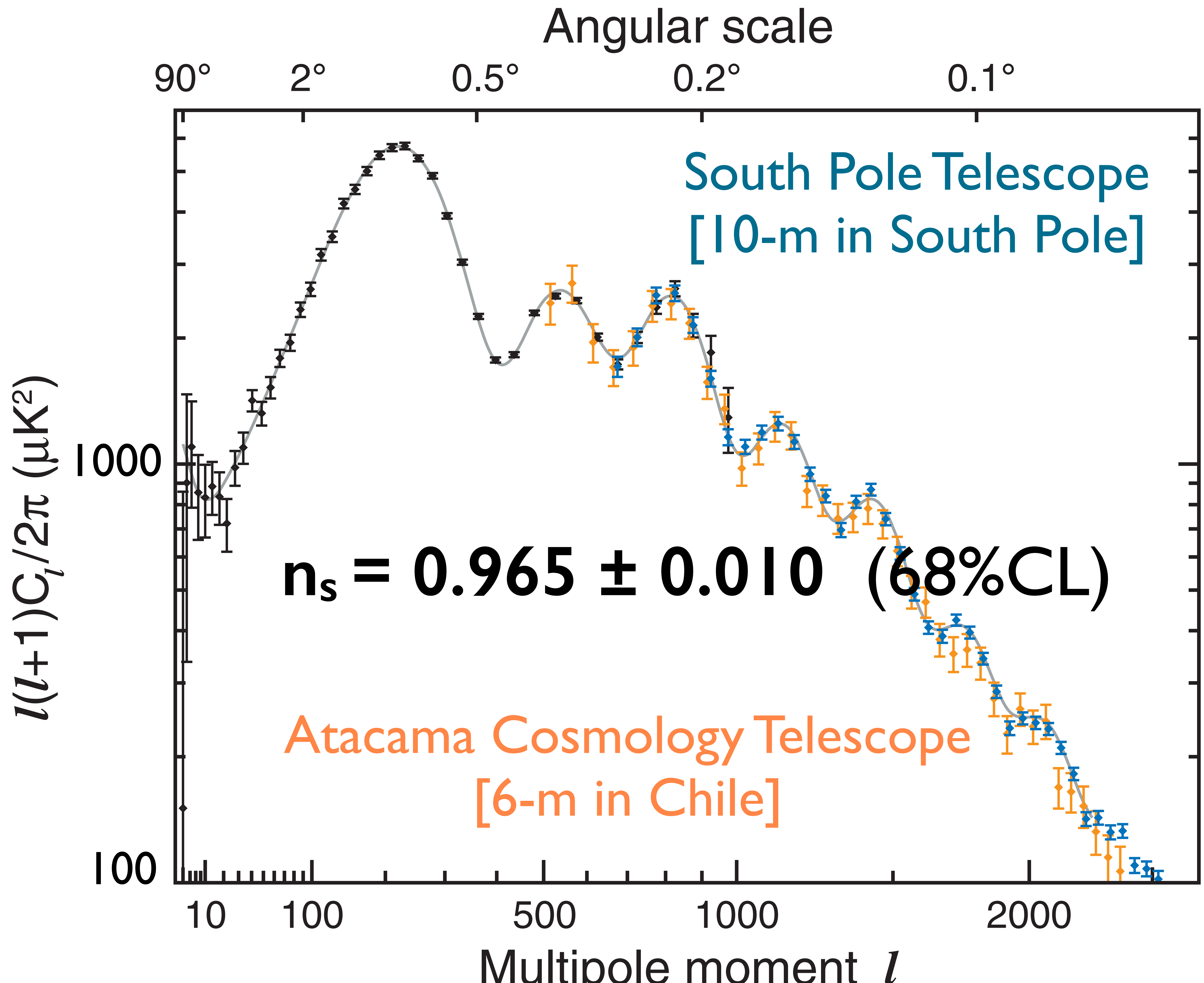
Inflation Offers a Magnifier for Microscopic World

- 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.

- Measured value (WMAP 9-year data only):

$$\mathbf{n_s = 0.972 \pm 0.013}\ \text{(68\%CL)}$$

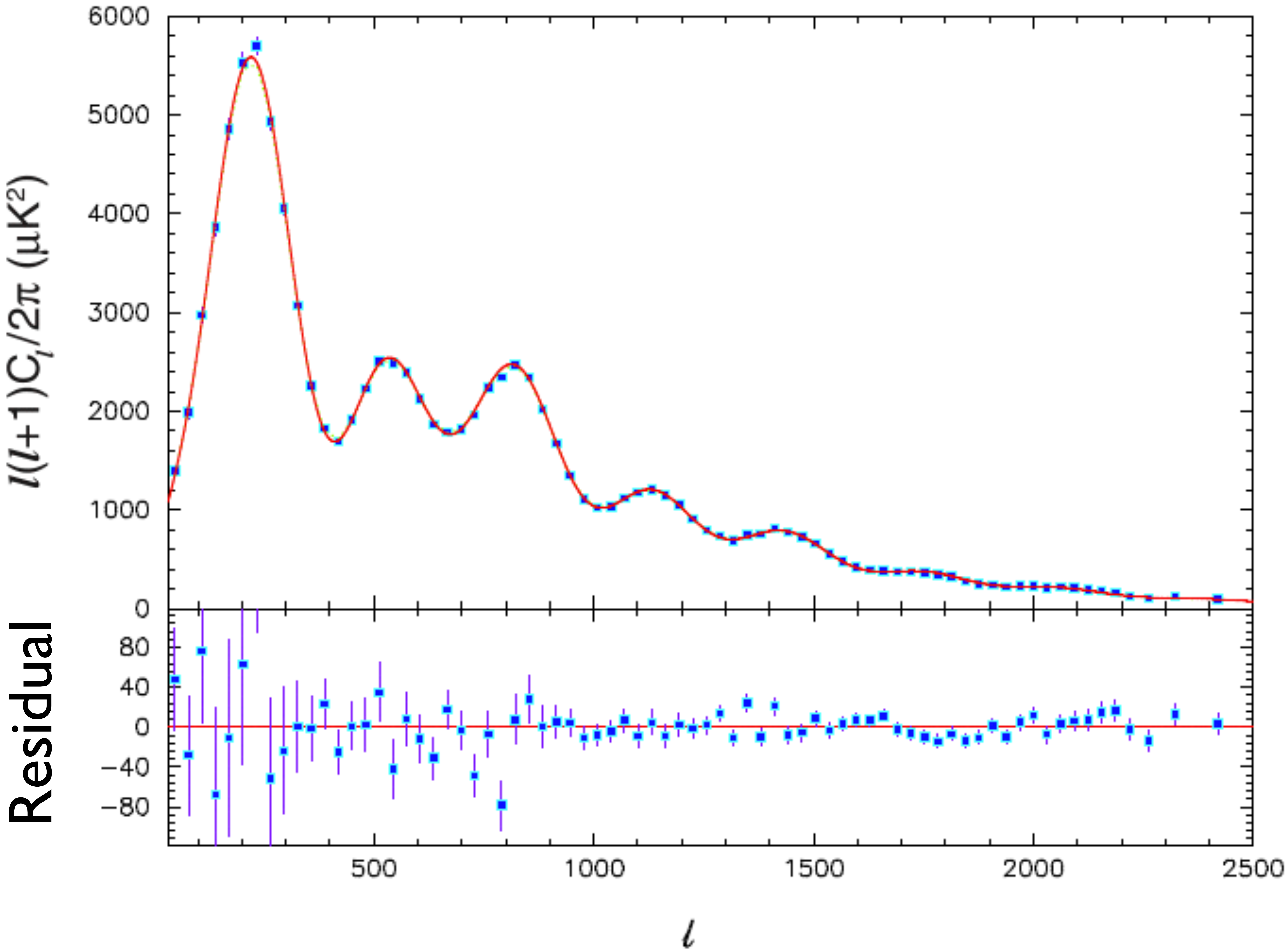

Angular scale
90°
2°
0.5°
0.2°
0.1°
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
$l(l+1)C_l/2\pi$ (μK^2)
1000
100
10
100
500
1000
2000
Multipole moment l



$$n_s = 0.965 \pm 0.010 \quad (68\%CL)$$

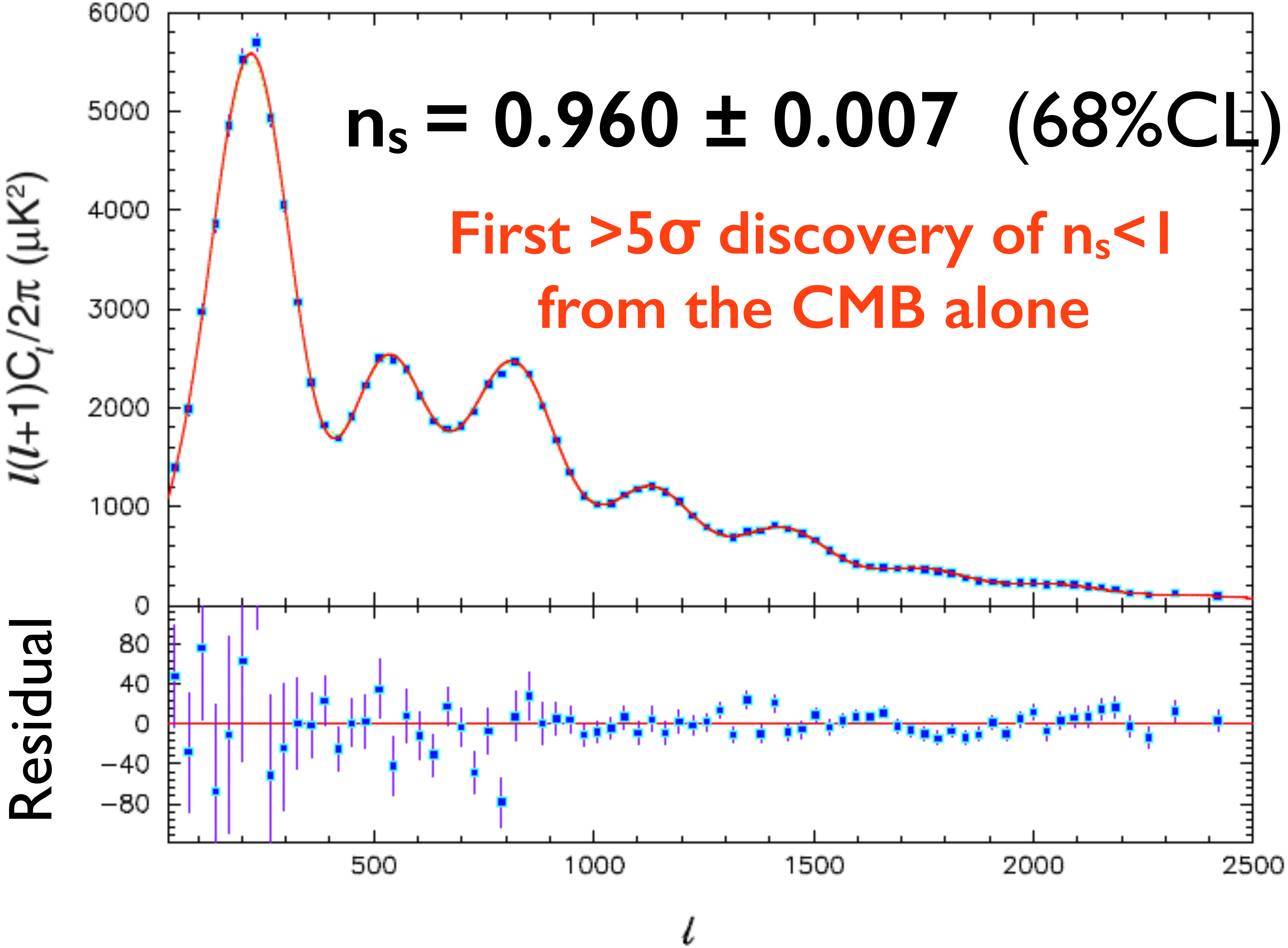
Planck (2013)

Planck Result!



Planck (2013)

Planck Result!



Starobinsky (1979)

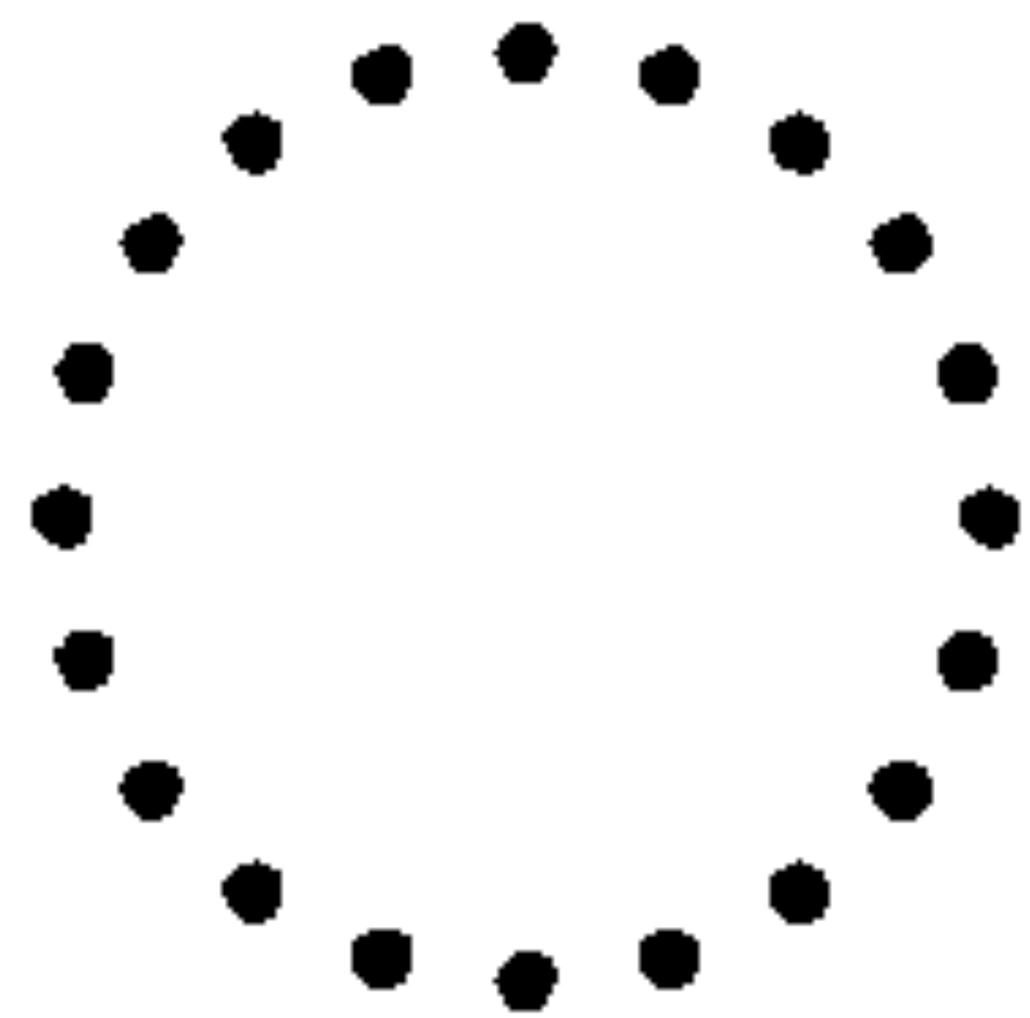
(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

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

[h = "strain"]

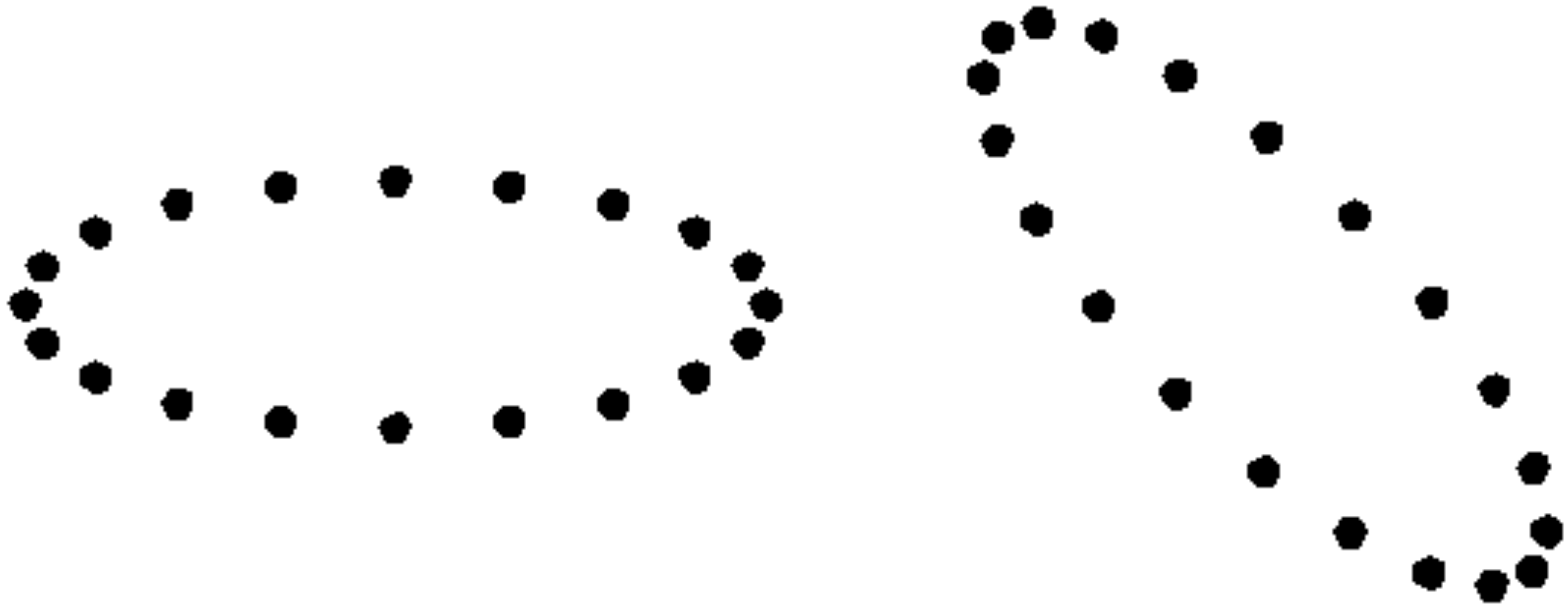
- Quantum fluctuations also generate ripples in space-time, i.e., gravitational waves, by the same mechanism.
- Primordial gravitational waves generate temperature anisotropy in CMB.

Gravitational waves are coming toward you... What do you do?



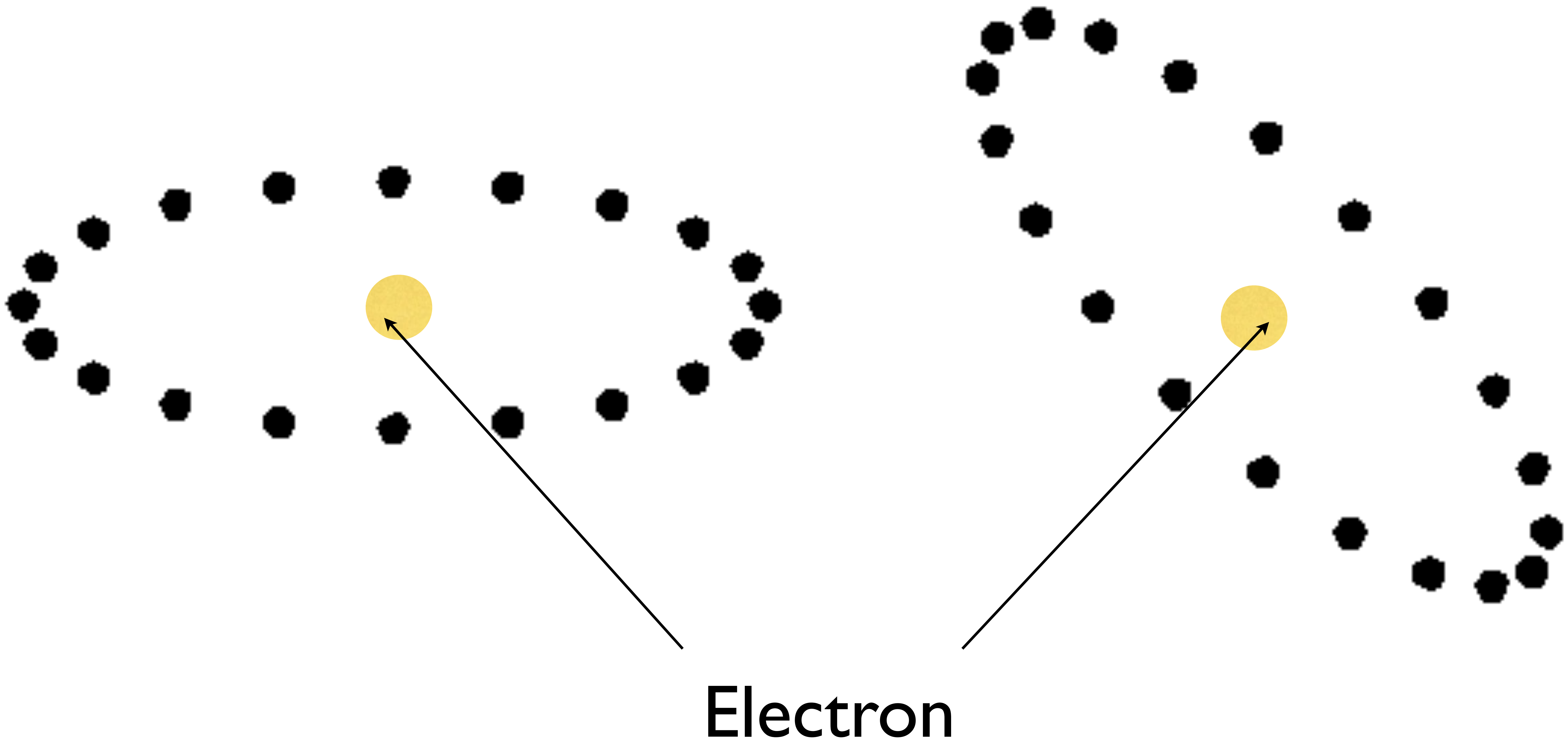
- Gravitational waves stretch space, causing particles to move.

Two Polarization States of GW

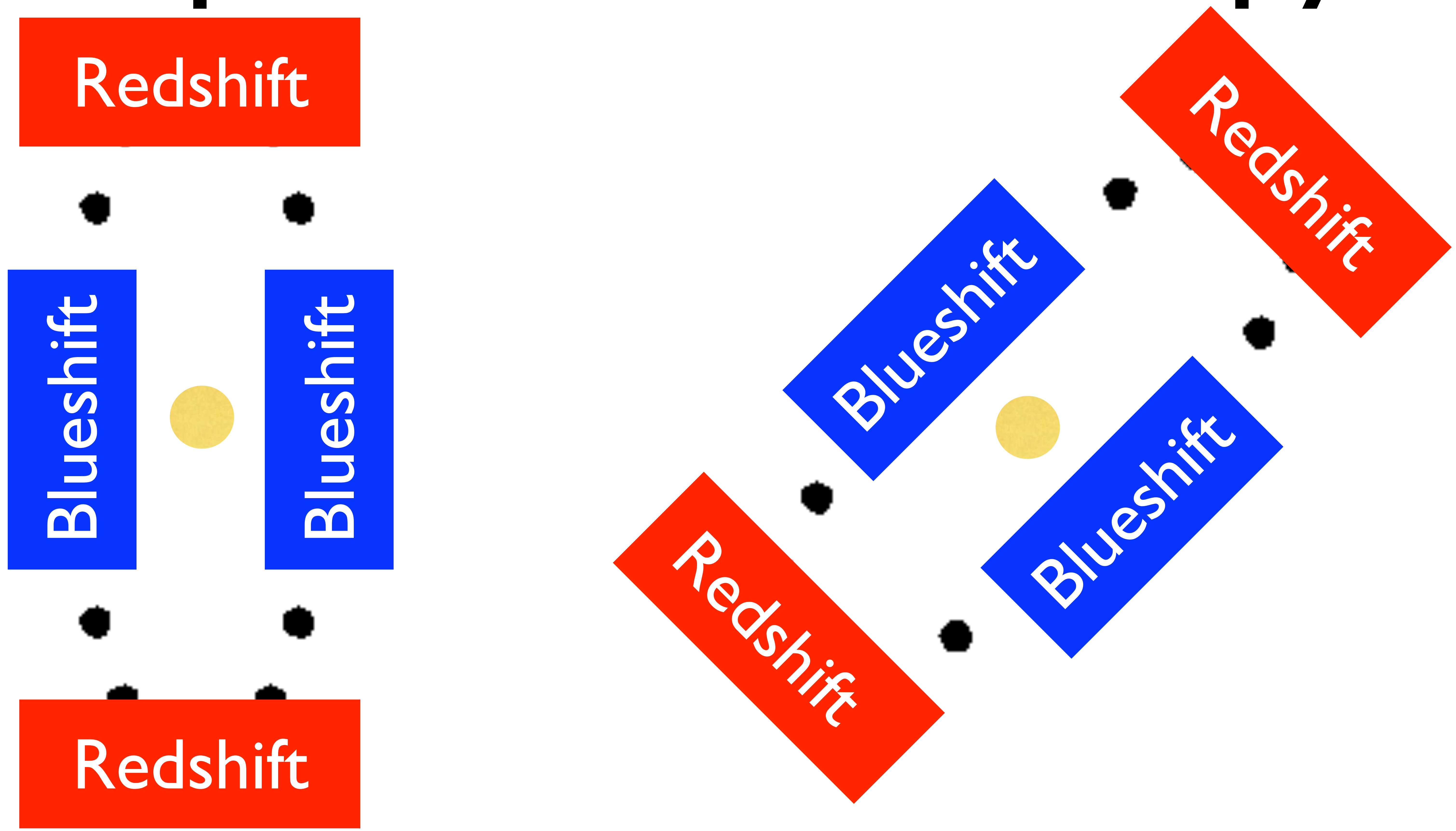


- This is great - this will automatically generate quadrupolar anisotropy around electrons!

From GW to temperature anisotropy



From GW to temperature anisotropy

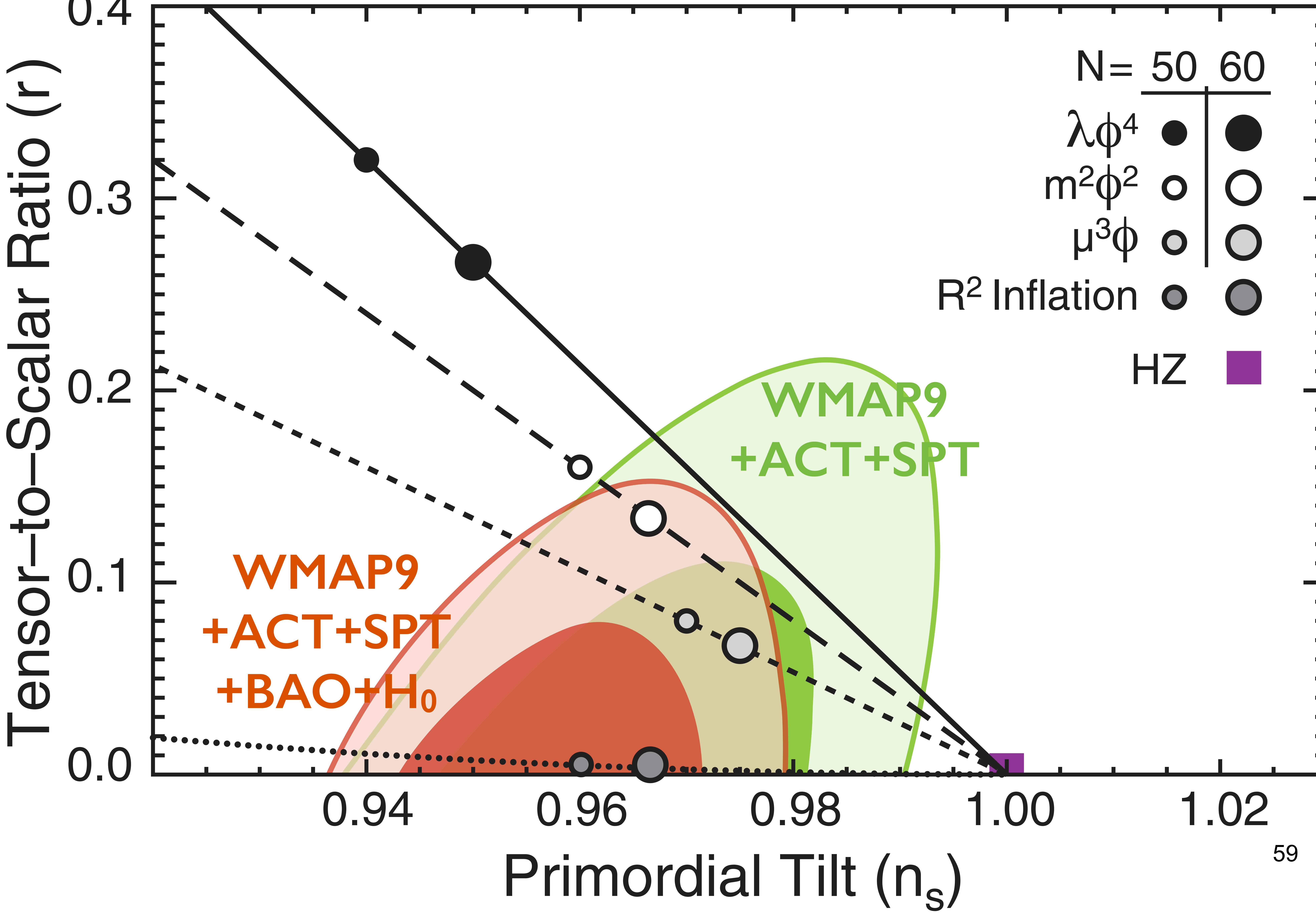


“Tensor-to-scalar Ratio,” r

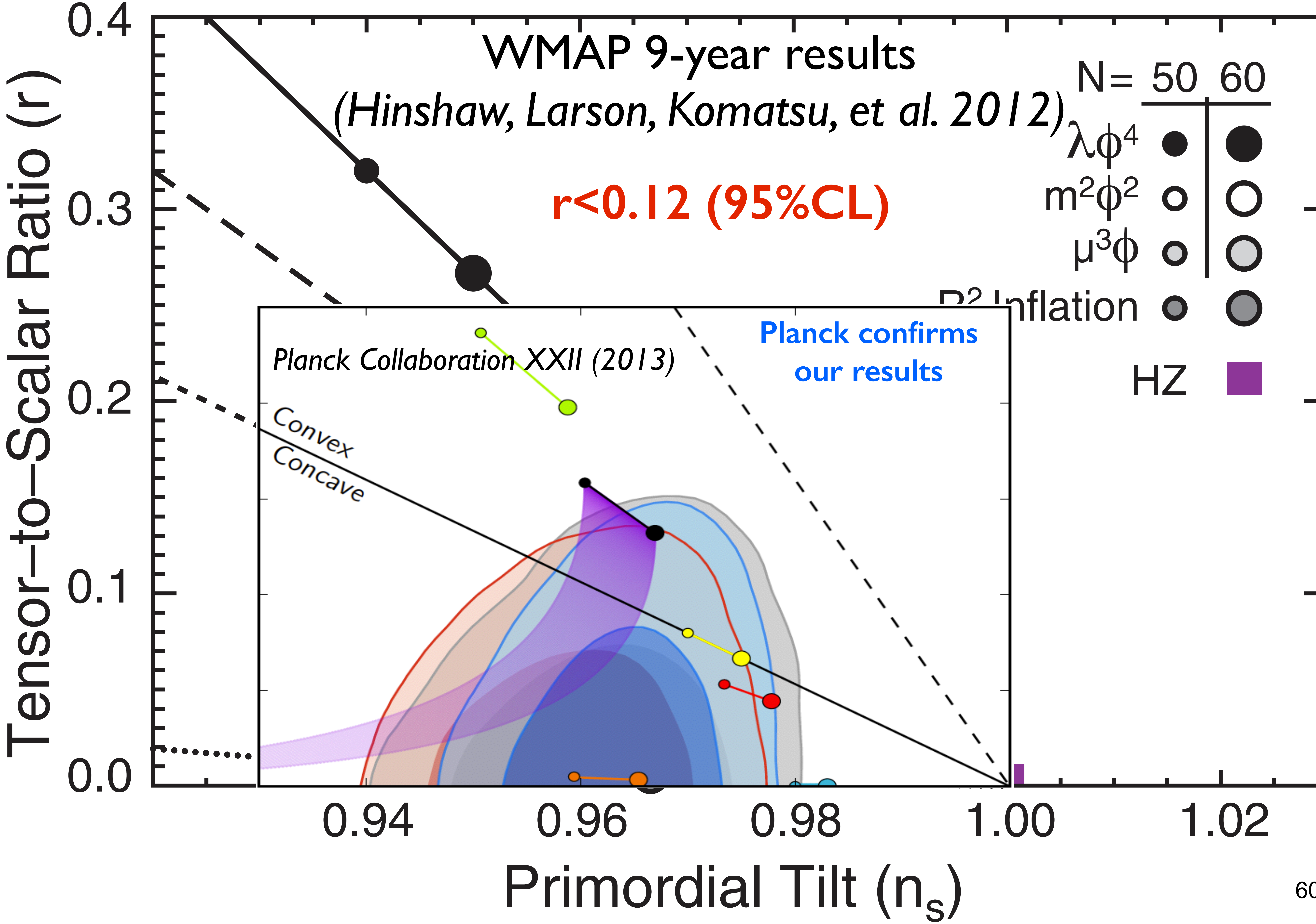
r = [Power in Gravitational Waves]

/ [Power in Gravitational Potential]

Inflation predicts r <~ 1



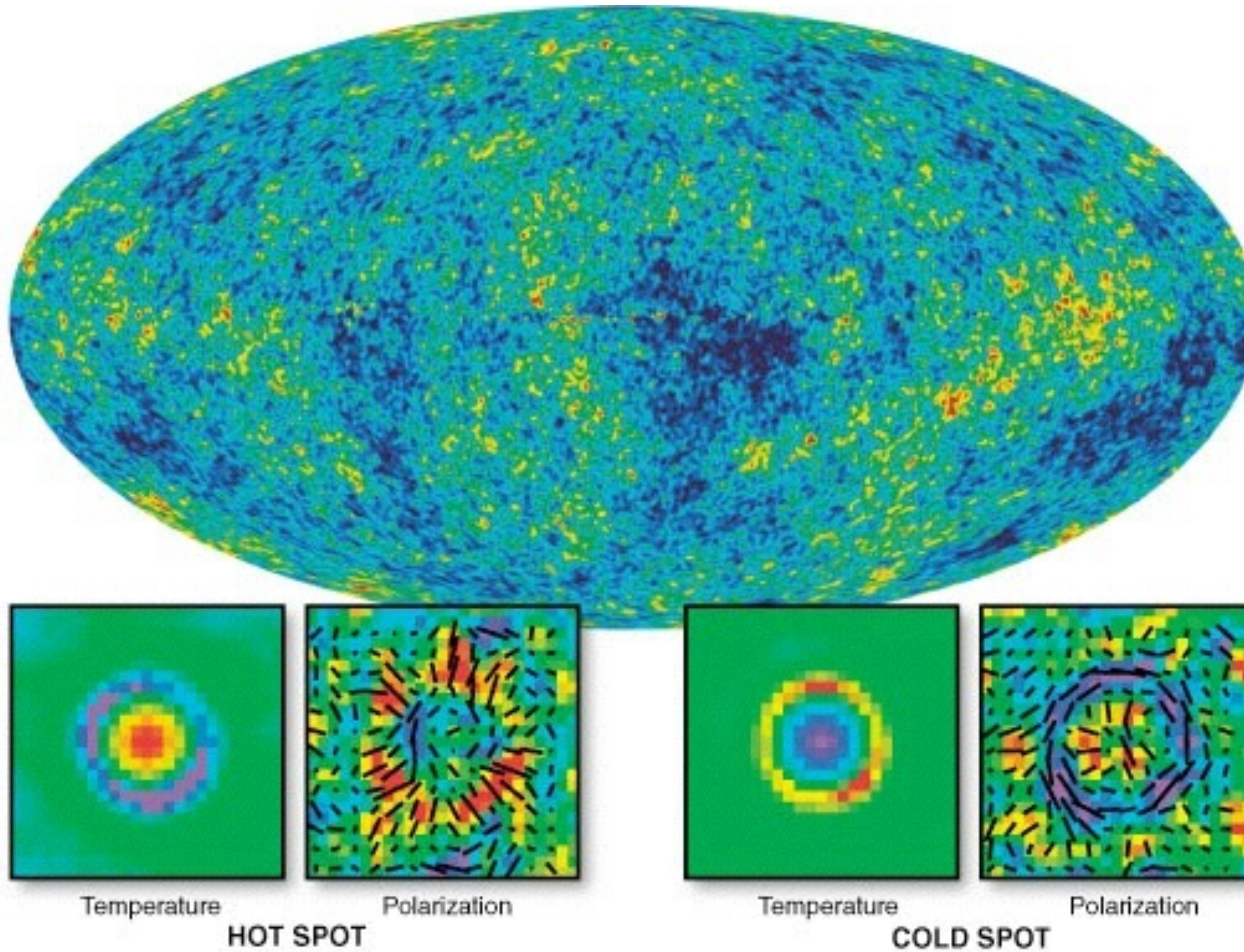
Tensor–to–Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
R^2 Inflation
HZ
WMAP9
+ACT+SPT
WMAP9
+ACT+SPT
+BAO+H_0


WMAP 9-year results
(Hinshaw, Larson, Komatsu, et al. 2012)
r<0.12 (95%CL)
N= 50 60
λϕ⁴
m²ϕ²
μ³ϕ
R² Inflation
HZ
Planck Collaboration XXII (2013)
Planck confirms our results
Convex
Concave
Tensor-to-Scalar Ratio (r)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)

Has inflation happened?

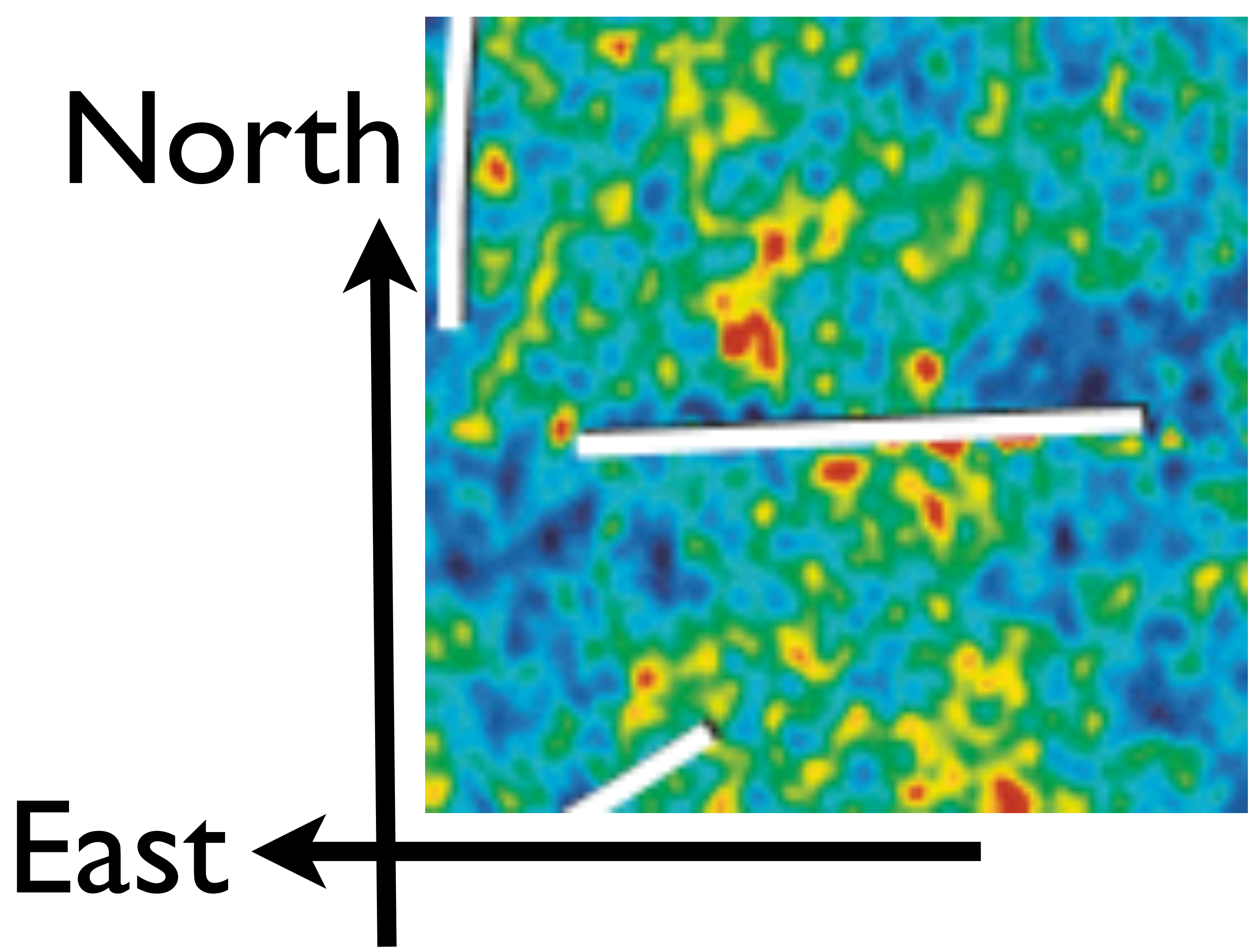
- If anyone asks you this question, your answer **must** always be:
  - “*We don’t know yet.*”
- Decisive evidence should come from polarization of CMB.

CMB Polarization

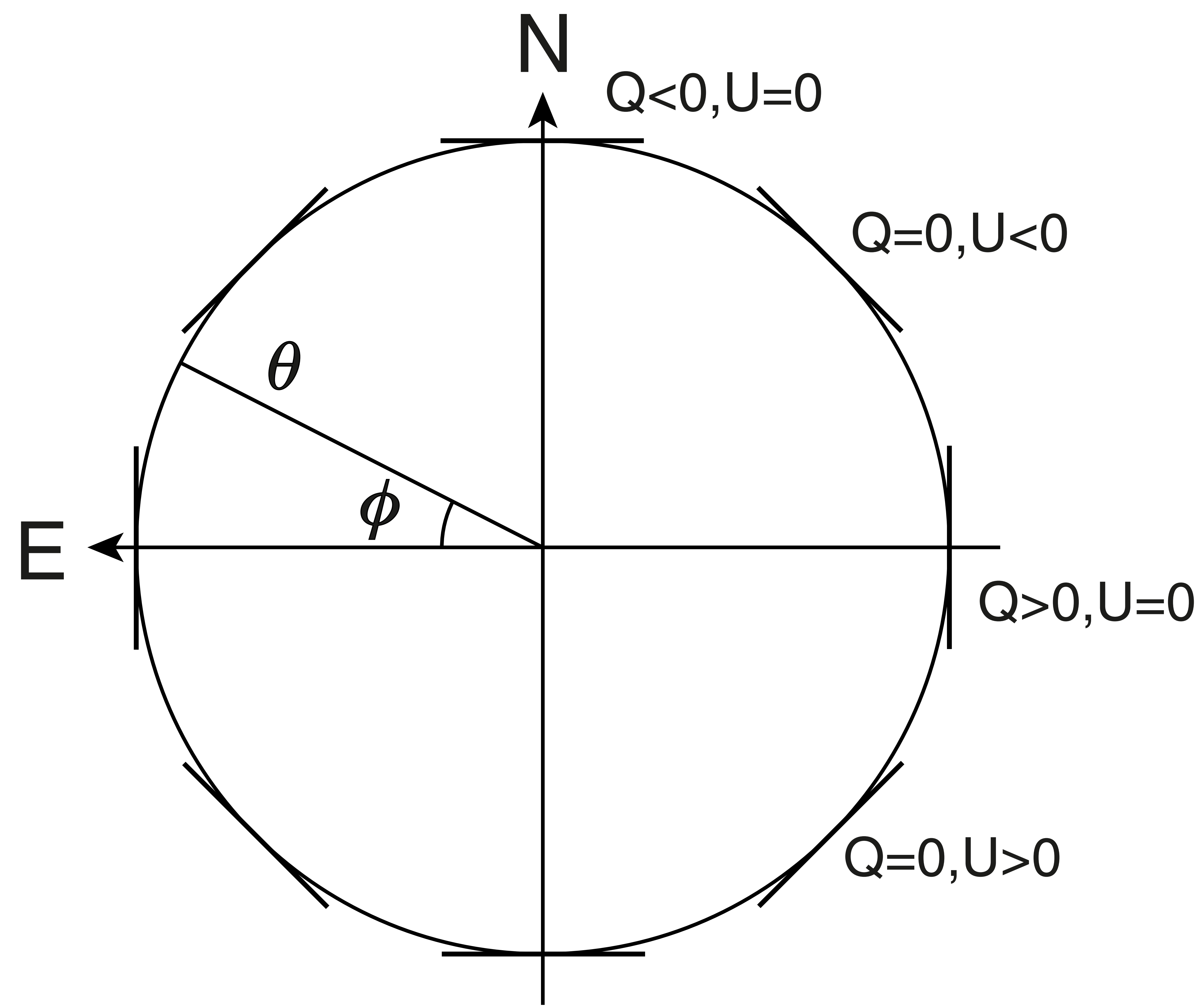


- *CMB is (very weakly) polarized!*

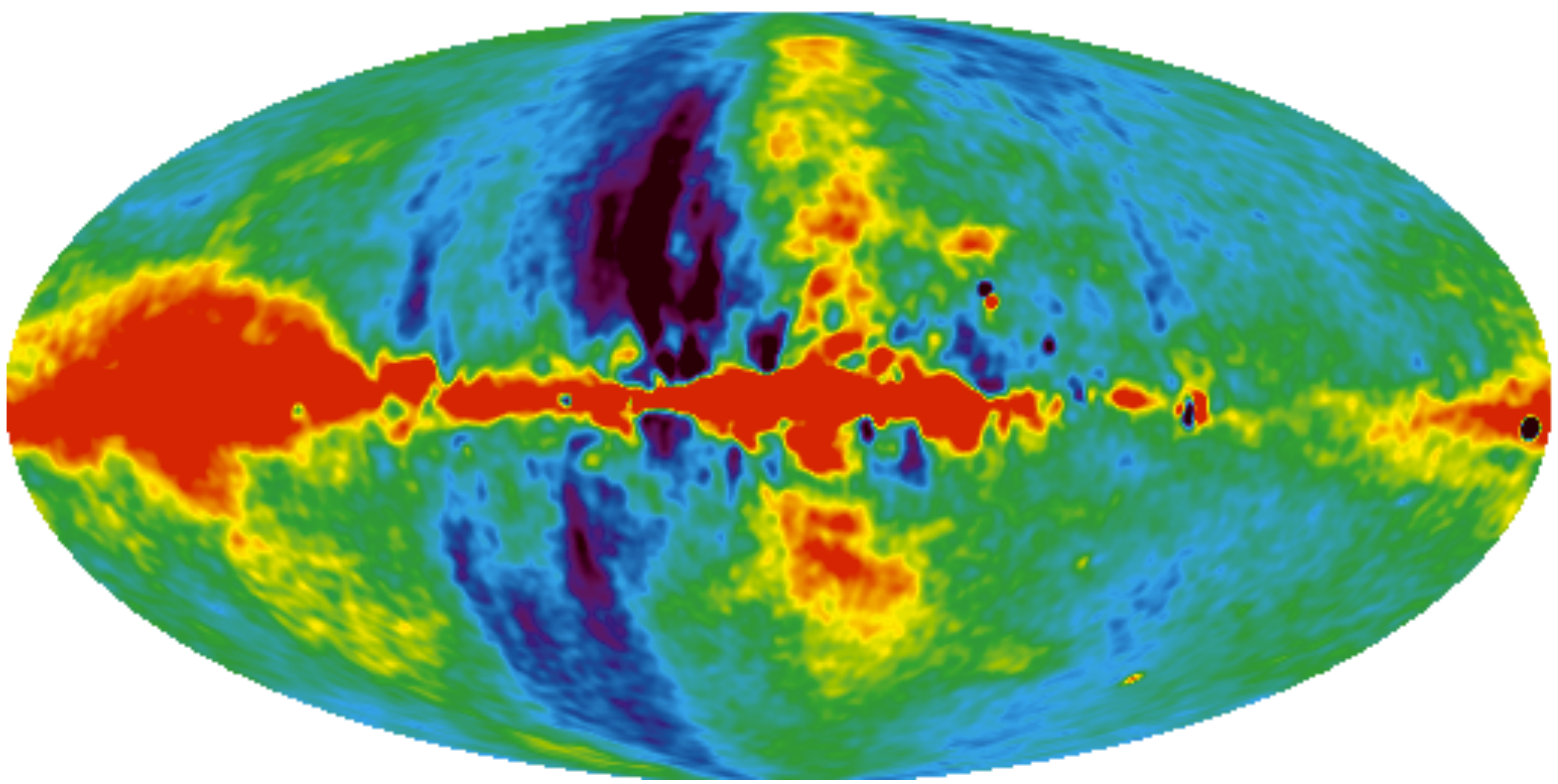
“Stokes Parameters”



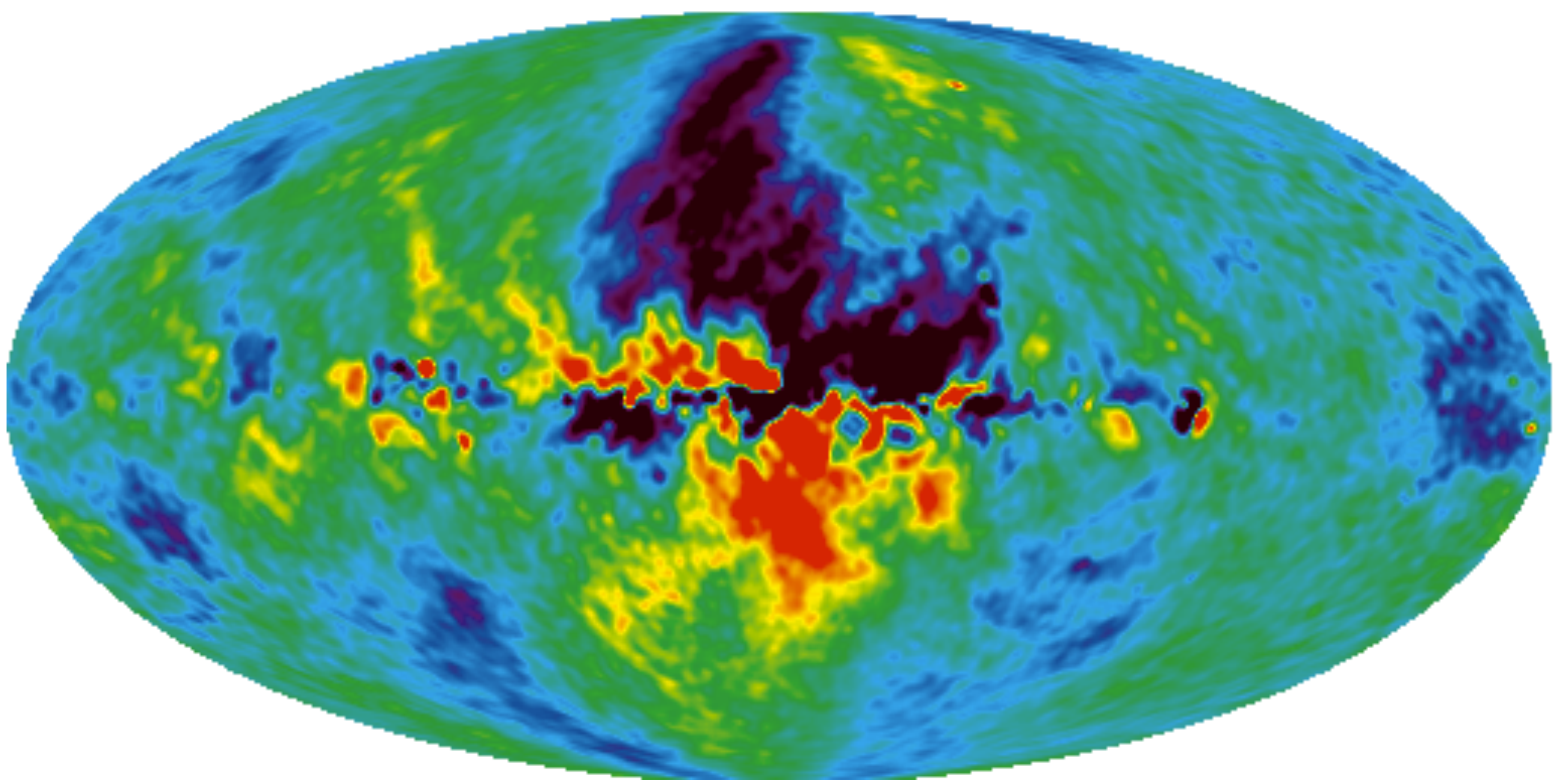
Q<0; U=0



23 GHz [polarized]

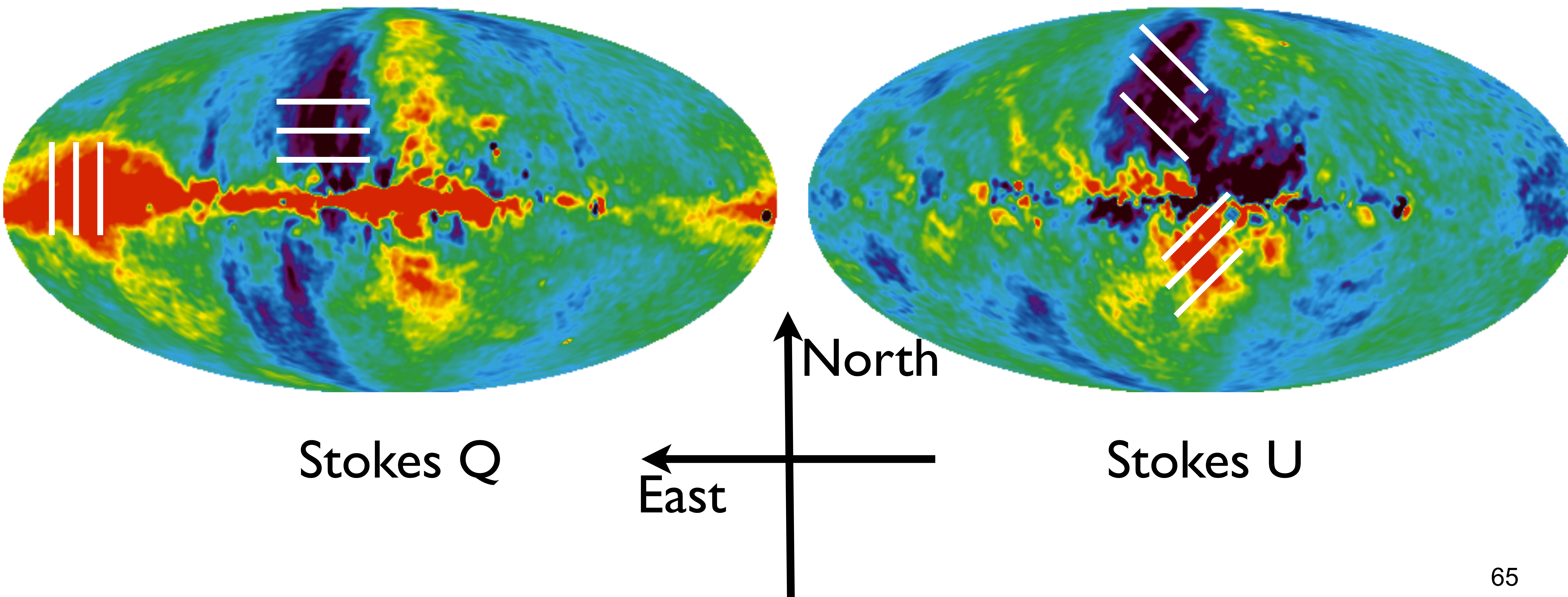


Stokes Q



Stokes U

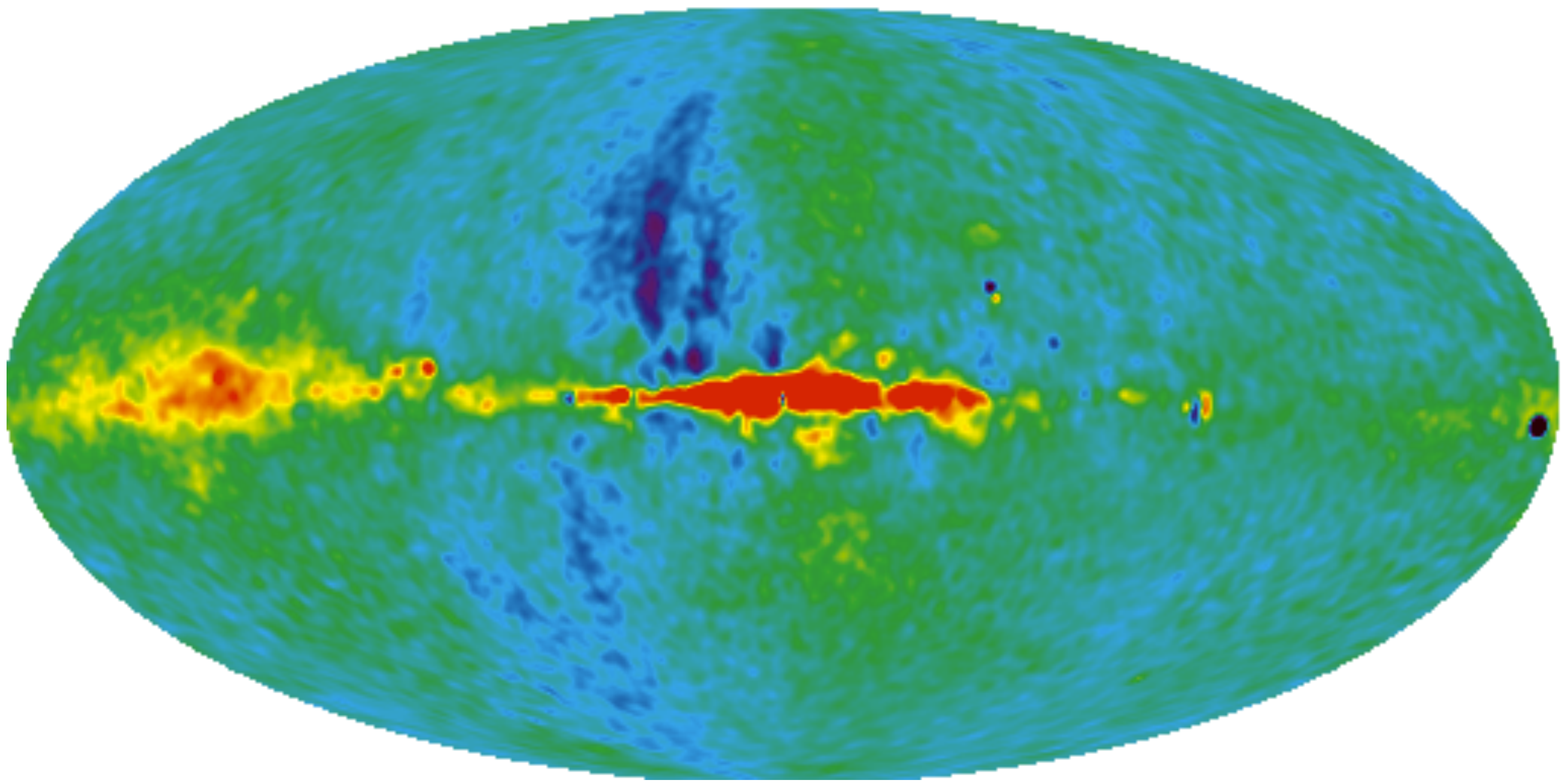
23 GHz [polarized]



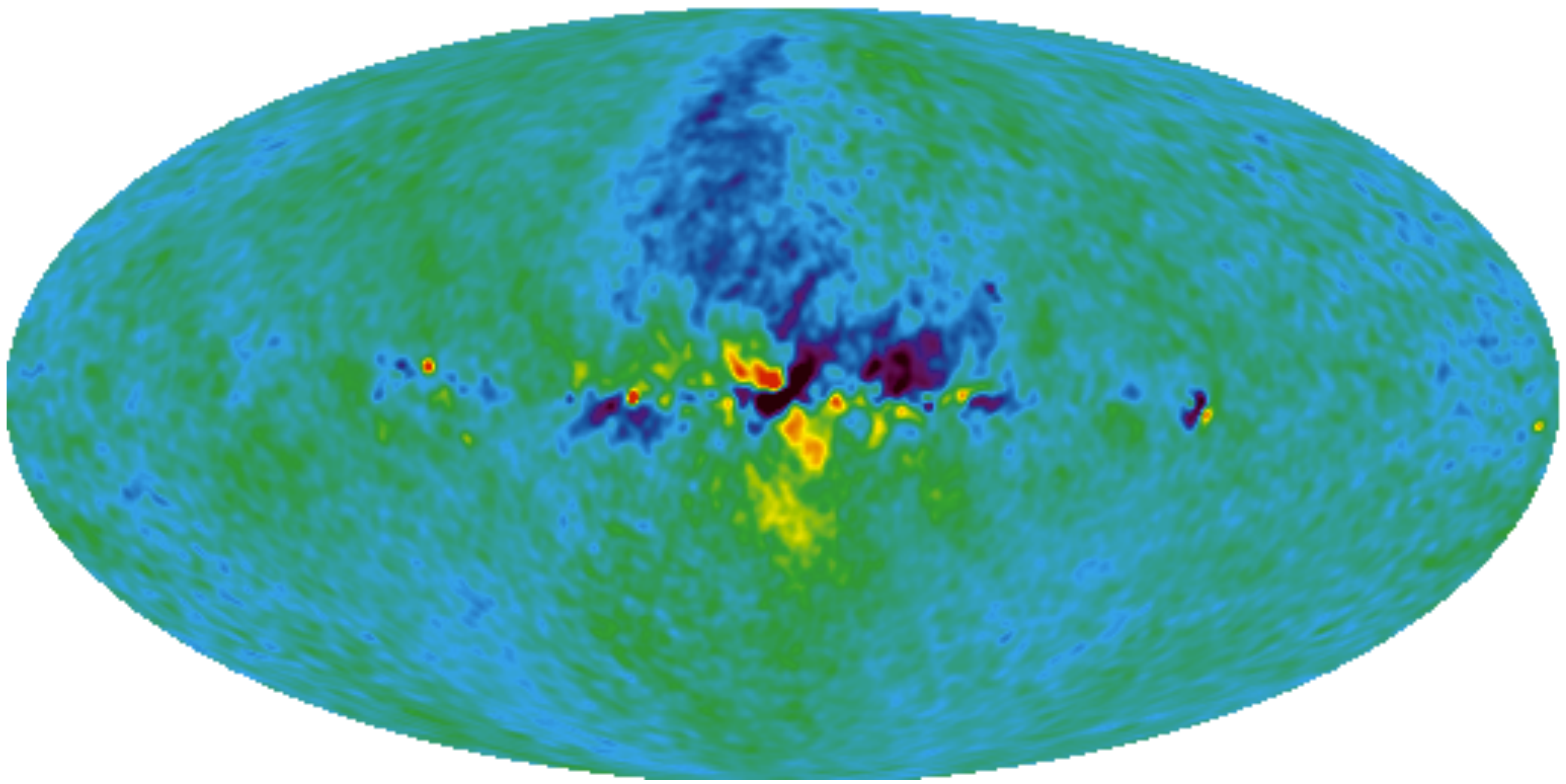
Stokes Q

Stokes U

33 GHz [polarized]

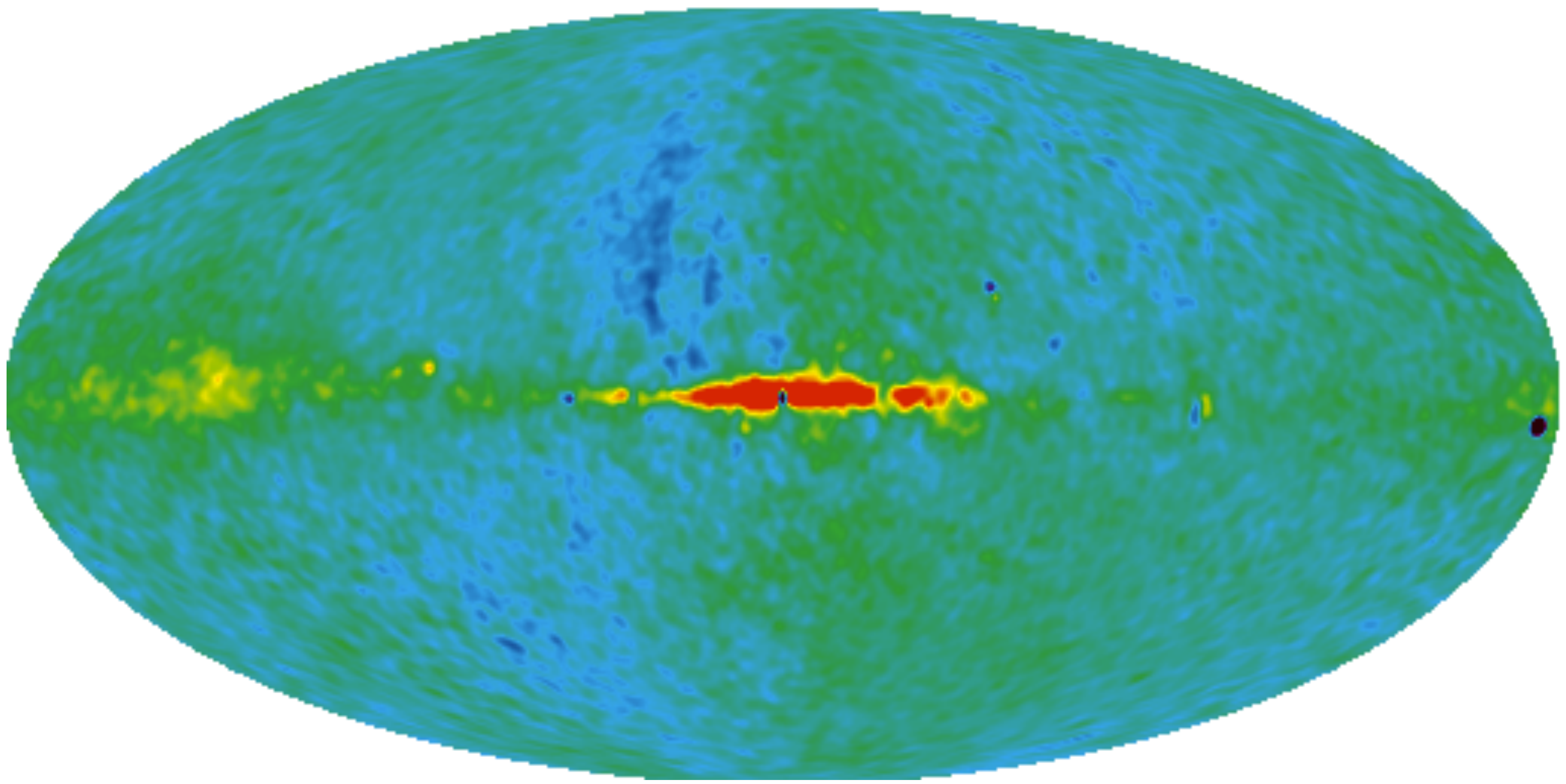


Stokes Q

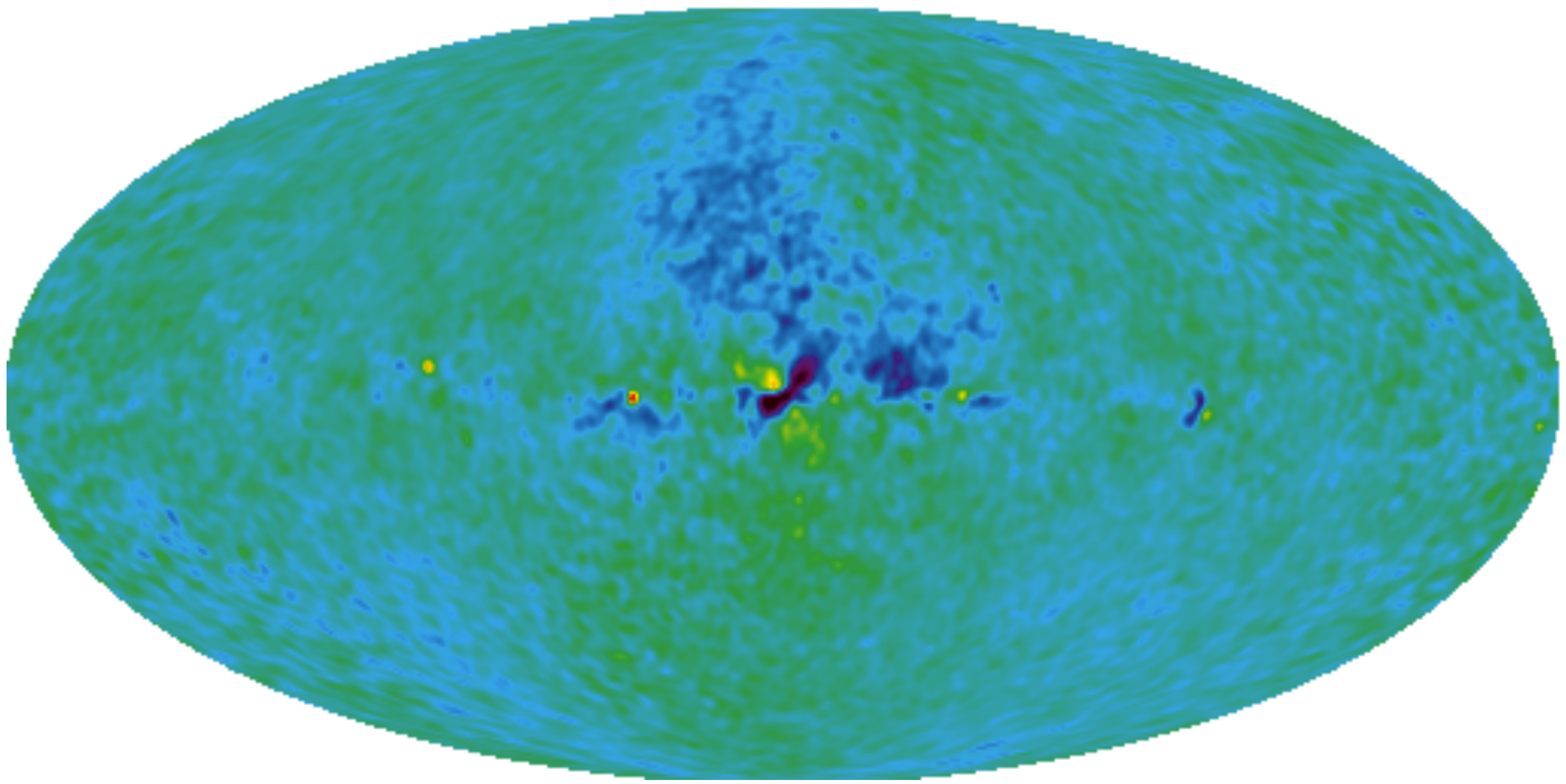


Stokes U

41 GHz [polarized]

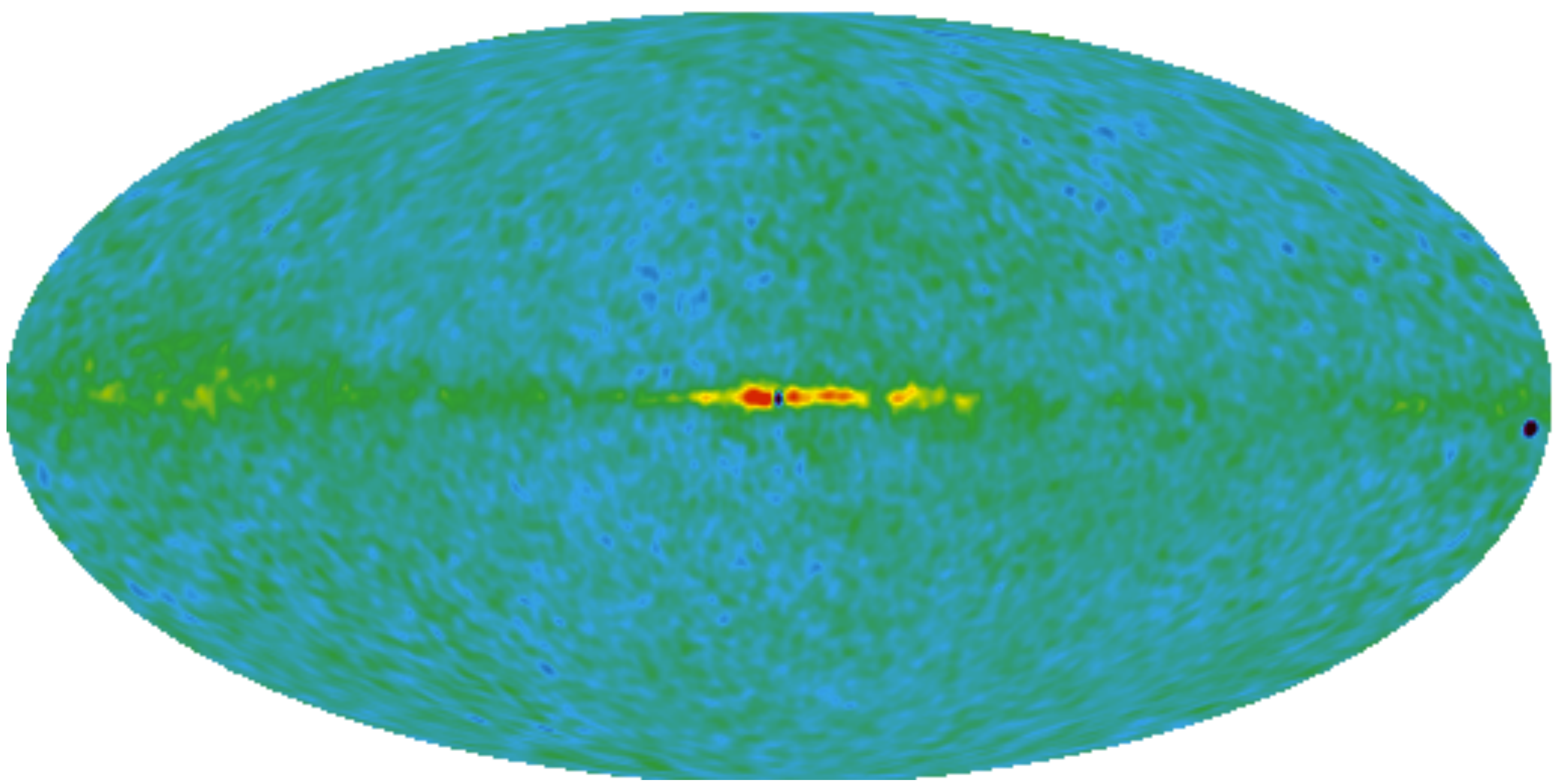


Stokes Q

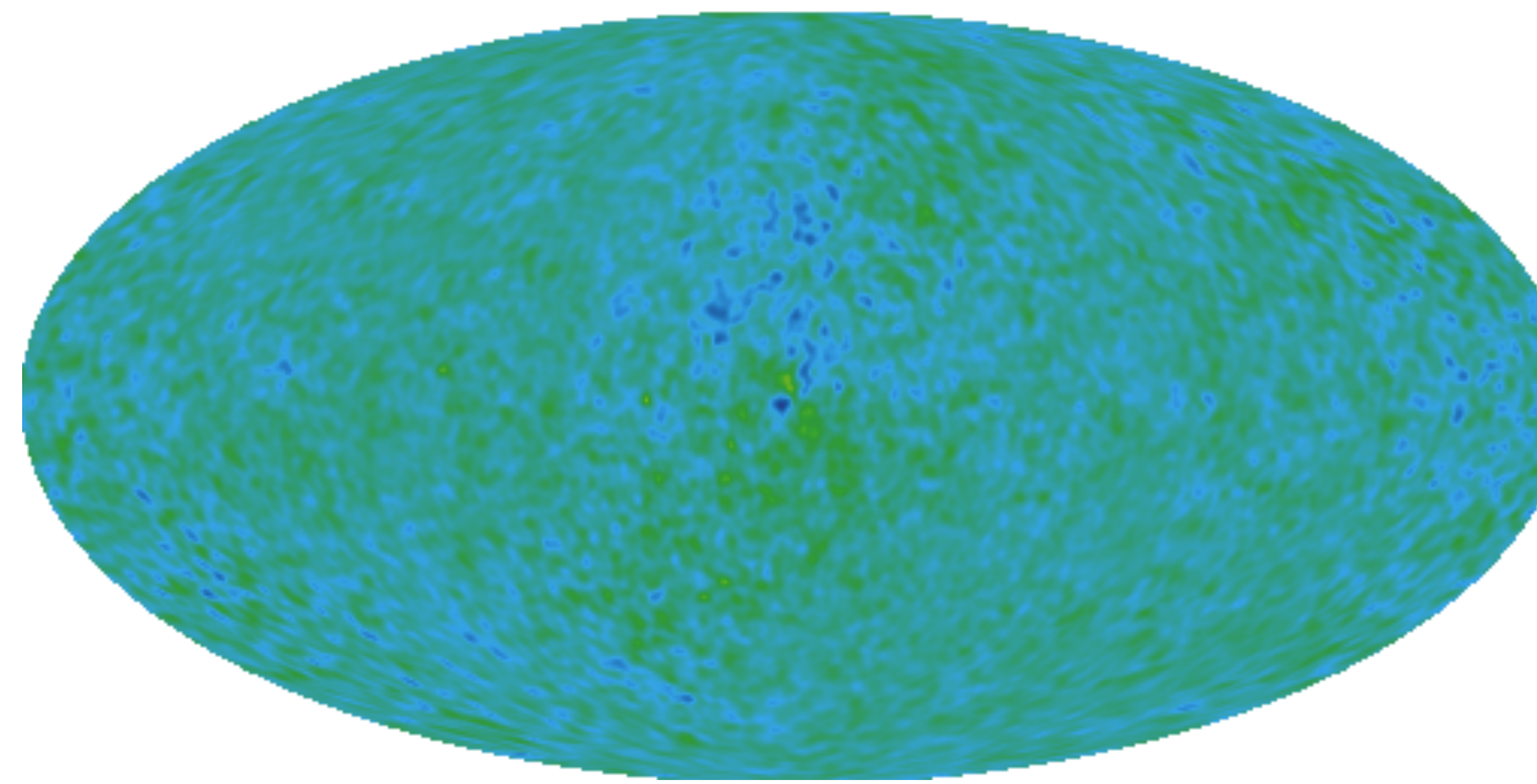


Stokes U

61 GHz [polarized]

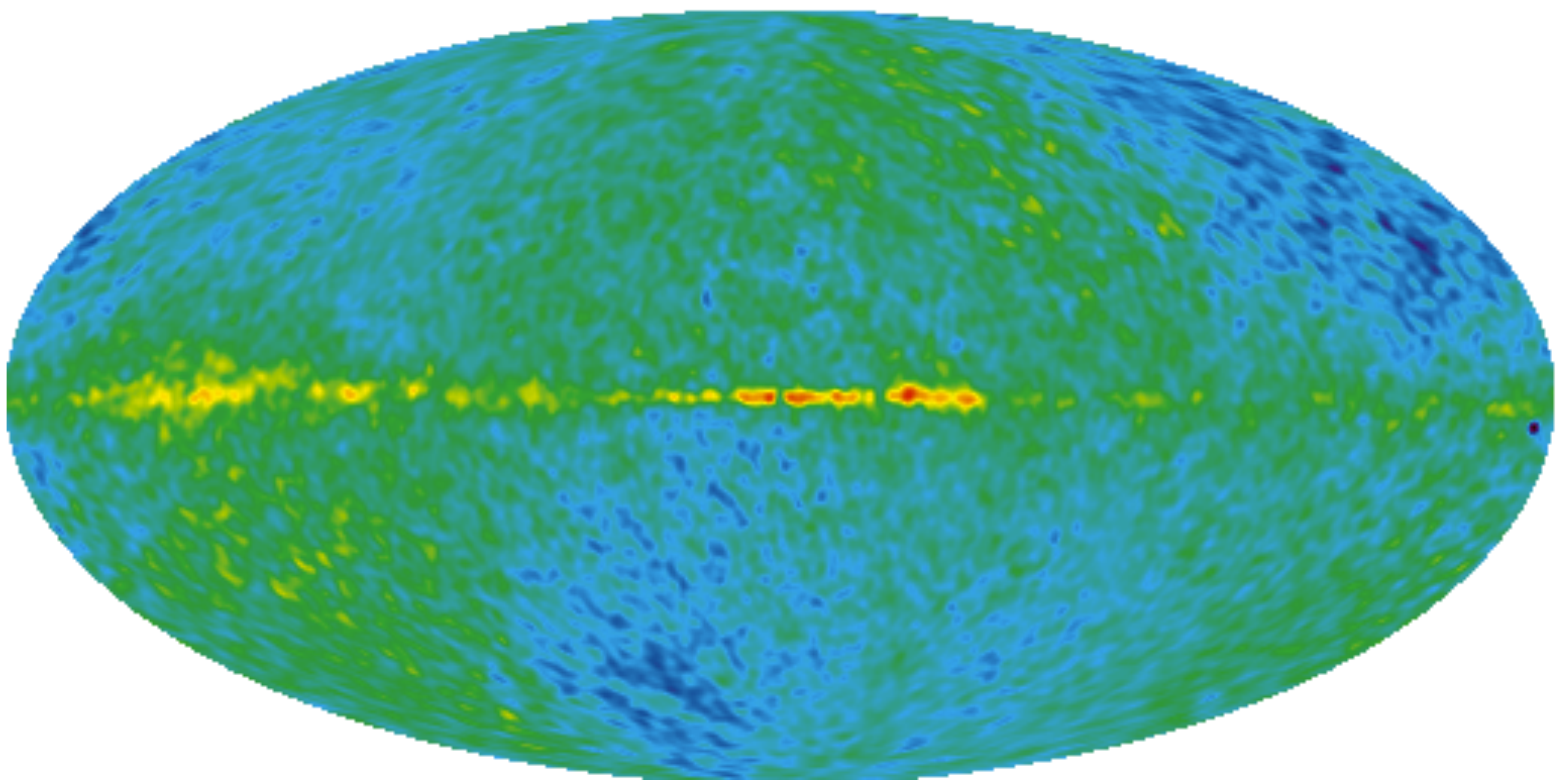


Stokes Q

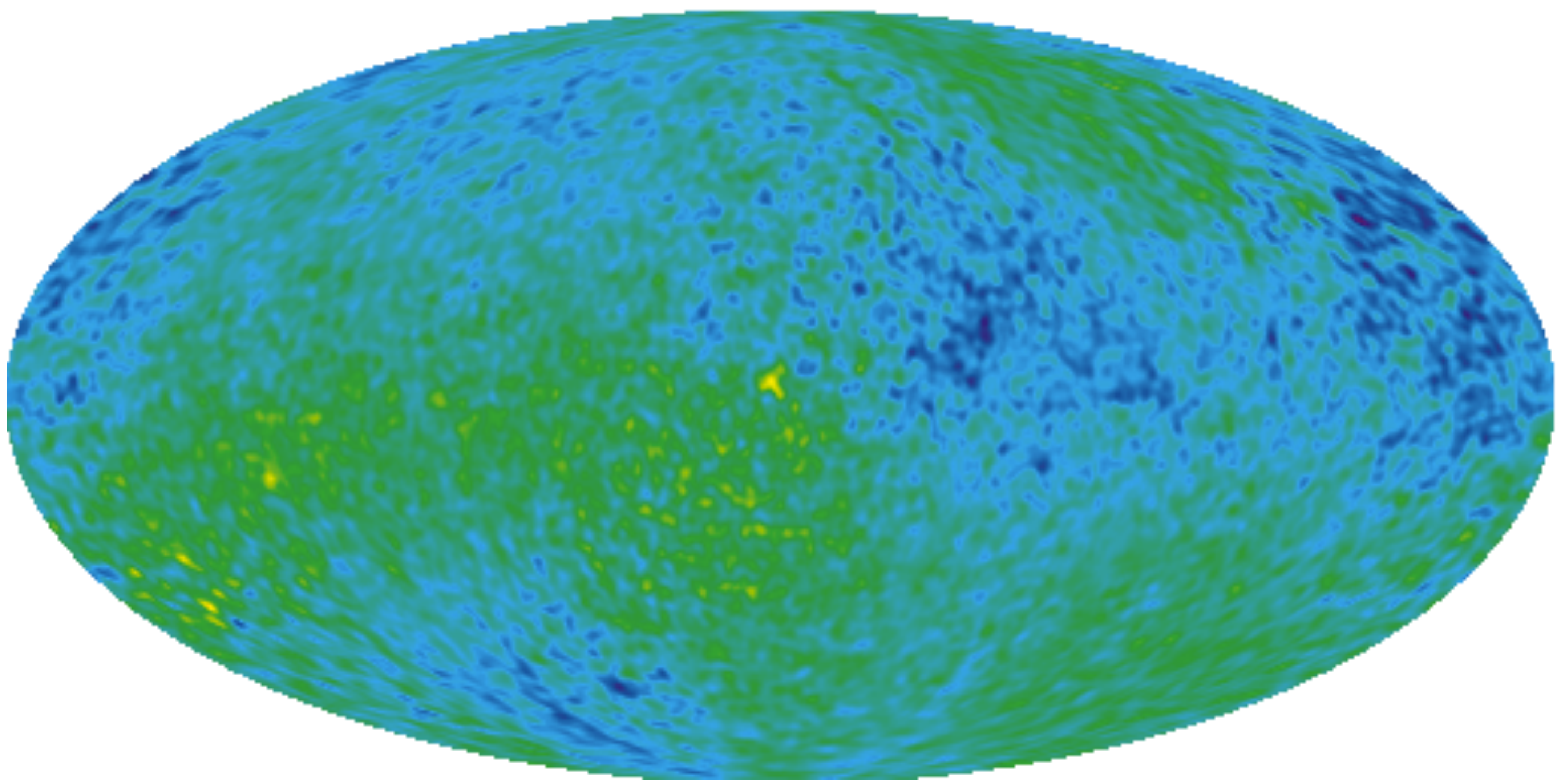


Stokes U

94 GHz [polarized]



Stokes Q



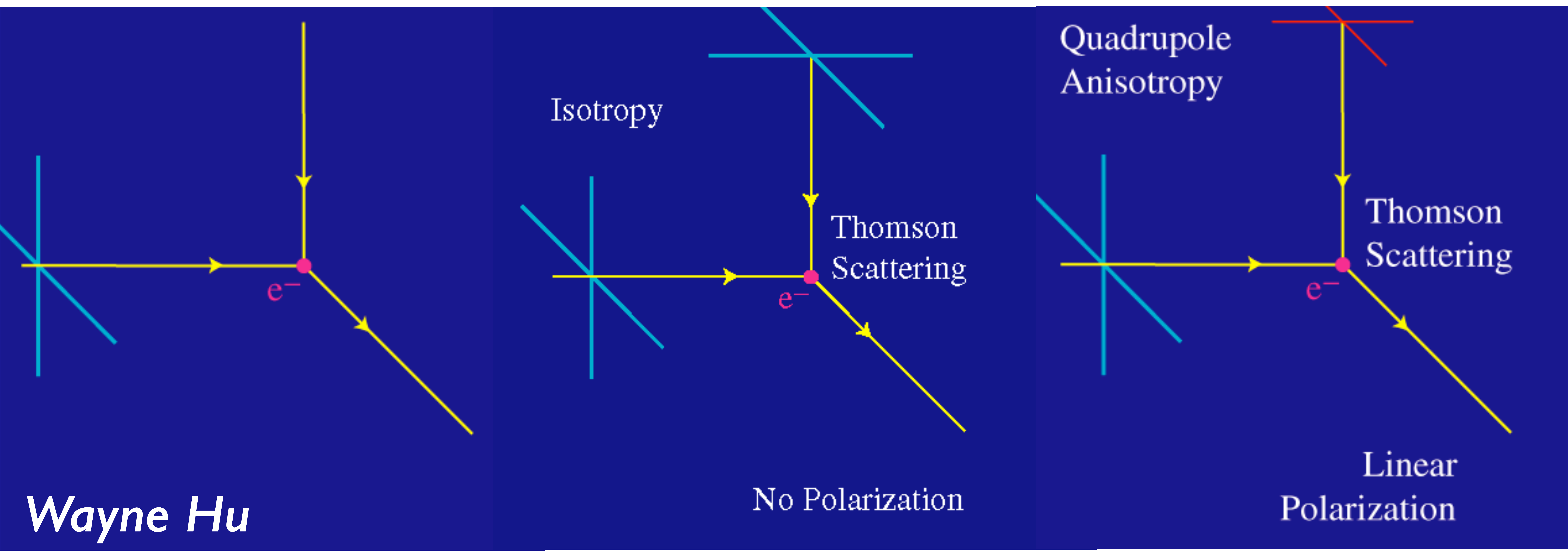
Stokes U

How many components?

1. **CMB**: $T_\nu \sim \nu^0$
2. **Synchrotron** (electrons going around magnetic fields): $T_\nu \sim \nu^{-3}$
3. ~~**Free-free** (electrons colliding with protons):~~ $\cancel{T_\nu \sim \nu^{-2}}$
4. **Dust** (heated dust emitting thermal emission): $T_\nu \sim \nu^2$
5. ~~**Spinning dust** (rapidly rotating tiny dust grains): T_ν~complicated~~

*You need at least **THREE** frequencies to separate them!*

Physics of CMB Polarization

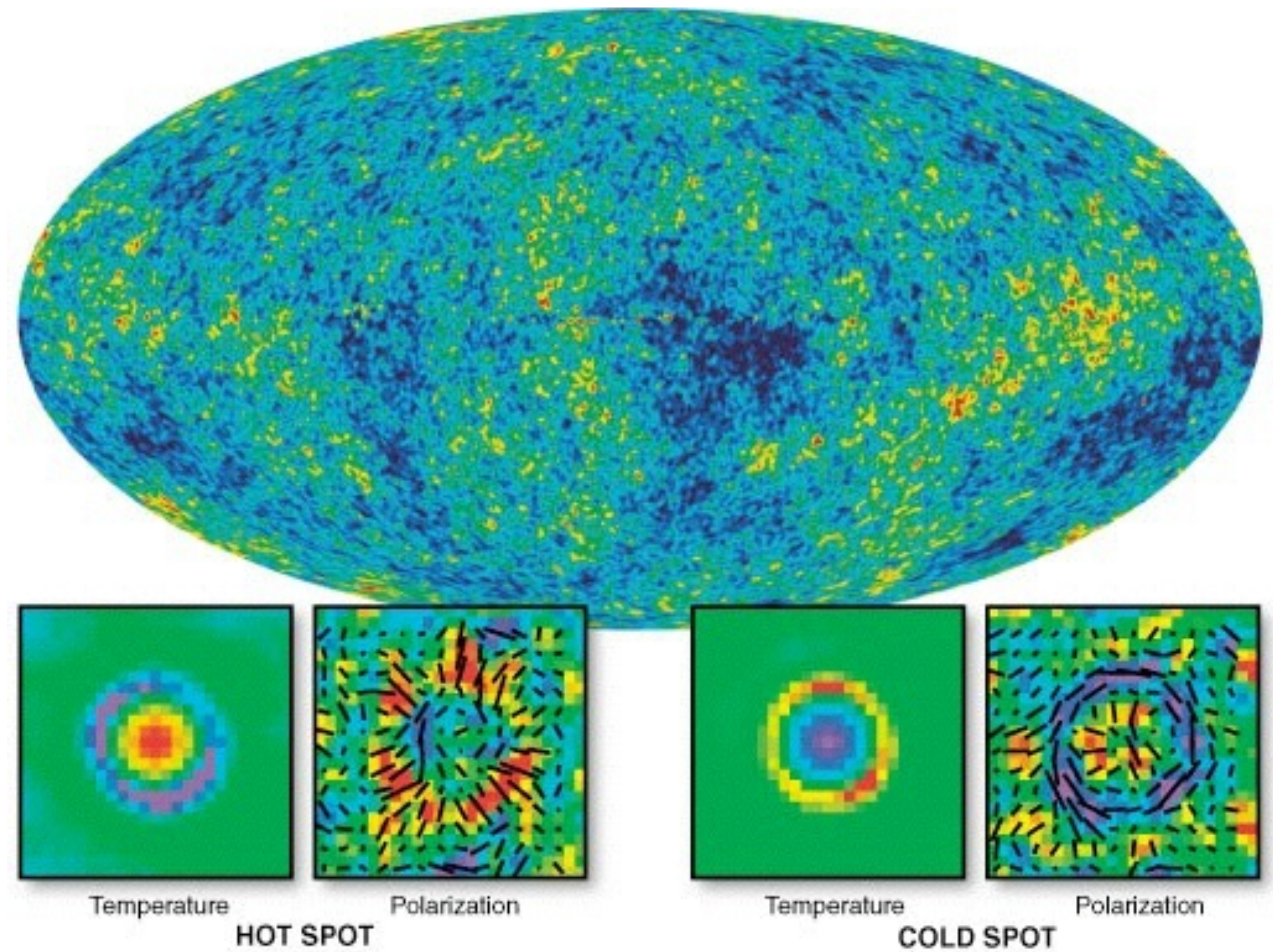


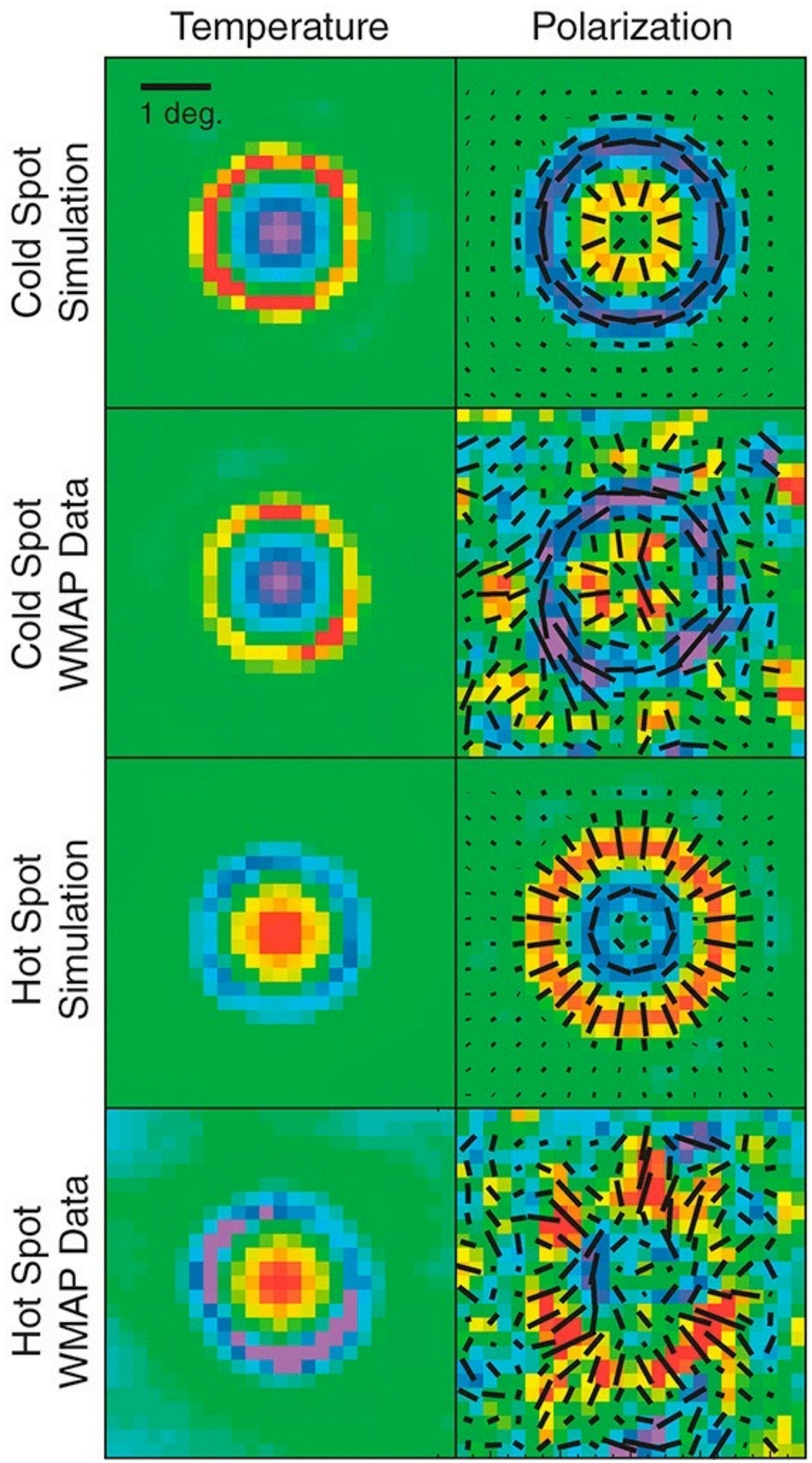
- CMB Polarization is created by a local temperature **quadrupole** anisotropy.

Stacking Analysis

- Stack polarization images around temperature hot and cold spots.

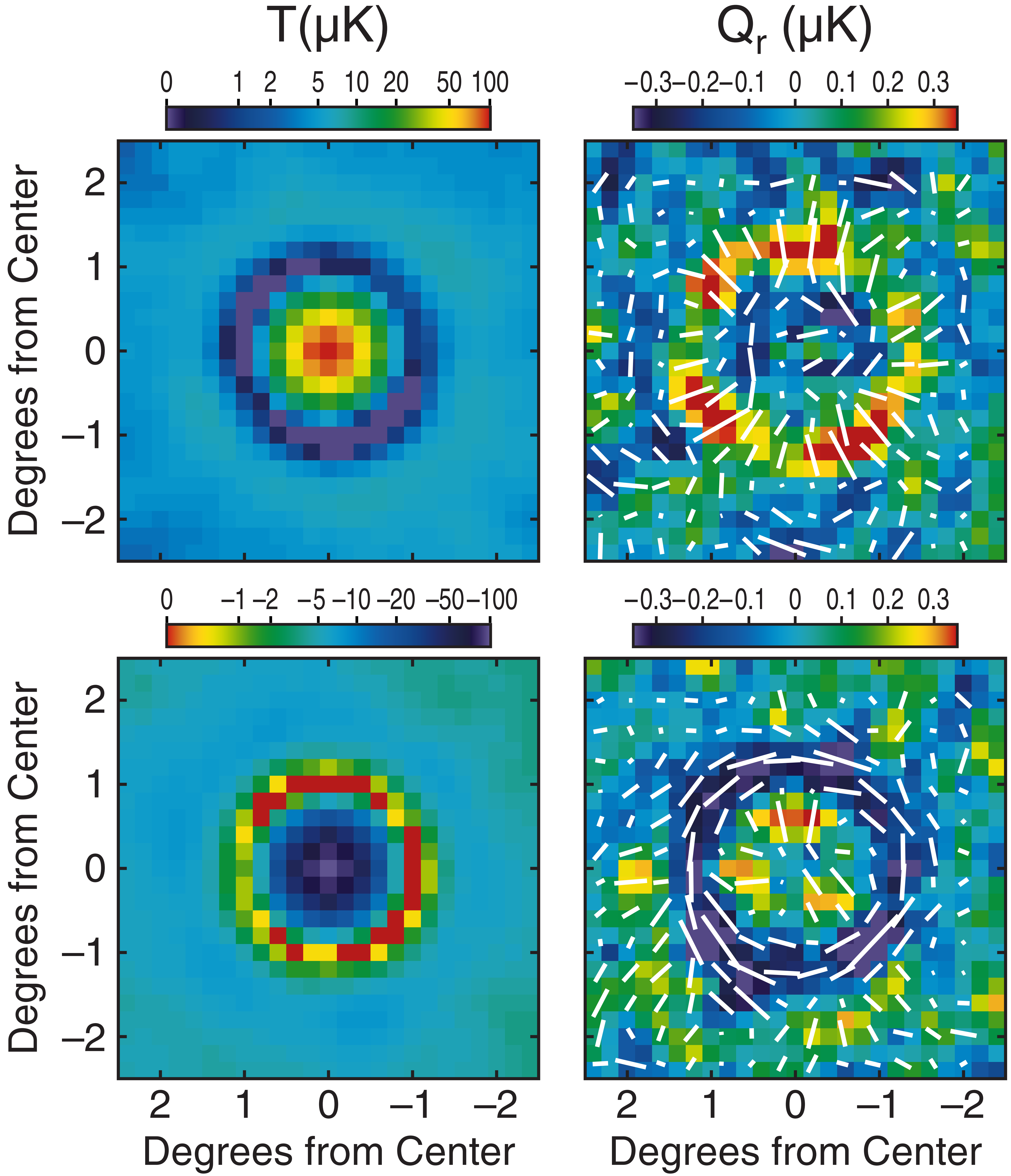
- Outside of the Galaxy mask (not shown), there are 11536 hot spots and 11752 cold spots.





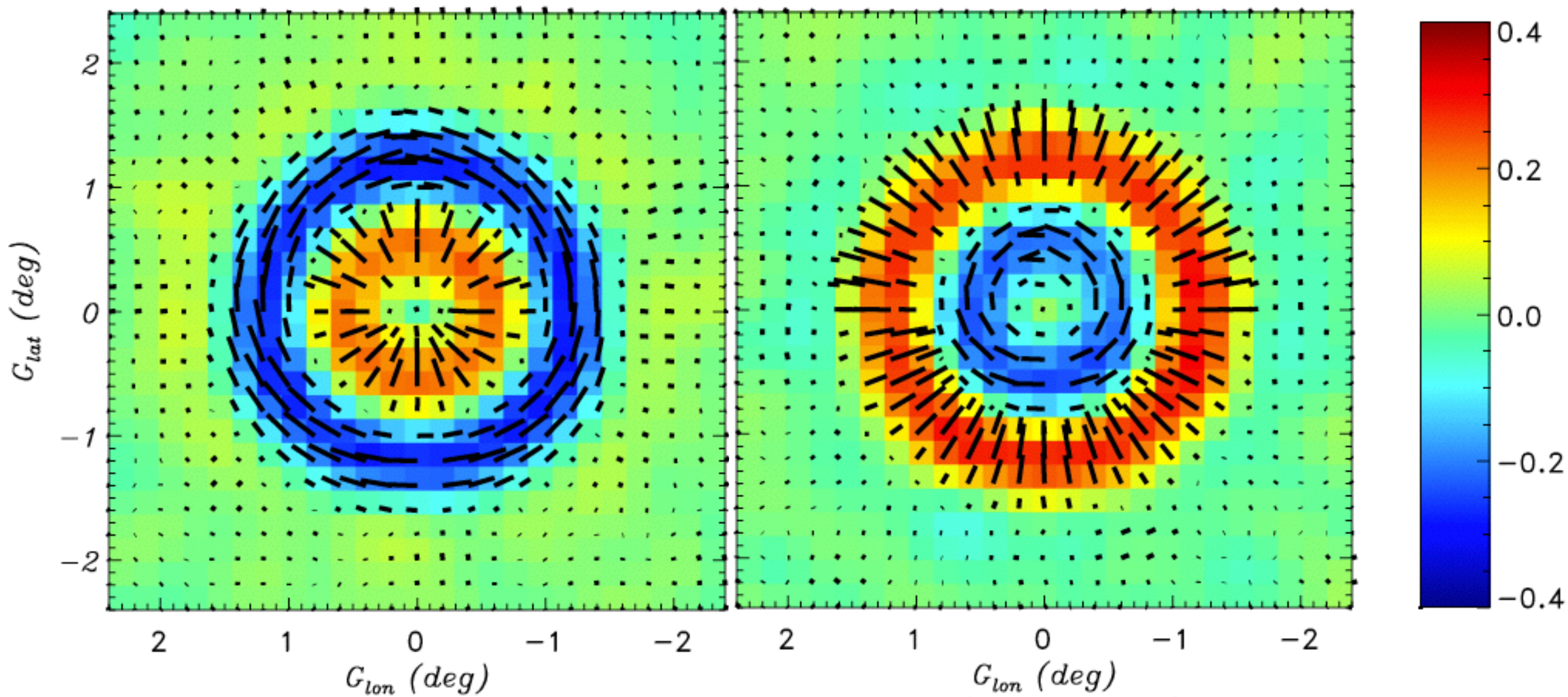
Radial and Tangential Polarization Patterns around Temp. Spots

- All hot and cold spots are stacked
- "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 7-year overall significance level: 8σ



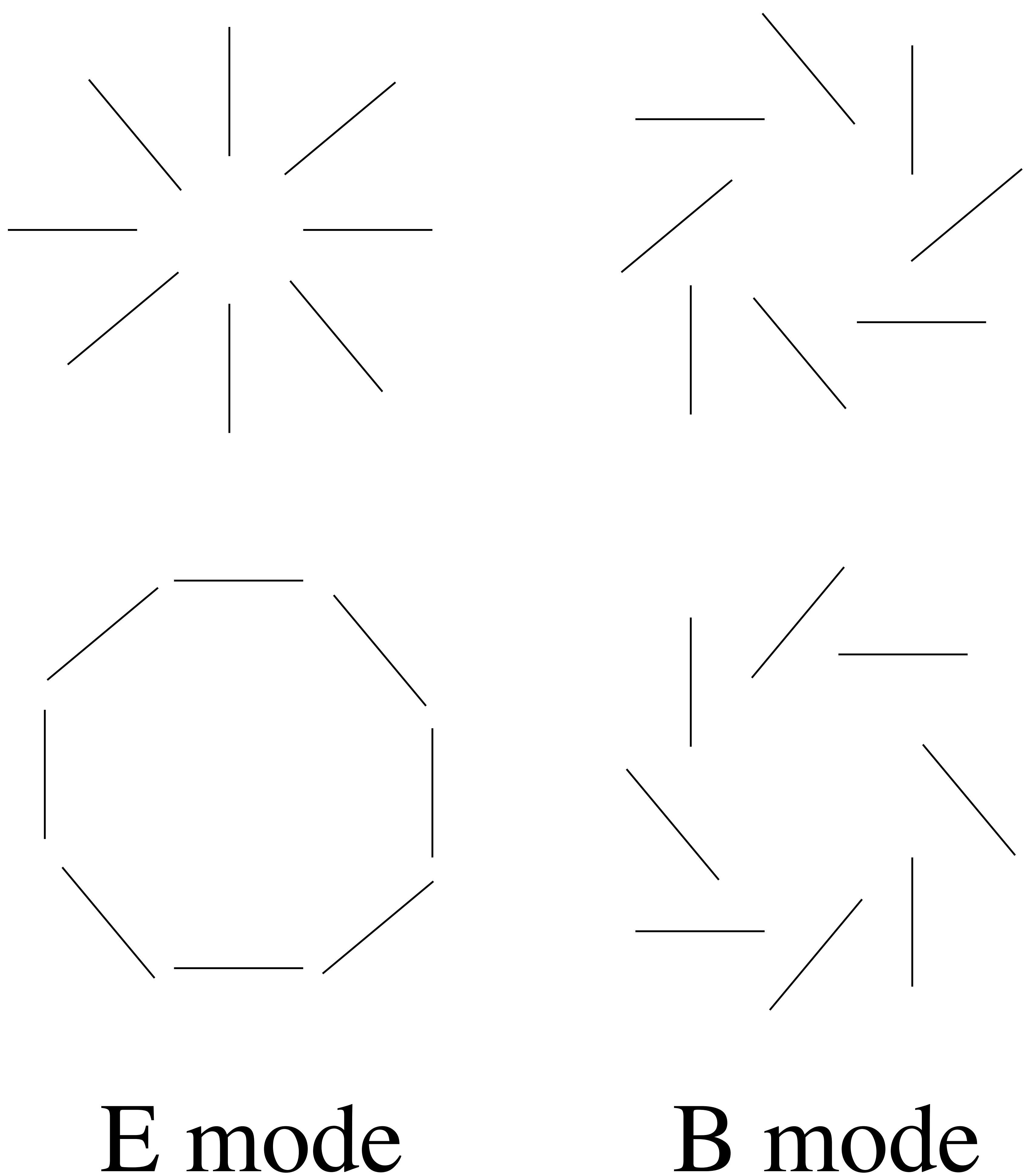
- The 9-year overall significance level: 10σ

Planck Data!



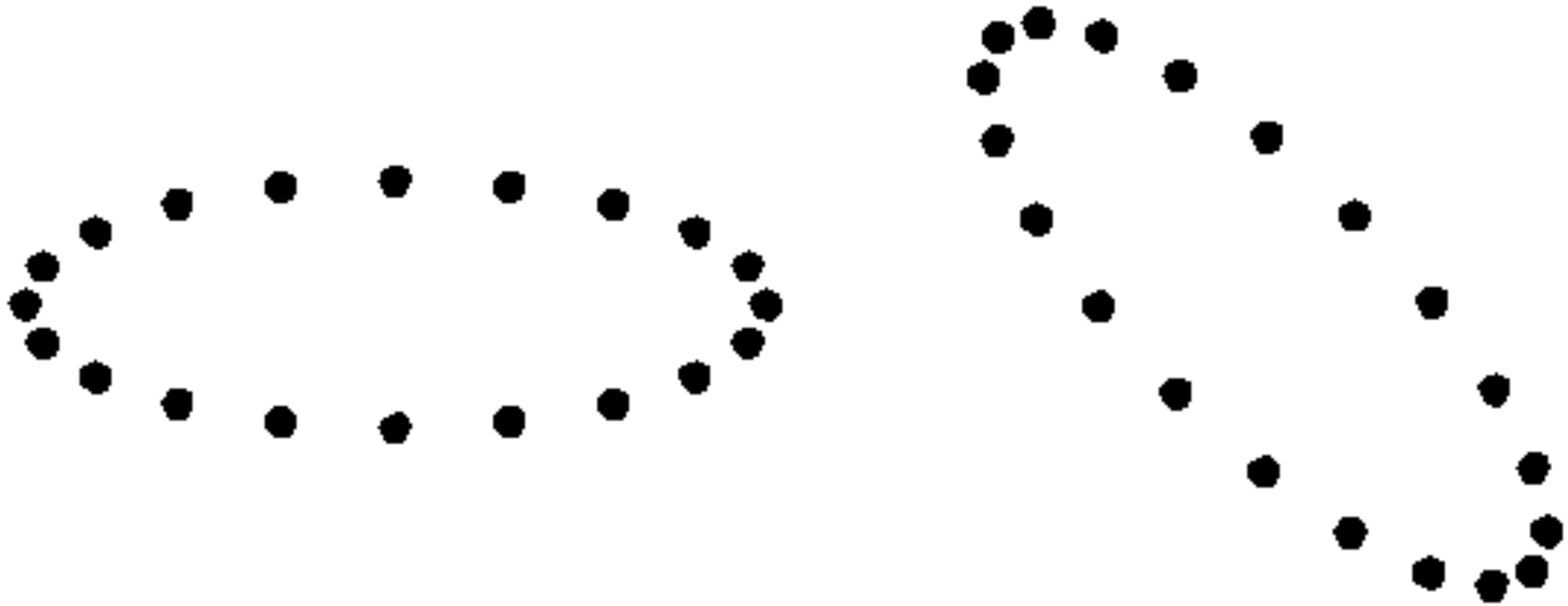
Q_r (cold spots) Q_r (hot spots)

E-mode and B-mode



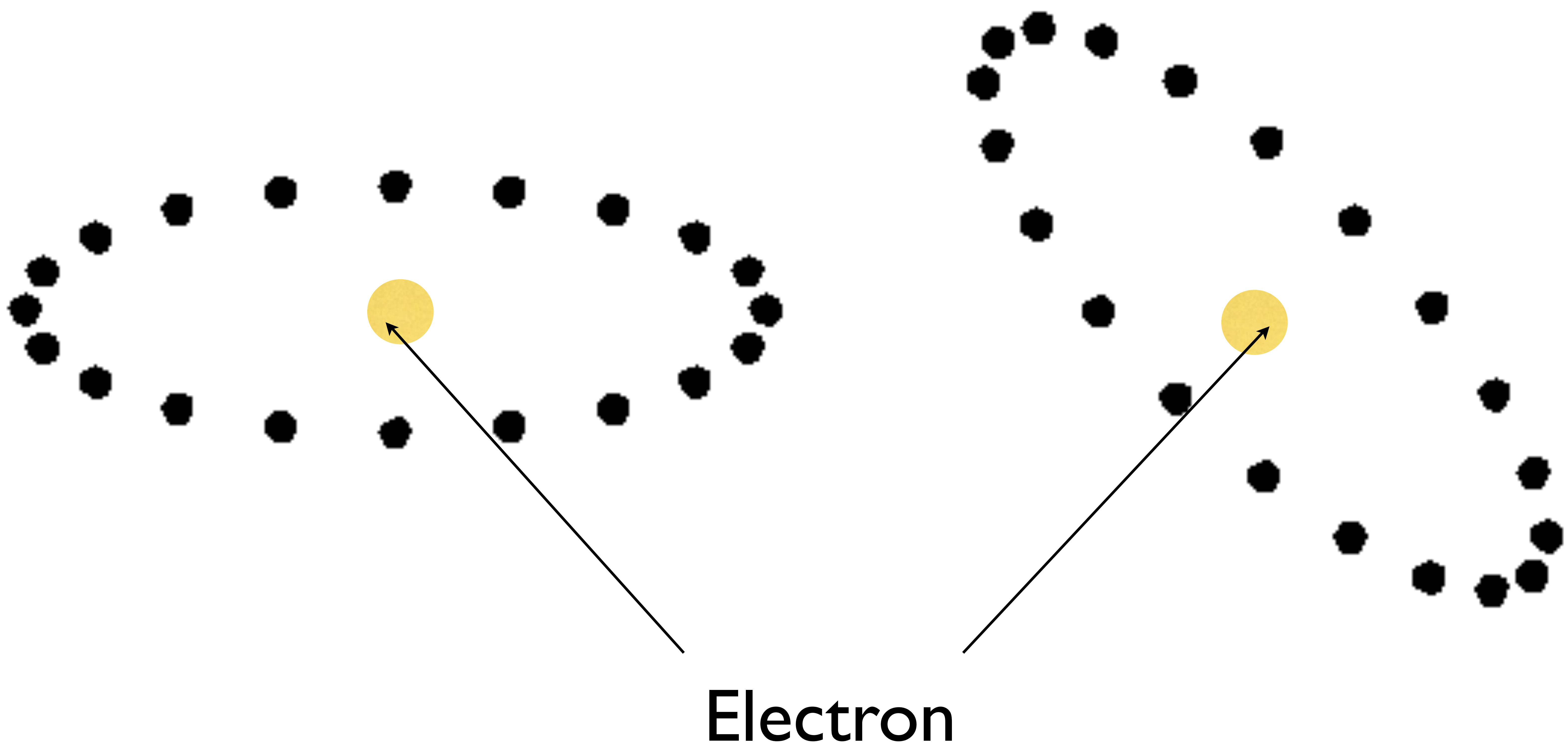
- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

Two Polarization States of GW

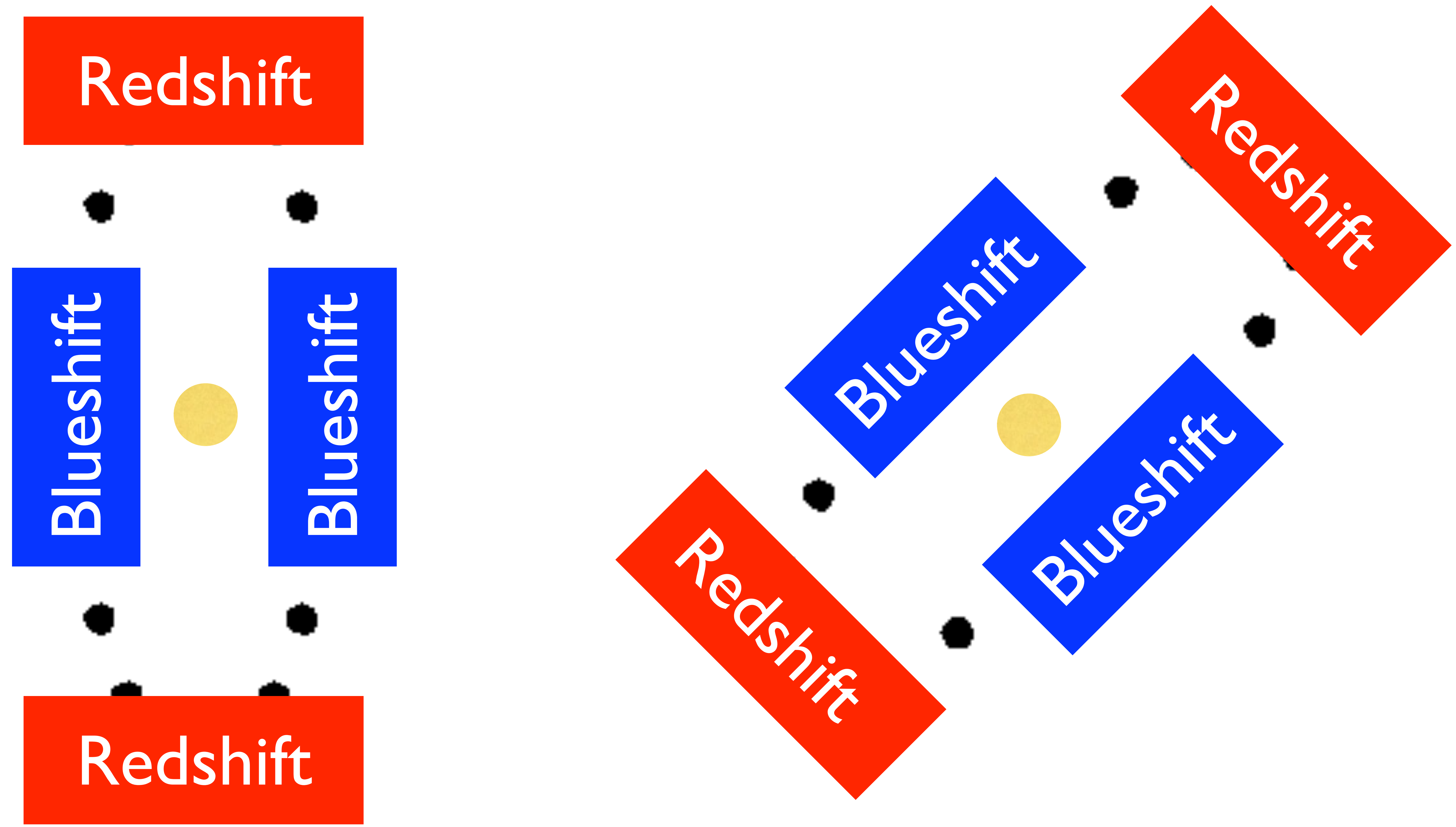


- This is great - this will automatically generate quadrupolar anisotropy around electrons!

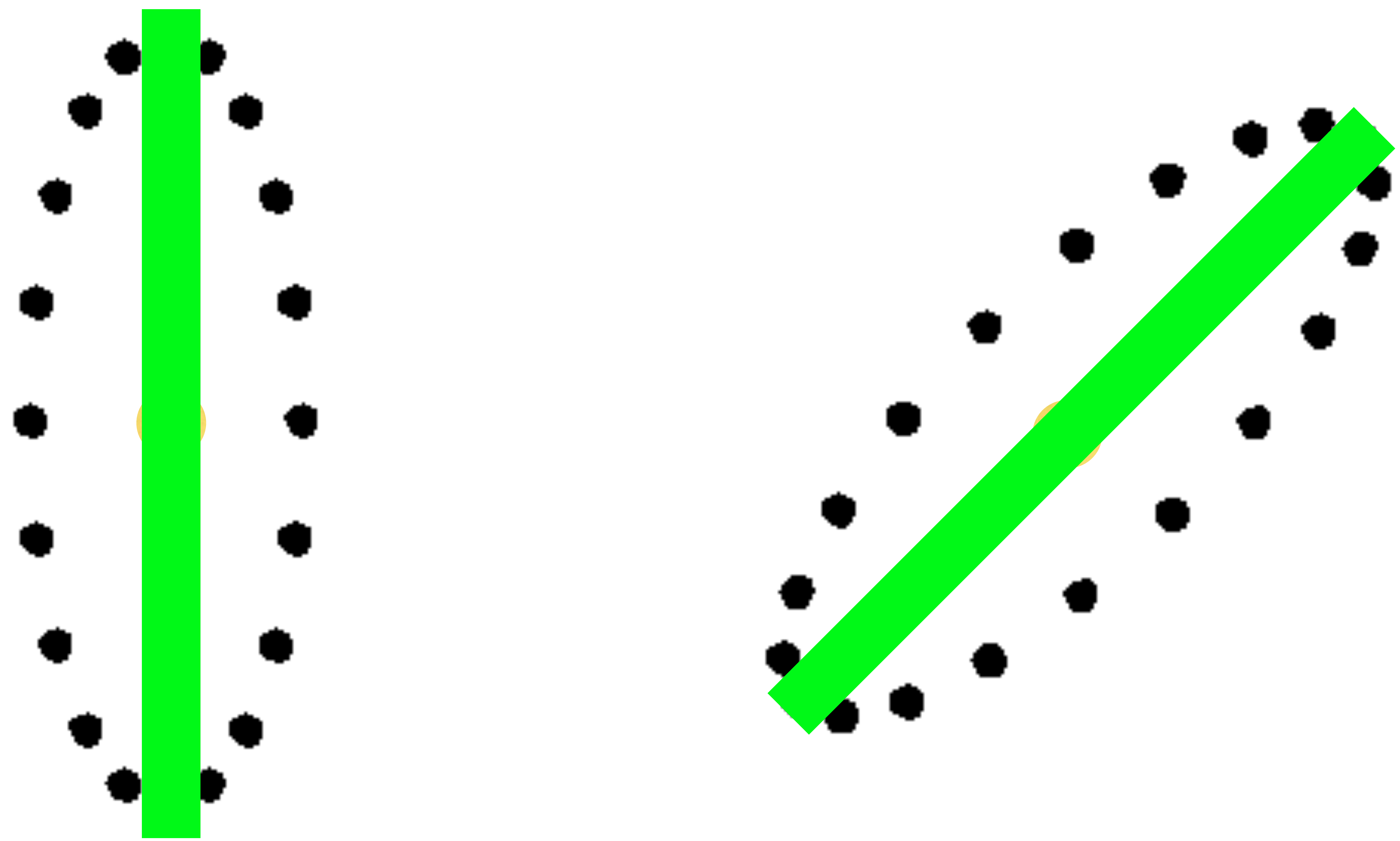
From GW to CMB Polarization



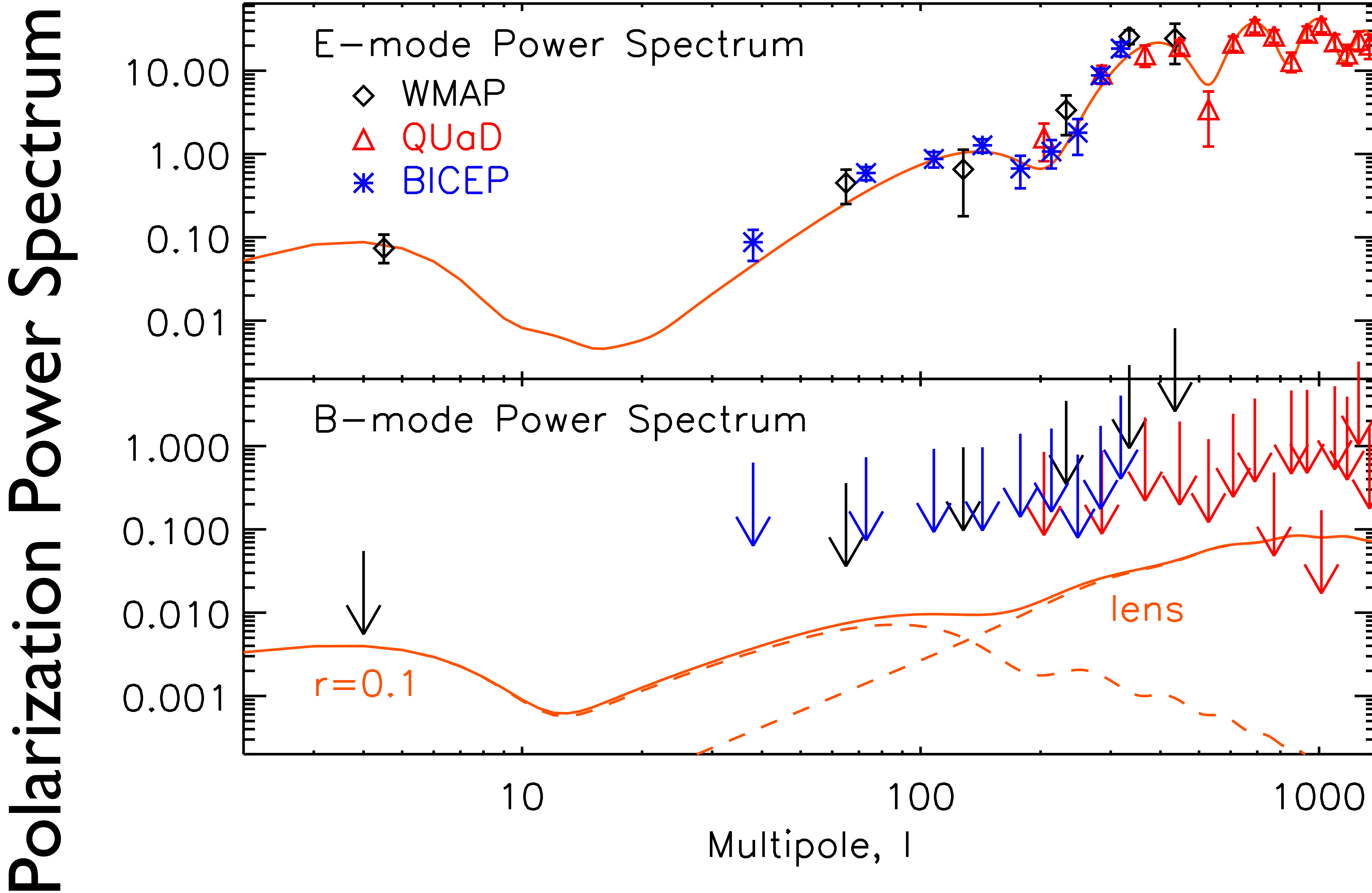
From GW to CMB Polarization



From GW to CMB Polarization



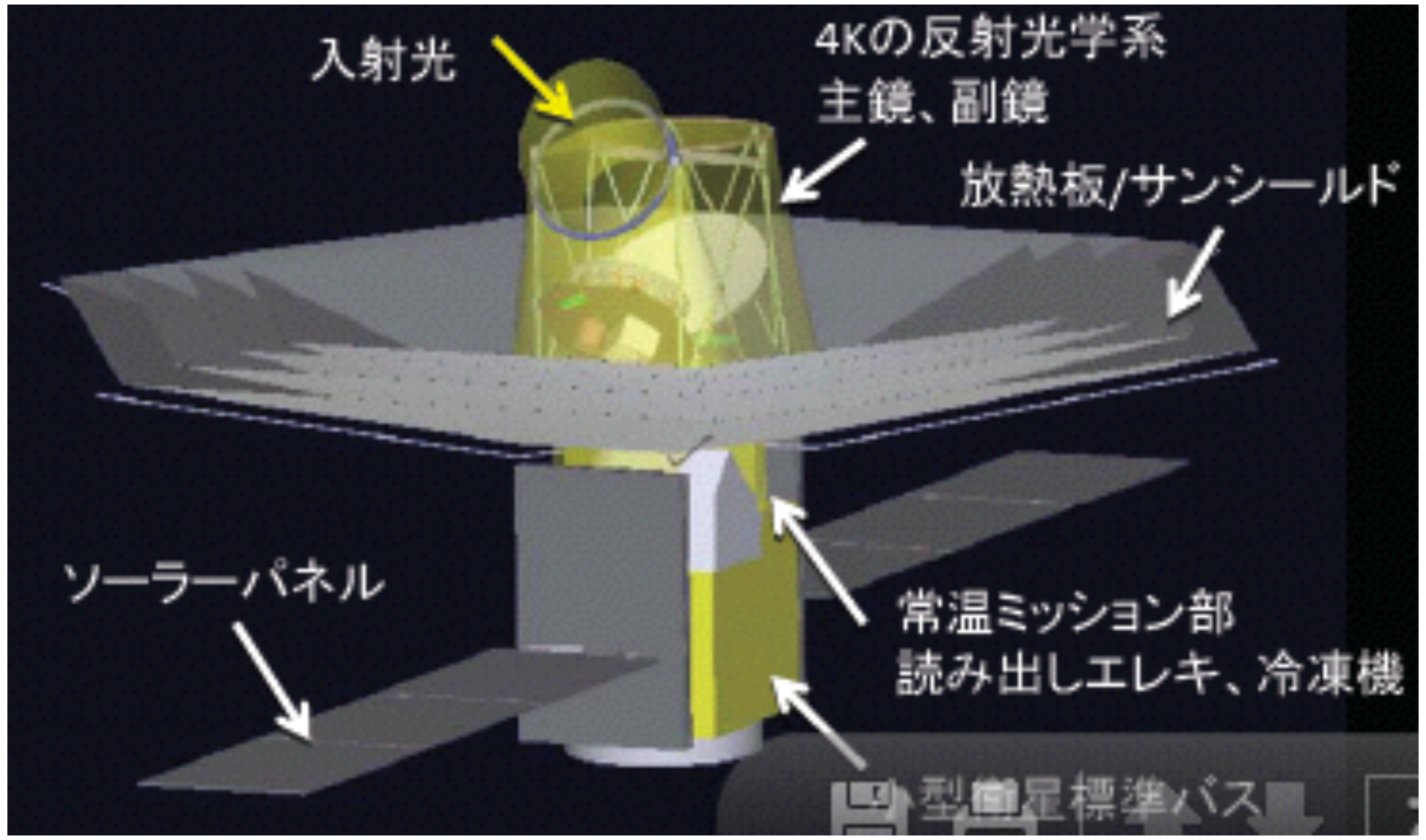
Gravitational waves can produce
both E- and B-mode polarization

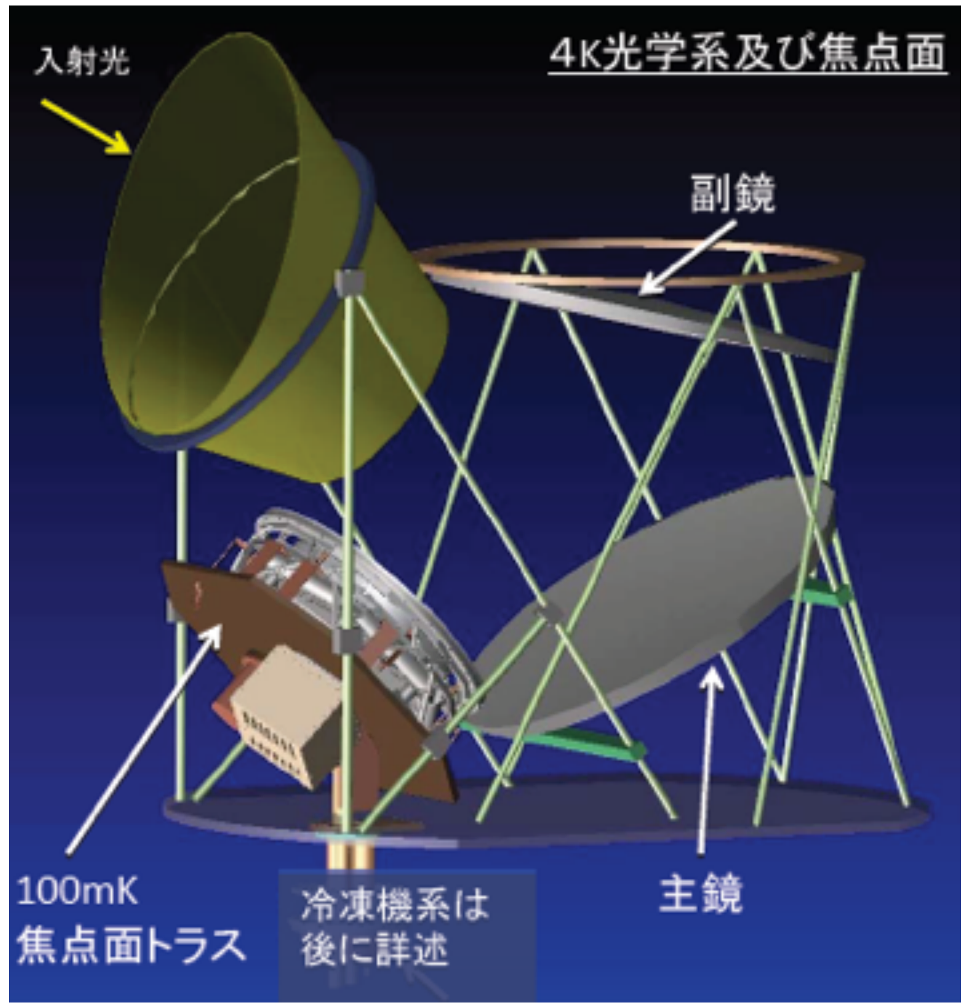


- No detection of B-mode polarization yet. **B-mode is the next holy grail!**

LiteBIRD

- Next-generation polarization-sensitive microwave experiment. Target launch date: ~2020
- Led by Prof. Masashi Hazumi (KEK); a collaboration of ~60 scientists in Japan, USA, Canada, and Germany
- We aim at detecting signatures of gravitational waves in the cosmic microwave background, down to **r~0.001**





Summary

- WMAP has completed 9 years of observations
- 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
    - **n_s=0.96 discovered with >5σ**
- Next Big Thing: **Primordial gravitational waves**