



# Critical Tests of Theory of the Early Universe Using the Cosmic Microwave Background

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# 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 ( $\sim 0.5\mu\text{m}$ )



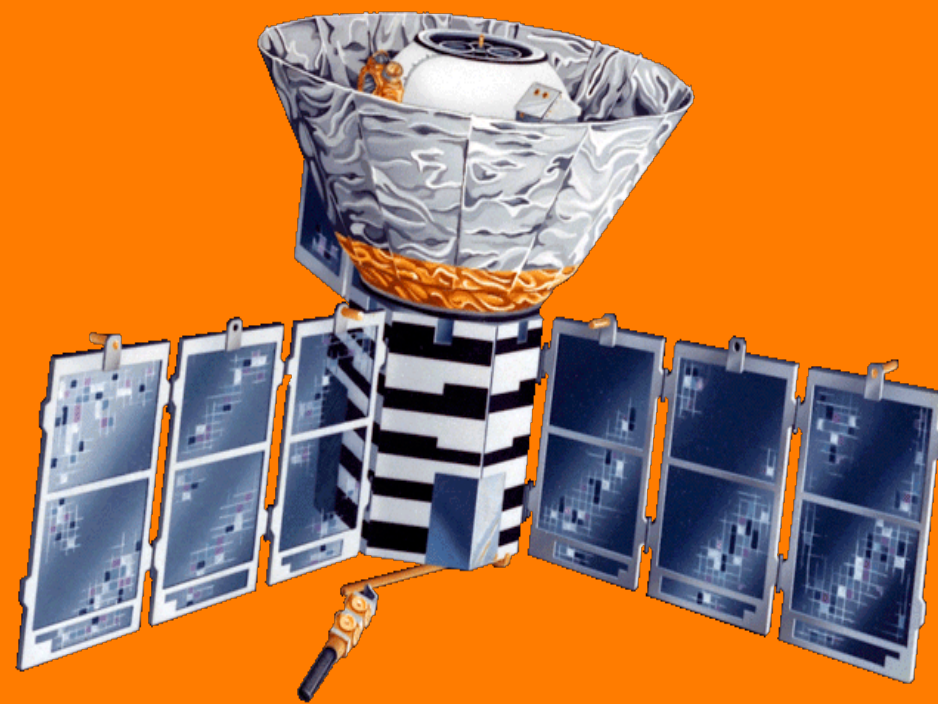


# Night Sky in Microwave (~1mm)

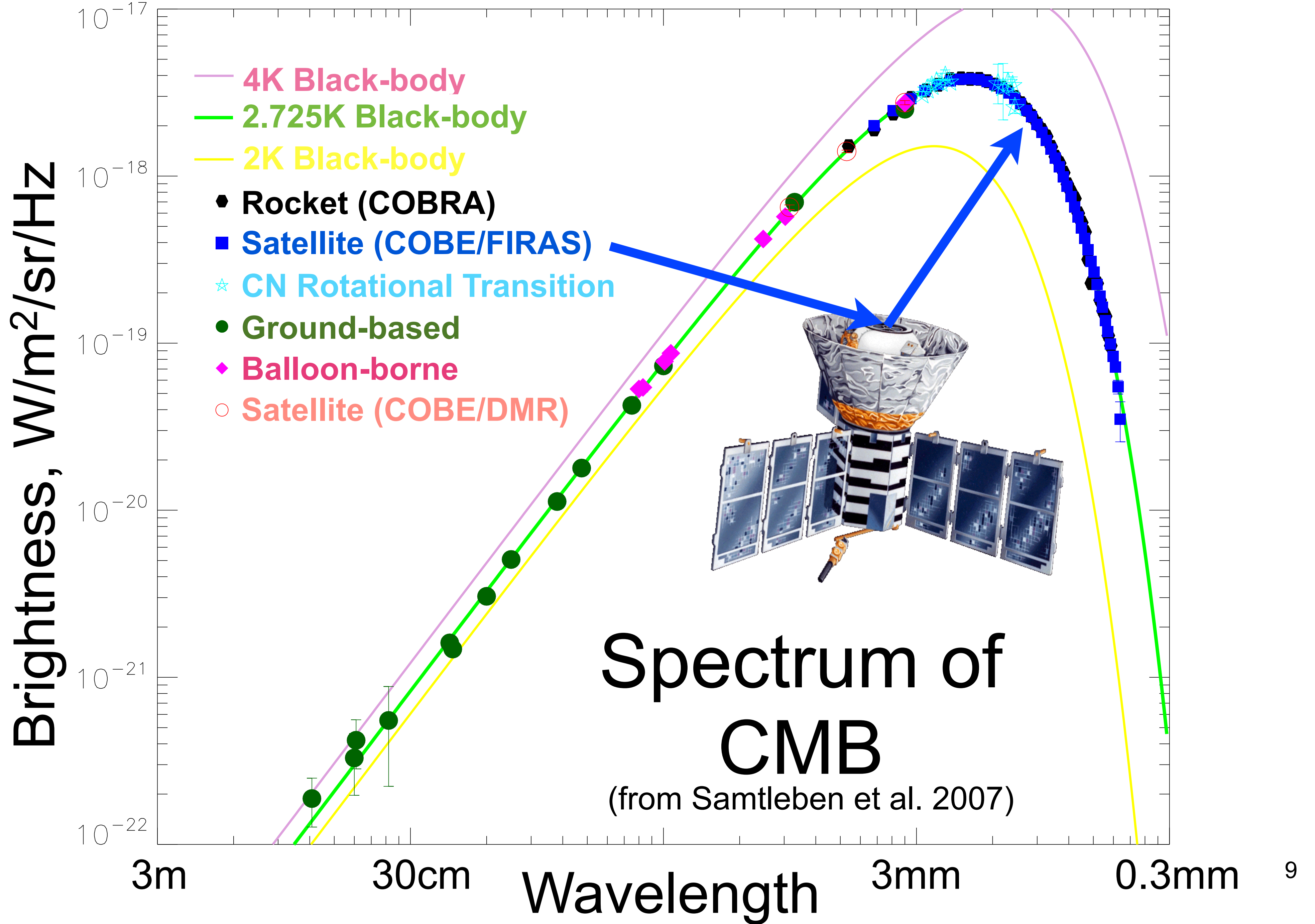


# Night Sky in Microwave ( $\sim 1\text{mm}$ )

$T_{\text{today}} = 2.725\text{K}$



***COBE Satellite, 1989-1993***

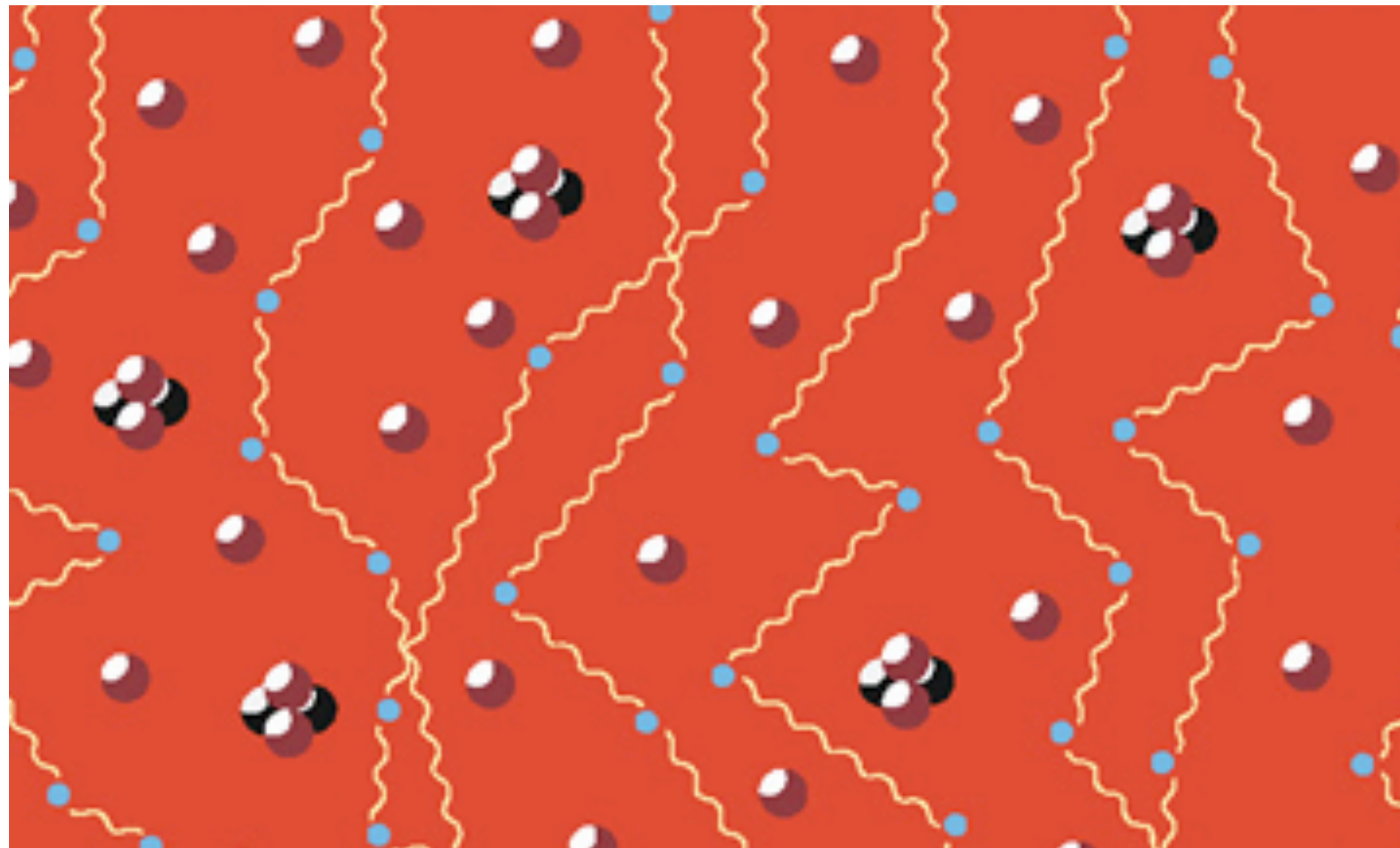


# How was CMB created?

- 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  $\rho_{\text{DM}}/\rho_{\text{H,He}} \sim 5$ )



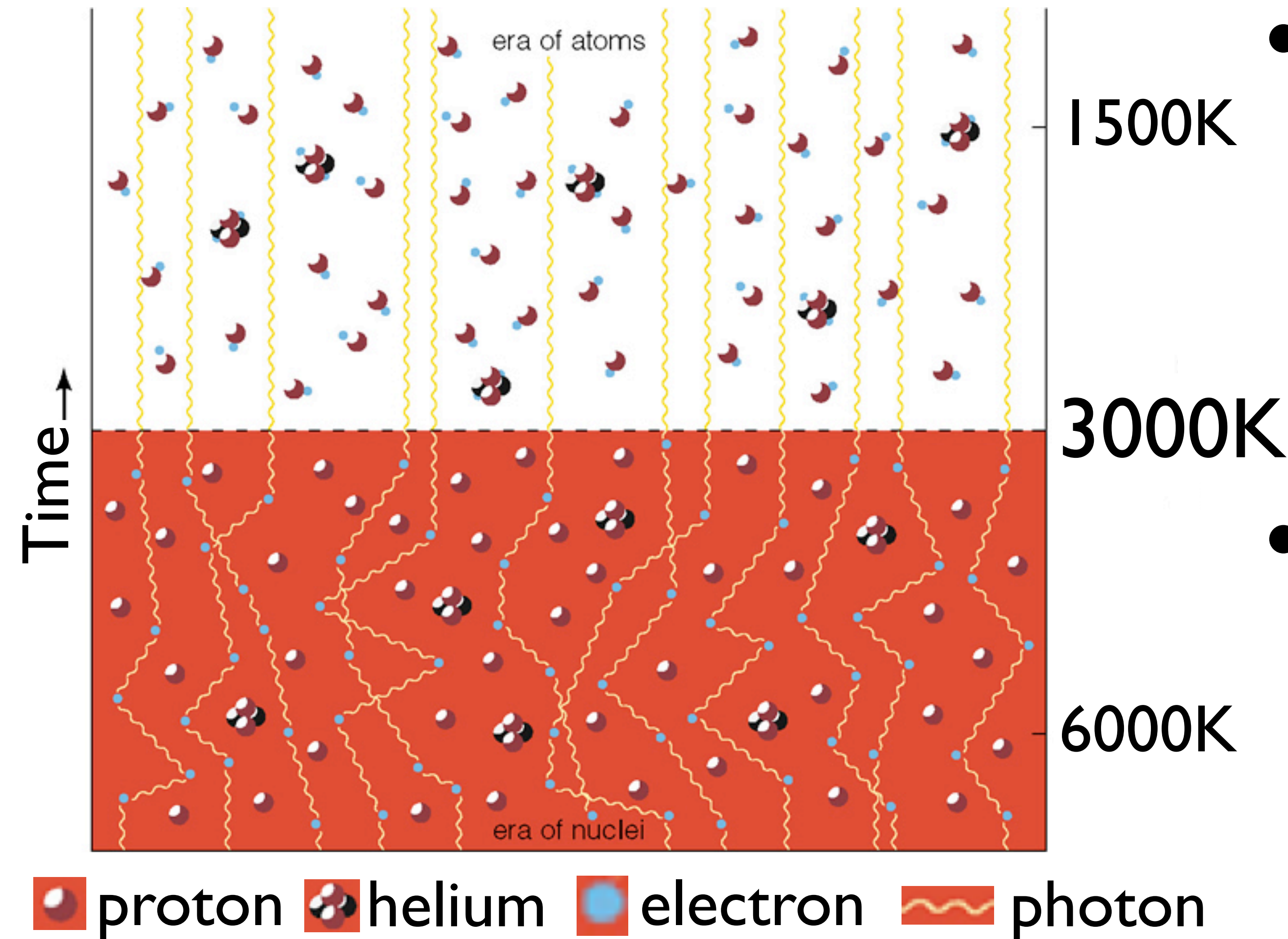
# Universe as a hot soup



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

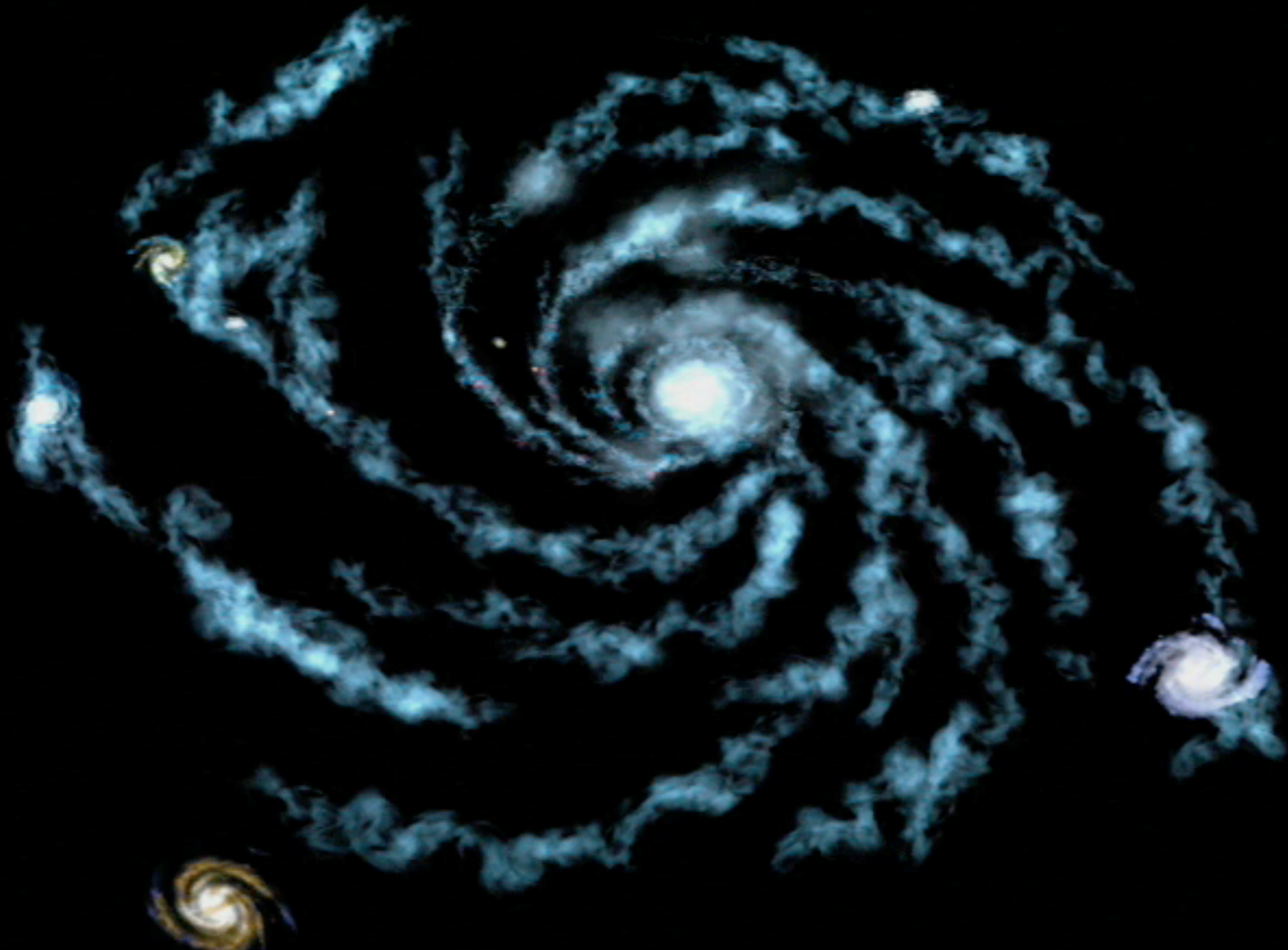


# Recombination and Decoupling



- [**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.

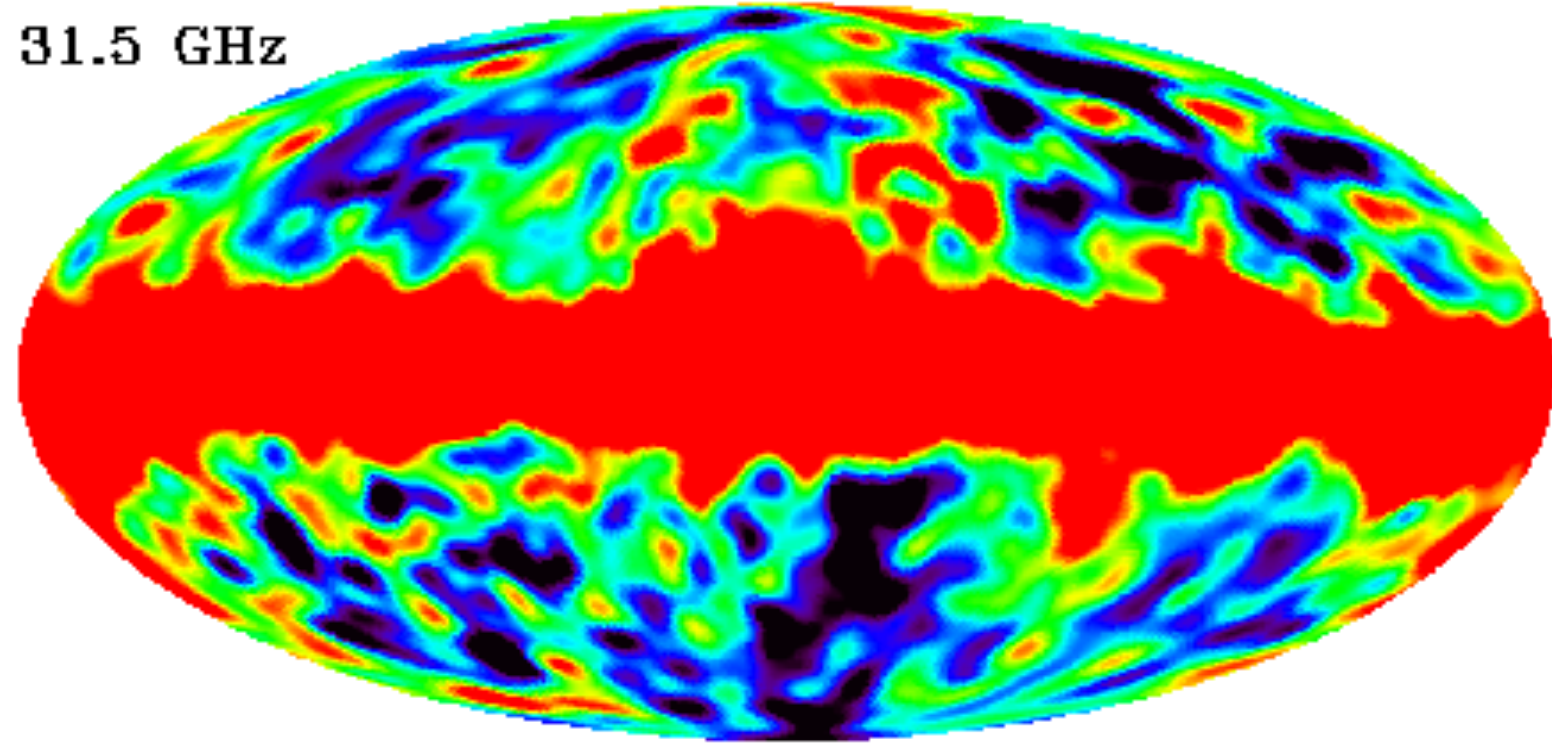




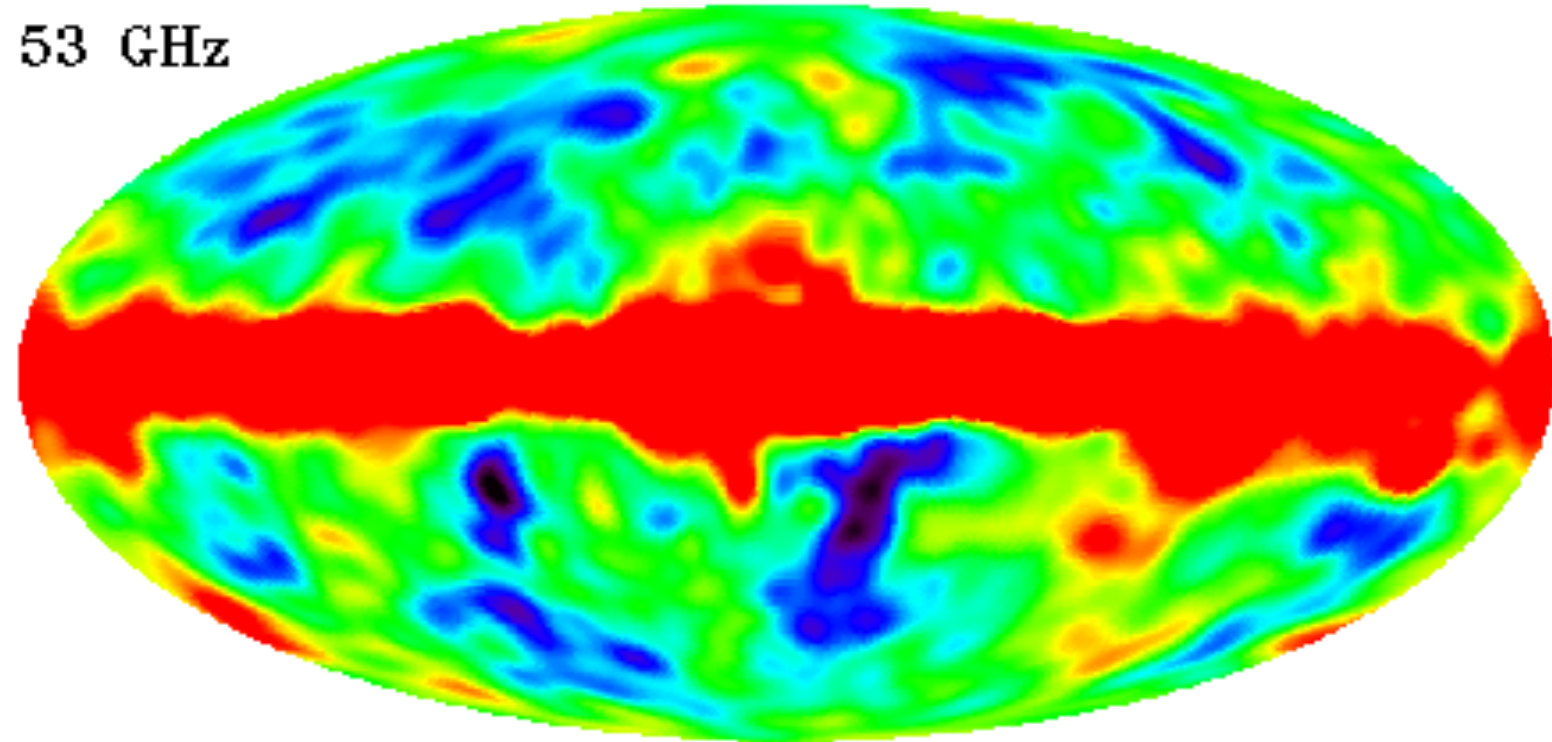


# COBE/DMR, 1992

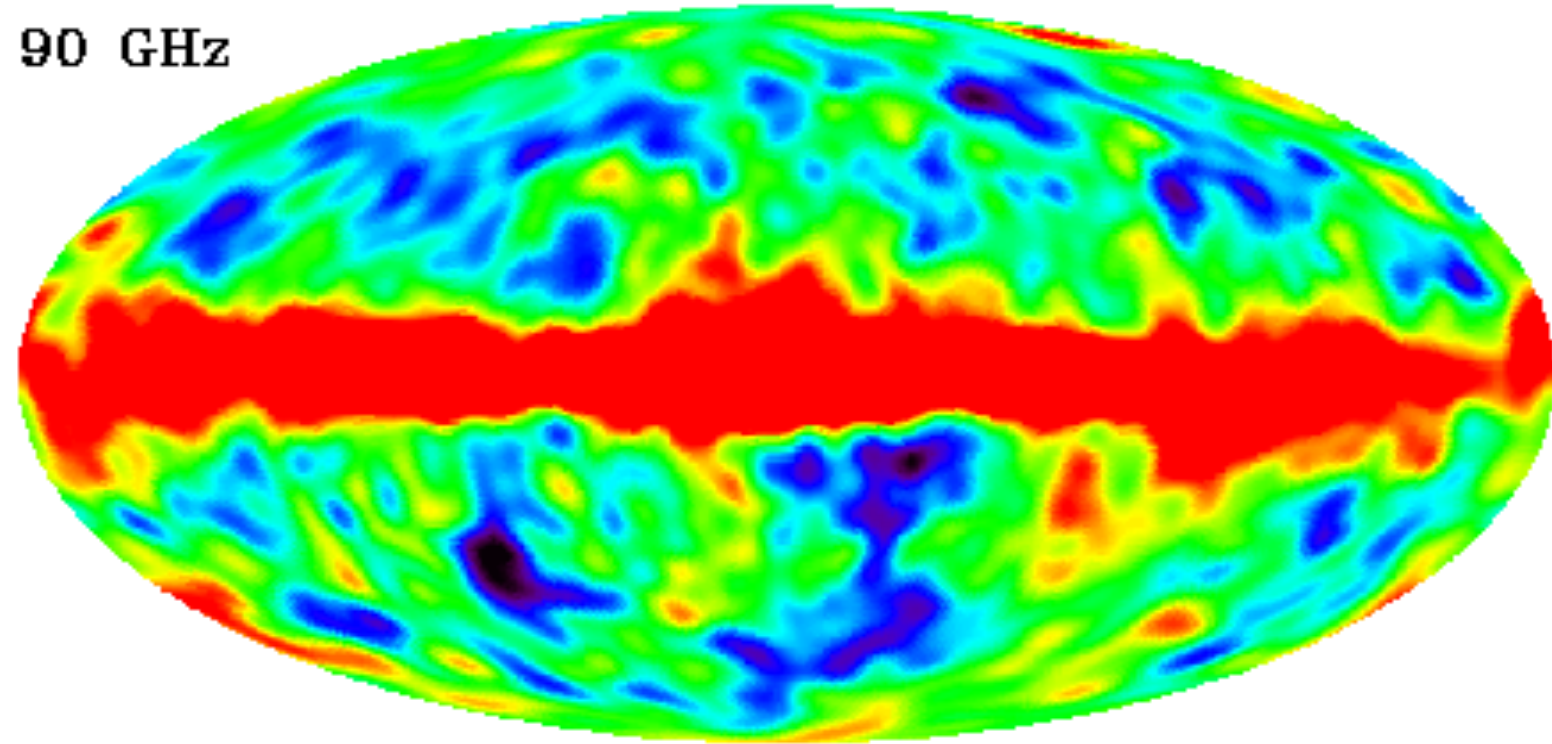
31.5 GHz



53 GHz



90 GHz



-100  $\mu\text{K}$   +100  $\mu\text{K}$

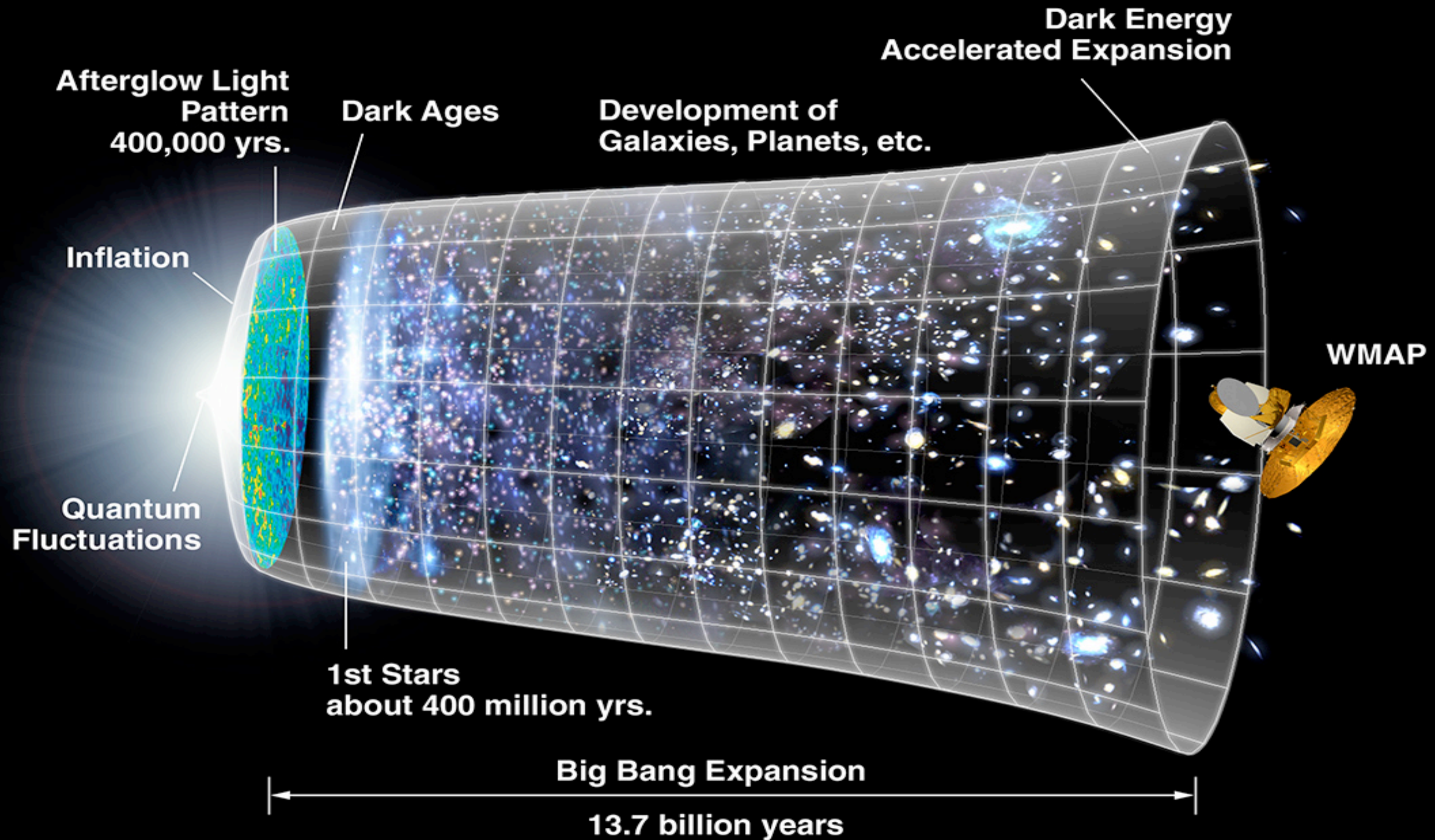


• **Isotropic?**

• **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.



# WMAP at Lagrange 2 (L2) Point

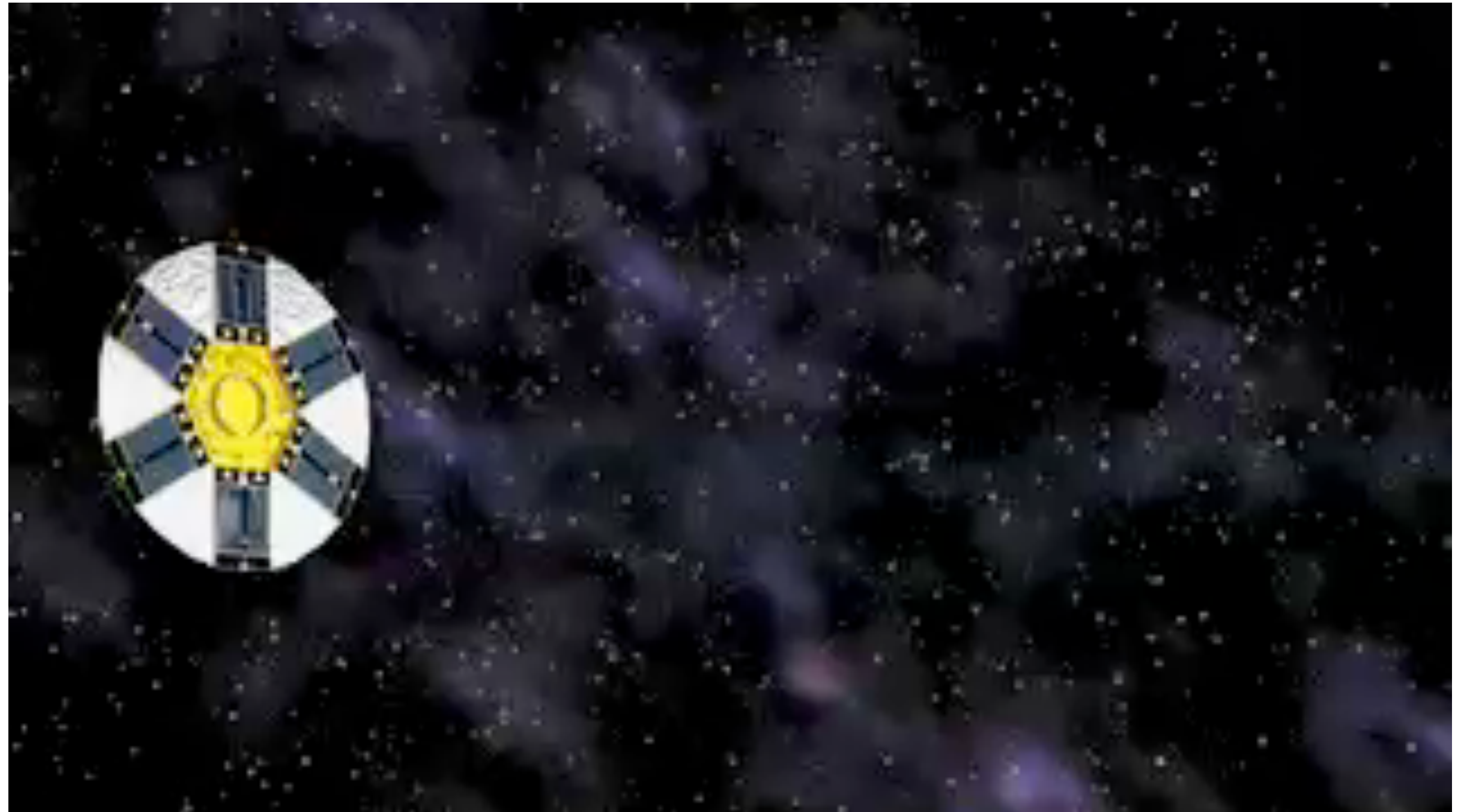
June 2001:  
WMAP launched!

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**

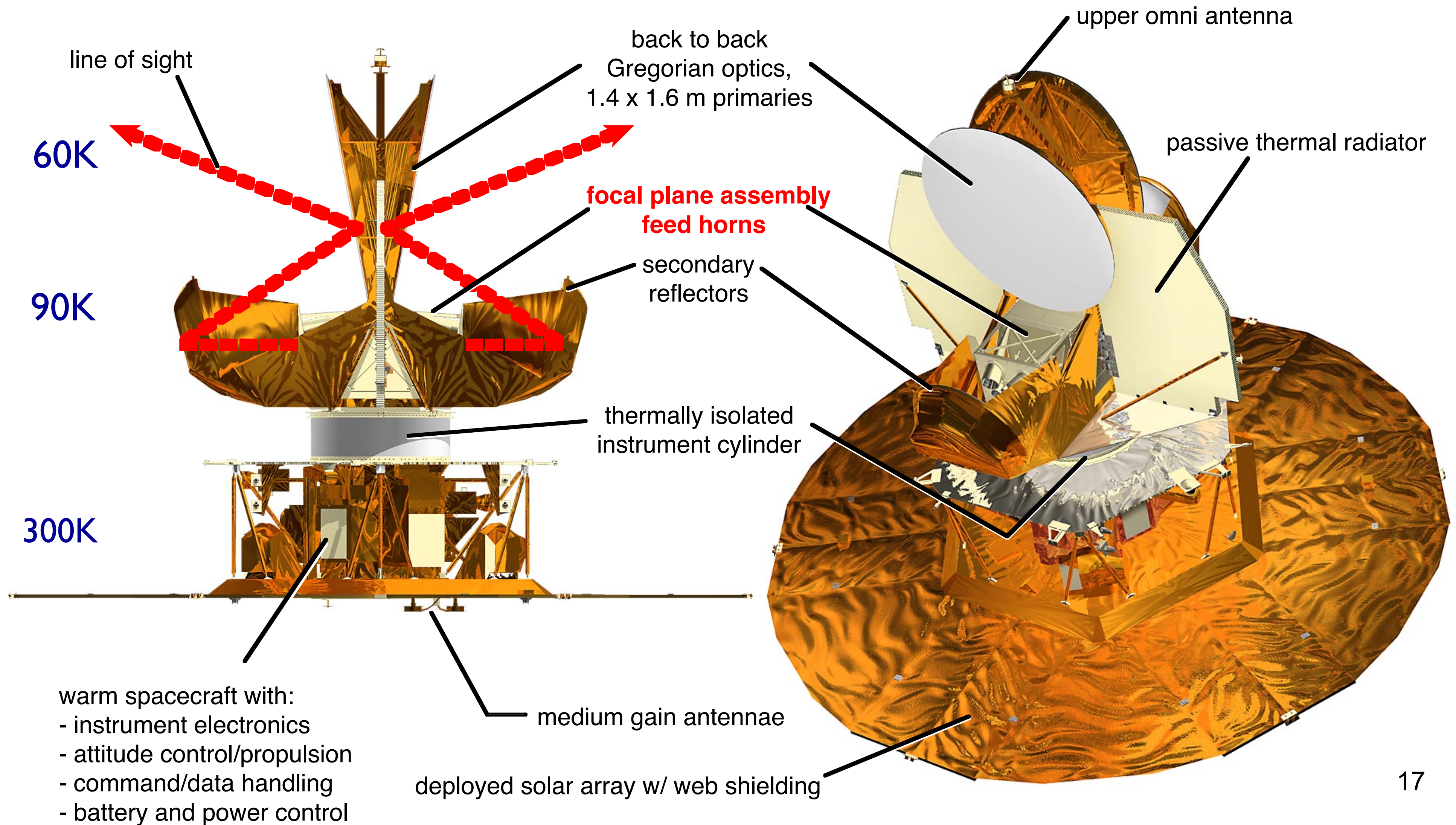


- L2 is a million miles from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them



# WMAP Spacecraft

## Radiative Cooling: No Cryogenic System

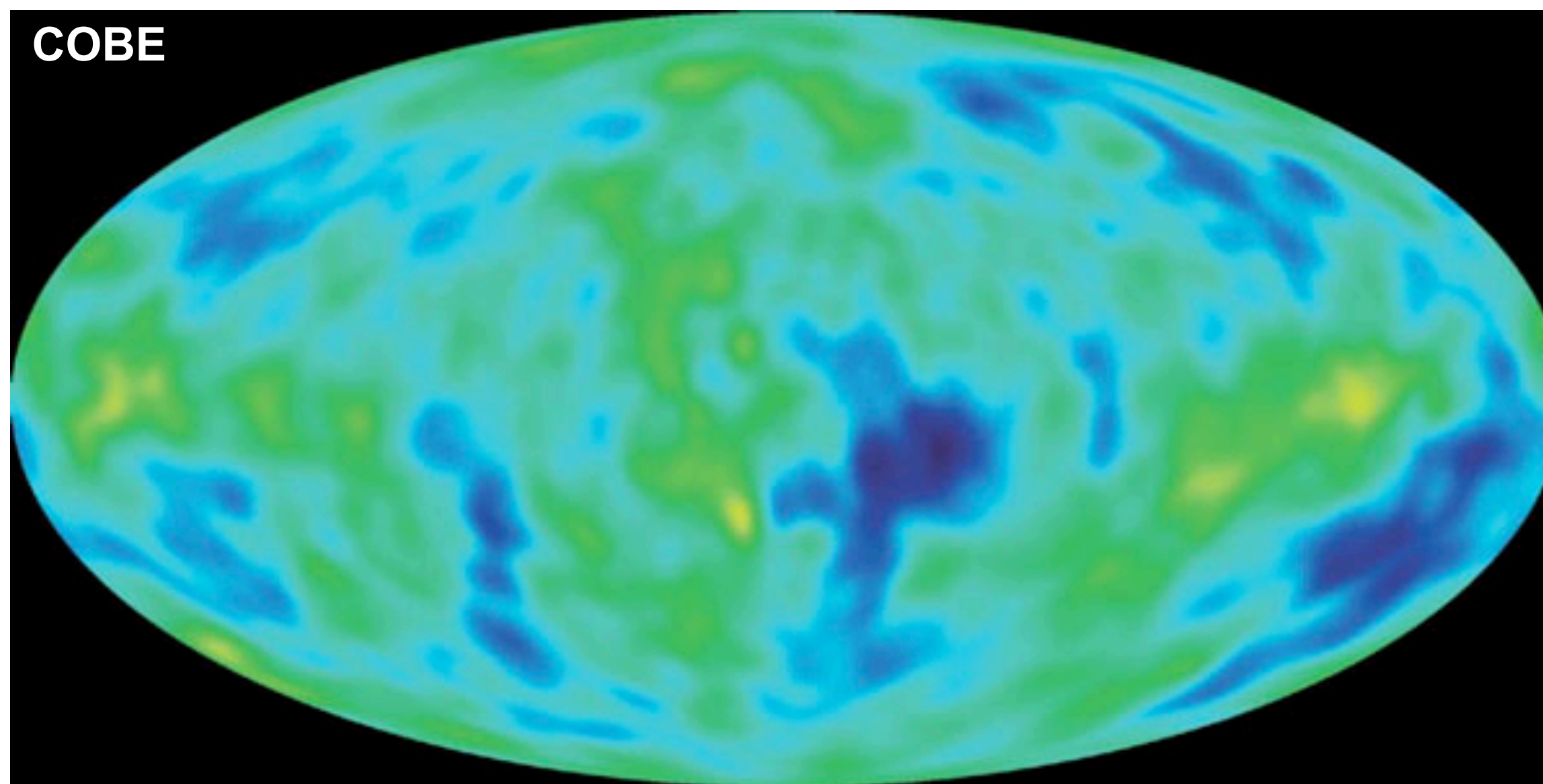




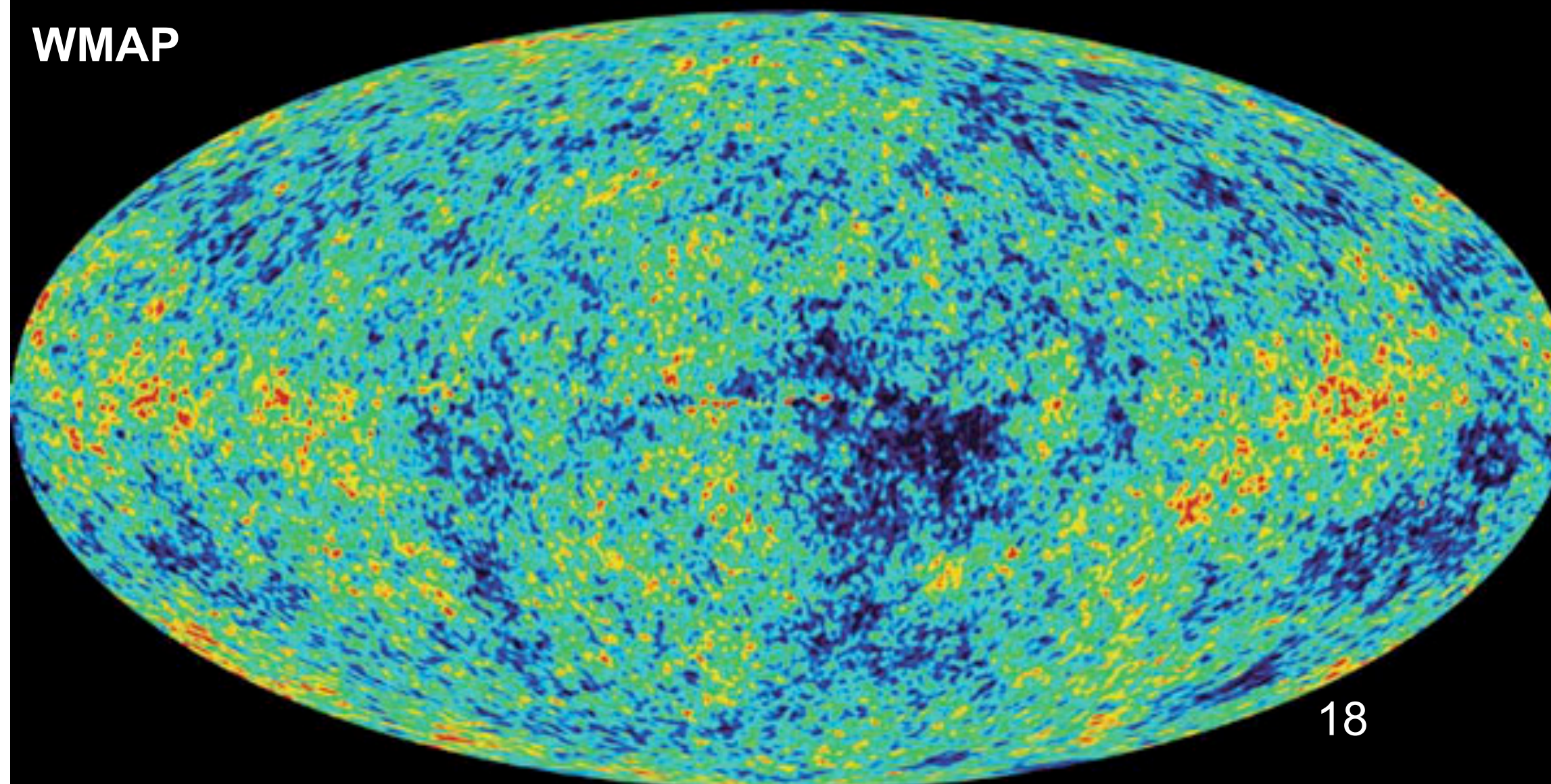
# COBE to WMAP (x35 better resolution)



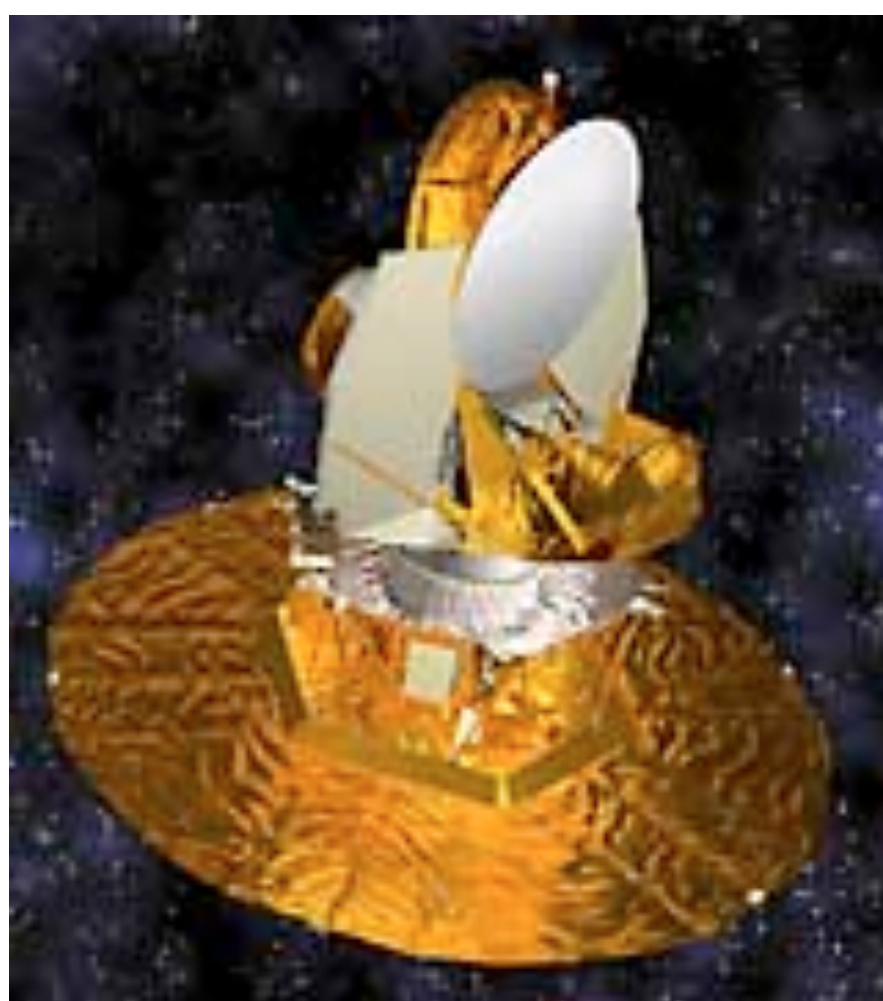
COBE  
1989



WMAP



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.olta
- 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*” [Astrophysical Journal Supplement Series \(ApJS\), 192, 14 \(2011\)](#)
- **Gold et al.**, “*Galactic Foreground Emission*” [ApJS, 192, 15 \(2011\)](#)
- **Weiland et al.**, “*Planets and Celestial Calibration Sources*” [ApJS, 192, 19 \(2011\)](#)
- **Bennett et al.**, “*Are There CMB Anomalies?*” [ApJS, 192, 17 \(2011\)](#)
- **Larson et al.**, “*Power Spectra and WMAP-Derived Parameters*” [ApJS, 192, 16 \(2011\)](#)
- **Komatsu et al.**, “*Cosmological Interpretation*” [ApJS, 192, 18 \(2011\)](#)



# Cosmic Pie Chart: 7-year

## ● Standard Model

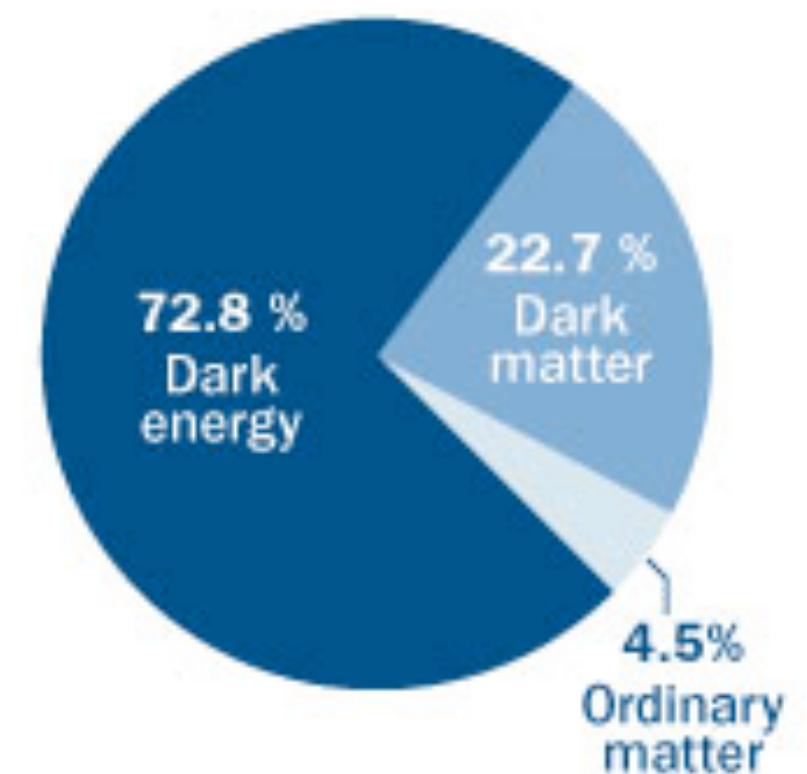
- H&He = **4.58%** ( $\pm 0.16\%$ )
- Dark Matter = **22.9%** ( $\pm 1.5\%$ )
- Dark Energy = **72.5%** ( $\pm 1.6\%$ )
- $H_0 = 70.2 \pm 1.4$  km/s/Mpc
- Age of the Universe = 13.76 billion years ( $\pm 0.11$  billion years)

## Universal Stats

Age of the universe today  
**13.75 billion years**

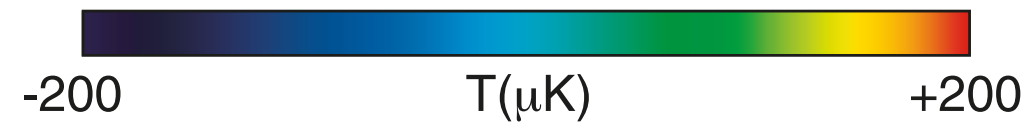
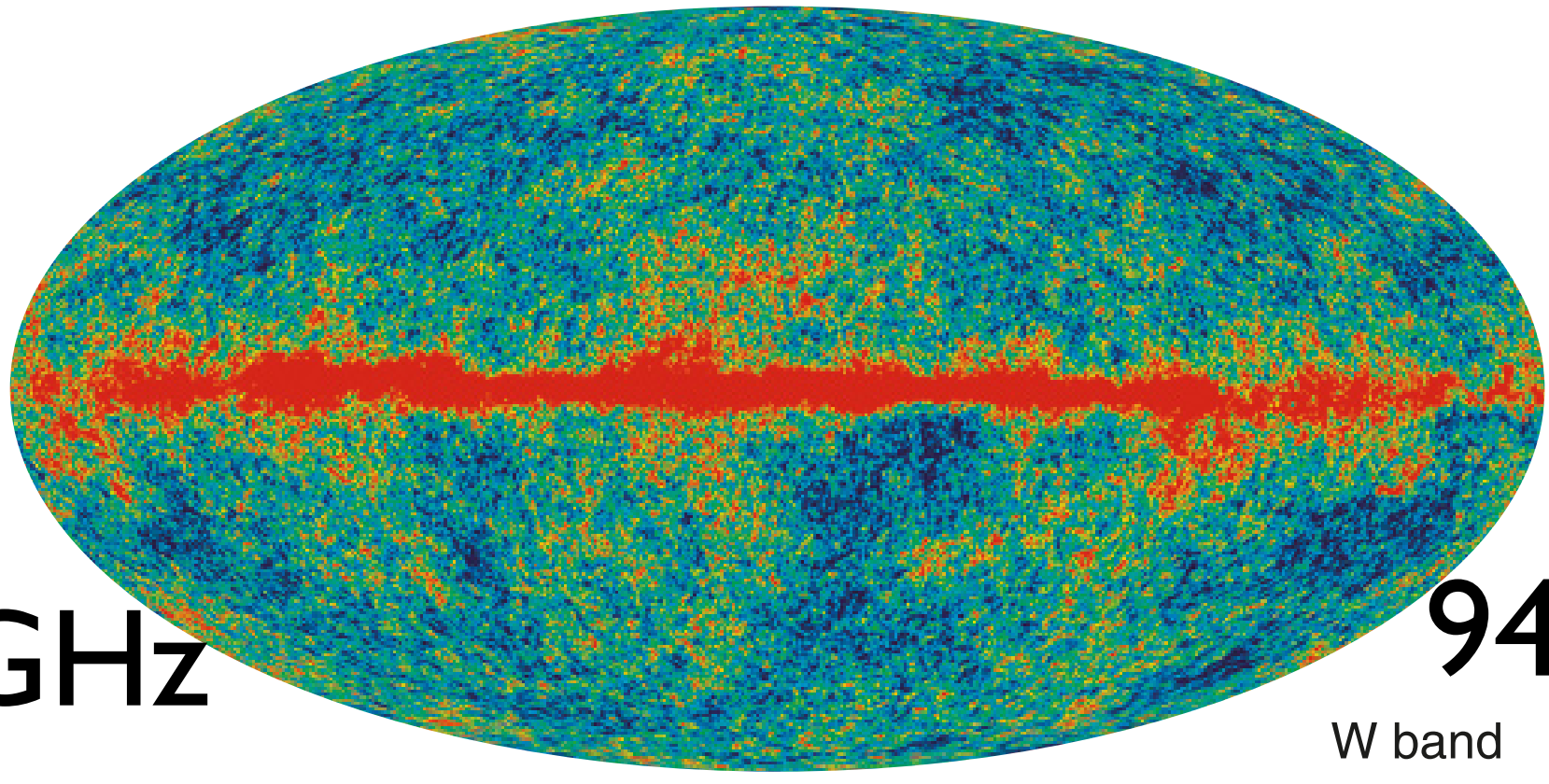
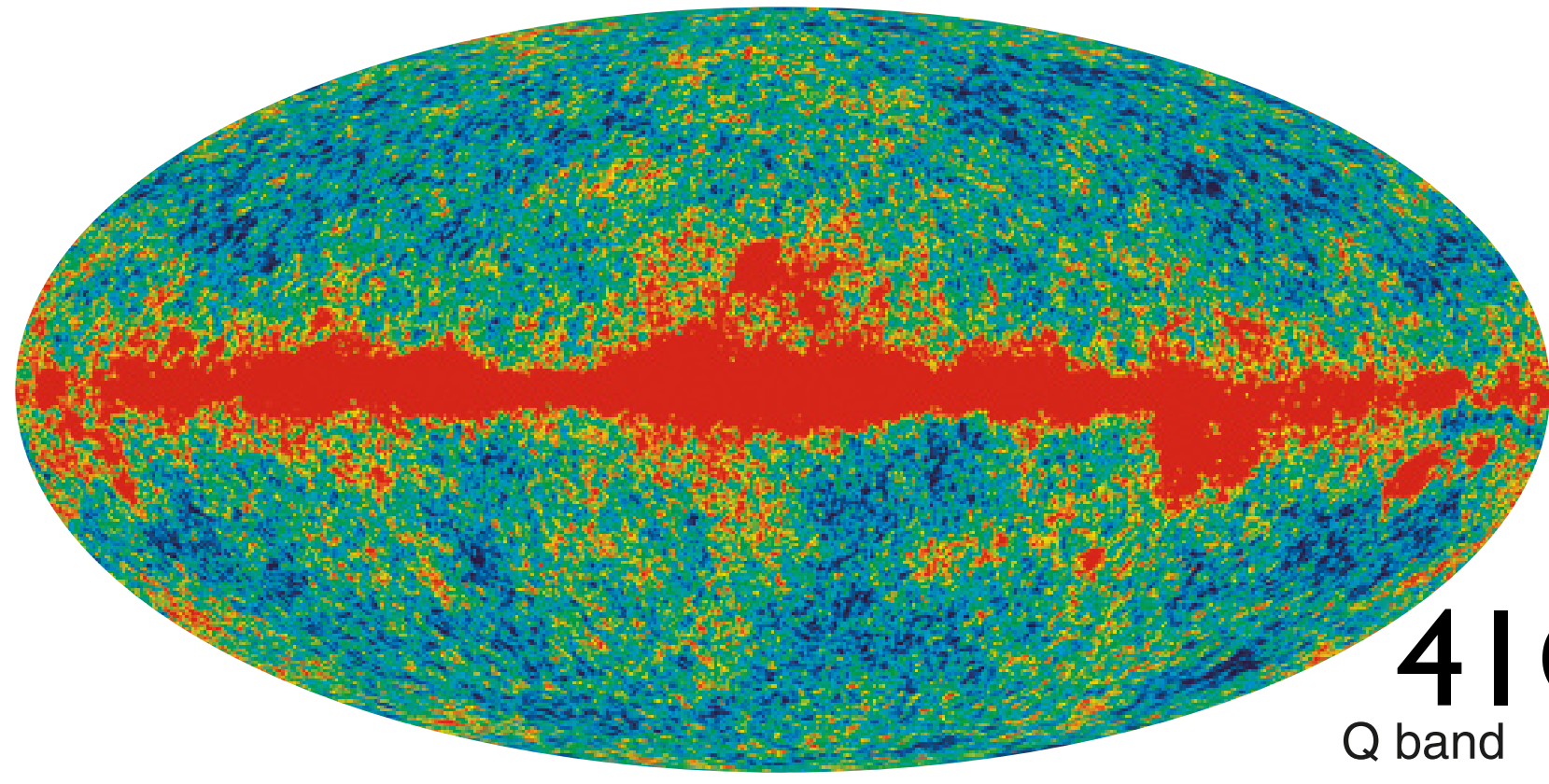
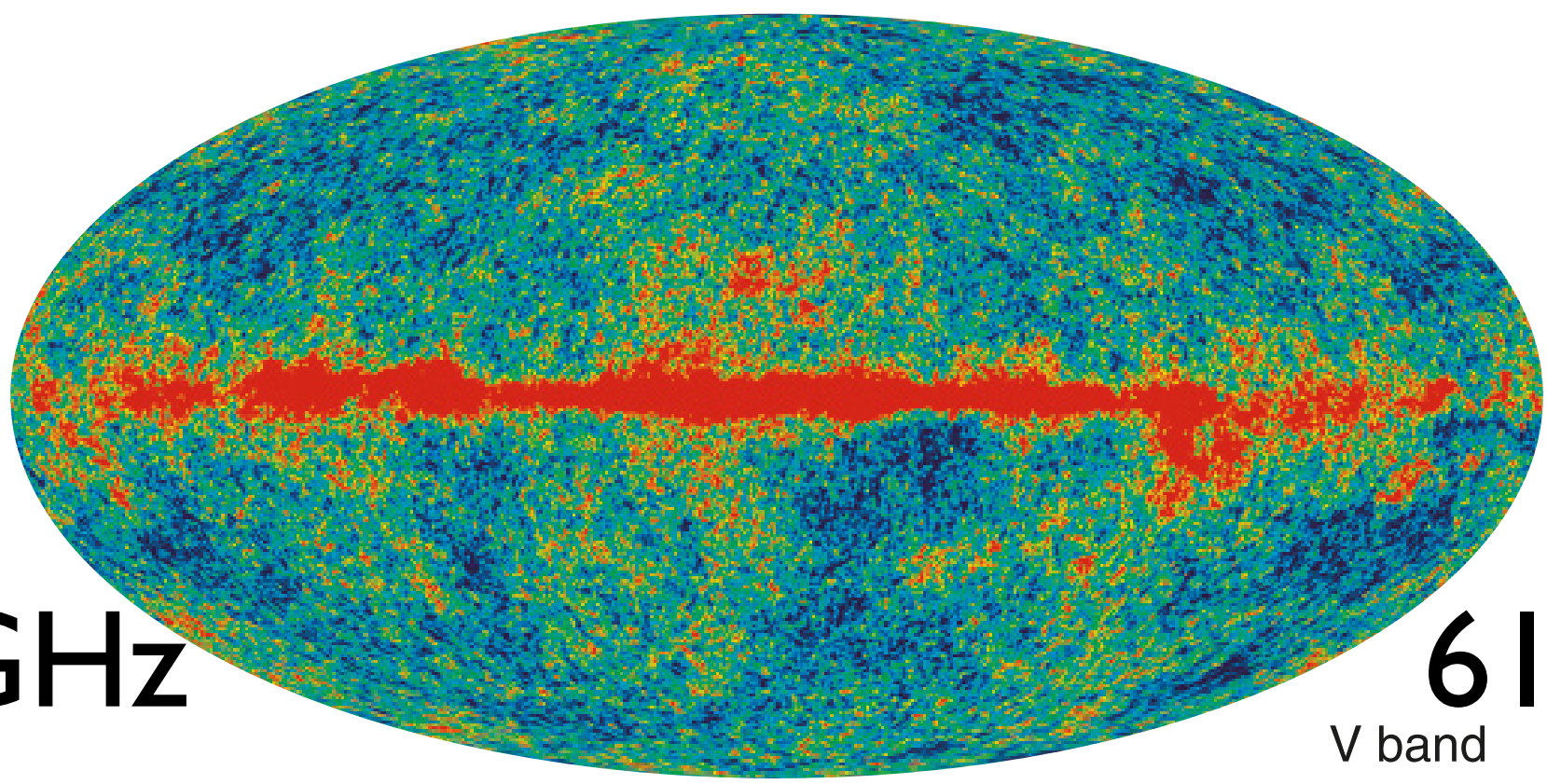
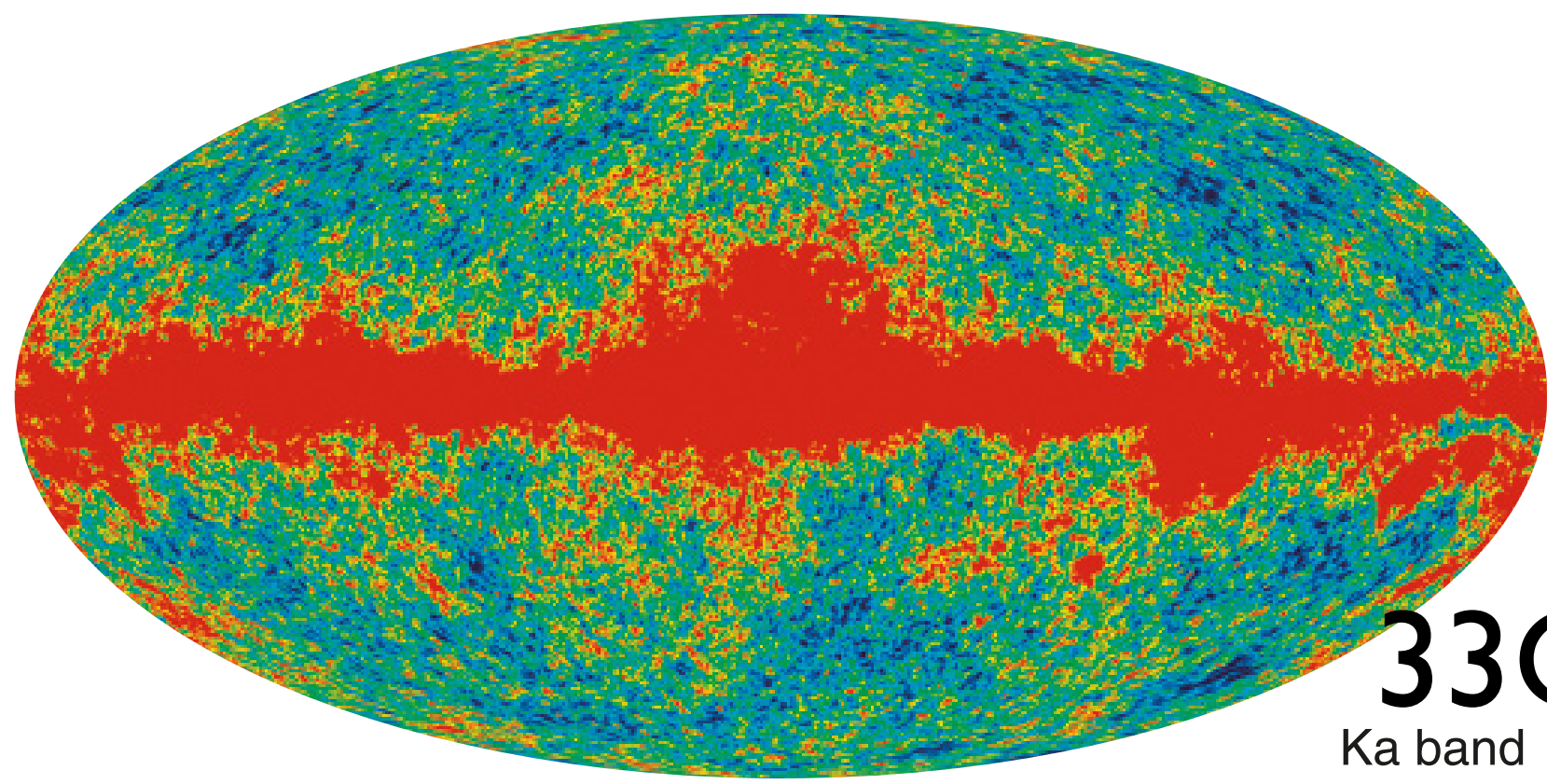
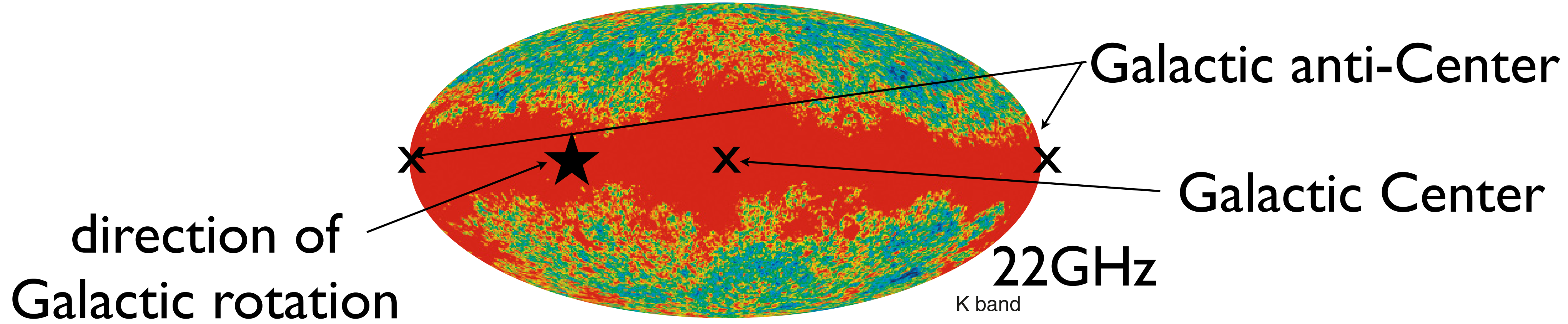
Age of the cosmos at  
time of reionization  
**457 million years**

Universe composition



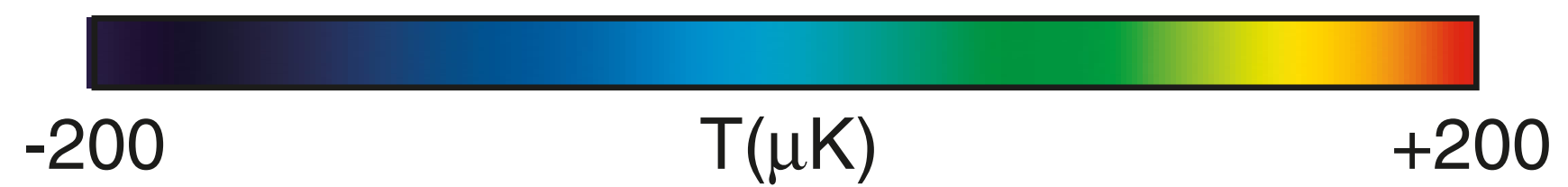
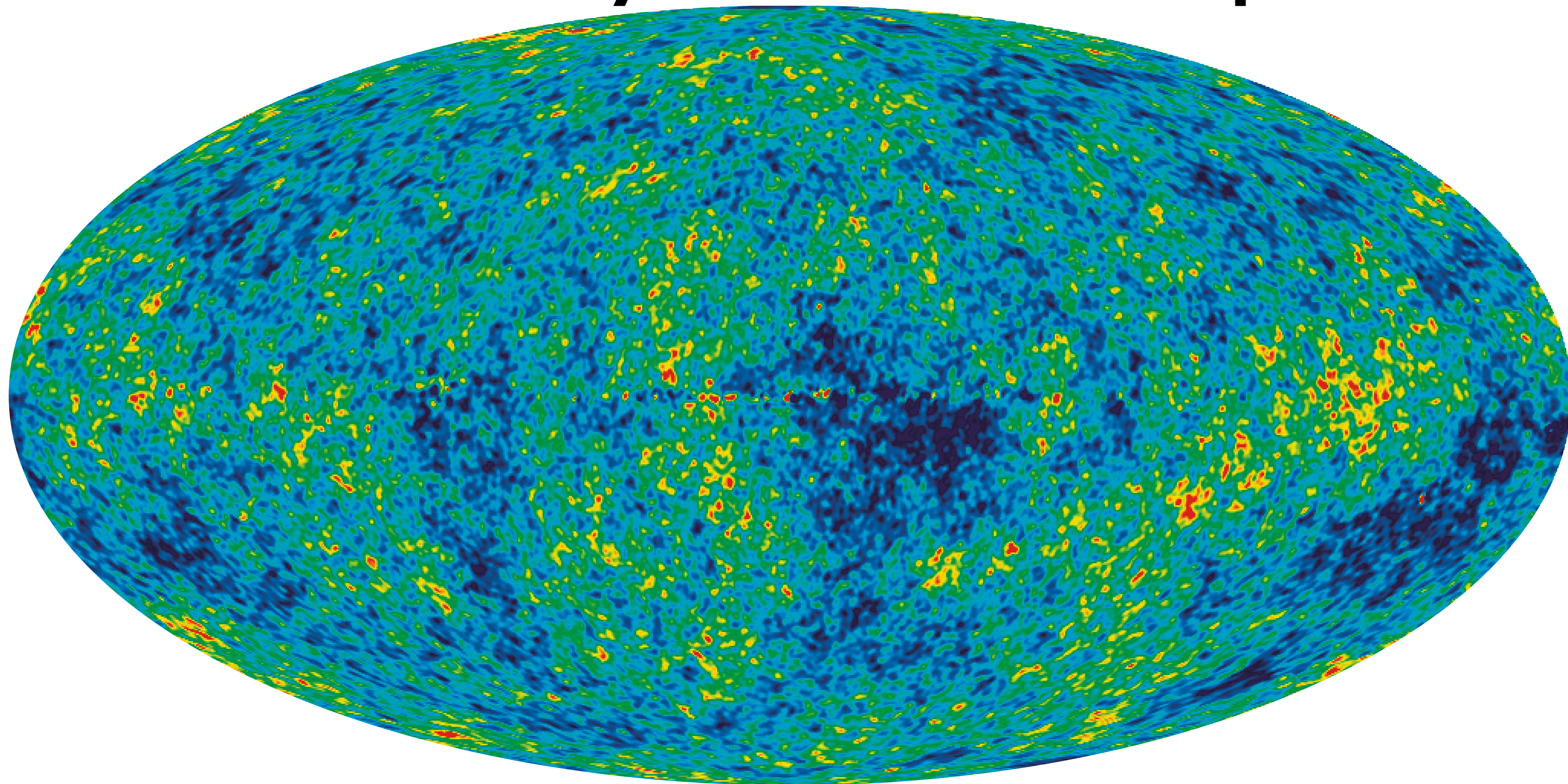
*“ScienceNews” article on  
the WMAP 7-year results*

***How did we obtain these numbers?***





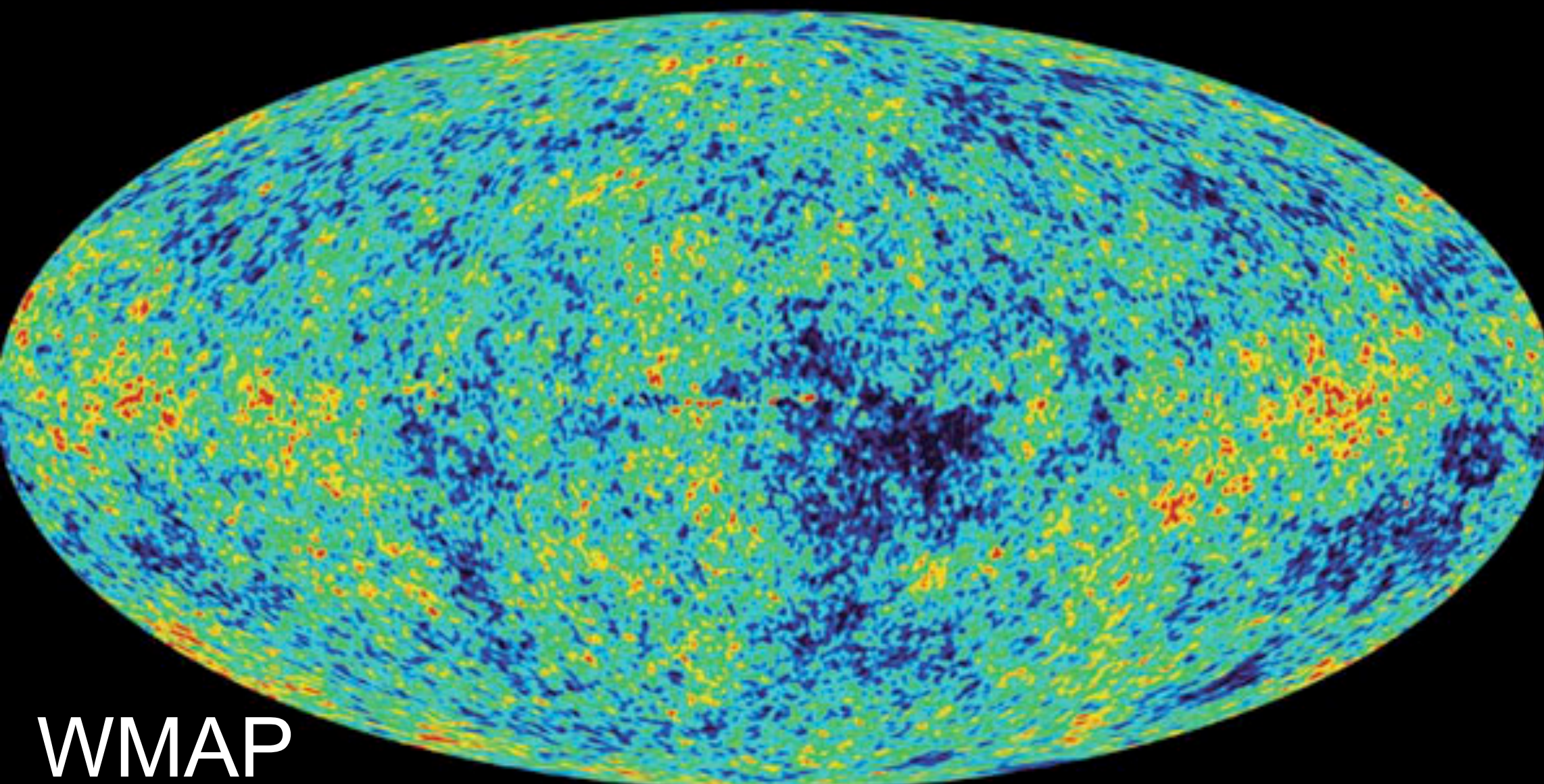
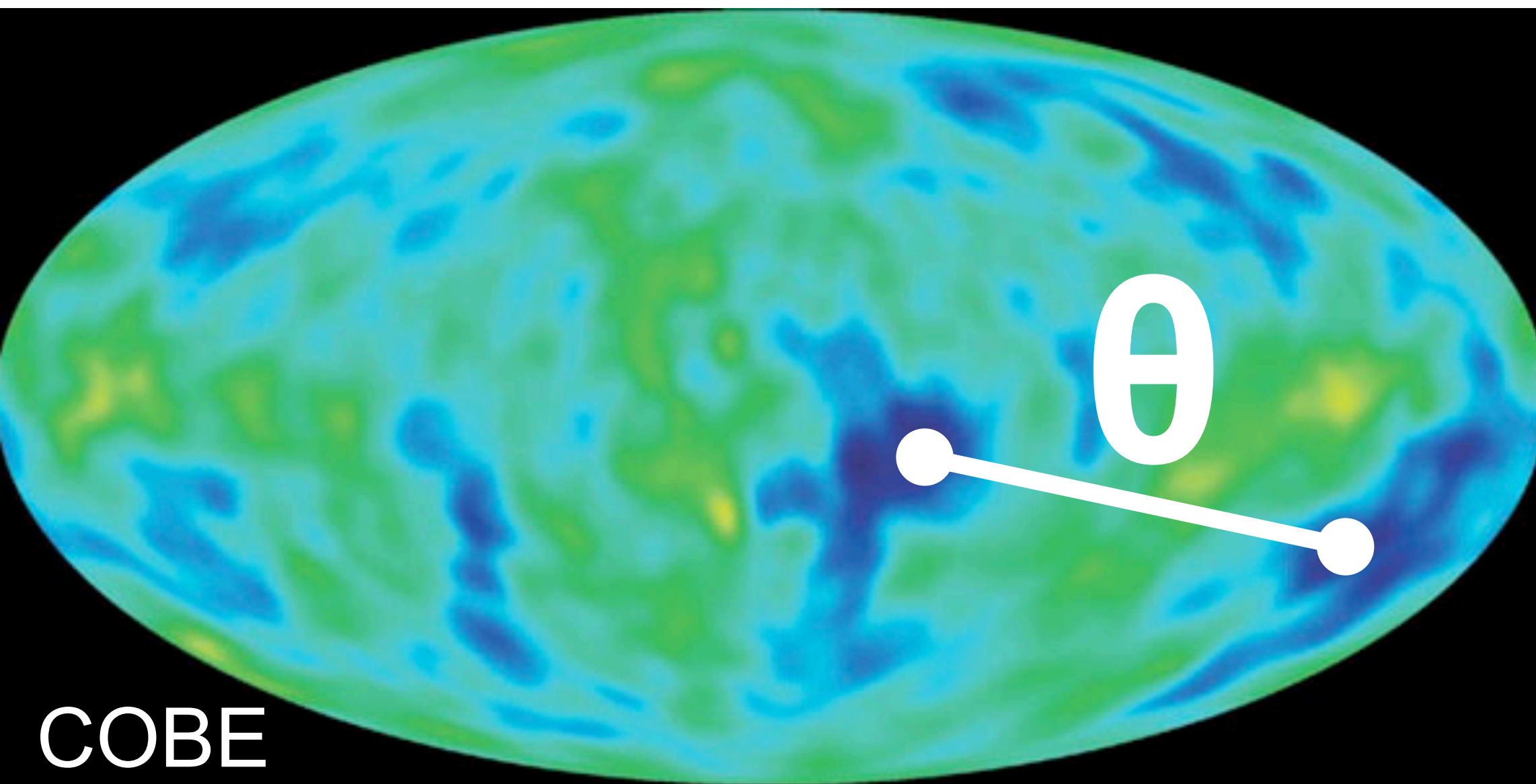
# Galaxy-cleaned Map



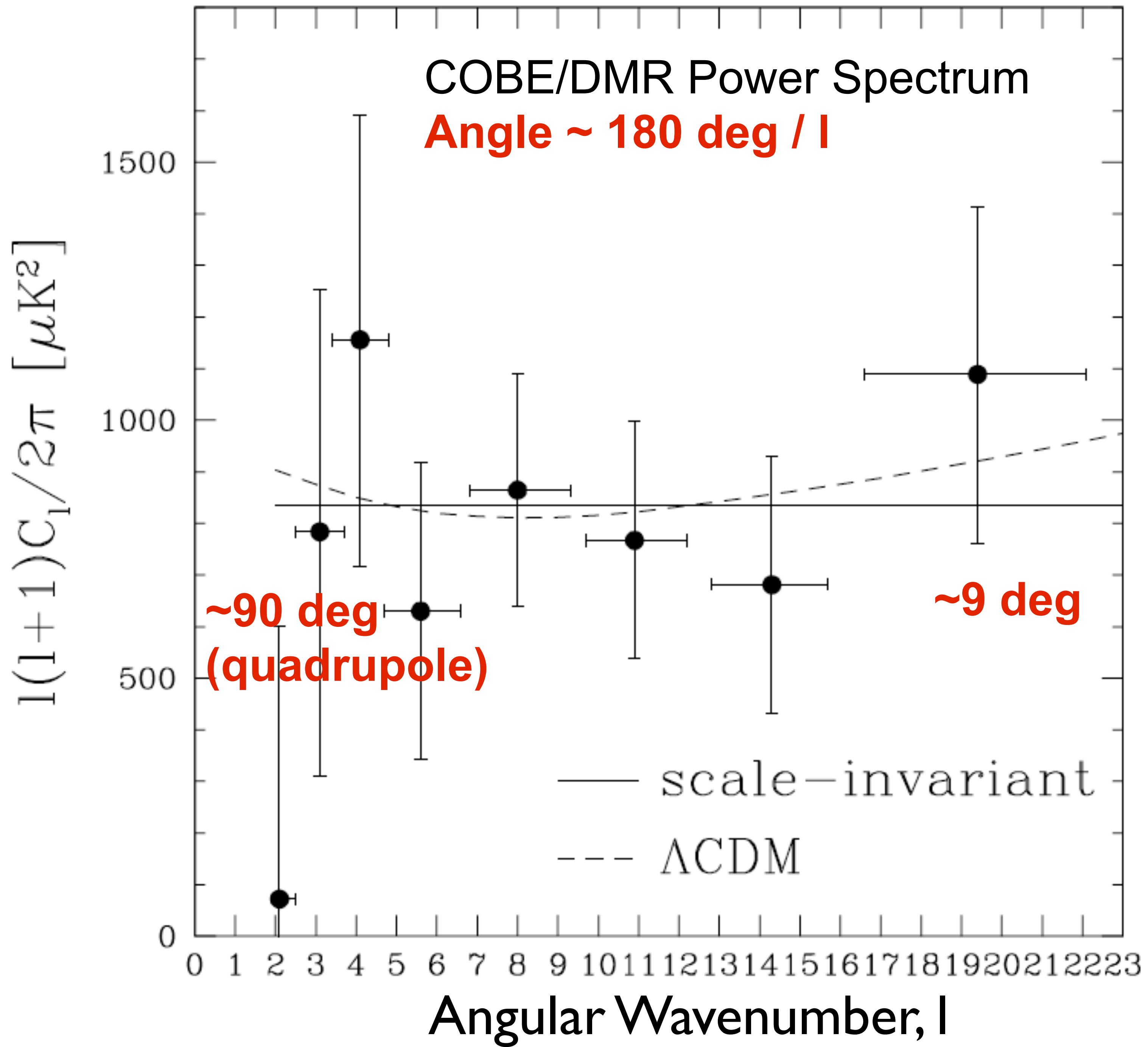


# Analysis: 2-point Correlation

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

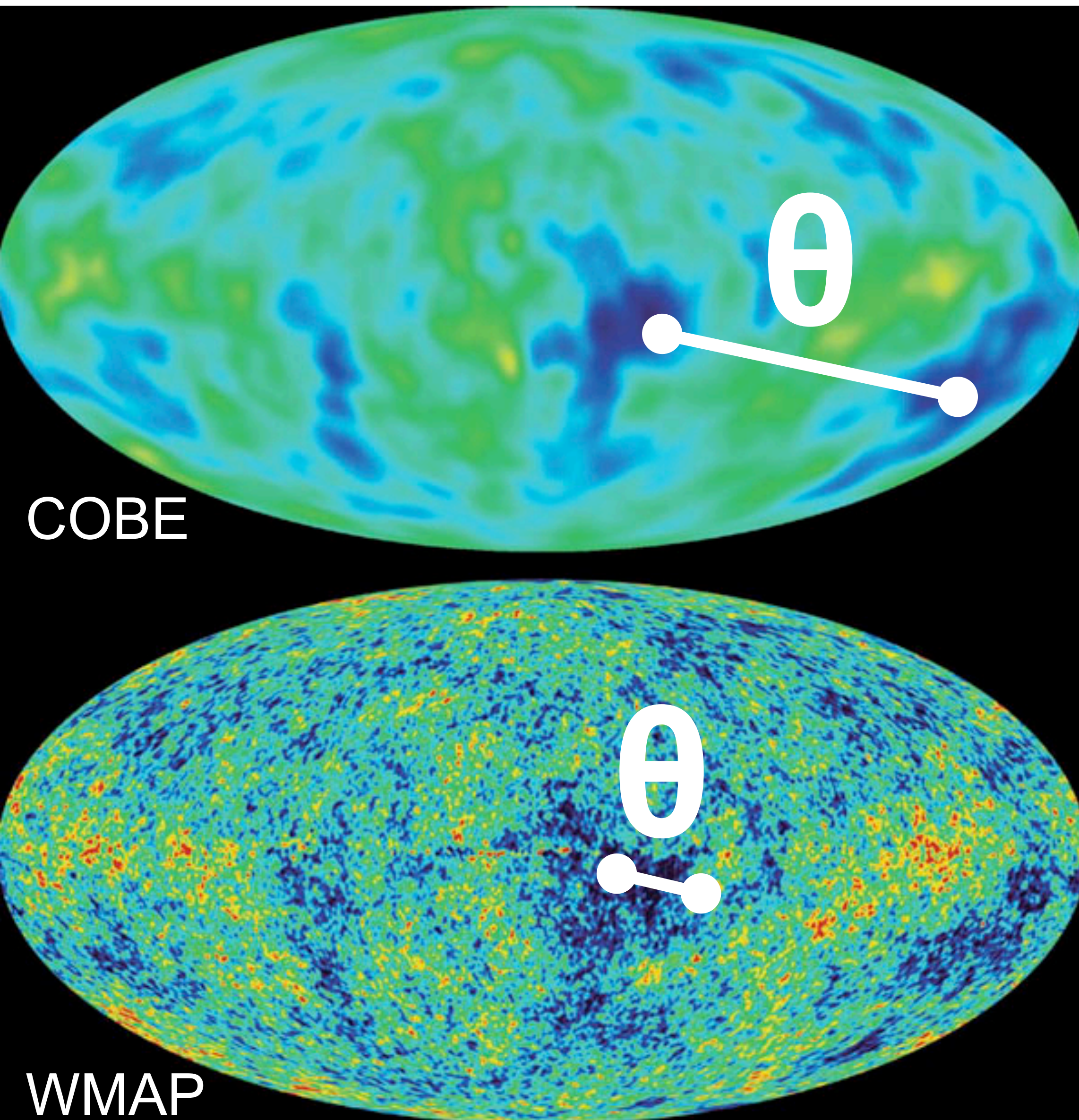








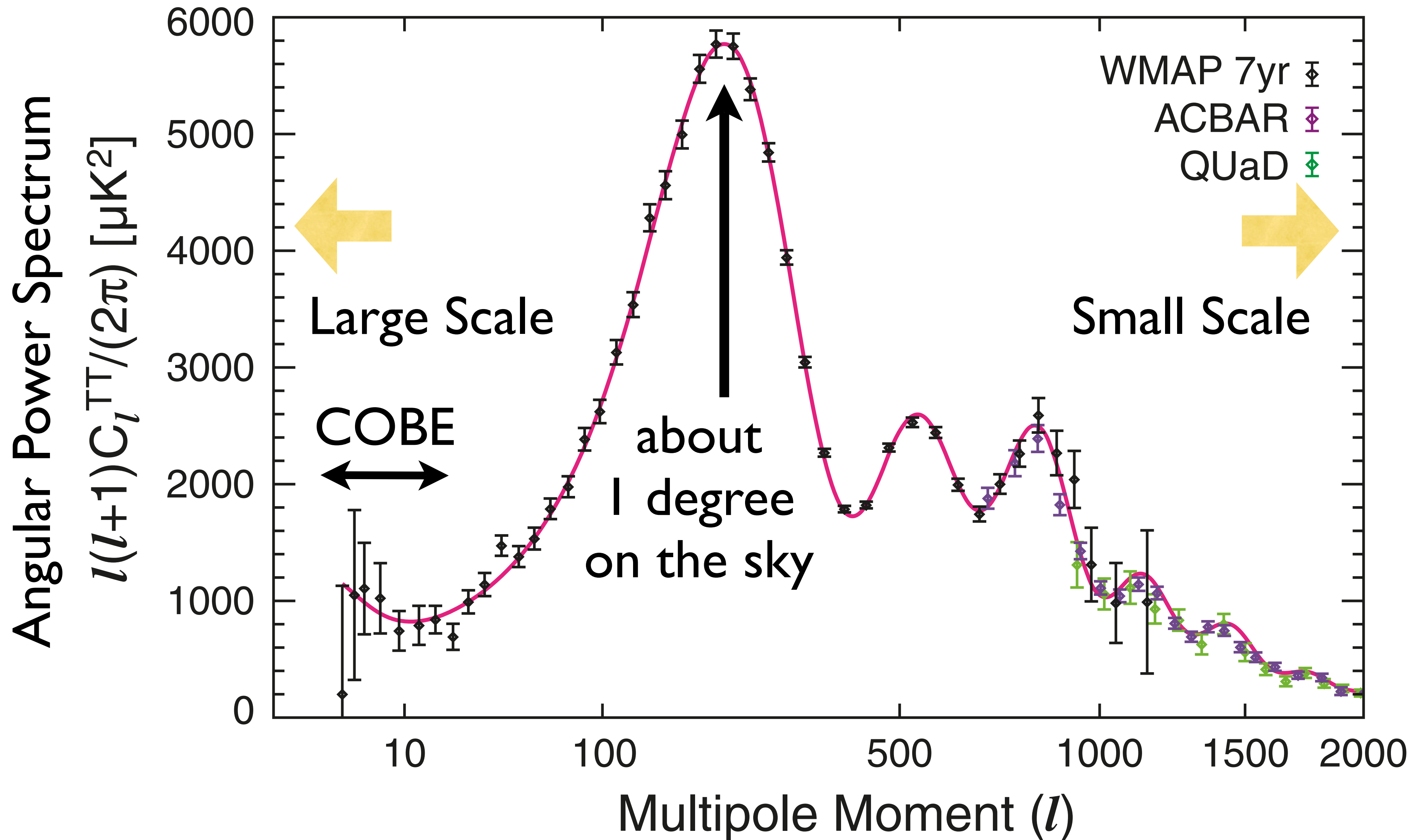
# COBE To WMAP



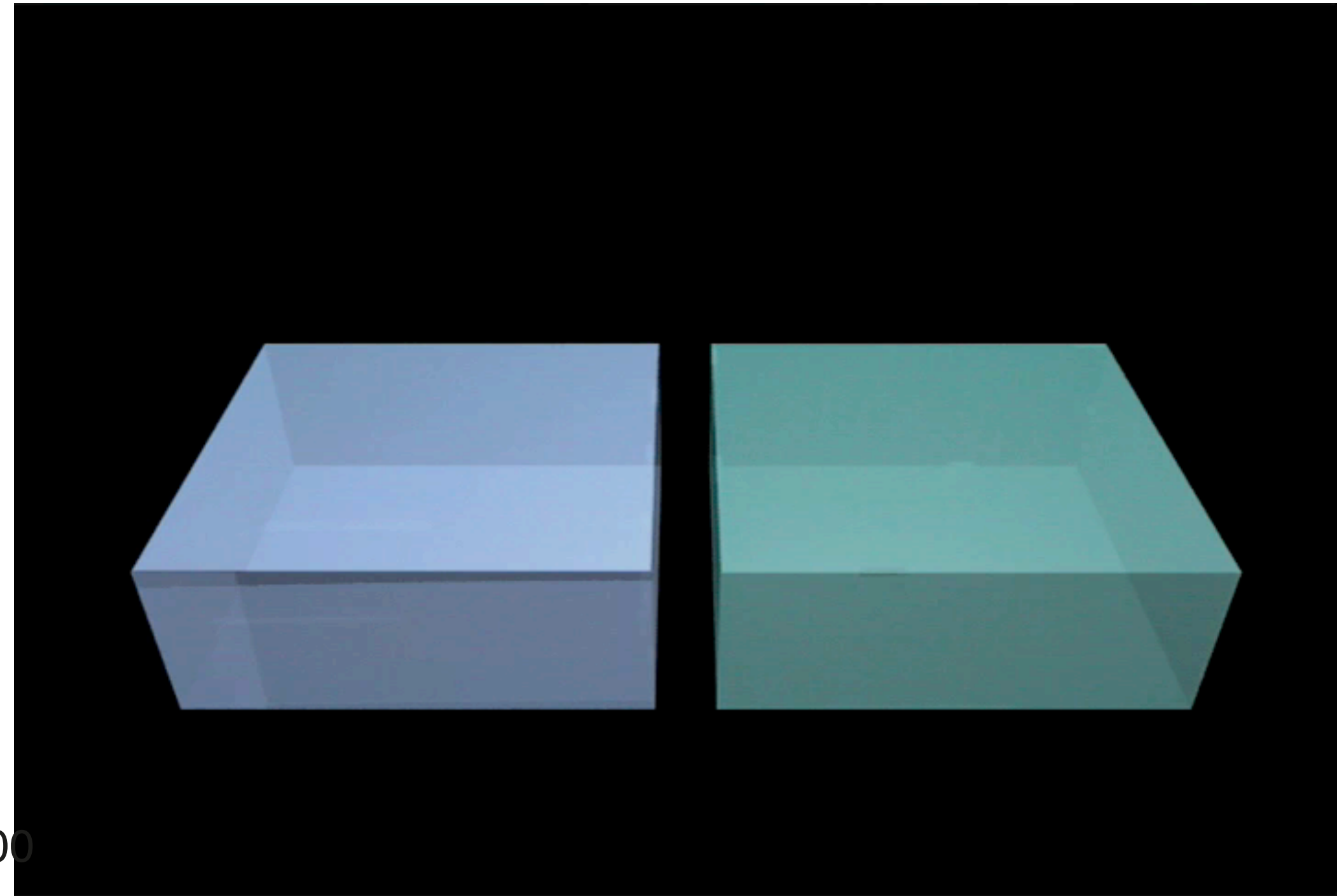
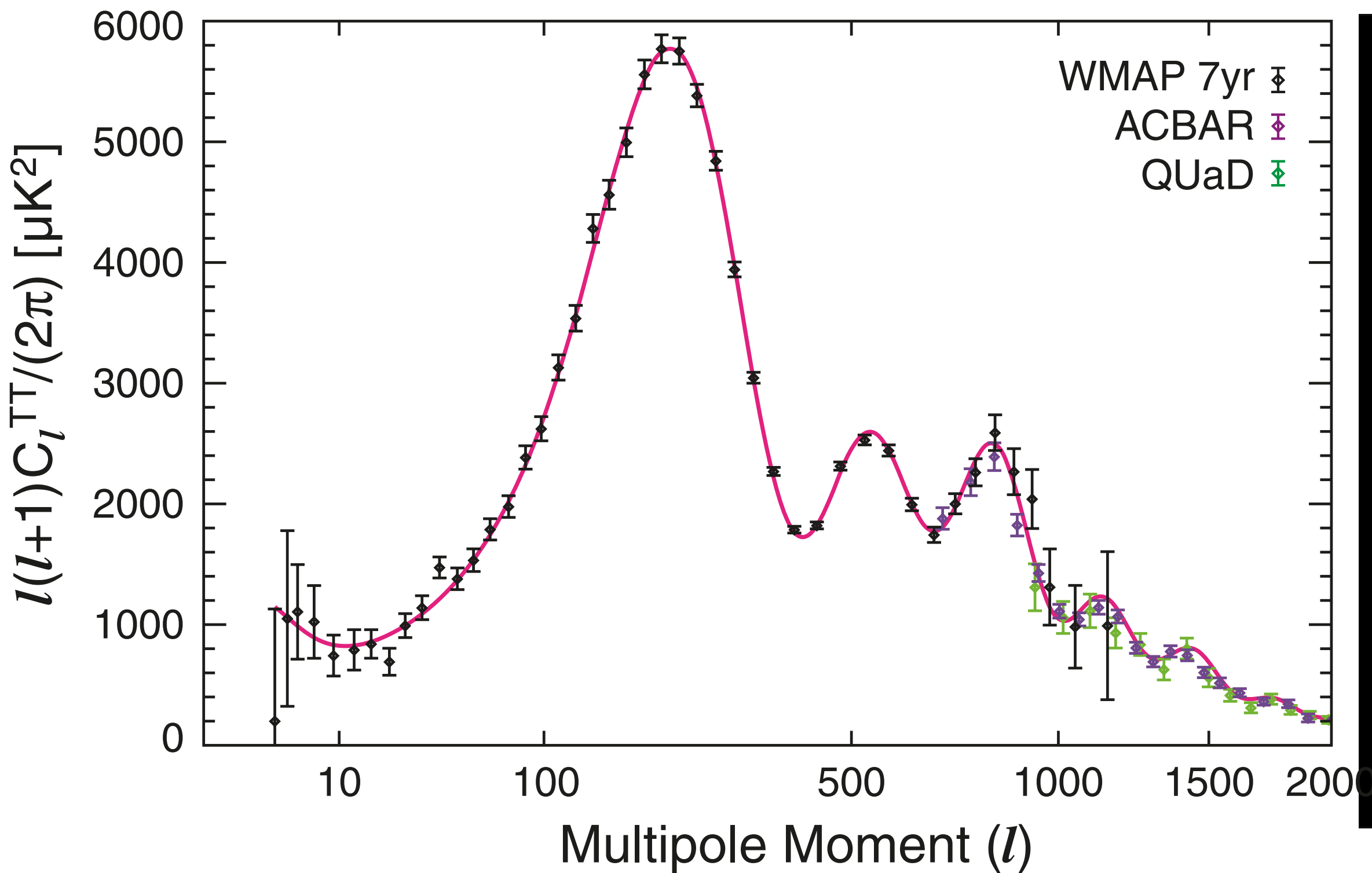
- COBE is unable to resolve the structures below  $\sim 7$  degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?



# WMAP Power Spectrum



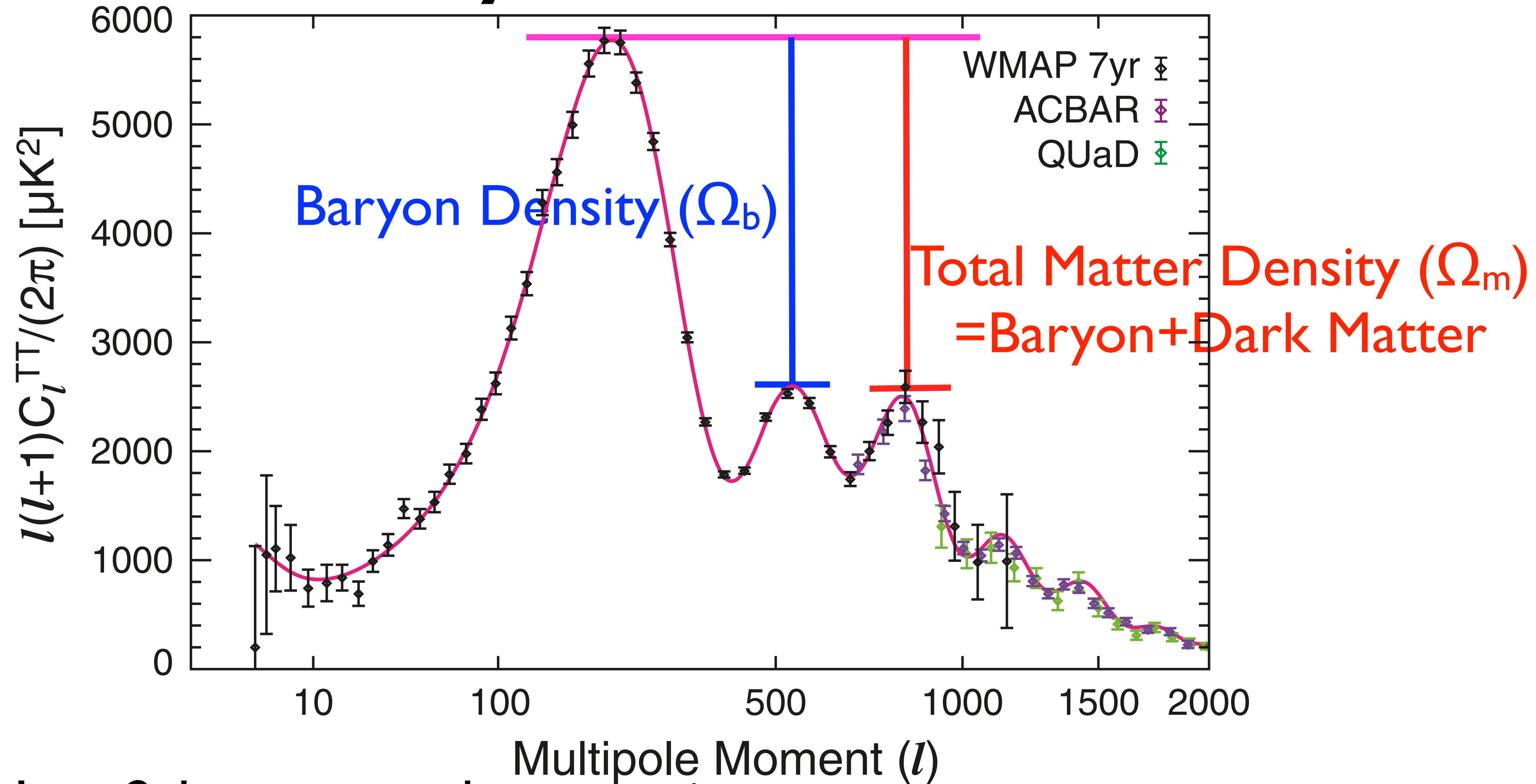
# The Cosmic Sound Wave



- “*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

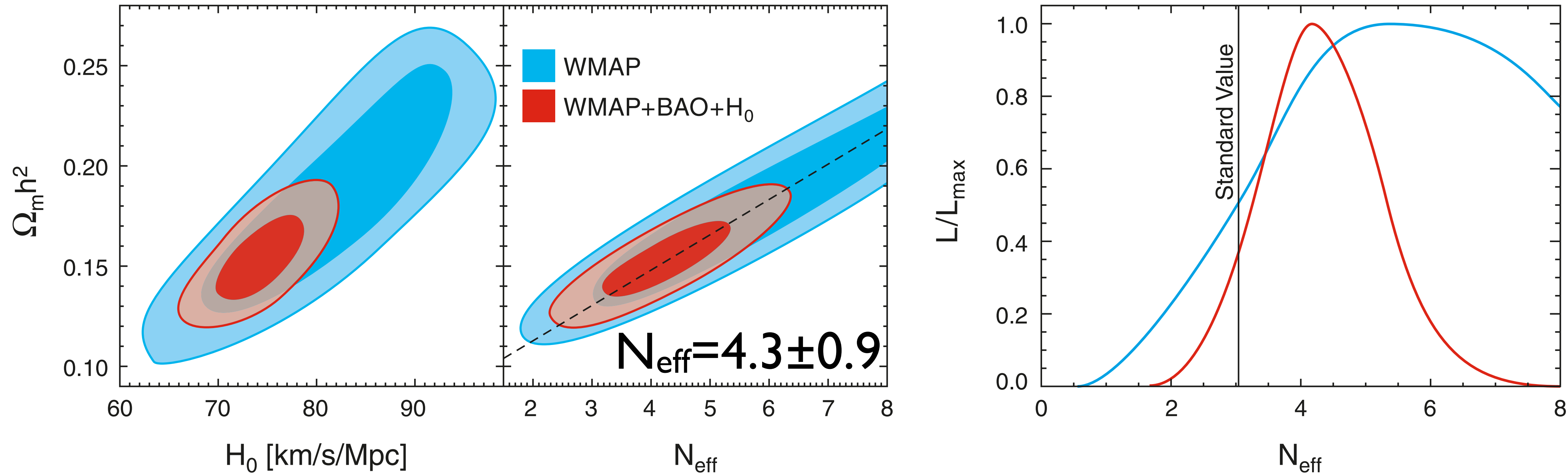


- $l$ -to-2: baryon-to-photon ratio
- $l$ -to-3: matter-to-radiation ratio ( $z_{\text{EQ}}$ : equality redshift)

# 3rd-peak “Spectroscopy”

- Total Matter = Baryons (H&He) + Dark Matter
- Total Radiation = Photons + Neutrinos (+new radiation)
  - Neutrino temperature =  $(4/11)^{1/3}$  Photon temperature
- So, for a given assumed value of the number of neutrino species (or the number of new radiation species, i.e., zero), we can measure the dark matter density.
- Or, we can get the dark matter density from elsewhere, and determine the number of radiation species!

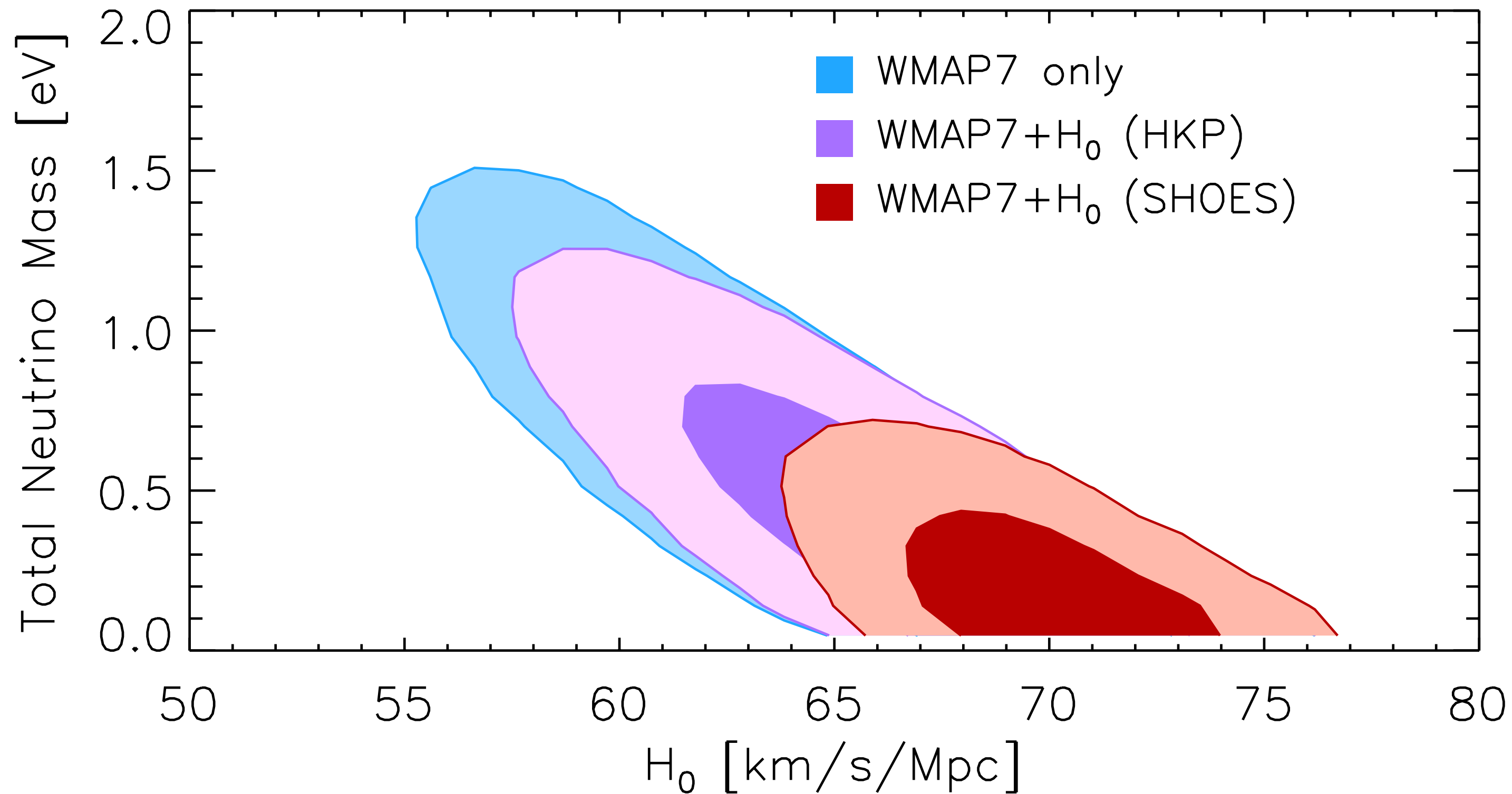
# “3rd peak spectroscopy”: Number of Relativistic Species



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

← from external data
← from 3rd peak

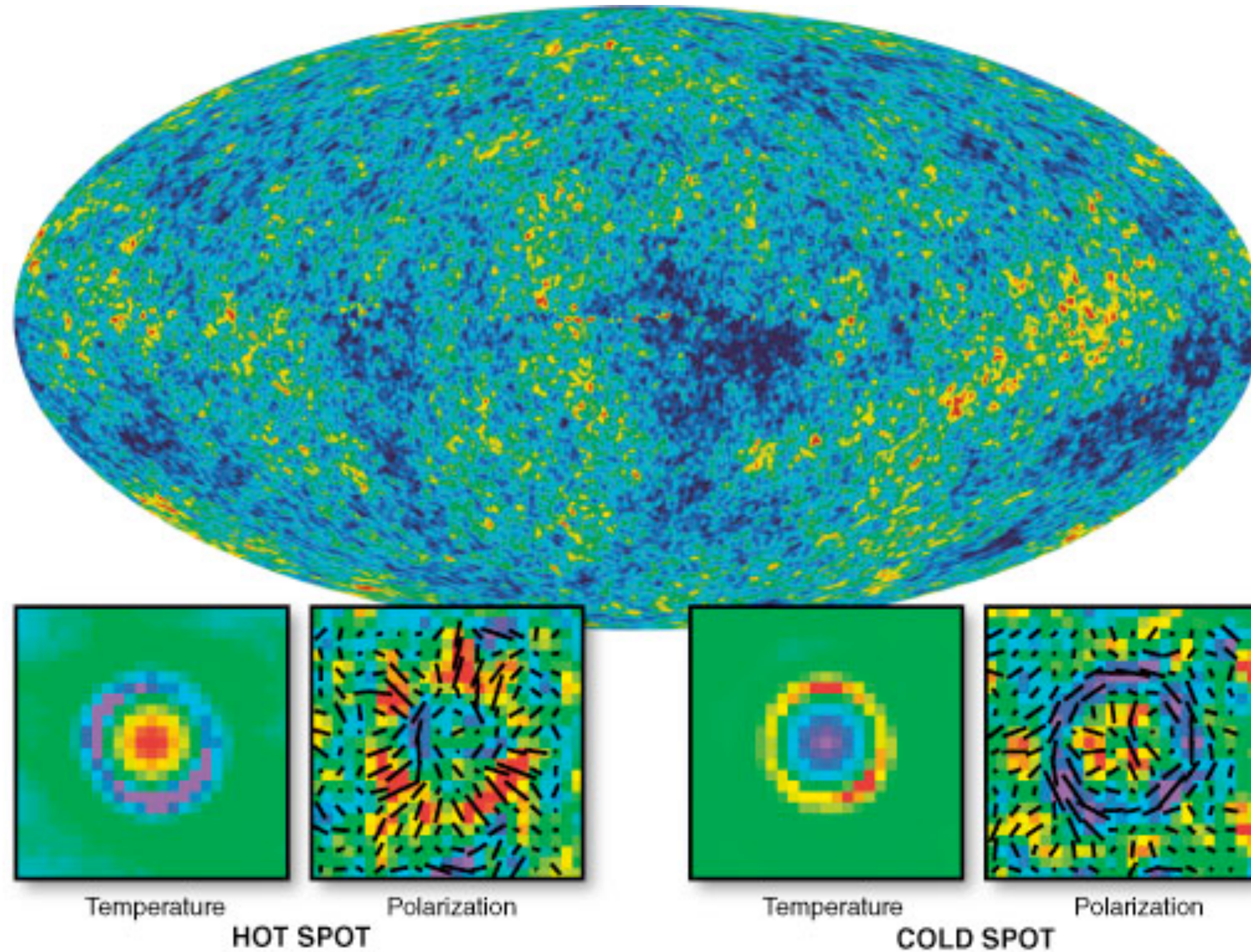
# And, the mass of neutrinos



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



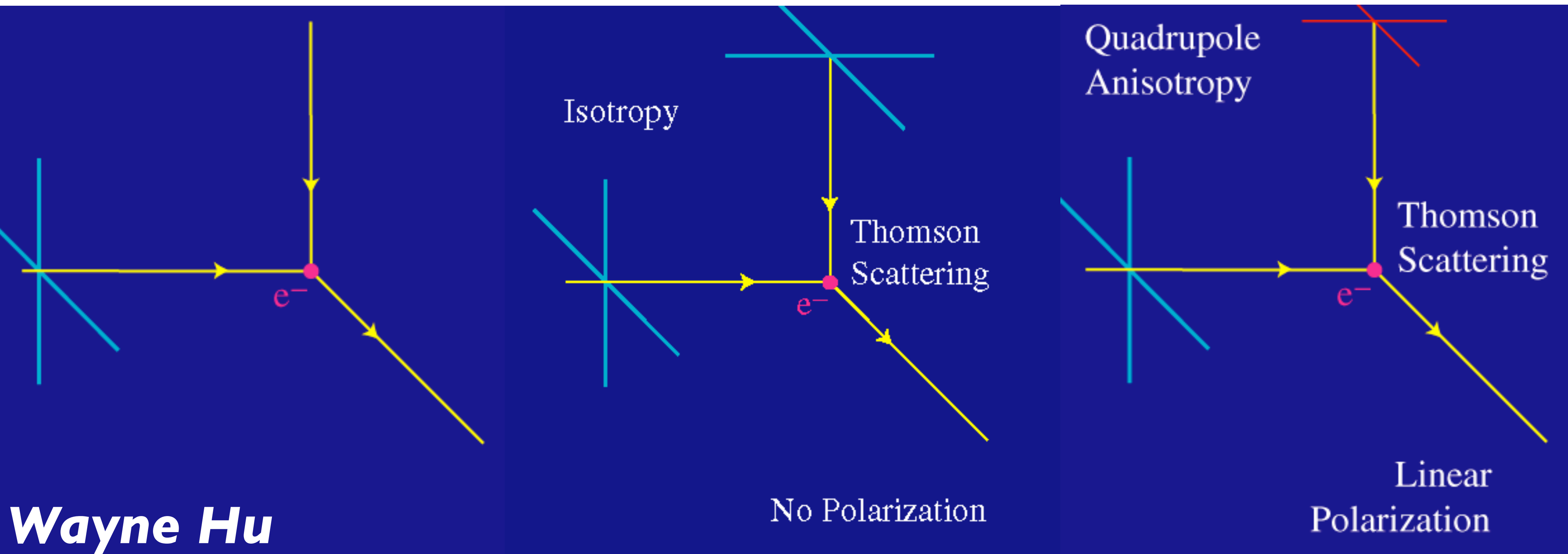
# CMB Polarization



- *CMB is (very weakly) polarized!*

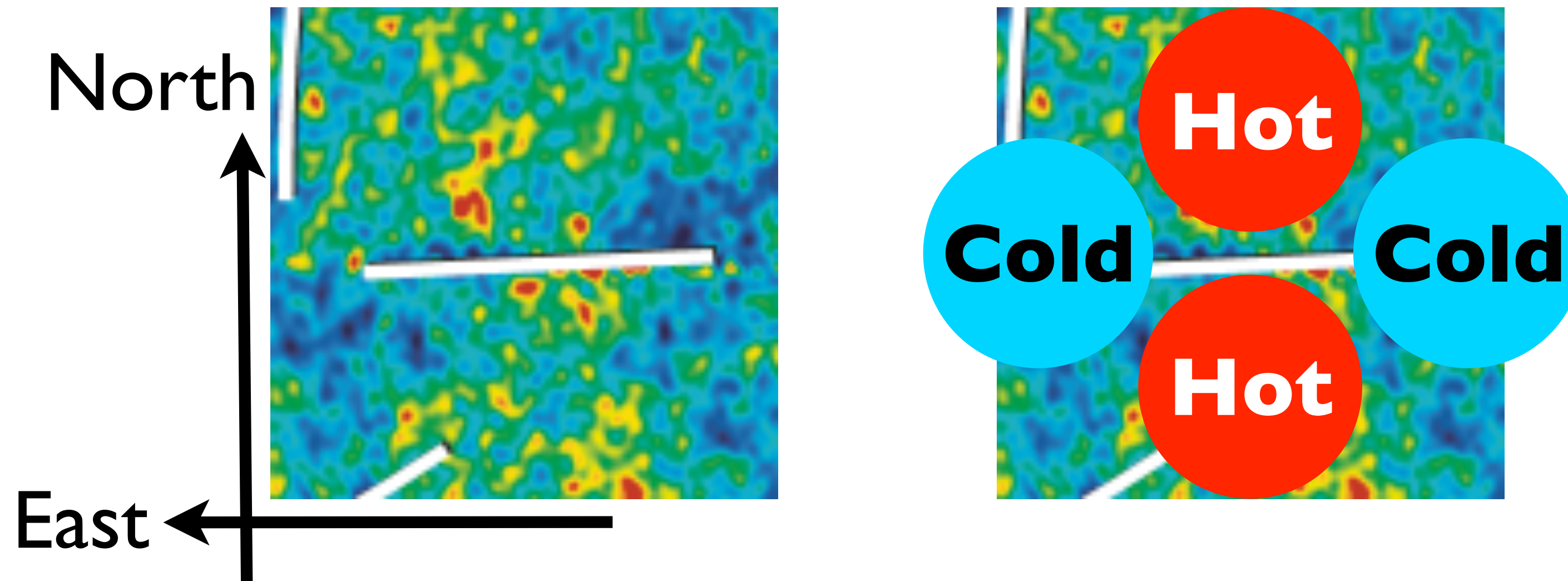


# Physics of CMB Polarization



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

# Principle



- **Polarization direction is parallel to “hot.”**

# CMB Polarization on Large Angular Scales ( $>2$ deg)

Matter Density



Potential

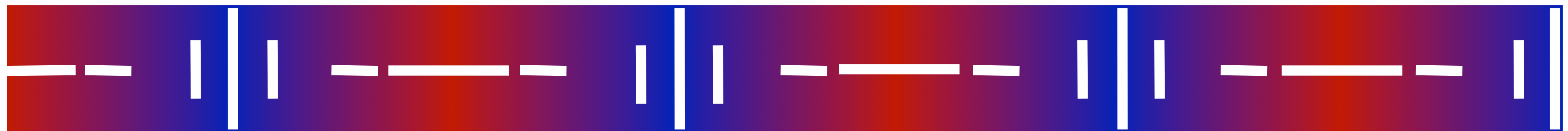


$$\Delta T/T = (\text{Newton's Gravitation Potential})/3$$

$\Delta T$



Polarization



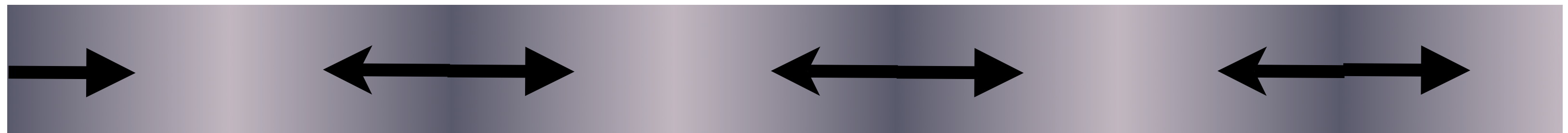
- How does the photon-baryon plasma move?



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

*Zaldarriaga & Harari (1995)*

Matter Density

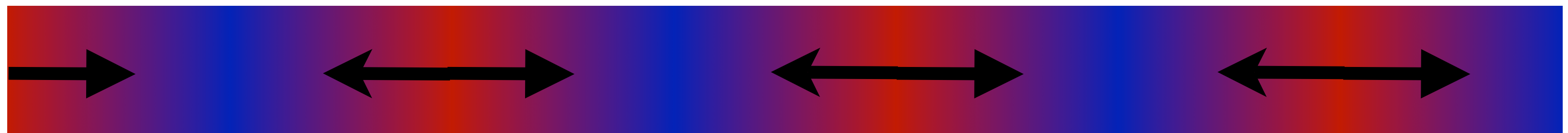


Potential

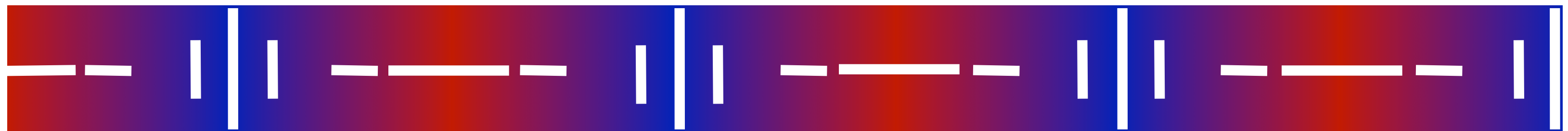


$$\Delta T/T = (\text{Newton's Gravitation Potential})/3$$

$\Delta T$

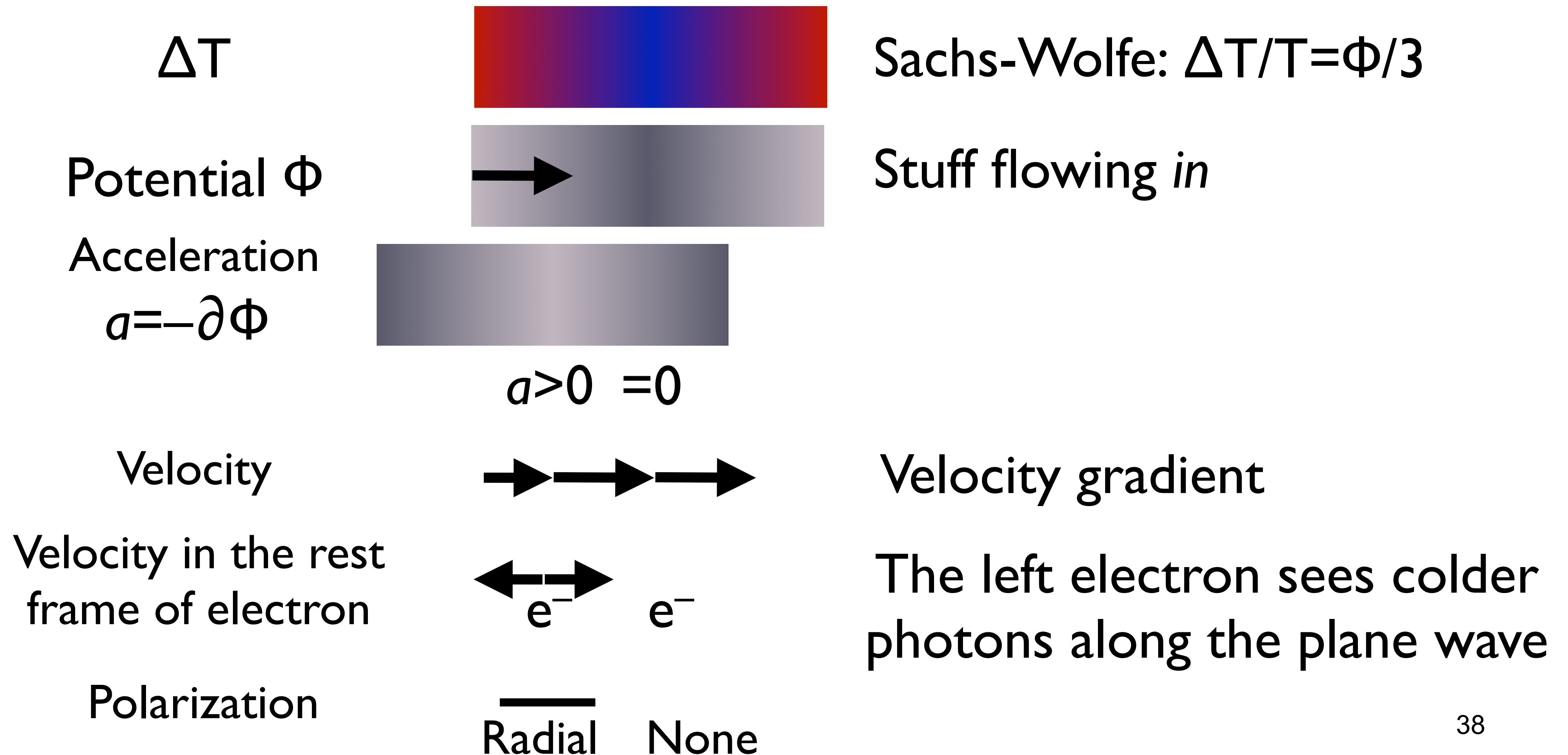


Polarization

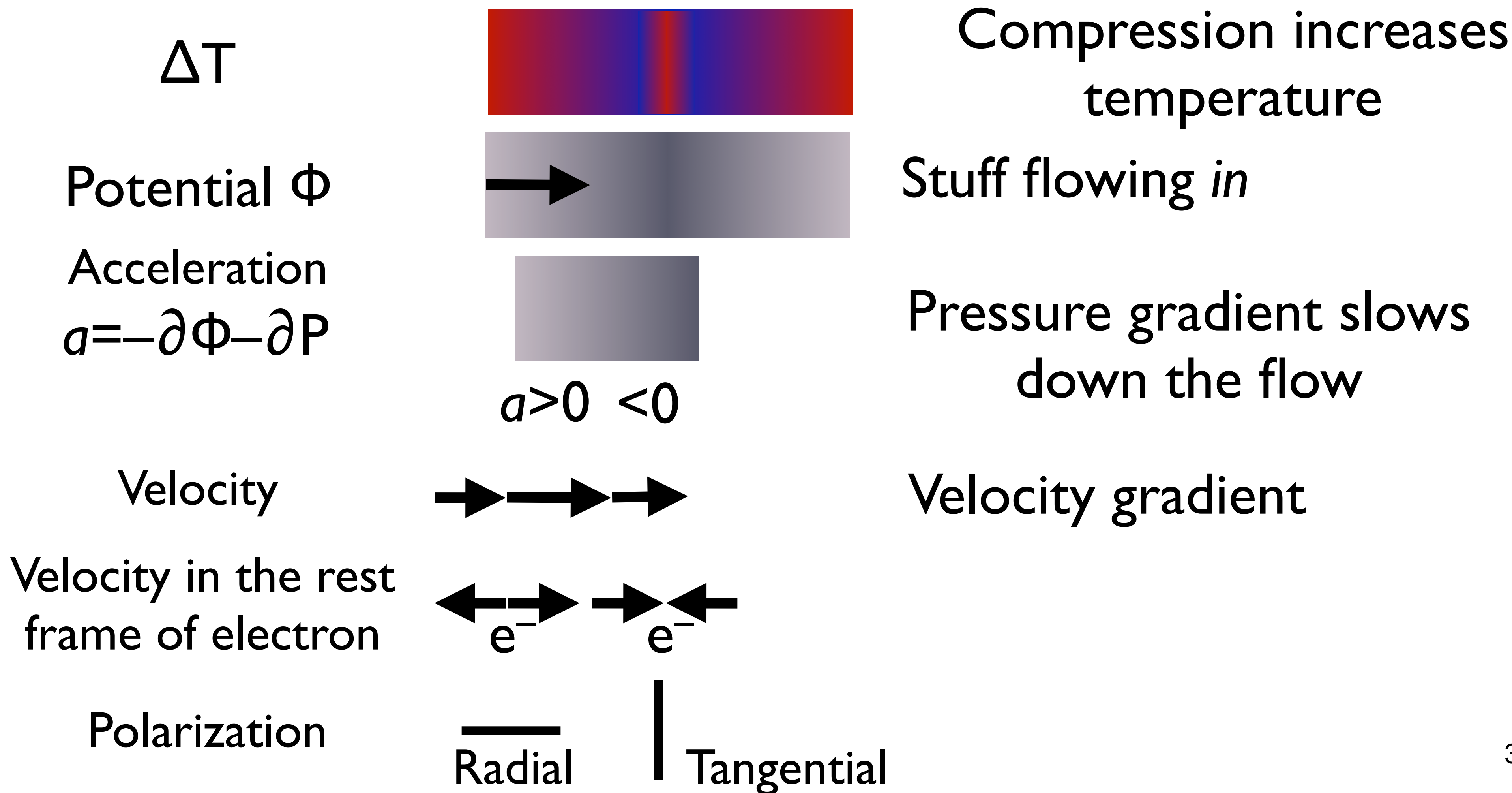


- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern

# Quadrupole From Velocity Gradient (Large Scale)



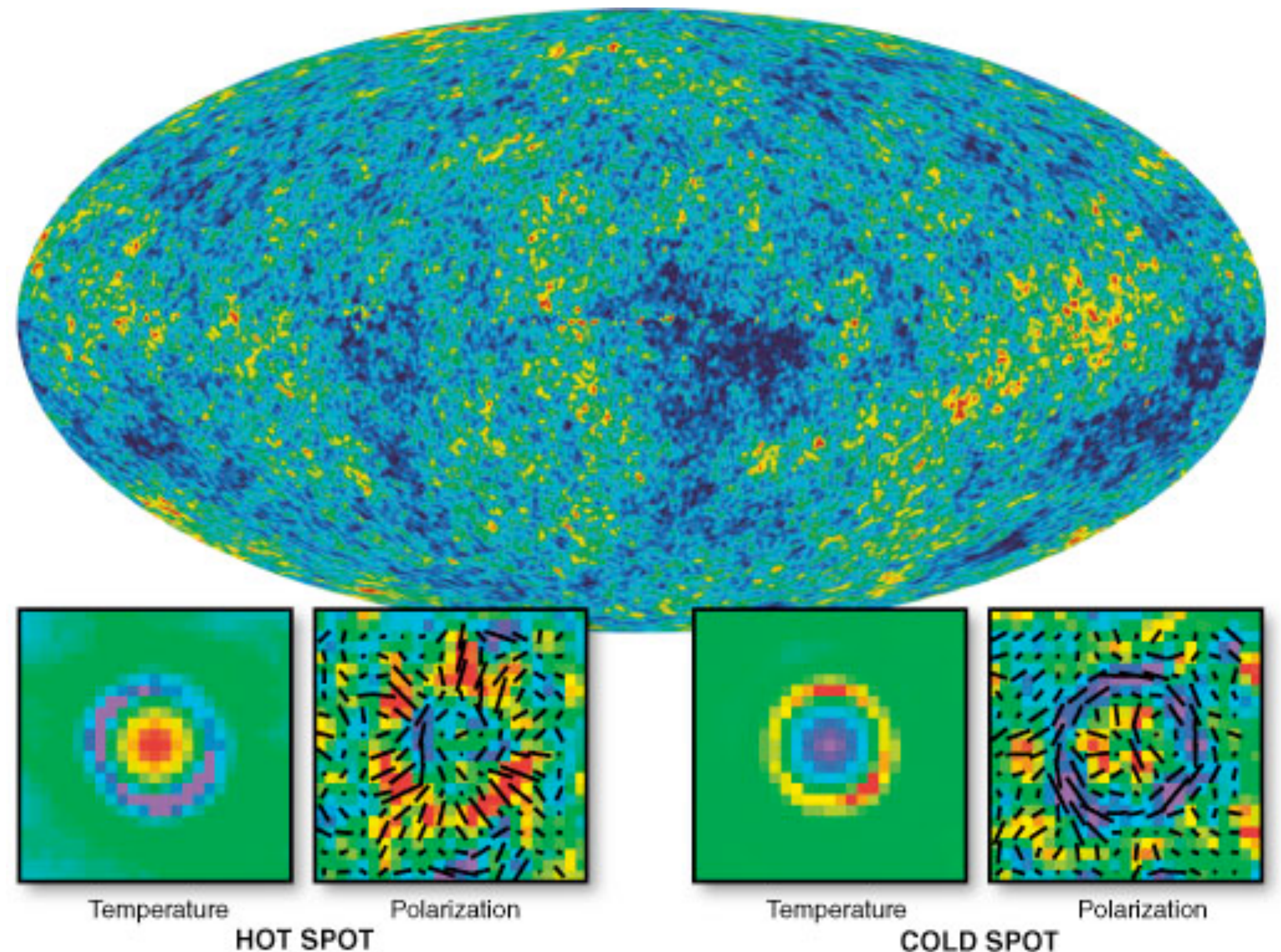
# Quadrupole From Velocity Gradient (Small Scale)





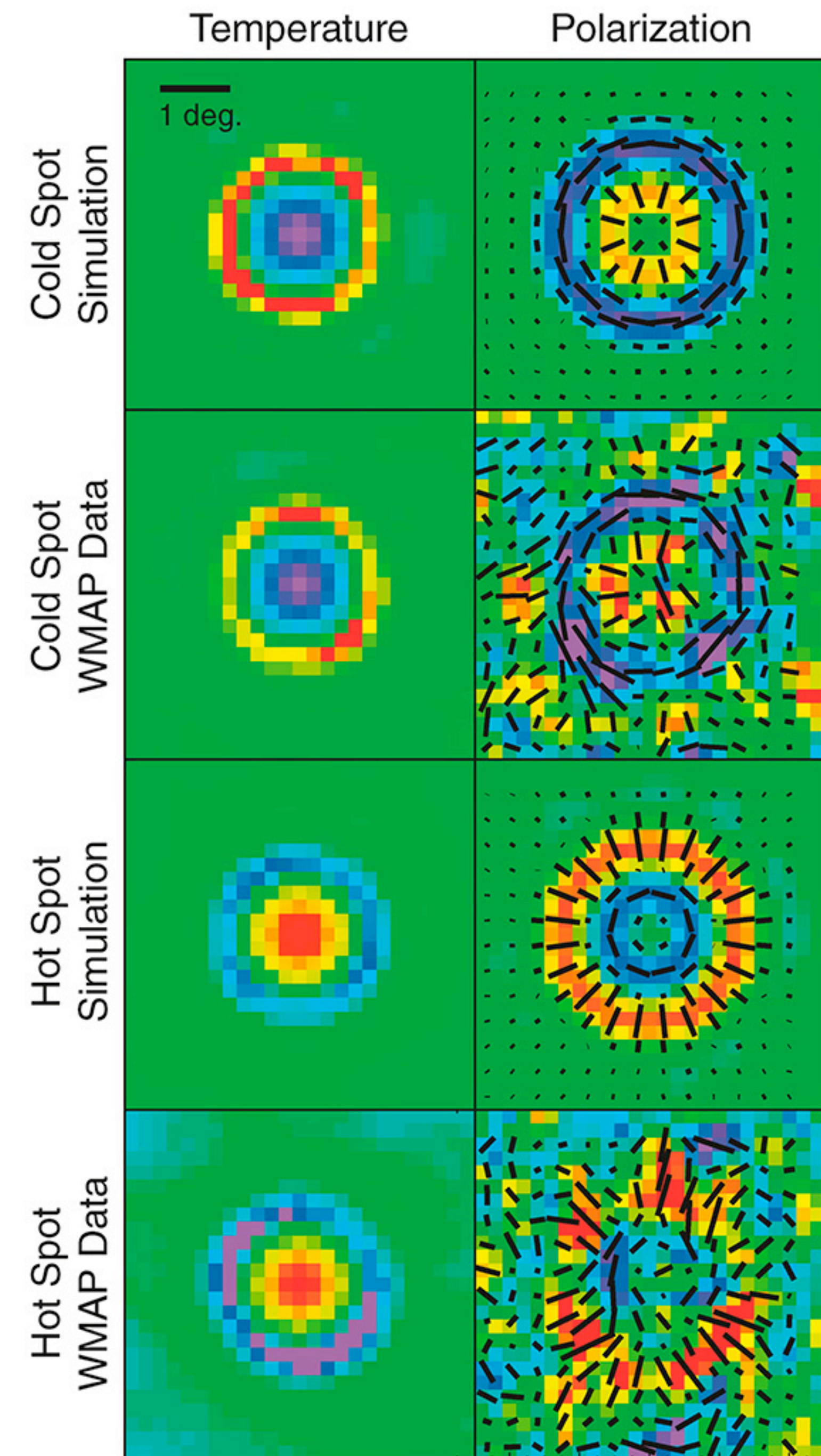
# Stacking Analysis

- 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**.



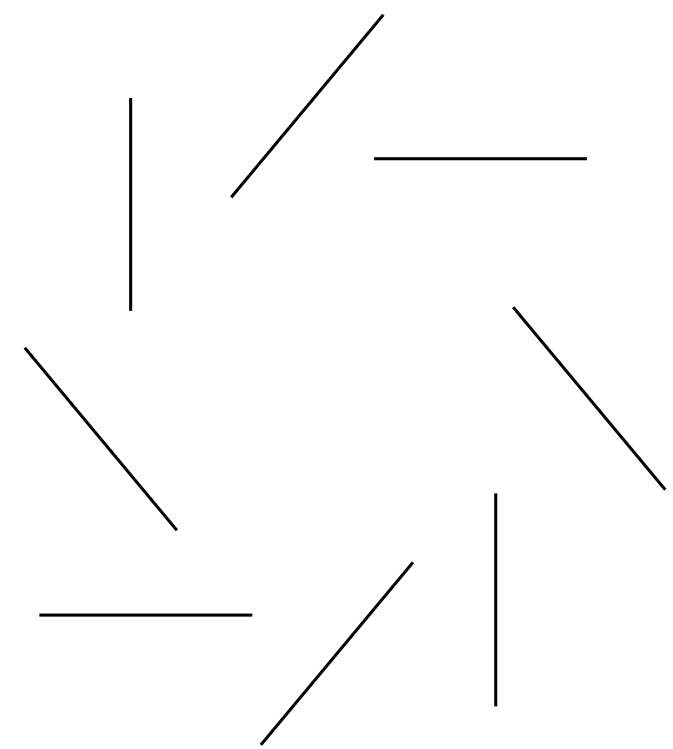
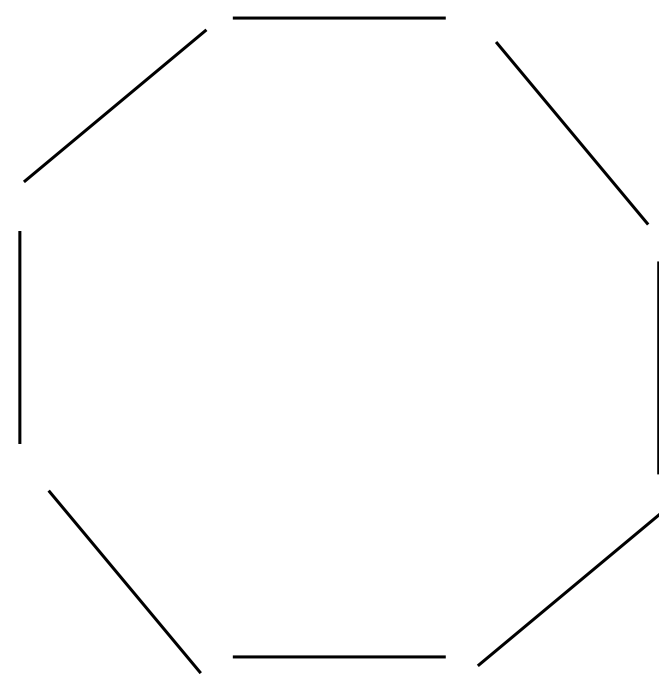
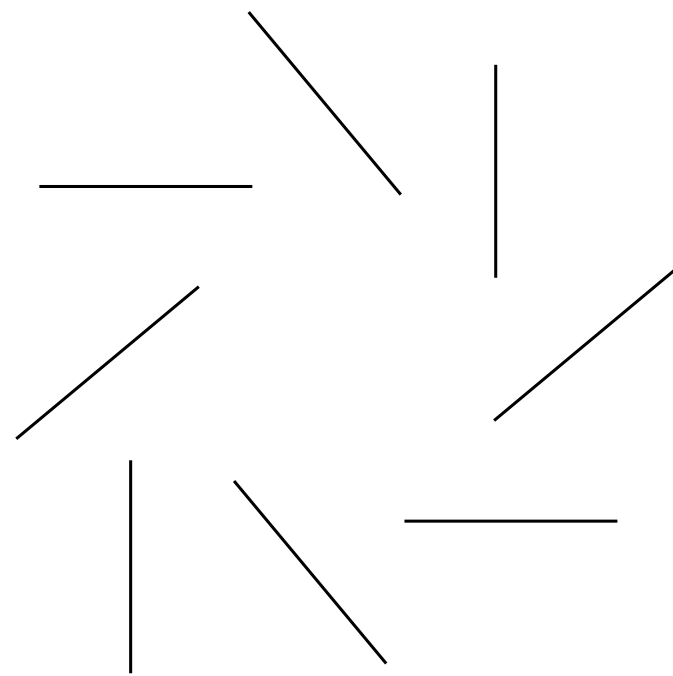
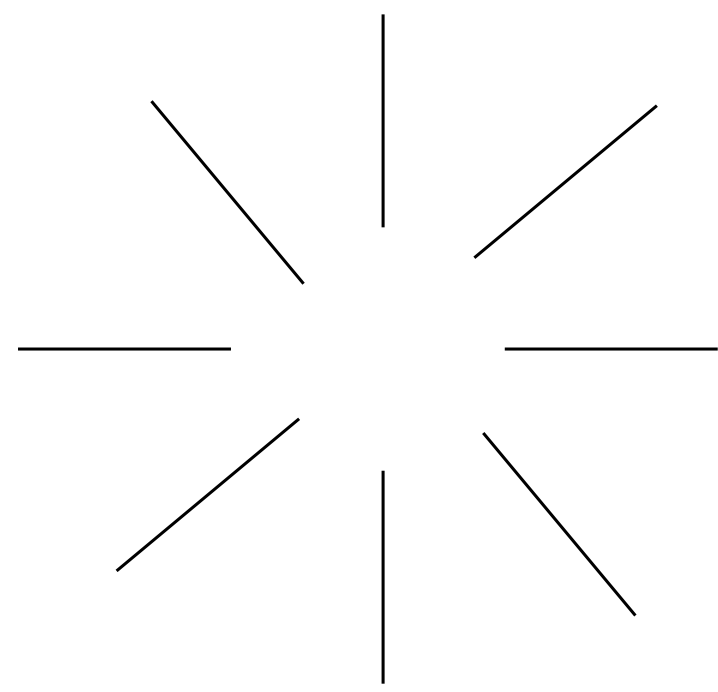


# Two-dimensional View



- All hot and cold spots are stacked
- “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:  $8\sigma$

# E-mode and B-mode

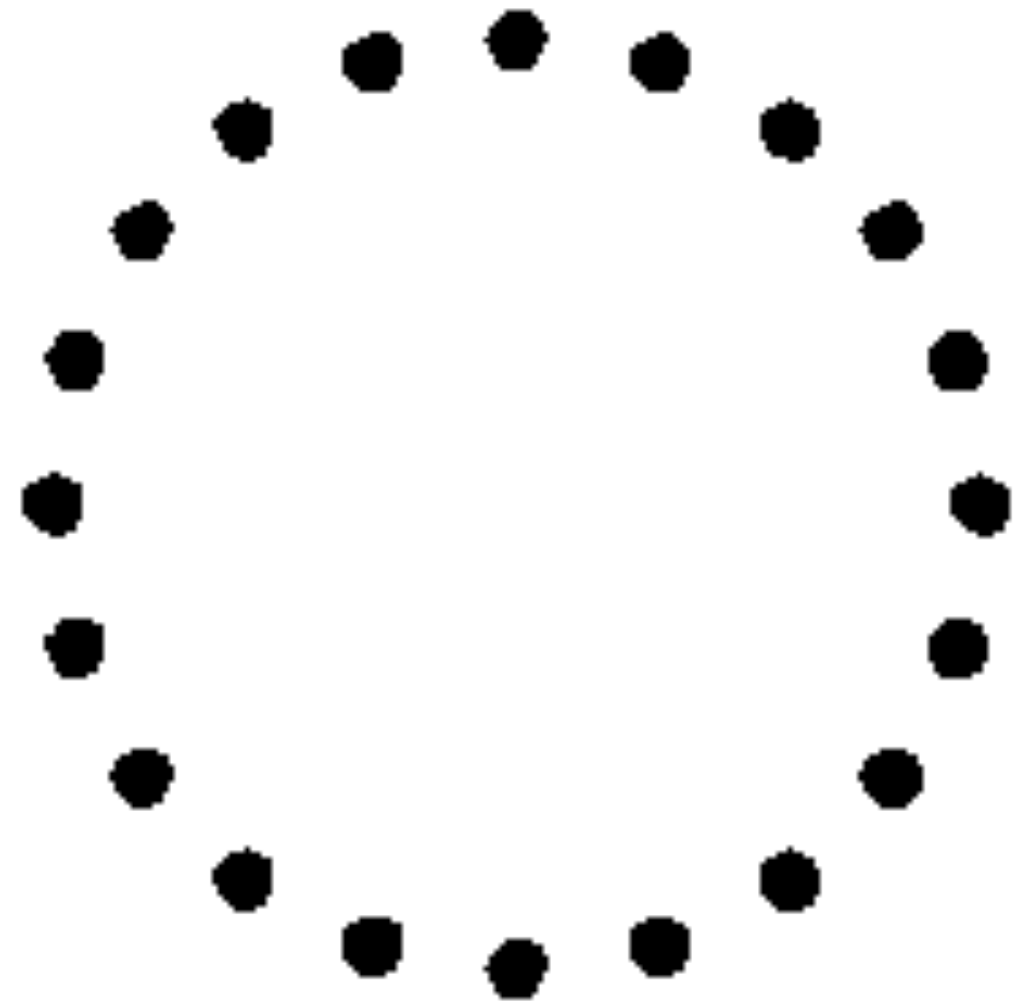


E mode

B mode

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

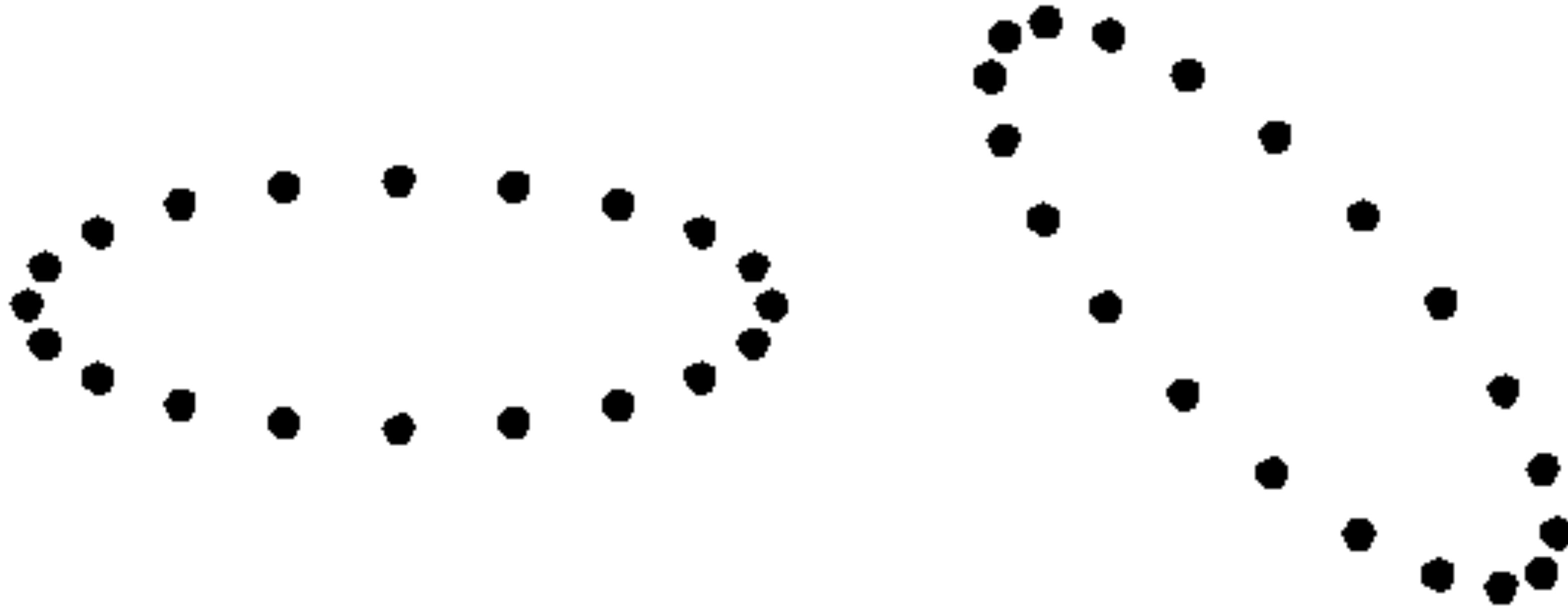
# Gravitational waves are coming toward you... What do you do?



- Gravitational waves stretch space, causing particles to move.

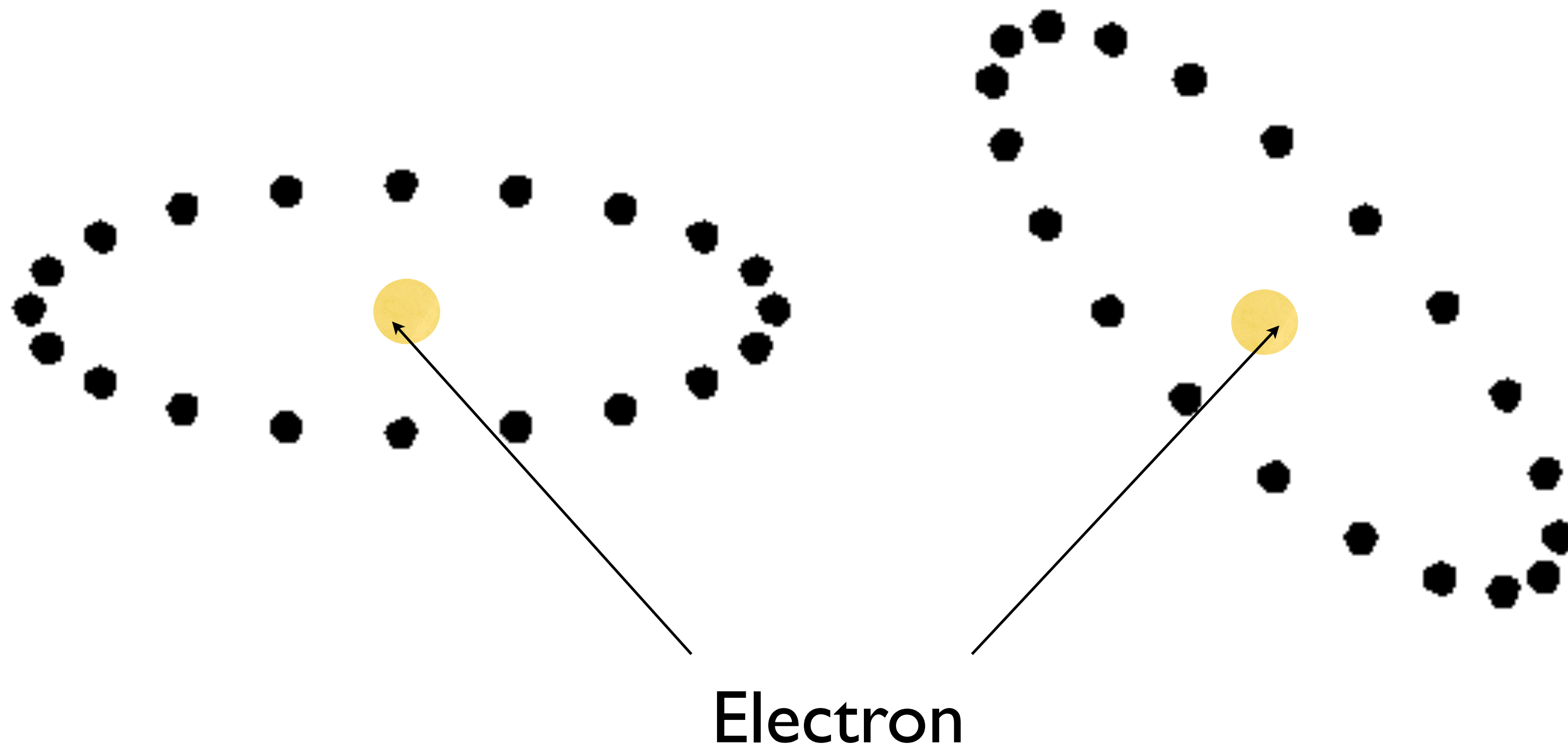


# Two Polarization States of GW



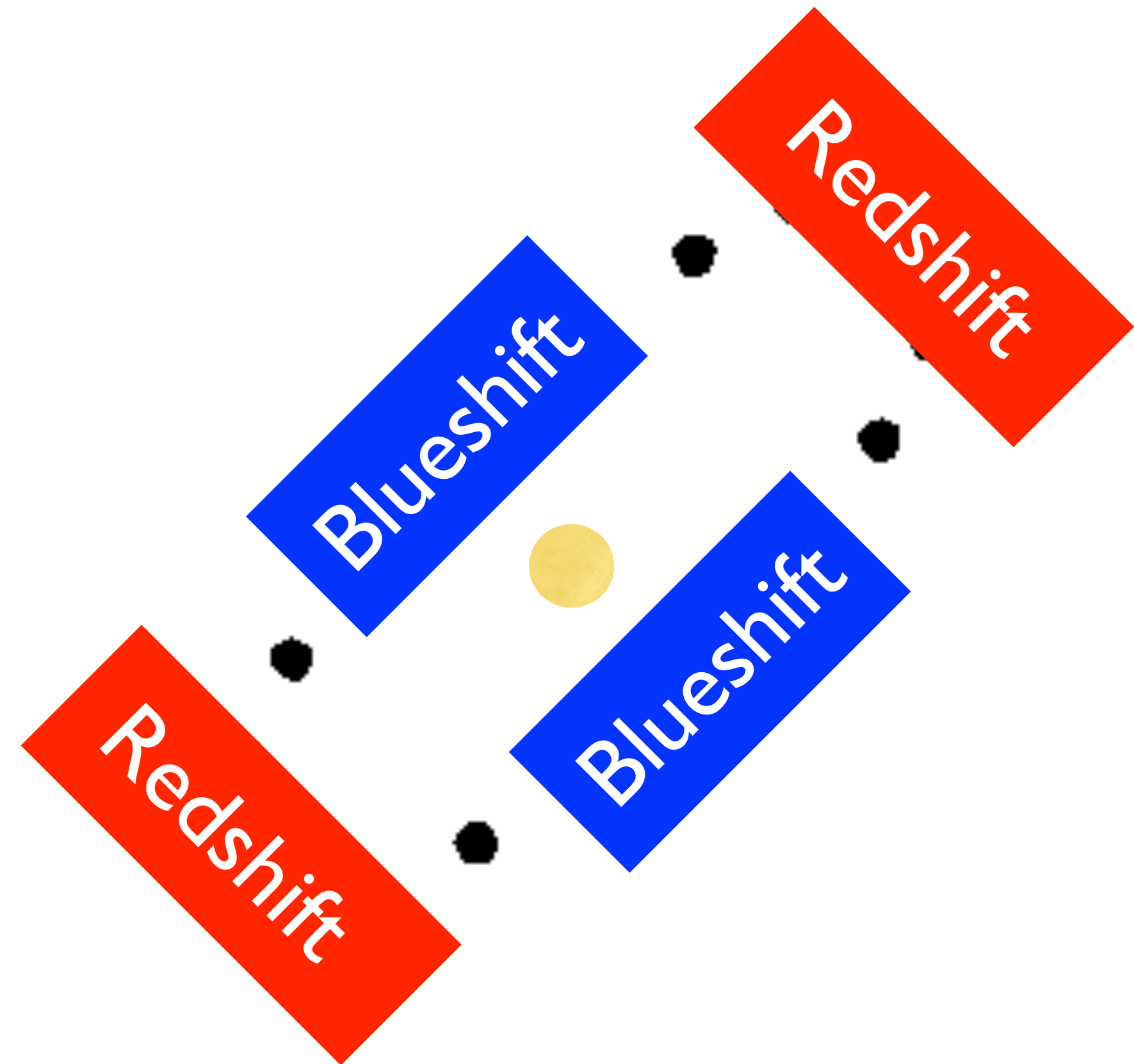
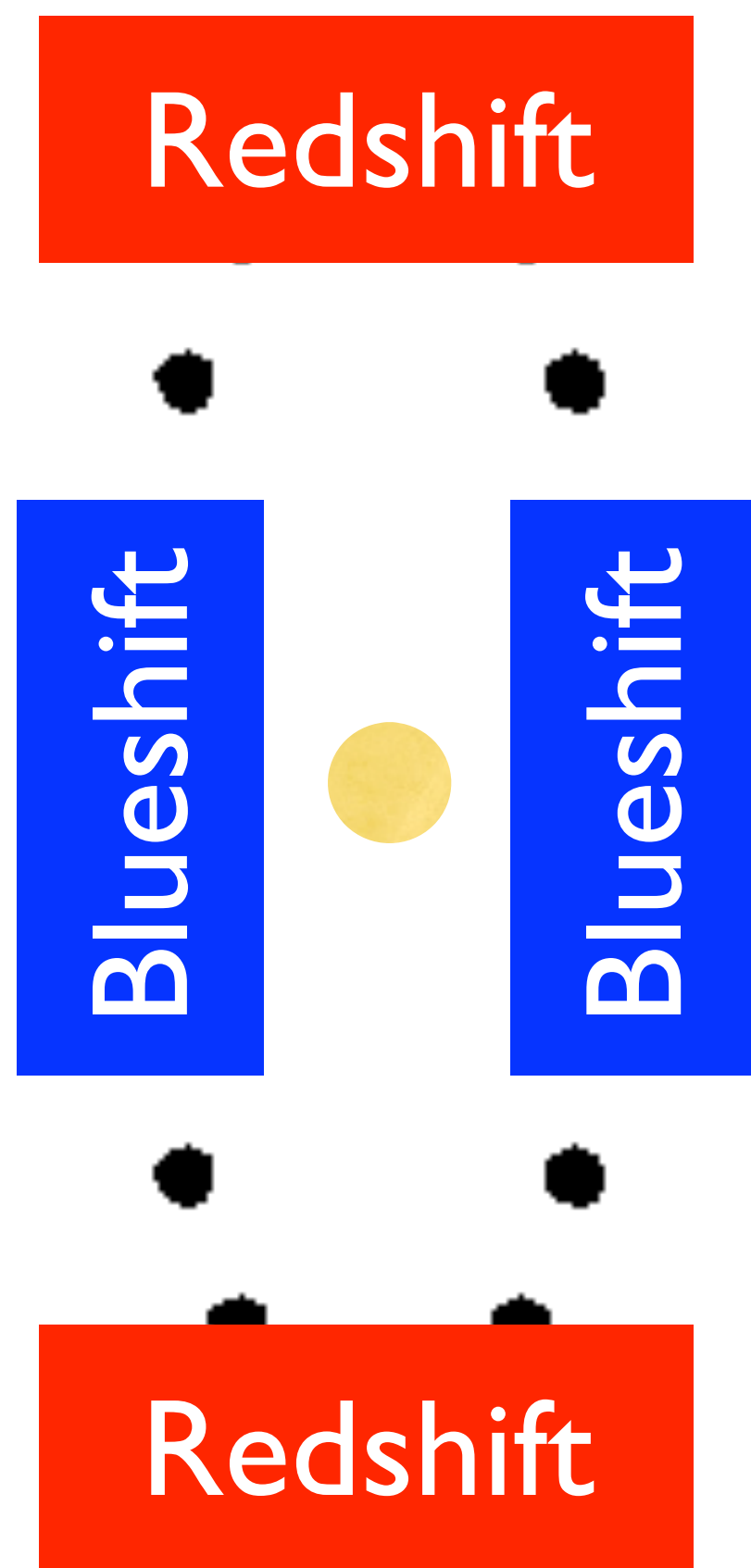
- This is great - this will automatically generate quadrupolar anisotropy around electrons!

# From GW to CMB Polarization

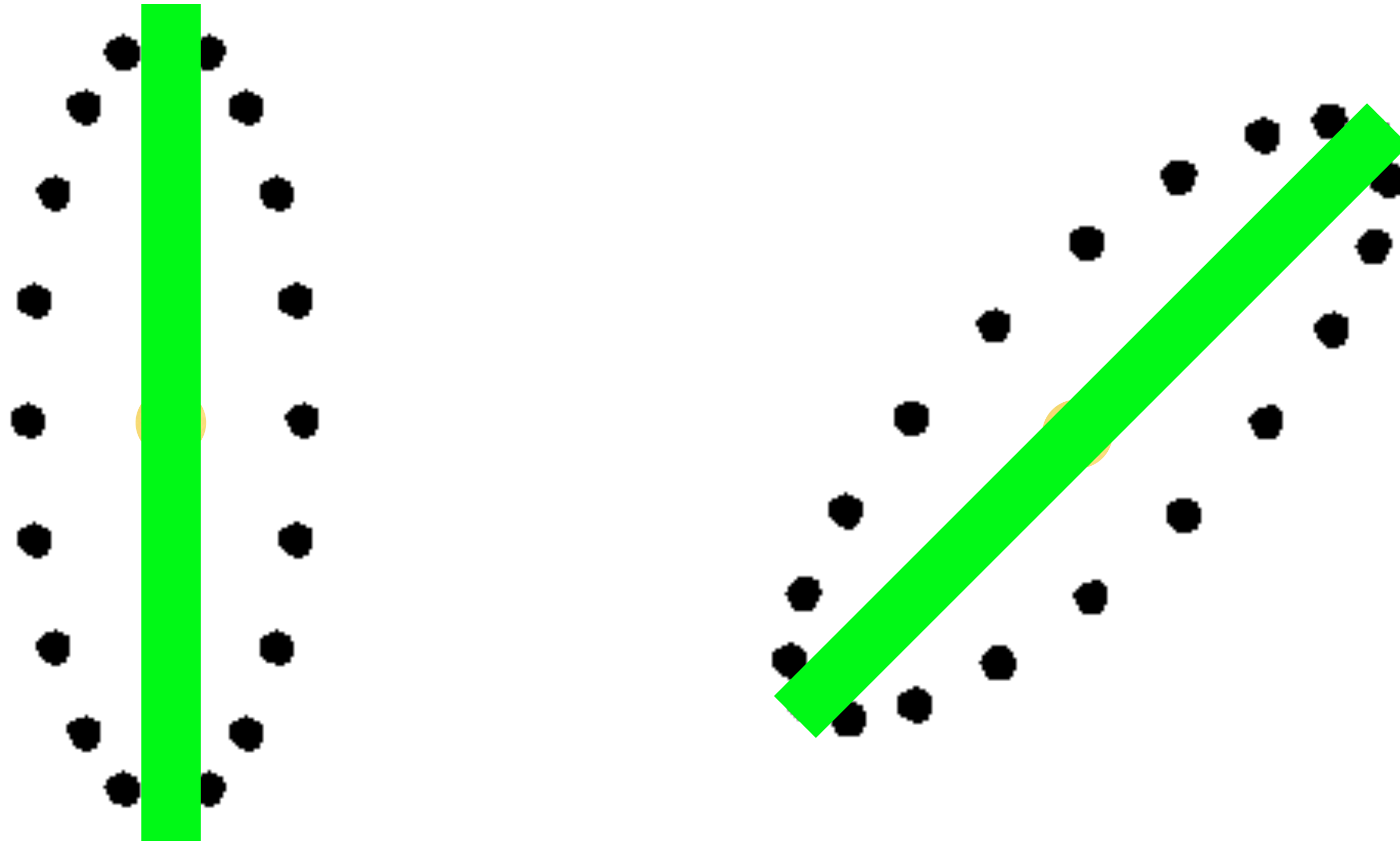




# From GW to CMB Polarization



# From GW to CMB Polarization



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

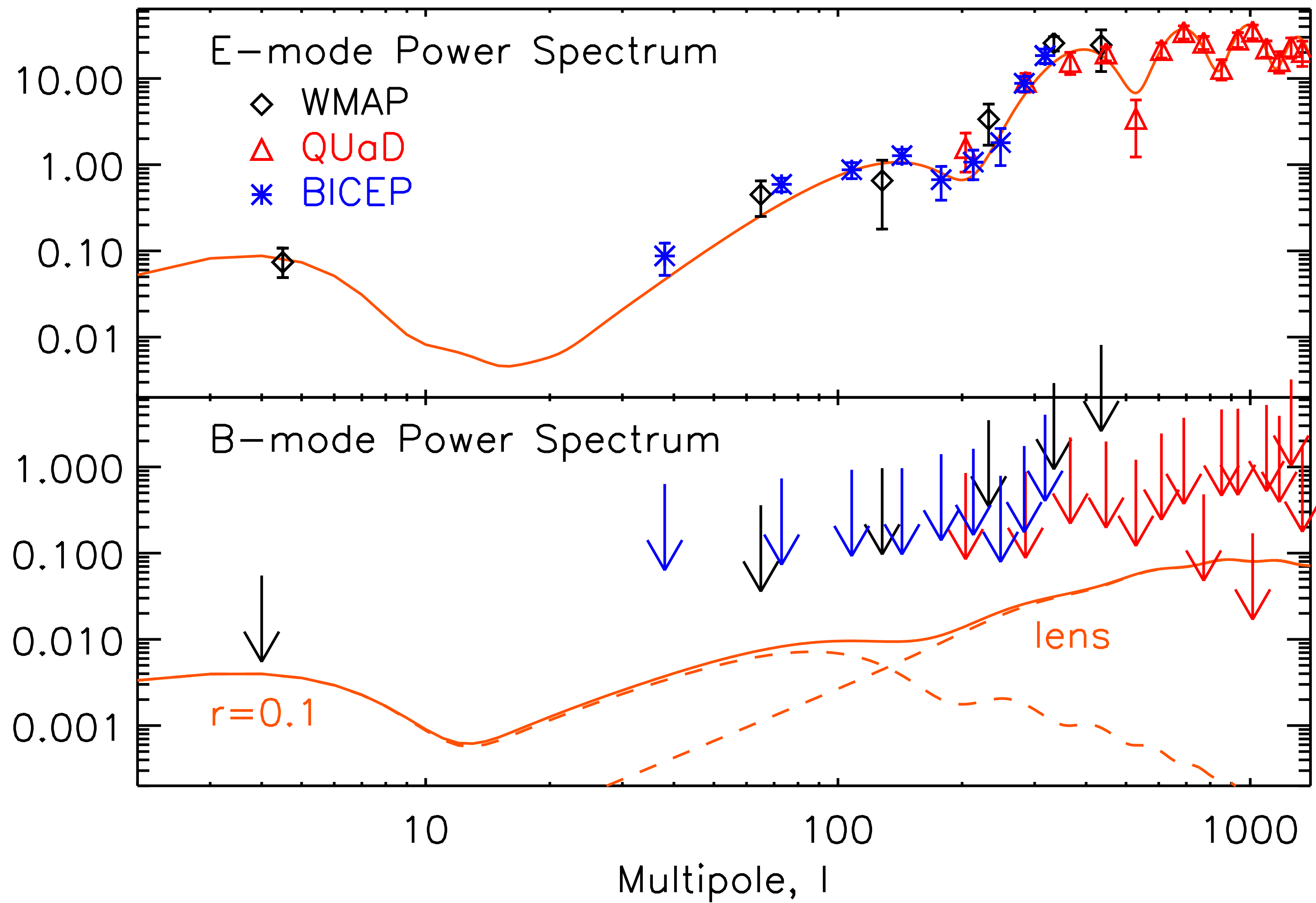


“Tensor-to-scalar Ratio,”  $r$

$$r = \frac{[\text{Power in Gravitational Waves}]}{[\text{Power in Gravitational Potential}]}$$

Theory of “Cosmic Inflation” predicts  $r \ll 1$   
– I will come back to this in a moment

# Polarization Power Spectrum



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

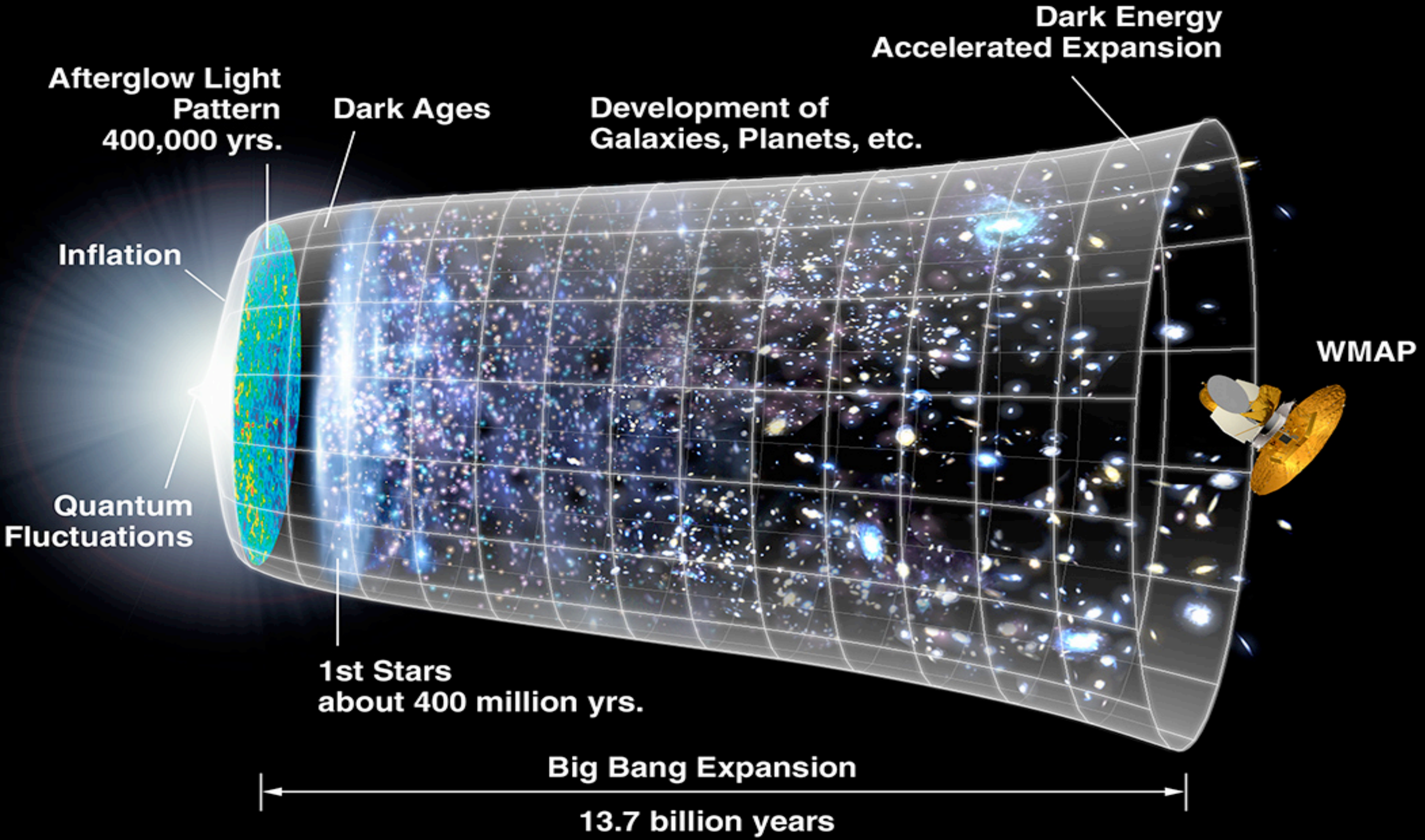


# Theory of the Very Early Universe

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



# Cosmic Inflation = Very Early Dark Energy

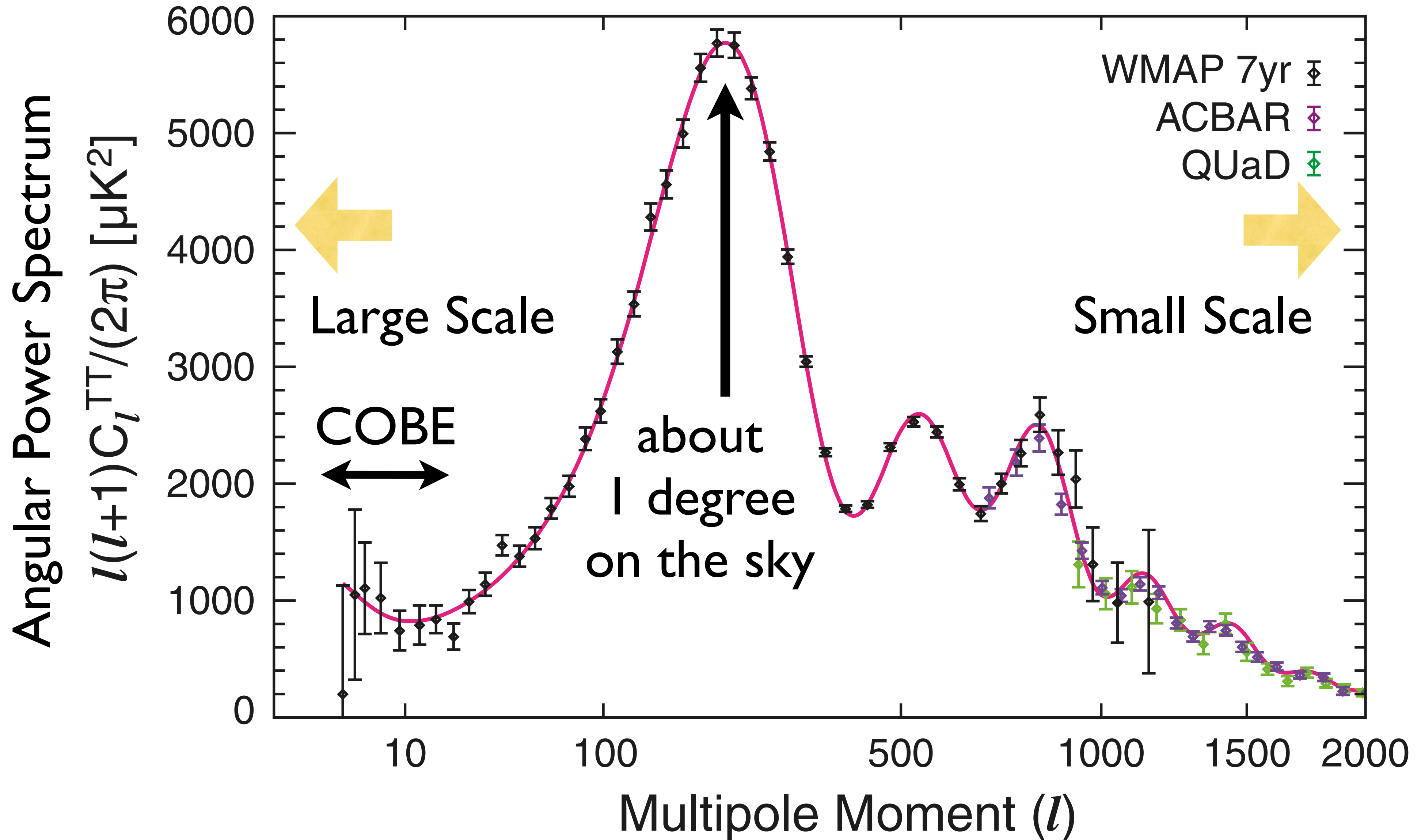




# Origin of Fluctuations

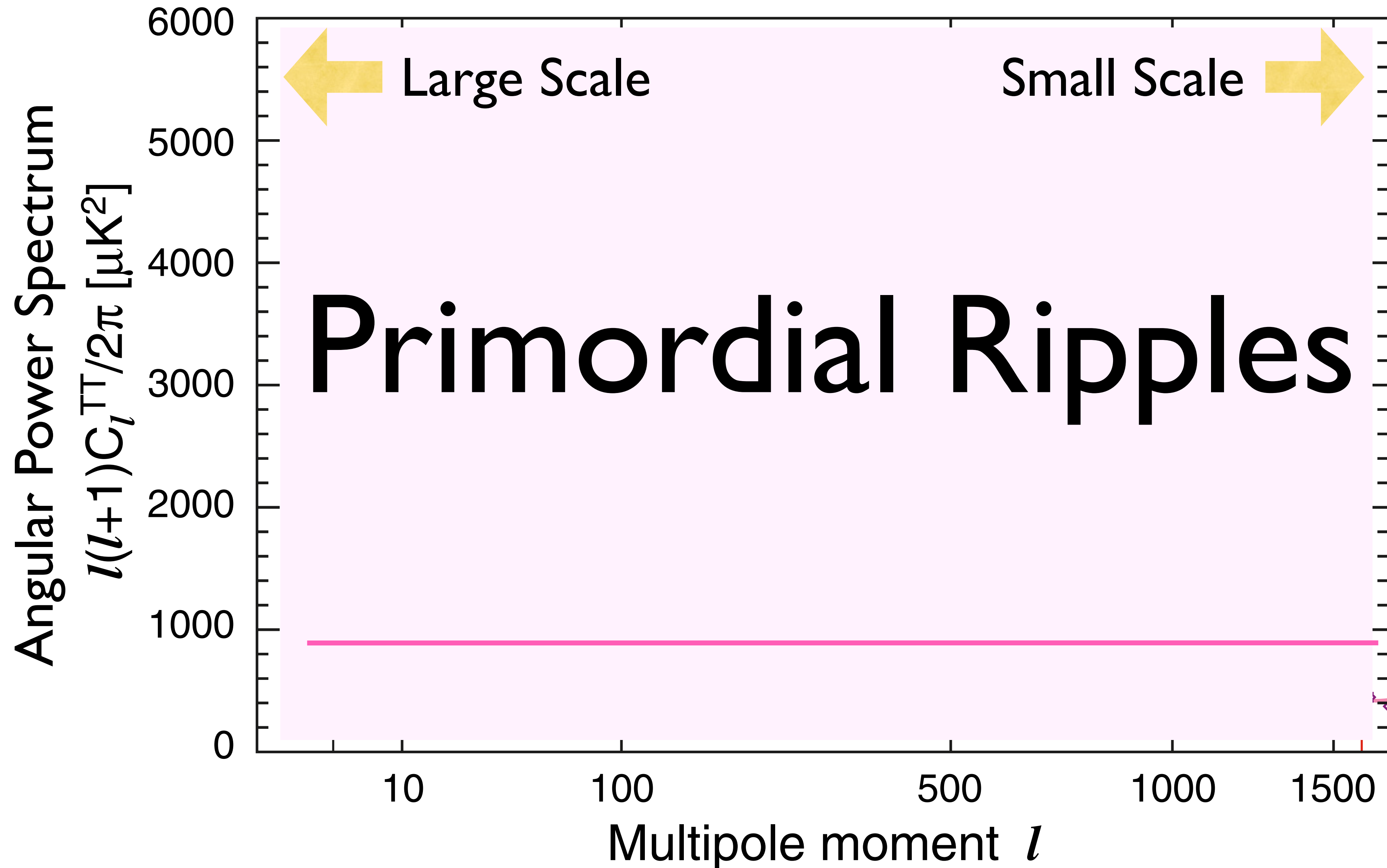
- OK, back to the cosmic hot soup.
- The sound waves were created when we perturbed it.
- “We”? **Who?**
- Who actually perturbed the cosmic soup?
- **Who generated the original (seed) ripples?**

# WMAP Power Spectrum

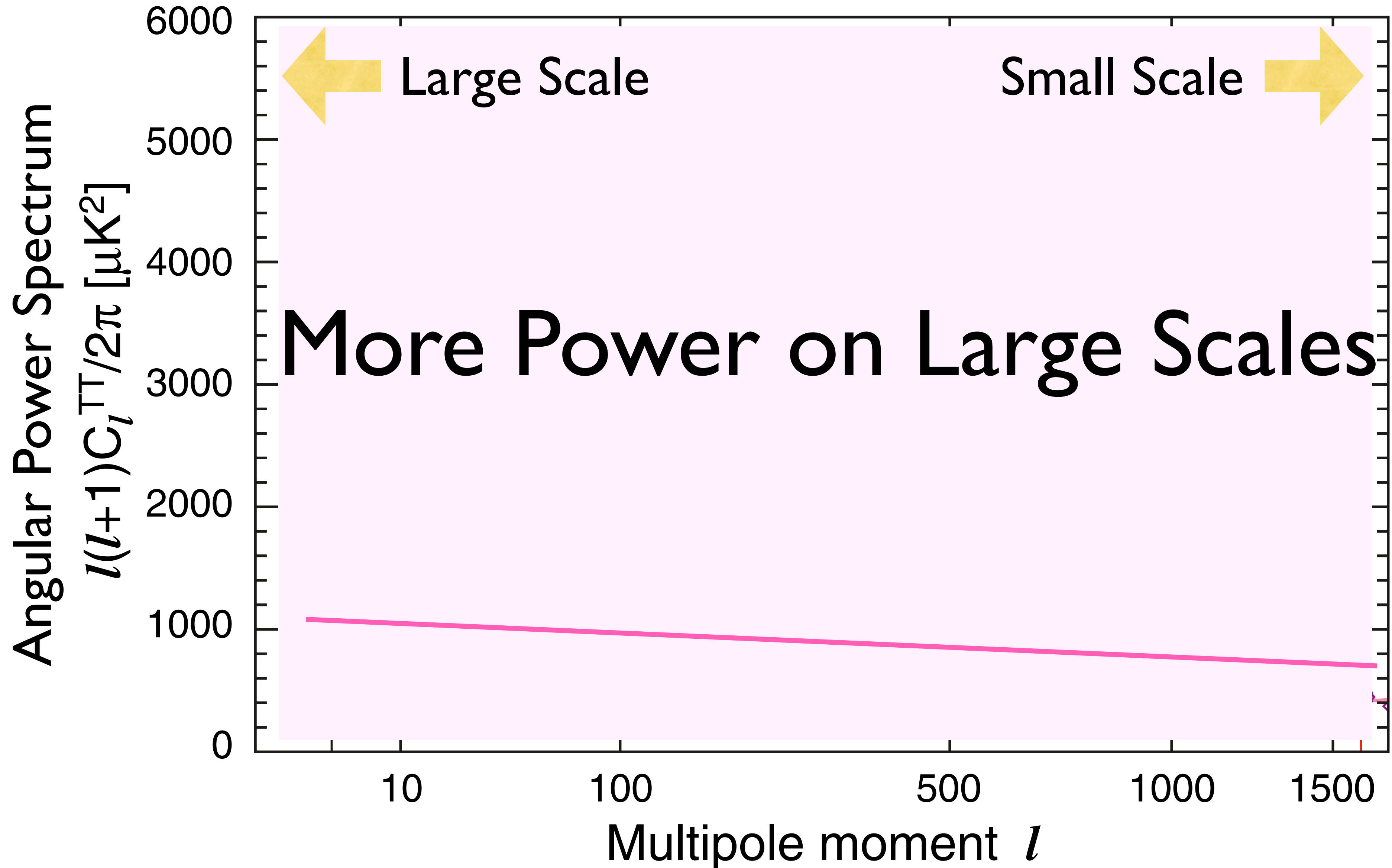




# Getting rid of the Sound Waves

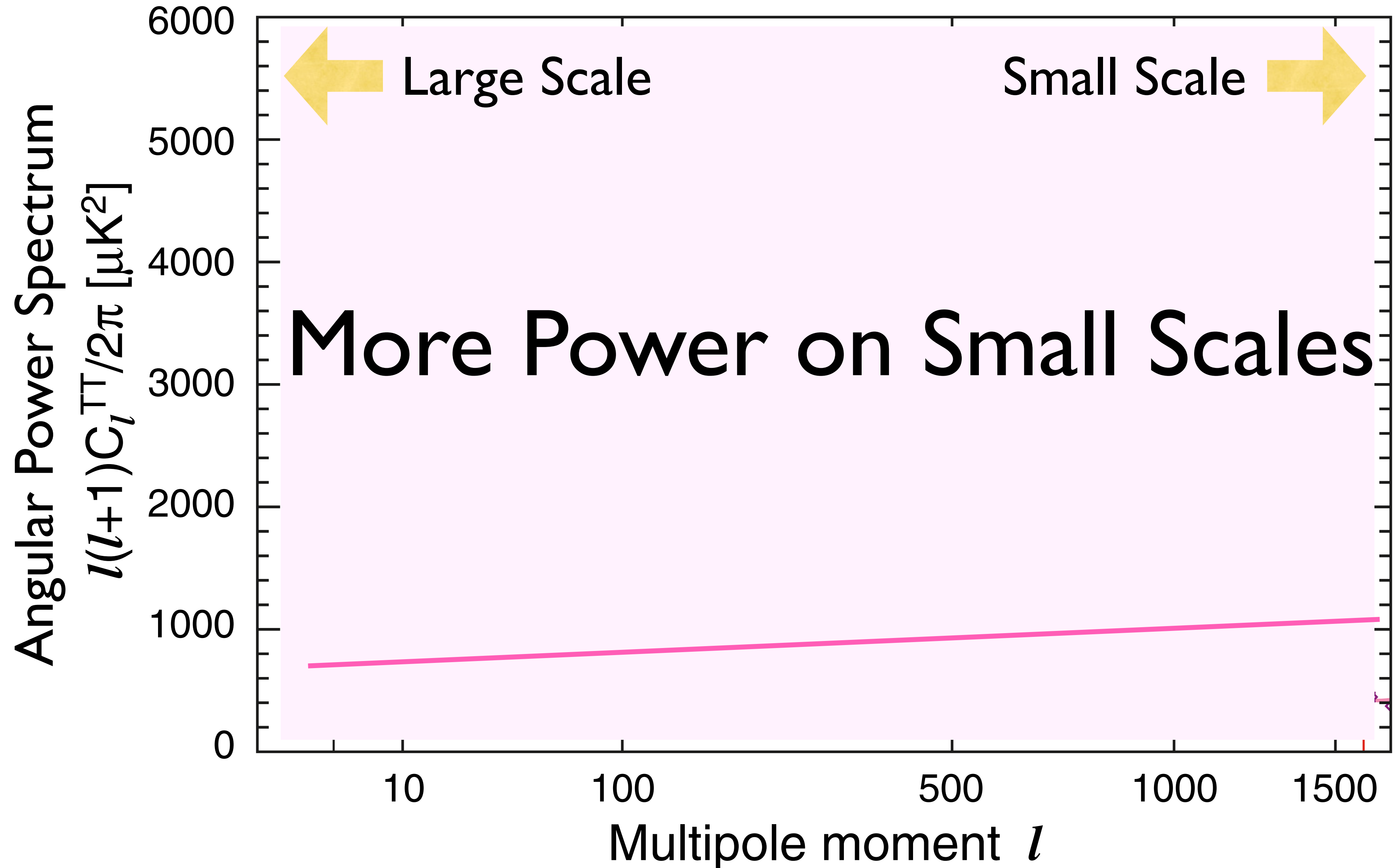


# The Early Universe Could Have Done This Instead

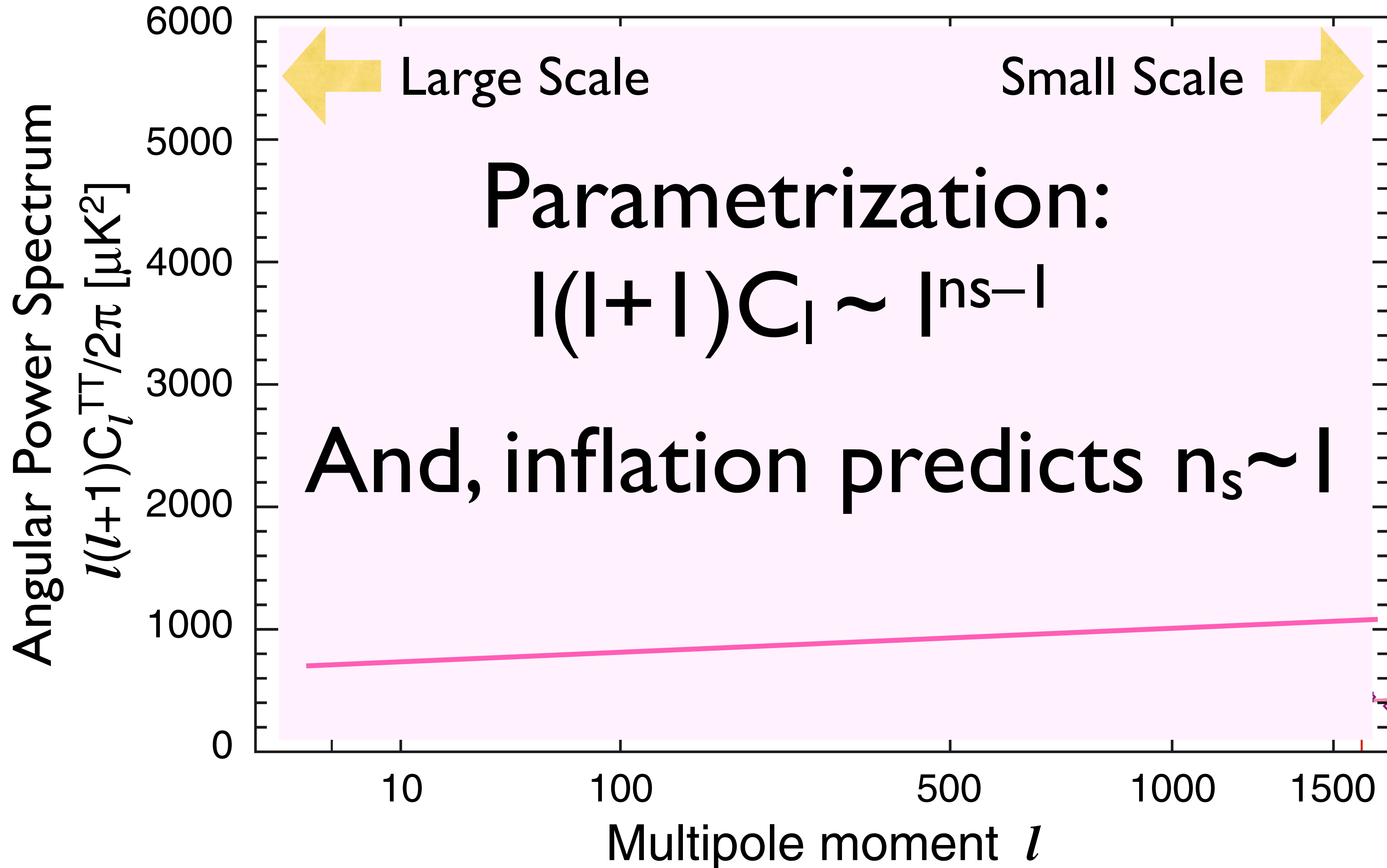




...or, This.



...or, This.





# 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!

# 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

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

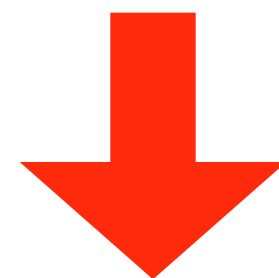
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like  $10^{-36}$  second old
  - (Expansion Rate)  $\sim 1/(\text{Time})$ 
    - which is a big number! ( $\sim 10^{12}\text{GeV}$ )
- *Quantum fluctuations were important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

# Stretching Micro to Macro

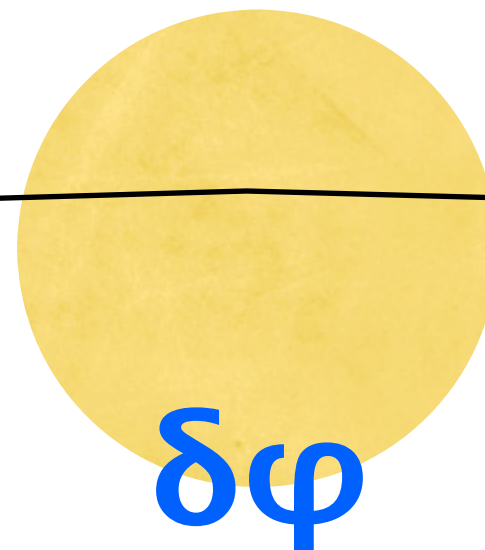
Macroscopic size at which gravity becomes important



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.
- Measured value:  $n_s = 0.968 \pm 0.012$  (68%CL)

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

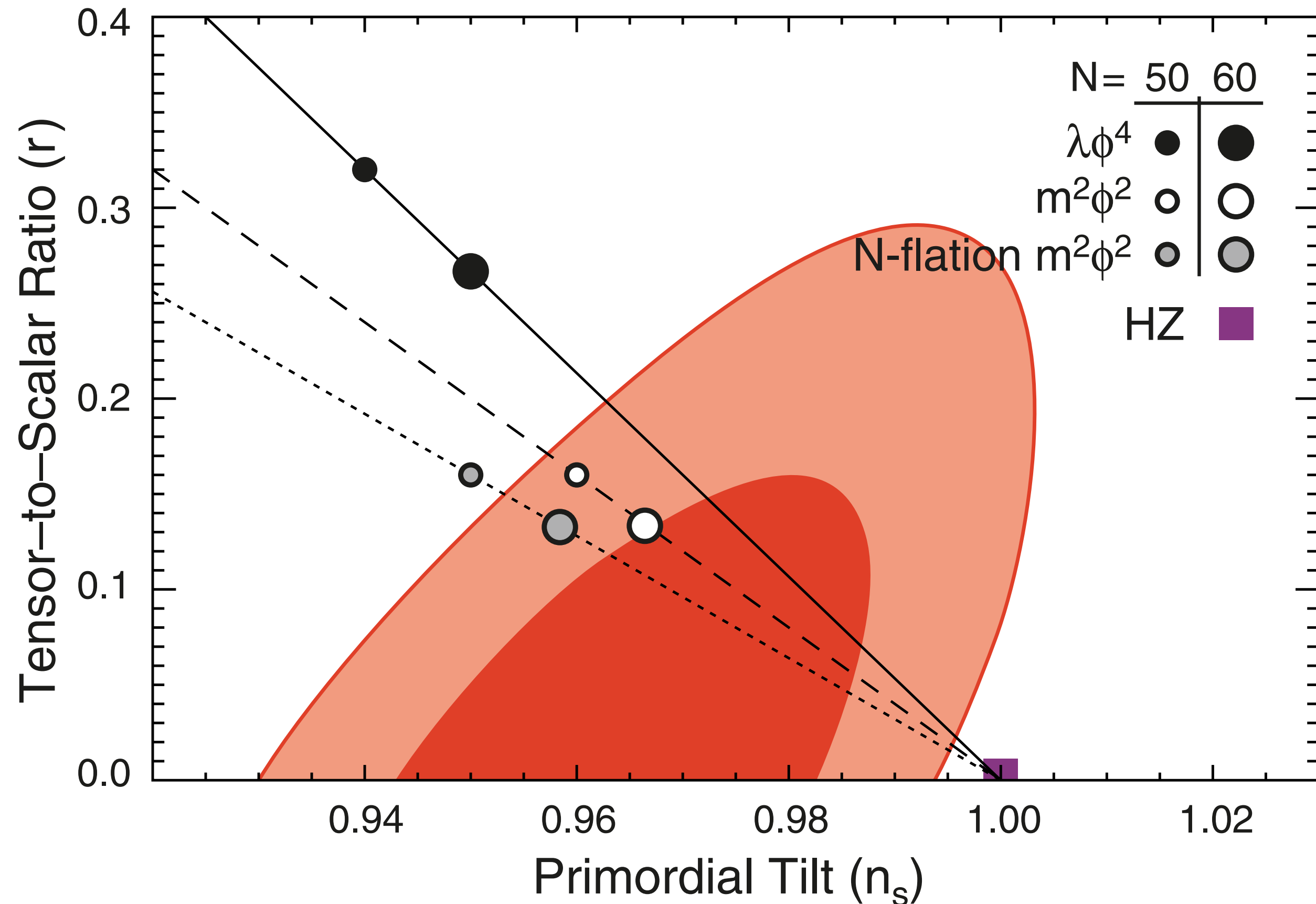
$$h = (\text{Expansion Rate}) / (2^{1/2} \pi M_{\text{planck}}) \text{ [in natural units]}$$

[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.**”

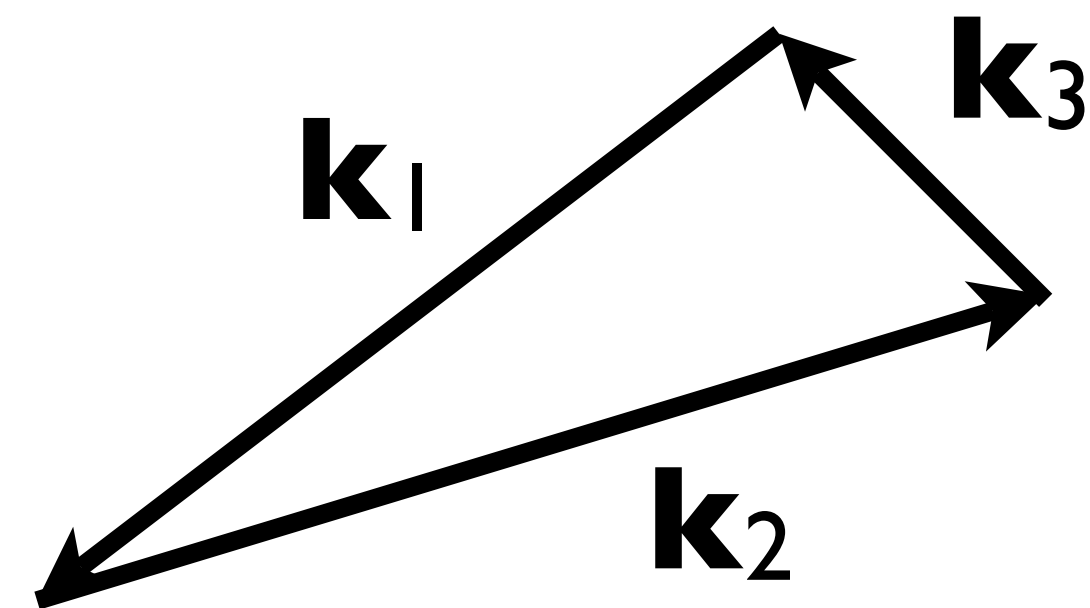


# Probing Inflation (2-point Function)



- Joint constraint on the primordial tilt,  $n_s$ , and the tensor-to-scalar ratio,  $r$ .
- $r < 0.24$  (95%CL)

# Bispectrum

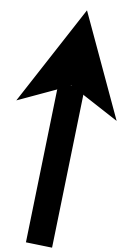


- Three-point function!

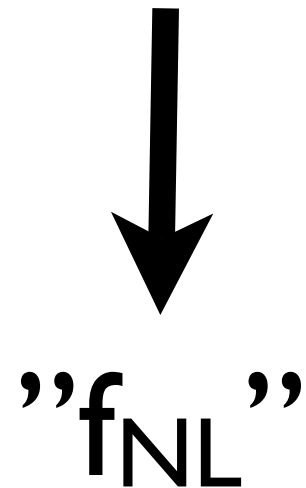
- $B_\zeta(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$

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

model-dependent function



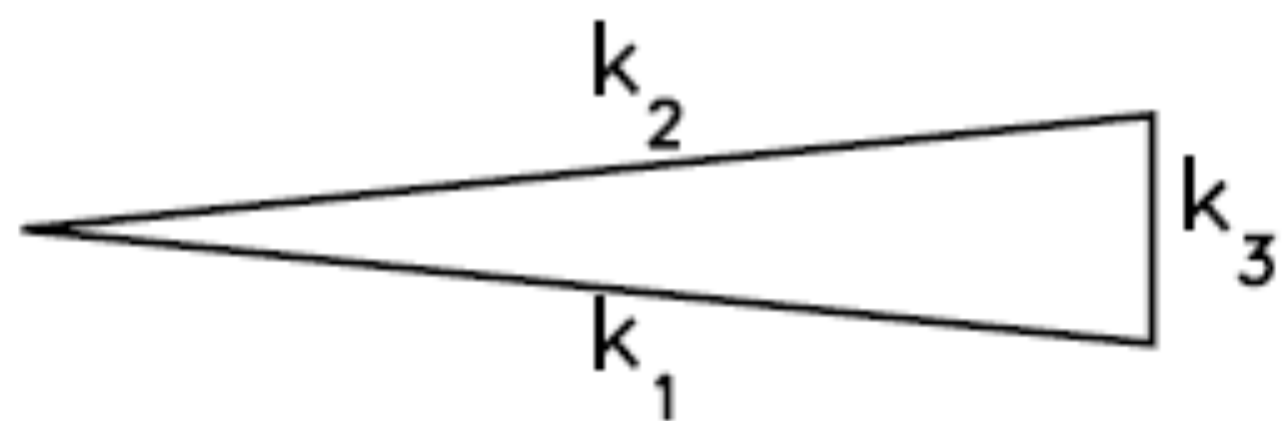
Primordial fluctuation



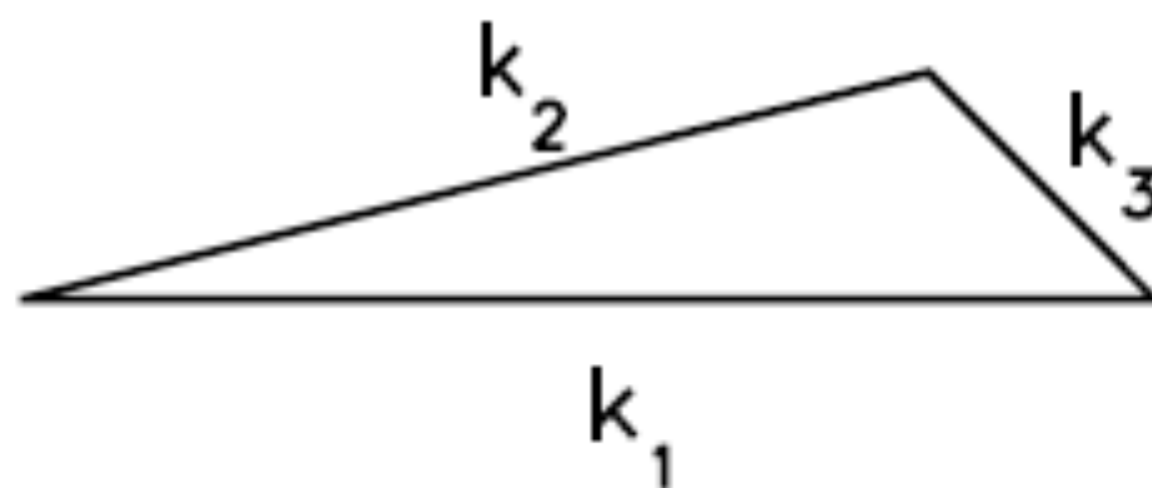
"f<sub>NL</sub>"



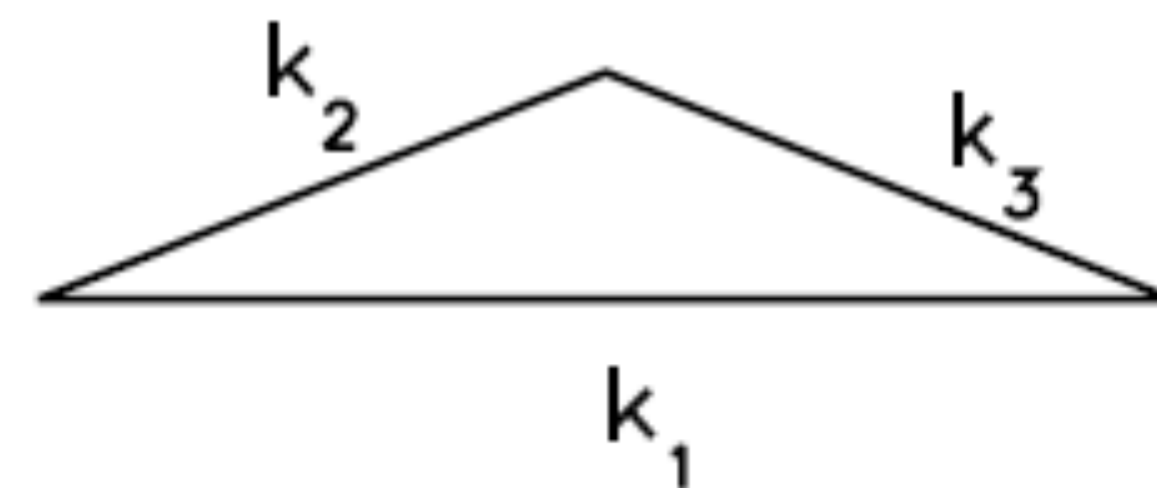
(a) squeezed triangle  
( $k_1 \approx k_2 \gg k_3$ )



(b) elongated triangle  
( $k_1 = k_2 + k_3$ )

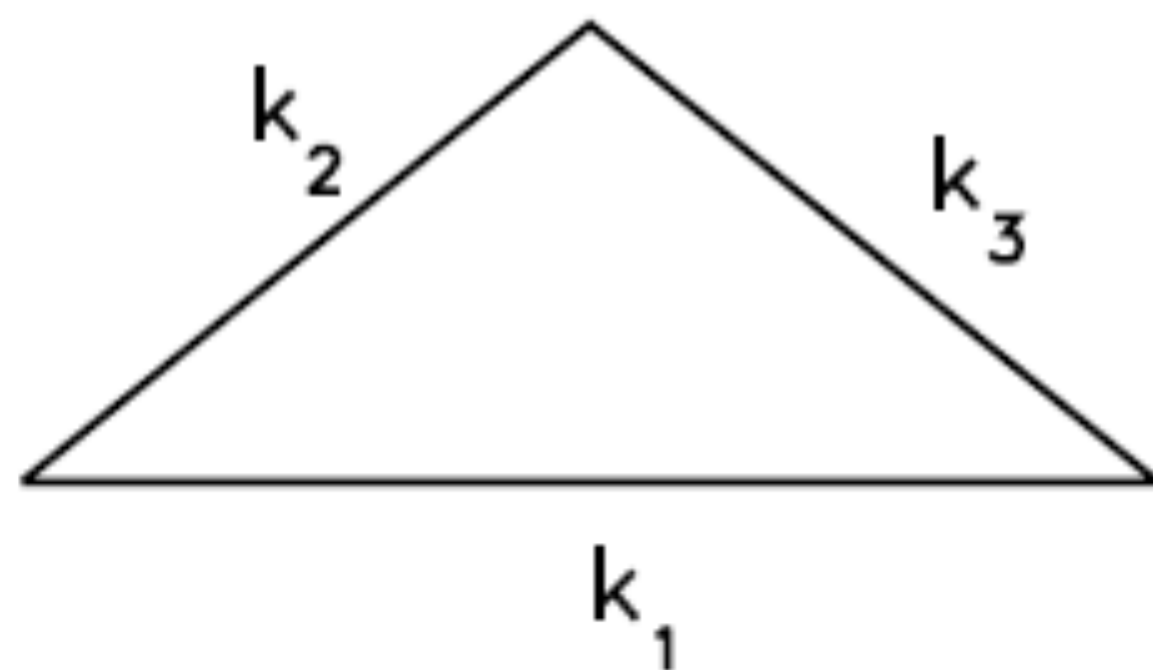


(c) folded triangle  
( $k_1 = 2k_2 = 2k_3$ )

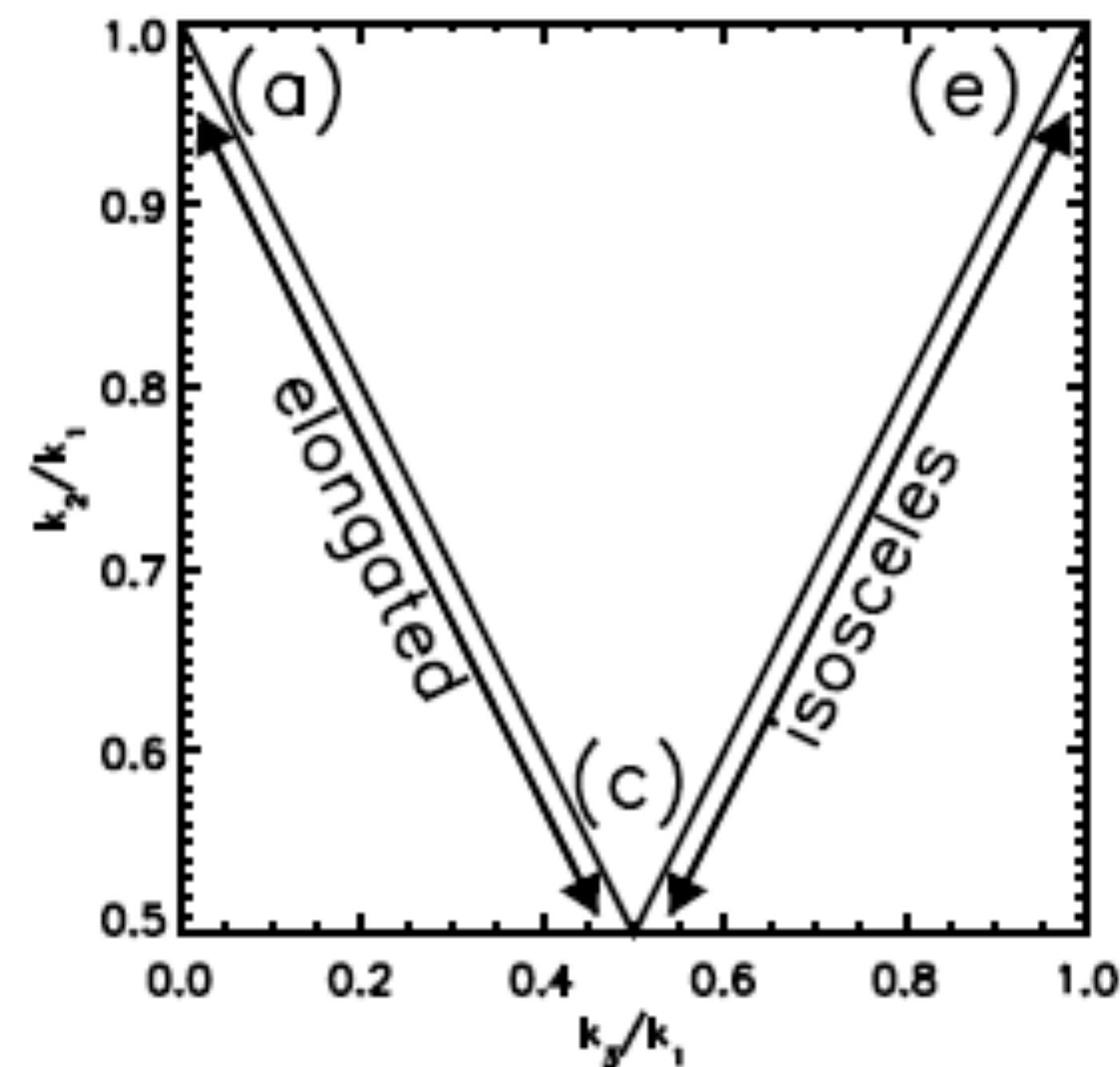
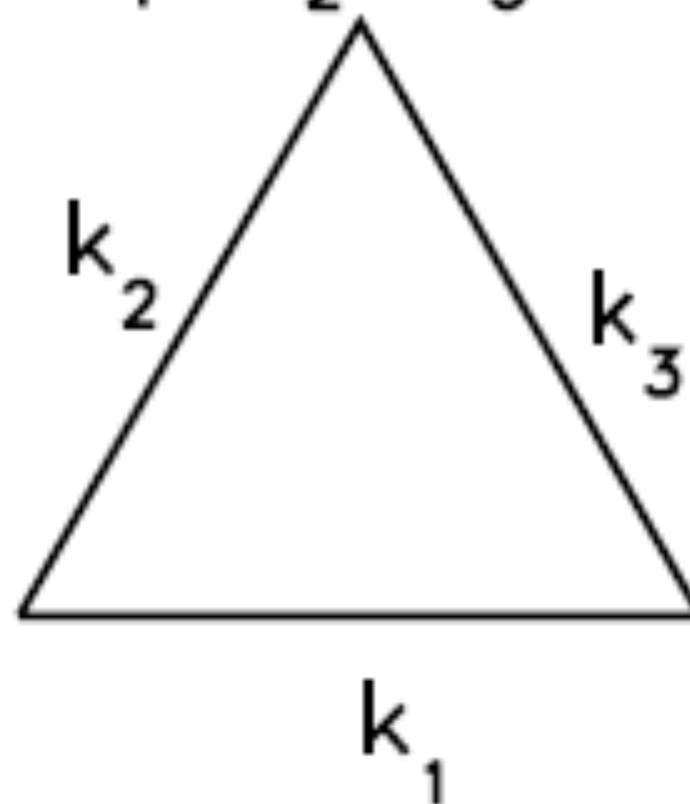


## MOST IMPORTANT

(d) isosceles triangle  
( $k_1 > k_2 = k_3$ )



(e) equilateral triangle  
( $k_1 = k_2 = k_3$ )



# 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  $f_{\text{NL}}=0.02$ .
- Detection of  $f_{\text{NL}} > 1$  would rule out ALL single-field models!
- No detection of 3-point functions of primordial curvature perturbations. The 95% CL limits are:
  - $-10 < f_{\text{NL}} < 74$
  - The WMAP data are consistent with the prediction of **simple single-field inflation** models:  $1-n_s \approx r \approx f_{\text{NL}}$

# Summary

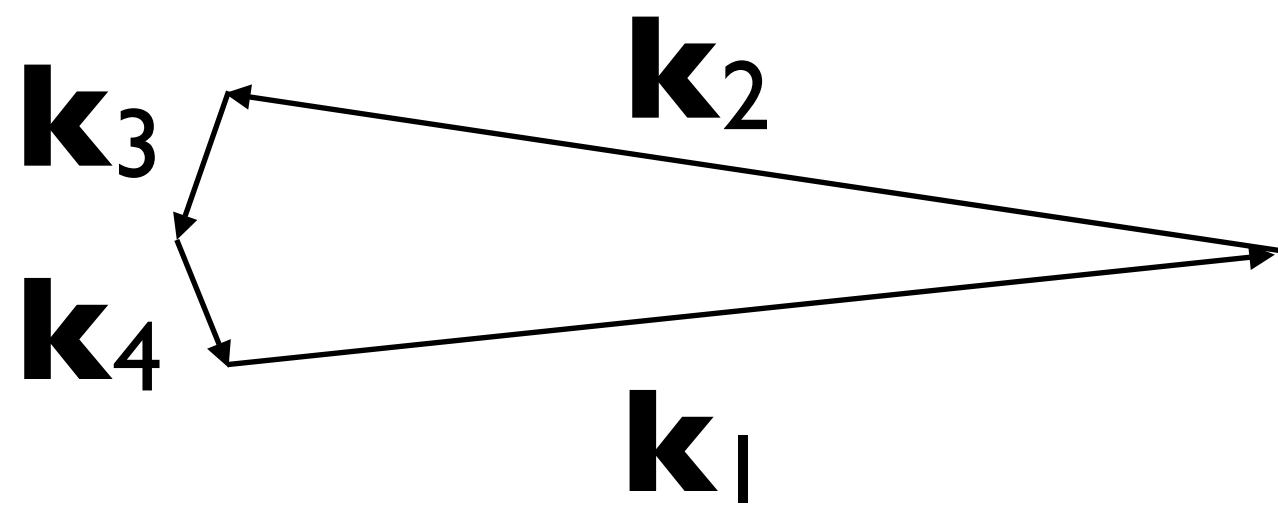
- CMB is the fossil light of the Big Bang.
- We could determine the age, composition, expansion rate, etc., from CMB.
- We could even push the boundary farther back in time, probing the origin of fluctuations in the very early Universe: inflationary epoch at ultra-high energies.
- Next Big Thing: **Primordial gravitational waves.**
- The 3-point function: **Powerful test of inflation.**



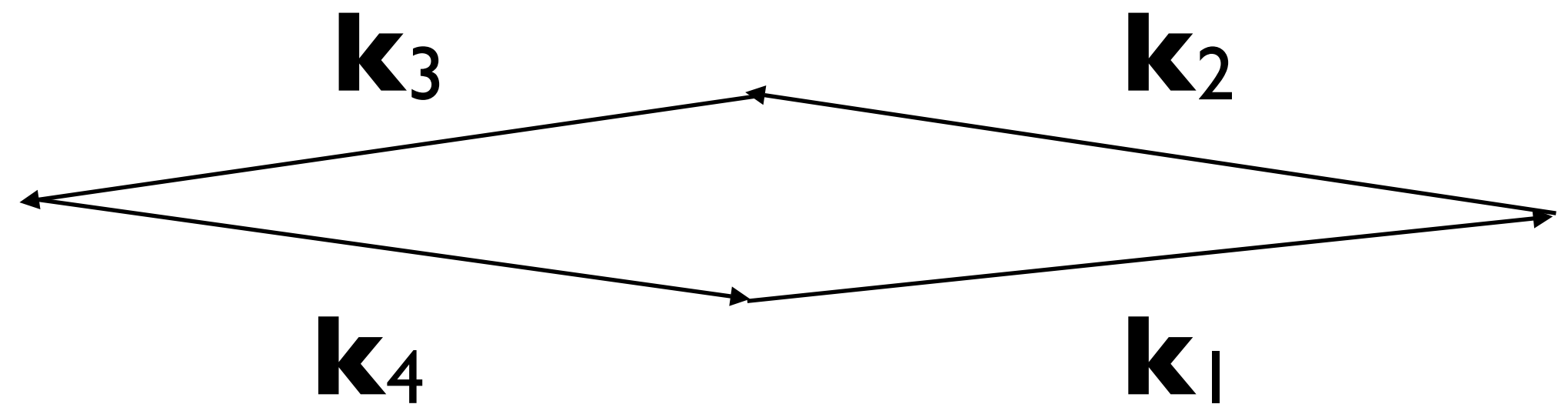
# Trispectrum

- $T_{\zeta}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4) = (2\pi)^3 \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 + \mathbf{k}_4) \{ \mathbf{g}_{NL} [(54/25) P_{\zeta}(k_1) P_{\zeta}(k_2) P_{\zeta}(k_3) + \text{cyc.}] + \mathbf{T}_{NL} [P_{\zeta}(k_1) P_{\zeta}(k_2) (P_{\zeta}(|\mathbf{k}_1 + \mathbf{k}_3|) + P_{\zeta}(|\mathbf{k}_1 + \mathbf{k}_4|)) + \text{cyc.}] \}$

*The local form consistency relation,  $\tau_{NL} = (6/5)(f_{NL})^2$ , may not be respected – additional test of multi-field inflation!*

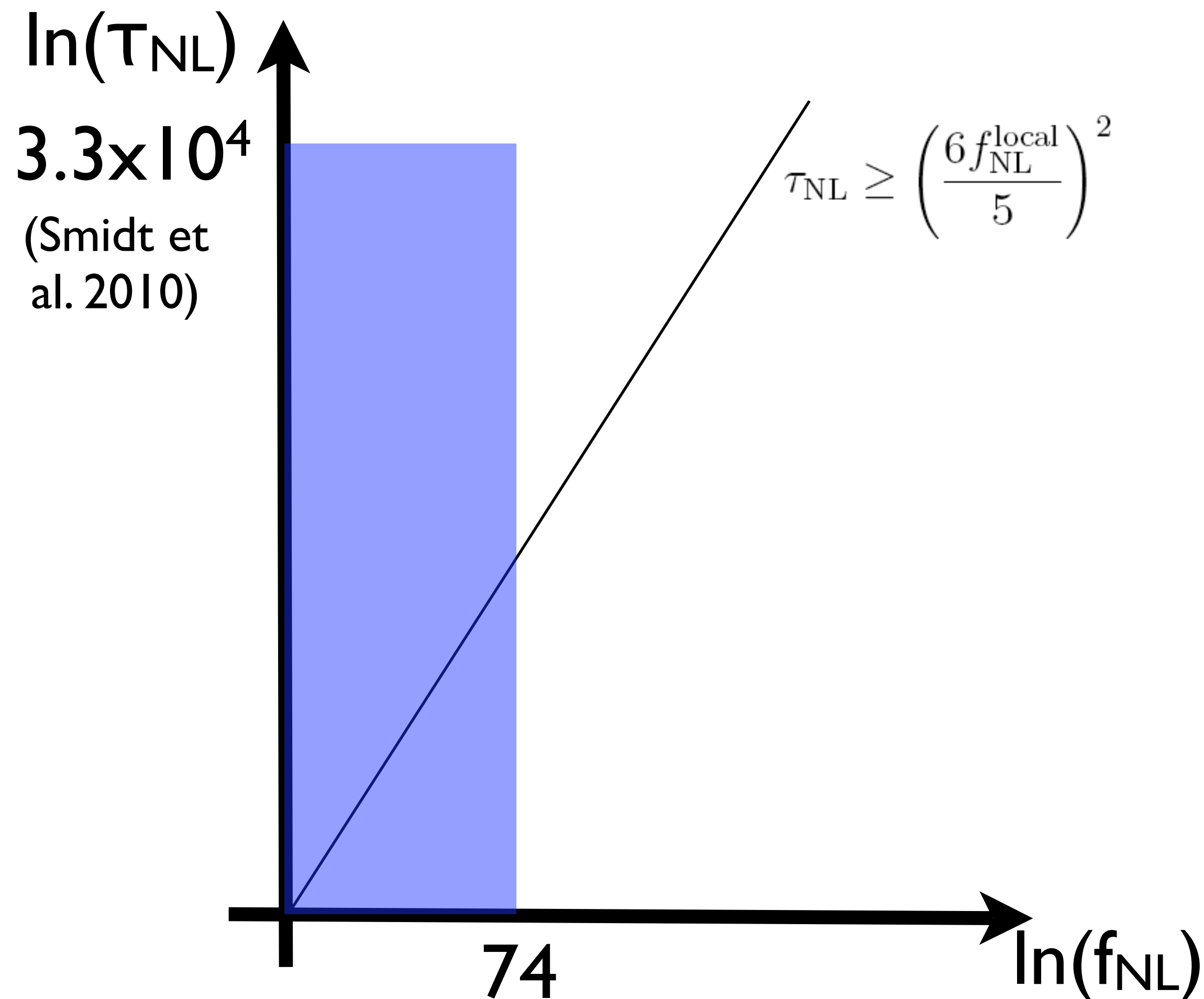


$g_{NL}$



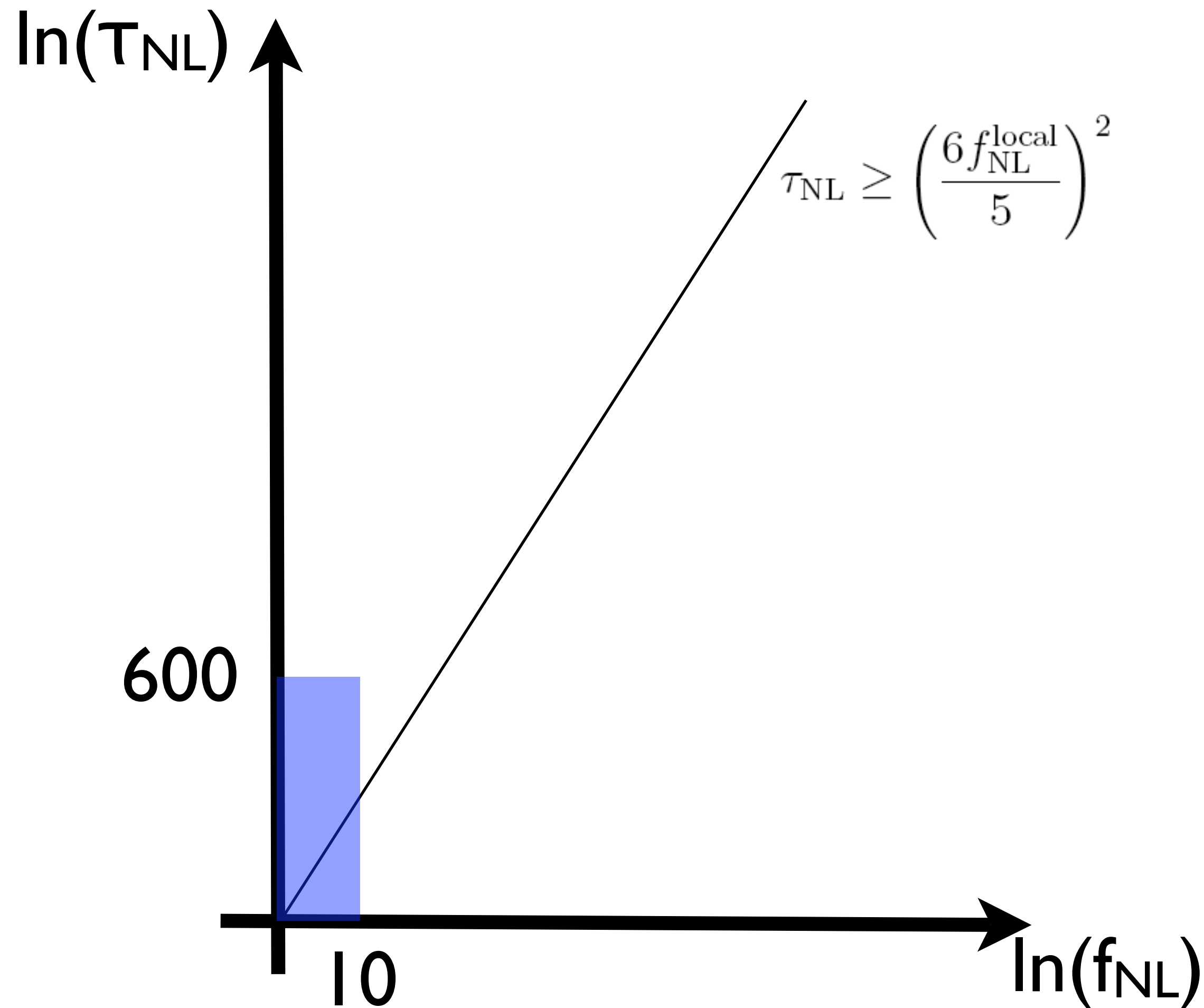
$\tau_{NL}$

# The diagram that you should take away from this talk.



- The current limits from WMAP 7-year are consistent with single-field or multi-field models.
- So, let's play around with the future.

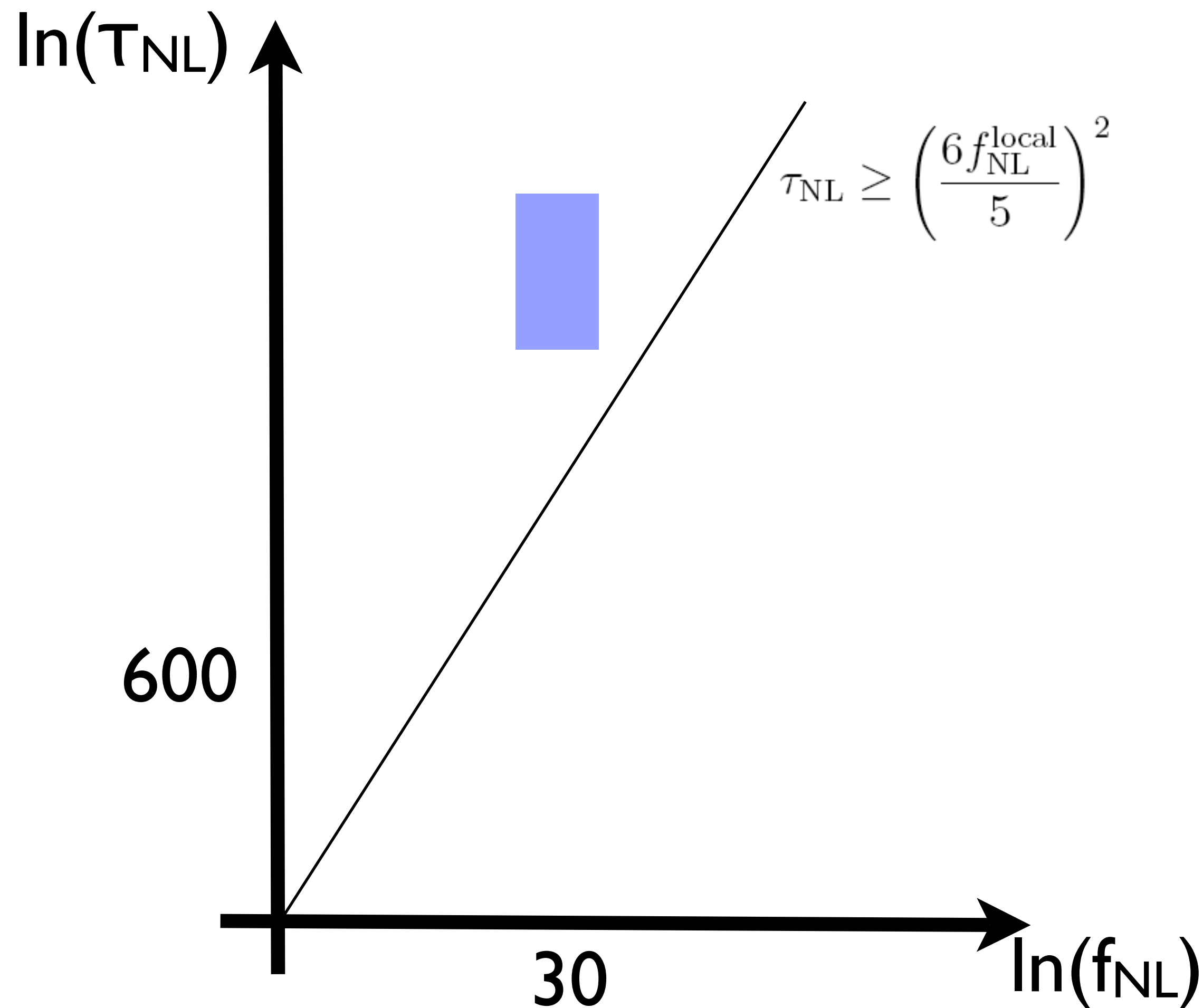
# Case A: Single-field Happiness



- No detection of anything after Planck. Single-field survived the test (for the moment: the future galaxy surveys can improve the limits by a factor of ten).

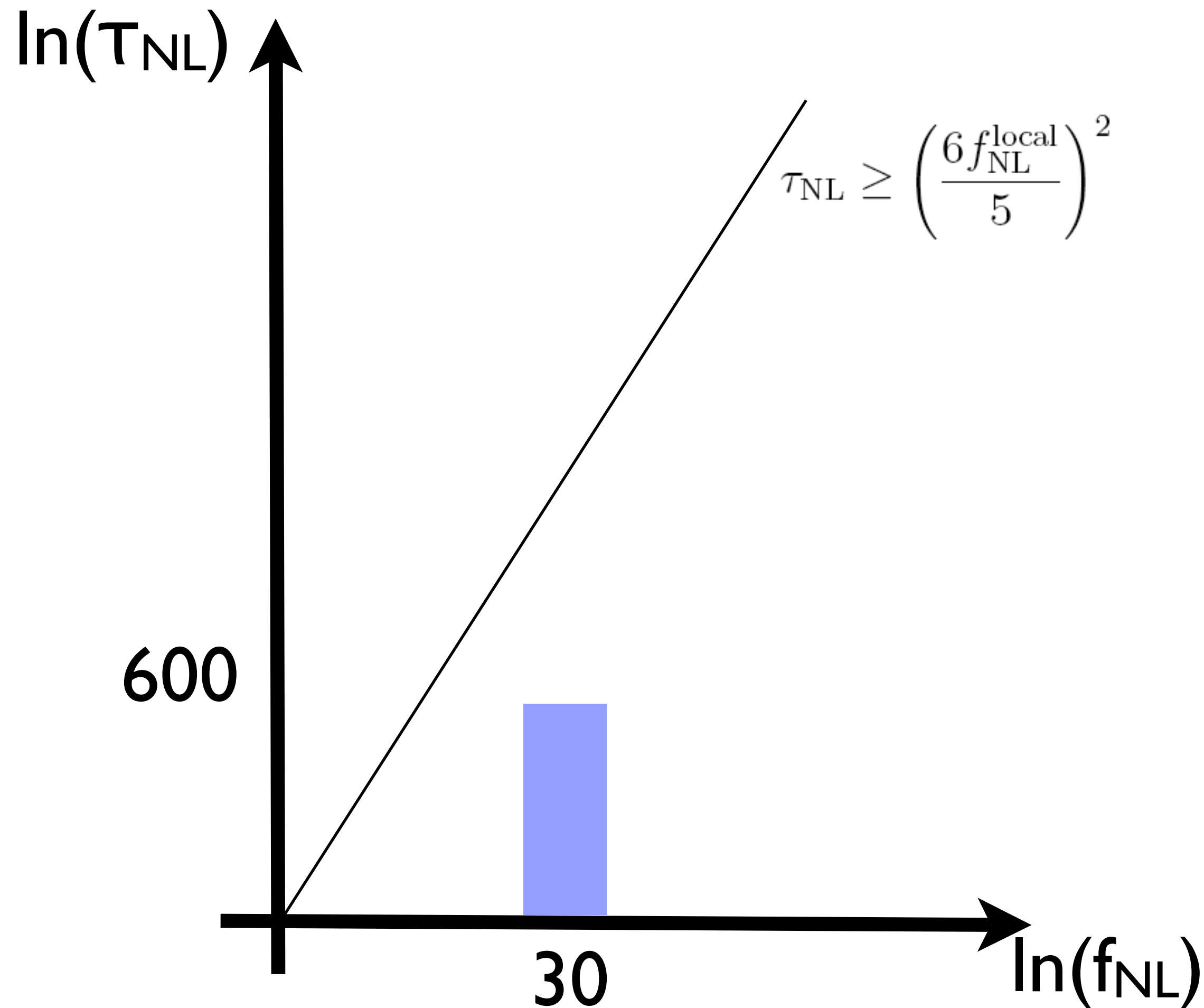


# Case B: Multi-field Happiness



- $f_{\text{NL}}$  is detected. Single-field is dead.
- But,  $\tau_{\text{NL}}$  is also detected, in accordance with the Suyama-Yamaguchi inequality, as expected from most (if not all - left unproven) of multi-field models.

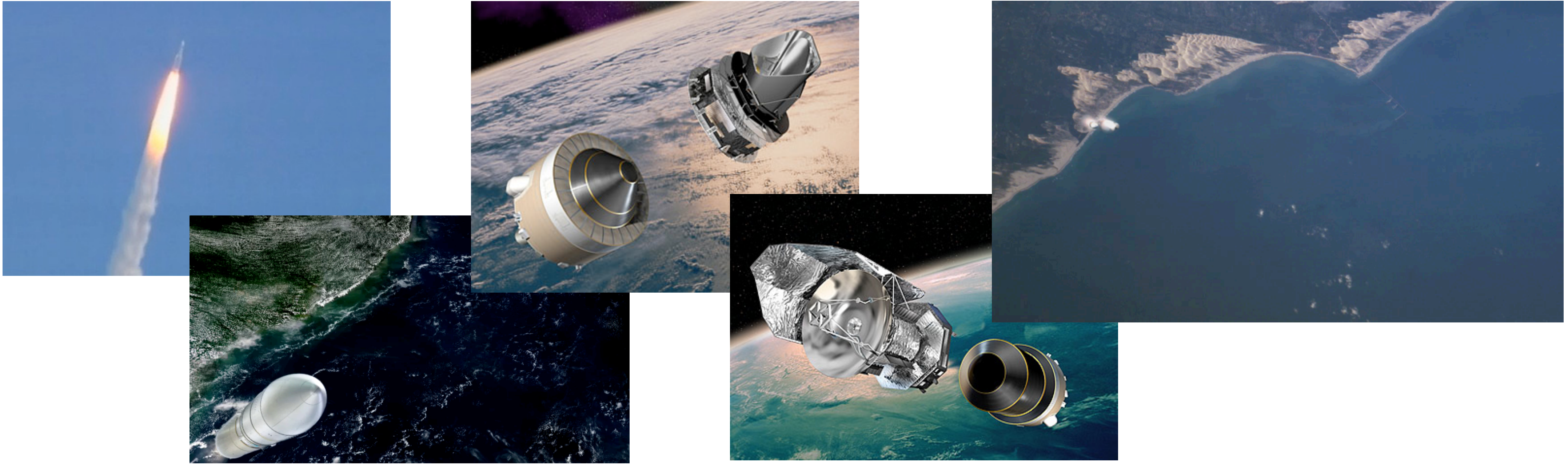
# Case C: Madness



- $f_{\text{NL}}$  is detected. Single-field is dead.
- But,  $\tau_{\text{NL}}$  is **not** detected, inconsistent with the Suyama-Yamaguchi inequality.
- (With the caveat that this may not be completely general) BOTH the single-field and multi-field are gone.



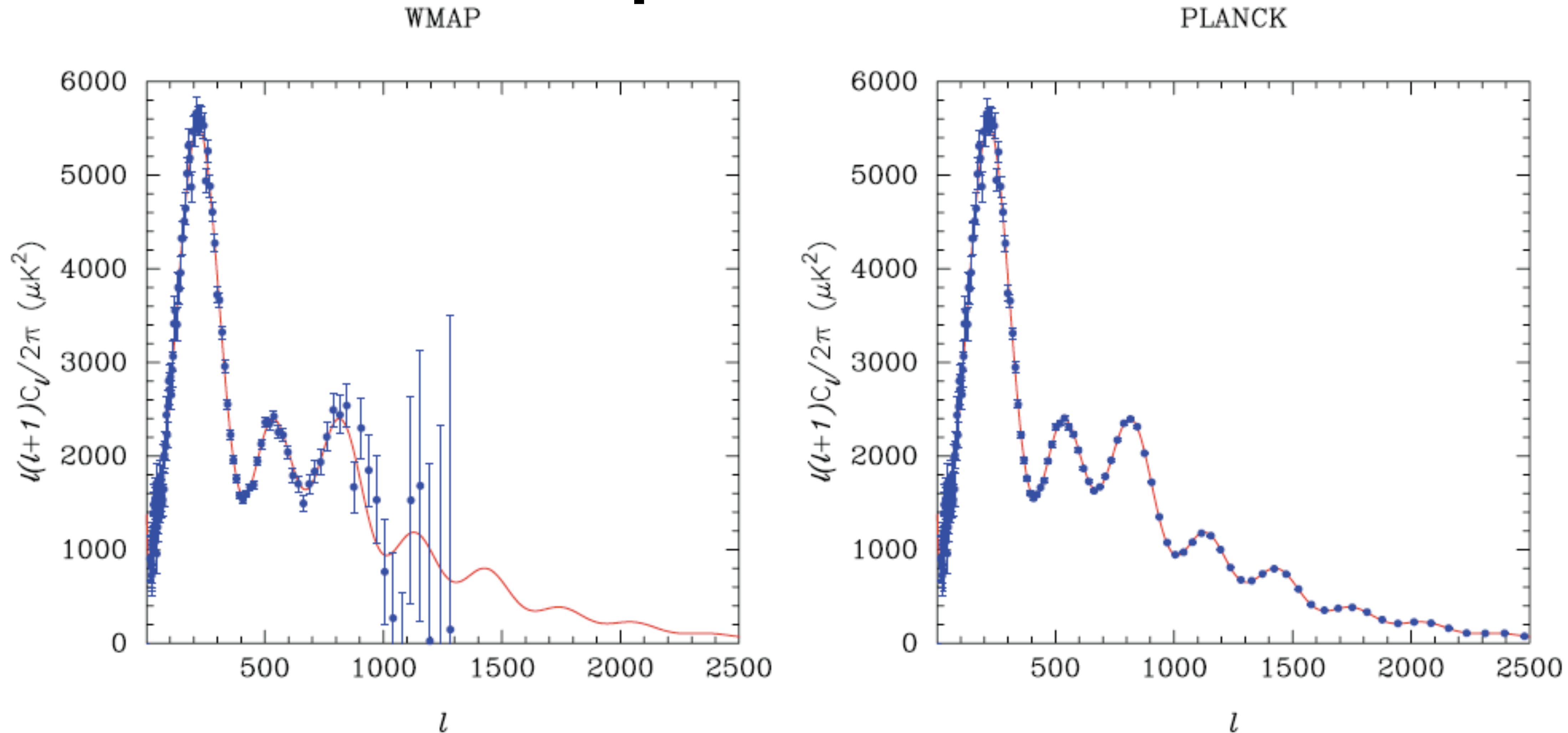
# Planck Launched!



- The Planck satellite was successfully launched from French Guiana on May 14, 2009.
- Separation from the Herschel satellite was also successful.
- Planck has mapped the full sky already - results expected to be released in December, 2012.

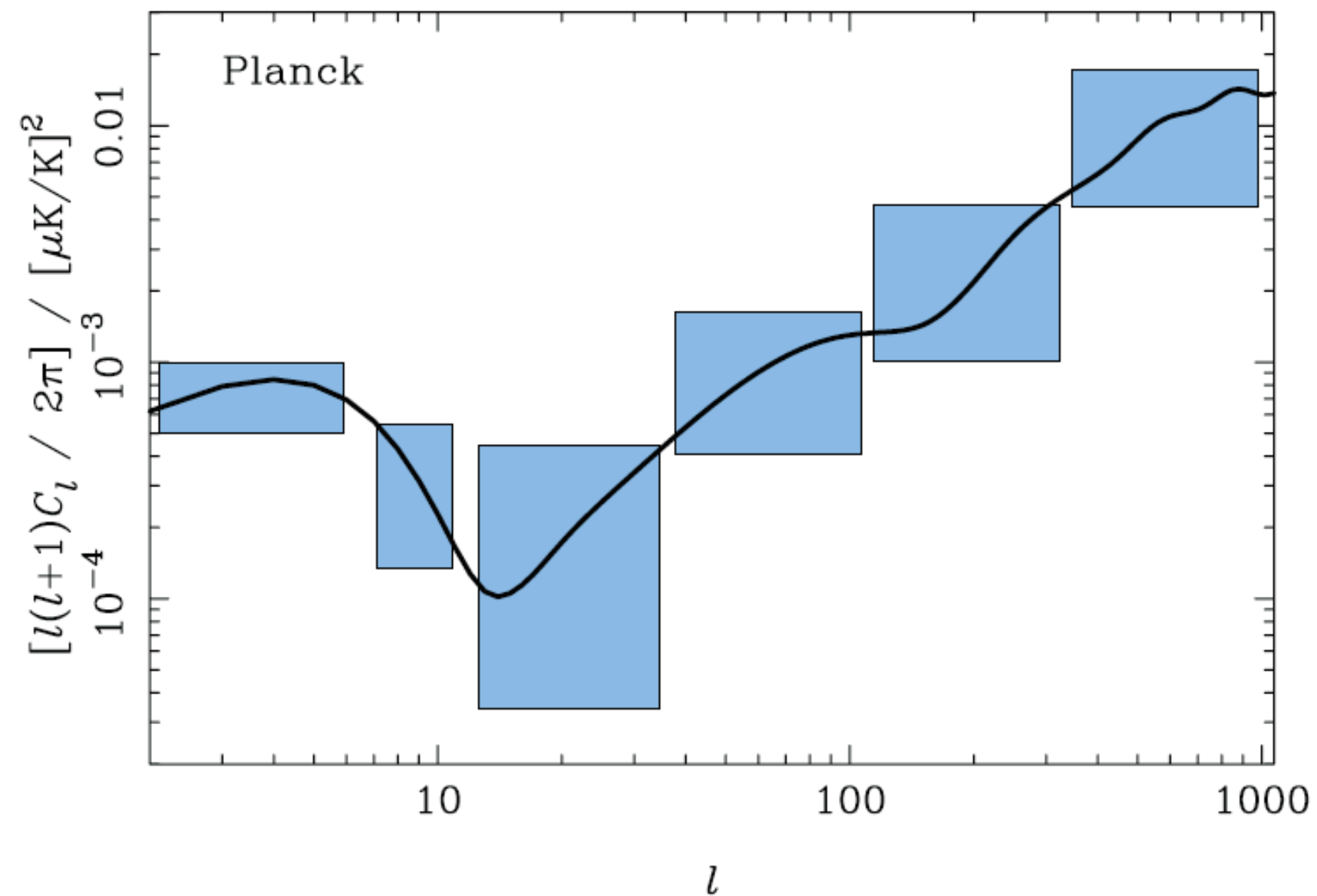
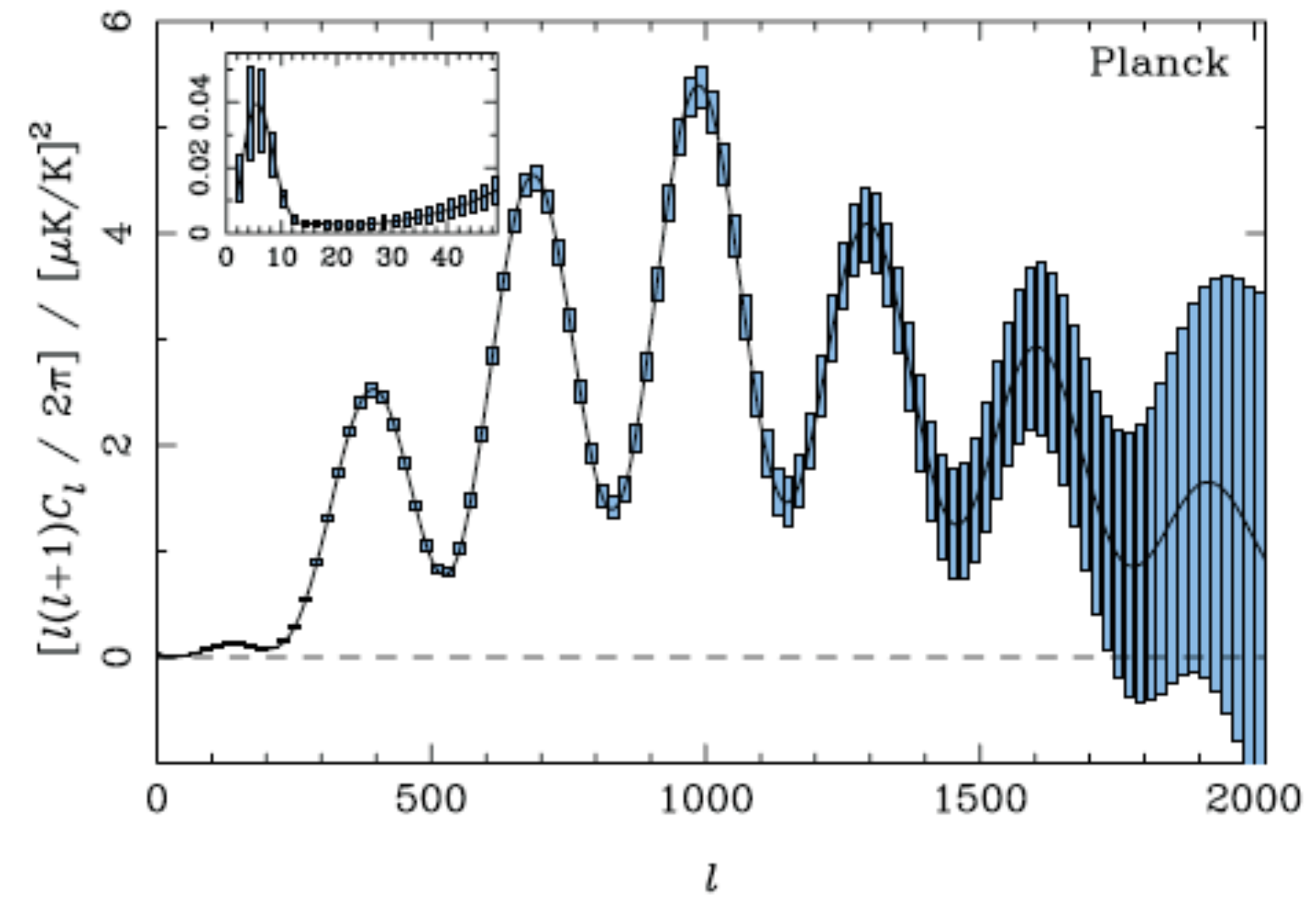
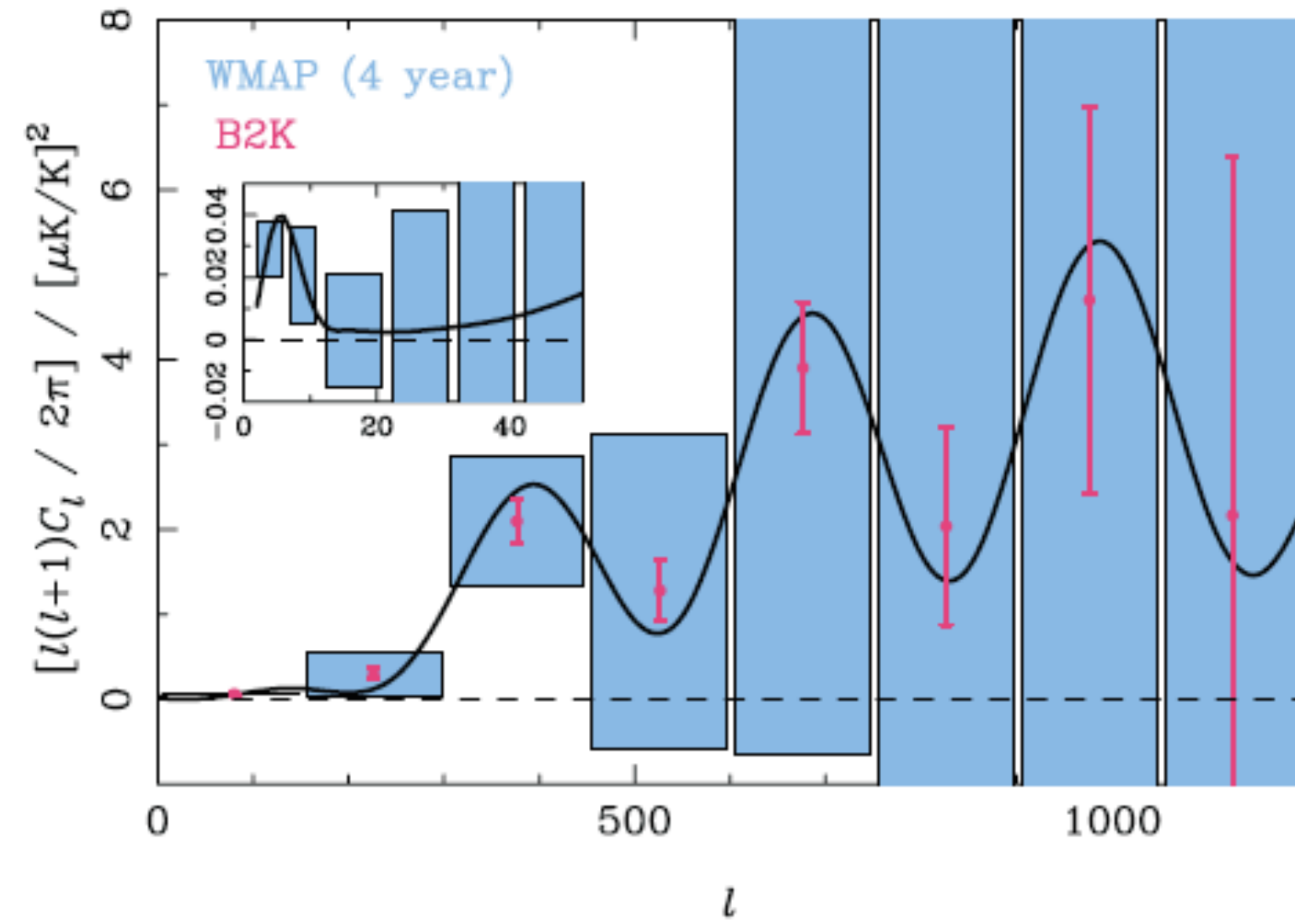


# Planck: Expected $C_l$ Temperature



- WMAP:  $l \sim 1000 \Rightarrow$  Planck:  $l \sim 3000$

# Planck: Expected $C_l$ Polarization



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

# E-mode

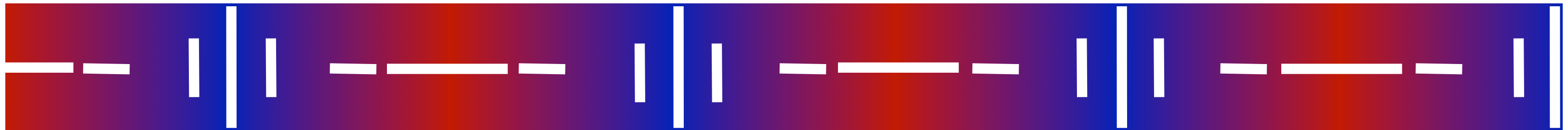
Potential



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

→  
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

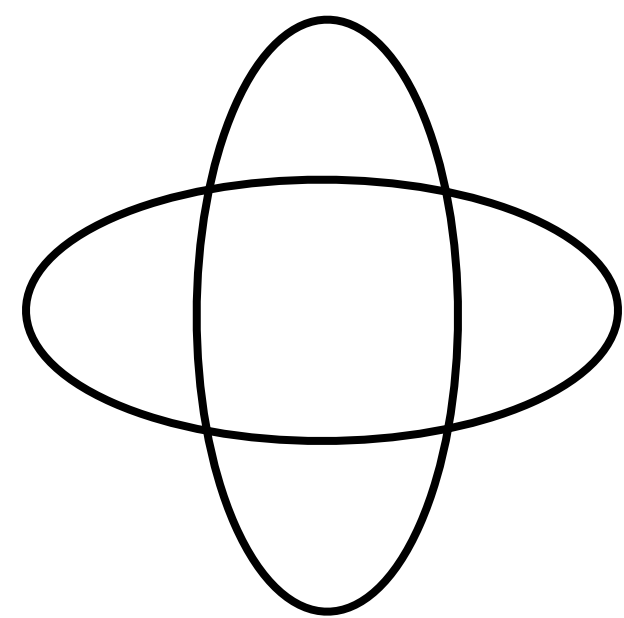
Polarization  
Direction



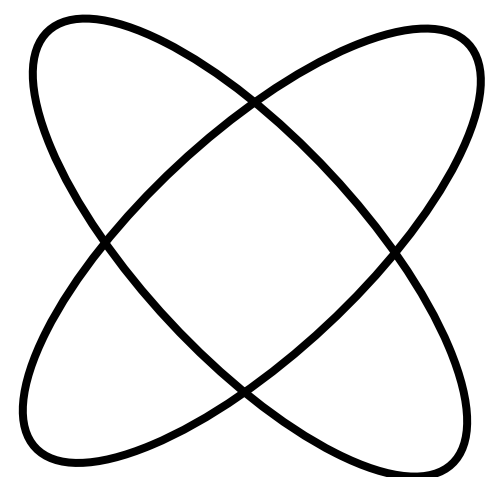
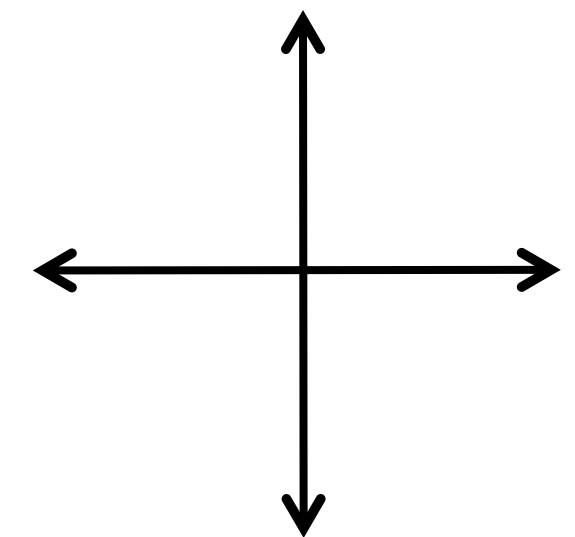
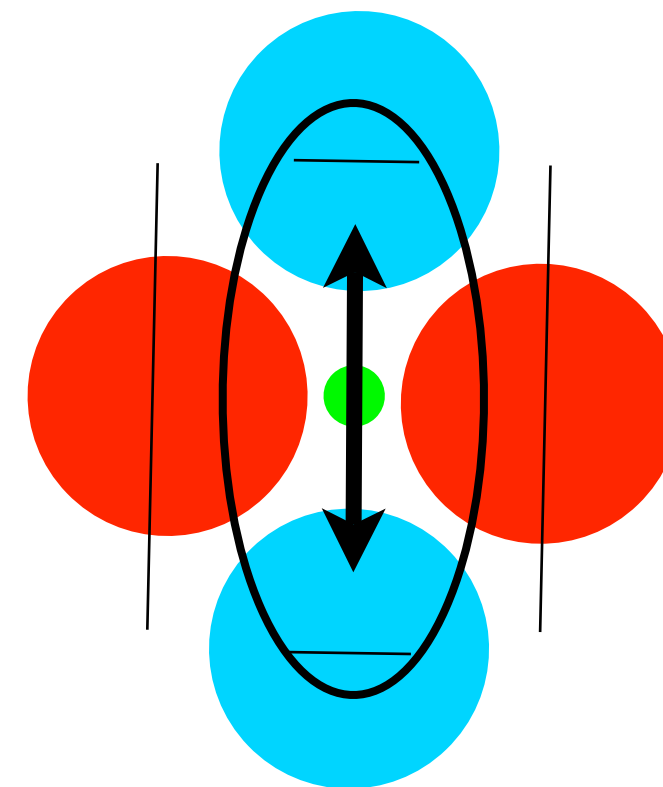
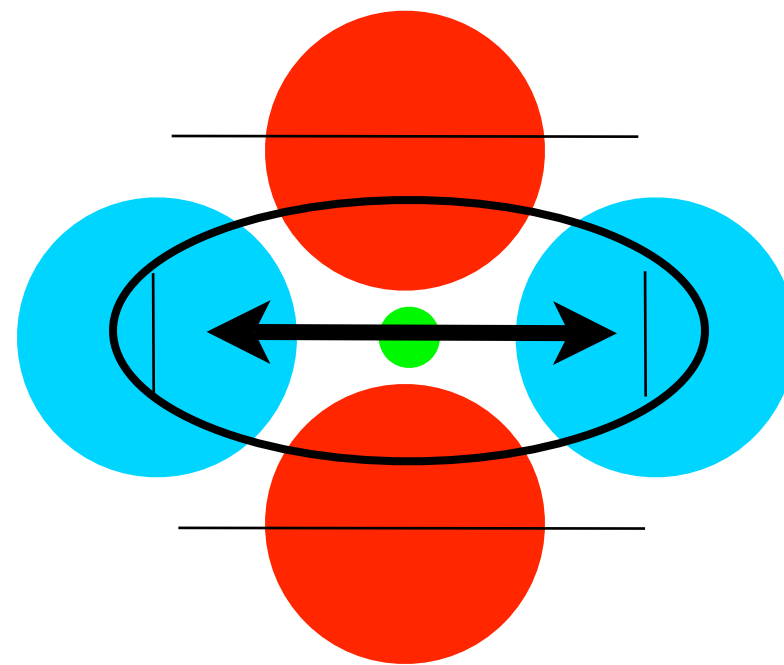
- **B-mode**: the polarization directions are tilted by 45 degrees relative to the direction of the plane wave perturbation.

# Gravitational Waves and Quadrupole

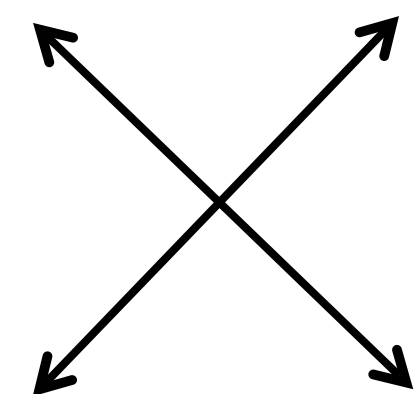
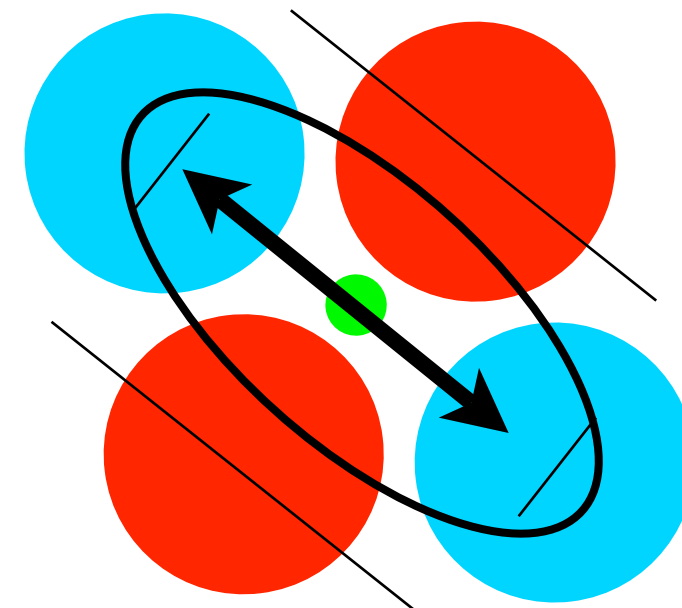
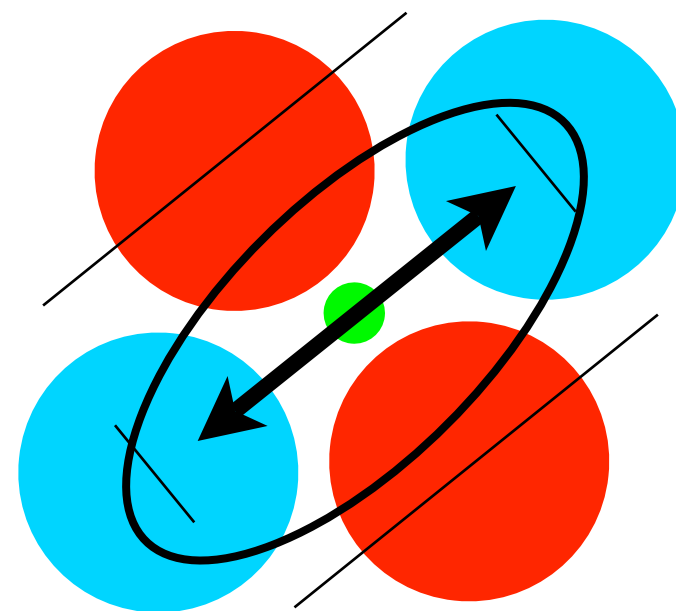
- Gravitational waves stretch space with a quadrupole pattern.



“+ mode”



“X mode”



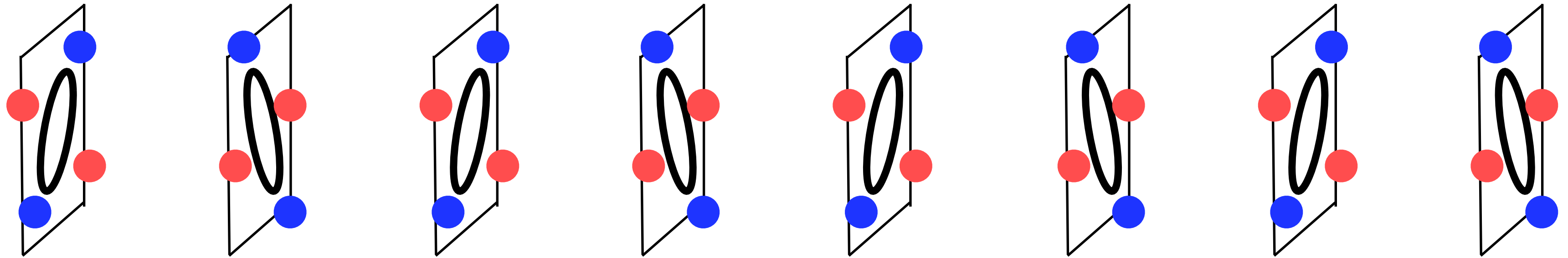
# Quadrupole from G.W.

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

Direction of the plane wave of G.W.



$h_x$



temperature



polarization



**B-mode**

- B-mode polarization generated by  $h_x$



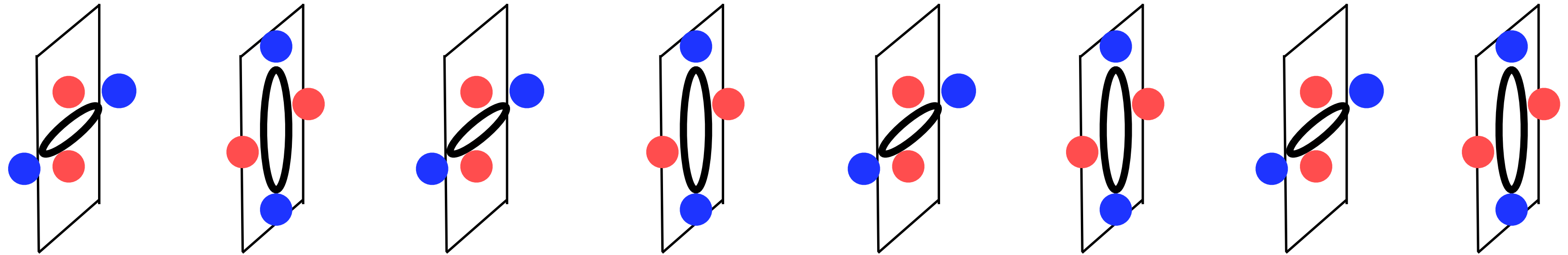
# Quadrupole from G.W.

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

Direction of the plane wave of G.W.



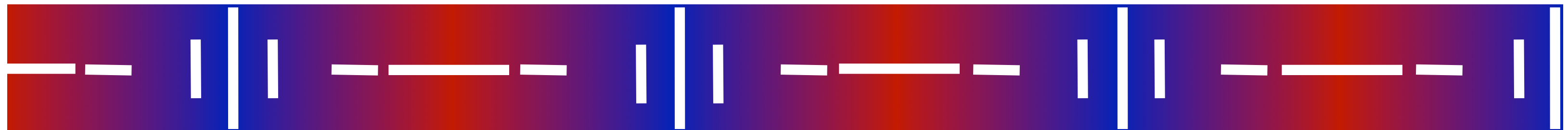
$h_+$



temperature



polarization



E-mode

- E-mode polarization generated by  $h_+$