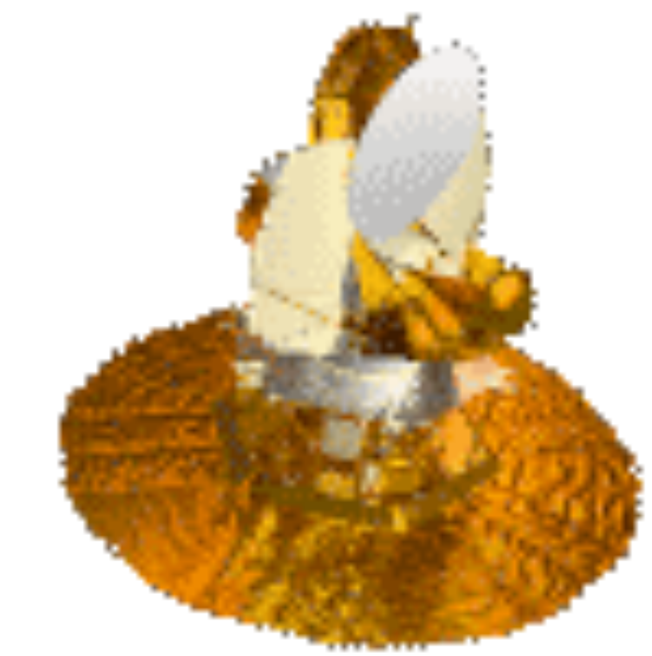


# Critical Tests of Theory of the Early Universe Using the Cosmic Microwave Background

**Eiichiro Komatsu** (Texas Cosmology Center, UT Austin)

Colloquium, TIFR, November 30, 2011

# 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)

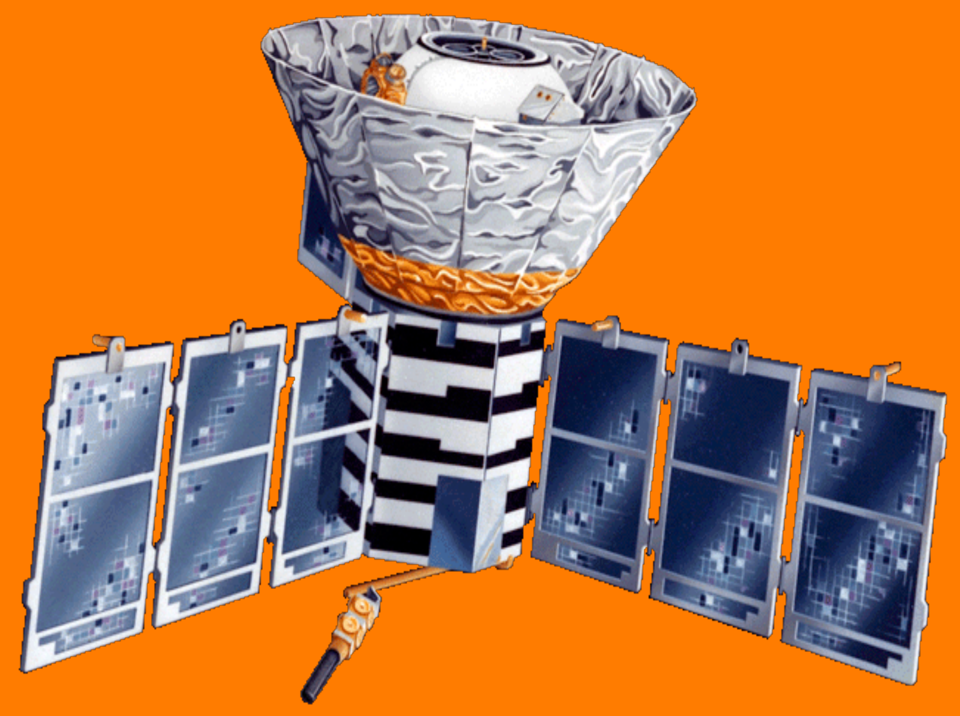
courtesy University of Arizona

# Night Sky in Microwave (~1mm)

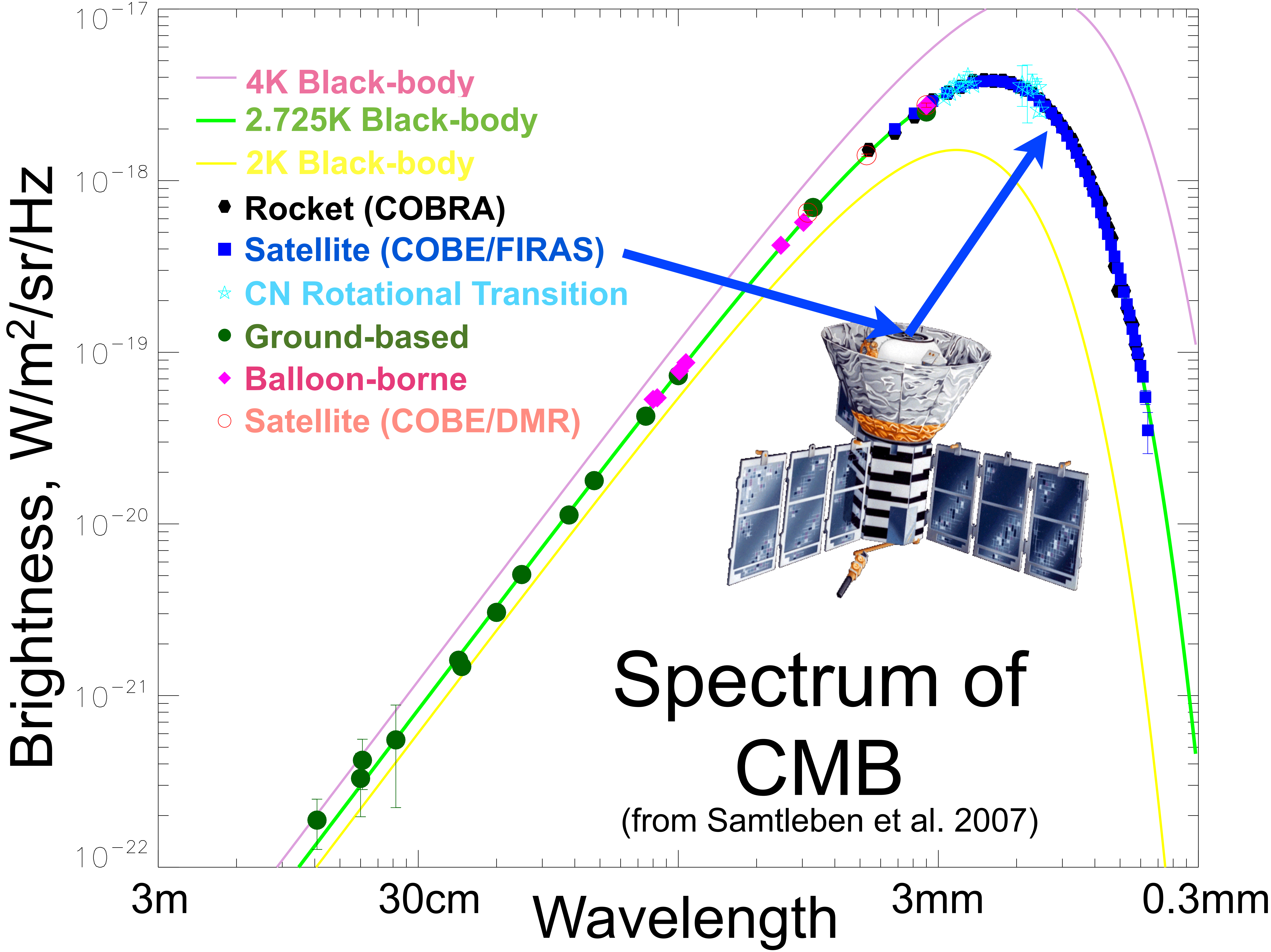
courtesy University of Arizona

# Night Sky in Microwave (~1mm)

$T_{today}$=2.725K



*COBE Satellite, 1989-1993*

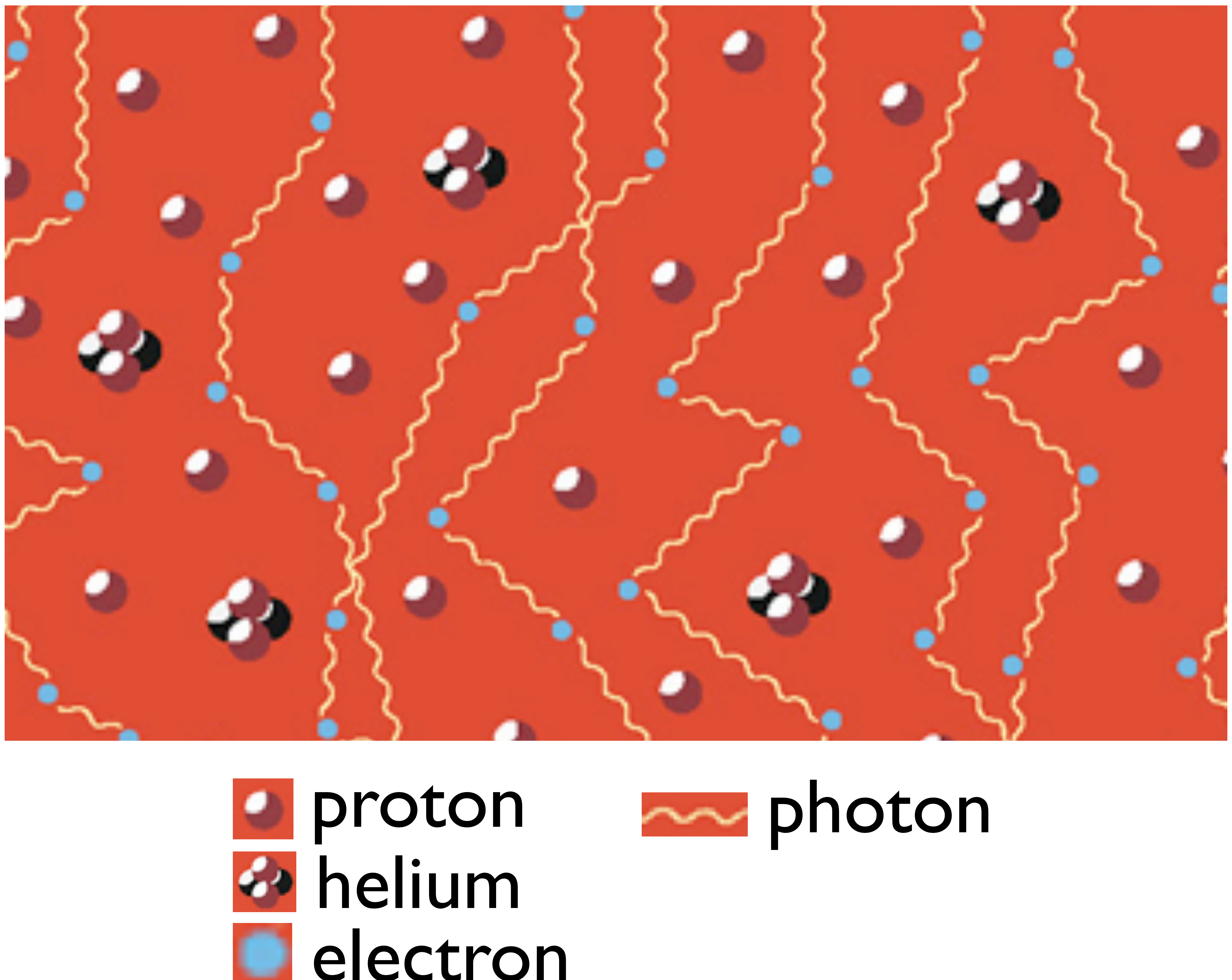


4K Black-body
2.725K Black-body
2K Black-body
Rocket (COBRA)
Satellite (COBE/FIRAS)
CN Rotational Transition
Ground-based
Balloon-borne
Satellite (COBE/DMR)
Spectrum of CMB
(from Samtleben et al. 2007)
Brightness, W/m²/sr/Hz
$10^{-17}$
$10^{-18}$
$10^{-19}$
$10^{-20}$
$10^{-21}$
$10^{-22}$
3m
30cm
3mm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

# How was CMB created?

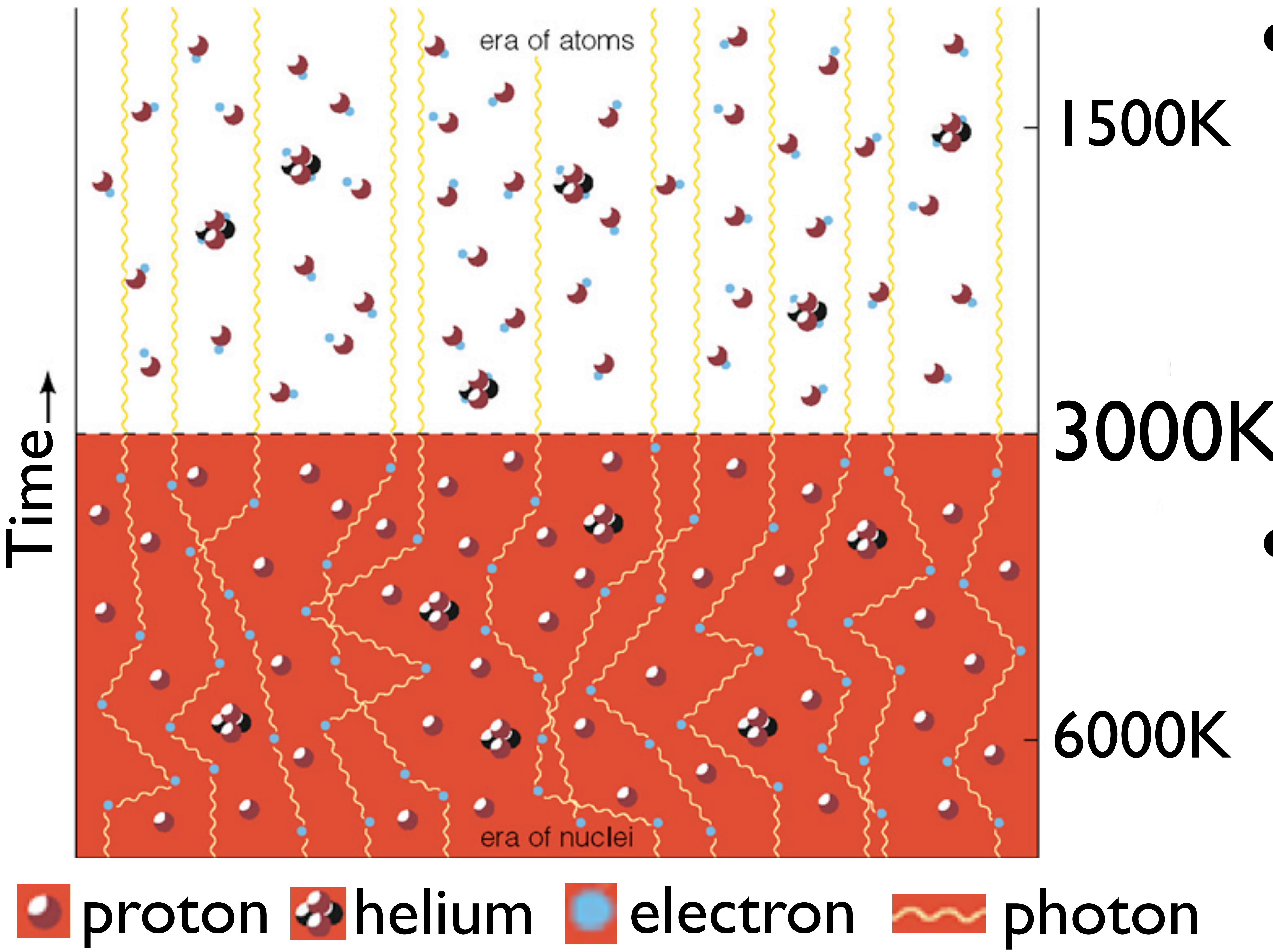
- When the Universe was hot, it was a hot soup made of:
  - Protons, electrons, and helium nuclei
  - Photons and neutrinos
  - Dark matter (DM)
    - DM does not do much, except for providing a a gravitational potential because $\rho_{DM}/\rho_{H,He}$~5)

# Universe as a hot soup

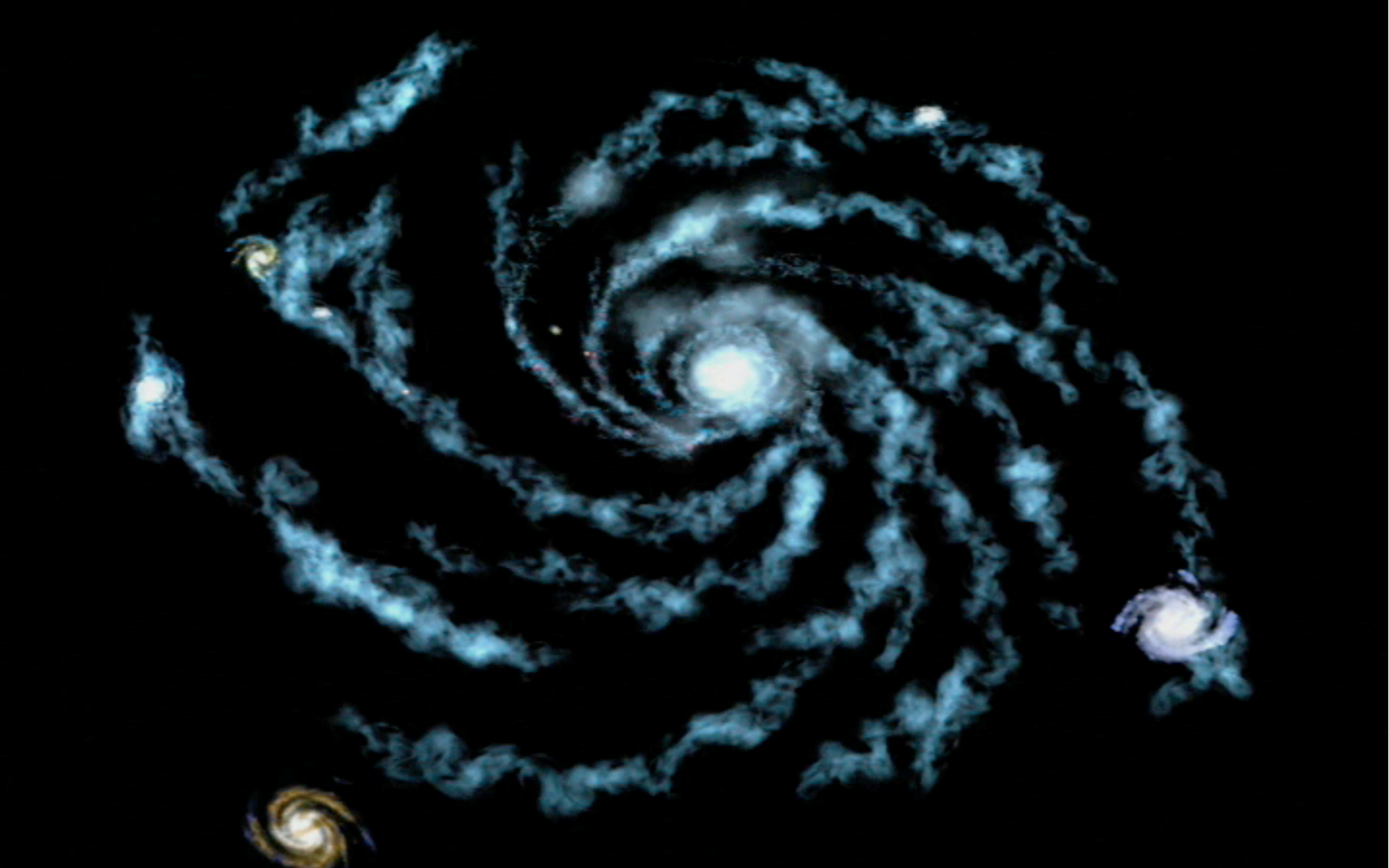



- Free electrons can scatter photons efficiently.
- Photons cannot go very far.

# Recombination and Decoupling

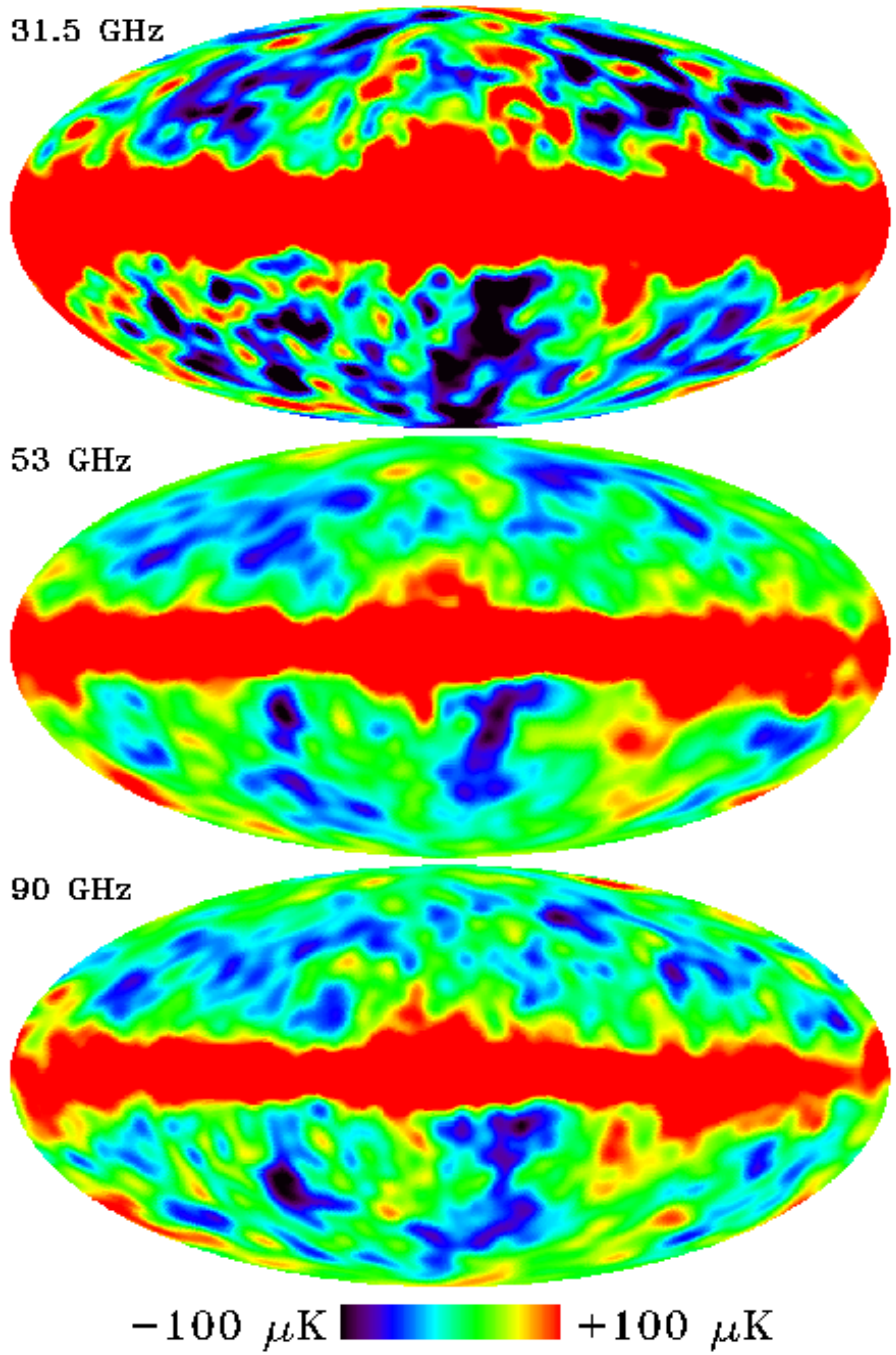



- [***recombination***] When the temperature falls below 3000 K, almost all electrons are captured by protons and helium nuclei.
- [***decoupling***] Photons are no longer scattered. I.e., photons and electrons are no longer coupled.



# COBE/DMR, 1992

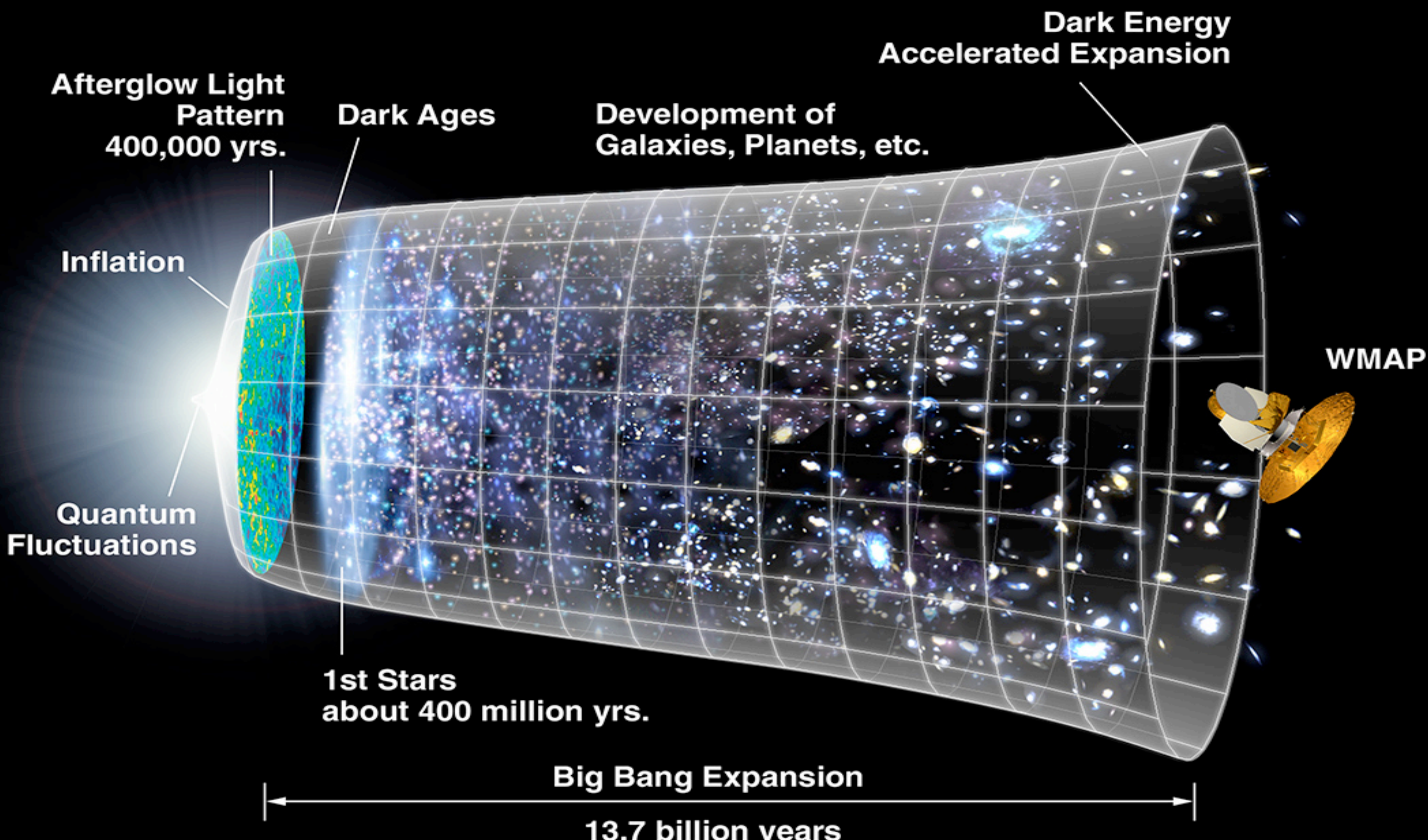
*Smoot et al. (1992)*




•**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

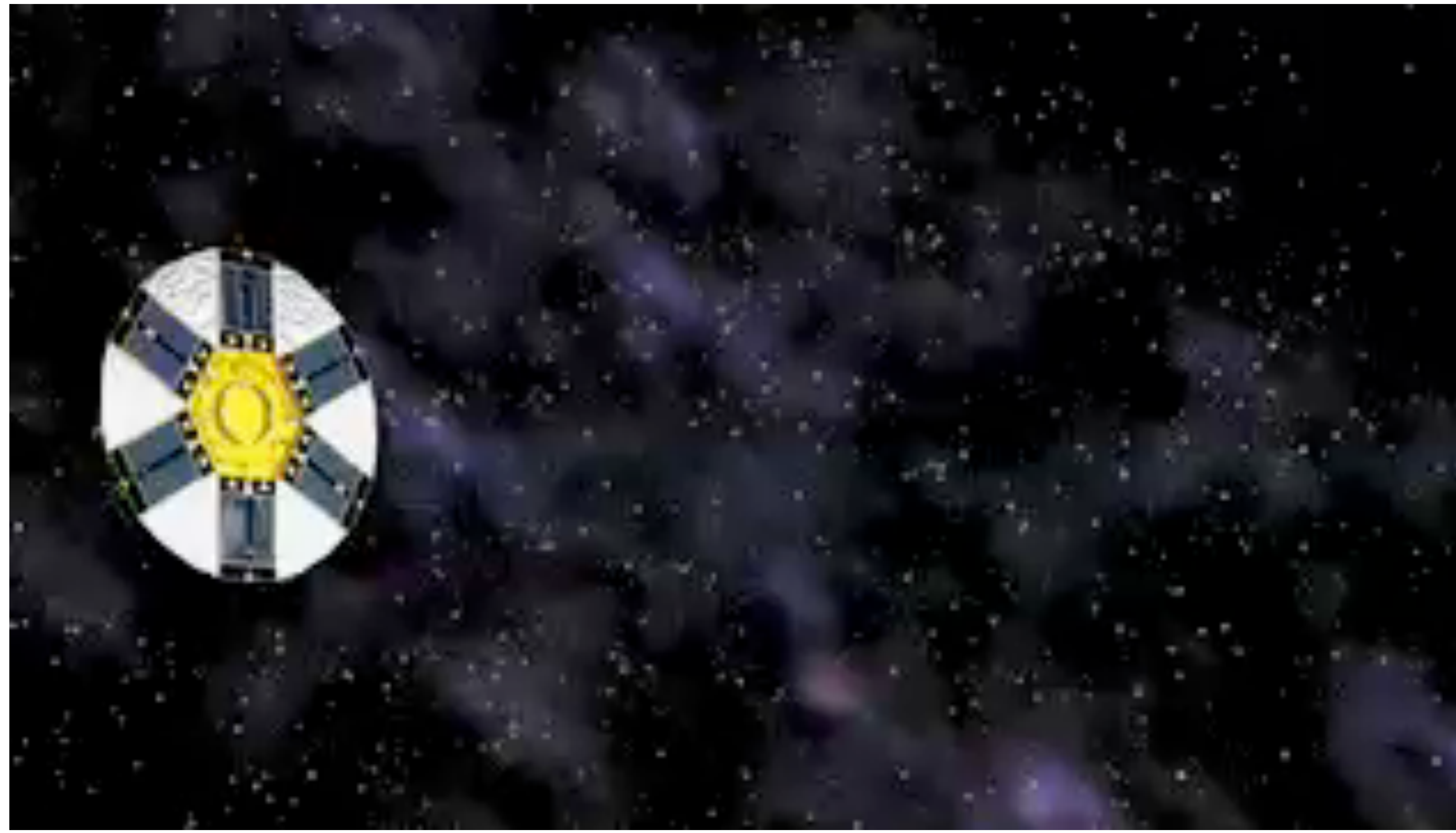
June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release

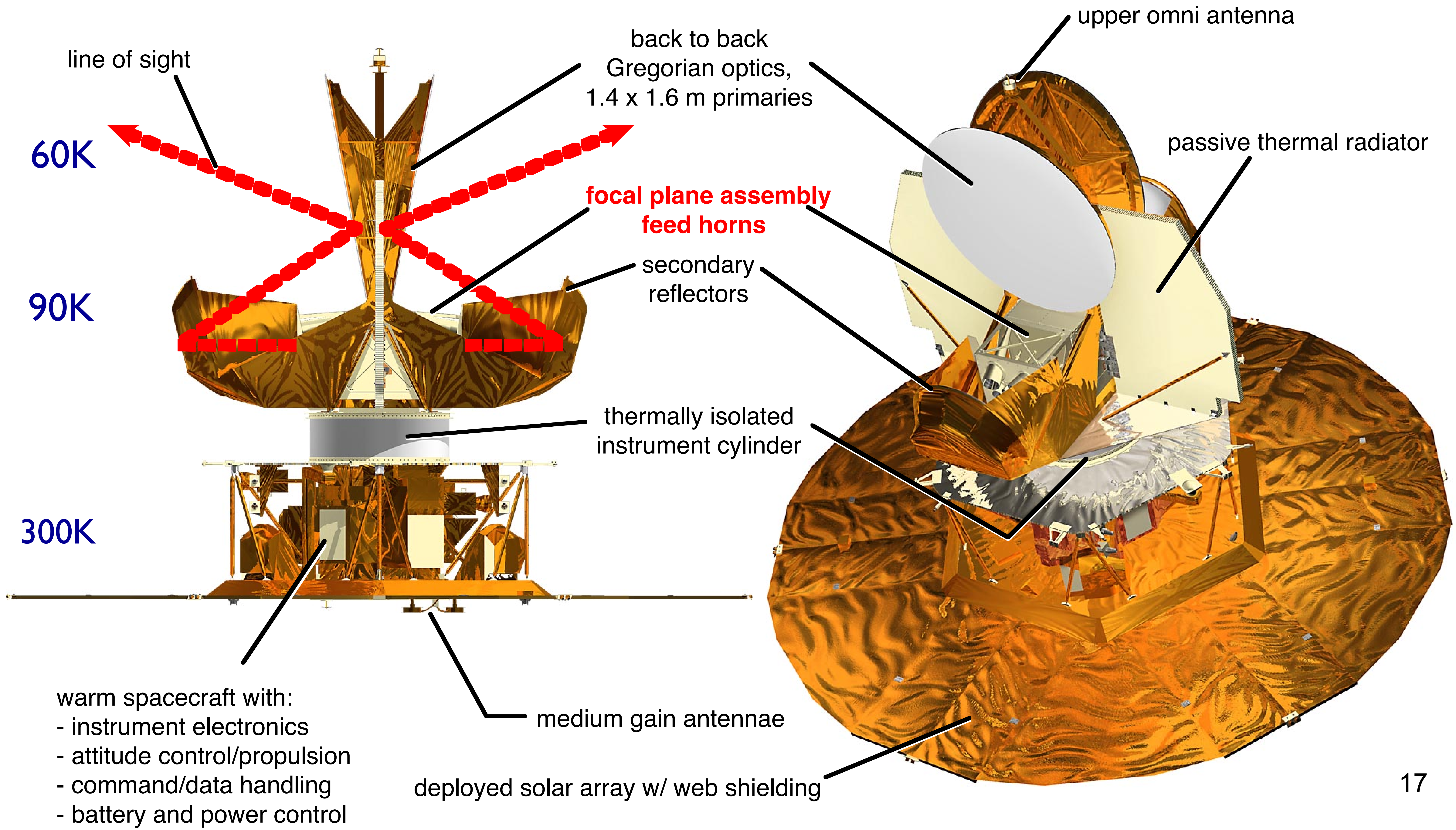
**January 2010:
The seven-year data release**



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

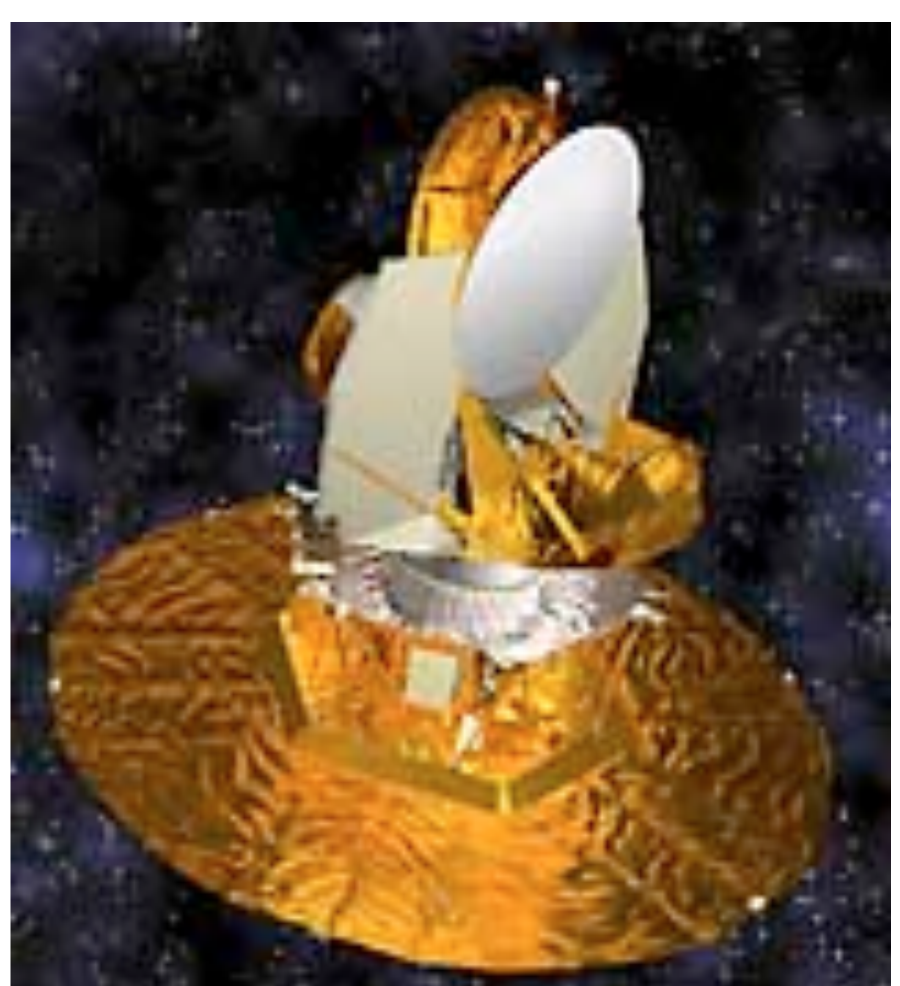
# *WMAP* Spacecraft

## Radiative Cooling: No Cryogenic System

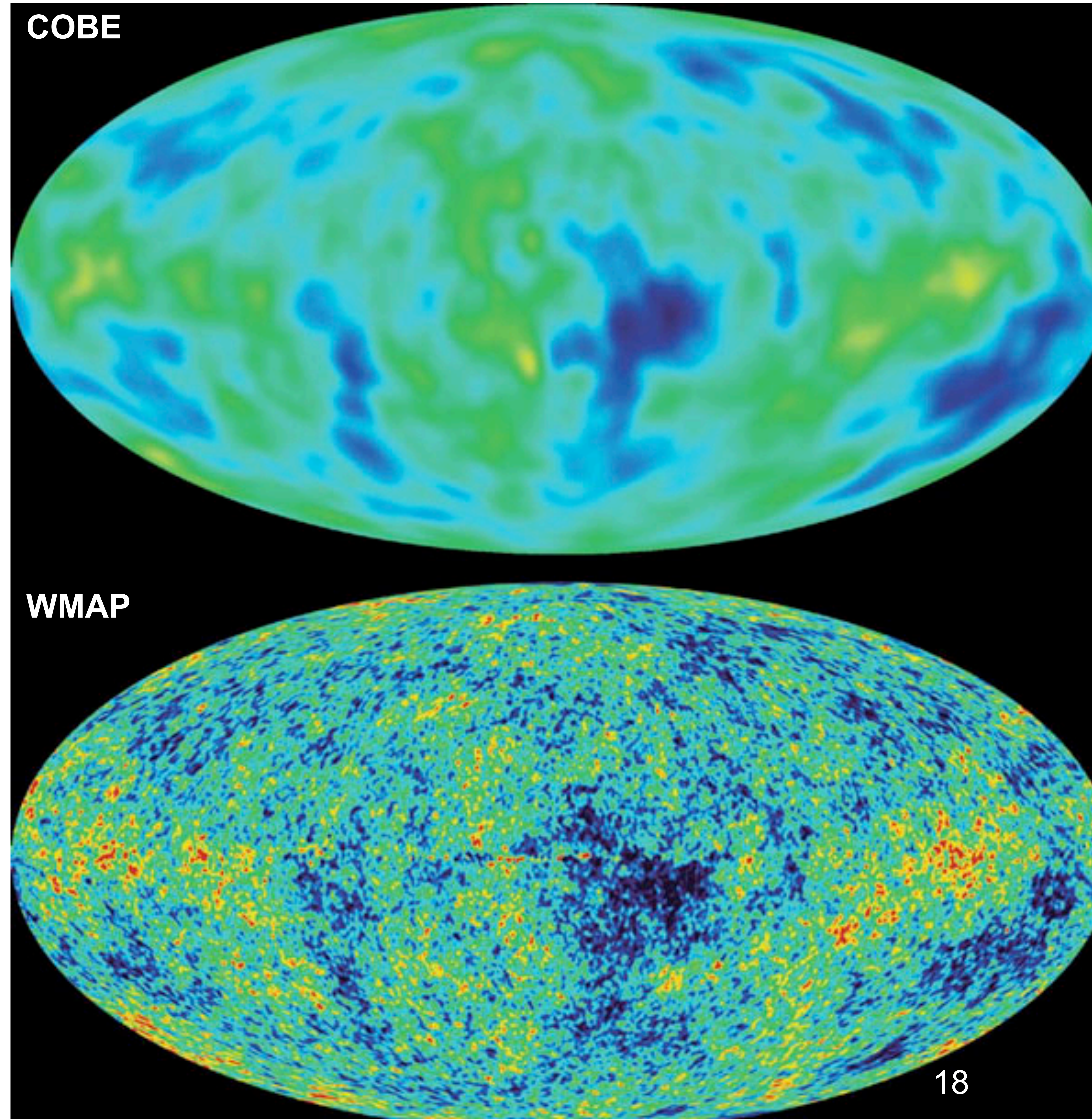


# COBE to WMAP (x35 better resolution)

COBE
1989



WMAP
2001



# WMAP 7-Year Science Team

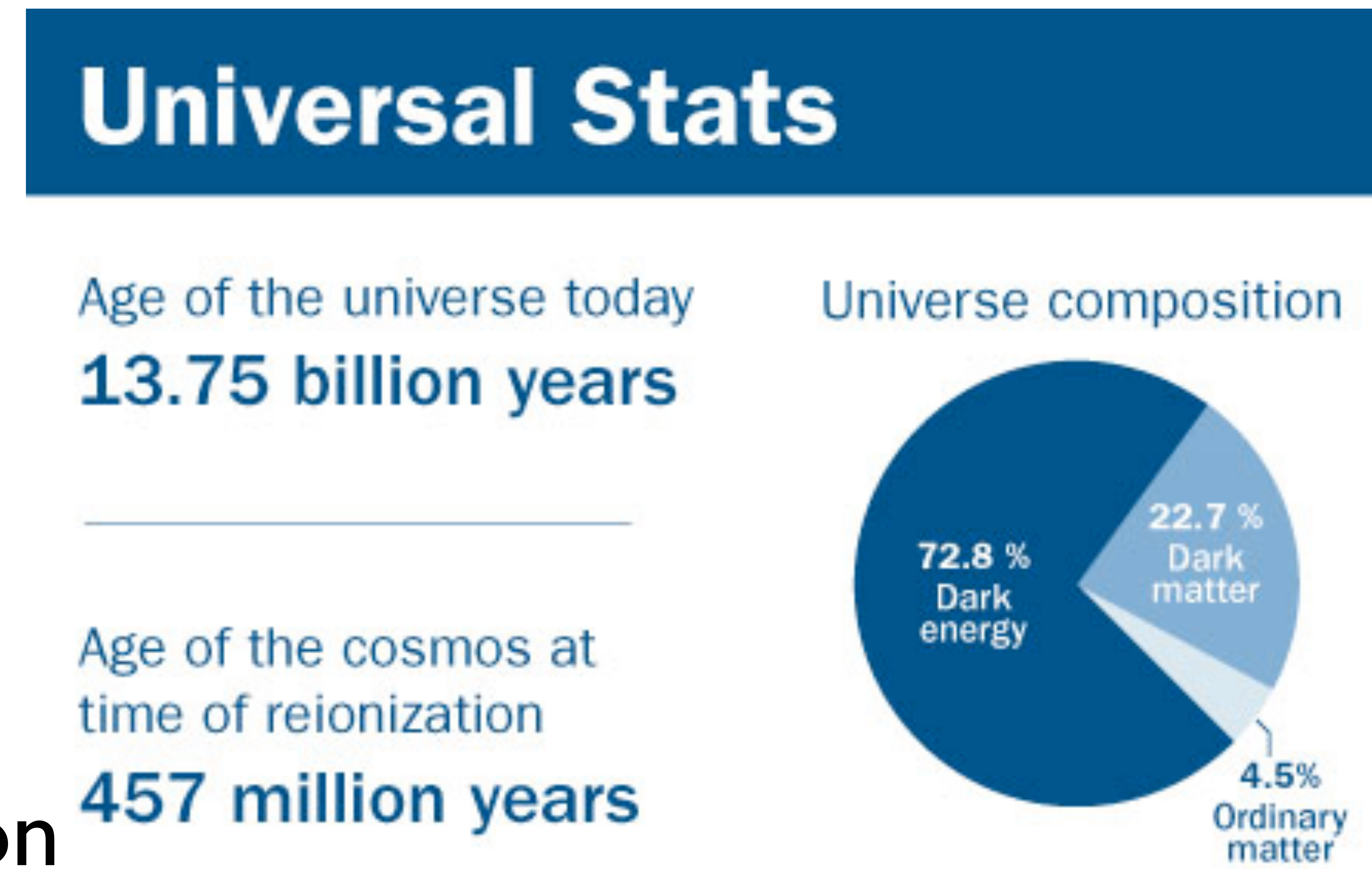
- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright
- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta
- K.M. Smith
- C. Barnes
- R.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

# WMAP 7-Year Papers

- **Jarosik et al.**, "*Sky Maps, Systematic Errors, and Basic Results*" 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)

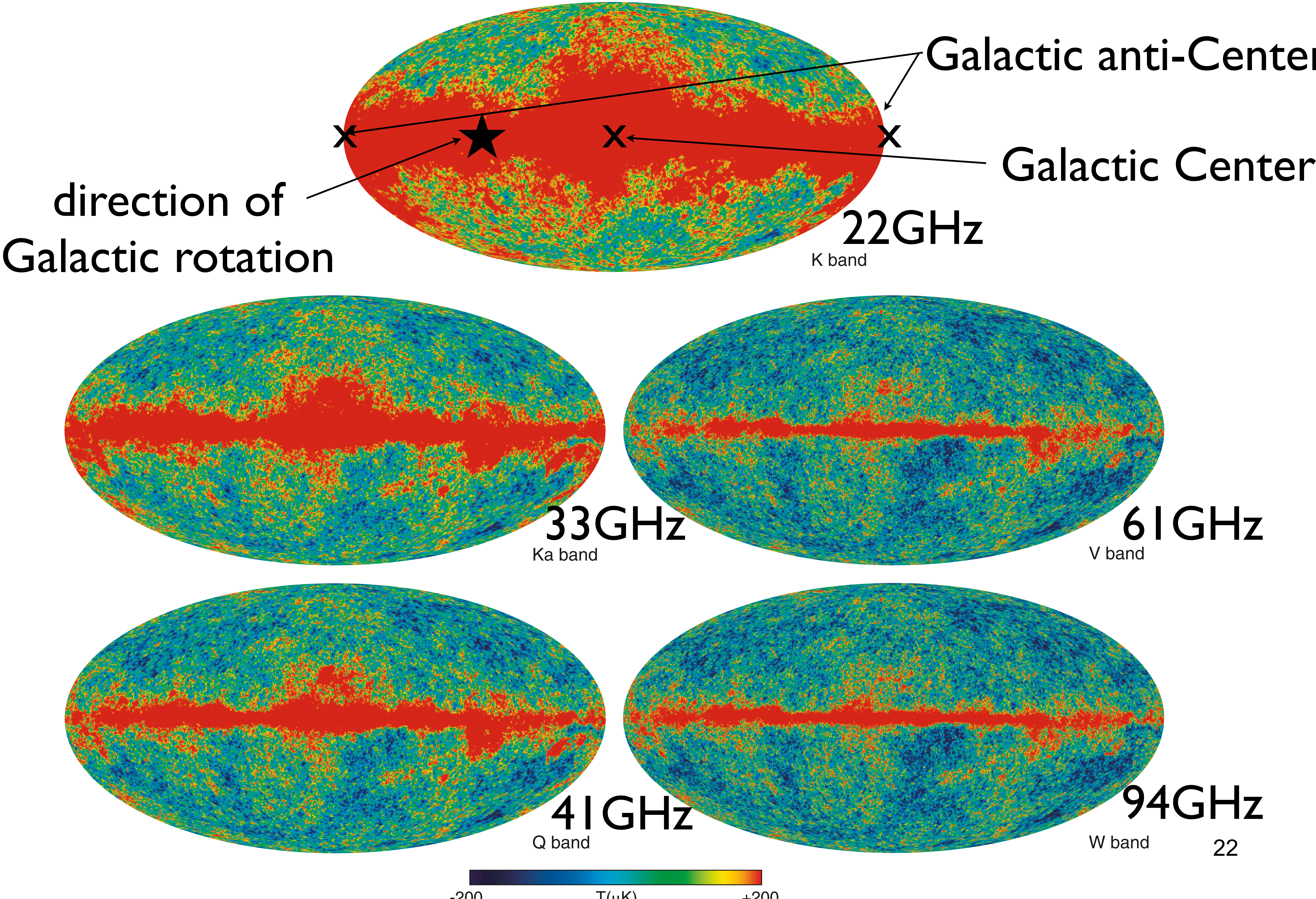
# Cosmic Pie Chart: 7-year

- **Standard Model**
  - H&He = **4.58**% (±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)

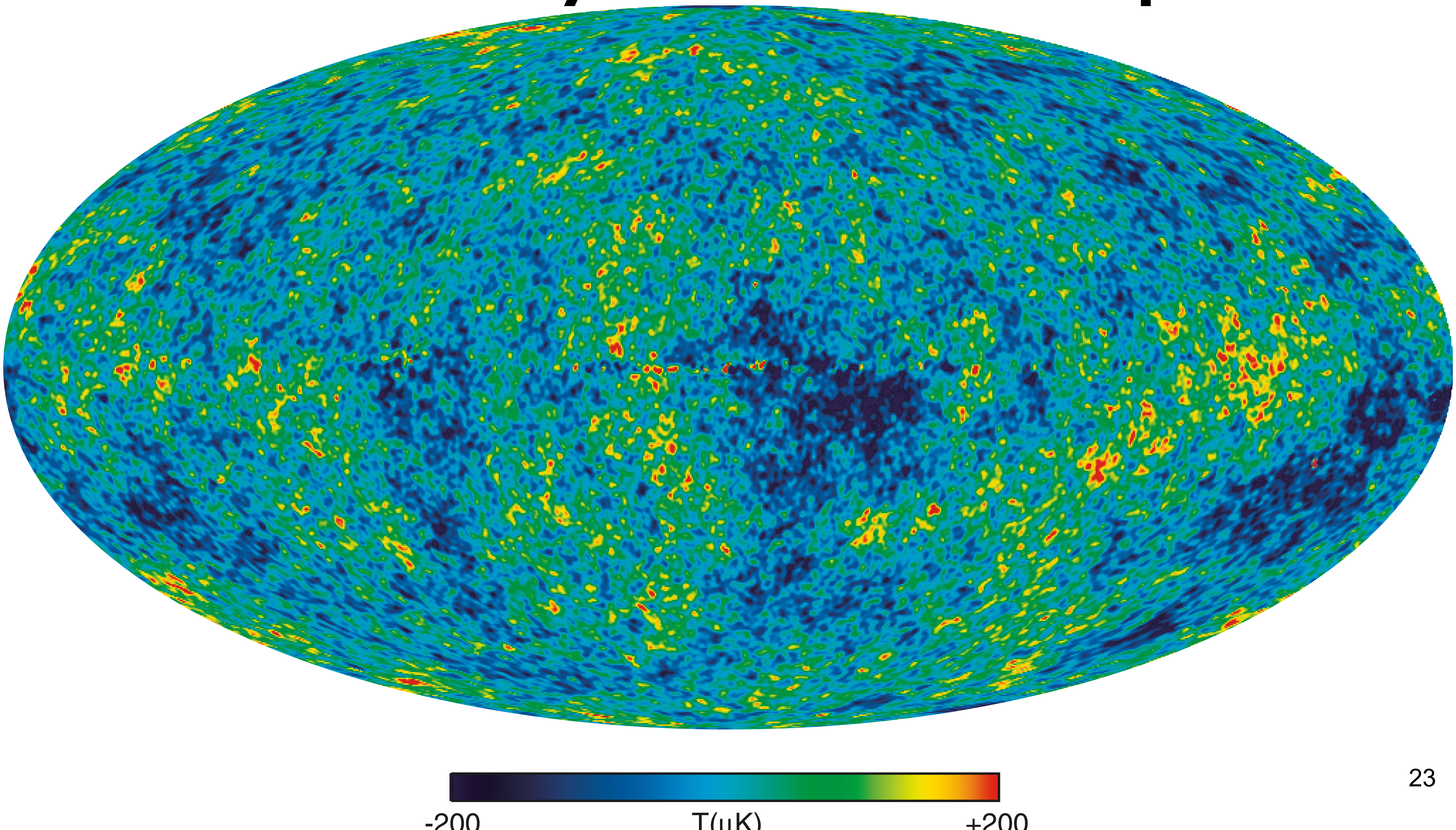


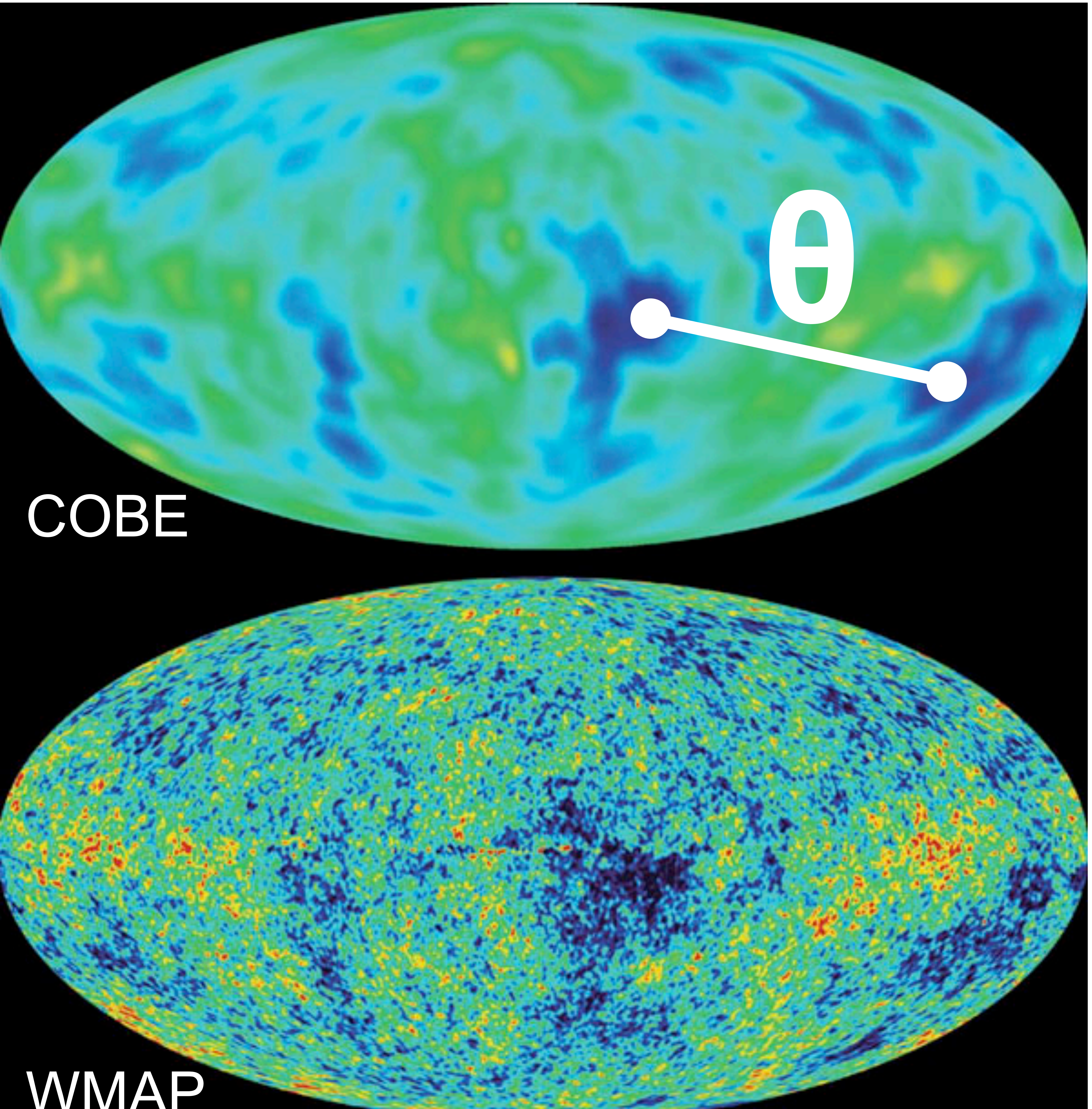

*"ScienceNews" article on the WMAP 7-year results*

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


Galactic anti-Center
Galactic Center
direction of
Galactic rotation
22GHz
K band
33GHz
Ka band
61GHz
V band
41GHz
Q band
94GHz
W band
-200
T(μK)
+200

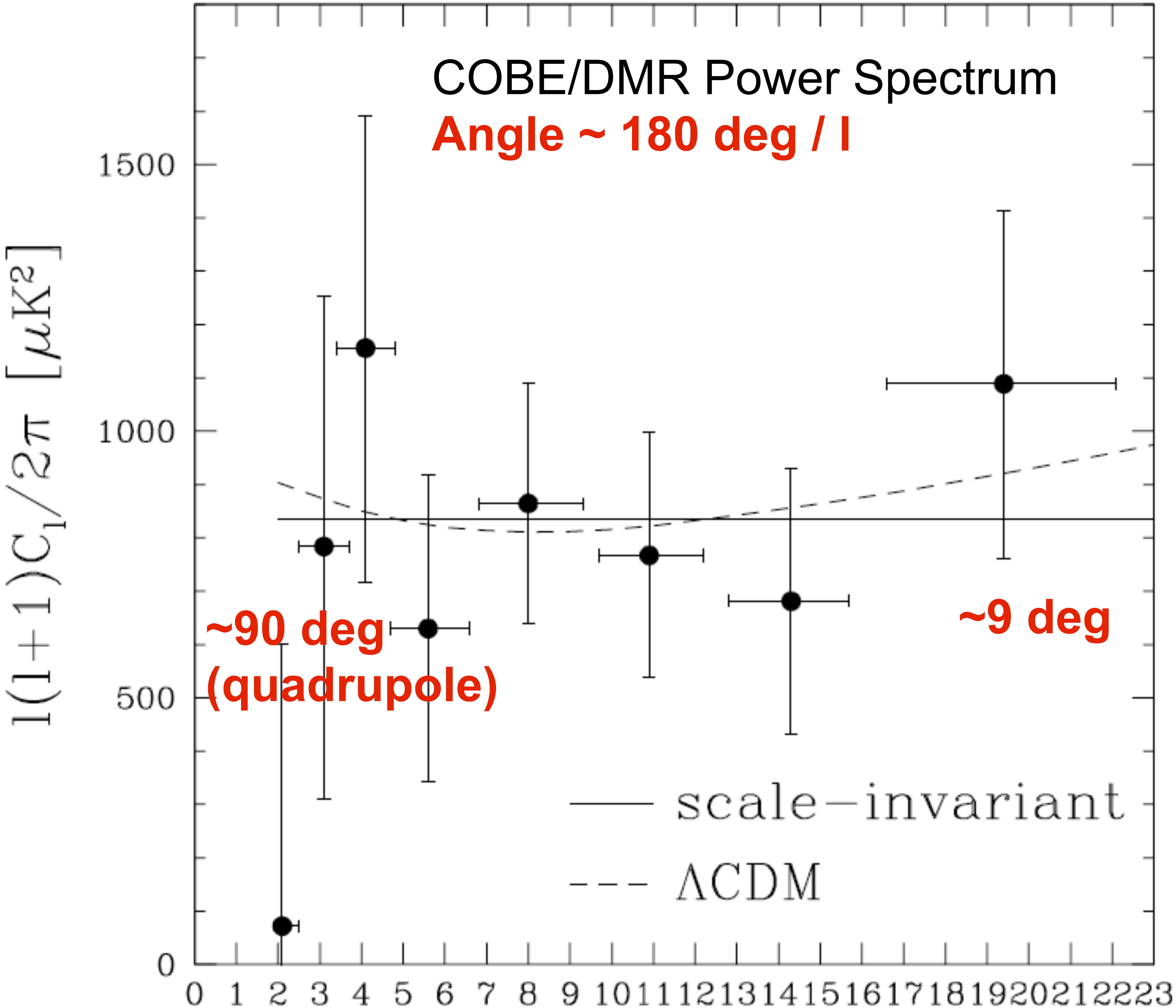
# Galaxy-cleaned Map



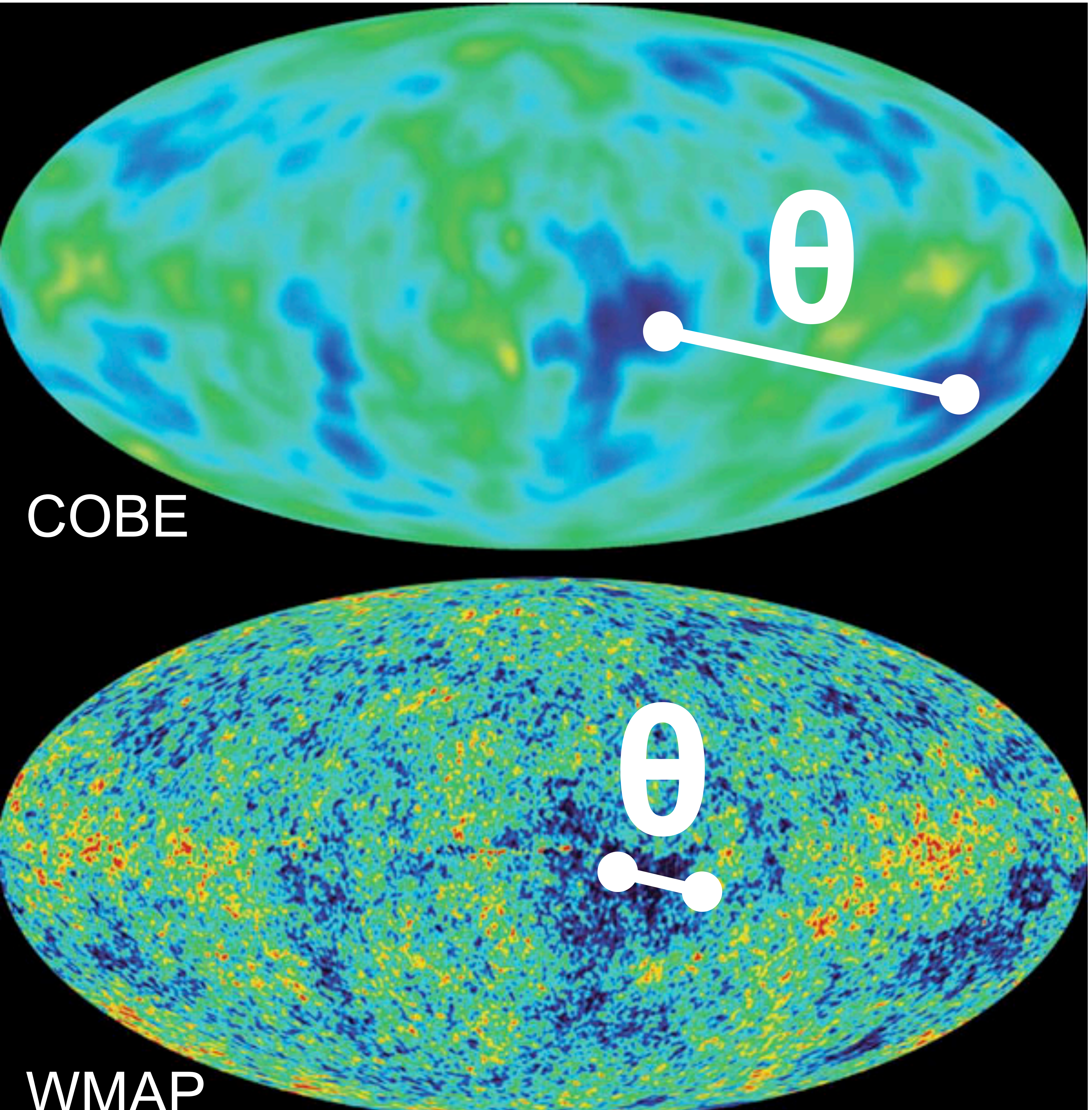



# Analysis:
# 2-point Correlation

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



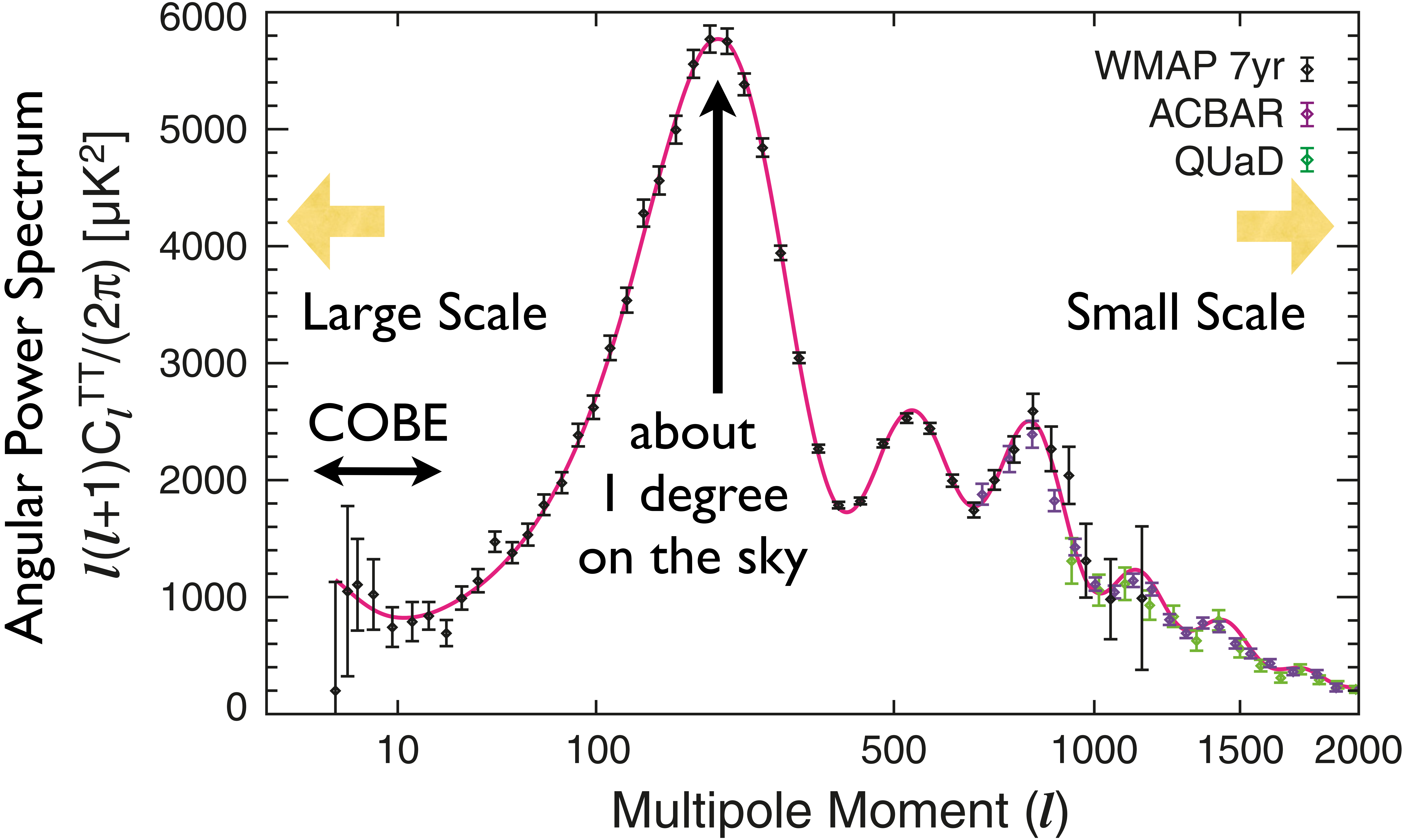

Angular Wavenumber, l



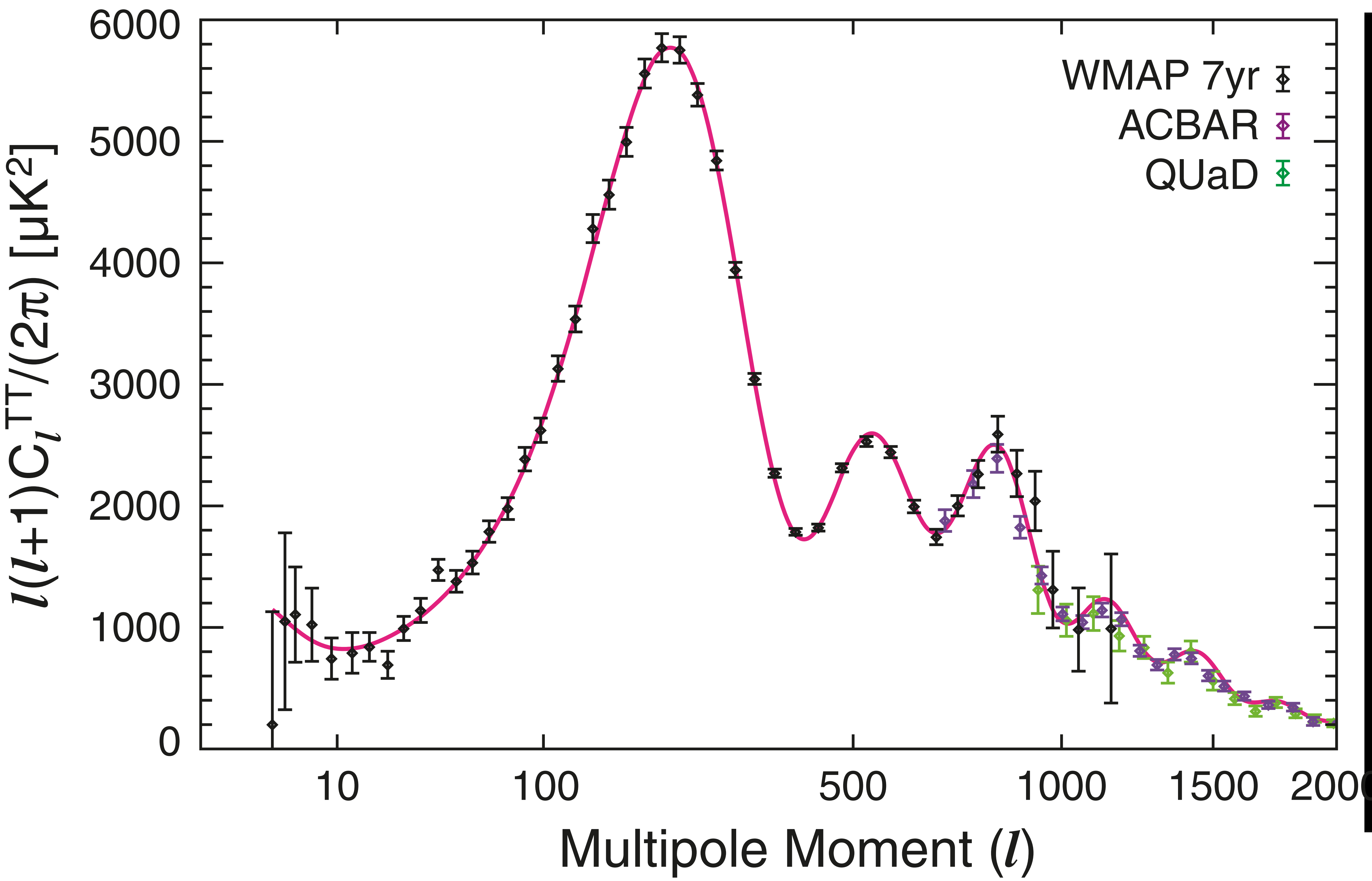

# COBE To WMAP

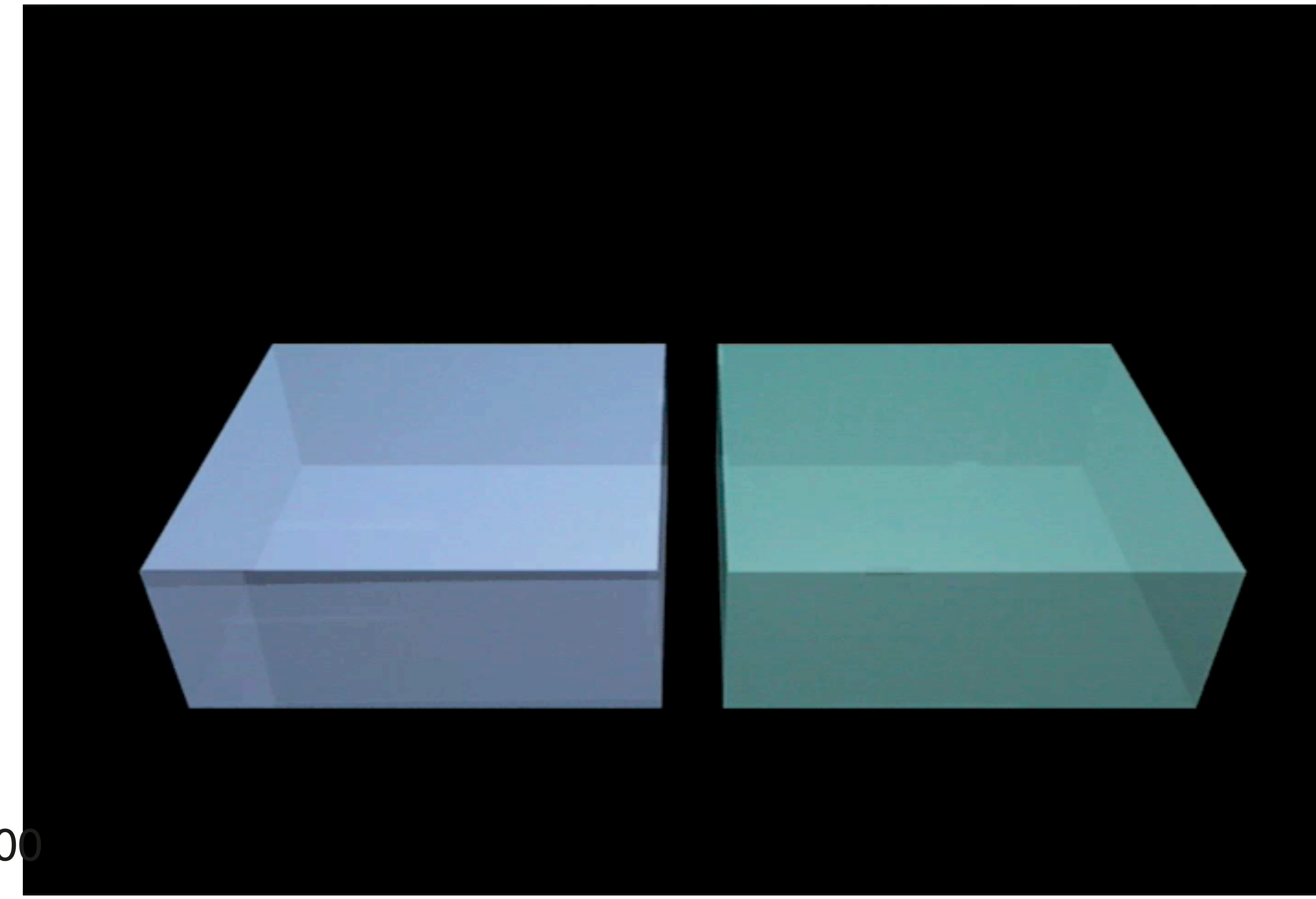
- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

# WMAP Power Spectrum



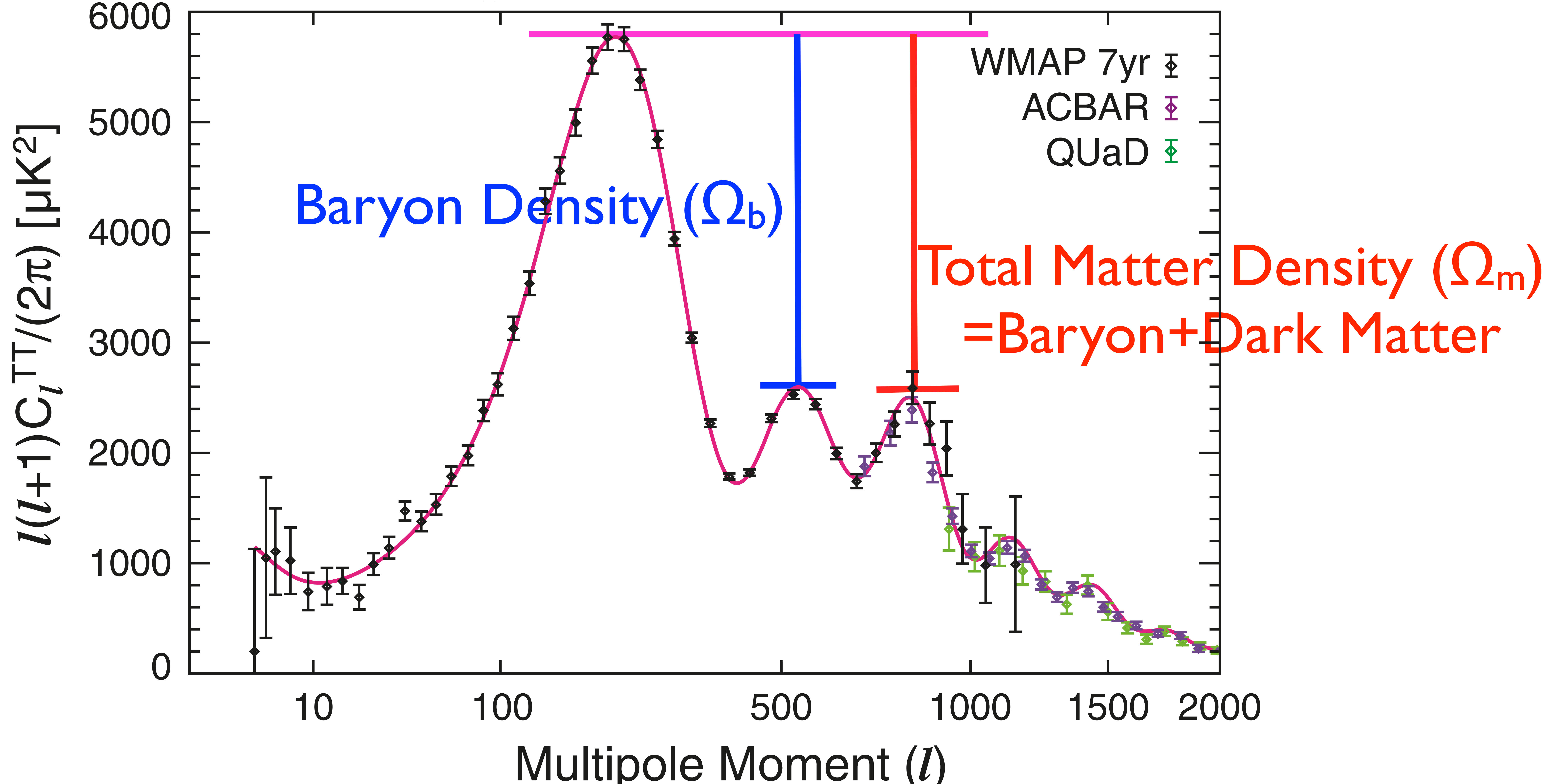
# The Cosmic Sound Wave



- *"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

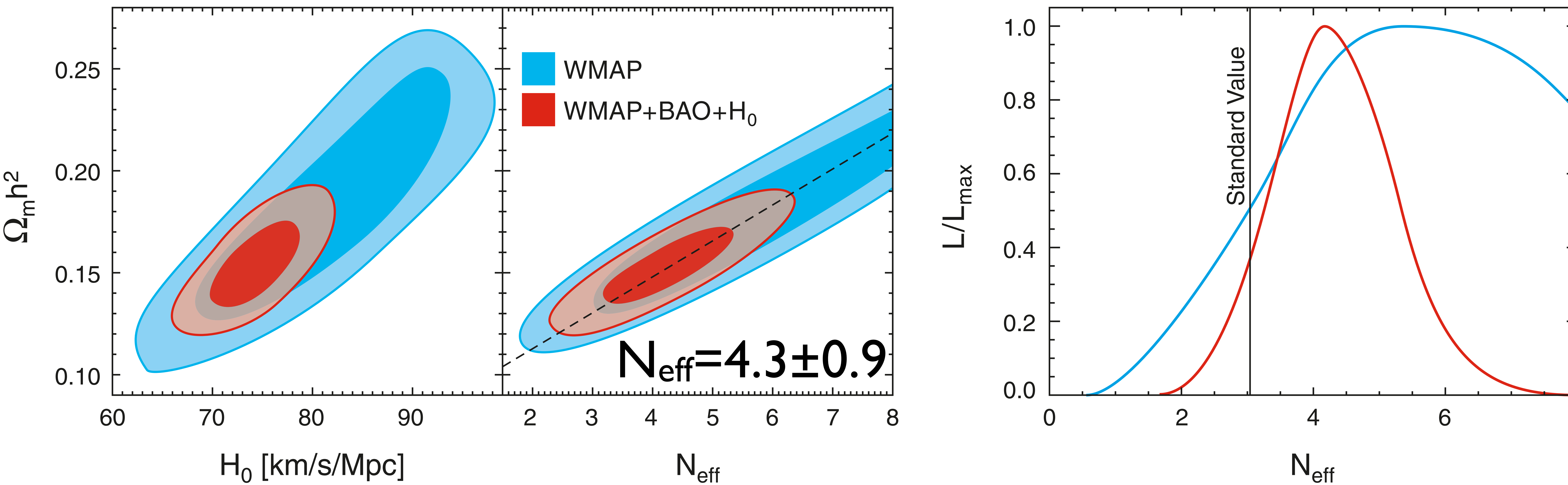



- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio ($z_{EQ}$: equality redshift)

# 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

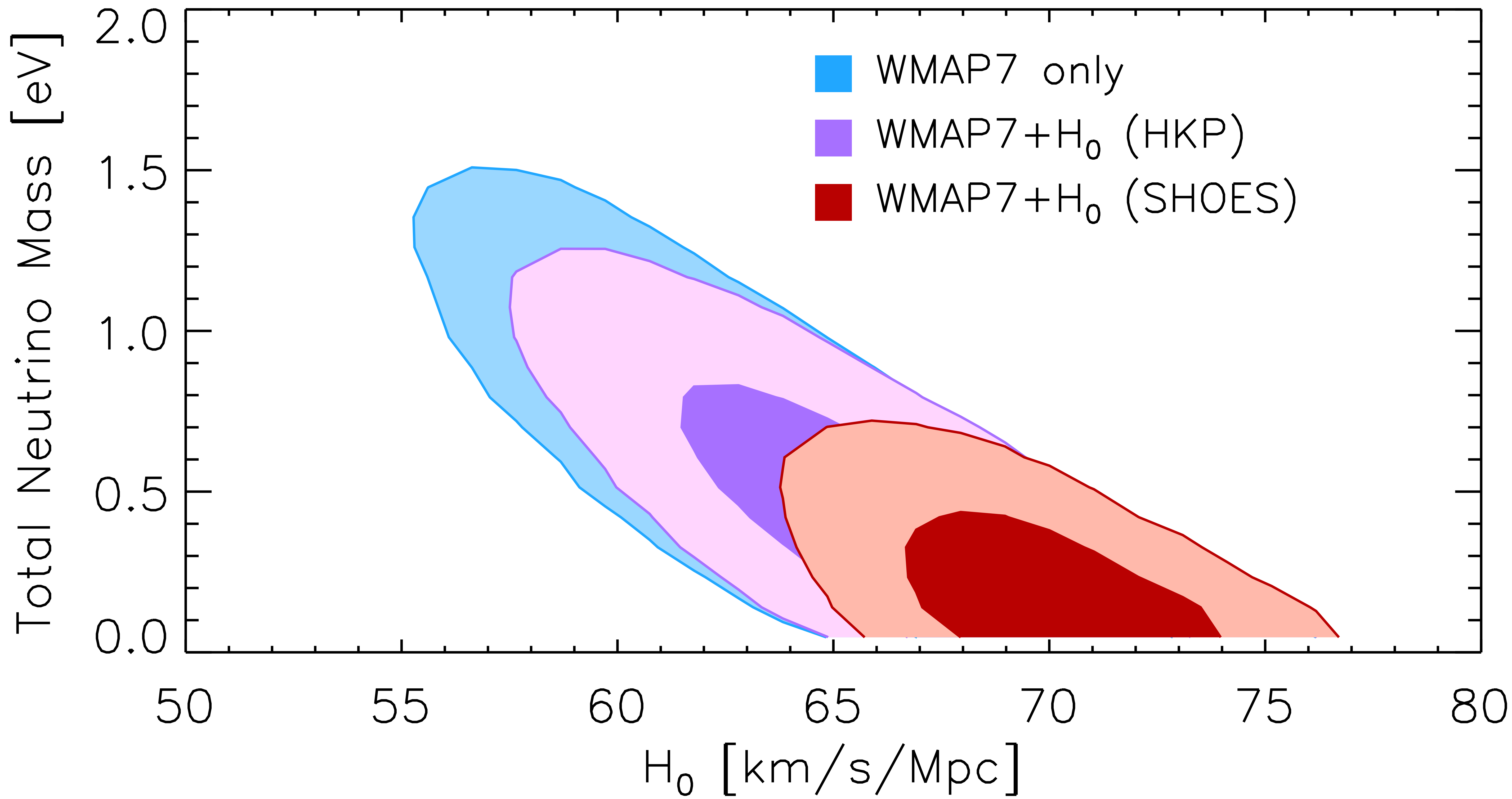



from external data

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

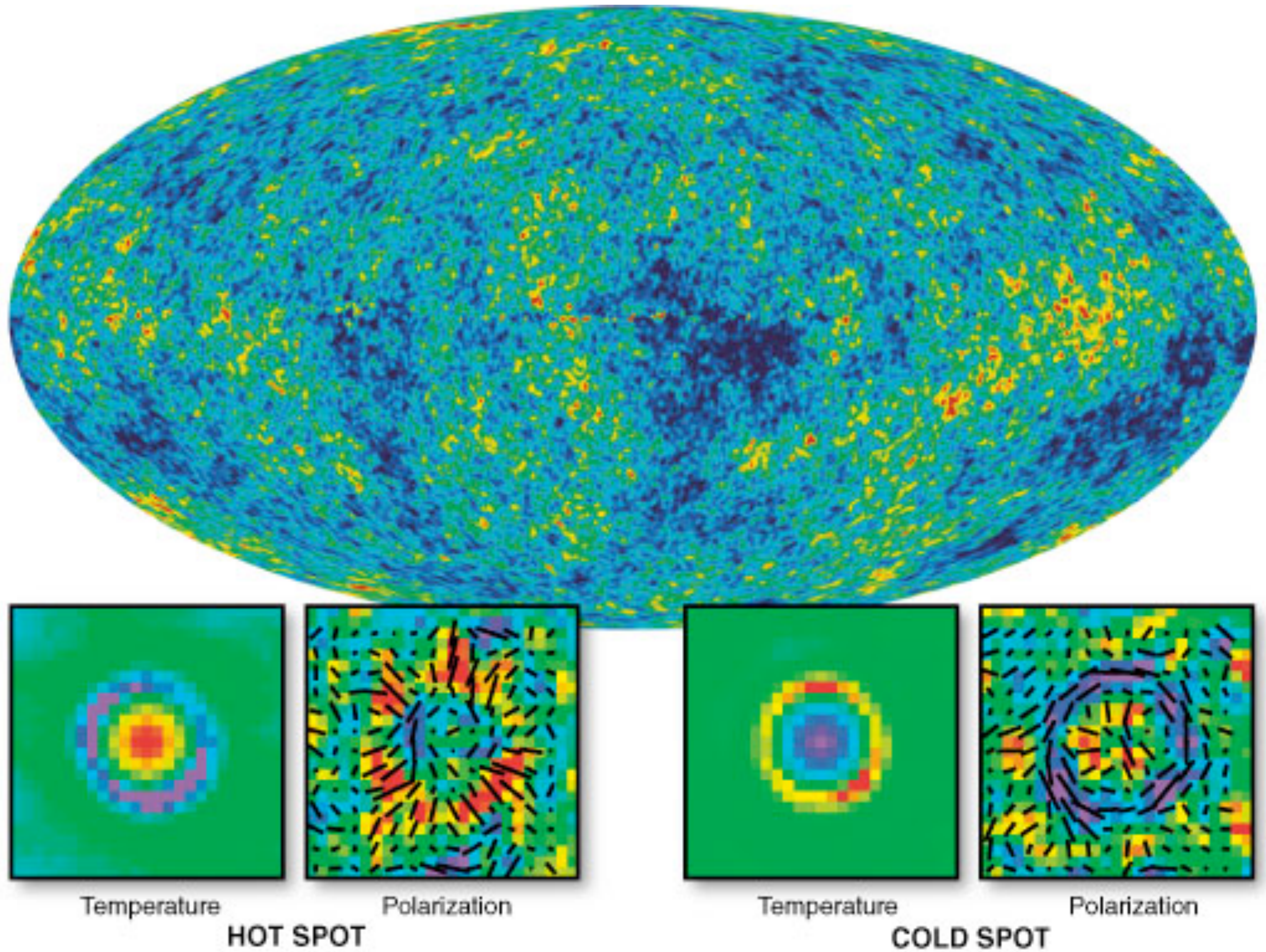
from 3rd peak

# And, the mass of neutrinos



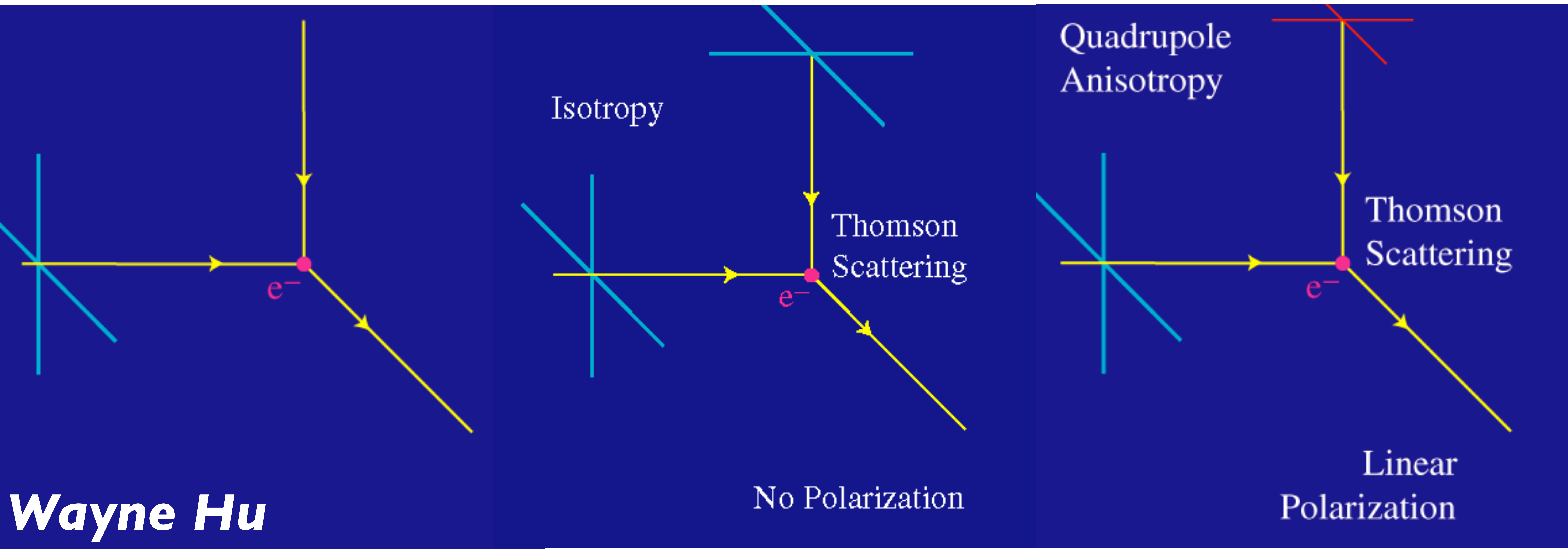

- WMAP data combined with the local measurement of the expansion rate ($H_0$), we get $\sum m_\nu < 0.6$ eV (95%CL)

# CMB Polarization



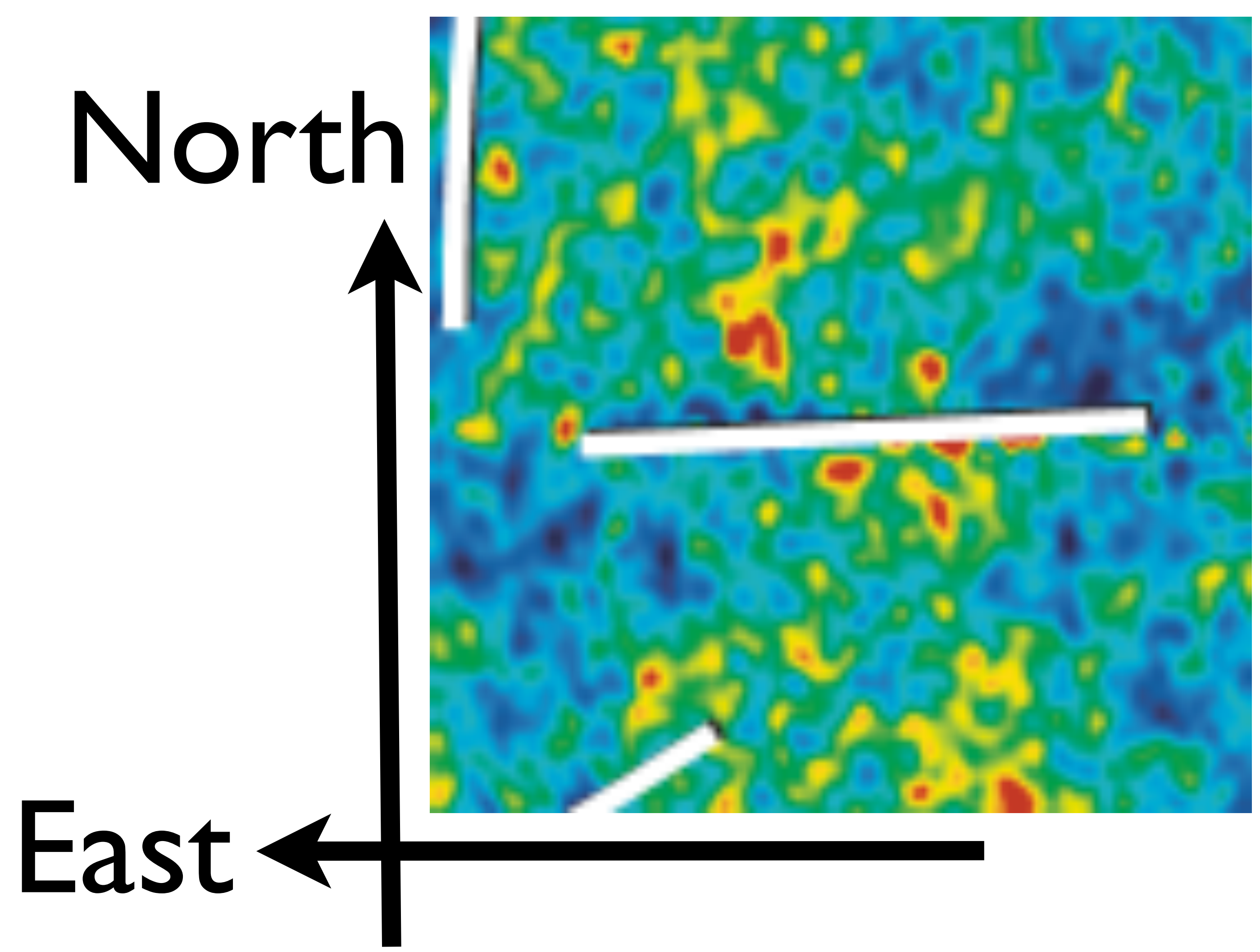

- *CMB is (very weakly) polarized!*

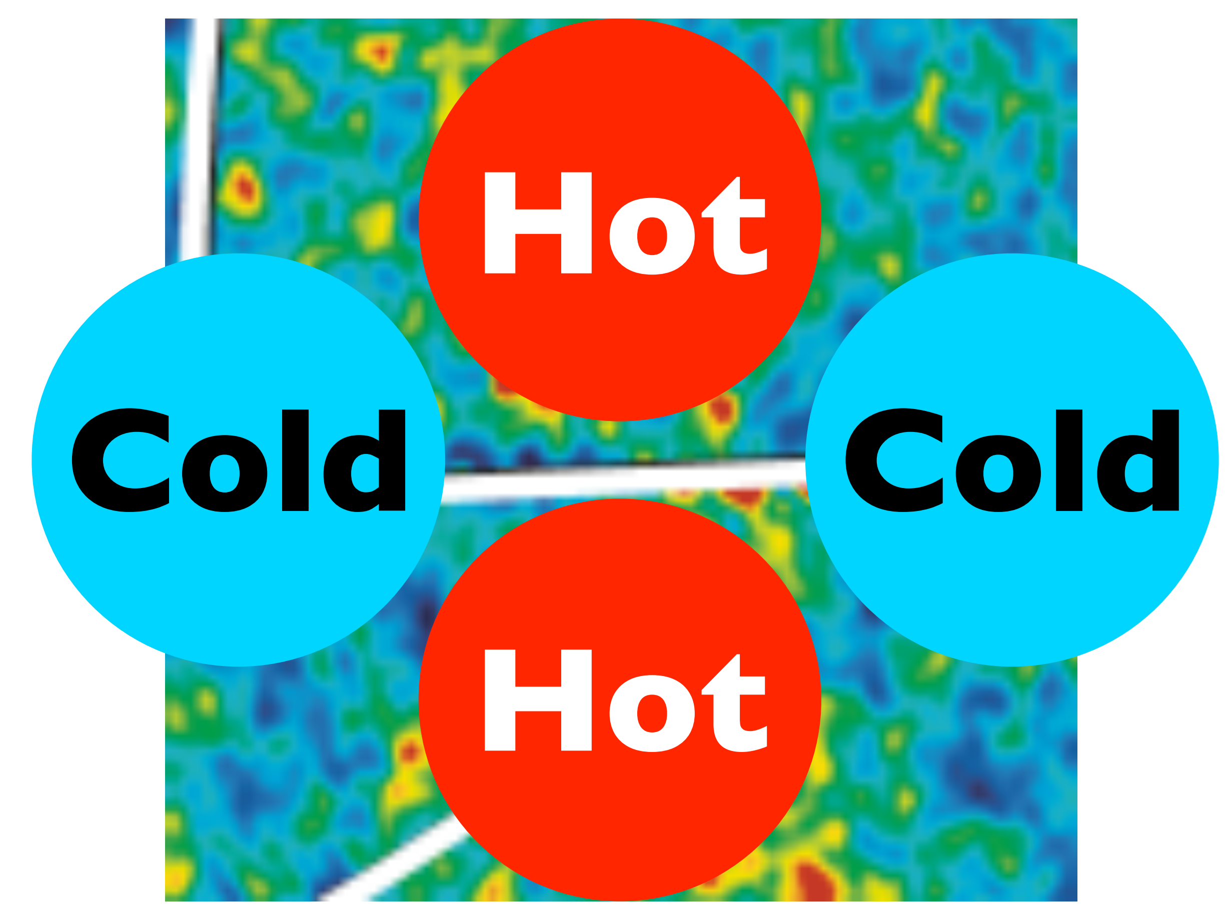
# Physics of CMB Polarization




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

# Principle




- **Polarization direction is parallel to "hot."**

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

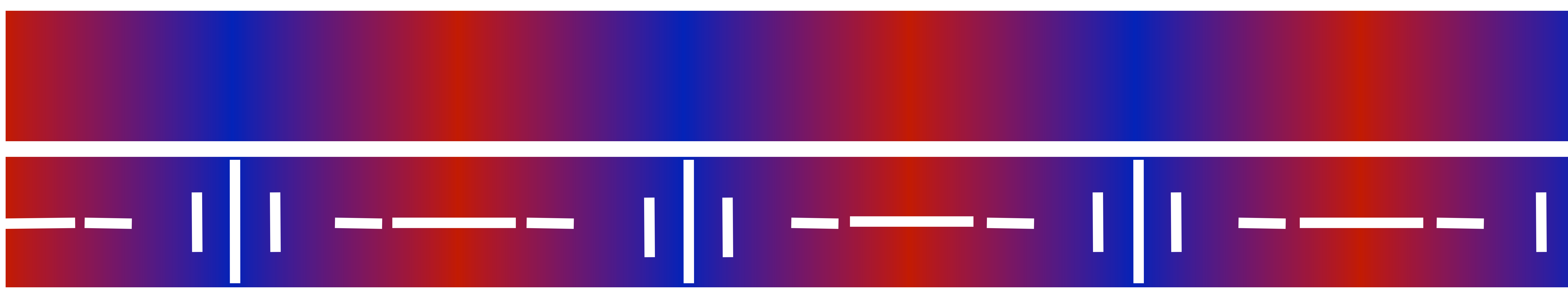
Matter Density

Potential

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

$\Delta T$

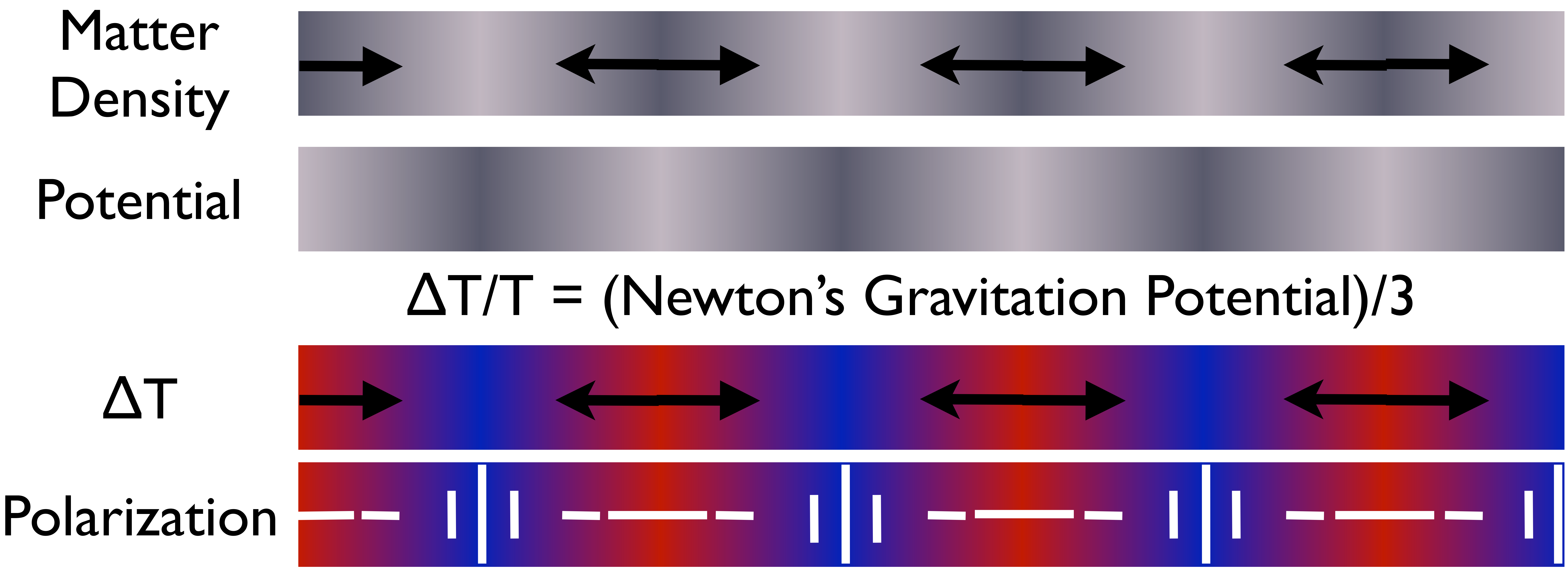
Polarization



- How does the photon-baryon plasma move?

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

*Zaldarriaga & Harari (1995)*



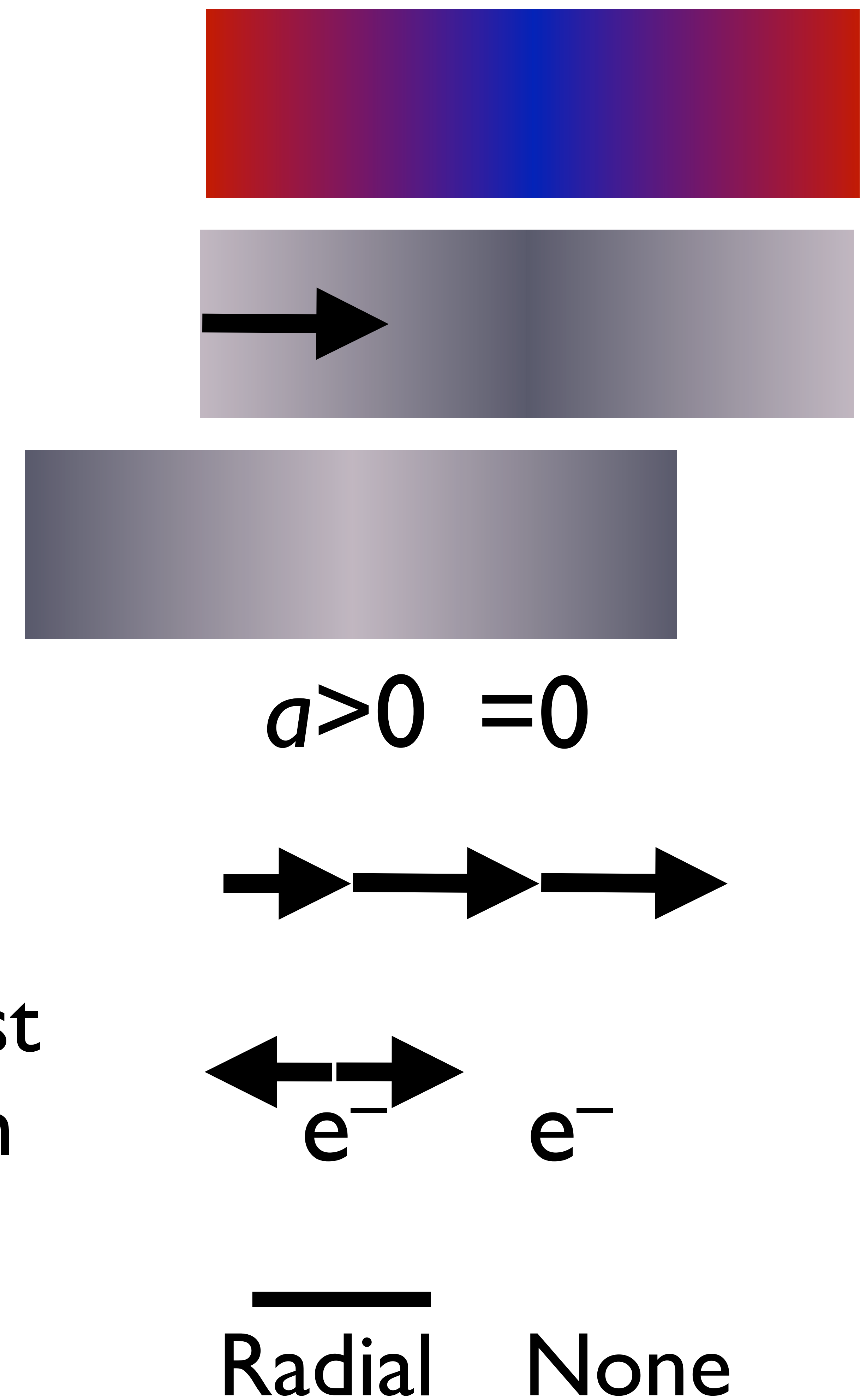

- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern

# Quadrupole From Velocity Gradient (Large Scale)

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

Potential $\Phi$ — 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)

$\Delta T$ — Compression increases temperature

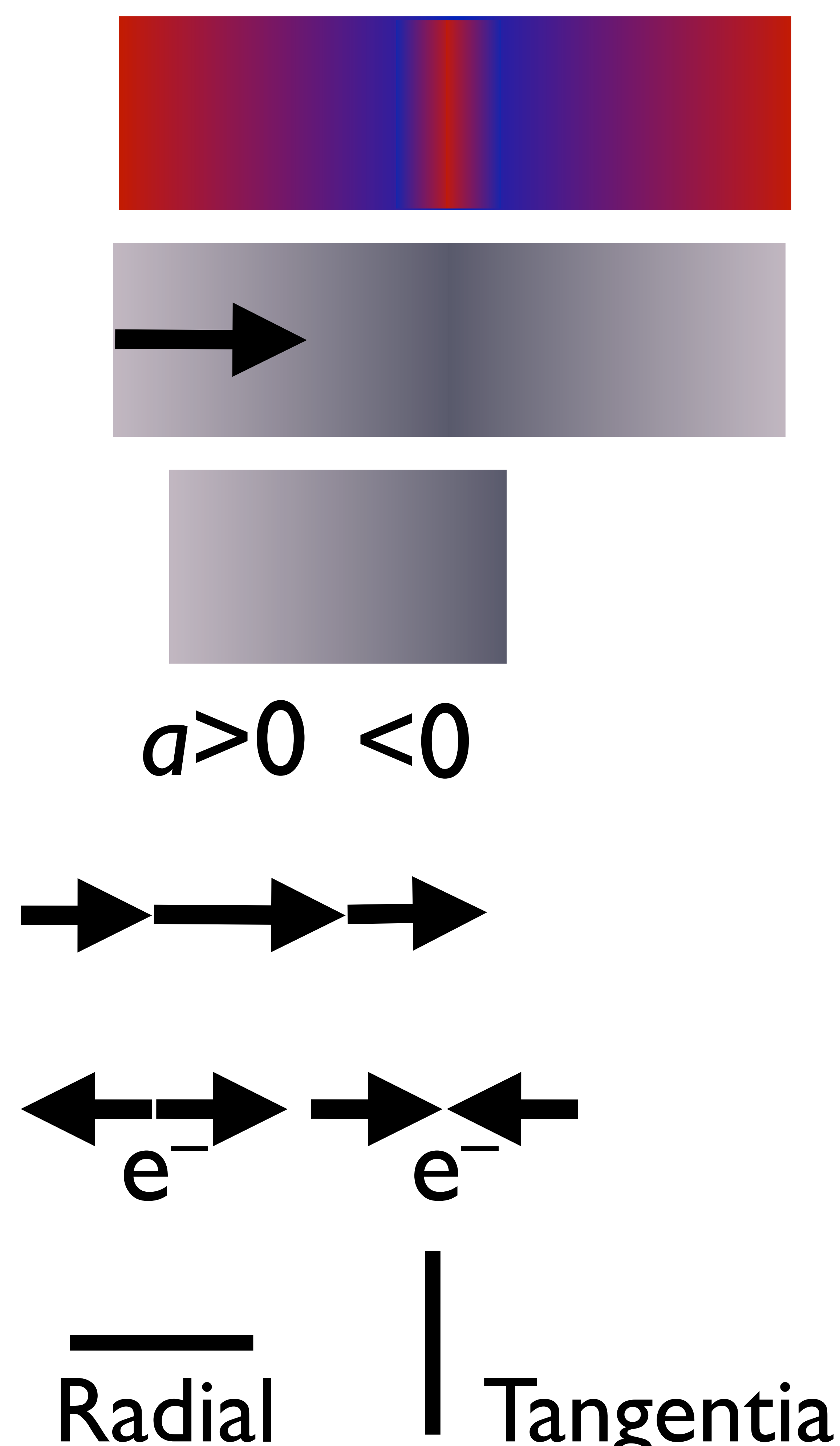
Potential $\Phi$ — Stuff flowing *in*

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

Velocity — Velocity gradient

Velocity in the rest frame of electron

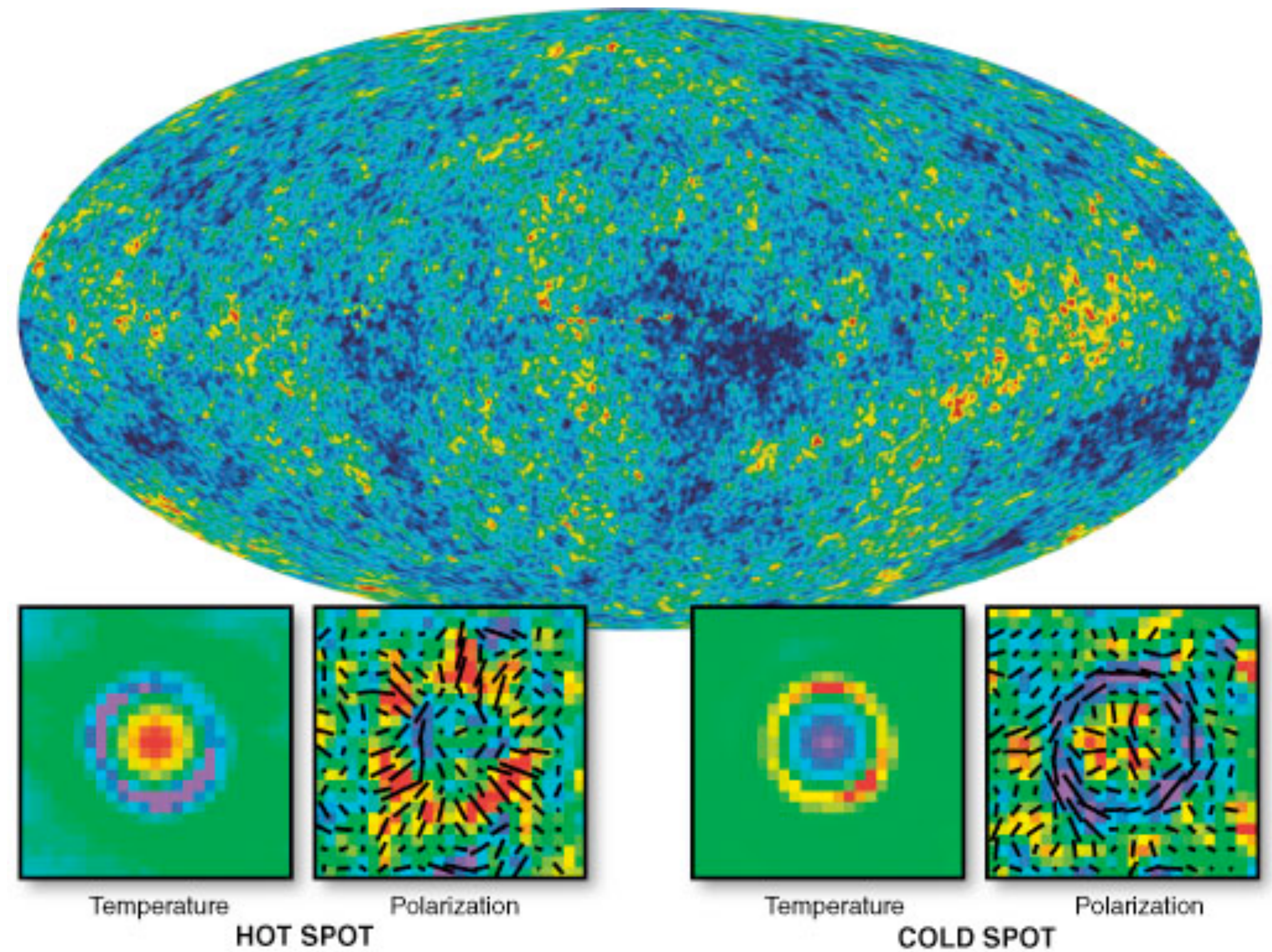
Polarization

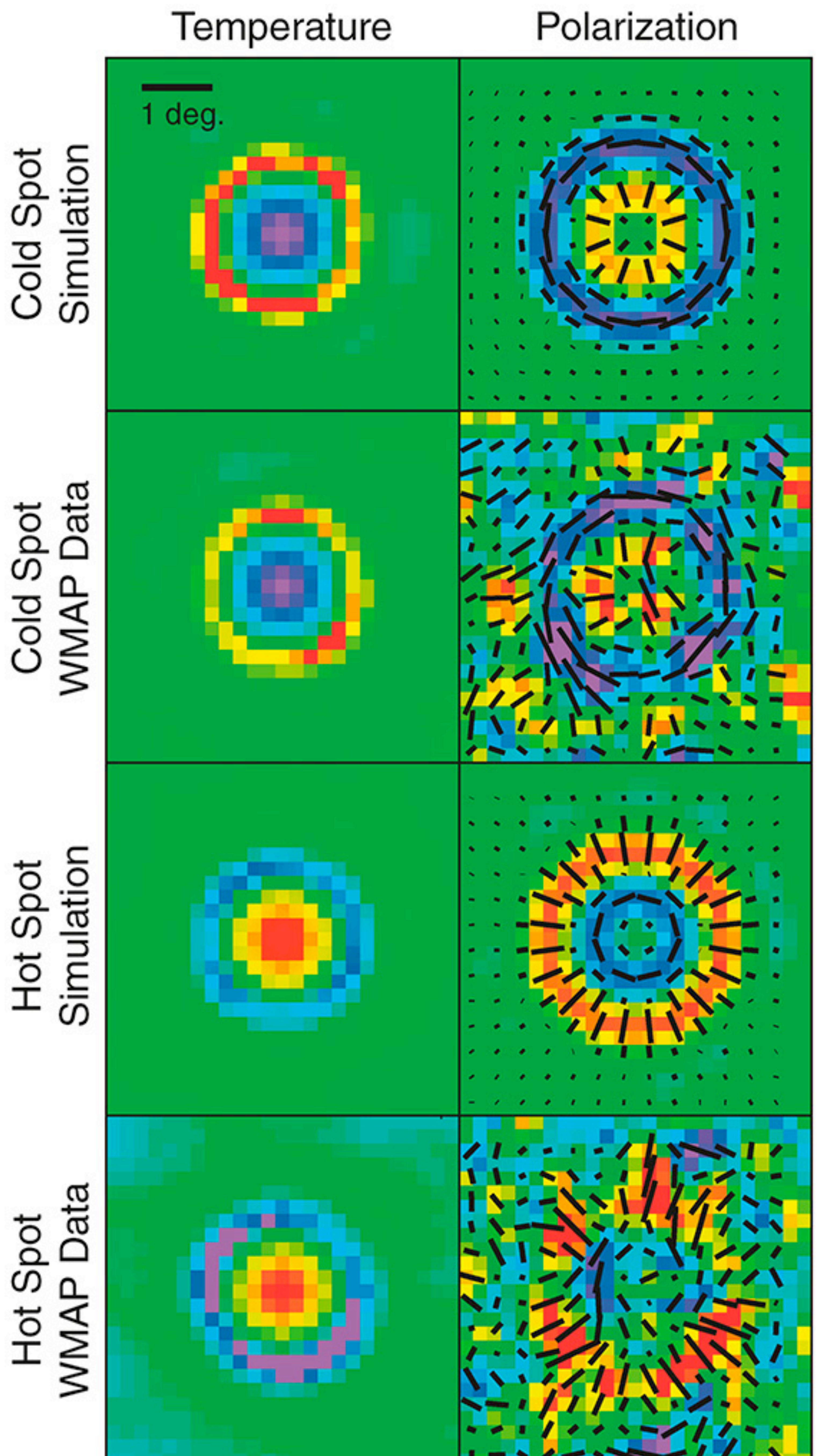


# Stacking Analysis

- 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**.

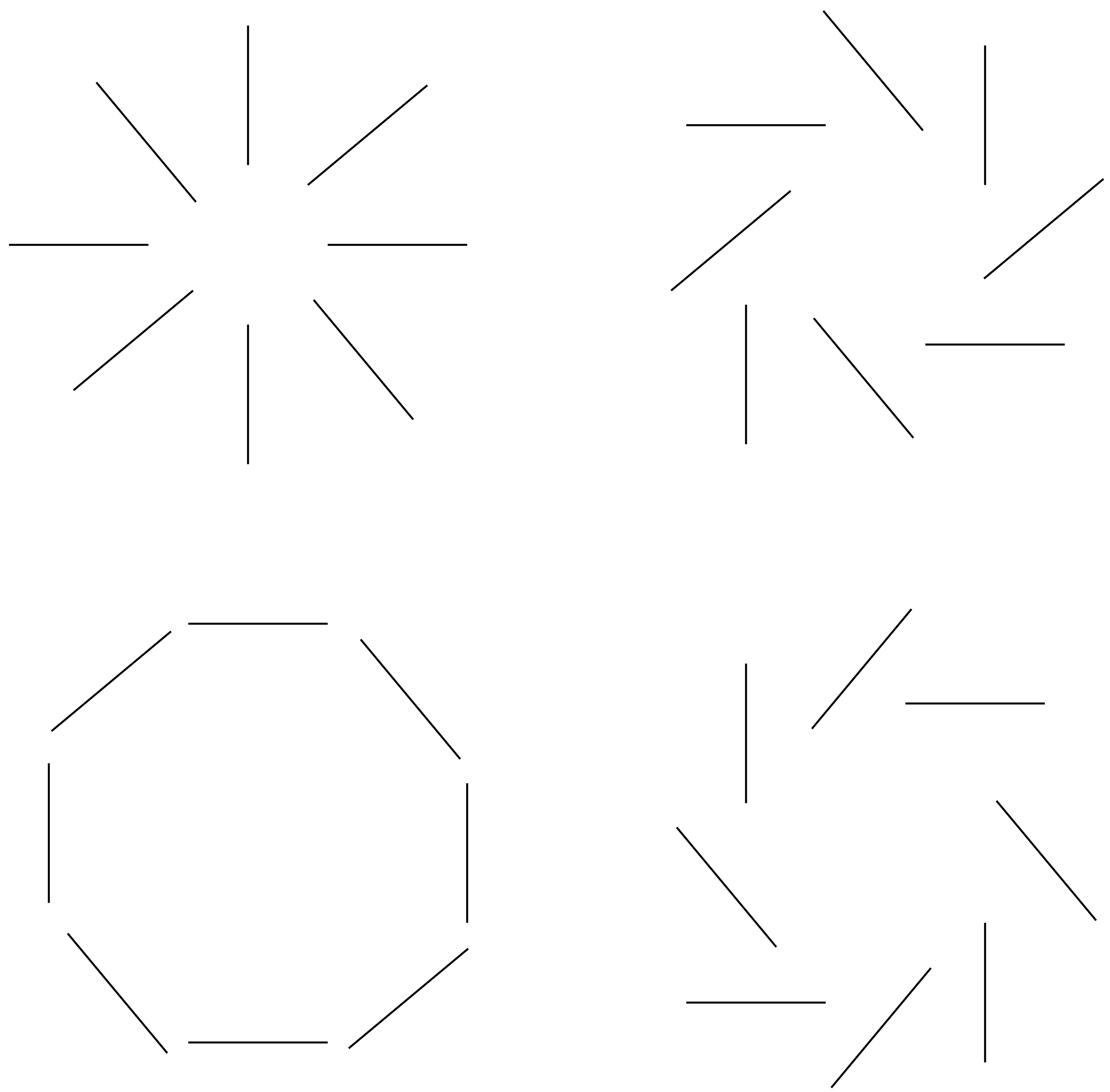





# Two-dimensional View

- All hot and cold spots are stacked
- "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$\sigma$

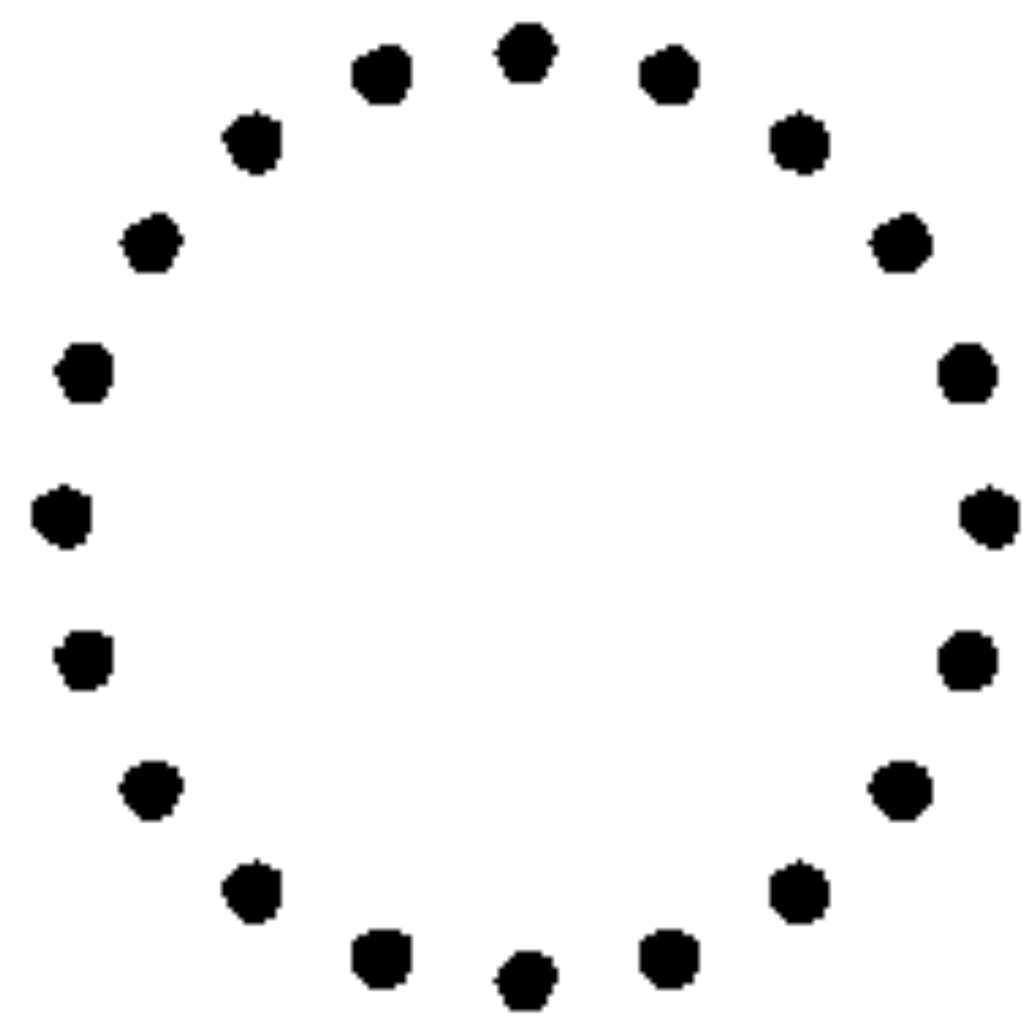
# E-mode and B-mode



E mode B mode

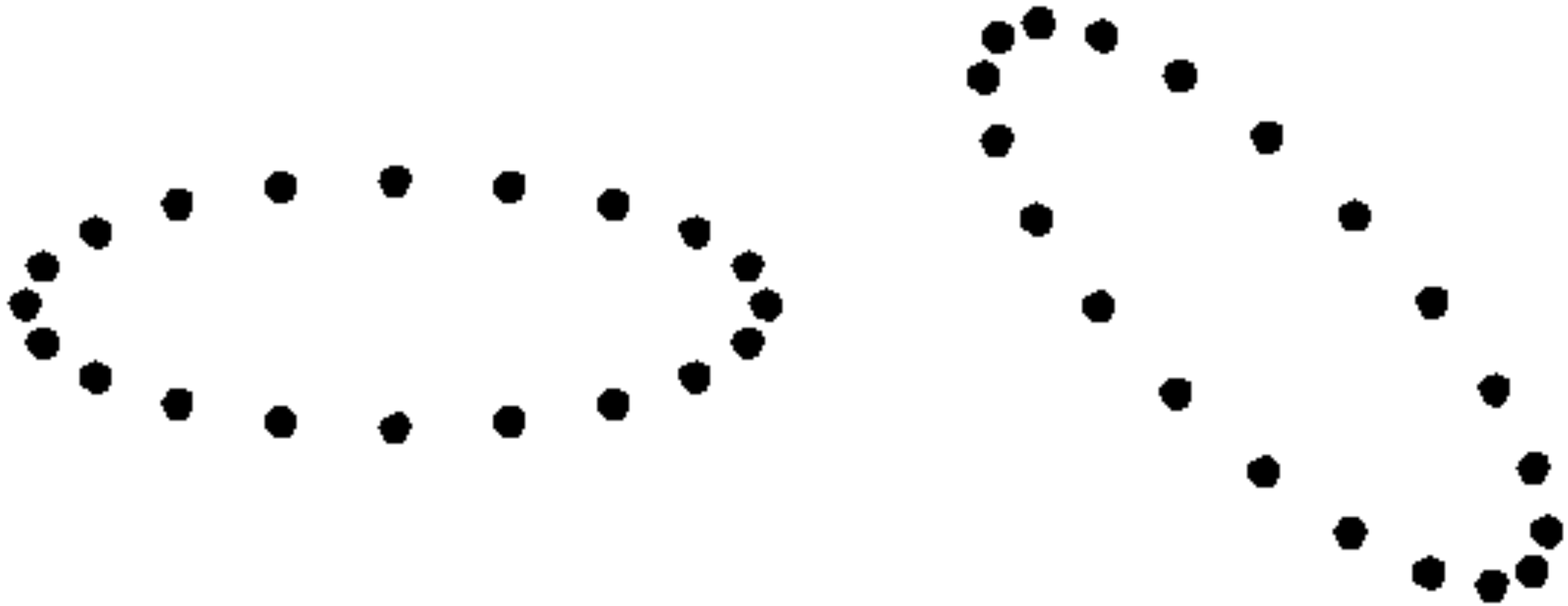
- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

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



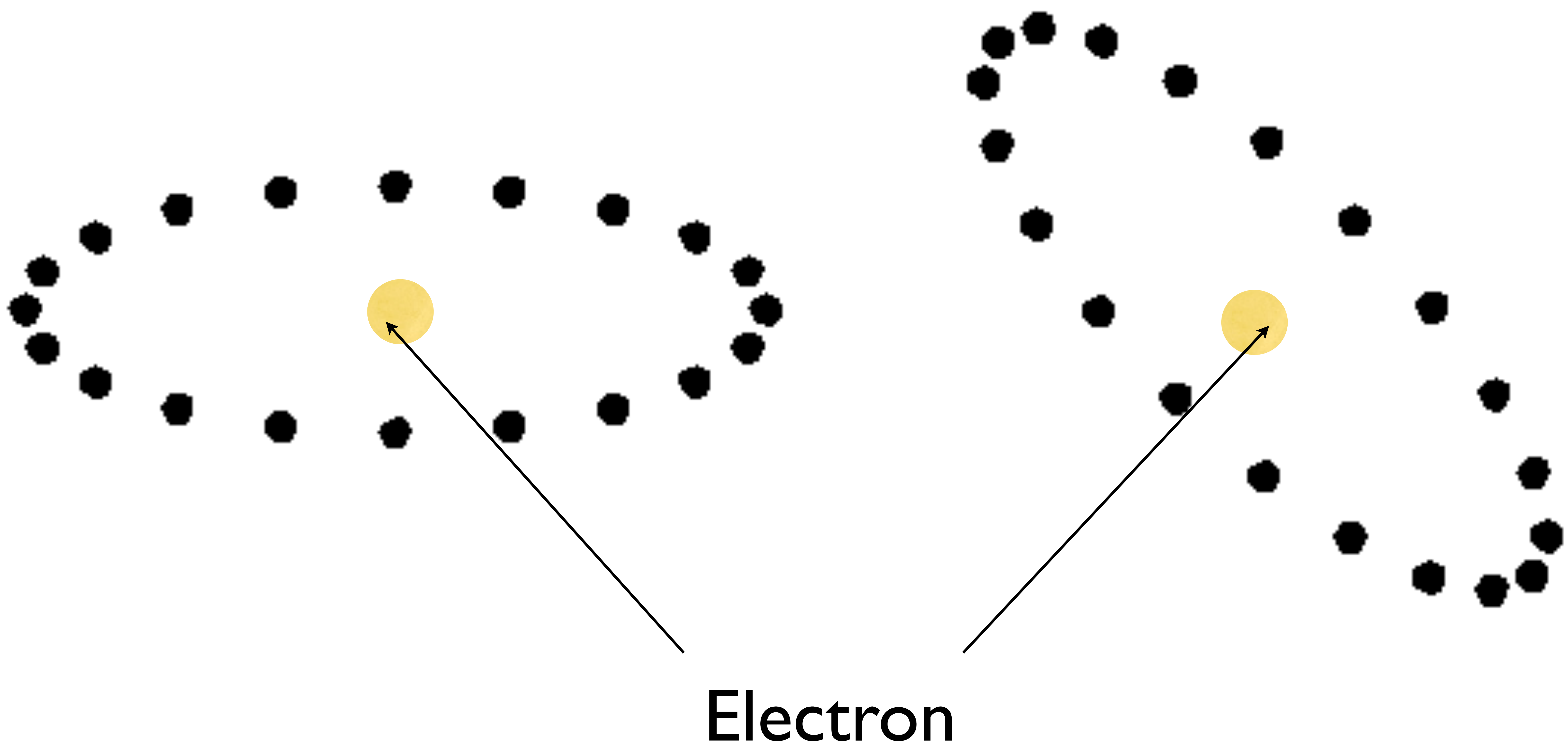
- Gravitational waves stretch space, causing particles to move.

# Two Polarization States of GW

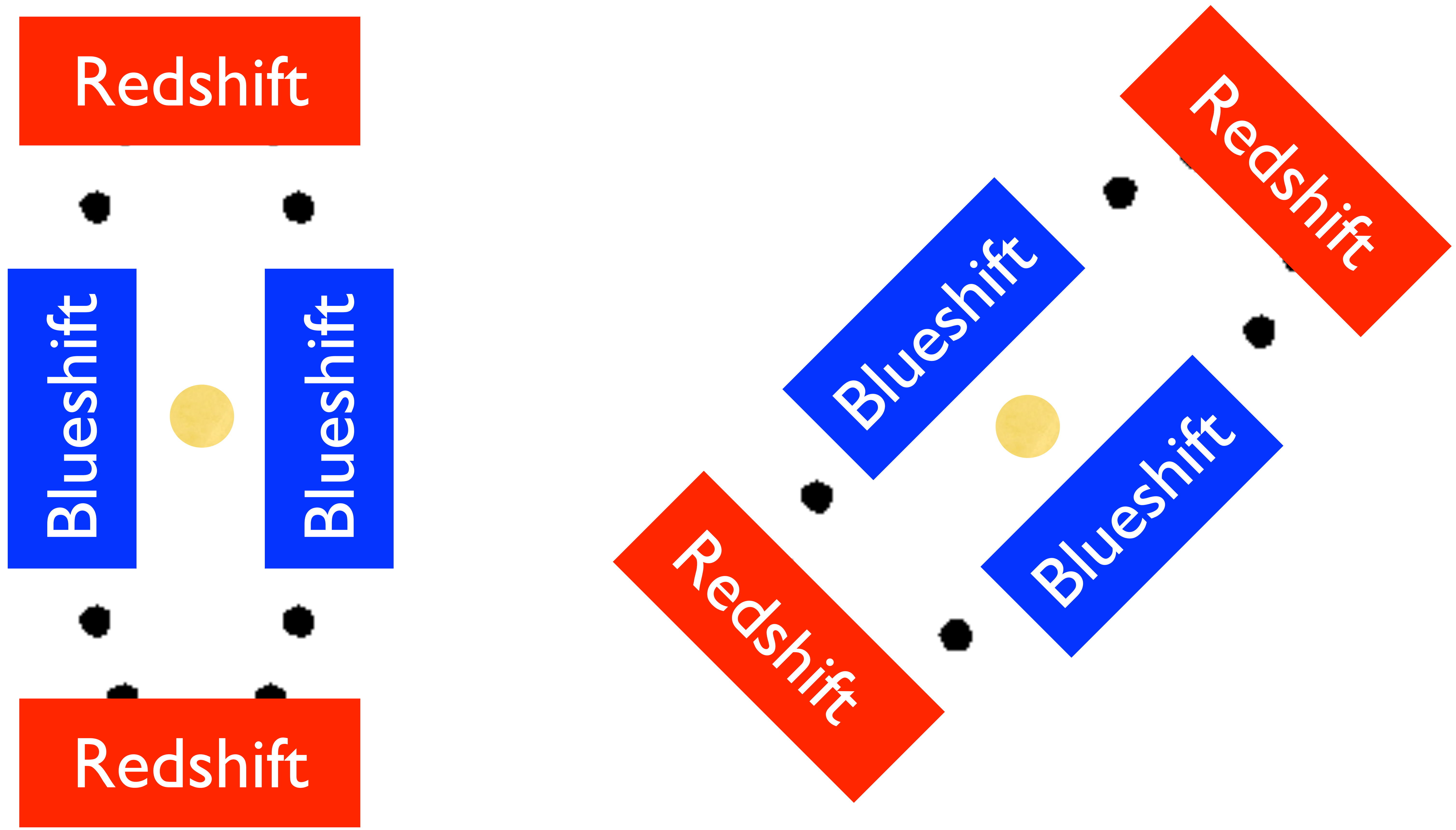


- This is great - this will automatically generate quadrupolar anisotropy around electrons!

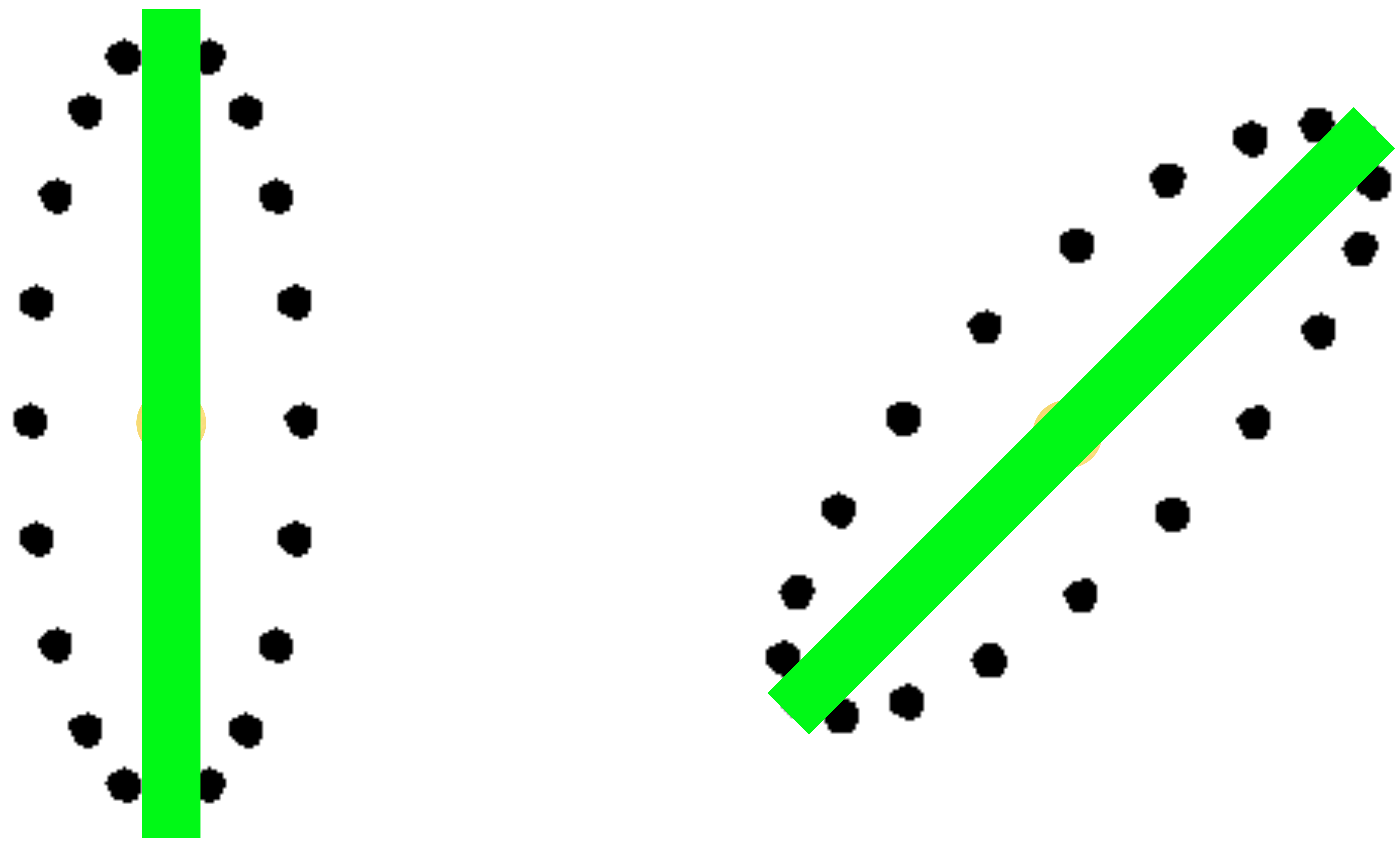
# From GW to CMB Polarization



# From GW to CMB Polarization



# From GW to CMB Polarization



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

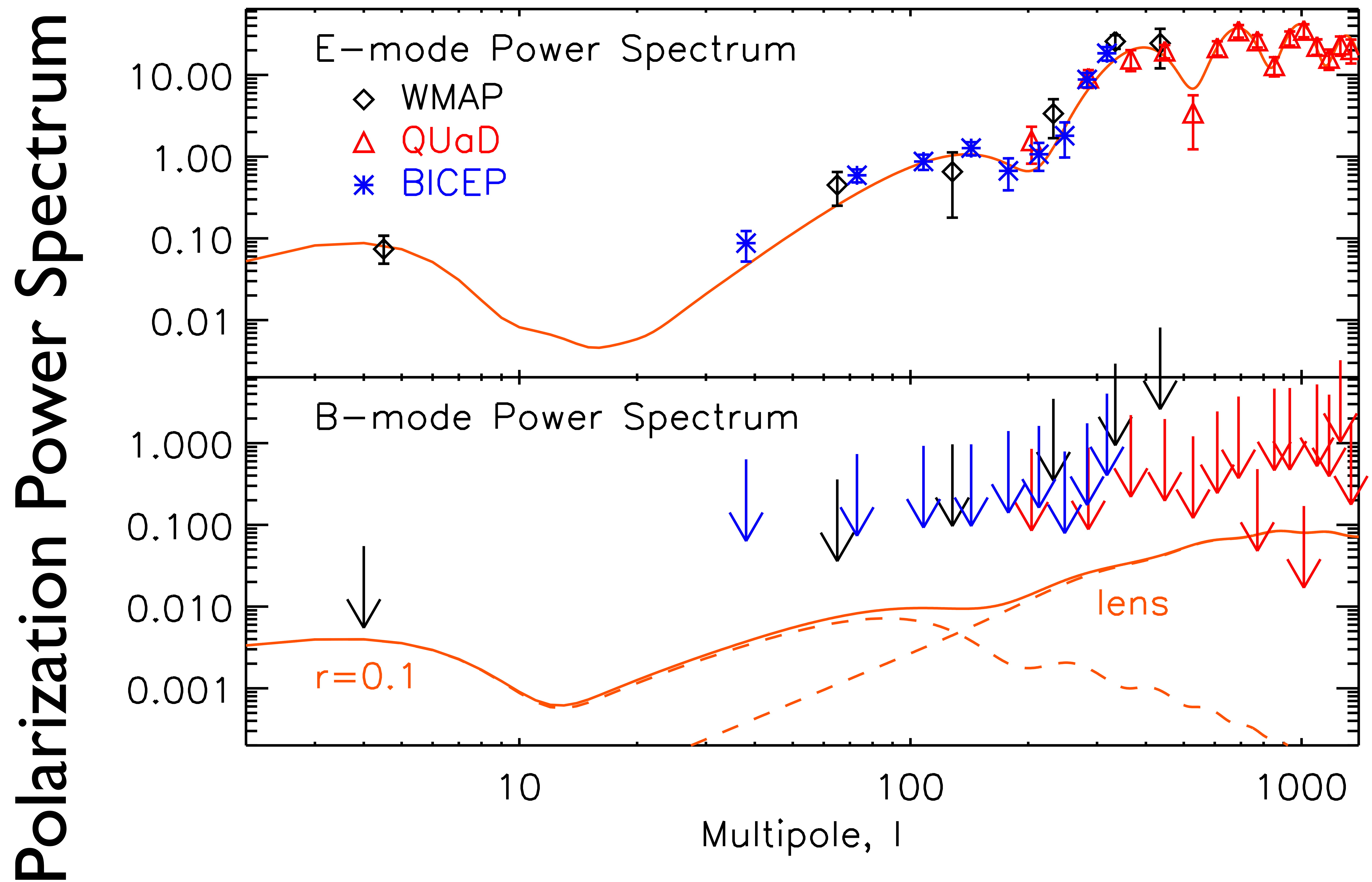
# “Tensor-to-scalar Ratio,” r

**r** = [Power in Gravitational Waves]

/ [Power in Gravitational Potential]

Theory of “Cosmic Inflation” predicts r <~ 1

– I will come back to this in a moment




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

# Theory of the Very Early Universe

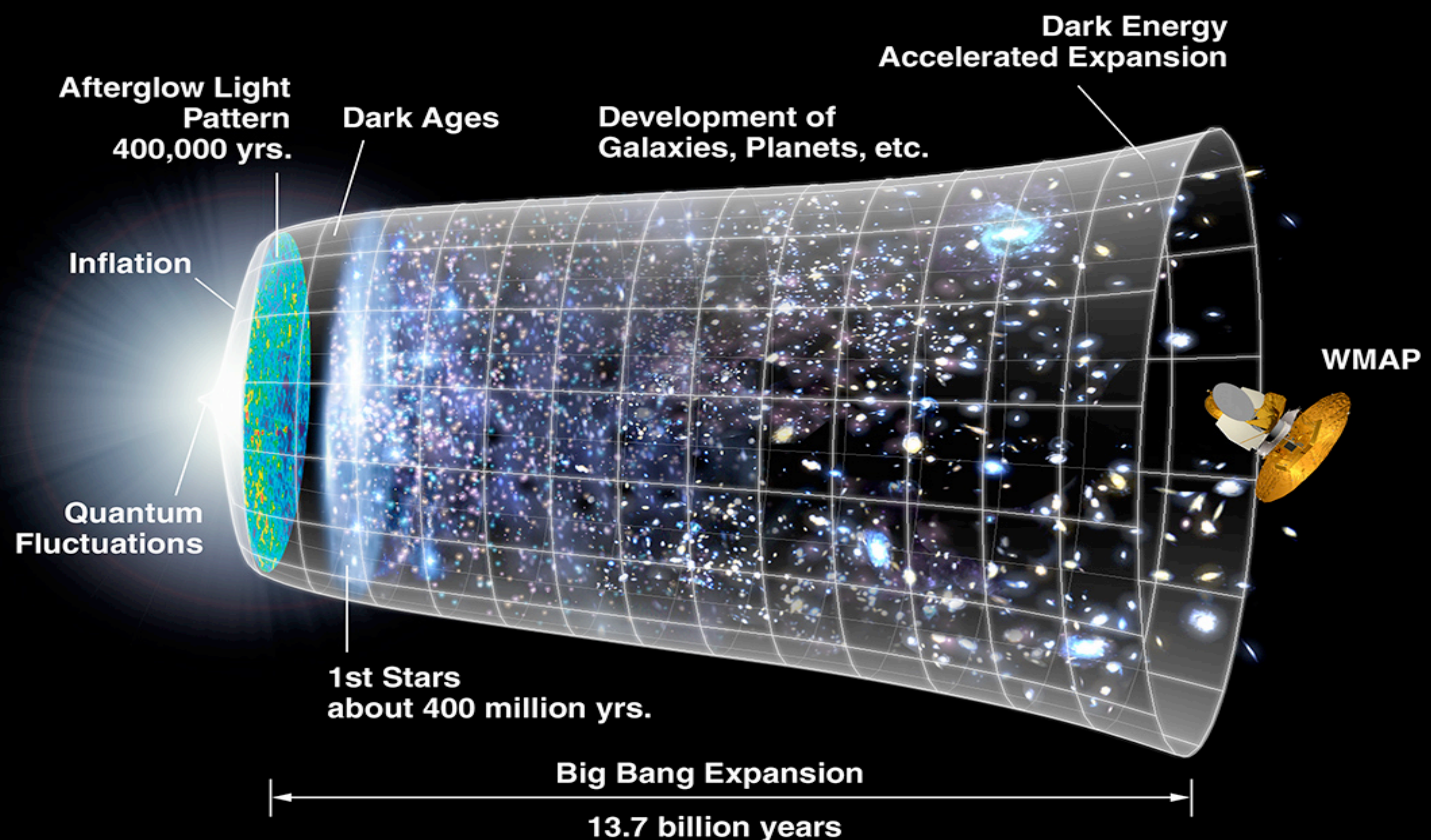
- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  *(Guth 1981; Linde 1982; Albrecht & Steinhardt 1982; Starobinsky 1980)*

  - 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



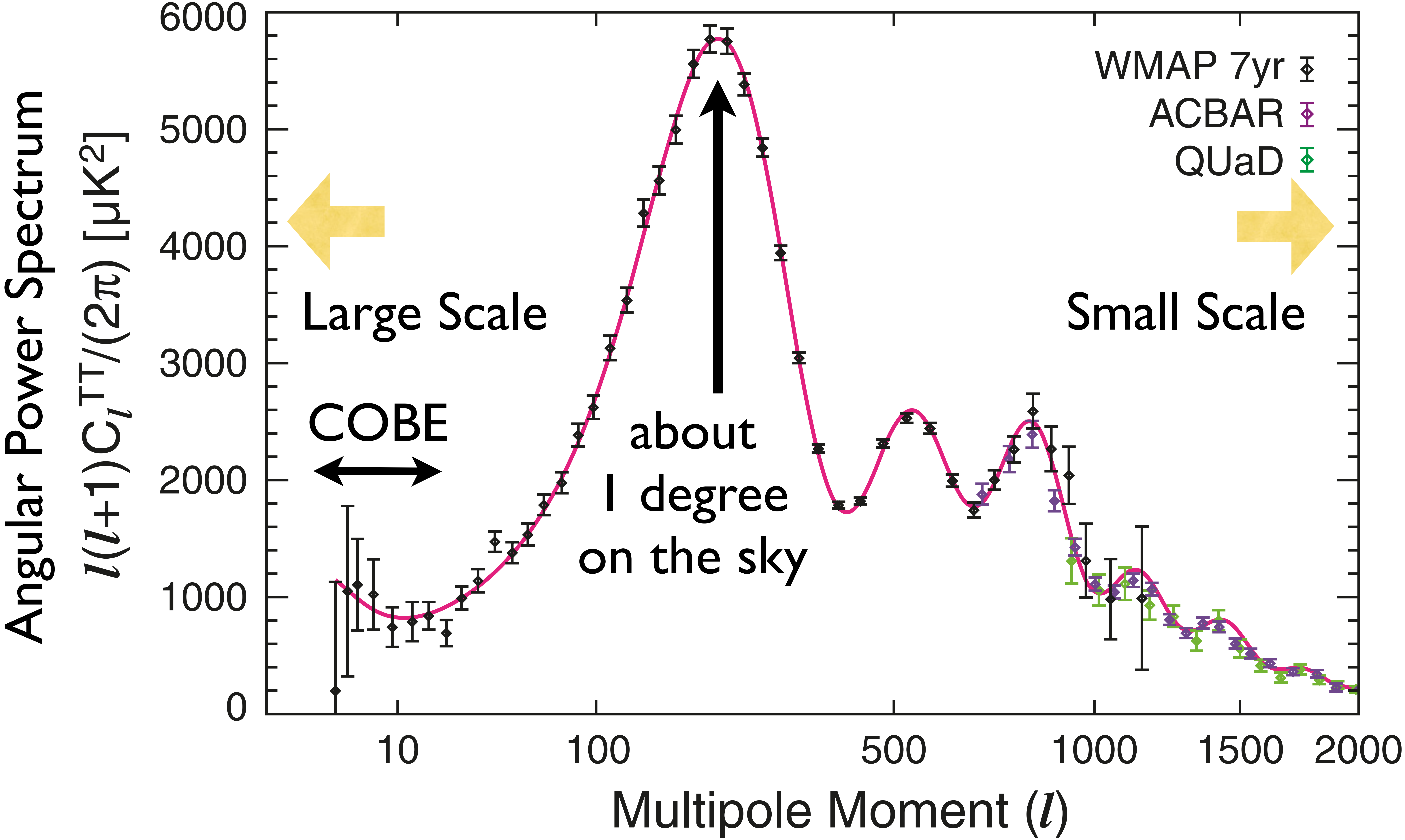



NASA/WMAP Science Team

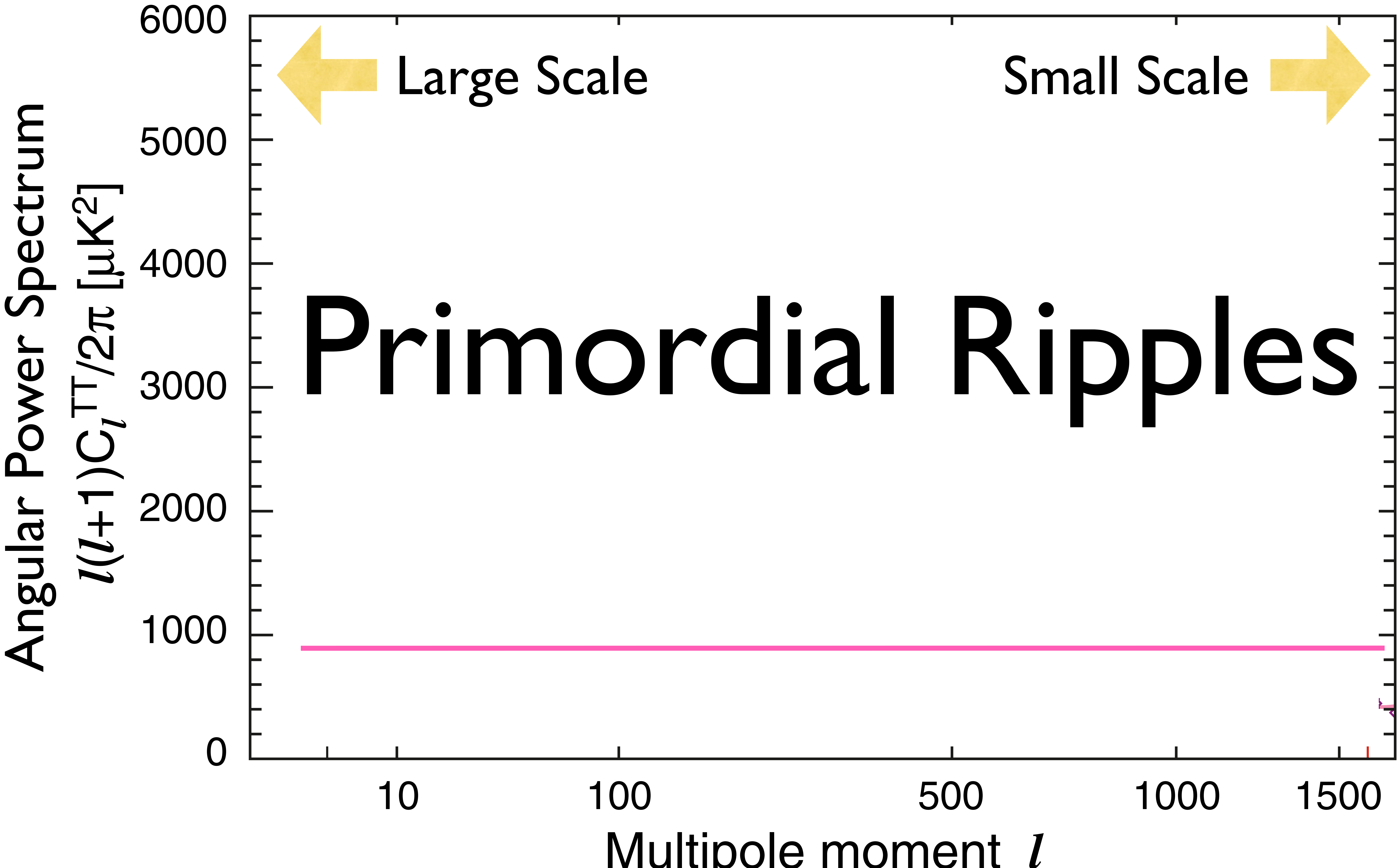
# Origin of Fluctuations

- 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?**

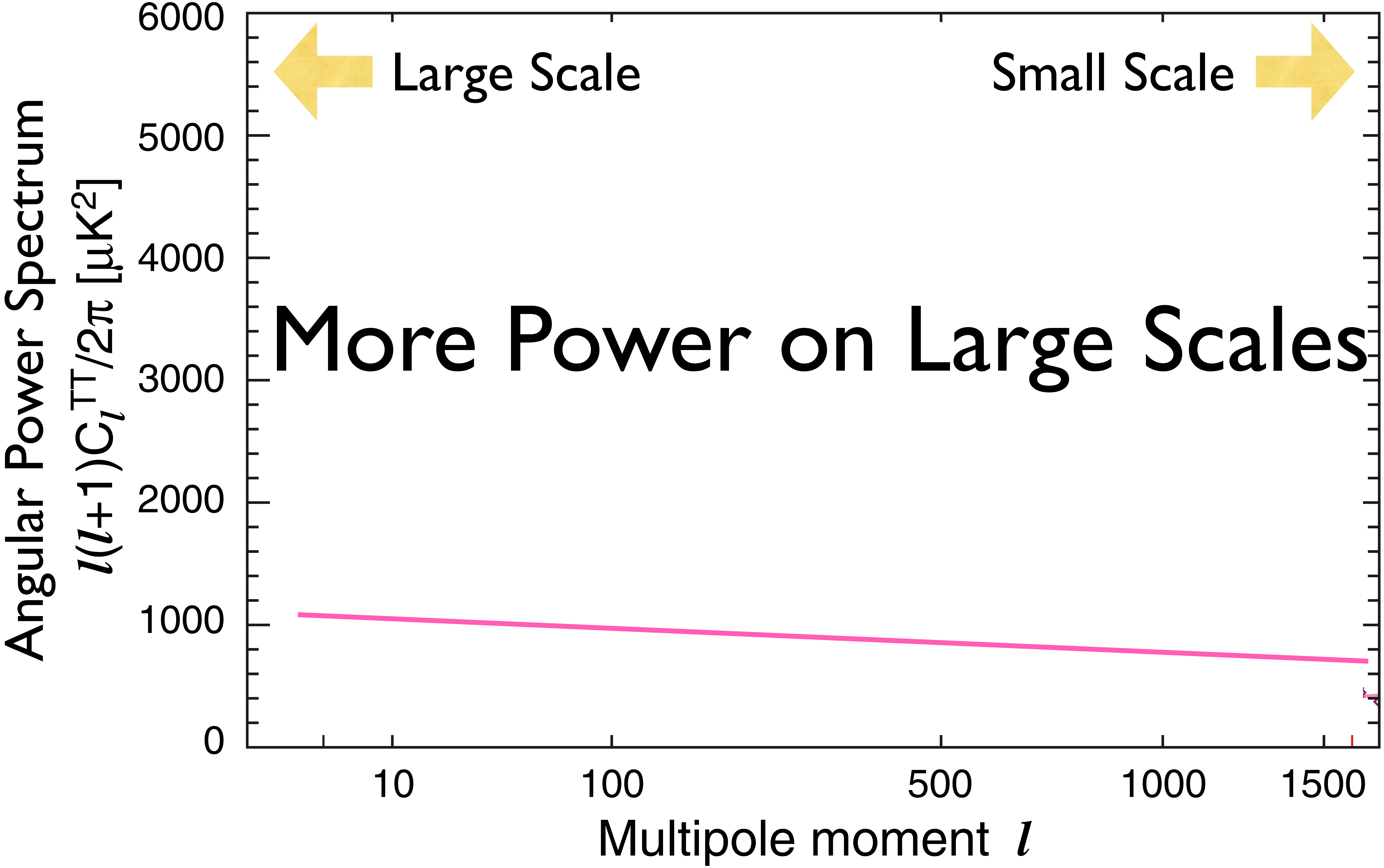
# WMAP Power Spectrum



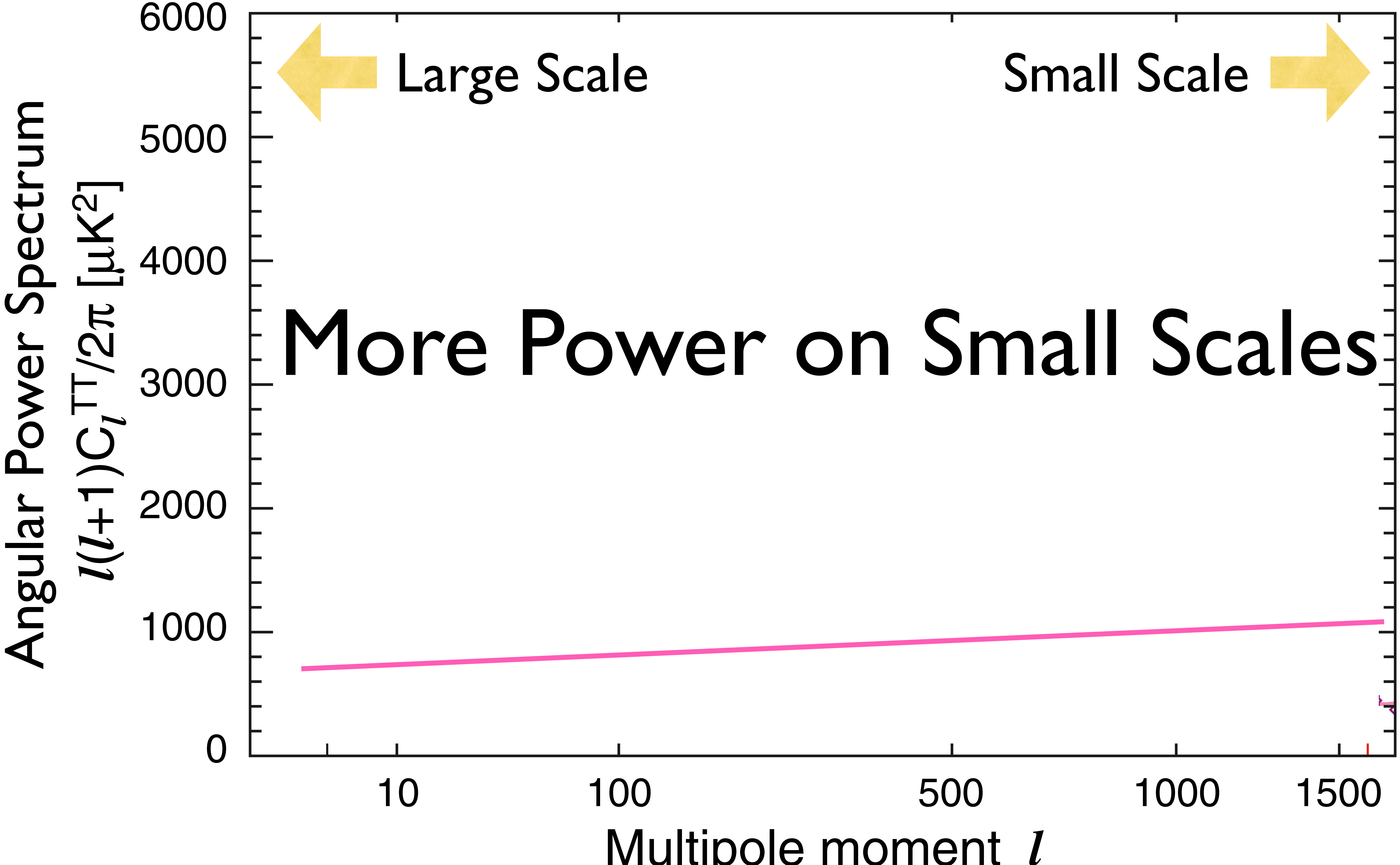
# Getting rid of the Sound Waves



# The Early Universe Could Have Done This Instead

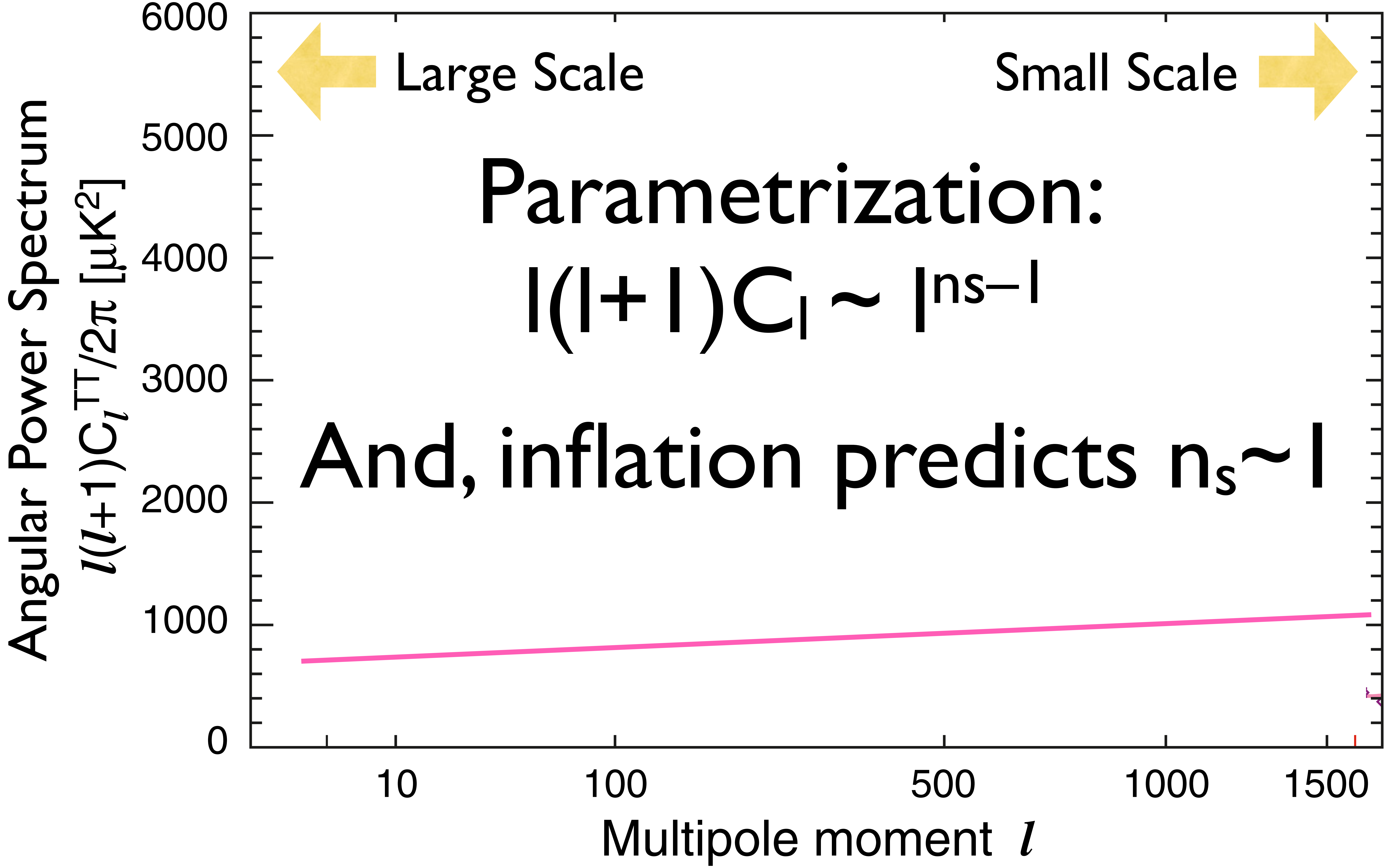


# ...or, This.



Large Scale
Small Scale
More Power on Small Scales
Angular Power Spectrum
l(l+1)C_l^TT/2π [μK²]
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 $n_s \sim 1$
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Angular Power Spectrum
$l(l+1)C_l^{TT}/2\pi$ [μK$^2$]
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!

*Mukhanov & Chibisov (1981); Guth & Pi (1982); Starobinsky (1982); Hawking (1982); Bardeen, Turner & Steinhardt (1983)*

# (Scalar) Quantum Fluctuations

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

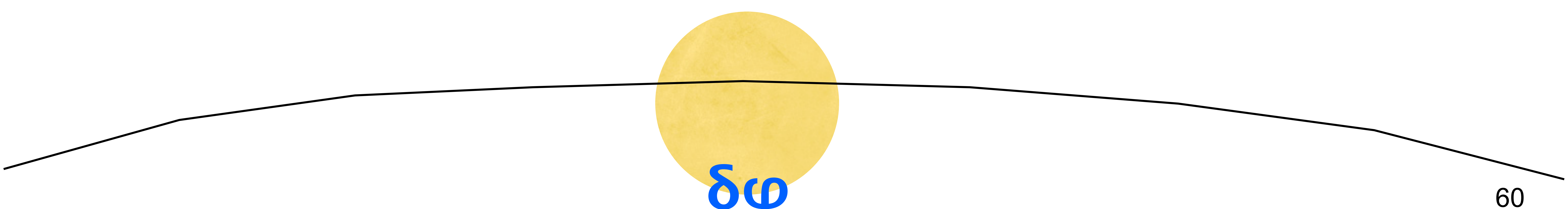
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like $10^{-36}$ second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~$10^{12}$GeV)
  - *Quantum fluctuations were important during inflation!*

# 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.

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

*Starobinsky (1979)*

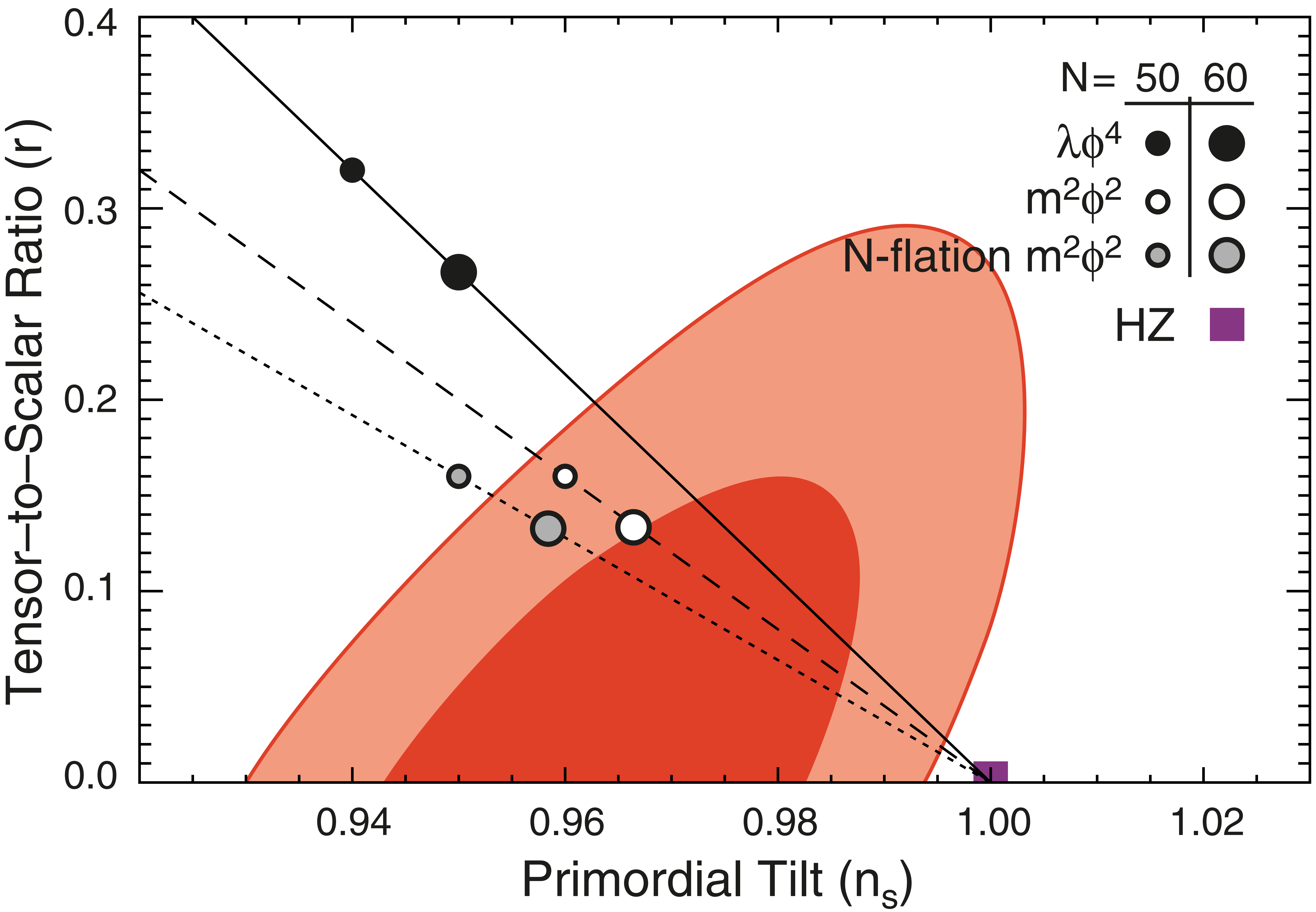
# (Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

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

[h = "strain"]

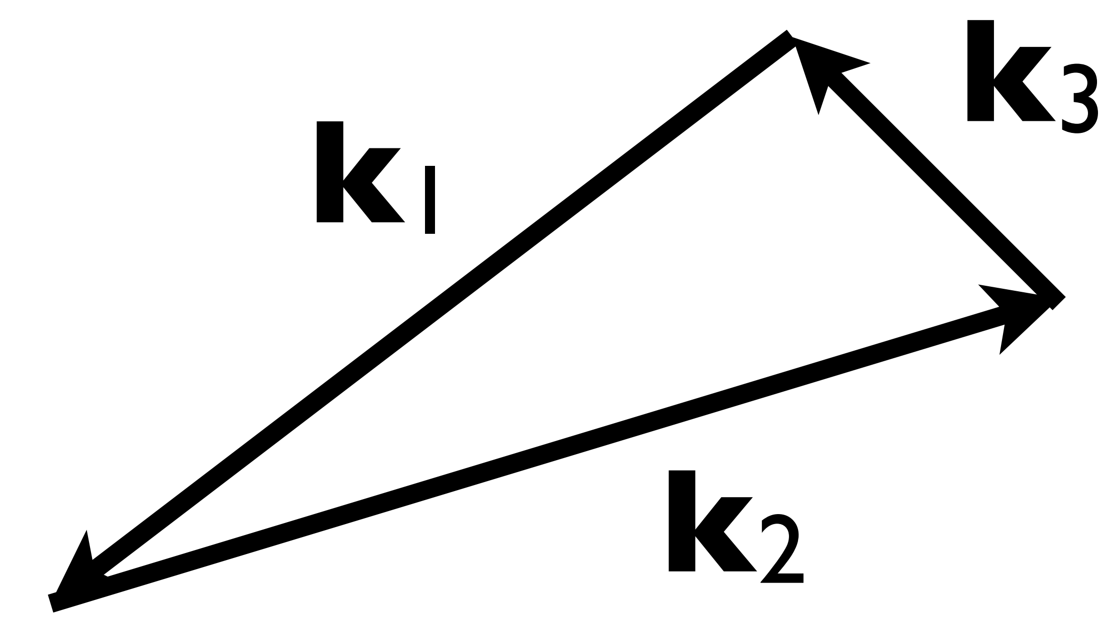
- Quantum fluctuations also generate ripples in space-time, i.e., gravitational waves, by the same mechanism.
- Primordial gravitational waves generate temperature anisotropy in CMB, as well as polarization in CMB with a distinct pattern called "**B-mode polarization**."

# Probing Inflation (2-point Function)




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

# Bispectrum

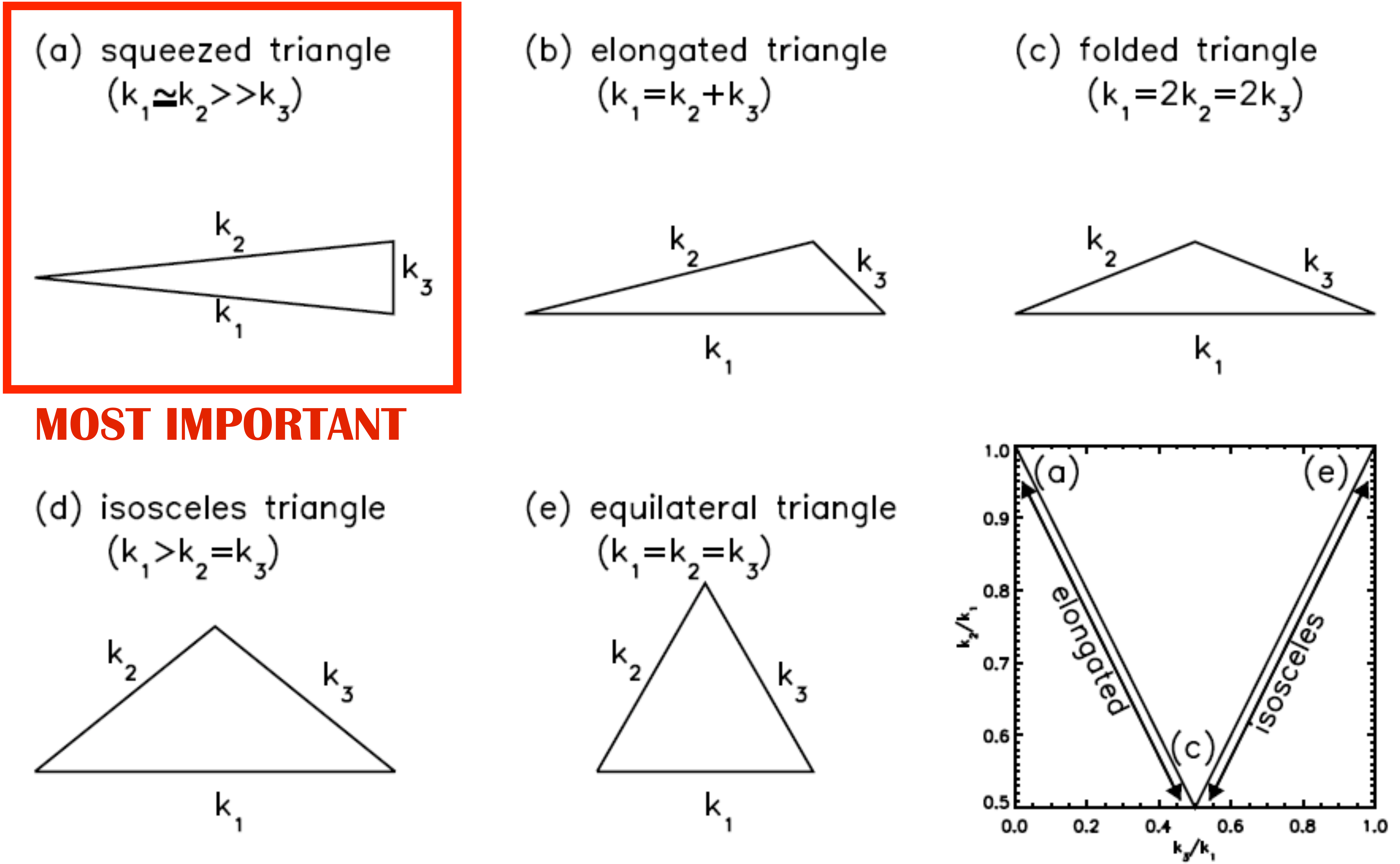



- Three-point function!
- $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$
  $= \langle \zeta_{\mathbf{k}1} \zeta_{\mathbf{k}2} \zeta_{\mathbf{k}3} \rangle = (\text{amplitude}) \times (2\pi)^3 \delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) F(k_1,k_2,k_3)$

model-dependent function

Primordial fluctuation

"$f_{NL}$"



(a) squeezed triangle
(k1≃k2>>k3)
k2
k3
k1
MOST IMPORTANT
(b) elongated triangle
(k1=k2+k3)
k2
k3
k1
(c) folded triangle
(k1=2k2=2k3)
k2
k3
k1
(d) isosceles triangle
(k1>k2=k3)
k2
k3
k1
(e) equilateral triangle
(k1=k2=k3)
k2
k3
k1
(a)
(e)
(c)
elongated
isosceles
k2/k1
k3/k1
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0

# 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: $1-n_s \approx r \approx f_{NL}$

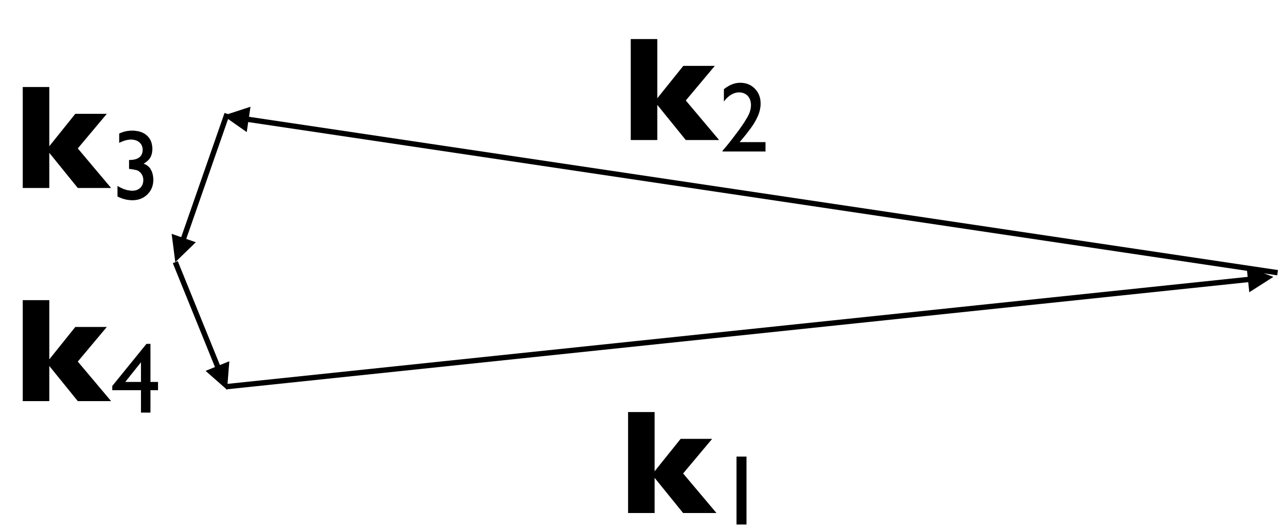
# Summary

- 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**.

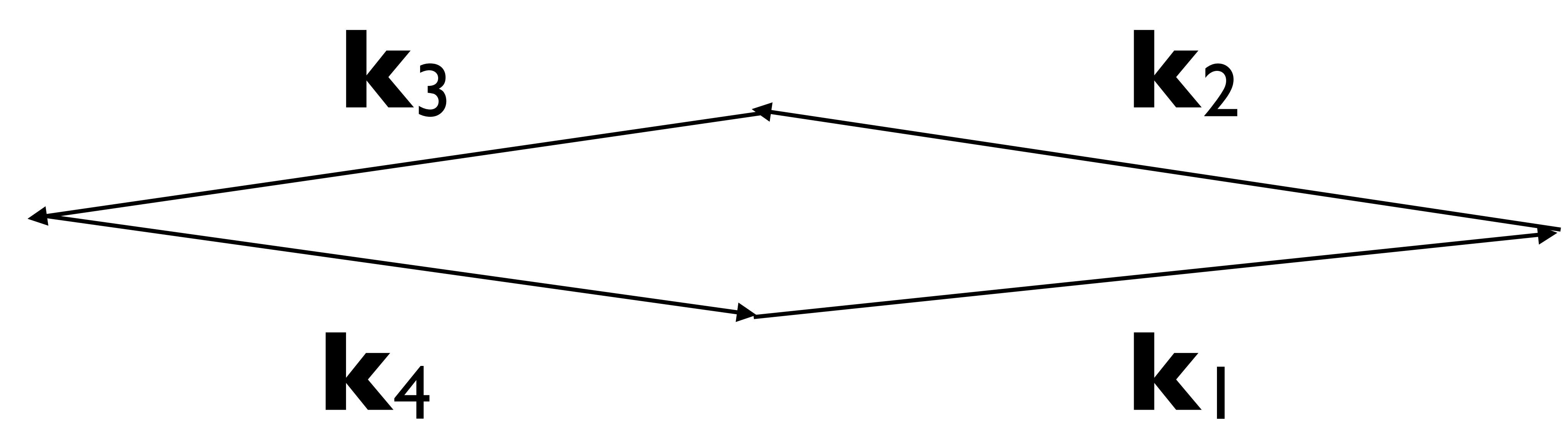
# Trispectrum

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

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

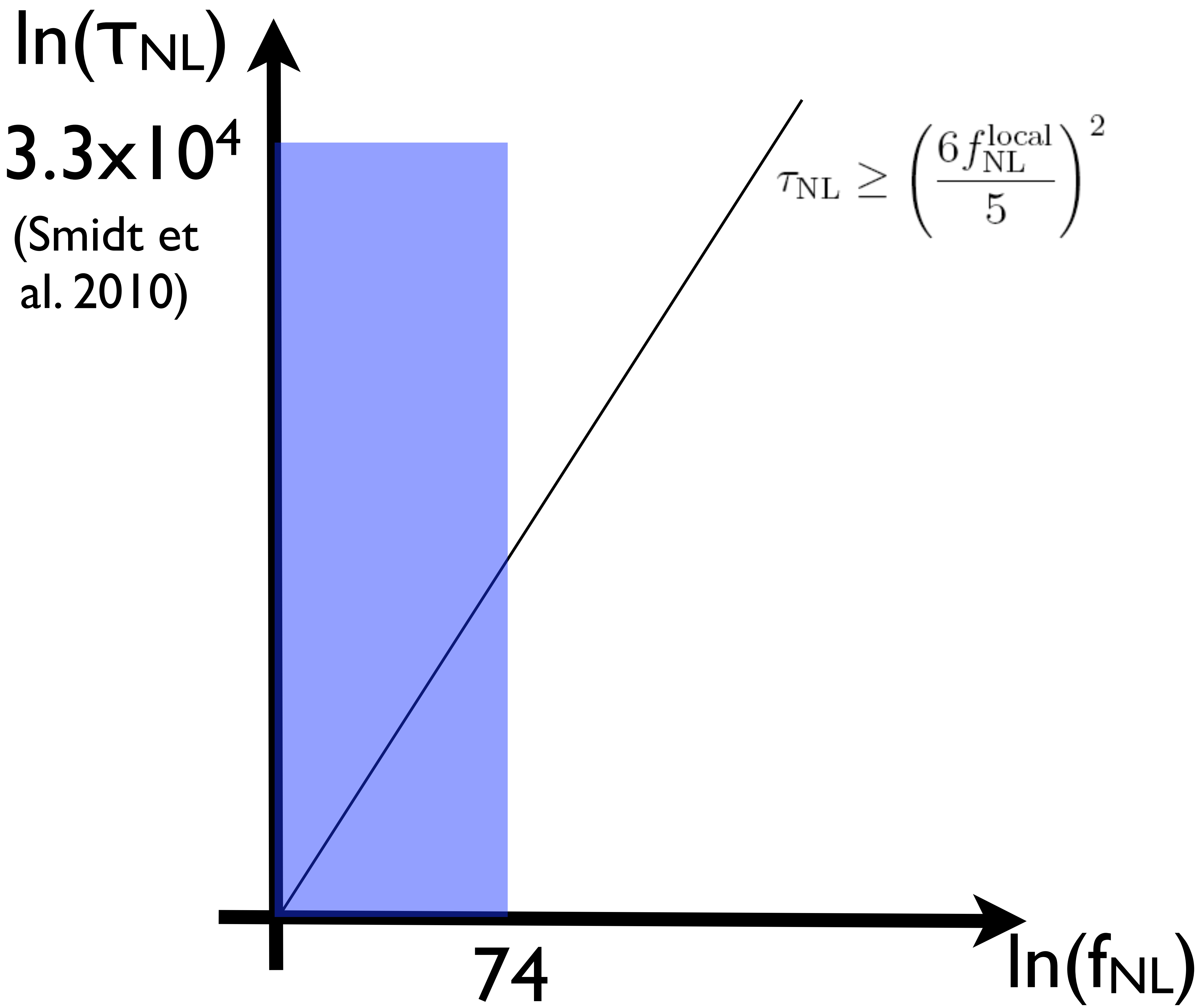



$g_{NL}$



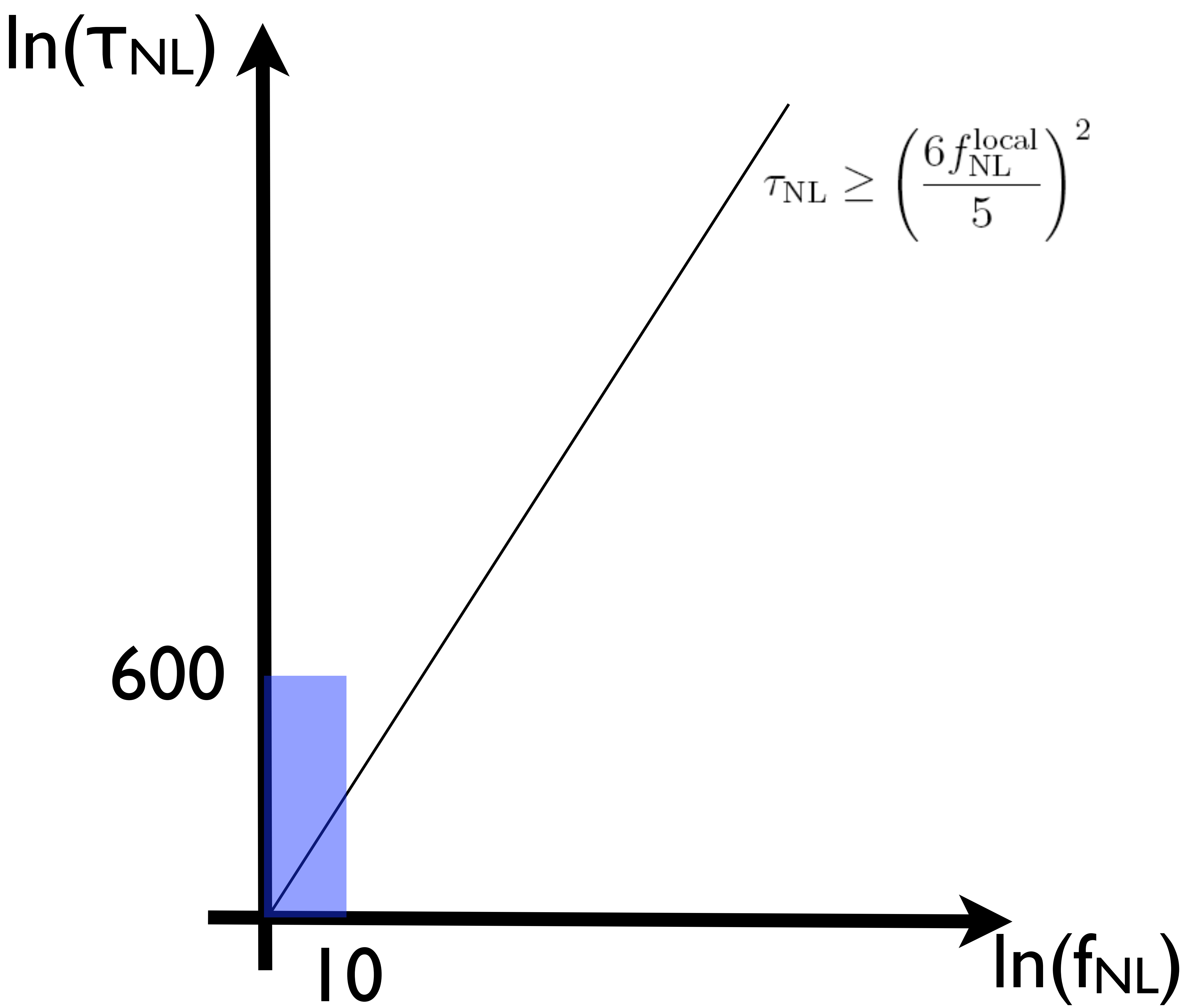

$\tau_{NL}$

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



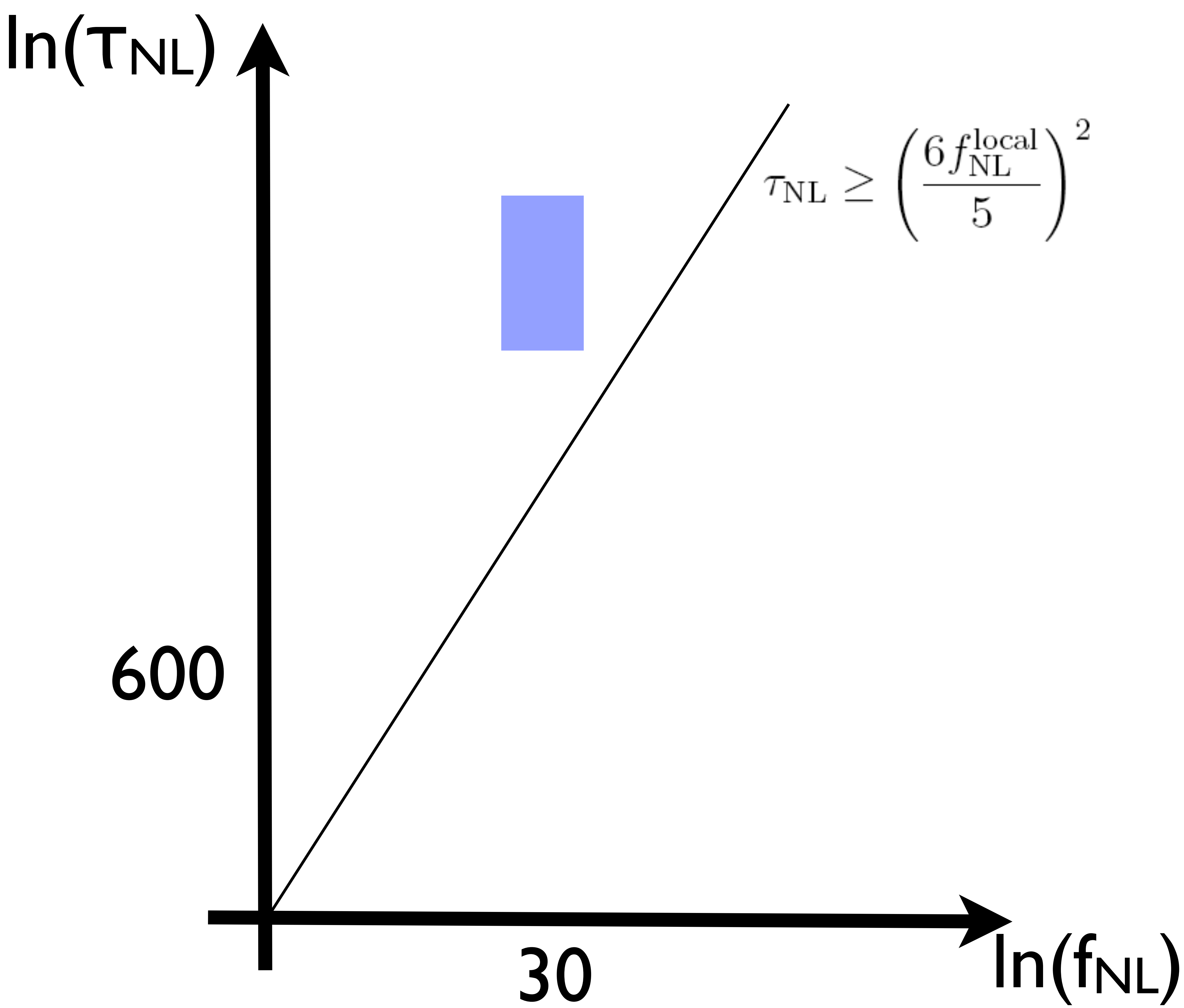

- The current limits from WMAP 7-year are consistent with single-field or multi-field models.
- So, let's play around with the future.

# Case A: Single-field Happiness



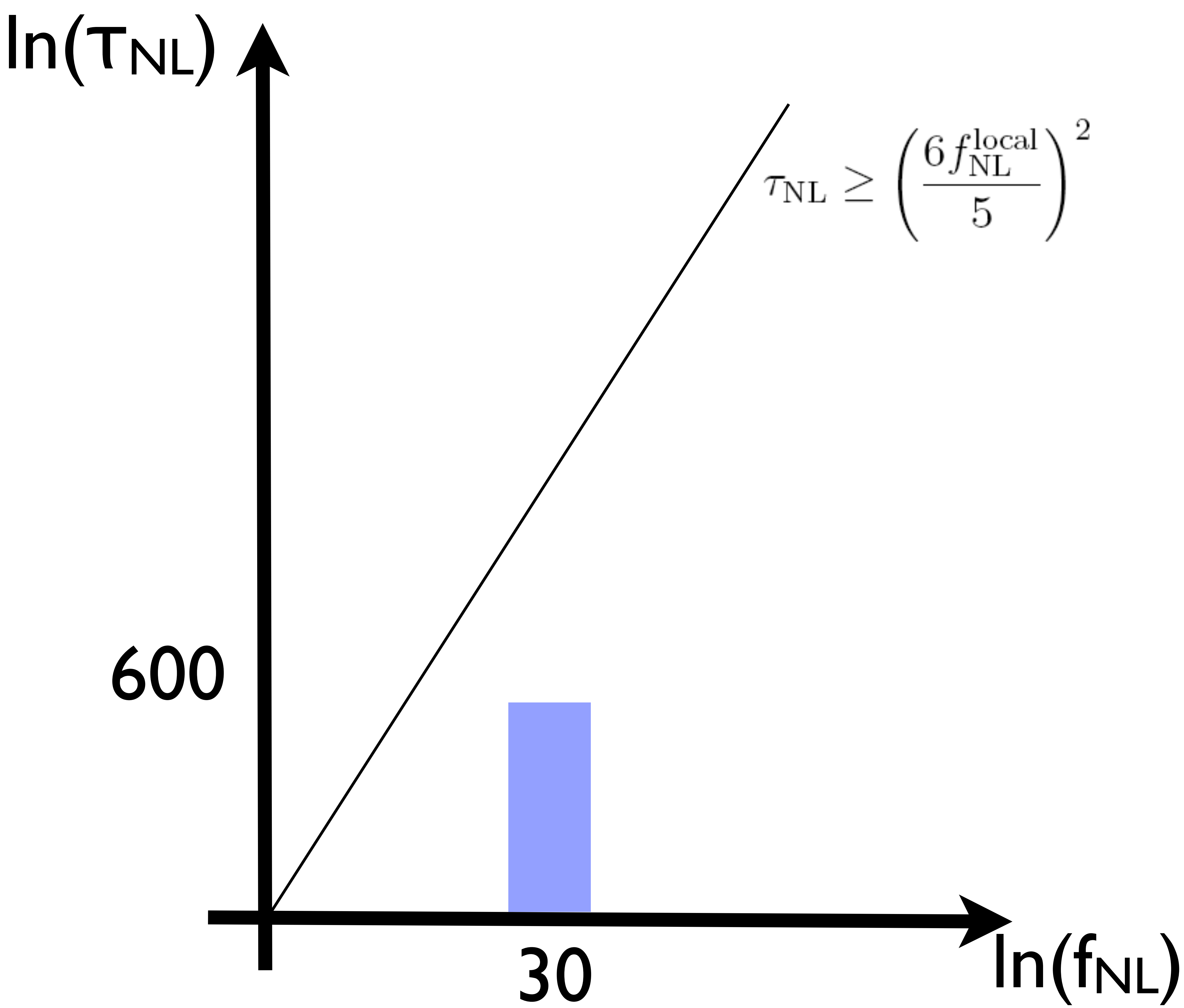

- No detection of anything after Planck. Single-field survived the test (for the moment: the future galaxy surveys can improve the limits by a factor of ten).

# Case B: Multi-field Happiness



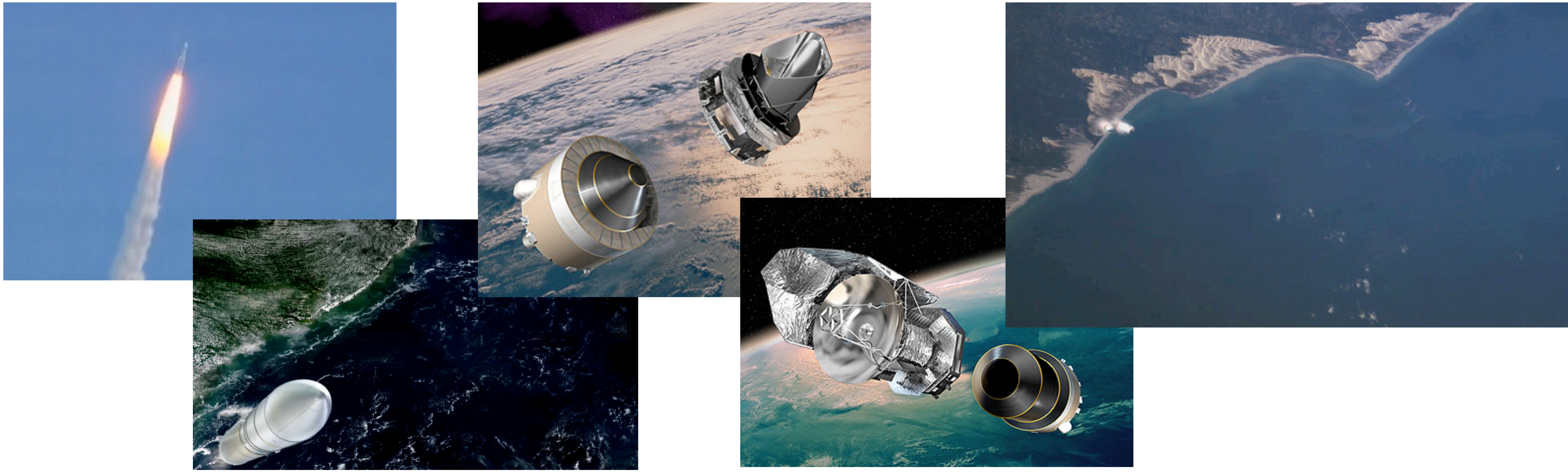

- $f_{NL}$ is detected. Single-field is dead.
- But, $\tau_{NL}$ is also detected, in accordance with the Suyama-Yamaguchi inequality, as expected from most (if not all - left unproven) of multi-field models.

# Case C: Madness



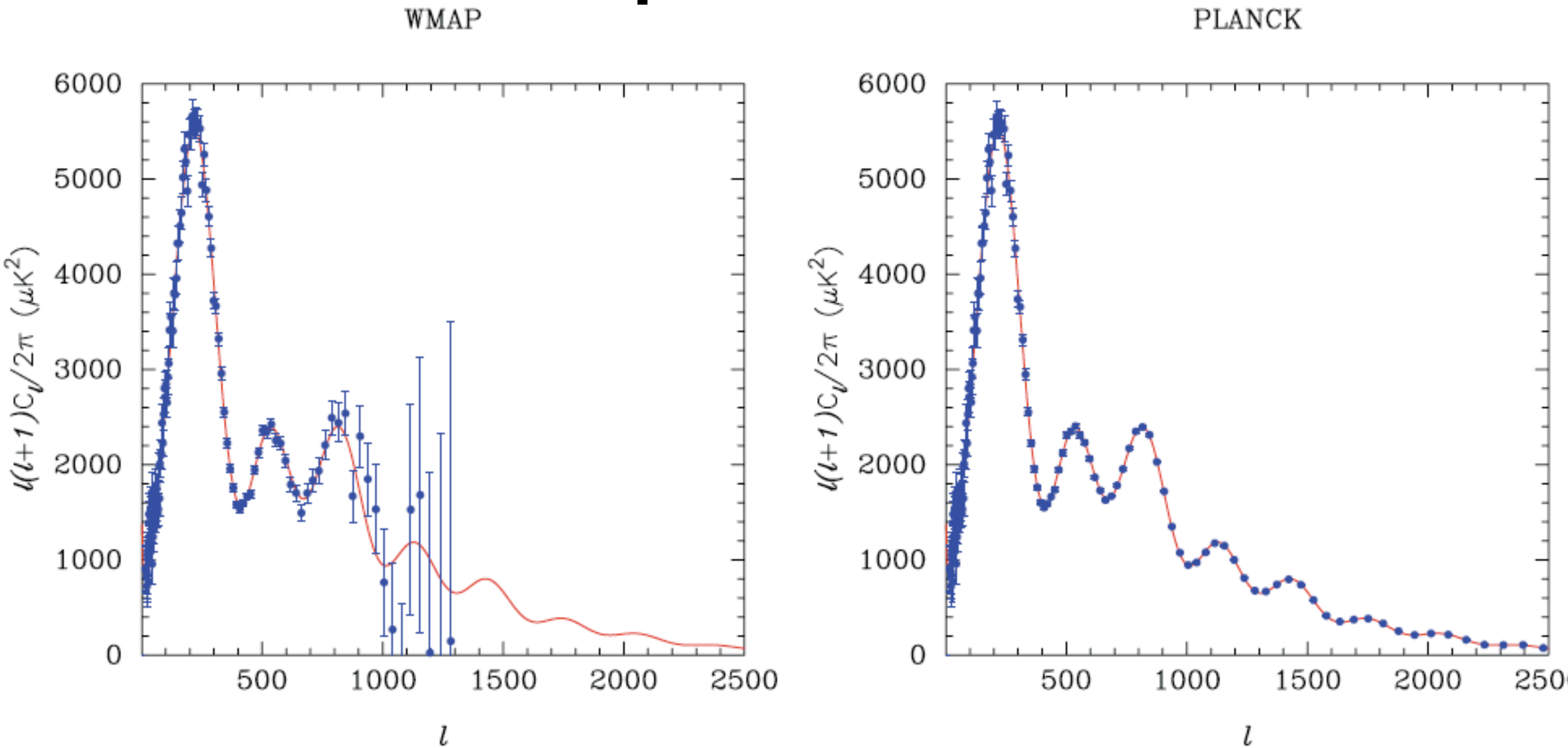

- $f_{NL}$ is detected. Single-field is dead.
- But, $\tau_{NL}$ is **not** detected, inconsistent with the Suyama-Yamaguchi inequality.
- (With the caveat that this may not be completely general) BOTH the single-field and multi-field are gone.

# Planck Launched!



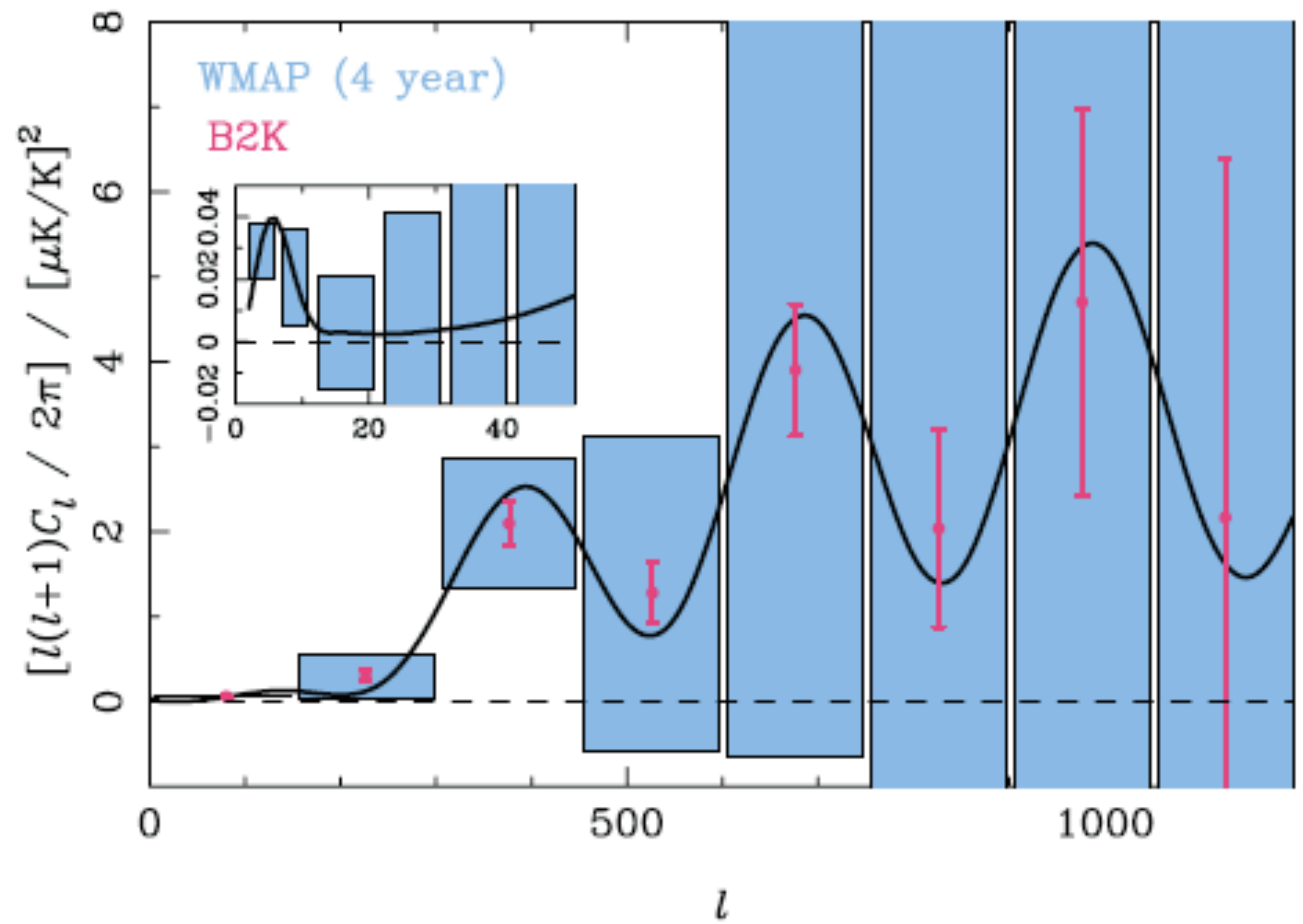
- The Planck satellite was successfully launched from French Guiana on May 14, 2009.
- Separation from the Herschell satellite was also successful.
- Planck has mapped the full sky already - results expected to be released in December, 2012.

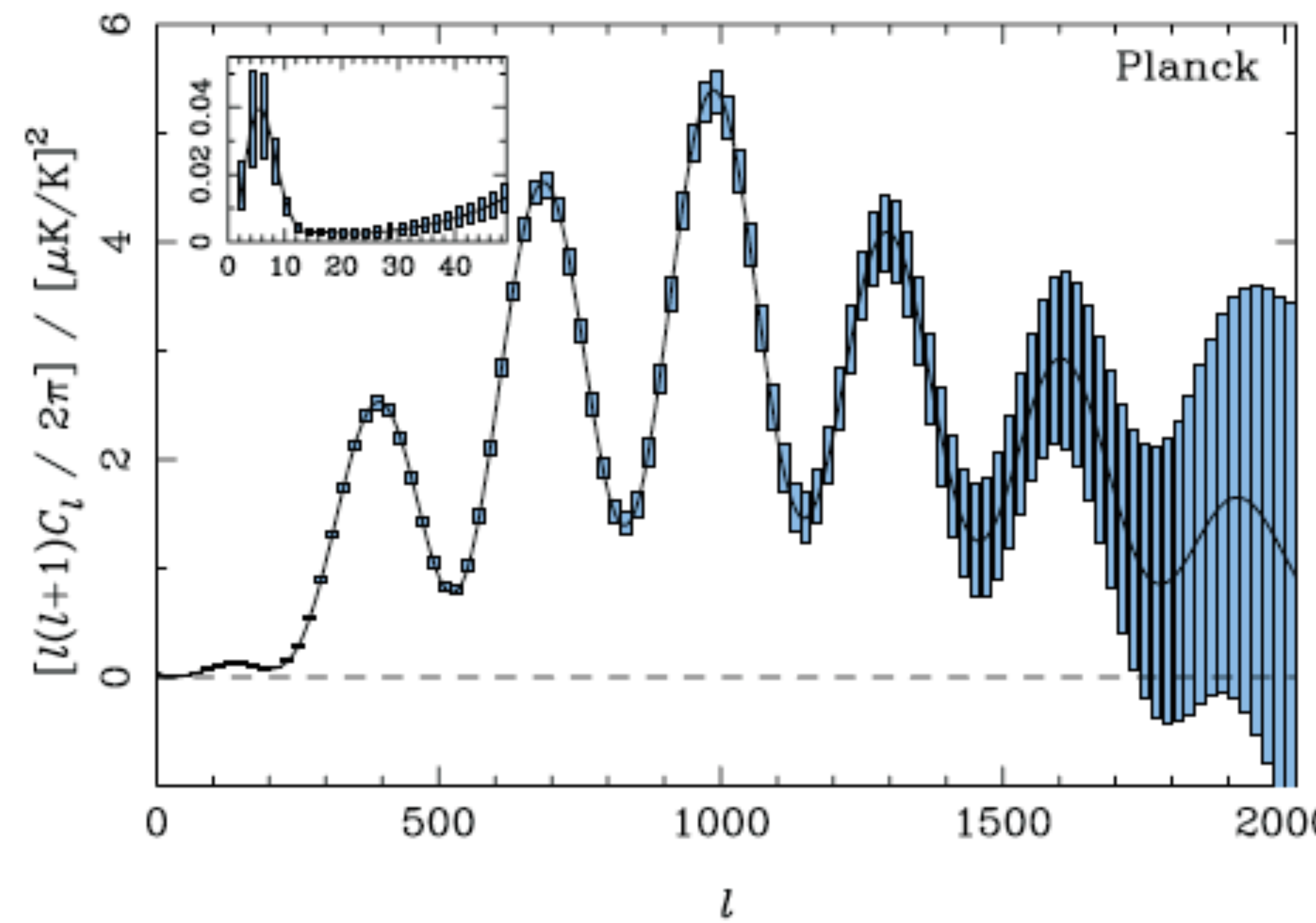
# Planck: Expected $C_l^{Temperature}$

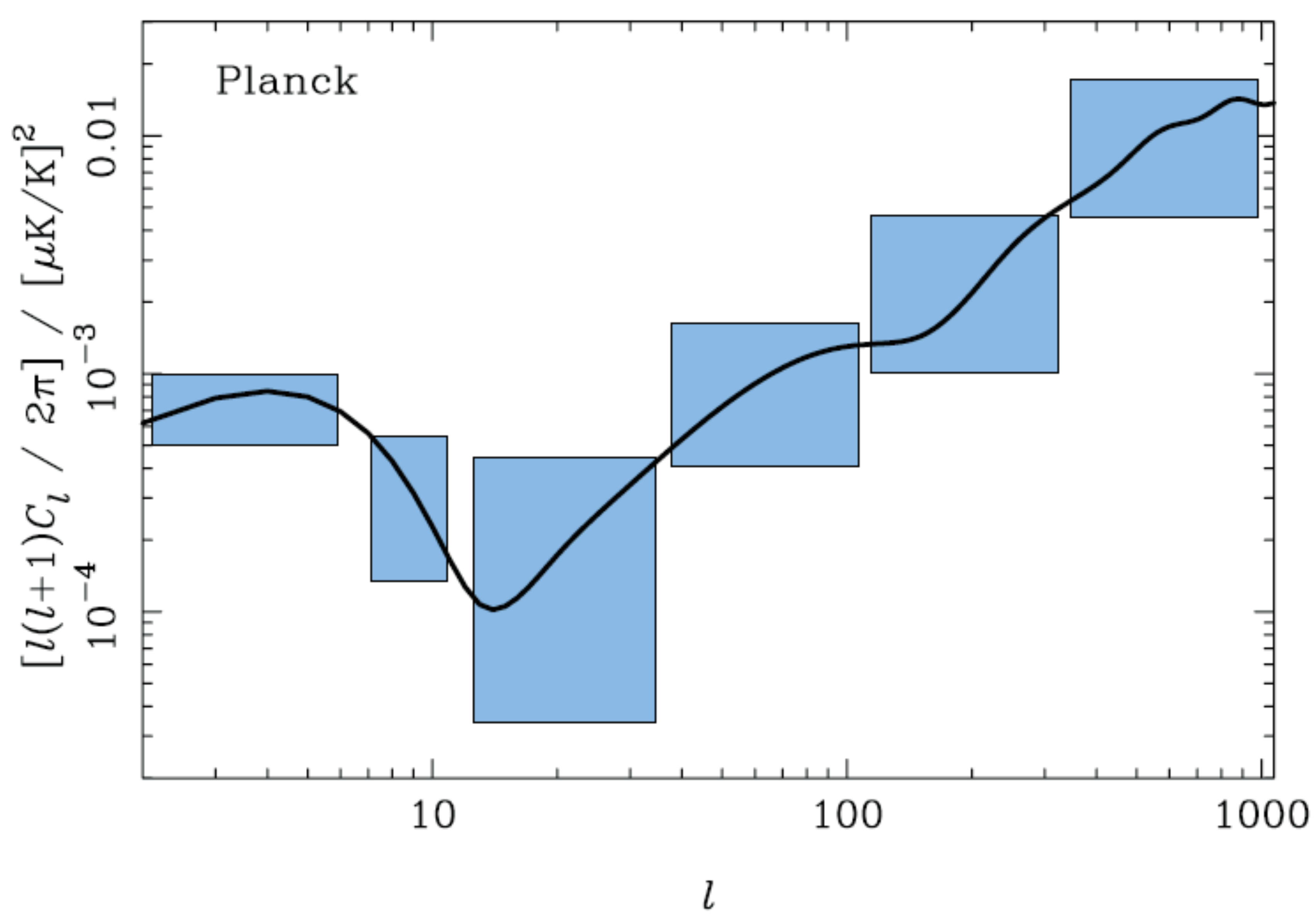



- WMAP: l~1000 => Planck: l~3000

# Planck: Expected $C_l^{Polarization}$

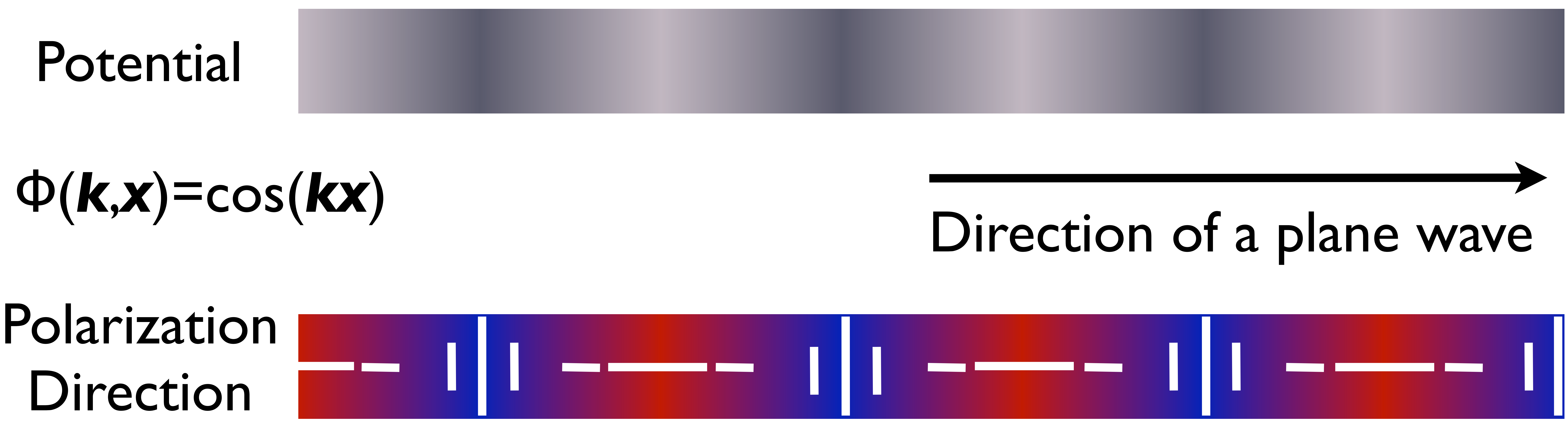



- (Above) E-modes
- (Left) B-modes (r=0.3)

# E-mode



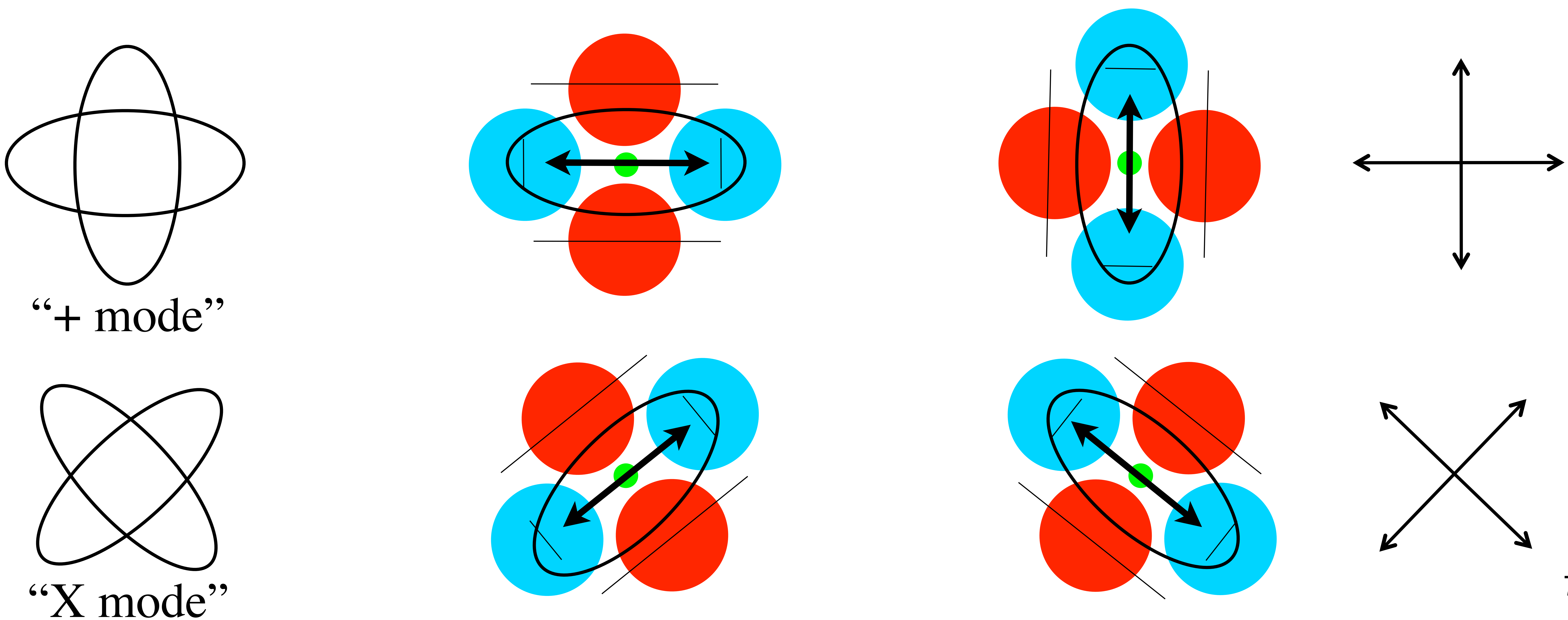

- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

# B-mode

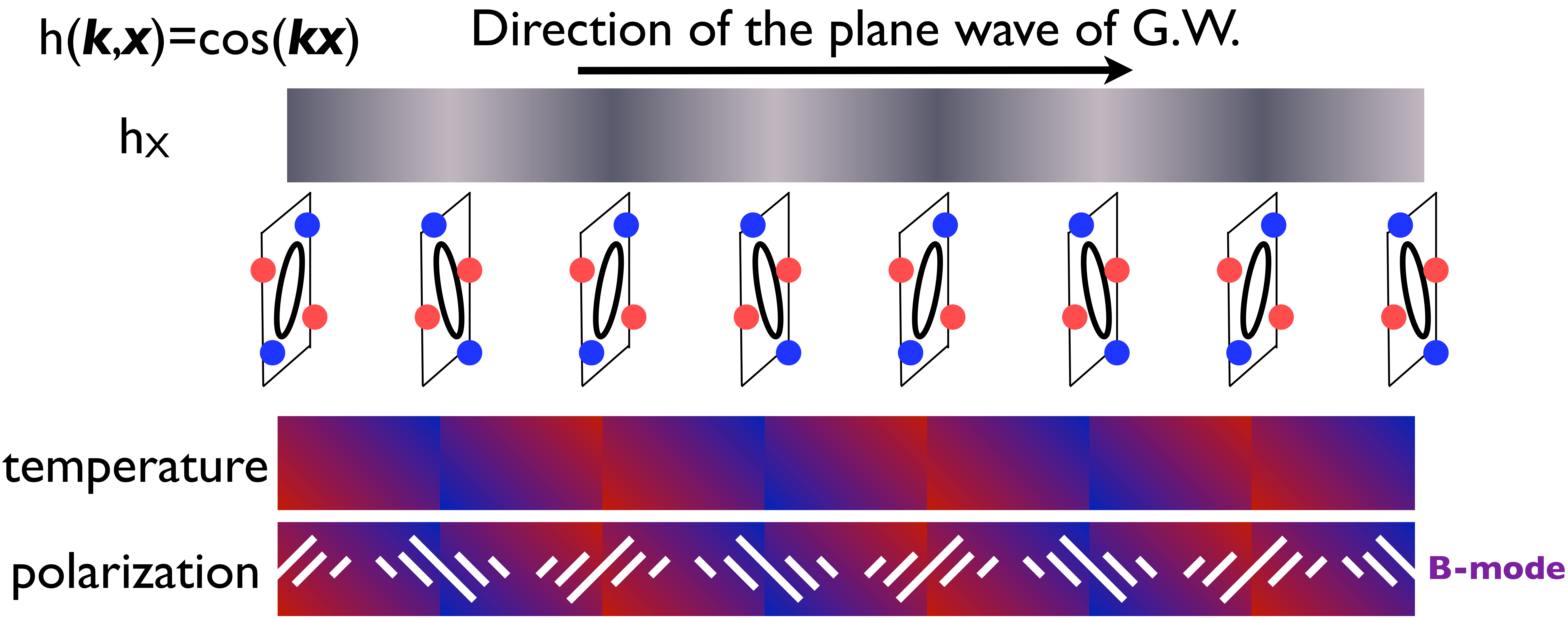

- **B-mode**: the polarization directions are tilted by 45 degrees relative to the direction of the plane wave perturbation.

# Gravitational Waves and Quadrupole

- Gravitational waves stretch space with a quadrupole pattern.



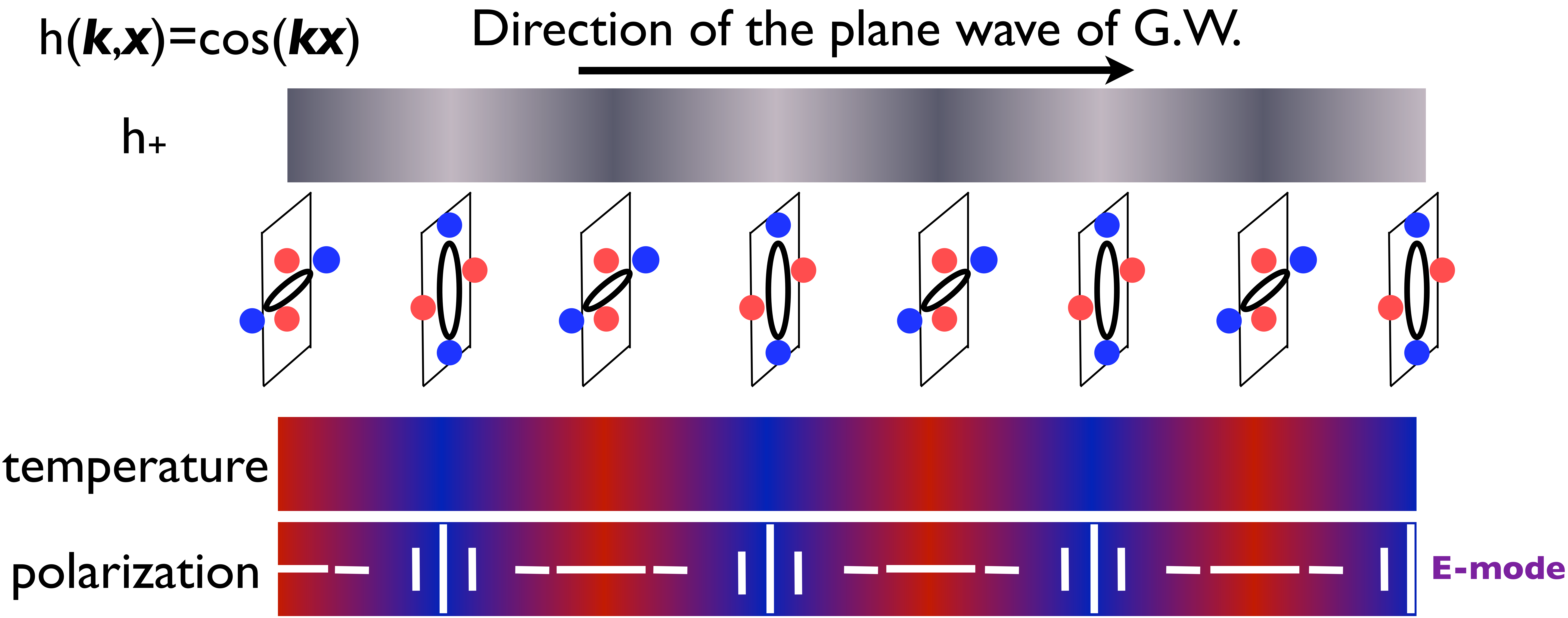
# Quadrupole from G.W.




- B-mode polarization generated by hx

# Quadrupole from G.W.

h(***k***,***x***)=cos(***kx***)




- E-mode polarization generated by h+