Physics of theCosmic Microwave Background

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Guest Lecture, Universität Würzburg, April 17, 2014

Cosmology: The Questions

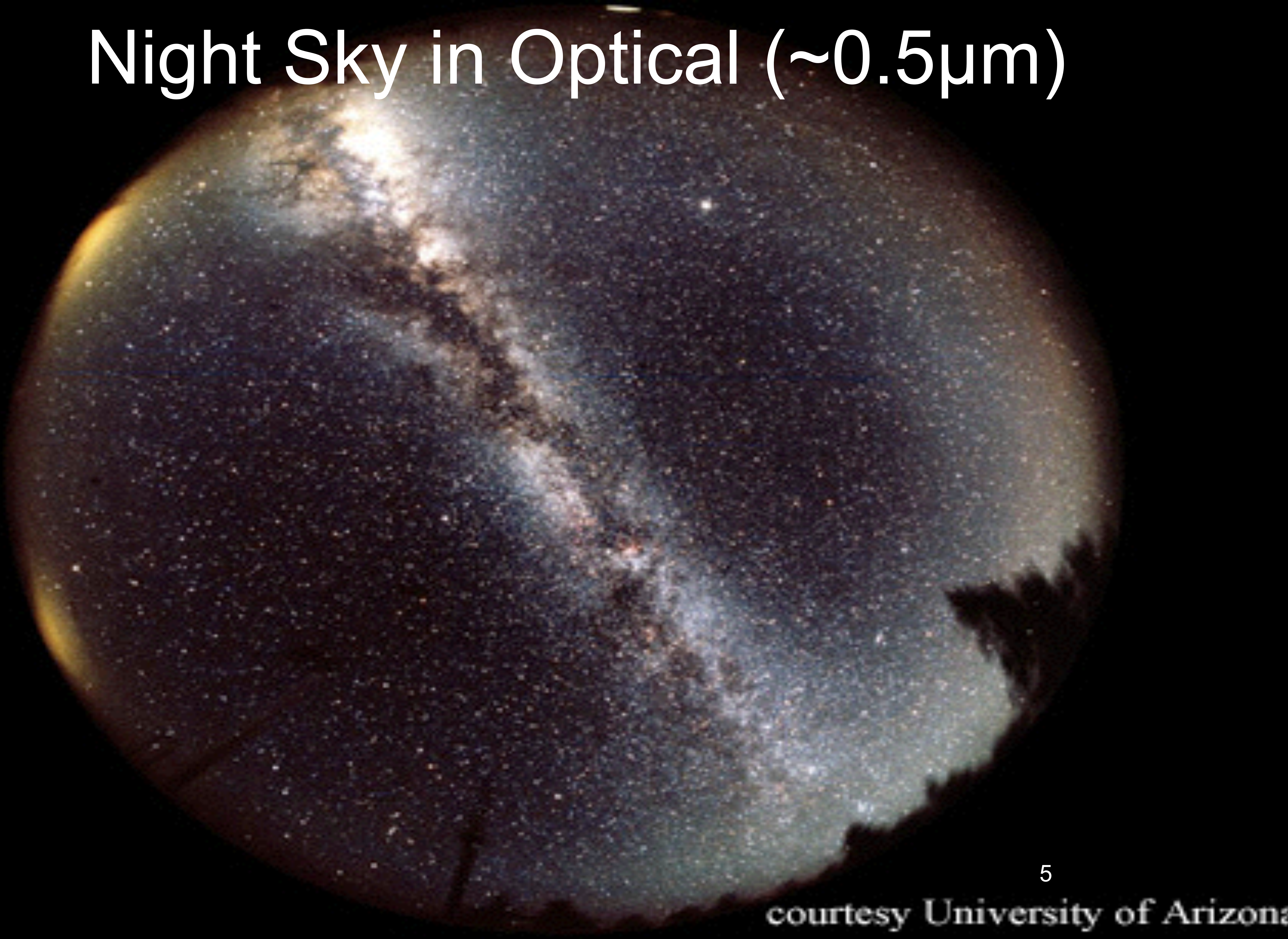
- How much do we understand our Universe?
  - How old is it?
  - How big is it?
  - What shape does it take?
  - What is it made of?
  - How did it begin?

The Breakthrough

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

From "Cosmic Voyage"

Night Sky in Optical (~0.5μm)

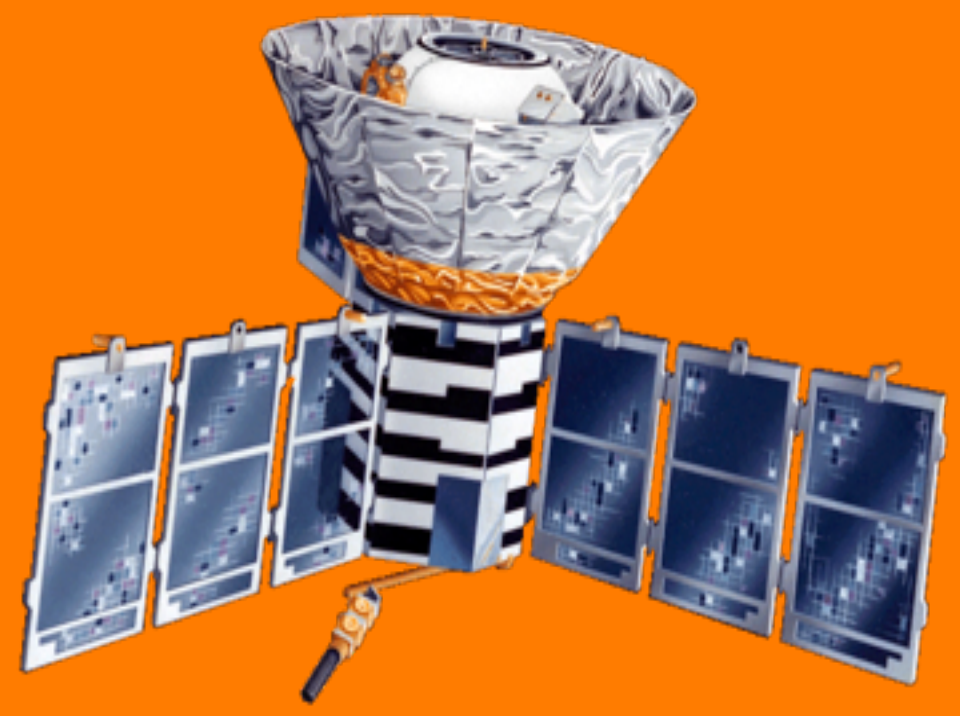


Night Sky in Microwave (~1mm)

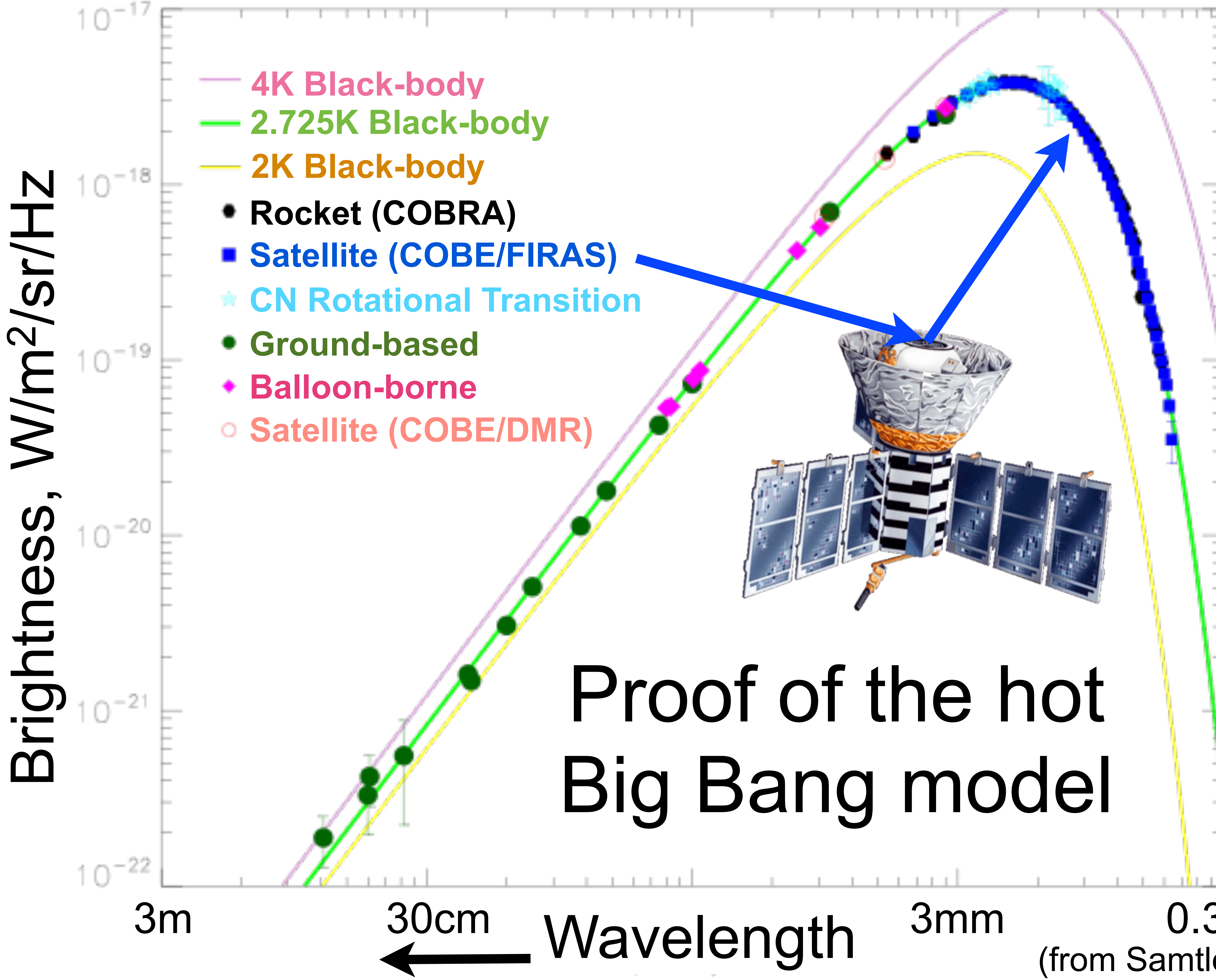
courtesy University of Arizona

Night Sky in Microwave (~1mm)

T_{today}=2.725K

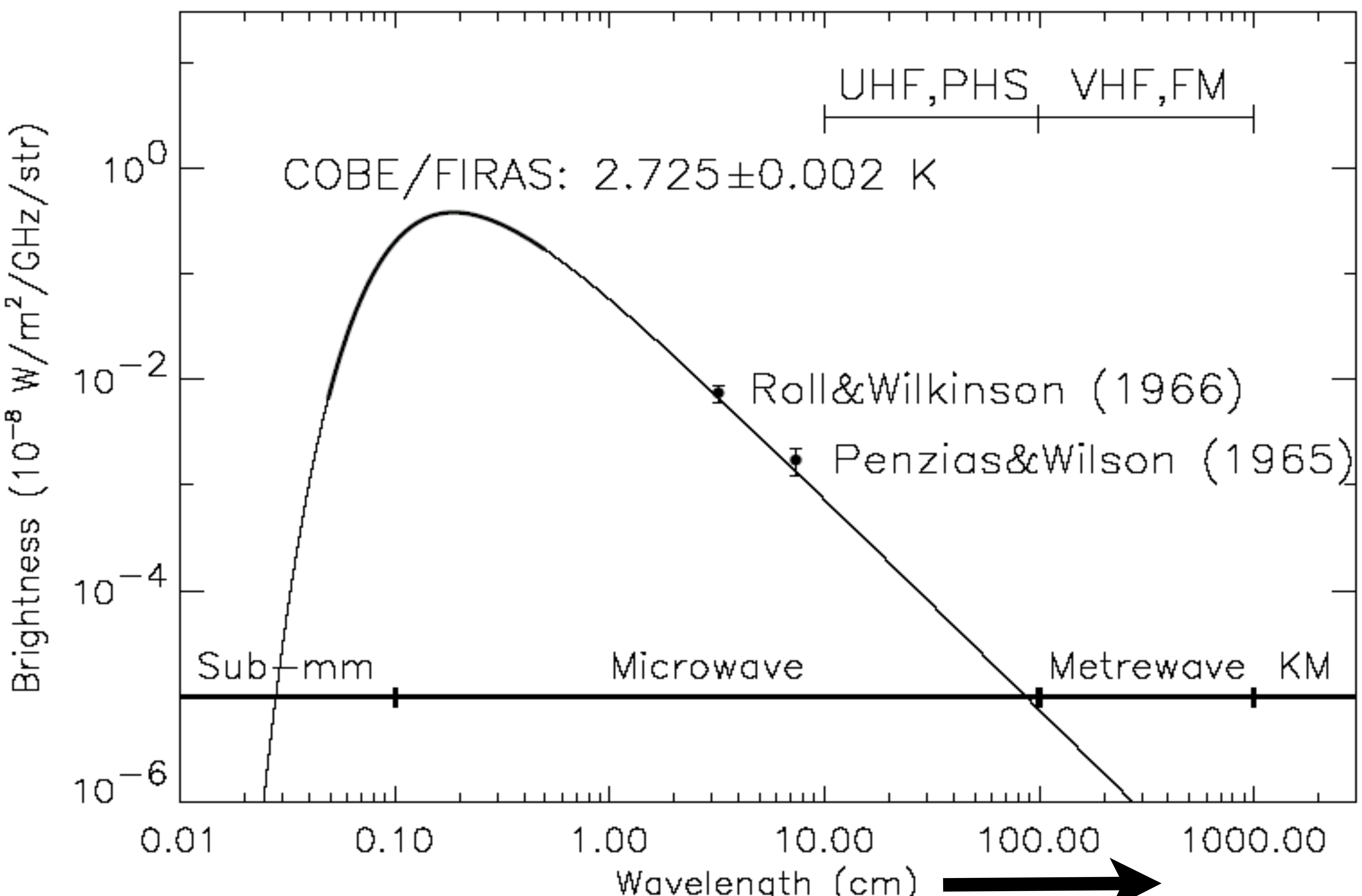


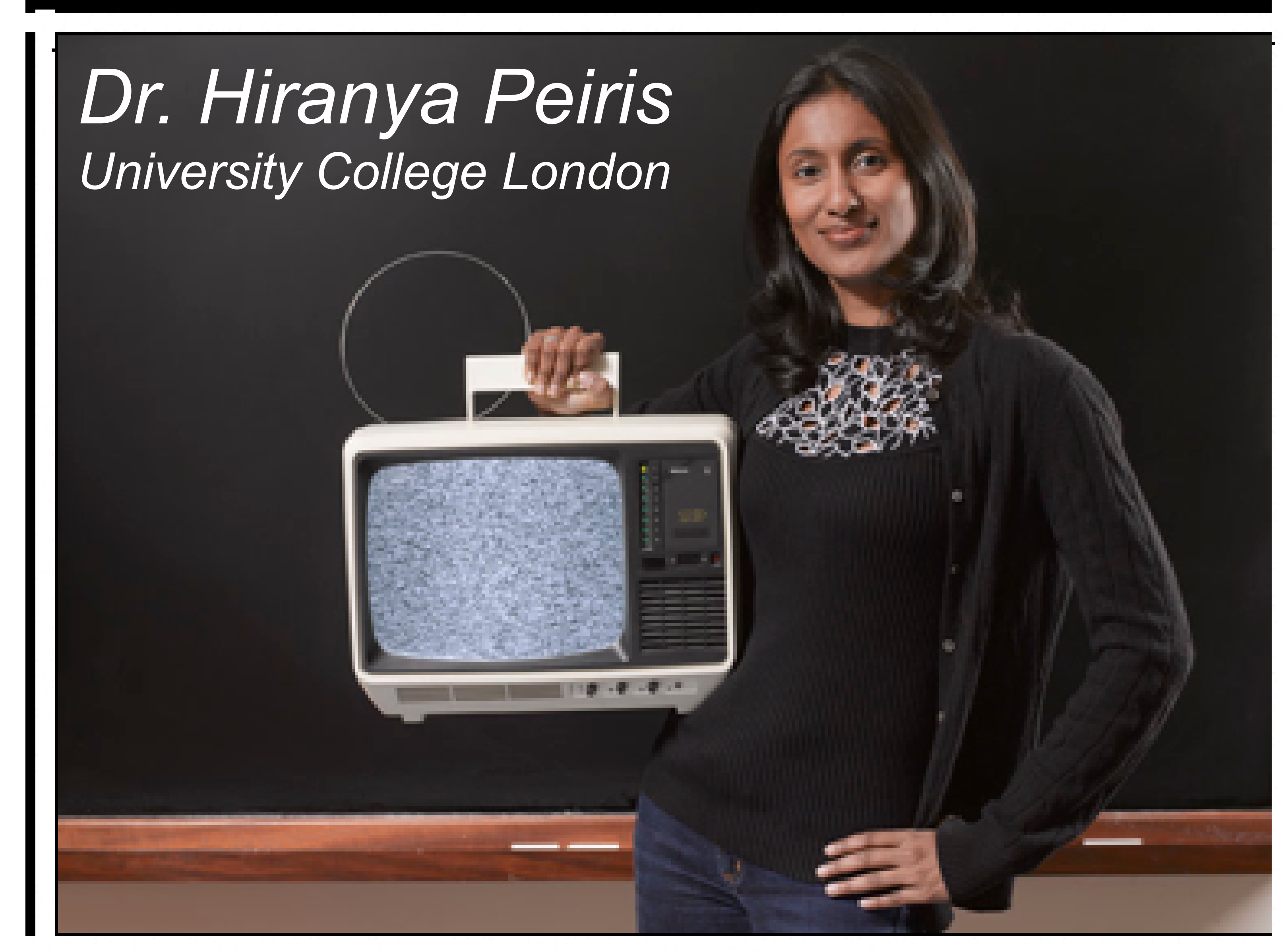
COBE Satellite, 1989-1993



(from Samtleben et al. 2007)

- The spectrum of CMB has a peak at 1.1mm.
- Let's compare it with…
  - –Microwave oven: 12cm
  - –Cellular phone: 20cm
  - –UHF Television: 39-64cm
  - –FM radio: 3m
  - –AM radio: 300m





You can "see" CMB by TV (not by a cable TV of course!).

Perhaps you can "hear" CMB by a cell phone?

Arno Penzias & Robert Wilson, 1965

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

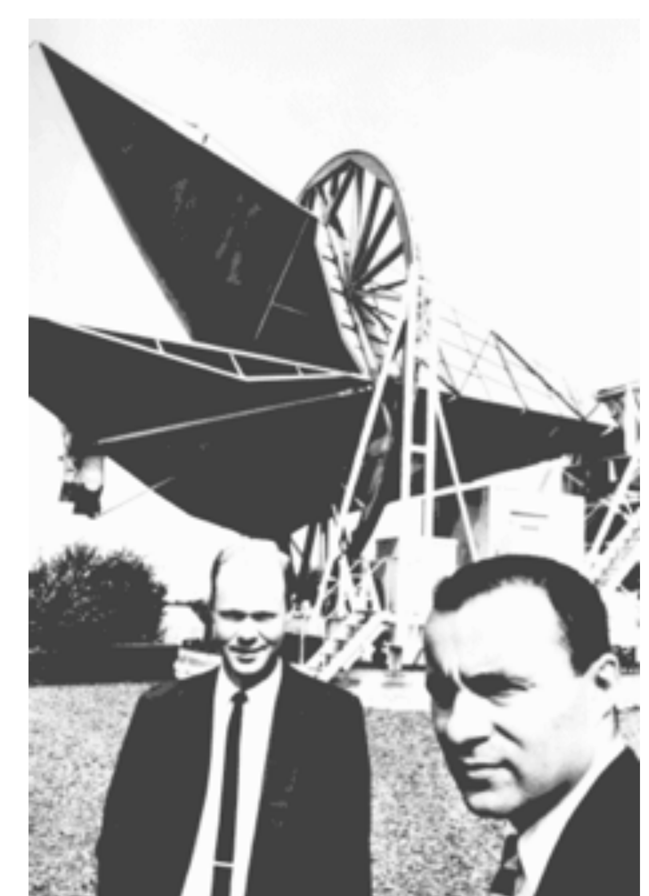
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our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

- **Isotropic**

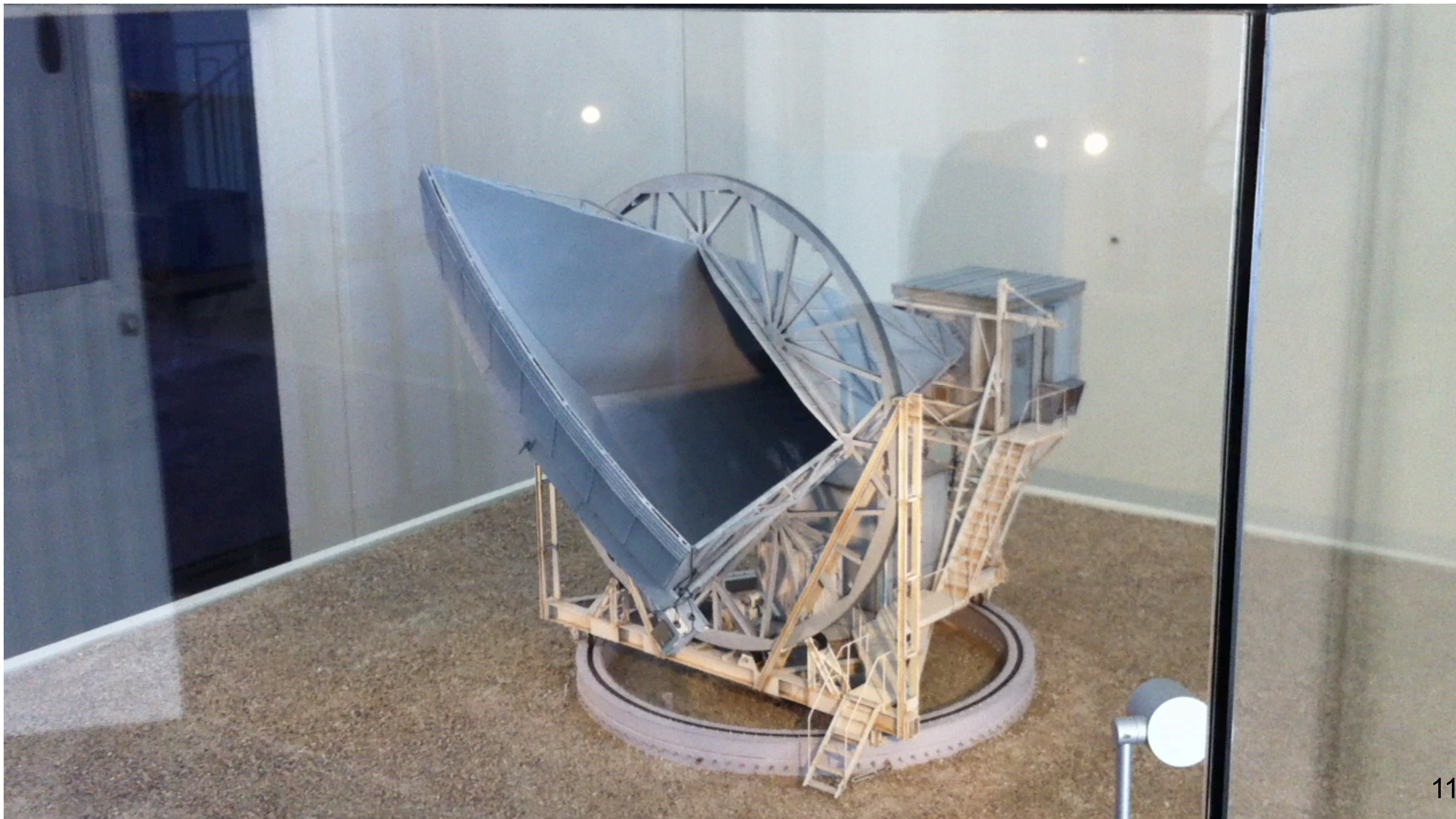
A. A. Penzias
R. W. Wilson

May 13, 1965

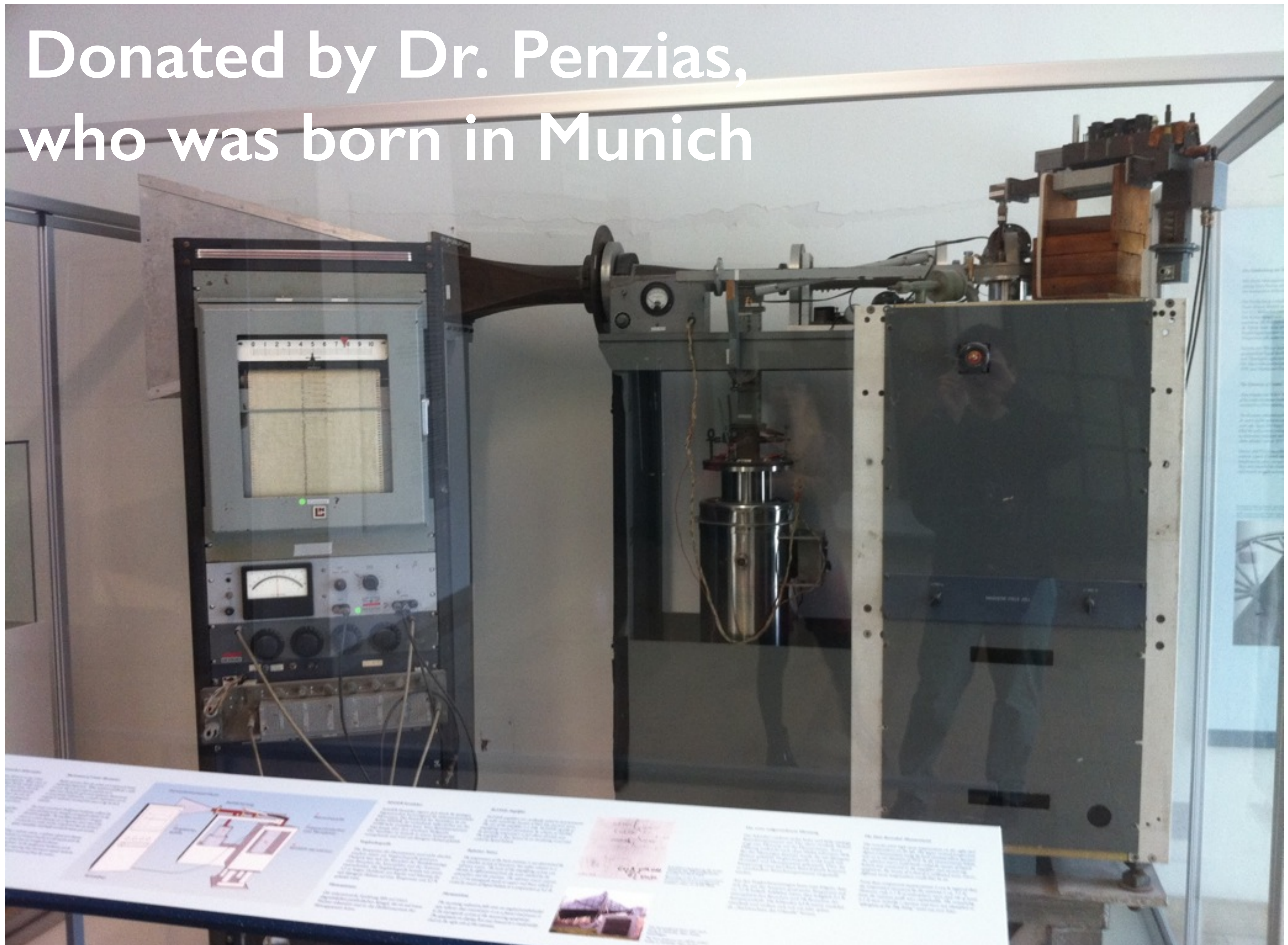
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

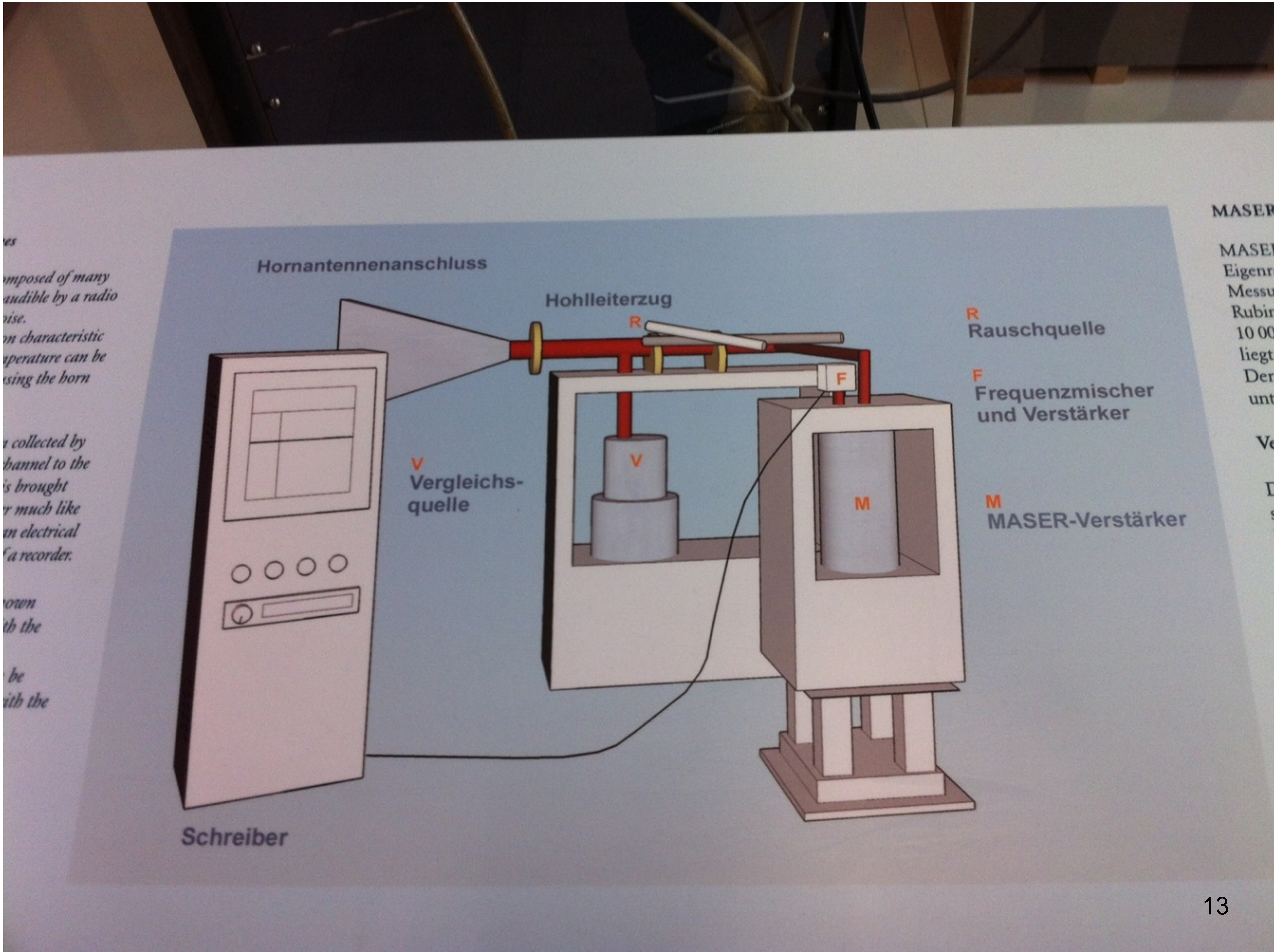


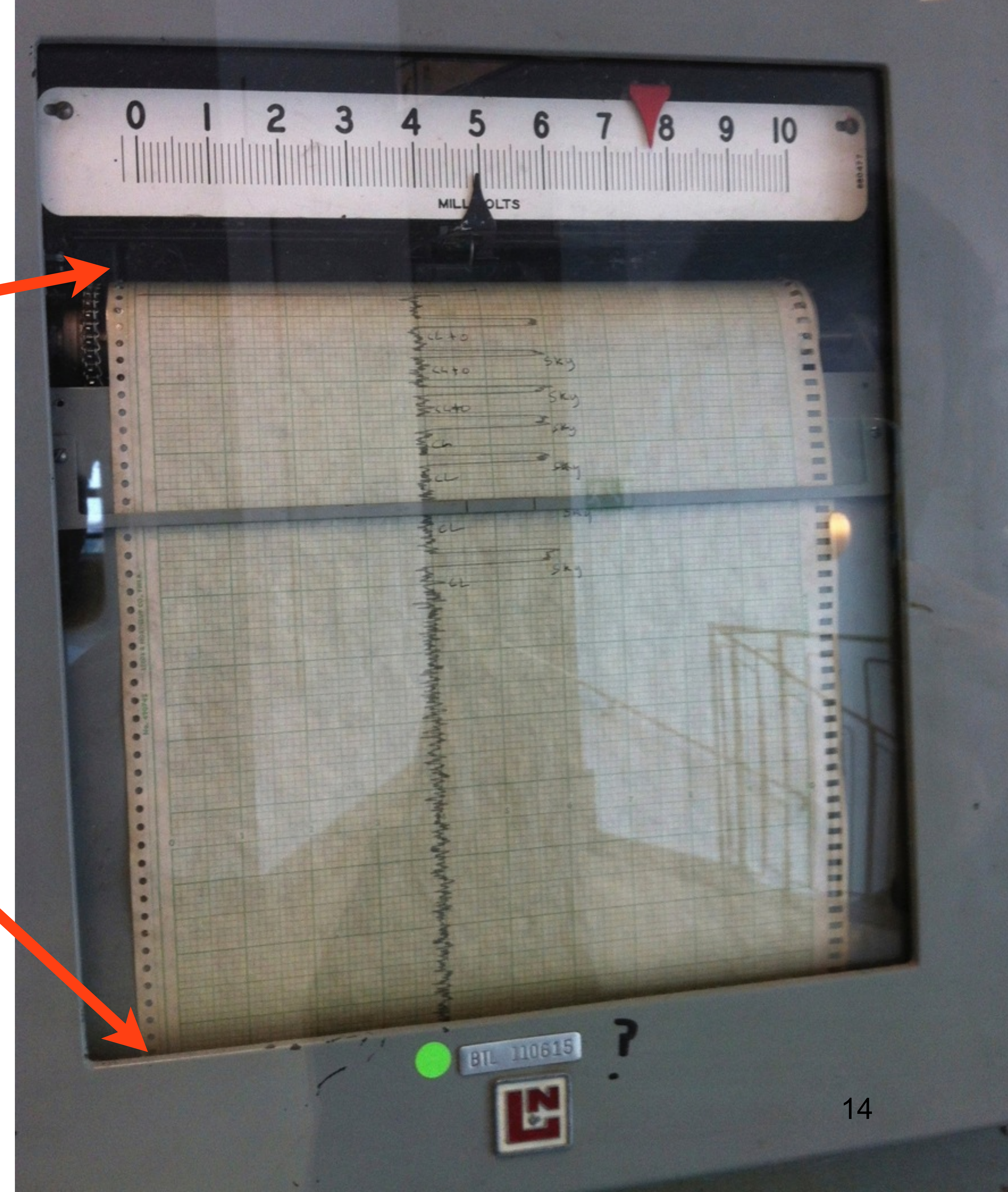
1:25 model at Deutsches Museum



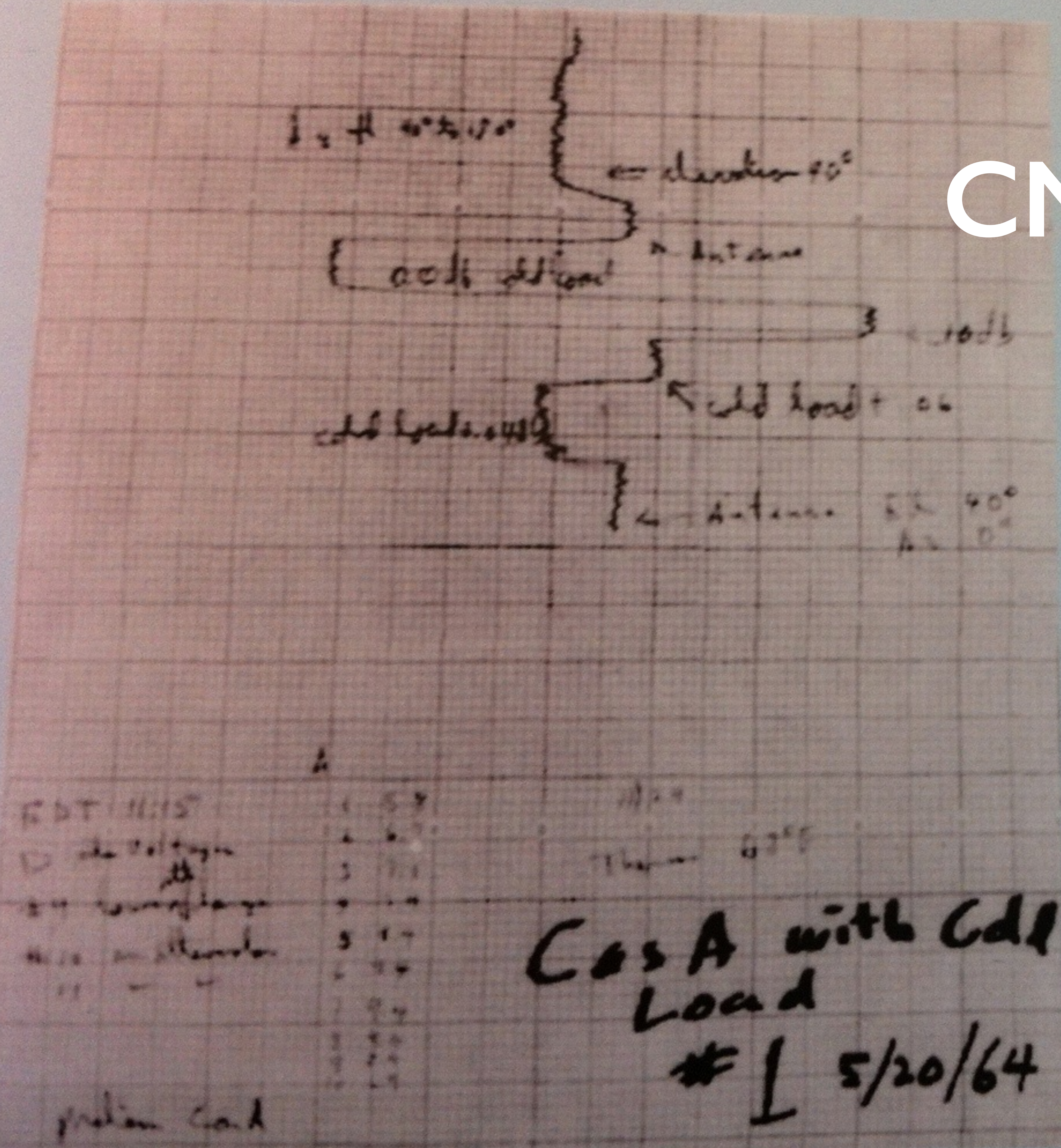
The REAL back-end system of the Penzias-Wilson experiment, exhibited at Deutsches Museum




Hornantennenanschluss
Hohlleiterzug
R
Rauschquelle
F
Frequenzmischer
und Verstärker
V
Vergleichs-
quelle
M
MASER-Verstärker
Schreiber


0 1 2 3 4 5 6 7 8 9 10
BTL 110615

May 20, 1964
CMB "Discovered"



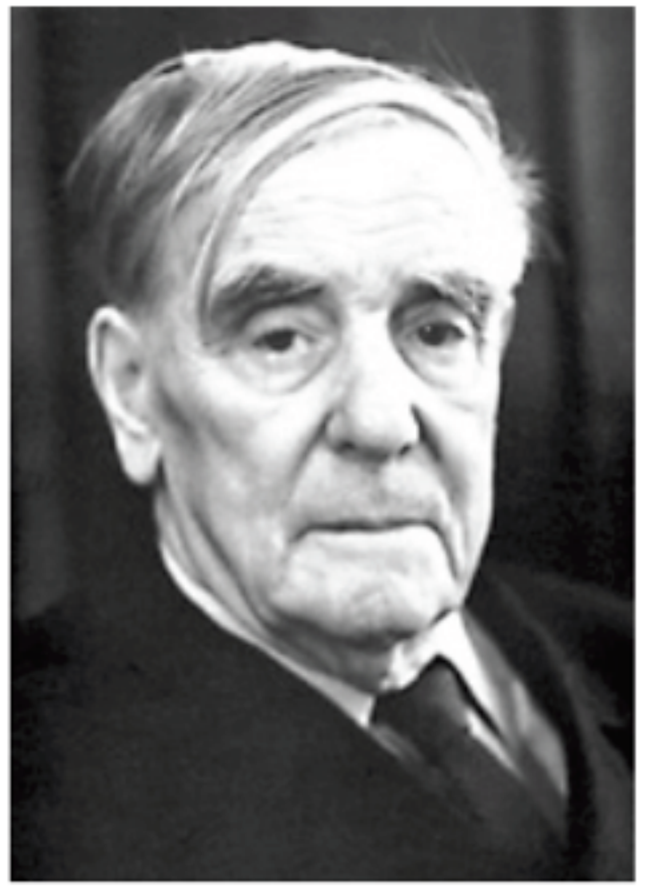
Schreiberaufzeichnung der ersten Messung des Mikrowellenhintergrundes am 20.5.1964

Recording of the first measurement of cosmic microwave background radiation taken on 5/20/1964.

The Nobel Prize in Physics 1978

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

"For their discovery of cosmic microwave background radition"



Pyotr Leonidovich Kapitsa

1/2 of the prize

USSR

Academy of Sciences
Moscow, USSR

b. 1894
d. 1984

Arno Allan Penzias

1/4 of the prize

USA

Bell Laboratories
Holmdel, NJ, USA

b. 1933
(in Munich, Germany)

Robert Woodrow Wilson

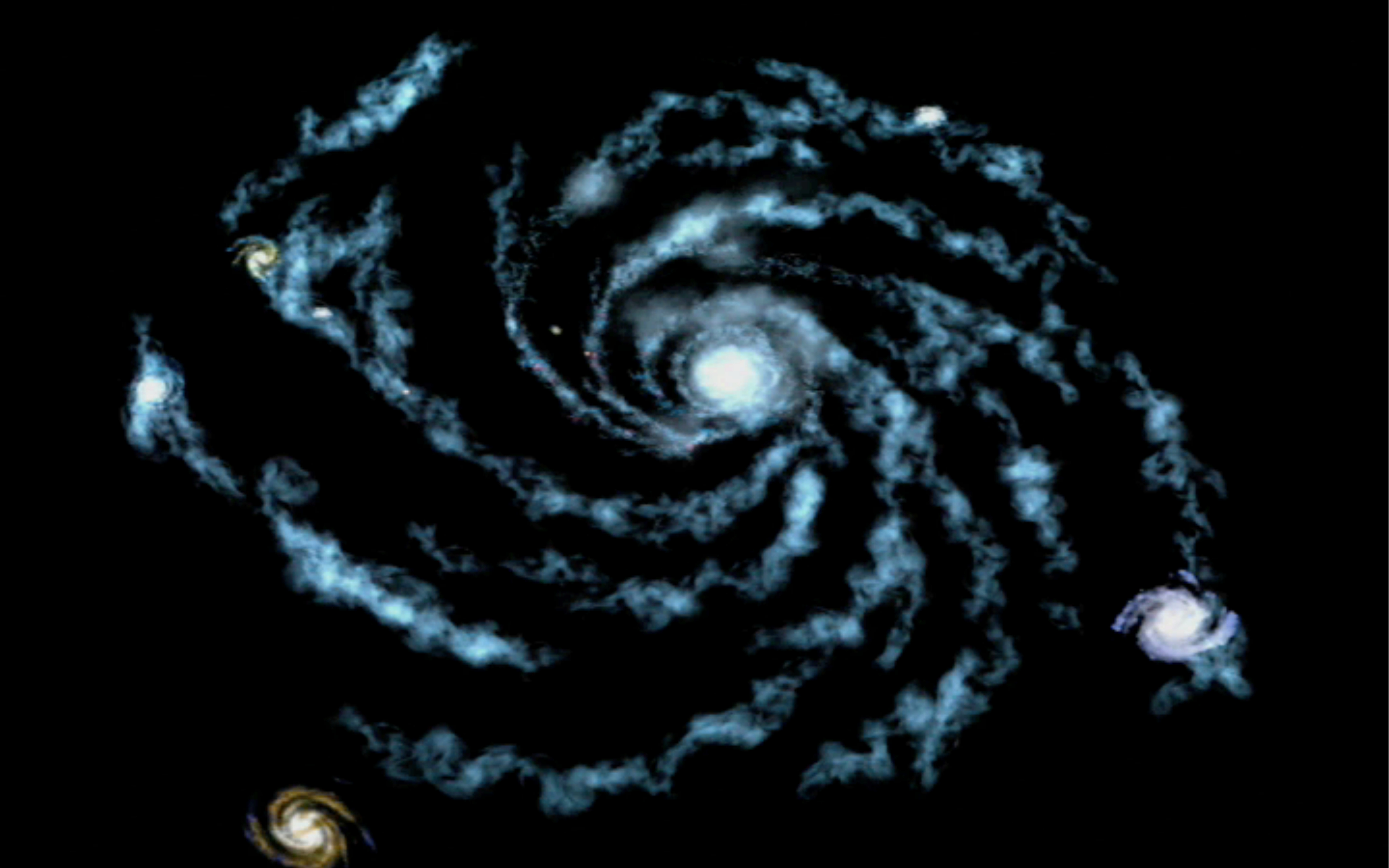
1/4 of the prize

USA

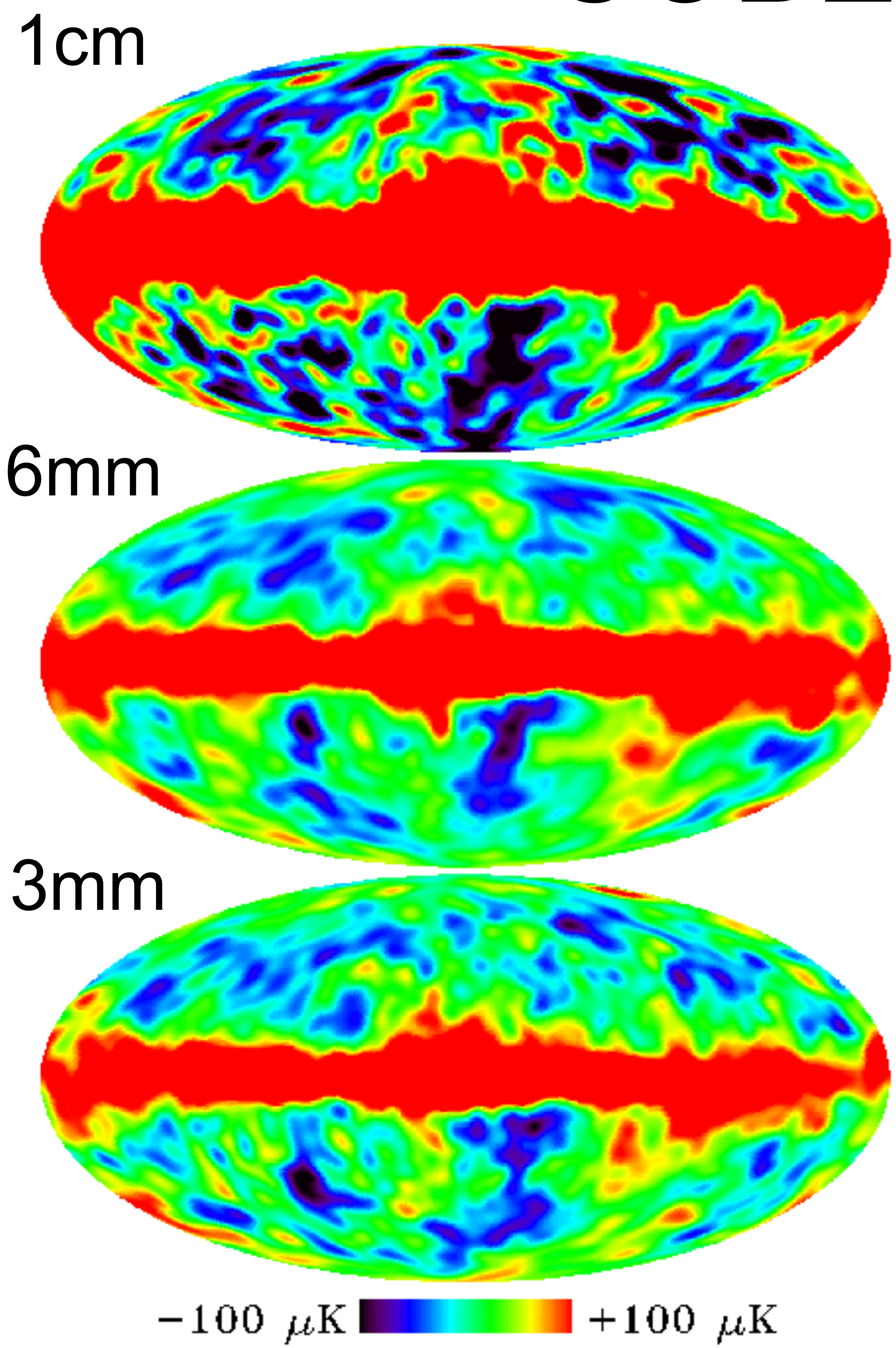
Bell Laboratories
Holmdel, NJ, USA

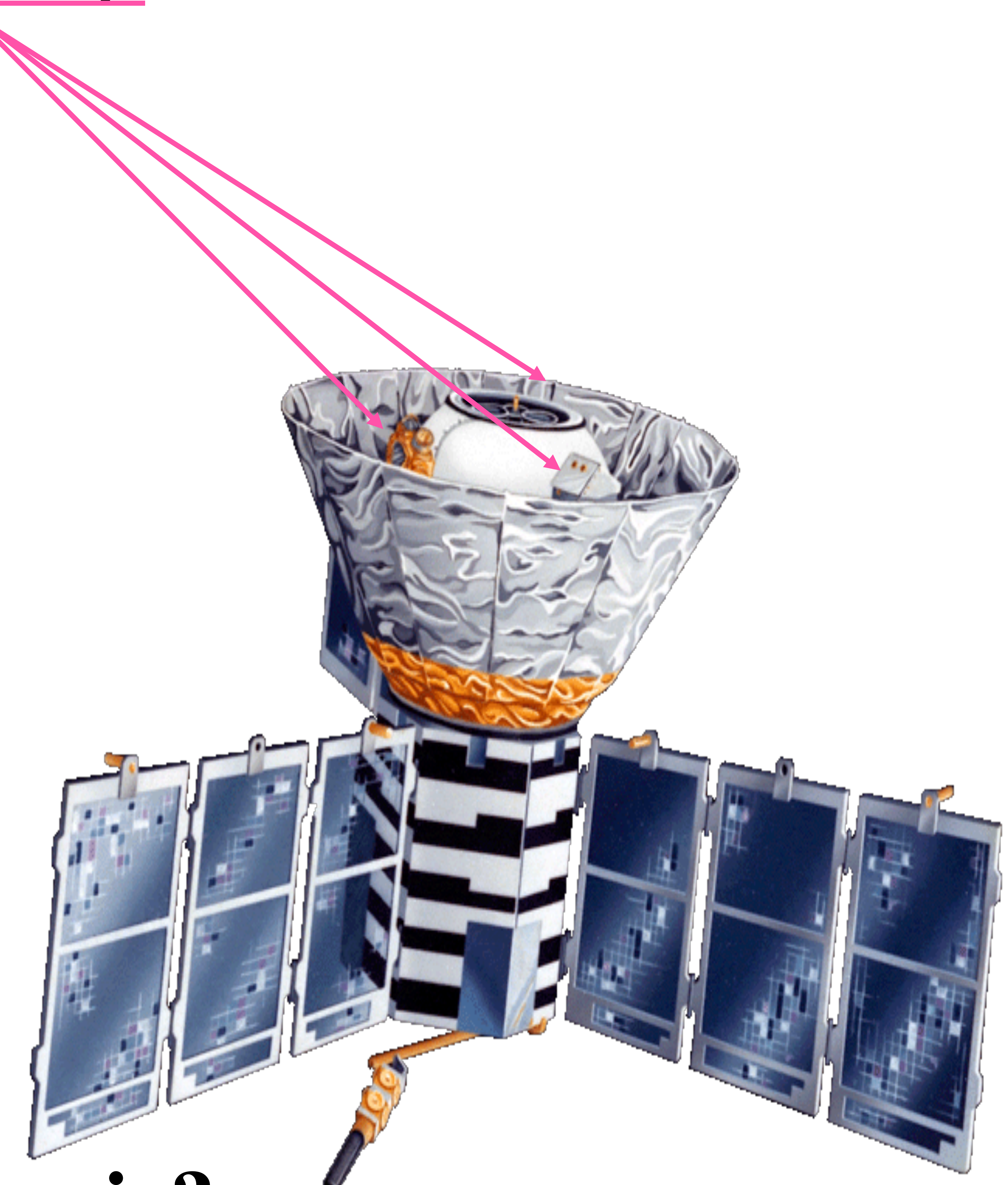
b. 1936

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



COBE/DMR, 1992

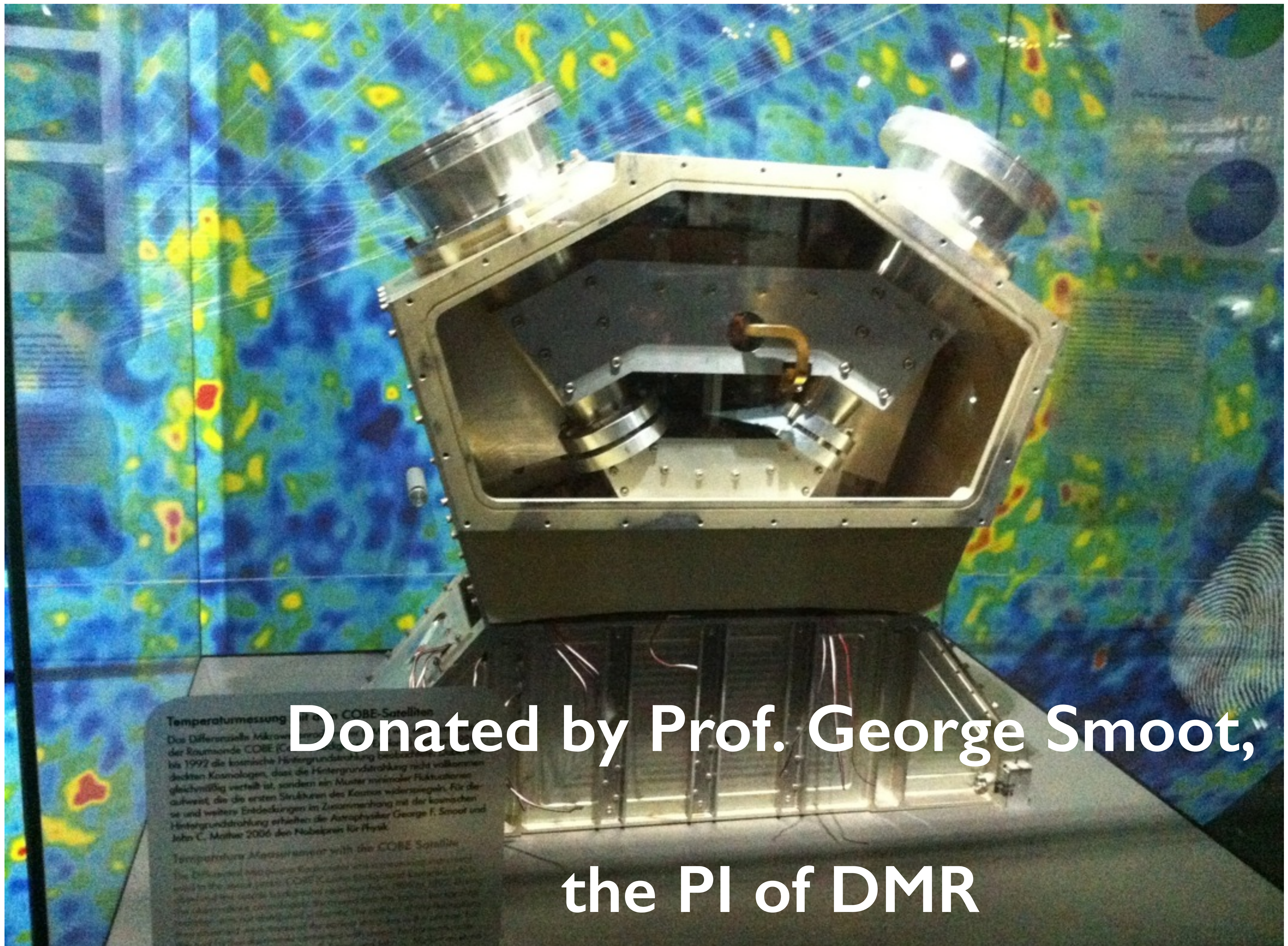




•Isotropic?

•CMB is anisotropic! (at the 1/100,000 level)

A spare unit of COBE/DMR (λ=1cm)



Donated by Prof. George Smoot,

the PI of DMR

The Nobel Prize in Physics 2006

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

Photo: NASA

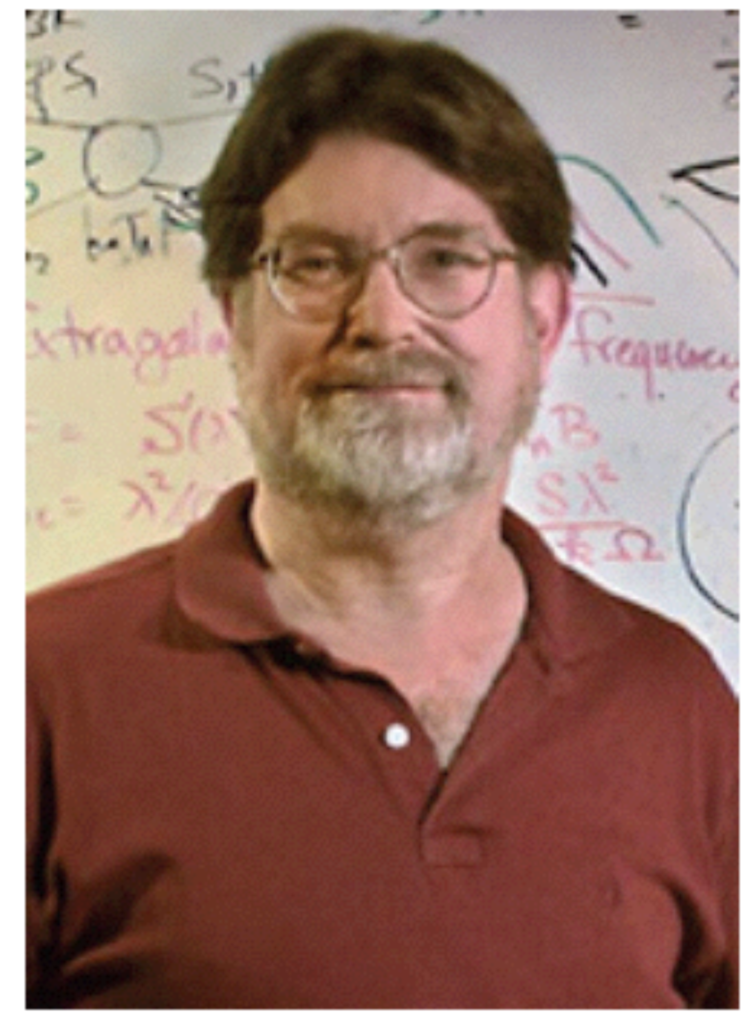


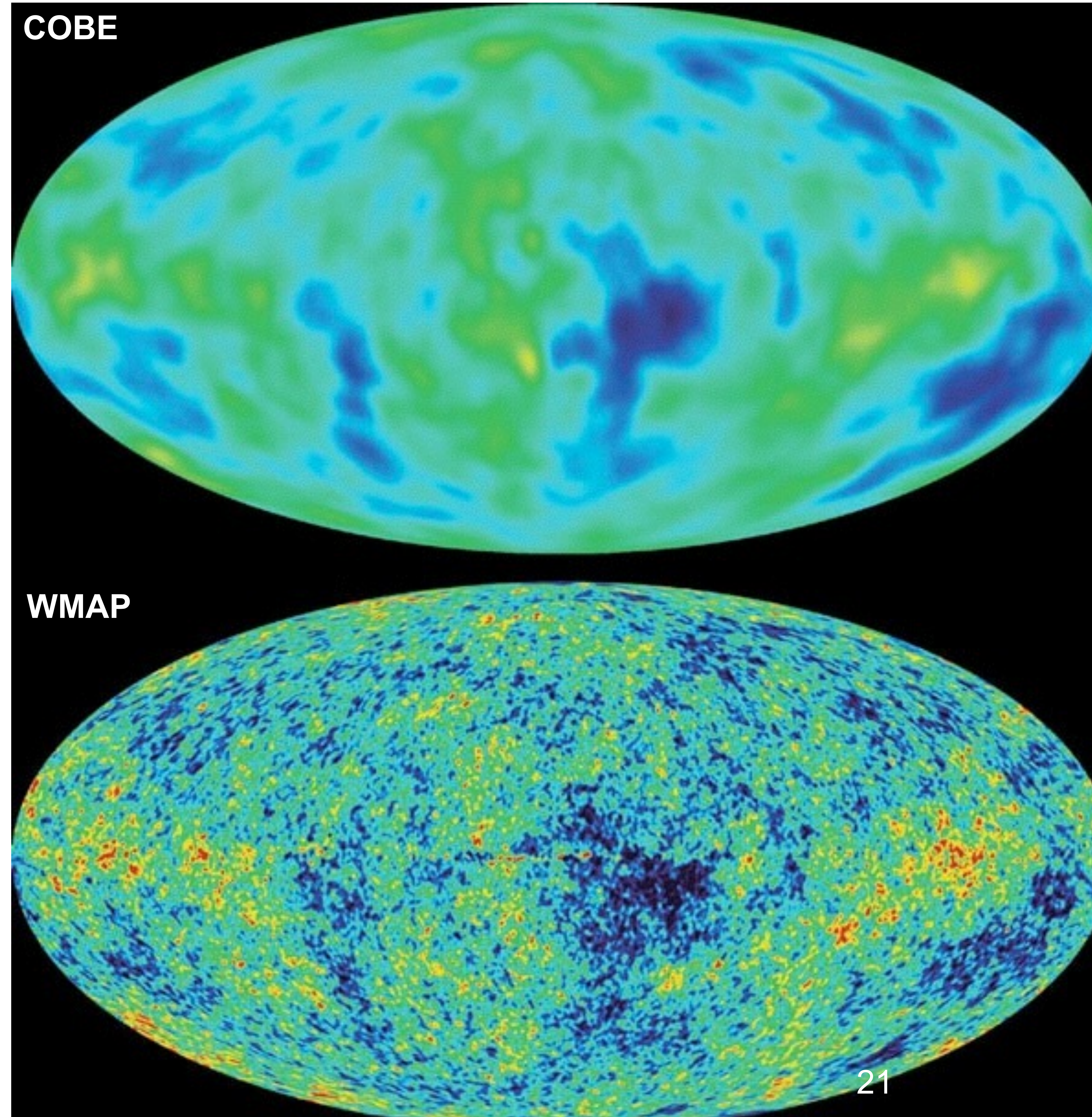
Photo: R. Kaltschmidt/LBNL

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

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

COBE to WMAP (x35 better resolution)

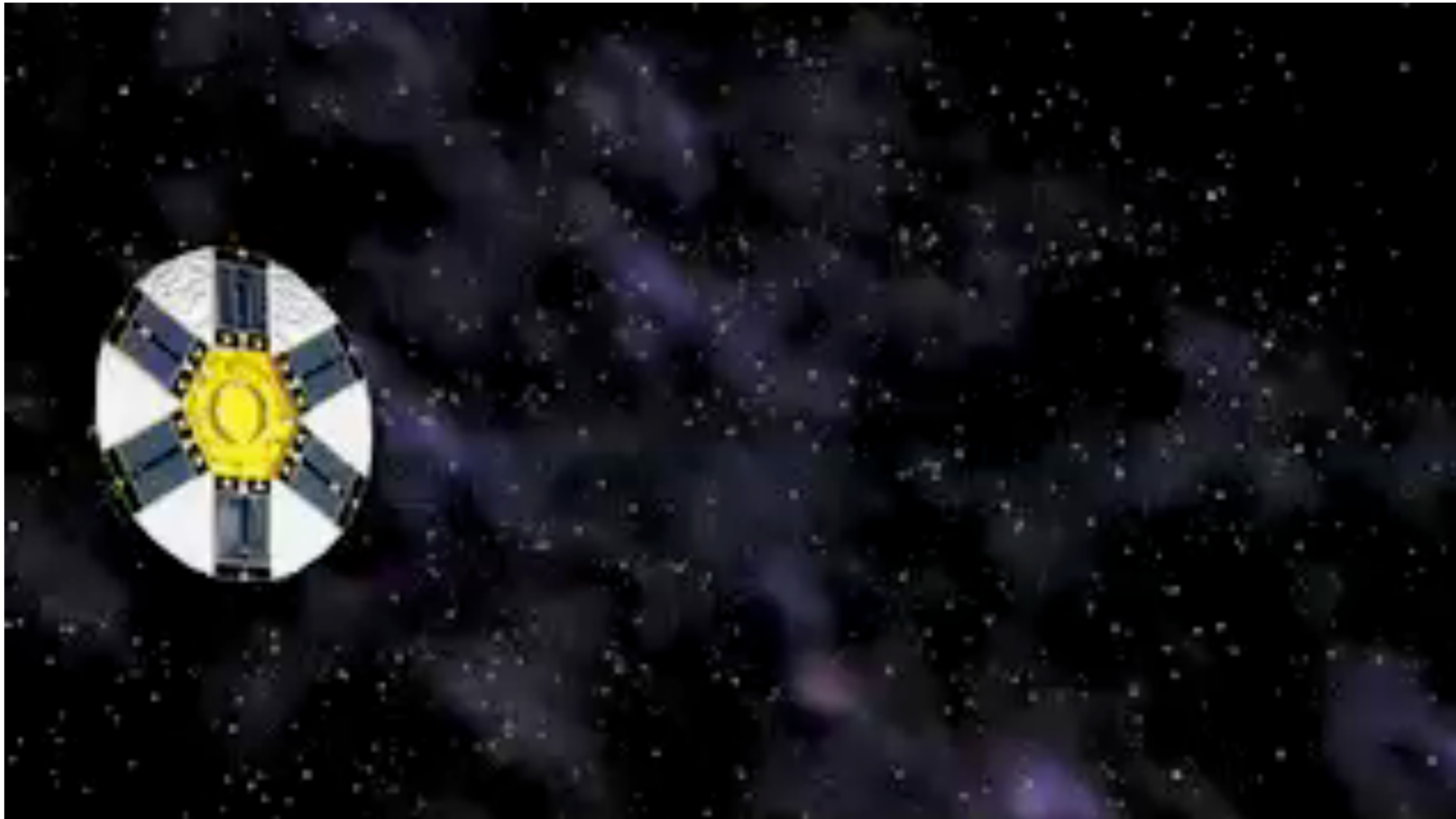
COBE
1989



WMAP
2001

Wilkinson Microwave Anisotropy Probe

WMAP at Lagrange 2 (L2) Point

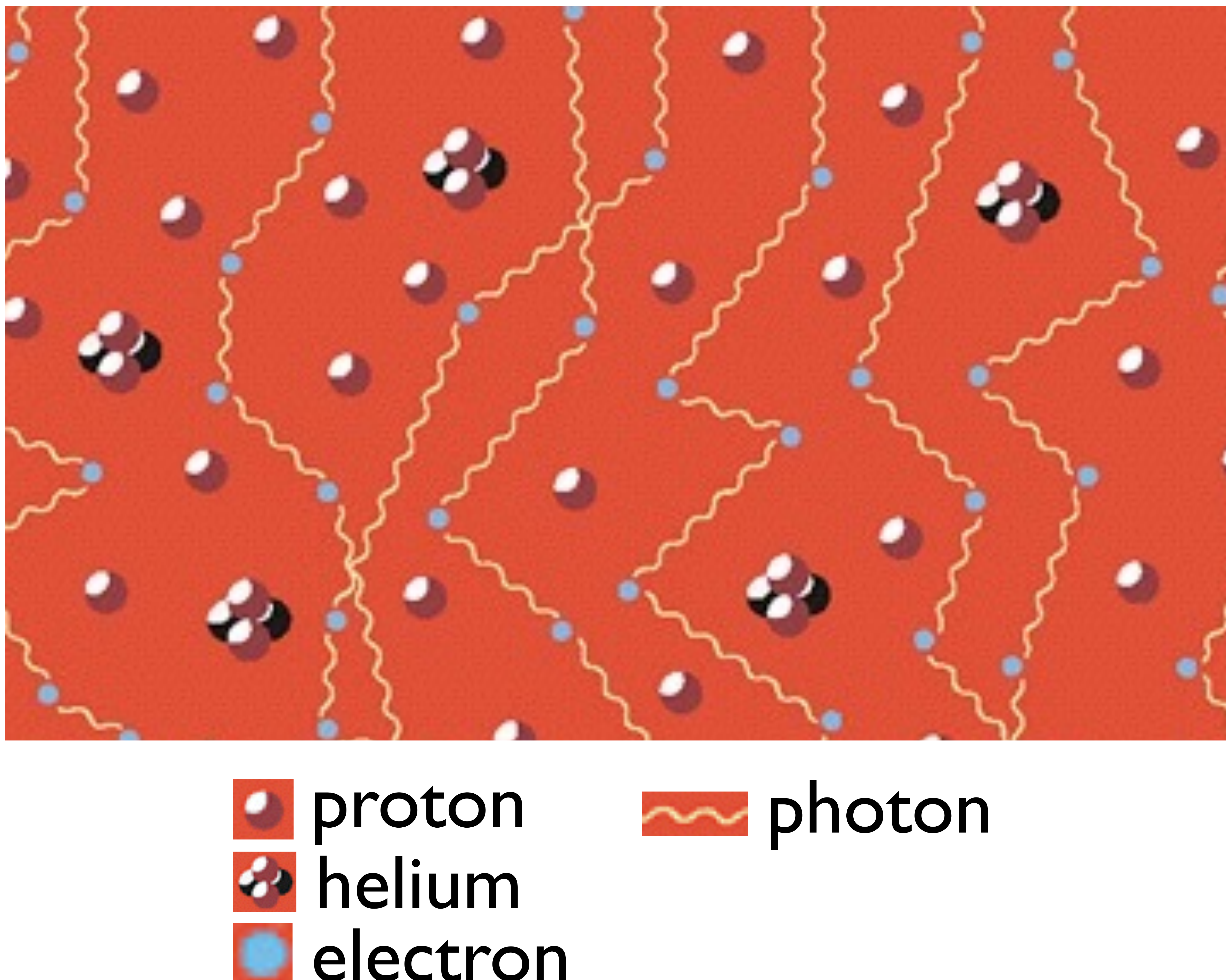


- L2 is 1.5 million kilometers from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

How was CMB created?

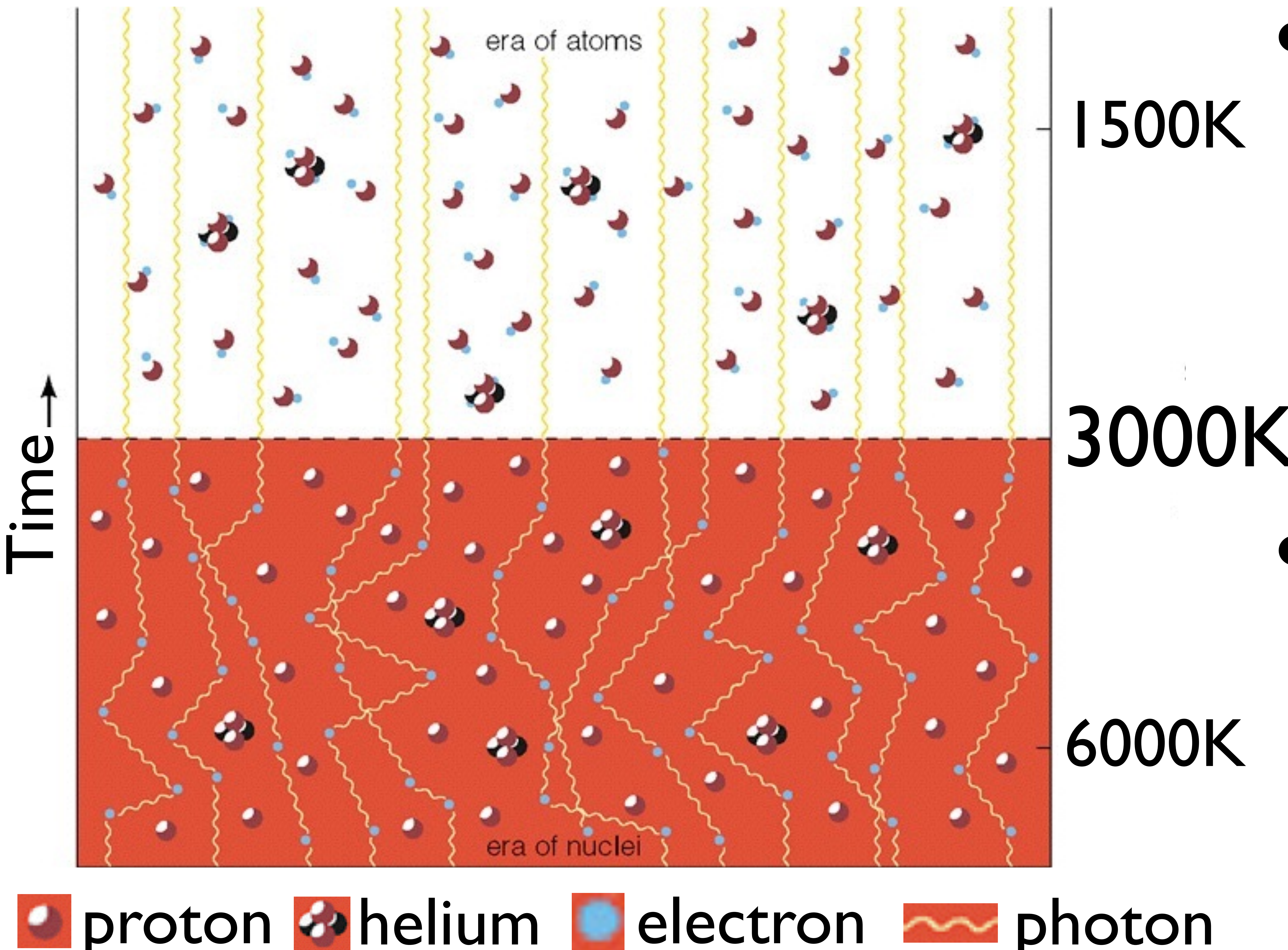
- When the Universe was hot...
  - The Universe was a hot soup made of:
    - Protons, electrons, and helium nuclei
    - Photons and neutrinos
    - Dark matter

Universe as a hot soup

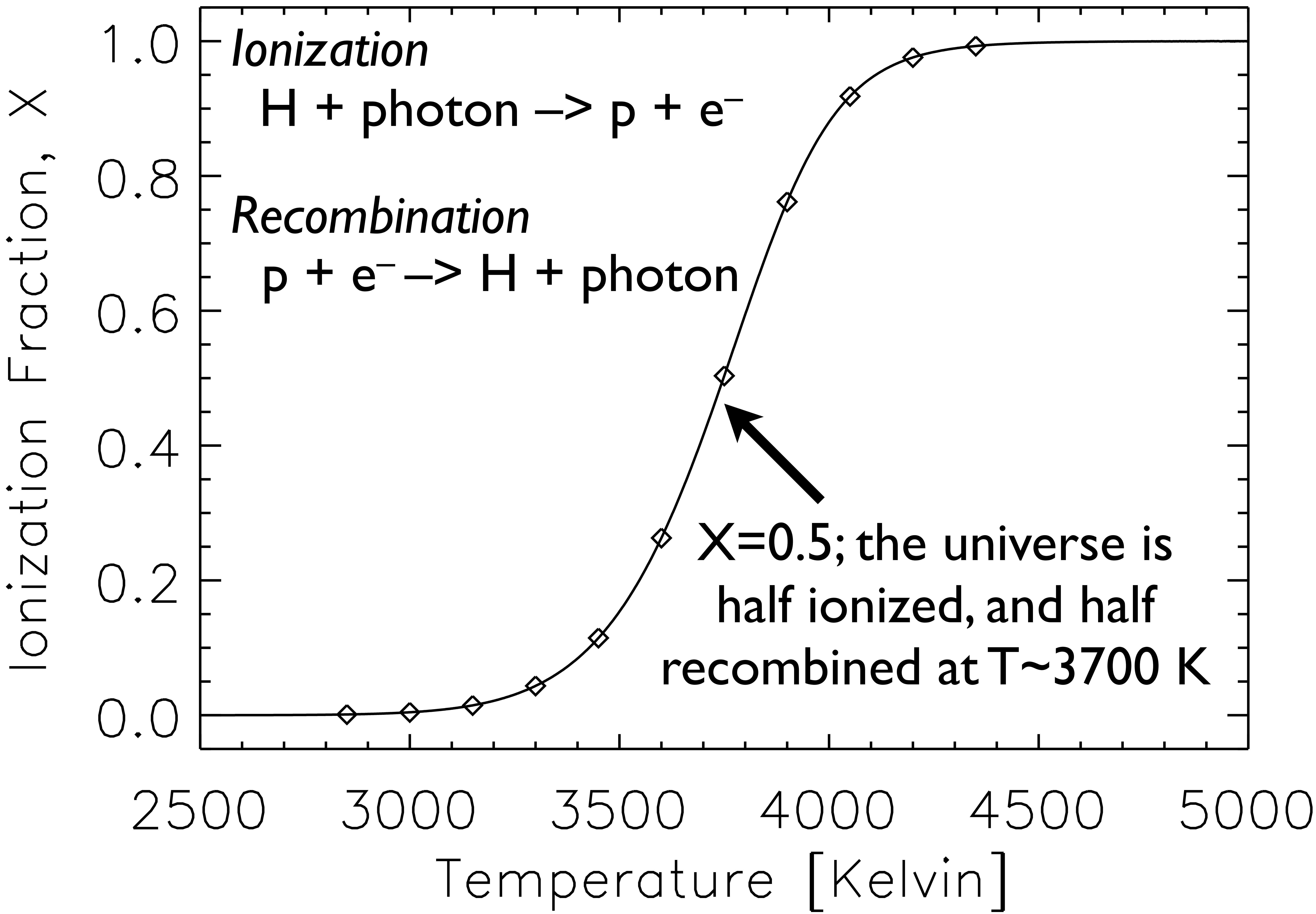


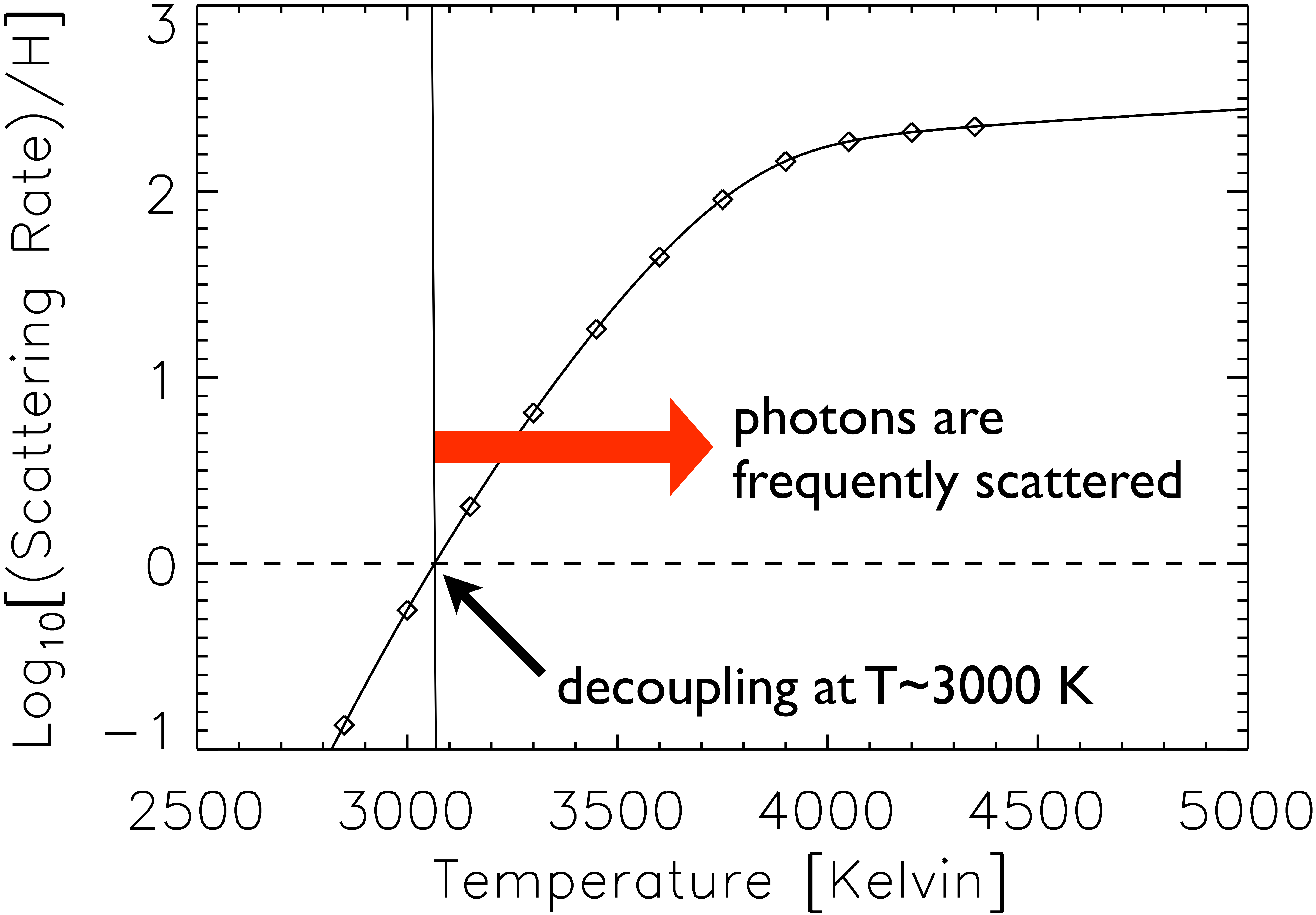
- Free electrons can scatter photons efficiently.
- Photons cannot go very far.

Recombination and Decoupling



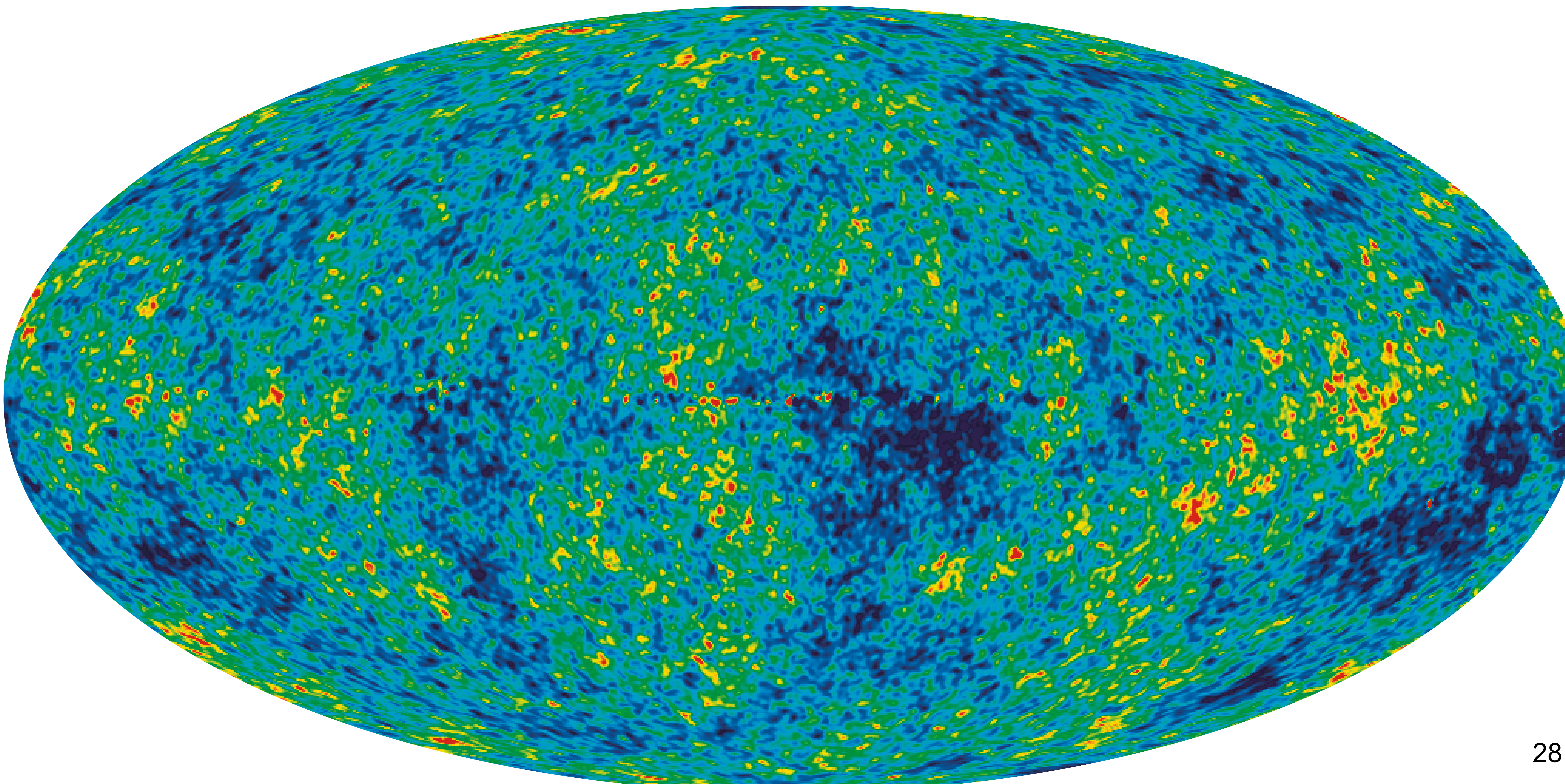
- [*recombination*] When the temperature falls below 3000 K, almost all electrons are captured by protons and helium nuclei.
- [*decoupling*] Photons are no longer scattered. I.e., photons and electrons are no longer coupled.


Ionization
H + photon –> p + e⁻
Recombination
p + e⁻ –> H + photon
X=0.5; the universe is
half ionized, and half
recombined at T~3700 K
Ionization Fraction, X
1.0
0.8
0.6
0.4
0.2
0.0
2500
3000
3500
4000
4500
5000
Temperature [Kelvin]

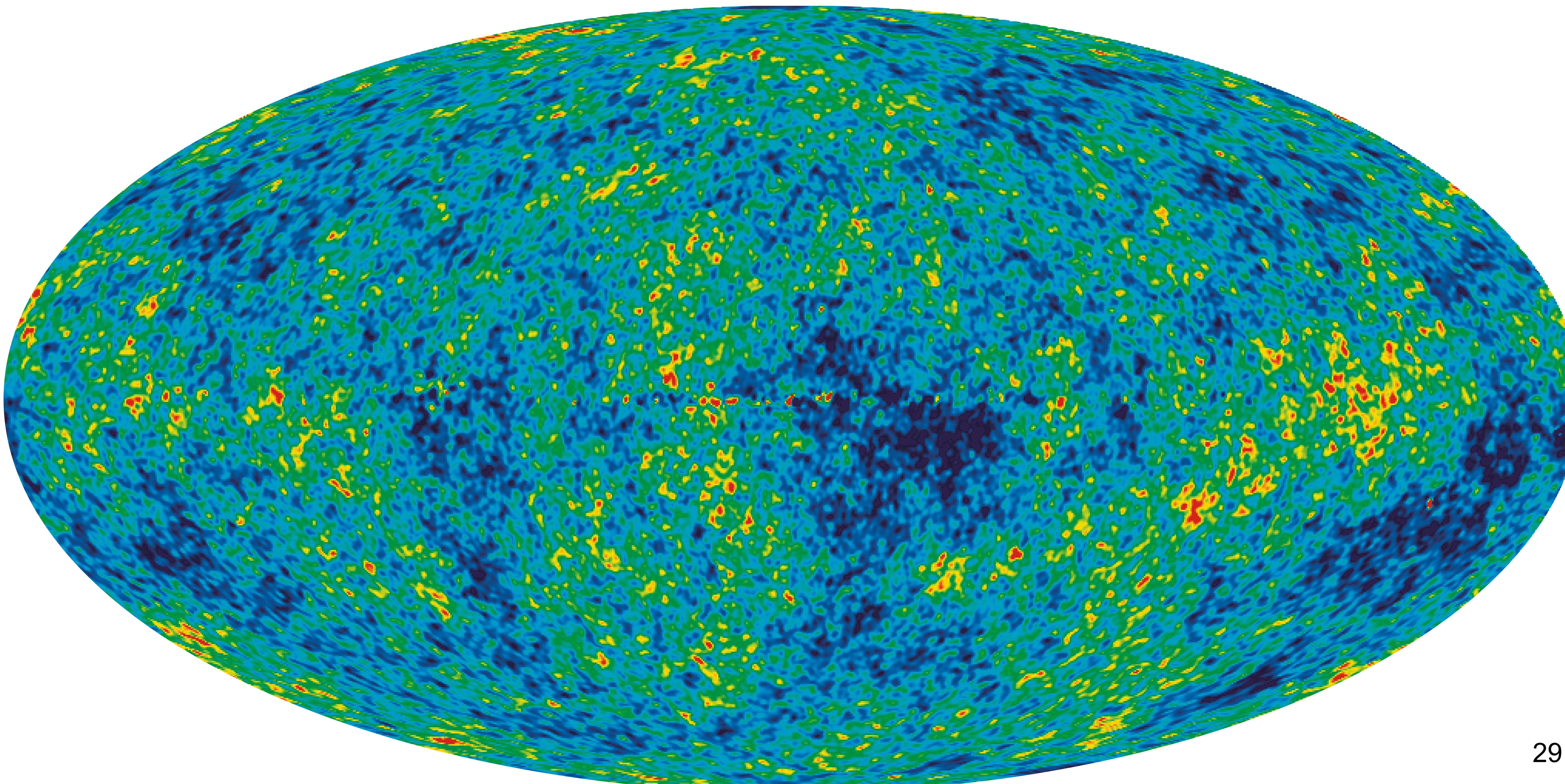


3
2
1
0
−1
2500
3000
3500
4000
4500
5000
Temperature [Kelvin]
Log10[(Scattering Rate)/H]
photons are
frequently scattered
decoupling at T~3000 K

A direct image of the Universe when it was 3000 K.



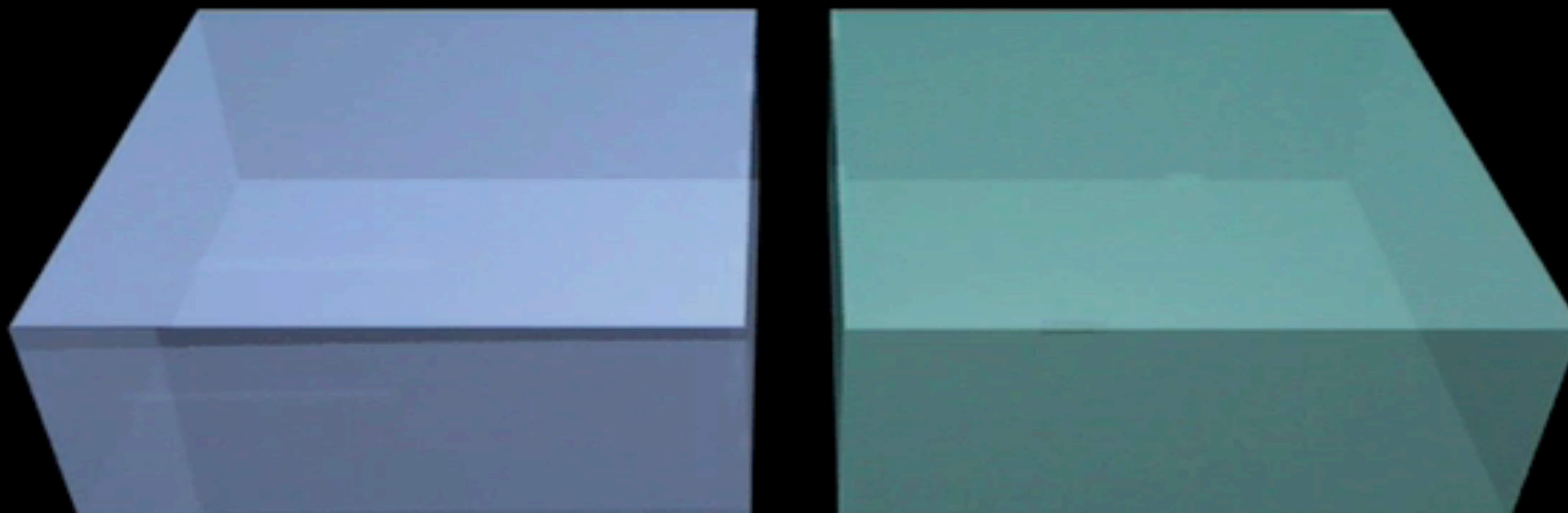
How were these ripples created?



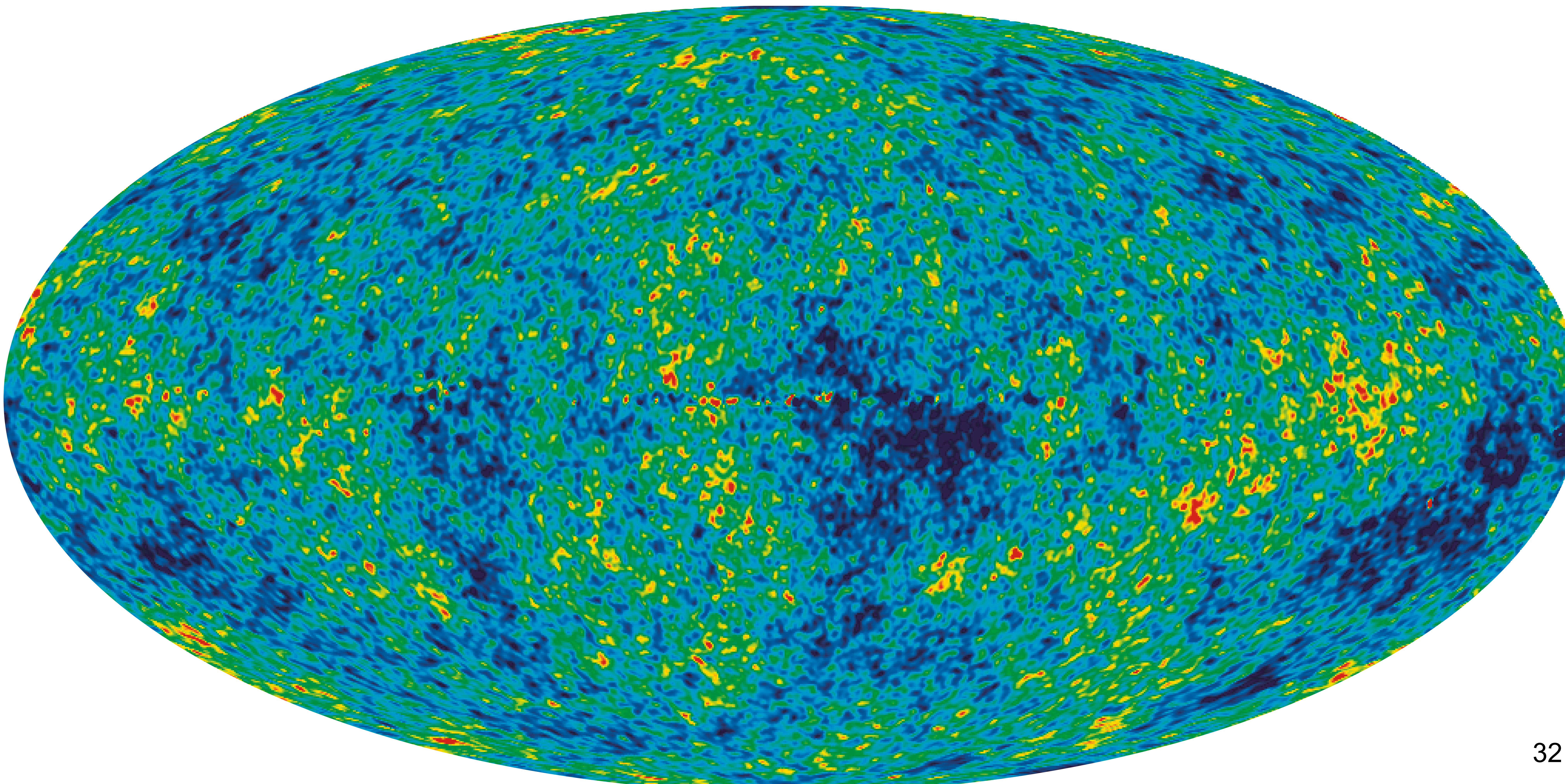
Have you dropped potatoes in a soup?

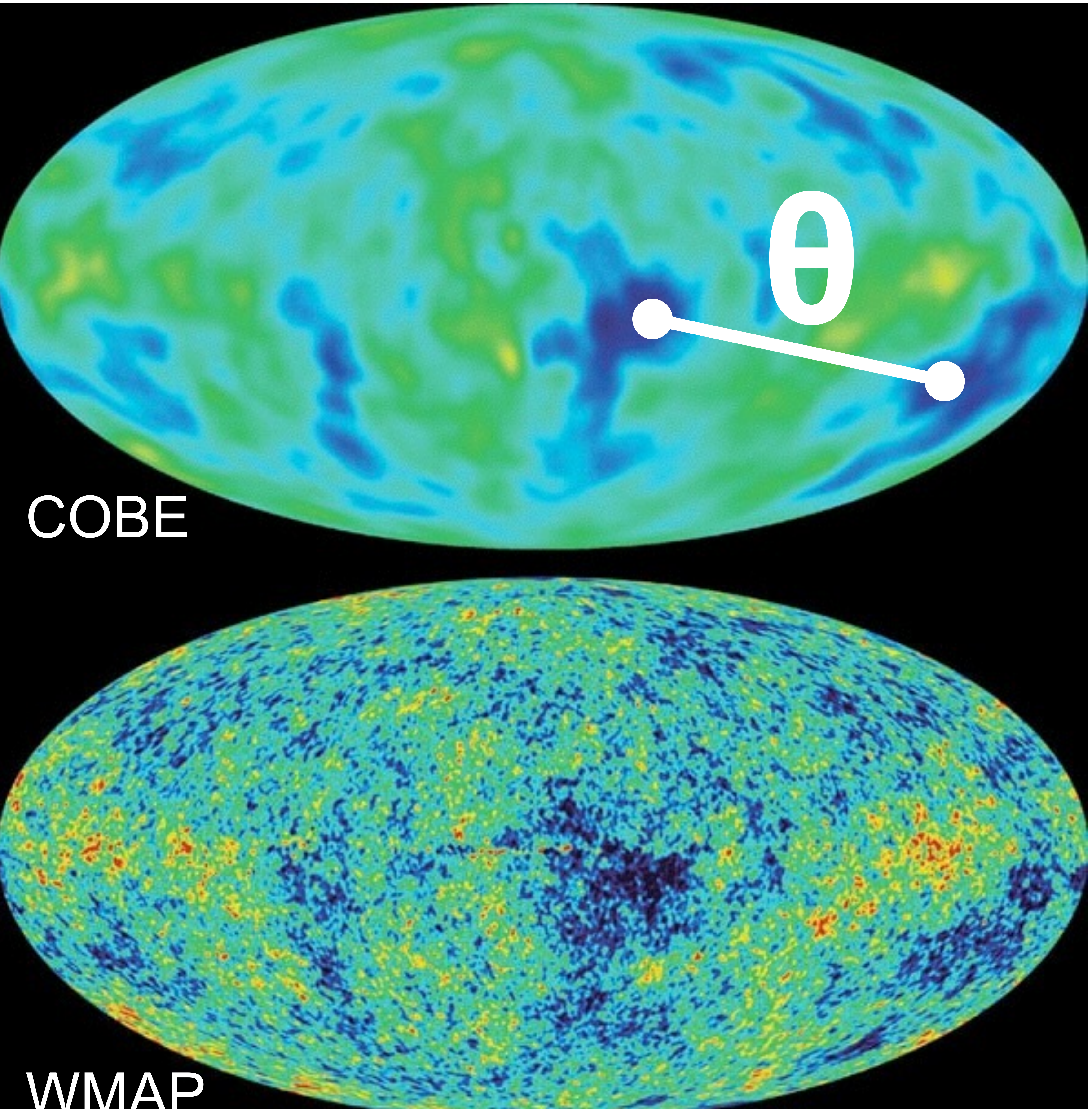
- What would happen if you “perturb” the soup?

The Cosmic Sound Wave



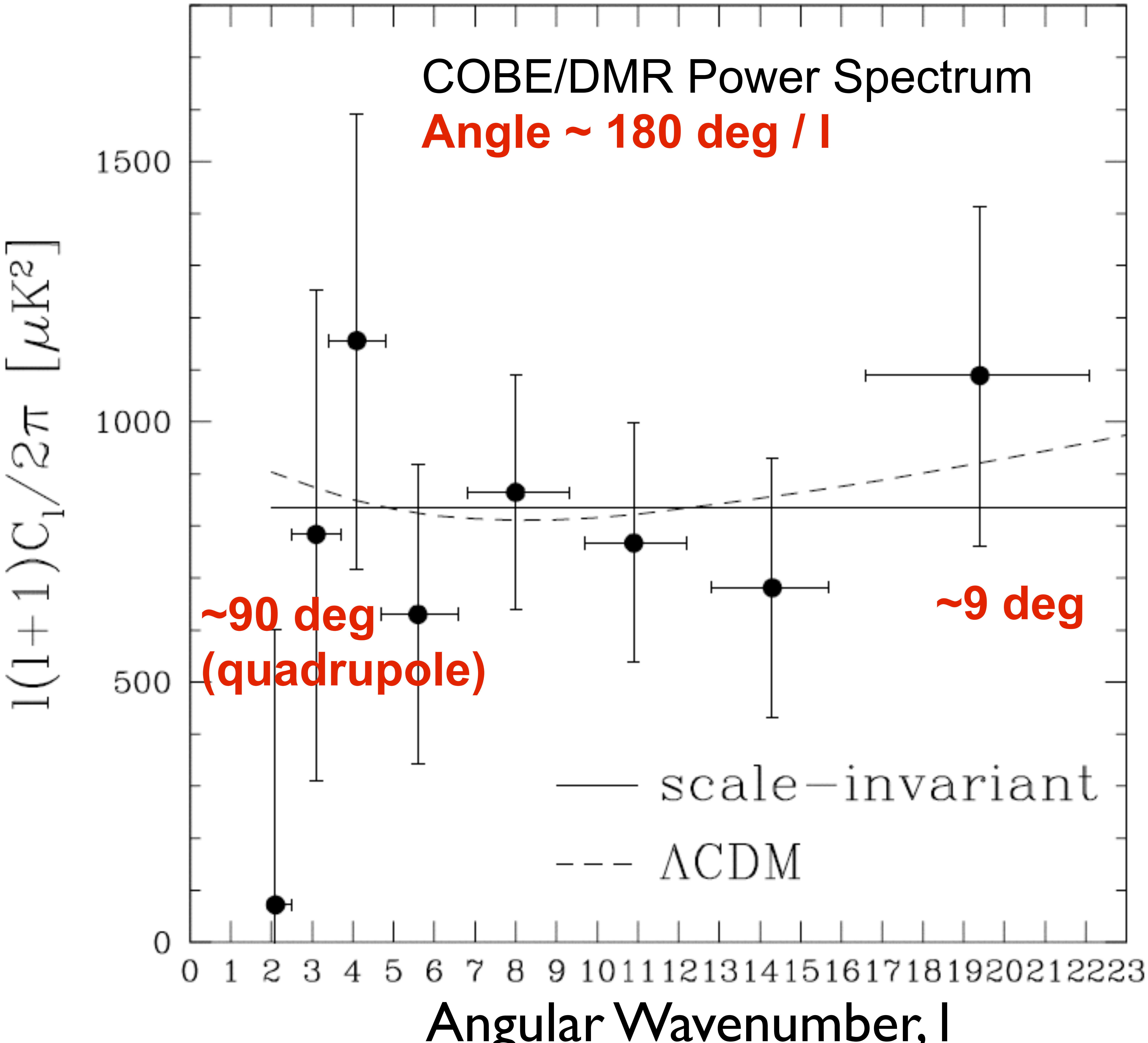
Can You See the Sound Wave?



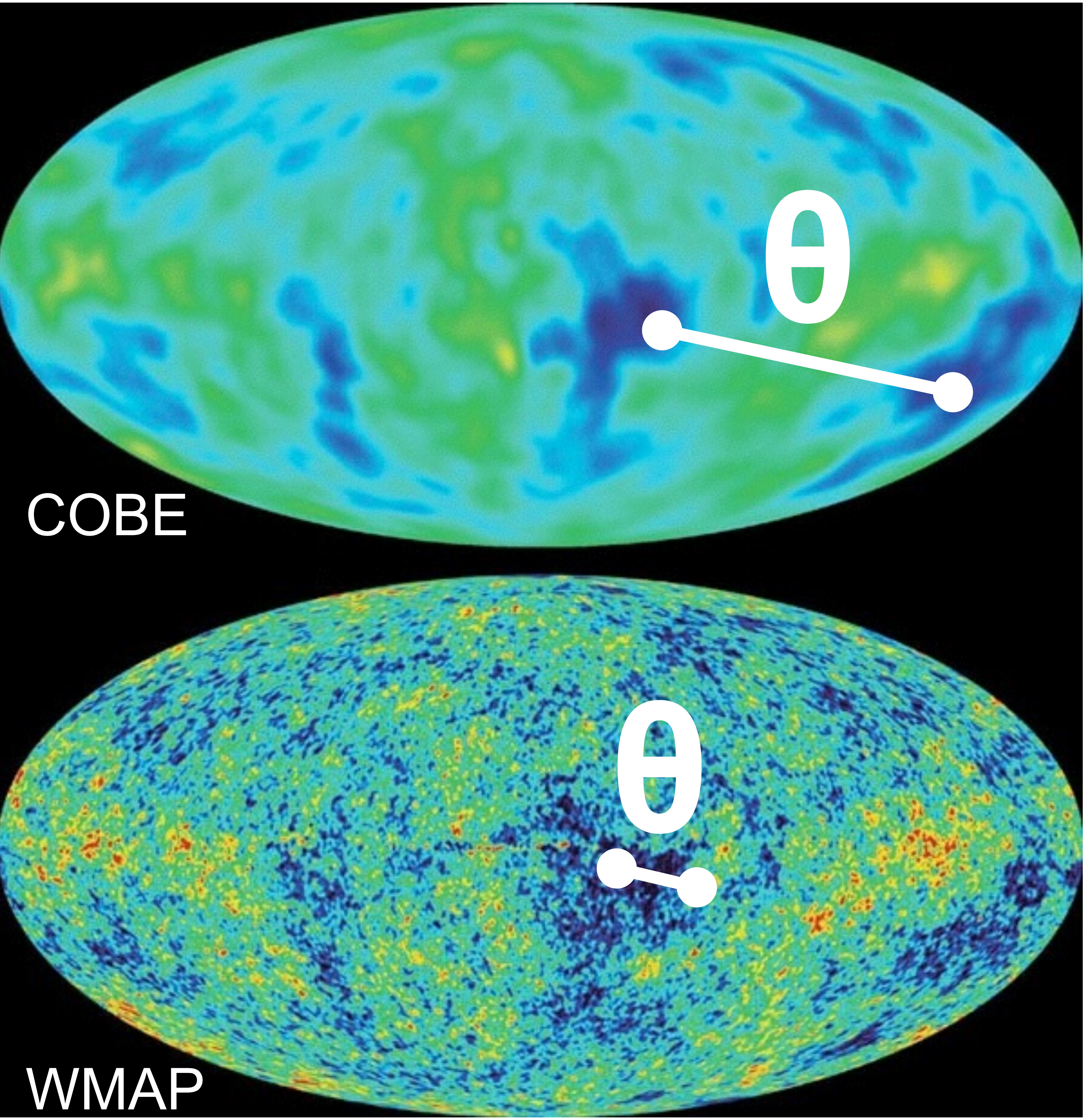


Analysis: 2-point Correlation

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



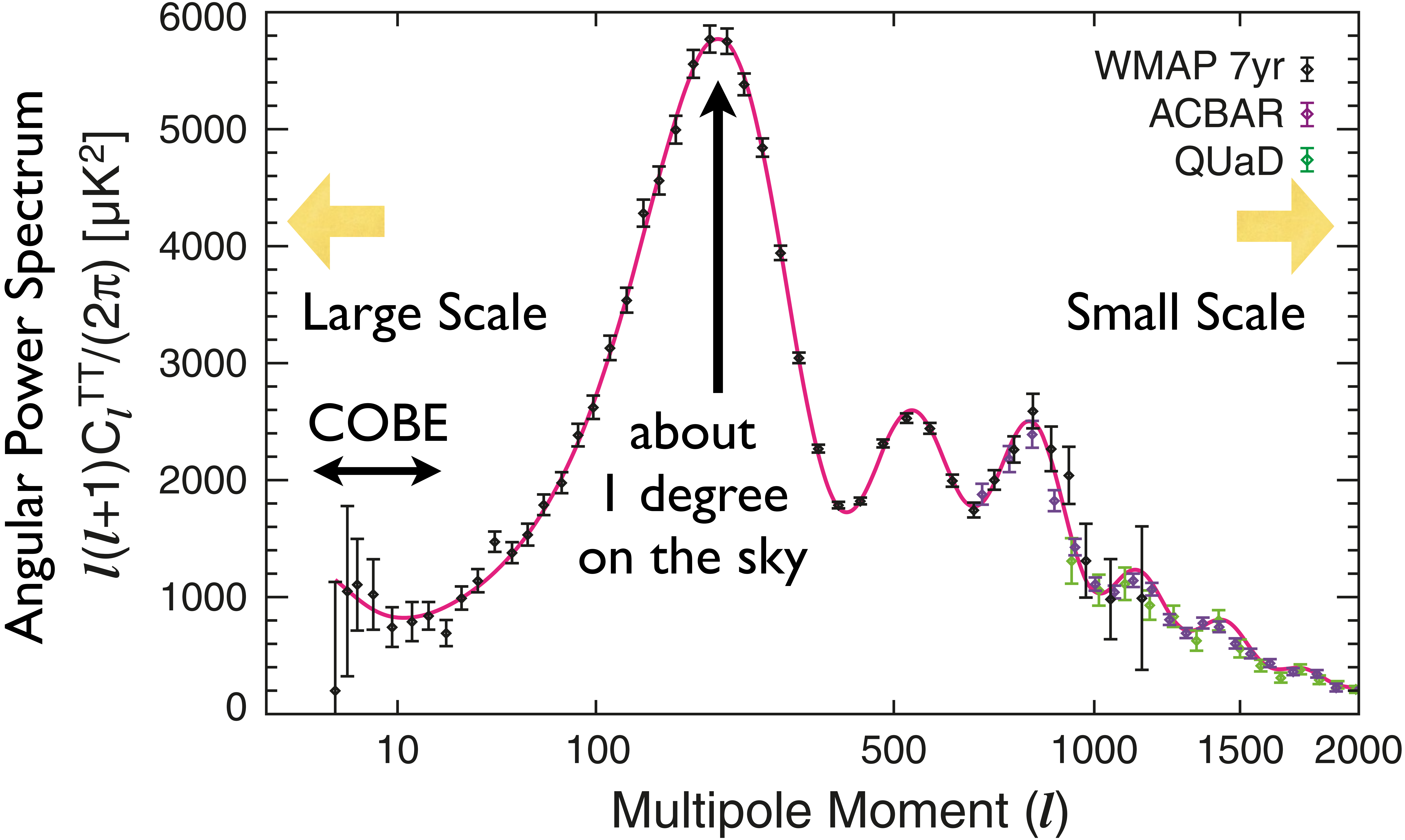
COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
$l(l+1)C_l/2\pi\ [\mu K^2]$
0
500
1000
1500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Angular Wavenumber, l



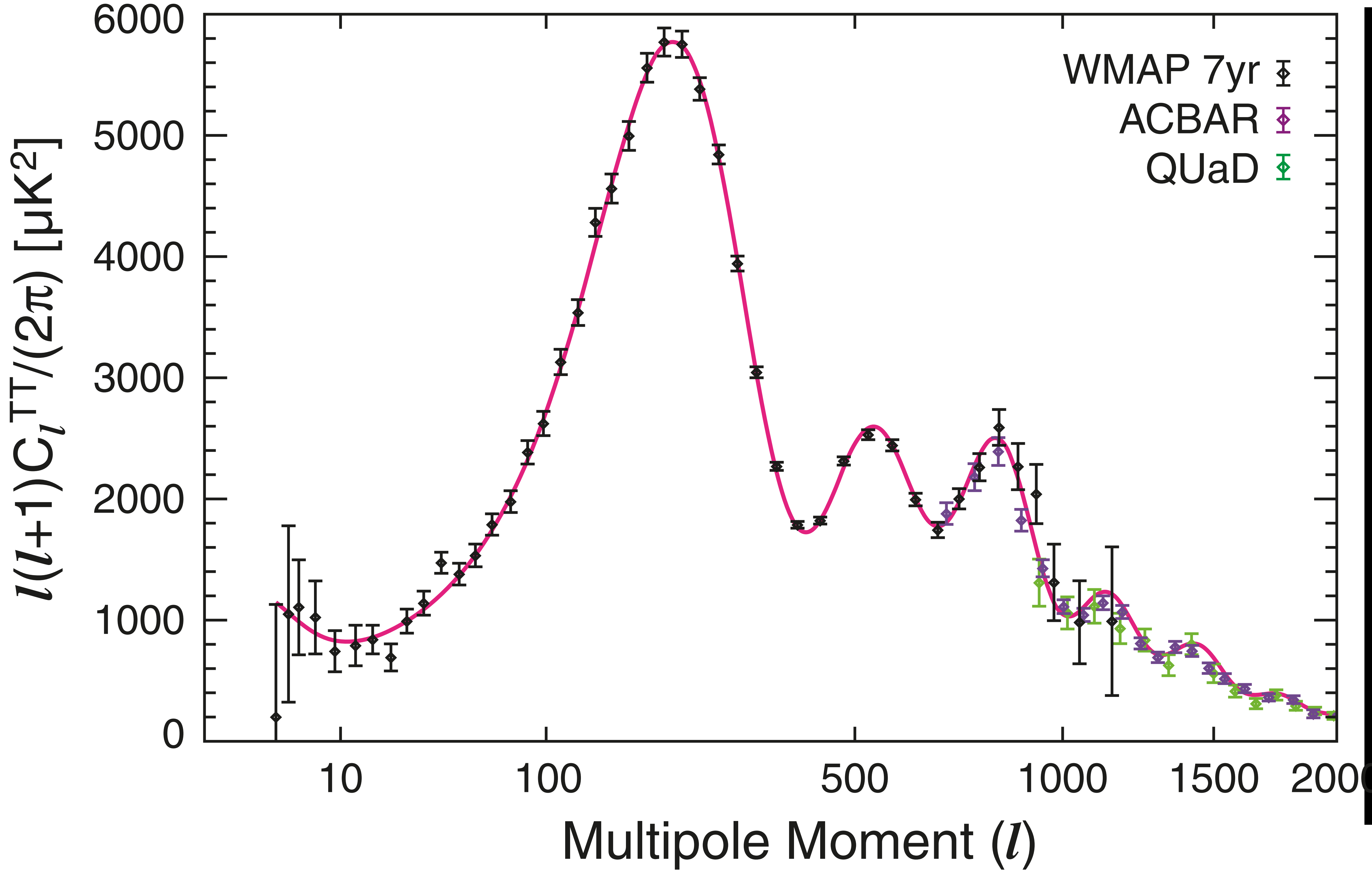
COBE To WMAP

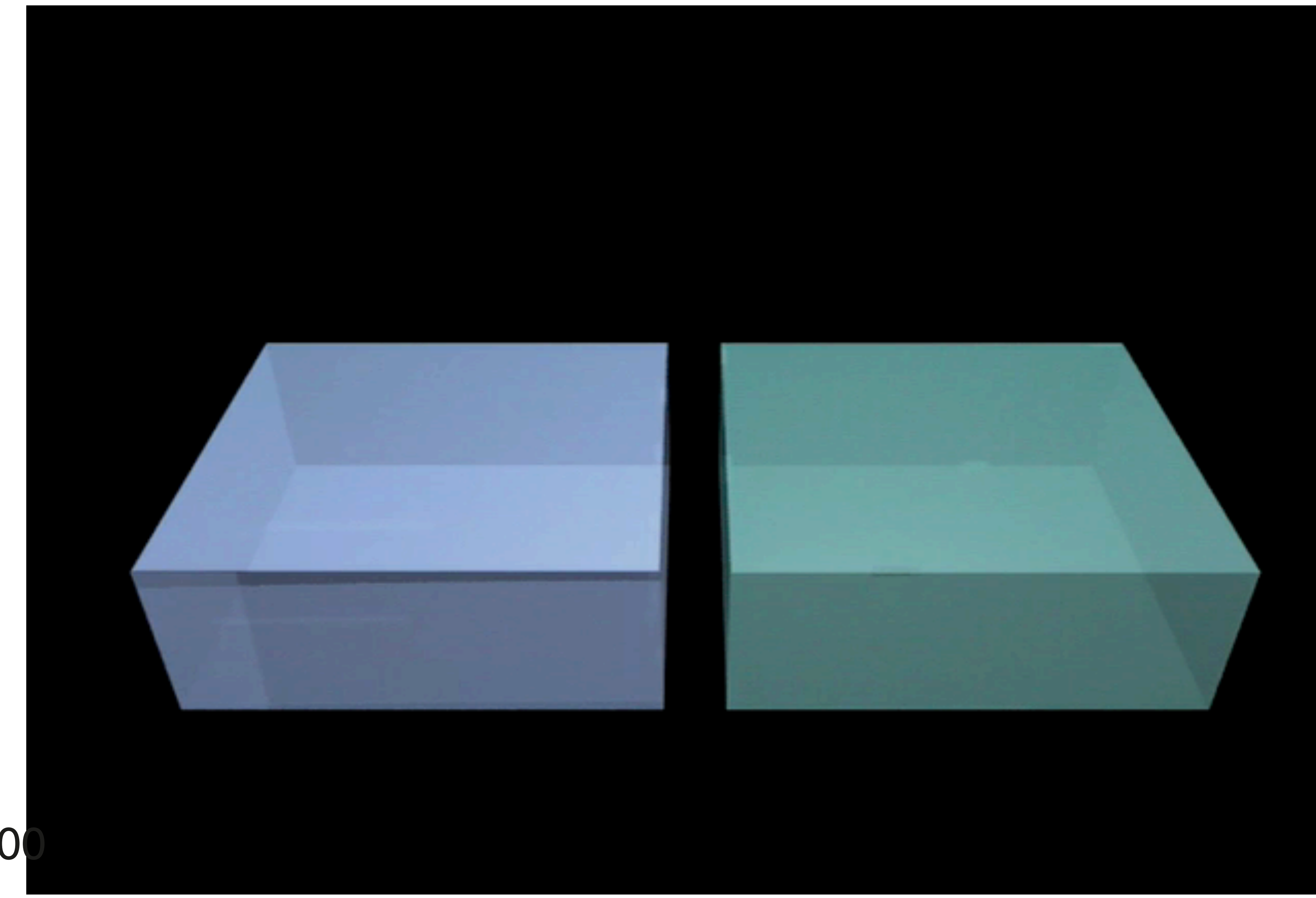
- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP Power Spectrum



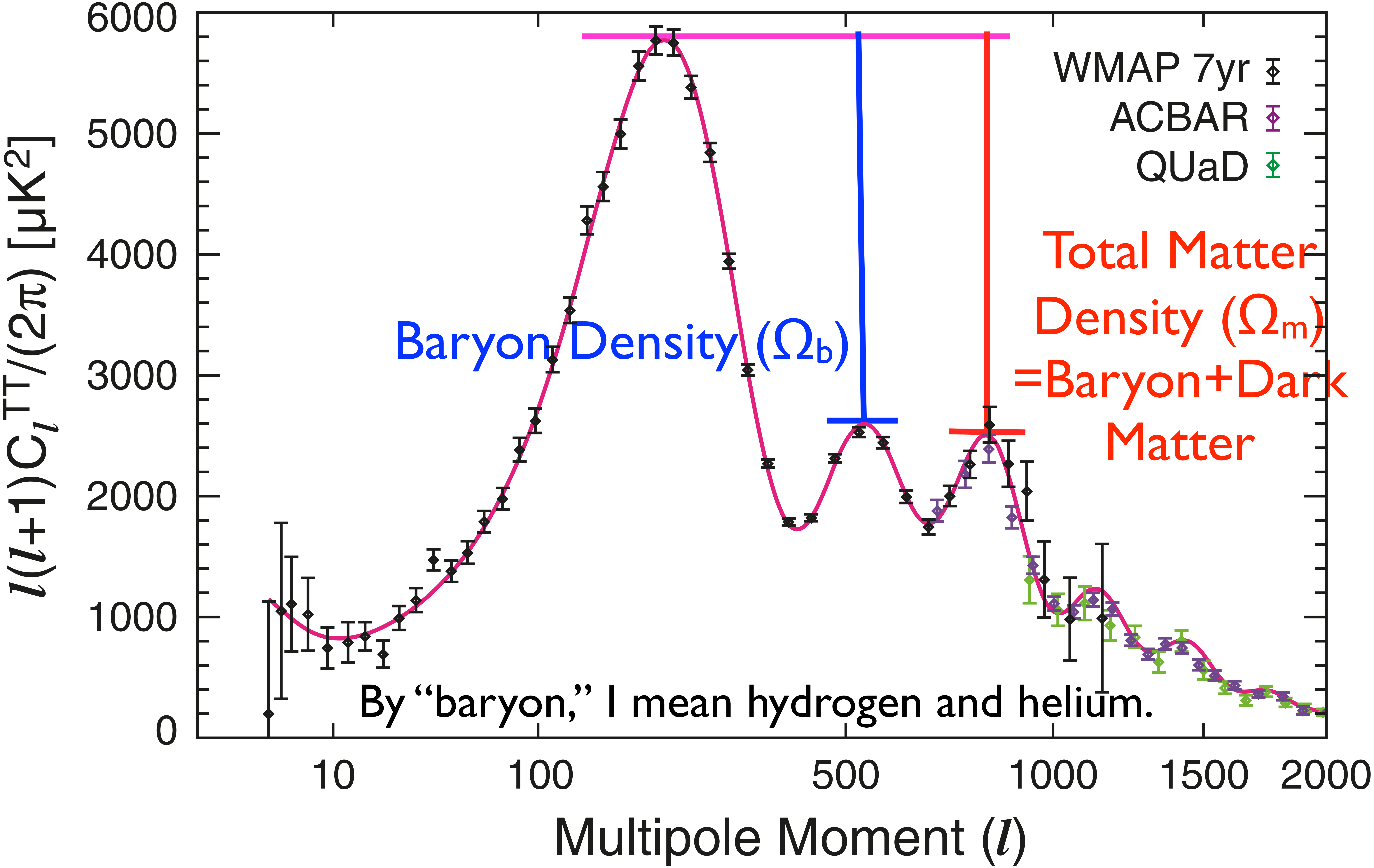
The Cosmic Sound Wave





- *"The Universe as a potato 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



How baryons and photons move together

$$\dot{\delta}_B = -\frac{k}{a}V_B - 3\dot{\Phi}, \qquad R \equiv 3\rho_B/(4\rho_\gamma)$$

$$\dot{\delta}_\gamma = -\frac{4}{3}\frac{k}{a}V_\gamma - 4\dot{\Phi},$$

$$\dot{V}_B = -\frac{\dot{a}}{a}V_B + \frac{k}{a}\Psi + \frac{\sigma_T n_e}{R}(V_\gamma - V_B),$$

$$\dot{V}_\gamma = \frac{1}{4}\frac{k}{a}\delta_\gamma + \frac{k}{a}\Psi + \sigma_T n_e(V_B - V_\gamma),$$

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1+2\Phi)\delta_{ij}dx^i dx^j$$

Combine three equations into one and simplify:

$$R \equiv 3\rho_B/(4\rho_\gamma)$$

$$\Psi = -\Phi \text{ and } \dot{\Phi} = 0$$

$$\ddot{\delta}_\gamma + \frac{1+2R}{1+R}\frac{\dot{a}}{a}\dot{\delta}_\gamma + \frac{1}{3(1+R)}\frac{k^2}{a^2}\delta_\gamma = \frac{4}{3}\frac{k^2}{a^2}\Phi$$

- A wave equation, with the "speed of sound" given by the speed of light divided by sqrt[3(1+R)]
- Photon's acoustic oscillation is influenced by baryons

Further simplify [with WKB]

$$\frac{\partial^2}{\partial t^2}\left[\frac{1}{4}\delta_\gamma - (1+R)\Phi\right] + \frac{k^2 c_s^2}{a^2}\left[\frac{1}{4}\delta_\gamma - (1+R)\Phi\right] = 0$$

c_s is the speed of sound, $c_s^2 \equiv 1/[3(1+R)]$

- Solution:

$$\frac{1}{4}\delta_\gamma = (1+R)\Phi + A\cos(kr_s) + B\sin(kr_s)$$

r_s is the "sound horizon" defined by $r_s \equiv \int_0^{t_*} c_s \frac{dt}{a} = 147$ Mpc

Initial Conditions

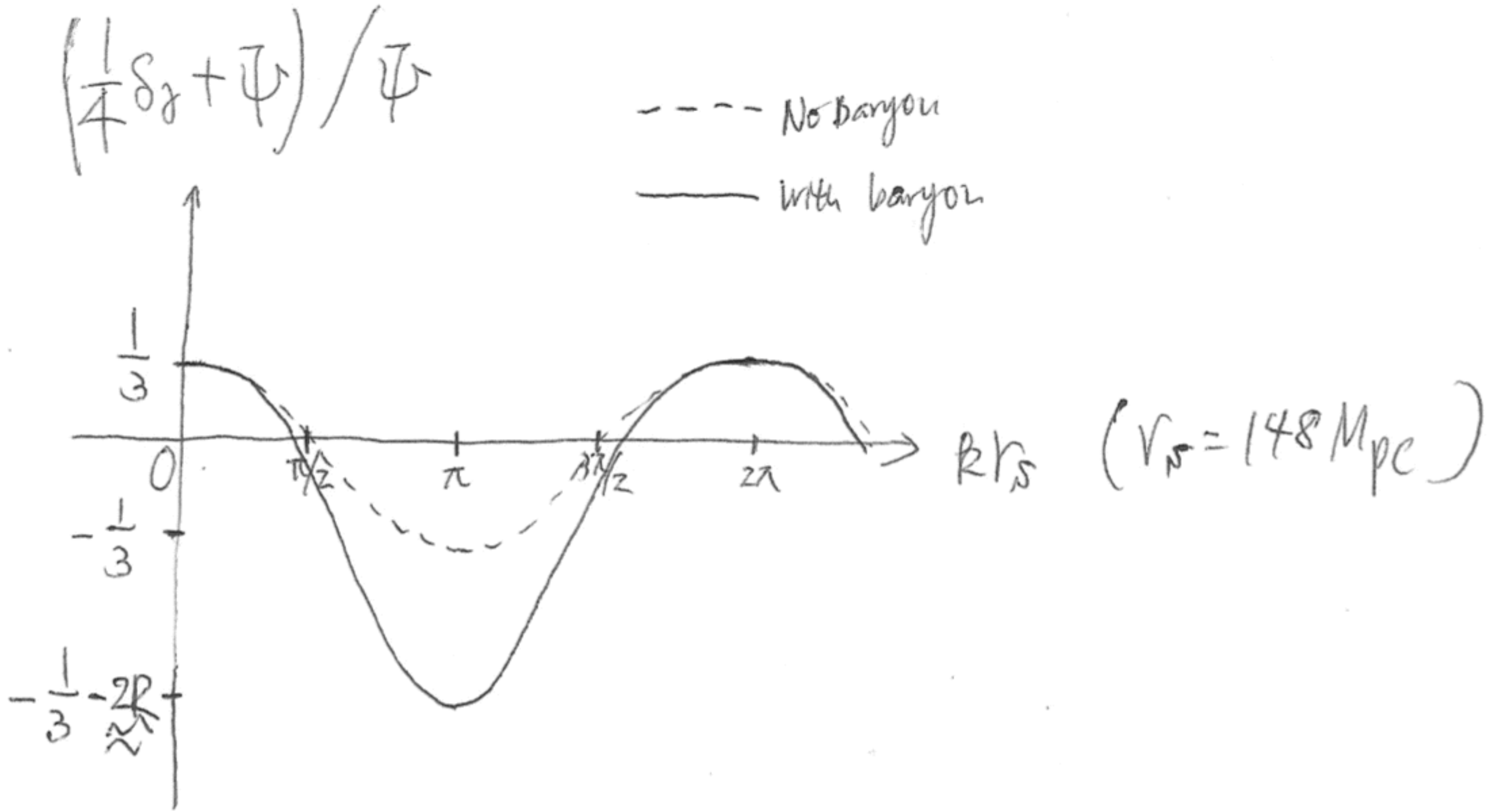
- On "super sound-horizon scales" [$kr_s << 1$], the photon and matter density perturbations are given by *the adiabatic condition*:

$$\frac{1}{4}\delta_\gamma = \frac{1}{3}\delta_m = \frac{2}{3}\Phi$$

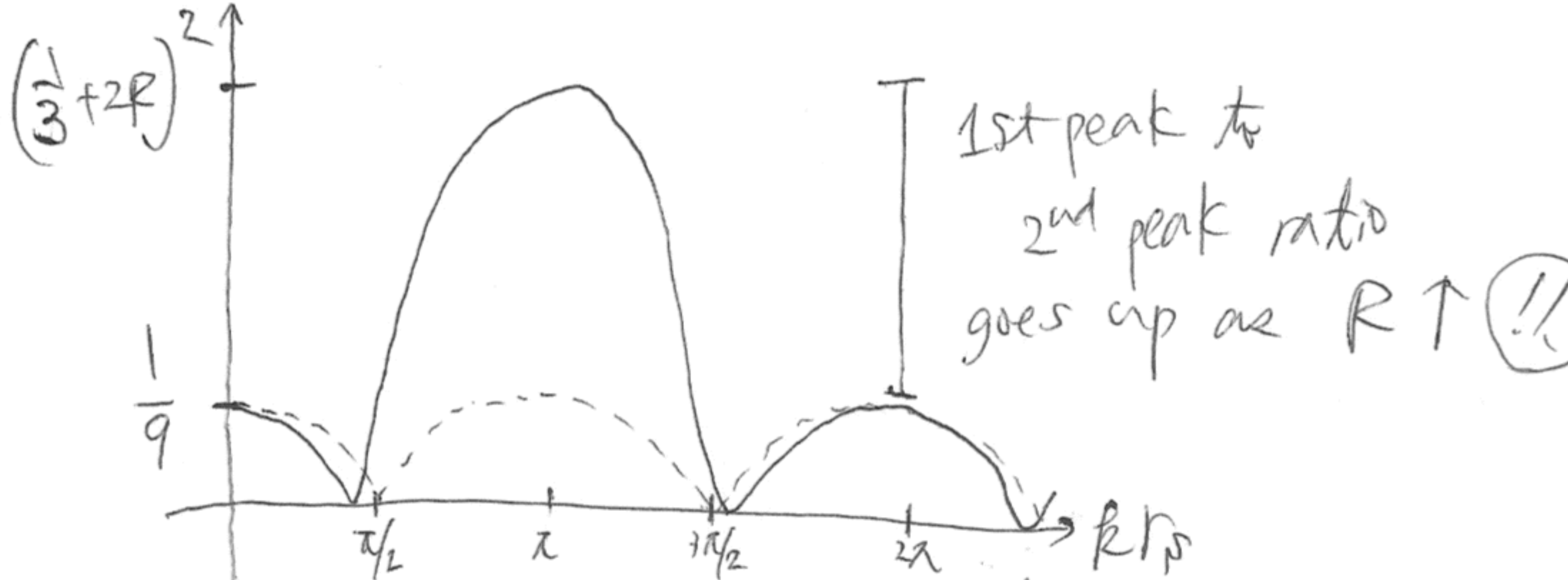
- Using this, we obtain:

$$\frac{1}{4}\delta_\gamma = (1+R)\Phi - \left(\frac{1}{3}+R\right)\Phi\cos(kr_s)$$

How baryons affect the photon density perturbation

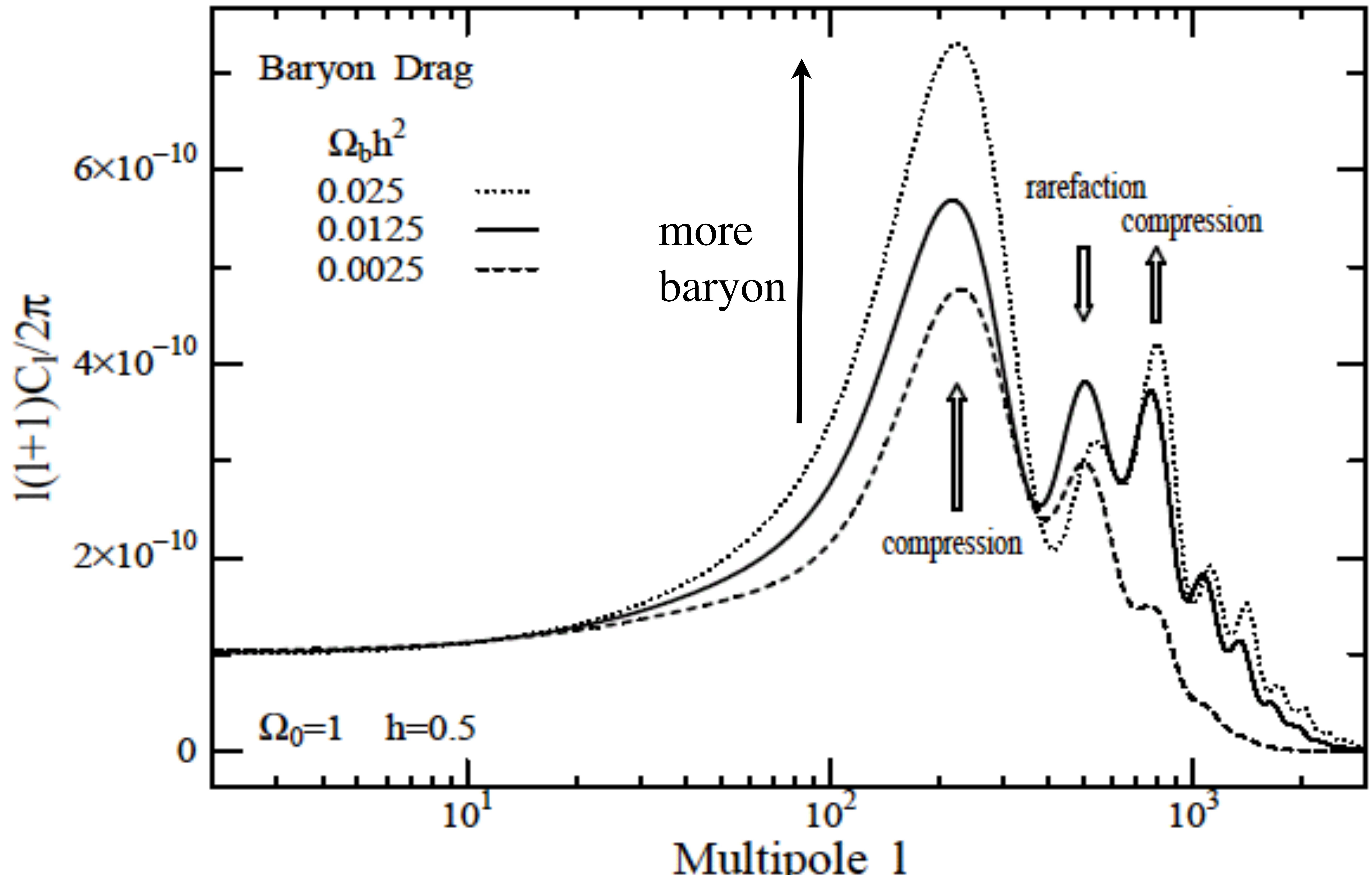


How baryons affect the [photon density perturbation]^2



$$\left[\begin{array}{l} l_{1st} = k_{1st}\, d_A = \pi \dfrac{d_A}{r_s} \approx 300 \\ l_{2nd} = k_{2nd}\, d_A = 2\pi \dfrac{d_A}{r_s} \approx 600 \end{array}\right.$$

Determining Baryon Density From C_l



Effects of baryons

- …or the effects of any mass that interacts with photons.
- More baryons -> the heights of the odd peaks are enhanced with respect to the even peaks
- How about the effects of mass that does not interact with photons?
  - Gravitational redshift/blueshift

How photons lose/gain energy gravitationally

- The geodesic equation for the photon 4-momentum:

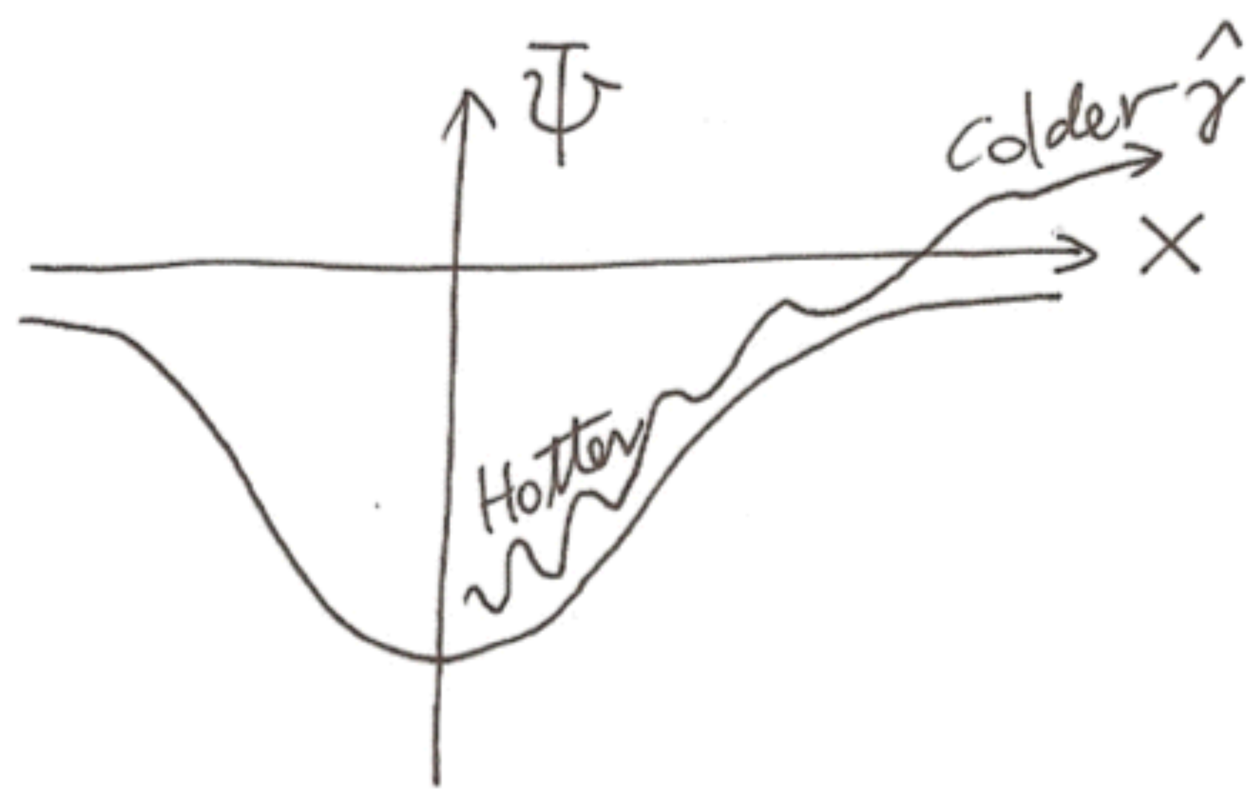
$$\frac{dp^\mu}{d\lambda} + \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta = 0$$

- gives a change of the photon energy as:

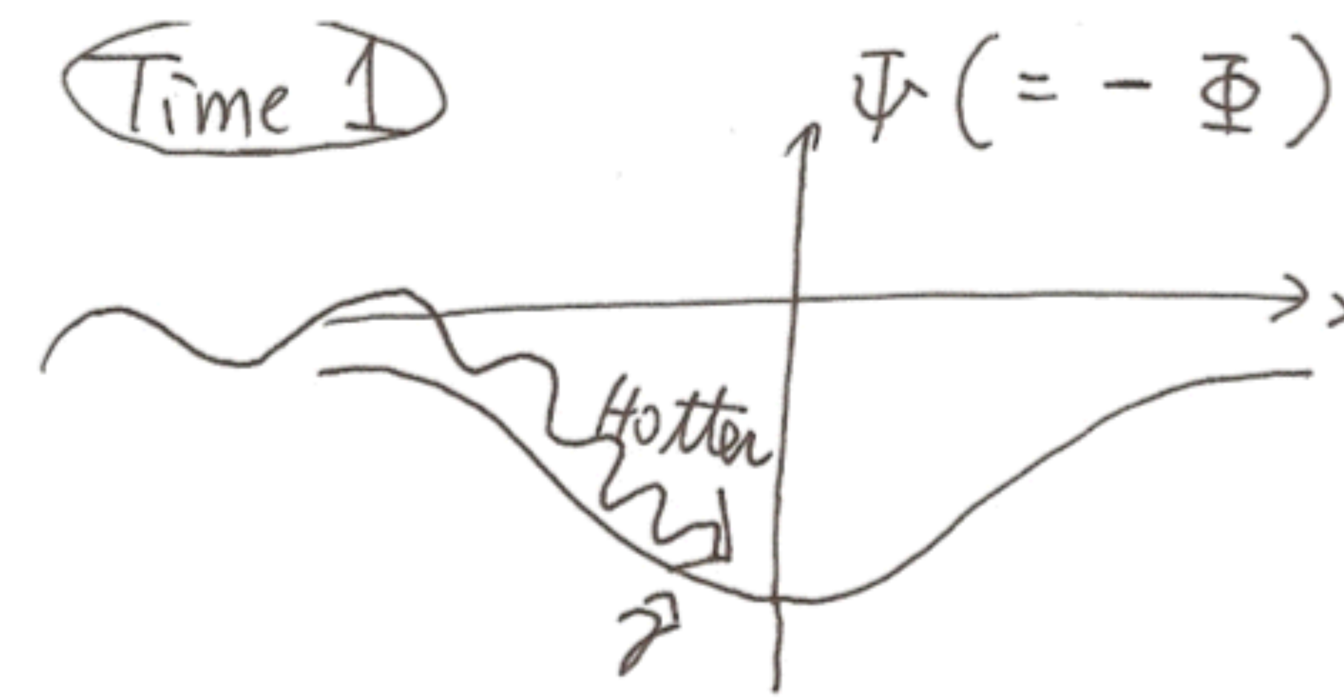
$$\frac{1}{p}\frac{dp}{dt} = -\frac{1}{a}\frac{da}{dt} - \frac{d\Psi}{dt} + \frac{\partial\Psi}{\partial t} - \frac{\partial\Phi}{\partial t}$$

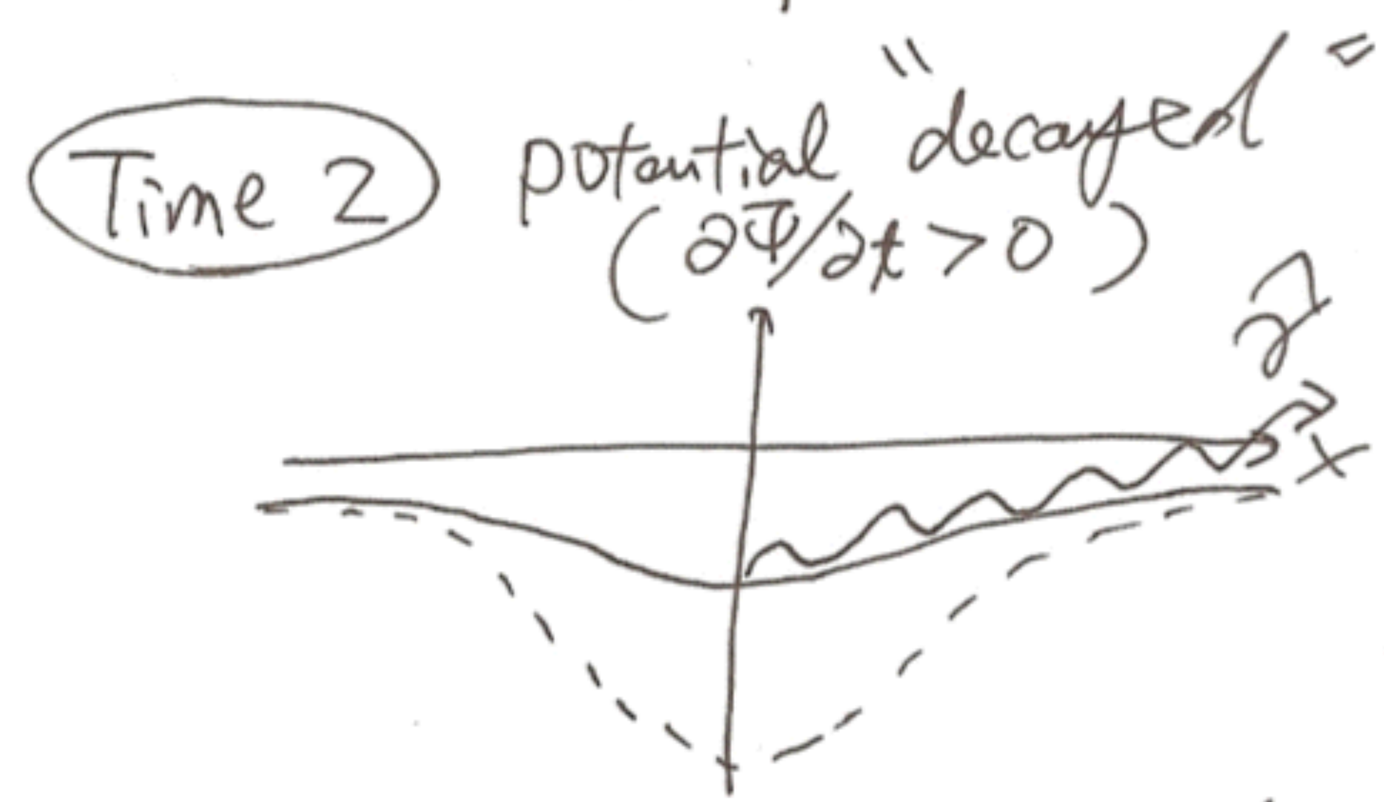
$$\ln(ap)_{\mathcal{O}} = \ln(ap)_{\mathcal{E}} + (\Psi_{\mathcal{E}} - \Psi_{\mathcal{O}}) + \int_{t_{\mathcal{E}}}^{t_{\mathcal{O}}} dt \frac{\partial}{\partial t}(\Psi - \Phi)$$

"$\mathcal{O}$" and "$\mathcal{E}$" denote the observed and emitted epochs



$$\frac{1}{p}\frac{dp}{dt} = -\frac{\gamma^i}{a}\frac{\partial\Psi}{\partial x^i}$$





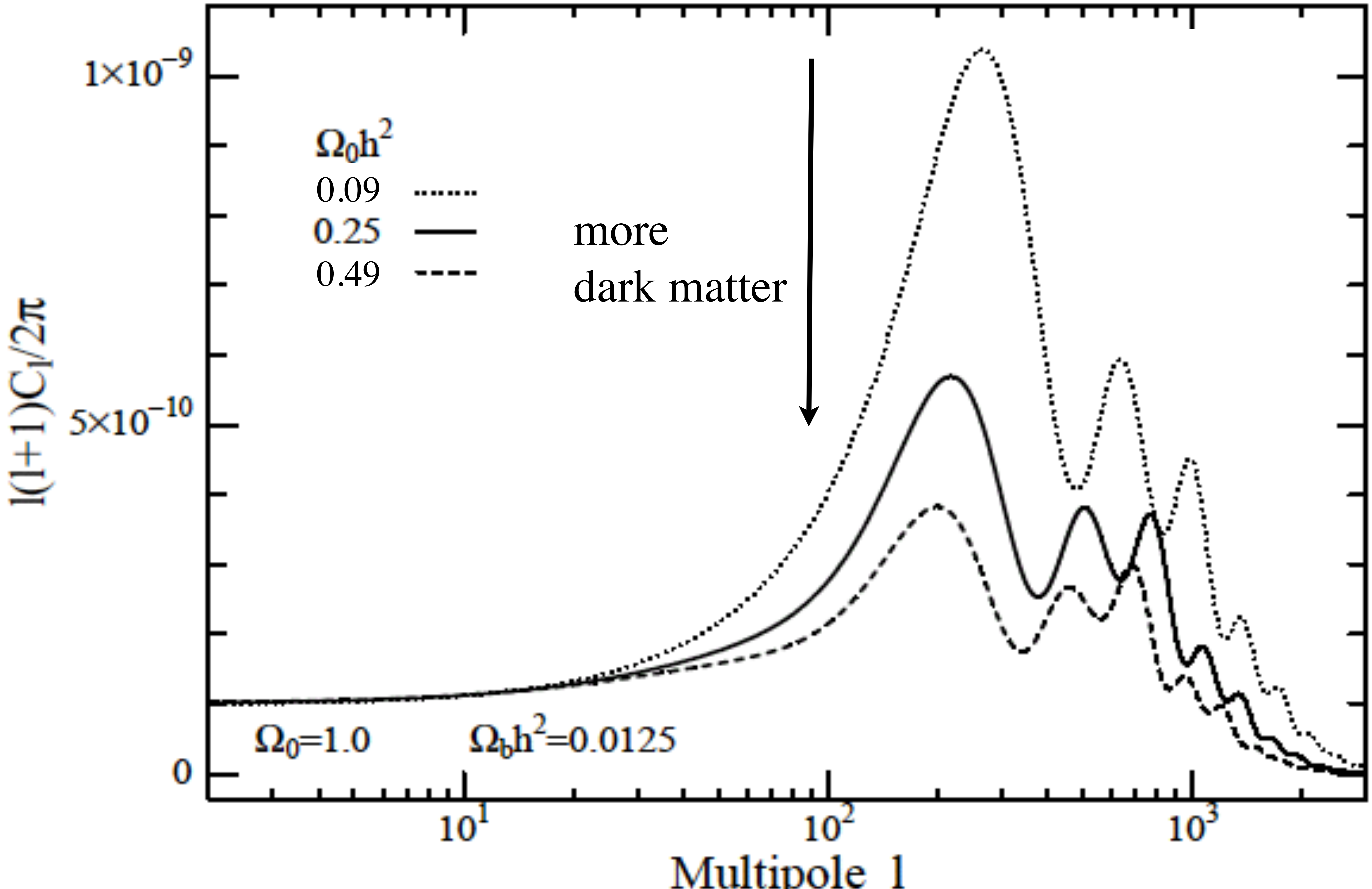
⇒ Net Gain of Energy

$$\frac{1}{p}\frac{dp}{dt} = -\frac{\partial\Phi}{\partial t} = \frac{\partial\Psi}{\partial t}$$

Gravitational potentials decay at two epochs

- Gravitational potentials decay when the expansion rate is too fast for matter to clump together. This happens when:
  - Radiation contributes significantly to the energy density of the universe [early time contribution]
  - Dark energy contributes significantly to the energy density of the universe [late time contribution]

Determining Dark Matter Density From C_l

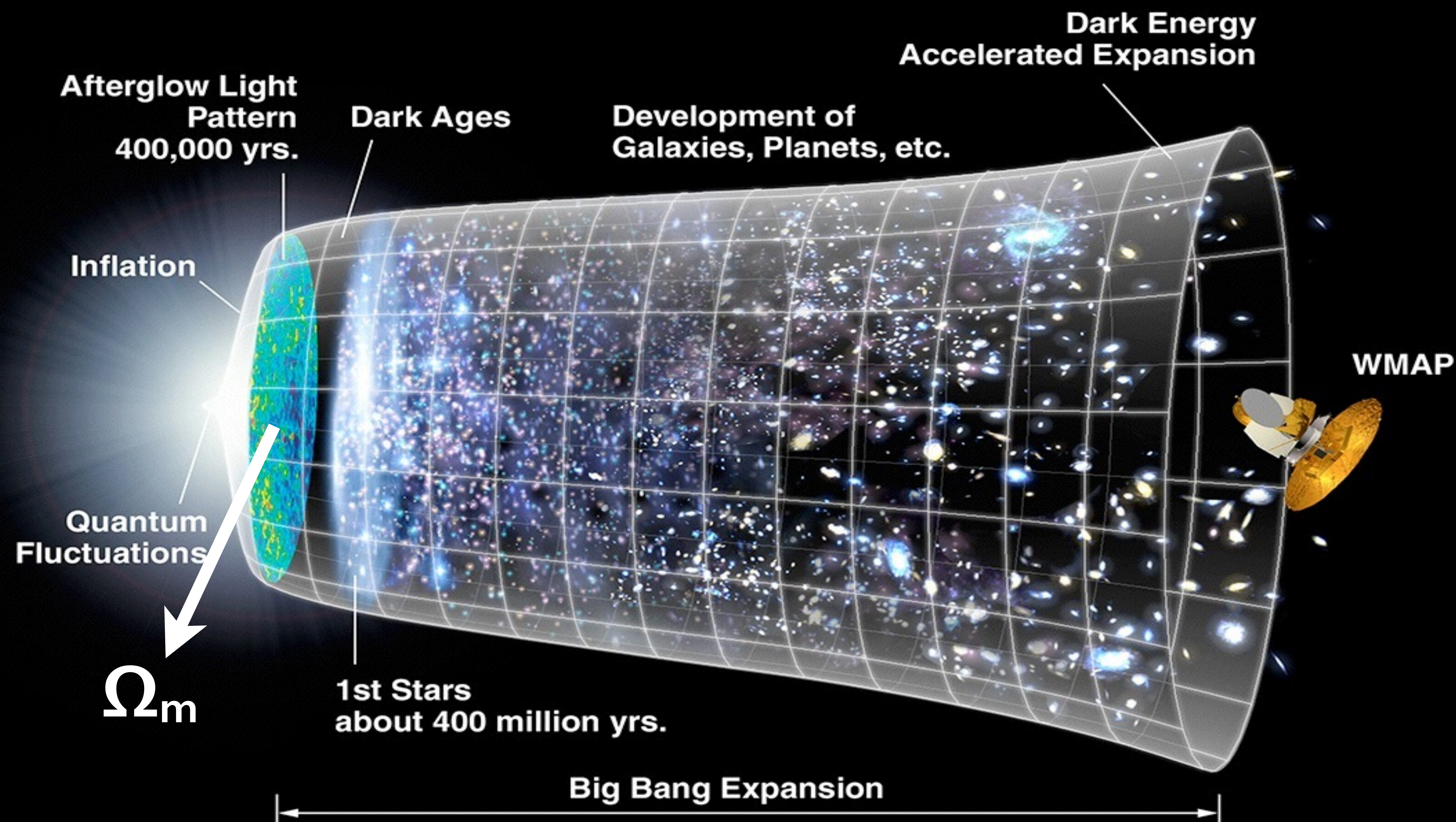


Effects of dark matter

- …or the effects of any mass that does not interacts with photons but contributes to a gravitational potential

- Less dark matter [i.e., radiation more important in the energy density] -> the height of the first peak is enhanced with respect to the other peaks

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



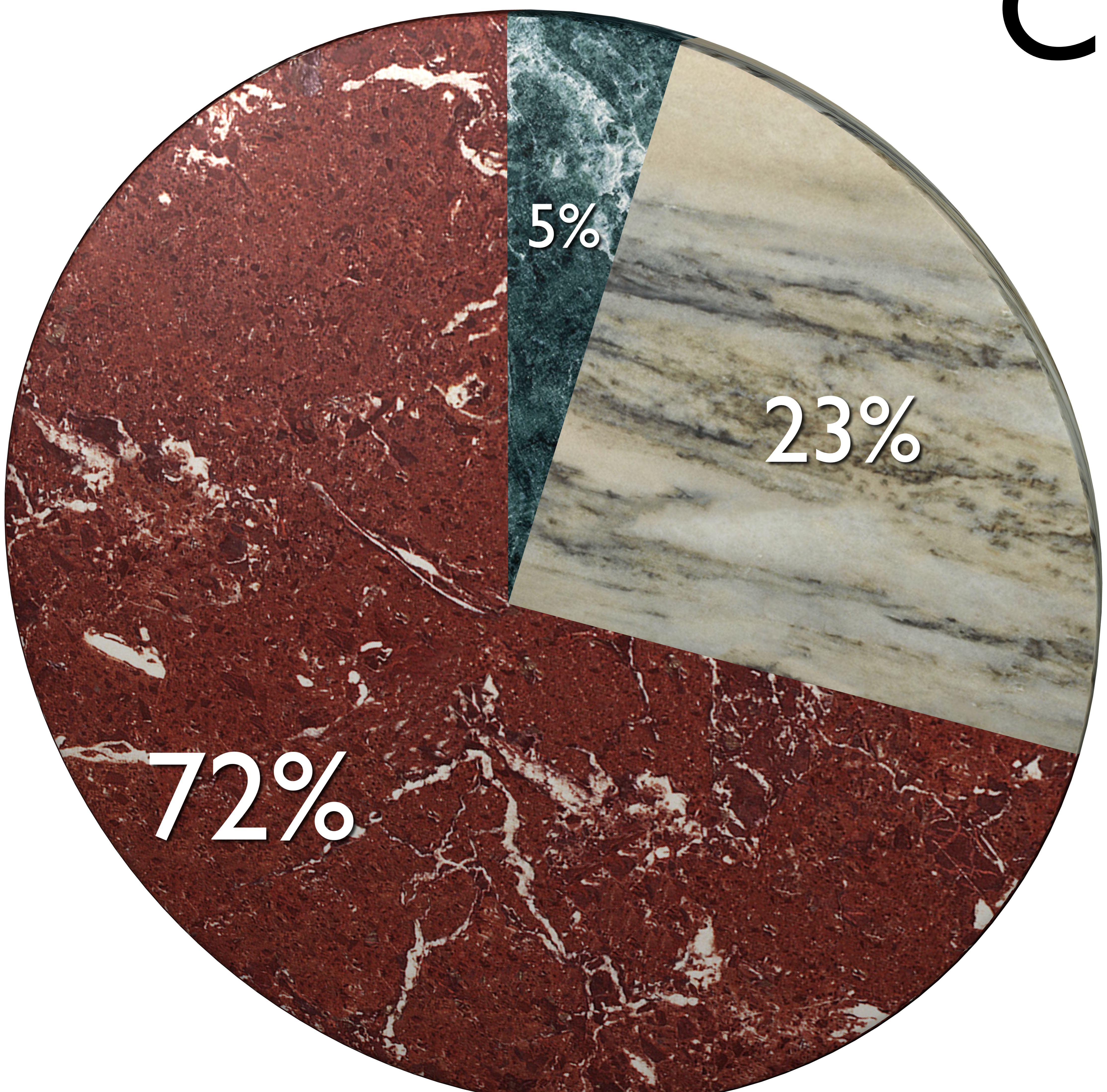
- Angular Diameter Distance to z=1090

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

dark energy

Composition of the Universe

Cosmic Pie Chart



- Cosmological observations (CMB, galaxies, supernovae) over the last decade told us that **we don't understand much of the Universe**.

Hydrogen & Helium
Dark Matter
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?**

Theory of the Very Early Universe

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

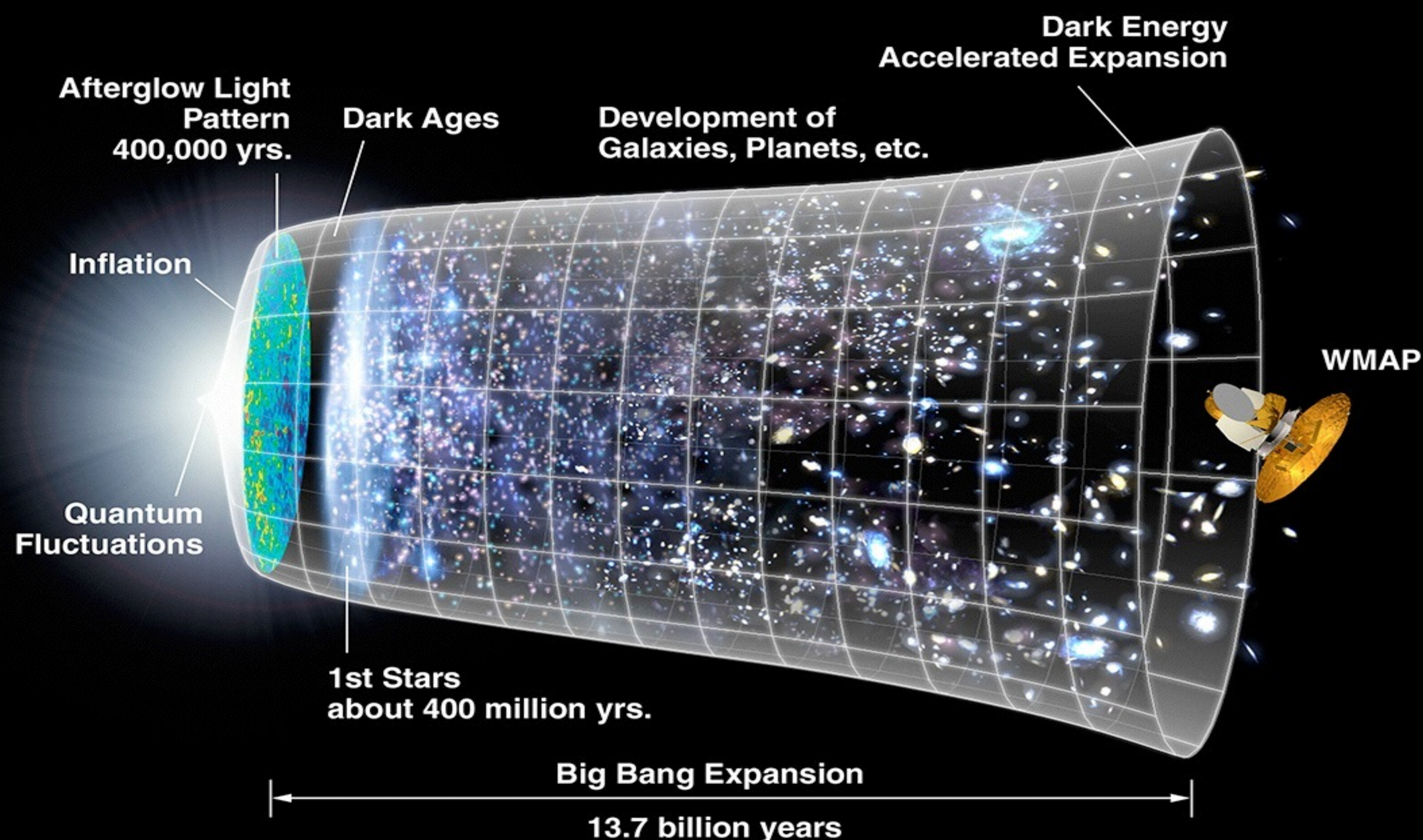
  (Starobinsky 1980; Sato 1981; Guth 1981; Linde 1982; Albrecht & Steinhardt 1982; Starobinsky 1980)

  - 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*"**

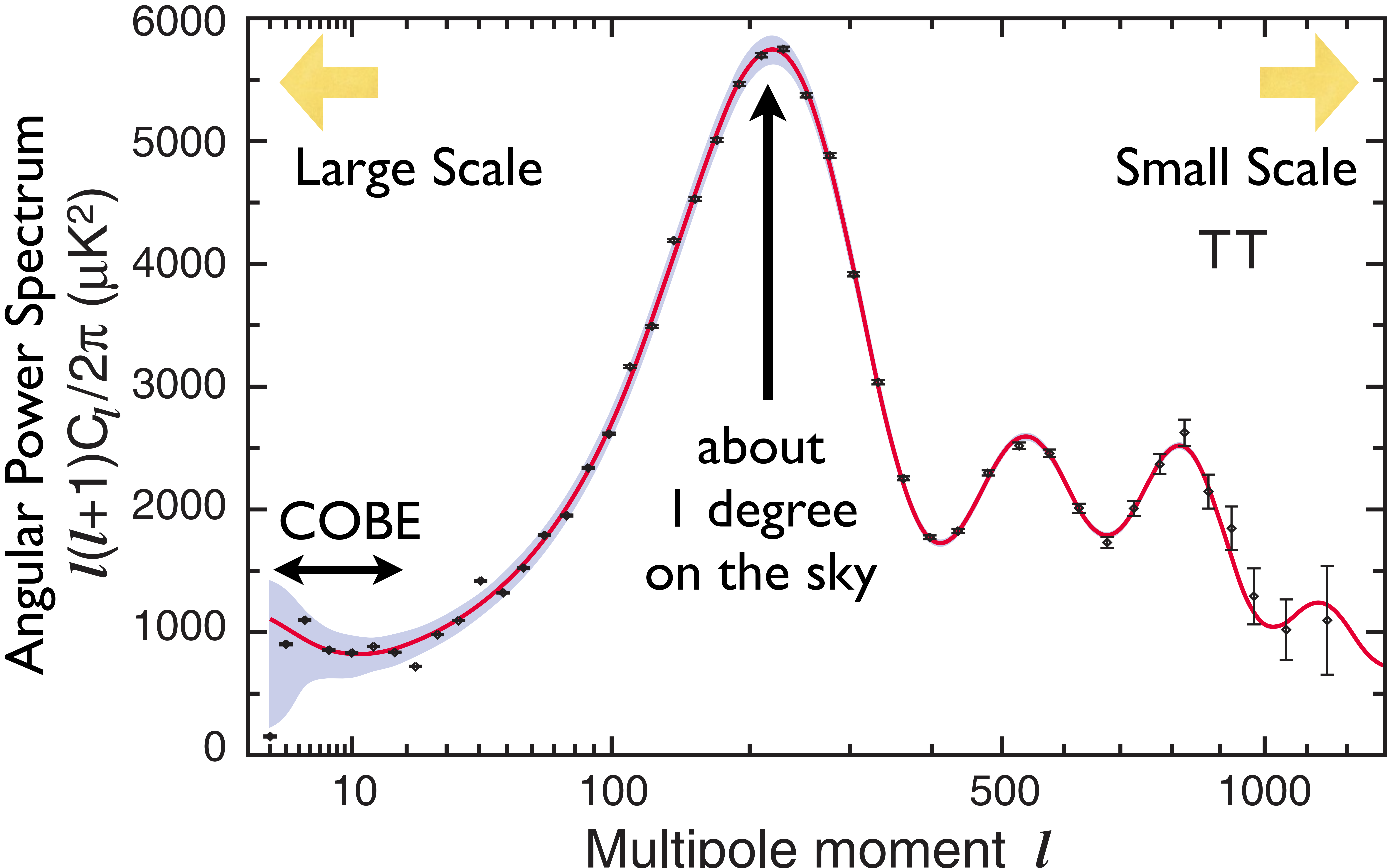
  - In a tiny fraction of a second, the size of an atomic nucleus (~10^{-15}m) would be stretched to 1 A.U. (~10^{11}m), at least.

Cosmic Inflation = Very Early Dark Energy

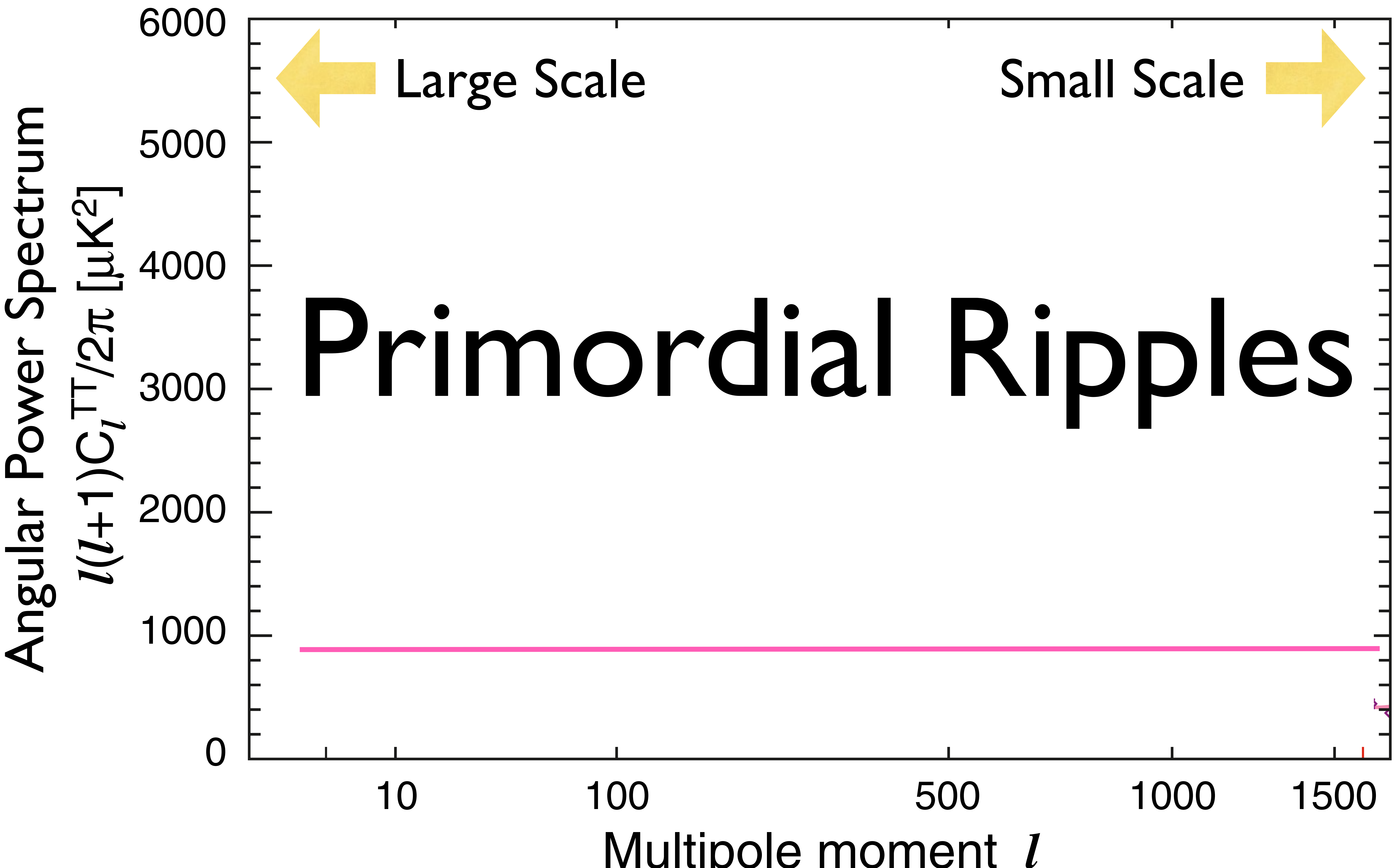


NASA/WMAP Science Team

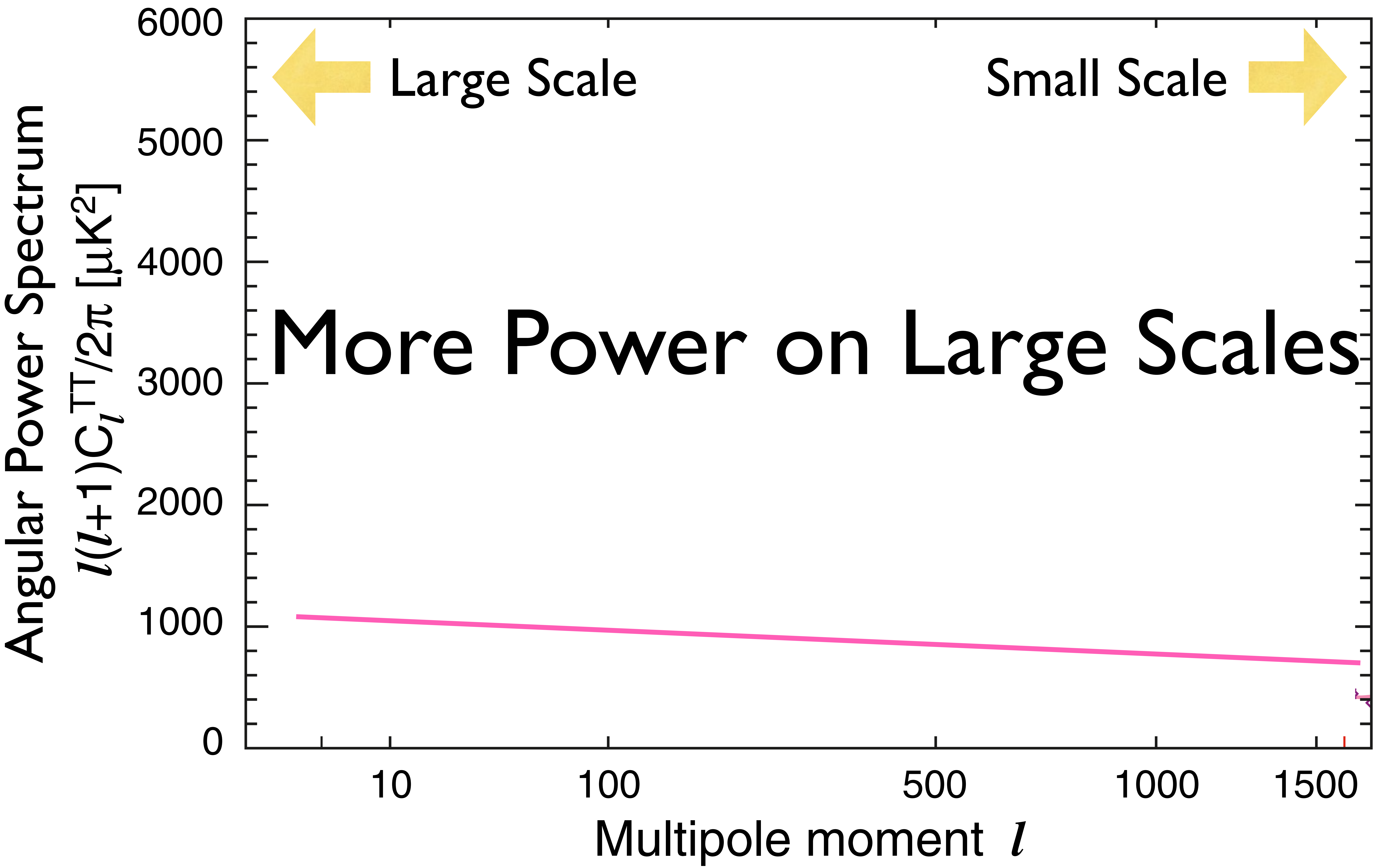
WMAP 9-year Power Spectrum



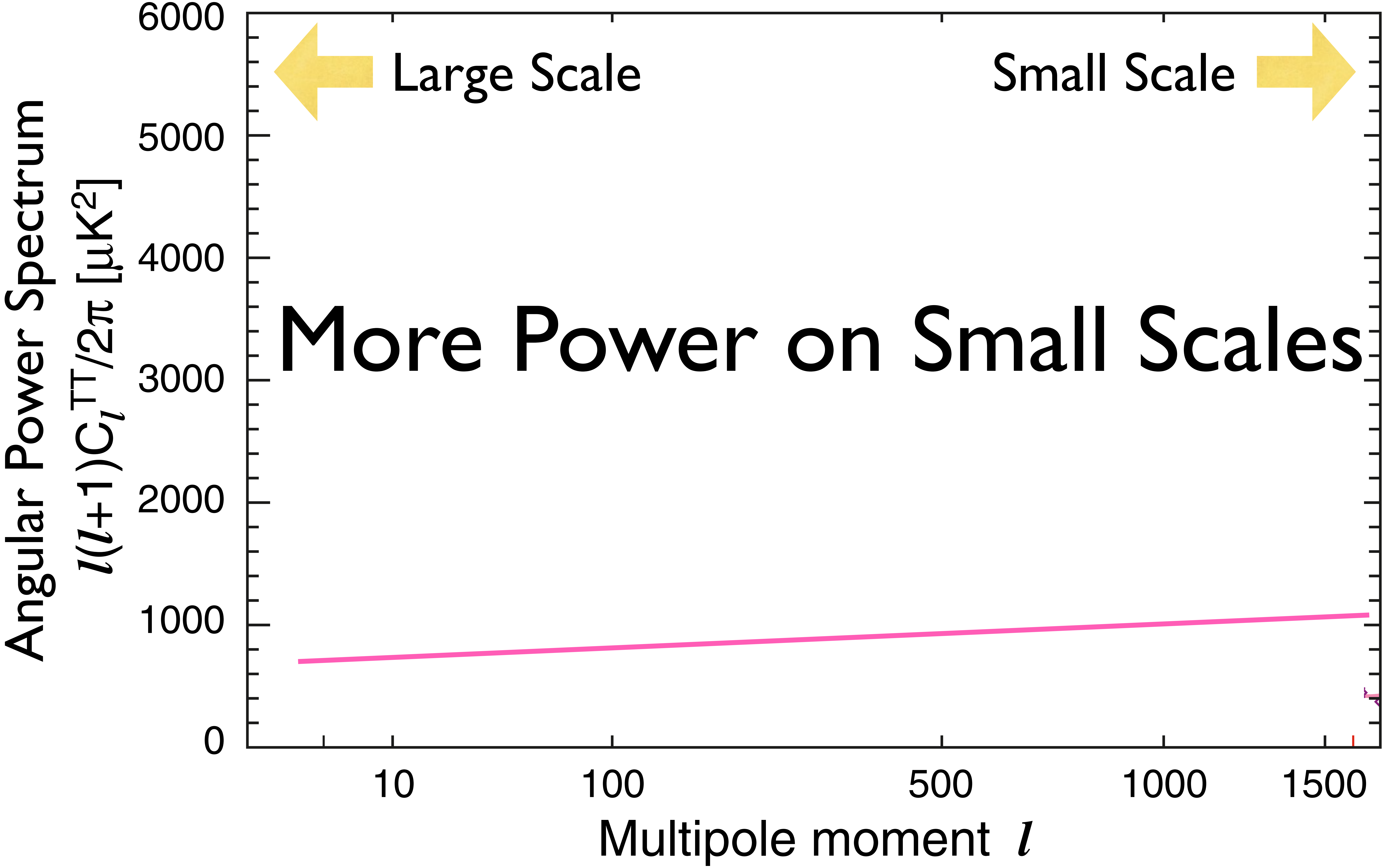
Getting rid of the Sound Waves



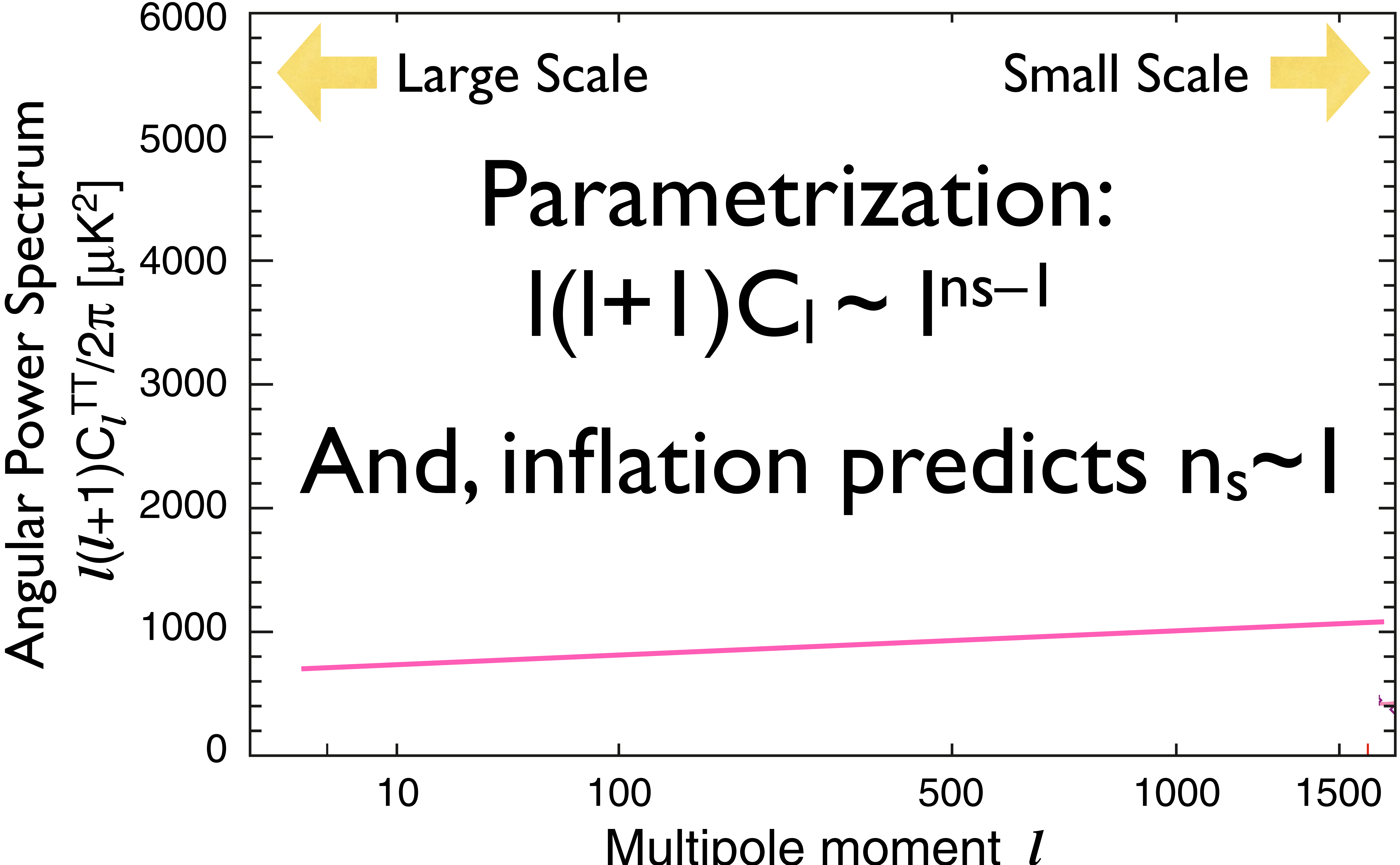
The Early Universe Could Have Done This Instead



...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.



Parametrization:

$$l(l+1)C_l \sim l^{n_s-1}$$

And, inflation predicts $n_s \sim 1$

Theory Says...

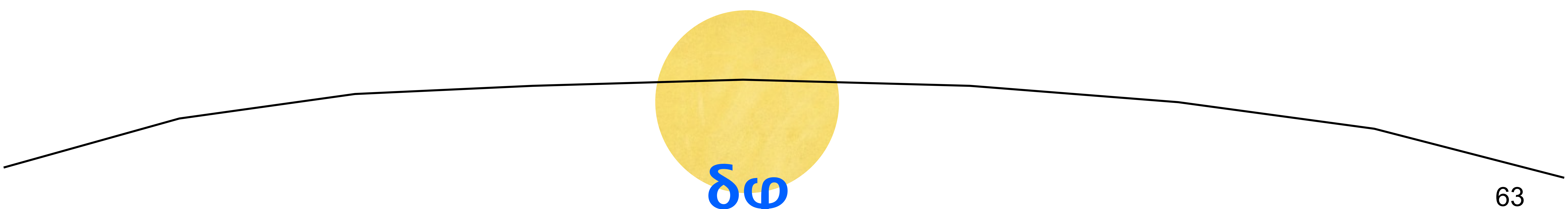
- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  - The expansion of our Universe ***accelerated*** in a tiny fraction of a second after its birth.
  - the primordial ripples were created by ***quantum fluctuations*** during inflation, and
  - 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

Quantum fluctuations on microscopic scales

INFLATION!



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]

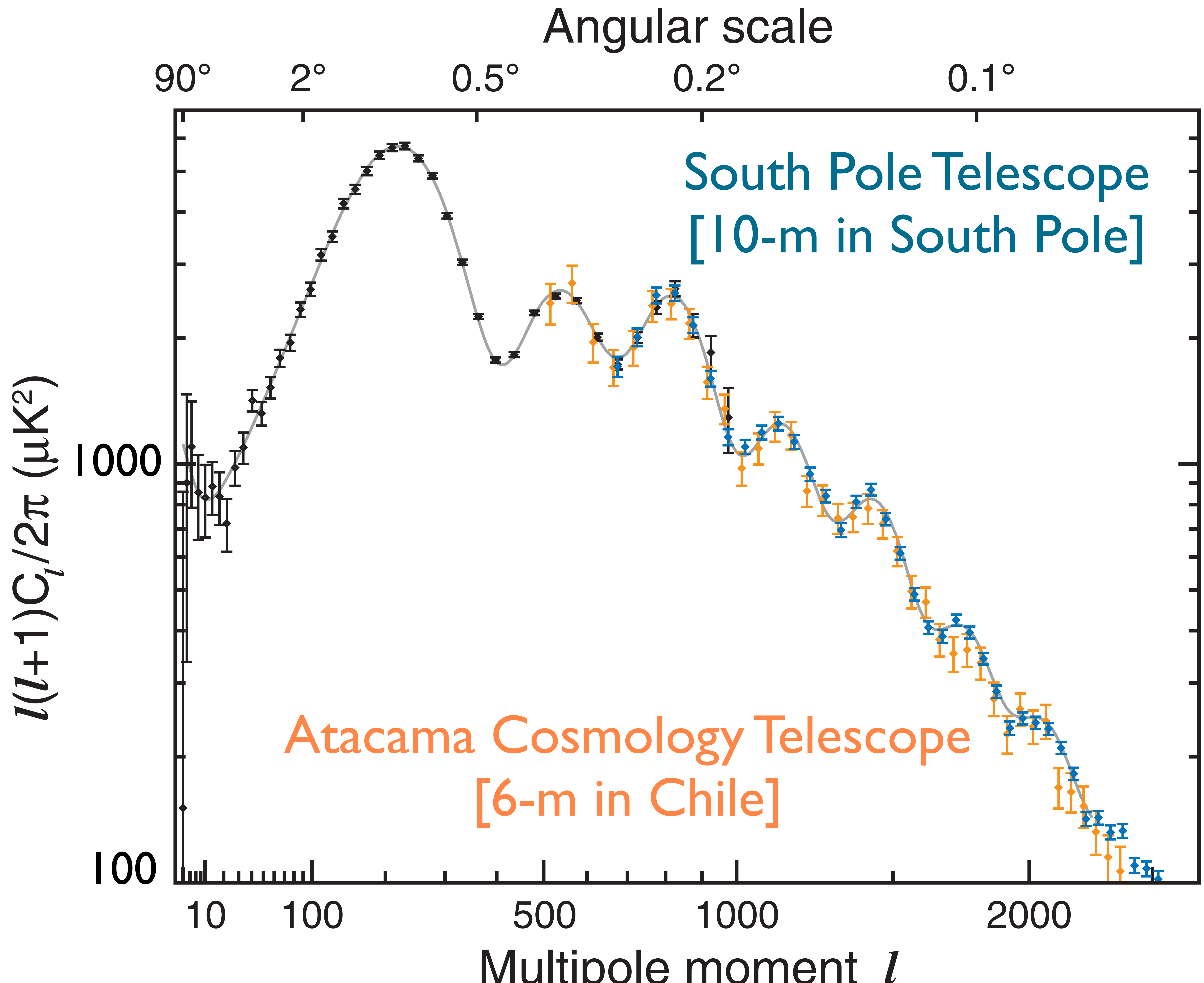
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-36} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

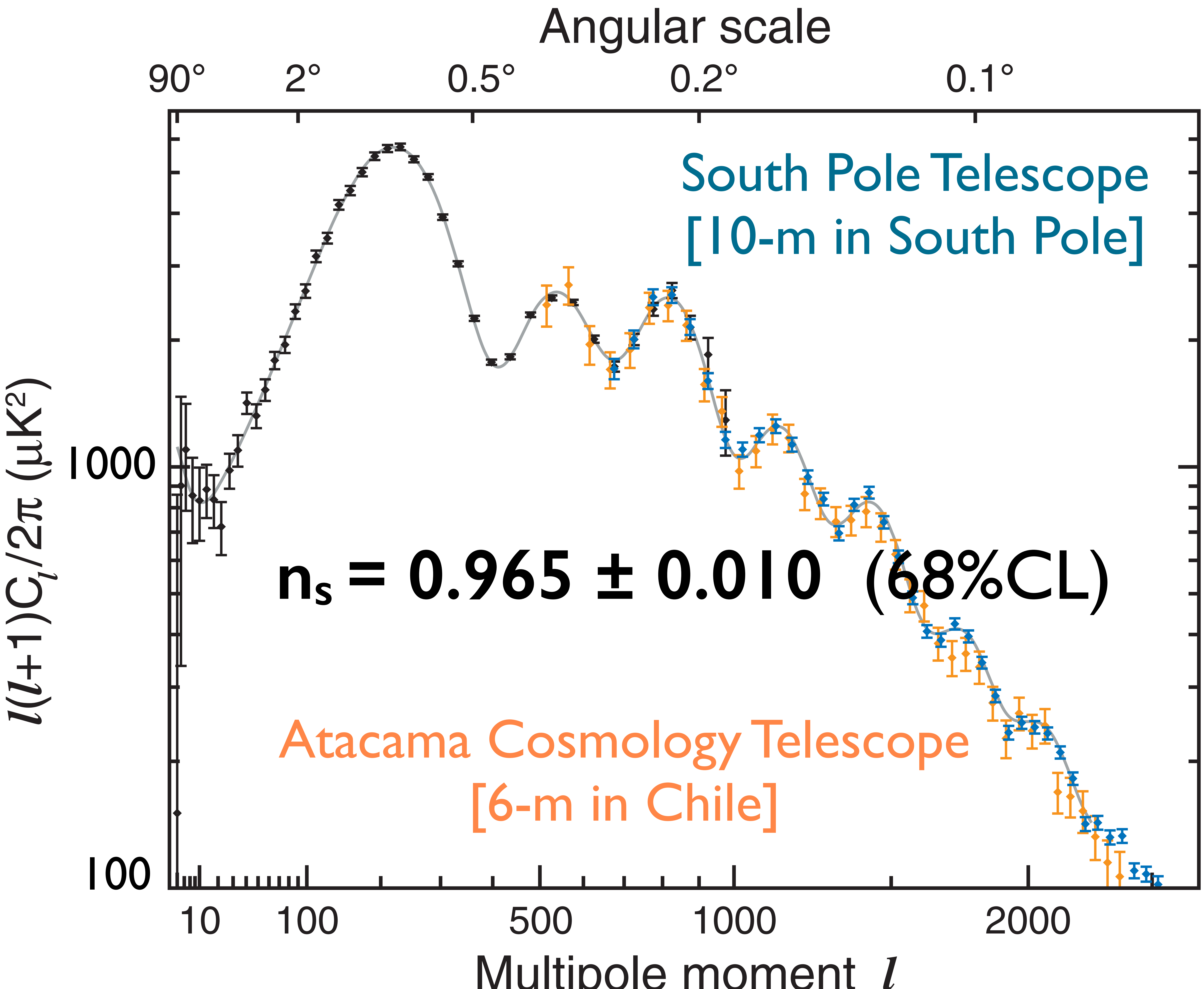
Inflation Offers a Magnifier for Microscopic World

- 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):

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

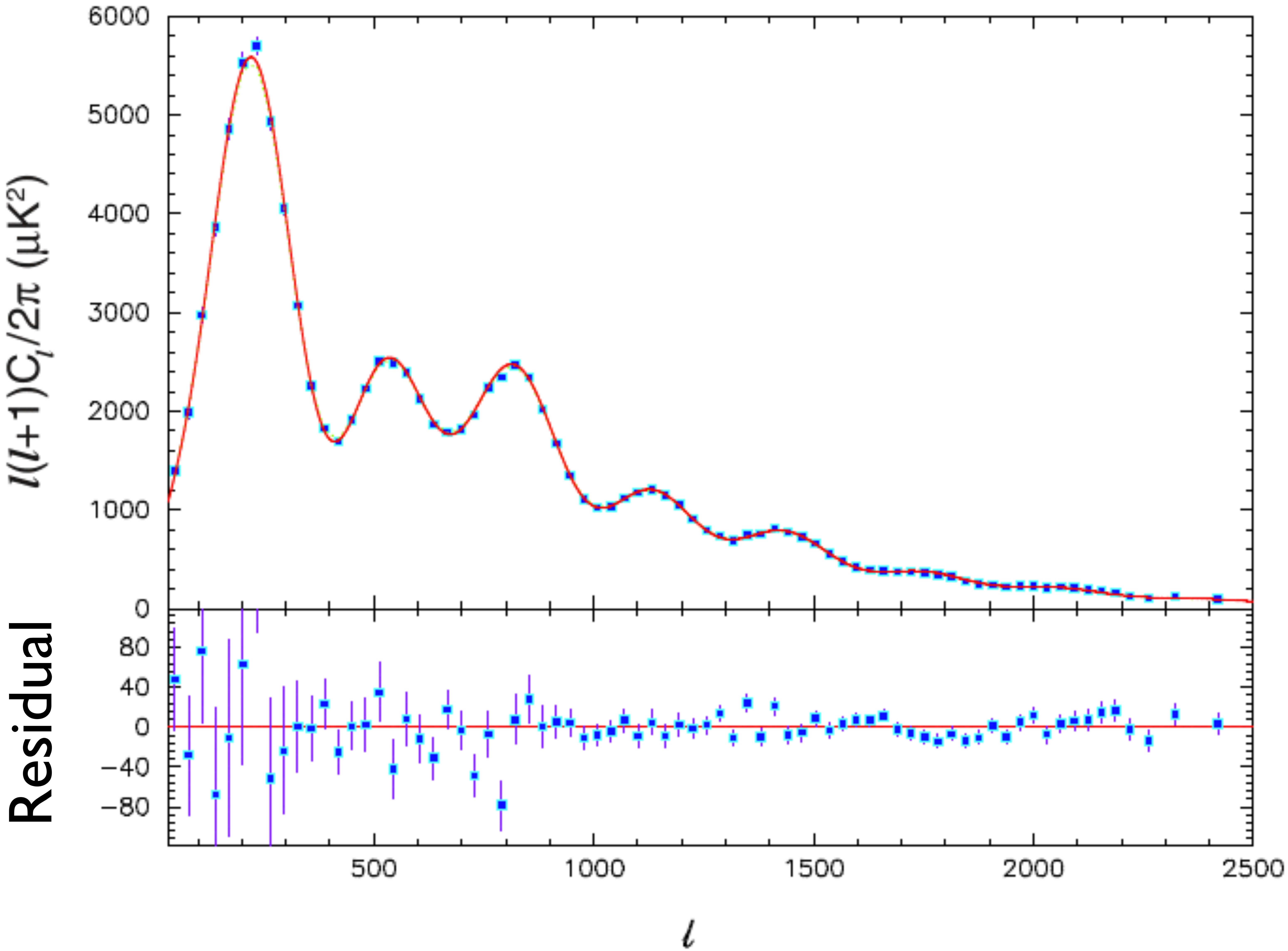

Angular scale
90°
2°
0.5°
0.2°
0.1°
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
$l(l+1)C_l/2\pi$ (μK^2)
1000
100
10
100
500
1000
2000
Multipole moment l



Angular scale
90°
2°
0.5°
0.2°
0.1°
South Pole Telescope
[10-m in South Pole]
$l(l+1)C_l/2\pi$ (μK^2)
1000
100
$n_s = 0.965 \pm 0.010$ (68%CL)
Atacama Cosmology Telescope
[6-m in Chile]
10
100
500
1000
2000
Multipole moment l

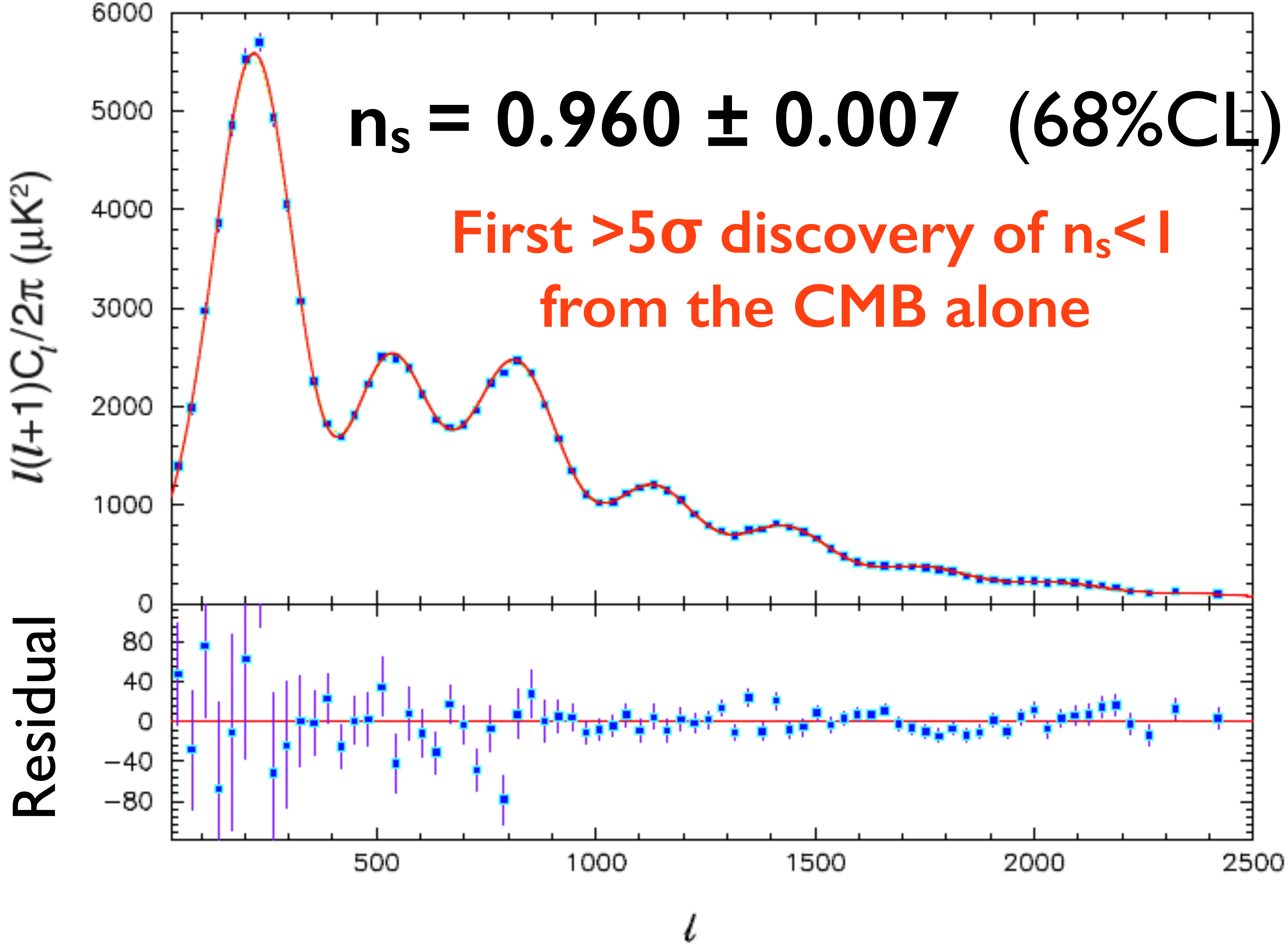
Planck Result!

Planck (2013)



Planck (2013)

Planck Result!



GRUBER
FOUNDATION

July 11, 2013

COSMOLOGY

2013 Gruber Cosmology Prize Citation

The Gruber Foundation proudly presents the 2013 Cosmology Prize to Viatcheslav Mukhanov and Alexei Starobinsky for their profound contribution to inflationary cosmology and the theory of inflationary perturbations of the metric. These developments changed our views on the origin of our universe and on the mechanism of formation of its structure.

Viatcheslav Mukhanov

Alexei Starobinsky

Starobinsky (1979)

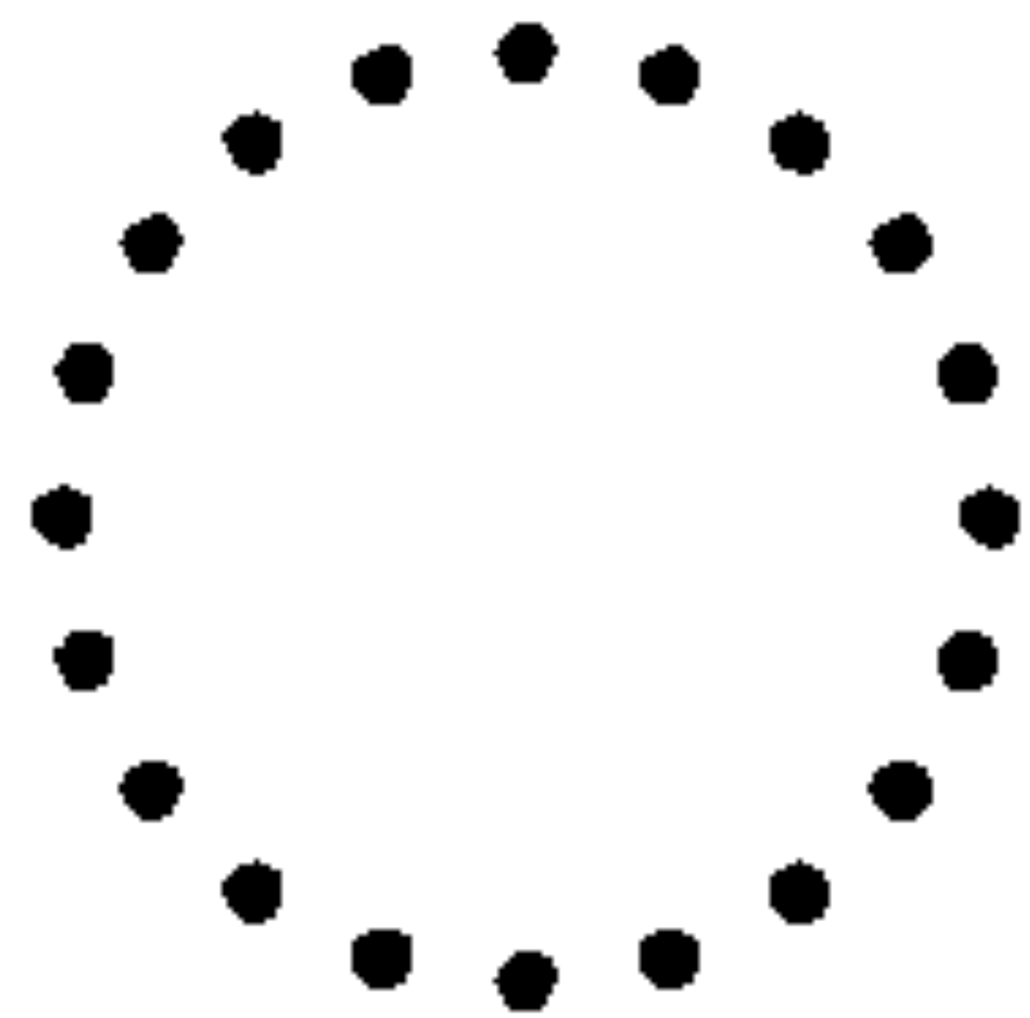
(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

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

[h = "strain"]

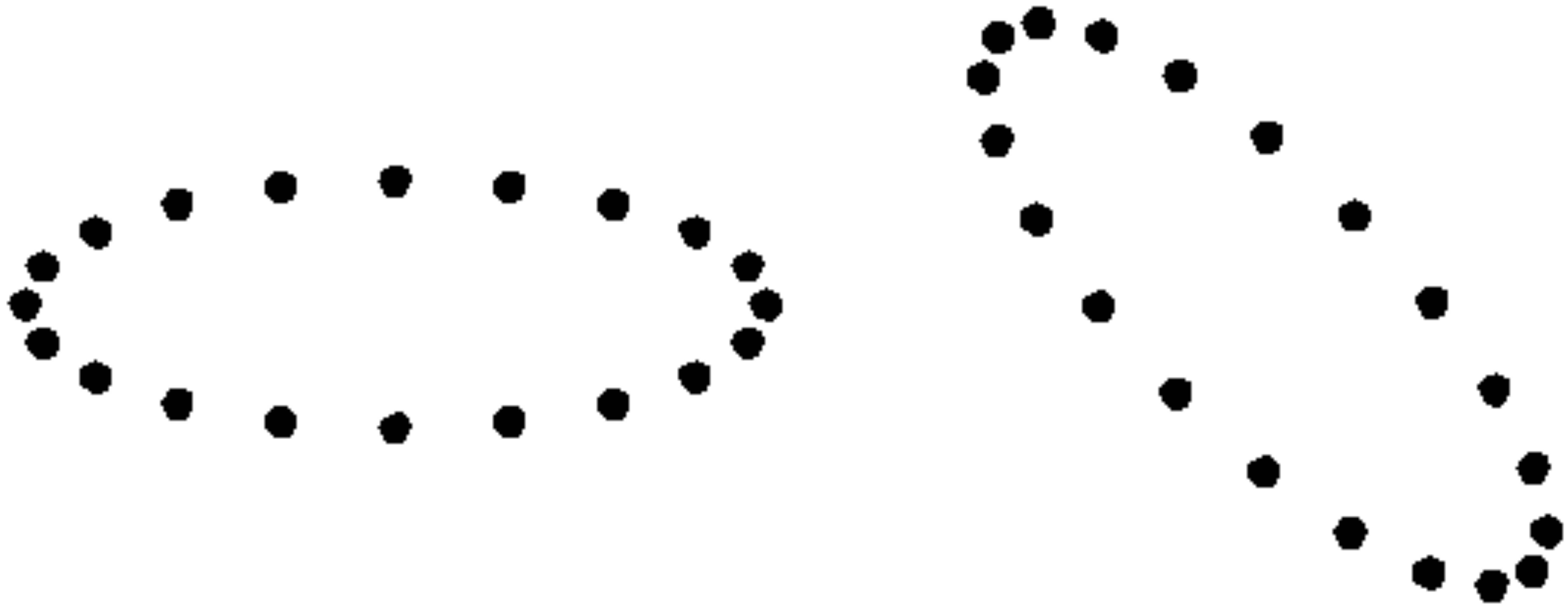
- Quantum fluctuations also generate ripples in space-time, i.e., gravitational waves, by the same mechanism.
- Primordial gravitational waves generate temperature anisotropy in CMB.

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



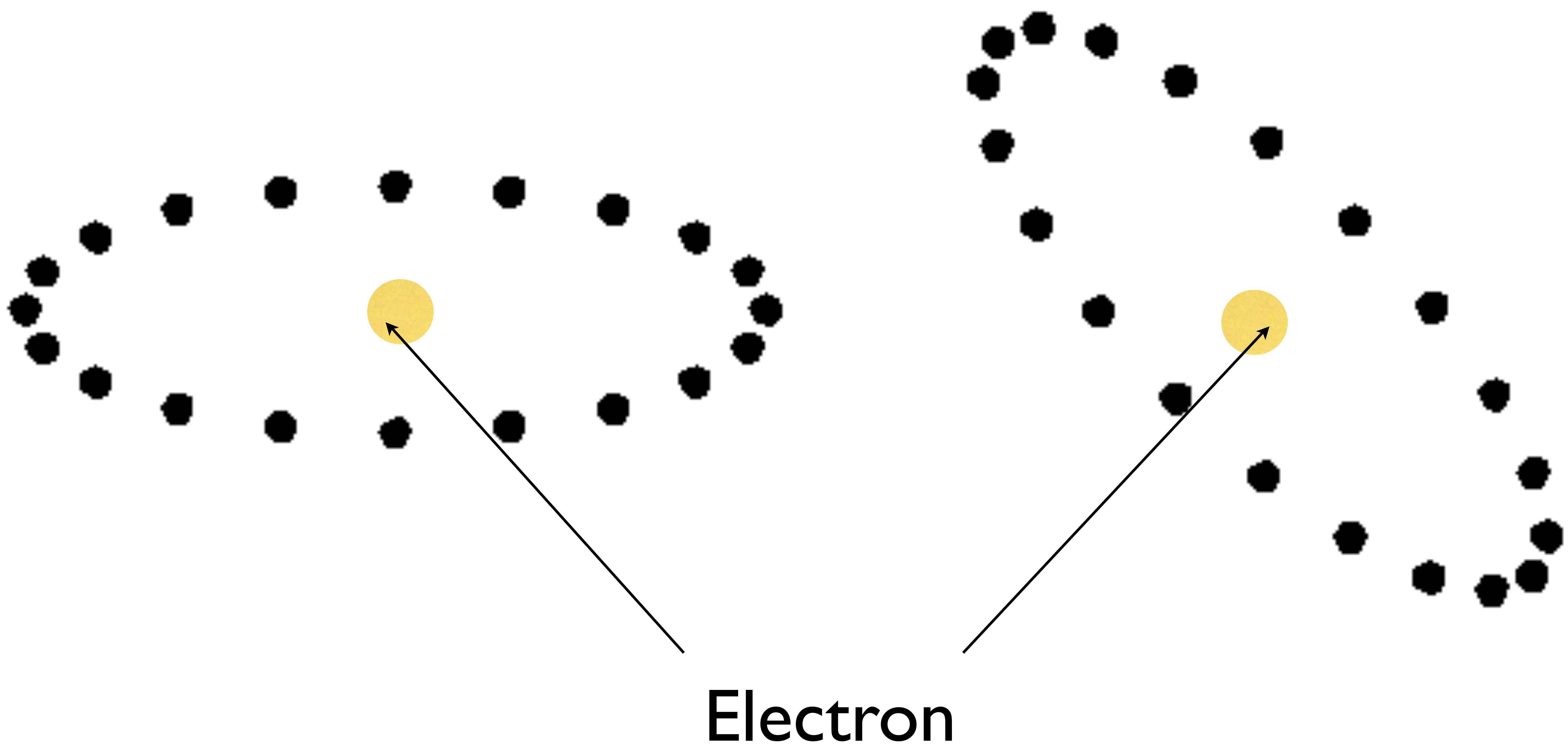
- Gravitational waves stretch space, causing particles to move.

Two Polarization States of GW

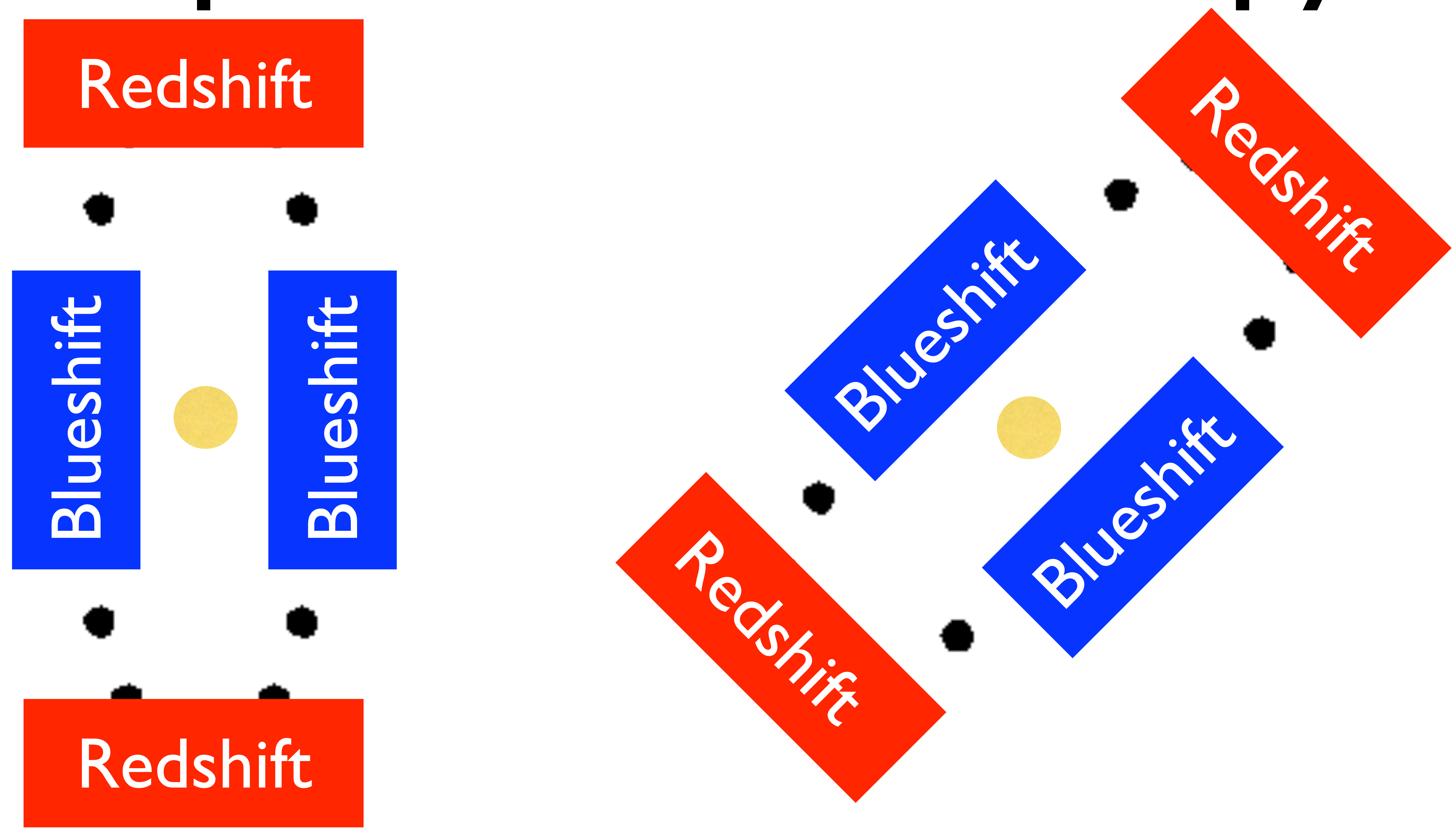


- This is great - this will automatically generate quadrupolar anisotropy around electrons!

From GW to temperature anisotropy



From GW to temperature anisotropy

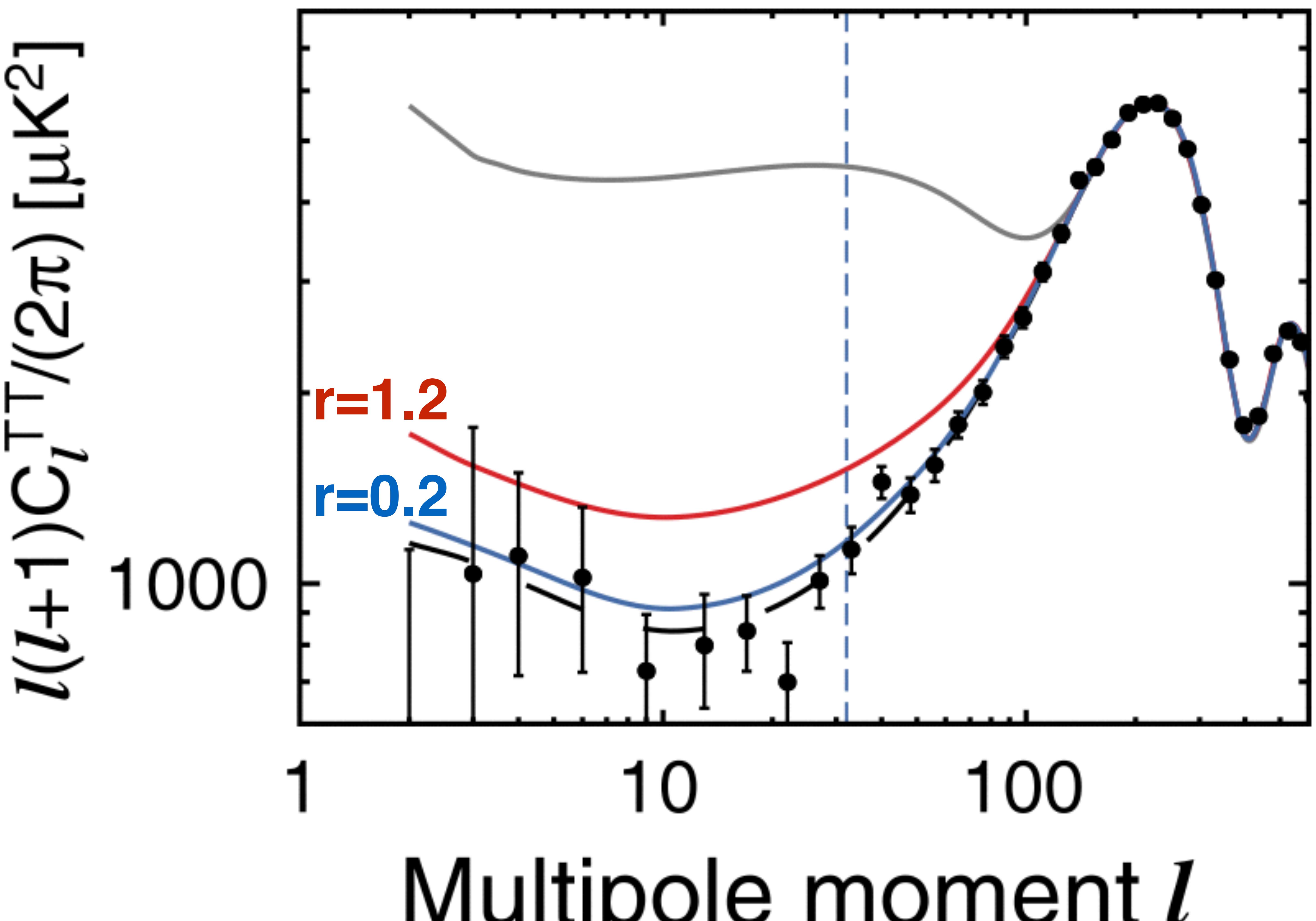


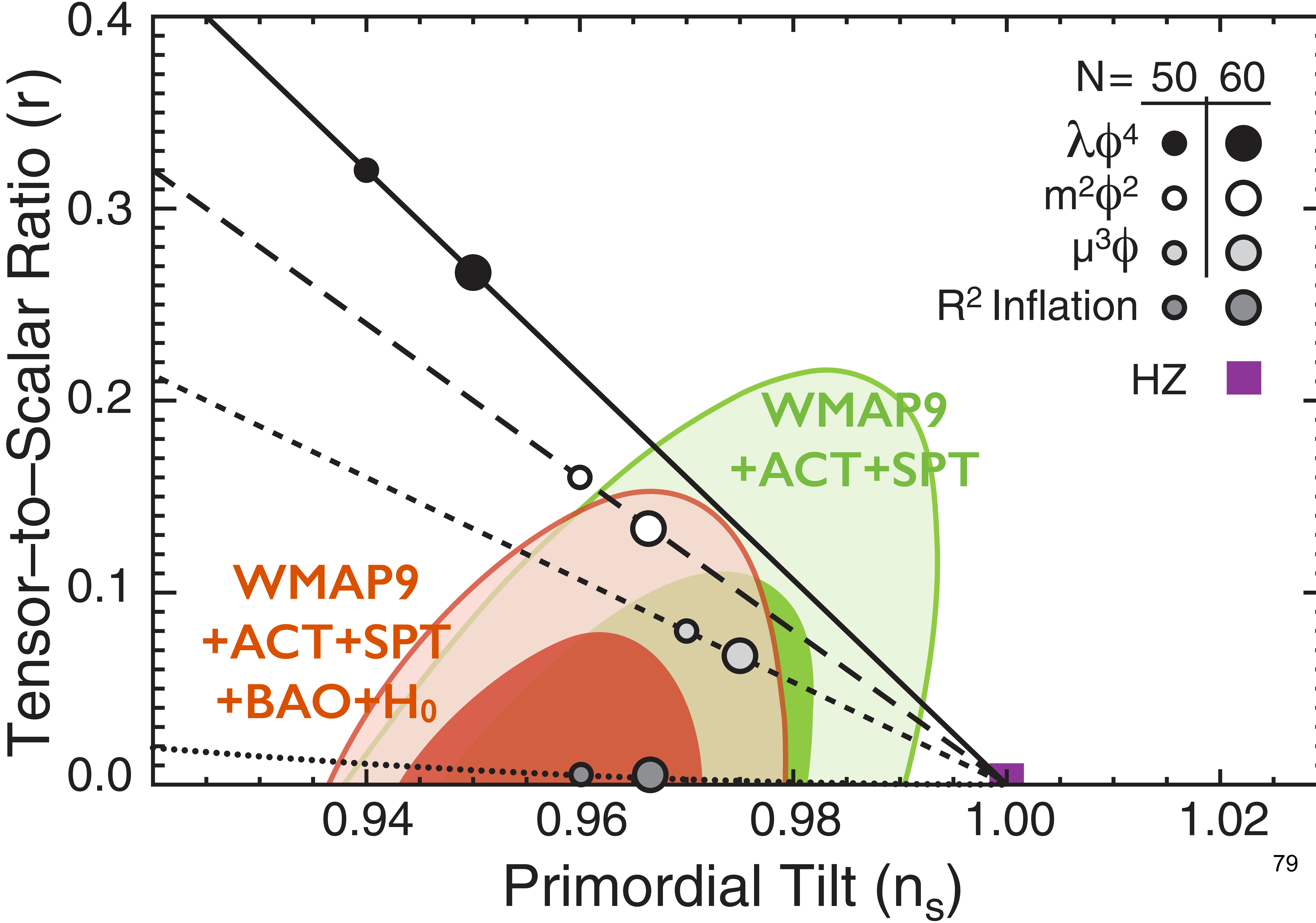
“Tensor-to-scalar Ratio,” r

r = [Power in Gravitational Waves]
/ [Power in Gravitational Potential]

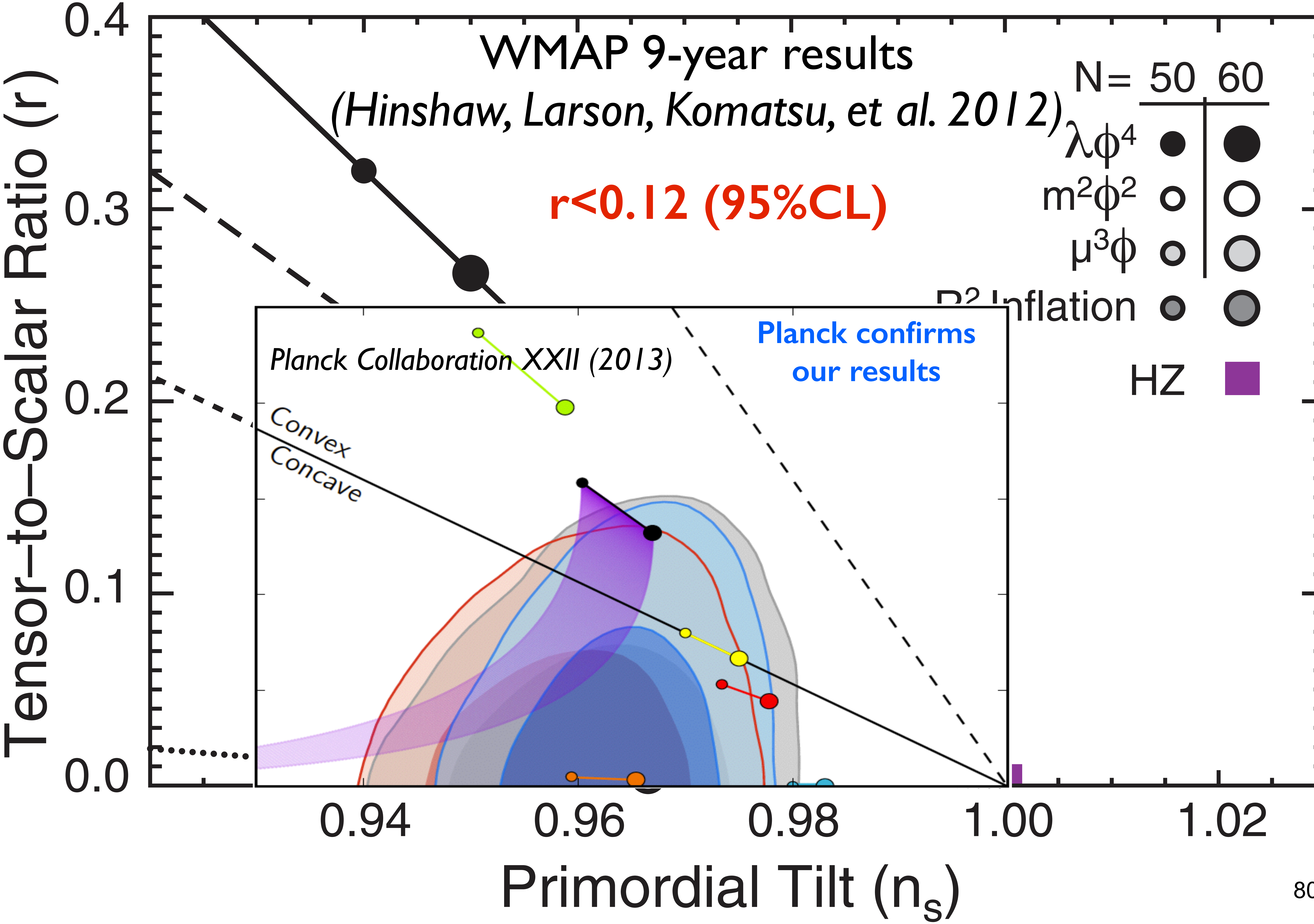
Inflation predicts r <~ 1

Limit from Temperature



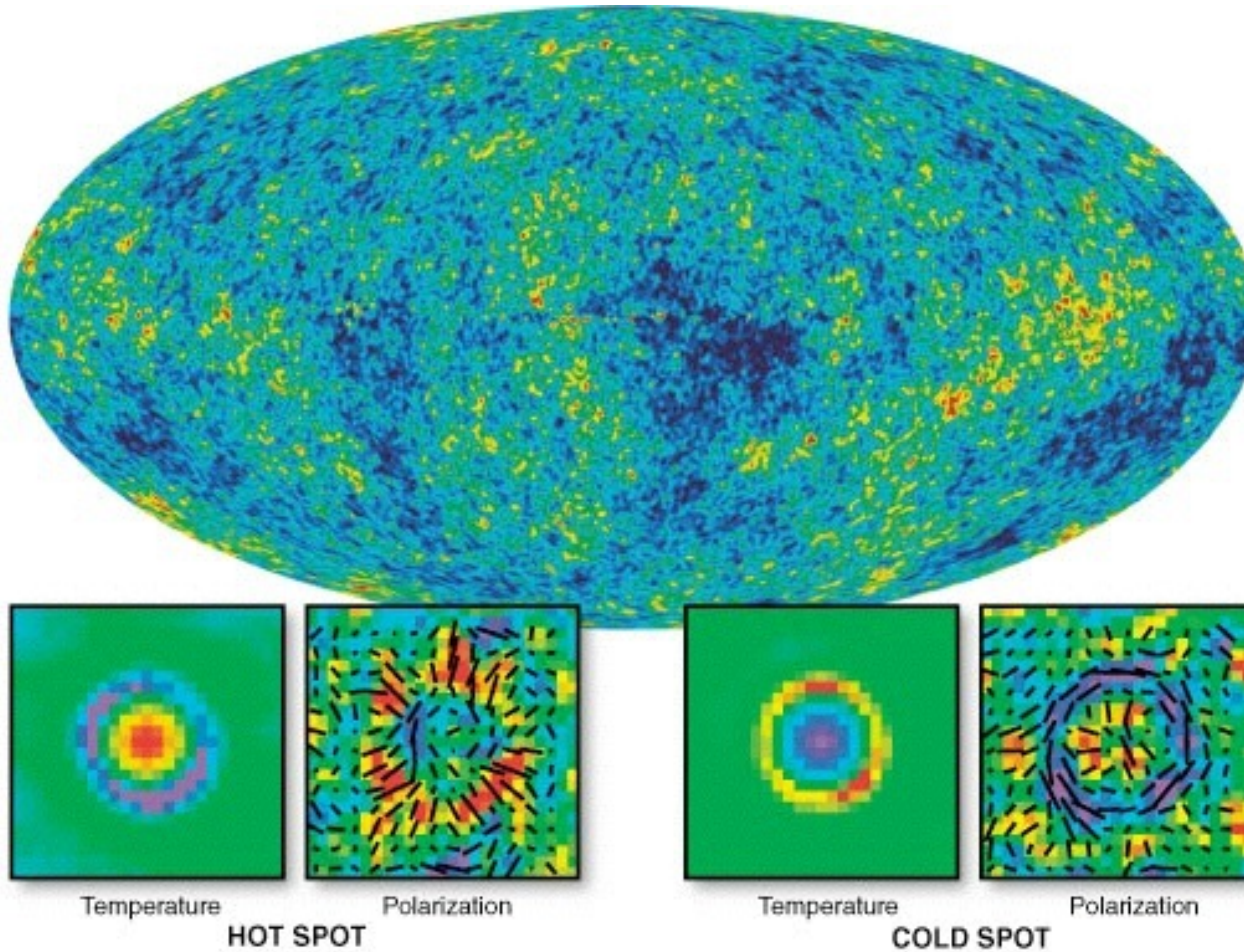


0.4
0.3
0.2
0.1
0.0
Tensor–to–Scalar Ratio (r)
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
R^2 Inflation
HZ
WMAP9
+ACT+SPT
WMAP9
+ACT+SPT
+BAO+H_0



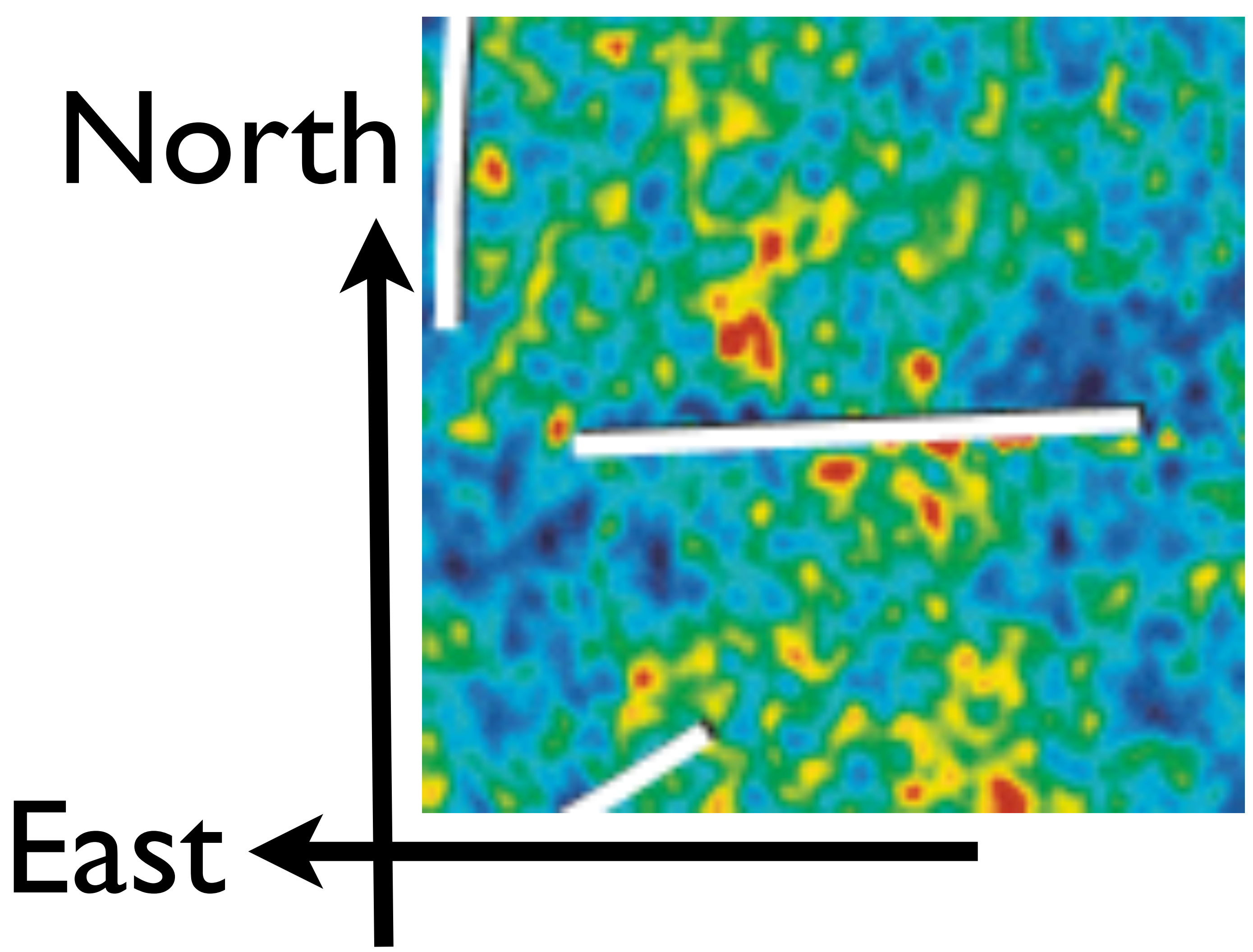
WMAP 9-year results
(Hinshaw, Larson, Komatsu, et al. 2012)
r<0.12 (95%CL)
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
R^2 Inflation
HZ
Planck Collaboration XXII (2013)
Planck confirms our results
Convex
Concave
Tensor-to-Scalar Ratio (r)
Primordial Tilt (n_s)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02

CMB Polarization

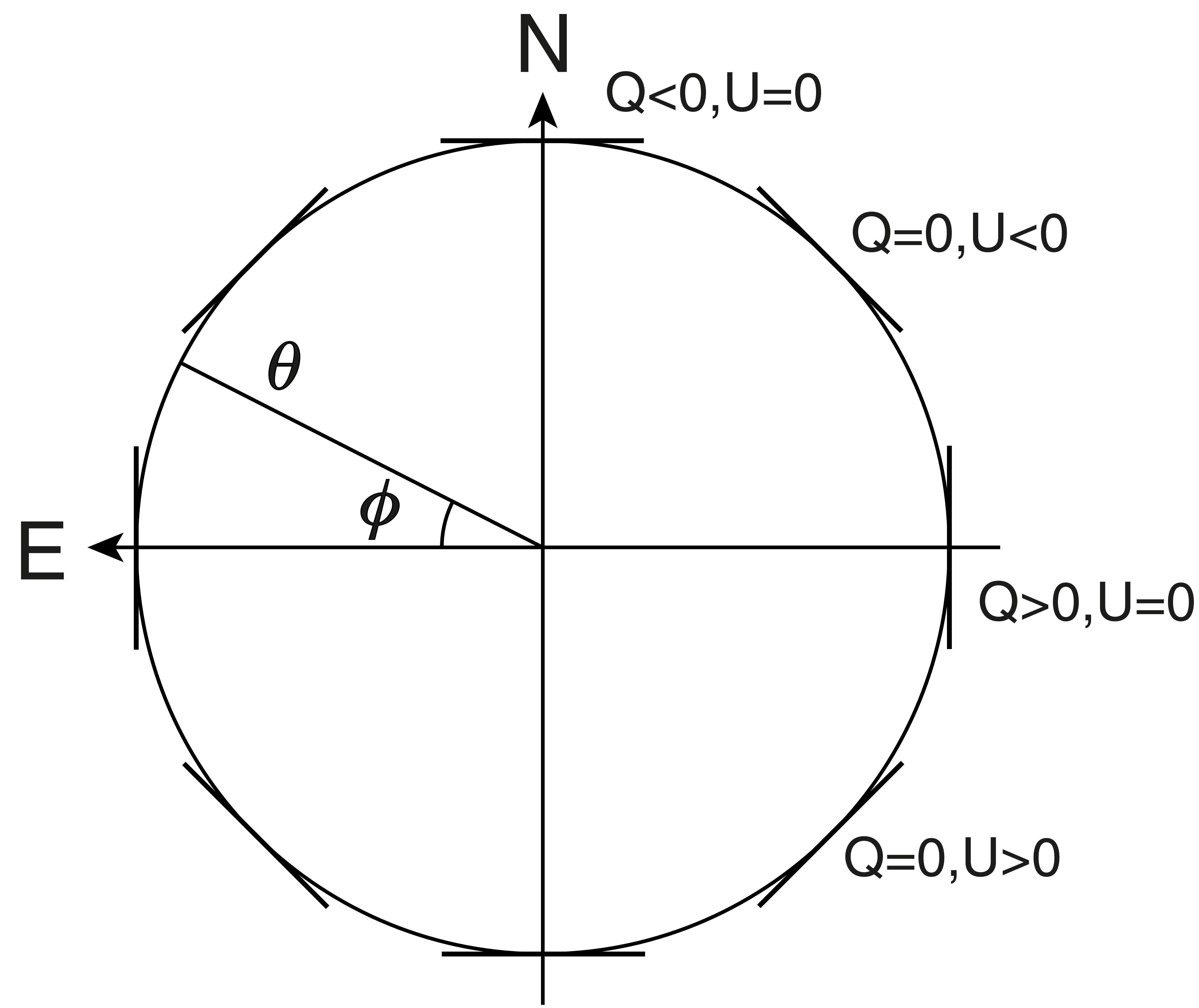


- *CMB is (very weakly) polarized!*

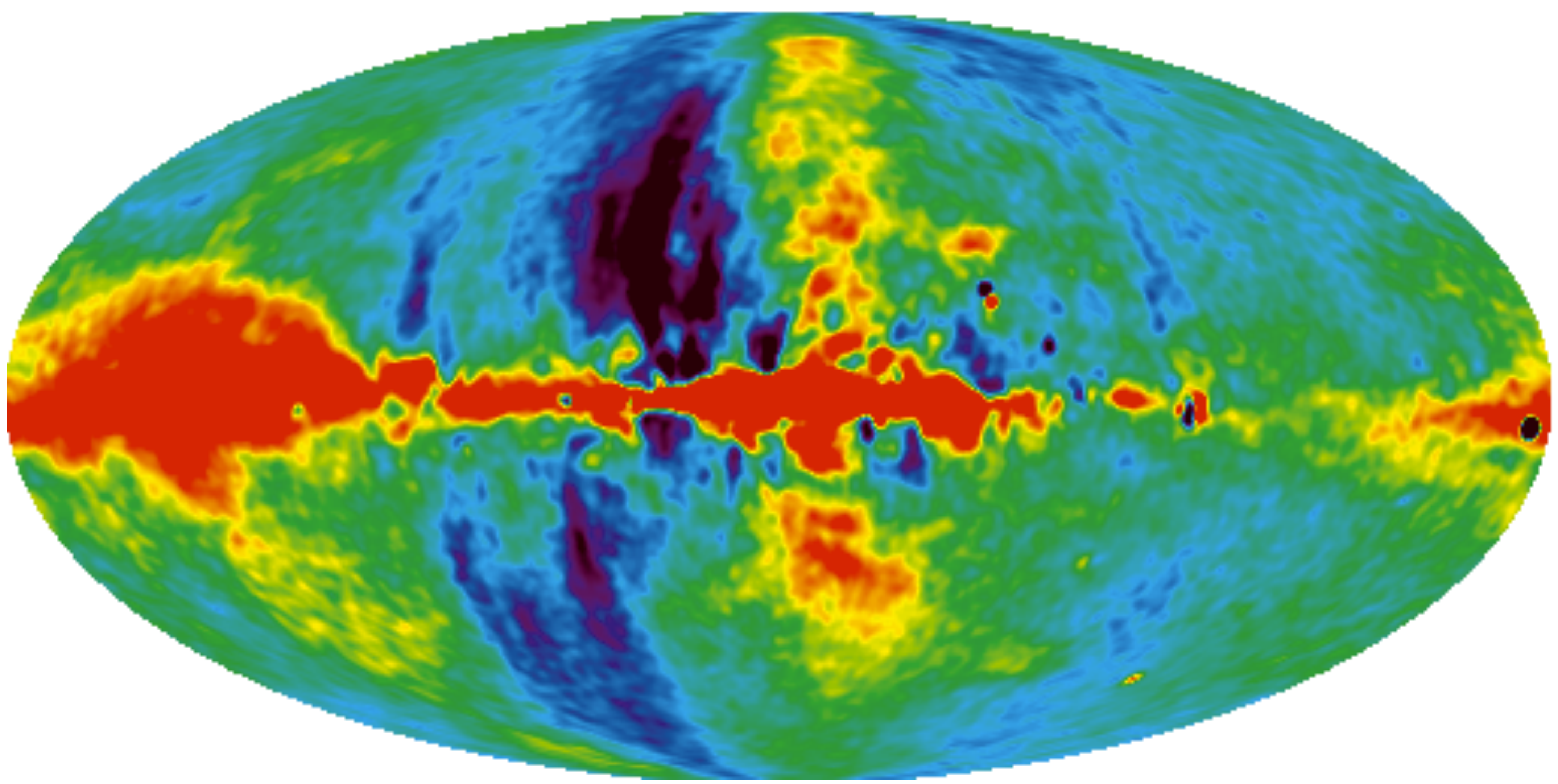
“Stokes Parameters”



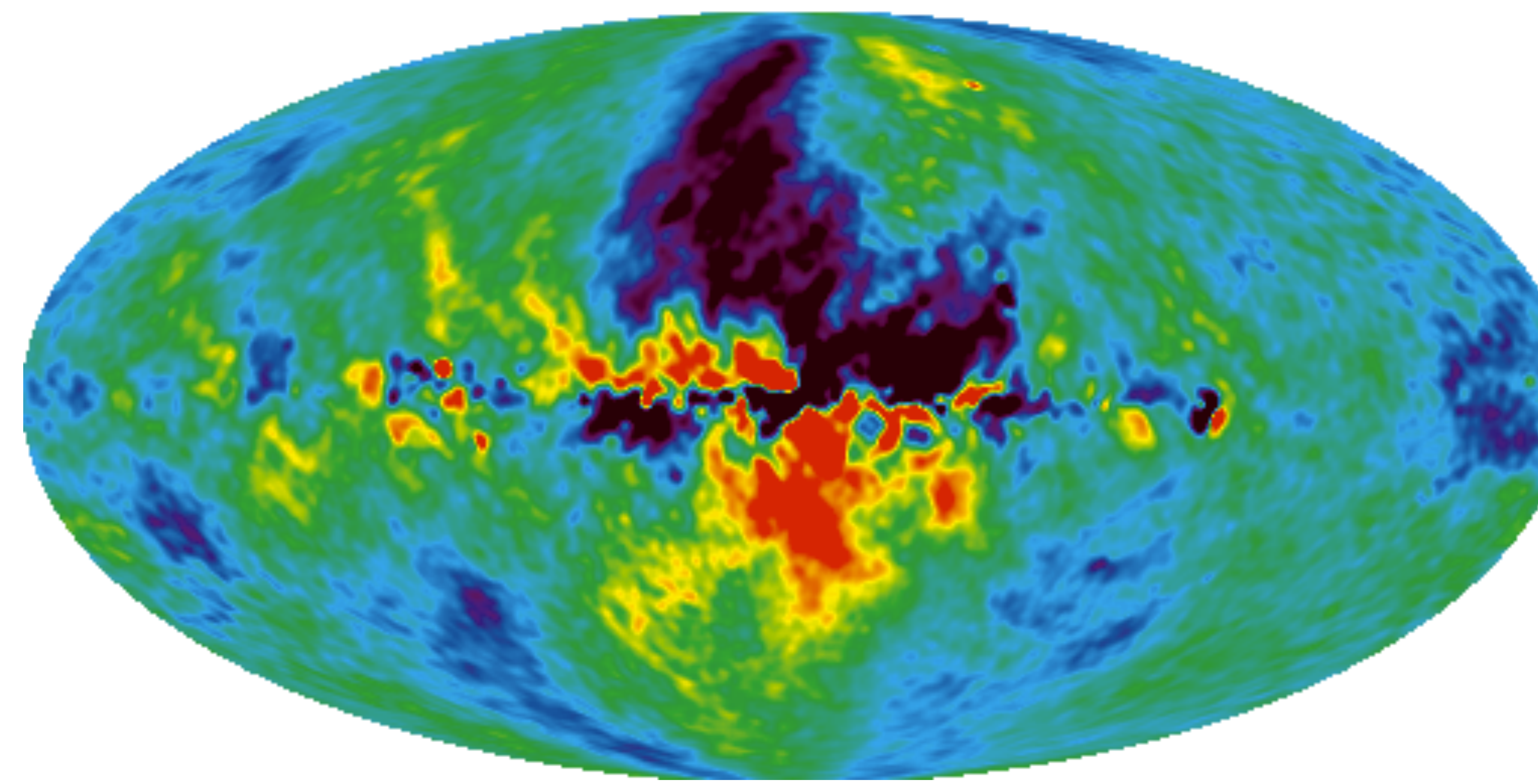
Q<0; U=0



23 GHz [polarized]

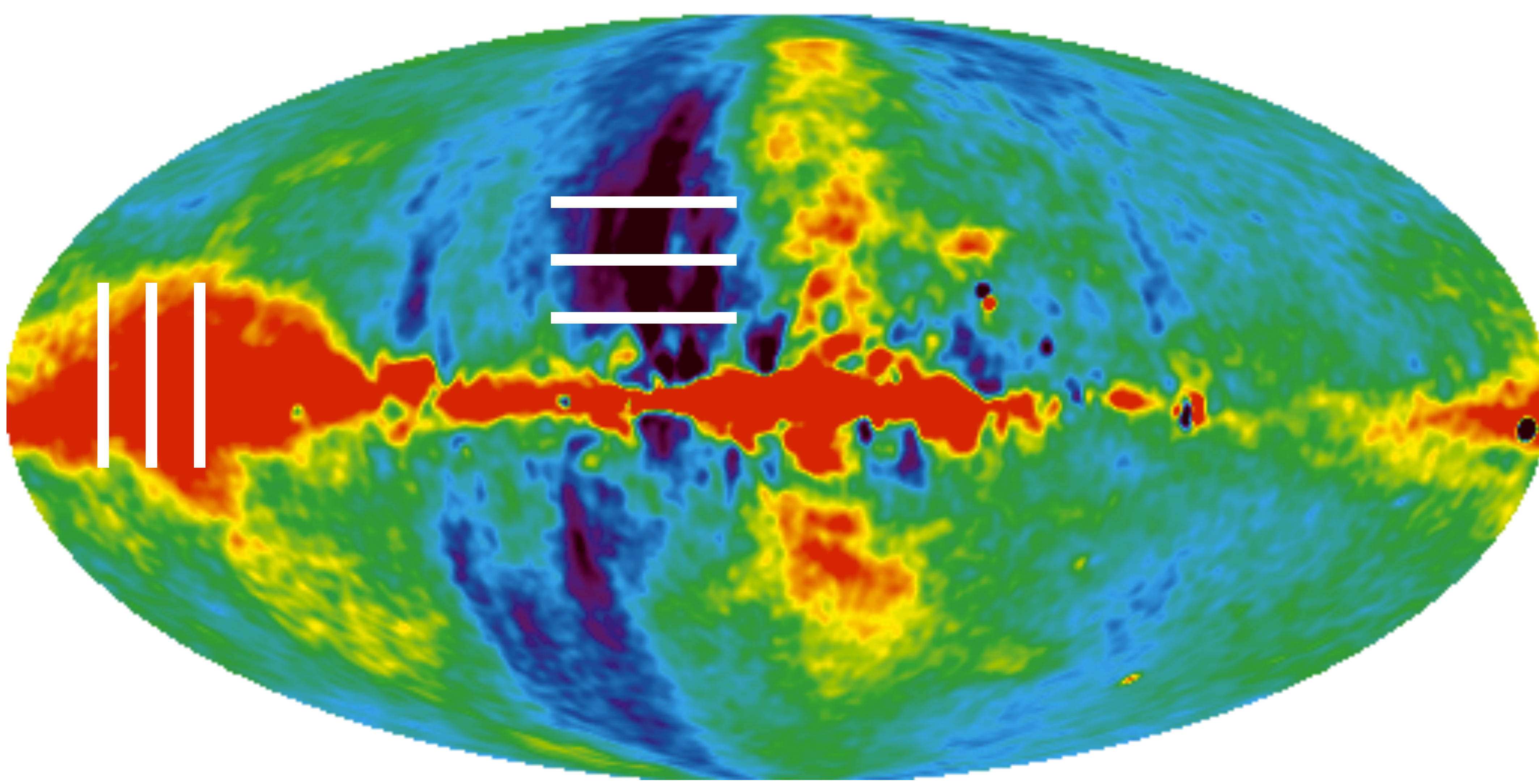


Stokes Q

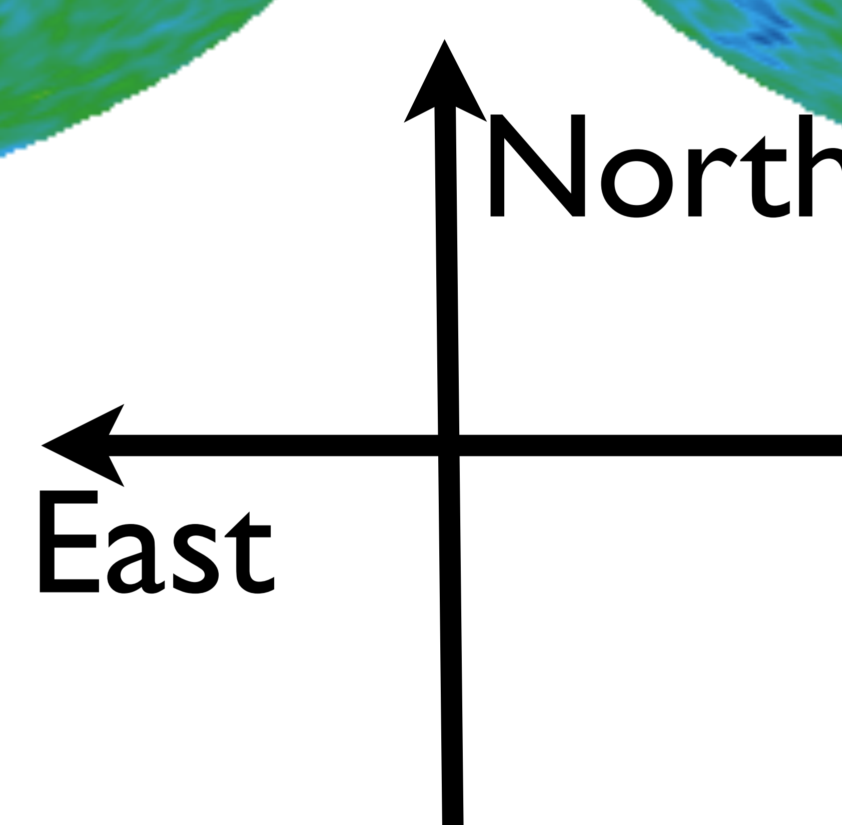


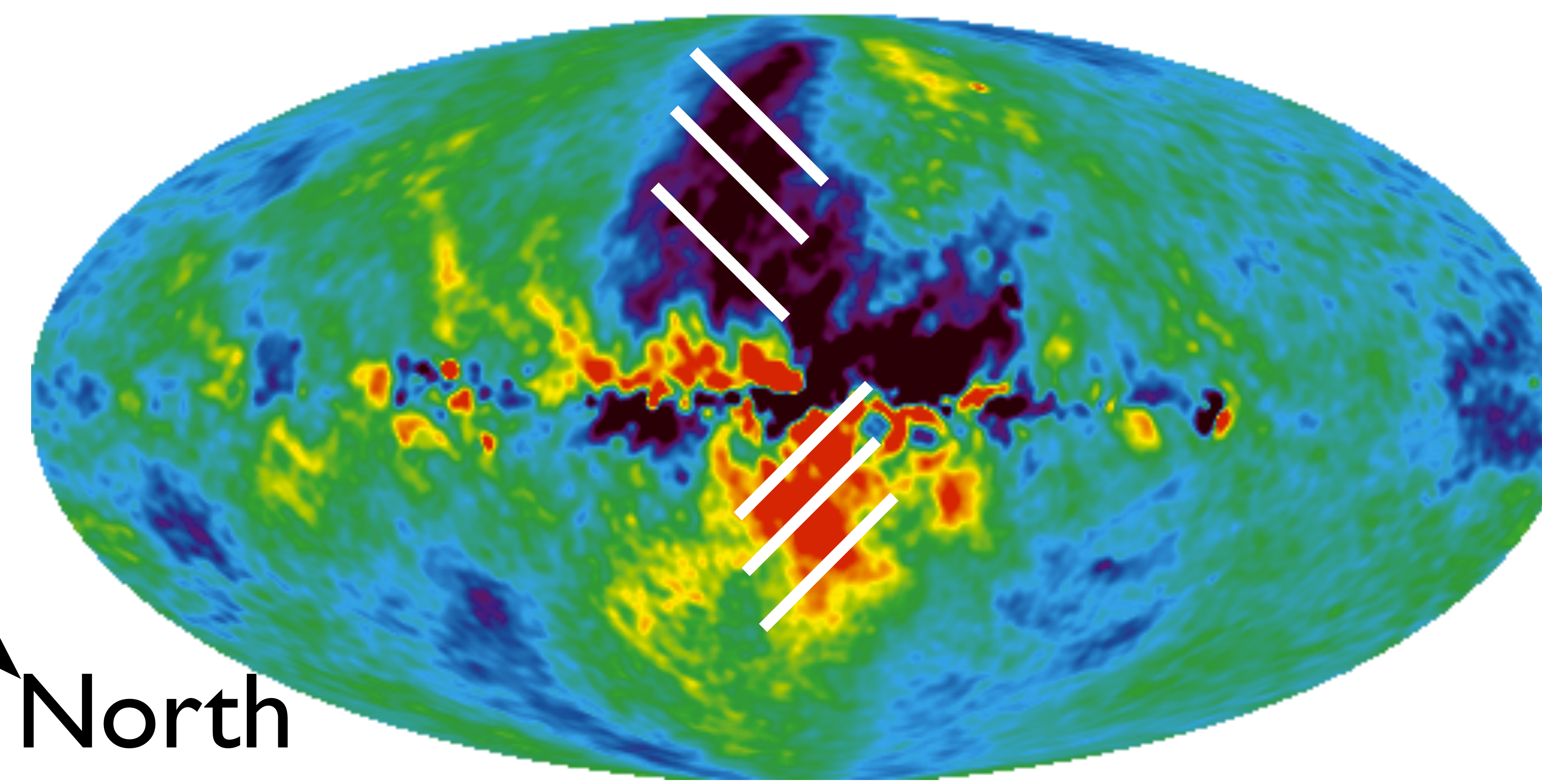
Stokes U

23 GHz [polarized]



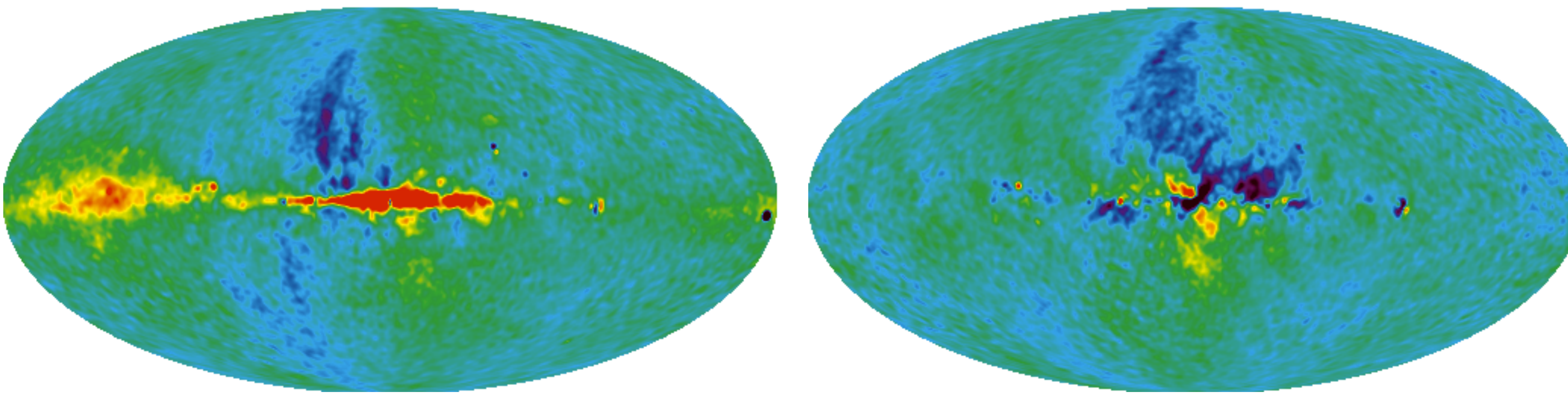
Stokes Q





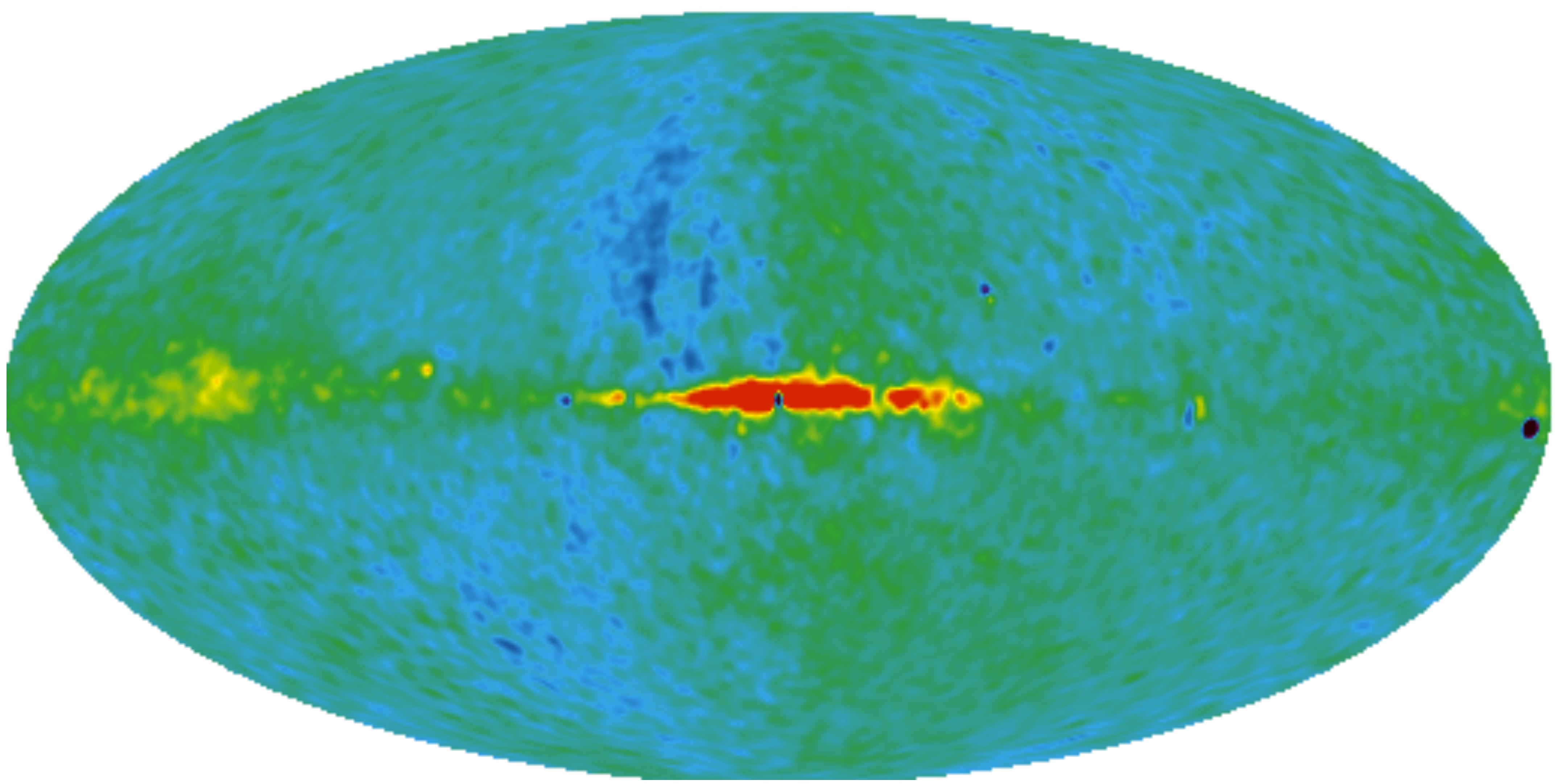
Stokes U

33 GHz [polarized]

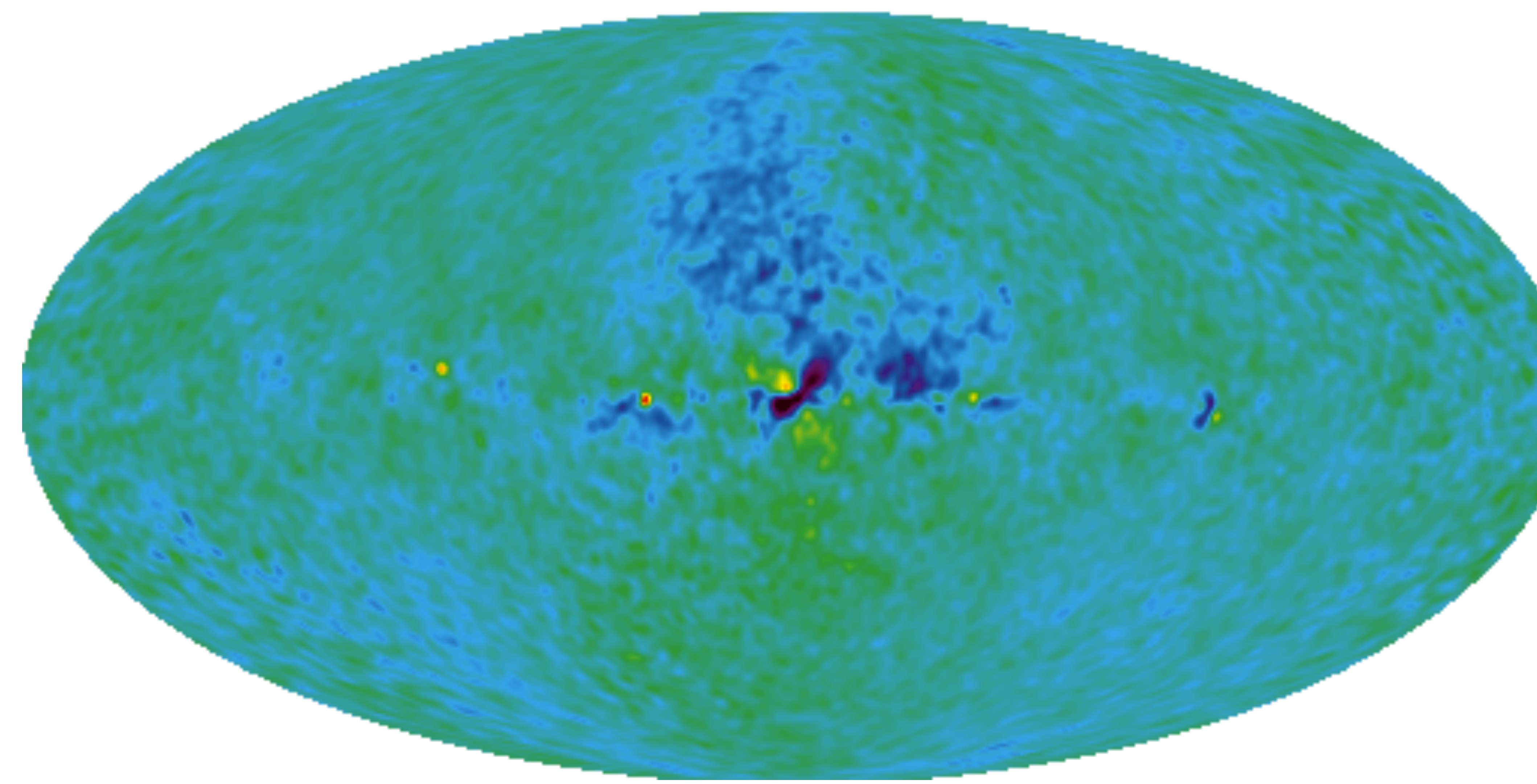


Stokes Q Stokes U

41 GHz [polarized]

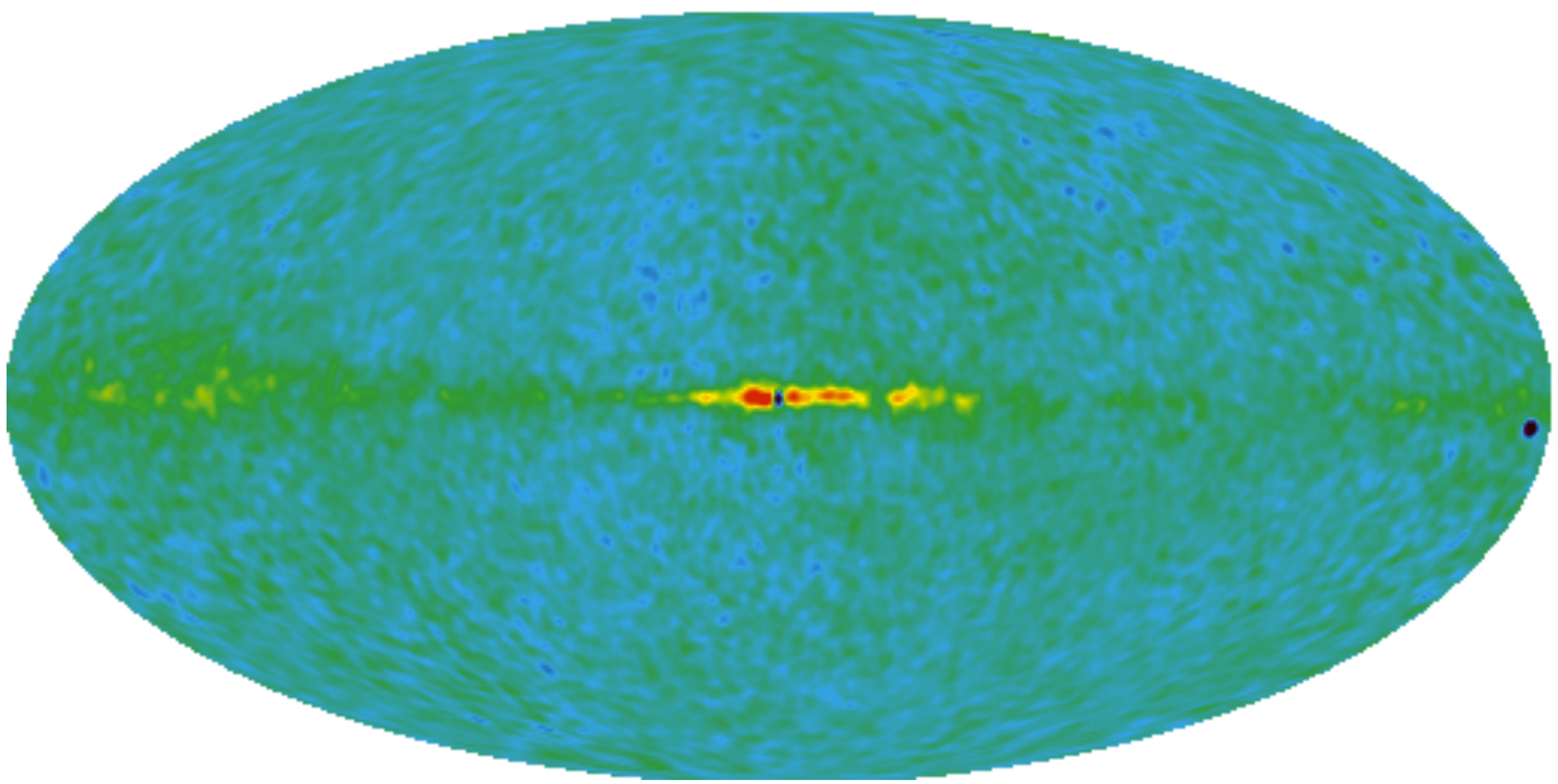


Stokes Q

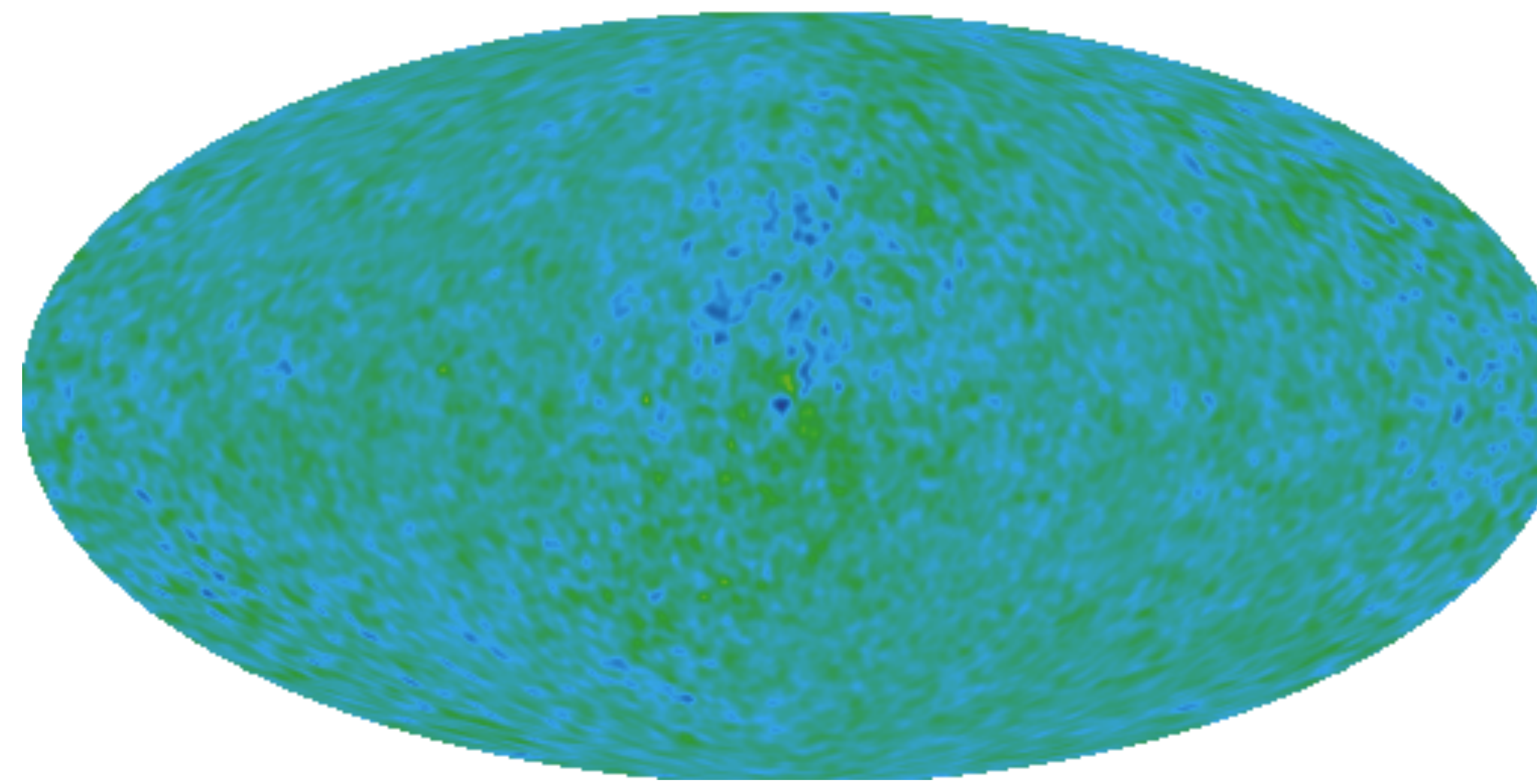


Stokes U

61 GHz [polarized]

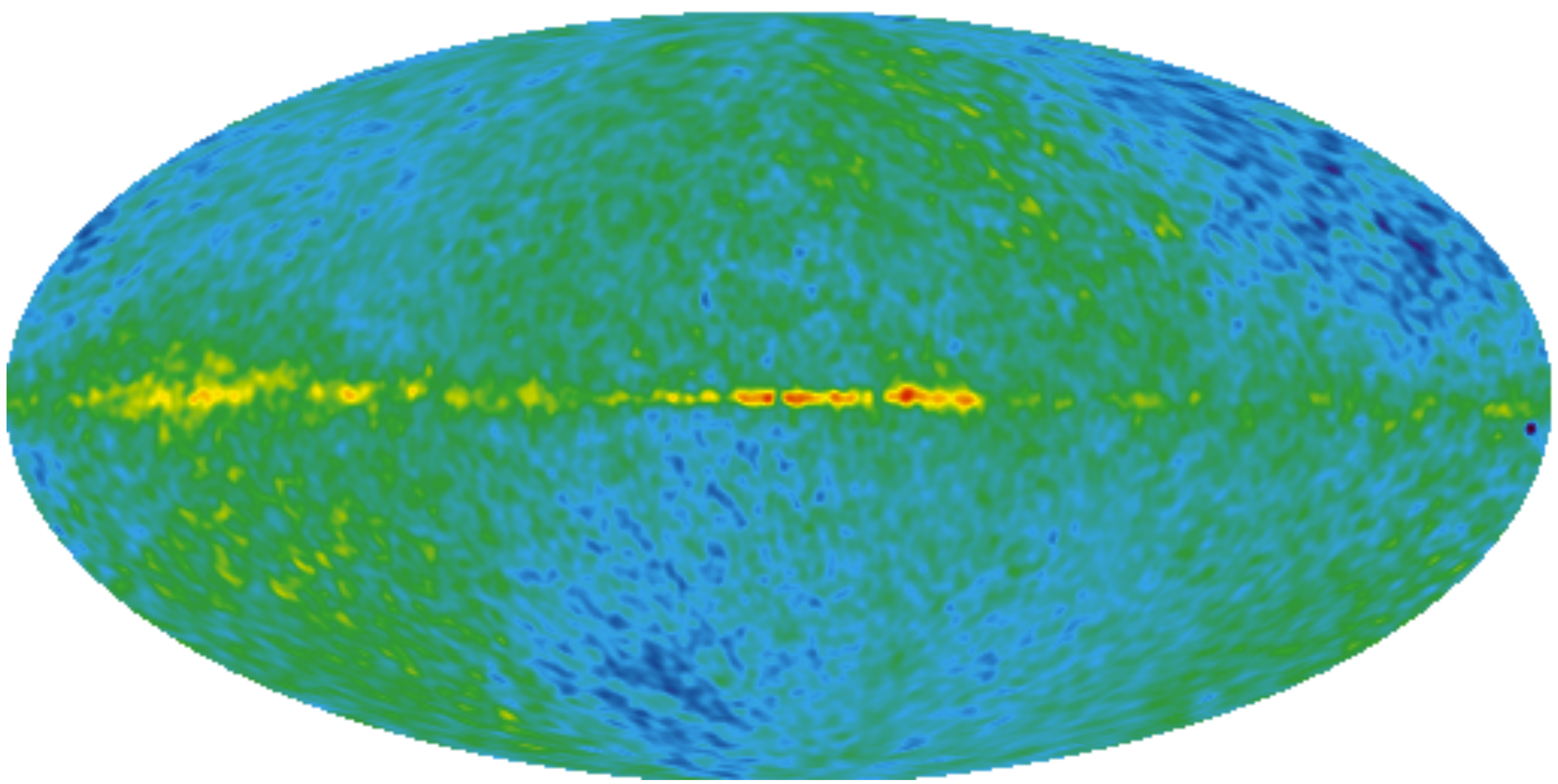


Stokes Q

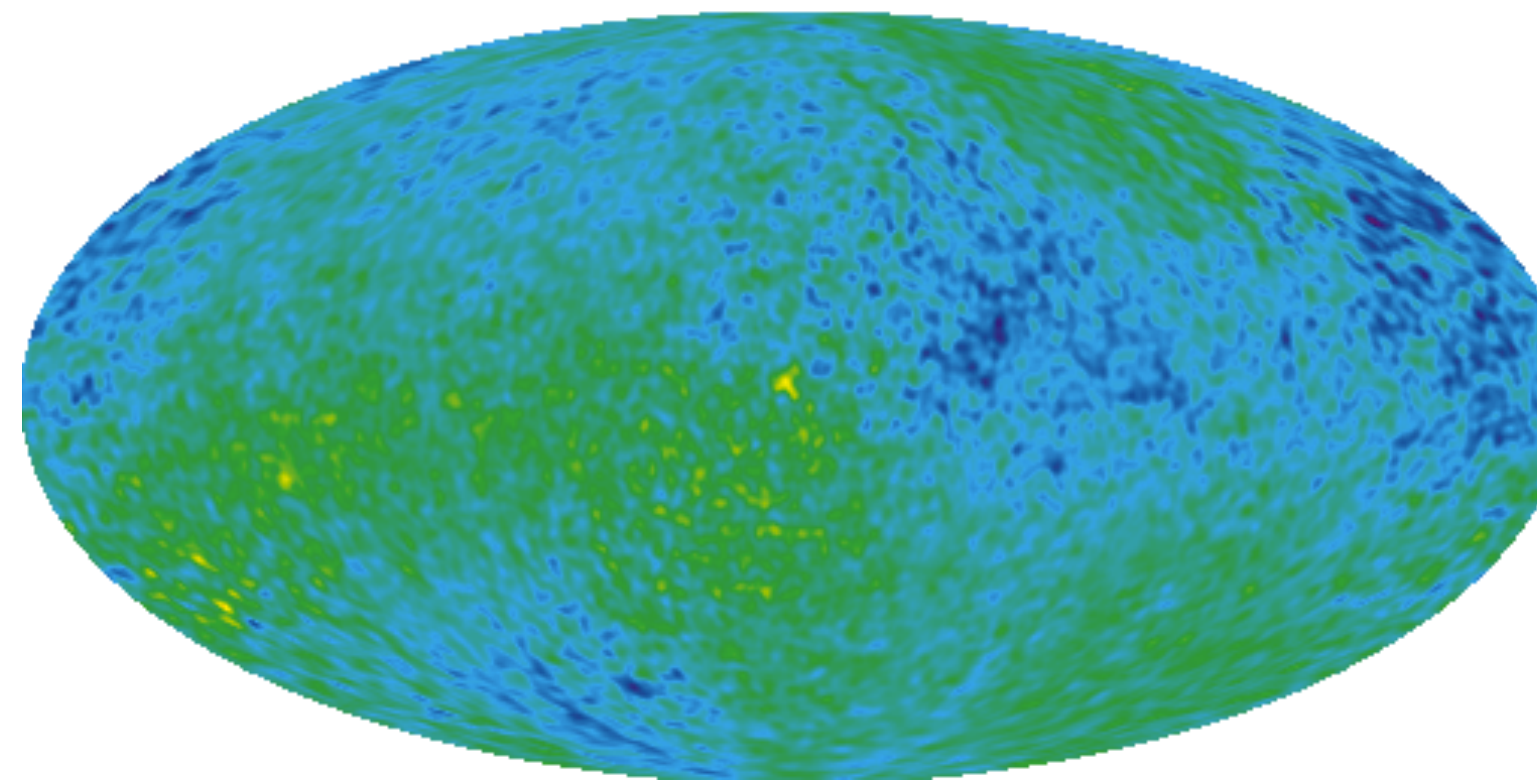


Stokes U

94 GHz [polarized]



Stokes Q



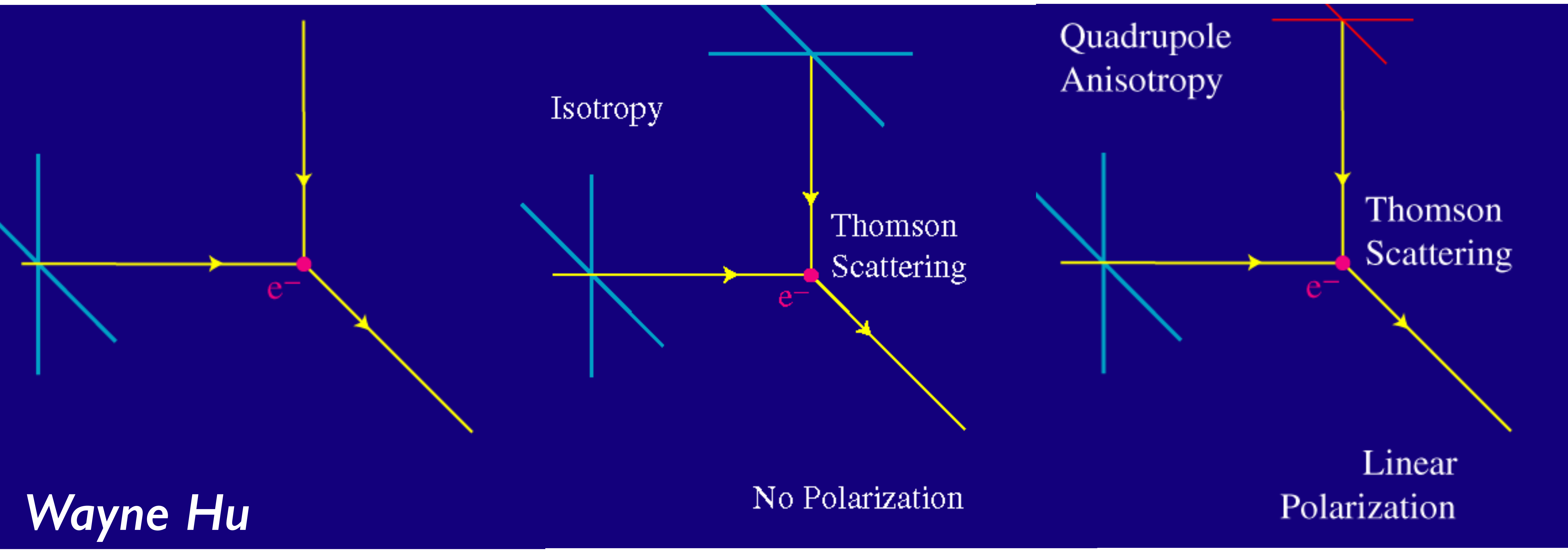
Stokes U

How many components?

1. **CMB**: $T_\nu \sim \nu^0$
2. **Synchrotron** (electrons going around magnetic fields): $T_\nu \sim \nu^{-3}$
3. **Dust** (heated dust emitting thermal emission): $T_\nu \sim \nu^2$

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

Physics of CMB Polarization



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

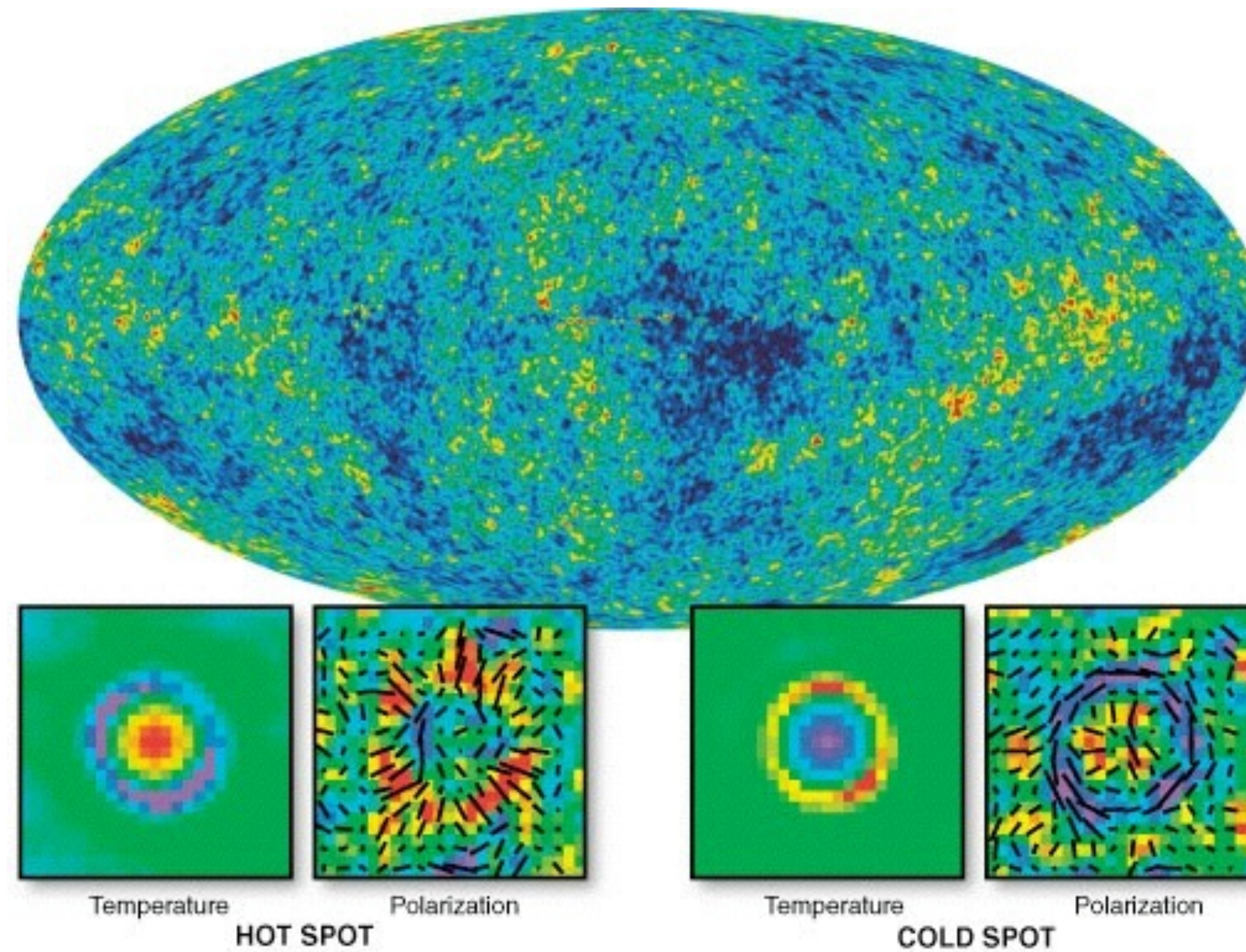
Origin of Quadrupole

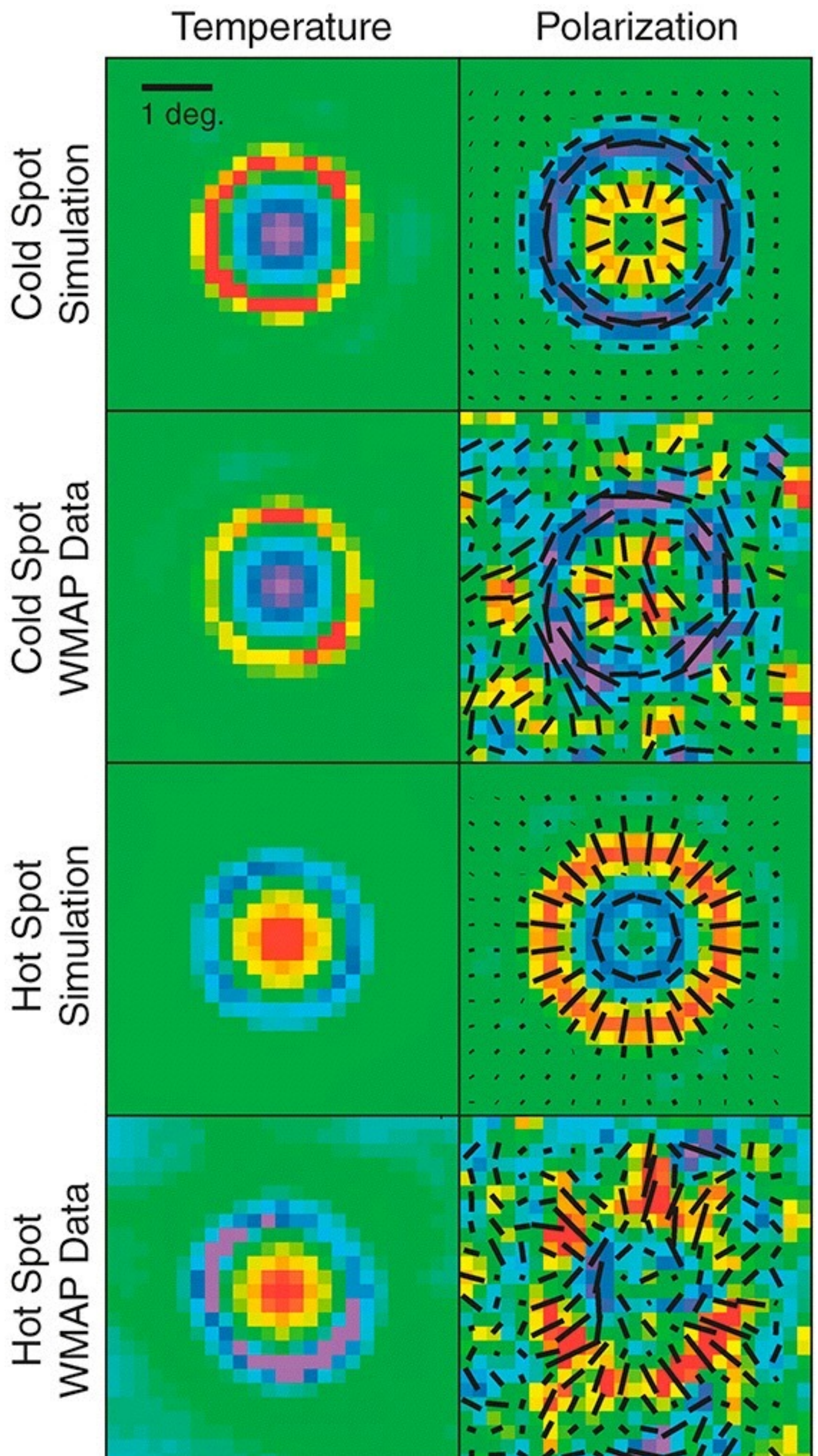
- Scalar perturbations: motion of electrons with respect to photons
- Tensor perturbations: gravitational waves

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.

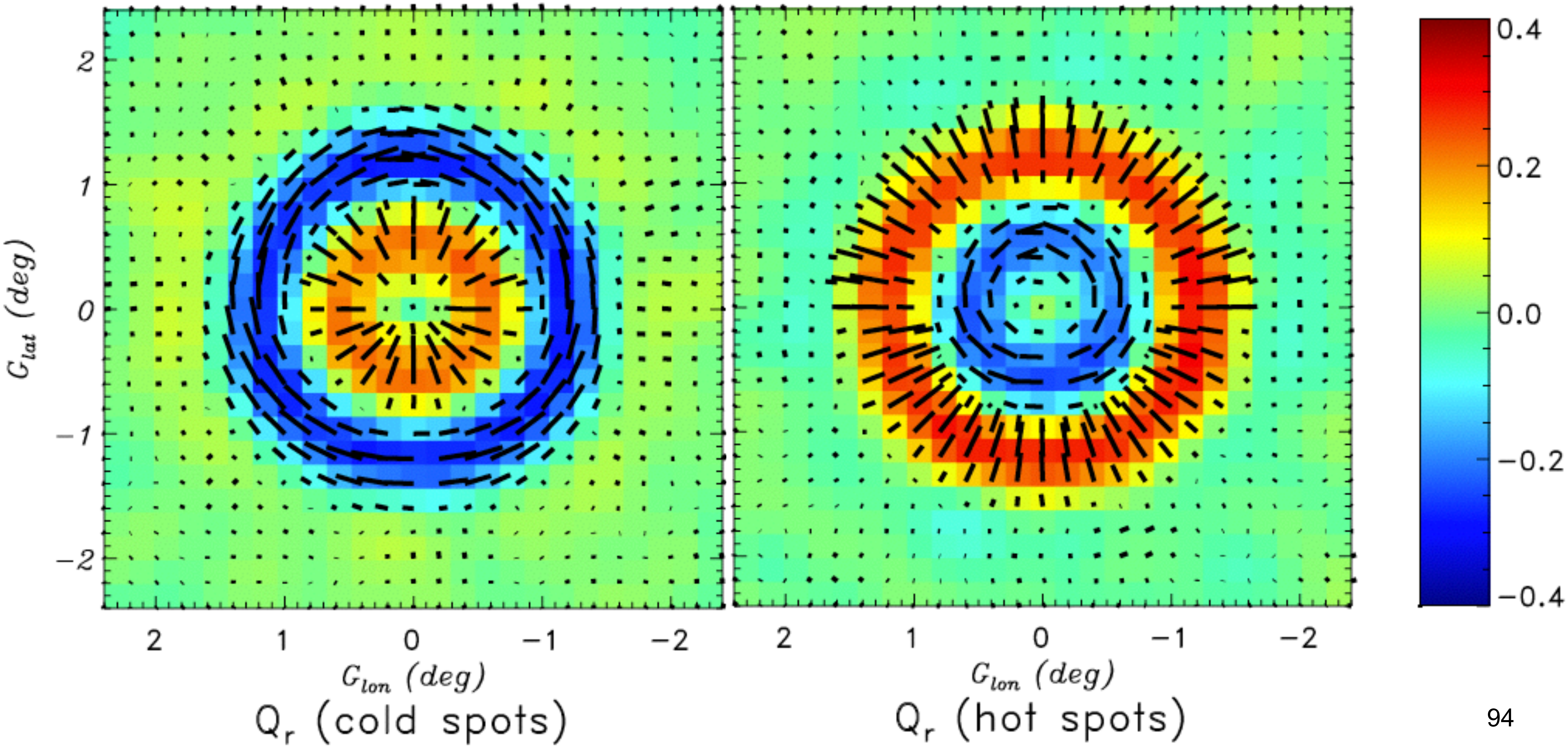




Radial and Tangential Polarization Patterns around Temp. Spots

- 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

Planck Data!



0.4
0.2
0.0
−0.2
−0.4
2
1
0
−1
−2
G_{lat} (deg)
G_{lon} (deg)
Q_r (cold spots)
Q_r (hot spots)

Quadrupole From Velocity Gradient (Large Scale)

ΔT

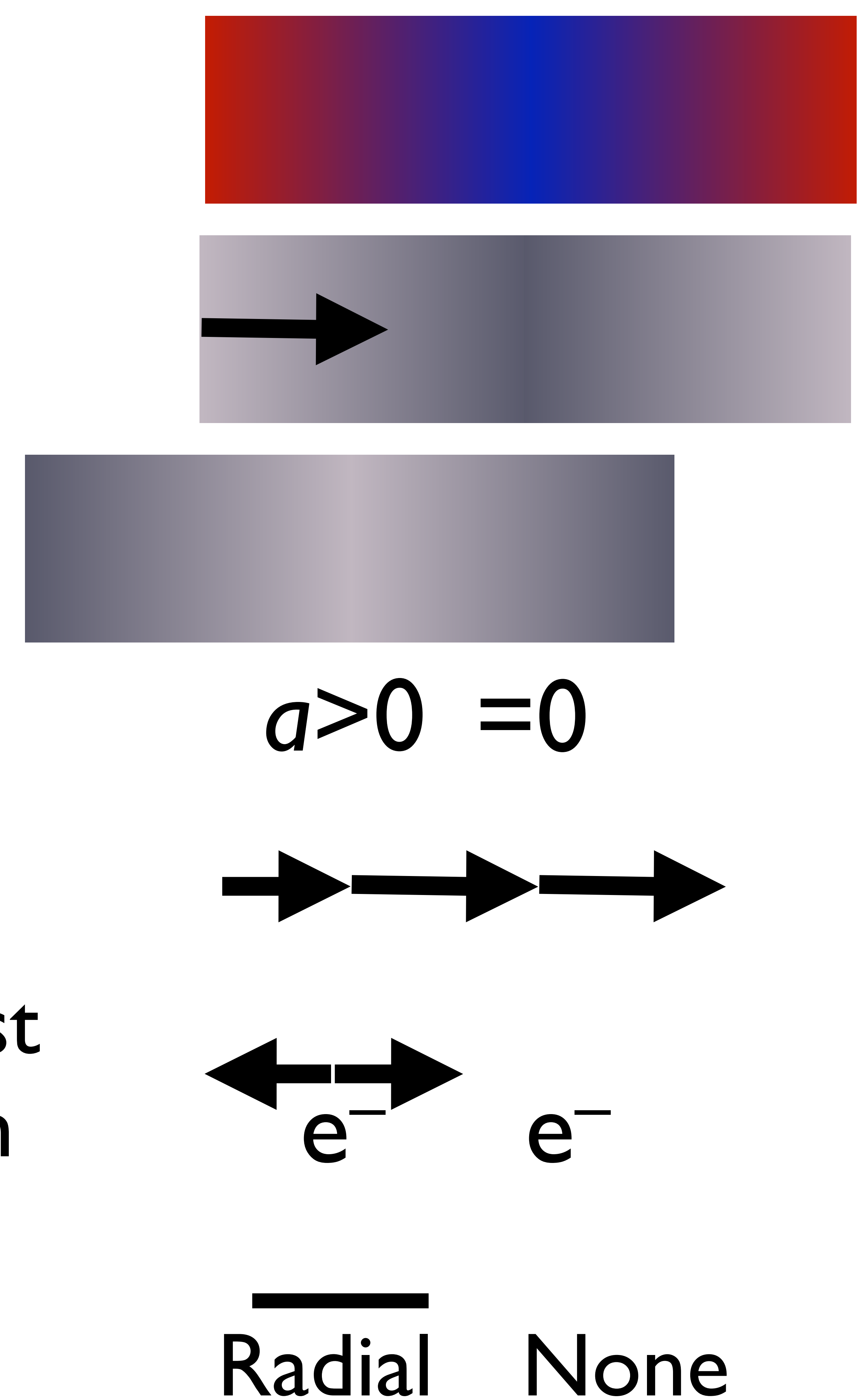
Potential Φ

Acceleration
$a = -\partial\Phi$

Velocity

Velocity in the rest frame of electron

Polarization



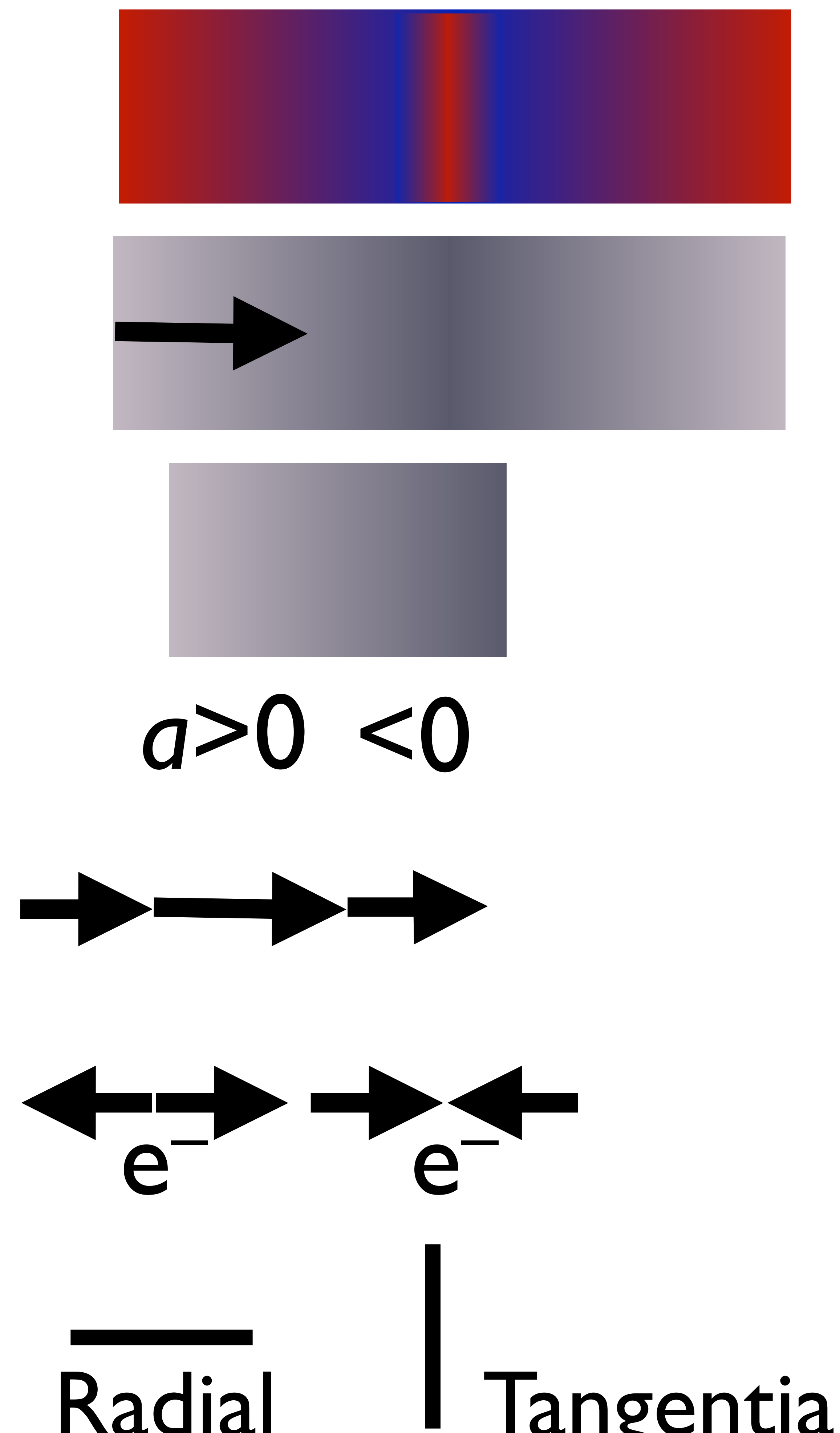
Sachs-Wolfe: $\Delta T/T = \Phi/3$

Stuff flowing *in*

Velocity gradient

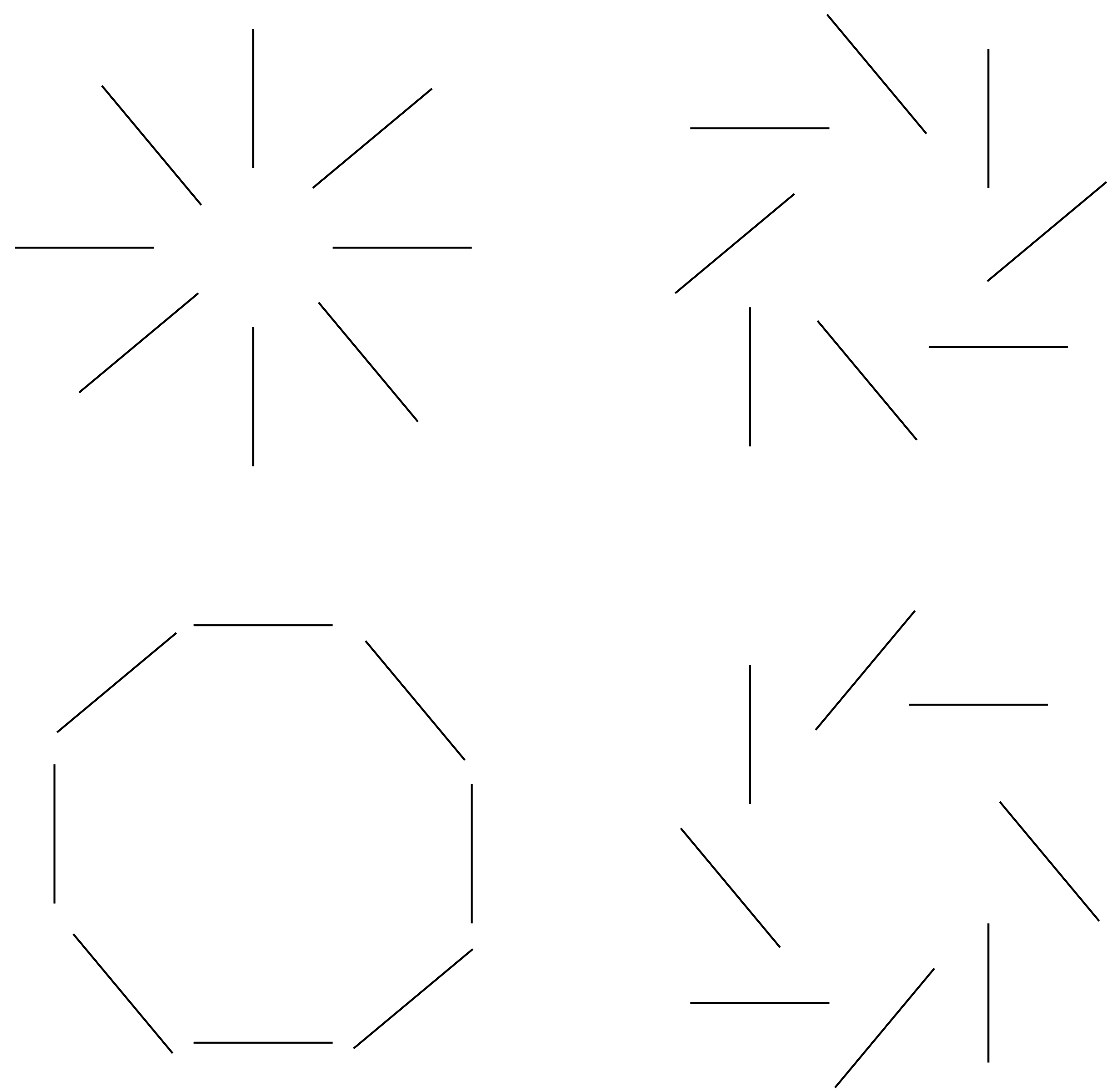
The left electron sees colder photons along the plane wave

Quadrupole From Velocity Gradient (Small Scale)



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

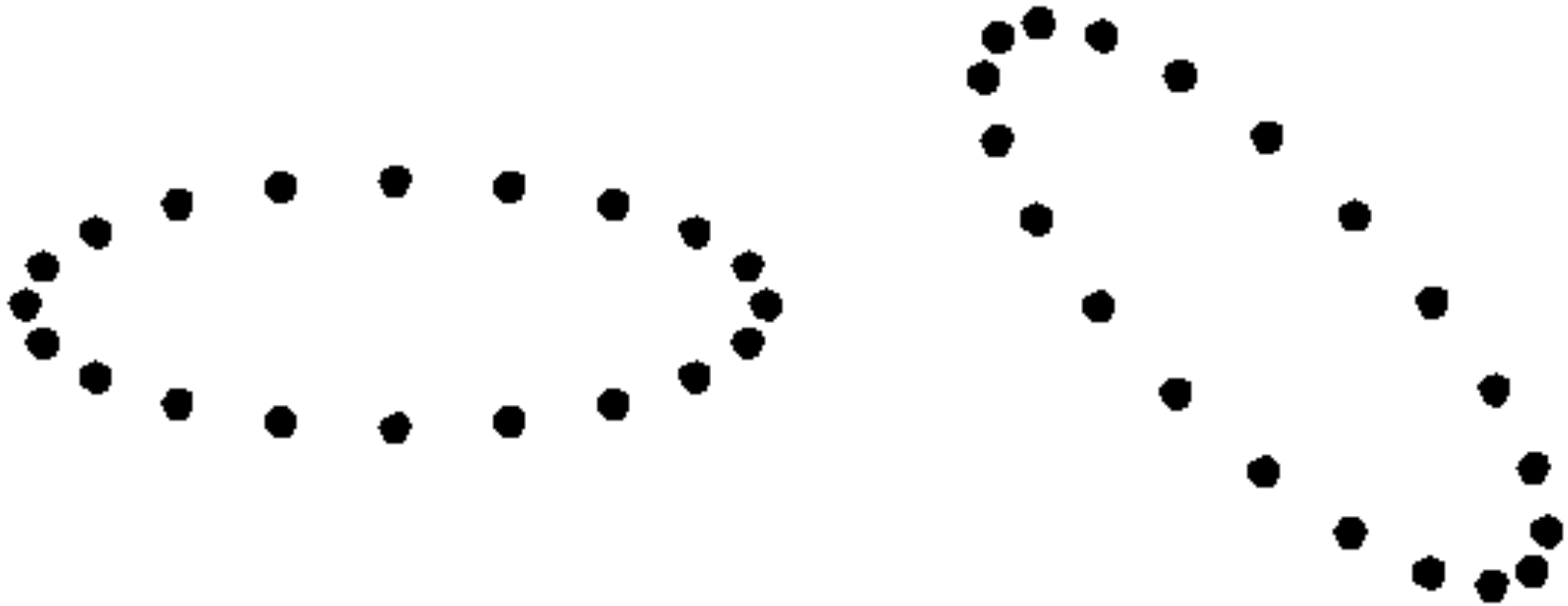
E-mode and B-mode



E mode B mode

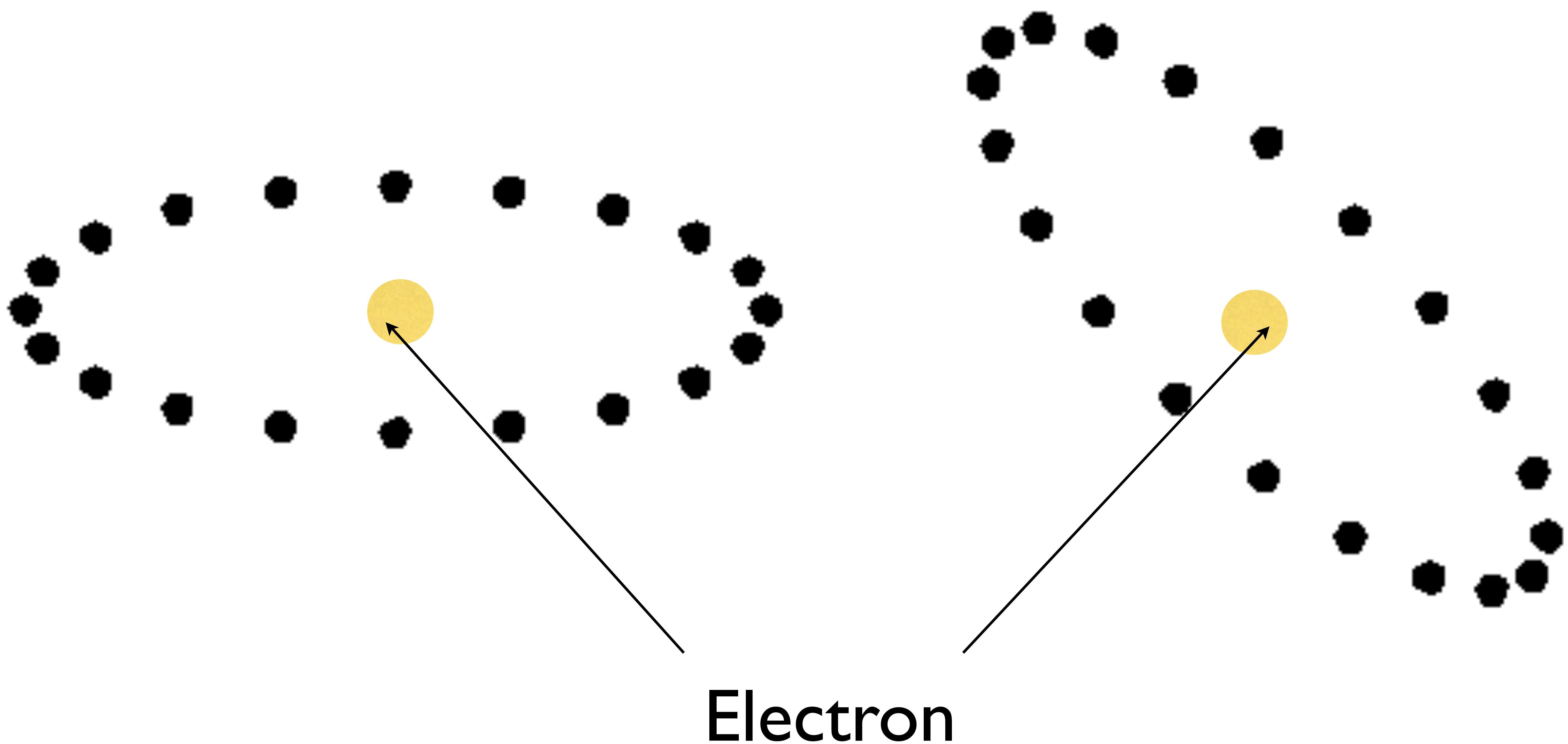
- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

Two Polarization States of GW

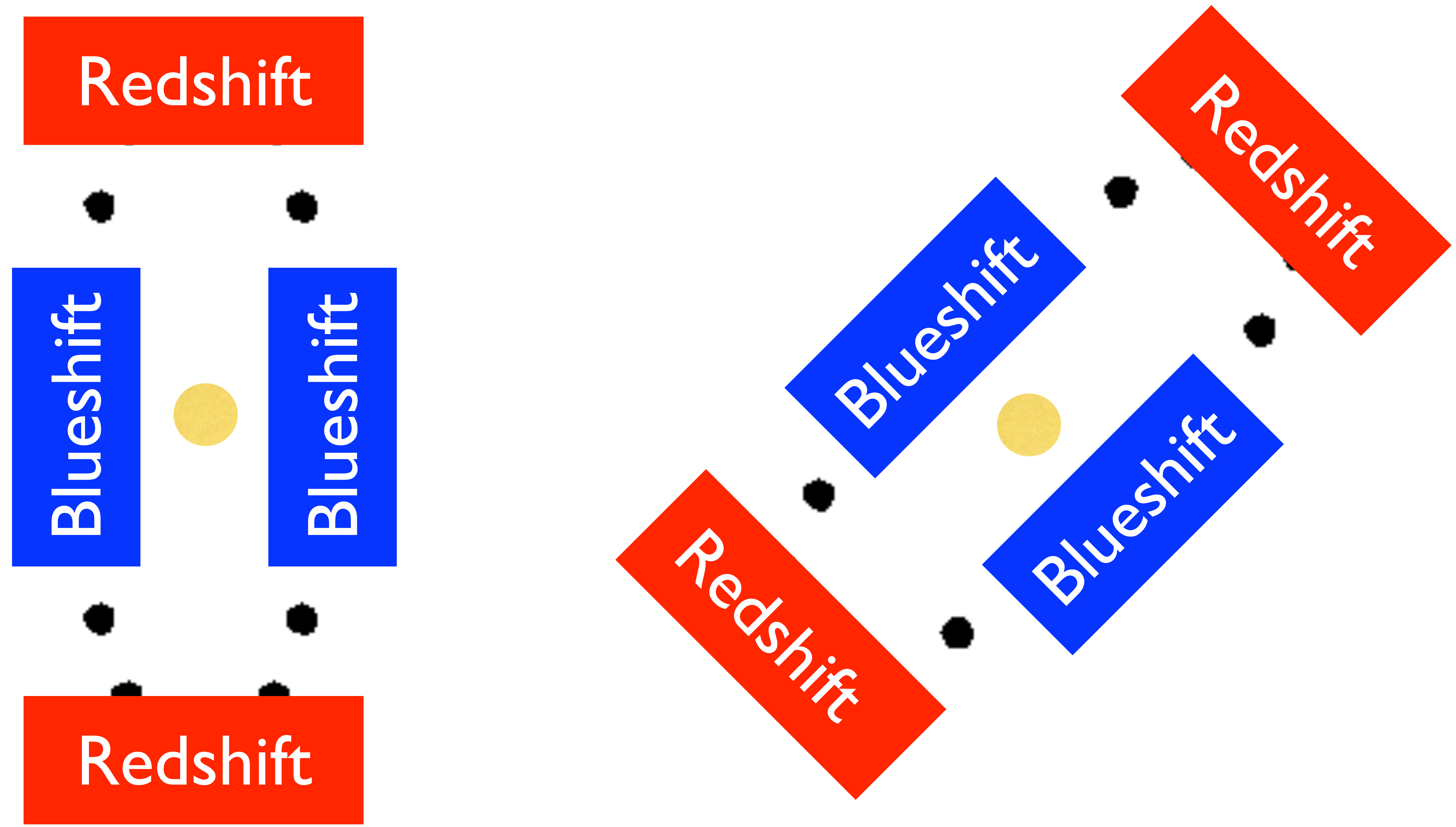


- This is great - this will automatically generate quadrupolar anisotropy around electrons!

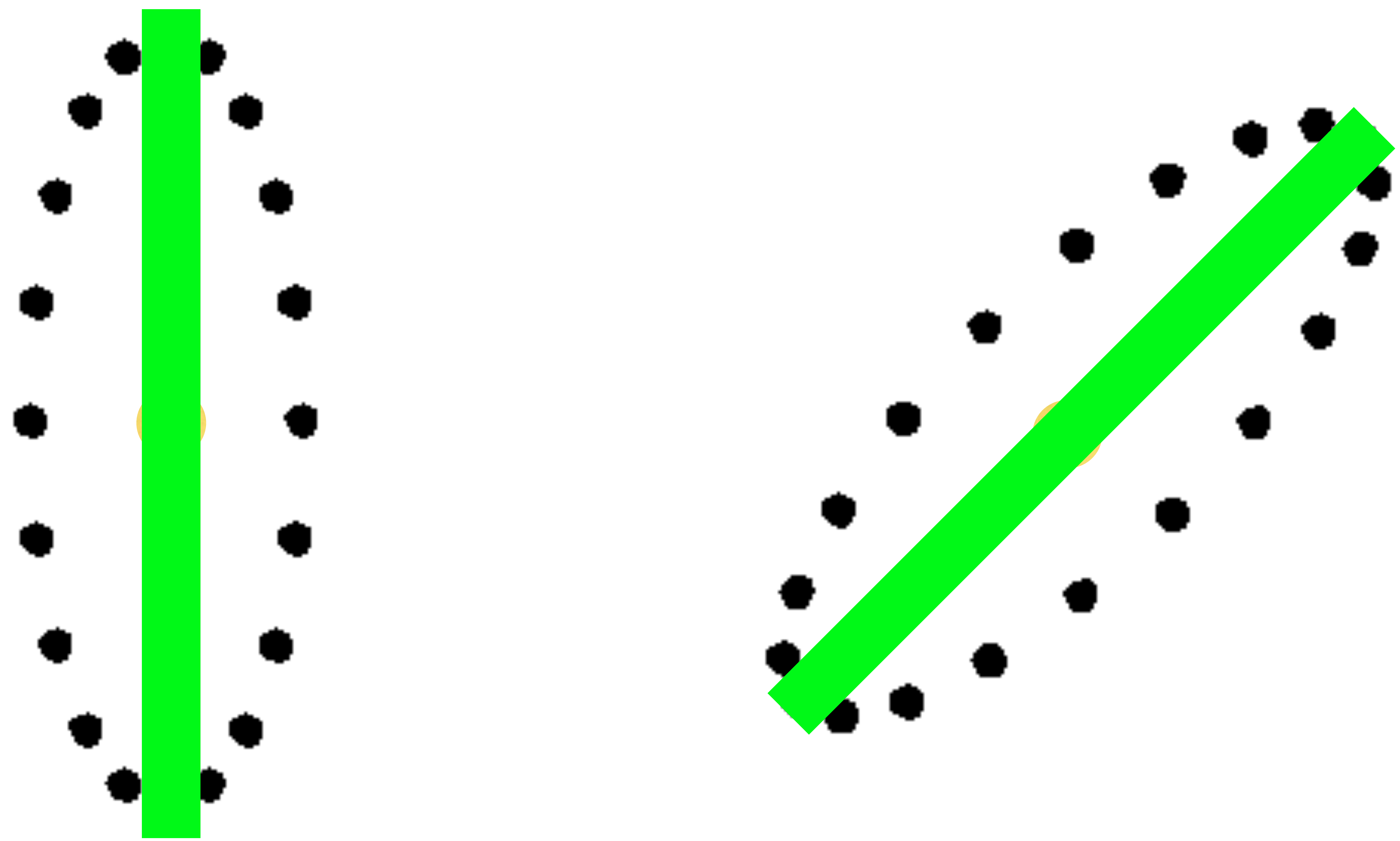
From GW to CMB Polarization



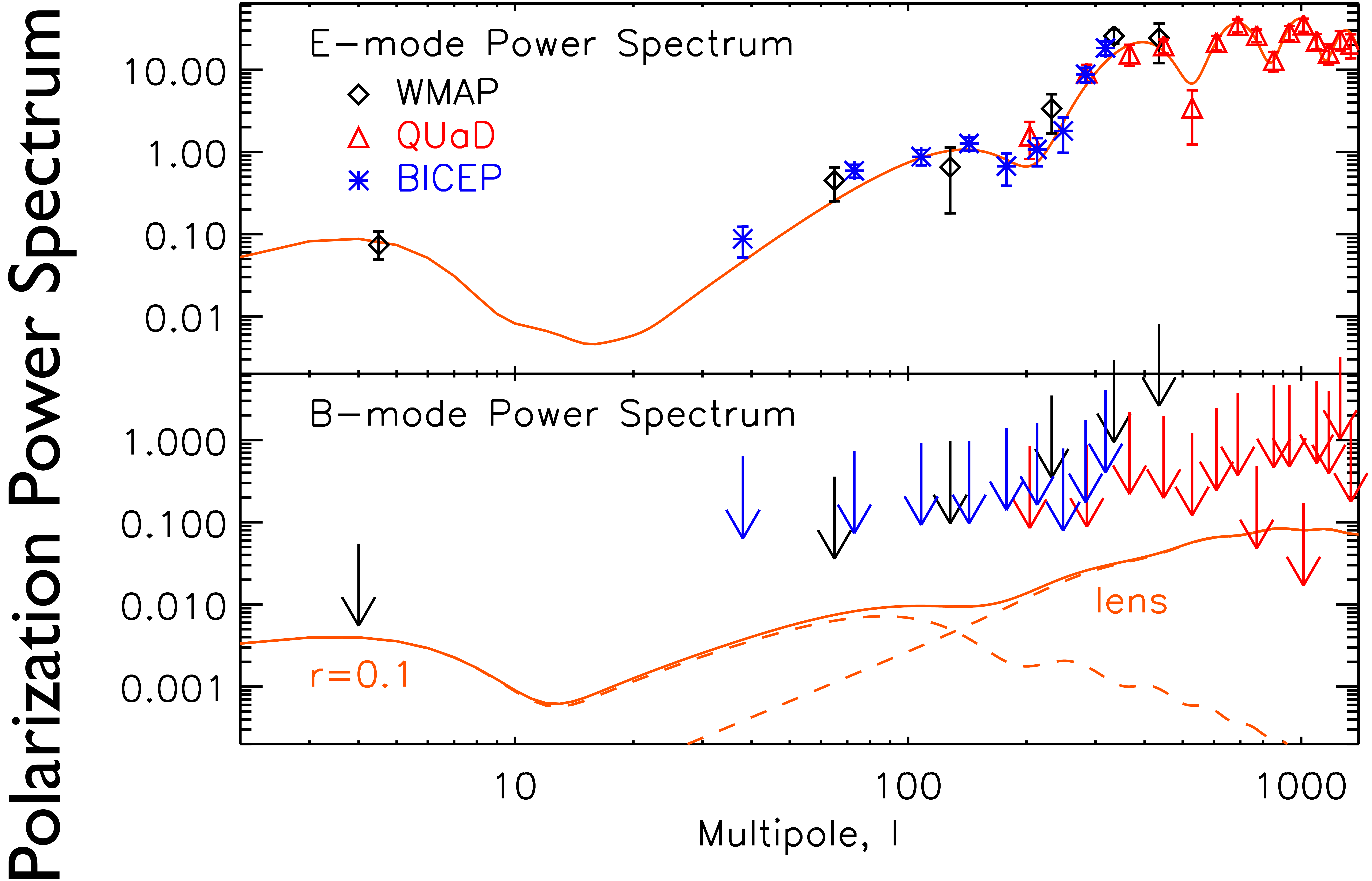
From GW to CMB Polarization



From GW to CMB Polarization



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

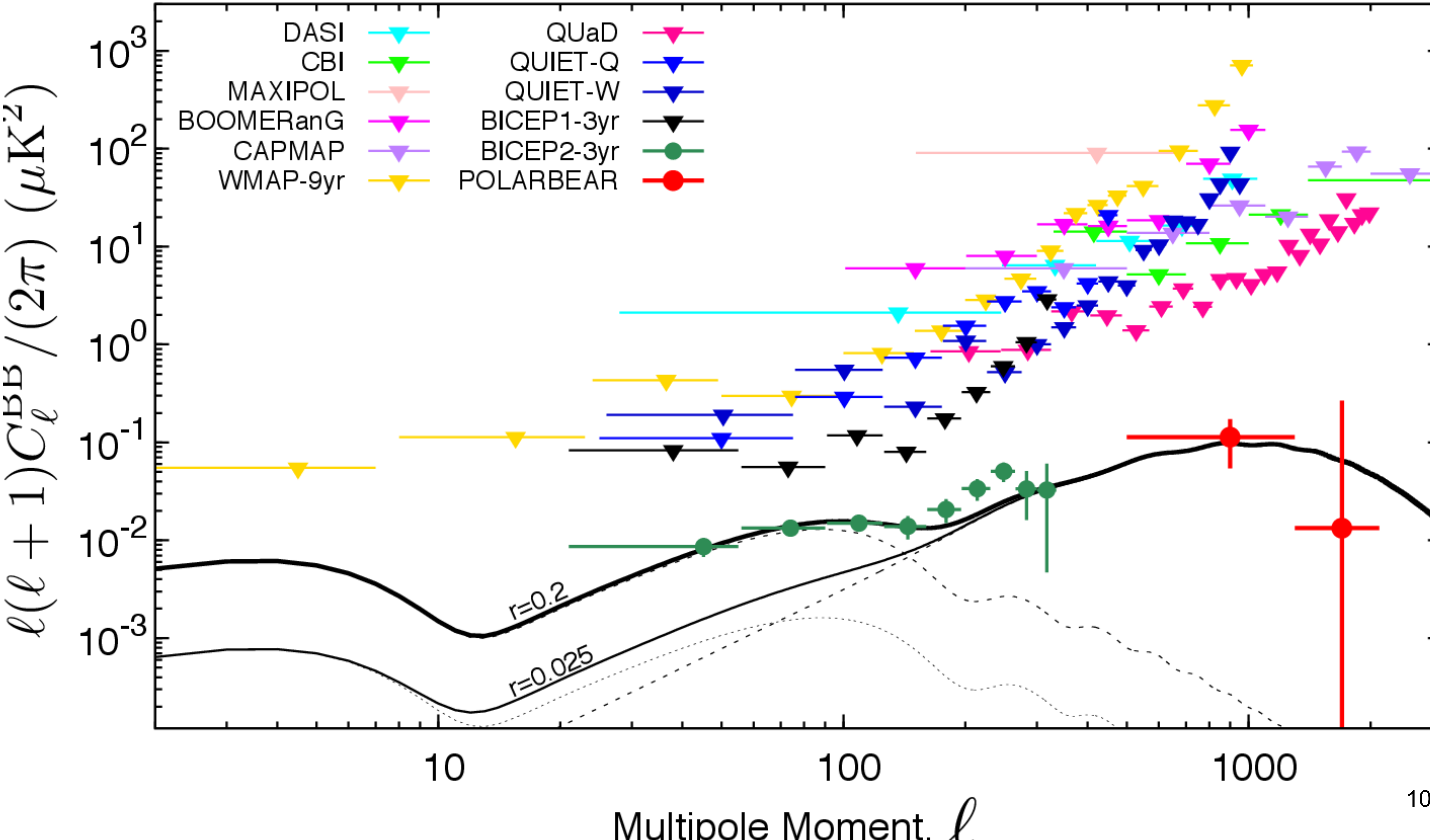


- No detection of B-mode polarization at degree scales, *before March 17*

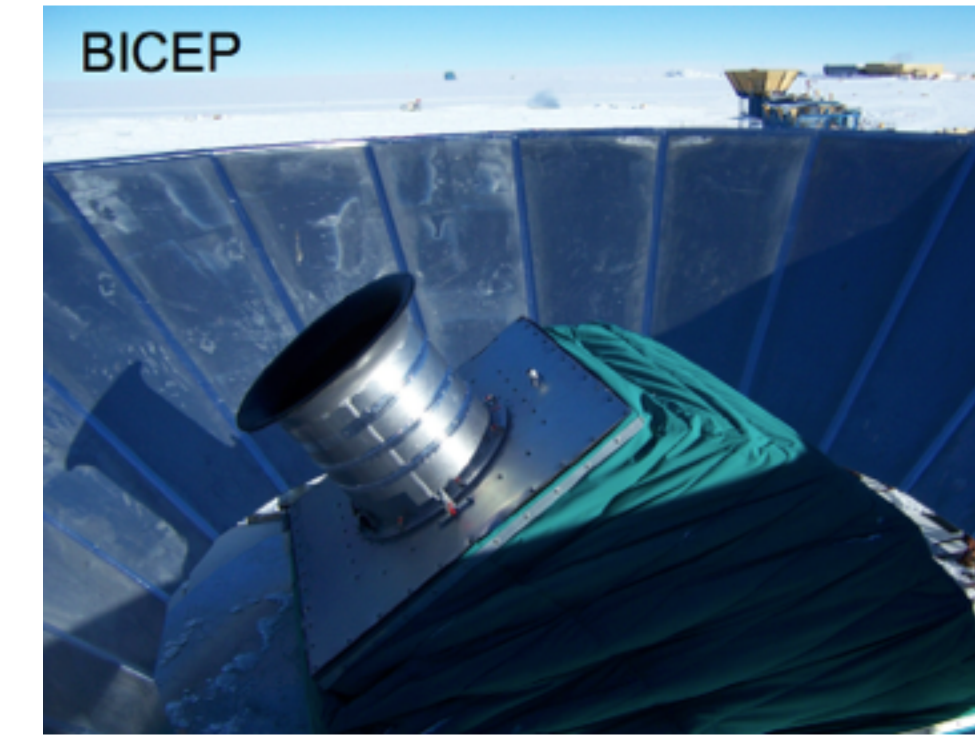
Then…

- 10:45 (Eastern Standard Time), March 17, 2014

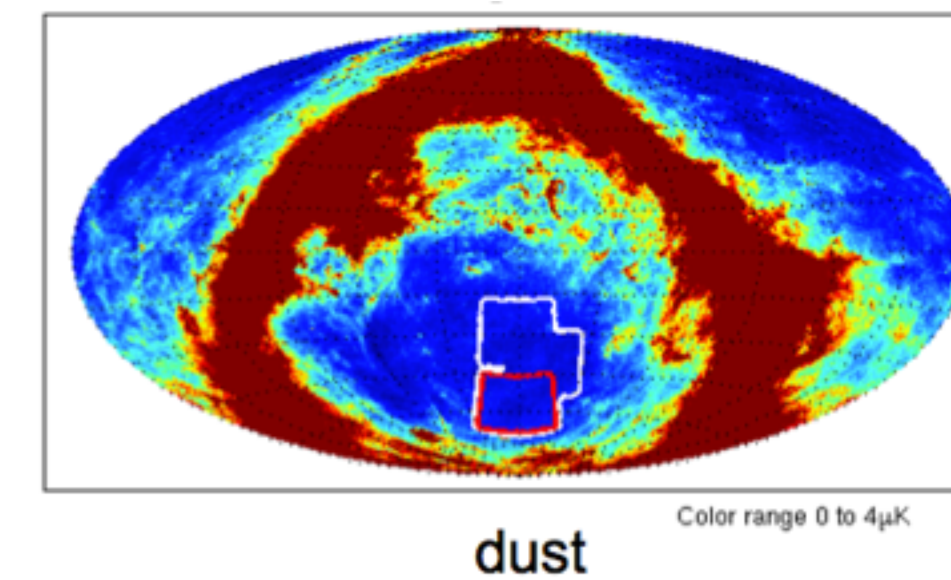
*Courtesy of Yuji Chinone, with the POLARBEAR data points



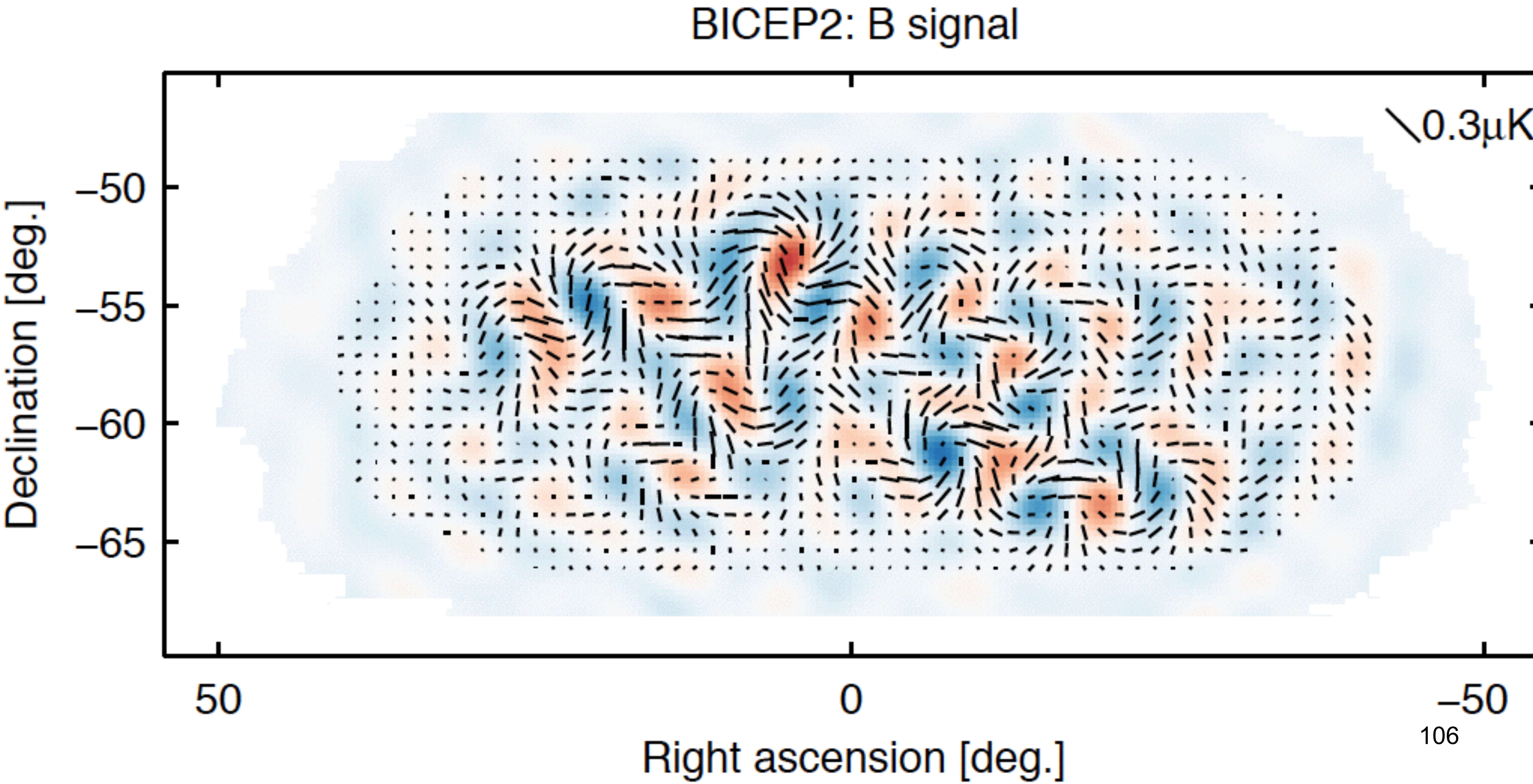
What is BICEP2?



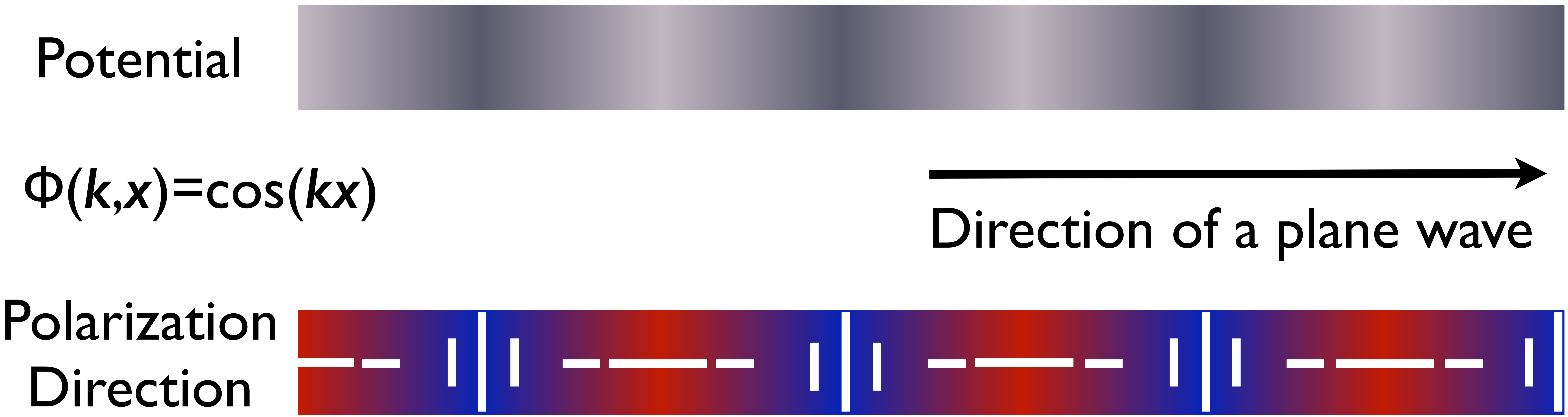
- A small [26 cm] refractive telescope at South Pole
- 512 bolometers working at 150 GHz
- Observed 380 square degrees for three years [2010-2012]



- Previous: BICEP1 at 100 and 150 GHz [2006-2008]
- On-going: Keck Array = 5 x BICEP2 at 150 GHz [2011-2013] and additional detectors at 100 and 220 GHz [2014-]


BICEP2: B signal
0.3μK
−50
−55
−60
−65
Declination [deg.]
50
0
−50
Right ascension [deg.]

E-mode

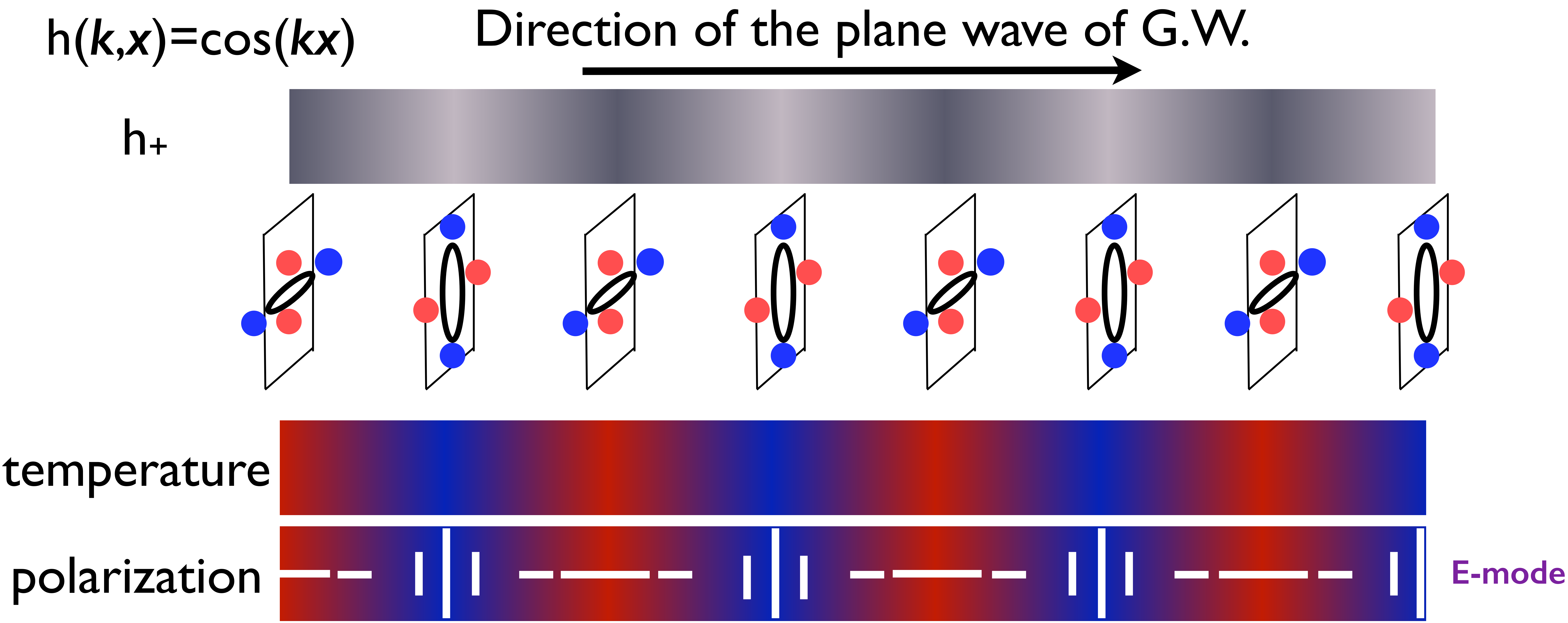


- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

B-mode

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

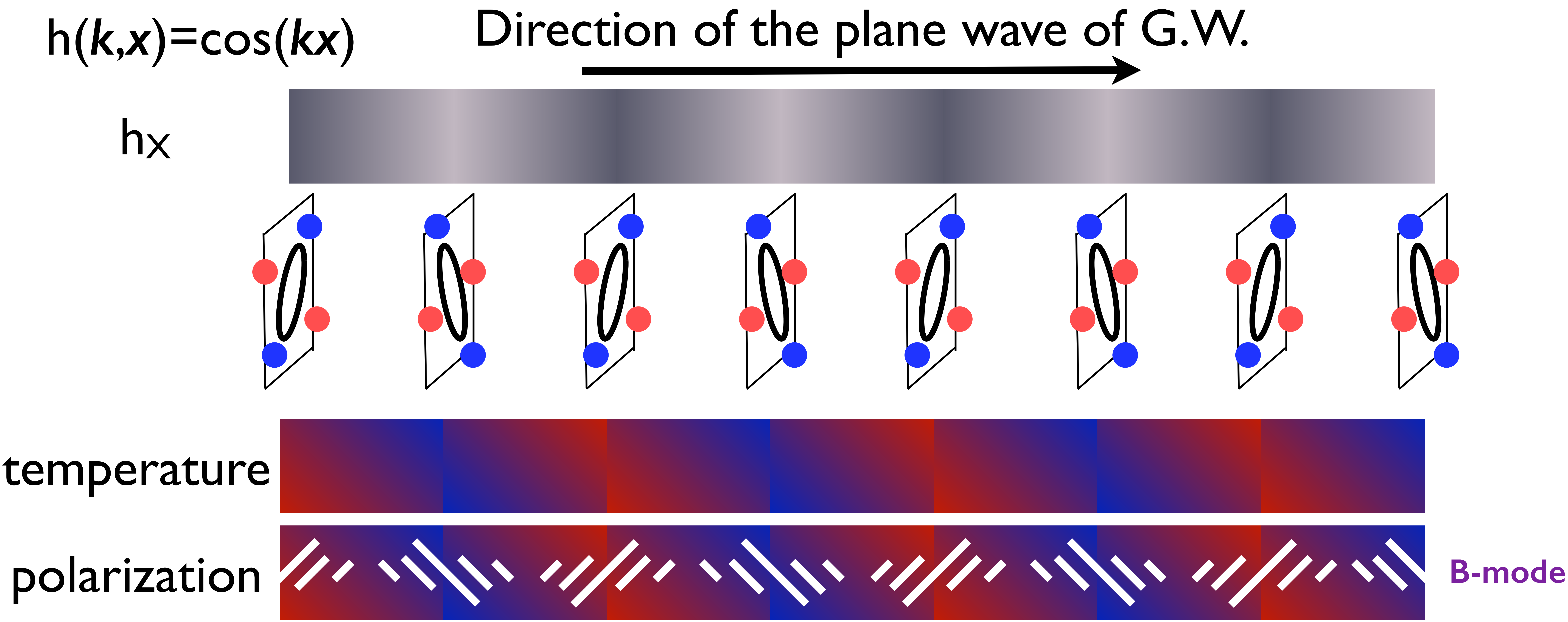
Quadrupole from G.W.



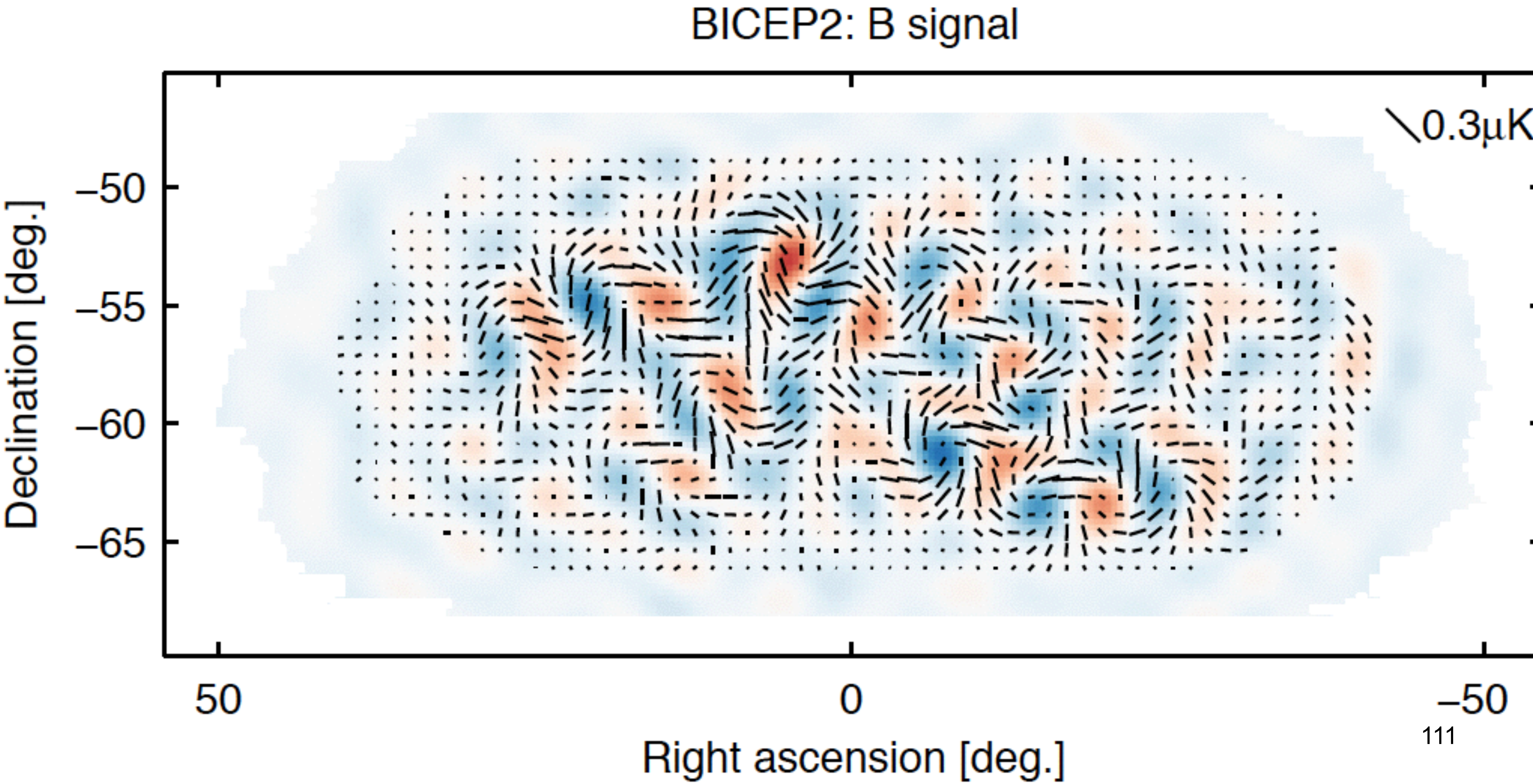
- E-mode polarization generated by h_+

Quadrupole from G.W.

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



- B-mode polarization generated by h×


BICEP2: B signal
0.3μK
−50
−55
−60
−65
Declination [deg.]
50
0
−50
Right ascension [deg.]

Implication of the measured tensor-to-scalar ratio

- The measured r is directly connected to the potential energy of a field driving inflation.
- **r = 0.2 implies 2x10^{16} GeV**
  - Grand Unification Scale! Inflation is a phenomenon of the high[est] energy physics
- r = 0.2 also implies that a field driving inflation moved by ~ 5 x Planck Mass. A challenge to model building

Is the signal cosmological?

- Worries:
  - Is it from Galactic foreground emission, e.g., dust?
  - Is it from imperfections in the experiment, e.g., detector mismatches?

Eiichiro Komatsu
March 14 near Munich

If detection of the primordial B-modes were to be reported on Monday, I would like see:

[1] Detection (>3 sigma each) in more than one frequency, like 100 GHz and 150 GHz giving the same answers to within the error bars.

[2] Detection (could be a couple of sigmas each) in a few multipole bins, i.e., not in just one big multipole bin.

Then I will believe it!

facebook

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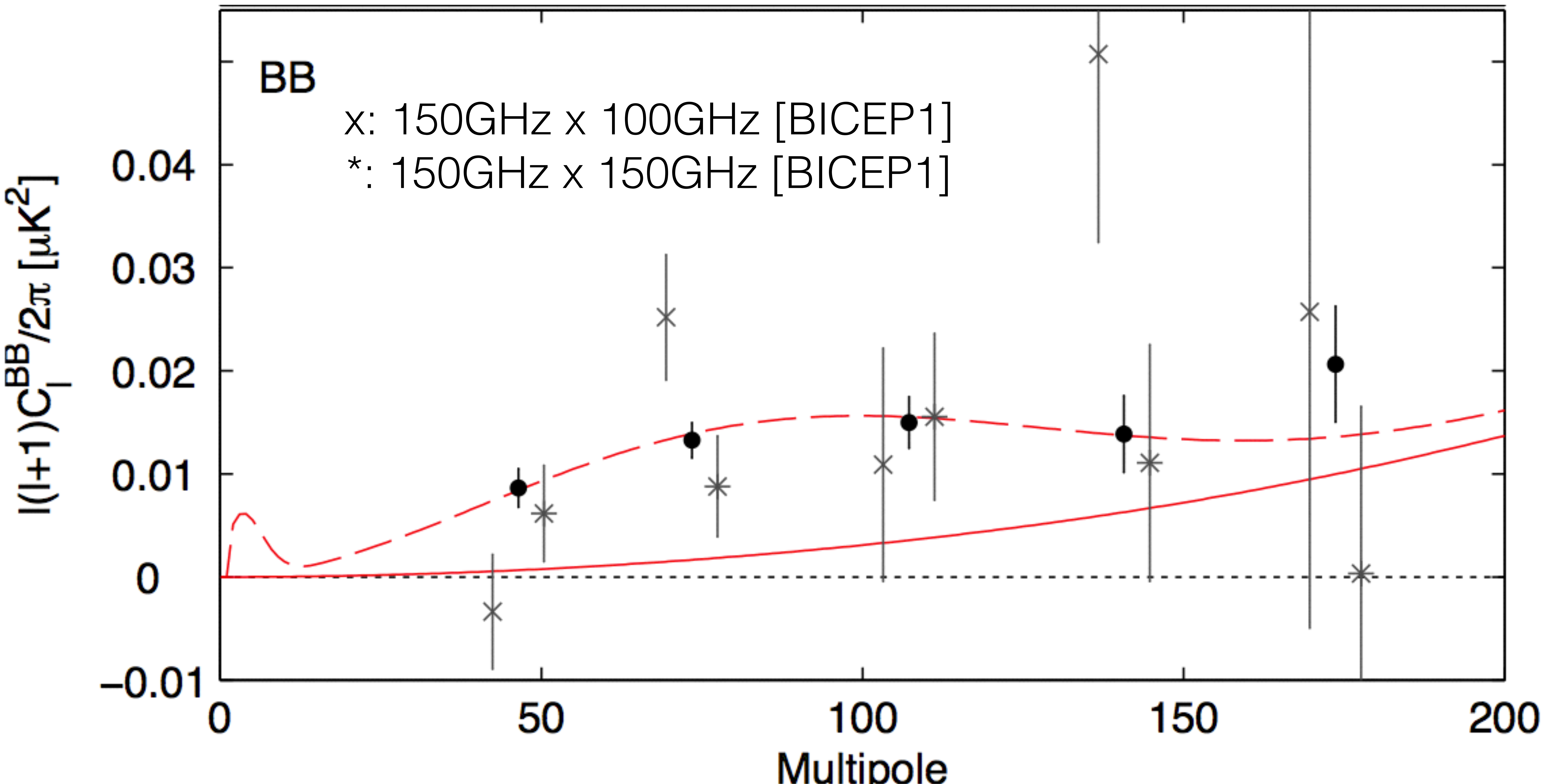
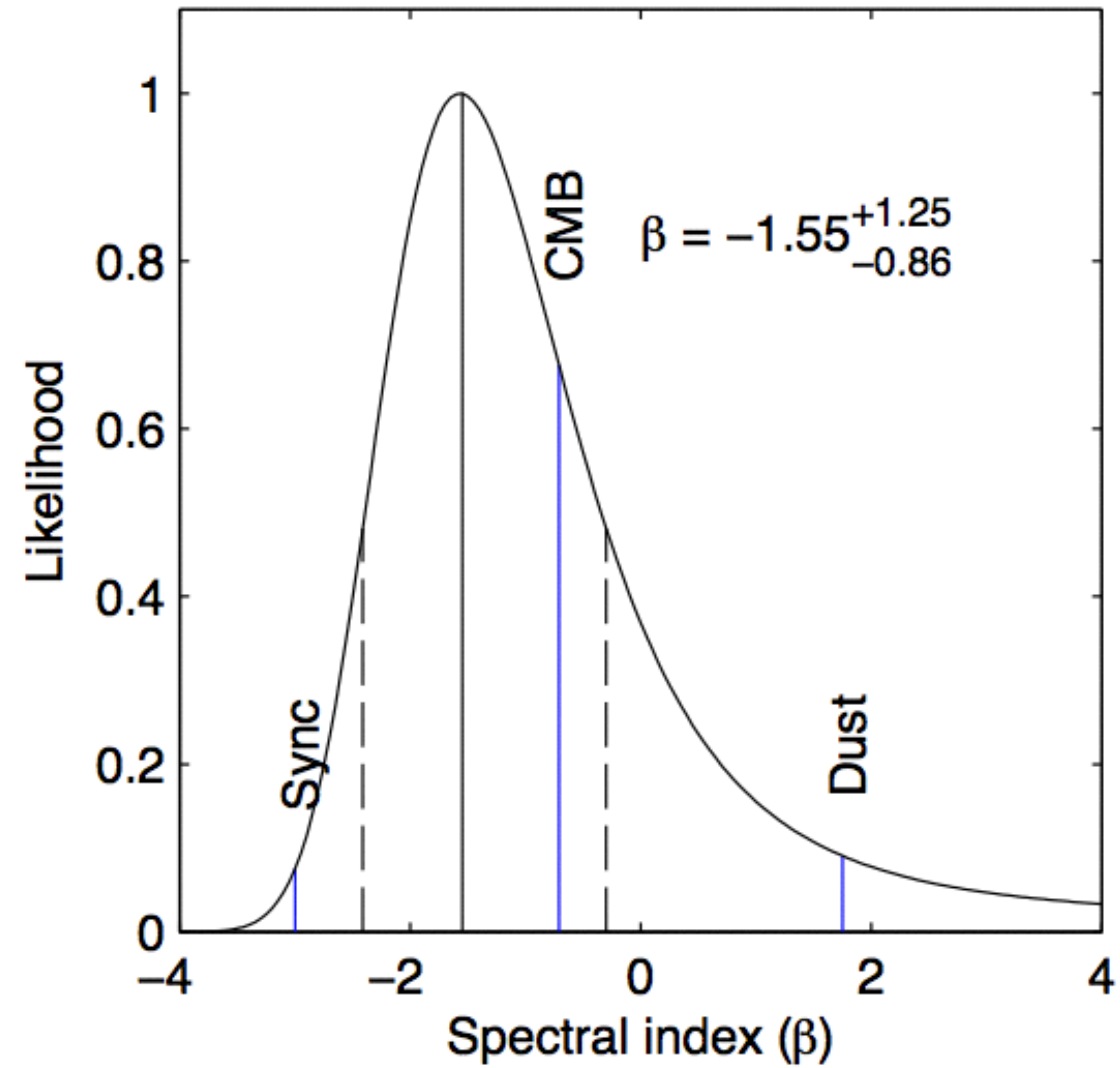


No 100 GHz x 100 GHz [yet]

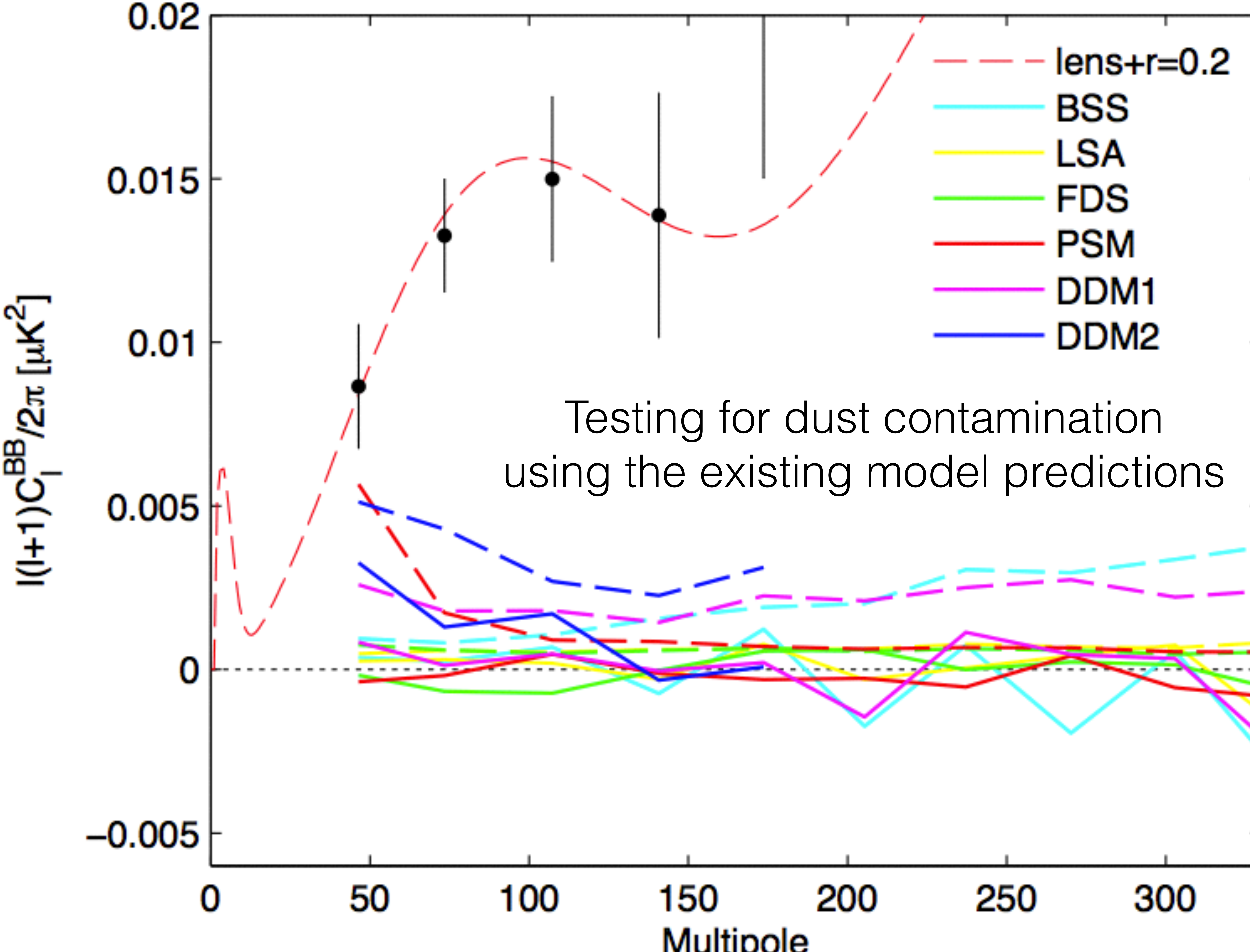


- Using the 100x150 GHz cross, they are able to "reject" representative spectra of synchrotron and dust at ~2 sigma level.

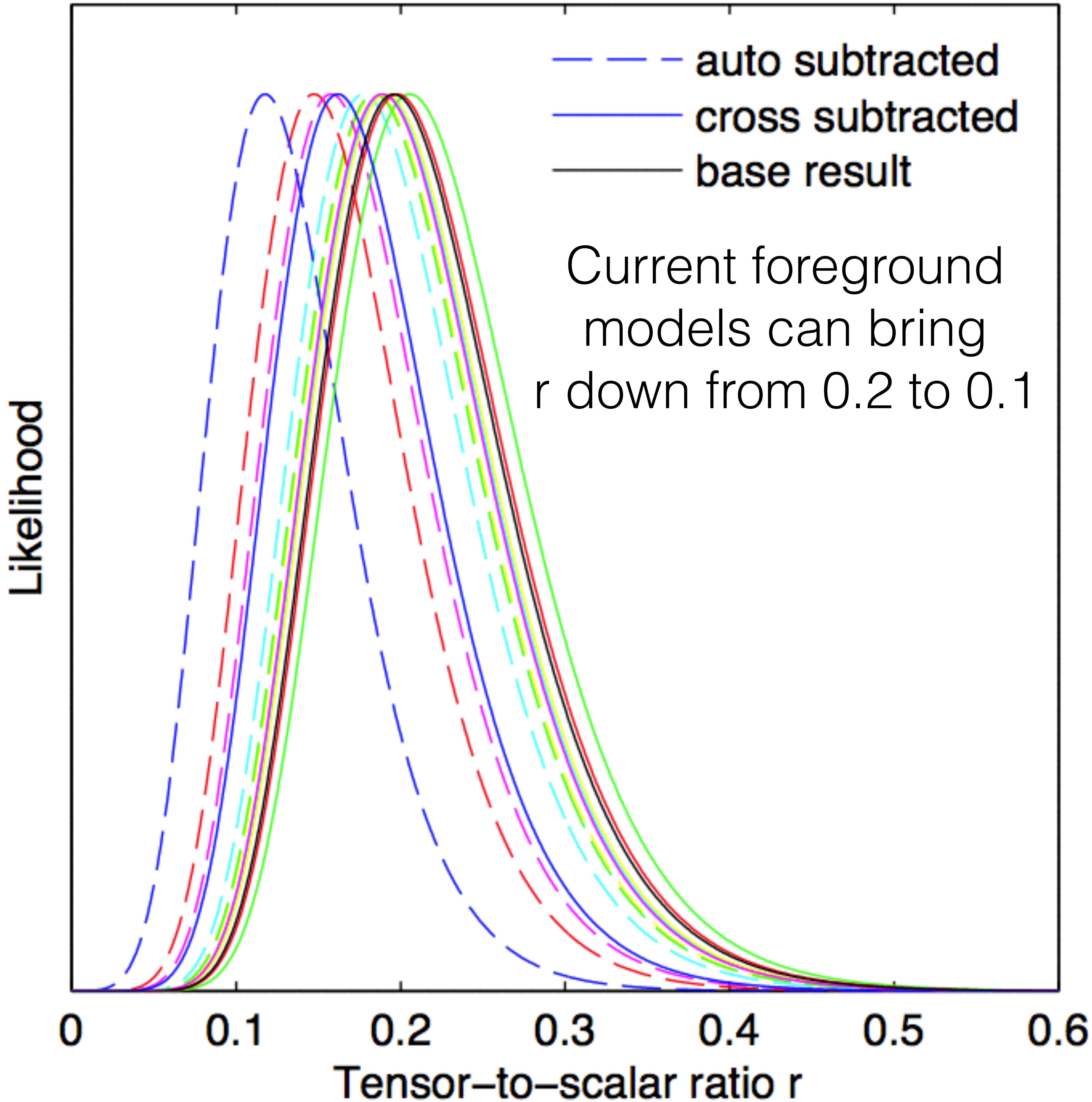
- In other words, **it is only ~2 sigma level that they can claim the cosmological origin of the signal.**

Recap

- CMB is the fossil light of the Big Bang, and the oldest light that one can ever hope to measure directly.
  - The present-day temperature is 2.7 K.
- The CMB photons were decoupled from electrons when the universe was 3000 K.
- The ripples in CMB form sound waves, and we can use these waves to measure the baryon density, dark matter density, geometry, the age of the universe, etc.
- We think that the cosmic inflation in the very early universe created these ripples from quantum fluctuations.
- And gravitational waves!



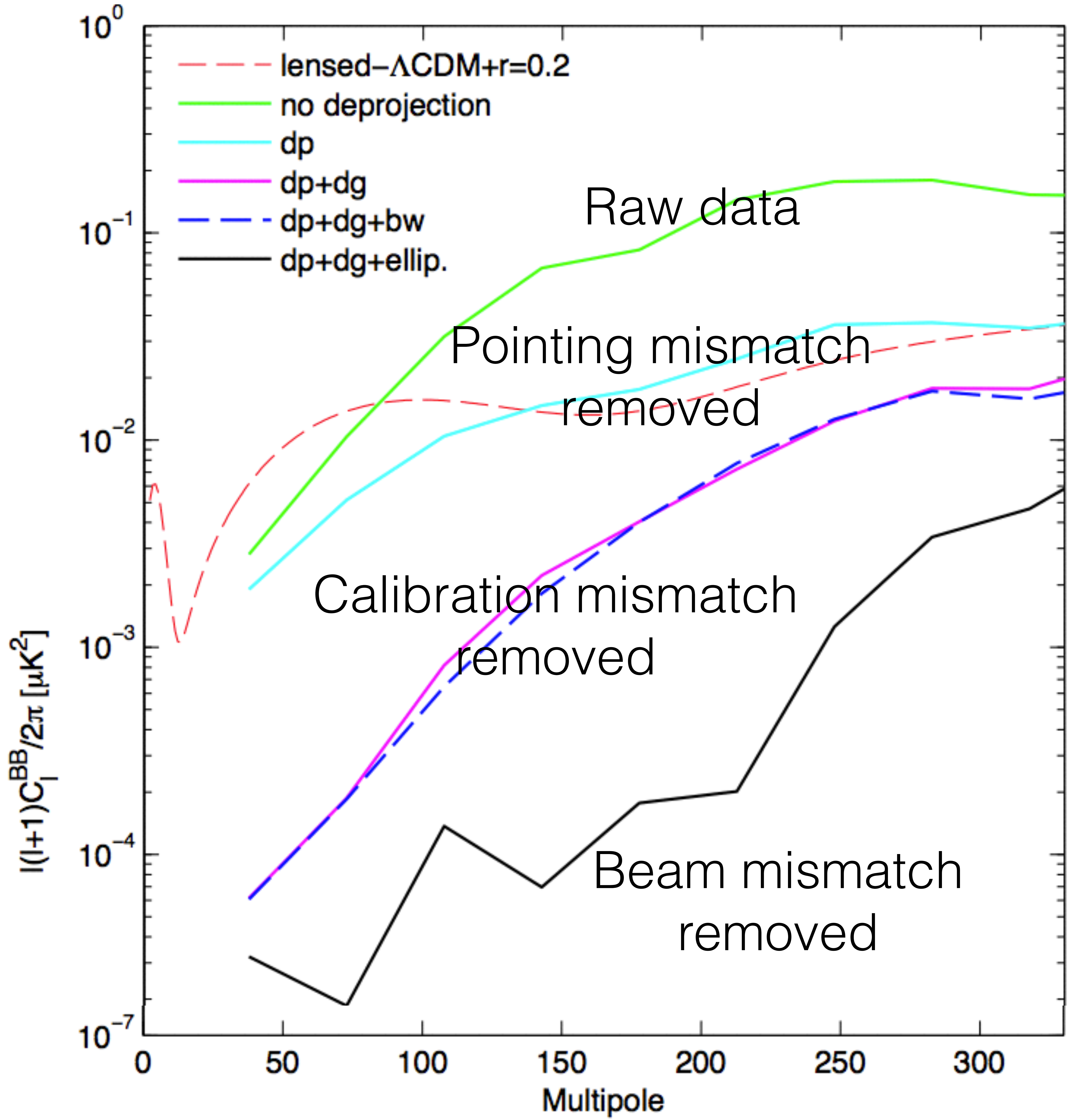
Testing for dust contamination
using the existing model predictions



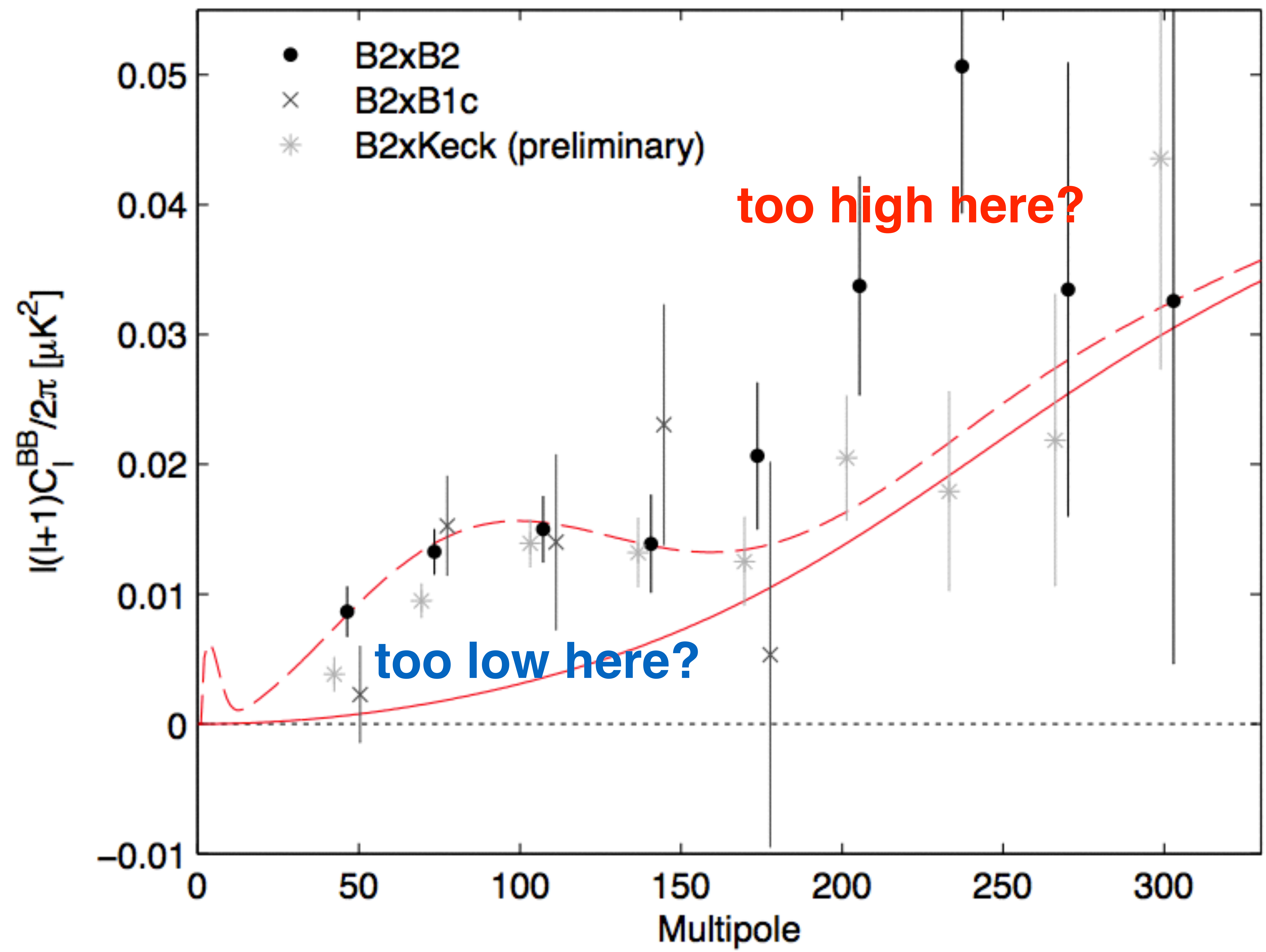
Current foreground models can bring r down from 0.2 to 0.1

Instrumental Effects

- BICEP2 measures polarization by taking the outputs of two detectors
- If the properties of these detectors are different, the temperature-to-polarization leakage occurs
  - Two detectors seeing different locations in the sky
  - Two detectors receiving slightly different frequencies
  - Two detectors calibrated with a slight mis-calibration
  - Two detectors having different beams in the sky


lensed−ΛCDM+r=0.2
no deprojection
dp
dp+dg
dp+dg+bw
dp+dg+ellip.
Raw data
Pointing mismatch removed
Calibration mismatch removed
Beam mismatch removed
$l(l+1)C_l^{BB}/2\pi$ [μK²]
Multipole
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-7}
0
50
100
150
200
250
300

Worries raised at FB so far



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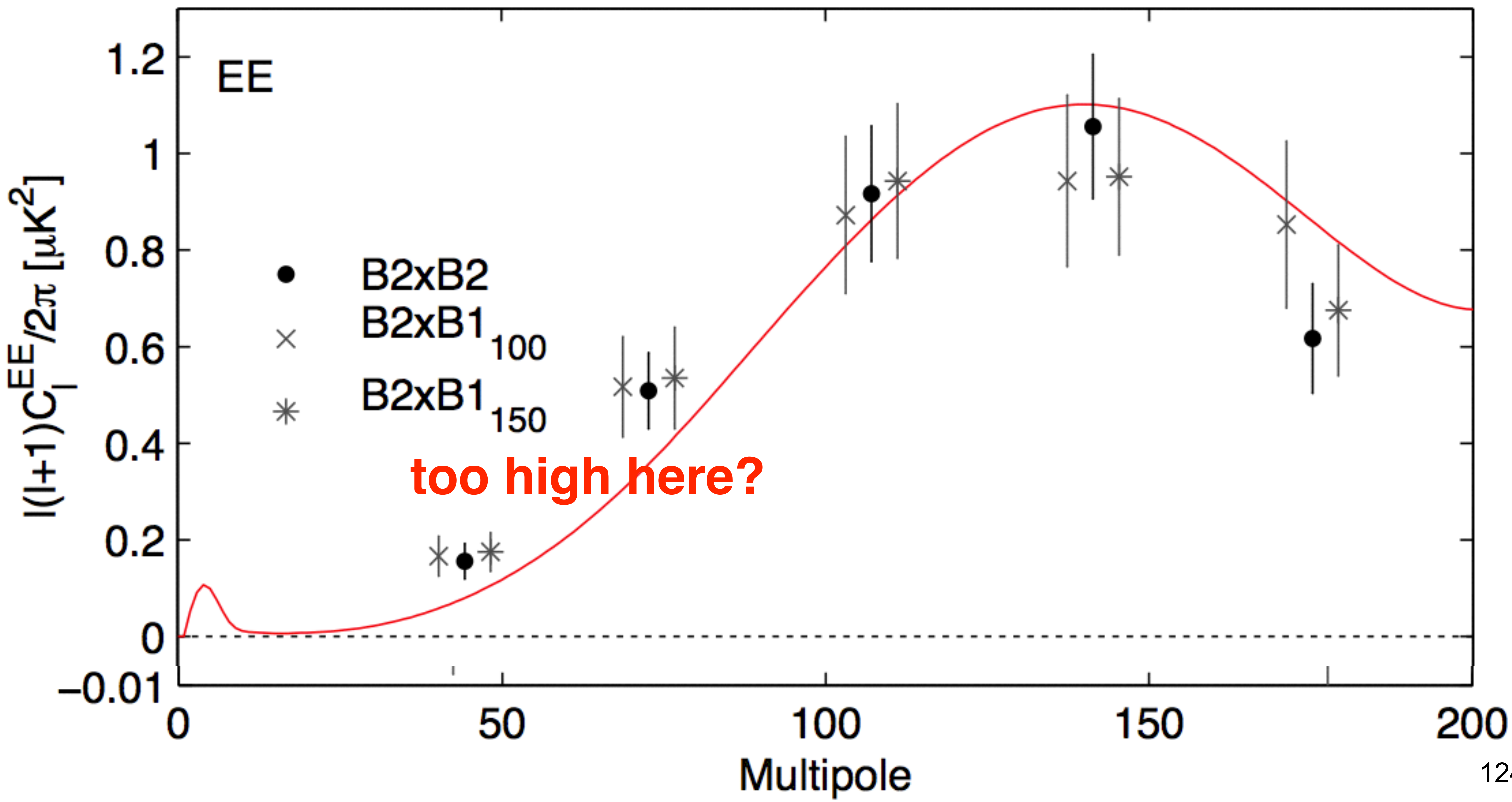

“Reconciling” T and B

- The **Planck** temperature data suggest **r<0.11** [95%CL], assuming a power-law scalar power spectrum and adiabatic perturbations
- The **BICEP2** data suggest **r~0.1-0.2**
  - *The lower r values not a problem*
  - The higher r values would require a modification to the model:
    - Scale-dependent power-law scalar perturbation spectrum
    - A new perturbation source [anti]correlated with adiabatic perturbations, e.g., isocurvature
    - A cut-off of the scalar power at the largest scale -> a probe of the beginning of inflation?