Recent Results from CMB Experiments

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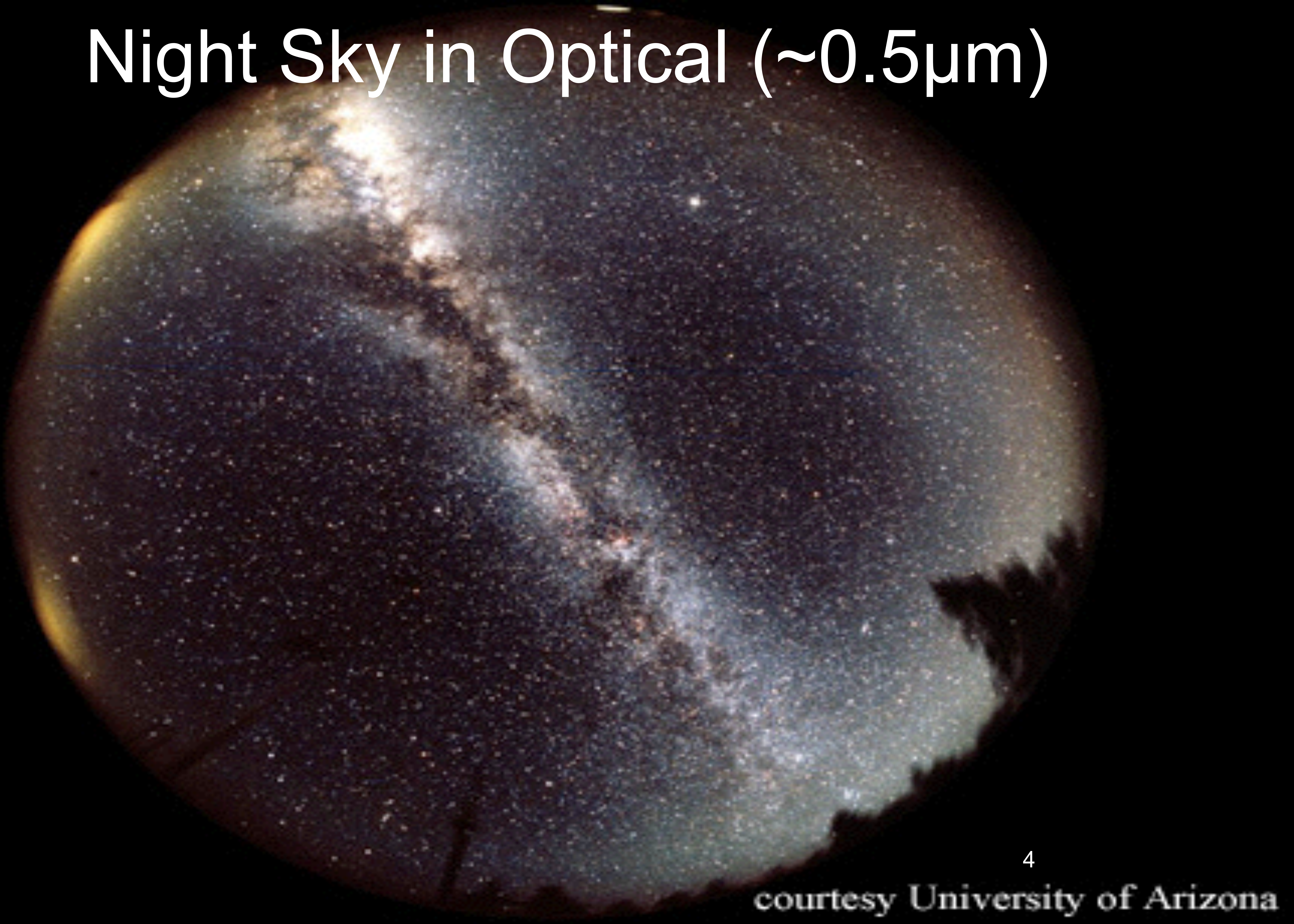
Schule für Astroteilchenphysik, October 16, 2014

The Breakthrough

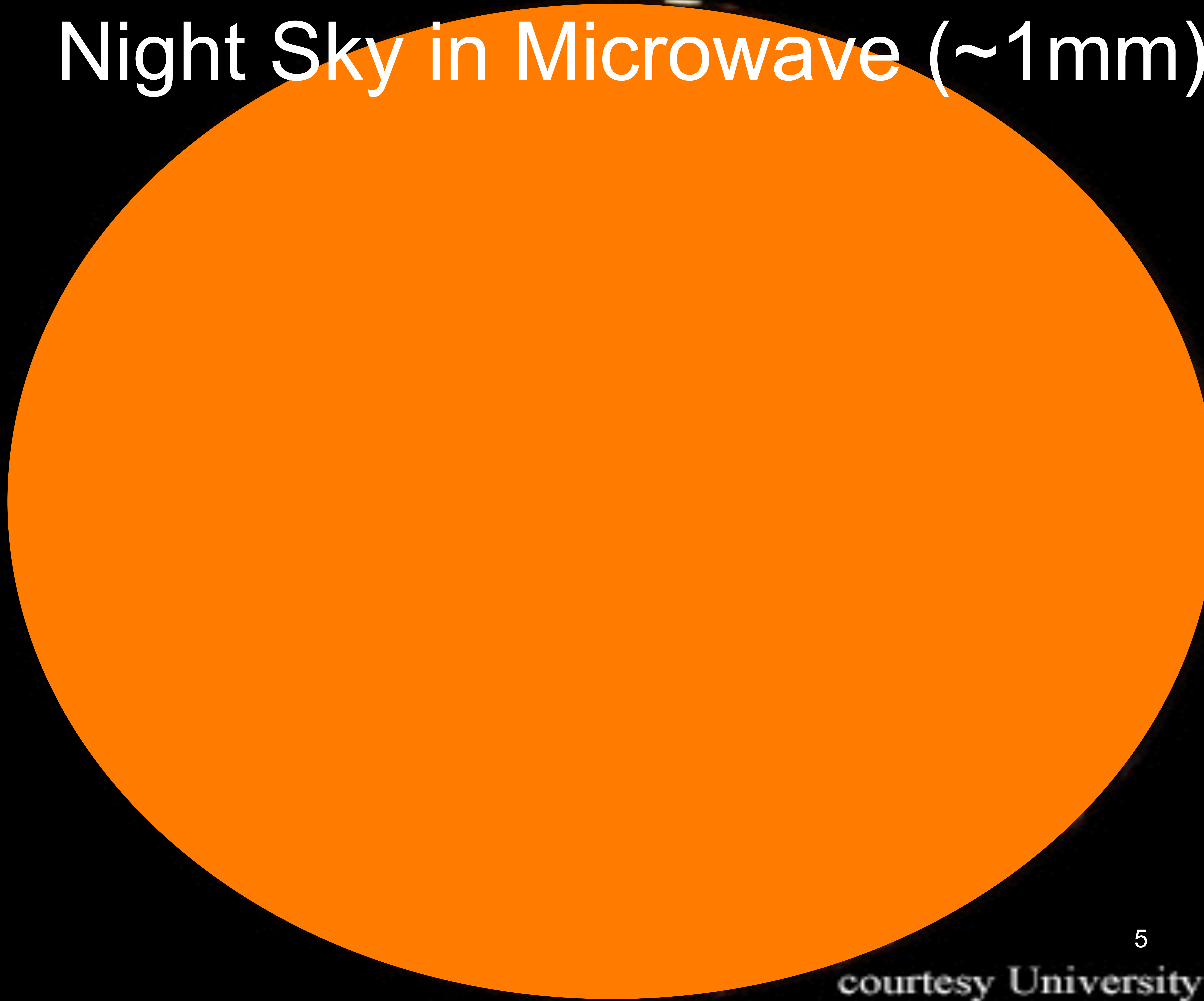
- Now we can **observe** the physical condition of the Universe when it was very young.

From "Cosmic Voyage"

Night Sky in Optical (~0.5μm)



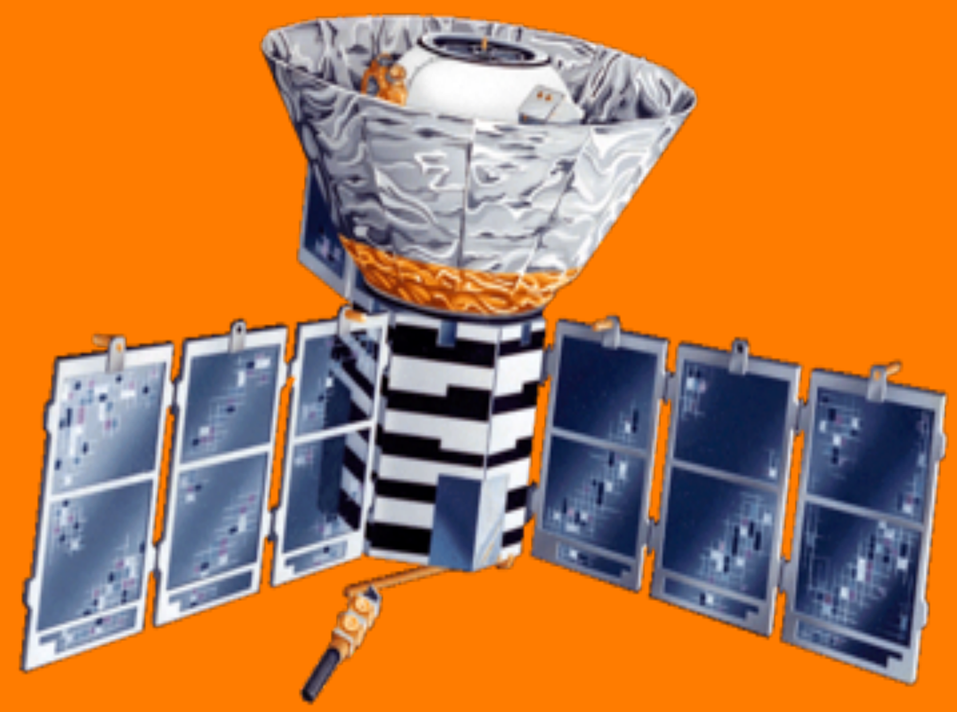
Night Sky in Microwave (~1mm)



courtesy University of Arizona

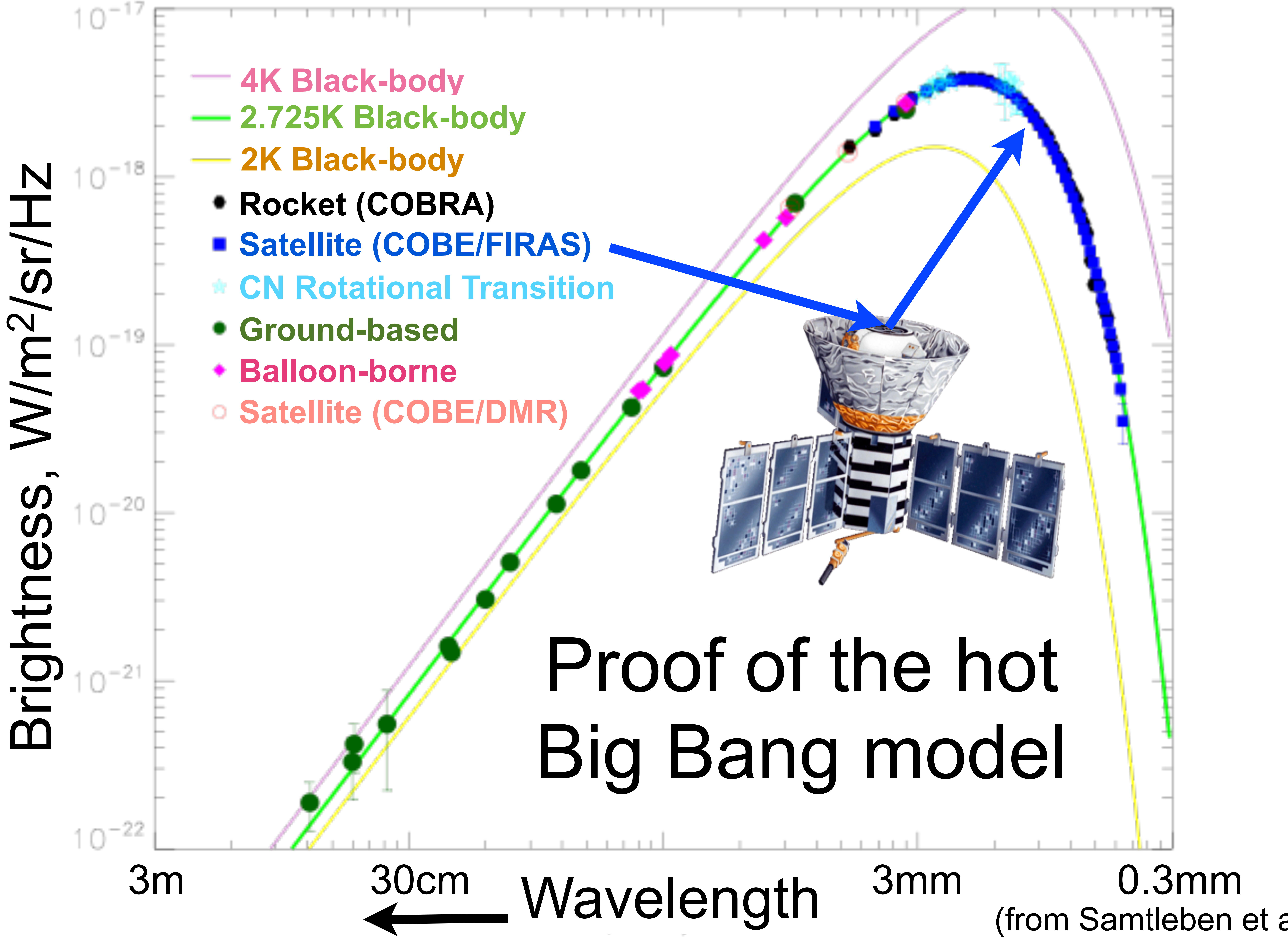
Night Sky in Microwave (~1mm)

$$T_{today}=2.725K$$



COBE Satellite, 1989-1993

courtesy University of Arizona



(from Samtleben et al. 2007)

Arno Penzias & Robert Wilson, 1965

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

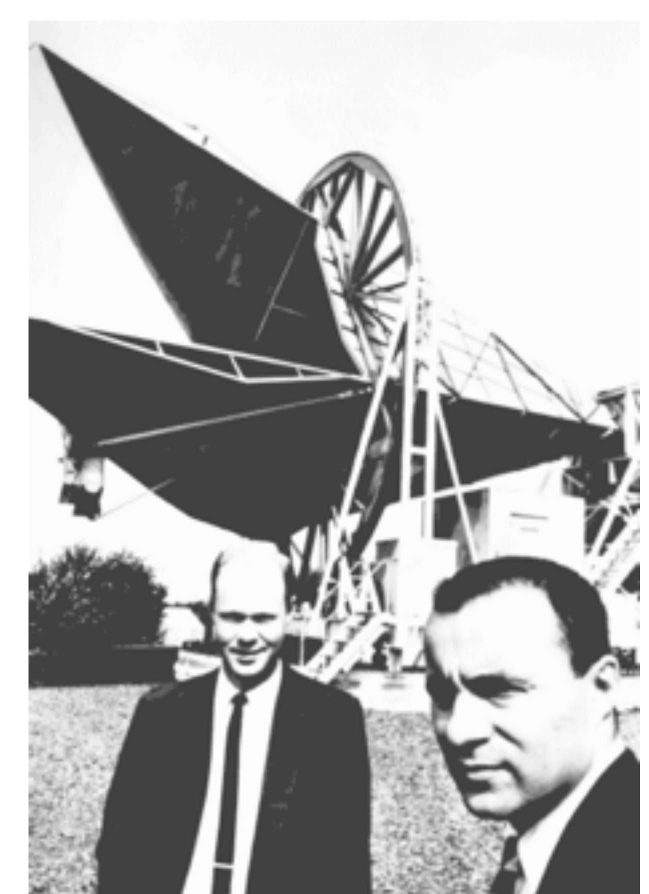
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our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

- **Isotropic**

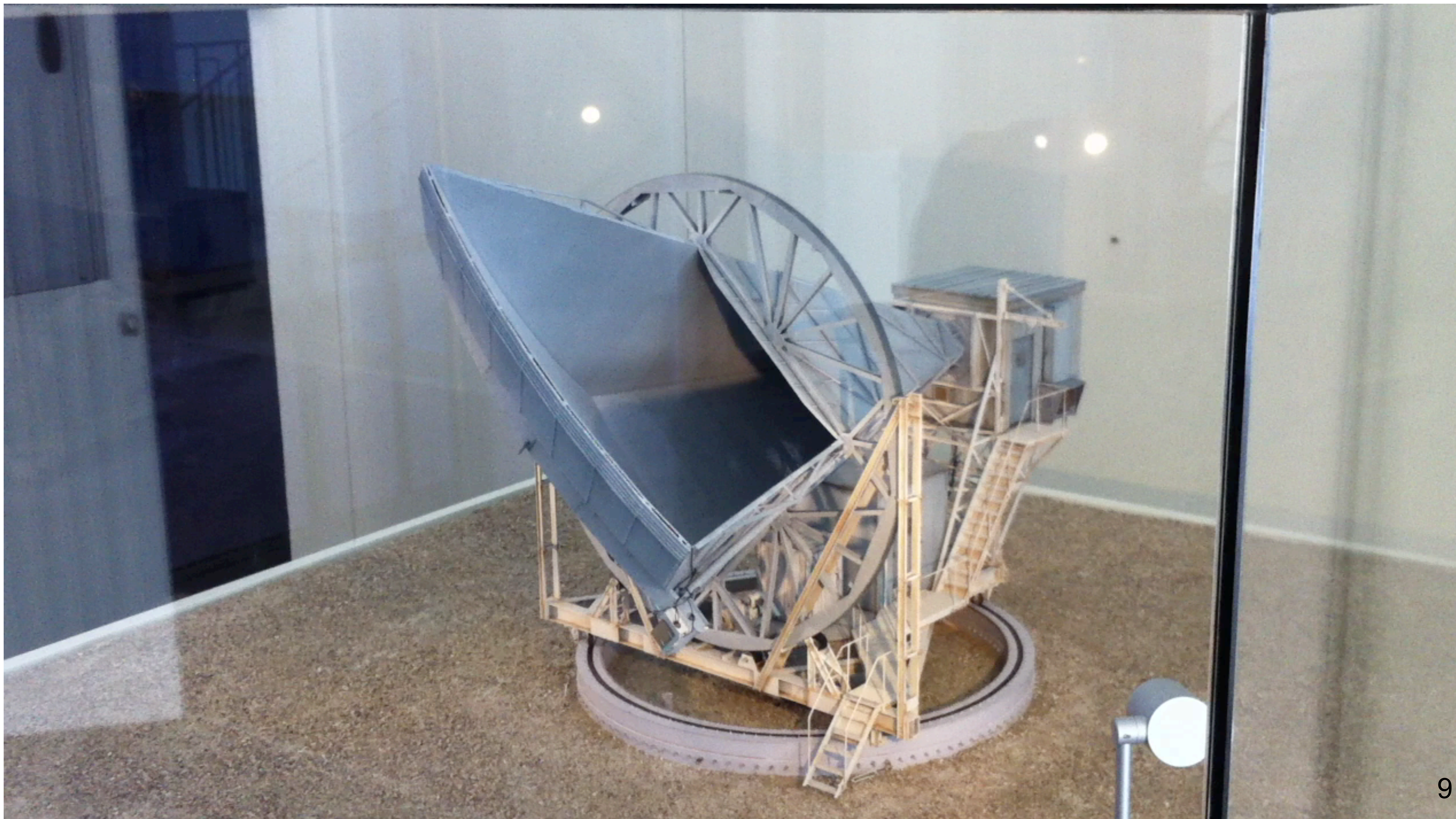
A. A. PENZIAS
R. W. WILSON

May 13, 1965

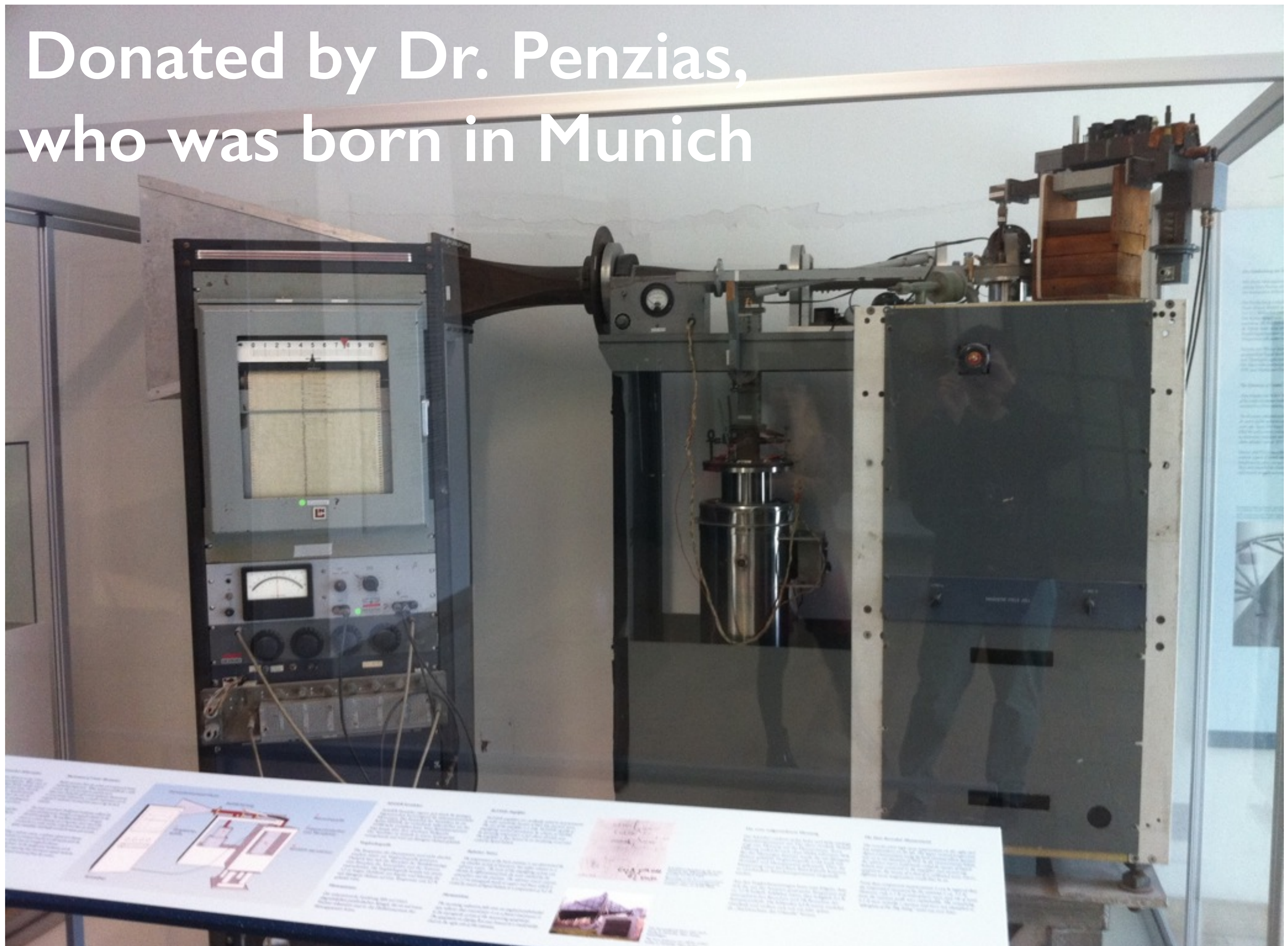
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

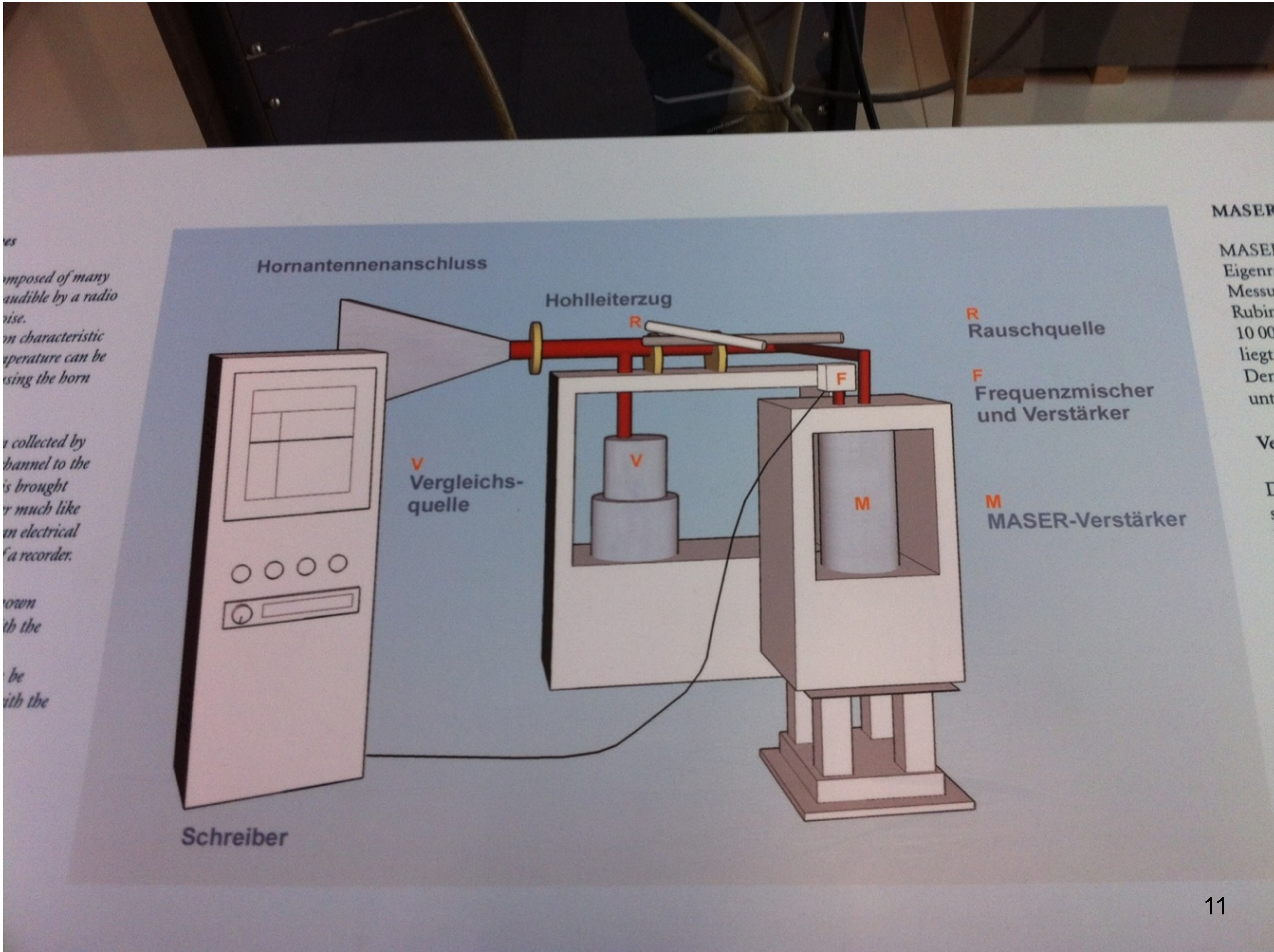


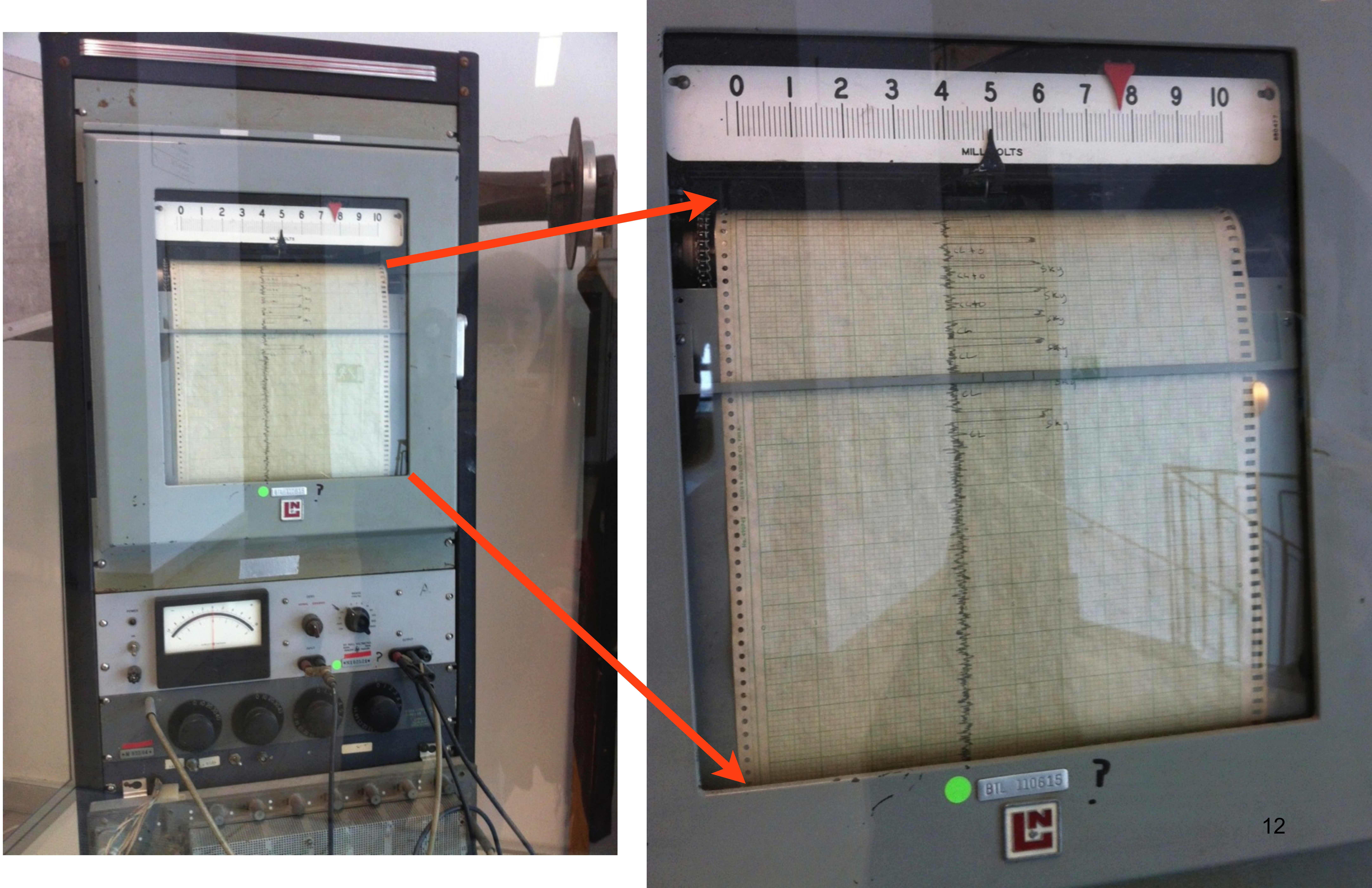
1:25 model at Deutsches Museum



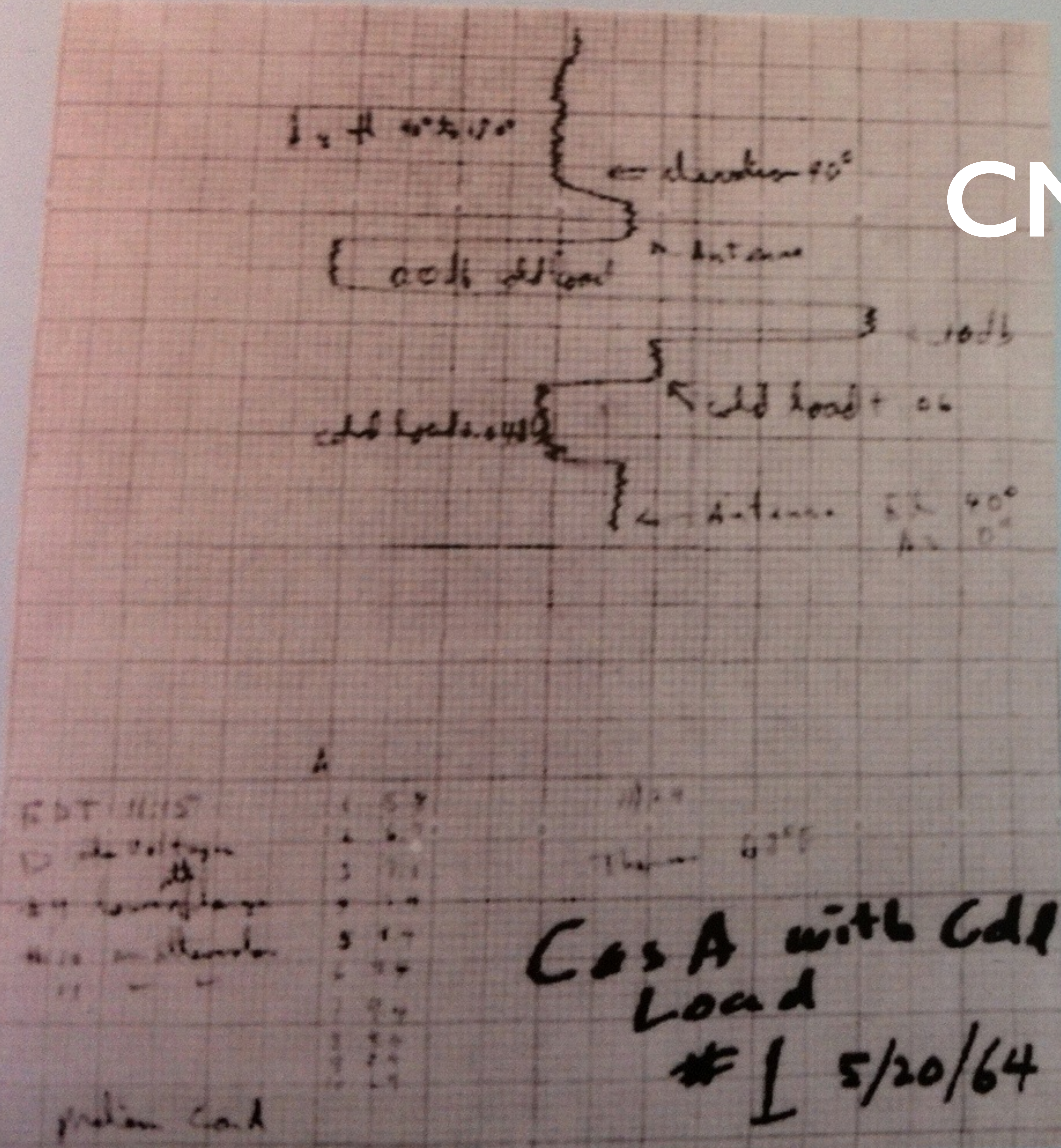
The REAL back-end system of the Penzias-Wilson experiment, exhibited at Deutsches Museum




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

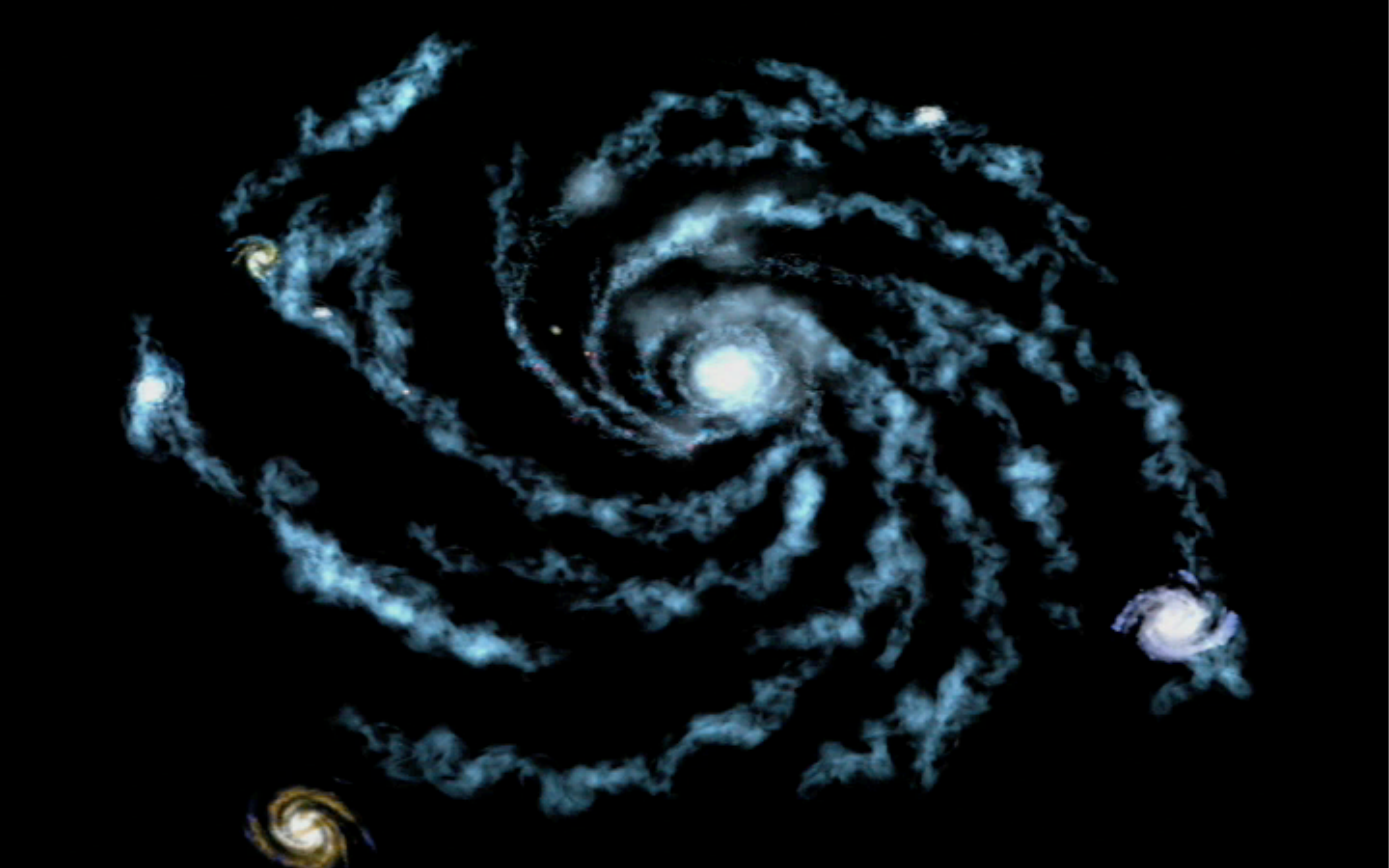

0 1 2 3 4 5 6 7 8 9 10
BTL 110615

May 20, 1964
CMB "Discovered"



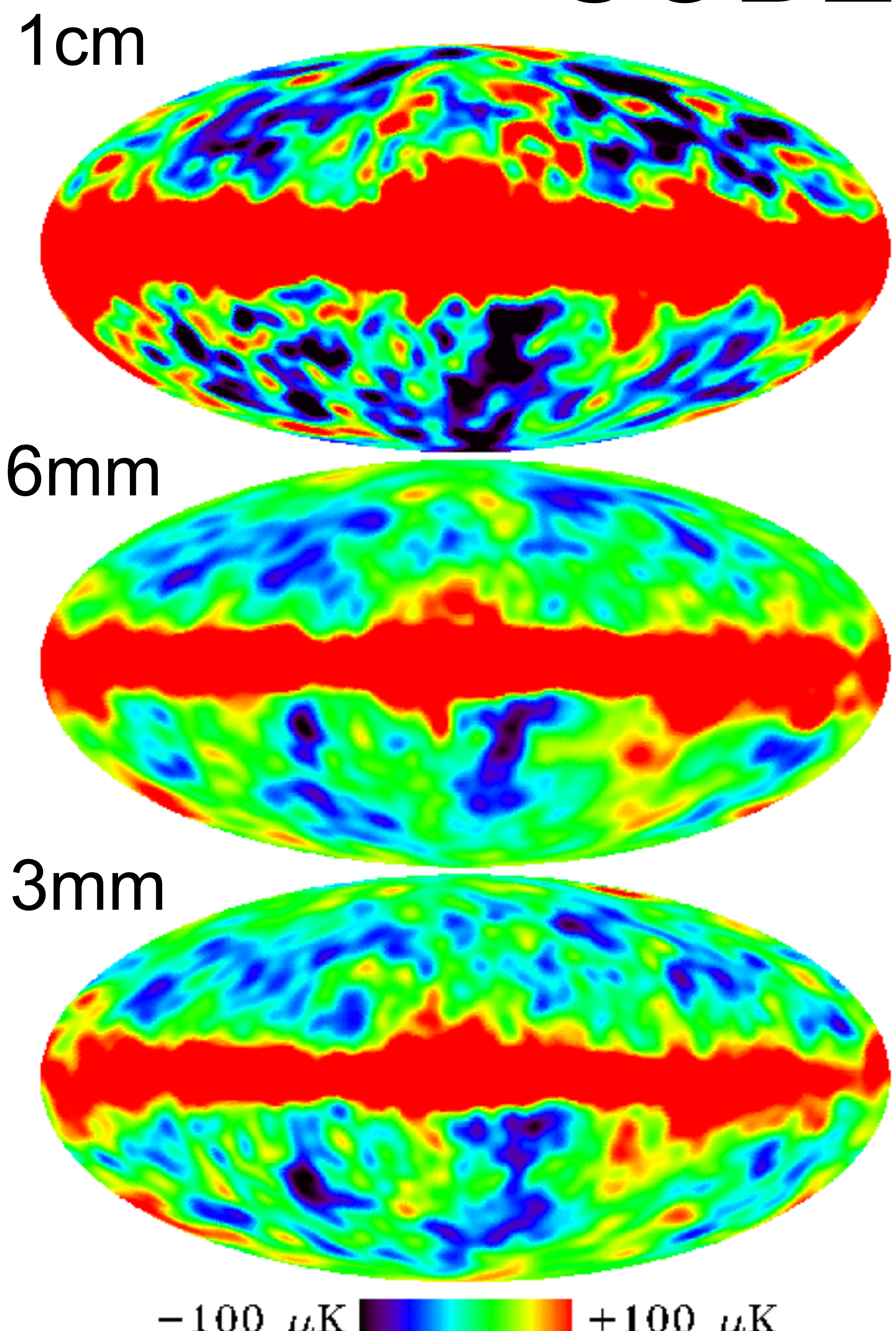
Schreiberaufzeichnung der ersten Messung des Mikrowellenhintergrundes am 20.5.1964

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



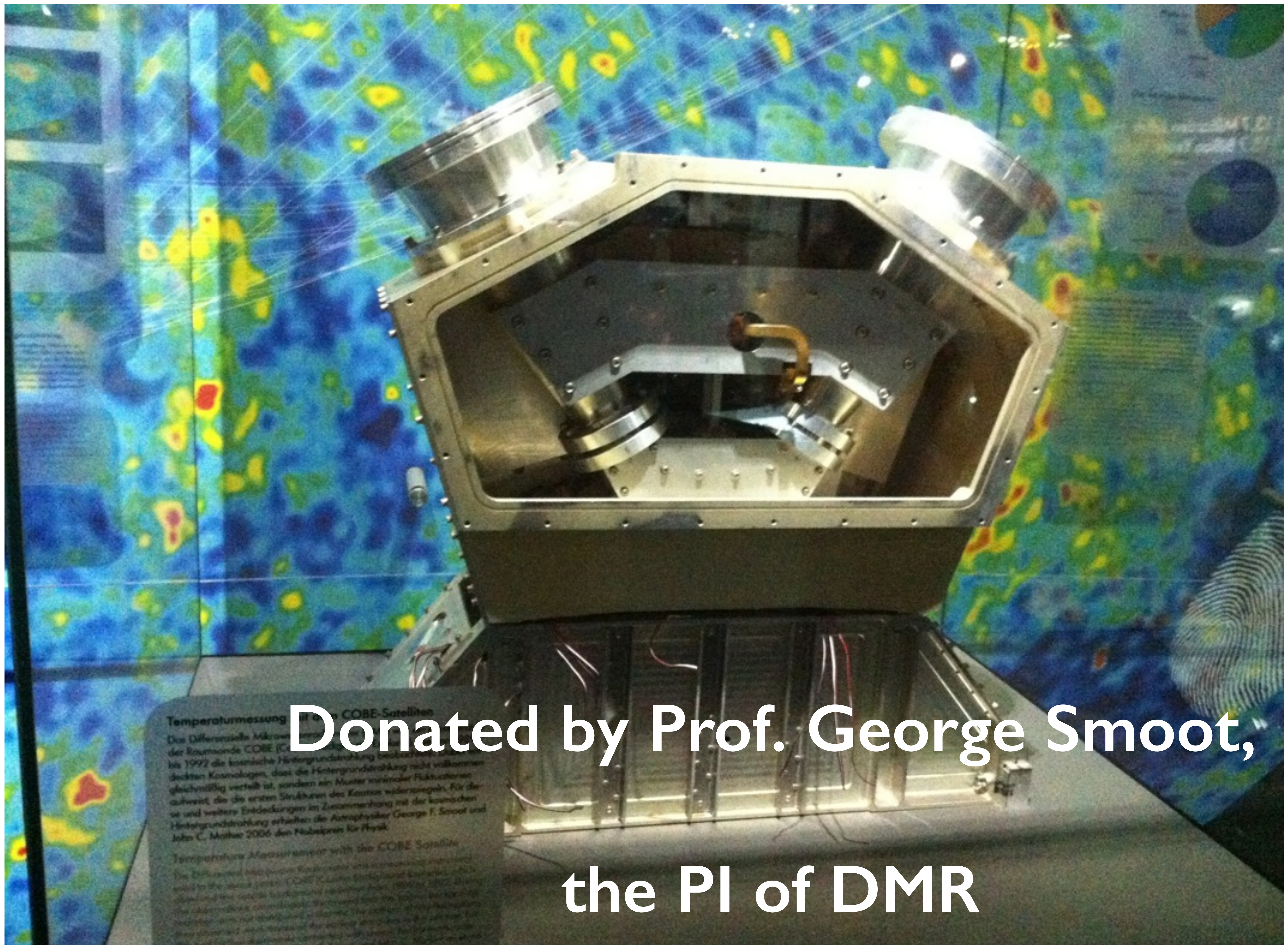
Smoot et al. (1992)

COBE/DMR, 1992



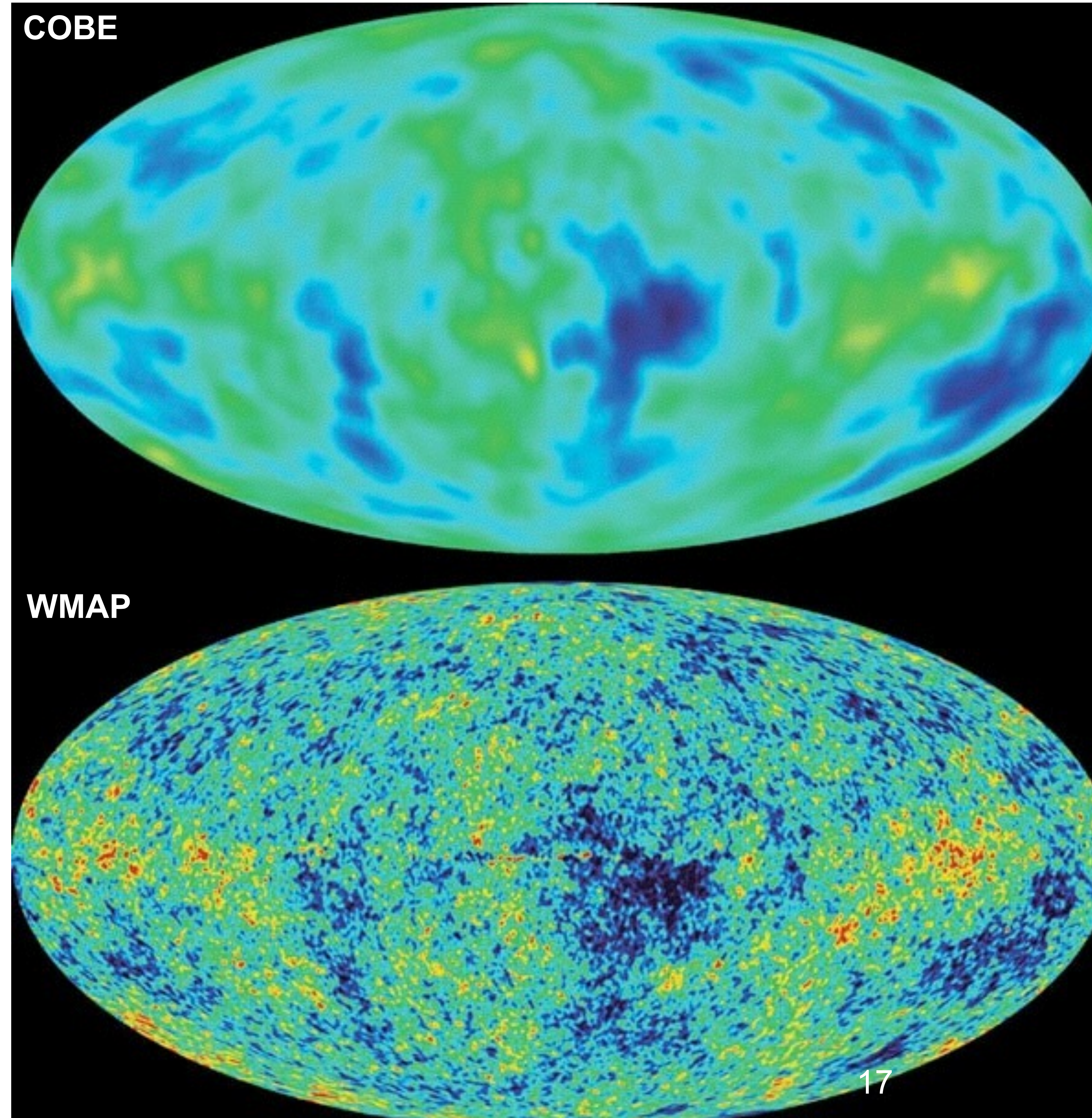
- Isotropic?
- CMB is anisotropic! (at the 1/100,000 level)

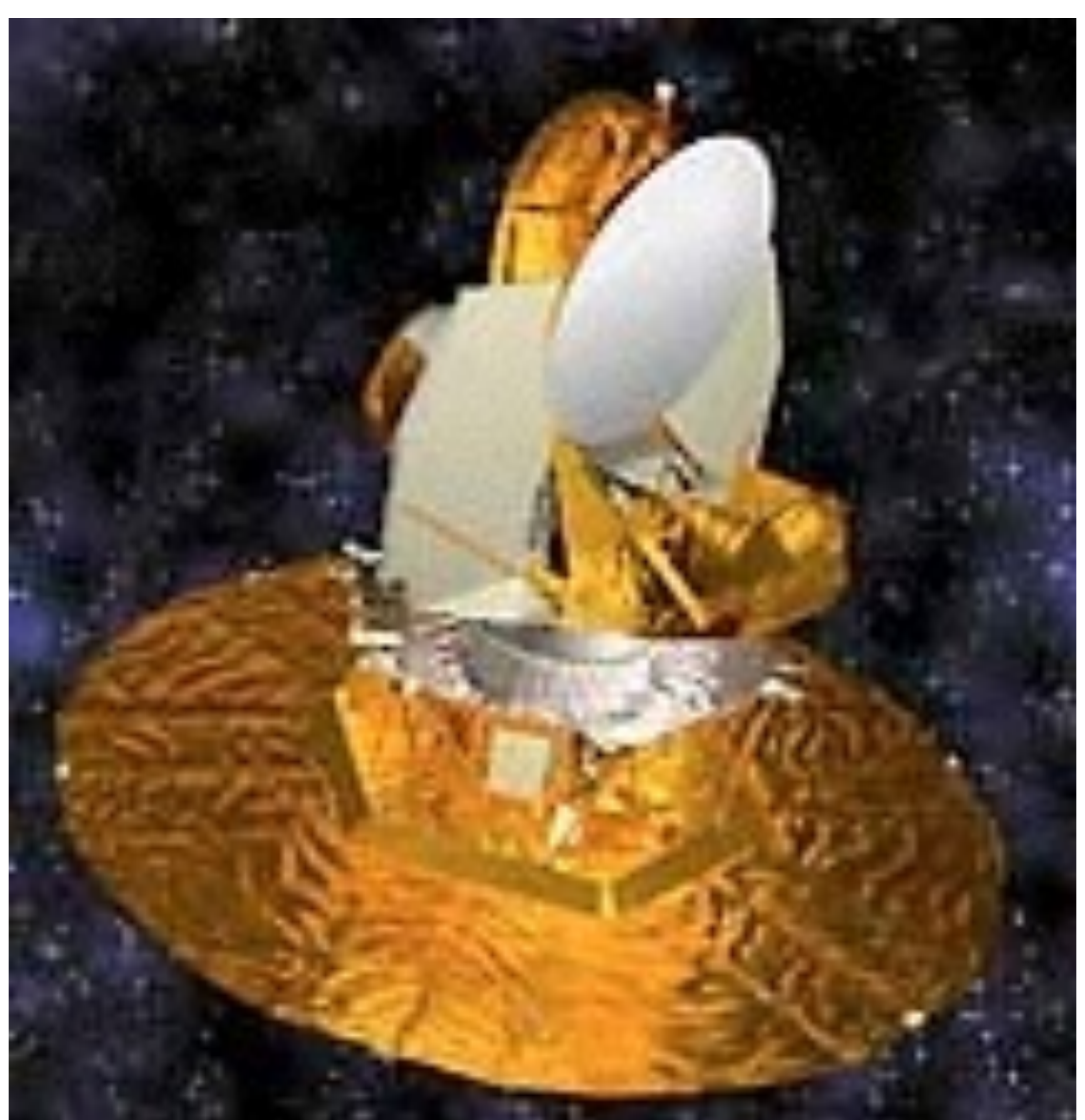
A spare unit of COBE/DMR (λ=1cm)



COBE to WMAP (x35 better resolution)

COBE
1989

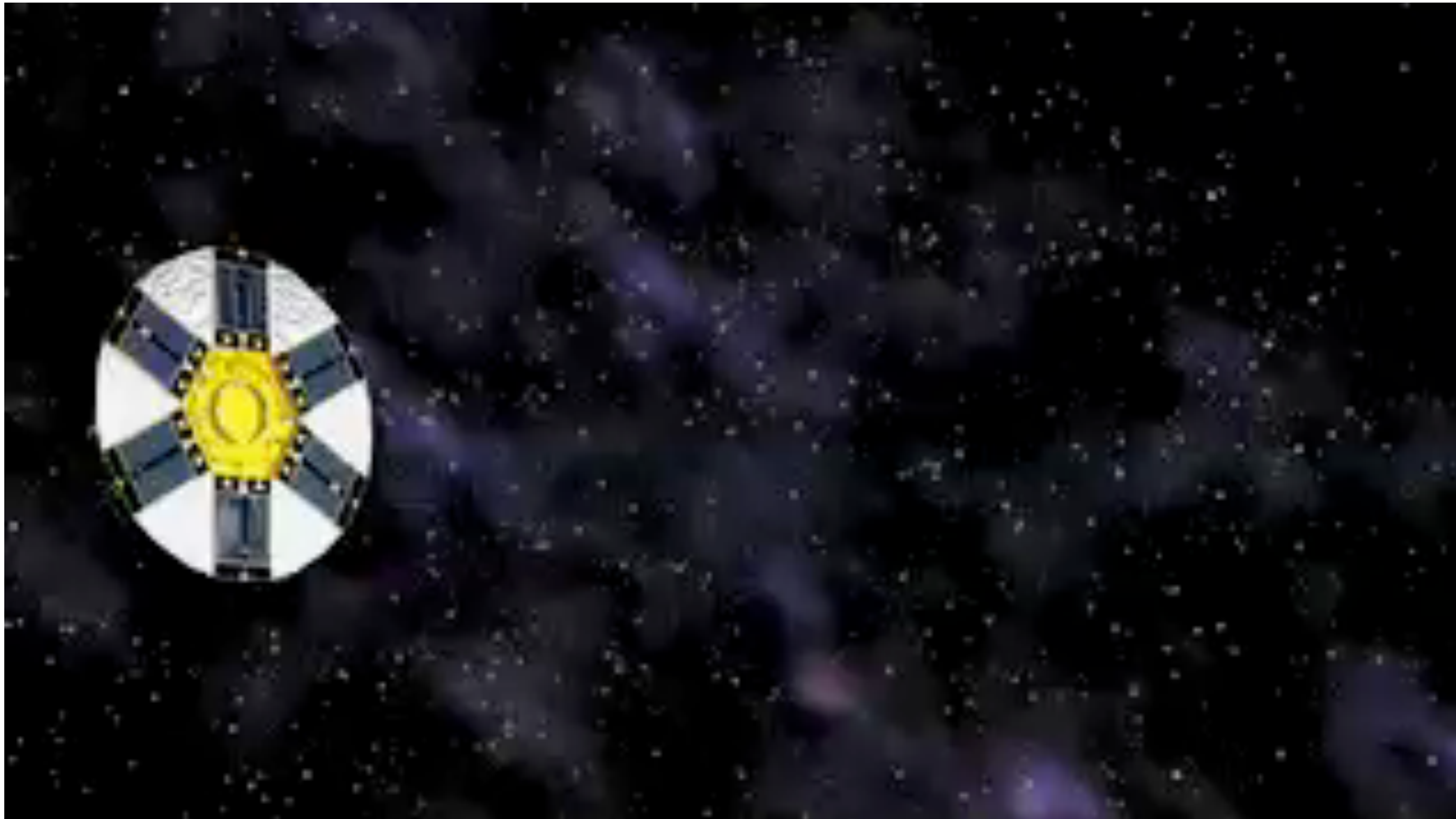




WMAP
2001

Wilkinson Microwave Anisotropy Probe

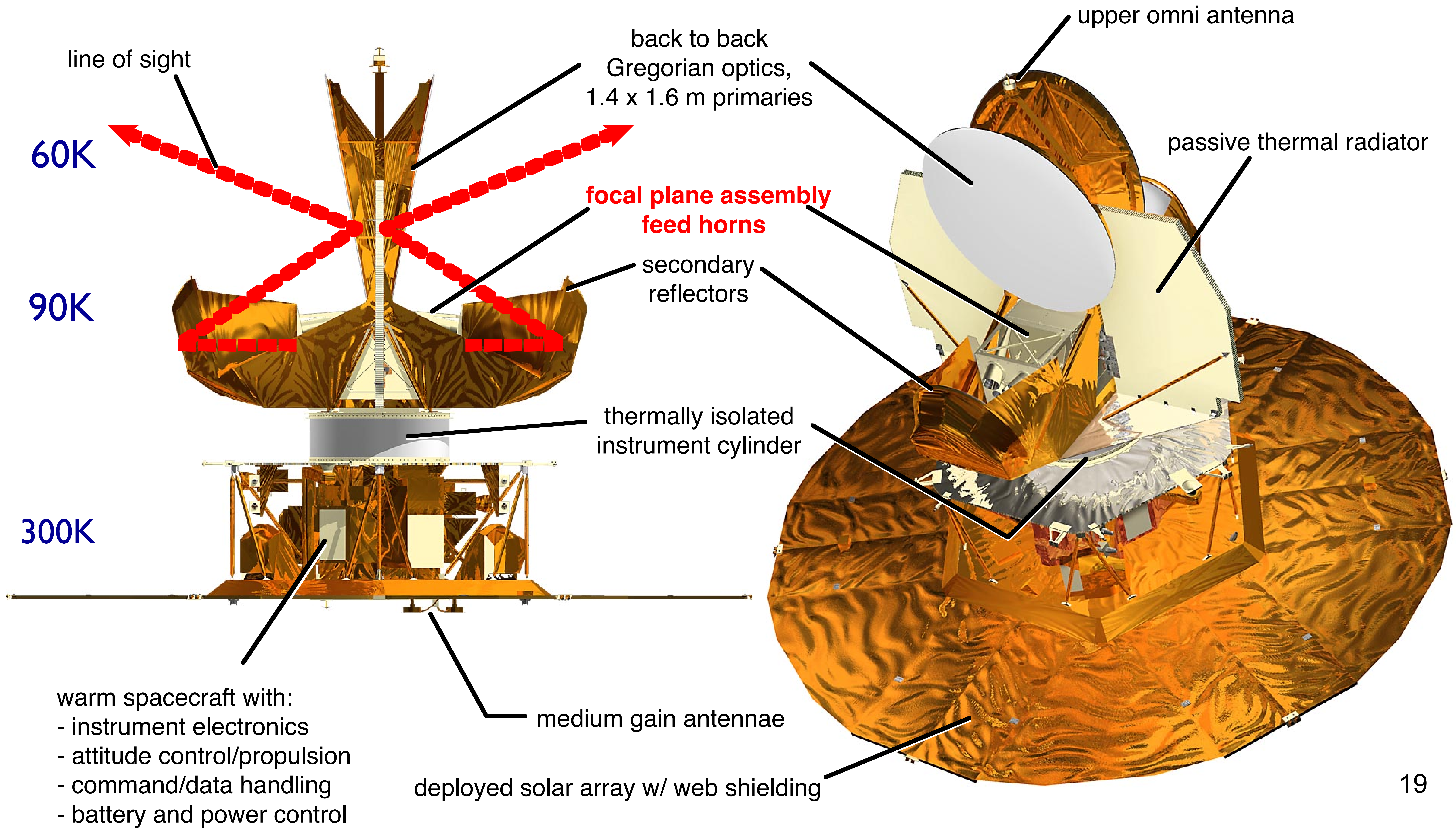
WMAP at Lagrange 2 (L2) Point



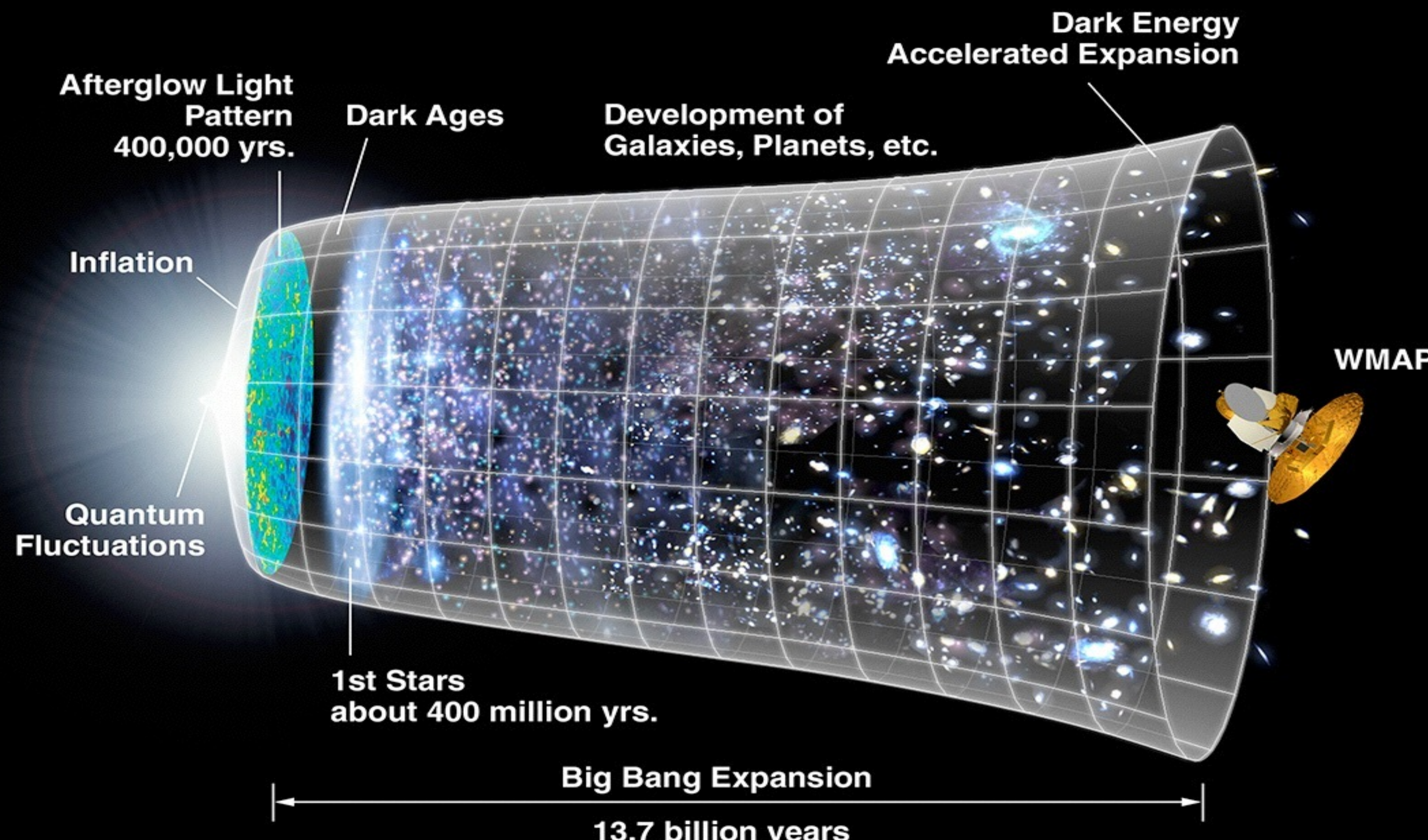
- L2 is 1.5 million kilometers from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

WMAP Spacecraft

Radiative Cooling: No Cryogenic System



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

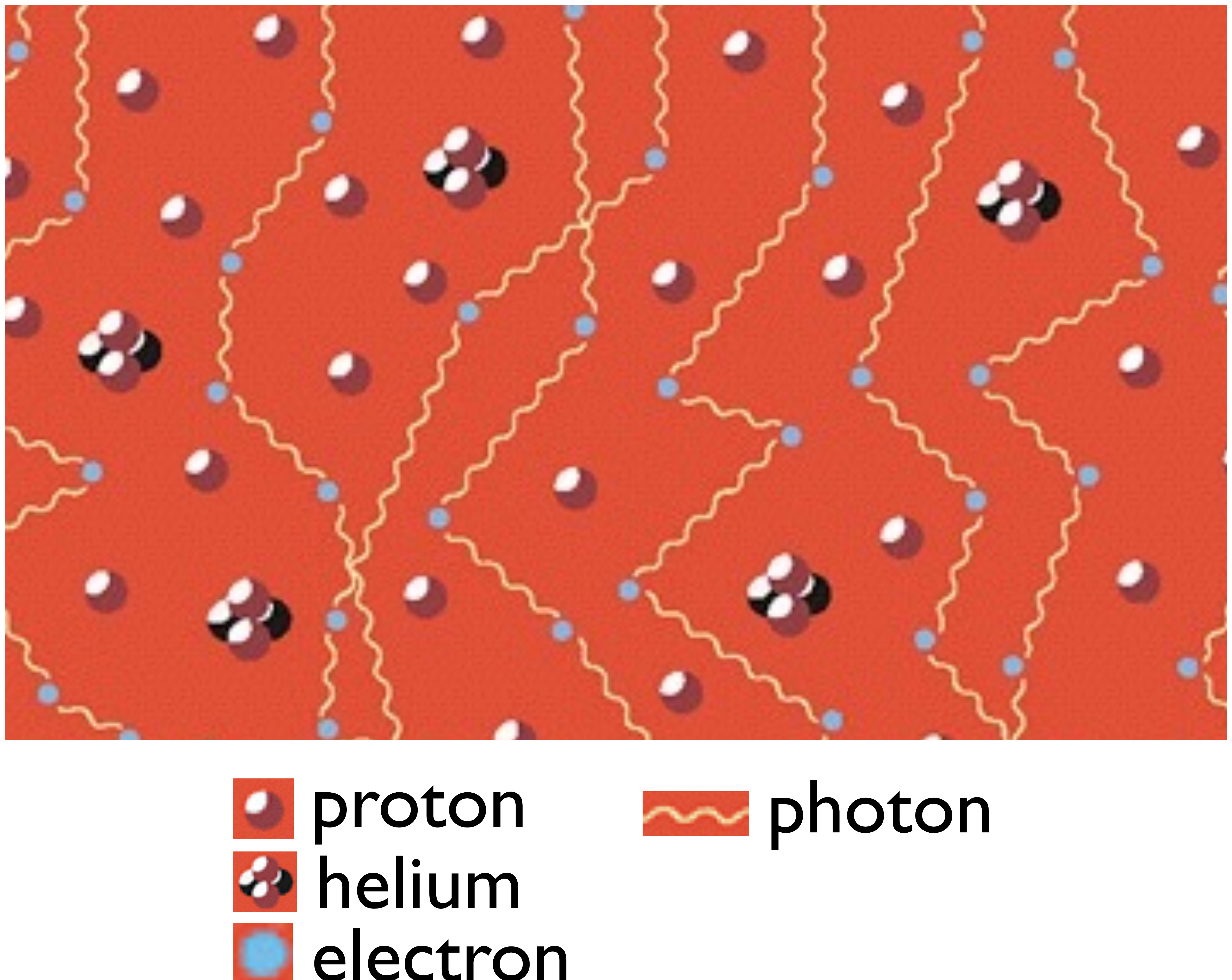


- When the Universe was 3000K (~380,000 years after the Big Bang), electrons and protons were combined to form neutral hydrogen.

How was CMB created?

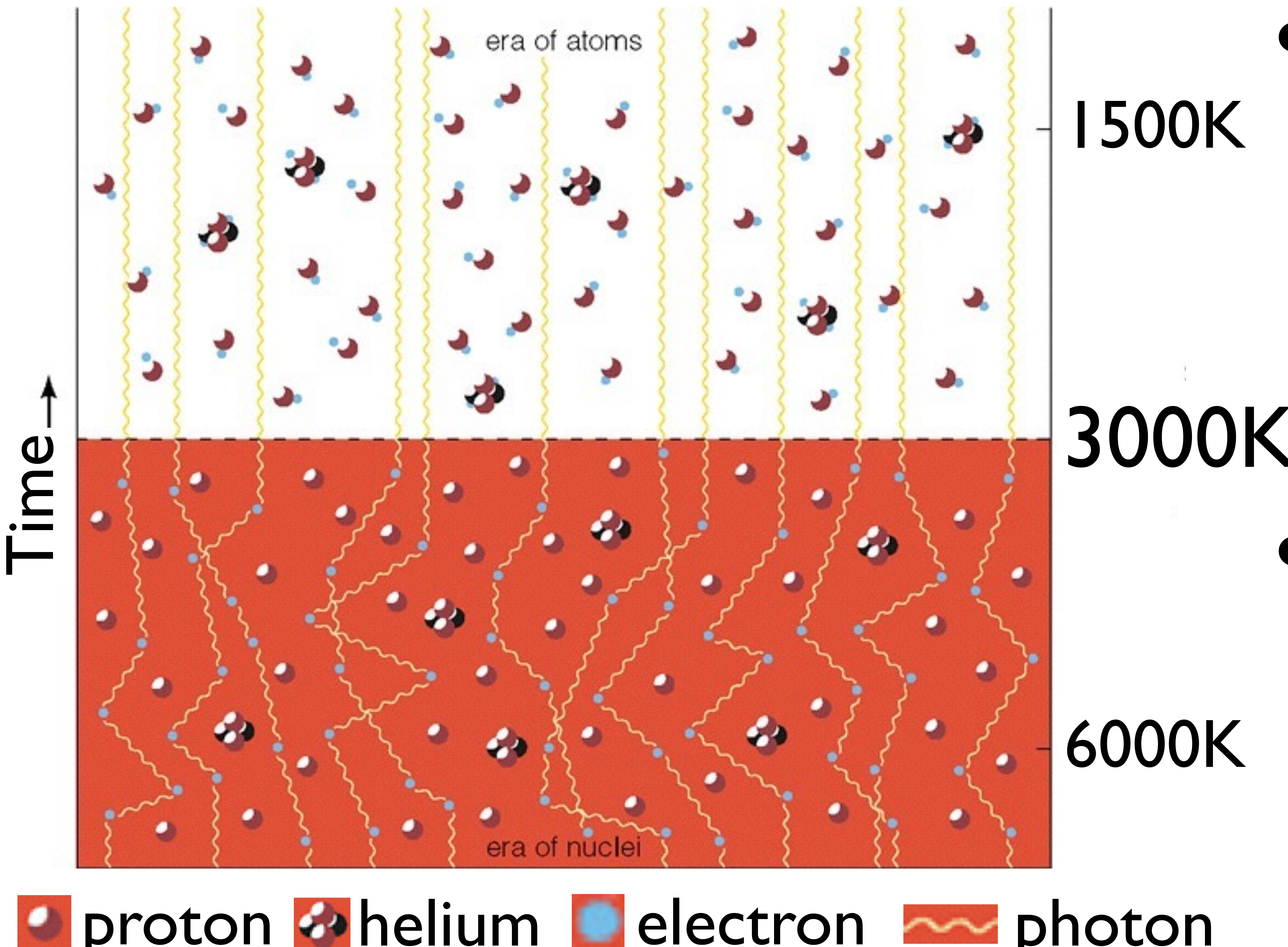
- When the Universe was hot...
  - The Universe was a hot soup made of:
    - Protons, electrons, and helium nuclei
    - Photons and neutrinos
    - Dark matter

Universe as a hot soup

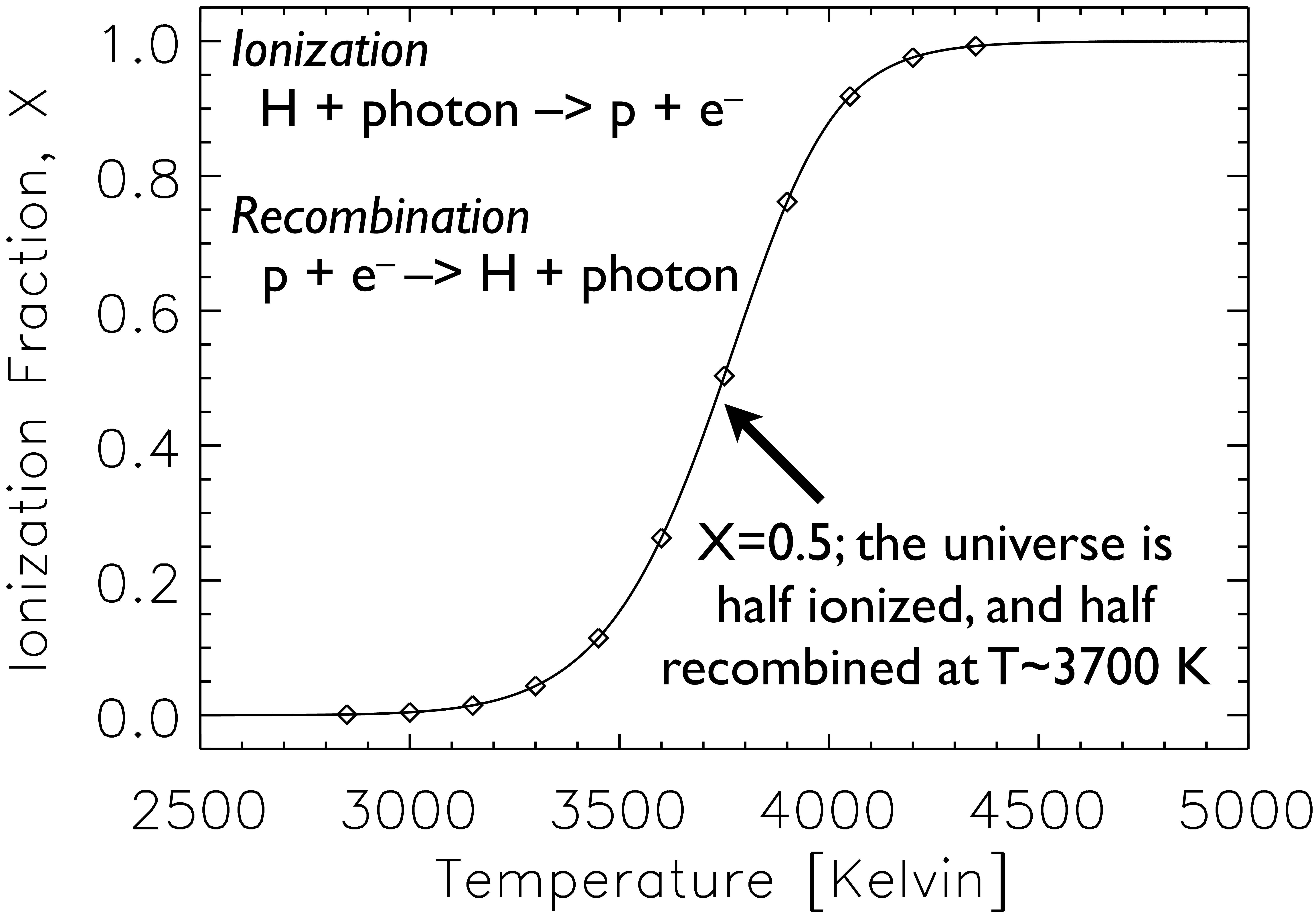


- Free electrons can scatter photons efficiently.
- Photons cannot go very far.

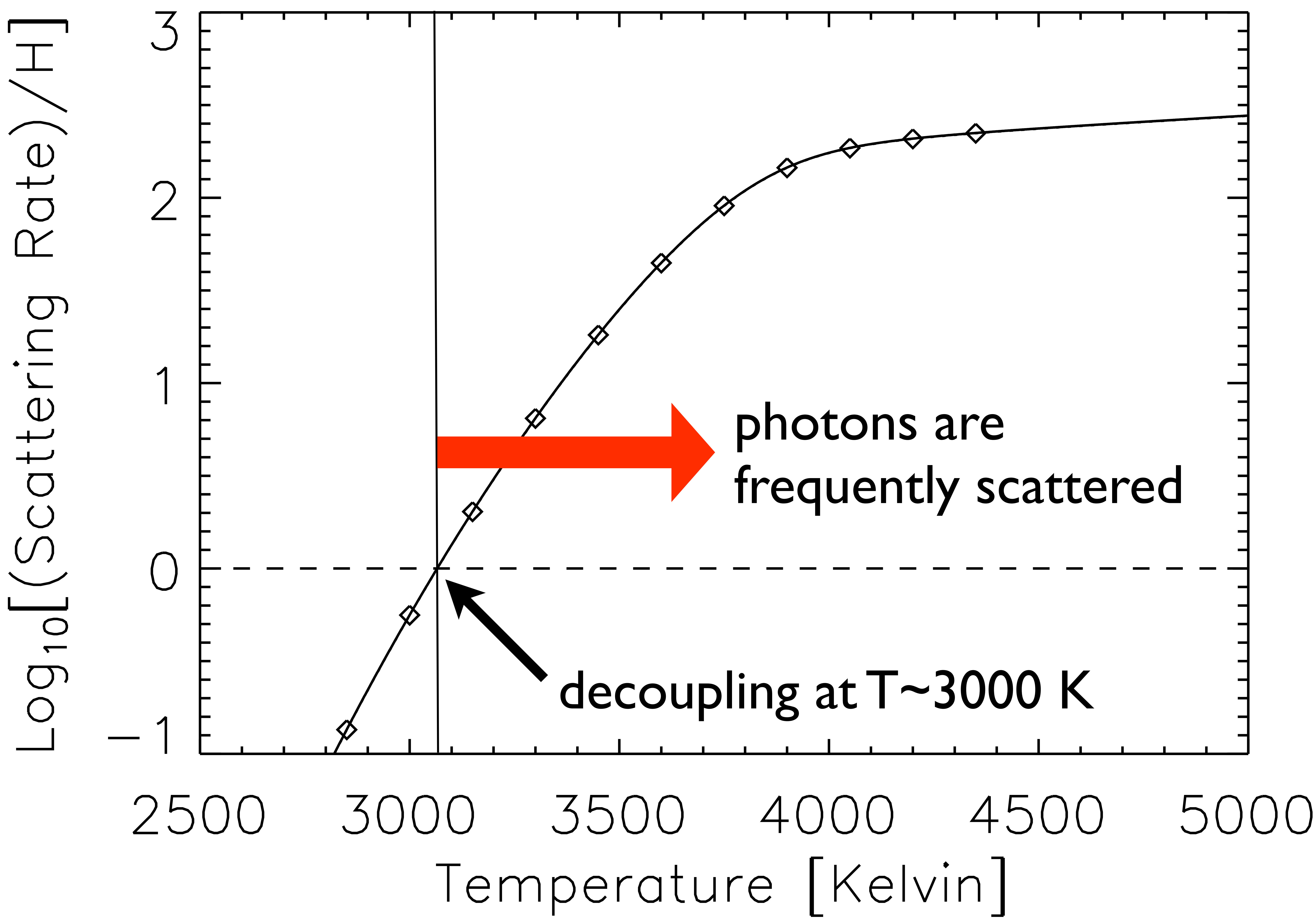
Recombination and Decoupling



- [*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.

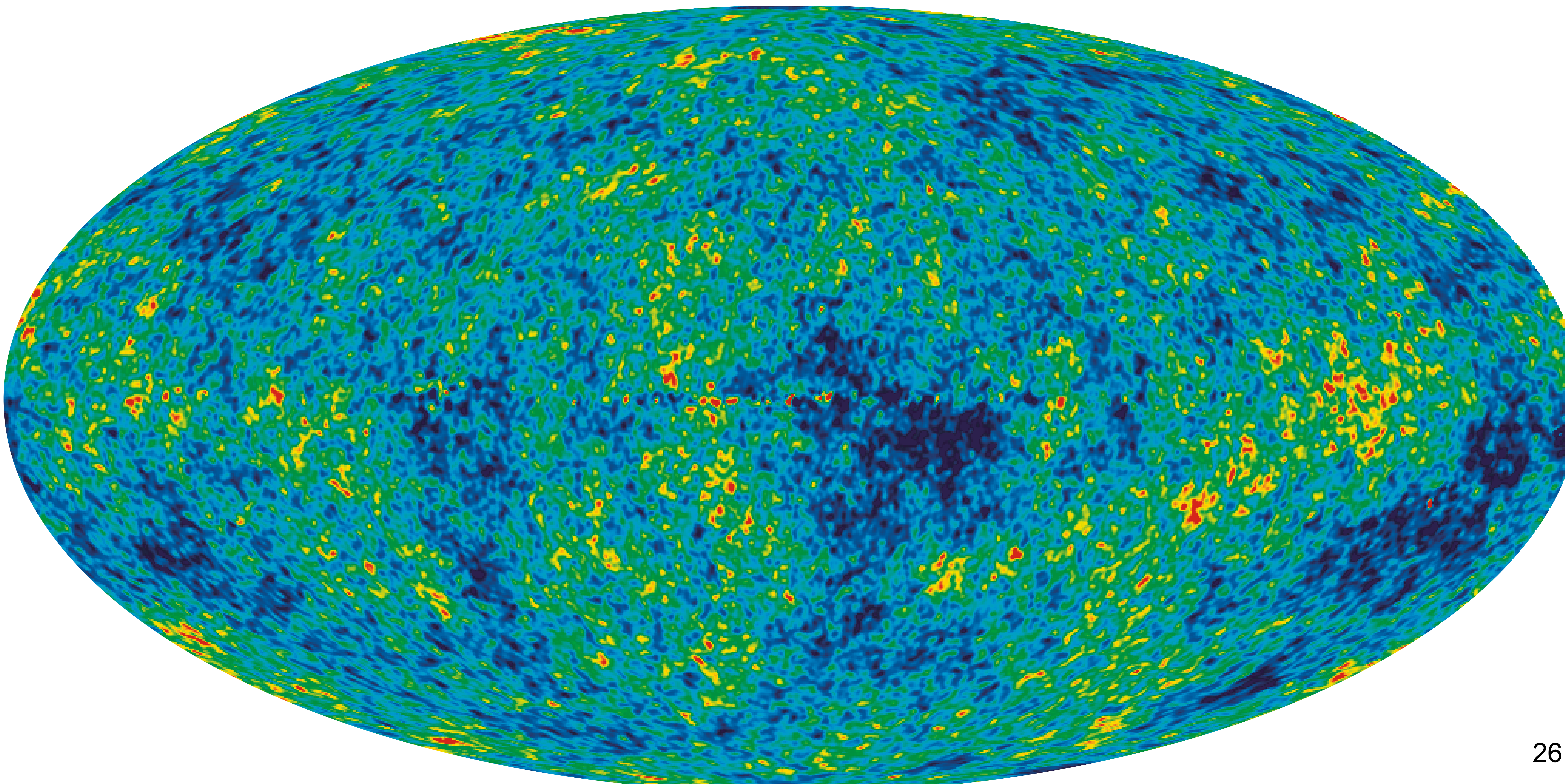


Ionization
H + photon –> p + e⁻
Recombination
p + e⁻ –> H + photon
X=0.5; the universe is half ionized, and half recombined at T~3700 K
1.0
0.8
0.6
0.4
0.2
0.0
Ionization Fraction, X
2500
3000
3500
4000
4500
5000
Temperature [Kelvin]

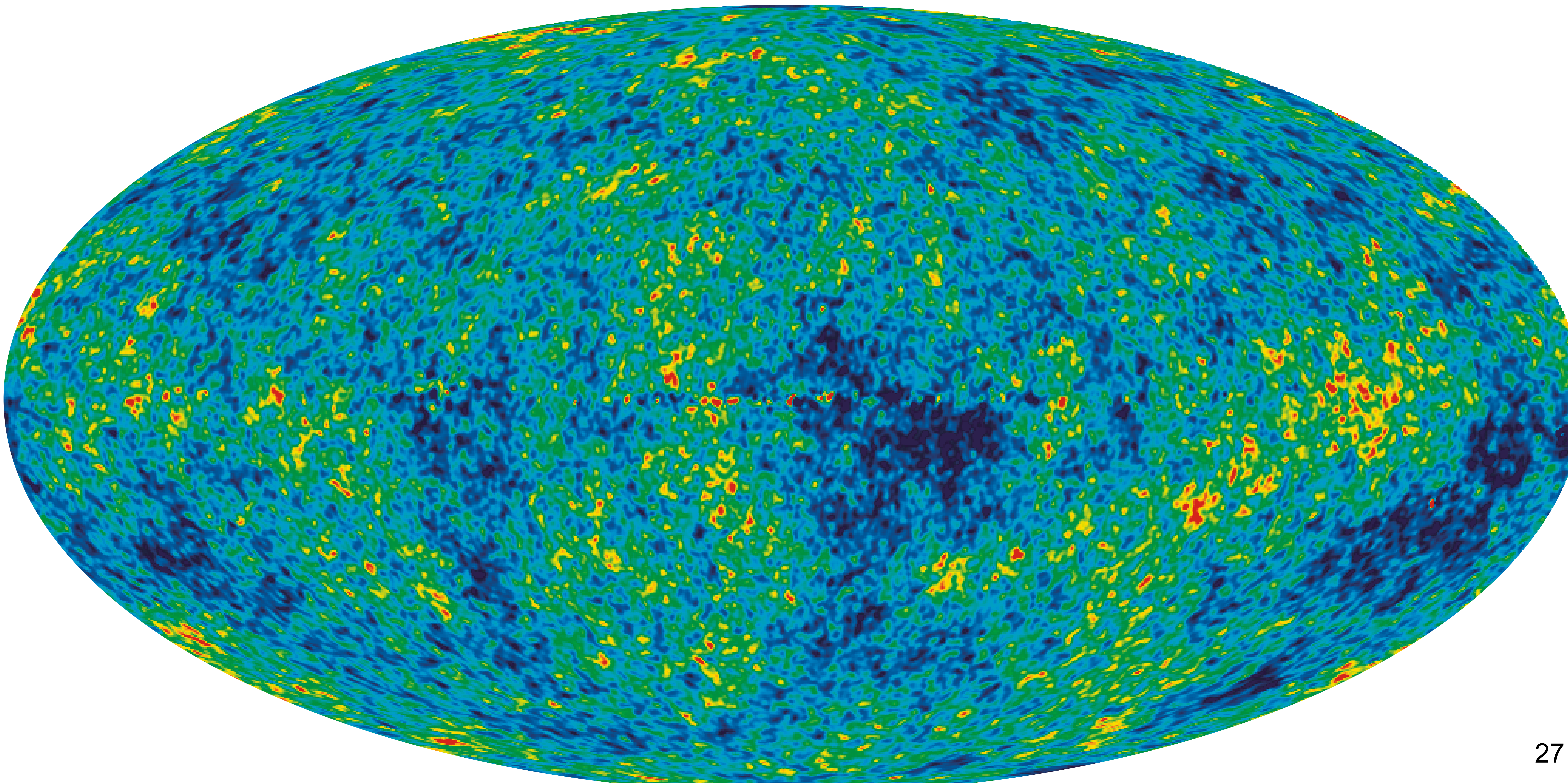


photons are
frequently scattered
decoupling at T~3000 K
Log$_{10}$[(Scattering Rate)/H]
3
2
1
0
−1
2500
3000
3500
4000
4500
5000
Temperature [Kelvin]

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



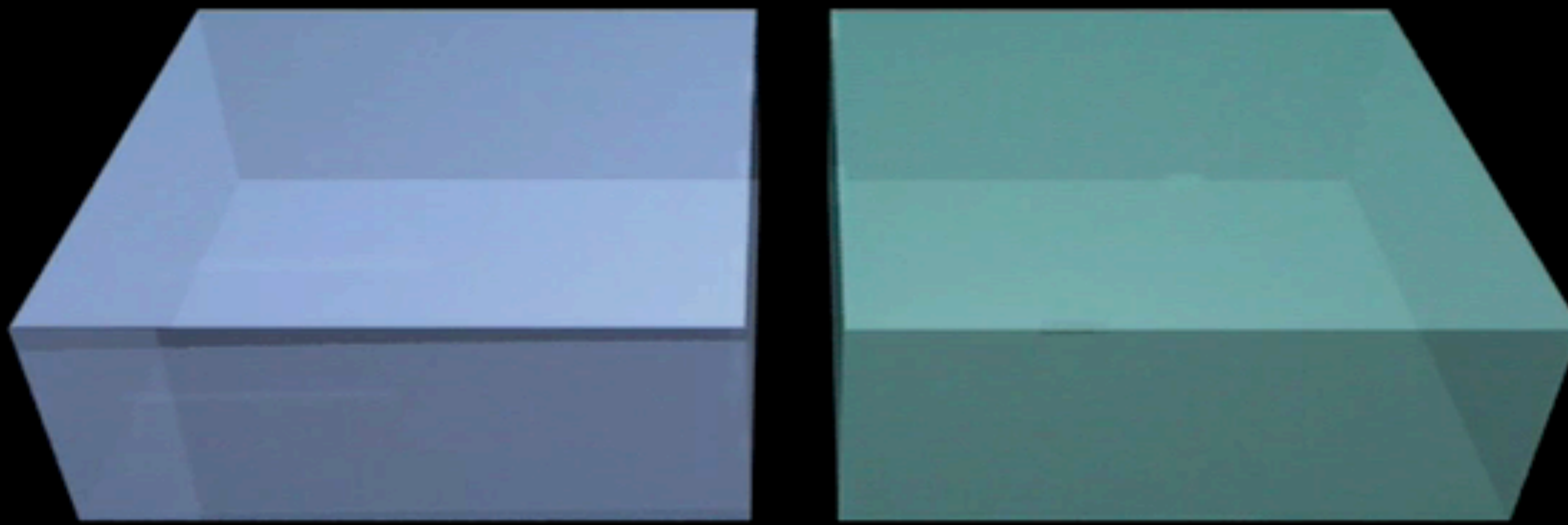
How were these ripples created?



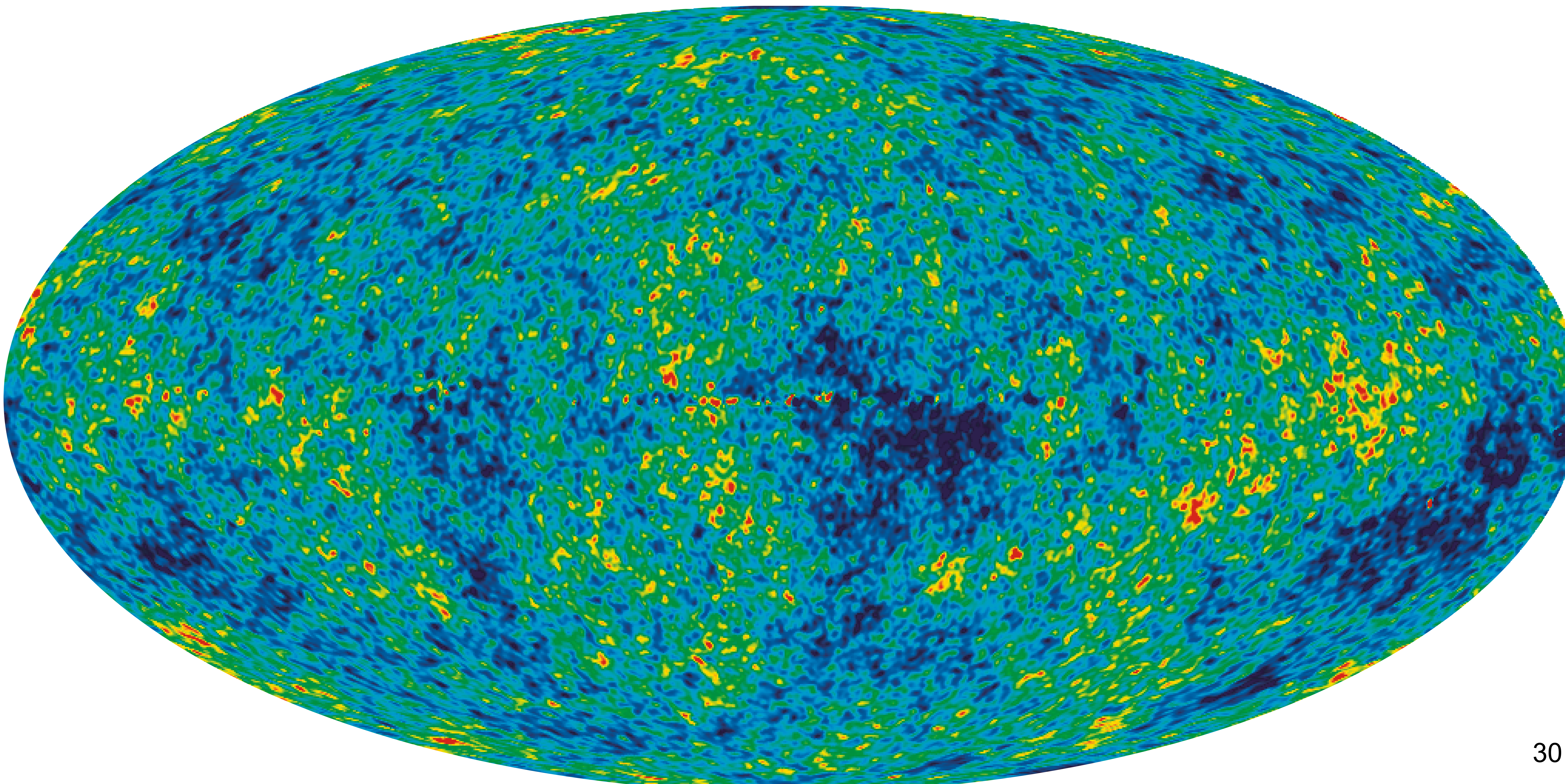
Have you dropped potatoes in a soup?

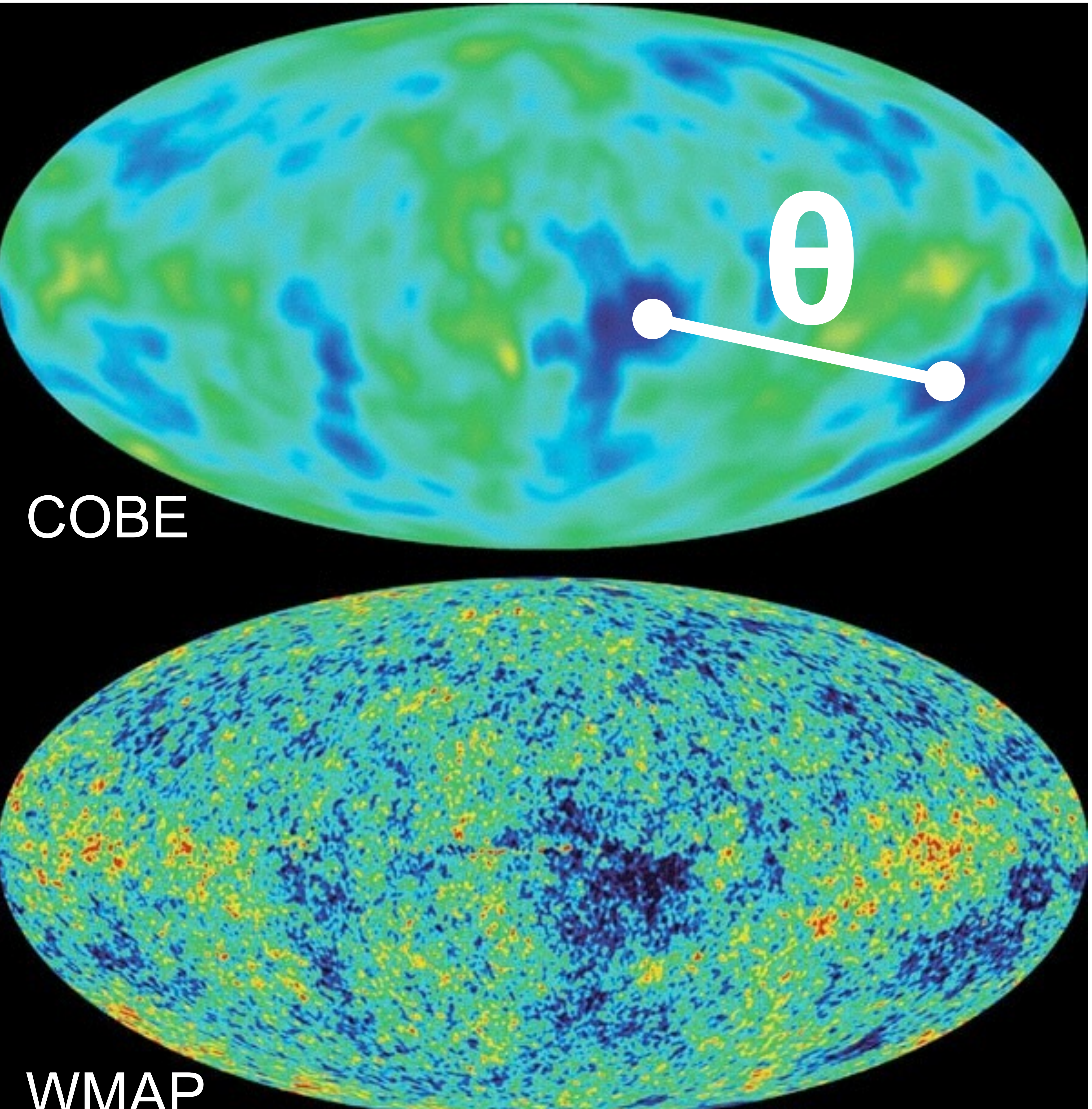
- What would happen if you “perturb” the soup?

The Cosmic Sound Wave



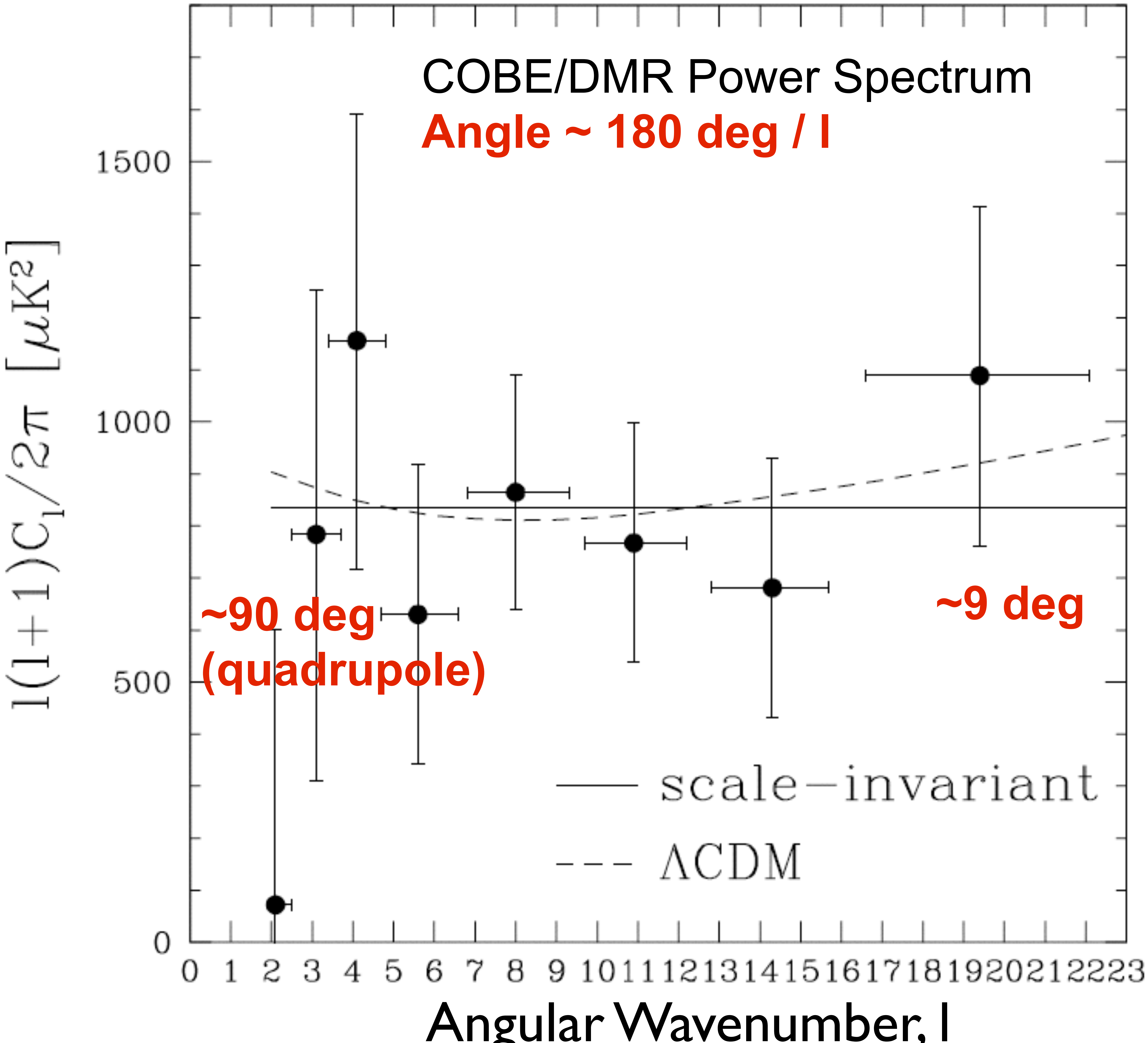
Can You See the Sound Wave?

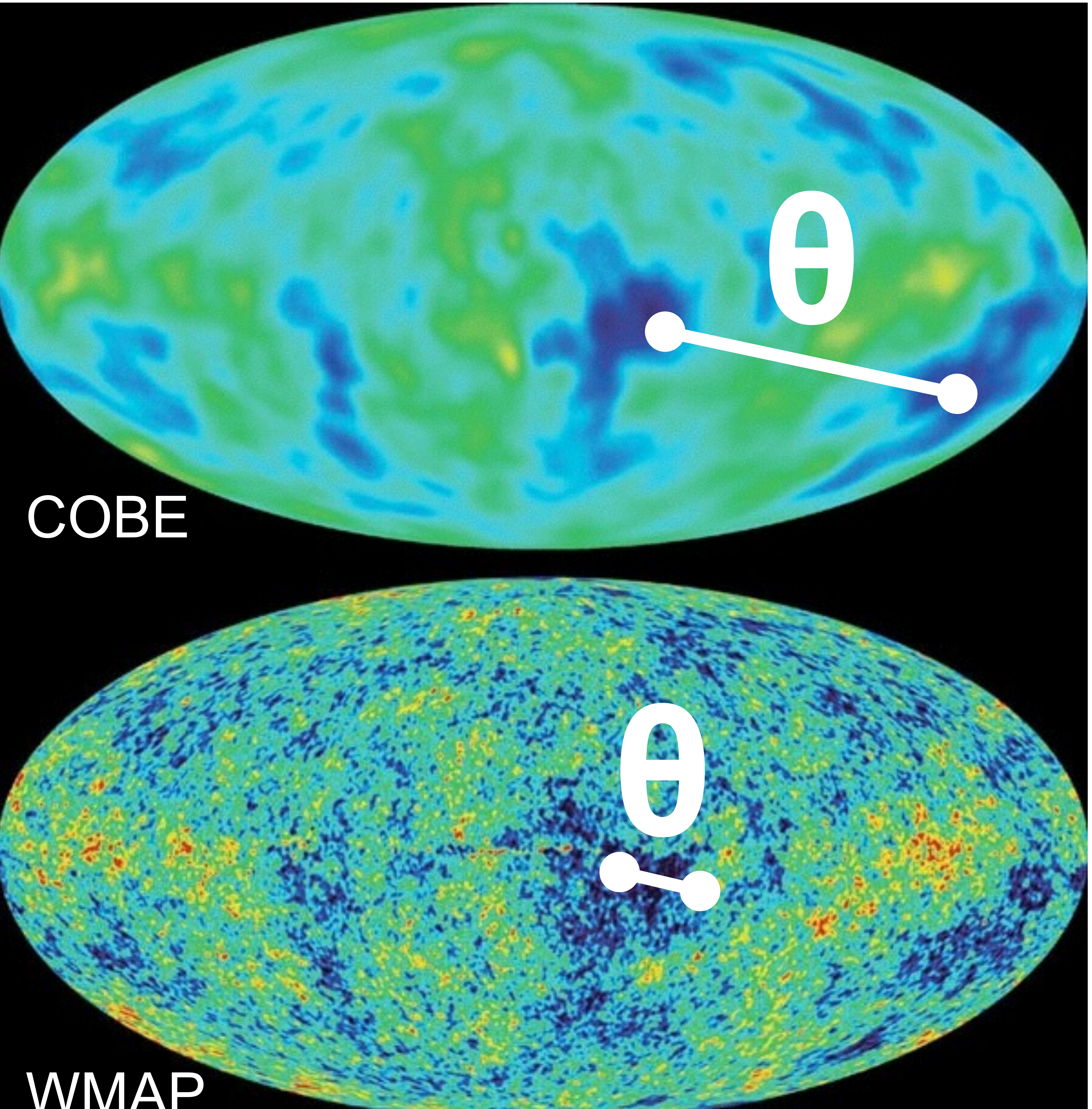




Analysis: 2-point Correlation

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

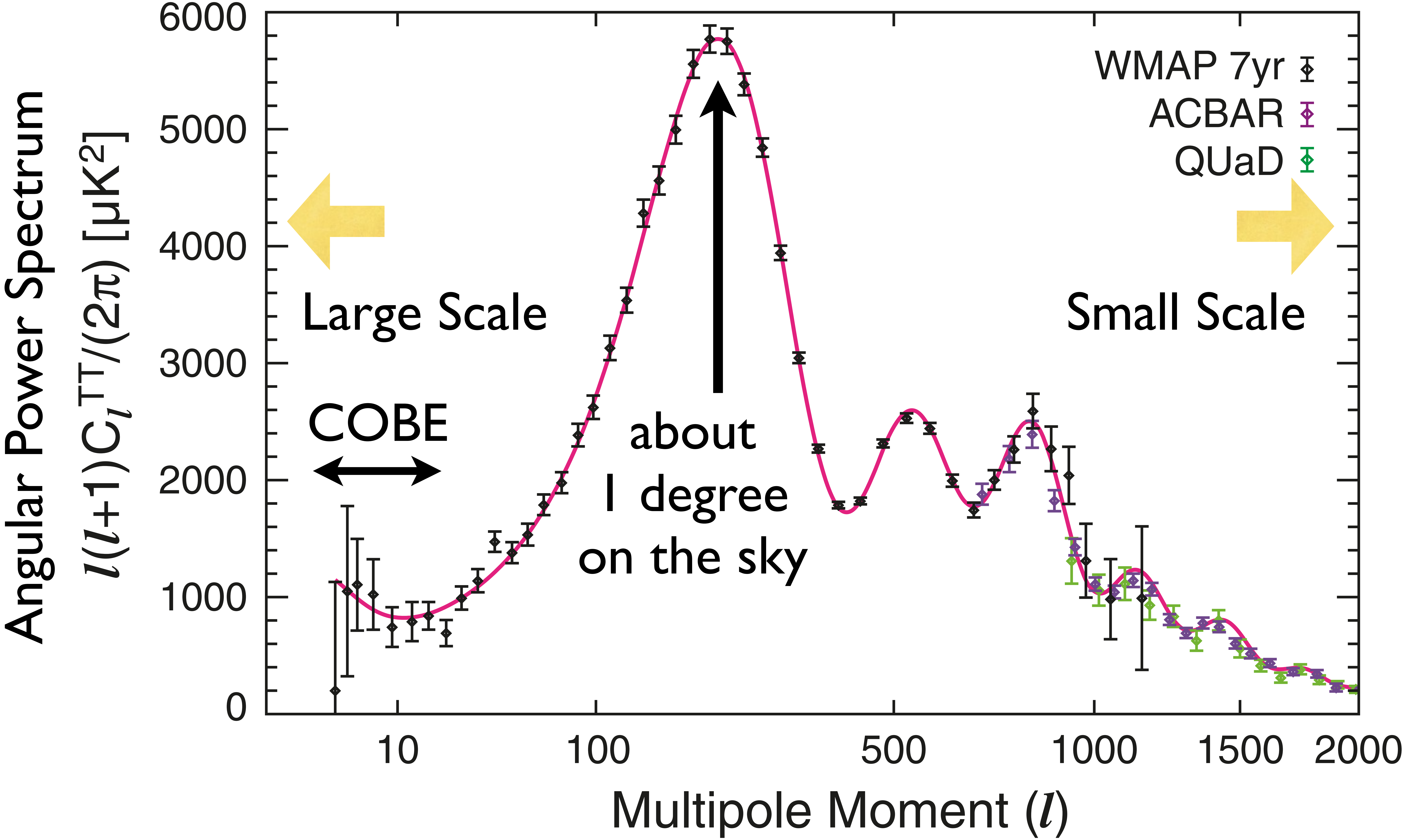

COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
l(l+1)C_l/2π [μK²]
Angular Wavenumber, l
0
500
1000
1500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23



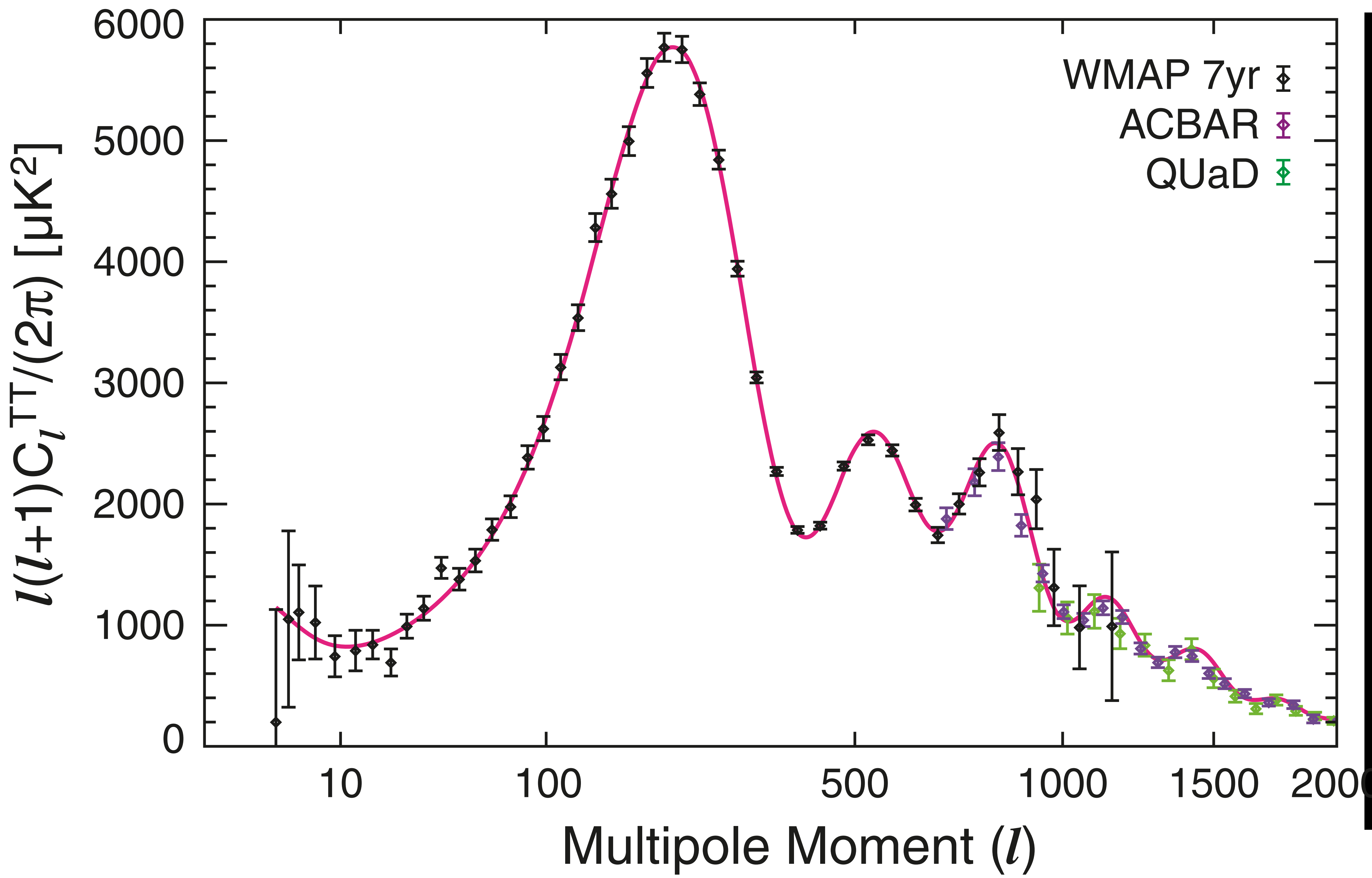
COBE To WMAP

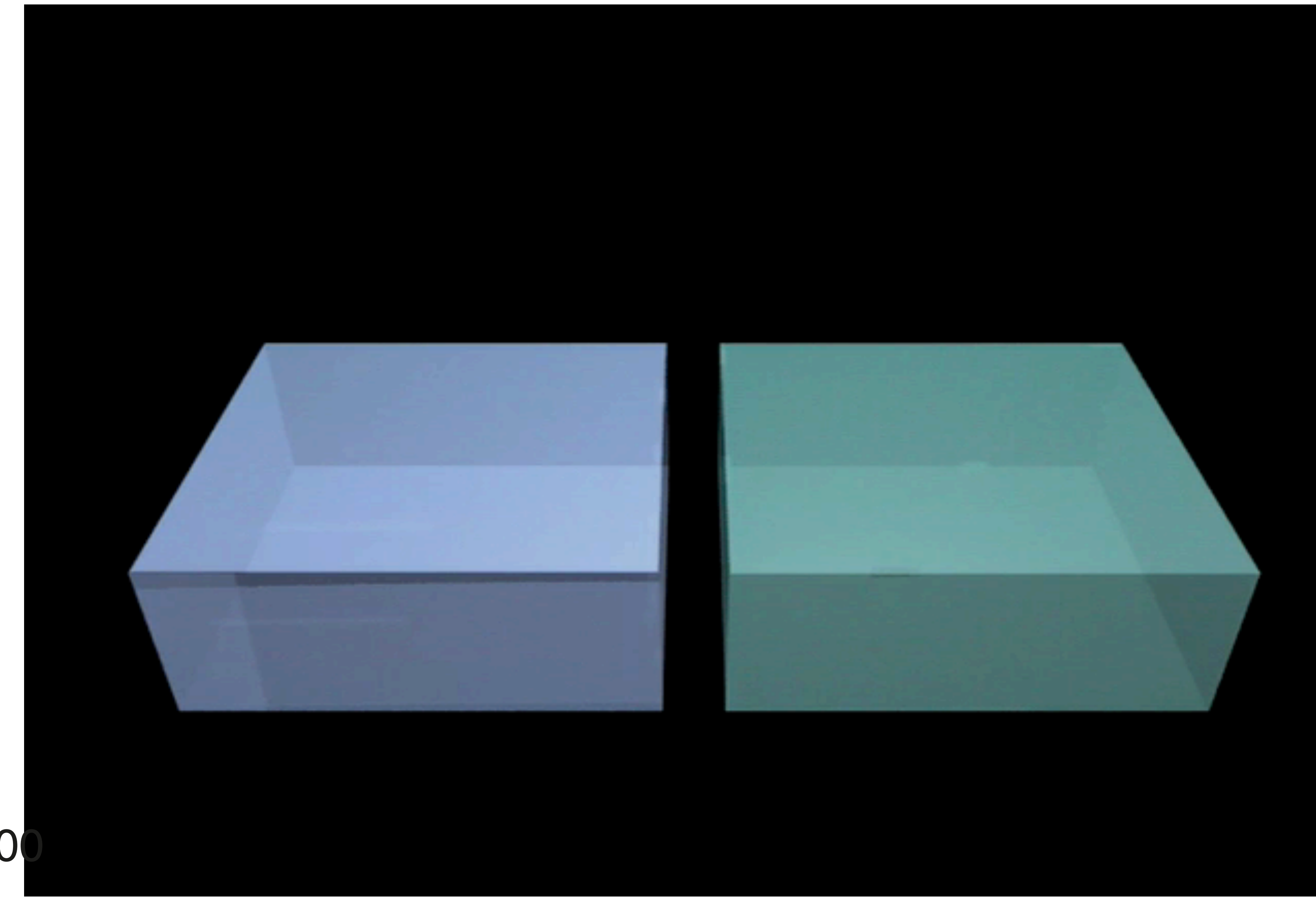
- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP Power Spectrum



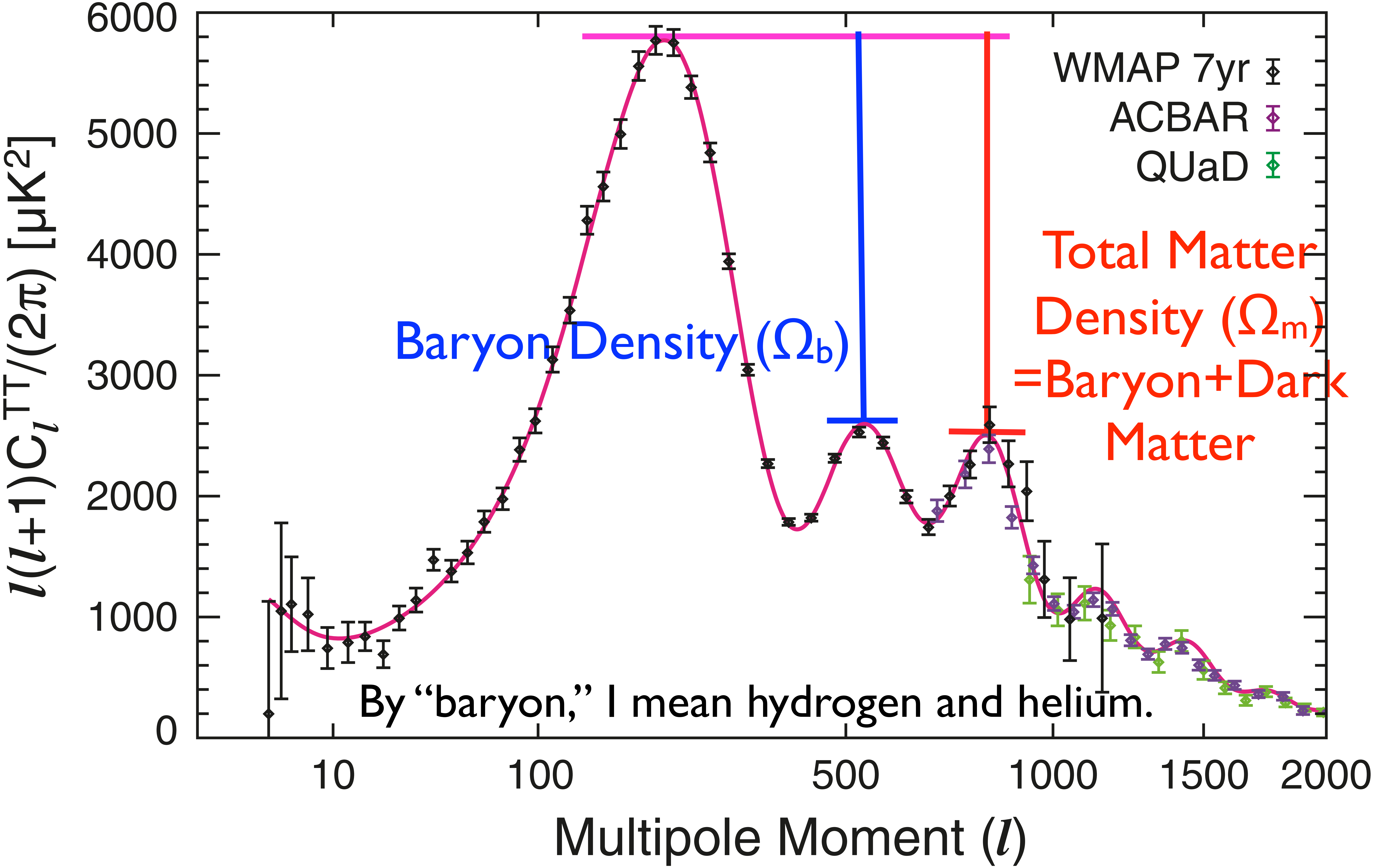
The Cosmic Sound Wave





- *"The Universe as a 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:

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

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

Initial Conditions

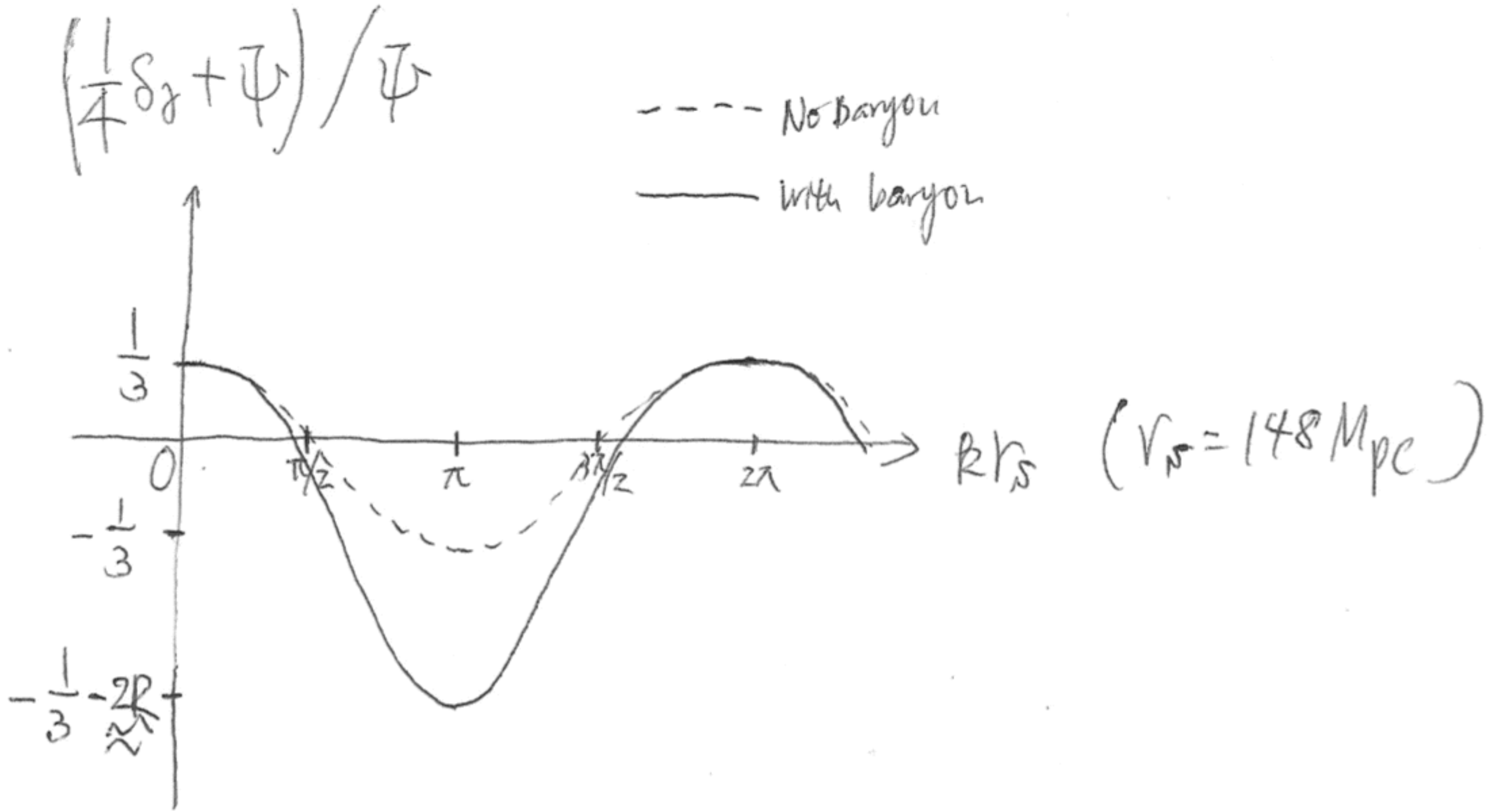
- On "super sound-horizon scales" [$kr_s << 1$], the photon and matter density perturbations are given by *the adiabatic condition*:

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

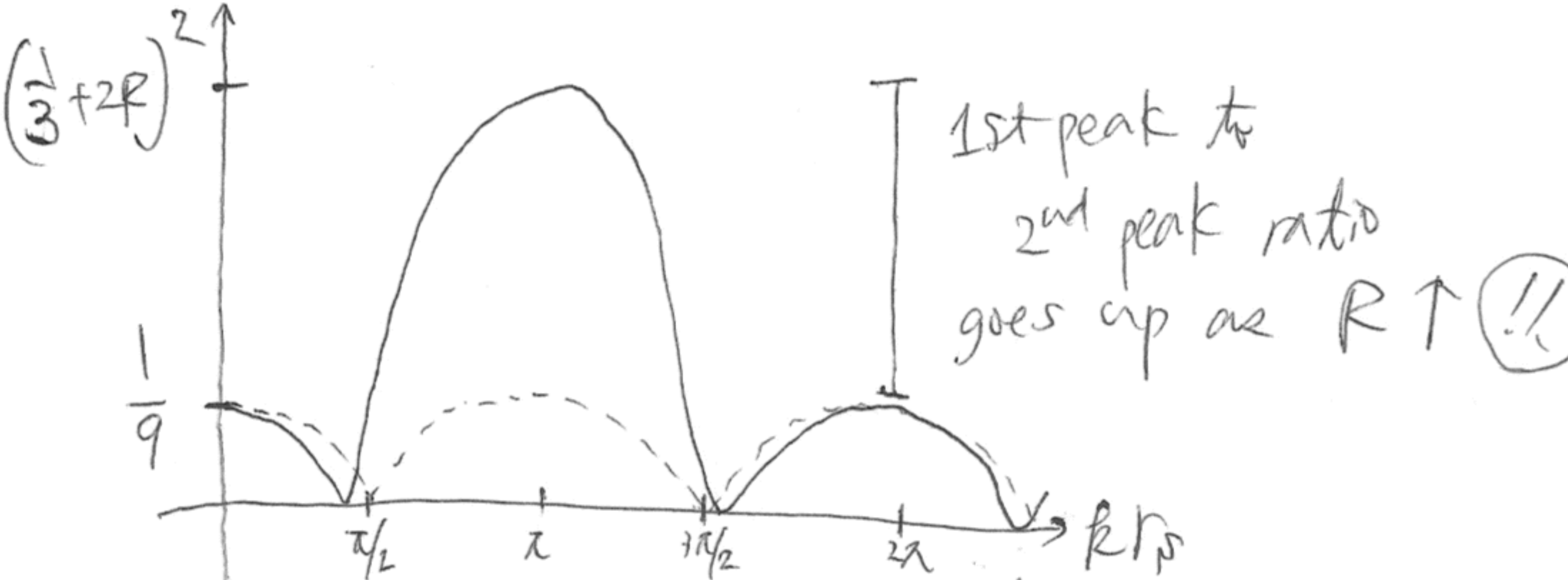
- Using this, we obtain:

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

How baryons affect the photon density perturbation



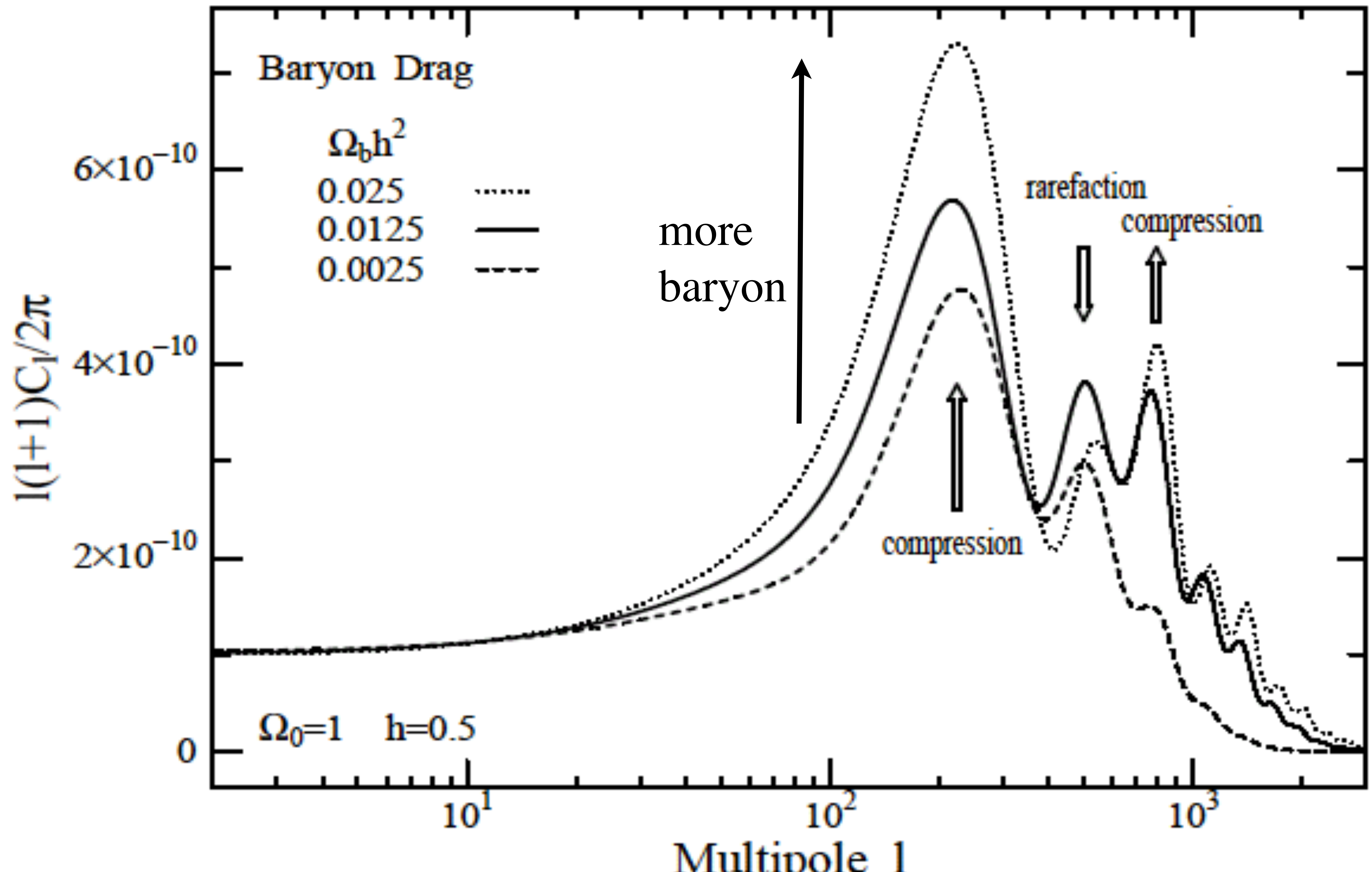
How baryons affect the [photon density perturbation]^2



$$l_{1st} = k_{1st}\, d_A = \pi \frac{d_A}{r_s} \approx 300$$

$$l_{2nd} = k_{2nd}\, d_A = 2\pi \frac{d_A}{r_s} \approx 600$$

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:

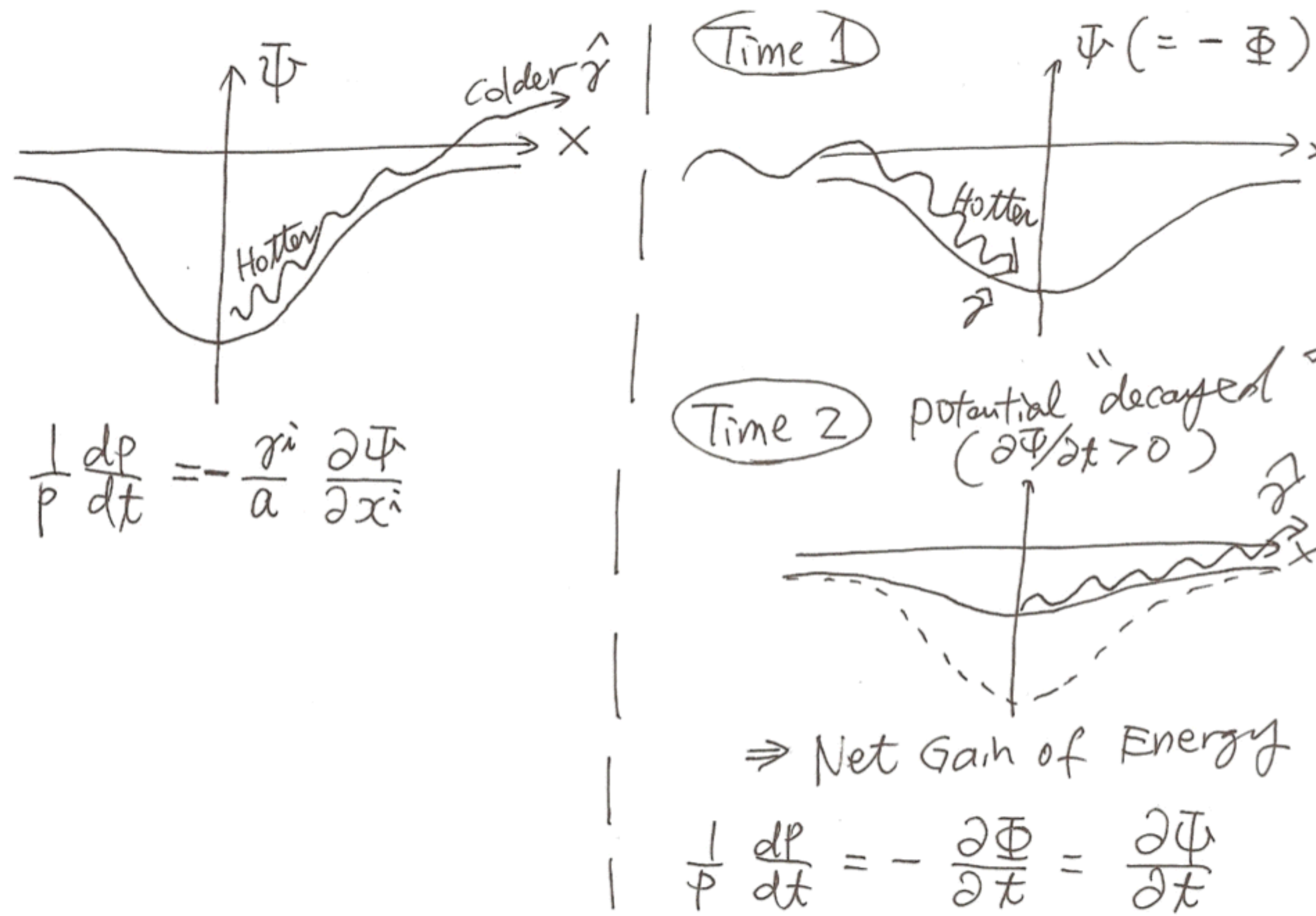
$$\frac{dp^\mu}{d\lambda} + \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta = 0$$

- gives a change of the photon energy as:

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

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

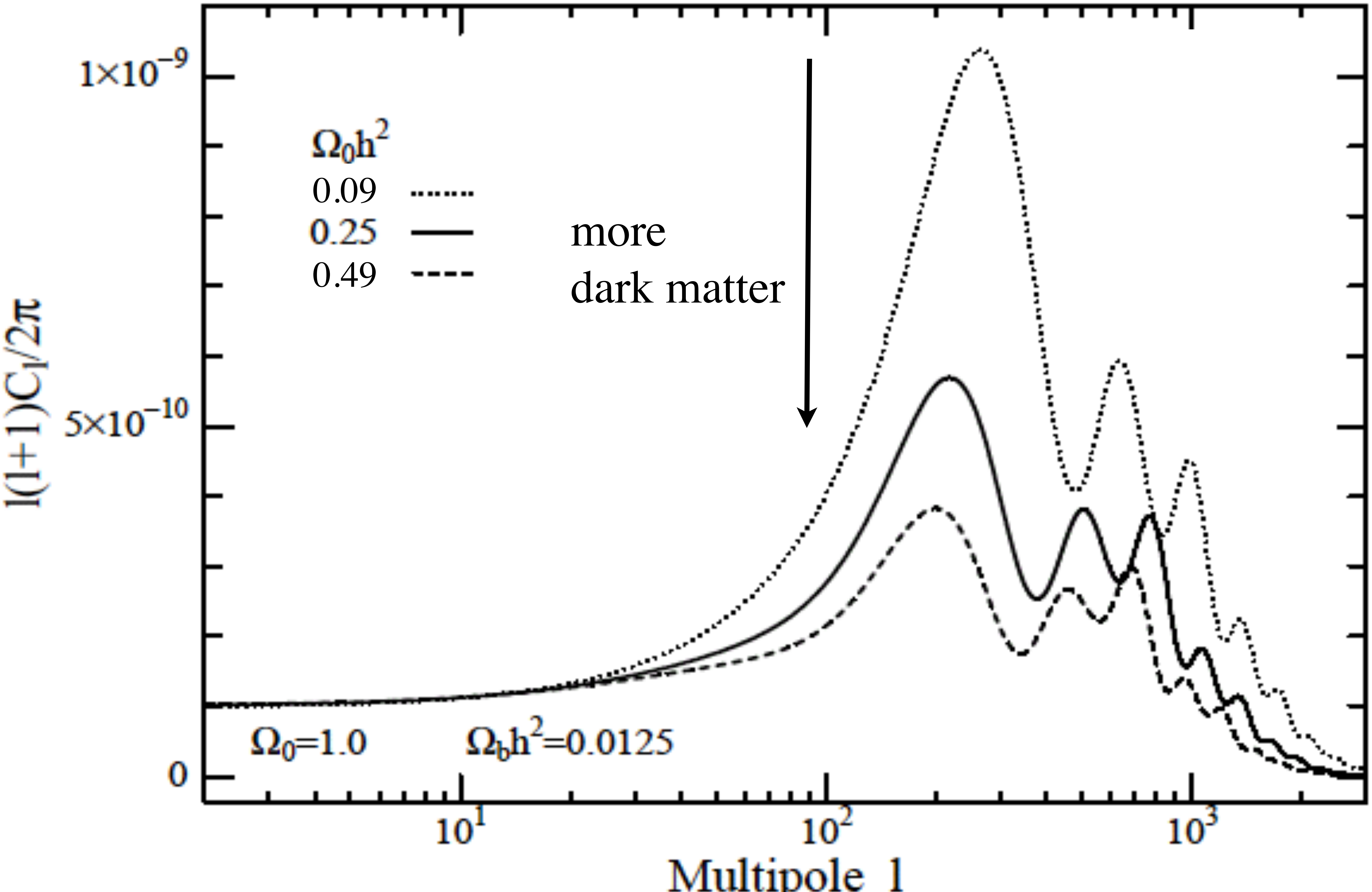
"$\mathcal{O}$" and "$\mathcal{E}$" denote the observed and emitted epochs



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]

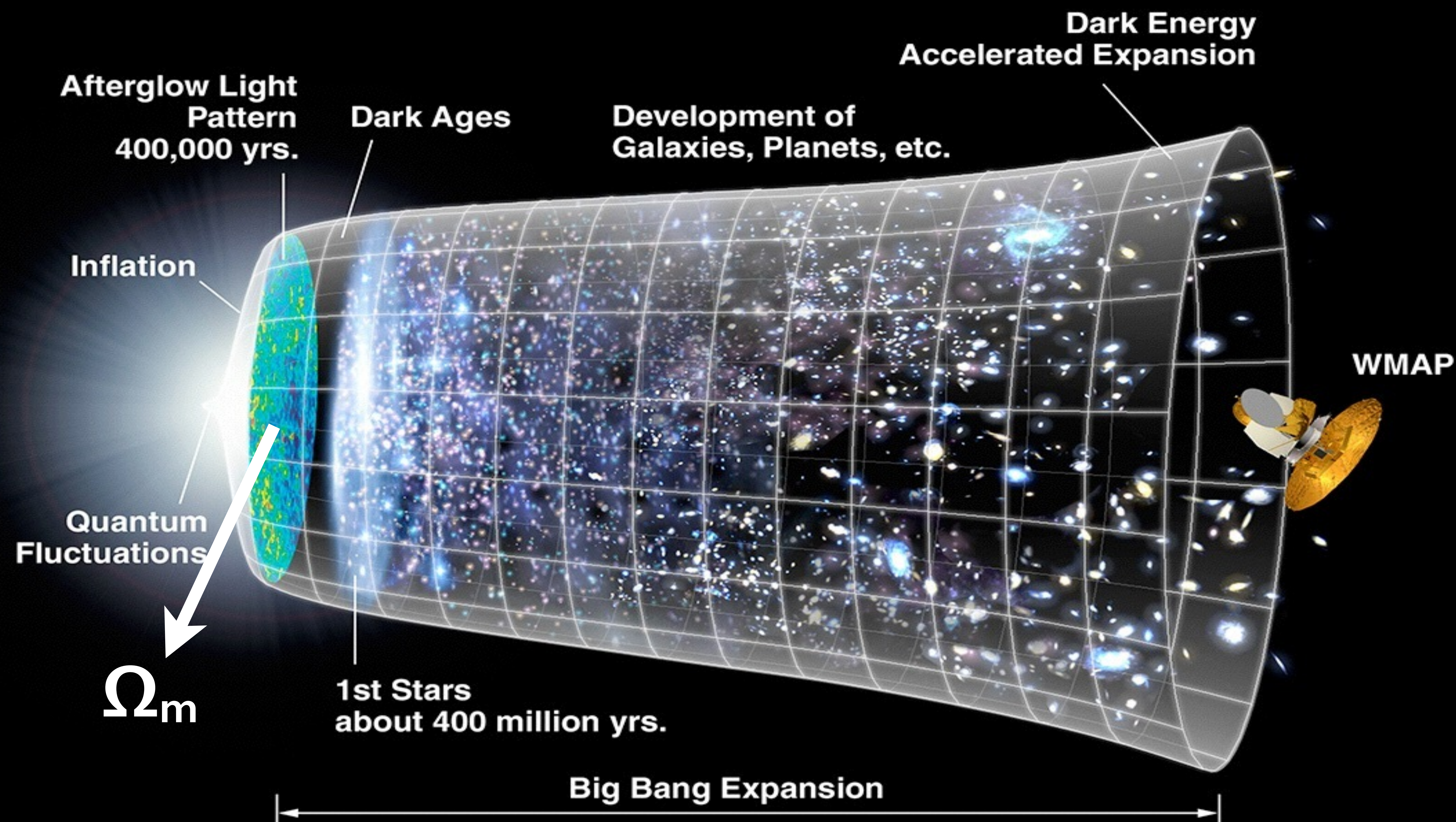
Determining Dark Matter Density From C_l



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



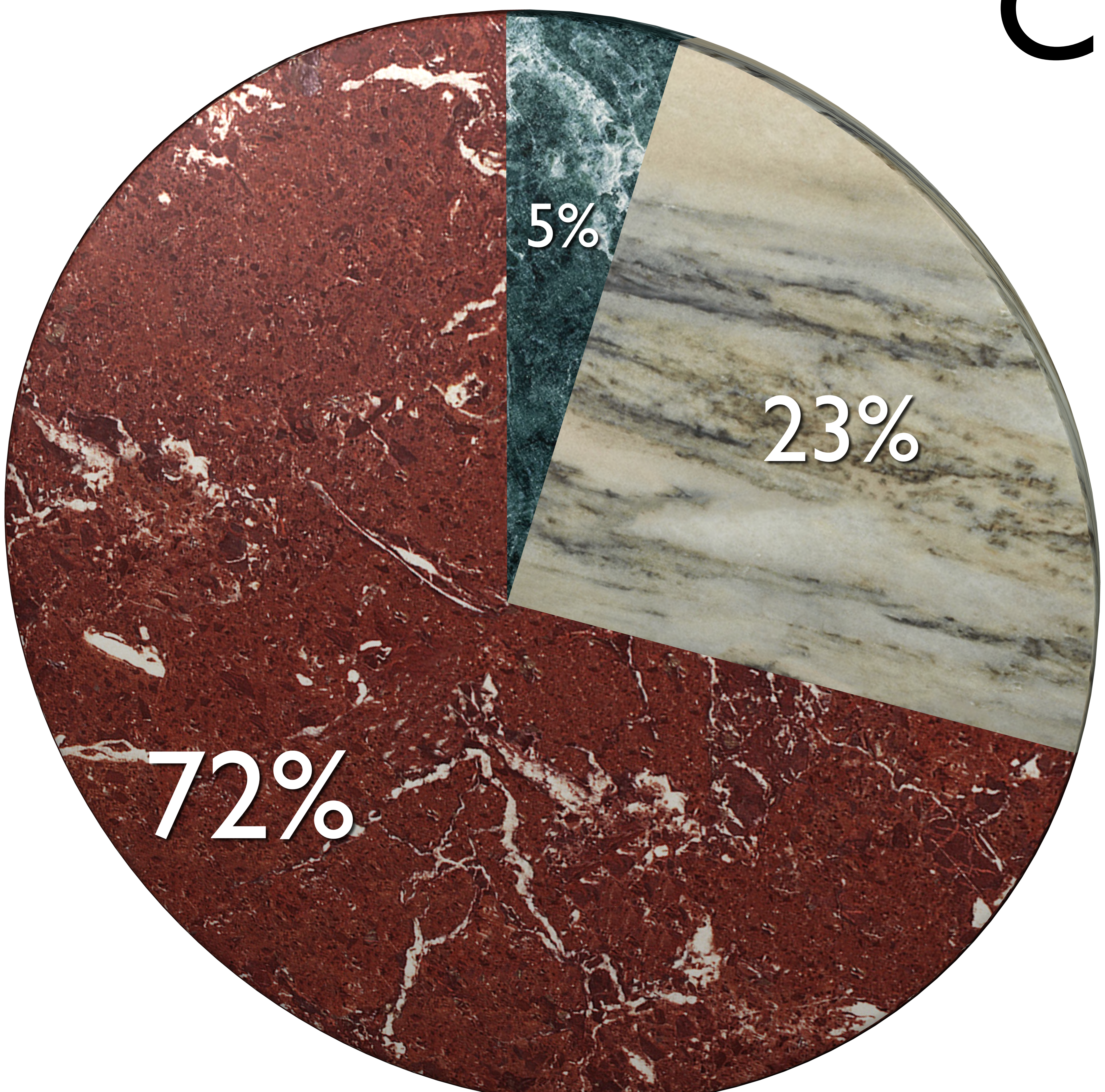
- Angular Diameter Distance to z=1090

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

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?**

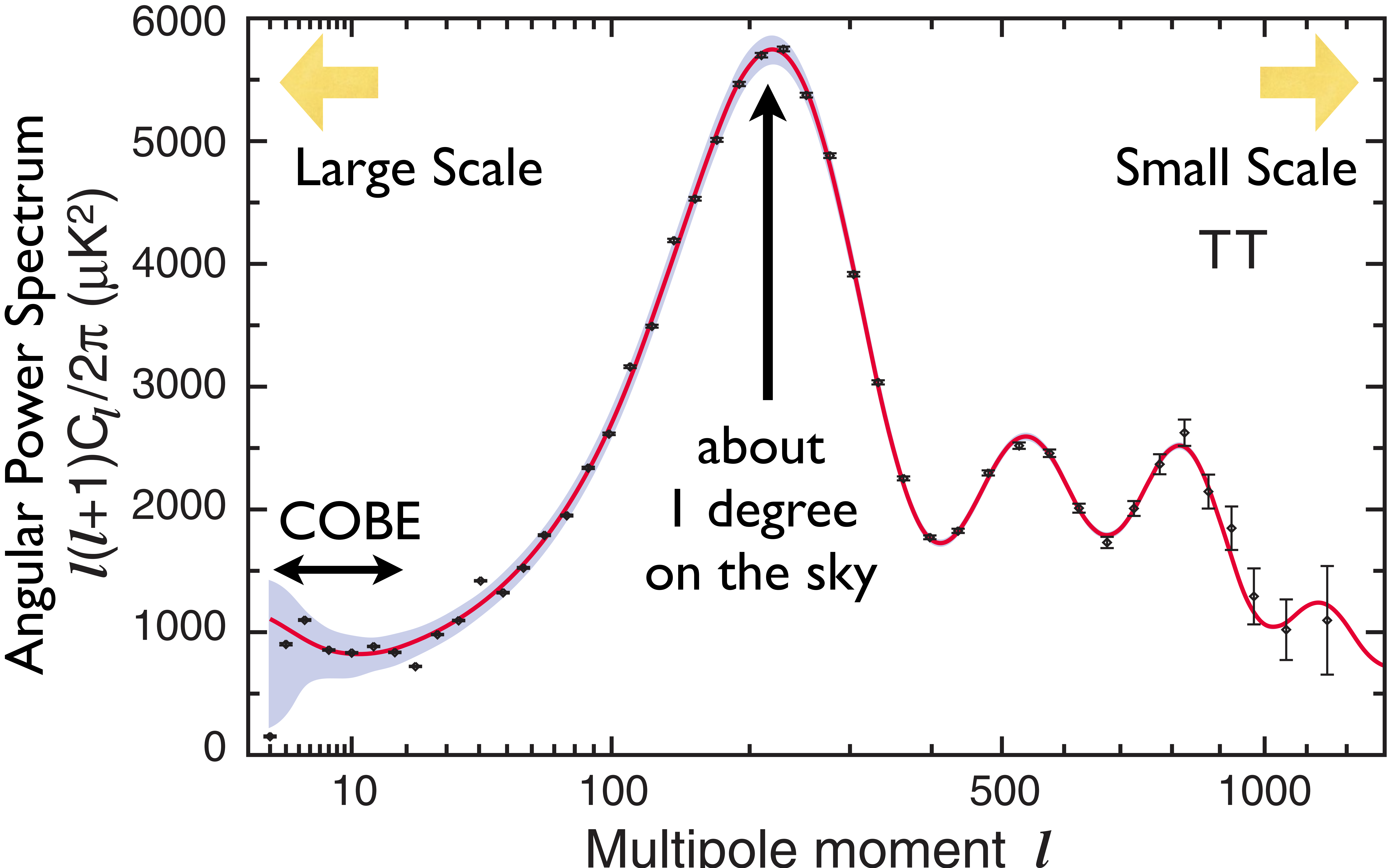
Theory of the Very Early Universe

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

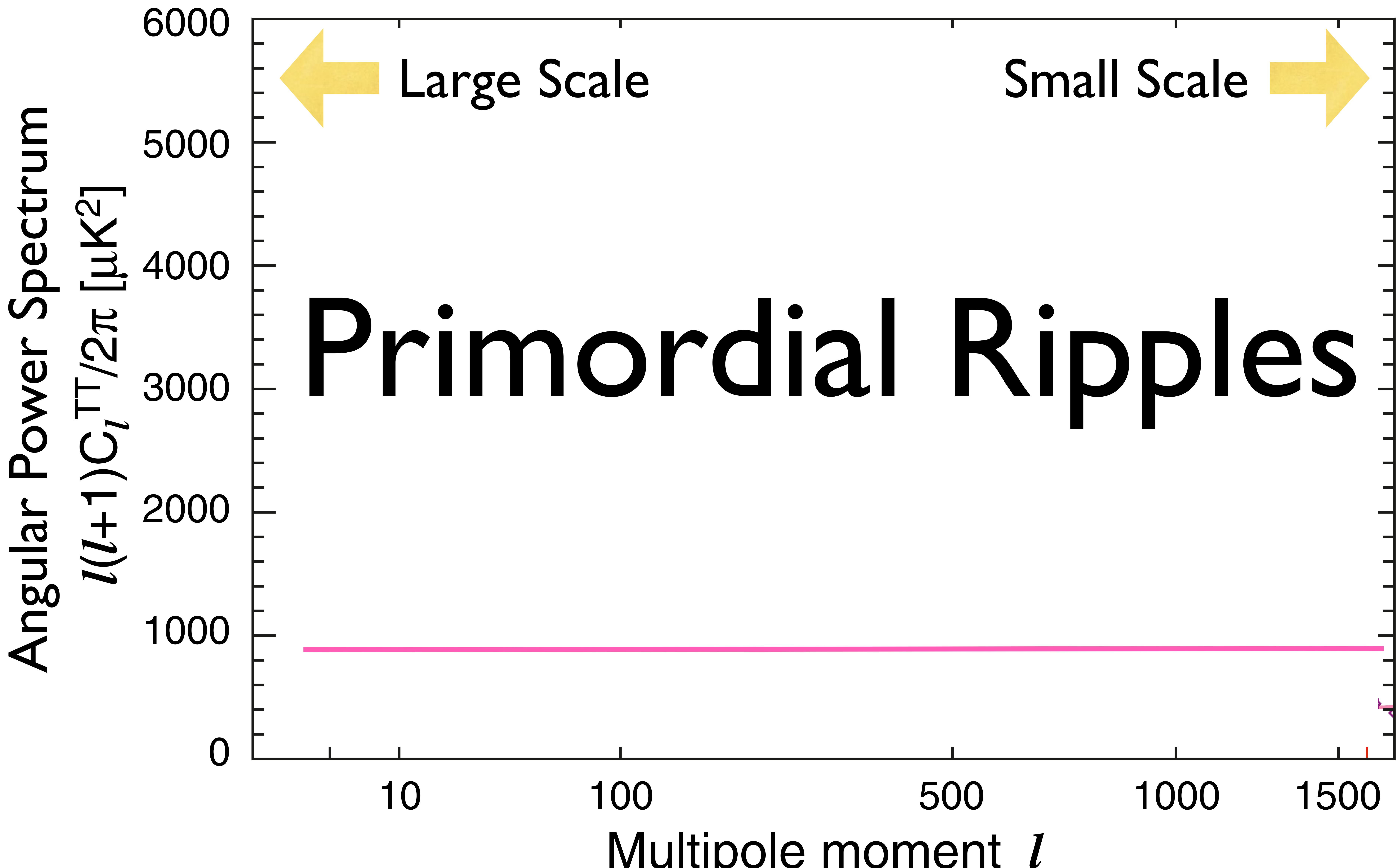
  (Starobinsky 1980; Sato 1981; Guth 1981; Linde 1982; Albrecht & Steinhardt 1982; Starobinsky 1980)

  - 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.

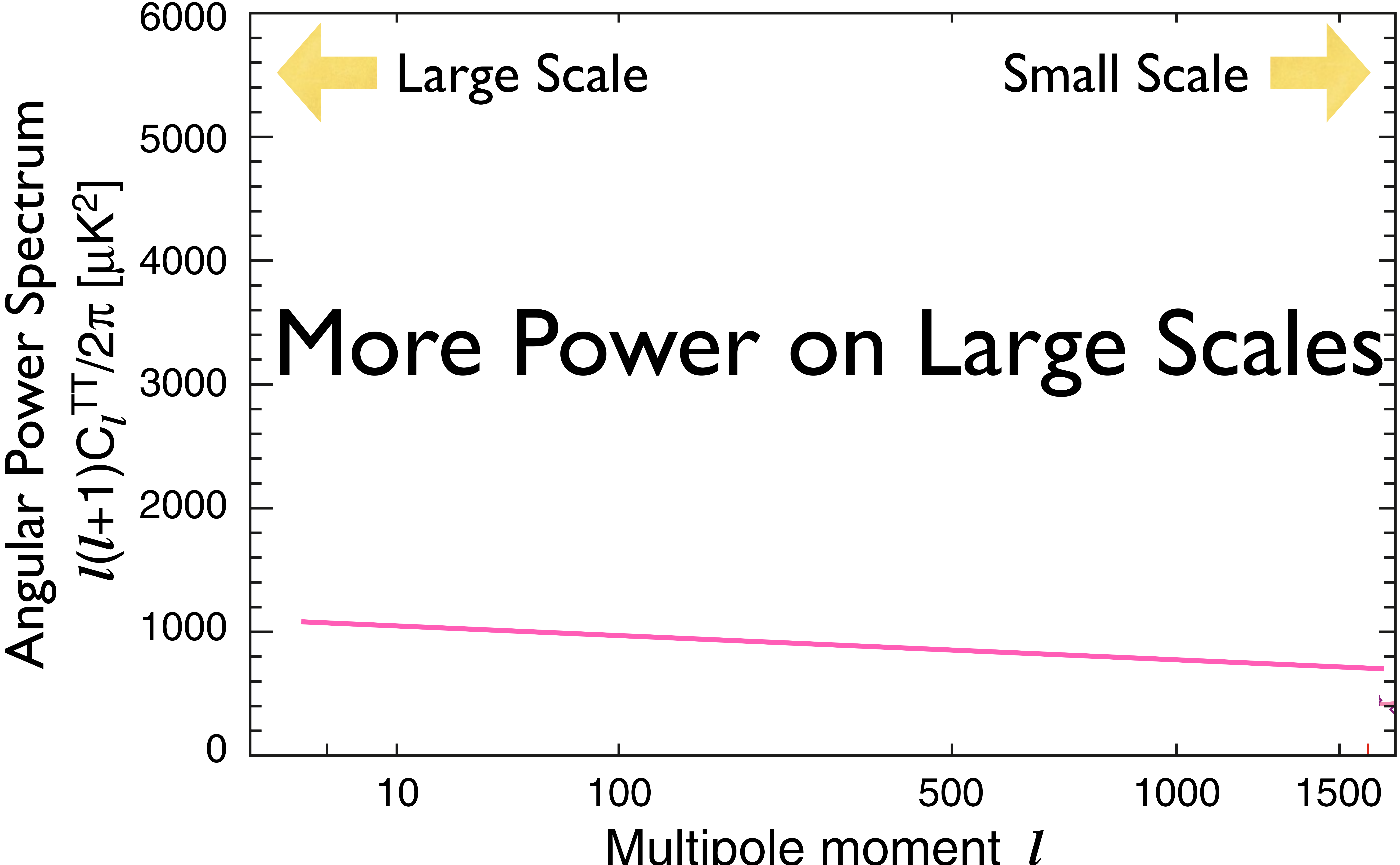
WMAP 9-year Power Spectrum



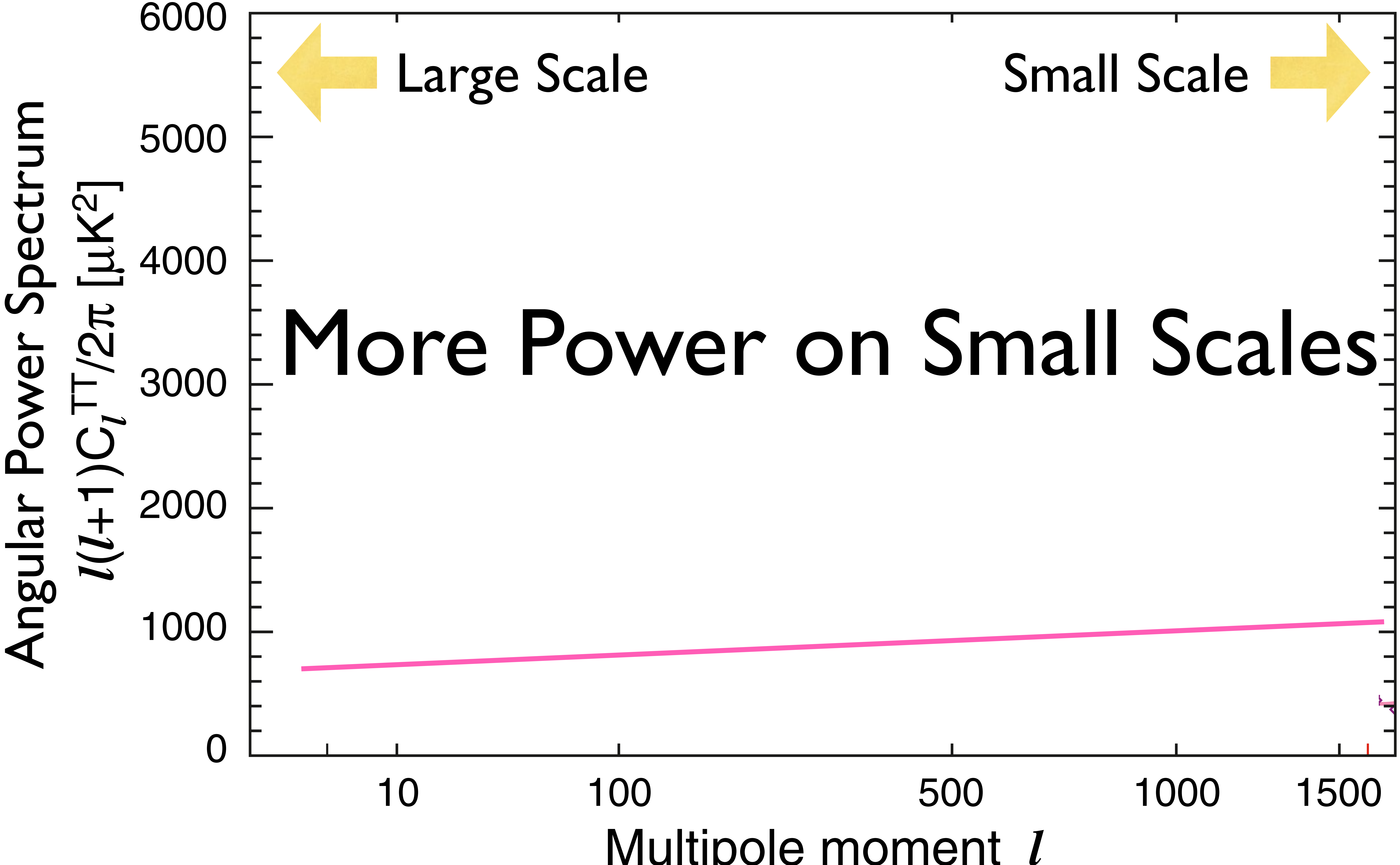
Getting rid of the Sound Waves



The Early Universe Could Have Done This Instead

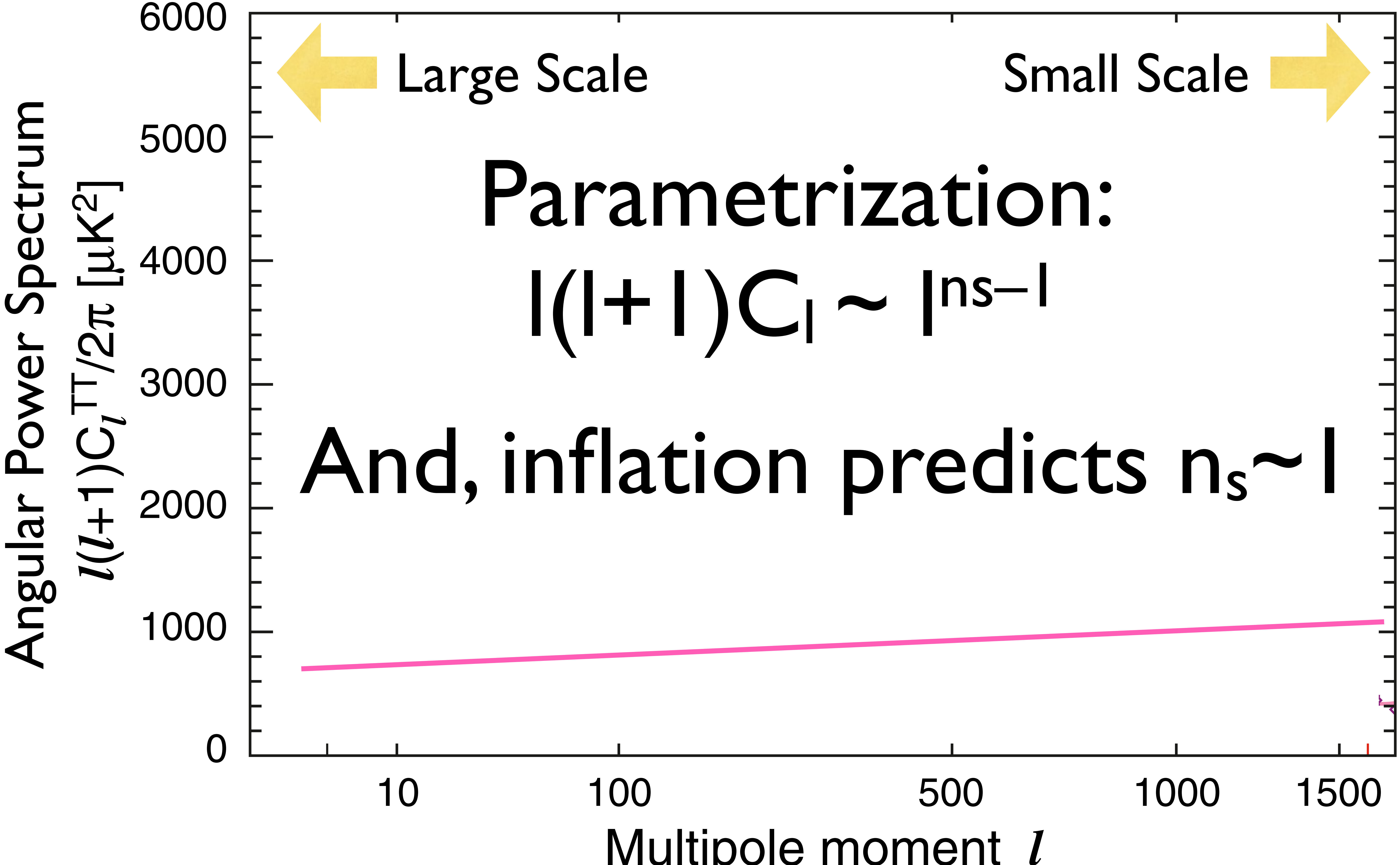


...or, This.



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:

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

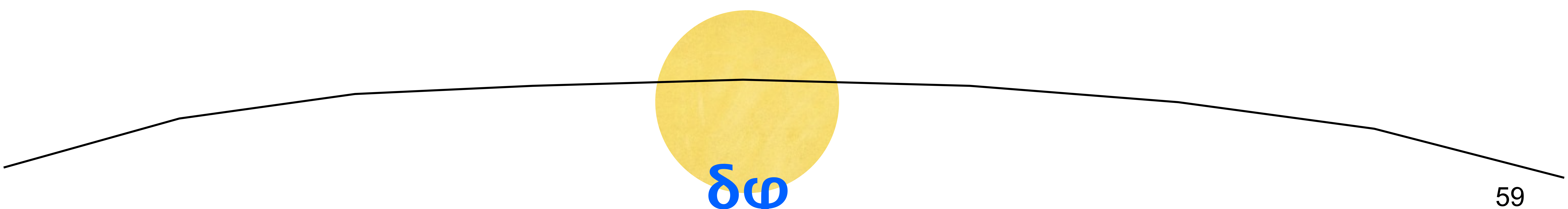
And, inflation predicts $n_s \sim 1$

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]

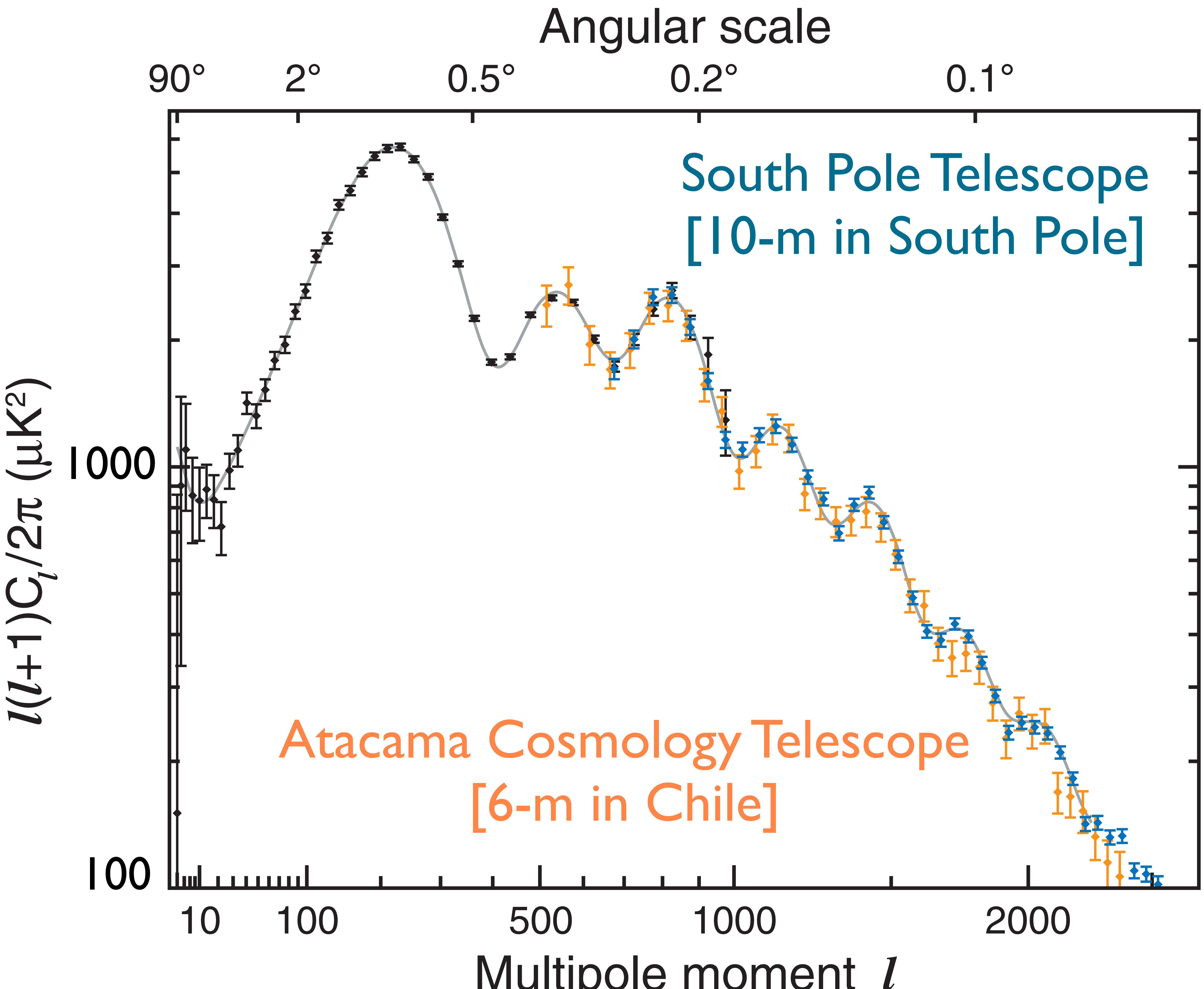
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-36} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

Inflation Offers a Magnifier for Microscopic World

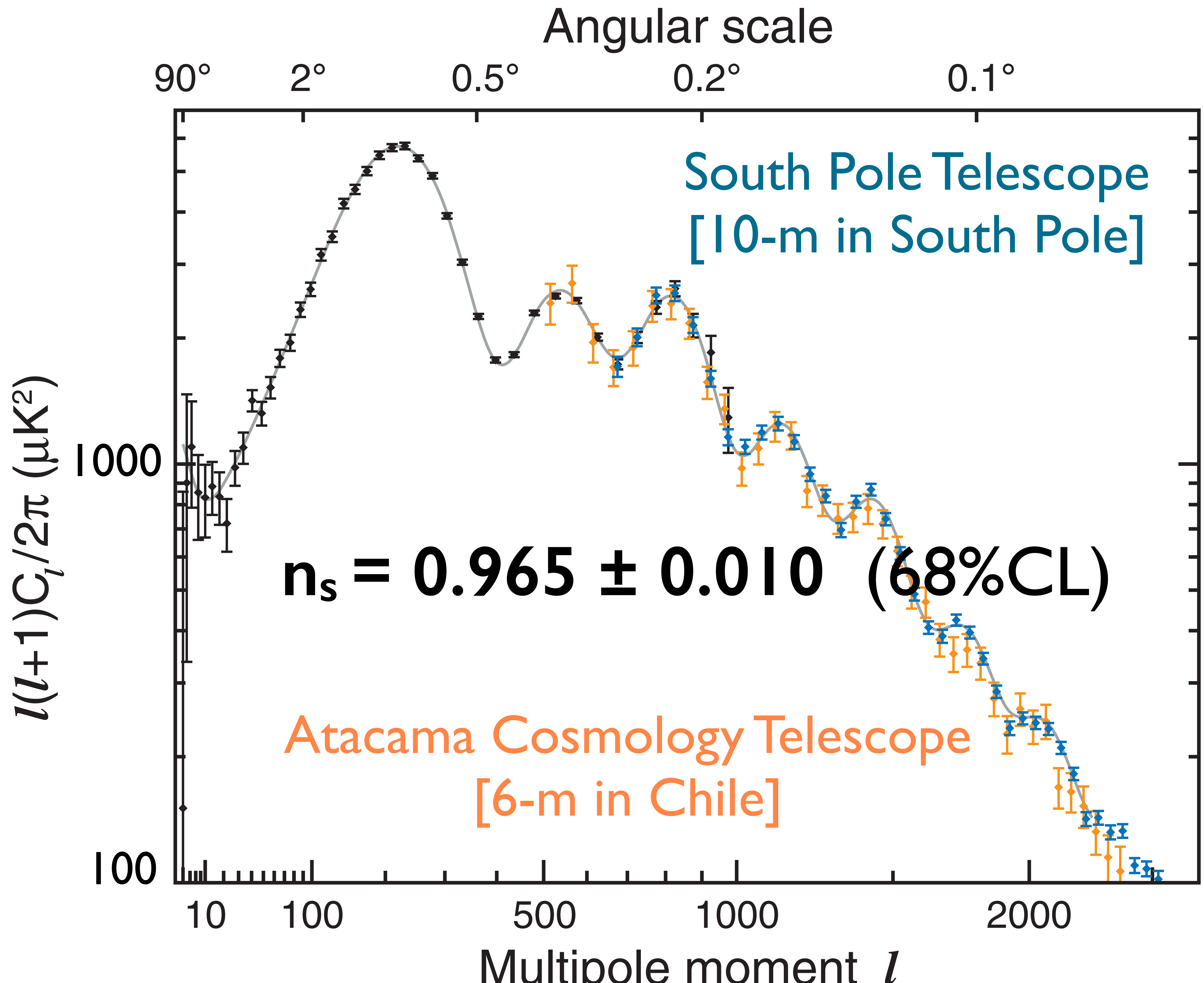
- Using the *power spectrum of primordial fluctuations* imprinted in CMB, we can observe the quantum phenomena at the ultra high-energy scales that would never be reached by the particle accelerator.

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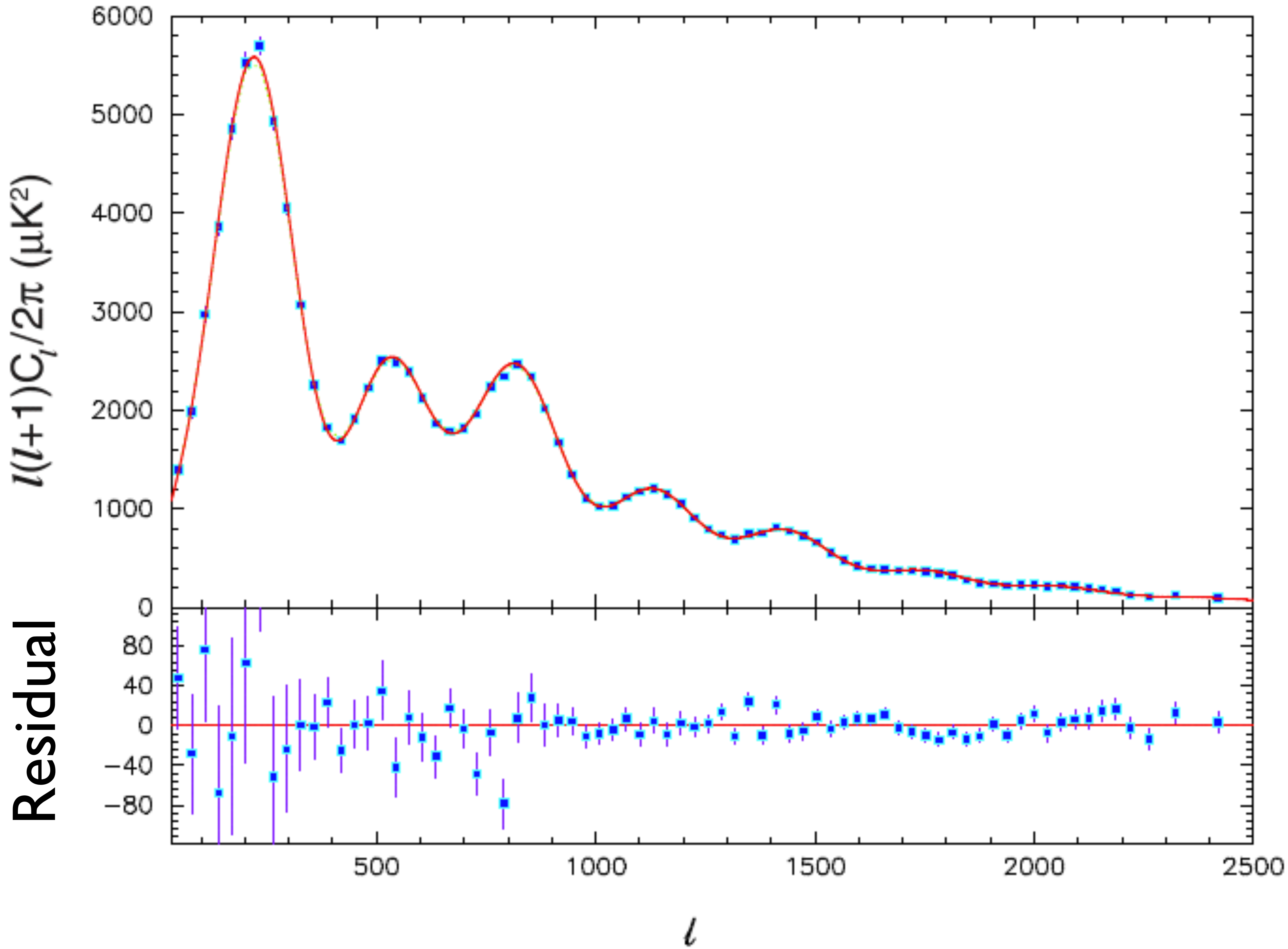
Multipole moment l

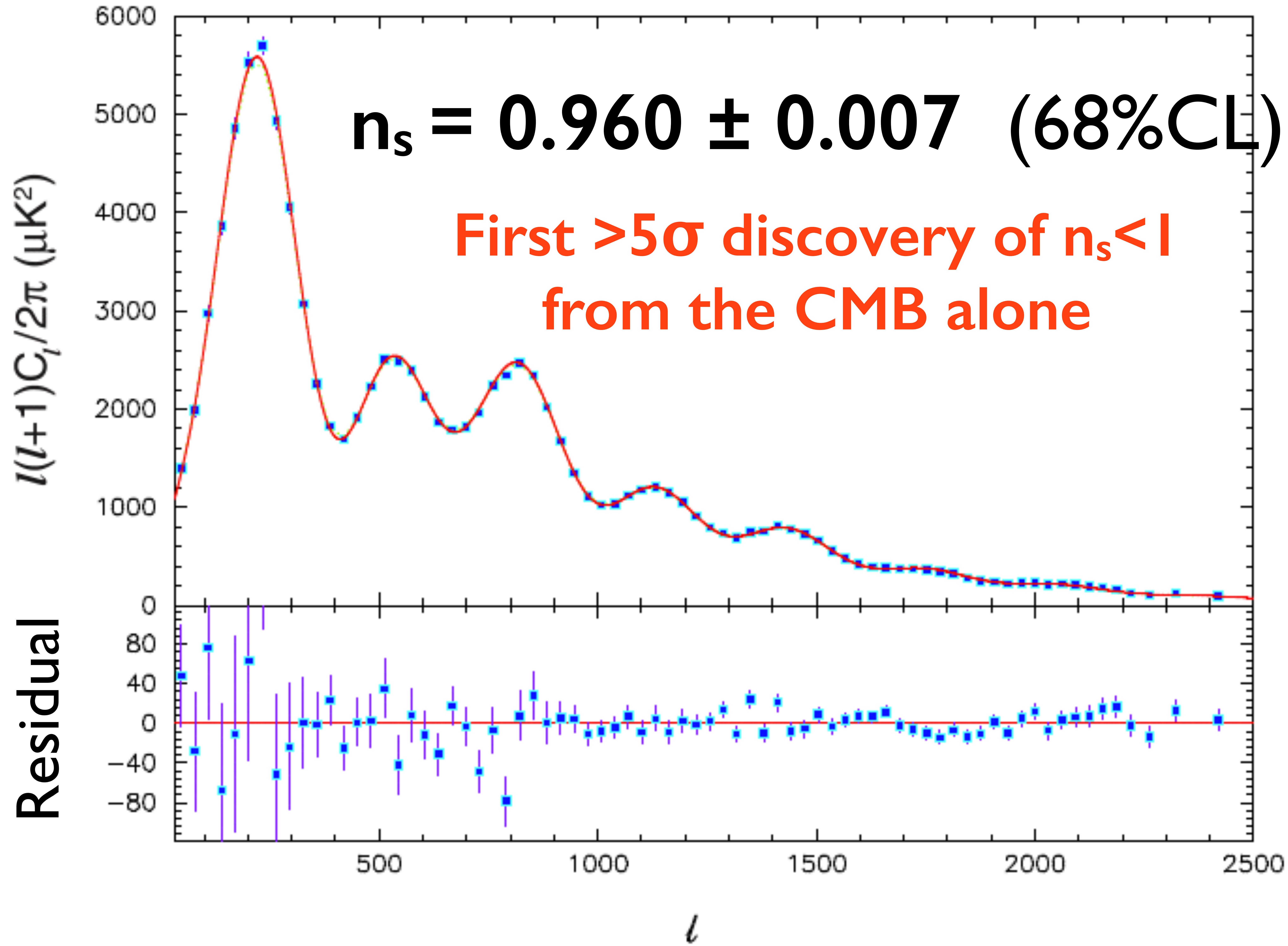
Planck (2013)

Planck Result!



Planck (2013)

Planck Result!



Starobinsky (1979)

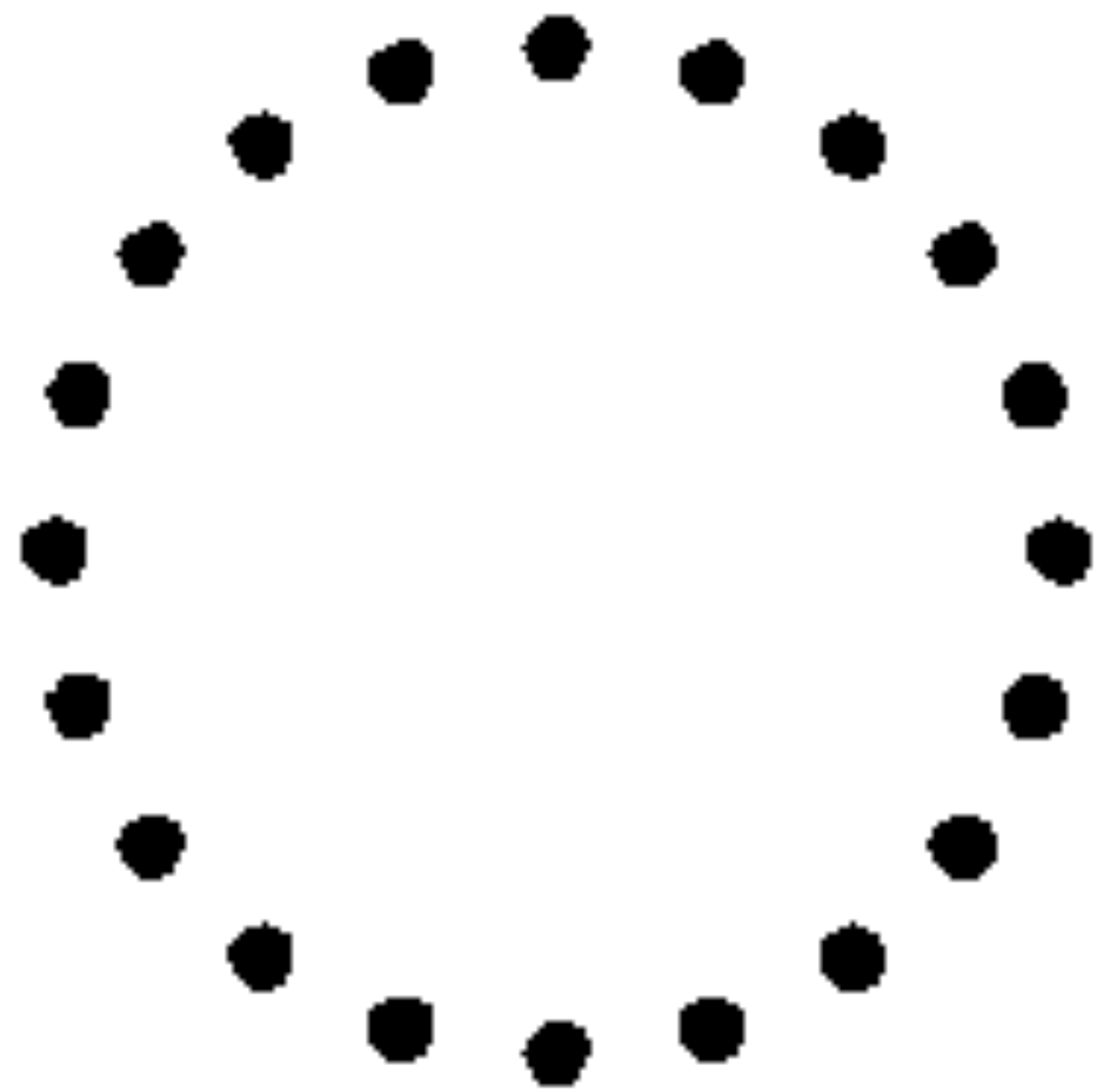
(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

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

[h = "strain"]

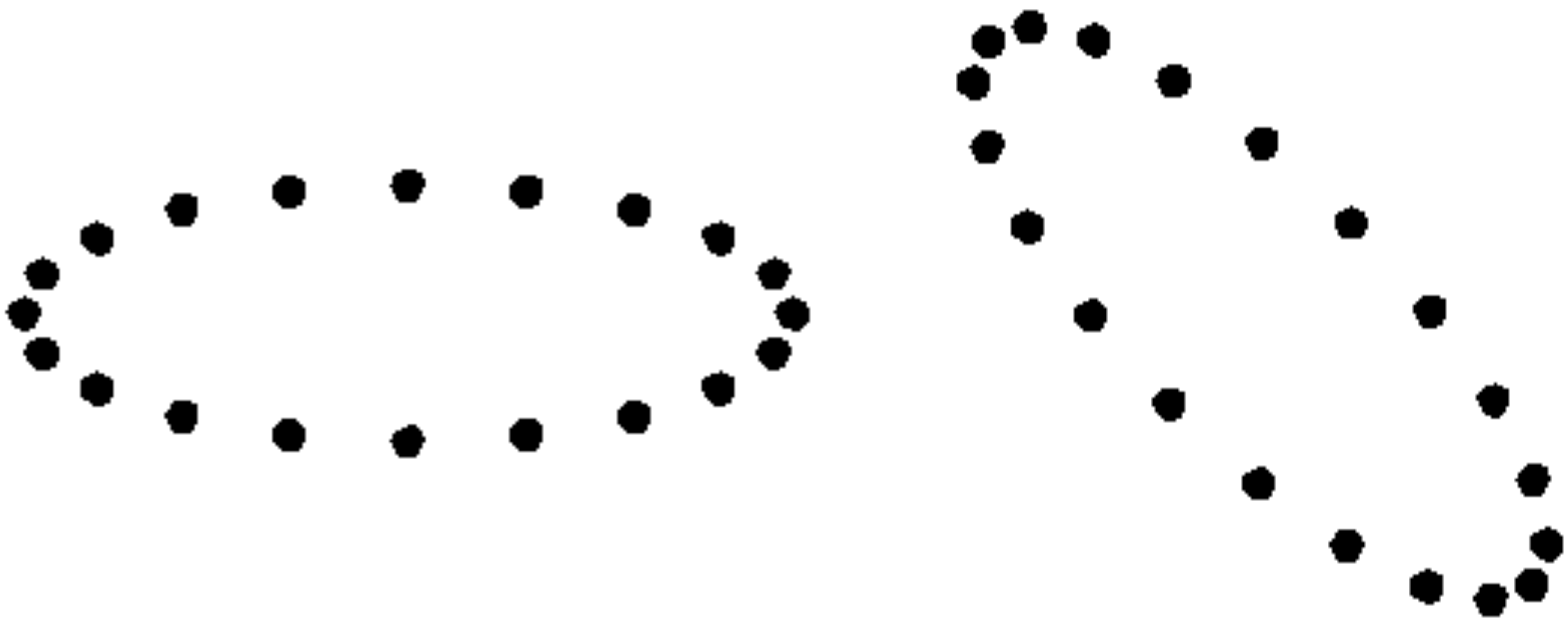
- Quantum fluctuations also generate ripples in space-time, i.e., gravitational waves, by the same mechanism.
- Primordial gravitational waves generate temperature anisotropy in CMB.

Gravitational waves are coming toward you!



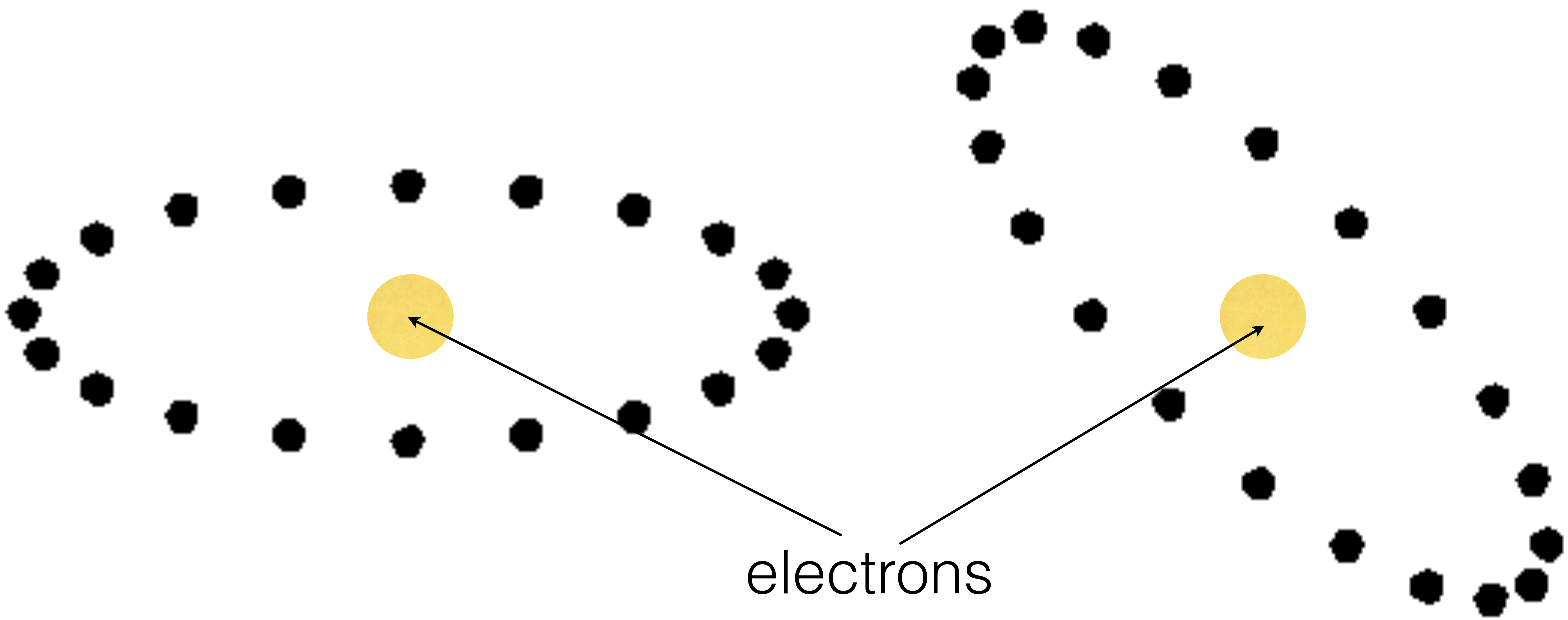
- What do they do to the distance between particles?

Two GW modes

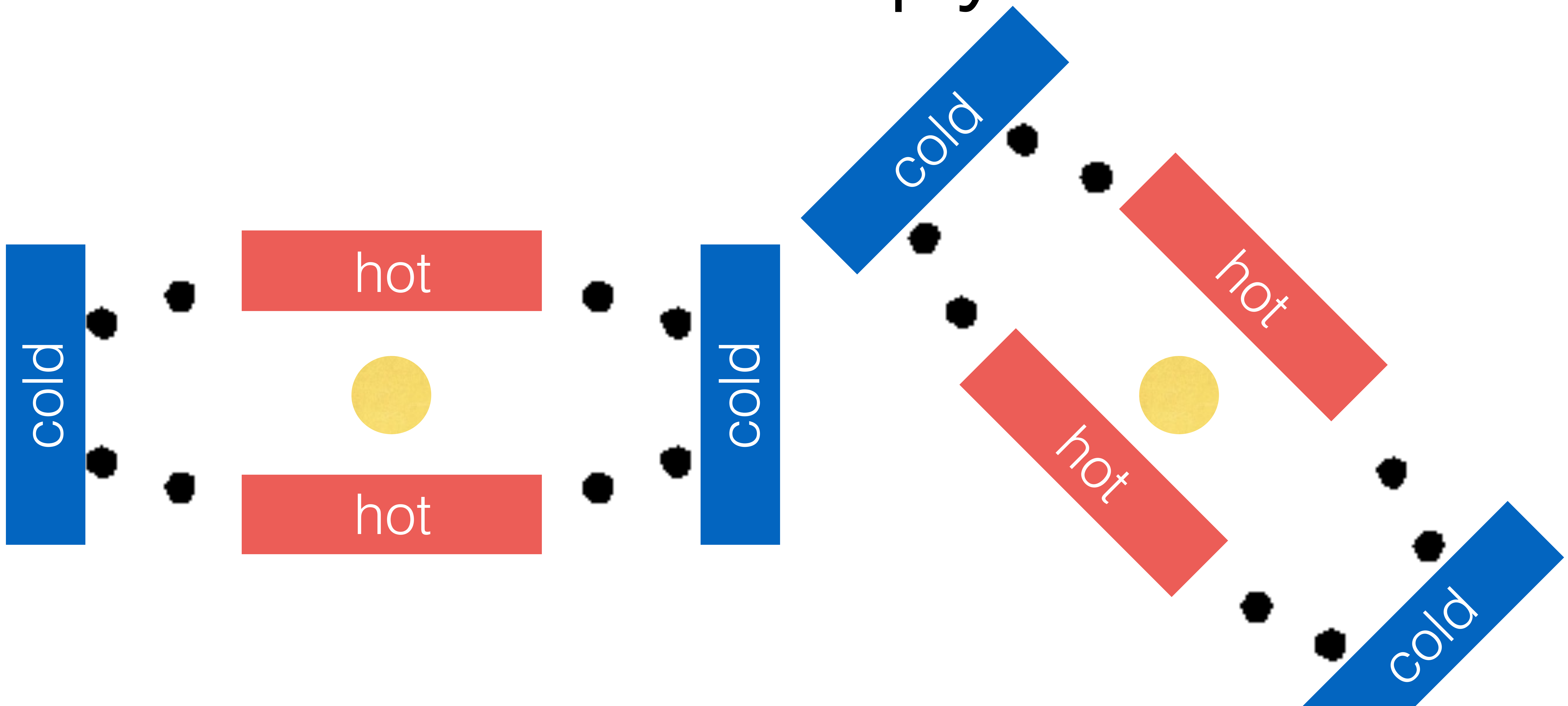


- Anisotropic stretching of space generates quadrupole temperature anisotropy. How?

GW to temperature anisotropy



GW to temperature anisotropy



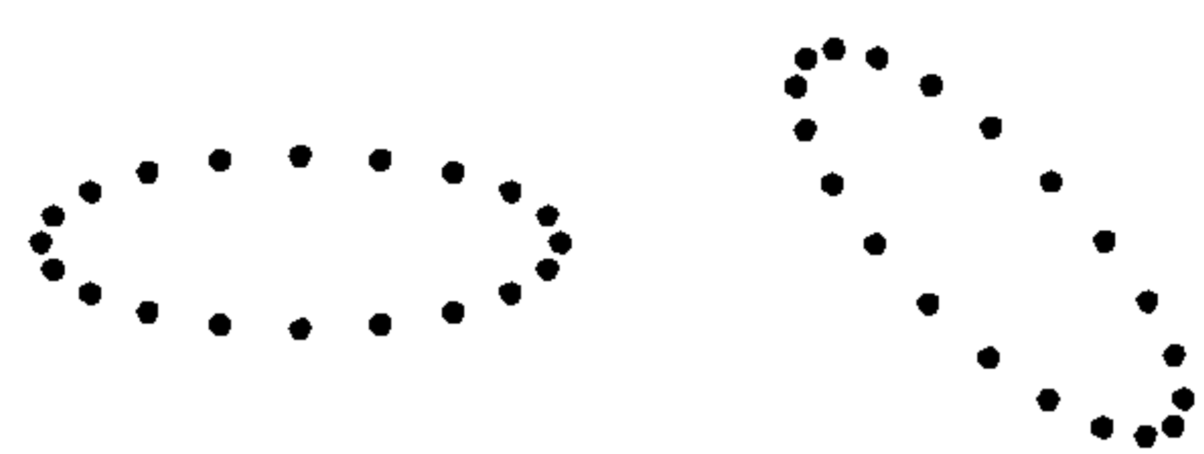
- Stretching of space -> temperature drops
- Contraction of space -> temperature rises

We measure distortions in space

- A distance between two points in space

$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

- ζ: "curvature perturbation" (scalar mode)
  - Perturbation to the determinant of the spatial metric
- h_{ij}: "gravitational waves" (tensor mode)
  - Perturbation that does not change the determinant (area)



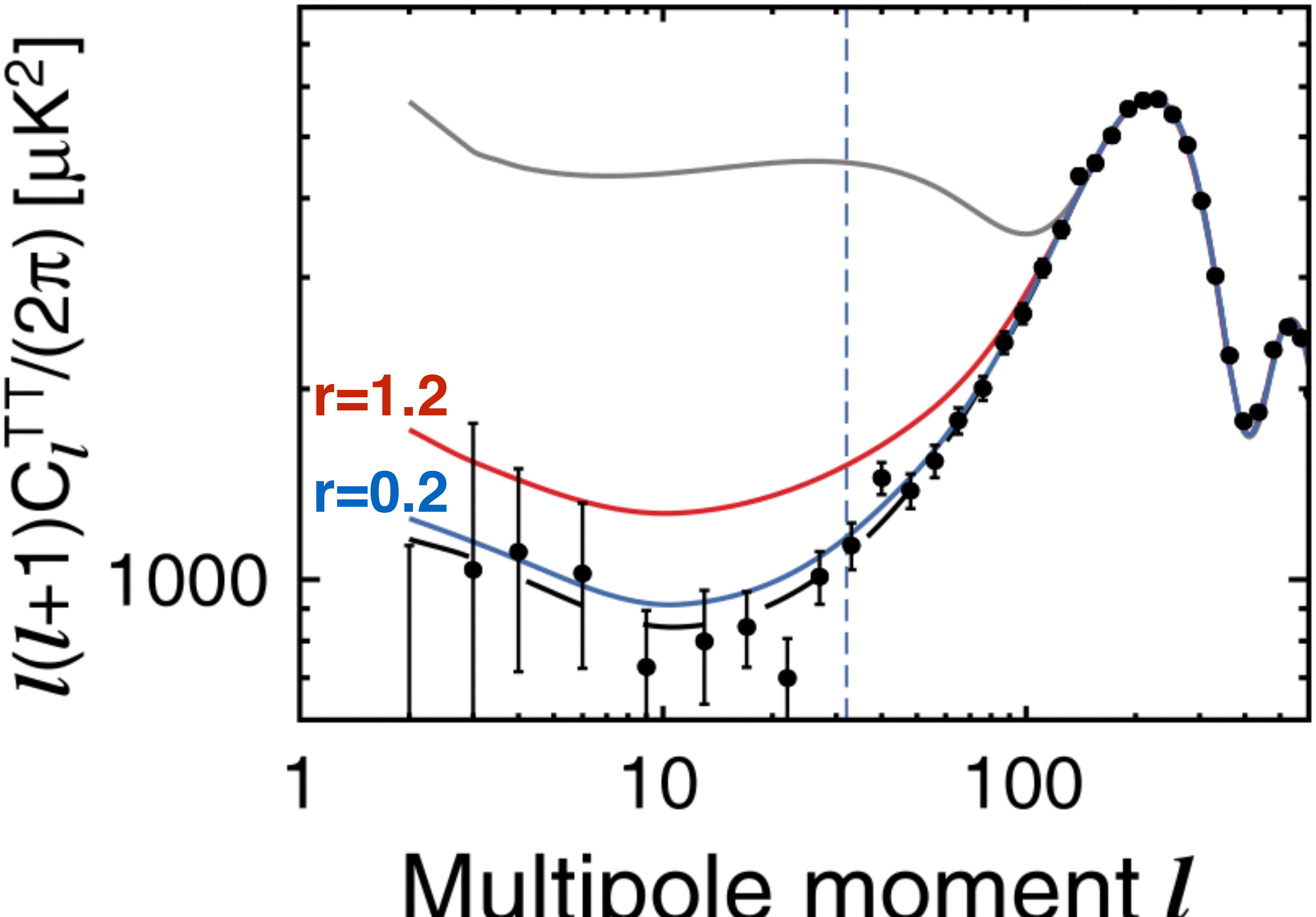
$$\sum_i h_{ii} = 0$$

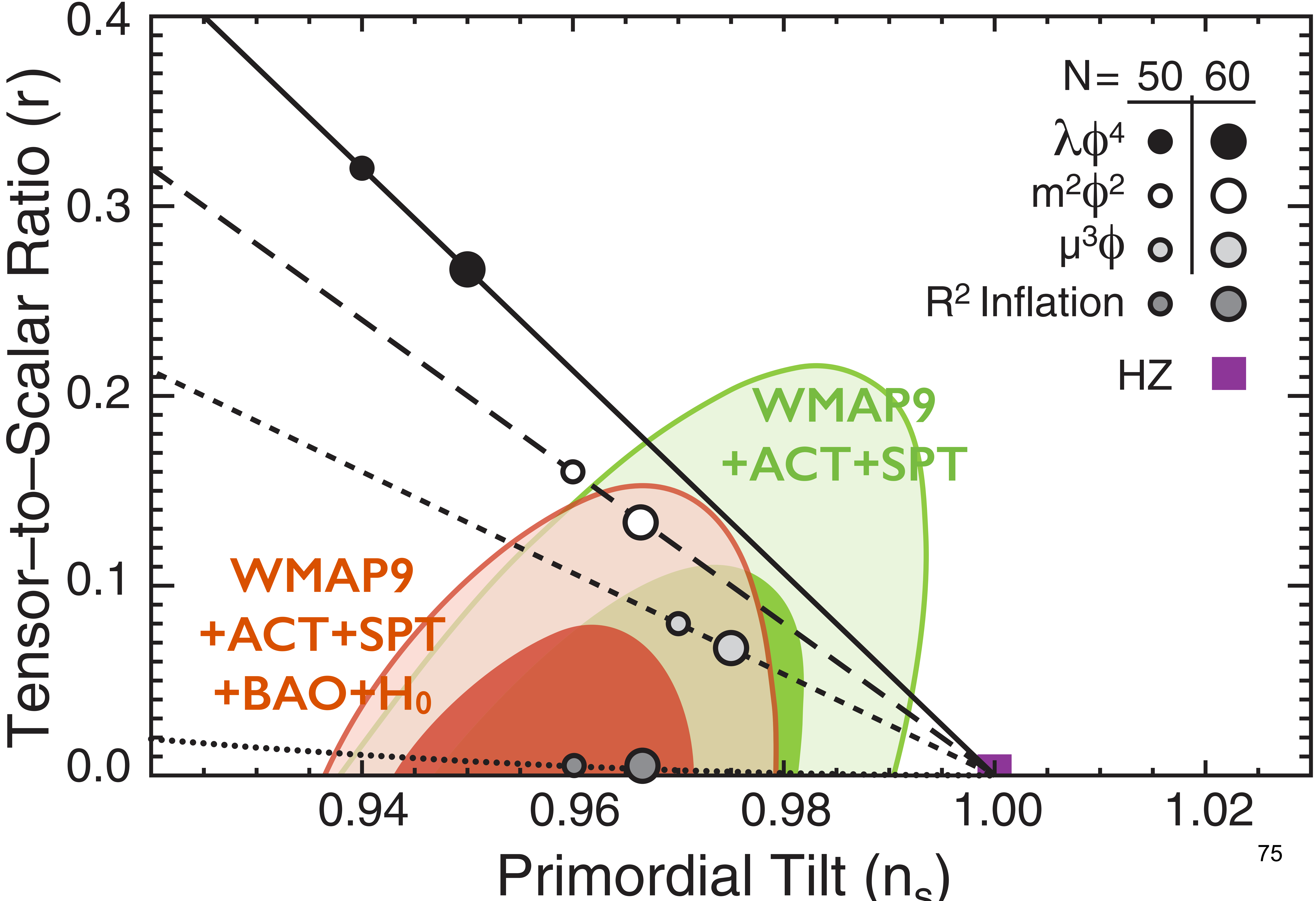
Tensor-to-scalar Ratio

$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

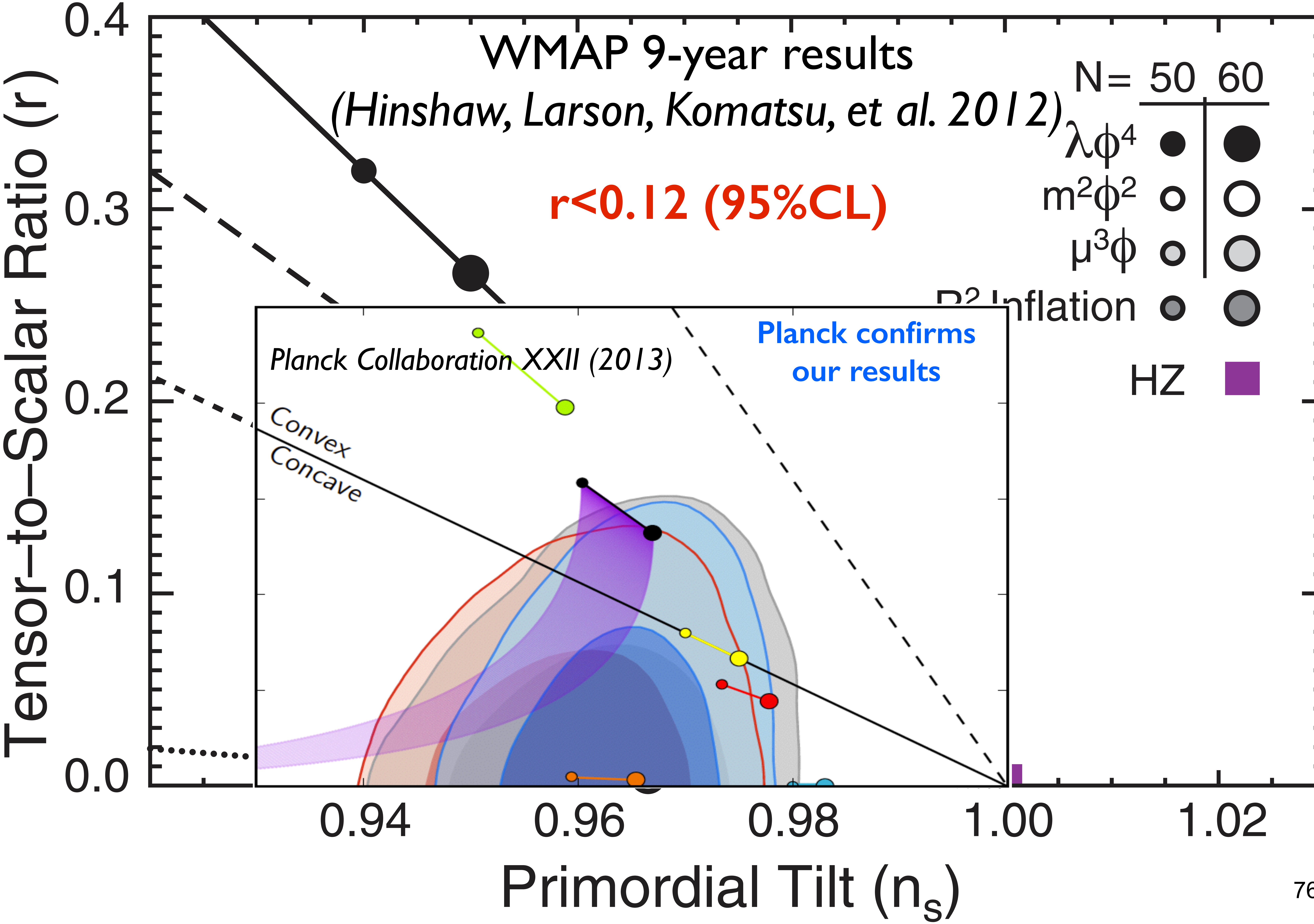
- The BICEP2 results suggest **r~0.2**, if we do not subtract any foregrounds

Limit from Temperature



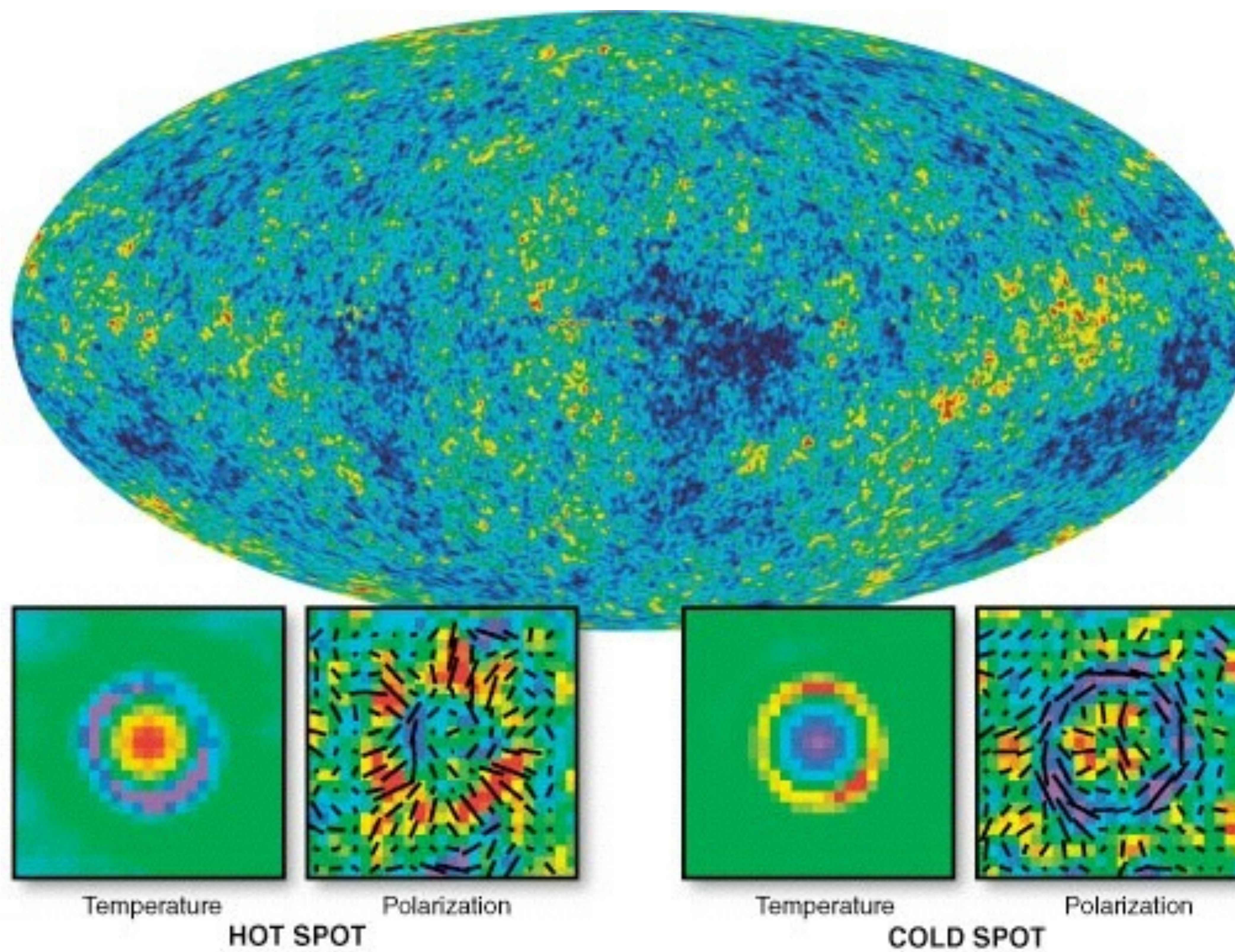


Tensor-to-Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
R^2 Inflation
HZ
WMAP9
+ACT+SPT
WMAP9
+ACT+SPT
+BAO+H_0



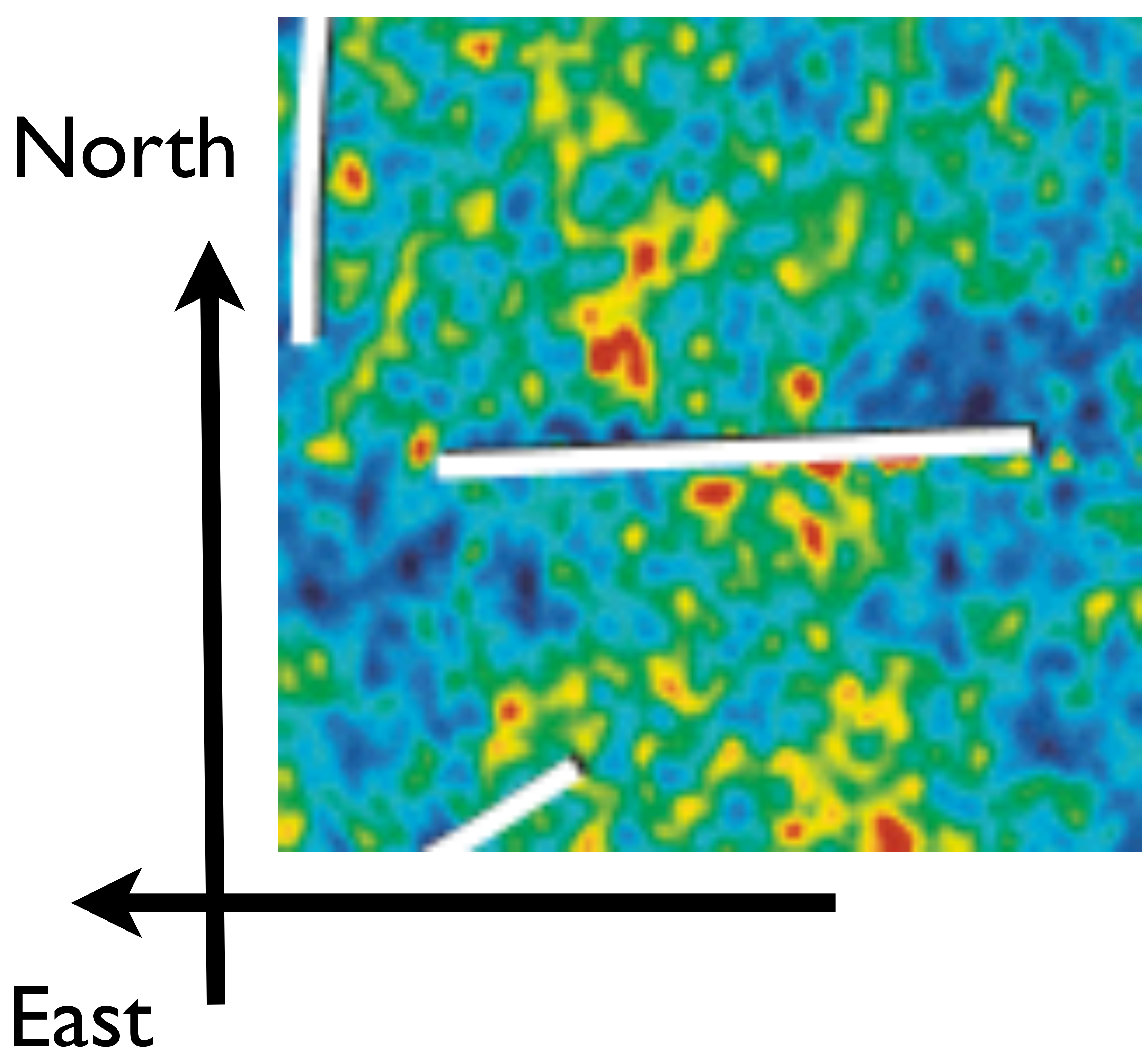
WMAP 9-year results
(Hinshaw, Larson, Komatsu, et al. 2012)
r<0.12 (95%CL)
N= 50 60
λφ4
m2φ2
μ3φ
R2 Inflation
HZ
Planck Collaboration XXII (2013)
Planck confirms
our results
Convex
Concave
Tensor-to-Scalar Ratio (r)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (ns)

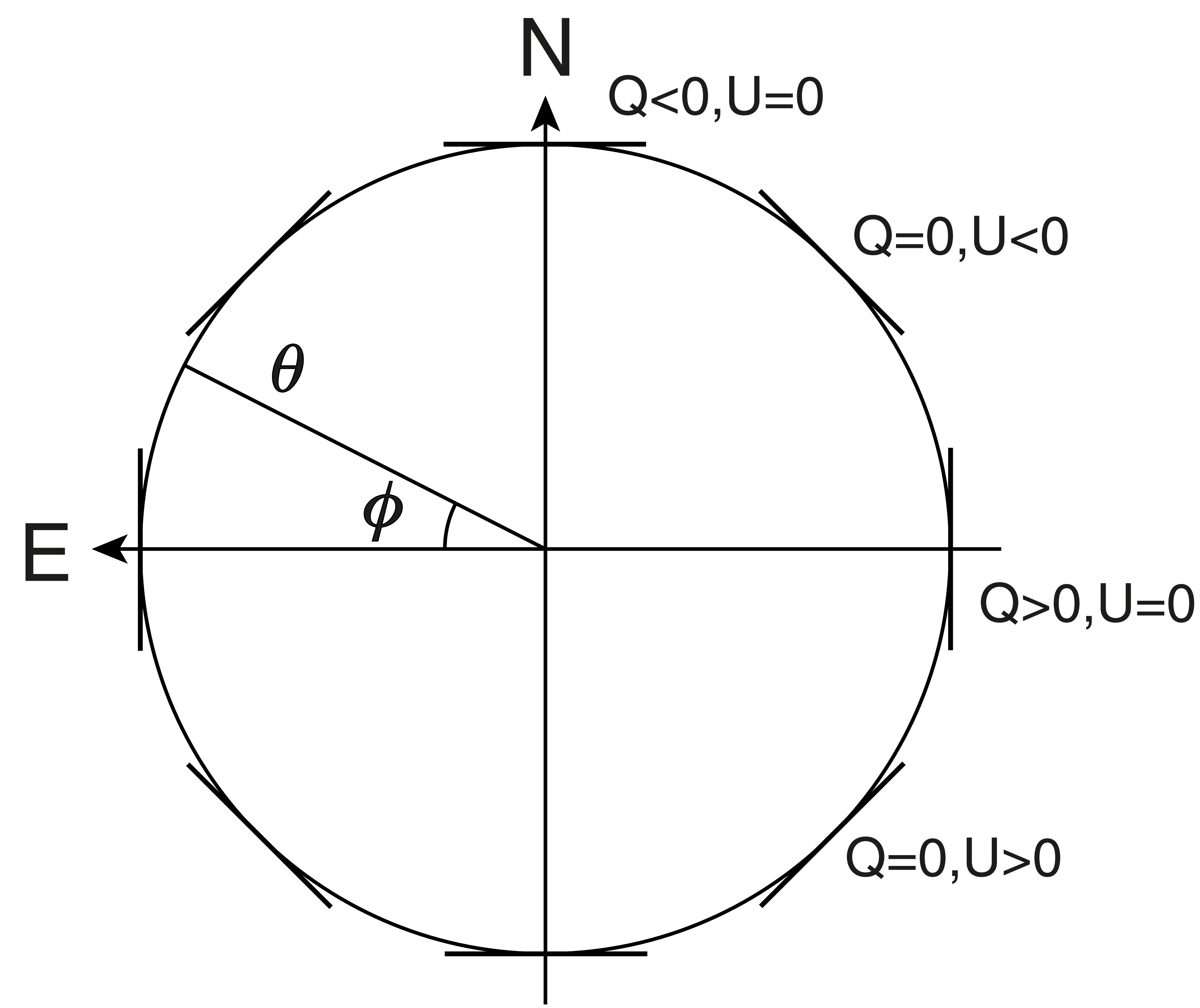
CMB Polarisation



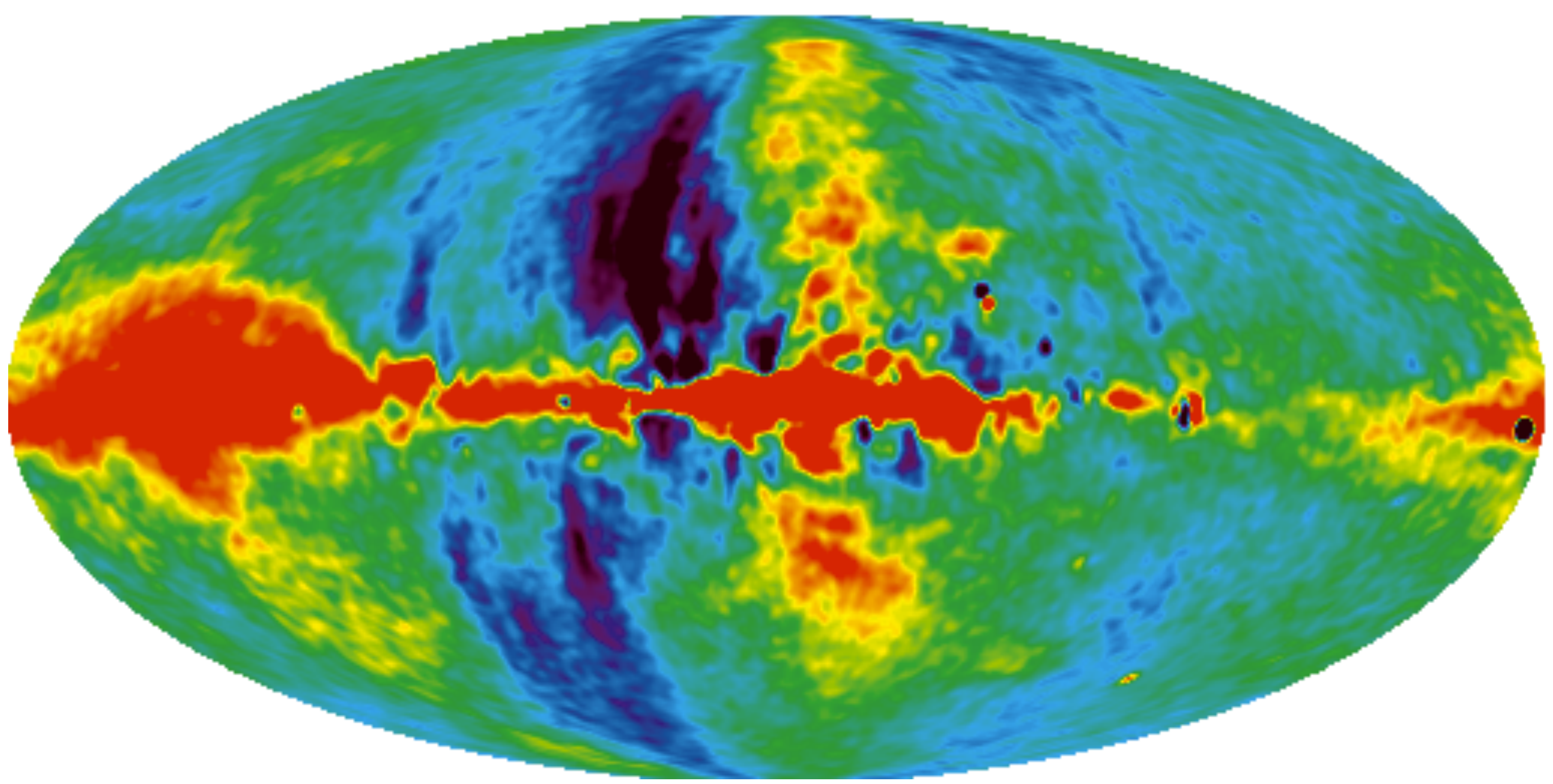
- CMB is [weakly] polarised!

Stokes Parameters

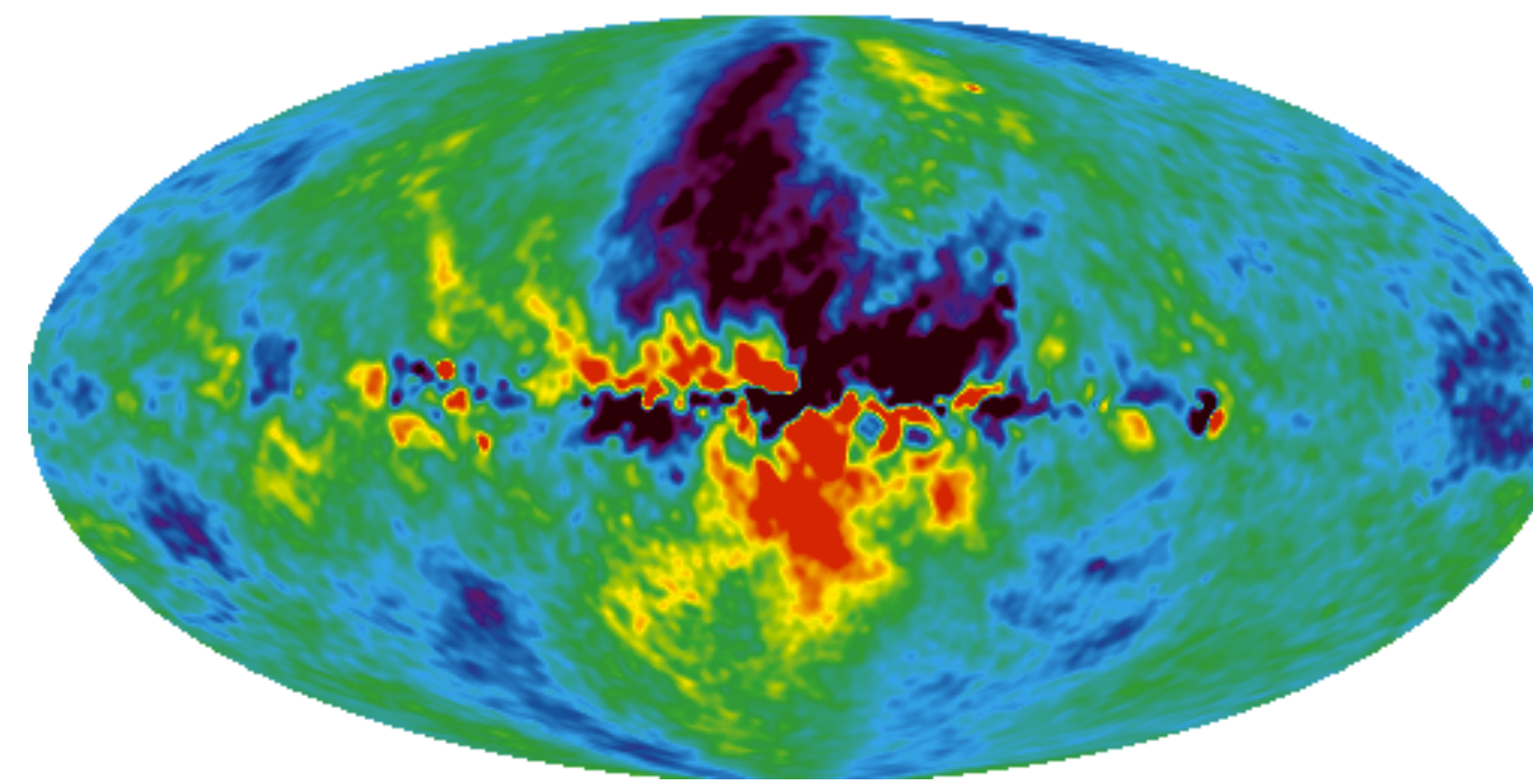




23 GHz



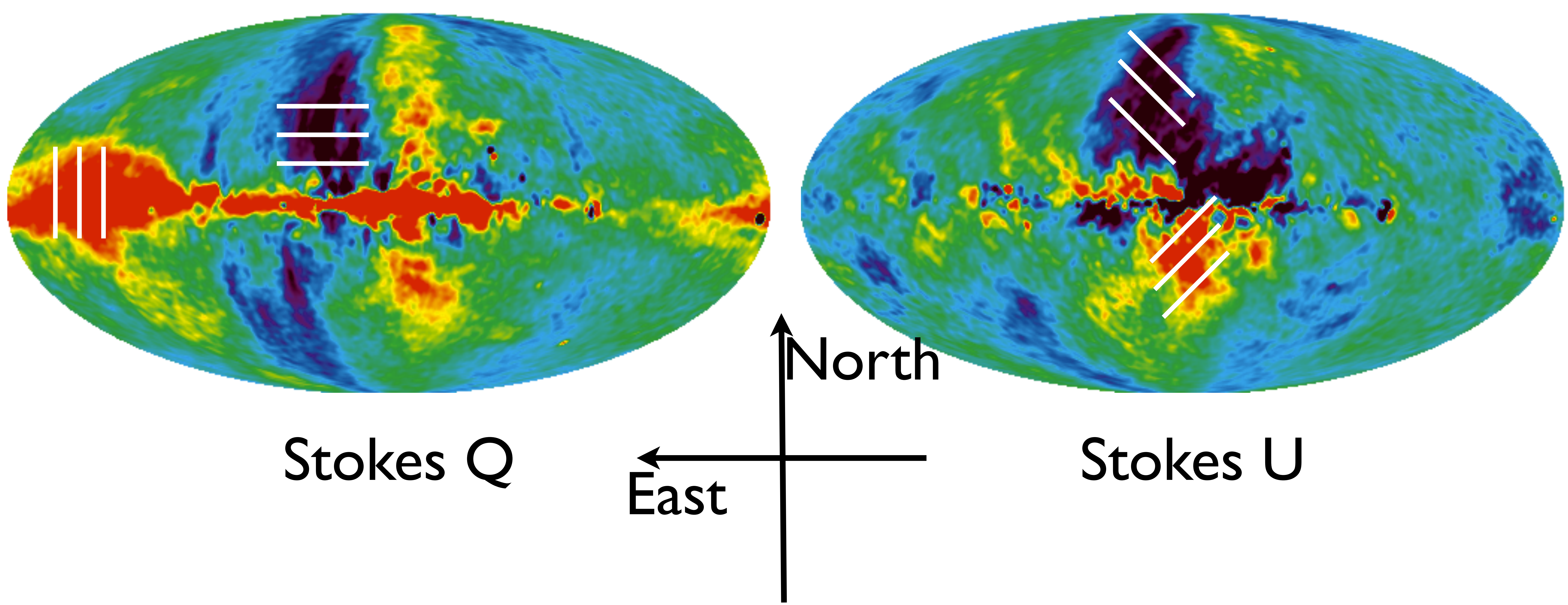
Stokes Q



Stokes U

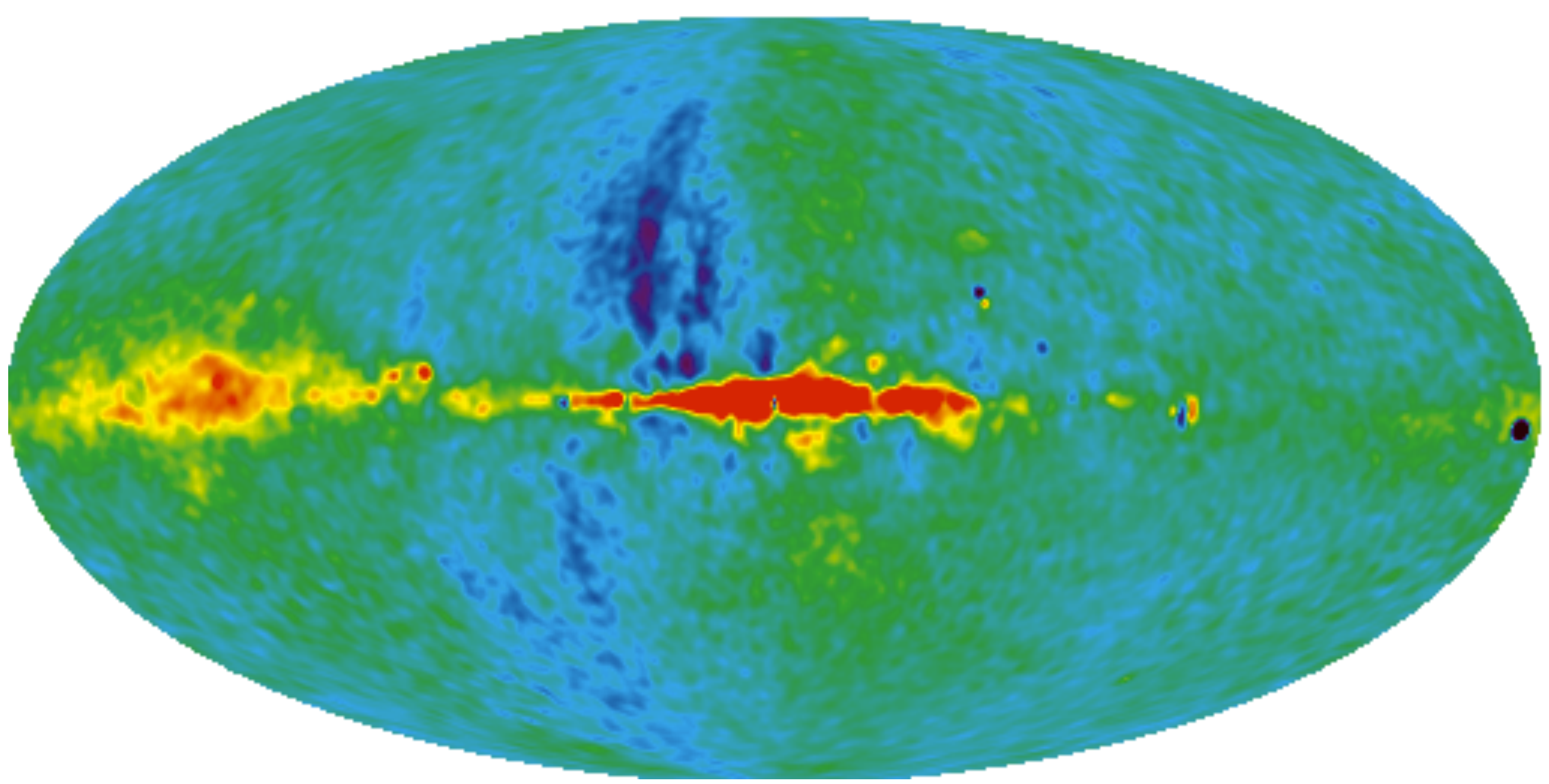
WMAP Collaboration

23 GHz [13 mm]

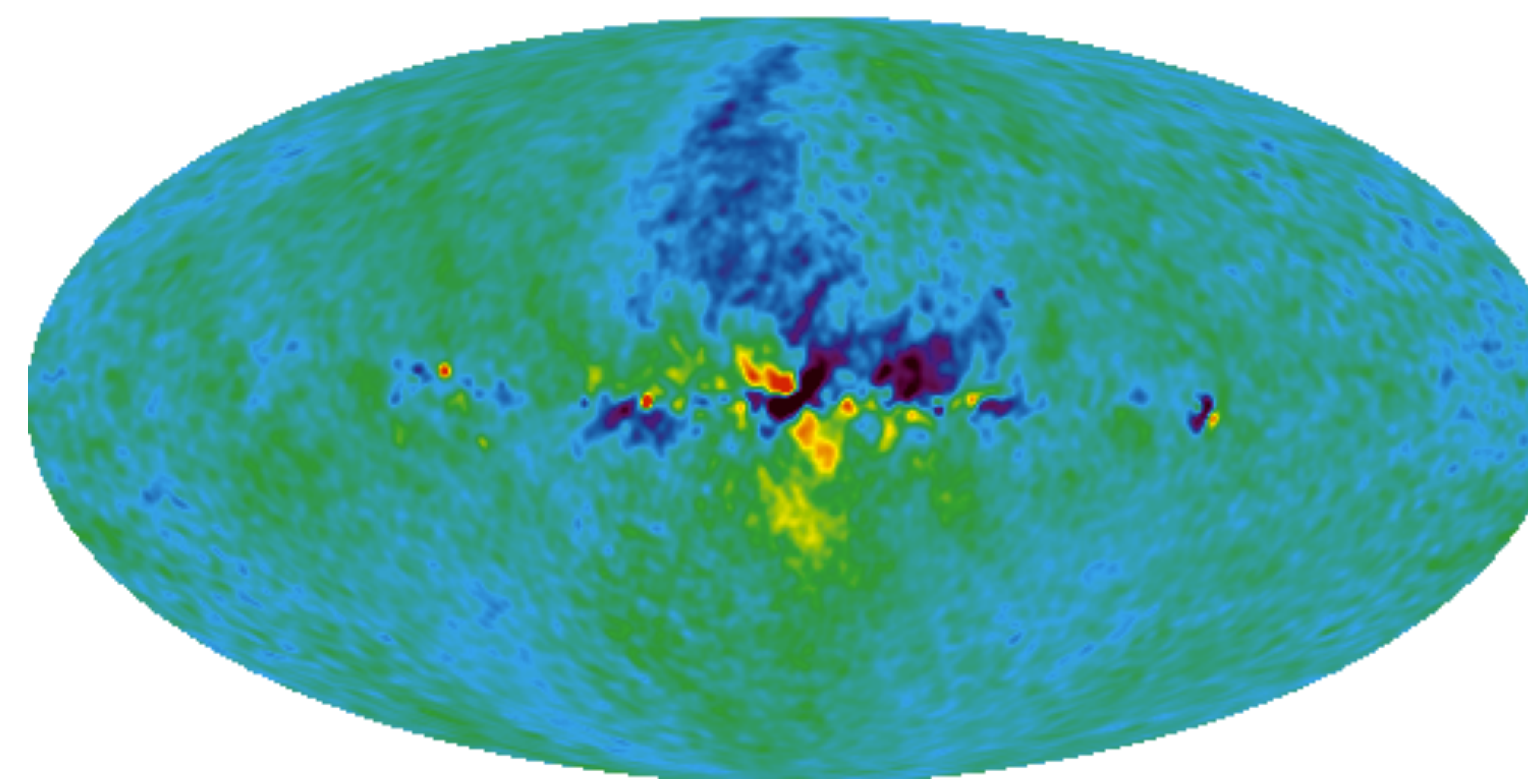


WMAP Collaboration

33 GHz [9.1 mm]

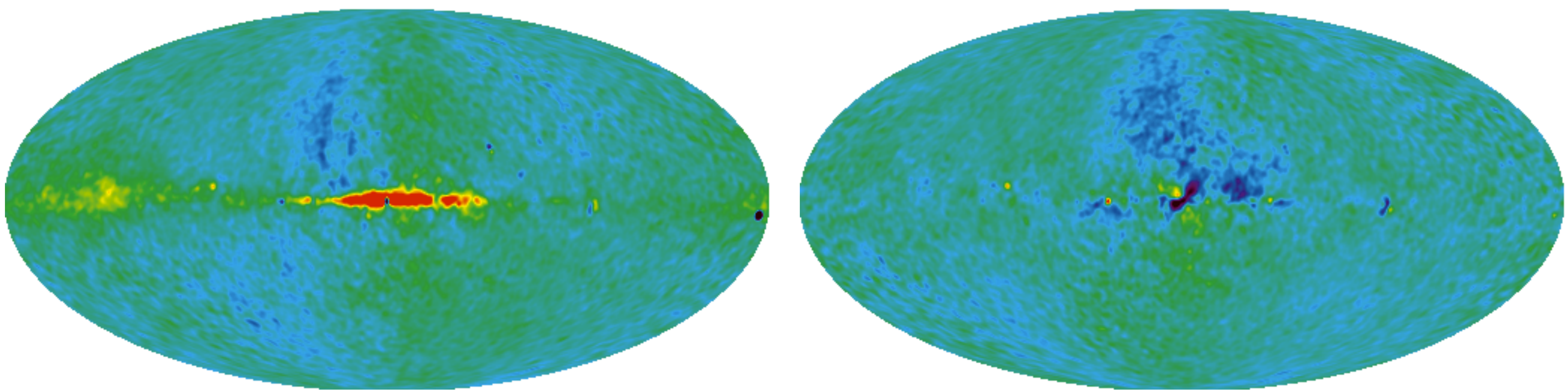


Stokes Q



Stokes U

41 GHz [7.3 mm]

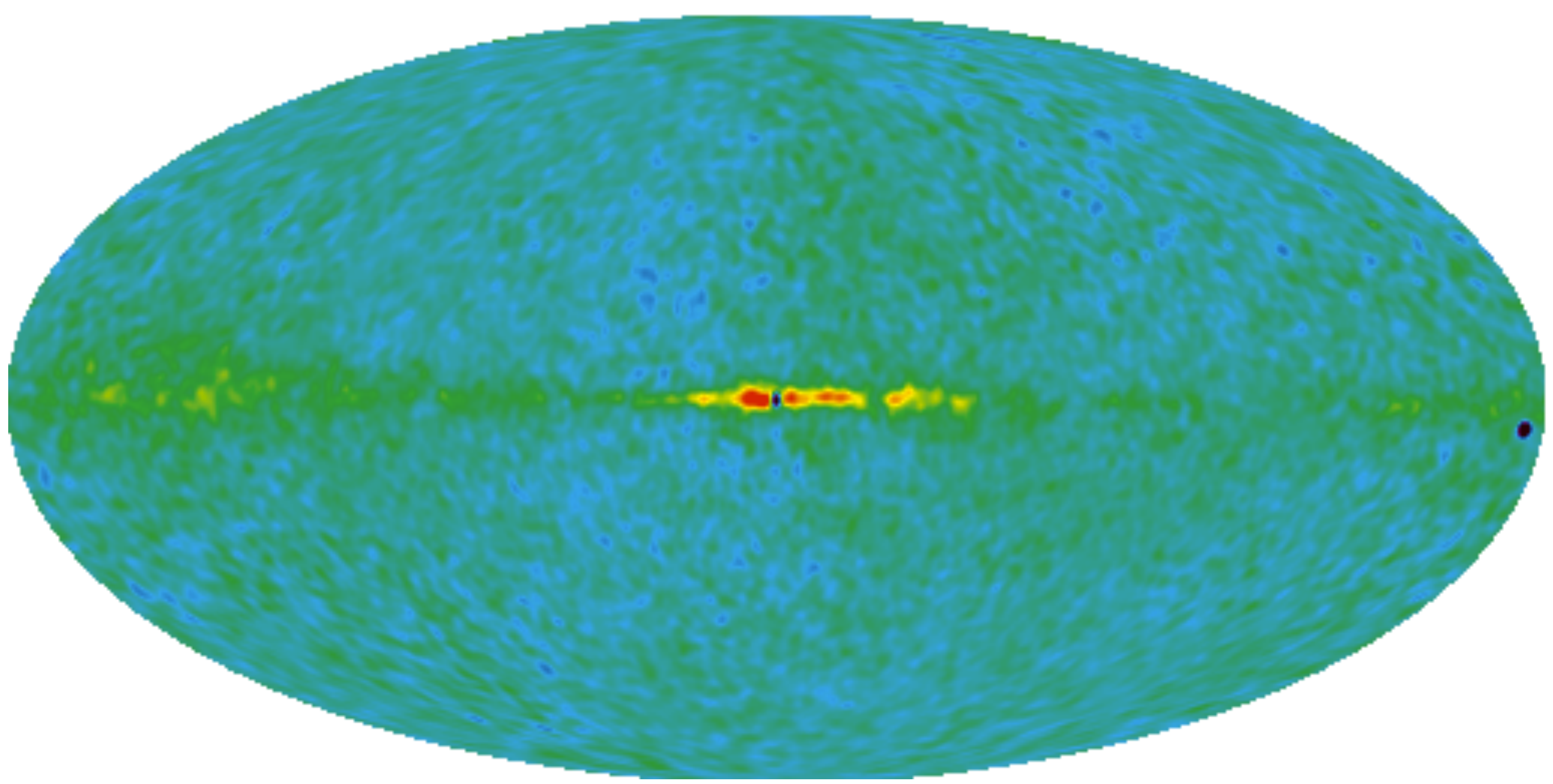


Stokes Q

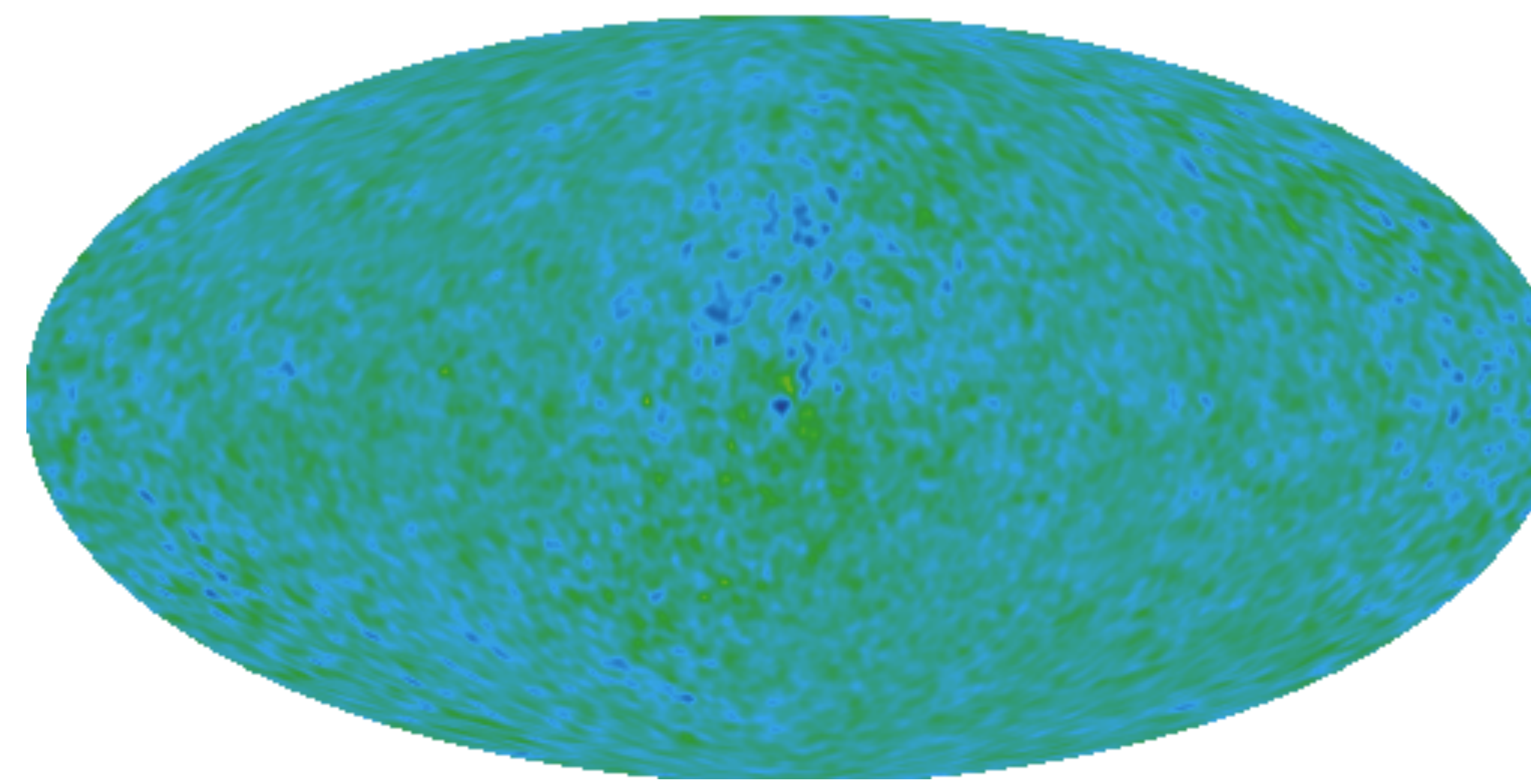
Stokes U

WMAP Collaboration

61 GHz [4.9 mm]

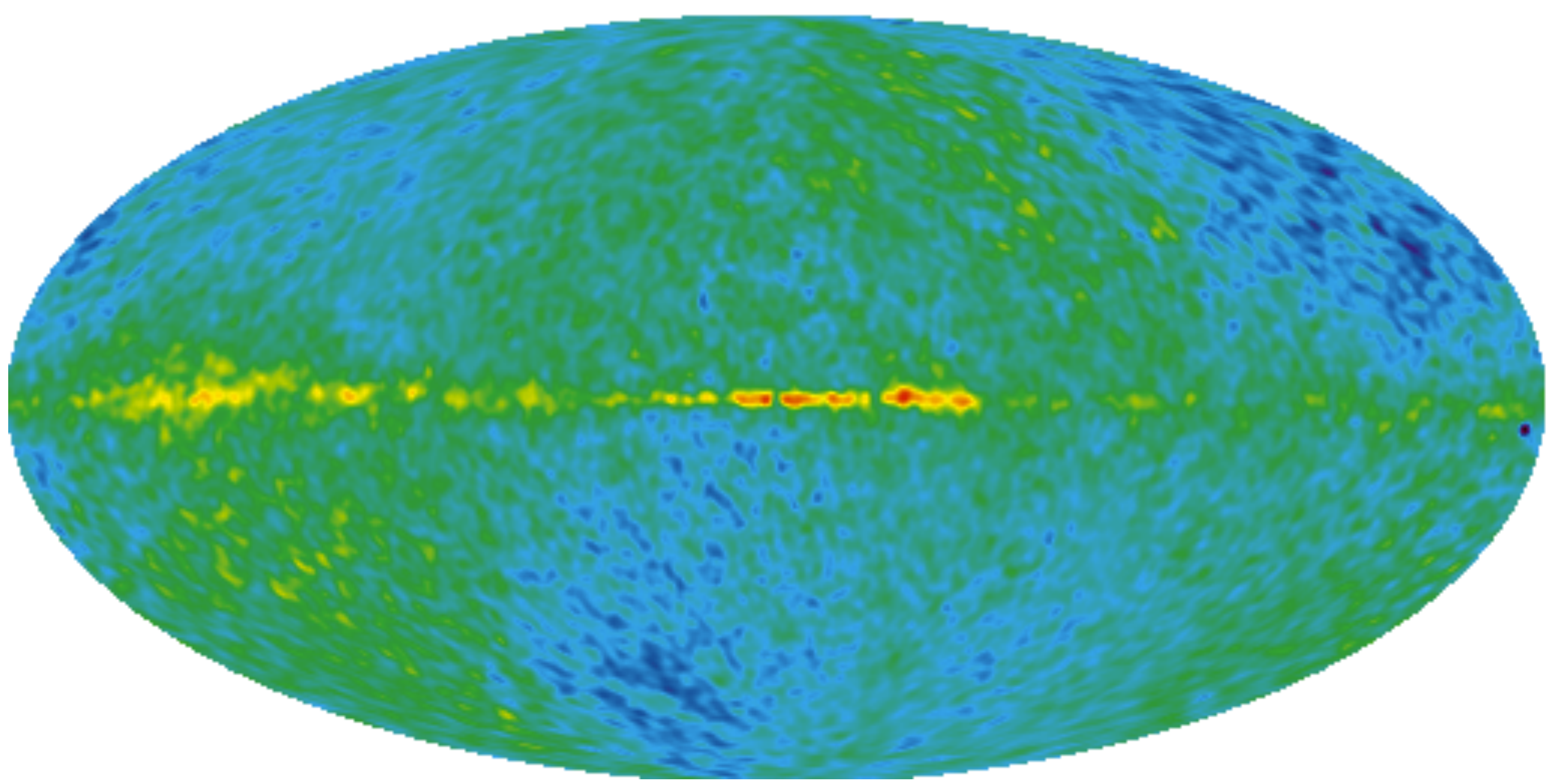


Stokes Q

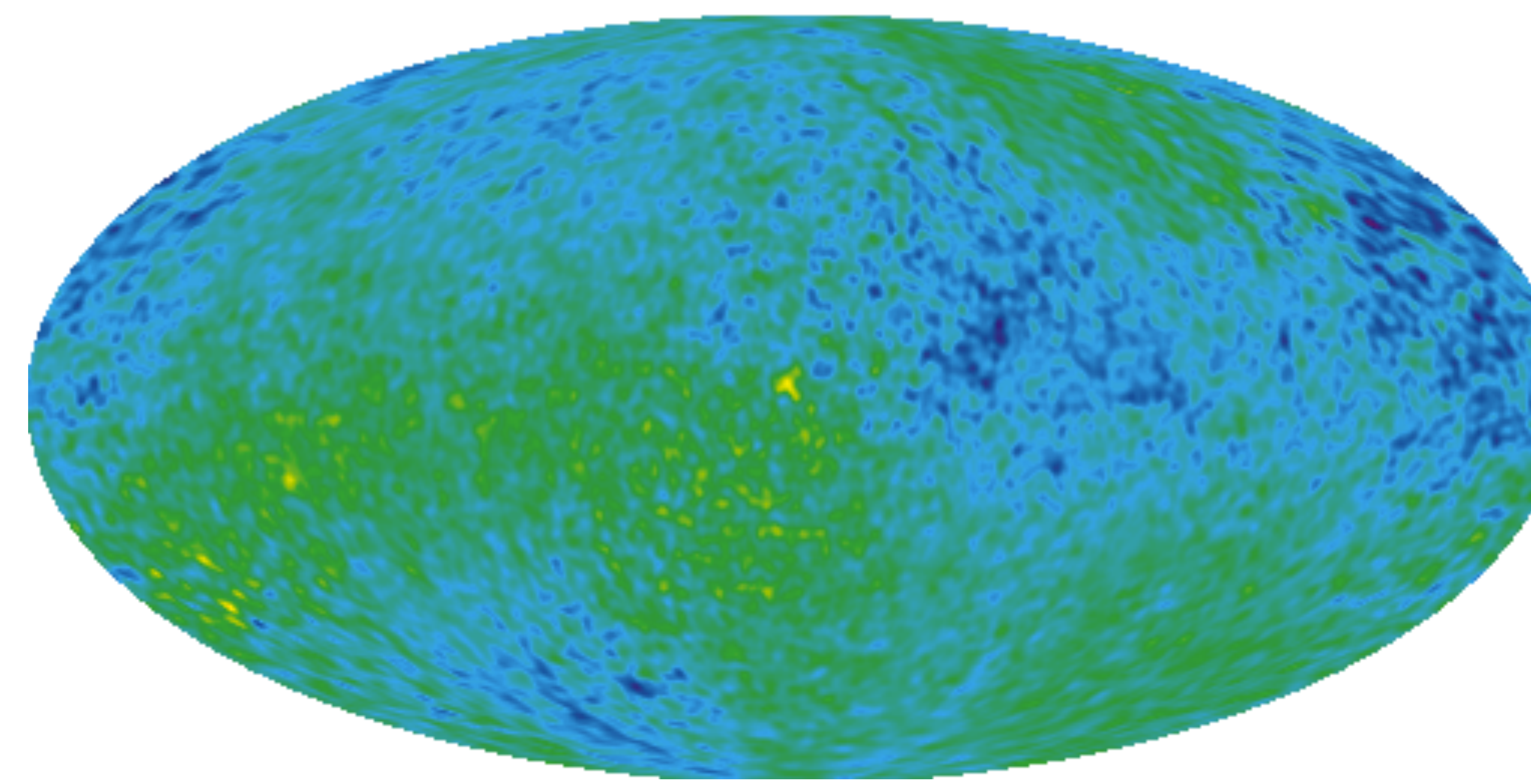


Stokes U

94 GHz [3.2 mm]



Stokes Q

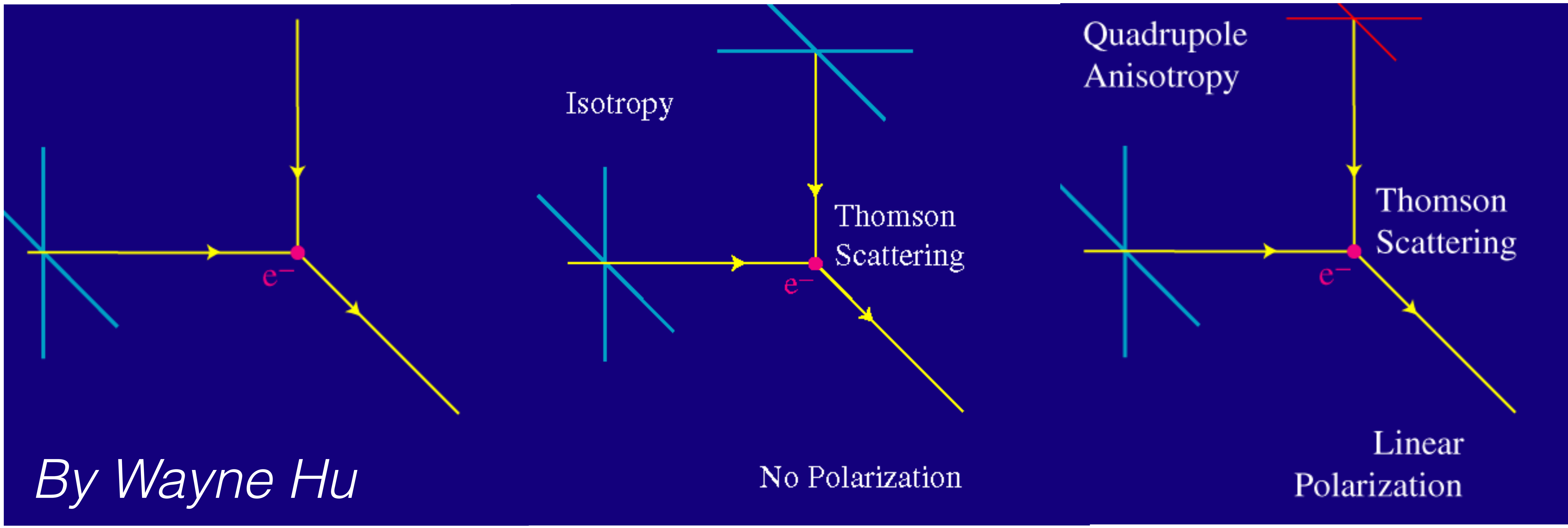


Stokes U

How many components?

- CMB: $T_\nu \sim \nu^0$
- Synchrotron: $T_\nu \sim \nu^{-3}$
- Dust: $T_\nu \sim \nu^2$
- Therefore, we need **at least** 3 frequencies to separate them

Physics of CMB Polarisation



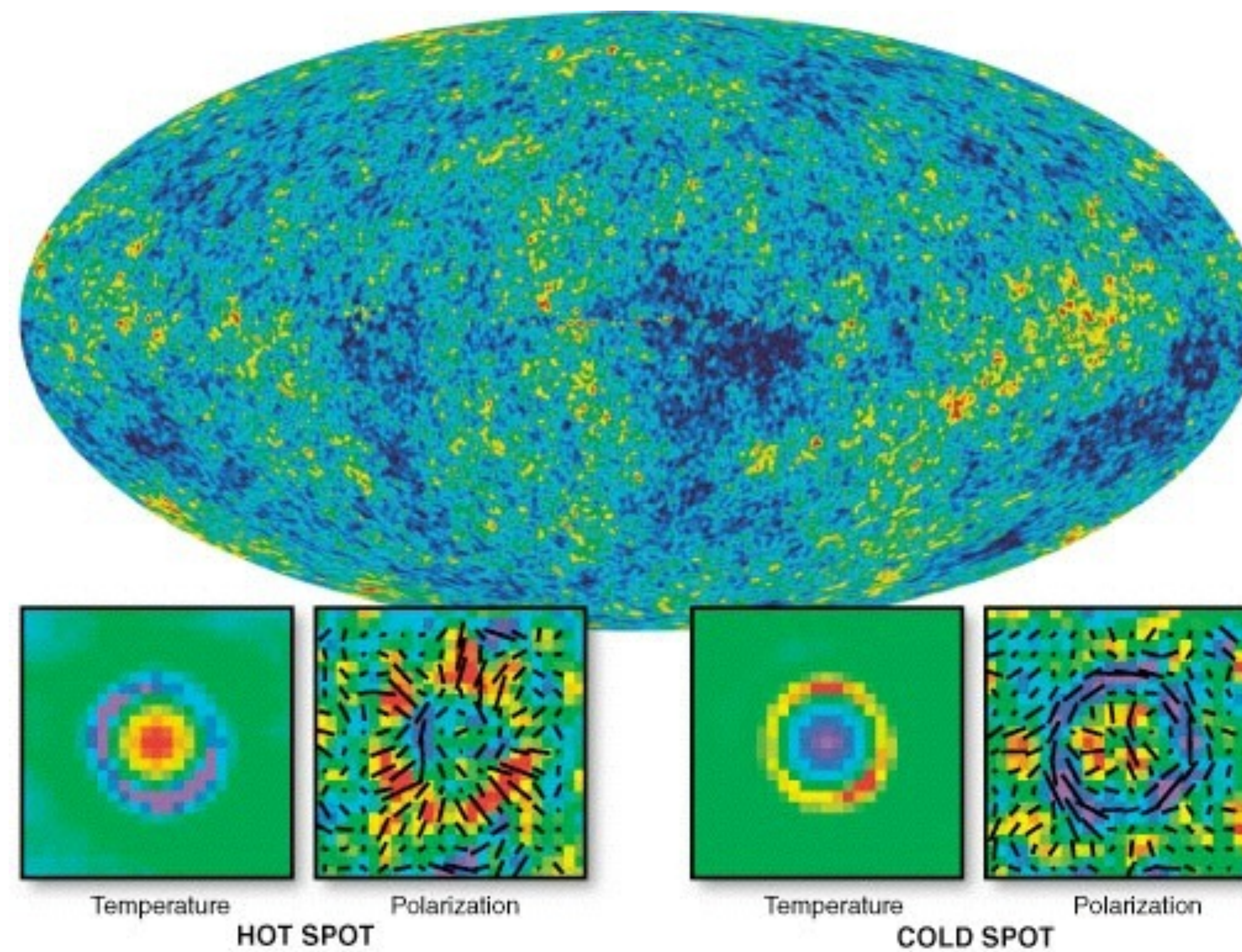
- Necessary and sufficient conditions for generating polarisation in CMB:
  - Thomson scattering
  - Quadrupolar temperature anisotropy around an electron

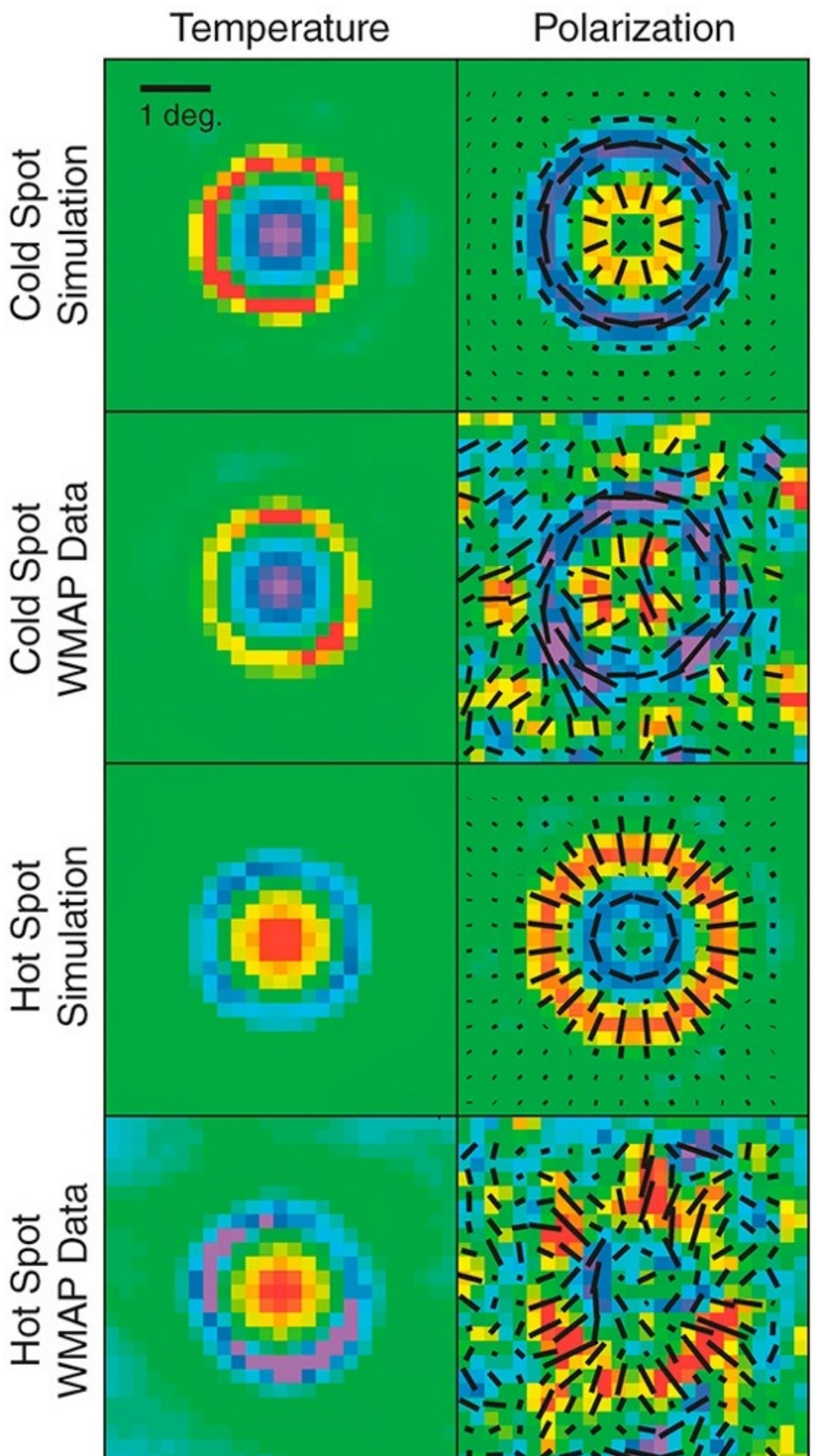
Origin of Quadrupole

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

Seeing polarisation in the WMAP data

- Average polarisation data around cold and hot temperature spots
- Outside of the Galaxy mask [not shown], there are 11536 hot spots and 11752 cold spots
- Averaging them beats the noise down



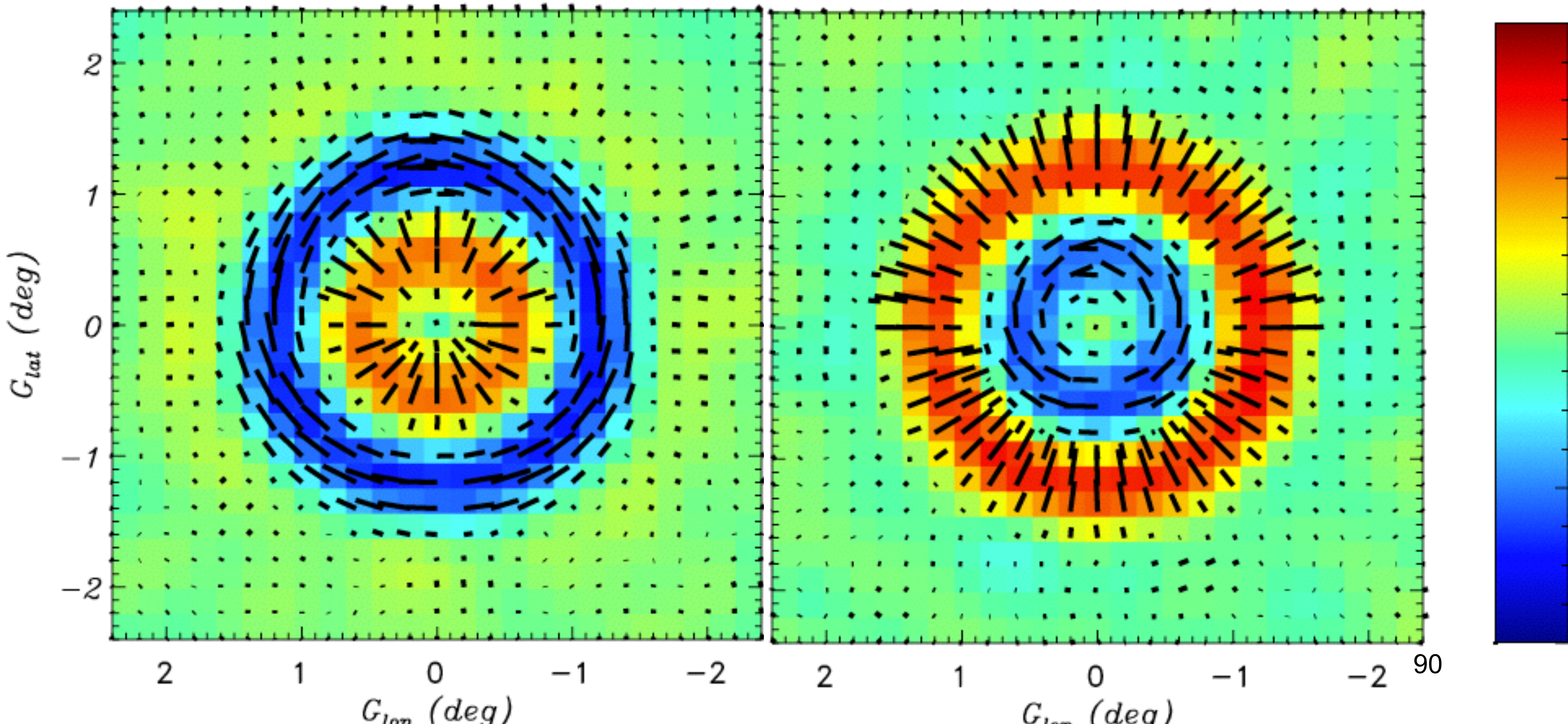


WMAP Collaboration

Radial and tangential polarisation around temperature spots

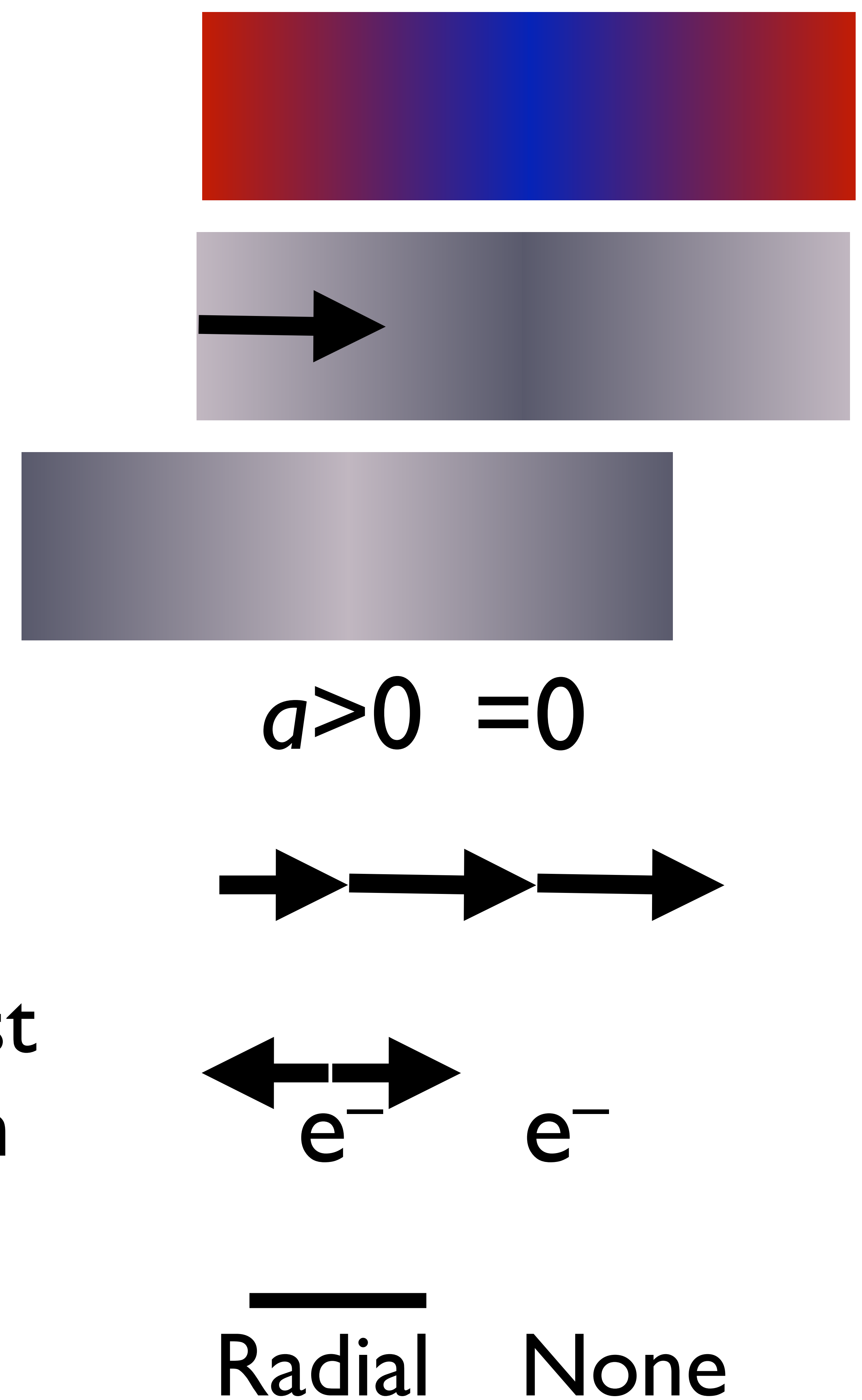
- This shows polarisation generated by the plasma flowing into gravitational potentials
- Signatures of the “scalar mode” fluctuations in polarisation
- These patterns are called “**E modes**”

Planck Data!



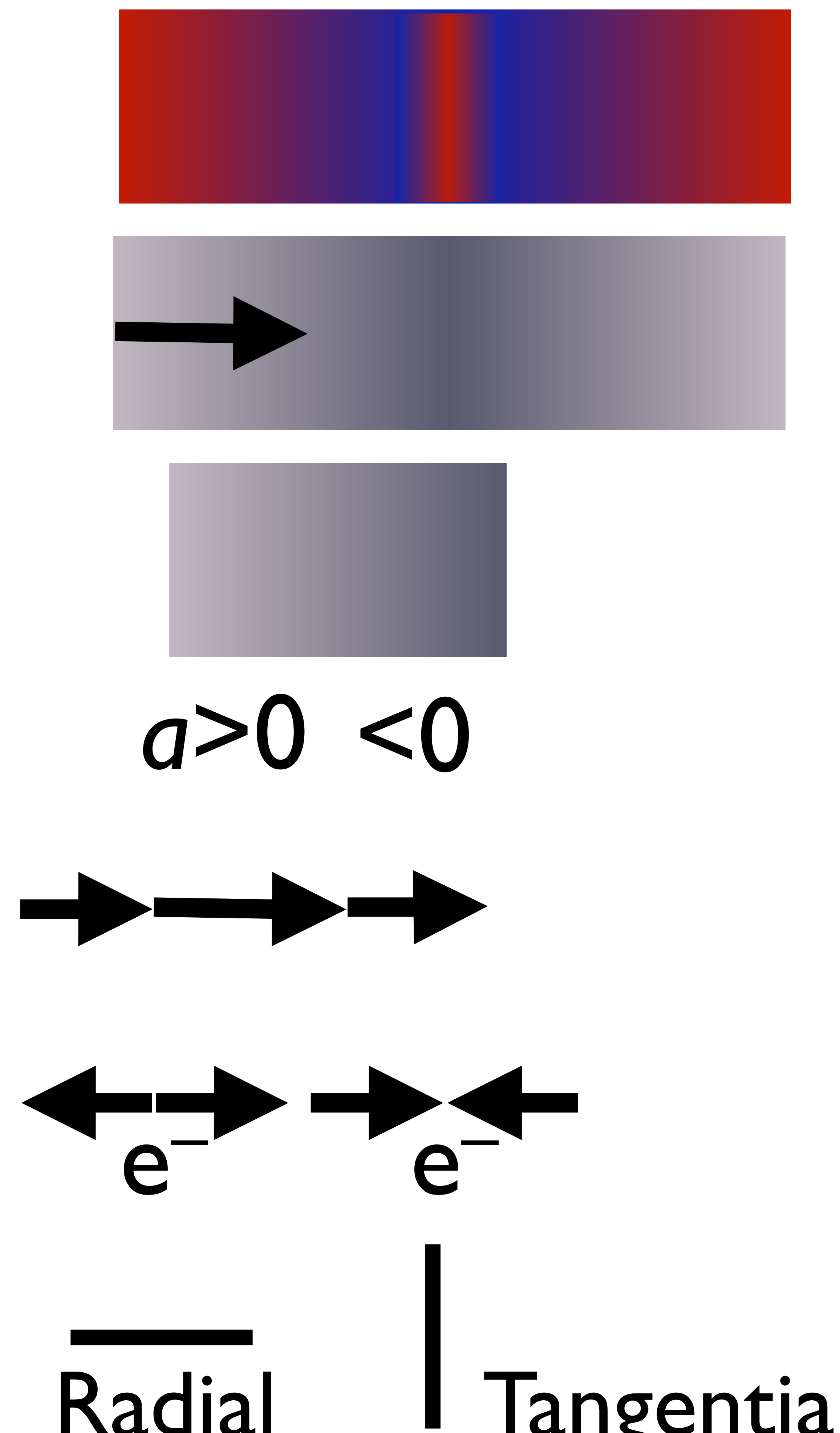
Q_r (cold spots) Q_r (hot spots)

Quadrupole From Velocity Gradient (Large Scale)



ΔT	Sachs-Wolfe: $\Delta T/T=\Phi/3$
Potential Φ	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)



ΔT — Compression increases temperature

Potential Φ — Stuff flowing *in*

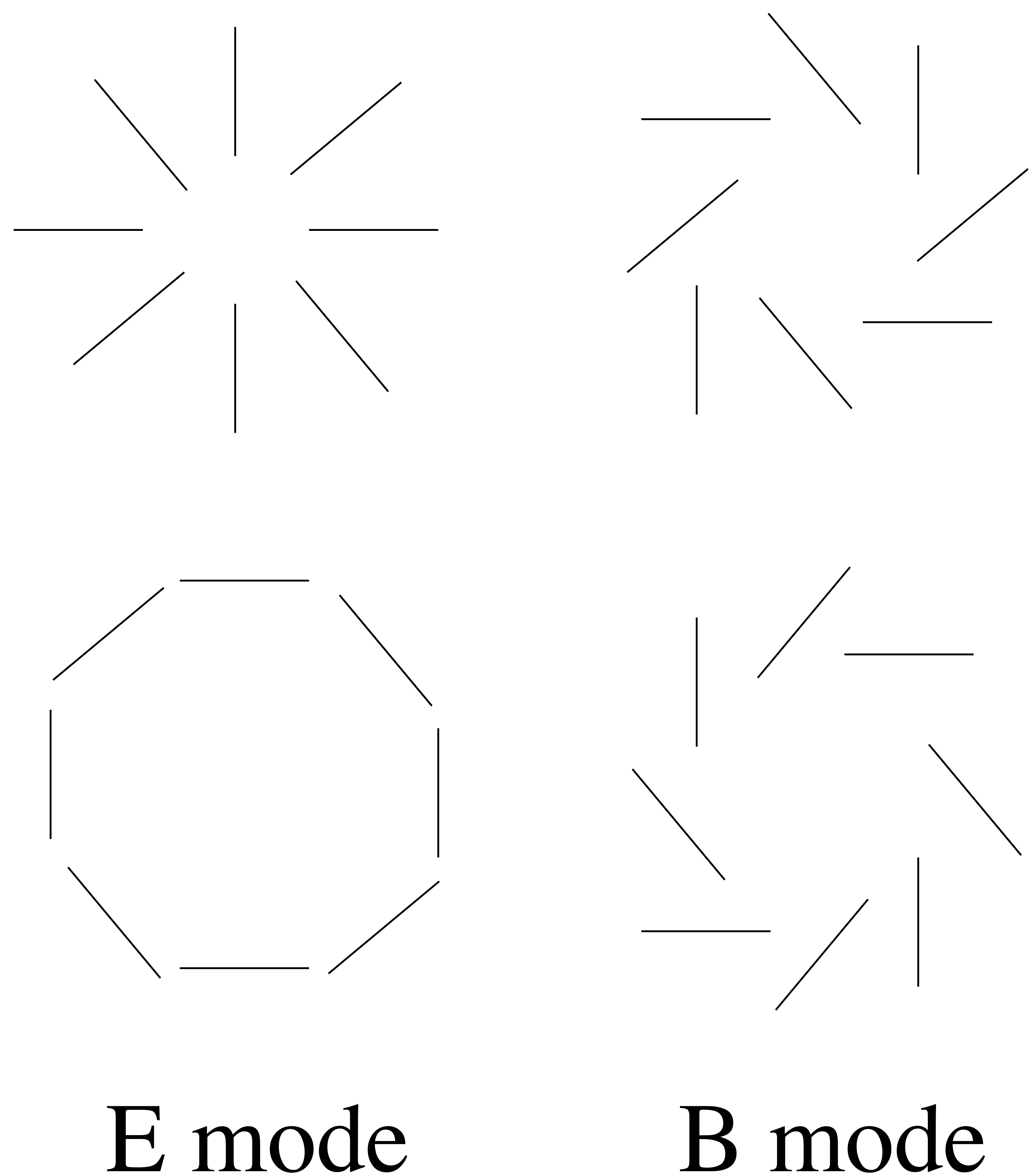
Acceleration $a = -\partial\Phi - \partial P$ — Pressure gradient slows down the flow

Velocity — Velocity gradient

Velocity in the rest frame of electron

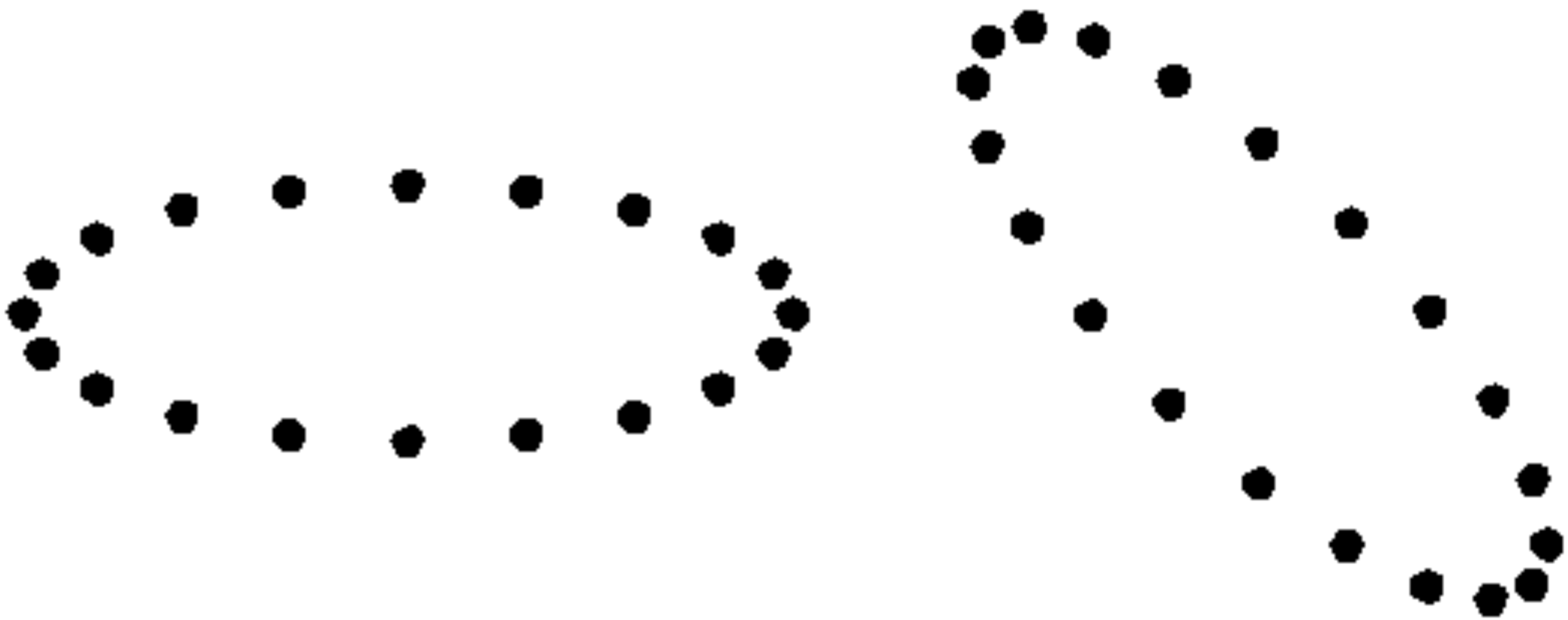
Polarization

E-mode and B-mode



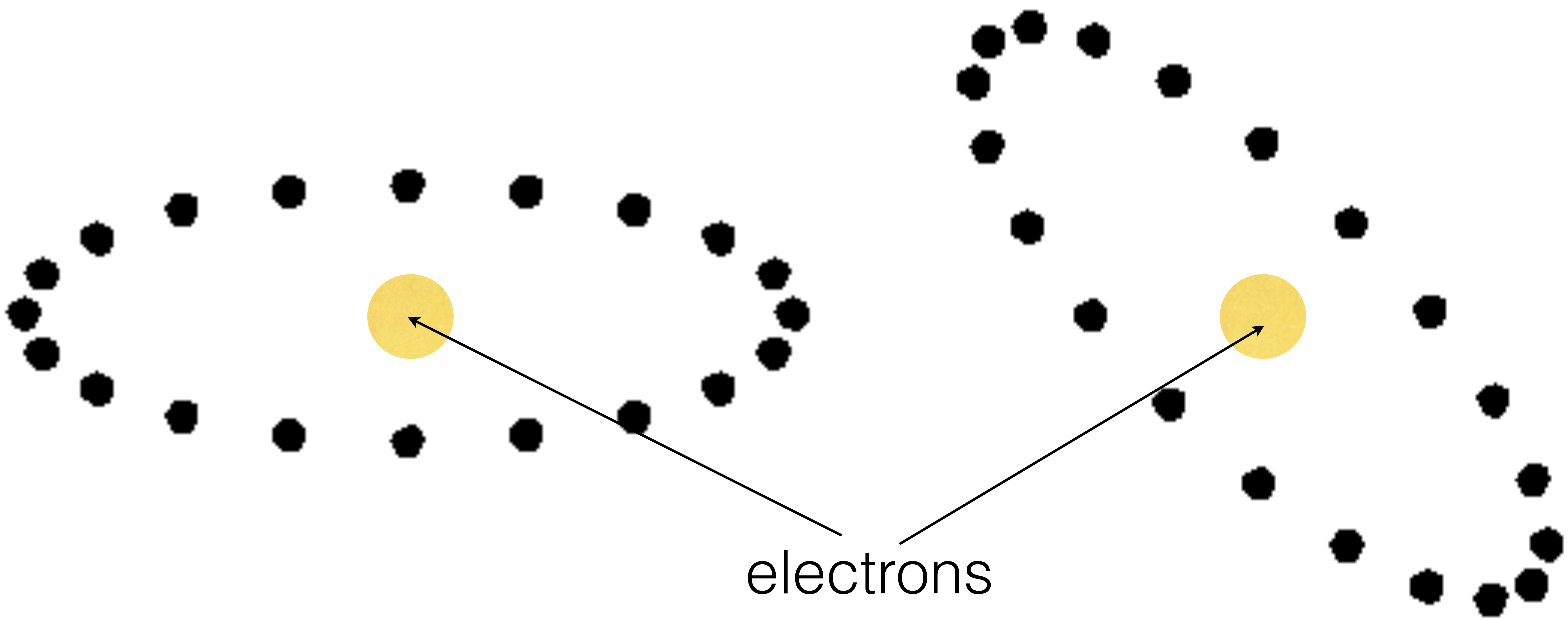
- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

Two GW modes

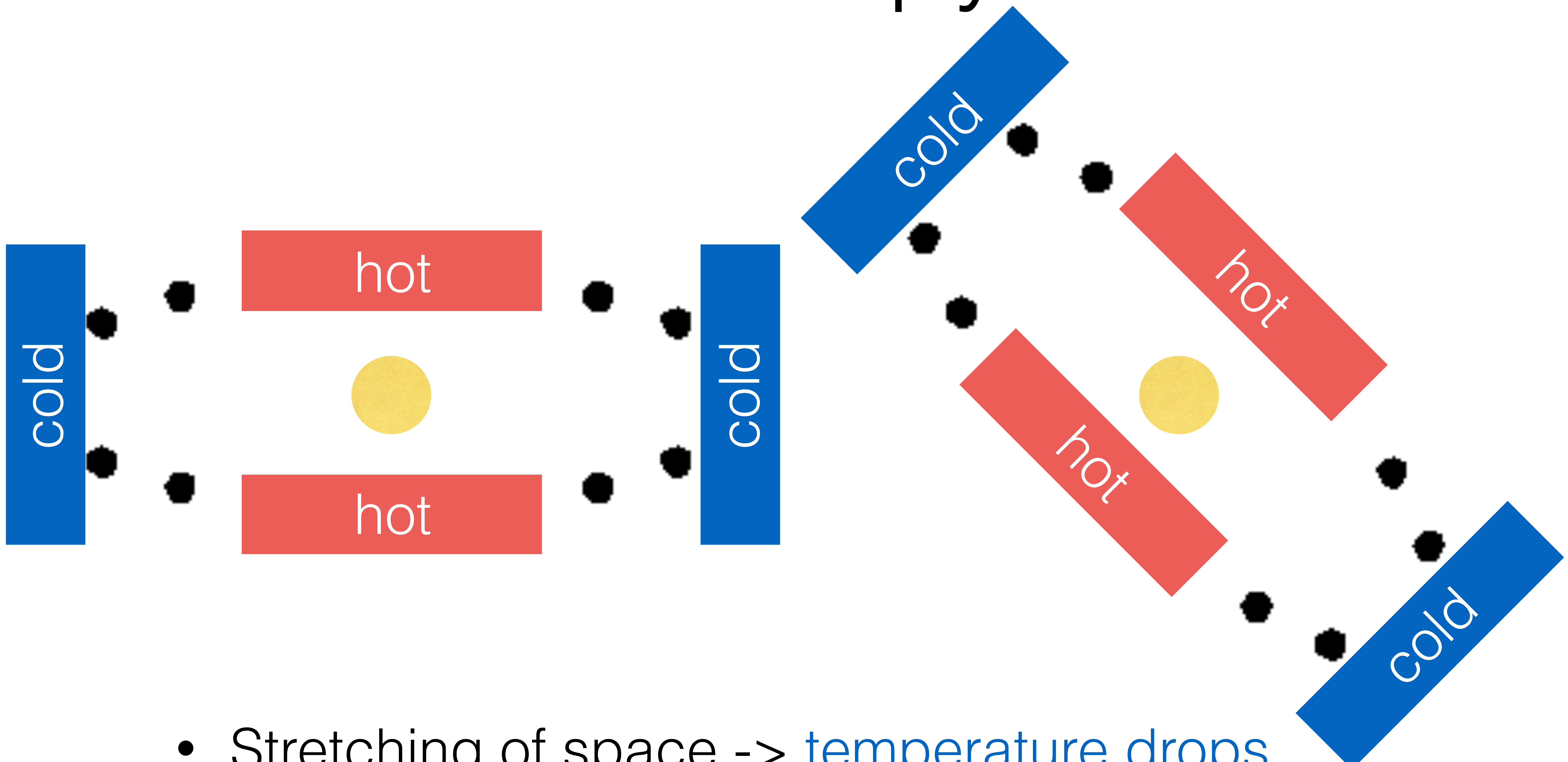


- Anisotropic stretching of space generates quadrupole temperature anisotropy. How?

GW to temperature anisotropy

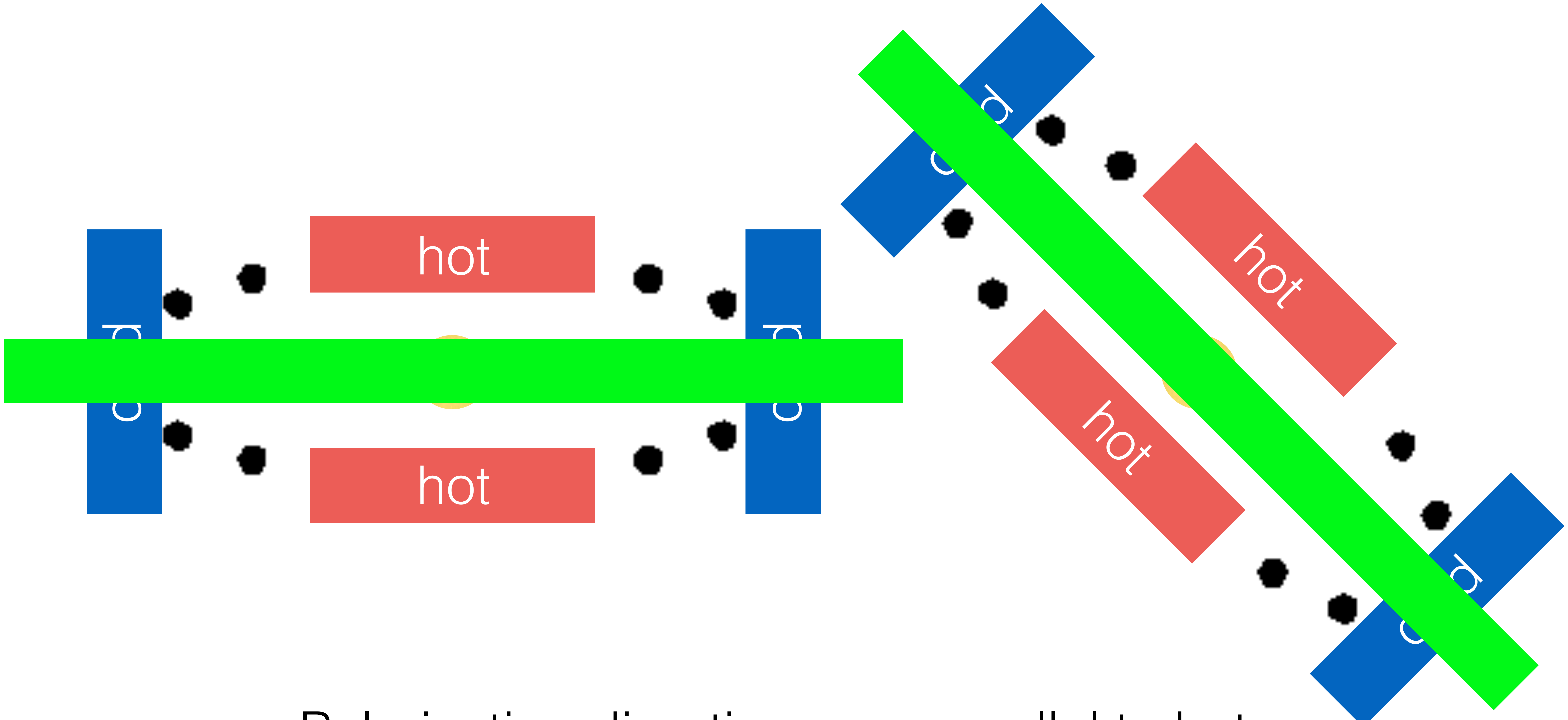


GW to temperature anisotropy

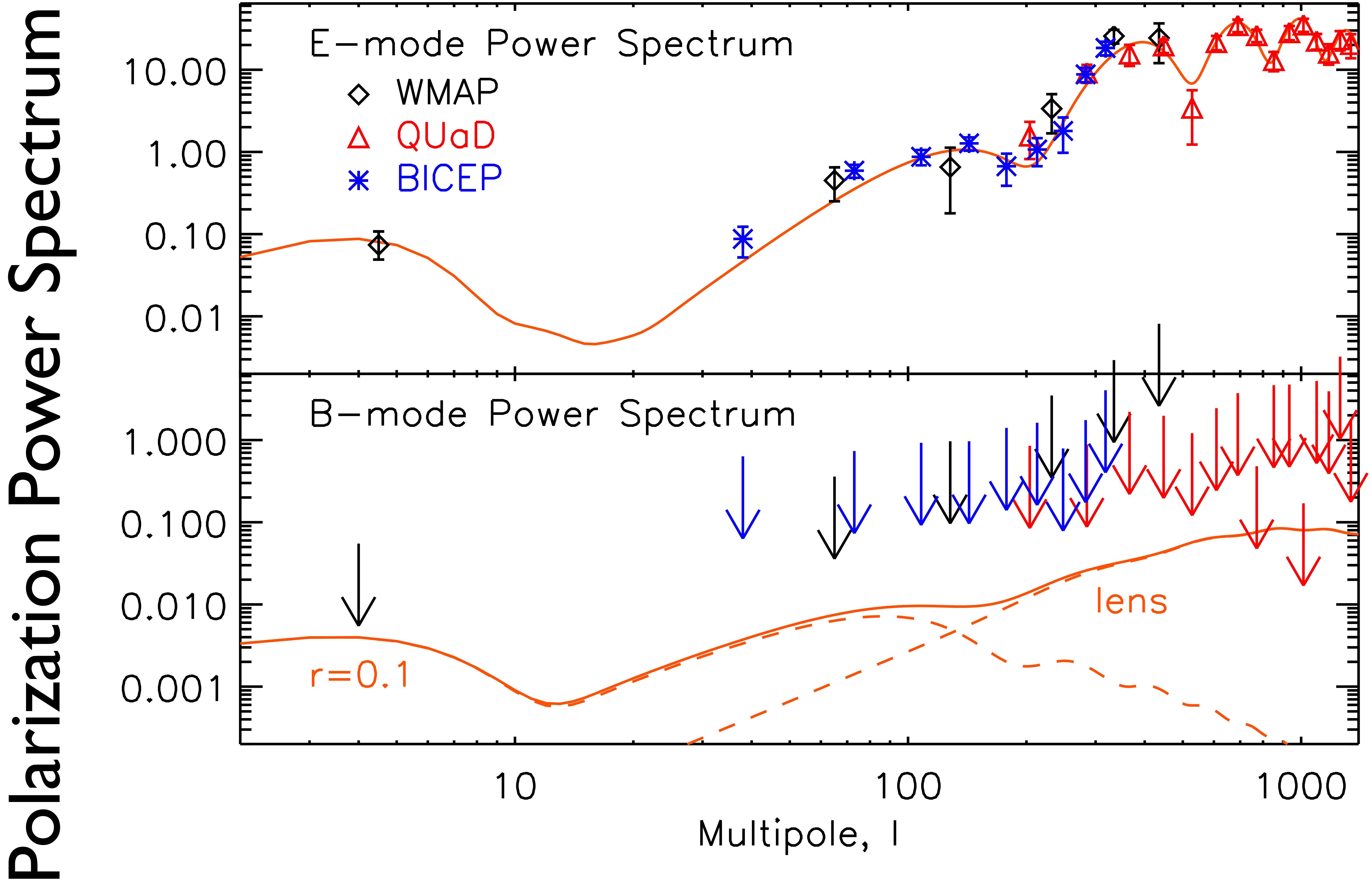


- Stretching of space -> temperature drops
- Contraction of space -> temperature rises

Then to polarisation!



- Polarisation directions are parallel to hot regions

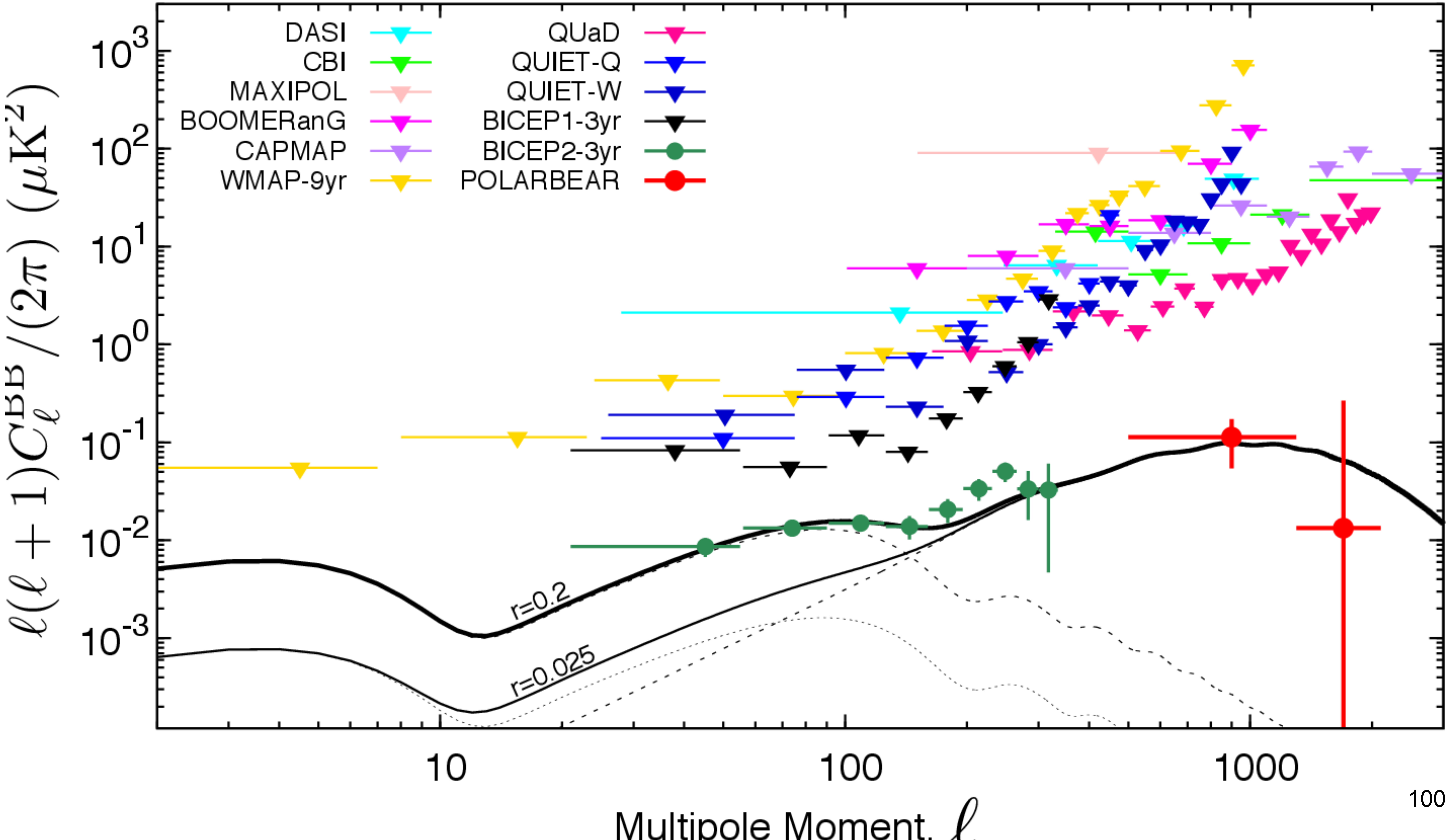


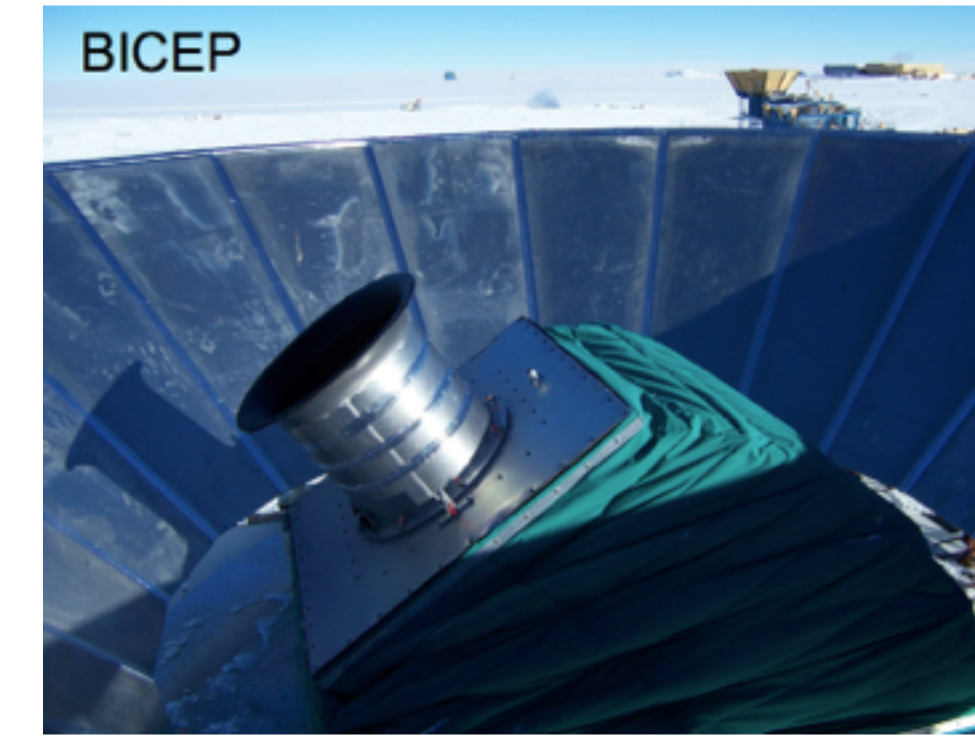
- No detection of B-mode polarization at degree scales, *before March 17*

March 17, 2014

BICEP2’s announcement

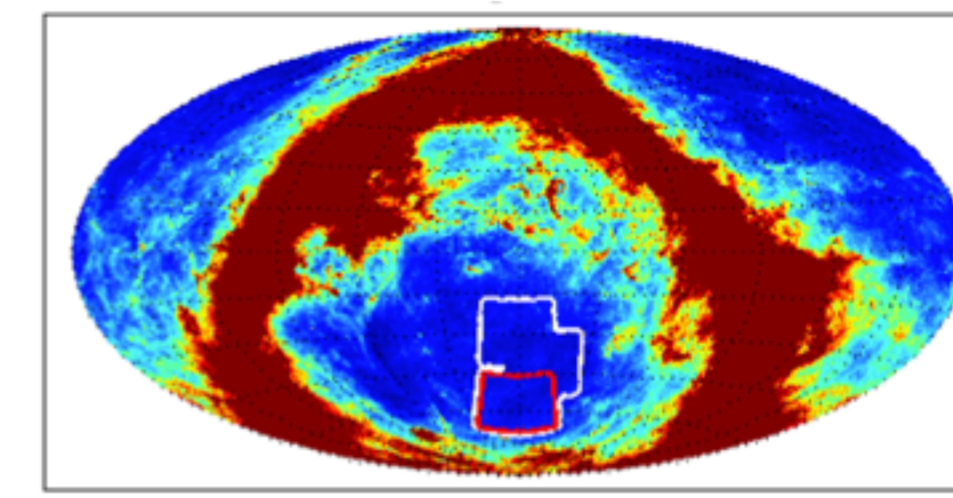
*Courtesy of Yuji Chinone, with the POLARBEAR data points





What is BICEP2?

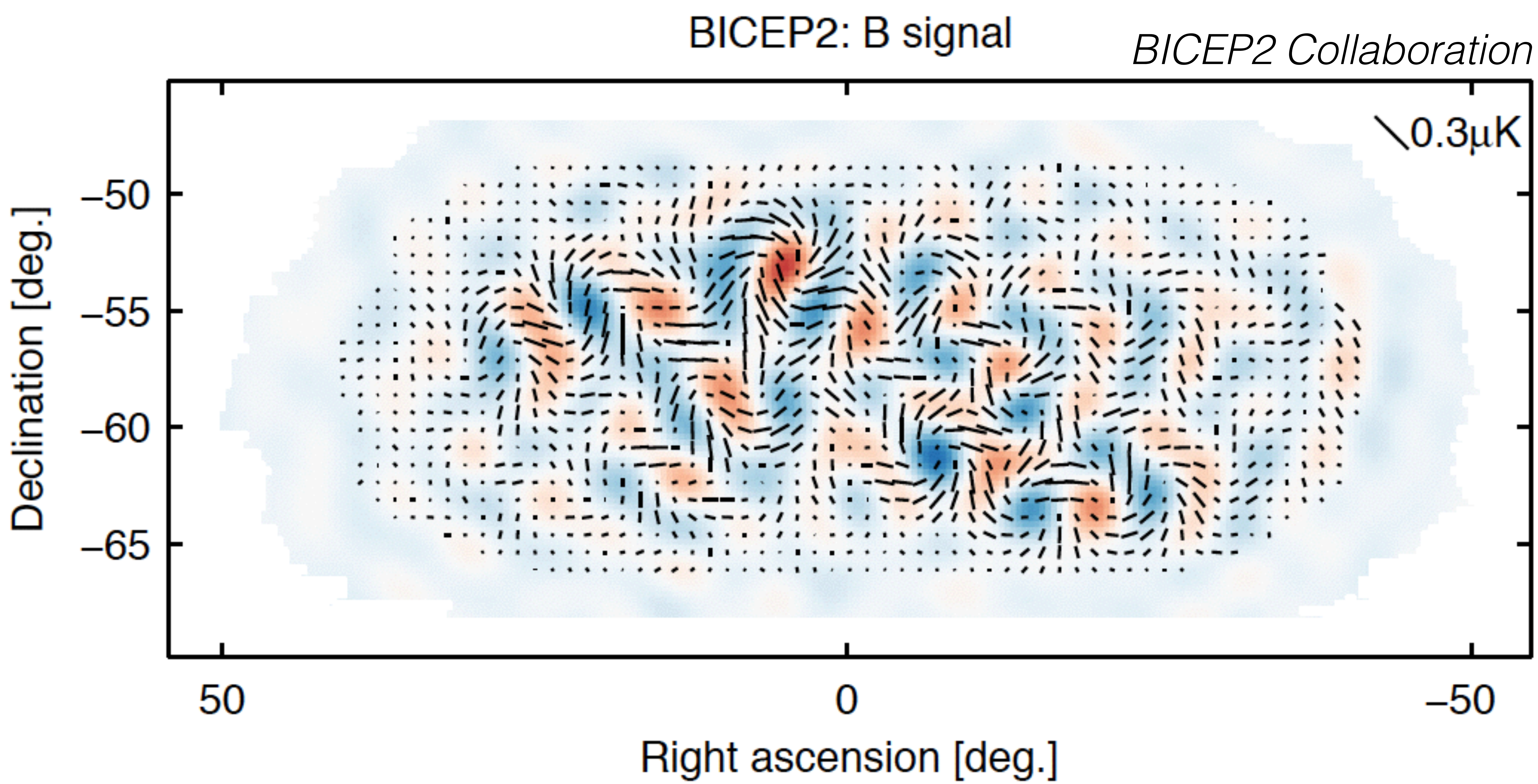
- A small [26 cm] refractive telescope at South Pole
- 512 bolometers working at 150 GHz
- Observed 380 square degrees for three years [2010-2012]



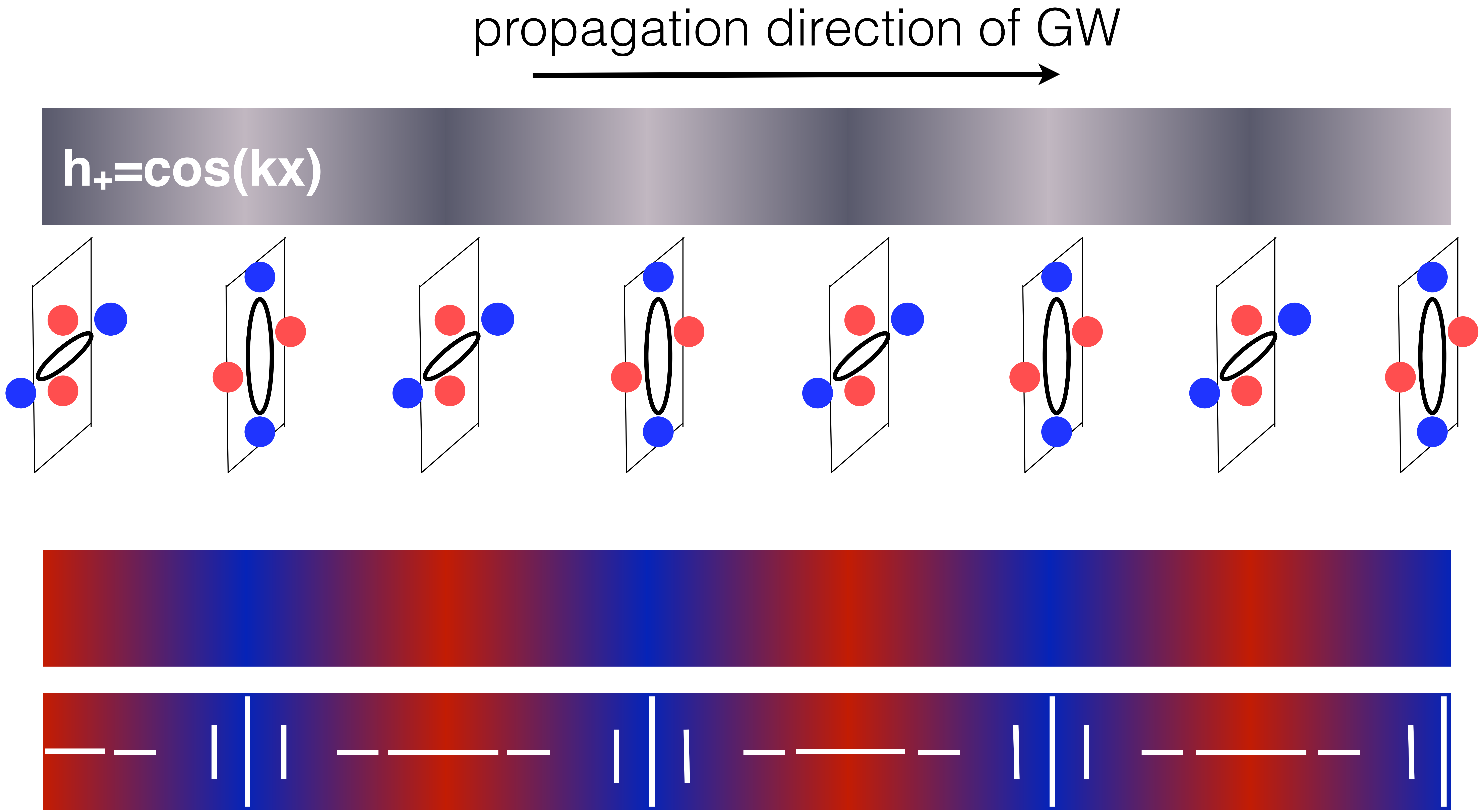
dust

- 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-]

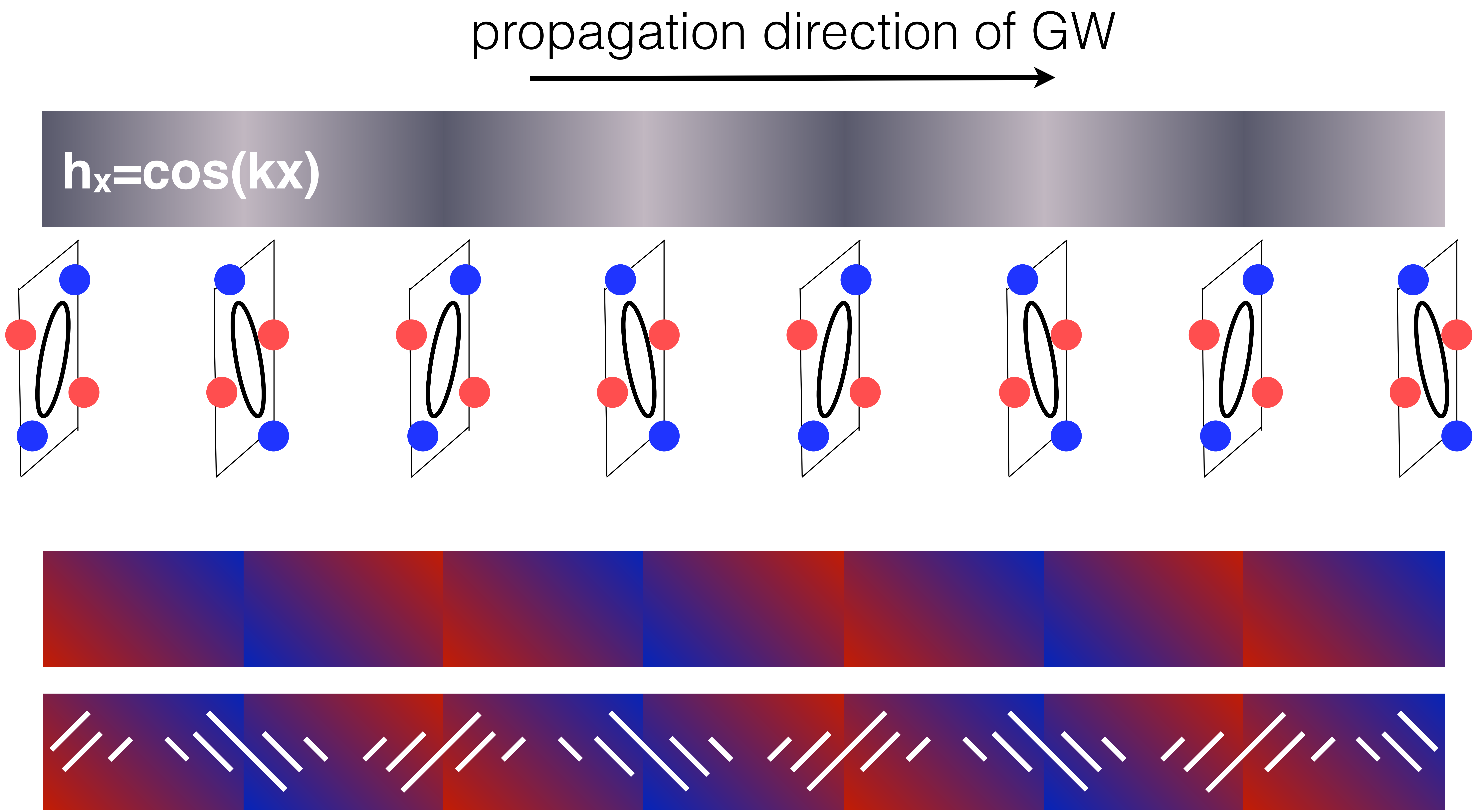
Signature of gravitational waves in the sky [?]



Let’s try to understand what is shown in this plot,
assuming that it is due to gravitational waves



Polarisation directions perpendicular/parallel to the wavenumber vector -> **E mode polarisation**



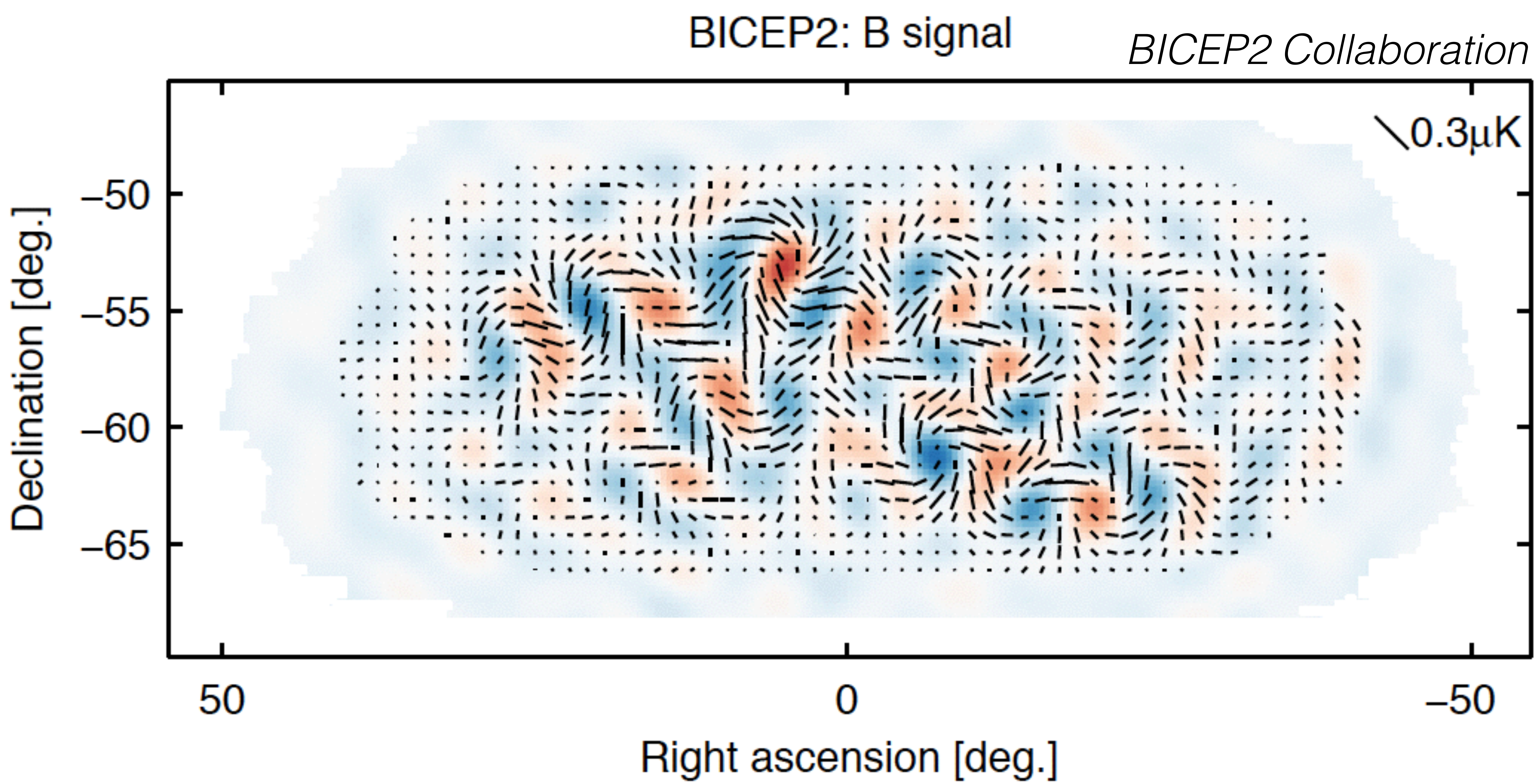
Polarisation directions 45 degrees tilted from to the wavenumber vector -> **B mode polarisation**

Important note:

- Definition of h_+ and $h_\times$ depends on coordinates, but definition of E- and B-mode polarisation does not depend on coordinates
- Therefore, h_+ does not always give E; $h_\times$ does not always give B
    - The important point is that **h_+ and $h_\times$ always coexist**. When a linear combination of h_+ and $h_\times$ produces E, another combination produces B

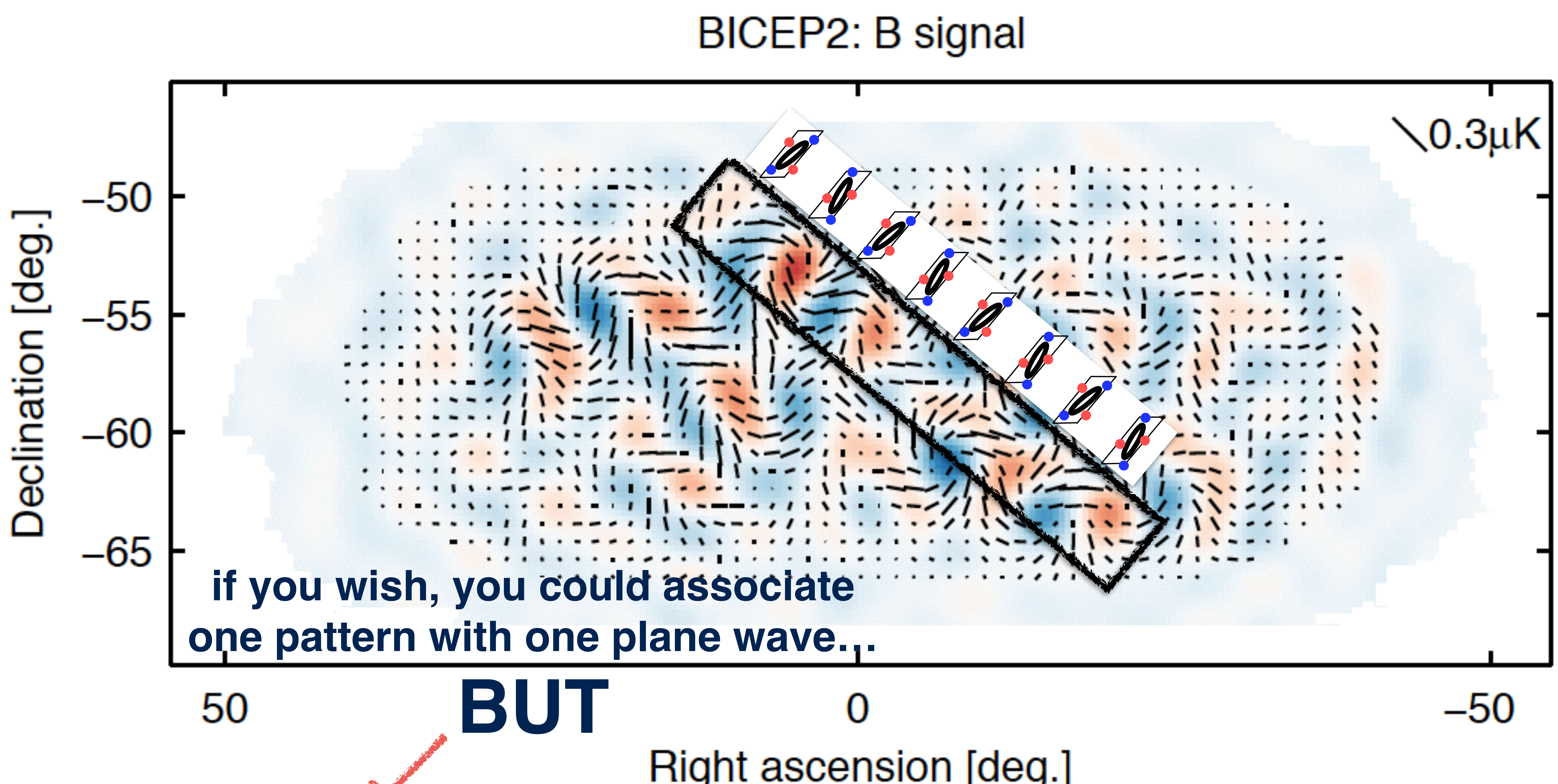
Signature of gravitational waves in the sky [?]

BICEP2 Collaboration



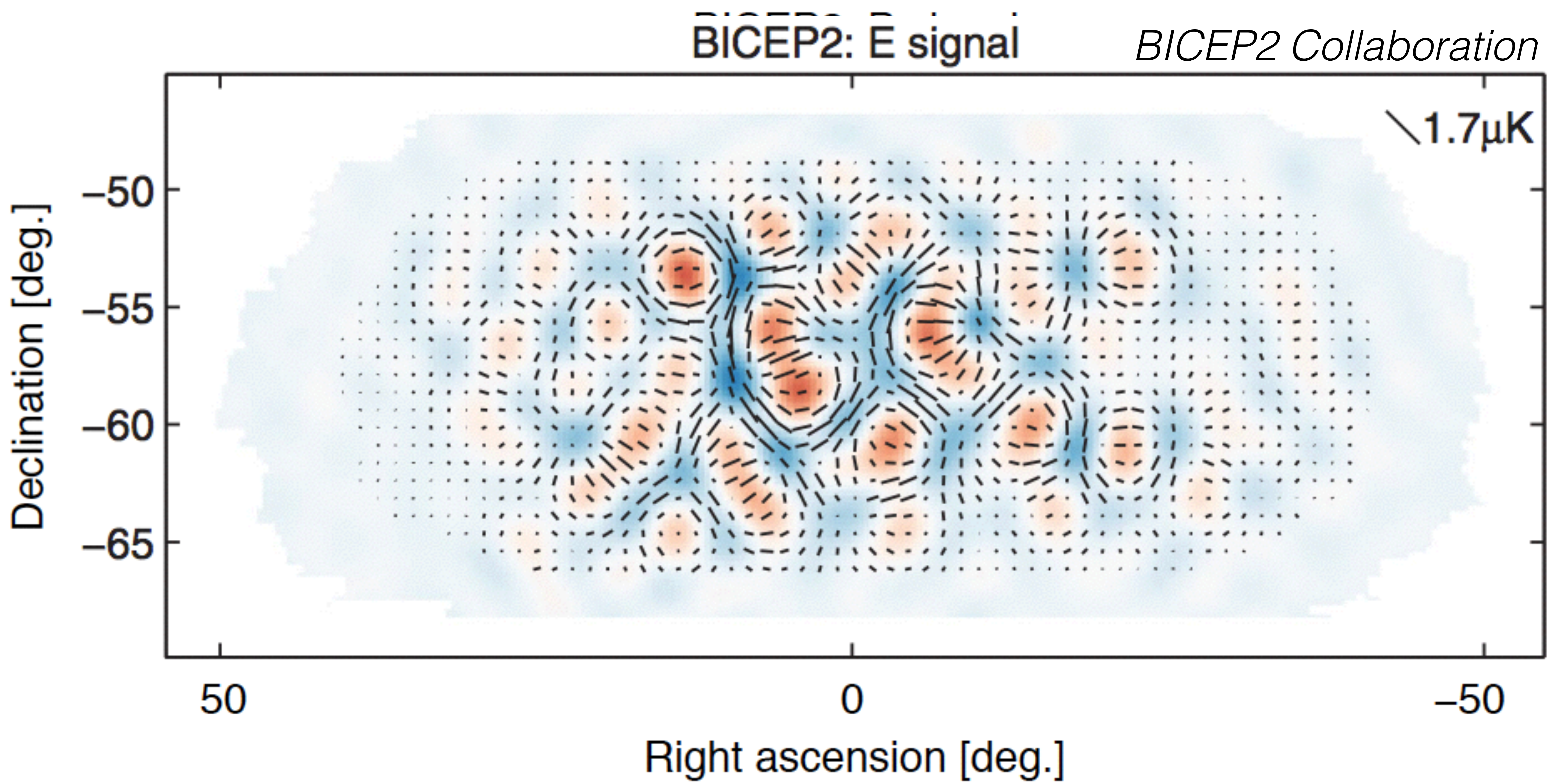
<u>CAUTION</u>: we are NOT seeing a single plane wave propagating perpendicular to our line of sight

Signature of gravitational waves in the sky [?]



CAUTION: we are NOT seeing a single plane wave propagating perpendicular to our line of sight

There are E modes in the sky as well



The E-mode polarisation is totally dominated by the scalar-mode fluctuations [density waves]

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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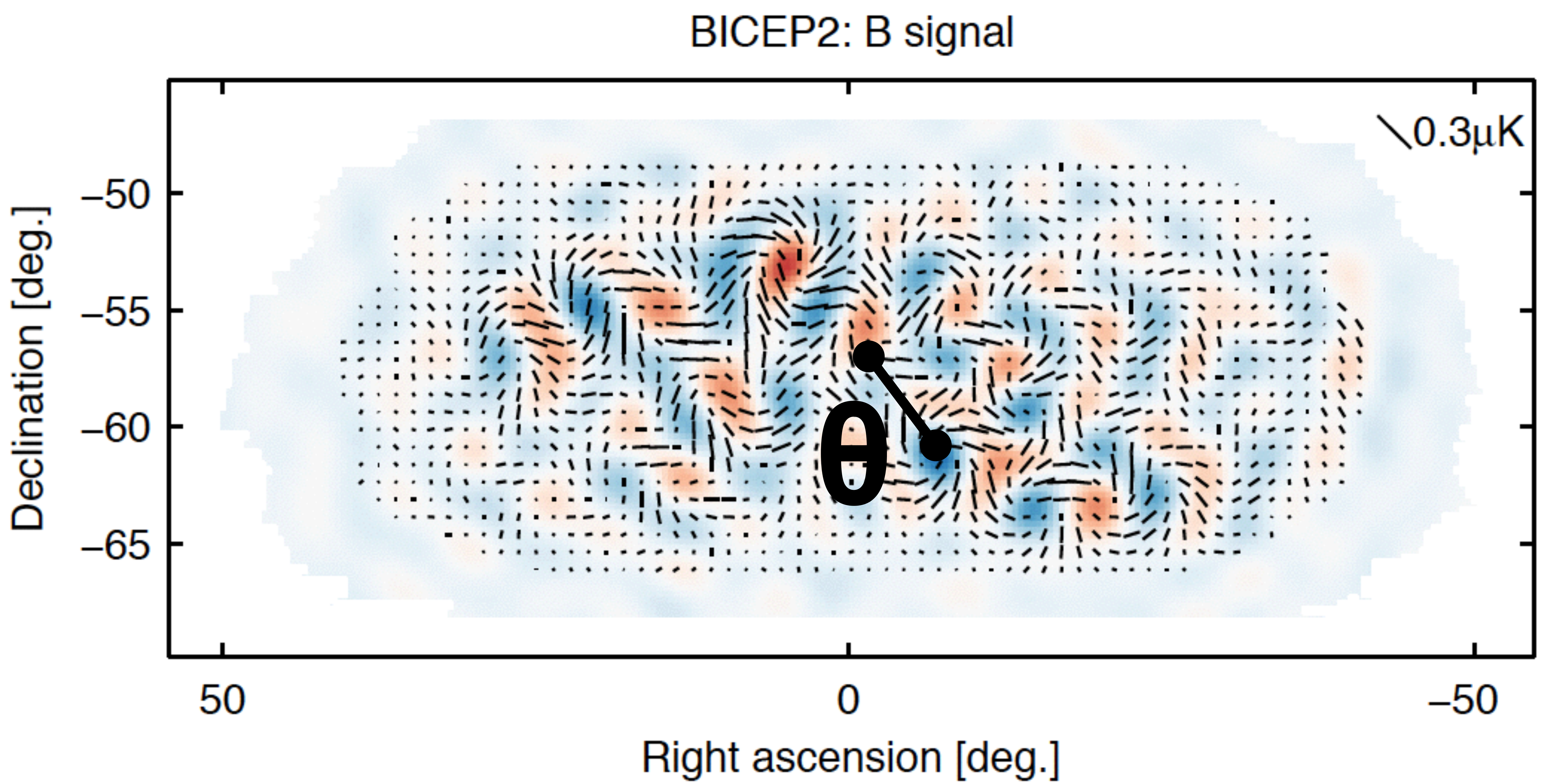
facebook

Analysis: Two-point Correlation Function

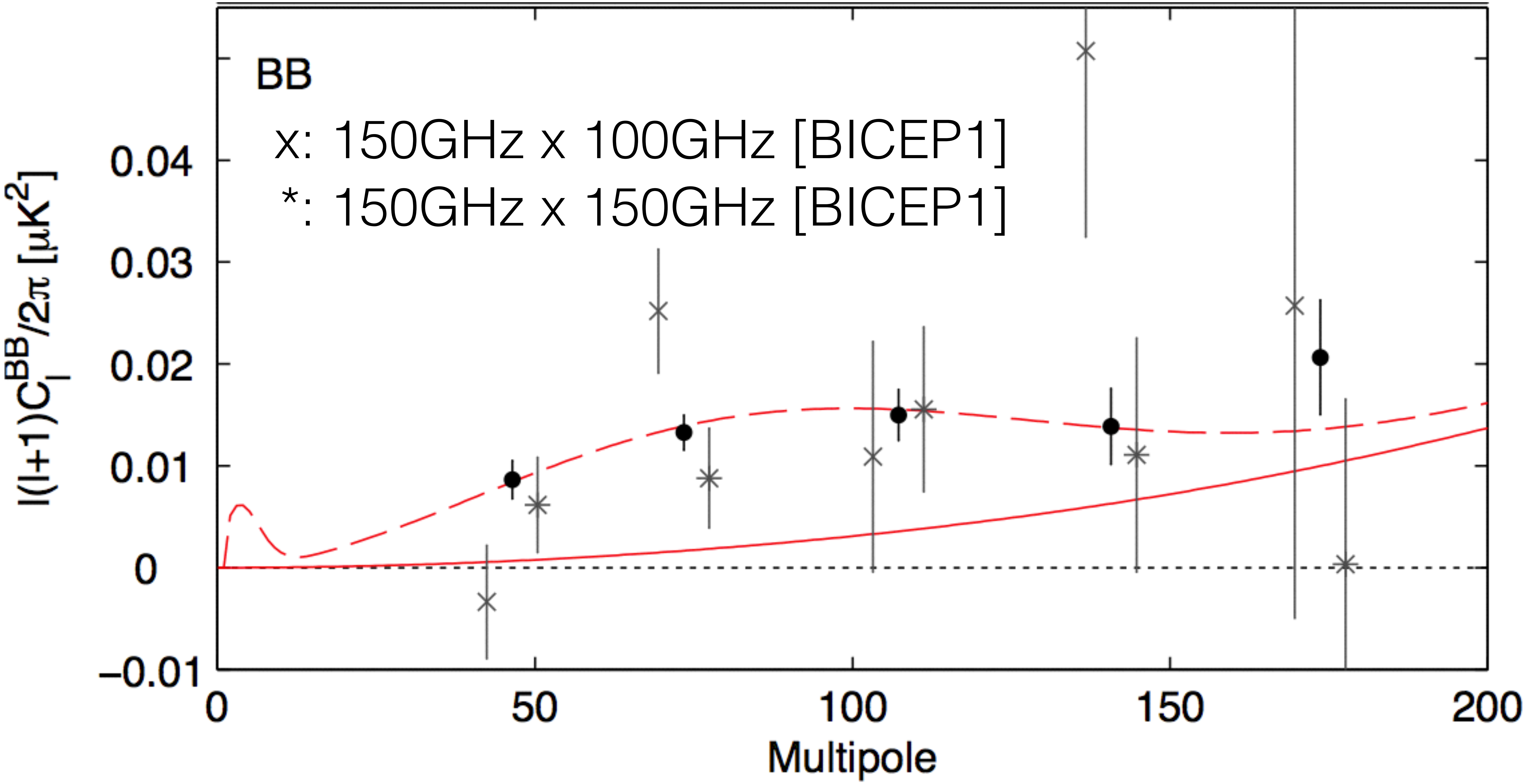


$$C(\theta) = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C_\ell P_\ell(\cos\theta)$$

C_ℓ is the "power spectrum" with

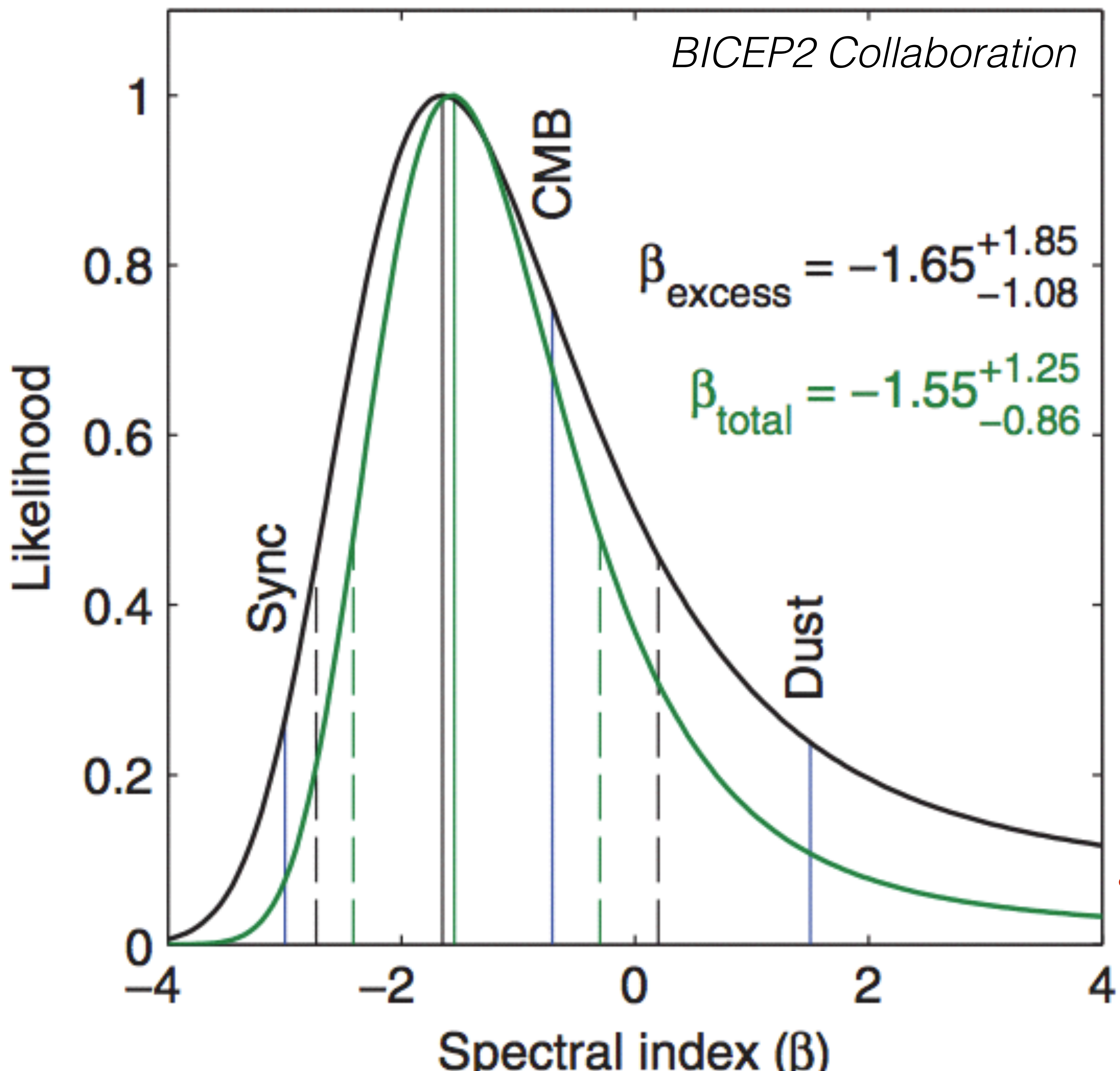
$$\ell \approx \frac{\pi}{\theta}$$

BICEP2 Collaboration



No 100 GHz x 100 GHz [yet]

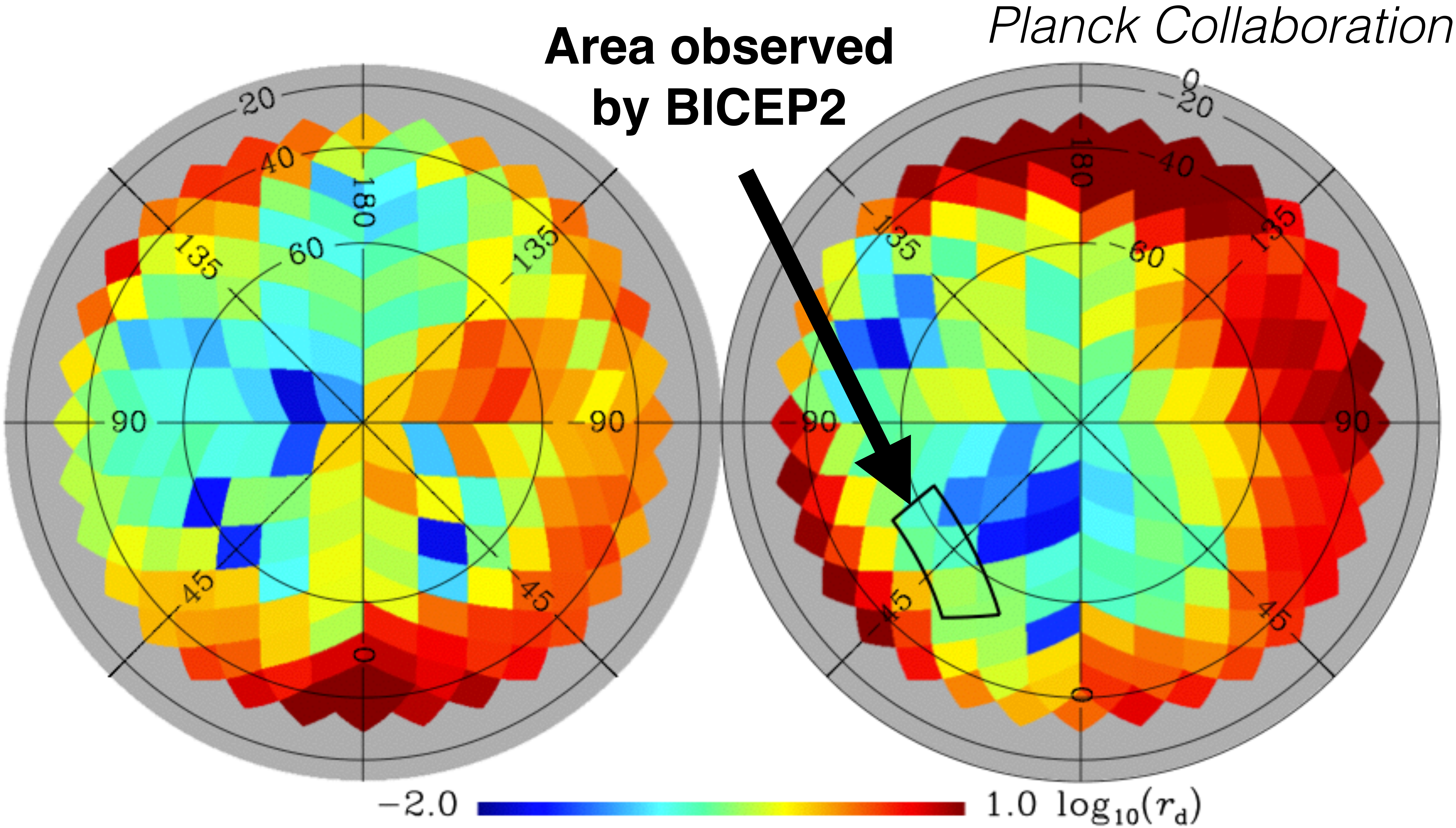
Can we rule out synchrotron or dust?



- **The answer is No**

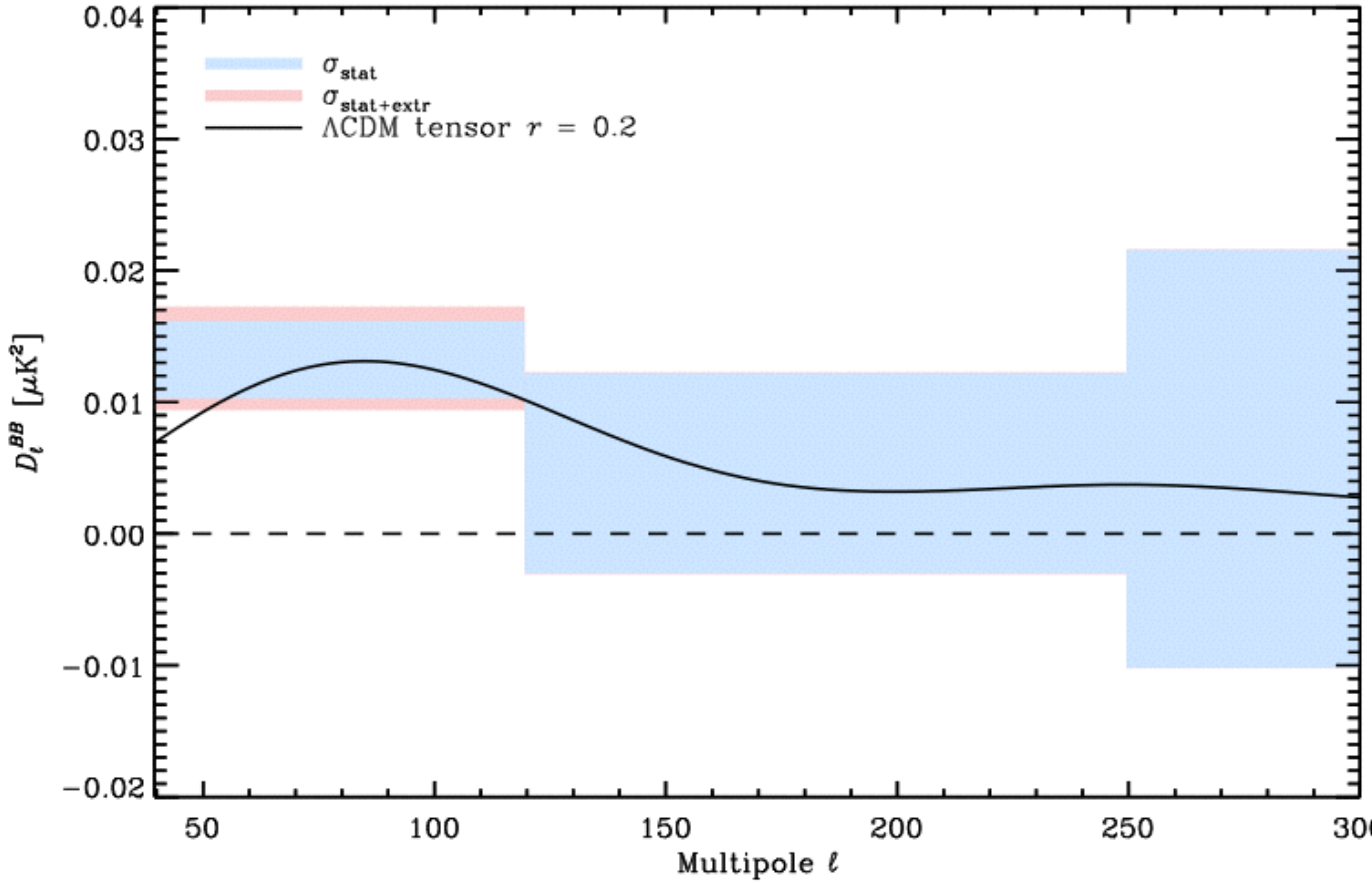
September 22, 2014

Planck’s Intermediate Paper on Dust



- Values of the “tensor-to-scalar ratio” equivalent to the B-mode power spectrum seen at various locations in the sky

Planck Collaboration



- Planck measured the B-mode power spectrum at 353 GHz well
- Extrapolating it down to 150 GHz appears to explain all of the signal seen by BICEP2…

Previous Situation [before Monday]

- No strong evidence that the detected signal is not cosmological
- No strong evidence that the detected signal is cosmological, either

Current Situation

- Planck shows the evidence that the detected signal is not cosmological, but is due to dust
- No strong evidence that the detected signal is cosmological