

# Results from the Wilkinson Microwave Anisotropy Probe (WMAP)

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Deutsche Physikalische Gesellschaft, March 16, 2015



# Cosmology, where GR is **absolutely essential**

- The distance between two points in space increases because of dynamical space, as predicted by GR

$$ds^2 = -dt^2 + a^2(t)d\mathbf{x}^2$$

- Einstein's field equations relate changes in  $a(t)$  to the energy contents of the universe:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

# Hubble Scale

- The most important scale in cosmology is the “Hubble scale”.
- The Hubble expansion rate,  $H(t)$ , is defined by

$$H(t) \equiv \frac{\dot{a}}{a}$$

- The Hubble time,  $1/H$ , is roughly equal to the age of the Universe
- The Hubble length,  $c/H$ , is roughly equal to the radius of the visible Universe (i.e., “horizon size”)

# Hubble Scale

$$H(t) \equiv \frac{\dot{a}}{a}$$

- The Hubble time,  $1/H$ , is roughly equal to the age of the Universe
- The Hubble length,  $c/H$ , is roughly equal to the radius of the visible Universe (i.e., “horizon size”) at a given time
- **The Newtonian picture breaks down completely on or above the Hubble length. GR is essential**



# Inhomogeneous Universe

- Ignoring gravitational waves, the distance between two points in spacetime is given by (in Newtonian gauge):

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(t)(1 + 2\Phi)d\mathbf{x}^2$$

- Einstein's field equations determine the evolution of two potentials  $\Phi$  and  $\Psi$ , given perturbations in the energy contents of the Universe
- These potentials then determine, e.g., how photons lose or gain energy as they propagate through an inhomogeneous universe

# Propagation of photons in an inhomogeneous universe

- The geodesic equation for the photon 4-momentum:

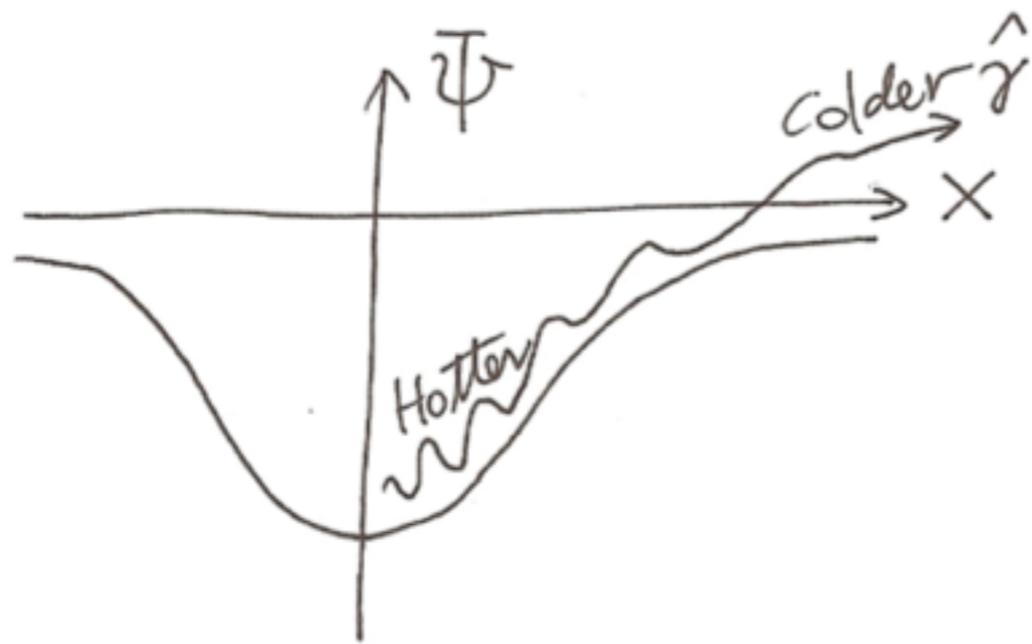
$$\frac{dp^\mu}{d\lambda} + \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta = 0$$

- determines the evolution of the photon energy in an inhomogeneous universe as

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

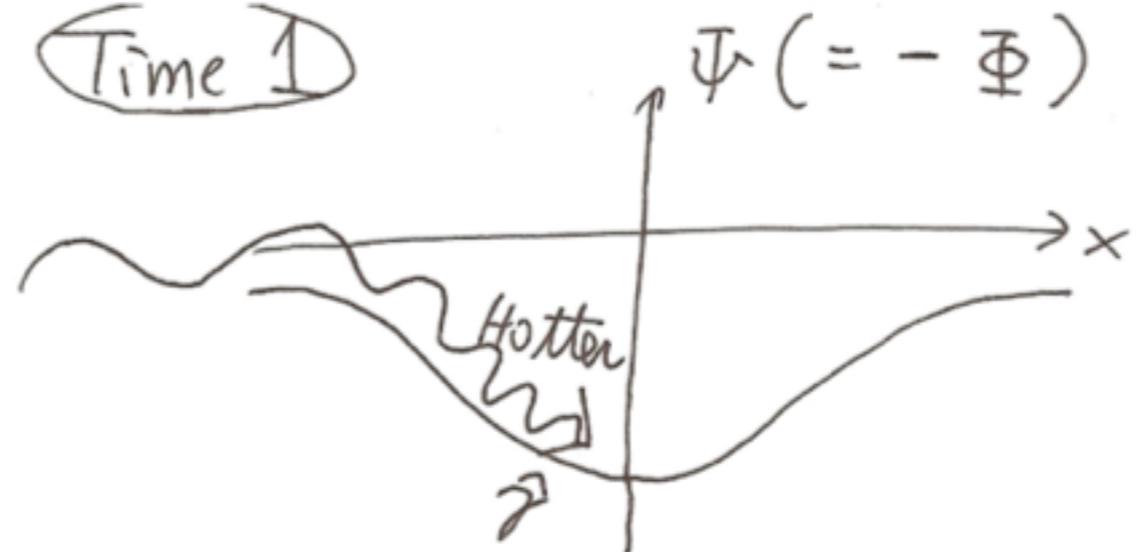
$$\ln(ap)_O = \ln(ap)_E + (\Psi_E - \Psi_O) + \int_{t_E}^{t_O} dt \frac{\partial}{\partial t} (\Psi - \Phi)$$

“O” and “E” denote the observed and emitted epochs

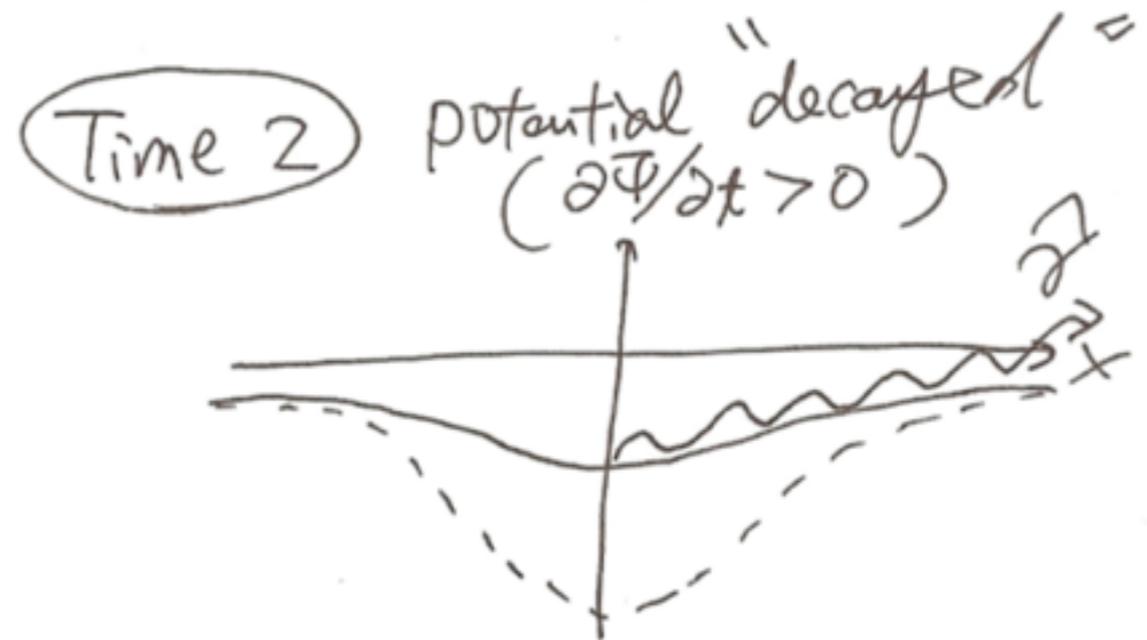


$$\frac{1}{p} \frac{dp}{dt} = -\frac{\gamma^i}{a} \frac{\partial \Psi}{\partial x^i}$$

Time 1



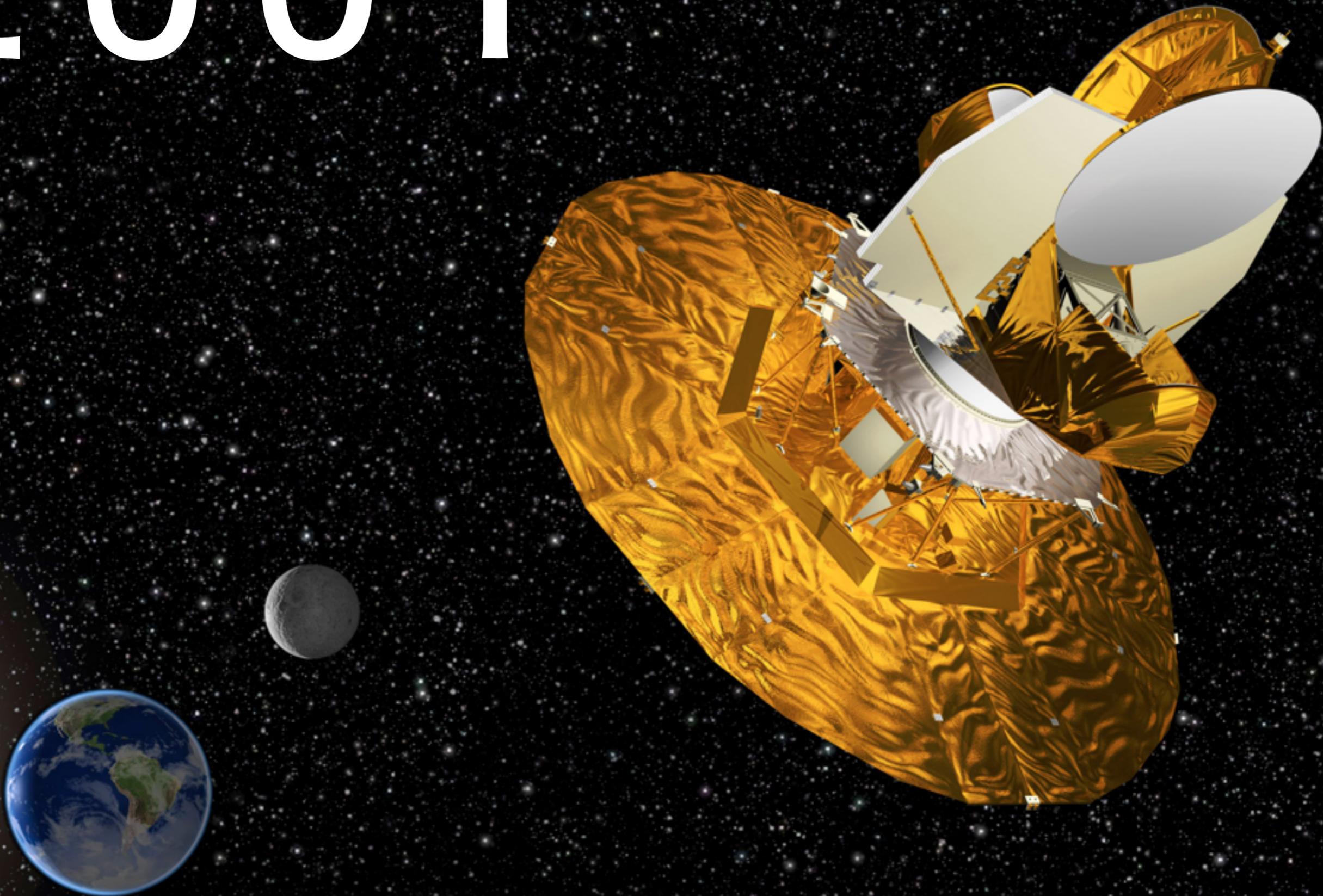
Time 2



⇒ Net Gain of Energy

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

2001

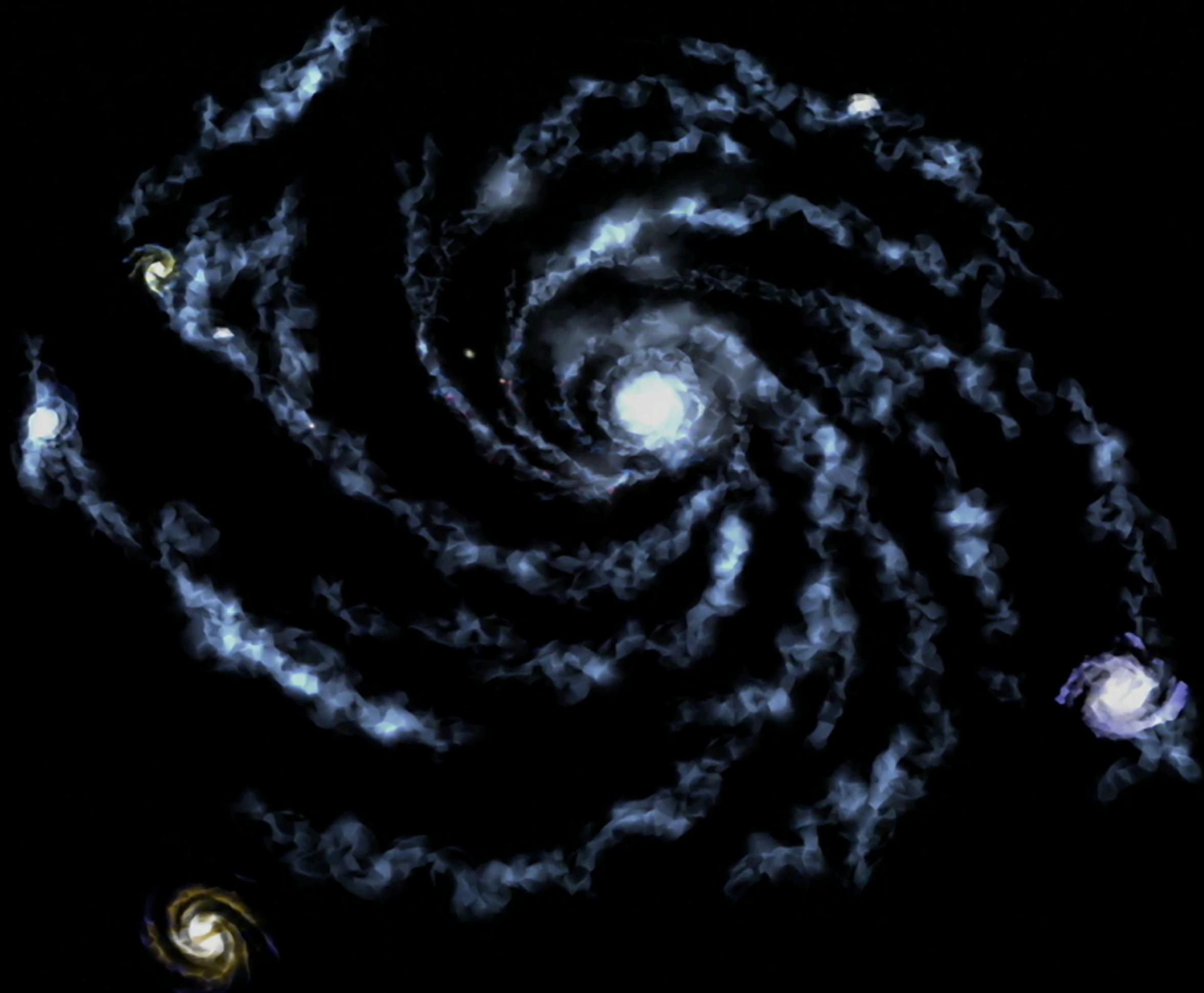


# WMAP Science Team

July 19, 2002

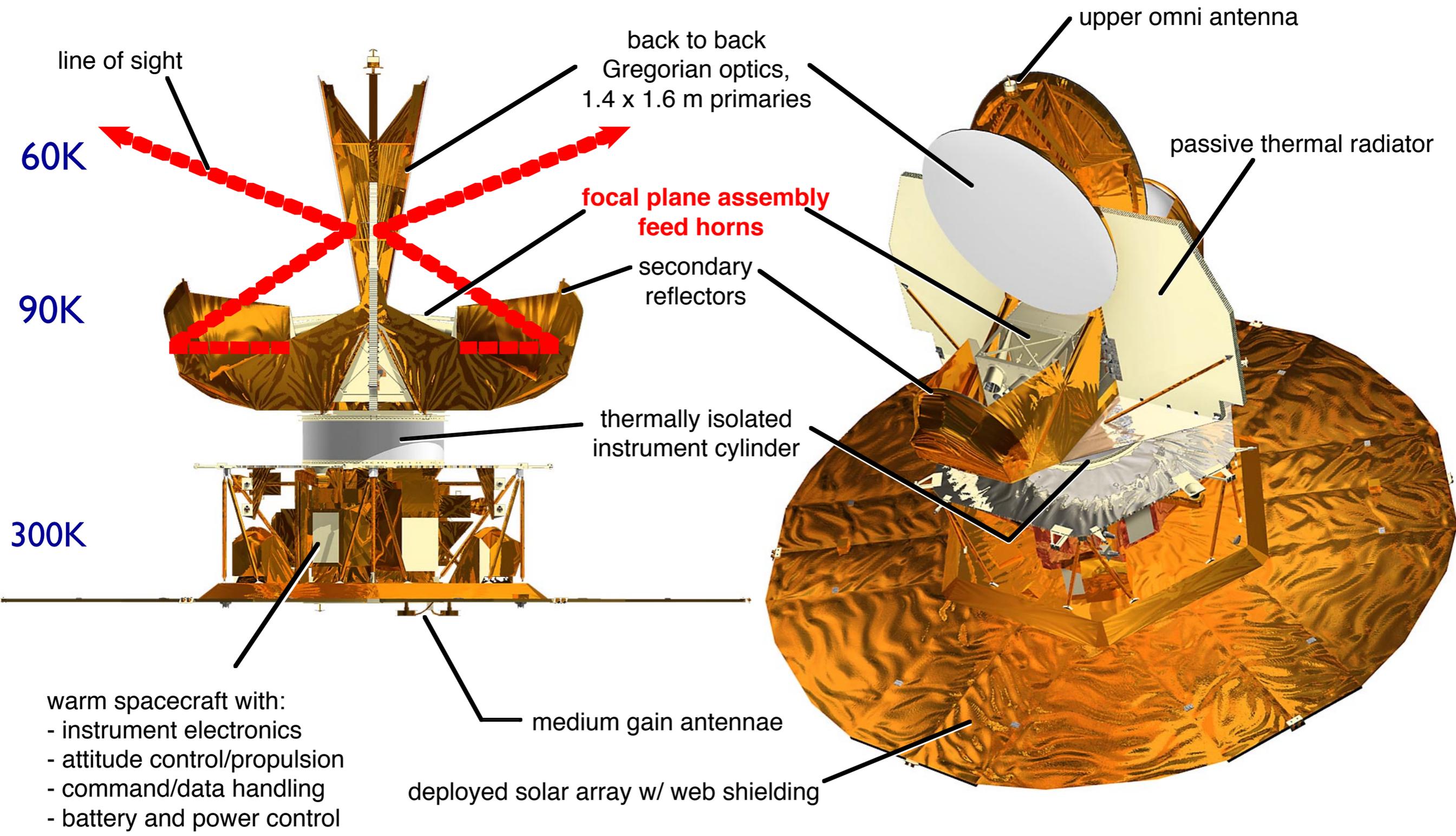


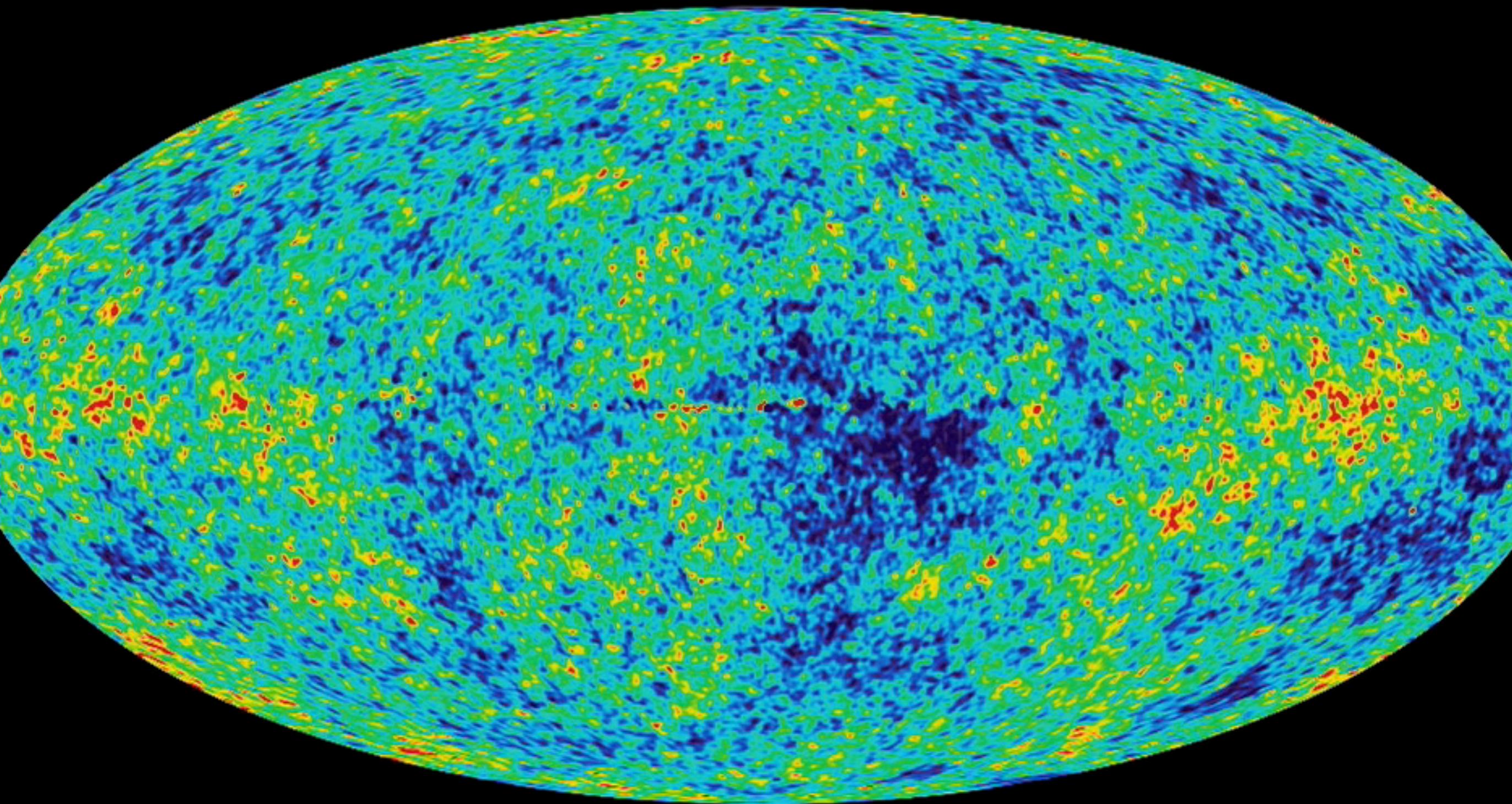
- WMAP was launched on June 30, 2001
- The WMAP mission ended after 9 years of operation

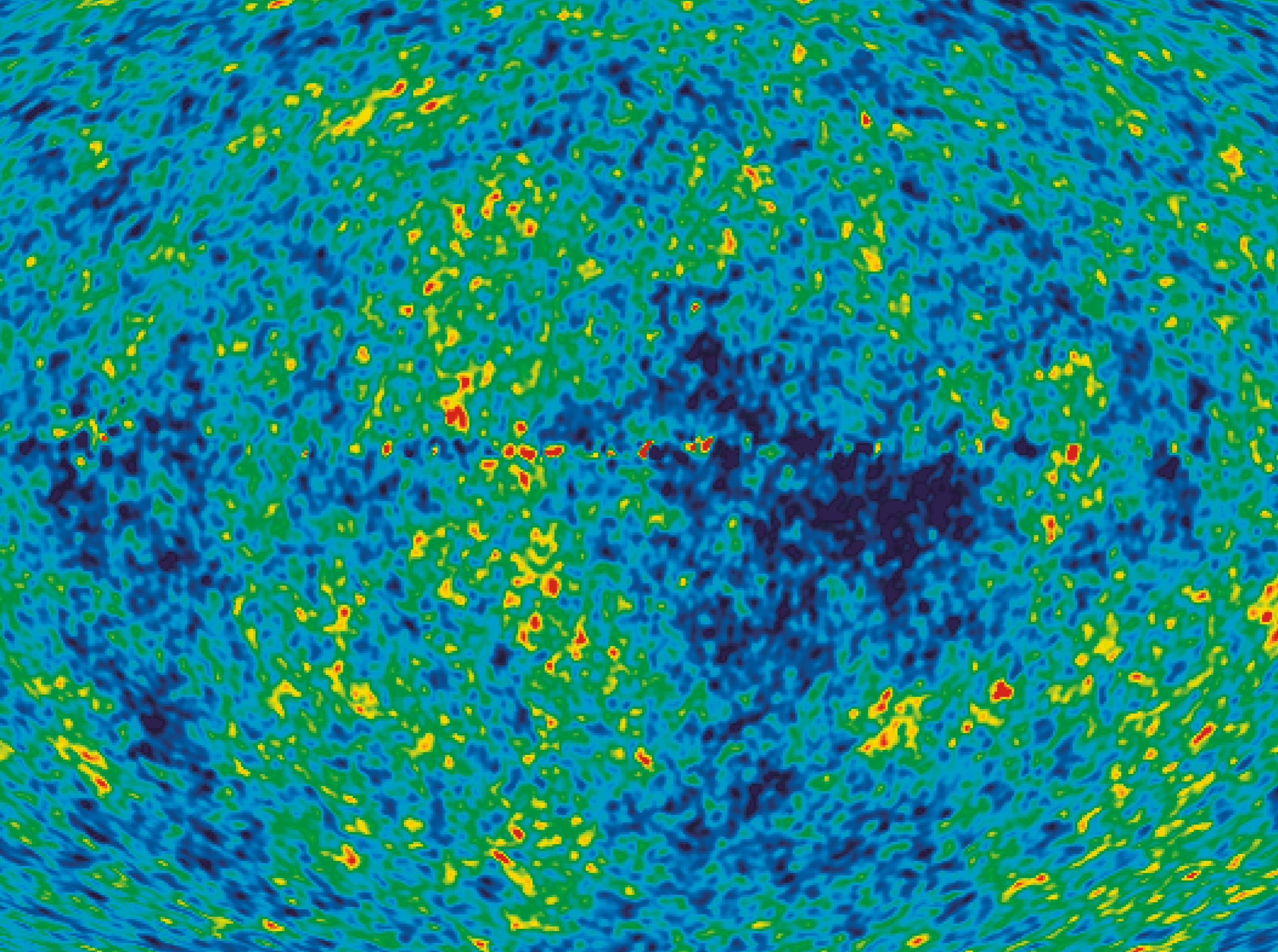


# WMAP Spacecraft

## No cryogenic components







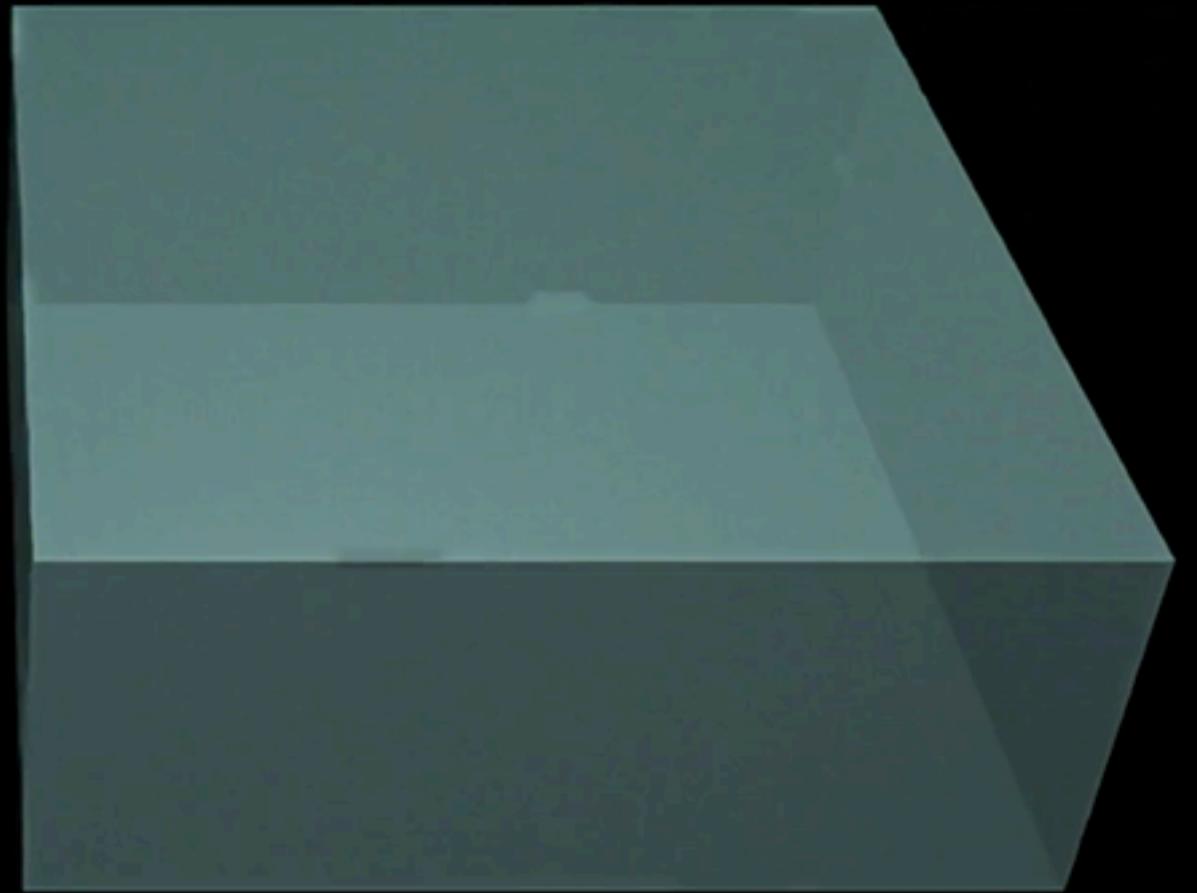
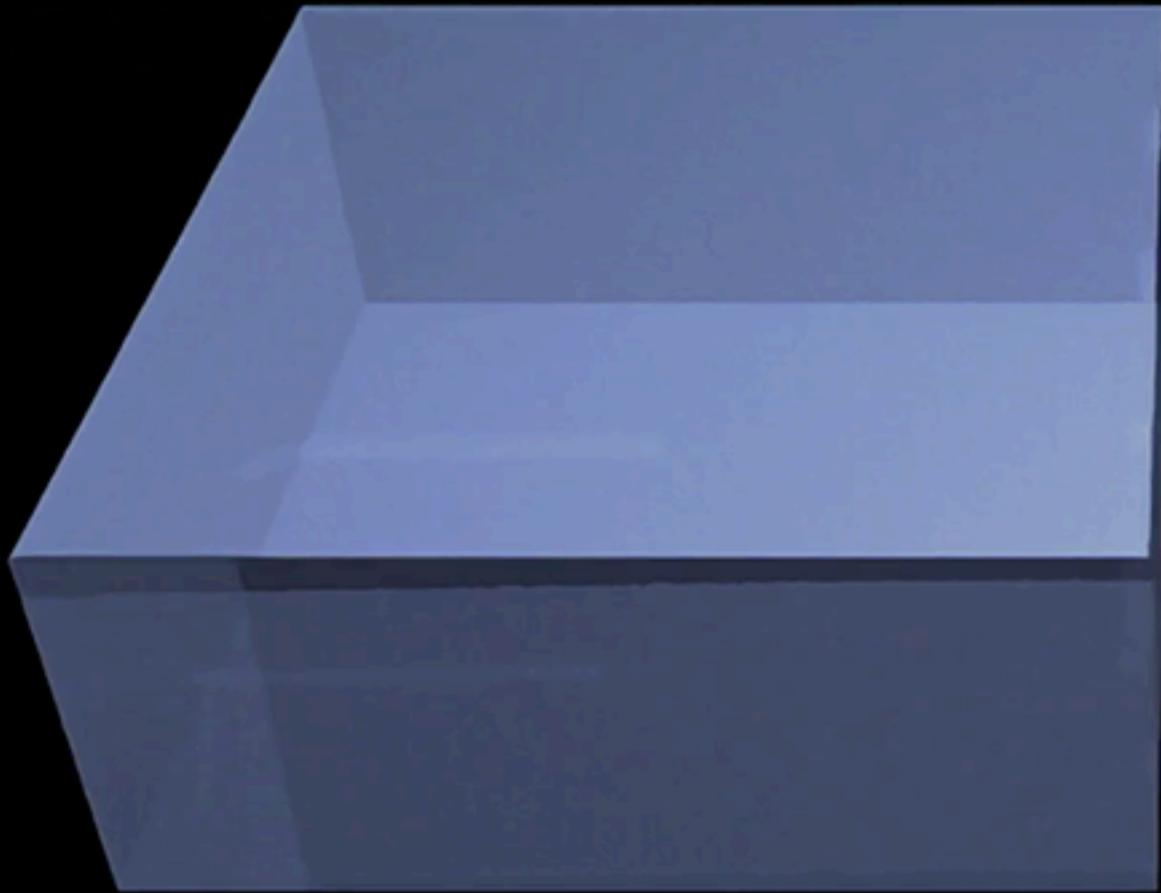
# Our Origin

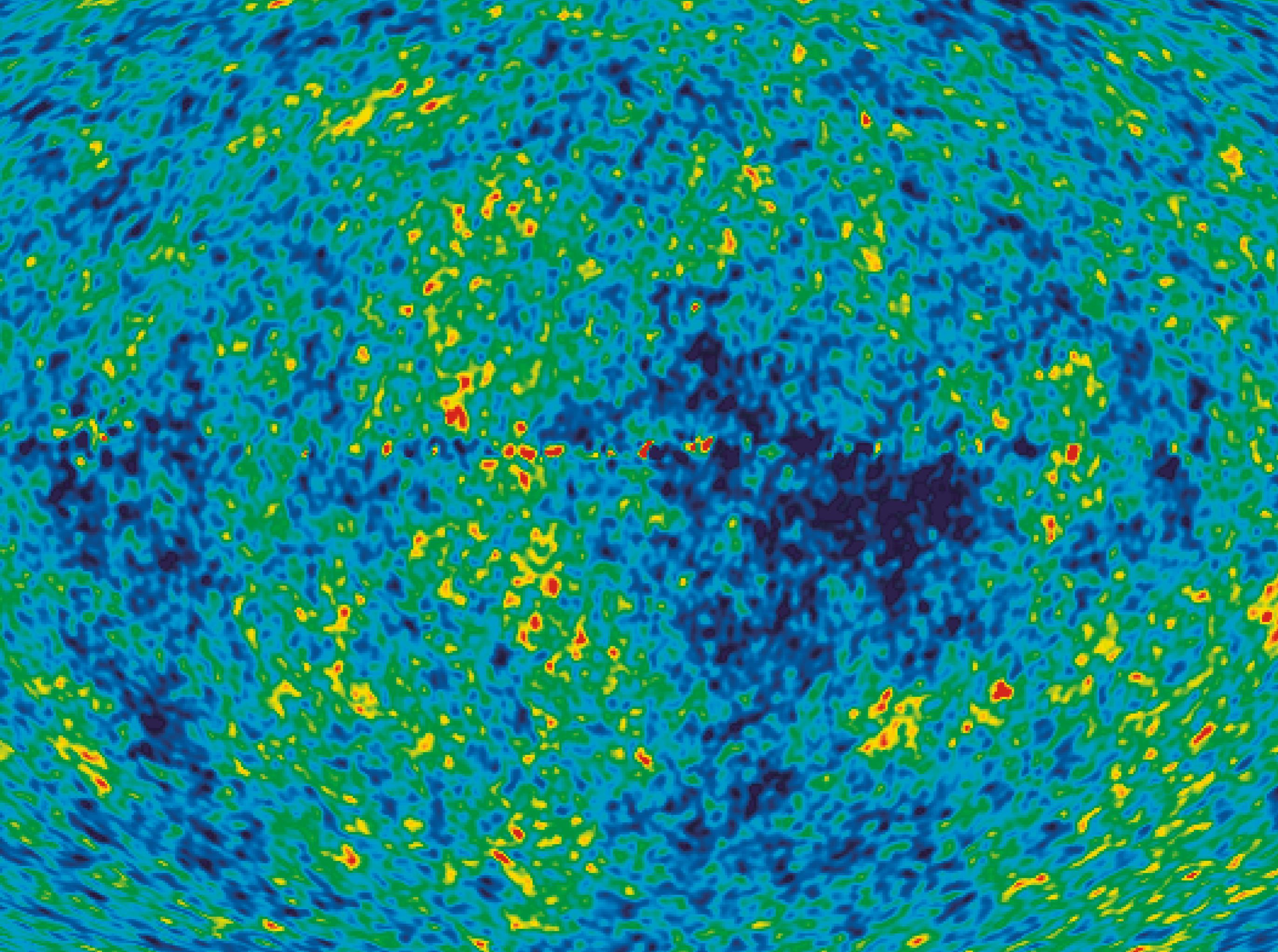
- WMAP taught us that **galaxies, stars, planets, and ourselves originated from tiny fluctuations in the early Universe**



# Kosmische Miso Suppe

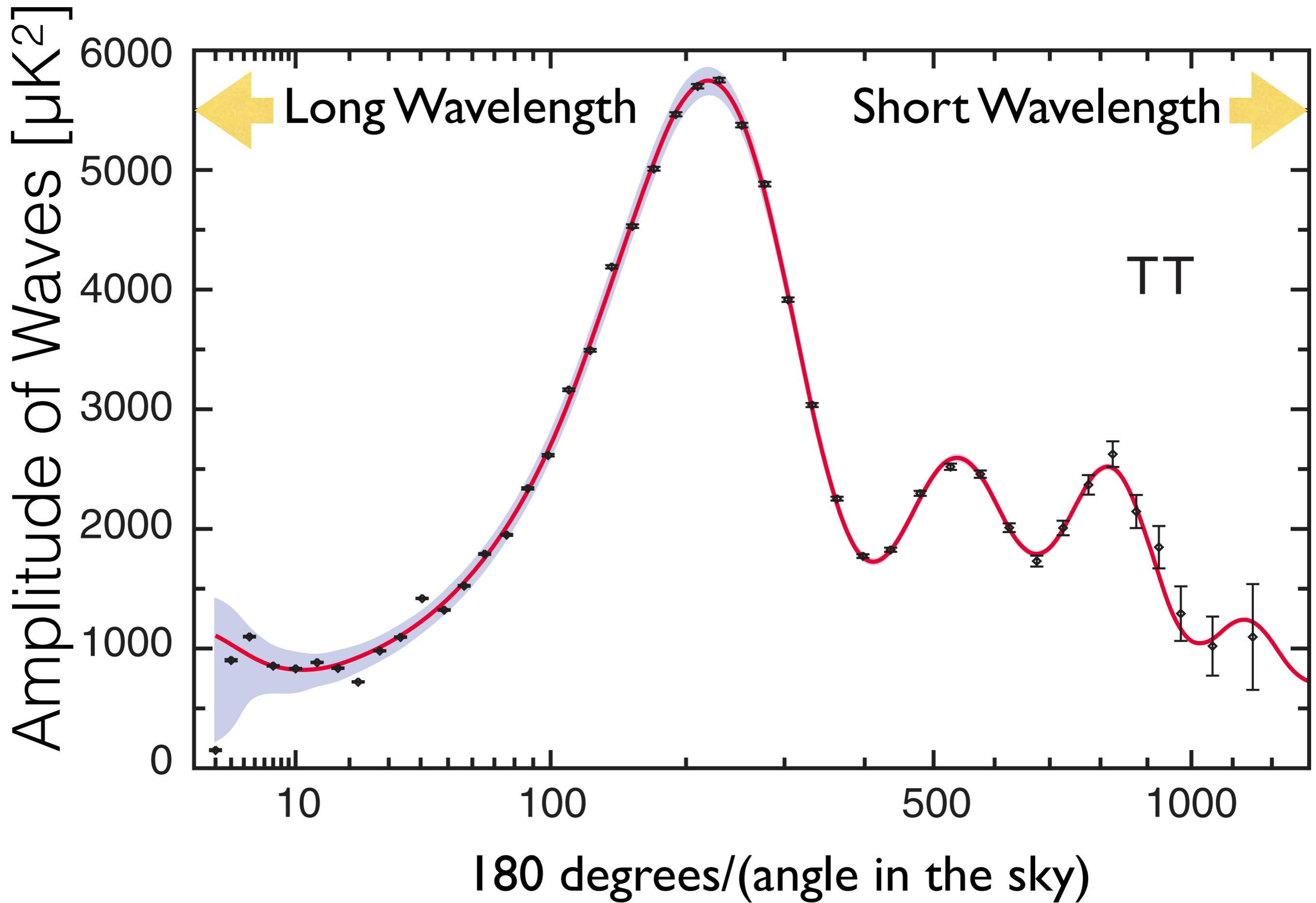
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching how ripples are created and propagate throughout the soup

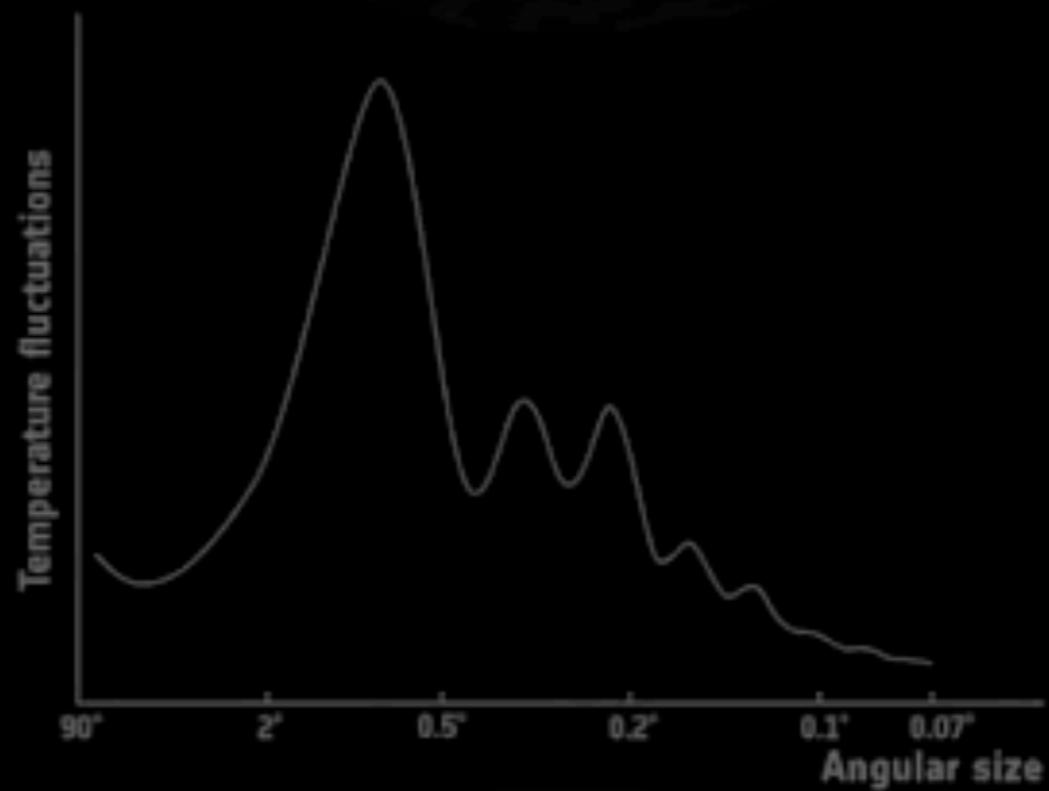




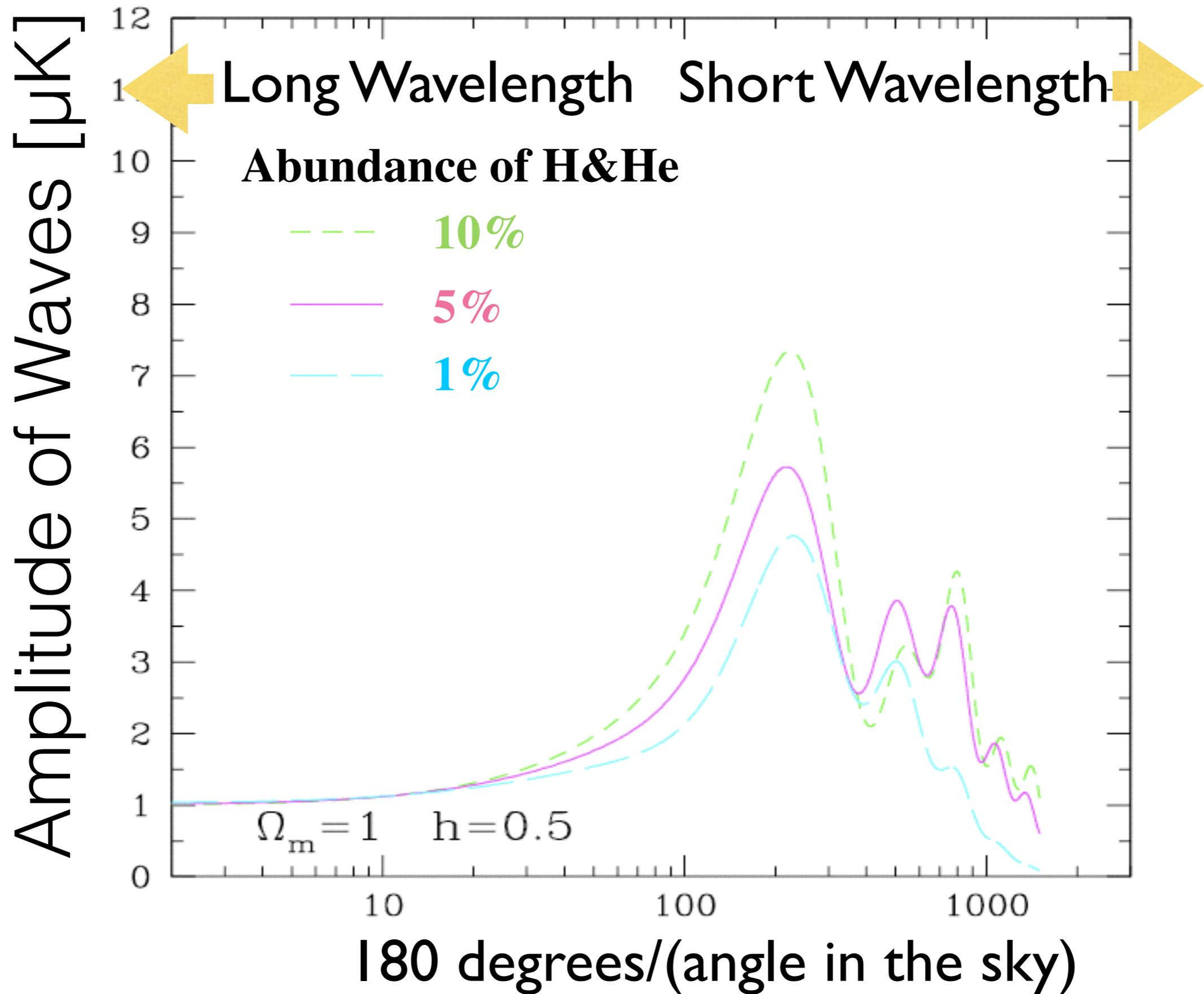
# Data Analysis

- Decompose temperature fluctuations in the sky into a set of waves with various wavelengths
- Make a diagram showing the strength of each wavelength





# Measuring Abundance of H&He



# How baryons and photons move together

- “Baryons” = protons and helium nuclei

$$\dot{\delta}_B = -\frac{k}{a}V_B - 3\dot{\Phi},$$

$$\dot{\delta}_\gamma = -\frac{4k}{3a}V_\gamma - 4\dot{\Phi}, \quad R \equiv 3\rho_B/(4\rho_\gamma)$$

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

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

Combine three equations into one and simplify using

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

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

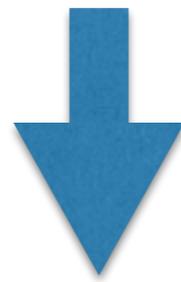
$$R \equiv 3\rho_B / (4\rho_\gamma)$$

- Wave equation! With the “speed of sound” given by the speed of light times  $1/\sqrt{3(1 + R)}$

# Solution: The Acoustic Oscillation!

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

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



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

$r_s$  is the “sound horizon” defined by  $r_s \equiv \int_0^{t^*} c_s \frac{dt}{a} = 147 \text{ Mpc}$

# Adiabatic Initial Condition

- On “super horizon scales”, where the wavelength of fluctuations is larger than the horizon size, the fluctuations are set by the initial conditions

- Adiabatic initial condition:  $\frac{1}{4}\delta_\gamma = \frac{1}{3}\delta_m = \frac{2}{3}\Phi$

- Thus:

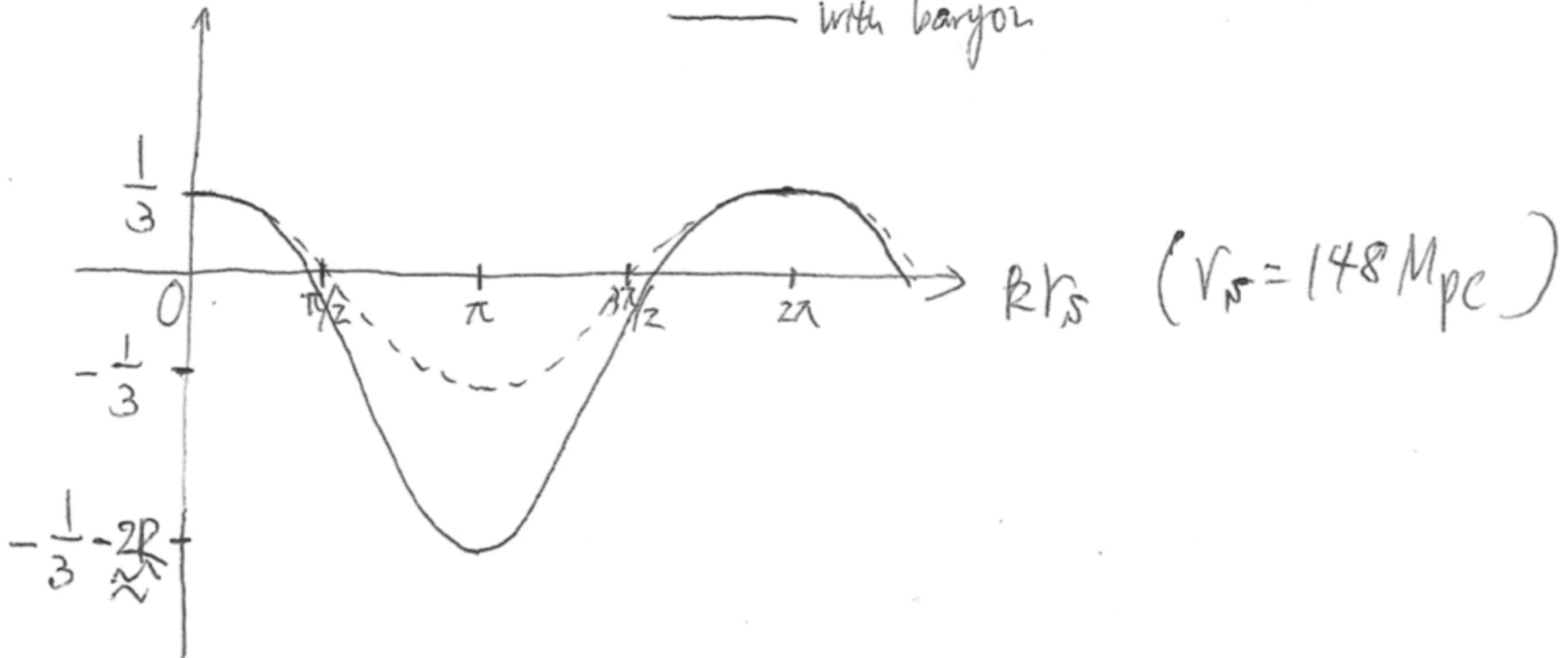
$$\frac{1}{4}\delta_\gamma = (1 + R)\Phi - \left(\frac{1}{3} + R\right)\Phi \cos(kr_s)$$

# How baryons affect photon density fluctuations

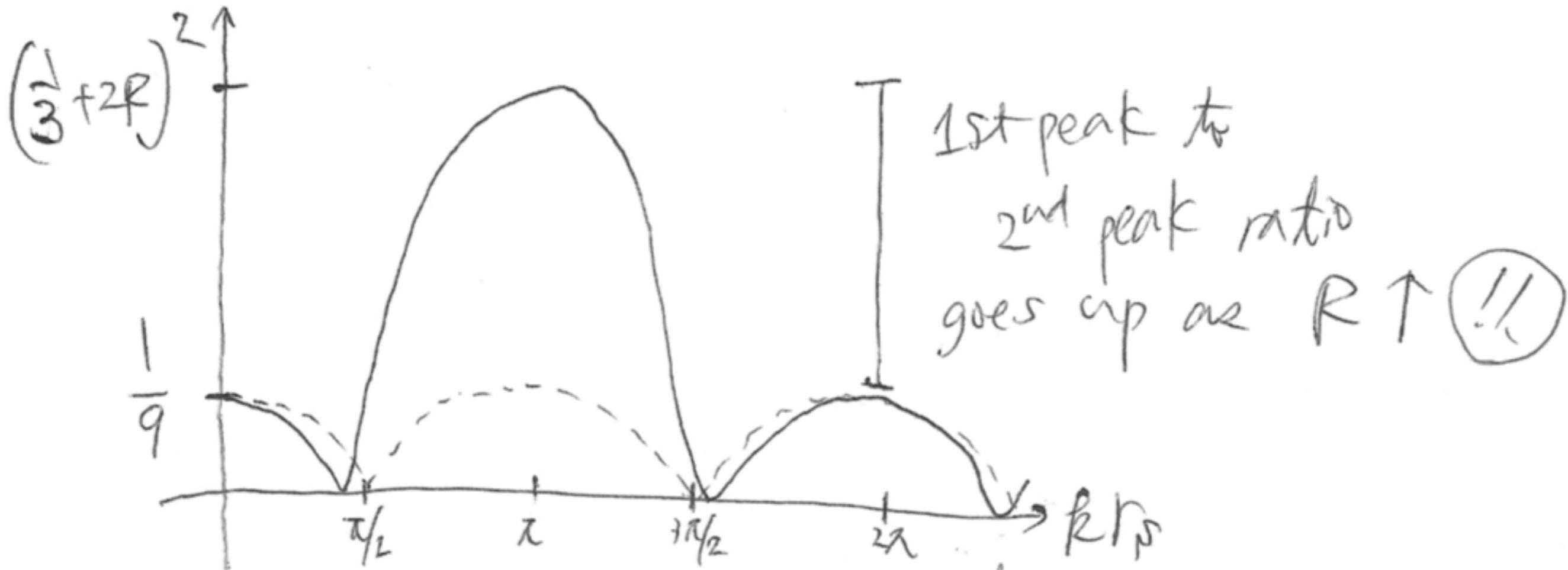
$$\left(\frac{1}{4}\delta_\gamma + \bar{\Psi}\right) / \bar{\Psi}$$

--- No baryon

— with baryon

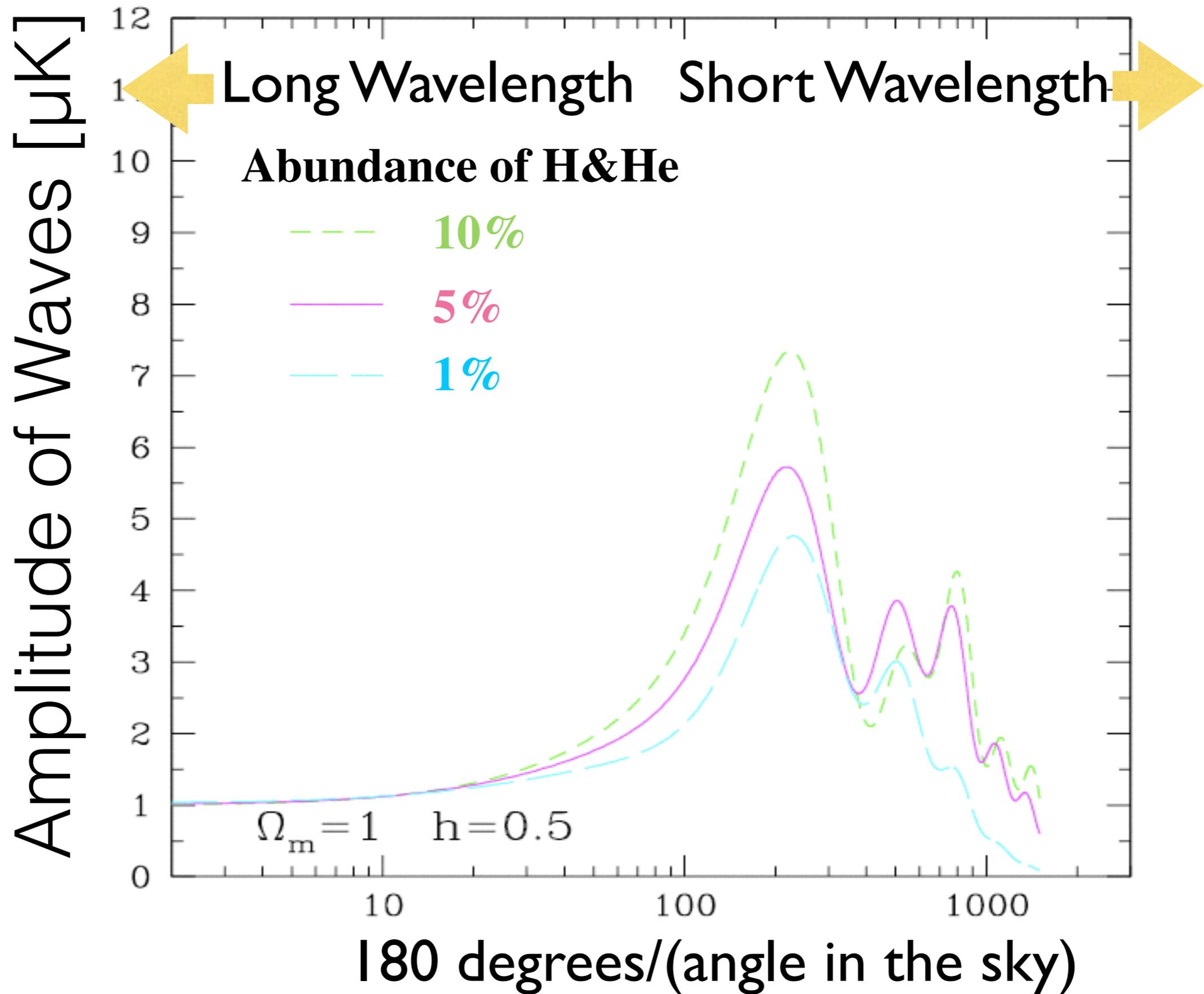


# How baryons affect [photon density fluctuations]<sup>2</sup>

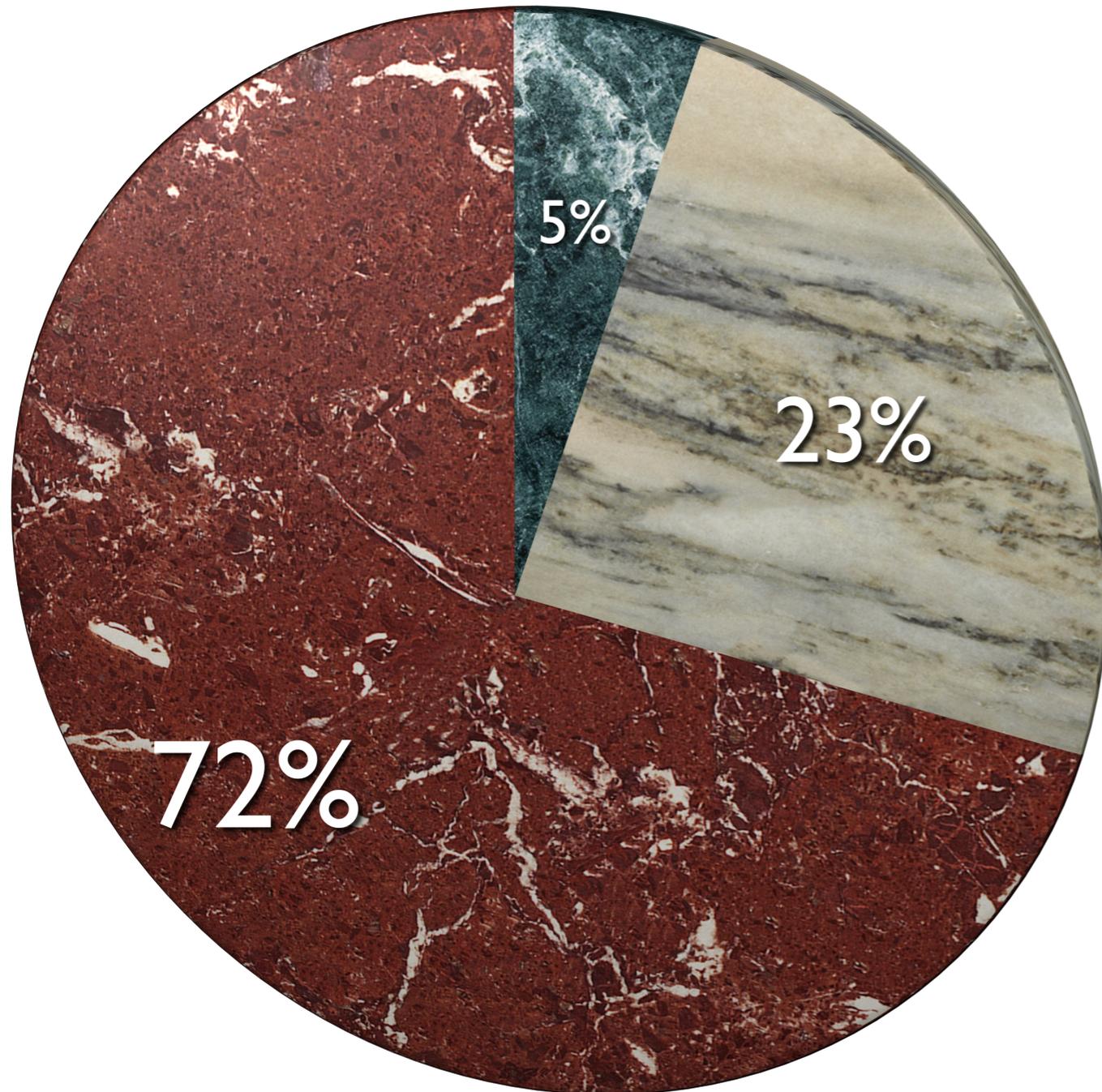


$$\left[ \begin{aligned} l_{1st} &= k_{1st} \Delta A = \pi \frac{\Delta A}{r_s} \approx 300 \\ l_{2nd} &= k_{2nd} \Delta A = 2\pi \frac{\Delta A}{r_s} \approx 600 \end{aligned} \right.$$

# Measuring Abundance of H&He



# Cosmic Pie Chart

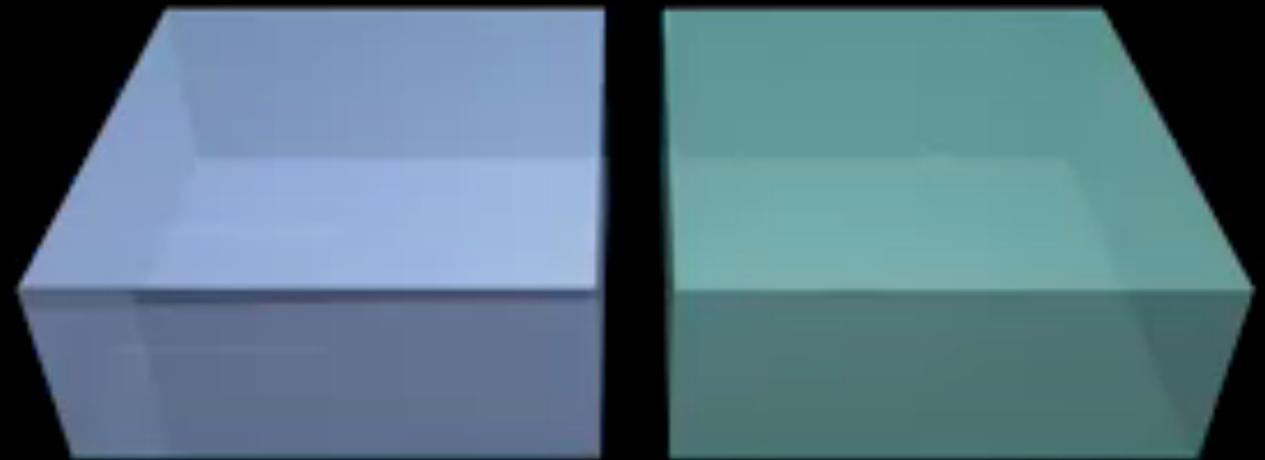


- WMAP determined the abundance of various components in the Universe
- As a result, **we came to realise that we do not understand 95% of our Universe...**

- H&He
- Dunkle Materie
- Dunkle Energie

# Origin of Fluctuations

- Who dropped those Tofus into the cosmic Miso soup?





Werner Heisenberg  
(1901–1976)

Slava Mukhanov  
[Prof. at LMU]



# Leading Idea

- **Quantum Mechanics at work in the early Universe**  
*(Mukhanov & Chibisov, 1981)*
- **Werner Heisenberg's Uncertainty Principle:**
  - **[Energy you can borrow] x [Time you borrow]  $\sim h$**
  - **Time was very short in the early Universe =  
You could borrow a lot of energy**
- **Those energies became the origin of fluctuations**
- How did quantum fluctuations on the microscopic scales become macroscopic fluctuations over cosmological sizes?

# Outstanding Questions

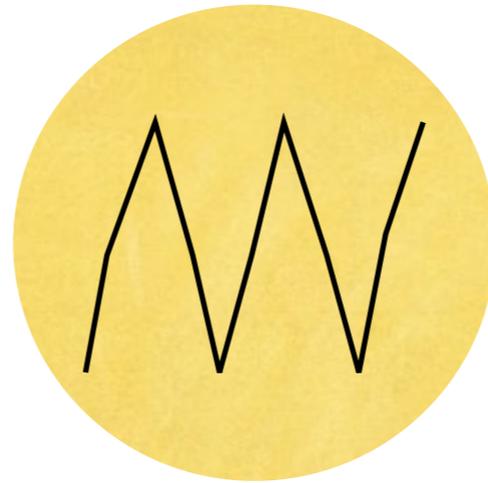
- Where does anisotropy in CMB temperature come from?
  - This is the origin of galaxies, stars, planets, and everything else we see around us, including ourselves
- The leading idea: **quantum fluctuations in vacuum, stretched to cosmological length scales** by a rapid exponential expansion of the universe called “*cosmic inflation*” in the very early universe

# Cosmic Inflation

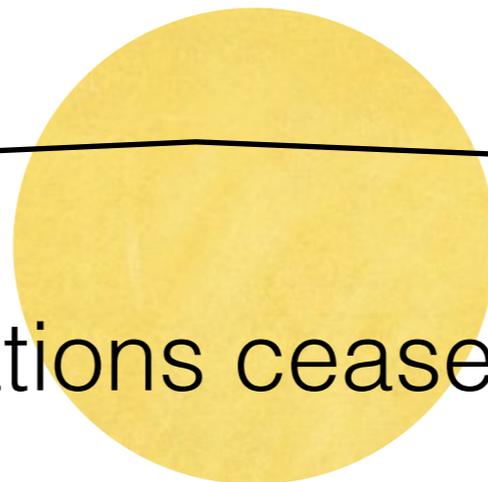
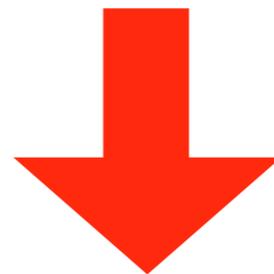
- In a tiny fraction of a second, the size of an atomic nucleus became the size of the Solar System
- In  $10^{-36}$  second, space was stretched by at least a factor of  $10^{26}$

# Stretching Micro to Macro

Quantum fluctuations on  
microscopic scales



# Inflation!



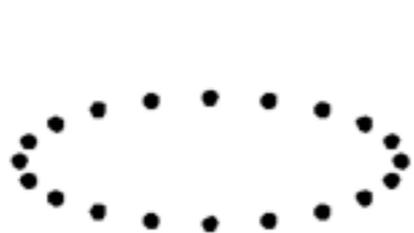
- Quantum fluctuations cease to be quantum
- Become macroscopic, classical fluctuations

# Scalar and Tensor Modes

- A distance between two points in space

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

- $\zeta$ : “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)



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

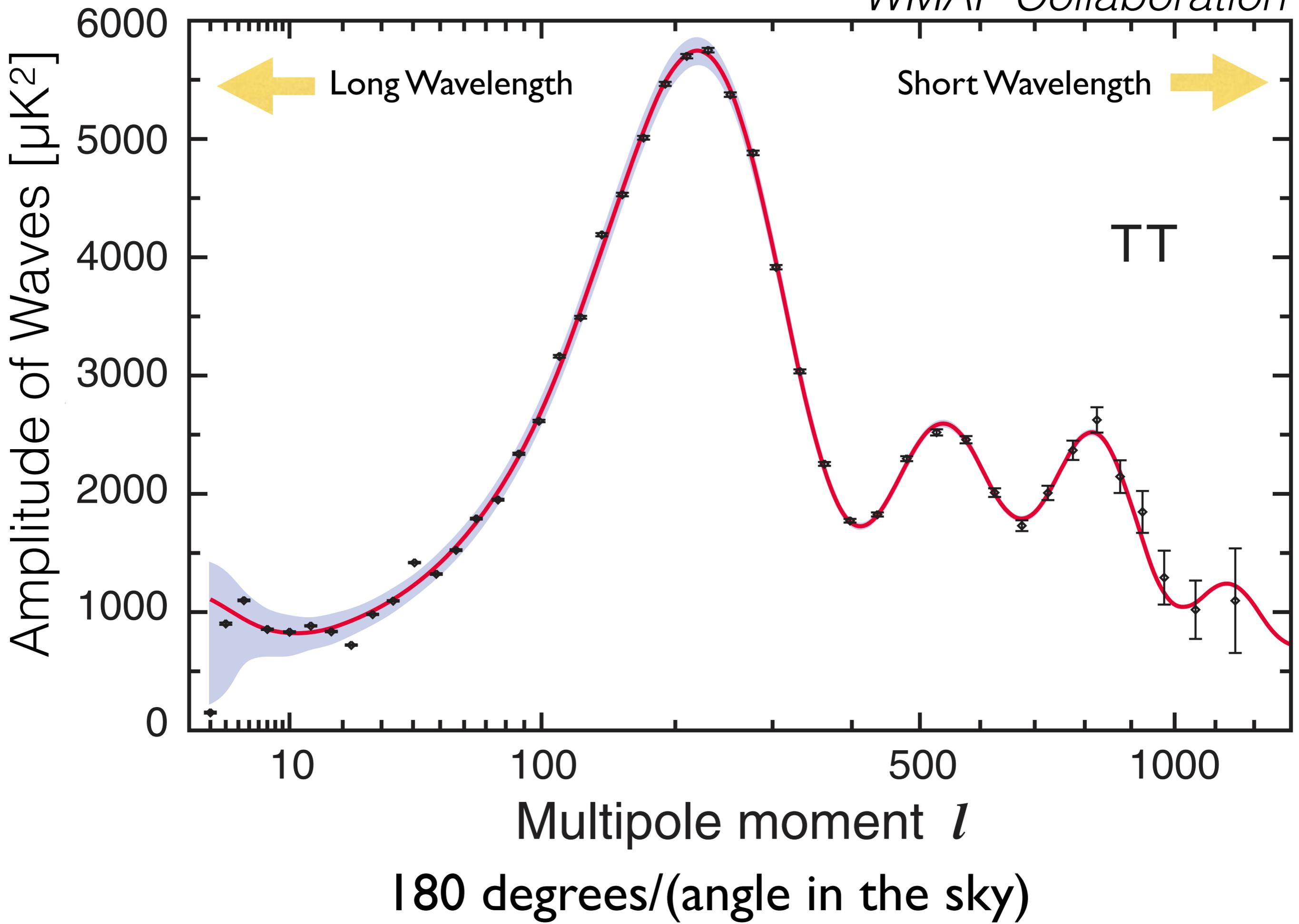
# Tensor-to-scalar Ratio

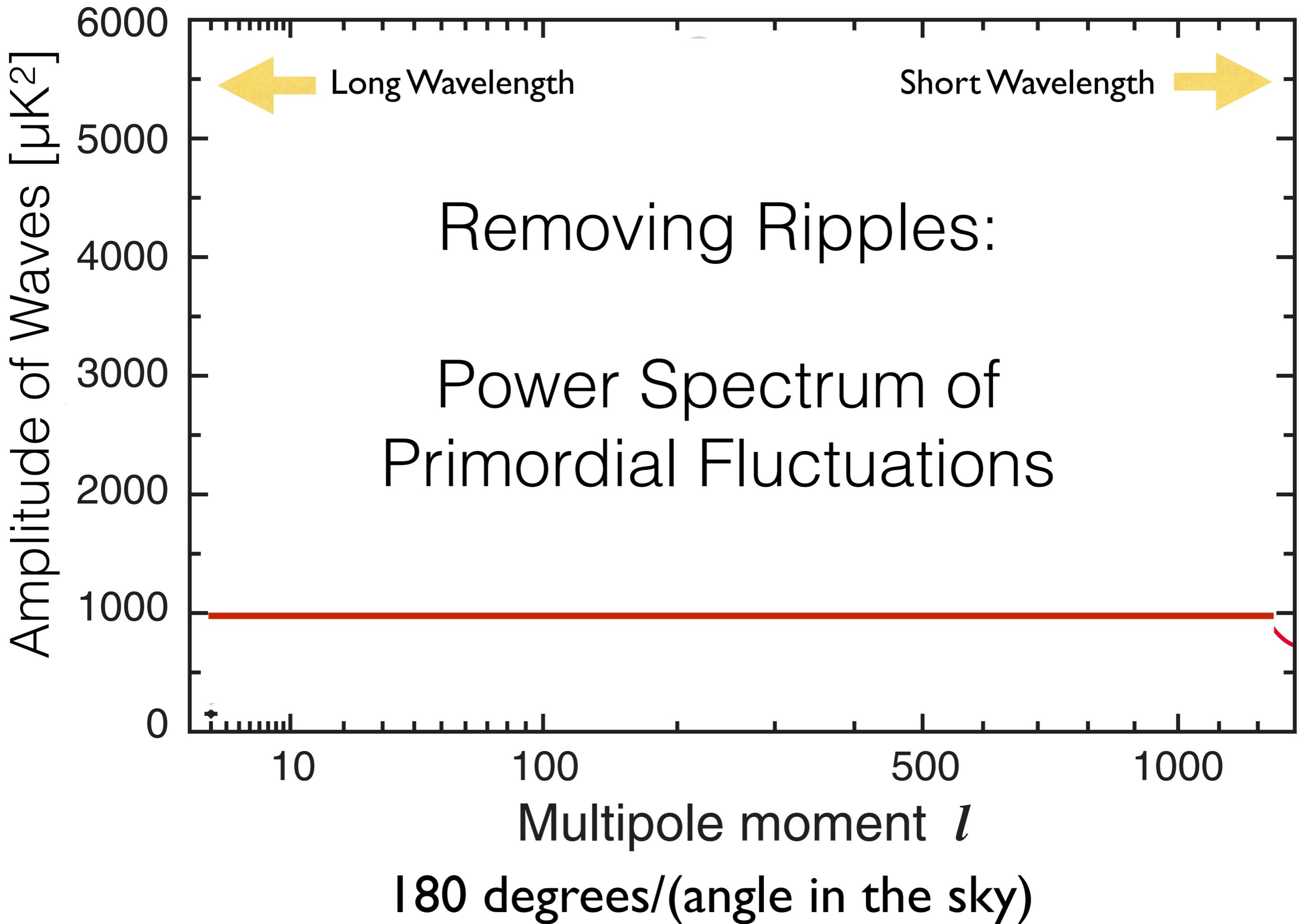
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

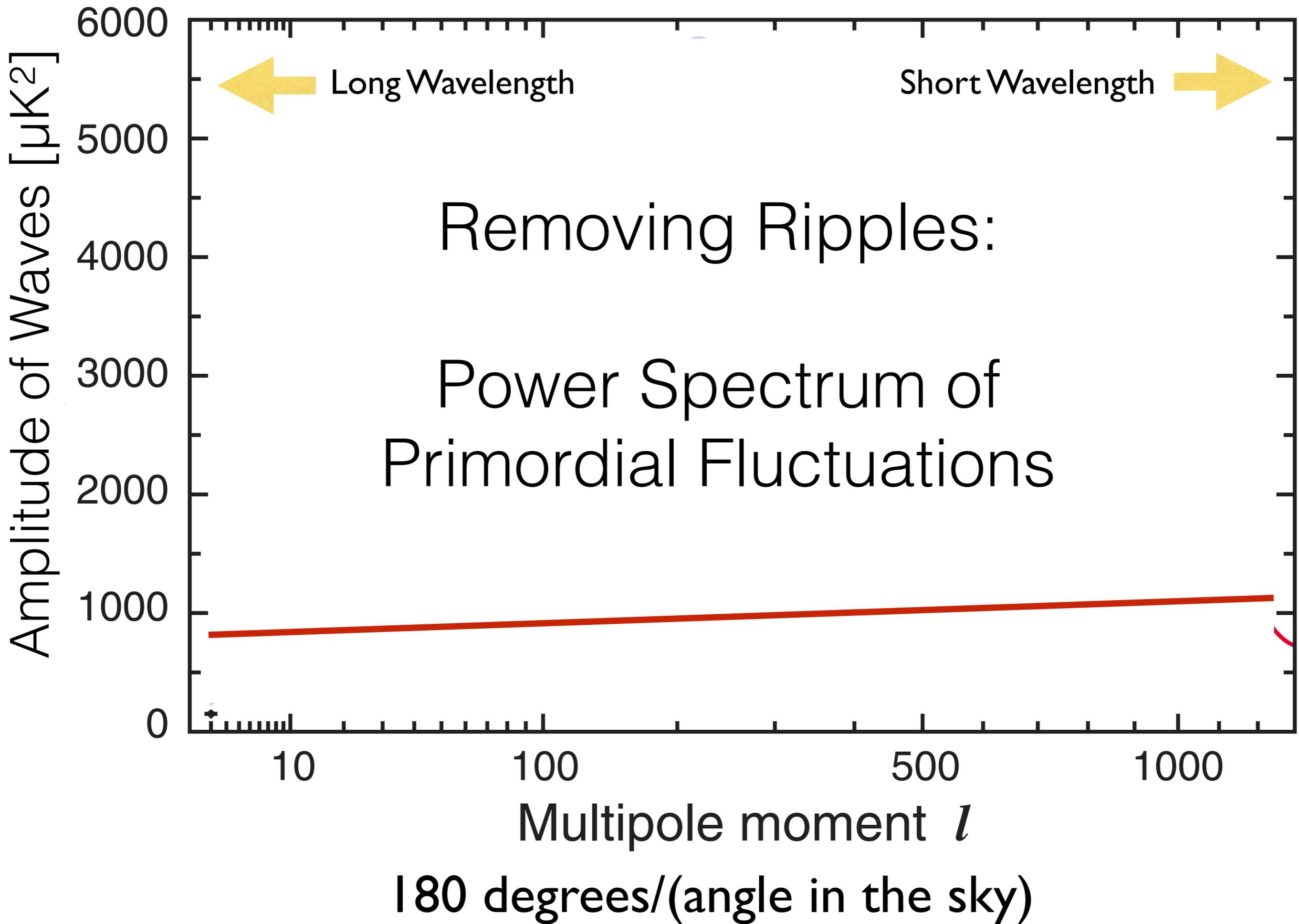
- We really want to find this quantity!
- **The upper bound from the temperature anisotropy data:  $r < 0.1$  [WMAP & Planck]**

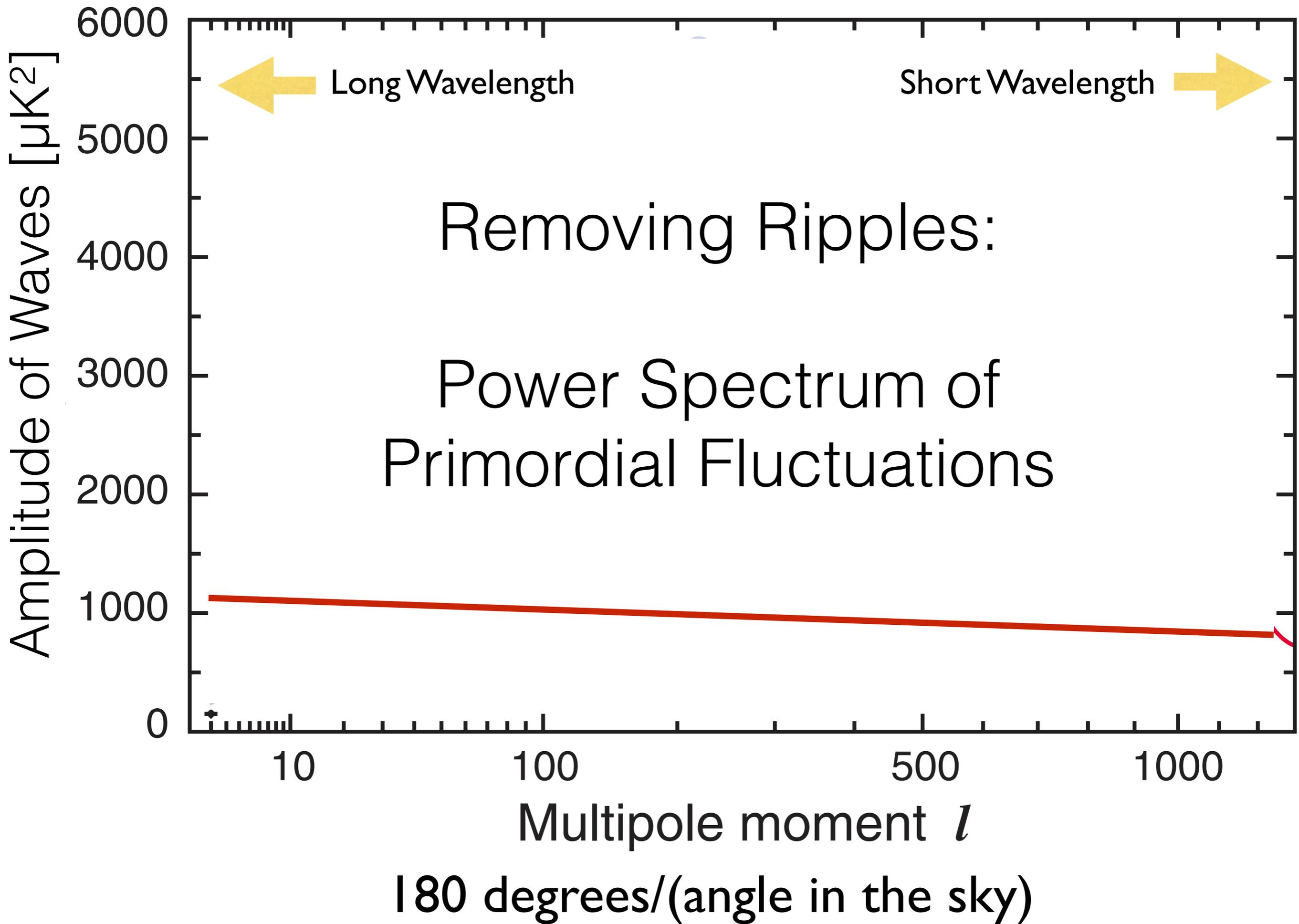
# Fluctuations are proportional to $H$

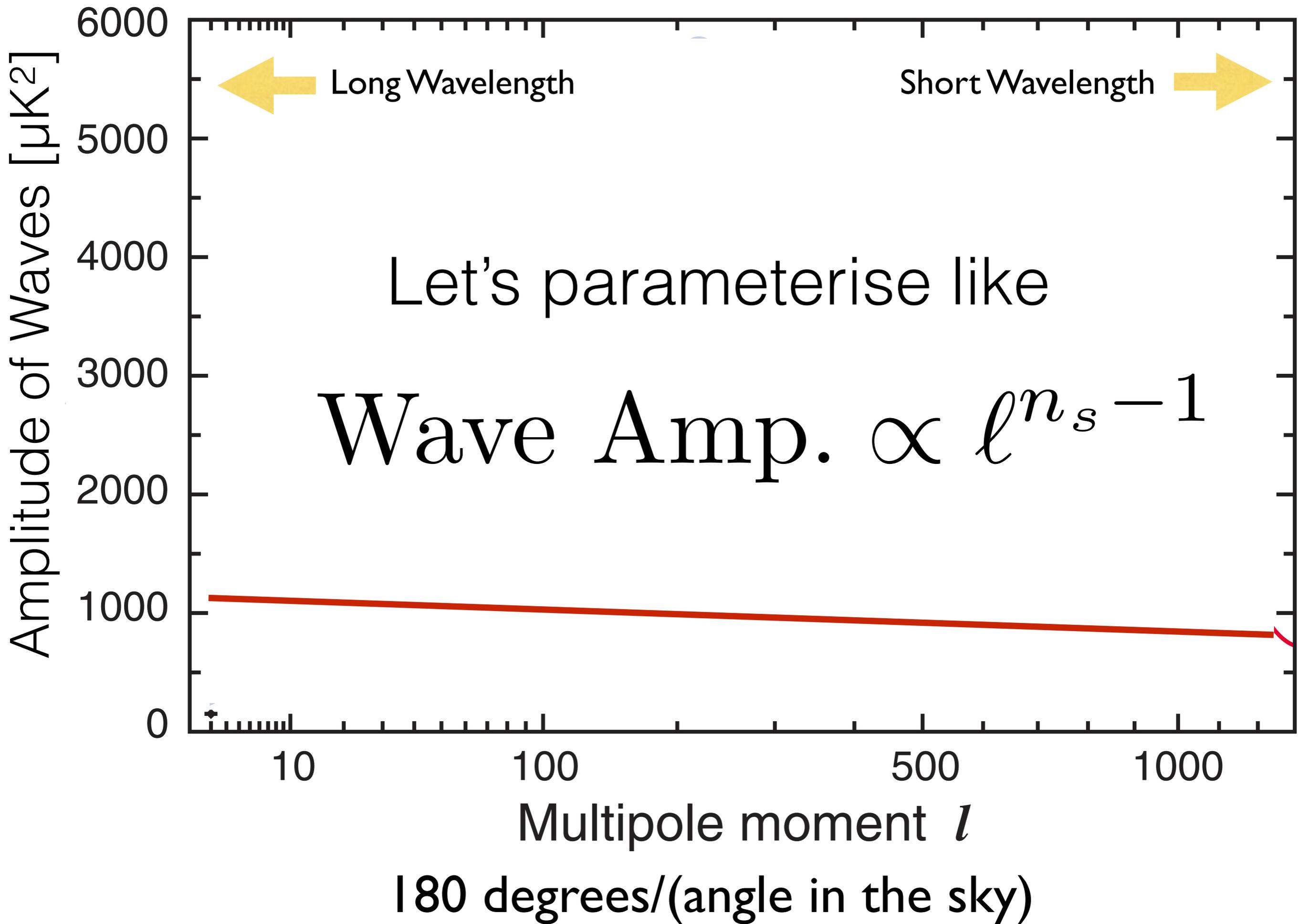
- [Energy you can borrow] x [Time you borrow] = constant
- $H \equiv \frac{\dot{a}}{a}$  [This has units of 1/time]
- Then, **both  $\zeta$  and  $h_{ij}$  are proportional to  $H$**
- Inflation occurs in  $10^{-36}$  second - this is such a short period of time that you can borrow a lot of energy!  
 **$H$  during inflation in energy units is  $10^{14}$  GeV**

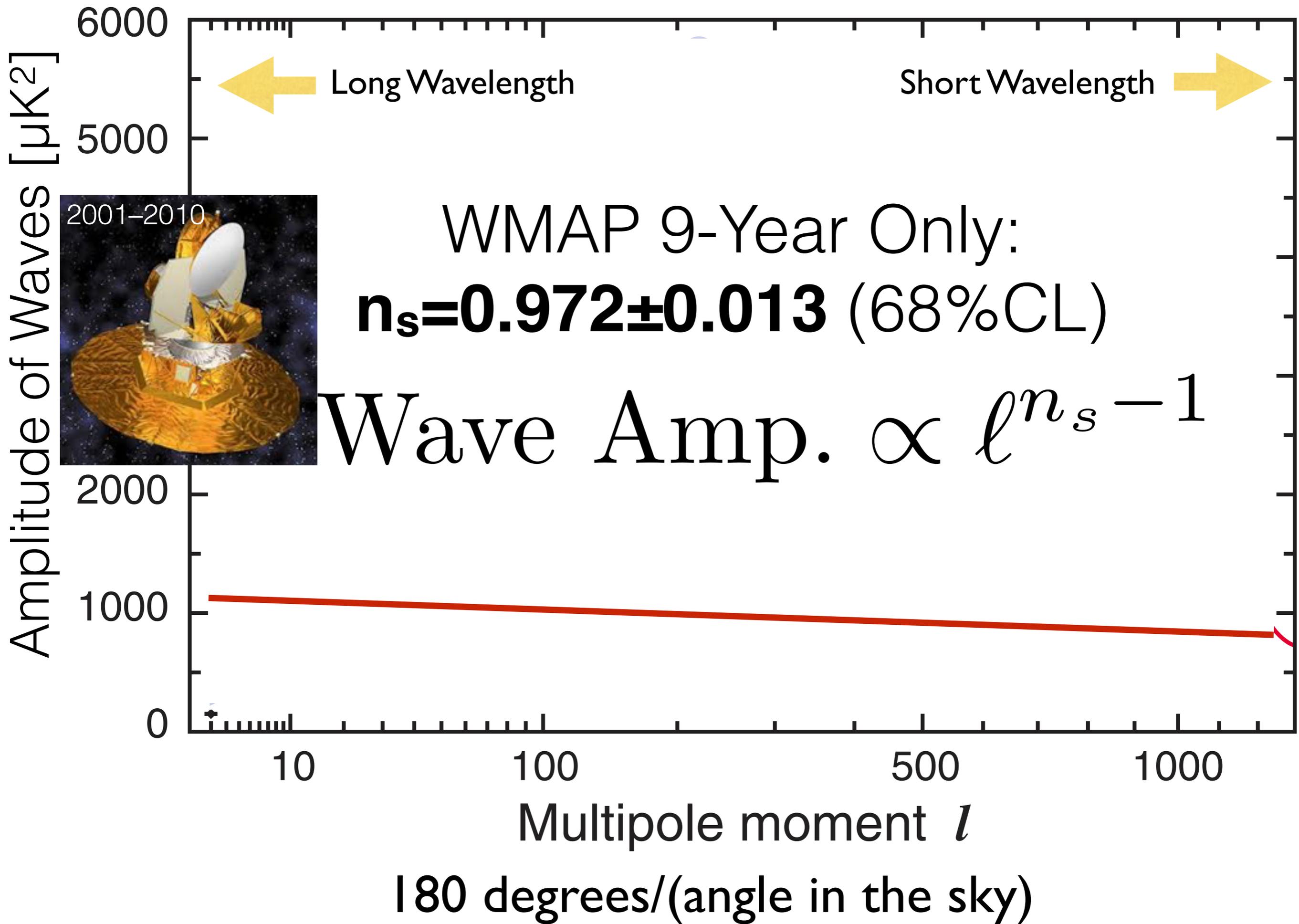


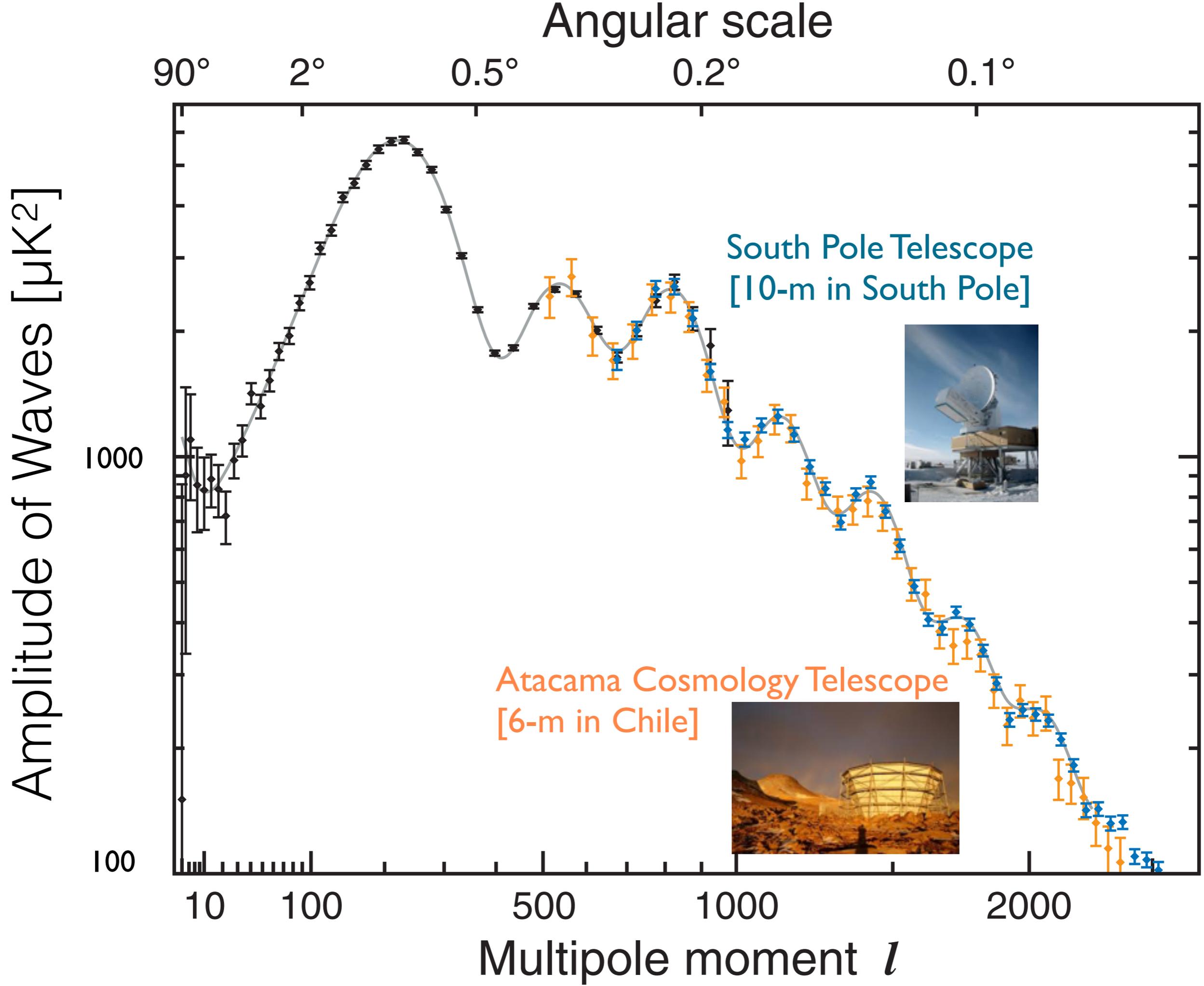


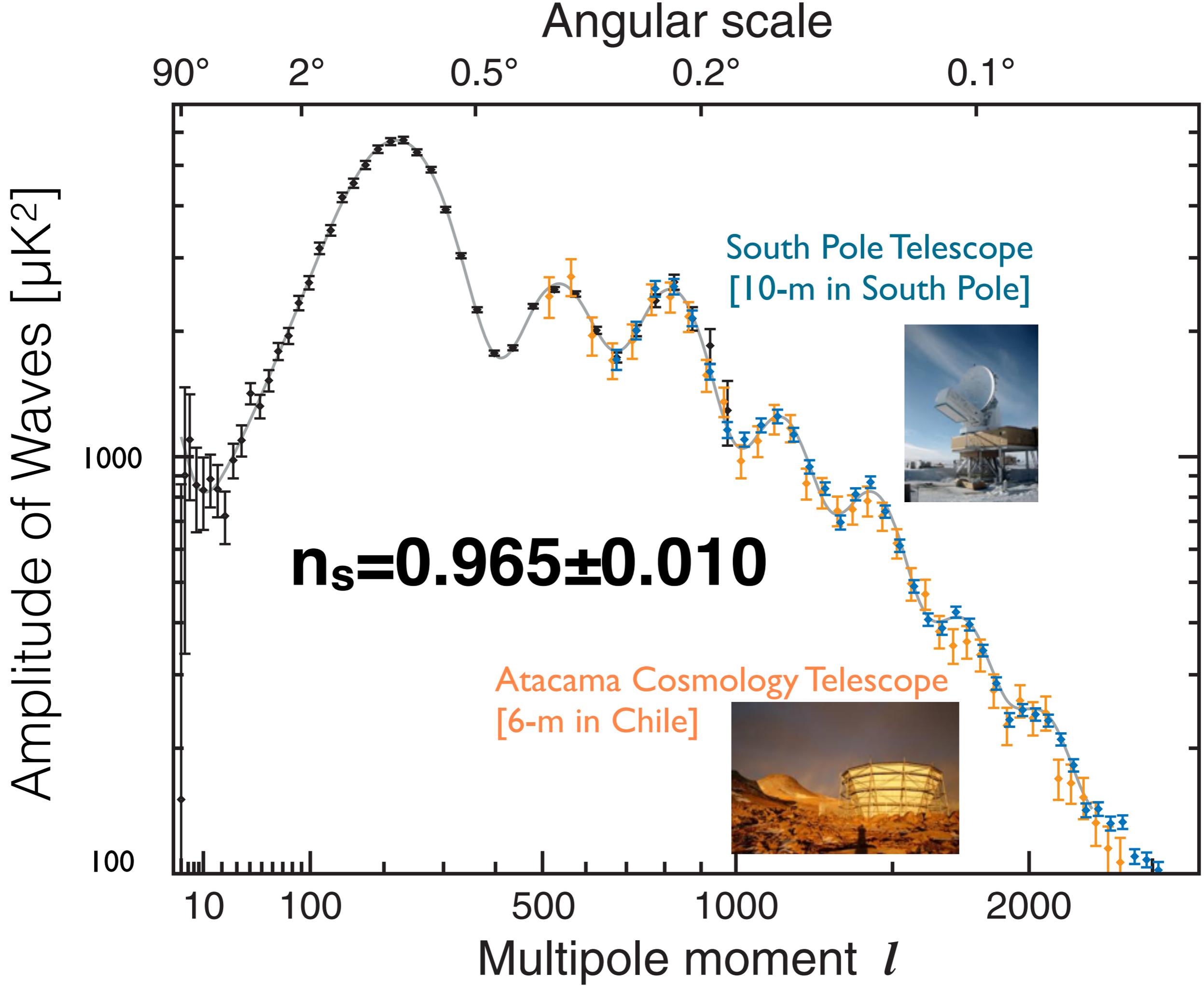






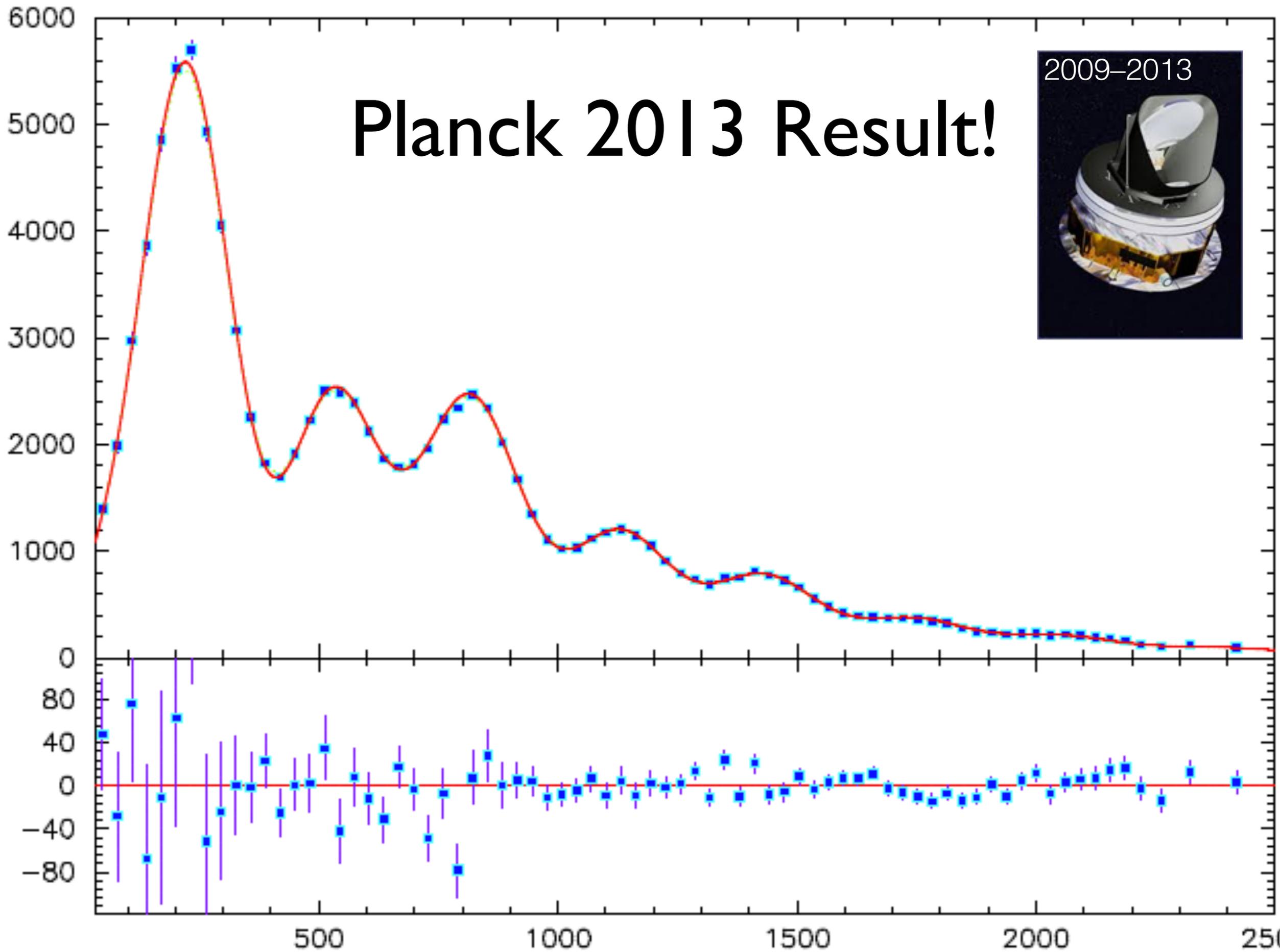
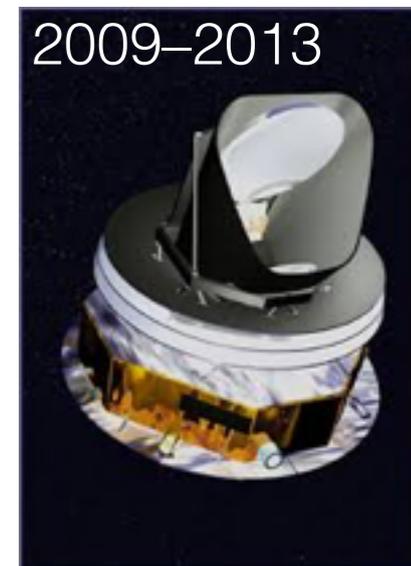






Residual Amplitude of Waves [ $\mu\text{K}^2$ ]

# Planck 2013 Result!



$180 \text{ degrees}/(\text{angle in the sky})$

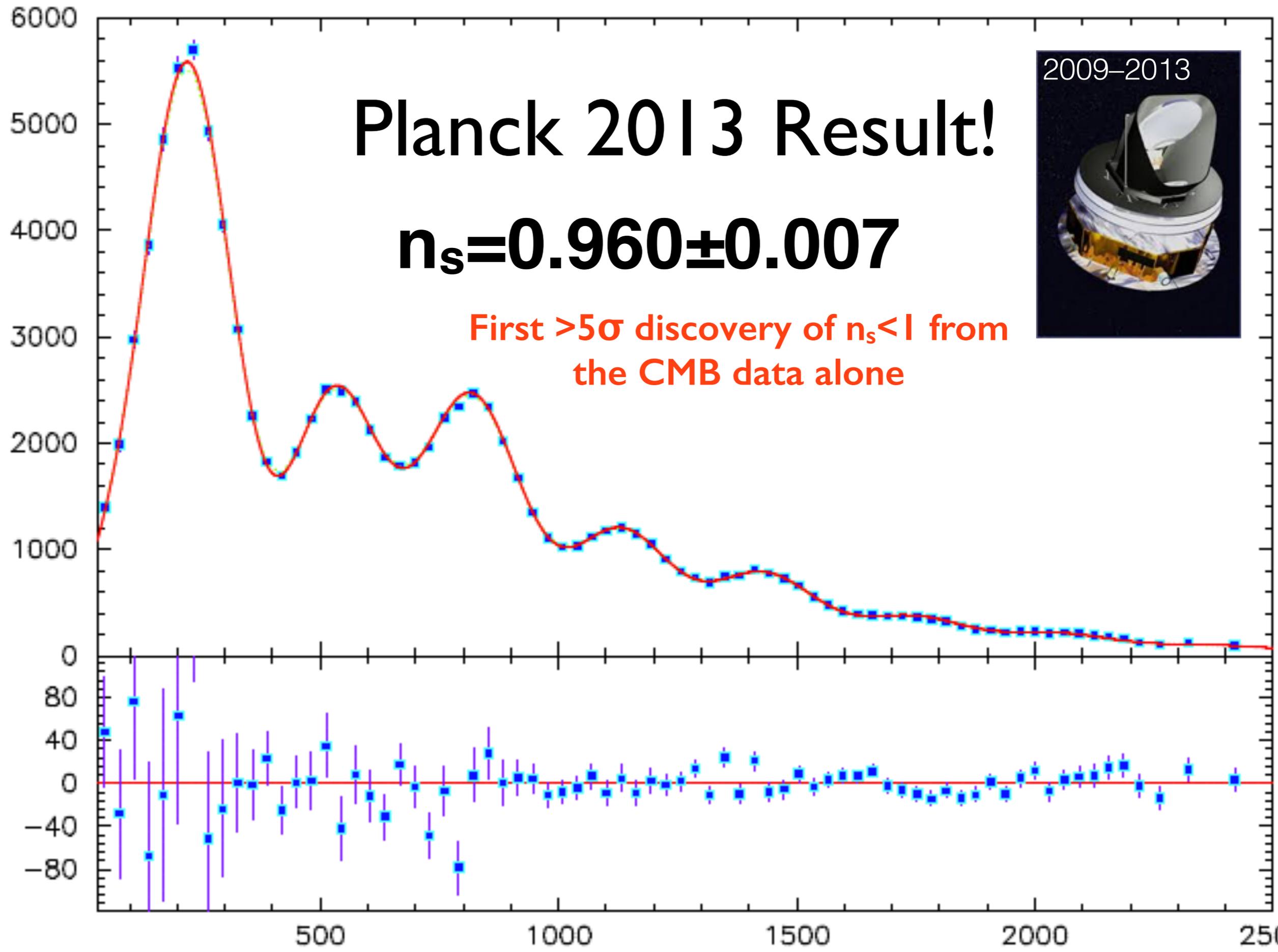
Residual Amplitude of Waves [ $\mu\text{K}^2$ ]



# Planck 2013 Result!

$$n_s = 0.960 \pm 0.007$$

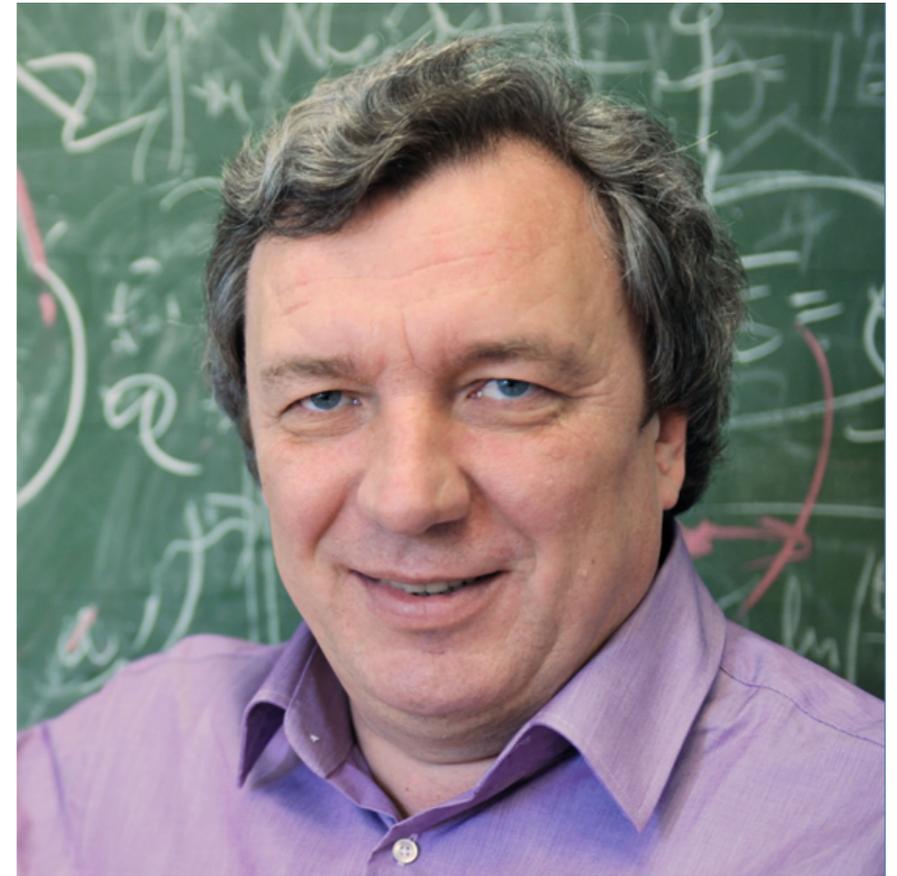
First  $>5\sigma$  discovery of  $n_s < 1$  from the CMB data alone



$180 \text{ degrees}/(\text{angle in the sky})$

Predicted in 1981.  
Finally discovered in 2013  
by WMAP and Planck

- Inflation must end
- Inflation predicts  $n_s \sim 1$ , but not exactly equal to 1. Usually  $n_s < 1$  is expected
- **The discovery of  $n_s < 1$  has been the dream of cosmologists since 1992,** when the CMB anisotropy was discovered and  $n_s \sim 1$  (to within 10%) was indicated



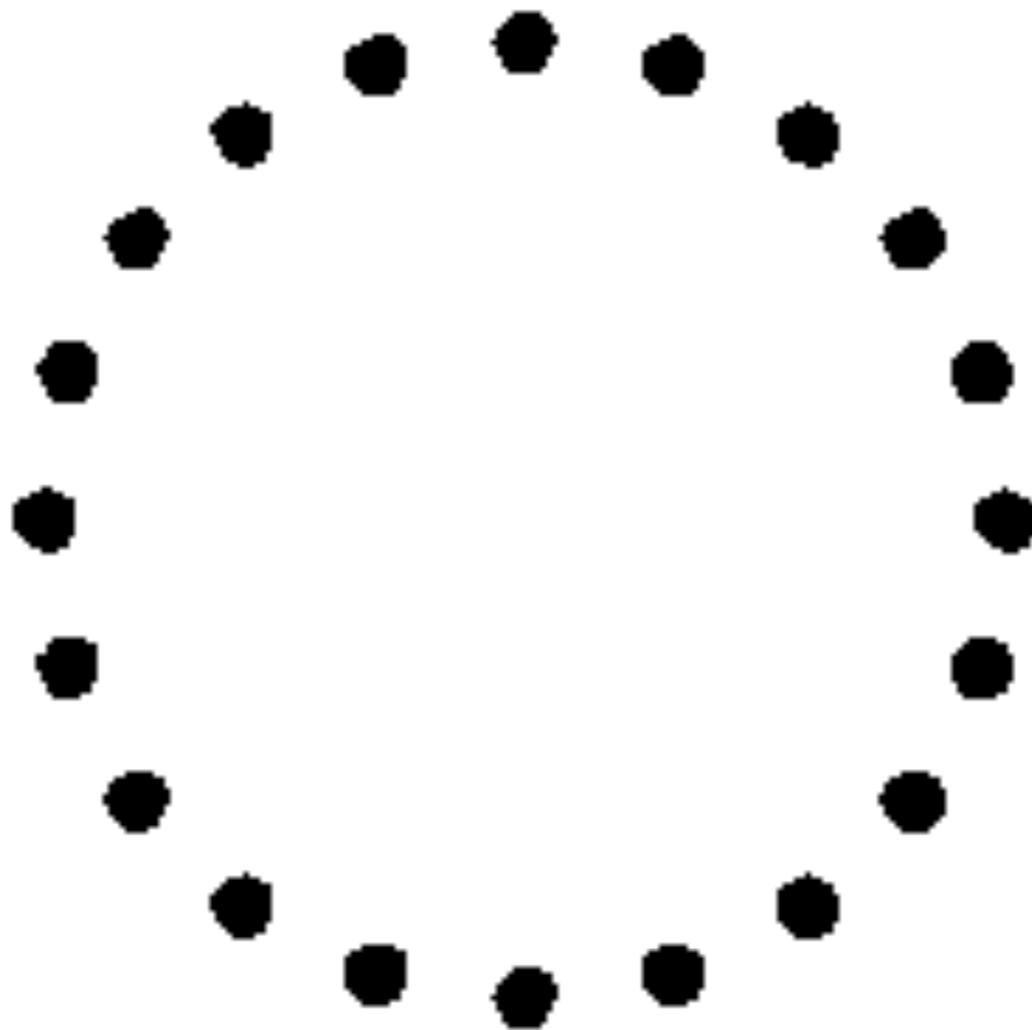
*Slava Mukhanov said in his 1981 paper that  $n_s$  should be less than 1*

# CMB Research: Next Frontier

## Primordial Gravitational Waves

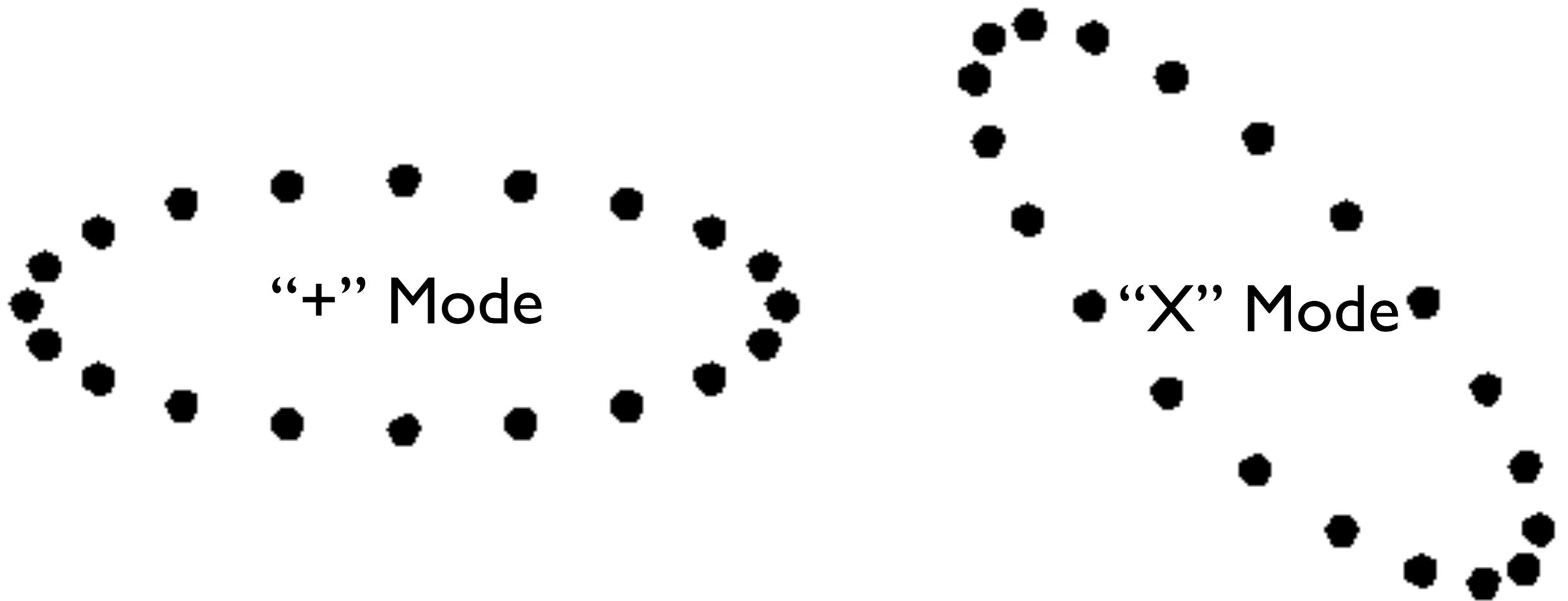
*Extraordinary claims require extraordinary evidence.  
The same quantum fluctuations could also generate  
gravitational waves, and we wish to find them*

# Gravitational Waves Are Coming Toward You!



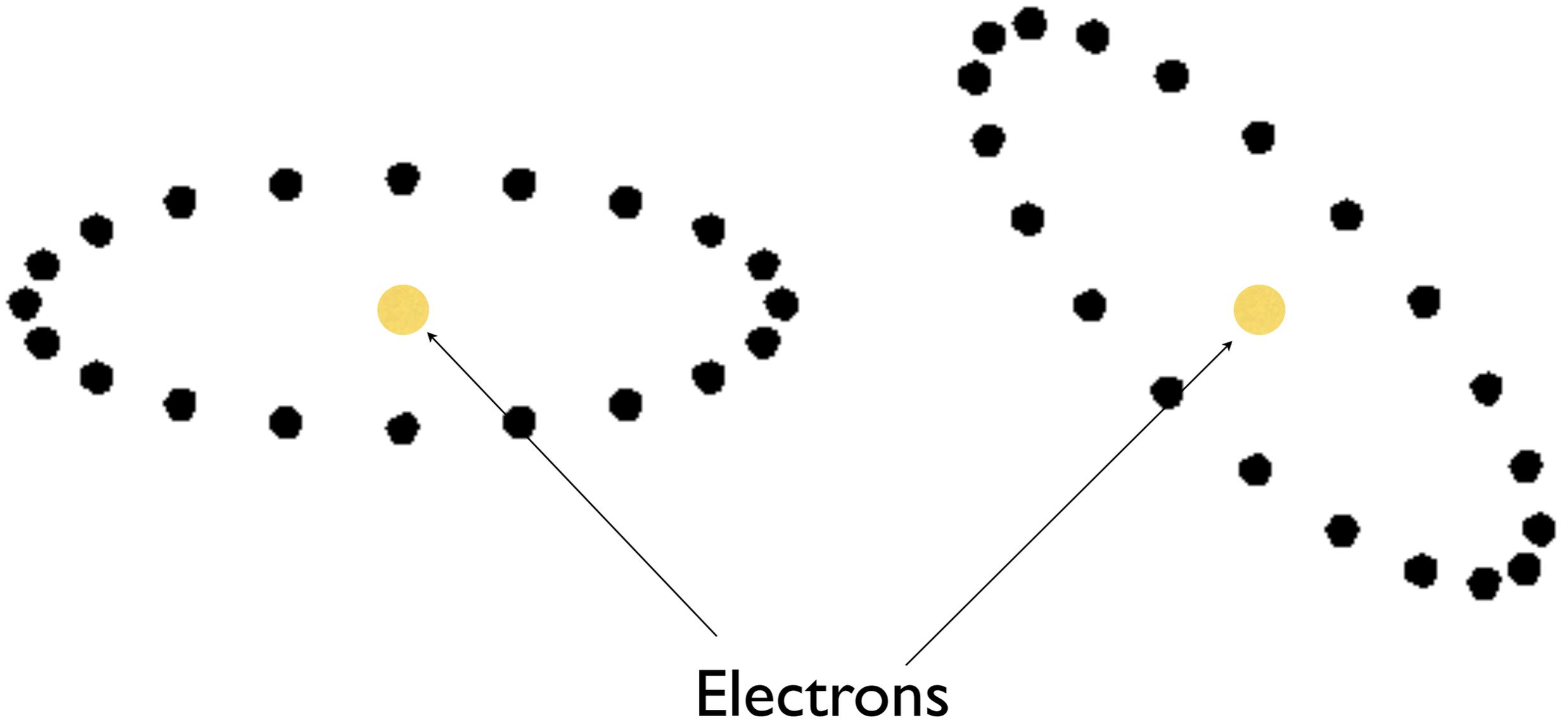
Gravitational waves stretch and contract space,  
moving particles

# Two Modes

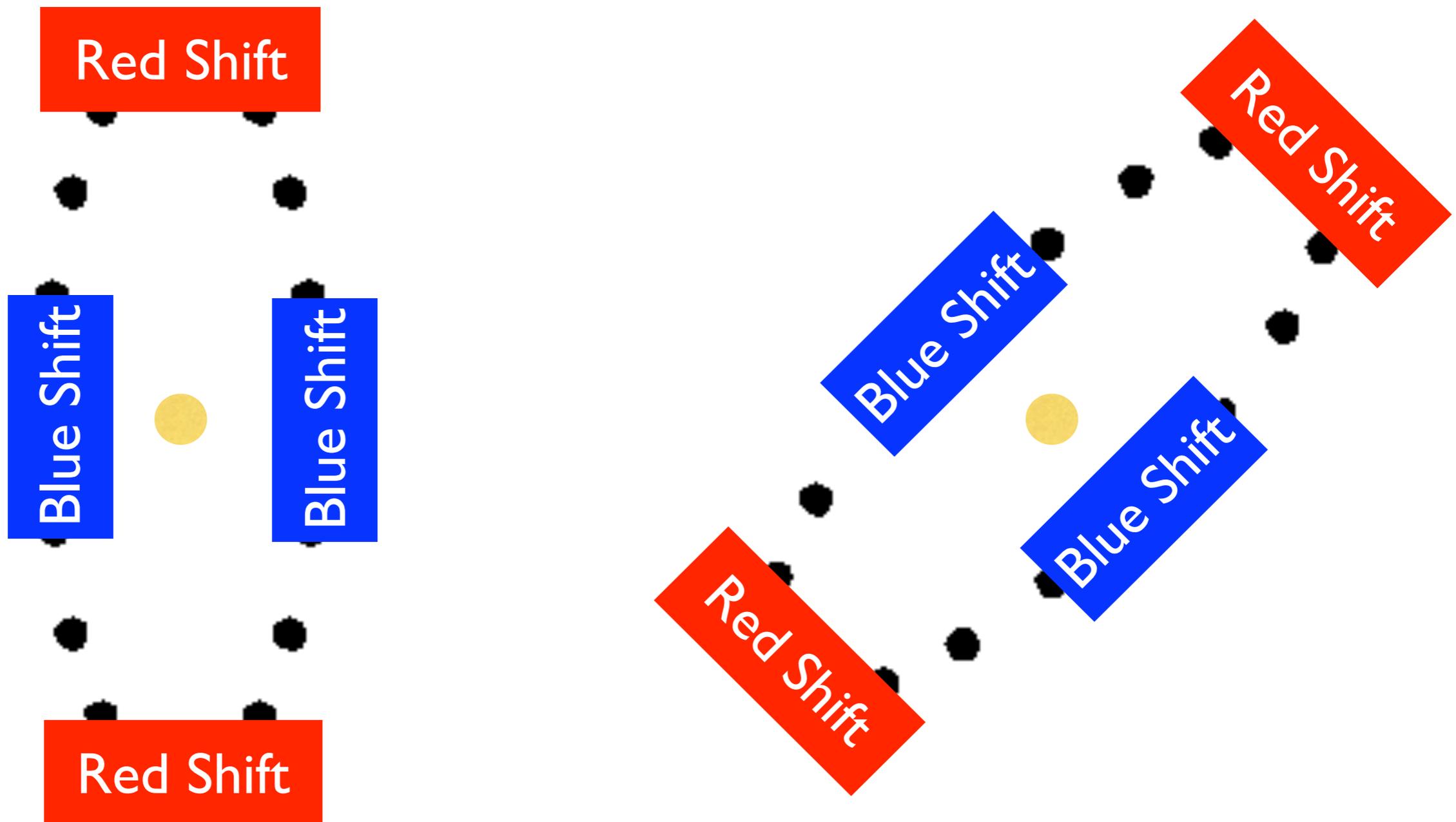


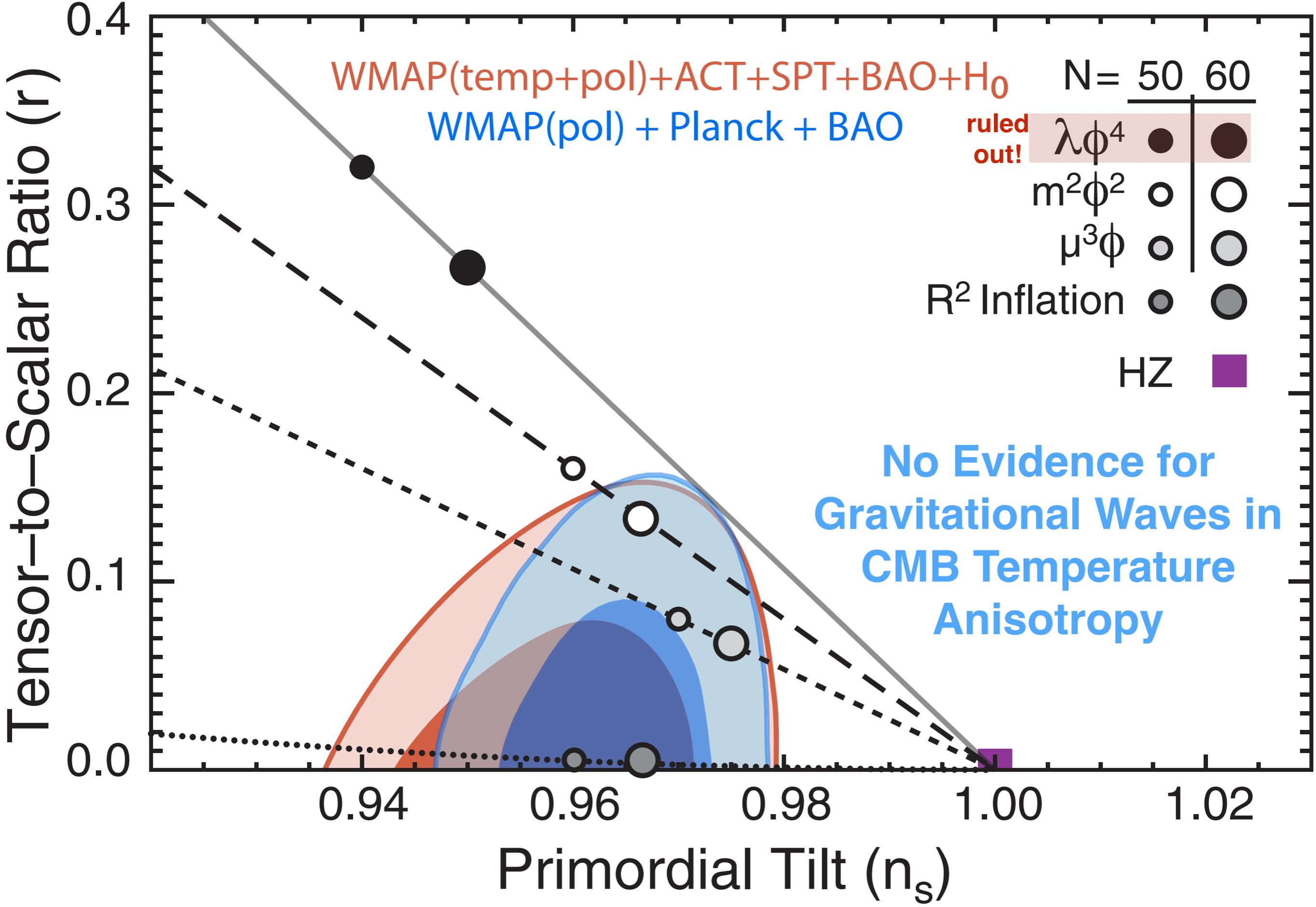
How do they change temperatures?

# Gravitational Waves to Temperature Fluctuations

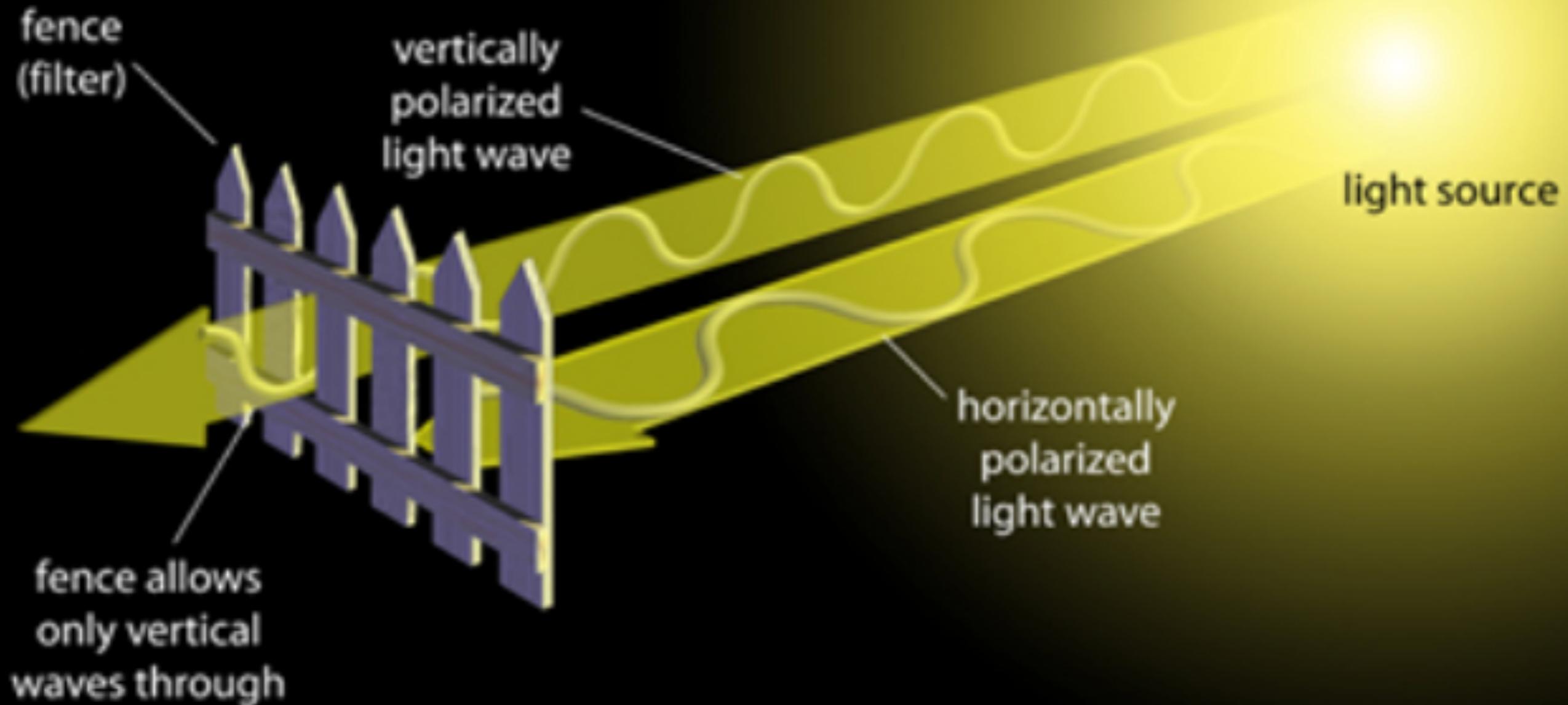


# Gravitational Waves to Temperature Fluctuations



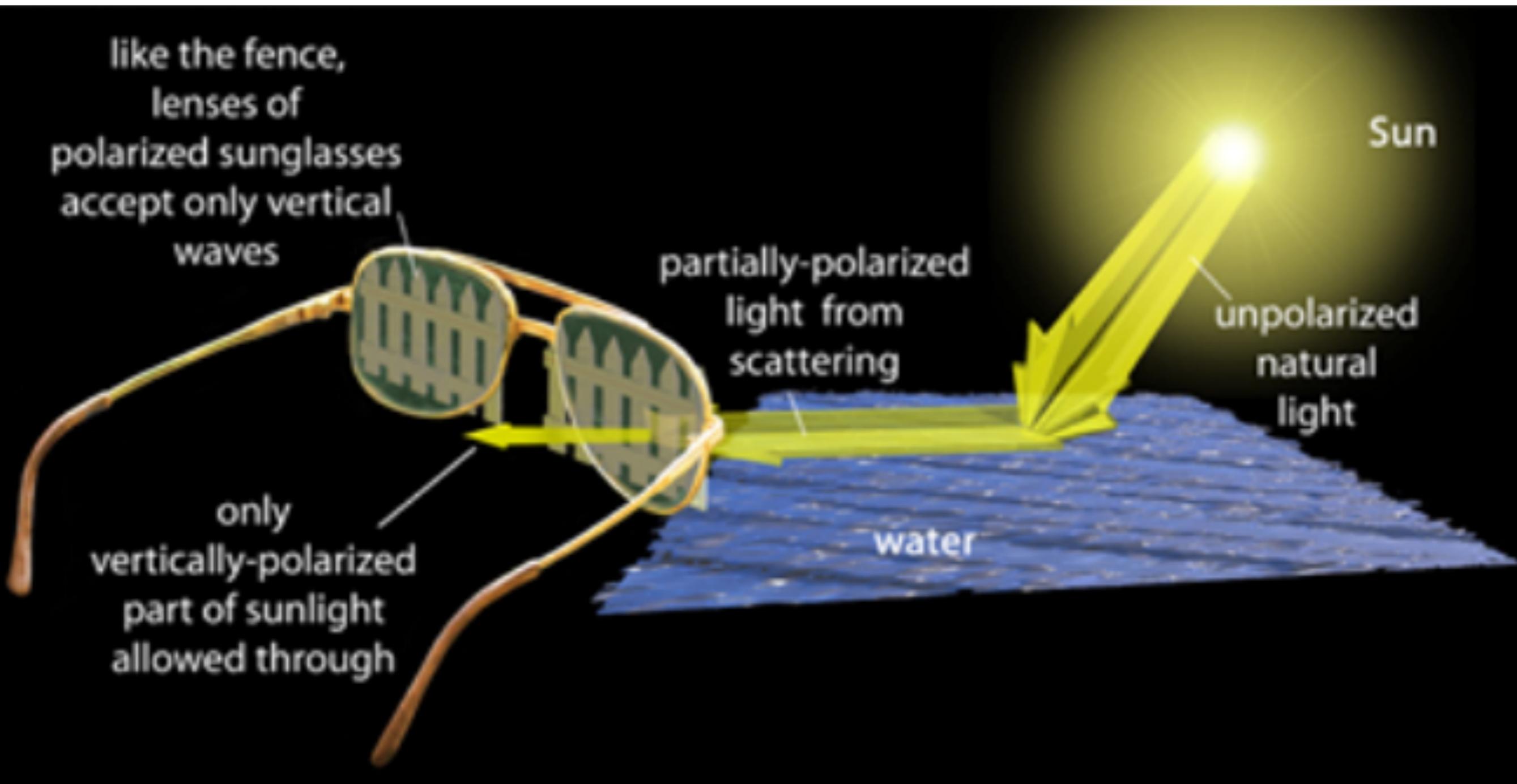


# Polarisation of Light



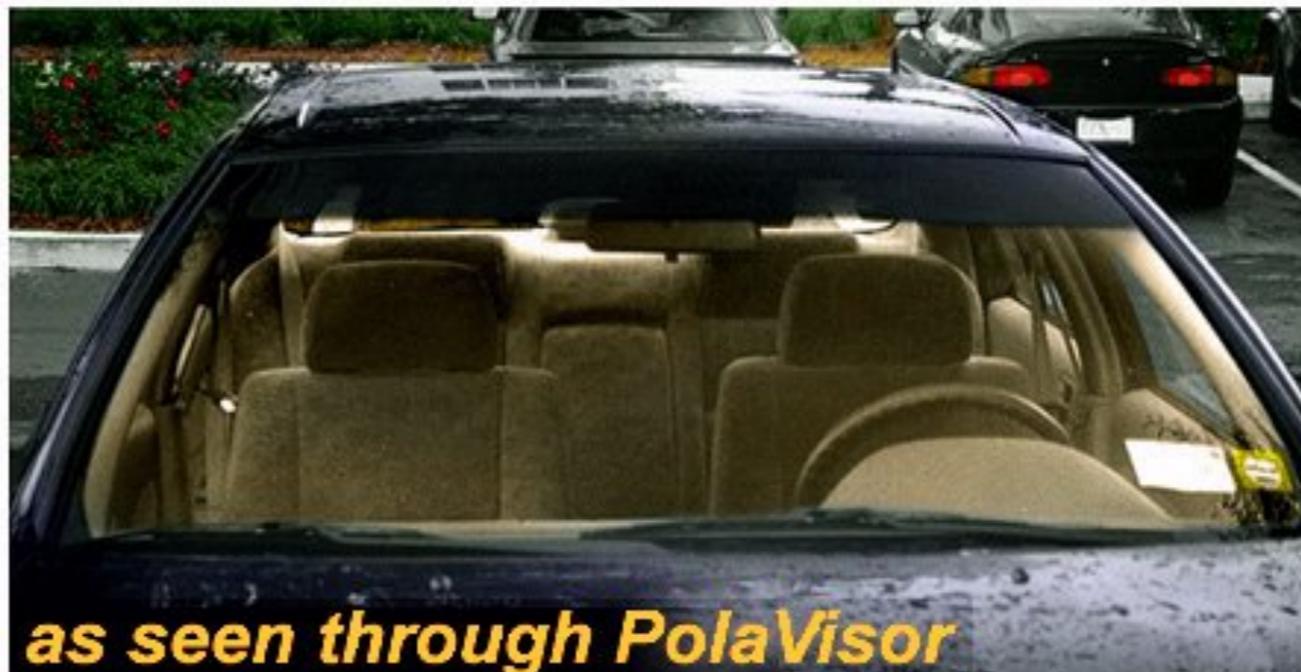
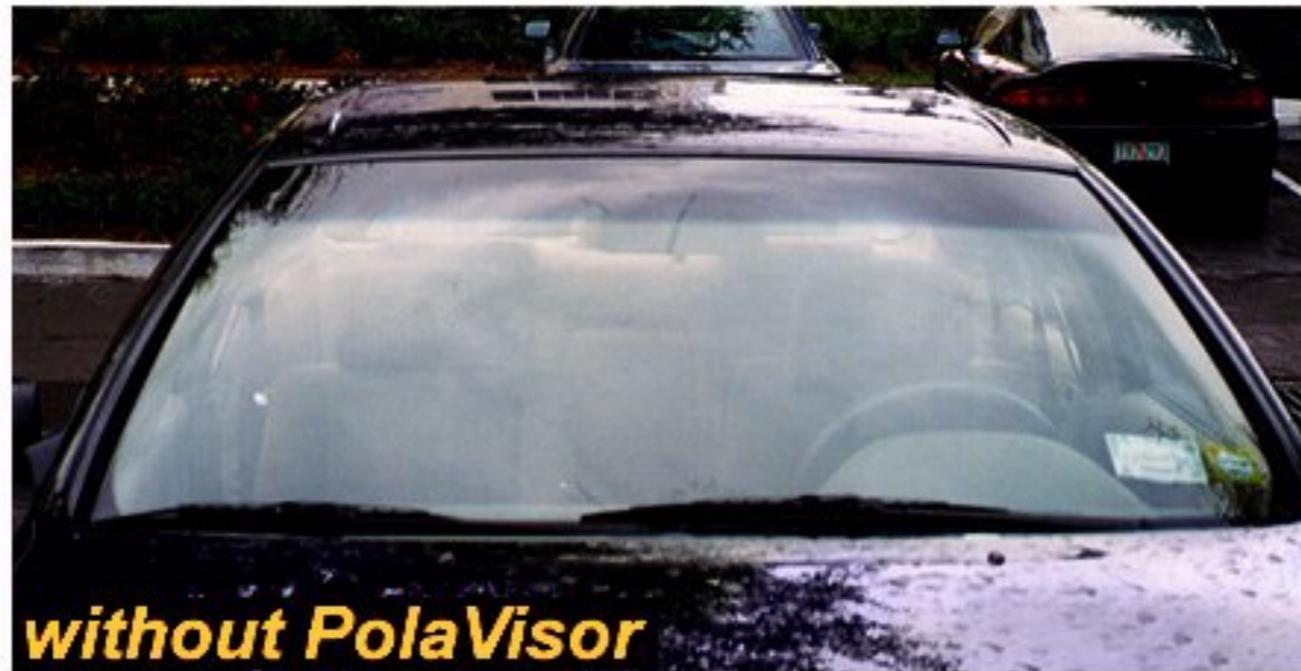
Light waves oscillate in various directions. We say “light is polarised,” when one particular direction dominates

# Ex. 1: Reflection by Sea



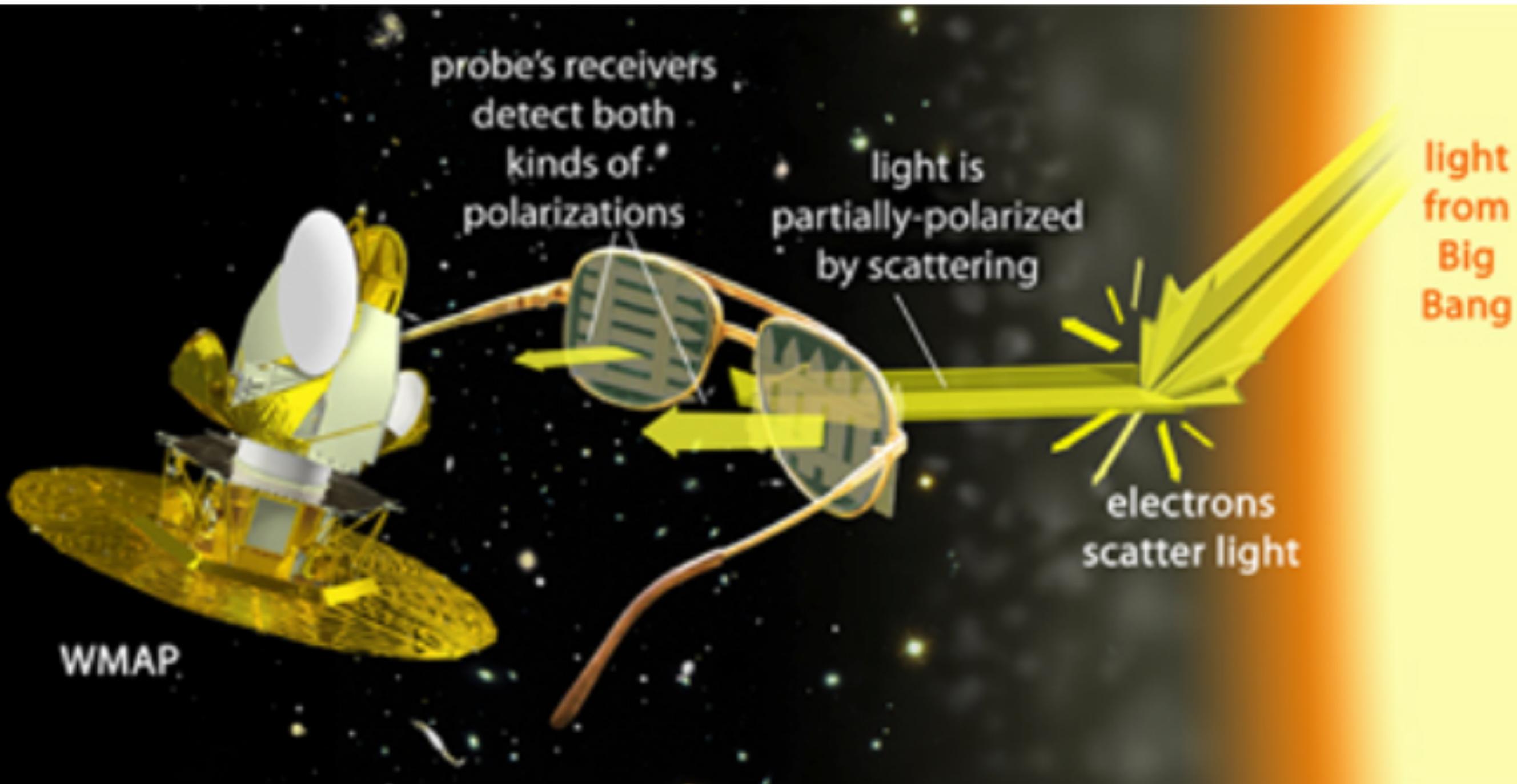
Sun light reflected by the surface of the sea is polarised horizontally. Using sunglasses transmitting only vertical polarisation eliminates the reflected sun light

# Ex. 2: Windshield



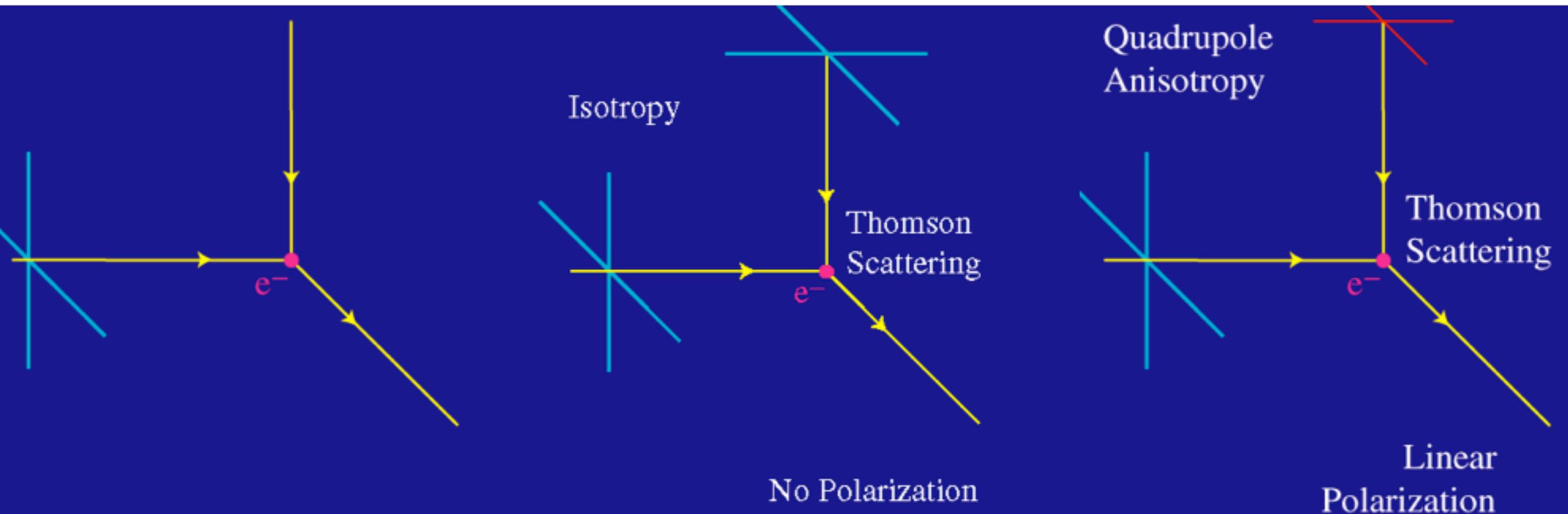
We can see through the interior of a car with polarised sunglasses transmitting only vertical polarisation

# Ex. 3: CMB



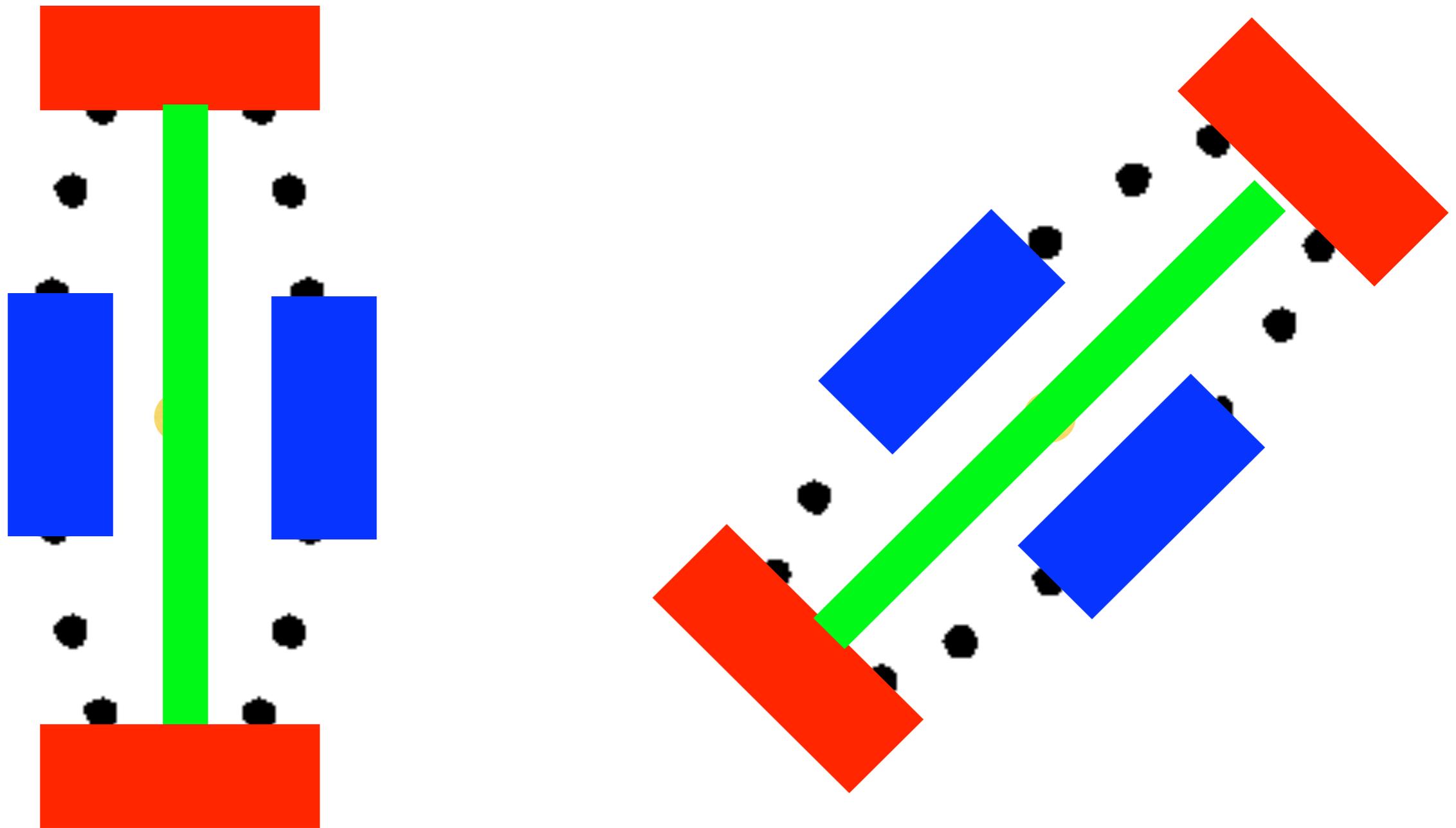
Scattering by electrons makes CMB polarised in various directions

# Physics of Polarisation



Polarisation is generated when light is scattered by an electron

# Gravitational Waves to Polarisation!



March 17, 2014

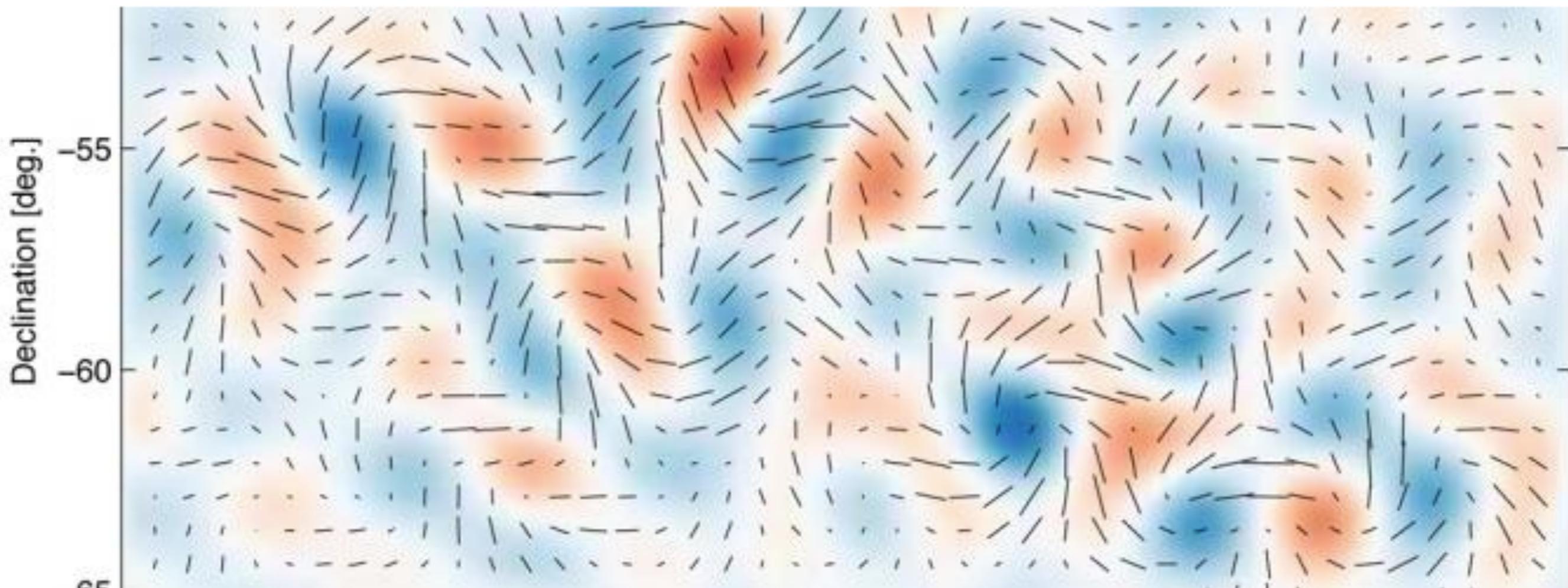
BICEP2's announcement



## First Direct Evidence of Cosmic Inflation

**Release No.:** 2014-05

**For Release:** Monday, March 17, 2014 - 10:45am



**Cambridge, MA** - Almost 14 billion years ago, the universe we inhabit burst into existence in an extraordinary event that initiated the Big Bang. In the first fleeting fraction of a second, the universe expanded exponentially, stretching far beyond the view of our best telescopes. All this, of course, was just theory.

# Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

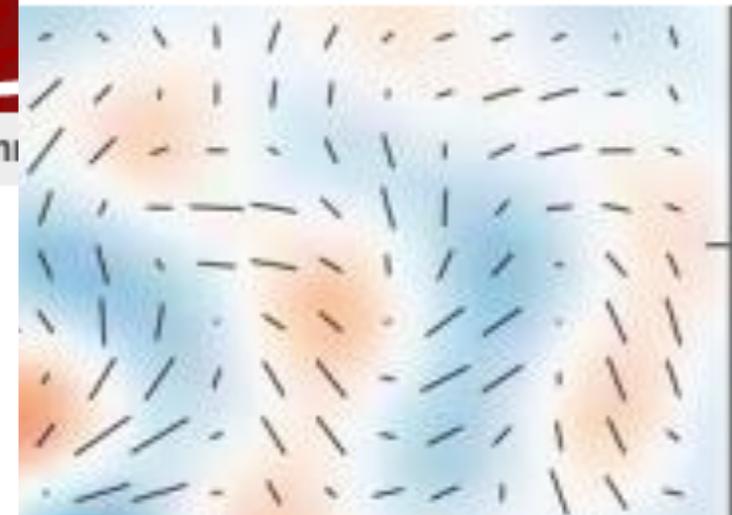


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17 March 2014 Last updated at 14:46 GMT



## Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos  
Science correspondent, BBC News



Cambridge, MA - Almost 14 billion years ago, a tiny speck of light that initiated the Big Bang. In the far beyond the view of our best tel

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Home > Wissen > Urknall > Urknall - Gravitationswellen belegen inflationäres Universum

Süddeutsche.de als Startseite einrichten

17. März 2014, 17:34 Gravitationswellen

## Signale aus der Geburtsstunde des Universums *Von Patrick Illinger*

January 30, 2015

Joint Analysis of BICEP2 data and Planck data

# Speck of Interstellar Dust Obscures Glimpse of Big Bang

By DENNIS OVERBYE JAN. 30, 2015

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30 January 2015 Last updated at 20:54 GMT



## Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos

Science correspondent, BBC News

Süddeutsche.de

Wissen

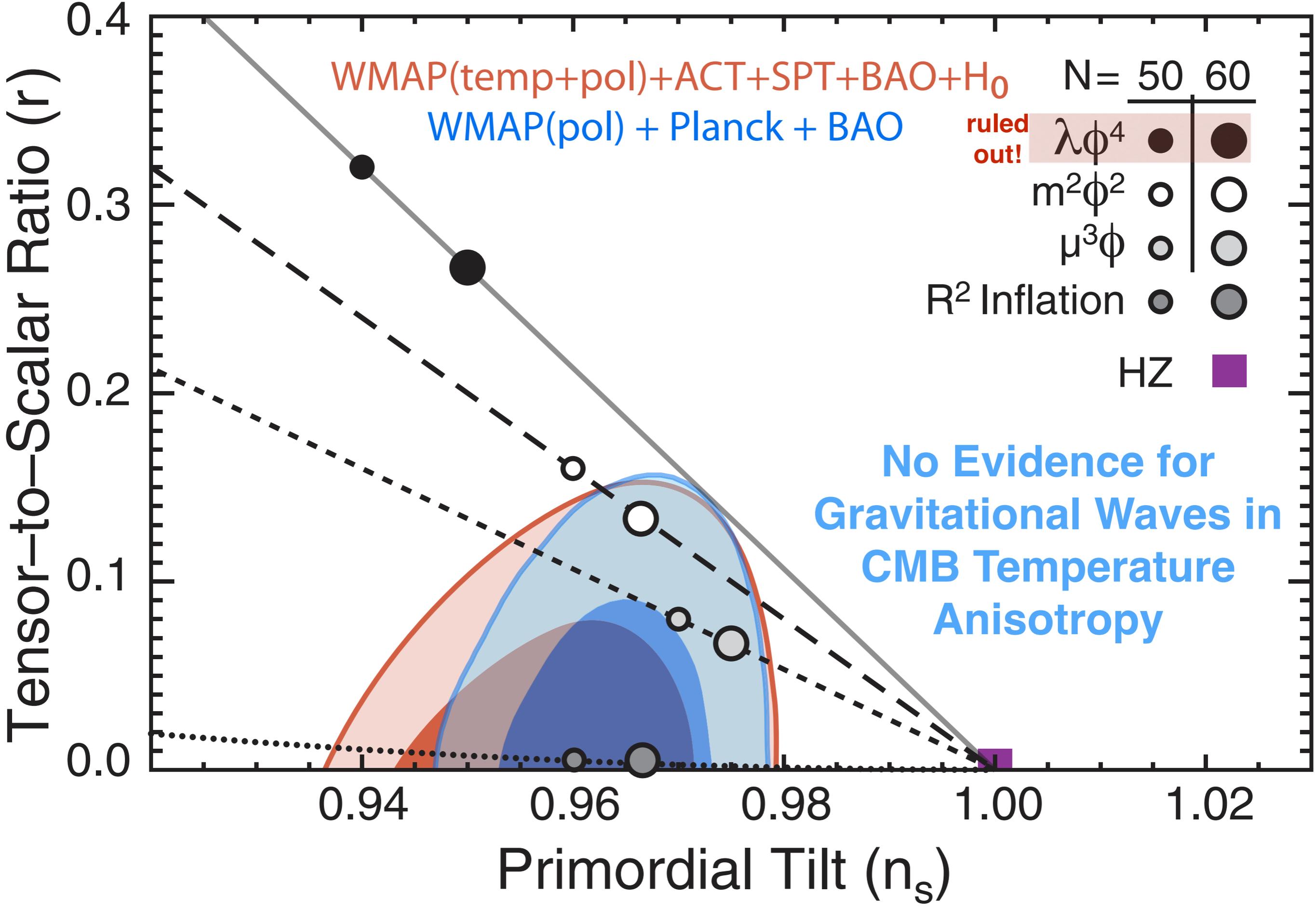
[Politik](#) [Panorama](#) [Kultur](#) [Wirtschaft](#) [Sport](#) [München](#) [Bayern](#) [Digital](#) [Auto](#) [Reise](#) [Video](#)[Home](#) [Wissen](#) [Kosmologie - Urknall-Forscher gestehen Irrtum ein](#)[Süddeutsche.de als Startseite einrichten](#)

Hir

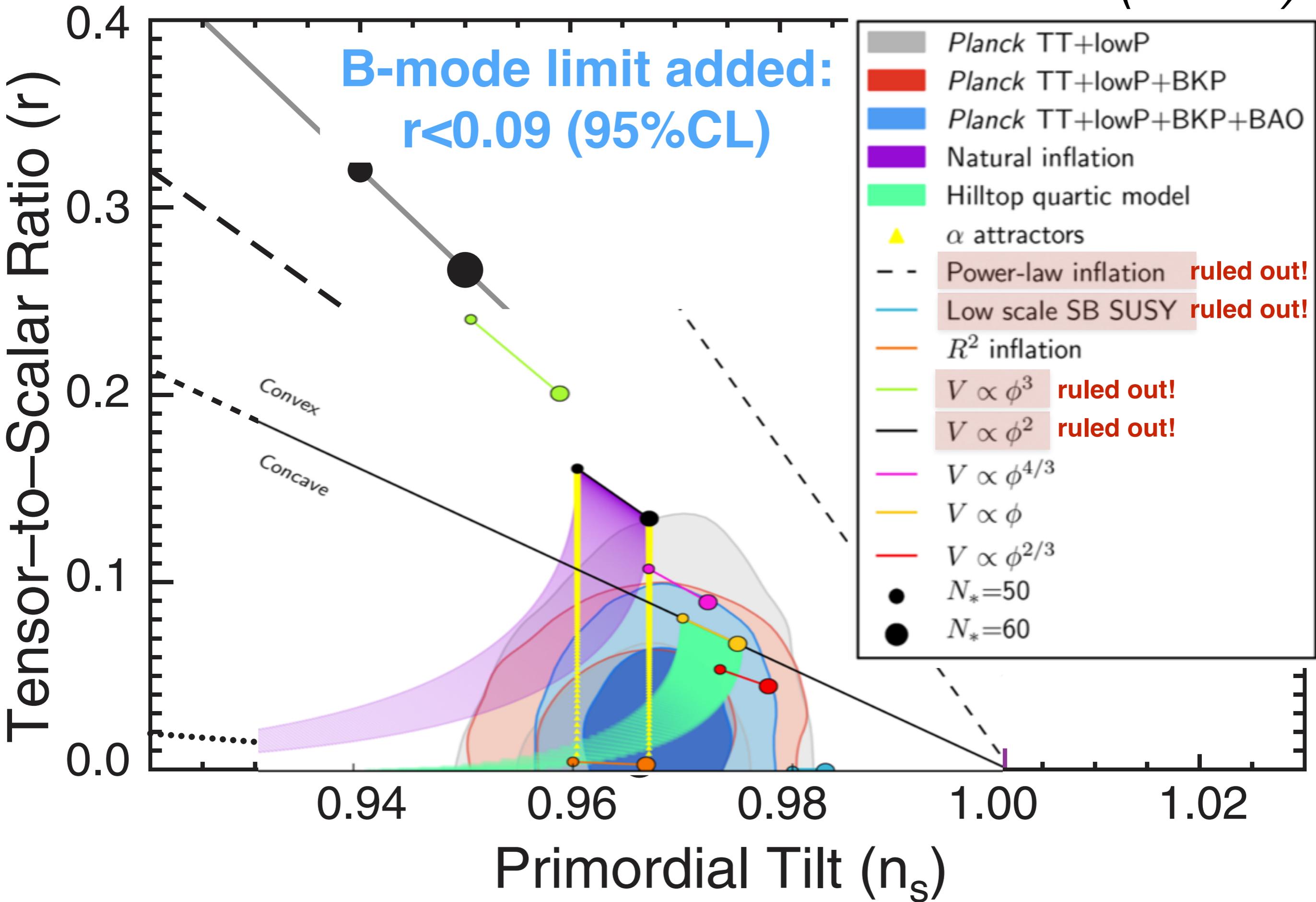
1. Februar 2015, 22:19 Kosmologie

## Urknall-Forscher gestehen Irrtum ein

Von Marlene Weiß



# Planck Collaboration (2015)



# Current Situation

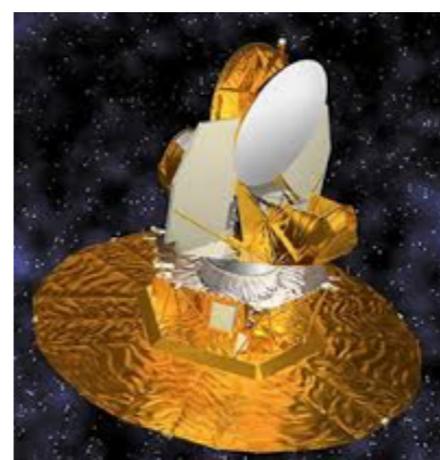
- Planck shows the evidence that the detected signal is not cosmological, but is due to dust
- No strong evidence that the detected signal is cosmological



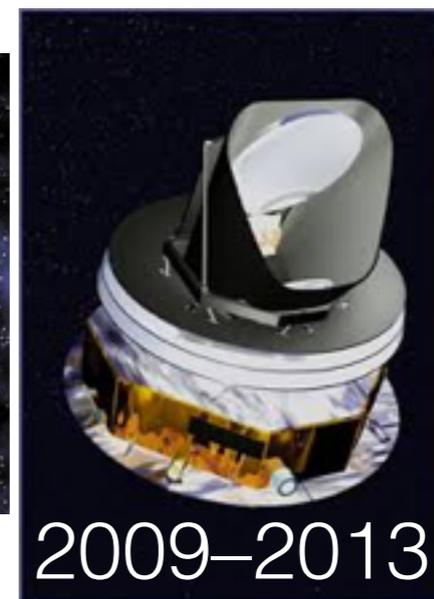
**The search continues!!**



1989–1993



2001–2010



2009–2013



202X–

# JAXA

+ possibly NASA

## LiteBIRD

2022– [proposed]



# Conclusion

- GR is essential for cosmology
- The WMAP data provide the precise and accurate determinations of the composition of the universe, and provide strong evidence for inflation
- The next goal: unambiguous measurement of the primordial B-mode polarisation from inflation
- **LiteBIRD** proposal: a CMB polarisation satellite in early 2020. Fingers crossed!