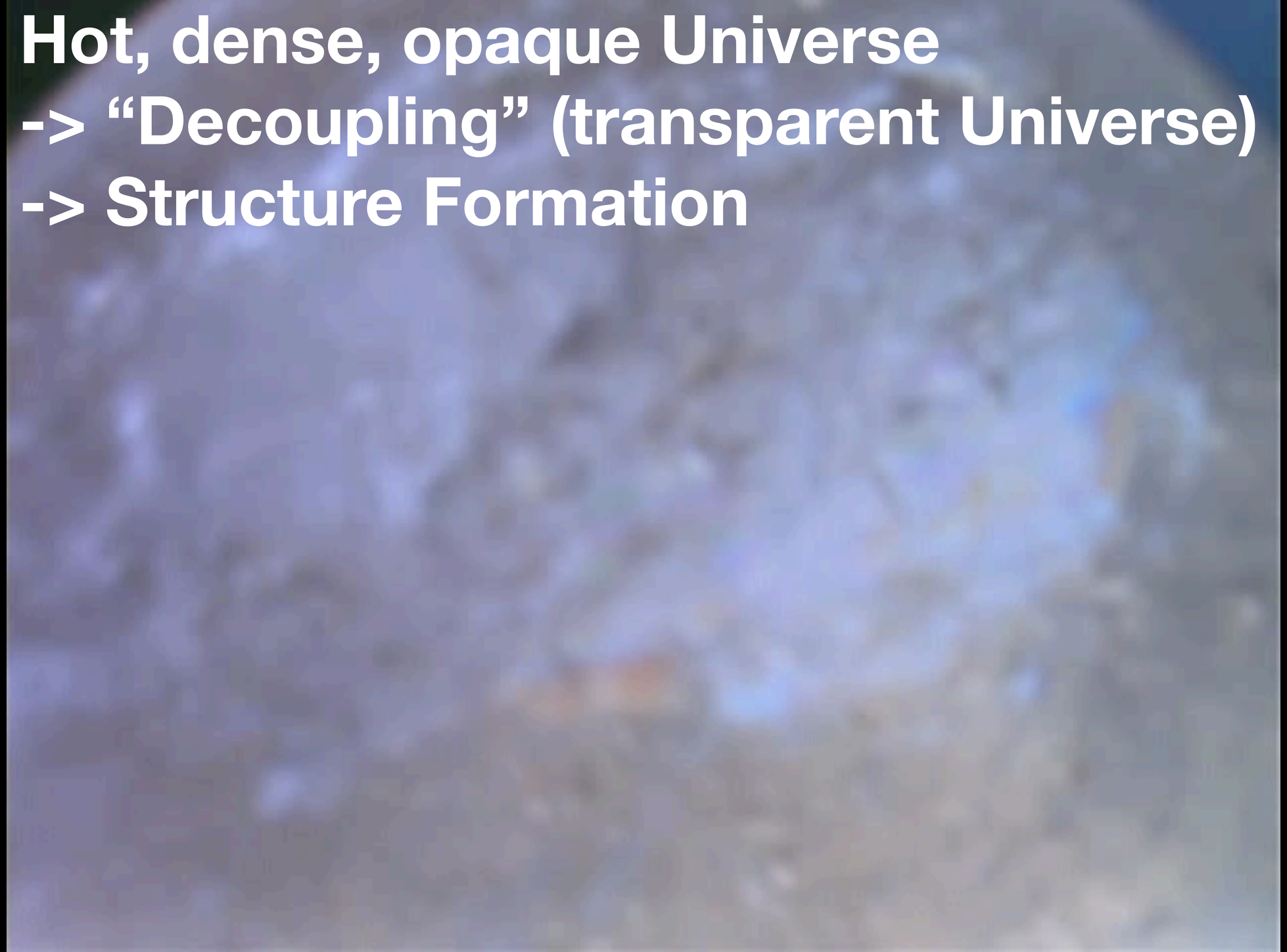
Finding Cosmic Inflation

The origin of all structures we see in the Universe

Eiichiro Komatsu (Max Planck Institute for Astrophysics)

Ta-You Wu Lecture, the University of Michigan, October 17, 2022

吳大猷講座



Hot, dense, opaque Universe

-> “Decoupling” (transparent Universe)

-> Structure Formation

From “Cosmic Voyage” (1996)

Sky in Optical (~0.5μm)

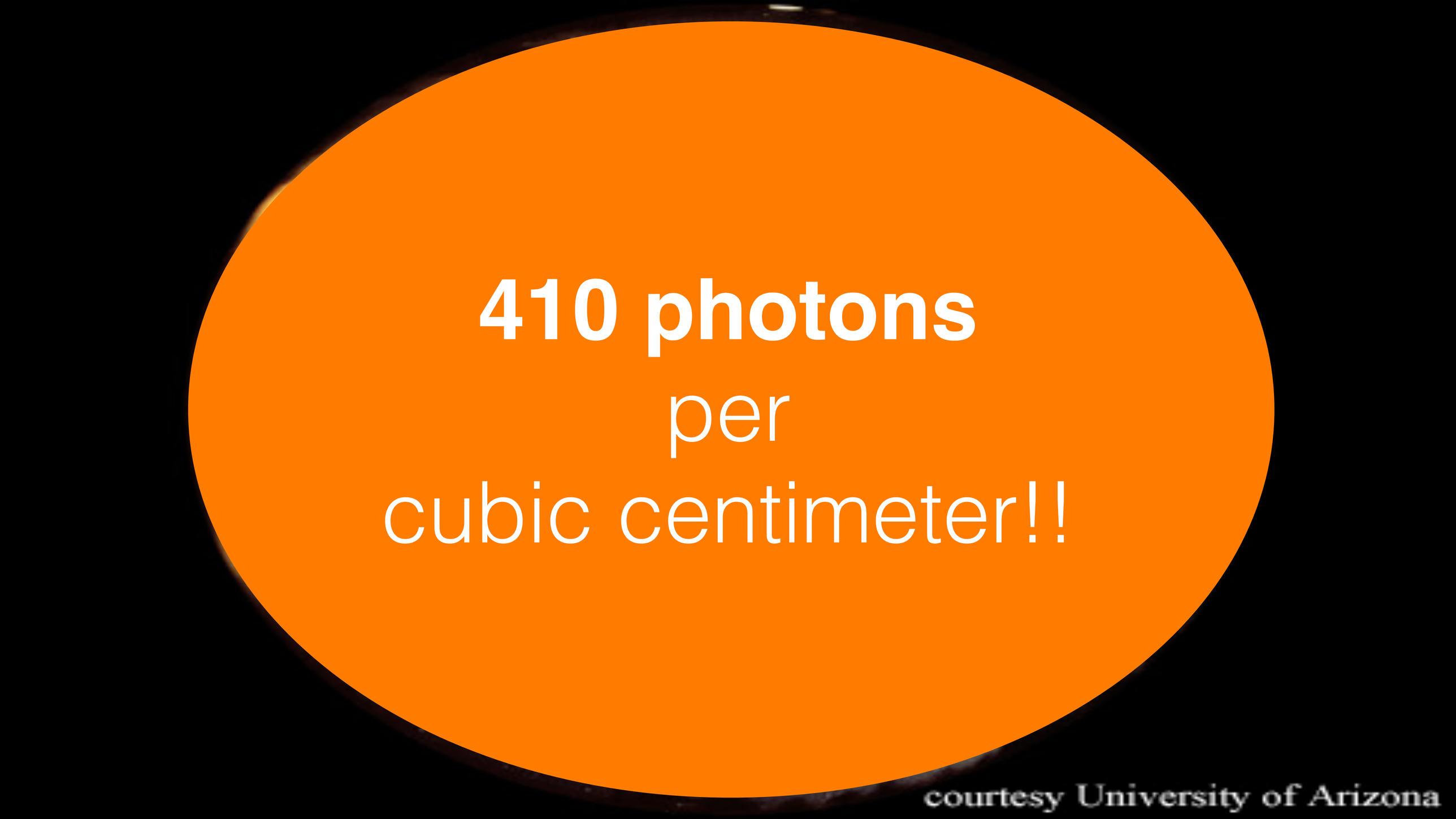
Sky in Microwave (~1mm)

Sky in Microwave (~1mm)

Light from the fireball Universe, filling our sky (2.7K)

The Cosmic Microwave Background (CMB)

courtesy University of Arizona


410 photons
per
cubic centimeter!!
courtesy University of Arizona

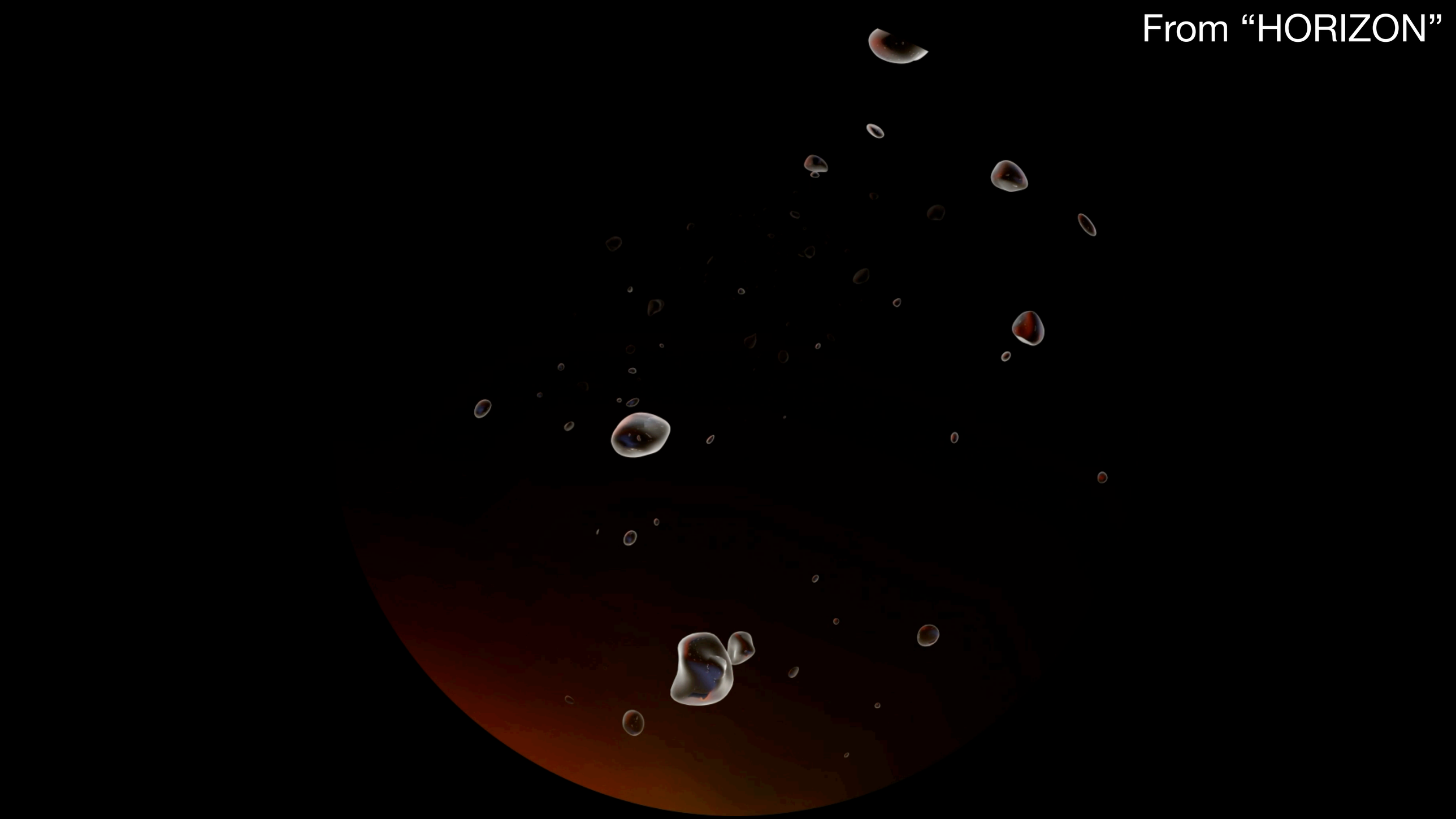
YouTube BE

horizon edge of the visible universe

Full-dome movie for planetarium

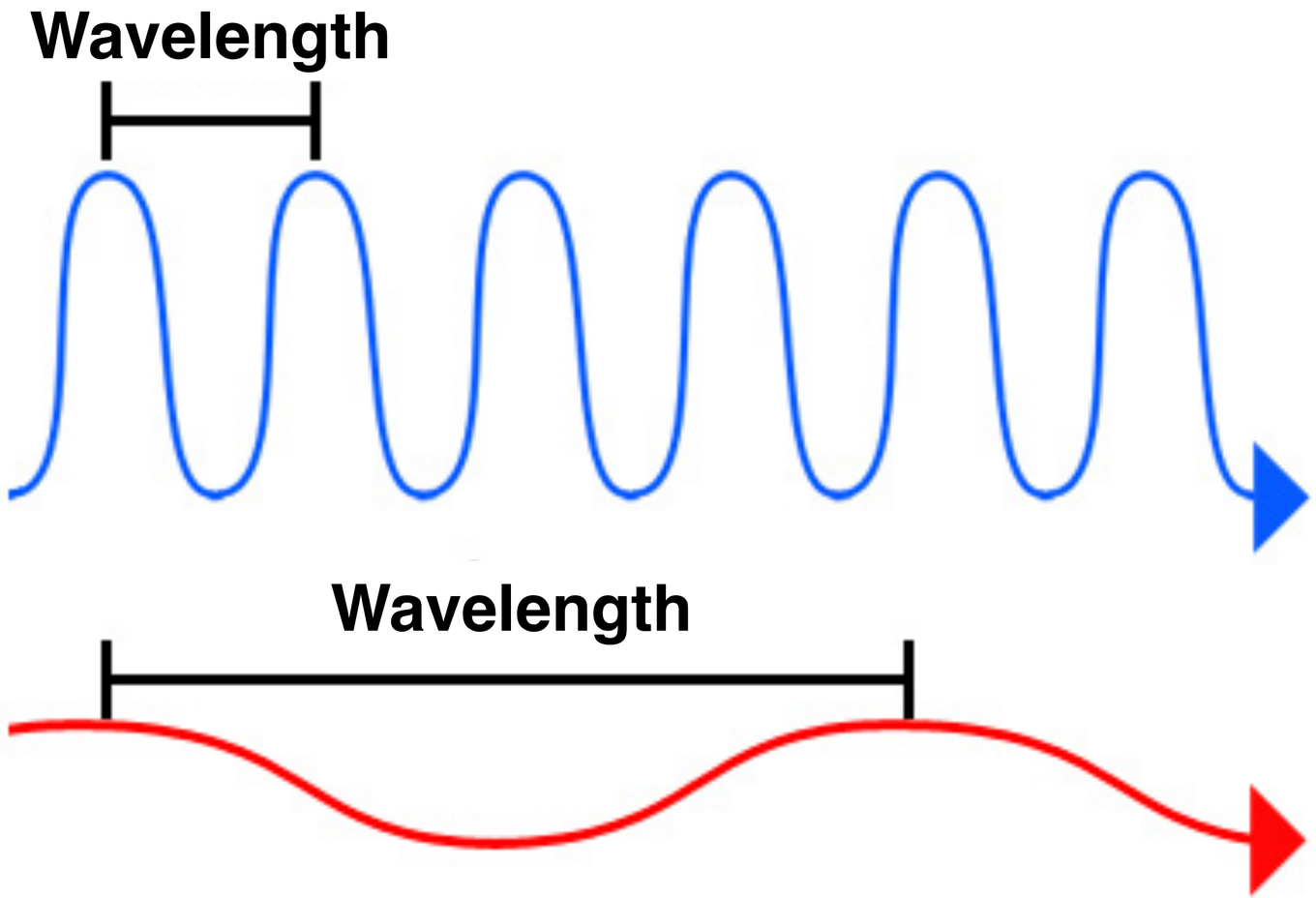
Director: Hiromitsu Kohsaka

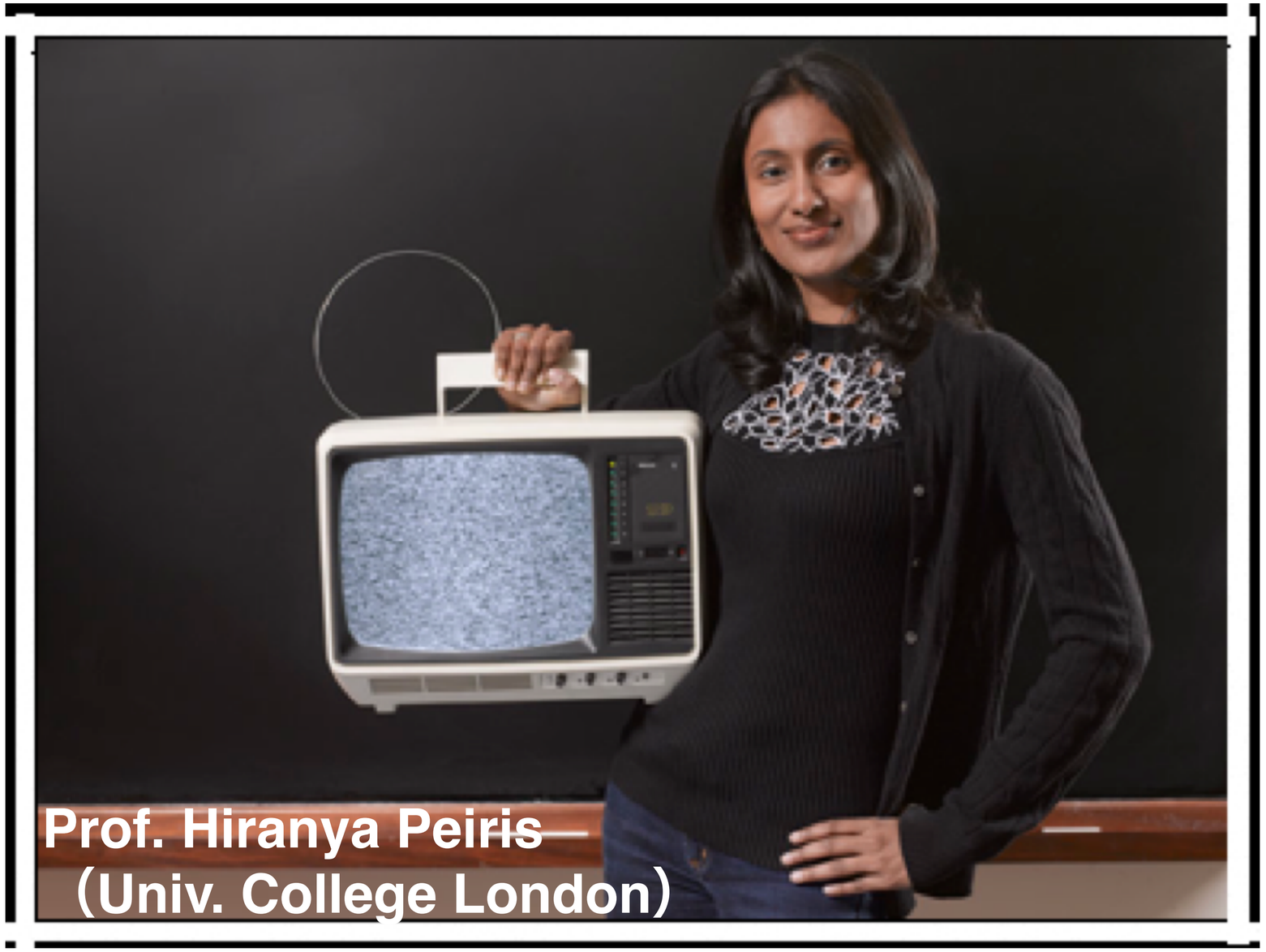
HORIZON :Beyond the Edge of the Visible Universe [Trailer]


From “HORIZON”

Wavelength of Light

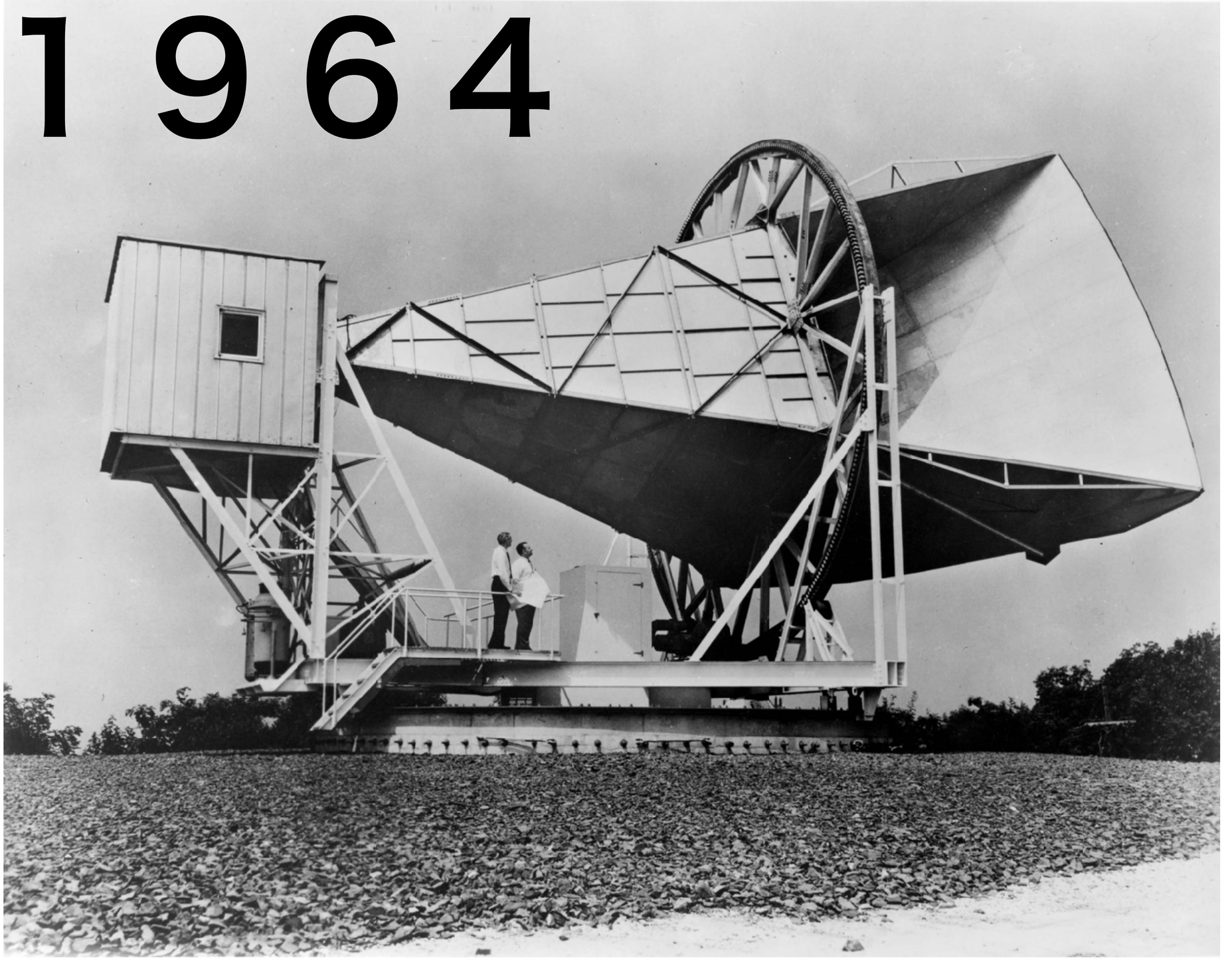
- **Visible light is**
  - shorter wavelength
  - 380–740 nanometers
- **Microwave is**
  - longer wavelength
  - millimeter to centimeter



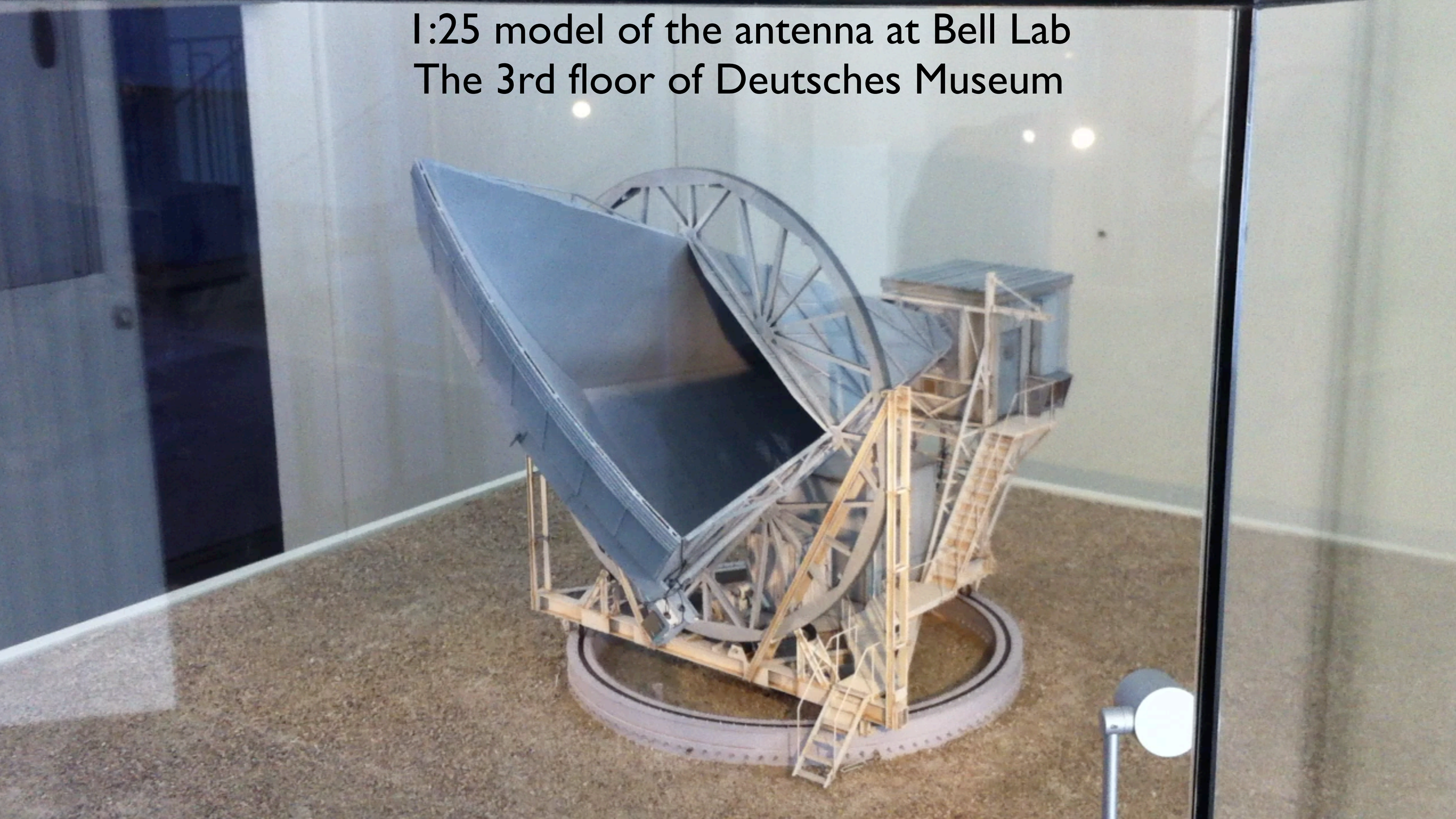


All you need to do is to detect radio waves. For example, 1% of noise on the TV is from the fireball Universe

1964

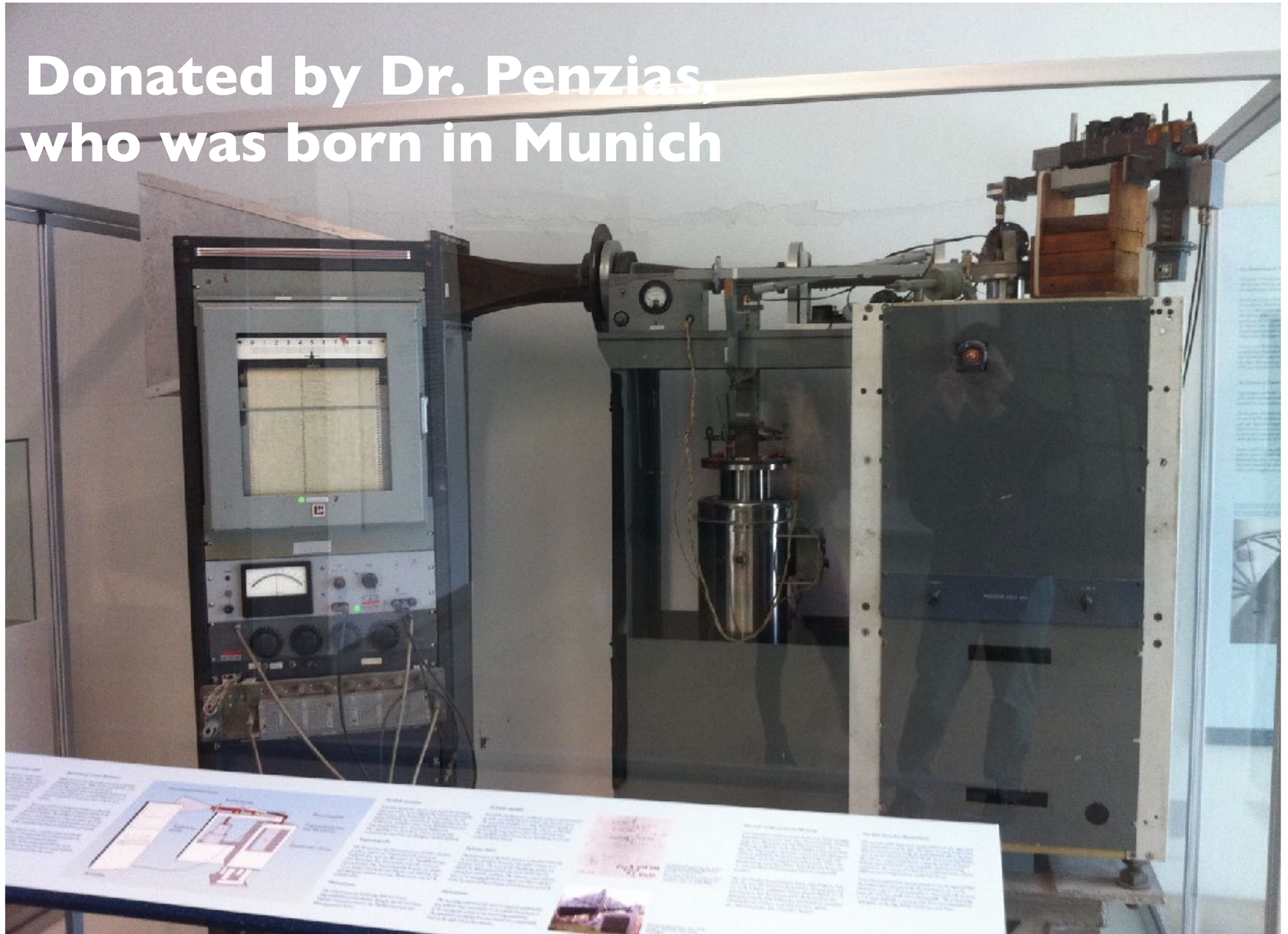


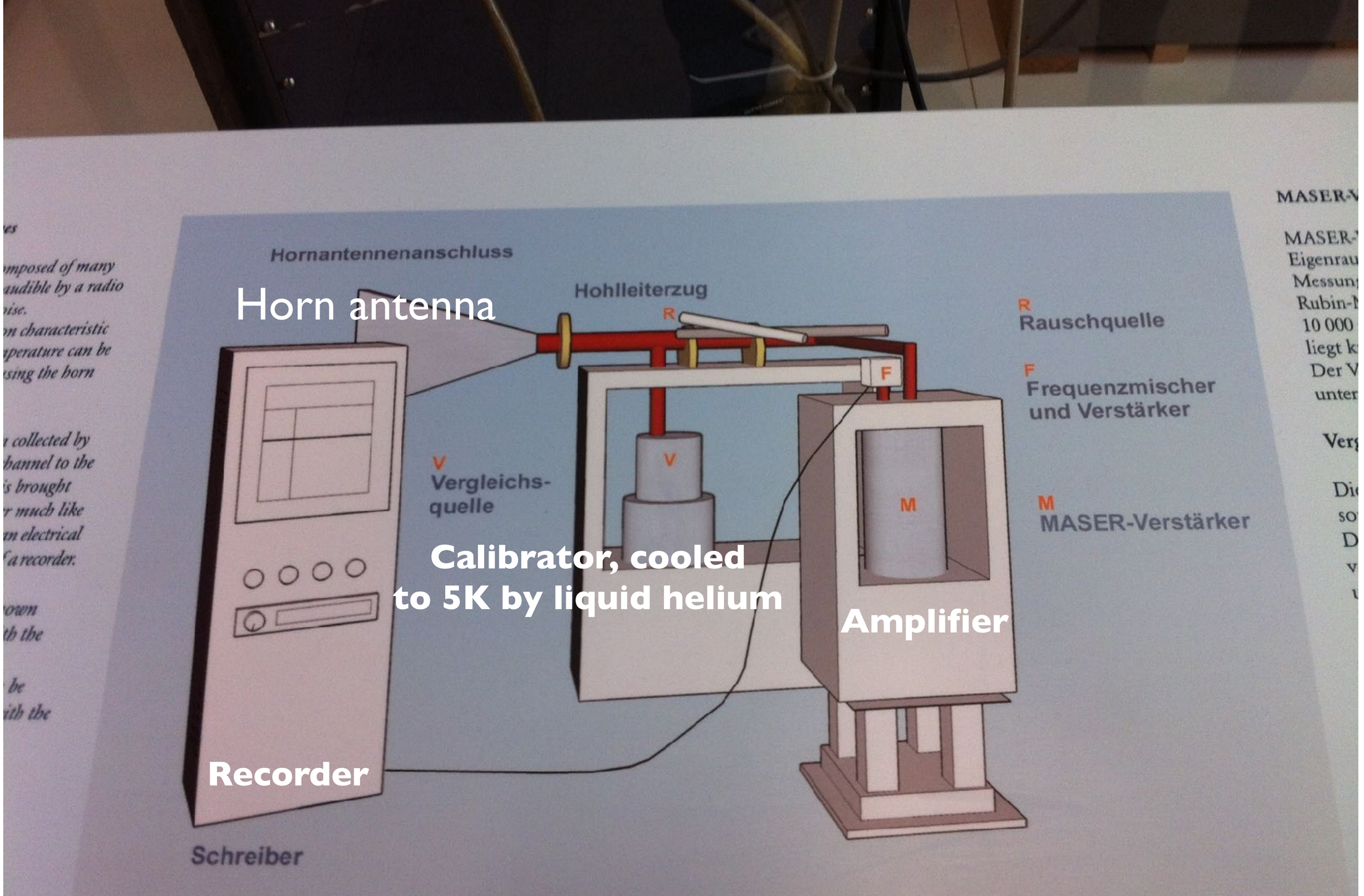
1:25 model of the antenna at Bell Lab
The 3rd floor of Deutsches Museum



The real detector system used by Penzias & Wilson
The 3rd floor of Deutsches Museum

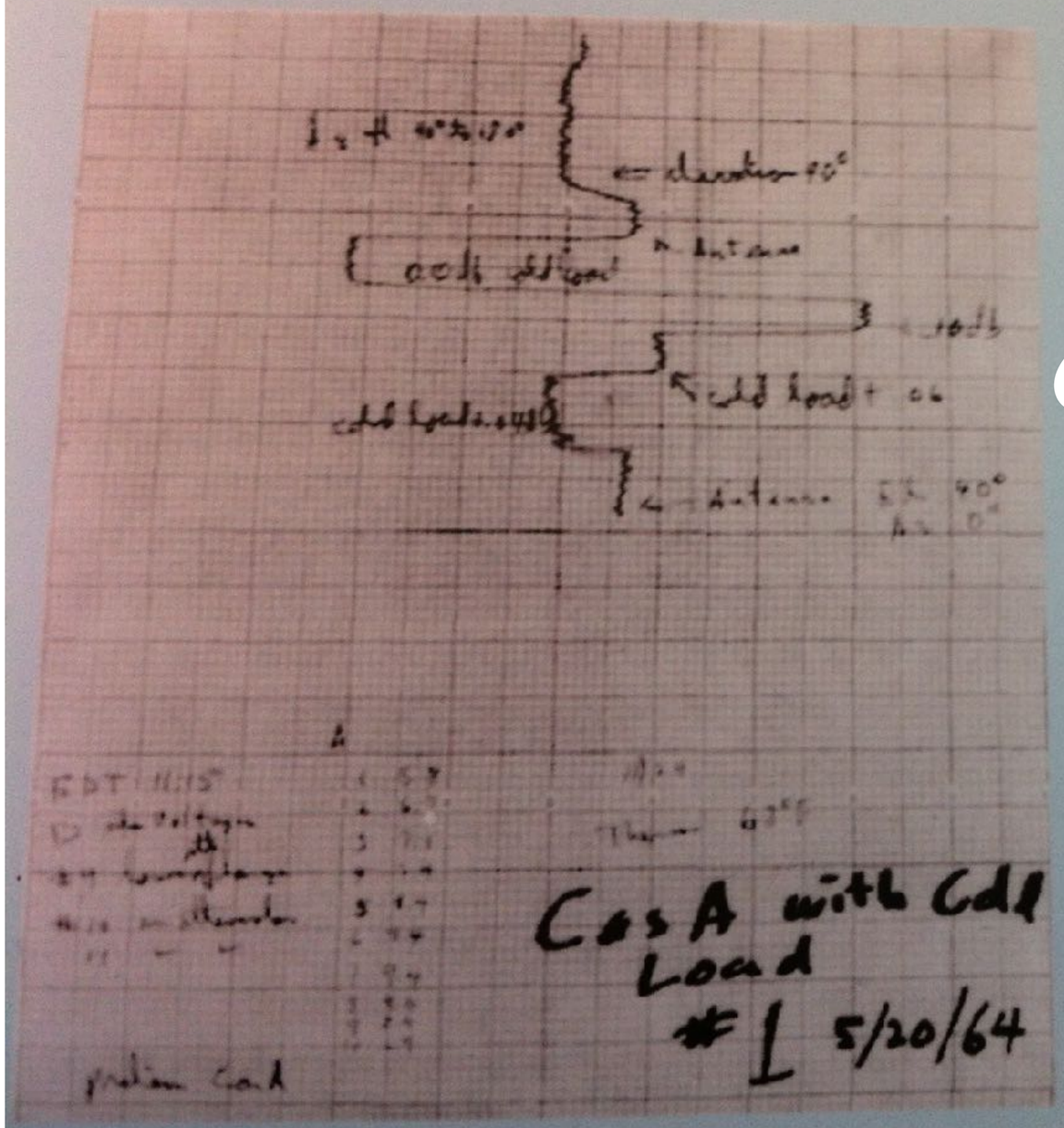
Arno Penzias




Hornantennenanschluss
Horn antenna
Hohlleiterzug
R
Rauschquelle
F
Frequenzmischer
und Verstärker
M
MASER-Verstärker
V
Vergleichs-
quelle
Calibrator, cooled
to 5K by liquid helium
Amplifier
Recorder
Schreiber

May 20, 1964
CMB
Discovered

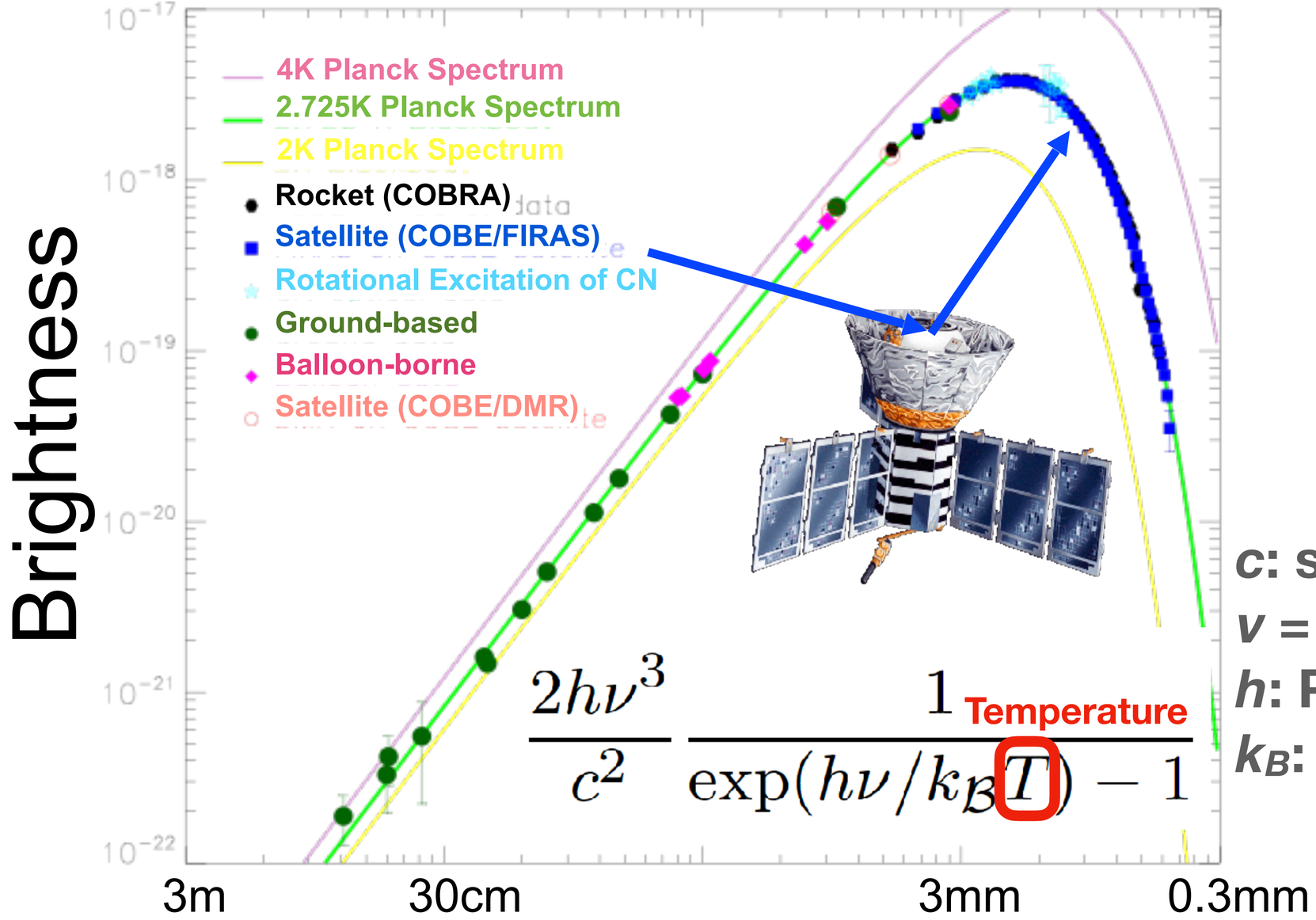
6.7–2.3–0.8–0.1
= 3.5±1.0 K



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.

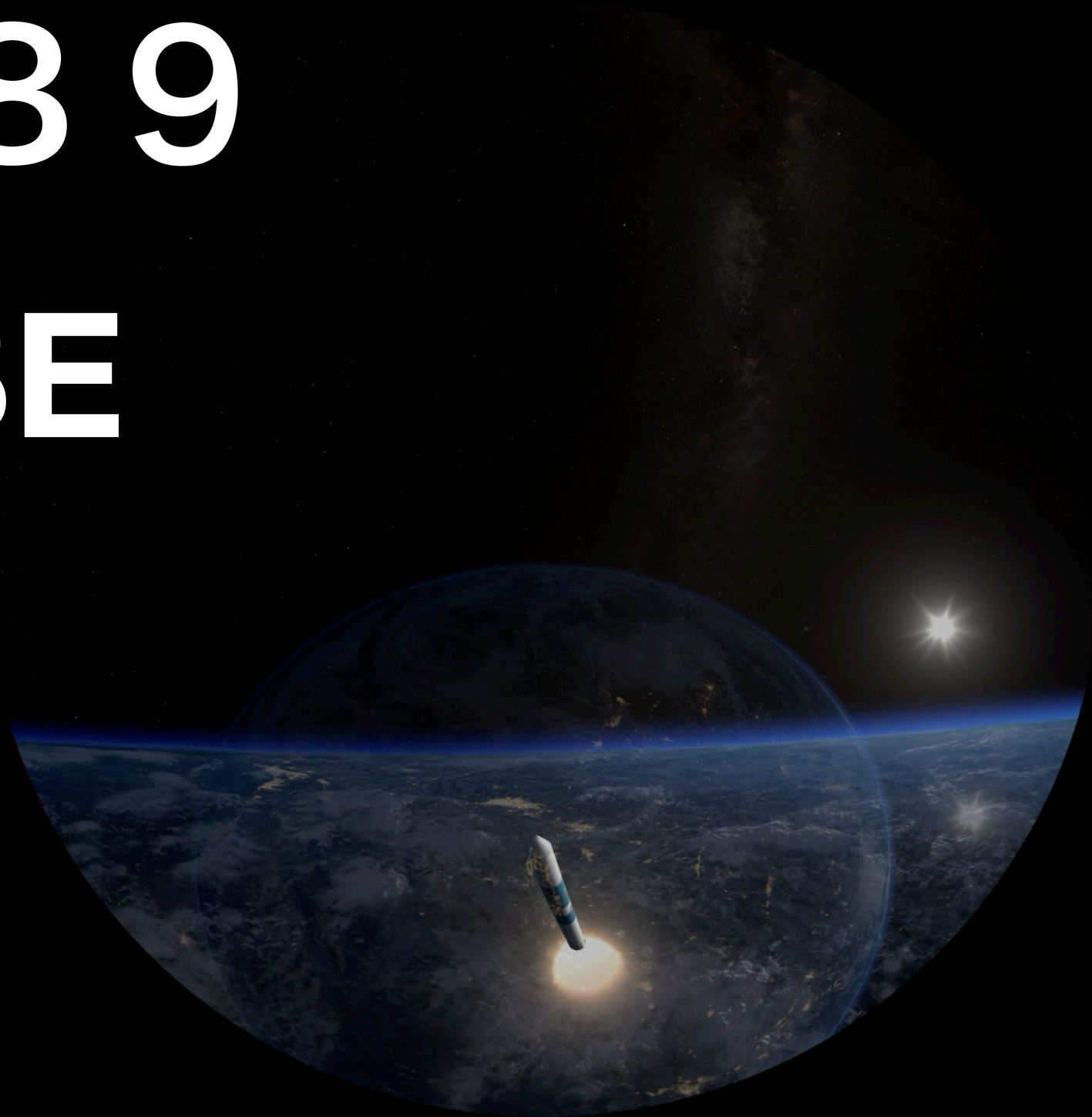
Spectrum of CMB = Spectrum of the fireball



***c*: speed of light**
***v* = *c* / wavelength**
***h*: Planck constant**
***k_B*: Boltzmann constant**

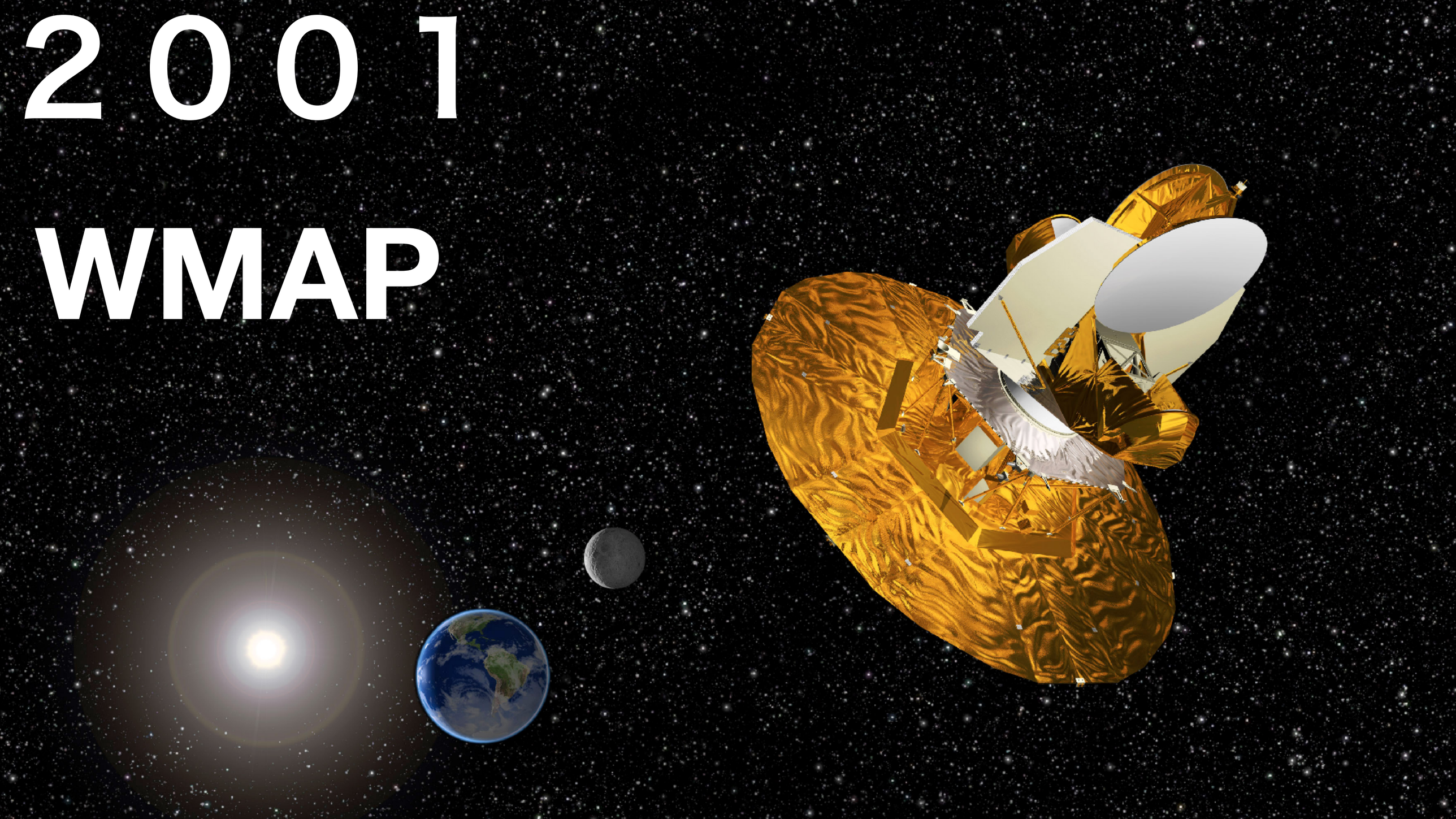
1989

СОВЕ



2001

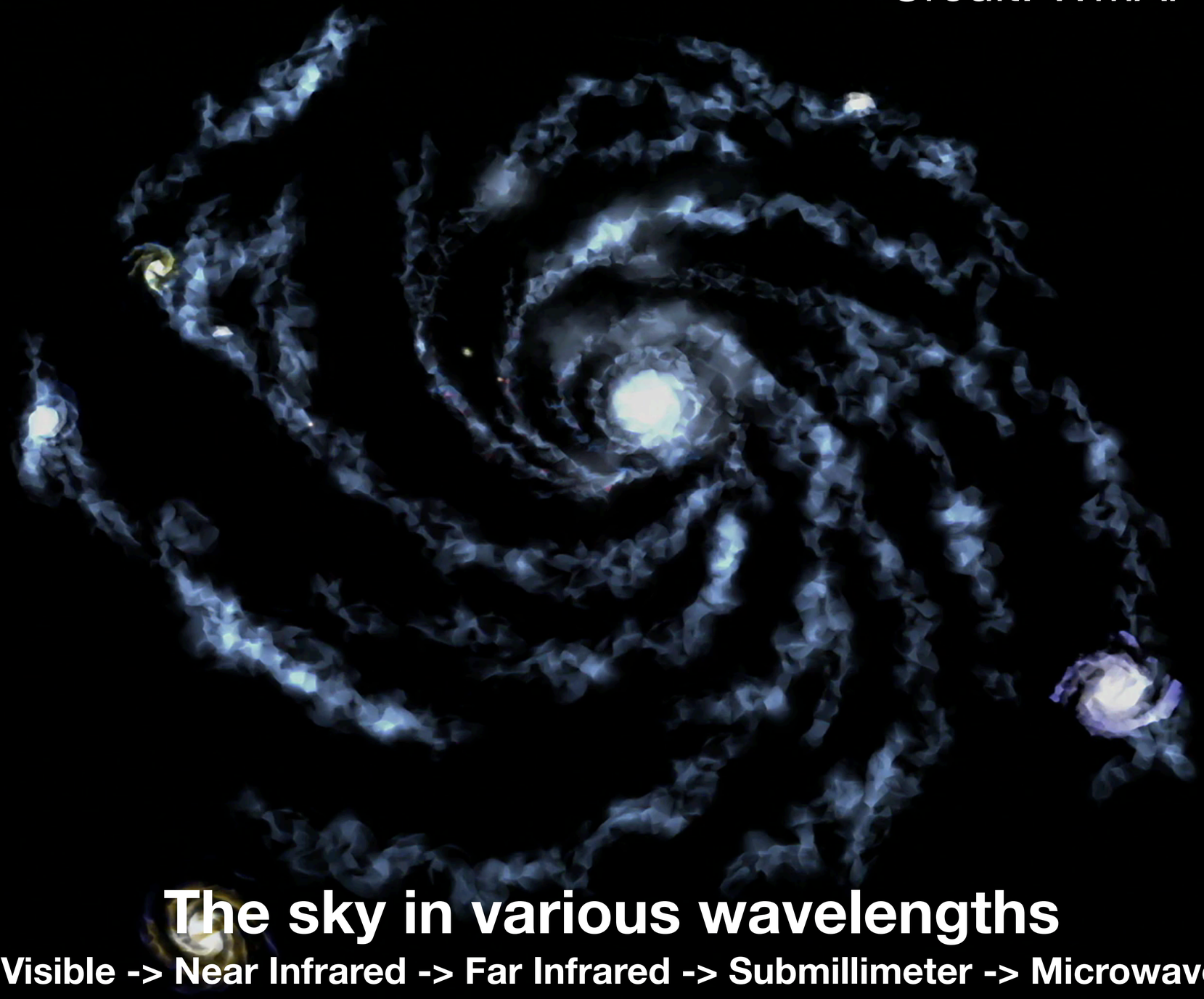
WMAP



WMAP Science Team
July 19, 2002

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

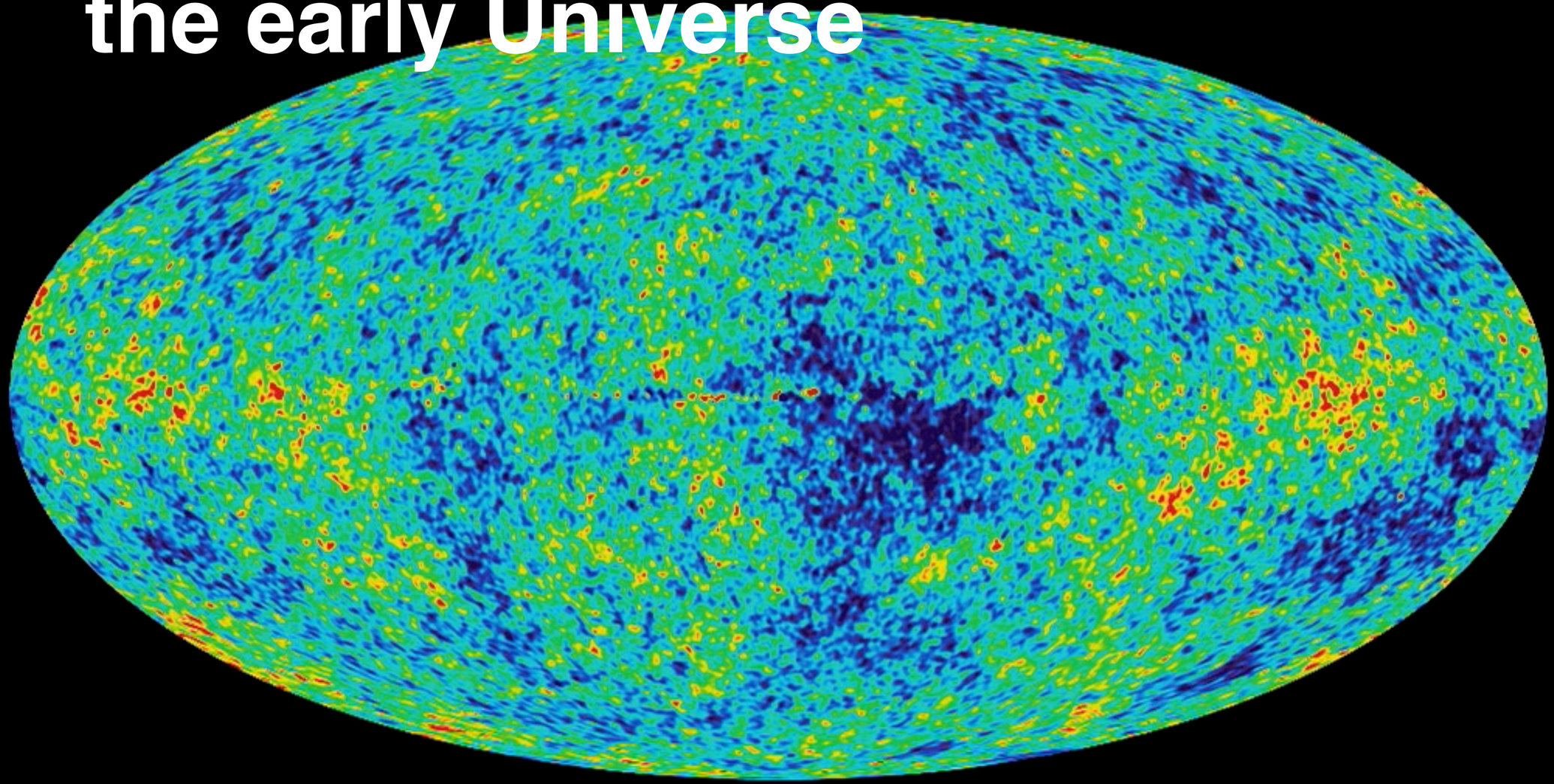
Credit: WMAP Science Team



The sky in various wavelengths

Visible -> Near Infrared -> Far Infrared -> Submillimeter -> Microwave

Our origin: Tiny fluctuations in the early Universe

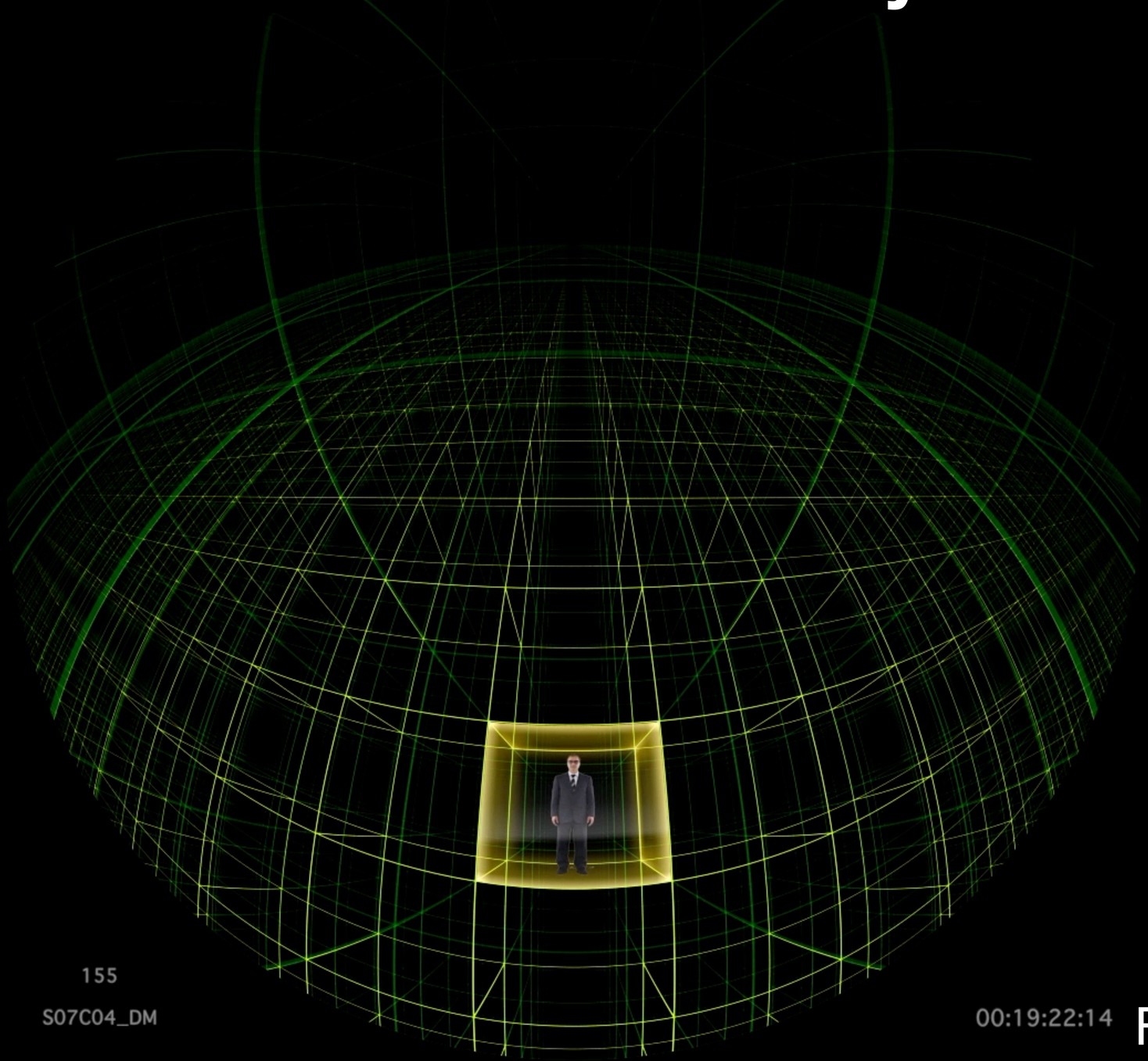


Credit: WMAP Science Team

A Remarkable Story

- Observations of the cosmic microwave background and their interpretation taught us that **all structures in the Universe** (galaxies, stars, planets, and eventually life) **originated from tiny fluctuations in the early Universe.**

Where did the CMB we see today come from?

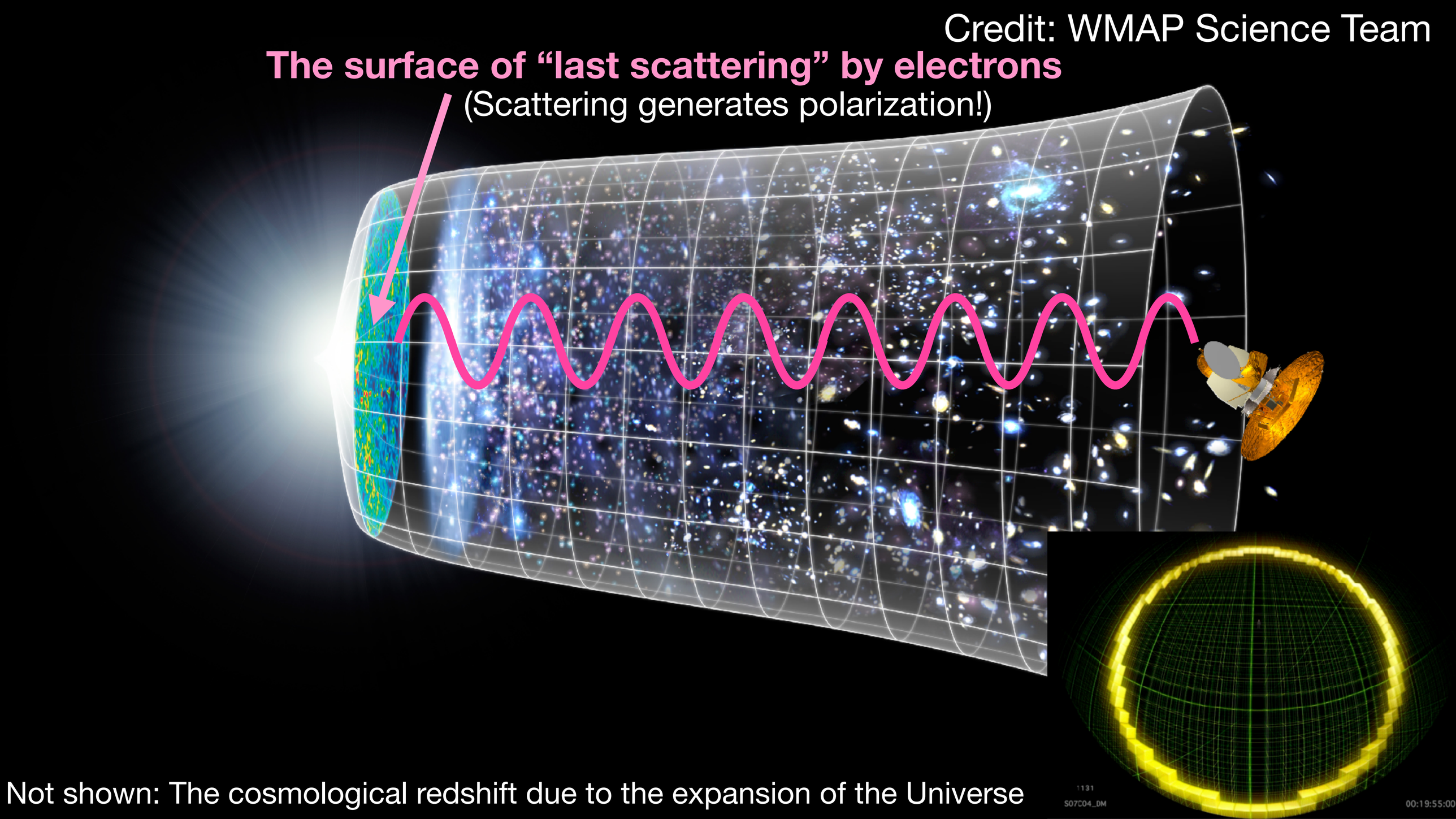


From “HORIZON”

Credit: WMAP Science Team

The surface of “last scattering” by electrons

(Scattering generates polarization!)

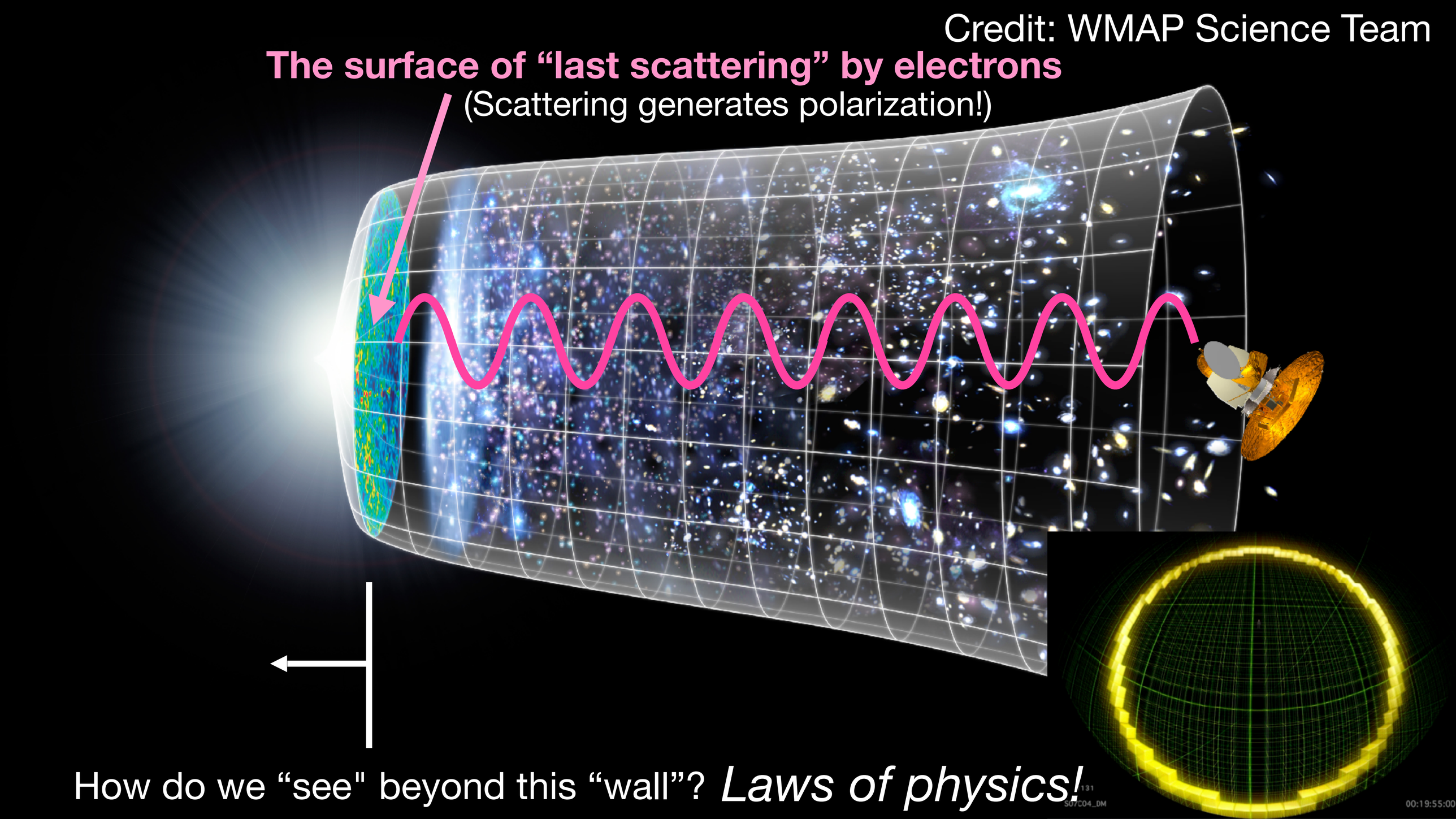


Not shown: The cosmological redshift due to the expansion of the Universe

Credit: WMAP Science Team

The surface of “last scattering” by electrons

(Scattering generates polarization!)



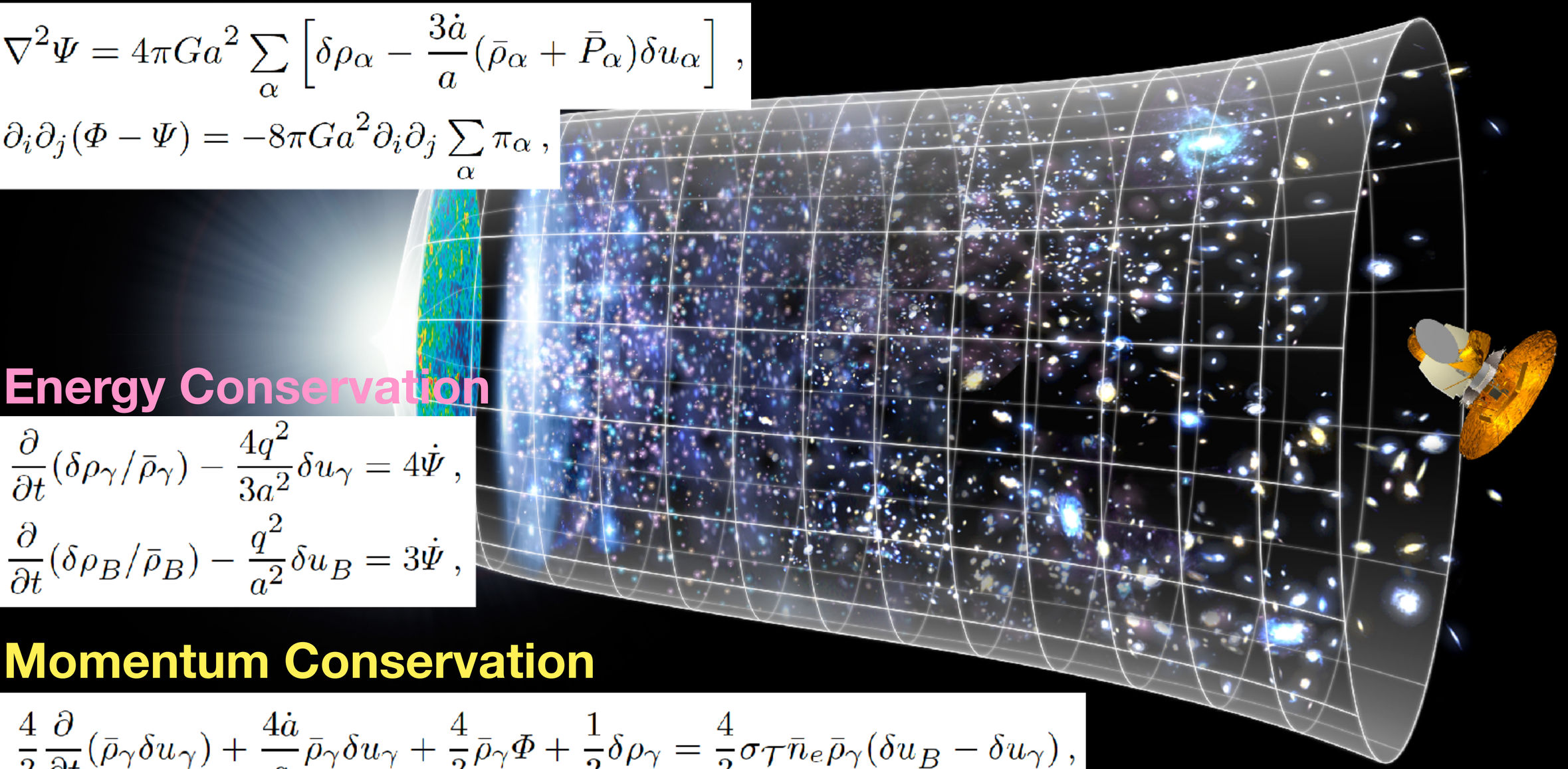
How do we “see" beyond this “wall”? *Laws of physics!*

Gravitational Field Equations (Einstein's Eq.)

$$\nabla^2\Psi = 4\pi G a^2 \sum_\alpha \left[\delta\rho_\alpha - \frac{3\dot{a}}{a}(\bar{\rho}_\alpha + \bar{P}_\alpha)\delta u_\alpha\right] ,$$

$$\partial_i\partial_j(\Phi - \Psi) = -8\pi G a^2 \partial_i\partial_j \sum_\alpha \pi_\alpha ,$$

Credit: WMAP Science Team



Energy Conservation

$$\frac{\partial}{\partial t}(\delta\rho_\gamma/\bar{\rho}_\gamma) - \frac{4q^2}{3a^2}\delta u_\gamma = 4\dot{\Psi} ,$$

$$\frac{\partial}{\partial t}(\delta\rho_B/\bar{\rho}_B) - \frac{q^2}{a^2}\delta u_B = 3\dot{\Psi} ,$$

Momentum Conservation

$$\frac{4}{3}\frac{\partial}{\partial t}(\bar{\rho}_\gamma\delta u_\gamma) + \frac{4\dot{a}}{a}\bar{\rho}_\gamma\delta u_\gamma + \frac{4}{3}\bar{\rho}_\gamma\Phi + \frac{1}{3}\delta\rho_\gamma = \frac{4}{3}\sigma_T\bar{n}_e\bar{\rho}_\gamma(\delta u_B - \delta u_\gamma) ,$$

$$\frac{\partial}{\partial t}(\bar{\rho}_B\delta u_B) + \frac{3\dot{a}}{a}\bar{\rho}_B\delta u_B + \bar{\rho}_B\Phi = -\frac{4}{3}\sigma_T\bar{n}_e\bar{\rho}_\gamma(\delta u_B - \delta u_\gamma) ,$$

Laws of physics!

Gravitational Field Equations

+

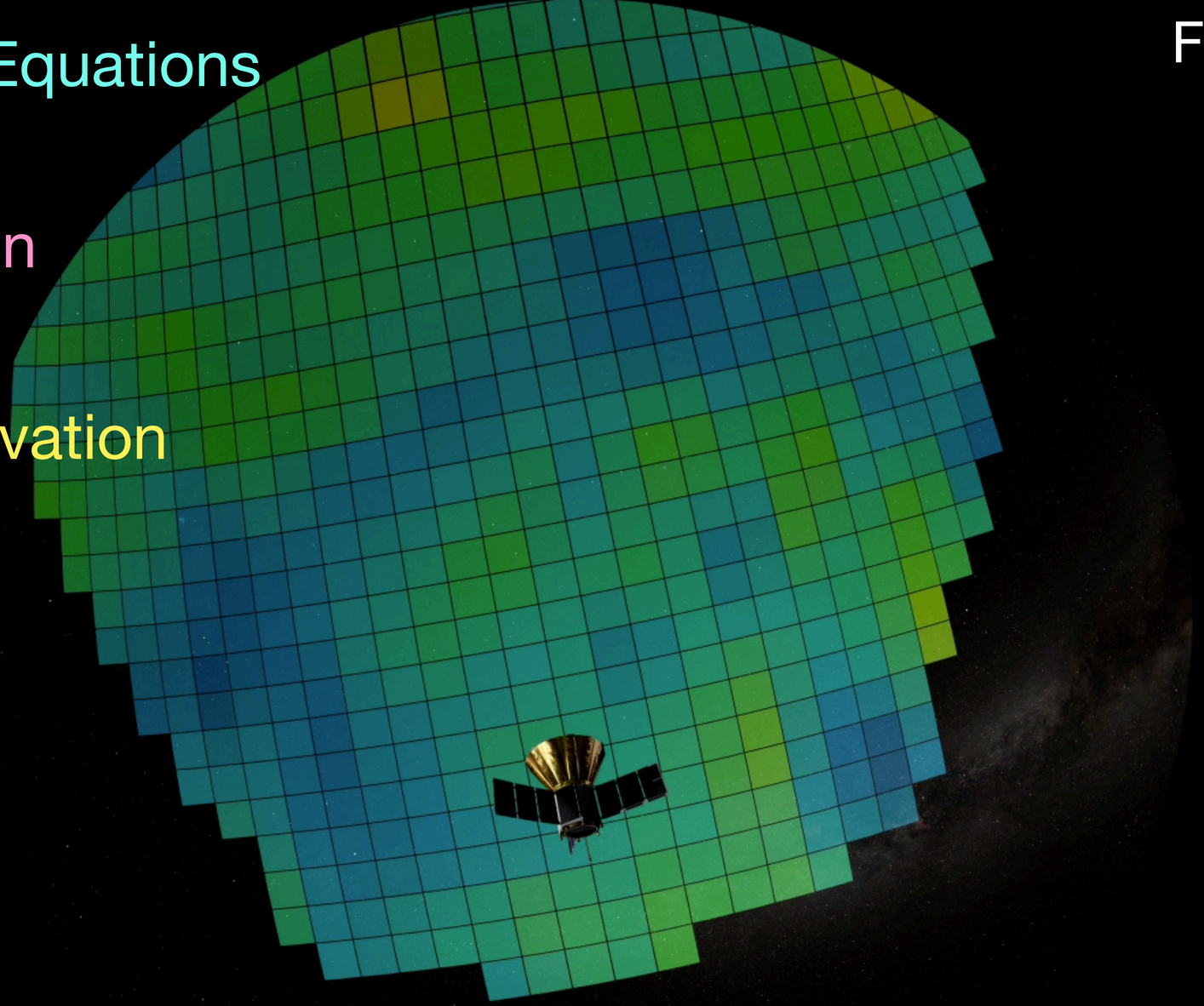
Energy Conservation

+

Momentum Conservation

=

Sound Waves!

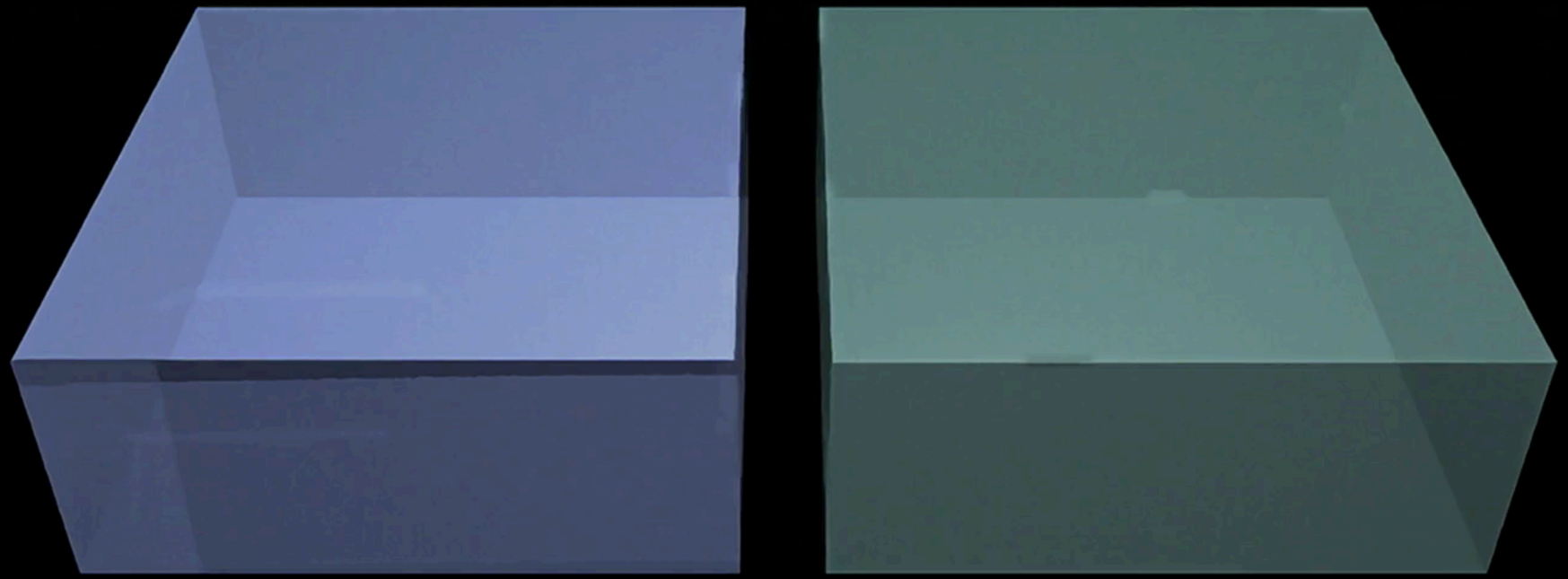


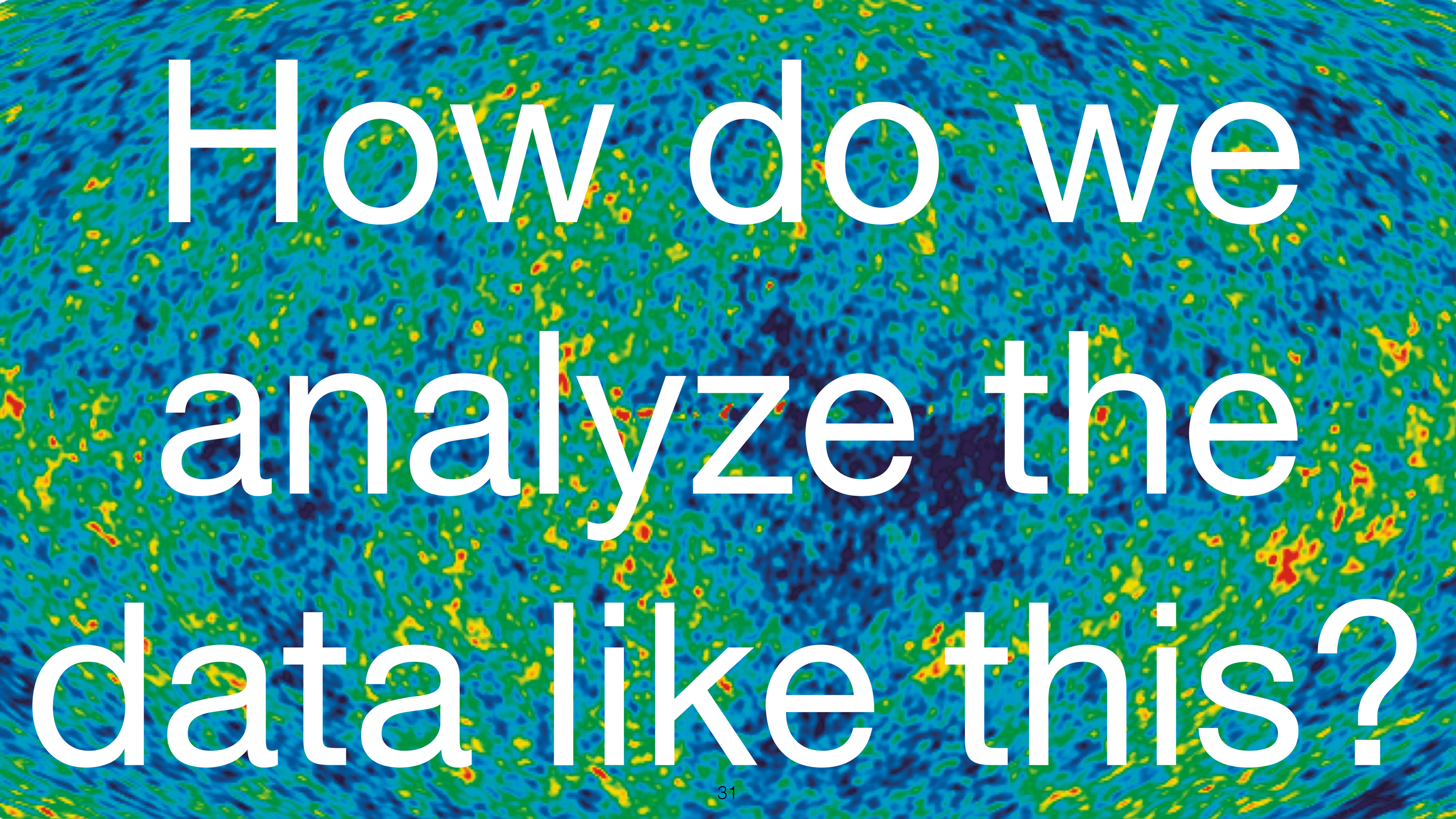
From “HORIZON”

The Cosmic Miso Soup

- 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

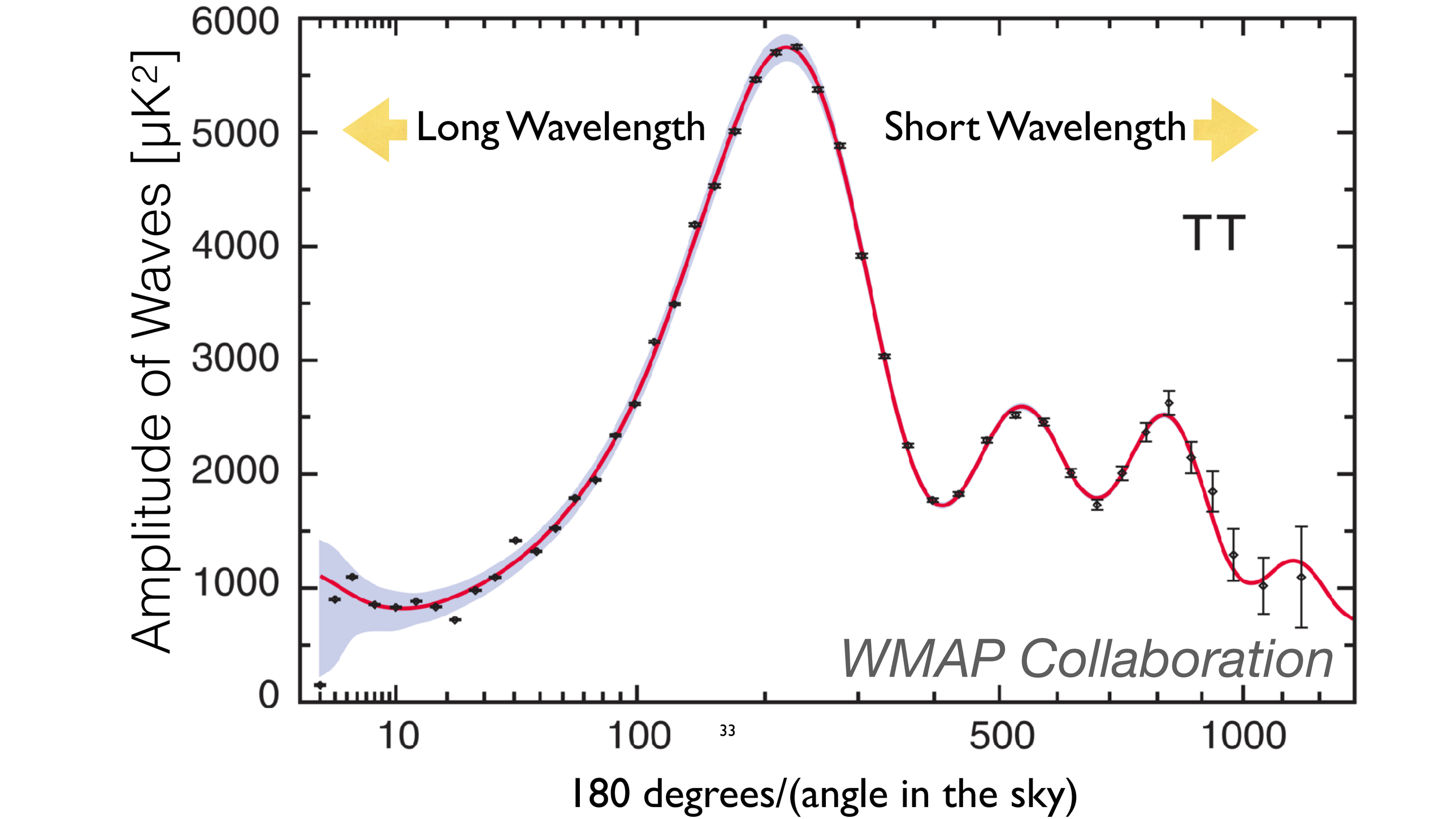
Credit: WMAP Science Team



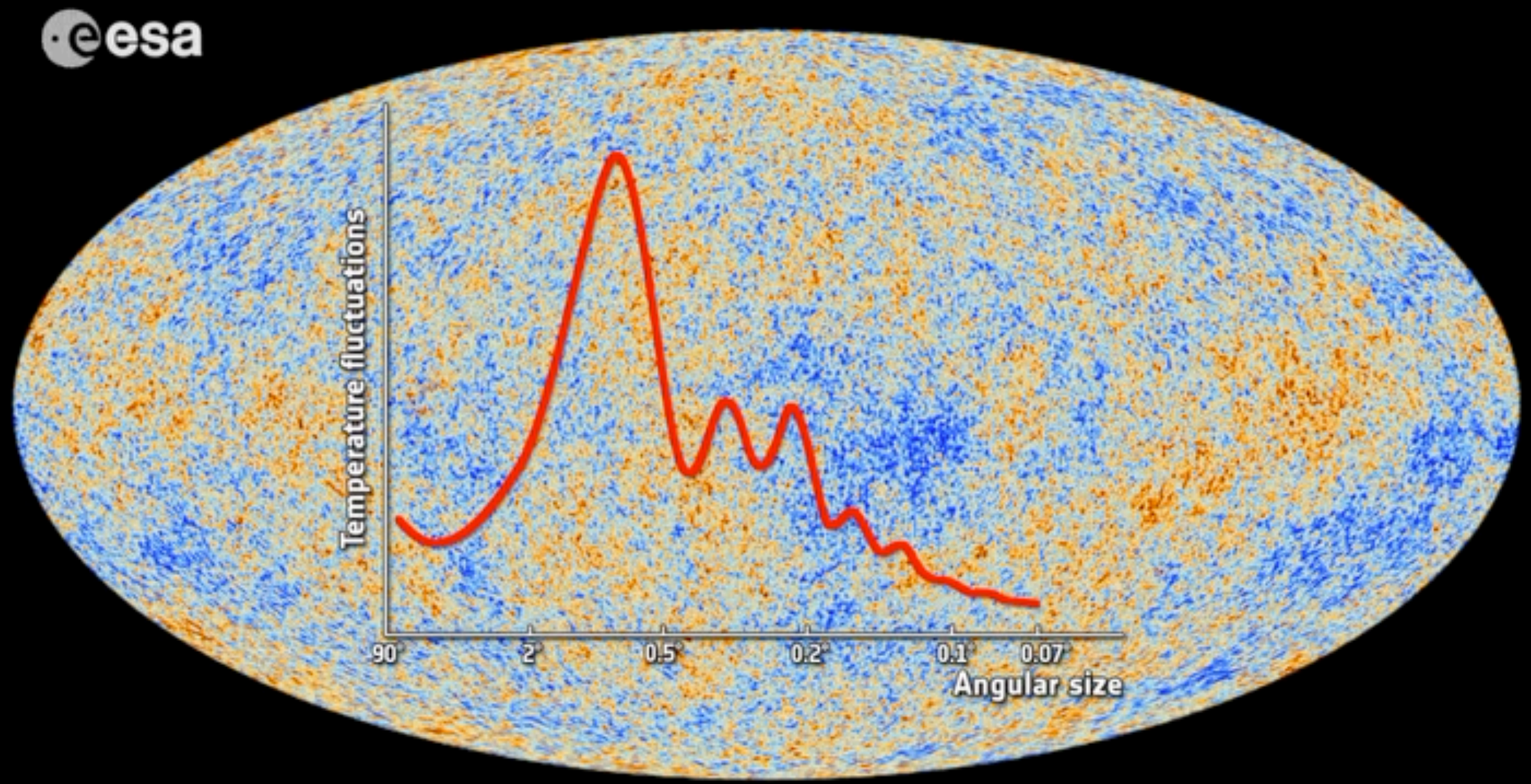

How do we
analyze the
data like this?

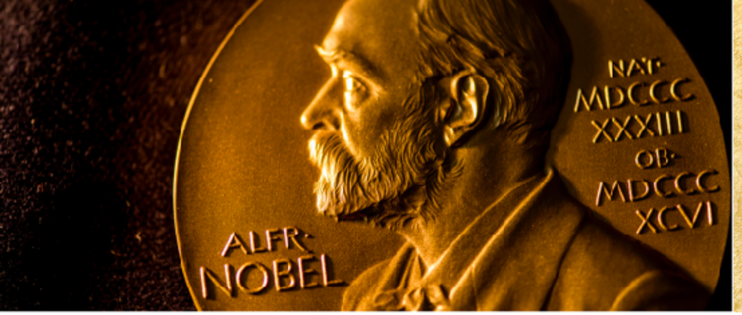
Data Analysis

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


Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
Short Wavelength
TT
WMAP Collaboration
10
100
500
1000
180 degrees/(angle in the sky)

Power Spectrum, Explained





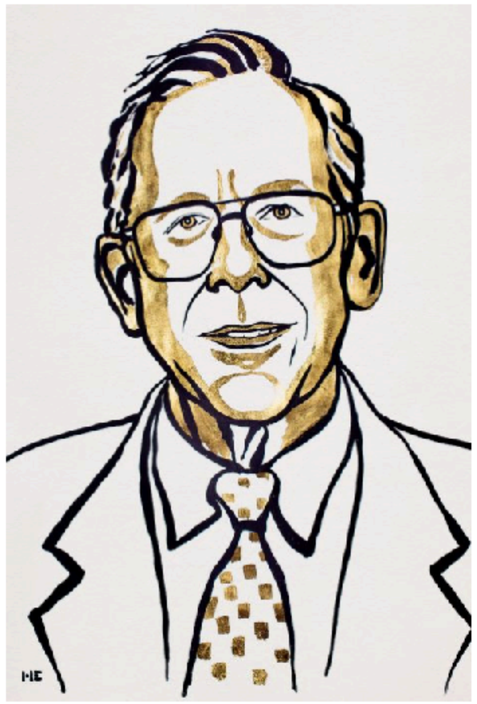
The Royal Swedish Academy of Sciences has decided to award the 2019 Nobel Prize in Physics to

JAMES PEEBLES

"for theoretical discoveries in physical cosmology"

Sound waves in the fireball Universe, predicted in 1970

James Peebles
Facts



Ill. Niklas Elmedhed. © Nobel Media. **https://www.nobelprize.org**

James Peebles
The Nobel Prize in Physics 2019

Born: 1935, Winnipeg, Canada

Affiliation at the time of the award: I
Princeton, NJ, USA

Prize motivation: "for theoretical dis
cosmology."

Prize share: 1/2

THE ASTROPHYSICAL JOURNAL, 162:815–836, December 1970

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

P. J. E. PEEBLES†
Joseph Henry Laboratories, Princeton University
AND
J. T. YU‡
Goddard Institute for Space Studies, NASA, New York
Received 1970 January 5; revised 1970 April 1

At the *ICGC2011* conference, Goa, India

Sound waves in the fireball Universe, predicted in 1970

Astrophysics and Space Science 7 (1970) 3–19.

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

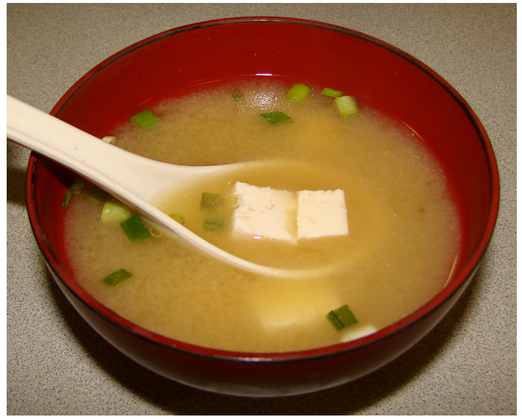
R. A. SUNYAEV and YA. B. ZELDOVICH
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)

Determine the composition of the Universe

The Universe as a “hot soup”

- The power spectrum allows us to determine the composition of the Universe, such as the density of atoms, dark matter, and dark energy.

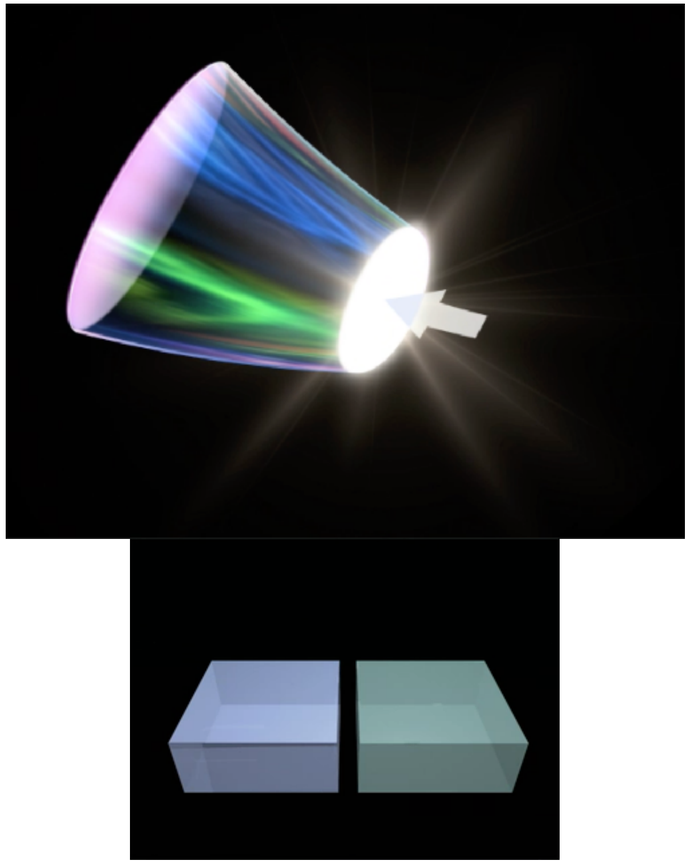


- **Definitive evidence that dark matter is not made of atoms!**

“Let’s give some impact to the beginning of this model”

- What gave the initial fluctuation to the cosmic hot soup?

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



Leading Idea:

- Quantum mechanics at work in the early Universe
  - “*We all came from quantum fluctuations*”
- But, how did the quantum fluctuation on the *microscopic* scale become *macroscopic* over large distances?
- **What is the missing link between the small and large scales?**

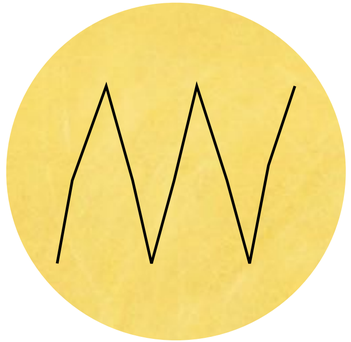
Gravity + Quantum

= The origin of all the structures we see in the Universe

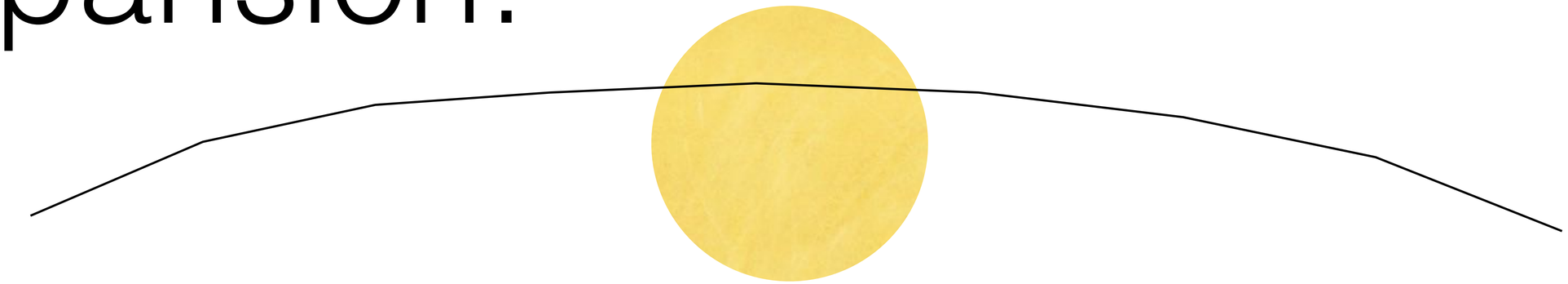
Starobinsky (1980); Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

Quantum mechanical fluctuation on microscopic scales



Exponential Expansion!



- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

What? How can we believe such a statement?

Only the data will decide!

Finding Cosmic Inflation

What does inflation predict?

- Due to expansion of space, the distance between two points is stretched in proportion to a(t).
- **The Hubble expansion rate** is defined as **$H(t) = a^{-1}(da/dt)$**. This has the units of [1/time].
  - In other words, **$a(t) = \exp[\int H(t)\,dt]$**.
  - During inflation, the distance between two points expands exponentially. This means **H(t) ~ constant**, which gives a(t) ~ exp(Ht).
- However, inflation must end. This means that **H(t) is a slowly decreasing function of time**.

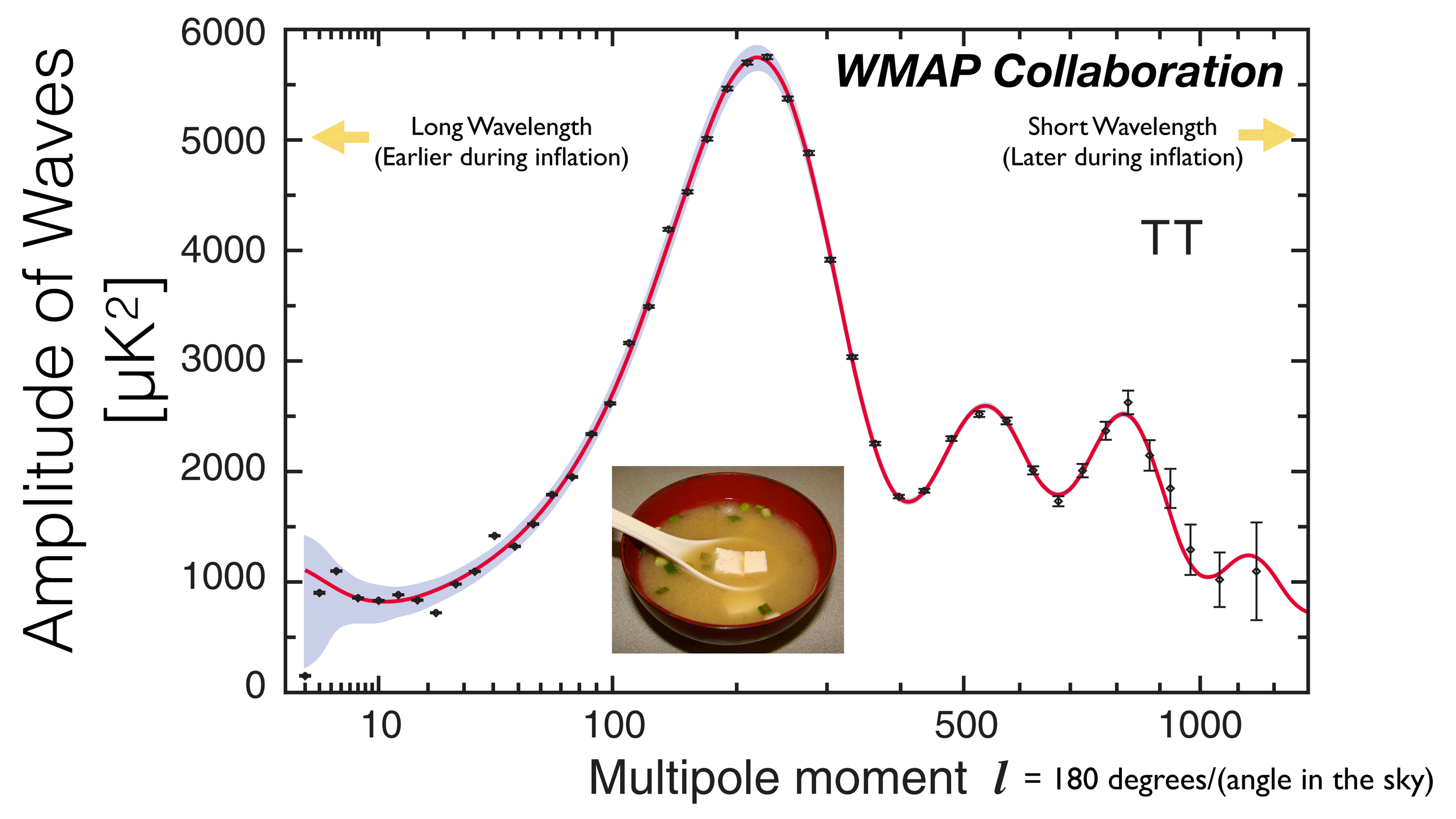
How can we test this?

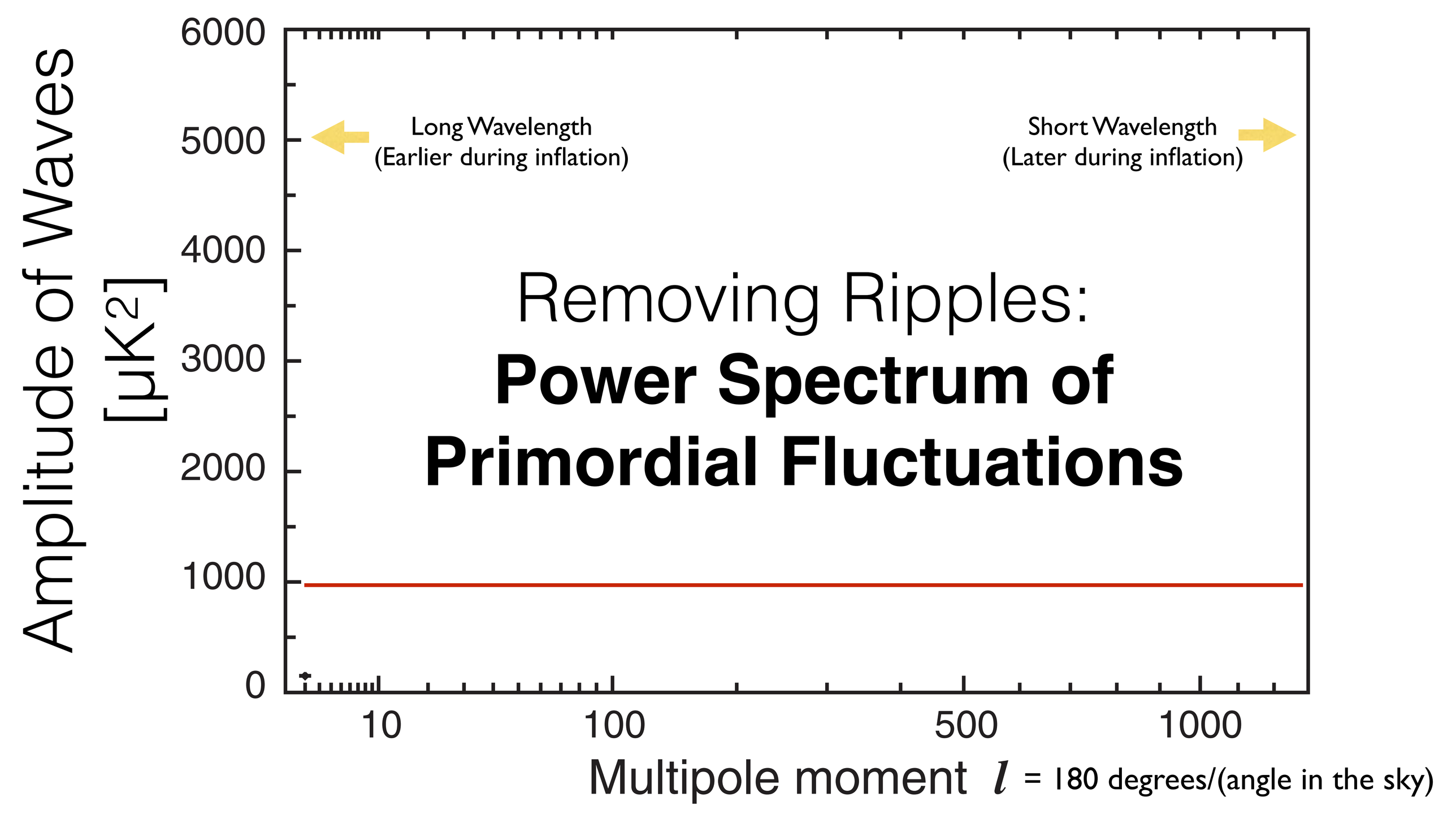
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

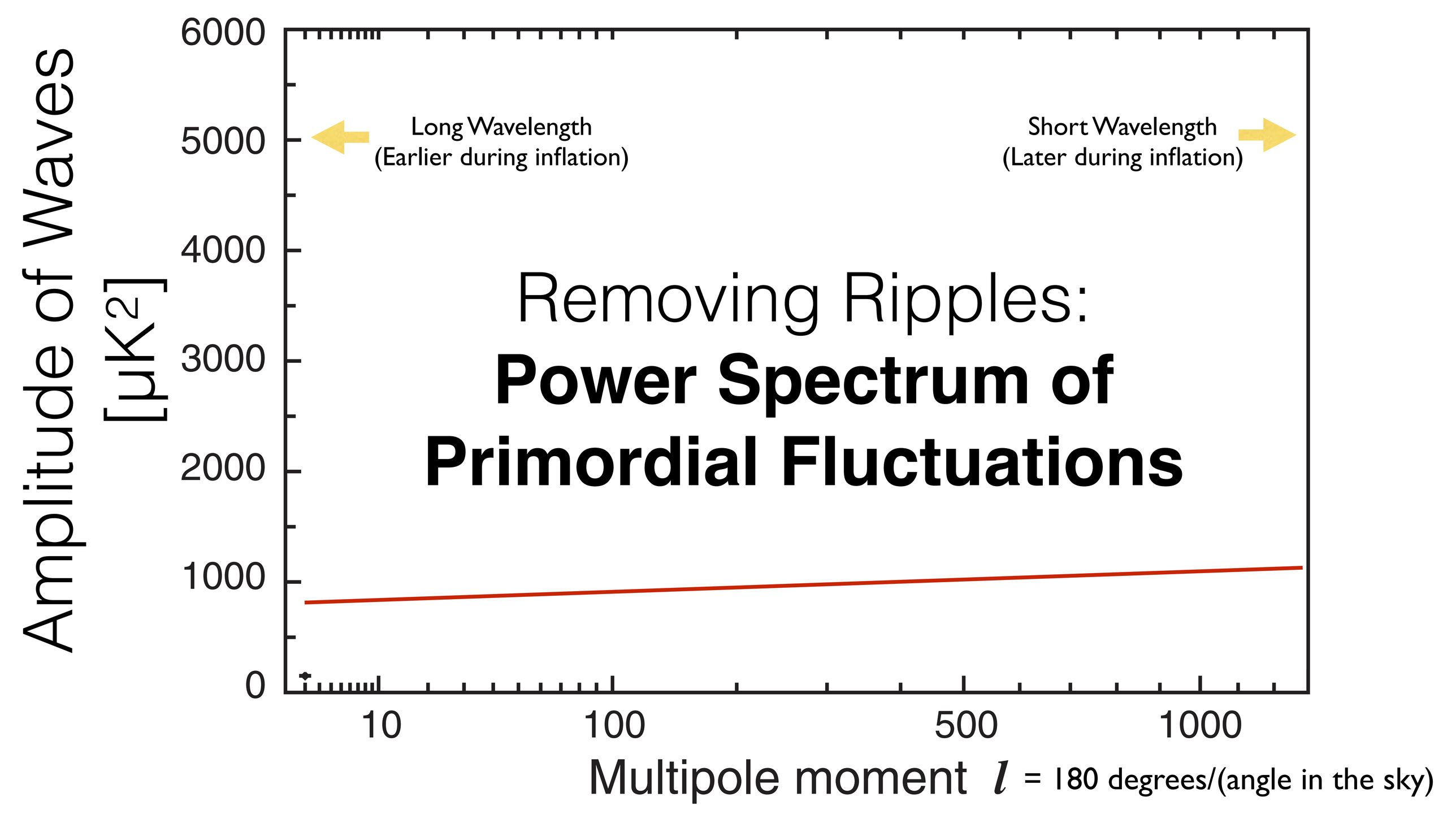
Finding Cosmic Inflation

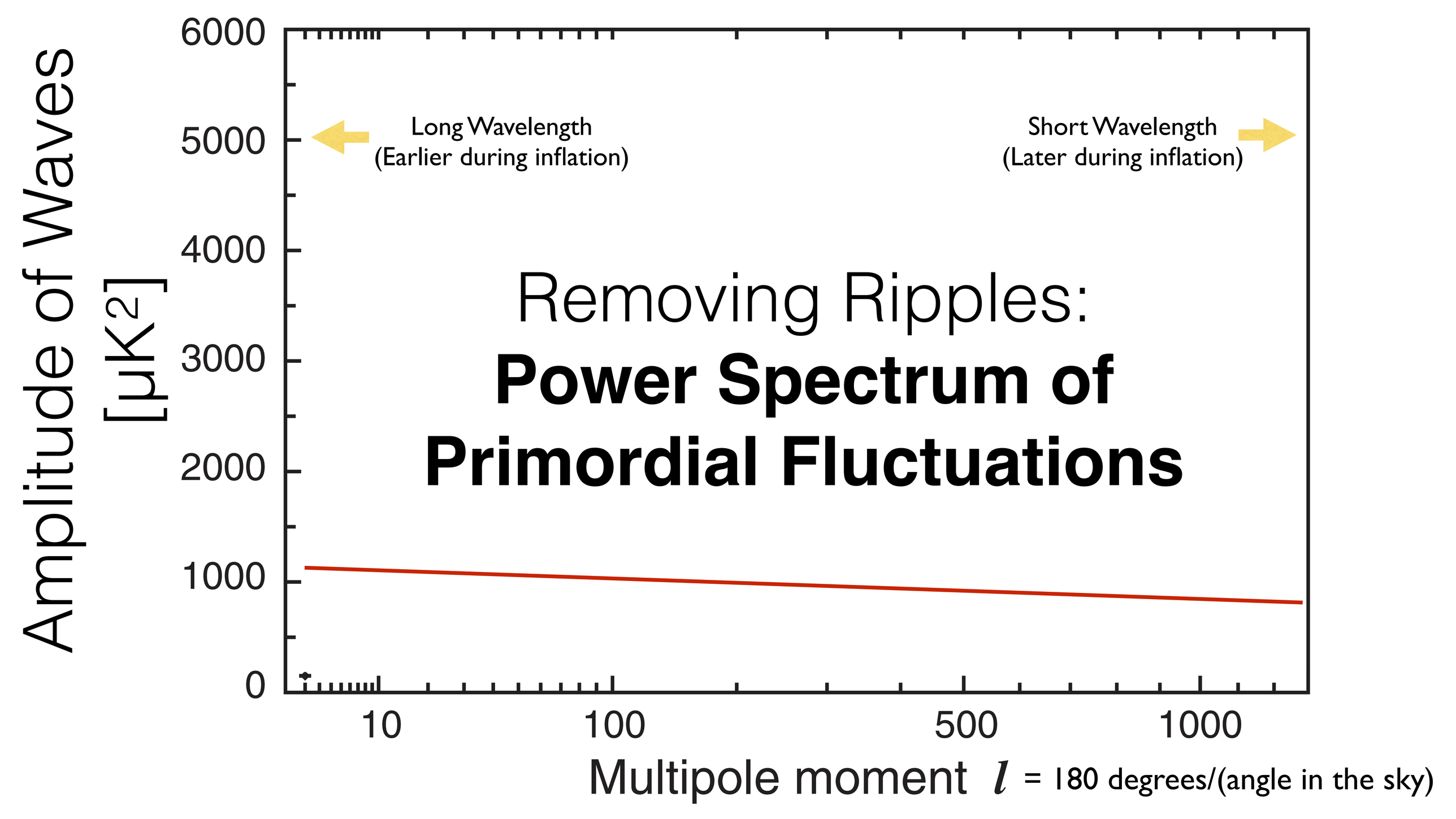
What does inflation predict for the density fluctuation?

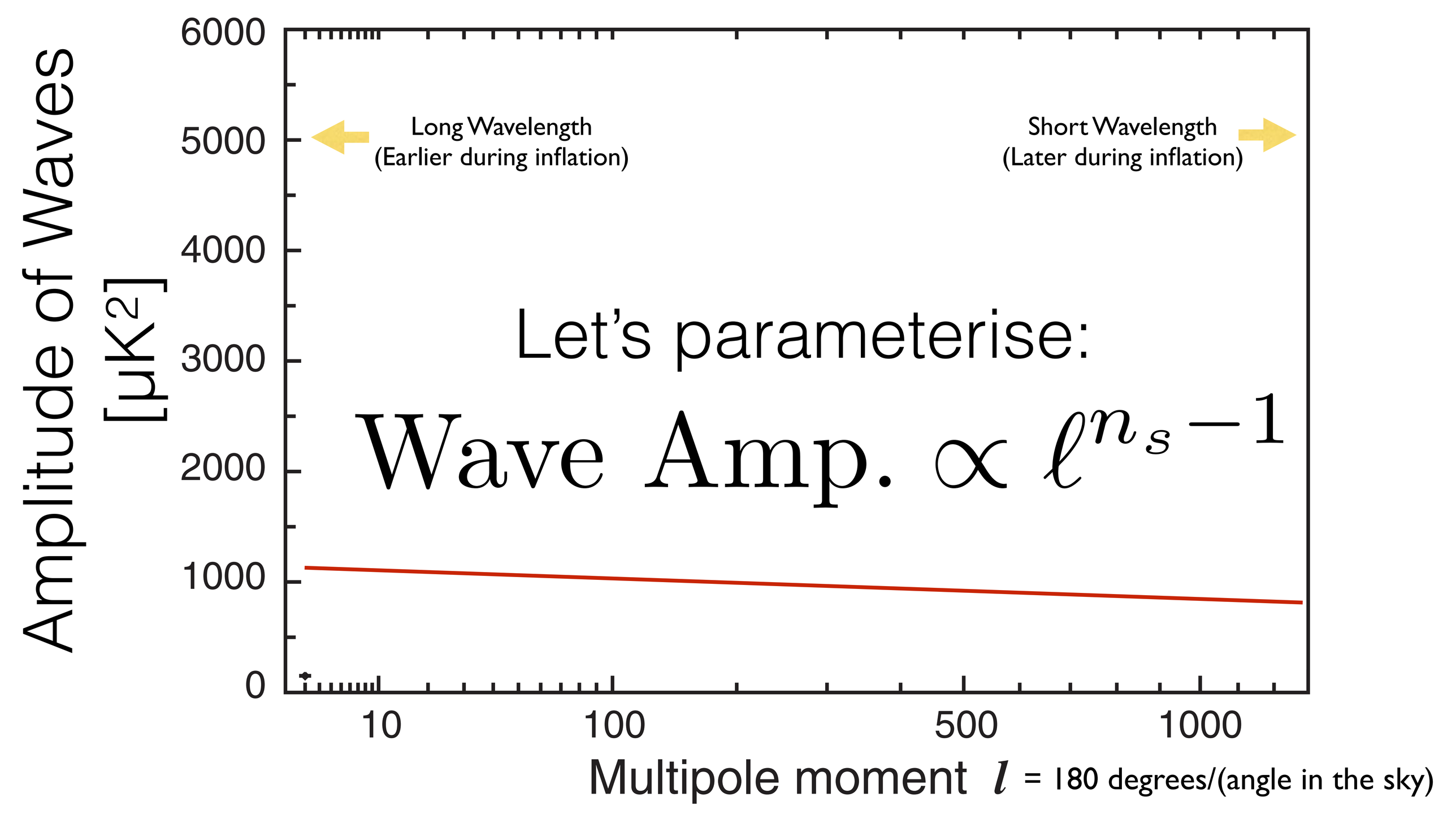
- During inflation, the density fluctuation is produced quantum mechanically.
- According to Quantum Mechanics during inflation,
  - **The strength of density fluctuation is proportional to H**
- **THE KEY**: The earlier the fluctuations are generated, the more its wavelength is stretched, and thus the bigger the angles they subtend in the sky. **Because H(t) is a decreasing function of time, inflation predicts that the amplitude of fluctuations on large angular scales is slightly larger than that on small angular scales!**

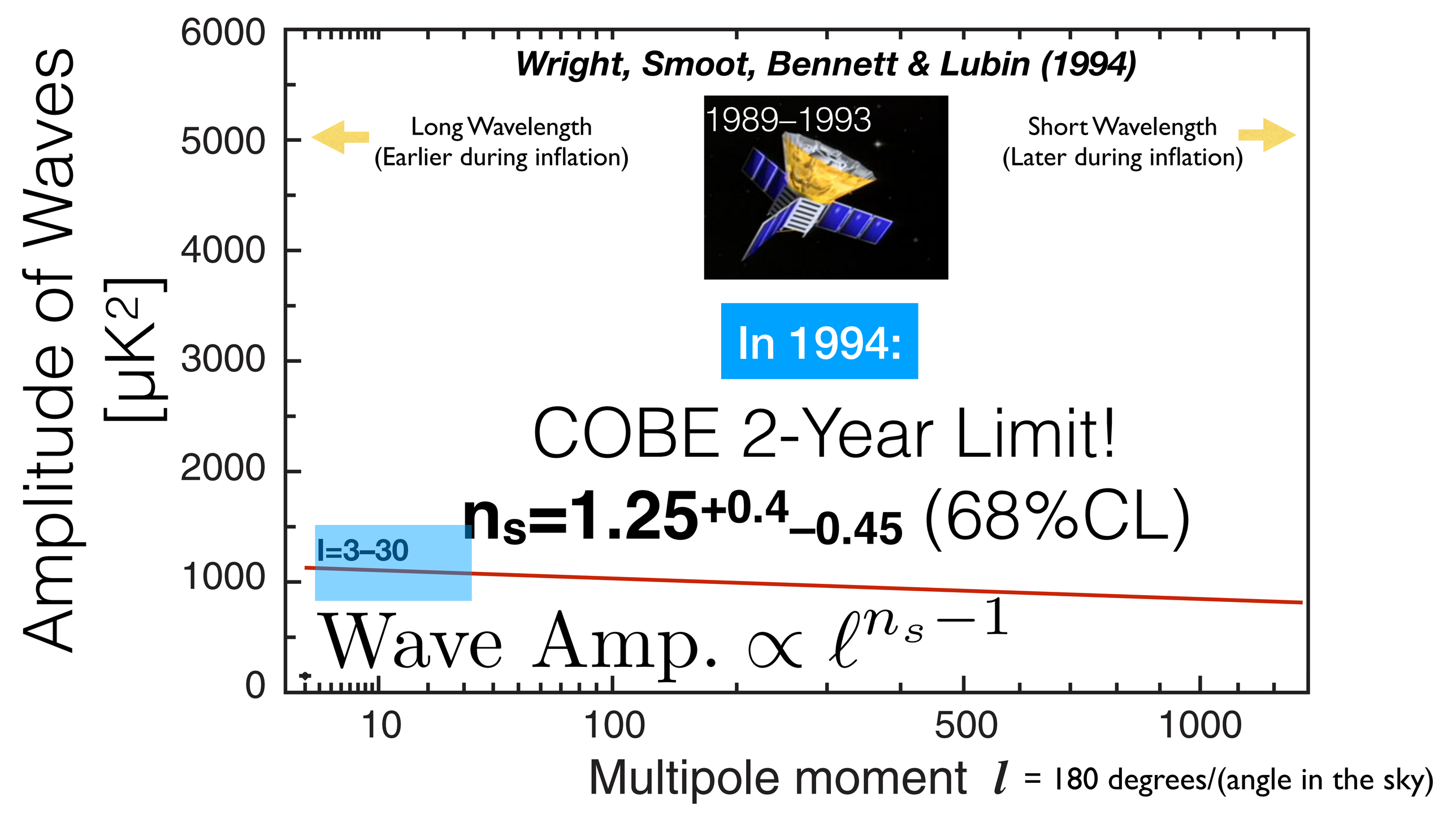

WMAP Collaboration
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
TT
Amplitude of Waves
[μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)

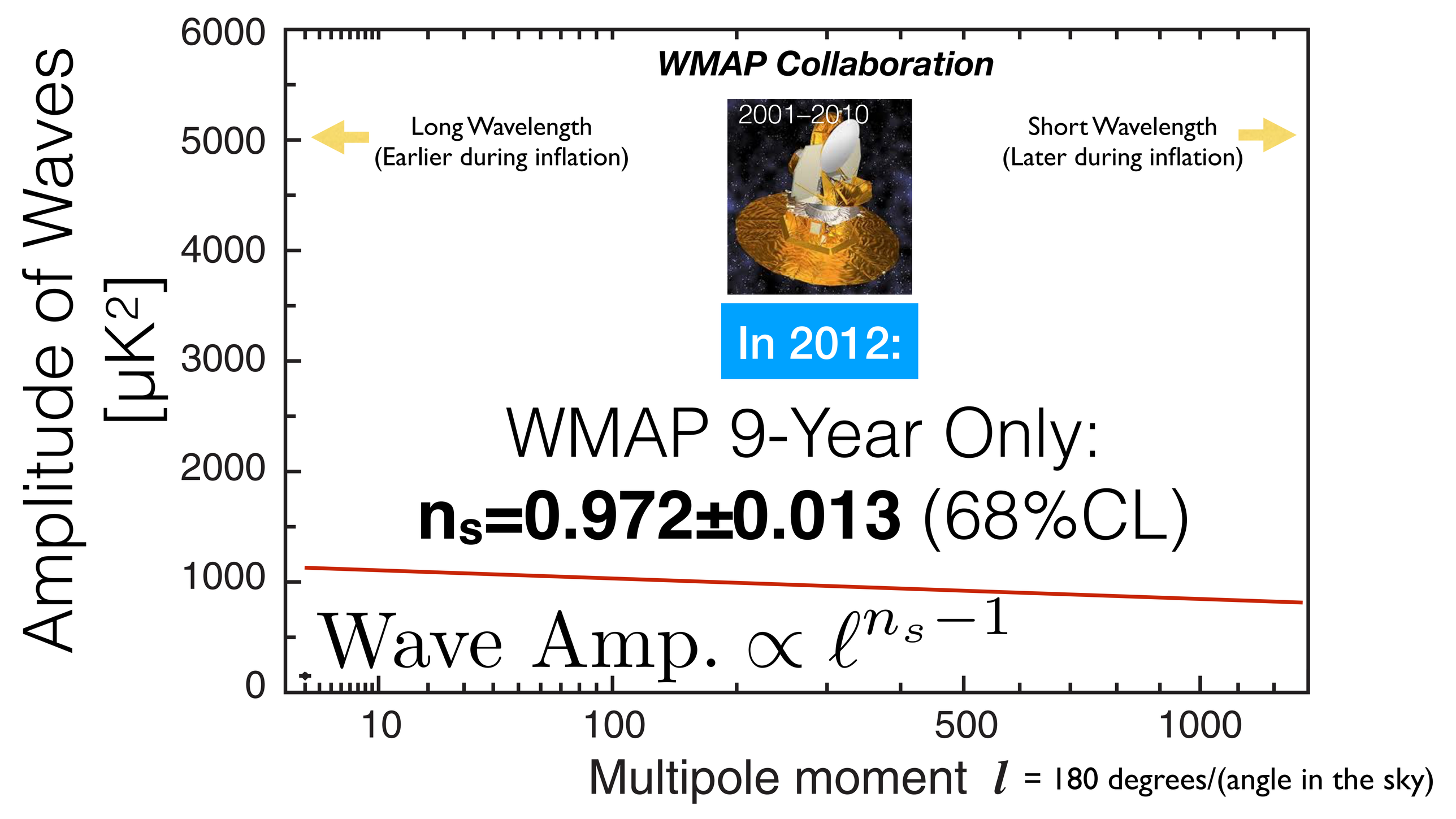

Amplitude of Waves
[μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)

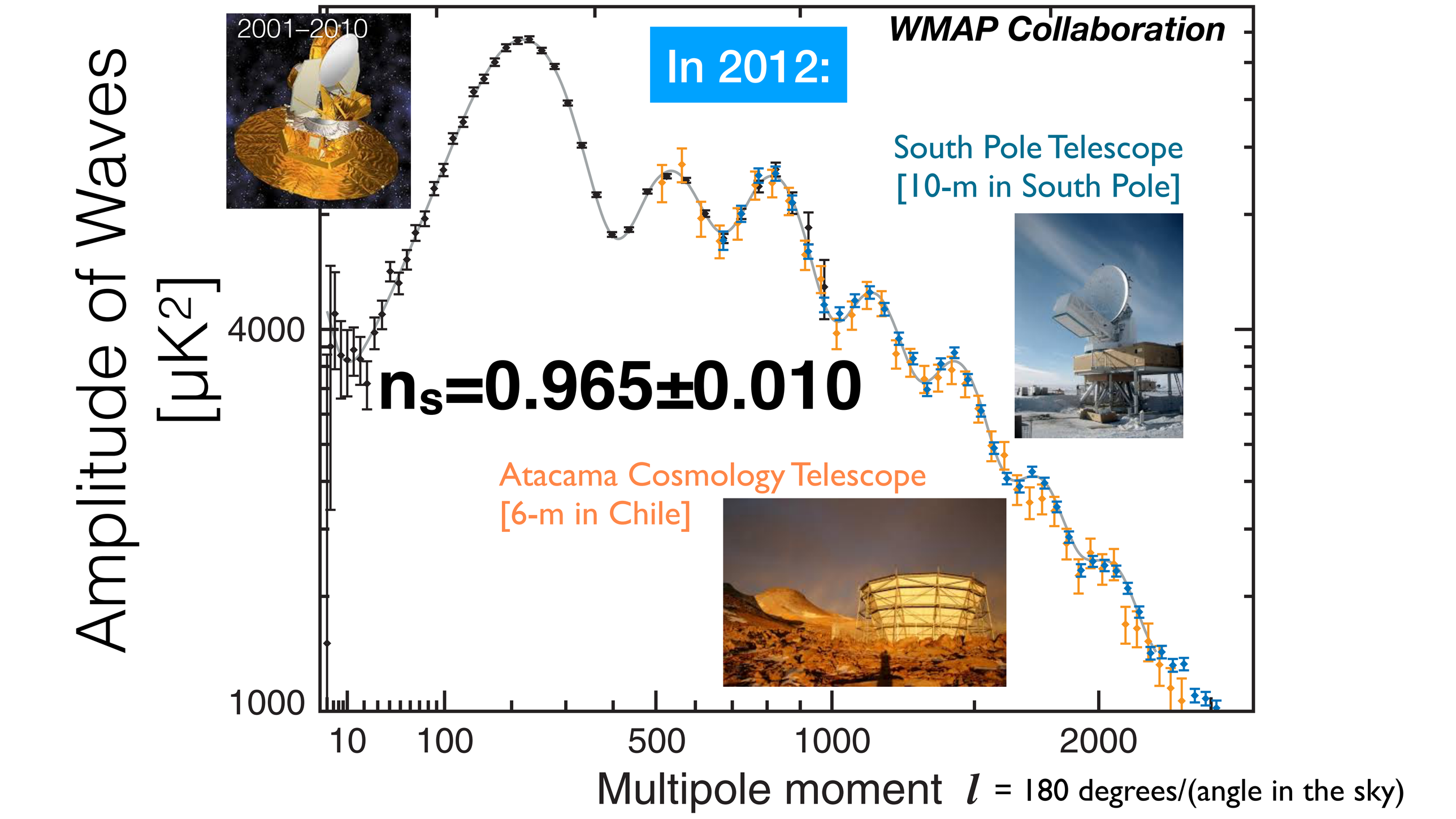

Amplitude of Waves
[μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)

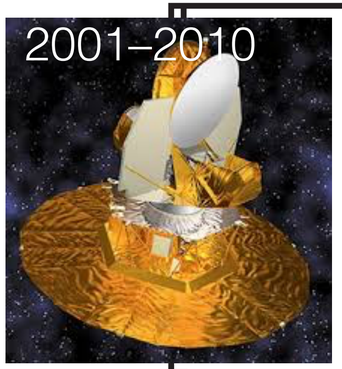

Amplitude of Waves
[μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)


Amplitude of Waves
[μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
Let's parameterise:
$\text{Wave Amp.} \propto \ell^{n_s - 1}$
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)


Wright, Smoot, Bennett & Lubin (1994)
Long Wavelength
(Earlier during inflation)
1989–1993
Short Wavelength
(Later during inflation)
In 1994:
COBE 2-Year Limit!
$n_s=1.25^{+0.4}_{-0.45}$ (68%CL)
l=3–30
Wave Amp. $\propto \ell^{n_s-1}$
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)


WMAP Collaboration
2001–2010
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
In 2012:
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
Wave Amp. $\propto \ell^{n_s-1}$
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)


2001–2010
WMAP Collaboration
In 2012:
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
n_s=0.965±0.010
Amplitude of Waves
[μK²]
4000
1000
10
100
500
1000
2000
Multipole moment l = 180 degrees/(angle in the sky)



WMAP Collaboration

In 2012:

South Pole Telescope
[10-m in South Pole]

First ~5σ discovery of $n_s<1$
from the CMB data combined
with the distribution of galaxies

$n_s=0.961\pm0.008$

Atacama Cosmology Telescope
[6-m in Chile]

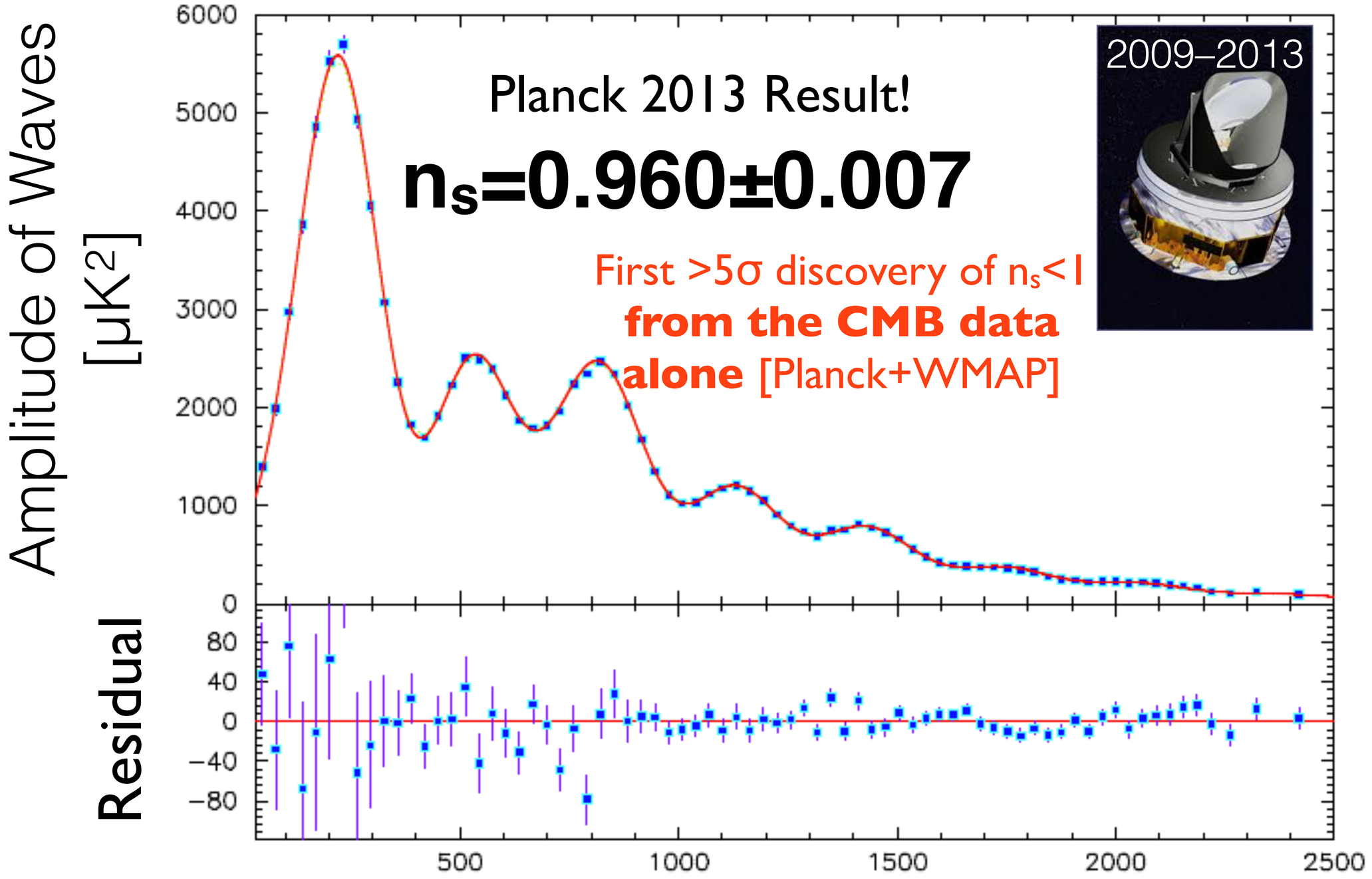
Amplitude of Waves [μK²]

4000

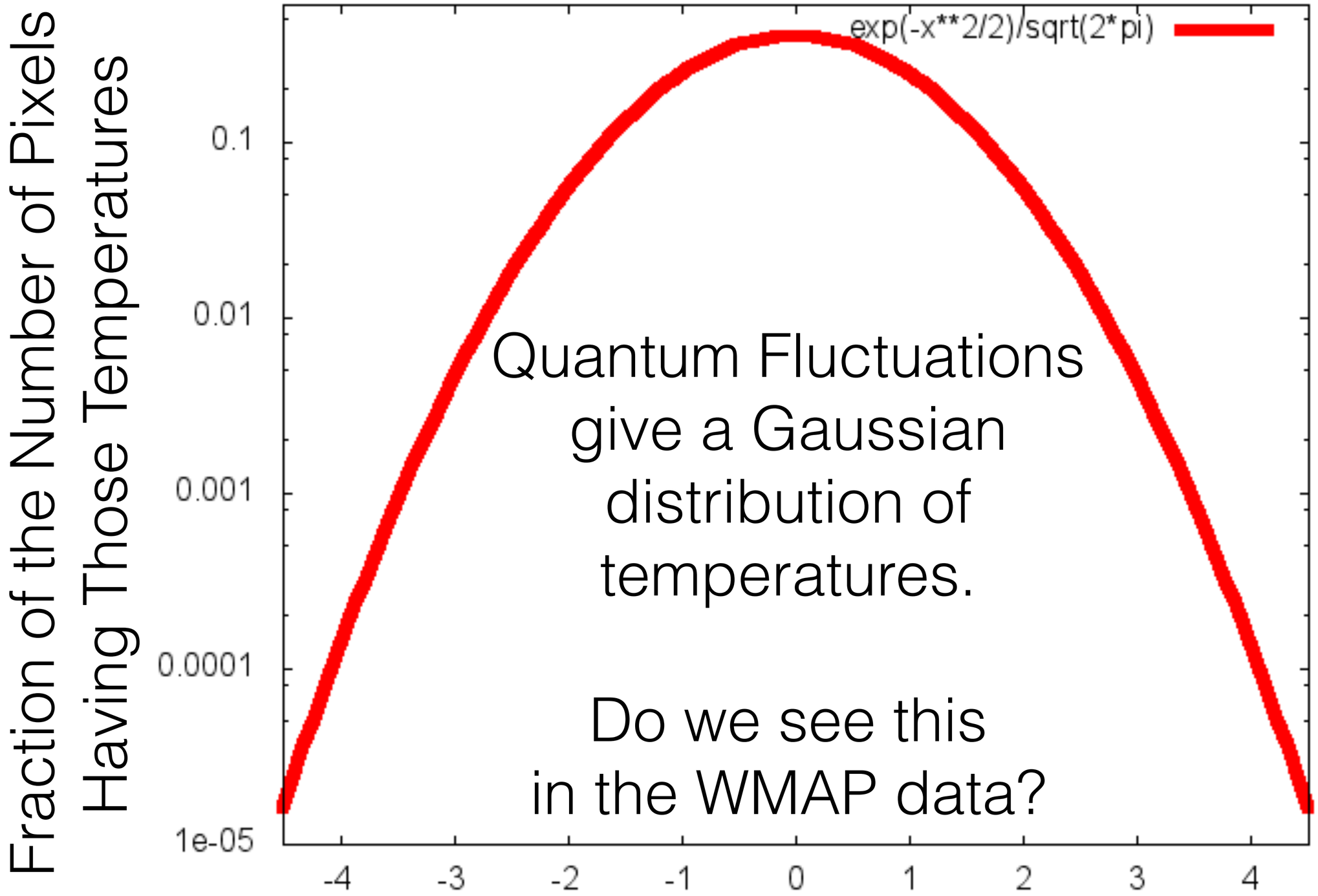
1000

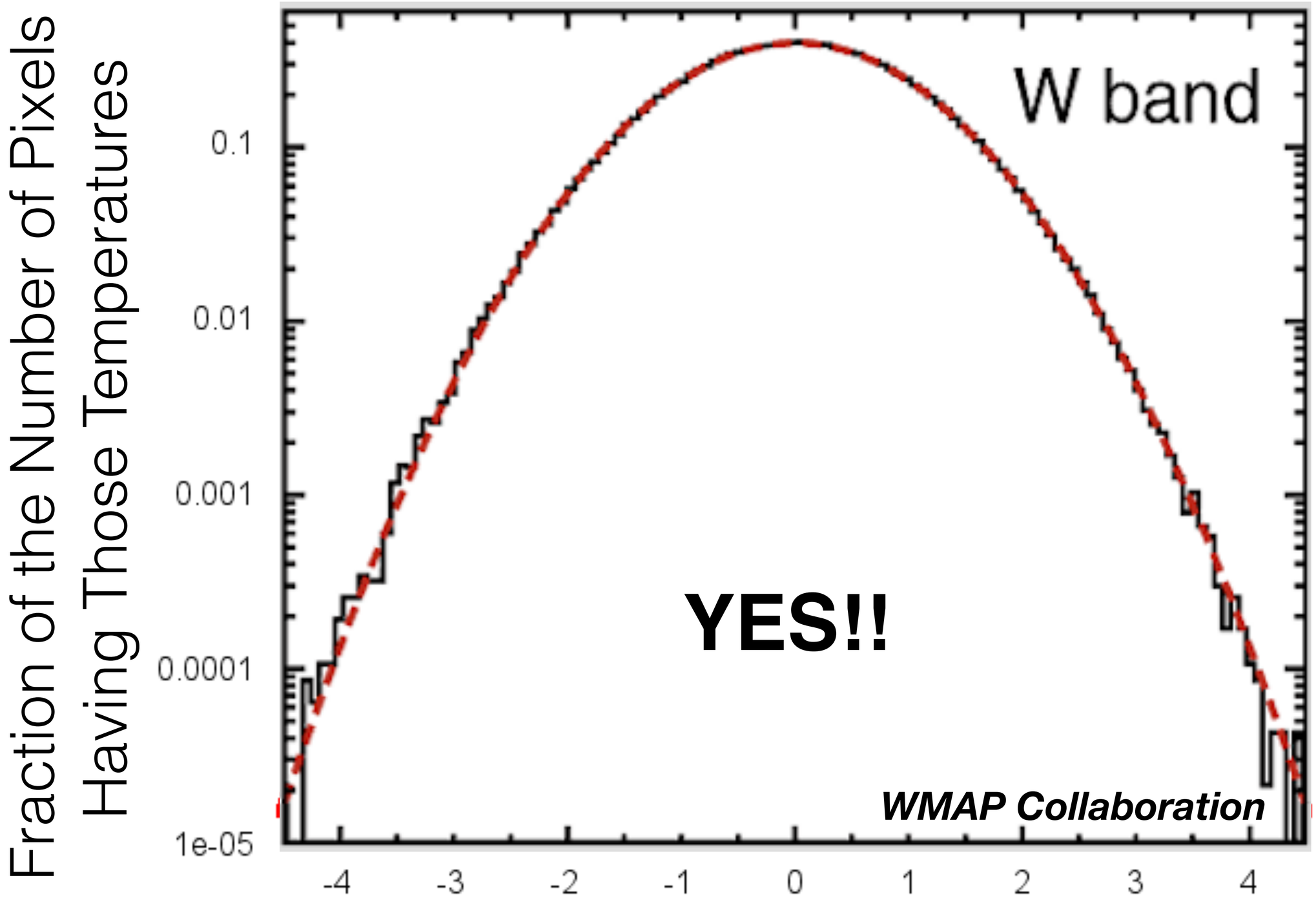
10 100 500 1000 2000

Multipole moment l = 180 degrees/(angle in the sky)



 ℓ = 180 degrees/(angle in the sky)


exp(-x**2/2)/sqrt(2*pi)
Fraction of the Number of Pixels Having Those Temperatures
0.1
0.01
0.001
0.0001
1e-05
-4
-3
-2
-1
0
1
2
3
4
[Values of Temperatures in the Sky Minus 2.725 K] / [Root Mean Square]
Quantum Fluctuations give a Gaussian distribution of temperatures.
Do we see this in the WMAP data?


Fraction of the Number of Pixels
Having Those Temperatures
W band
YES!!
WMAP Collaboration
0.1
0.01
0.001
0.0001
1e-05
-4
-3
-2
-1
0
1
2
3
4
[Values of Temperatures in the Sky Minus 2.725 K] / [Root Mean Square]

So, have we found inflation?

A lot of evidence in support of inflation exist already.

- Single-field slow-roll inflation looks very good:

✓ • $n_s < 1$

✓ • Gaussian fluctuations

✓ • Adiabatic fluctuations [no time to explain this today]

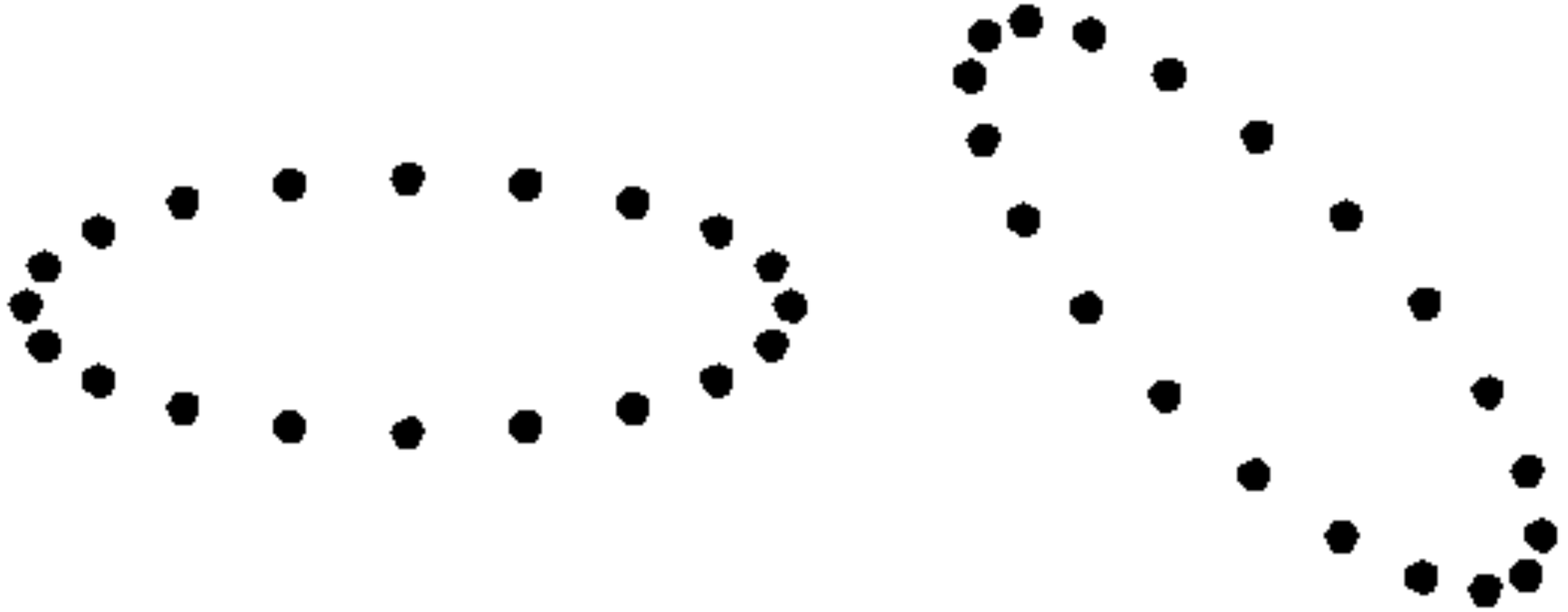
✓ • Super-horizon fluctuations [no time to explain this today]

- What more do we want? **Primordial gravitational waves**

- Why more evidence? Because "***extraordinary claim requires extraordinary evidence***" (Carl Sagan)

Gravitational waves are coming towards you!

To visualise the waves, watch motion of test particles.

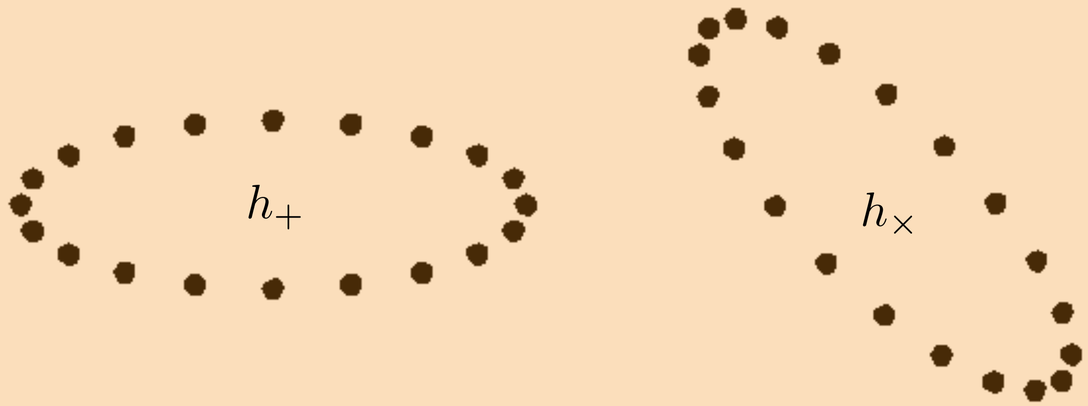


Sachs & Wolfe (1967)

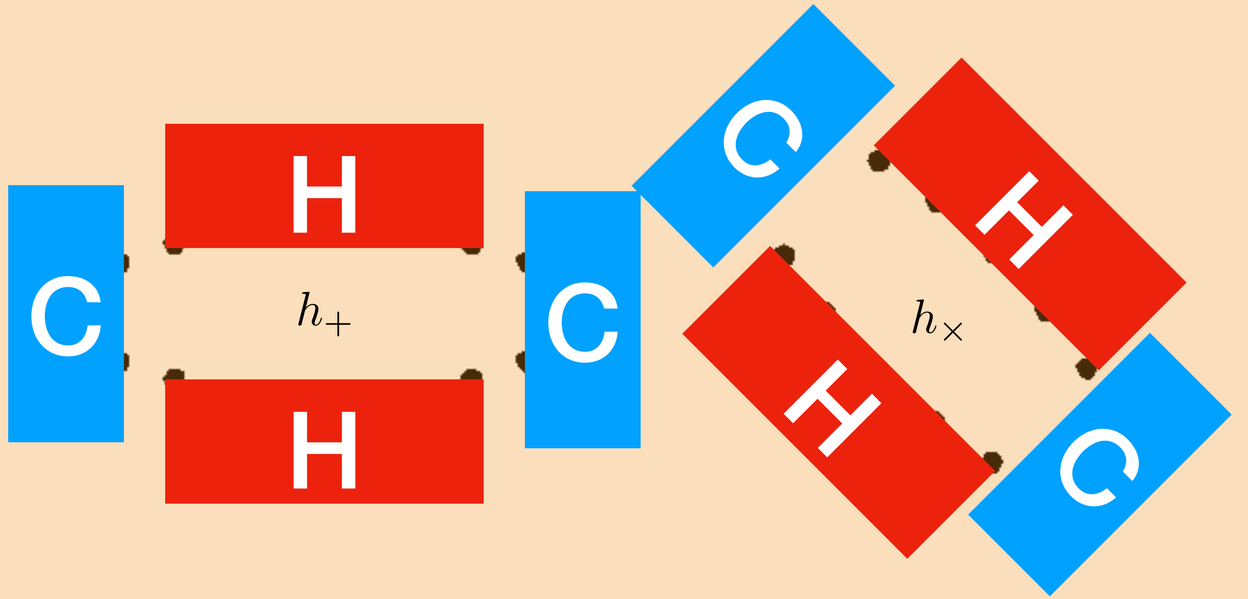
Detecting GW by CMB

Quadrupole temperature anisotropy generated by red- and blue-shifting of photons

Isotropic radiation field (CMB)



Isotropic radiation field (CMB)

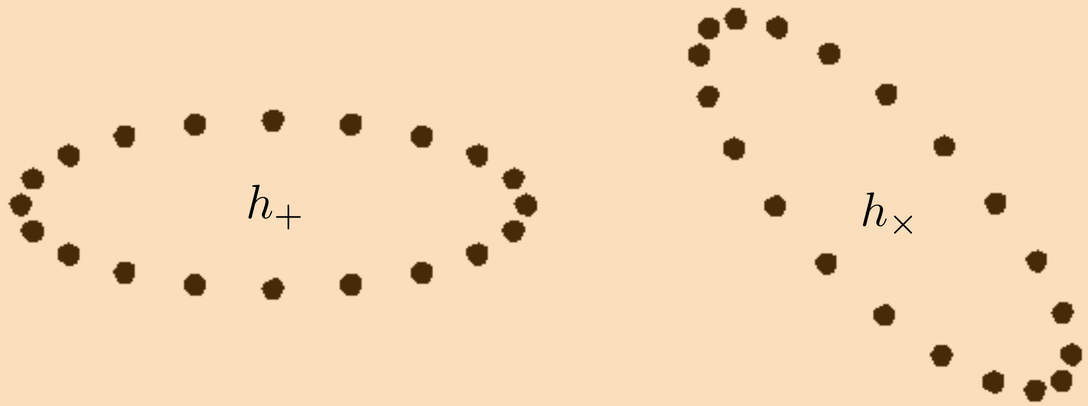


Sachs & Wolfe (1967)

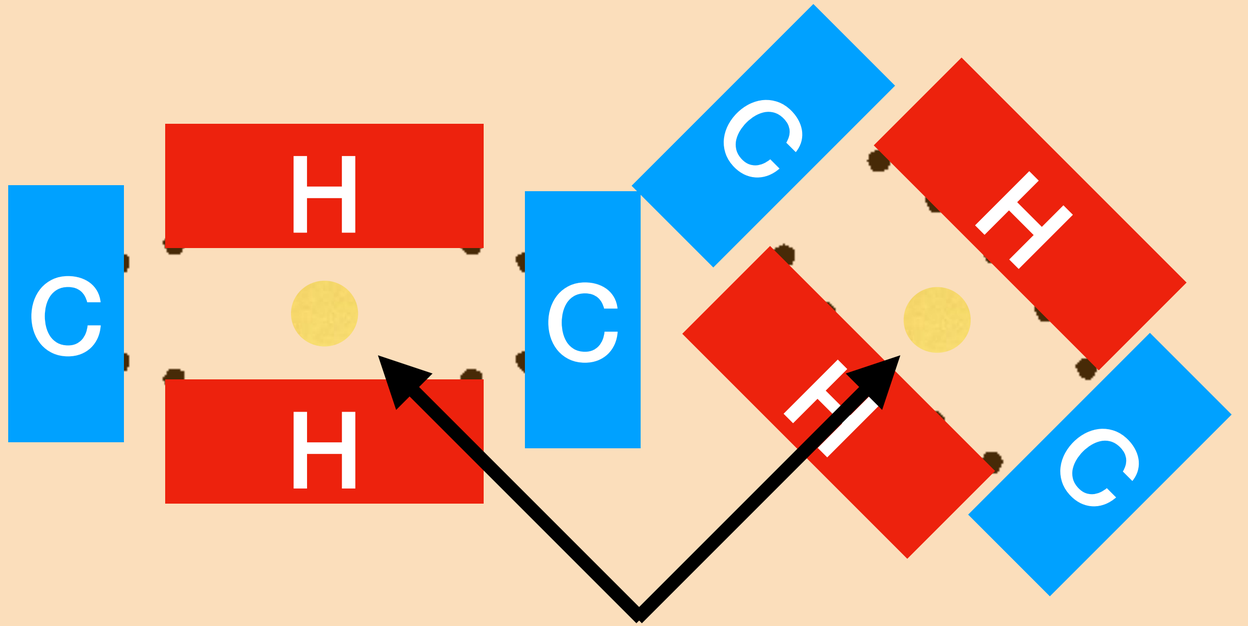
Detecting GW by CMB

Quadrupole temperature anisotropy generated by red- and blue-shifting of photons

Isotropic radiation field (CMB)



Isotropic radiation field (CMB)



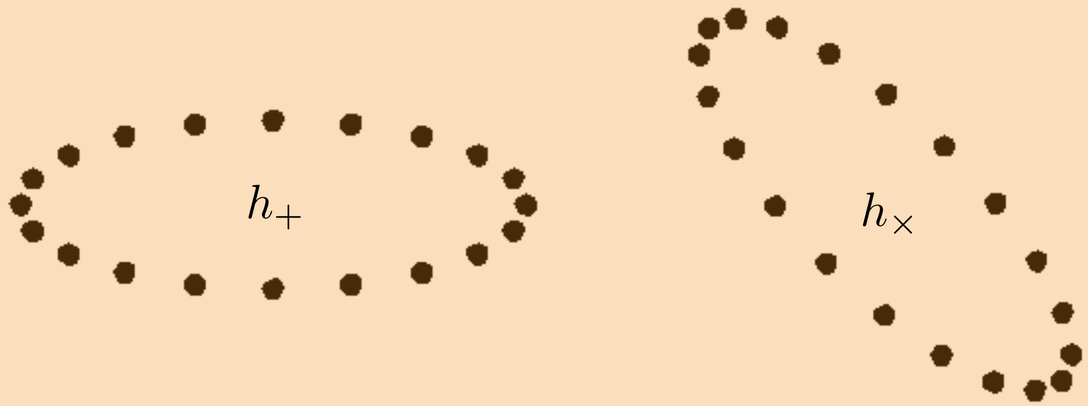
Electron

Polnarev (1985)

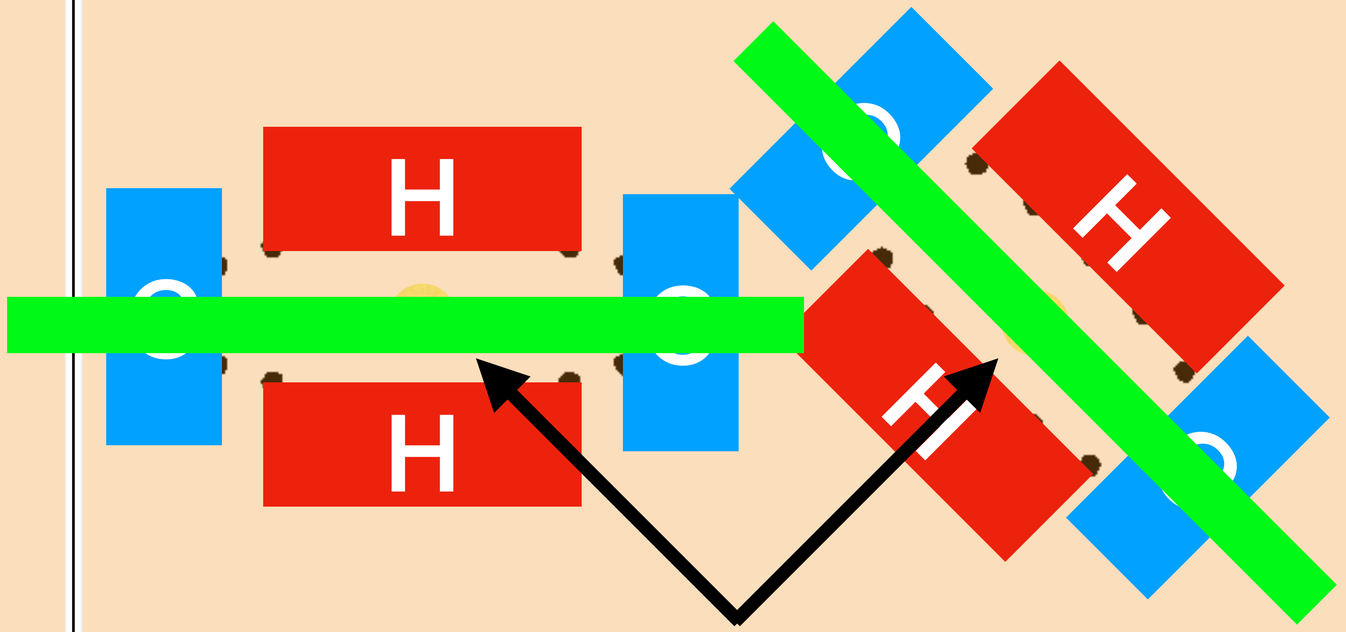
Detecting GW by CMB *Polarization*

Quadrupole temperature anisotropy scattered by an electron

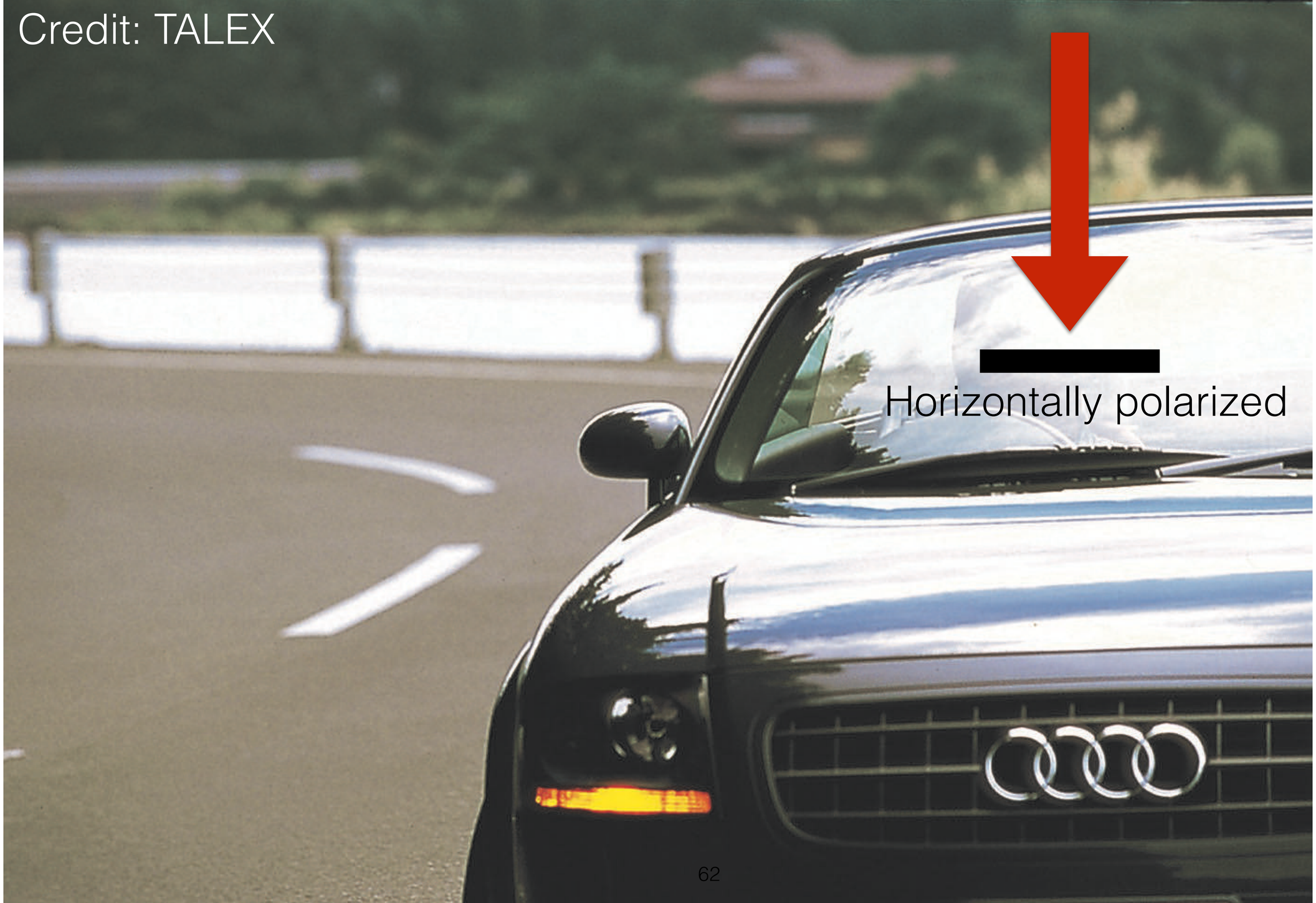
Isotropic radiation field (CMB)



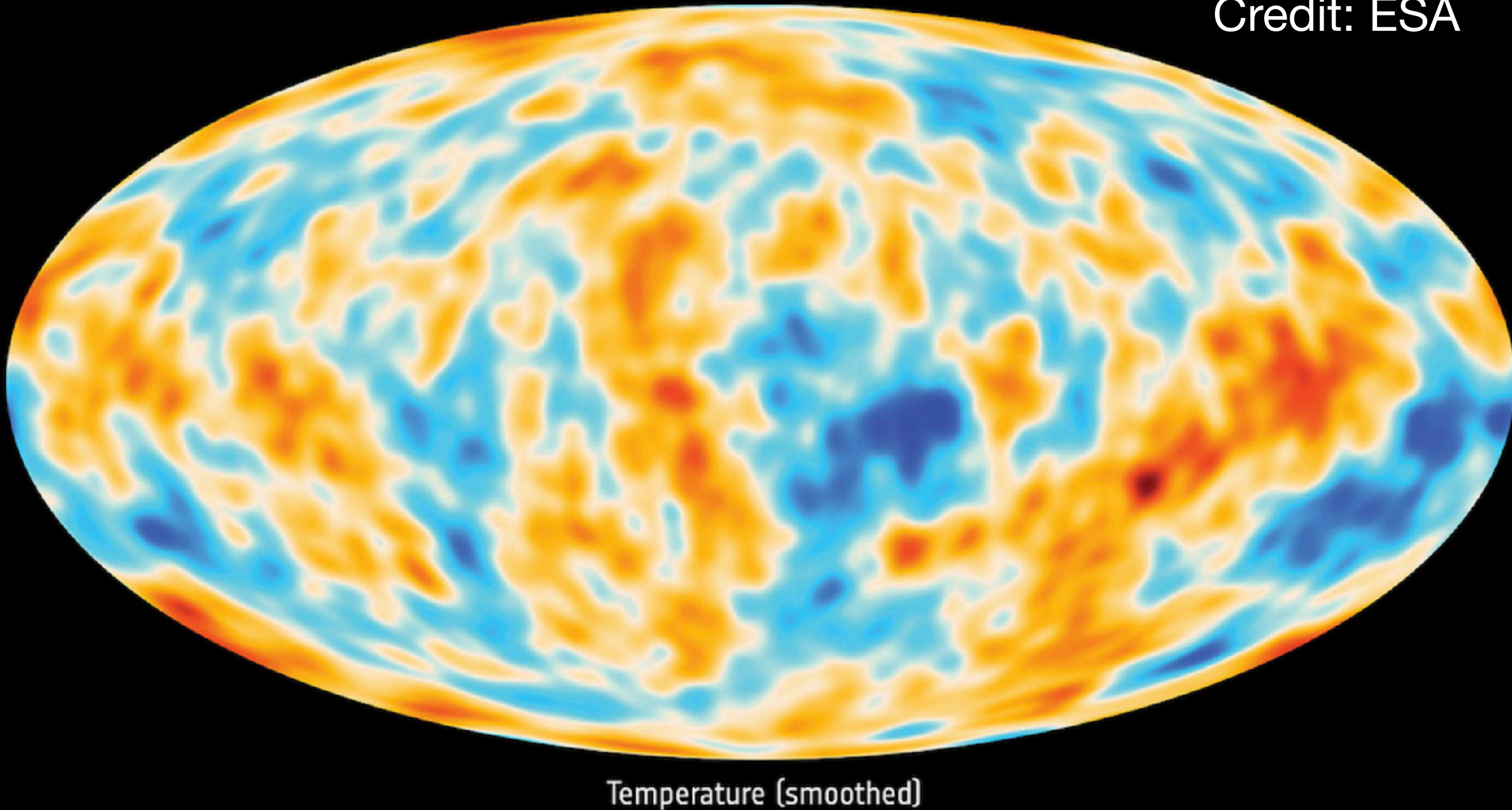
Isotropic radiation field (CMB)

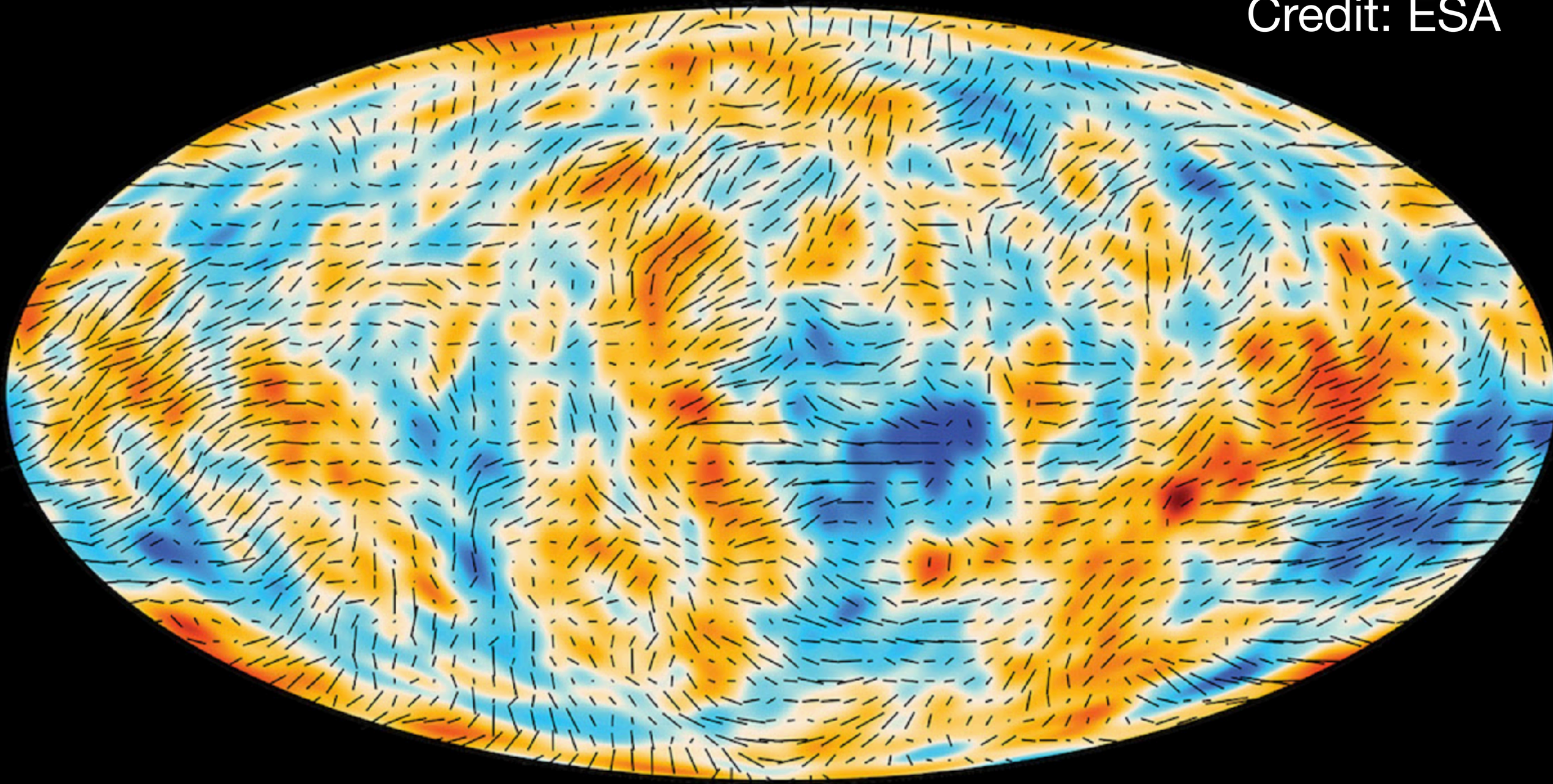


Electron


Credit: TALEX
Horizontally polarized


Credit: TALEX

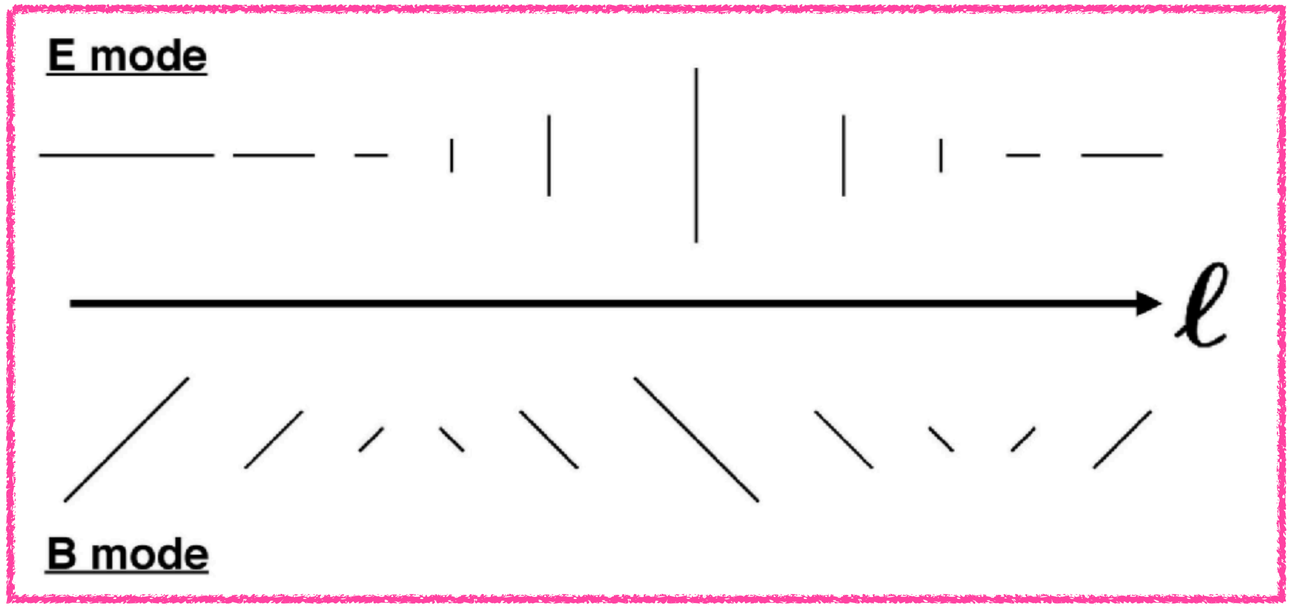

Credit: ESA
Temperature (smoothed)


Credit: ESA
Temperature (smoothed) + Polarisation

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

E- and B-mode decomposition

Concept defined in Fourier space



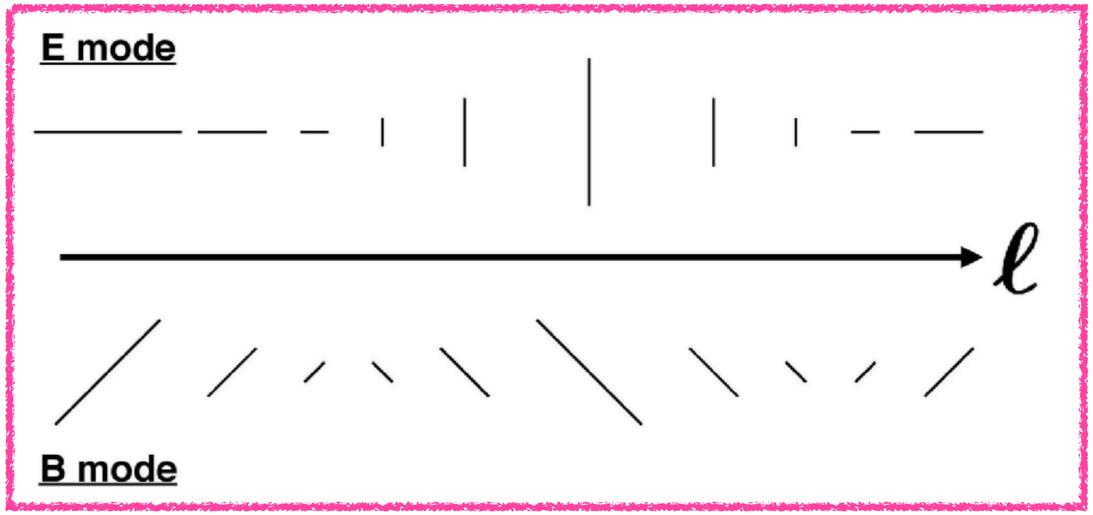
Direction of the wave vector

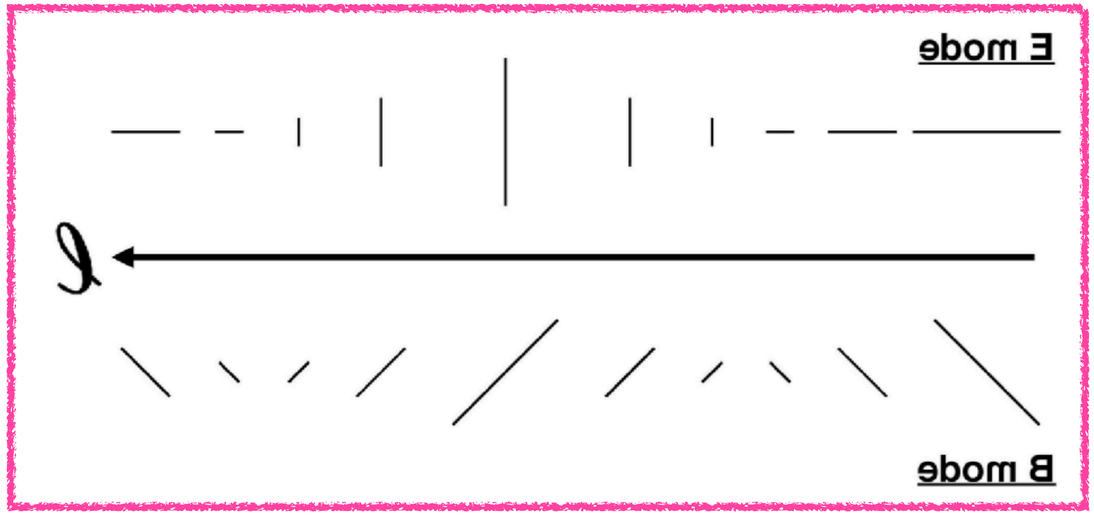
- **E-mode**：Polarization directions are **parallel or perpendicular** to the wave vector
- **B-mode**：Polarization directions are **45 degrees tilted** w.r.t the wave vector

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity Flip

E-mode remains the same, whereas B-mode changes the sign





- Two-point correlation functions invariant under the parity flip are

$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{BB}$$

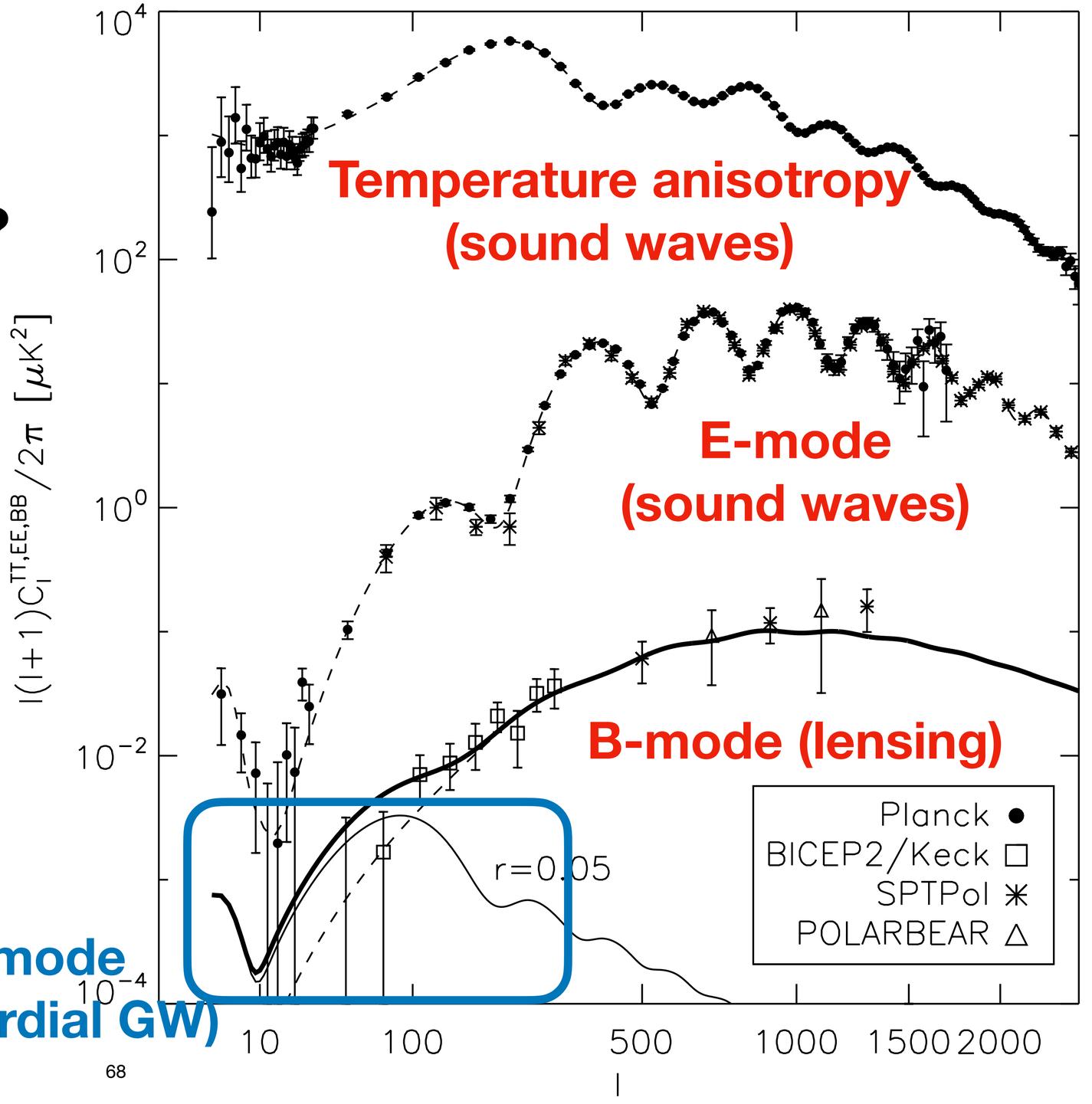
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

- The other combinations <TB> and <EB> are not invariant under the parity flip.
  - **[Side Note] We can use these combinations to probe parity-violating physics (e.g., axions)**

Power Spectra

Where are we? What is next?

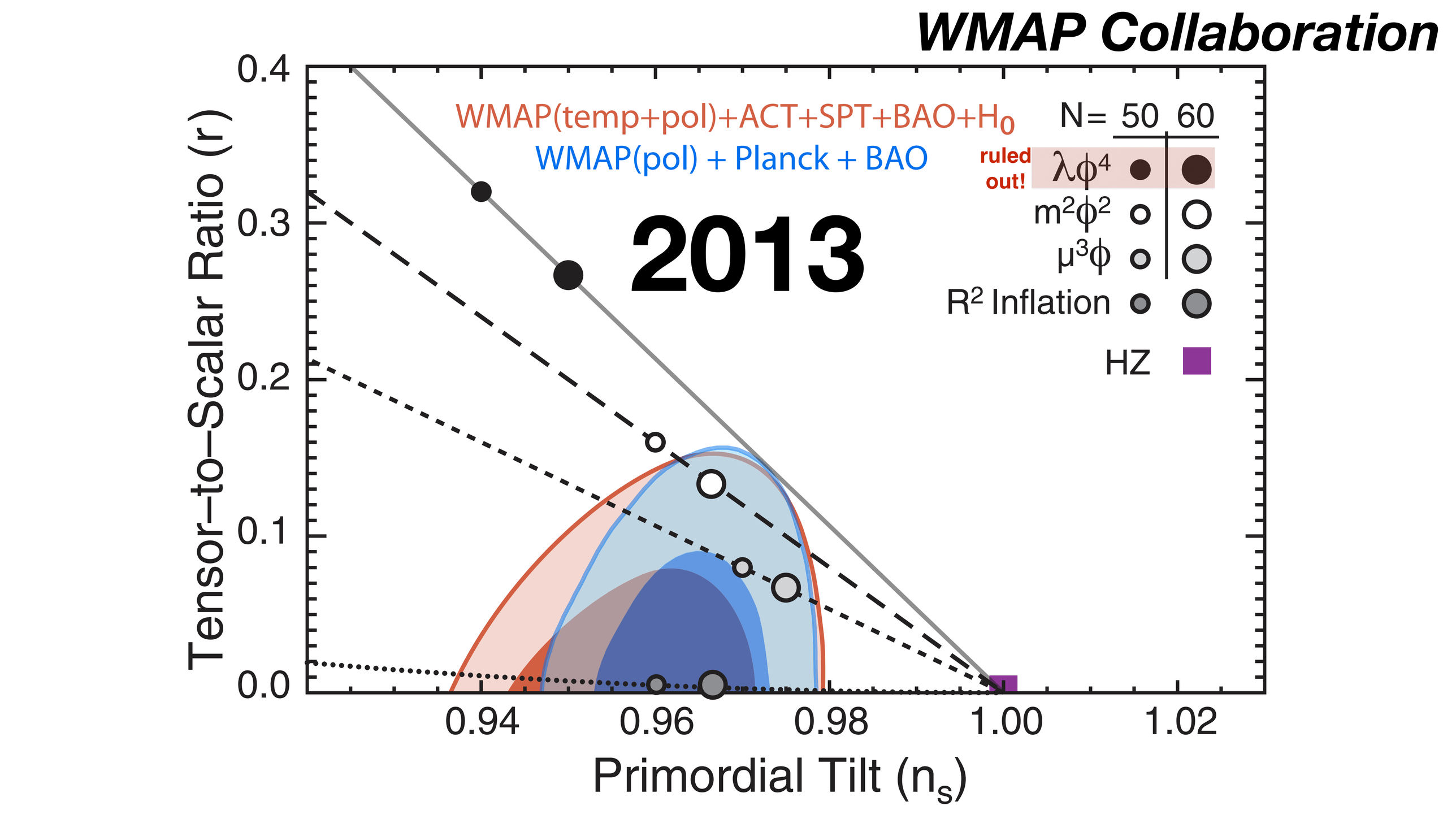
- The temperature and polarization power spectra originating from **the density fluctuation** have been measured.
- The next quest: **B-mode power spectrum from the primordial GW!**



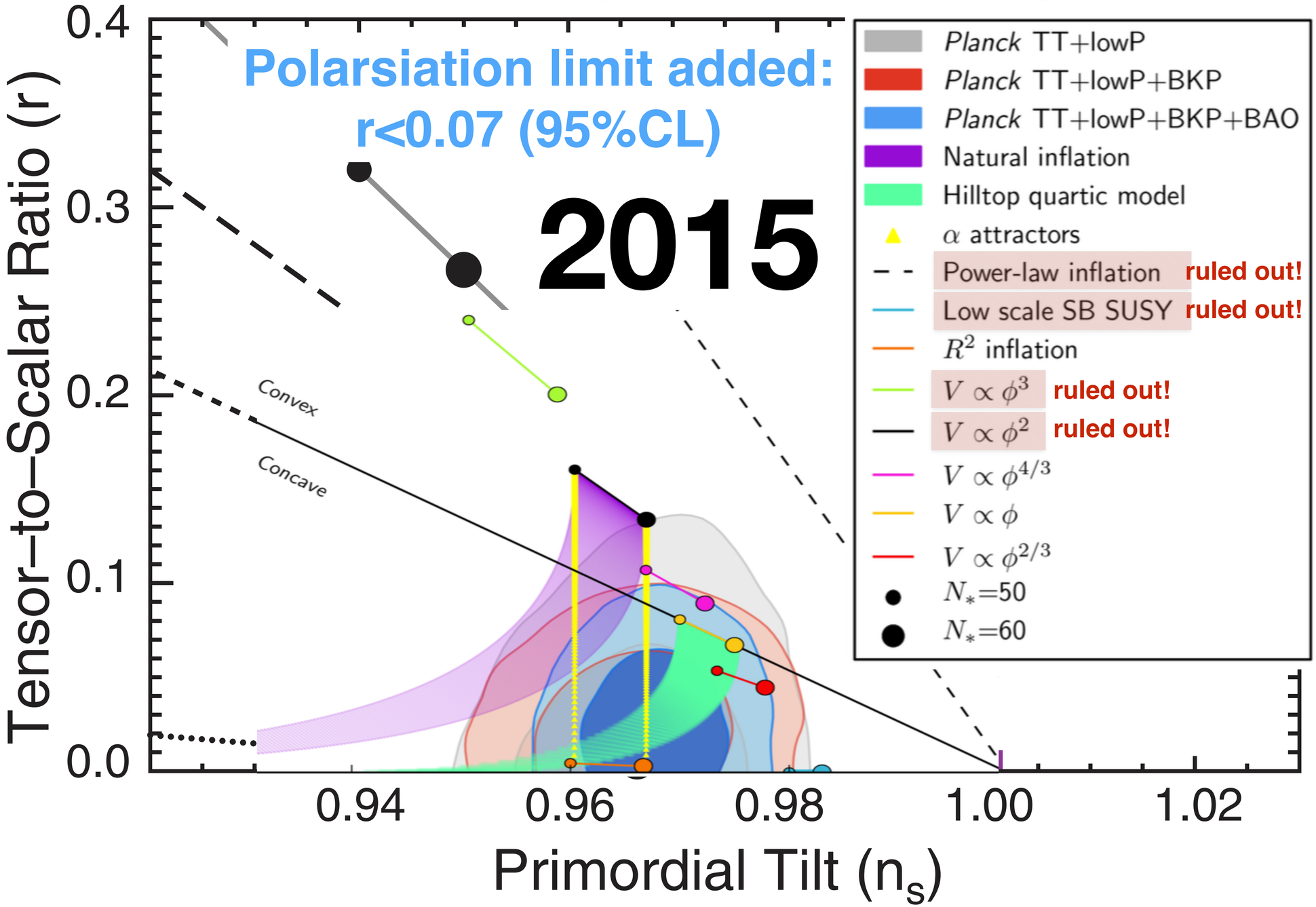
“Tensor-to-scalar Ratio” Parameter

$$r \equiv \left(\frac{\text{Gravitational Wave}}{\text{Density Fluctuation}} \right)^2$$

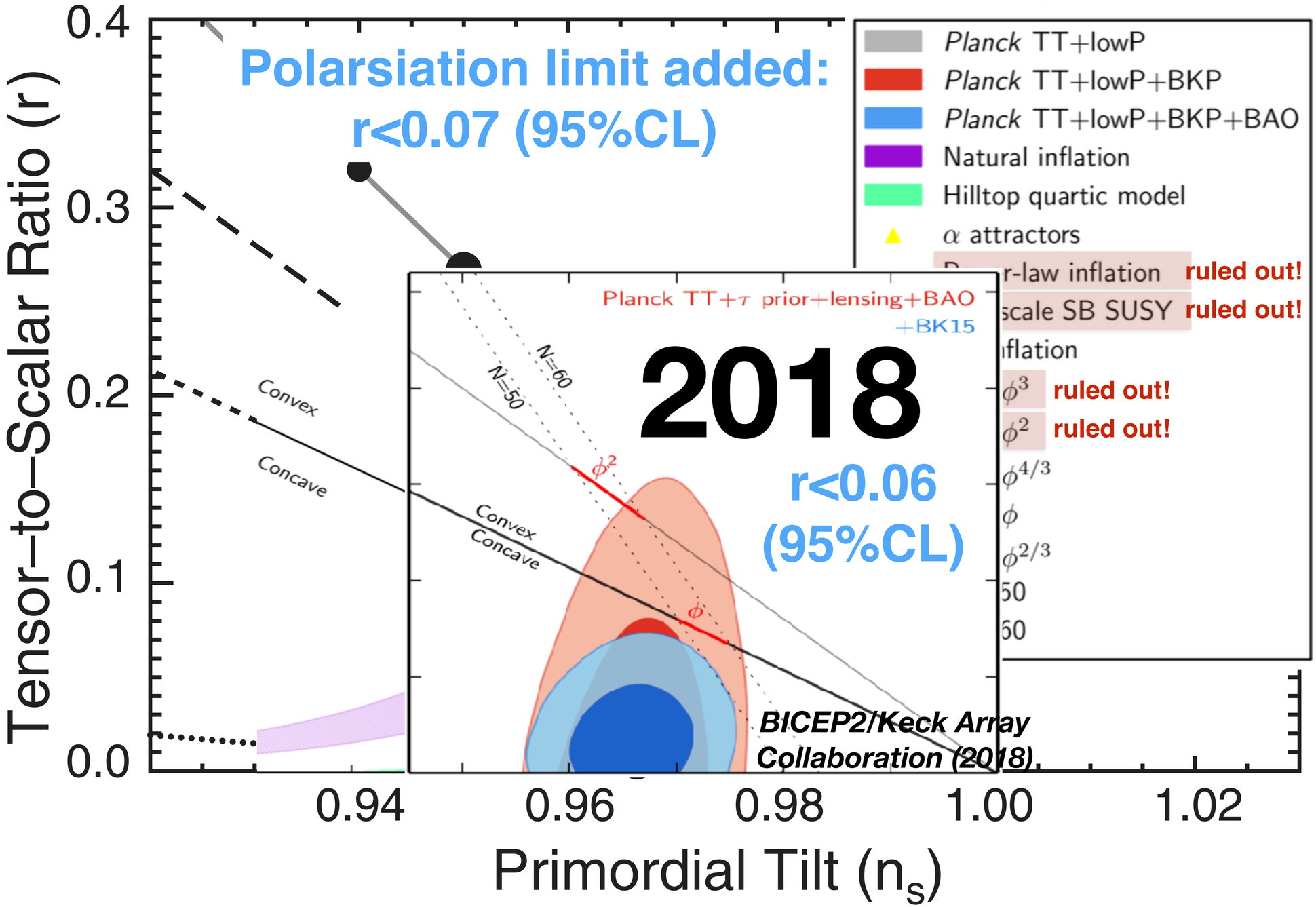
- **We really want to find this!** The current upper bound is **r<0.036**. (*BICEP2/Keck Array Collaboration, 2021)*


WMAP Collaboration
WMAP(temp+pol)+ACT+SPT+BAO+H0
WMAP(pol) + Planck + BAO
2013
N= 50 60
ruled out!
λϕ4
m2ϕ2
μ3ϕ
R2 Inflation
HZ
Tensor–to–Scalar Ratio (r)
Primordial Tilt (ns)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02

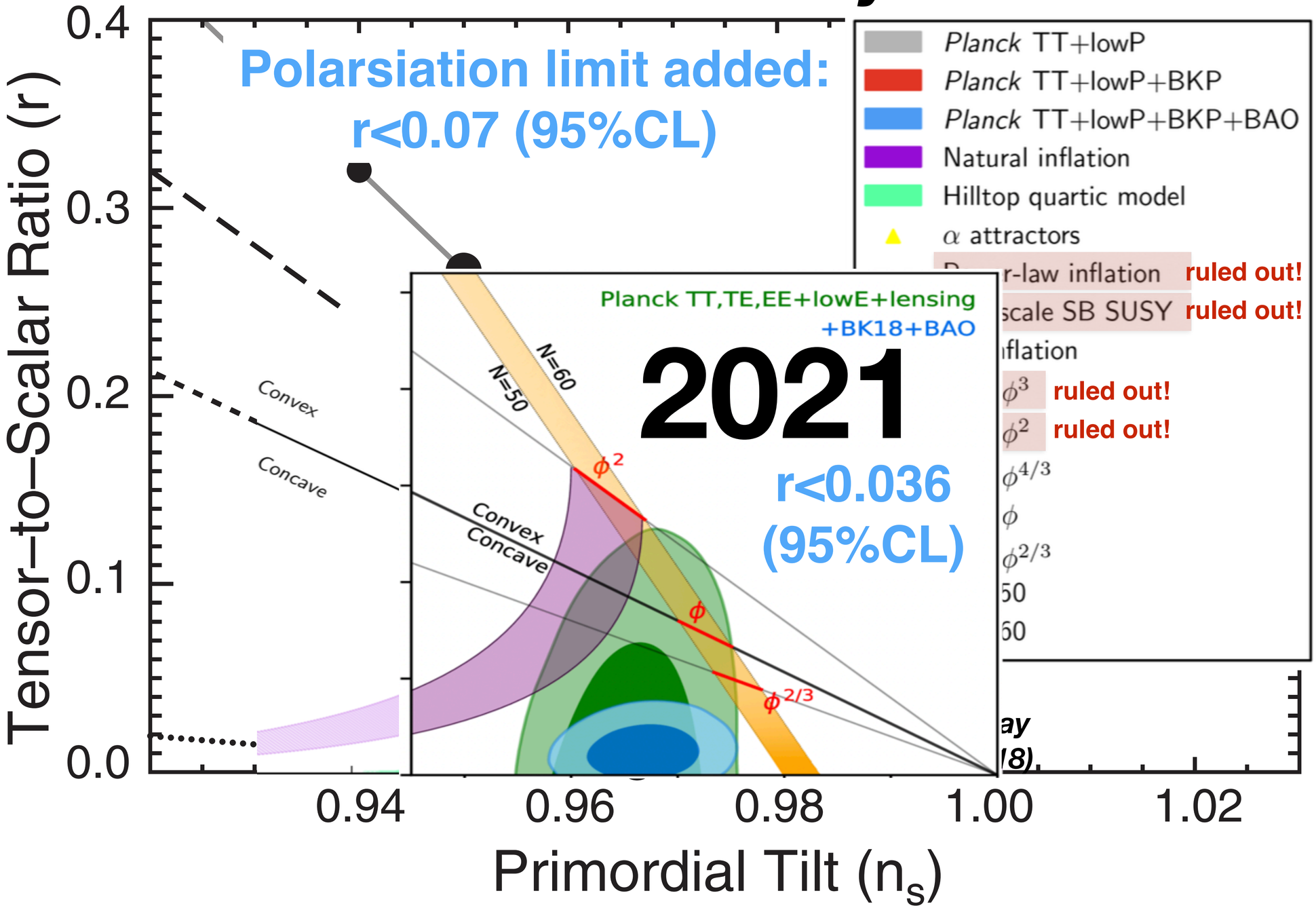
Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)



Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)



BICEP2/Keck Array Collaboration (2021)



What comes next?

Experimental Landscape

CMB-S4
Next Generation CMB Experiment

CMB Stages

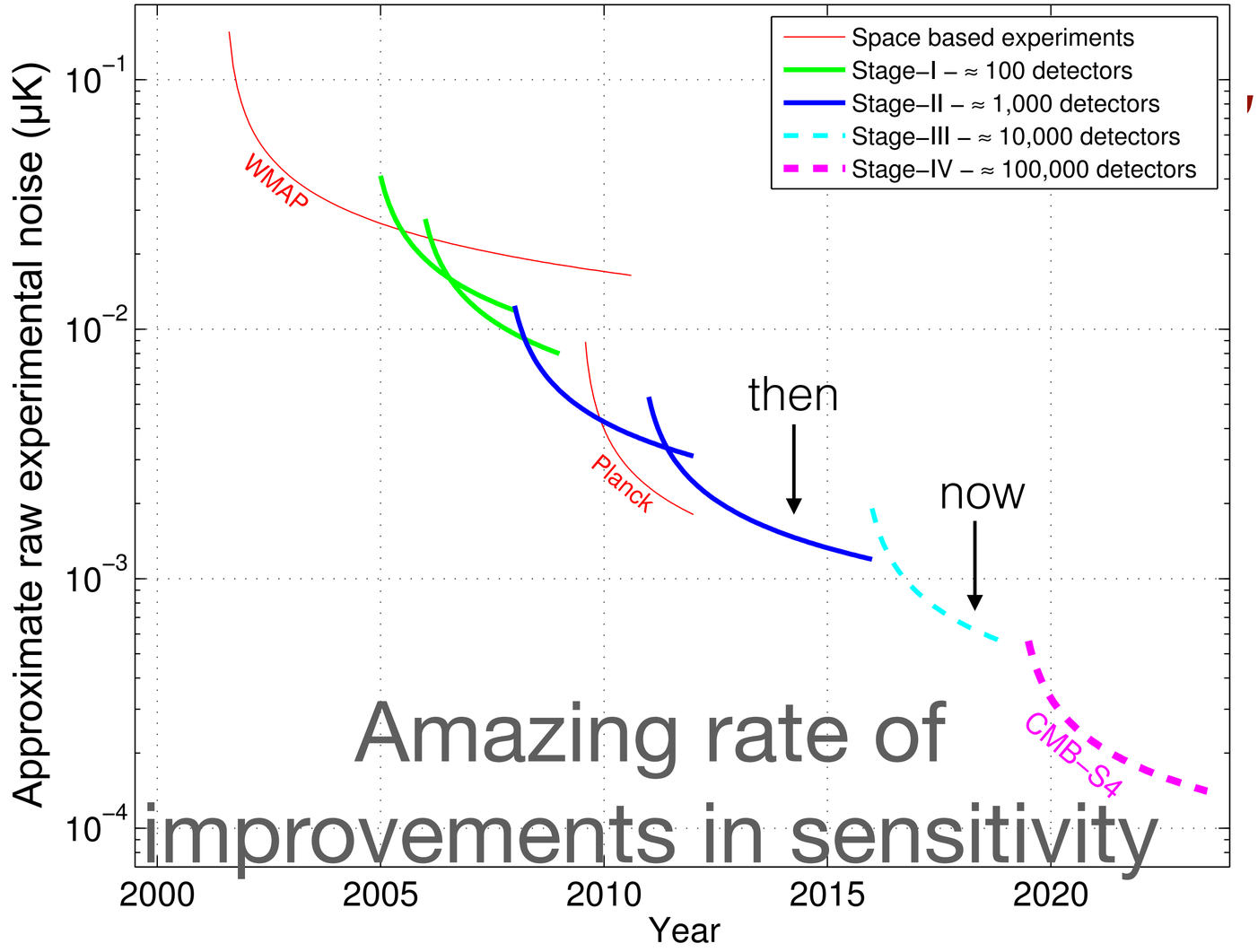
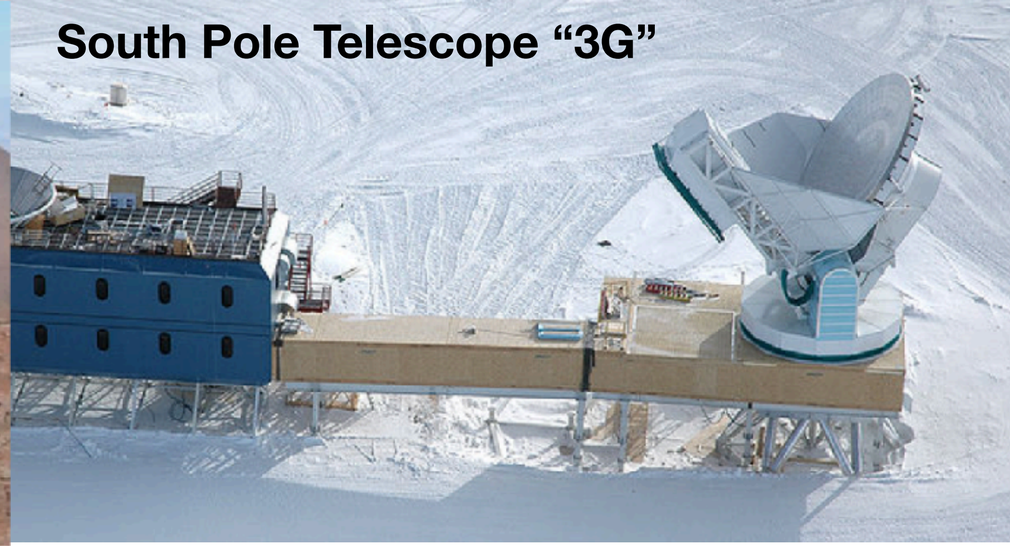
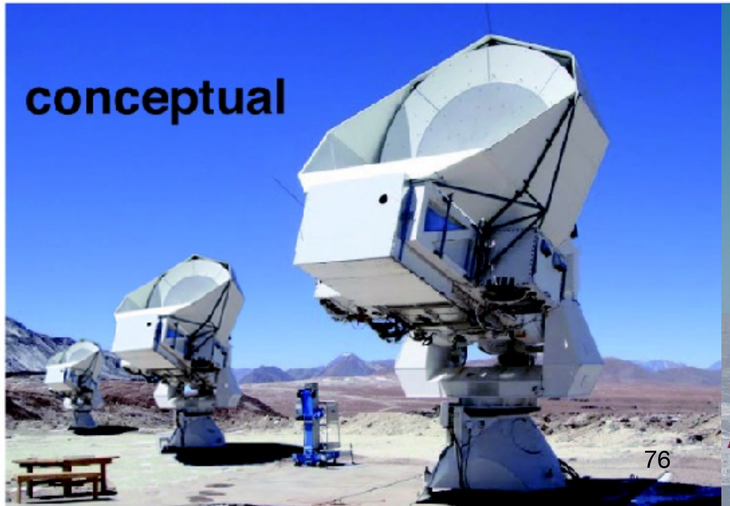


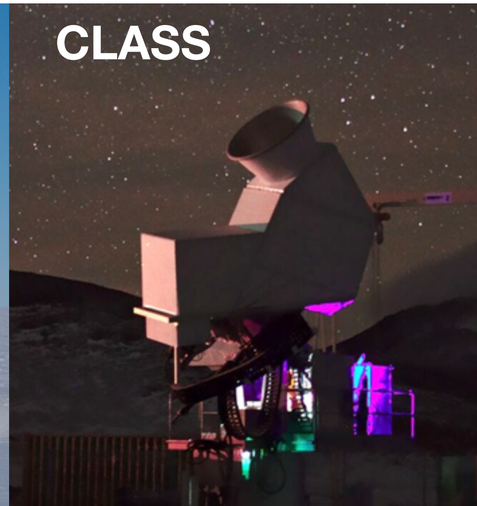
Figure by Clem Pryke for 2013 Snowmass documents



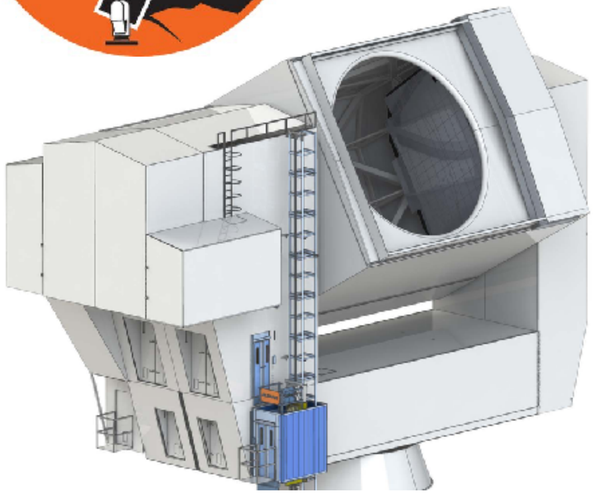
On-going Ground-based Experiments

The Simons Array





SIMONS OBSERVATORY



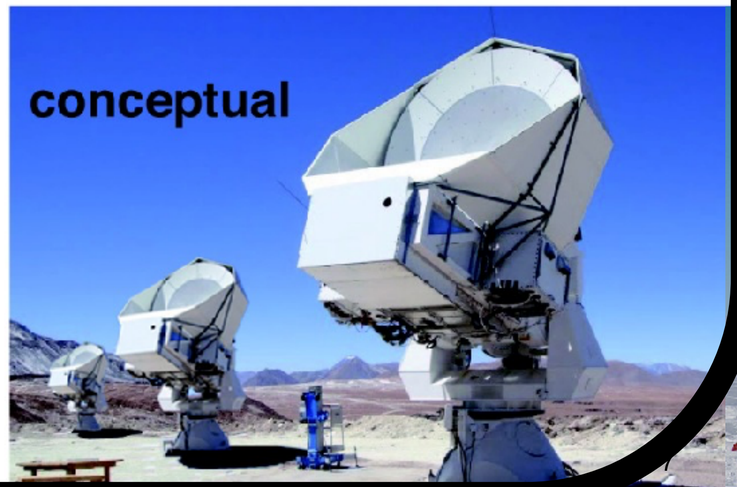
Early 2020s

~$100M

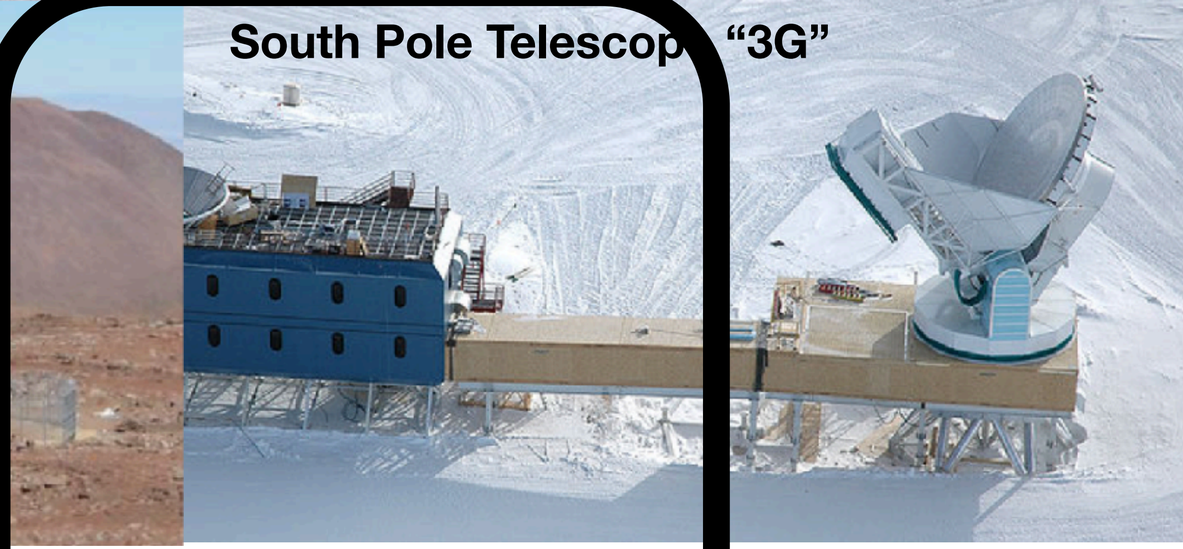
Advanced Atacama Cosmology Telescope

= +

The Simons Array



South Pole Telescope “3G”



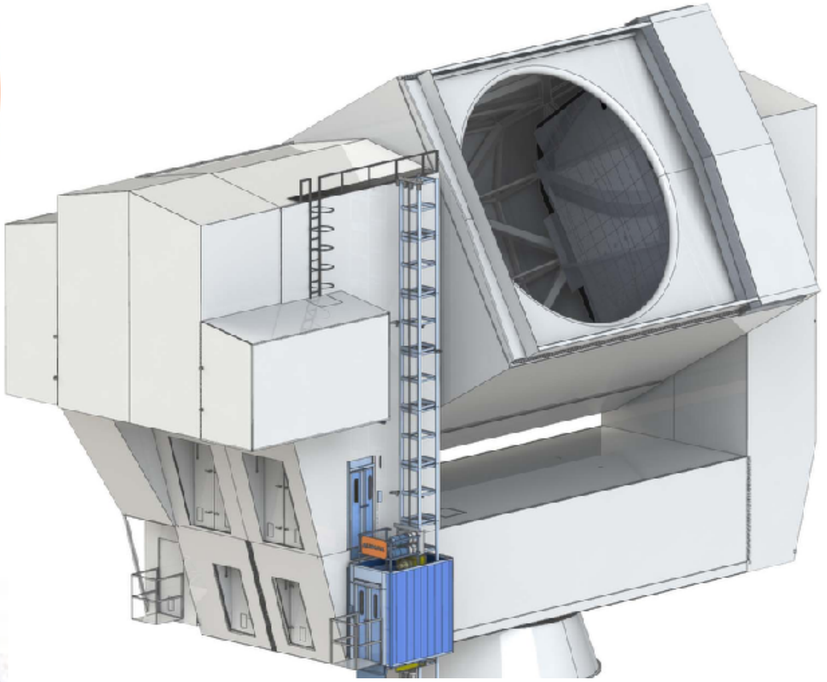
+ =

The South Pole Observatory

BICEP/Keck Array

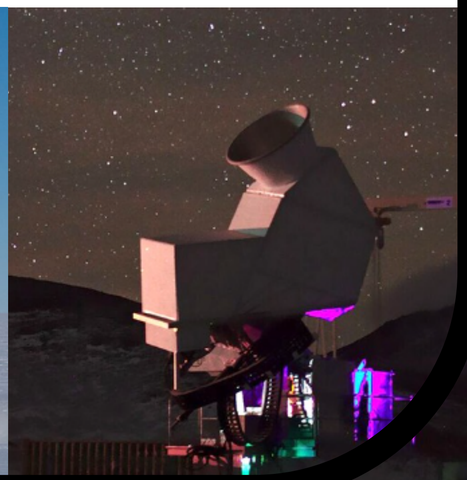
CLASS

SIMONS OBSERVATORY



CCAT-p

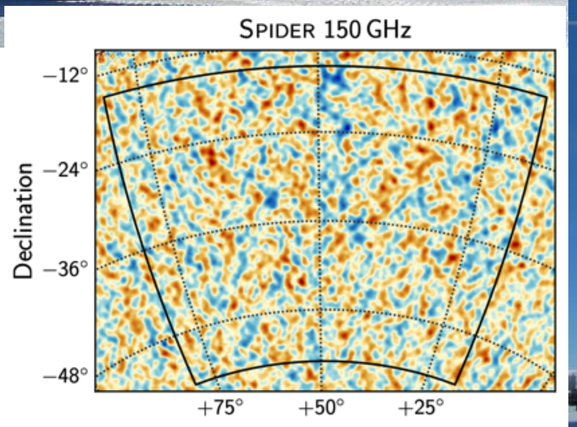
Bringing all together: US-led CMB Stage IV Late 2020s (~$600M)



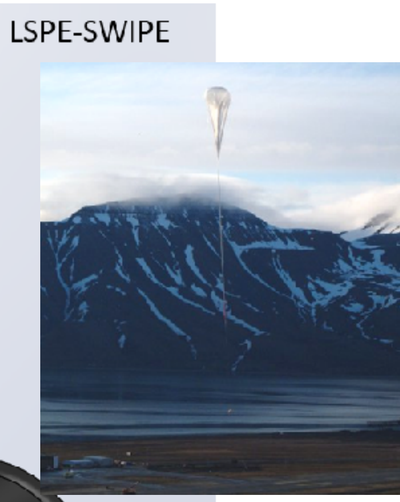
Balloons!

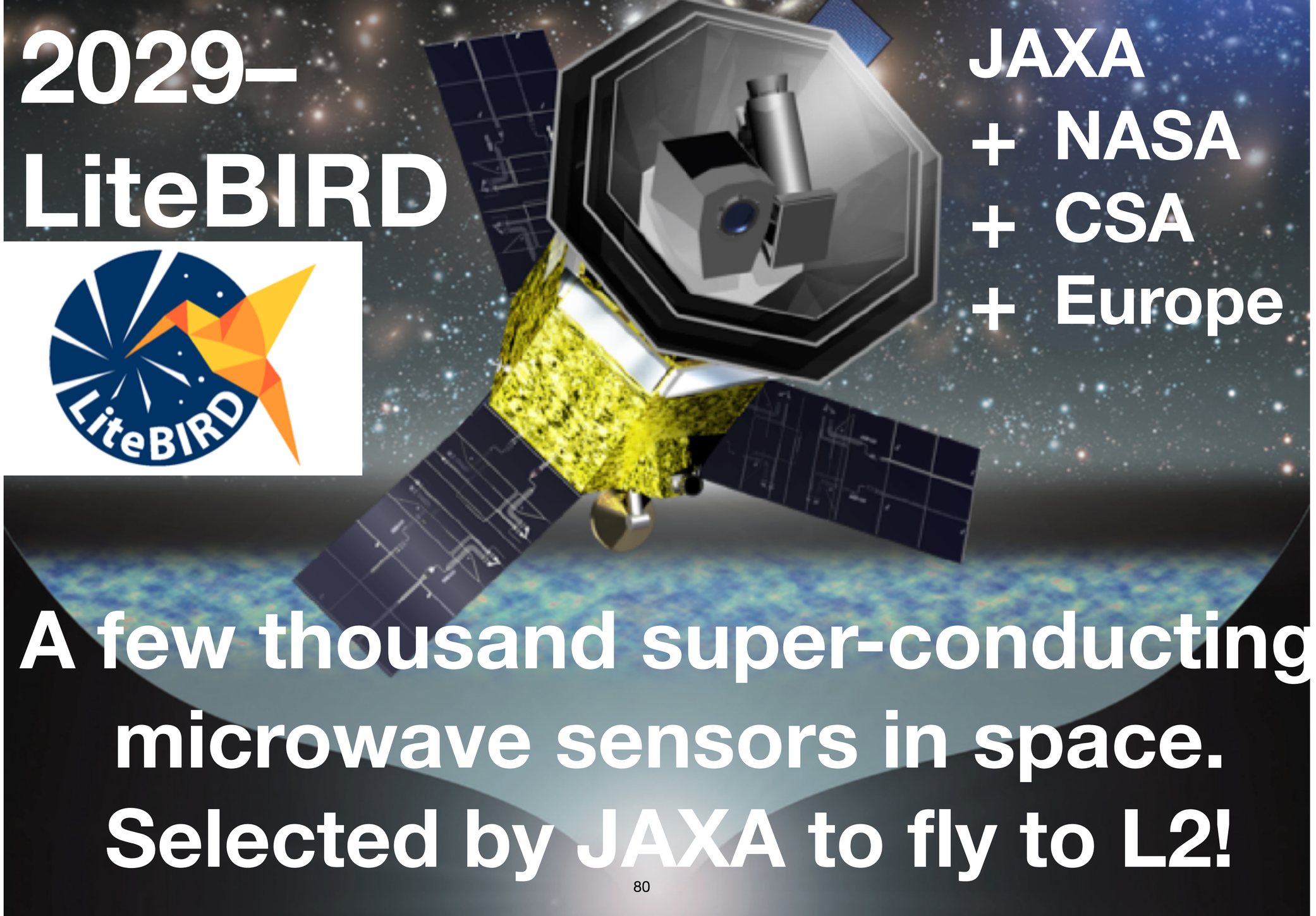
“Almost space”

SPIDER
(led by USA)



LSPE/SWIPE
(led by Italy)




2029–
LiteBIRD
JAXA
+ NASA
+ CSA
+ Europe
A few thousand super-conducting
microwave sensors in space.
Selected by JAXA to fly to L2!

Summary

Towards finding our origins

- **The Quest So Far:**
  - There is very good evidence that we all came from the quantum fluctuation in the early Universe, generated during the period of **cosmic inflation**.
- **The New Quest:**
  - Discovery of the primordial gravitational wave with the wavelength of billions of light years gives **definitive evidence for inflation.**
  - Hoping to find the first evidence from ground-based and balloon-borne experiments within the next 10 years.
  - Then, the definitive measurement will come from **LiteBIRD** in early 2030s.