Critical Tests of Theory of the Early Universe using the Cosmic Microwave Background

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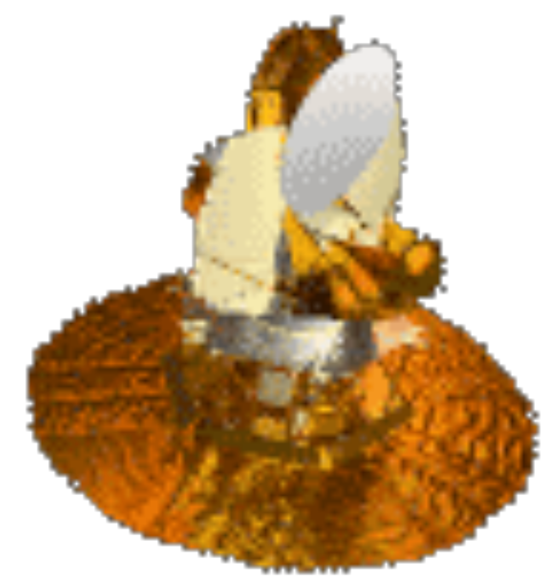
November 2, 2015

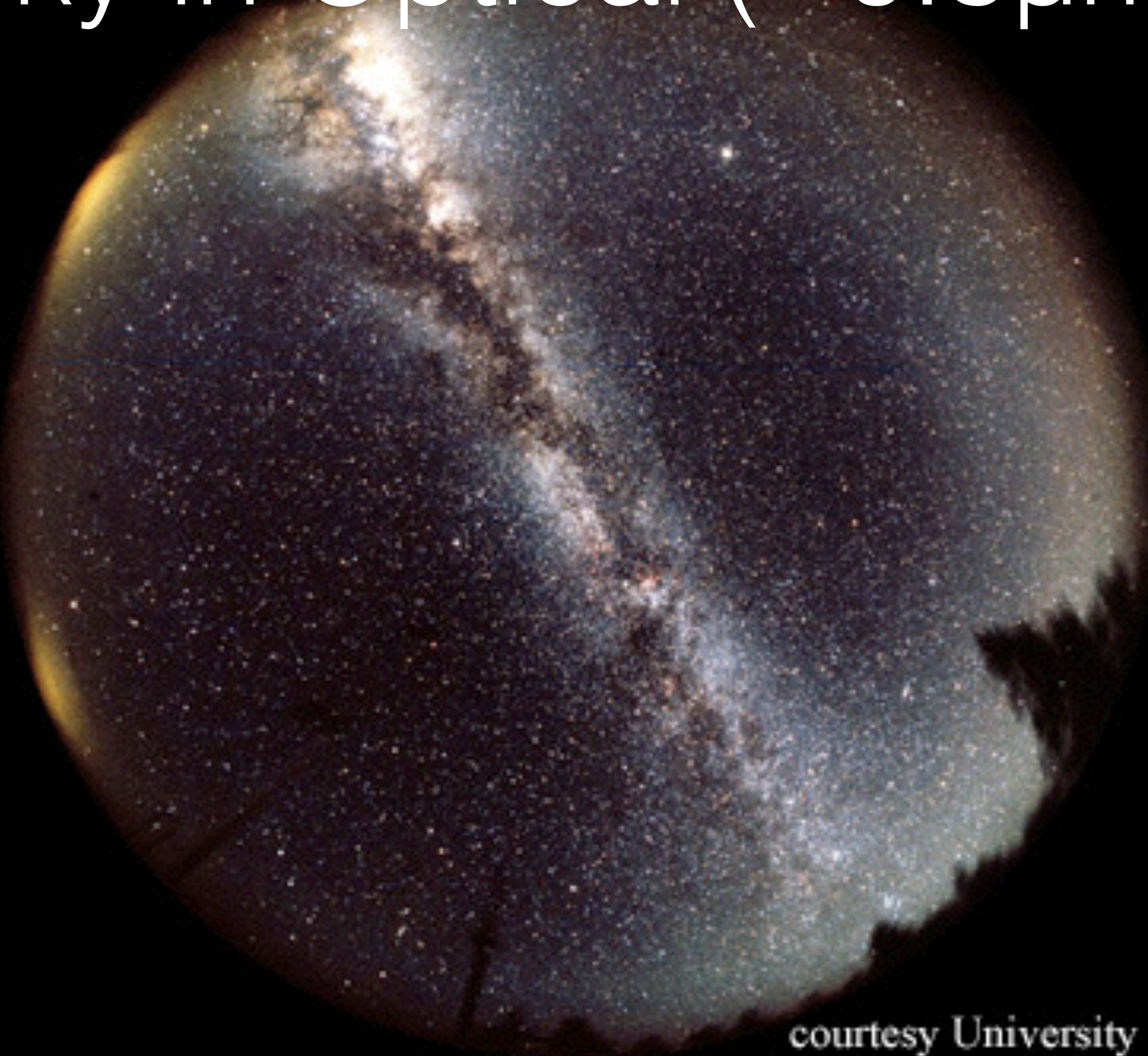


Breakthrough in Cosmological Research

- We can actually **see** the physical condition of the universe when it was very young

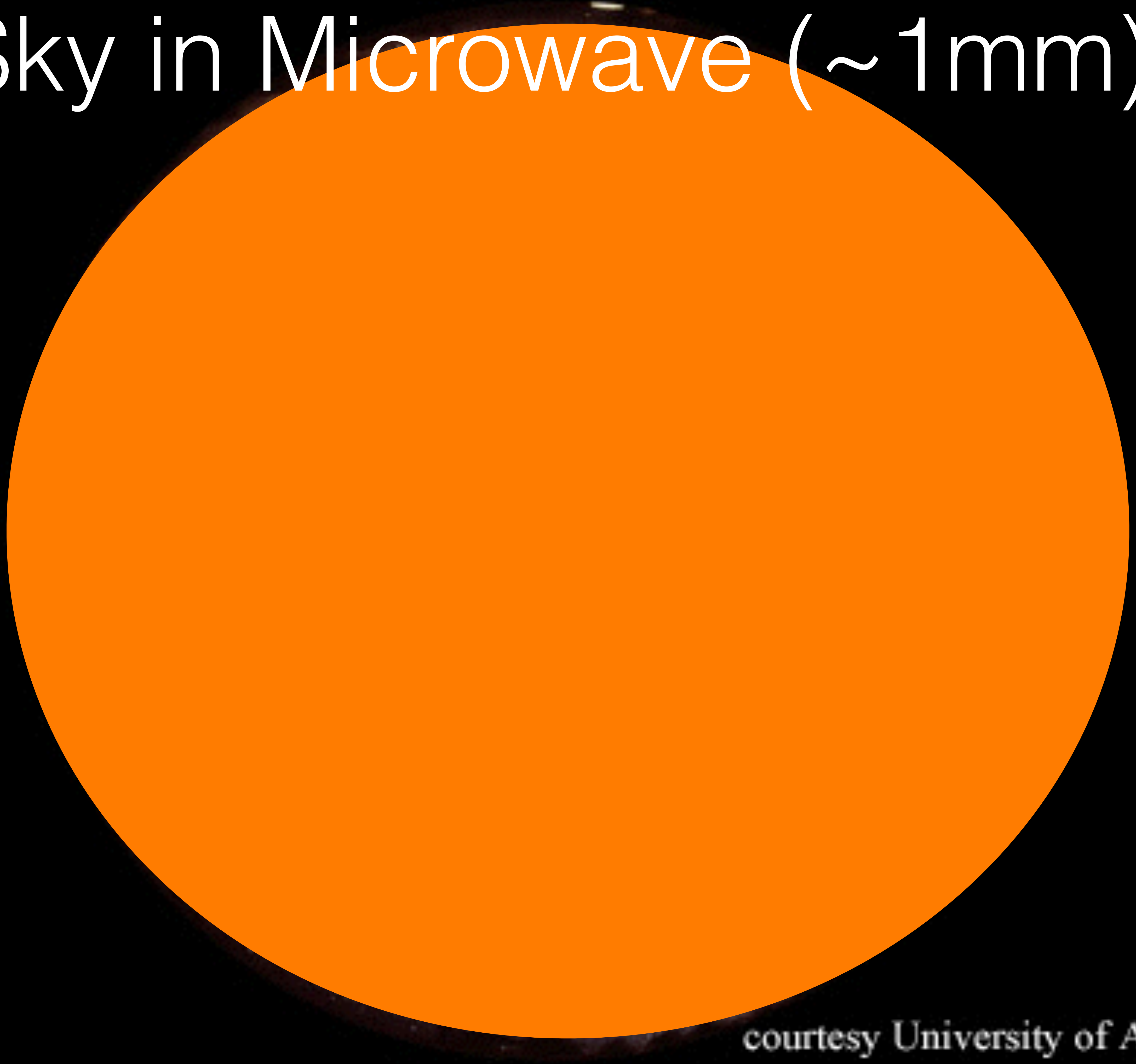

From "Cosmic Voyage"

Sky in Optical (~0.5μm)



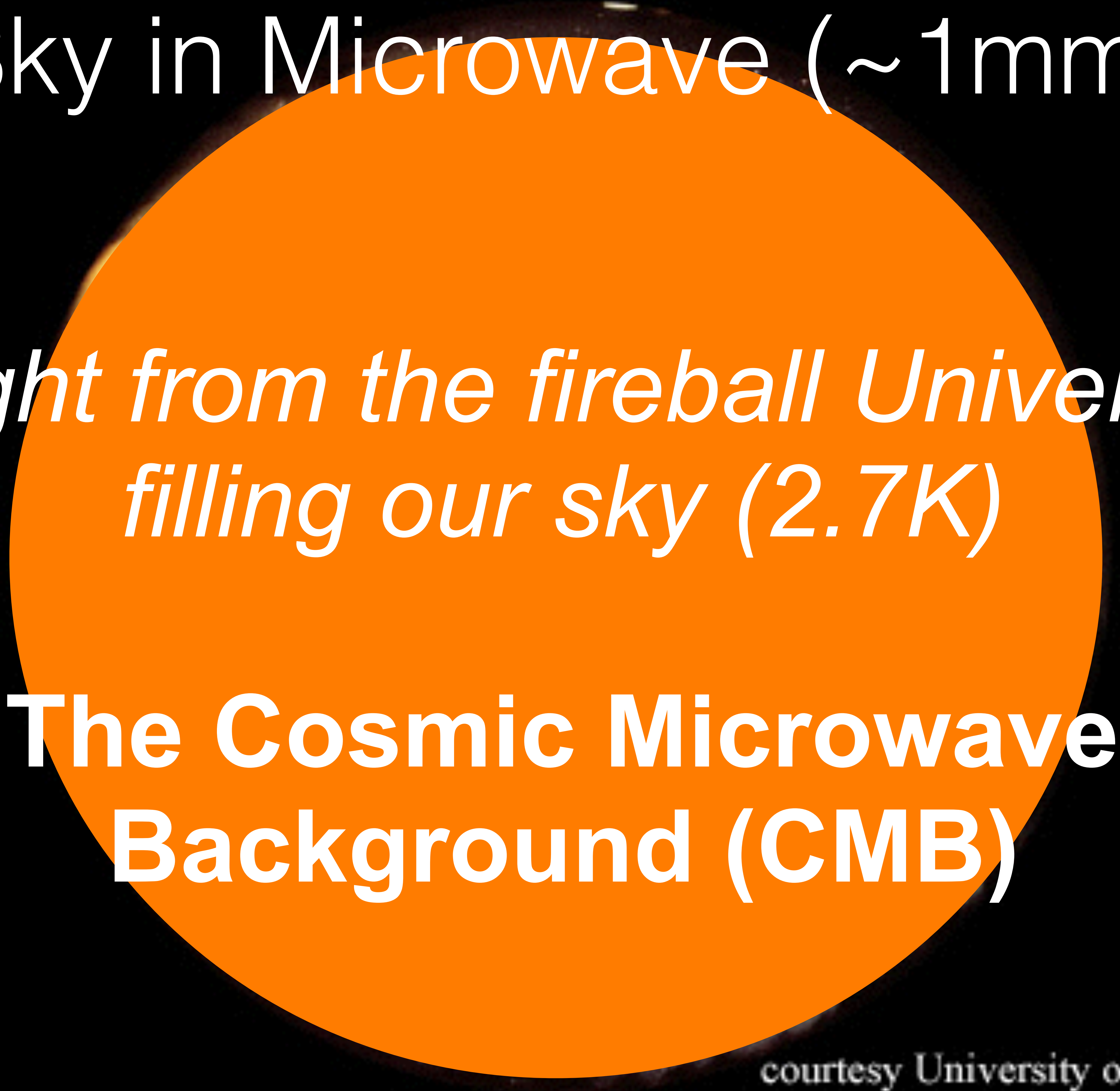
courtesy University of Arizona

Sky in Microwave (~1mm)



courtesy University of Arizona

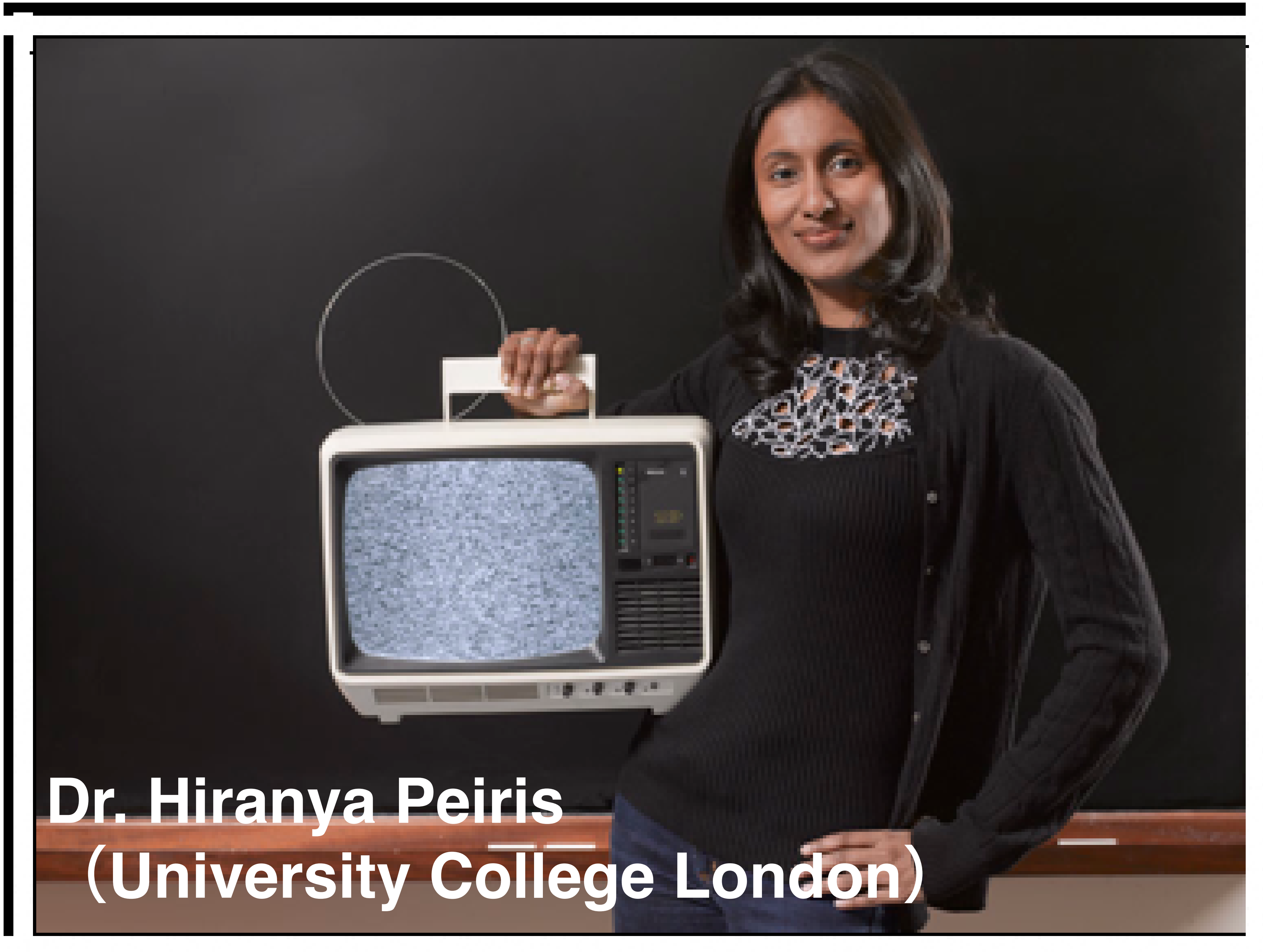
Sky in Microwave (~1mm)



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

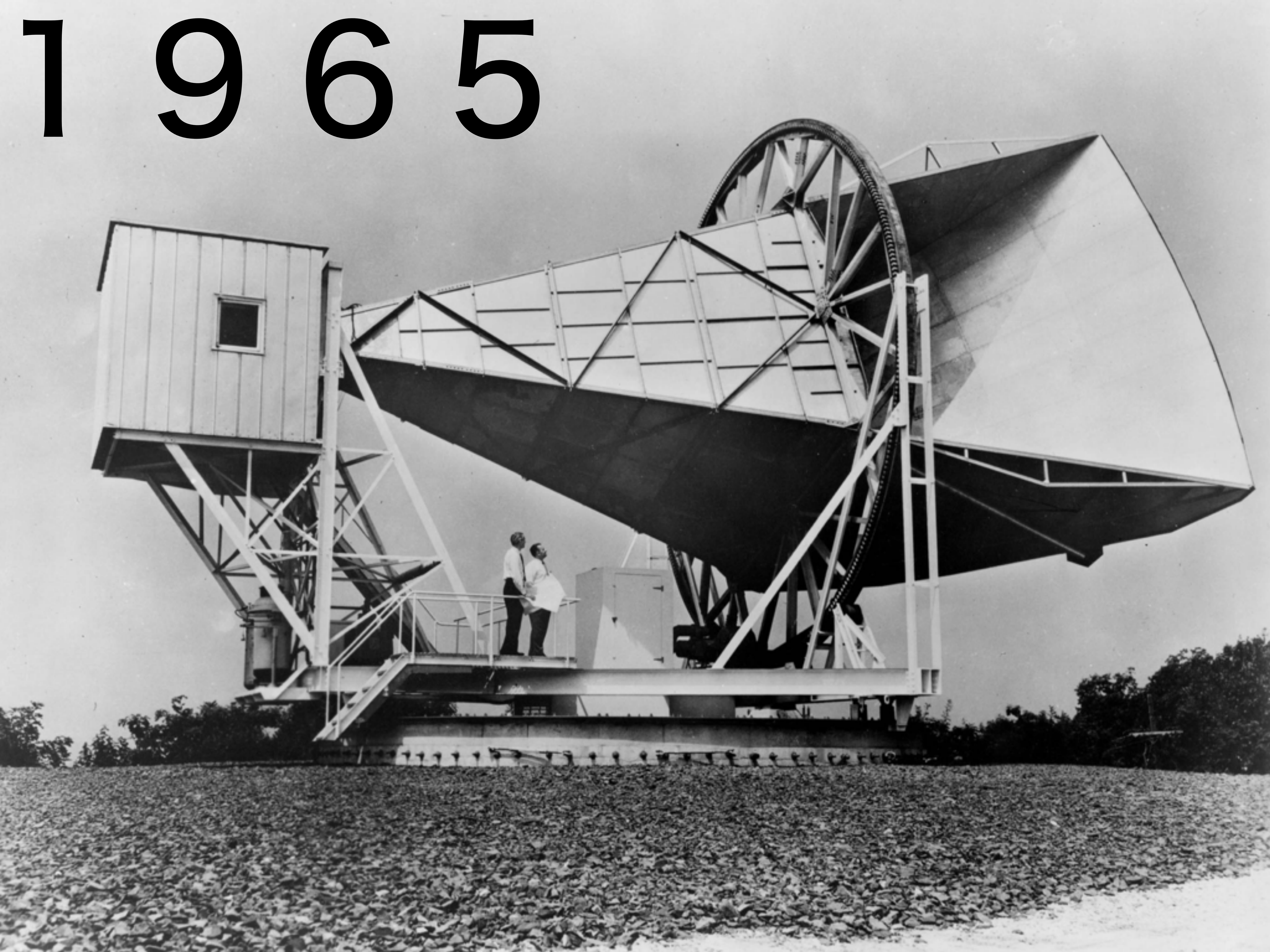
The Cosmic Microwave Background (CMB)

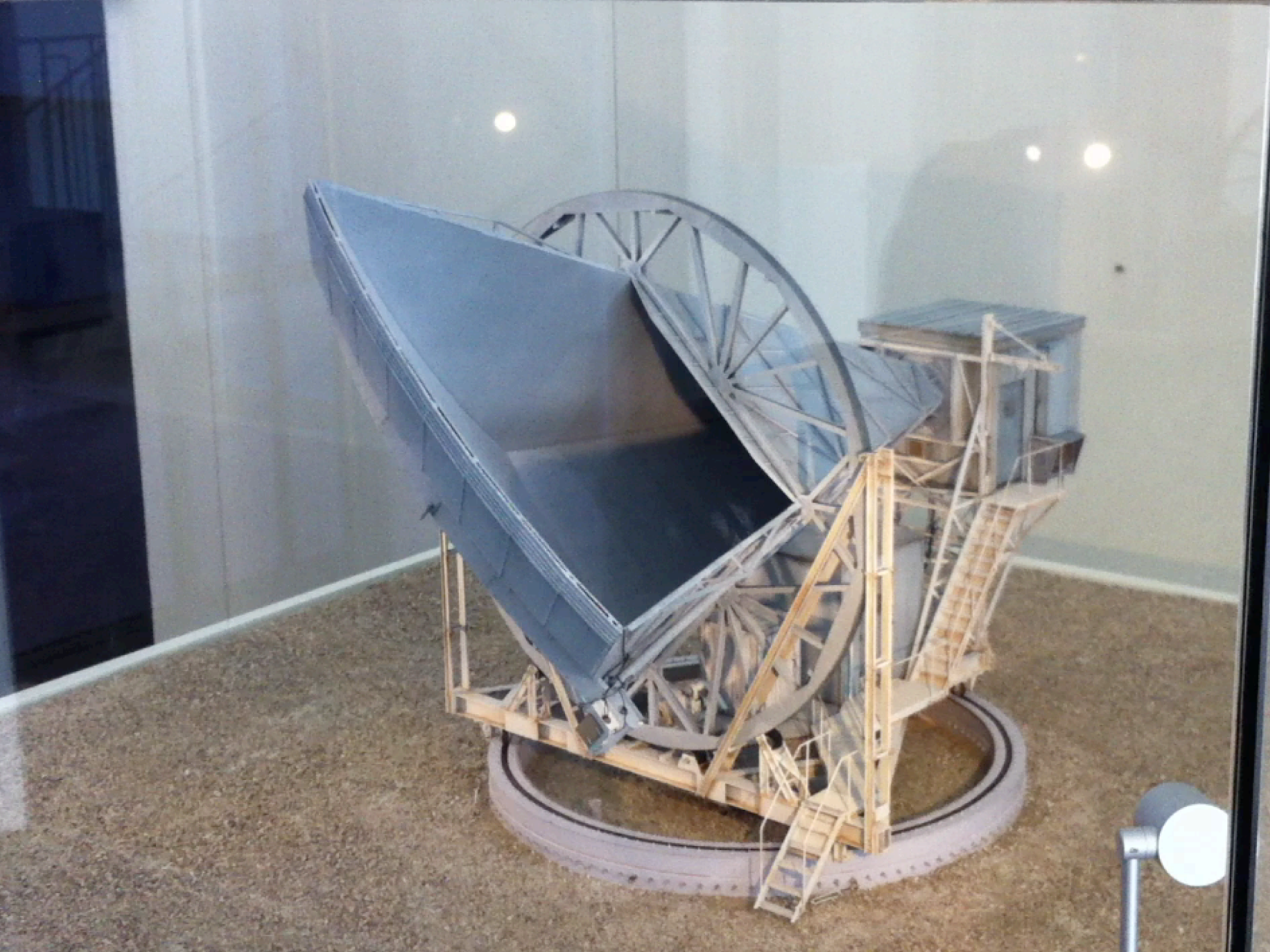
courtesy University of Arizona



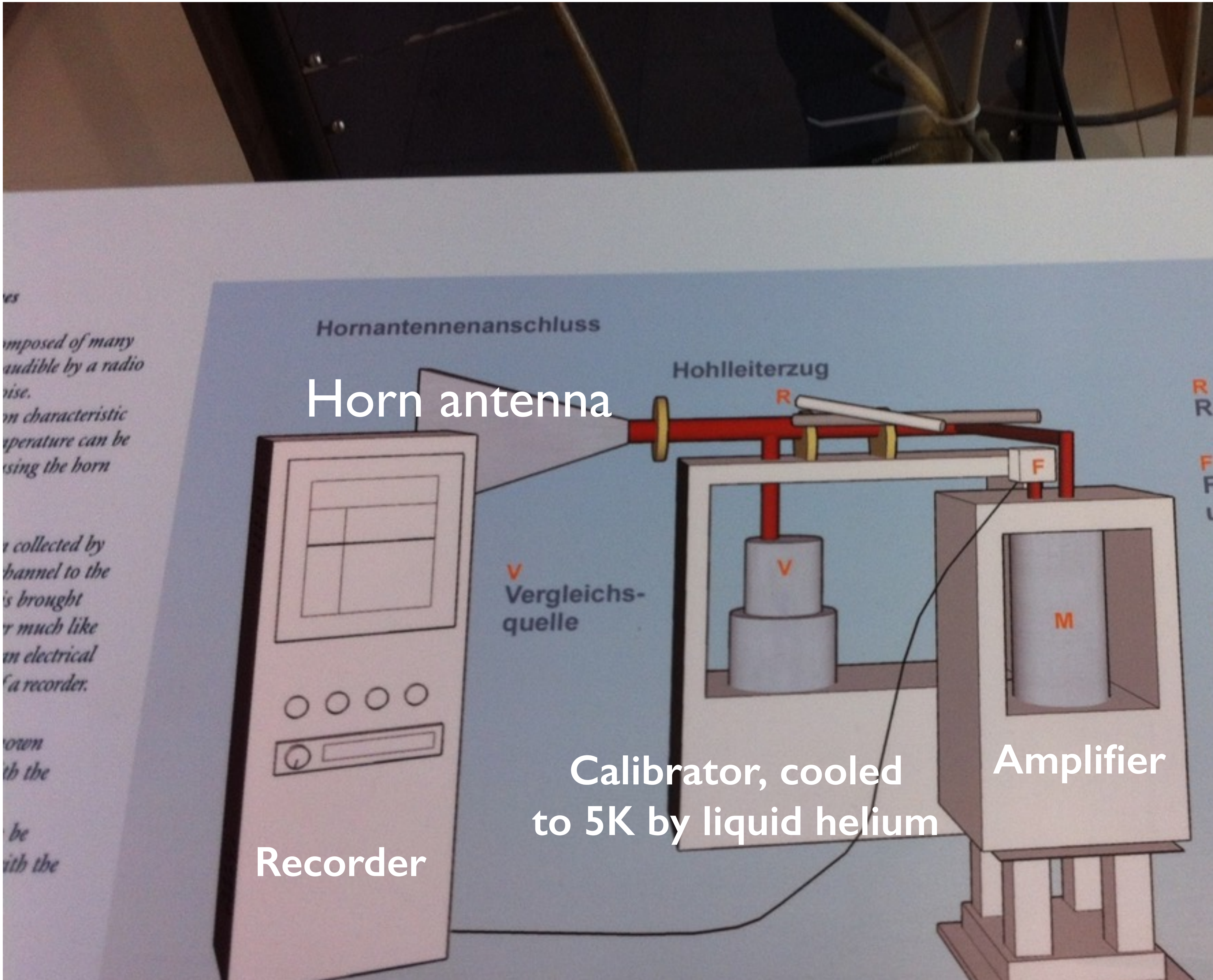
All you need to do is to detect radio waves. For example, 1% of noise on the TV is from the fireball Universe

1965



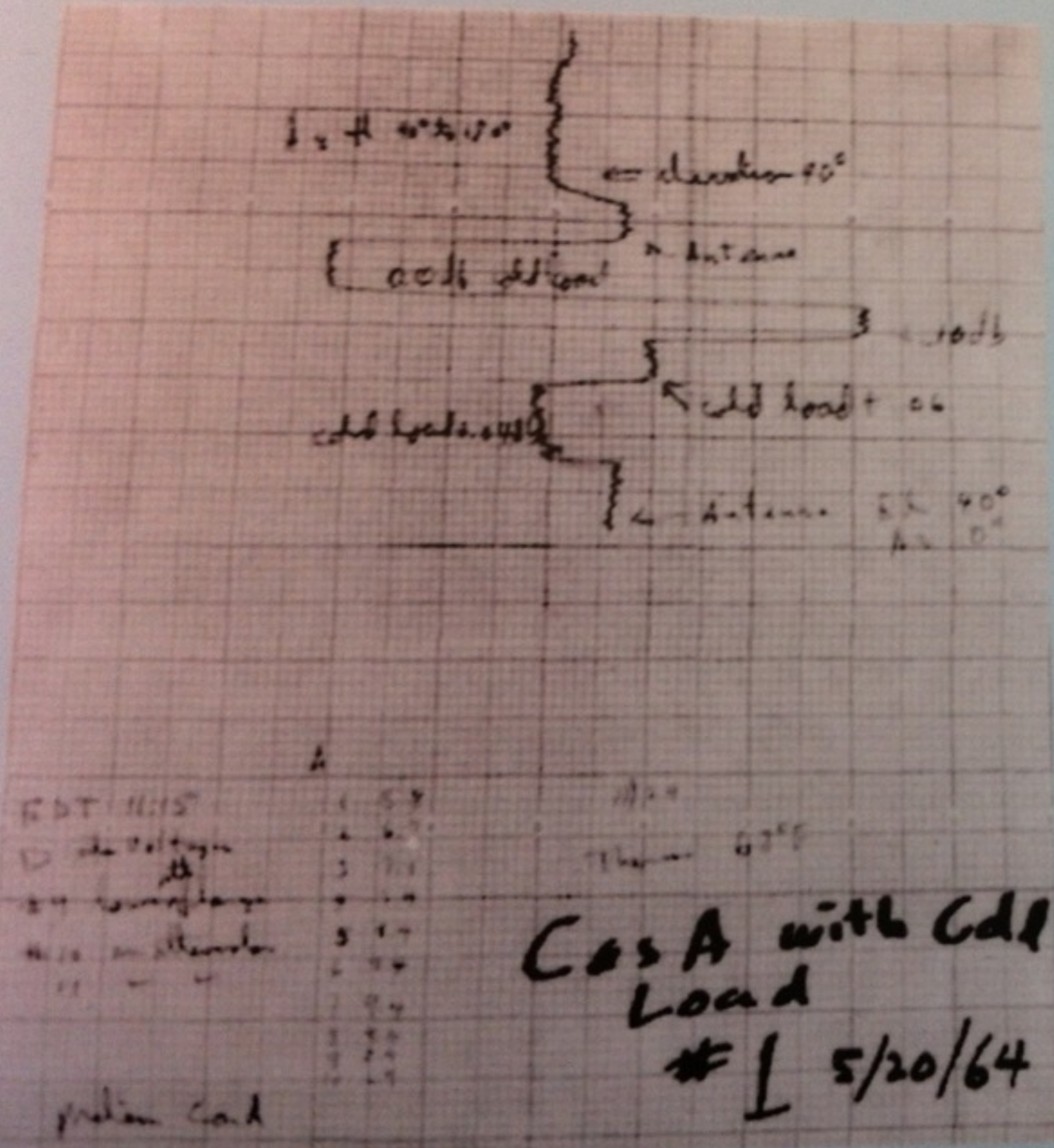


The real detector system used by Penzias & Wilson
The 3rd floor of Deutsches Museum


Hornantennenanschluss
Horn antenna
Hohlleiterzug
R
F
V
Vergleichs-
quelle
M
Recorder
Calibrator, cooled
to 5K by liquid helium
Amplifier

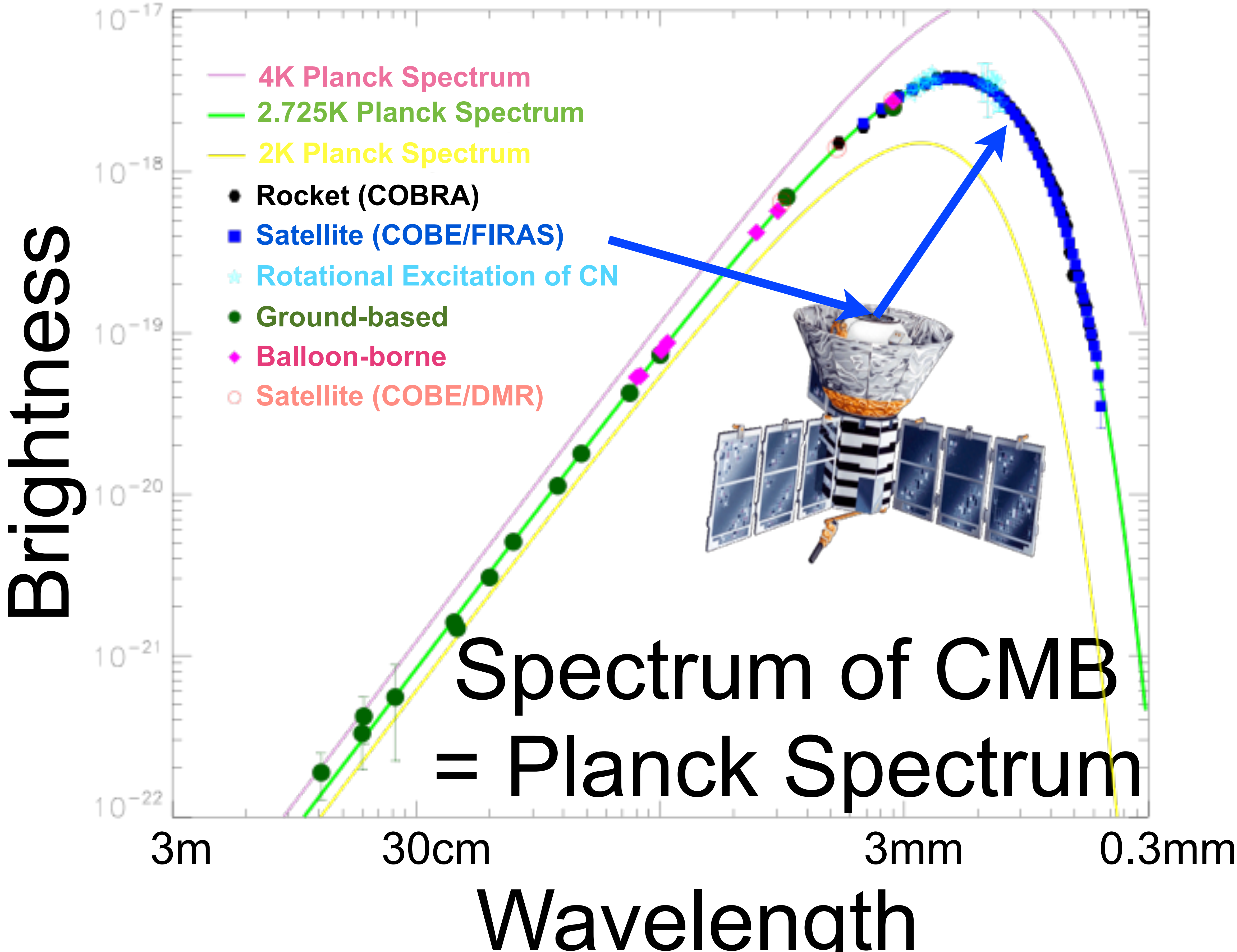
May 20, 1964
CMB Discovered

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.



4K Planck Spectrum
2.725K Planck Spectrum
2K Planck Spectrum
Rocket (COBRA)
Satellite (COBE/FIRAS)
Rotational Excitation of CN
Ground-based
Balloon-borne
Satellite (COBE/DMR)
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
Brightness
3m
30cm
3mm
0.3mm
Wavelength
Spectrum of CMB
= Planck Spectrum

Origin of CMB

- 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

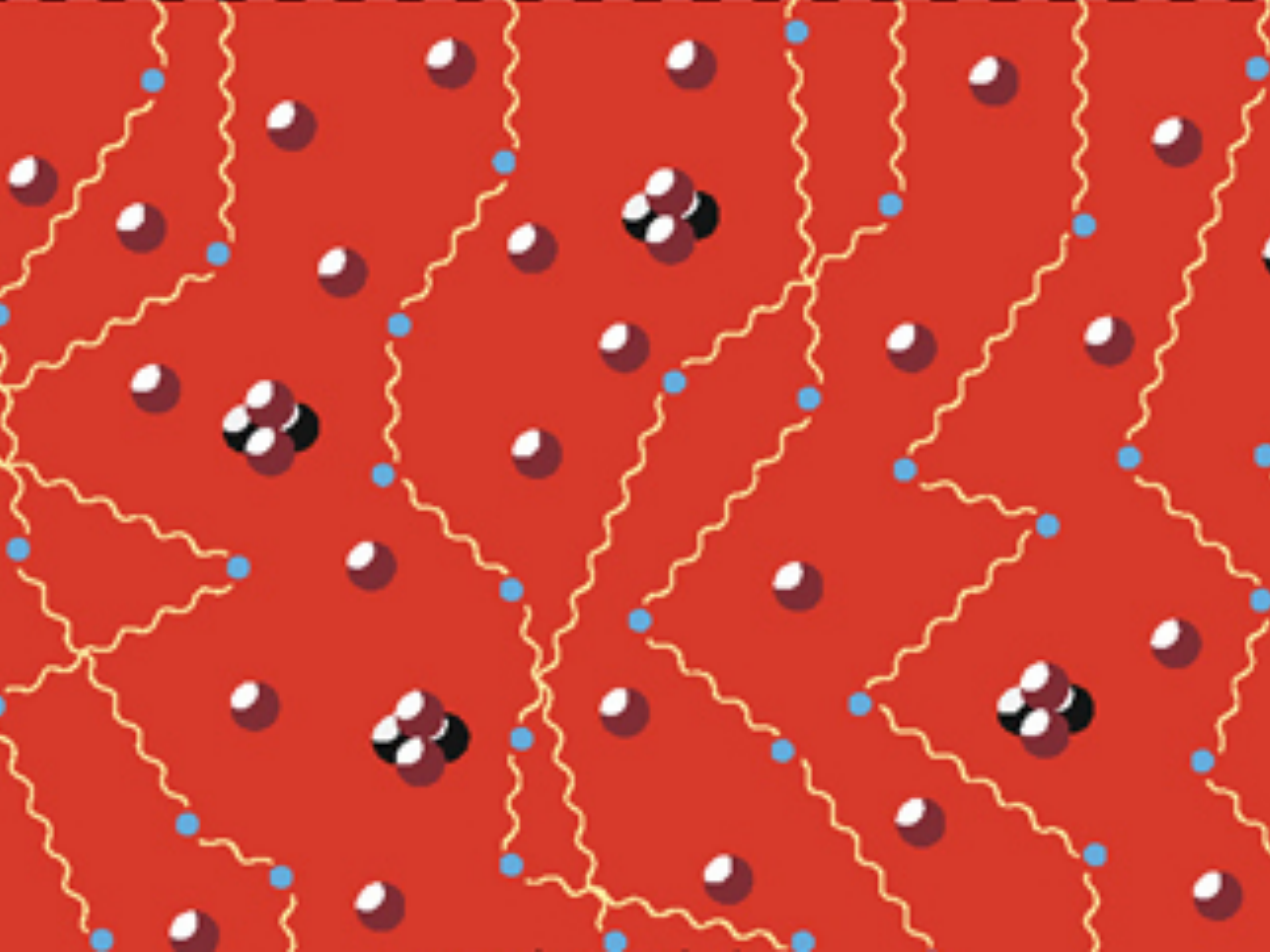
- This soup consists of:

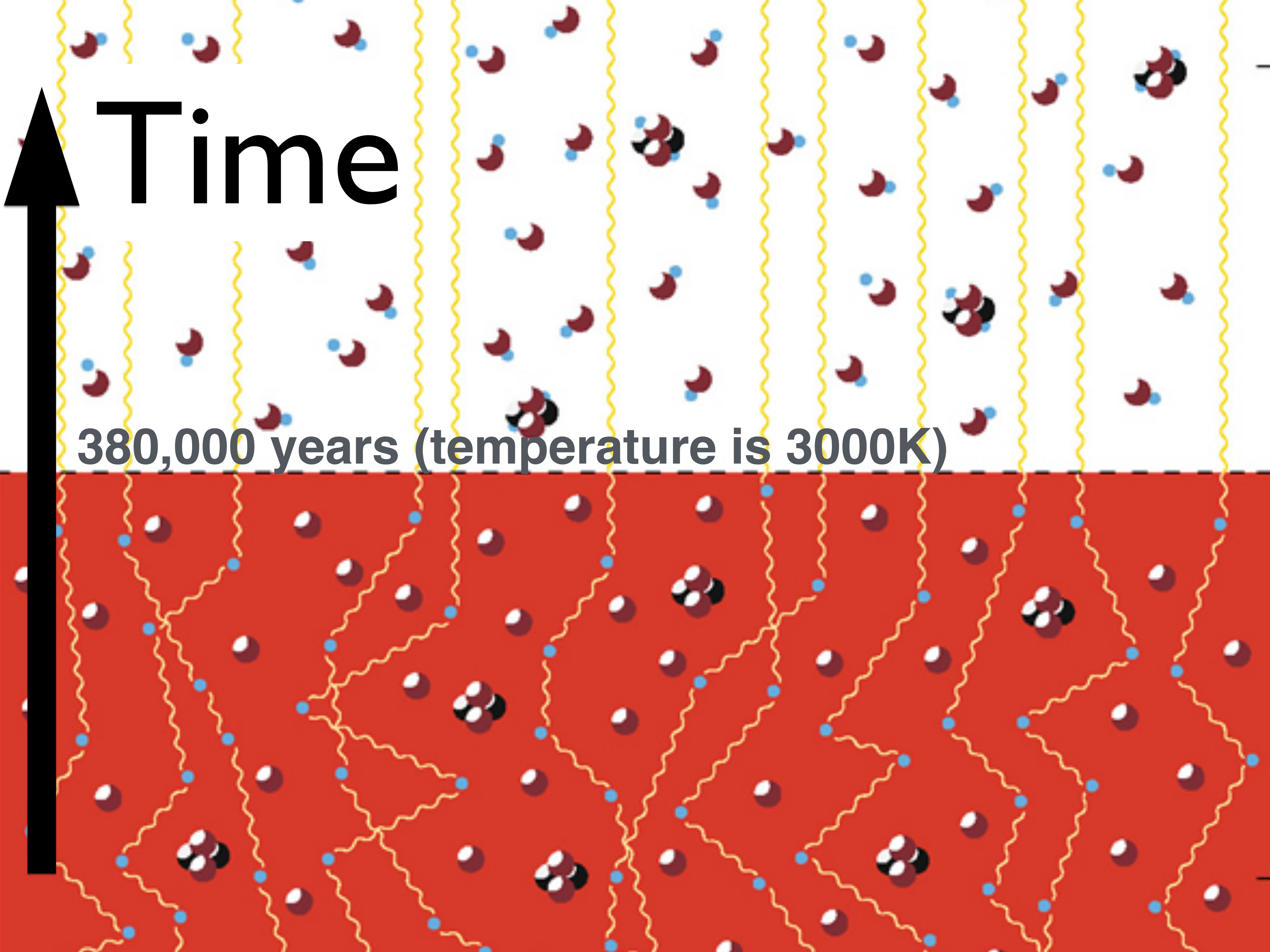
    - Protons, electrons, and helium nuclei

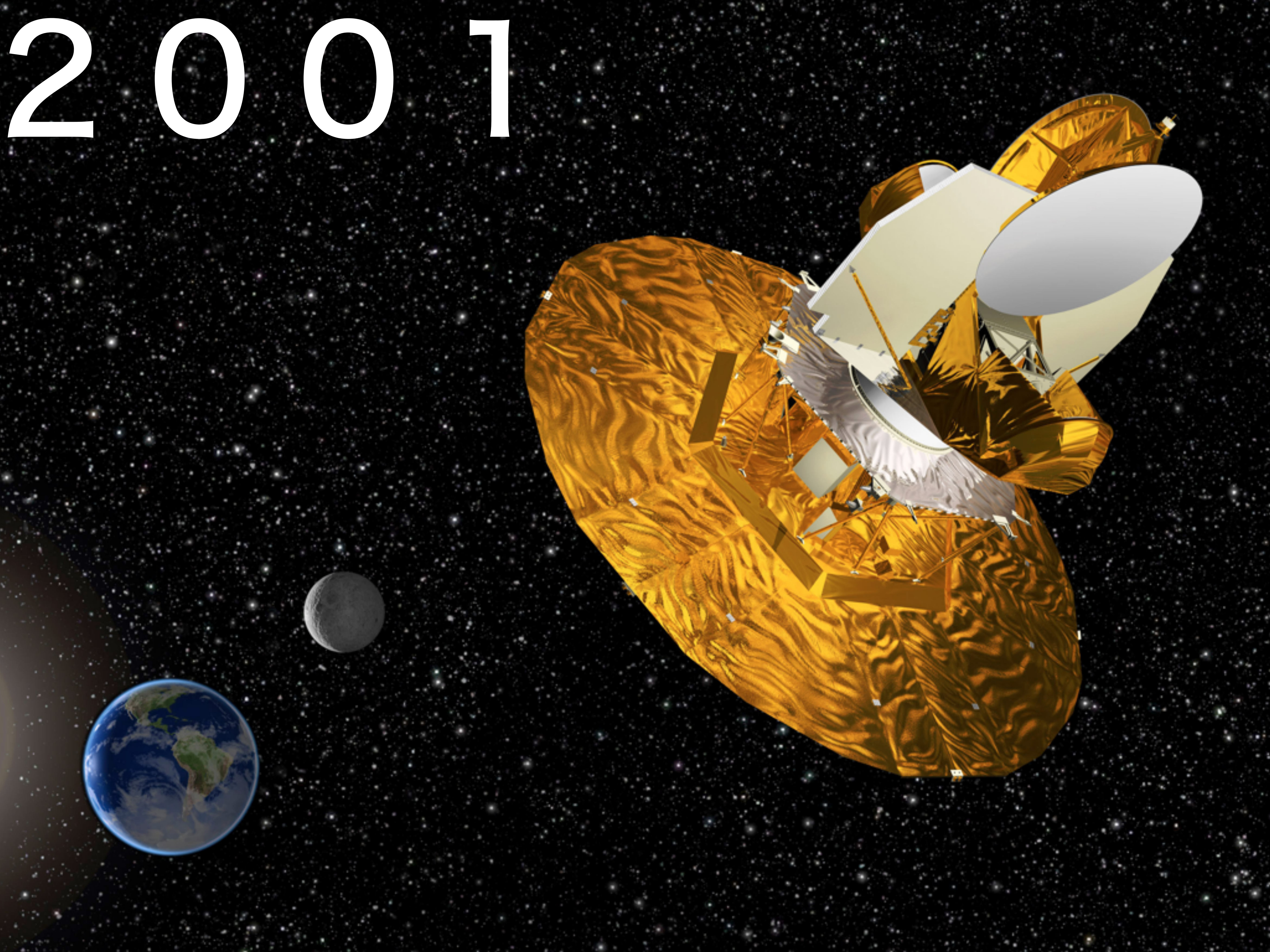
    - Photons, neutrinos

    - Dark matter

- Dark matter provides a “gravitational potential,” which can be thought of as a “soup bowl”

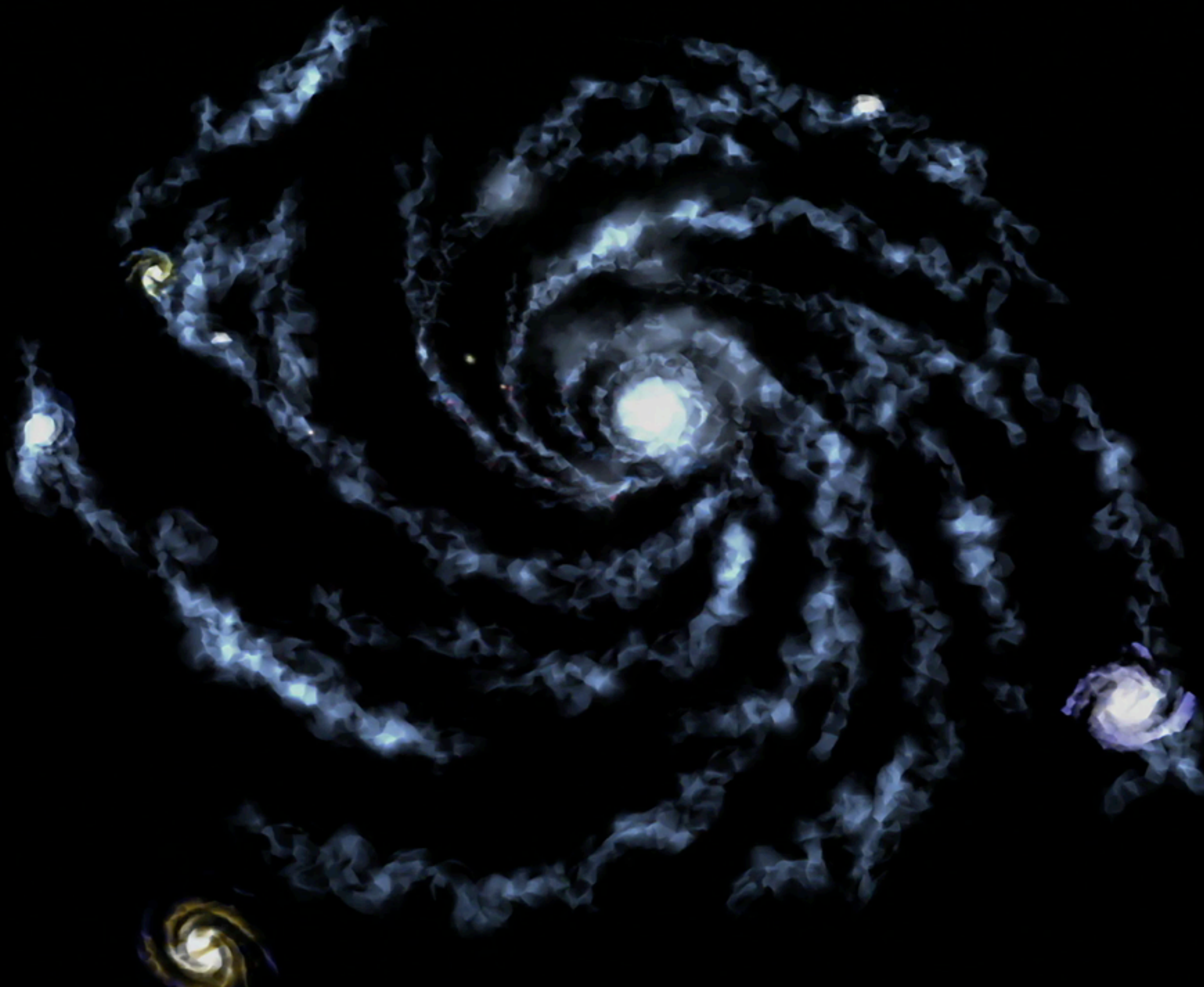



Time
380,000 years (temperature is 3000K)


2001

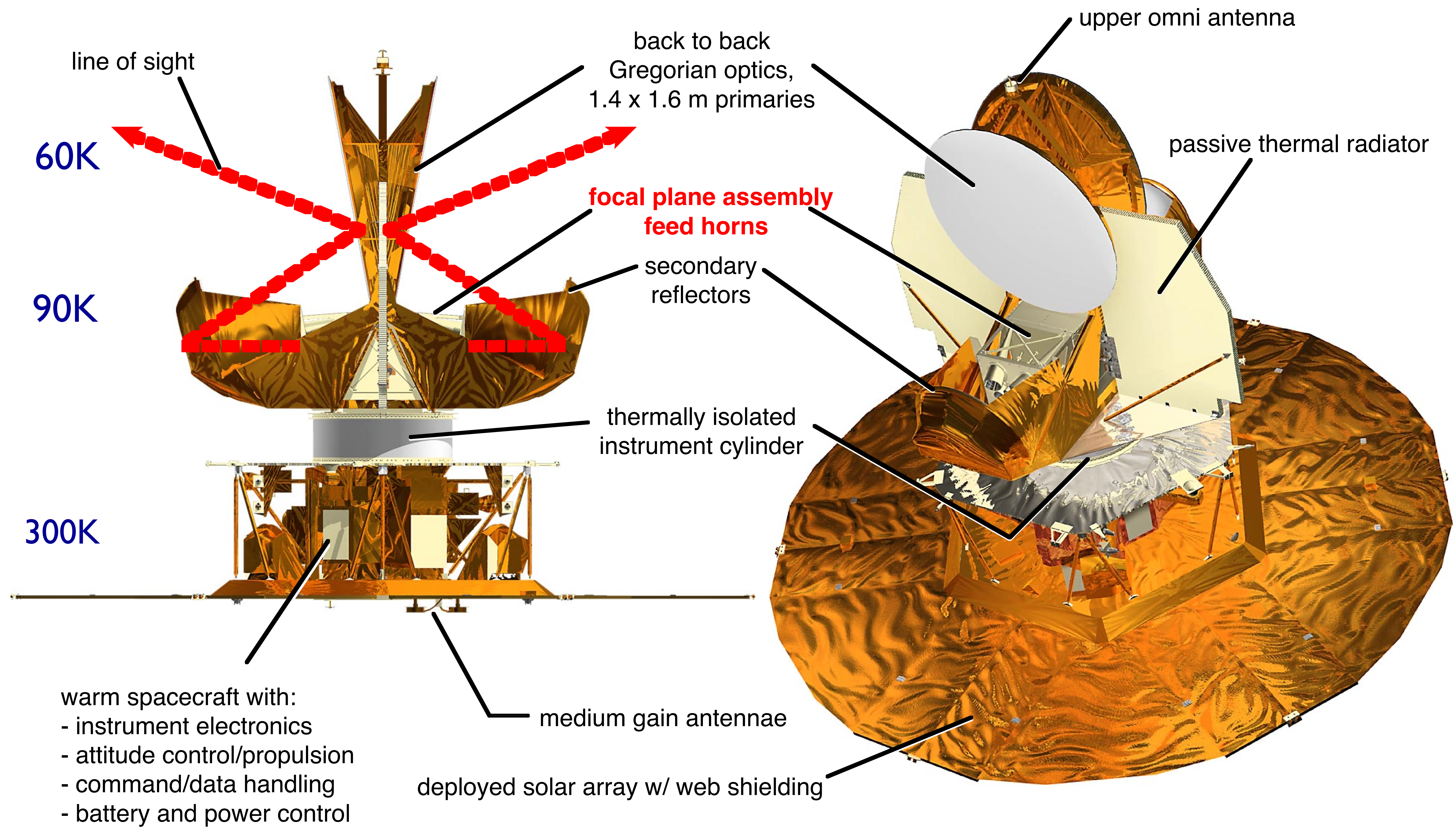
WMAP Science Team July 19, 2002

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



WMAP Spacecraft

No cryogenic components



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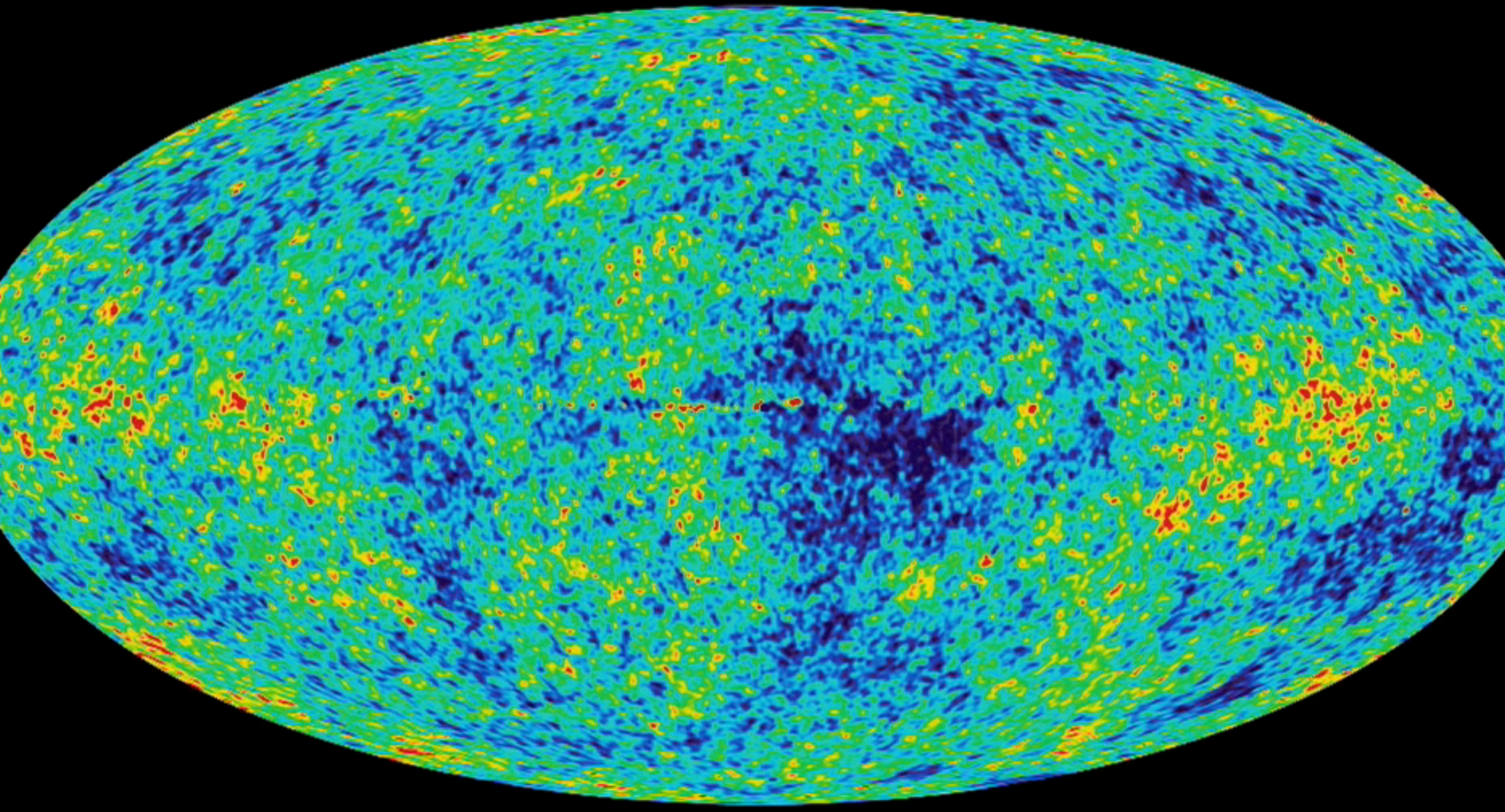
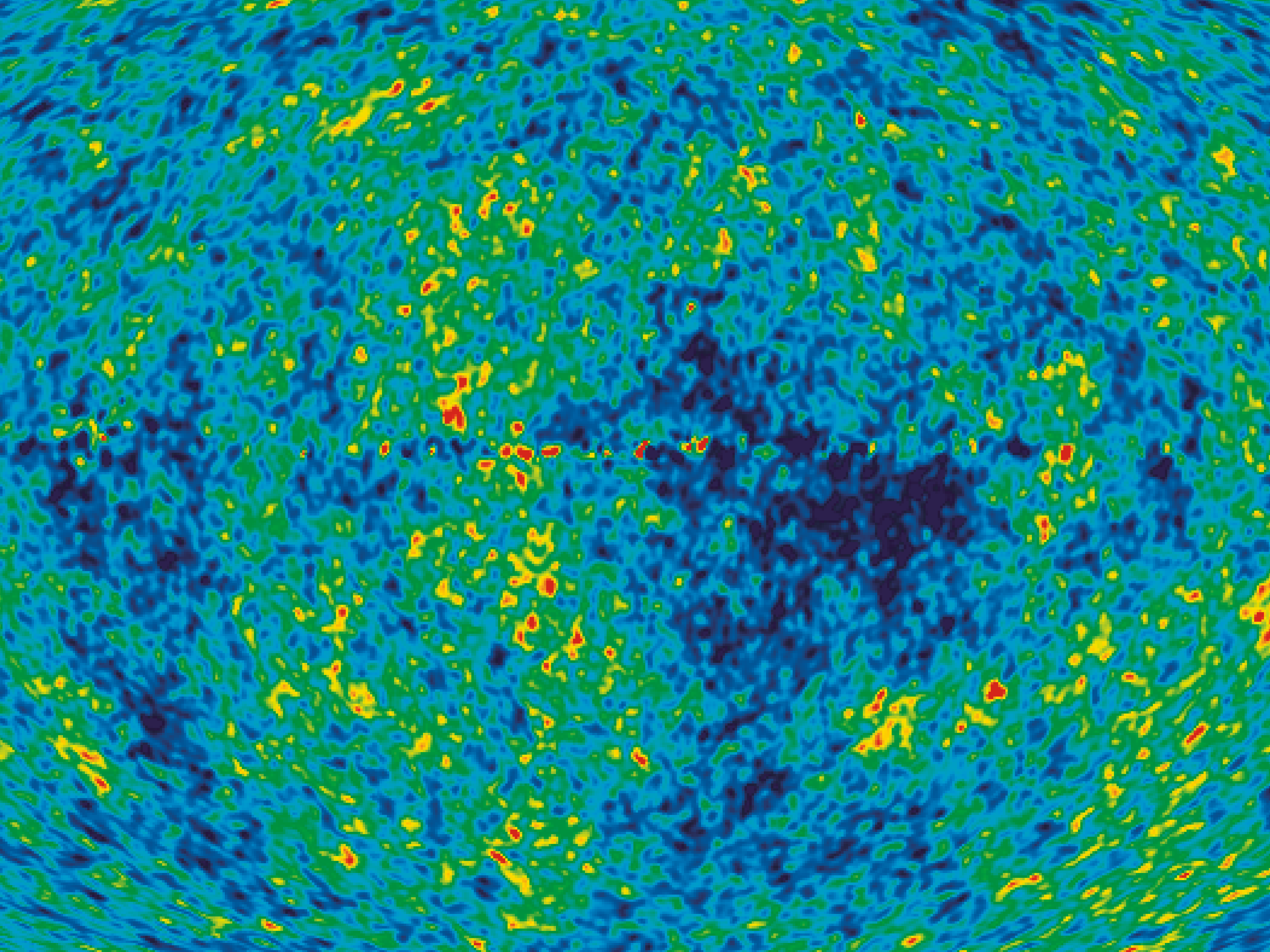


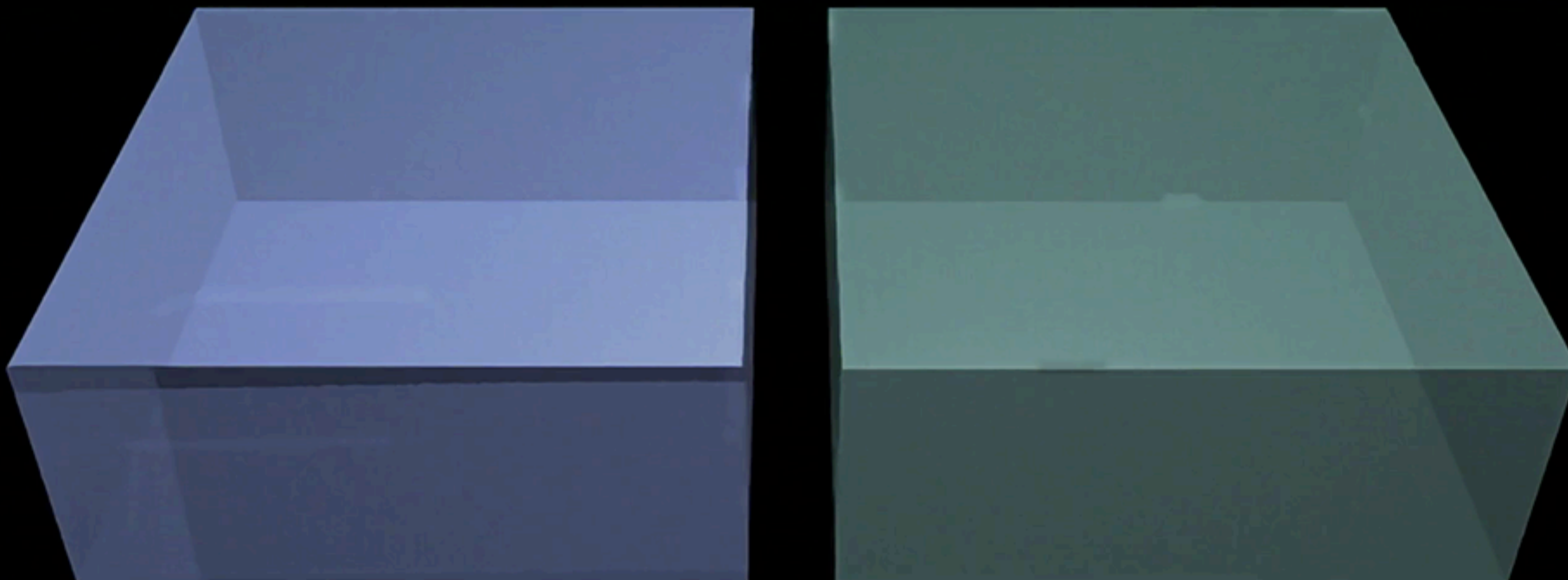


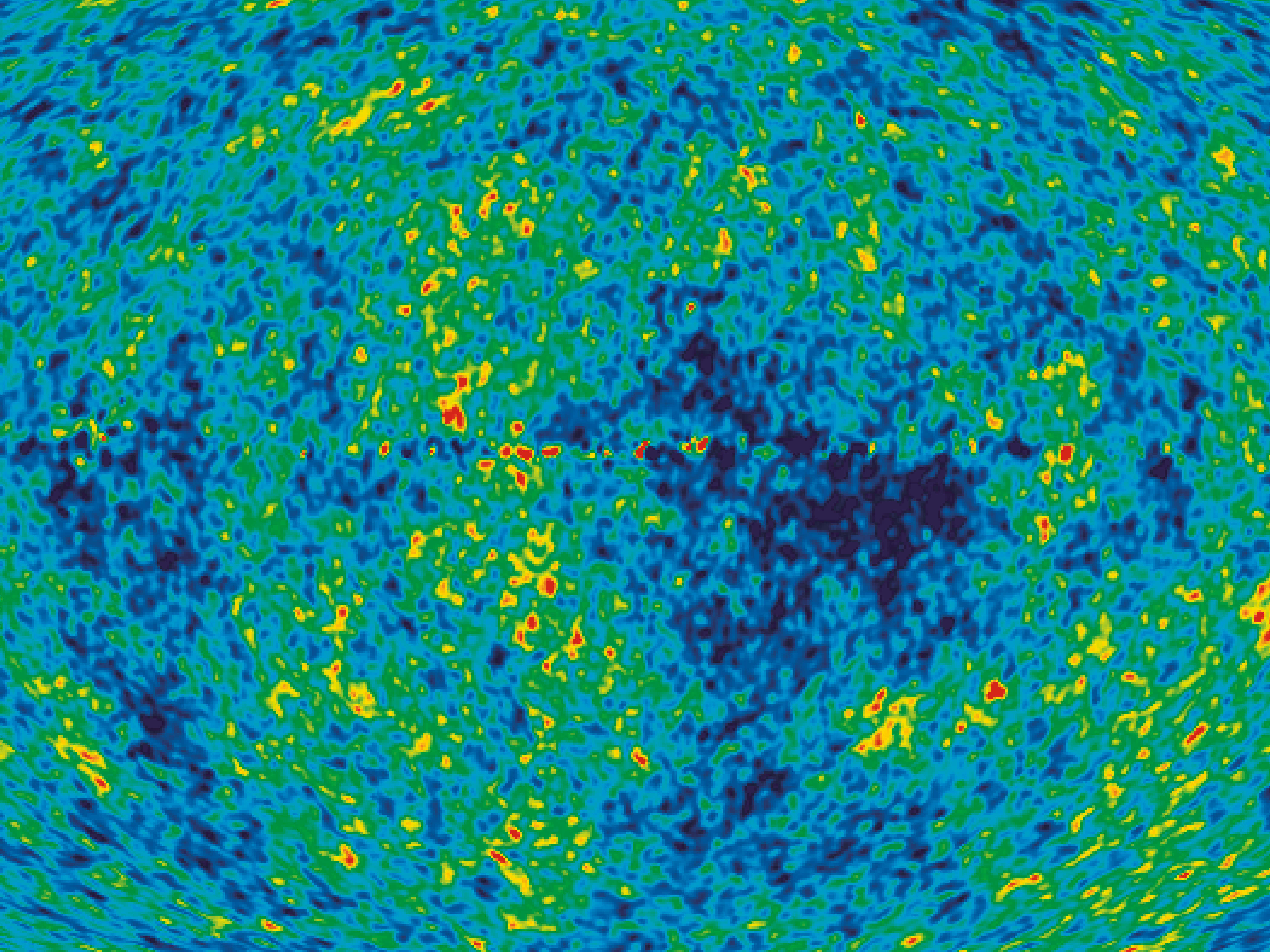
Our Origin

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

Kosmische Miso Soep

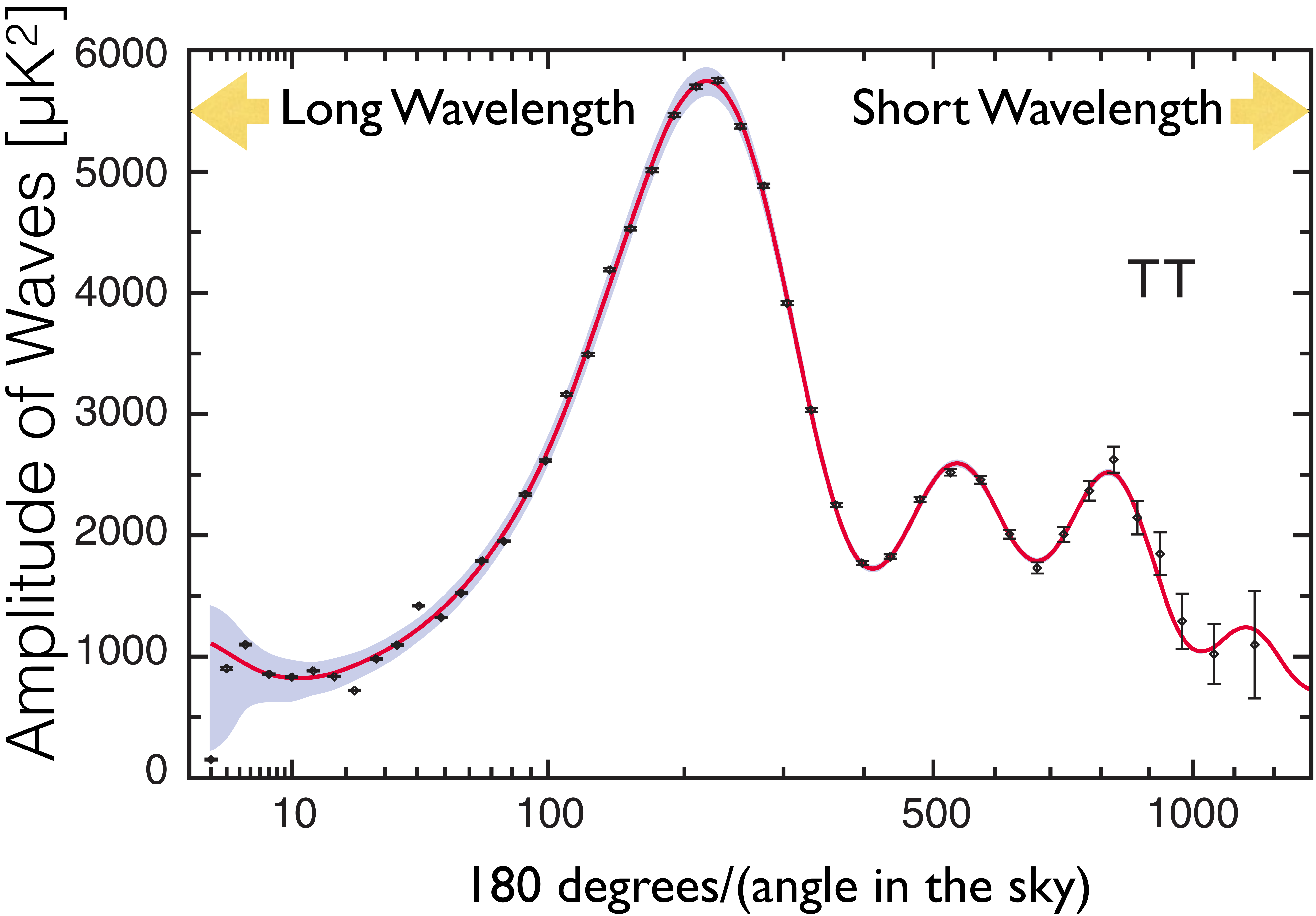
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching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

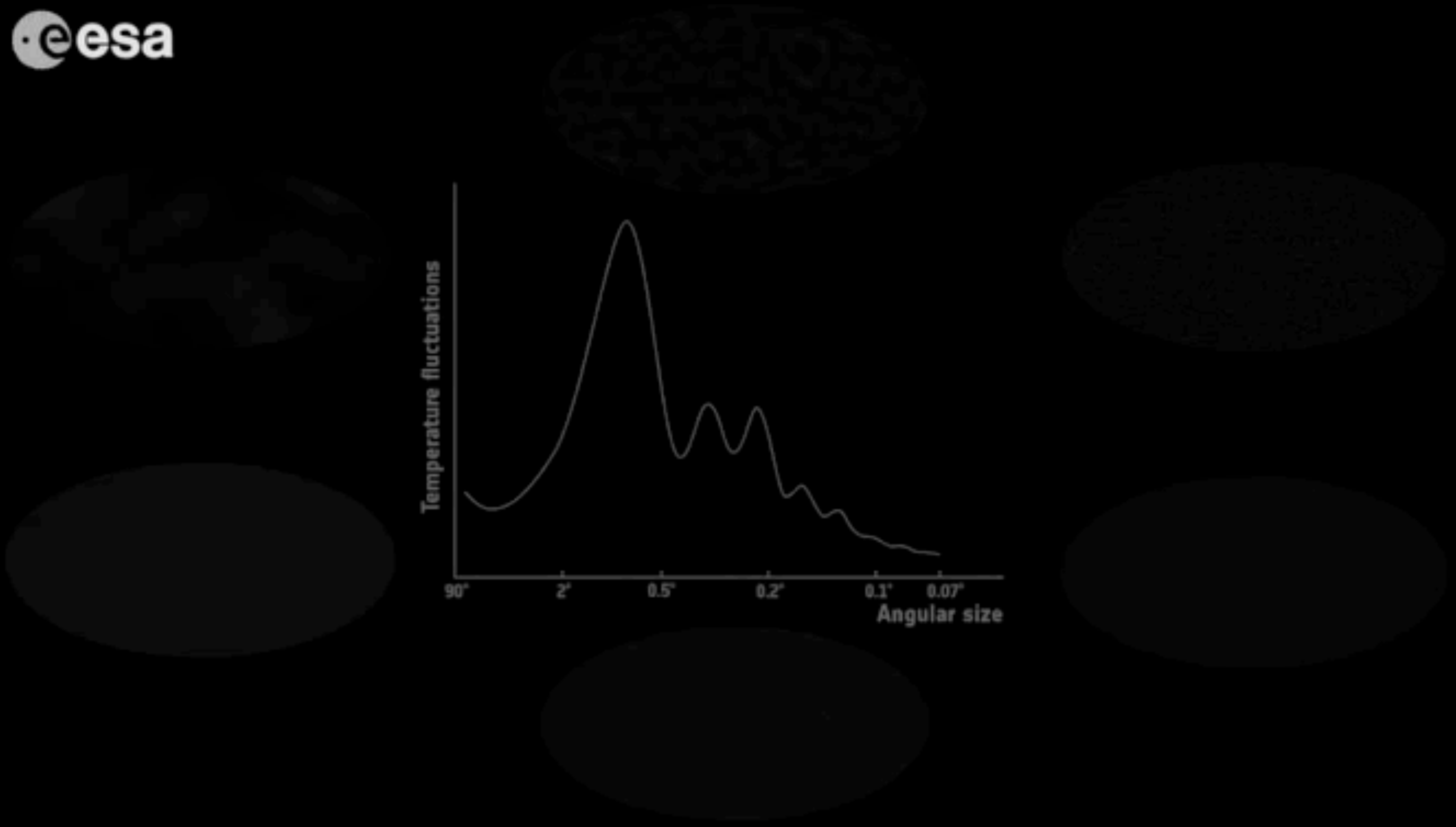




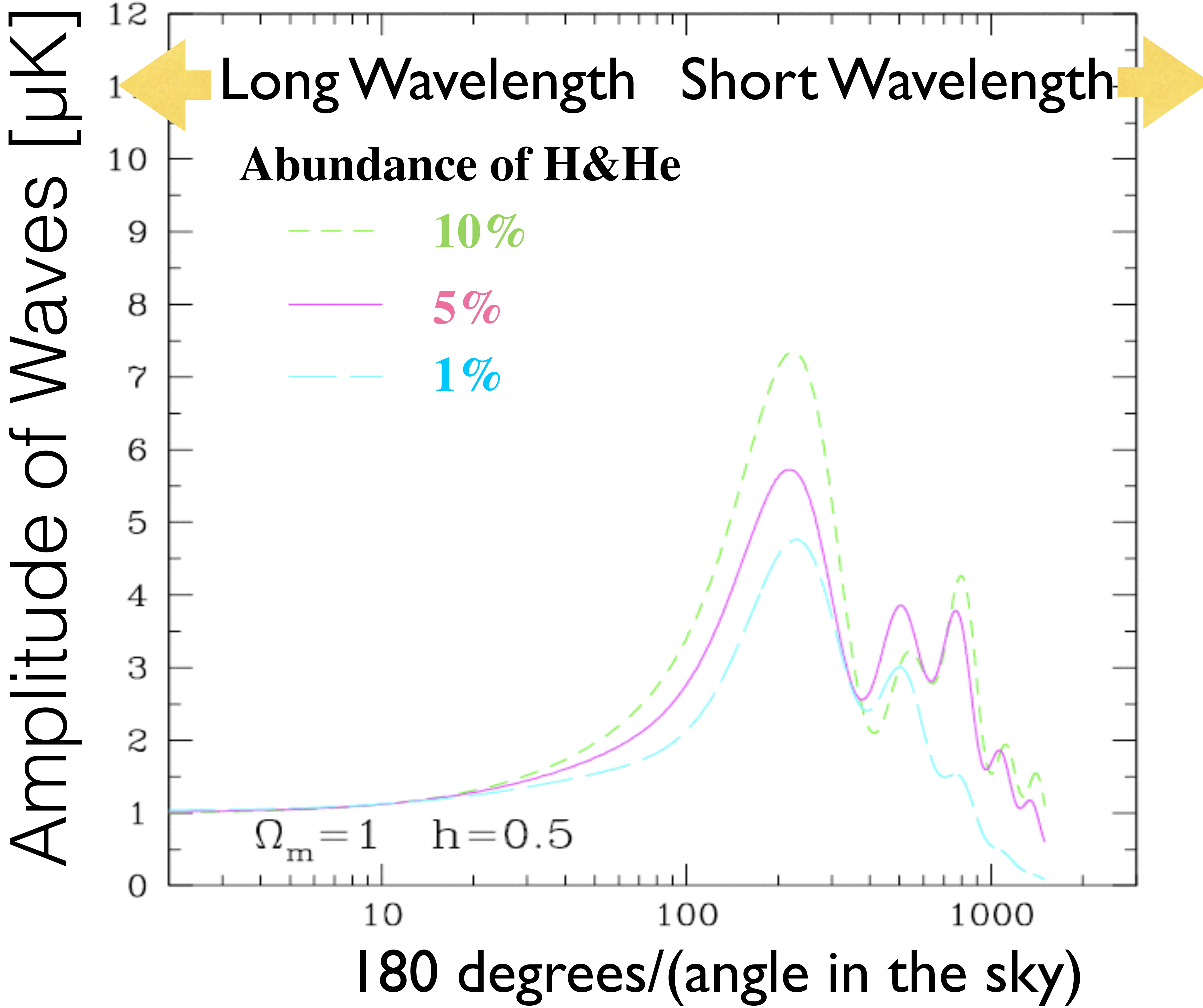
Data Analysis

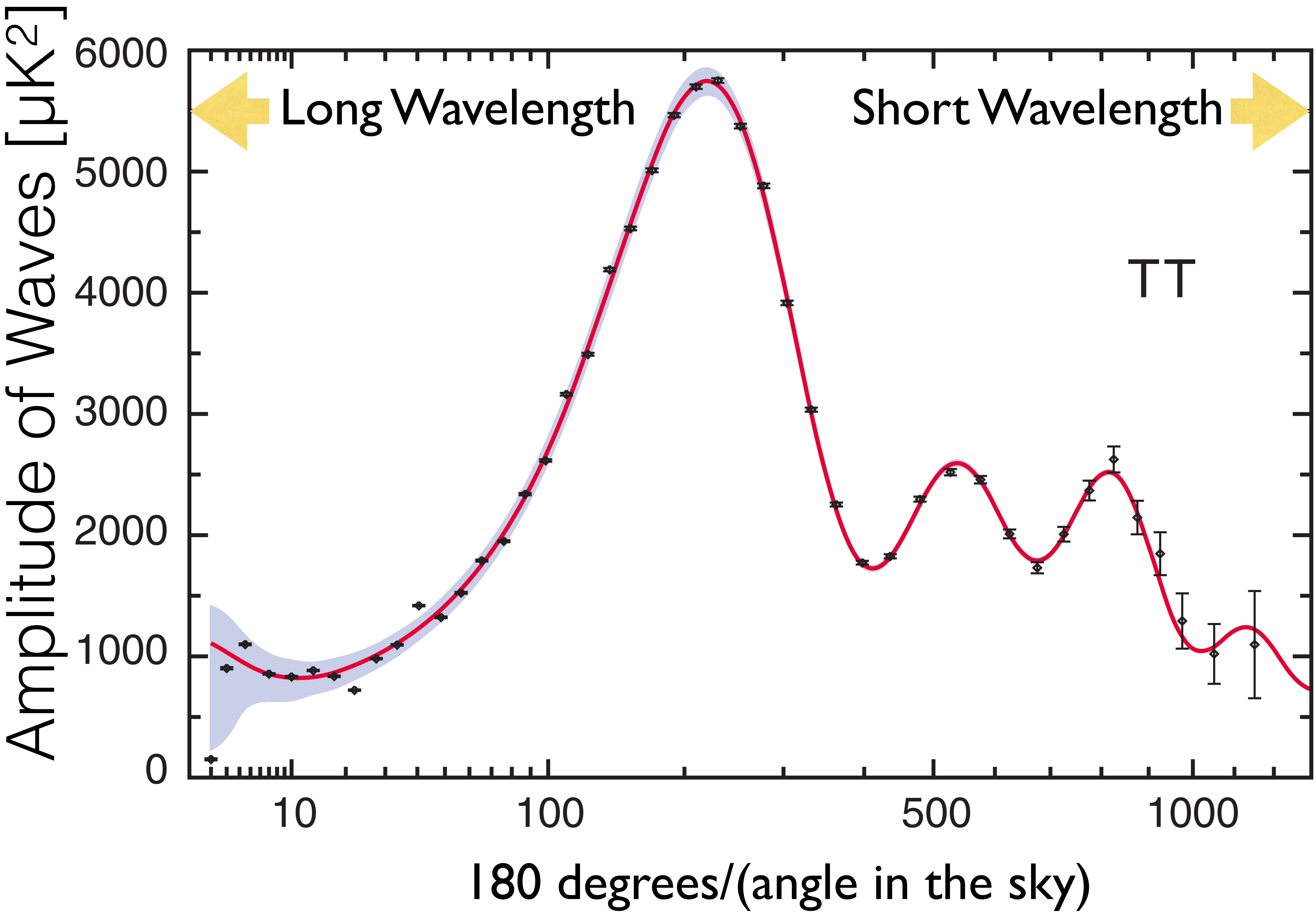
- Decompose temperature fluctuations in the sky into a set of waves with various wavelengths
- Make a diagram showing the strength of each wavelength


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


Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size

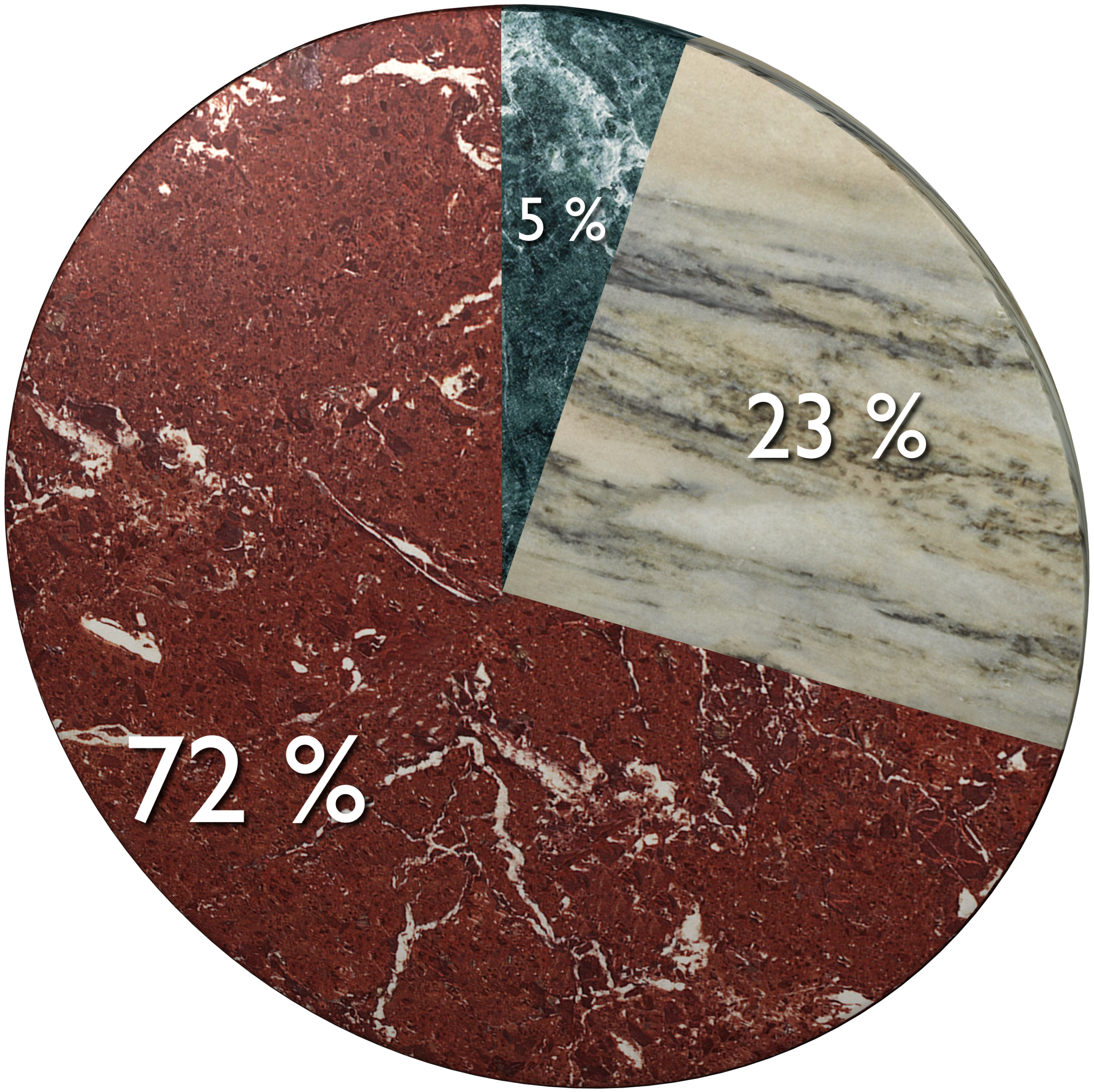
Measuring Abundance of H&He



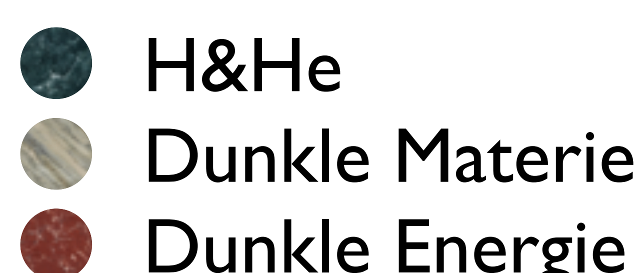


Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
Short Wavelength
TT
10
100
500
1000
180 degrees/(angle in the sky)

Cosmic Pie Chart

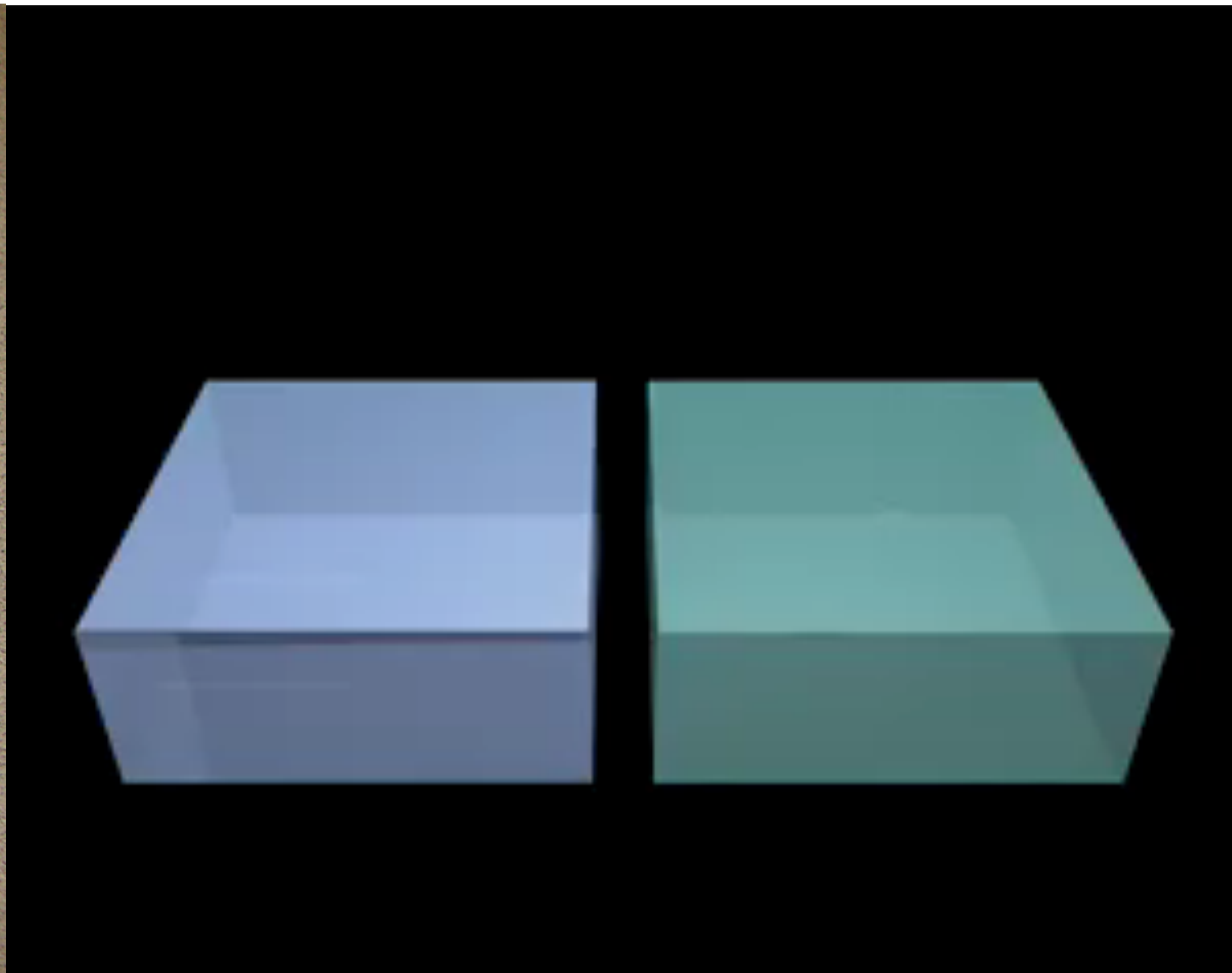


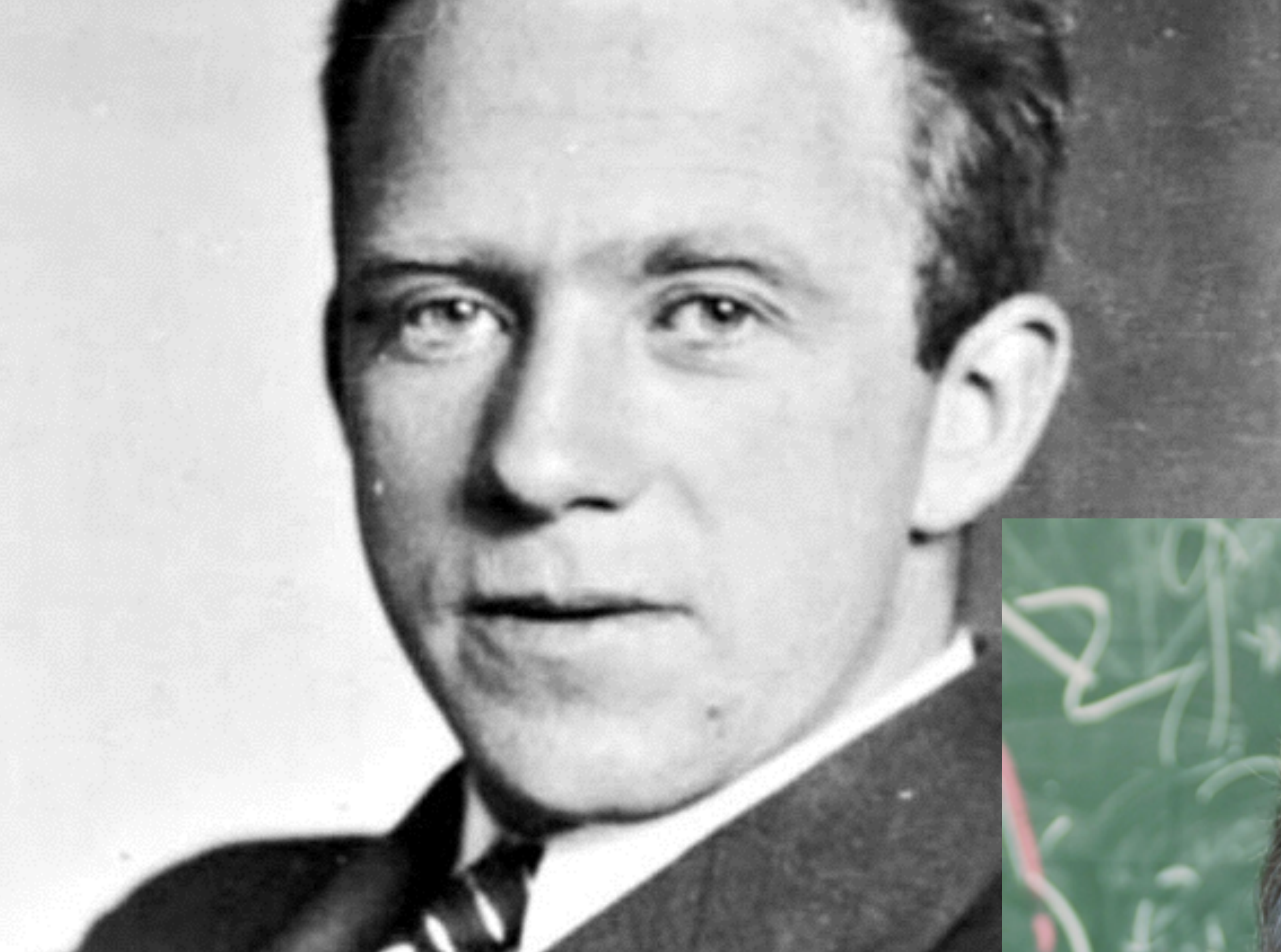
- WMAP determined the abundance of various components in the Universe
- As a result, **we came to realise that we do not understand 95% of our Universe…**



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] ~ 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?

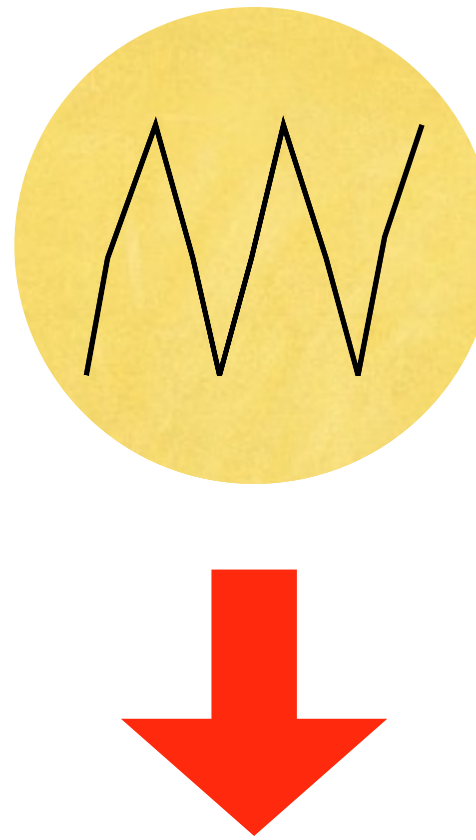
Starobinsky (1980); Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

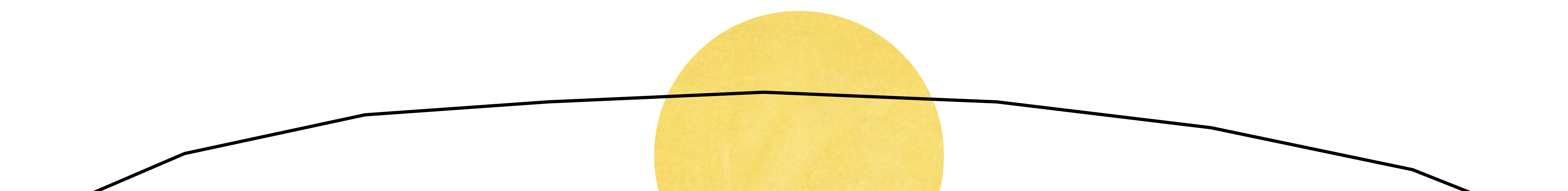
- In a tiny fraction of a second, the size of an atomic nucleus became the size of the Solar System
  - In 10^{-36} second, space was stretched by at least a factor of 10^{26}

Stretching Micro to Macro

Quantum fluctuations on microscopic scales



Inflation!



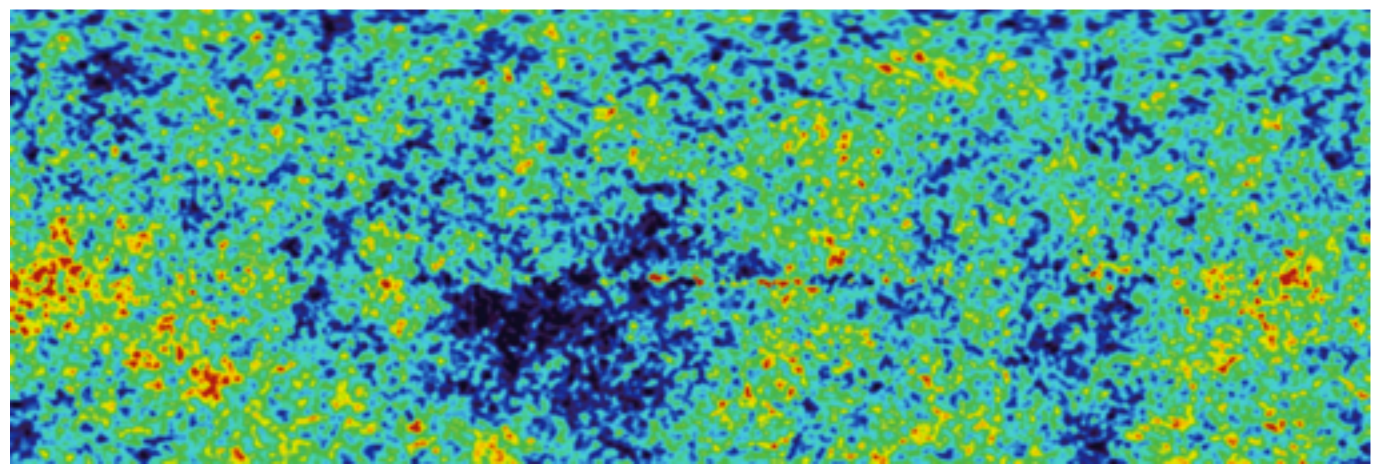
- Quantum fluctuations cease to be quantum
- Become macroscopic, classical fluctuations

Key Predictions of Inflation

ζ

scalar mode

- Fluctuations we observe today in CMB and the matter distribution originate from quantum fluctuations generated during inflation



h_{ij}

tensor mode

- There should also be *ultra-long-wavelength* gravitational waves generated during inflation

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)

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

Heisenberg's Uncertainty Principle

- [Energy you can borrow] x [Time you borrow] = constant

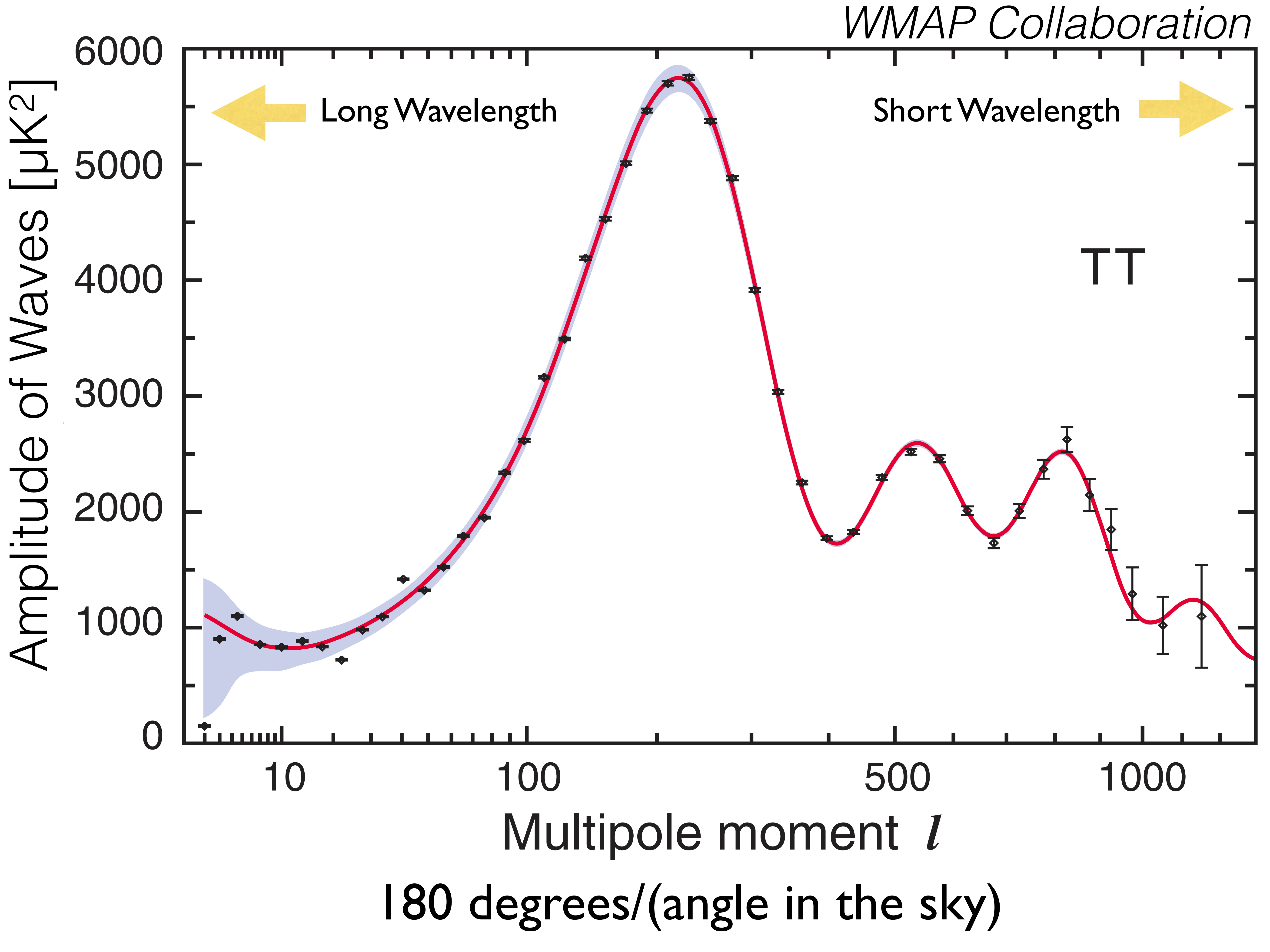
- Suppose that the distance between two points increases in proportion to **a(t)** [which is called the scale factor] by the expansion of the universe

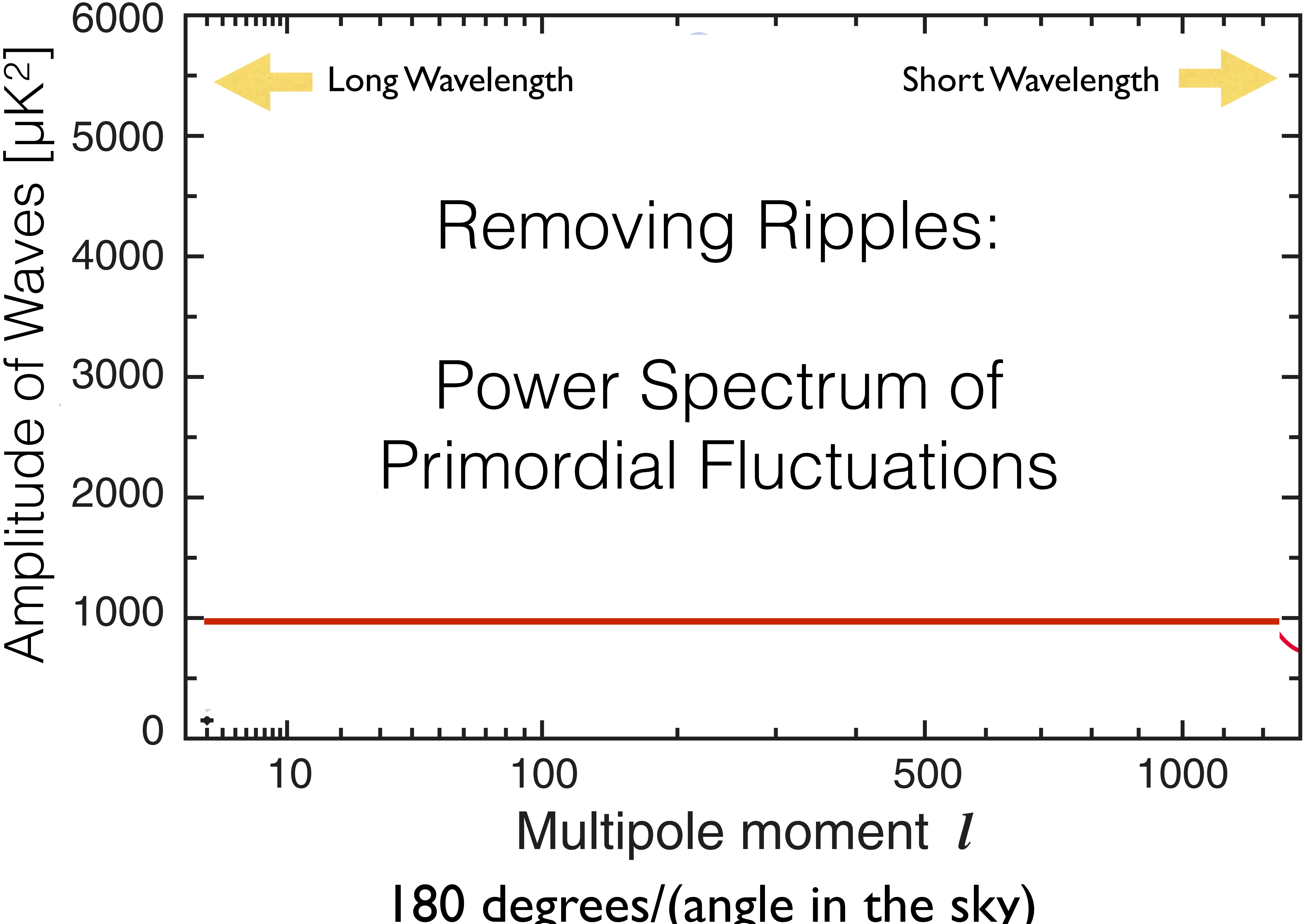
- Define the "expansion rate of the universe" as

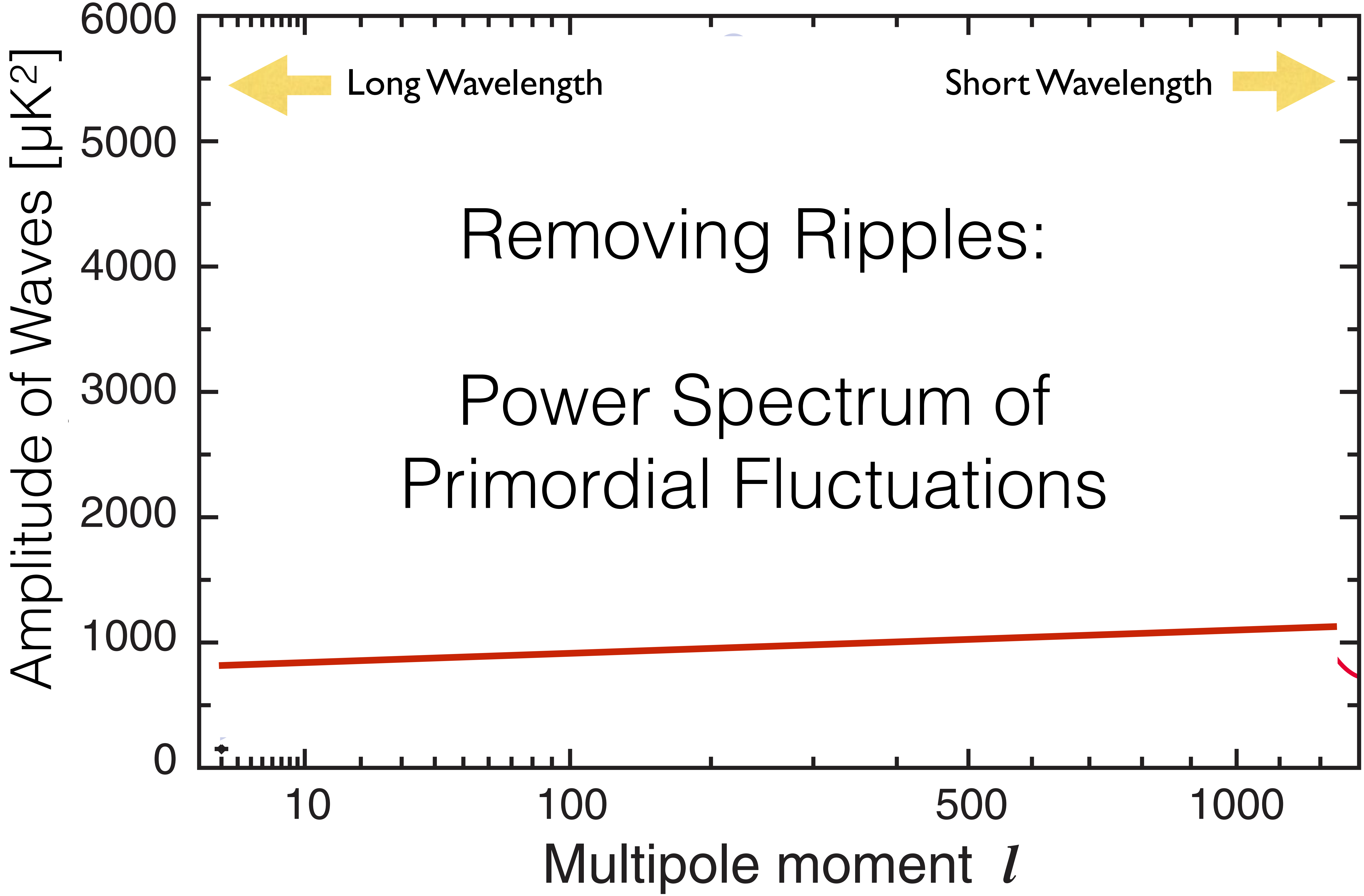
$$H \equiv \frac{\dot{a}}{a}$$ [This has units of 1/time]

Fluctuations are proportional to H

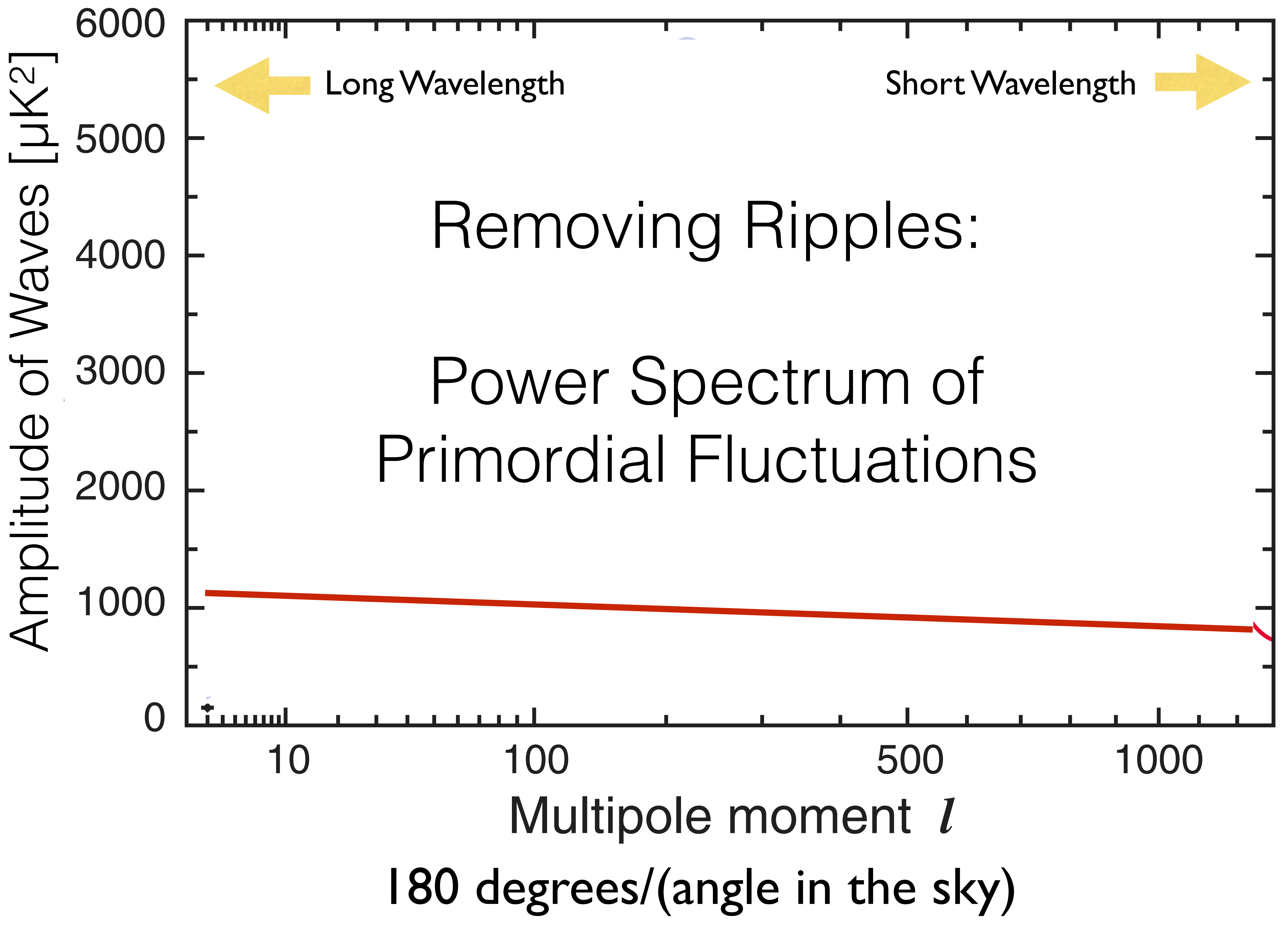
- [Energy you can borrow] x [Time you borrow] = constant
- $H \equiv \frac{\dot{a}}{a}$ [This has units of 1/time]
- Then, **both ζ and h_{ij} are proportional to H**
- Inflation occurs in 10^{-36} second - this is such a short period of time that you can borrow a lot of energy! **H during inflation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


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

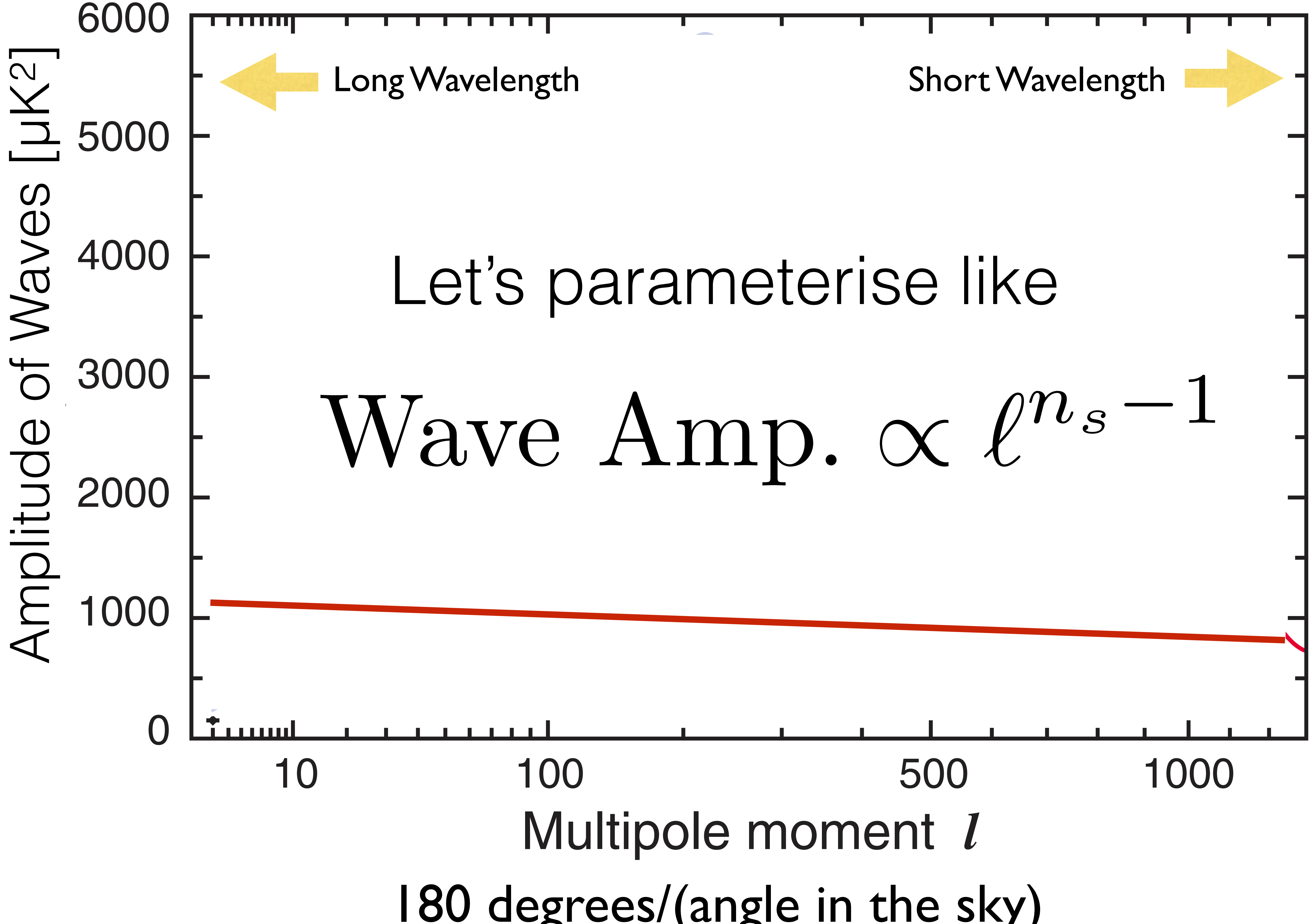

6000
5000
4000
3000
2000
1000
0
Amplitude of Waves [μK²]
Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

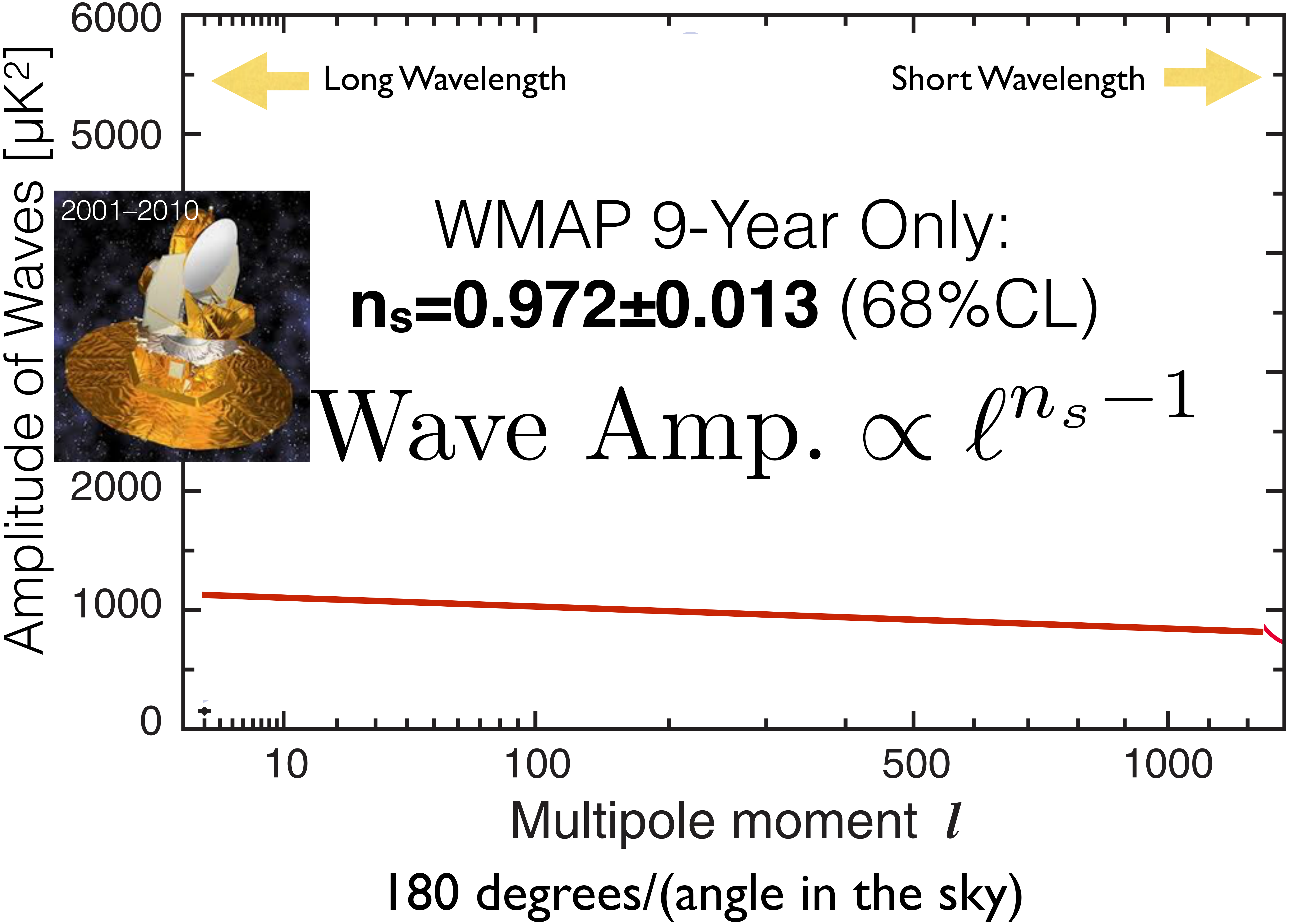


180 degrees/(angle in the sky)

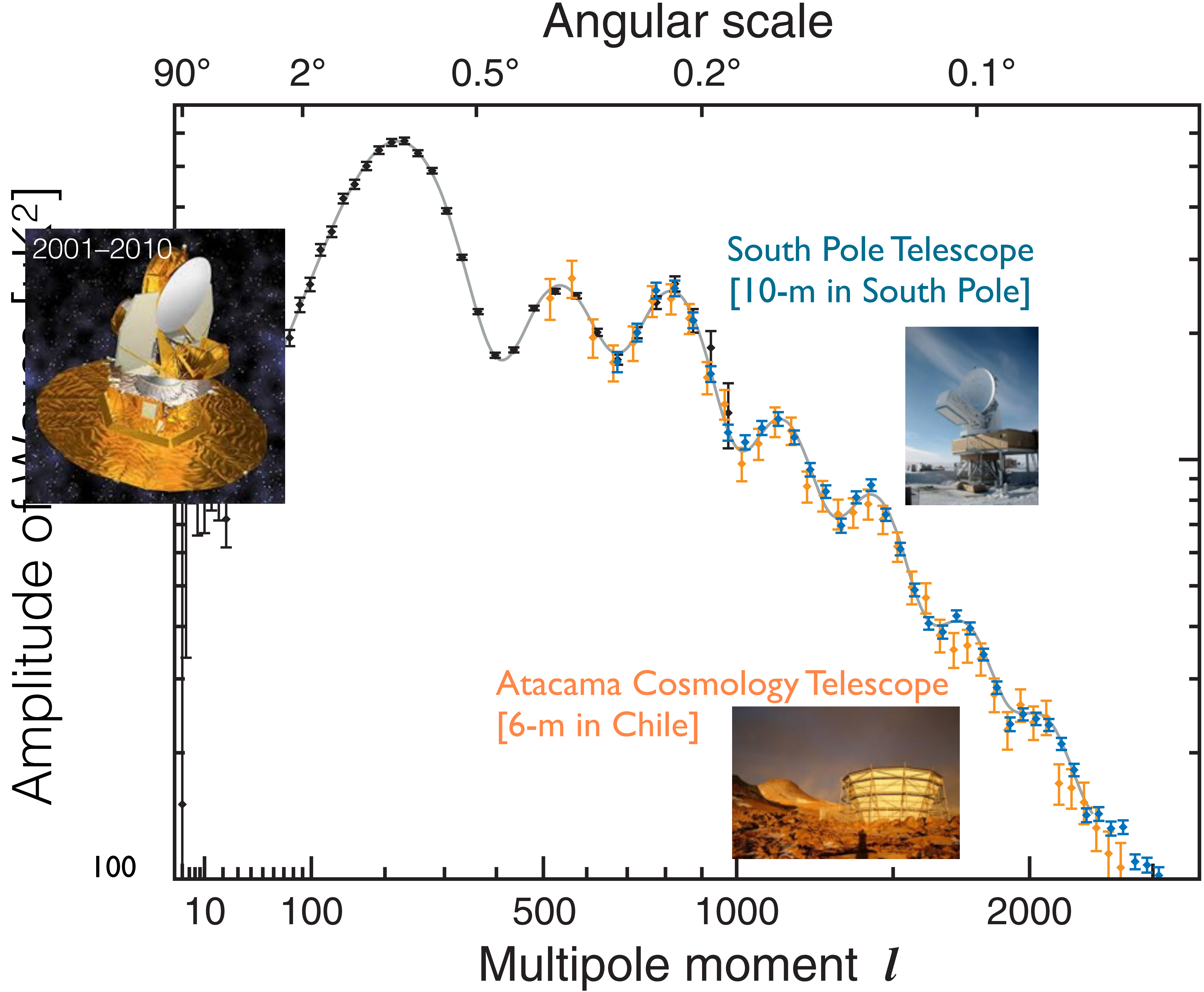


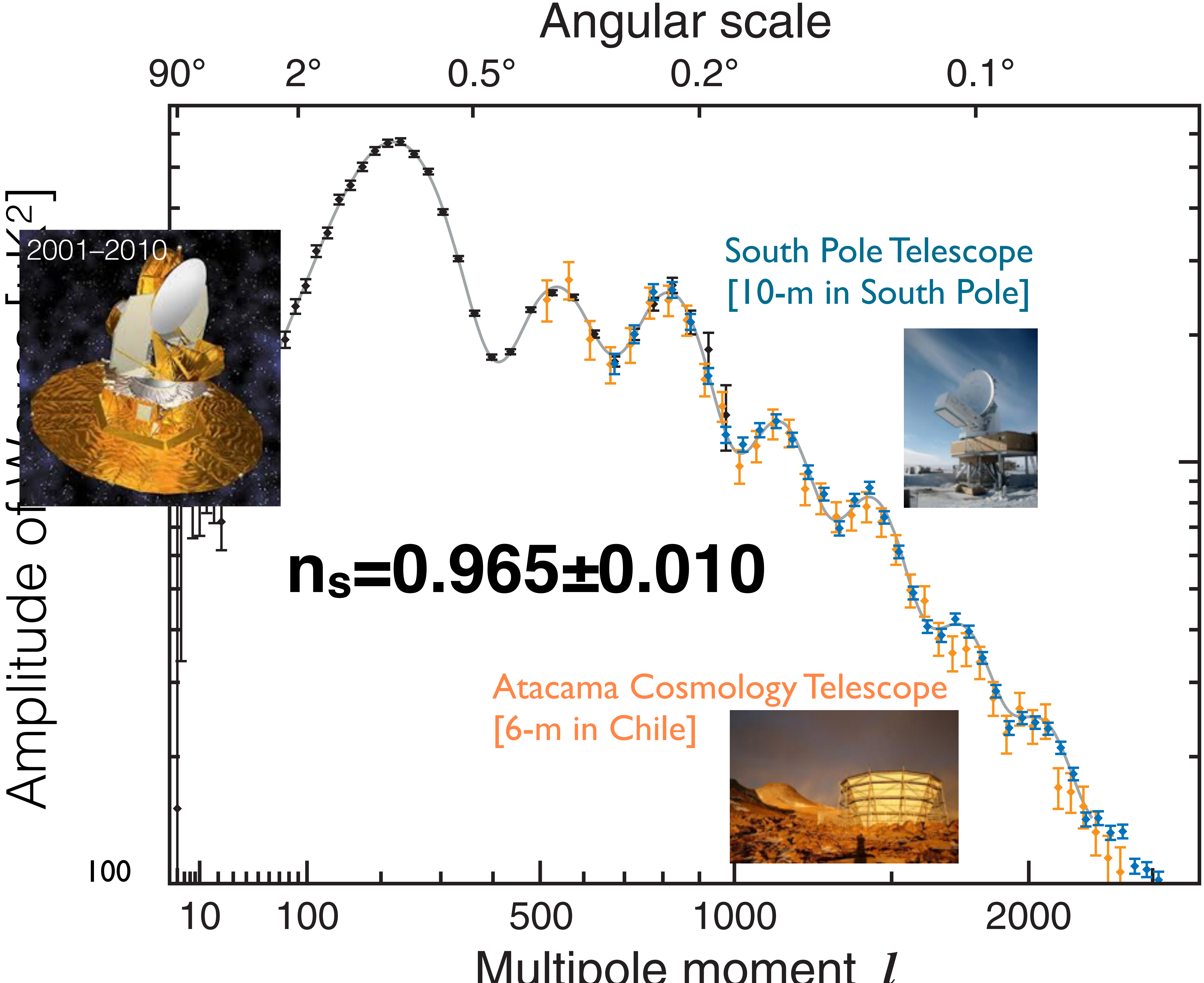
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)


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

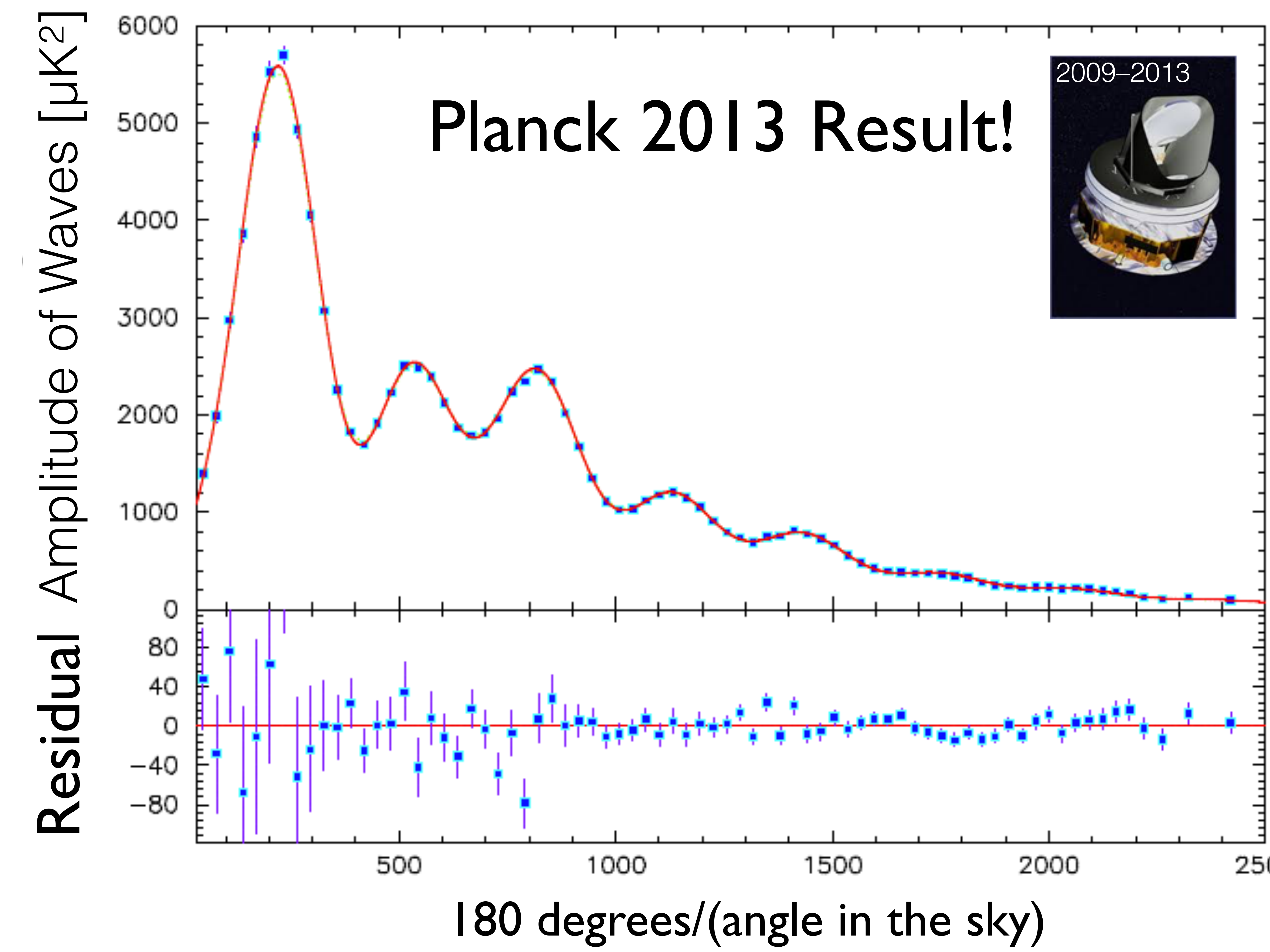


Amplitude of Waves [μK²]
6000
5000
2000
1000
0
Long Wavelength
Short Wavelength
2001–2010
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
$\text{Wave Amp.} \propto \ell^{n_s - 1}$
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

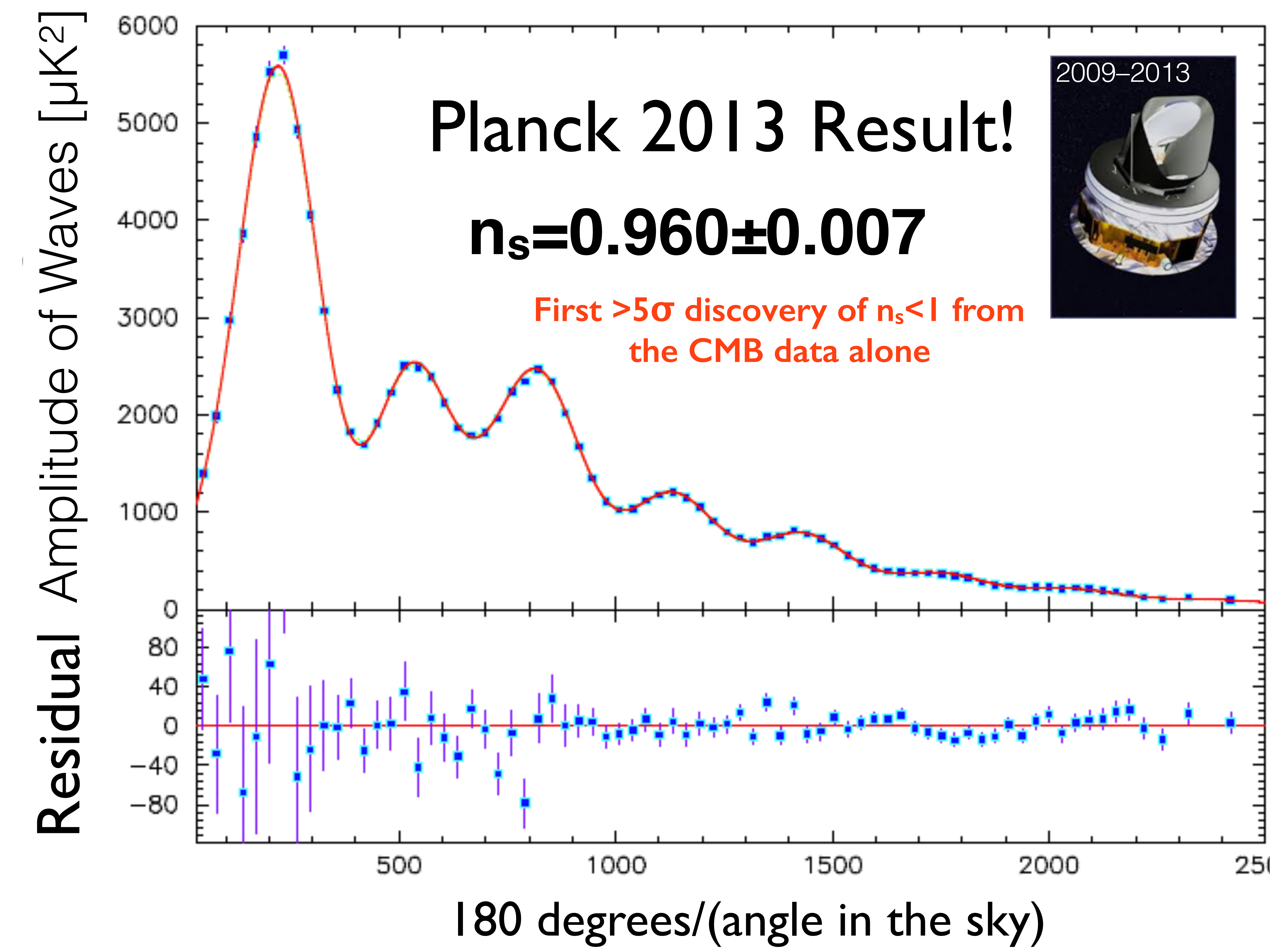

Angular scale
90°
2°
0.5°
0.2°
0.1°
2001–2010
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment l



Angular scale
90°
2°
0.5°
0.2°
0.1°
Amplitude of
2001–2010
South Pole Telescope
[10-m in South Pole]
ns=0.965±0.010
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment l



Planck 2013 Result!
2009–2013
Amplitude of Waves [μK^2]
Residual
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
250
180 degrees/(angle in the sky)



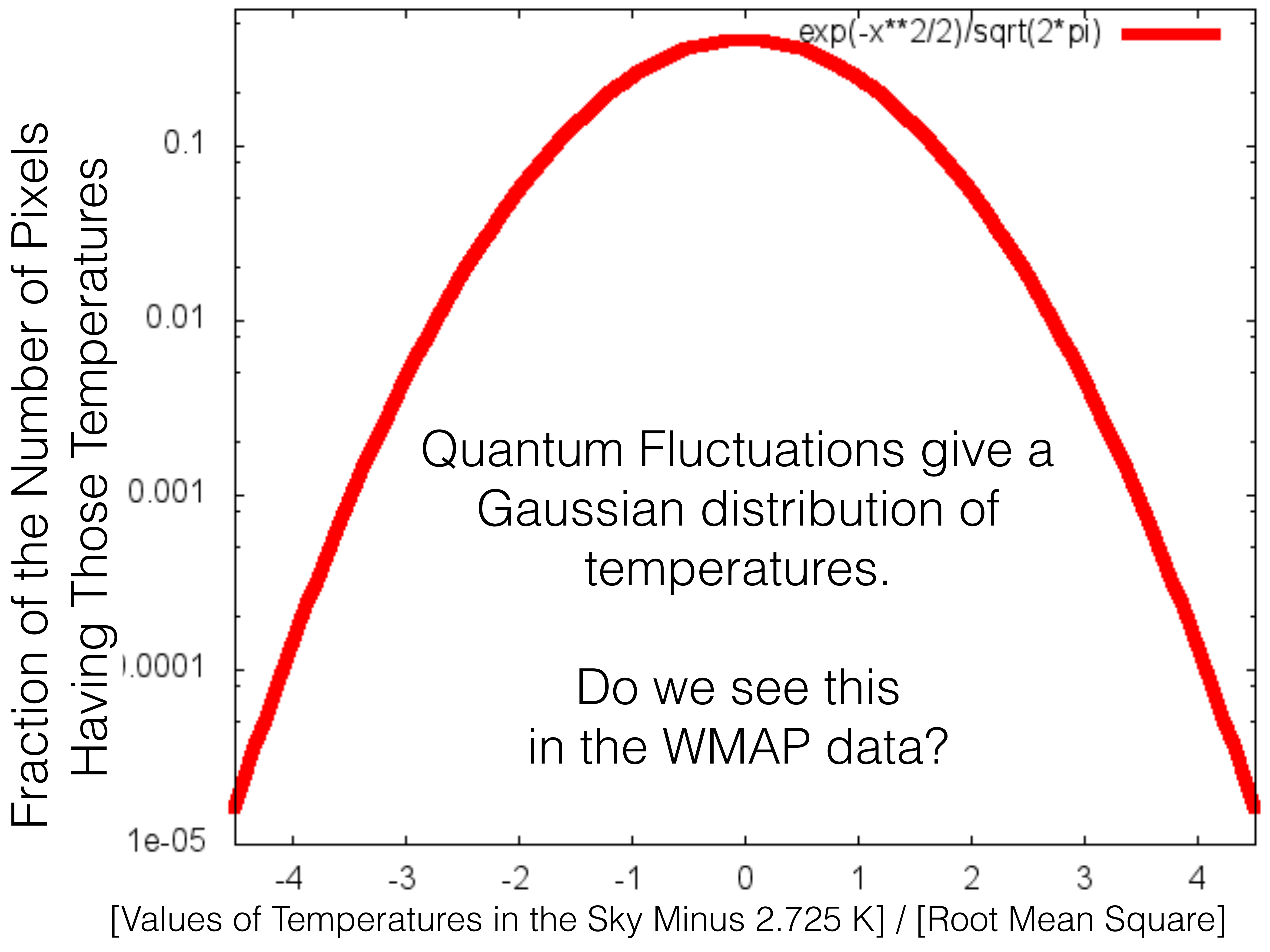
Planck 2013 Result!
n_s=0.960±0.007
First >5σ discovery of n_s<1 from the CMB data alone
2009–2013
Amplitude of Waves [μK^2]
Residual
180 degrees/(angle in the sky)
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000

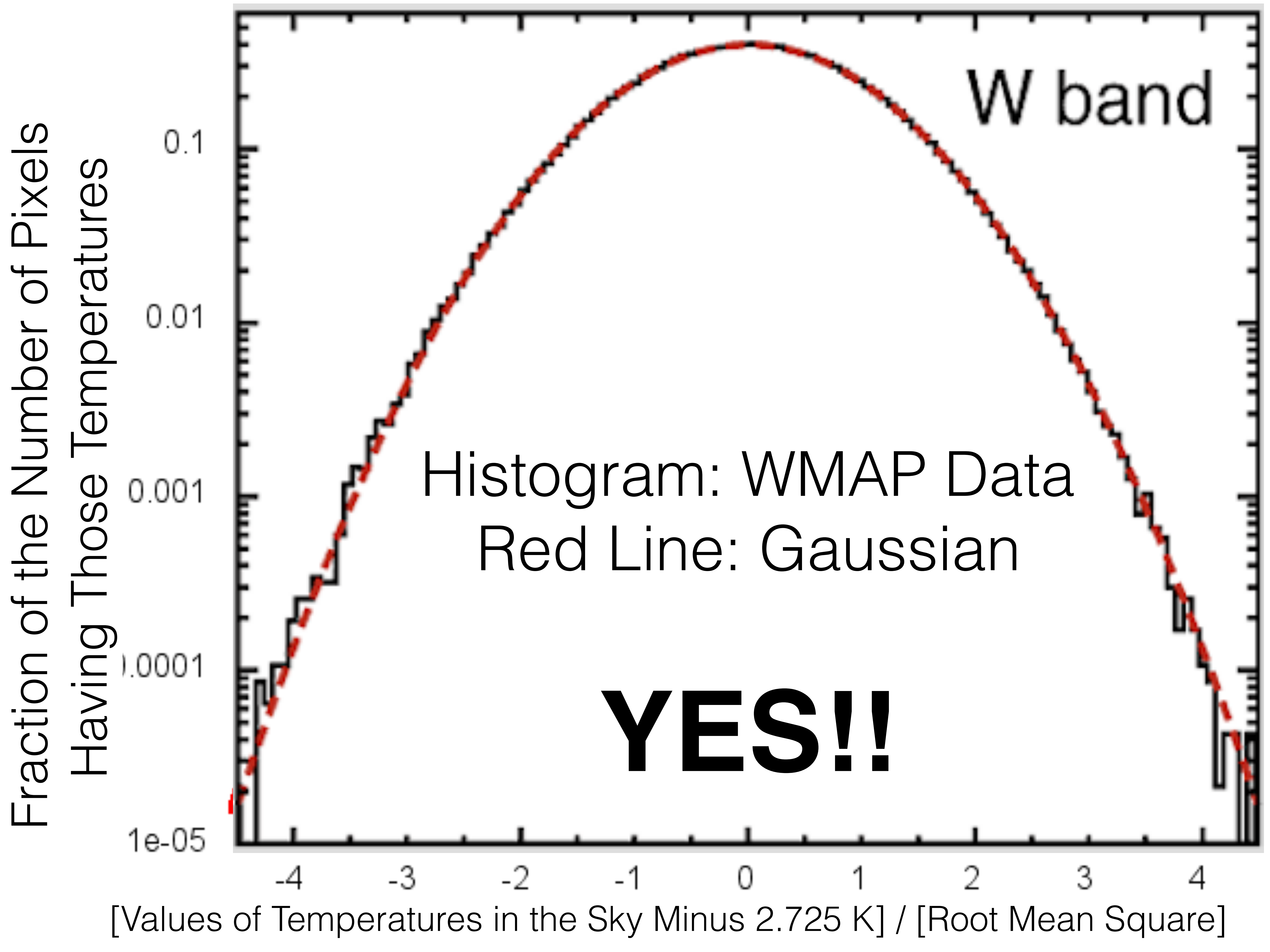
Predicted in 1981. Finally discovered in 2013 by WMAP and Planck

- 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 first discovered and $n_s \sim 1$ (to within 30%) was indicated

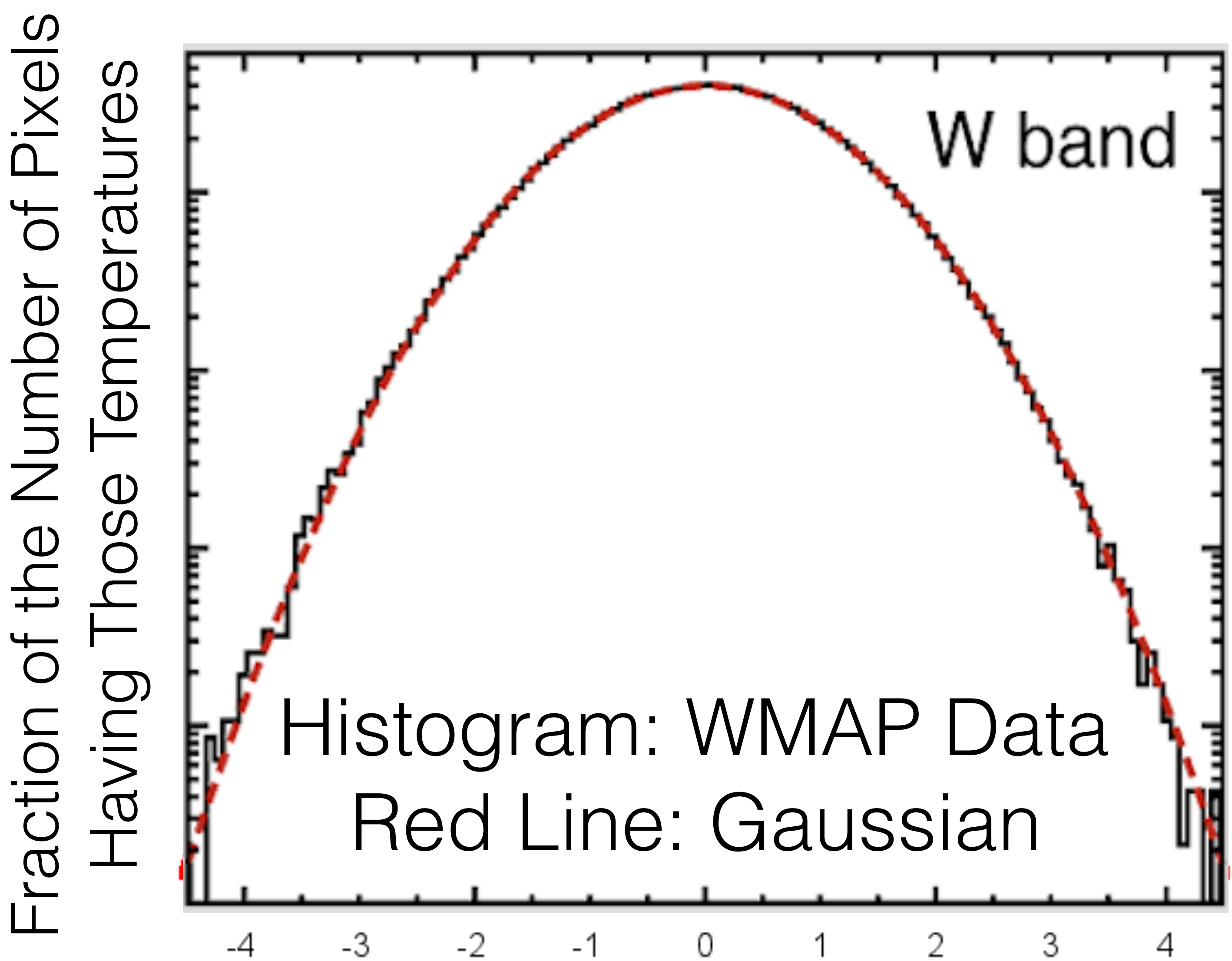
Slava Mukhanov said in his 1981 paper that n_s should be less than 1

How do we know that primordial fluctuations were of *quantum mechanical origin*?


exp(-x**2/2)/sqrt(2*pi)
0.1
0.01
0.001
0.0001
1e-05
-4
-3
-2
-1
0
1
2
3
4
Fraction of the Number of Pixels
Having Those Temperatures
[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?


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

Testing Gaussianity



[Values of Temperatures in the Sky Minus 2.725 K]/ [Root Mean Square]

Since a Gauss distribution is symmetric, it must yield a vanishing **3-point function**

$$\langle \delta T^3 \rangle \equiv \int_{-\infty}^{\infty} d\delta T \; P(\delta T)\delta T^3$$

More specifically, we measure this using temperatures at three different locations and average:

$$\langle \delta T(\hat{n}_1)\delta T(\hat{n}_2)\delta T(\hat{n}_3) \rangle$$

Non-Gaussianity:

A Powerful Test of Quantum Fluctuations

- The WMAP data show that the distribution of temperature fluctuations of CMB is **very precisely** Gaussian
  - with an upper bound on a deviation of **0.2%**
- With improved data provided by the Planck mission, the upper bound is now **0.03%**

CMB Research: Next Frontier

Primordial Gravitational Waves

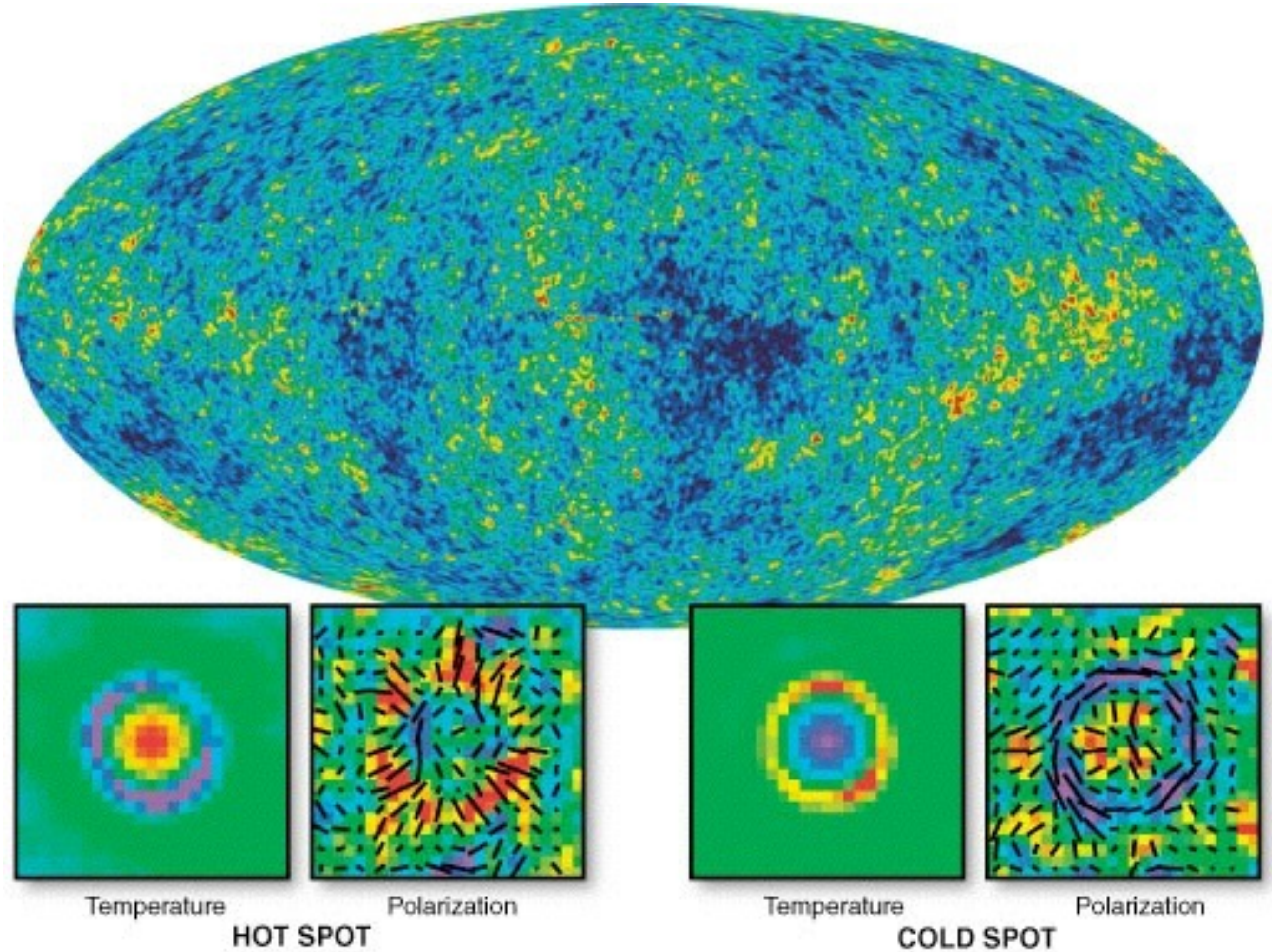
Extraordinary claims require extraordinary evidence. The same quantum fluctuations could also generate gravitational waves, and we wish to find them

Tensor-to-scalar Ratio

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

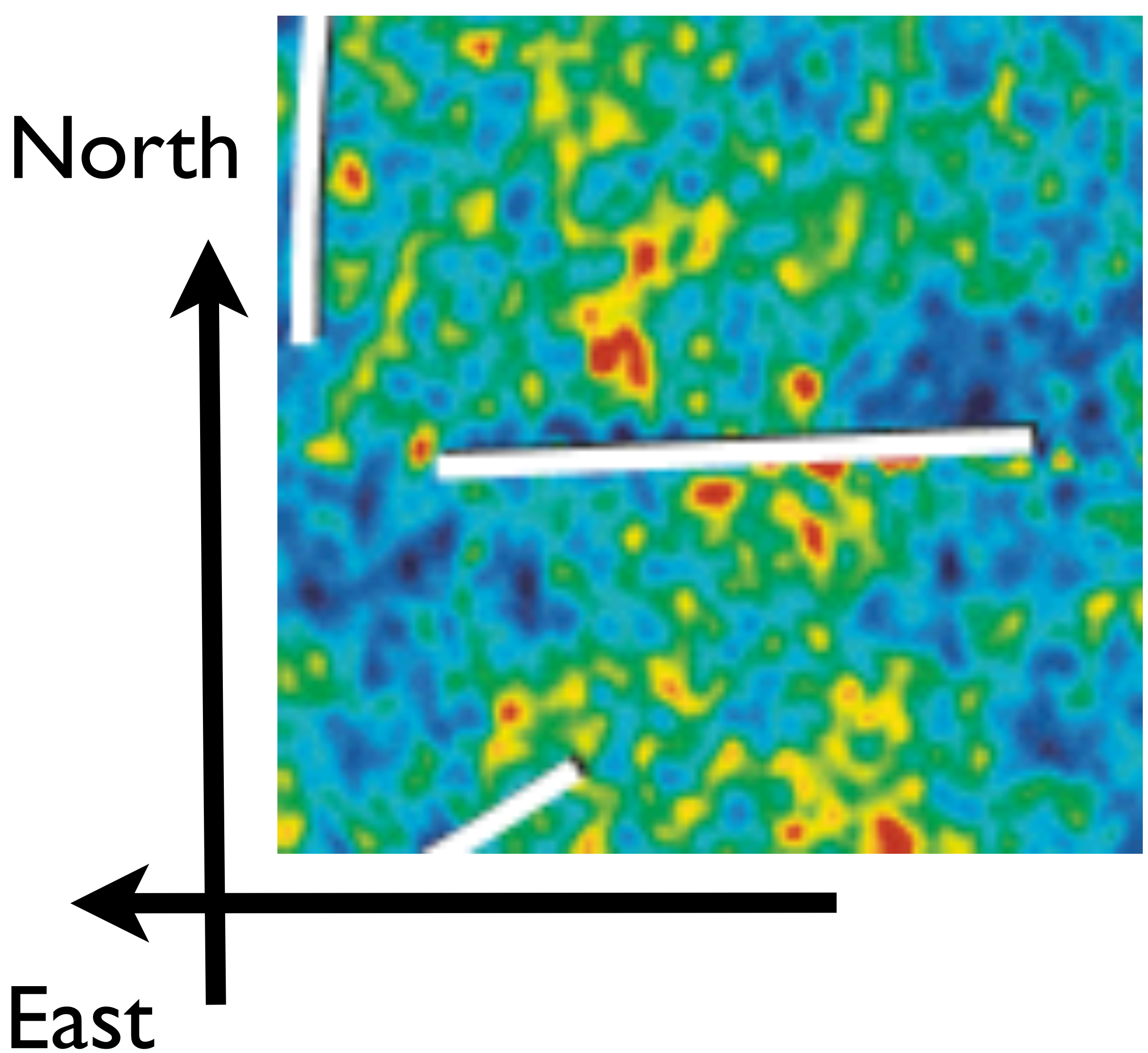
- We really want to find this quantity! **The current upper bound: r<0.1** [WMAP & Planck]

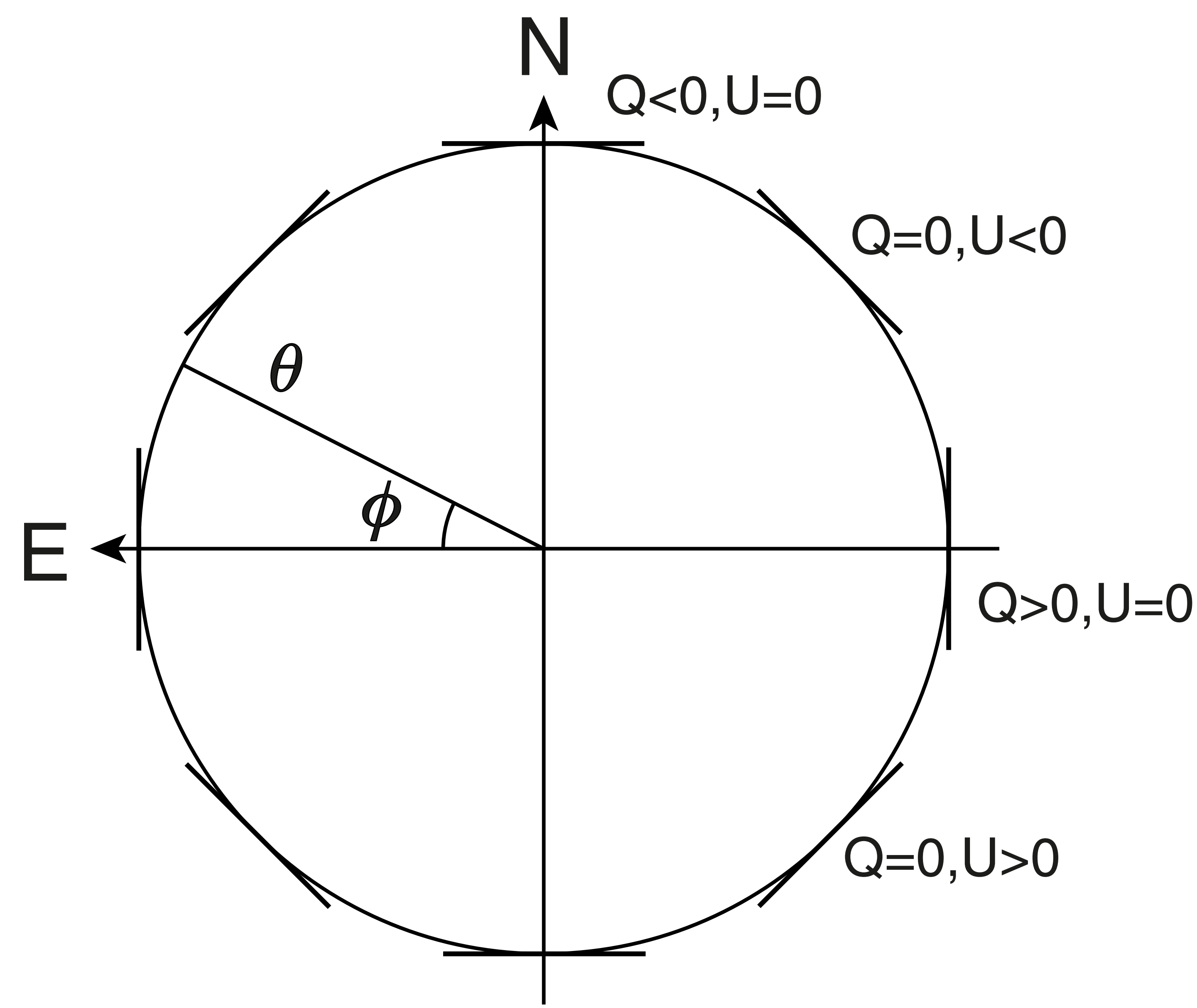
CMB Polarisation



- CMB is [weakly] polarised!

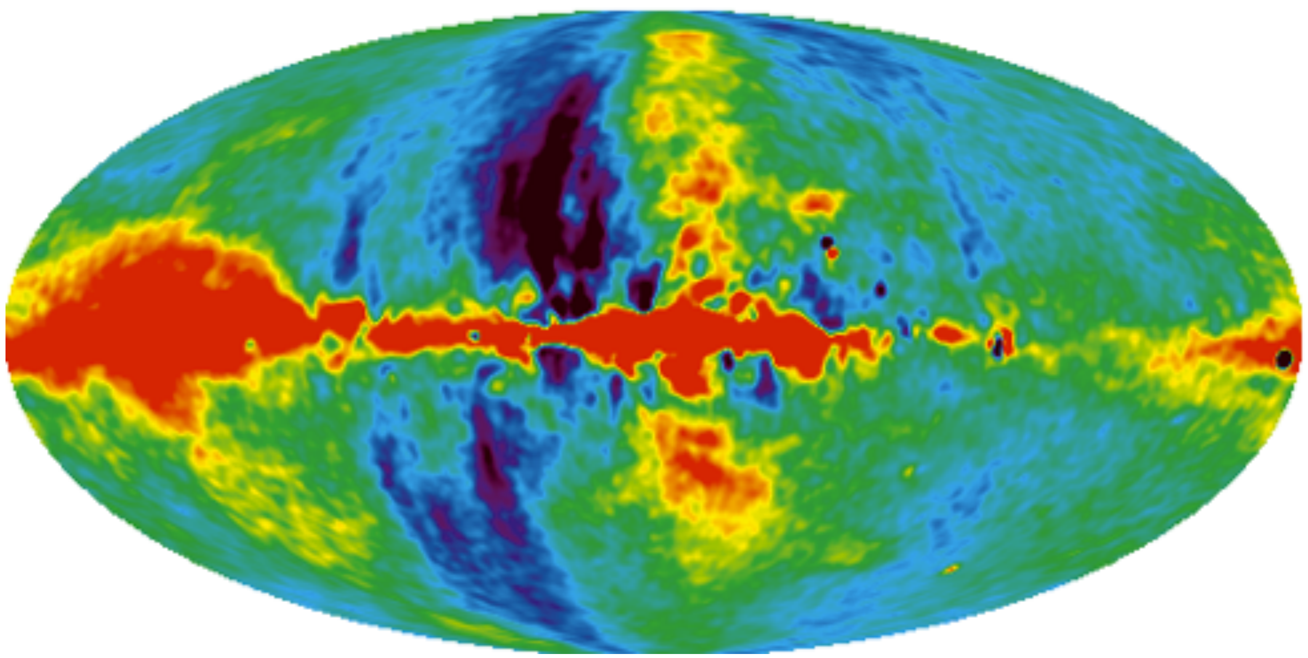
Stokes Parameters



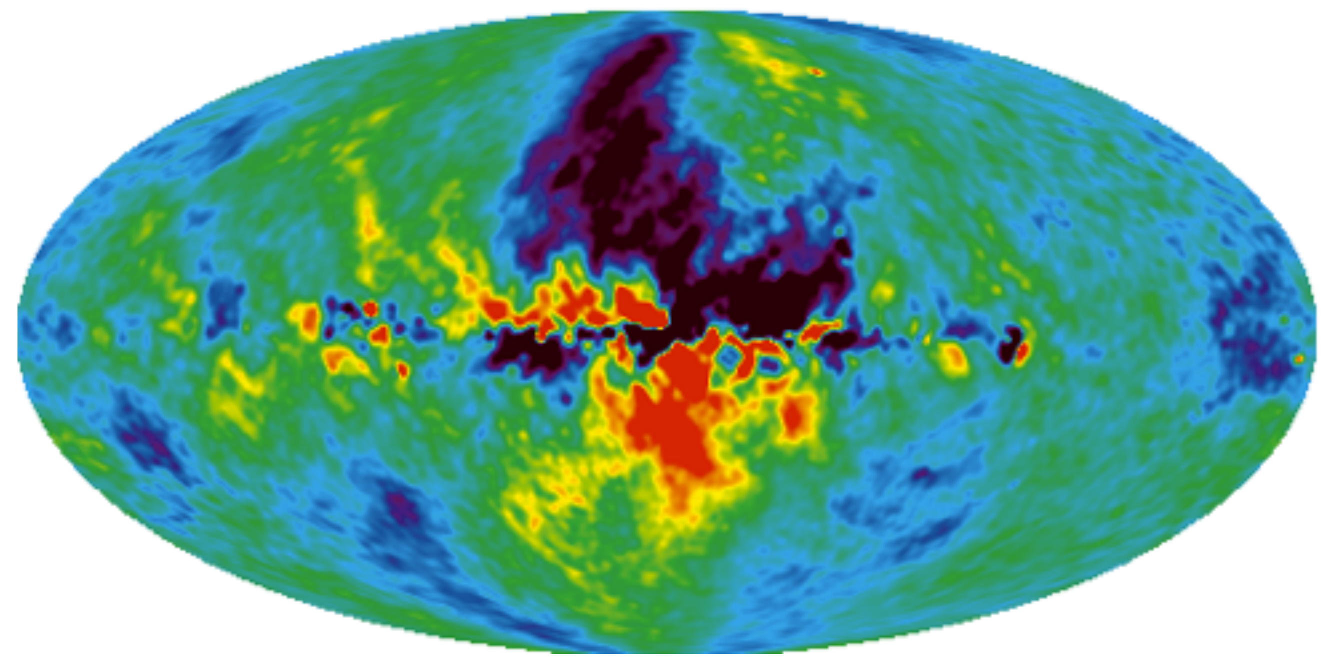


WMAP Collaboration

23 GHz



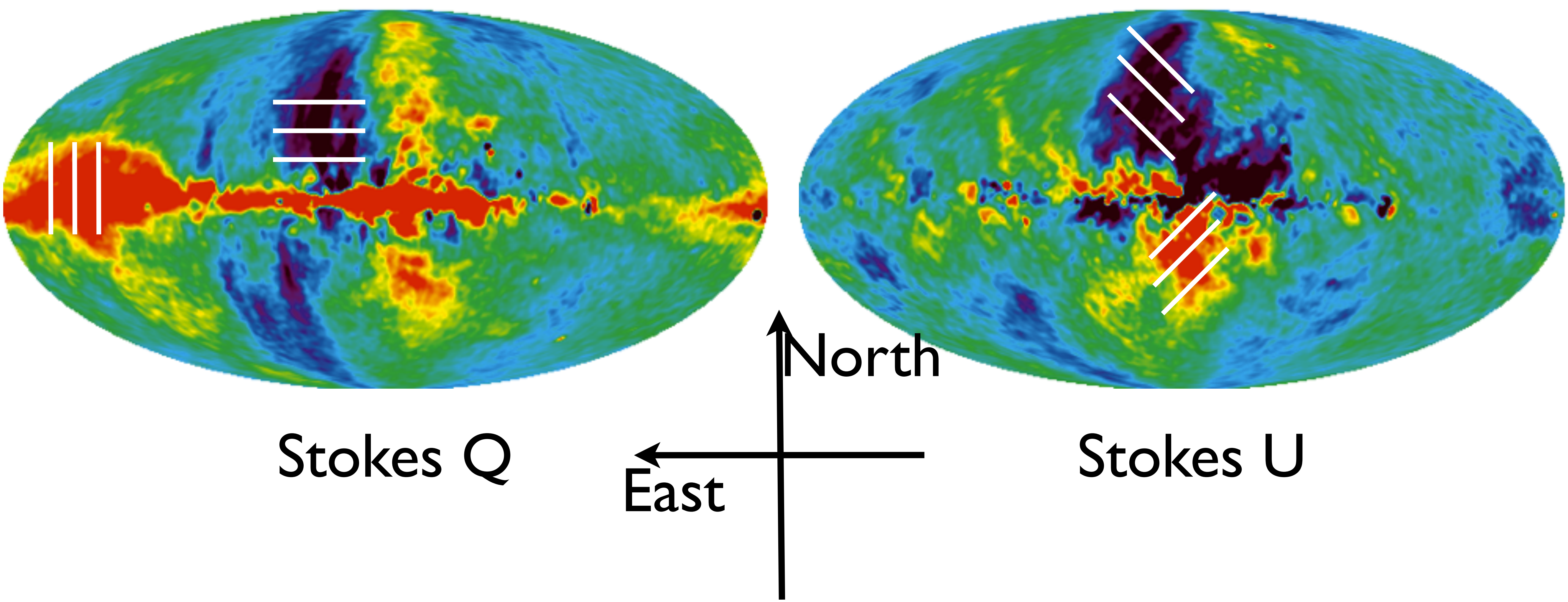
Stokes Q



Stokes U

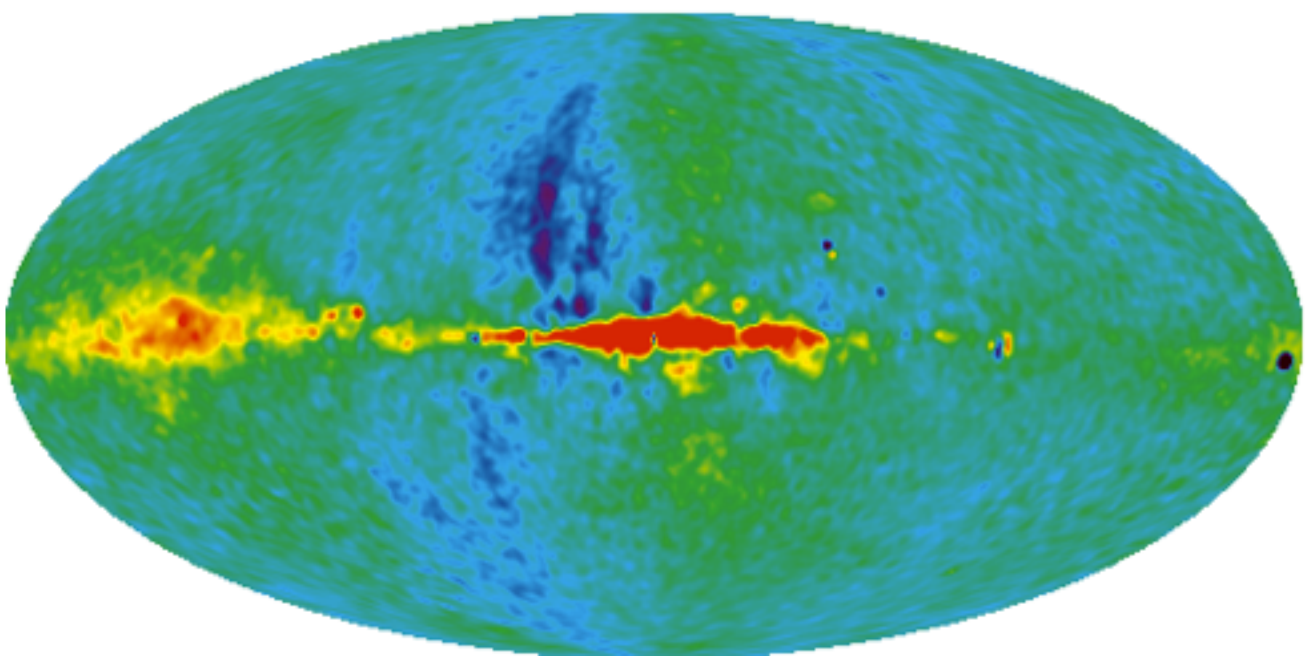
WMAP Collaboration

23 GHz [13 mm]

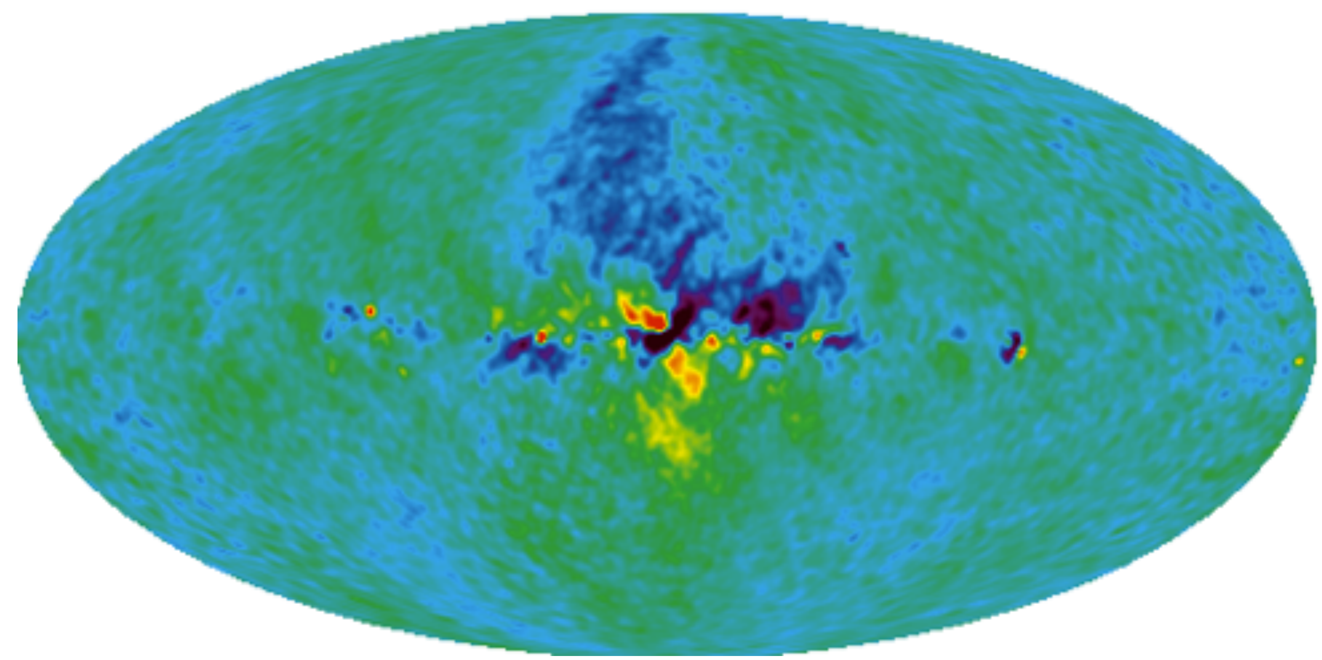


WMAP Collaboration

33 GHz [9.1 mm]



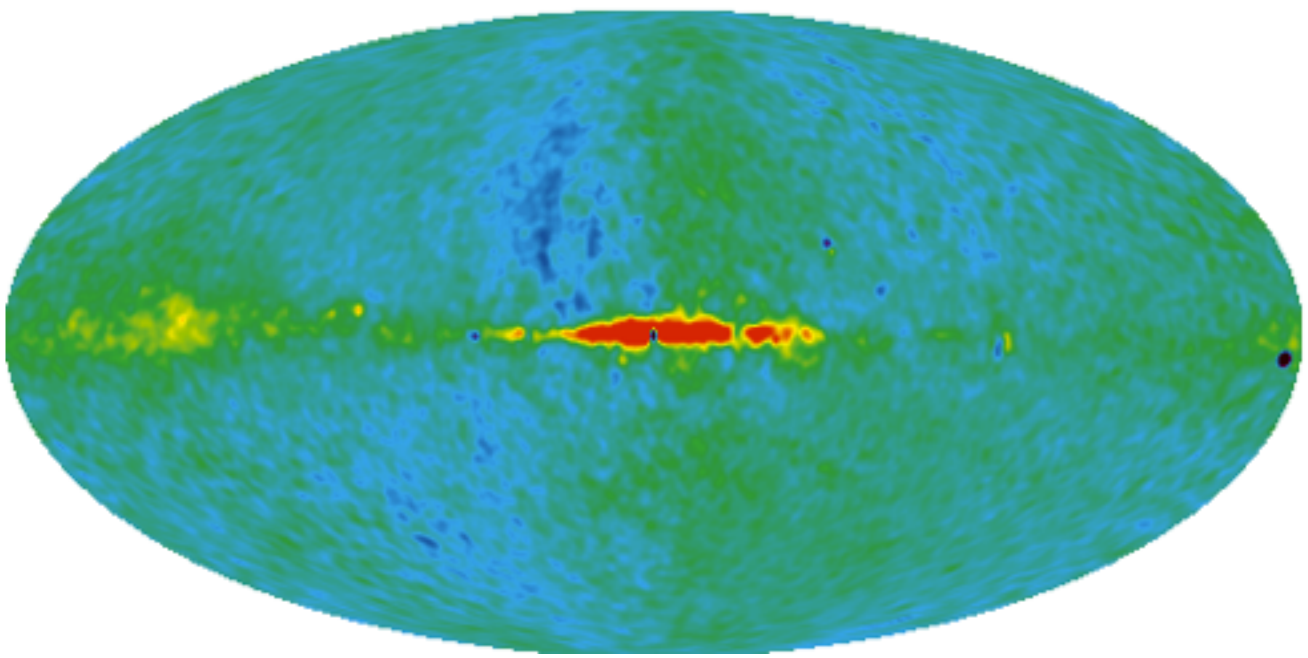
Stokes Q



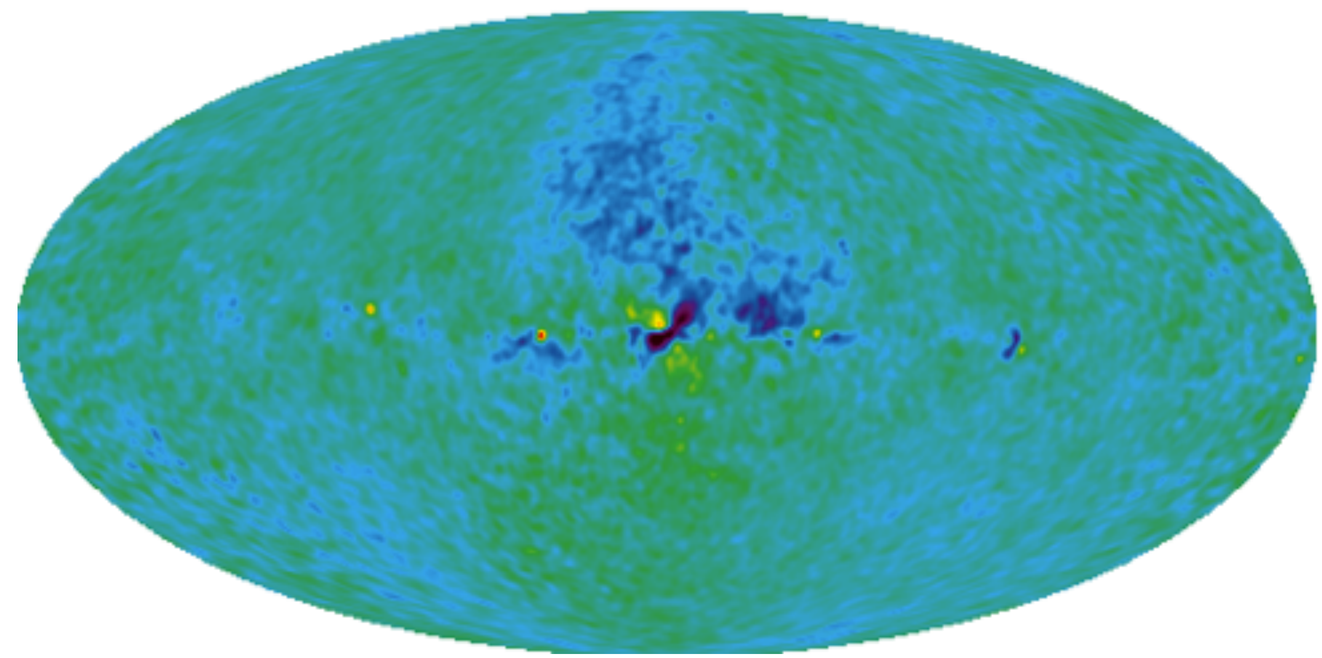
Stokes U

WMAP Collaboration

41 GHz [7.3 mm]



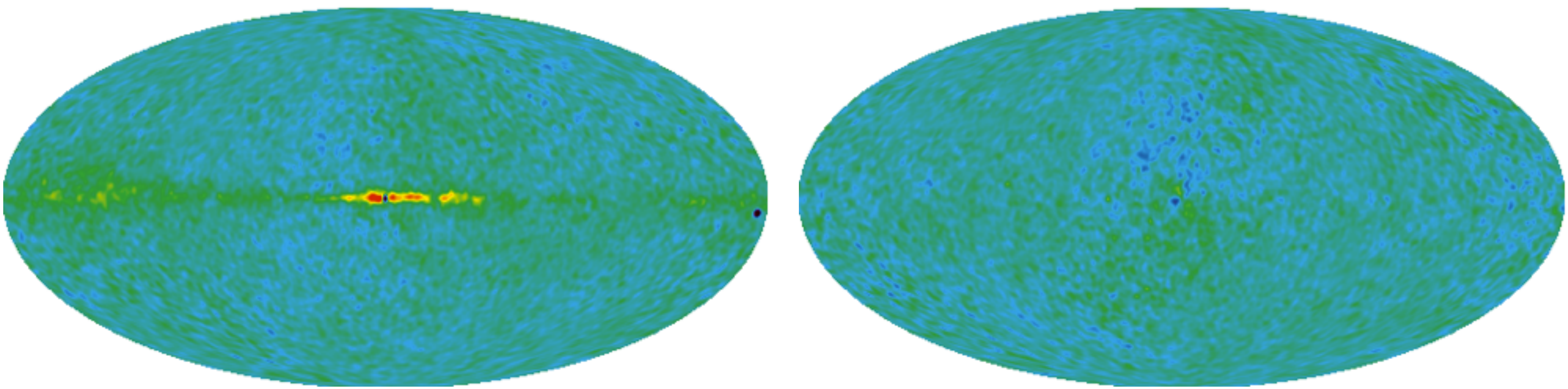
Stokes Q



Stokes U

WMAP Collaboration

61 GHz [4.9 mm]

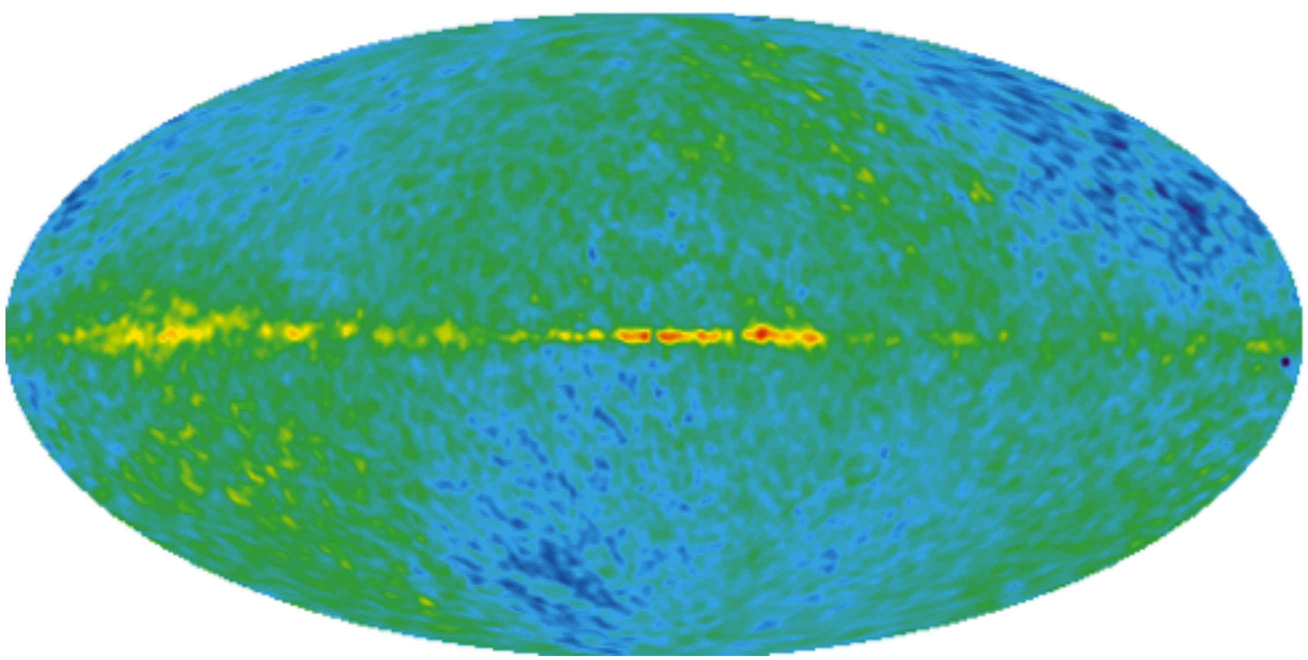


Stokes Q

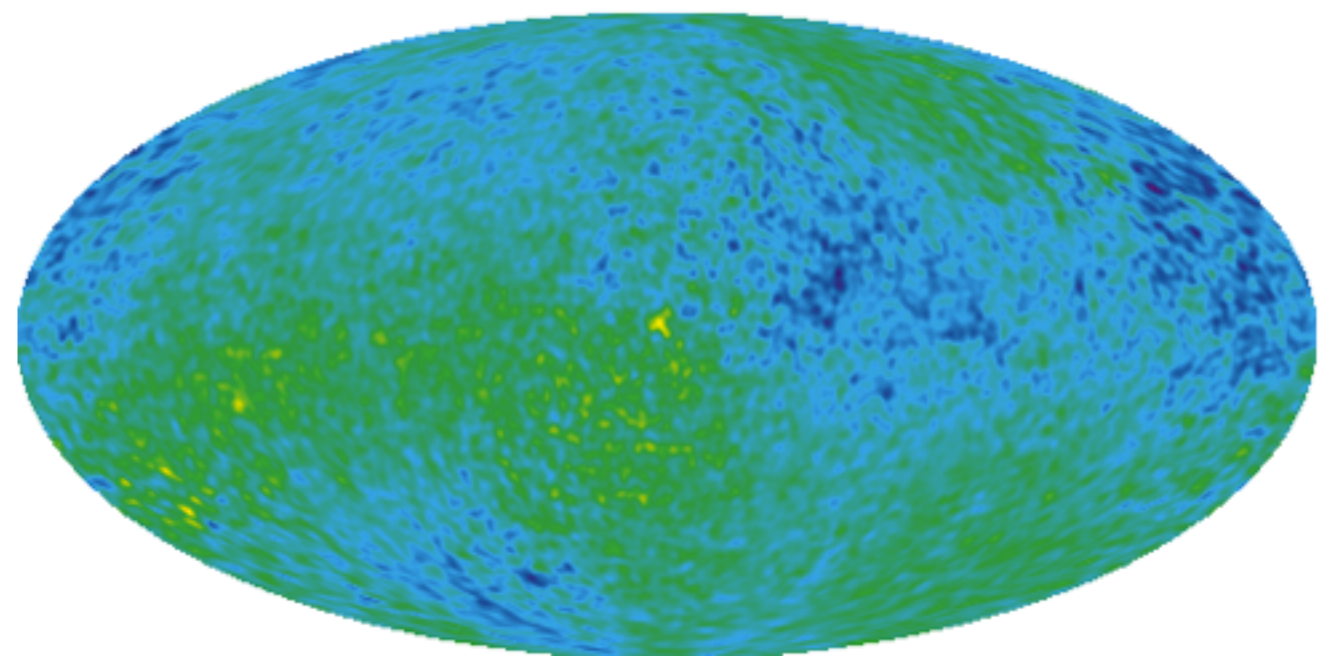
Stokes U

WMAP Collaboration

94 GHz [3.2 mm]



Stokes Q



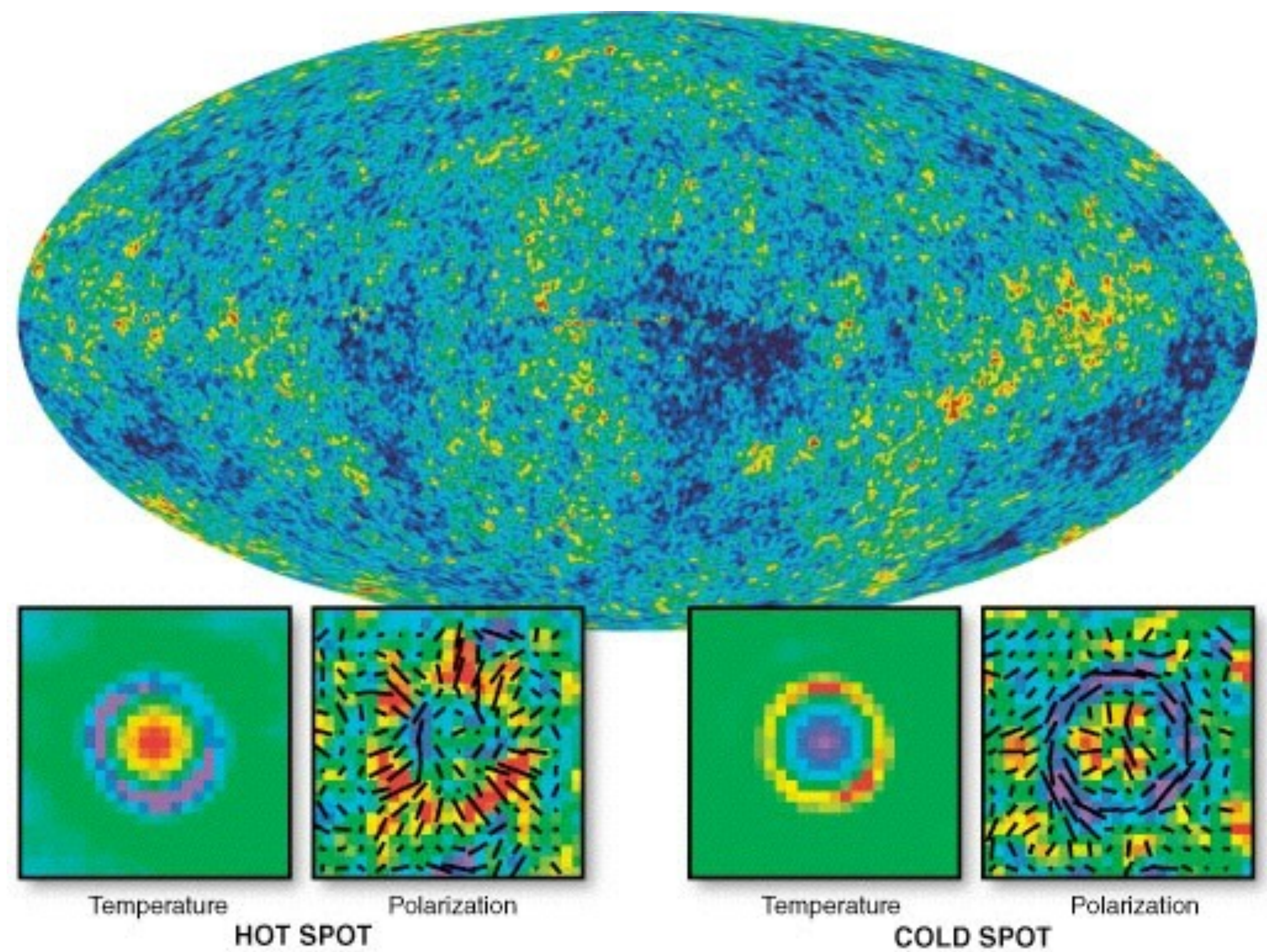
Stokes U

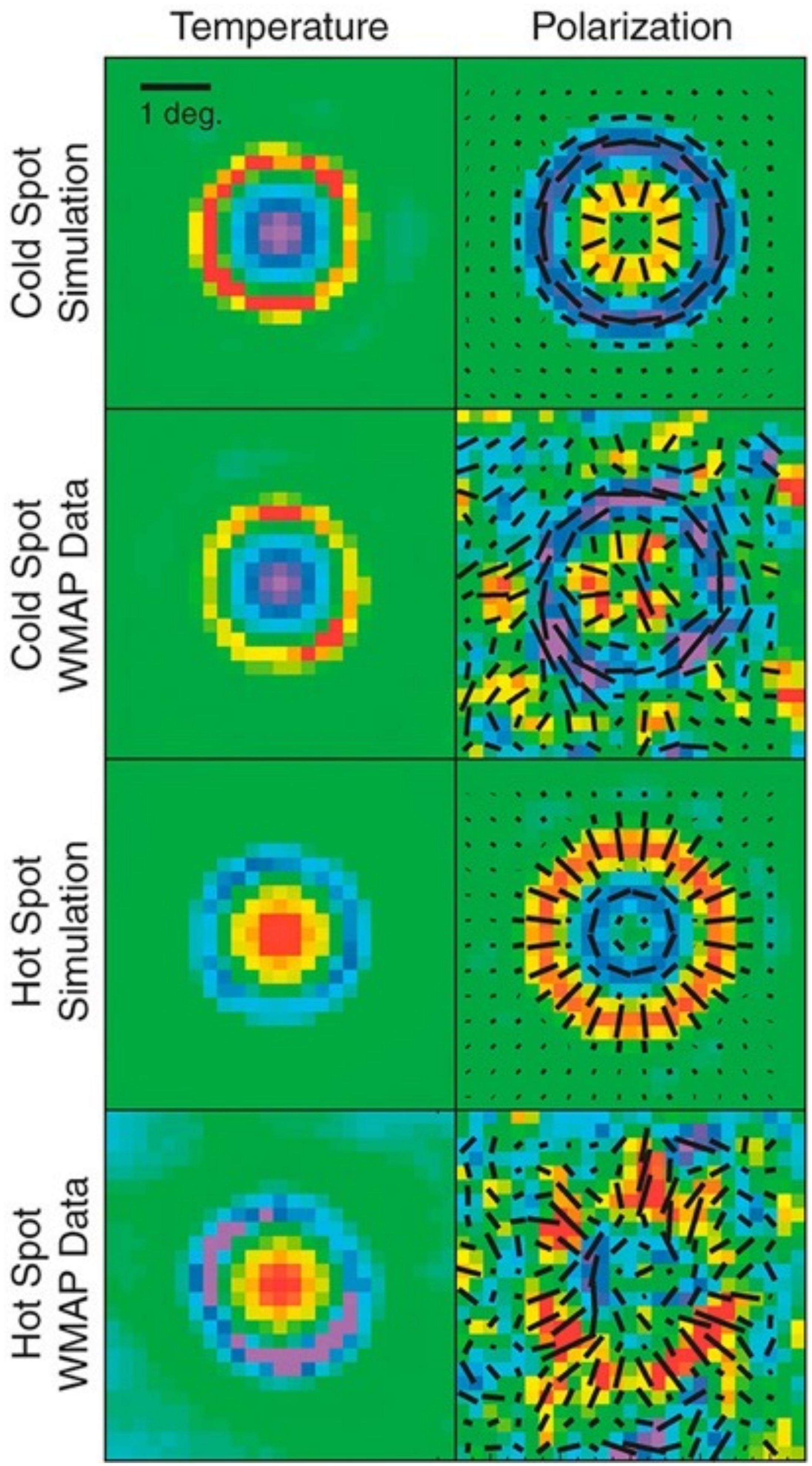
How many components?

- 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

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



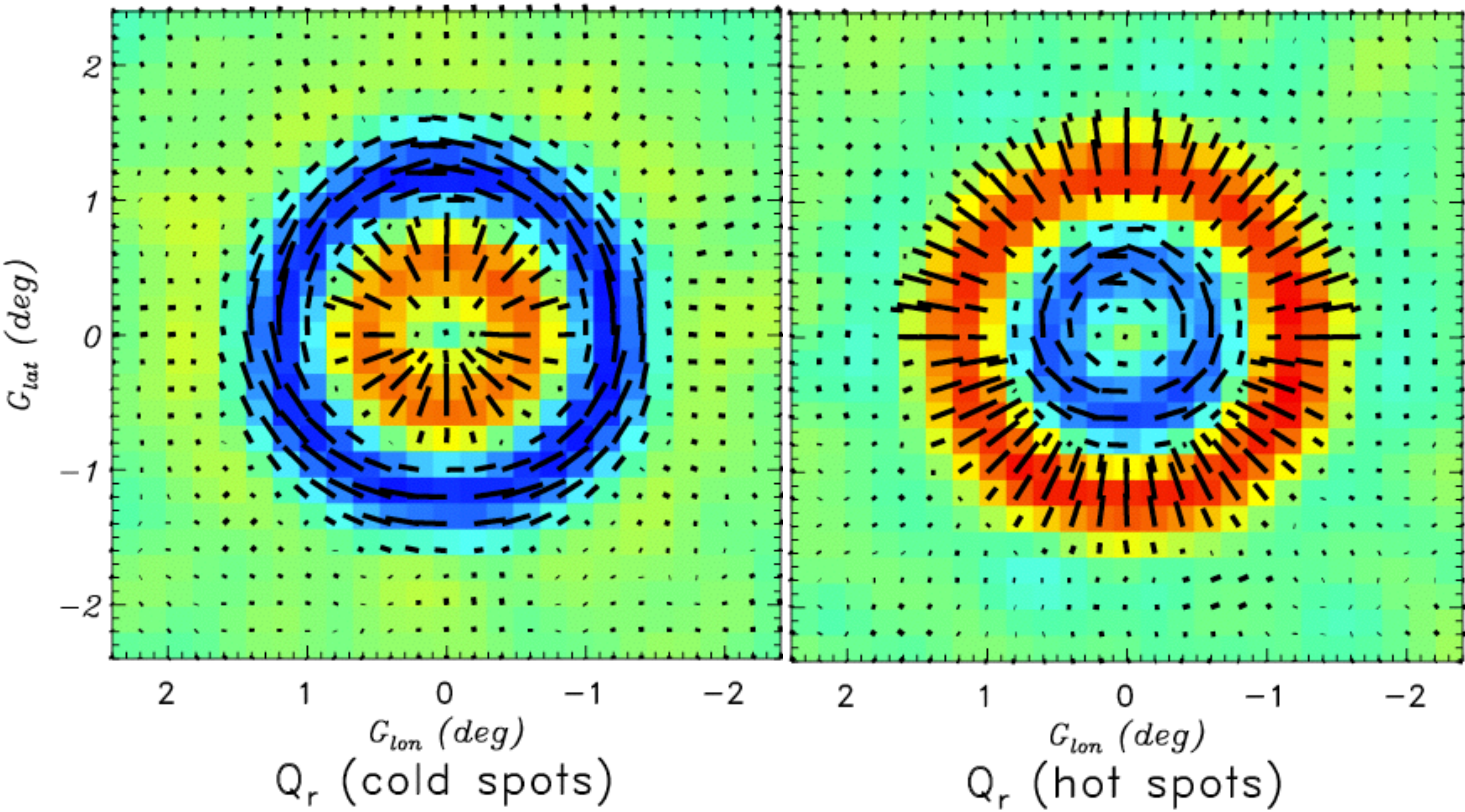


WMAP Collaboration

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**”

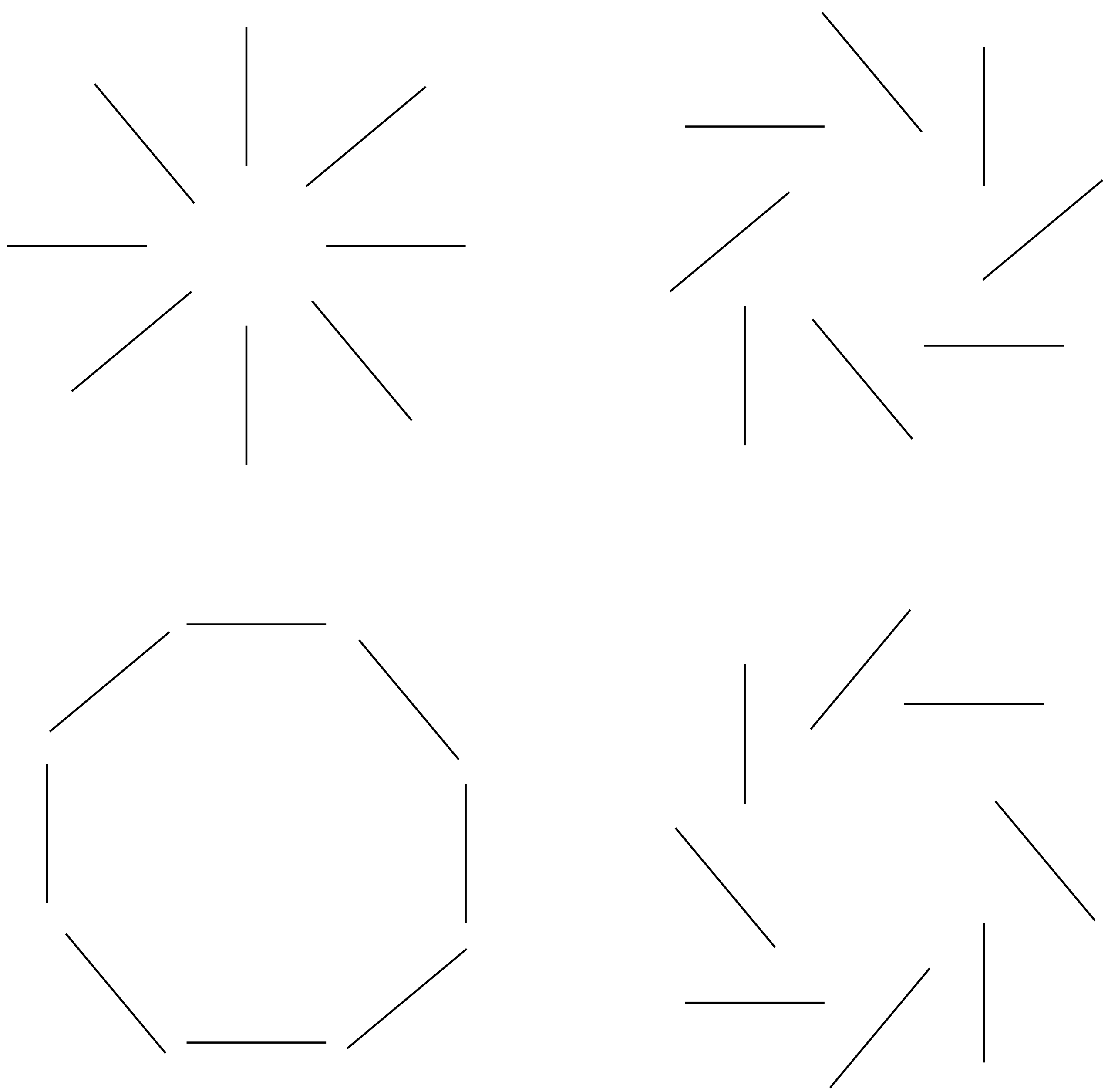
Planck Data!



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

Seljak & Zaldarriaga (1997); Kamionkowski et al. (1997)

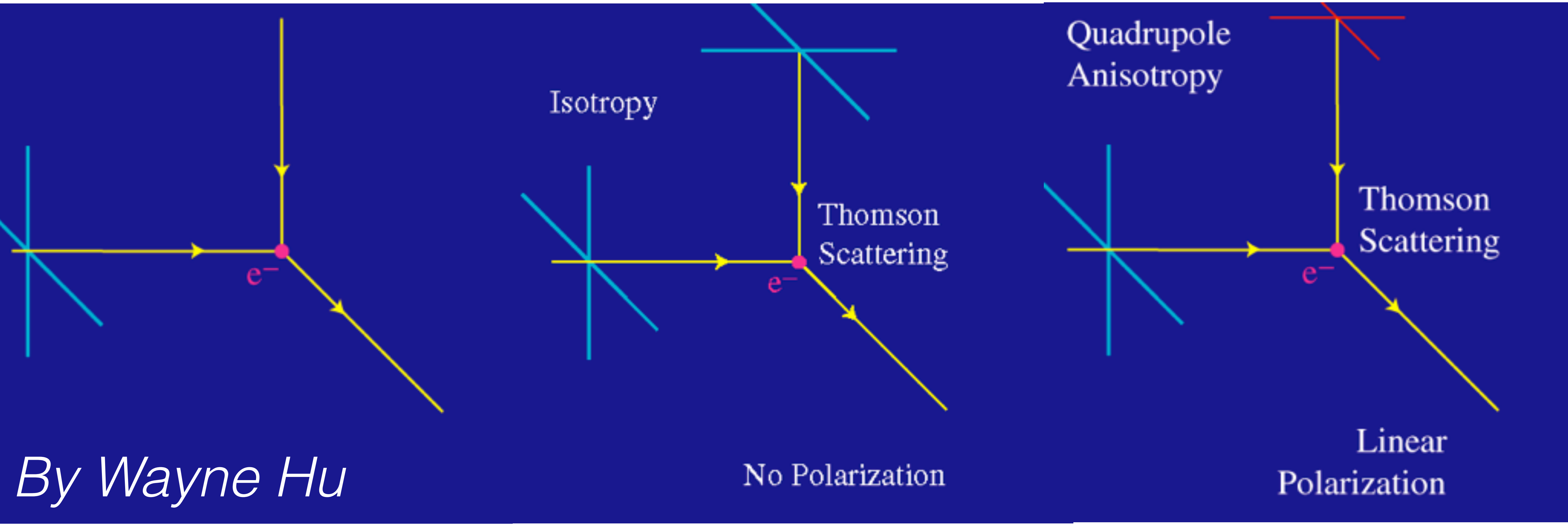
E and B modes



E mode B mode

- Density fluctuations [scalar modes] can only generate E modes
- Gravitational waves can generate both E and B modes

Physics of CMB Polarisation

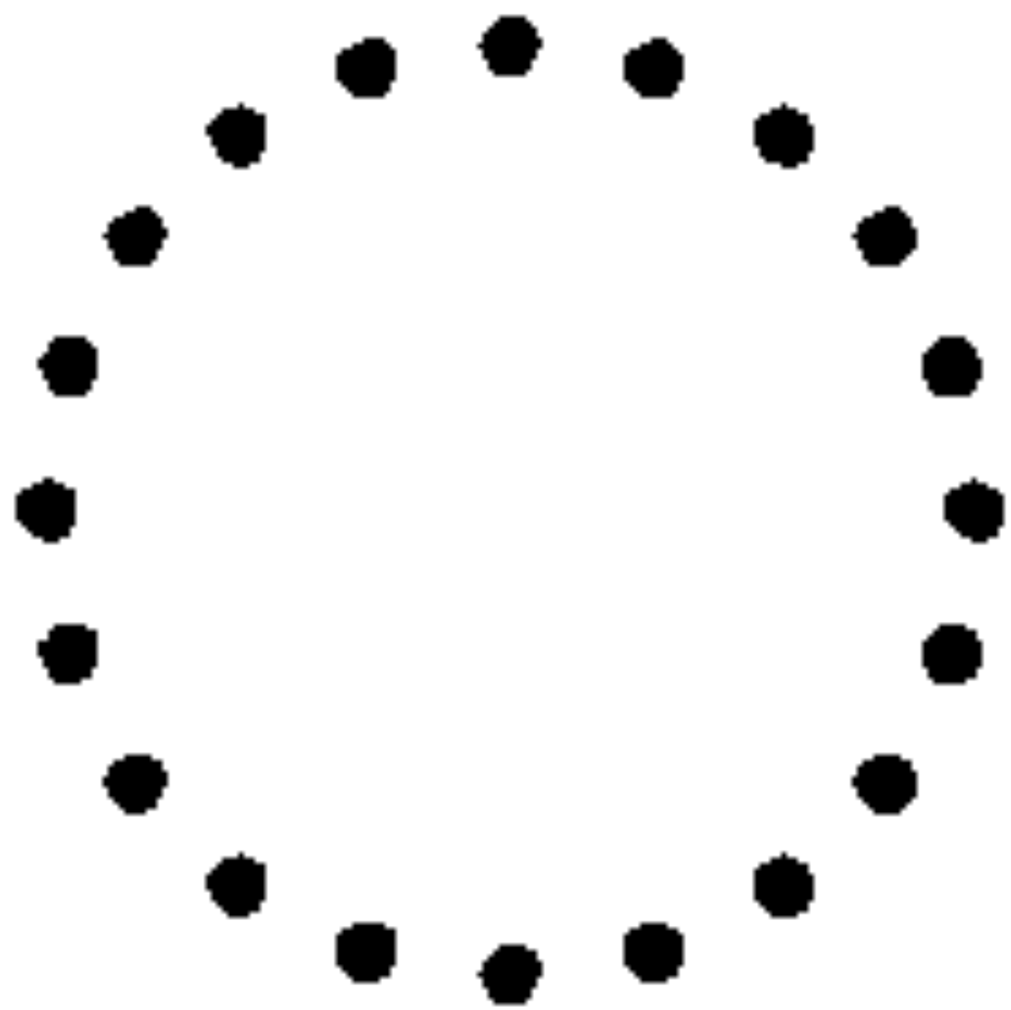


- Necessary and sufficient conditions for generating polarisation in CMB:
  - Thomson scattering
  - Quadrupolar temperature anisotropy around an electron

Origin of Quadrupole

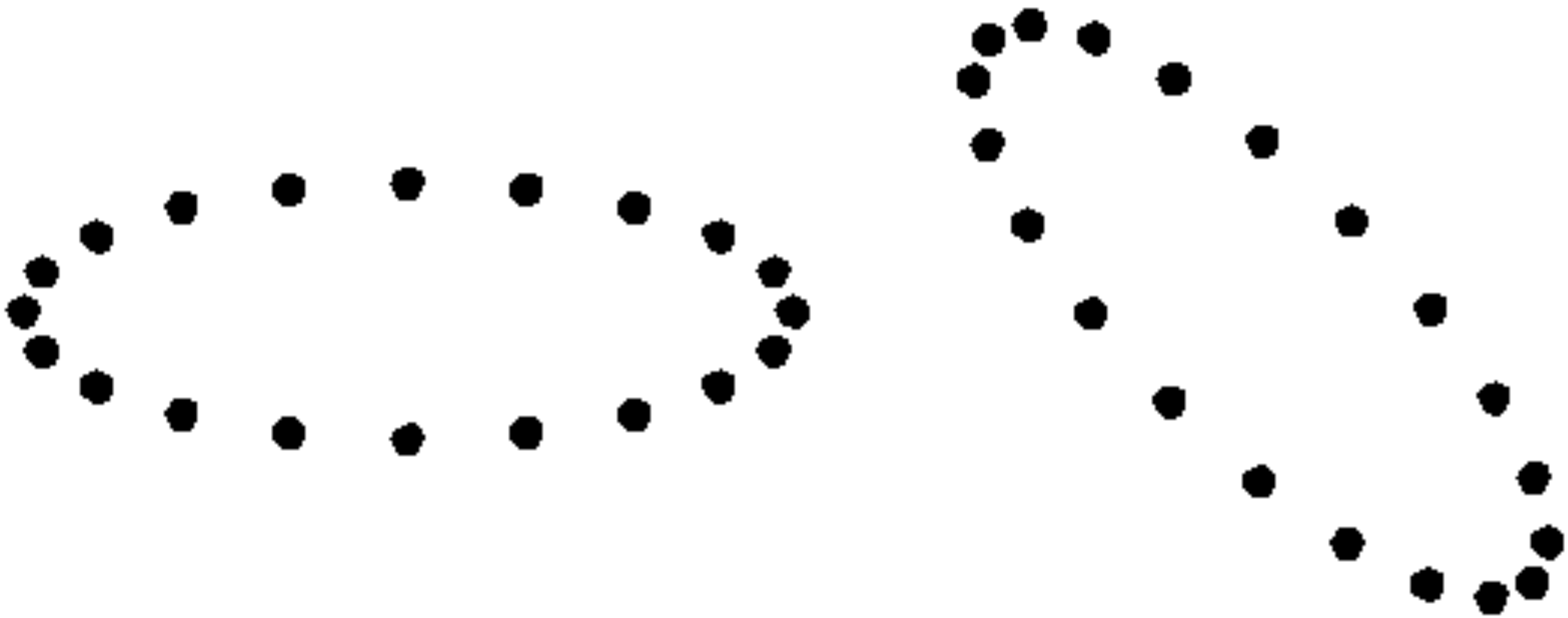
- **Scalar perturbations**: motion of electrons with respect to photons
- **Tensor perturbations**: gravitational waves

Gravitational waves are coming toward you!



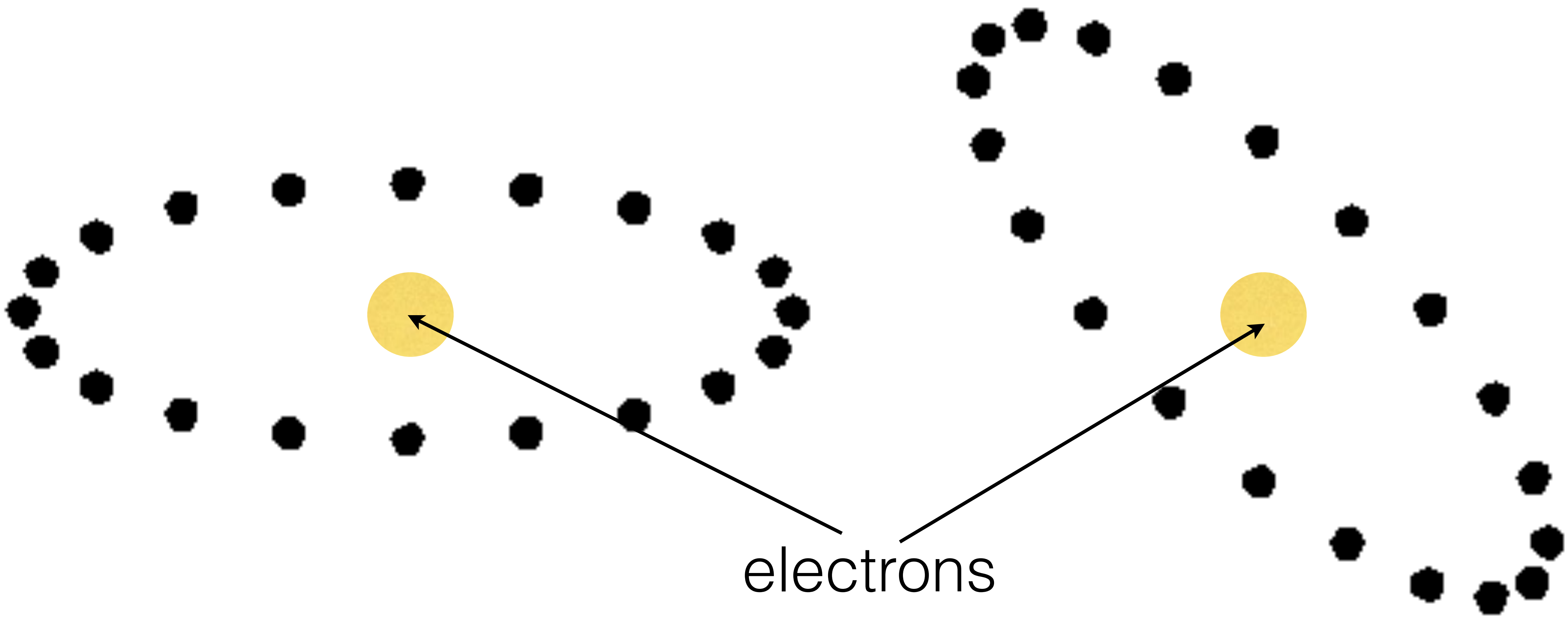
- What do they do to the distance between particles?

Two GW modes

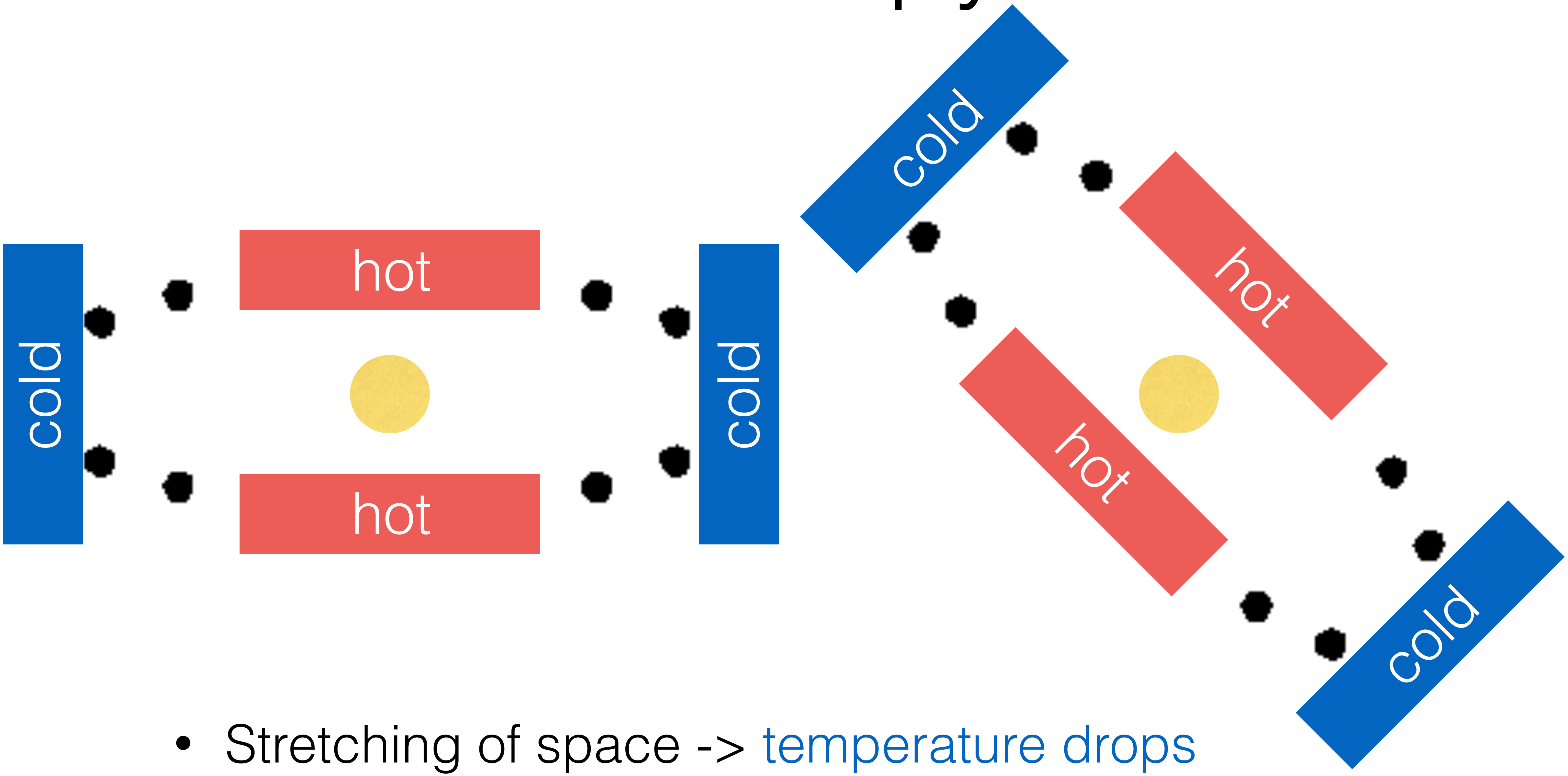


- Anisotropic stretching of space generates quadrupole temperature anisotropy. How?

GW to temperature anisotropy

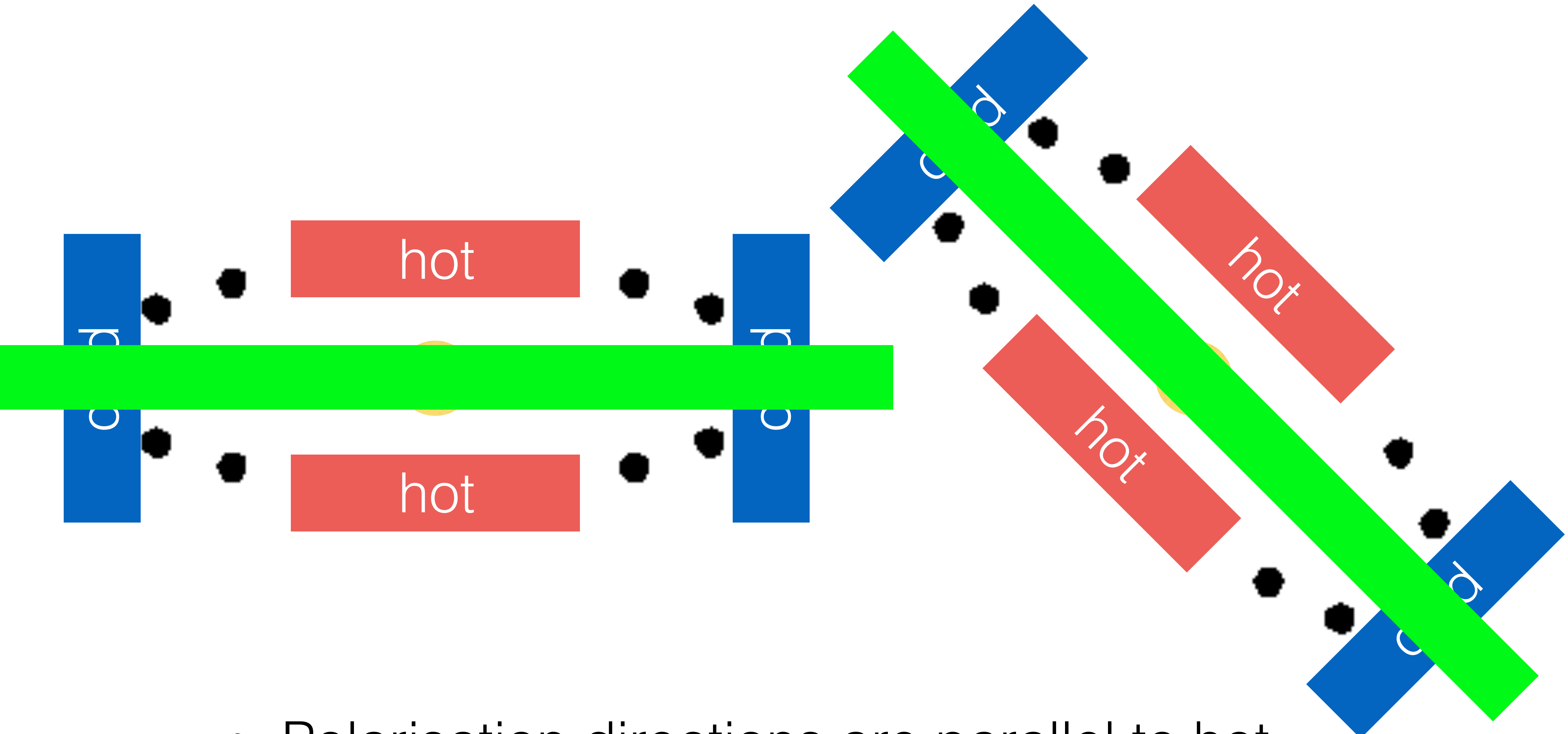


GW to temperature anisotropy



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

Then to polarisation!



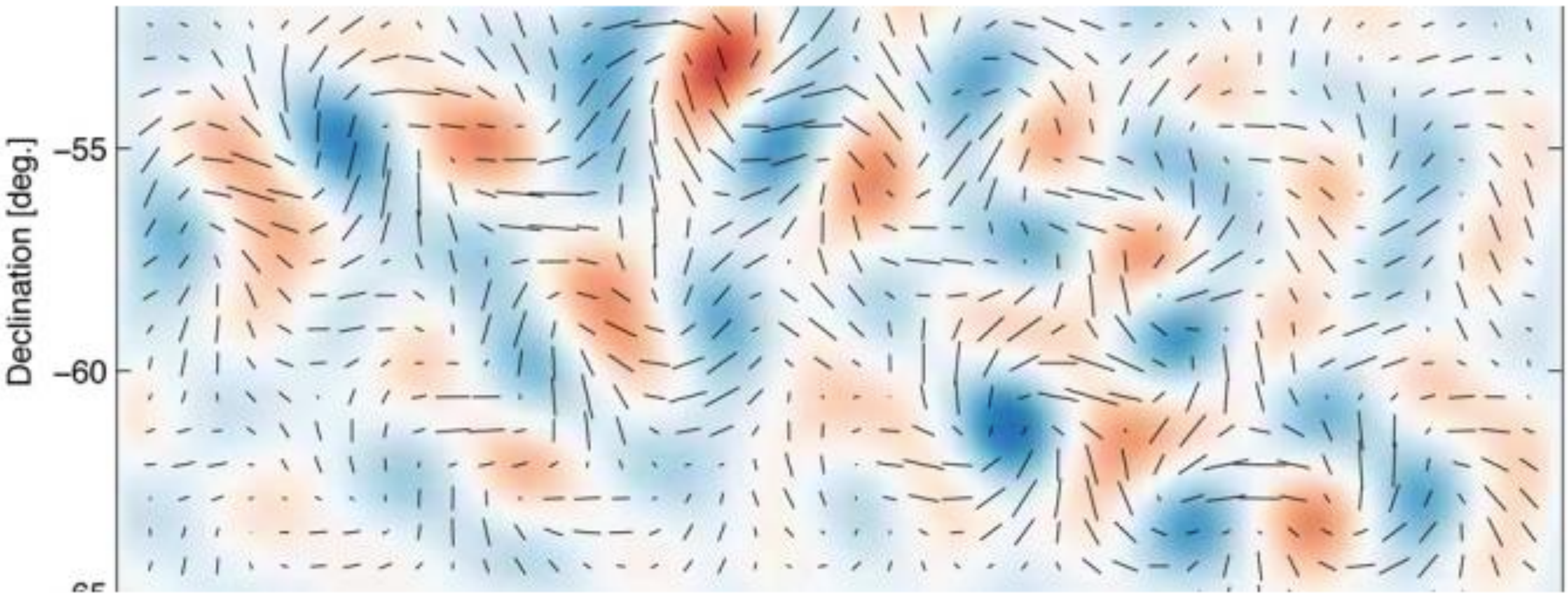
- Polarisation directions are parallel to hot regions

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 & COSMOS

The New York Times

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

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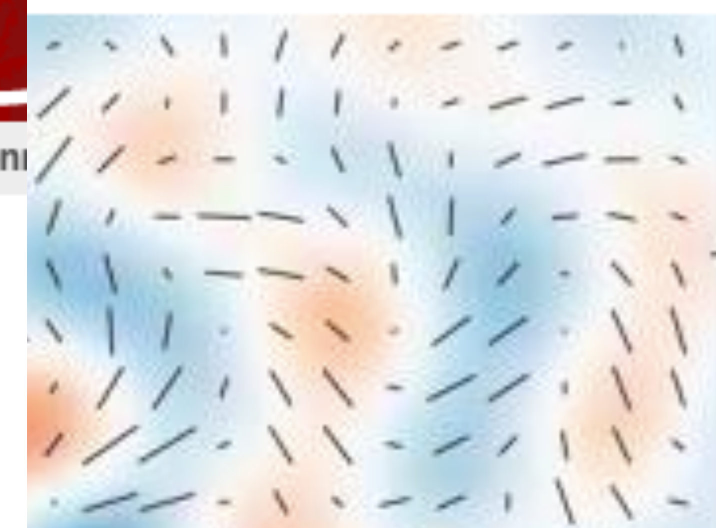

17 March 2014 Last updated at 14:46 GMT

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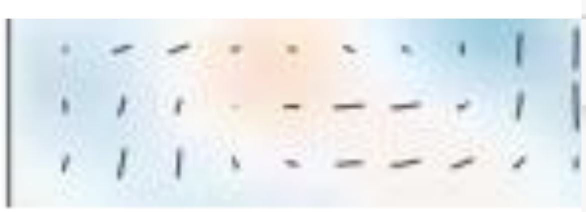
Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos

Science correspondent, BBC News



Cambridge, MA - Almost 14 billic
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

SCIENCE

The New York Times

Speck of Interstellar Dust Obscures Glimpse of Big Bang

By DENNIS OVERBYE JAN. 30, 2015

BBC

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30 January 2015 Last updated at 20:54 GMT

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Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos
Science correspondent, BBC News

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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

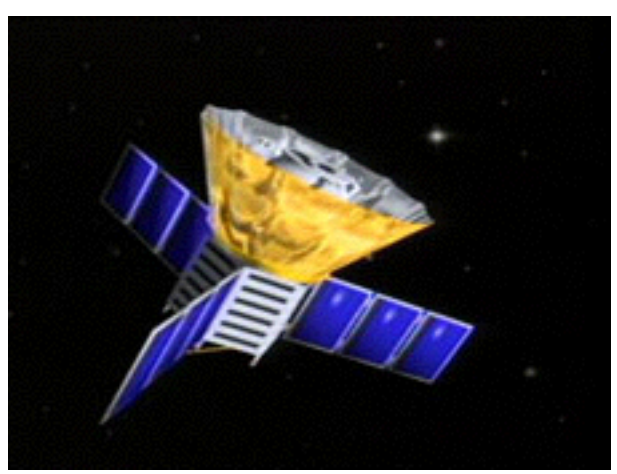
Von Marlene Weiß

Current Situation

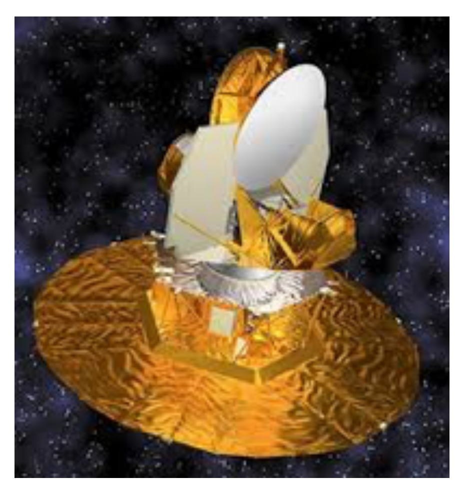
- Planck shows the evidence that the detected signal is not cosmological, but is due to dust

- No strong evidence that the detected signal is cosmological

The search continues!!



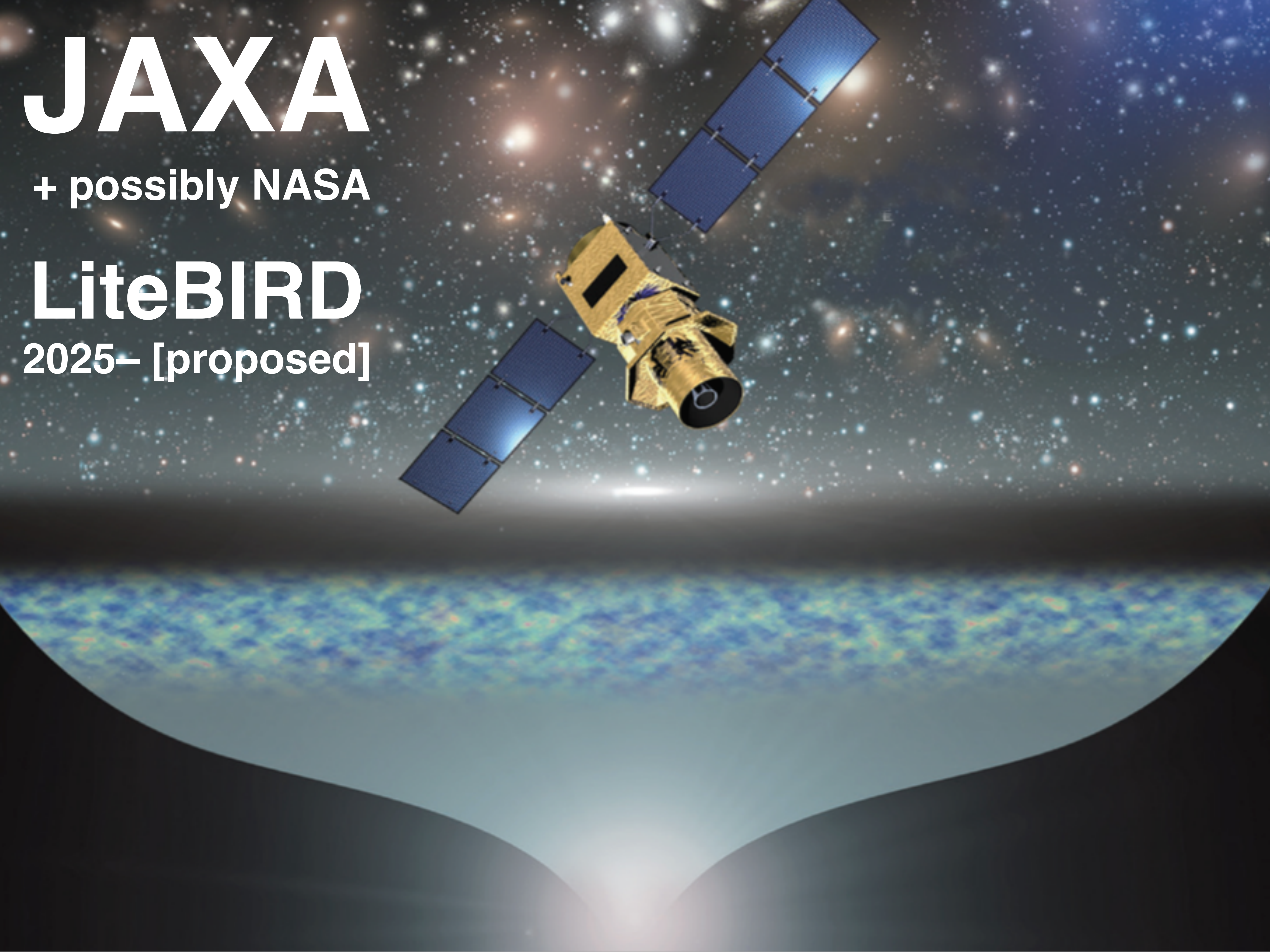
1989–1993



2001–2010

2009–2013

202X–


JAXA
+ possibly NASA
LiteBIRD
2025– [proposed]

JAXA

+ possibly NASA

LiteBIRD

2025– [proposed]

ESA

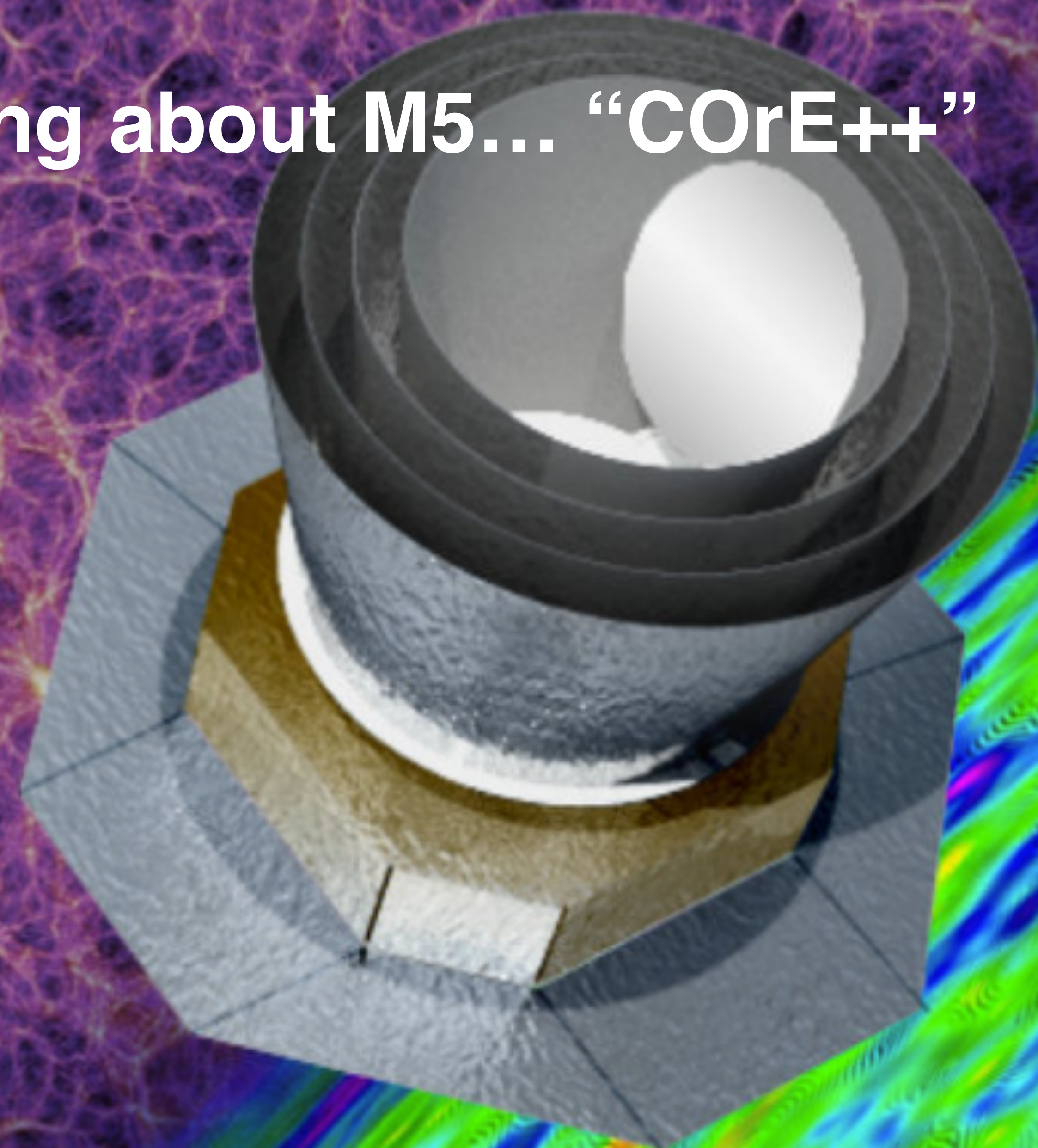
COrE+

+ possibly JAXA/NASA

Cosmic Origins Explorer+

Tried M4.

Now thinking about M5… “COrE++”



Conclusion

- The WMAP and Planck's temperature data provide **strong evidence for the quantum origin of structures in the universe**
- The next goal: unambiguous measurement of the primordial B-mode polarisation power spectrum
- **LiteBIRD** proposal: a B-mode CMB polarisation satellite in 2025
- **COrE++ (name TBD)**: proposal to ESA's M5 call under discussion