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

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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)

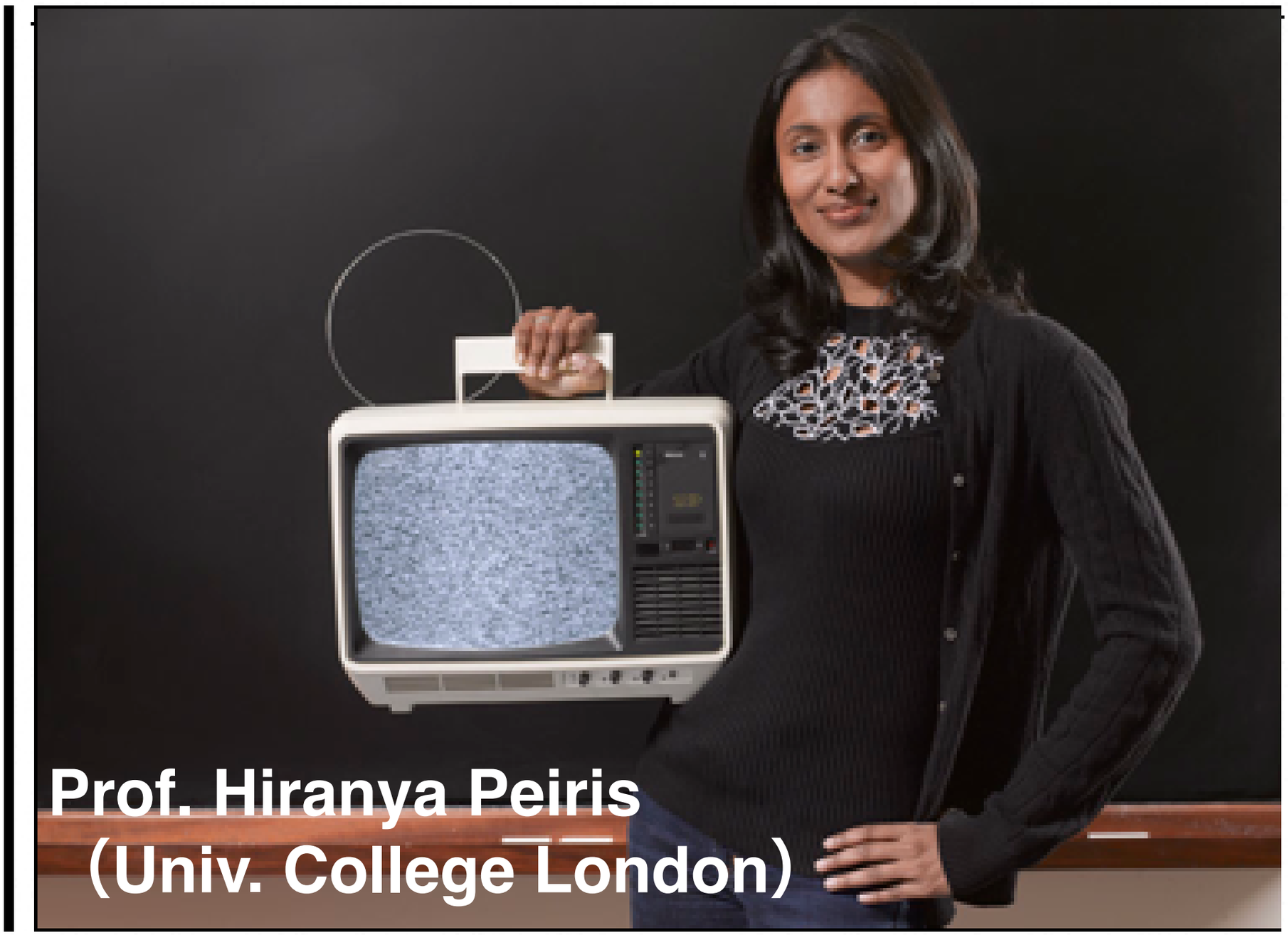
courtesy University of Arizona

410 photons

per

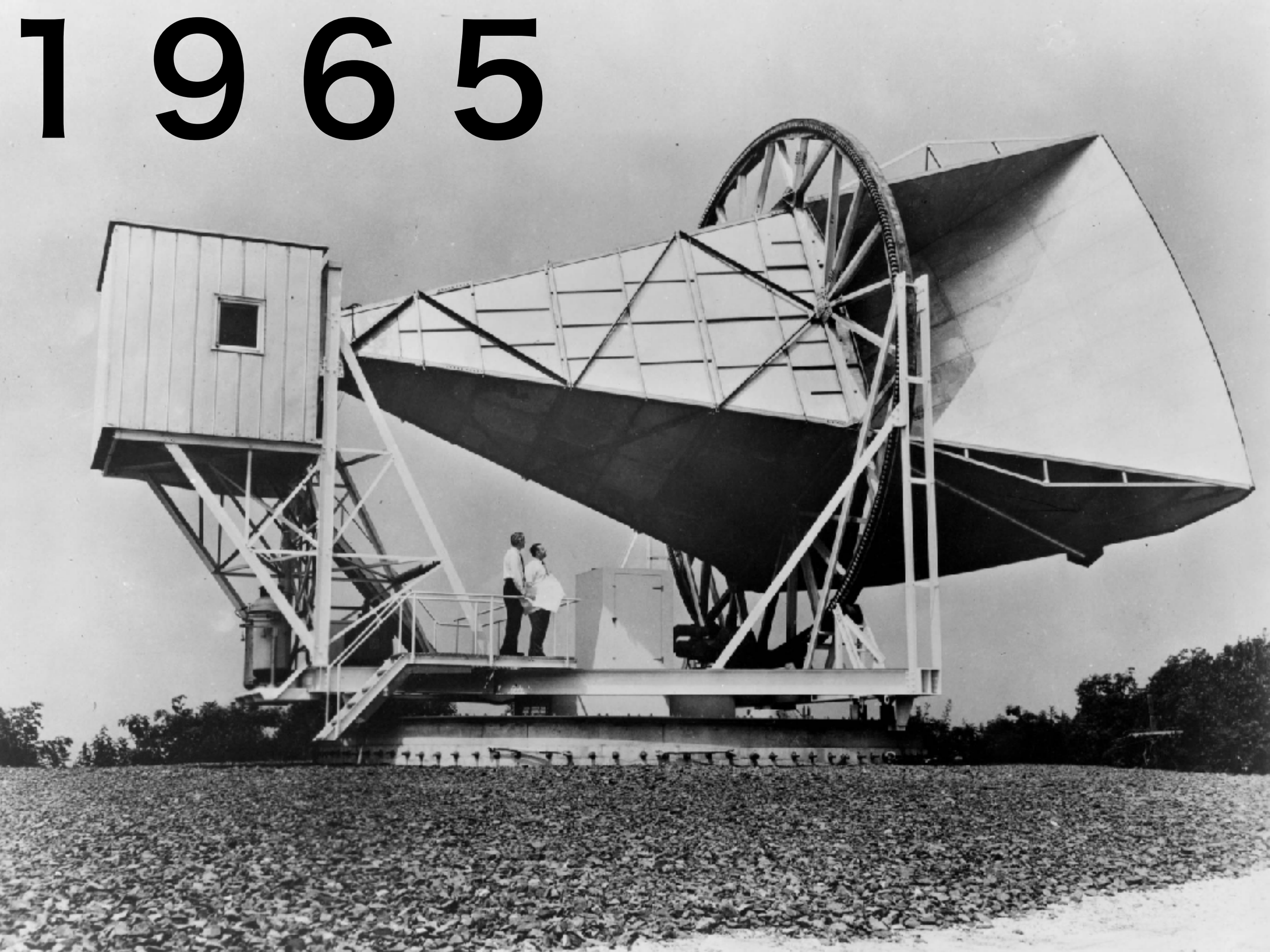
cubic centimeter!!

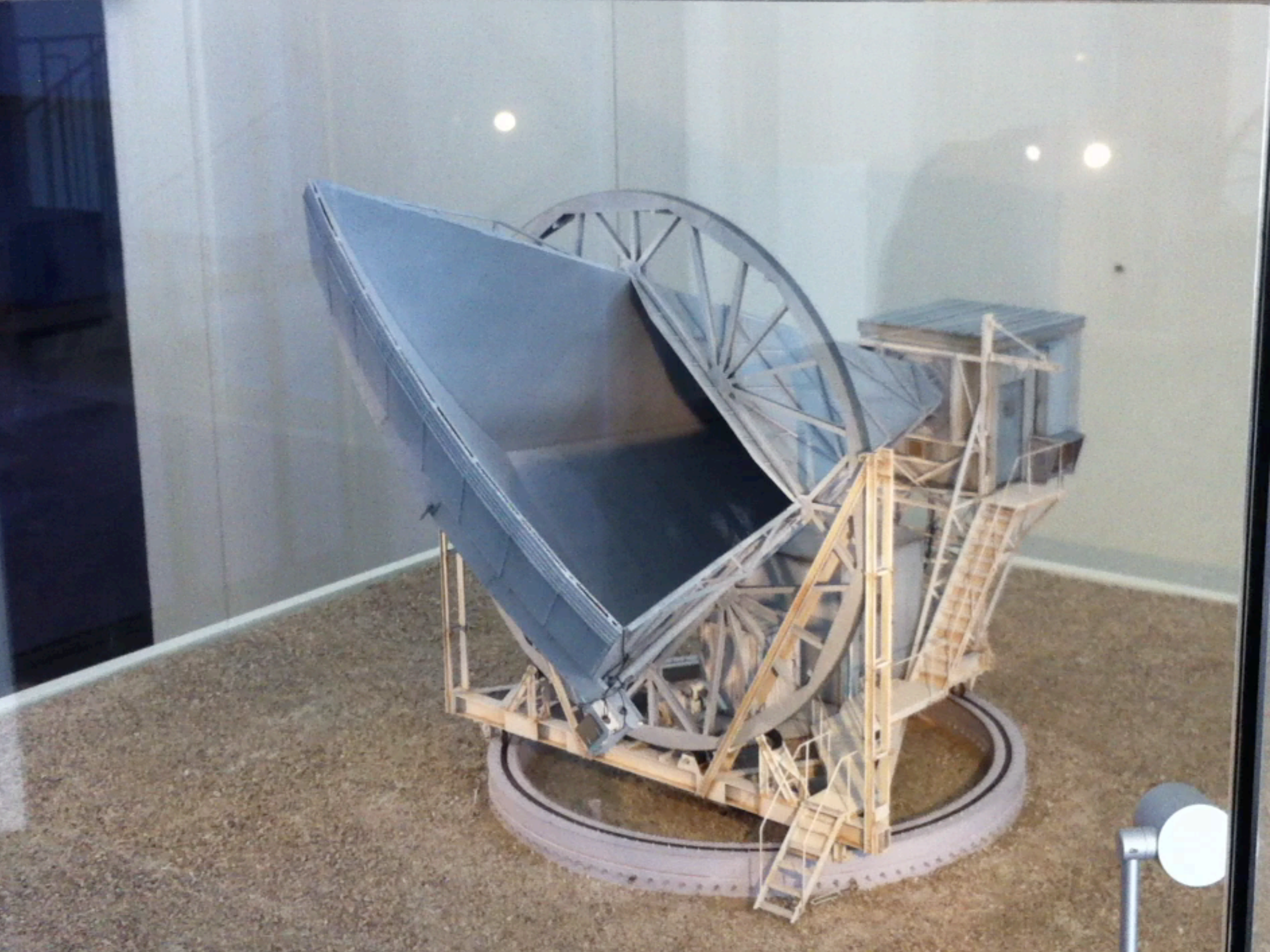
courtesy University of Arizona



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

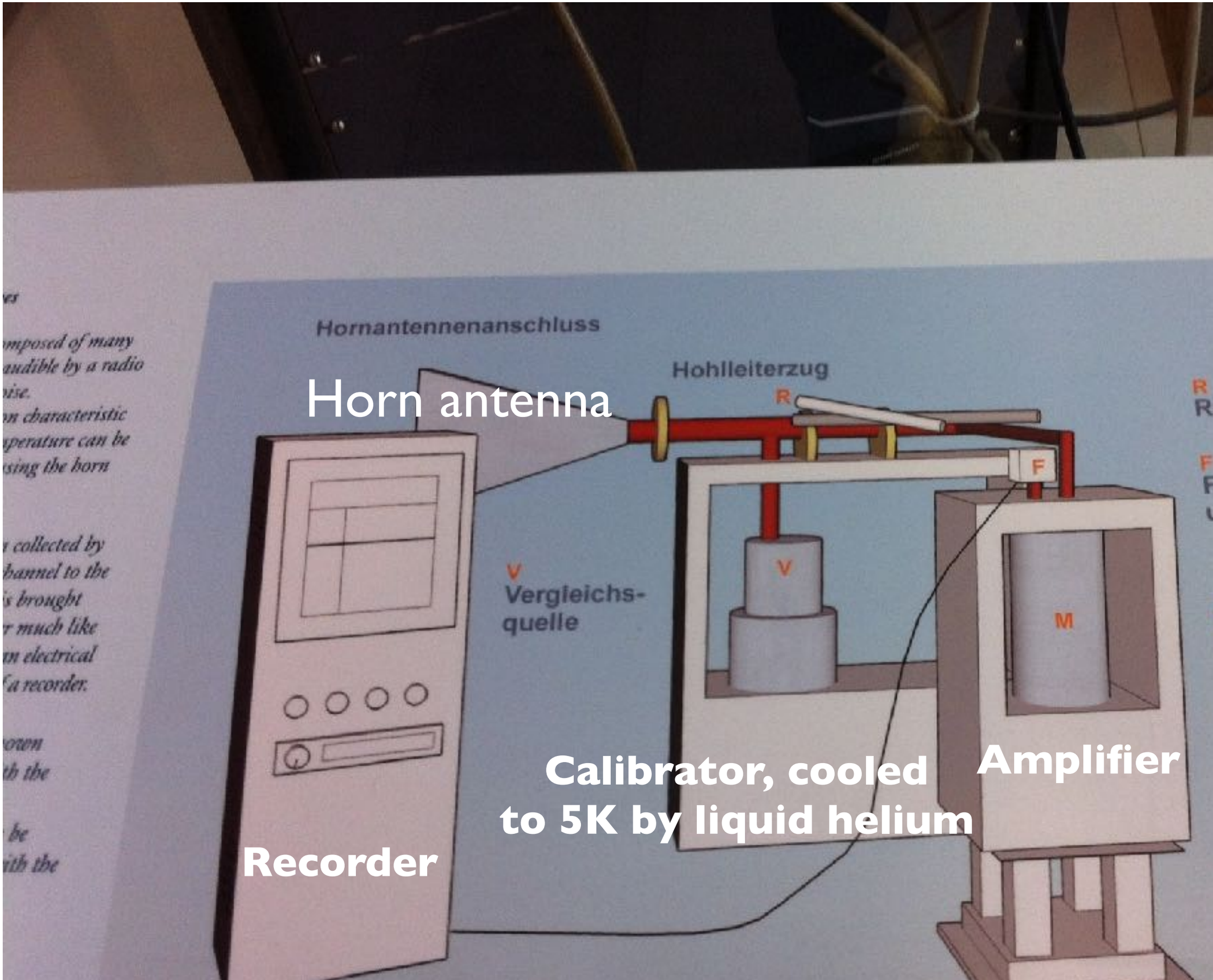
1965





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

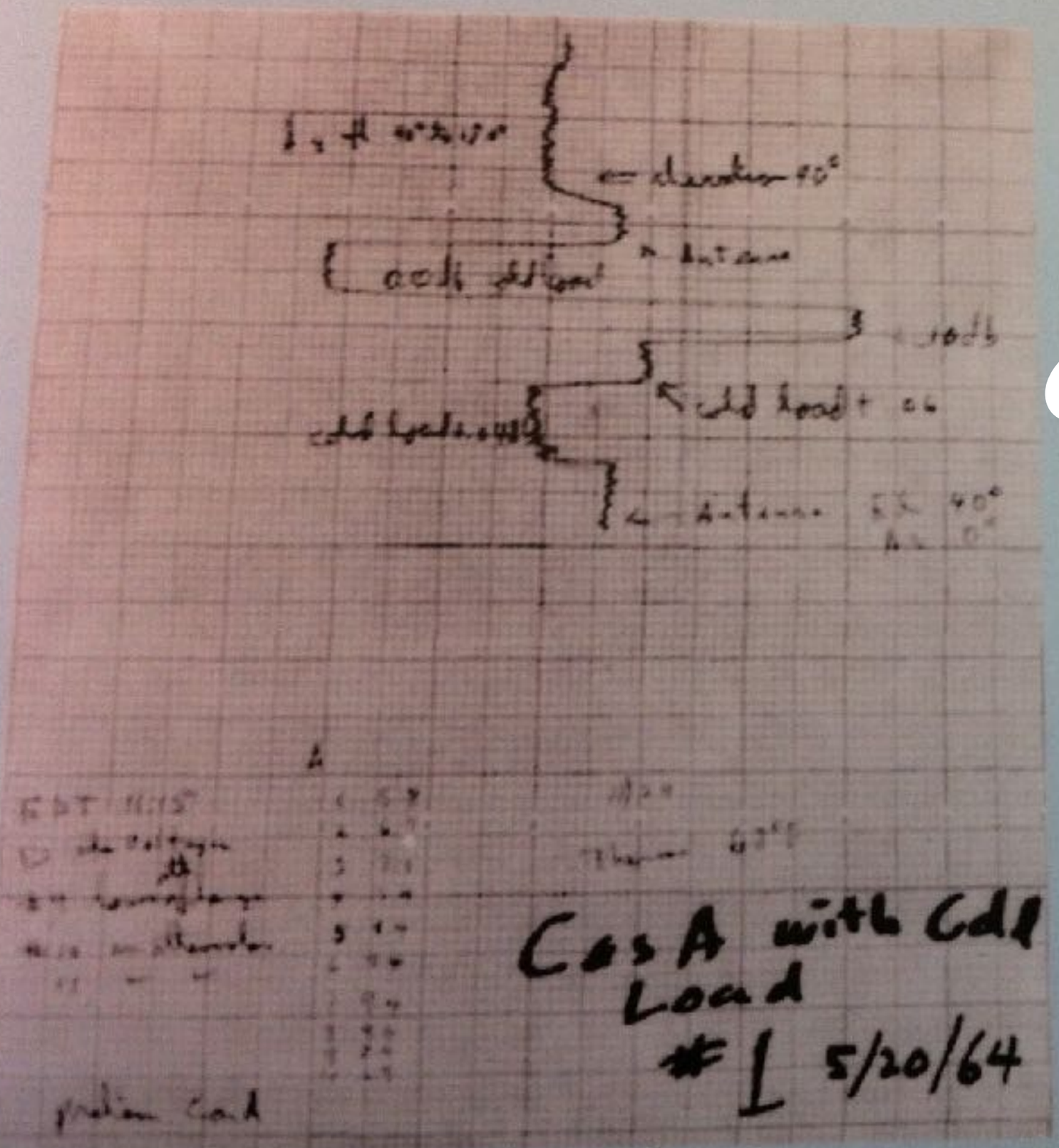
Donated by Dr. Penzias, who was born in Munich



Horn antenna

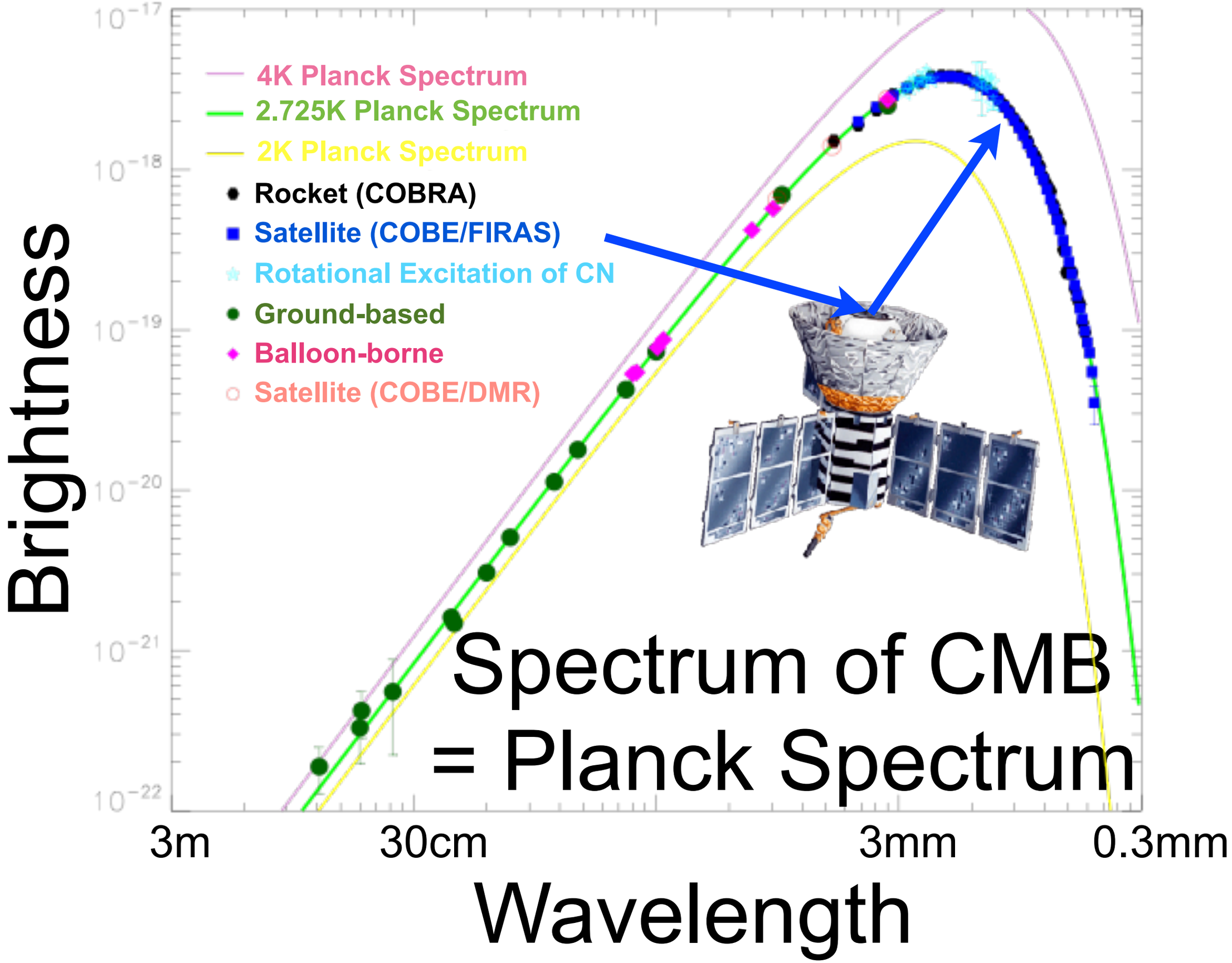
May 20, 1964
CMB
Discovered

6.7–2.3–0.8–0.1
= 3.5±1.0 K

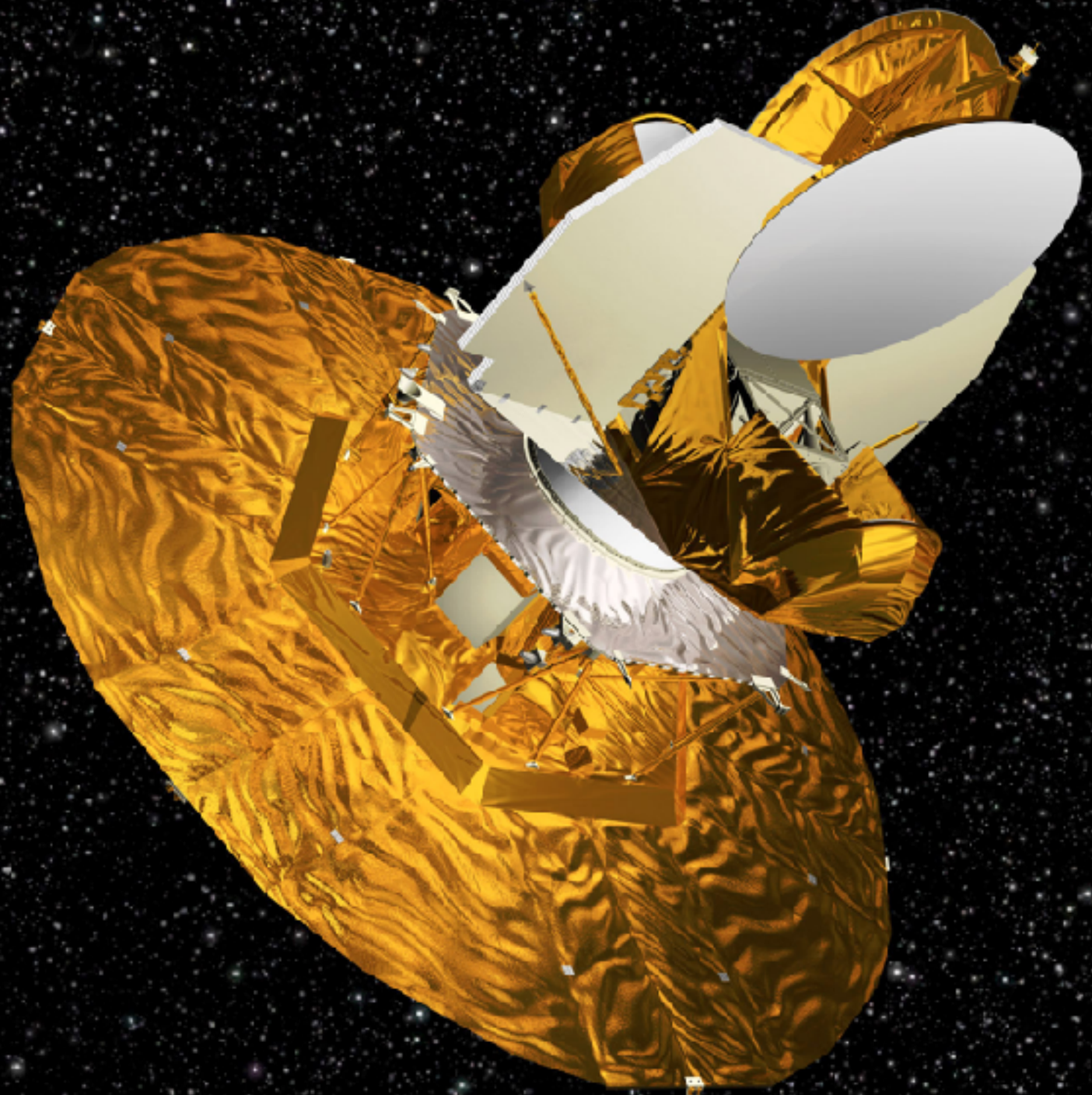


Schreiberaufzeichnung der ersten Messung des Mikrowellenhintergrundes am 20.5.1964

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)
Brightness
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
Spectrum of CMB
= Planck Spectrum
3m
30cm
3mm
0.3mm
Wavelength

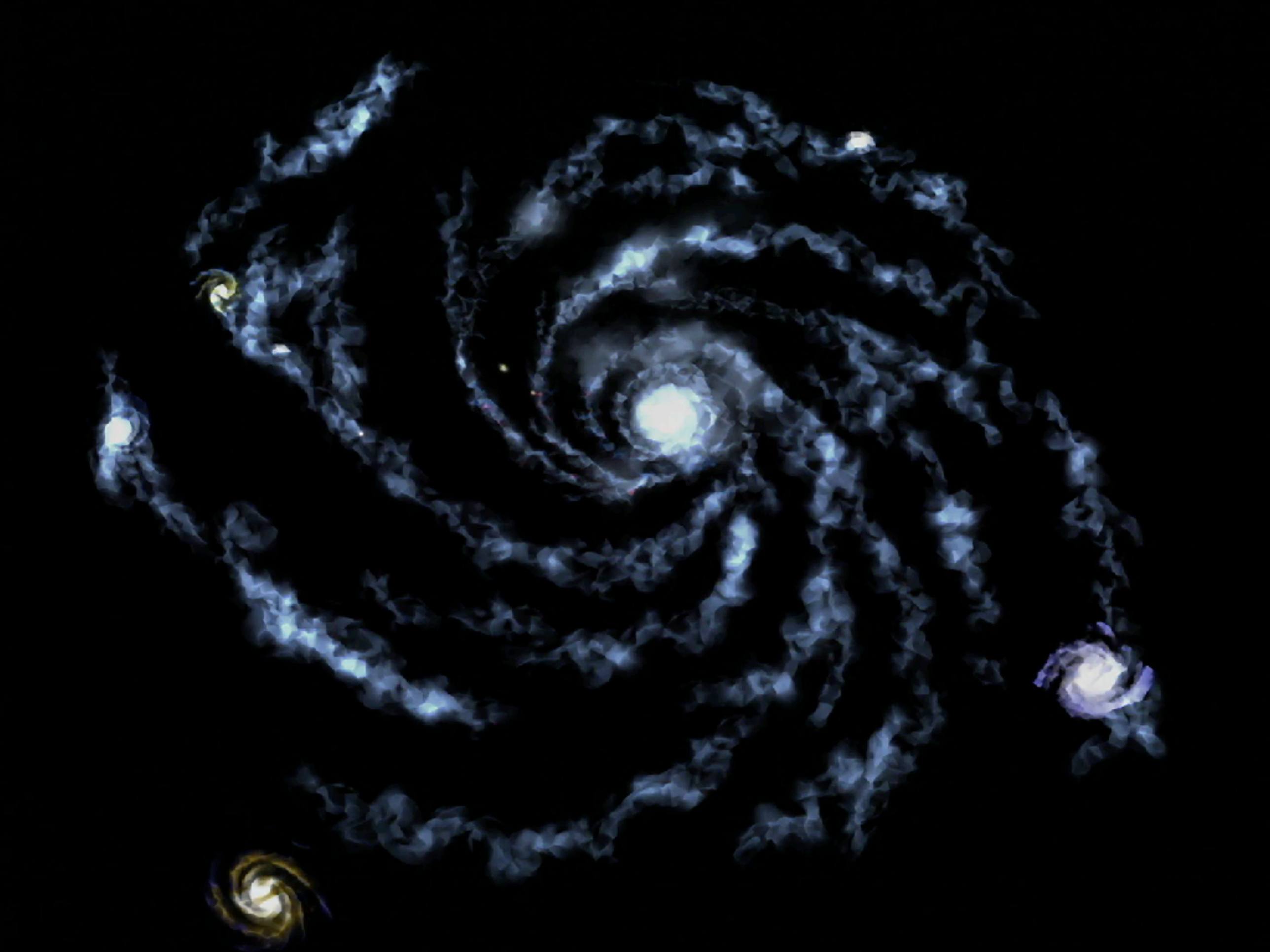
2001



WMAP Science Team

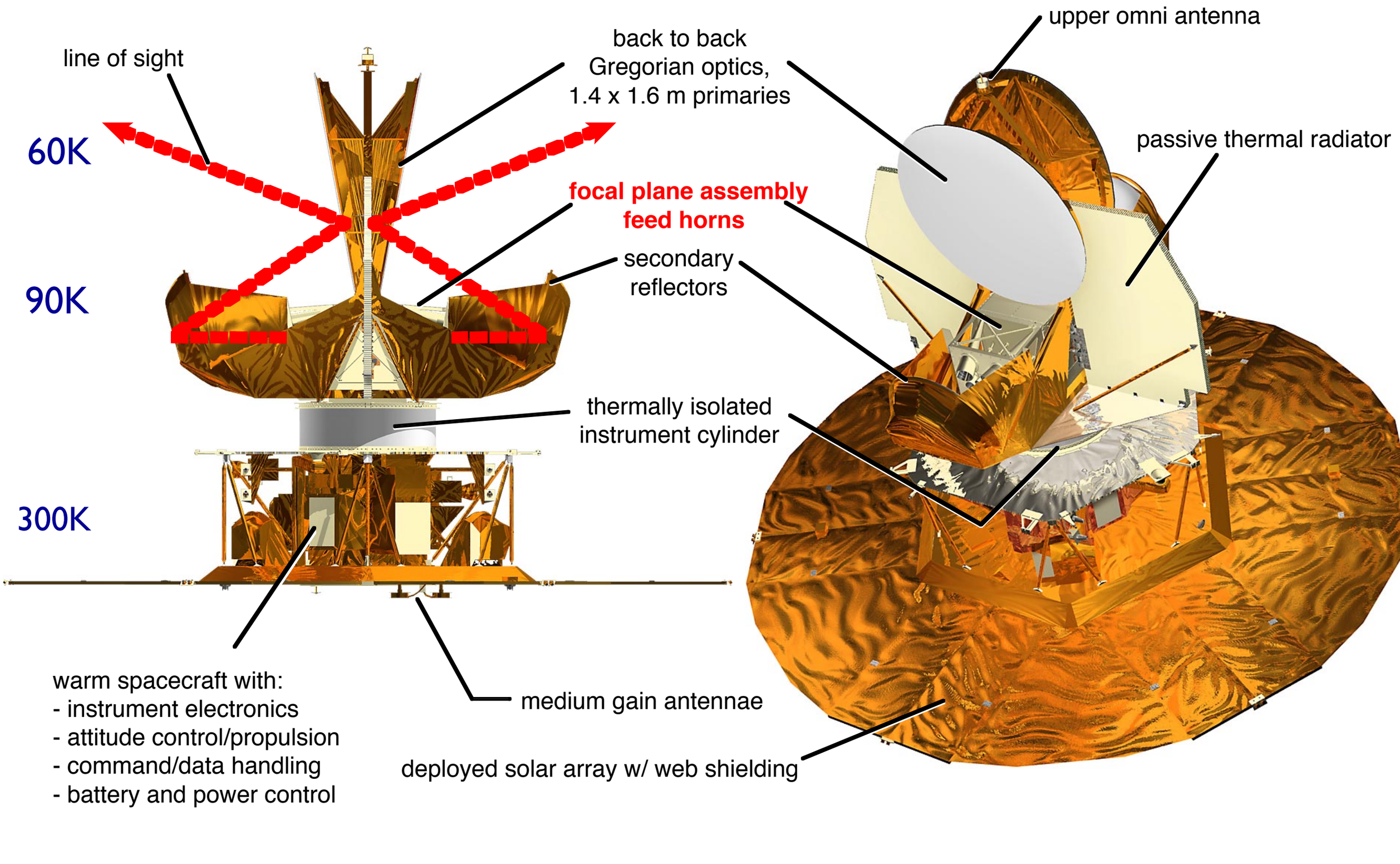
July 19, 2002

- 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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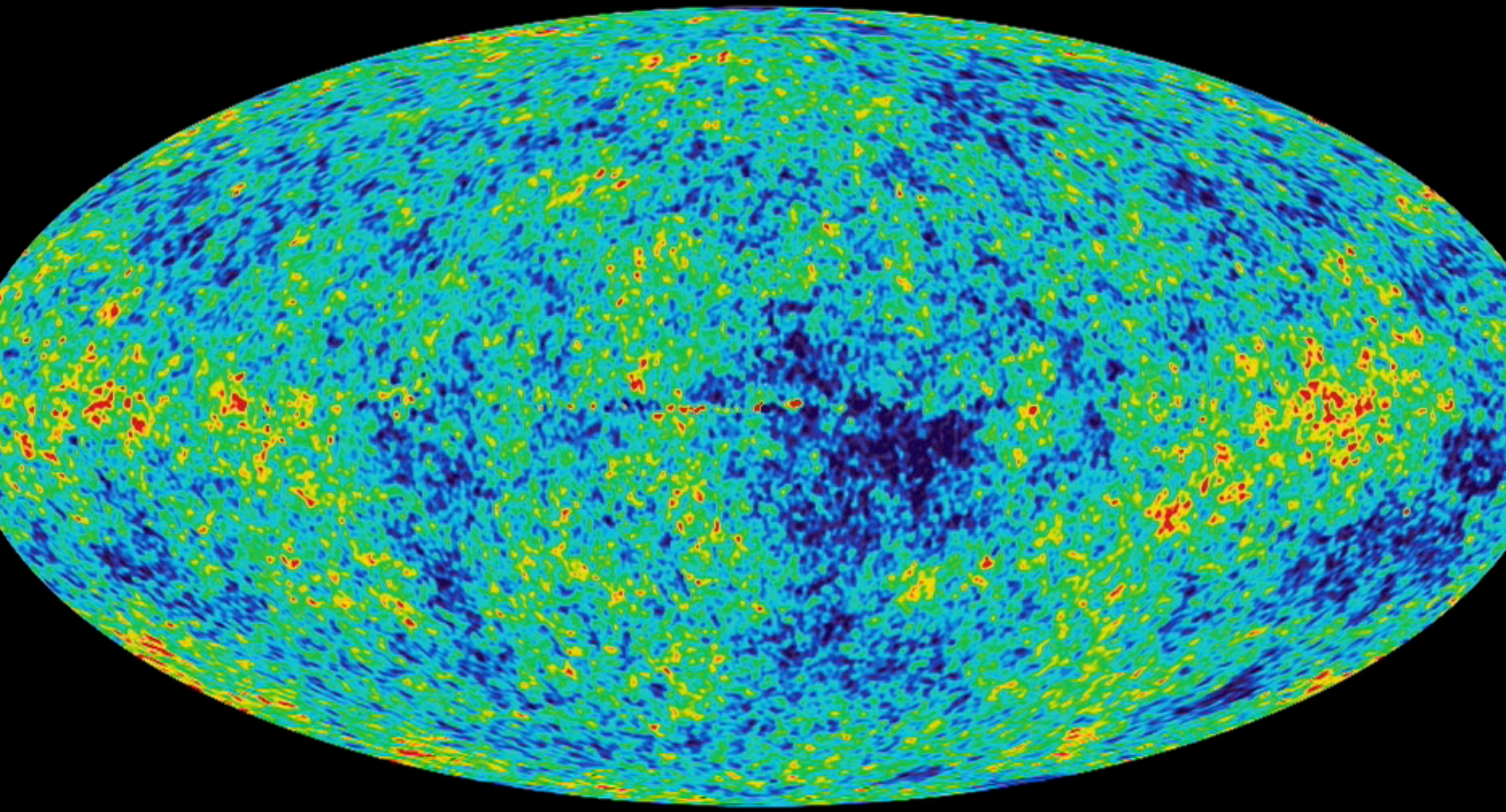
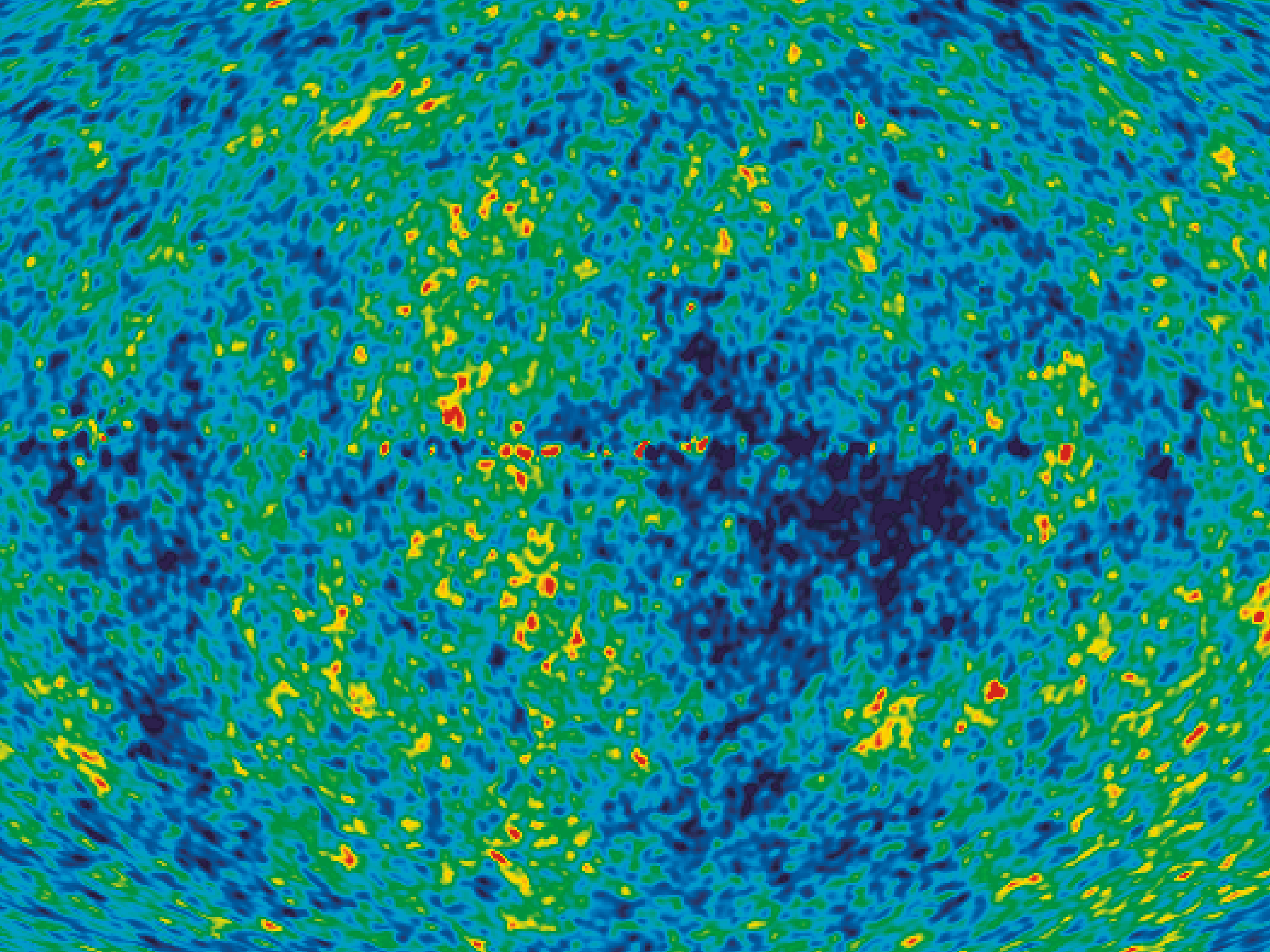


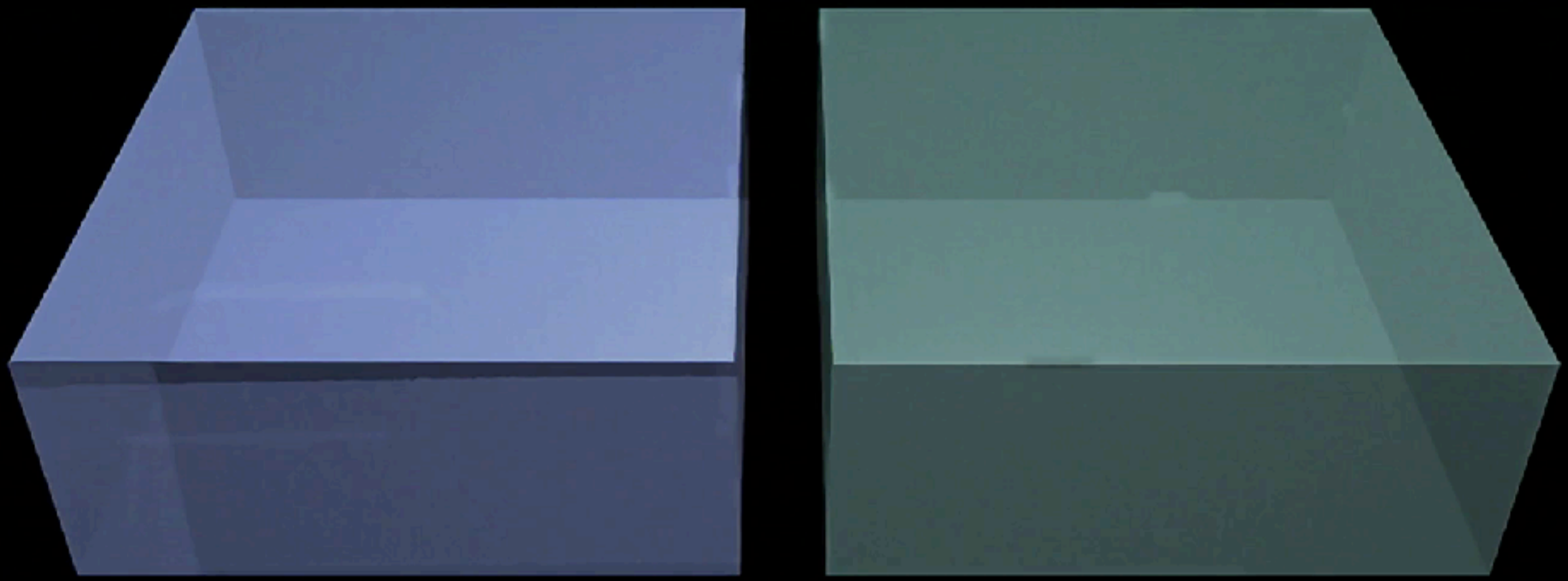


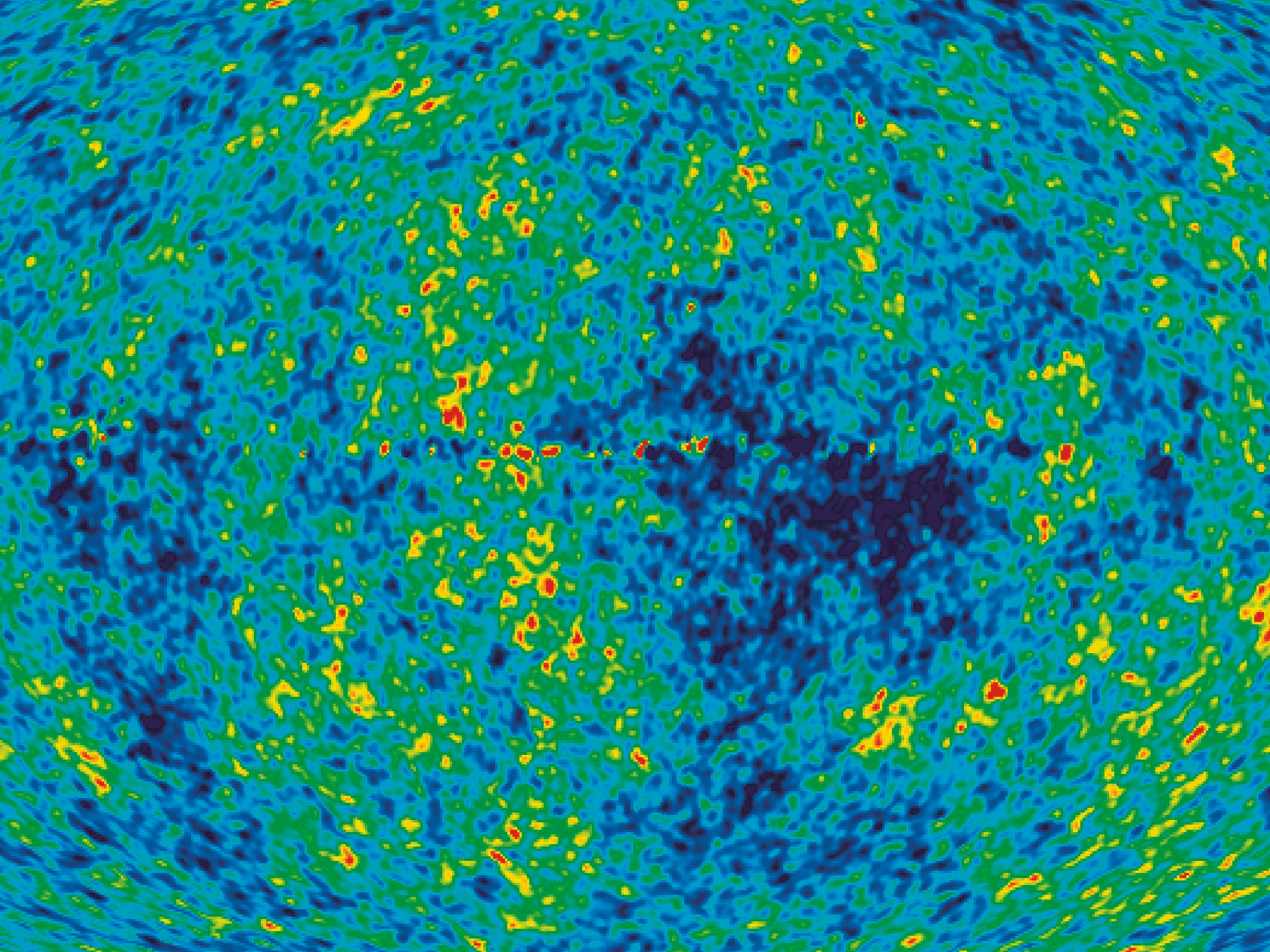
Our Origin

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

Kosmische Miso 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

Long Wavelength

Short Wavelength

TT

Amplitude of Waves [μK²]

6000

5000

4000

3000

2000

1000

0

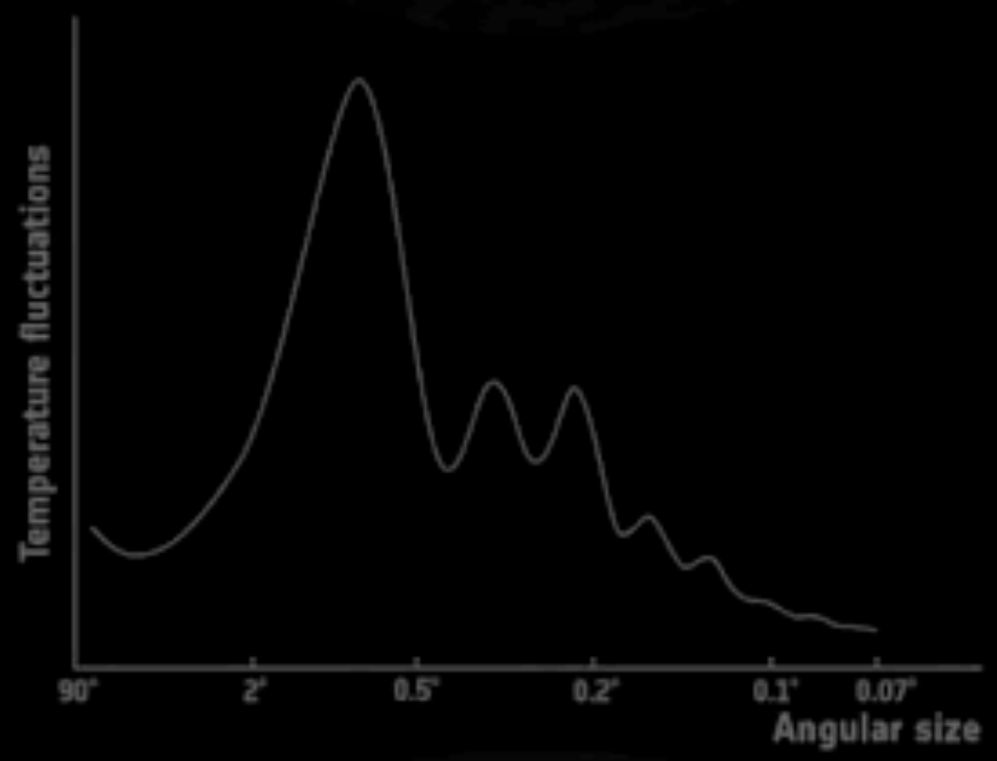
10

100

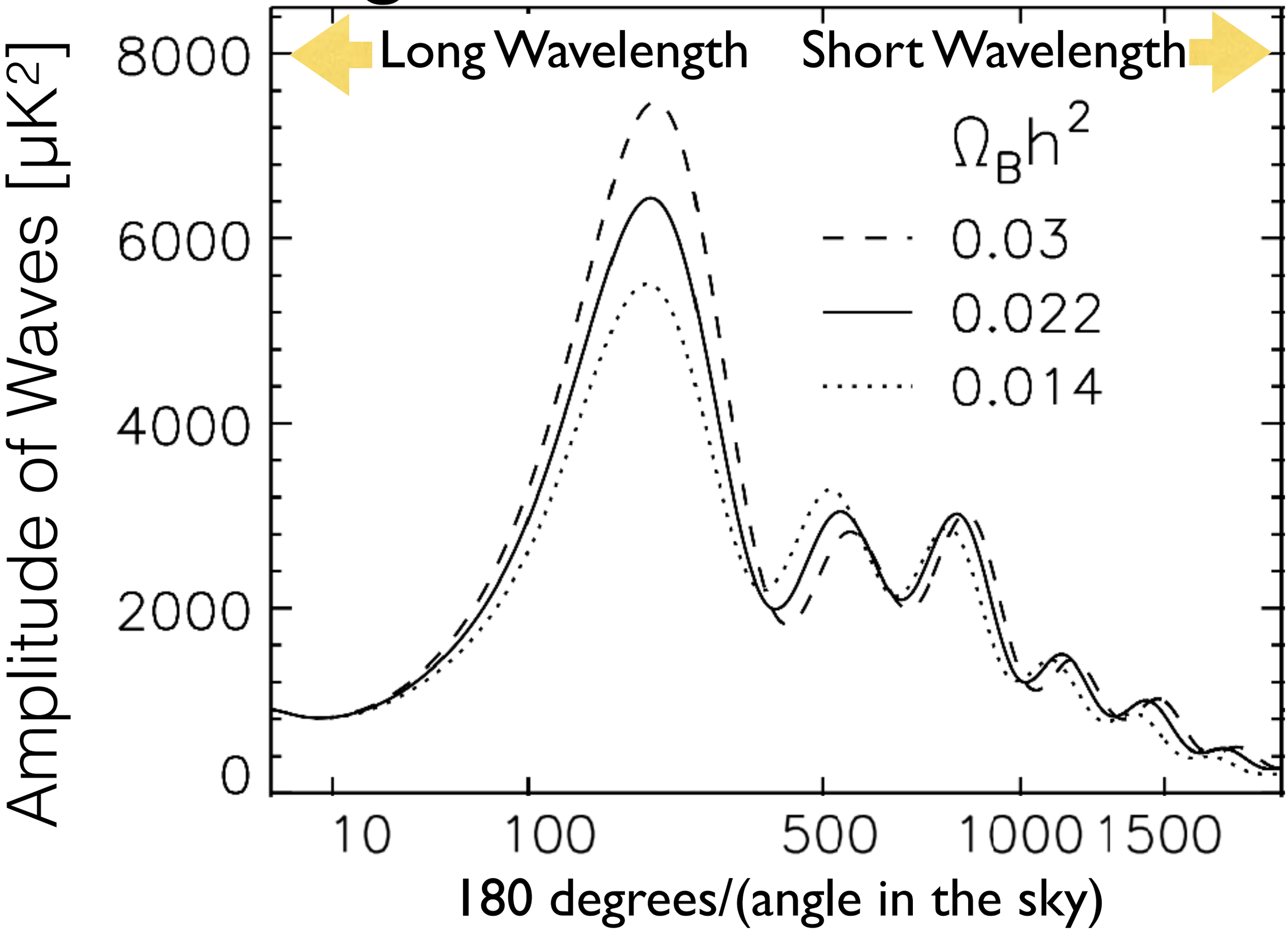
500

1000

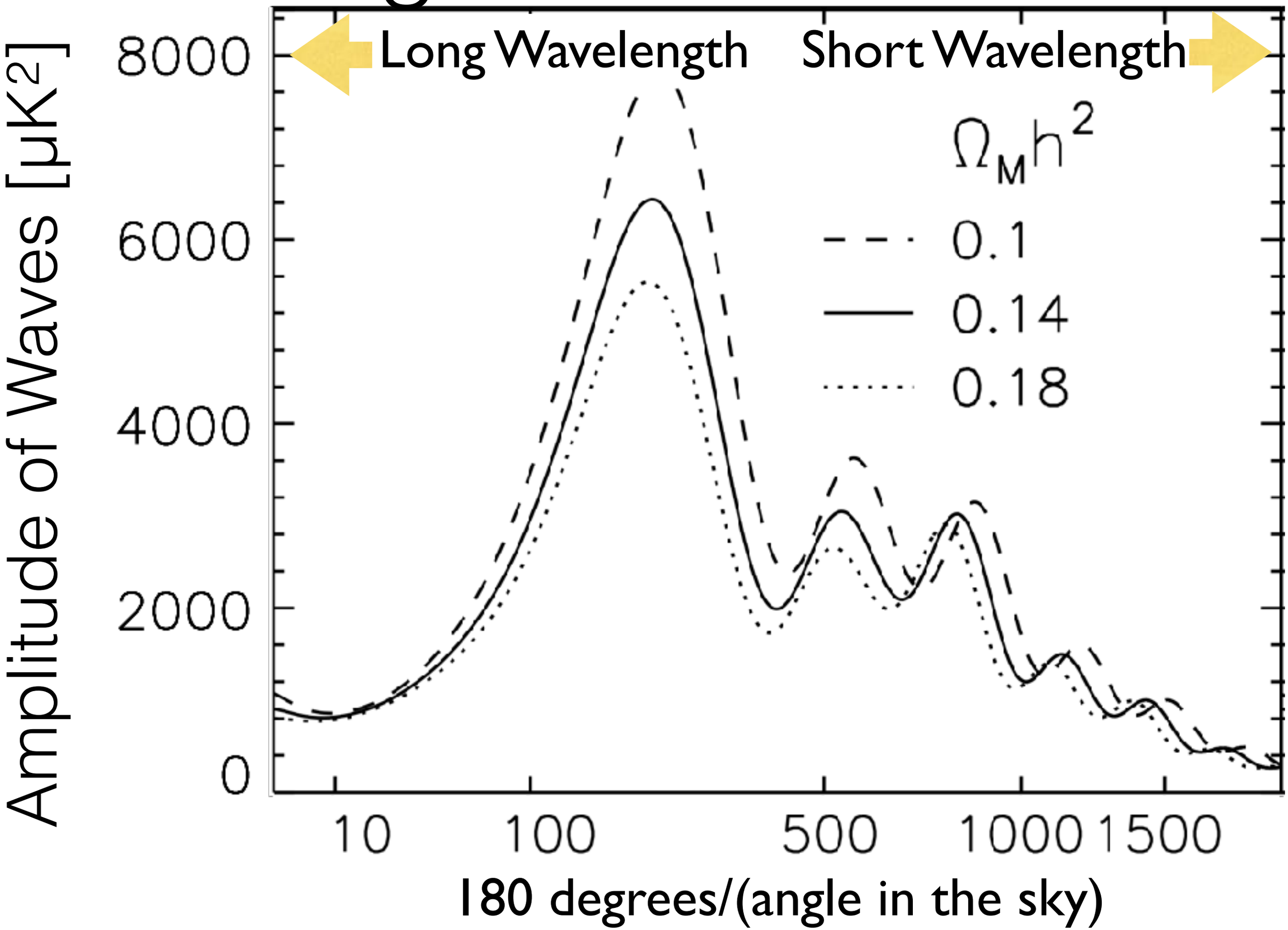
180 degrees/(angle in the sky)


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

Measuring Abundance of H&He



Measuring Total Matter Density



Long Wavelength

Short Wavelength

TT

Amplitude of Waves [μK²]

6000

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4000

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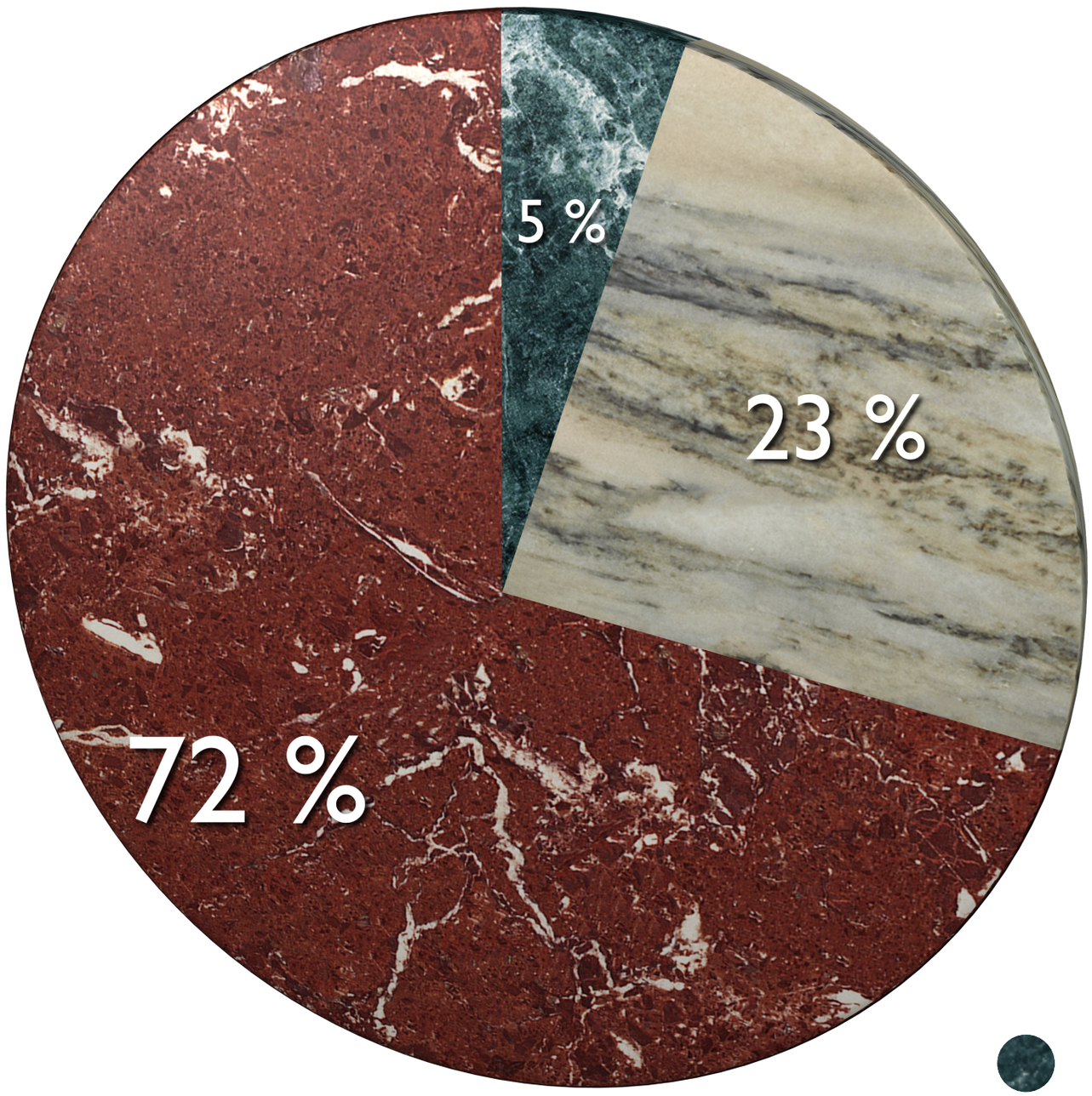
1000

180 degrees/(angle in the sky)

Cosmic Pie Chart



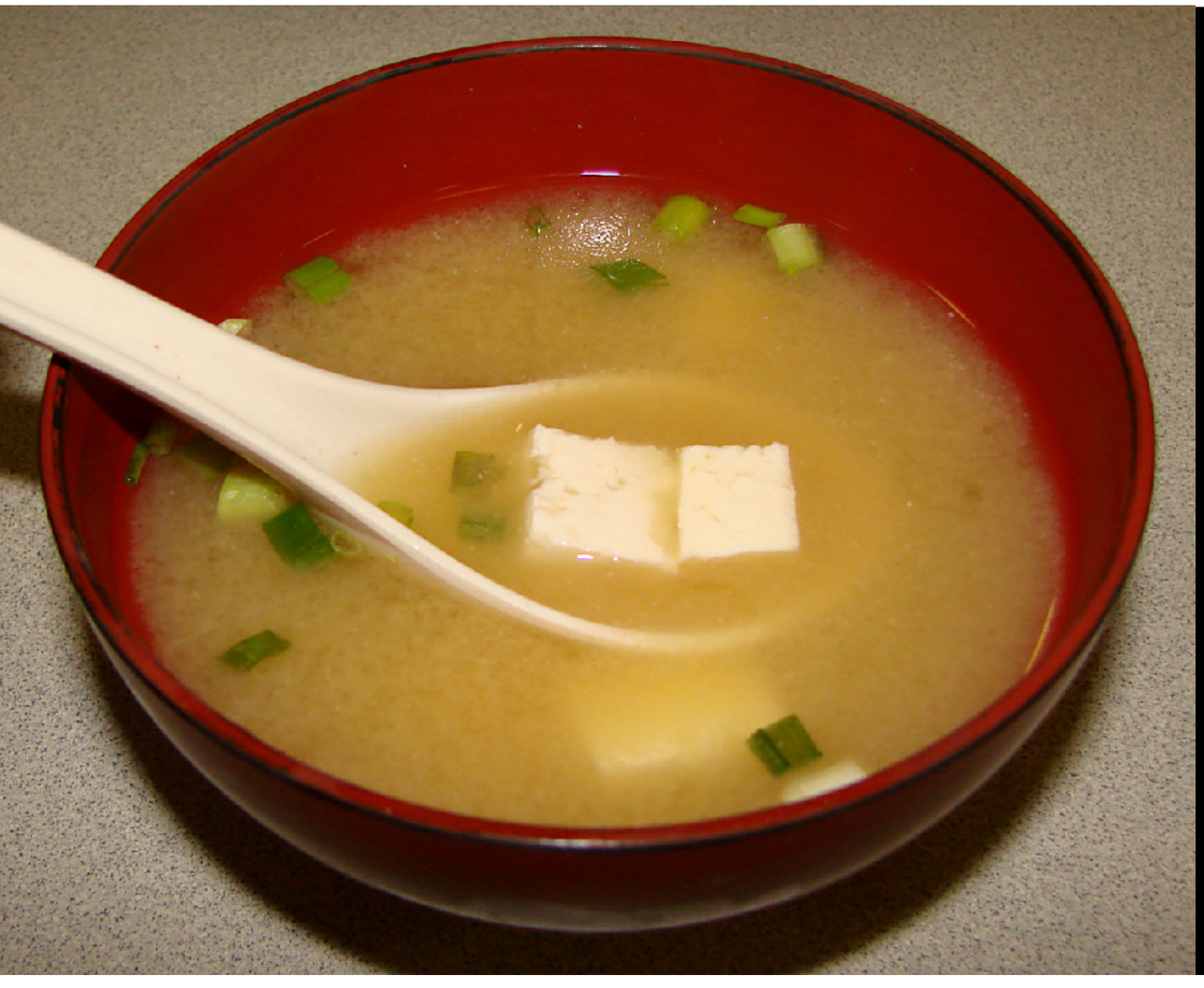
- WMAP determined the abundance of various components in the Universe

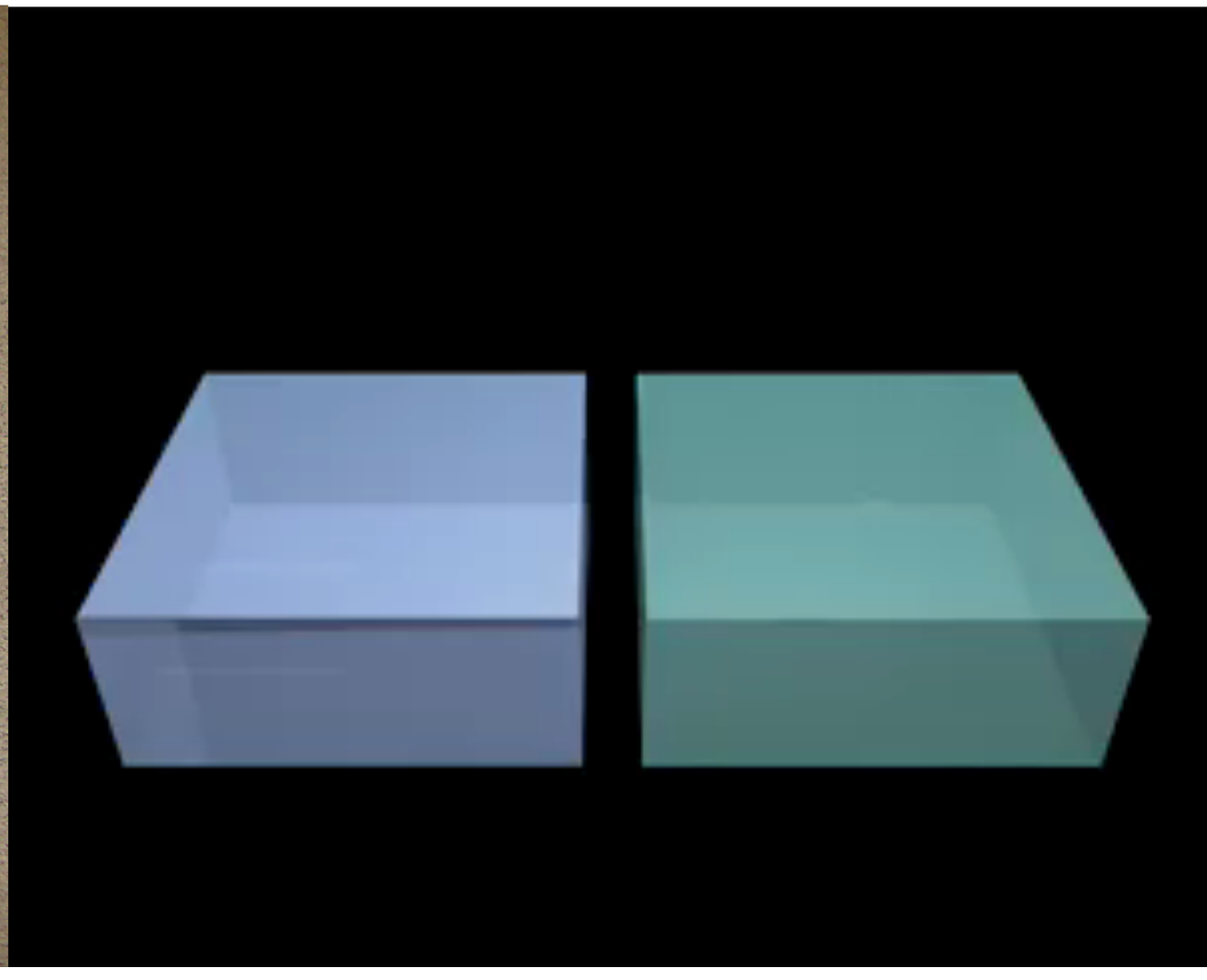
- As a result, **we came to realise that we do not understand 95% of our Universe...**

H&He
Dark Energy
Dark Matter

Origin of Fluctuations

- Who dropped those Tofus into the cosmic Miso soup?





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

Leading Idea

- **Quantum Mechanics at work in the early Universe**

- 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

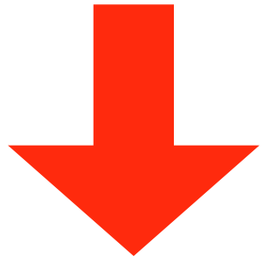
- In a tiny fraction of a second, the size of an atomic nucleus became the size of the Solar System

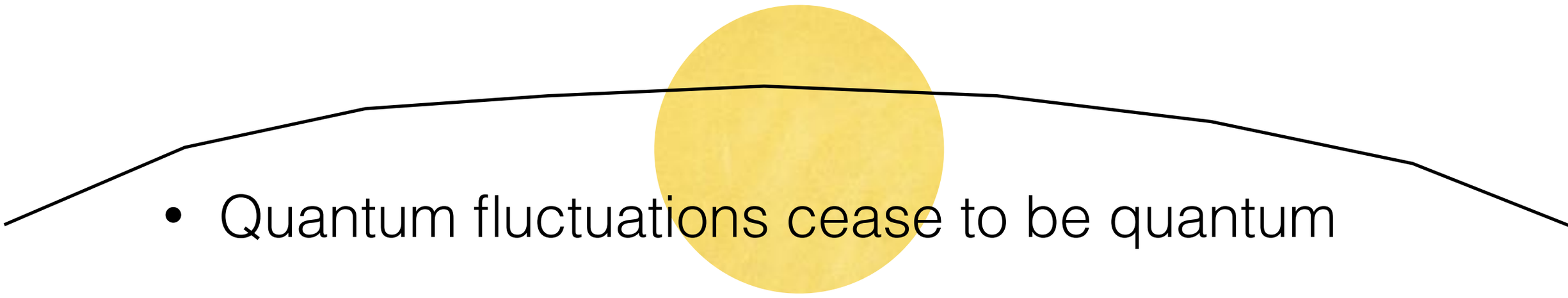
- In 10^{-36} second, space was stretched by at least a factor of 10^{26}

Stretching Micro to Macro

Quantum fluctuations on microscopic scales

Inflation!





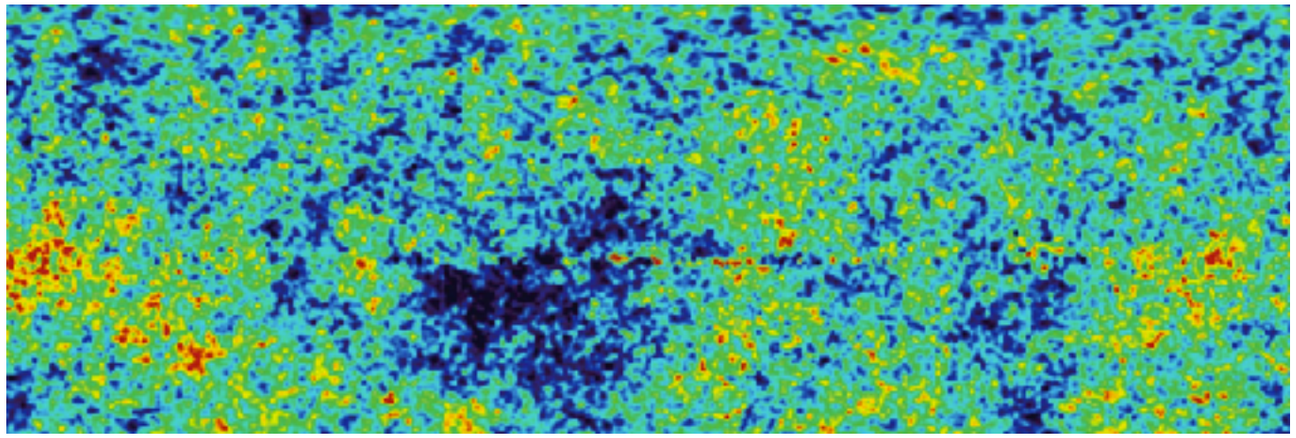
- Quantum fluctuations cease to be quantum
- Become macroscopic, classical fluctuations

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

Long Wavelength

Short Wavelength

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)

Long Wavelength

Short Wavelength

Removing Ripples:

Power Spectrum of Primordial Fluctuations

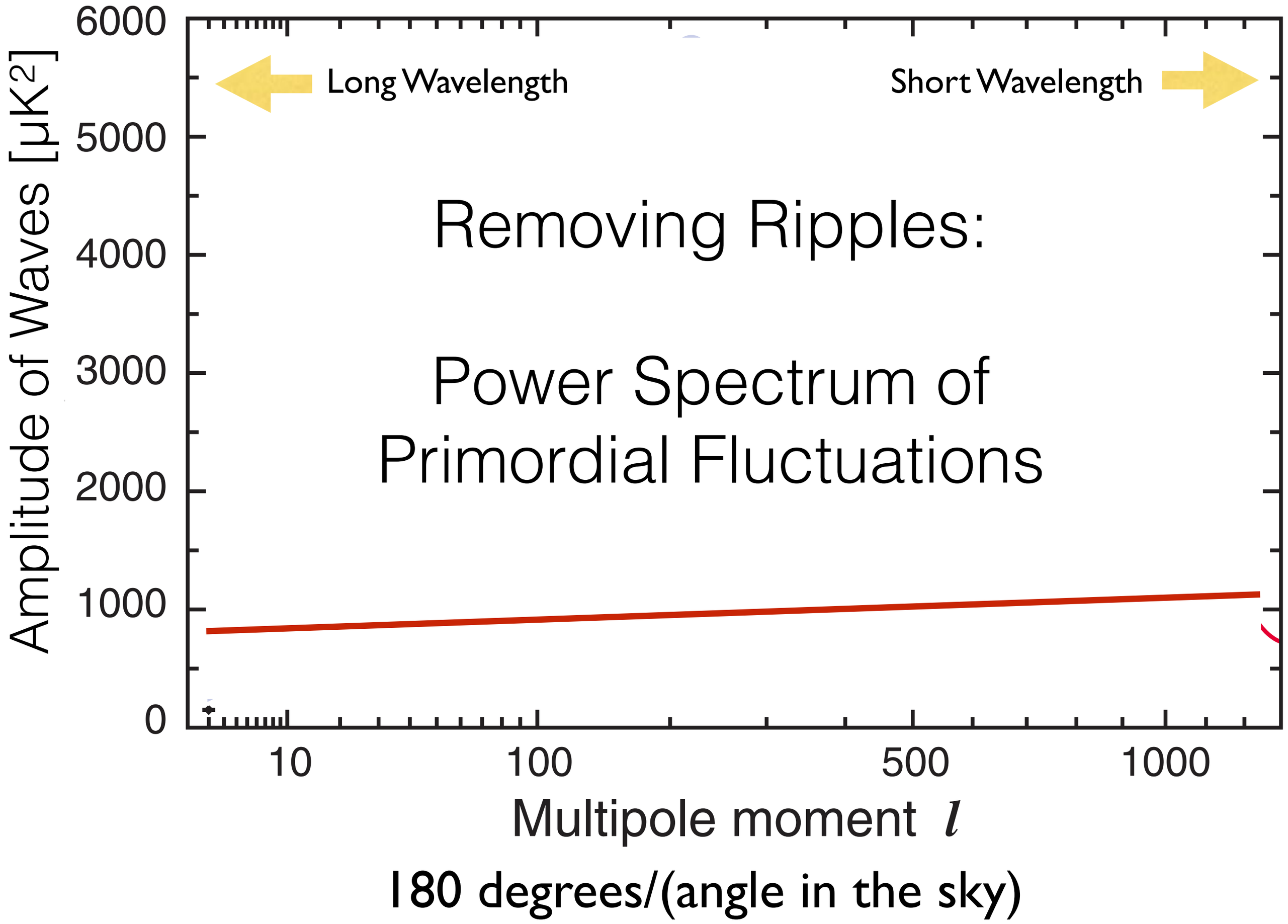
Amplitude of Waves [μK^2]

6000
5000
4000
3000
2000
1000
0

10
100
500
1000

Multipole moment l

180 degrees/(angle in the sky)


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

Long Wavelength

Short Wavelength

Removing Ripples:

Power Spectrum of Primordial Fluctuations

Amplitude of Waves [μK^2]

6000
5000
4000
3000
2000
1000
0

10
100
500
1000

Multipole moment l

180 degrees/(angle in the sky)

Long Wavelength

Short Wavelength

Let's parameterise like

$$\text{Wave Amp.} \propto \ell^{n_s - 1}$$

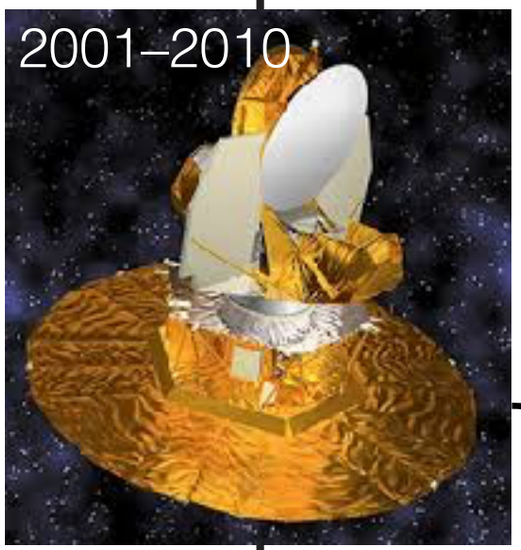
Amplitude of Waves [μK²]

6000
5000
4000
3000
2000
1000
0

10
100
500
1000

Multipole moment l

180 degrees/(angle in the sky)



WMAP 9-Year Only:

n_s=0.972±0.013 (68%CL)

$$\text{Wave Amp.} \propto \ell^{n_s-1}$$

Long Wavelength

Short Wavelength

Amplitude of Waves [μK²]

6000
5000
2000
1000
0

10
100
500
1000

Multipole moment l

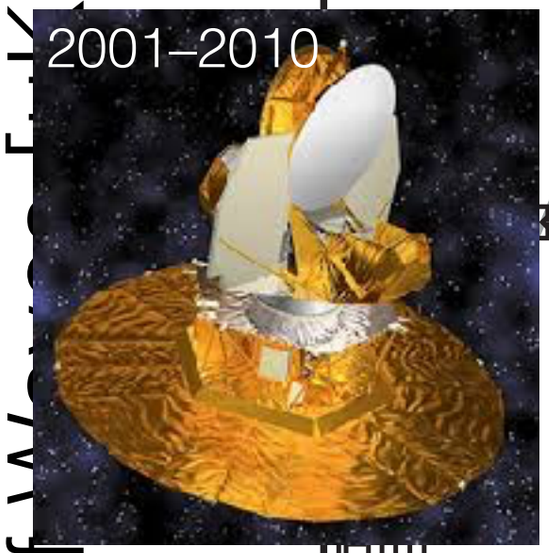
180 degrees/(angle in the sky)

Angular scale

90° 2° 0.5° 0.2° 0.1°

Amplitude of [μK^2]

2001–2010



South Pole Telescope
[10-m in South Pole]

Atacama Cosmology Telescope
[6-m in Chile]

100

10 100 500 1000 2000

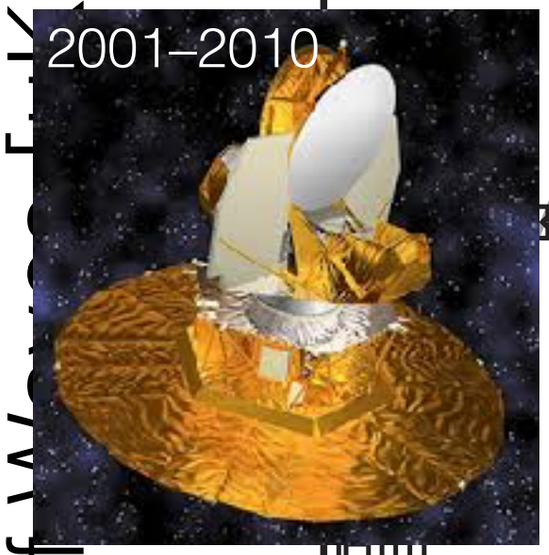
Multipole moment l

Angular scale

90° 2° 0.5° 0.2° 0.1°

Amplitude of Wave [μK^2]

2001–2010



South Pole Telescope
[10-m in South Pole]

n_s=0.965±0.010

Atacama Cosmology Telescope
[6-m in Chile]

100

10 100 500 1000 2000

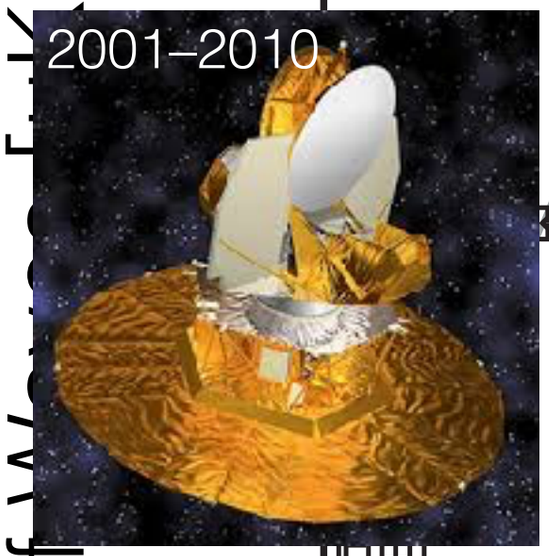
Multipole moment l

Angular scale

90° 2° 0.5° 0.2° 0.1°

Amplitude of [μK^2]

2001–2010



South Pole Telescope
[10-m in South Pole]

n_s=0.961±0.008

~5σ discovery of n_s<1 from the CMB data combined with SDSS

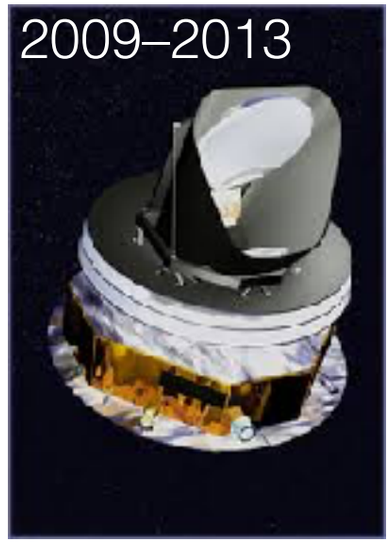
Atacama Cosmology Telescope
[6-m in Chile]

100

10 100 500 1000 2000

Multipole moment l

Planck 2013 Result!



Residual Amplitude of Waves [μK²]

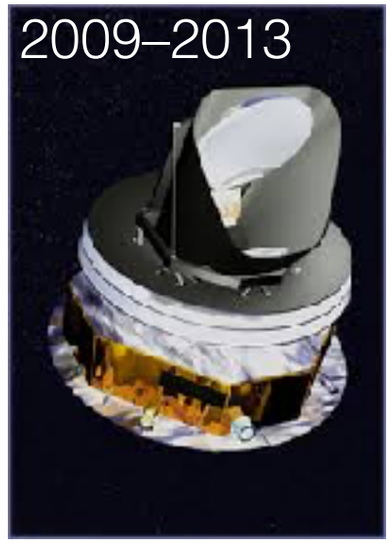
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000

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

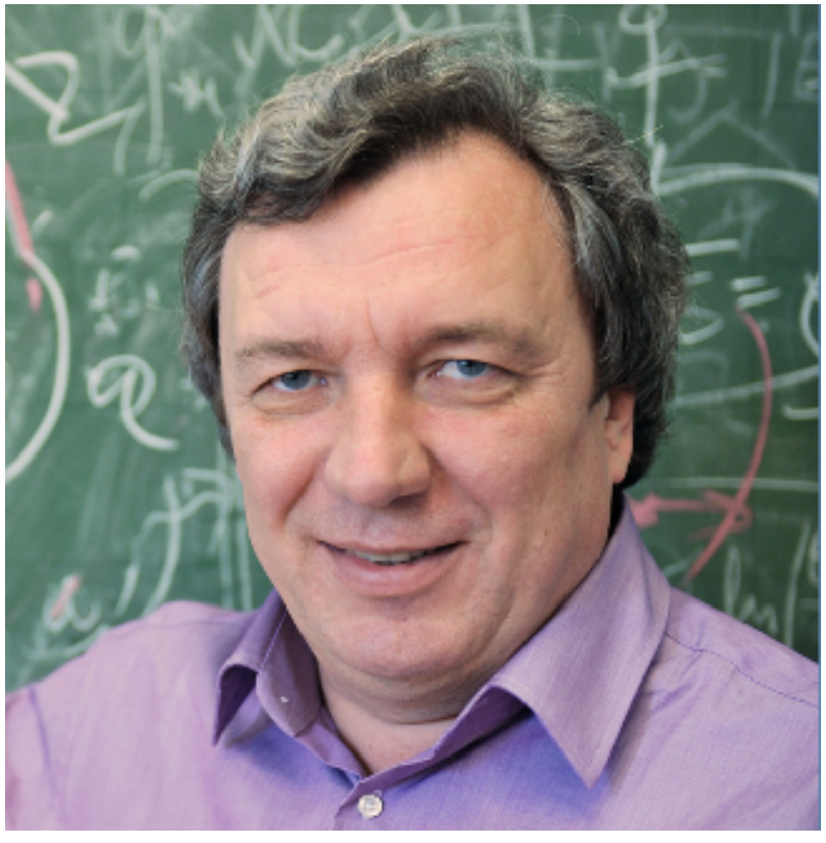


Residual Amplitude of Waves [μK²]

180 degrees/(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 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)

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

0.1
0.01
0.001
.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]

W band

Histogram: WMAP Data

Red Line: Gaussian

YES!!

Fraction of the Number of Pixels Having Those Temperatures

0.1

0.01

0.001

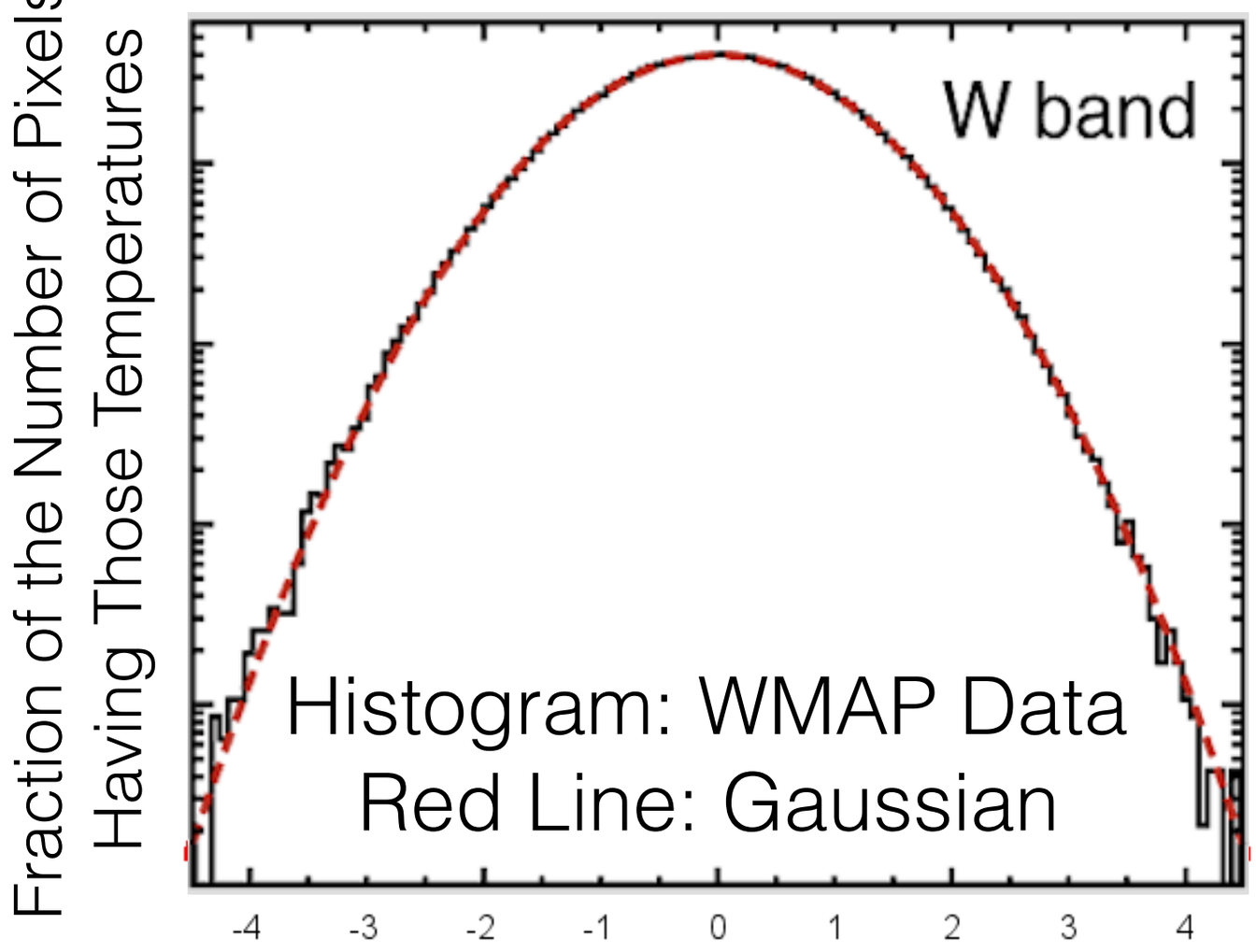
.0001

1e-05

-4 -3 -2 -1 0 1 2 3 4

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

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

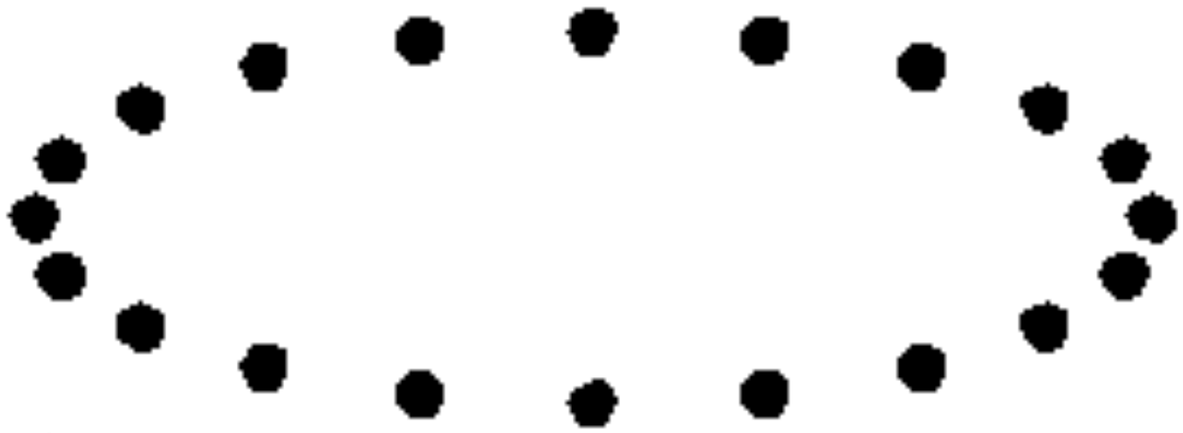
Primordial Gravitational Waves

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

Measuring GW

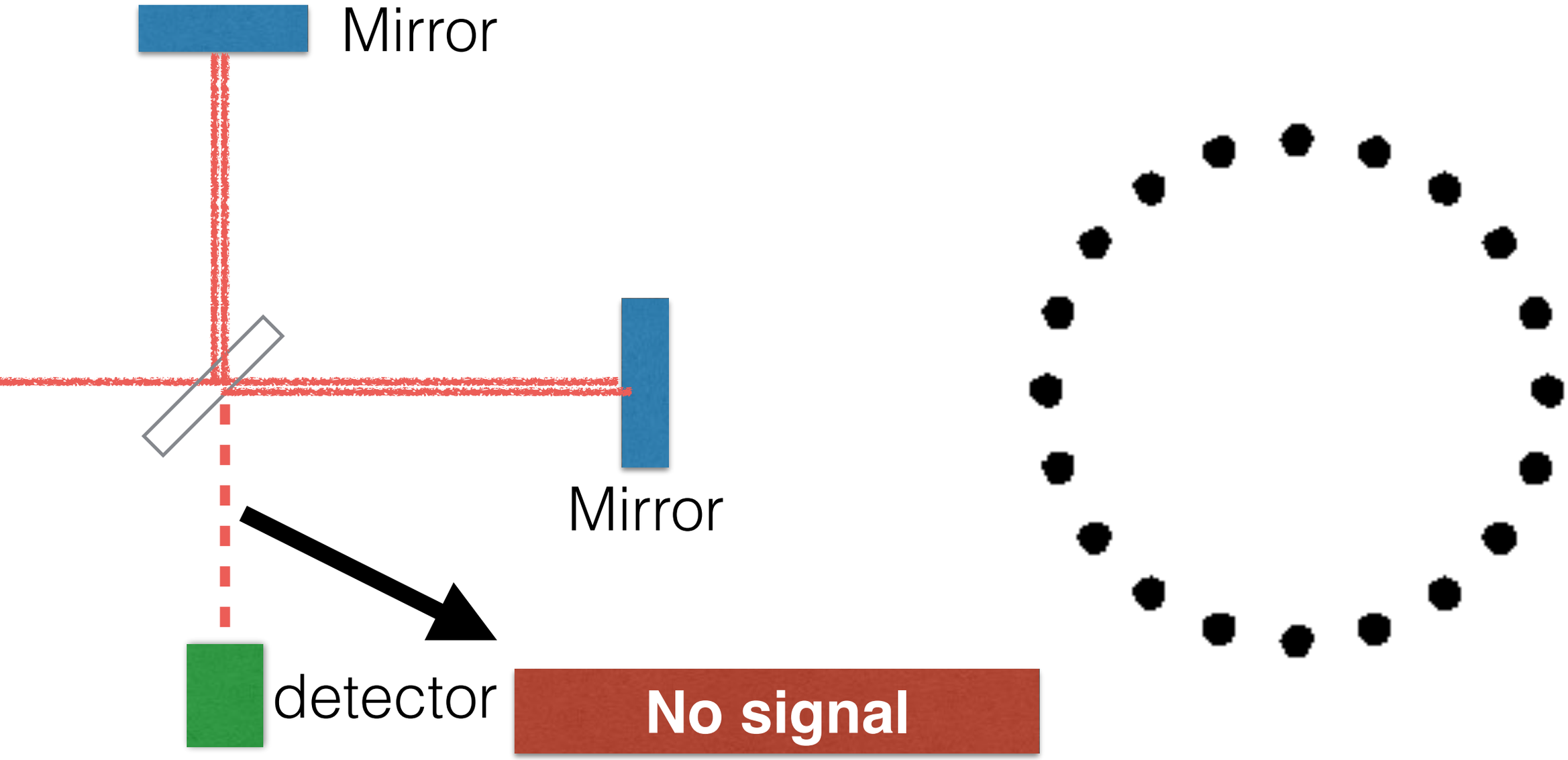
- GW changes the distances between two points

$$d\ell^2 = d\mathbf{x}^2 = \sum_{ij} \delta_{ij} dx^i dx^j$$

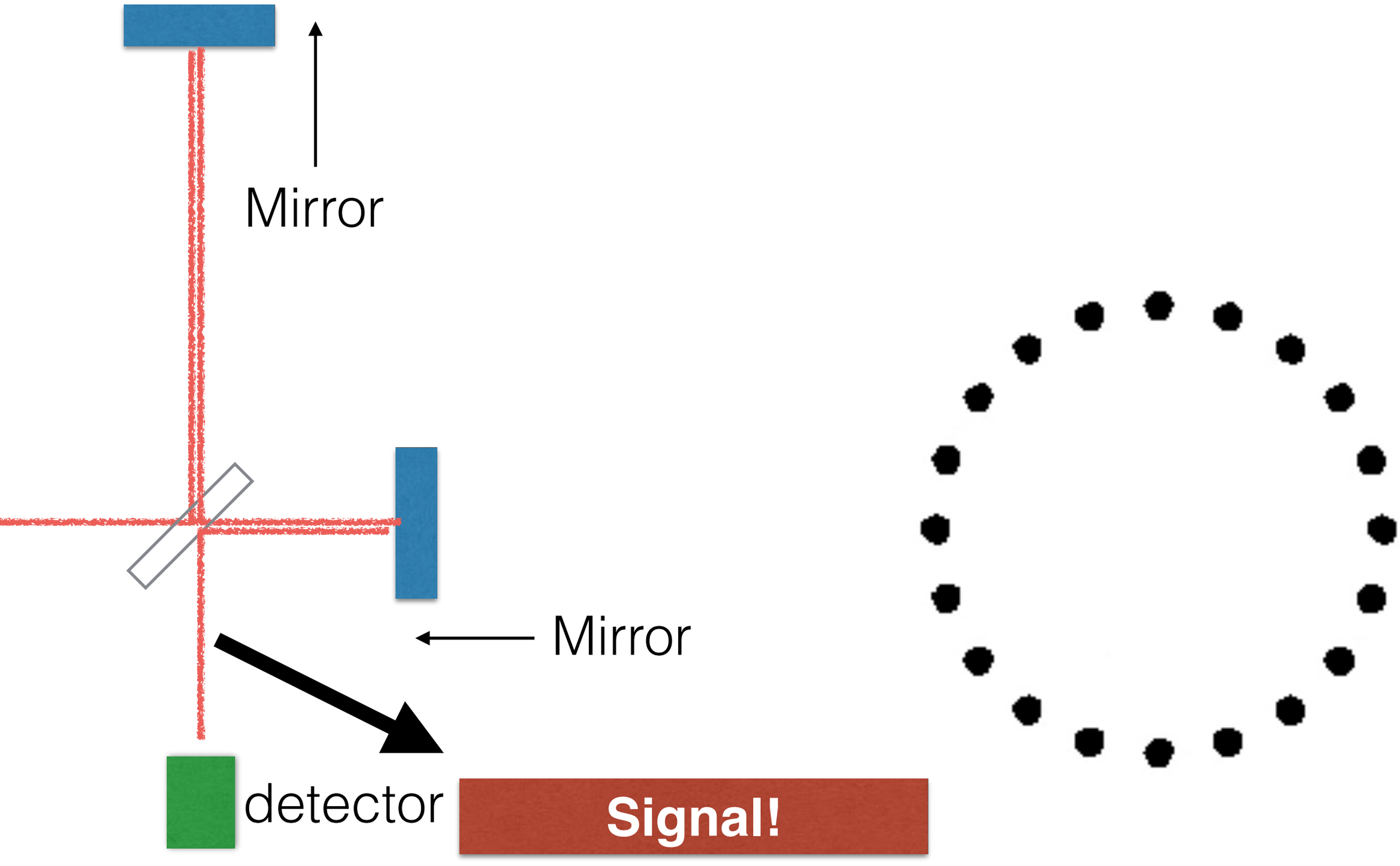


$$d\ell^2 = \sum_{ij} (\delta_{ij} + h_{ij}) dx^i dx^j$$

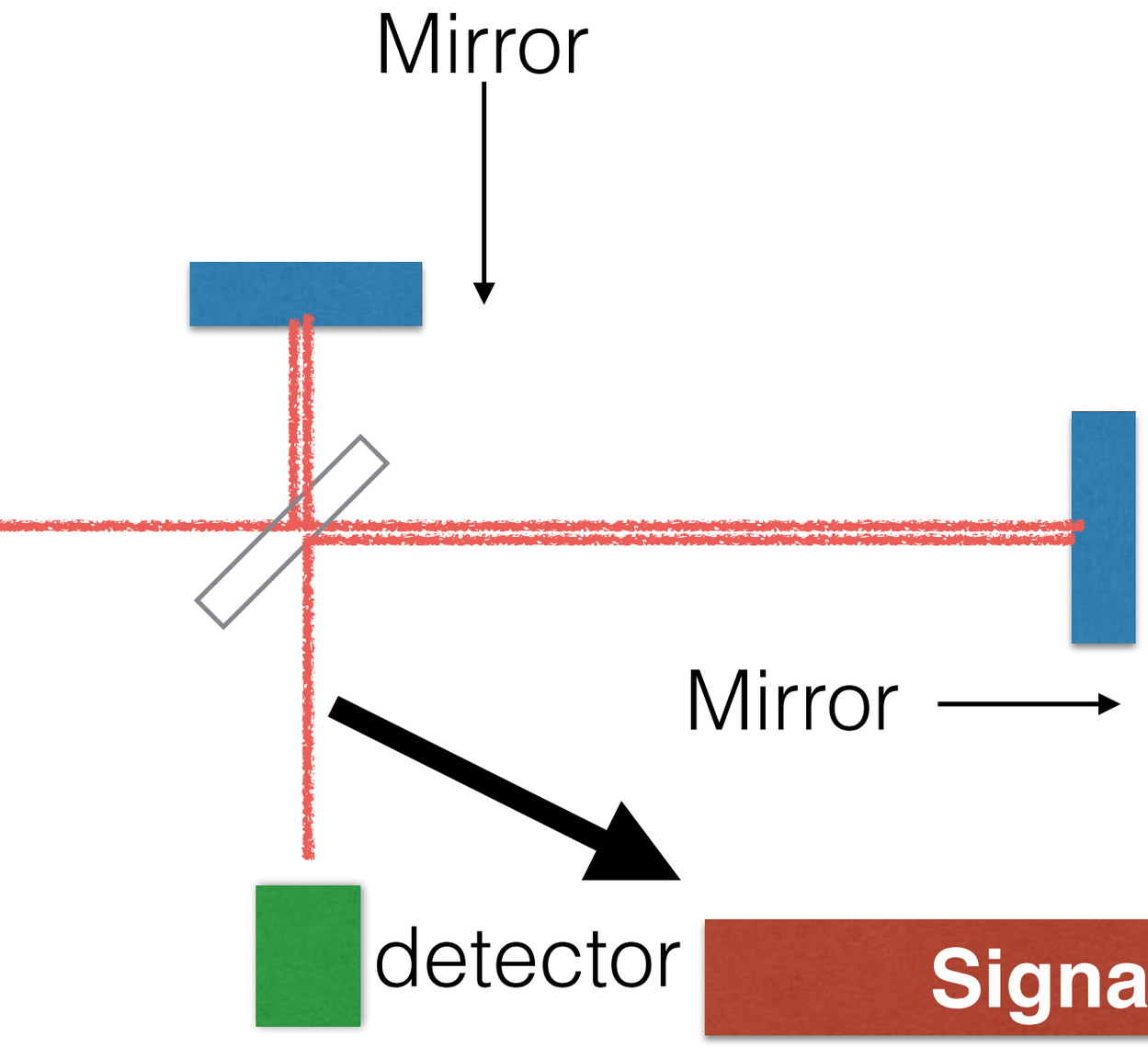
Laser Interferometer

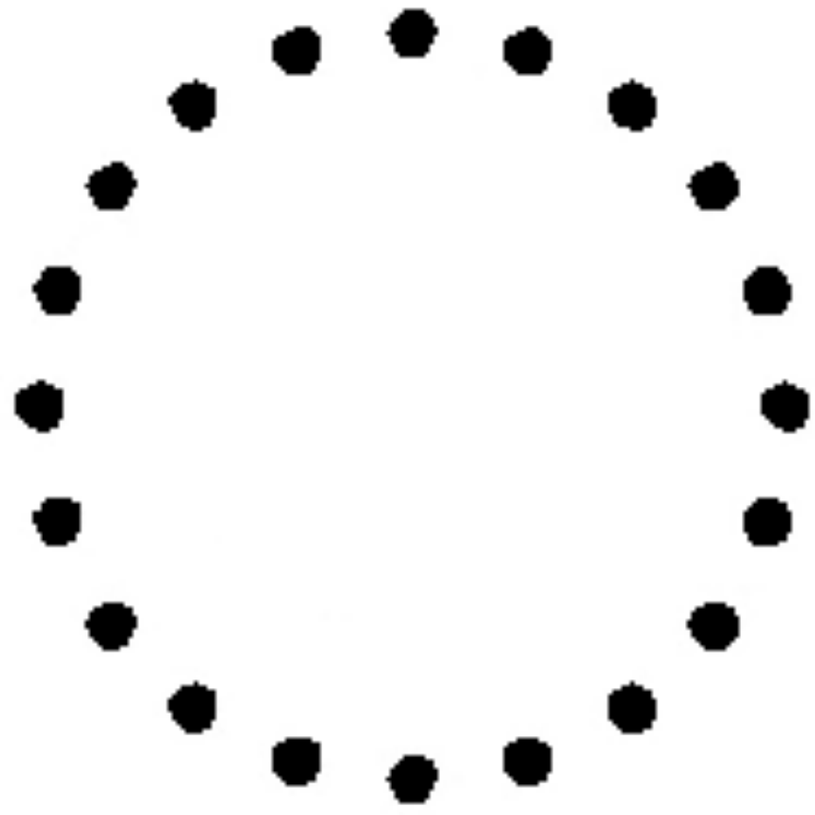


Laser Interferometer



Laser Interferometer





LIGO detected GW from binary blackholes, with the wavelength of thousands of kilometres

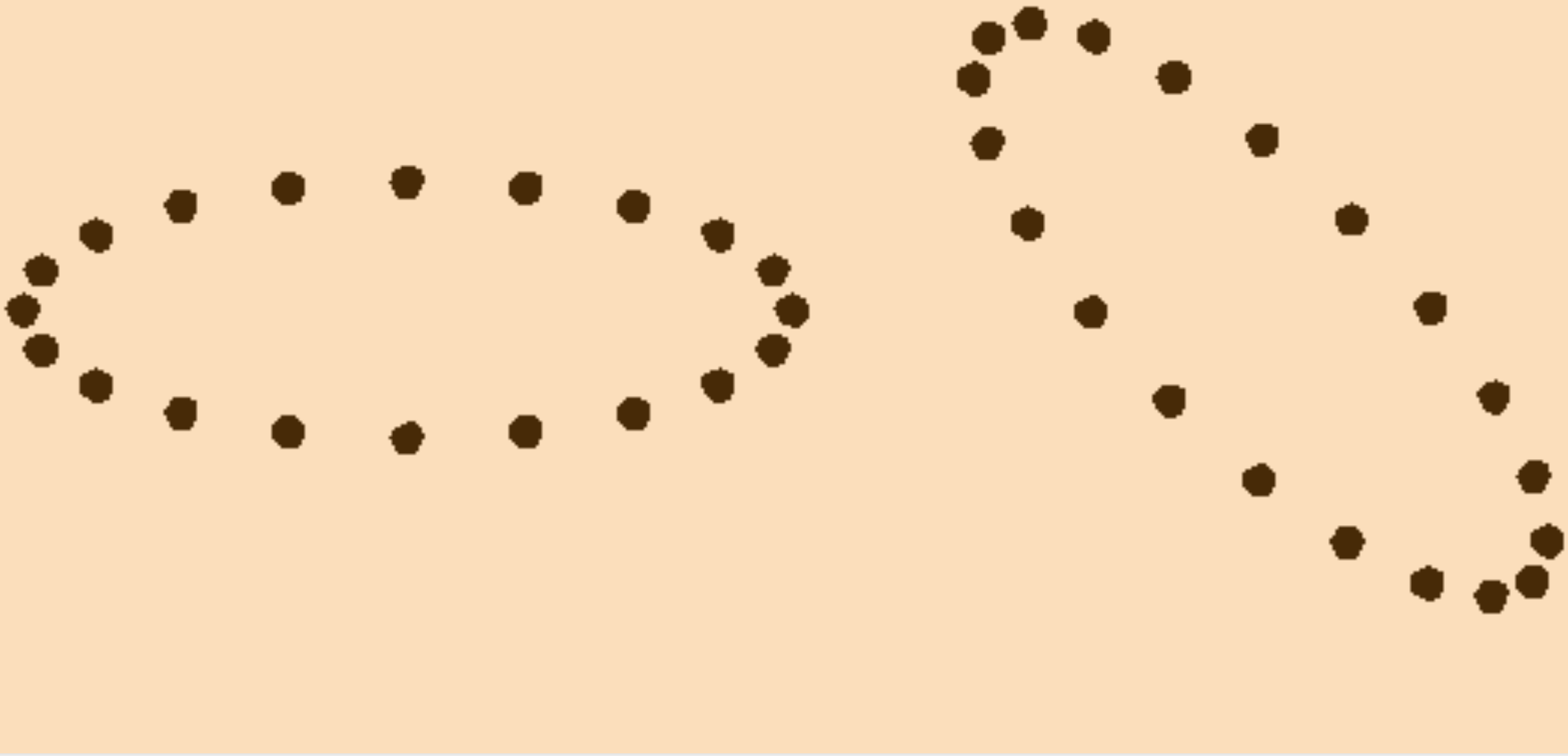
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

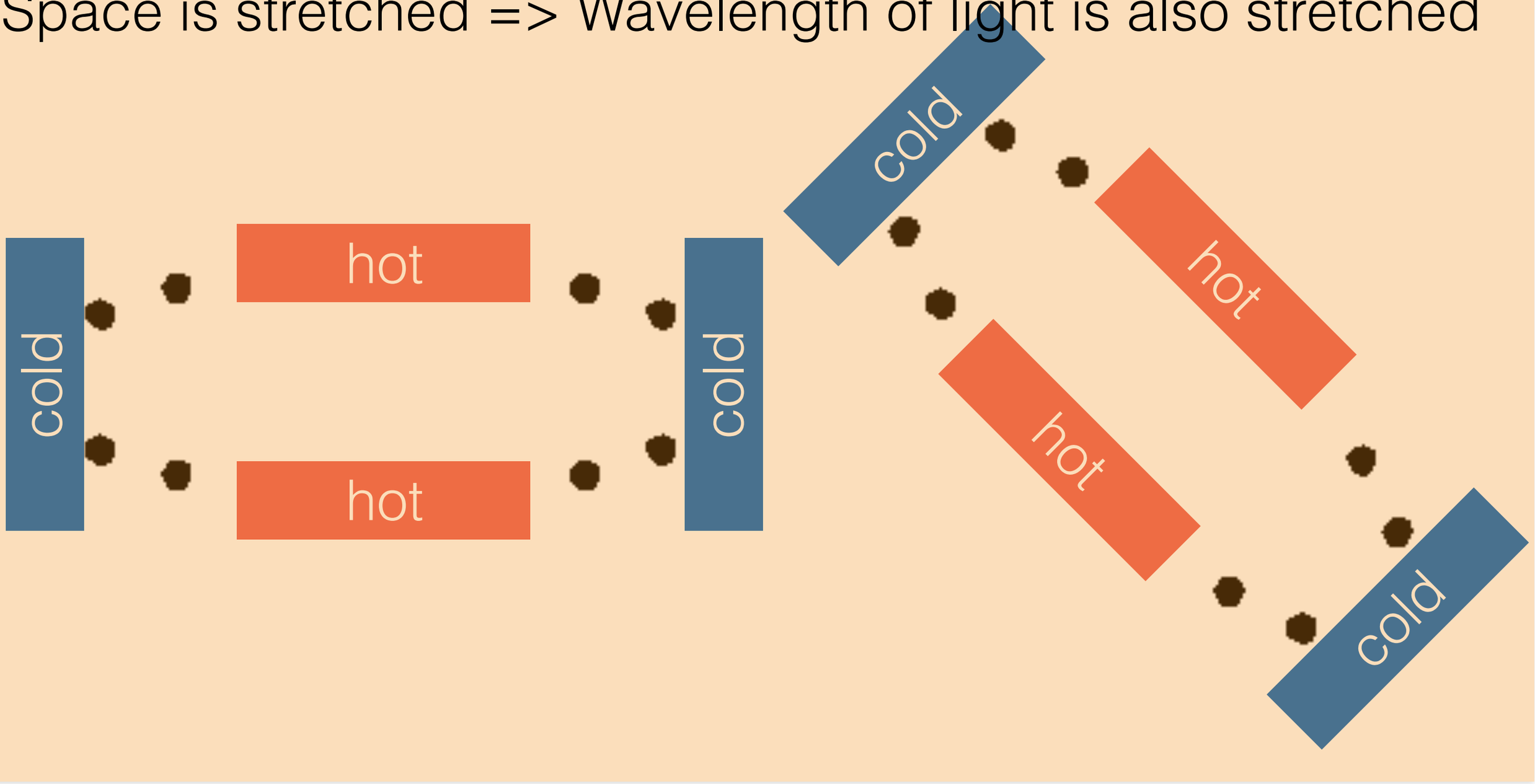
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



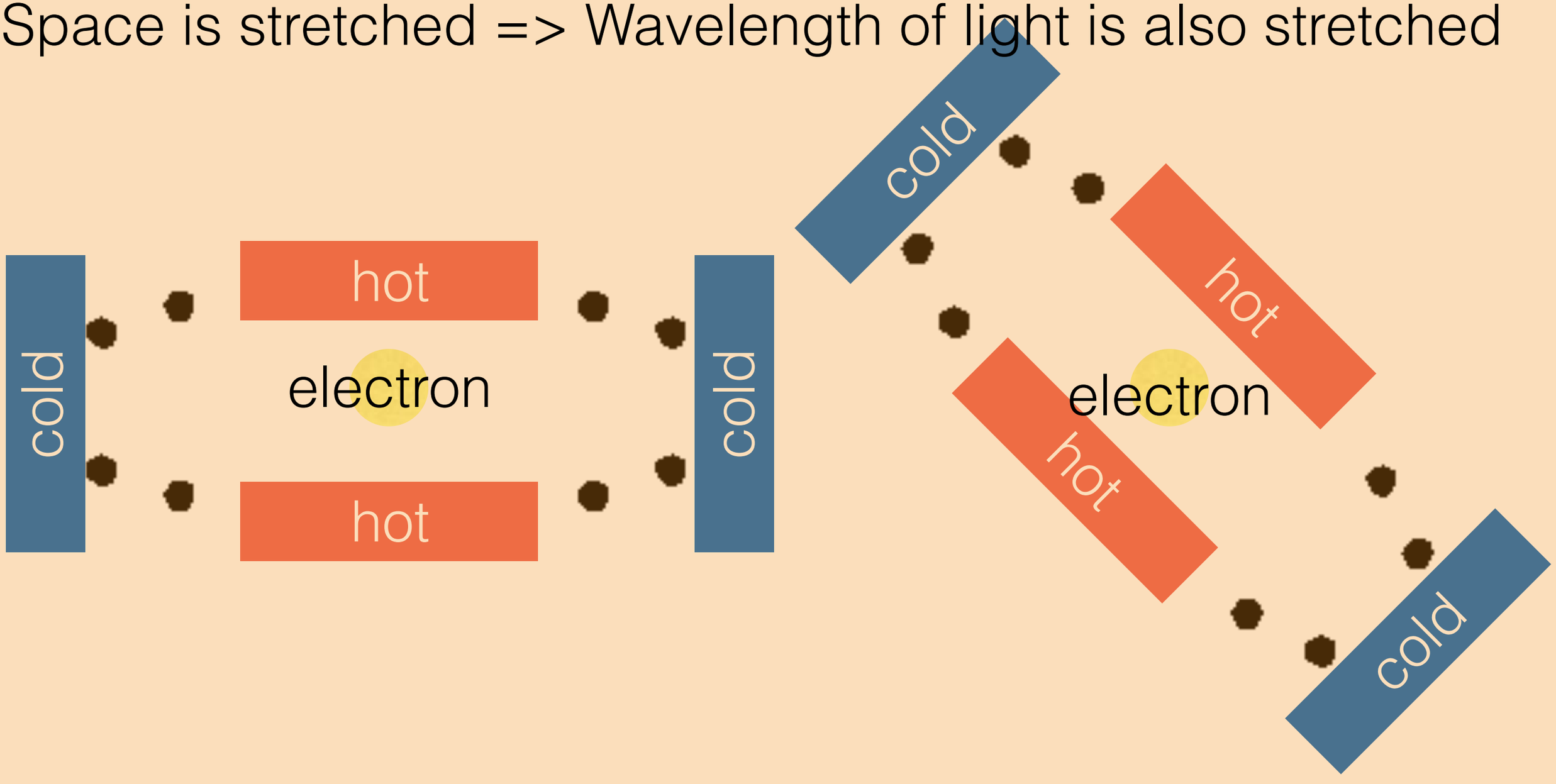
Detecting GW by CMB

Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB
Polarisation

Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB
Polarisation

Space is stretched => Wavelength of light is also stretched

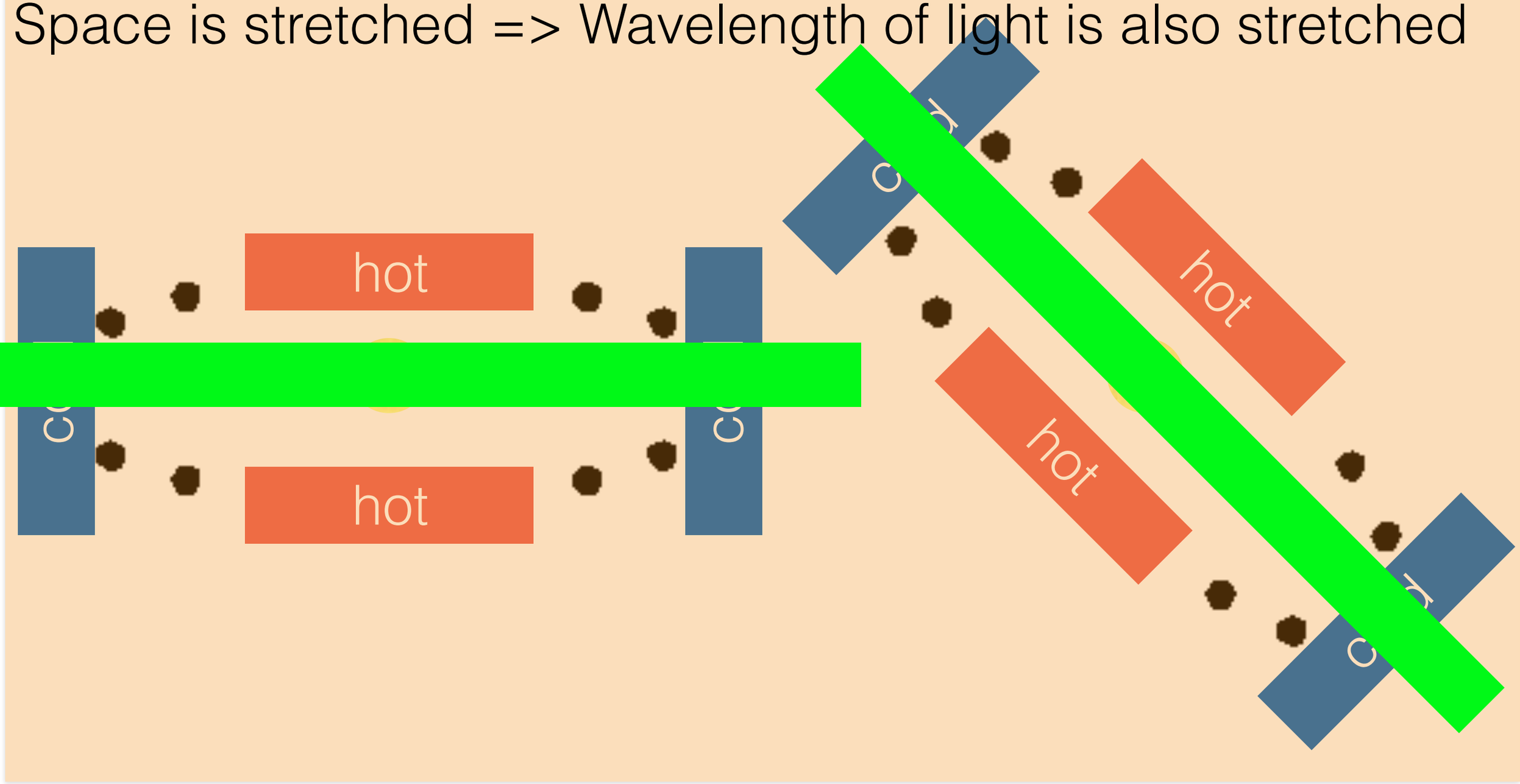


Photo Credit: TALEX

Photo Credit: TALEX

If polarisation from GW is found…

- Then what?

- The next step is to nail the specific model of inflation

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<0.07

WMAP(temp+pol)+ACT+SPT+BAO+H_0

WMAP(pol) + Planck + BAO

N=	50	60
ruled out! $\lambda\phi^4$	●	●
$m^2\phi^2$	○	○
$\mu^3\phi$	○	○
R^2 Inflation	○	○
HZ	■	

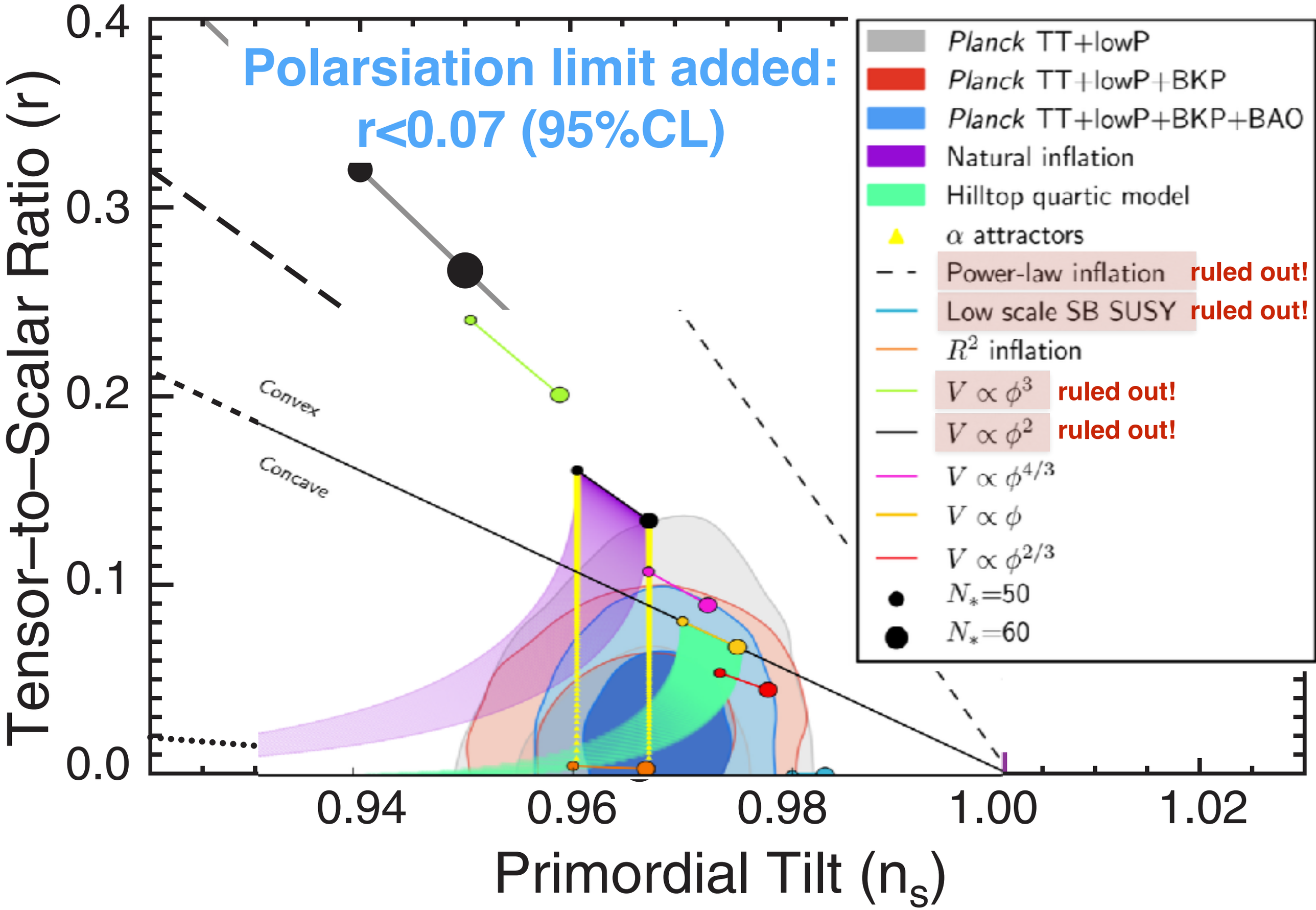
Tensor–to–Scalar Ratio (r)

0.4
0.3
0.2
0.1
0.0

0.94
0.96
0.98
1.00
1.02

Primordial Tilt (n_s)

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



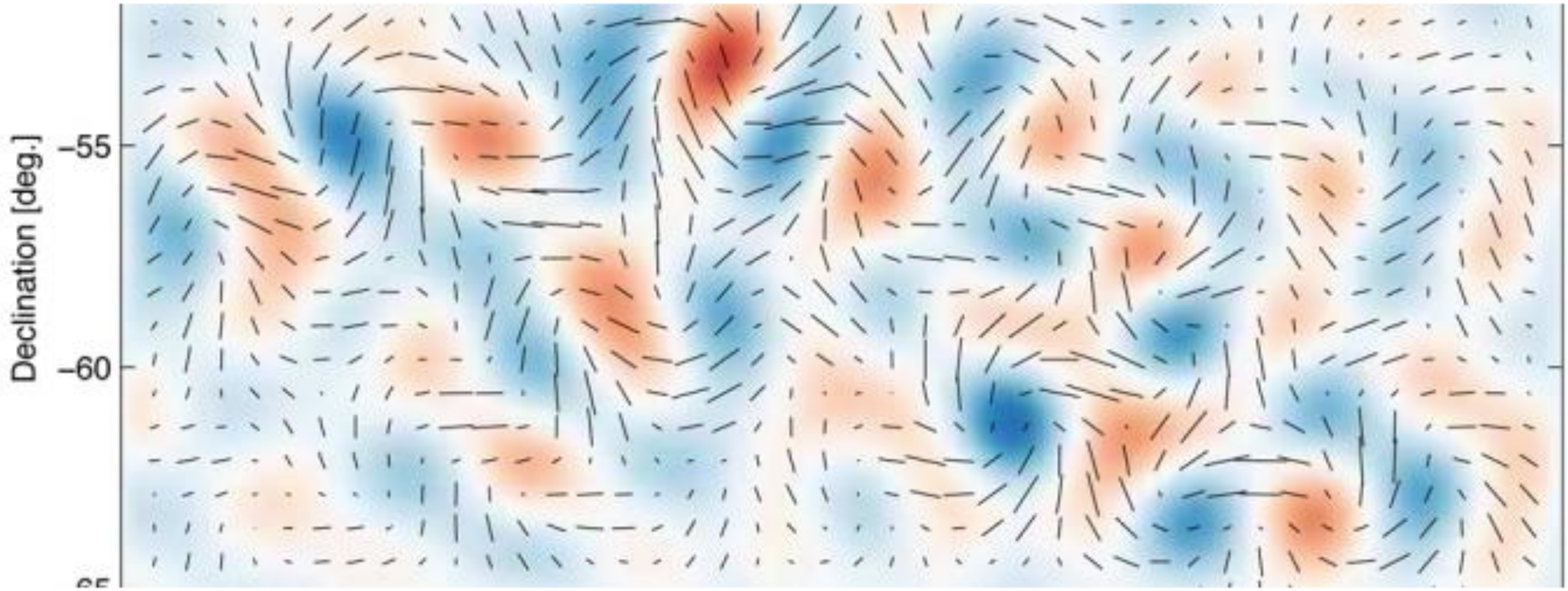
March 17, 2014

BICEP2's announcement

First Direct Evidence of Cosmic Inflation

Release No.: 2014-05

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



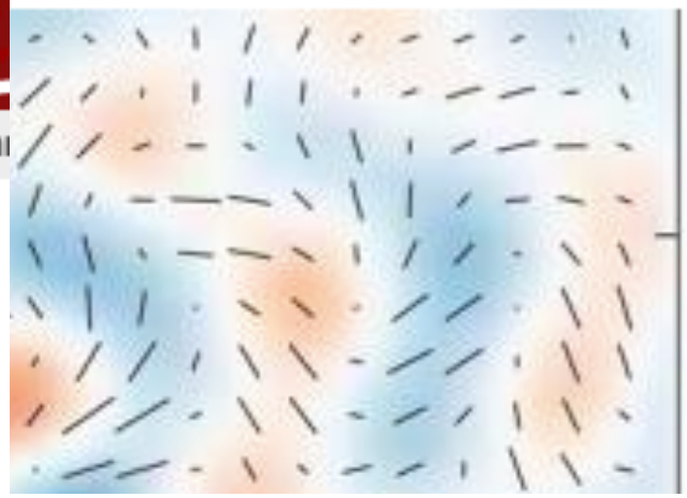
Cambridge, MA - Almost 14 billion years ago, the universe we inhabit burst into existence in an extraordinary event that initiated the Big Bang. In the first fleeting fraction of a second, the universe expanded exponentially, stretching far beyond the view of our best telescopes. All this, of course,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

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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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Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos
Science correspondent, BBC News

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1. Februar 2015, 22:19 Kosmologie

Urknall-Forscher gestehen Irrtum ein

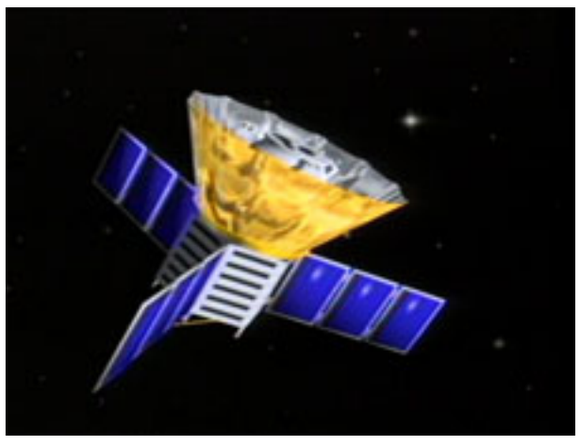
Von Marlene Weiß

Current Situation

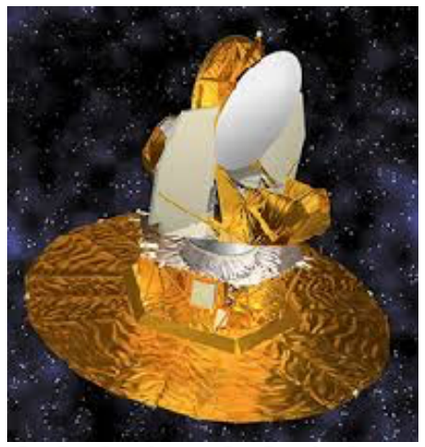
- Planck shows the evidence that the detected signal is not cosmological, but is due to dust

- No strong evidence that the detected signal is cosmological

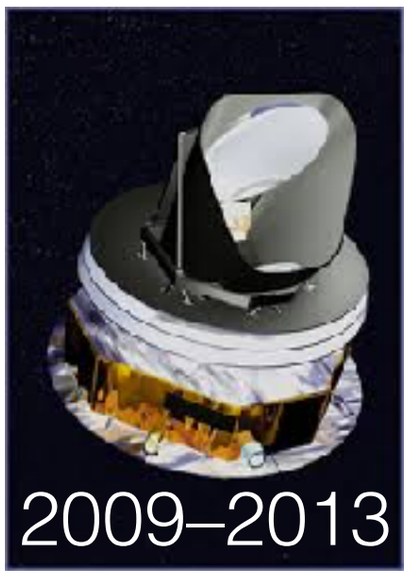
The search continues!!



1989–1993



2001–2010



2009–2013

202X–

JAXA

+ possibly NASA

LiteBIRD

2025– [proposed]

Target 1σ uncertainty:

$\delta r = 10^{-3}$

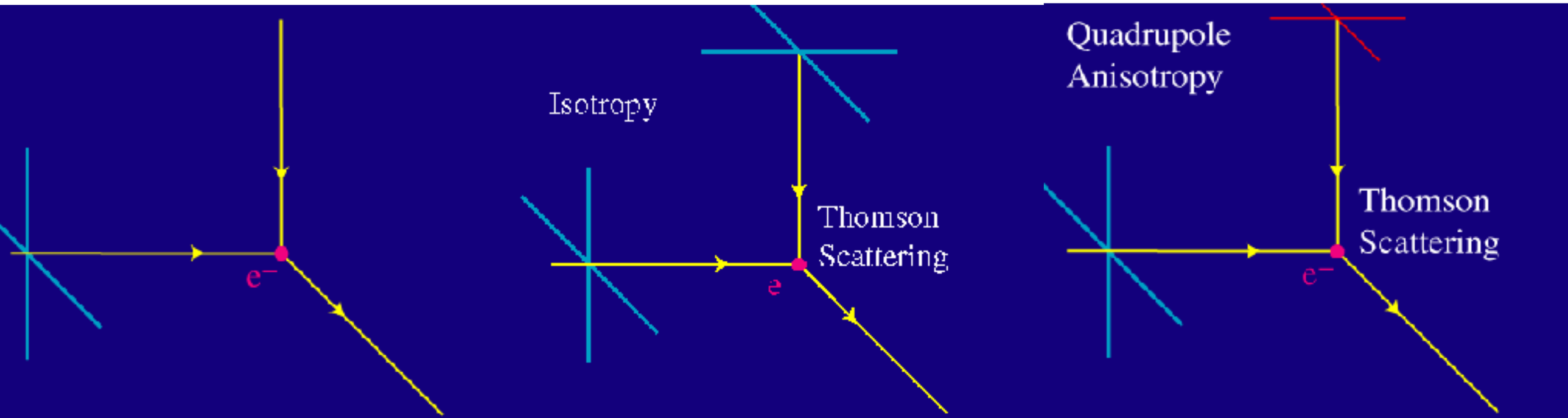
Conclusion

- 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 polarisation from gravitational waves

- **LiteBIRD** proposal: a CMB polarisation satellite in 2025

Physics of CMB Polarisation



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