

Cosmic Microwave Background: Seeing the Early Universe

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
Elitenetzwerk FORUM, January 26, 2015

Seeing the Early Universe

- Astronomers often talk about the early Universe as if they were there to see it...
- The stories told by astronomers are remarkable, but aren't they just imaginations of astronomers?
- Although we cannot be there physically, **we can observe the phenomena in the early Universe using powerful telescopes**
- We are not making stuff up!

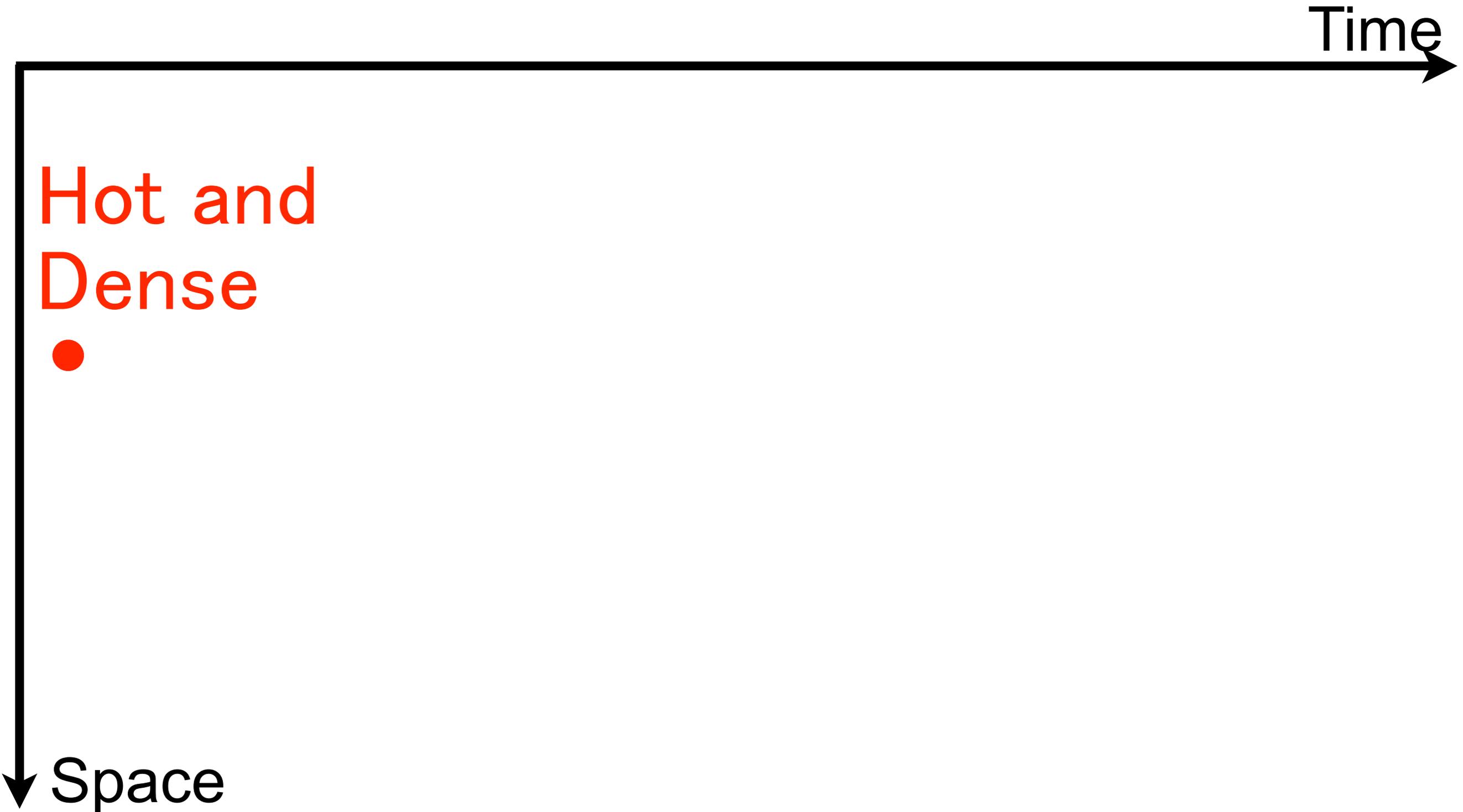
Seeing the Early Universe

- The goal of my presentation is to show you how we are seeing and studying the early Universe directly using the **light from the epoch of the fireball Universe**
- For the next 45 minutes, you will be hearing the well-established results from a series of observations and measurements made over the last half century
- So, please sit back and enjoy learning about what it is like to ***see the early Universe***



Fireball Universe

Time



Hot and
Dense

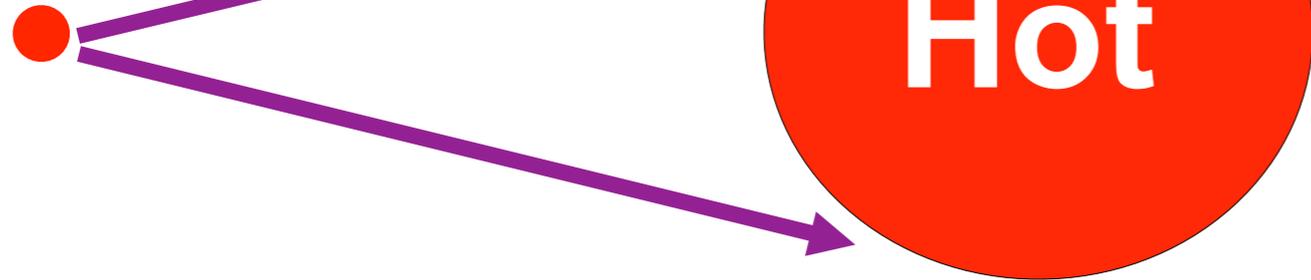


Space

Fireball Universe

Time

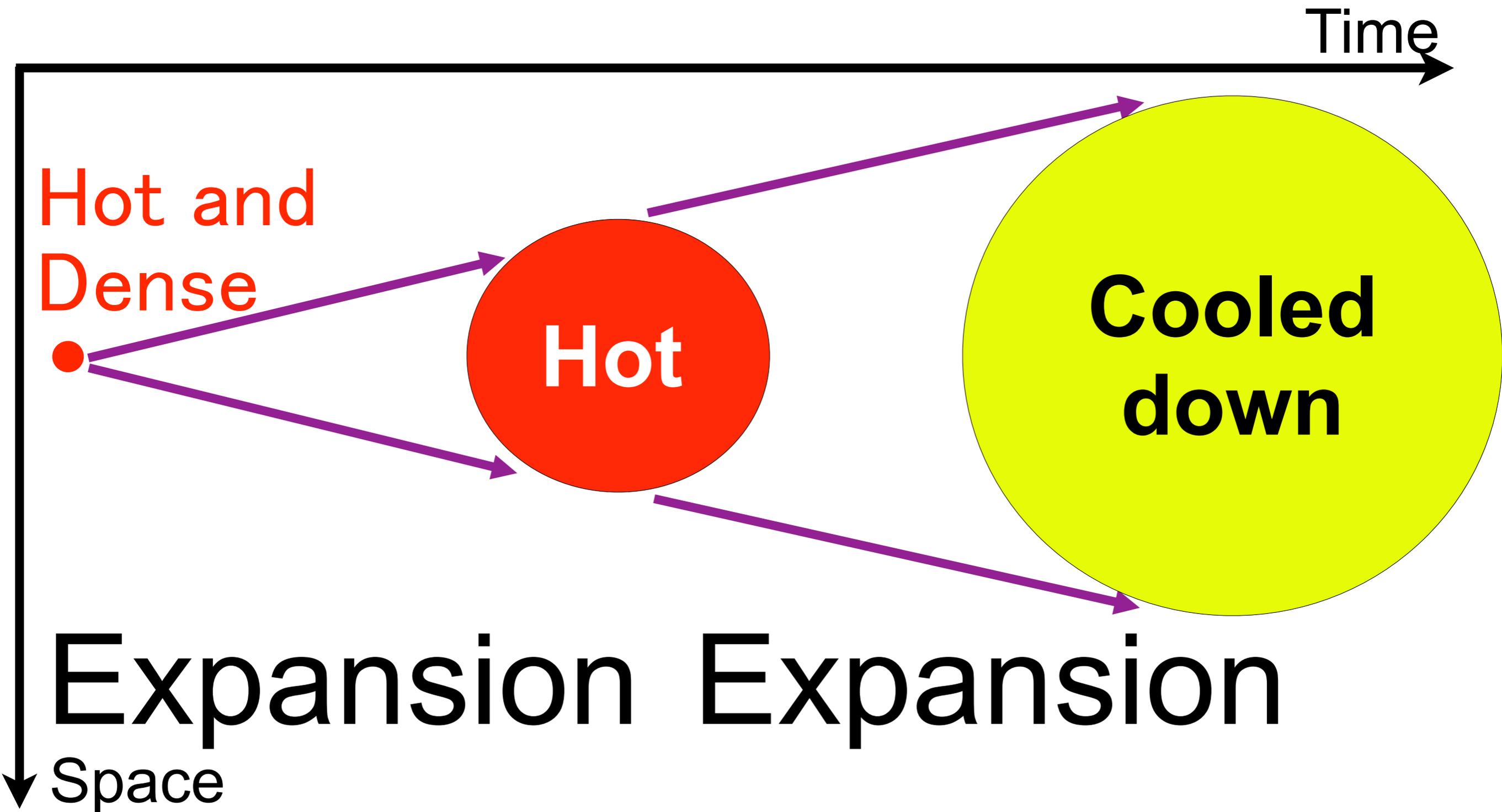
Hot and
Dense



Expansion

Space

Fireball Universe



Definitive Result

- Those photons which filled the fireball Universe are still with us
- There are **410 such photons per cubic centimetre**
- Due to the expansion of space and cooling down, these photons are cold, and their wavelength is in the radio/microwave region

A woman with long dark hair, wearing a black cardigan over a black top with a colorful patterned collar, stands against a dark background. She is holding a vintage, light-colored television set with a handle on top. The television screen displays a blue and white static pattern. The entire image is framed by a thick black border.

Dr. Hiranya Peiris
(University College London)

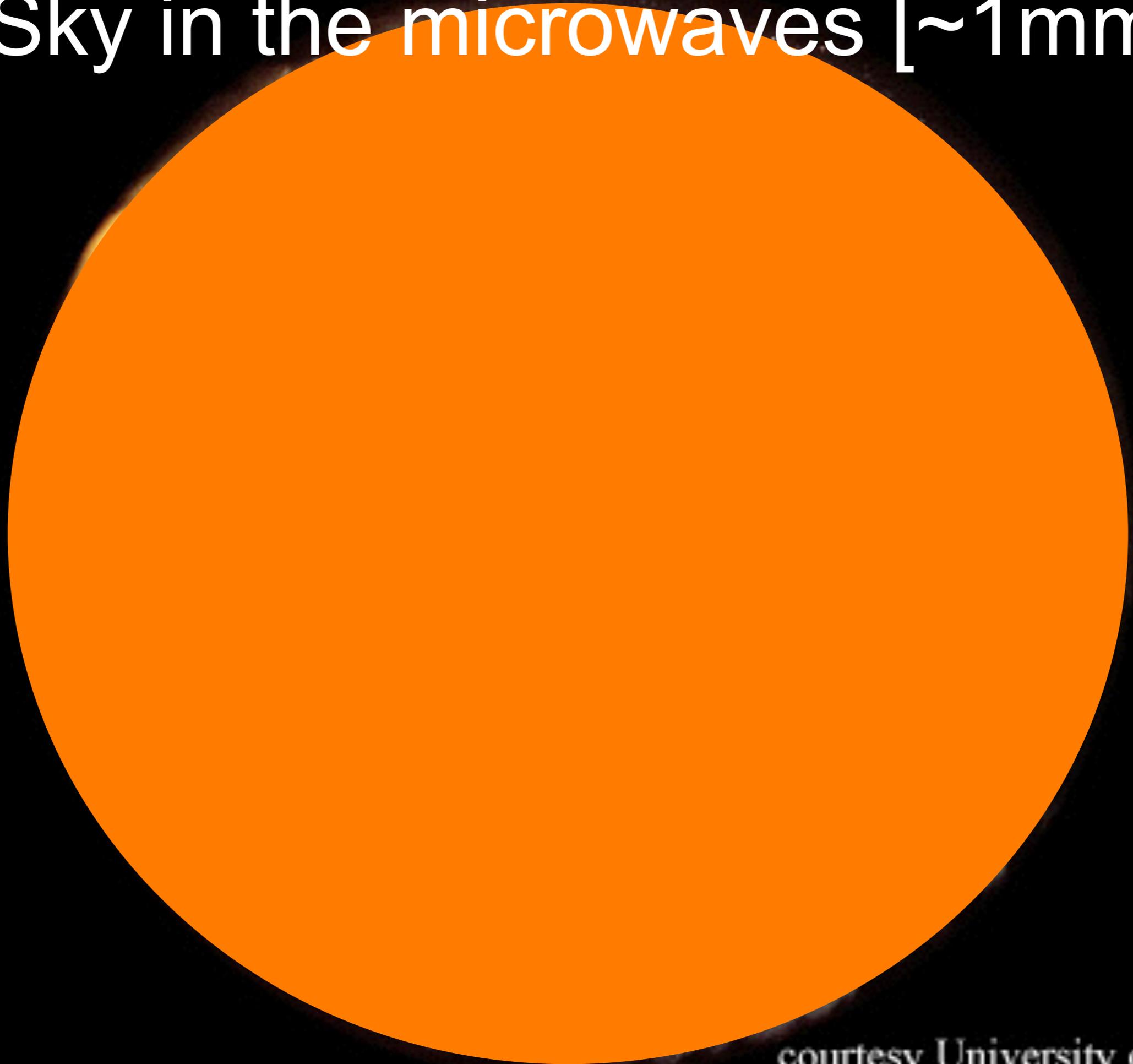
All you need to do is to detect radio waves. For example, 1% of noise on the TV is from the fireball Universe

Sky in the visible light [$\sim 500\text{nm}$]



courtesy University of Arizona

Sky in the microwaves [$\sim 1\text{mm}$]



courtesy University of Arizona

Sky in the microwaves [$\sim 1\text{mm}$]

*Light from the fireball Universe
filling our sky*

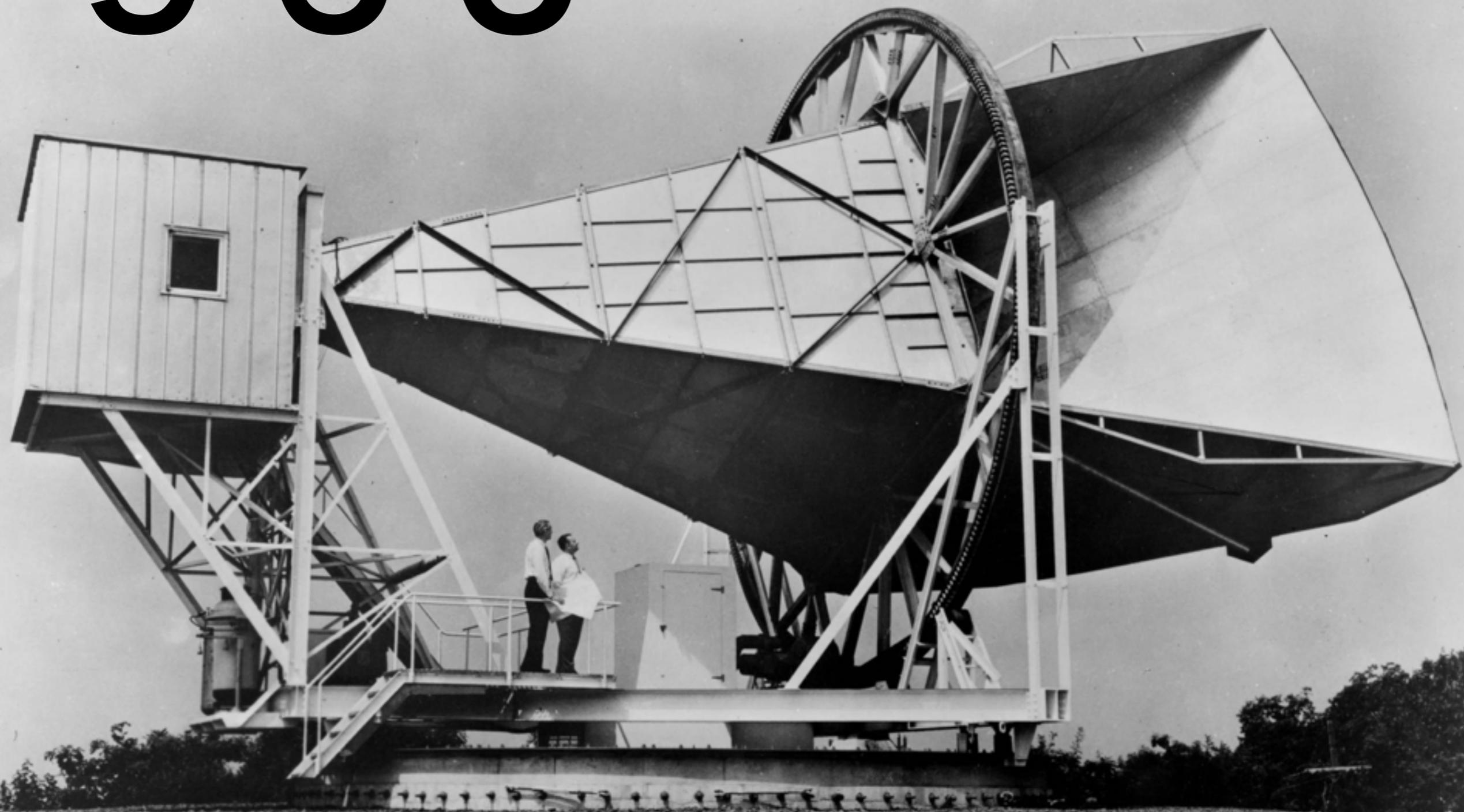
**The Cosmic Microwave
Background (CMB)**

Temperature of CMB

-270.5°C

2.7K in absolute
temperature

1965

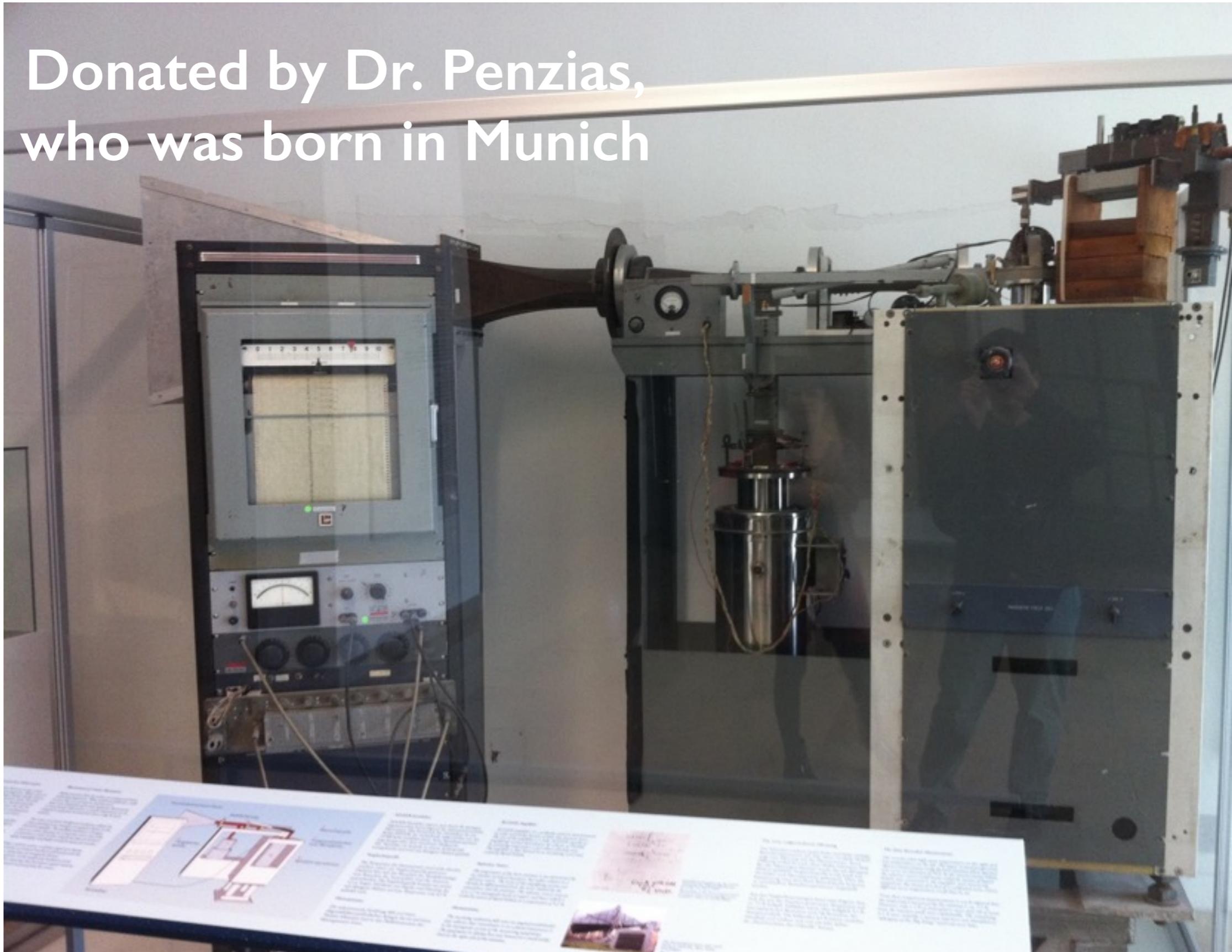




The real detector system used by Penzias & Wilson The 3rd floor of Deutsches Museum



Donated by Dr. Penzias,
who was born in Munich



es
composed of many
audible by a radio
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on characteristic
perature can be
using the horn

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rown
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Hornantennenanschluss

Horn antenna

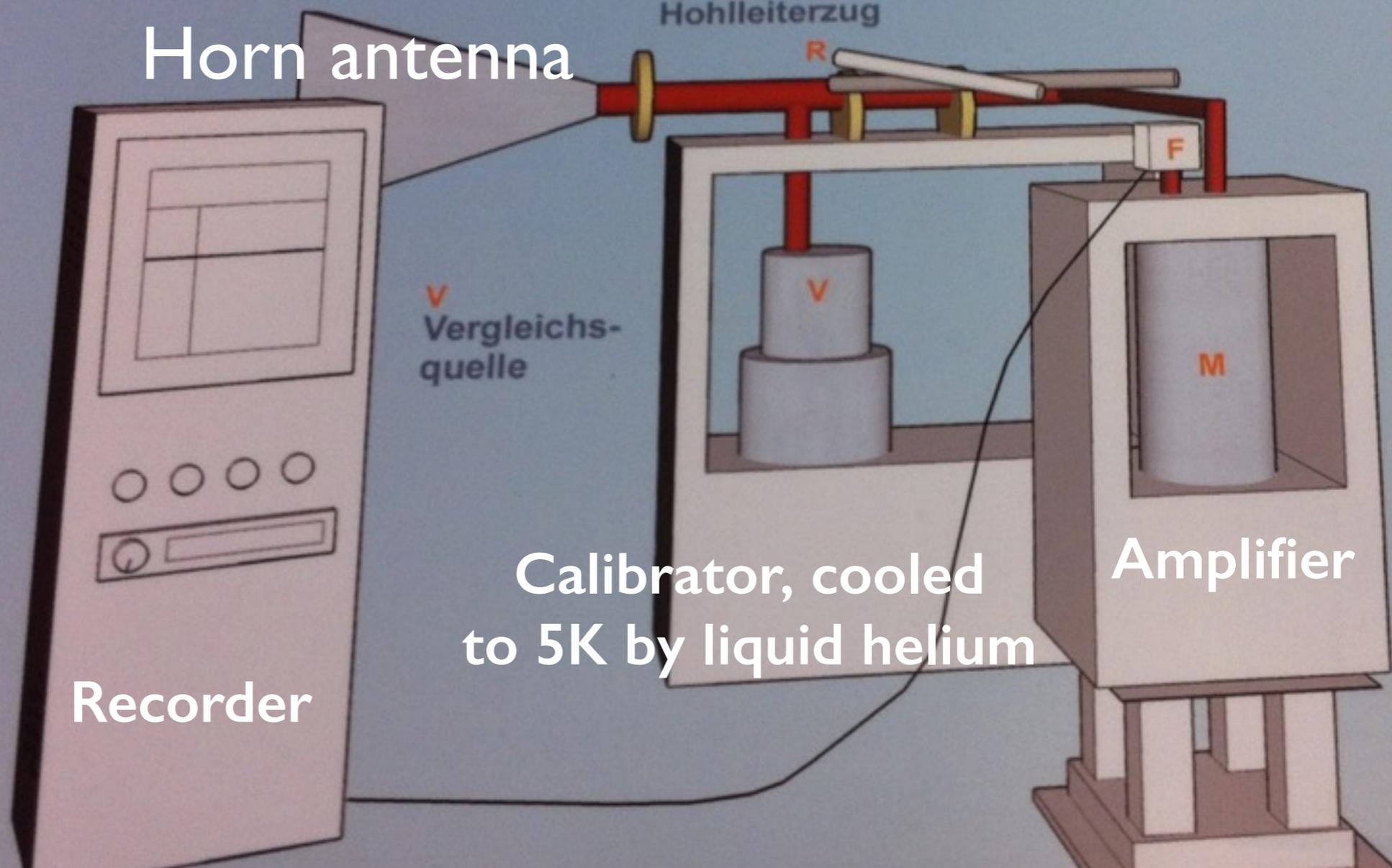
Hohlleiterzug

V
Vergleichs-
quelle

Recorder

Calibrator, cooled
to 5K by liquid helium

Amplifier



Hornantennenanschluss

Hohlleiterzug

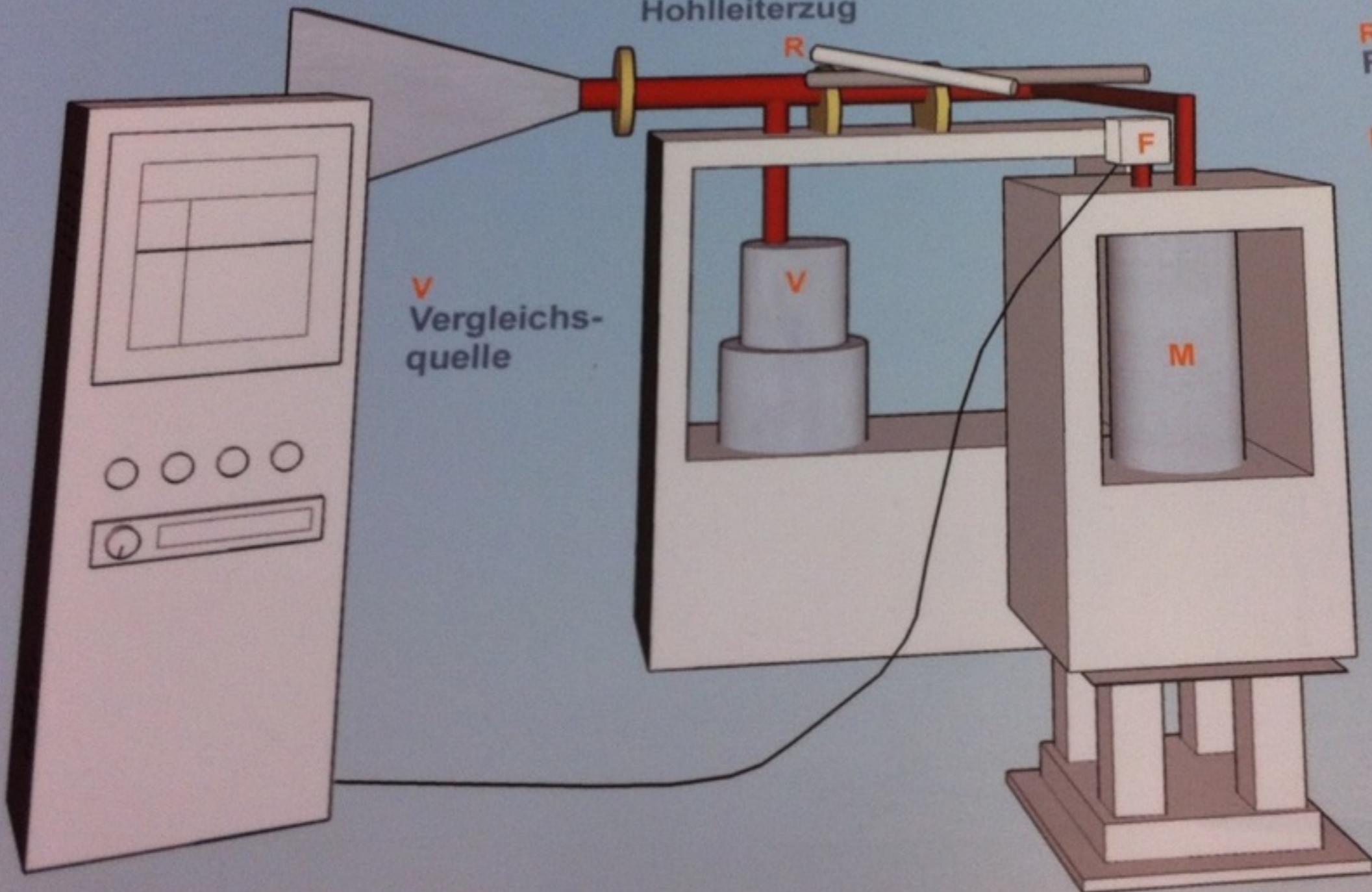
R
Rauschquelle

F
Frequenzmischer
und Verstärker

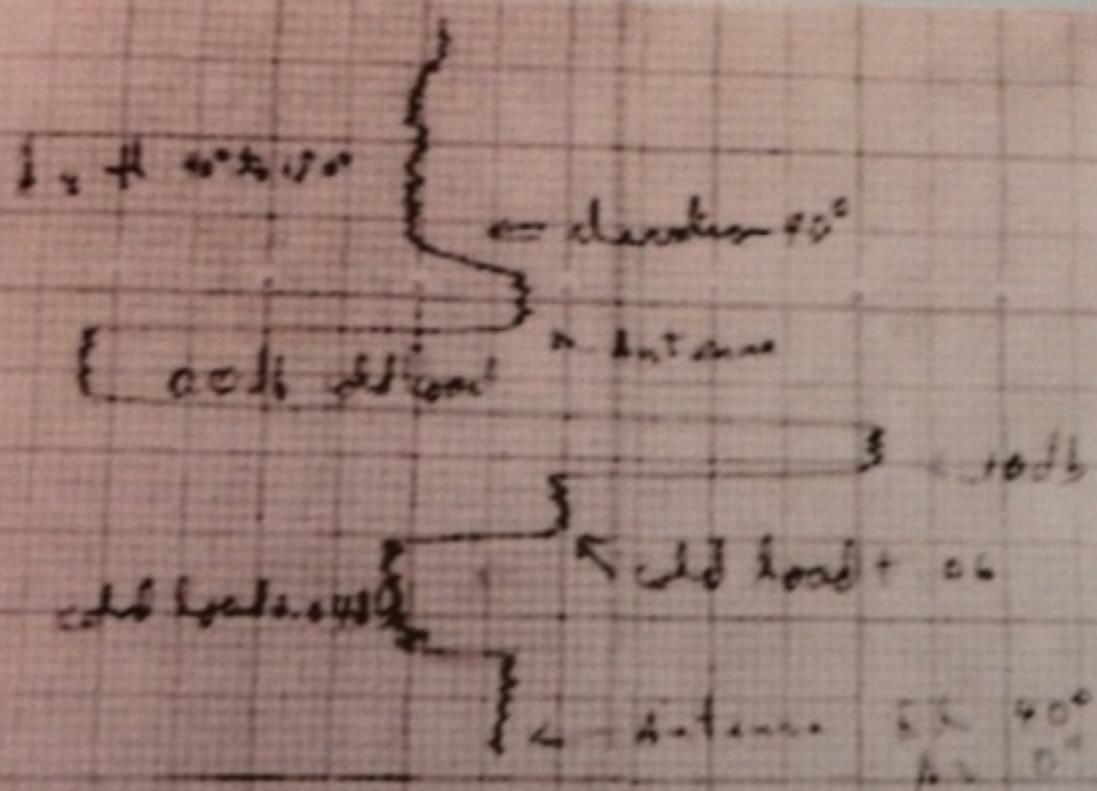
V
Vergleichs-
quelle

M
MASER-Verstärker

Schreiber



May 20, 1964 CMB Discovered



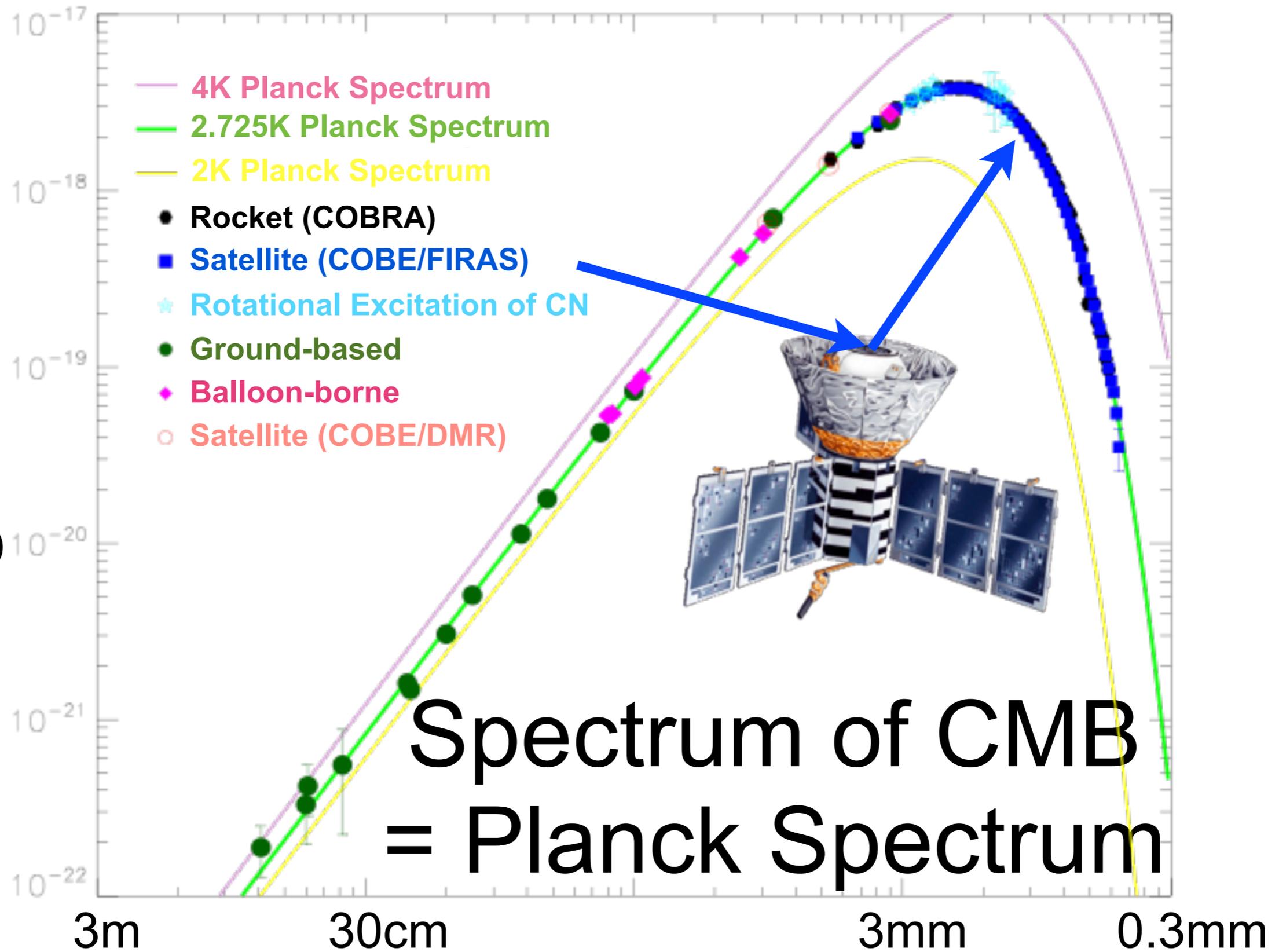
$$6.7 - 2.3 - 0.8 - 0.1 = 3.5 \pm 1.0 \text{ K}$$

	A
EDT 11:15	1.57
12:00 Voltage	2.67
12:00 Current	3.71
12:00 Resistance	4.14
12:00 Inductance	5.17
12:00 Capacitance	6.20
12:00 Power	7.23
12:00 Energy	8.26
12:00 Entropy	9.29
12:00 Information	10.32
12:00 Entropy	11.35
12:00 Information	12.38
12:00 Entropy	13.41
12:00 Information	14.44
12:00 Entropy	15.47
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12:00 Entropy	91.69
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12:00 Entropy	95.81
12:00 Information	96.84
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12:00 Entropy	196.75
12:00 Information	197.78
12:00 Entropy	198.81
12:00 Information	199.84
12:00 Entropy	200.87

Cos A with Cold Load
| 5/20/64

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.

Brightness



Fireball Universe, Observed

- The **Planck spectrum** is achieved only when matter and radiation are exchanging energies frequently
 - Called “thermal equilibrium”
 - Imagine a blast furnace (Hochofen)
- Today’s Universe is not in thermal equilibrium (we die otherwise), which means that **the Universe was in thermal equilibrium in the past - fireball Universe** [Urknalls]

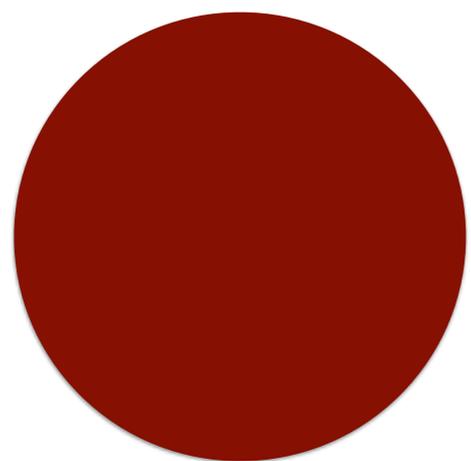


Max Planck (1858-1947)

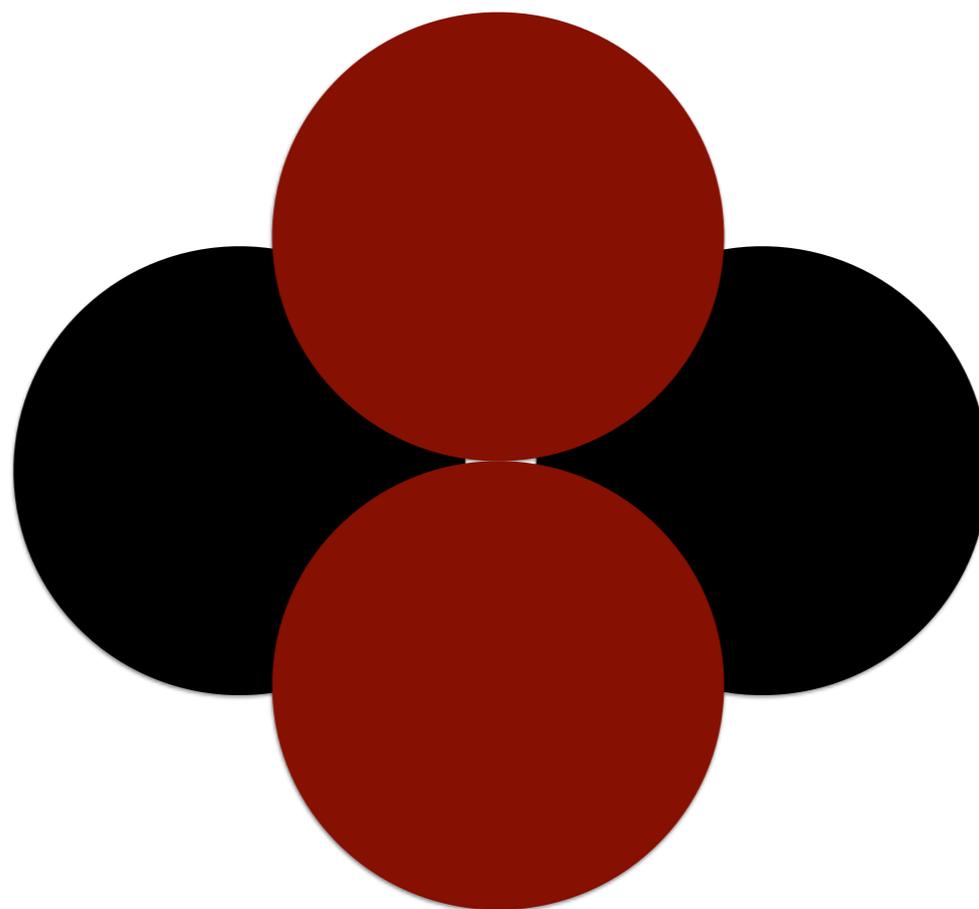


Origin of CMB

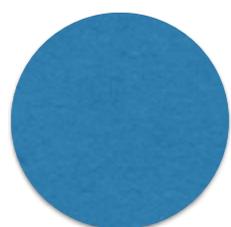
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- This soup consists of:
 - Protons, electrons, and helium nuclei
 - Photons, neutrinos
 - Dark matter
- Dark matter provides a “gravitational potential,” which can be thought of as a “soup bowl”



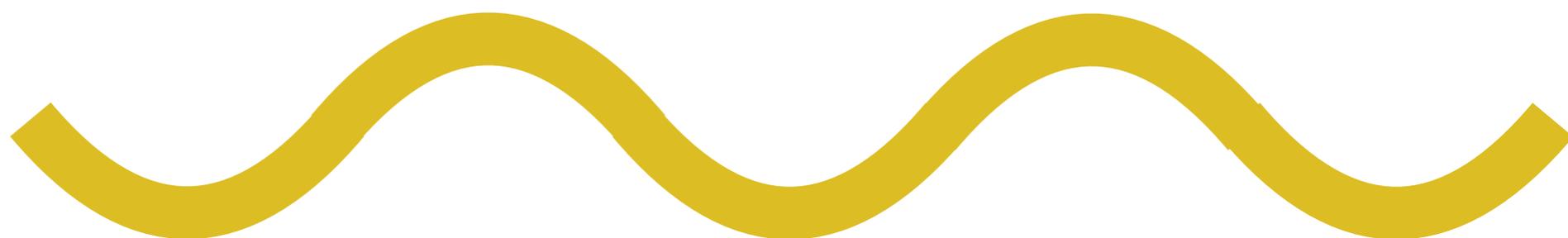
Protons



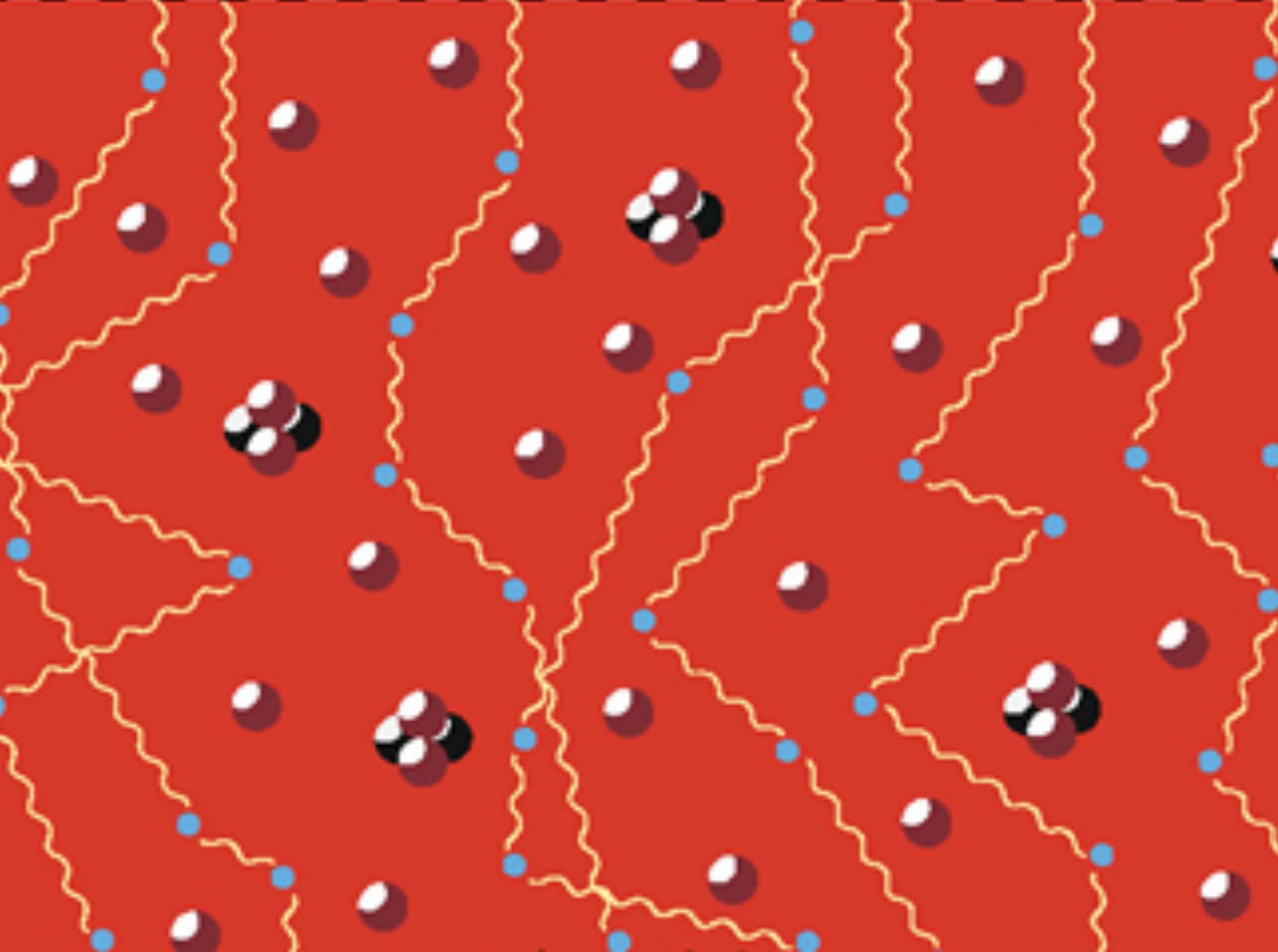
Helium
Nuclei



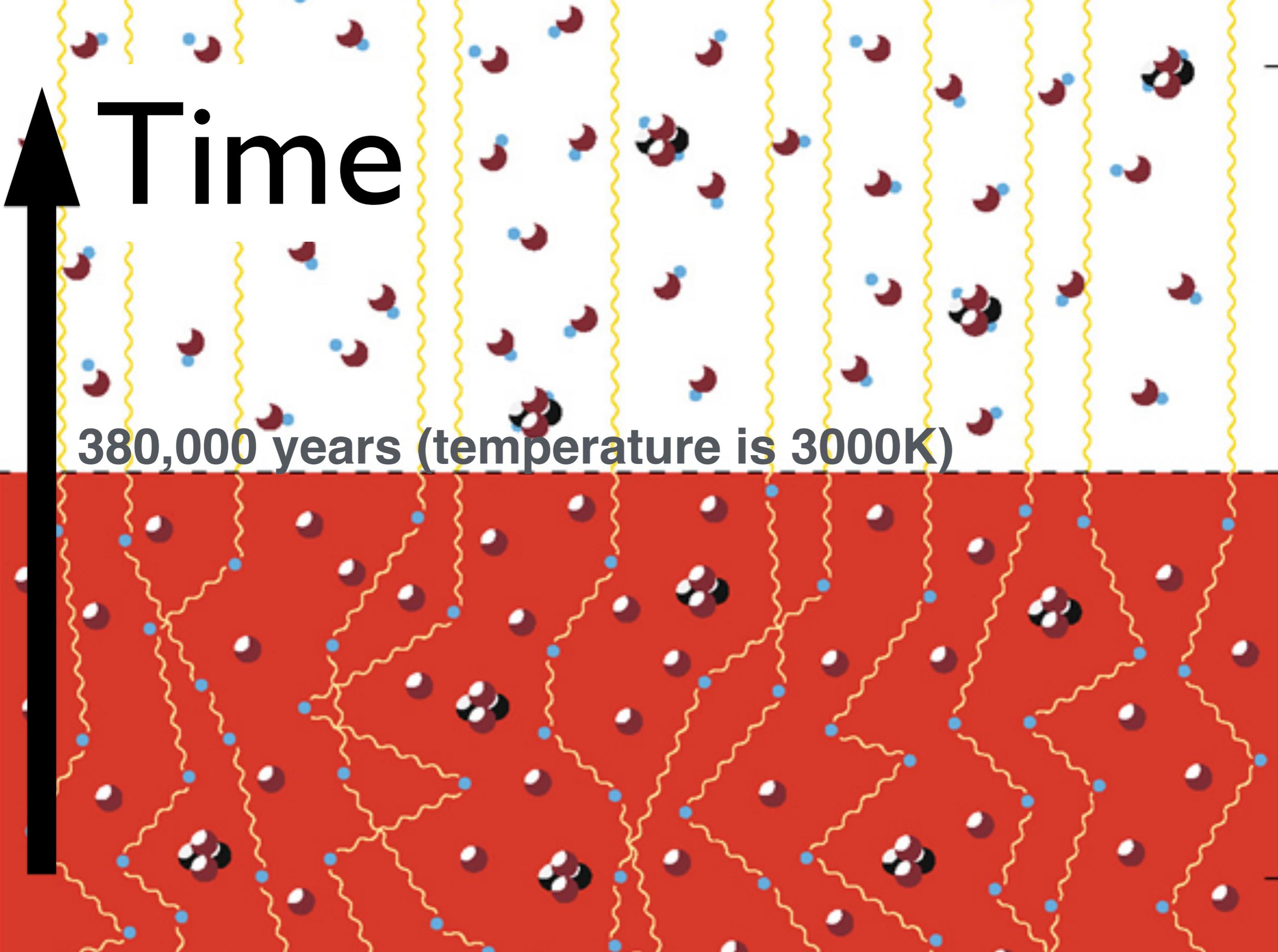
Electrons



Photons

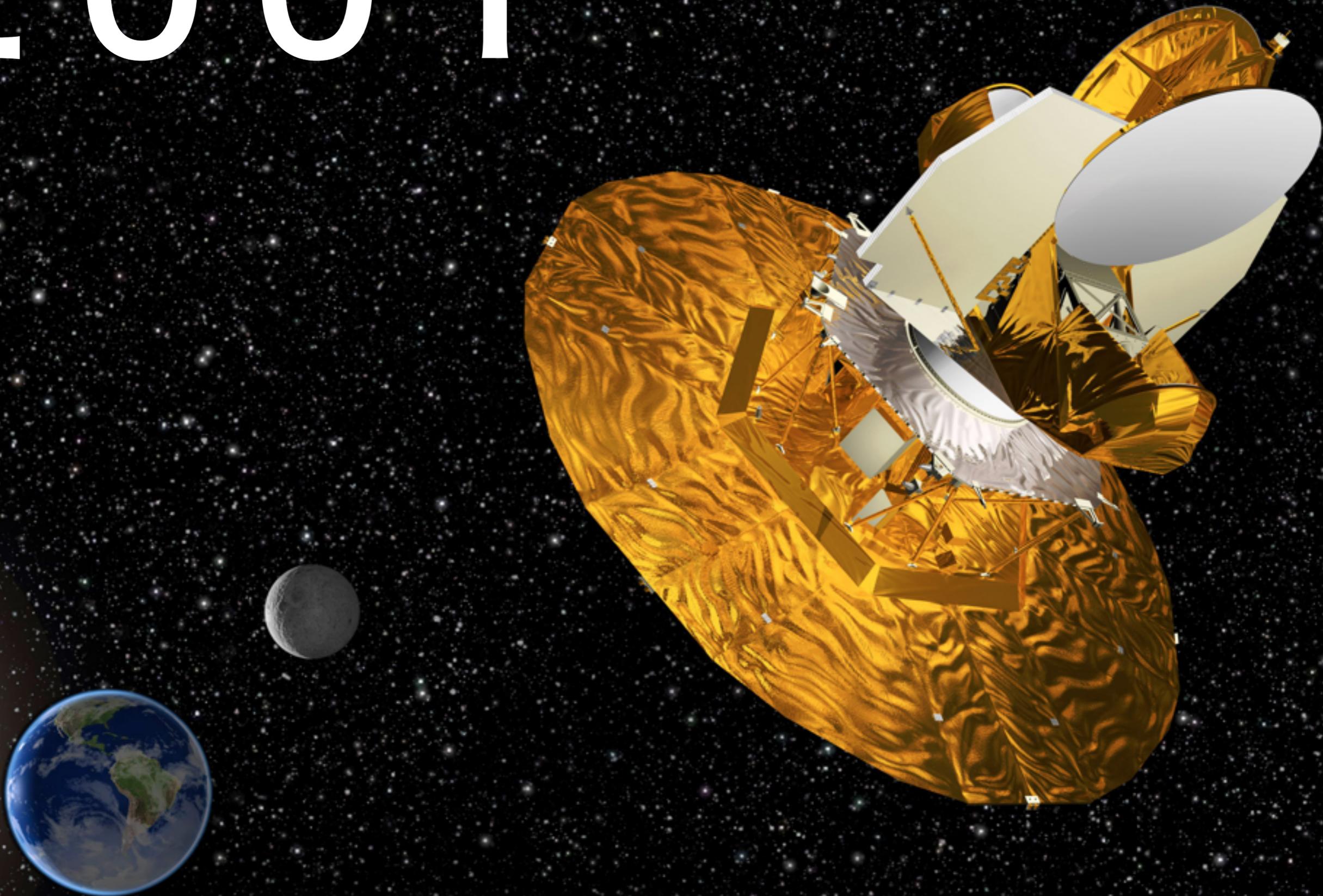


Time



380,000 years (temperature is 3000K)

2001

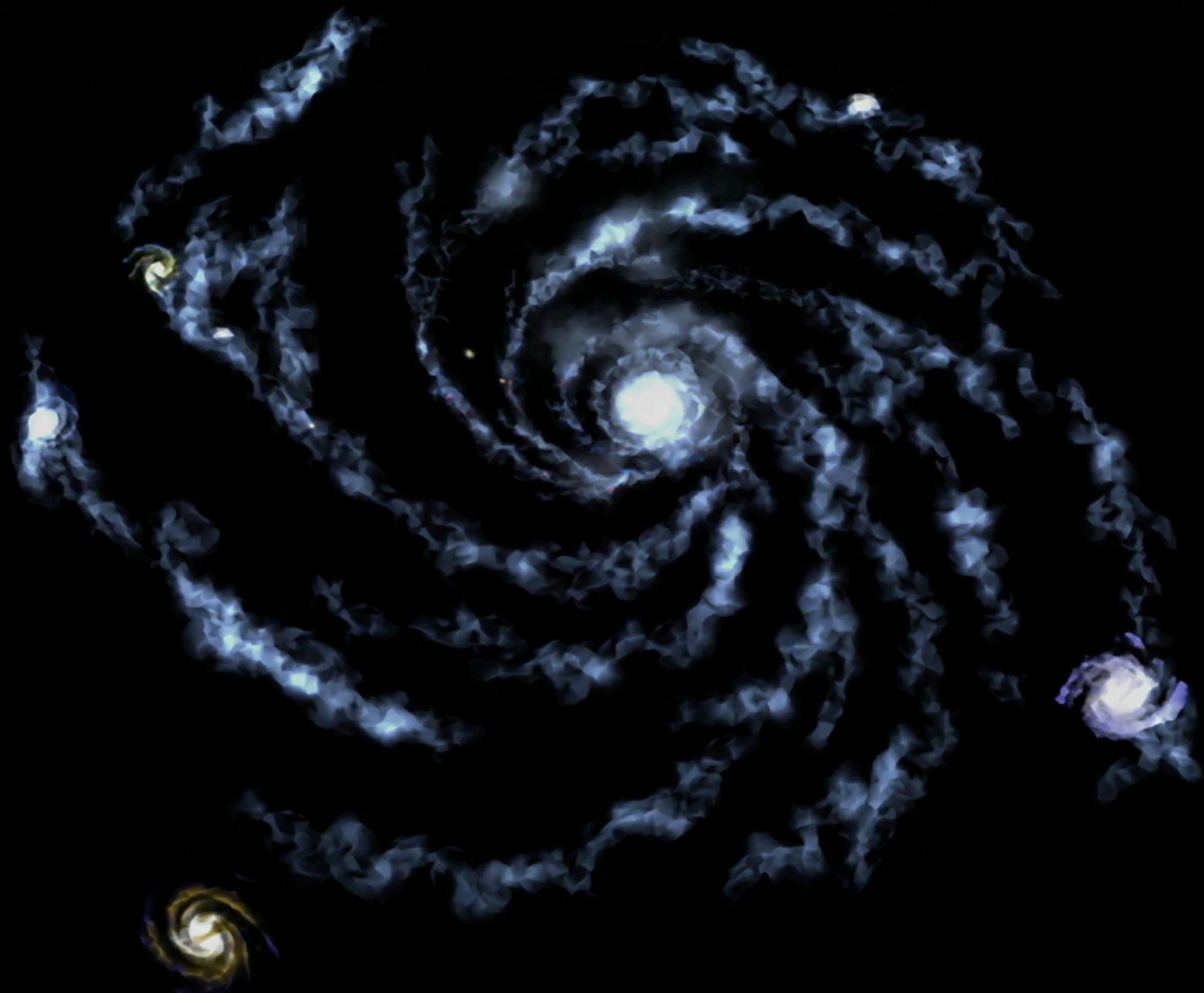


WMAP Science Team

July 19, 2002

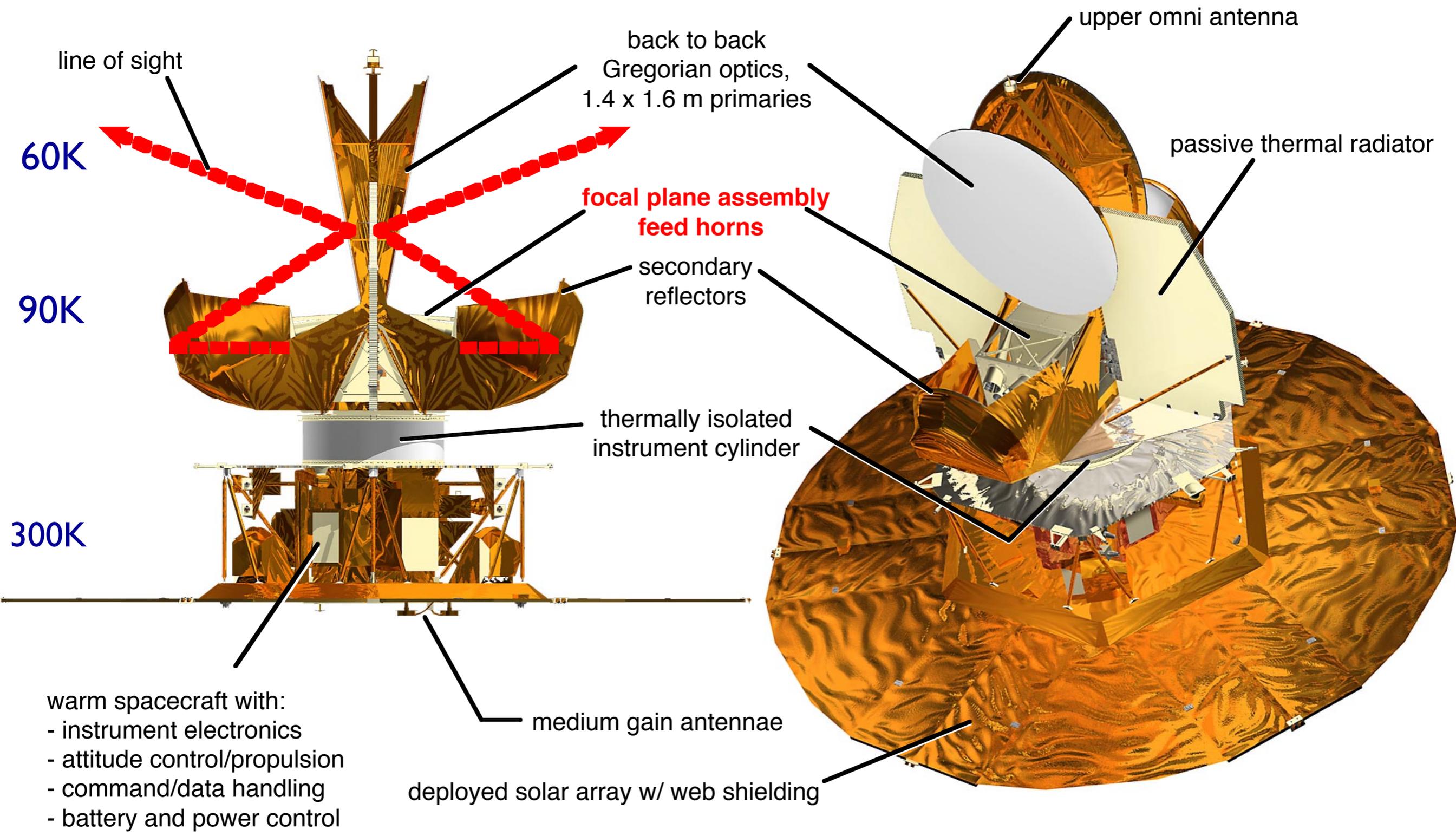


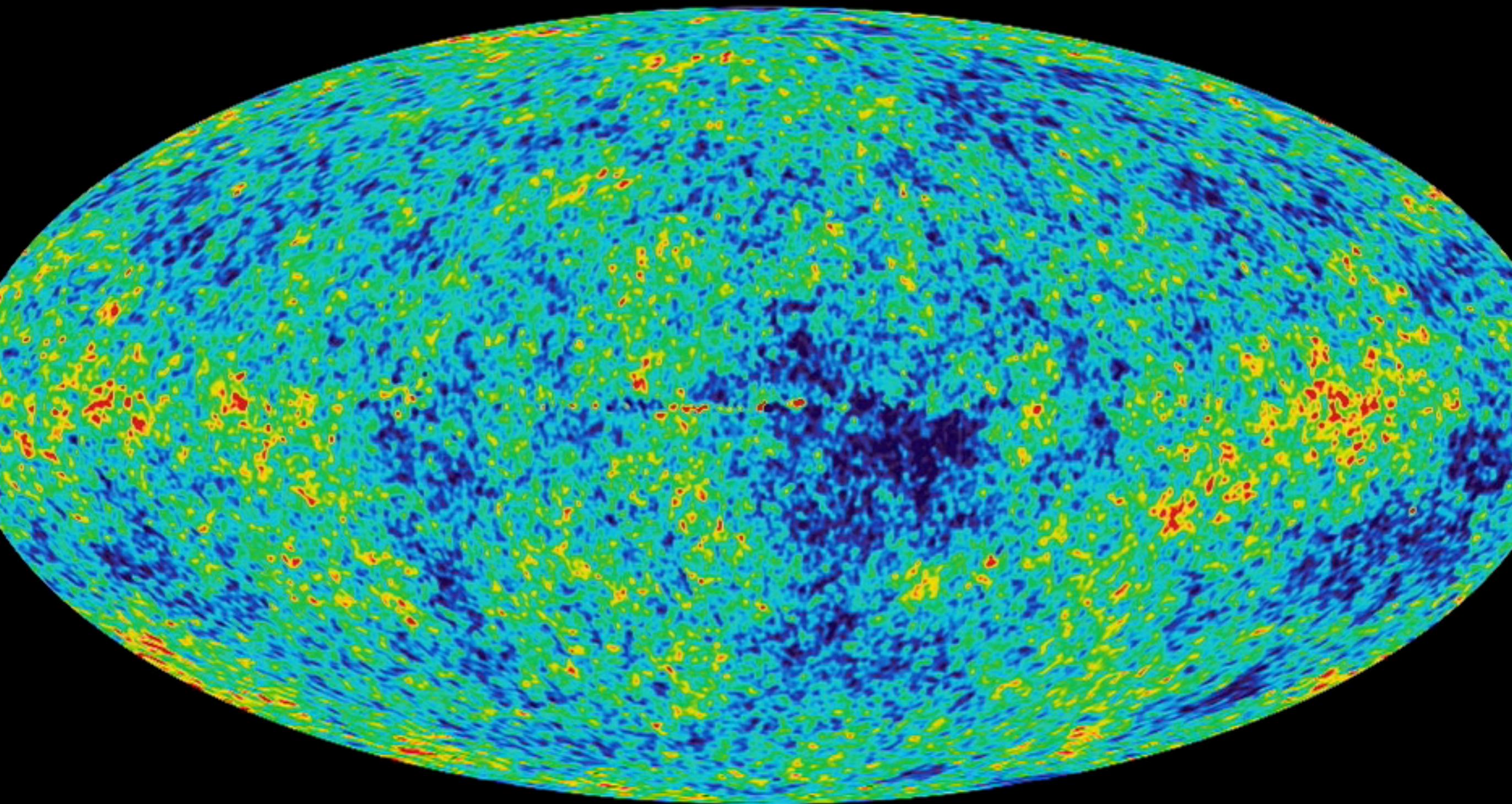
- WMAP was launched on June 30, 2001
- The WMAP mission ended after 9 years of operation

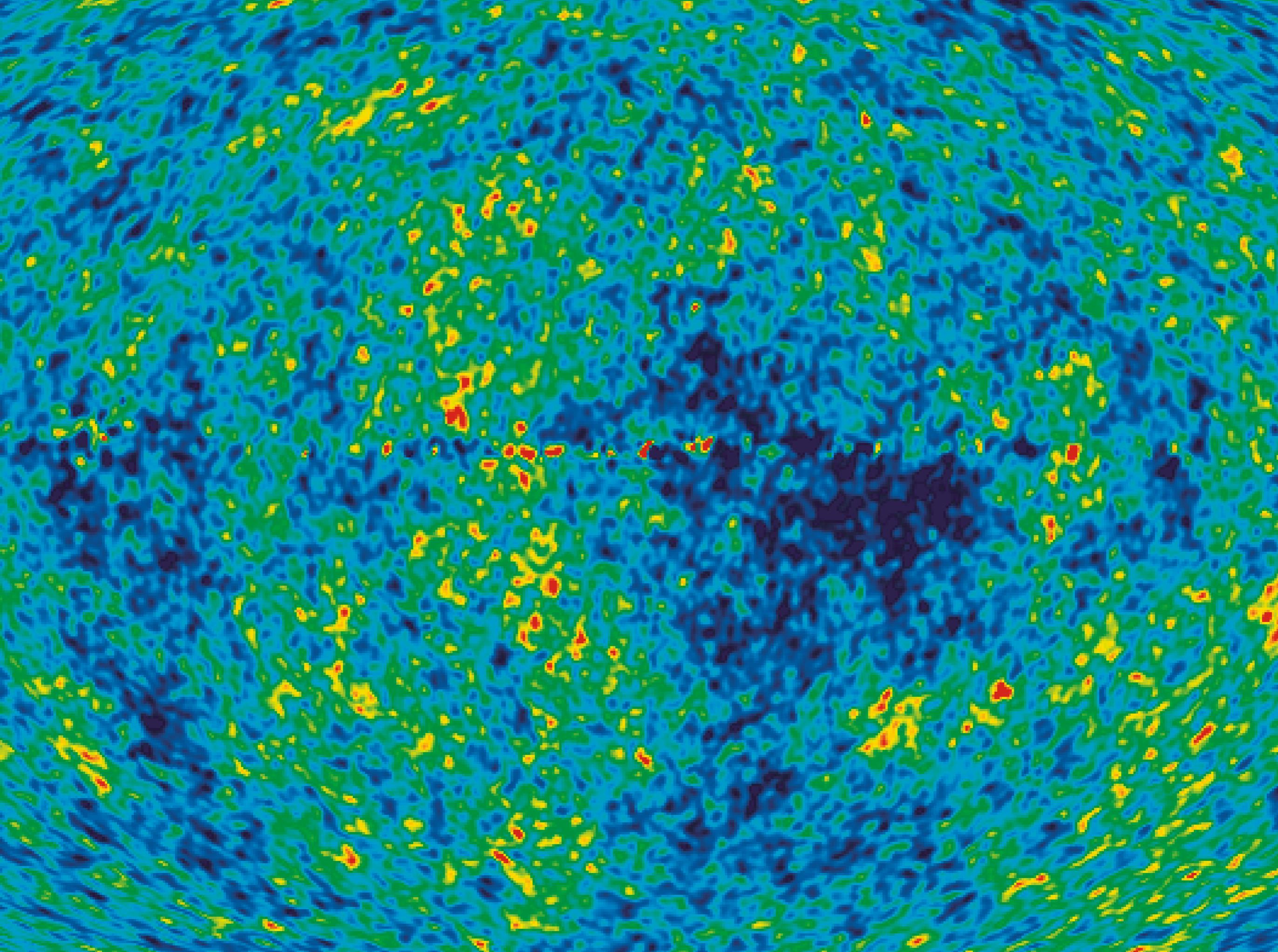


WMAP Spacecraft

No cryogenic components







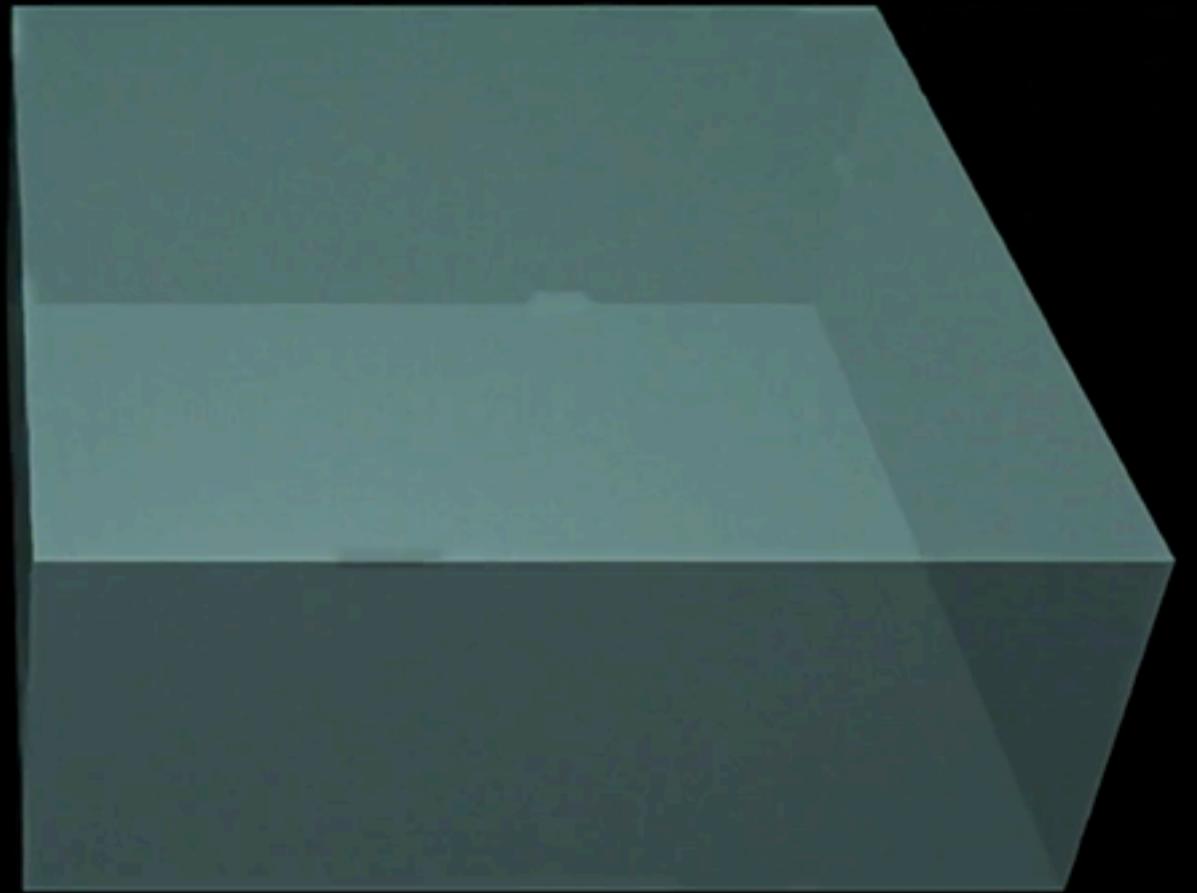
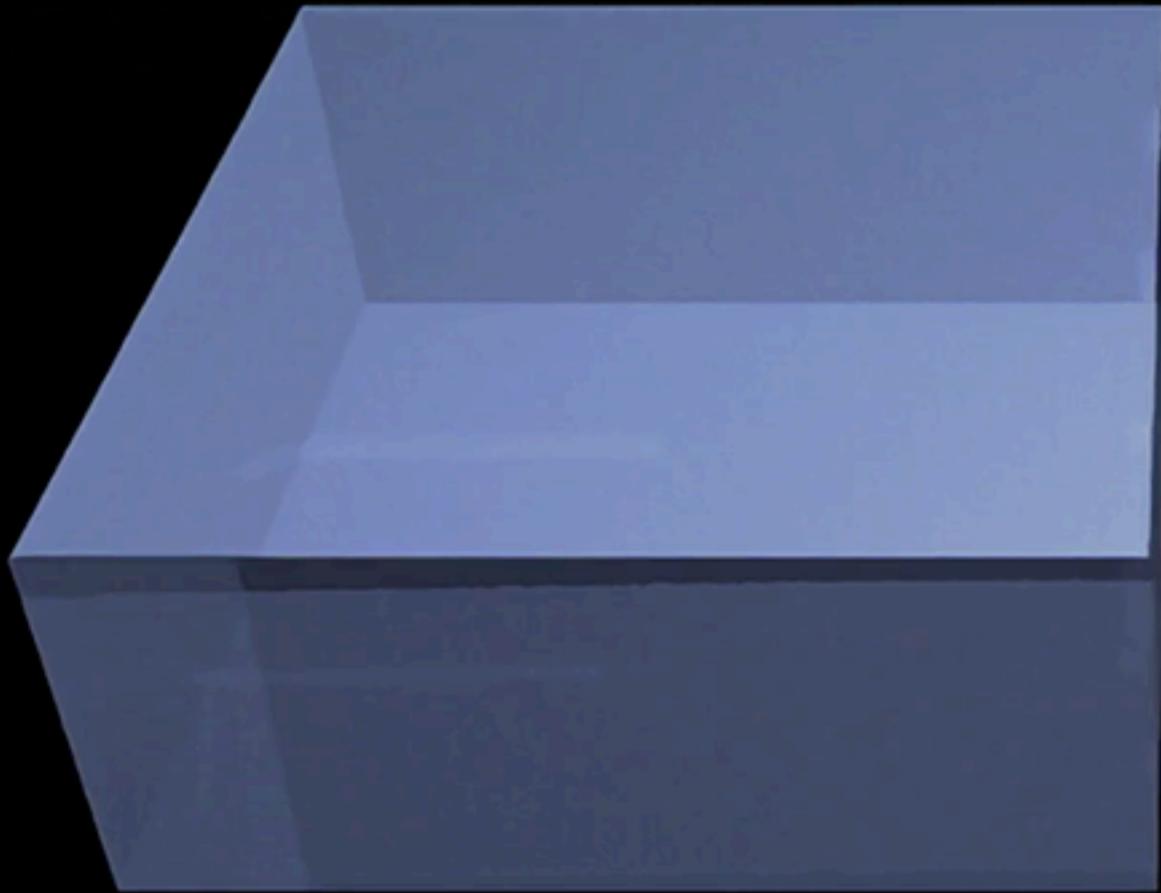
Our Origin

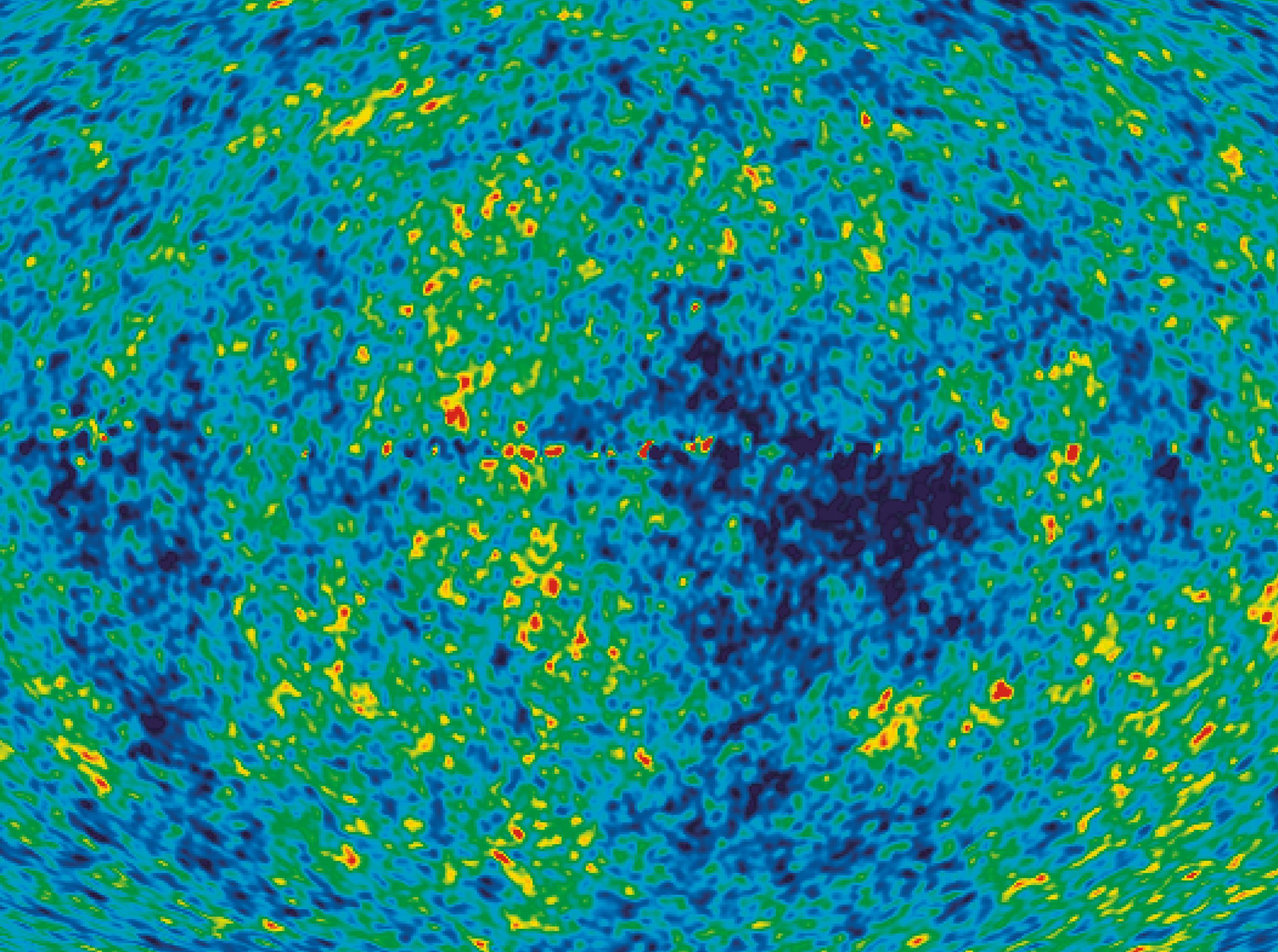
- WMAP taught us that **galaxies, stars, planets, and ourselves originated from tiny fluctuations in the early Universe**



Kosmische Miso Suppe

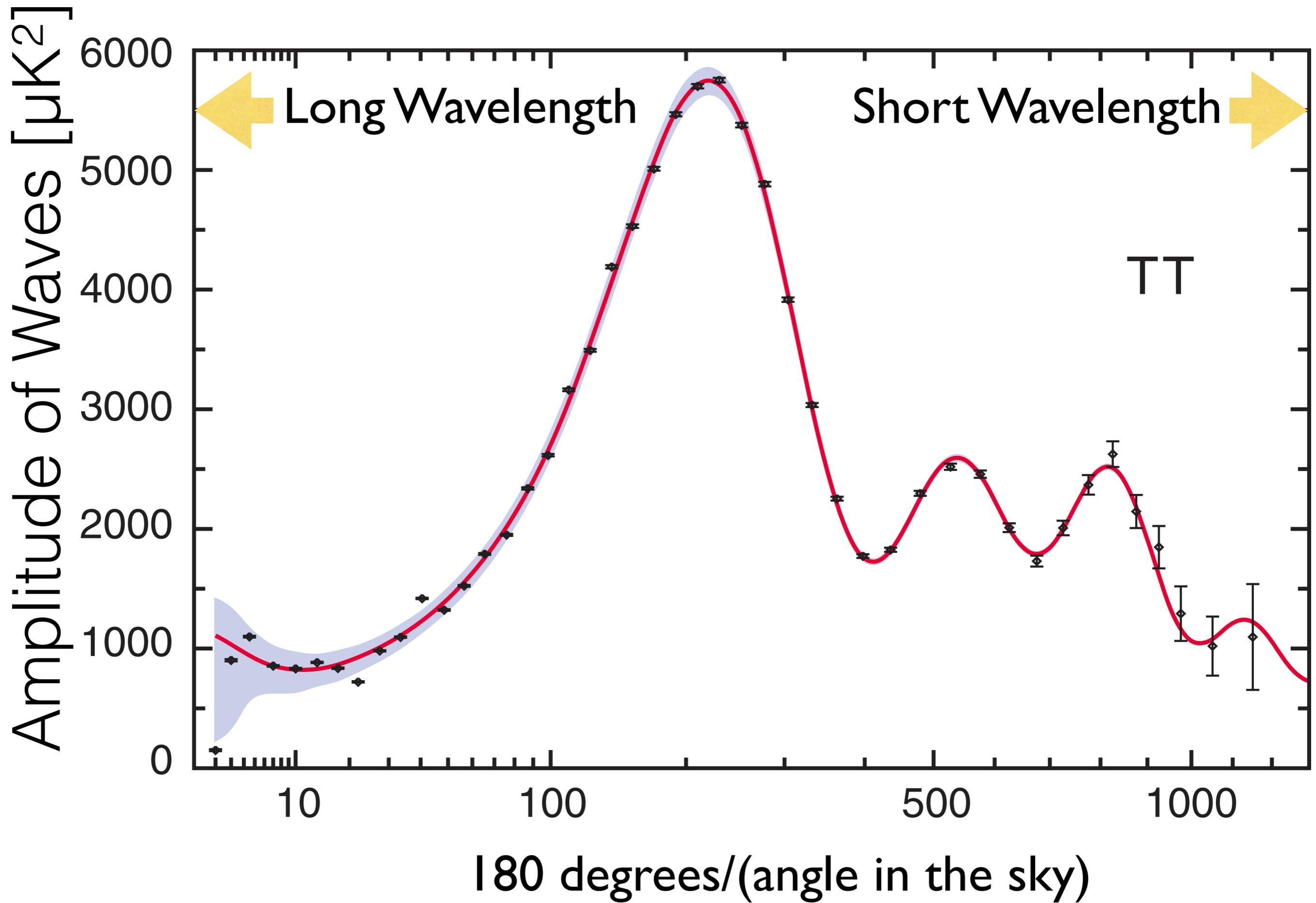
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching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

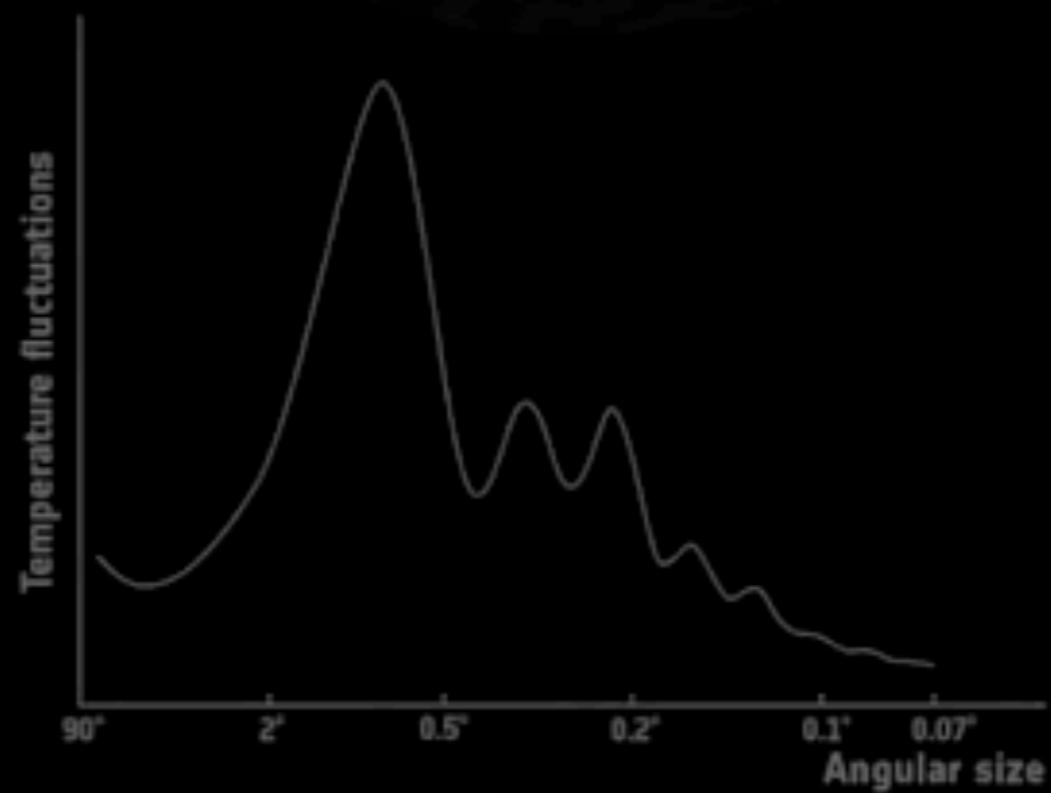




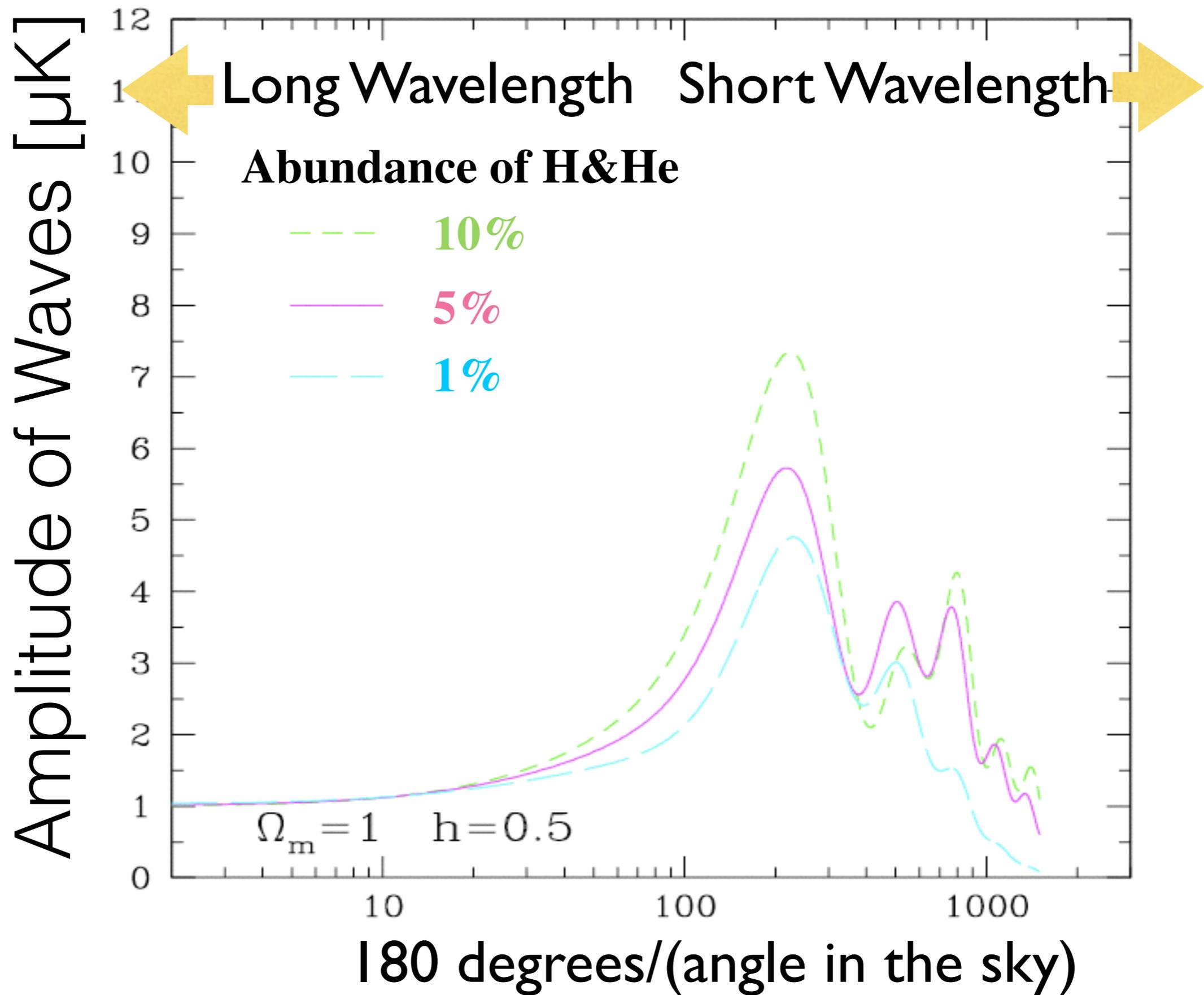
Data Analysis

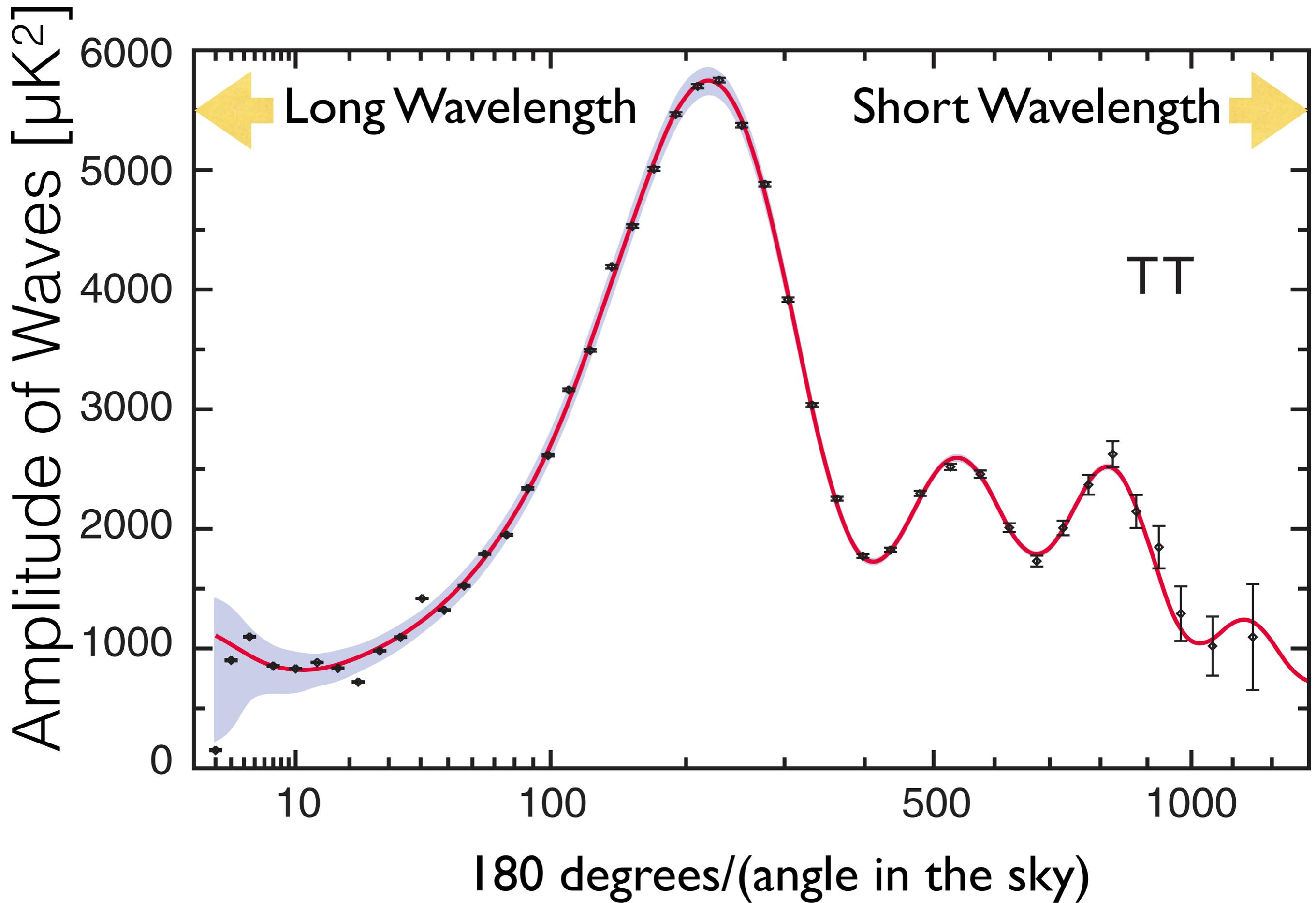
- Decompose temperature fluctuations in the sky into a set of waves with various wavelengths
- Make a diagram showing the strength of each wavelength



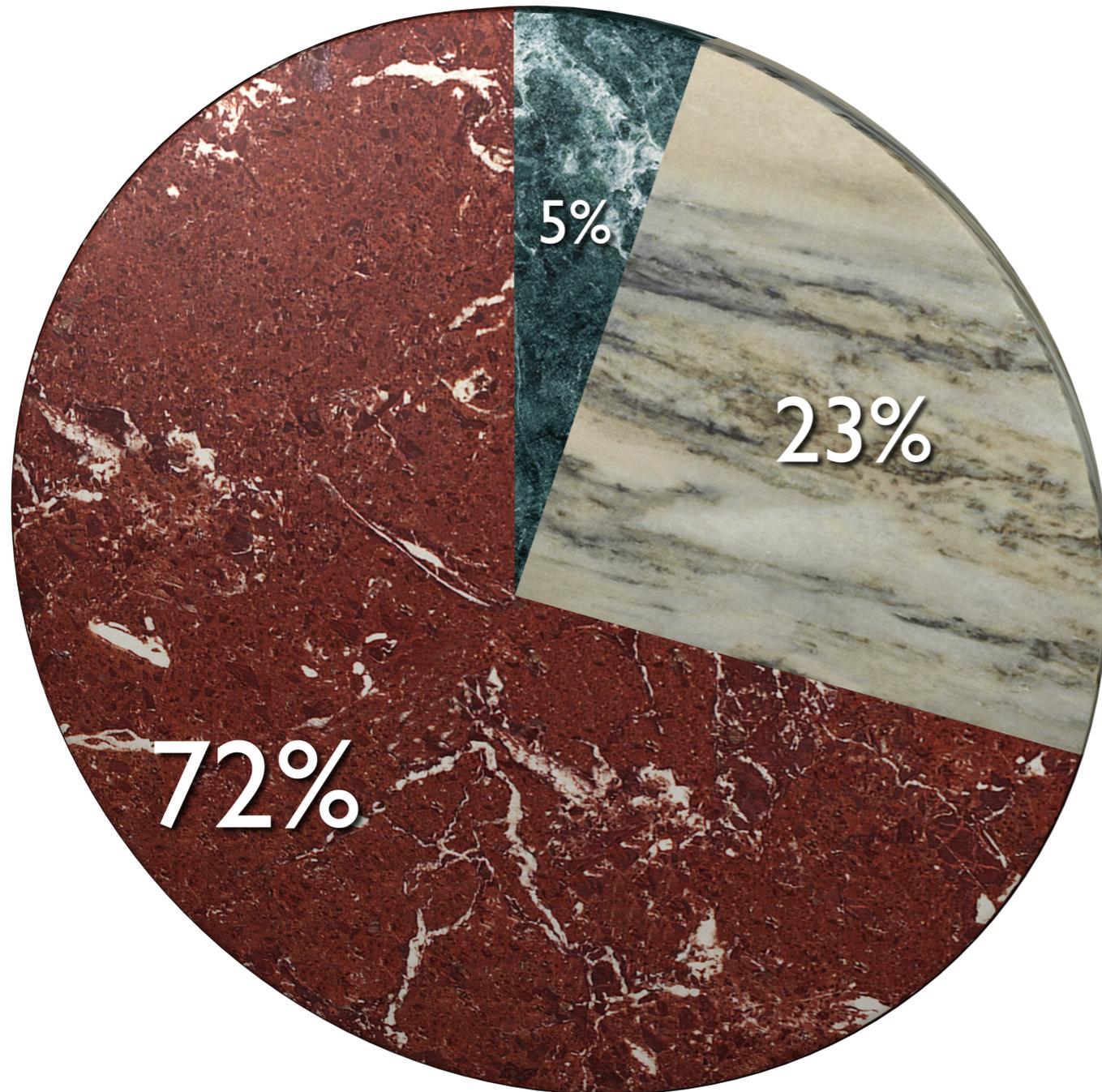


Measuring Abundance of H&He





Cosmic Pie Chart

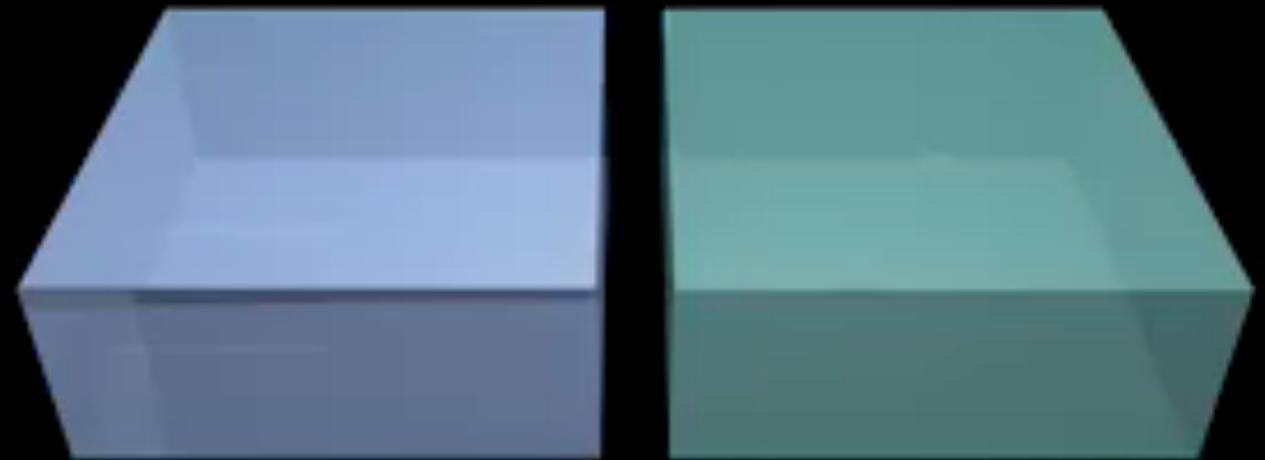


- WMAP determined the abundance of various components in the Universe
- As a result, **we came to realise that we do not understand 95% of our Universe...**

- 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

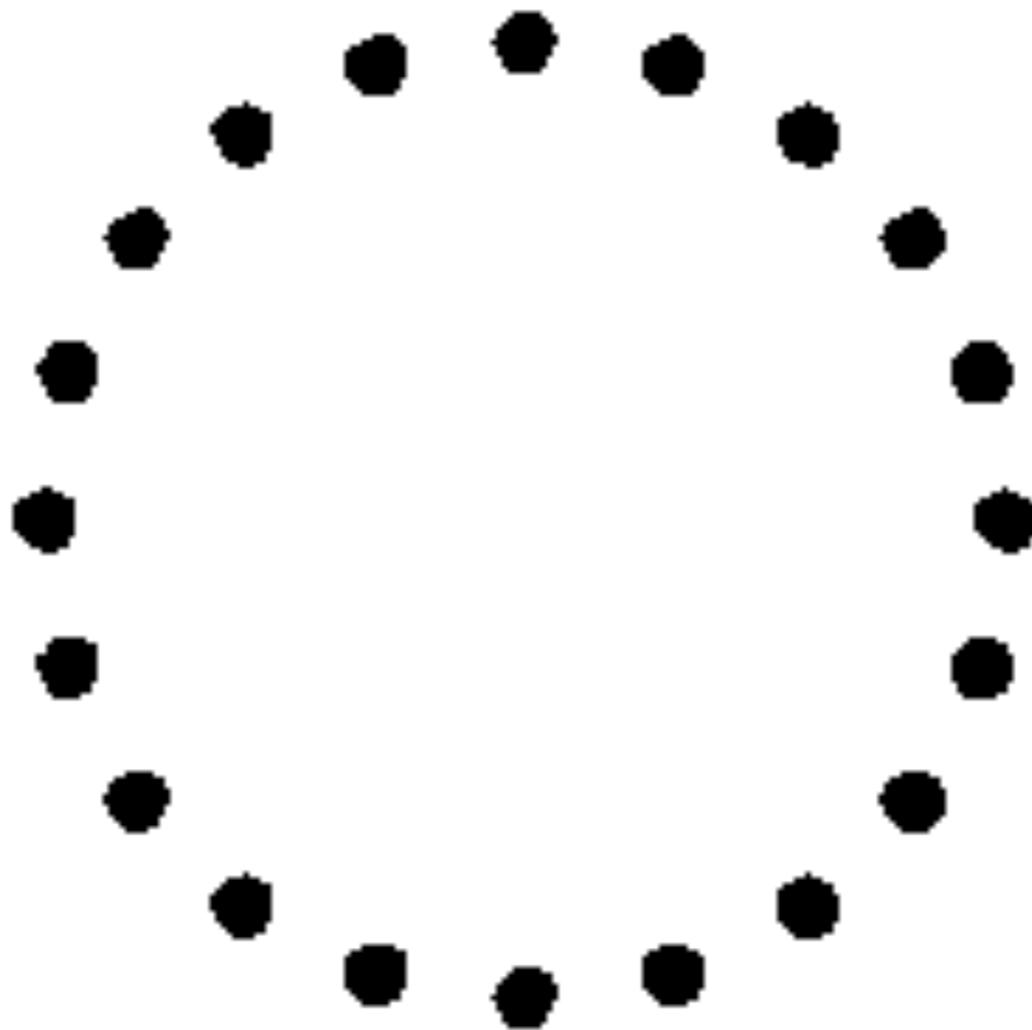
- **Quantum Mechanics at work in the early Universe**
(Mukhanov & Chibisov, 1981)
- **Werner Heisenberg's Uncertainty Principle:**
 - **[Energy you can borrow] x [Time you borrow] $\sim h$**
 - **Time was very short in the early Universe =
You could borrow a lot of energy**
- **Those energies became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

CMB Research: Next Frontier

Primordial Gravitational Waves

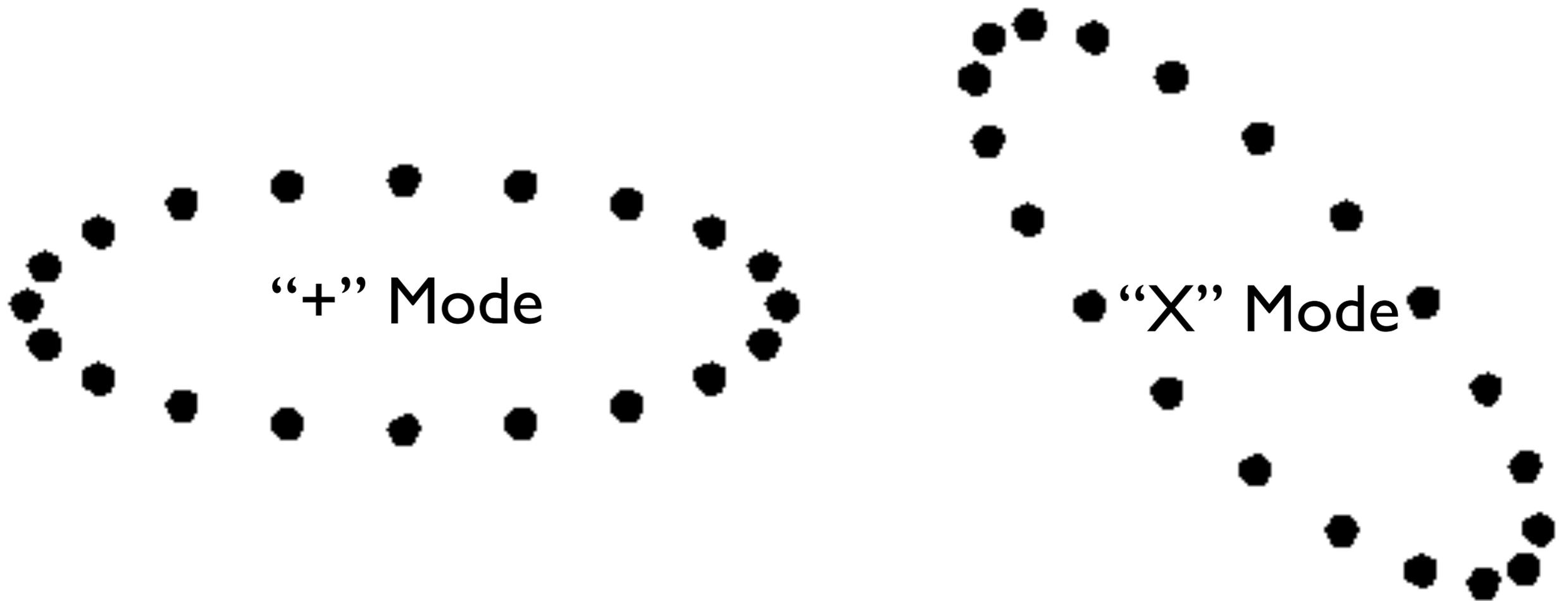
*Extraordinary claims require extraordinary evidence.
The same quantum fluctuations could also generate
gravitational waves, and we wish to find them*

Gravitational Waves Are Coming Toward You!



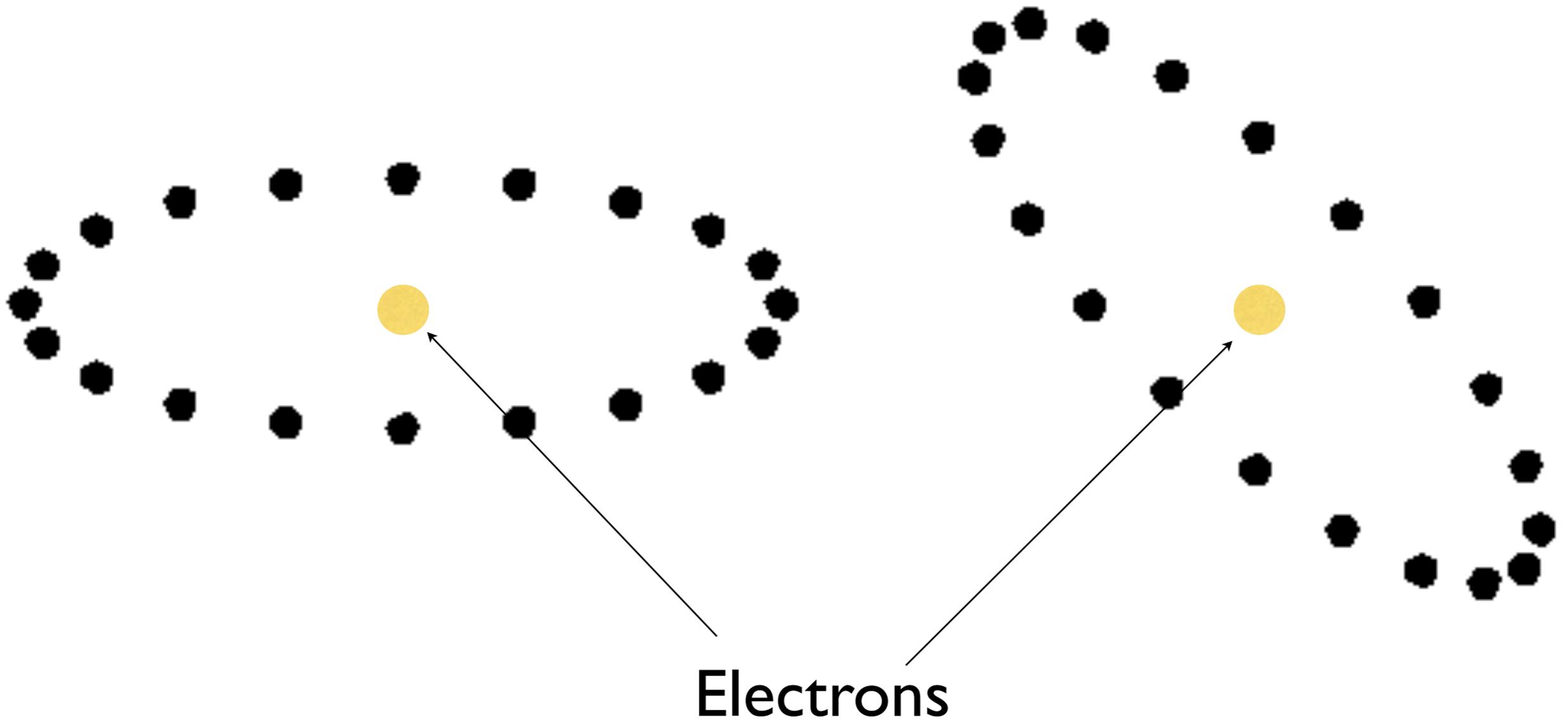
Gravitational waves stretch and contract space,
moving particles

Two Modes

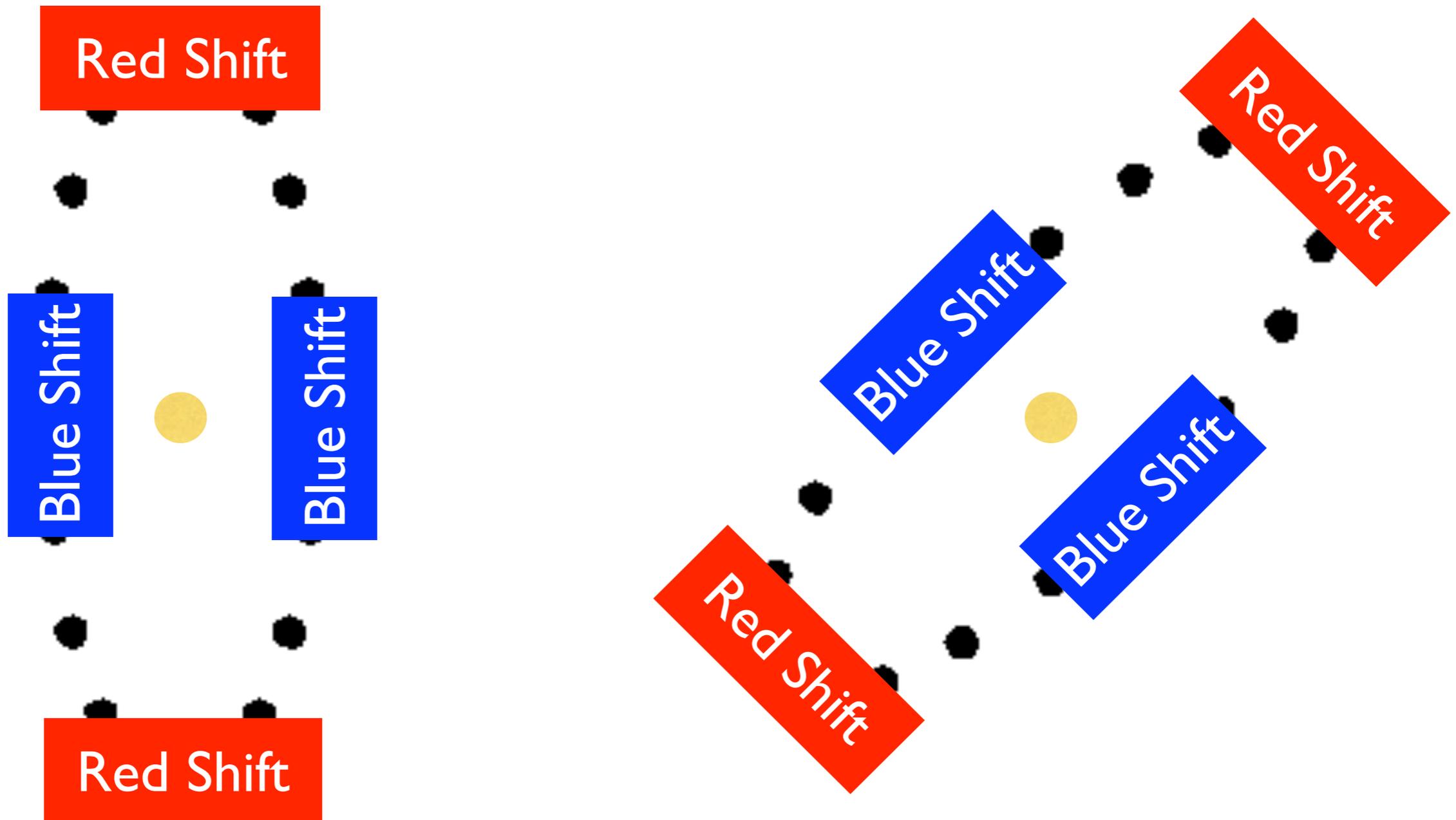


How do they change temperatures?

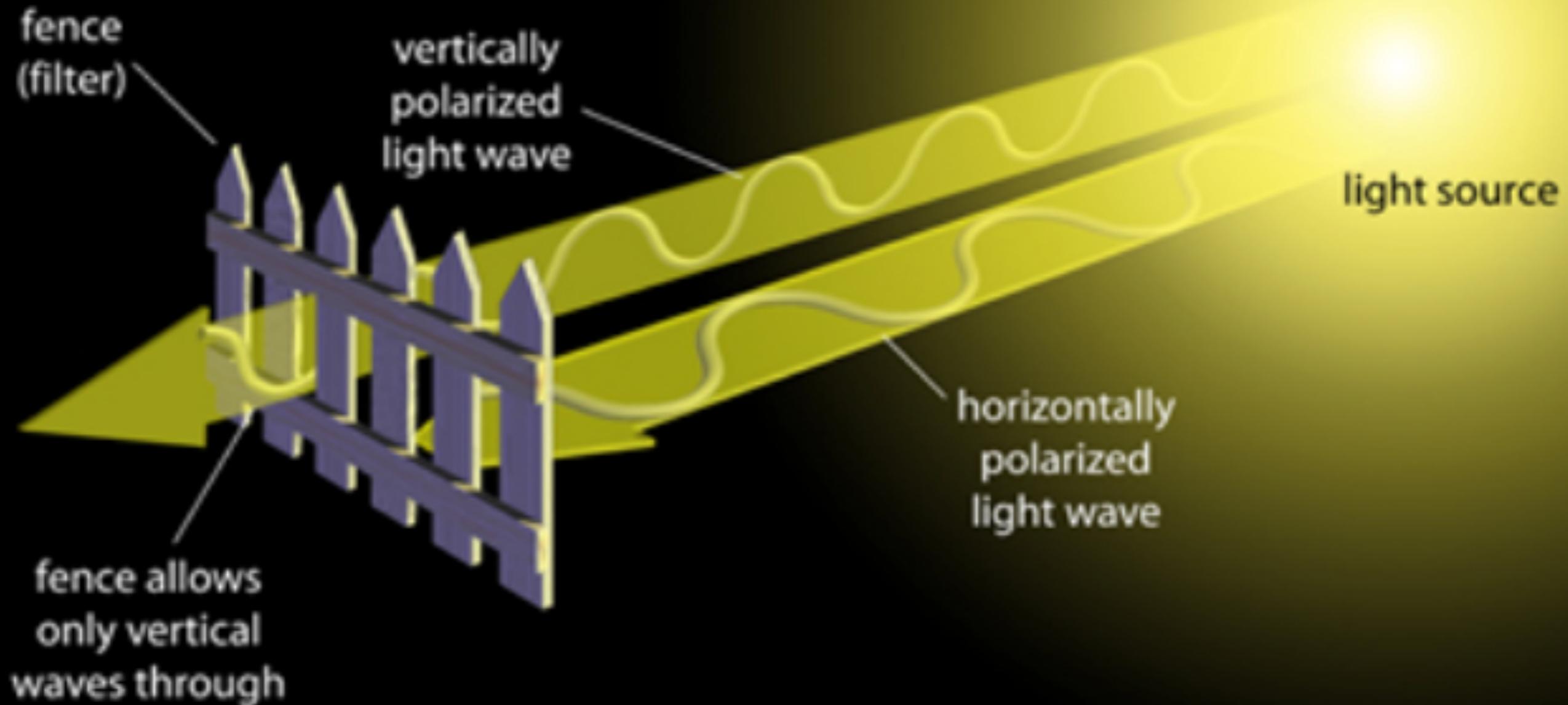
Gravitational Waves to Temperature Fluctuations



Gravitational Waves to Temperature Fluctuations

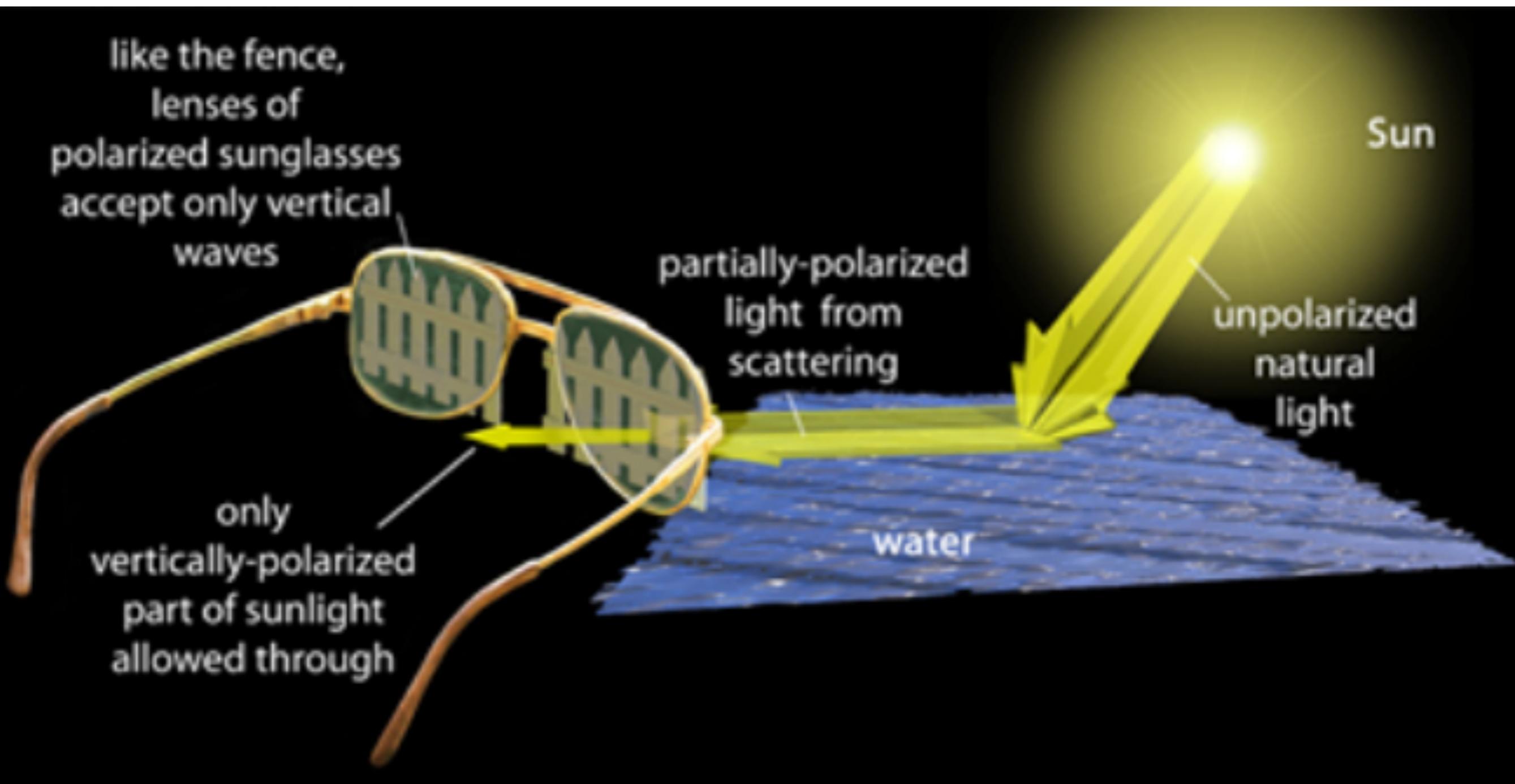


Polarisation of Light



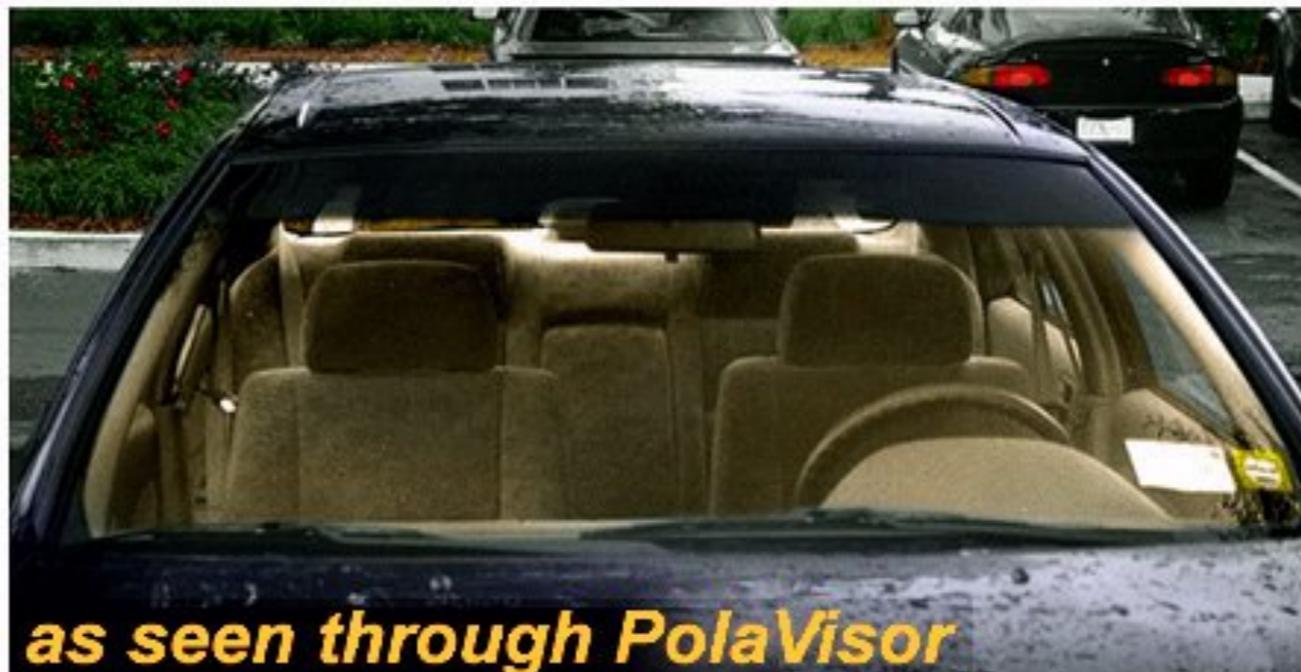
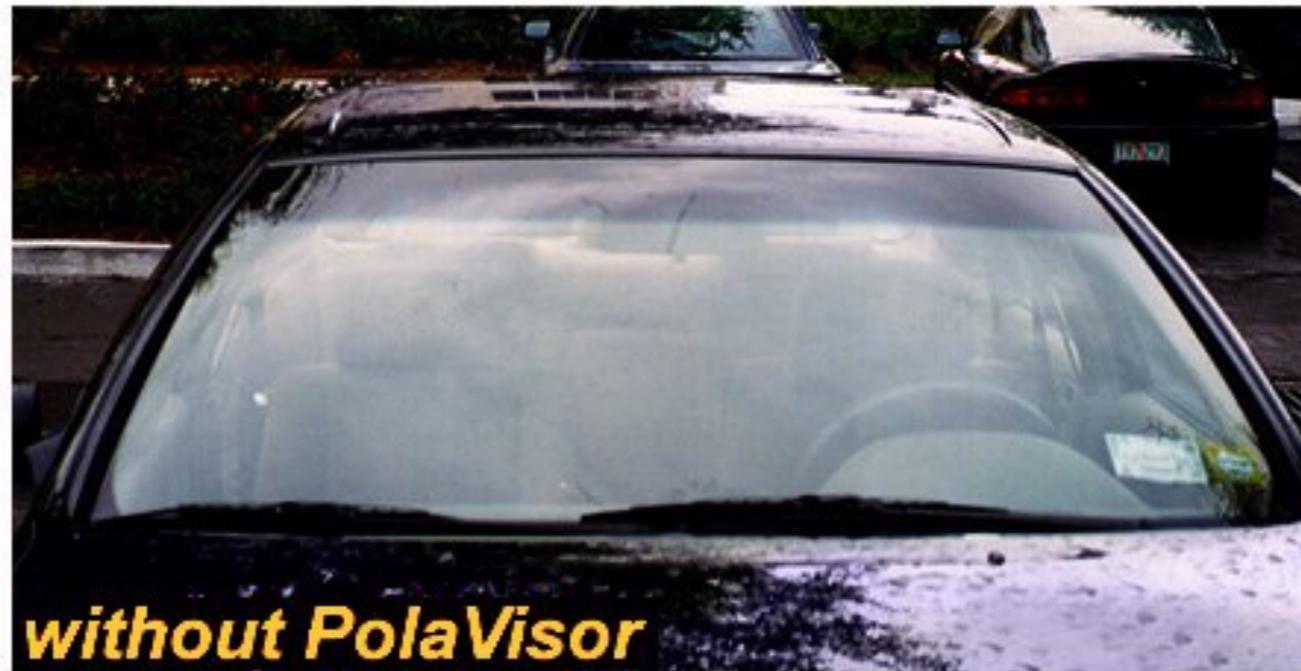
Light waves oscillate in various directions. We say “light is polarised,” when one particular direction dominates

Ex. 1: Reflection by Sea



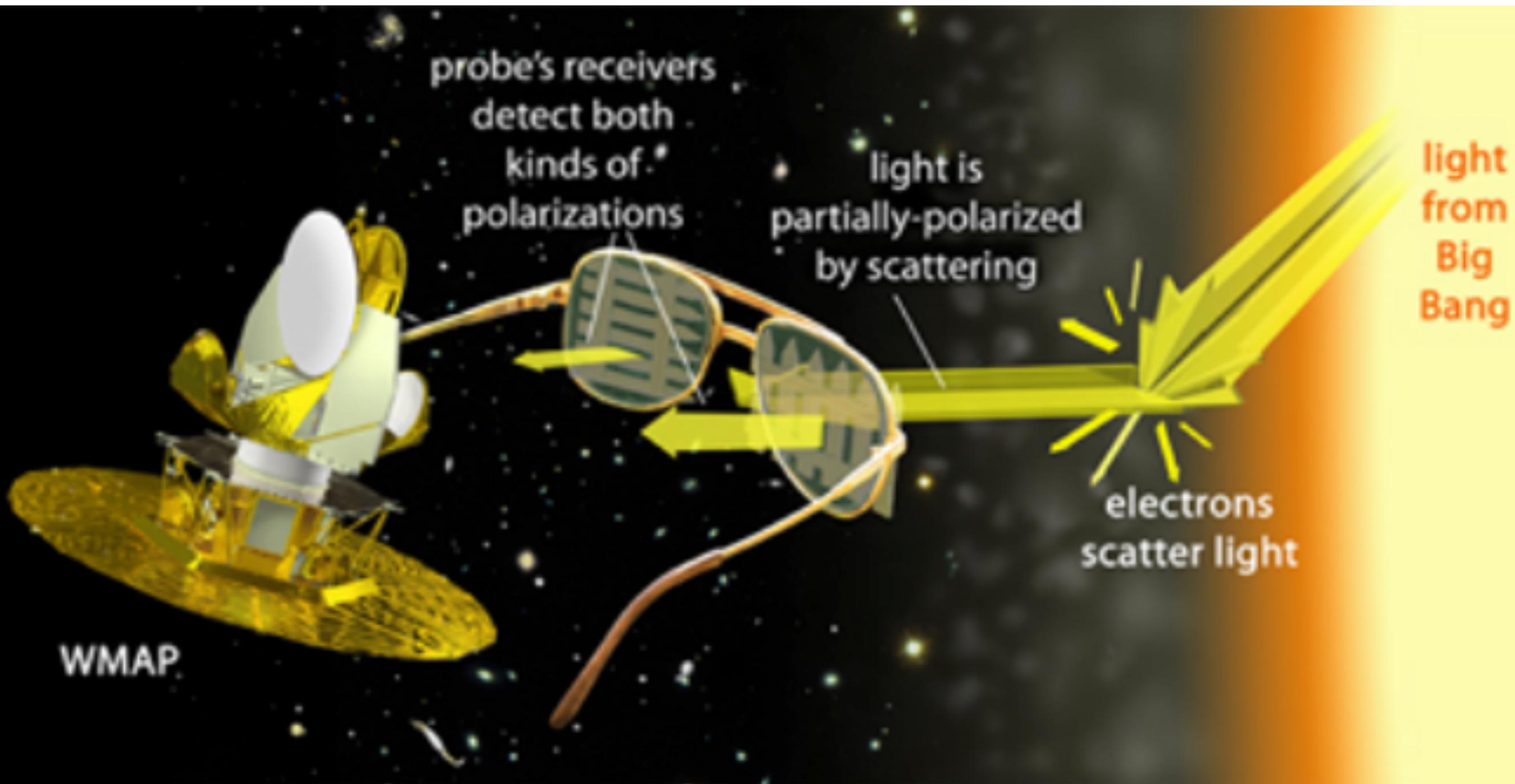
Sun light reflected by the surface of the sea is polarised horizontally. Using sunglasses transmitting only vertical polarisation eliminates the reflected sun light

Ex. 2: Windshield



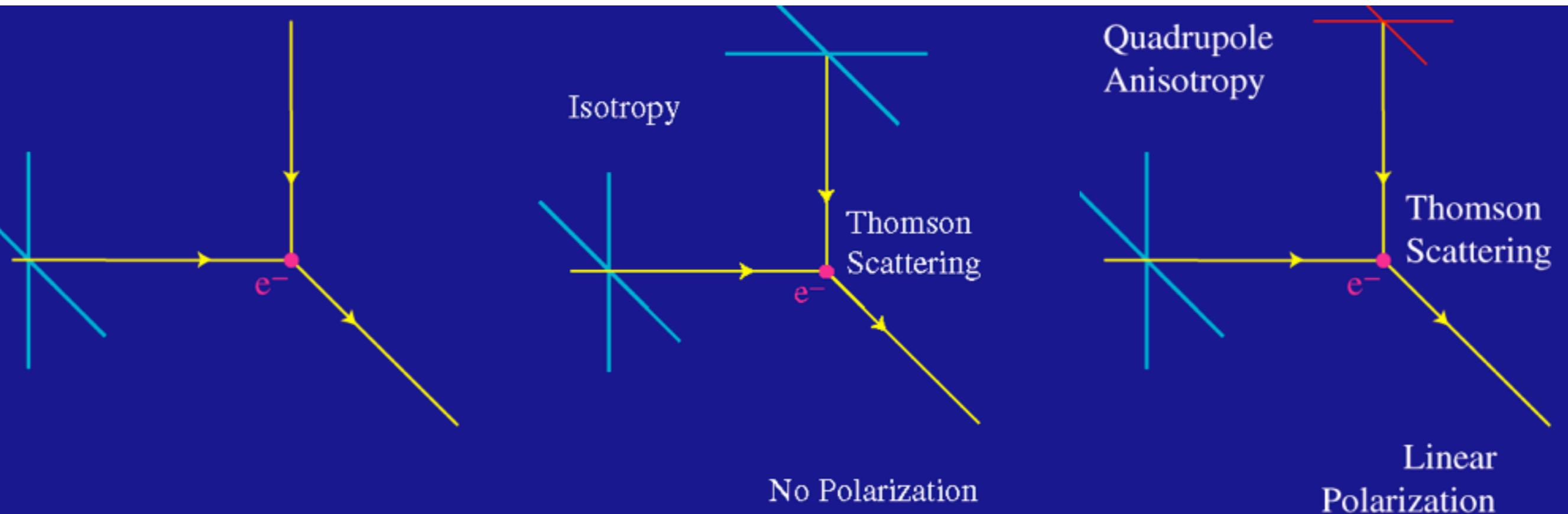
We can see through the interior of a car with polarised sunglasses transmitting only vertical polarisation

Ex. 3: CMB



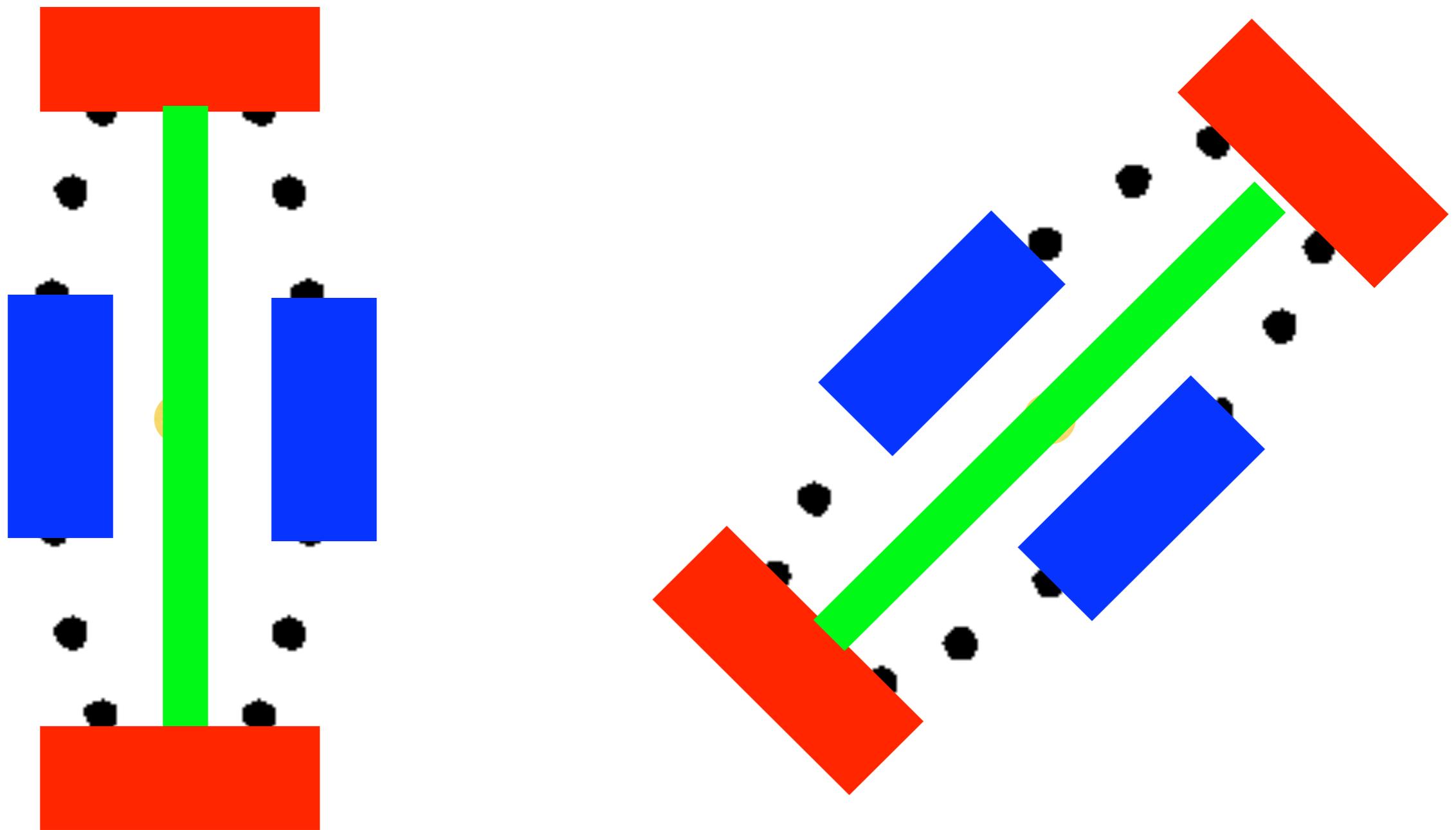
Scattering by electrons makes CMB polarised in various directions

Physics of Polarisation



Polarisation is generated when light is scattered by an electron

Gravitational Waves to Polarisation!

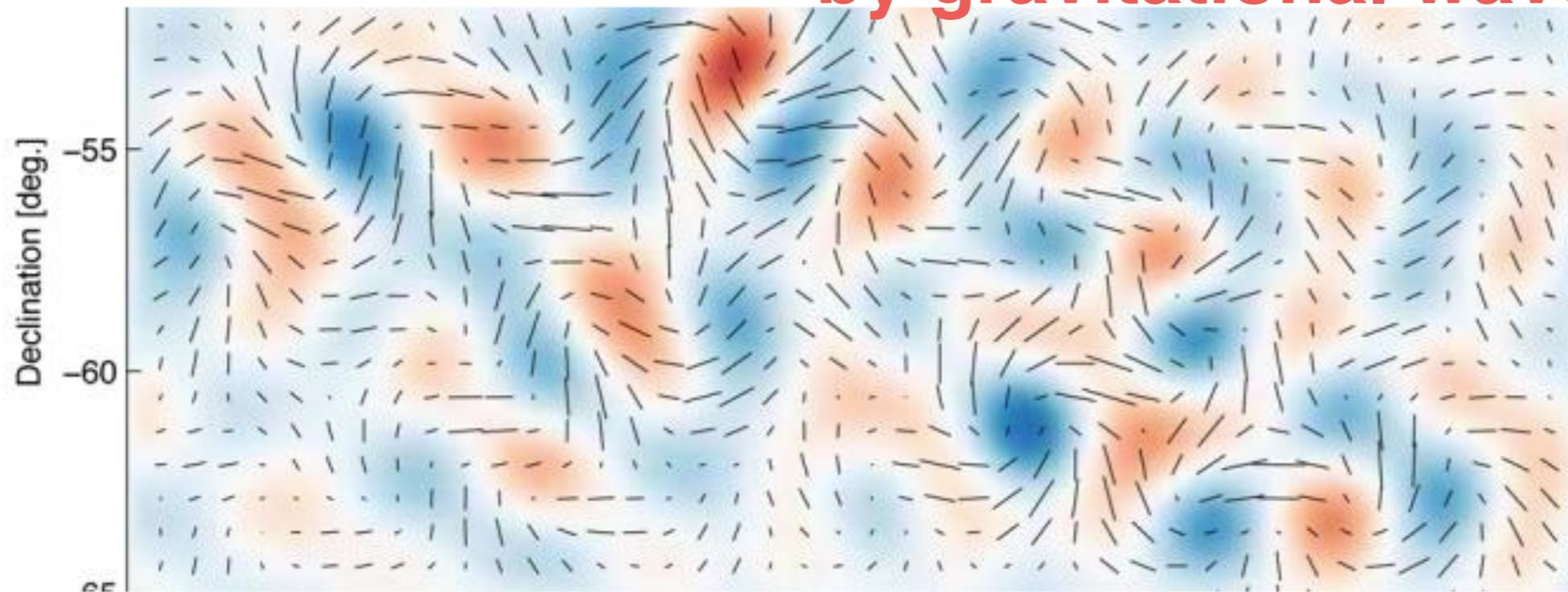


First Direct Evidence of Cosmic Inflation

Release No.: 2014-05

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

March 17, 2014: CMB Polarisation
by gravitational waves discovered?



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.

Researchers from the BICEP2 collaboration today announced the first direct evidence for this cosmic inflation. Their data also represent the first images of gravitational waves, or ripples in space-time. These waves have been described as the "first tremors of the Big Bang." Finally, the data confirm a deep connection between quantum mechanics and general relativity.

"Detecting this signal is one of the most important goals in cosmology today. A lot of work by a lot of people has led up to this point," said John Kovac (Harvard-Smithsonian Center for Astrophysics), leader of the BICEP2 collaboration.



17 March 2014 Last updated at 14:46 GMT



First Direct Evidence of Cosmic

Release No.: 2014-05

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

Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos
Science correspondent, BBC News



Declination [deg.]
-55
-60

SPACE & COSMOS

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

17. März 2014, 17:34 Gravitationswellen

Signale aus der Geburtsstunde des Universums



Eiichiro Komatsu

March 14 near Munich 

If detection of the primordial B-modes were to be reported on Monday, I would like see:

[1] Detection (>3 sigma each) in more than one frequency, like 100 GHz and 150 GHz giving the same answers to within the error bars.

[2] Detection (could be a couple of sigmas each) in a few multipole bins, i.e., not in just one big multipole bin.

Then I will believe it!

The Facebook logo, consisting of the word "facebook" in white lowercase letters on a dark blue rectangular background.

facebook



Eiichiro Komatsu

March 14 near Munich

If detection of the primordial B-modes were to be reported on Monday, I would like see:

 detection (>3 sigma each) in more than one frequency, like 100 GHz and 150 GHz giving the same answers to within the error bars.

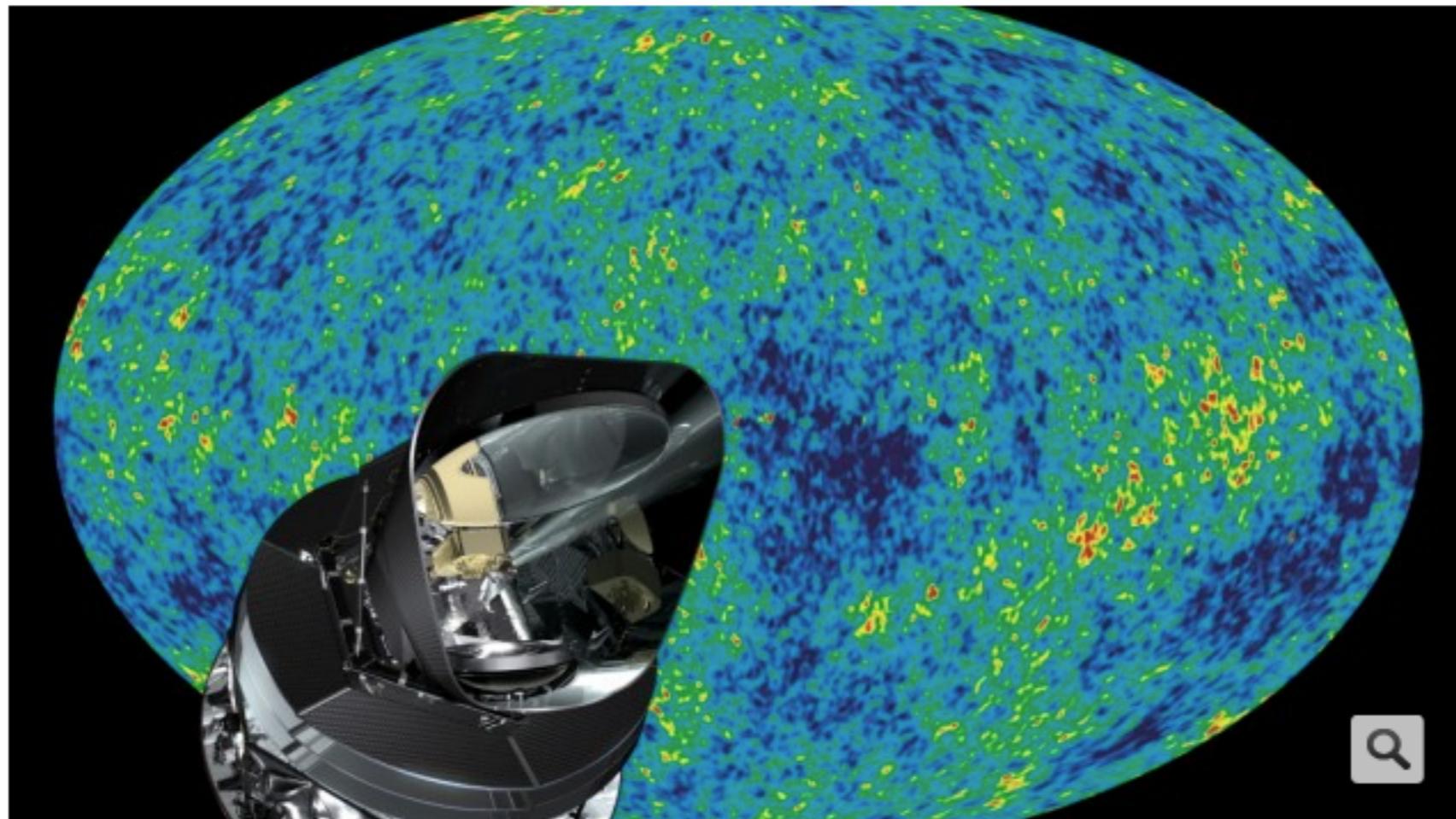
 detection (could be a couple of sigmas each) in a few multipole bins, i.e., not just one big multipole bin.

Then I will believe it!

facebook

22. September 2014, 10:43 Gravitationswellen vom Urknall

Im Zweifel nur Staub



Der Planck-Satellit vor dem Bild des kosmischen Mikrowellenhintergrunds. Die Daten des Satelliten lassen Schlüsse über die früheste Geschichte des Universums zu. (Foto:)

Vor einem halben Jahr sorgte ein Teleskop am Südpol für Aufsehen: Ein Signal aus der ersten Sekunde des Universums wollte das Bicep2-Team aufgefangen haben. Doch nun weckt eine neue Studie starke Zweifel an der Sensation.

Von Robert Gast

Current Situation

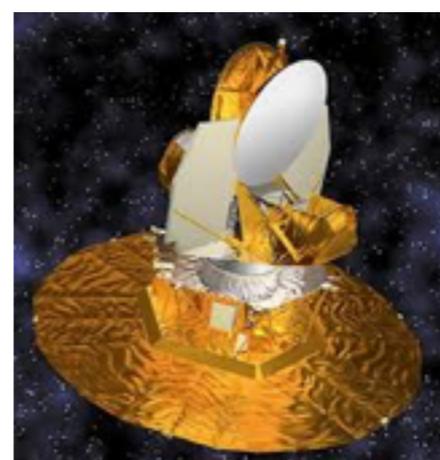
- Planck shows the evidence that the detected signal is not cosmological, but is due to dust
- No strong evidence that the detected signal is cosmological



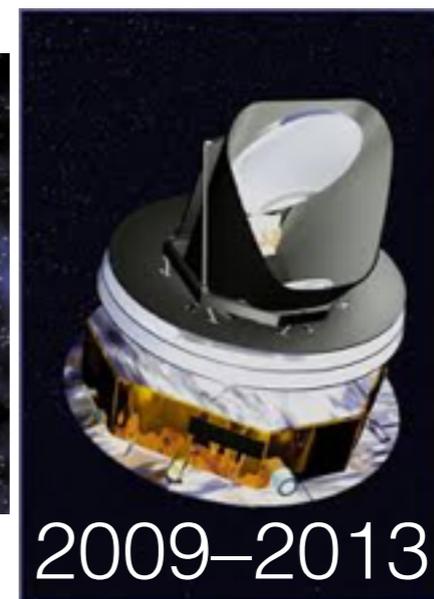
The search continues!!



1989–1993



2001–2010



2009–2013



202X–

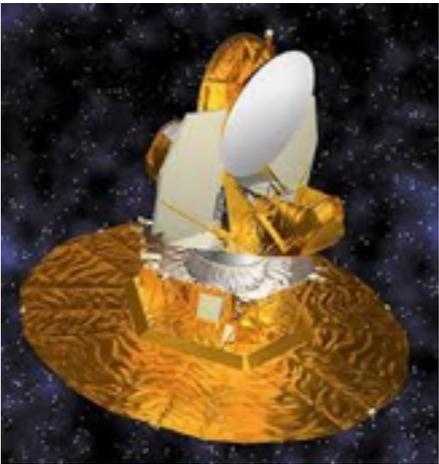
A proposal in response to the ESA Call for
a Medium-size mission opportunity
for a launch in 2025

COrE+

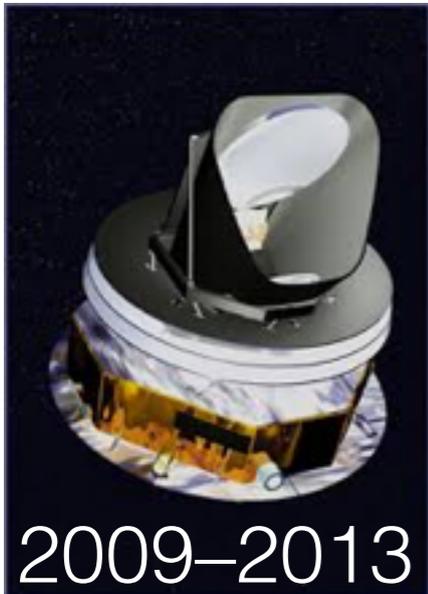
Cosmic Origins Explorer+



1989–1993

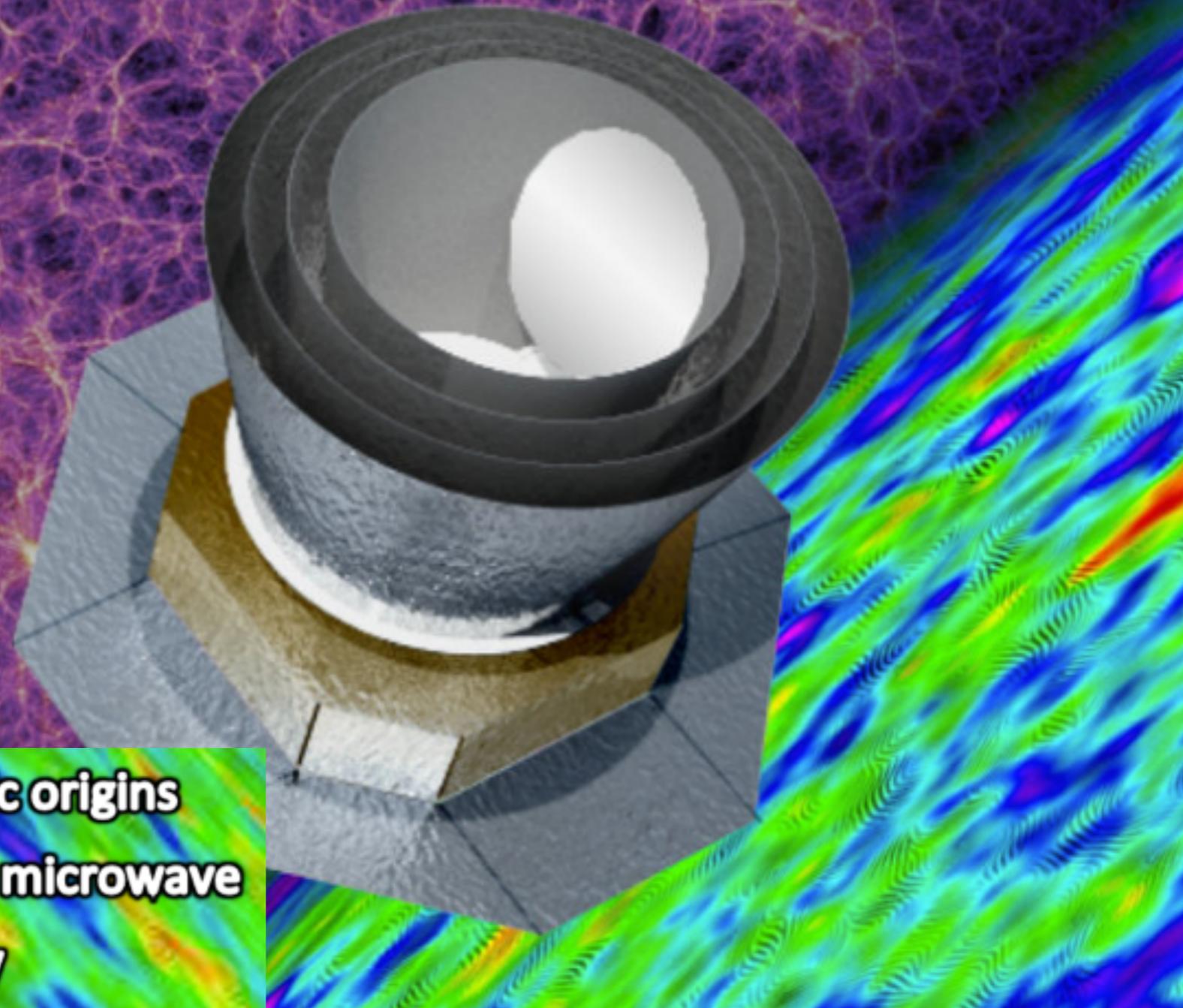


2001–2010



2009–2013

The search continues!



**A satellite mission for probing cosmic origins
through a high sensitivity survey of the microwave
polarisation of the entire sky**

Summary

- We are seeing physical conditions of the early Universe using CMB
- Our origin goes back to tiny fluctuations that existed in the early Universe
- Quantum fluctuations? We wish to find also gravitational waves from the early Universe
 - **COrE+: fingers crossed!**