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

Eiichiro Komatsu
(Max-Planck-Institut für Astrophysik)

Plücker Lecture, Universität Bonn
11. Oktober, 2019

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"

James Peebles

https://www.nobelprize.org

Facts

Ill. Niklas Elmedhed. © Nobel Media.

James Peebles
The Nobel Prize in Physics 2019

Born: 1935, Winnipeg, Canada

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

Prize motivation: "for theoretical discoveries in physical cosmology."

Prize share: 1/2

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"

Breakthrough in Cosmological Research

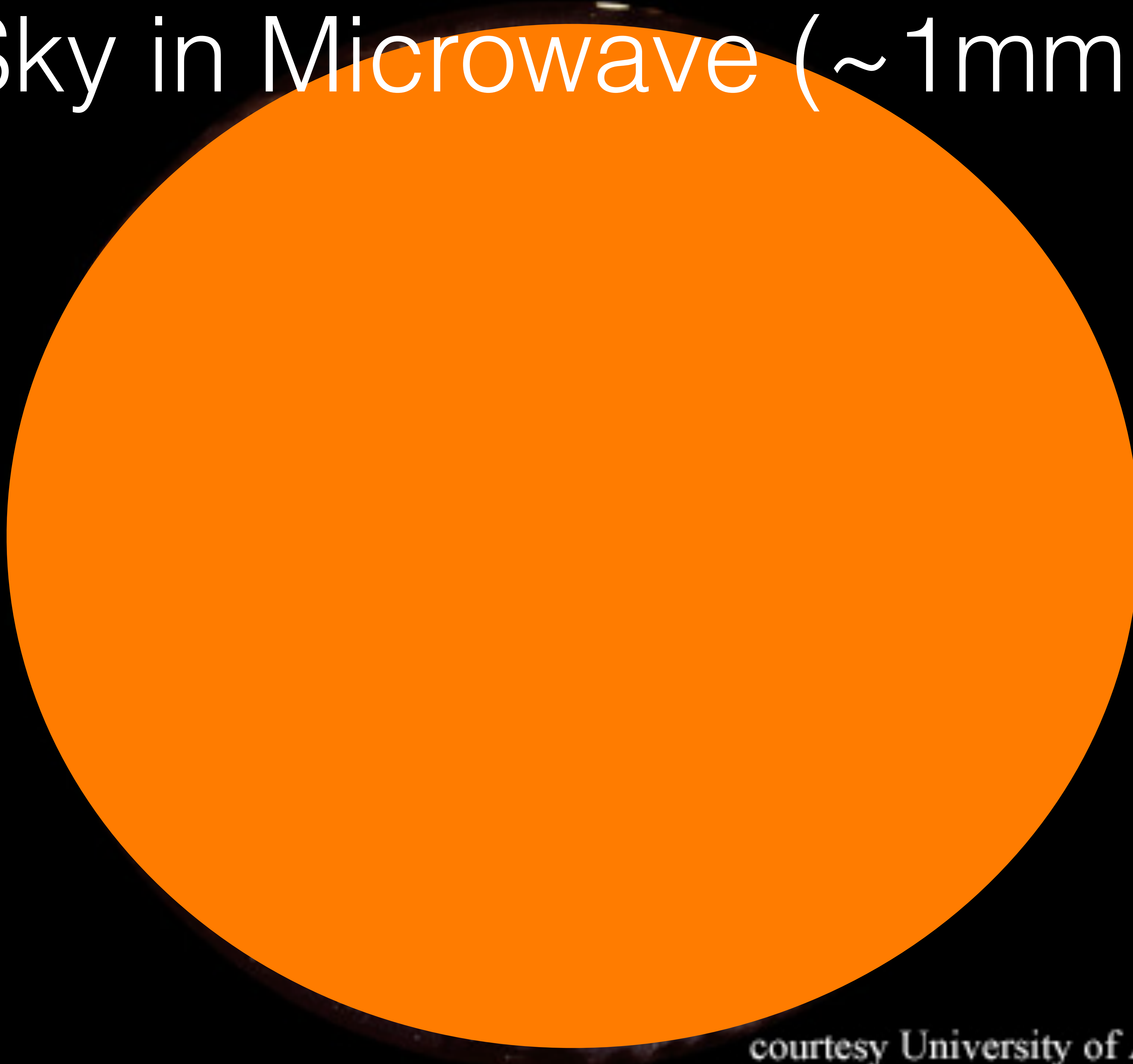
- We can actually **see** the physical condition of the universe when it was very young

From "Cosmic Voyage"

Sky in Optical (~0.5μm)

courtesy University of Arizona

Sky in Microwave (~1mm)

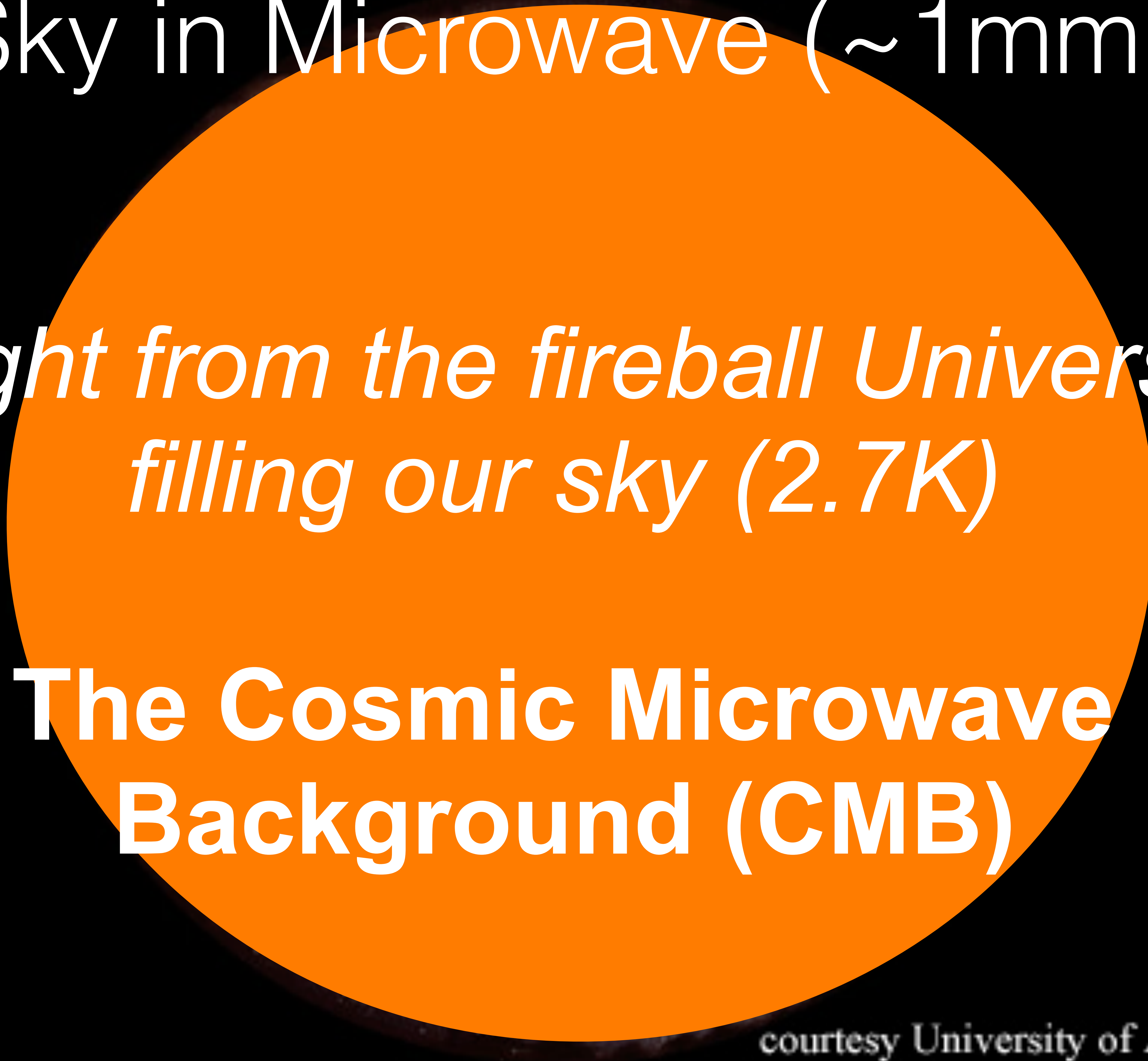


courtesy University of Arizona

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!!

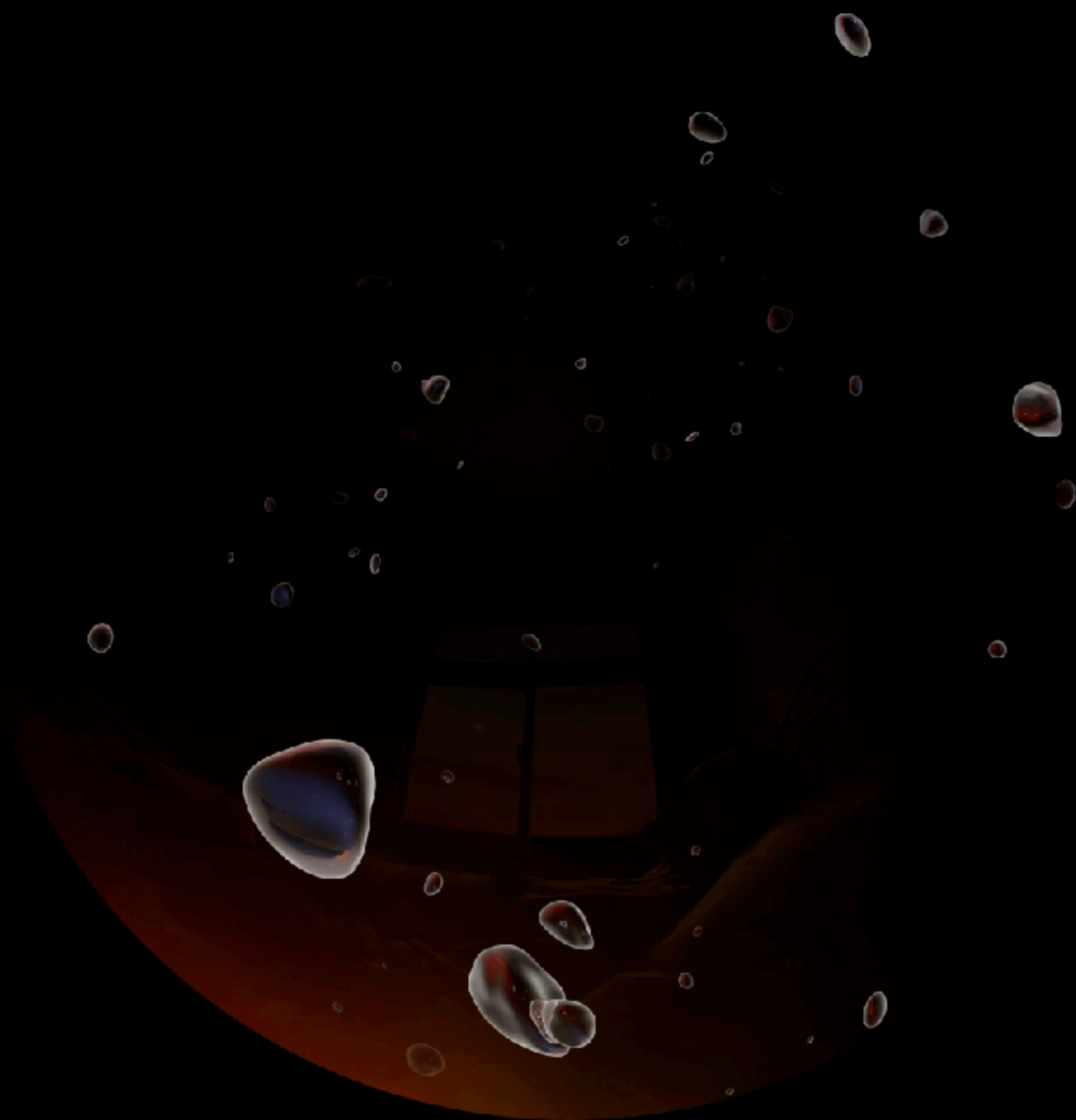
courtesy University of Arizona

YouTube BE horizon edge of the visible universe

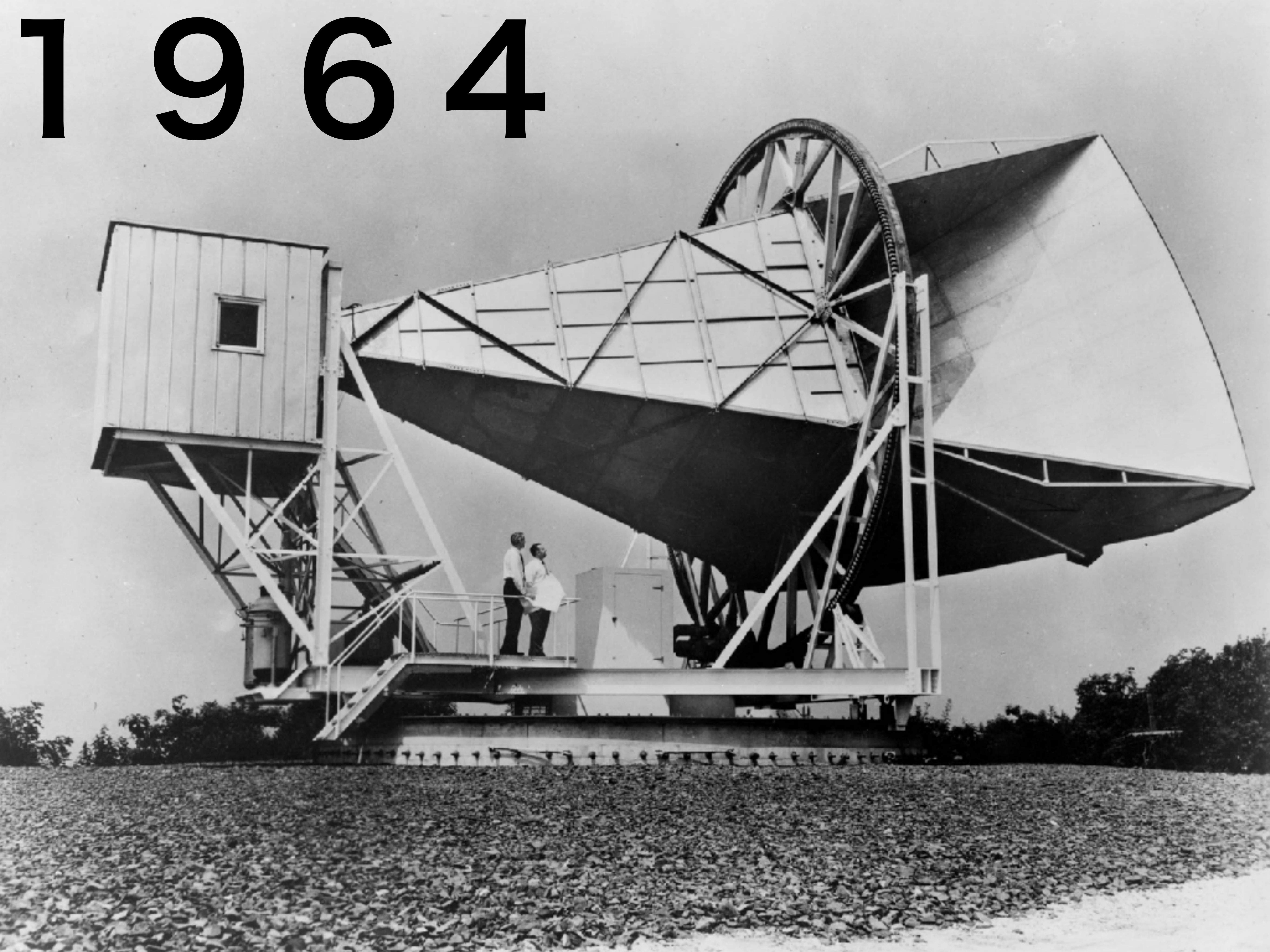
Full-dome movie for planetarium

Director: Hiromitsu Kohsaka

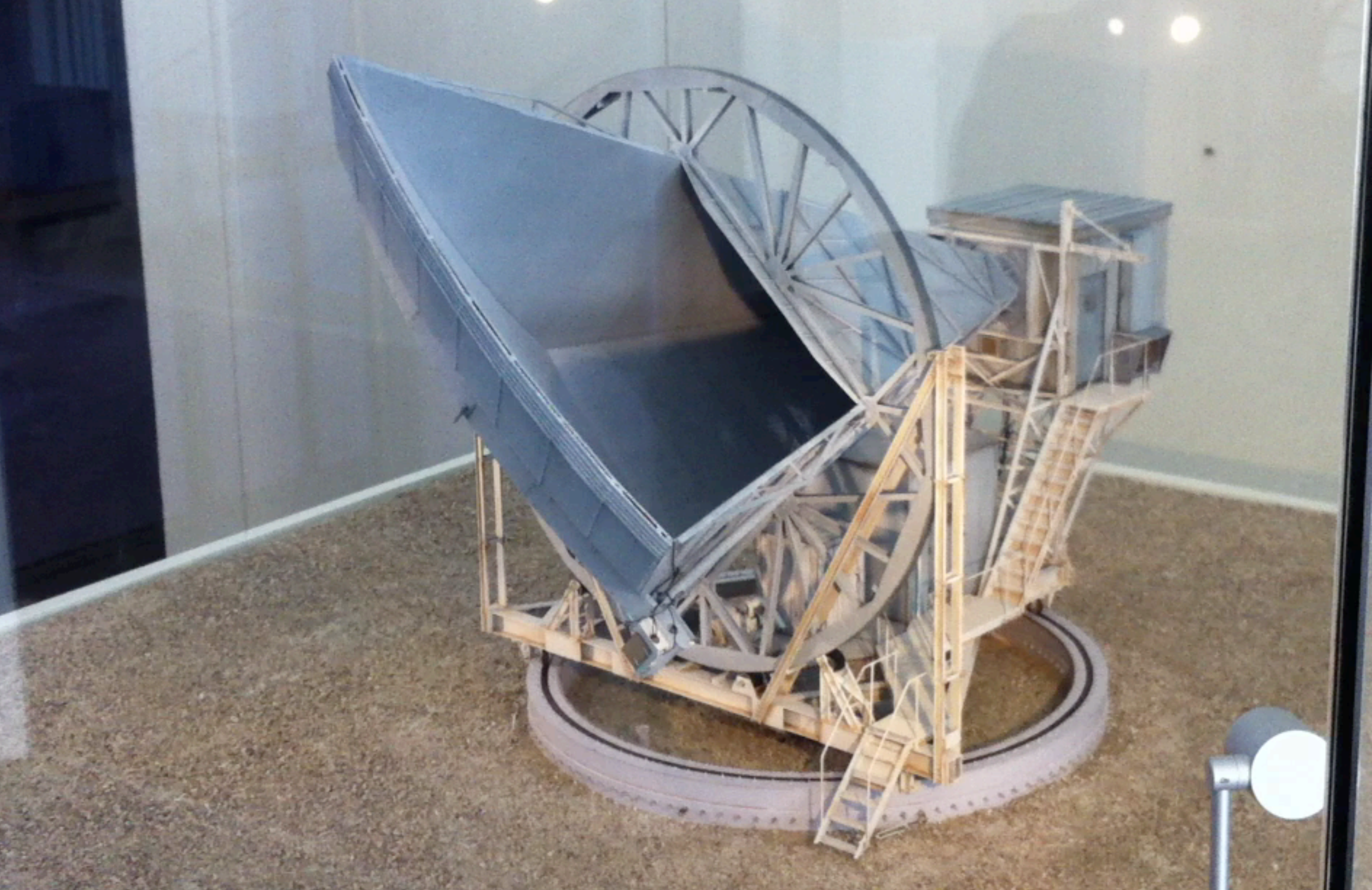
HORIZON :Beyond the Edge of the Visible Universe [Trailer]

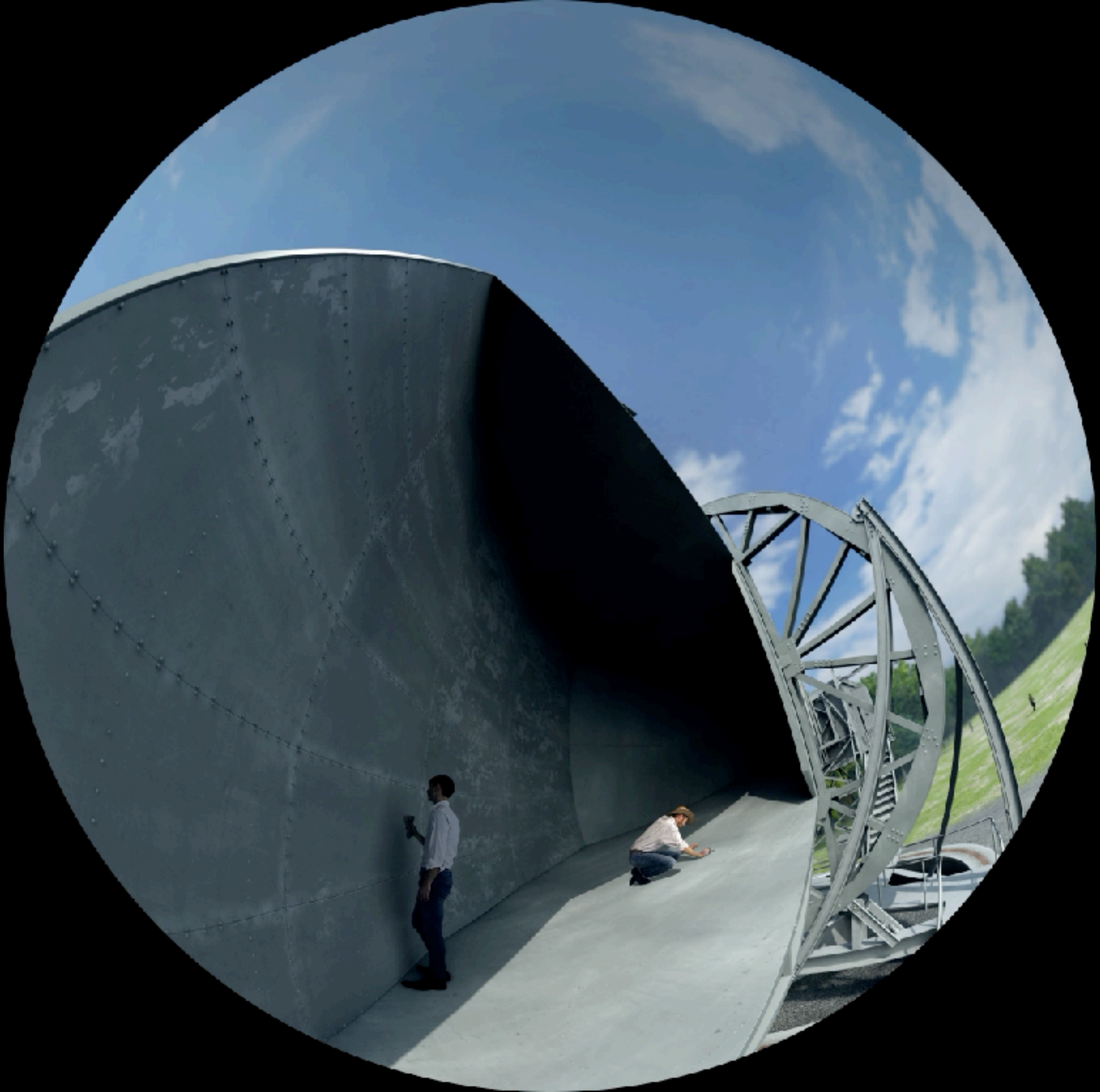


1964

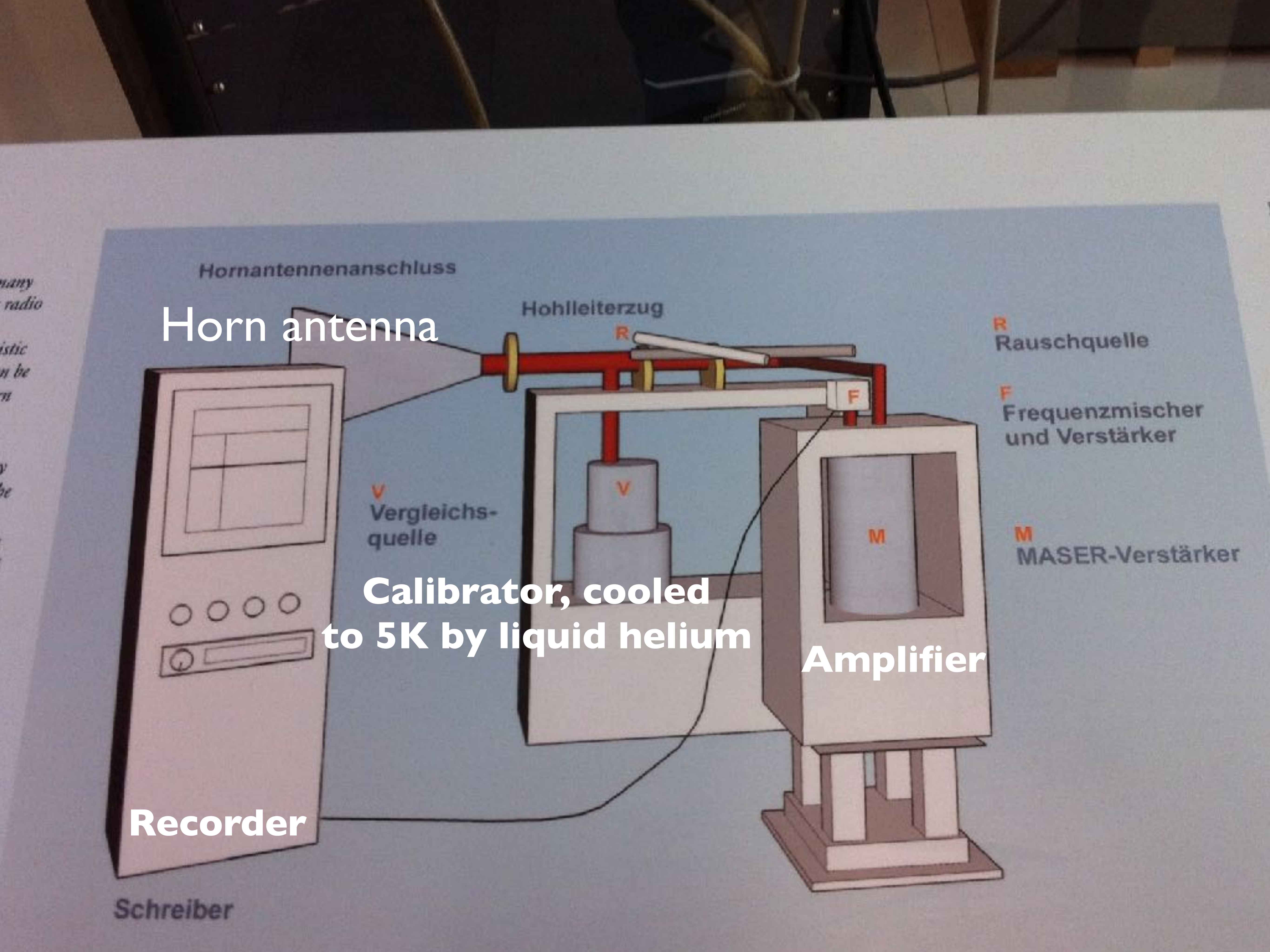


1:25 model of the antenna at Bell Lab
The 3rd floor of Deutsches Museum





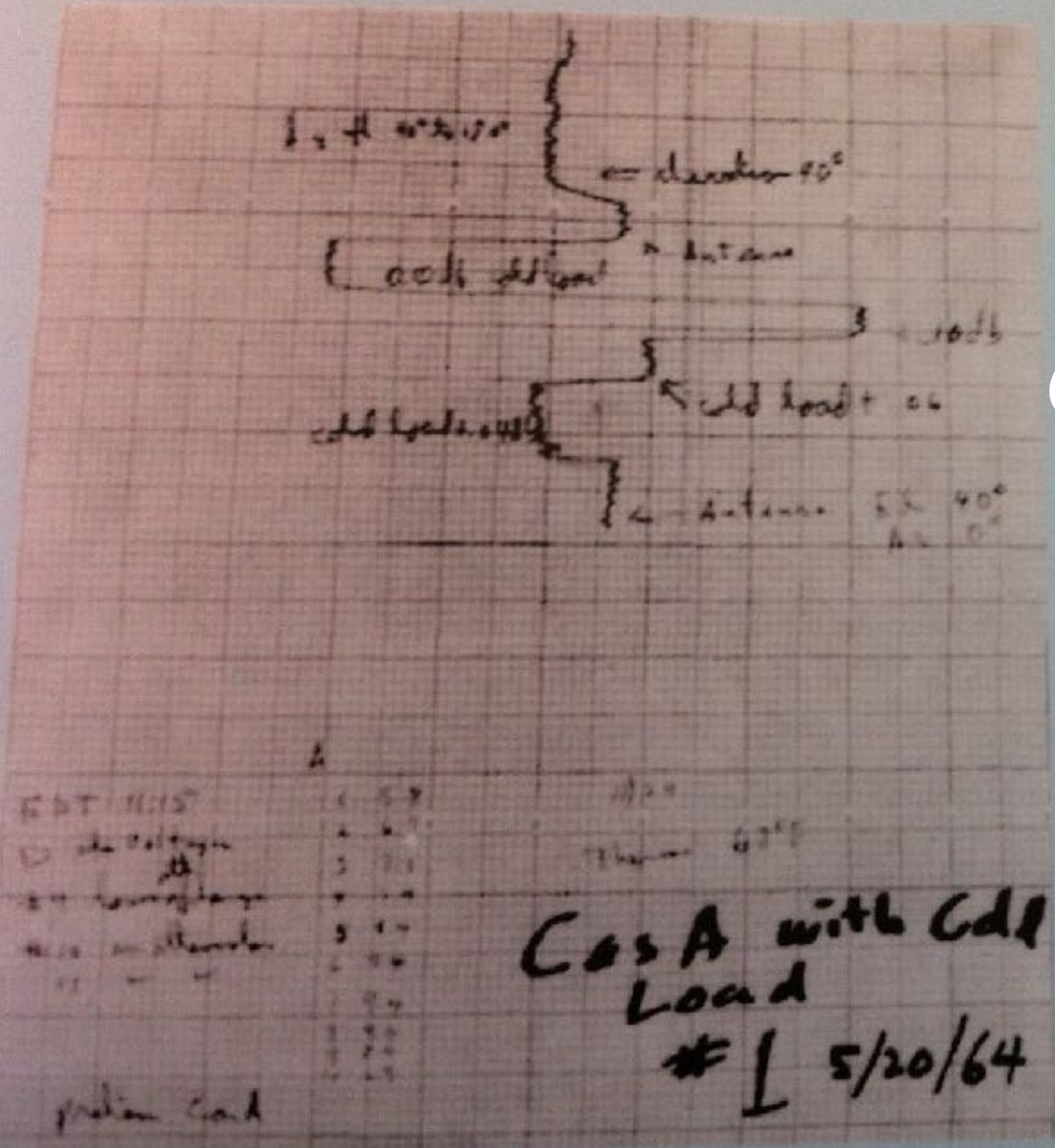
The real detector system used by Penzias & Wilson
The 3rd floor of Deutsches Museum



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

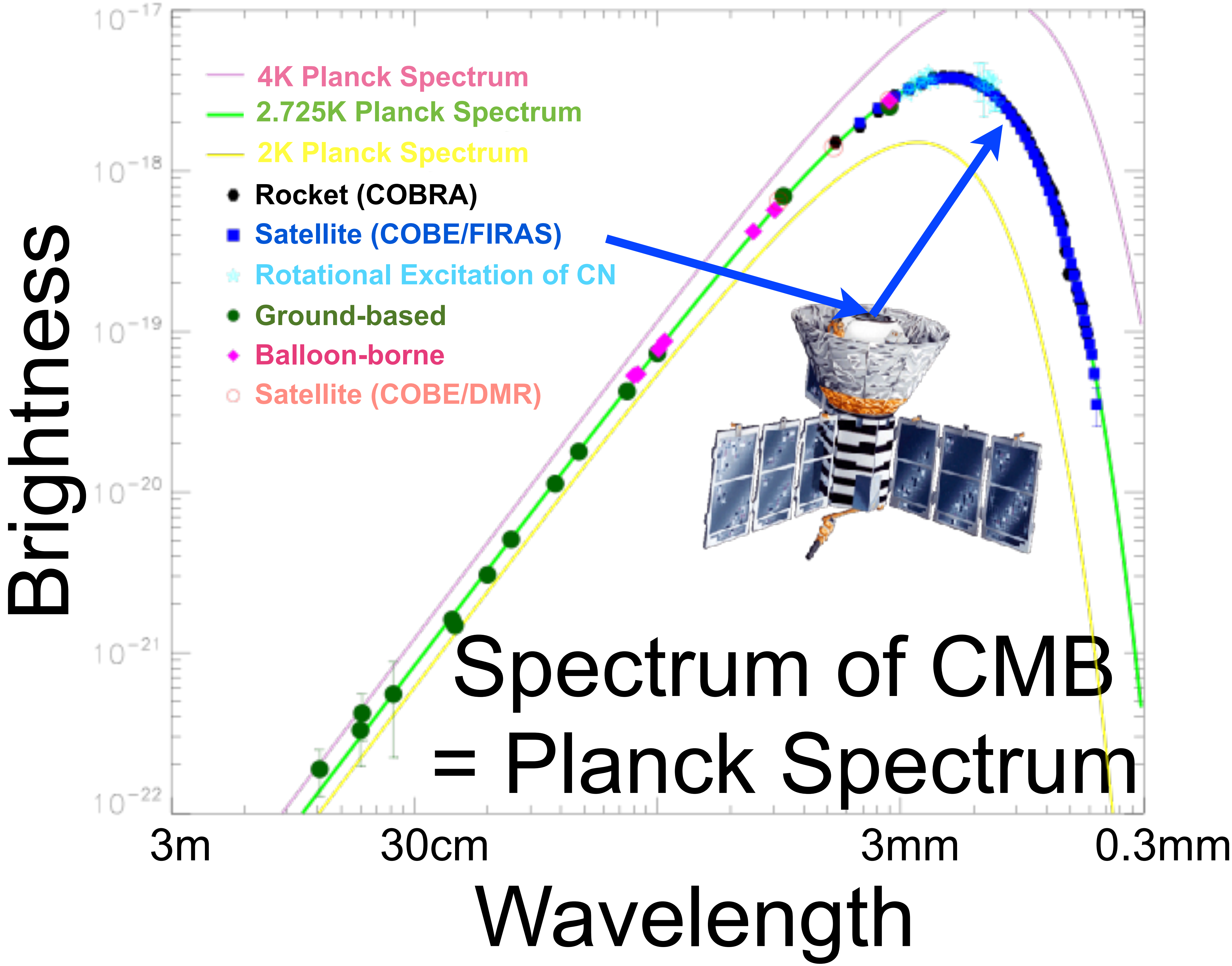
May 20, 1964
CMB
Discovered

6.7–2.3–0.8–0.1
= 3.5±1.0 K



Schreiberaufzeichnung der ersten Messung des Mikrowellenhintergrundes am 20.5.1964

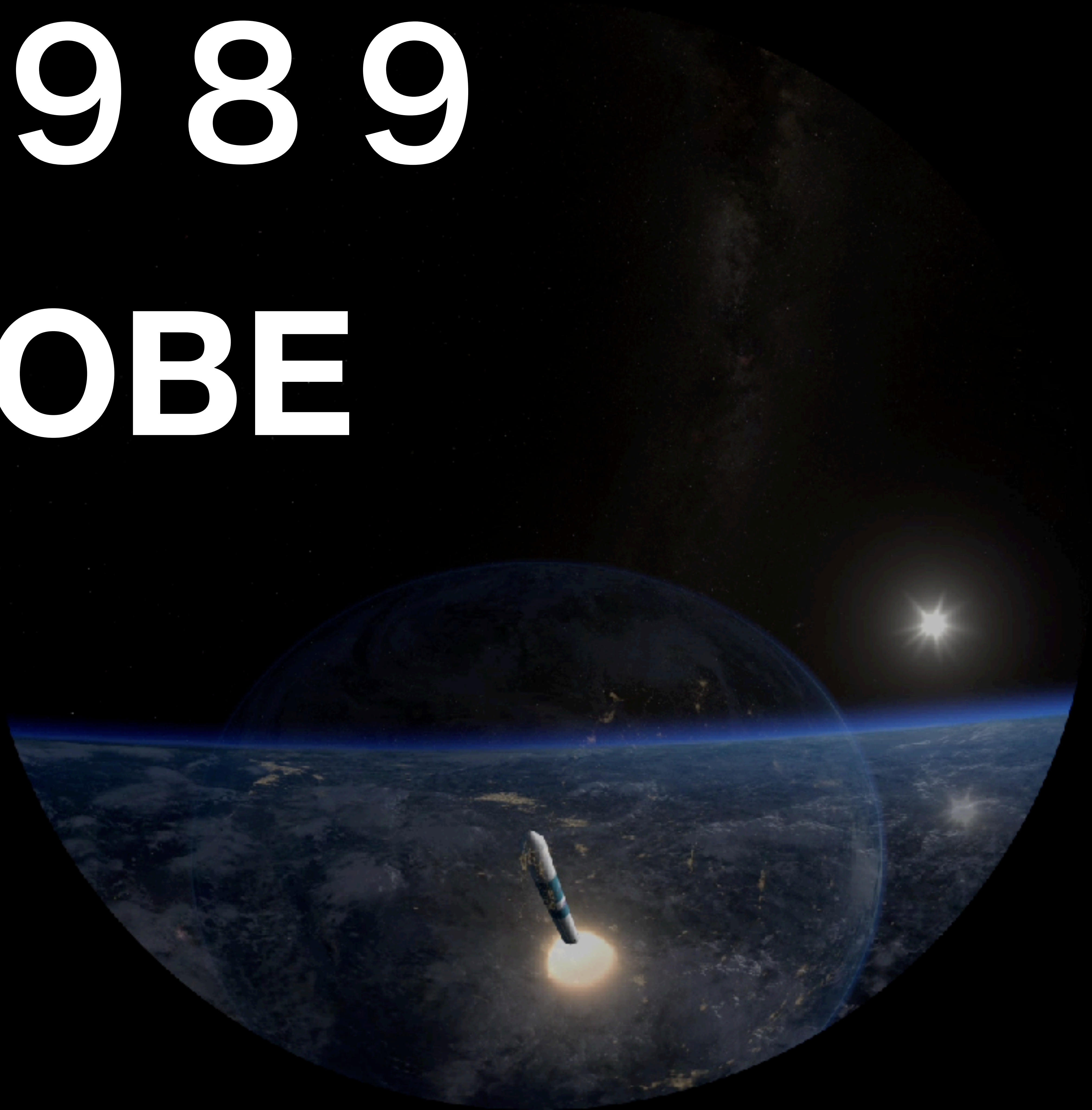
Recording of the first measurement of cosmic microwave background radiation taken on 5/20/1964.

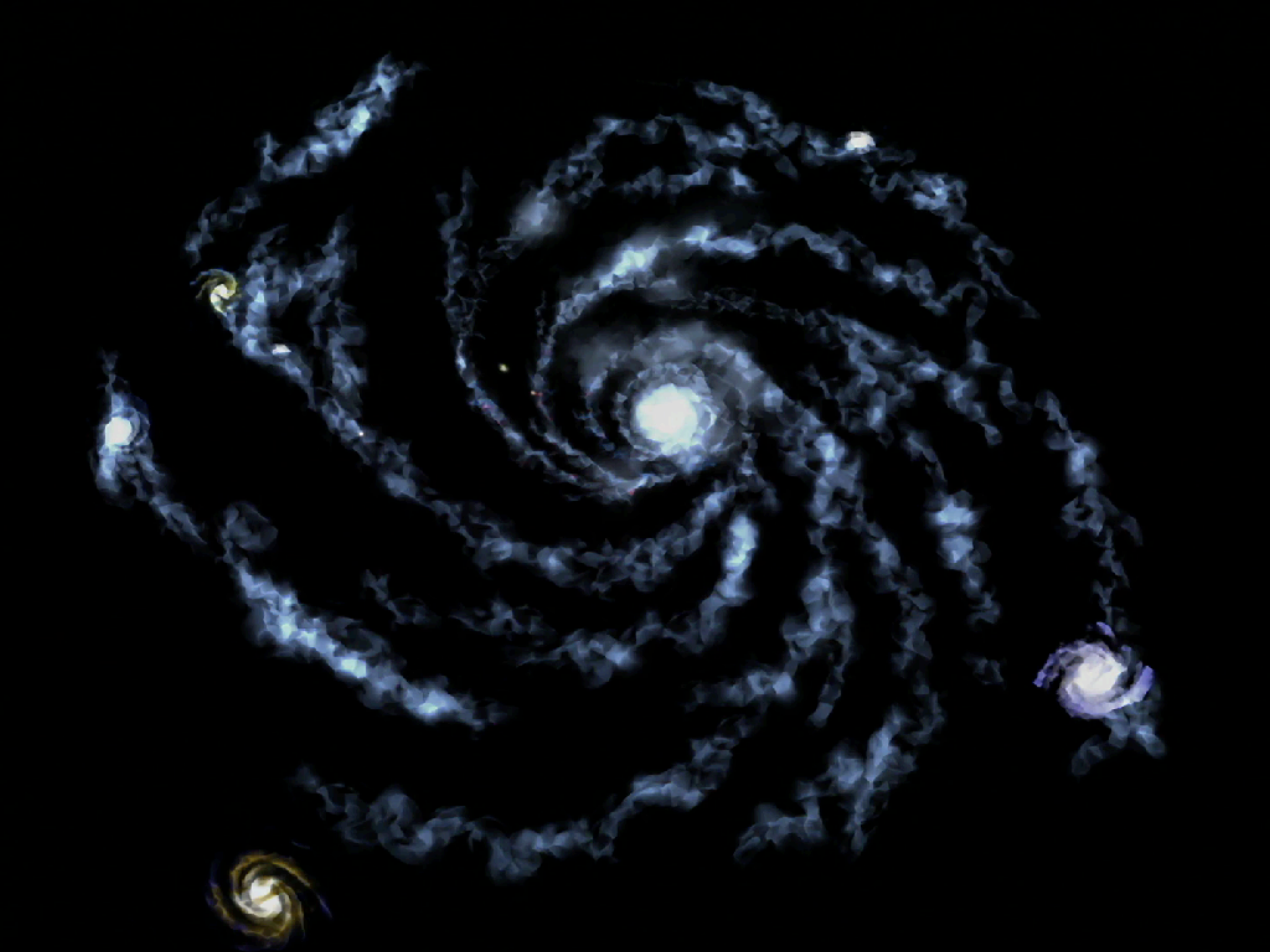


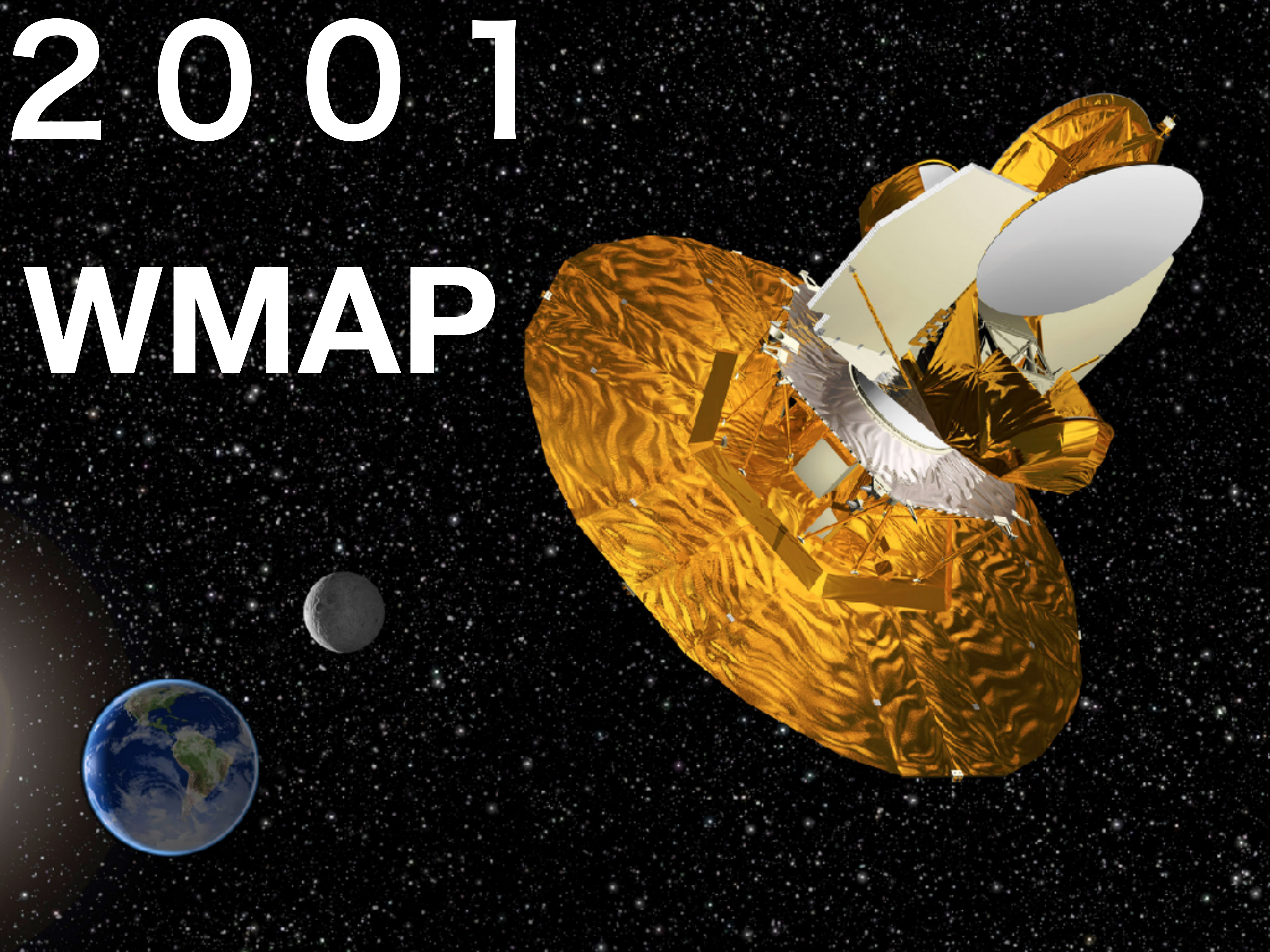
Brightness
4K Planck Spectrum
2.725K Planck Spectrum
2K Planck Spectrum
Rocket (COBRA)
Satellite (COBE/FIRAS)
Rotational Excitation of CN
Ground-based
Balloon-borne
Satellite (COBE/DMR)
Spectrum of CMB
= Planck Spectrum
3m
30cm
3mm
0.3mm
Wavelength

１９８９

COBE



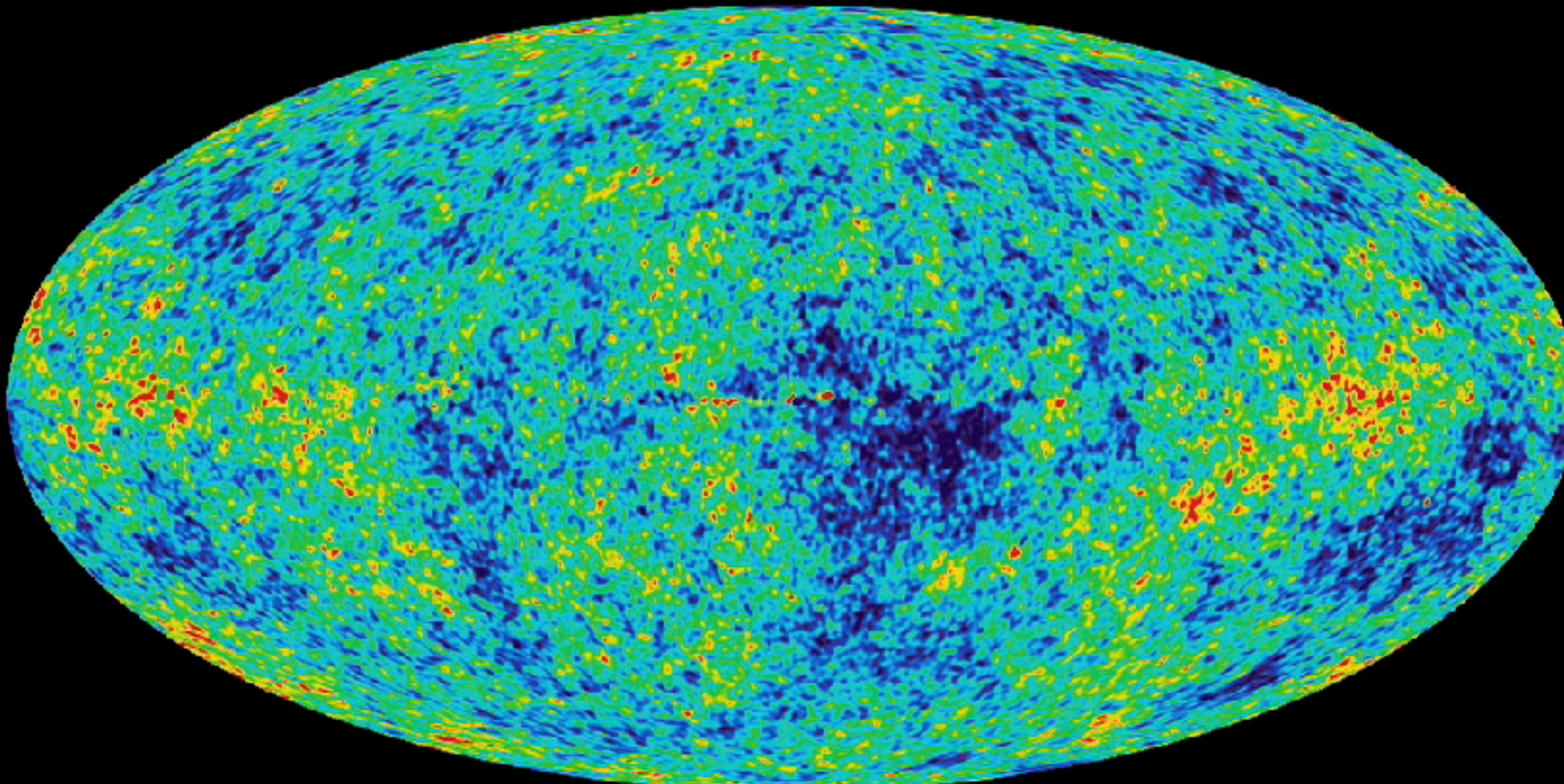



2001
WMAP

WMAP Science Team
July 19, 2002

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

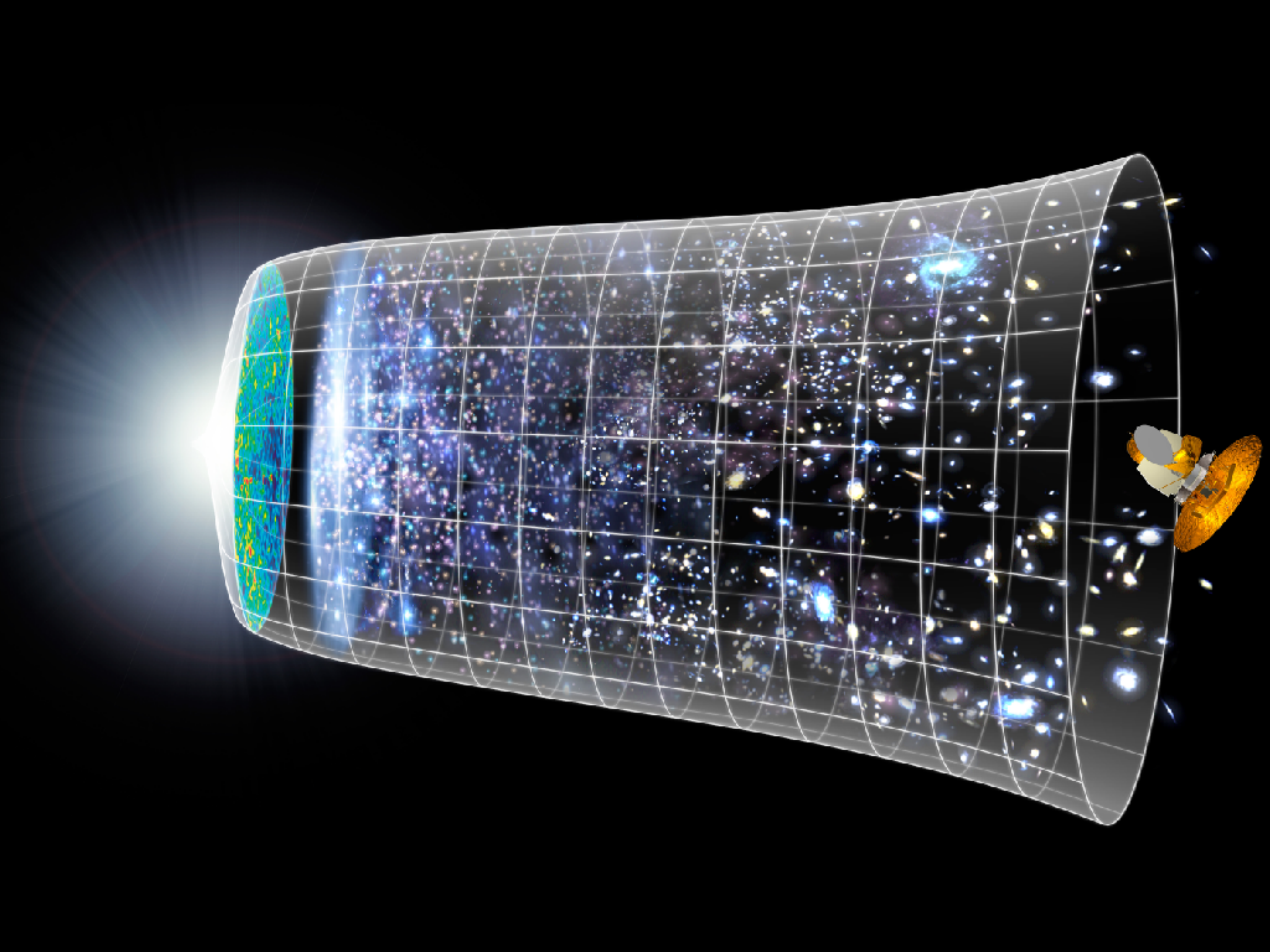

2001 WMAP

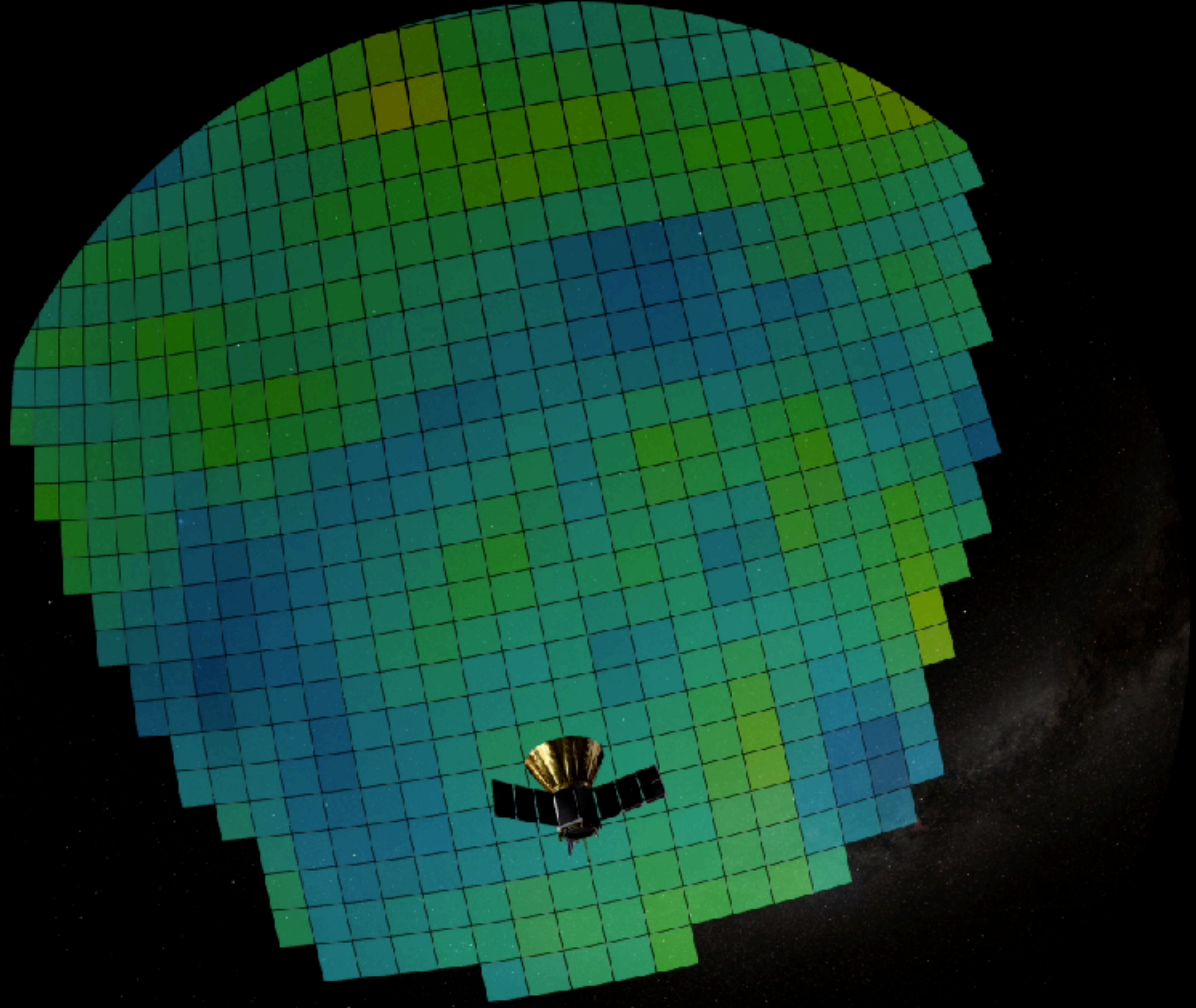


A Remarkable Story

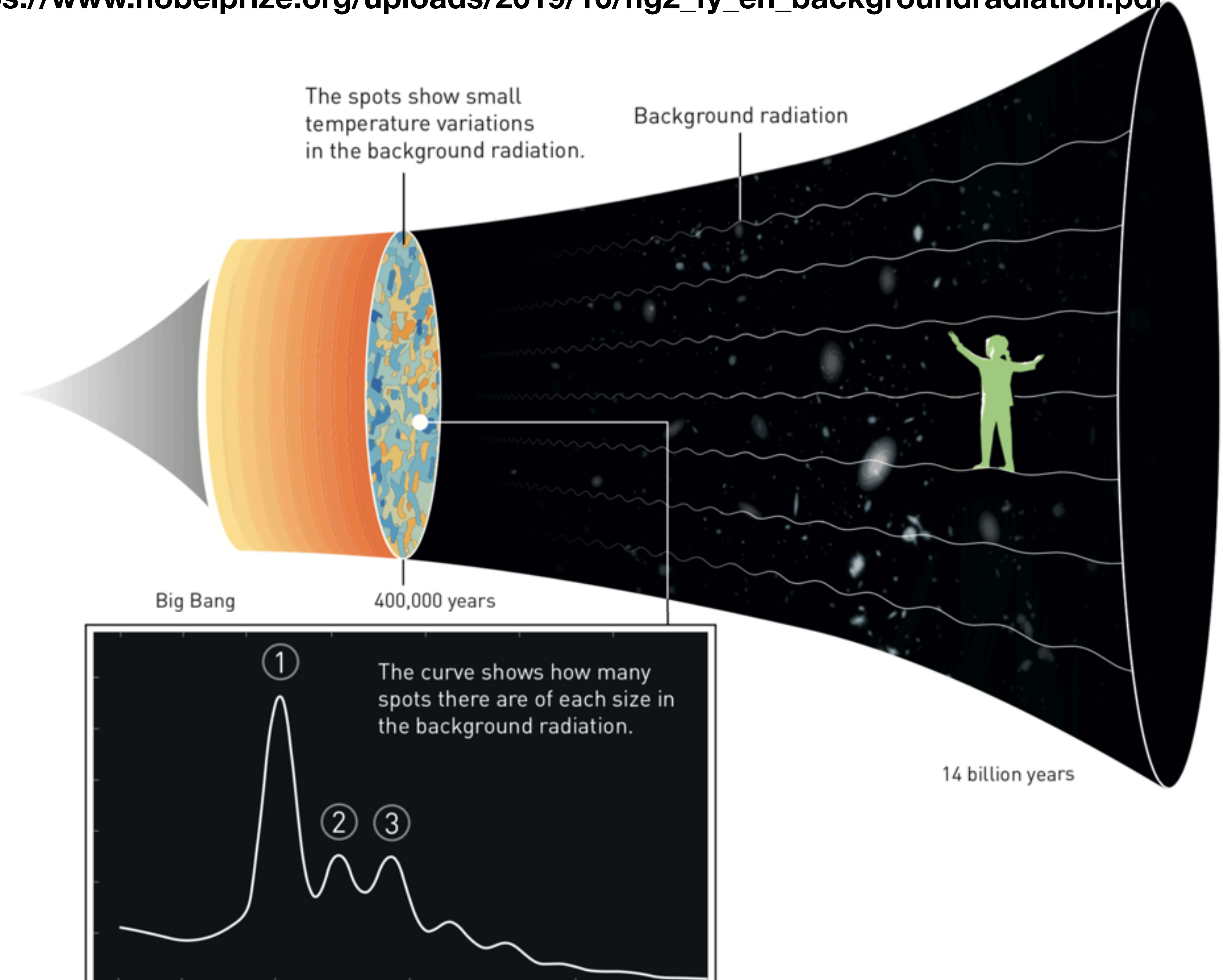
- Observations of the cosmic microwave background and their interpretation taught us that **galaxies, stars, planets, and ourselves originated from tiny fluctuations in the early Universe**

- *But, **what generated the initial fluctuations?***



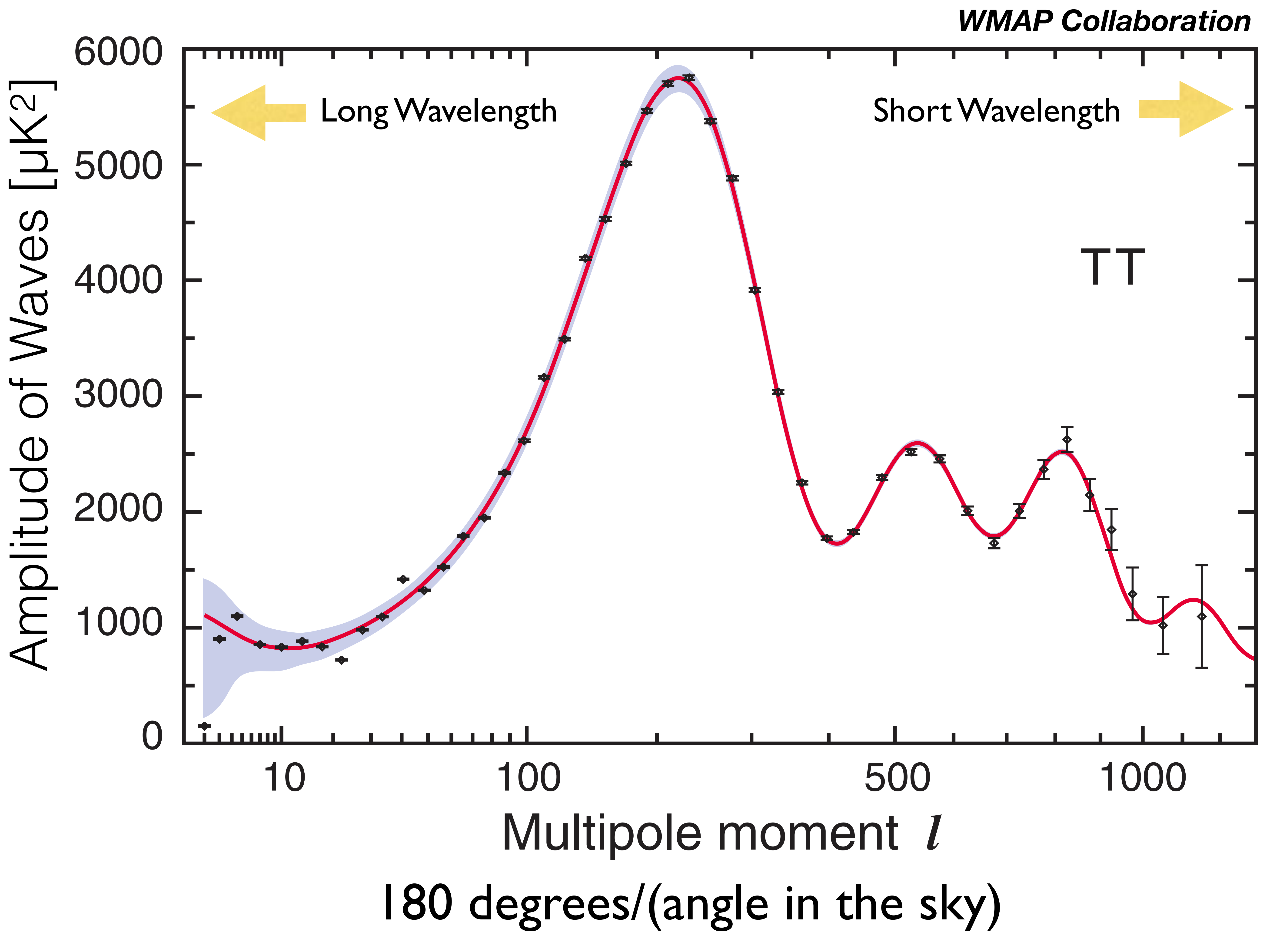


https://www.nobelprize.org/uploads/2019/10/fig2_fy_en_backgroundradiation.pdf

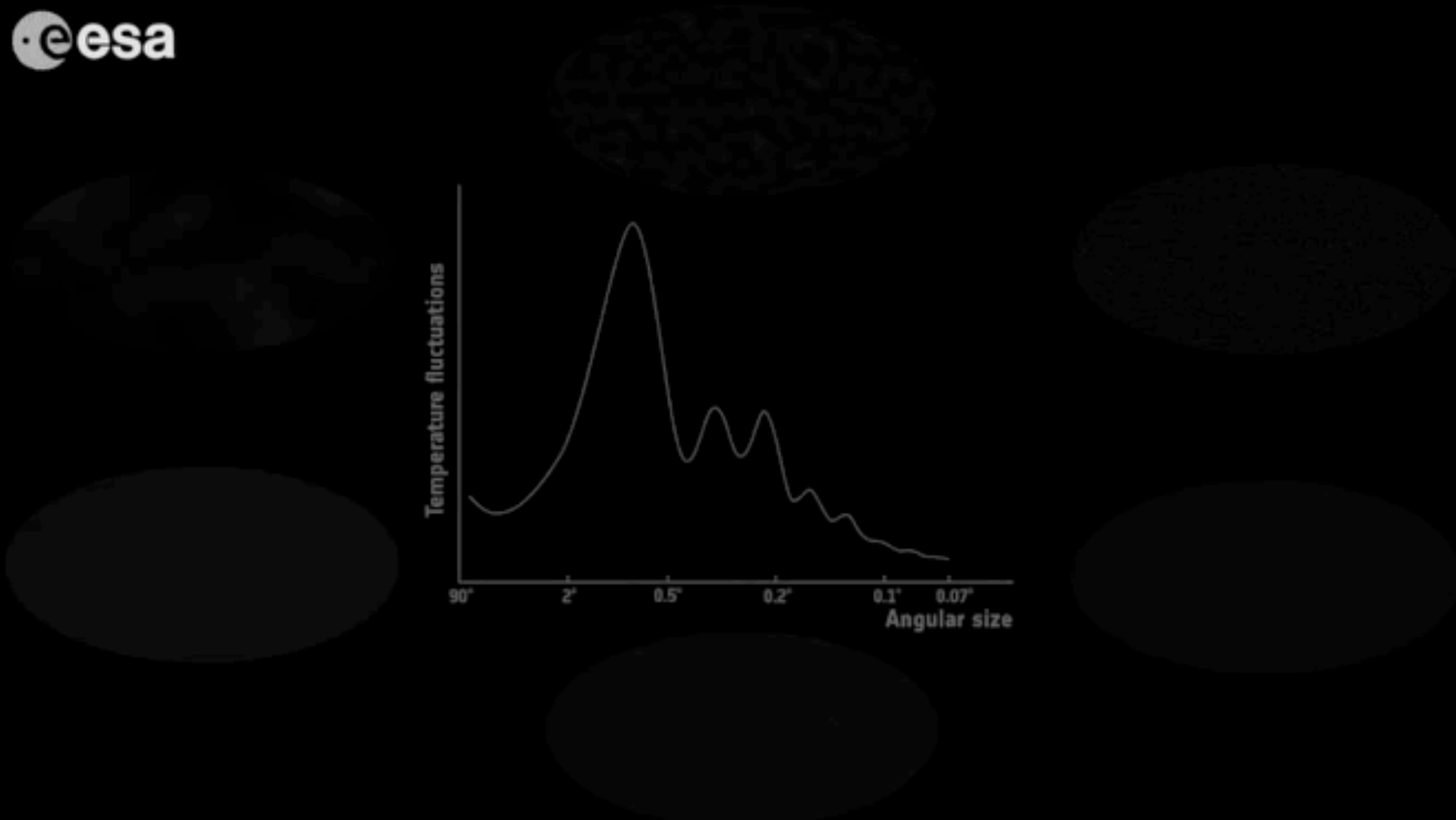


Data Analysis

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

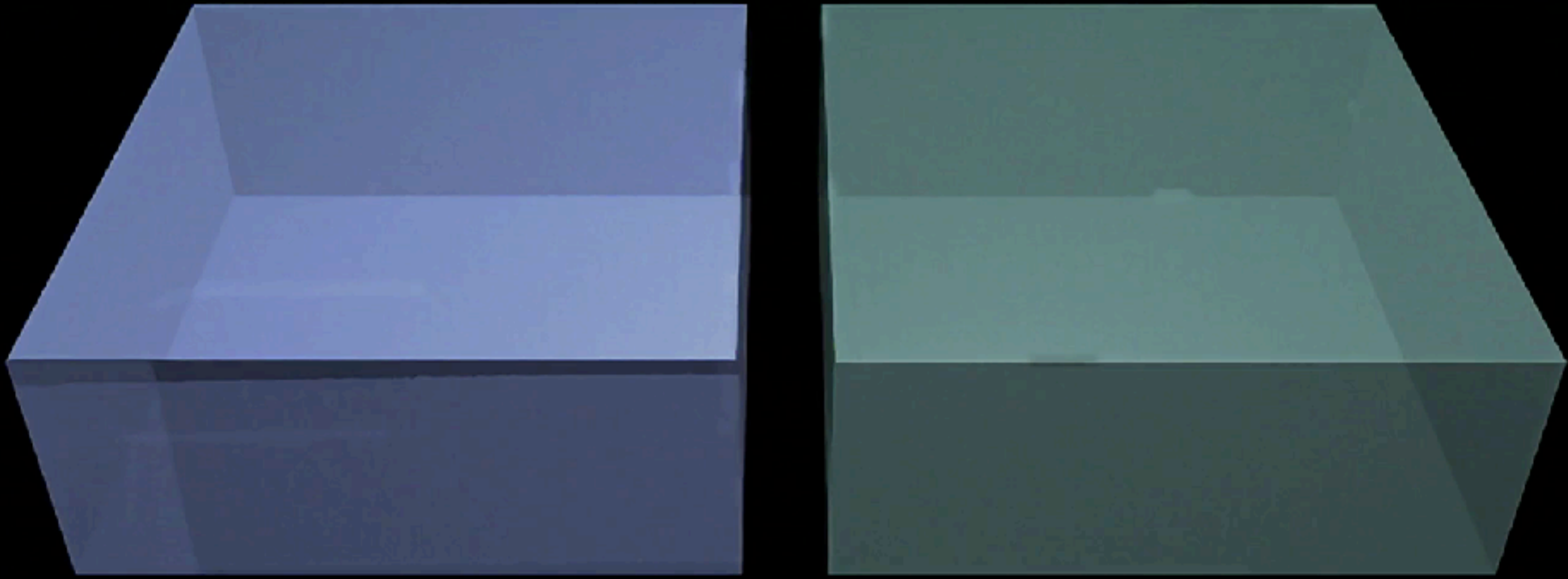

WMAP Collaboration
Long Wavelength
Short Wavelength
TT
Amplitude of Waves [μK^2]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

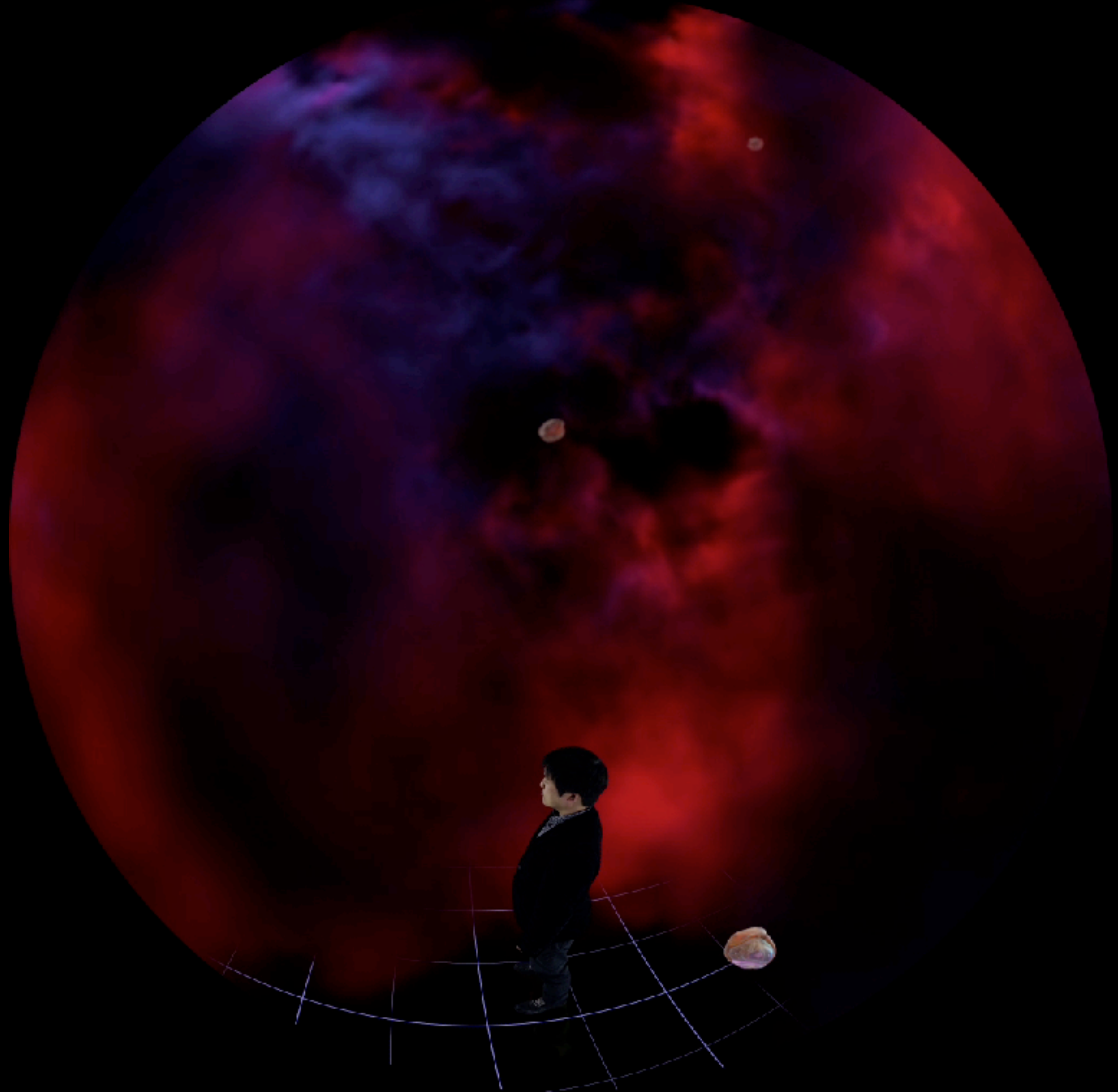
Power spectrum, explained



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





Sound waves, predicted in 1970

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

https://www.aip.org

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

Sound waves, 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.

The Franklin Institute of Physics


Die Tat von Kitzbühel: Warum tötet ein Mann eine ganze Familie? ▸ Panorama

Süddeutsche Zeitung

MÜNCHNER NEUESTE NACHRICHTEN AUS POLITIK, KULTUR, WIRTSCHAFT UND SPORT

Das Streiflicht

Von fernen Welten

Wo steht der Mensch im Kosmos? Drei Physiker haben zumindest den Anfang einer Antwort geliefert. Dafür erhalten sie den Nobelpreis

▸ Wissen, Seite 14

spielen

Mit der Kaffeetasse durchs Universum

Exoplaneten und Strukturen in der kosmischen Hintergrundstrahlung: Der Physik-Nobelpreis geht in diesem Jahr an drei Forscher, die unsere Vorstellung vom Kosmos verändert haben

VON MARLENE WEISS

„Wir schauen in den Anfang des Universums hinein – und das Beste kommt erst noch"

Der Schweizer Physiker Didier Queloz, geboren 1966.

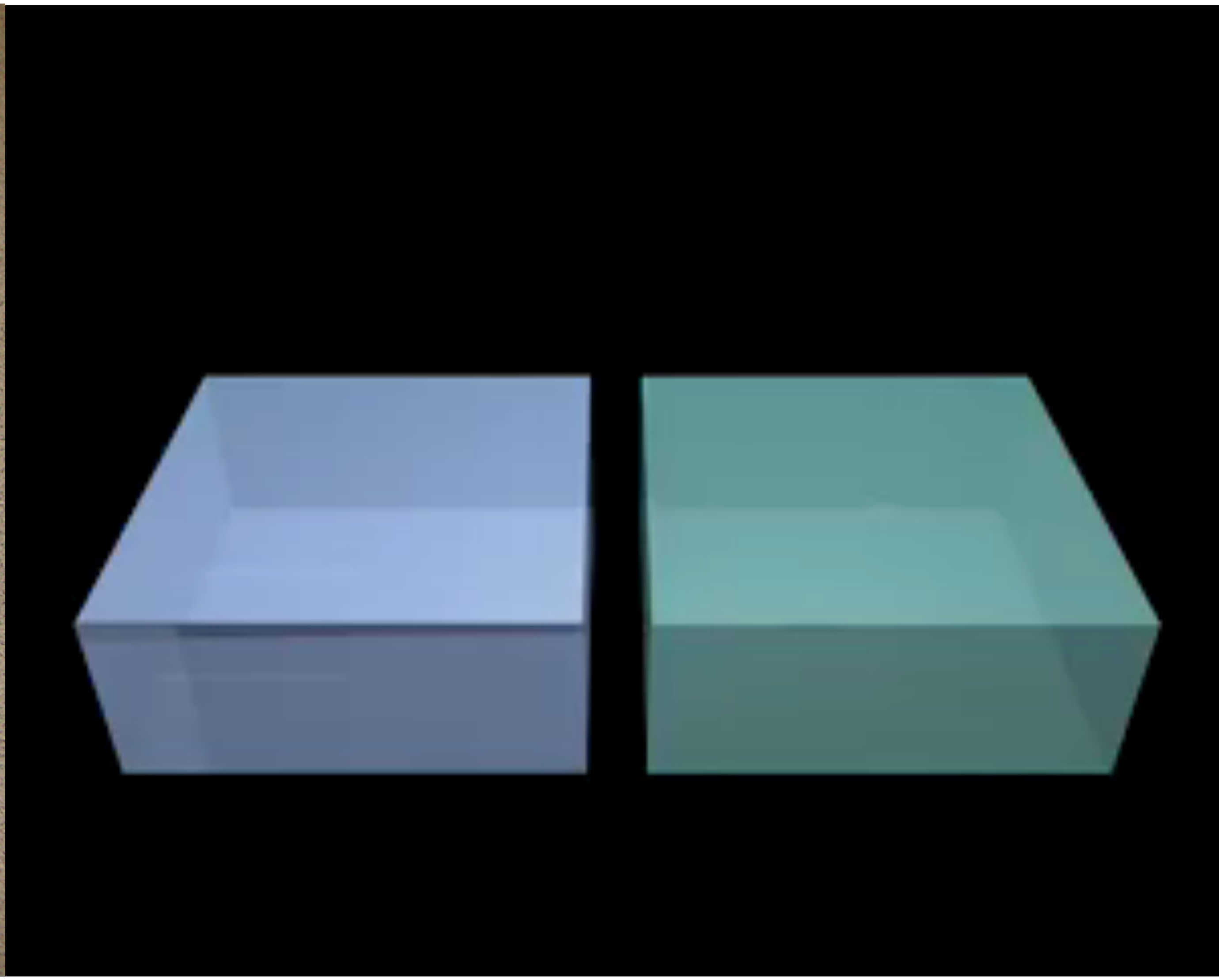
Der kanadische Kosmologe James Peebles, 84.

Der Schweizer Astronom Michel Mayor wurde 1942 ... geboren.

Allerdings wundert er sich, dass sein Institutskollege Rashid Sunyaev nicht mit ausgezeichnet wurde, der parallel ähnliche Arbeit geleistet hat: "Jeder im Feld weiß, dass beide die Anerkennung verdienen, wir alle bauen auf ihrer Arbeit auf", sagt Komatsu.

Origin of Fluctuations

- Who dropped those Tofus into the cosmic Miso soup?

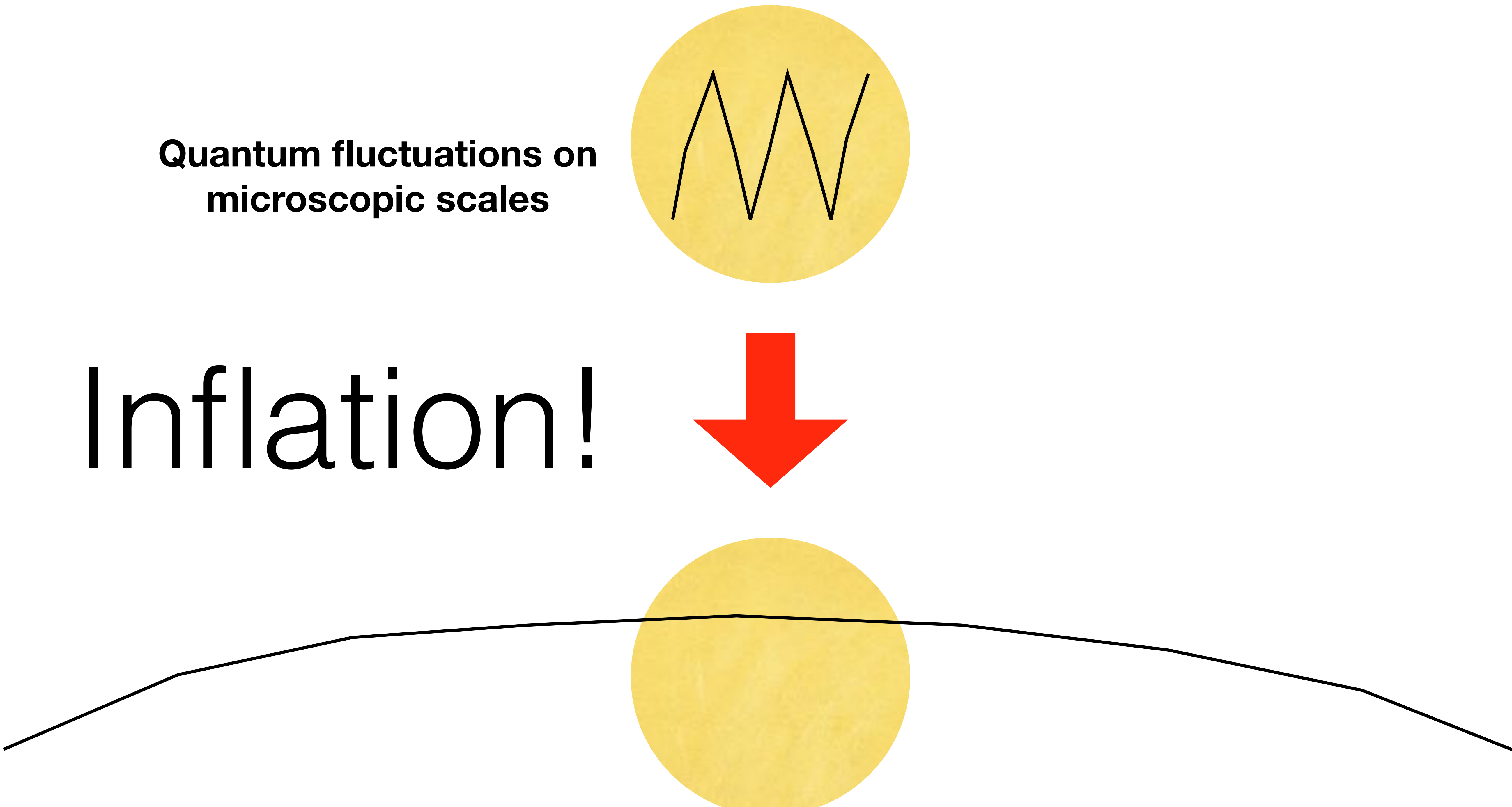
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

Leading Idea

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

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

Cosmic Inflation



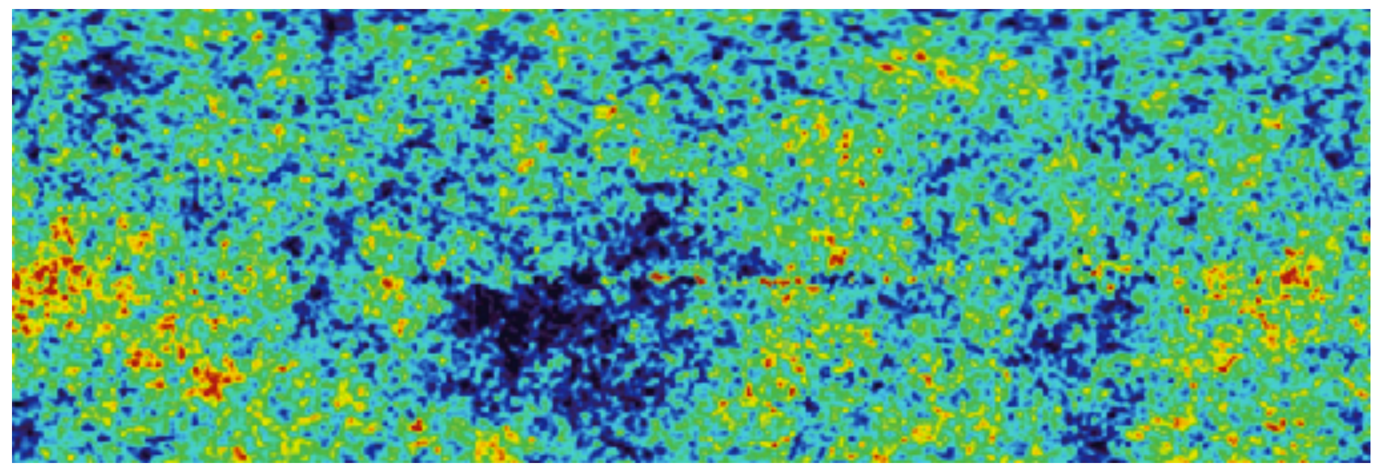
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

Key Predictions

ζ

scalar mode

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



h_{ij}

tensor mode

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

Starobinsky (1979)

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 alter the determinant

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

We measure distortions in space

- A distance between two points in space

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

scale factor

- **ζ** : "curvature perturbation" (scalar mode)
  - Perturbation to the determinant of the spatial metric
- **h_{ij}** : "gravitational waves" (tensor mode)
  - Perturbation that does not alter the determinant

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

Finding Inflation

- Inflation is the accelerated, quasi-exponential expansion. Defining the Hubble expansion rate as **H(t)=dln(a)/dt**, we must find

$$\frac{\ddot{a}}{a} = \dot{H} + H^2 > 0 \quad \rightarrow \quad \epsilon \equiv -\frac{\dot{H}}{H^2} < 1$$

Actually, we rather need ε << 1

Have we found inflation?

$$\epsilon \equiv -\frac{\dot{H}}{H^2}$$

- *Have we found ε << 1?*
- To achieve this, we need to map out **H(t)**, and show that it does not change very much with time

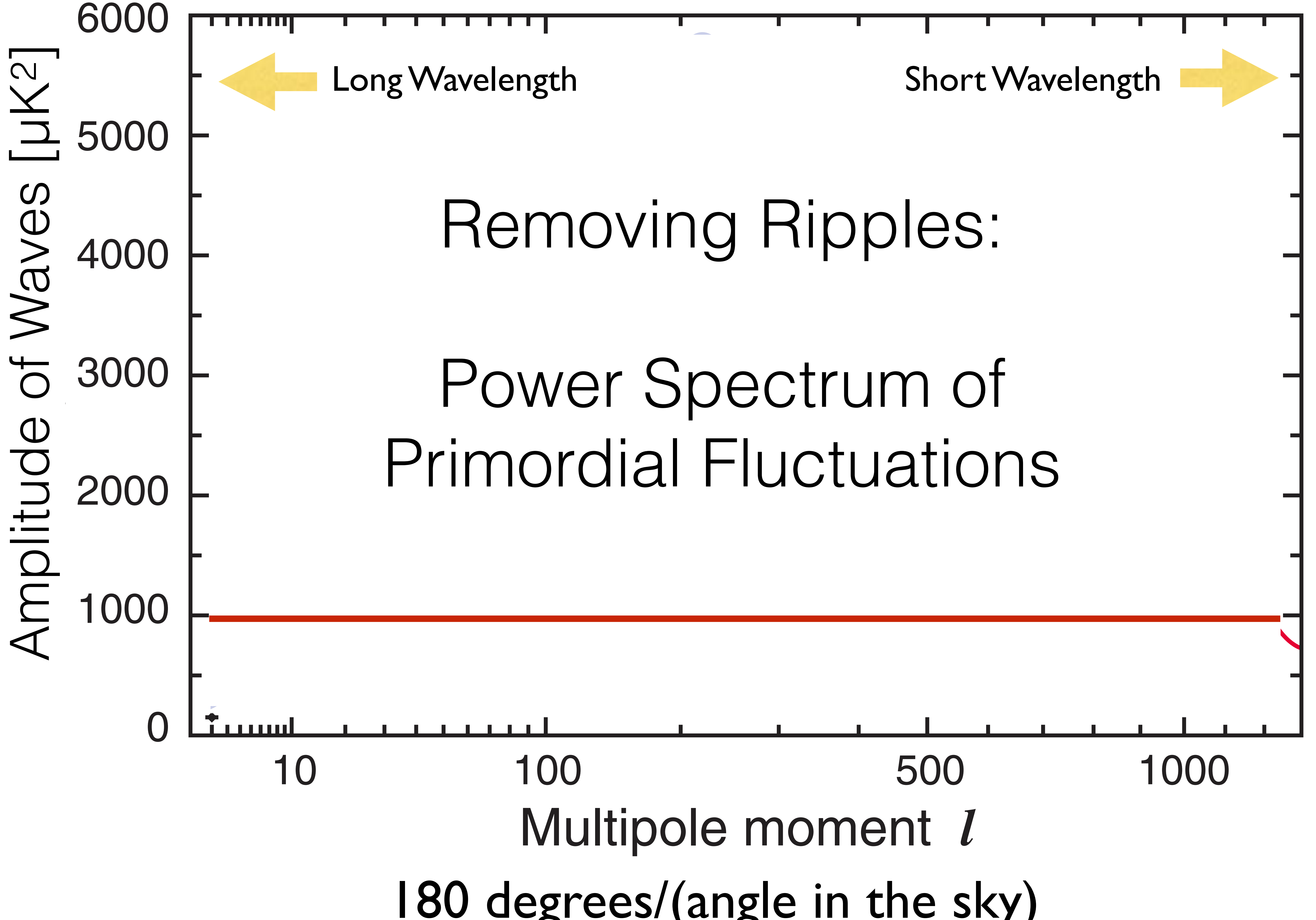
Fluctuations are proportional to H

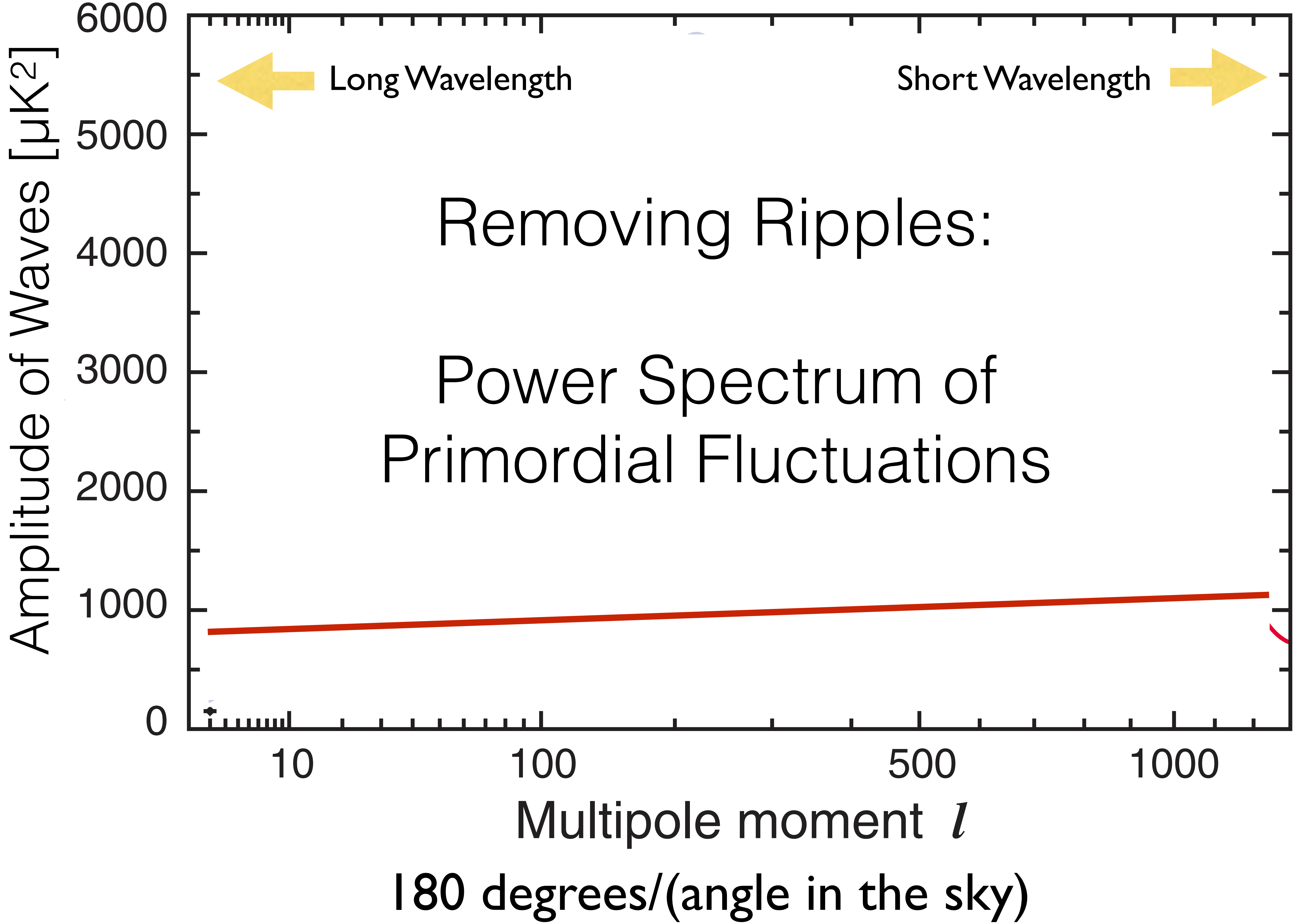
- **Both scalar (ζ) and tensor (h_{ij}) perturbations are proportional to H**

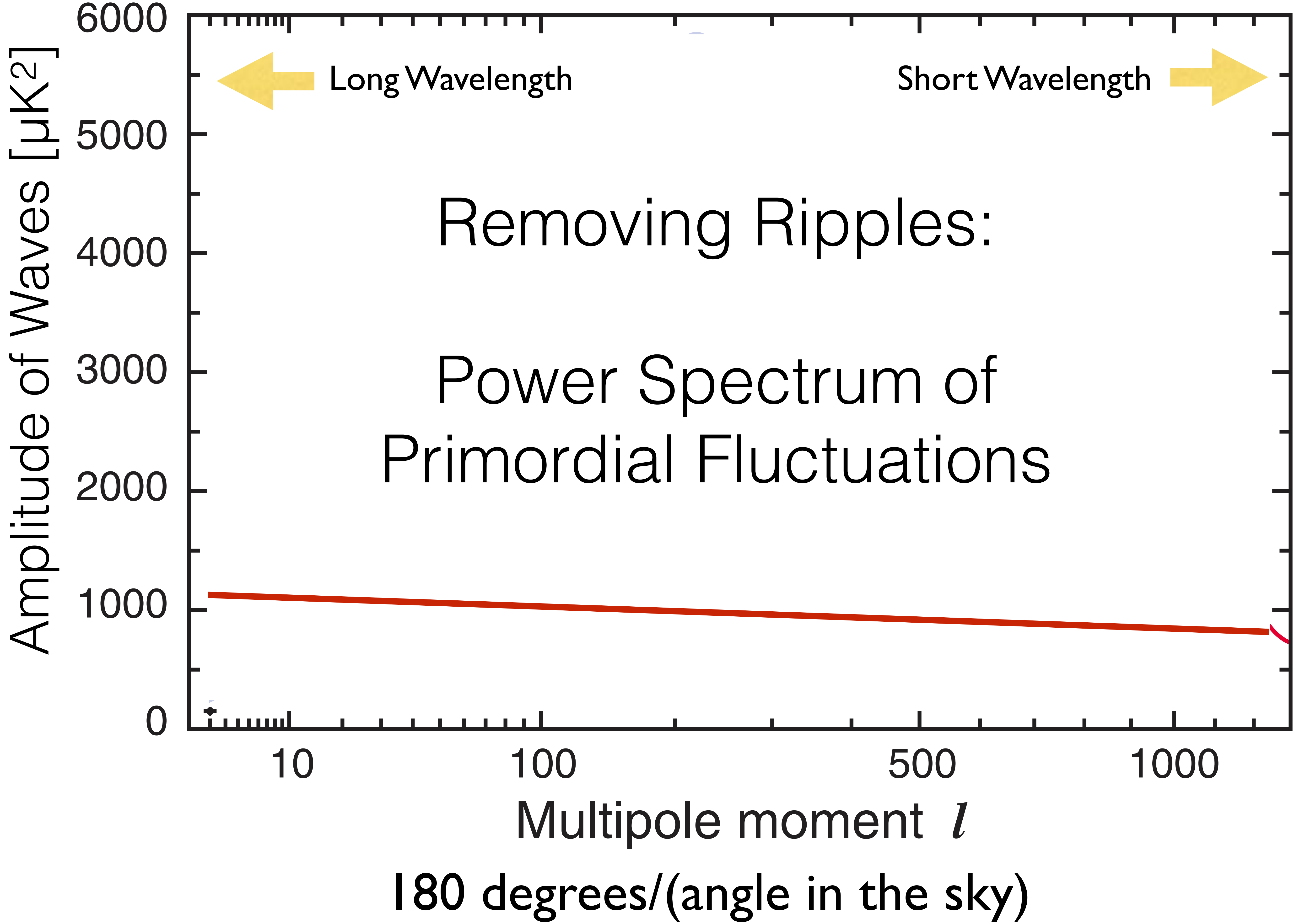
  - Consequence of the uncertainty principle

    - [energy you can borrow] ~ [time you borrow]$^{-1}$ ~ H

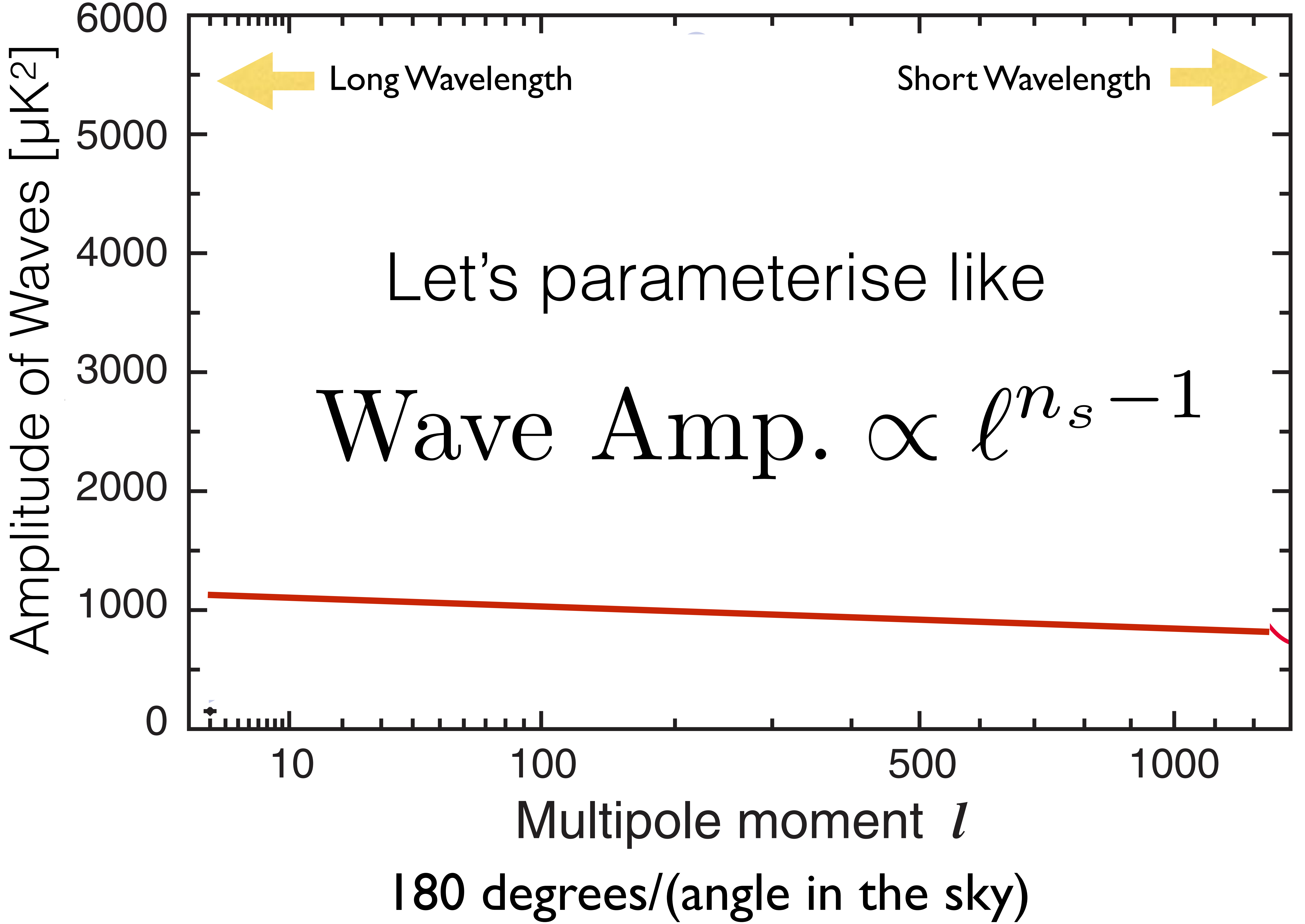
  - **THE KEY**: The earlier the fluctuations are generated, the more its wavelength is stretched, and thus the bigger the angles they subtend in the sky. **We can map H(t) by measuring CMB fluctuations over a wide range of angles**


Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
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)

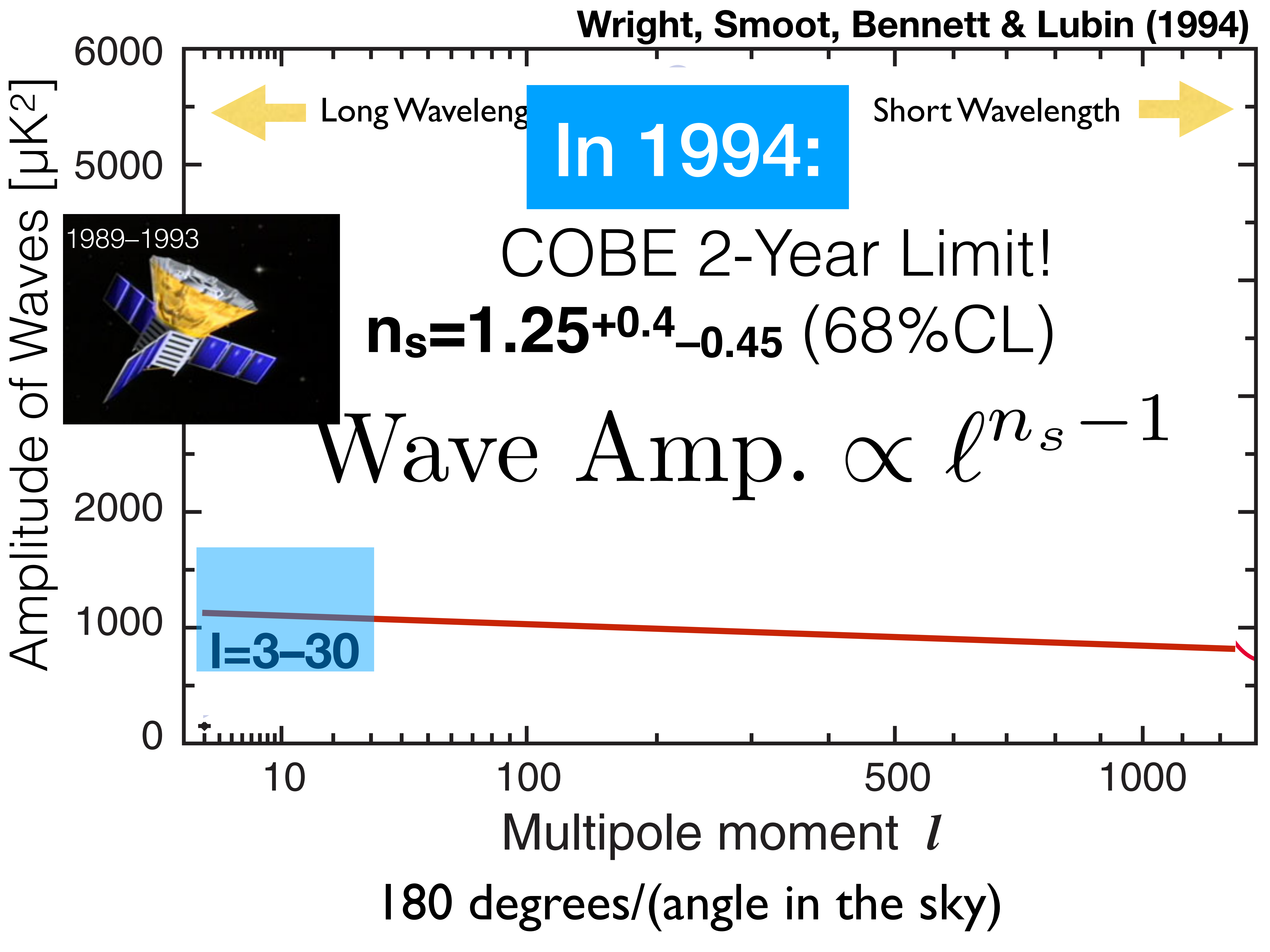


Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of Primordial Fluctuations
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

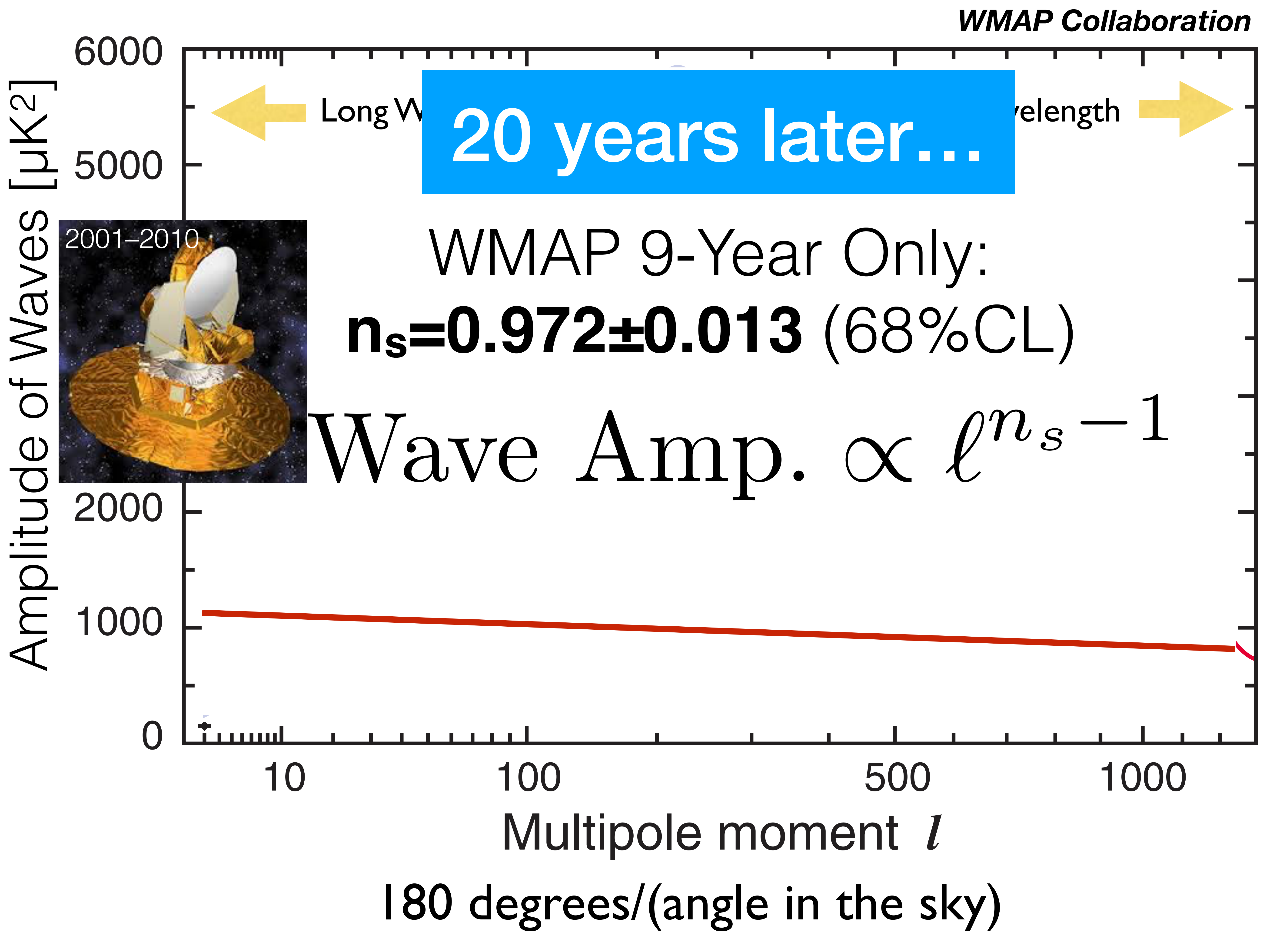


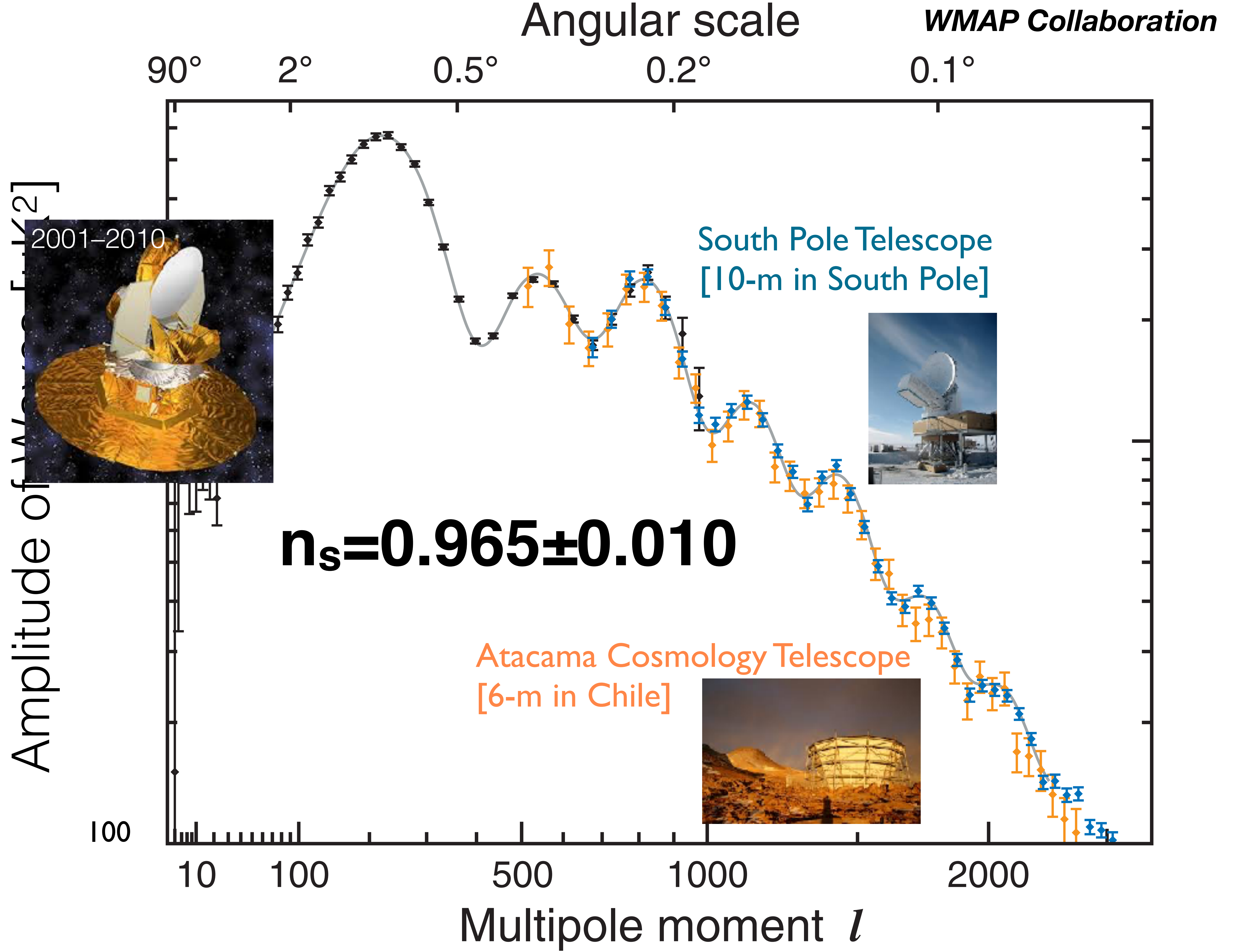
Let's parameterise like

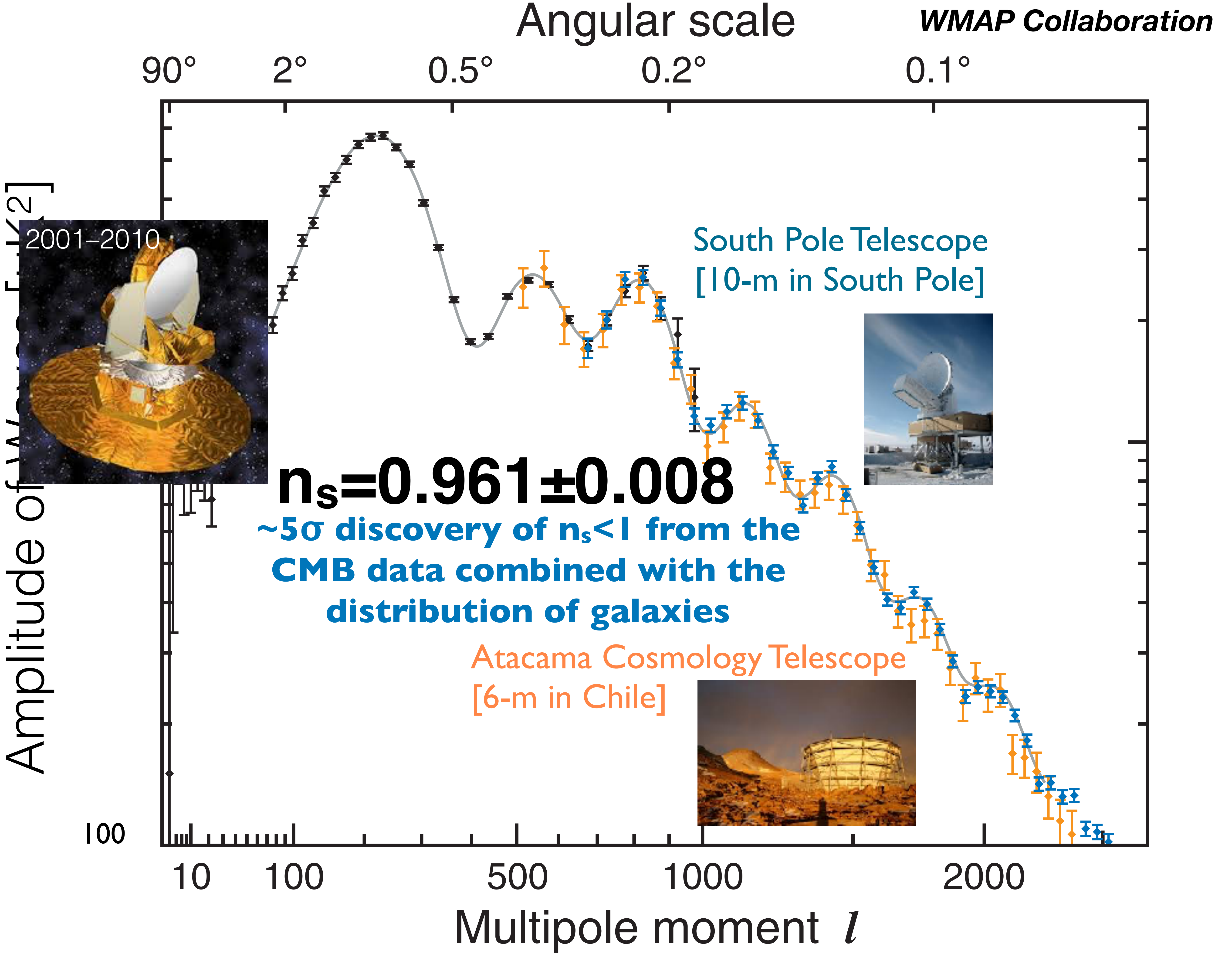
$$\text{Wave Amp.} \propto \ell^{n_s - 1}$$



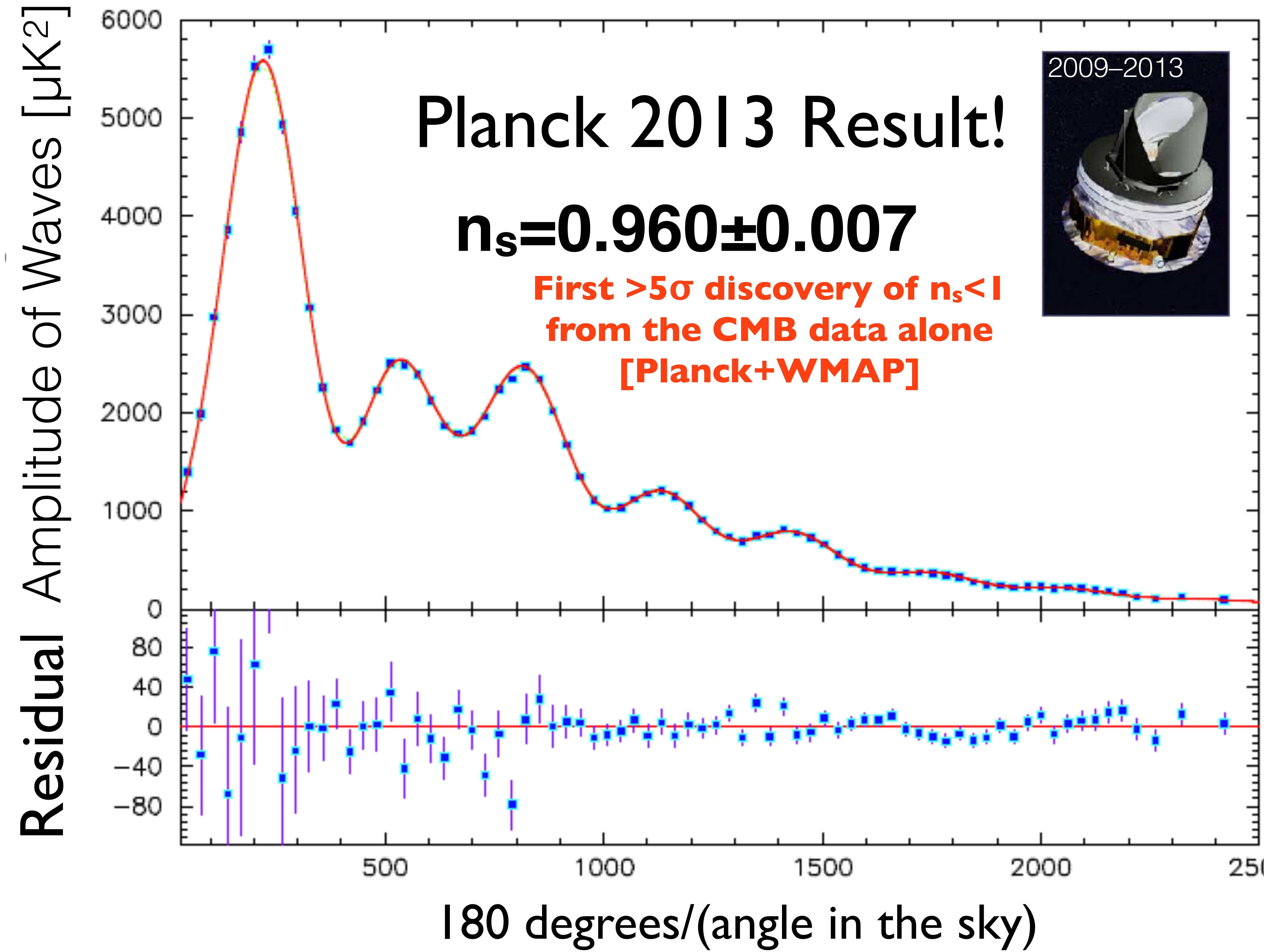
Wright, Smoot, Bennett & Lubin (1994)
Long Waveleng
Short Wavelength
In 1994:
1989–1993
COBE 2-Year Limit!
$n_s=1.25^{+0.4}_{-0.45}$ (68%CL)
$\text{Wave Amp.} \propto \ell^{n_s-1}$
l=3–30
Amplitude of Waves [μK^2]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

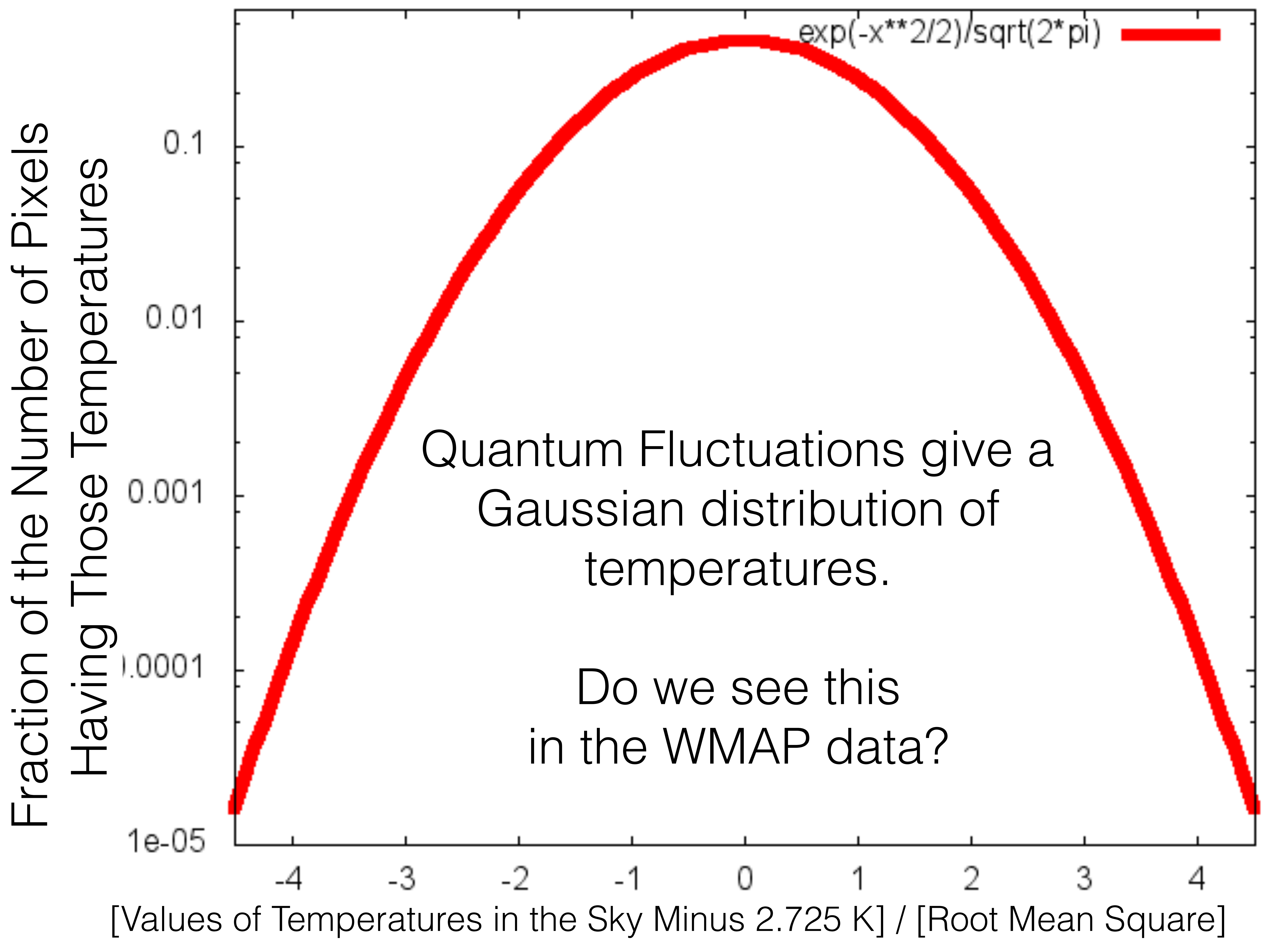

WMAP Collaboration
6000
5000
2000
1000
0
Amplitude of Waves [μK^2]
Long W
velength
20 years later...
2001–2010
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
$\text{Wave Amp.} \propto \ell^{n_s-1}$
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

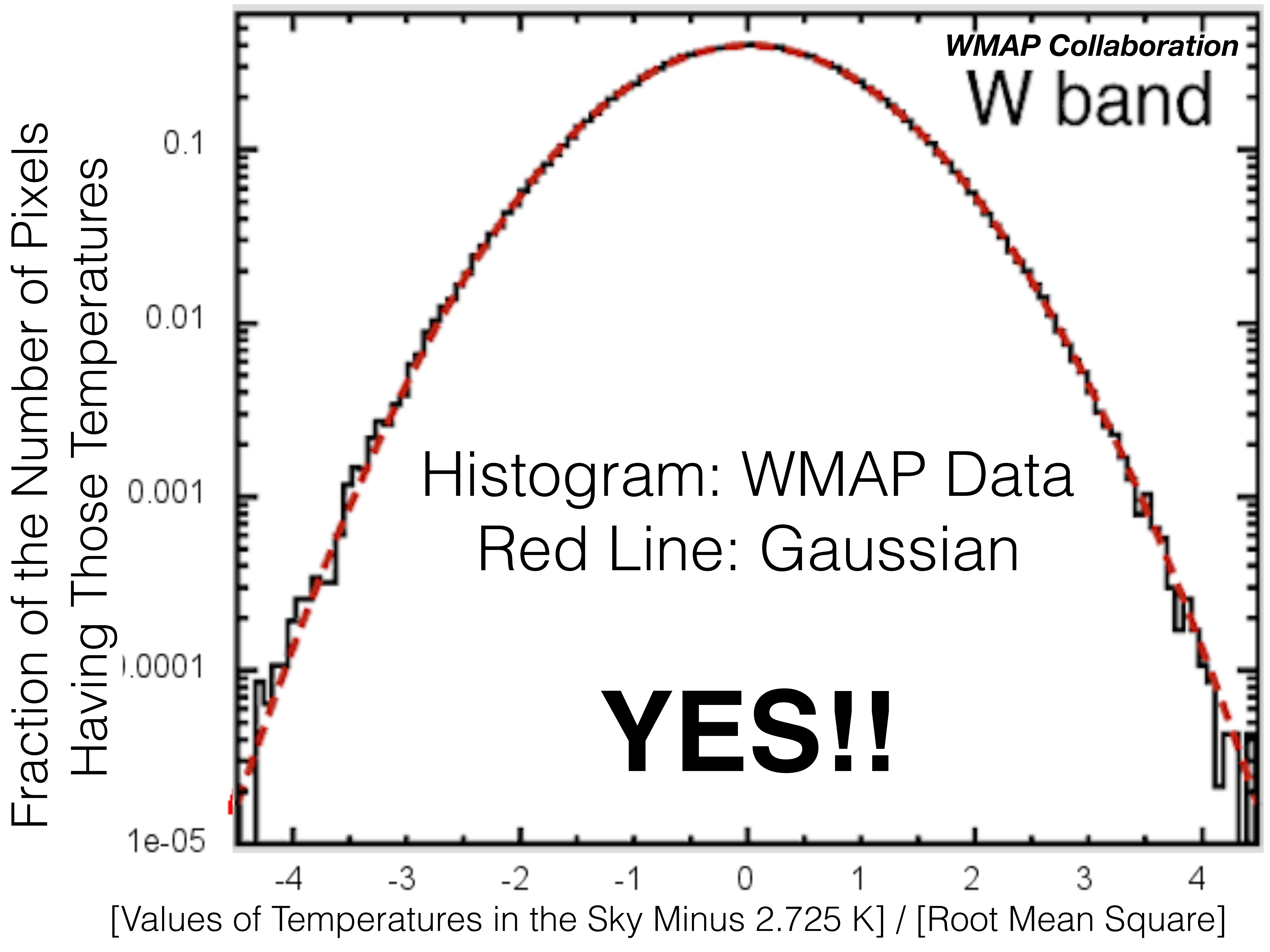

WMAP Collaboration
Angular scale
90°
2°
0.5°
0.2°
0.1°
2001–2010
South Pole Telescope
[10-m in South Pole]
n_s=0.965±0.010
Atacama Cosmology Telescope
[6-m in Chile]
Amplitude of
100
10
100
500
1000
2000
Multipole moment l



WMAP Collaboration
Angular scale
90°
2°
0.5°
0.2°
0.1°
Amplitude of
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 the
distribution of galaxies
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment l


Planck 2013 Result!
n_s=0.960±0.007
First >5σ discovery of n_s<1
from the CMB data alone
[Planck+WMAP]
2009–2013
Amplitude of Waves [μK²]
Residual
180 degrees/(angle in the sky)
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000


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
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]



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

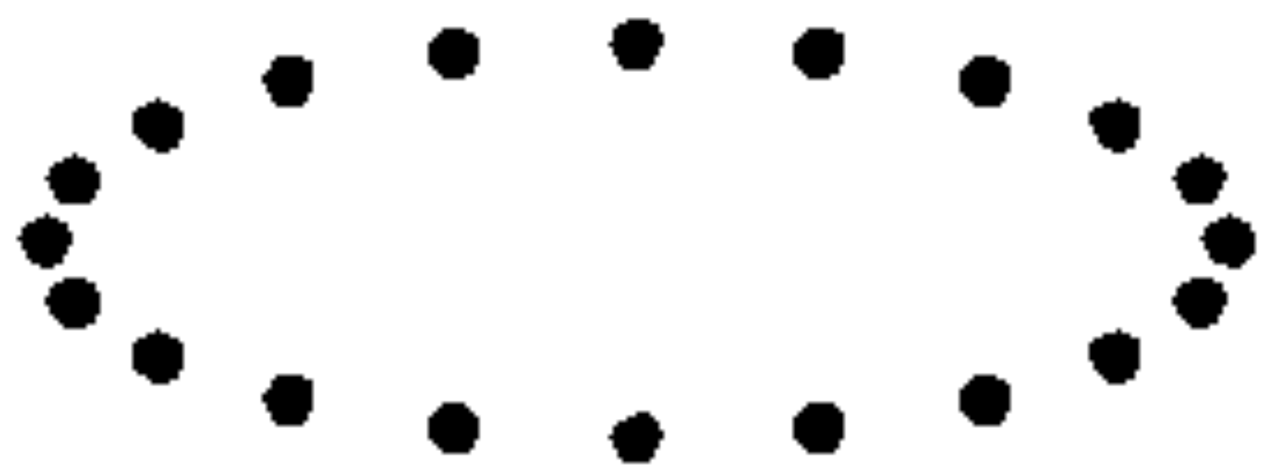
So, have we found inflation?

- Single-field slow-roll inflation looks remarkably good:
    - **Super-horizon fluctuation**
    - **Adiabaticity**
    - **Gaussianity**
    - **$n_s<1$**
- What more do we want? **Gravitational waves**. Why?
    - Because the "*extraordinary claim requires extraordinary evidence*"

Measuring GW

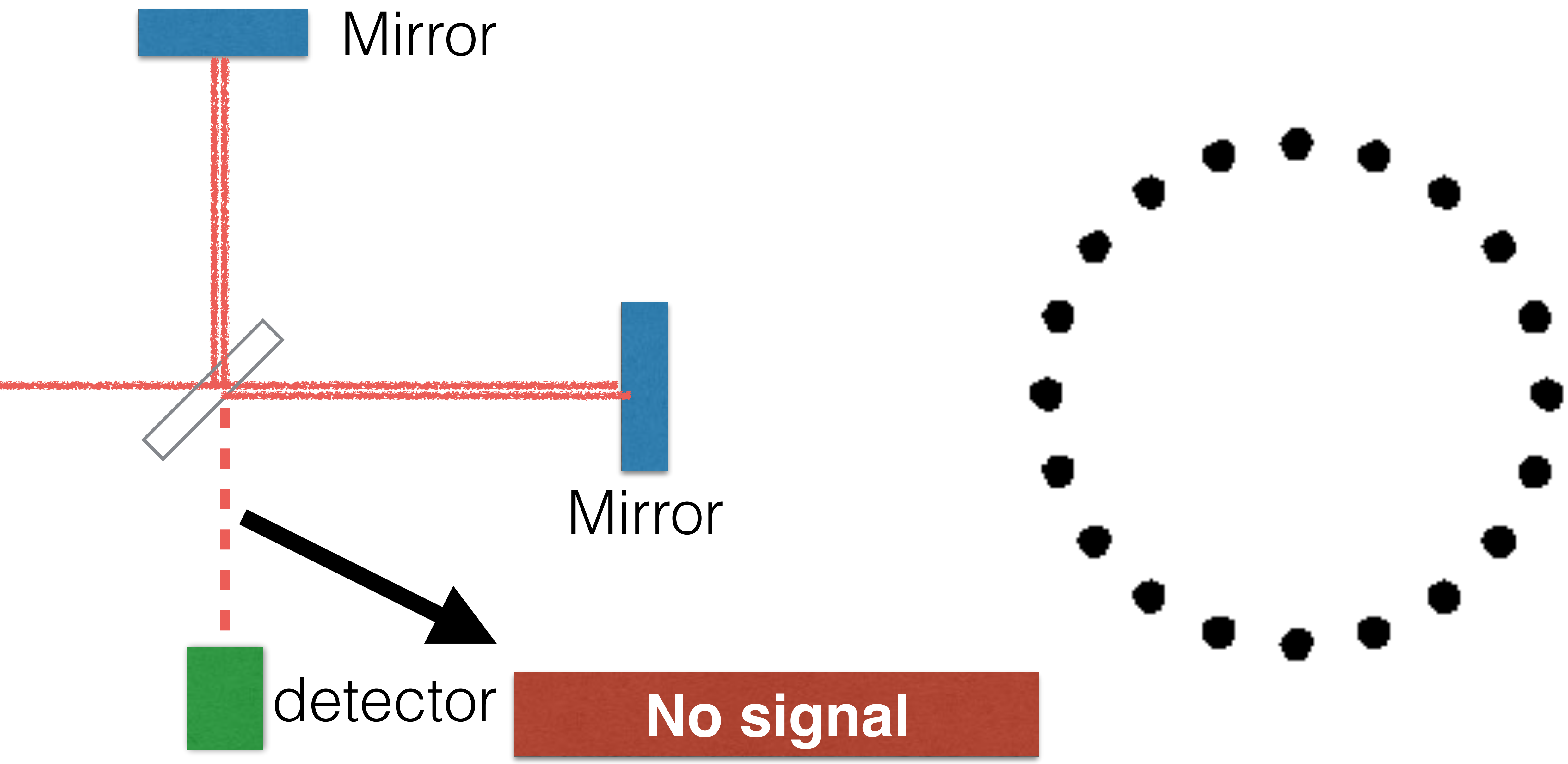
- GW changes distances between two points

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

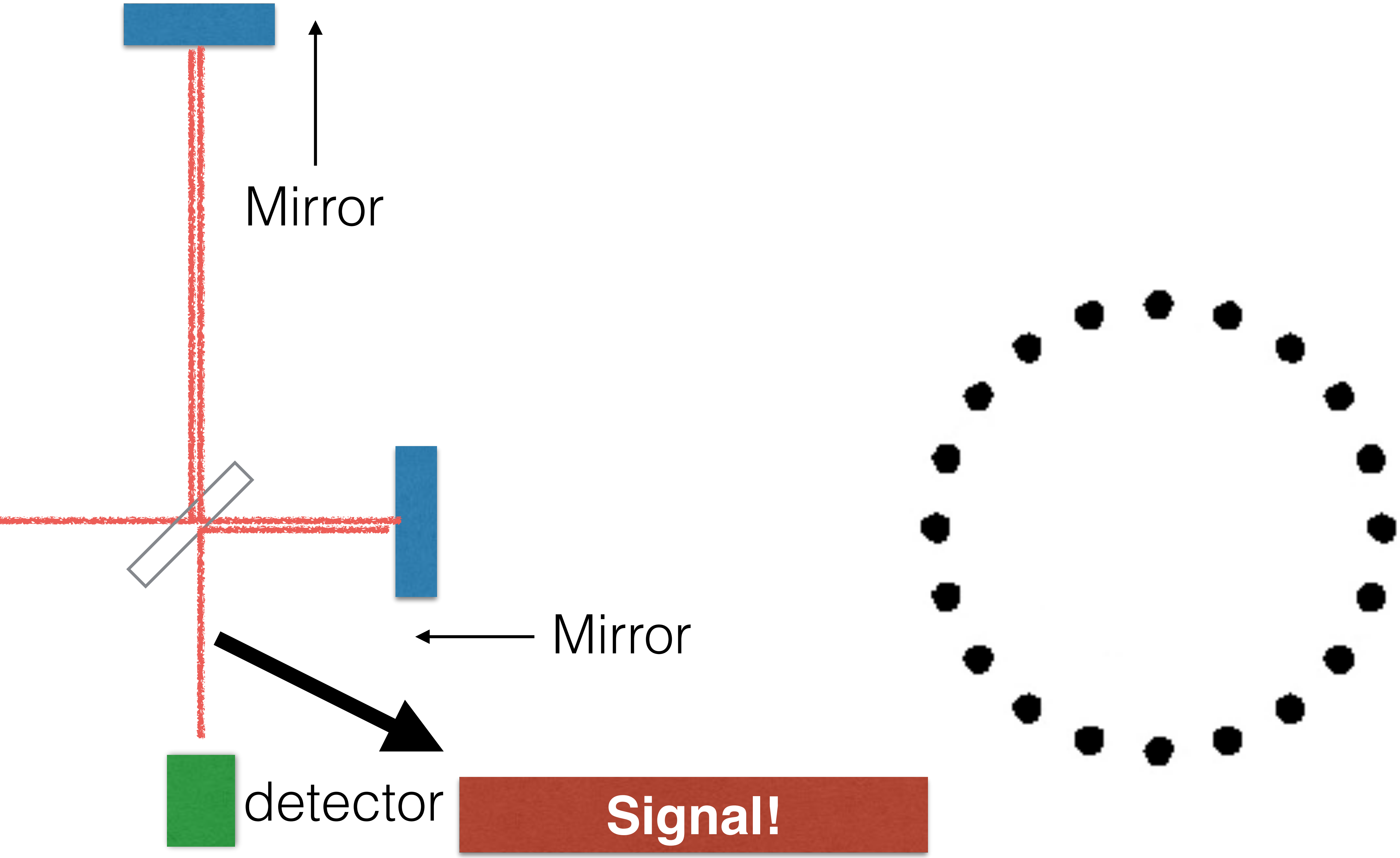


$$d\ell^2 = \sum_{ij} (\delta_{ij} + h_{ij}) dx^i dx^j$$

Laser Interferometer



Laser Interferometer



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

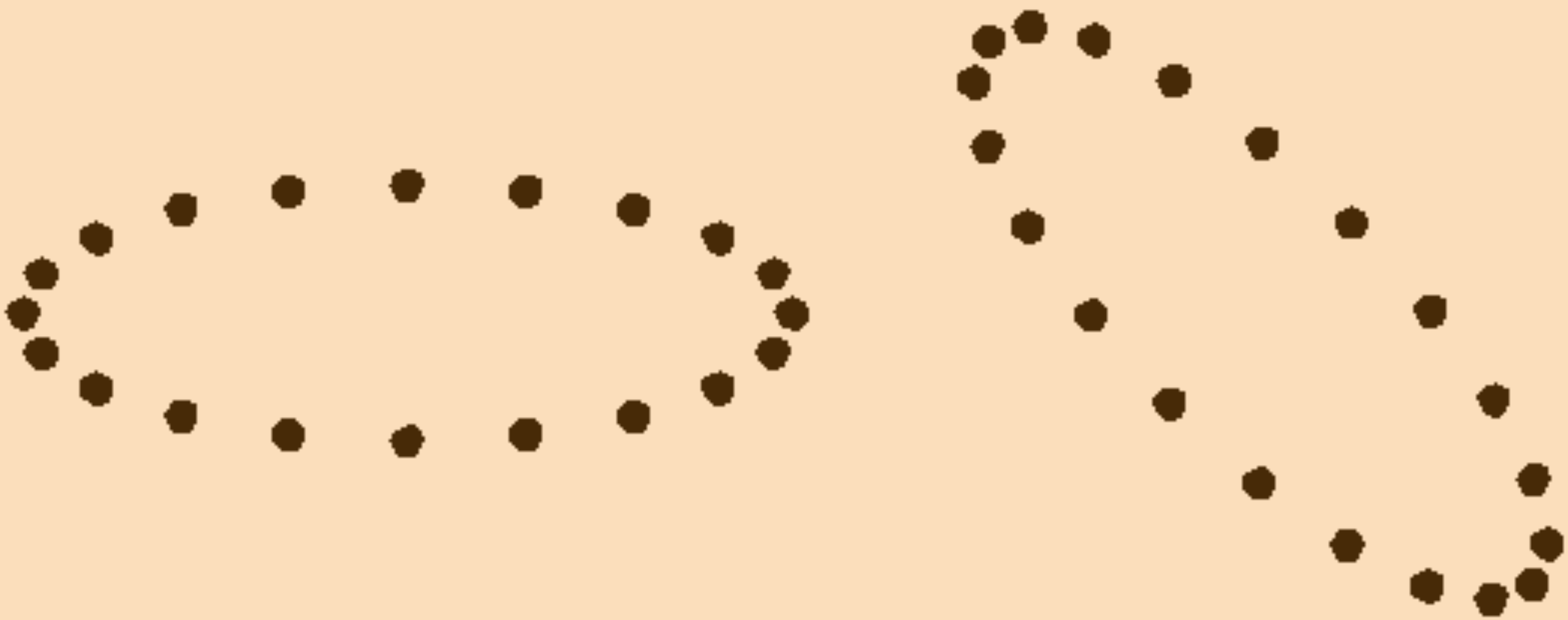
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

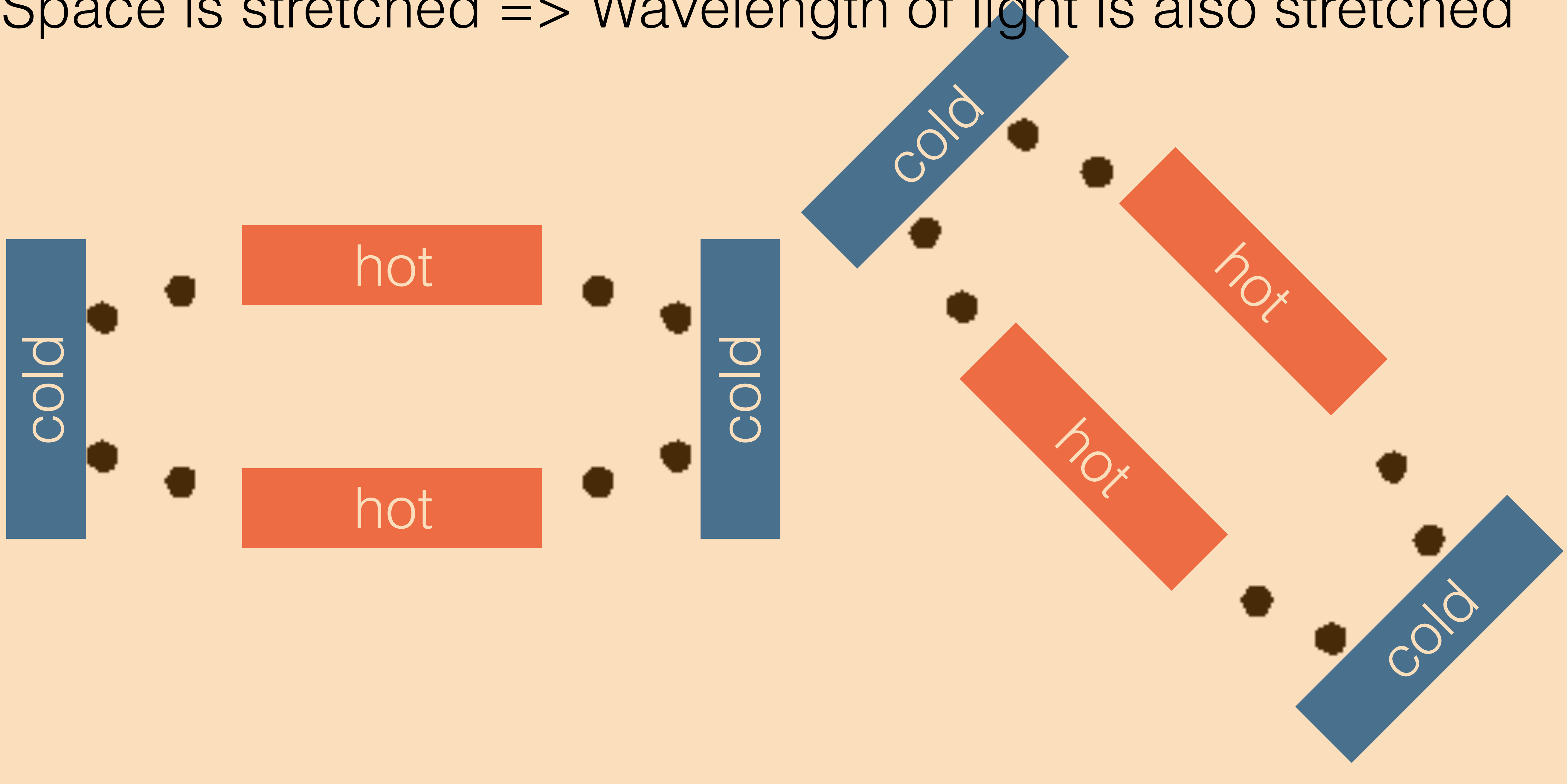
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



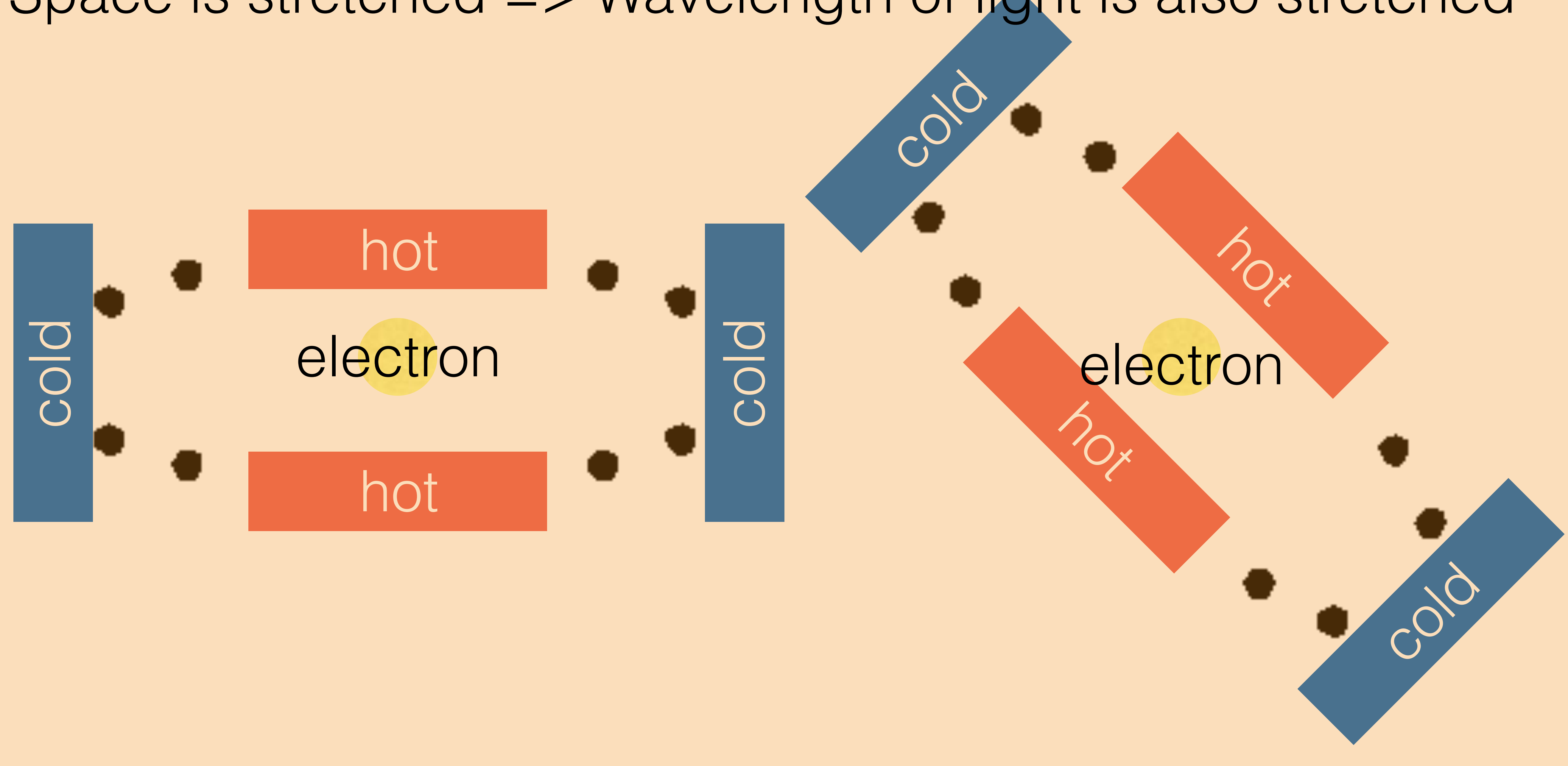
Detecting GW by CMB

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

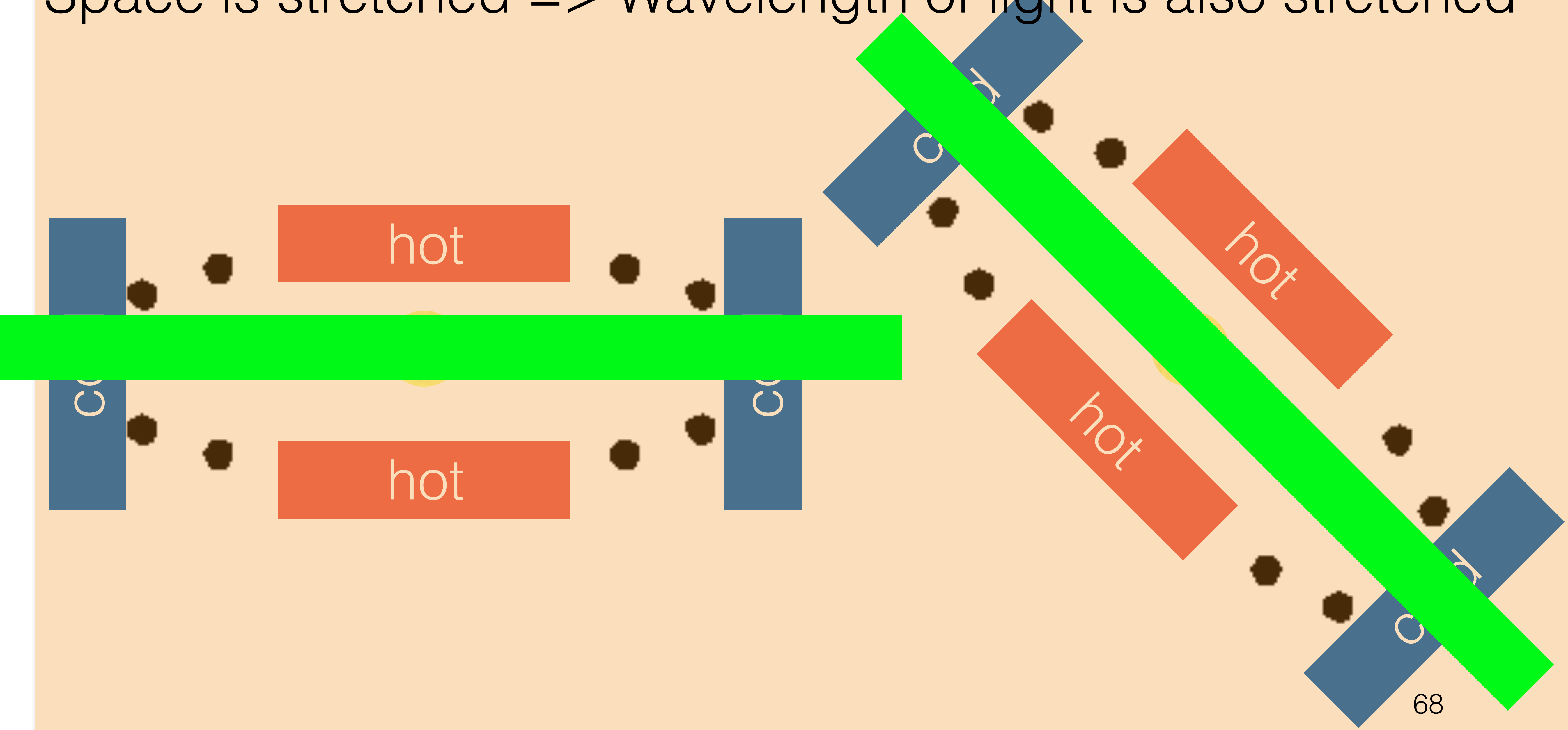



Photo Credit: TALEX
horizontally polarised

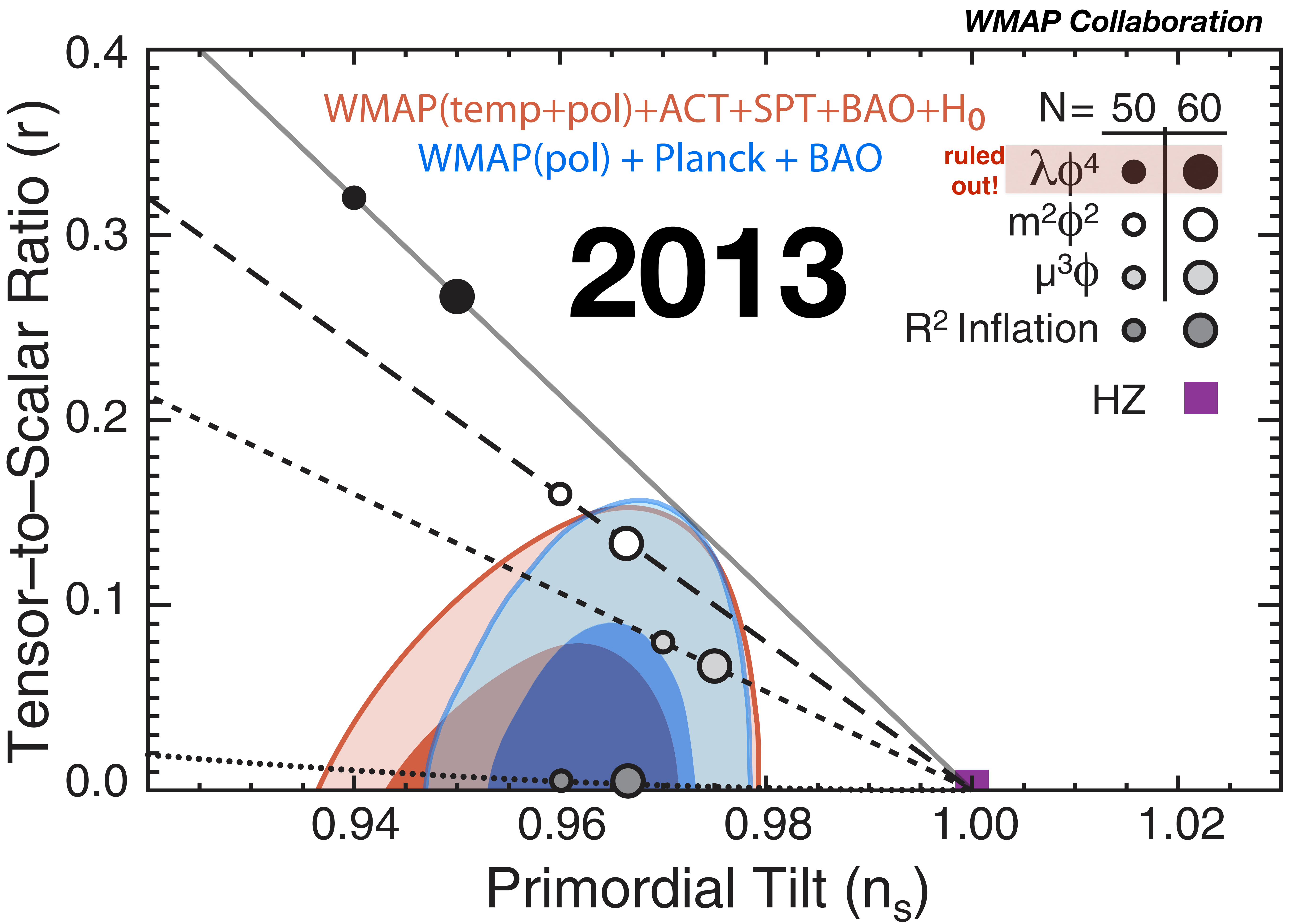
Photo Credit: TALEX

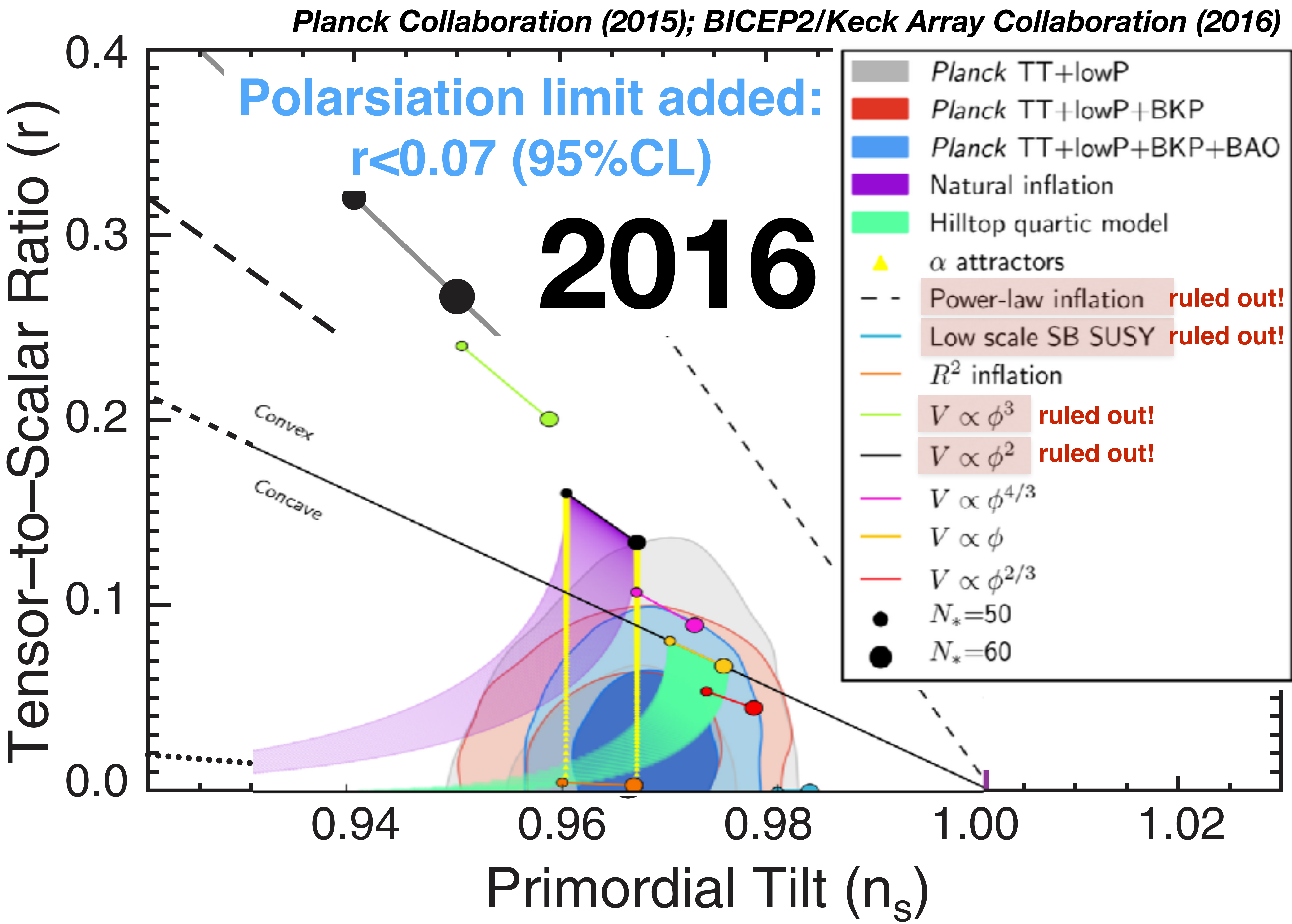
Tensor-to-scalar Ratio

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

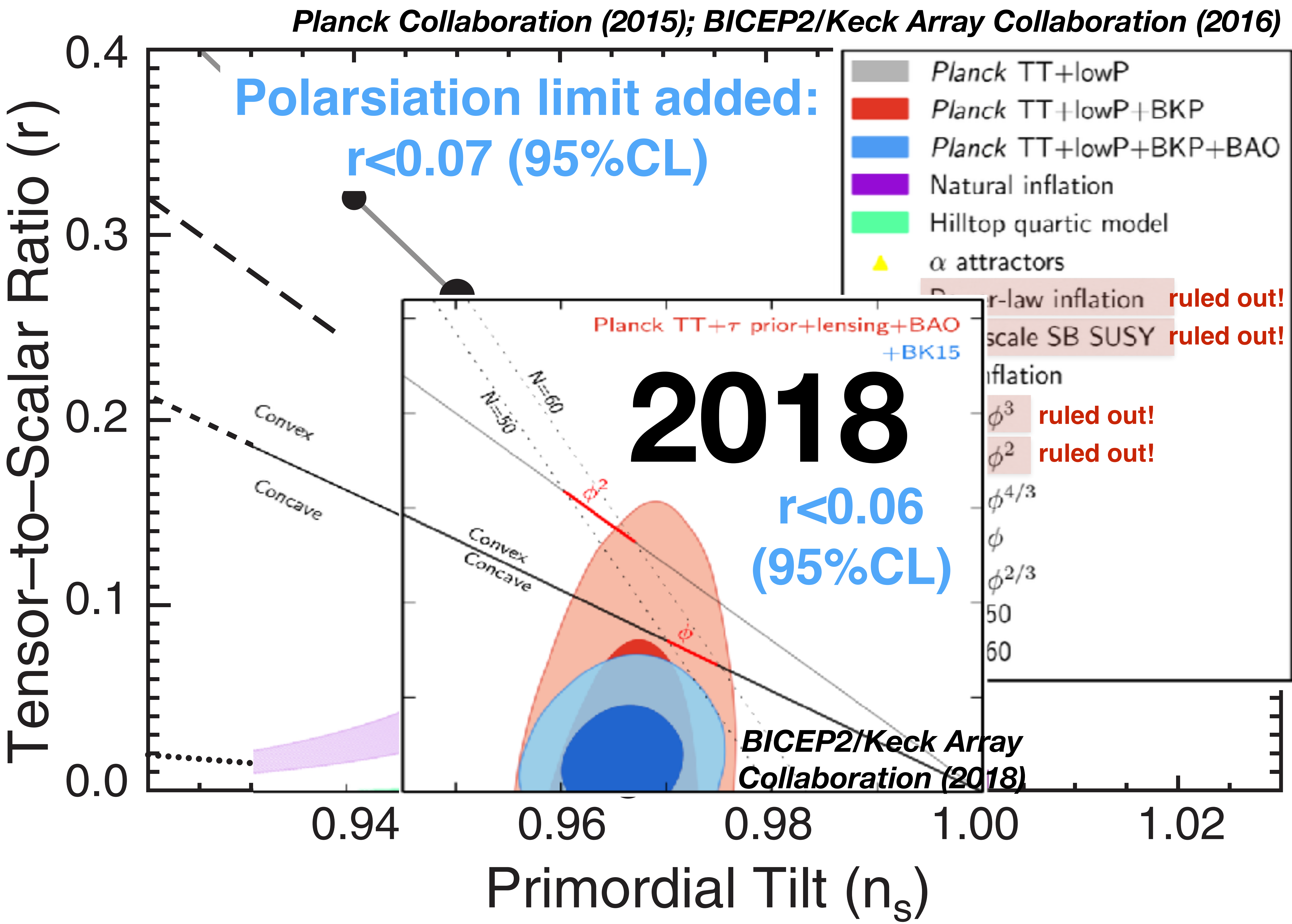
- We really want to find this! The current upper bound is **r<0.06** (95%CL)

BICEP2/Keck Array Collaboration (2018)


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)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (ns)



Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
2016
Tensor–to–Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
Primordial Tilt (n_s)
0.94
0.96
0.98
1.00
1.02
Convex
Concave
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
ruled out!
Low scale SB SUSY
ruled out!
R^2 inflation
V ∝ φ^3
ruled out!
V ∝ φ^2
ruled out!
V ∝ φ^{4/3}
V ∝ φ
V ∝ φ^{2/3}
N_*=50
N_*=60



Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
Tensor–to–Scalar Ratio (r)
Primordial Tilt (ns)
0.4
0.3
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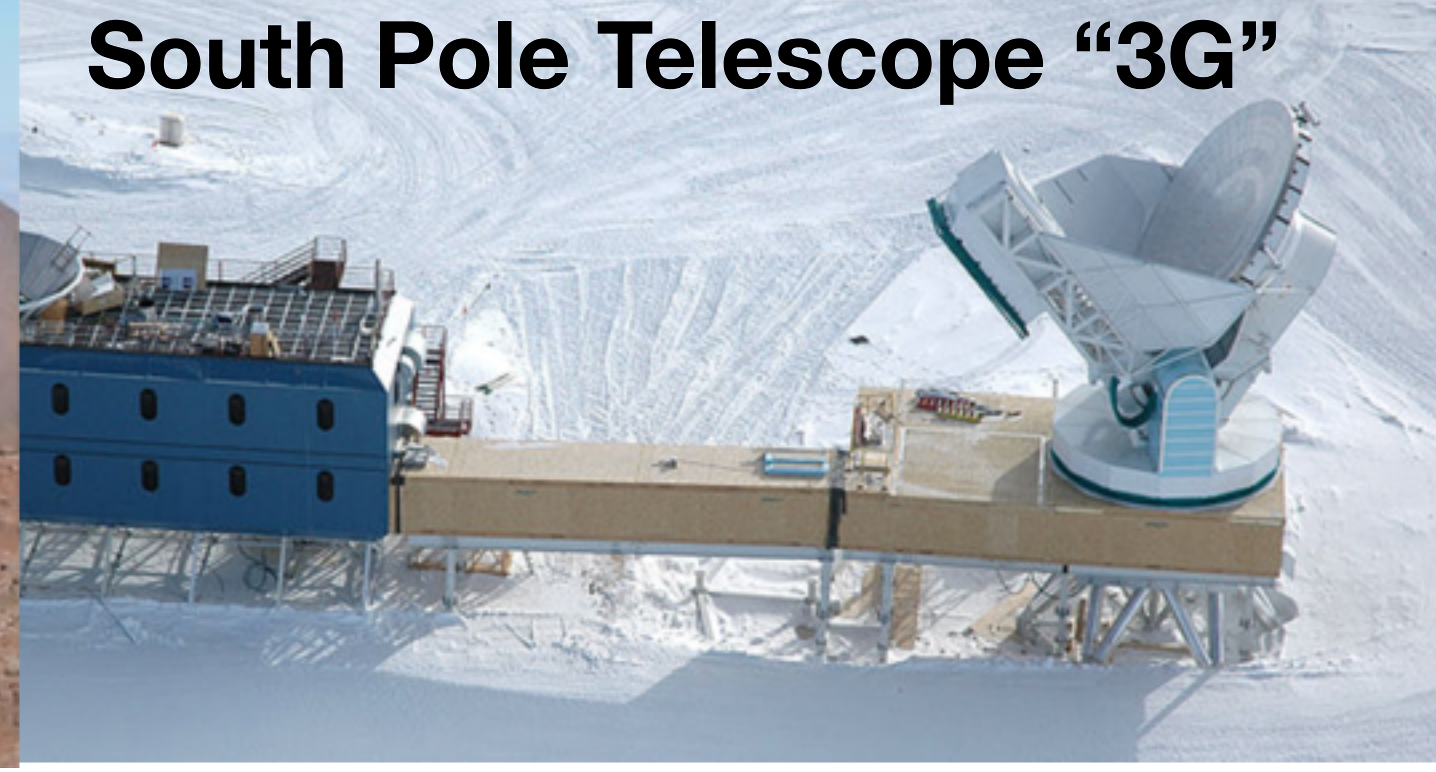
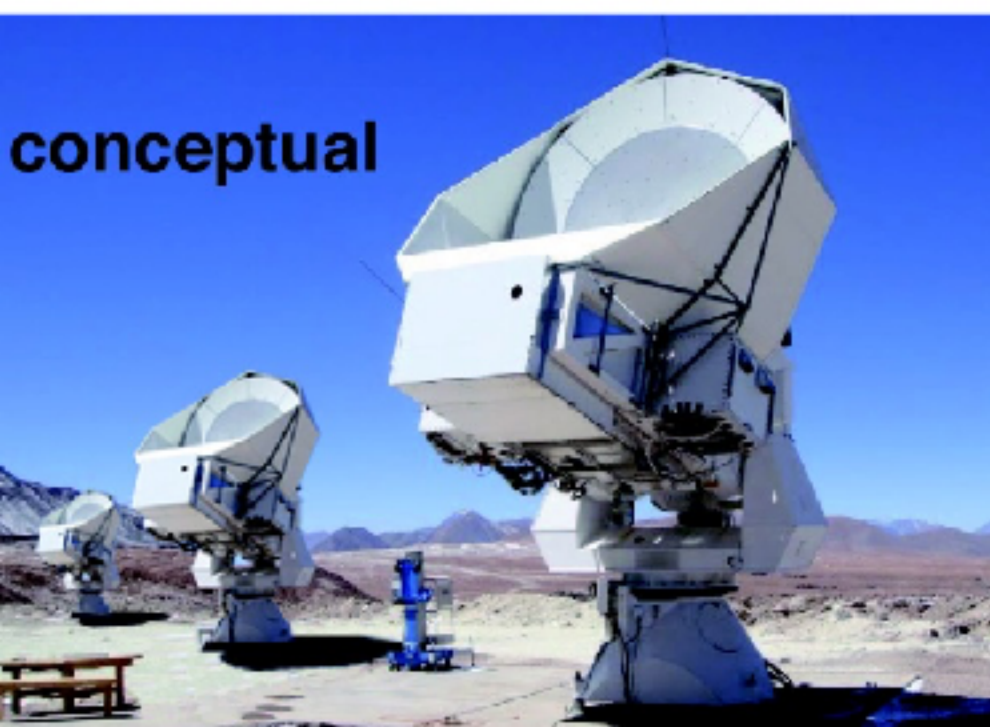
0.96
0.98
1.00
1.02
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
ruled out!
ruled out!
ruled out!
ruled out!
Convex
Concave
Planck TT+τ prior+lensing+BAO
+BK15
N=60
N=50
2018
r<0.06
(95%CL)
BICEP2/Keck Array
Collaboration (2018)

Experimental Landscape



What comes next?

The Simons Array



CMB-S4
Next Generation CMB Experiment

CMB Stages

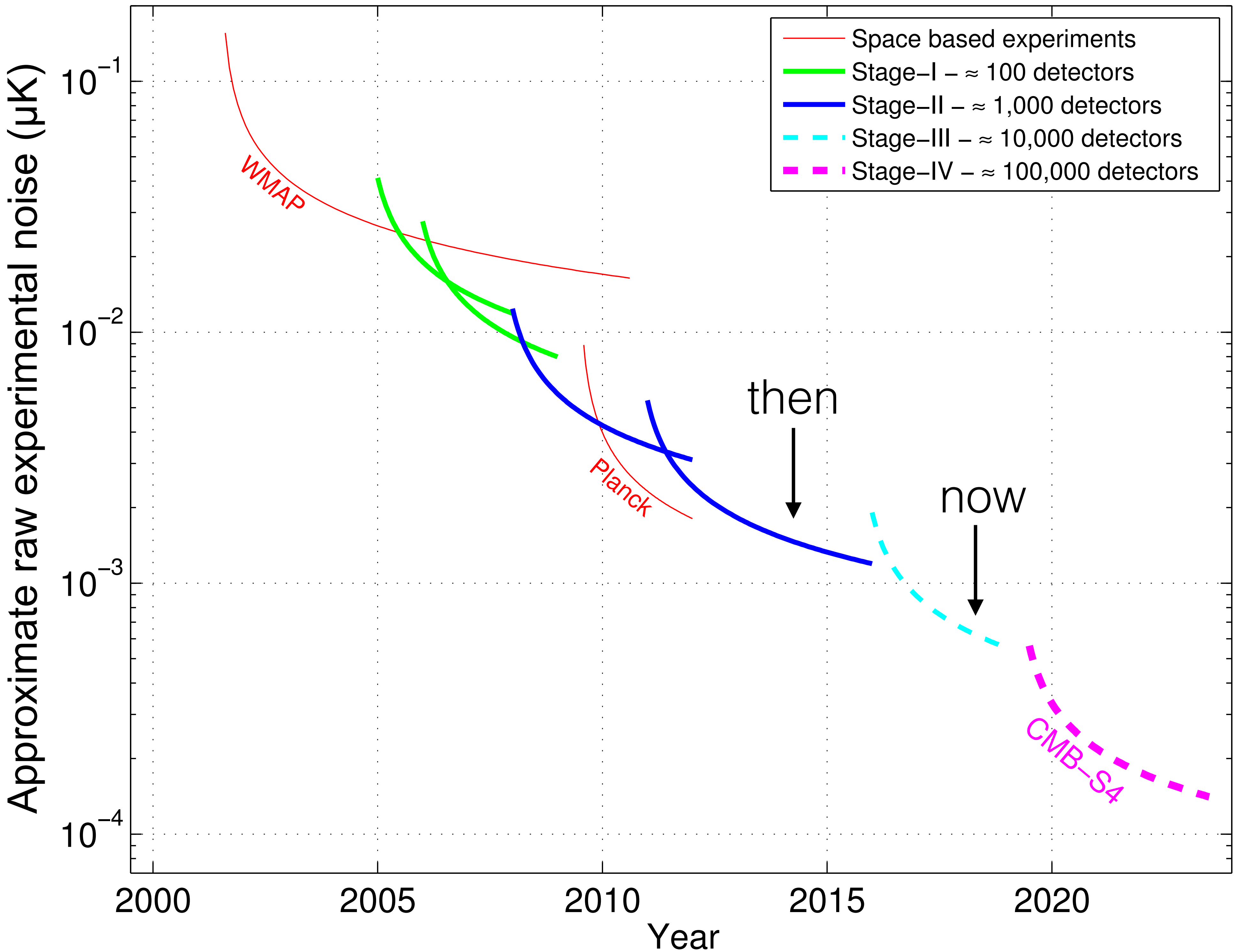


Figure by Clem Pryke for 2013 Snowmass documents

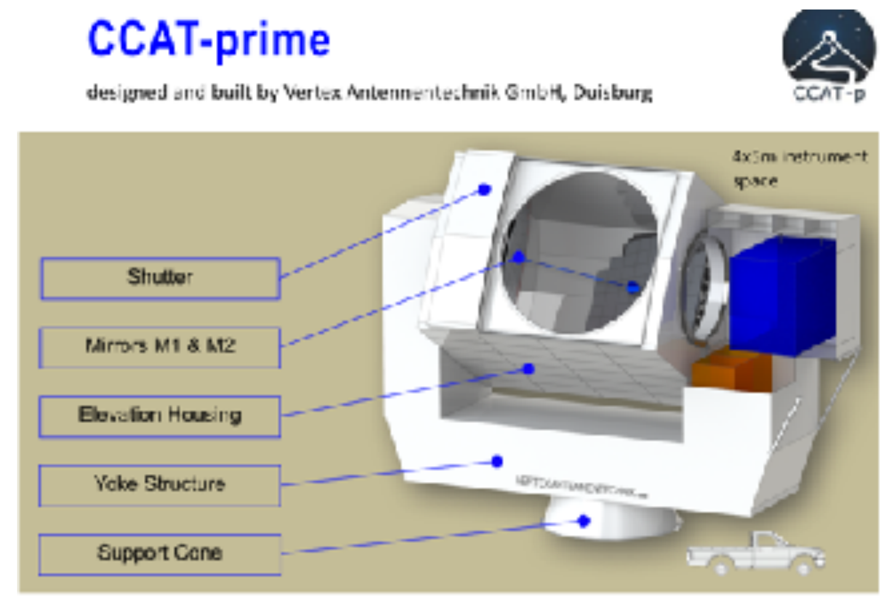
The Biggest Enemy: Polarised Dust Emission

- The upcoming data will **NOT** be limited by statistics, but by systematic effects such as the Galactic contamination
- **Solution**: Observe the sky at multiple frequencies, especially at high frequencies (>300 GHz)
- This is challenging, unless we have a superb, high-altitude site with low water vapour

- CCAT-prime!

A Game Changer

- **CCAT-prime**: 6-m, **Cross-dragone** design, on Cerro Chajnantor (5600 m)



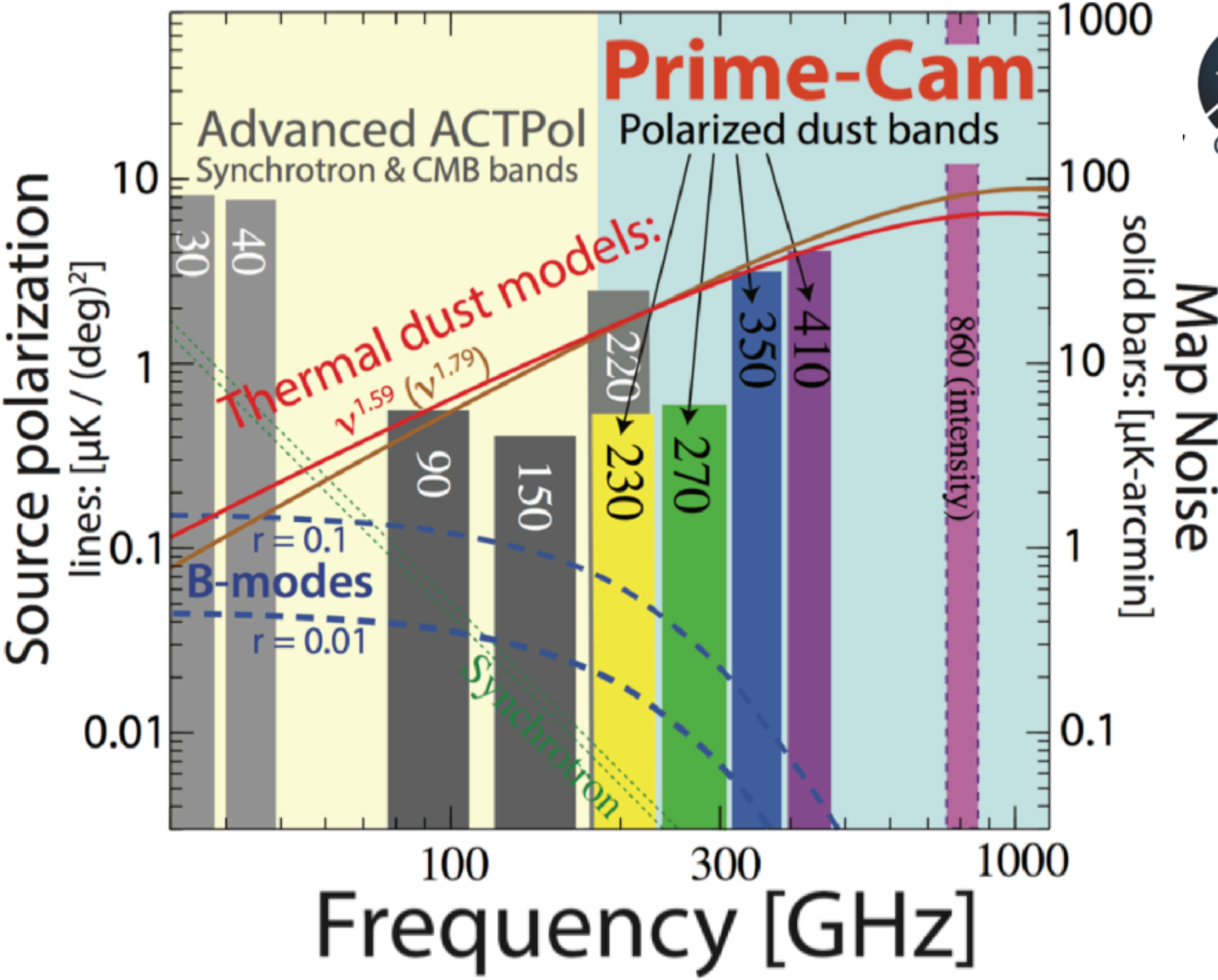
- **Germany makes great telescopes!**

- Design study completed, and the contract has been signed by “VERTEX Antennentechnik GmbH”

Cornell U. + German consortium + Canadian consortium + …

German consortium is led by Köln and Bonn

CCAT-prime Collaboration



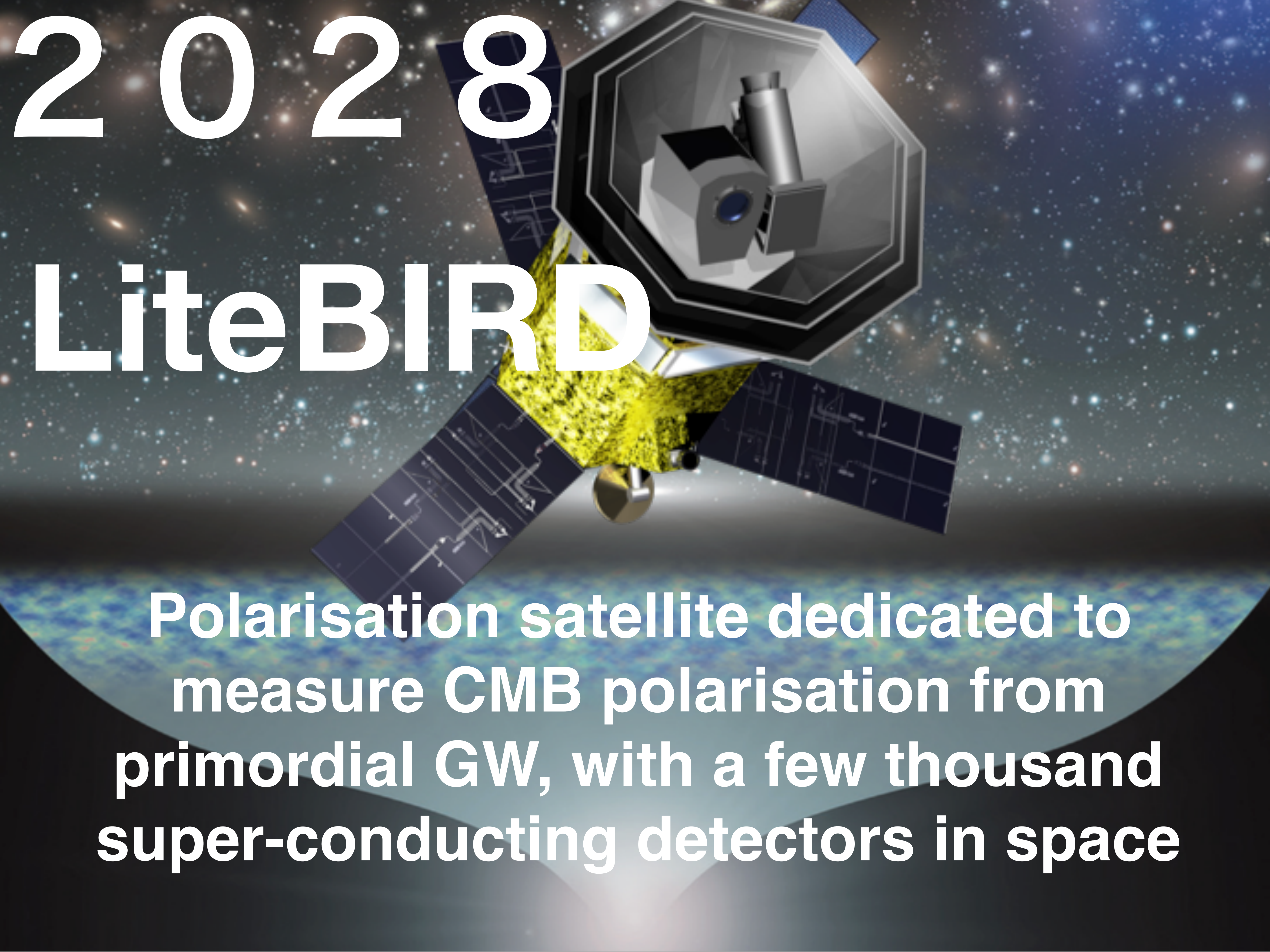
Frank Bertoldi's slide from the Florence meeting

Where is CCAT-p?

Cerro Chajnantor at 5600 m w/ TAO

To have more frequency coverage…

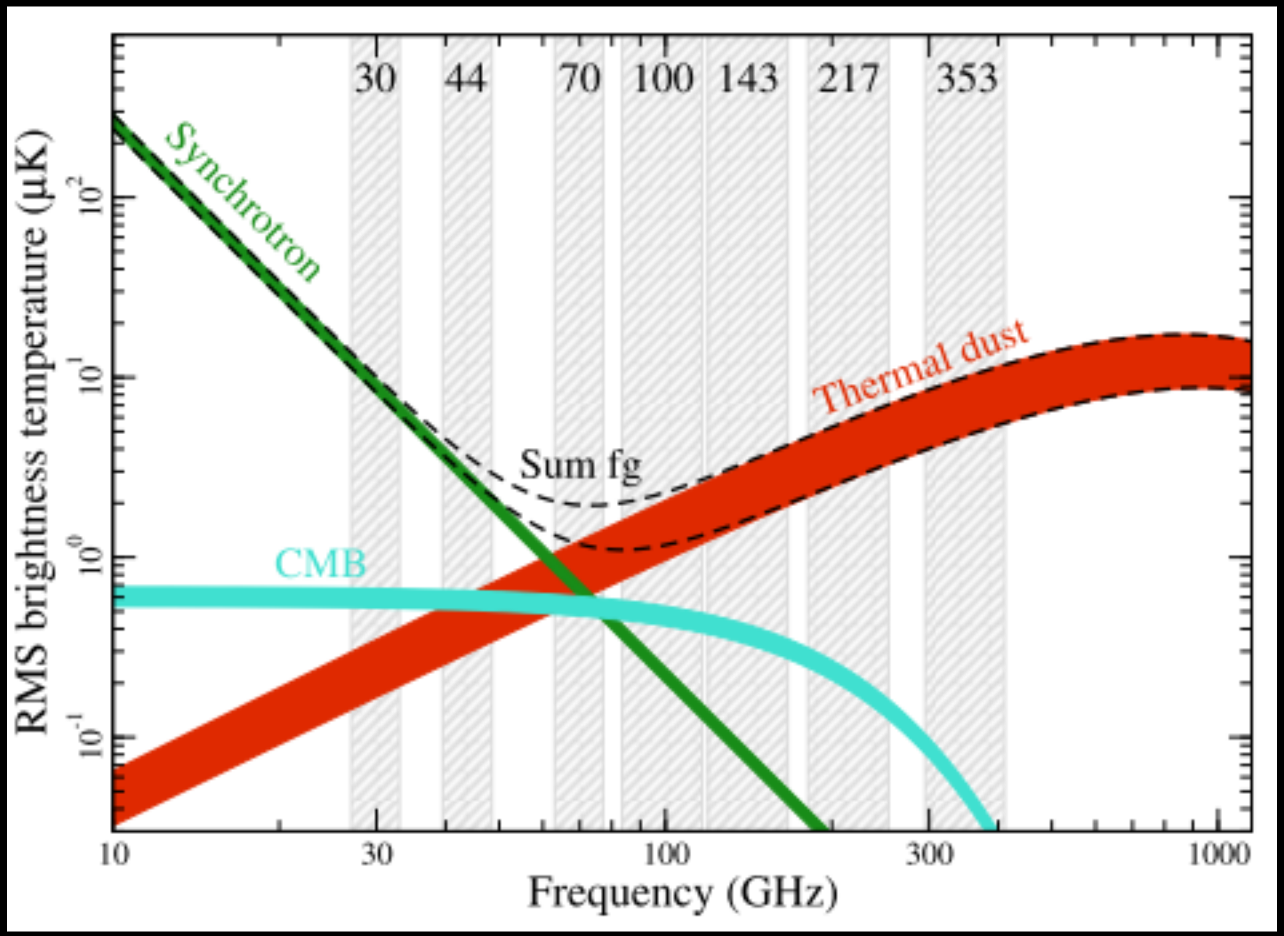

2028
LiteBIRD
Target: δr<0.001 (68%CL)
JAXA
+ participations from USA,
Canada, Europe


2028
LiteBIRD
Polarisation satellite dedicated to measure CMB polarisation from primordial GW, with a few thousand super-conducting detectors in space

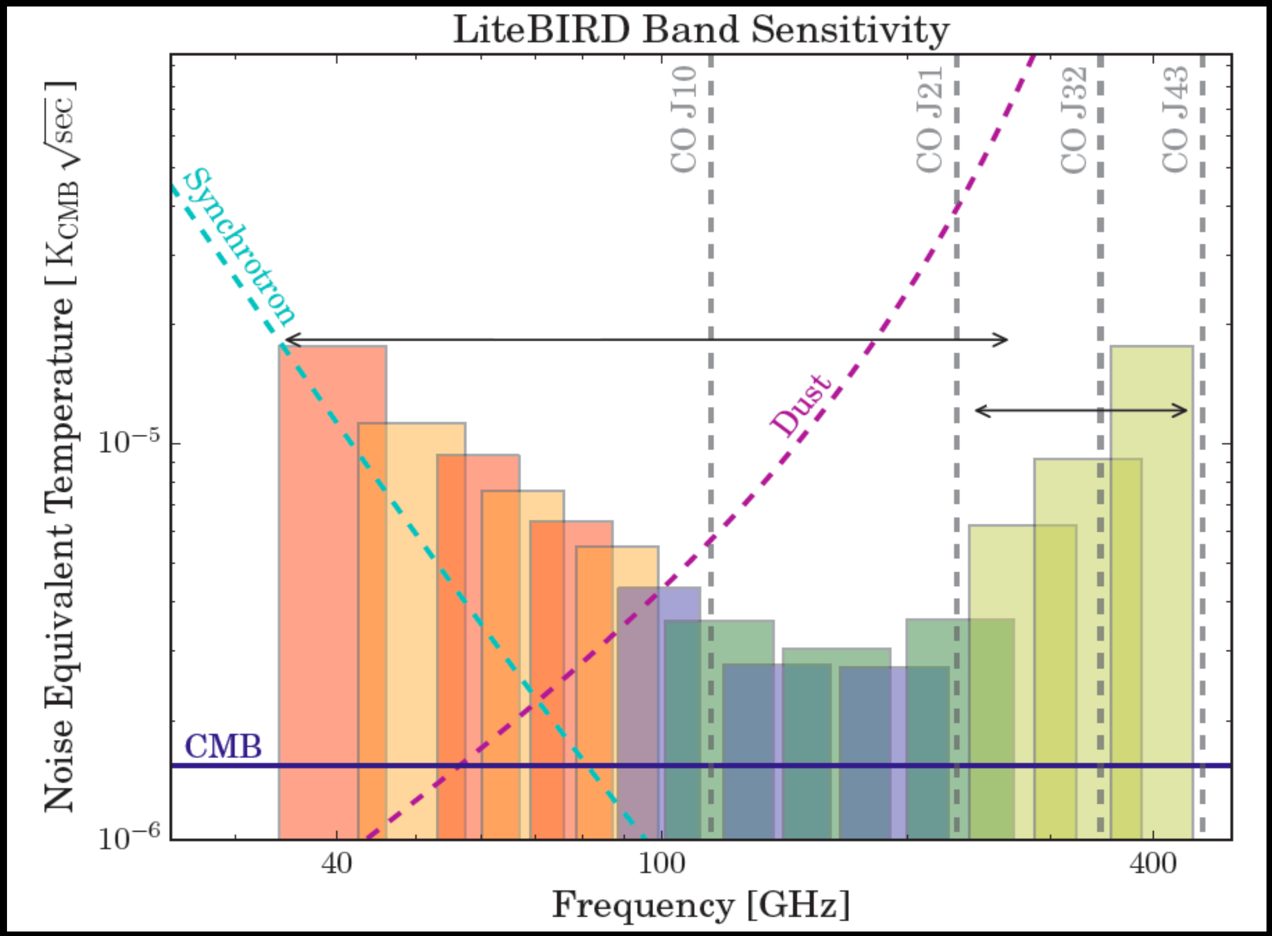
Summary

- **Theory of the early Universe**:
  - Inflation looks good: all the CMB data support it
- **Next frontier**:
  - Using CMB polarisation to find GWs from inflation. **Definitive evidence for inflation!**
  - With CCAT-prime [2021–], we plan to reach $r \sim 10^{-2}$, i.e., 10 times better than the current bound
  - With LiteBIRD [2028–], we plan to reach $r \sim 10^{-3}$

Foreground Removal



Polarized galactic emission (Planck X)



LiteBIRD: 15 frequency bands

- Polarized foregrounds
  - Synchrotron radiation and thermal emission from inter-galactic dust
  - Characterize and remove foregrounds
- 15 frequency bands between 40 GHz - 400 GHz
  - Split between Low Frequency Telescope (LFT) and High Frequency Telescope (HFT)
  - LFT: 40 GHz – 235 GHz
  - HFT: 280 GHz – 400 GHz

Slide courtesy Toki Suzuki (Berkeley)

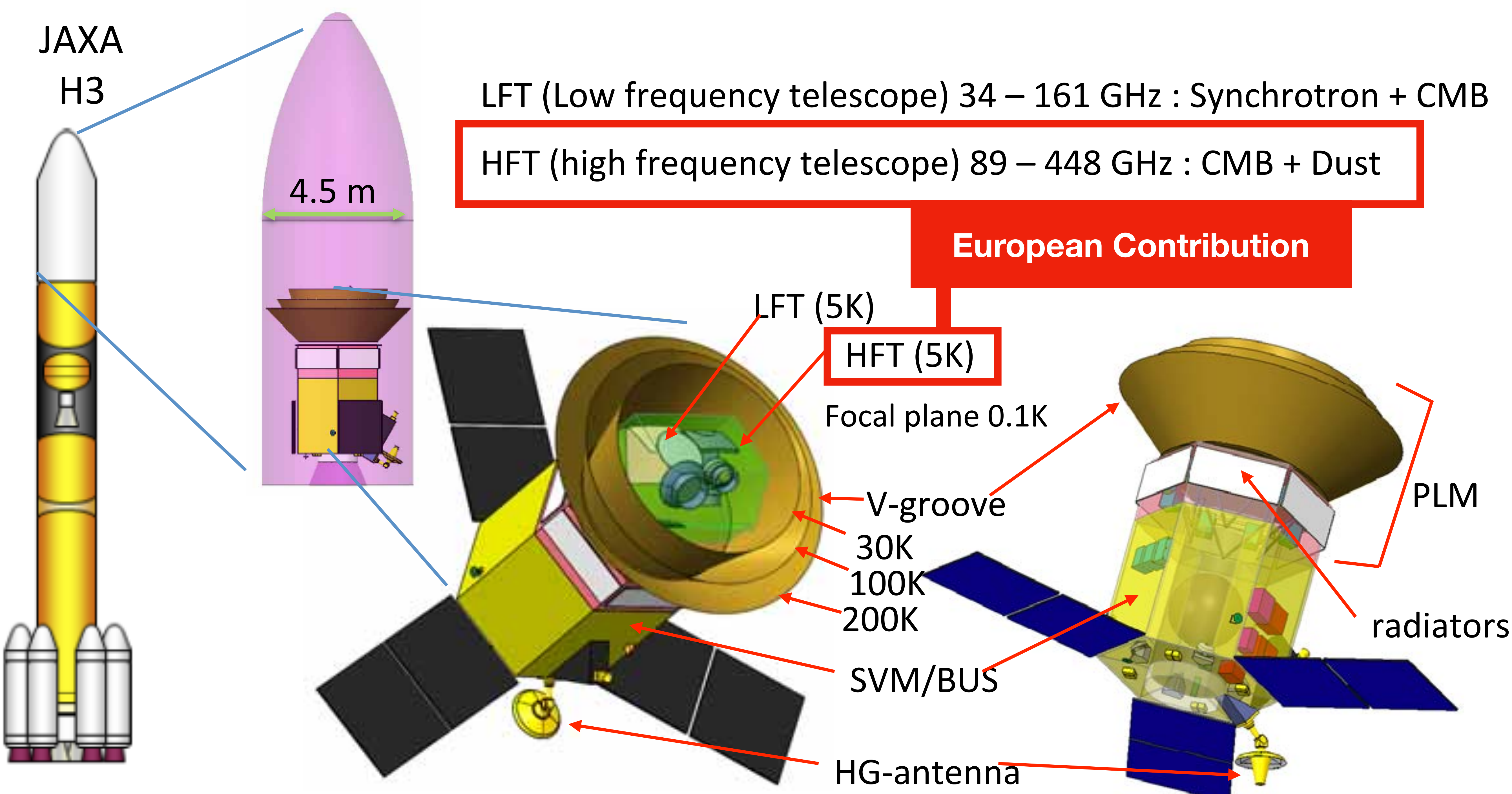
Slide courtesy Yutaro Sekimoto (ISAS/JAXA)

LiteBIRD Spacecraft

LFT (Low frequency telescope) 34 – 161 GHz : Synchrotron + CMB

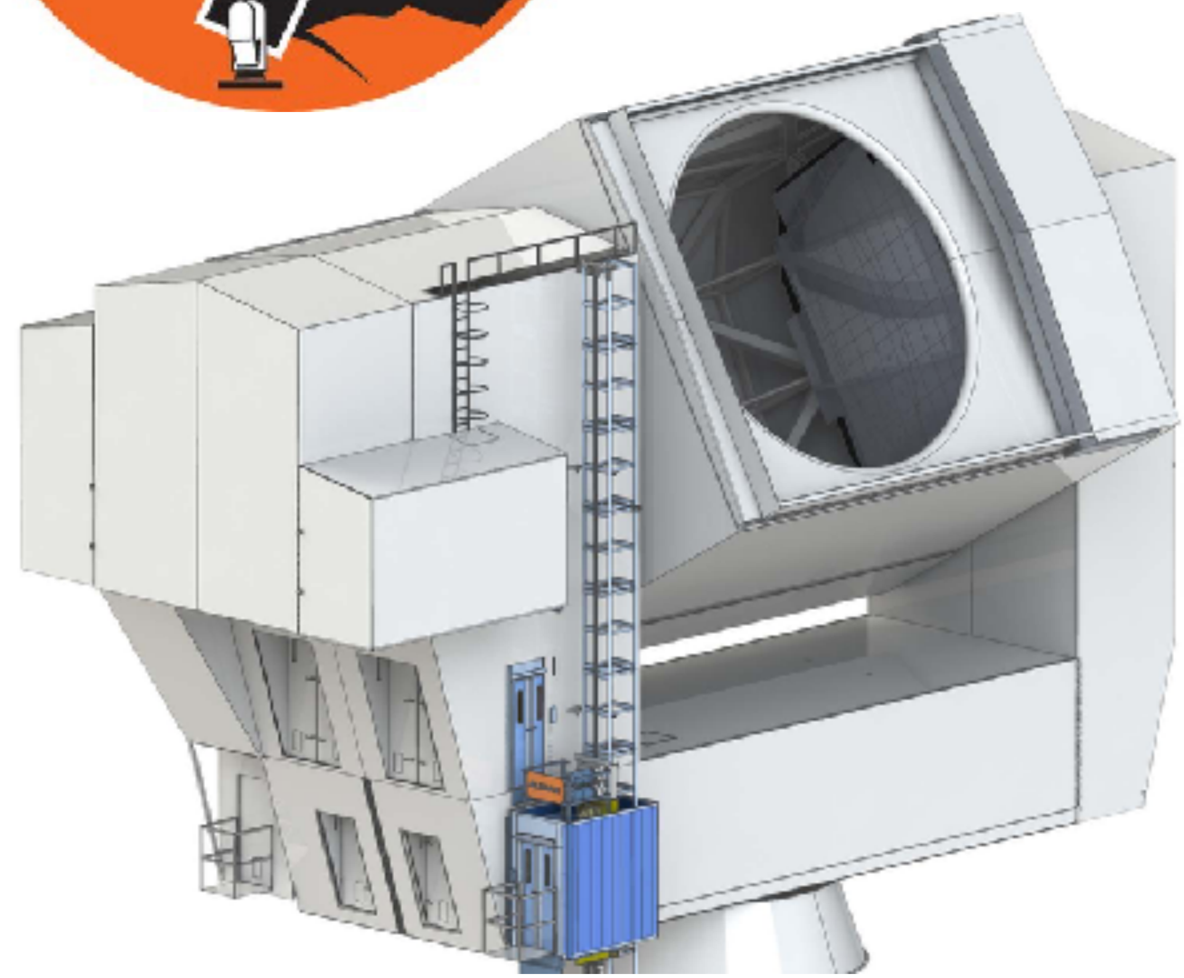
HFT (high frequency telescope) 89 – 448 GHz : CMB + Dust

European Contribution

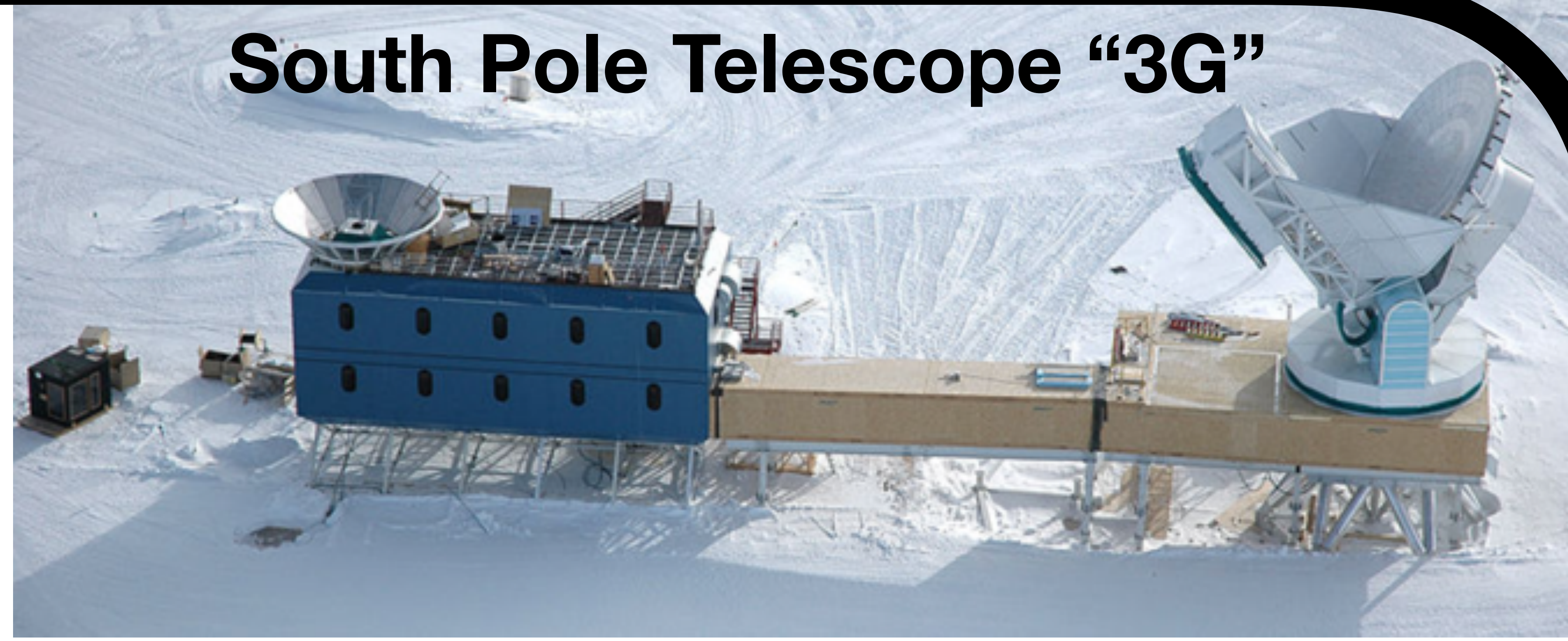


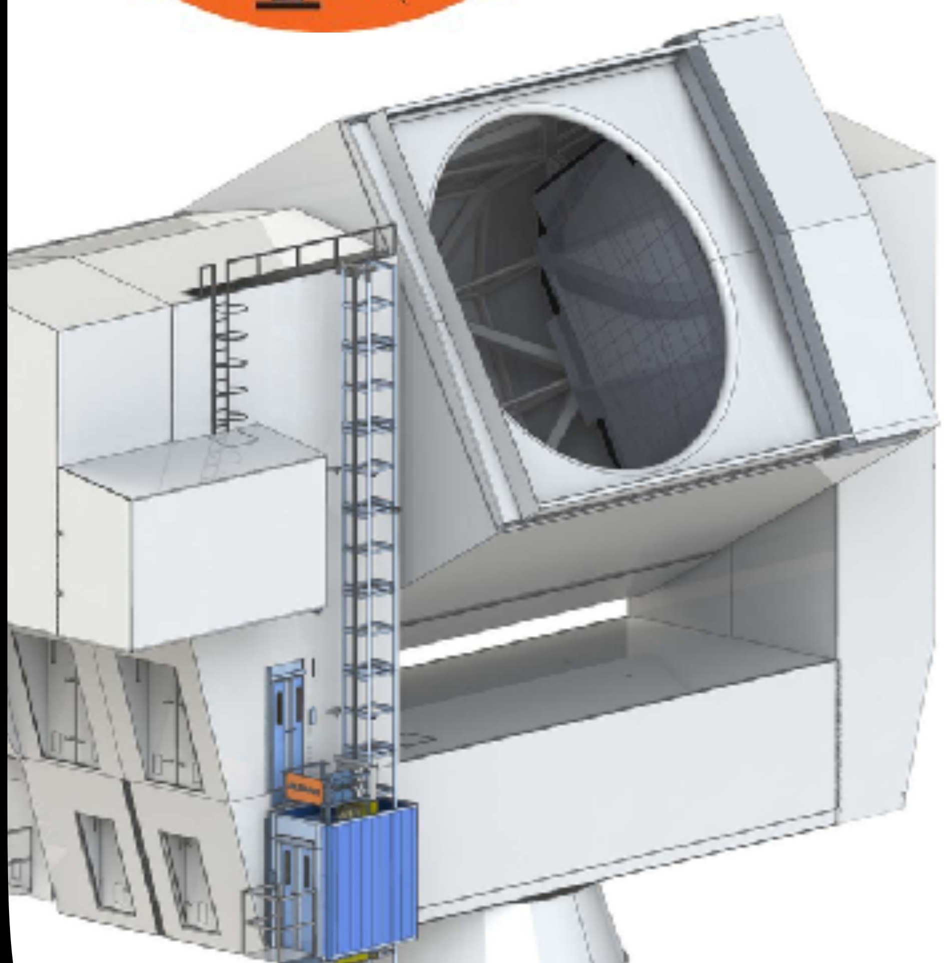
SIMONS
OBSERVATORY

The Simons Array



SIMONS OBSERVATORY





CMB-S4(?)