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

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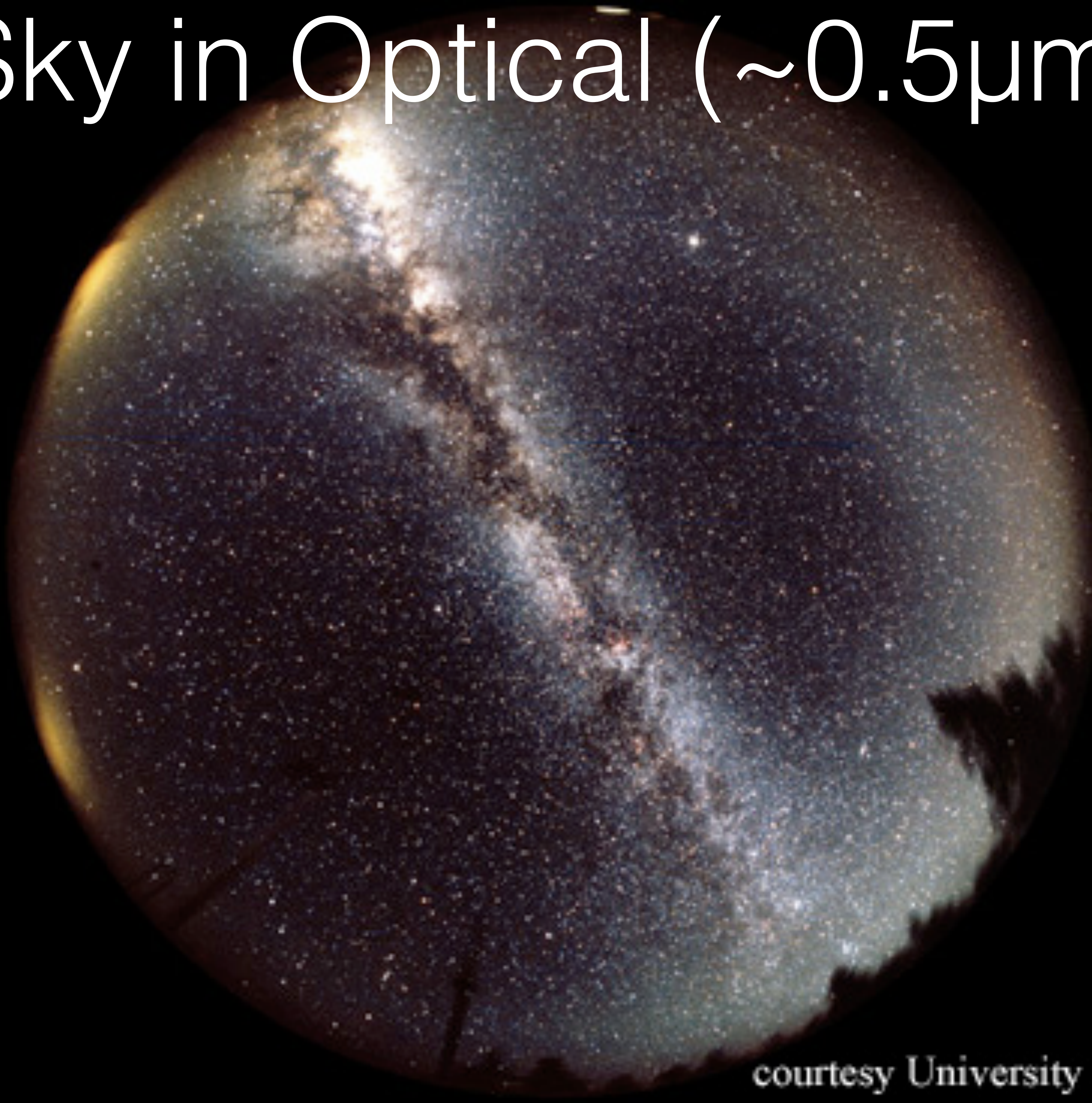
Kolloquiumsvortrag Physik, FAU
8. Mai, 2019

Breakthrough in Cosmological Research

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

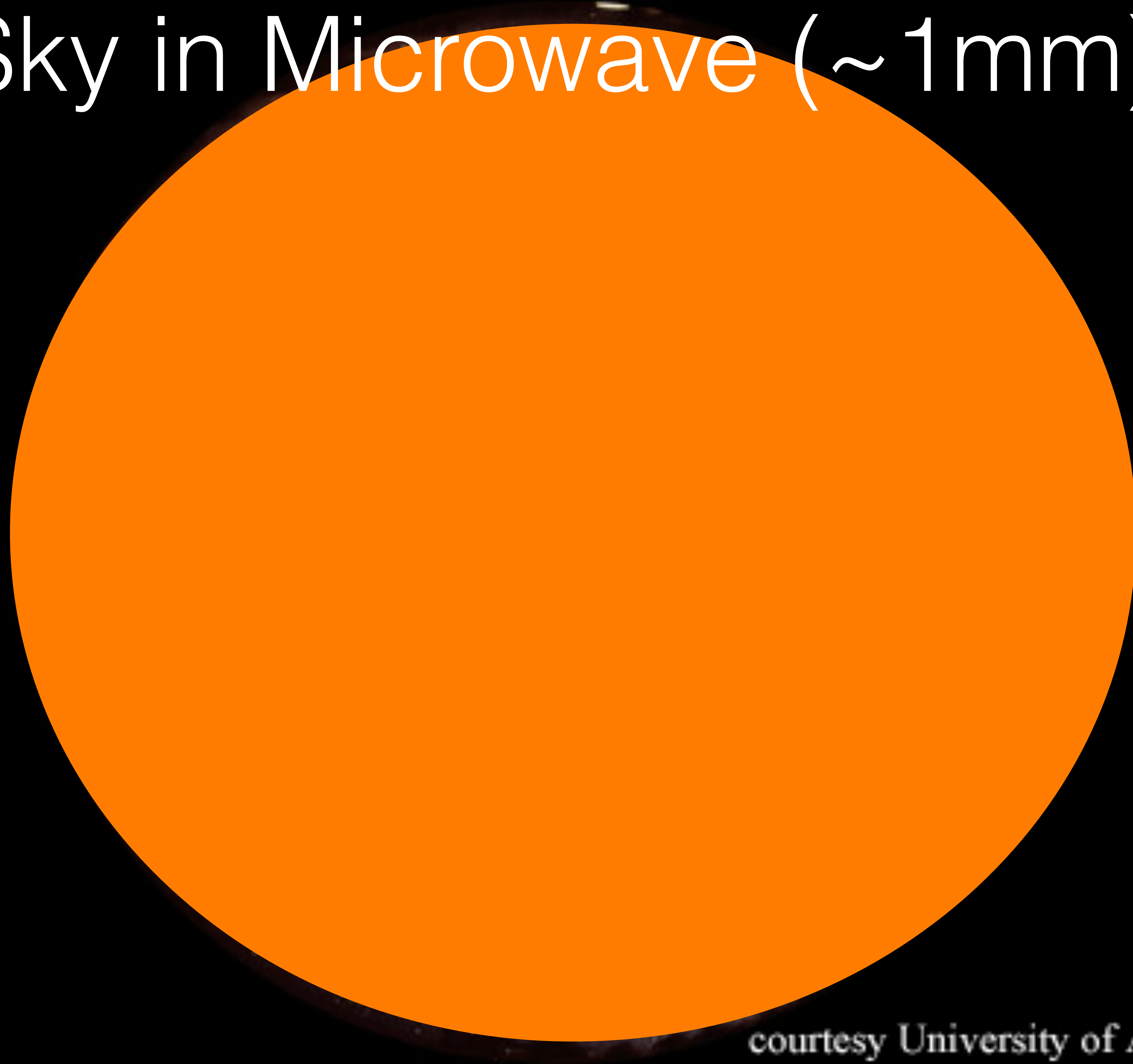
From "Cosmic Voyage"

Sky in Optical (~0.5μm)



courtesy University of Arizona

Sky in Microwave (~1mm)

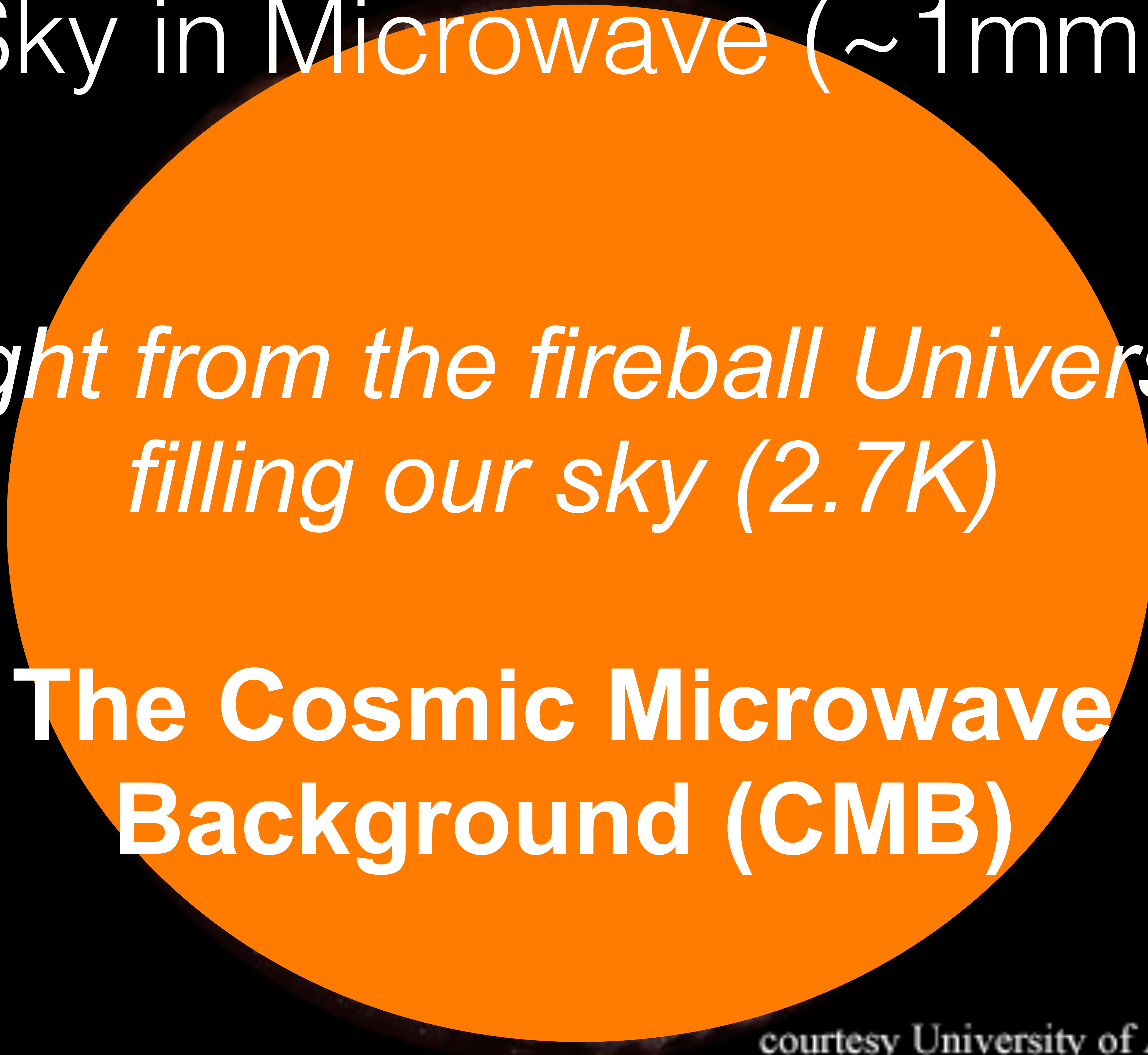


courtesy University of Arizona

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!!

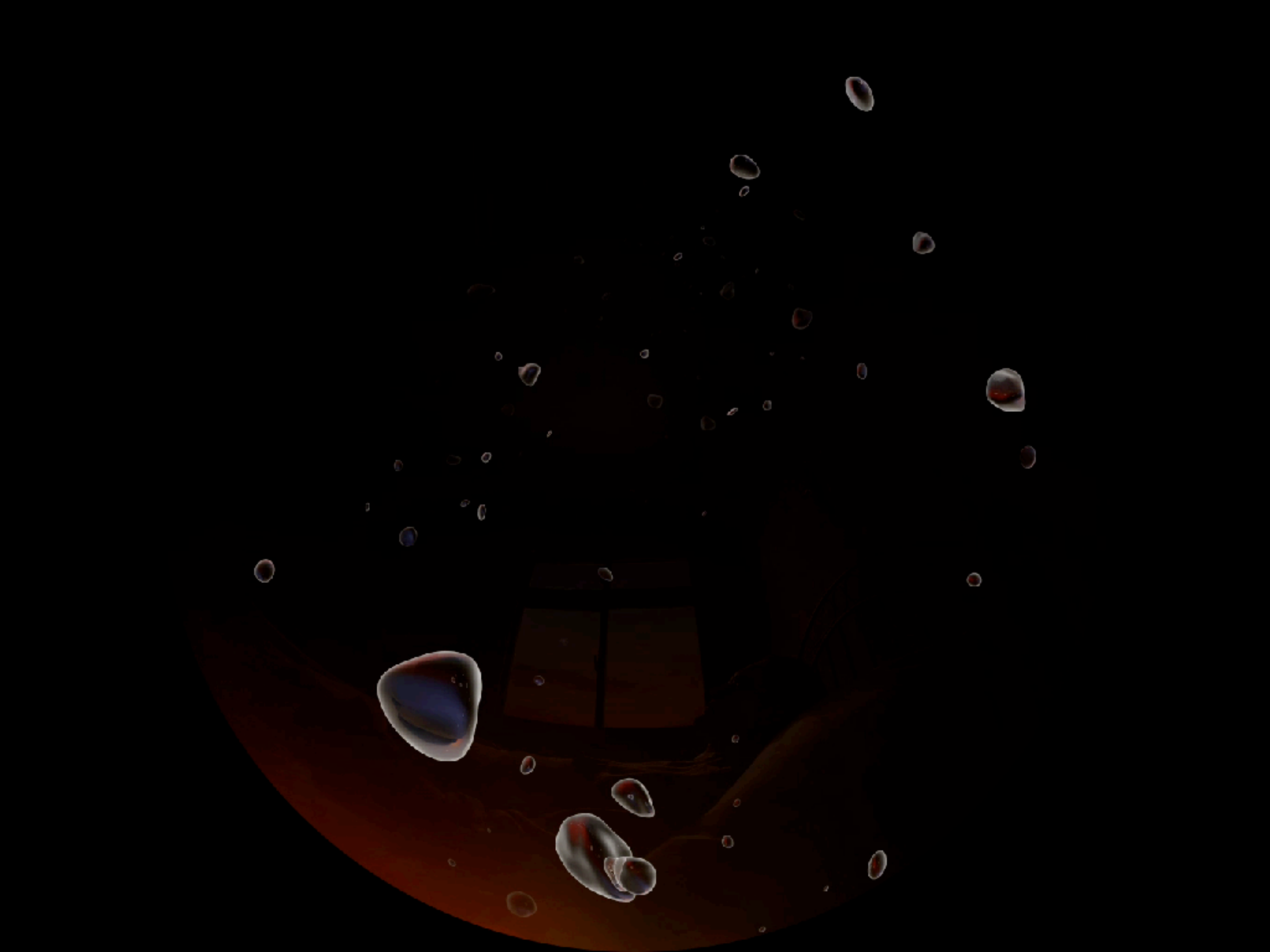
courtesy University of Arizona

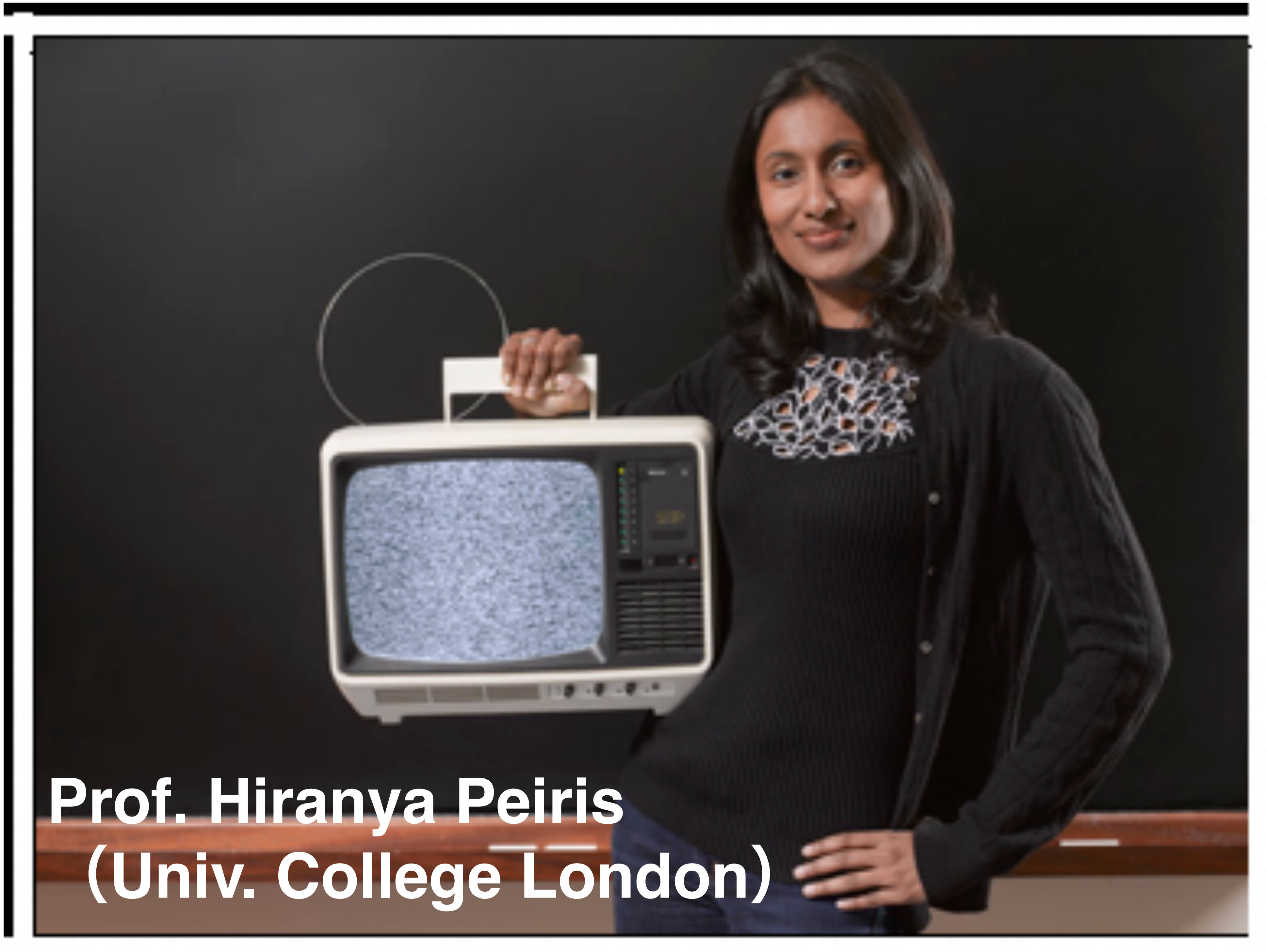
YouTube BE horizon edge of the visible universe

Full-dome movie for planetarium

Director: Hiromitsu Kohsaka

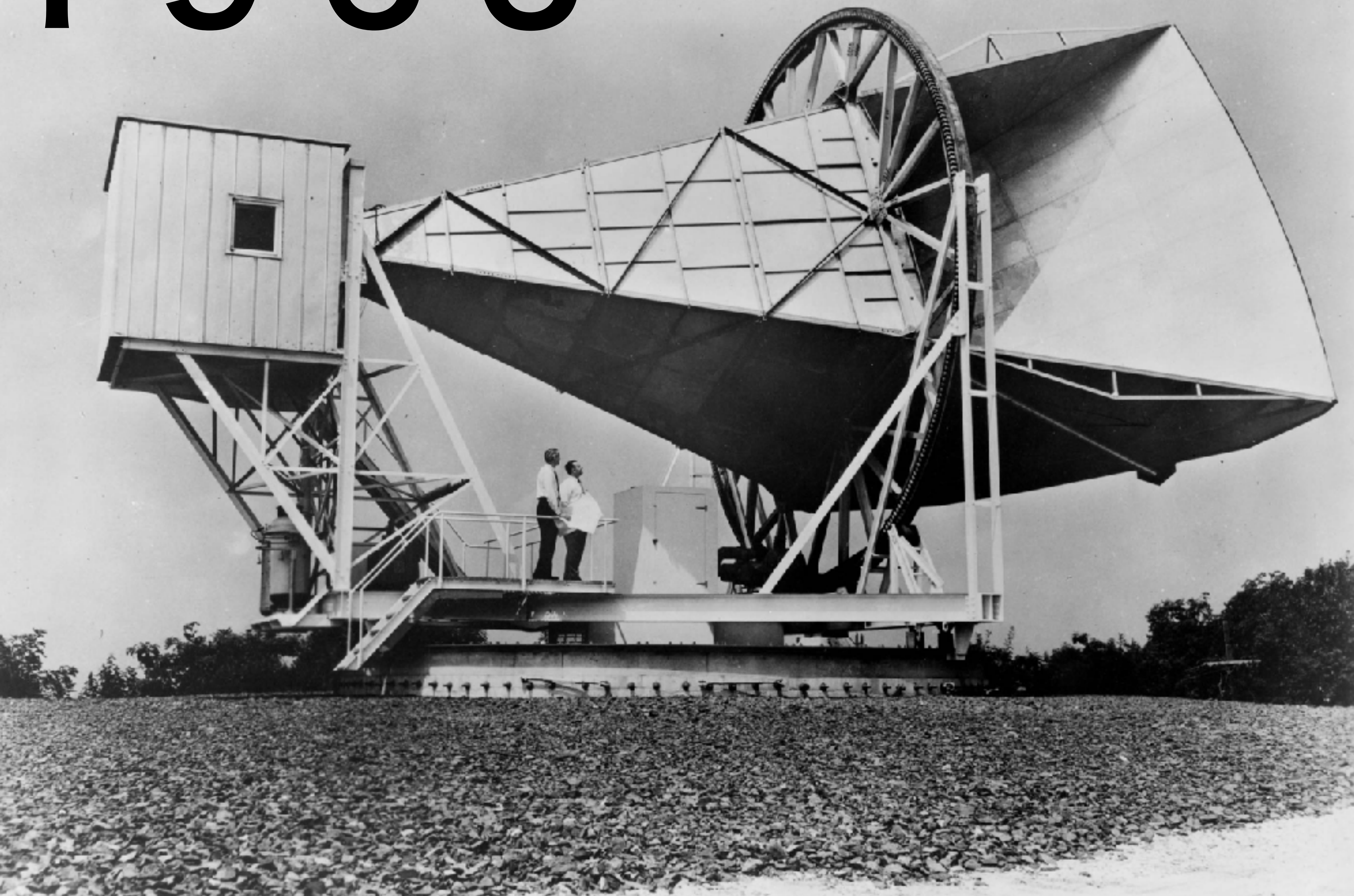
HORIZON :Beyond the Edge of the Visible Universe [Trailer]



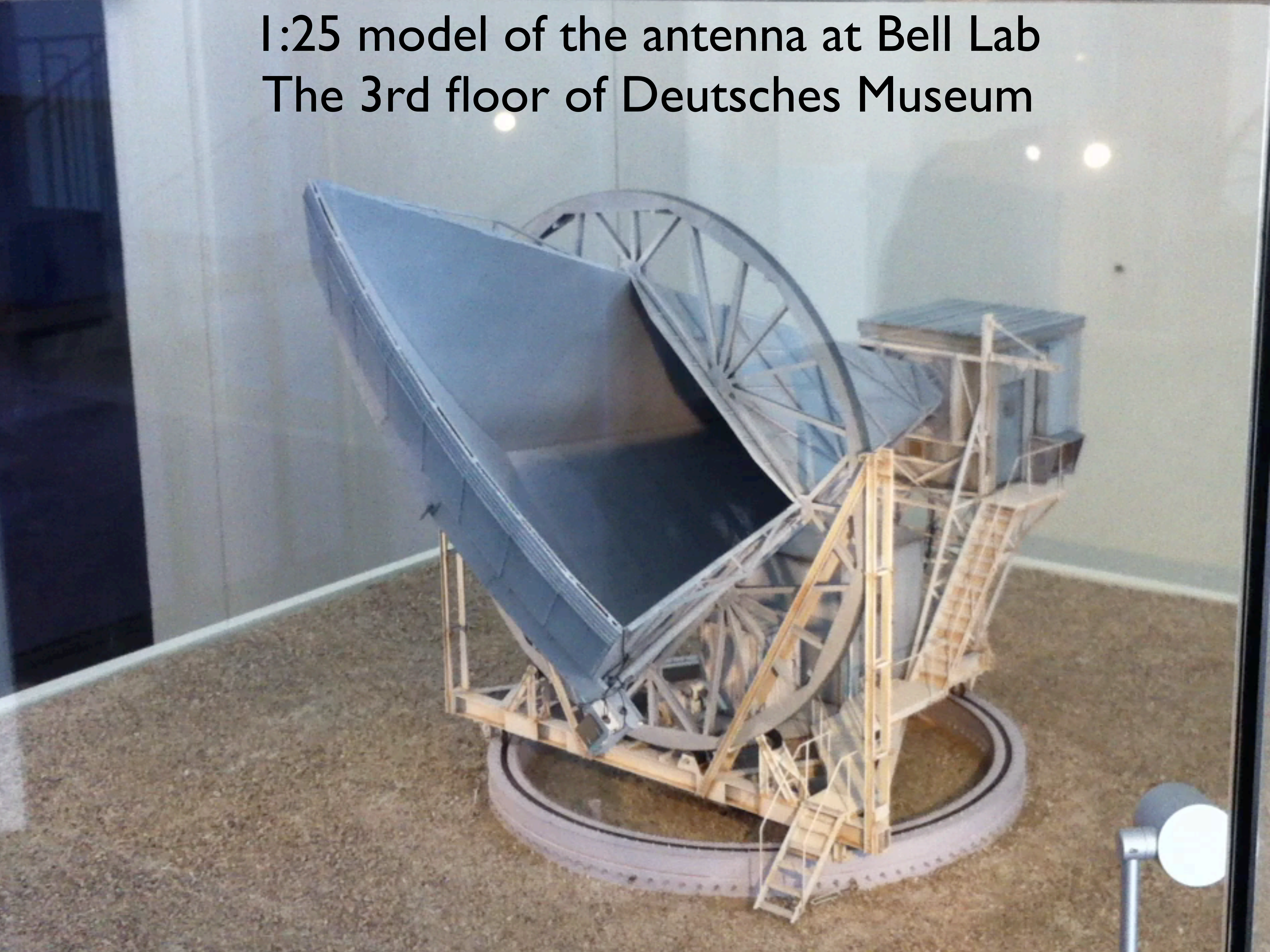


All you need to do is to detect radio waves. For example, 1% of noise on the TV is from the fireball Universe

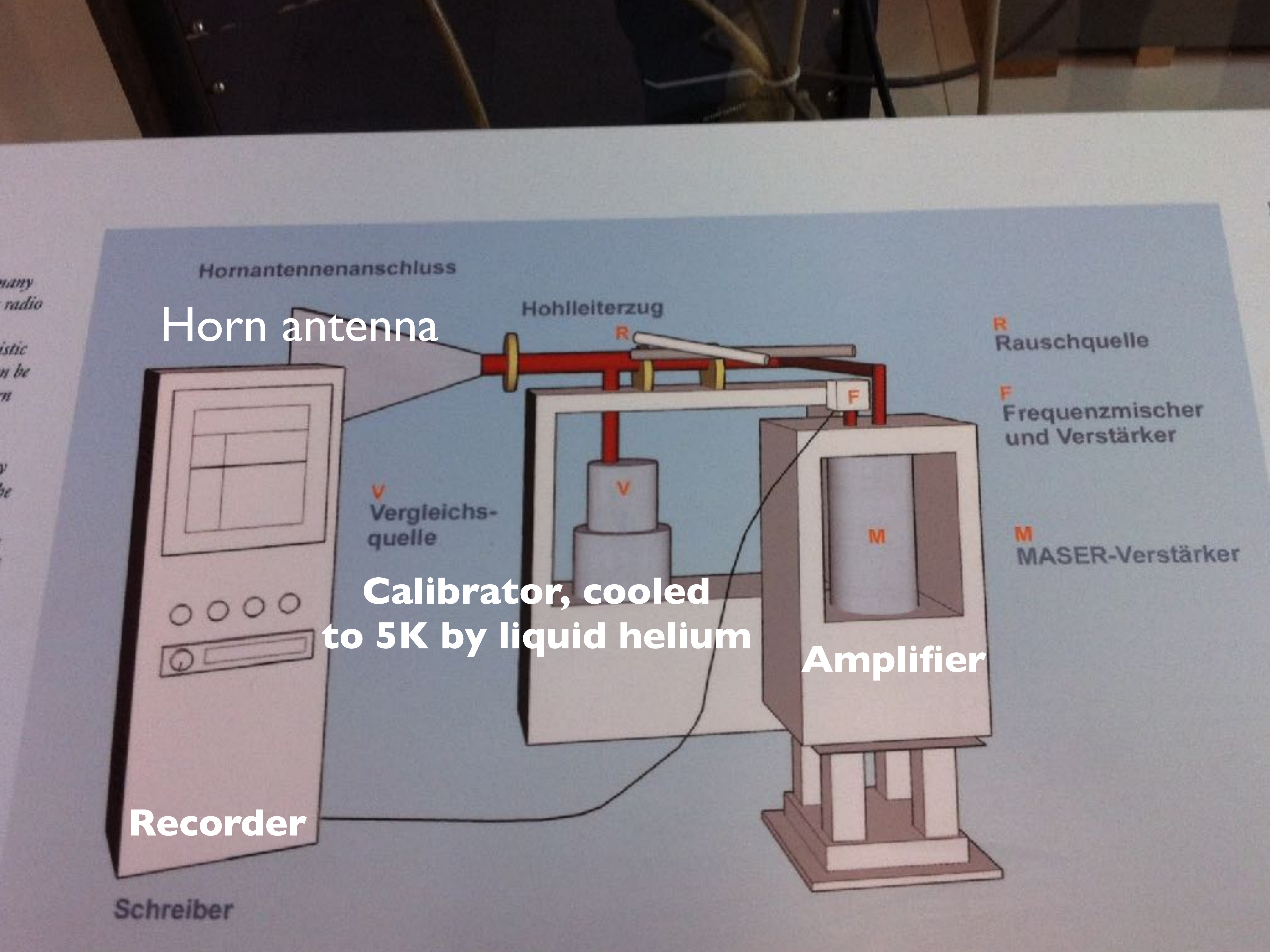
1965



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

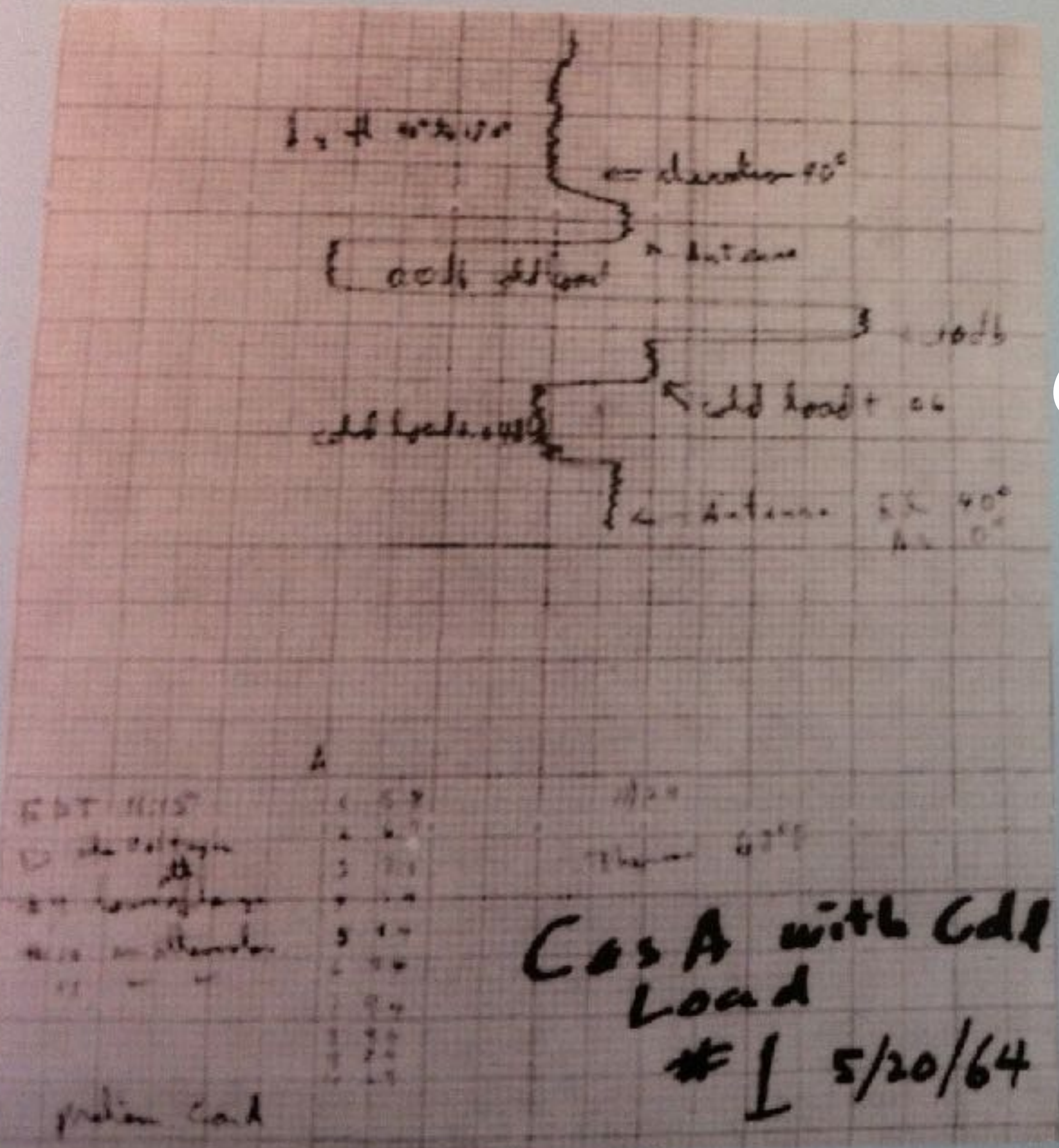


The real detector system used by Penzias & Wilson
The 3rd floor of Deutsches Museum


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

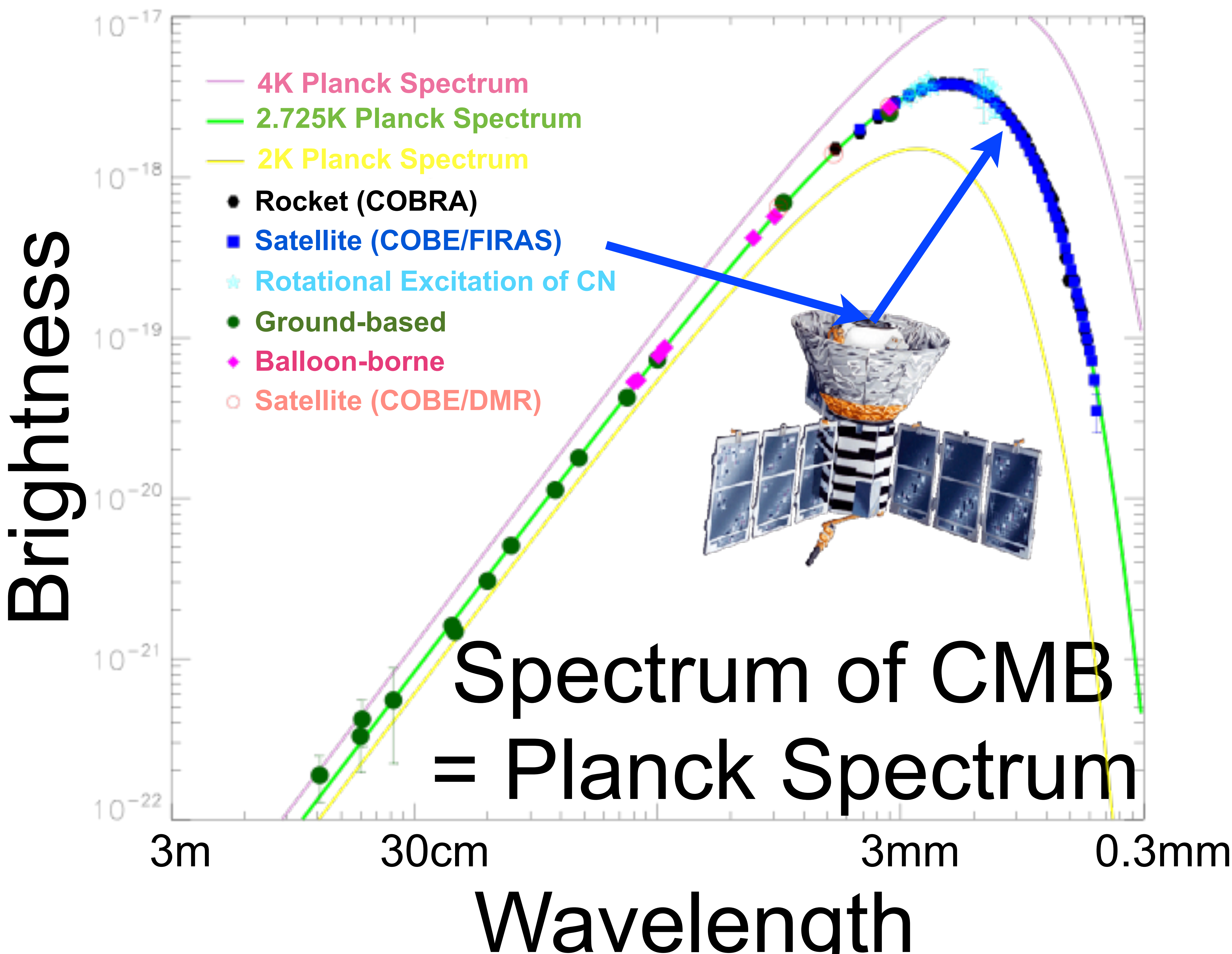
May 20, 1964 CMB Discovered

6.7–2.3–0.8–0.1 = 3.5±1.0 K

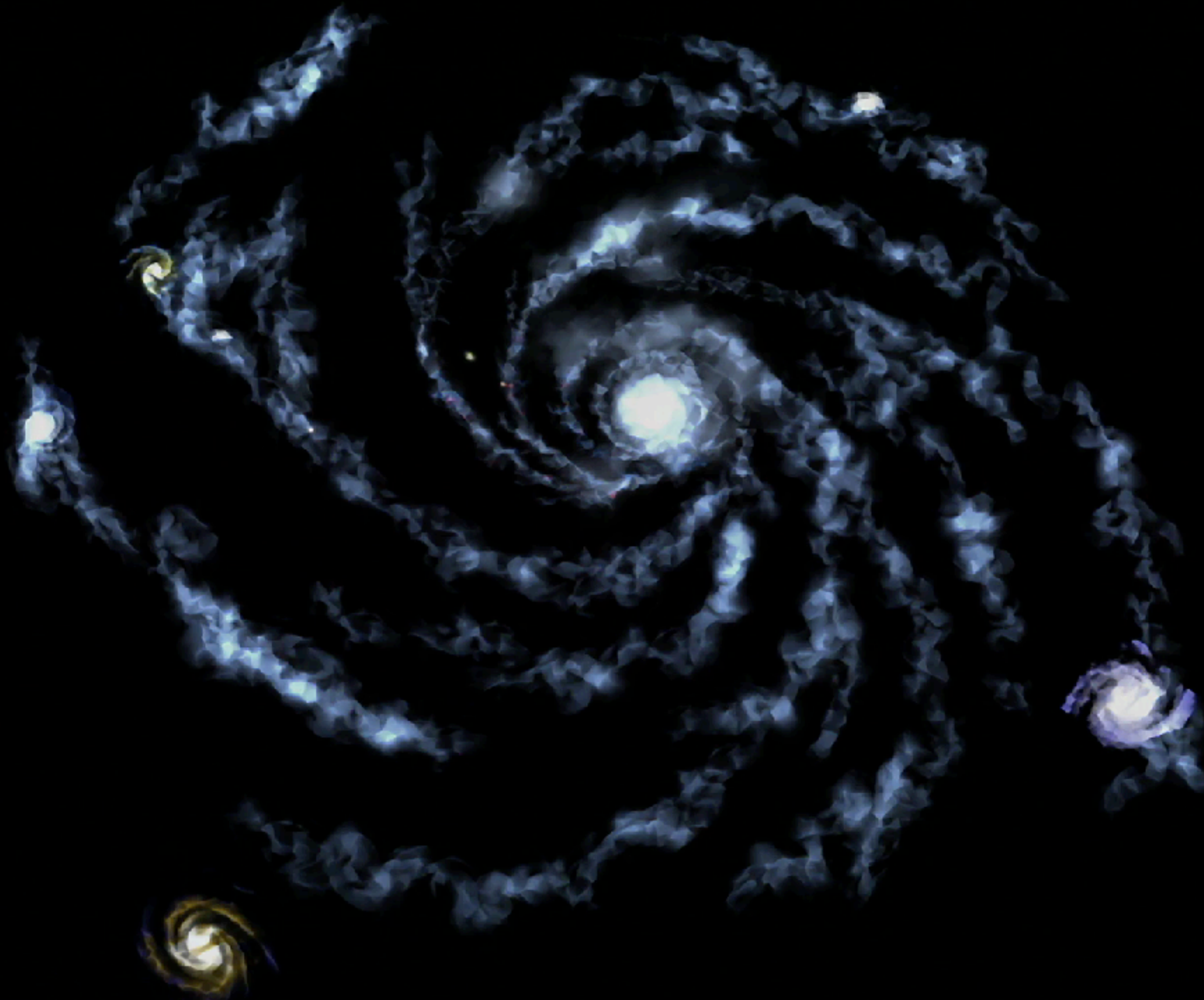


Schreiberaufzeichnung der ersten Messung des Mikrowellenhintergrundes am 20.5.1964

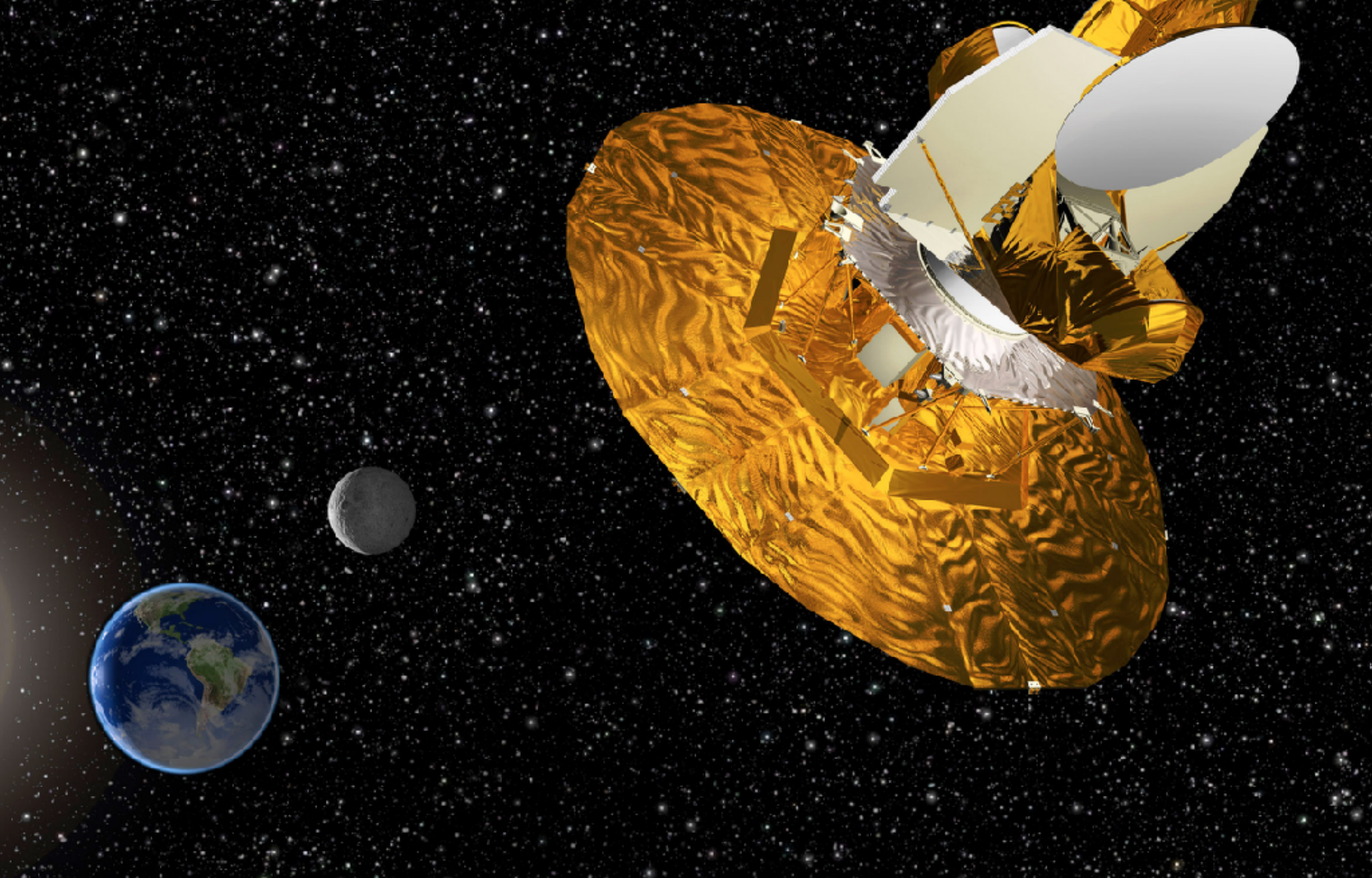
Recording of the first measurement of cosmic microwave background radiation taken on 5/20/1964.



Brightness
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
10⁻²¹
10⁻²²
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

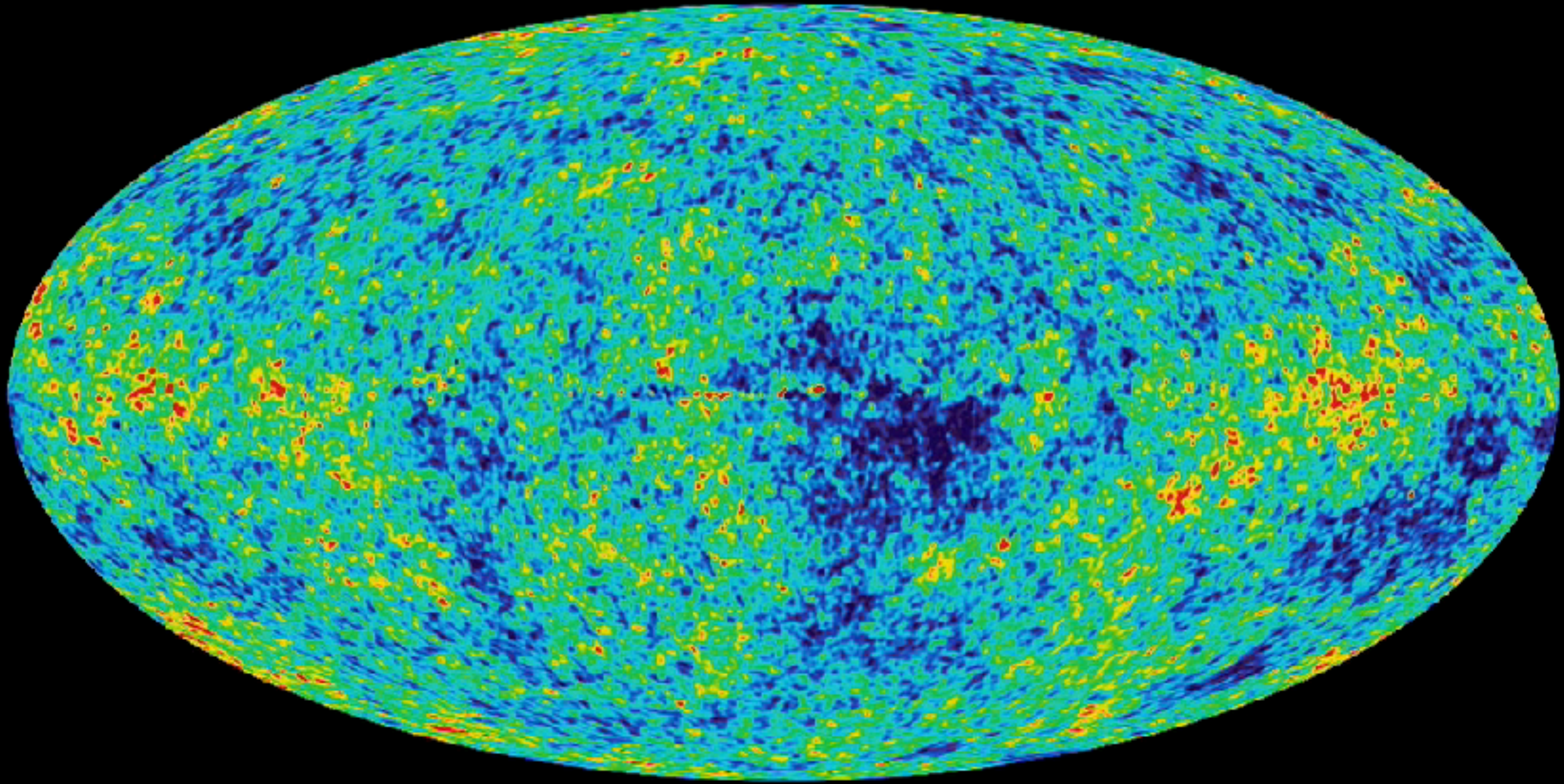


2001



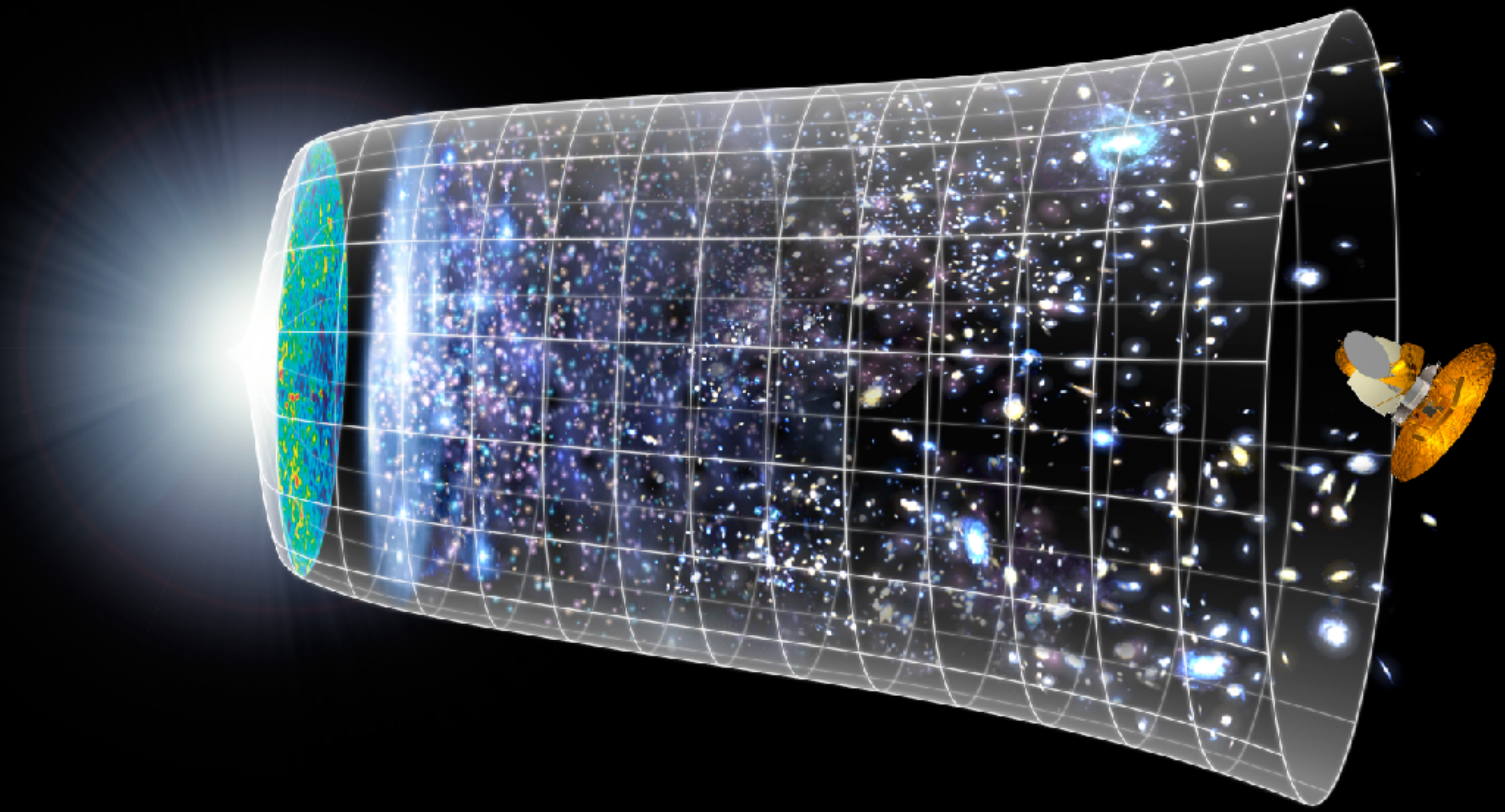
WMAP Science Team
July 19, 2002

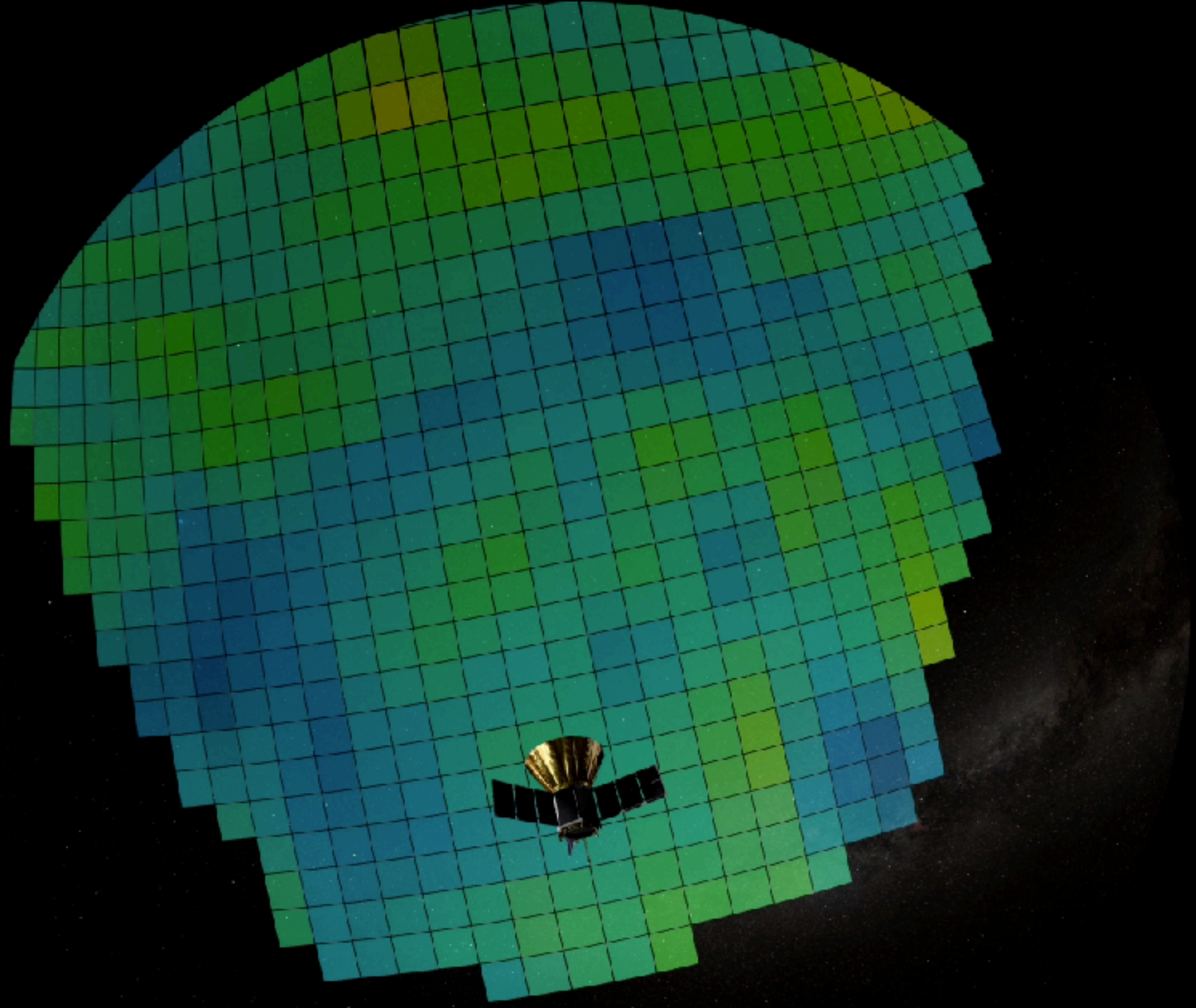
- WMAP was launched on June 30, 2001
- The WMAP mission ended after 9 years of operation



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?***





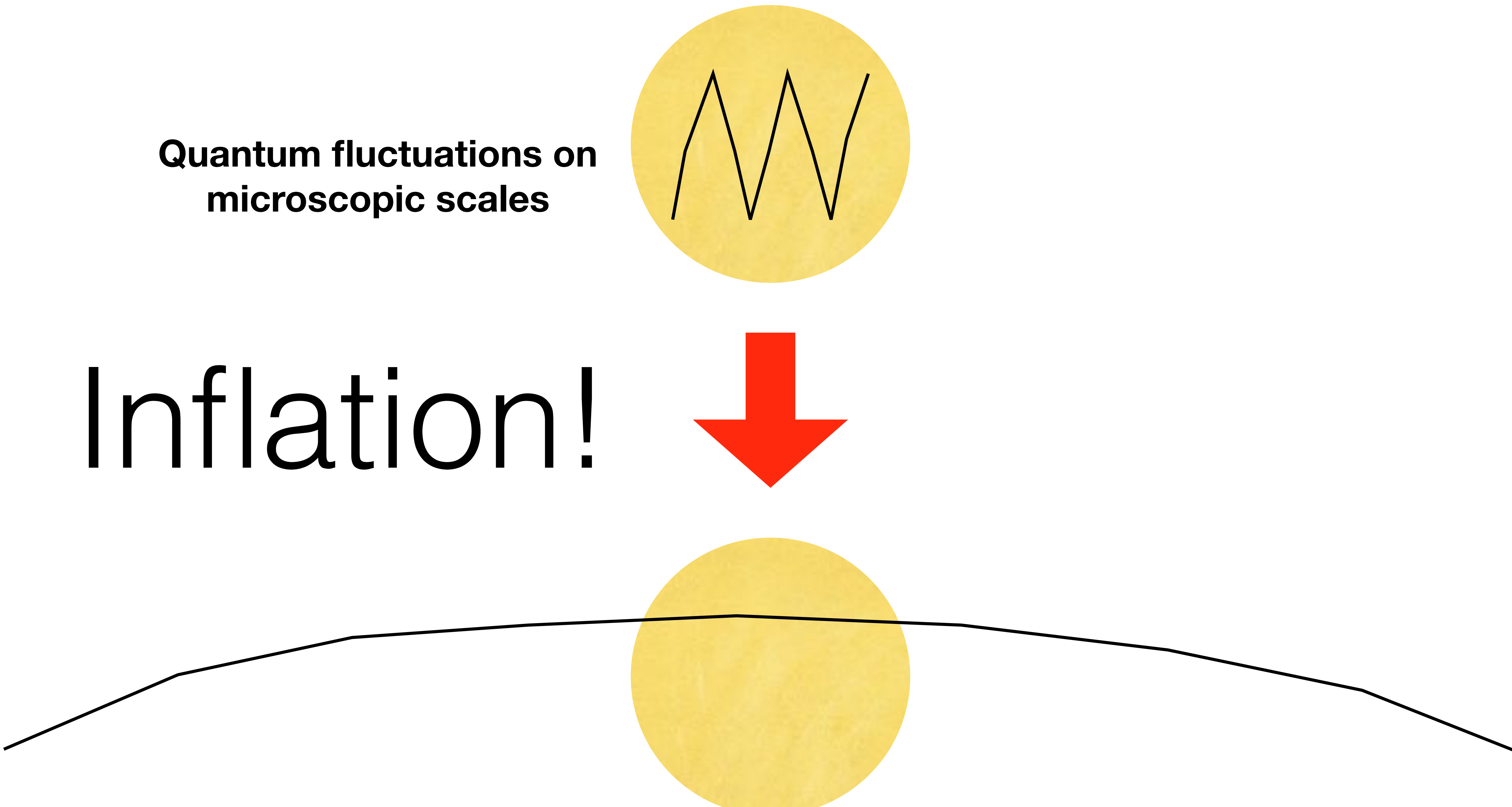
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

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



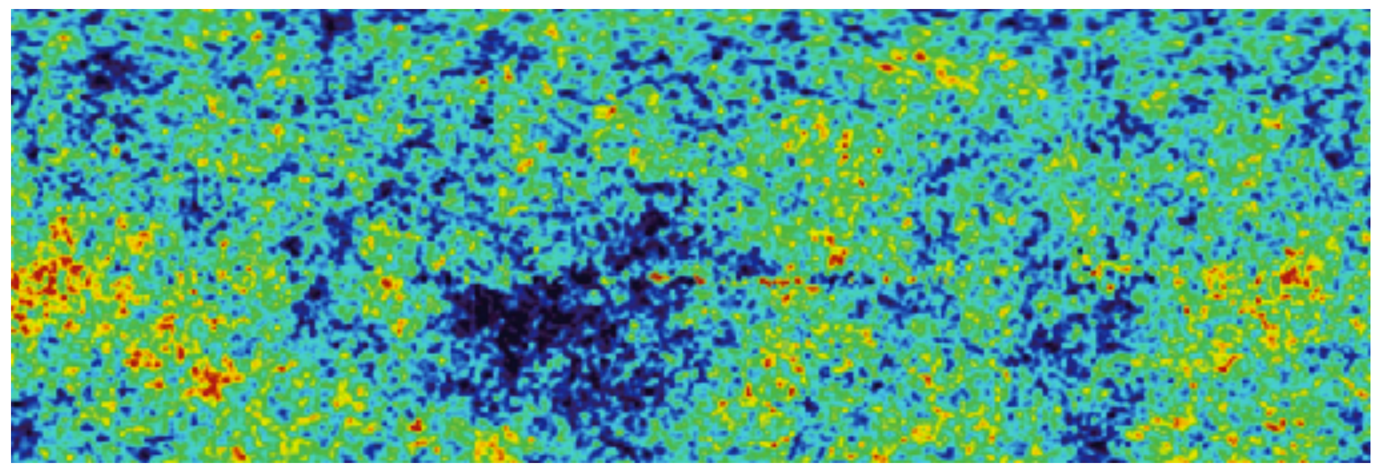
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

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**

Fluctuations are proportional to H

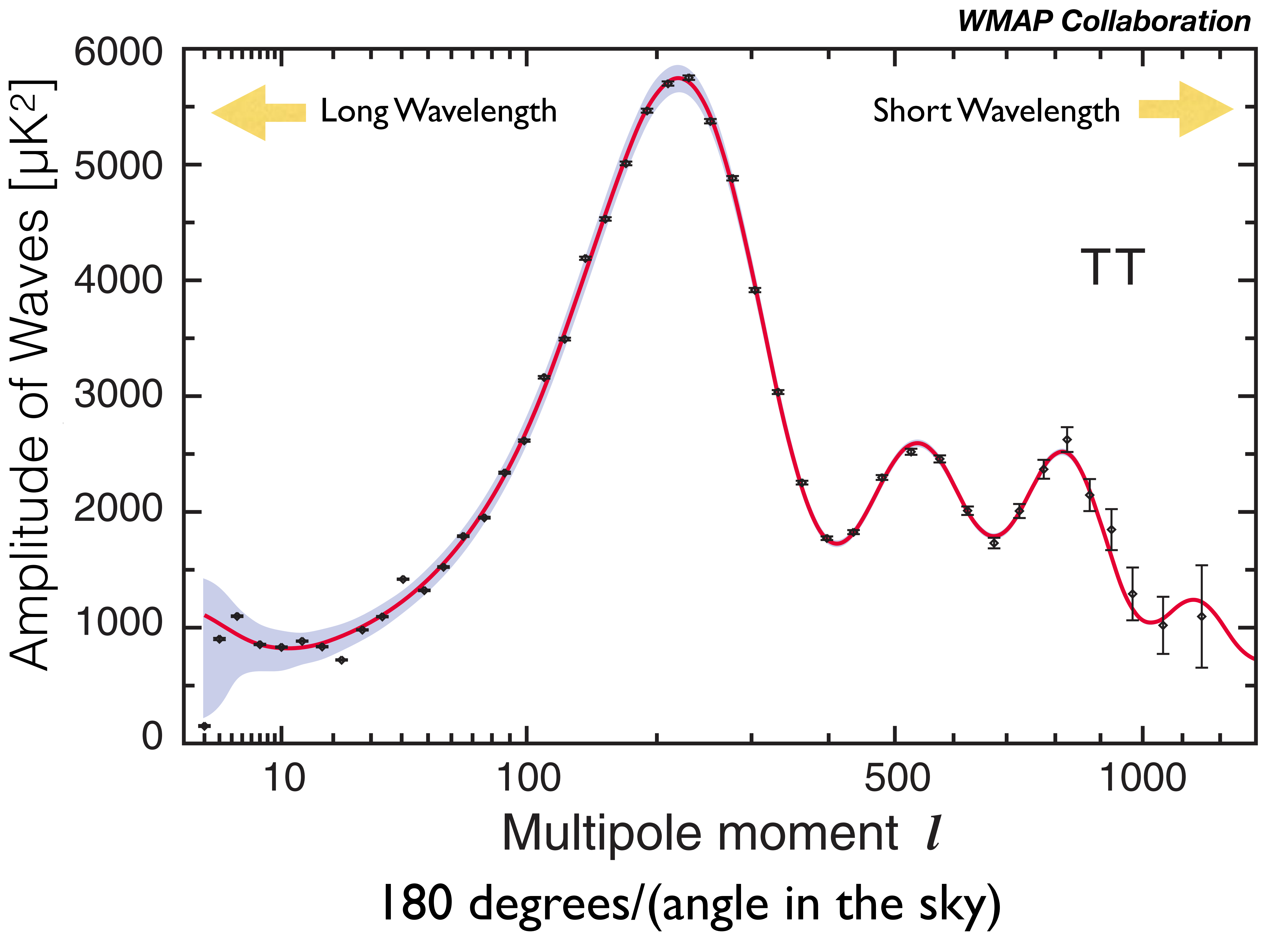
- **We can map H(t) by measuring CMB fluctuations over a wide range of angles**

  1. We want to show that the amplitude of CMB fluctuations does not depend very much on angles (i.e., $\varepsilon \ll 1$)

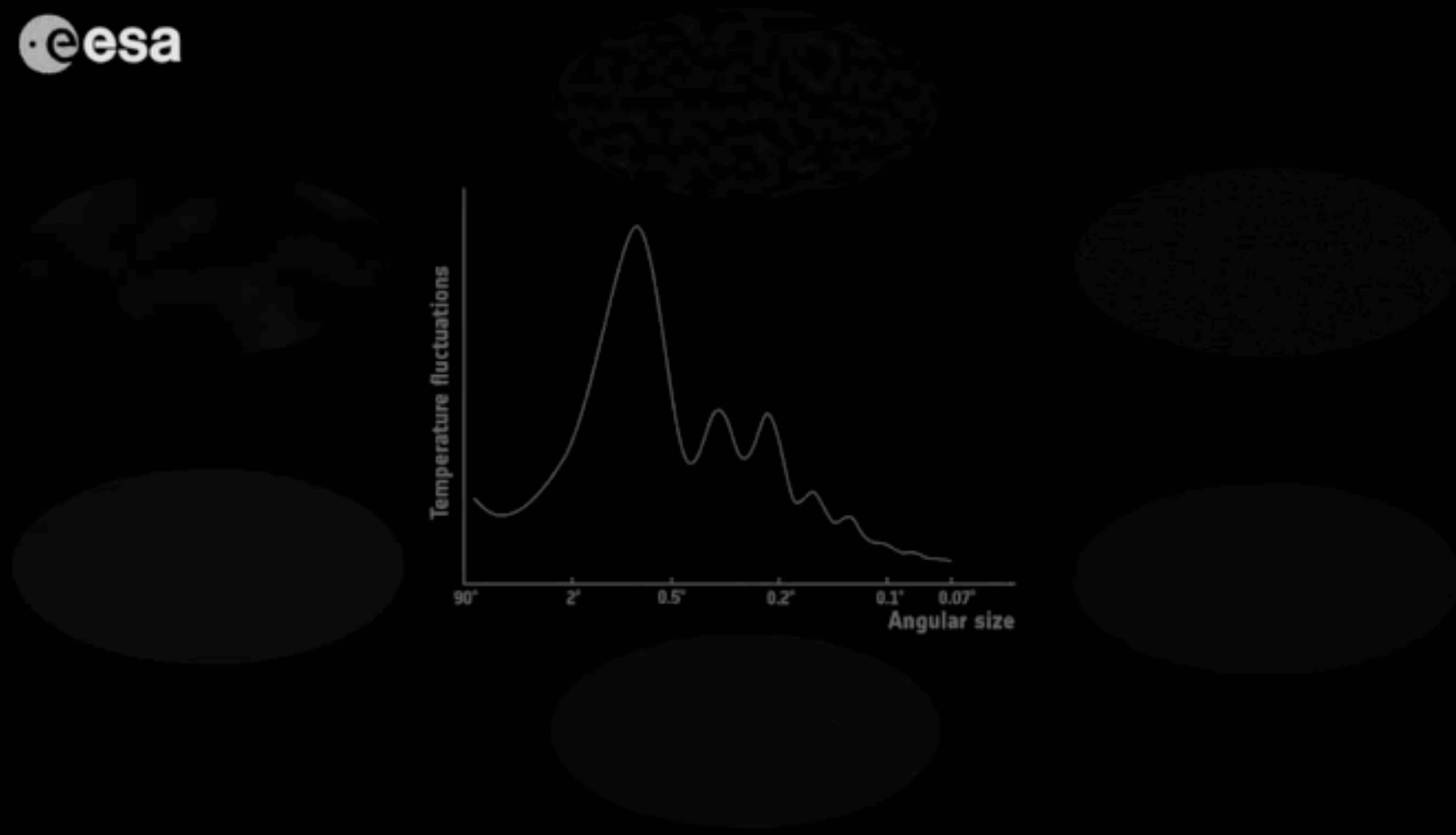
  2. Moreover, since inflation must end, H would be a decreasing function of time. It would be fantastic to show that the amplitude of CMB fluctuations actually DOES depend on angles such that the small scale has ***slightly*** smaller power

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

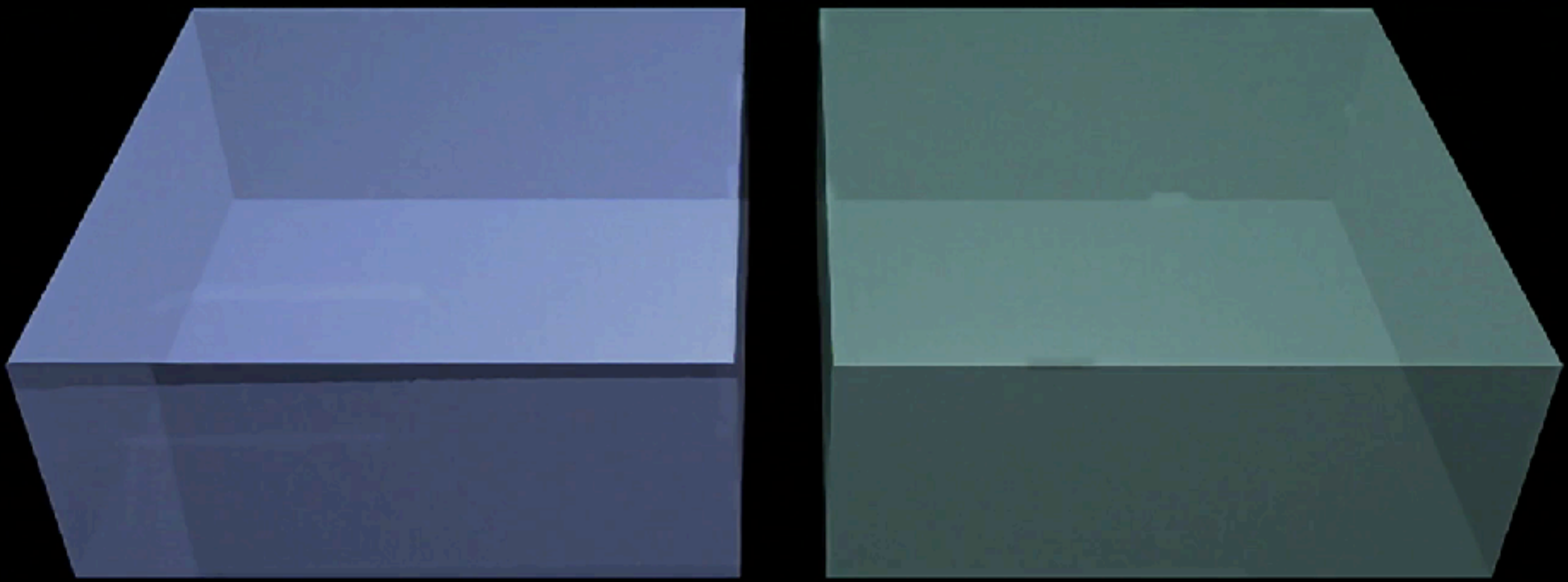

WMAP Collaboration
Amplitude of Waves [μK²]
Long Wavelength
Short Wavelength
TT
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

Power spectrum, explained

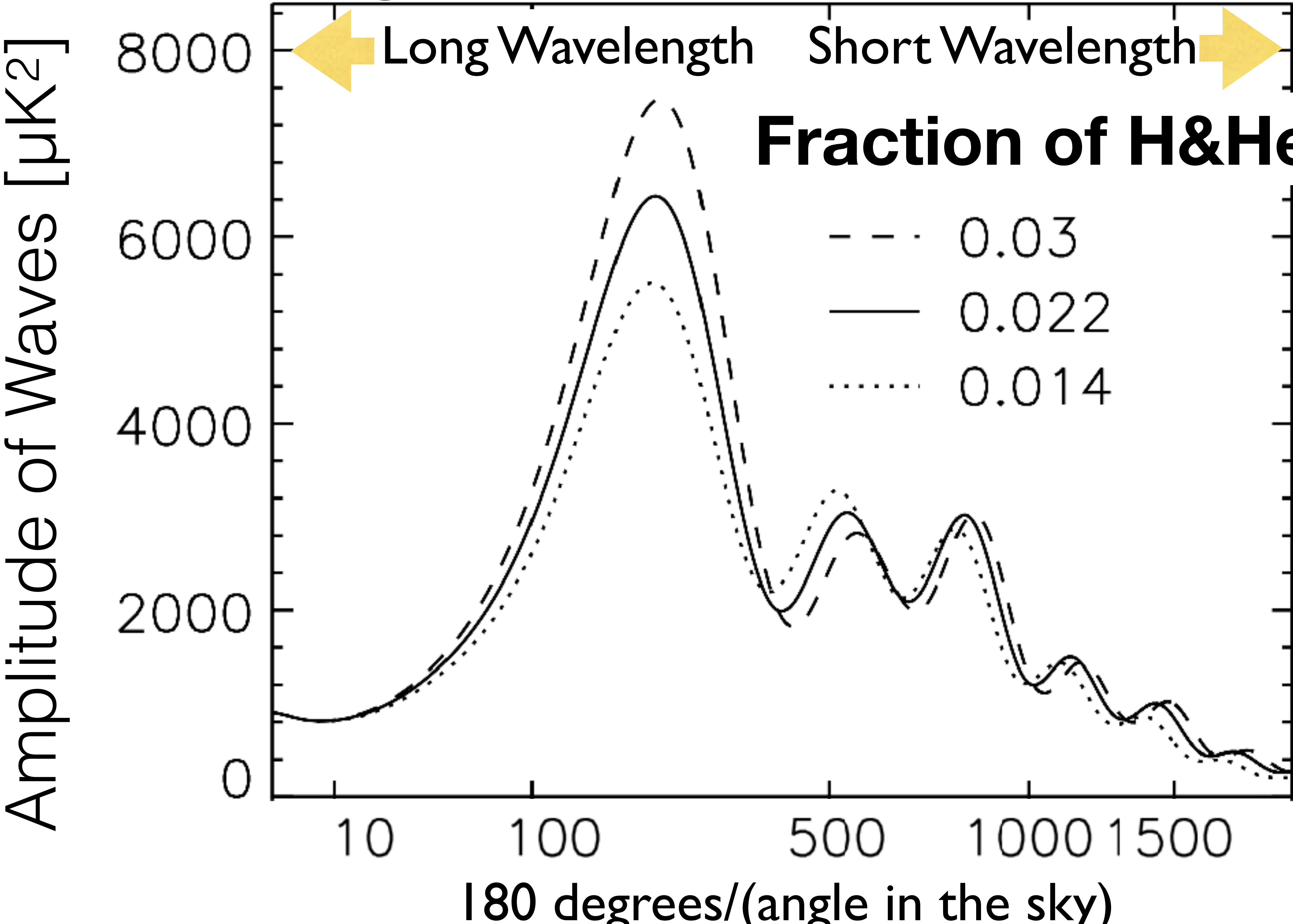


Kosmische Miso Suppe

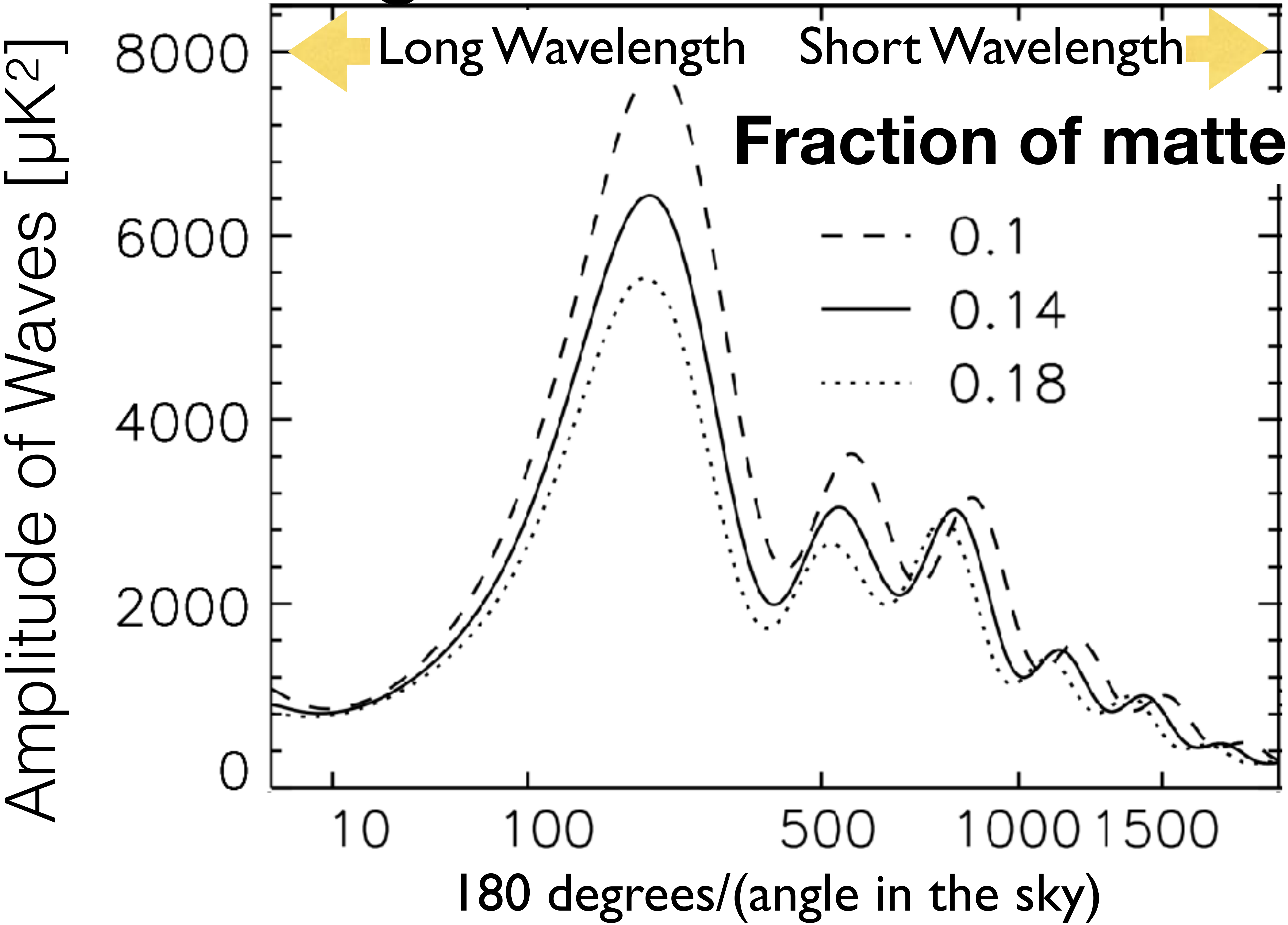
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching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



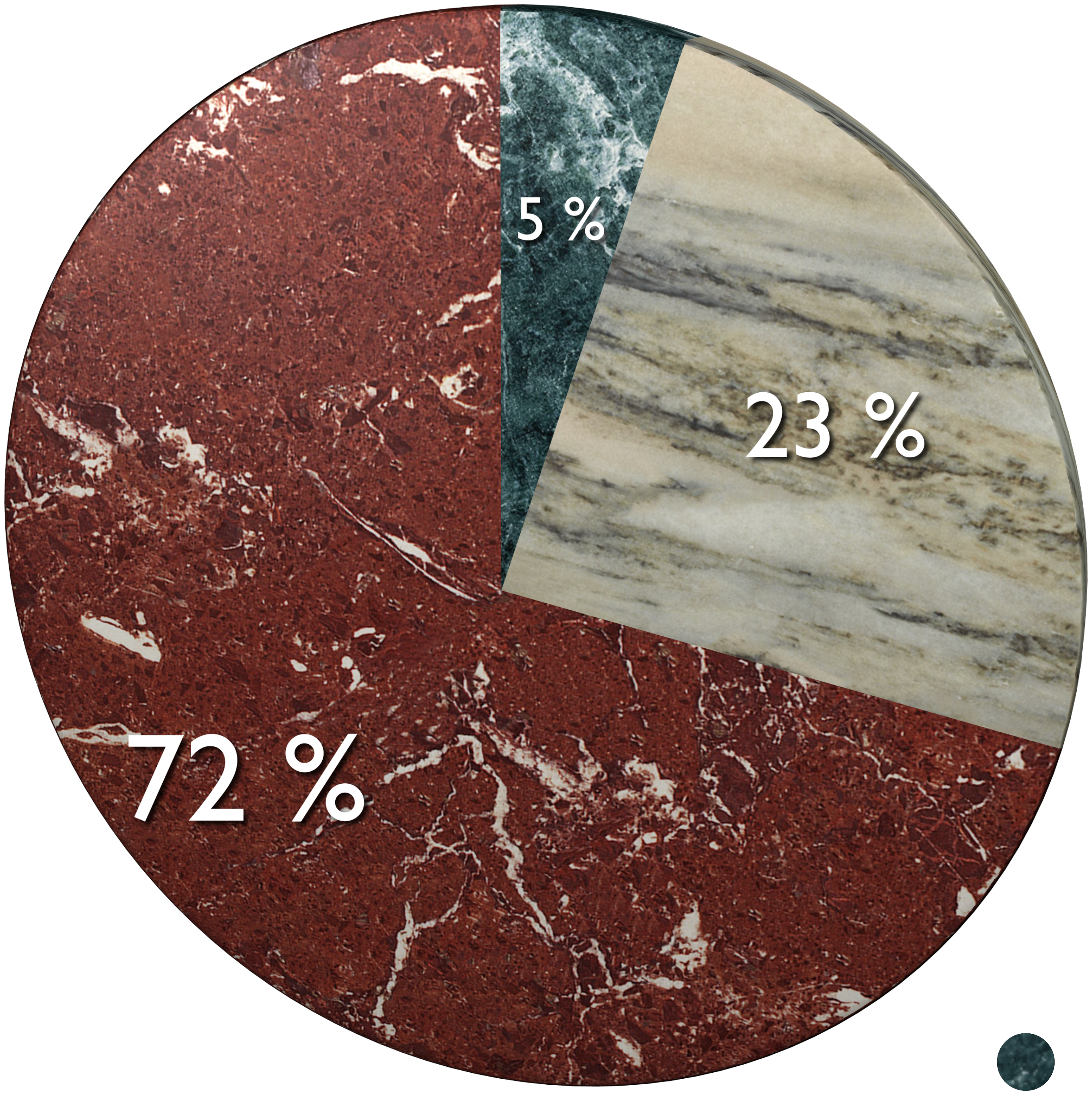
Measuring Abundance of H&He



Measuring ***Total*** Matter Density



Cosmic Pie Chart

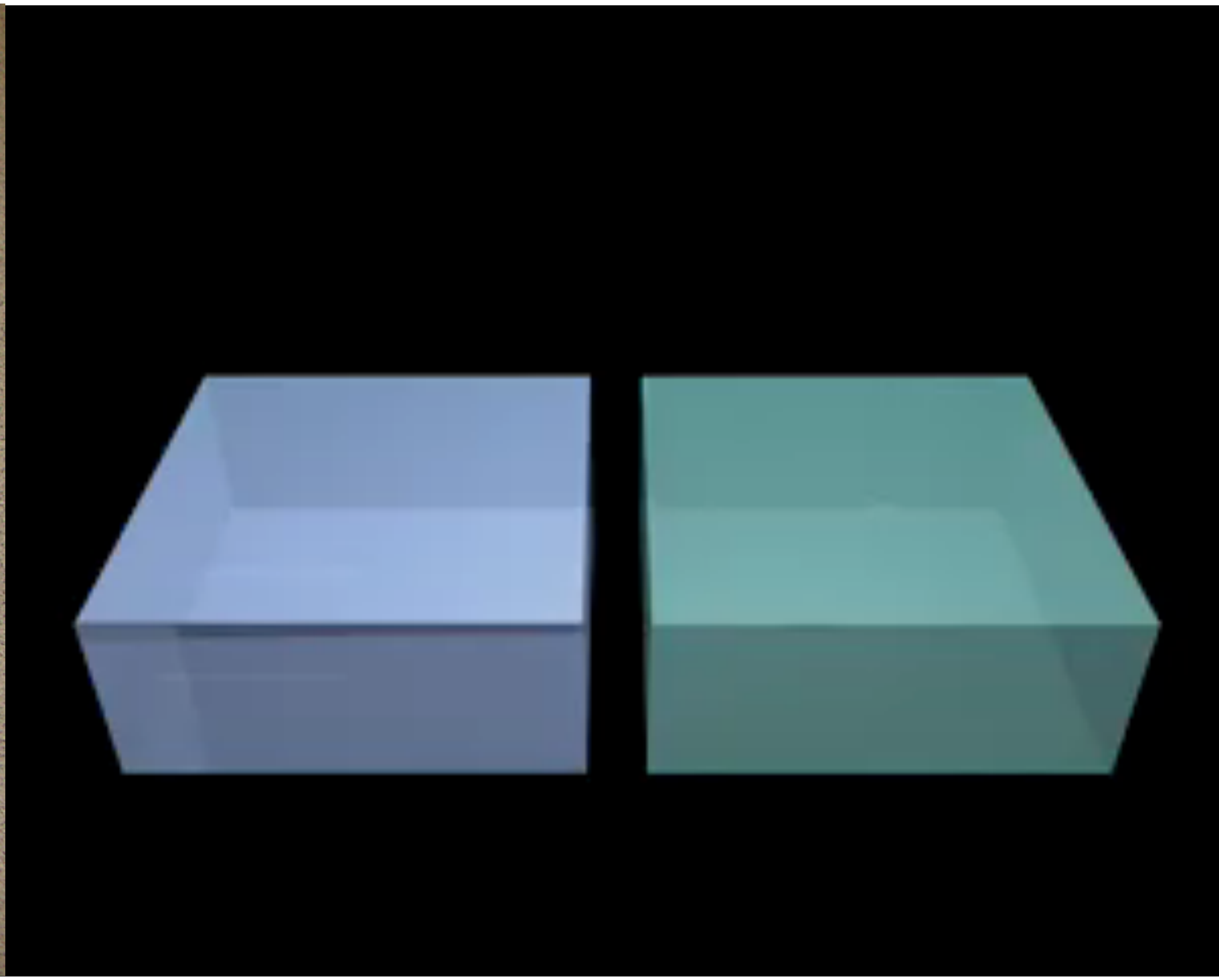


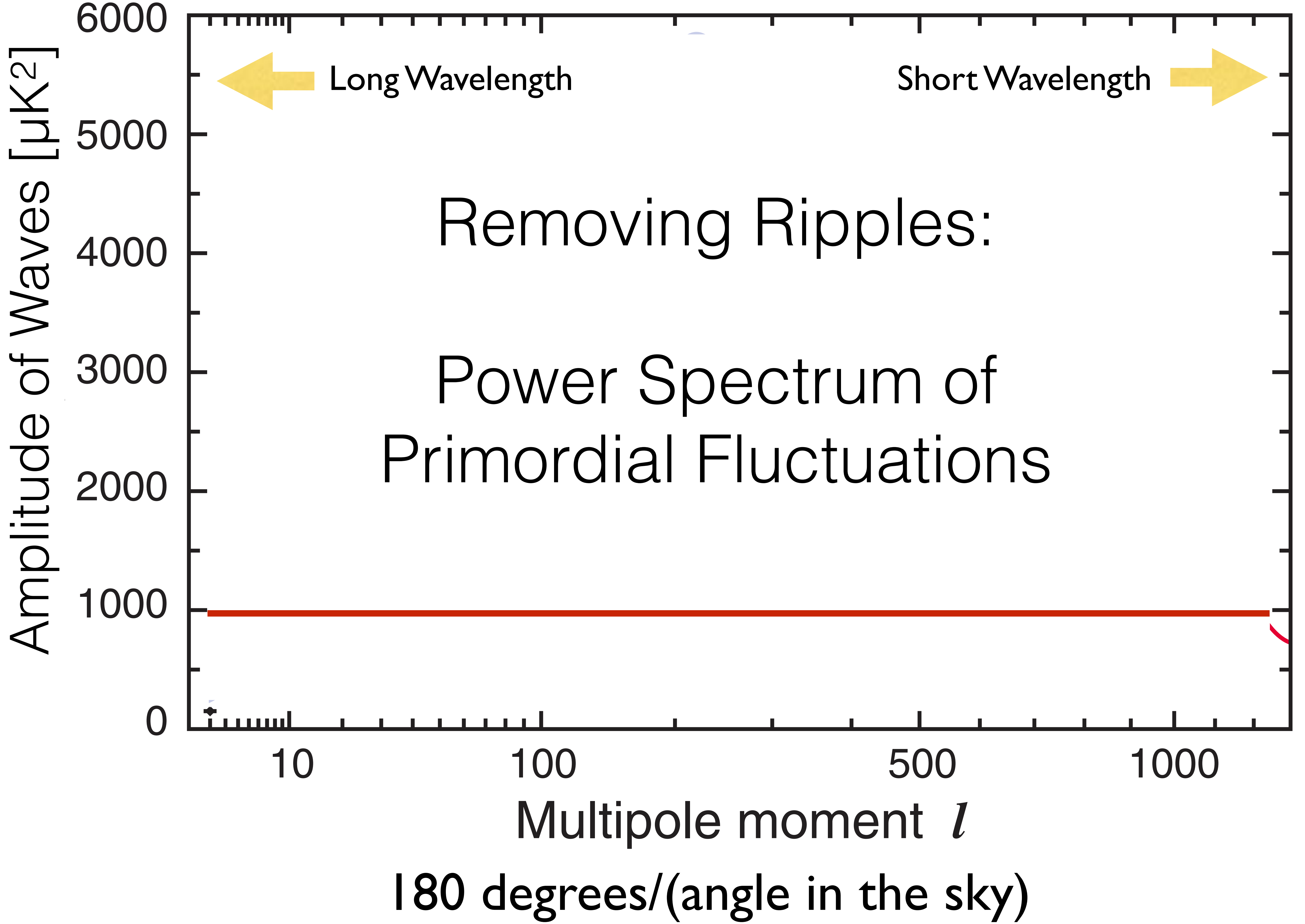
- WMAP determined the abundance of various components in the Universe
- As a result, **we came to realise that we do not understand 95% of our Universe...**

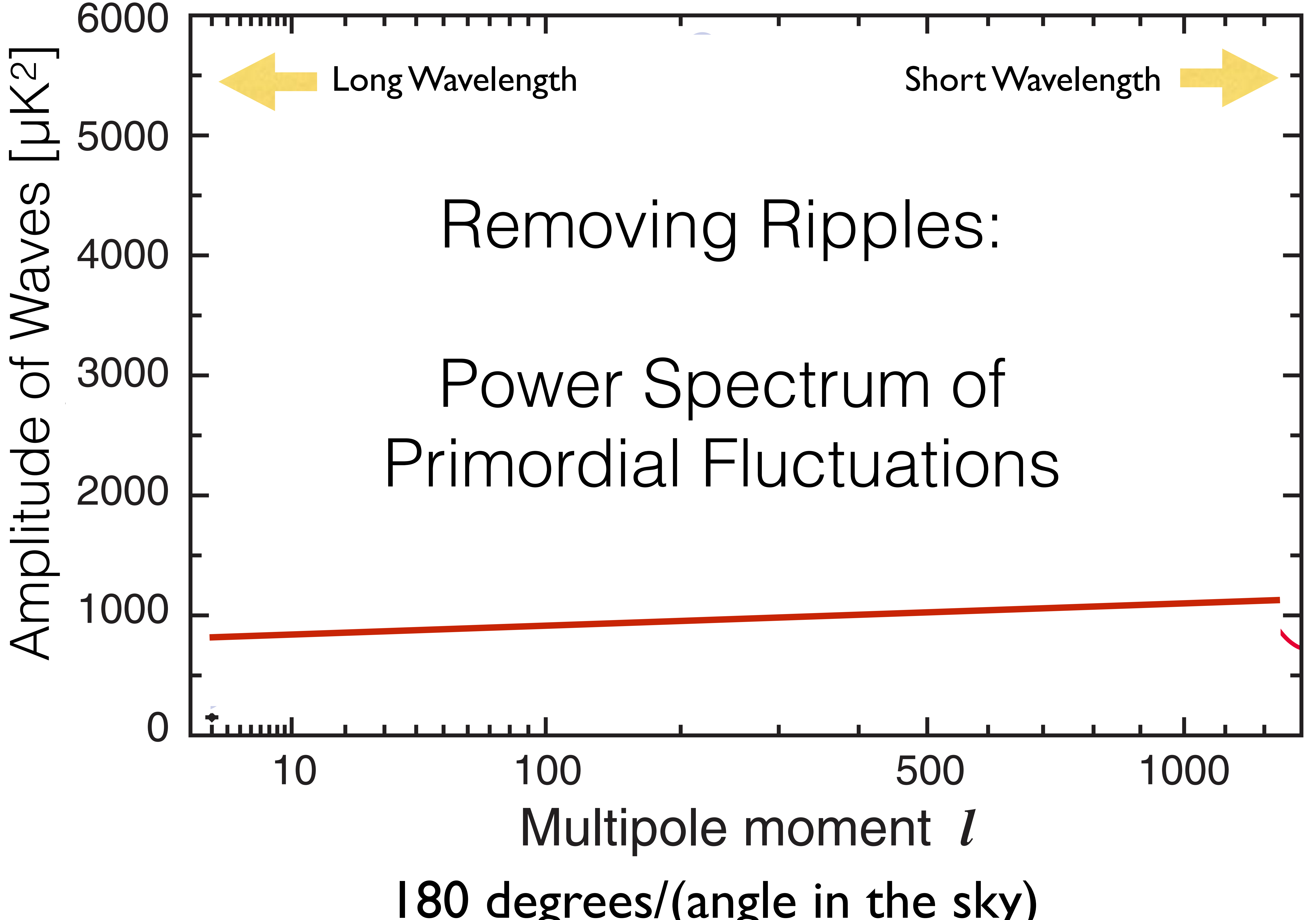
H&He
Dark Matter
Dark Energy

Origin of Fluctuations

- Who dropped those Tofus into the cosmic Miso soup?


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)


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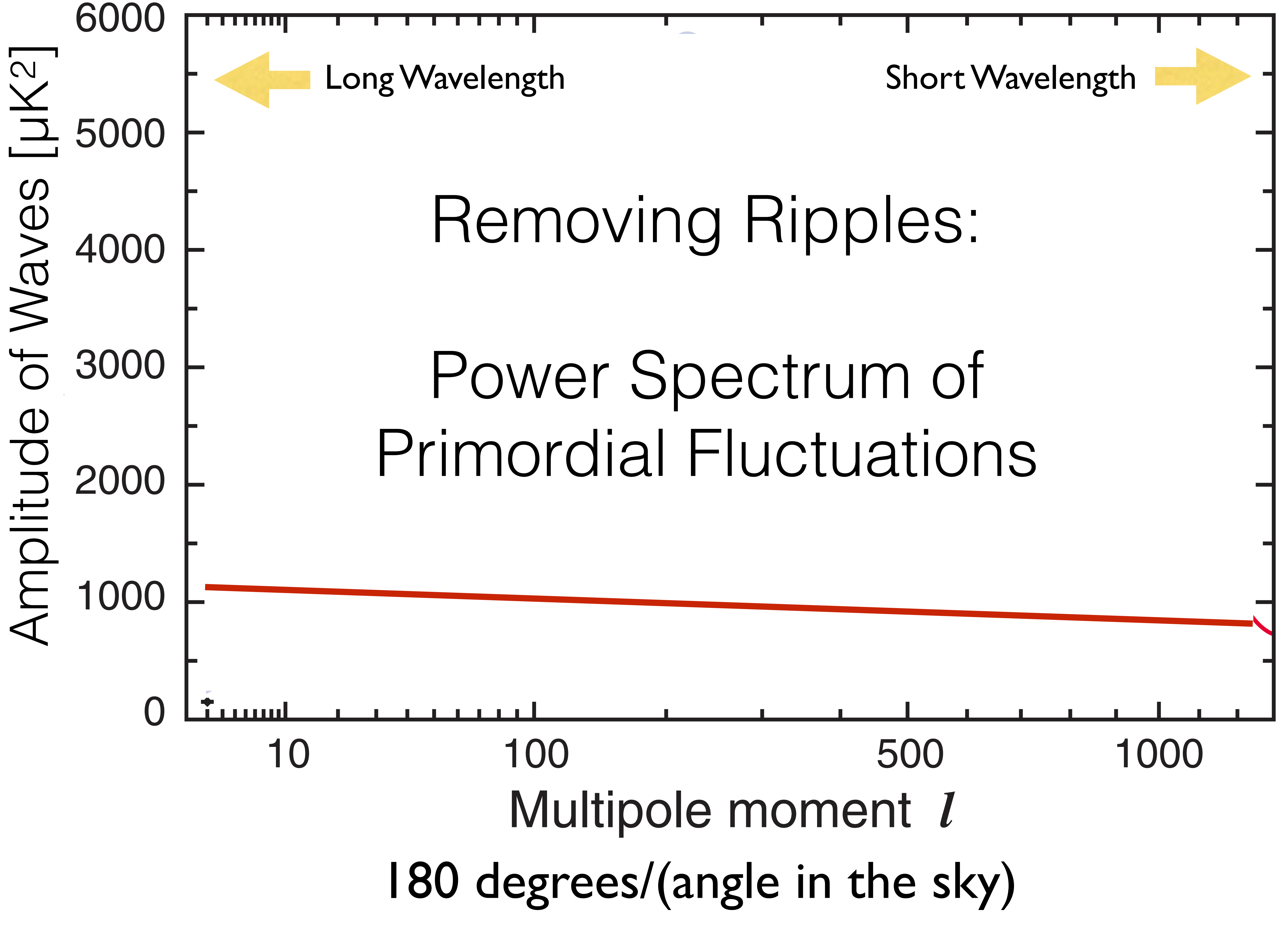
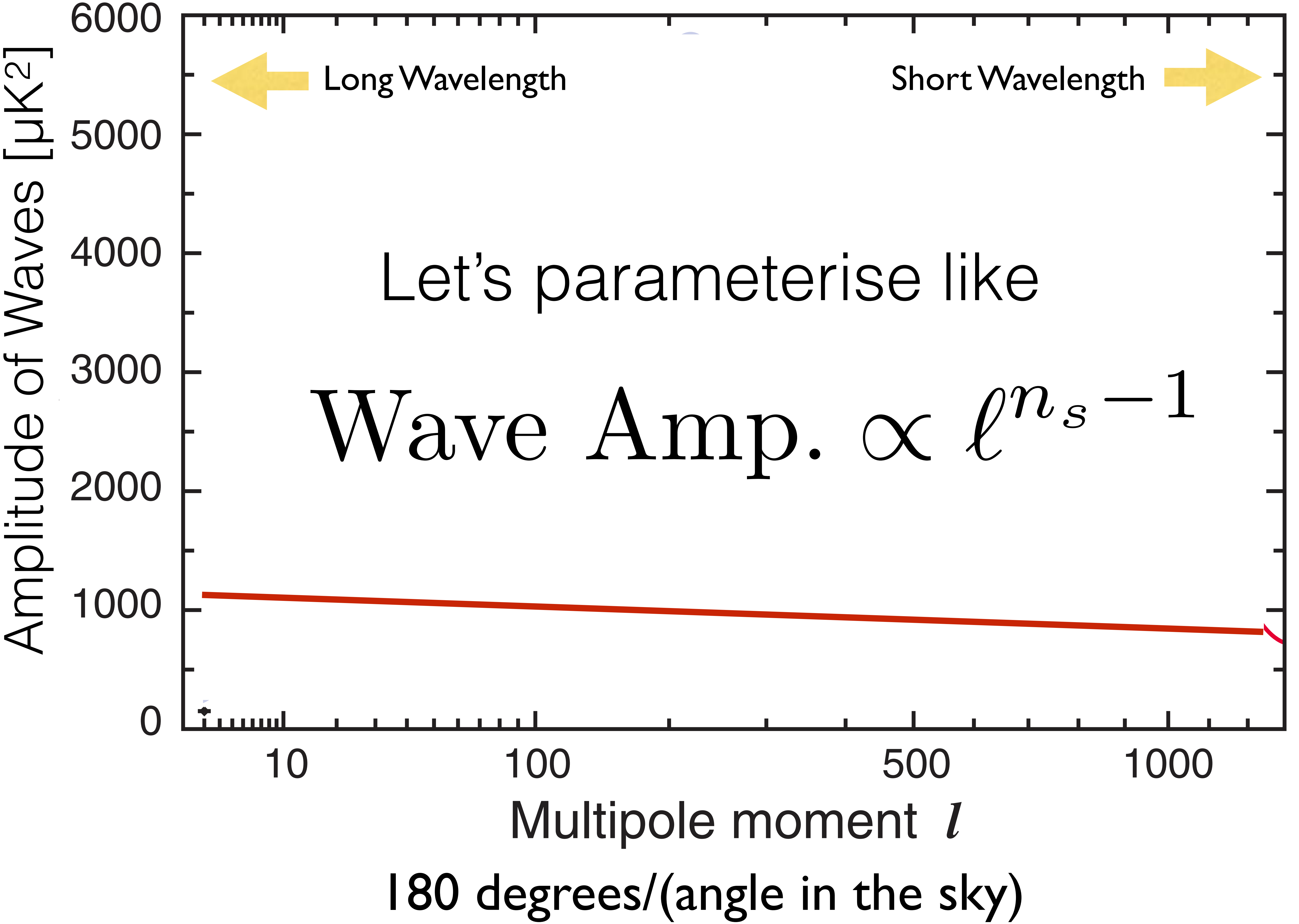
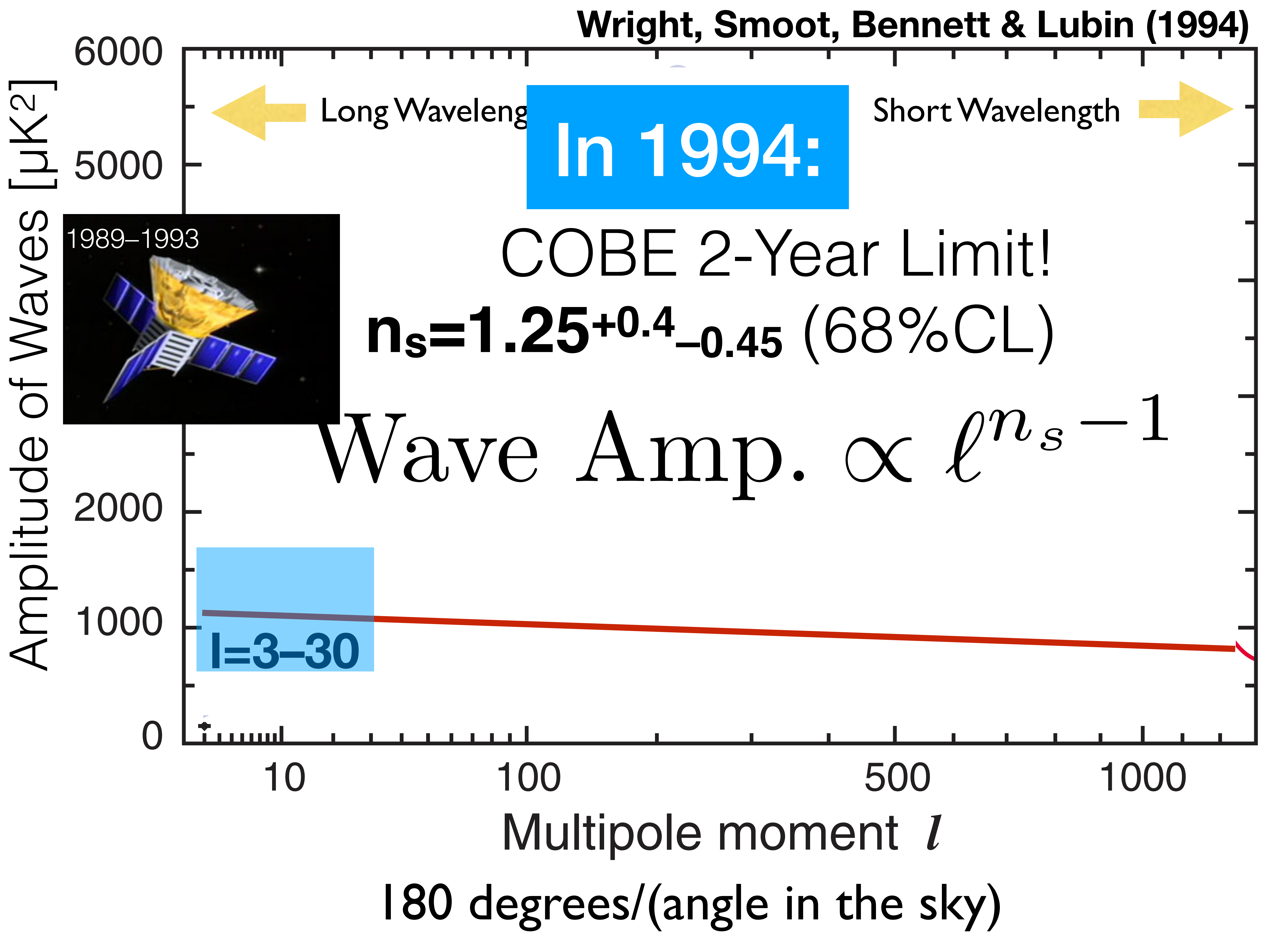
Multipole moment l
180 degrees/(angle in the sky)



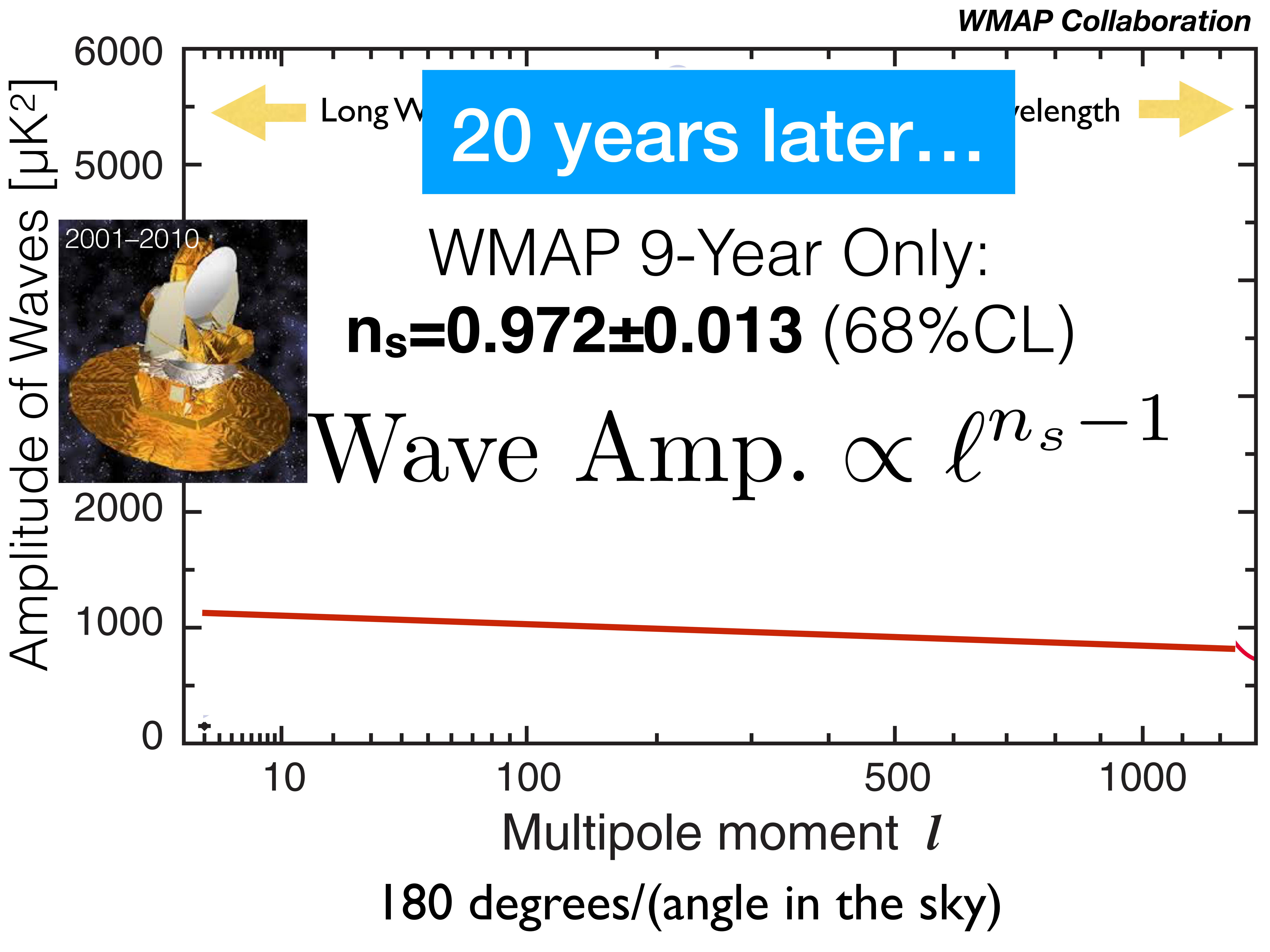
Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

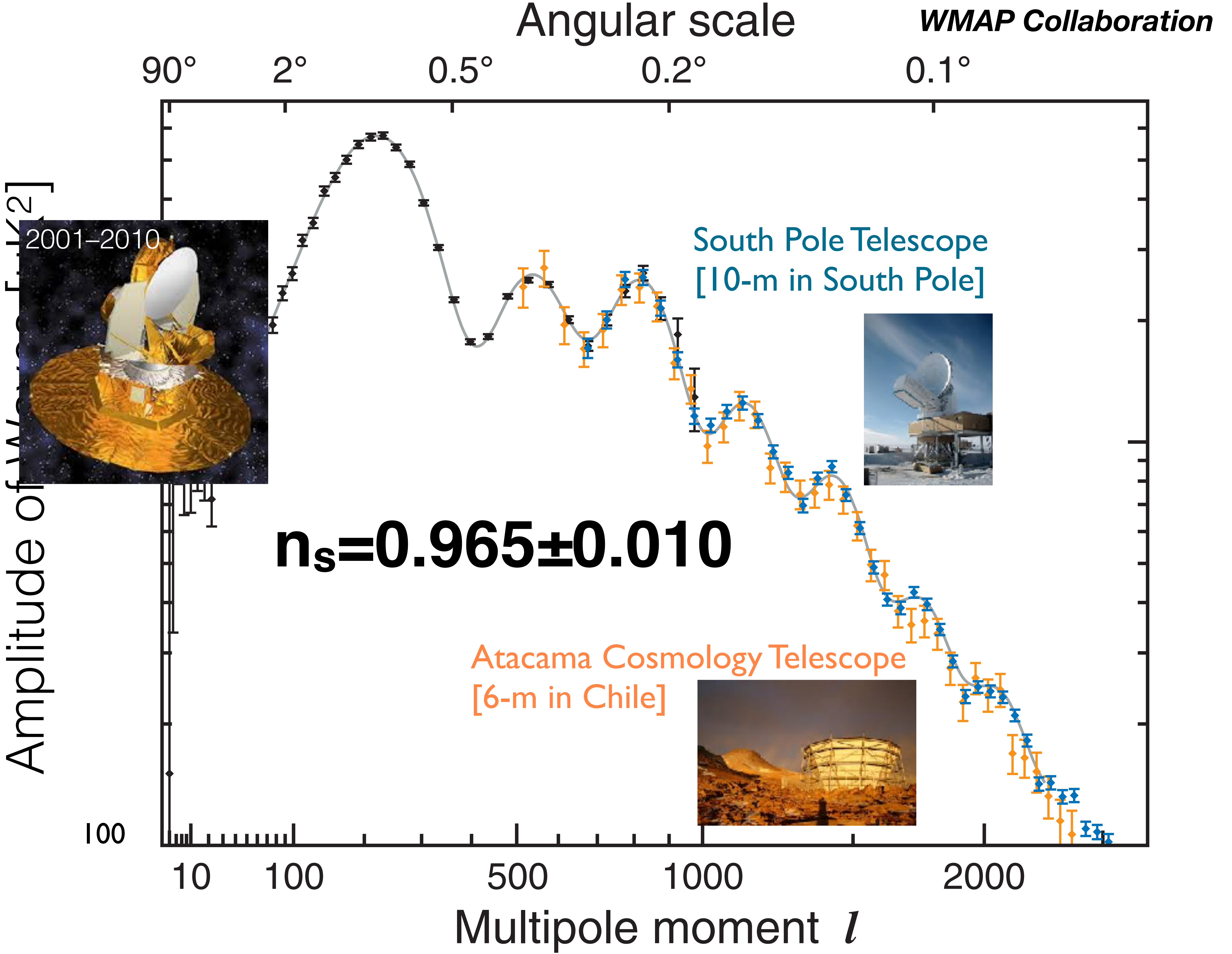


6000
5000
4000
3000
2000
1000
0
Amplitude of Waves [μK²]
Long Wavelength
Short Wavelength
Let's parameterise like
$\text{Wave Amp.} \propto \ell^{n_s - 1}$
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

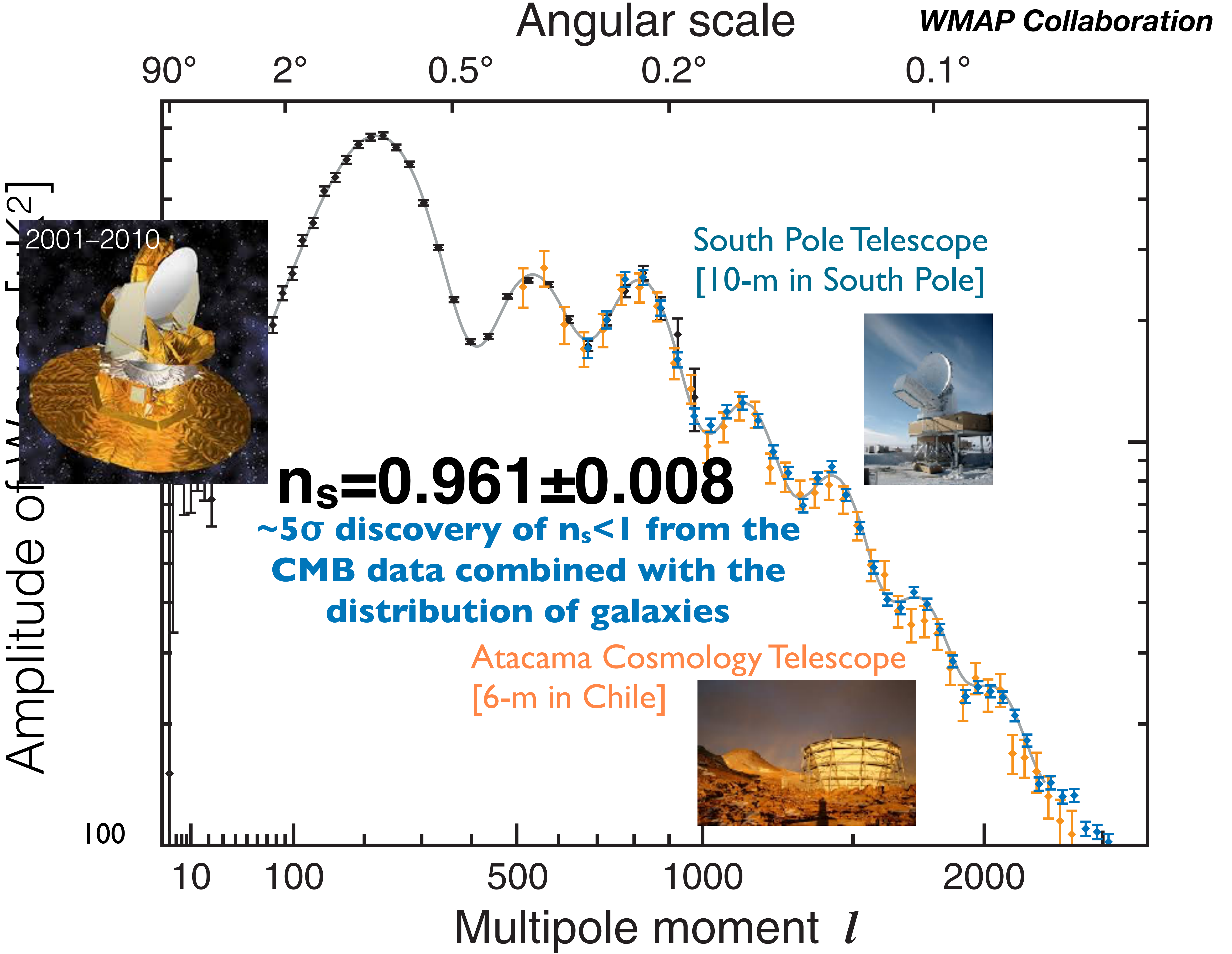


Wright, Smoot, Bennett & Lubin (1994)
In 1994:
Long Waveleng
Short Wavelength
1989–1993
COBE 2-Year Limit!
$n_s=1.25^{+0.4}_{-0.45}$ (68%CL)
$\text{Wave Amp.} \propto \ell^{n_s-1}$
l=3–30
Amplitude of Waves [μK²]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

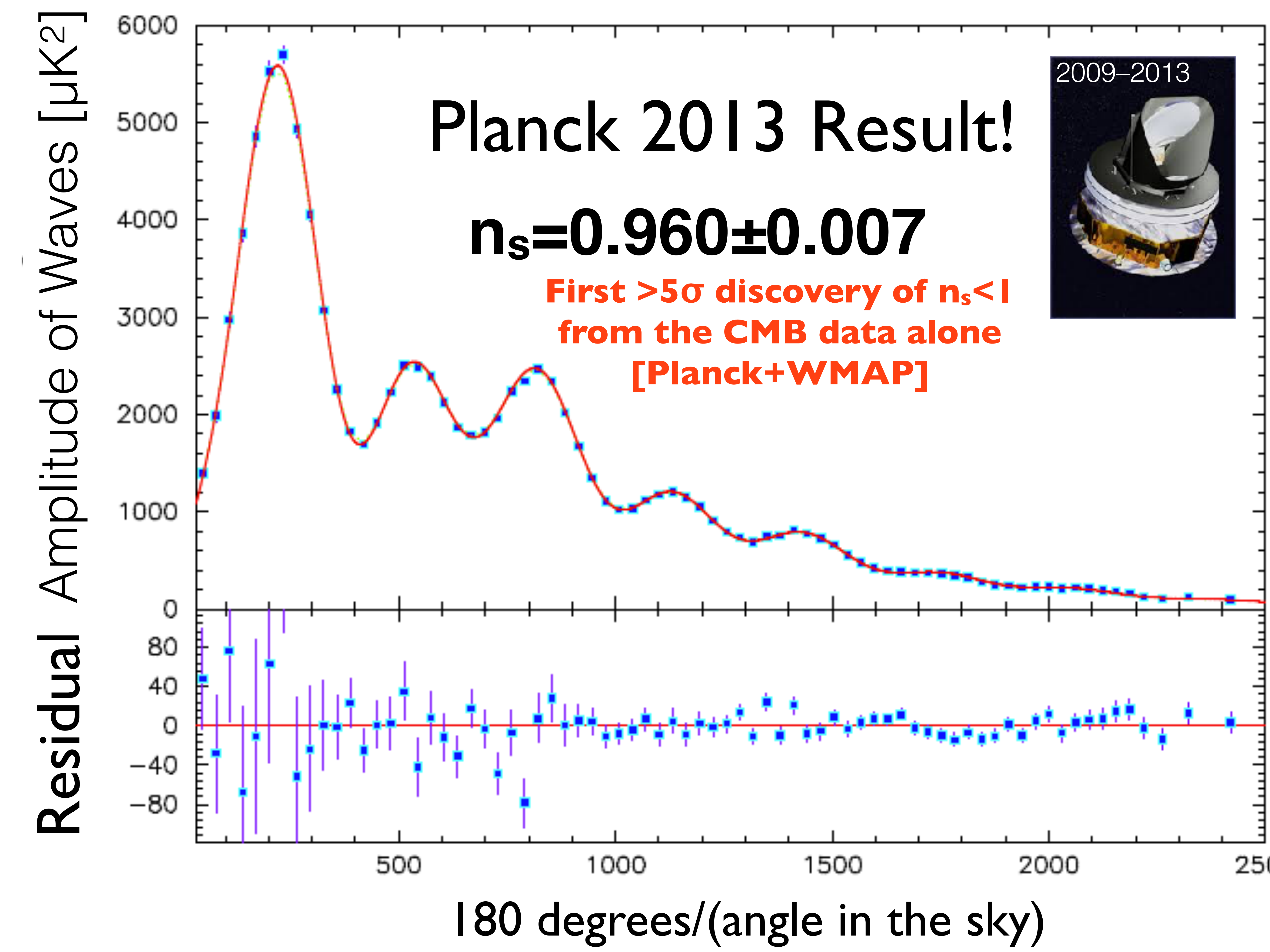

WMAP Collaboration
20 years later…
WMAP 9-Year Only:
$n_s = 0.972 \pm 0.013$ (68%CL)
$\text{Wave Amp.} \propto \ell^{n_s - 1}$
2001–2010
Long W
velength
Amplitude of Waves [μK^2]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



WMAP Collaboration
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]
n_s=0.965±0.010
Amplitude of
100
10
100
500
1000
2000
Multipole moment l

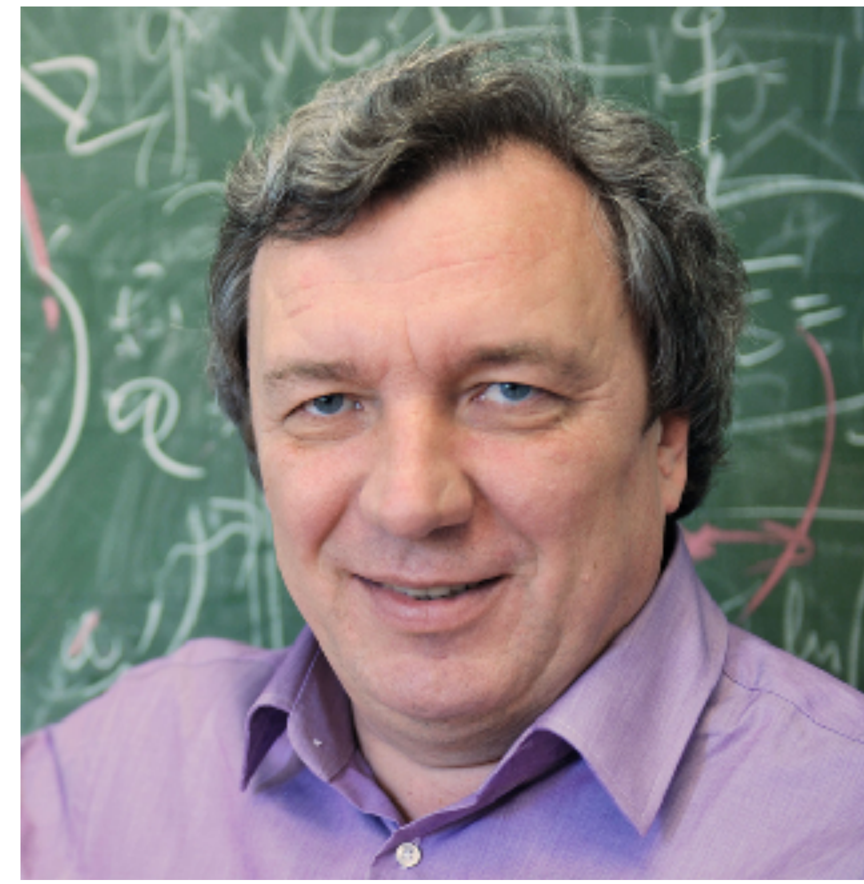


Angular scale
WMAP Collaboration
90°
2°
0.5°
0.2°
0.1°
Amplitude of Waves [μK^2]
2001–2010
South Pole Telescope
[10-m in South Pole]
ns=0.961±0.008
~5σ discovery of ns<1 from the CMB data combined with the distribution of galaxies
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole 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 [μK^2]
6000
5000
4000
3000
2000
1000
0
Residual
80
40
0
−40
−80
500
1000
1500
2000
180 degrees/(angle in the sky)

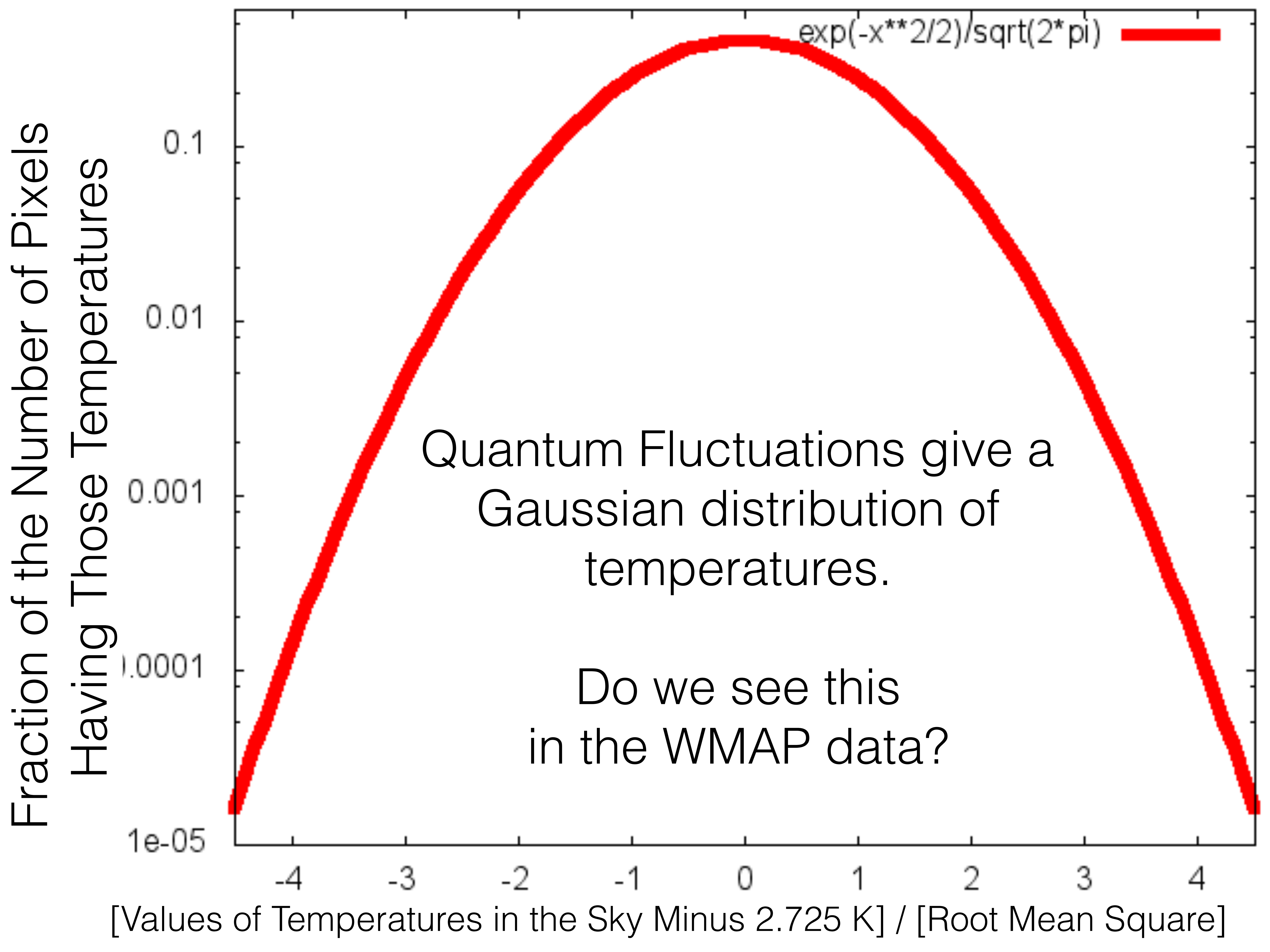
Predicted in 1981.
Finally discovered in 2013
by WMAP and Planck

- 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 $n_s \sim 1 (\pm 0.4)$ was indicated

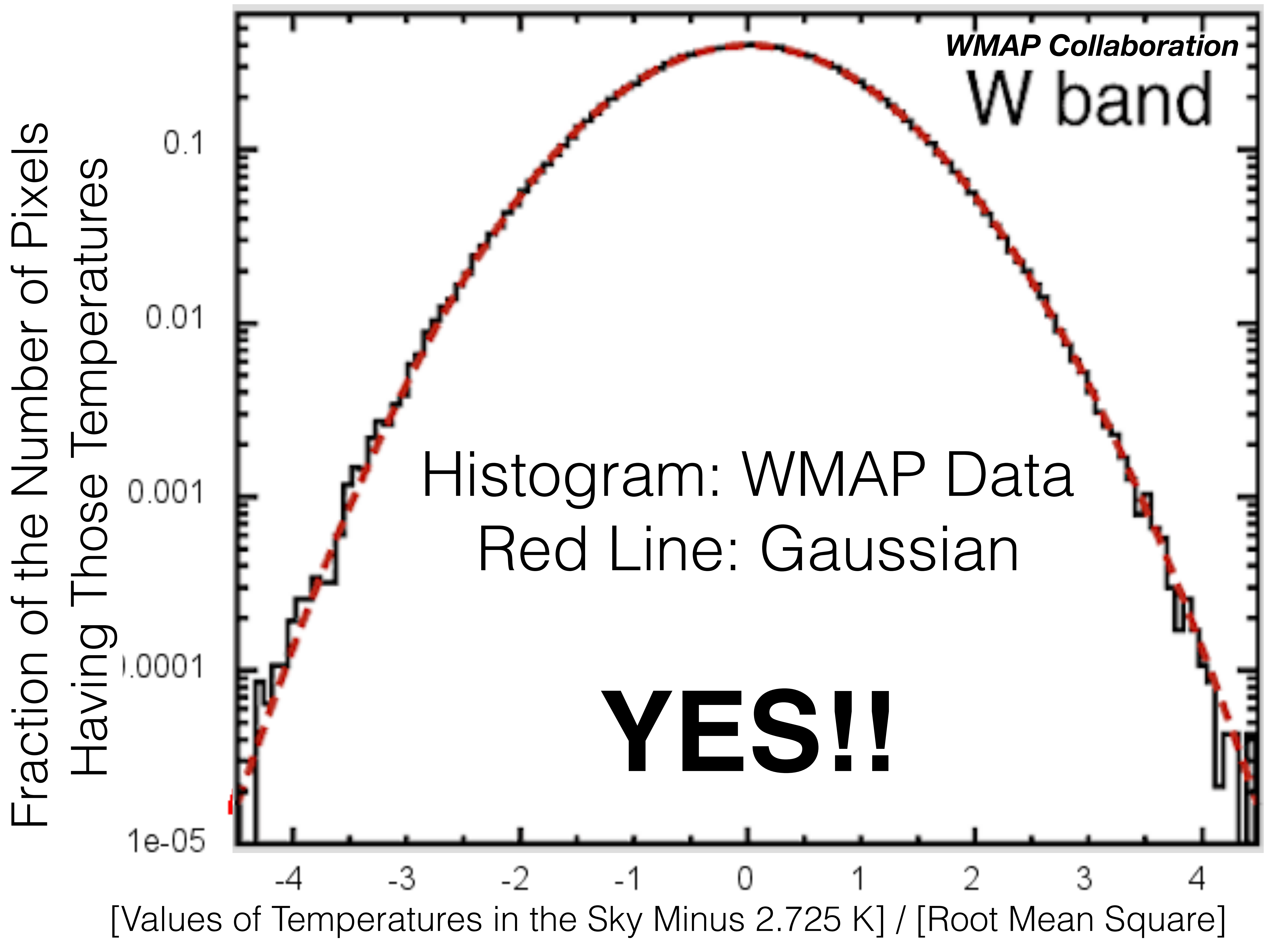


Slava Mukhanov (LMU) said in his 1981 paper that n_s should be less than 1

He was awarded
Max Planck Medal in 2015

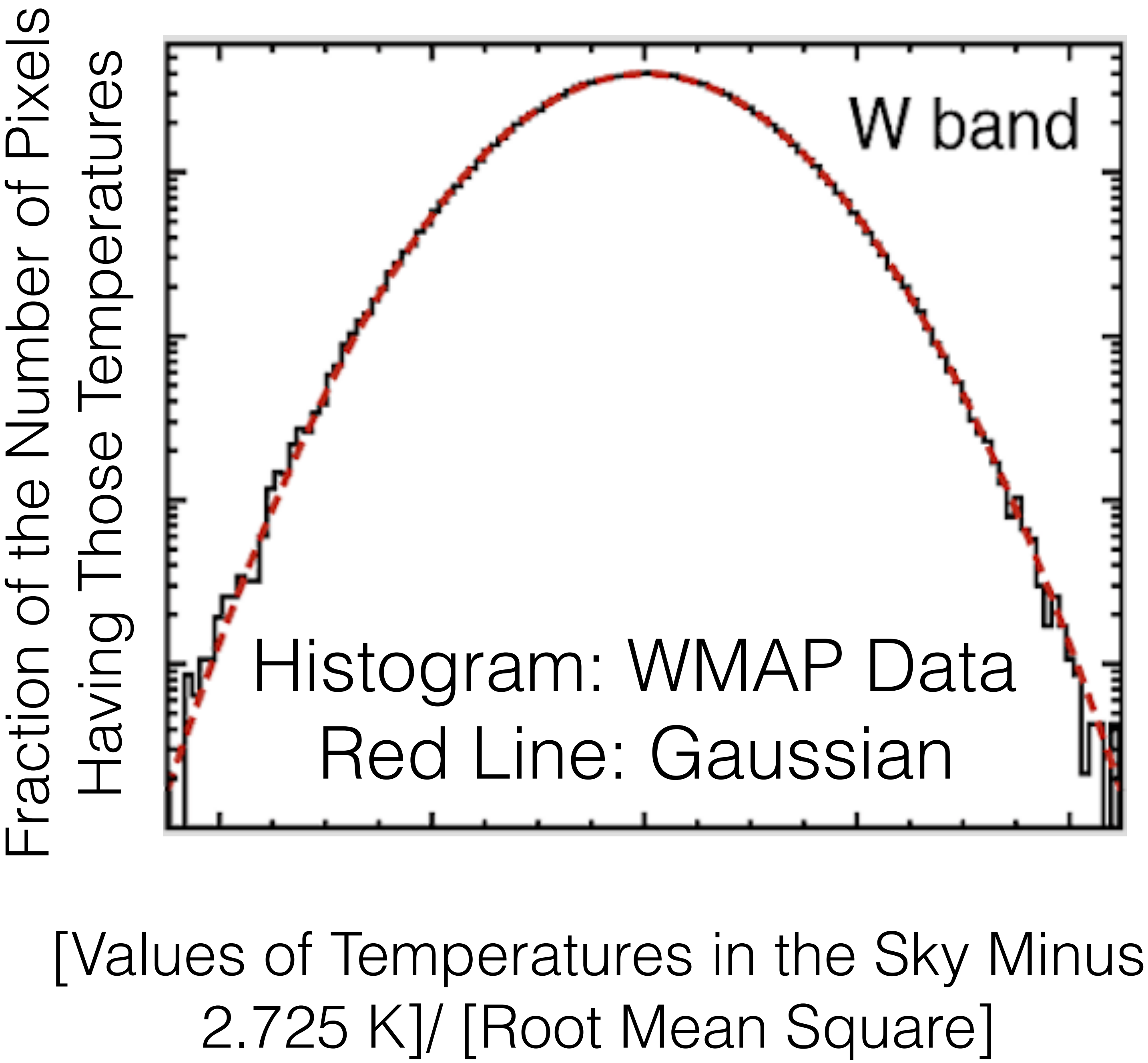


exp(-x**2/2)/sqrt(2*pi)
Fraction of the Number of Pixels
Having Those Temperatures
0.1
0.01
0.001
0.0001
1e-05
-4
-3
-2
-1
0
1
2
3
4
[Values of Temperatures in the Sky Minus 2.725 K] / [Root Mean Square]
Quantum Fluctuations give a
Gaussian distribution of
temperatures.
Do we see this
in the WMAP data?



WMAP Collaboration
W band
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]
Histogram: WMAP Data
Red Line: Gaussian
YES!!

Testing Gaussianity



- 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 by averaging the product of temperatures at three different locations in the sky

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

Lack of non-Gaussianity

- 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%** (95%CL)

$$\zeta(\mathbf{x}) = \zeta_{\rm gaus}(\mathbf{x}) + \frac{3}{5} f_{\rm NL} \zeta^2_{\rm gaus}(\mathbf{x})$$ **with** $$f_{\rm NL} = 37 \pm 20 \ (68\% \ {\rm CL})$$

WMAP 9-year Result

- The Planck data improved the upper bound by an order of magnitude: deviation is <**0.03%** (95%CL)

$$f_{\rm NL} = 0.8 \pm 5.0 \ (68\% \ {\rm CL})$$

Planck 2015 Result

So, have we found inflation?

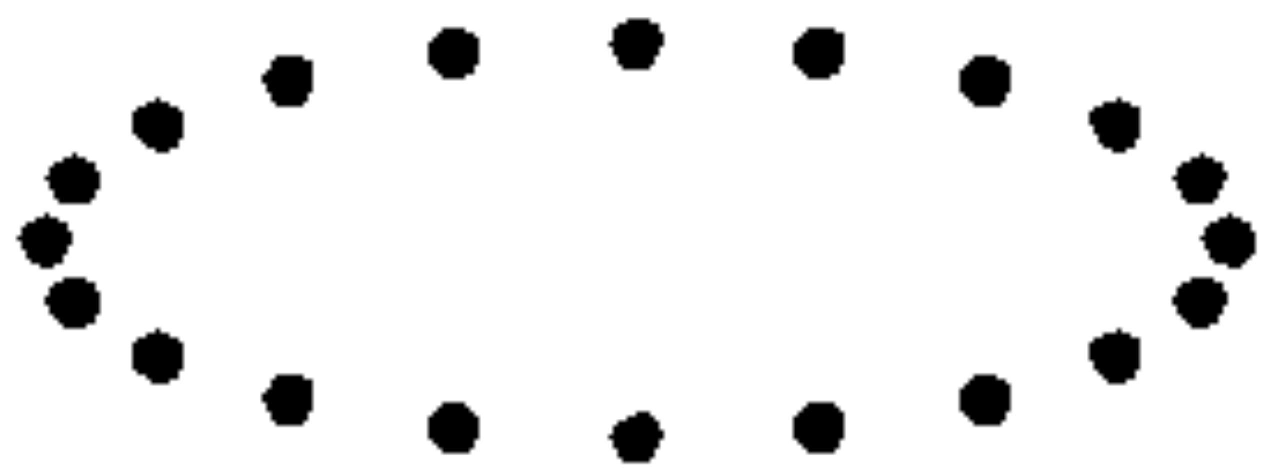
- Single-field slow-roll inflation looks remarkably good:
  - **Super-horizon fluctuation**
  - **Adiabaticity**
  - **Gaussianity**
  - **$n_s<1$**
- What more do we want? **Gravitational waves**. Why?
  - Because the "*extraordinary claim requires extraordinary evidence*"

Measuring GW

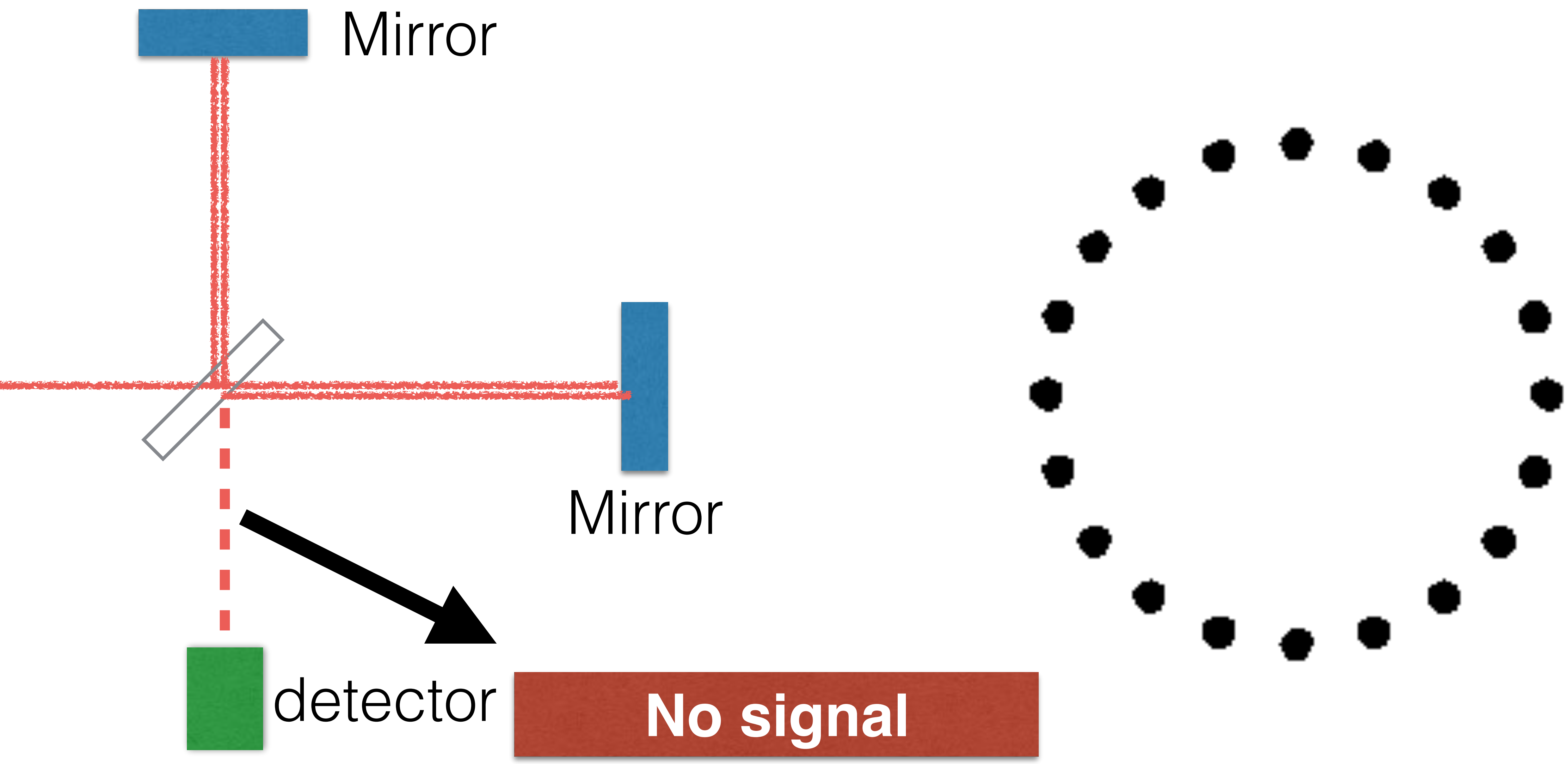
- GW changes distances between two points

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

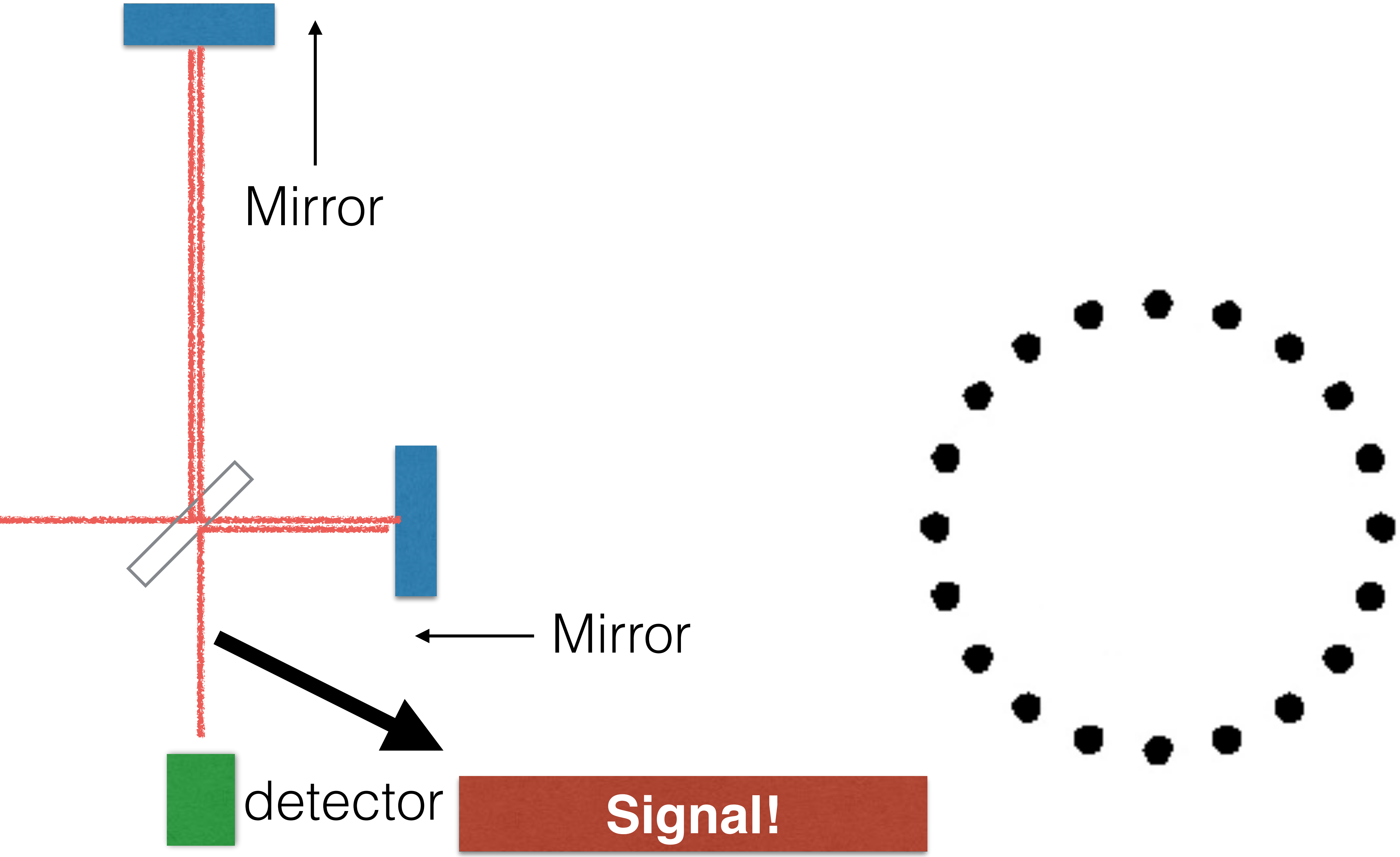
$$d\ell^2 = \sum_{ij} (\delta_{ij} + h_{ij}) dx^i dx^j$$



Laser Interferometer



Laser Interferometer



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

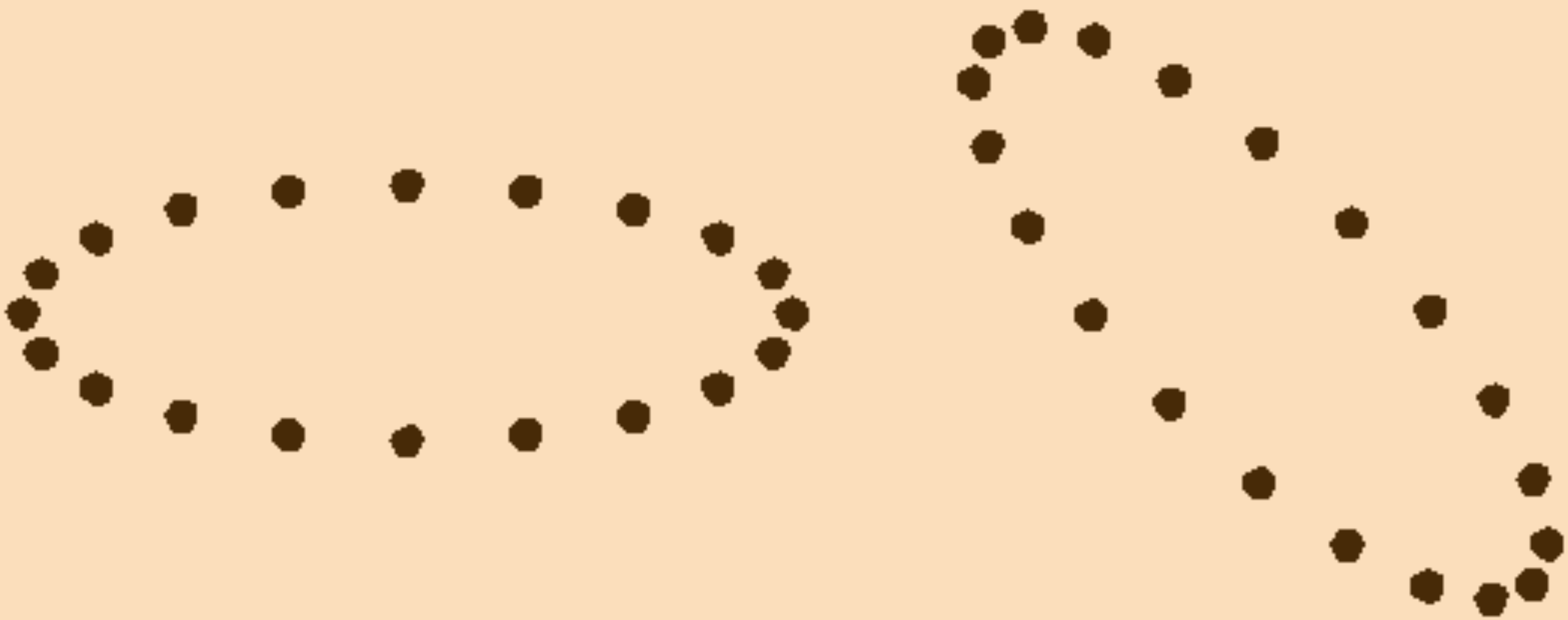
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

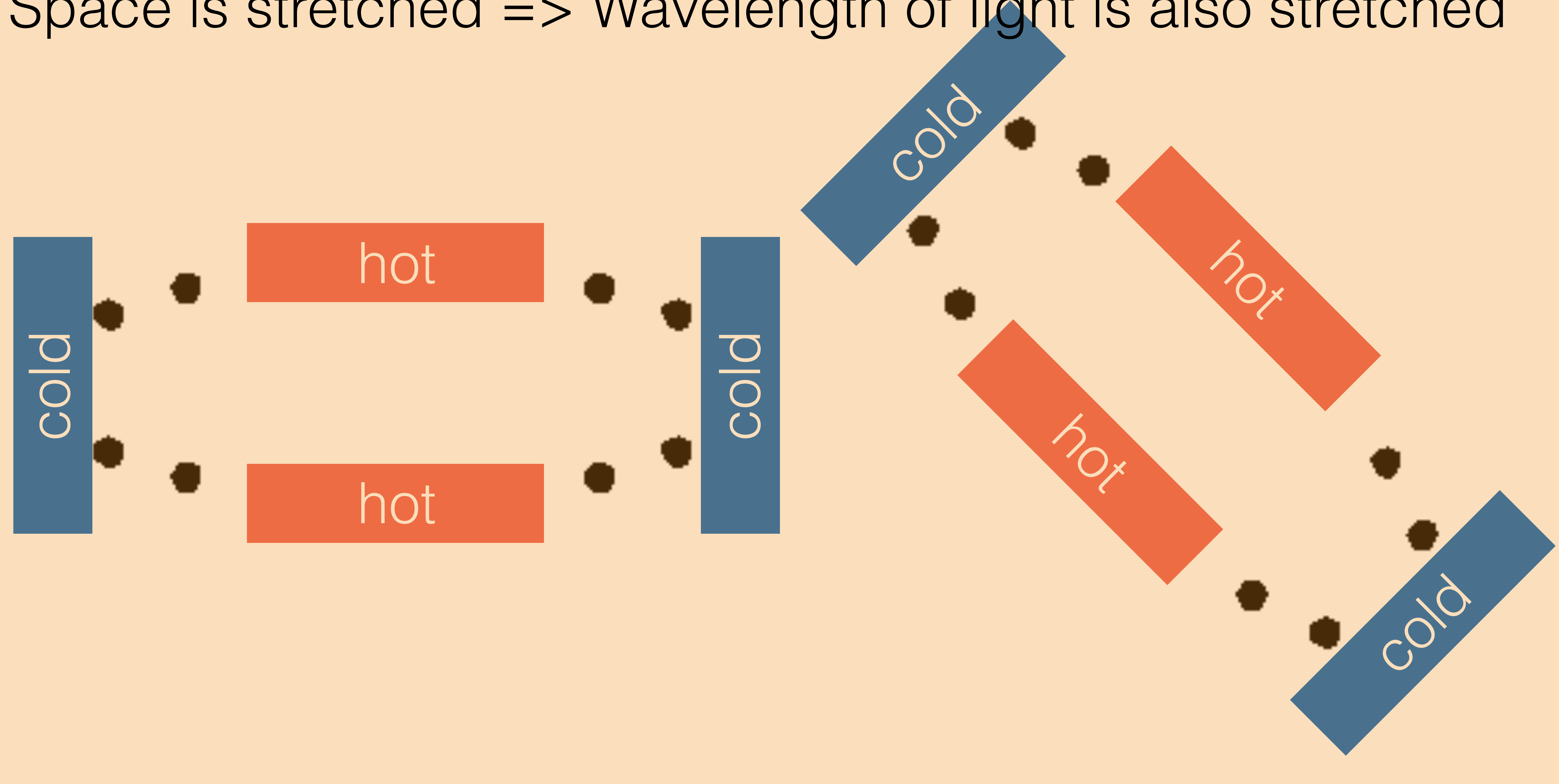
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



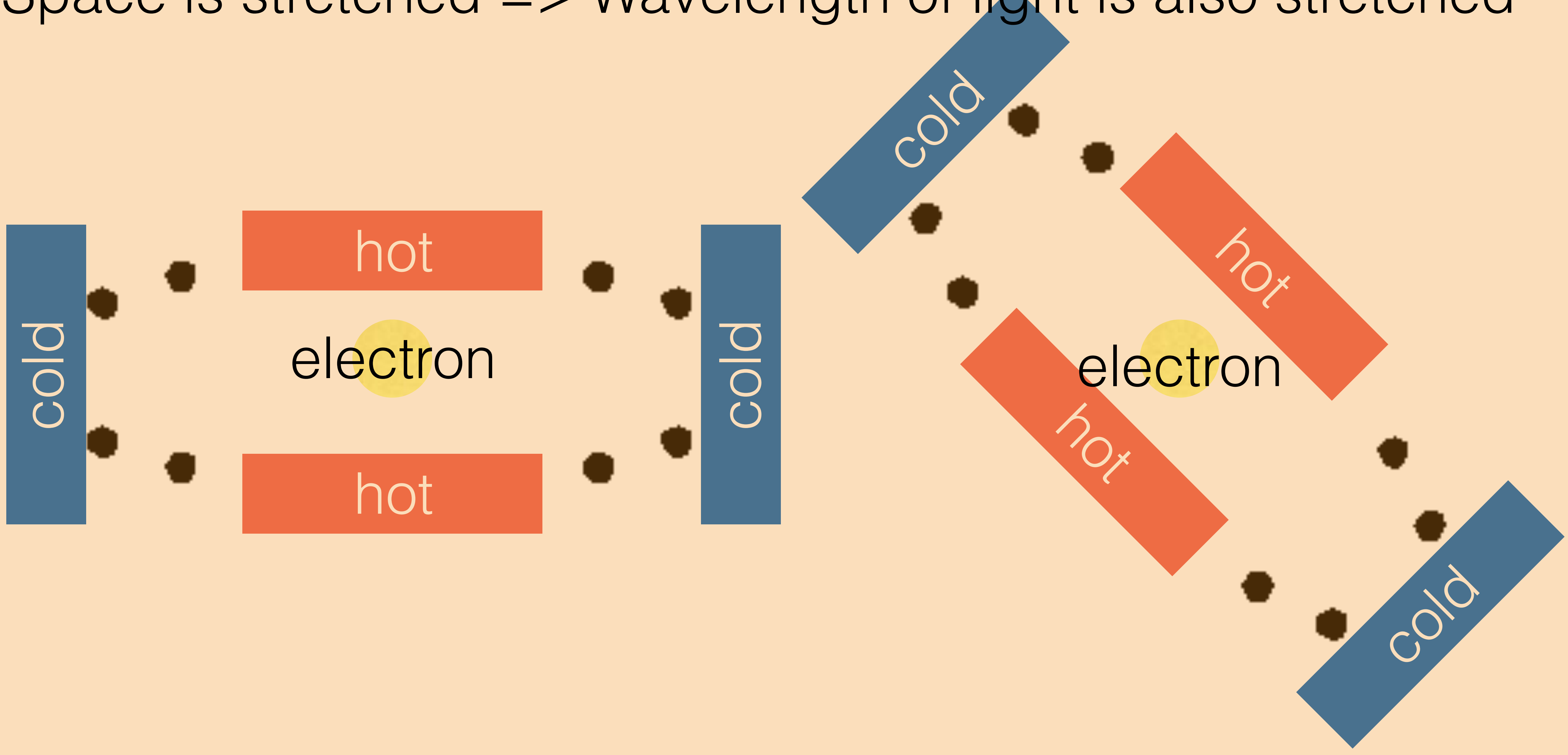
Detecting GW by CMB

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

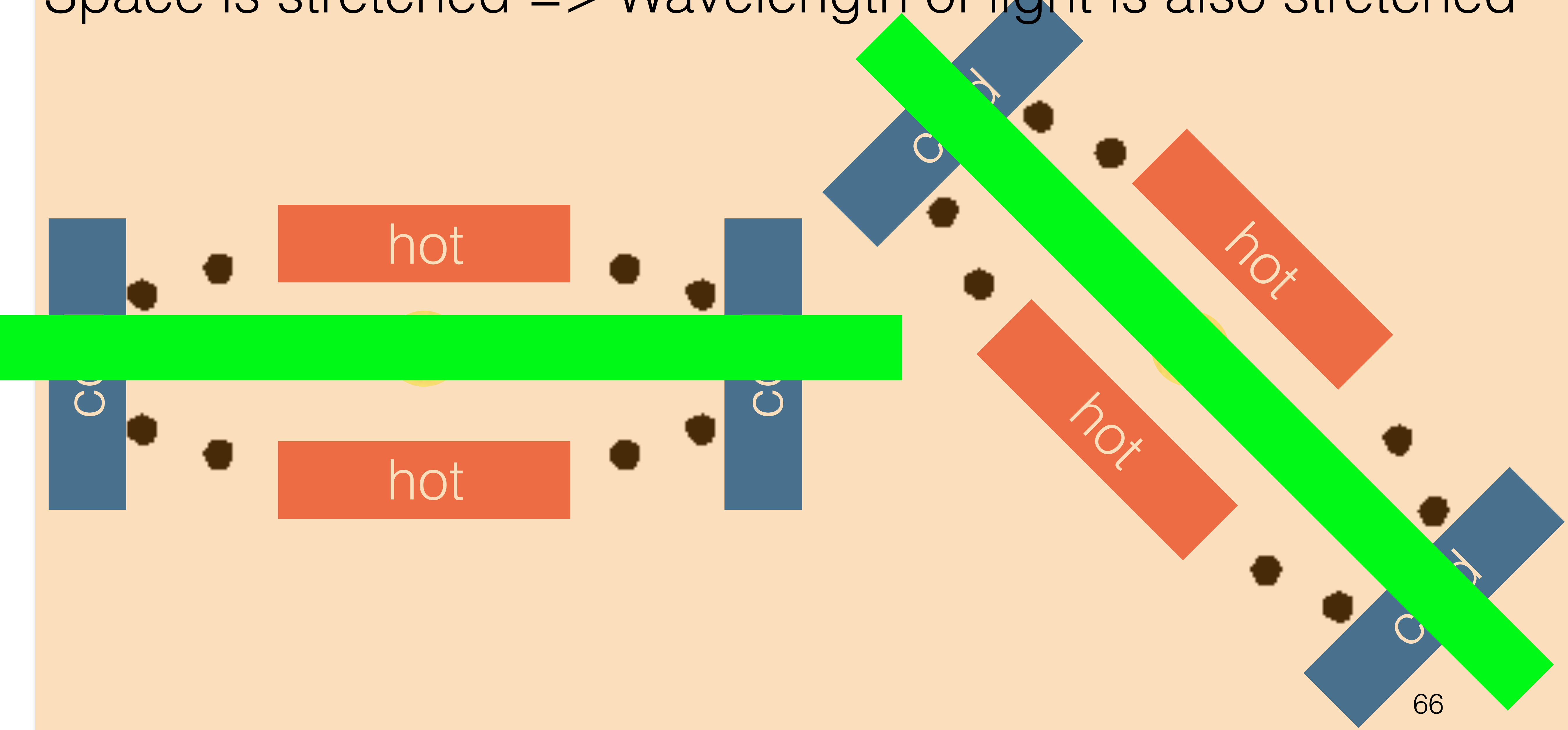



Photo Credit: TALEX
horizontally polarised

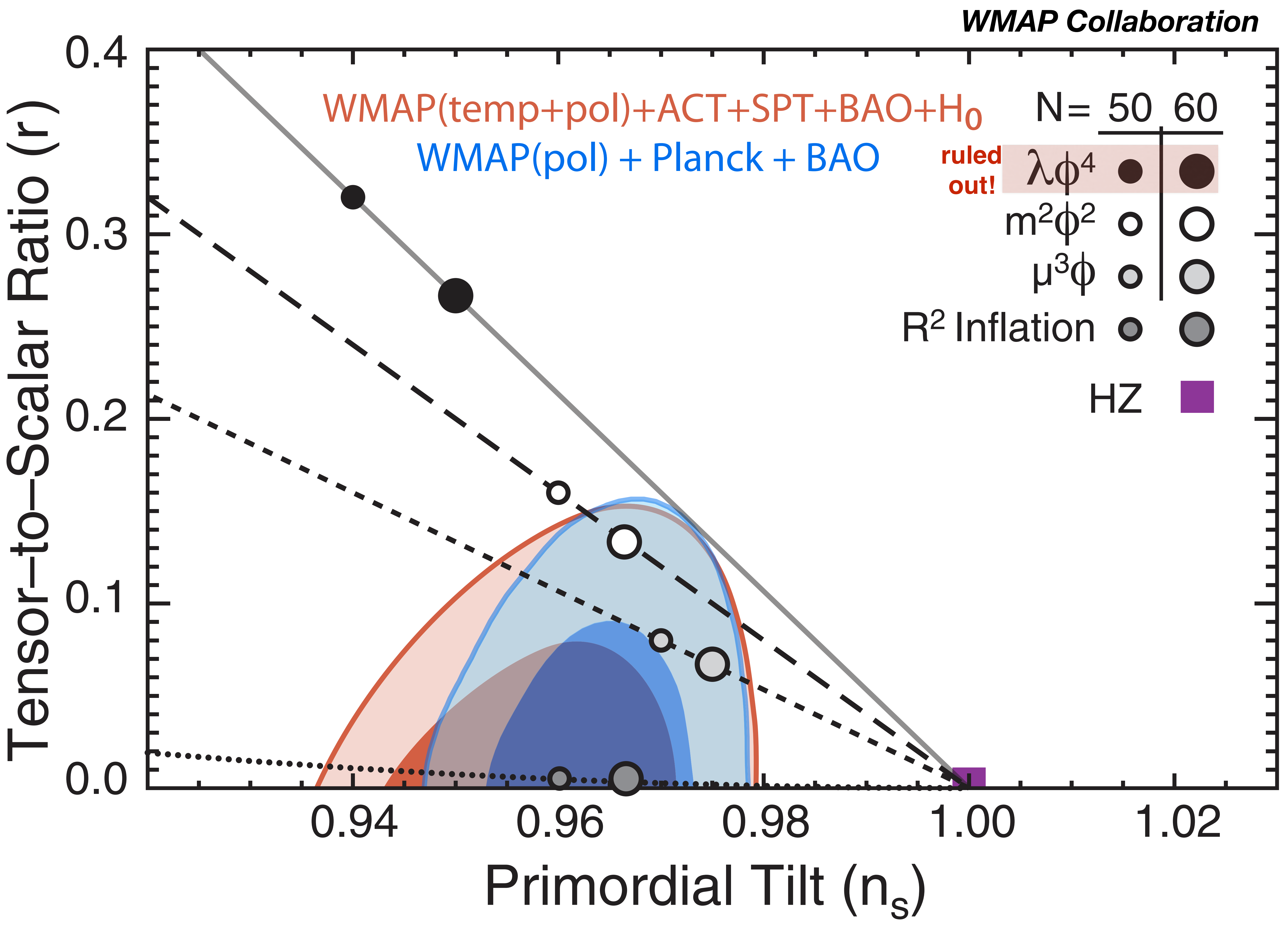
Photo Credit: TALEX

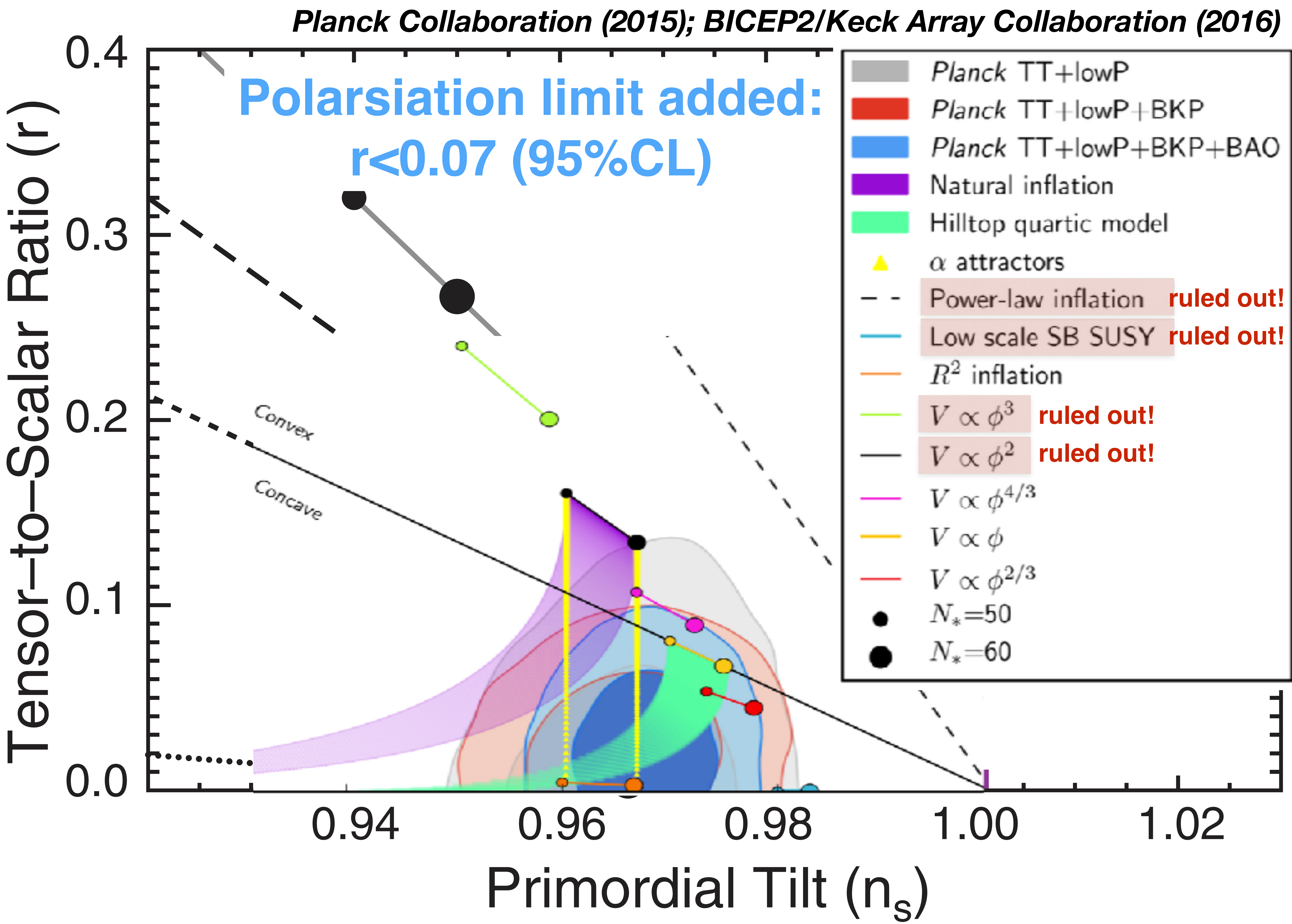
Tensor-to-scalar Ratio

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

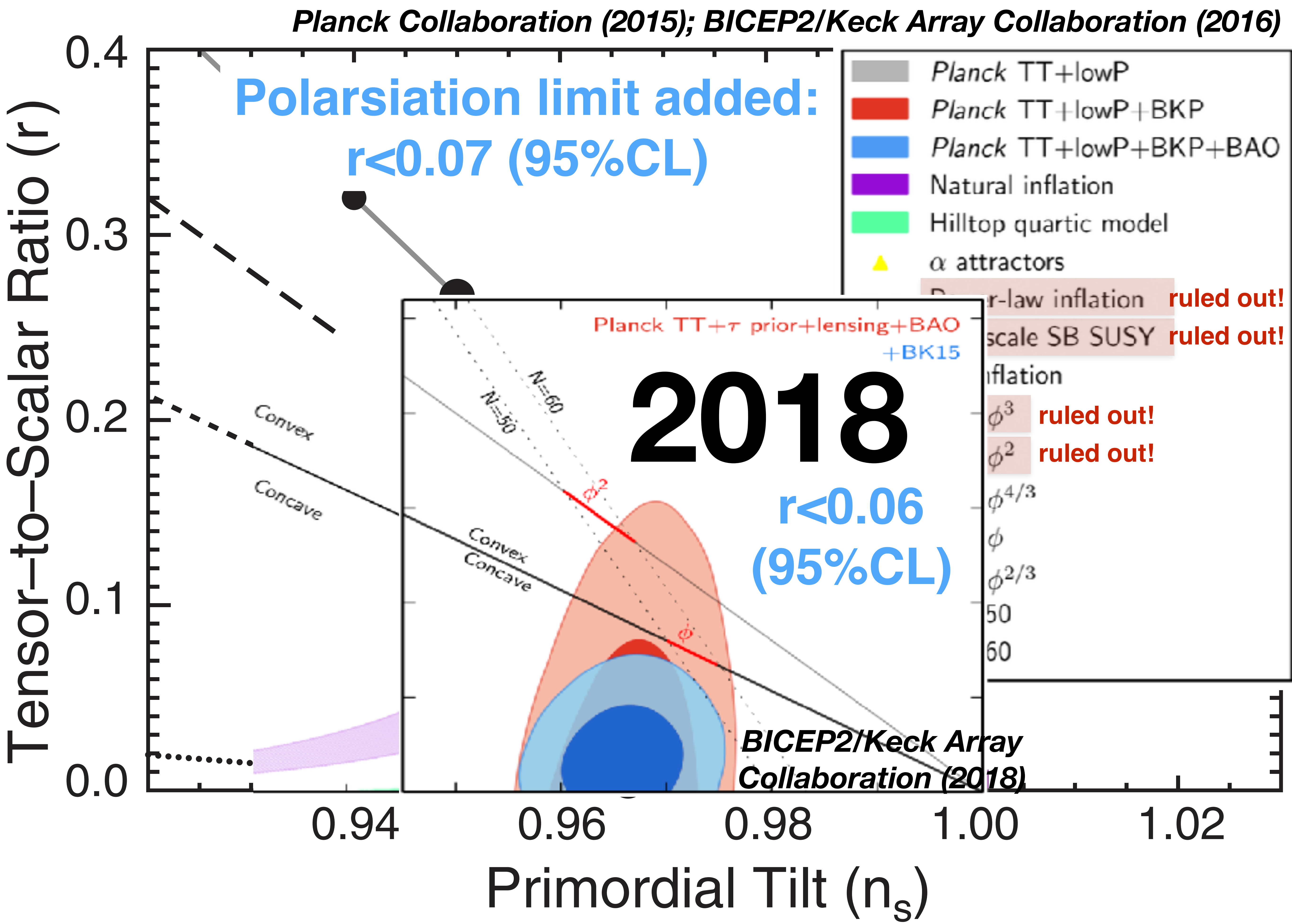
- We really want to find this! The current upper bound is **r<0.07** (95%CL)

BICEP2/Keck Array Collaboration (2016)


WMAP Collaboration
WMAP(temp+pol)+ACT+SPT+BAO+H0
WMAP(pol) + Planck + BAO
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)

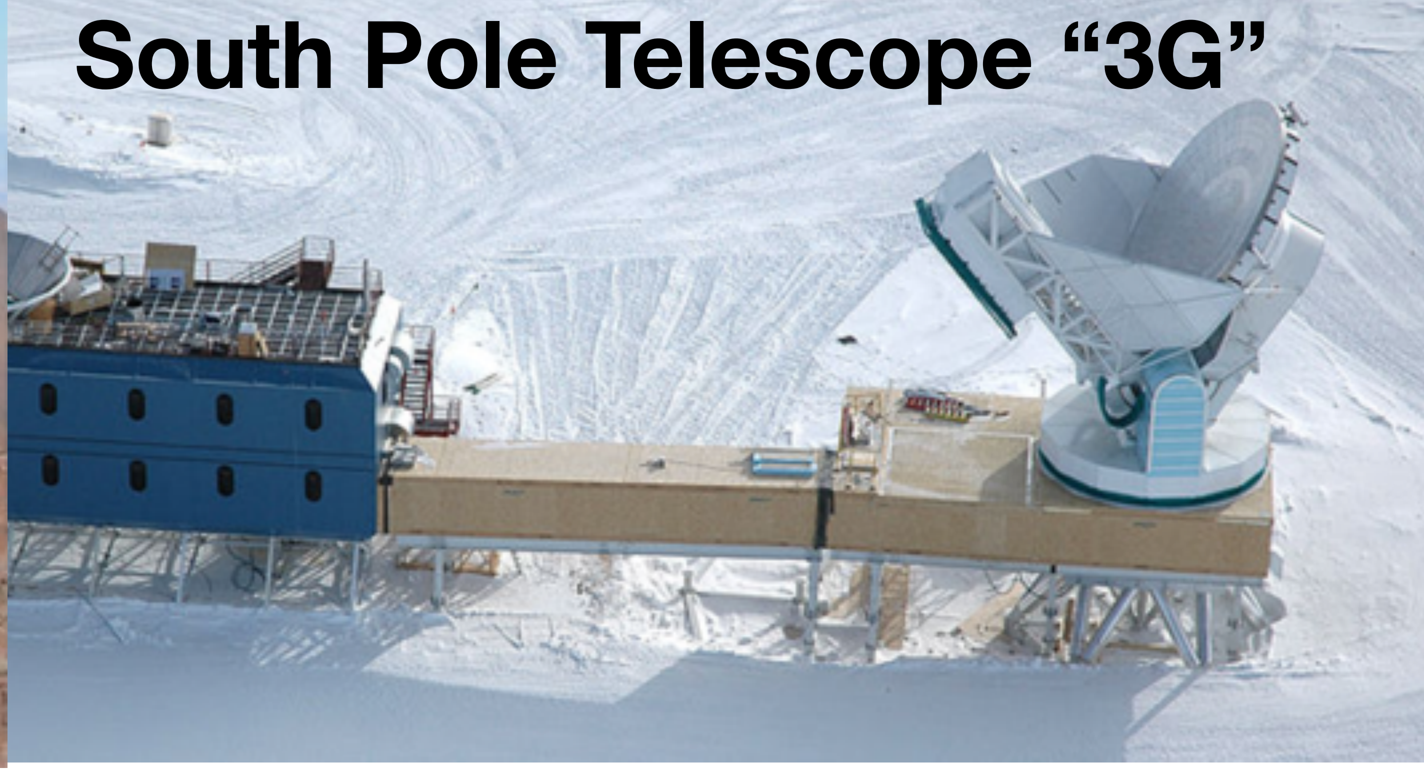


Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
Tensor–to–Scalar Ratio (r)
Primordial Tilt (n_s)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
Convex
Concave
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop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



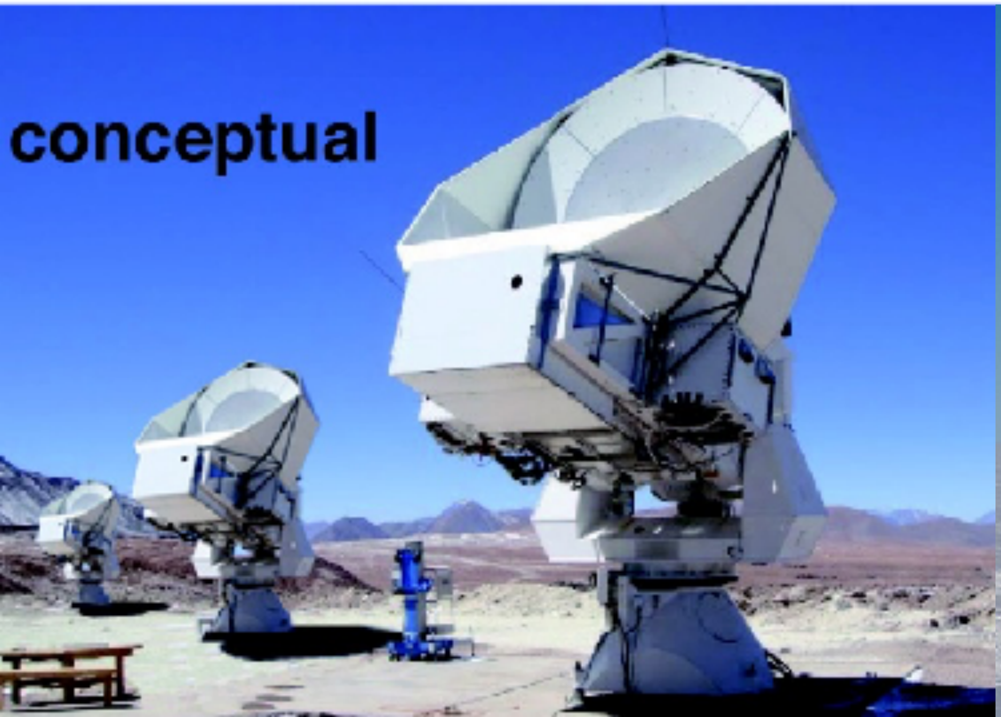
Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
ruled out!
ruled out!
ruled out!
ruled out!
Convex
Concave
Planck TT+τ prior+lensing+BAO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

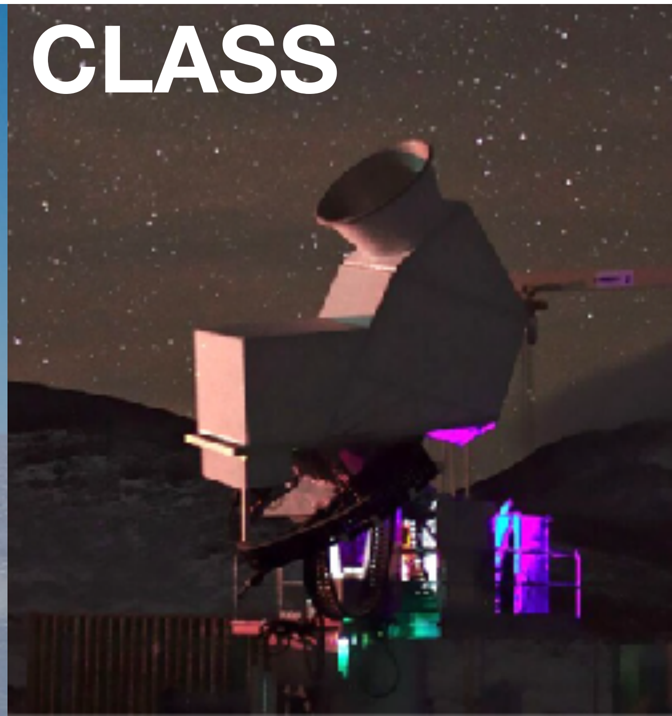
What comes next?



What comes next?

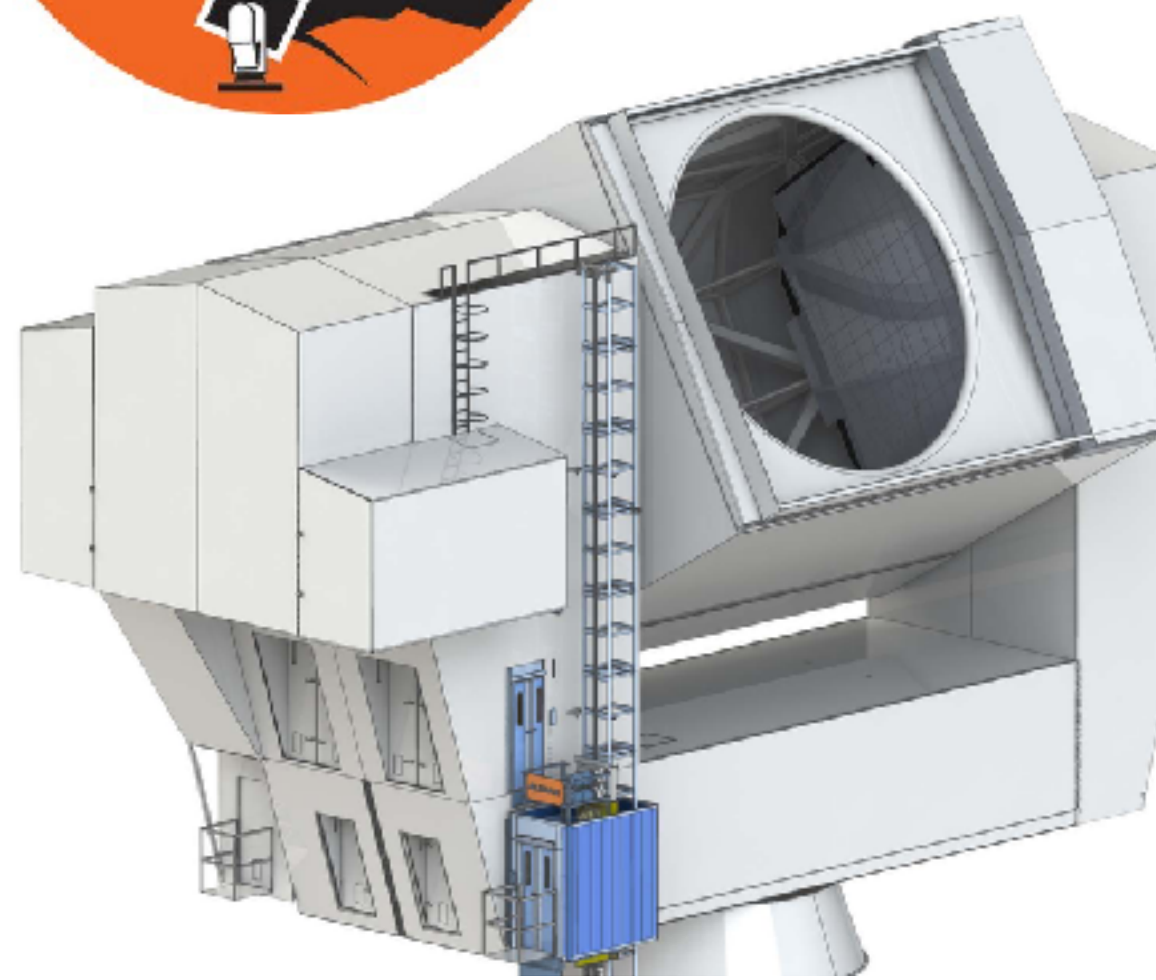
The Simons Array



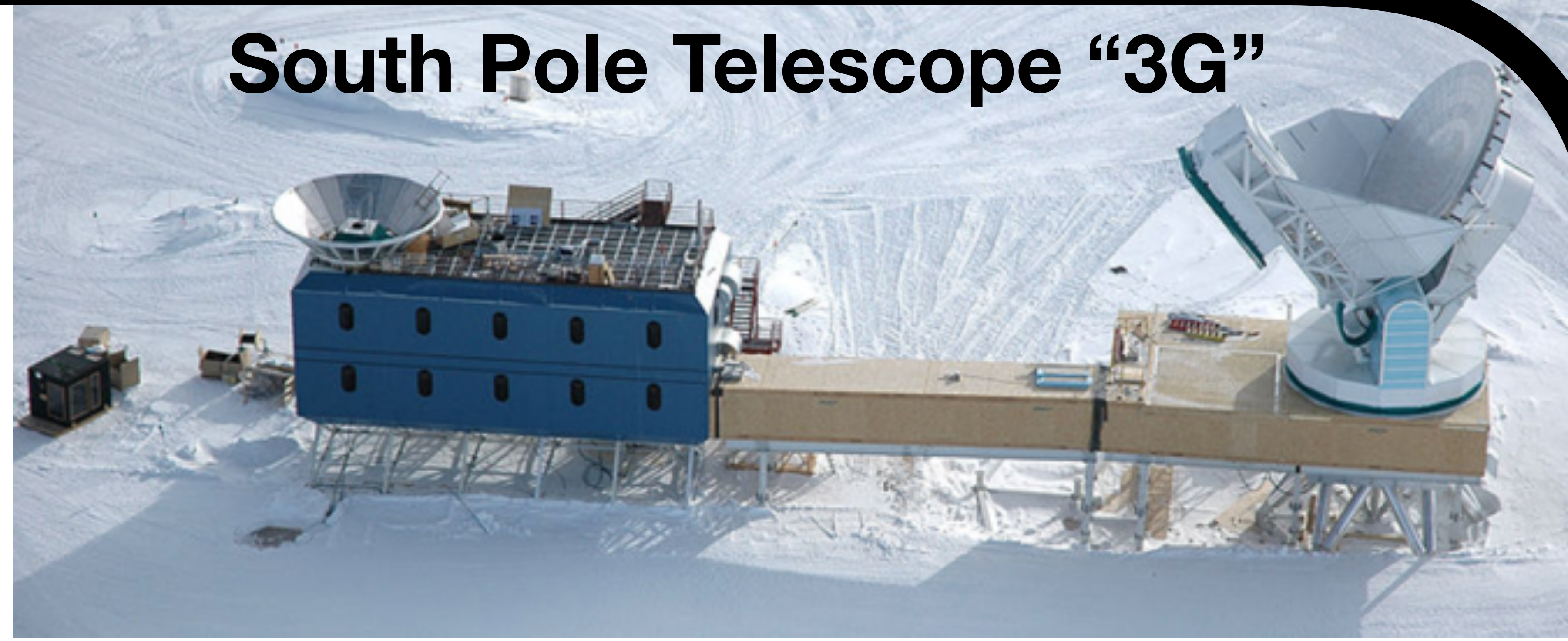


SIMONS
OBSERVATORY

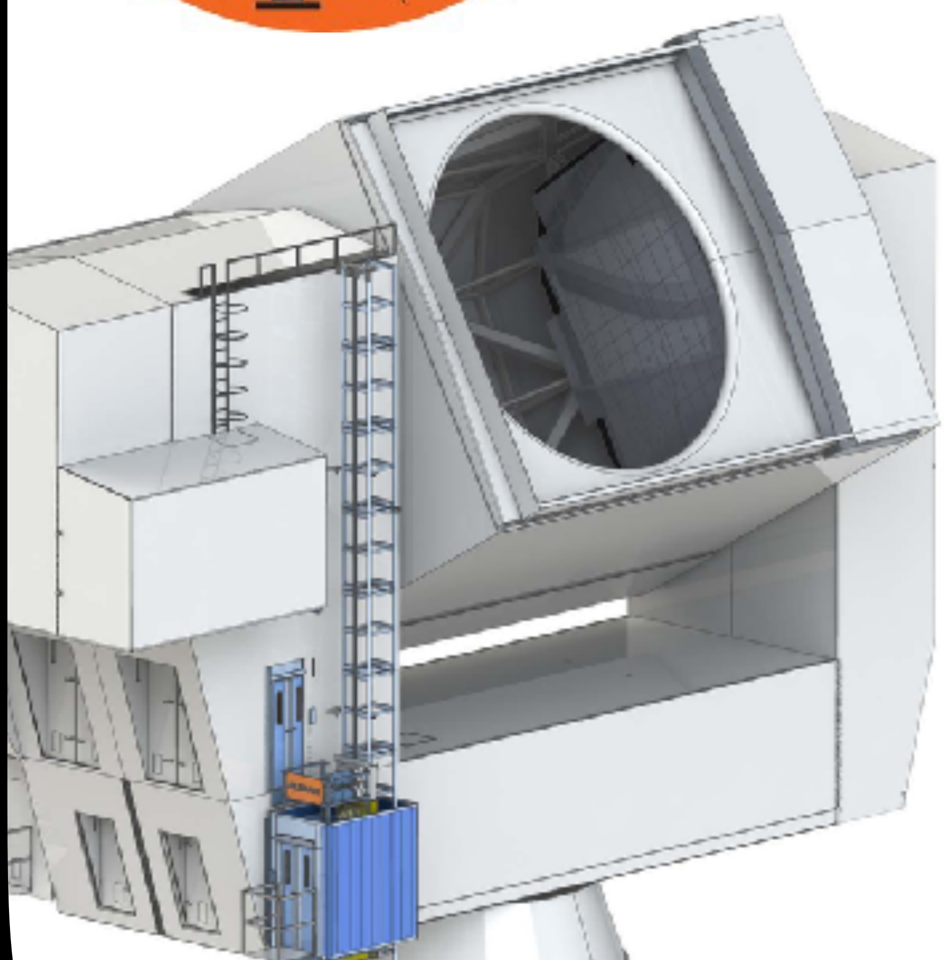
The Simons Array



SIMONS OBSERVATORY



CMB-S4(?)



CMB Stages

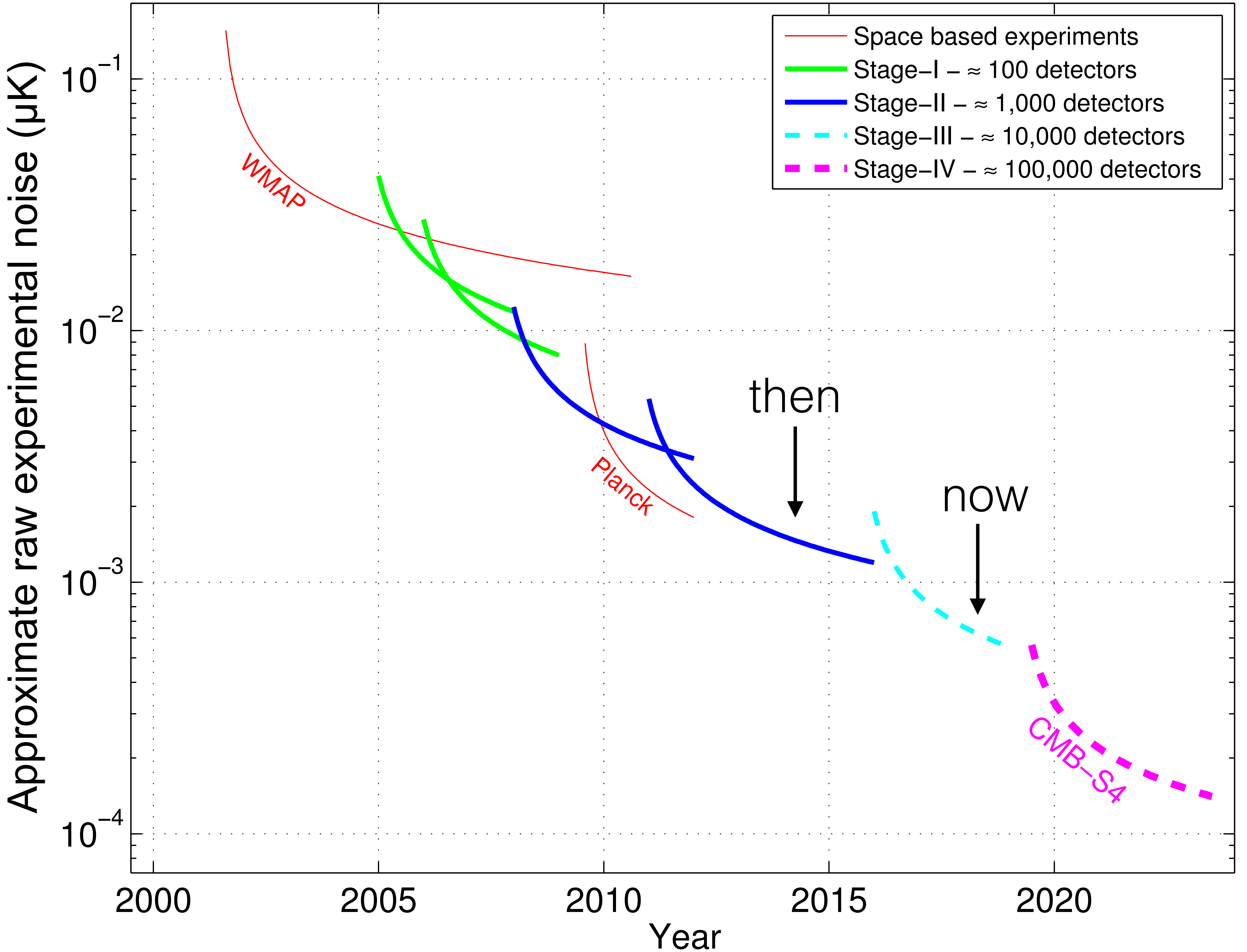


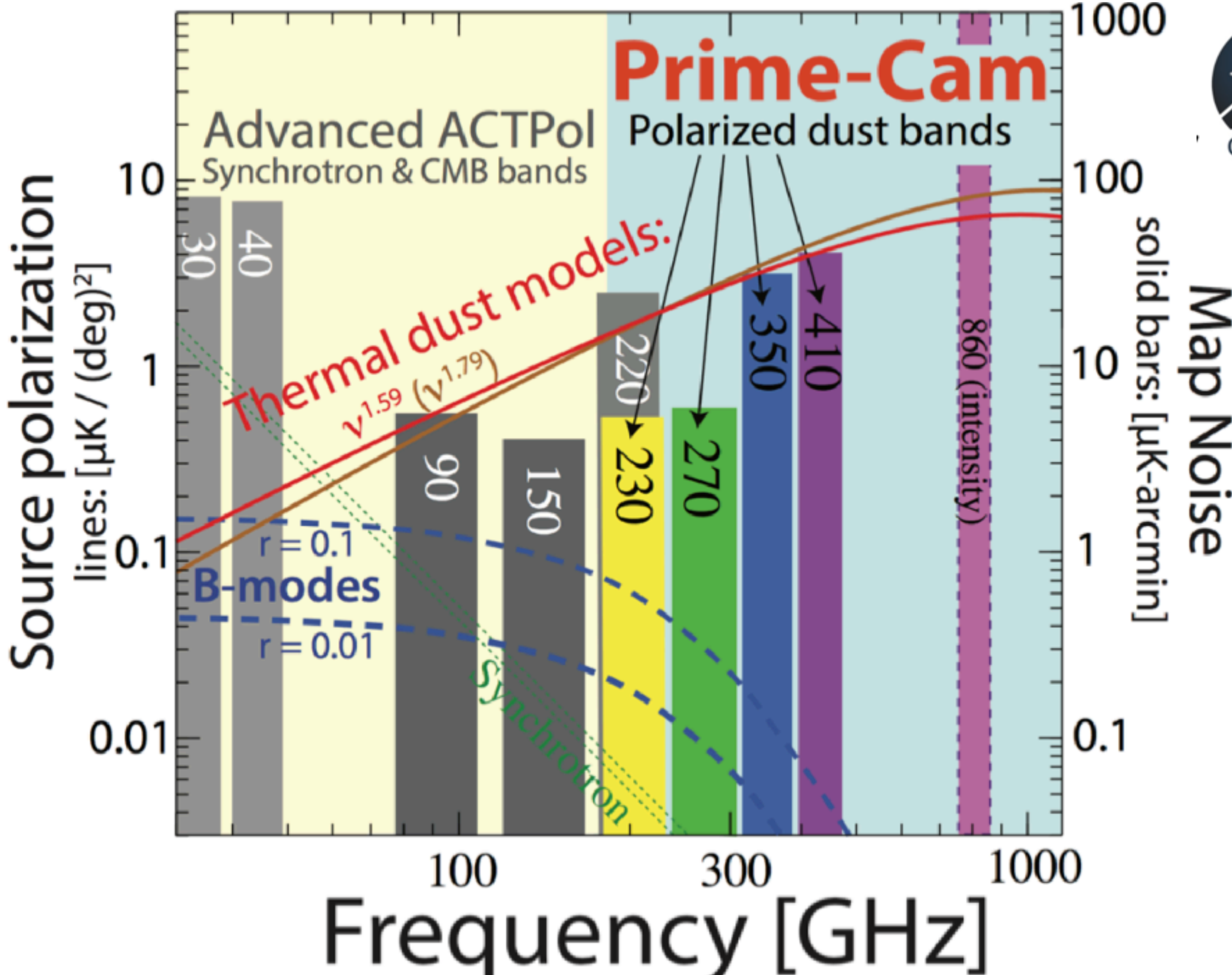
Figure by Clem Pryke for 2013 Snowmass documents

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-p!

CCAT-p Collaboration



Frank Bertoldi's slide from the Florence meeting

Where is CCAT-p?

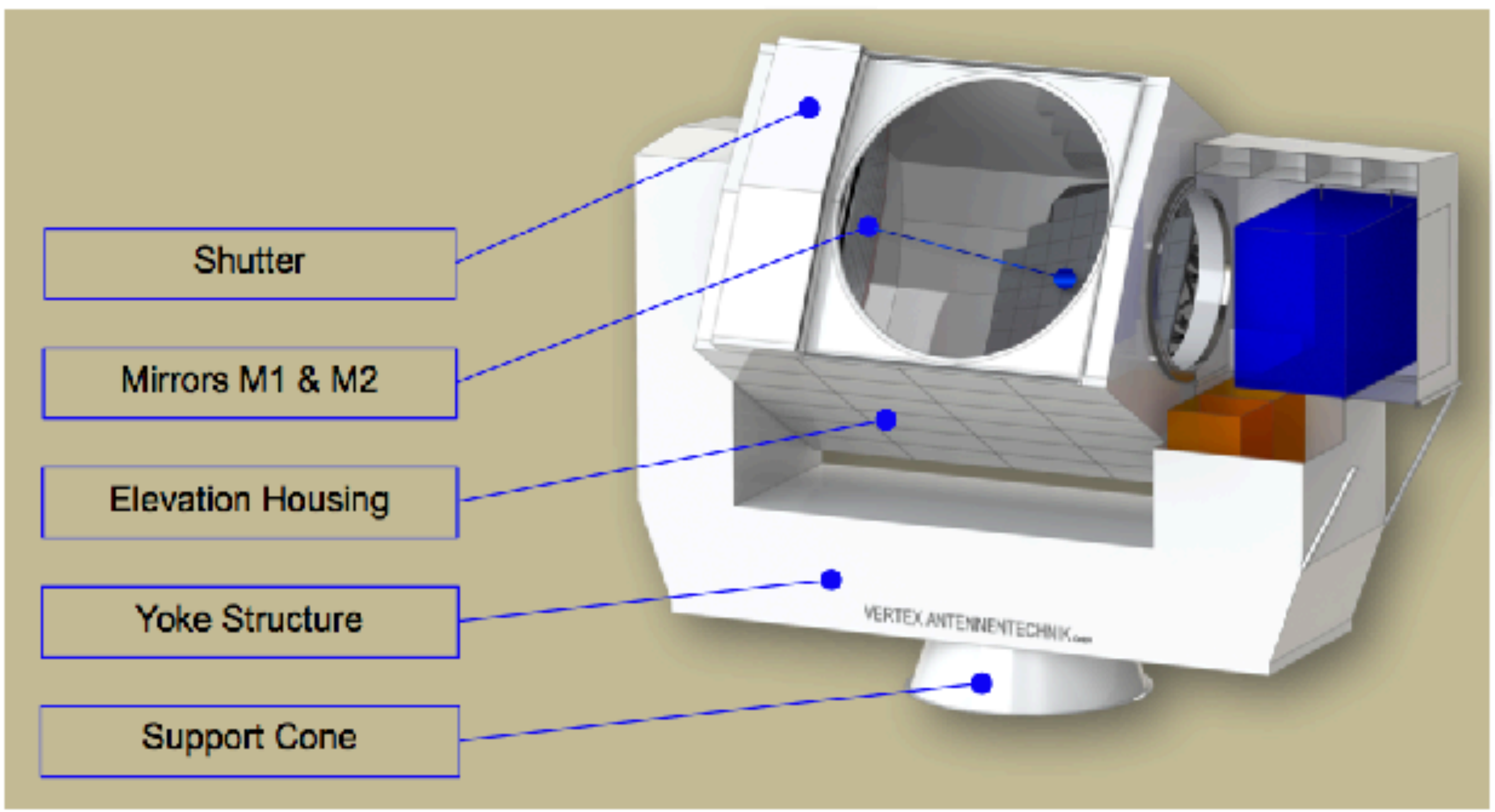
Cerro Chajnantor at 5600 m w/ TAO

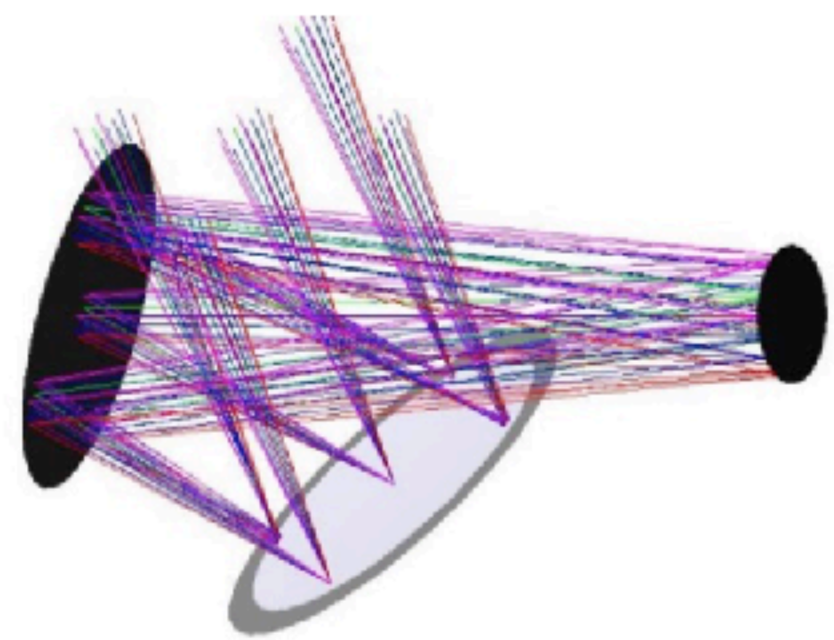
Frank Bertoldi's slide from the Florence meeting

What is CCAT-p?

CCAT-p

CCAT-prime is a high surface accuracy / throughput 6 m submm (0.3-3mm) telescope

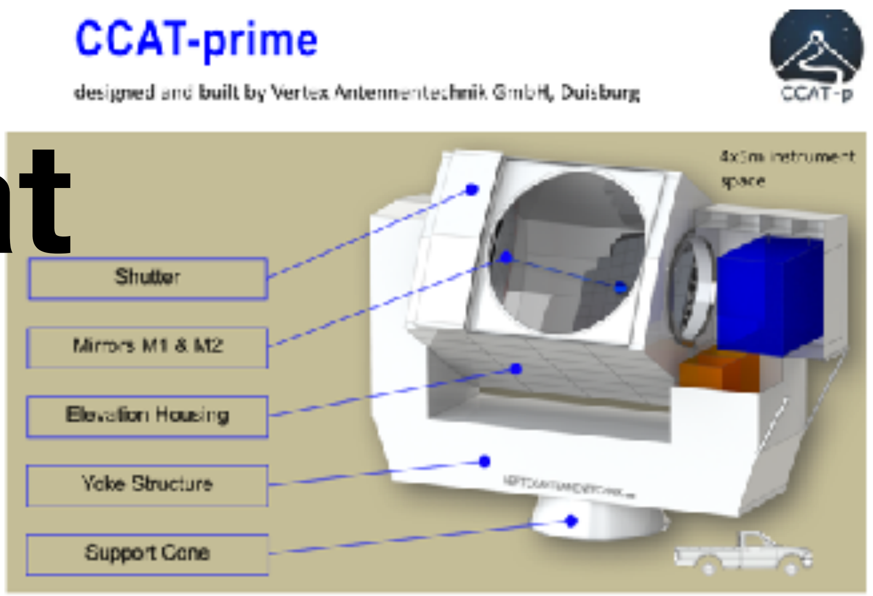




Cornell U. + German consortium + Canadian consortium + …

A Game Changer

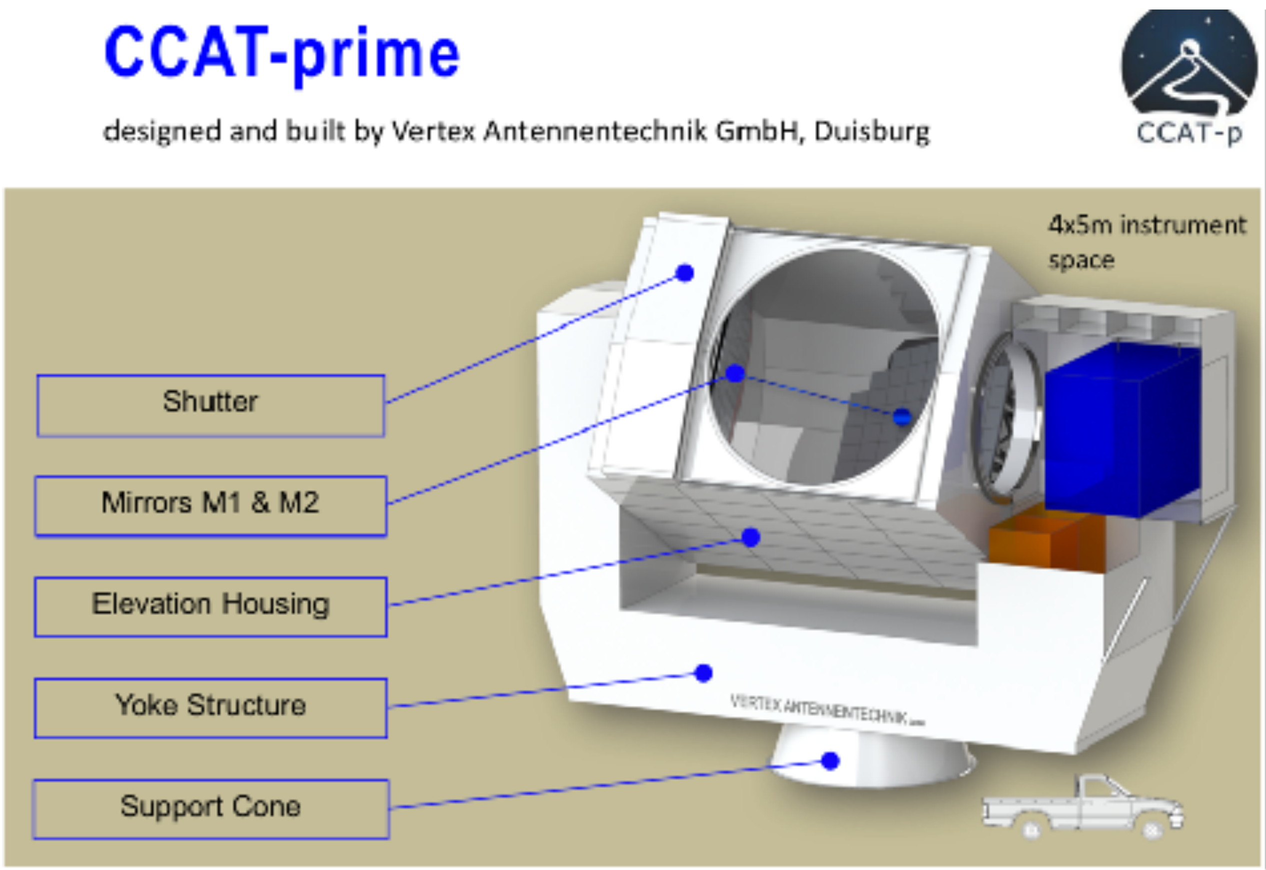
- **CCAT-p**: 6-m, **Cross-dragone** design, on Cerro Chajnantor (5600 m)

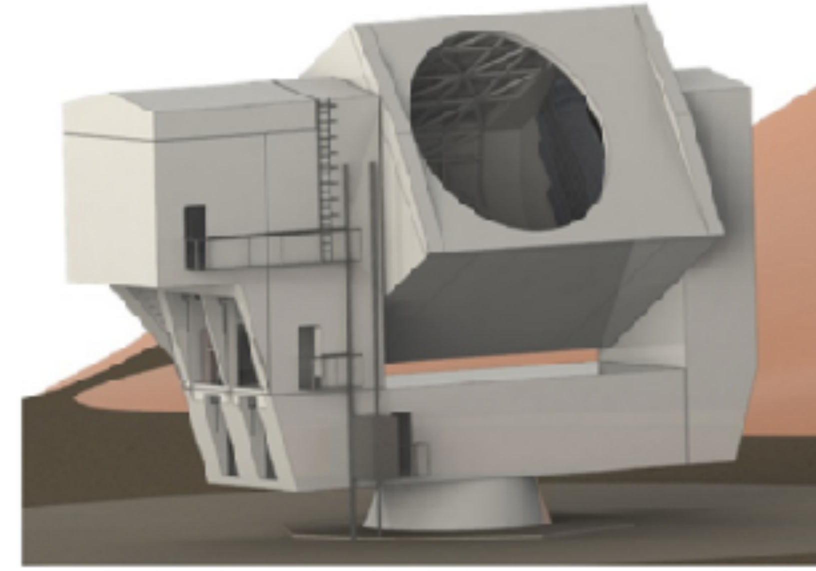


- **Germany makes great telescopes!**

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

    - CCAT-p is a great opportunity for Germany to make <u>significant contributions</u> towards the CMB S-4 landscape (both US and Europe) by providing telescope designs and the “lessons learned” with prototypes.





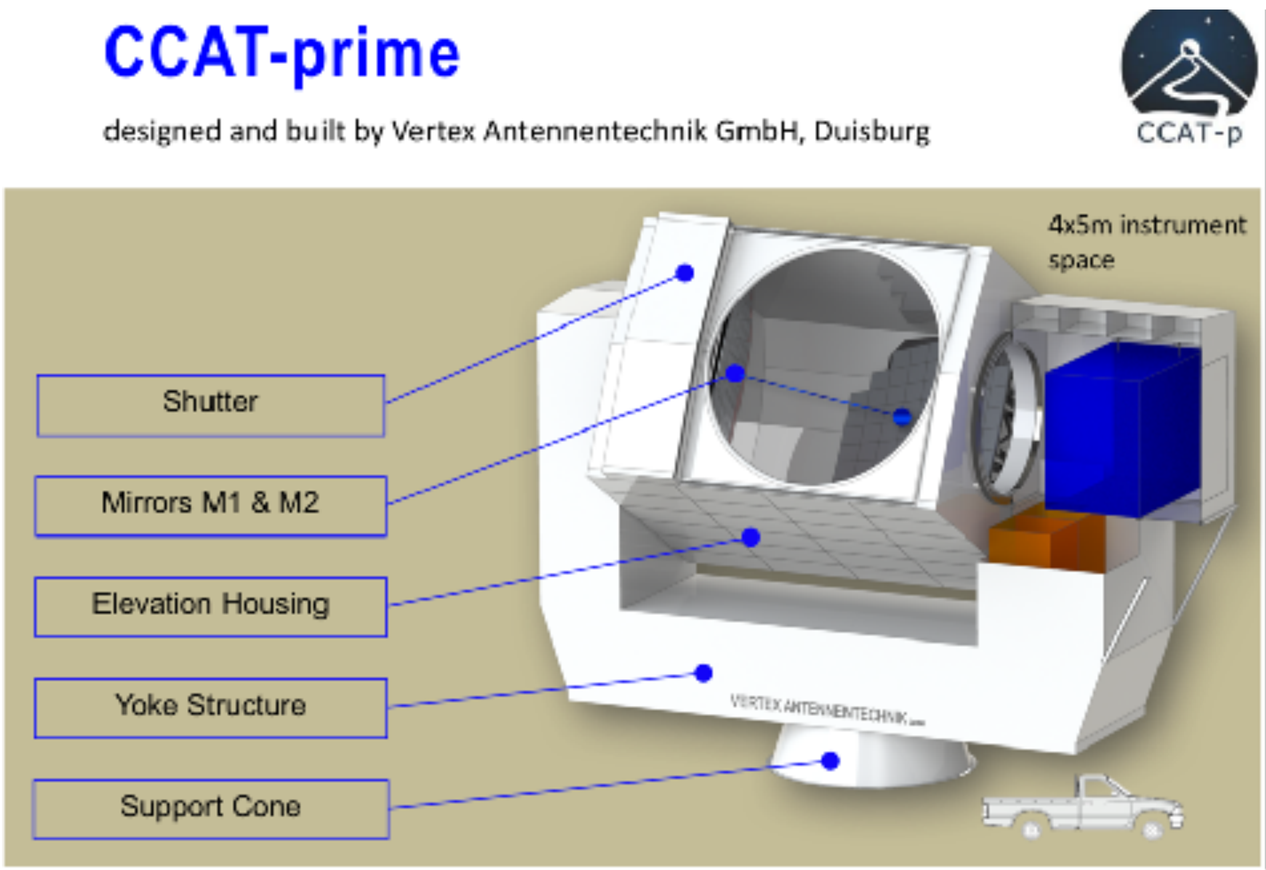
A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

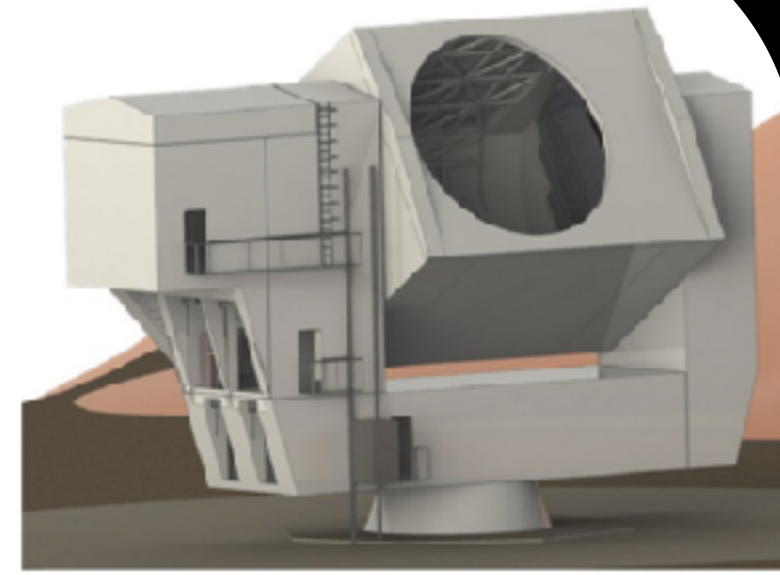
Simons Observatory (USA)

in collaboration

South Pole?

This could be "CMB-S4"





A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

Simons Observatory (USA)

in collaboration

South Pole?

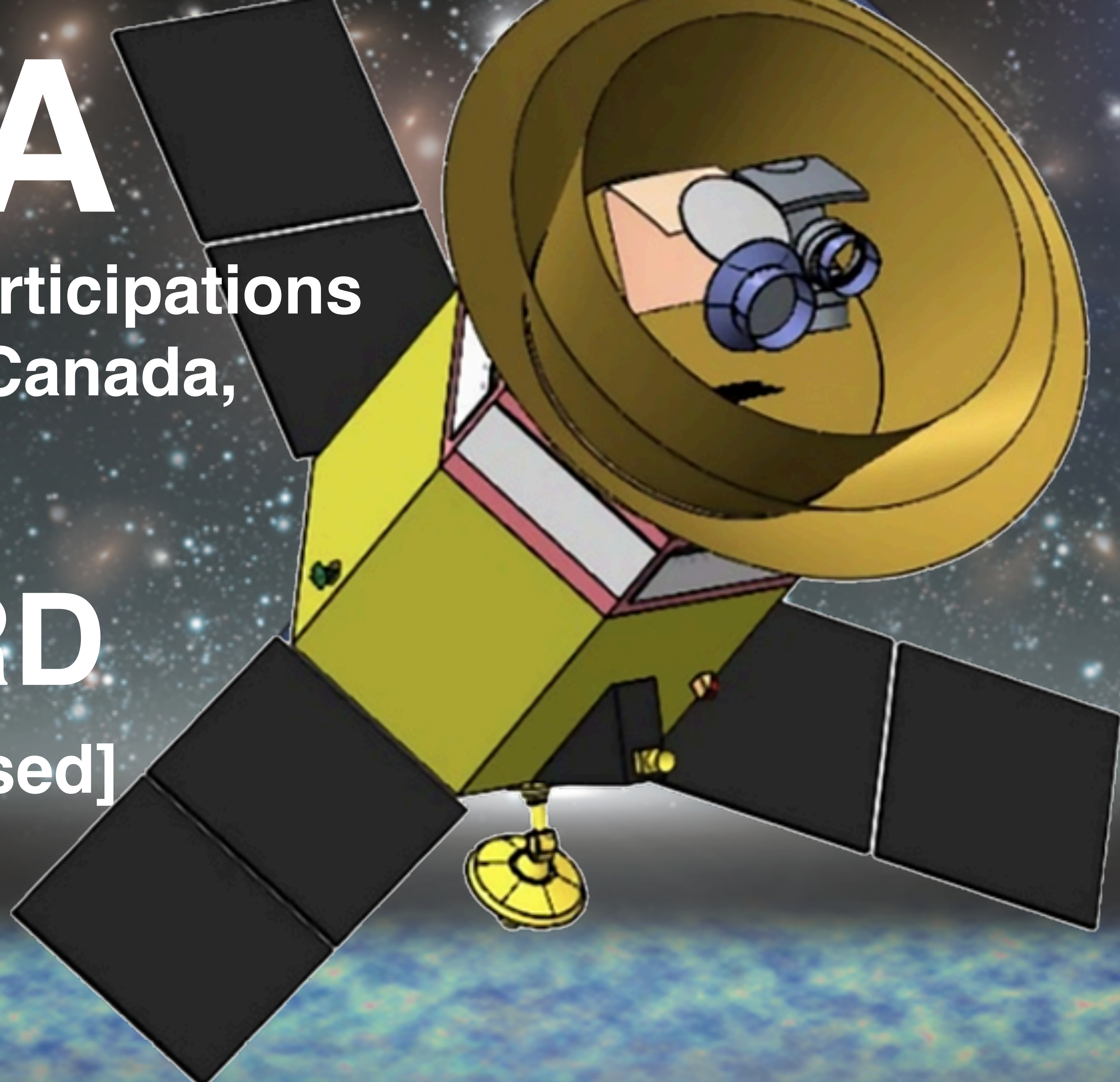
To have even more frequency coverage…

JAXA

+ possible participations from USA, Canada, Europe

LiteBIRD

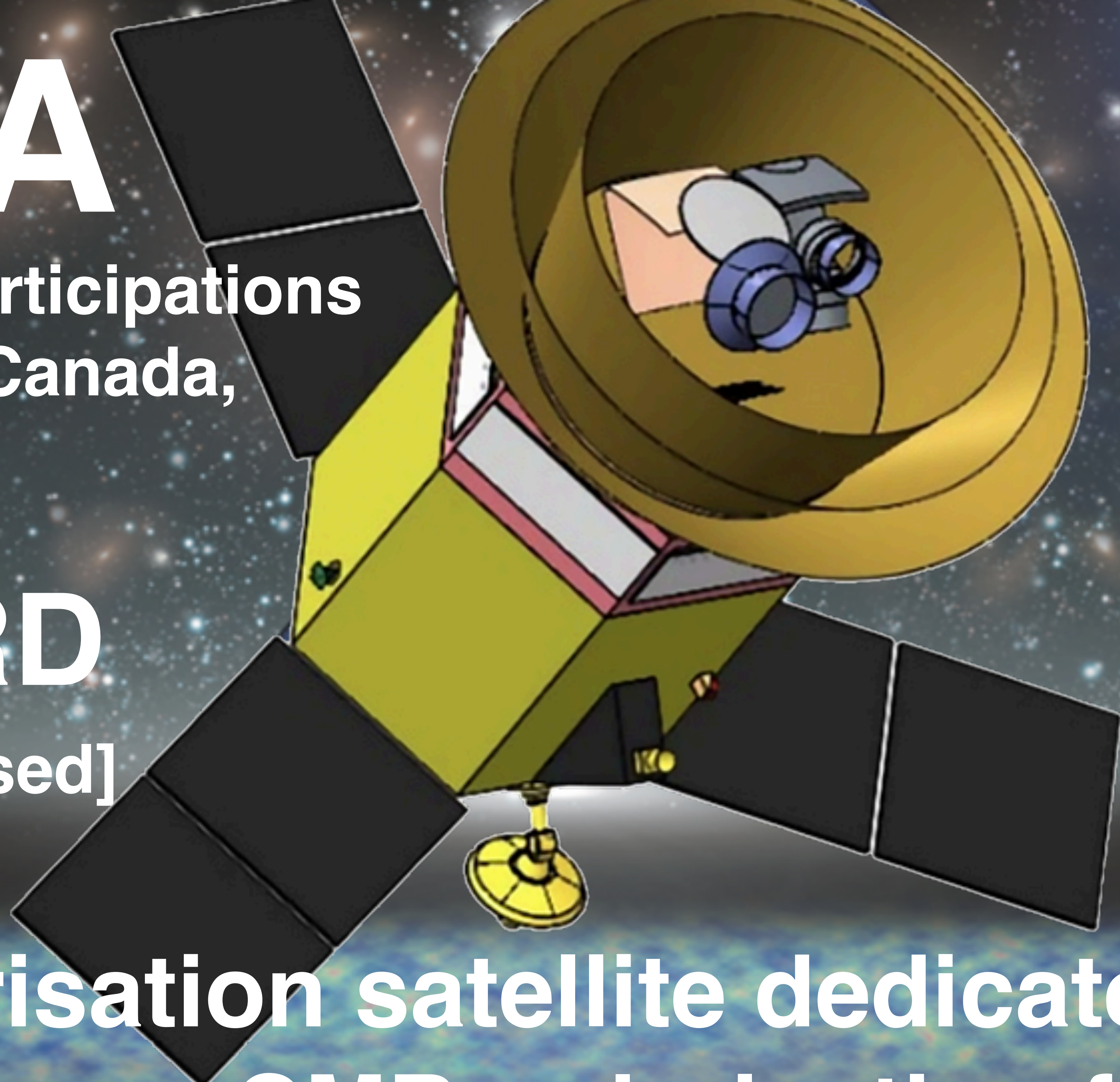
2027– [proposed]



Target: $\delta r<0.001$ (68%CL)

JAXA

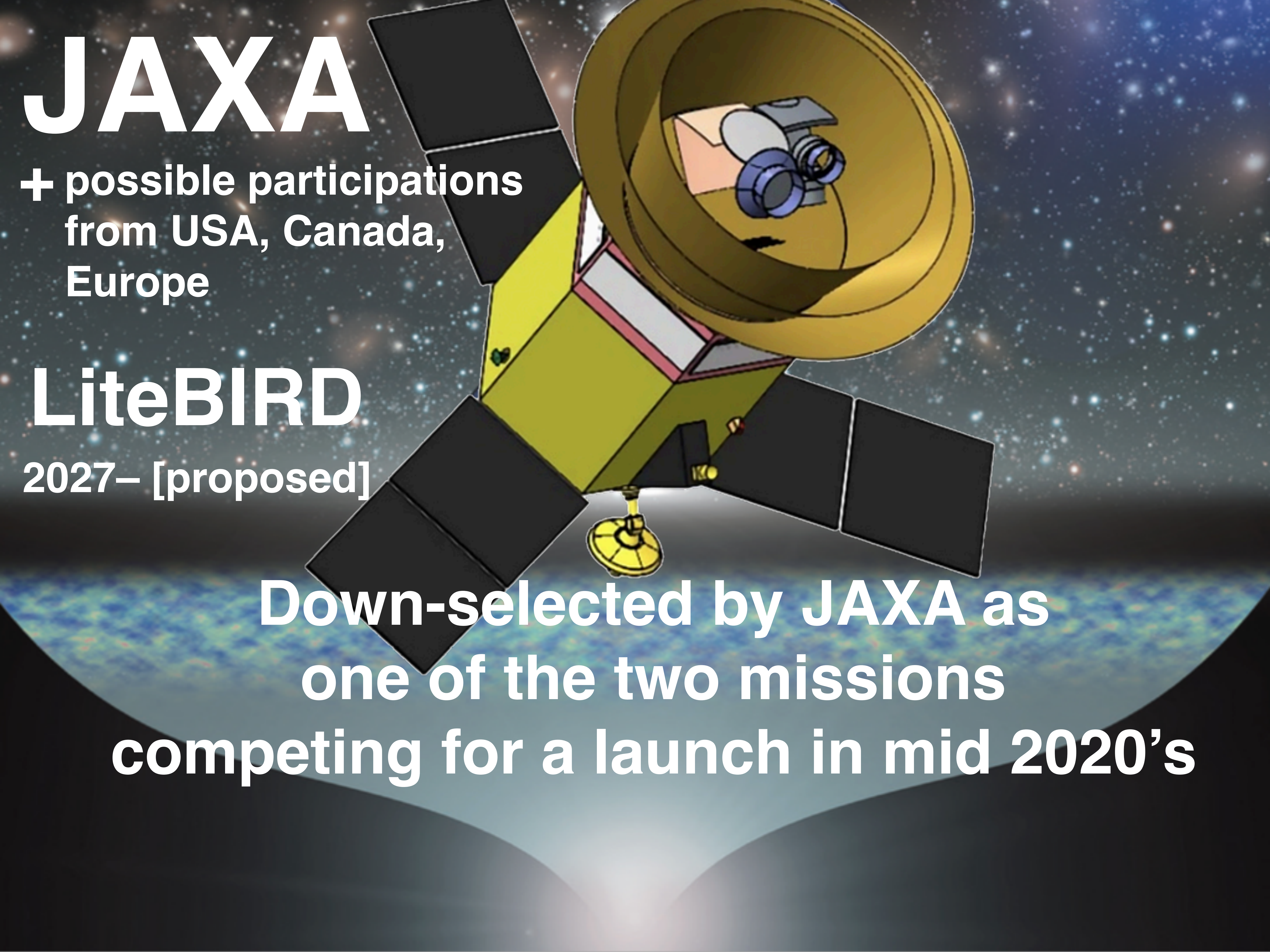
+ possible participations from USA, Canada, Europe



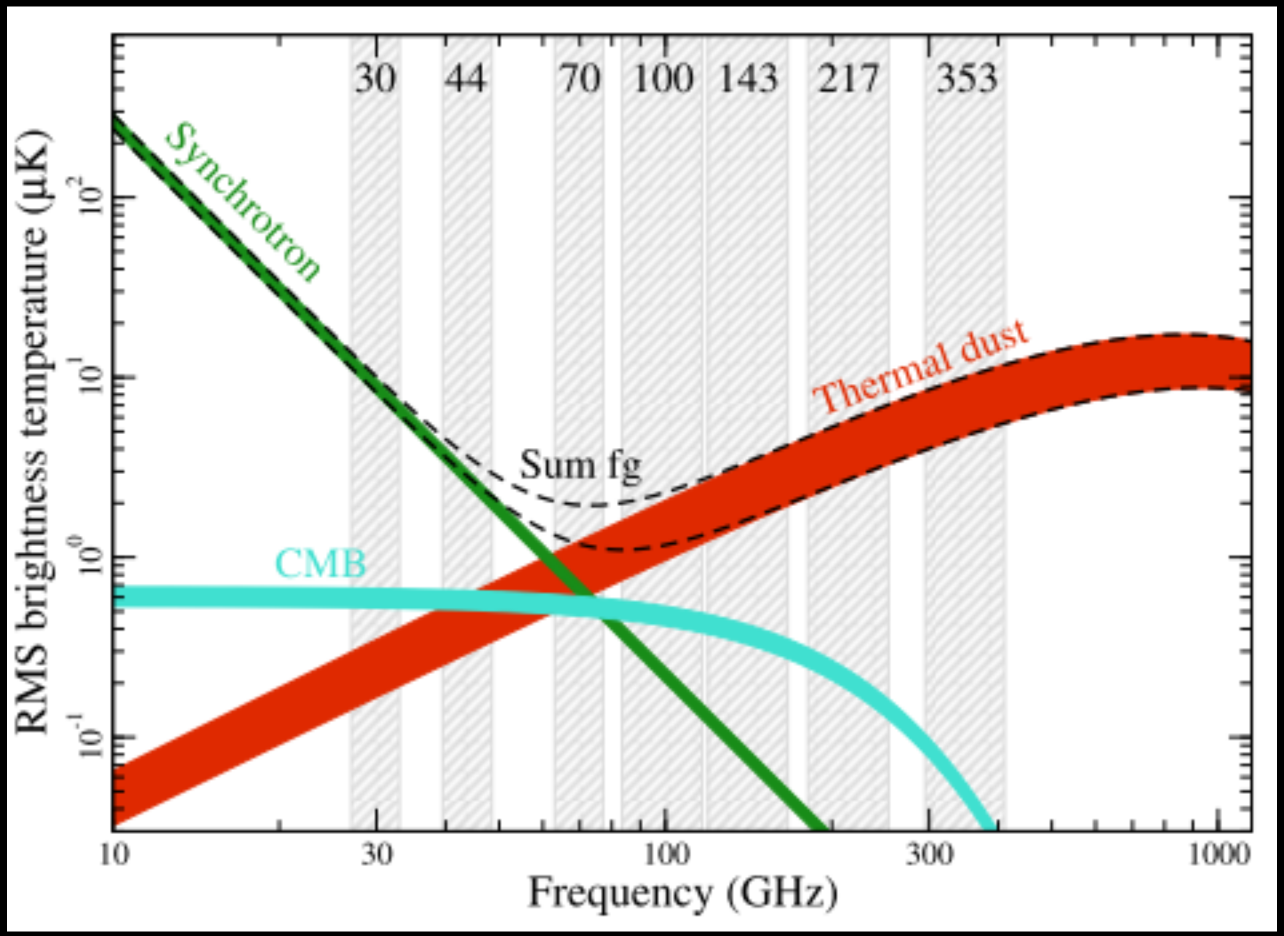
LiteBIRD

2027– [proposed]

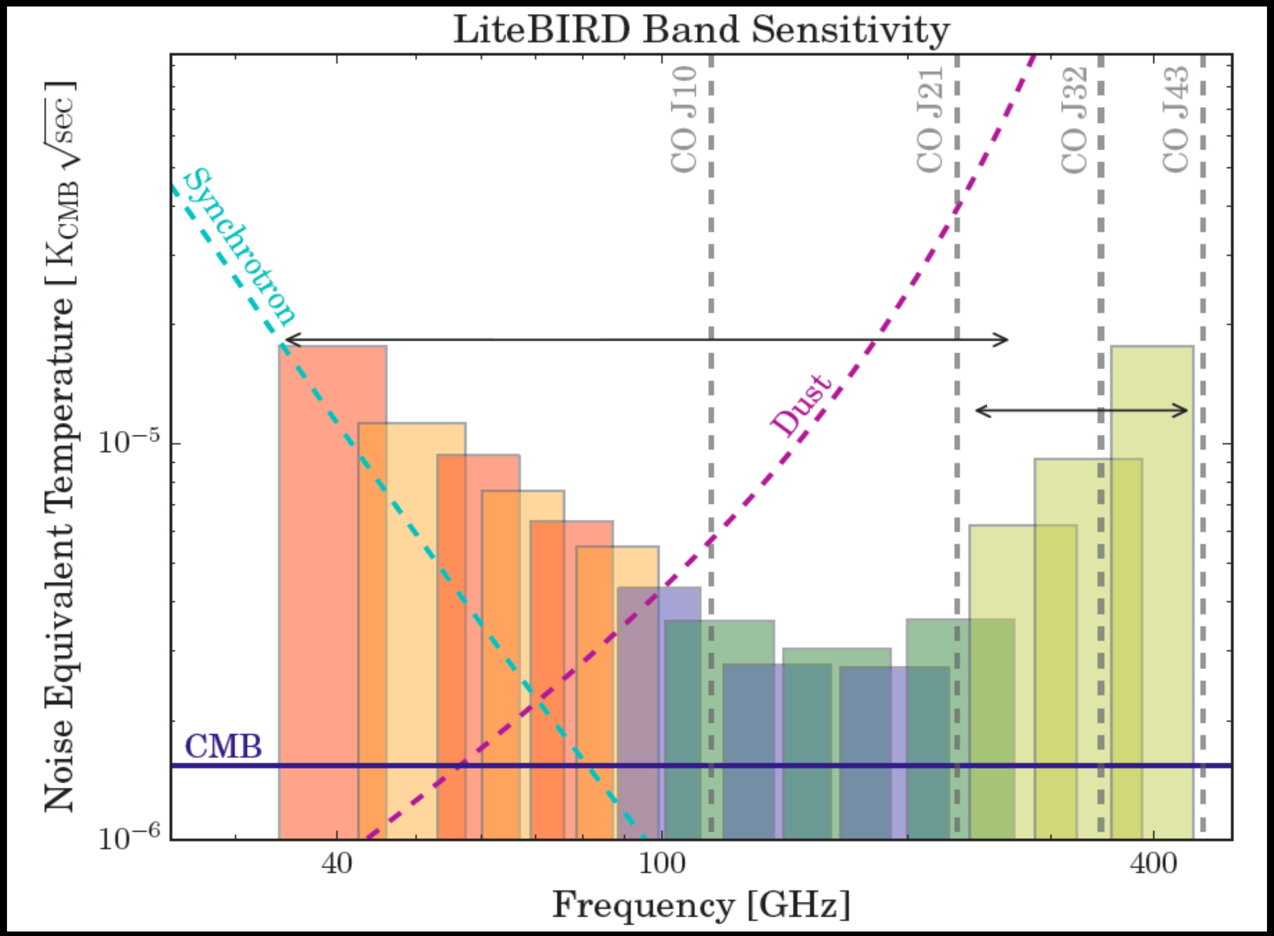
Polarisation satellite dedicated to measure CMB polarisation from primordial GW, with a few thousand super-conducting detectors in space


JAXA
+ possible participations from USA, Canada, Europe
LiteBIRD
2027– [proposed]
Down-selected by JAXA as one of the two missions competing for a launch in mid 2020's

Foreground Removal



Polarized galactic emission (Planck X)



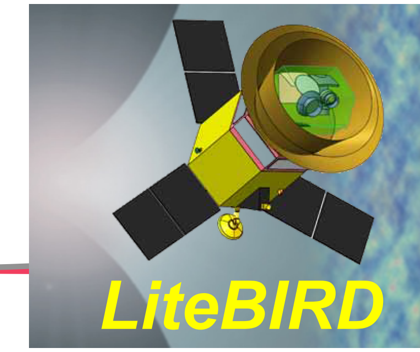
LiteBIRD: 15 frequency bands

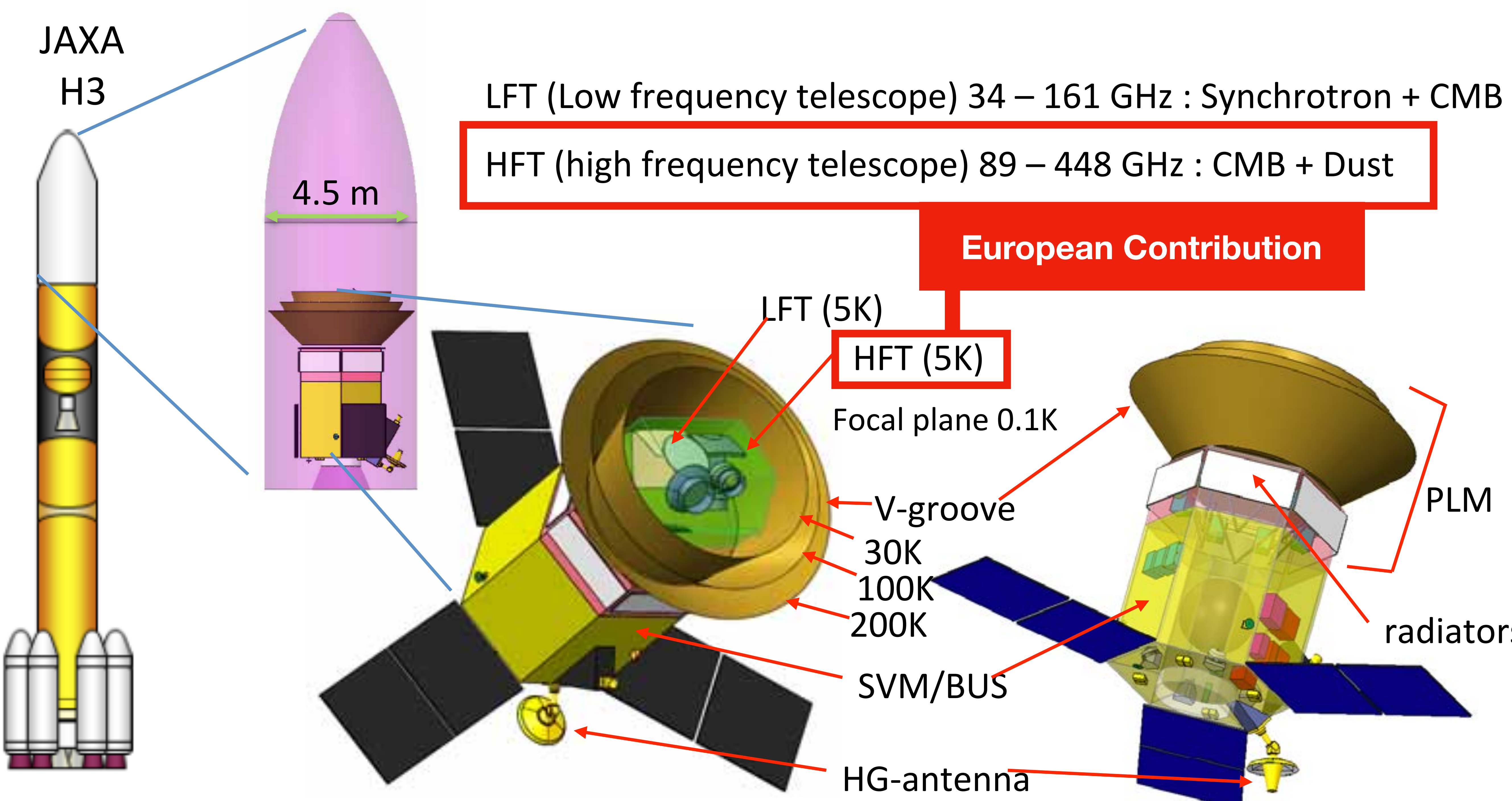
- Polarized foregrounds
  - Synchrotron radiation and thermal emission from inter-galactic dust
  - Characterize and remove foregrounds
- 15 frequency bands between 40 GHz - 400 GHz
  - Split between Low Frequency Telescope (LFT) and High Frequency Telescope (HFT)
  - LFT: 40 GHz – 235 GHz
  - HFT: 280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

Slide courtesy Toki Suzuki (Berkeley)

Slide courtesy Yutaro Sekimoto (ISAS/JAXA)

LiteBIRD Spacecraft





Summary

- 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-p we can remove the dust polarisation to reach $r \sim 10^{-2}$ **reliably**, i.e., 10 times better than the current bound
  - With LiteBIRD we plan to reach $r \sim 10^{-3}$, i.e., 100 times better than the current bound