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

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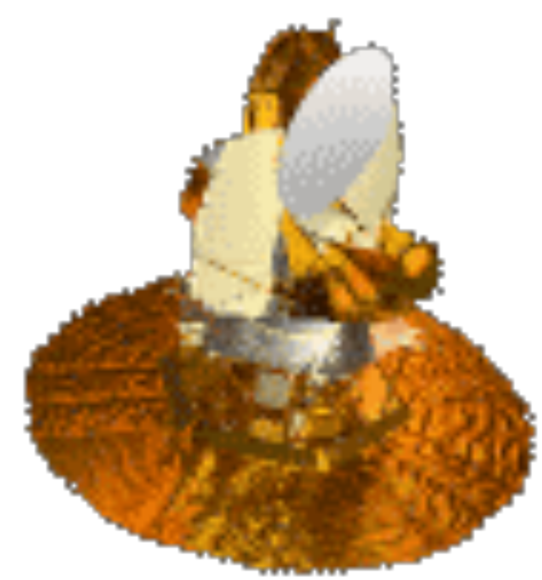


Breakthrough in Cosmological Research

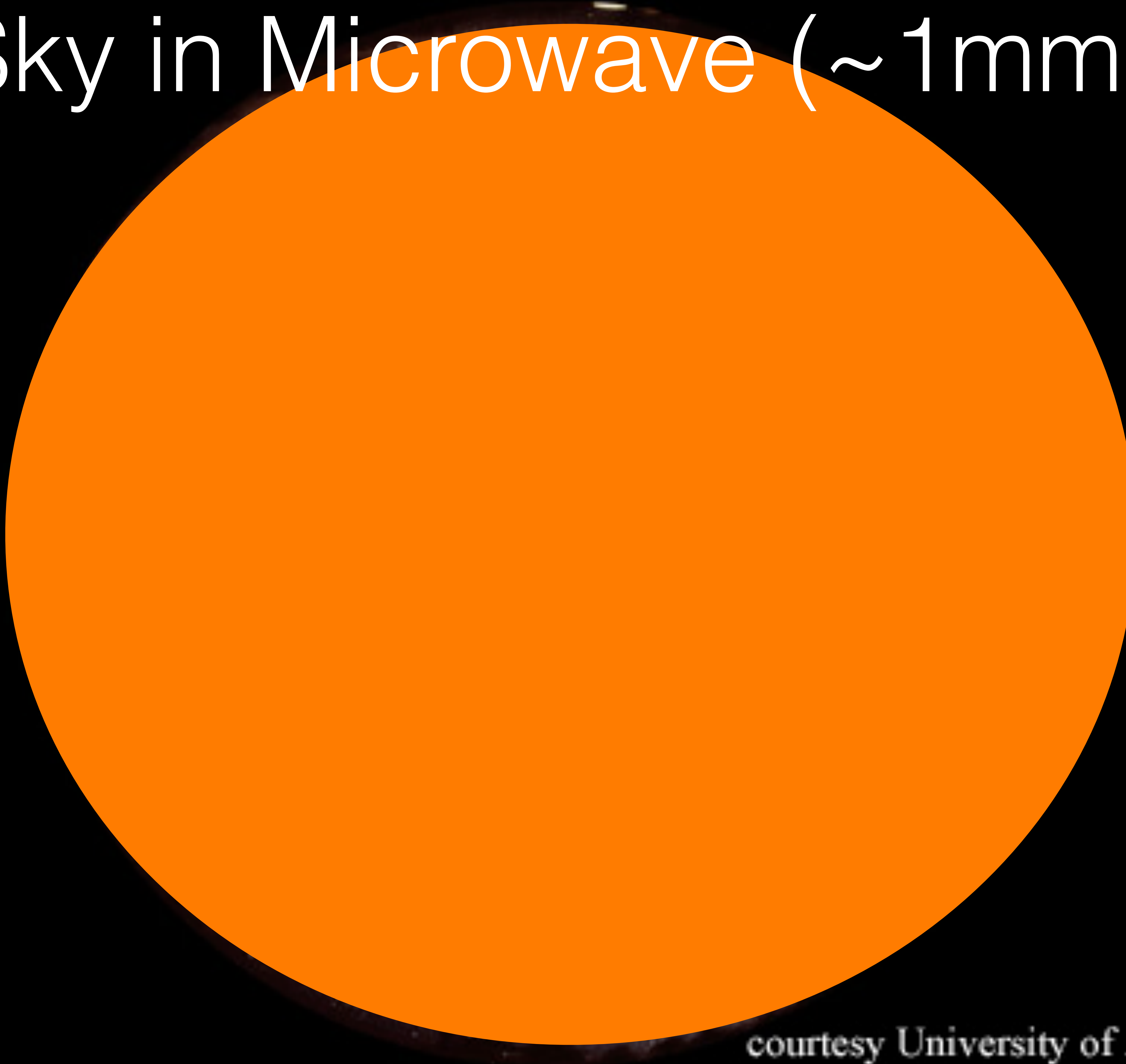
- We can actually **see** the physical condition of the universe when it was very young


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)

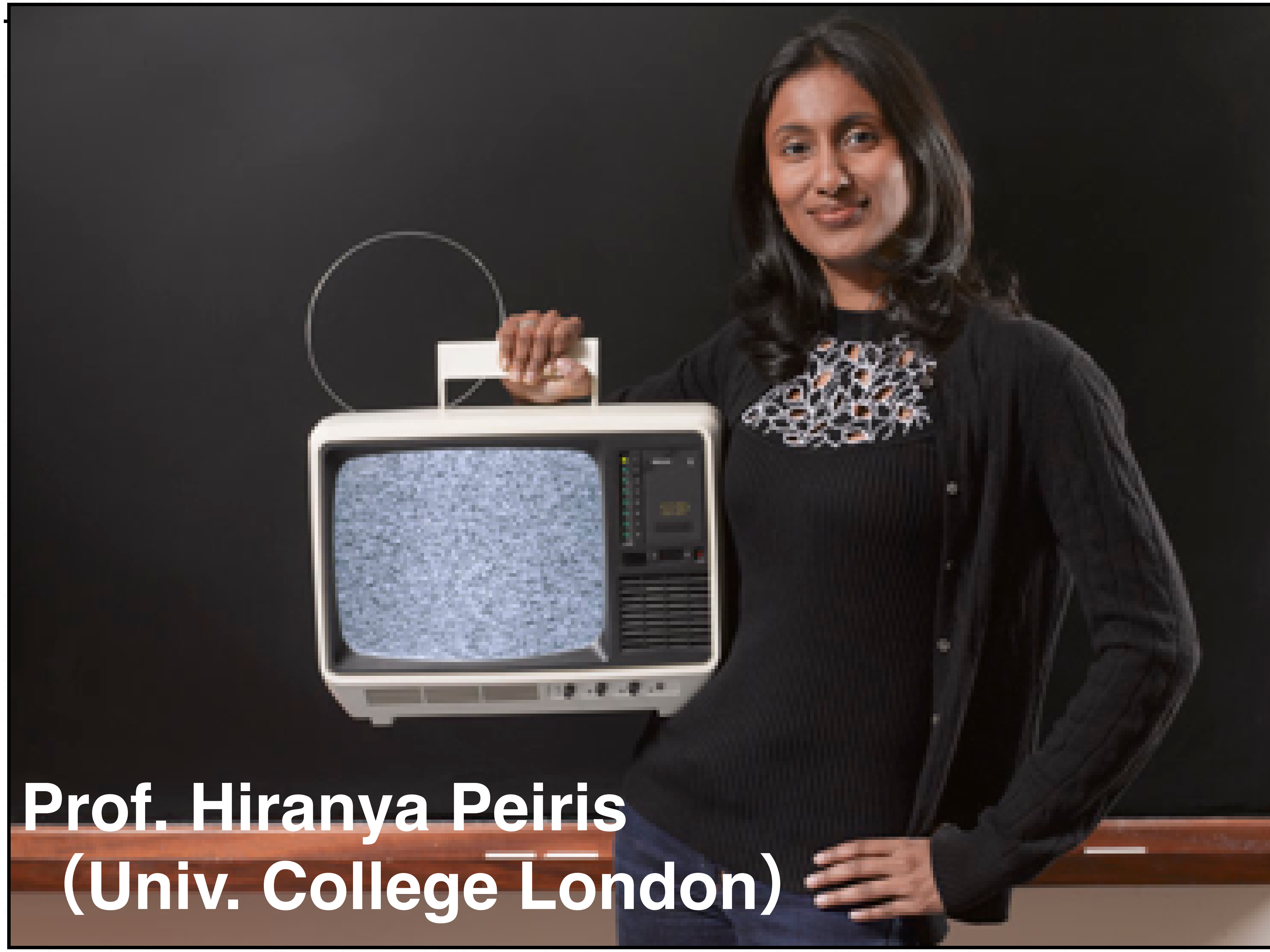
courtesy University of Arizona

410 photons

per

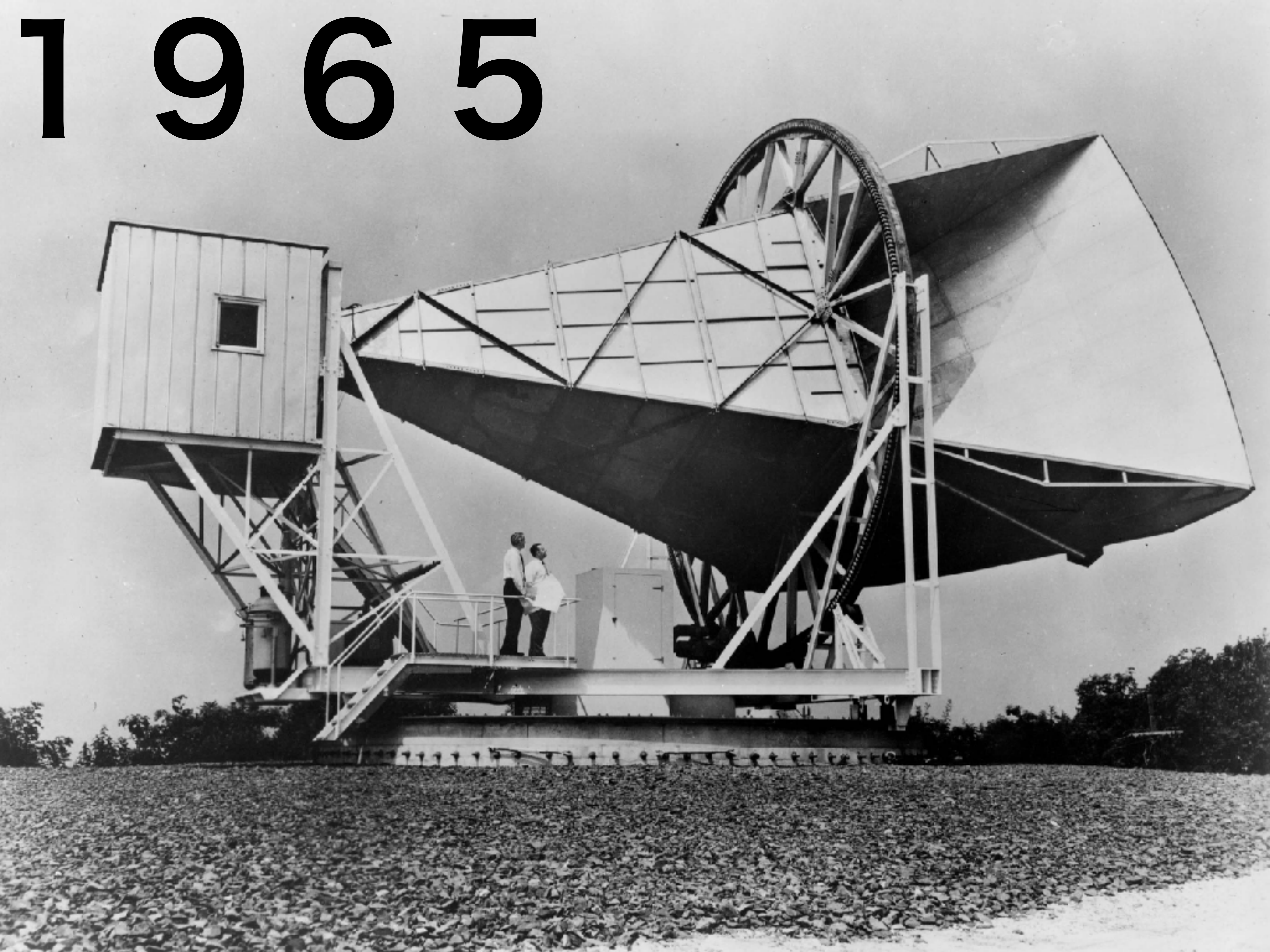
cubic centimeter!!

courtesy University of Arizona

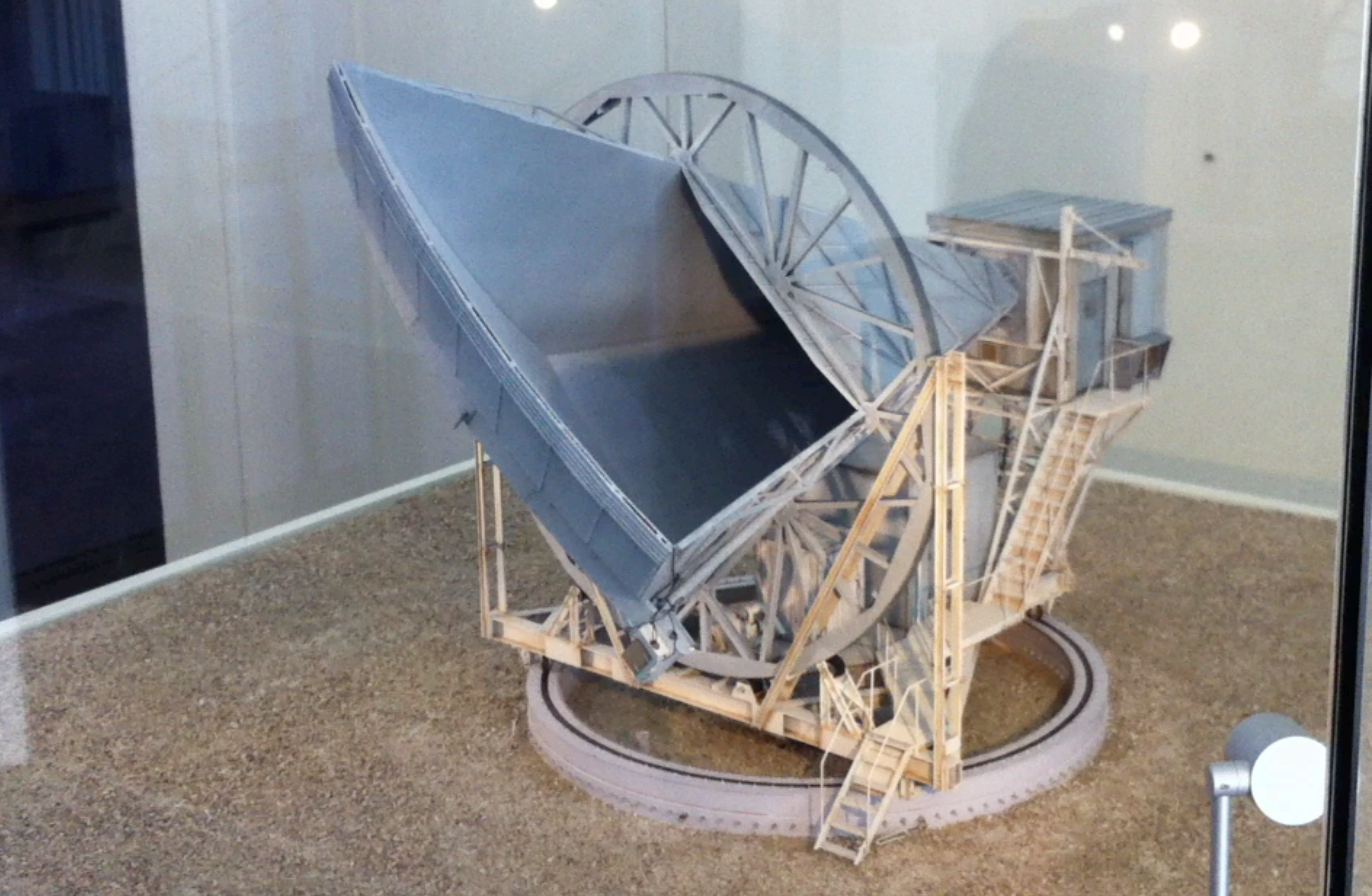


All you need to do is to detect radio waves. For example, 1% of noise on the TV is from the fireball Universe

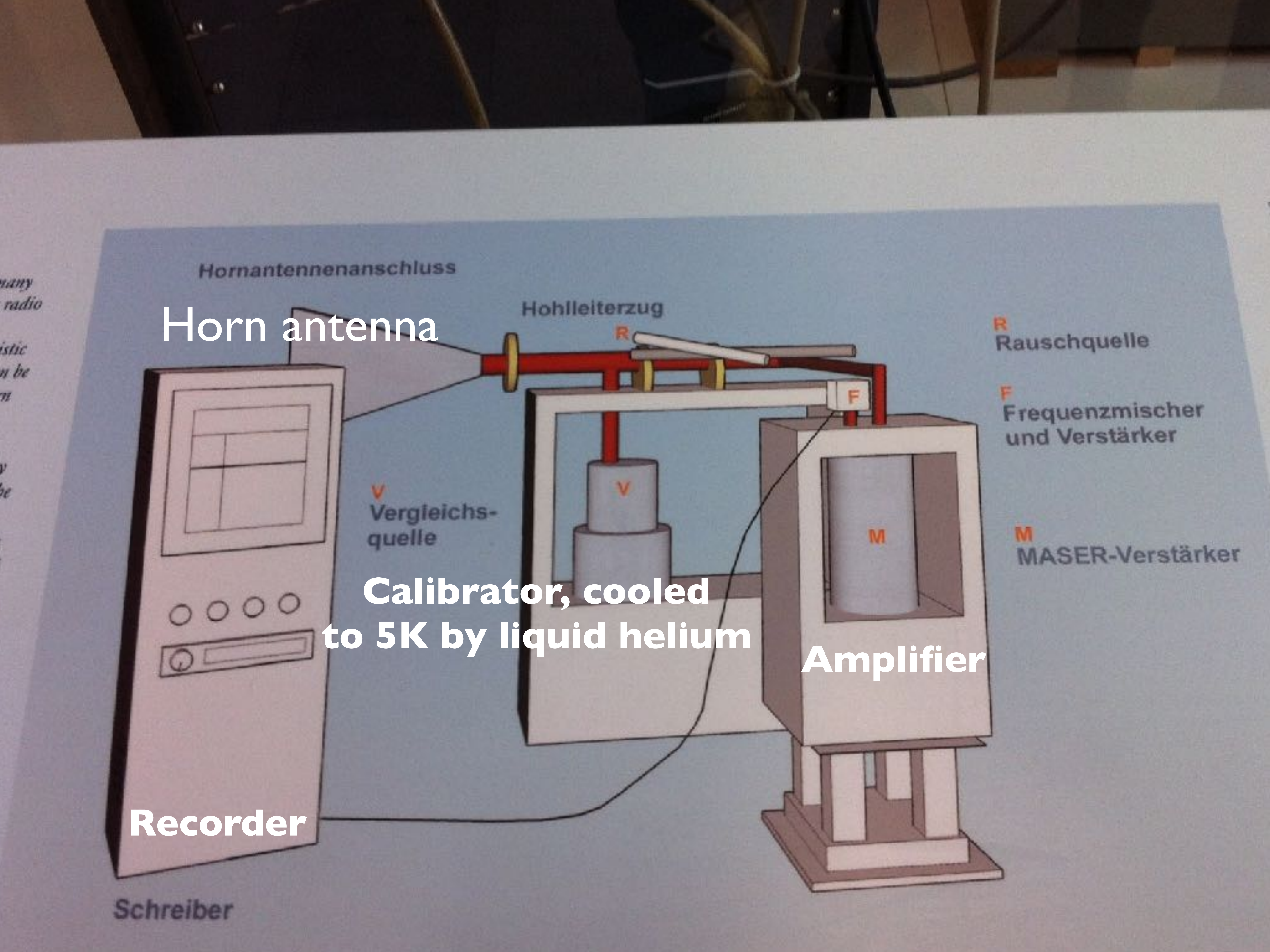
1965



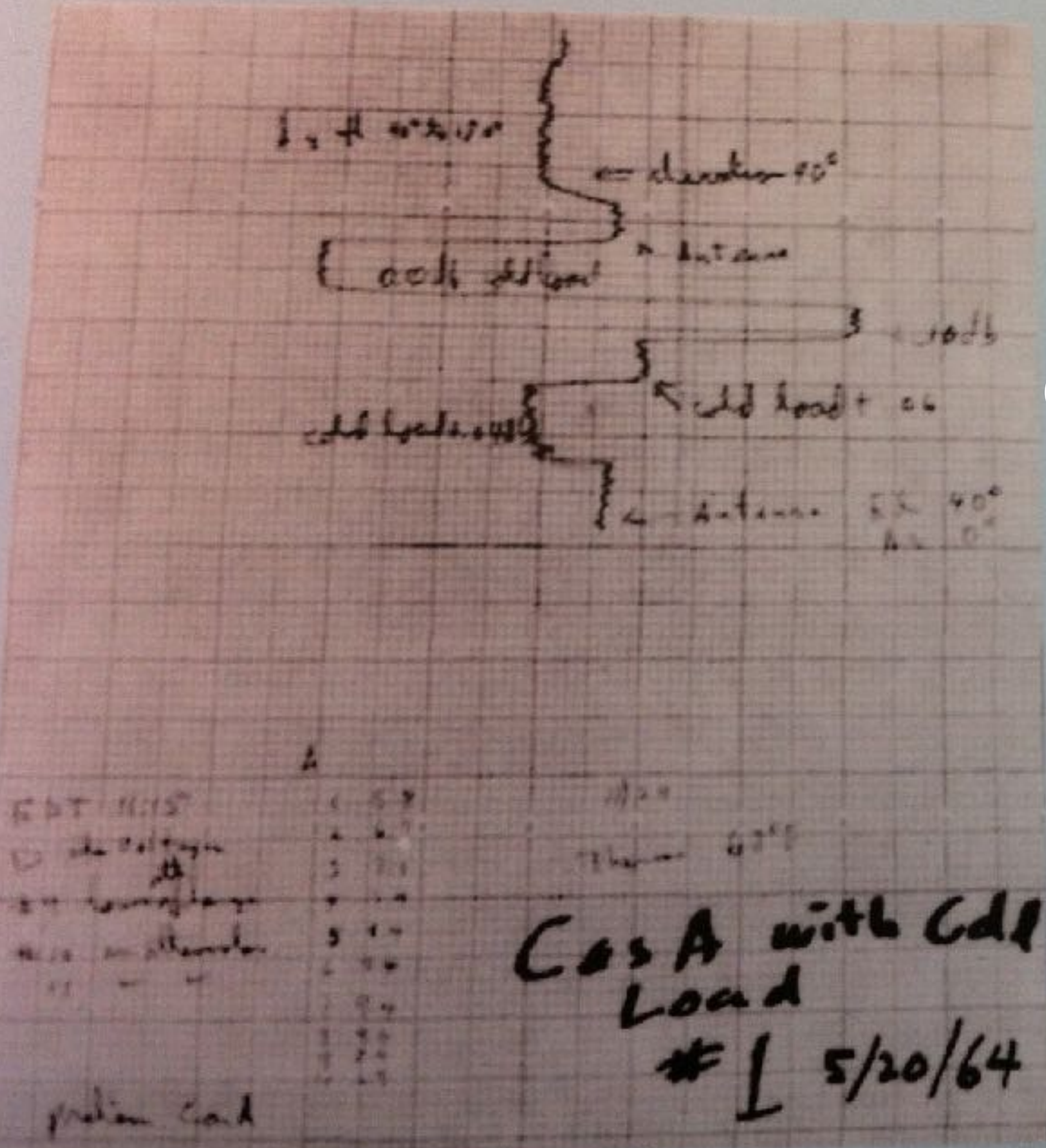
1:25 model of the antenna at Bell Lab
The 3rd floor of Deutsches Museum



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
Vergleichs-
quelle
V
M
M
MASER-Verstärker
Calibrator, cooled
to 5K by liquid helium
Amplifier
Recorder
Schreiber

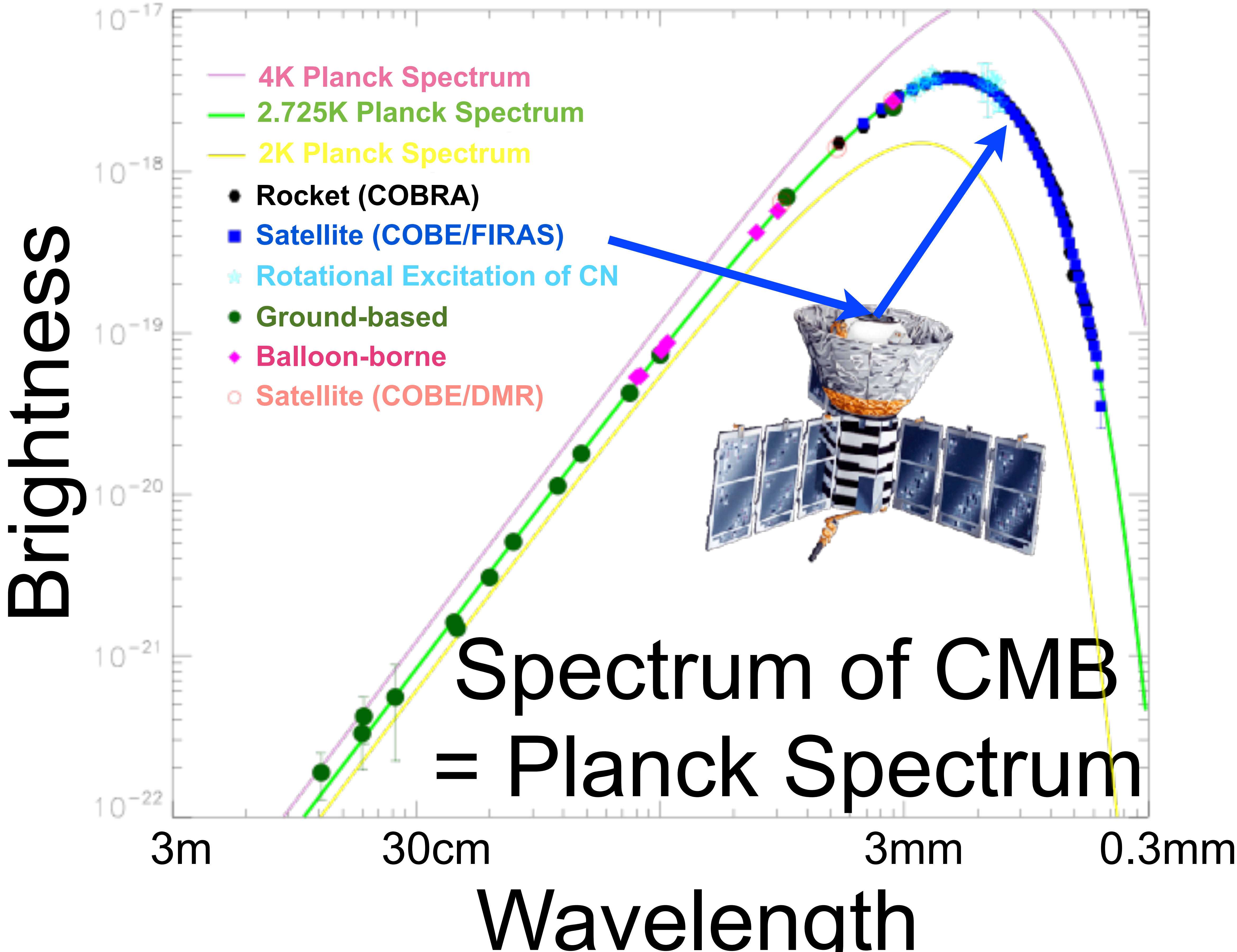
May 20, 1964 CMB Discovered



6.7–2.3–0.8–0.1 = 3.5±1.0 K

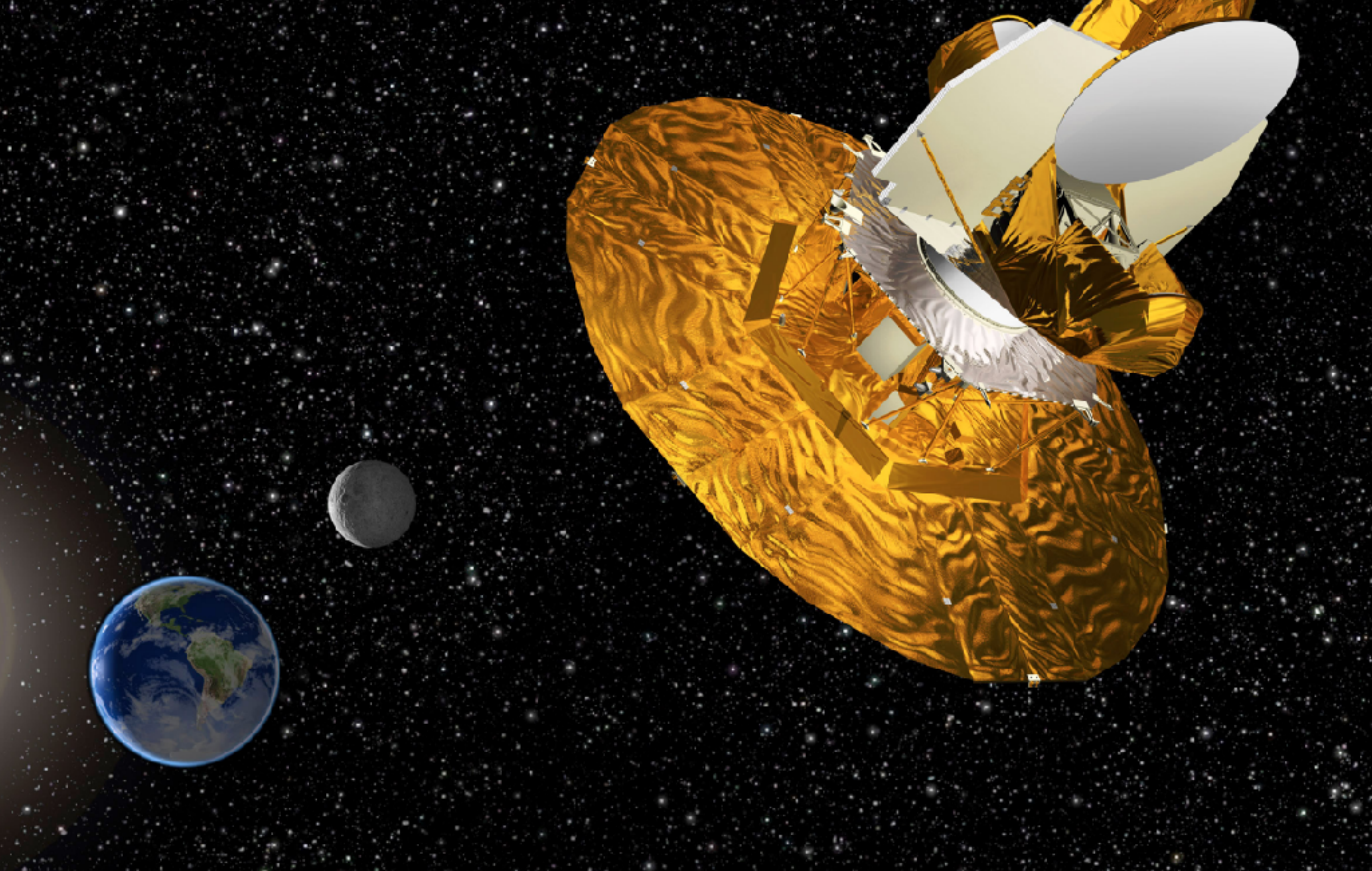
Schreiberaufzeichnung der ersten Messung des Mikrowellenhintergrundes am 20.5.1964

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



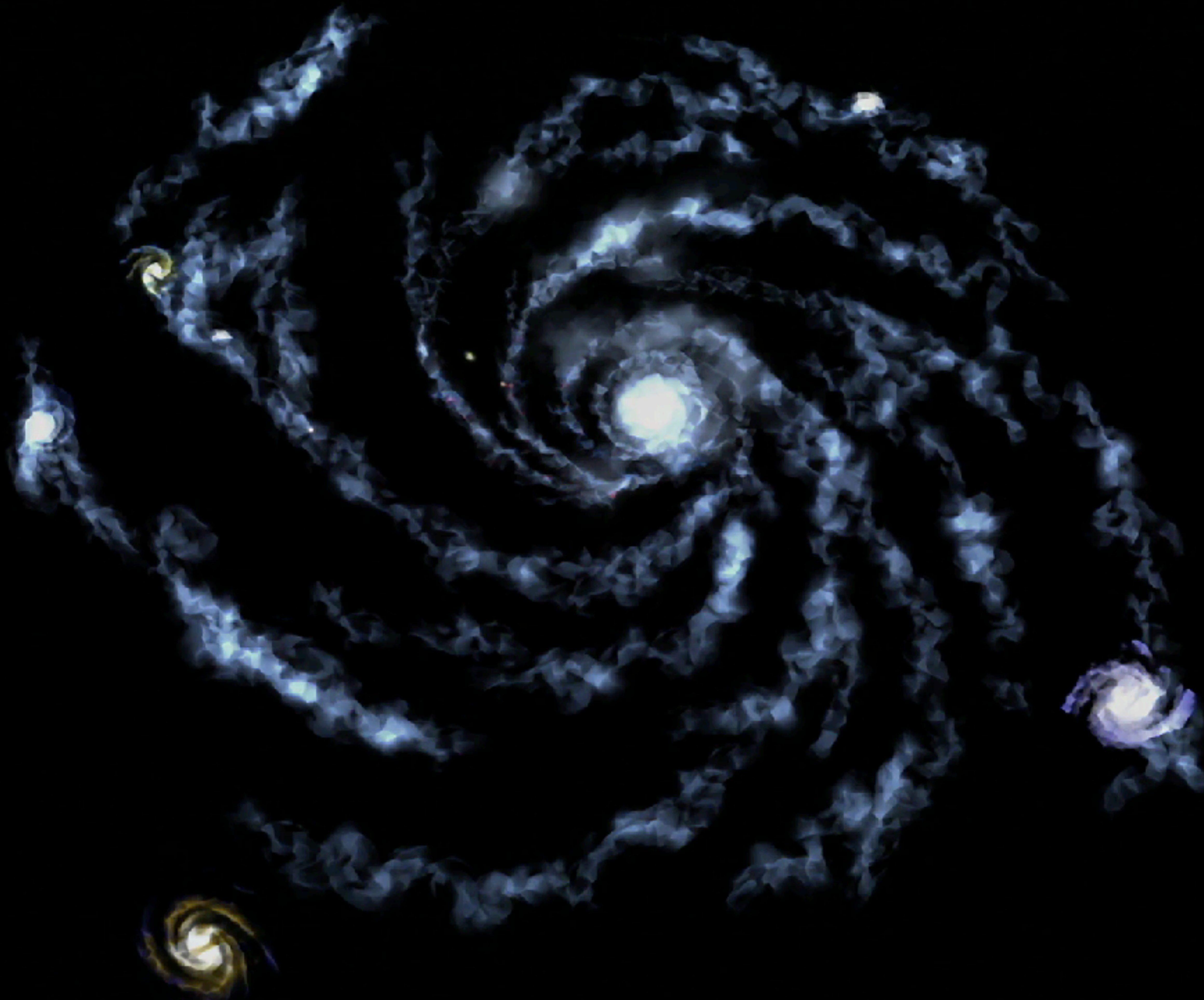
Spectrum of CMB
= Planck Spectrum

2001



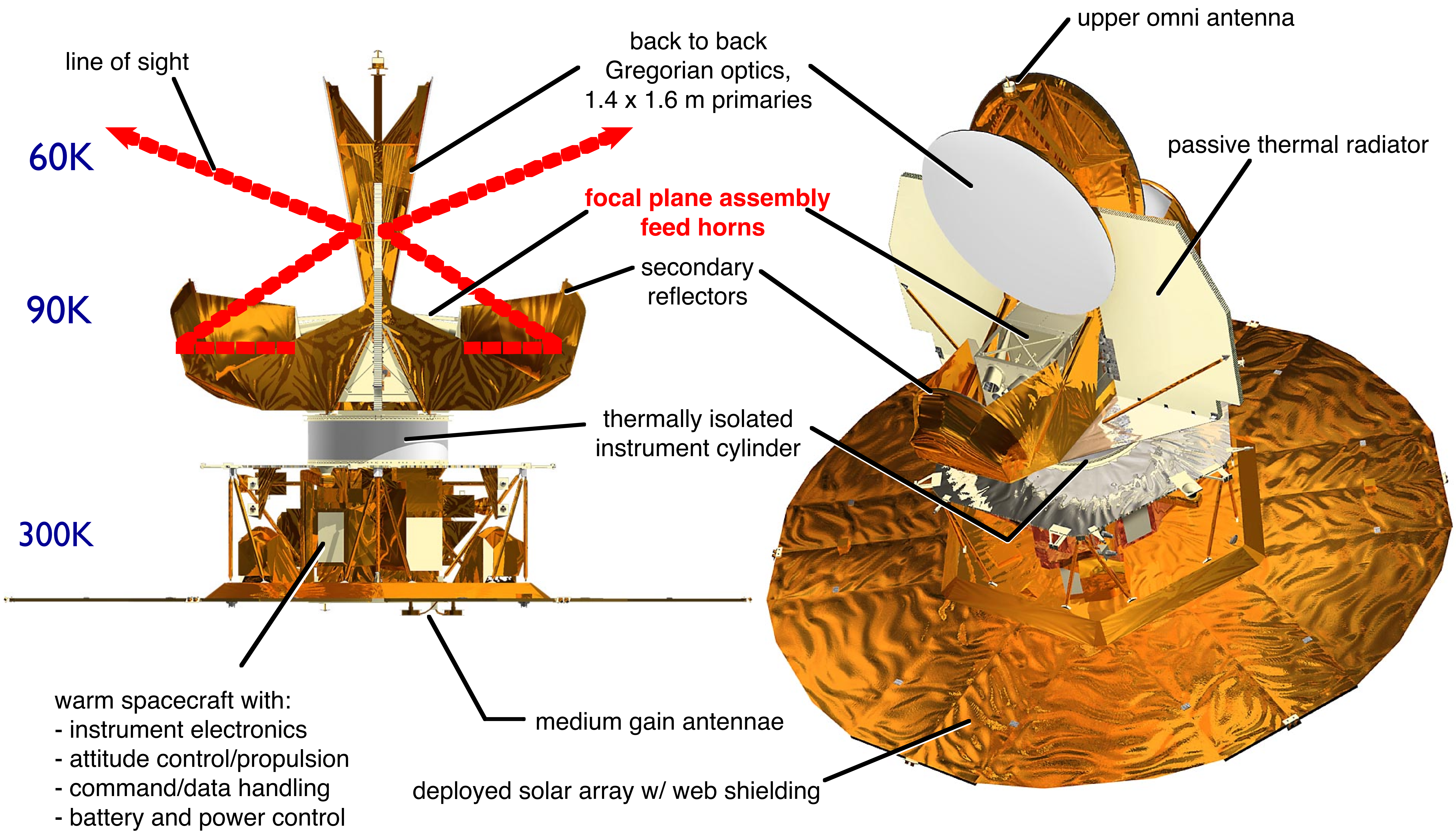
WMAP Science Team
July 19, 2002

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

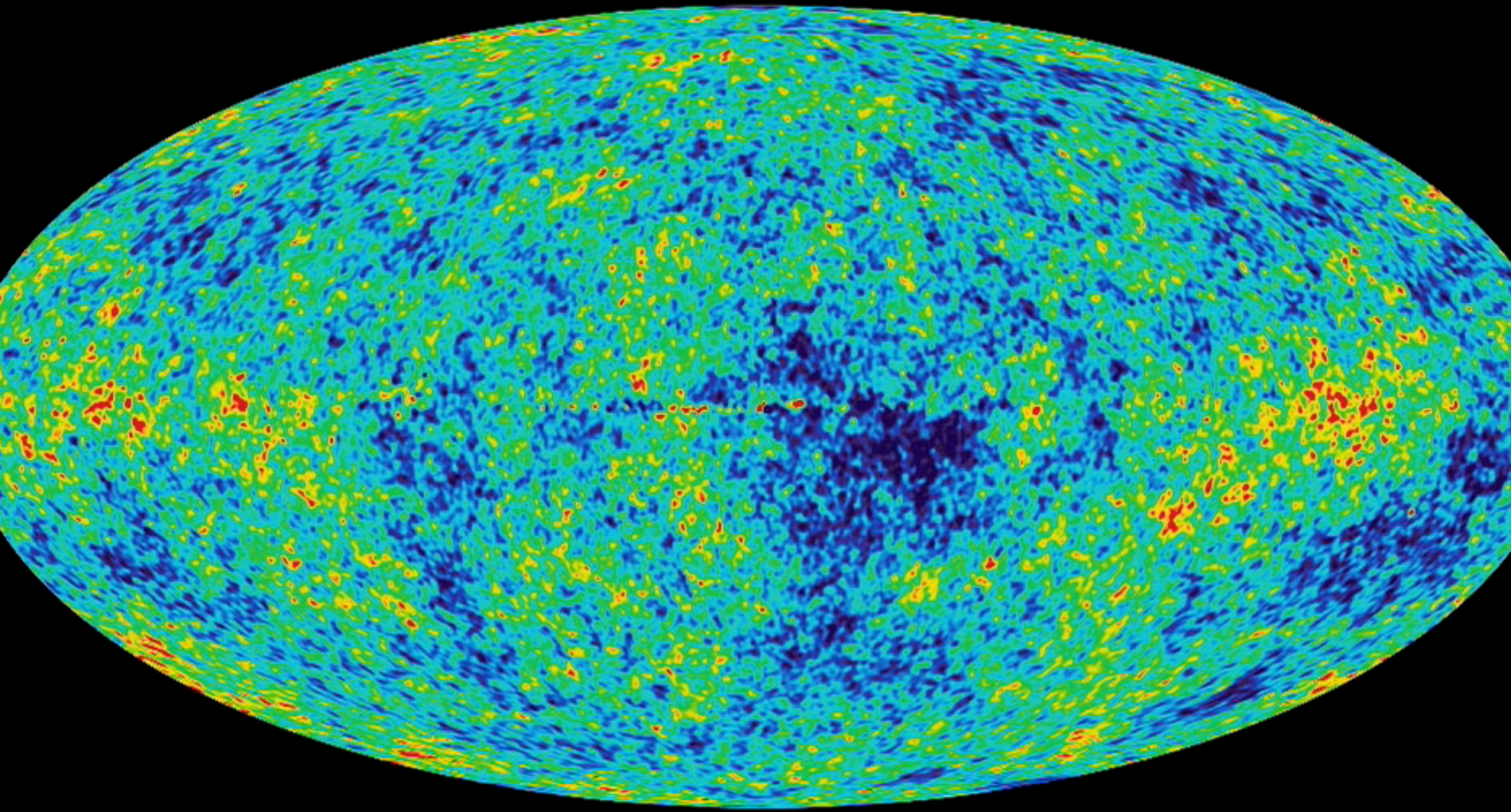


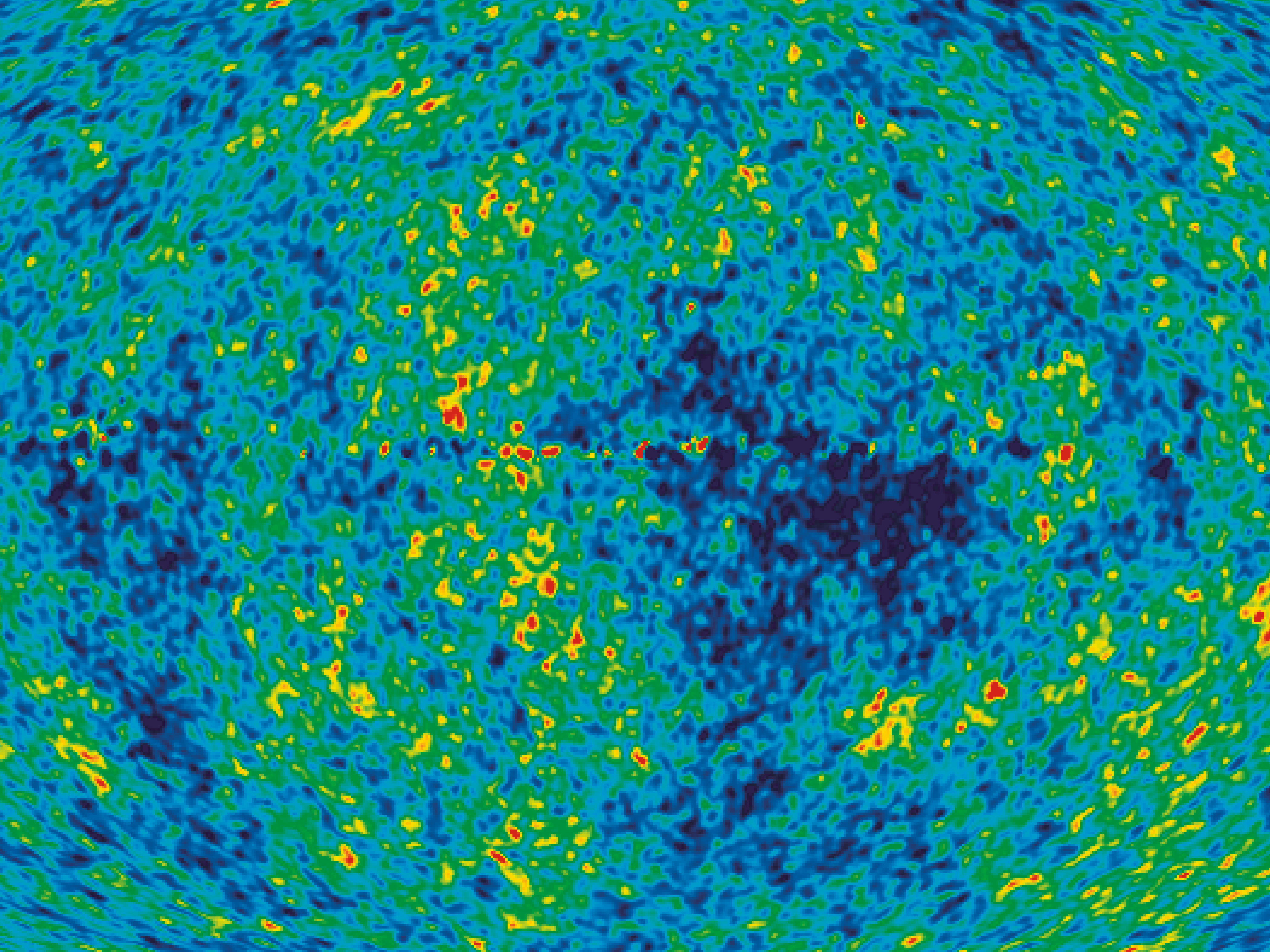
WMAP Spacecraft

No cryogenic components



MAP990422





Our Origin

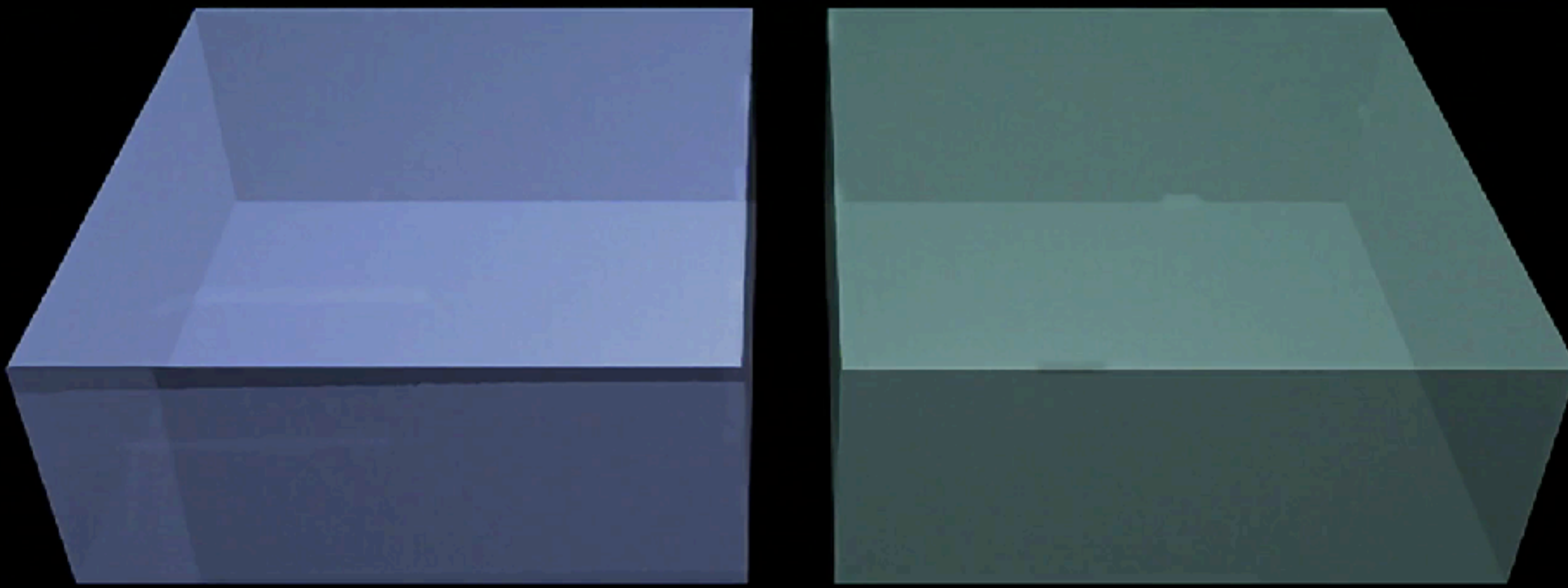
- WMAP taught us that **galaxies, stars, planets, and ourselves originated from tiny fluctuations in the early Universe**

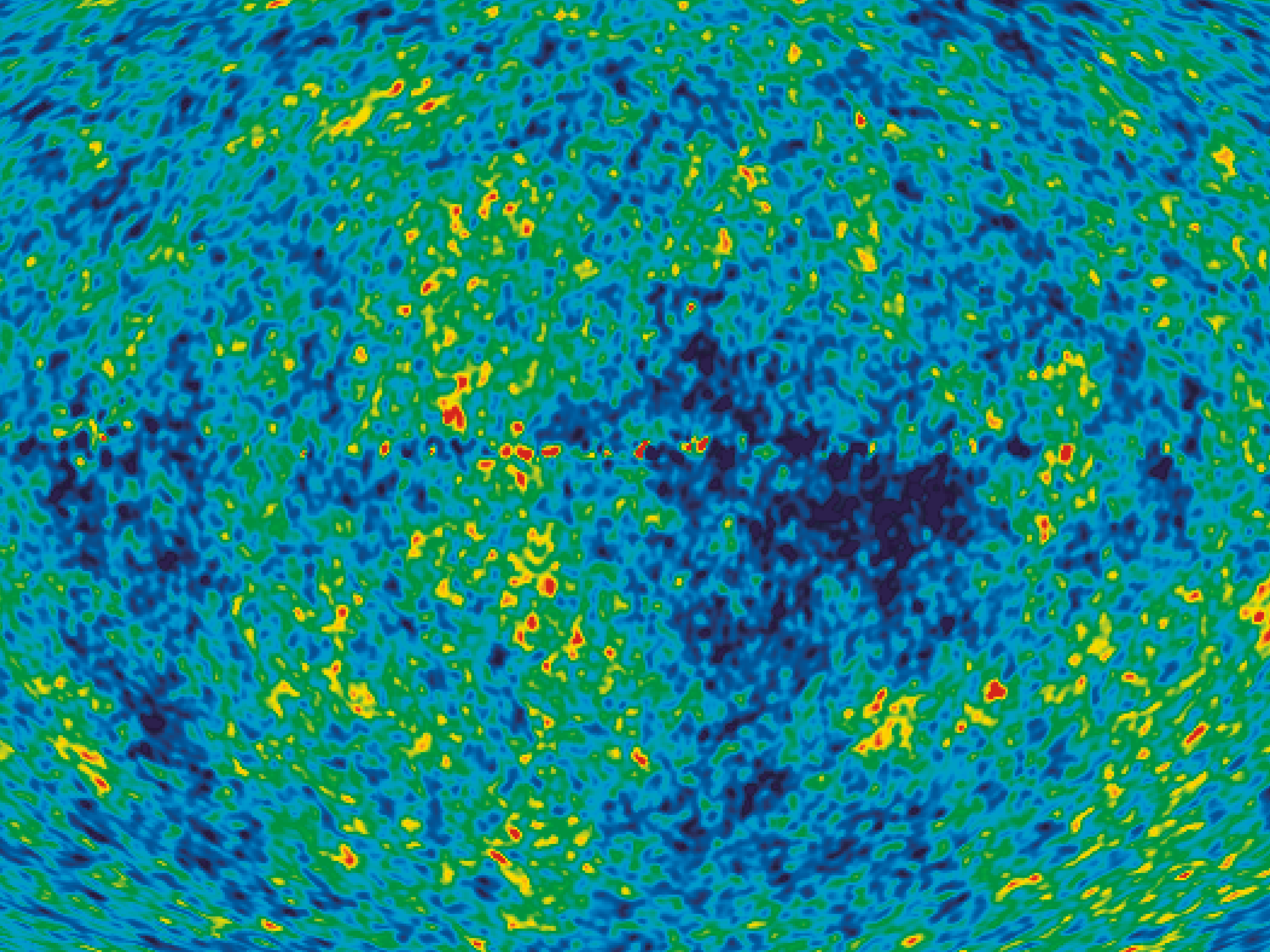
Sopa de Miso Cósmica

- 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

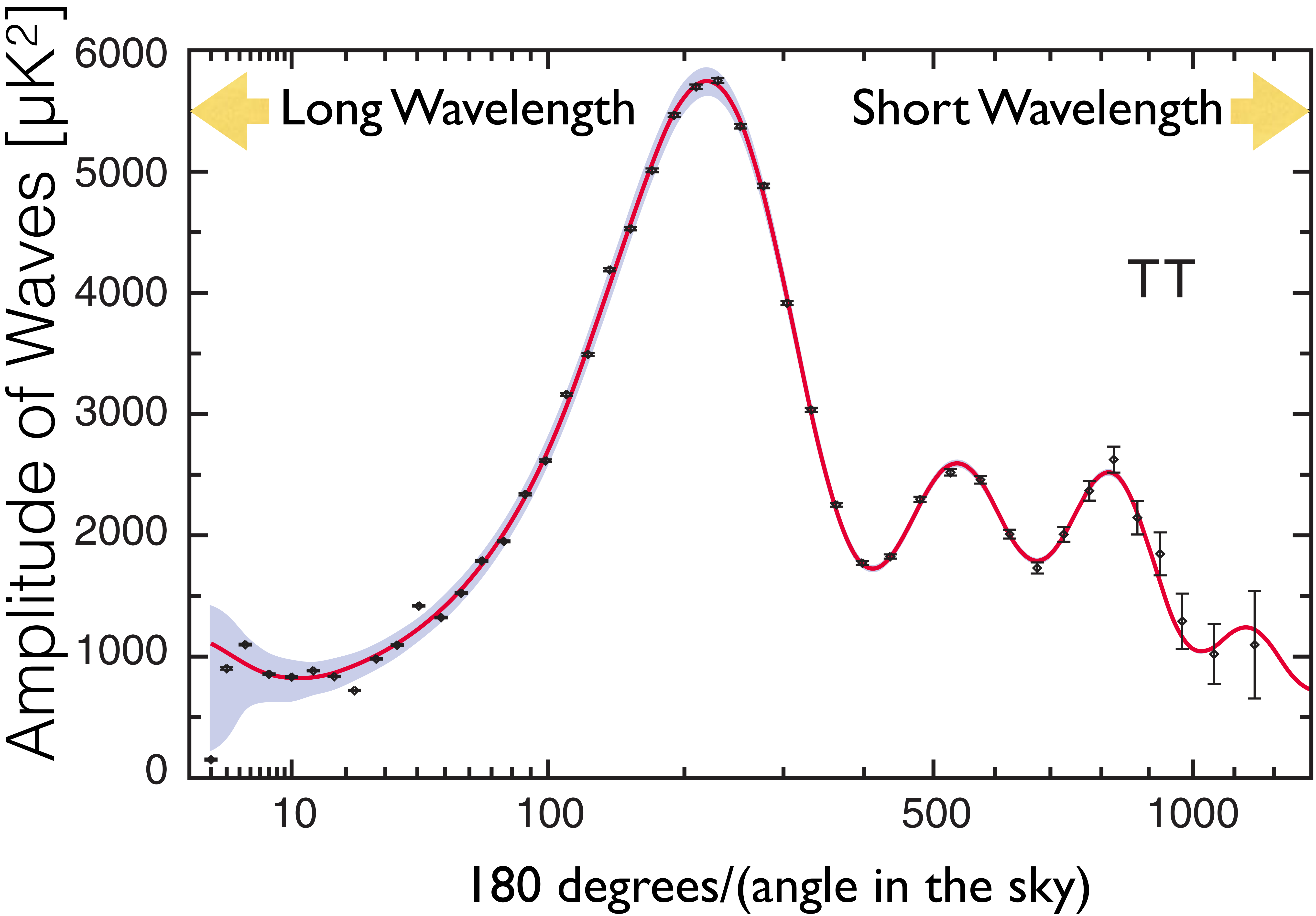
- And imagine watching how ripples are created and propagate throughout the soup



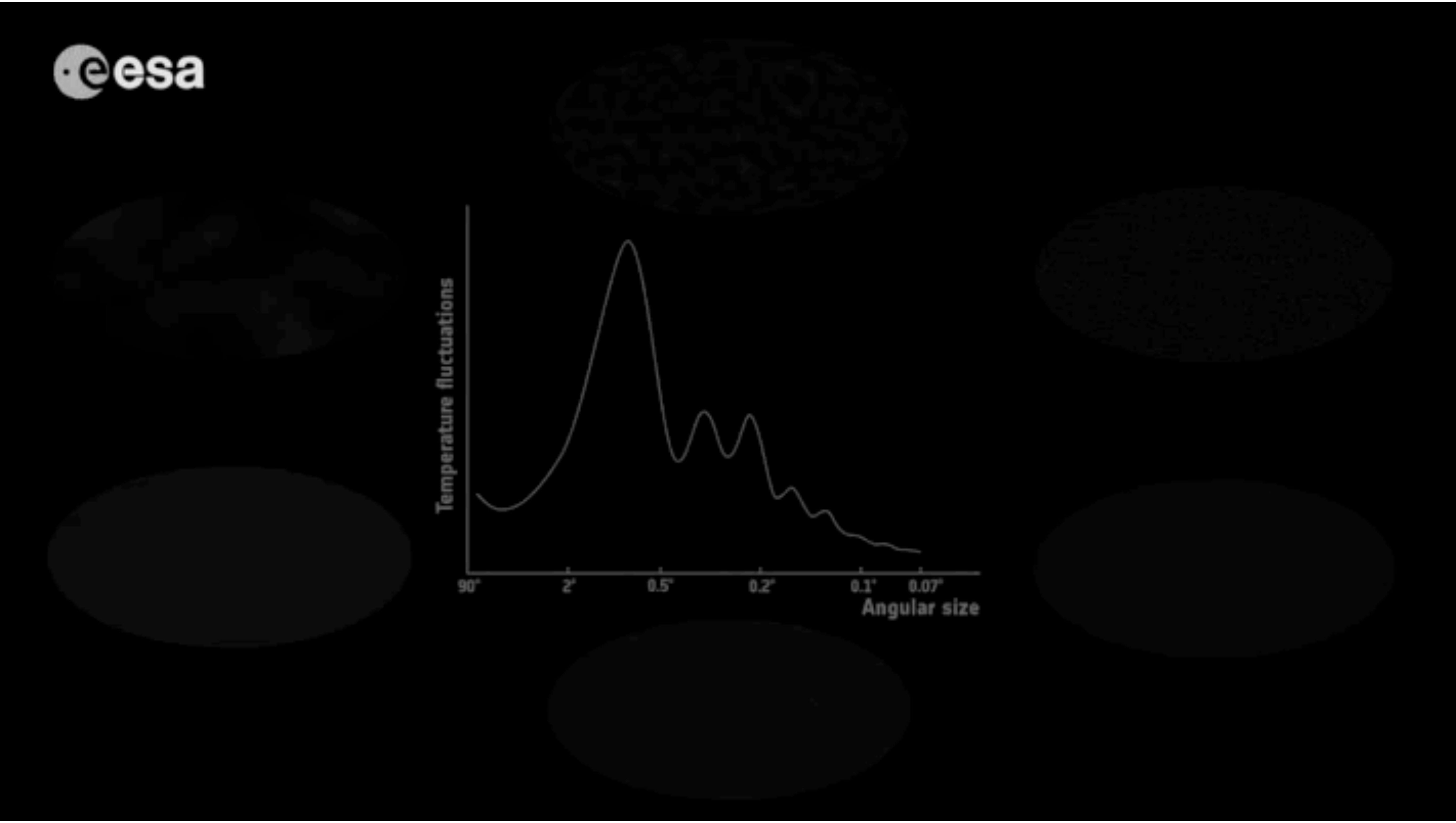


Data Analysis

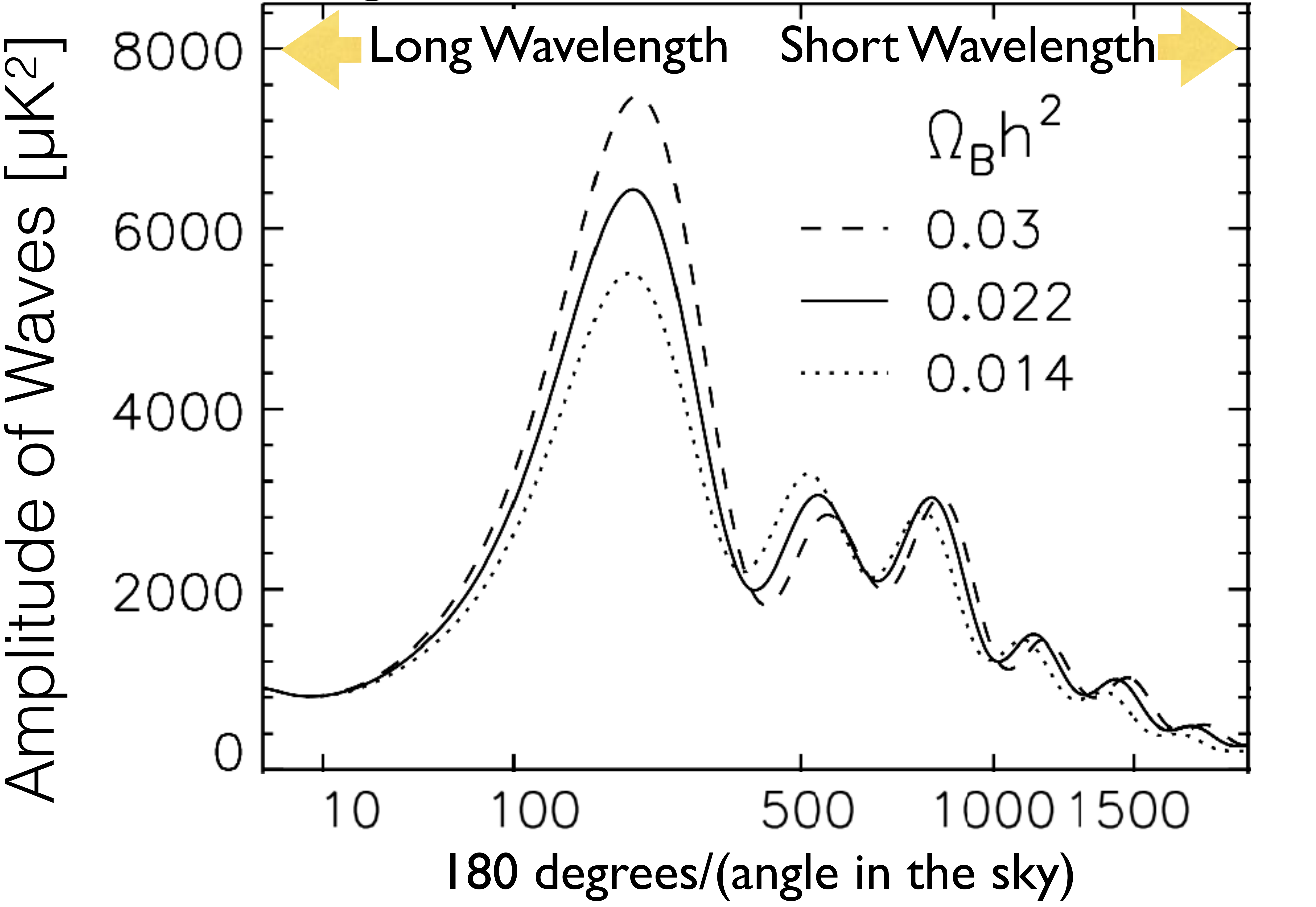
- Decompose temperature fluctuations in the sky into a set of waves with various wavelengths
- Make a diagram showing the strength of each wavelength



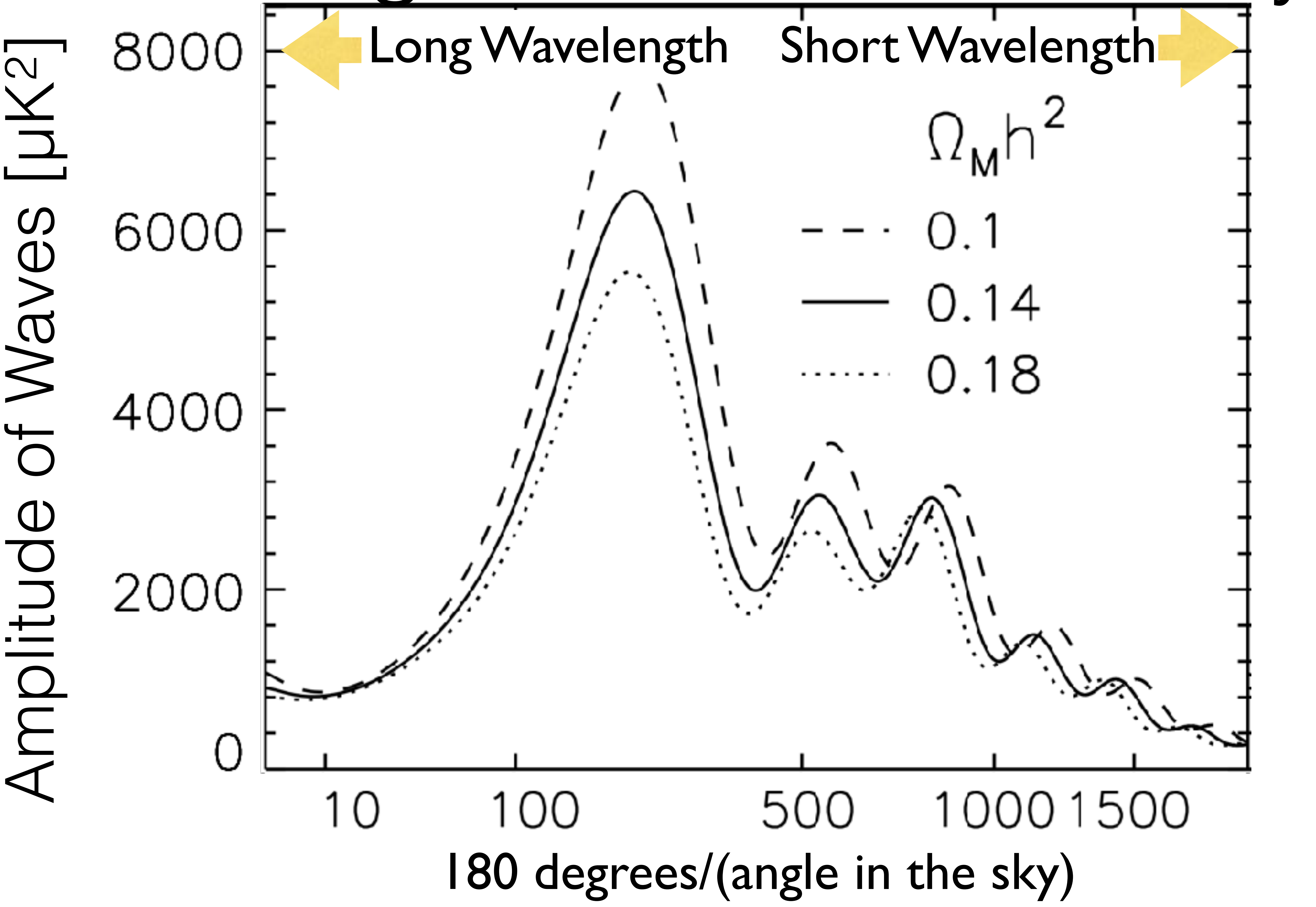
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
Short Wavelength
TT
10
100
500
1000
180 degrees/(angle in the sky)

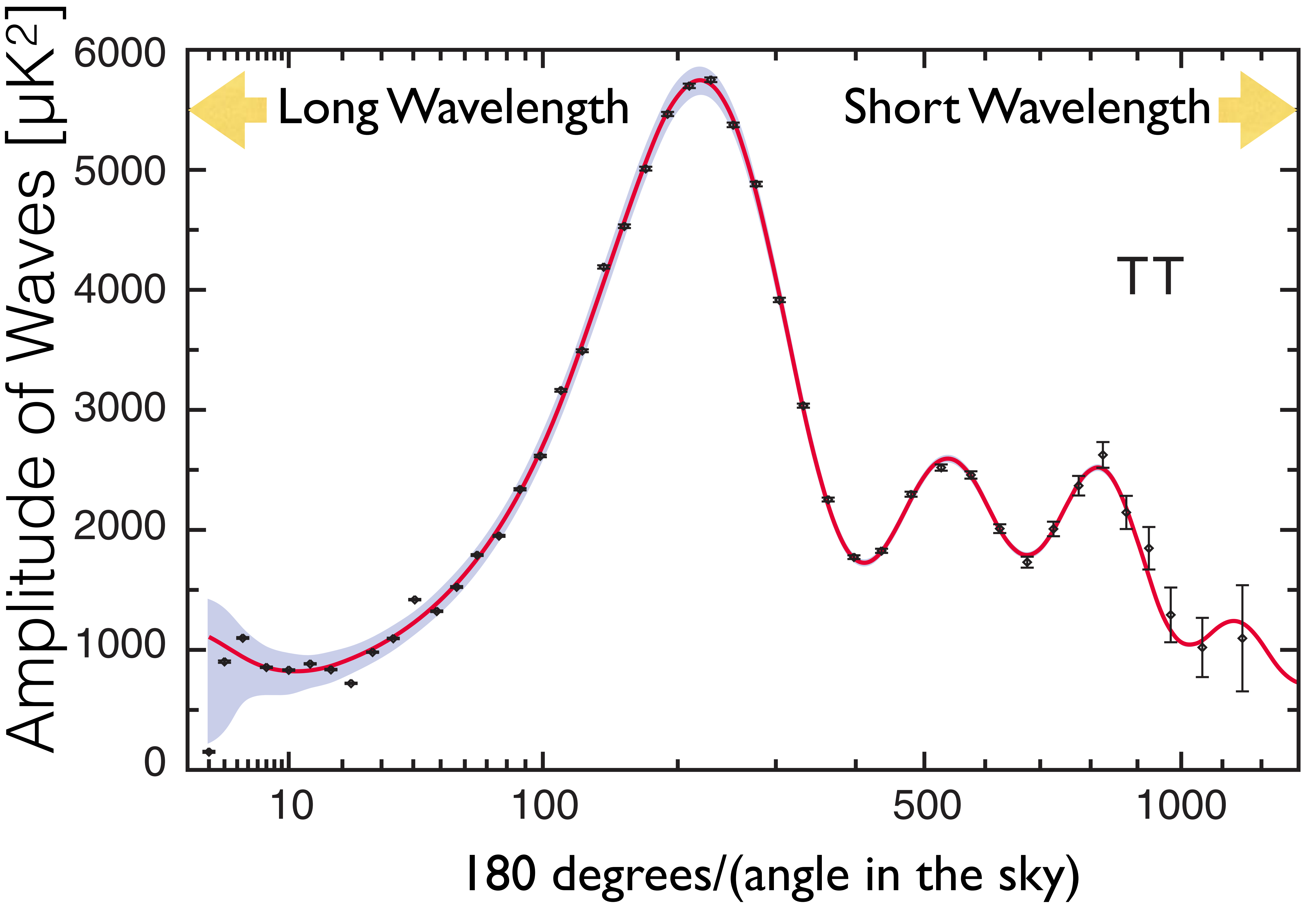

esa
Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size

Measuring Abundance of H&He



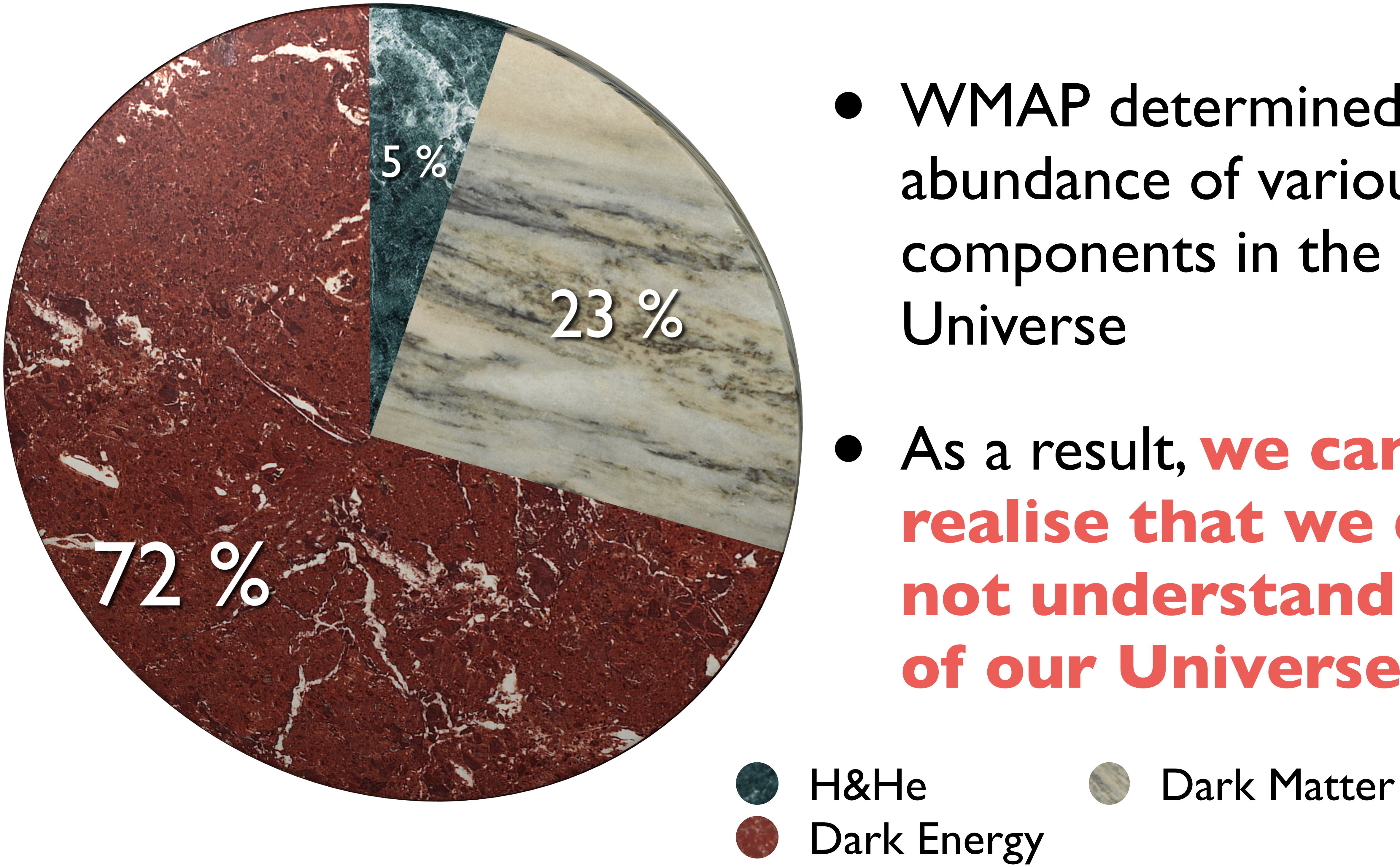
Measuring Total Matter Density





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

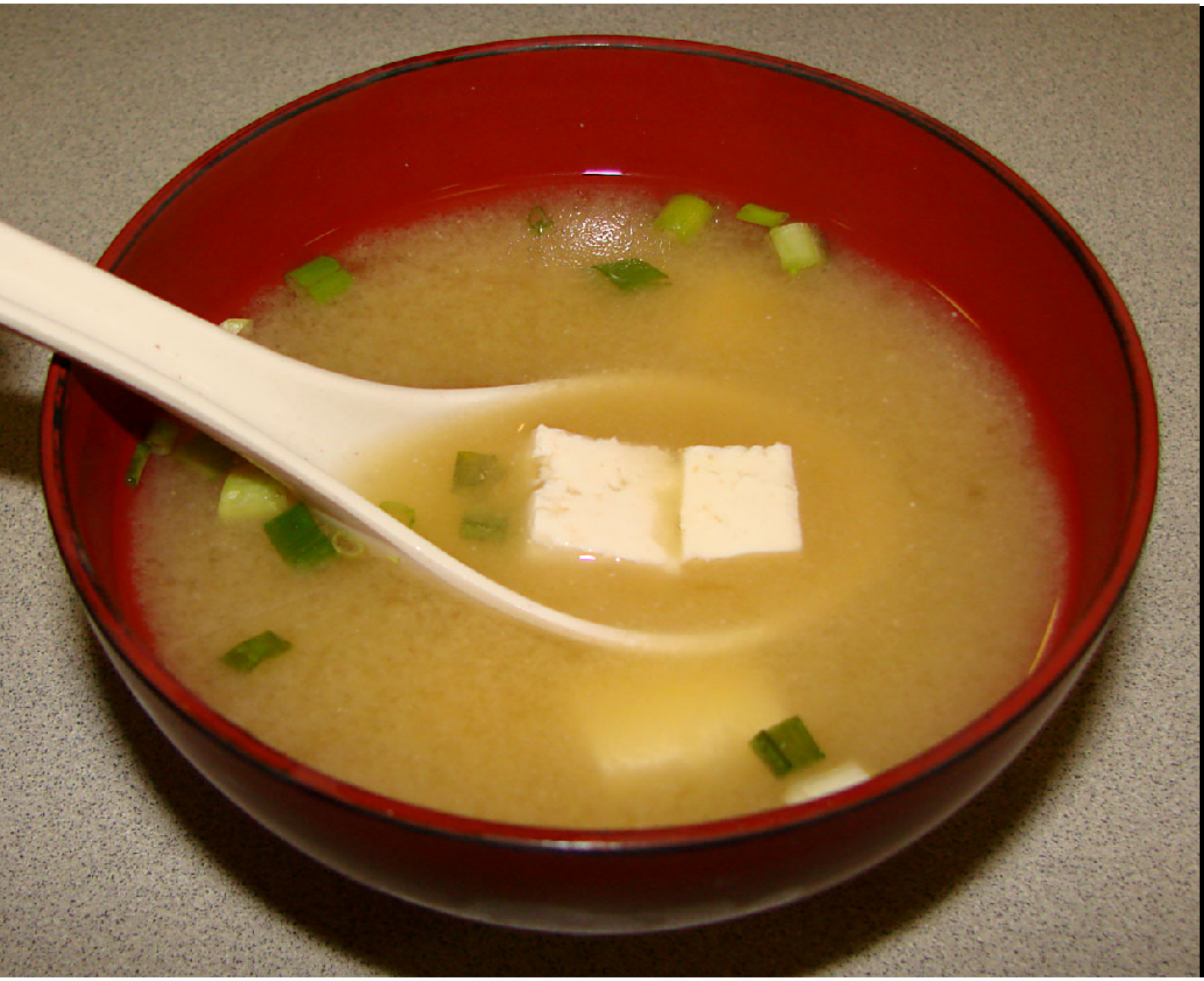
Cosmic Pie Chart

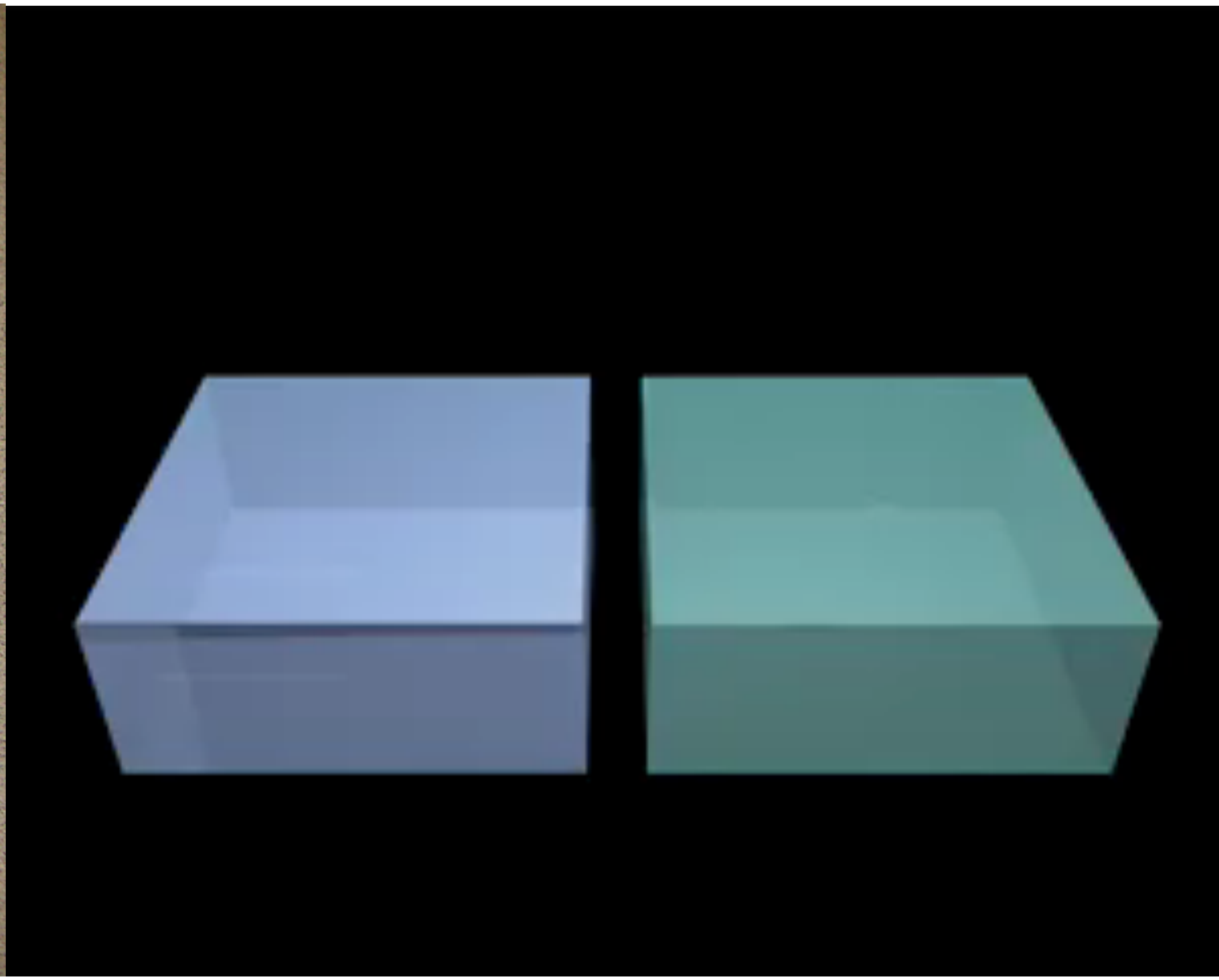


- WMAP determined the abundance of various components in the Universe
- As a result, **we came to realise that we do not understand 95% of our Universe...**

Origin of Fluctuations

- Who dropped those Tofus into the cosmic Miso soup?





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)

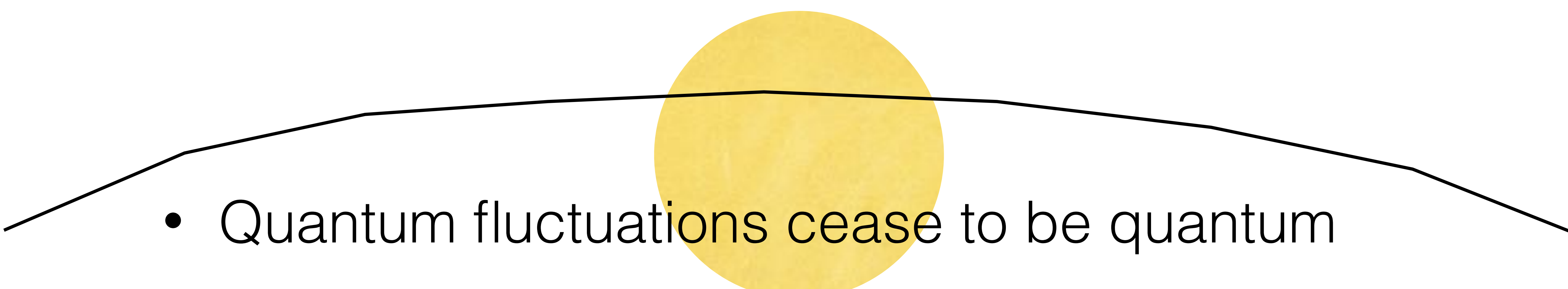
Cosmic Inflation

- 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!



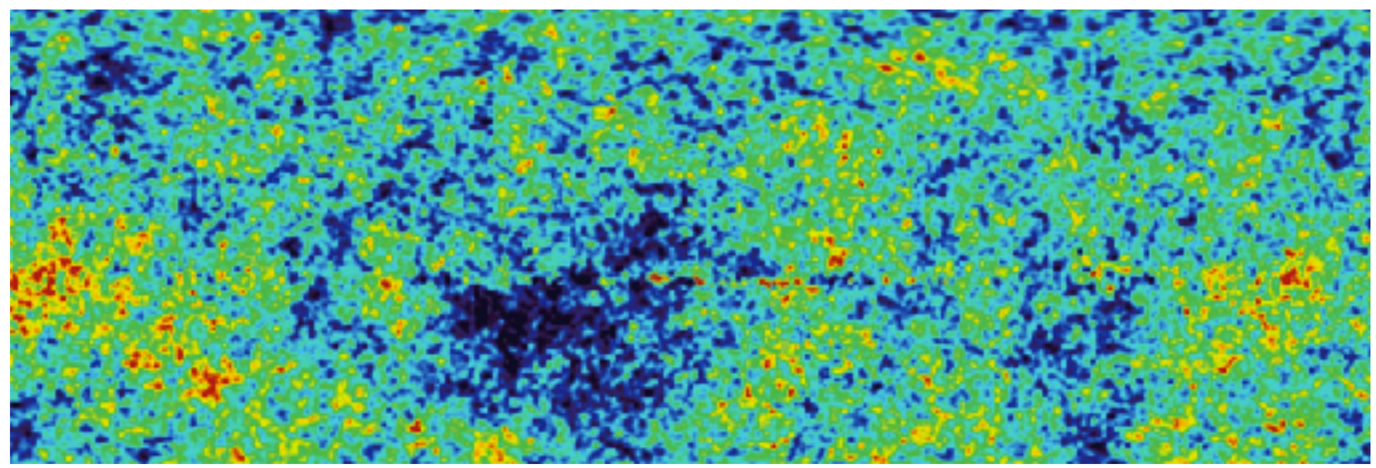
- Quantum fluctuations cease to be quantum
- Become macroscopic, classical fluctuations

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

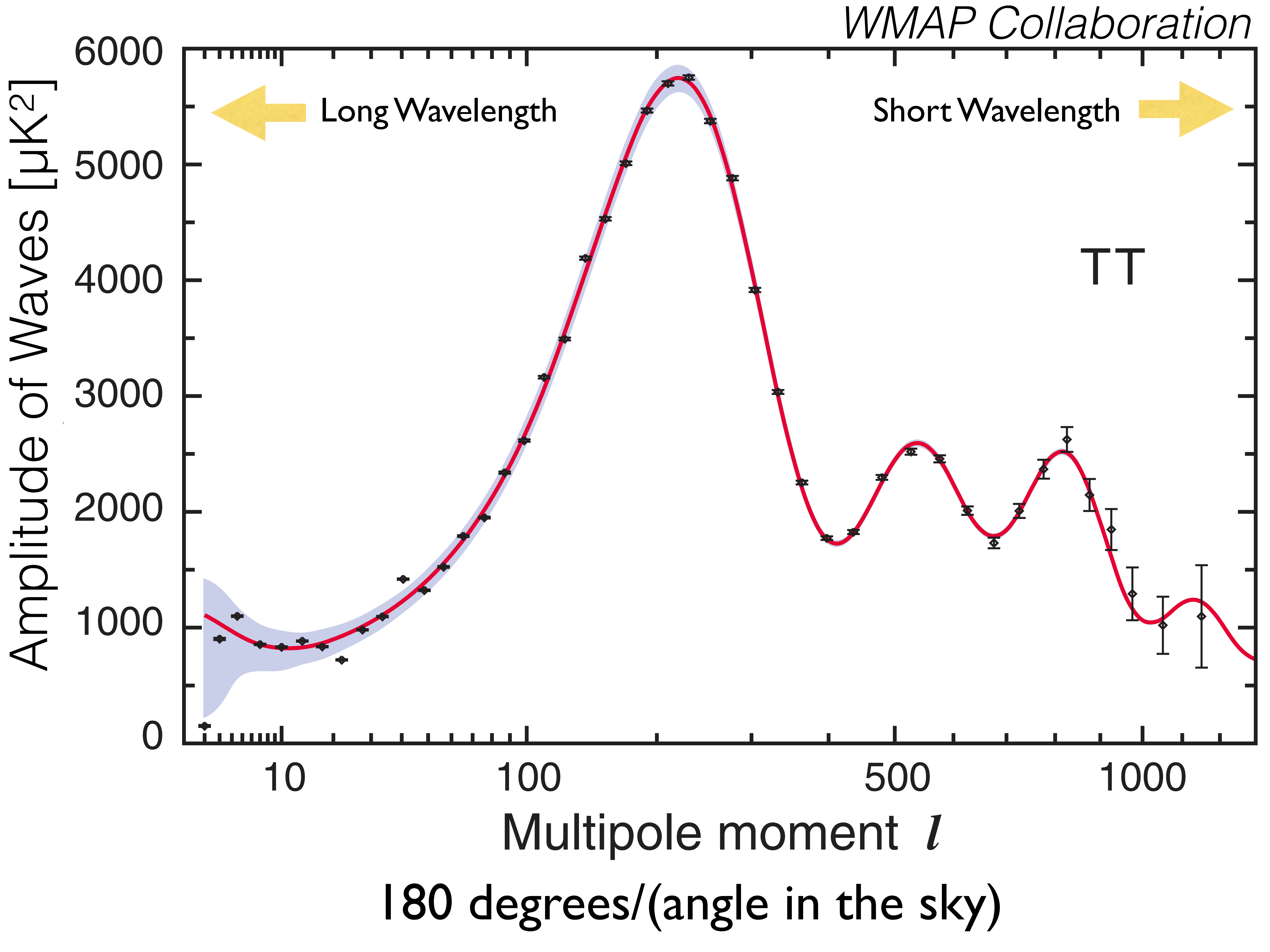
- Suppose that the distance between two points increases in proportion to **a(t)** [which is called the scale factor] by the expansion of the universe

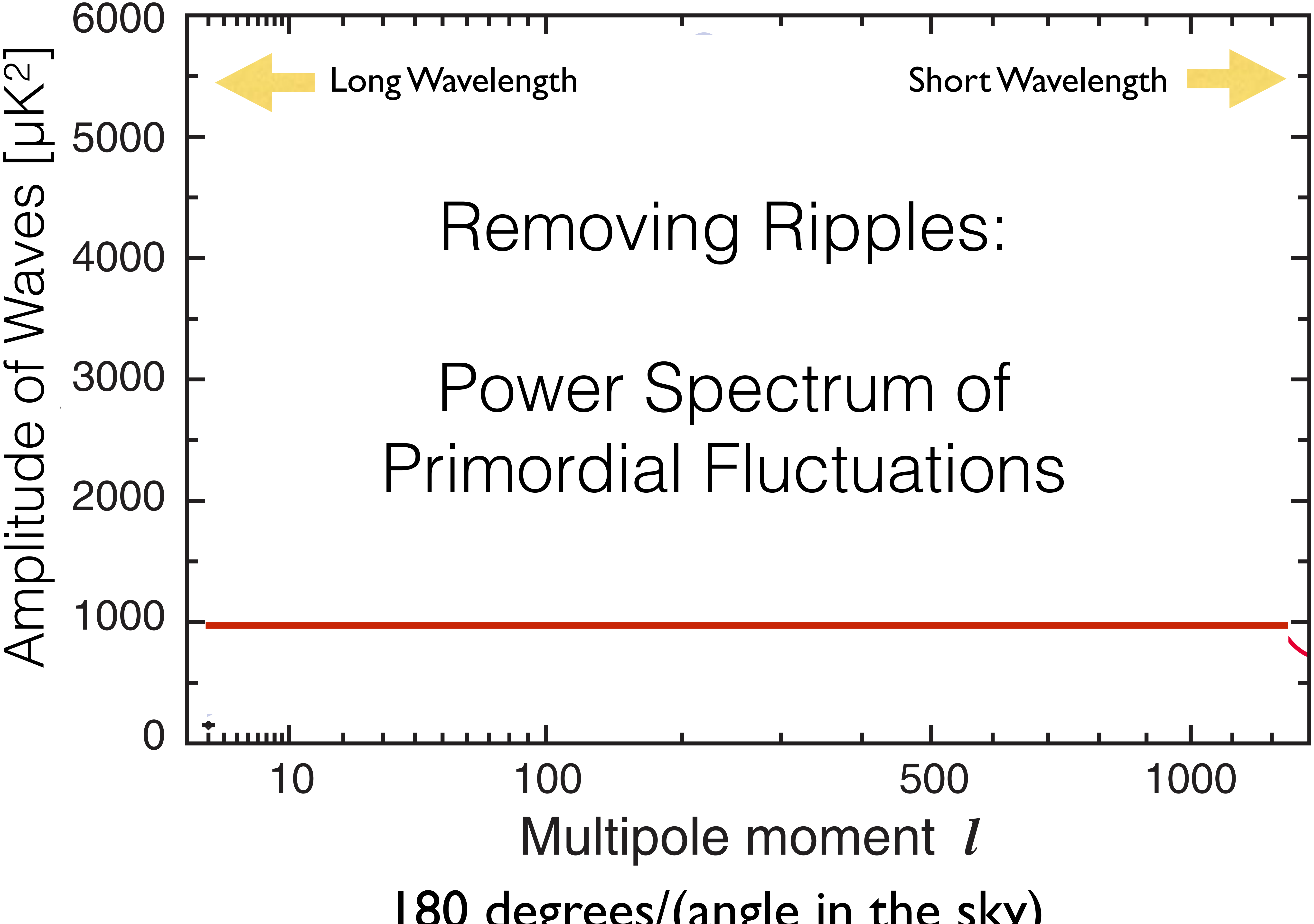
- Define the "expansion rate of the universe" as

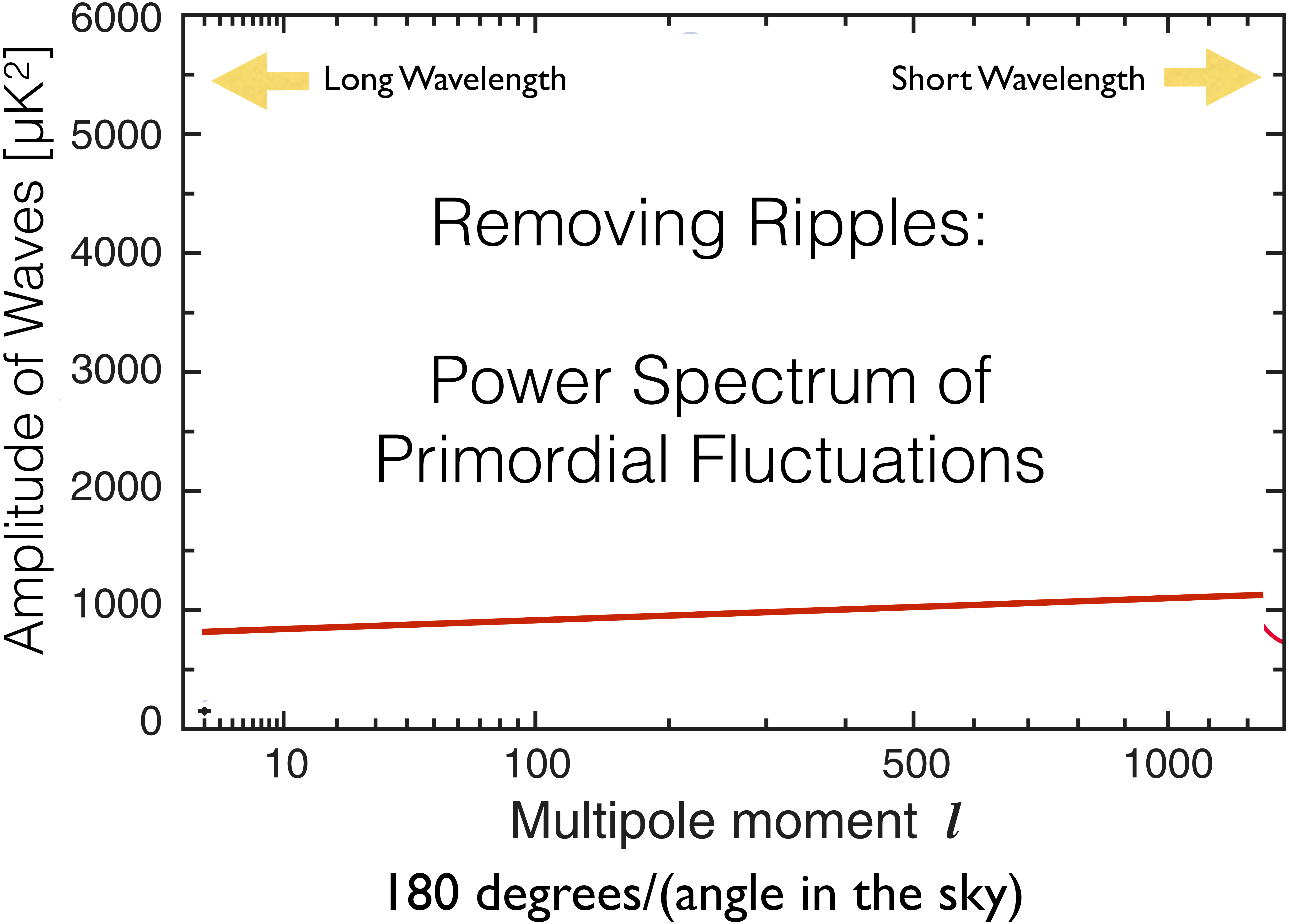
$$H \equiv \frac{\dot{a}}{a}$$ [This has units of 1/time]

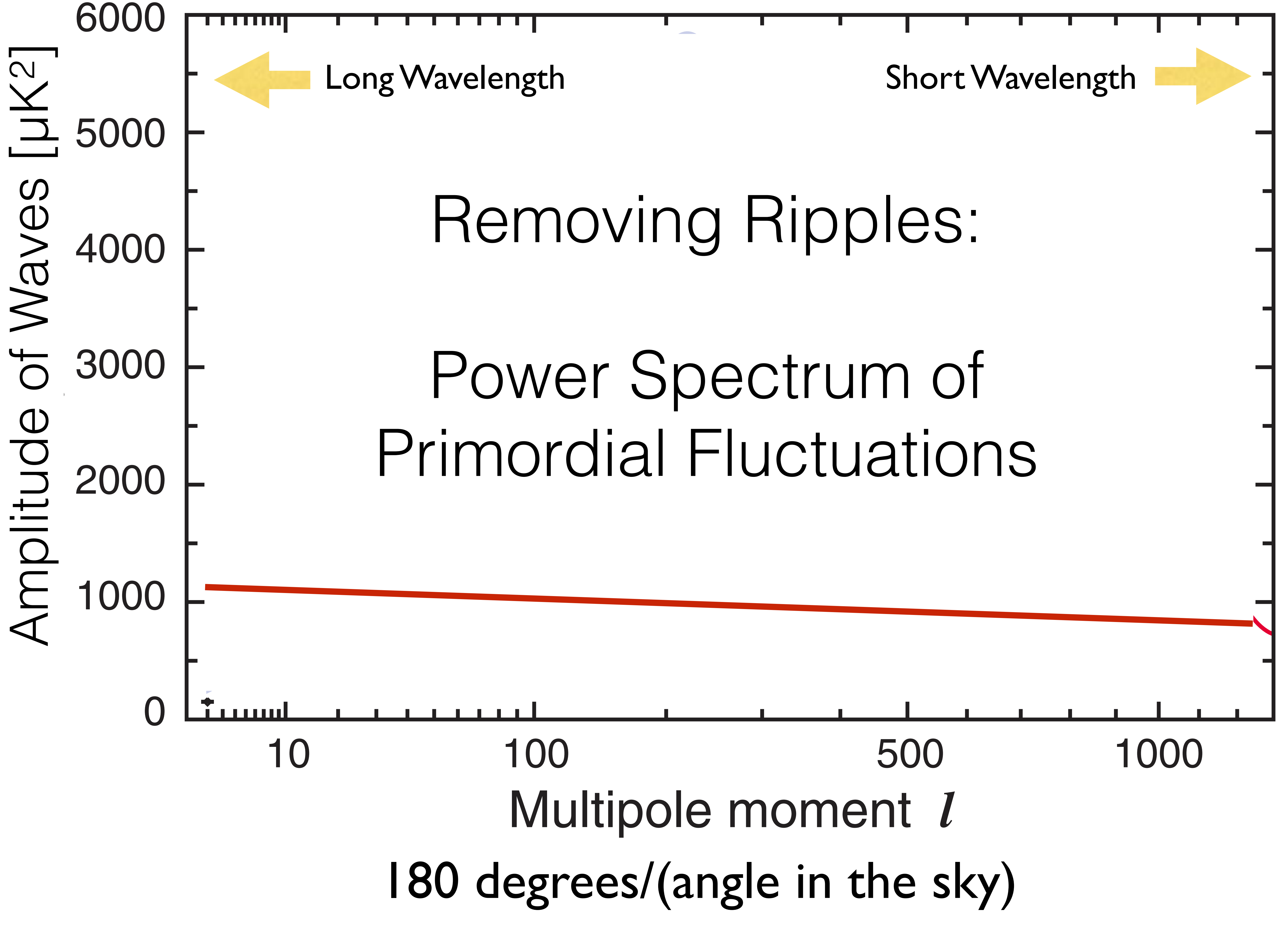
Fluctuations are proportional to H

- [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**

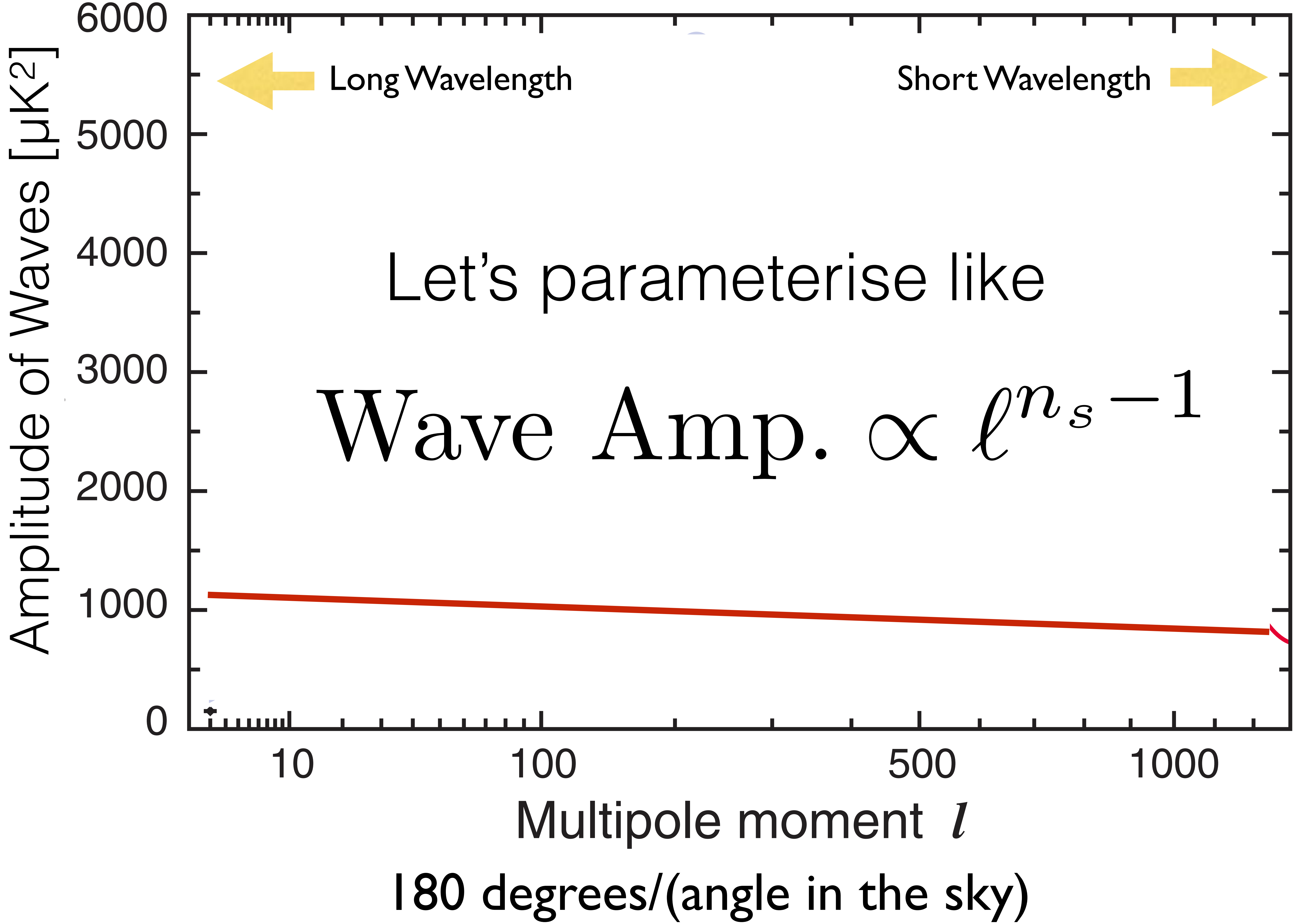

WMAP Collaboration
Long Wavelength
Short Wavelength
TT
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

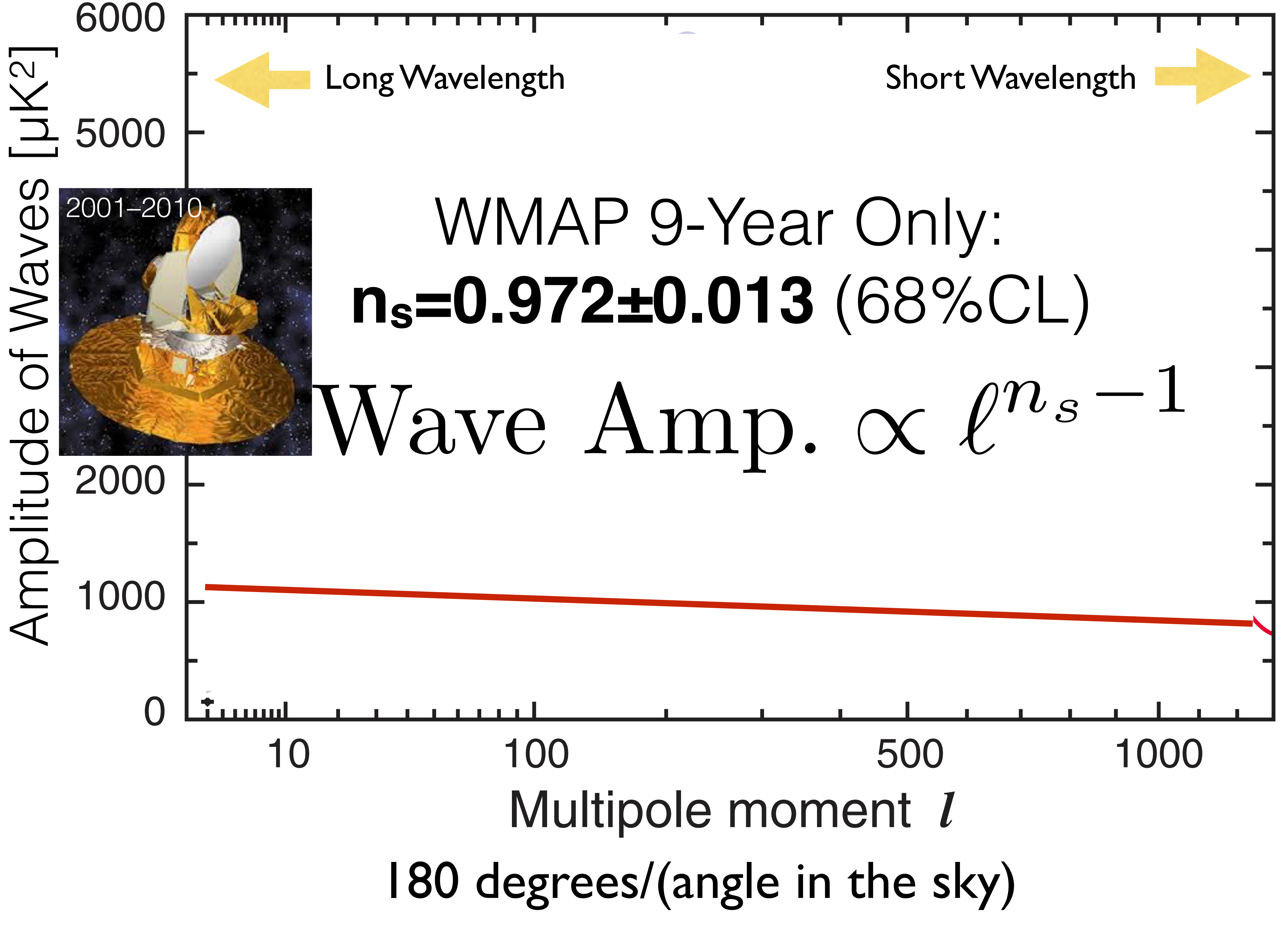

6000
5000
4000
3000
2000
1000
0
Amplitude of Waves [μK²]
Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)


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

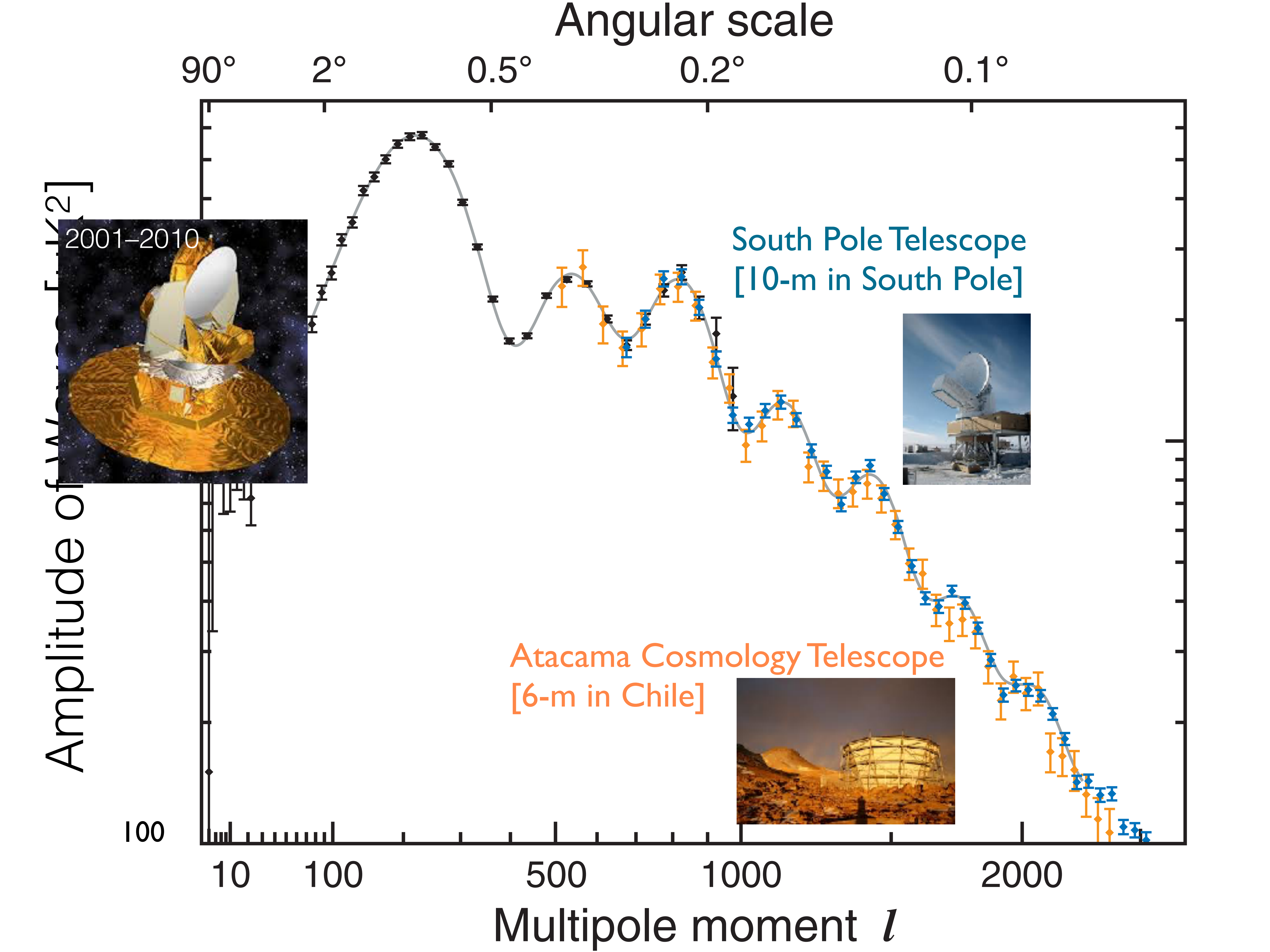


Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

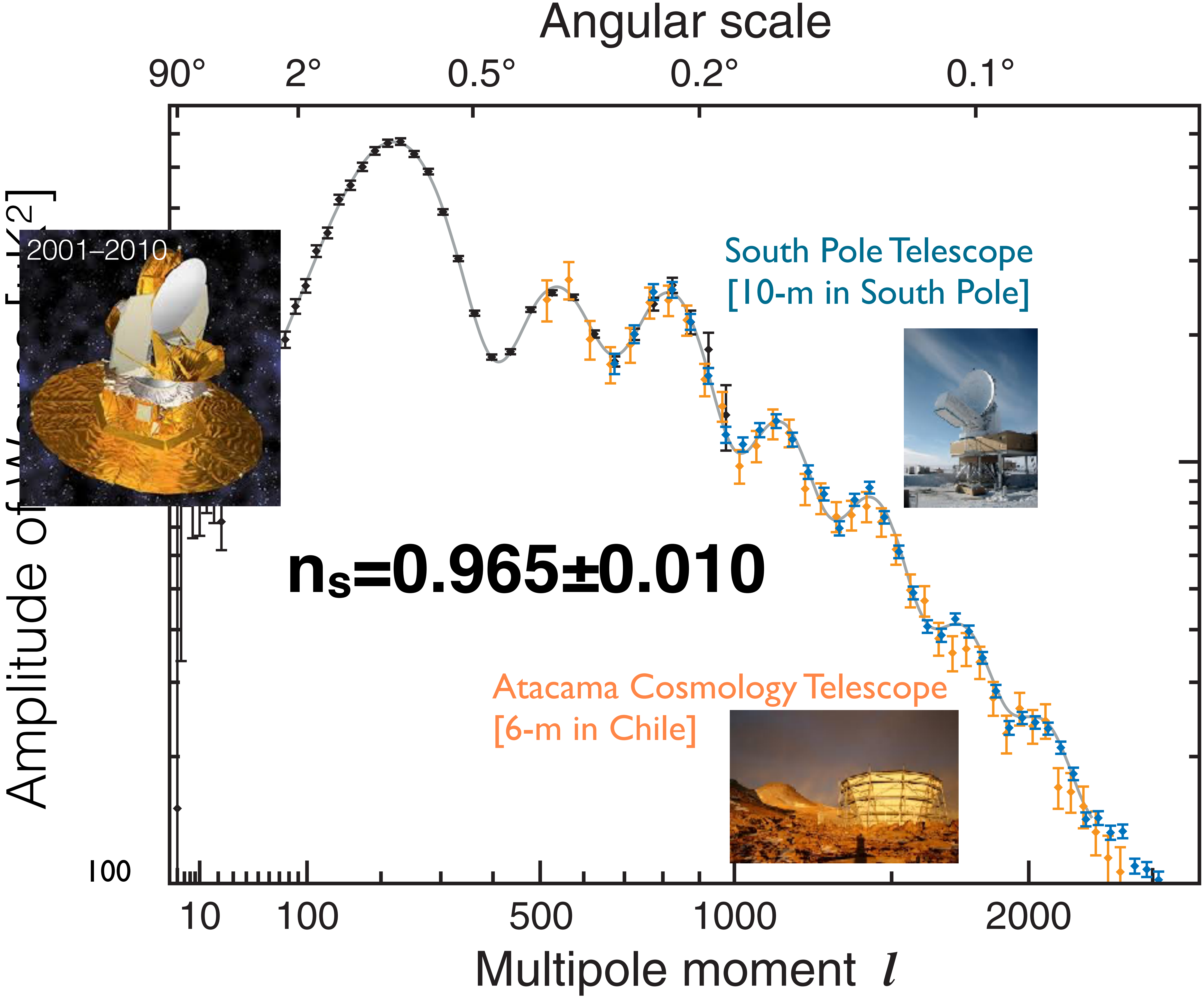

6000
5000
4000
3000
2000
1000
0
Amplitude of Waves [μK²]
Long Wavelength
Short Wavelength
Let's parameterise like
Wave Amp. $\propto \ell^{n_s - 1}$
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



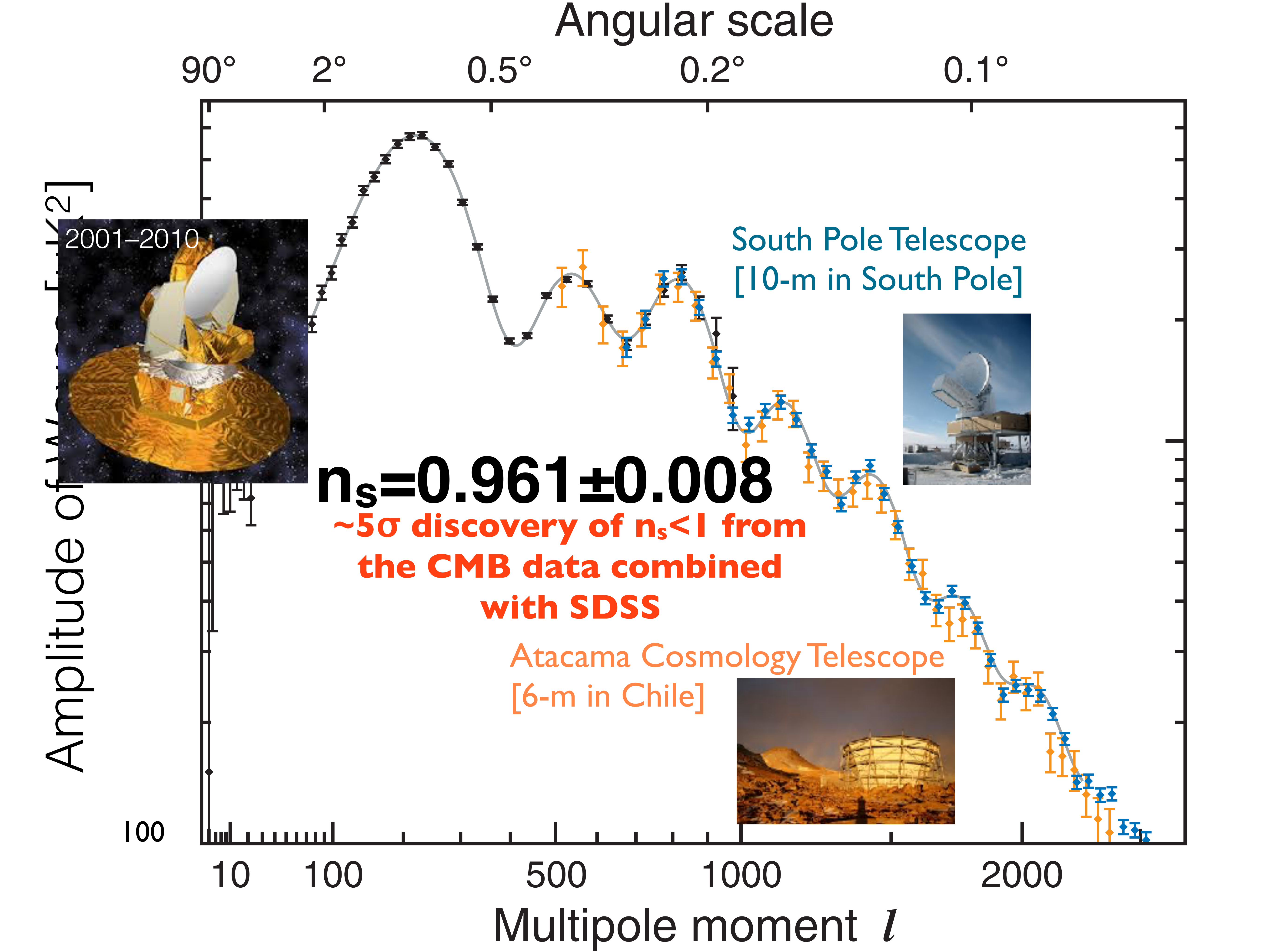
Long Wavelength
Short Wavelength
2001–2010
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
$\text{Wave Amp.} \propto \ell^{n_s-1}$
Amplitude of Waves [μK^2]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

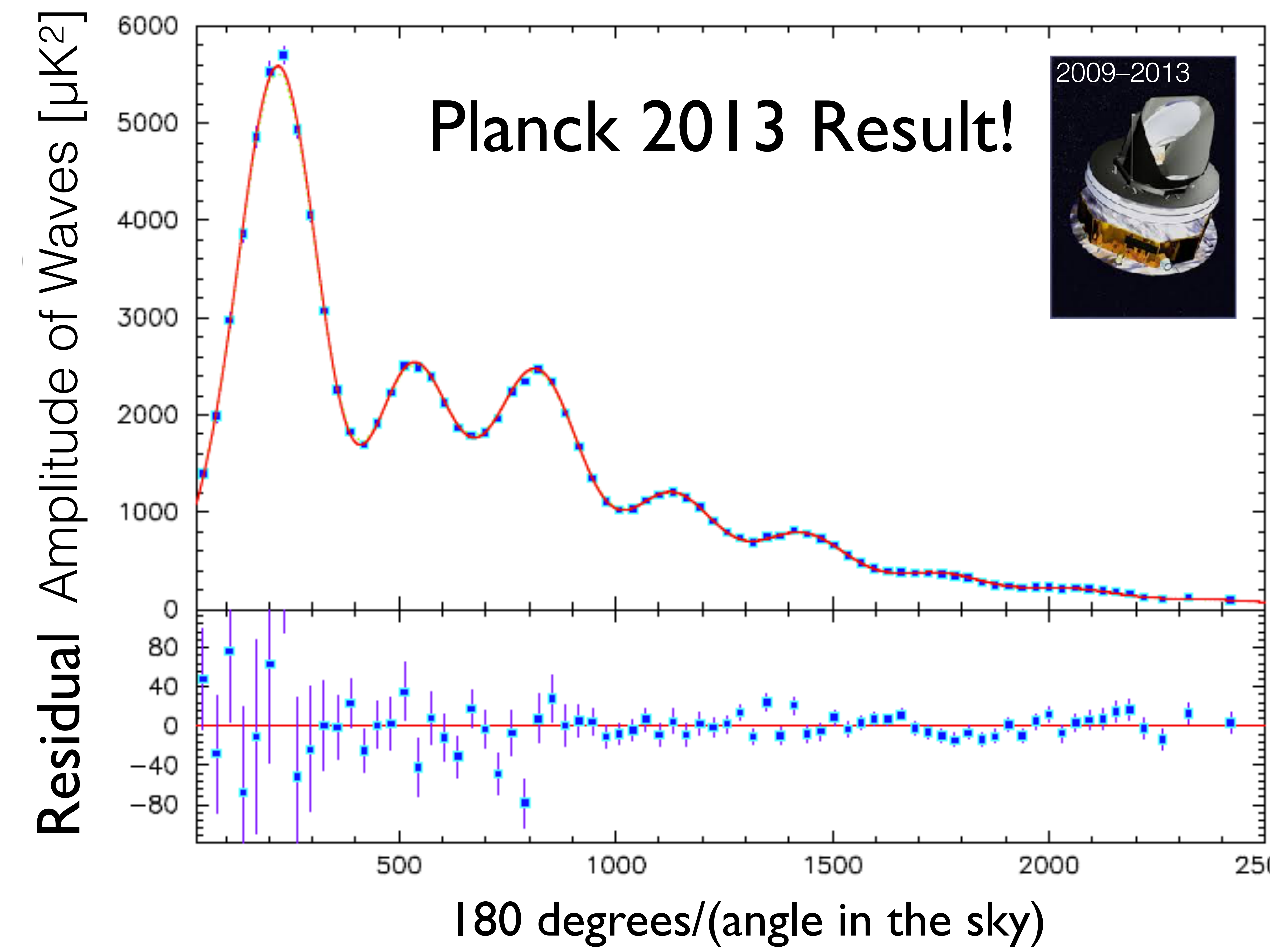


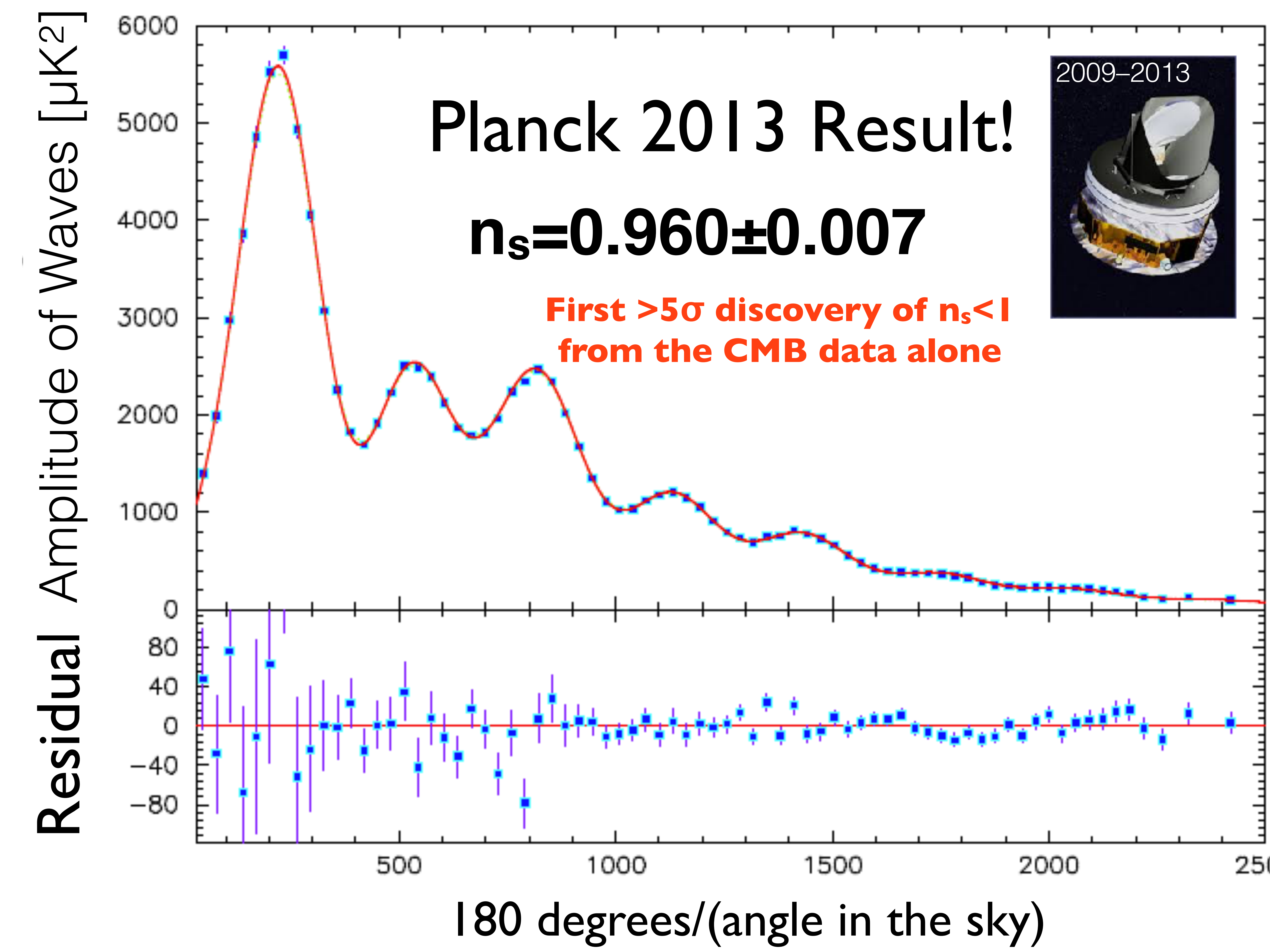
Angular scale
90°
2°
0.5°
0.2°
0.1°
South Pole Telescope
[10-m in South Pole]
2001–2010
Atacama Cosmology Telescope
[6-m in Chile]
Amplitude of
100
10
100
500
1000
2000
Multipole moment l



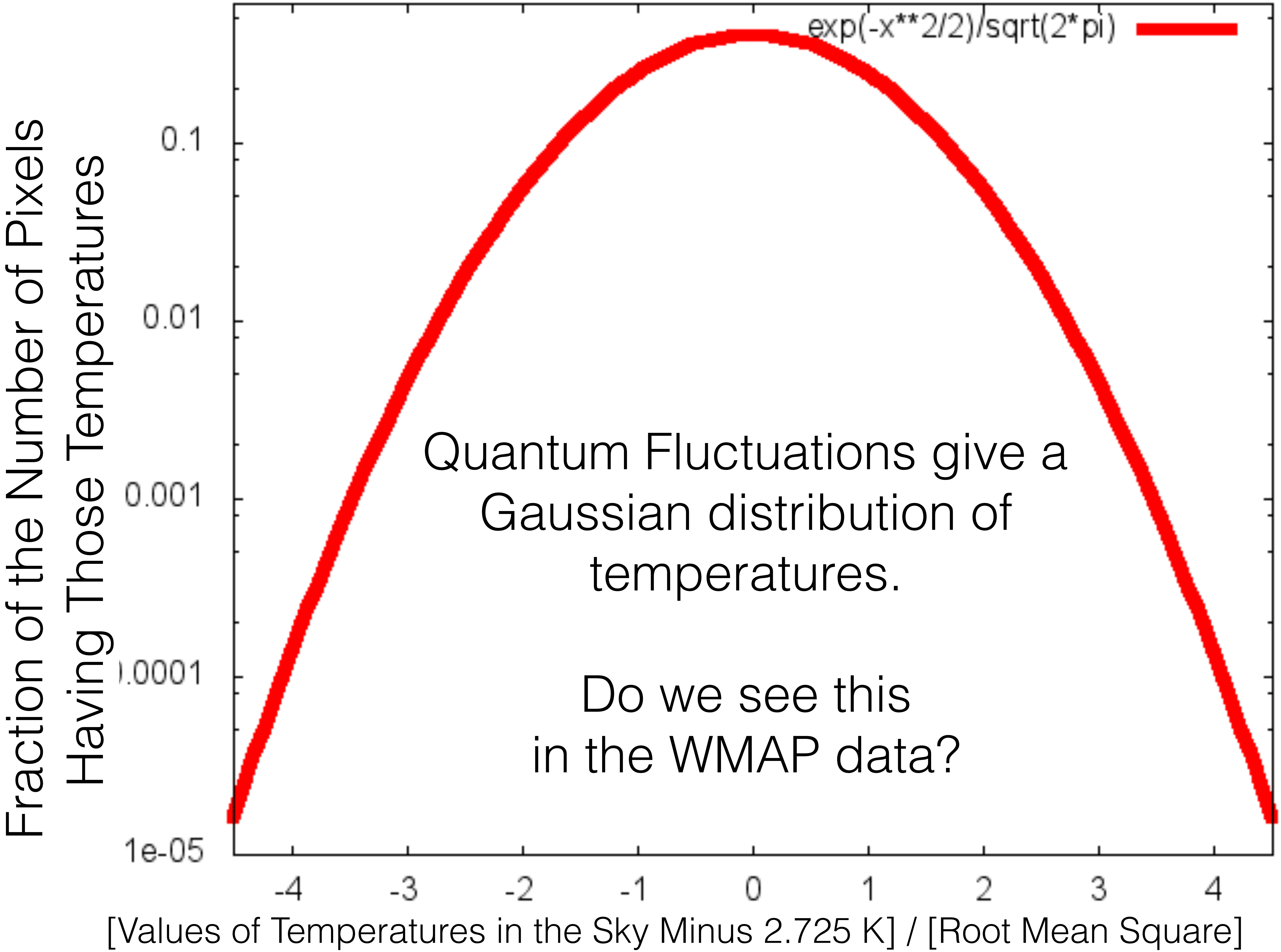
Angular scale
90°
2°
0.5°
0.2°
0.1°
2001–2010
South Pole Telescope
[10-m in South Pole]
n_s=0.965±0.010
Atacama Cosmology Telescope
[6-m in Chile]
Amplitude of
100
10
100
500
1000
2000
Multipole moment l

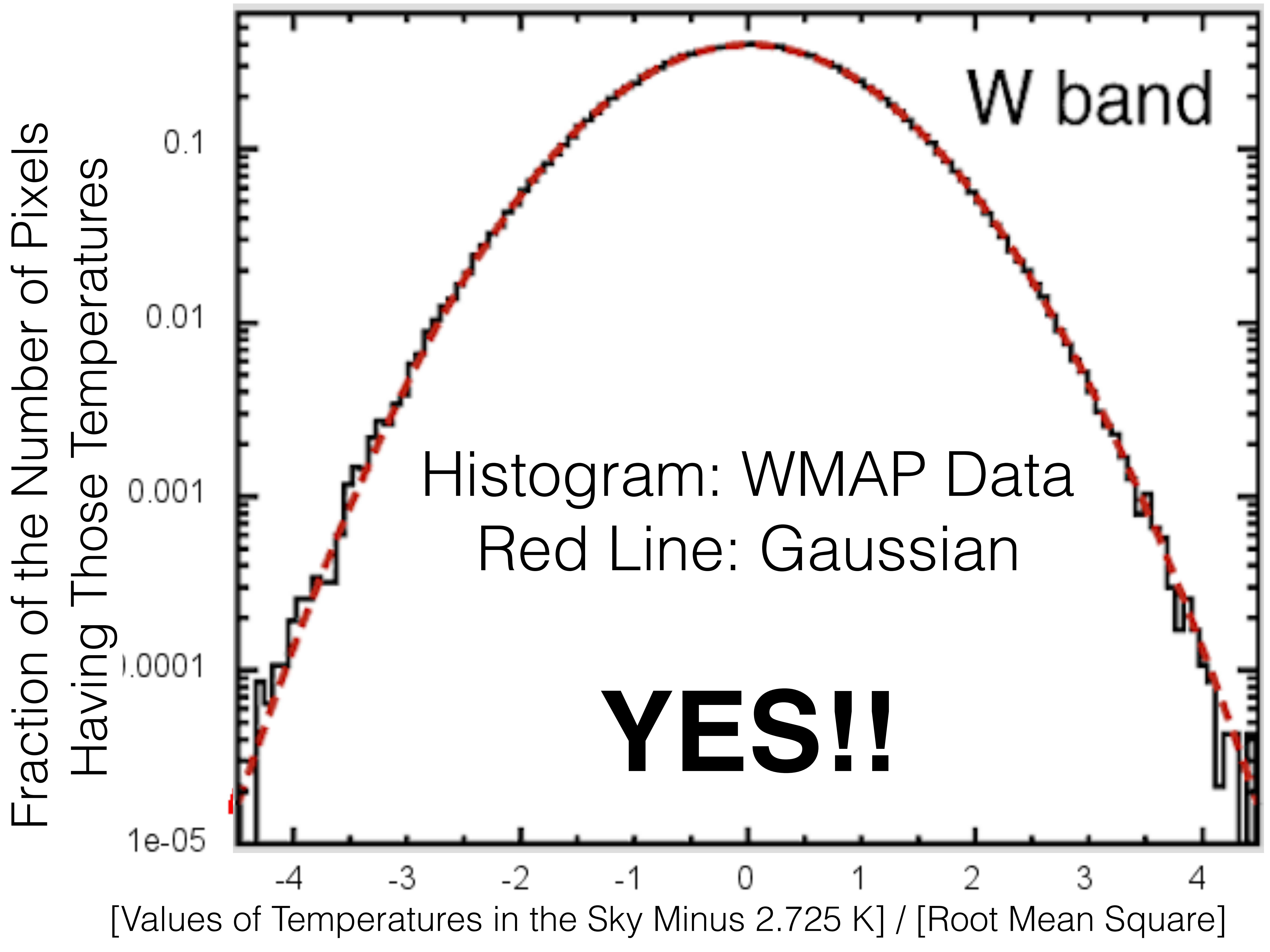

Angular scale
90°
2°
0.5°
0.2°
0.1°
2001–2010
South Pole Telescope
[10-m in South Pole]
n_s=0.961±0.008
~5σ discovery of n_s<1 from
the CMB data combined
with SDSS
Atacama Cosmology Telescope
[6-m in Chile]
Amplitude of
100
10
100
500
1000
2000
Multipole moment l


Planck 2013 Result!
2009–2013
Amplitude of Waves [μK²]
Residual
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
250
180 degrees/(angle in the sky)


Planck 2013 Result!
n_s=0.960±0.007
First >5σ discovery of n_s<1
from the CMB data alone
2009–2013
Amplitude of Waves [μK^2]
Residual
180 degrees/(angle in the sky)
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
250

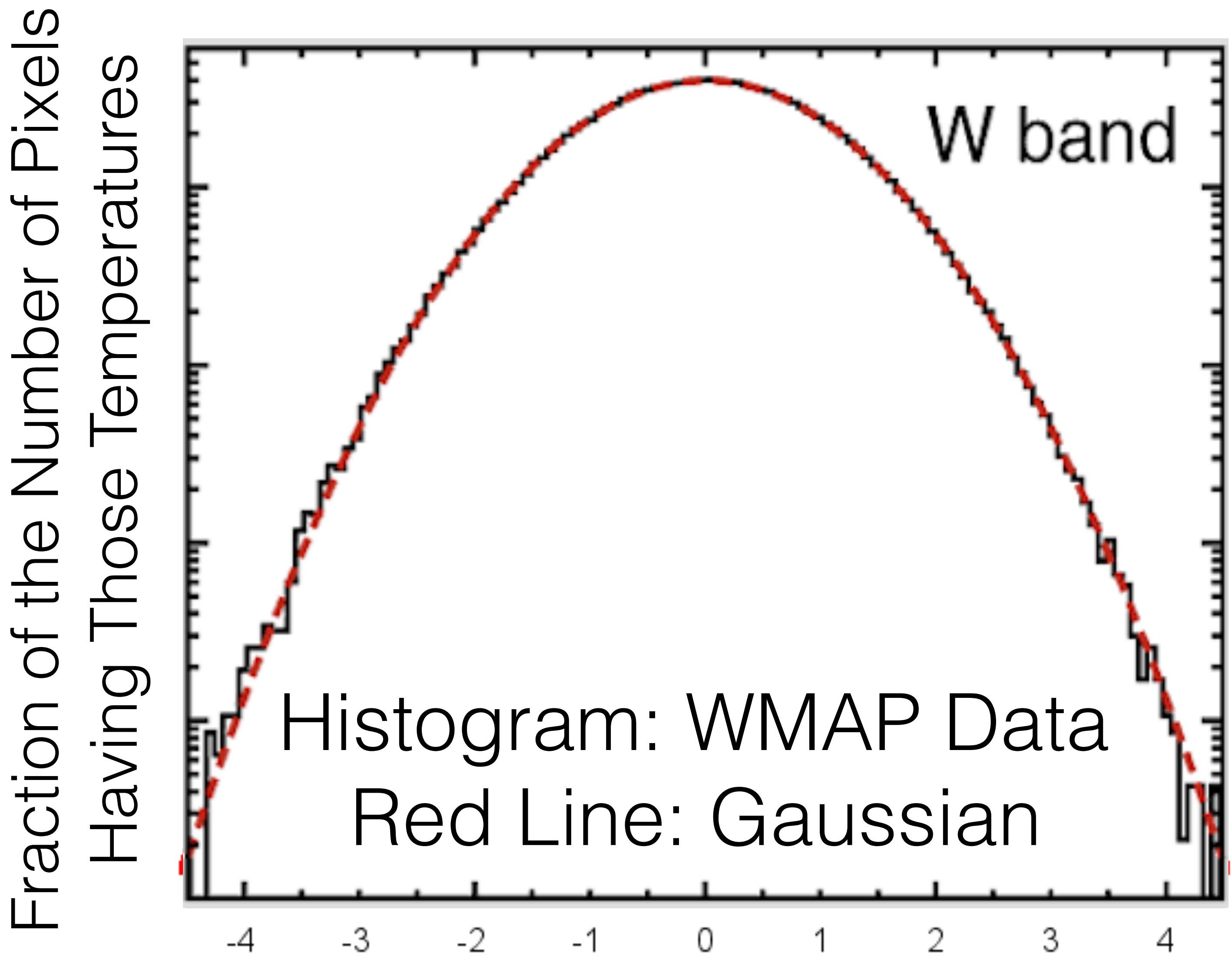
How do we know that primordial fluctuations were of *quantum mechanical origin*?


exp(-x**2/2)/sqrt(2*pi)
0.1
0.01
0.001
.0001
1e-05
-4
-3
-2
-1
0
1
2
3
4
Fraction of the Number of Pixels
Having Those Temperatures
[Values of Temperatures in the Sky Minus 2.725 K] / [Root Mean Square]
Quantum Fluctuations give a
Gaussian distribution of
temperatures.
Do we see this
in the WMAP data?



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

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:

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

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)

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

WMAP 9-year Result

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

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

Planck 2015 Result

CMB Research: Next Frontier

Primordial Gravitational Waves

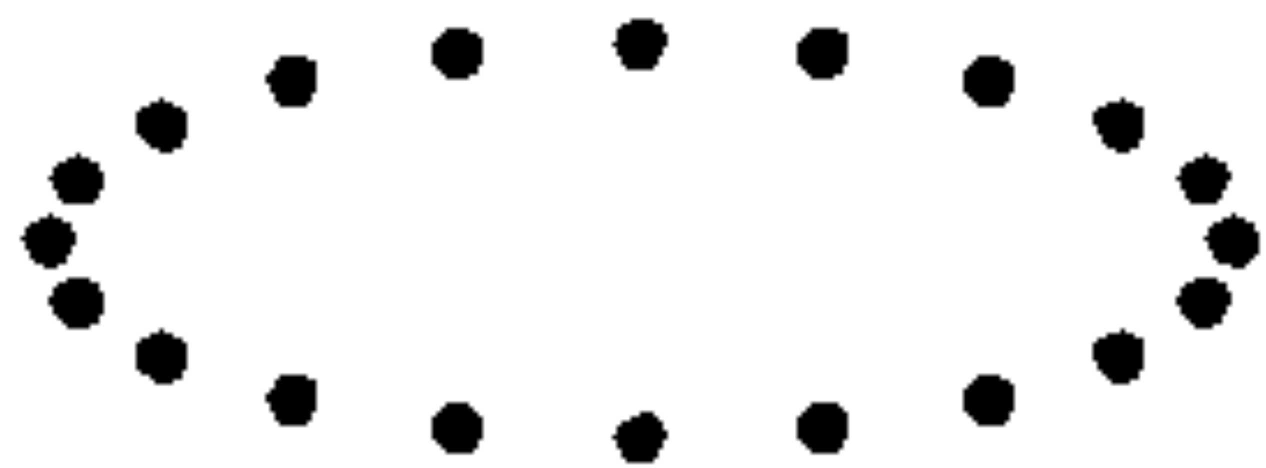
Extraordinary claims require extraordinary evidence.
The same quantum fluctuations could also generate gravitational waves, and we wish to find them

Measuring GW

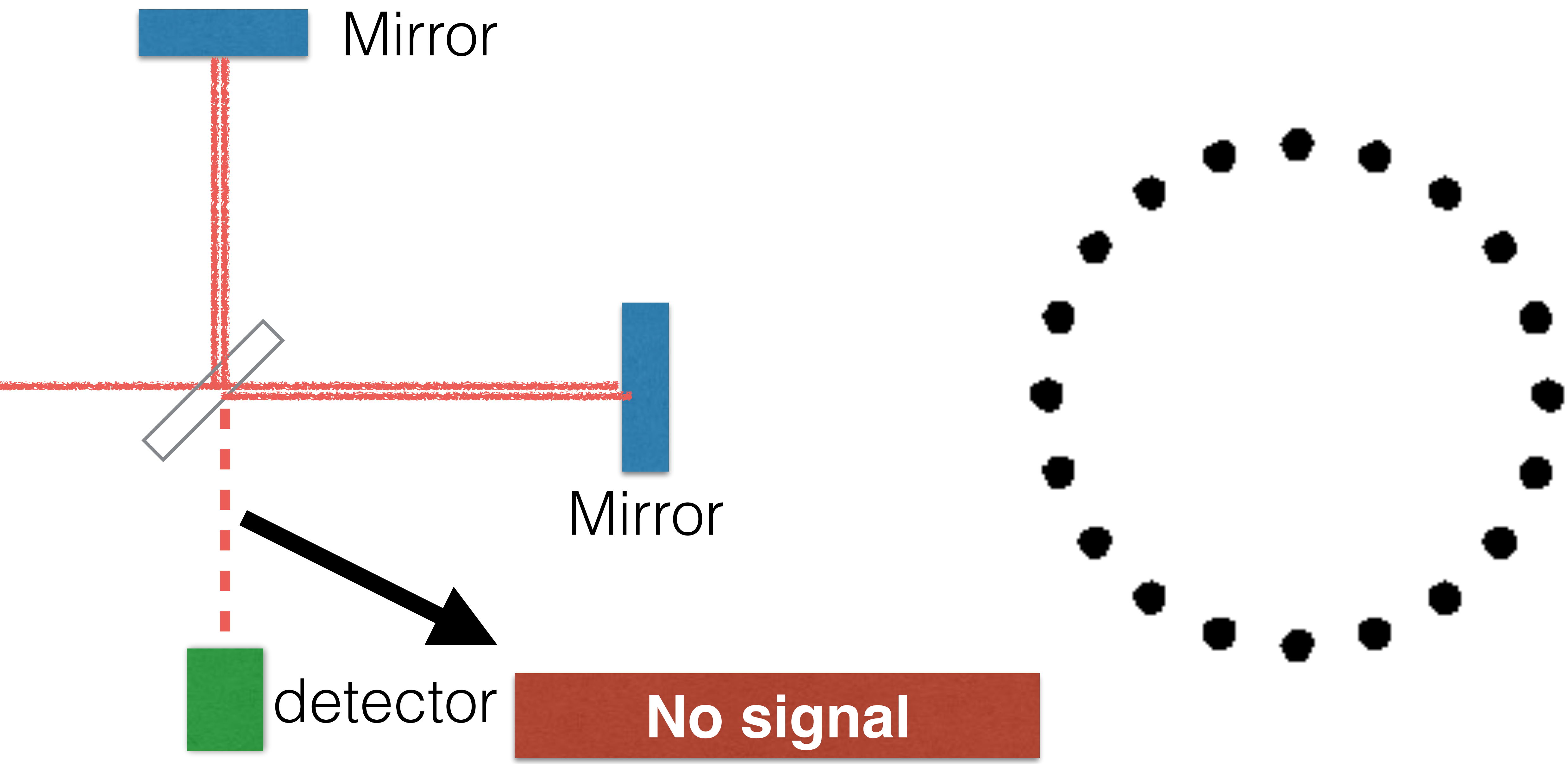
- GW changes the distances between two points

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

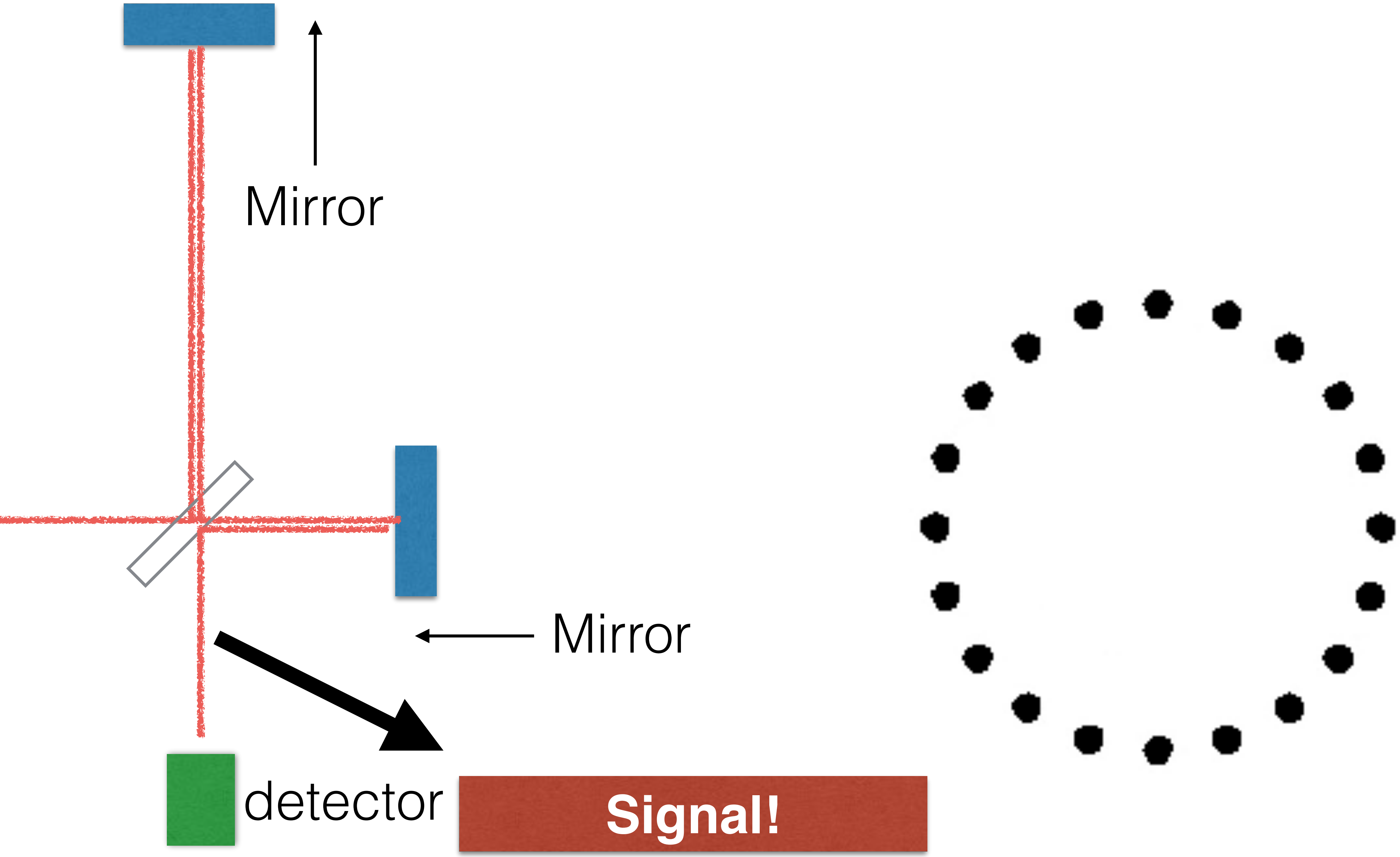
$$d\ell^2 = \sum_{ij} (\delta_{ij} + \underline{h_{ij}}) dx^i dx^j$$



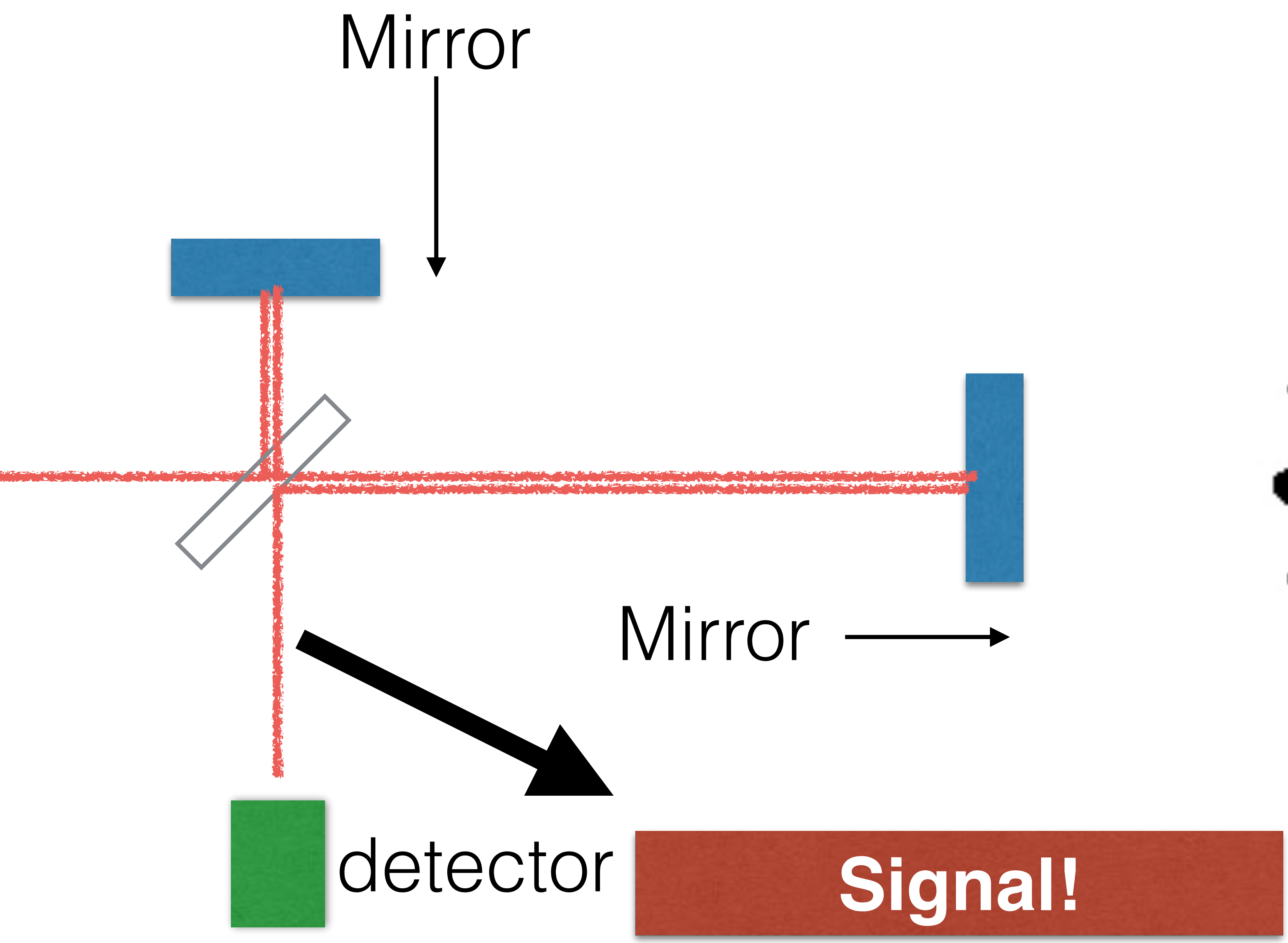
Laser Interferometer

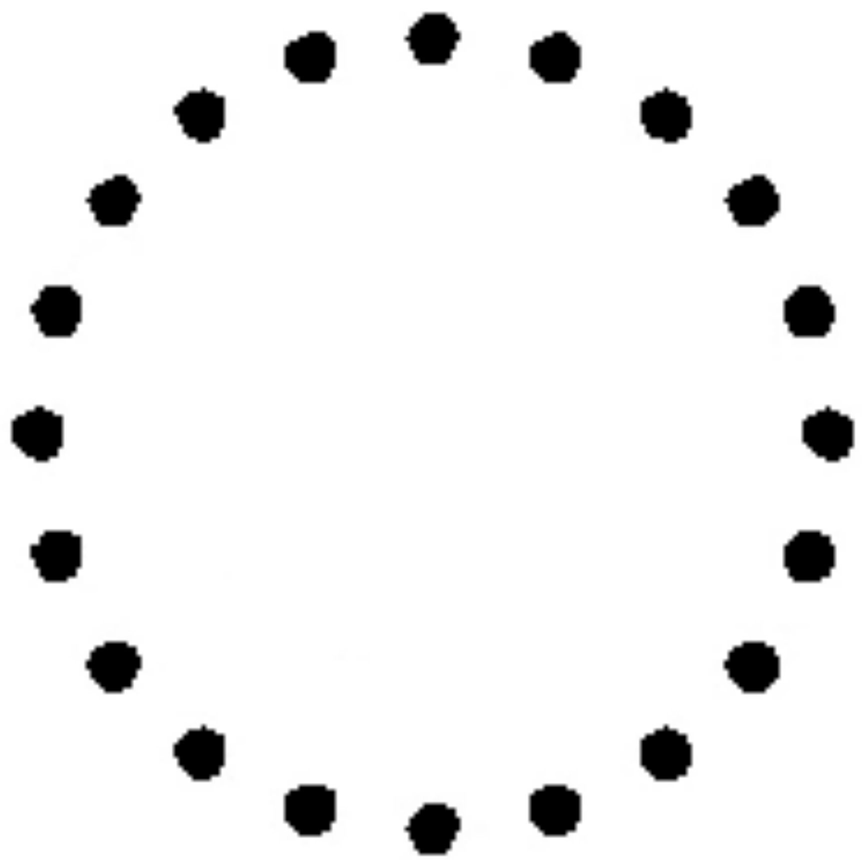


Laser Interferometer



Laser Interferometer





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

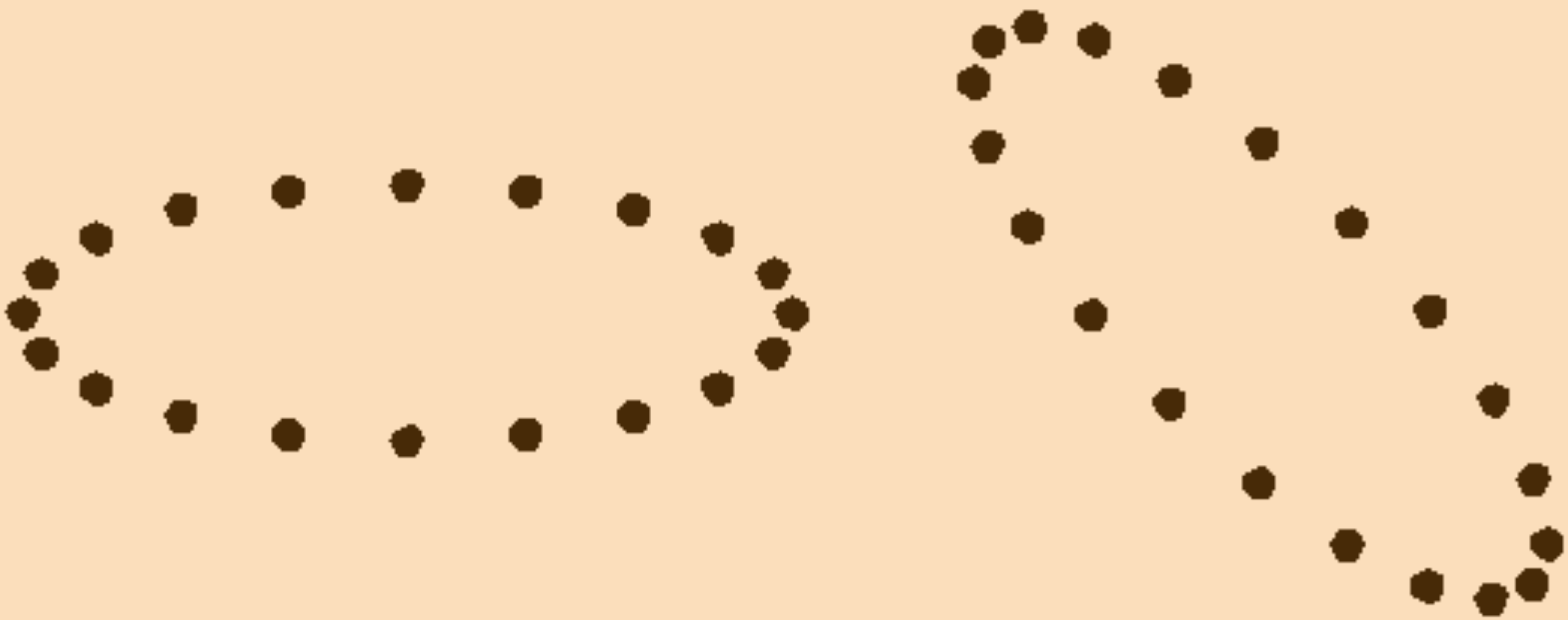
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

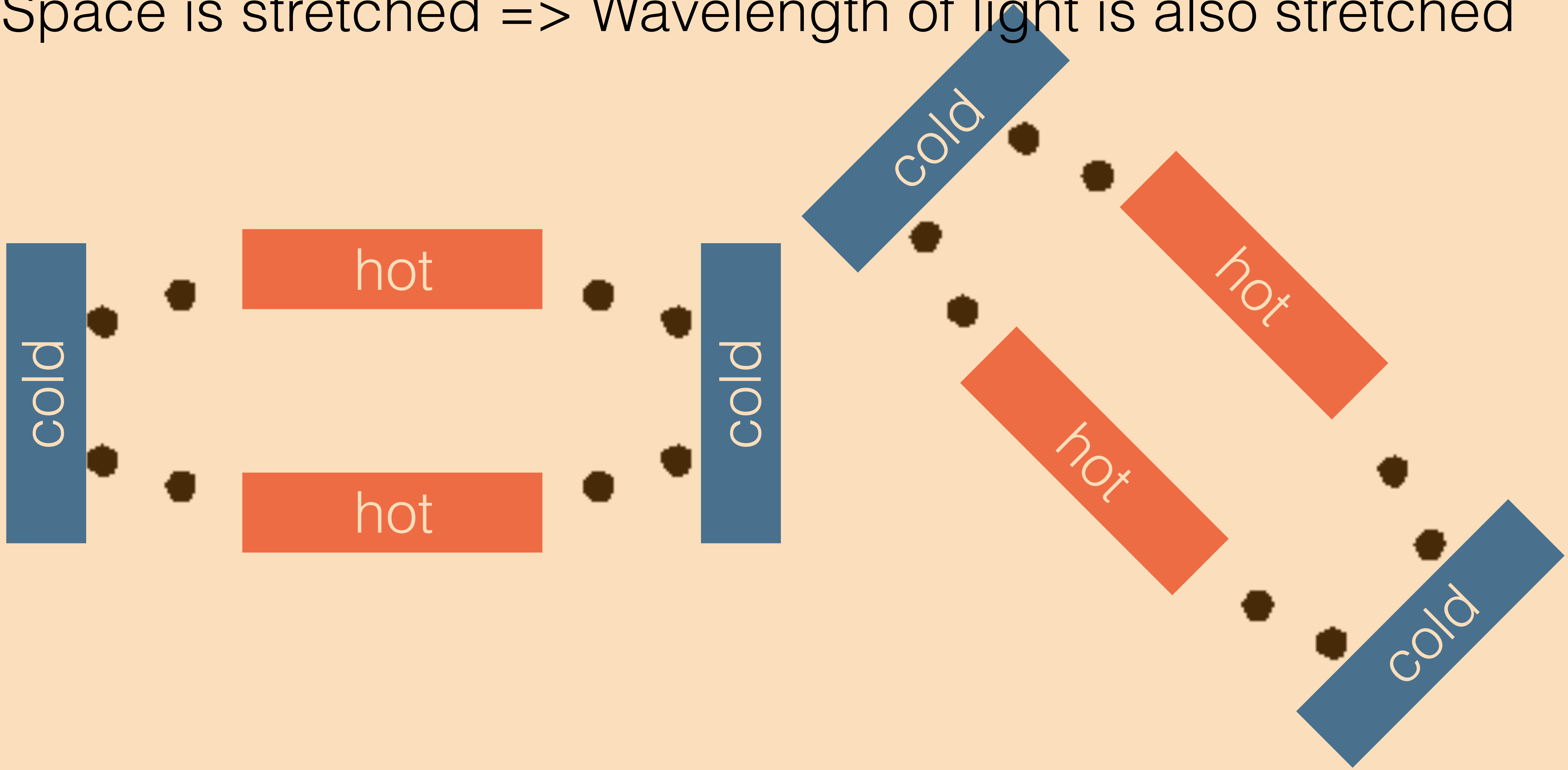
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



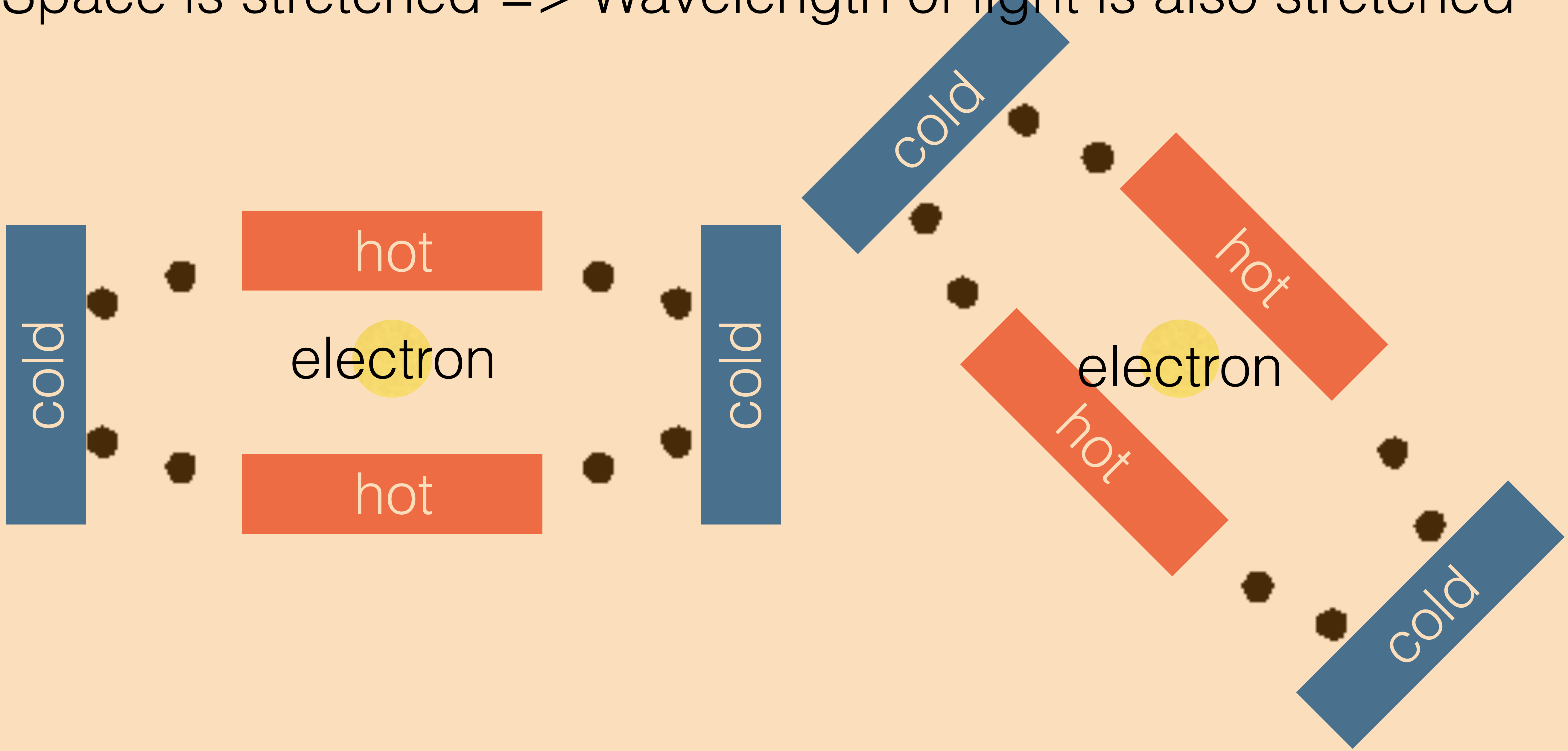
Detecting GW by CMB

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

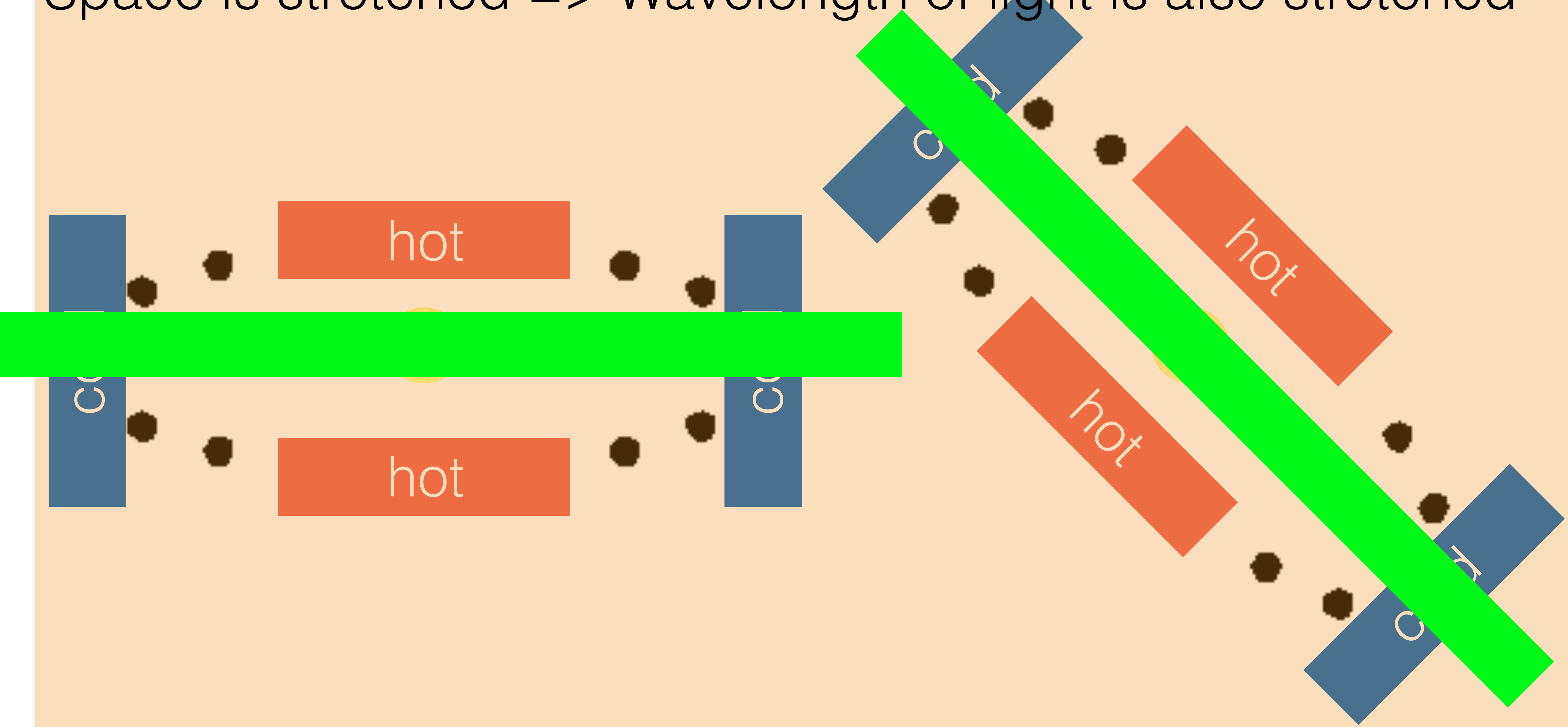



Photo Credit: TALEX
horizontally polarised

Photo Credit: TALEX

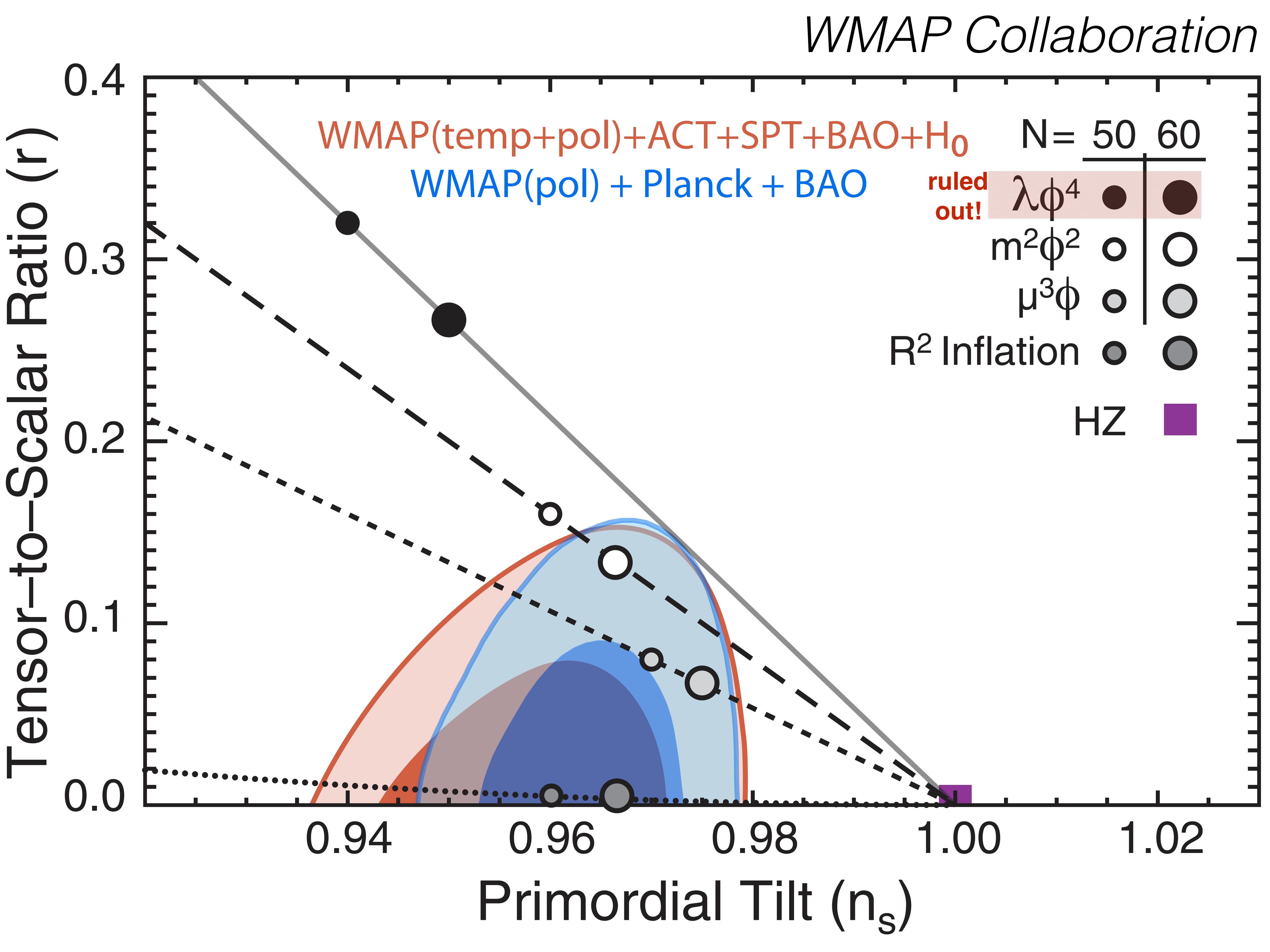
If polarisation from GW is found…

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

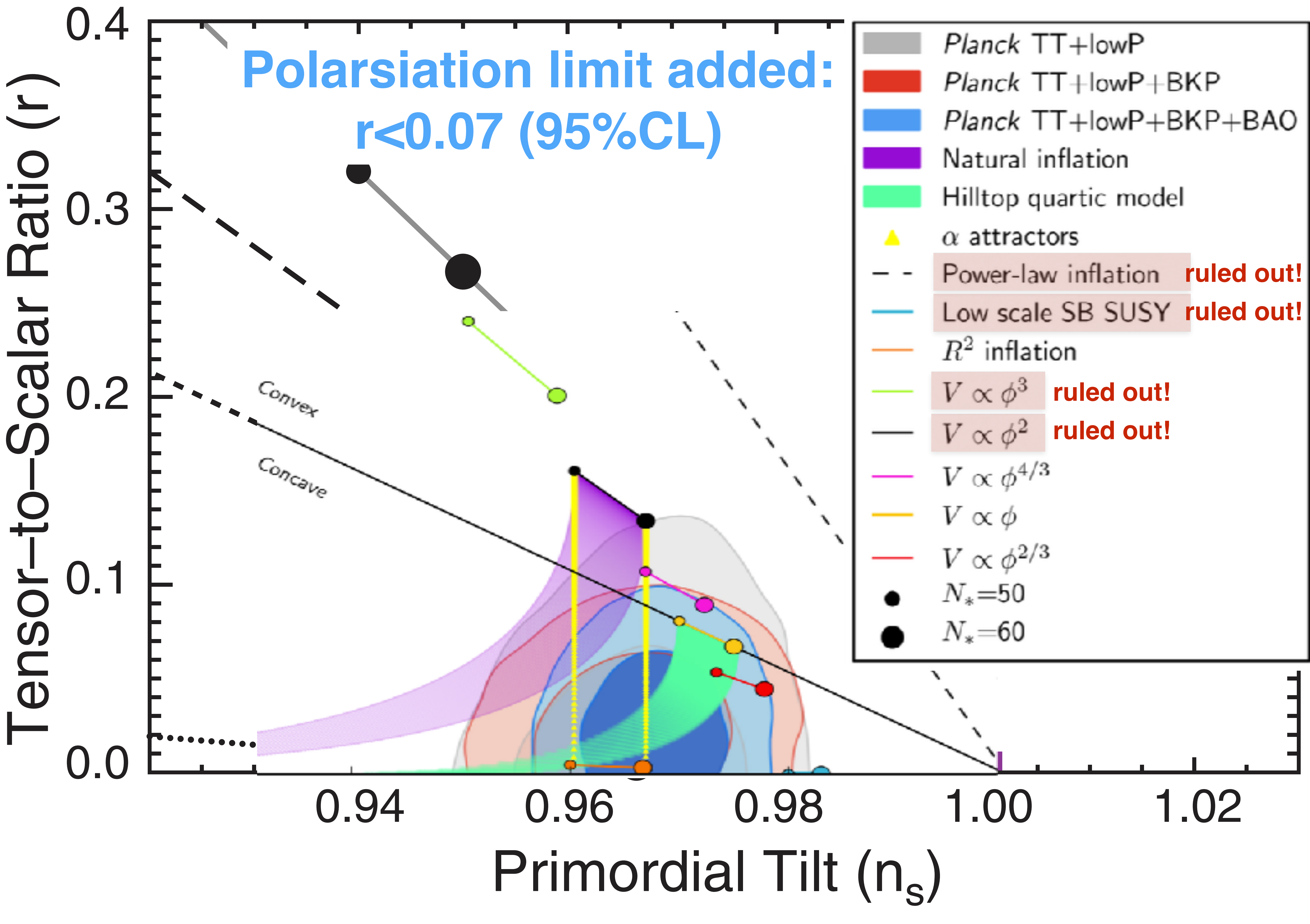
Tensor-to-scalar Ratio

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

- We really want to find this quantity!
  The current upper bound: r<0.07


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

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

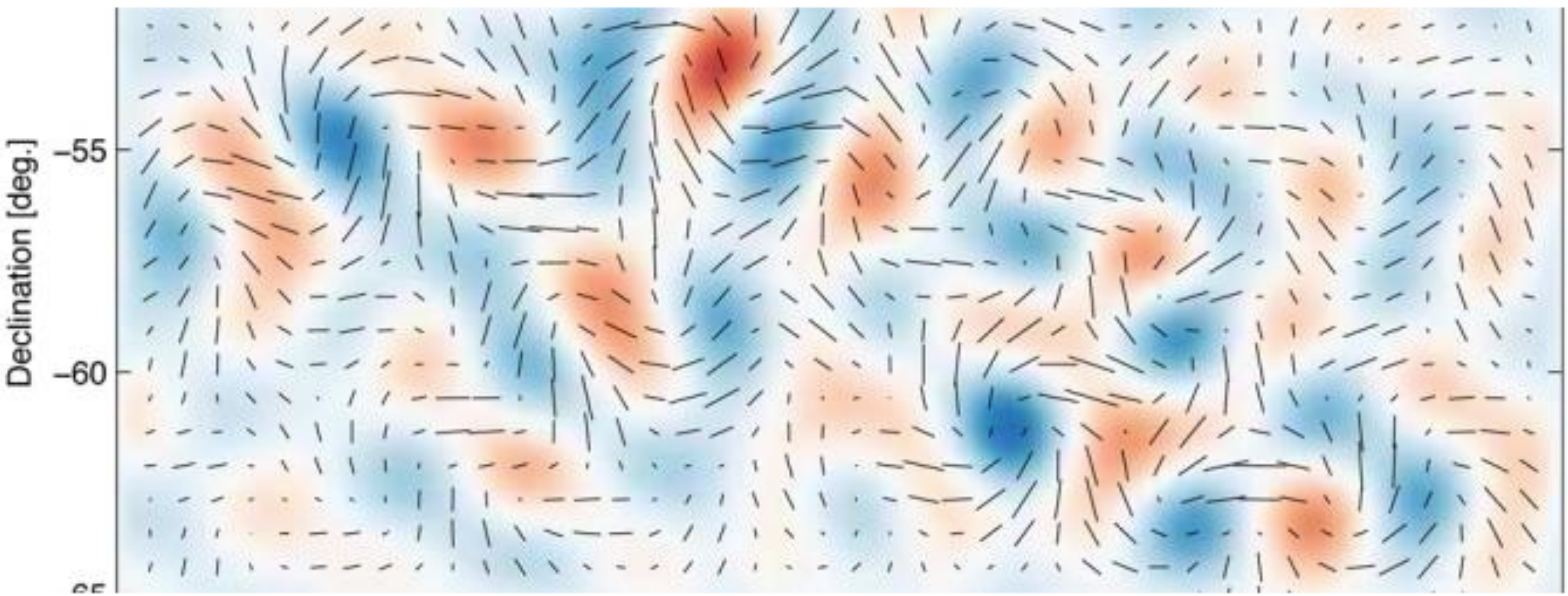


March 17, 2014

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

BBC

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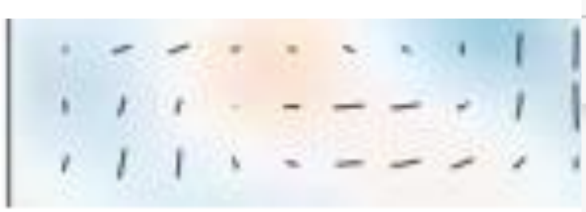
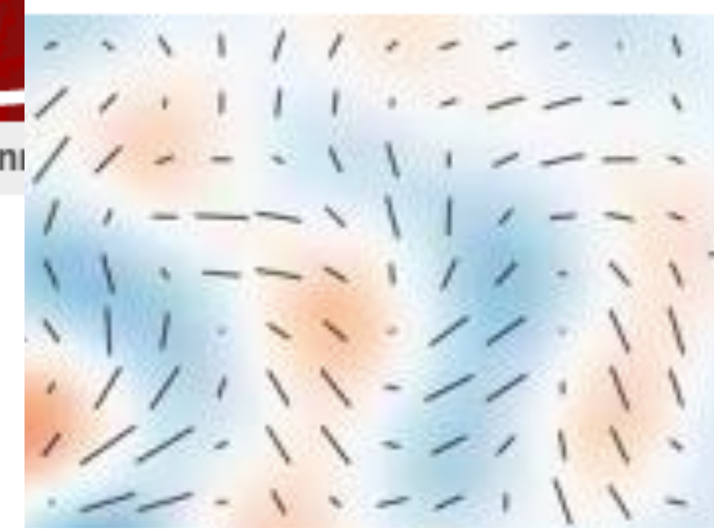
Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos
Science correspondent, BBC News



Cambridge, MA - Almost 14 billic
that initiated the Big Bang. In the
far beyond the view of our best tel



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Hir

17. März 2014, 17:34 Gravitationswellen

Signale aus der Geburtsstunde des Universums

Von Patrick Illinger

January 30, 2015

Joint Analysis of BICEP2 data and Planck data

SCIENCE

The New York Times

Speck of Interstellar Dust Obscures Glimpse of Big Bang

By DENNIS OVERBYE JAN. 30, 2015

BBC

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30 January 2015 Last updated at 20:54 GMT

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Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos
Science correspondent, BBC News

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Home > Wissen > Kosmologie - Urknall-Forscher gestehen Irrtum ein

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1. Februar 2015, 22:19 Kosmologie

Urknall-Forscher gestehen Irrtum ein

Von Marlene Weiß

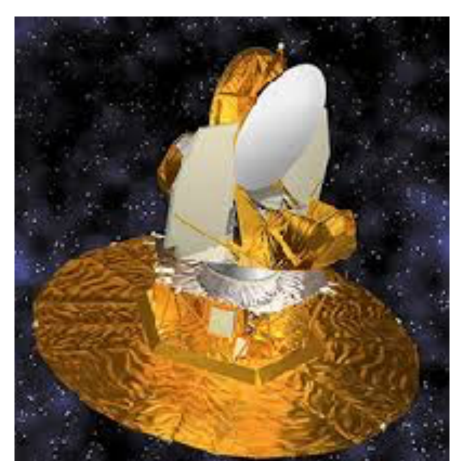
Current Situation

- 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

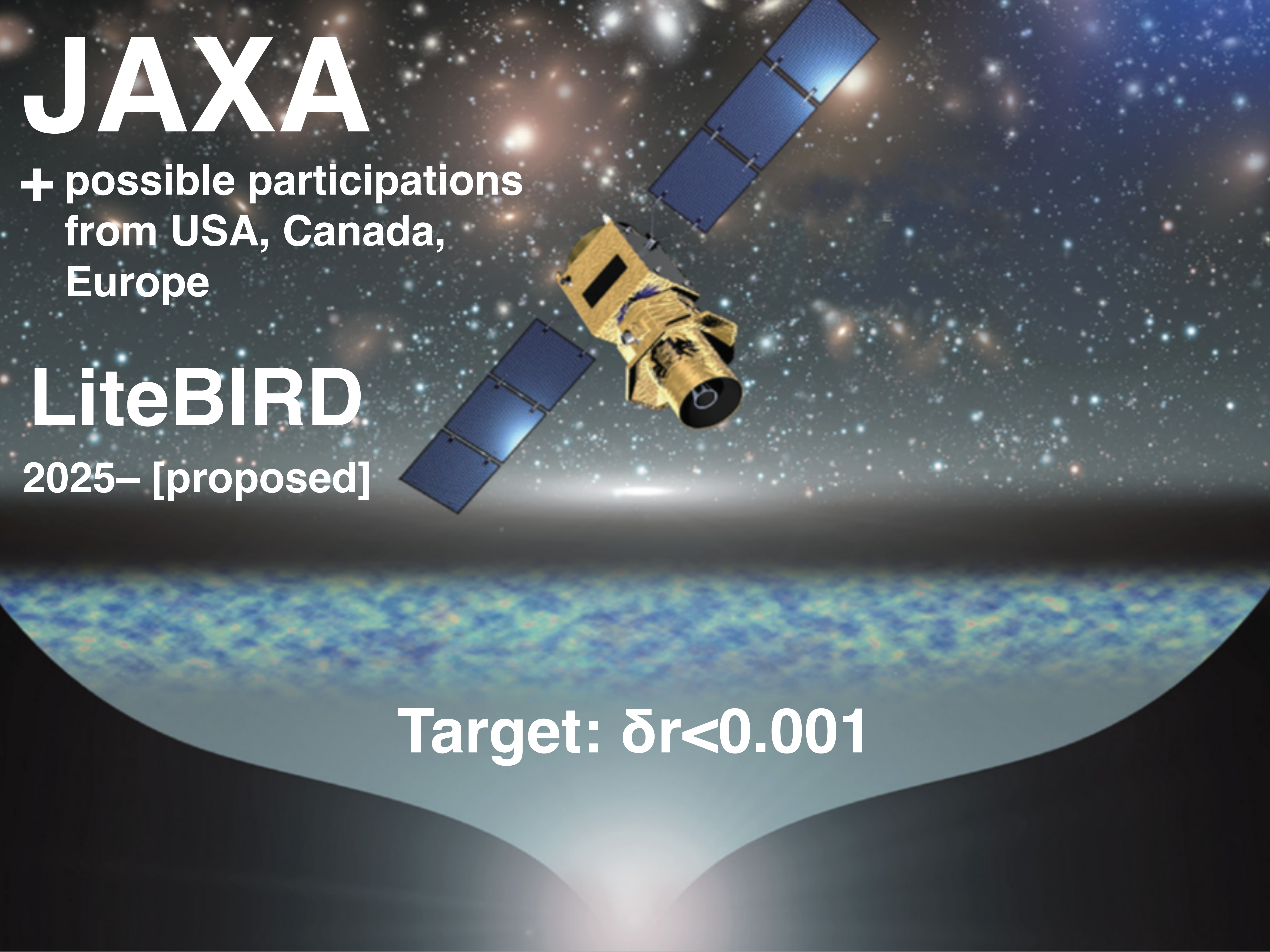
The search continues!!

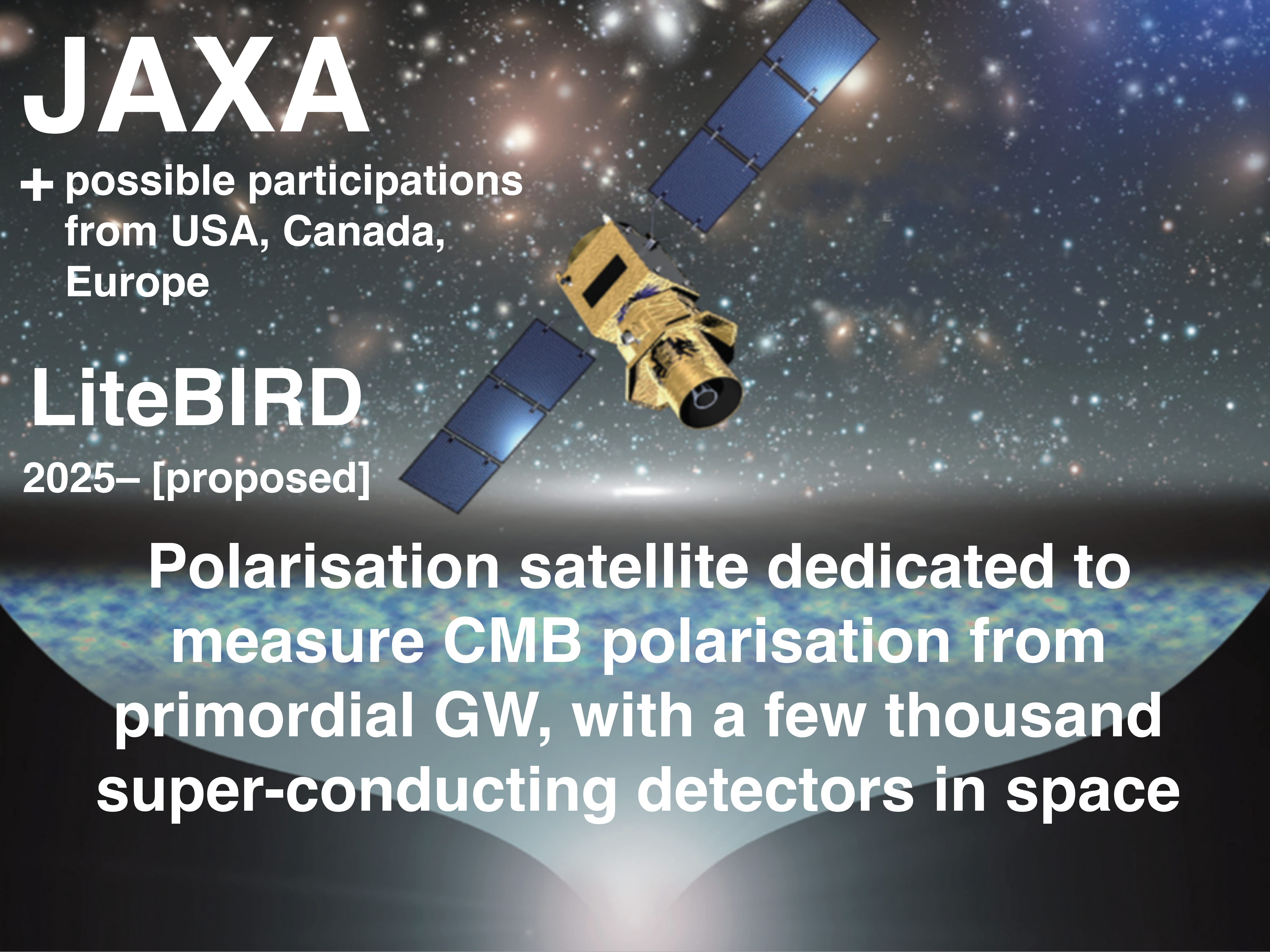

1989–1993

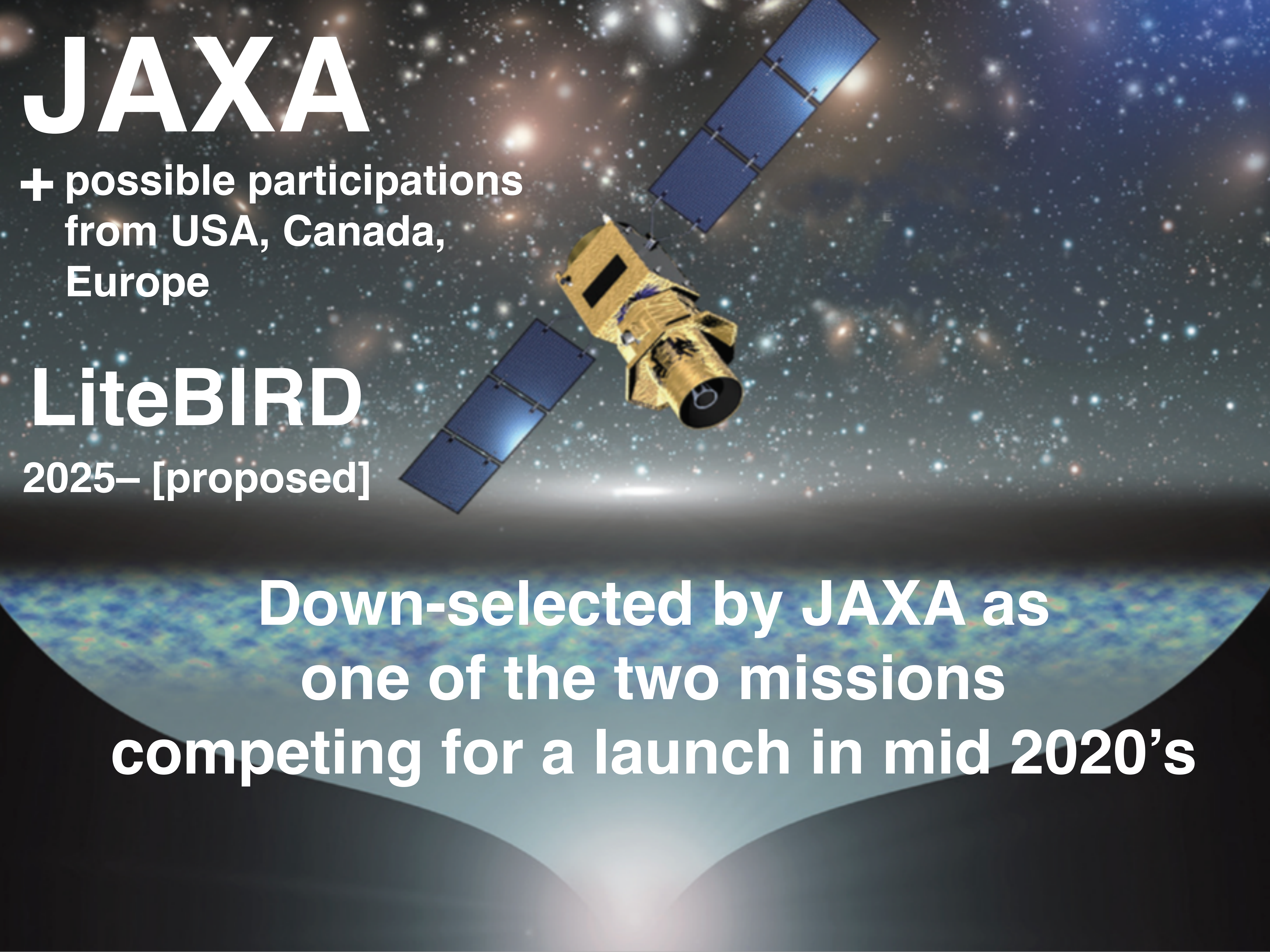

2001–2010


2009–2013


202X–


JAXA
+ possible participations from USA, Canada, Europe
LiteBIRD
2025– [proposed]
Target: δr<0.001

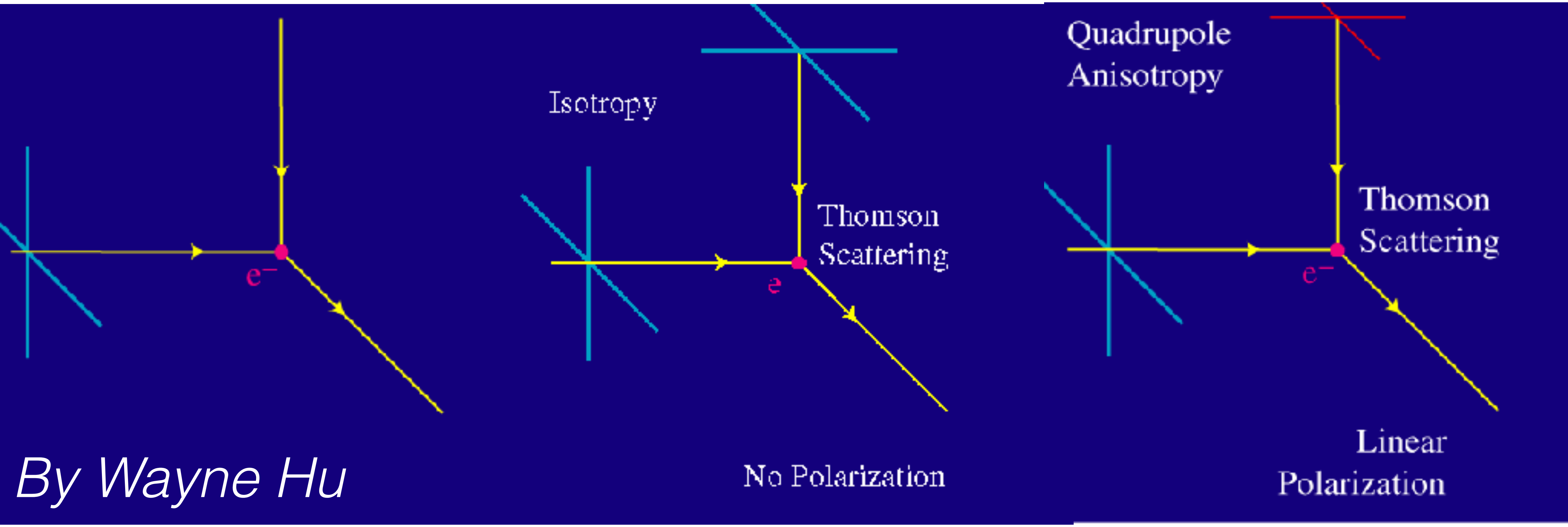

JAXA
+ possible participations from USA, Canada, Europe
LiteBIRD
2025– [proposed]
Polarisation satellite dedicated to measure CMB polarisation from primordial GW, with a few thousand super-conducting detectors in space


JAXA
+ possible participations from USA, Canada, Europe
LiteBIRD
2025– [proposed]
Down-selected by JAXA as one of the two missions competing for a launch in mid 2020’s

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 mid 2020's

Physics of CMB Polarisation



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