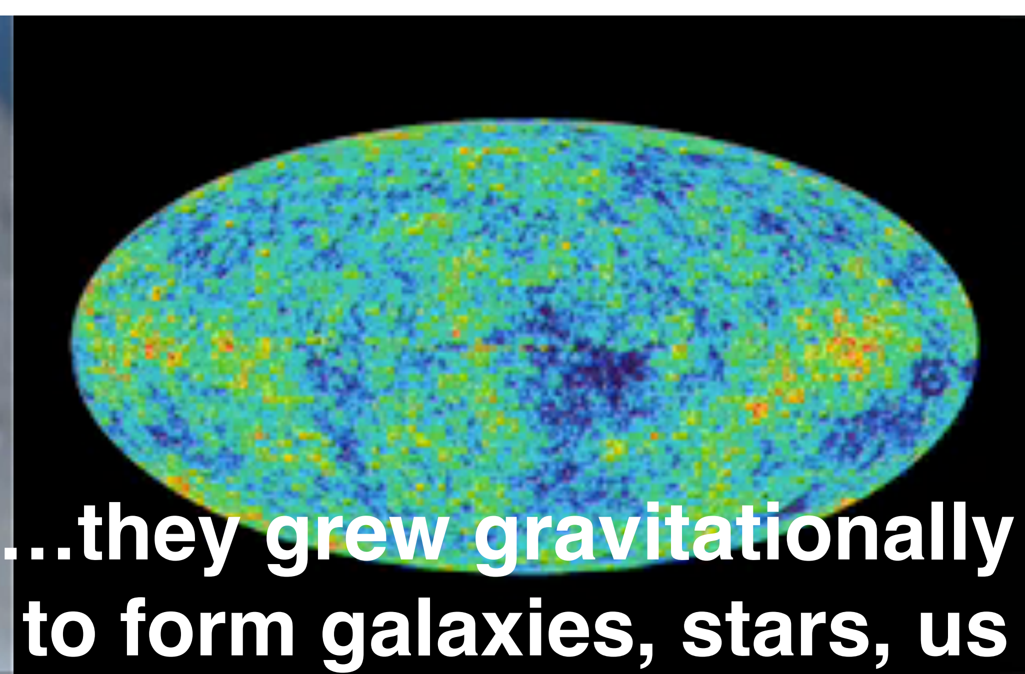
MPI für Astrophysik

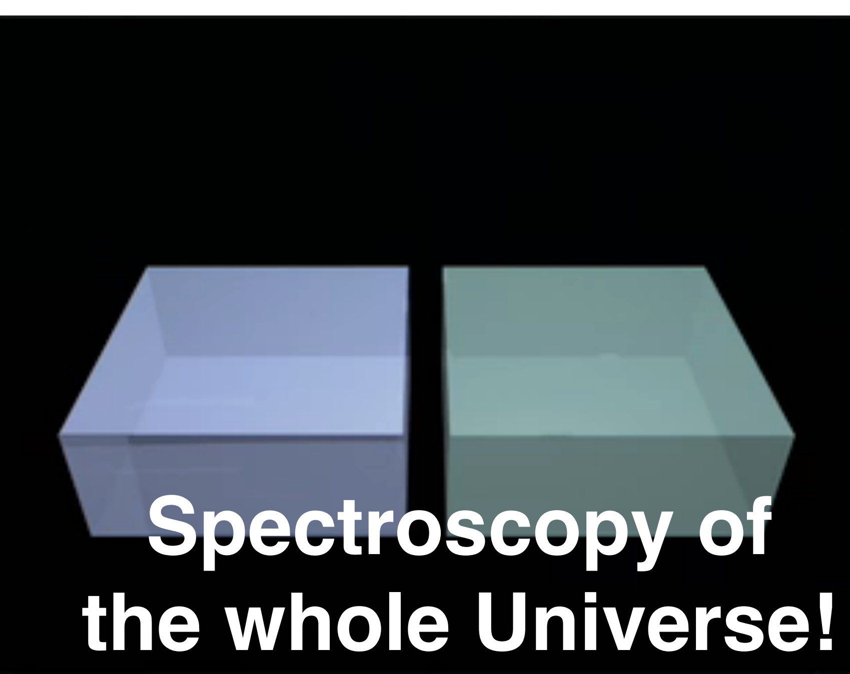
Where did we come from?

~A quest for the physics that operates at the beginning of our Universe~

Eiichiro Komatsu [Scientific Member **since 2012**]

CPTS Sektionssitzung, February 23, 2017



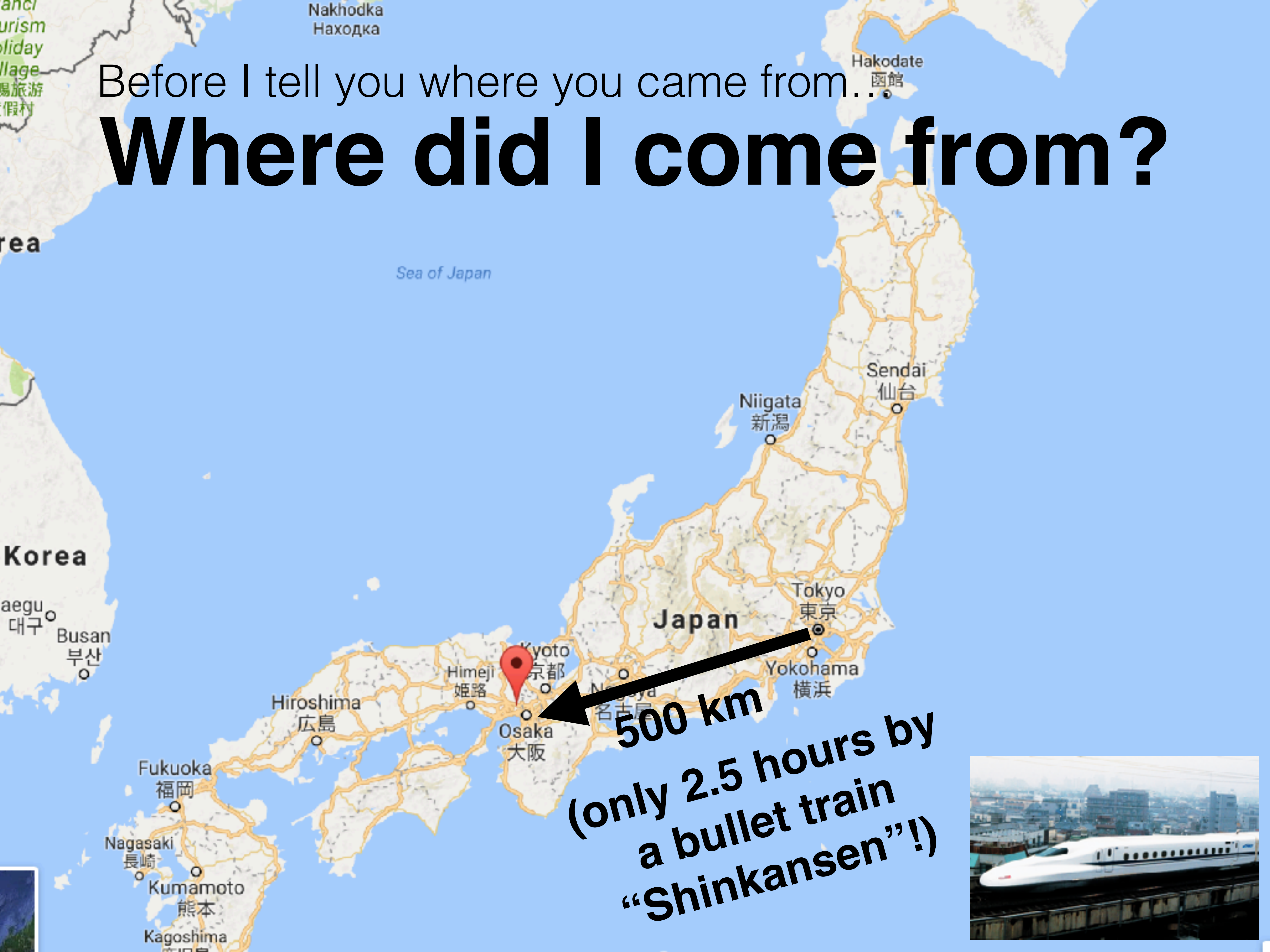


I am…

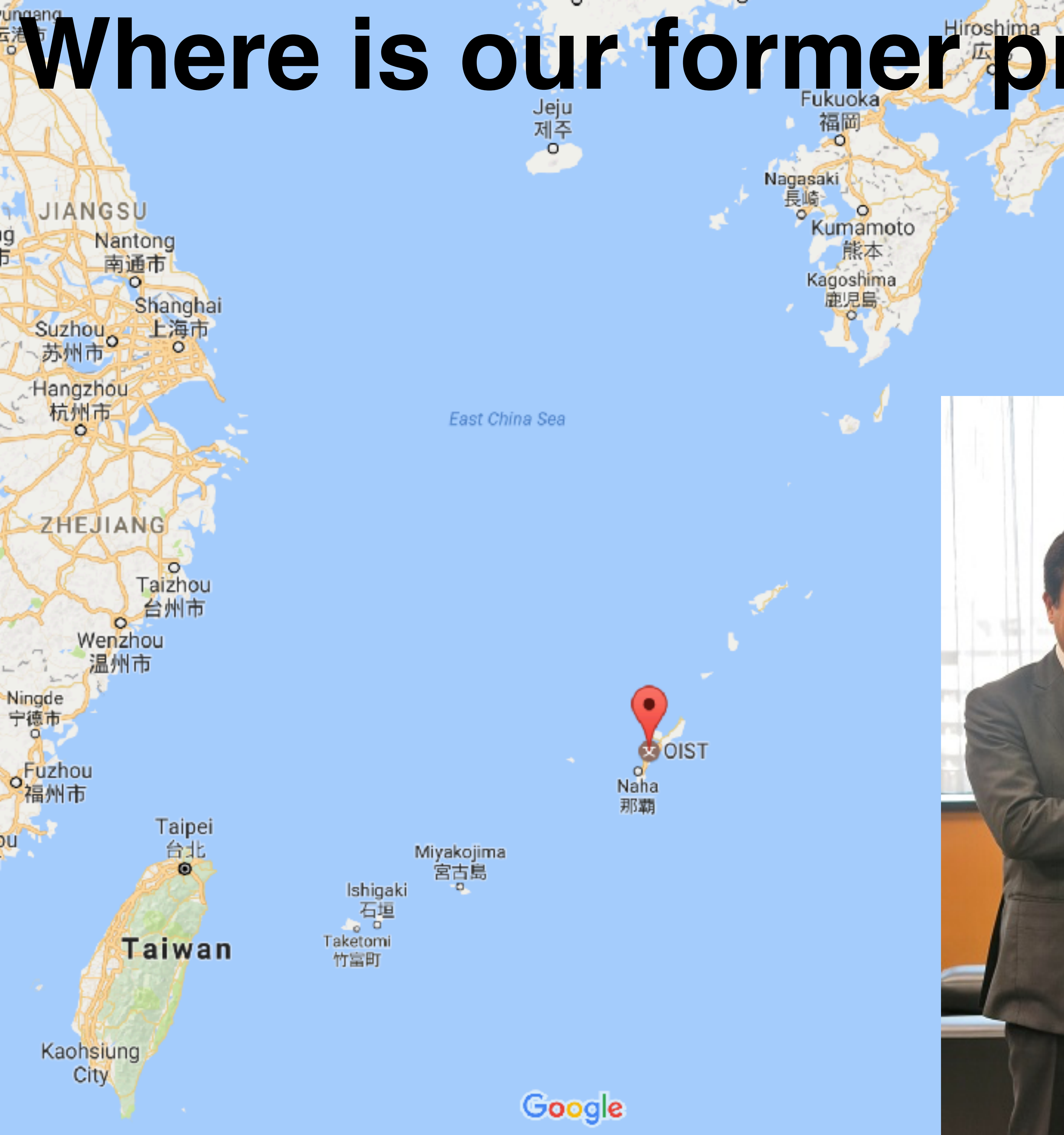
- a “cosmologist”
  - or, someone between astronomy and physics
- Theoretical and observational. I divide my research time into
  - ~2/3 theory, ~1/3 data analysis

Before I tell you where you came from…

Where did I come from?



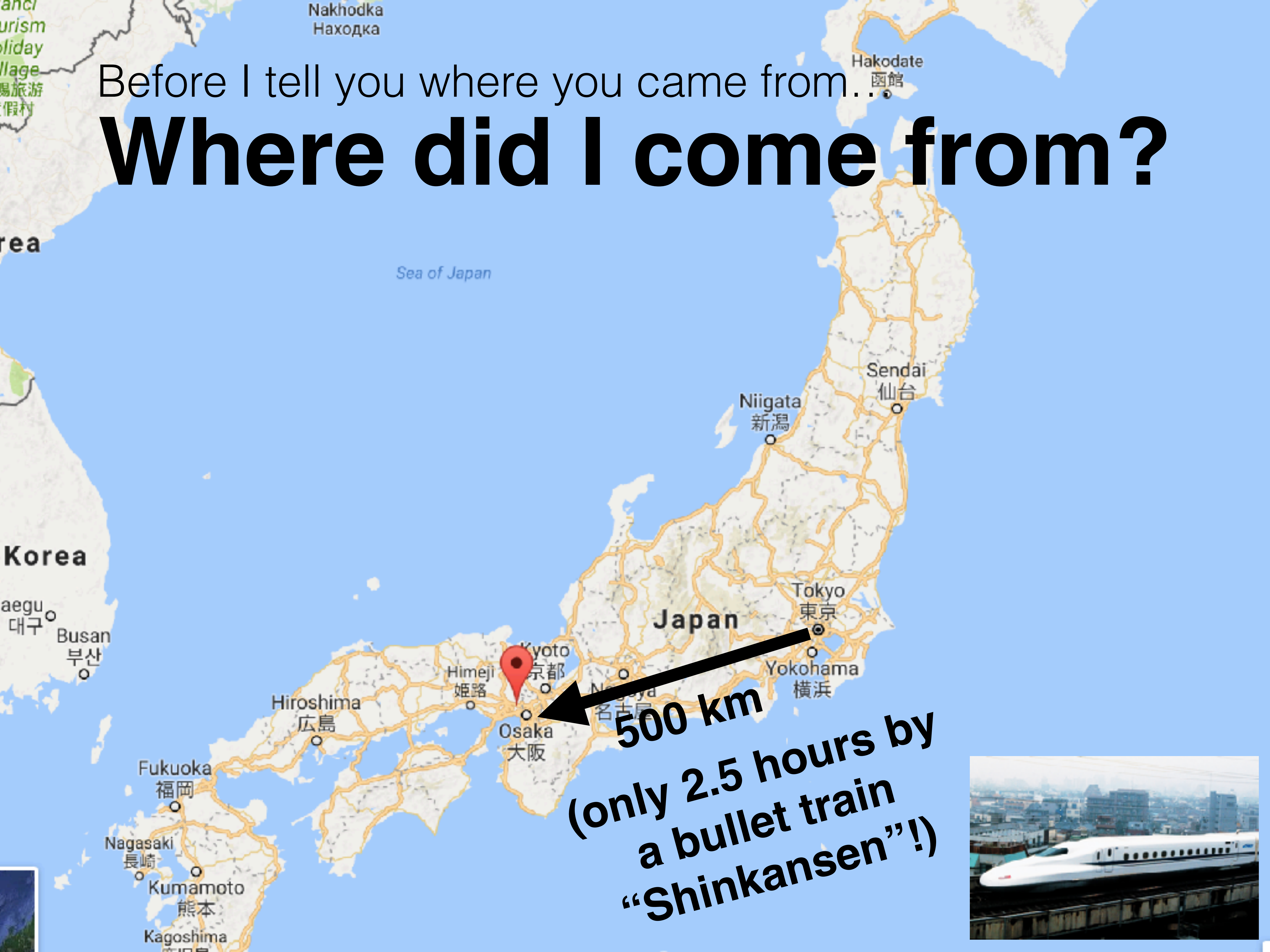
Where is our former president?



in office since
Jan 1, 2017

Before I tell you where you came from…

Where did I come from?



500 km

(only 2.5 hours by a bullet train "Shinkansen"!)

Before I tell you where you came from…

Where did I come from?

Bayern in Japan!!, because

- We speak funny dialects,
- Everyone else makes fun of us,
- But we are very proud of ourselves,
- Because we were once the center of the country

KANSAI Area

KANSAI
= **Bayern in Japan**

KANSAI Area

Takara-zuka
(220k)
"The Capital"
1.5 million
Kyoto
京都
Merchants and Comedians
2.7 million
Osaka
大阪
Beef and shoes
1.5 million
Kobe
神戸
50 km
30 km
KYOTO
HYOGO
SHIGA
OSAKA
NARA
Lake Biwa
琵琶湖
Osaka Bay
大阪湾
Tanba
丹波
Sasayama
篠山
Kyotanba
京丹波町
Takashima
高島
Hikone
彦根
Kusatsu
草津
Otsu
大津
Koka
甲賀
Kasai
加西
Himeji
姫路
Miki
三木
Kakogawa
加古川
Akashi
Takatsuki
Sakai
堺
Iga
伊賀
Nabari
名張
Kashihara
橿原
Soni
曽爾村
Awaji
淡路
Izumisano
泉佐野
Sennan
若狭町

Two things about Takarazuka that **every single Japanese knows**

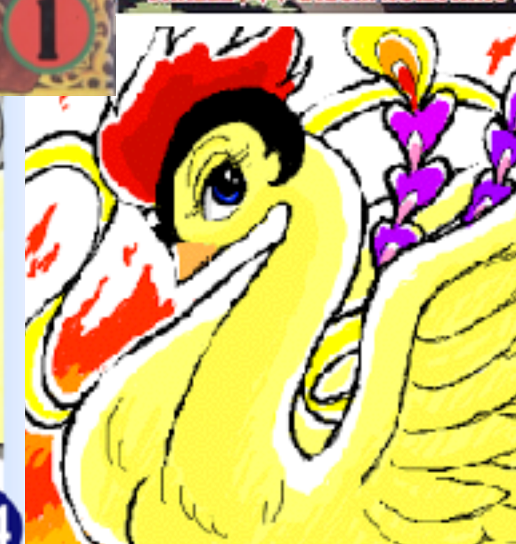
KAGEKI "Revue"

Female-only Musical Performance

Two things about Takarazuka that **every single Japanese knows**

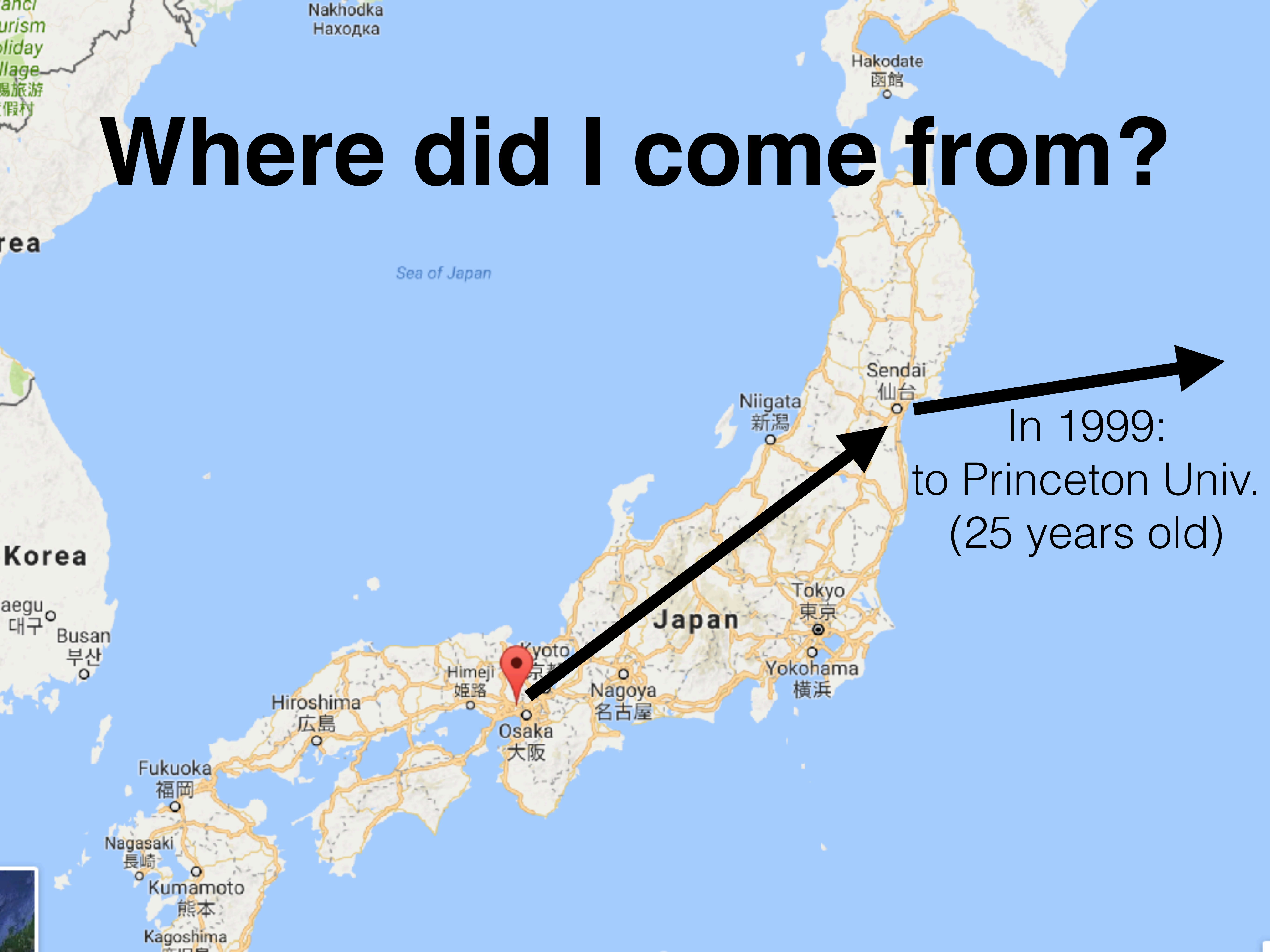
Osamu Tezuka

Godfather of “**Manga**” and “**Anime**”



Where did I come from?

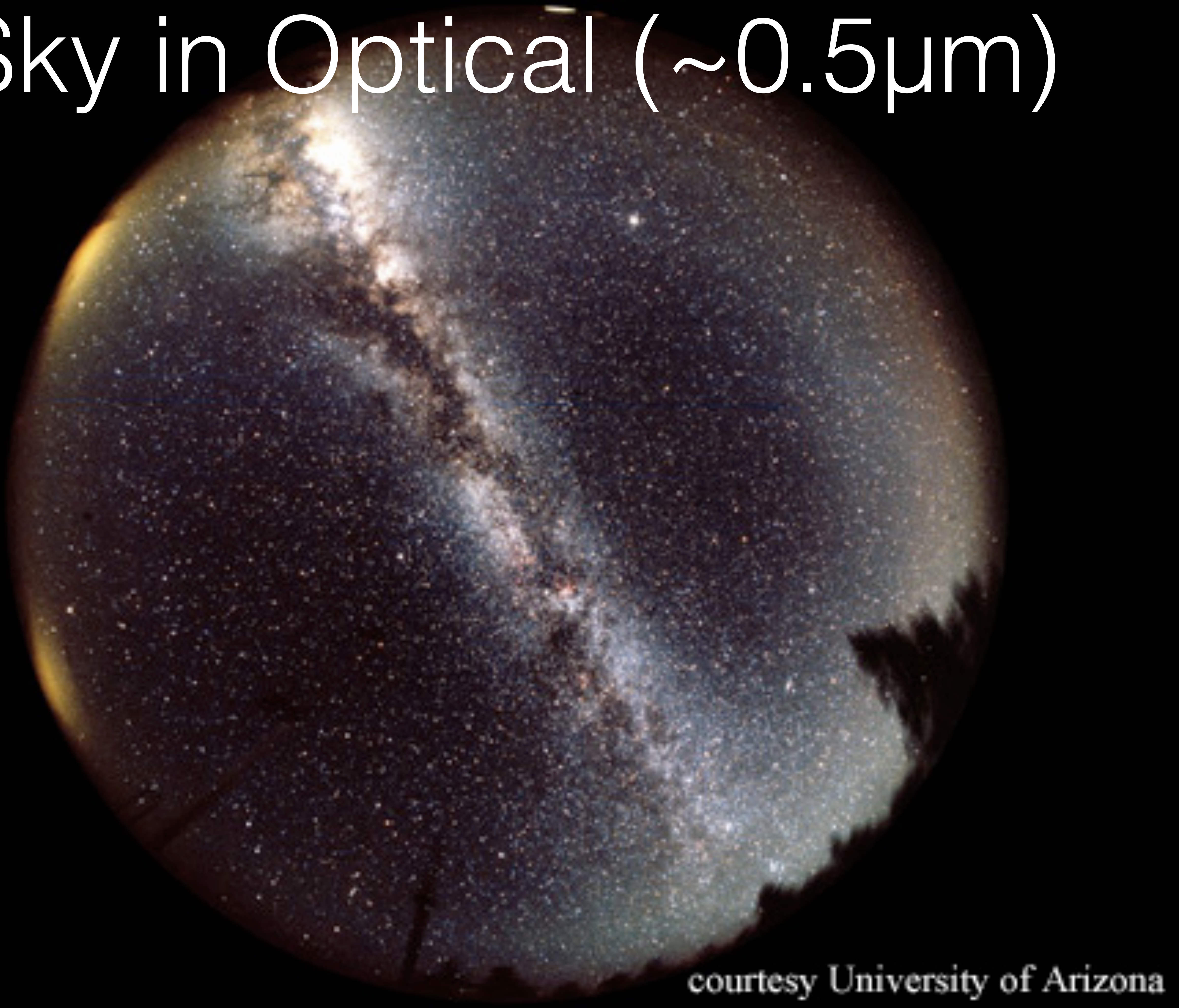
Where did I come from?



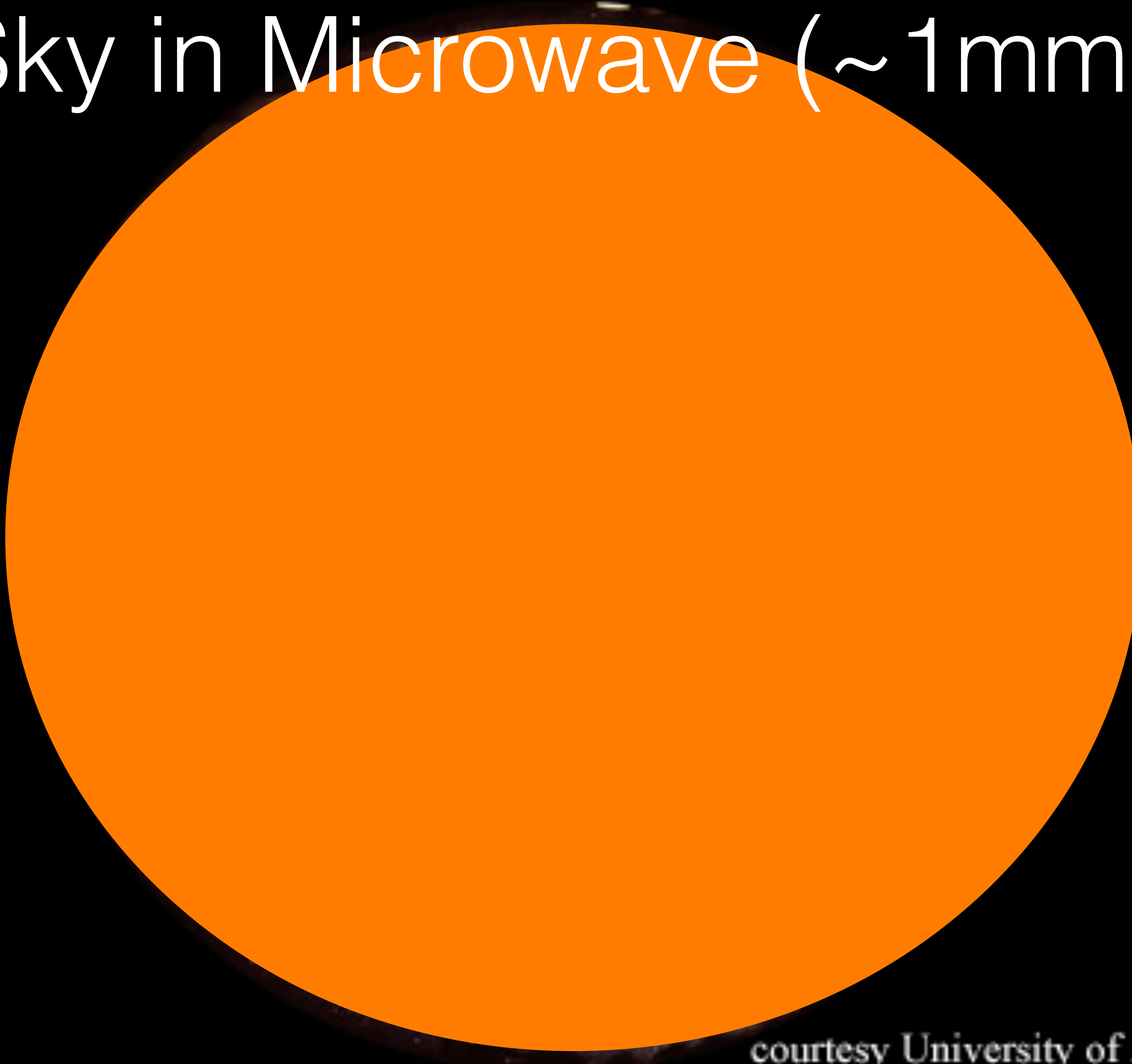
Why did I leave Japan?

- Because science I wanted to do for my PhD, i.e., **to learn about the beginning of the Universe using the light from the Big Bang**, was not possible in Japan in 1999

Sky in Optical (~0.5μm)

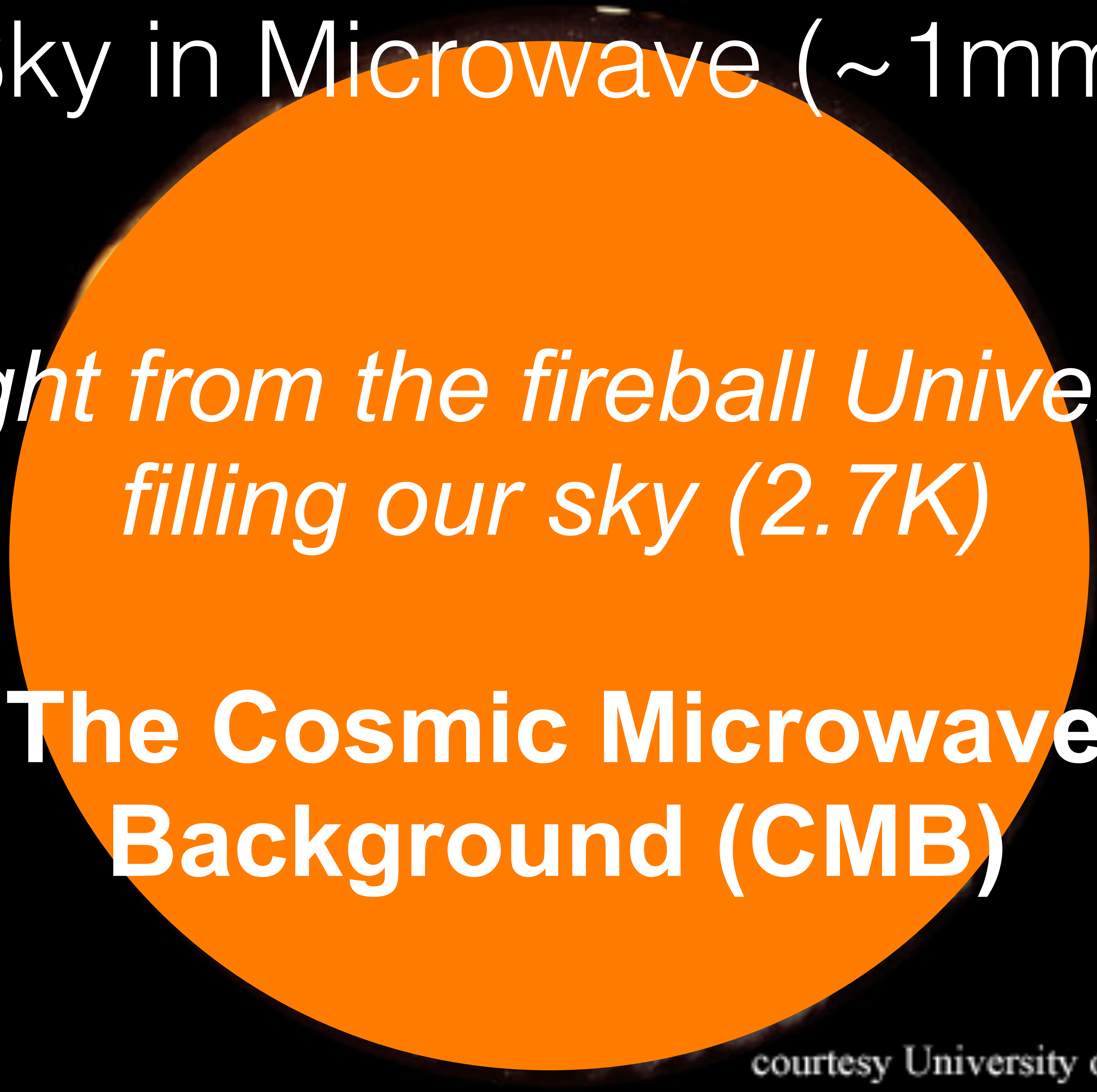


Sky in Microwave (~1mm)



courtesy University of Arizona

Sky in Microwave (~1mm)



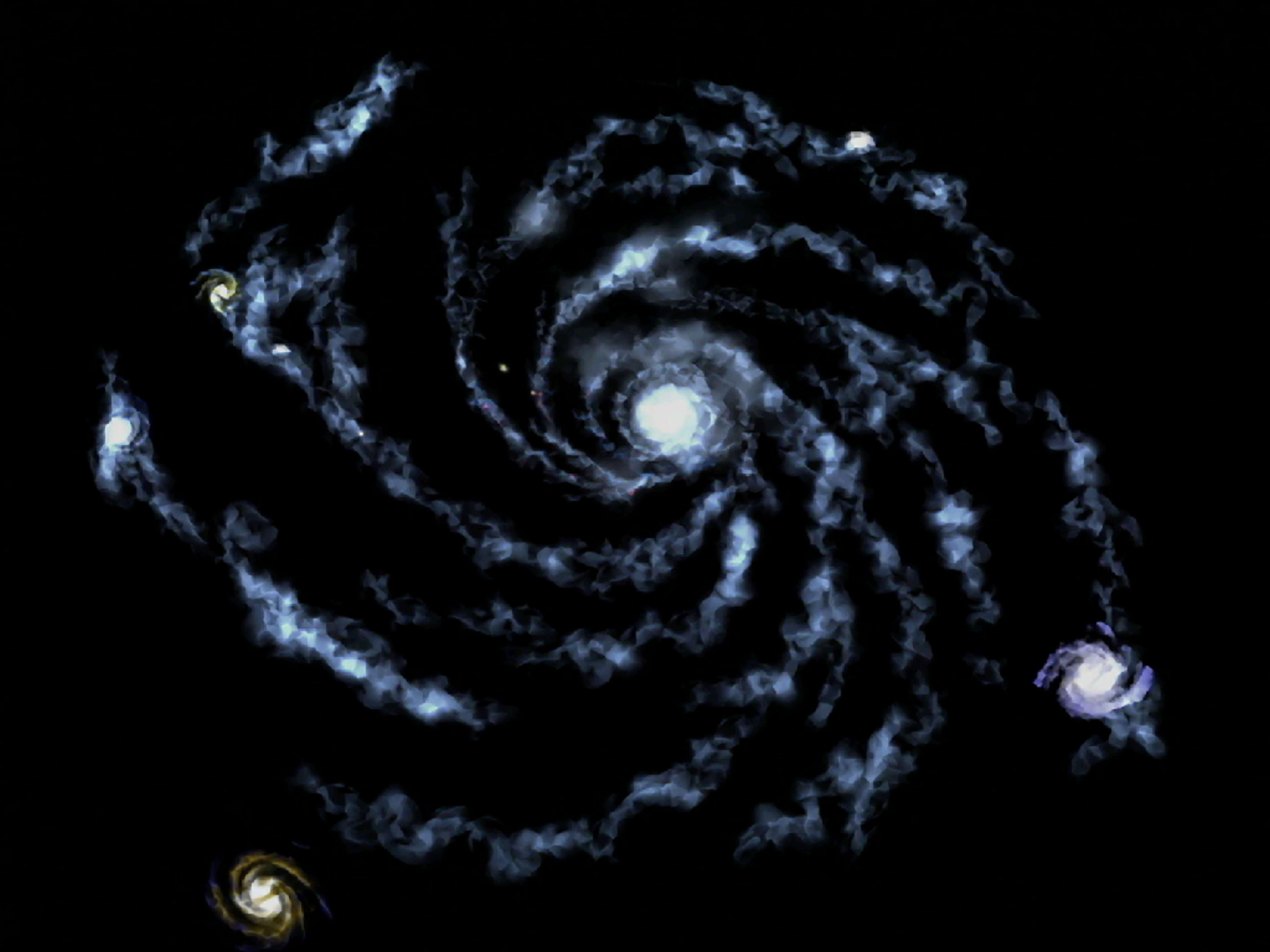
Light from the fireball Universe filling our sky (2.7K)

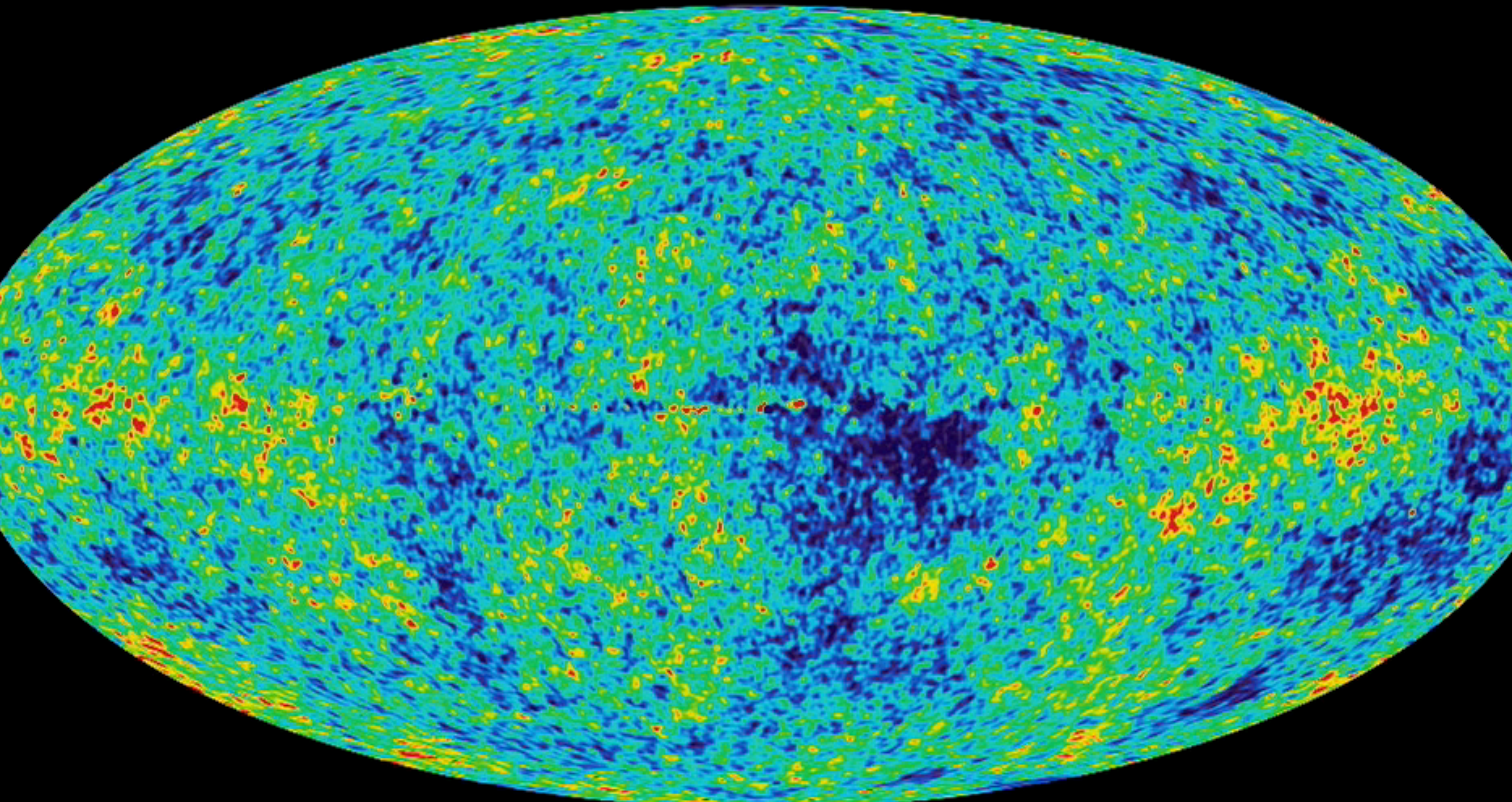
The Cosmic Microwave Background (CMB)

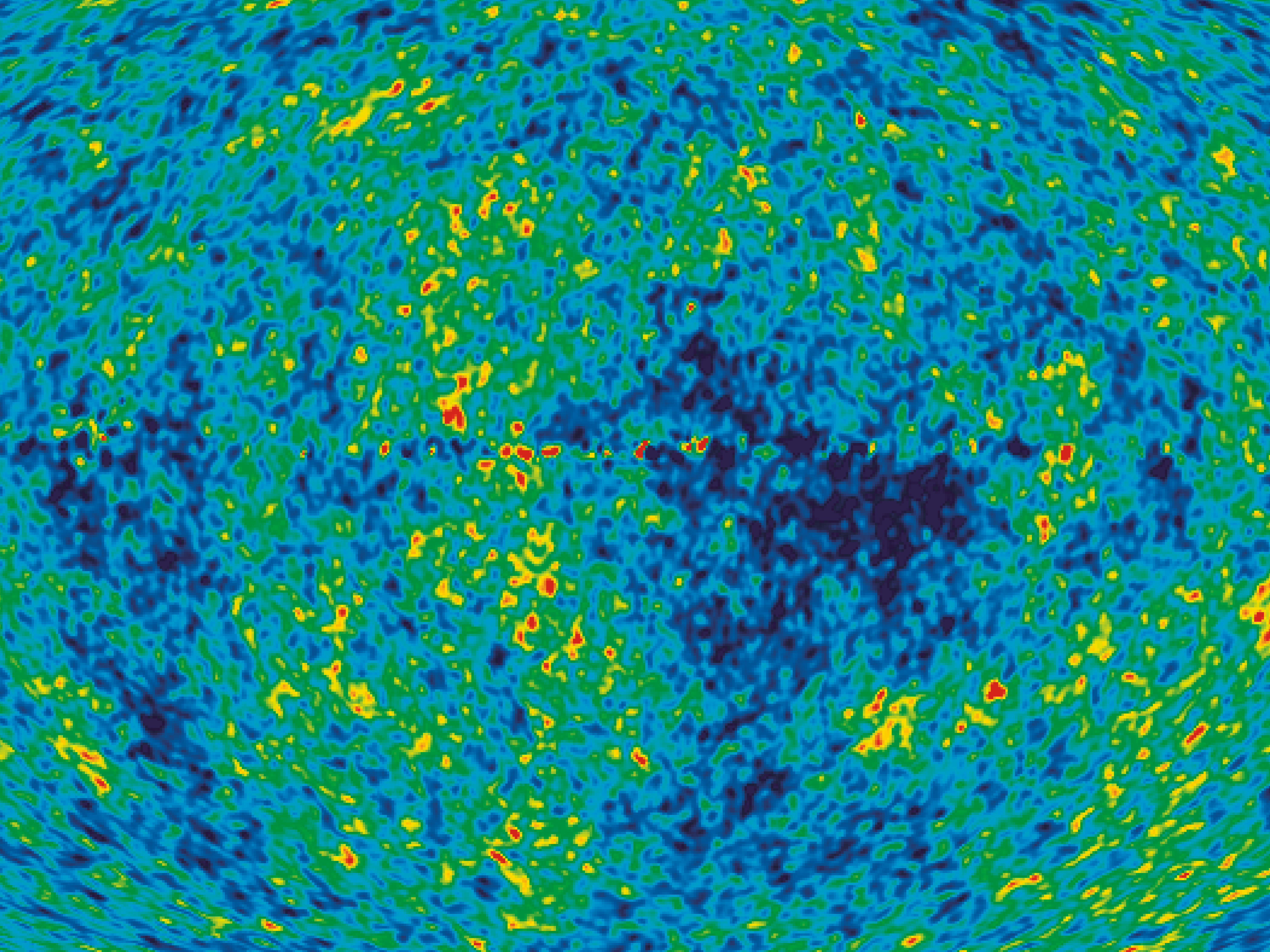
courtesy University of Arizona

WMAP Science Team
July 19, 2002

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





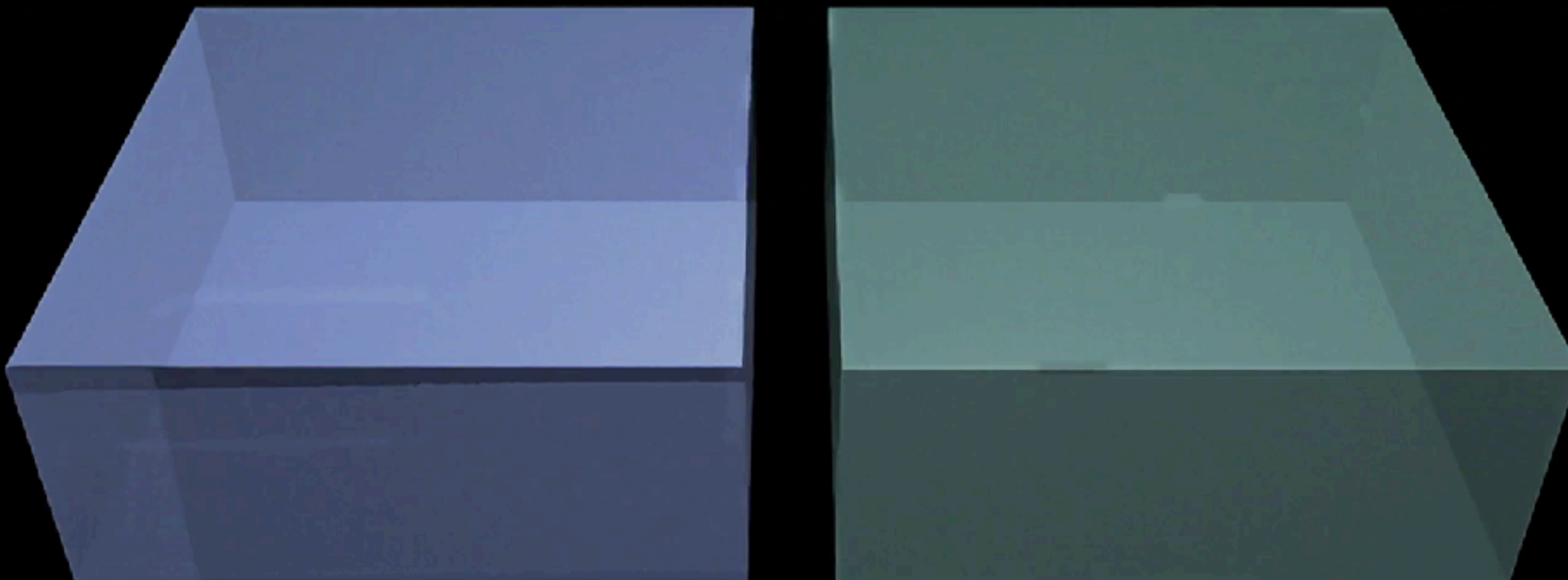


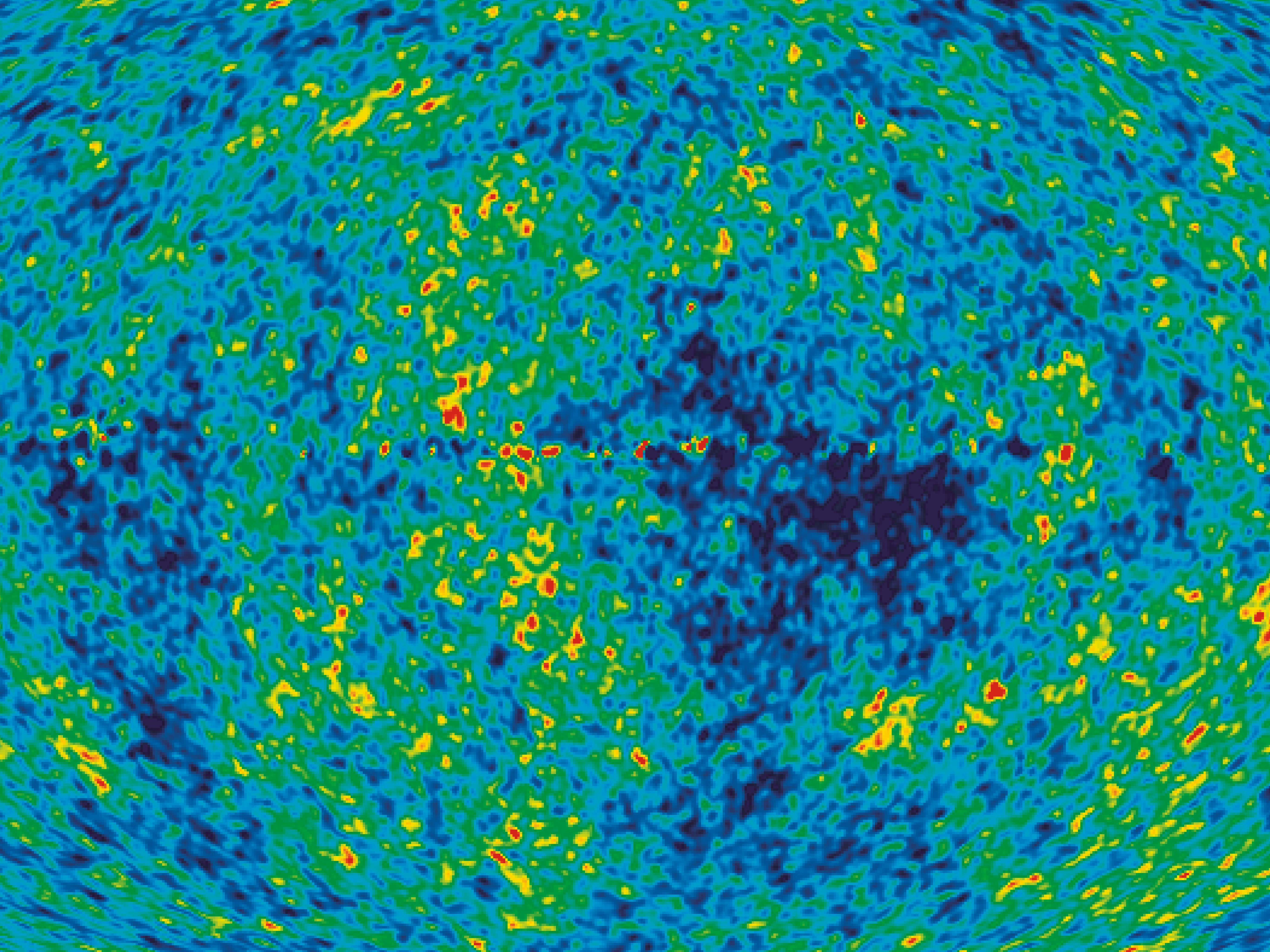
Our Origin

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

Kosmische Miso Suppe

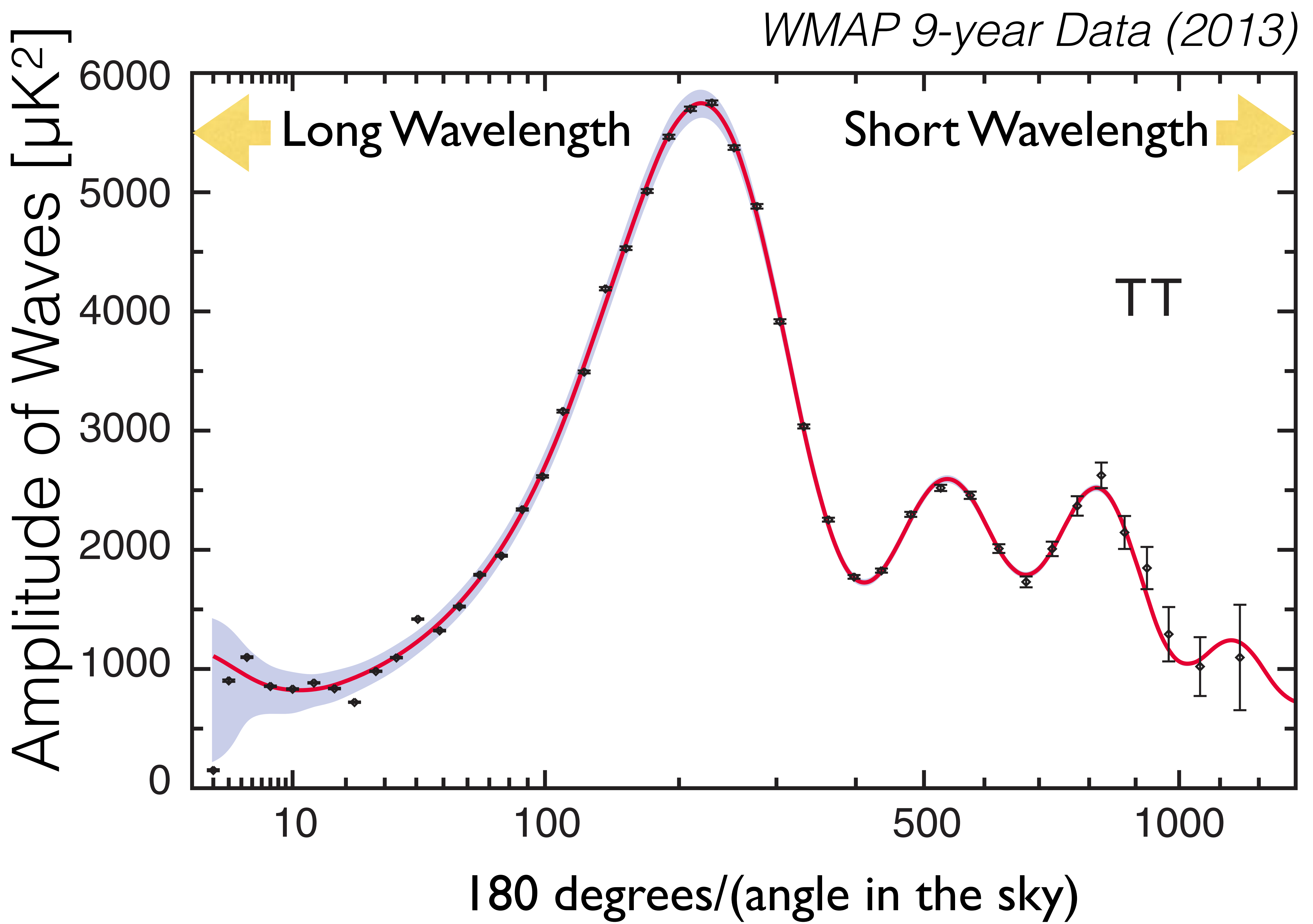
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching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



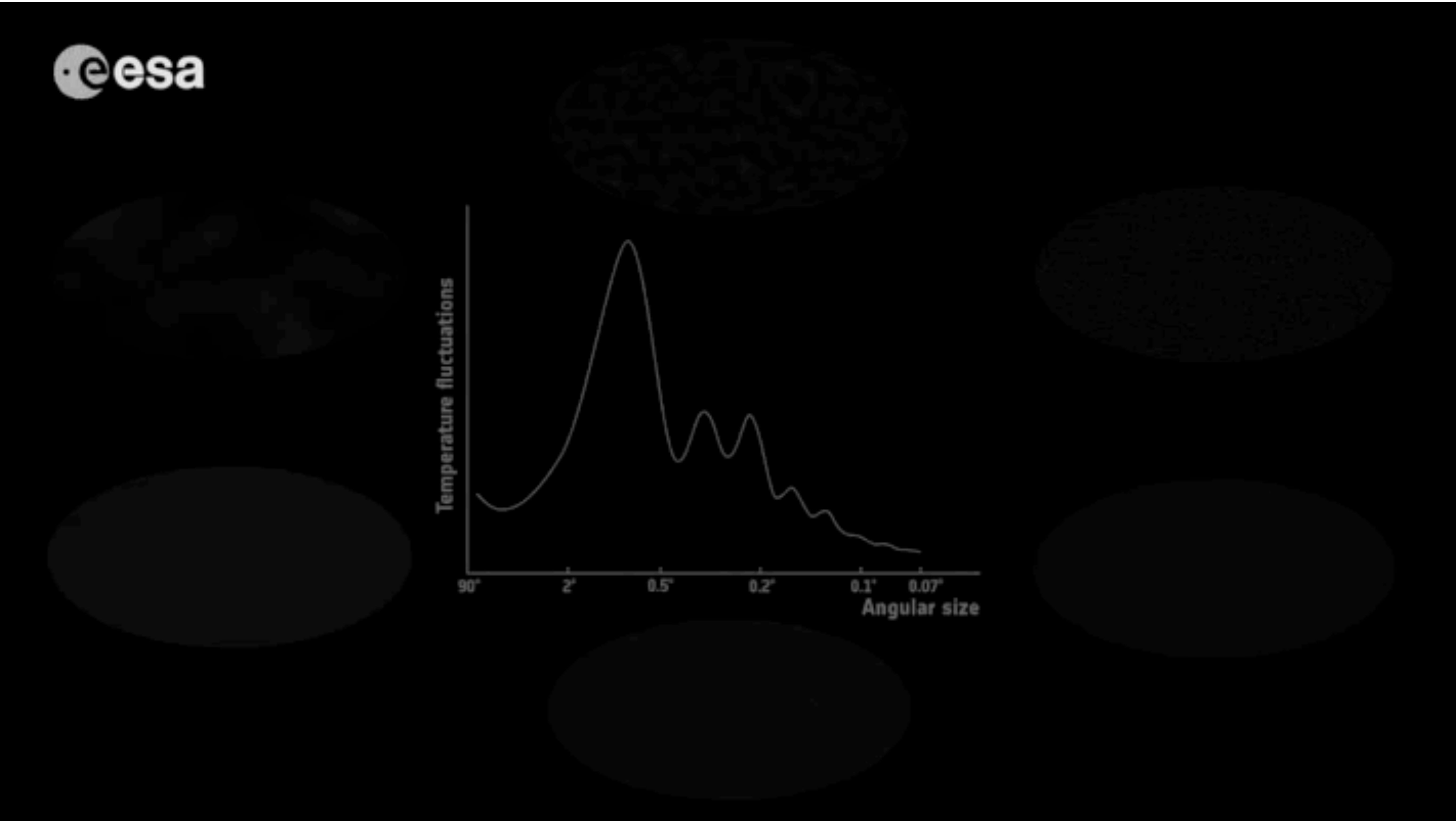


Data Analysis

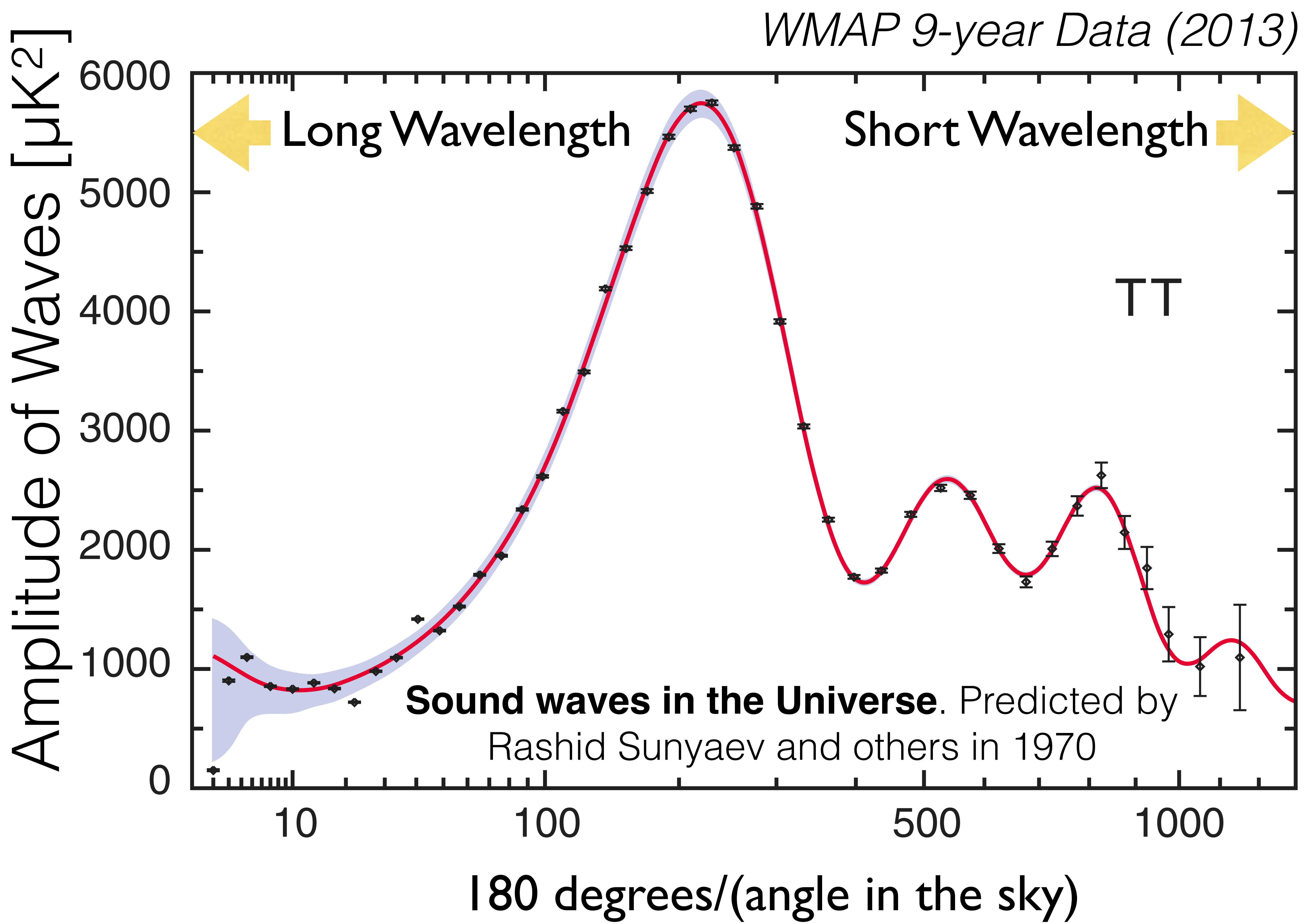
- Decompose temperature fluctuations in the sky into a set of waves with various wavelengths
- Make a diagram showing the strength of each wavelength



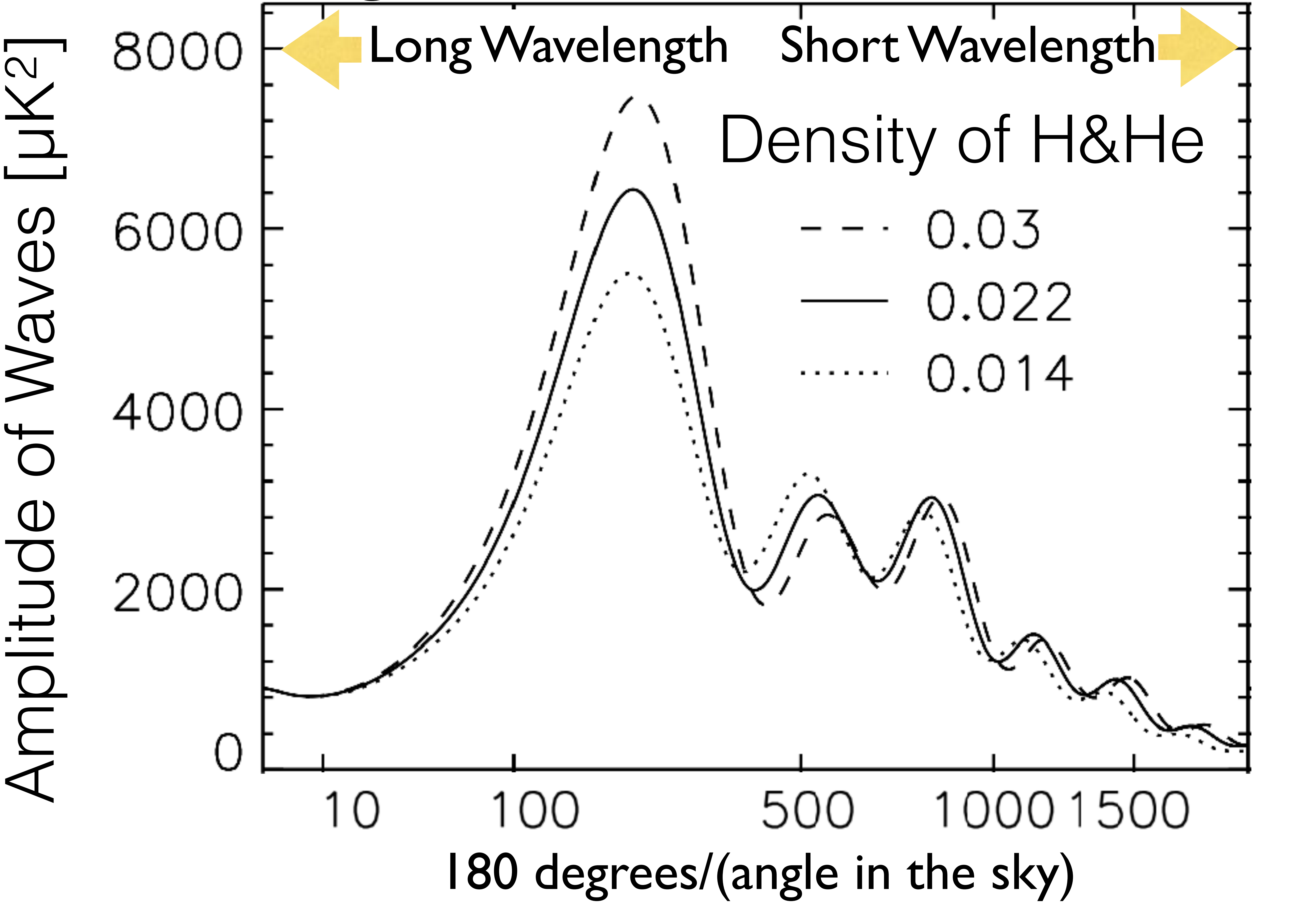
WMAP 9-year Data (2013)
Amplitude of Waves [μK2]
Long Wavelength
Short Wavelength
TT
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
180 degrees/(angle in the sky)



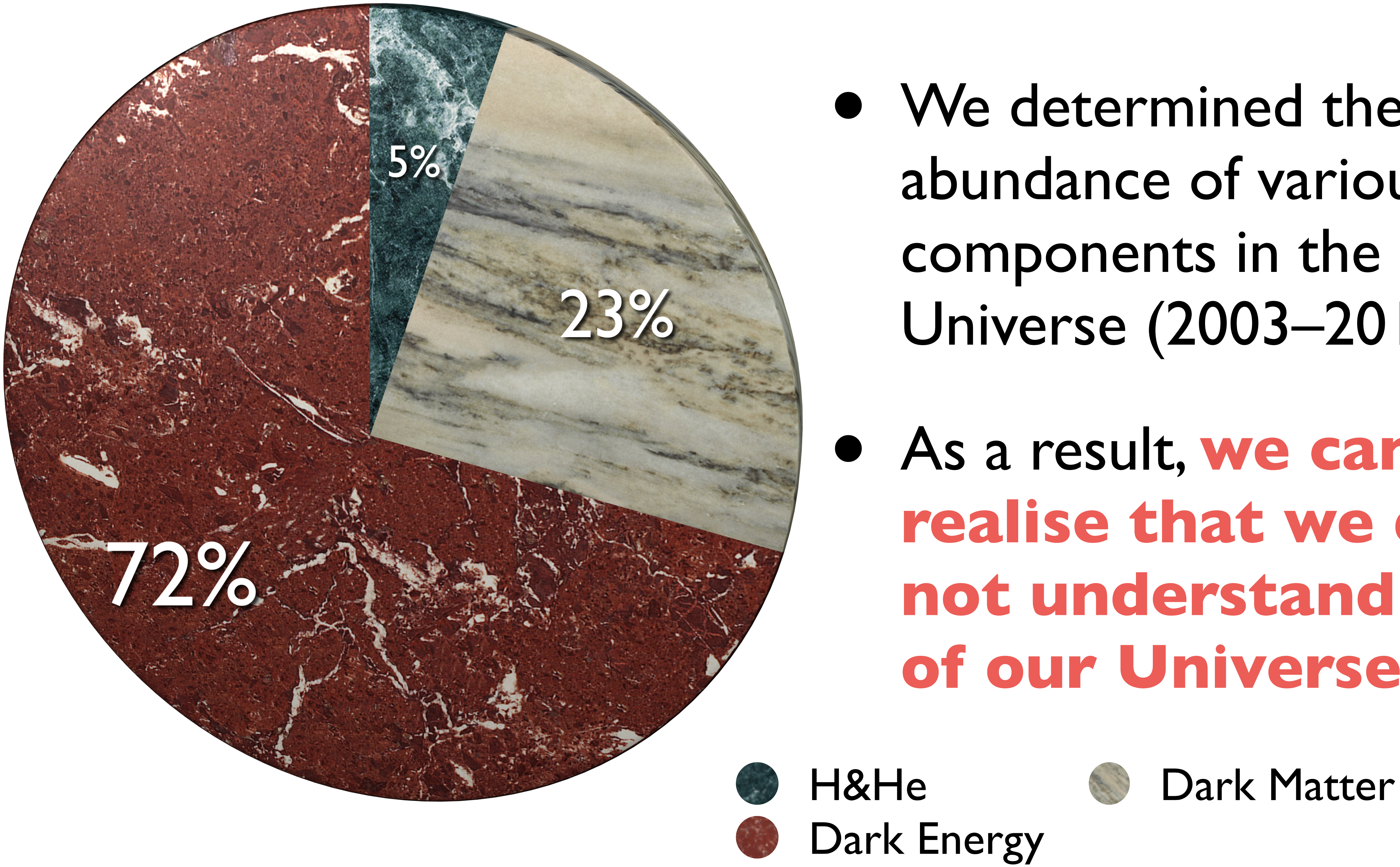
Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size


WMAP 9-year Data (2013)
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
Short Wavelength
TT
Sound waves in the Universe. Predicted by
Rashid Sunyaev and others in 1970
10
100
500
1000
180 degrees/(angle in the sky)

Measuring Abundance of H&He



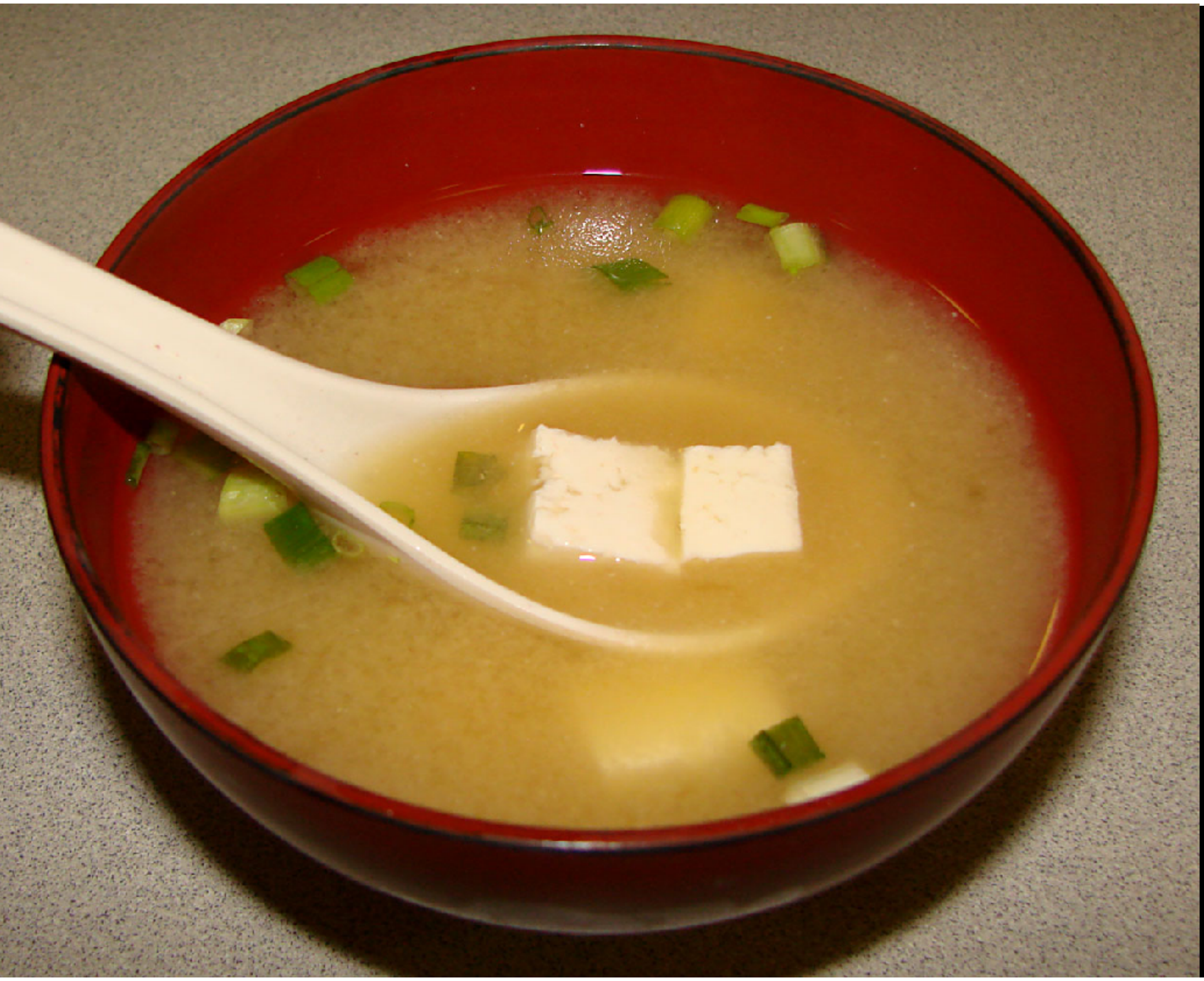
Cosmic Pie Chart

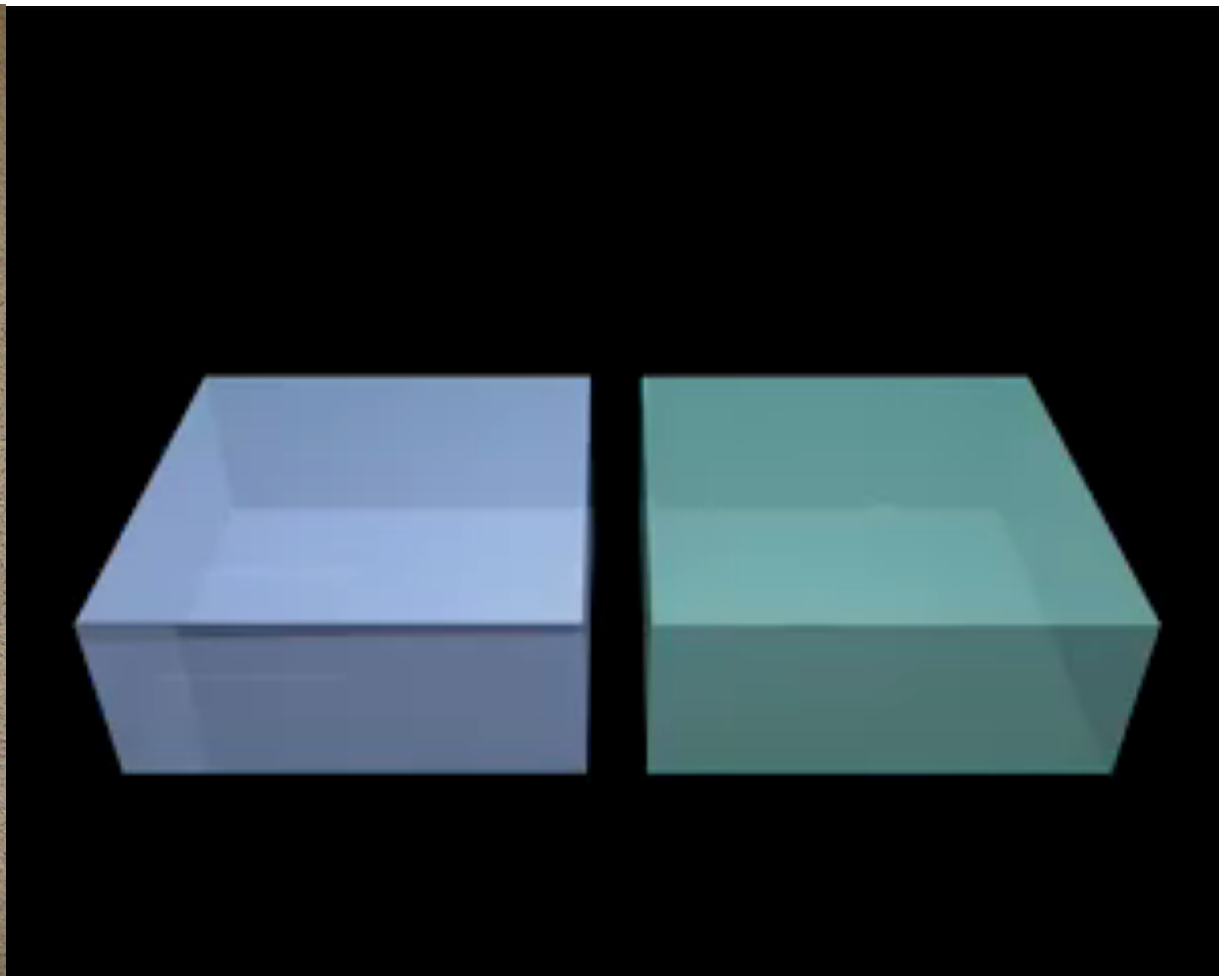


- We determined the abundance of various components in the Universe (2003–2013)
- As a result, **we came to realise that we do not understand 95% of our Universe…**

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**
- Heisenberg's 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?

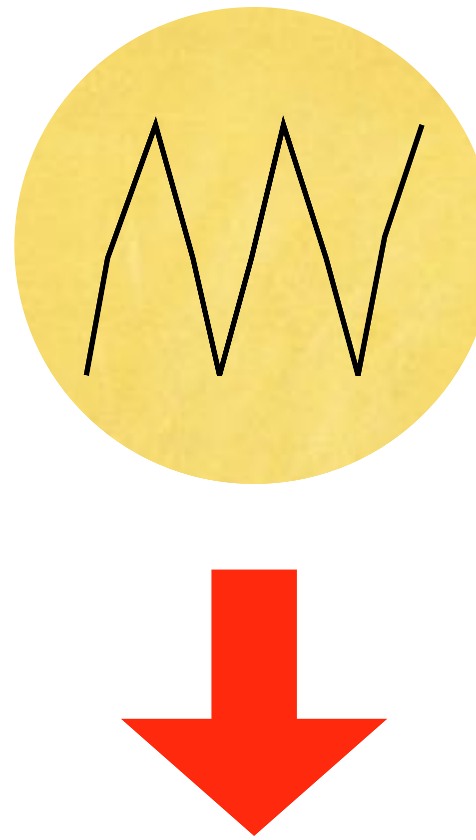
Starobinsky (1980); Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

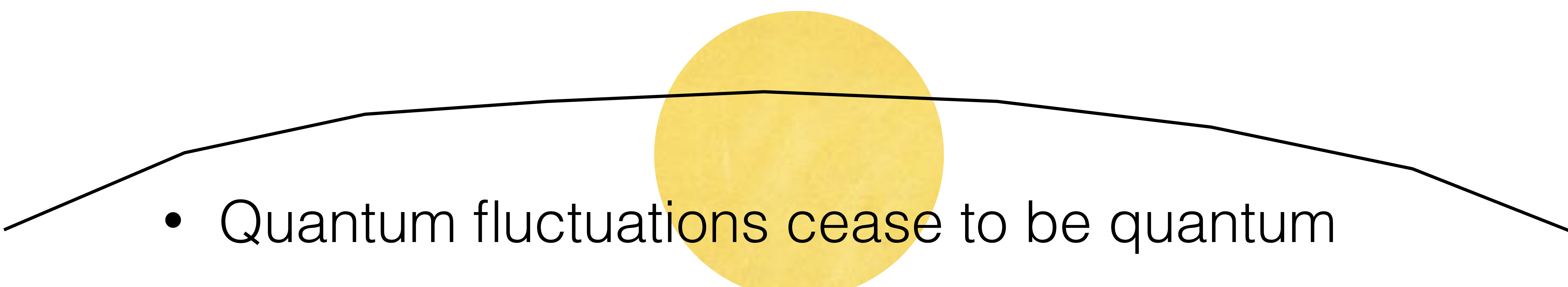
- In a tiny fraction of a second, the size of an atomic nucleus became the size of the Solar System
    - In 10^{-36} second, space was stretched by at least a factor of 10^{26}

Stretching Micro to Macro

Quantum fluctuations on microscopic scales



Inflation!



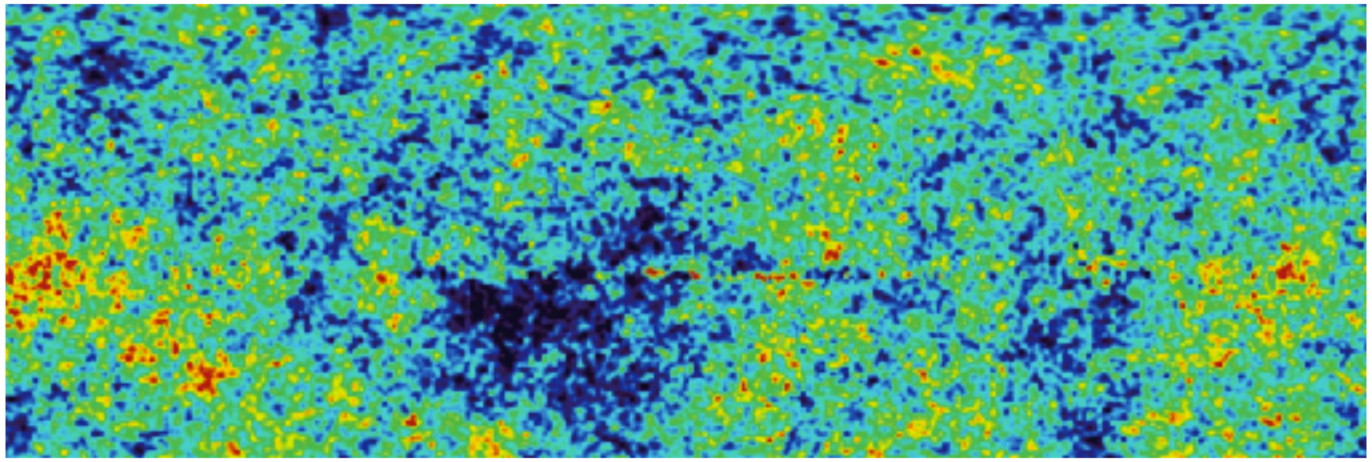
- Quantum fluctuations cease to be quantum
- Become macroscopic, classical fluctuations

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

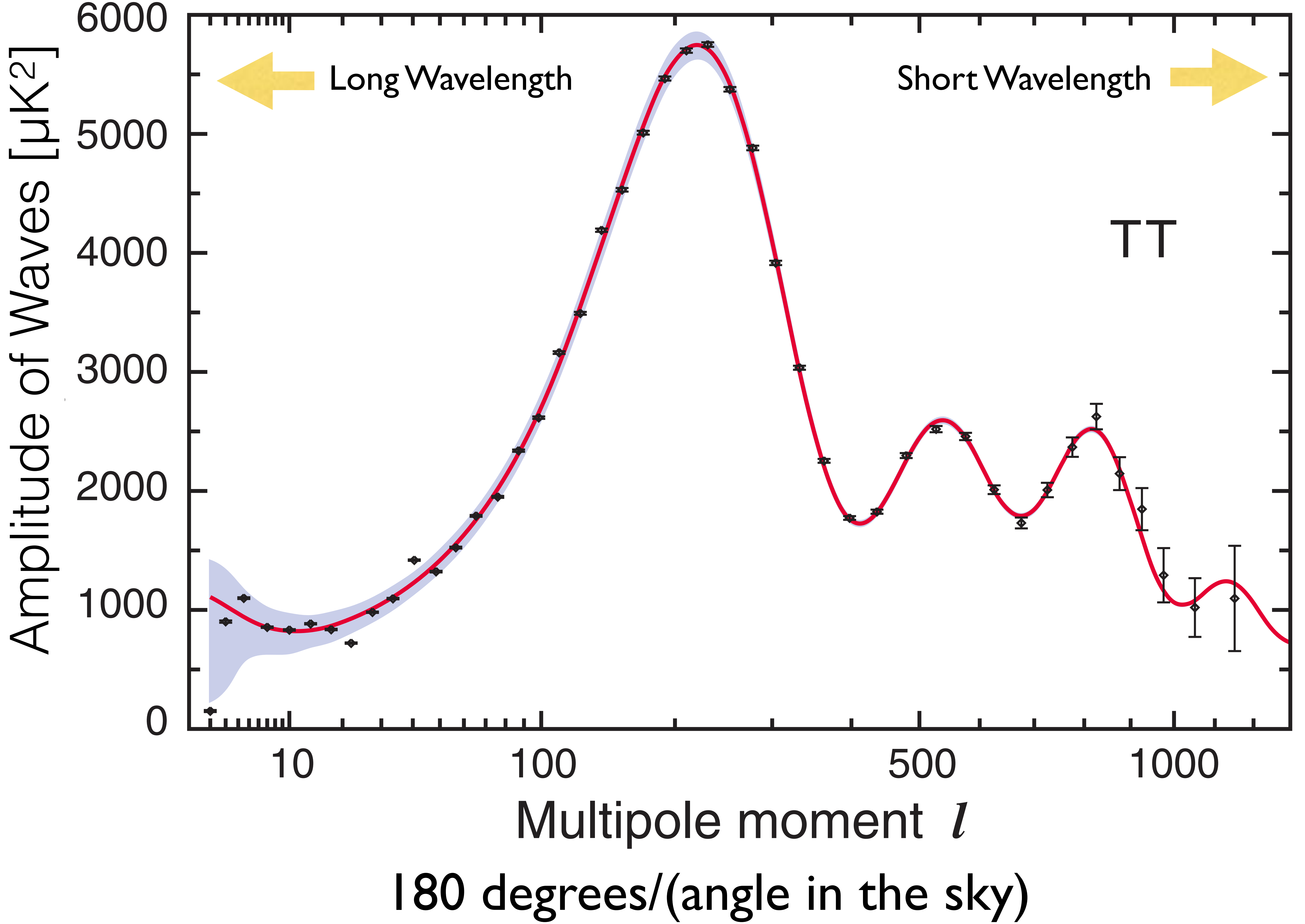
- Suppose that the distance between two points increases in proportion to **a(t)** [which is called the scale factor] by the expansion of the universe

- Define the "expansion rate of the universe" as

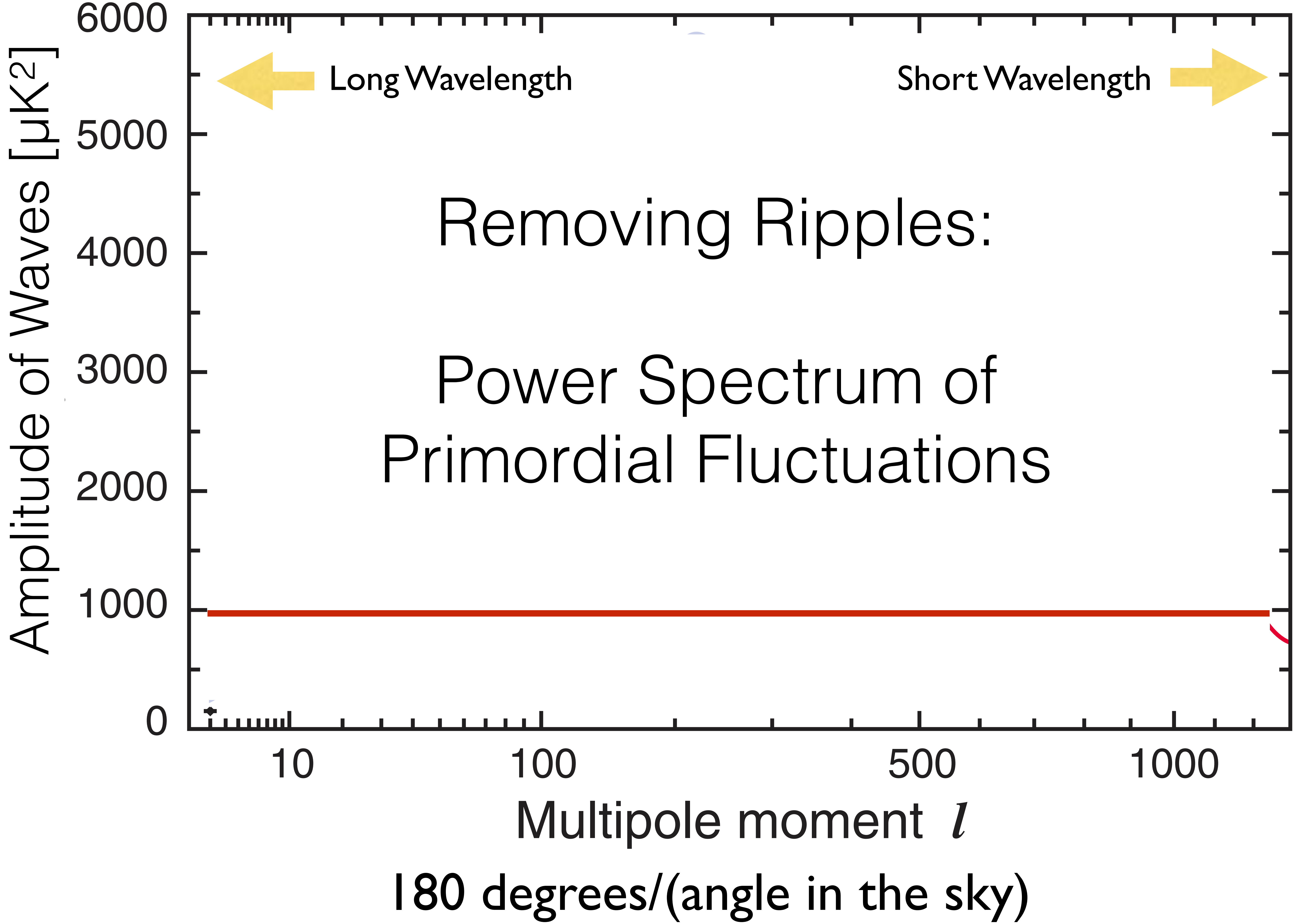
$$H \equiv \frac{\dot{a}}{a}$$ [This has units of 1/time]

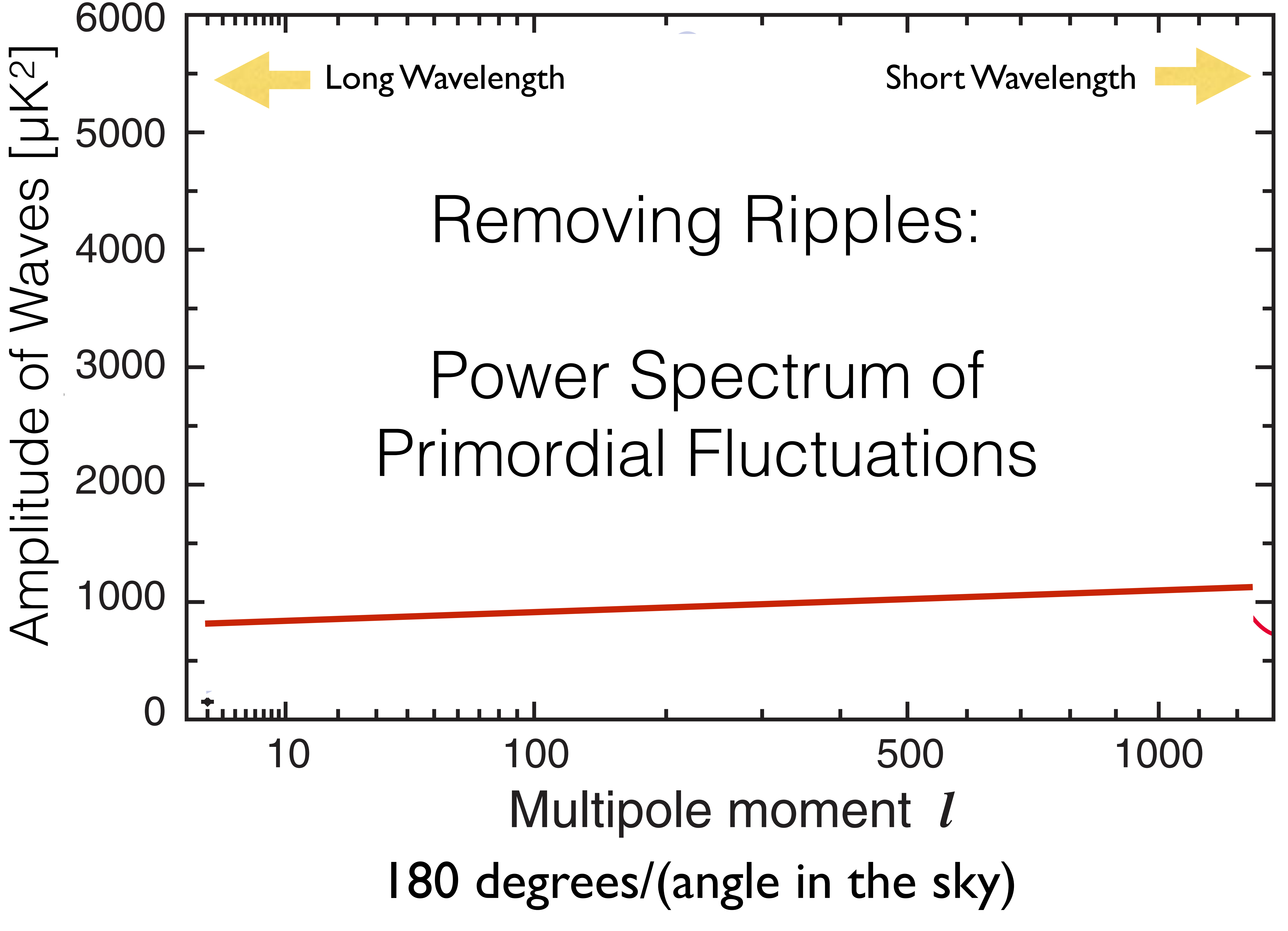
Fluctuations are proportional to H

- [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**



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)


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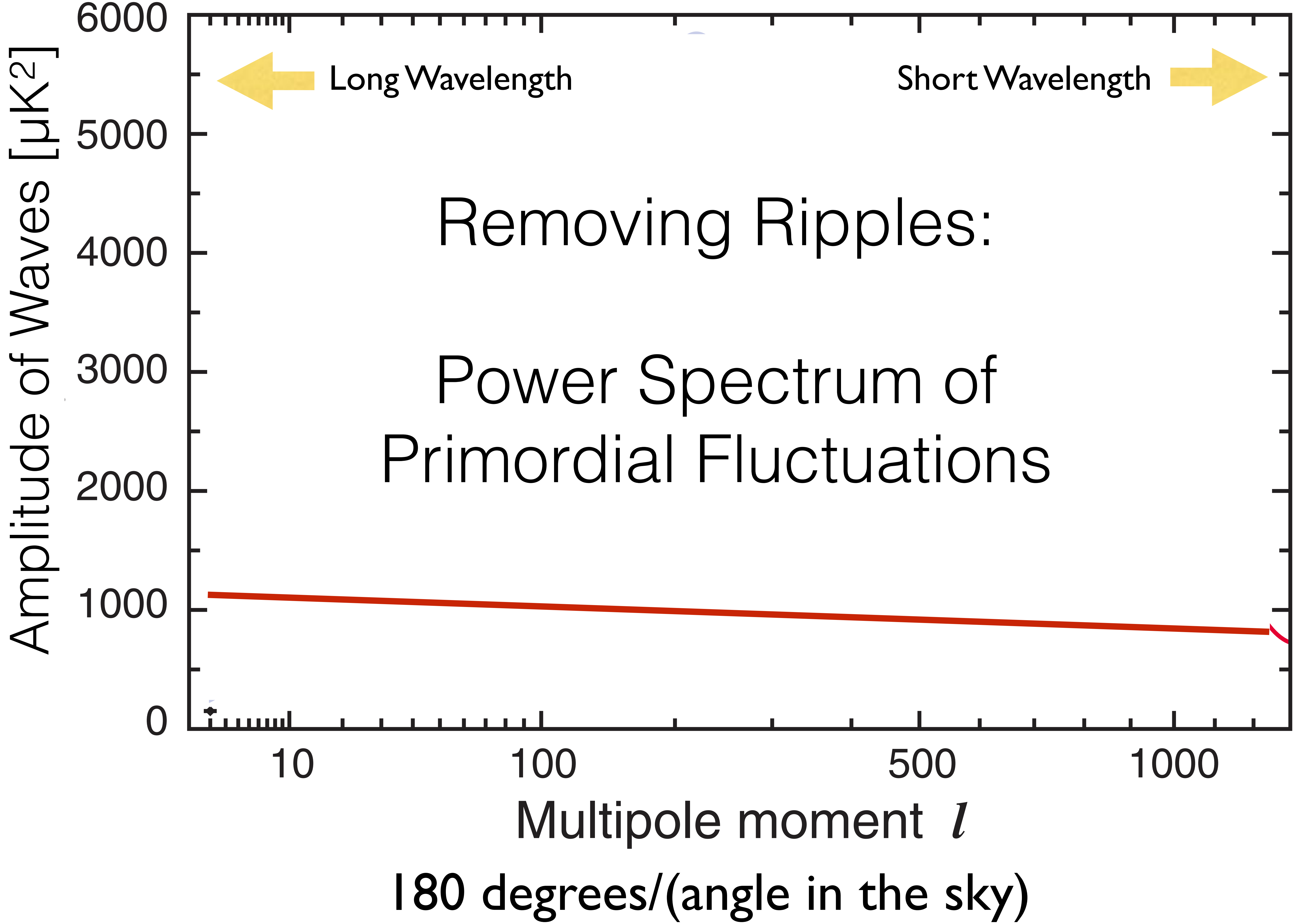
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)


Long Wavelength
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Power Spectrum of
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Amplitude of Waves [μK²]
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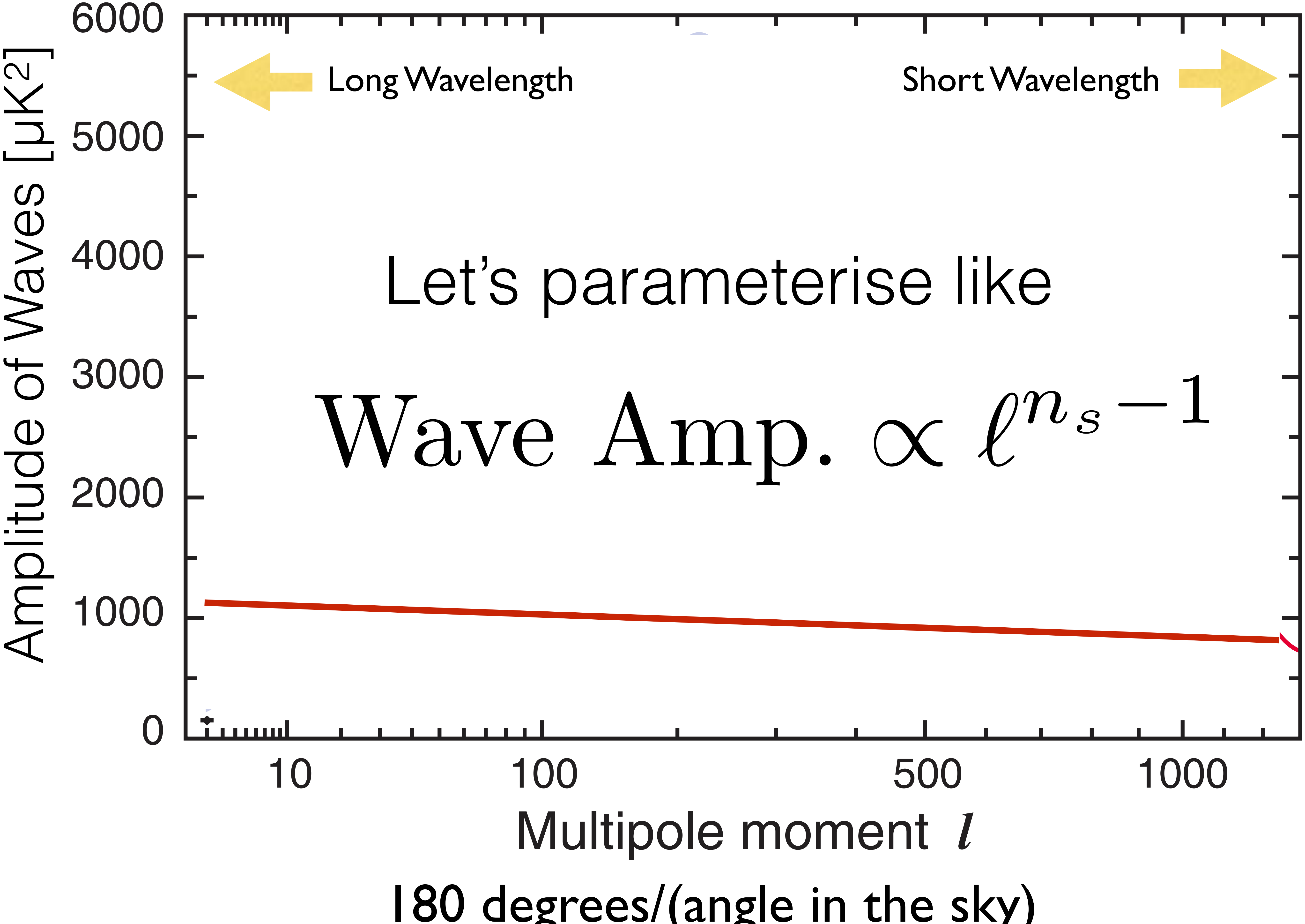
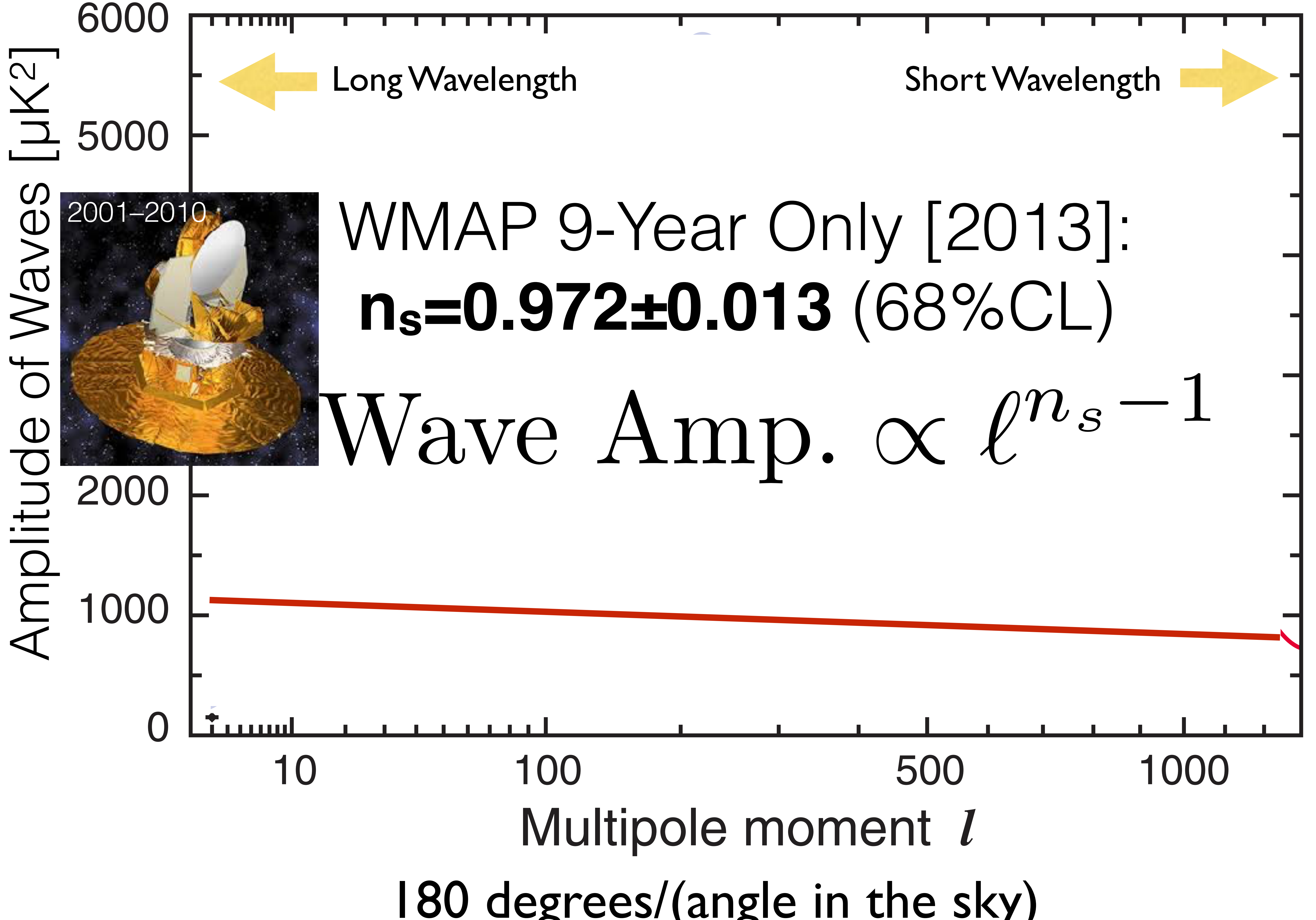
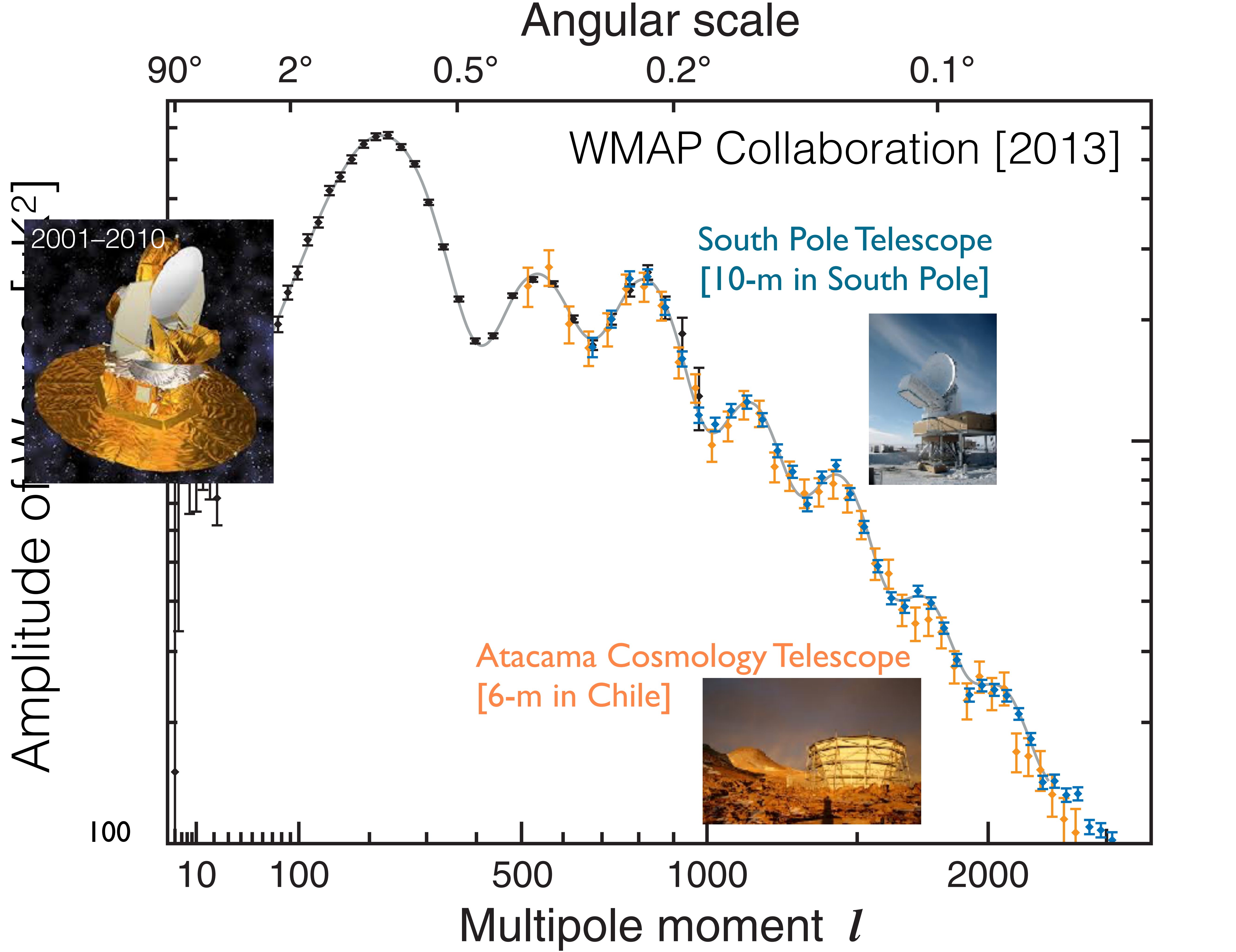
Multipole moment l
180 degrees/(angle in the sky)

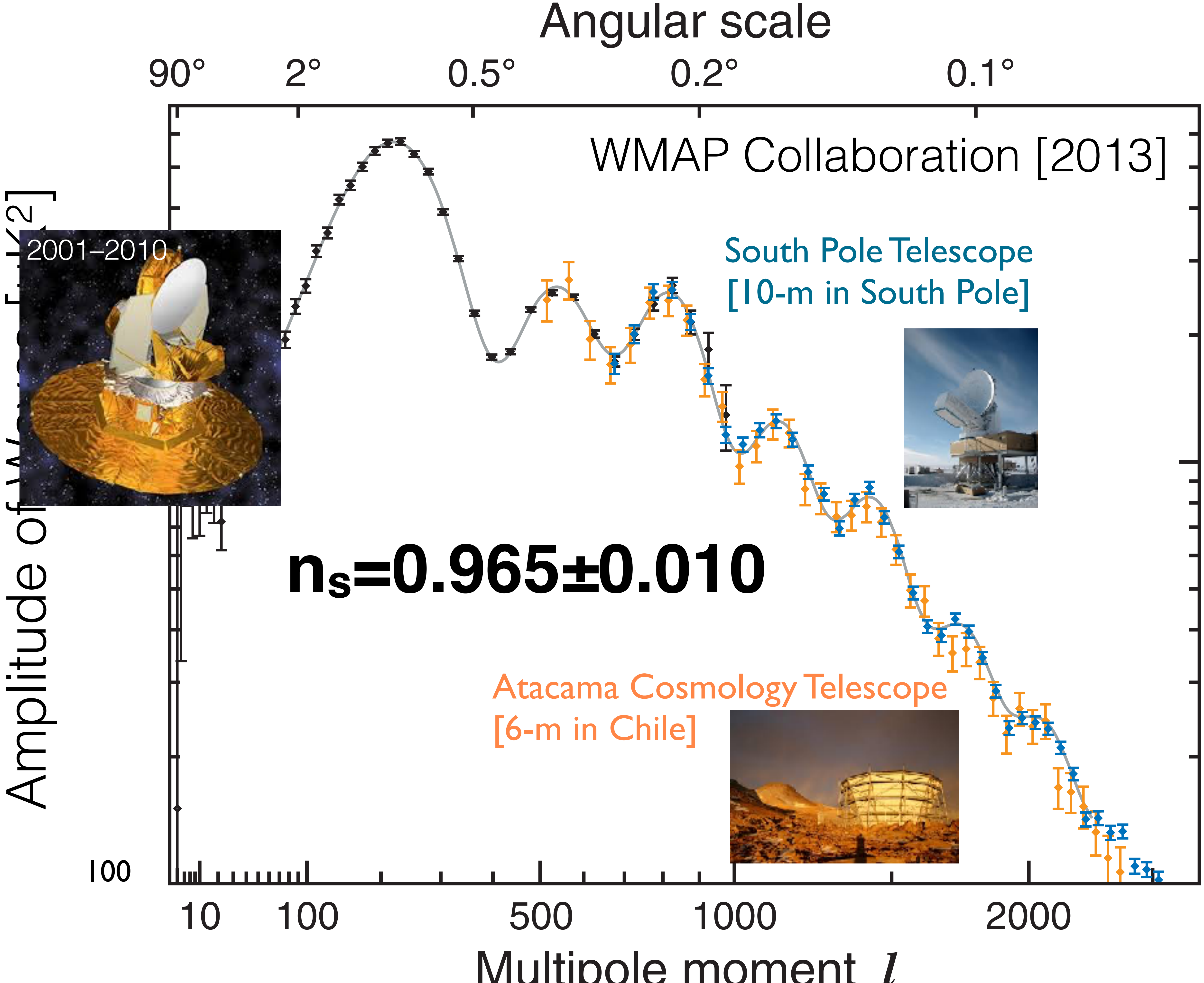


Long Wavelength
Short Wavelength
Let's parameterise like
$$\text{Wave Amp.} \propto \ell^{n_s - 1}$$
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

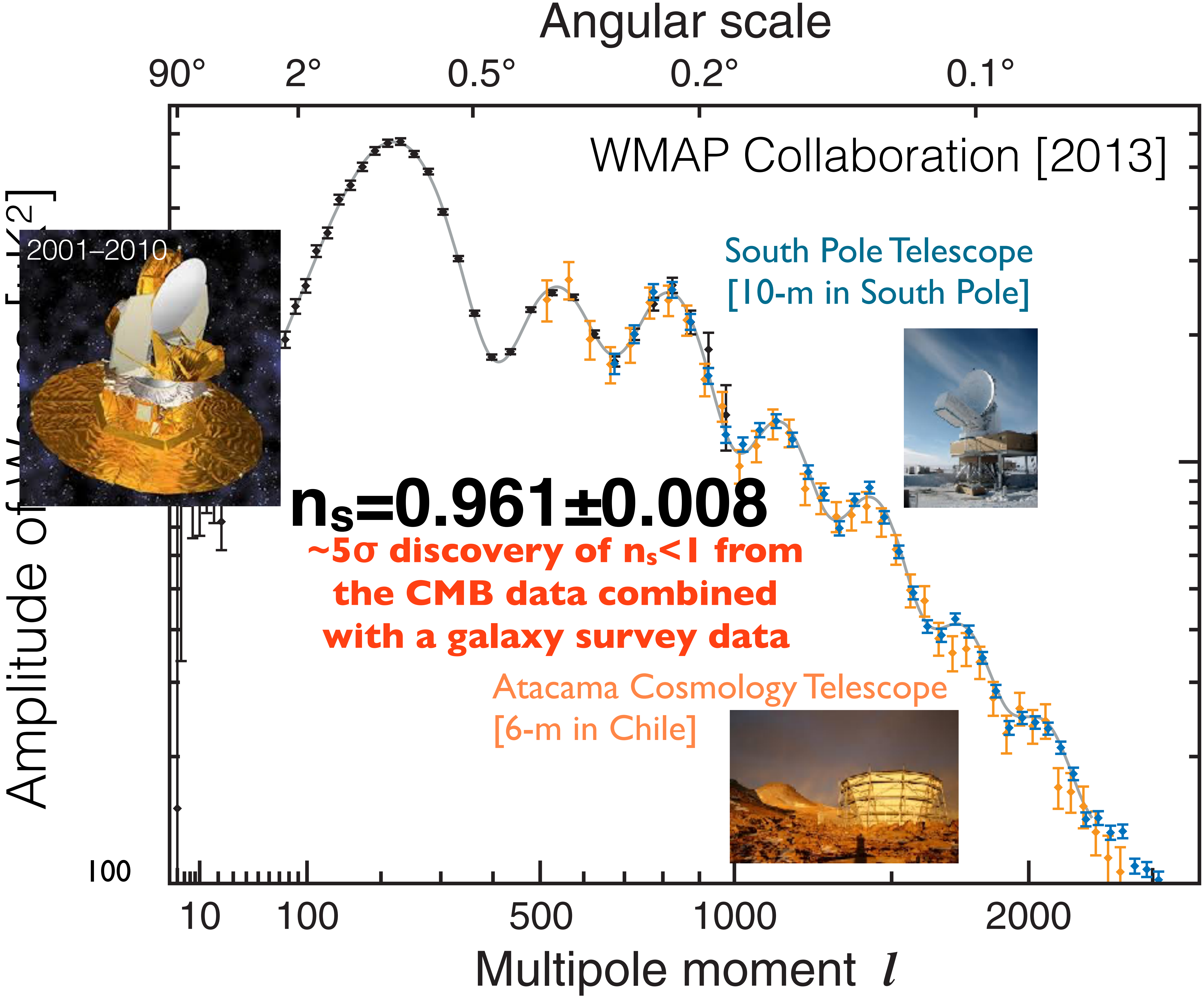


Long Wavelength
Short Wavelength
2001–2010
WMAP 9-Year Only [2013]:
n_s=0.972±0.013 (68%CL)
$\text{Wave Amp.} \propto \ell^{n_s - 1}$
Amplitude of Waves [μK²]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

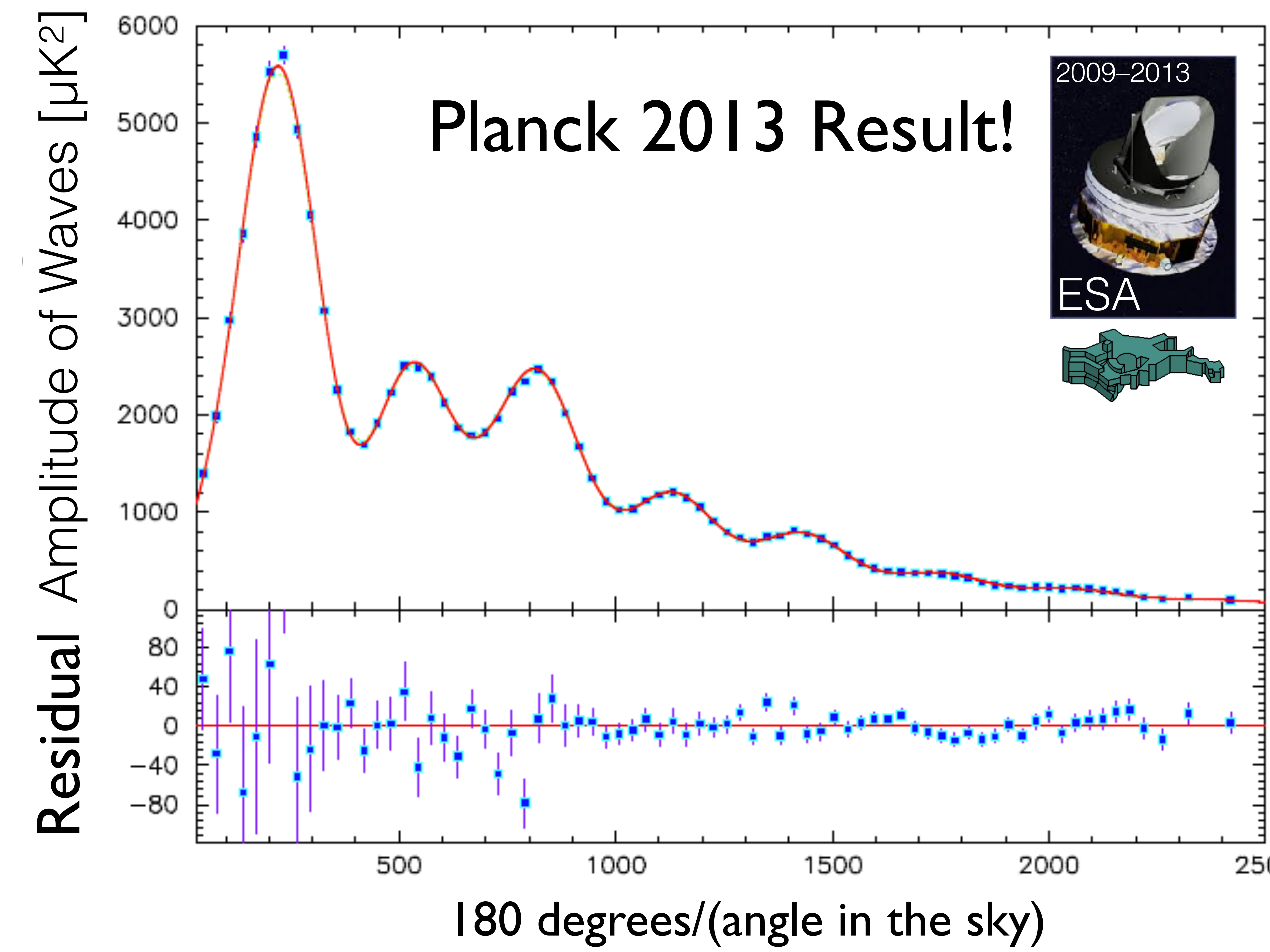

Angular scale
90°
2°
0.5°
0.2°
0.1°
WMAP Collaboration [2013]
2001–2010
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
Amplitude of
100
10
100
500
1000
2000
Multipole moment l

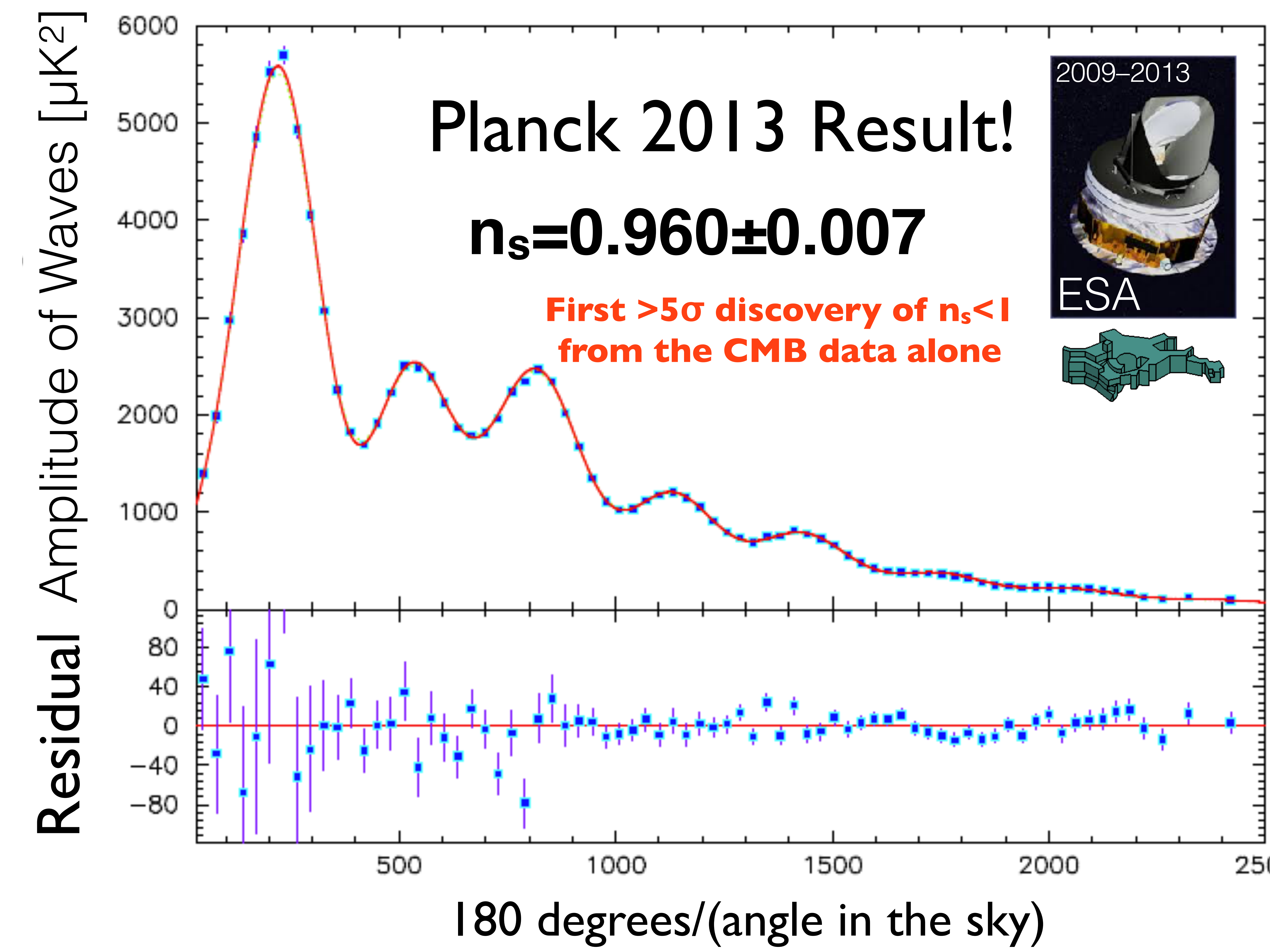


Angular scale
90°
2°
0.5°
0.2°
0.1°
WMAP Collaboration [2013]
2001–2010
South Pole Telescope
[10-m in South Pole]
n_s=0.965±0.010
Atacama Cosmology Telescope
[6-m in Chile]
Amplitude of
100
10
100
500
1000
2000
Multipole moment l



Angular scale
90°
2°
0.5°
0.2°
0.1°
WMAP Collaboration [2013]
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 a galaxy survey data
Atacama Cosmology Telescope
[6-m in Chile]
Amplitude of
100
10
100
500
1000
2000
Multipole moment l

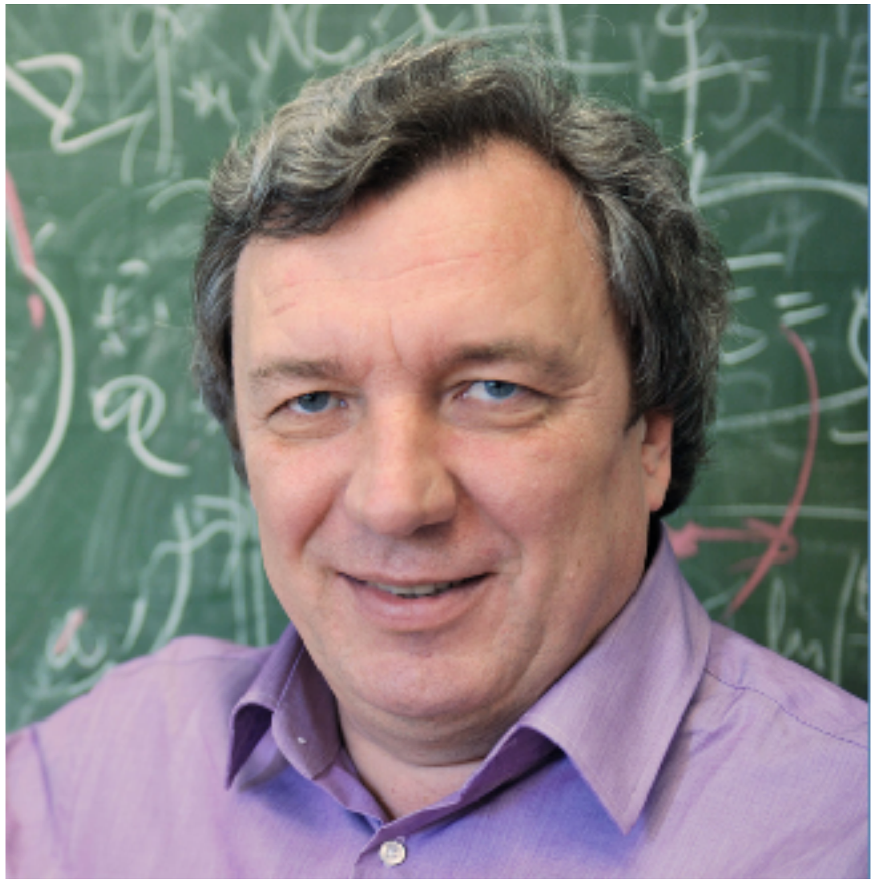

Planck 2013 Result!
2009–2013
ESA
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
Residual
80
40
0
−40
−80
500
1000
1500
2000
250
180 degrees/(angle in the sky)



Planck 2013 Result!
ns=0.960±0.007
First >5σ discovery of ns<1
from the CMB data alone
2009–2013
ESA
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

Predicted in 1981.
We discovered it finally in 2013

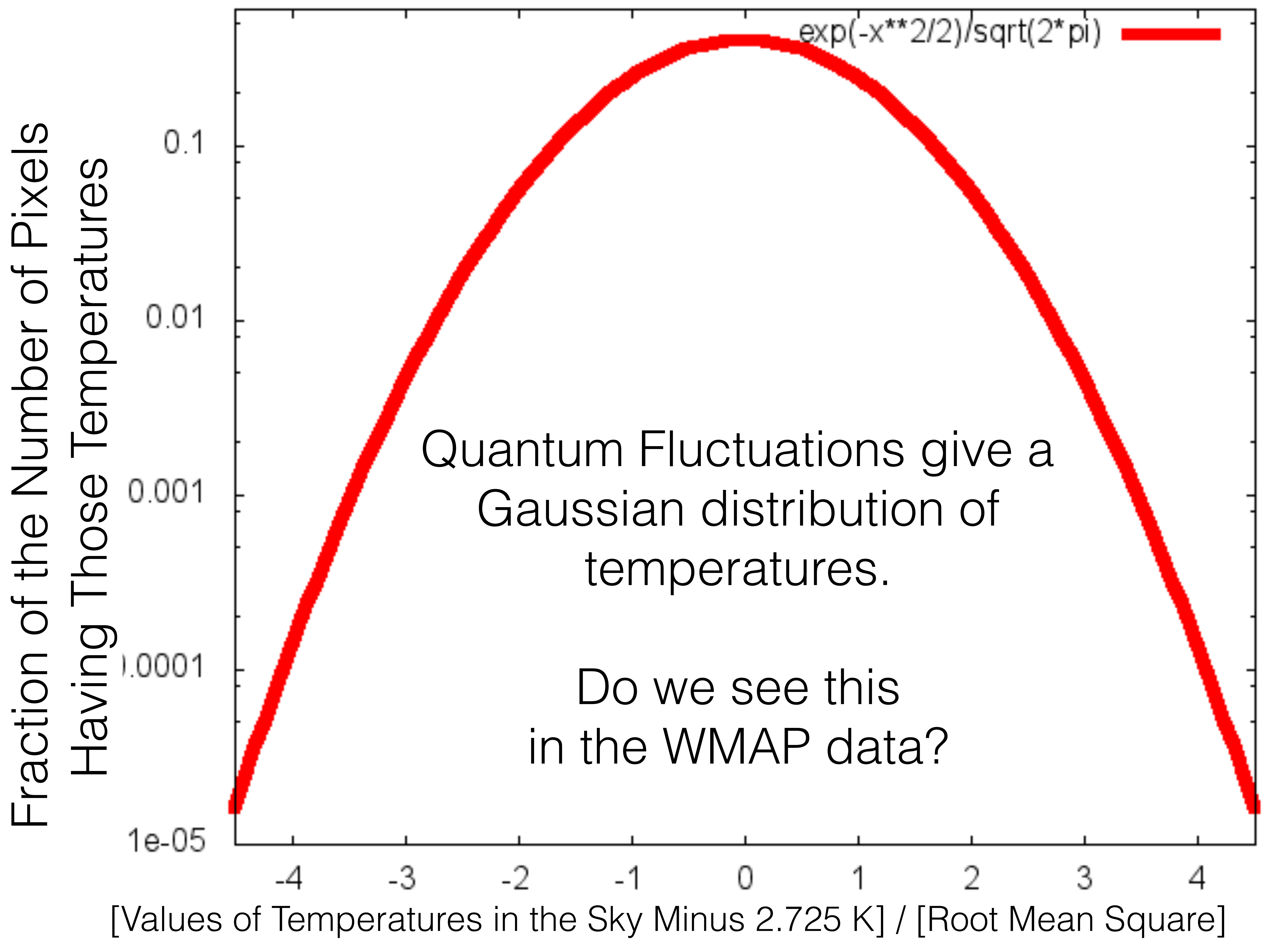
- Inflation must end
- Inflation predicts n_s~1, but not exactly equal to 1. Usually n_s<1 is expected
- **The discovery of n_s<1 has been the dream of cosmologists since 1992,** when the CMB anisotropy was first discovered and n_s~1 (to within 30%) was indicated

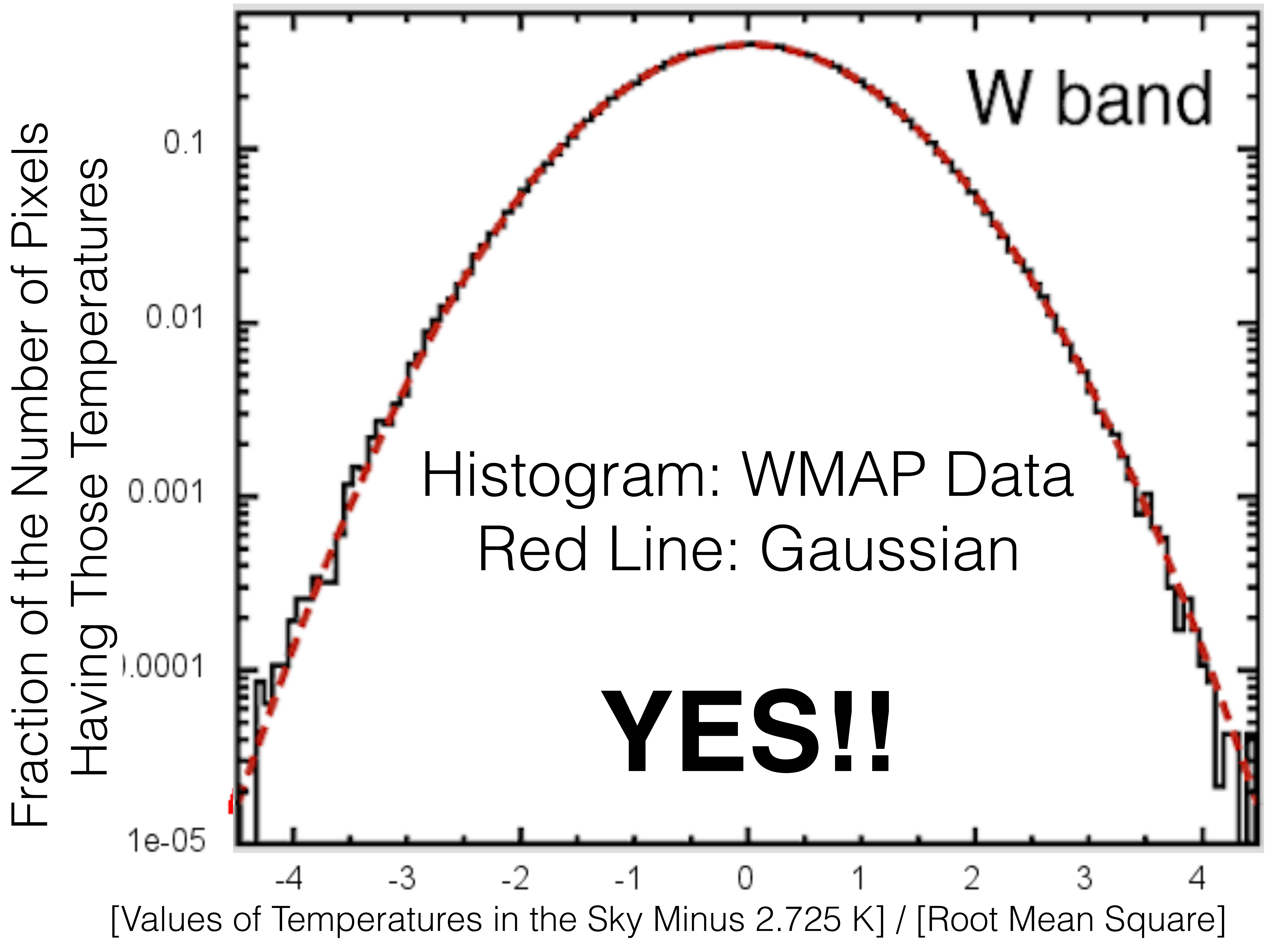


Slava Mukhanov (LMU) said in his 1981 paper that n_s should be less than 1

He was awarded Max Planck Medal in 2015

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


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?



W band
Histogram: WMAP Data
Red Line: Gaussian
YES!!
0.1
0.01
0.001
0.0001
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]

Non-Gaussianity:

A Powerful Test of Quantum Fluctuations

- The WMAP data show that the distribution of temperature fluctuations of CMB is **very precisely** Gaussian
  - with an upper bound on a deviation of **0.2%**
- With improved data provided by the Planck mission, the upper bound is now **0.03%**

CMB Research: Next Frontier

Primordial Gravitational Waves

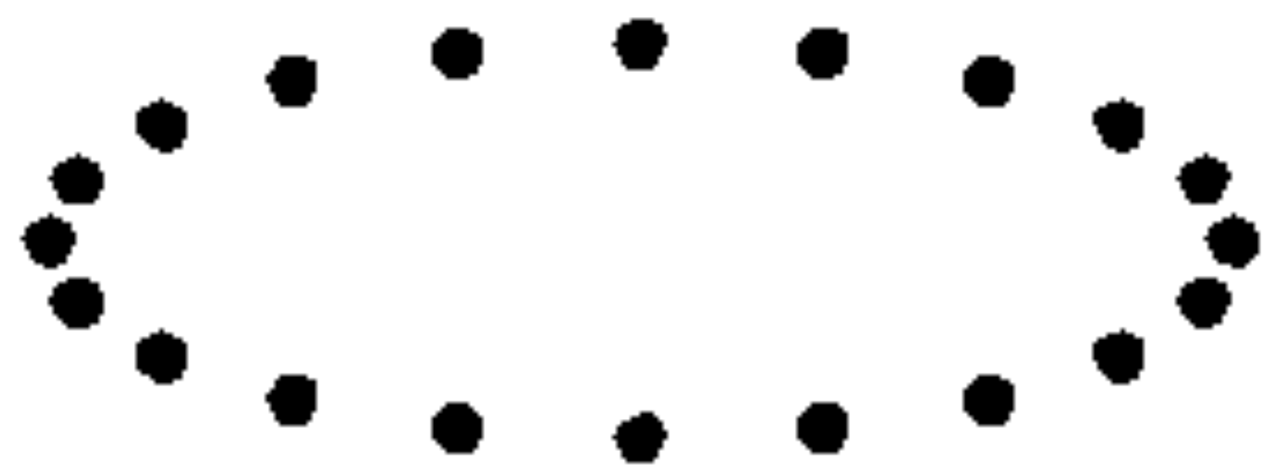
Extraordinary claims require extraordinary evidence. The same quantum fluctuations could also generate gravitational waves, and we wish to find them

Measuring GW

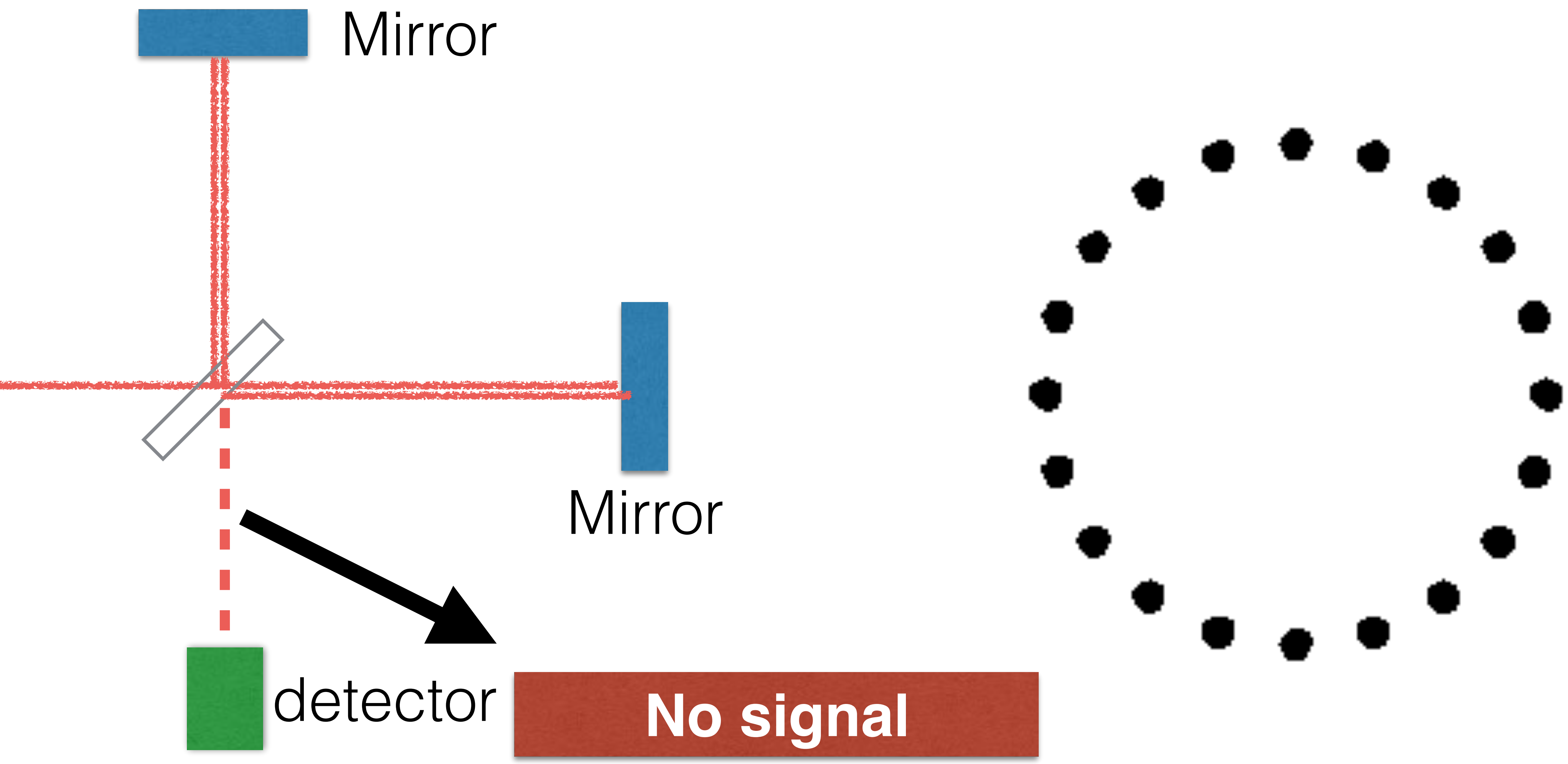
- GW changes the distances between two points

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

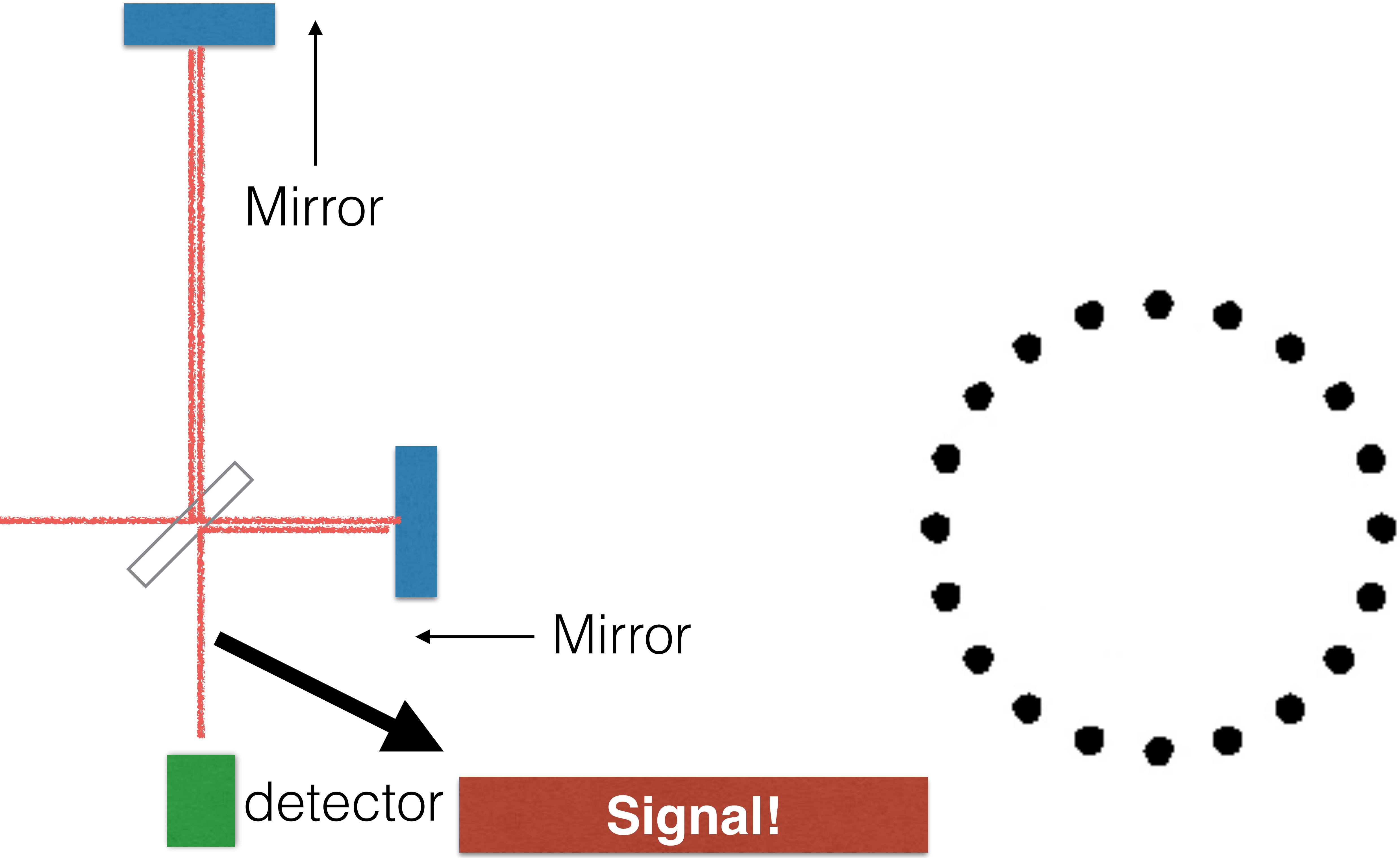
$$d\ell^2 = \sum_{ij} (\delta_{ij} + \underline{h_{ij}}) dx^i dx^j$$



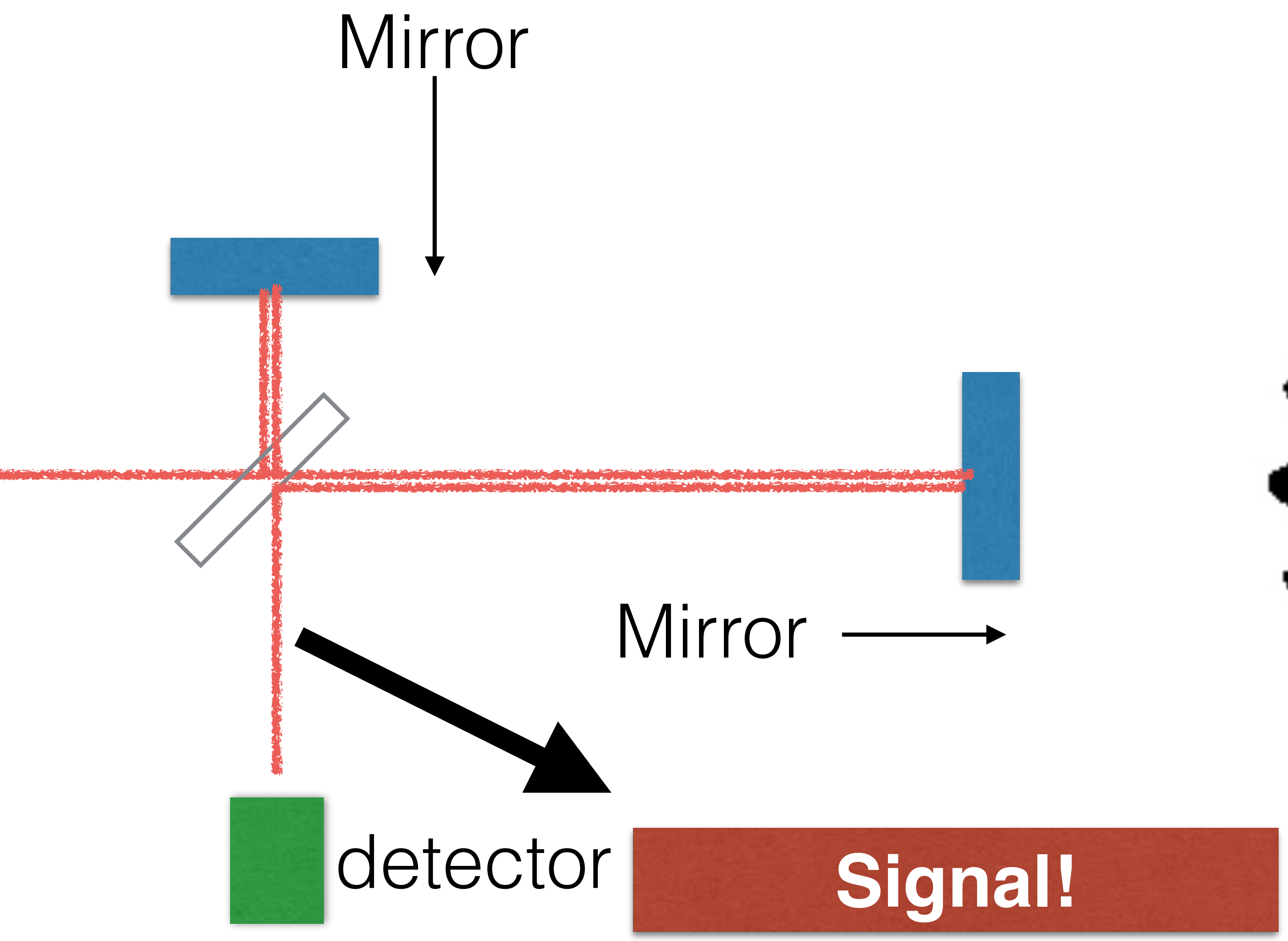
Laser Interferometer

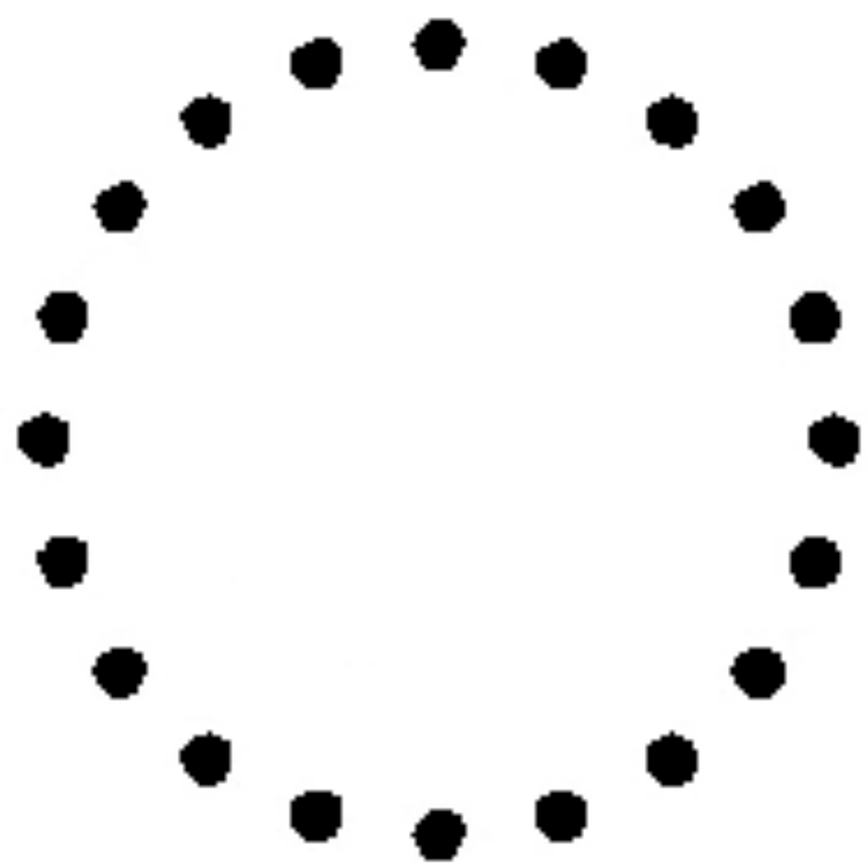


Laser Interferometer



Laser Interferometer





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

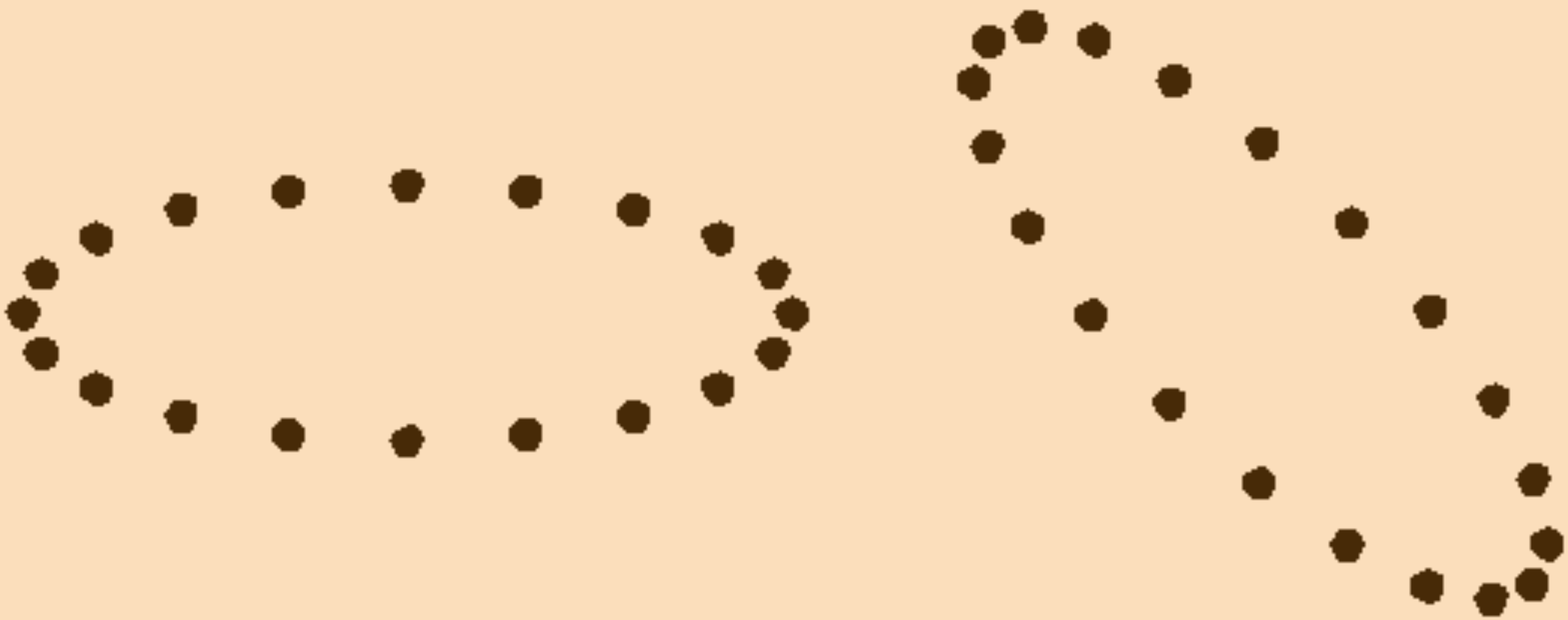
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

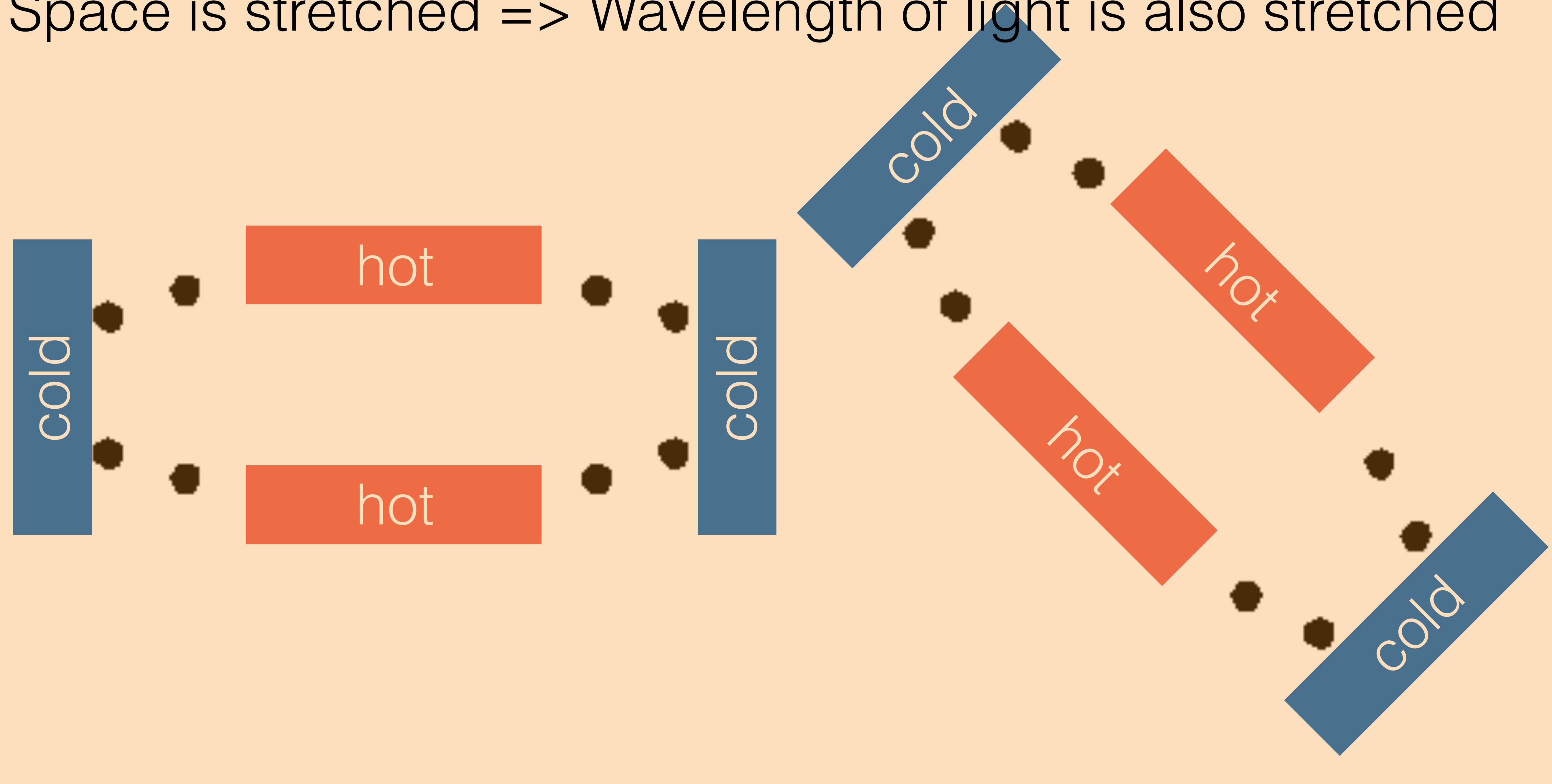
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



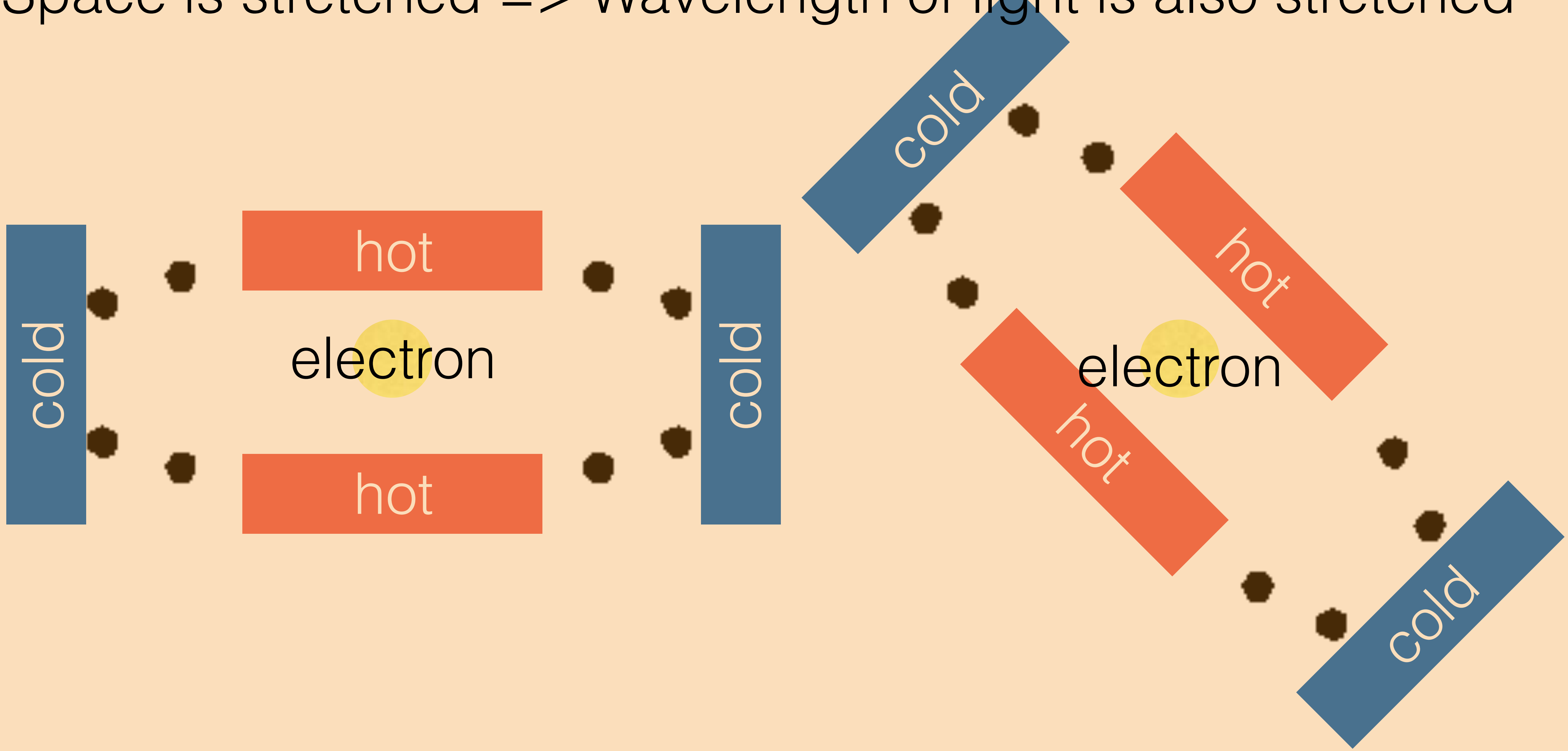
Detecting GW by CMB

Space is stretched => Wavelength of light is also stretched

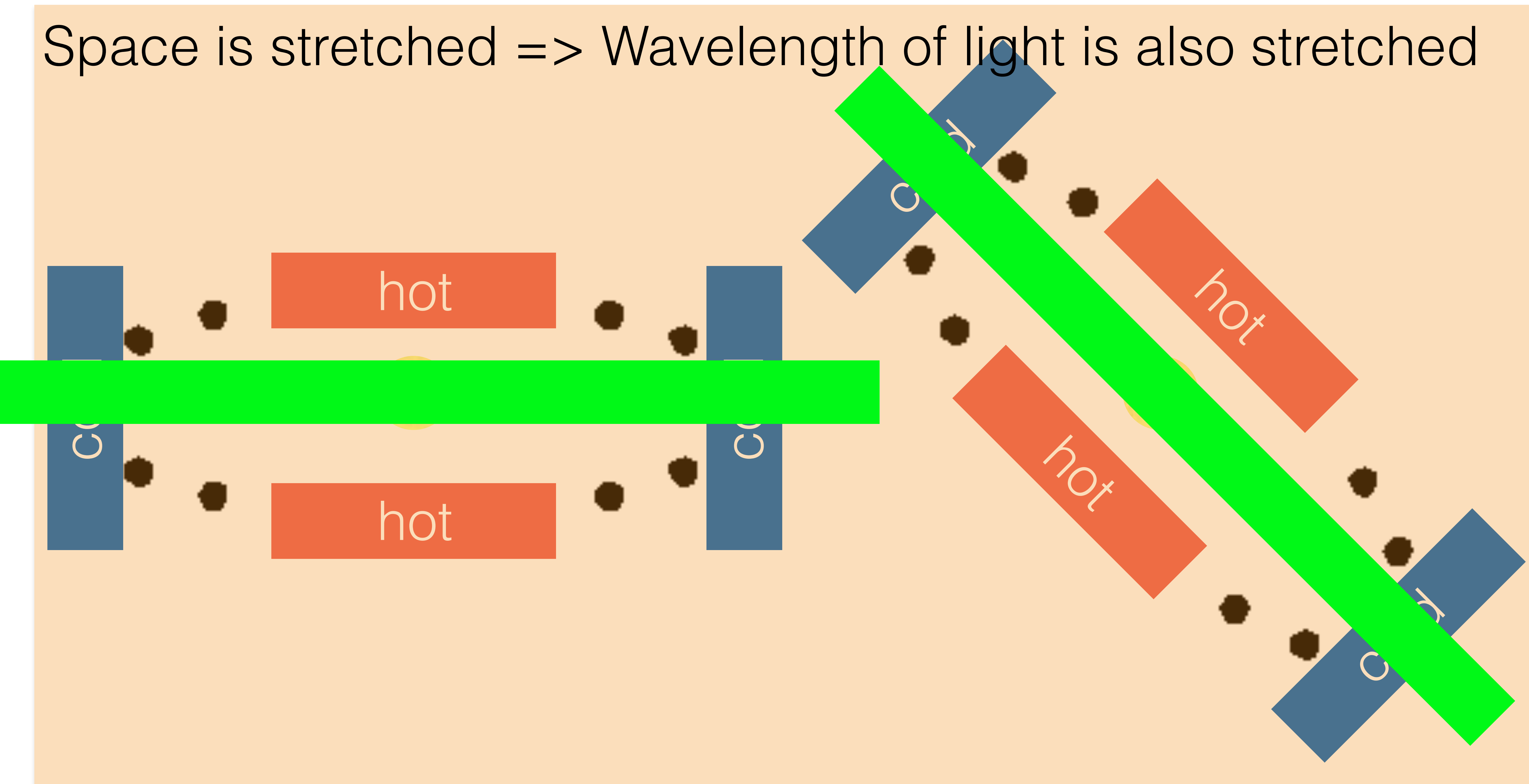


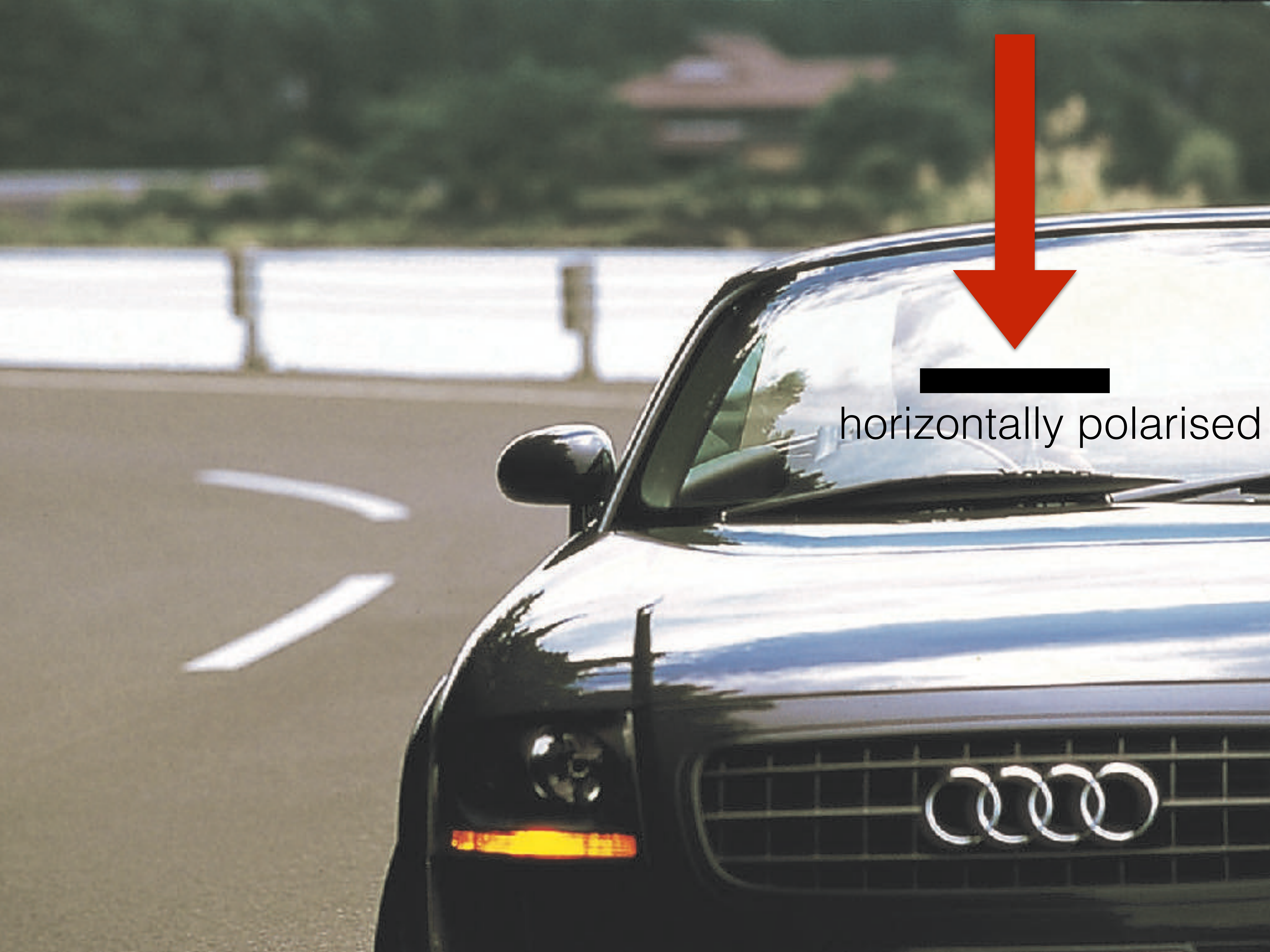
Detecting GW by CMB
Polarisation

Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB **Polarisation**




horizontally polarised

March 17, 2014

BICEP2’s announcement

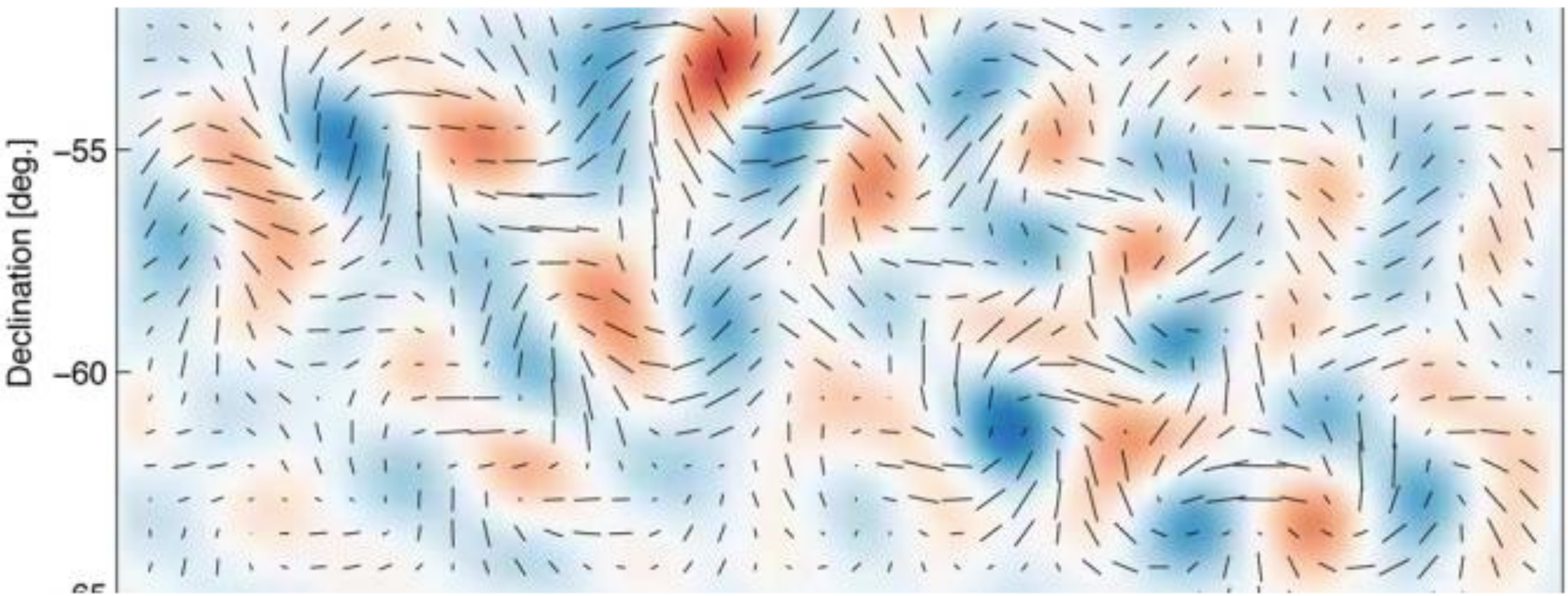
CfA Center for Astrophysics

About Research Education & Outreach Facilities Opportunities

First Direct Evidence of Cosmic Inflation

Release No.: 2014-05

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



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

SPACE & COSMOS

The New York Times

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

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17 March 2014 Last updated at 14:46 GMT

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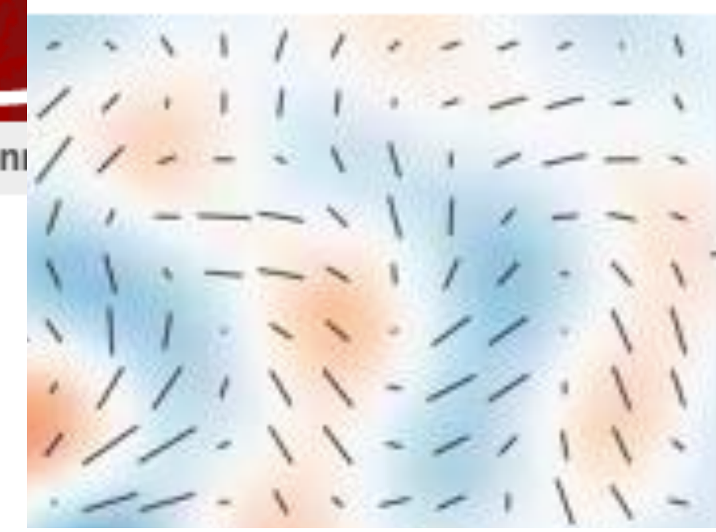
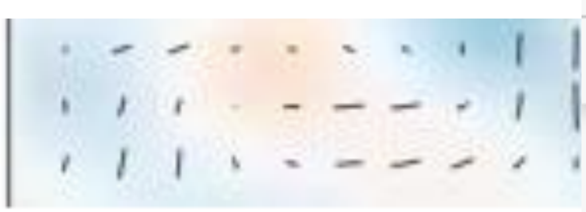


Cosmic inflation: 'Spectacular' discovery hailed

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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Süddeutsche.de als Startseite einrichten

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

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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

Süddeutsche.de als Startseite einrichten

1. Februar 2015, 22:19 Kosmologie

Urknall-Forscher gestehen Irrtum ein

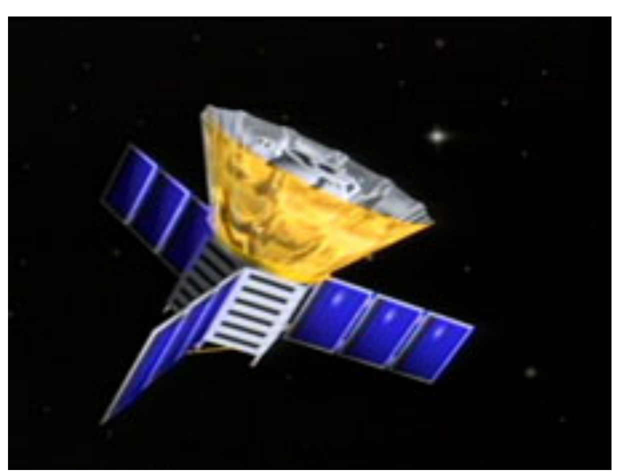
Von Marlene Weiß

Current Situation

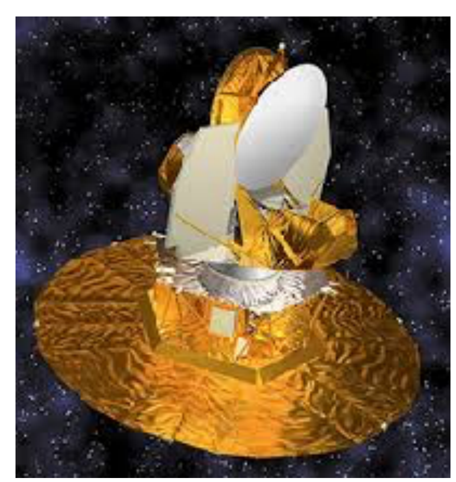
- Planck shows the evidence that the detected signal is not cosmological, but is due to dust

- No strong evidence that the detected signal is cosmological

The search continues!!



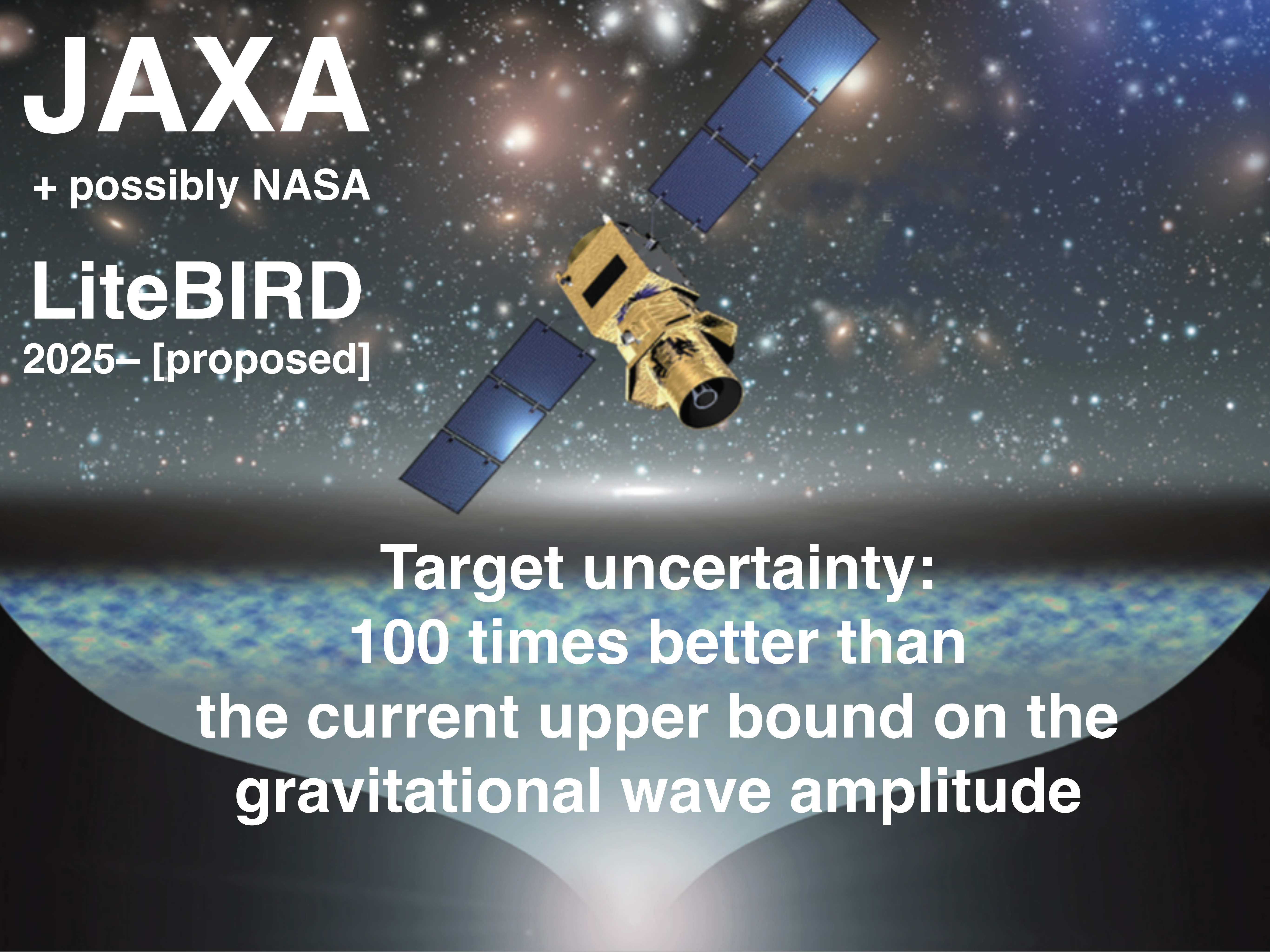
1989–1993



2001–2010

2009–2013

202X–


JAXA
+ possibly NASA
LiteBIRD
2025– [proposed]
Target uncertainty:
100 times better than
the current upper bound on the
gravitational wave amplitude

Summary

- Left my country to study the beginning of the Universe using physics and state-of-the-art data
- With the WMAP team [2001–2013], we:
  - Determined the age and composition of the Universe
  - Found strong evidence for the quantum origin of cosmic structures
- Now hoping to find decisive evidence for inflation by measuring primordial gravitational waves
  - The wavelength of billions of light years!

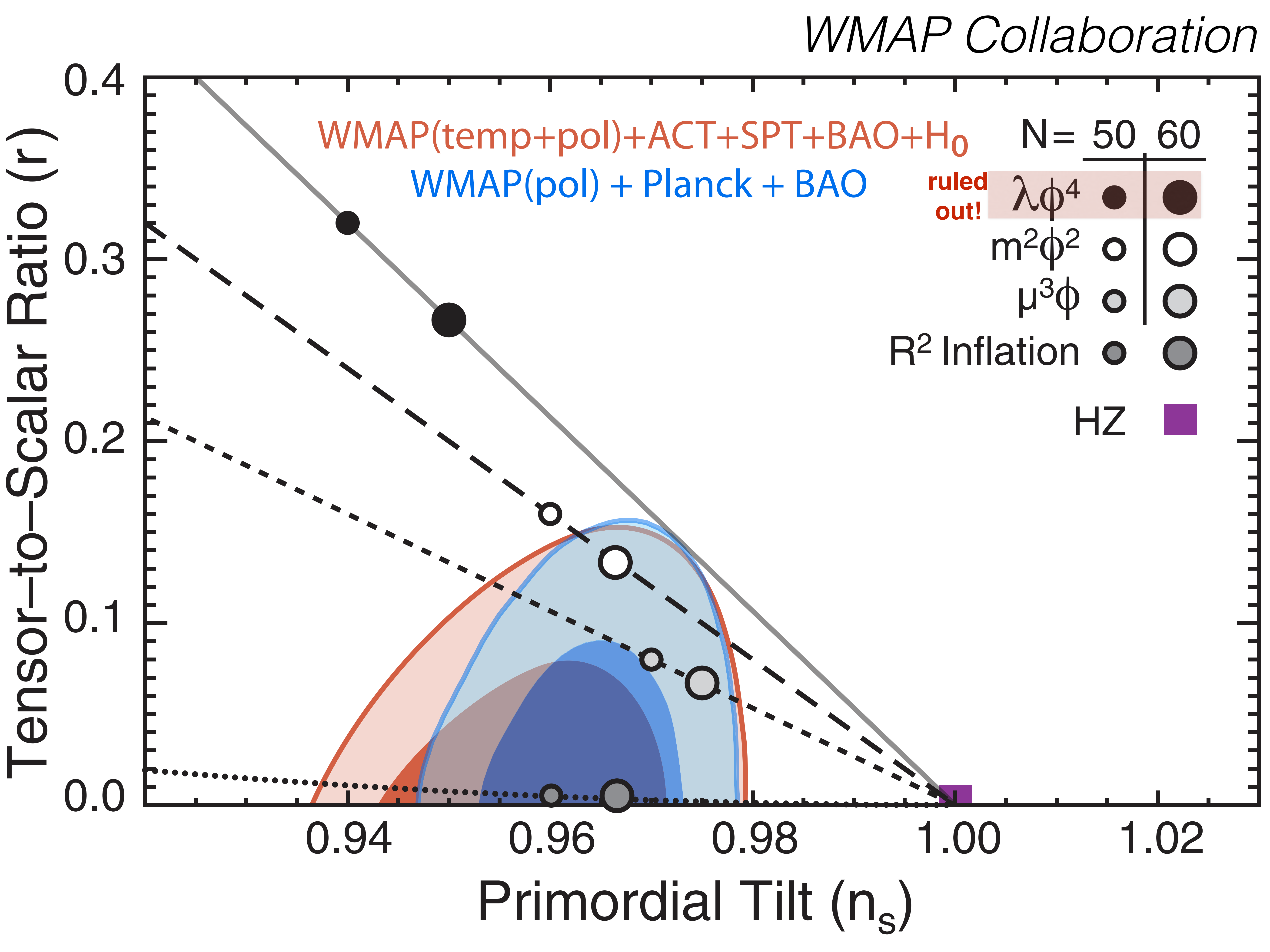
If polarisation from GW is found…

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