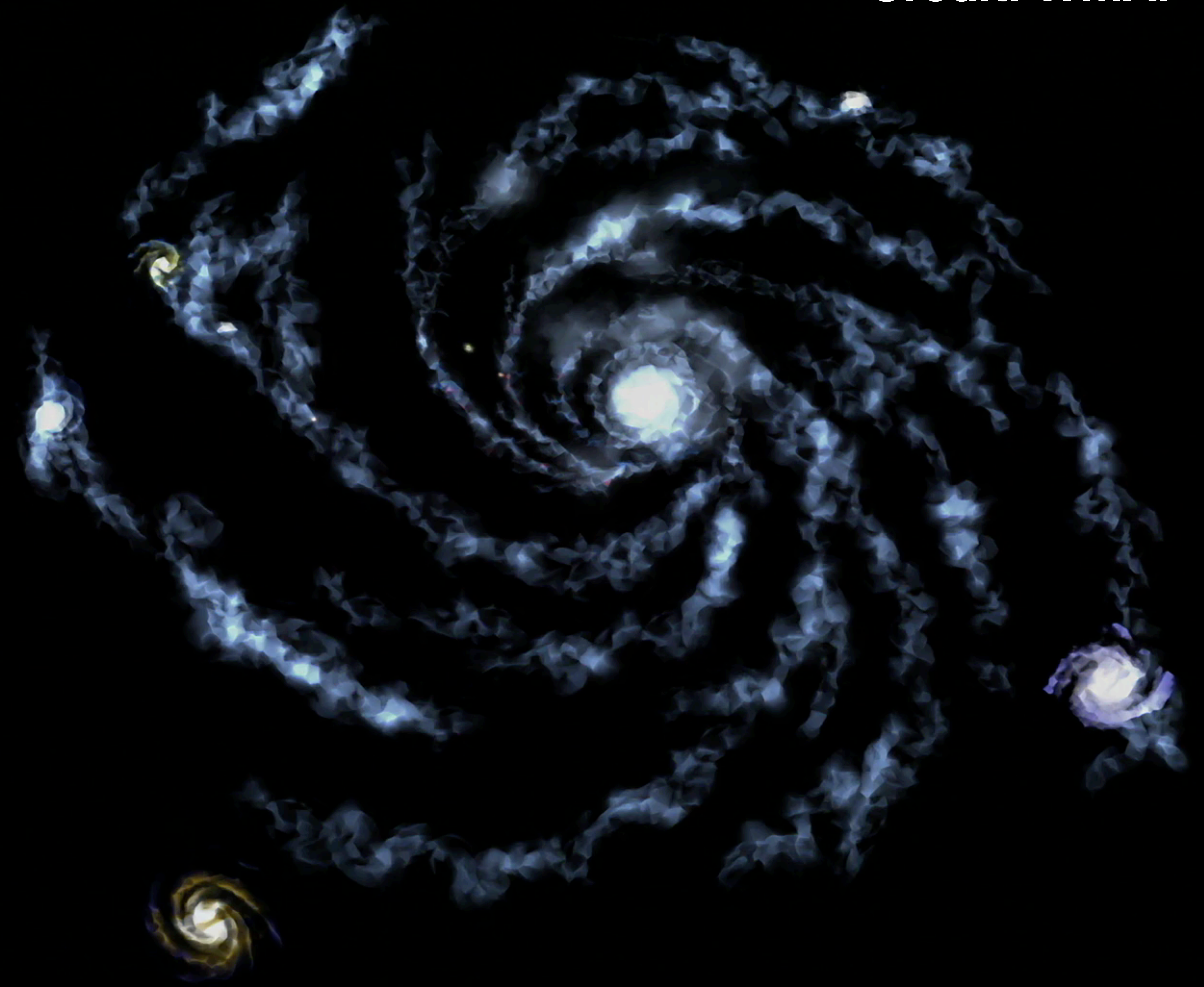
The New Quests for Physics of the Early Universe

Towards finding primordial gravitational waves

Eiichiro Komatsu (Max Planck Institute for Astrophysics)

Summer School on Galaxies and Cosmology, Institut Teknologi Bandung

September 25, 2020



Credit: WMAP Science Team

Credit: WMAP Science Team

How do “see" beyond the surface of last scattering?

YouTube BE

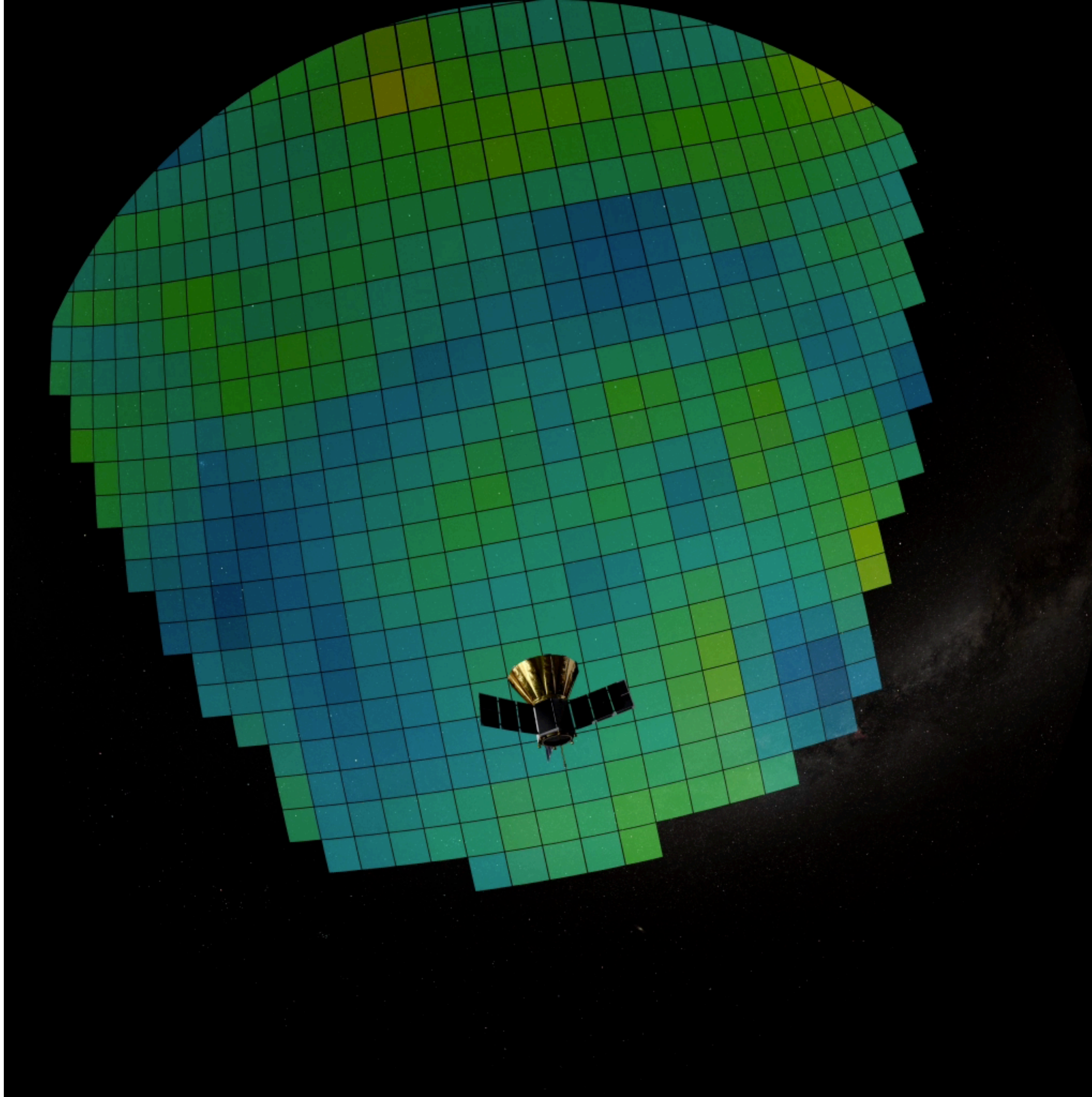
horizon edge of the visible universe

Full-dome movie for planetarium
Director: Hiromitsu Kohsaka

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

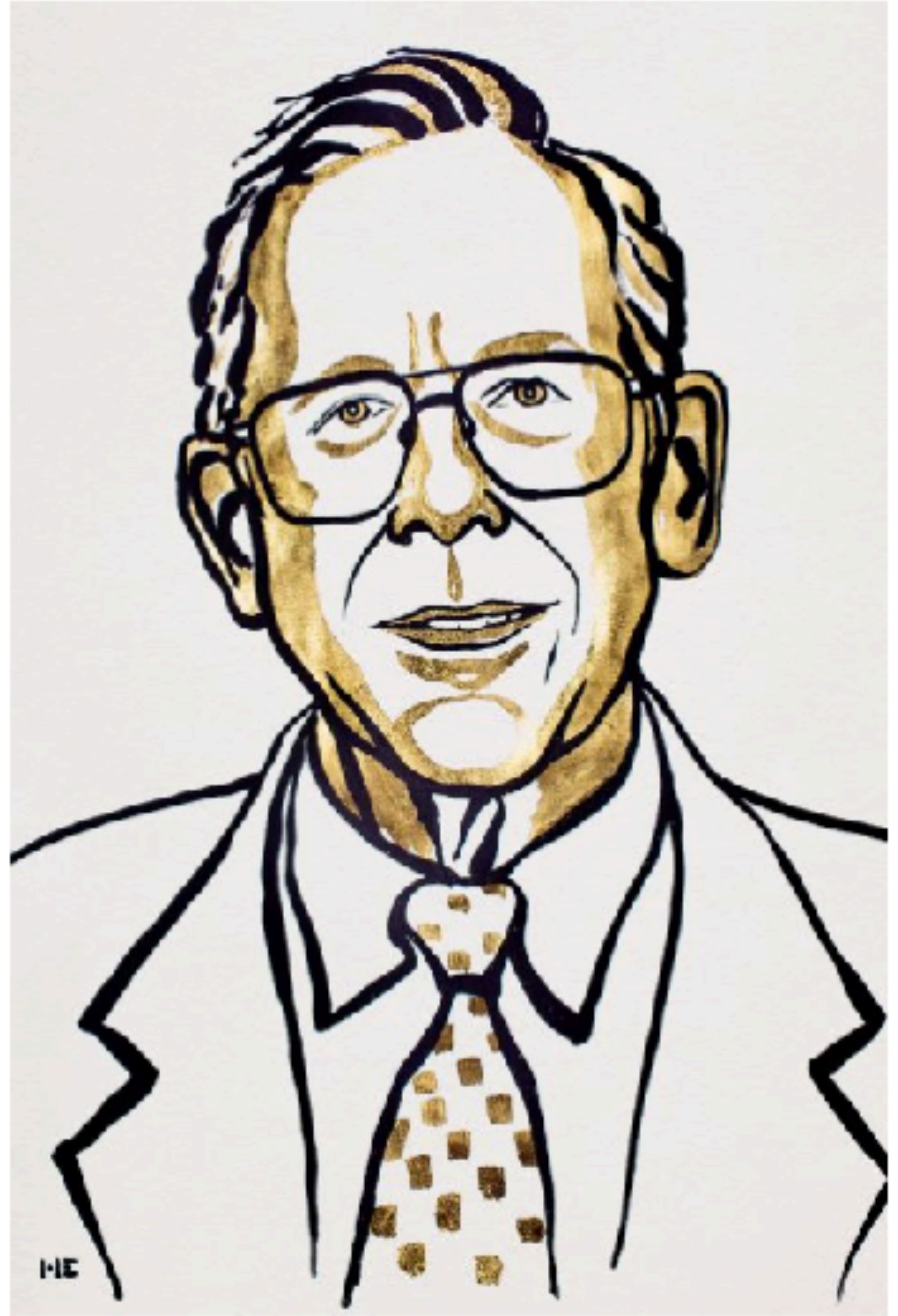
The Quest So Far…

with *sound waves* propagating in the "cosmic hot soup"



Sound waves in the fireball Universe, predicted in 1970

James Peebles
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: I
Princeton, NJ, USA

Prize motivation: "for theoretical dis
cosmology."

Prize share: 1/2

https://www.nobelprize.org

The Astrophysical Journal, 162:815–836, December 1970

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

At the *ICGC2011* conference, Goa, India

Sound waves in the fireball Universe, predicted in 1970

Astrophysics and Space Science 7 (1970) 3–19.

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

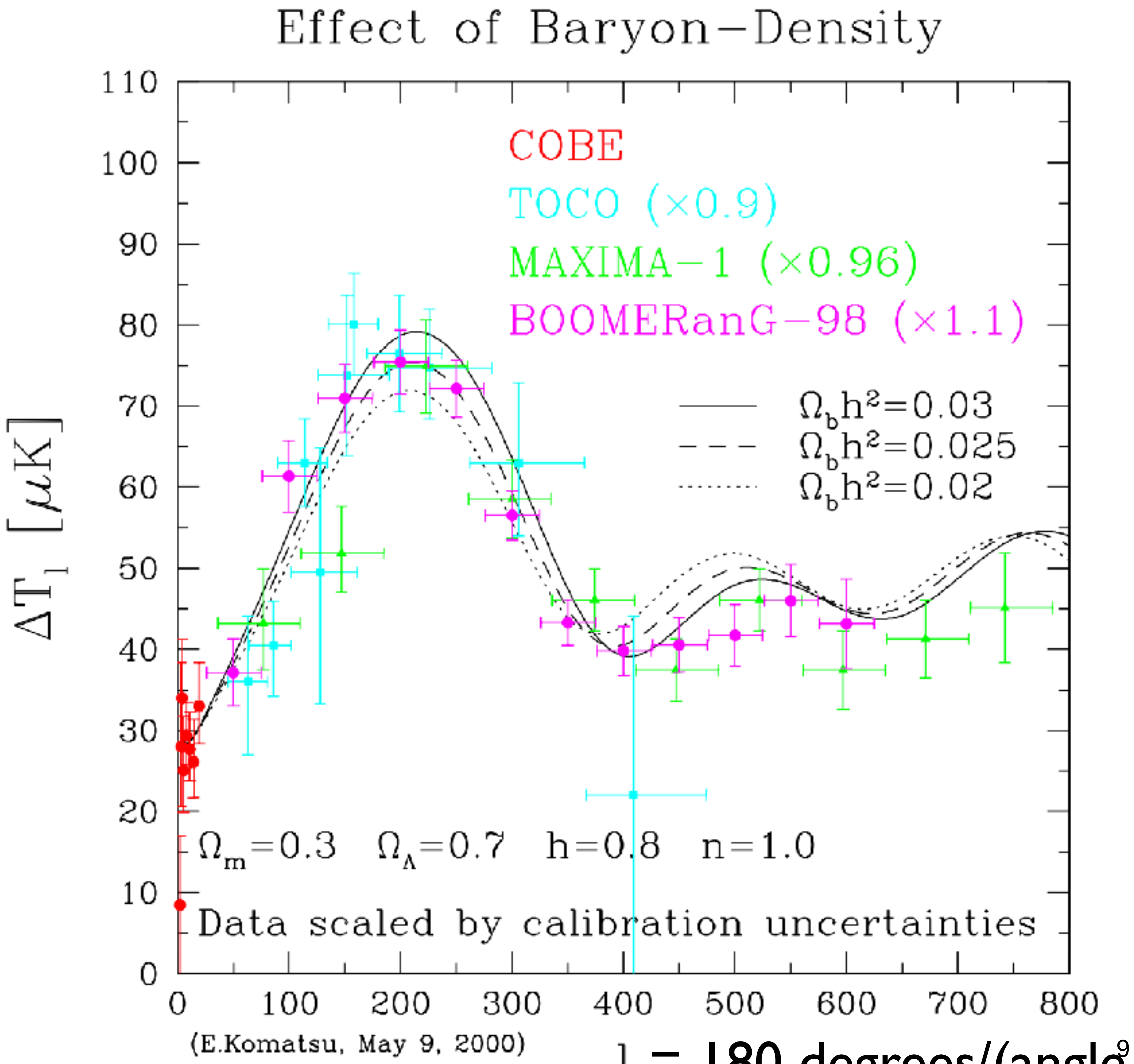
R. A. SUNYAEV and YA. B. ZELDOVICH
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)

Sound waves in the early Universe

Detected in 1999–2000, 30 years after the prediction!

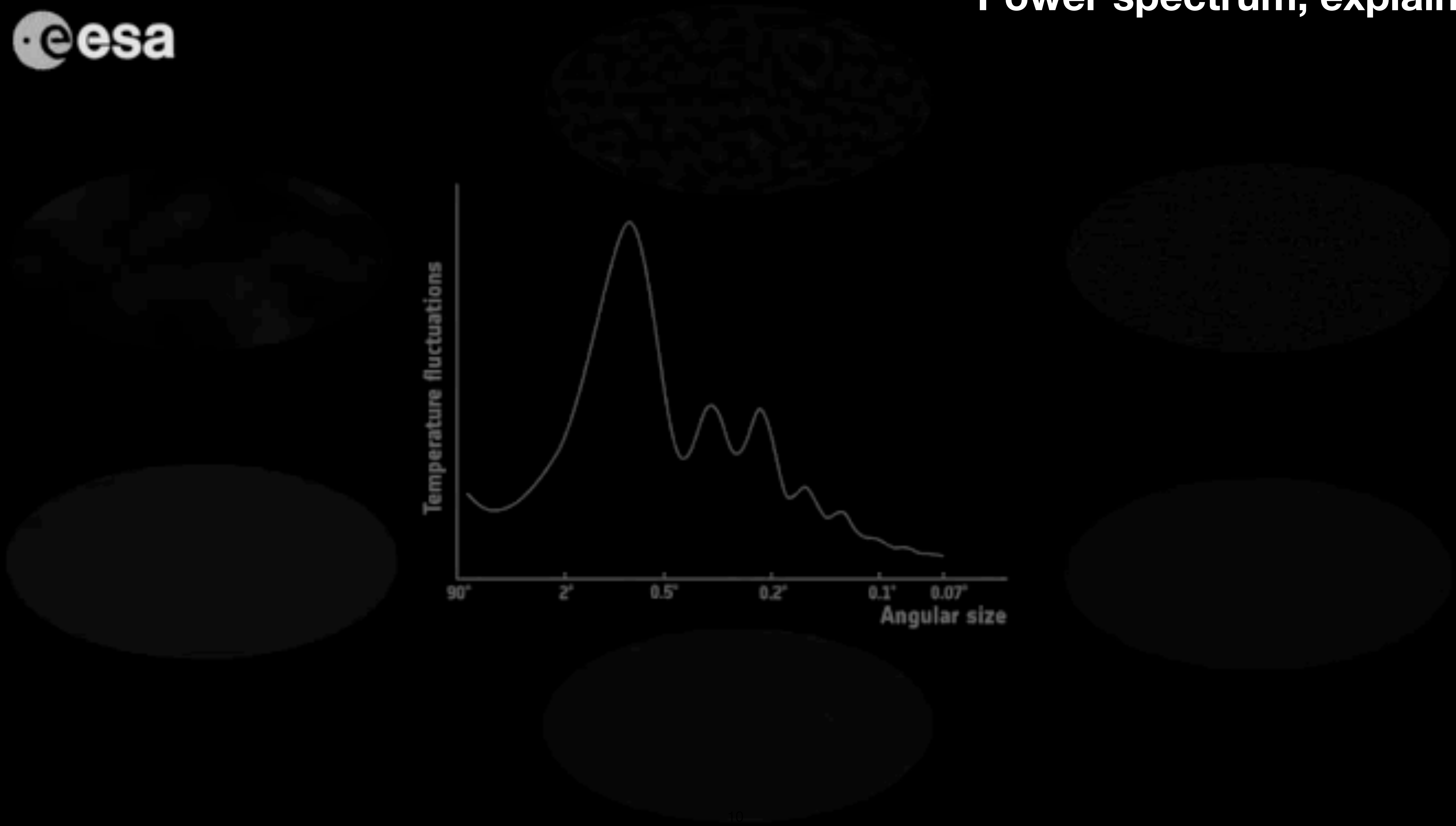
Power Spectrum



l = 180 degrees/(angle in the sky)

- A beautiful example of the success of theoretical physics!
- **The power spectrum** is a powerful tool to see the sound waves. What is the power spectrum?
- Decompose fluctuations in the sky into a set of cosine and sine waves, and plot the amplitude of waves as a function of the (inverse) of the wavelength.

Power spectrum, explained

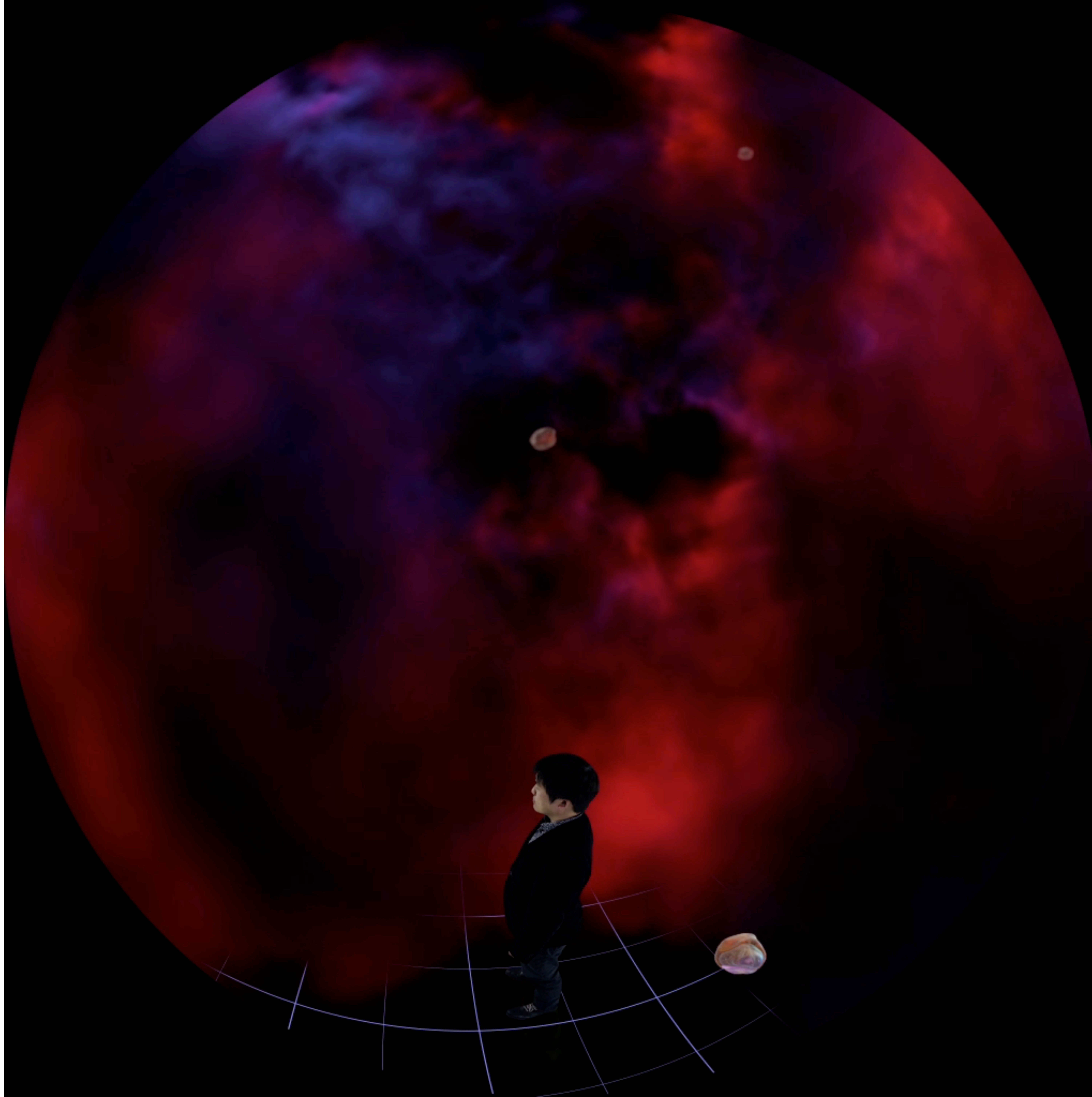


Determine the composition of the Universe

The Universe as a “hot soup”

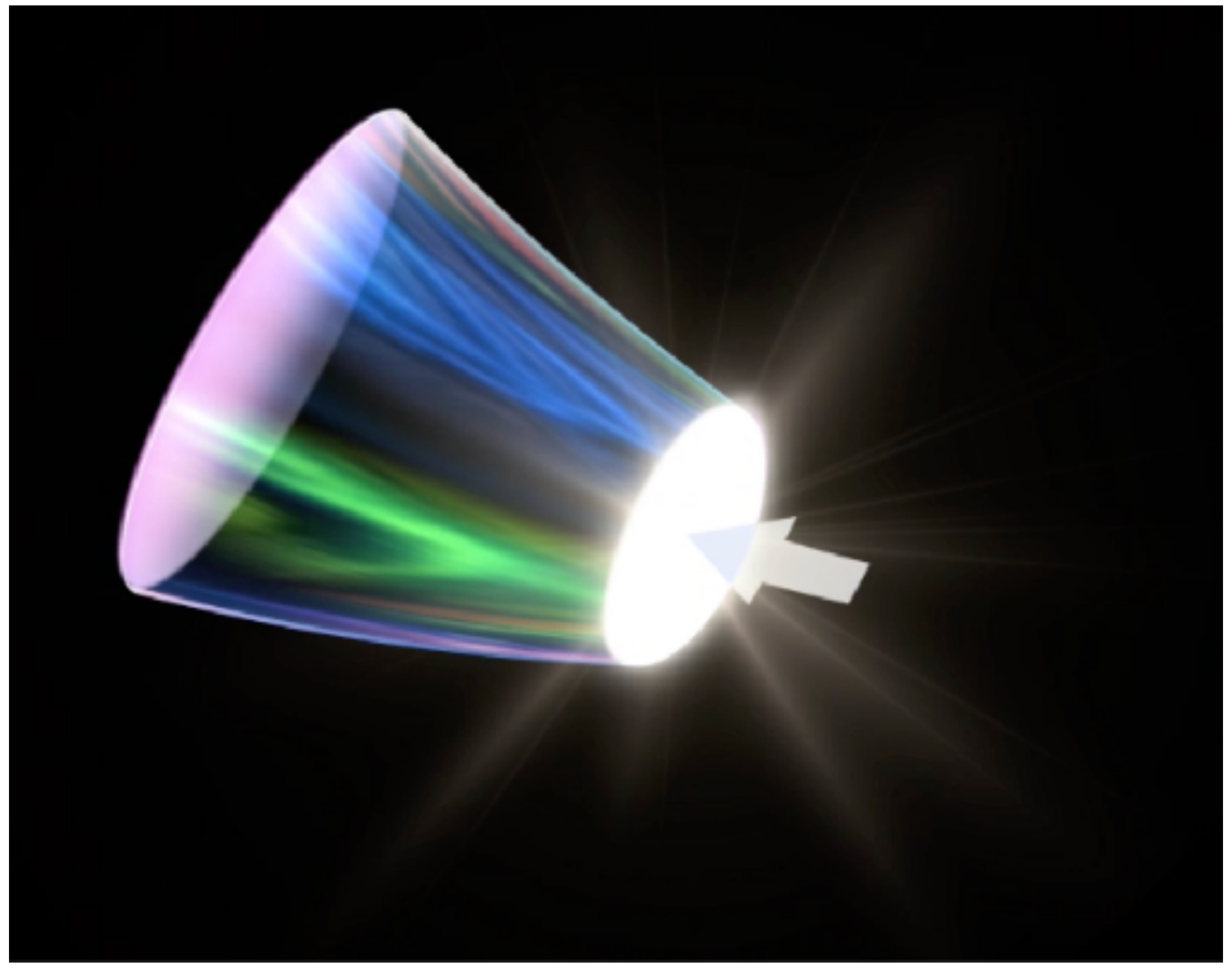
- The power spectrum allows us to determine the composition of the Universe, such as the density of atoms, dark matter, and dark energy.

- **Definitive evidence for non-baryonic nature of dark matter!**



“Let’s give some impact to the beginning of this model”

Did you hear that?



- What gave the initial fluctuation to the cosmic hot soup?

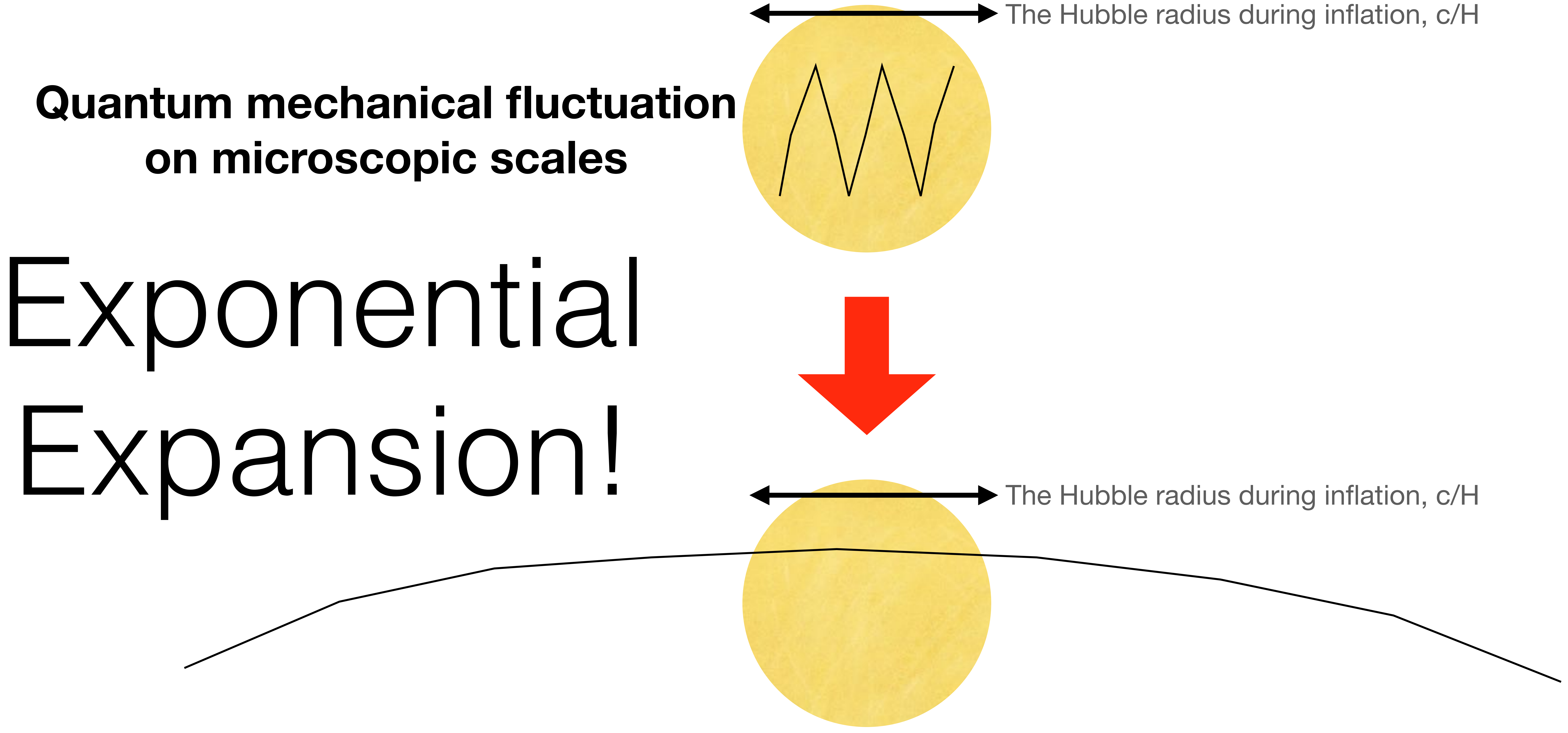
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

Leading Idea:

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

Finding Cosmic Inflation

What does inflation predict?

- The distance between two points is stretched as L ~ a(t), where **a(t) is the scale factor**.

- **The Hubble expansion rate** is defined as **H(t) = dln(a)/dt**. This has the units of [1/time].

  - The scale factor is then given by a(t) = exp[∫H(t)dt].

  - During inflation, the distance between two points expands exponentially. This means **H(t) ~ constant**, which gives a(t) ~ exp(Ht).

- However, inflation must end. This means that **H(t) is a slowly decreasing function of time**.

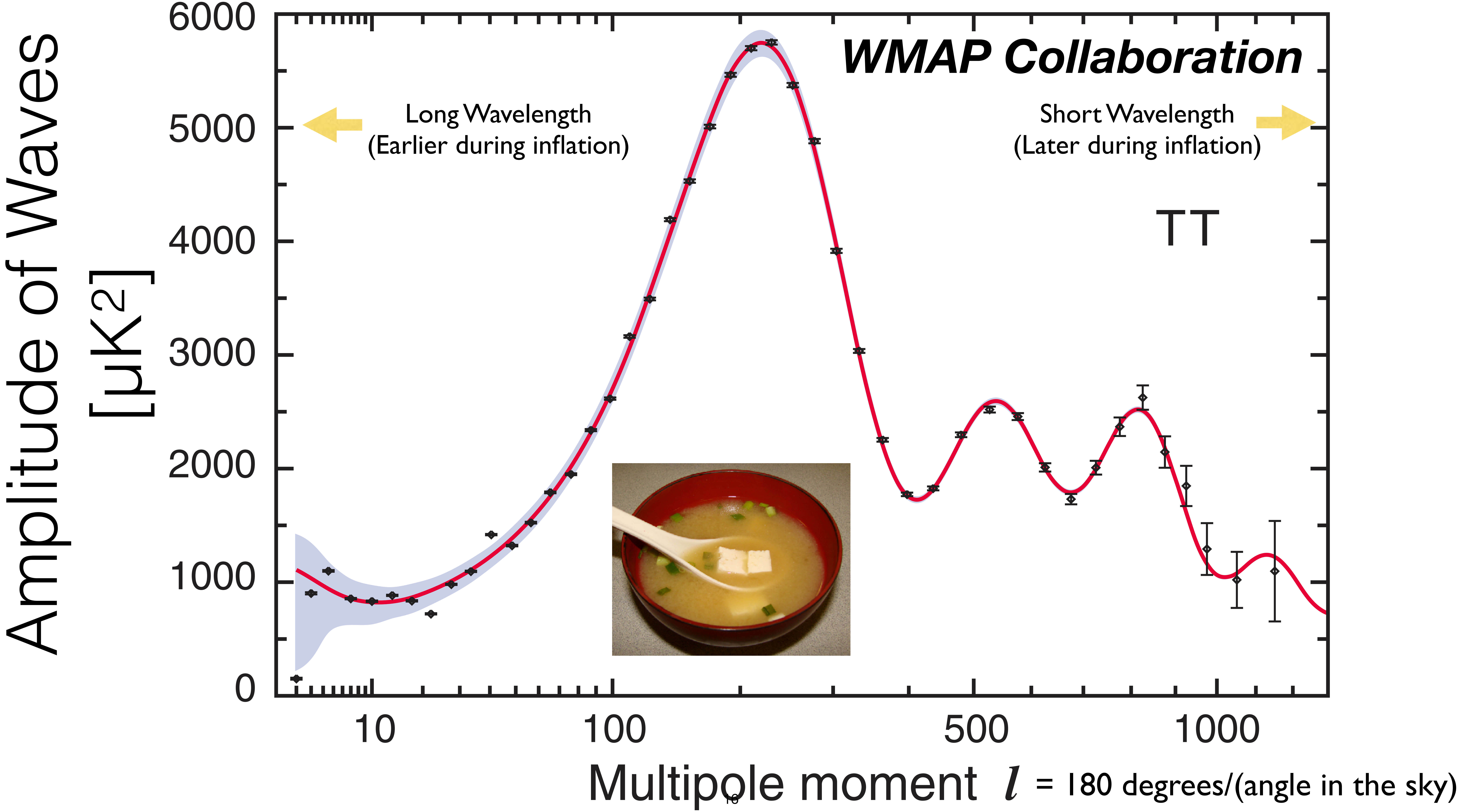
How can we test this?

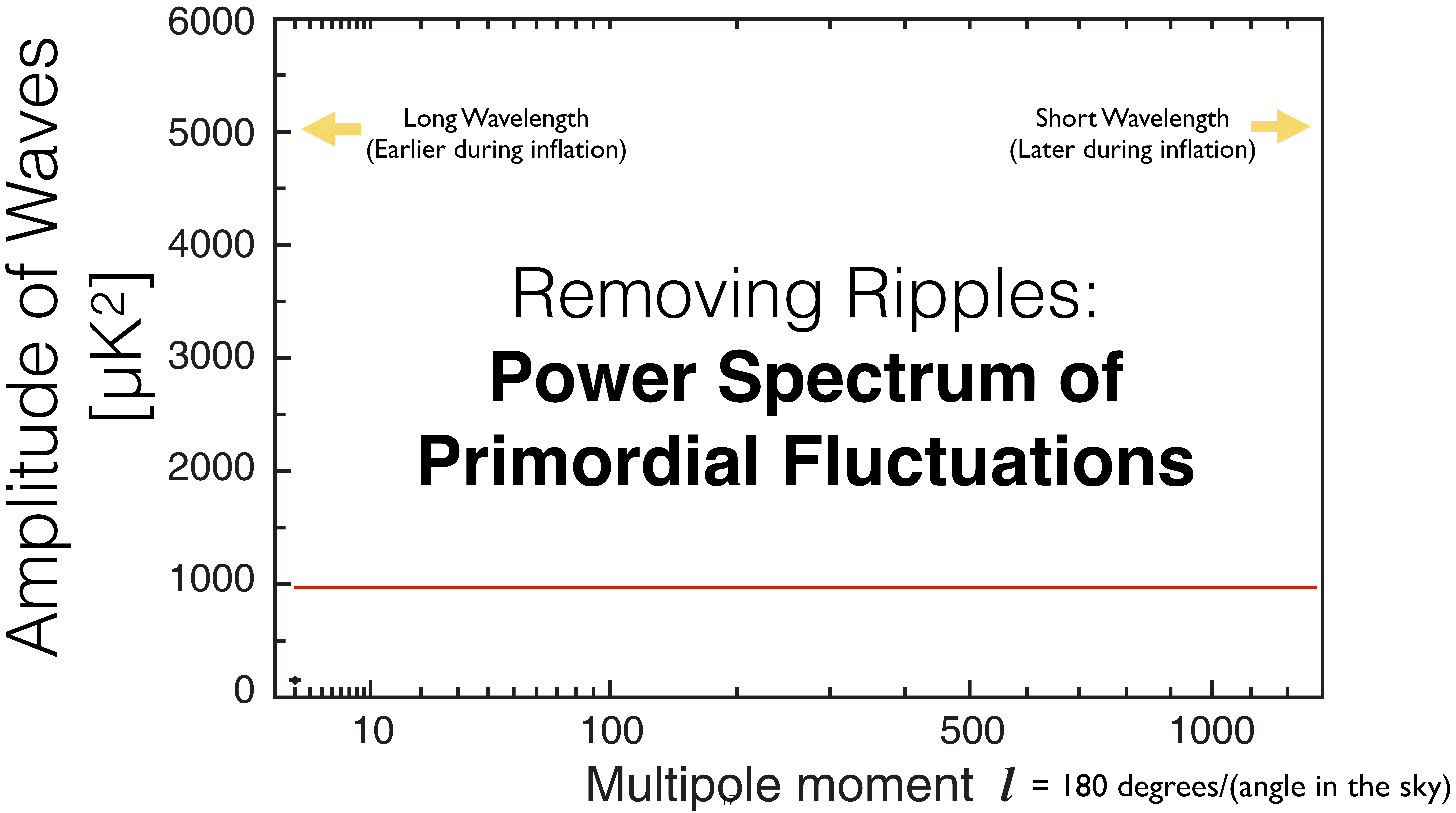
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

Finding Cosmic Inflation

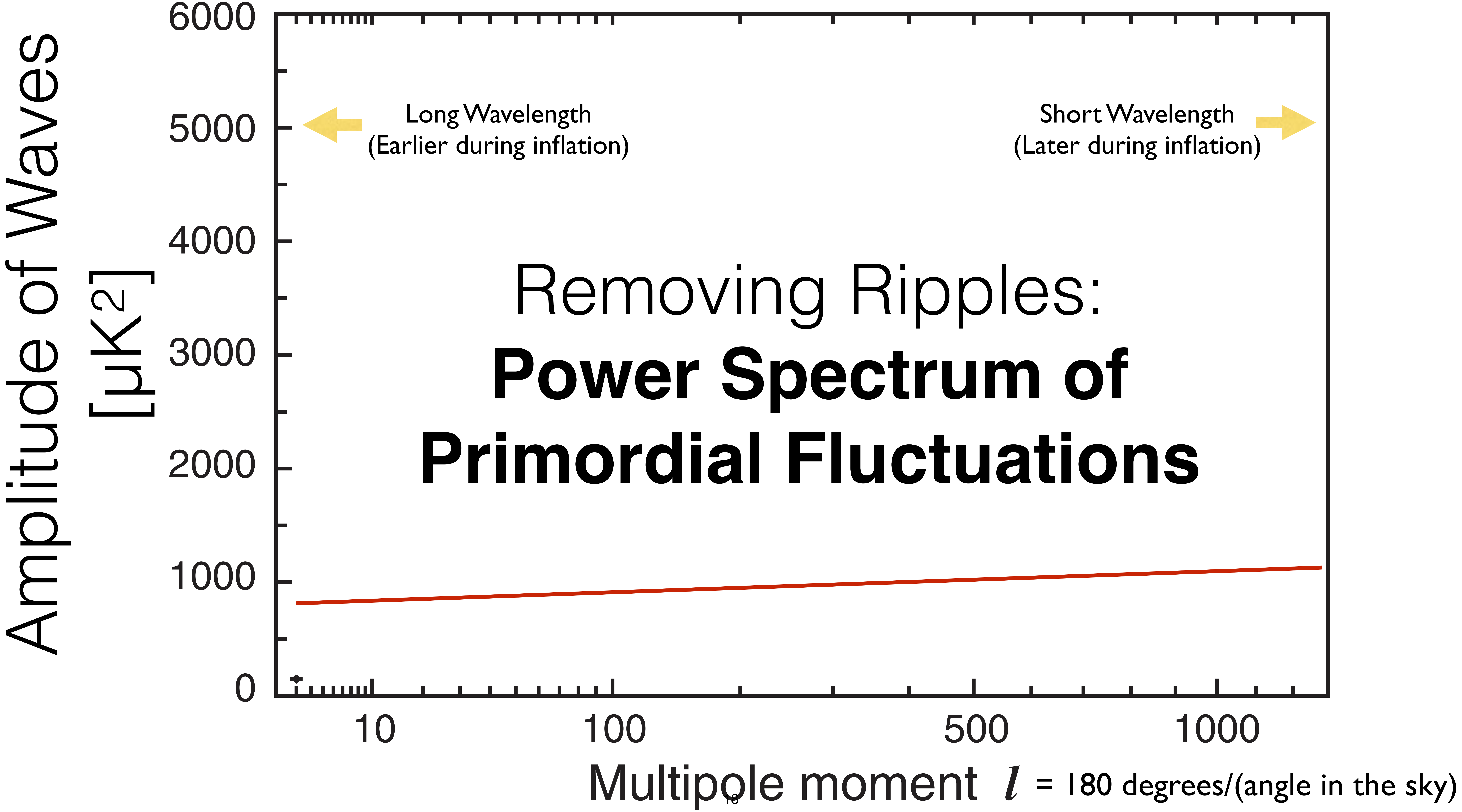
What does inflation predict for the scalar (density) fluctuation?

- During inflation, the density fluctuation is produced quantum mechanically.
- Heisenberg's uncertainty principle tells you:
    - [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. **Because H(t) is a decreasing function of time, inflation predicts that the amplitude of fluctuations on large angular scales is slightly larger than that on small angular scales!**


WMAP Collaboration
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
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)



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


Amplitude of Waves [μK²]
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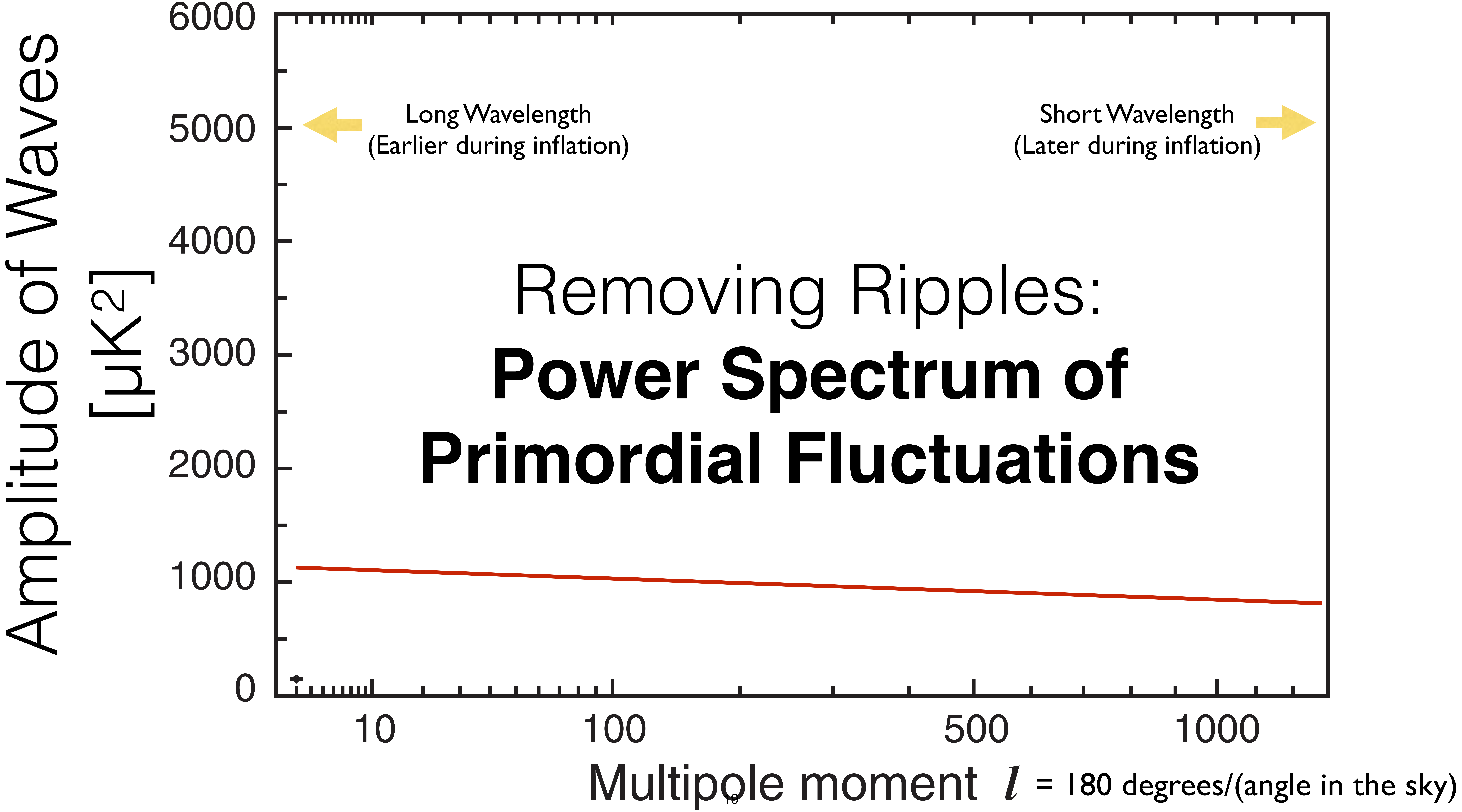
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Power Spectrum of
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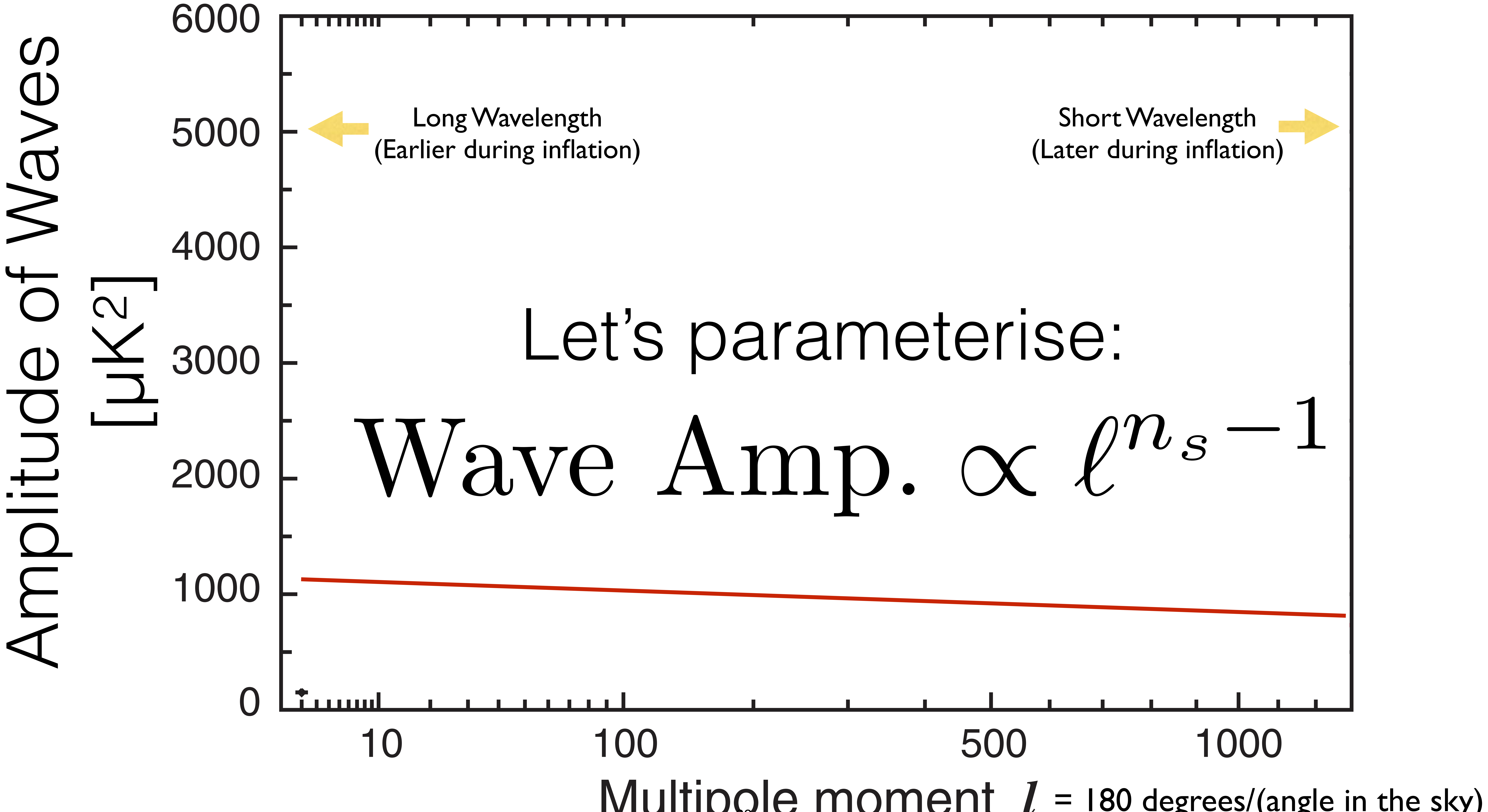
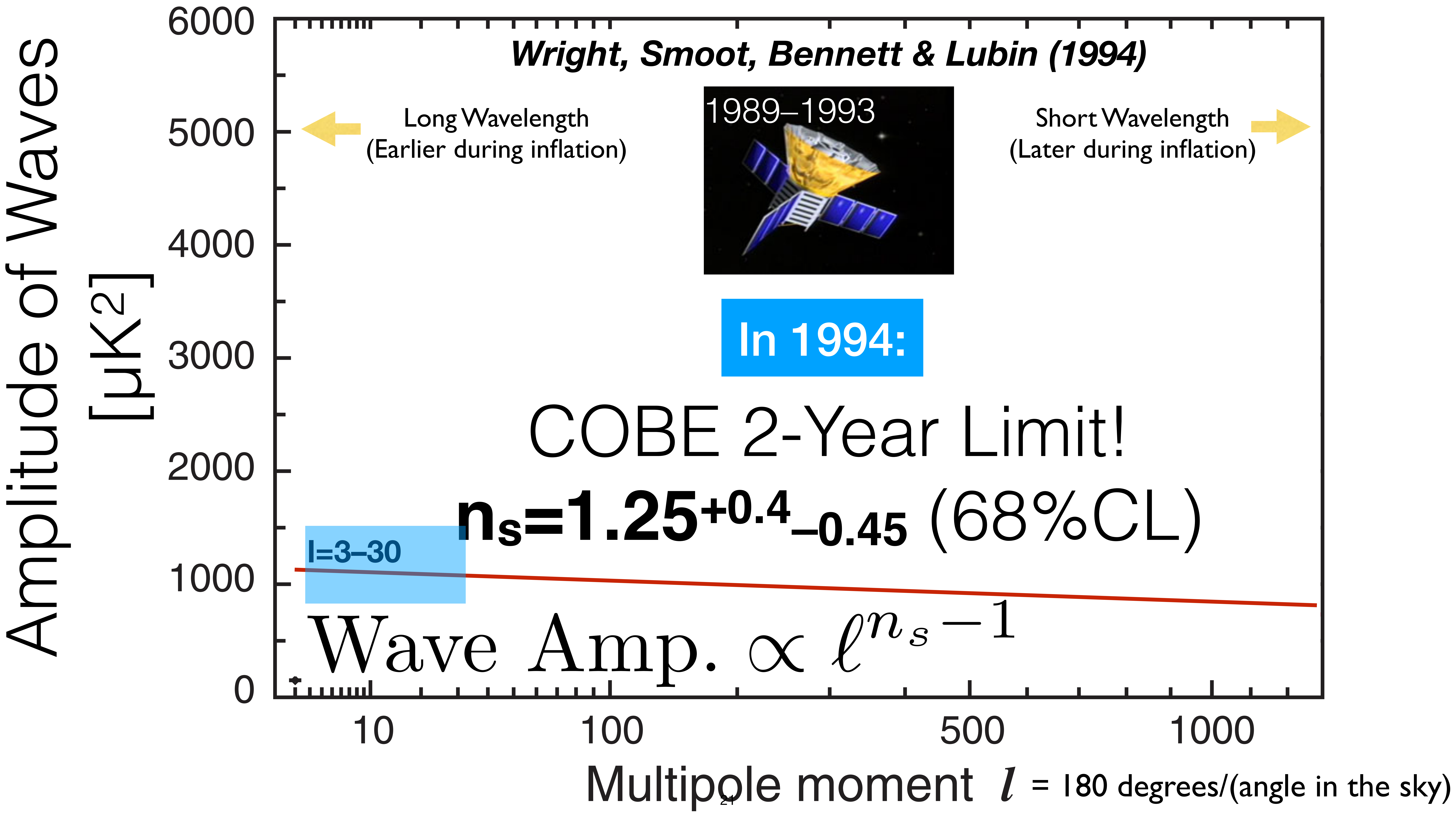
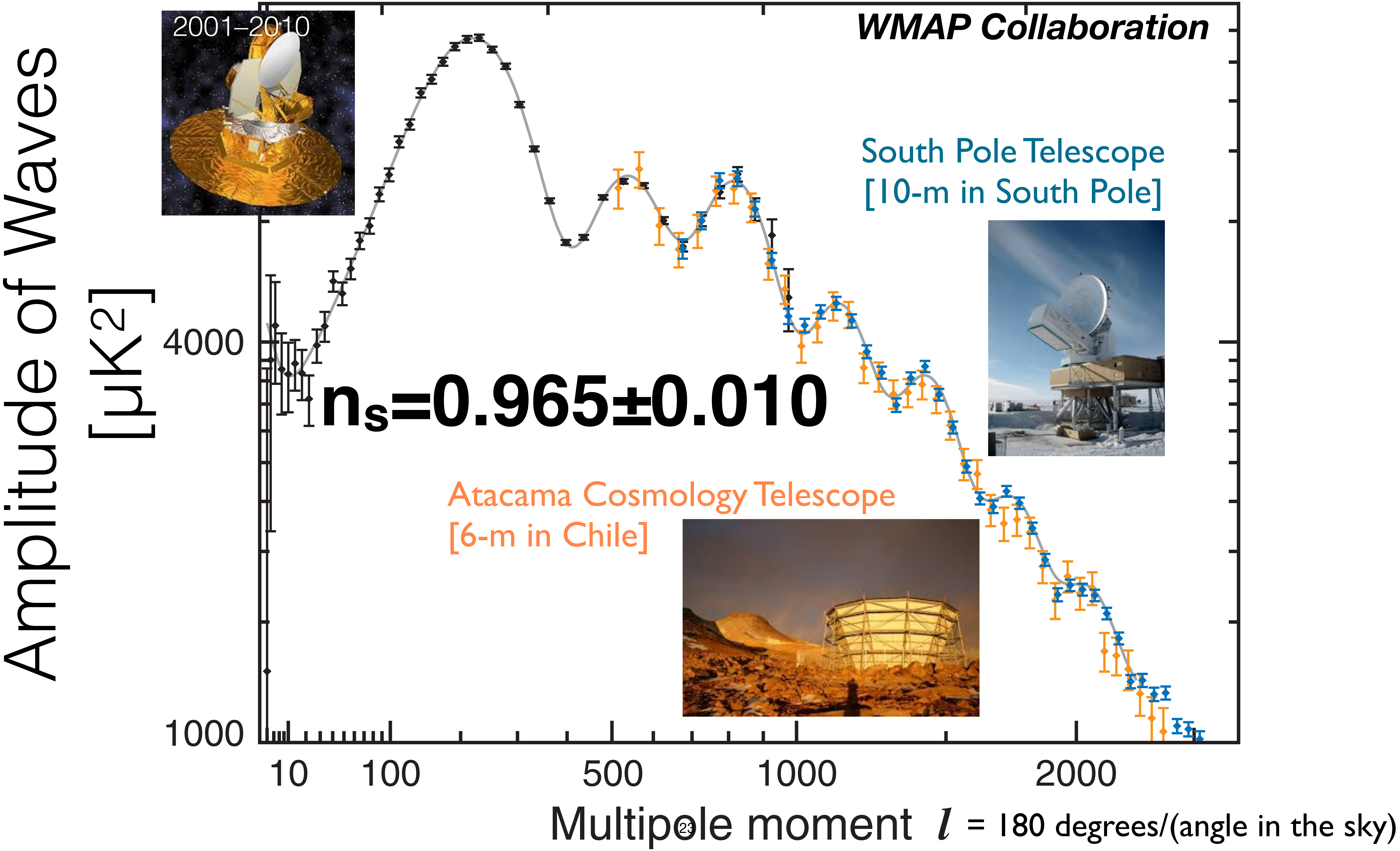
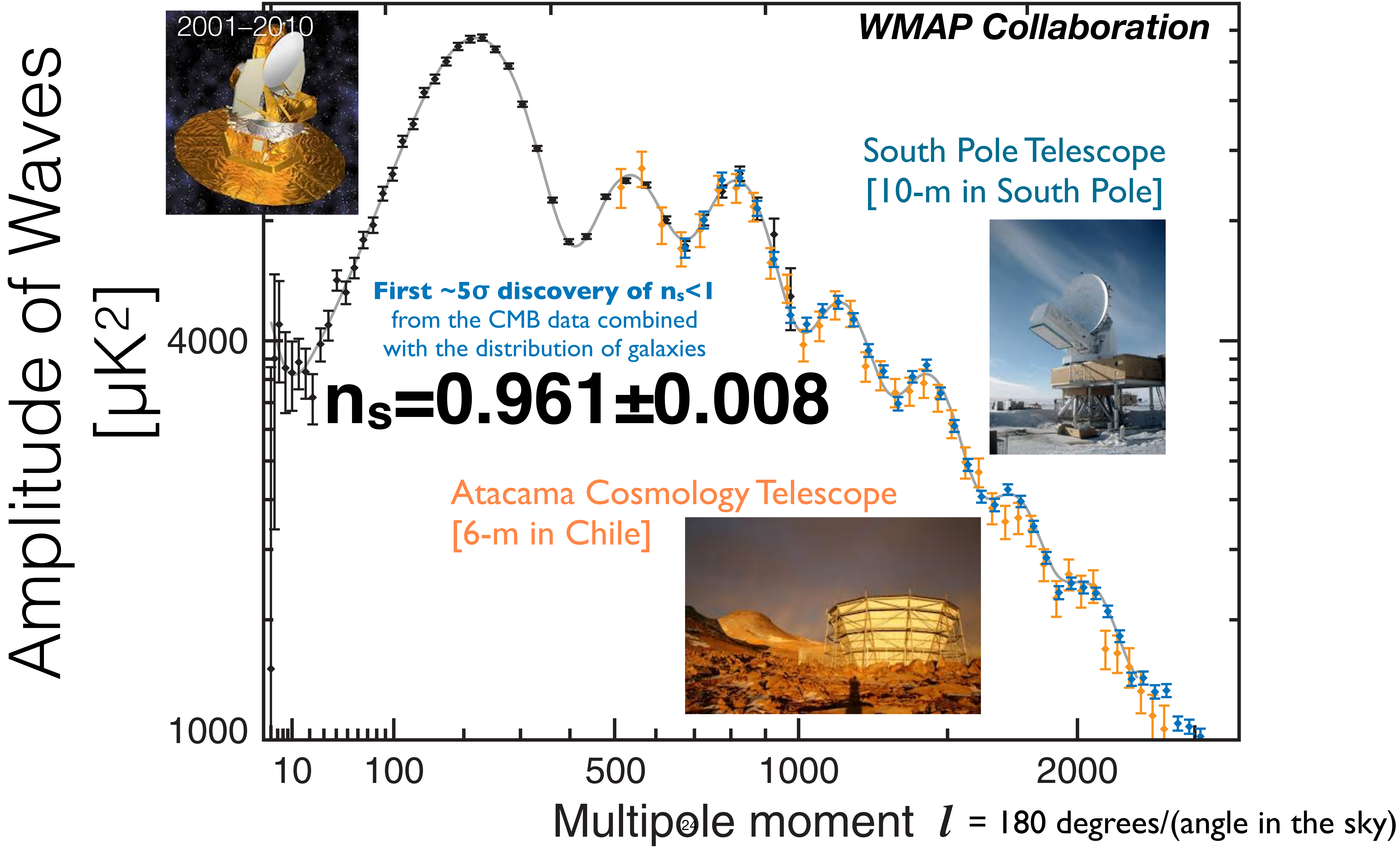
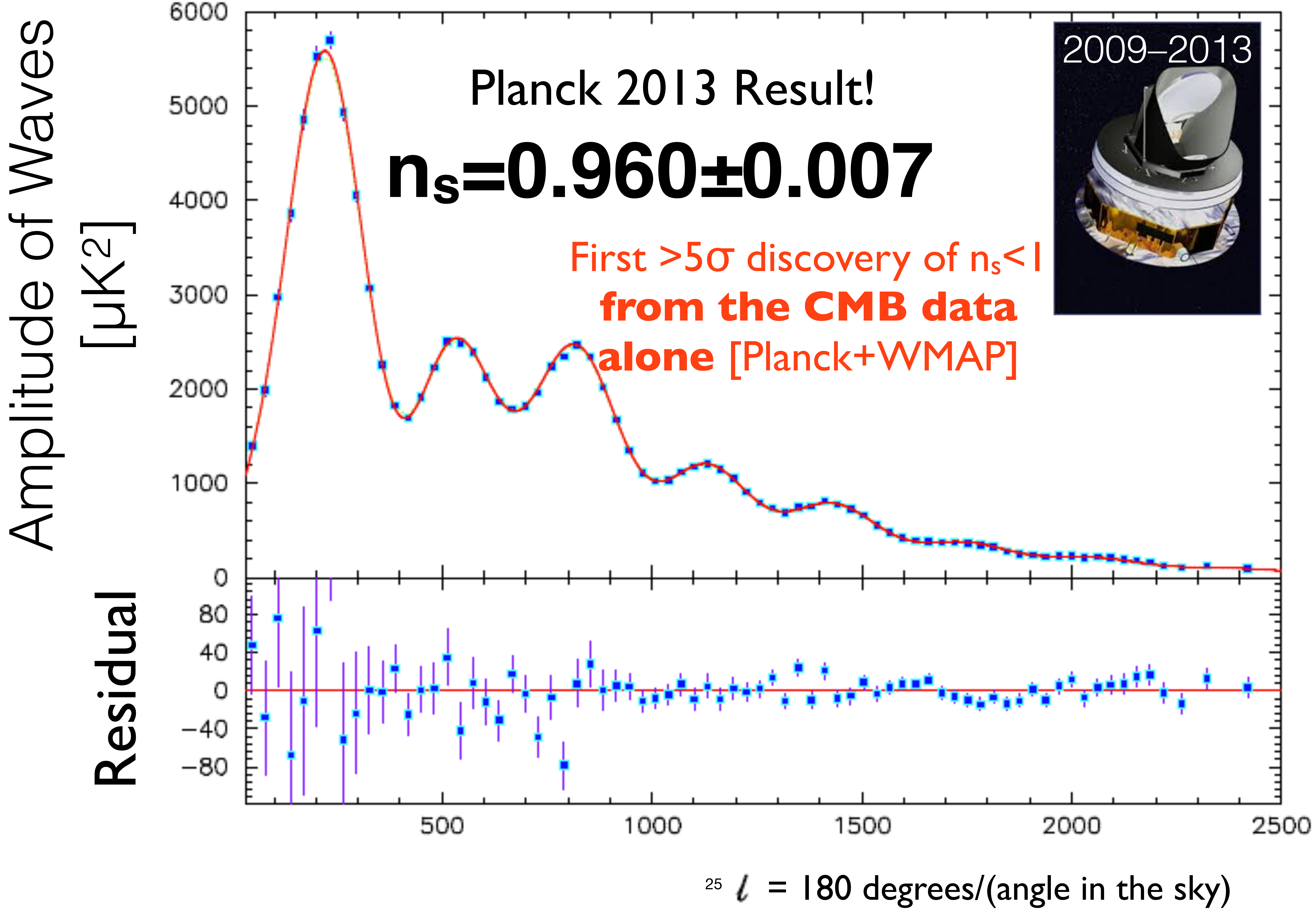

Amplitude of Waves
[μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
Let's parameterise:
$\text{Wave Amp.} \propto \ell^{n_s - 1}$
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)

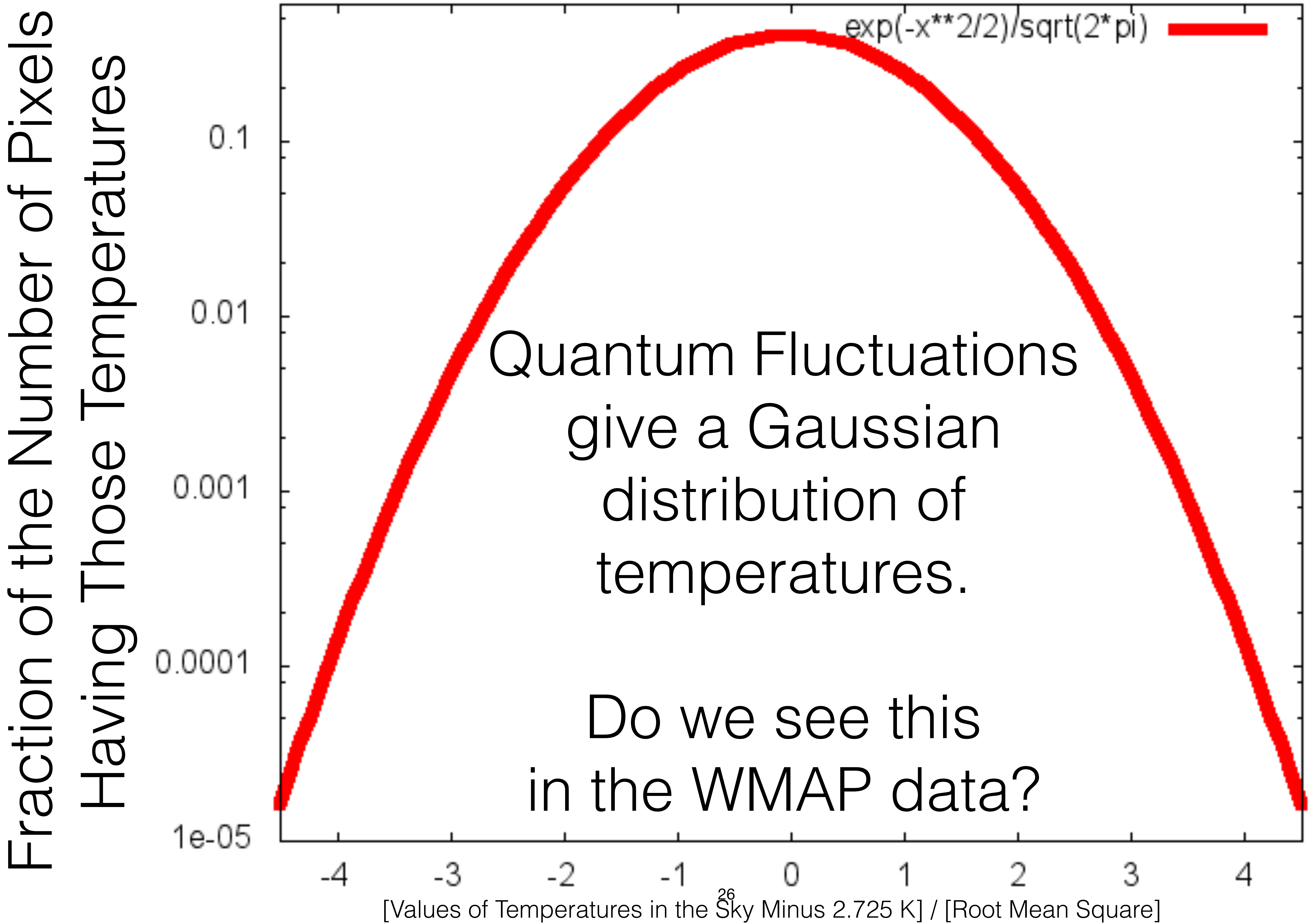

Wright, Smoot, Bennett & Lubin (1994)
1989–1993
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
In 1994:
COBE 2-Year Limit!
$n_s = 1.25^{+0.4}_{-0.45}$ (68%CL)
l=3–30
Wave Amp. $\propto \ell^{n_s - 1}$
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)

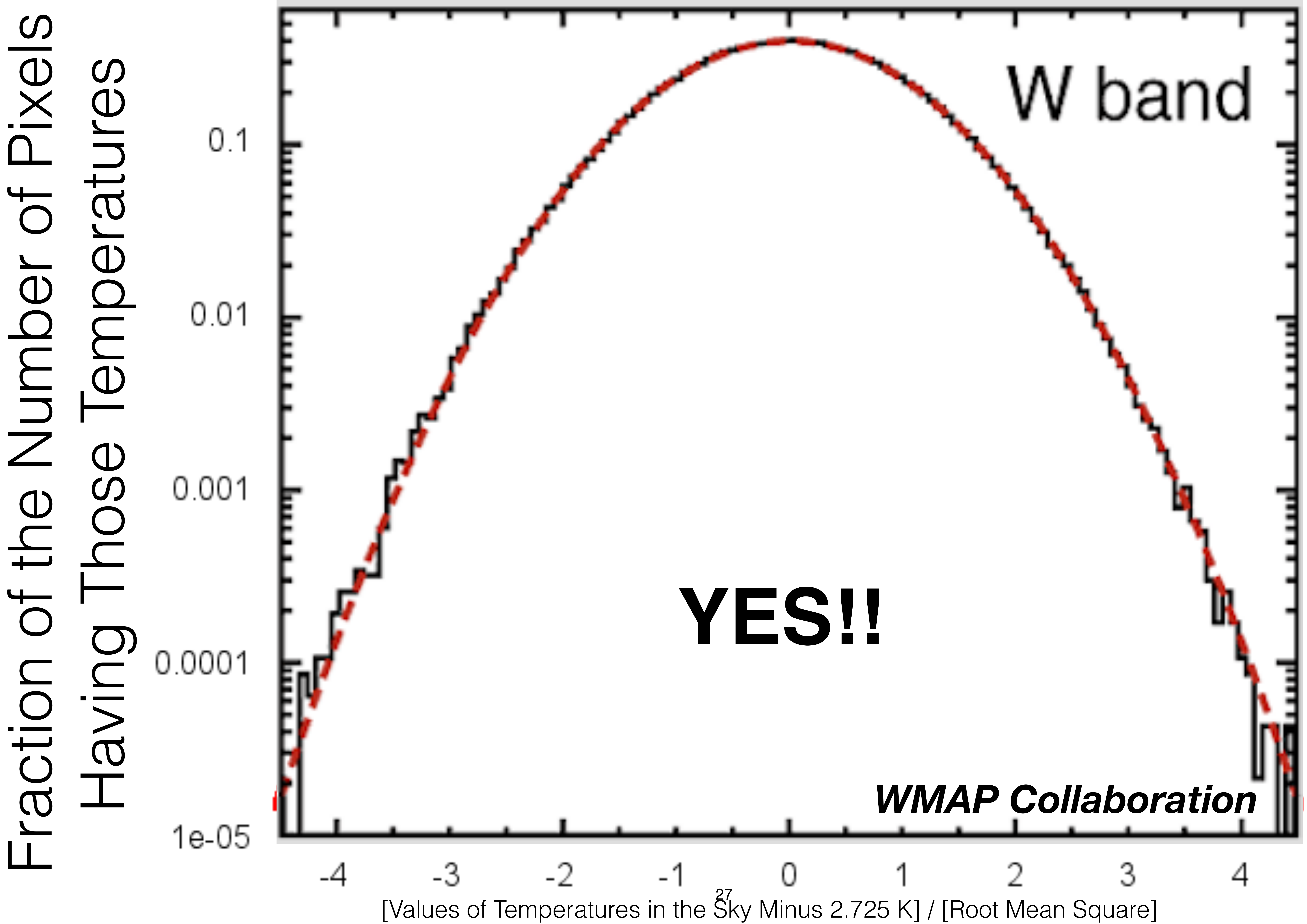

WMAP Collaboration
2001–2010
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
In 2012:
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
Wave Amp. $\propto \ell^{n_s-1}$
Amplitude of Waves [μK^2]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)


2001–2010
WMAP Collaboration
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
n_s=0.965±0.010
Amplitude of Waves [μK^2]
4000
1000
10
100
500
1000
2000
Multipole moment l = 180 degrees/(angle in the sky)


2001–2010
WMAP Collaboration
South Pole Telescope
[10-m in South Pole]
First ~5σ discovery of $n_s<1$
from the CMB data combined
with the distribution of galaxies
$n_s=0.961\pm0.008$
Atacama Cosmology Telescope
[6-m in Chile]
Amplitude of Waves
[μK^2]
4000
1000
10
100
500
1000
2000
Multipole moment l = 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 [Planck+WMAP]
2009–2013
Amplitude of Waves [μK^2]
Residual
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
2500
ℓ = 180 degrees/(angle in the sky)


Fraction of the Number of Pixels
Having Those Temperatures
exp(-x**2/2)/sqrt(2*pi)
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?


Fraction of the Number of Pixels
Having Those Temperatures
0.1
0.01
0.001
0.0001
1e-05
W band
YES!!
WMAP Collaboration
-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?

A lot of evidence in support of inflation exist already.

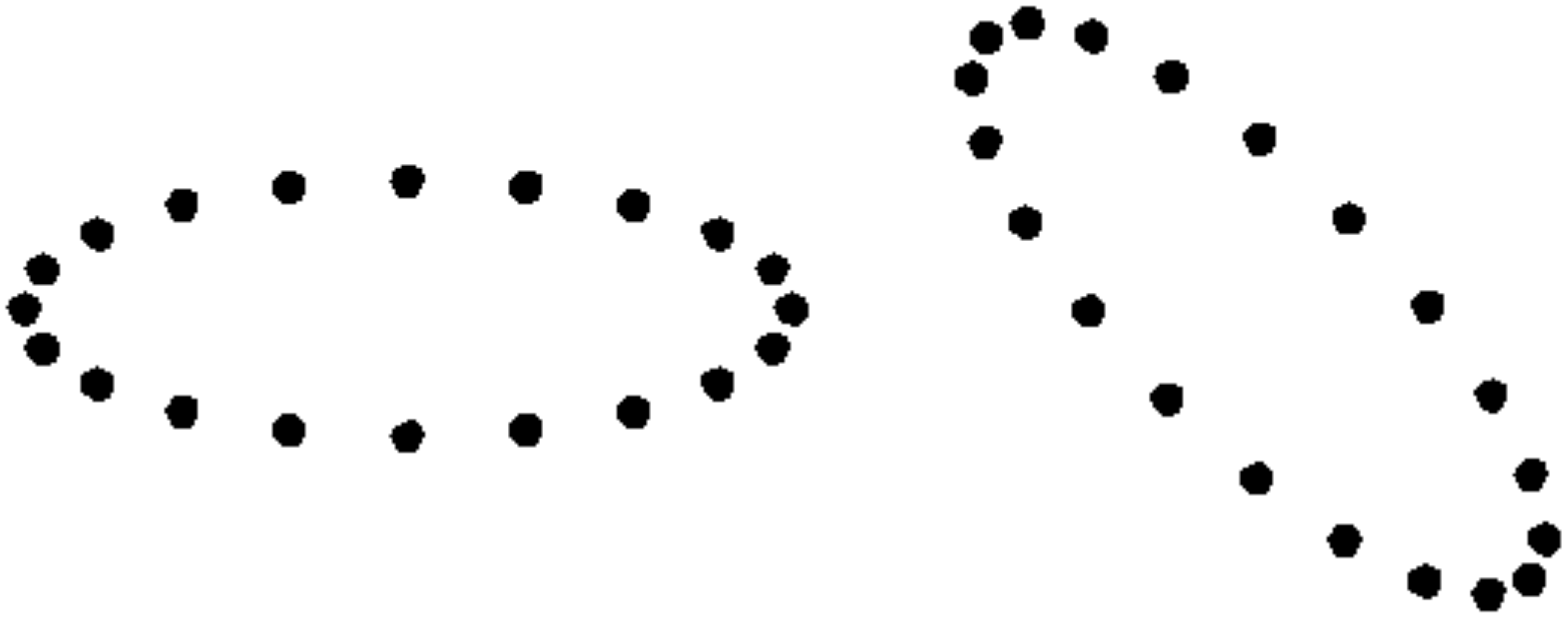
- Single-field slow-roll inflation looks very good:
  - ✓ $n_s < 1$
  - ✓ Gaussian fluctuations
  - ✓ Adiabatic fluctuations [no time to explain this today]
  - ✓ Super-horizon fluctuations [no time to explain this today]
- What more do we want? **Primordial gravitational waves**
- Why more evidence? Because "***extraordinary claim requires extraordinary evidence***" (Carl Sagan)

The New Quest: Primordial Gravitational Waves

Grishchuk (1974); Starobinsky (1979)

Gravitational waves are coming towards you!

To visualise the waves, watch motion of test particles.



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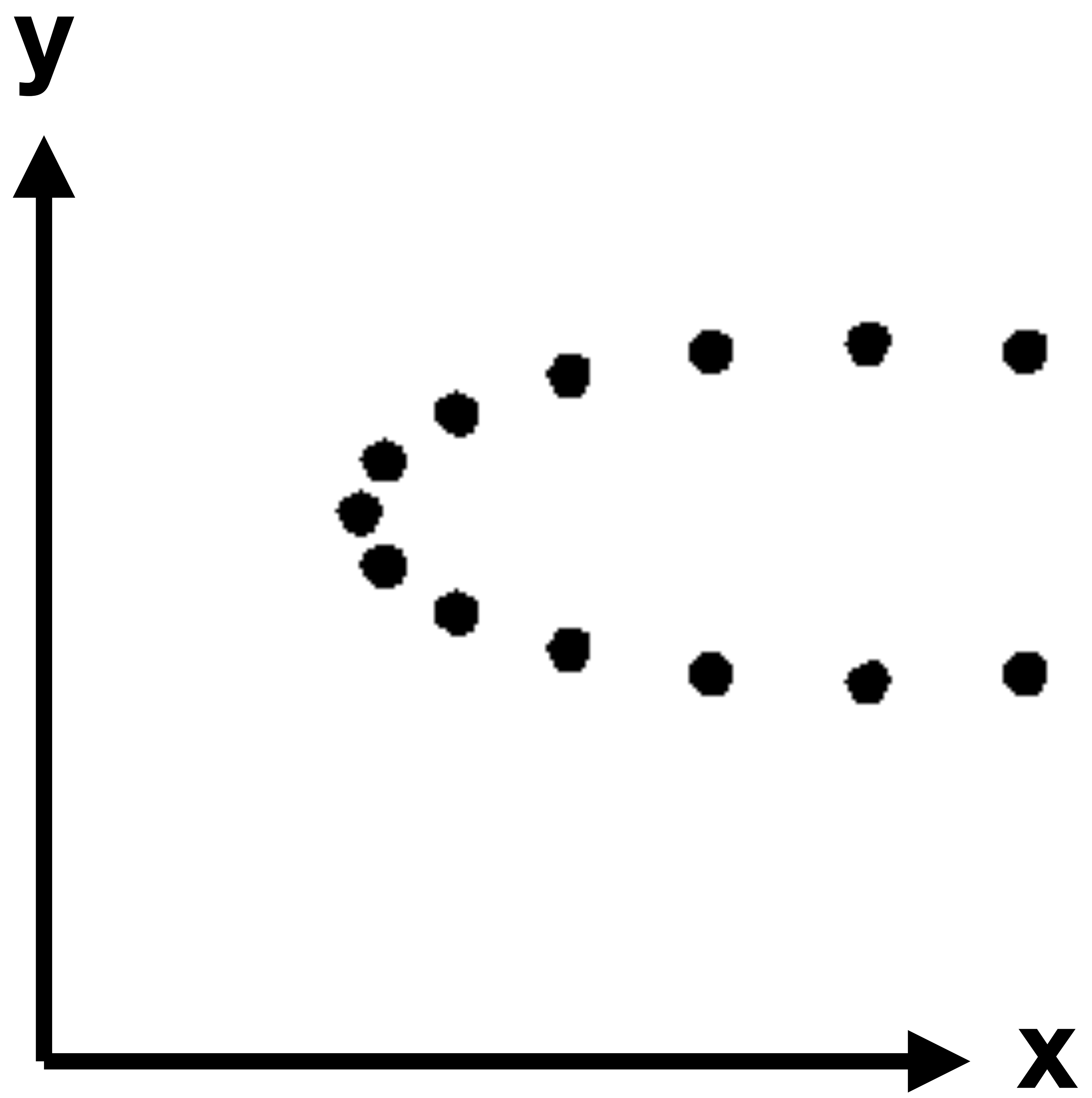


Distance between two points

- In Cartesian coordinates, the distance between two points in Euclidean space is

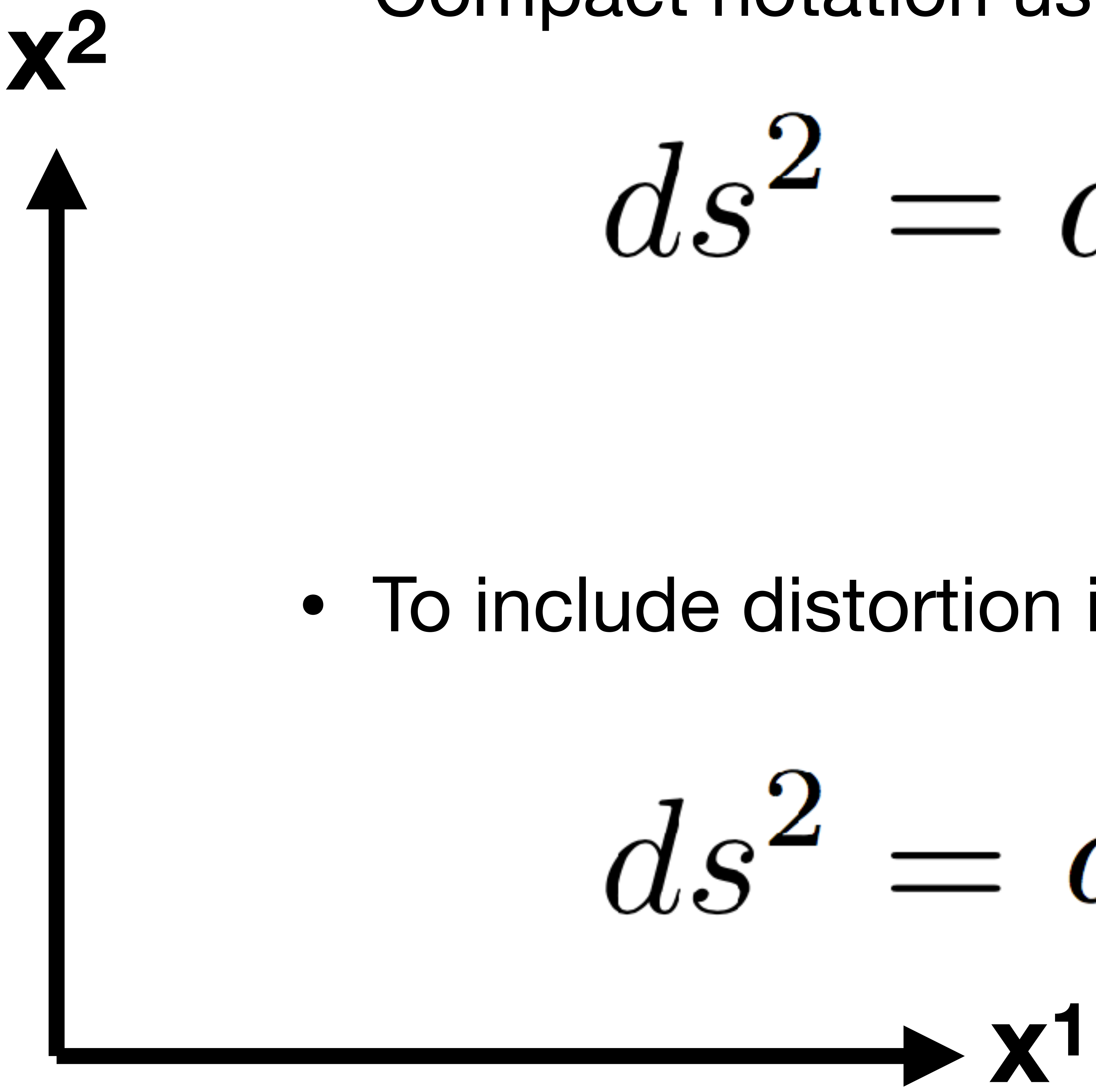
$$ds^2 = dx^2 + dy^2 + dz^2$$

- To include the isotropic expansion of space,

$$ds^2 = \boxed{a^2(t)}(dx^2 + dy^2 + dz^2)$$

Scale Factor

Distortion in space



- Compact notation using Kronecker's delta symbol:

$$ds^2 = a^2(t) \sum_{i=1}^{3} \sum_{j=1}^{3} \delta_{ij} \, dx^i \, dx^j$$

$$\boldsymbol{x} = (x, y, z)$$

$\delta_{ij} = 1$ for i=j;
$\delta_{ij} = 0$ otherwise

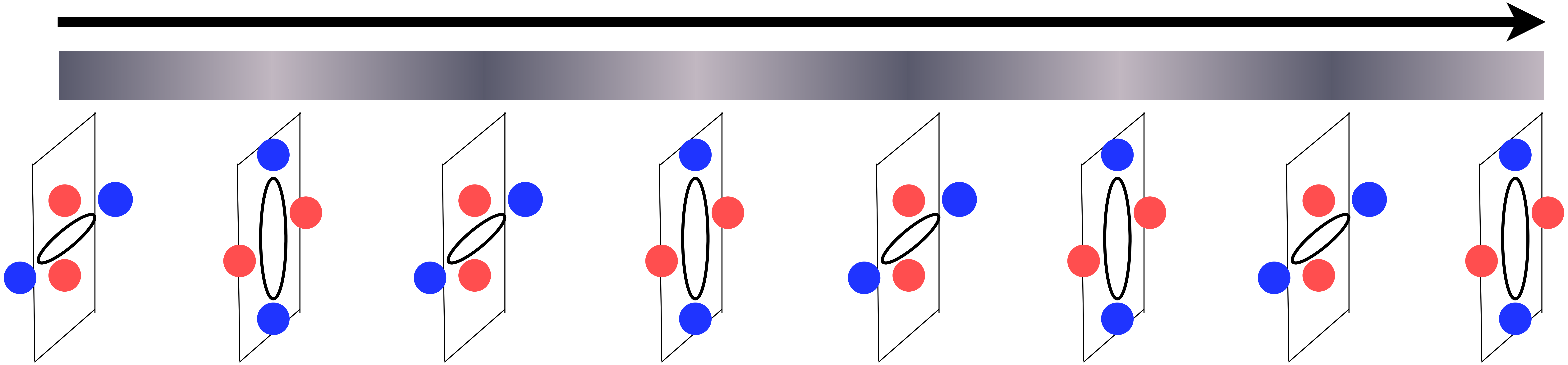
- To include distortion in space,

$$ds^2 = a^2 \sum_{i=1}^{3} \sum_{j=1}^{3} (\delta_{ij} + \boxed{h_{ij}}) dx^i dx^j$$

Distortion in space!

Four conditions for gravitational waves

- **The gravitational wave shall be <u>transverse.</u>**
  - The direction of distortion is perpendicular to the propagation direction $\vec{k}$

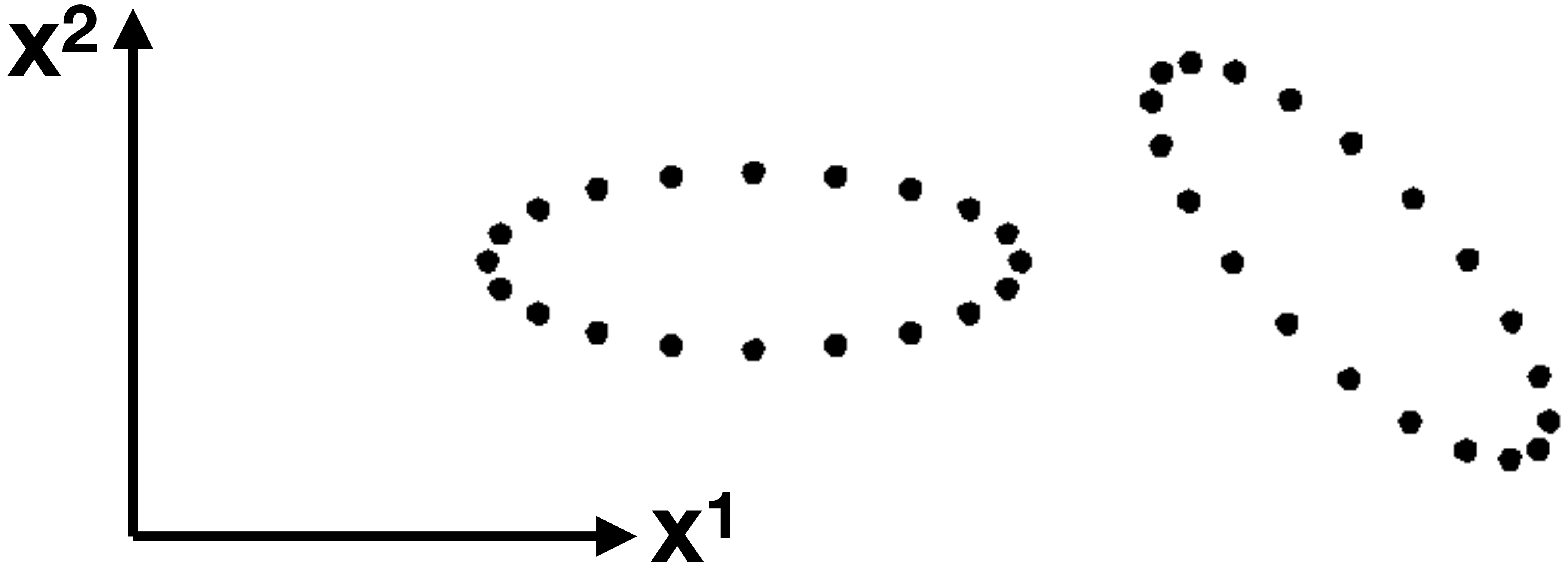


Thus, $$\sum_{i=1}^{3} k^i h_{ij} = 0$$ 3 conditions for h_{ij}

Four conditions for gravitational waves

- **The gravitational wave shall <u>not change the area</u>**
  - The determinant of $\delta_{ij}+h_{ij}$ is 1

$$ds^2 = a^2 \sum_{i=1}^{3} \sum_{j=1}^{3} (\delta_{ij} + h_{ij}) dx^i dx^j$$



Thus, $$\sum_{i=1}^{3} h_{ii} = 0$$

1 condition for h_{ij}

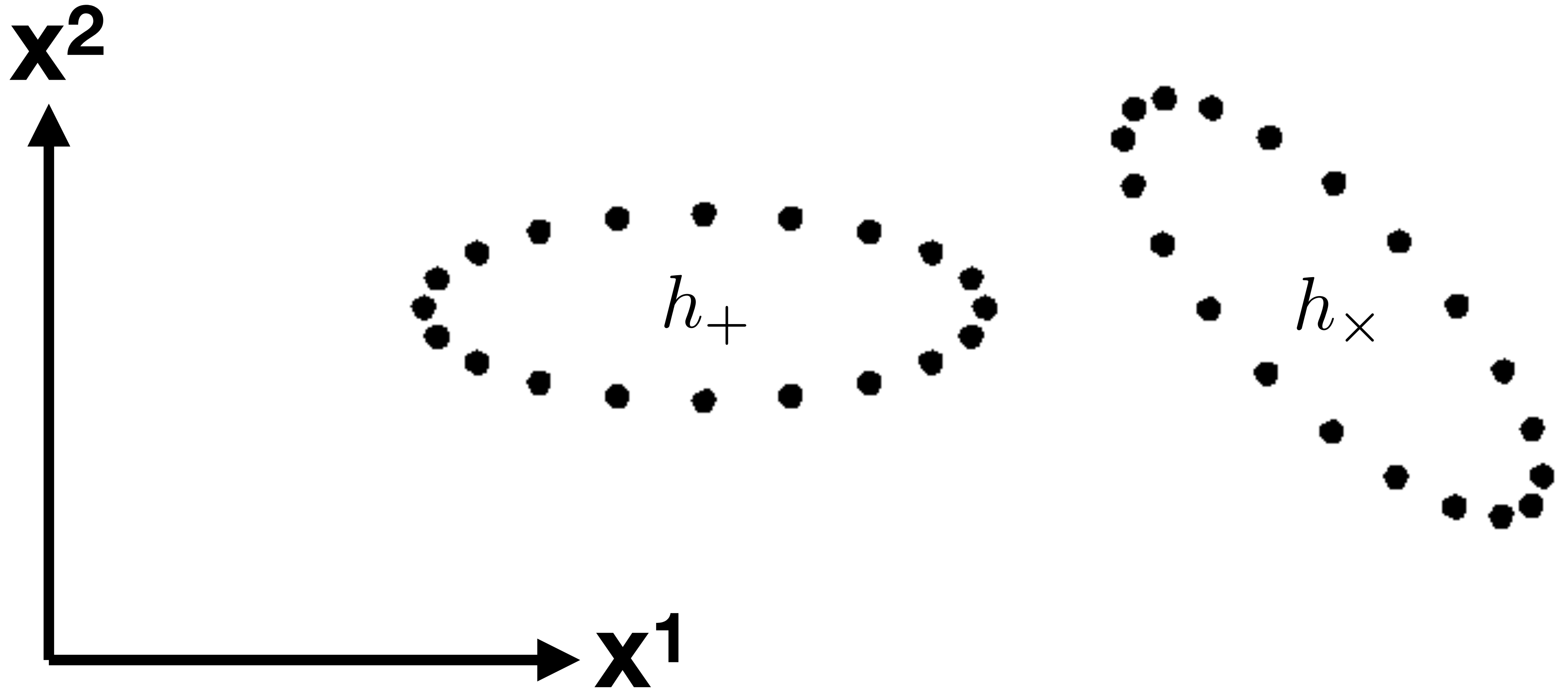
6 – 4 = 2 degrees of freedom for GW

We call them “plus” and “cross” modes

- The symmetric matrix h_{ij} has 6 components, but there are 4 conditions. Thus, we have two degrees of freedom.

- If the GW propagates in the x^3=z axis, non-vanishing components of h_{ij} are

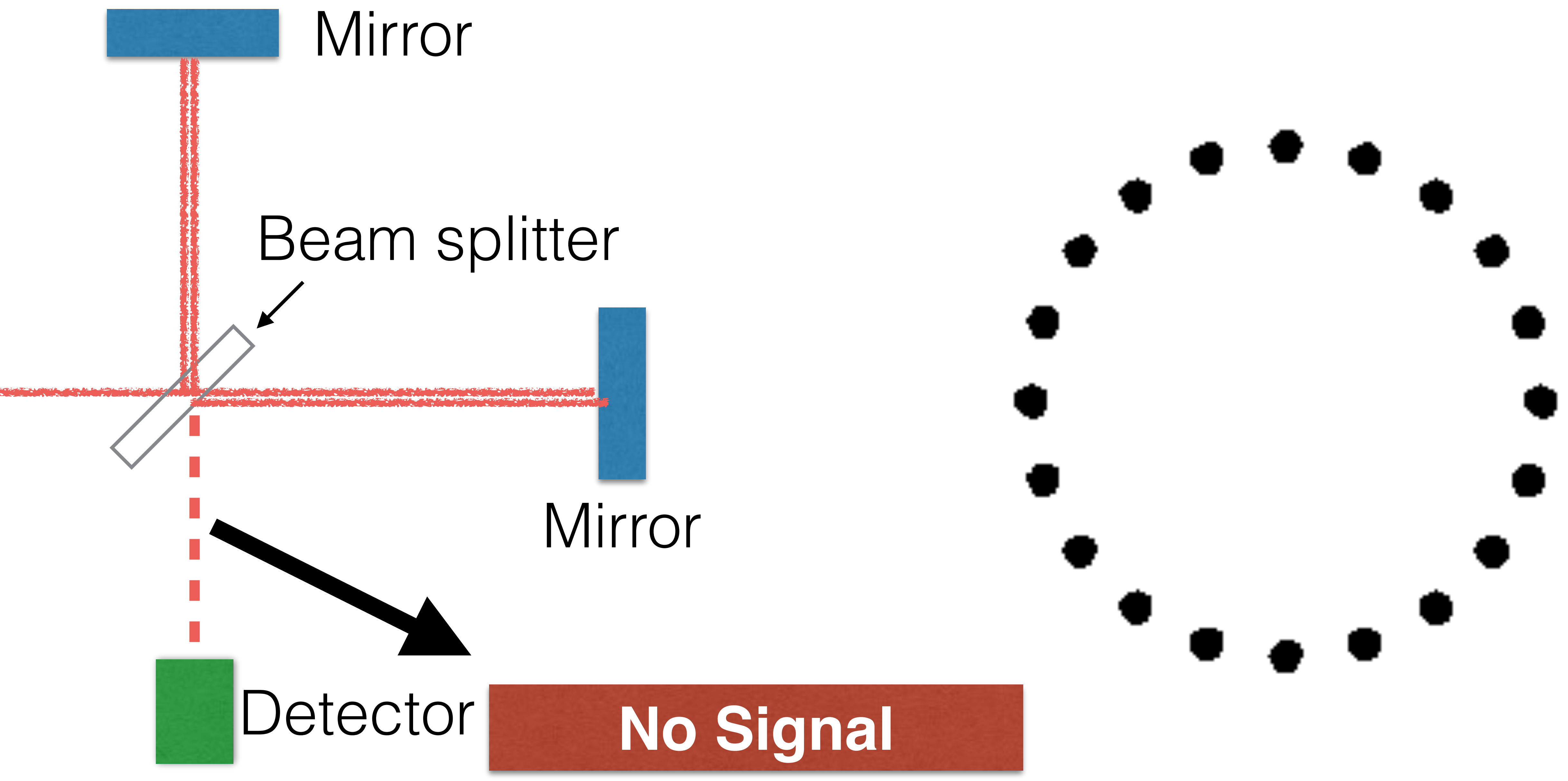
$$h_{ij} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



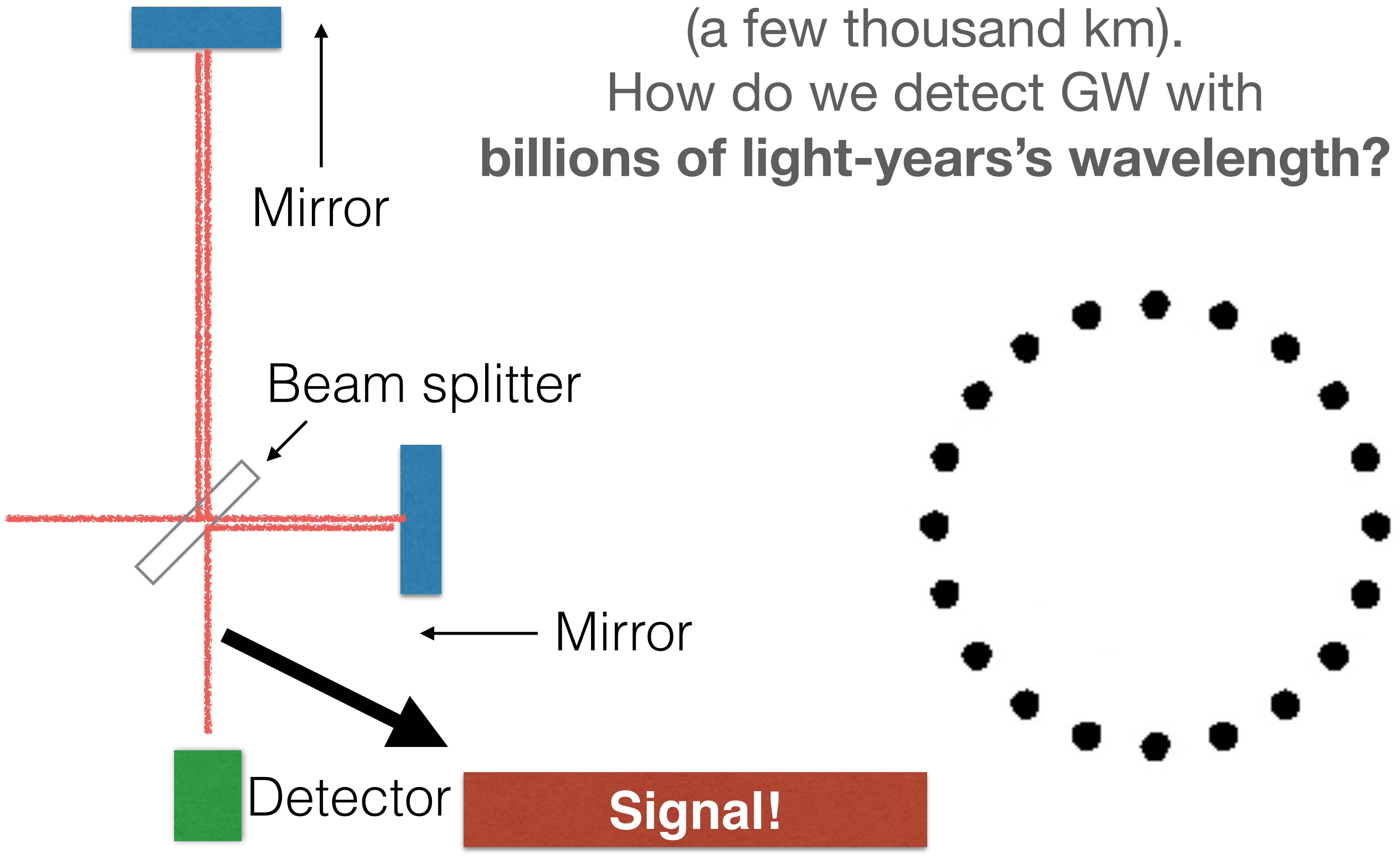
Propagation direction of GW $\vec{k}$
z
$h_+=\cos(kz)$
$h_\times=\cos(kz)$

How to detect GW?

Laser interferometer technique, used by LIGO and VIRGO



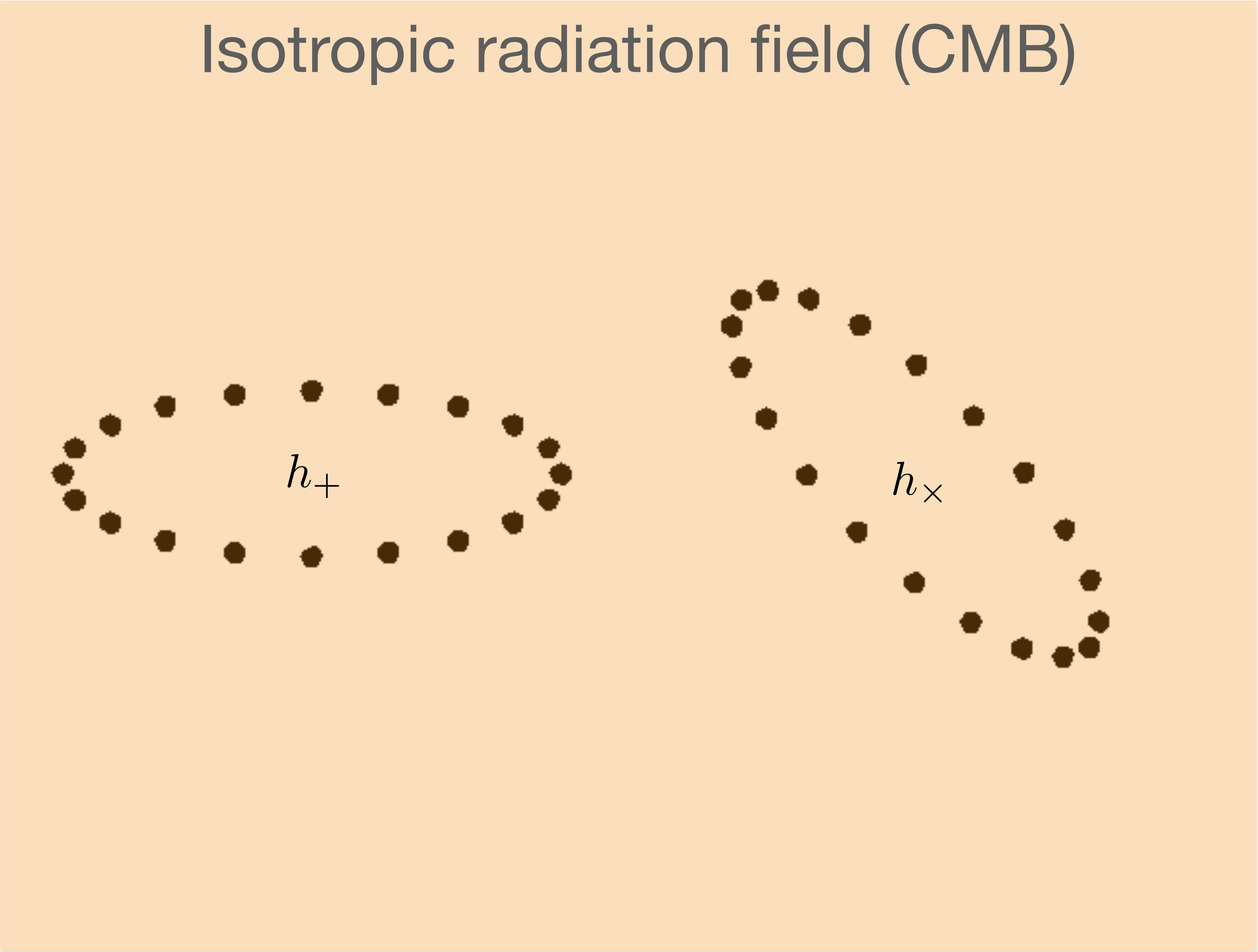
The wavelength of GW detectable by this method is the size of Earth (a few thousand km).
How do we detect GW with **billions of light-years's wavelength?**

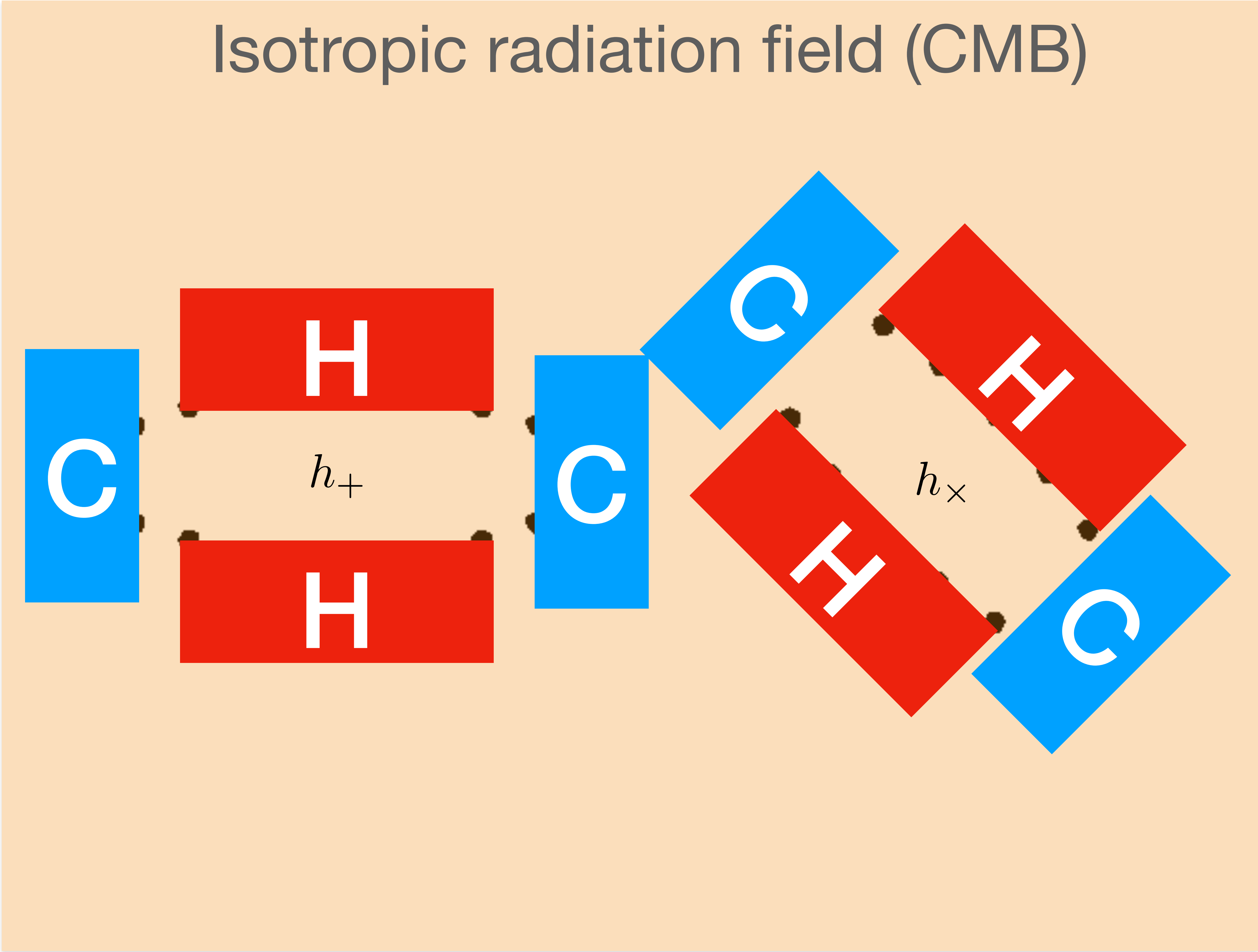


Sachs & Wolfe (1967)

Detecting GW by CMB

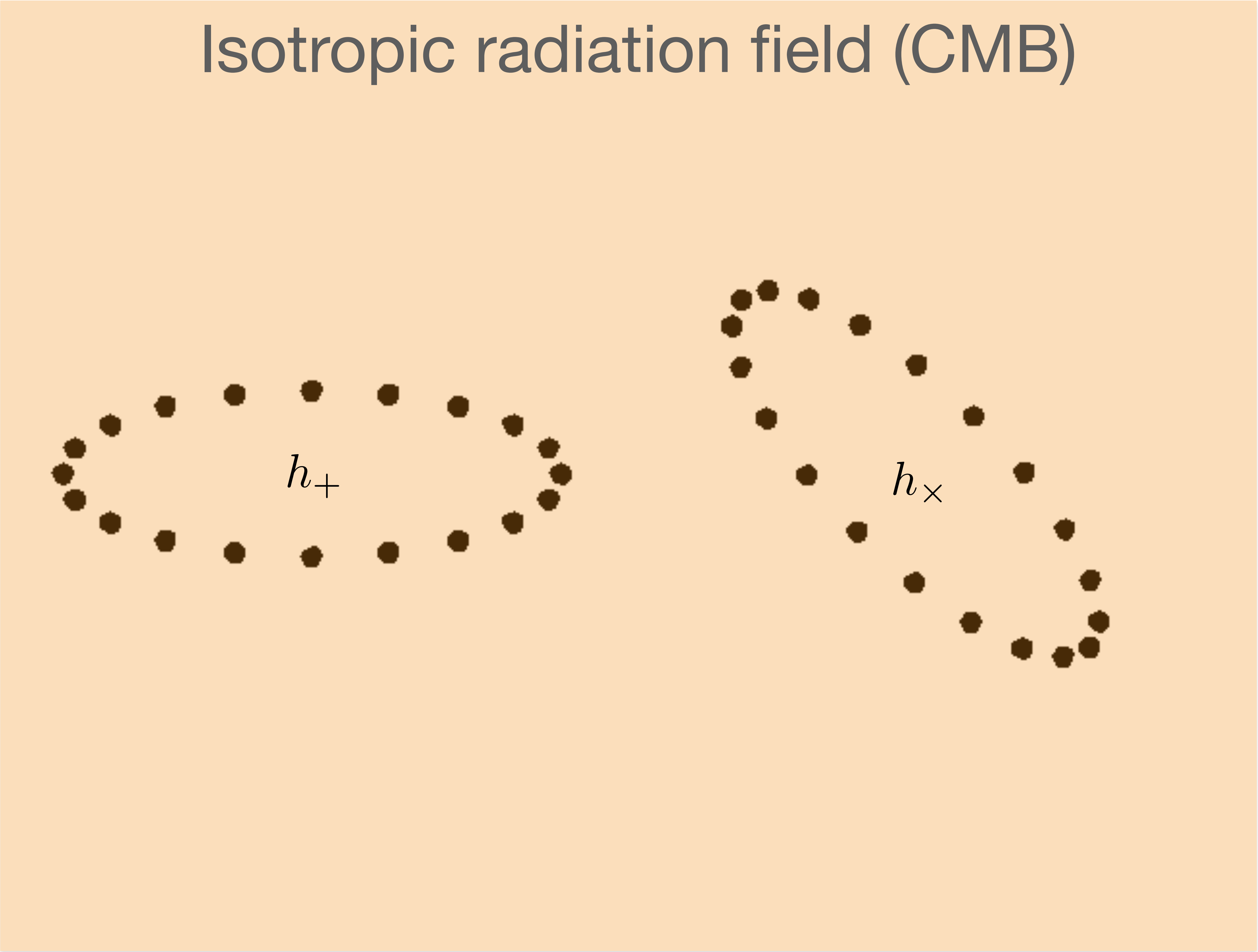
Quadrupole temperature anisotropy generated by red- and blue-shifting of photons

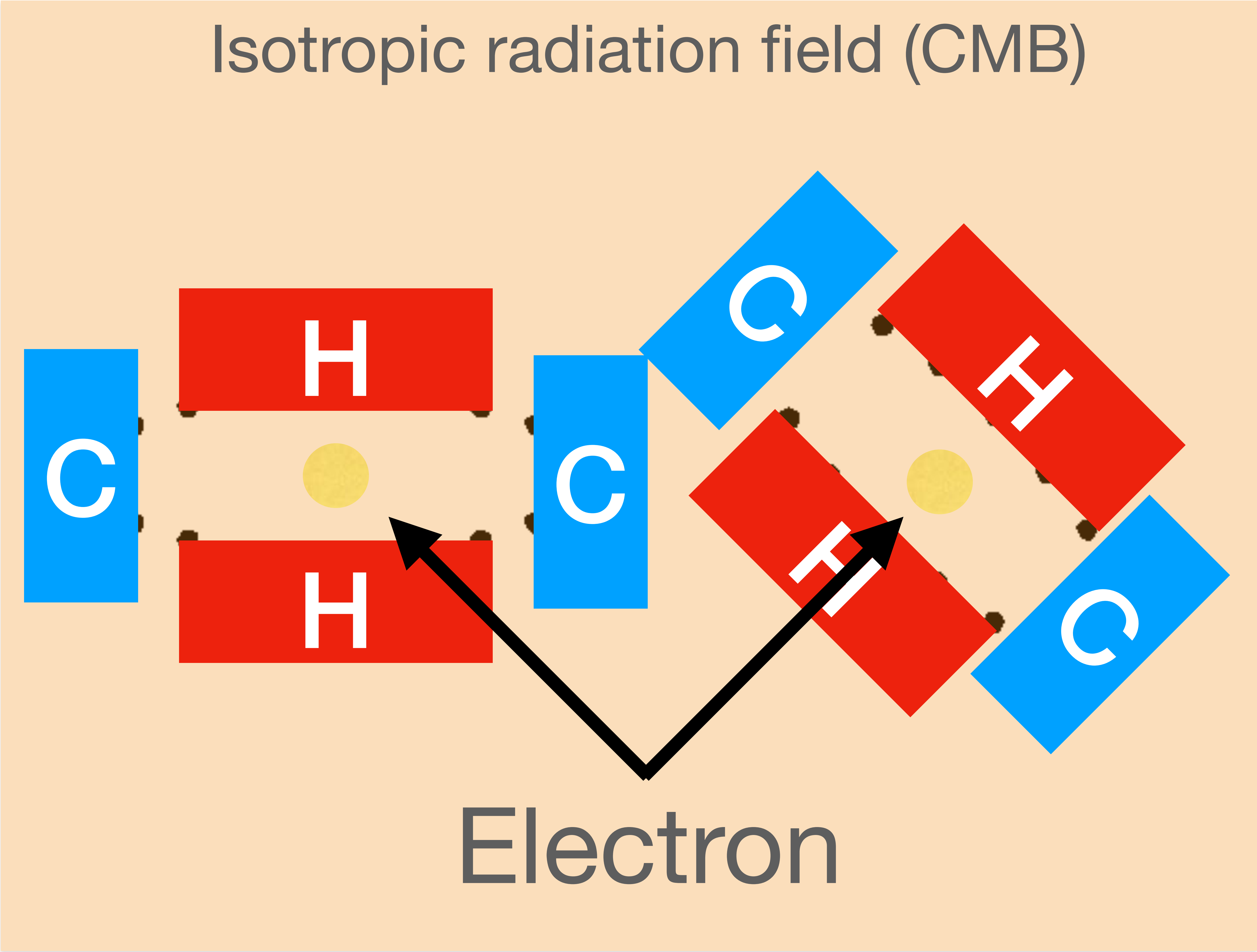




Detecting GW by CMB

Quadrupole temperature anisotropy generated by red- and blue-shifting of photons

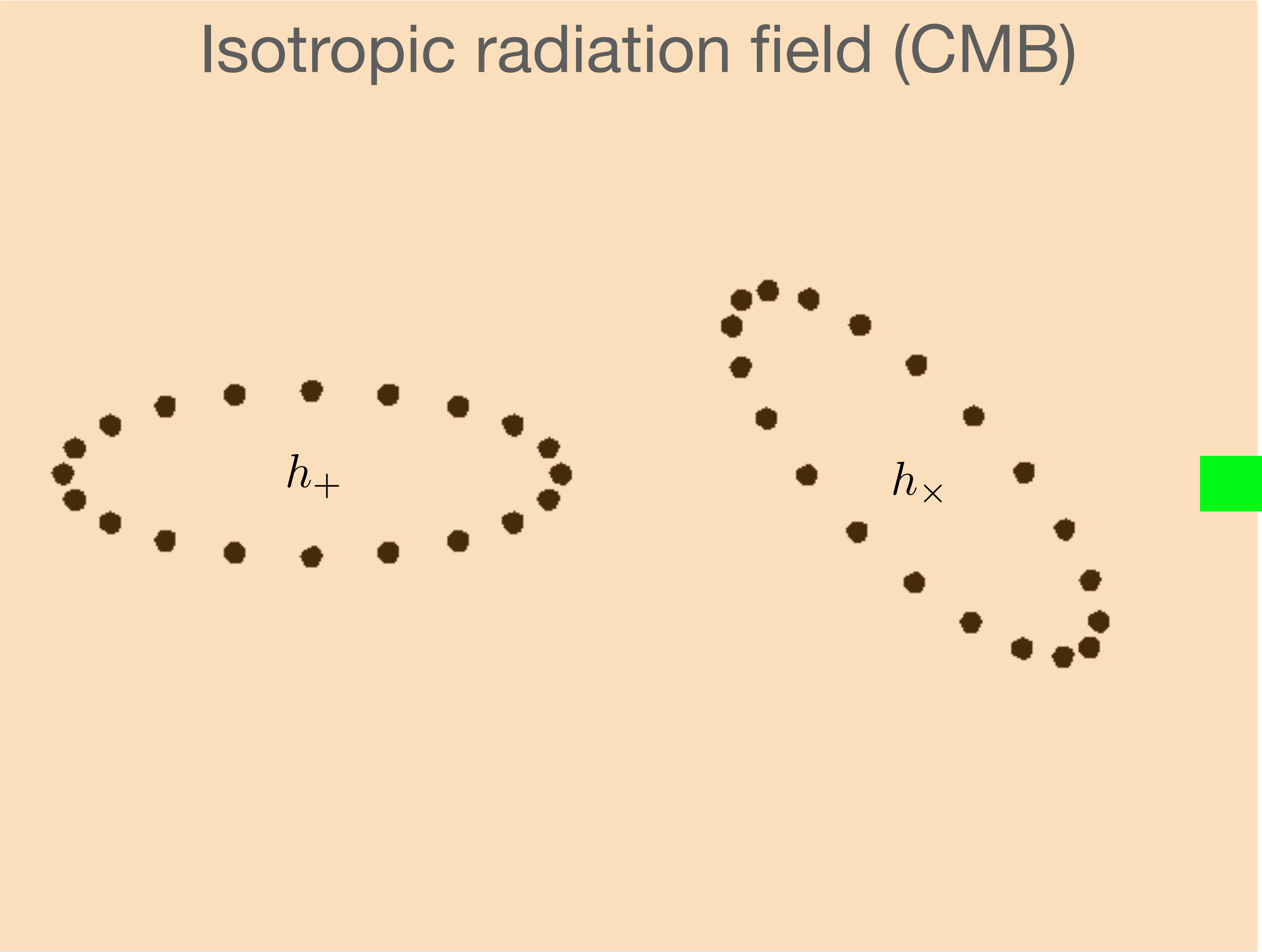


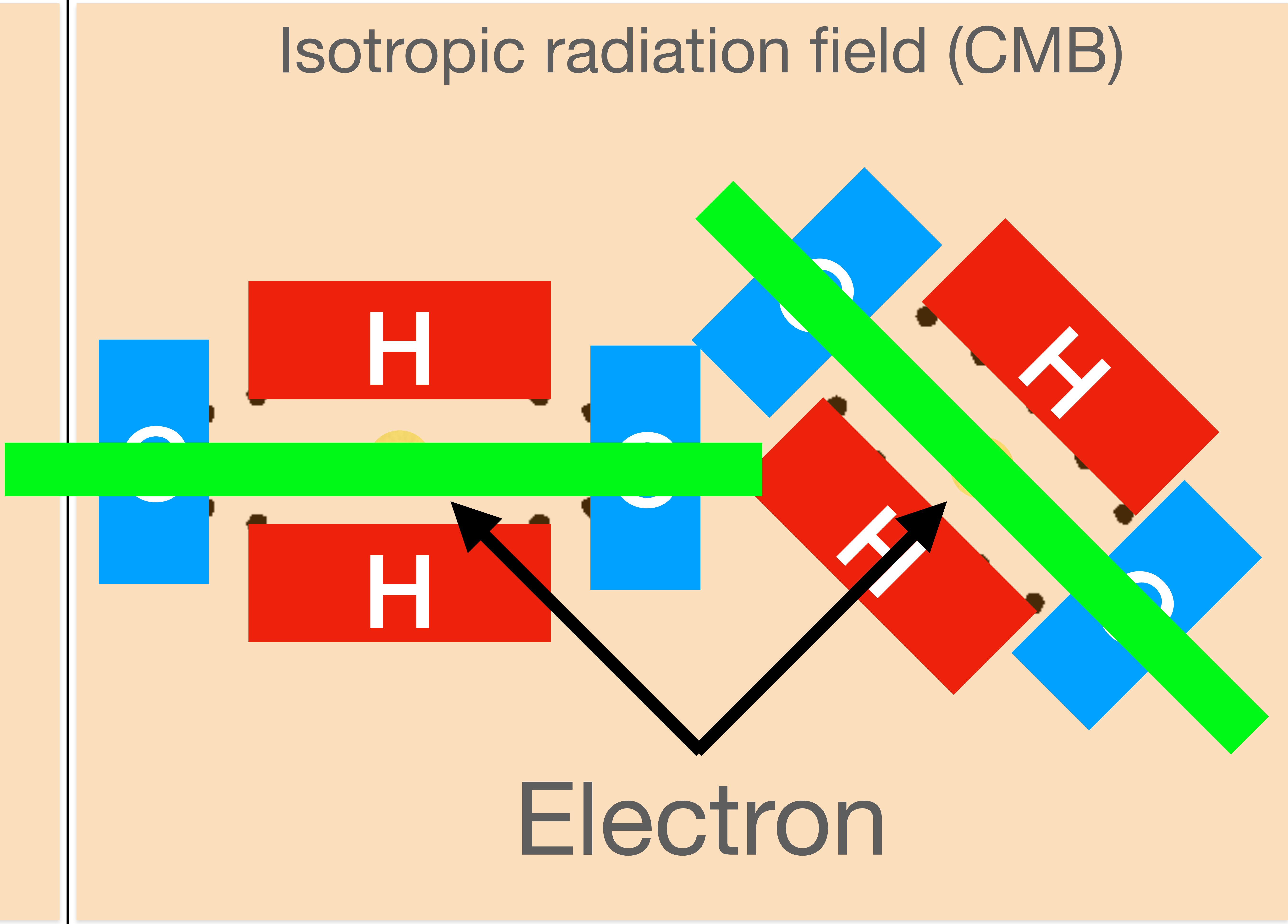


Polnarev (1985)

Detecting GW by CMB *Polarisation*

Quadrupole temperature anisotropy scattered by an electron





Credit: TALEX


Credit: TALEX

Physics of CMB Polarisation

Necessary and sufficient condition: Scattering and Quadrupole Anisotropy

Credit：Wayne Hu

Credit: ESA

Temperature (smoothed)

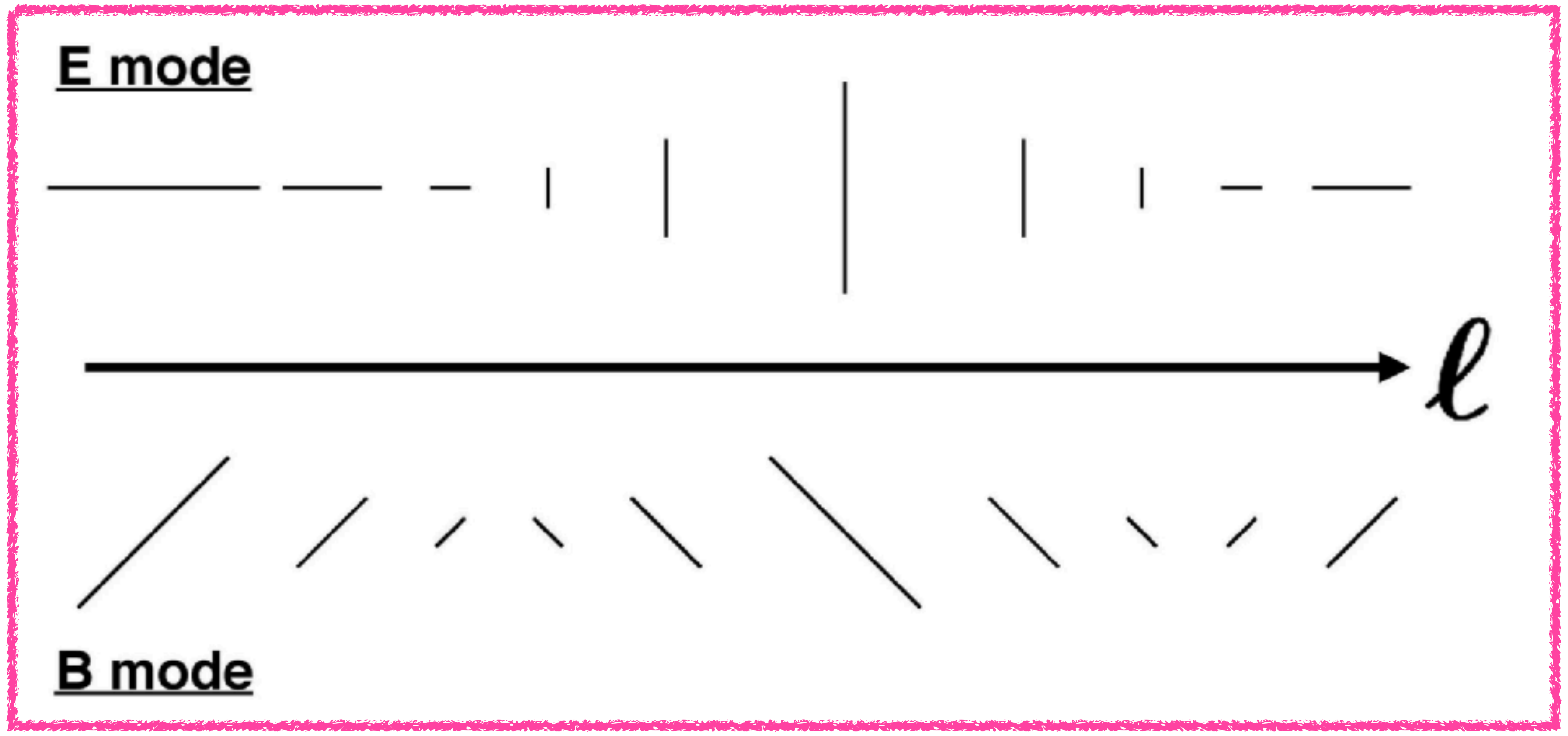
Credit: ESA

Temperature (smoothed) + Polarisation

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

E- and B-mode decomposition

Concept defined in Fourier space

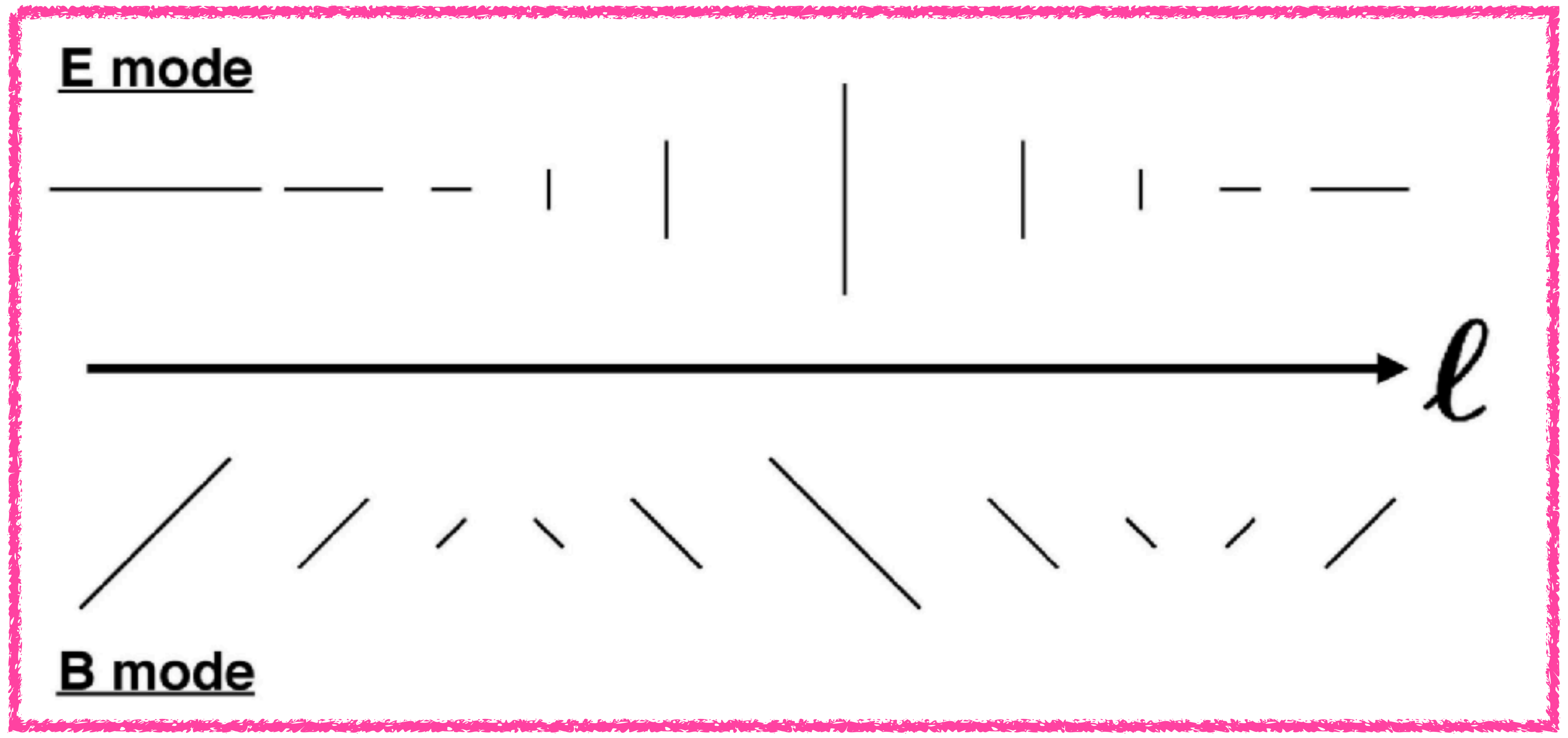


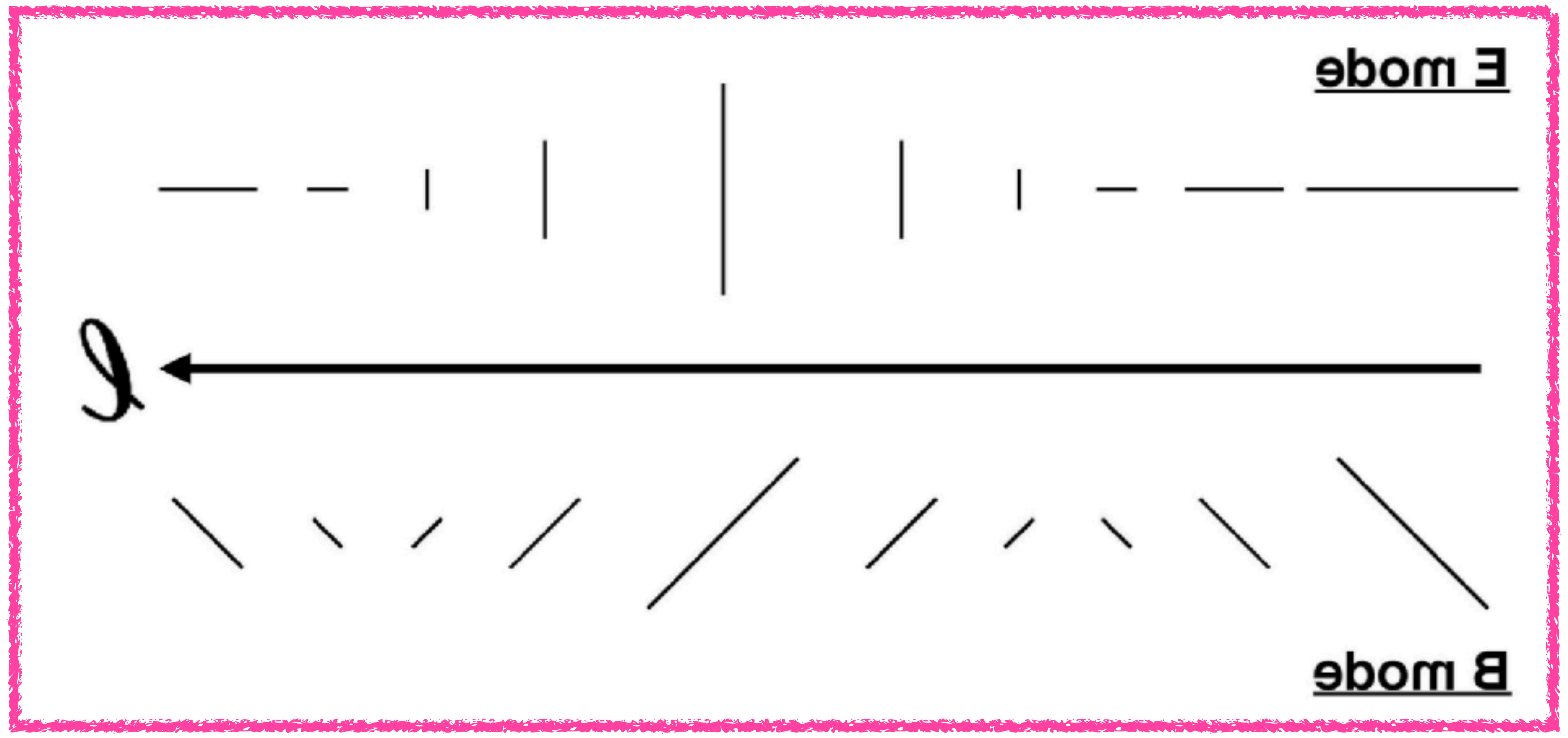
Direction of the Fourier wavenumber vector

- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

Parity Flip

E-mode remains the same, whereas B-mode changes the sign





- Two-point correlation functions invariant under the parity flip are

$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{BB}$$

$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

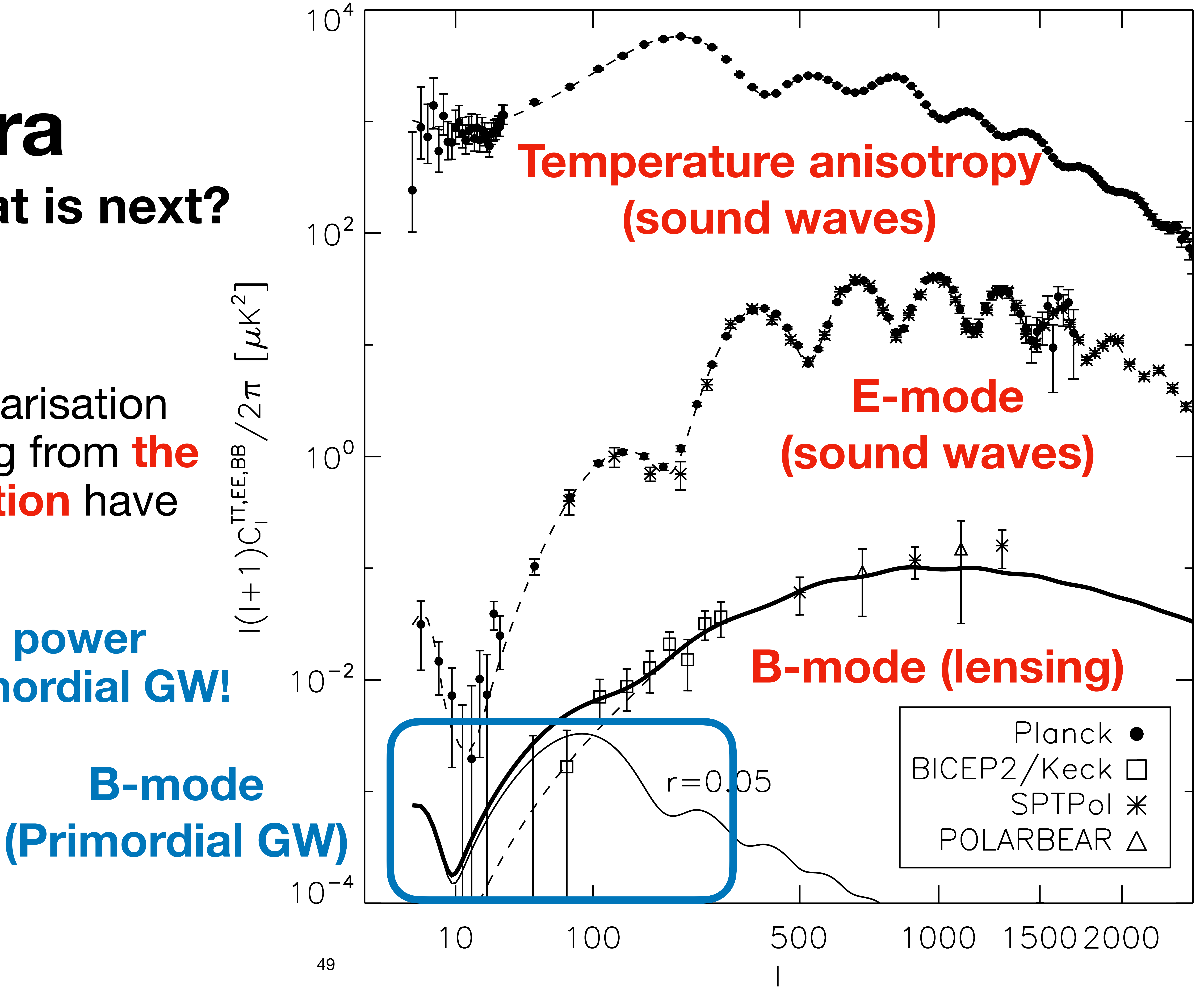
- The other combinations <TB> and <EB> are not invariant under the parity flip.
  - **We can use these combinations to probe parity-violating physics (e.g., axions)**

Power Spectra

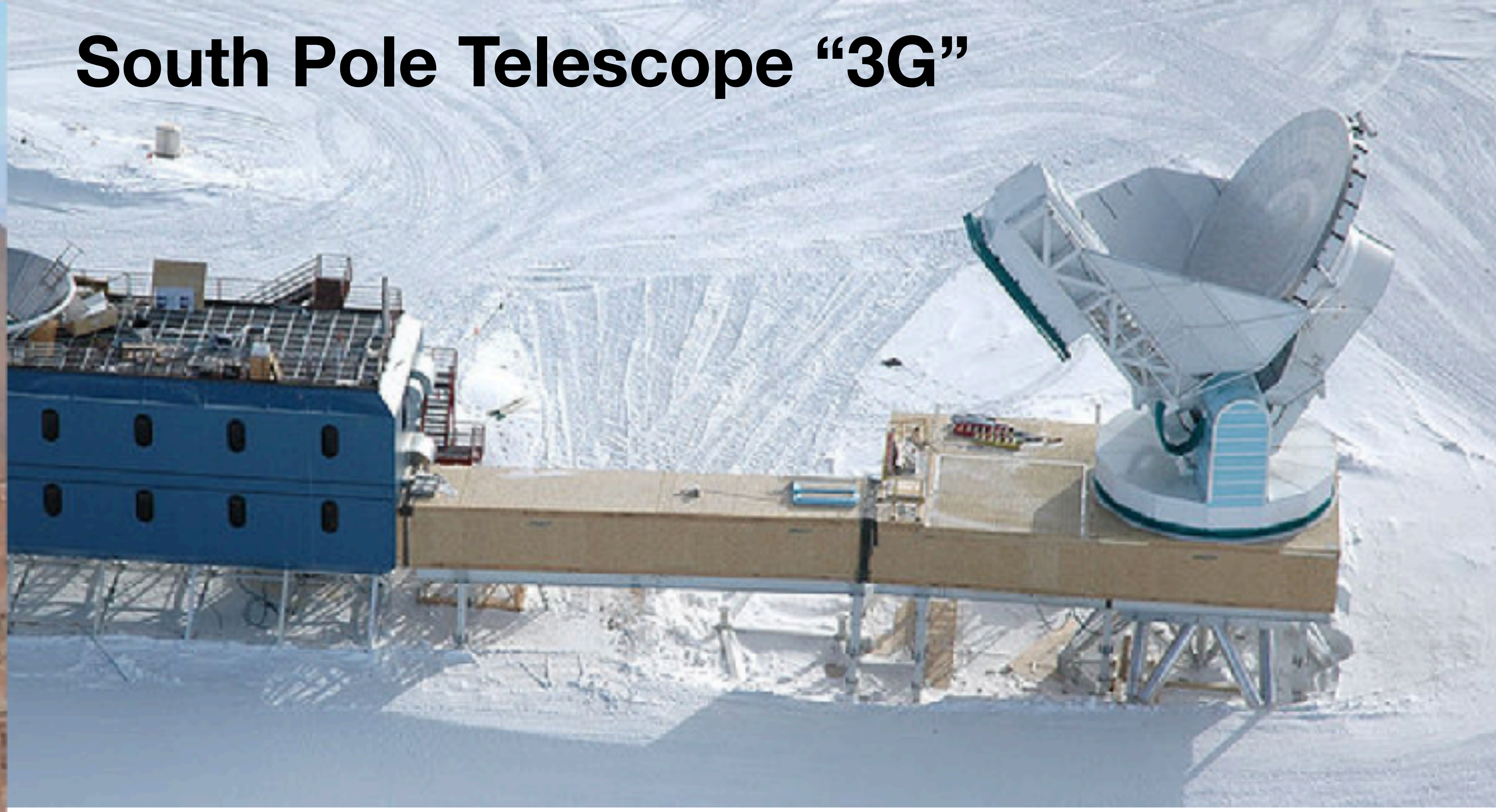
Where are we? What is next?

- The temperature and polarisation power spectra originating from **the scalar (density) fluctuation** have been measured.

- The next quest: **B-mode power spectrum from the primordial GW!**

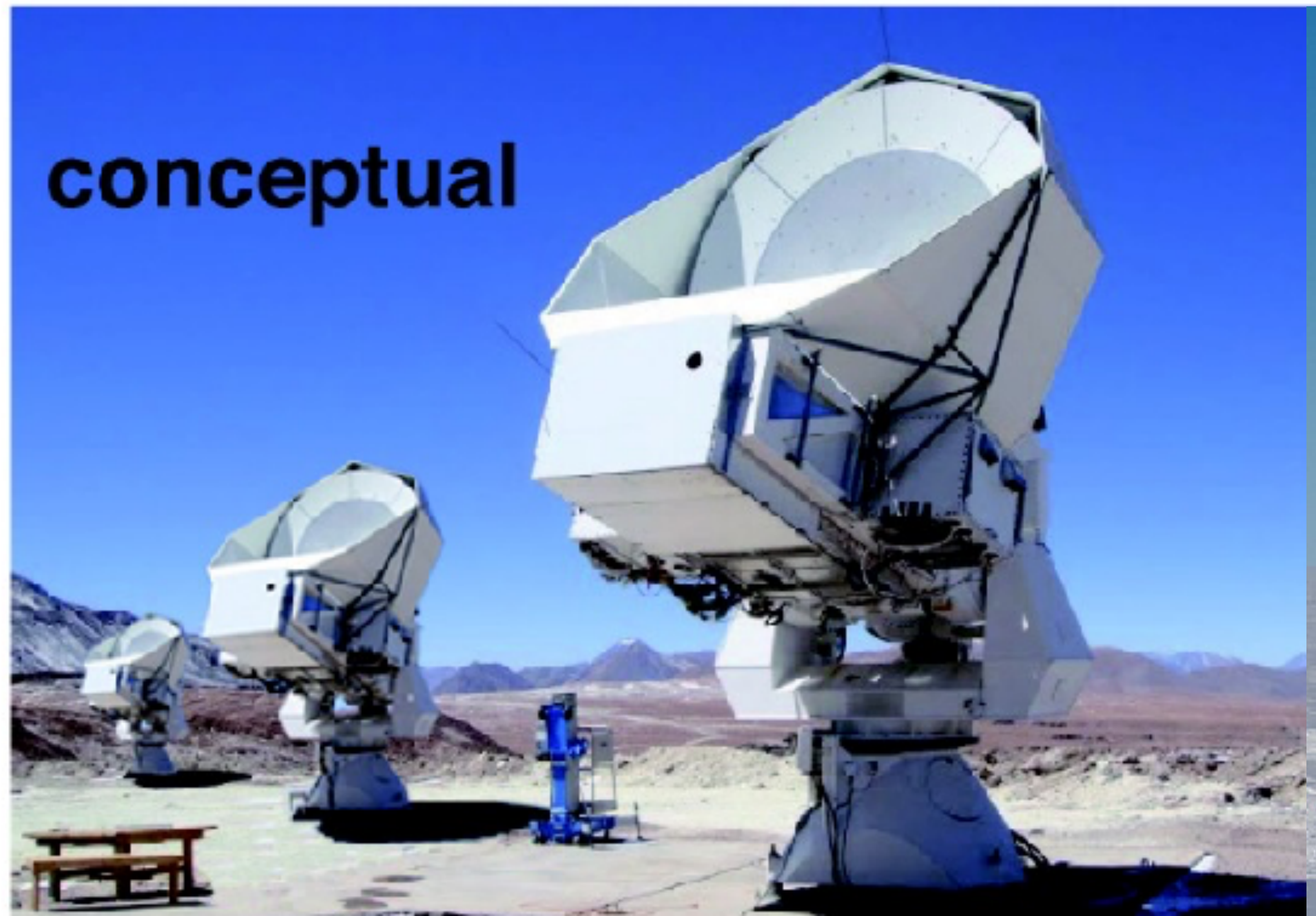


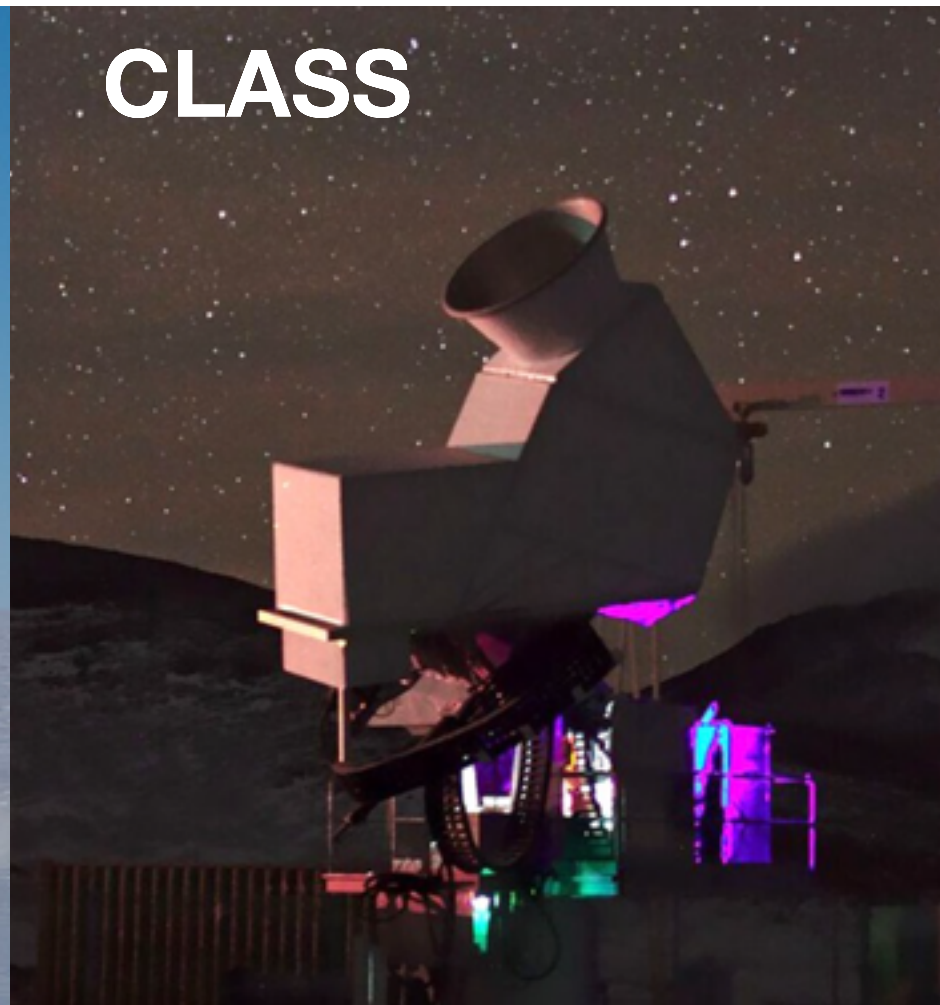
Experimental Landscape



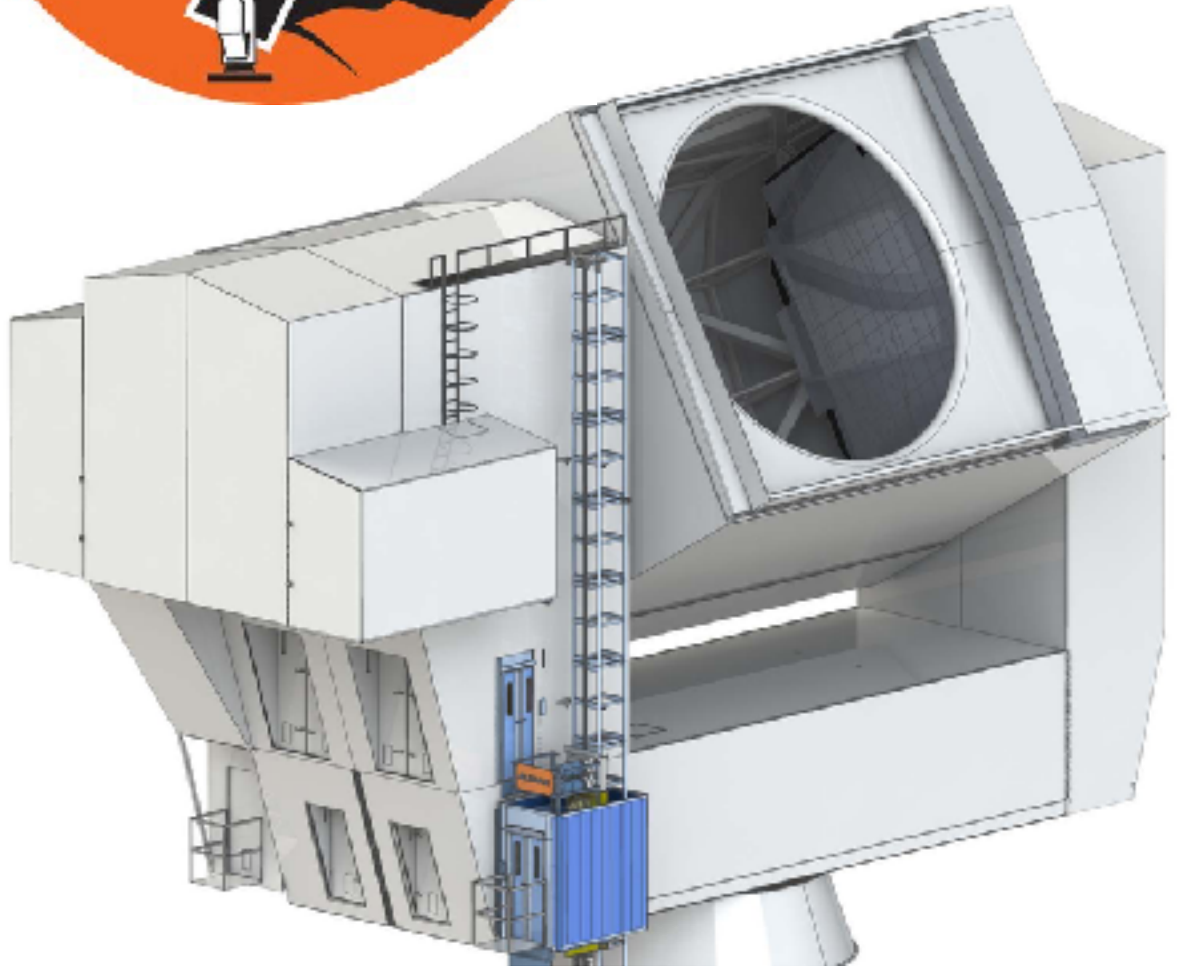
On-going Ground-based Experiments

The Simons Array



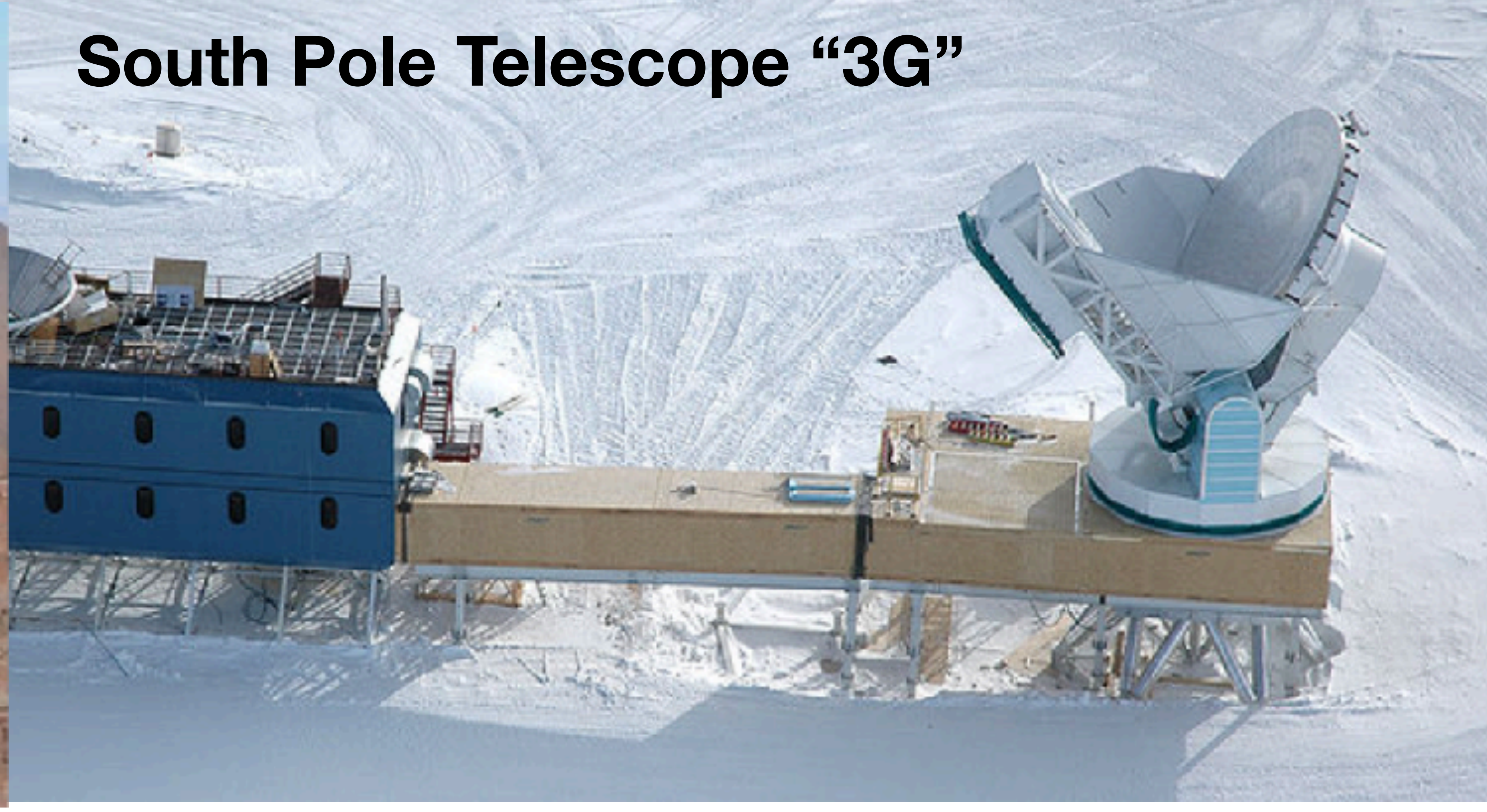


SIMONS OBSERVATORY

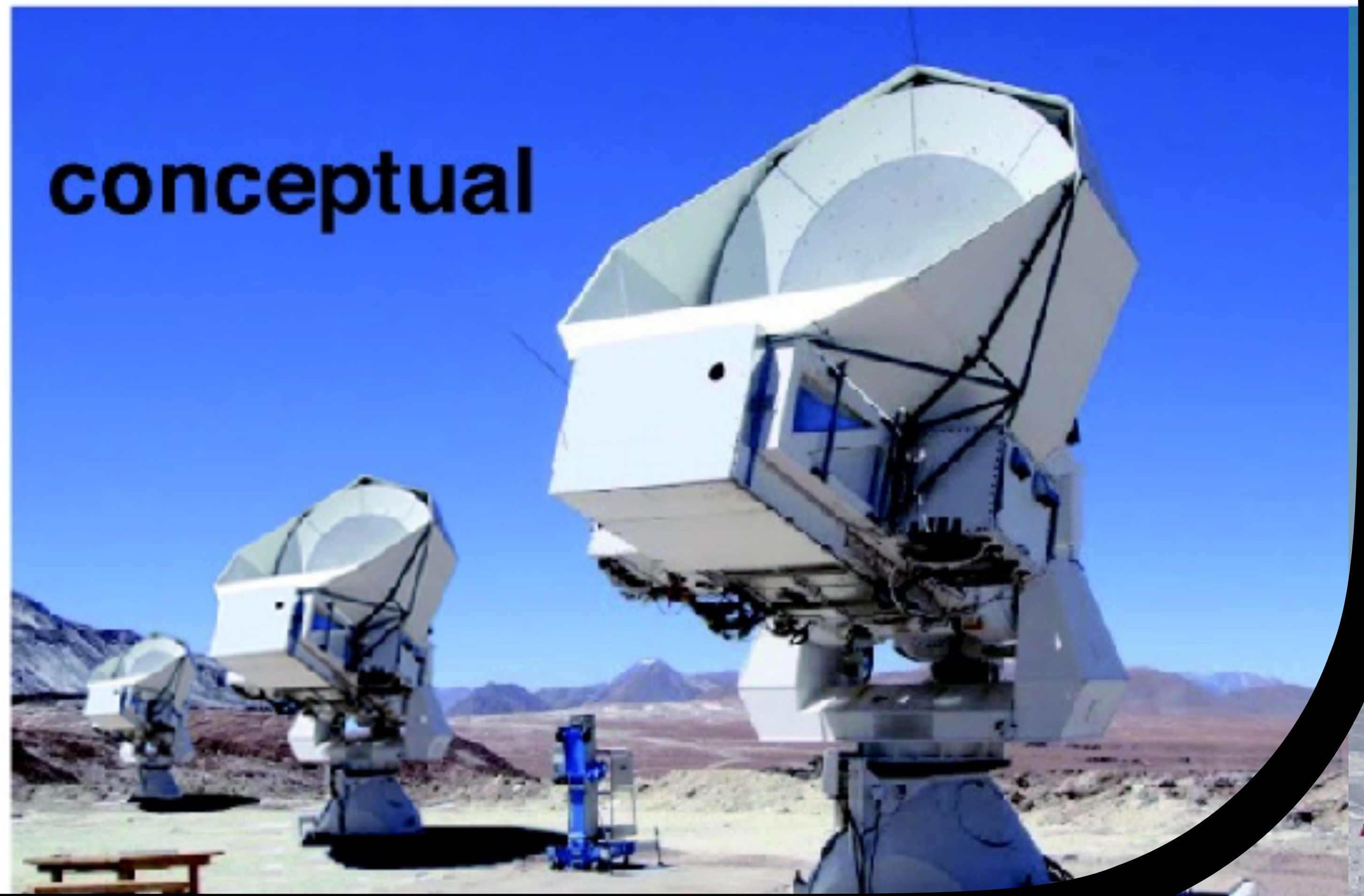


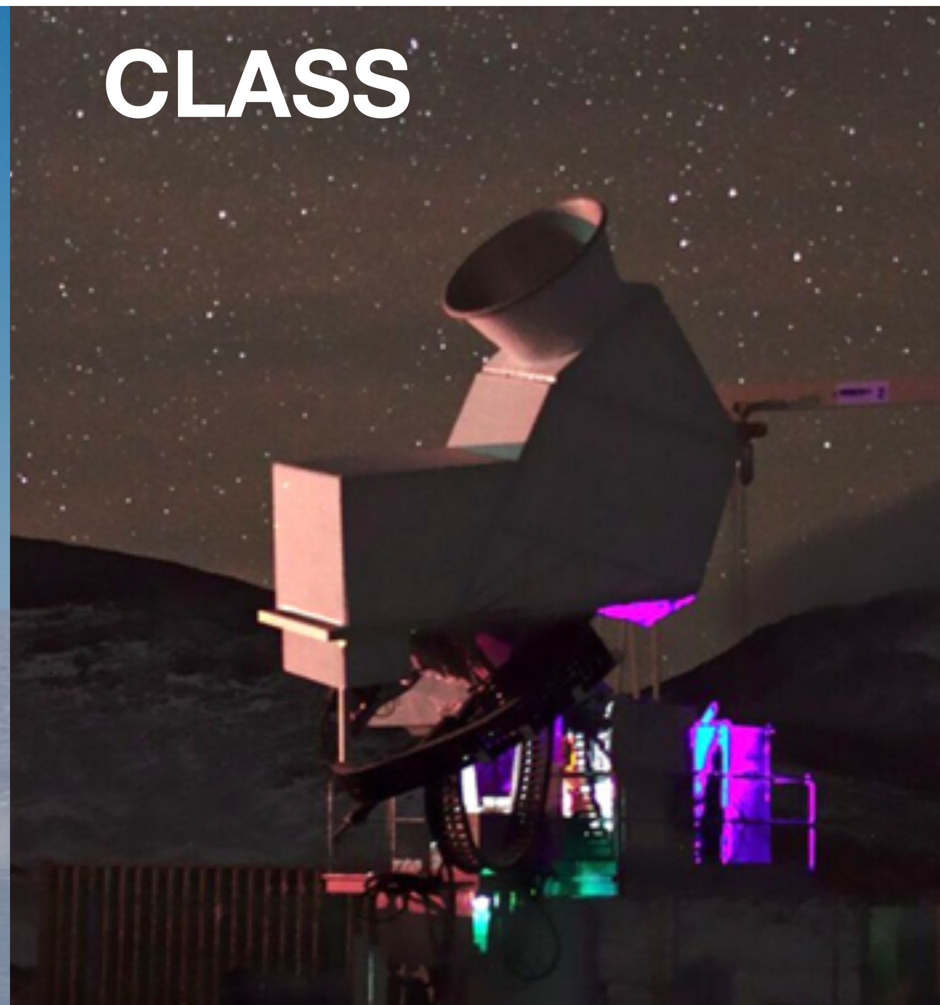
Early 2020s

~$100M

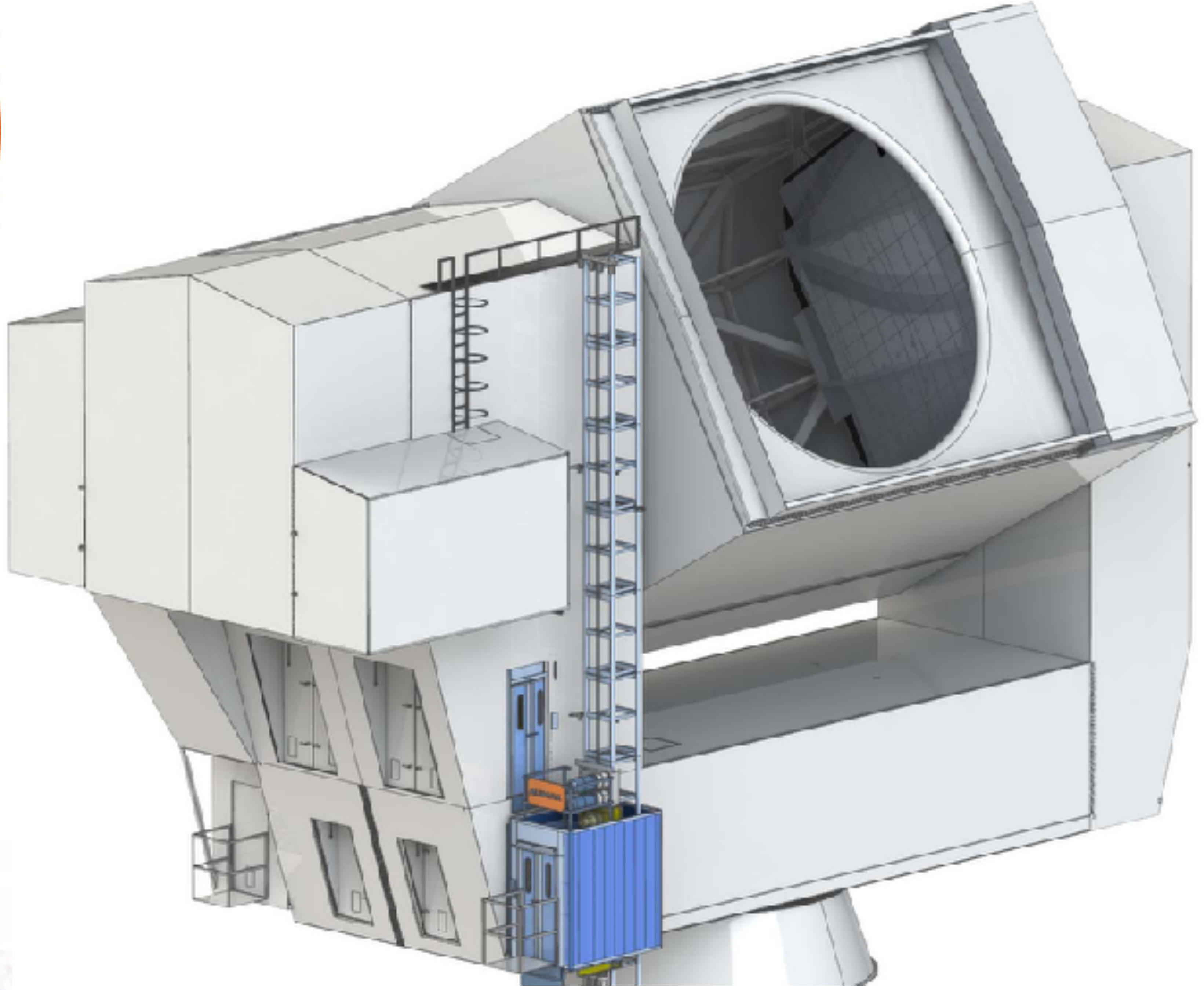


The Simons Array

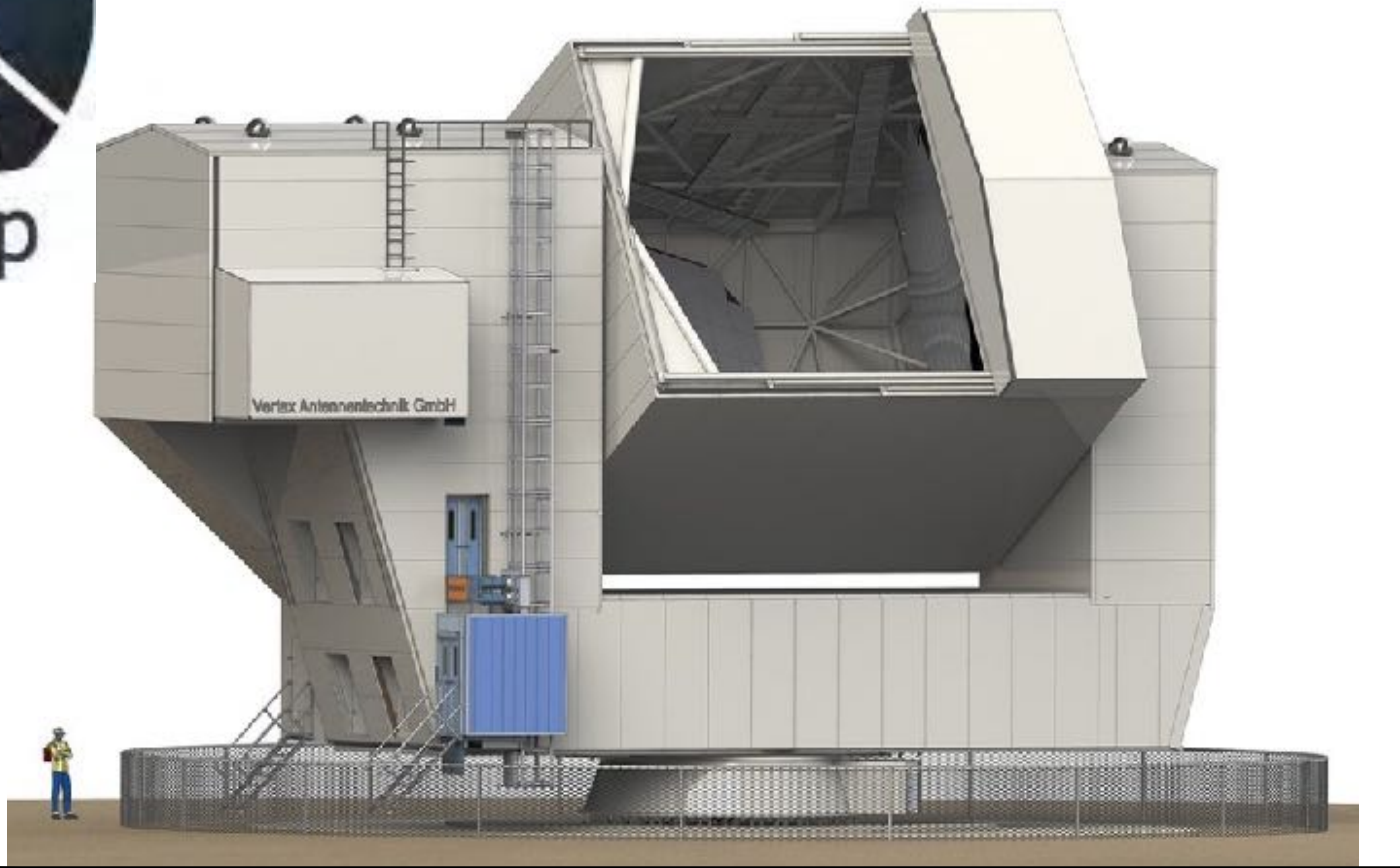




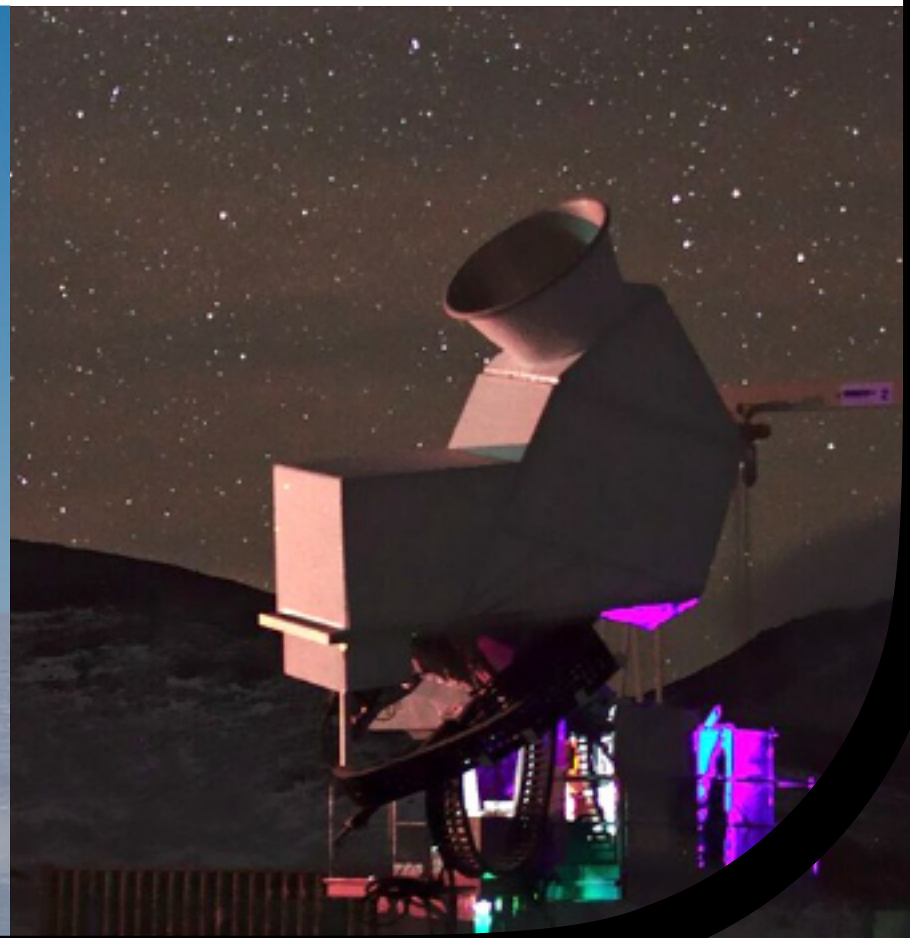
SIMONS OBSERVATORY



CCAT-p



Bringing all together:
CMB Stage IV
Late 2020s (~$600M)



CMB Stages

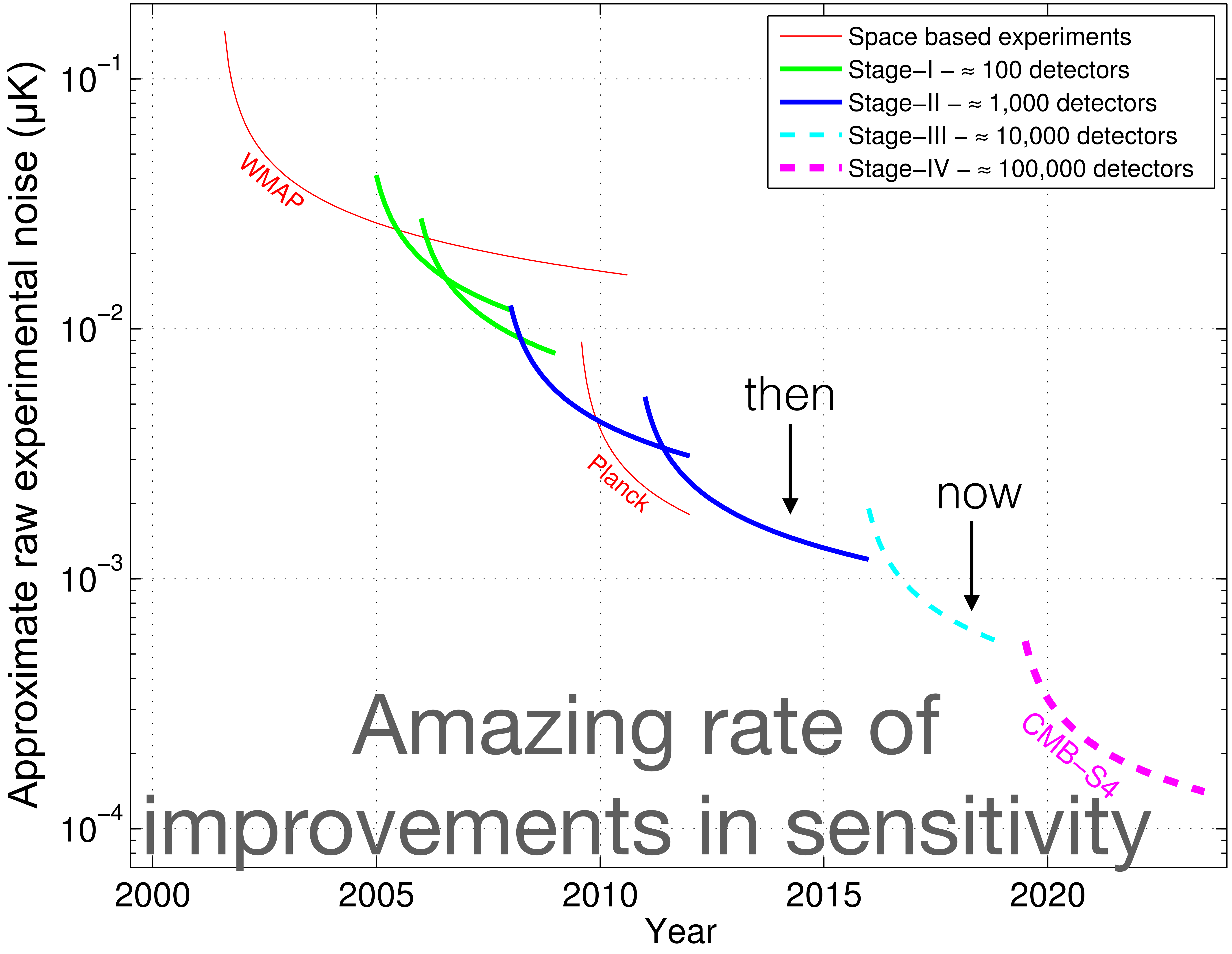
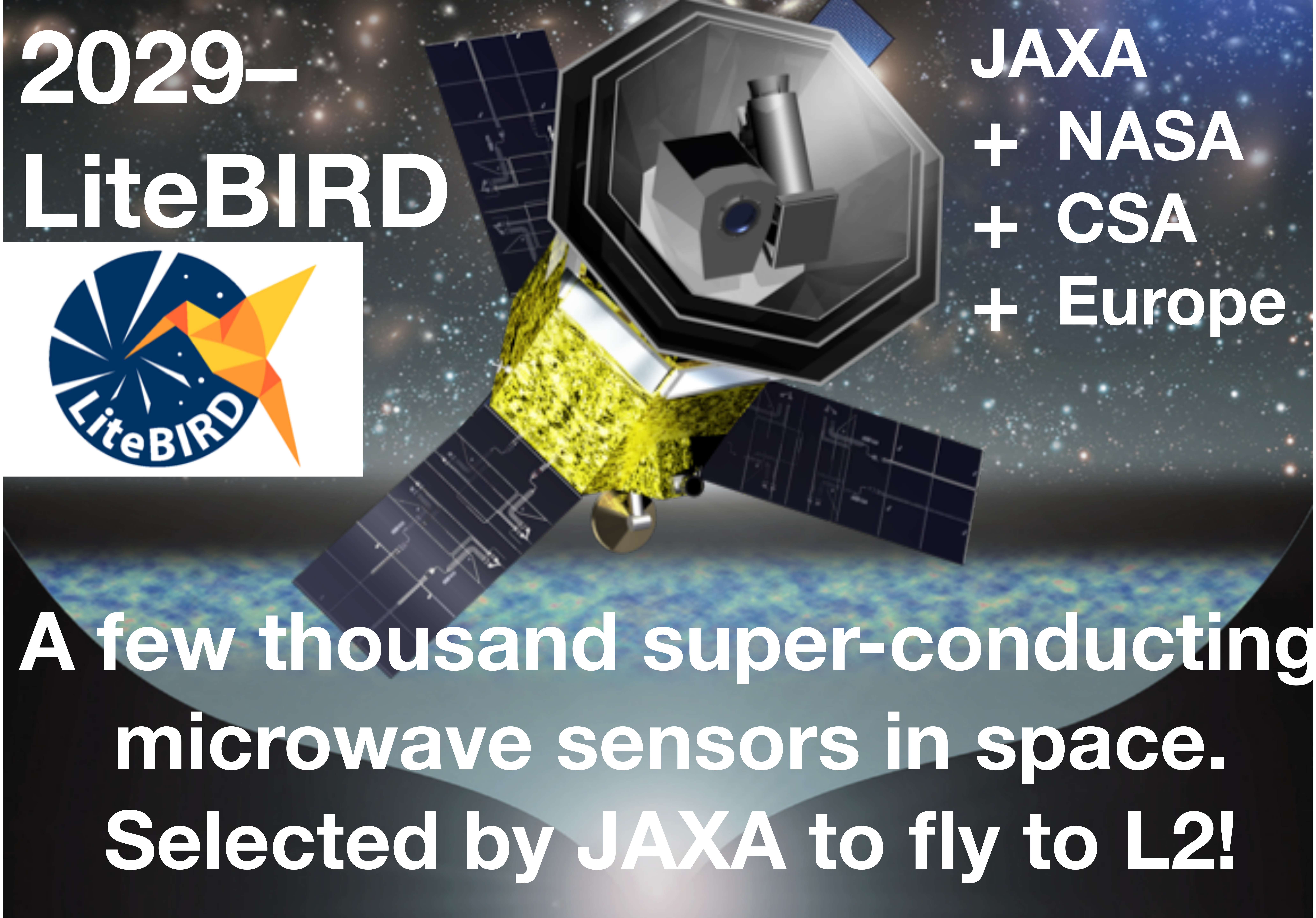


Figure by Clem Pryke for 2013 Snowmass documents


2029–
LiteBIRD
LiteBIRD
JAXA
+ NASA
+ CSA
+ Europe
A few thousand super-conducting
microwave sensors in space.
Selected by JAXA to fly to L2!

Summary

Towards finding primordial gravitational waves

- **The Quest So Far:** *Single-field slow-roll inflation looks very good.*
  - We have a lot of evidence for inflation, including $n_s<1$, Gaussiainity, adiabaticity, and super-horizon fluctuations
- **The New Quest:** *B-mode Polarisation from Primordial Gravitational Waves!*
  - Discovery of the primordial GW gives **definitive evidence for inflation.**
  - Hoping to find the first evidence from ground-based experiments within the next 10 years
  - Then, the definitive measurement will come from LiteBIRD in early 2030s!