Finding Gravitational Waves from the Early Universe

Eiichiro Komatsu (Max Planck Institute for Astrophysics)

DFA Colloquium, Univ. Padova, April 29, 2021

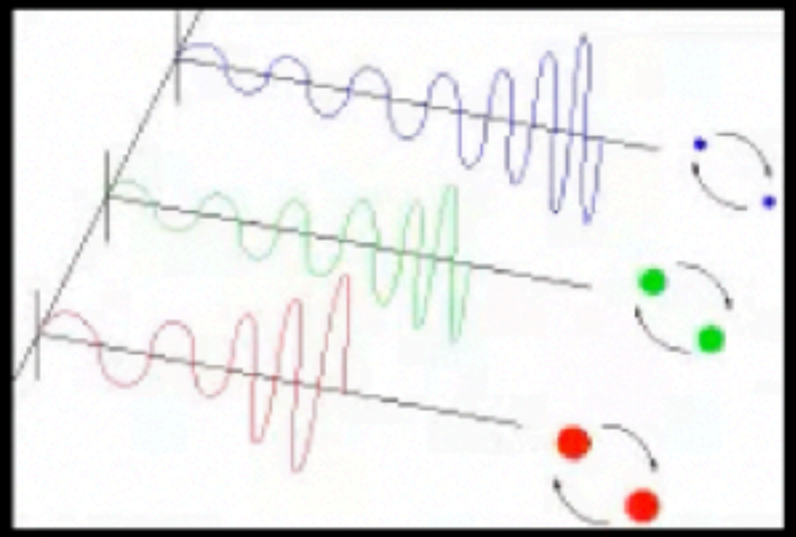
Colloquium by Prof. Barry Barish on March 25
https://www.youtube.com/watch?v=zisNgdgePjs&t=961s

Barry C. Barish - Probing the Universe with Gravitational Waves – Colloquia DFA

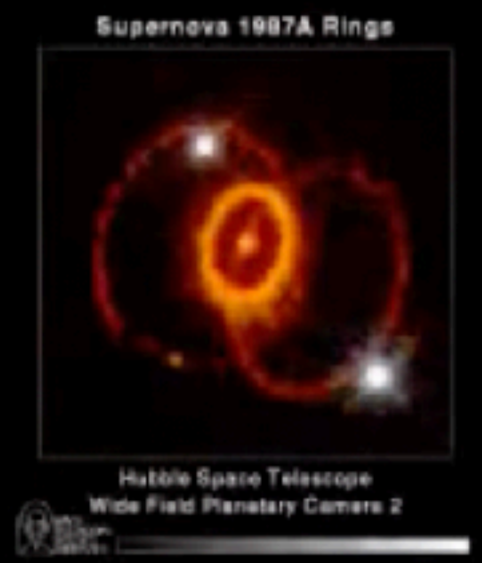
Astrophysical Sources

signatures

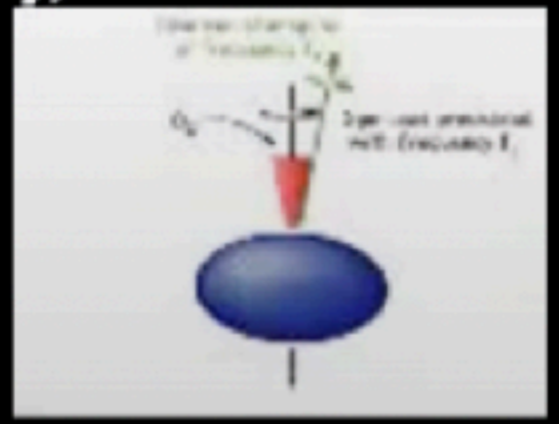
- Compact binary inspiral: *"chirps"*
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



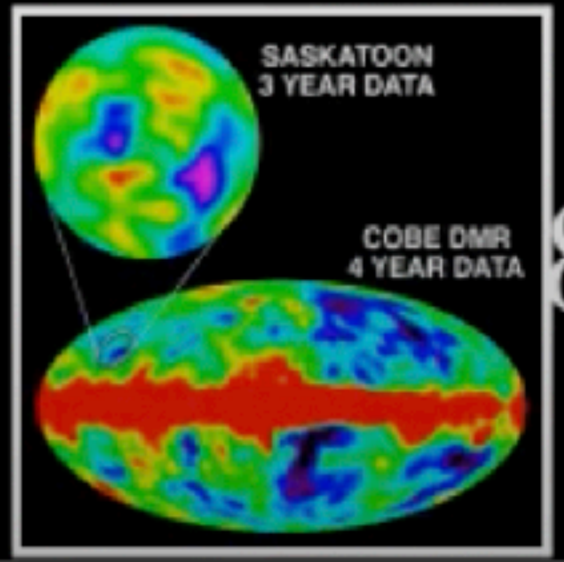
- Supernovae / GRBs: *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors



- Pulsars in our galaxy: *"periodic"*
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes



- Cosmological Signal *"stochastic background"*



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Università degli Studi di Padova

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16:01 / 1:22:22

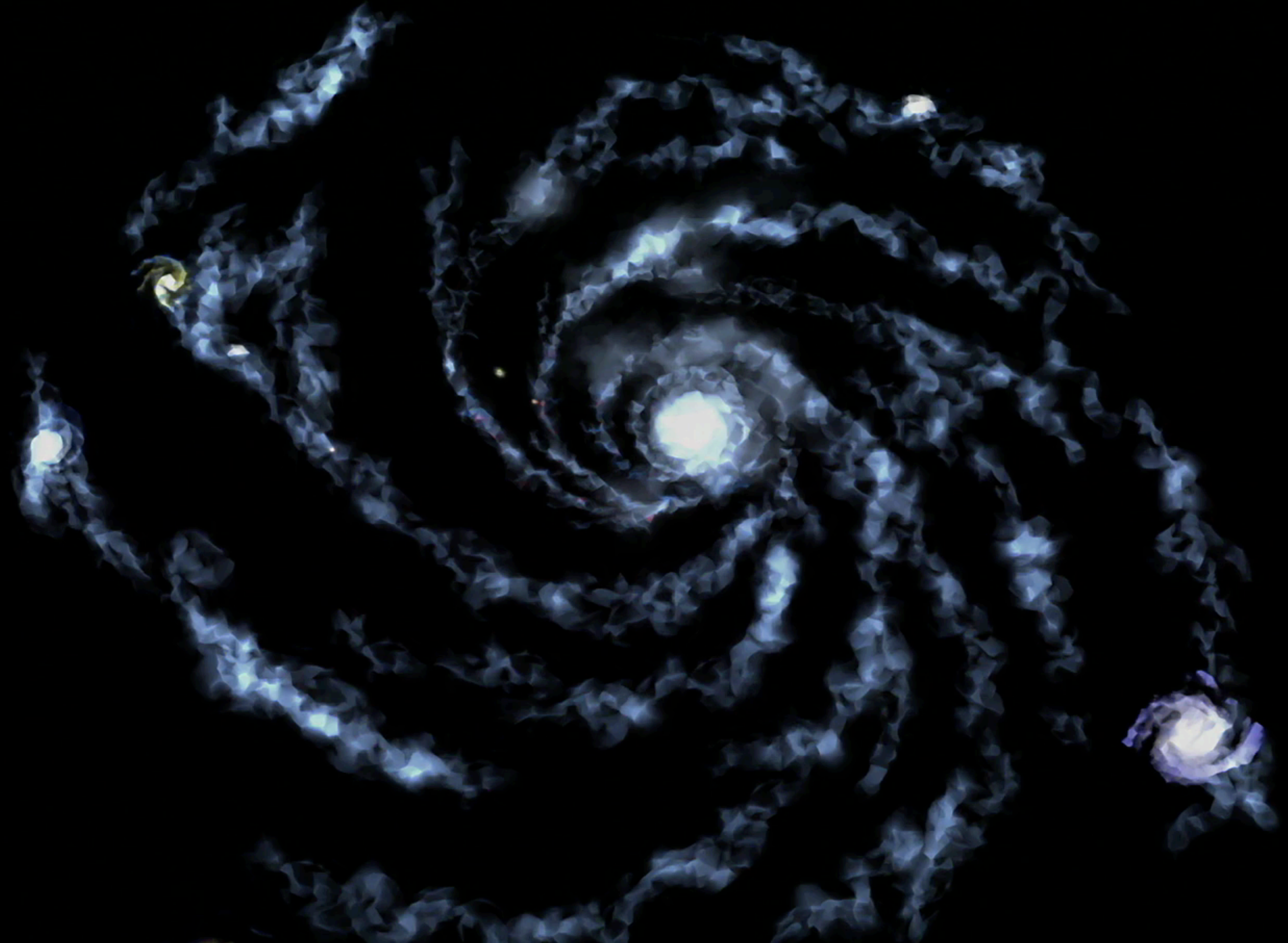
A quote from Prof. Barish

https://www.youtube.com/watch?v=zisNgdqePjs&t=961s

- *“Signals from the early Universe. That may be the most profound of all.”*

- This is the subject of today’s colloquium: ***Primordial* Gravitational Waves** from the Early Universe.
  - The tool: **Polarised light** of the cosmic microwave background (CMB).
  - We look for the signature of gravitational waves in polarisation of the fossil light of the fireball Universe.

Credit: WMAP Science Team



The sky in various wavelengths

Visible -> Near Infrared -> Far Infrared -> Submillimeter -> Microwave

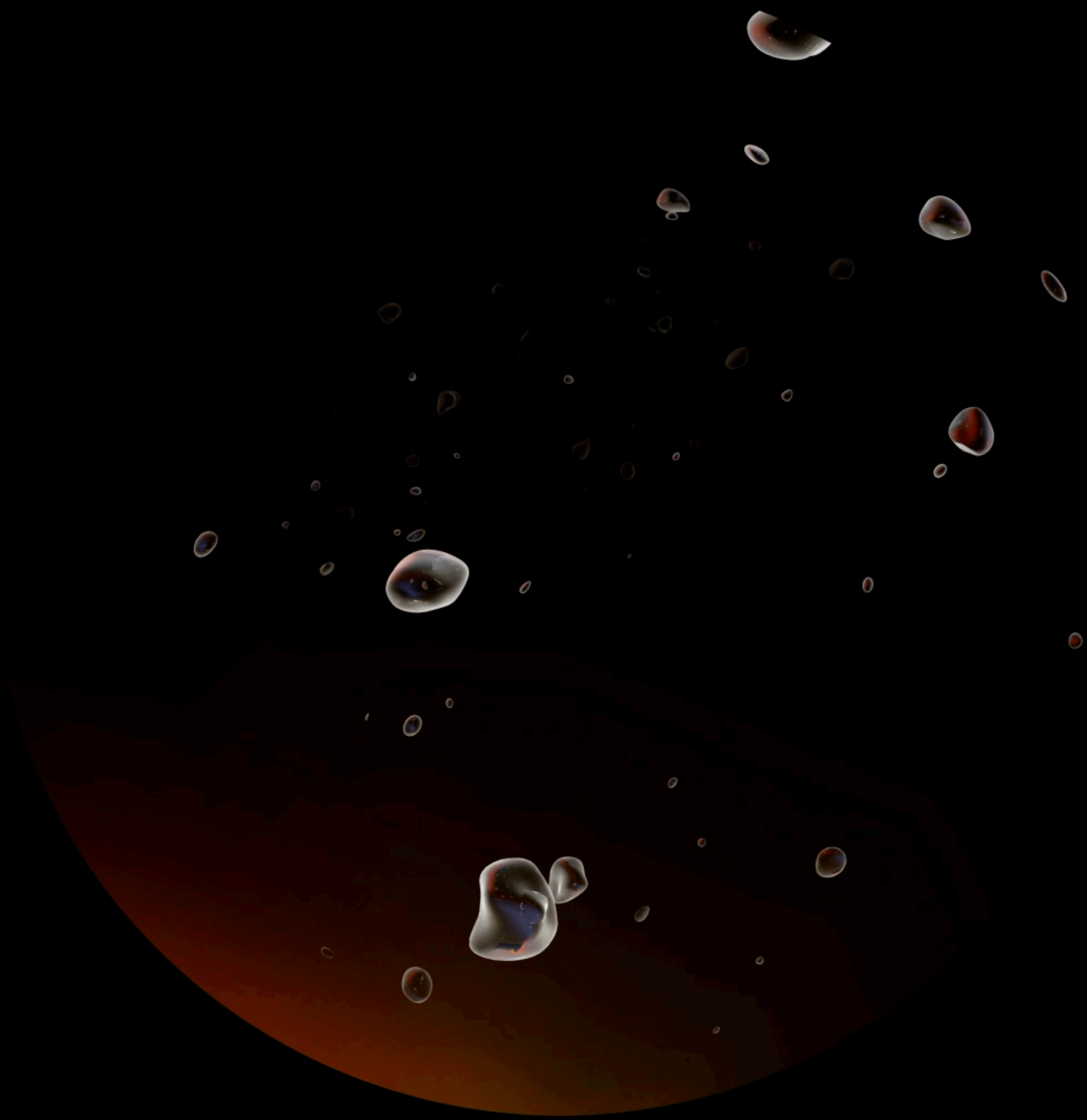
YouTube BE

horizon edge of the visible universe

Full-dome movie for planetarium

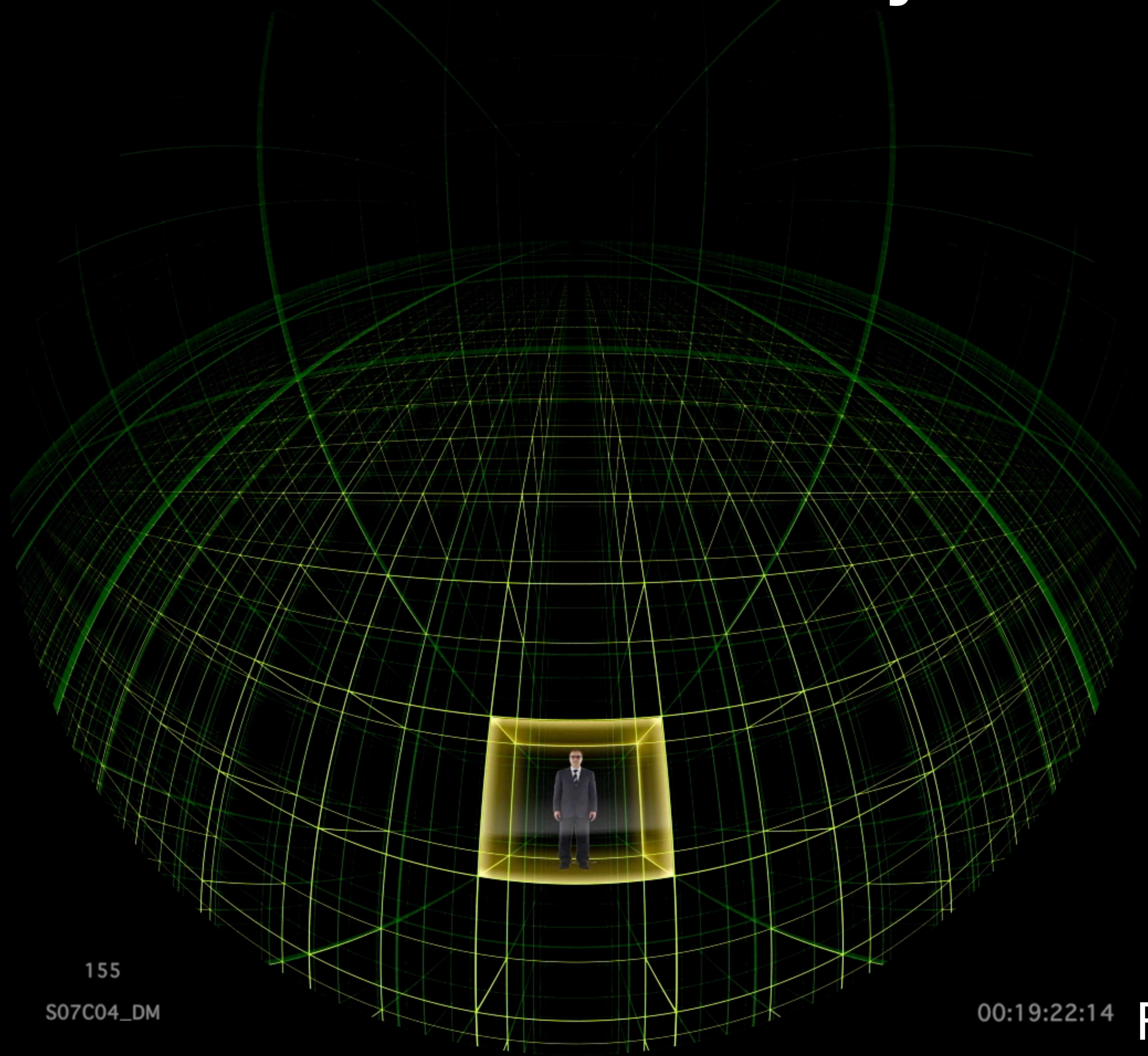
Director: Hiromitsu Kohsaka

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



From “HORIZON”

Where did the CMB we see today come from?

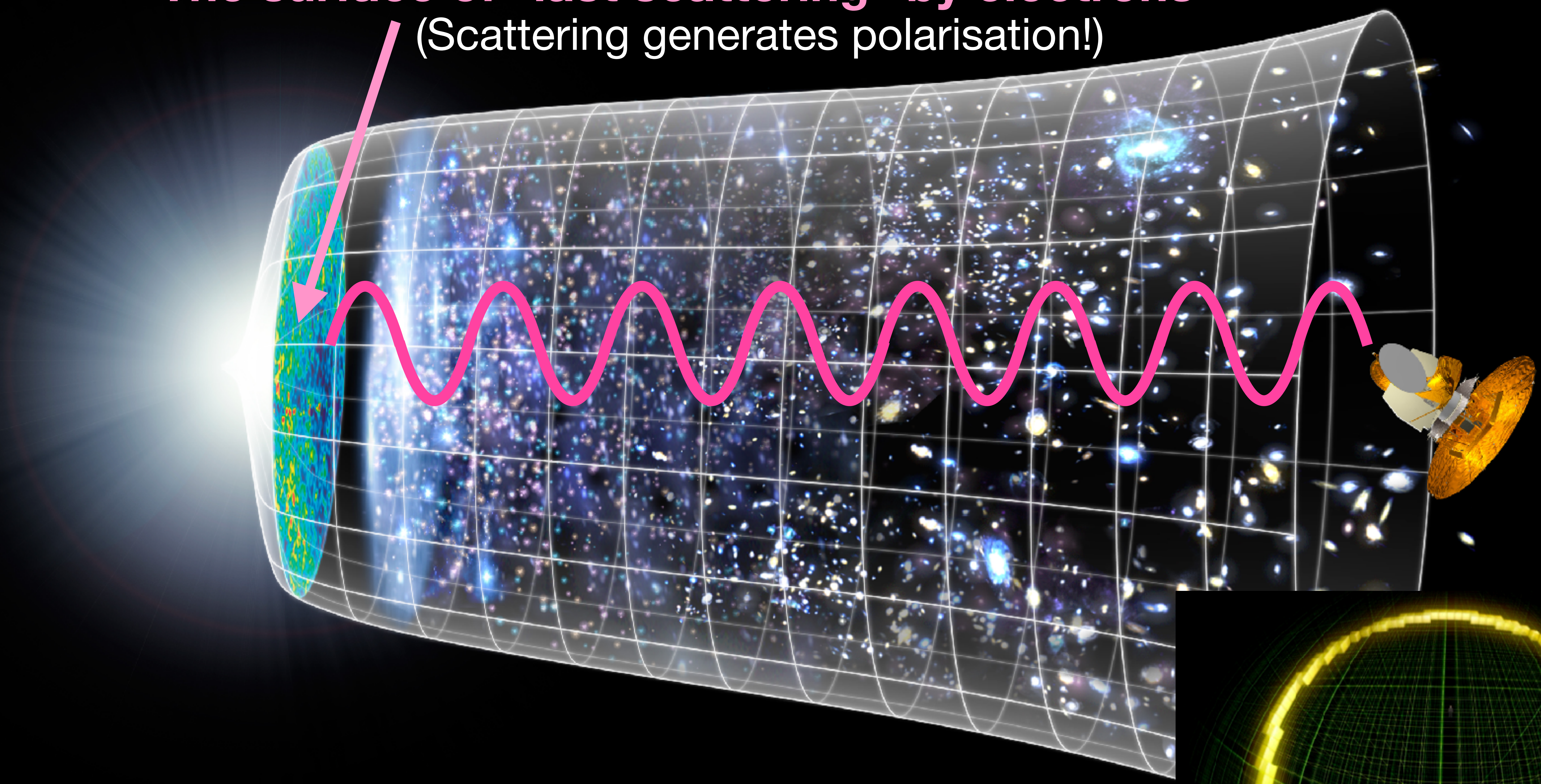


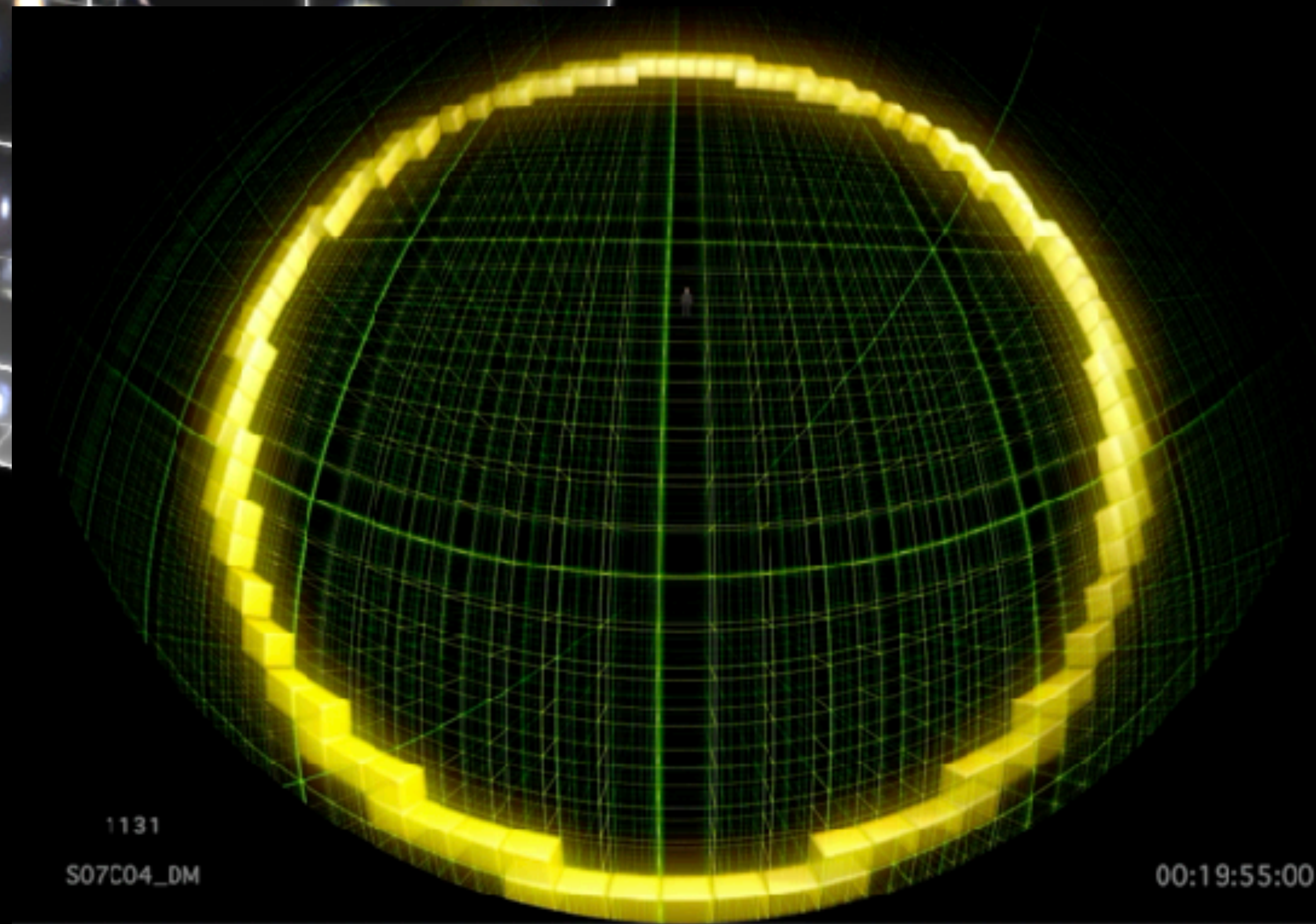
From “HORIZON”

Credit: WMAP Science Team

The surface of “last scattering” by electrons

(Scattering generates polarisation!)





Now shown: The cosmological redshift due to the expansion of the Universe


Credit: WMAP Science Team
The surface of "last scattering" by electrons
(Scattering generates polarisation!)
How do we "see" beyond this "wall"? *Laws of physics!*

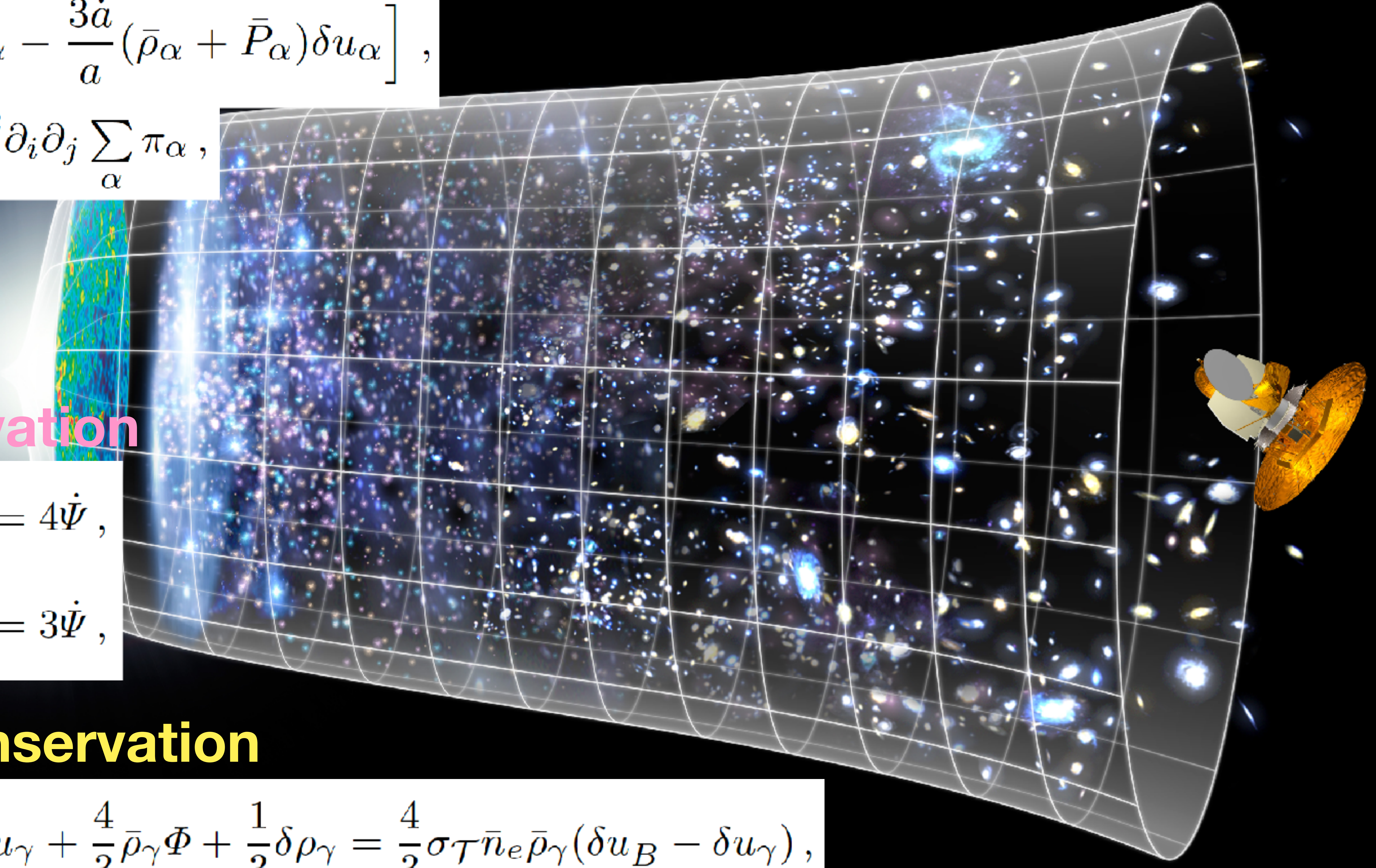
Before we talk about the gravitational waves, let's talk about the sound waves (scalar modes)

Credit: WMAP Science Team

Gravitational Field Equations (Einstein's Eq.)

$$\nabla^2\Psi = 4\pi G a^2 \sum_\alpha \left[\delta\rho_\alpha - \frac{3\dot{a}}{a}(\bar{\rho}_\alpha + \bar{P}_\alpha)\delta u_\alpha\right] ,$$

$$\partial_i\partial_j(\Phi - \Psi) = -8\pi G a^2 \partial_i\partial_j \sum_\alpha \pi_\alpha ,$$



Energy Conservation

$$\frac{\partial}{\partial t}(\delta\rho_\gamma/\bar{\rho}_\gamma) - \frac{4q^2}{3a^2}\delta u_\gamma = 4\dot{\Psi} ,$$

$$\frac{\partial}{\partial t}(\delta\rho_B/\bar{\rho}_B) - \frac{q^2}{a^2}\delta u_B = 3\dot{\Psi} ,$$

Momentum Conservation

$$\frac{4}{3}\frac{\partial}{\partial t}(\bar{\rho}_\gamma \delta u_\alpha) + \frac{4\dot{a}}{a}\bar{\rho}_\gamma\delta u_\gamma + \frac{4}{3}\bar{\rho}_\gamma\Phi + \frac{1}{3}\delta\rho_\gamma = \frac{4}{3}\sigma_{\mathcal{T}}\bar{n}_e\bar{\rho}_\gamma(\delta u_B - \delta u_\gamma) ,$$

$$\frac{\partial}{\partial t}(\bar{\rho}_B\delta u_B) + \frac{3\dot{a}}{a}\bar{\rho}_B\delta u_B + \bar{\rho}_B\Phi = -\frac{4}{3}\sigma_{\mathcal{T}}\bar{n}_e\bar{\rho}_\gamma(\delta u_B - \delta u_\gamma) ,$$

Laws of physics!

From “HORIZON”

Gravitational Field Equations

+

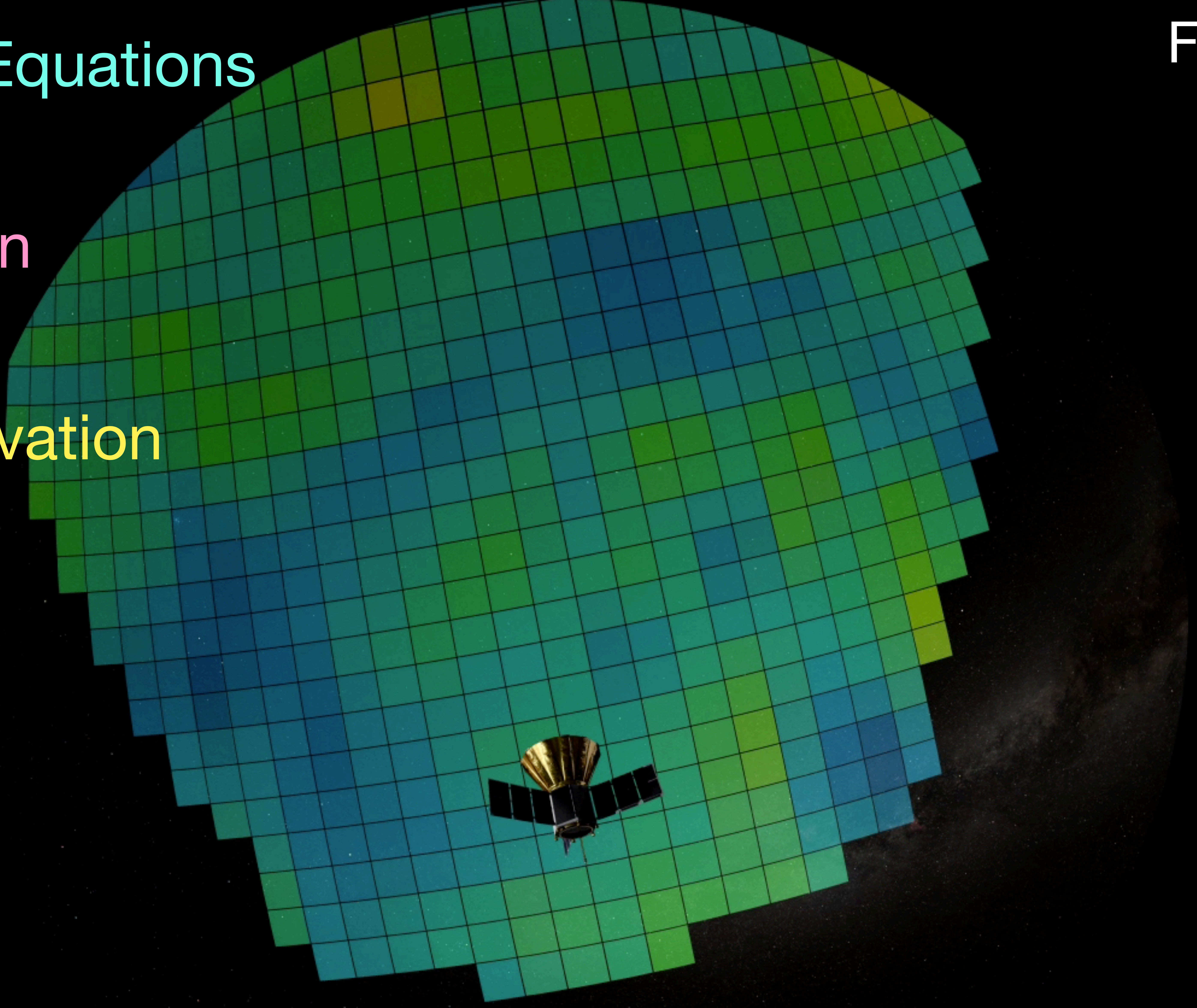
Energy Conservation

+

Momentum Conservation

=

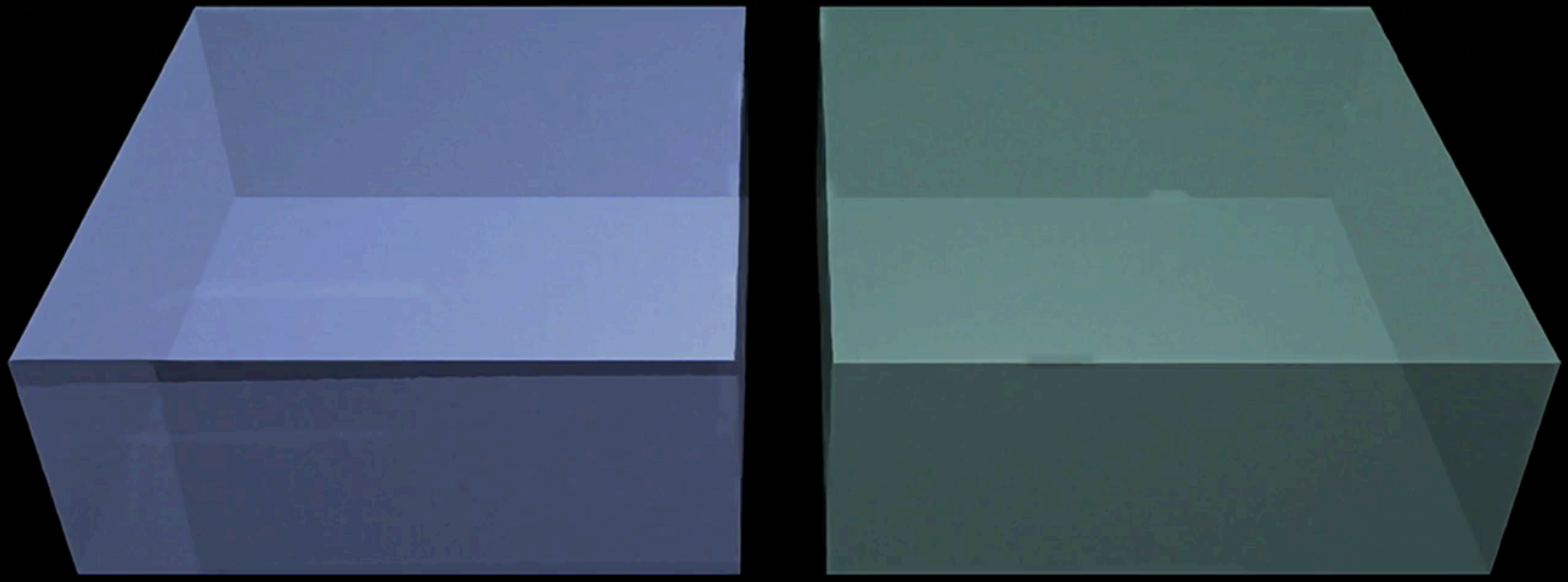
Sound Waves!



Zuppa di Miso Cosmica

- 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

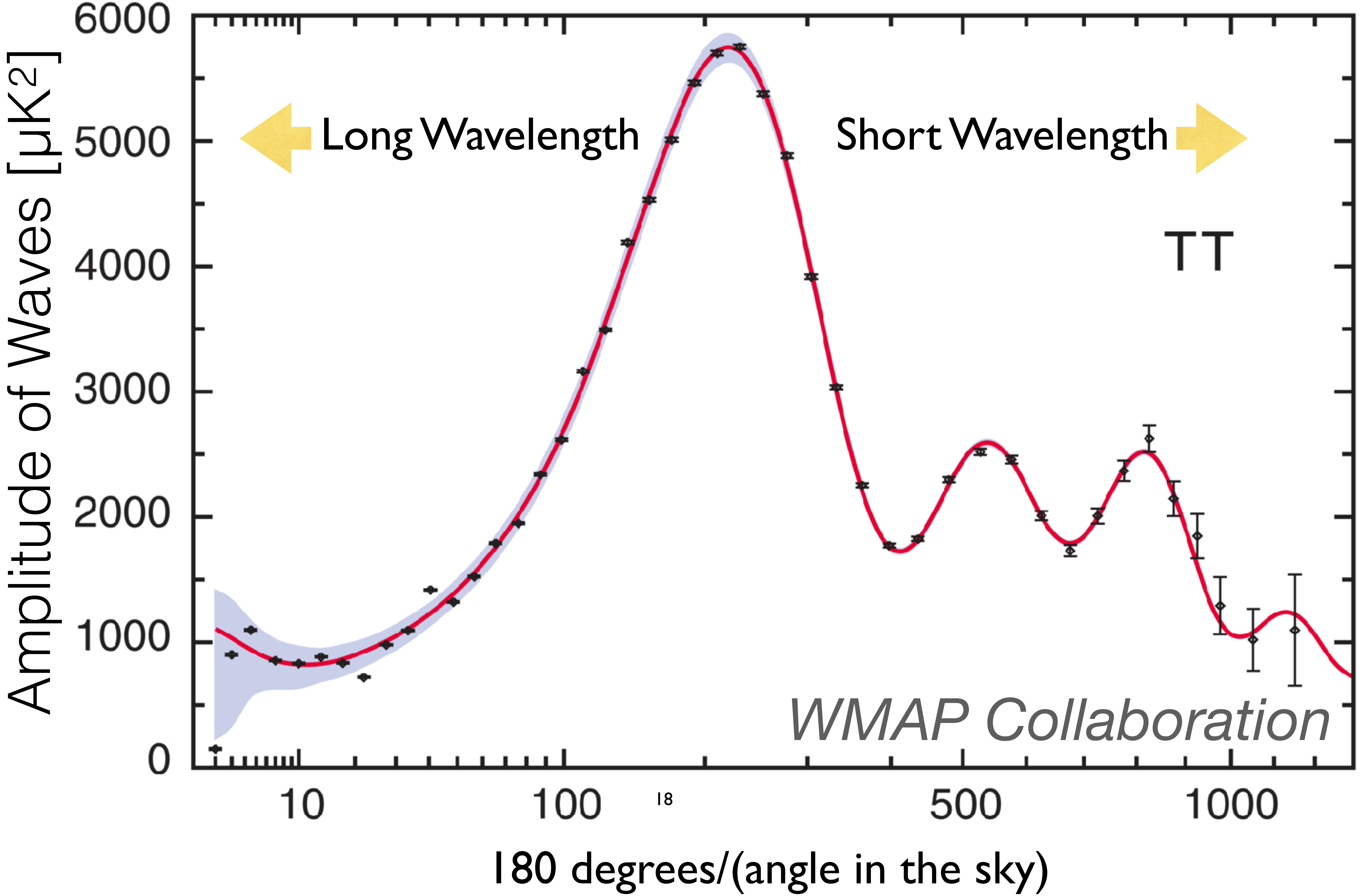
Credit: WMAP Science Team




How do we analyse the data like this?

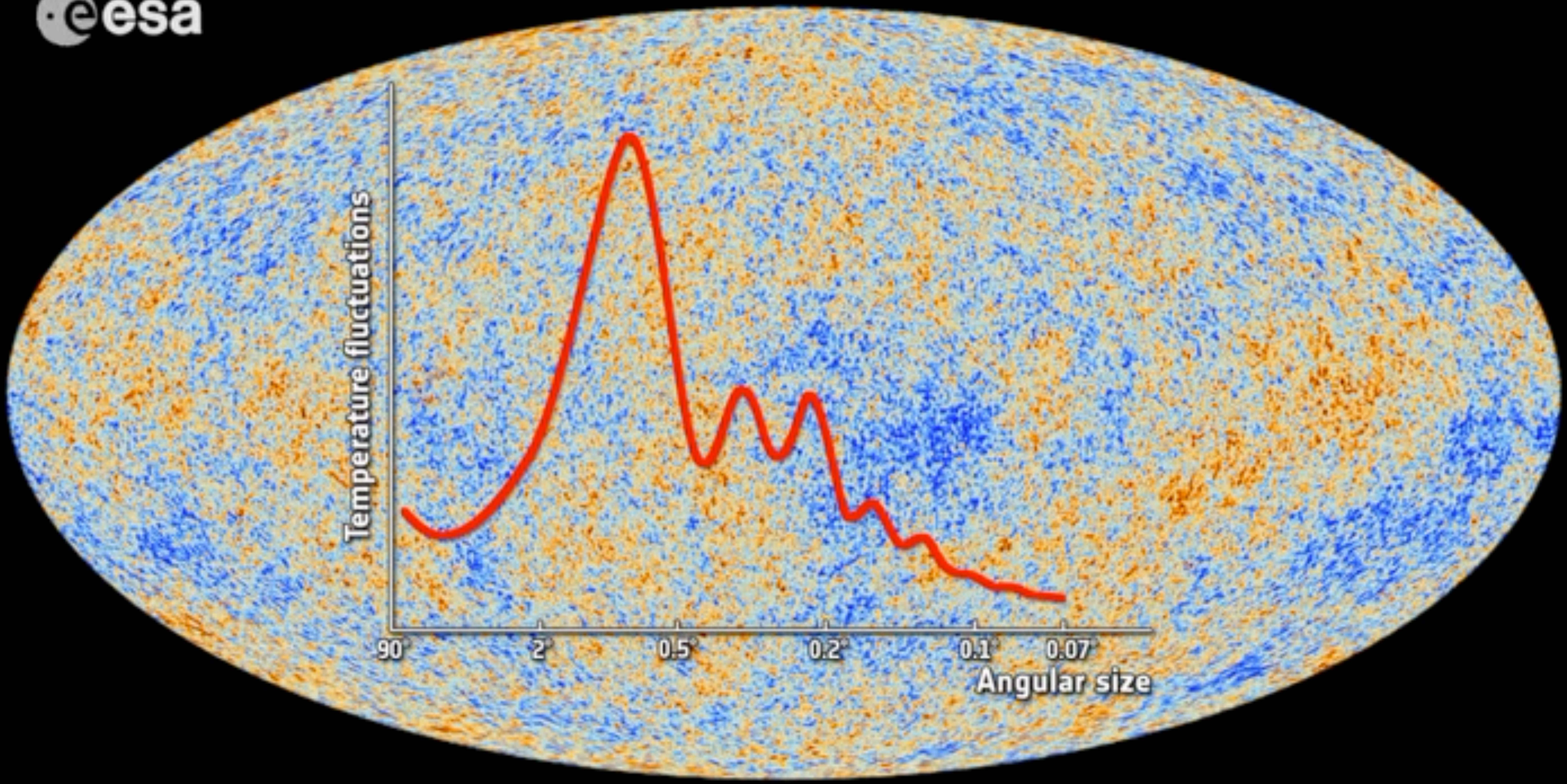
Data Analysis

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



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

Power Spectrum, Explained



The Royal Swedish Academy of Sciences has decided to award the 2019 Nobel Prize in Physics to

JAMES PEEBLES

"for theoretical discoveries in physical cosmology"

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*

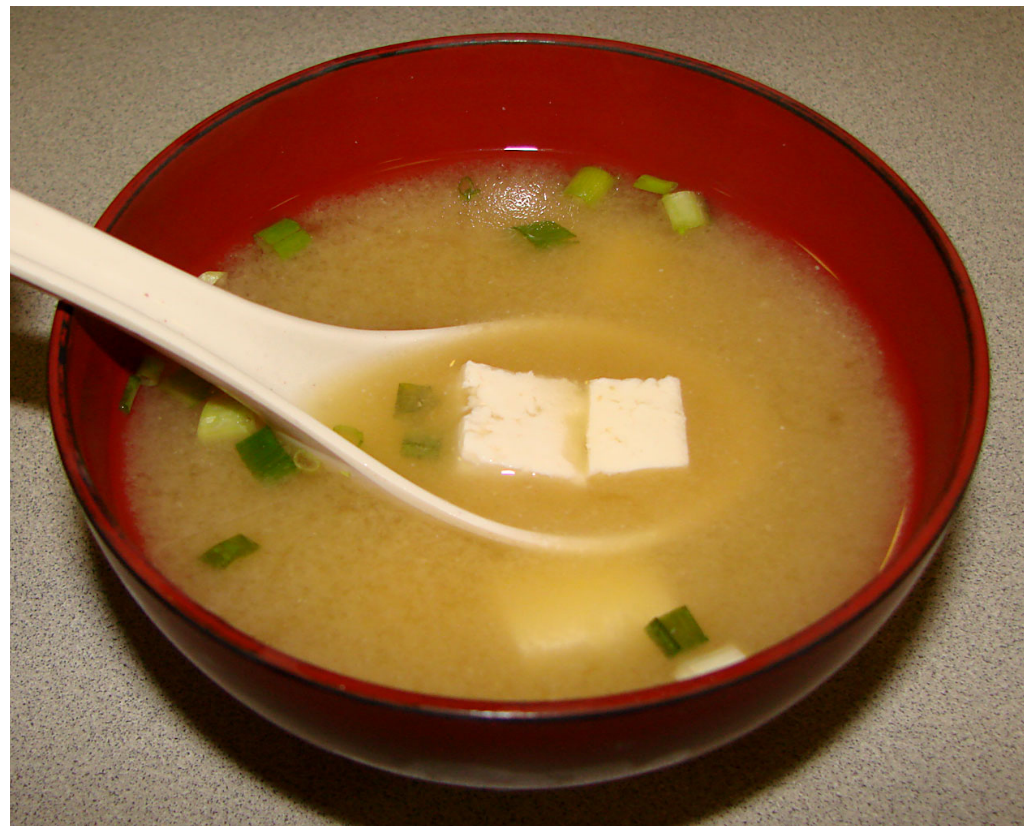
R. A. SUNYAEV and YA. B. ZELDOVICH
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)

Determine the composition of the Universe

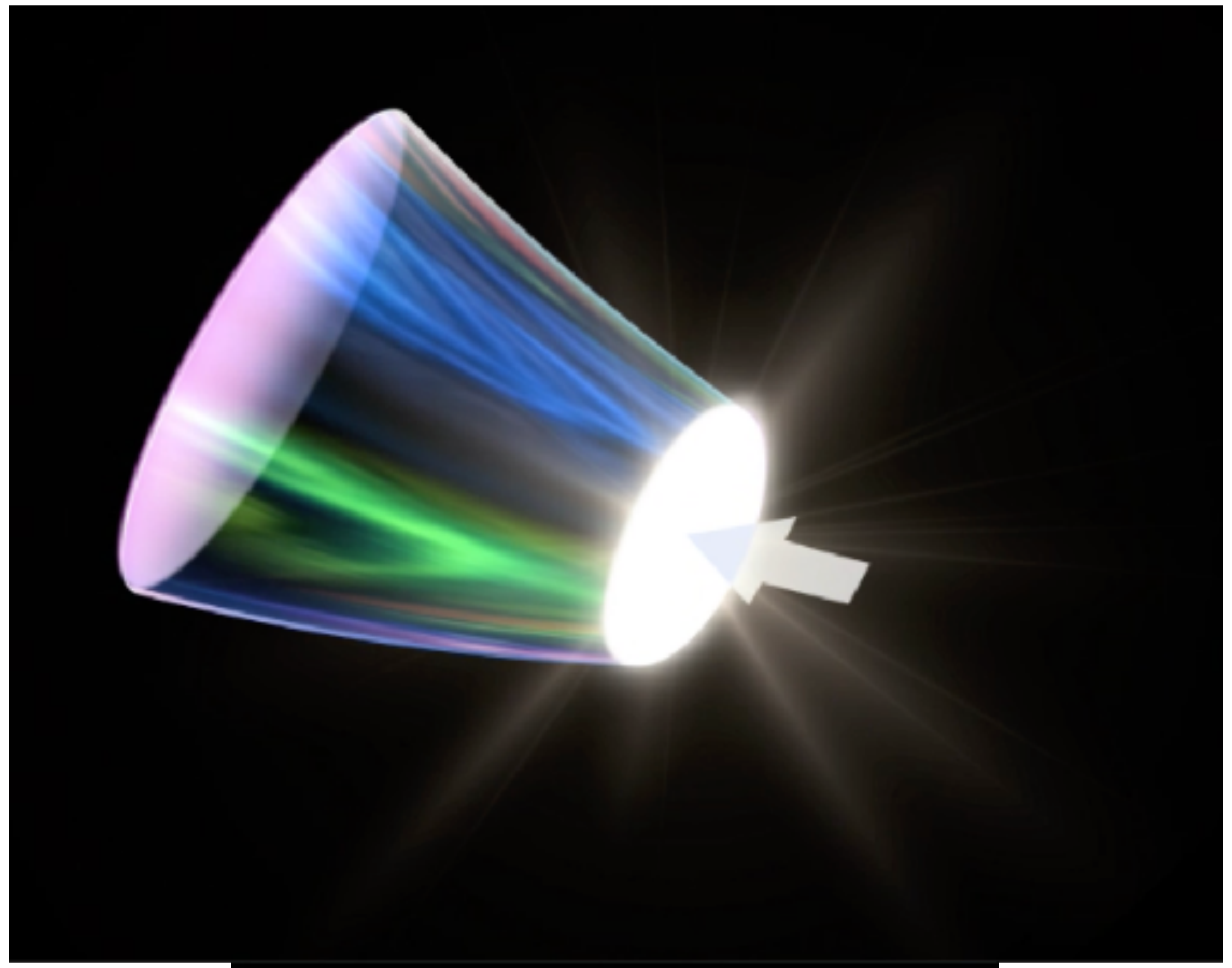
The Universe as a “hot soup”

- 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!**

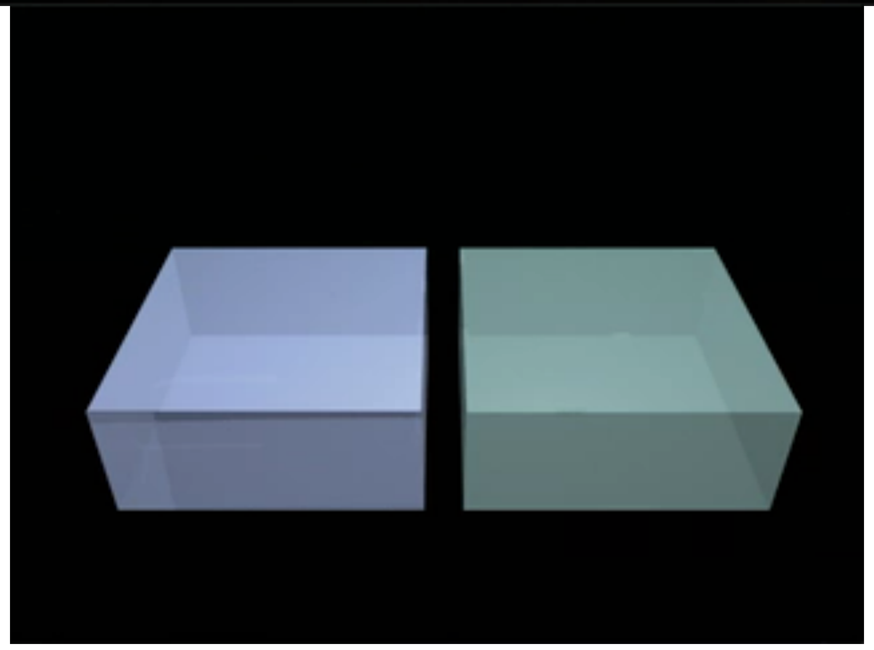
"Let's give some impact to the beginning of this model"



- 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:



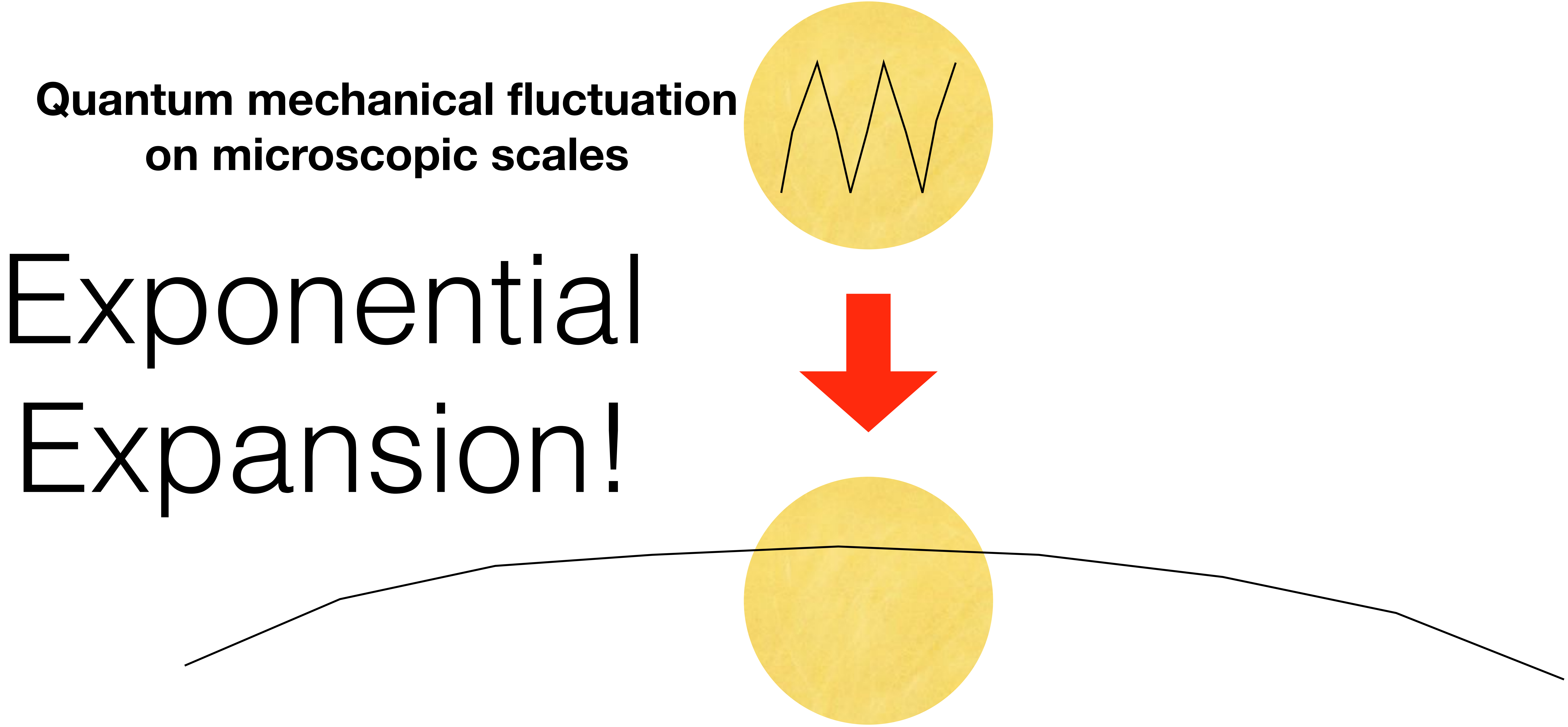
- Quantum mechanics at work in the early Universe
  - "*We all came from quantum fluctuations*"
- But, how did the quantum fluctuation on the *microscopic* scale become *macroscopic* over large distances?
- **What is the missing link between the small and large scales?**

Gravity + Quantum

= The origin of all the structures we see in the Universe

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 **$H(t) = d\ln(a)/dt$**. This has the units of [1/time].
    - The scale factor is then given by $a(t) = \exp[\int H(t)dt]$.
    - 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**.

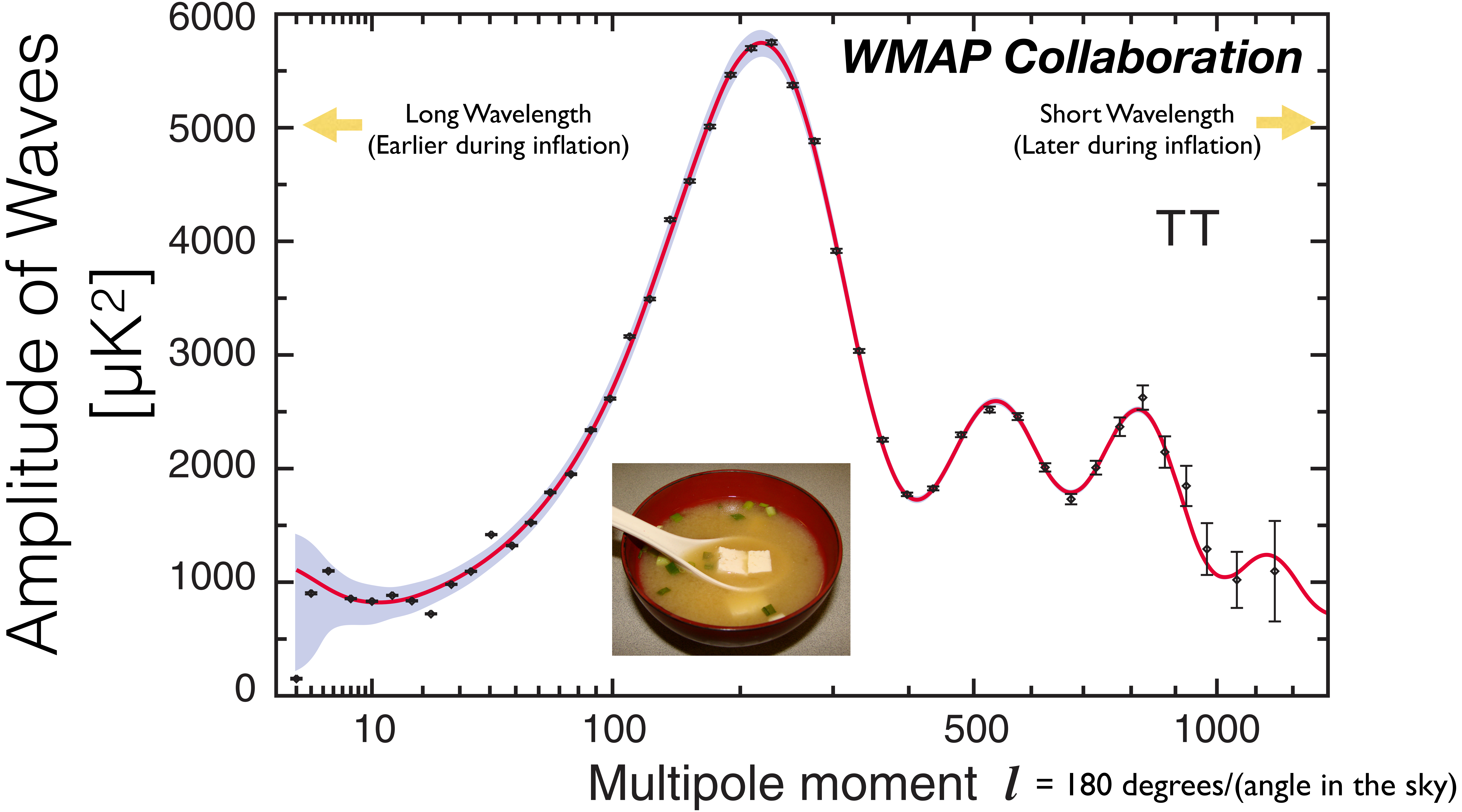
How can we test this?

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

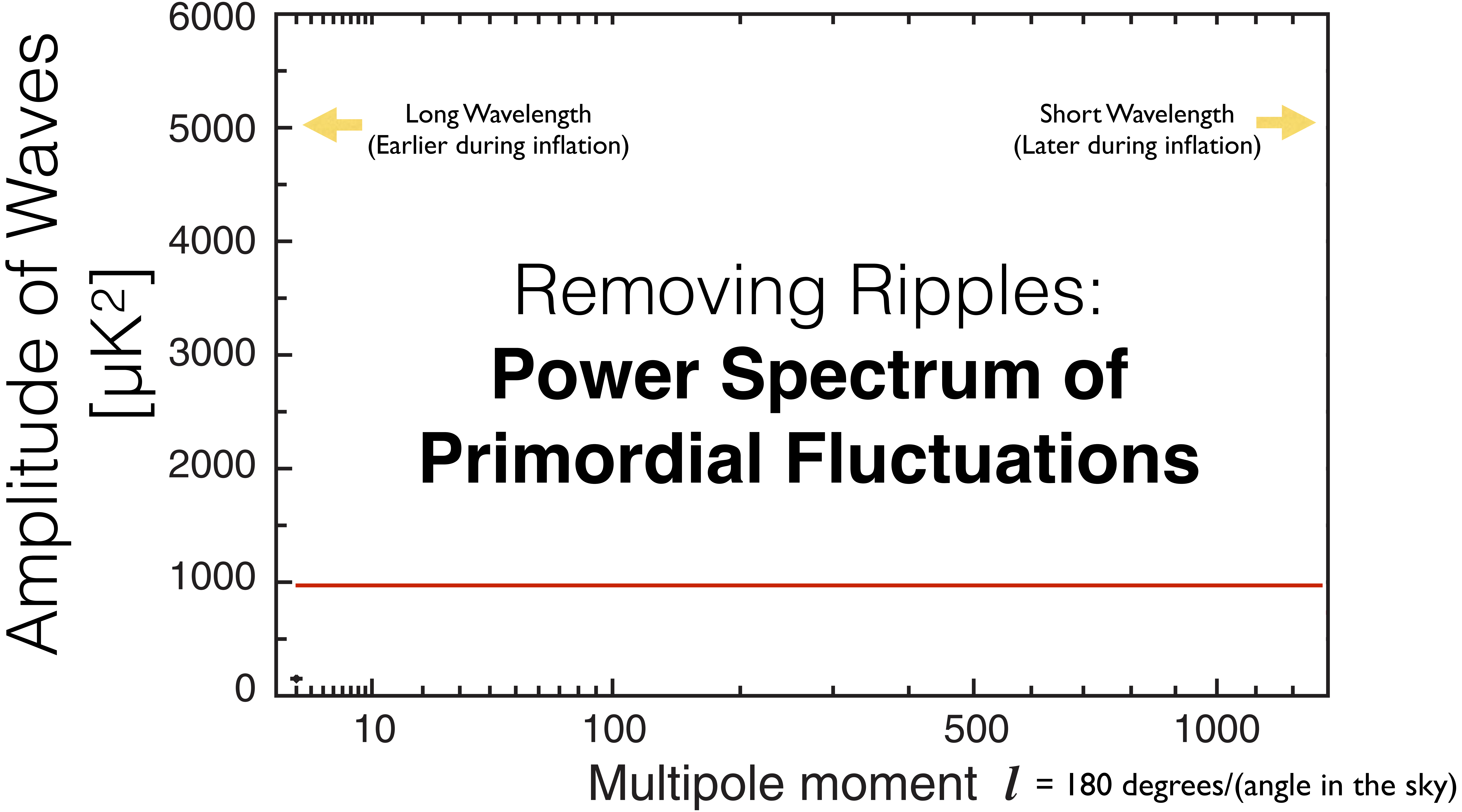
Finding Cosmic Inflation

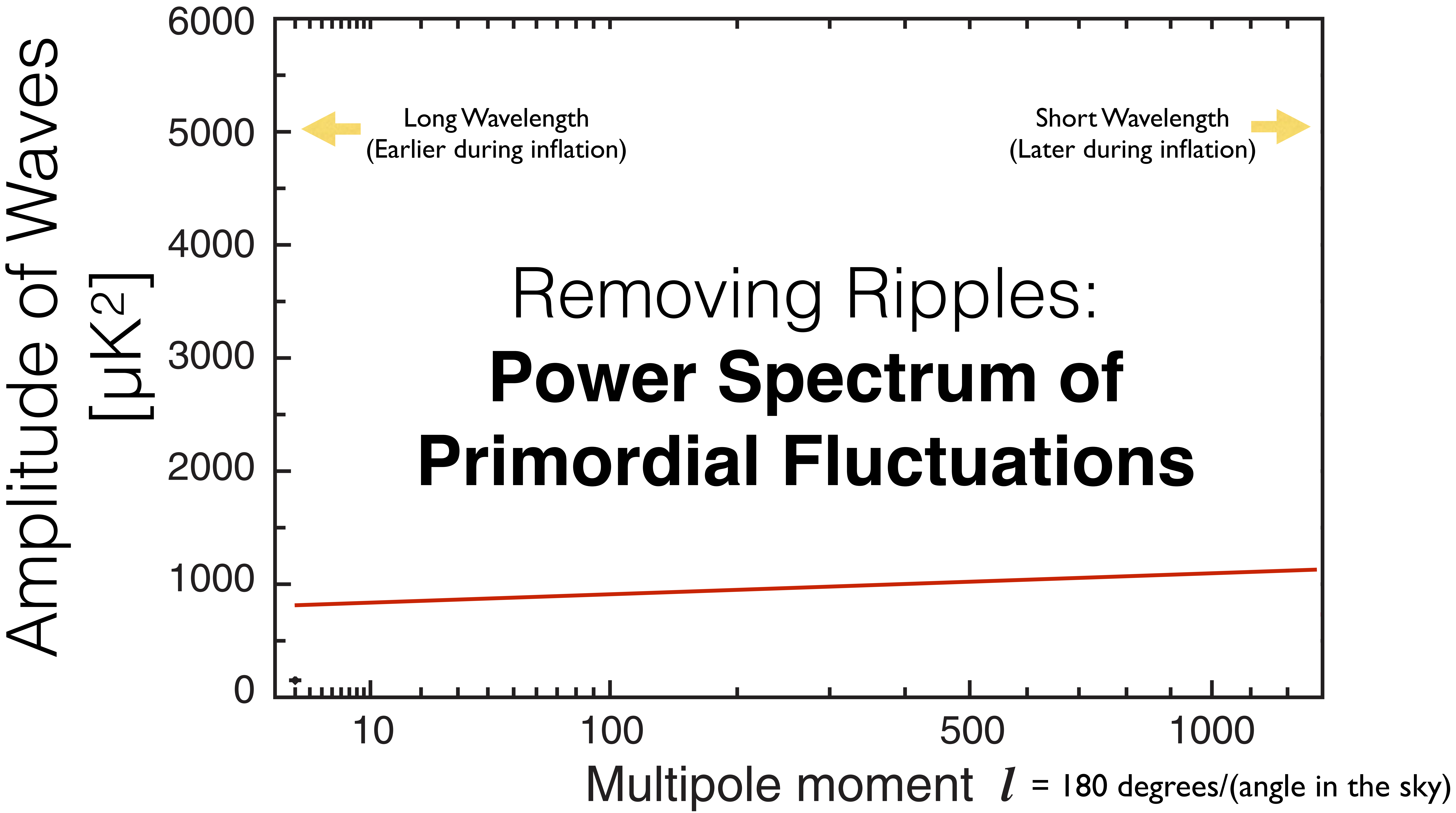
What does inflation predict for the scalar (density) fluctuation?

- 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)


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



Amplitude of Waves [μK²]
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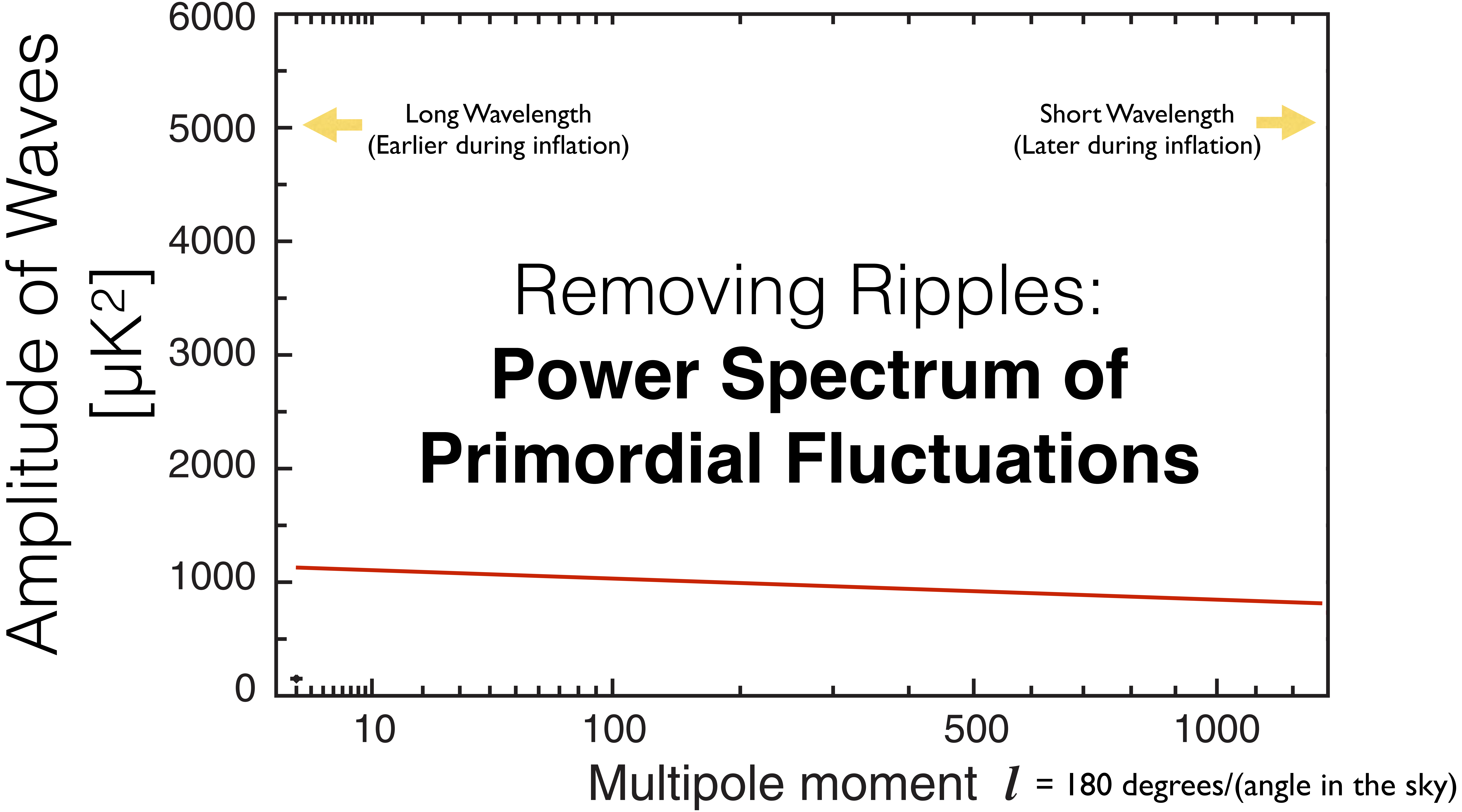
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0
Long Wavelength
(Earlier during inflation)
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Removing Ripples:
Power Spectrum of
Primordial Fluctuations
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100
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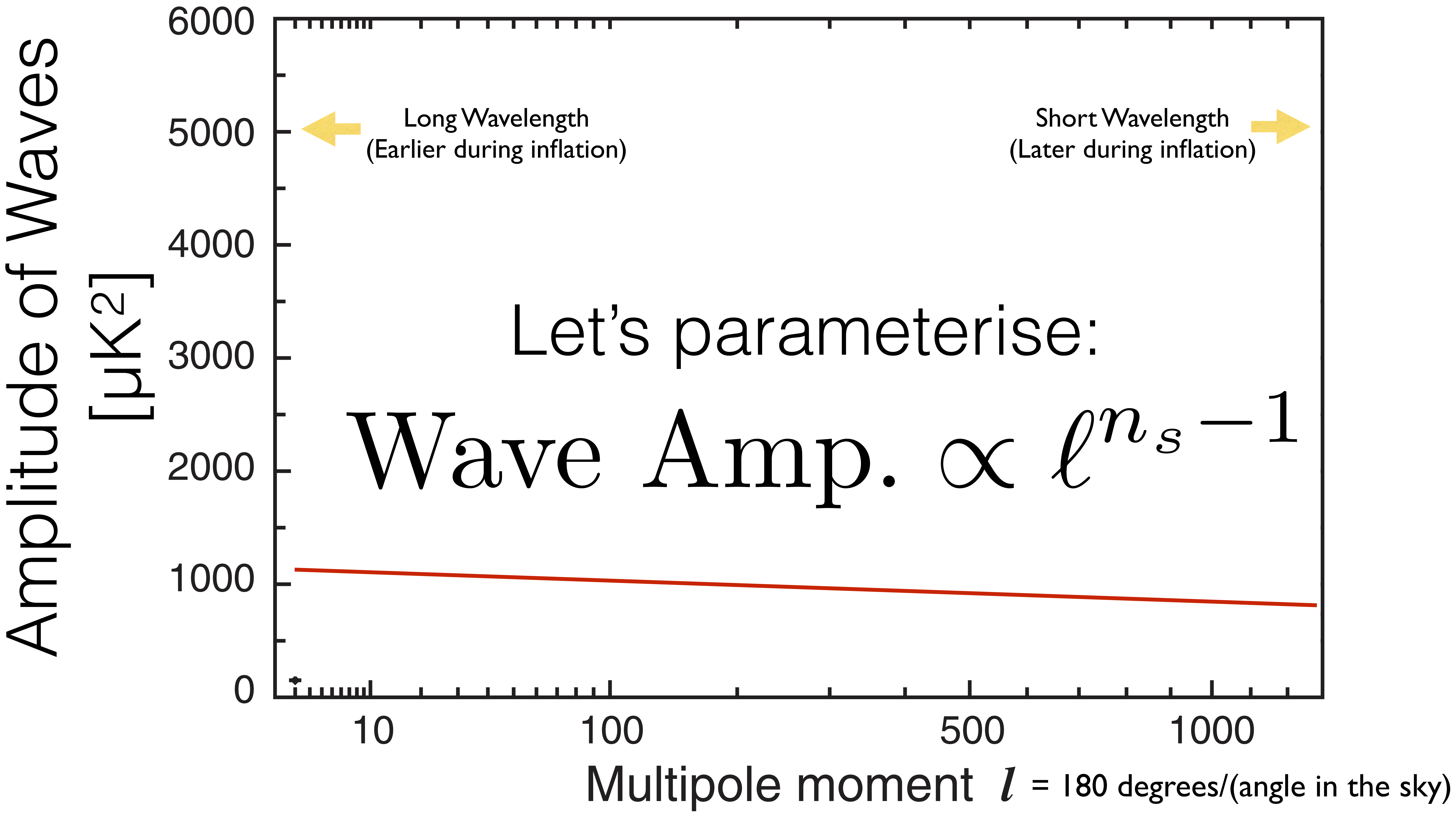
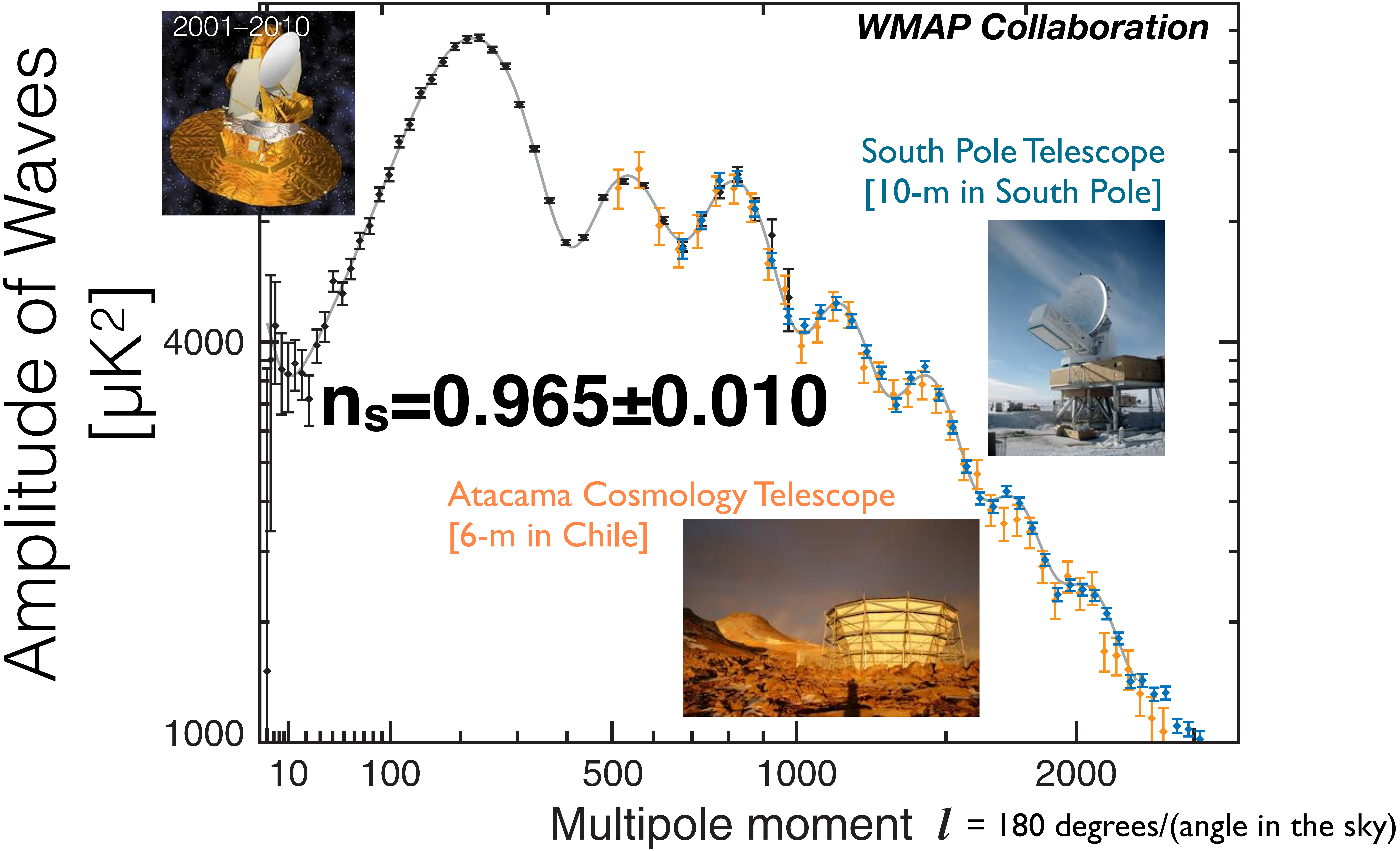
Multipole moment l = 180 degrees/(angle in the sky)



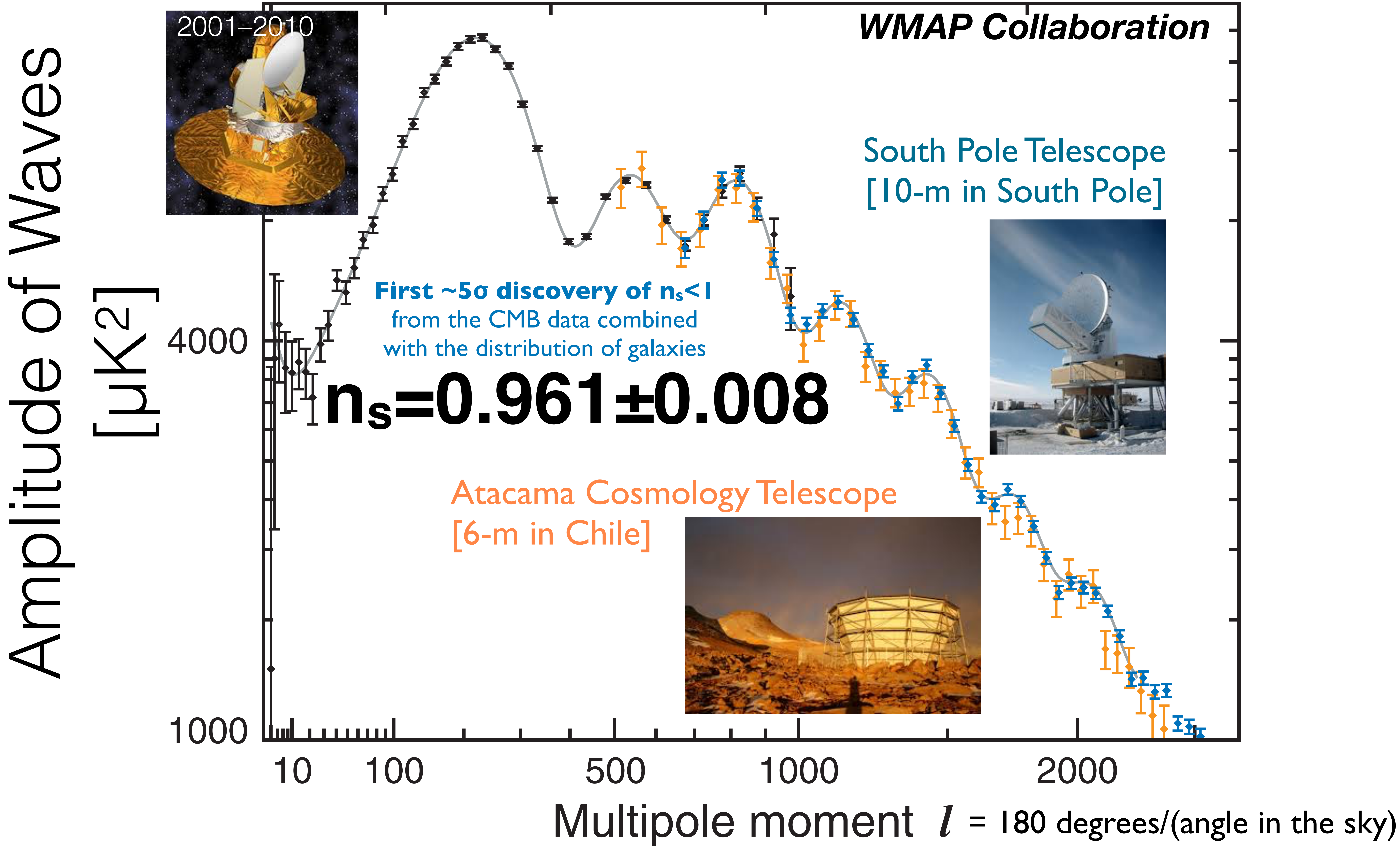
Amplitude of Waves
[μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
Let's parameterise:
Wave Amp. ∝ $\ell^{n_s - 1}$
10
100
500
1000
Multipole moment l = 180 degrees/(angle in the sky)

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

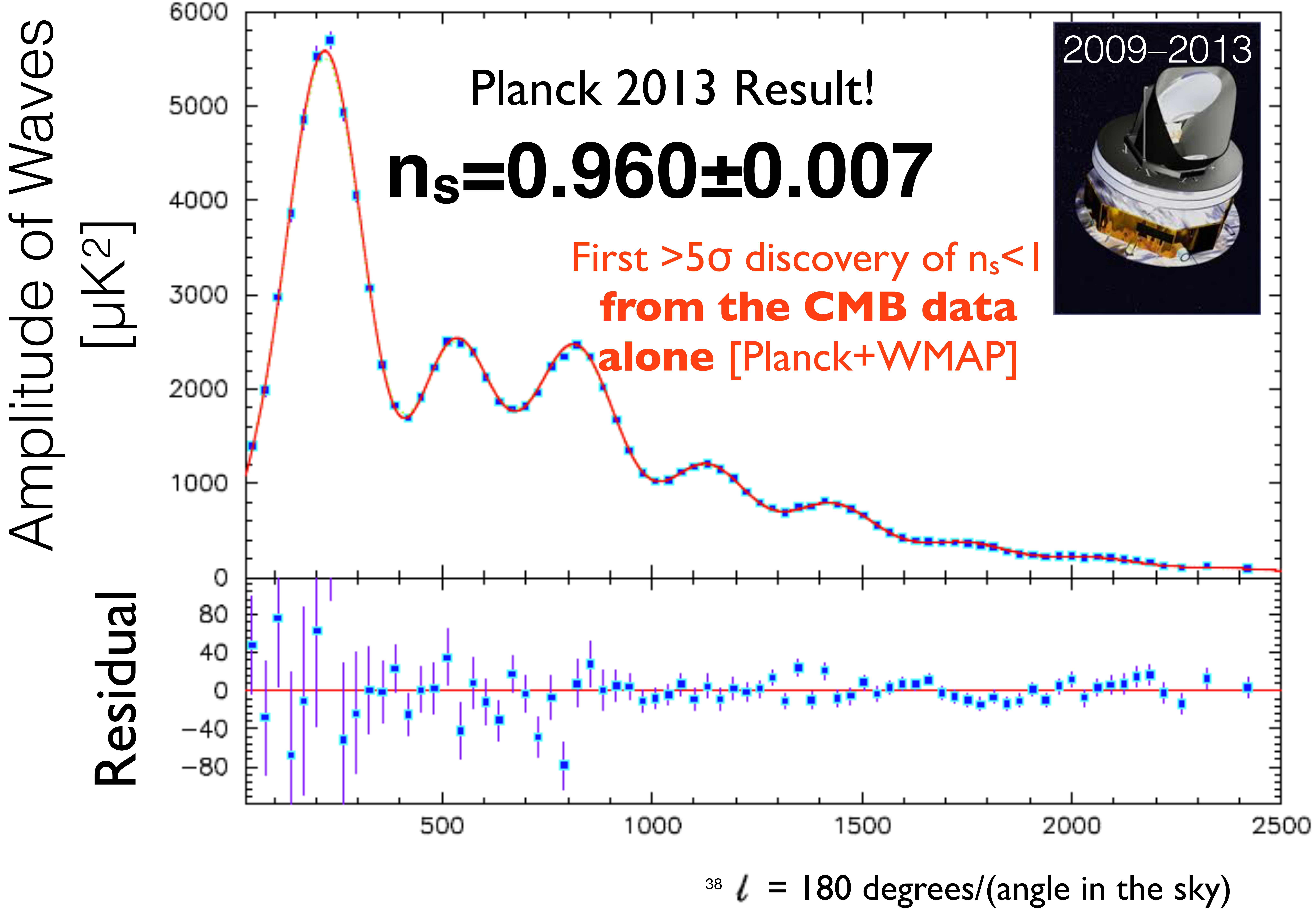

WMAP Collaboration
2001–2010
In 2012:
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
Long Wavelength
(Earlier during inflation)
Short Wavelength
(Later during inflation)
Wave Amp. $\propto \ell^{n_s-1}$
Amplitude of Waves [μK^2]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l = 180 degrees/(angle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



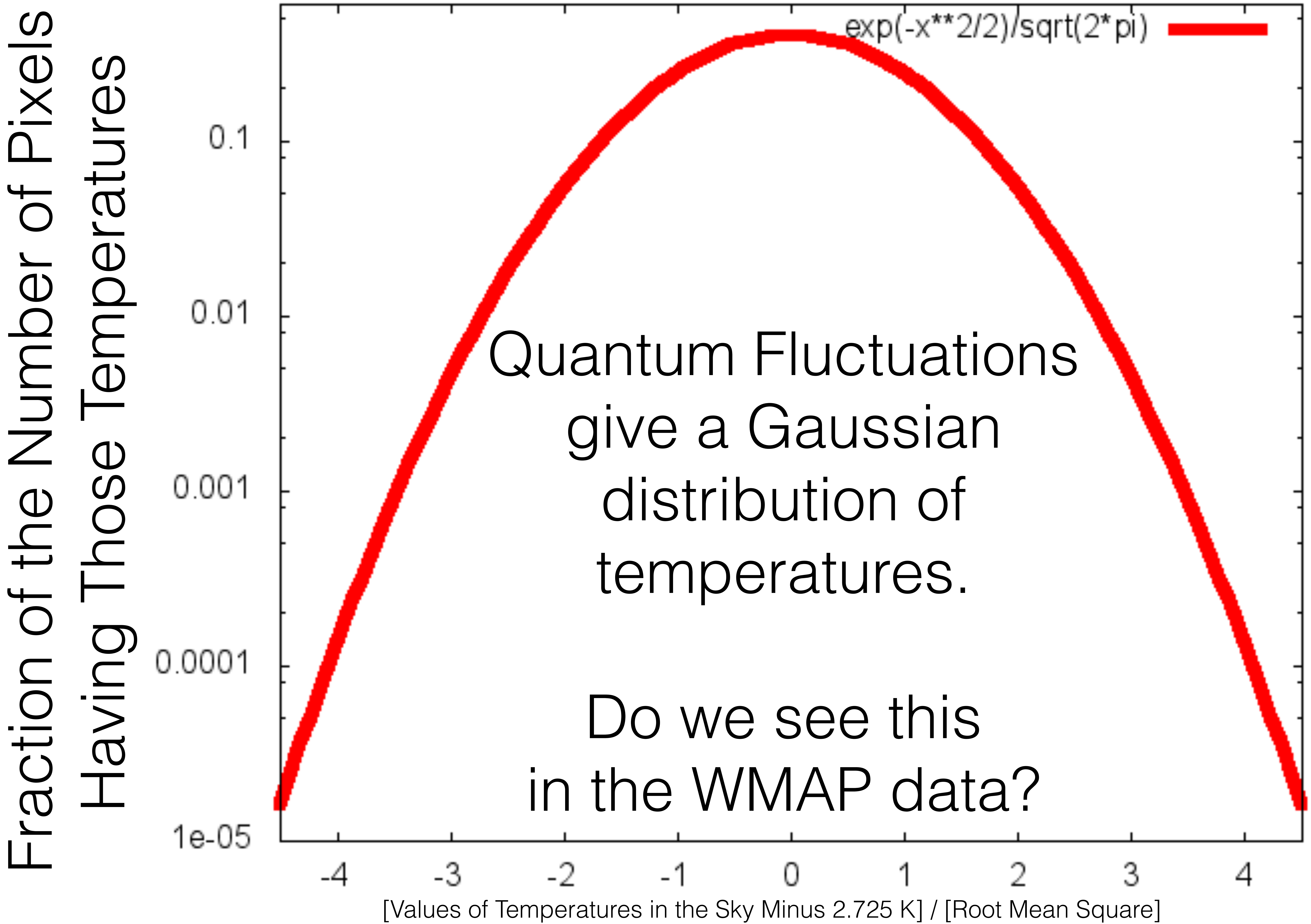
Amplitude of Waves [μK2]
2001–2010
WMAP Collaboration
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
ns=0.965±0.010
4000
1000
10
100
500
1000
2000
Multipole moment l = 180 degrees/(angle in the sky)

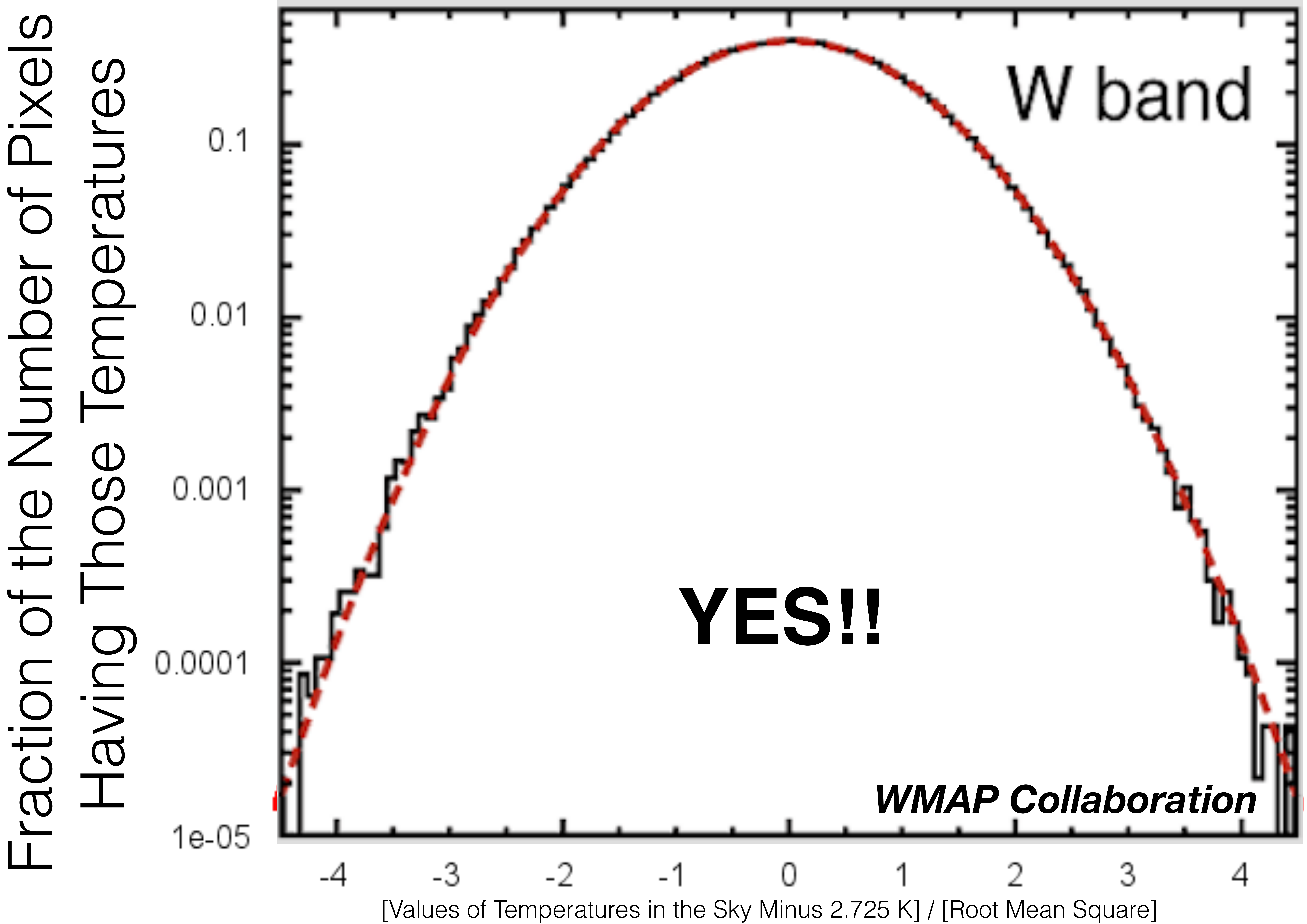


2001–2010
WMAP Collaboration
Amplitude of Waves [μK2]
4000
1000
First ~5σ discovery of ns<1
from the CMB data combined
with the distribution of galaxies
ns=0.961±0.008
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
10
100
500
1000
2000
Multipole moment l = 180 degrees/(angle 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 [μK²]
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
Quantum Fluctuations
give a Gaussian
distribution of
temperatures.
Do we see this
in the WMAP data?
[Values of Temperatures in the Sky Minus 2.725 K] / [Root Mean Square]


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

So, have we found inflation?

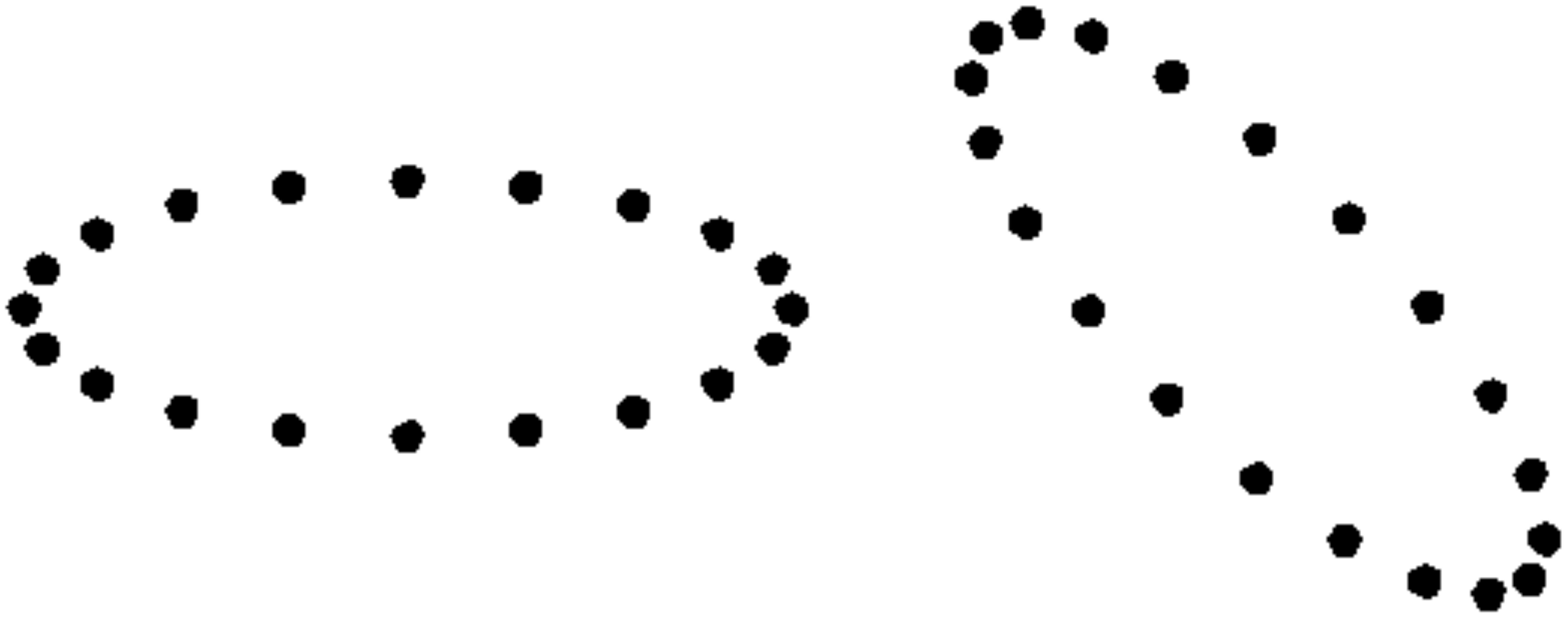
A lot of evidence in support of inflation exist already.

- 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)

Let’s talk about the gravitational waves (tensor modes)

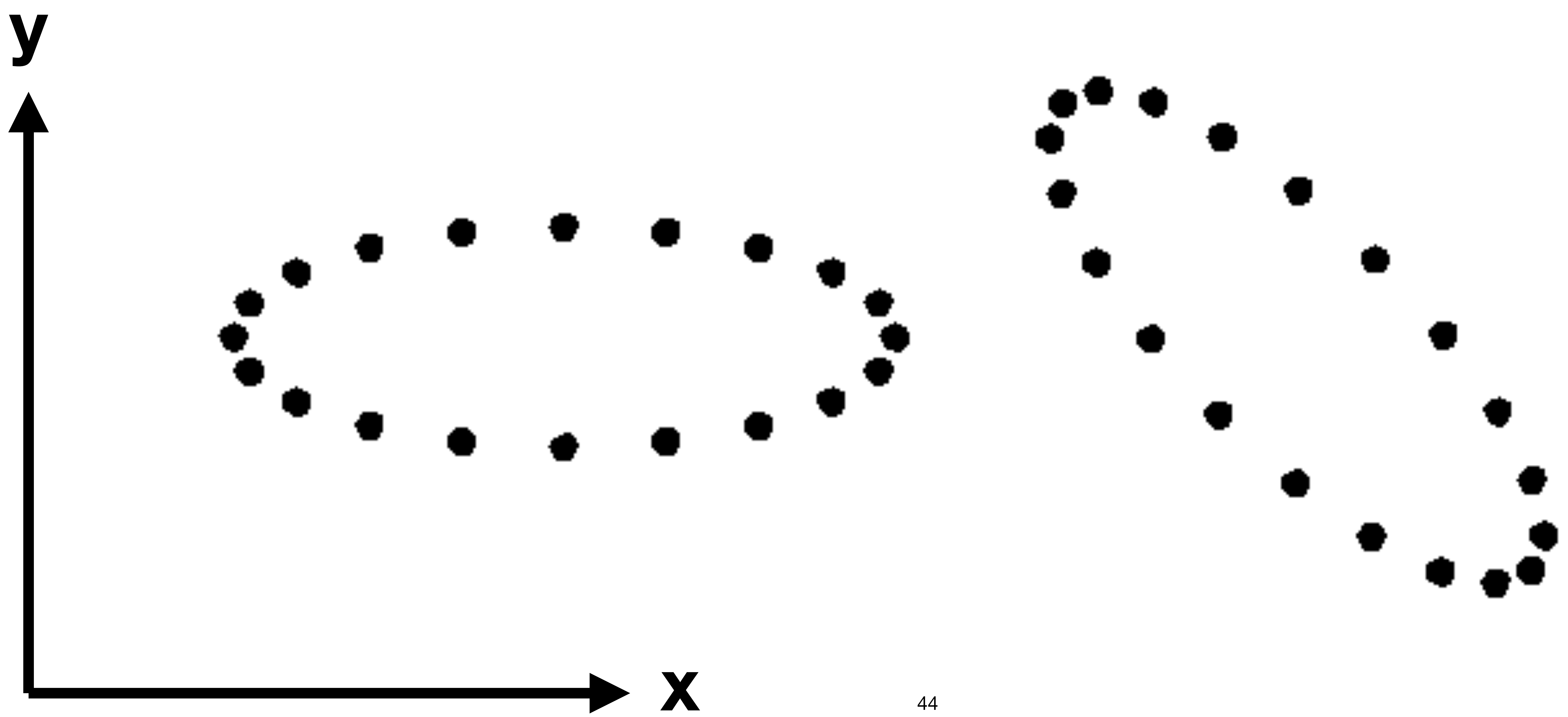
Gravitational waves are coming towards you!

To visualise the waves, watch motion of test particles.



Gravitational waves are coming towards you!

To visualise the waves, watch motion of test particles.



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

x^2

- Compact notation using Kronecker's delta symbol:

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

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

δ_{ij} = 1 for i=j;
δ_{ij} = 0 otherwise

- To include distortion in space,

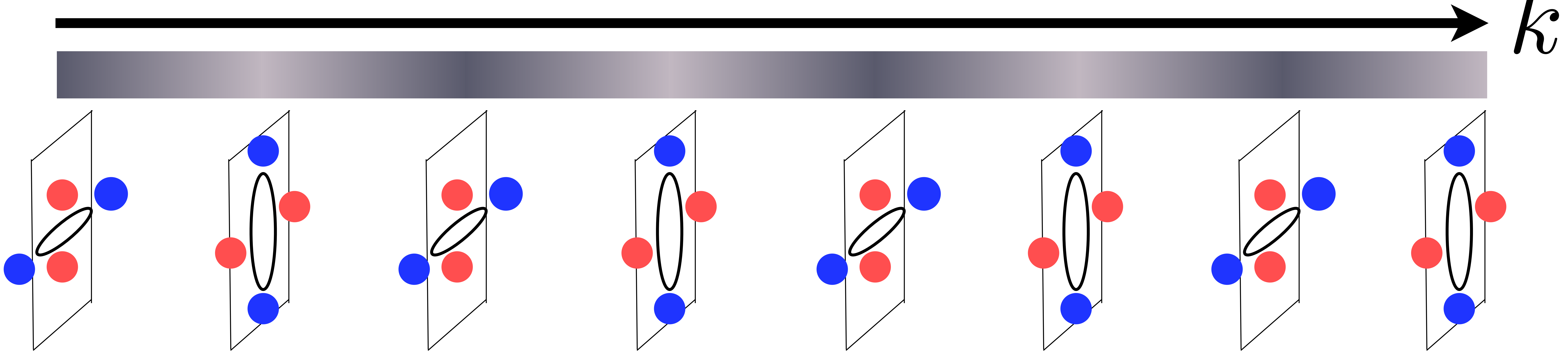
$$ds^2 = a^2 \sum_{i=1}^{3} \sum_{j=1}^{3} (\delta_{ij} + \boxed{h_{ij}}) dx^i dx^j$$

x^1

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 $\vec{k}$

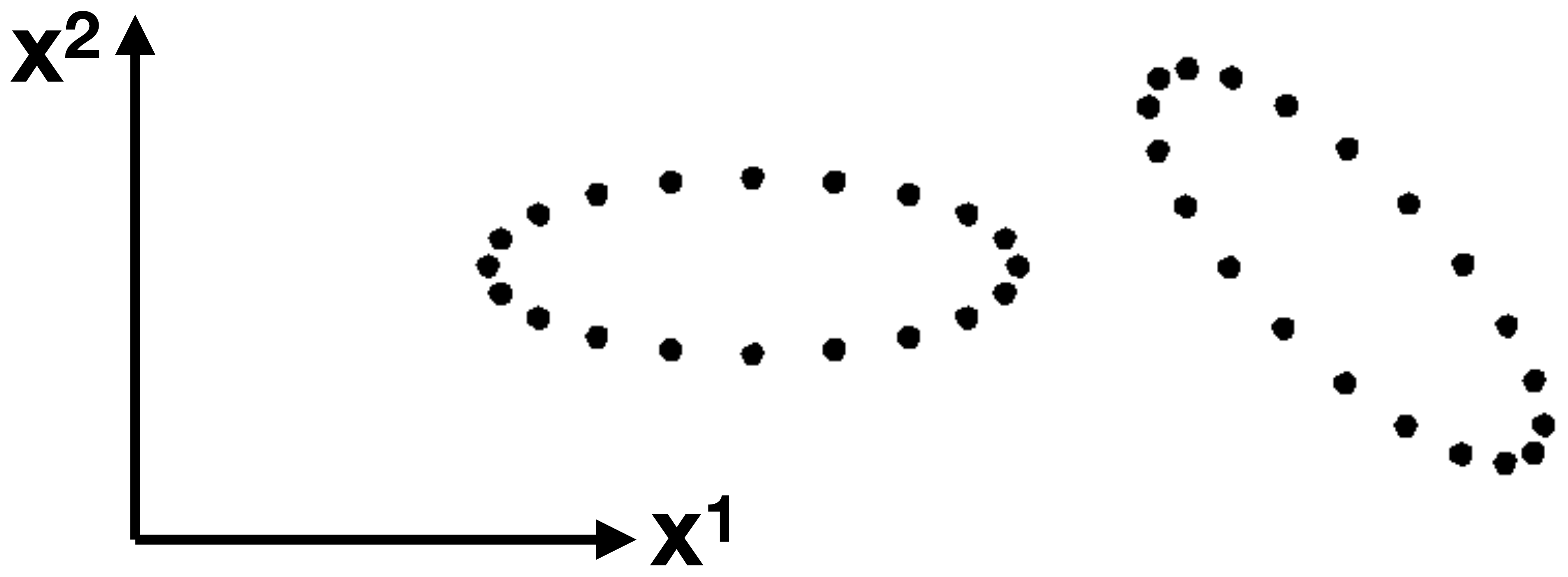


Thus, $$\sum_{i=1}^{3} k^i h_{ij} = 0$$ **3 conditions for h_{ij}**

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}

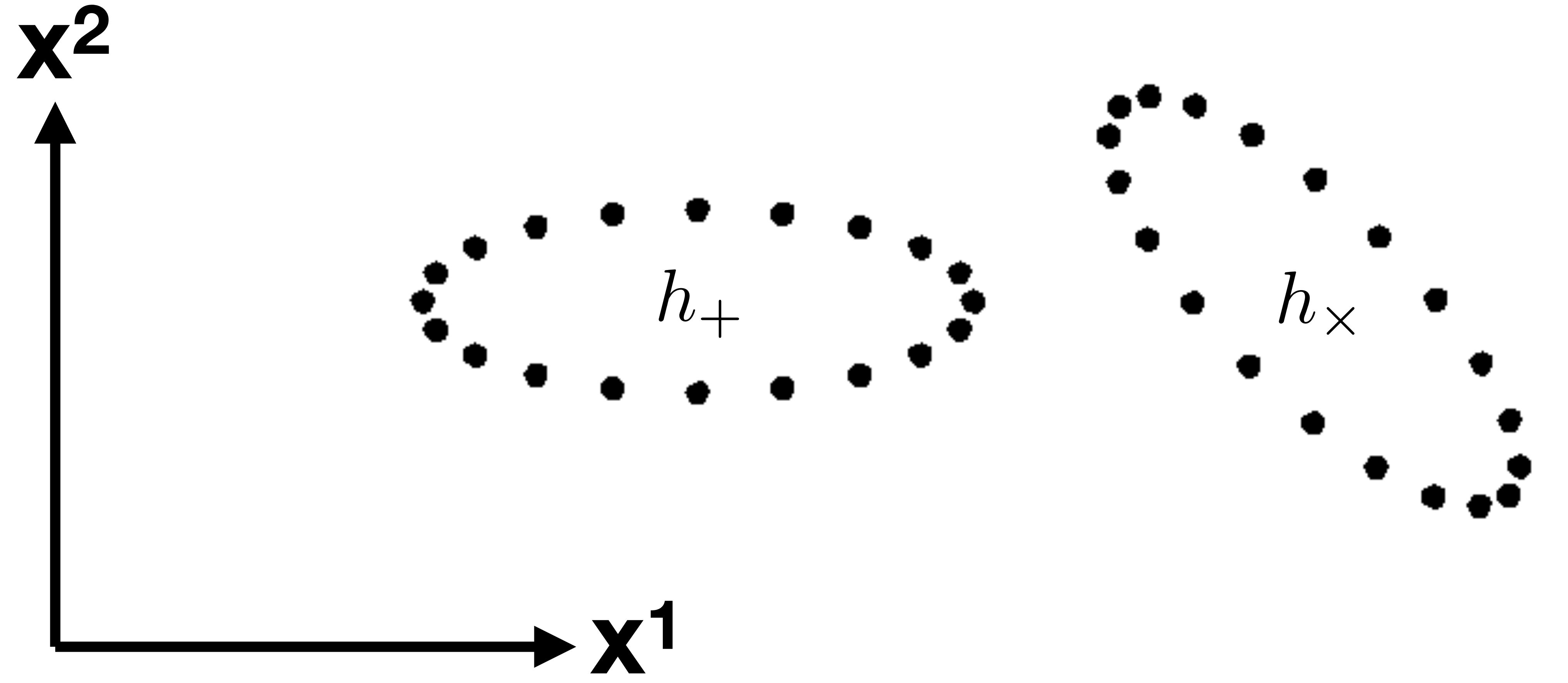
6 – 4 = 2 degrees of freedom for GW

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

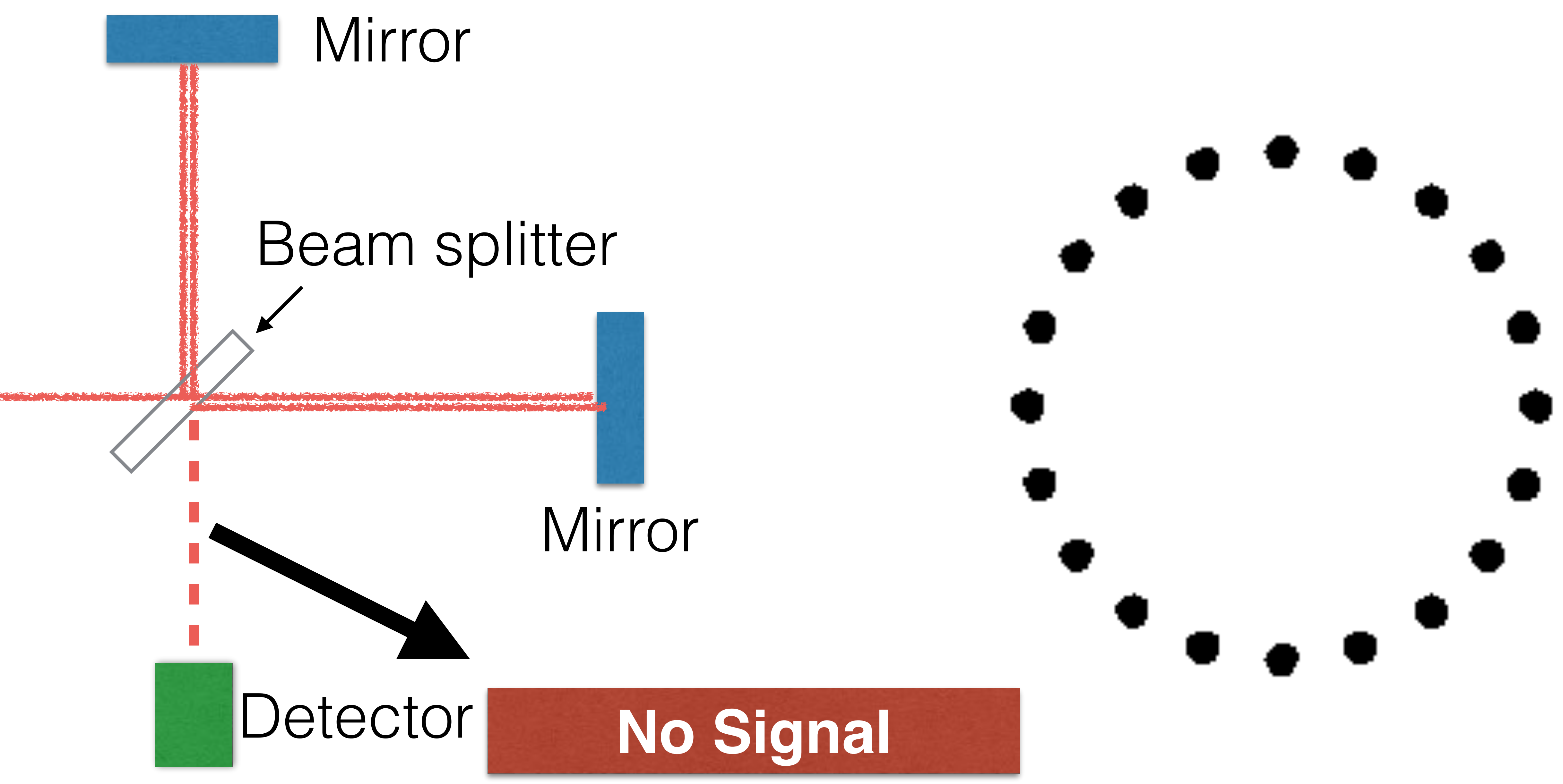
$$h_{ij} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



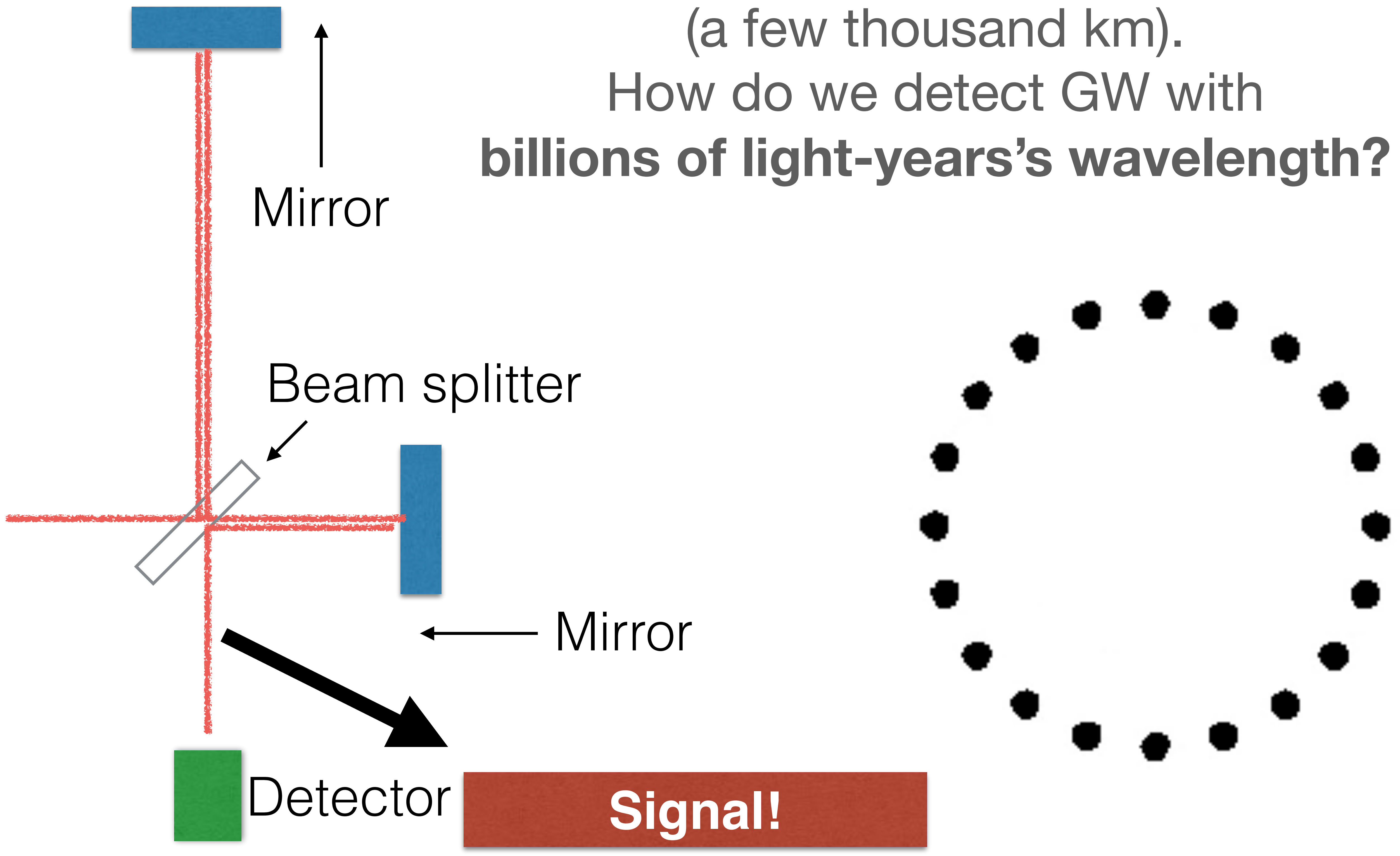
Propagation direction of GW $\vec{k}$
z
$h_+ = \cos(kz)$
$h_\times = \cos(kz)$

How to detect GW?

Laser interferometer technique, used by LIGO and VIRGO

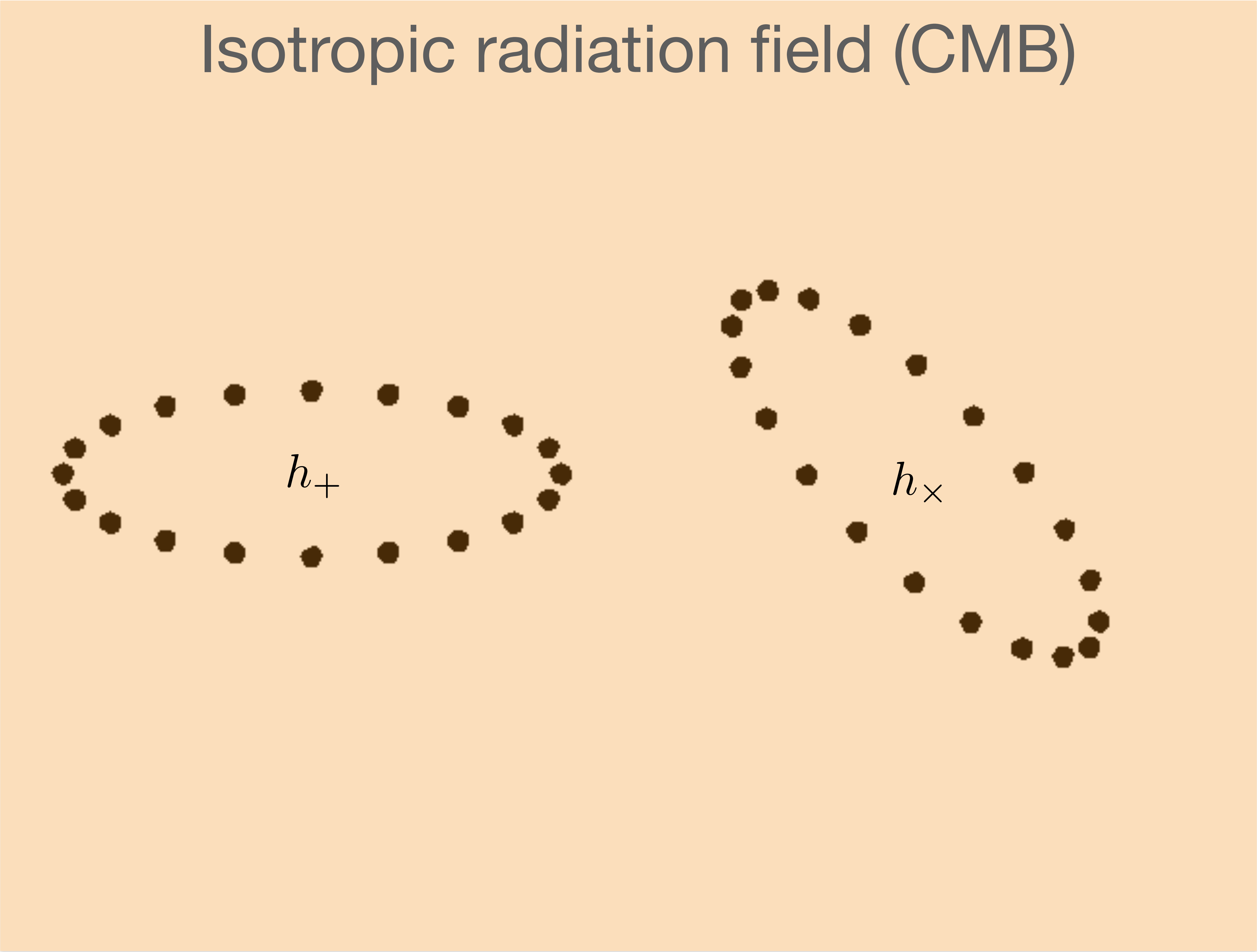


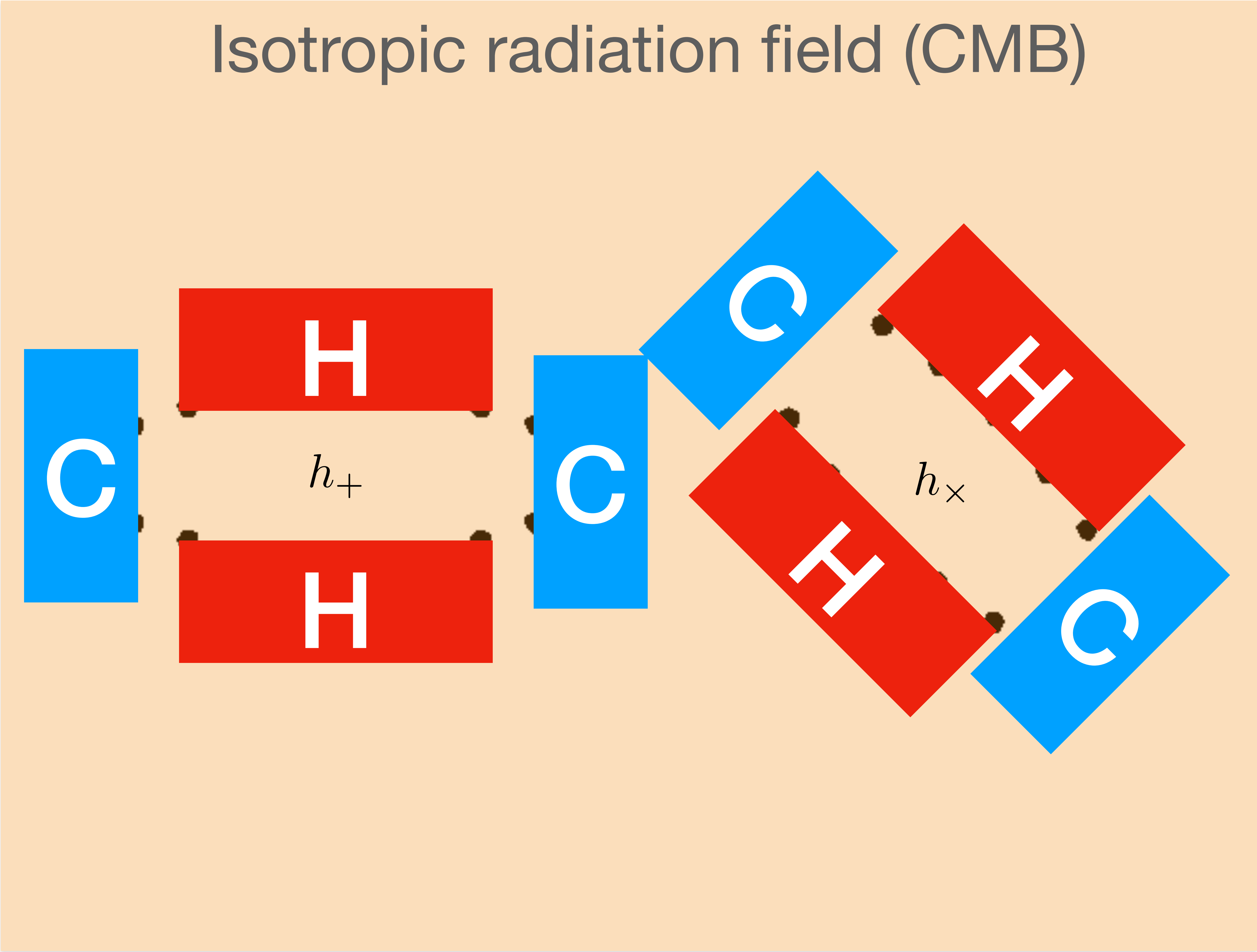
The wavelength of GW detectable by this method is the size of Earth (a few thousand km).
How do we detect GW with **billions of light-years's wavelength?**



Detecting GW by CMB

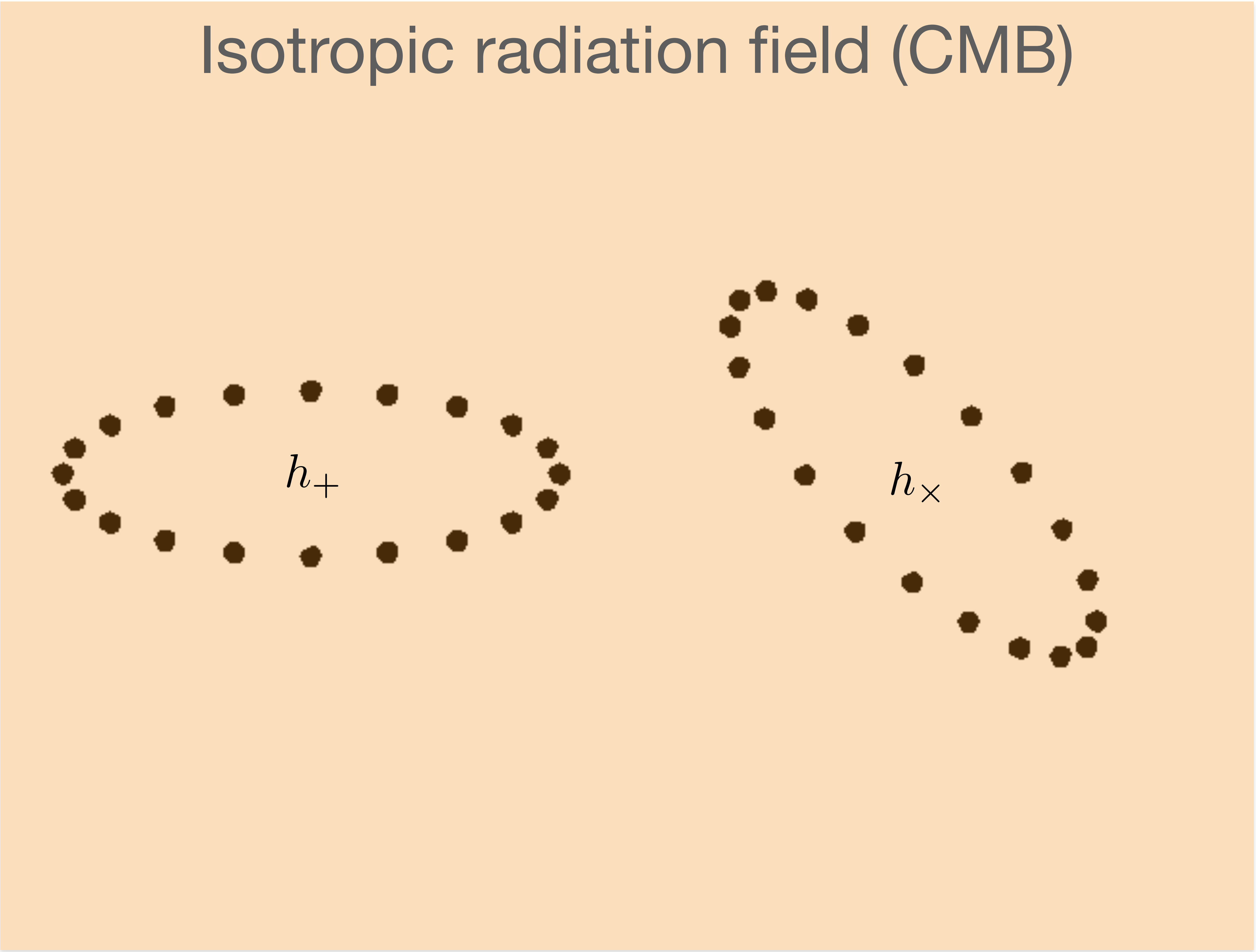
Quadrupole temperature anisotropy generated by red- and blue-shifting of photons

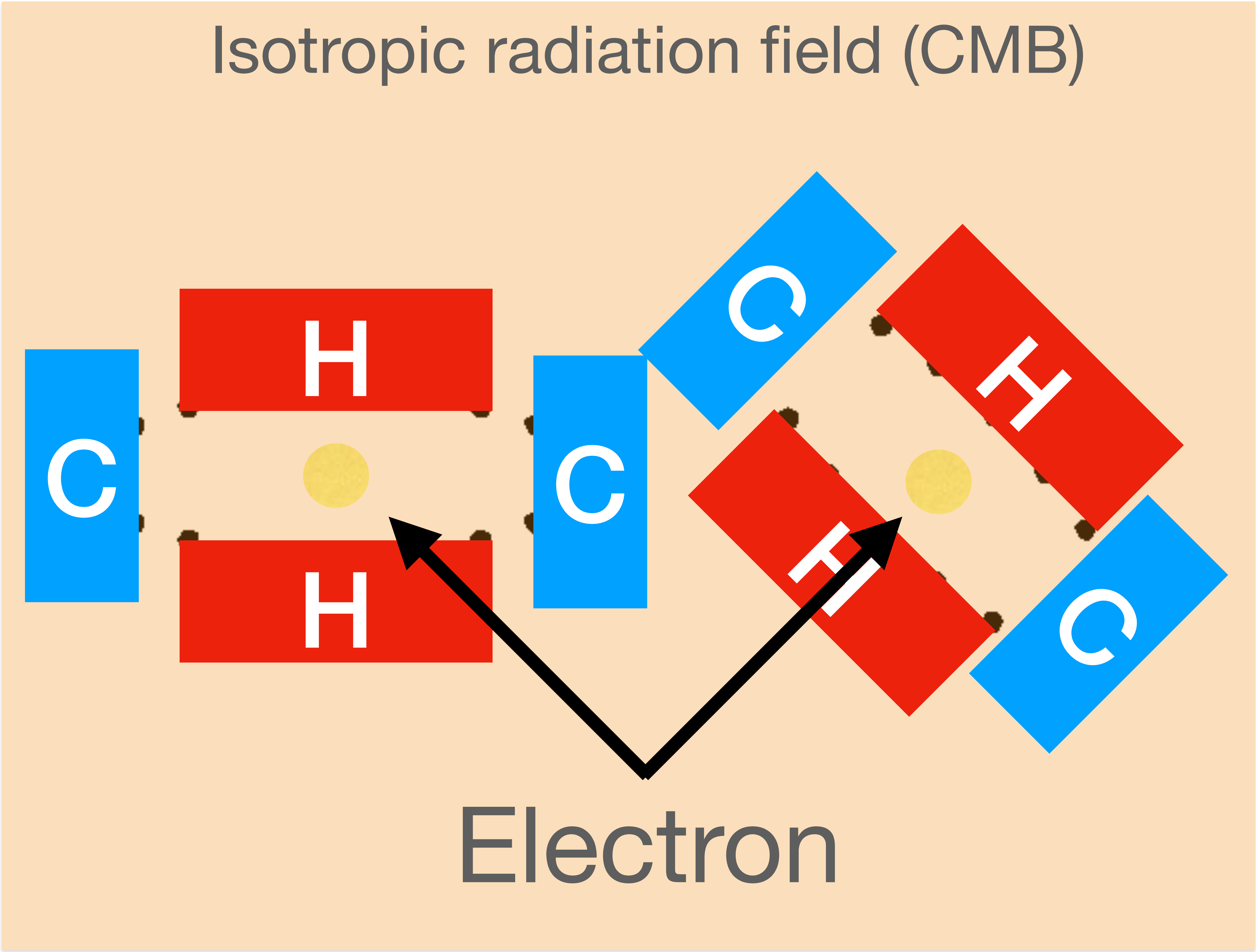




Detecting GW by CMB

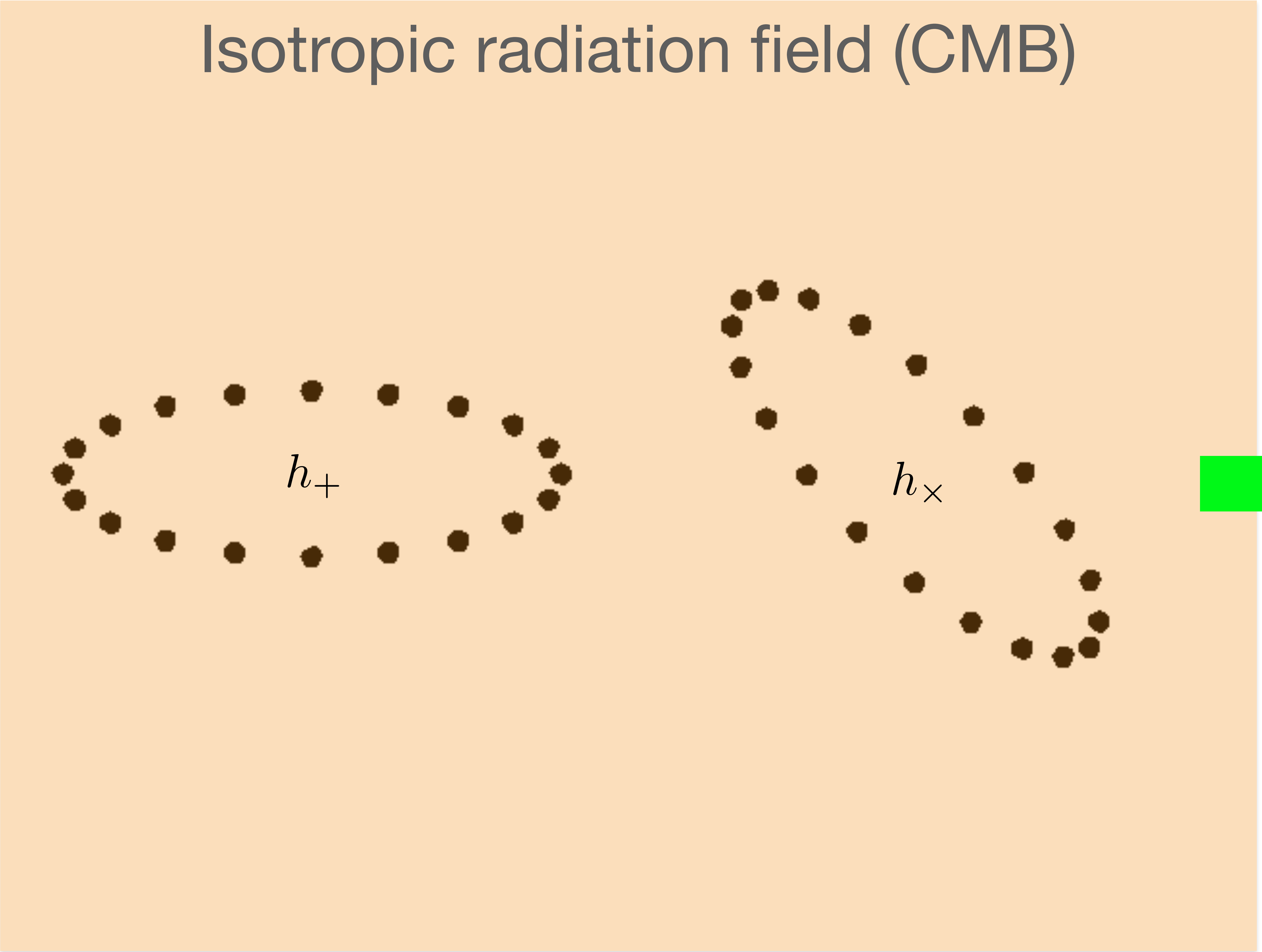
Quadrupole temperature anisotropy generated by red- and blue-shifting of photons

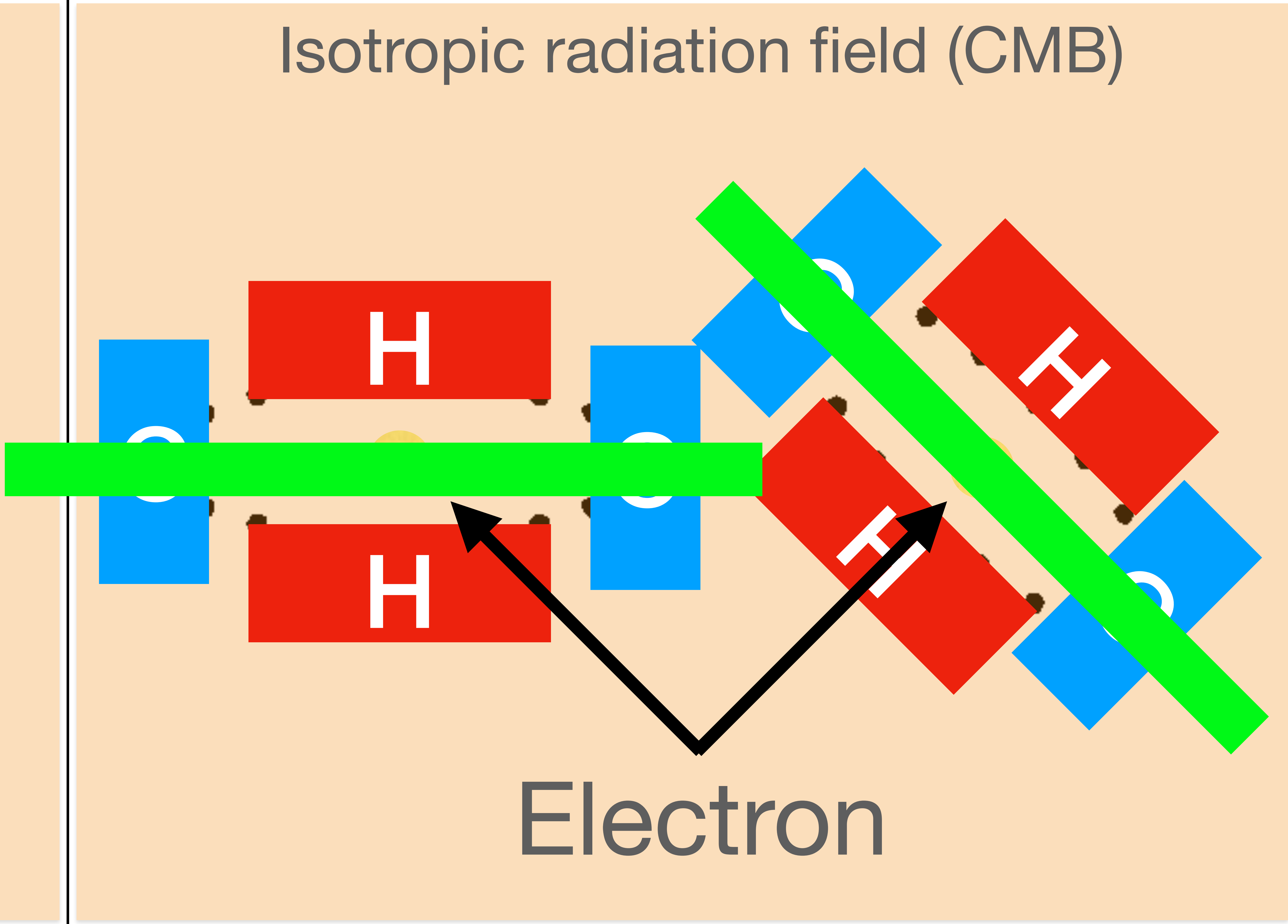




Detecting GW by CMB *Polarisation*

Quadrupole temperature anisotropy scattered by an electron






Credit: TALEX
Horizontally polarised


Credit: TALEX

Physics of CMB Polarisation

Necessary and sufficient condition: Scattering and Quadrupole Anisotropy

Credit：Wayne Hu


Temperature (smoothed)

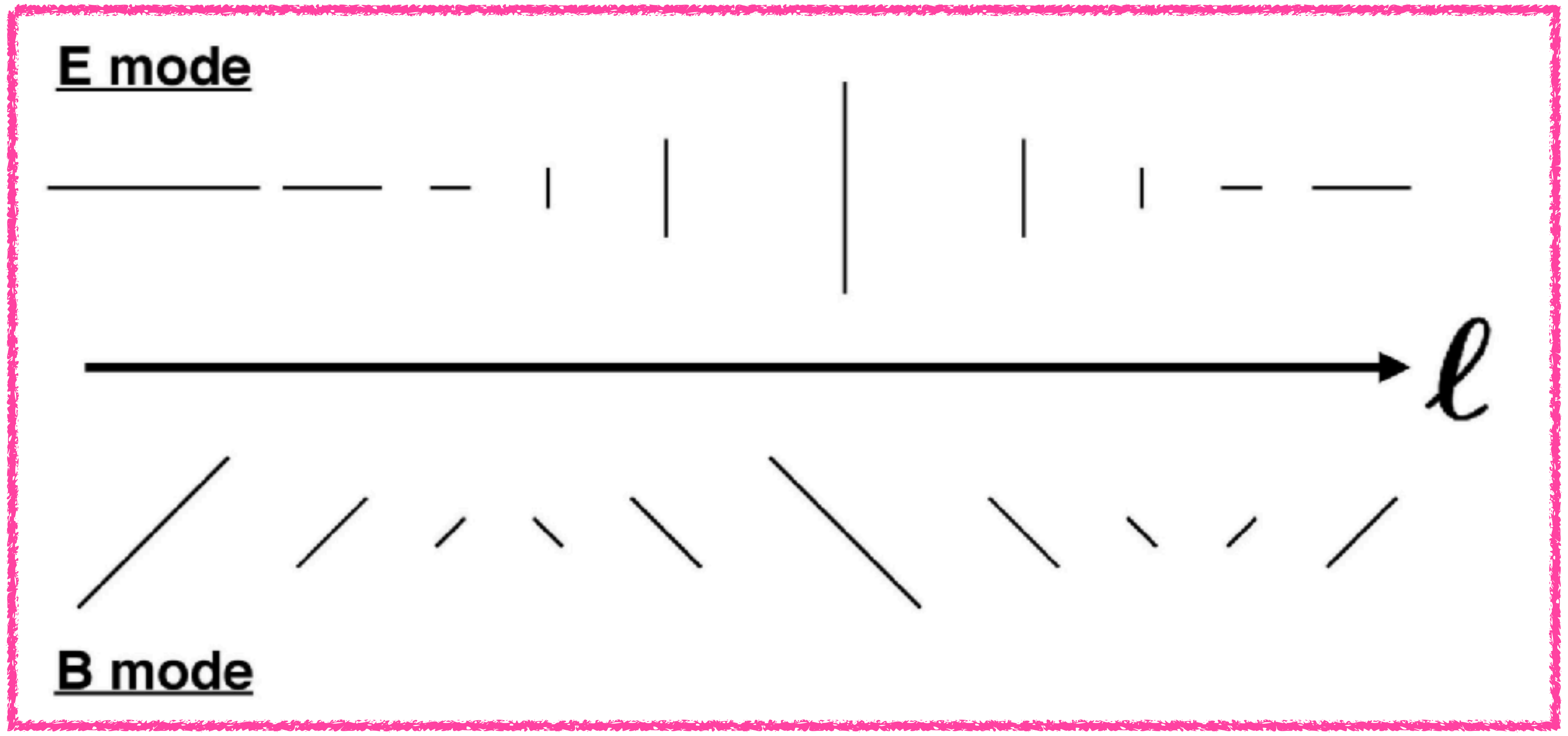
Credit: ESA

Temperature (smoothed) + Polarisation

Credit: ESA

E- and B-mode decomposition

Concept defined in Fourier space

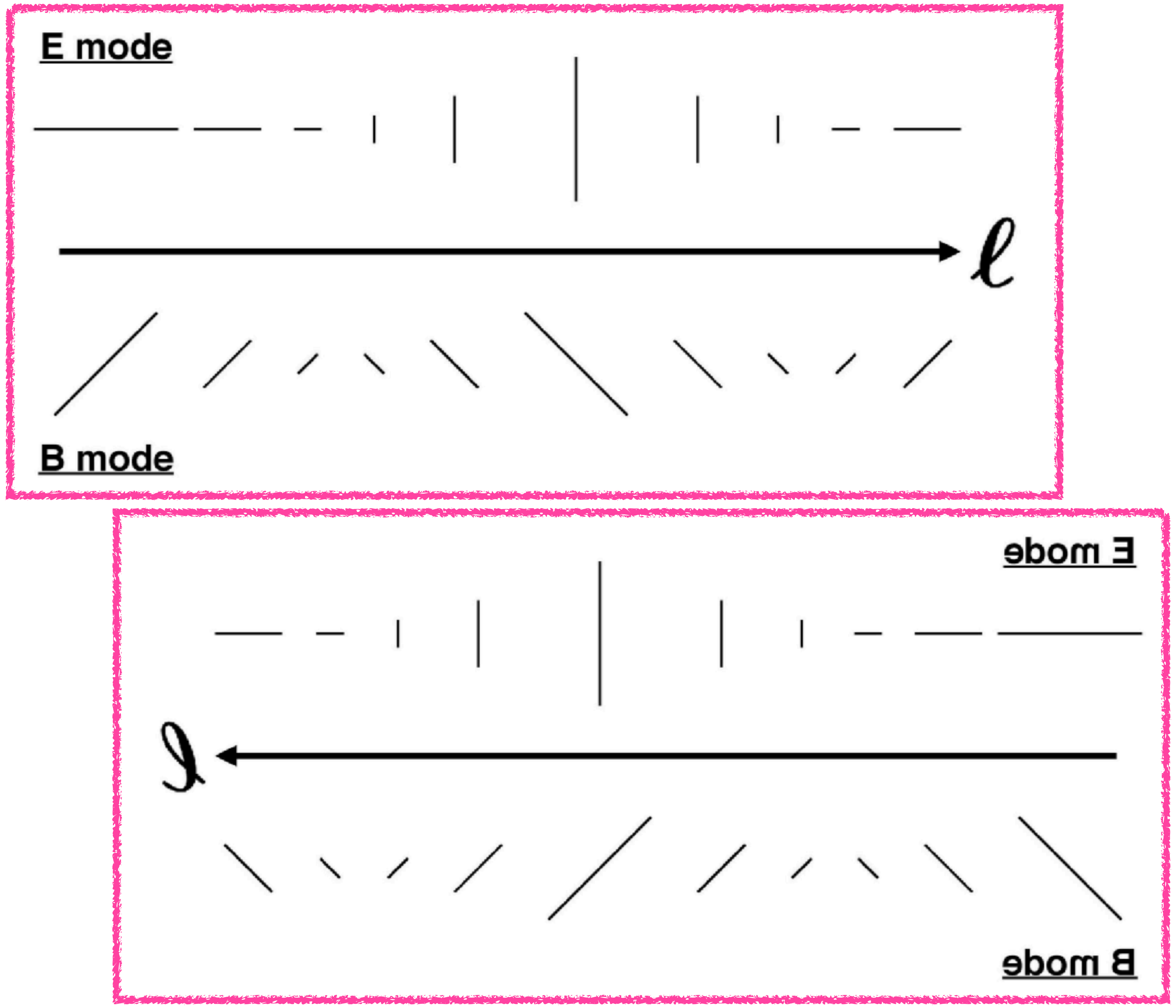


Direction of the Fourier wavenumber vector

- **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

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

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

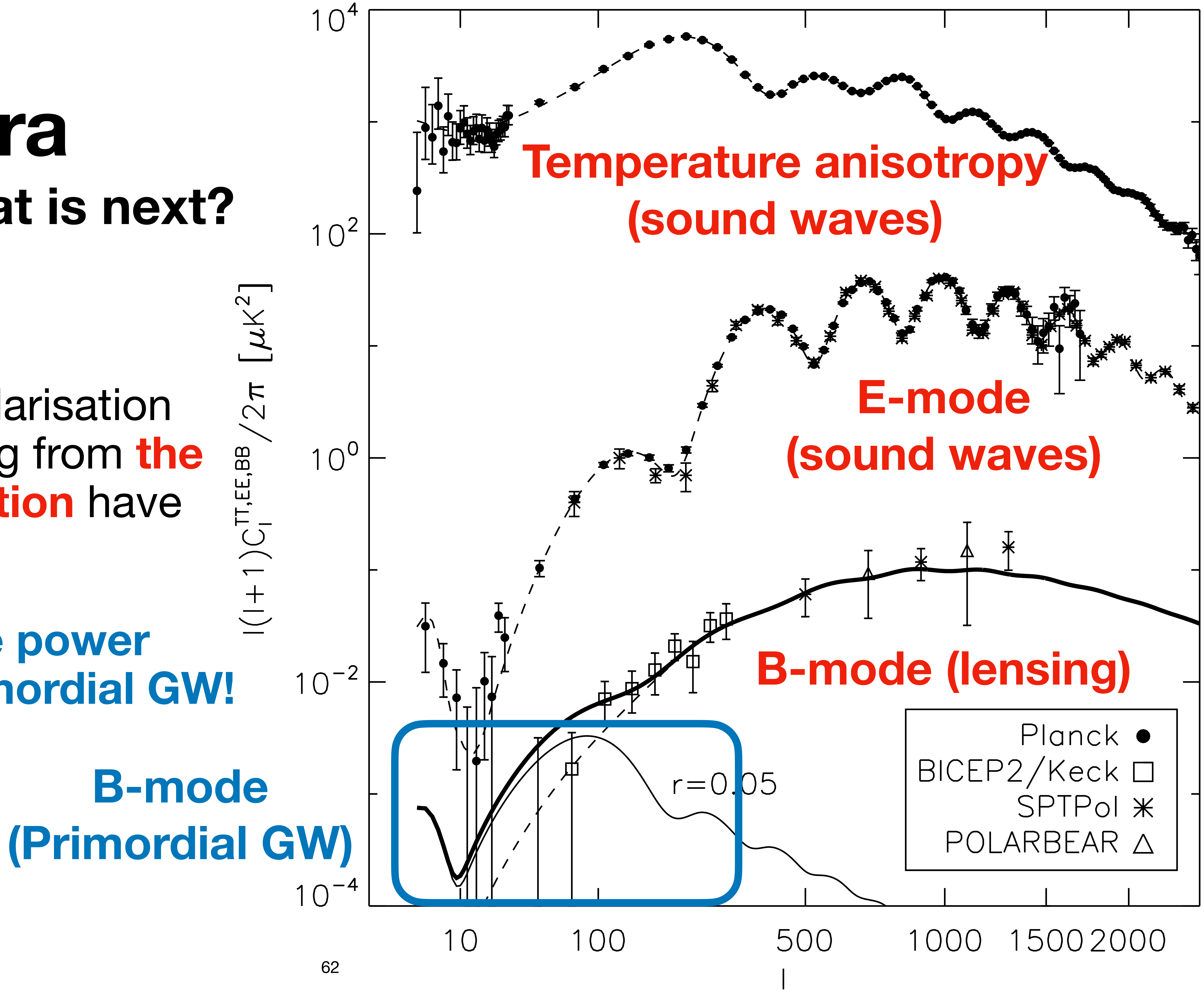
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

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

Power Spectra

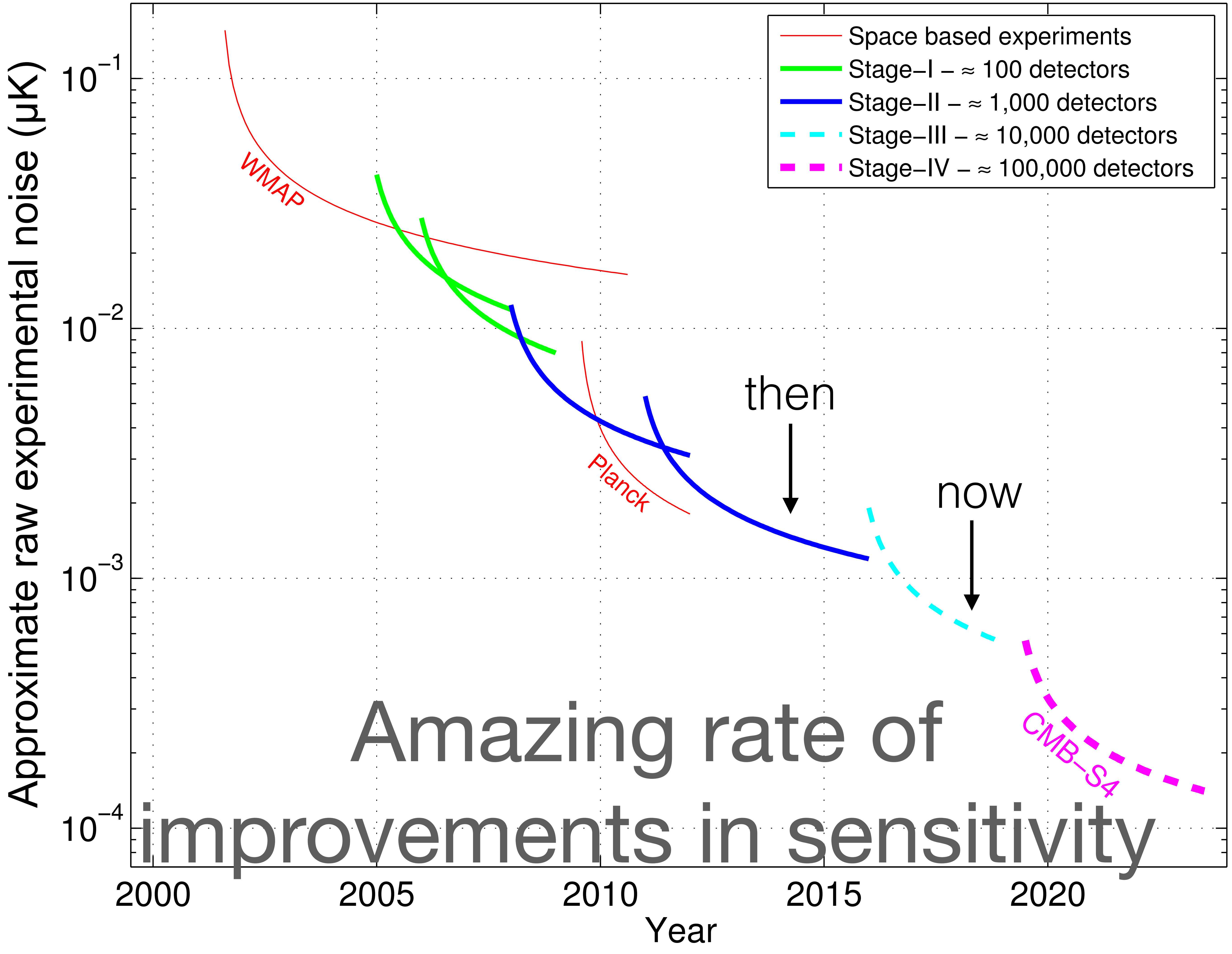
Where are we? What is next?

- 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!**



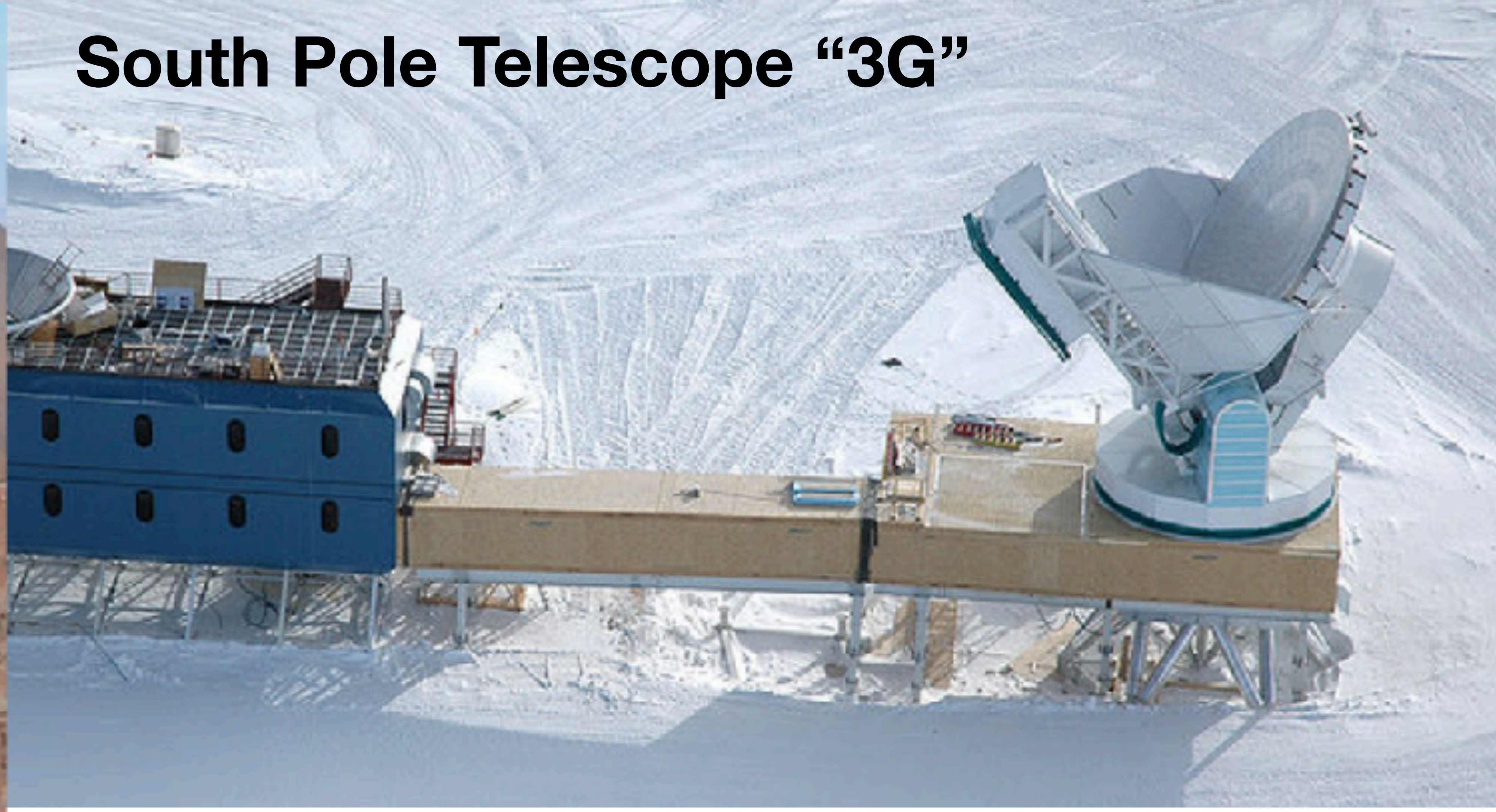
Experimental Landscape

CMB Stages



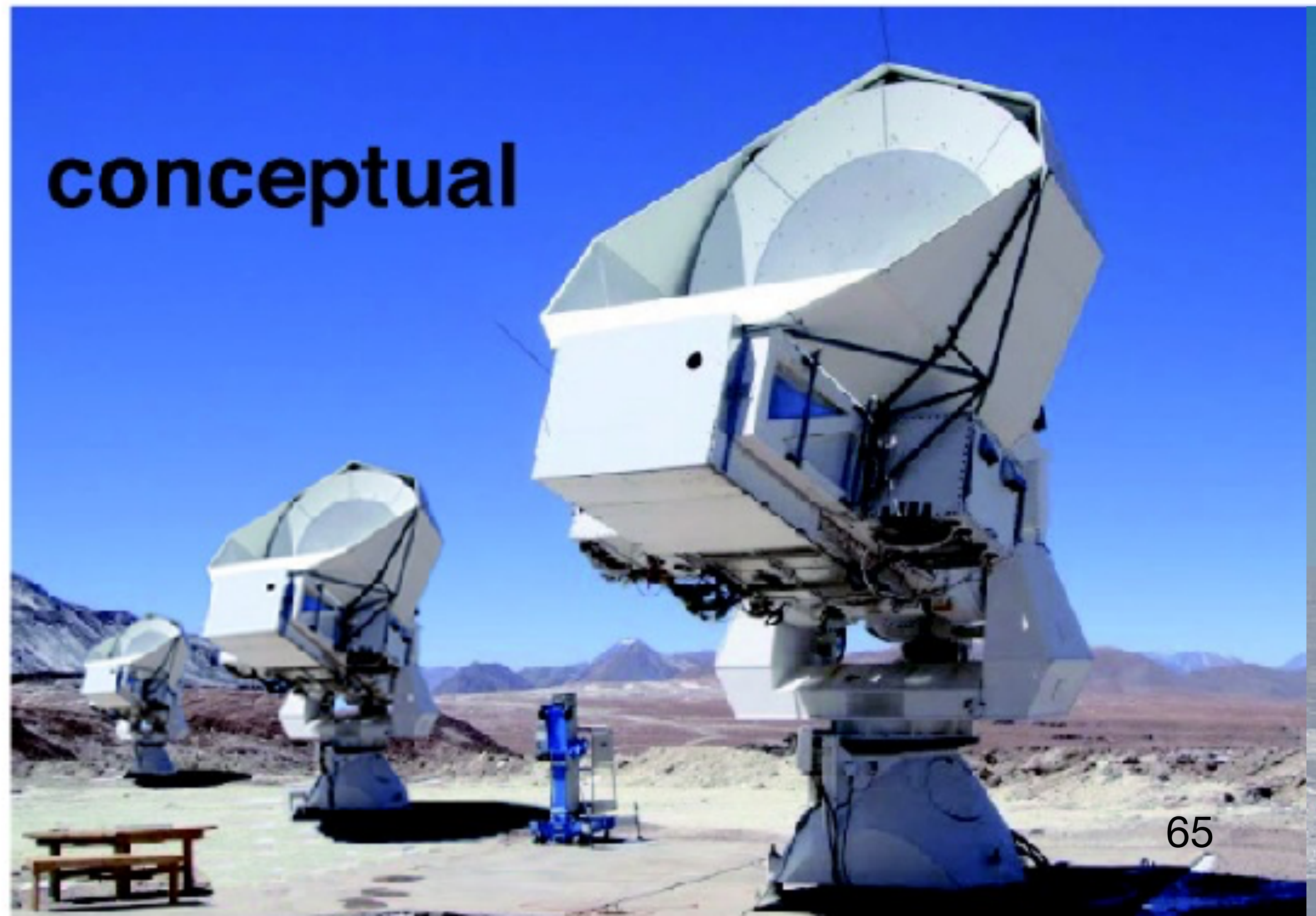
Amazing rate of improvements in sensitivity

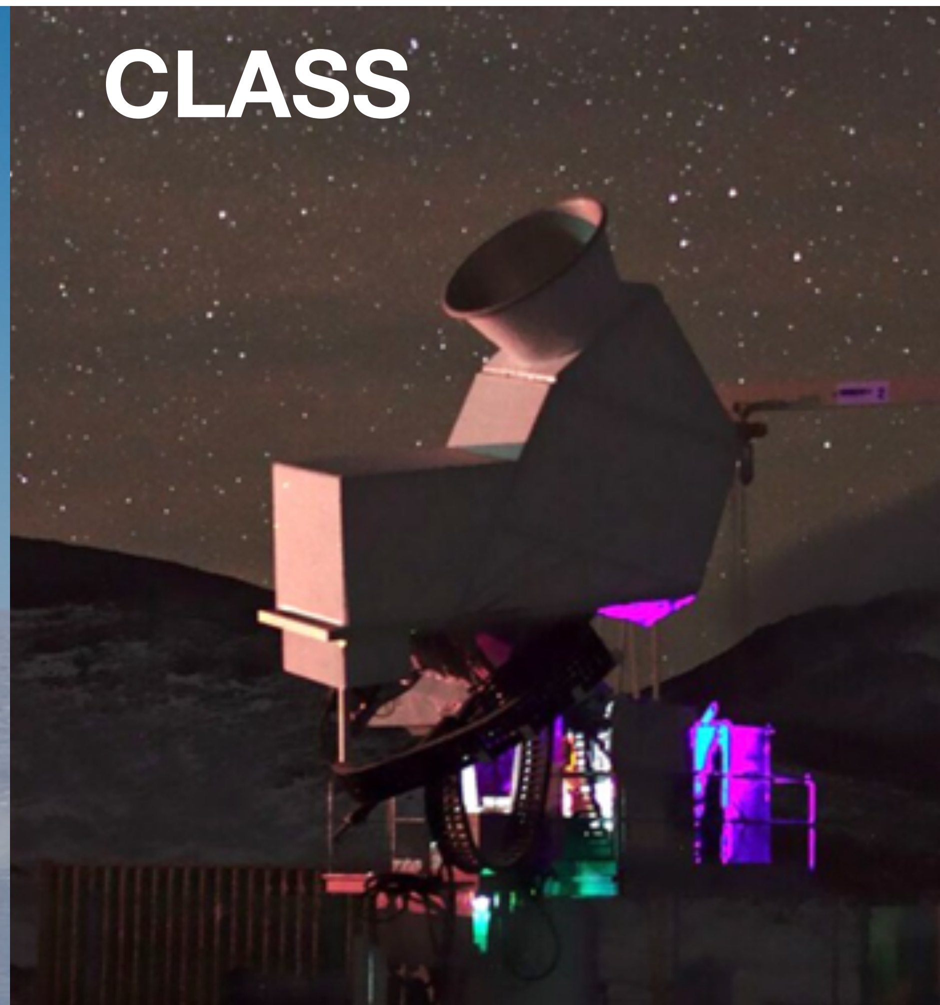
Figure by Clem Pryke for 2013 Snowmass documents

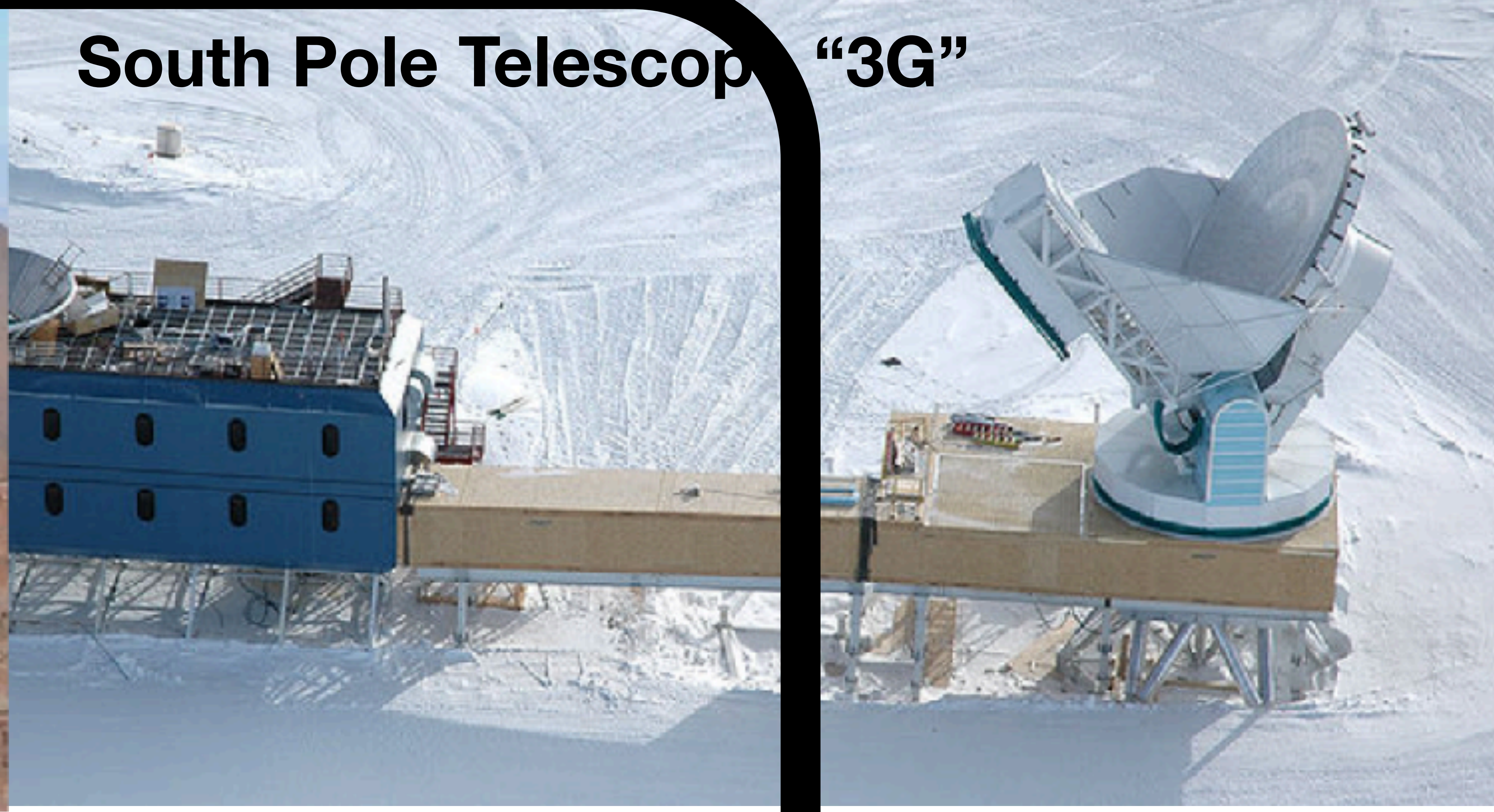


On-going Ground-based Experiments

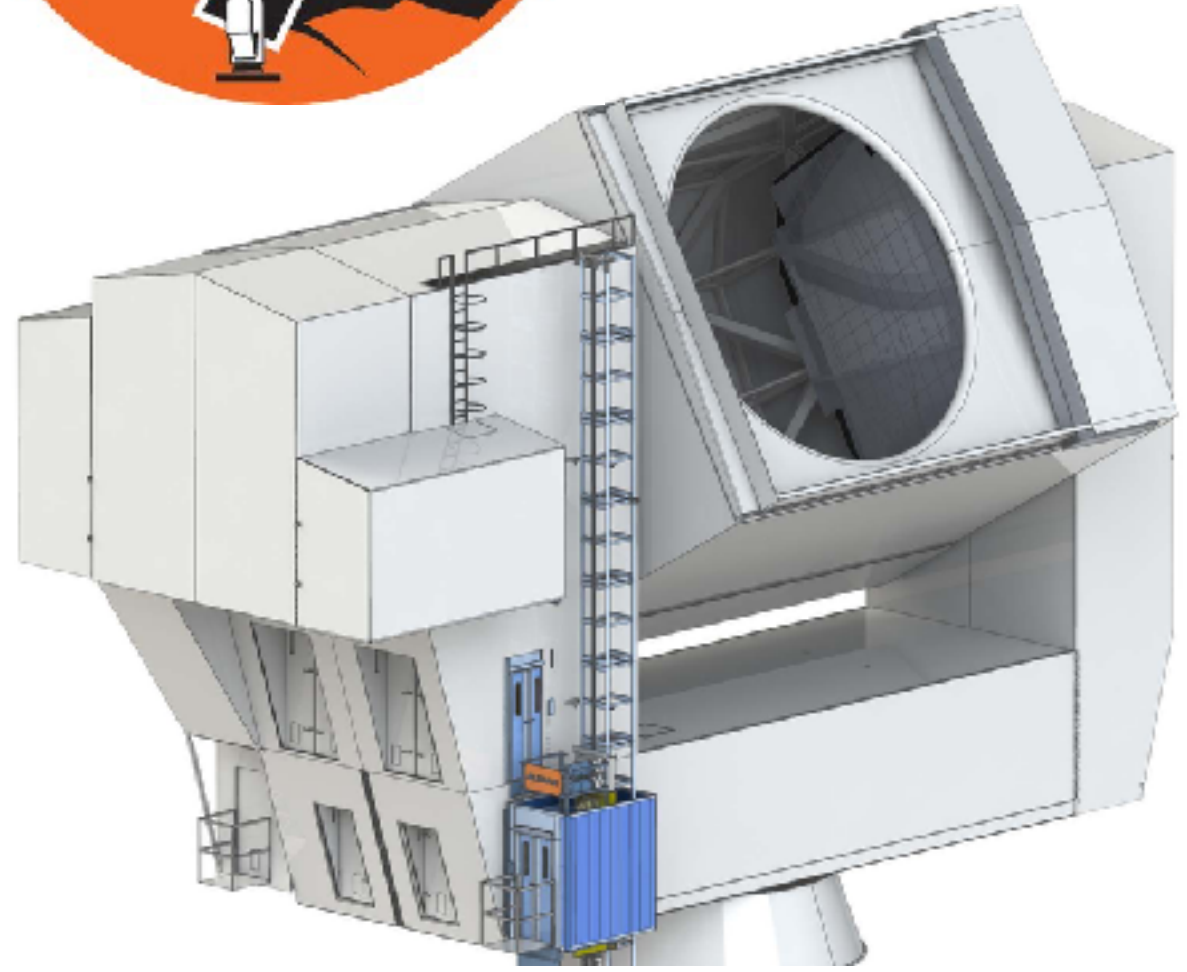
The Simons Array





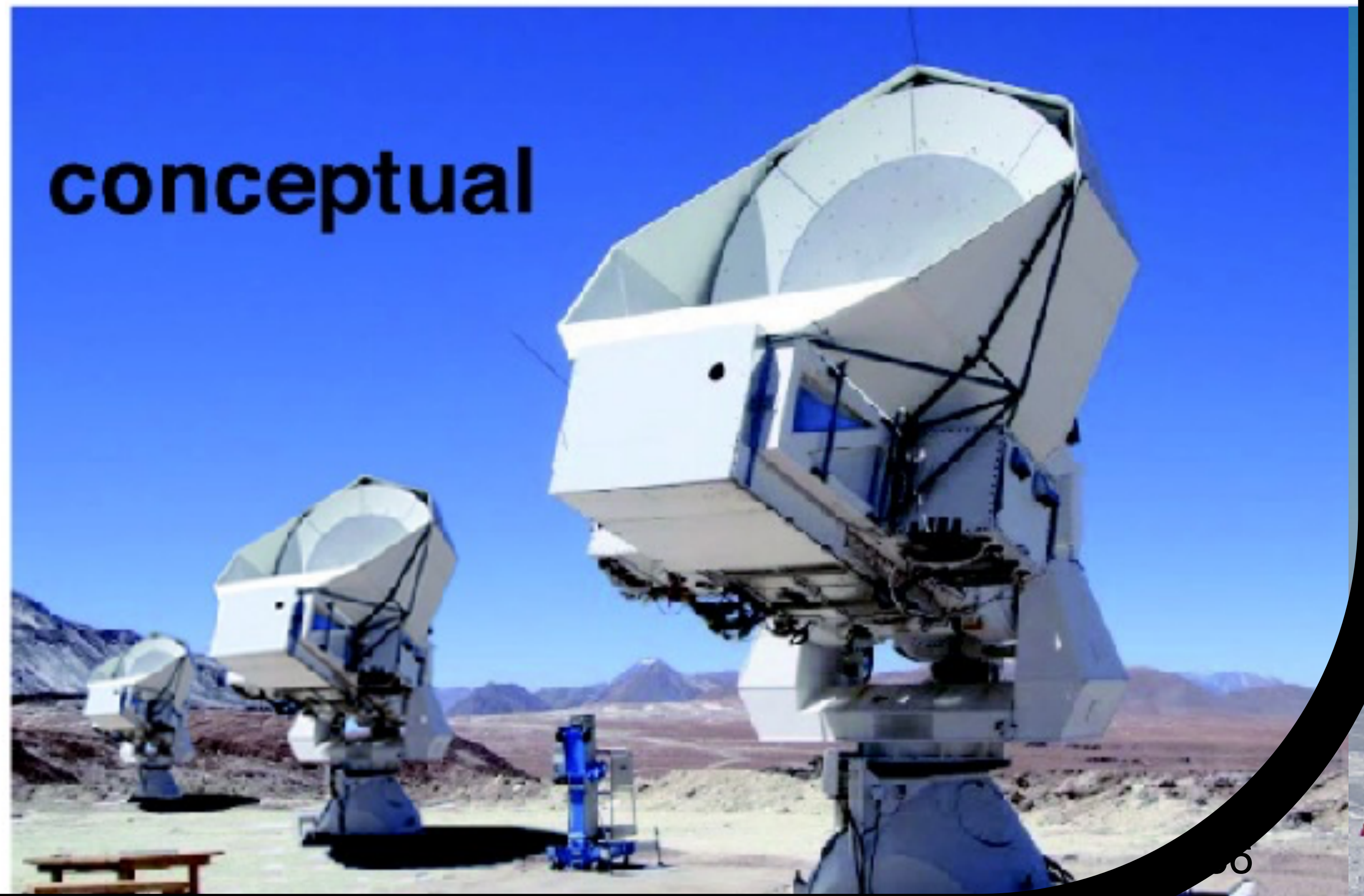


SIMONS OBSERVATORY



The Simons Array

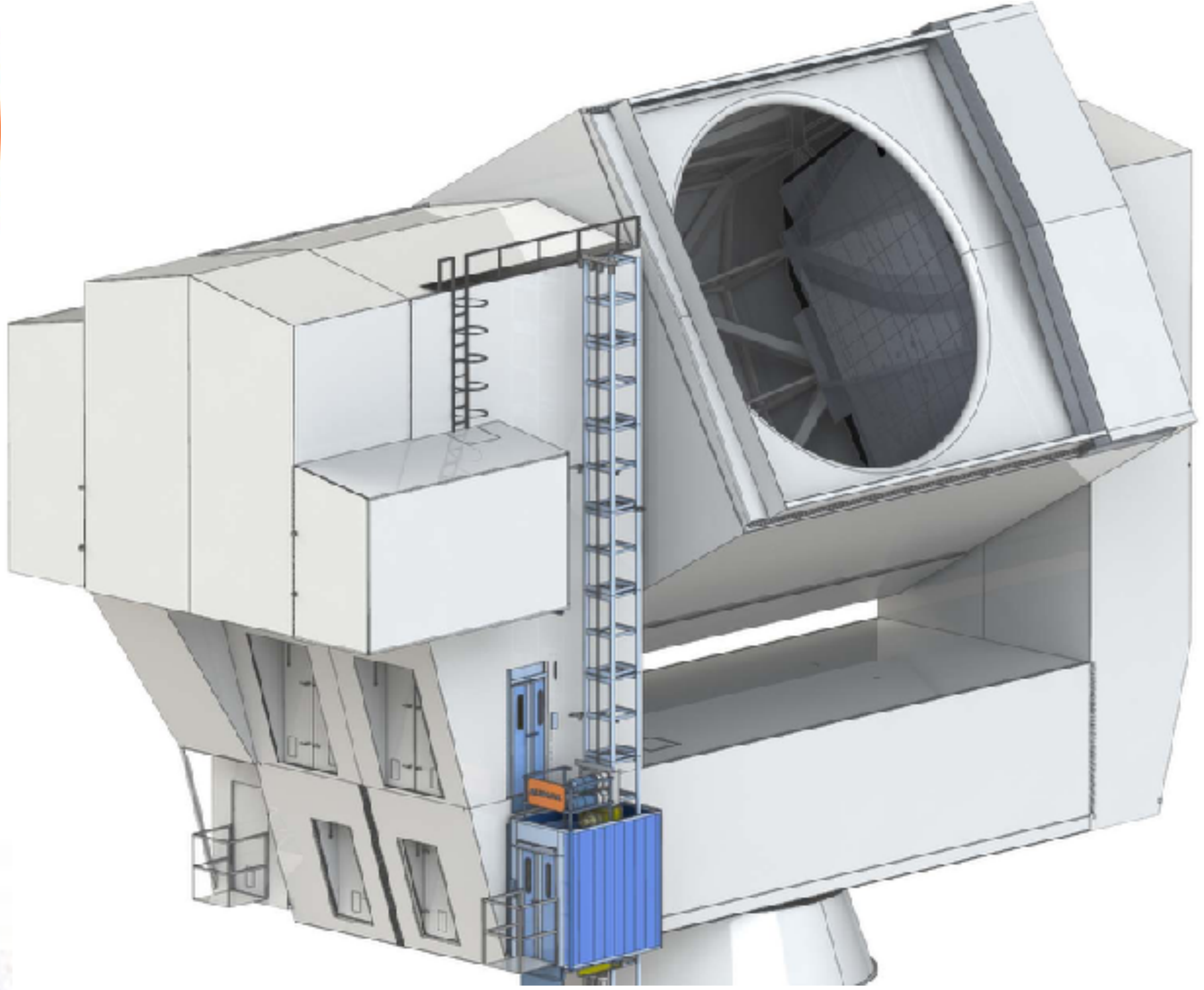
The South Pole Observatory



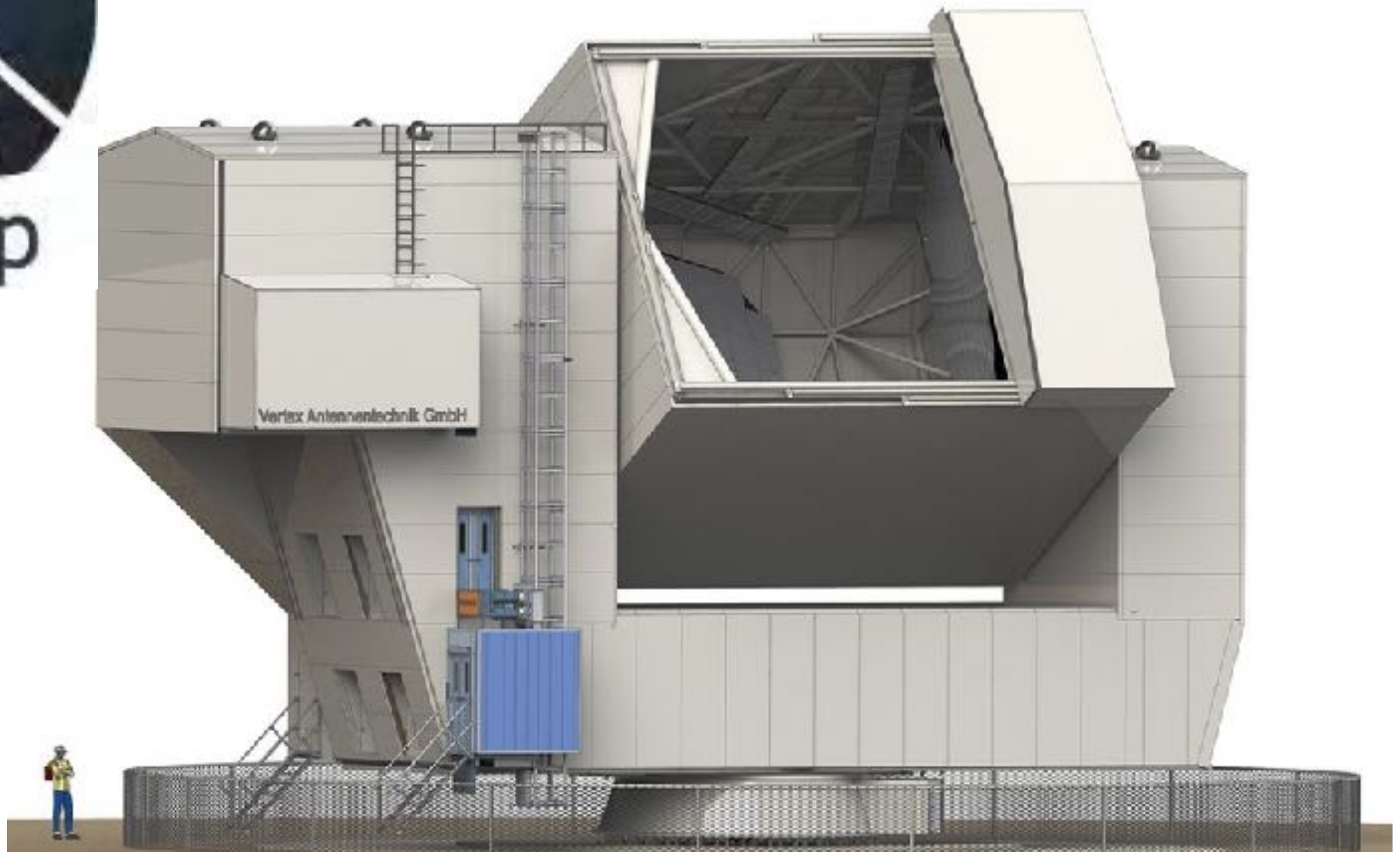
Early 2020s

~$100M

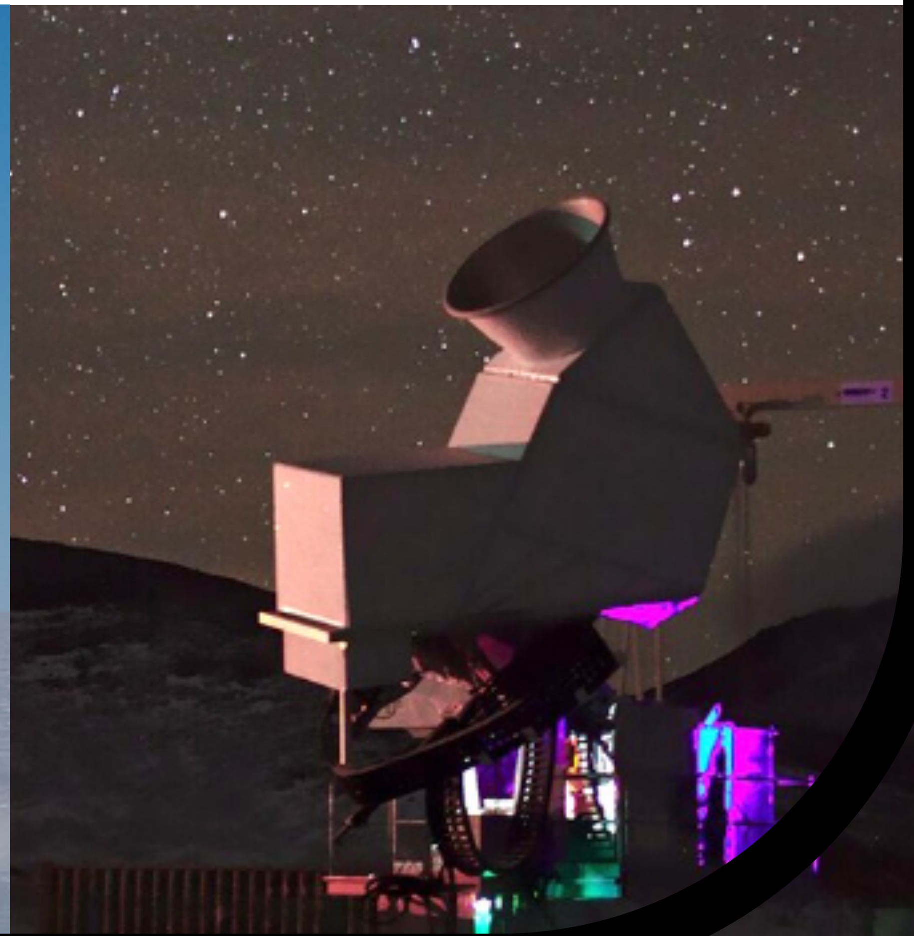
SIMONS OBSERVATORY

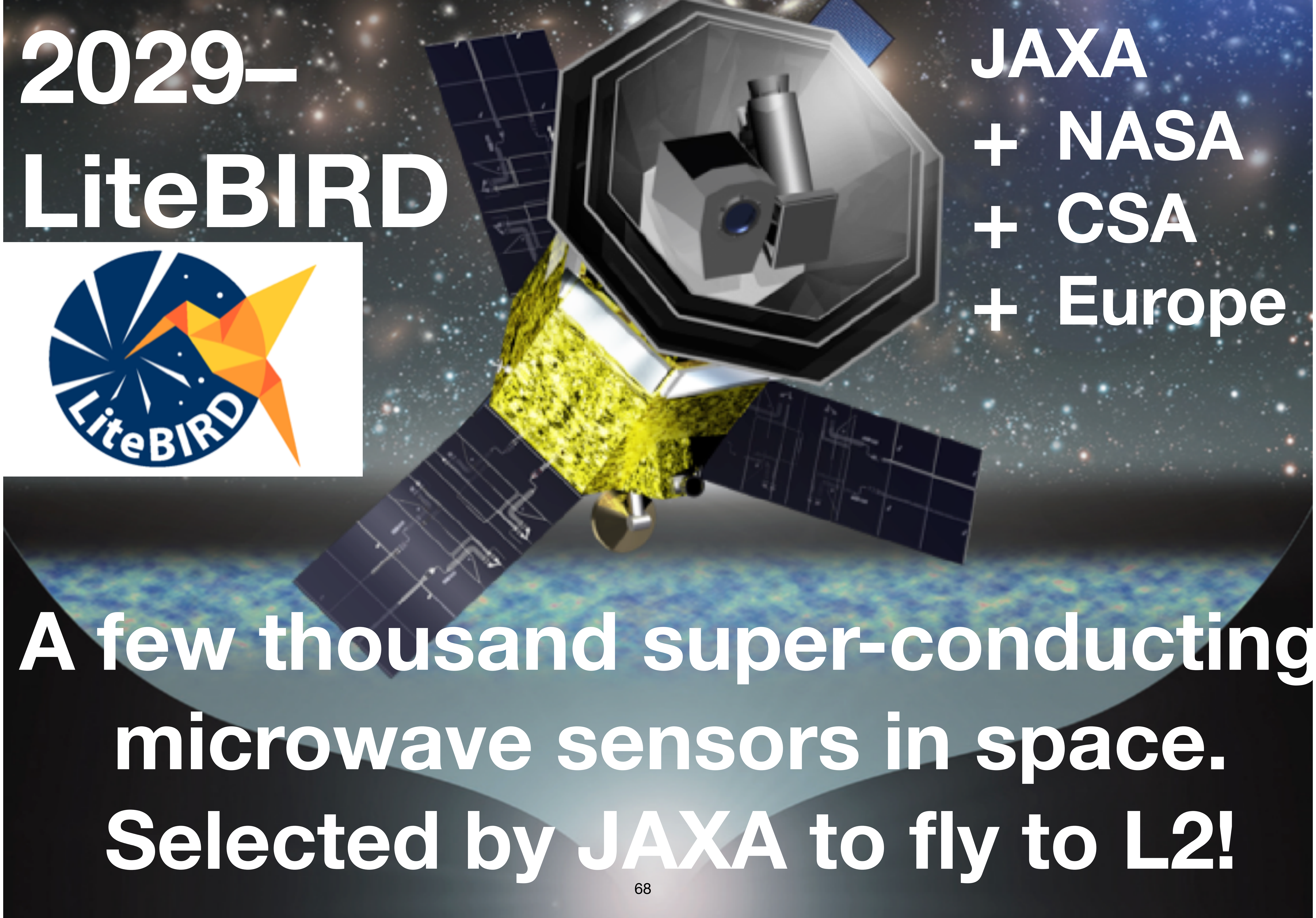


CCAT-p



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




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 our origins

- **The Quest So Far:**
  - There is very good evidence that we all came from the quantum fluctuation in the early Universe, generated during the period of **cosmic inflation**.
- **The New Quest:**
  - Discovery of the primordial gravitational wave with the wavelength of billions of light years 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.