

Finding Gravitational Waves from the Early Universe

**Finding the signature of gravitational waves in polarised light of
the fireball Universe**

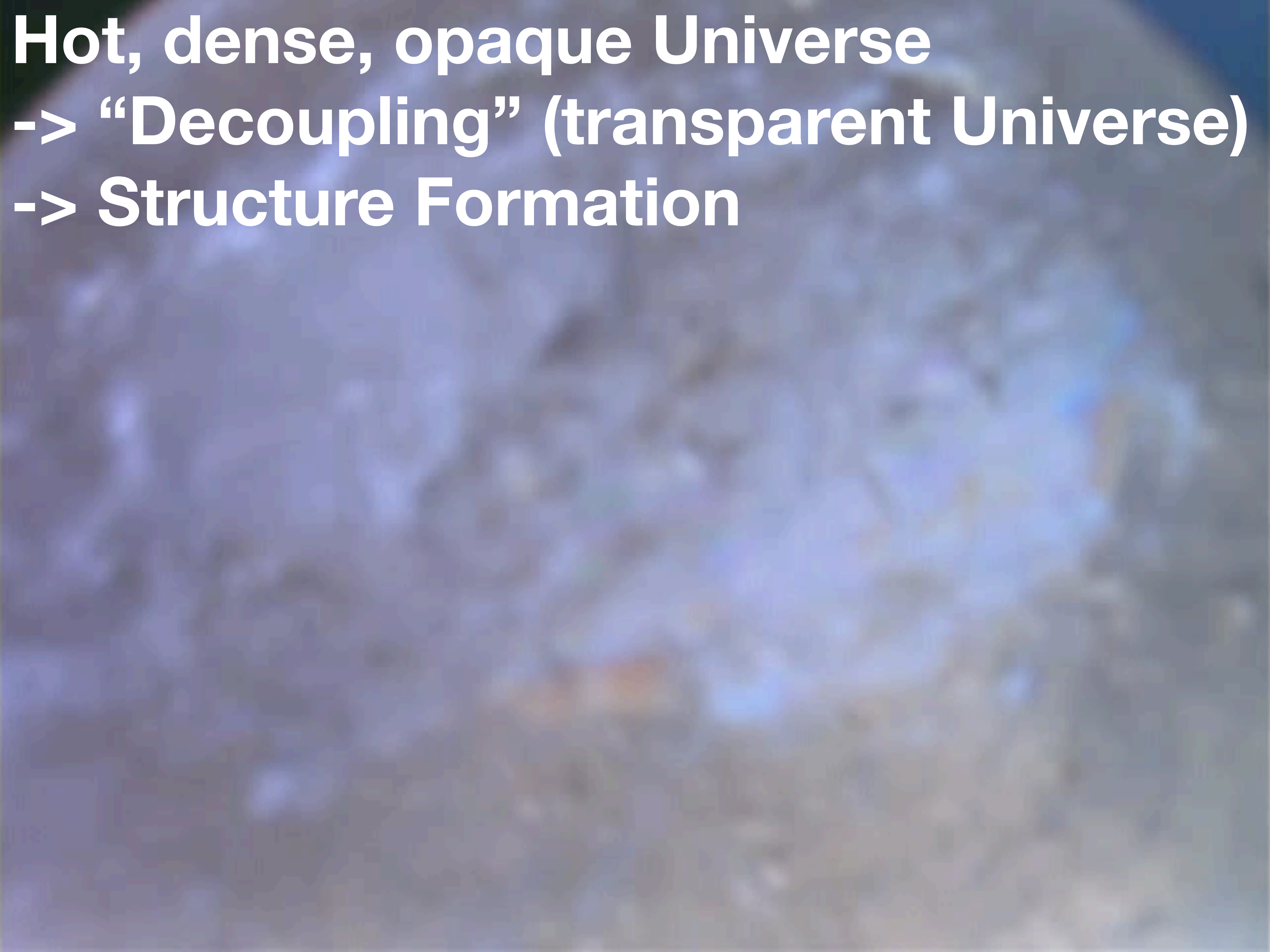
**Eiichiro Komatsu (Max Planck Institute for Astrophysics)
*Physics Discussion, ICTP-SAIFR / IFT-UNESP, May 5, 2021***

From “Cosmic Voyage” (1996)

Hot, dense, opaque Universe

-> “Decoupling” (transparent Universe)

-> Structure Formation

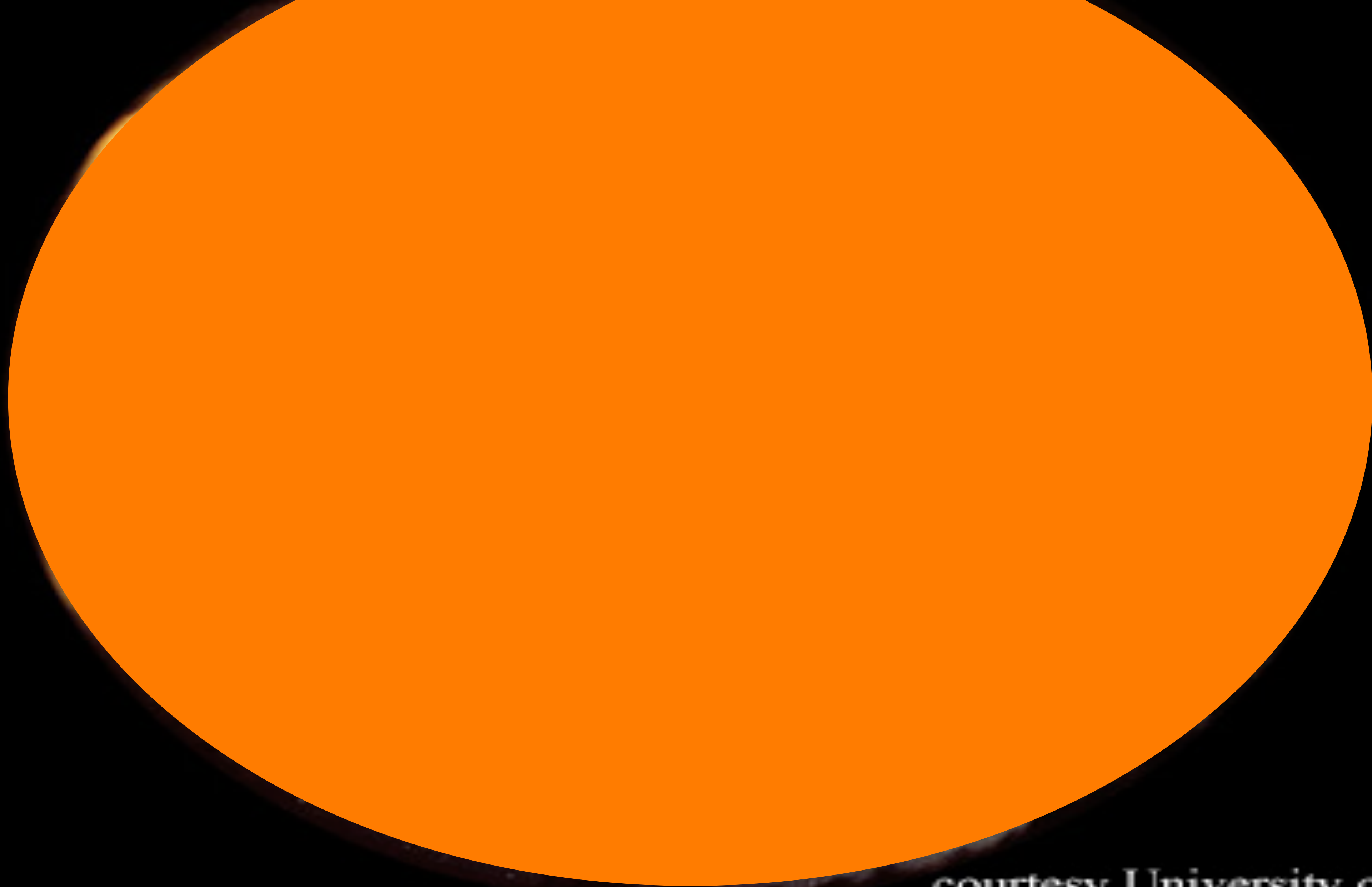


Sky in Optical ($\sim 0.5\mu\text{m}$)



courtesy University of Arizona

Sky in Microwave ($\sim 1\text{mm}$)



courtesy University of Arizona

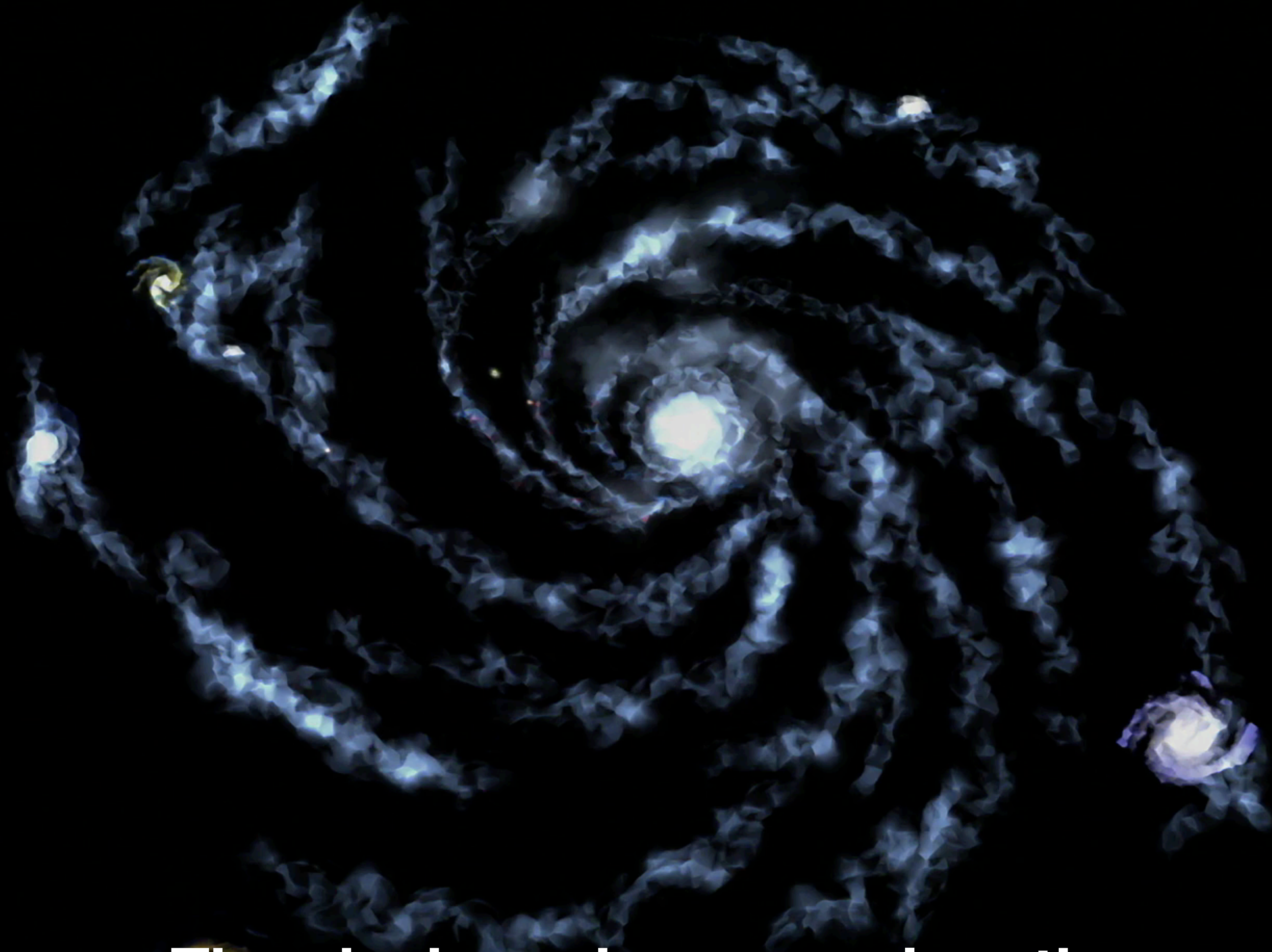
Sky in Microwave ($\sim 1\text{mm}$)

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

The Cosmic Microwave Background (CMB)

410 photons
per
cubic centimeter!!

Credit: WMAP Science Team



The sky in various wavelengths

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

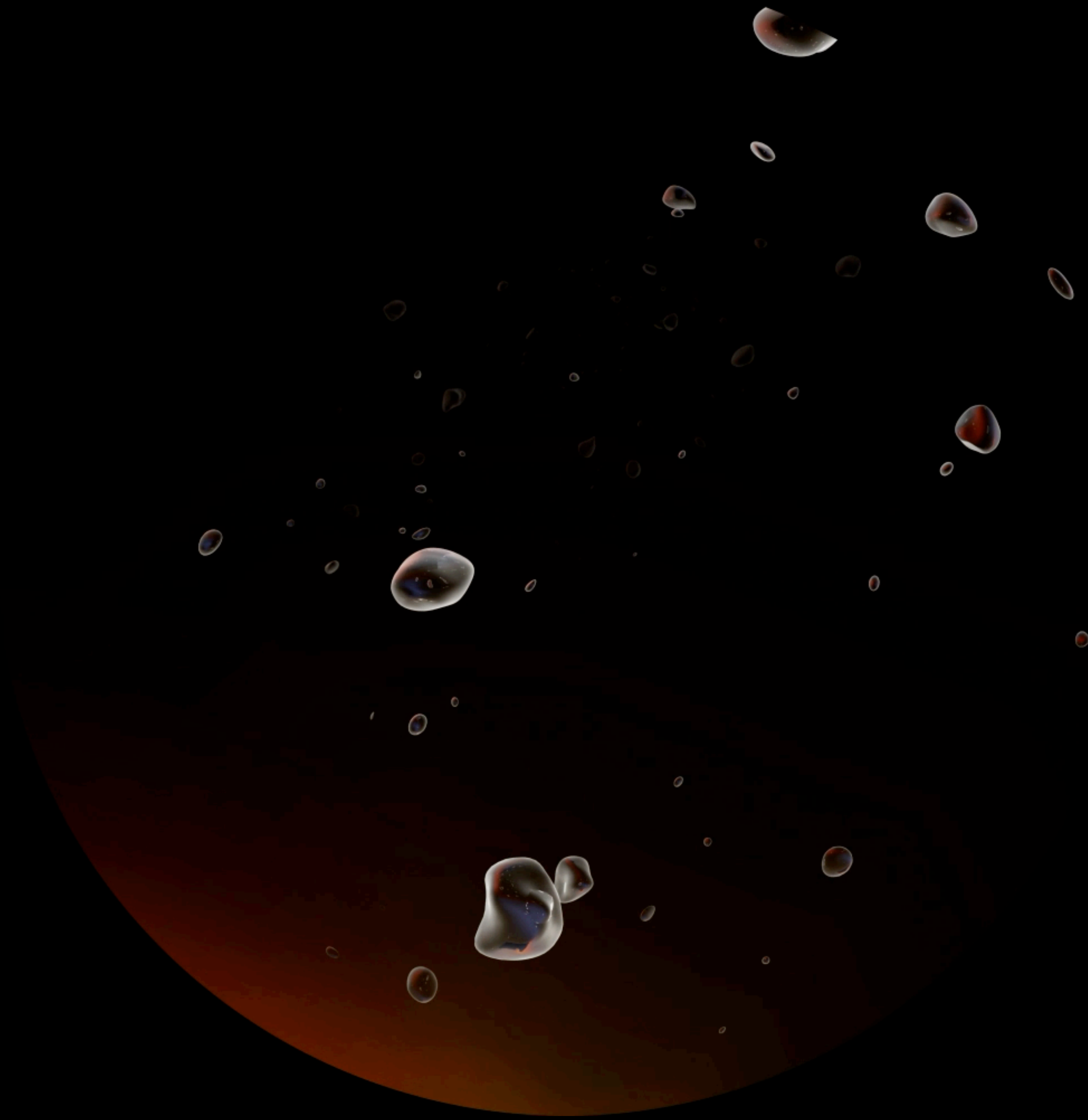
Full-dome movie for planetarium

Director: Hiromitsu Kohsaka

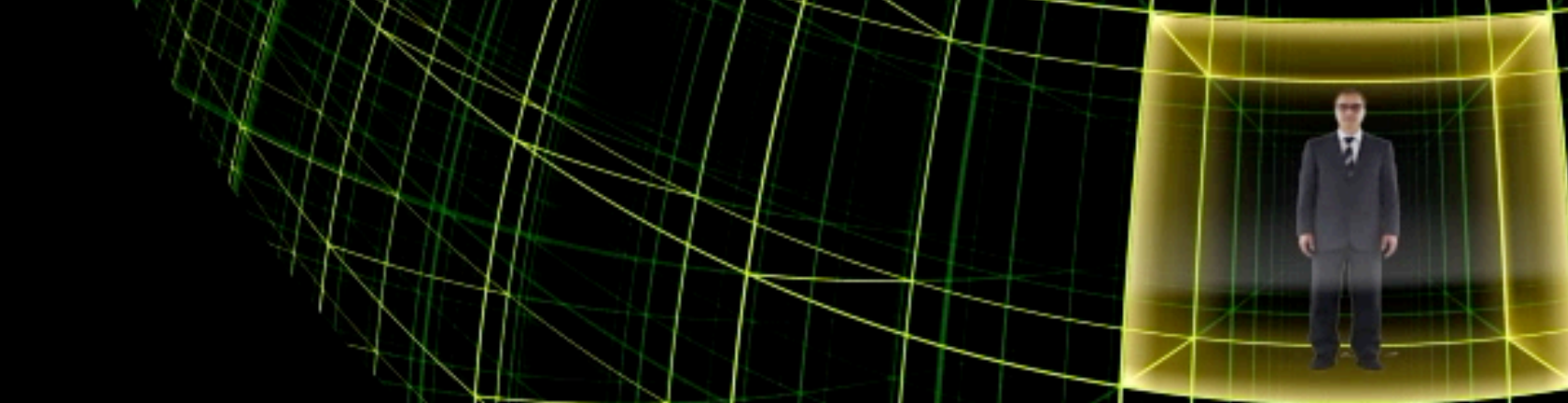


HORIZON :Beyond the Edge of the Visible Universe [Trailer]

From “HORIZON”



Where did the CMB we see today come from?



155

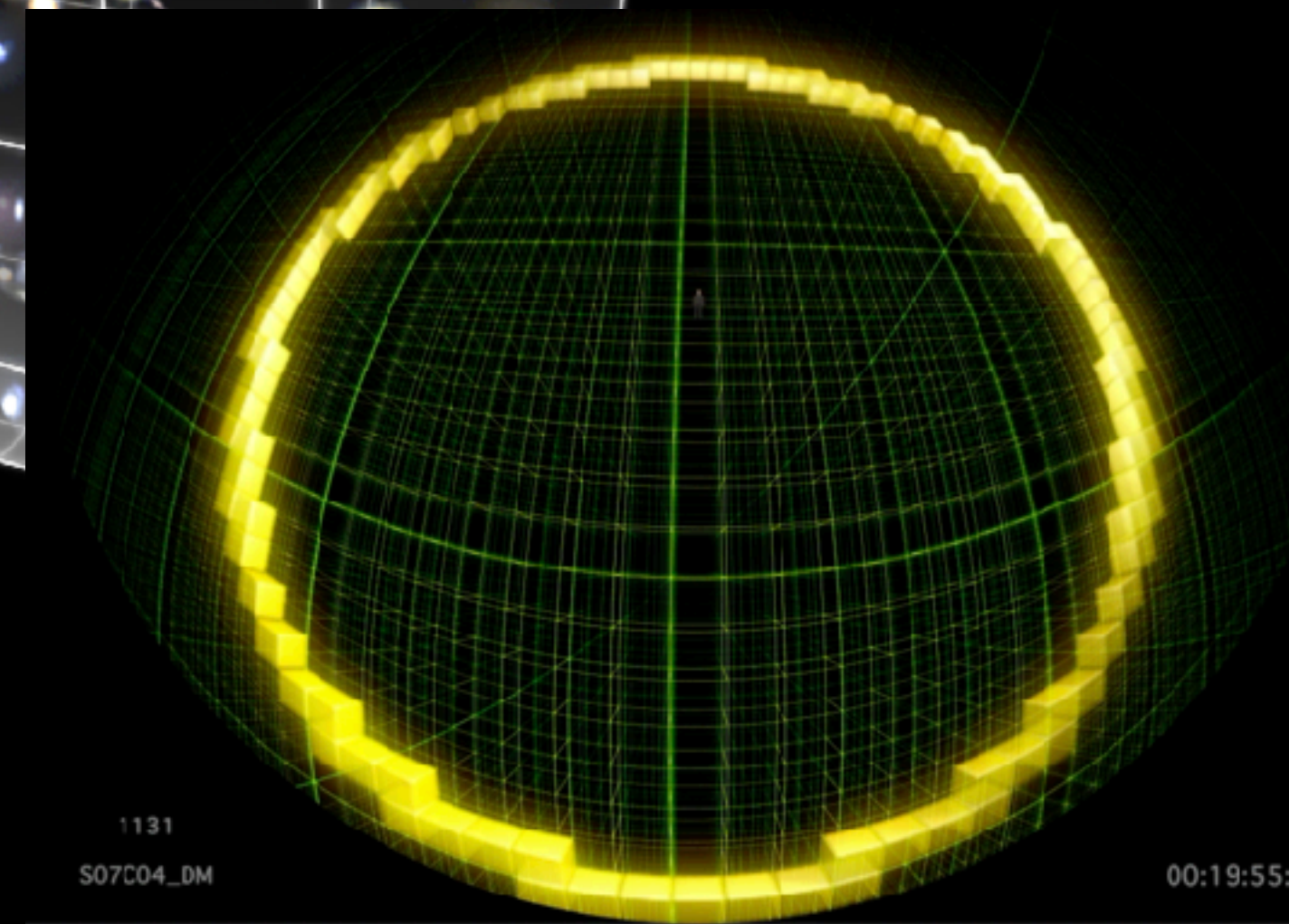
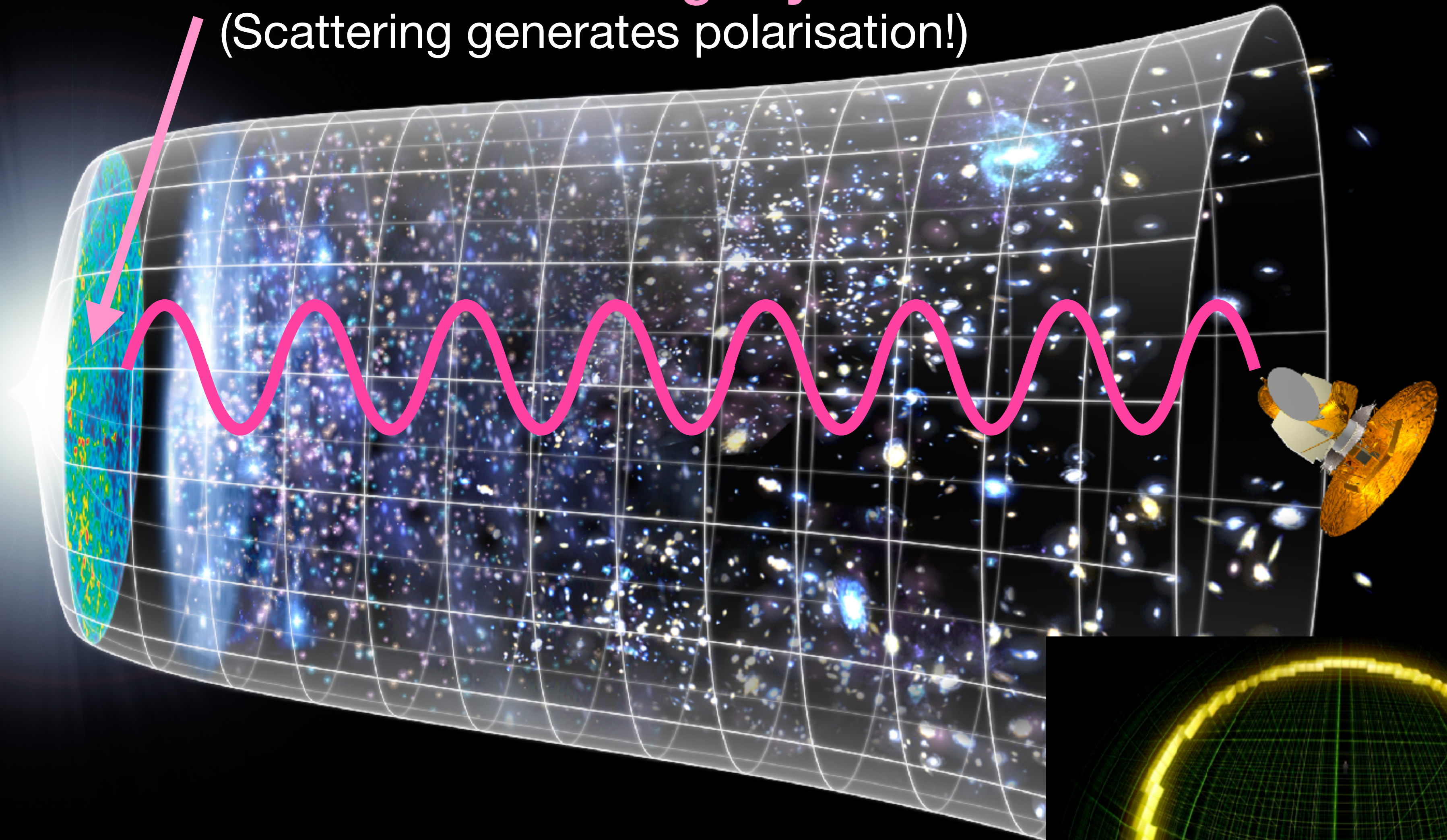
S07C04_DM

00:19:22:14

From “HORIZON”

The surface of “last scattering” by electrons

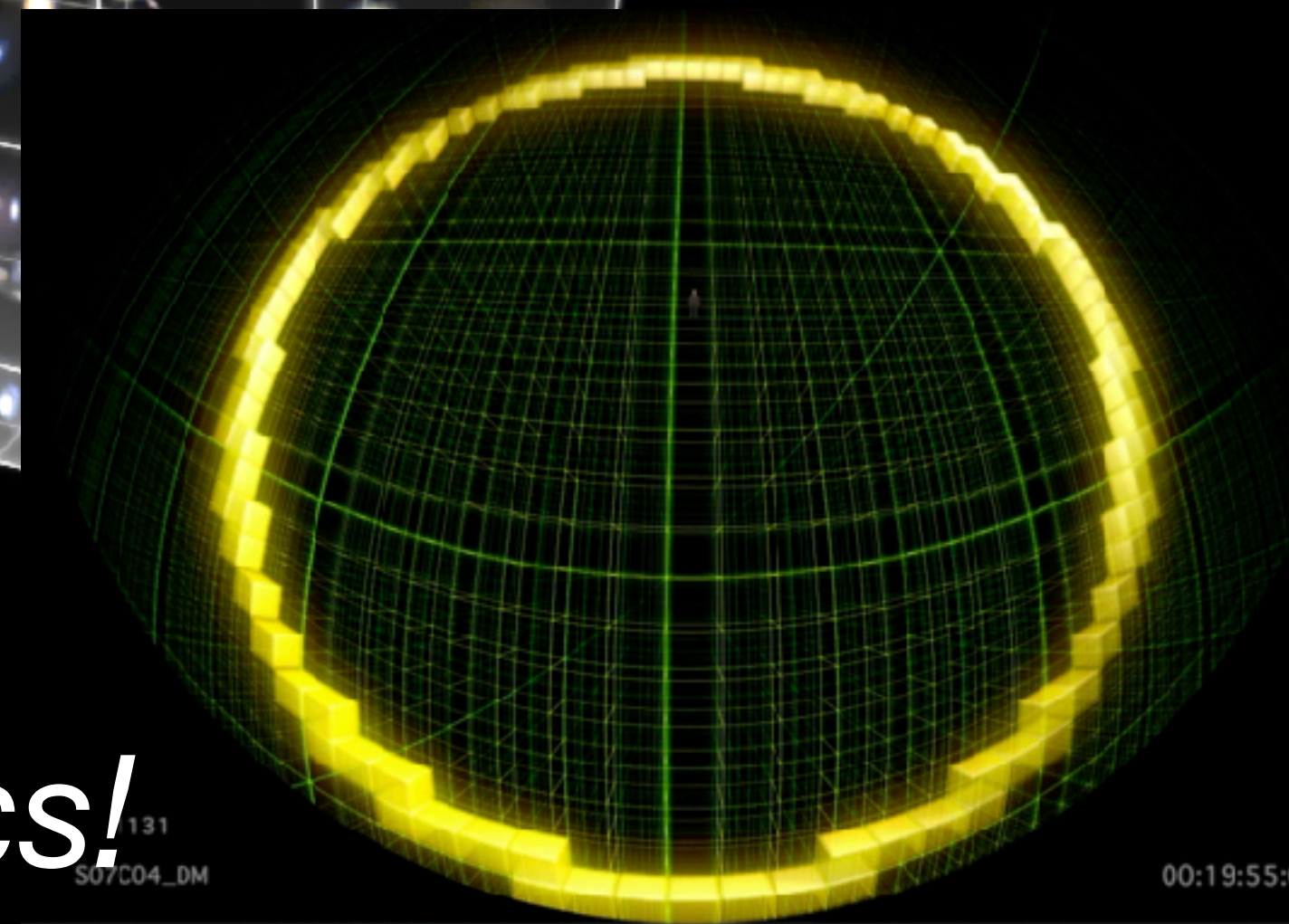
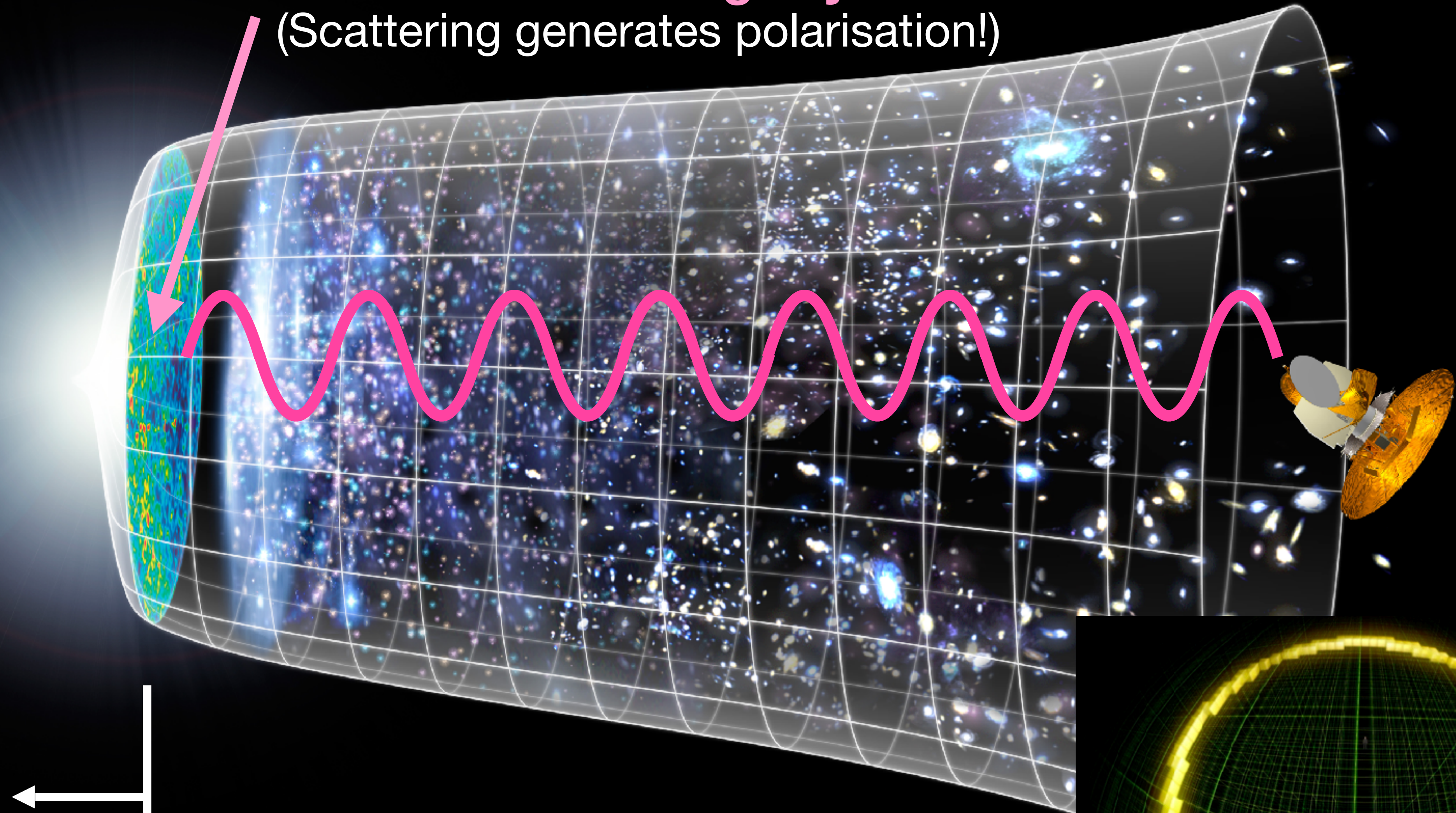
(Scattering generates polarisation!)



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

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)**

Gravitational Field Equations (Einstein's Eq.)

Credit: WMAP Science Team

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

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

Energy Conservation

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

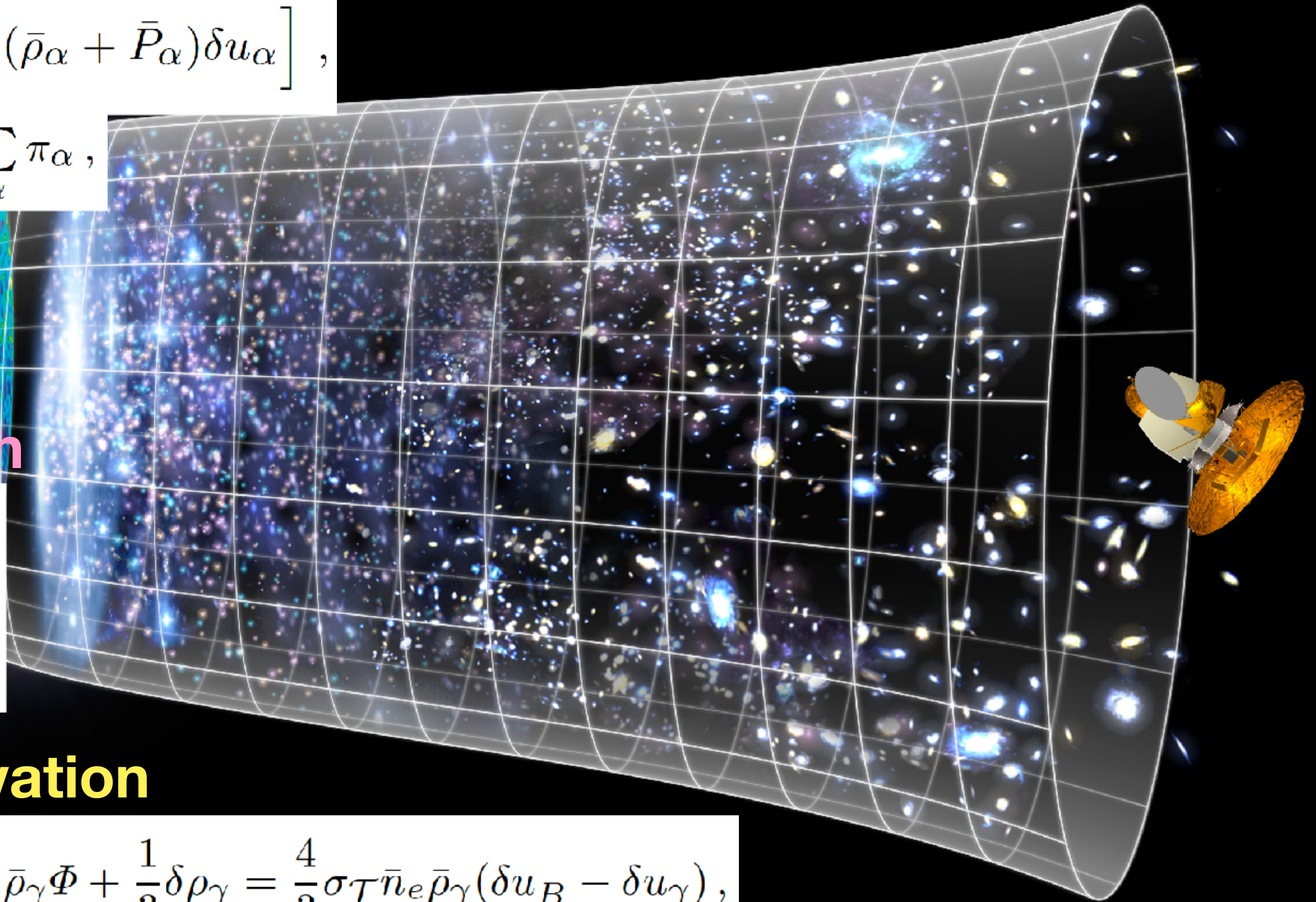
$$\frac{\partial}{\partial t} (\delta \rho_B / \bar{\rho}_B) - \frac{q^2}{a^2} \delta u_B = 3\dot{\Psi},$$

Momentum Conservation

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

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

Laws of physics!



Gravitational Field Equations

+

Energy Conservation

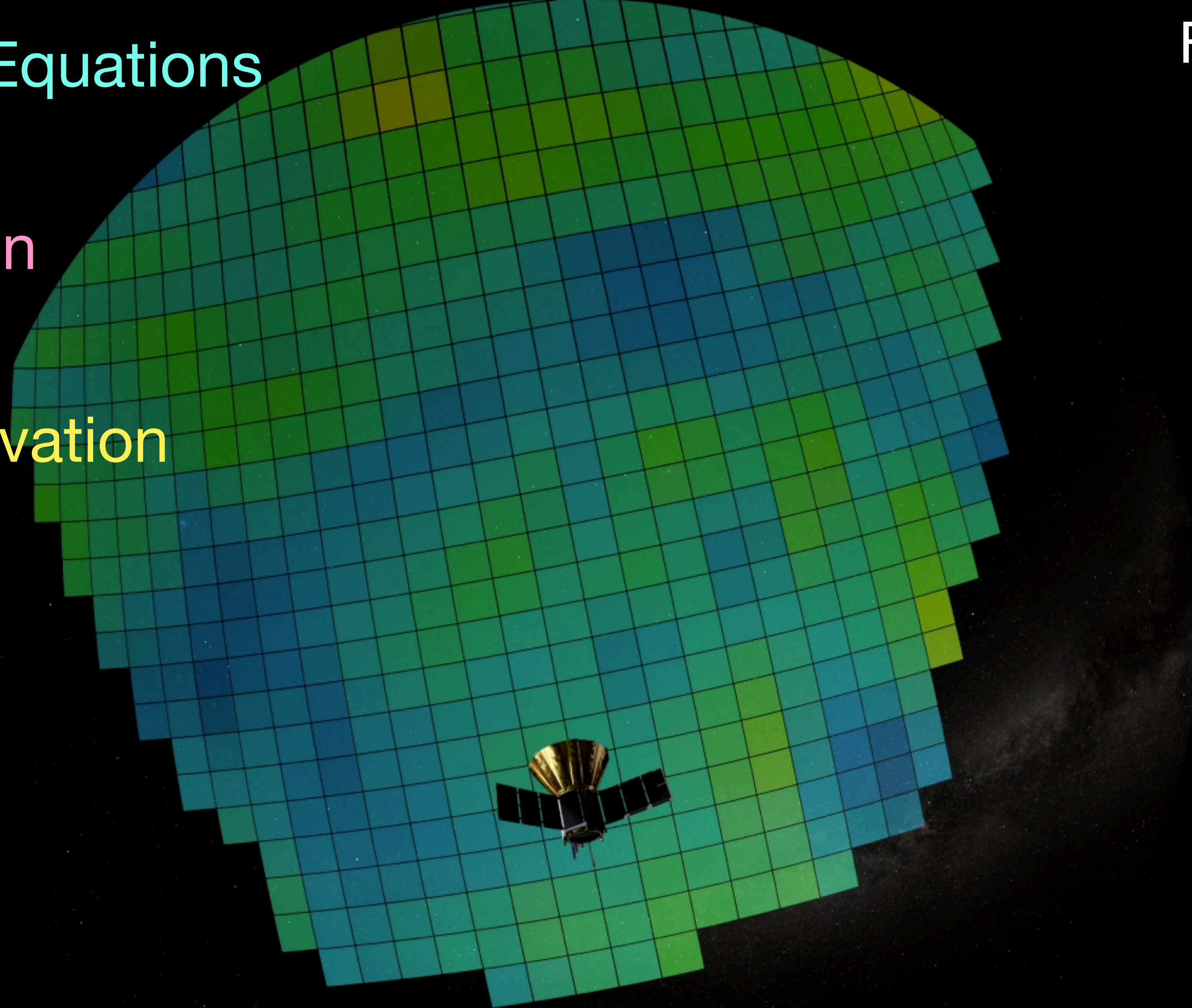
+

Momentum Conservation

||

Sound Waves!

From “HORIZON”

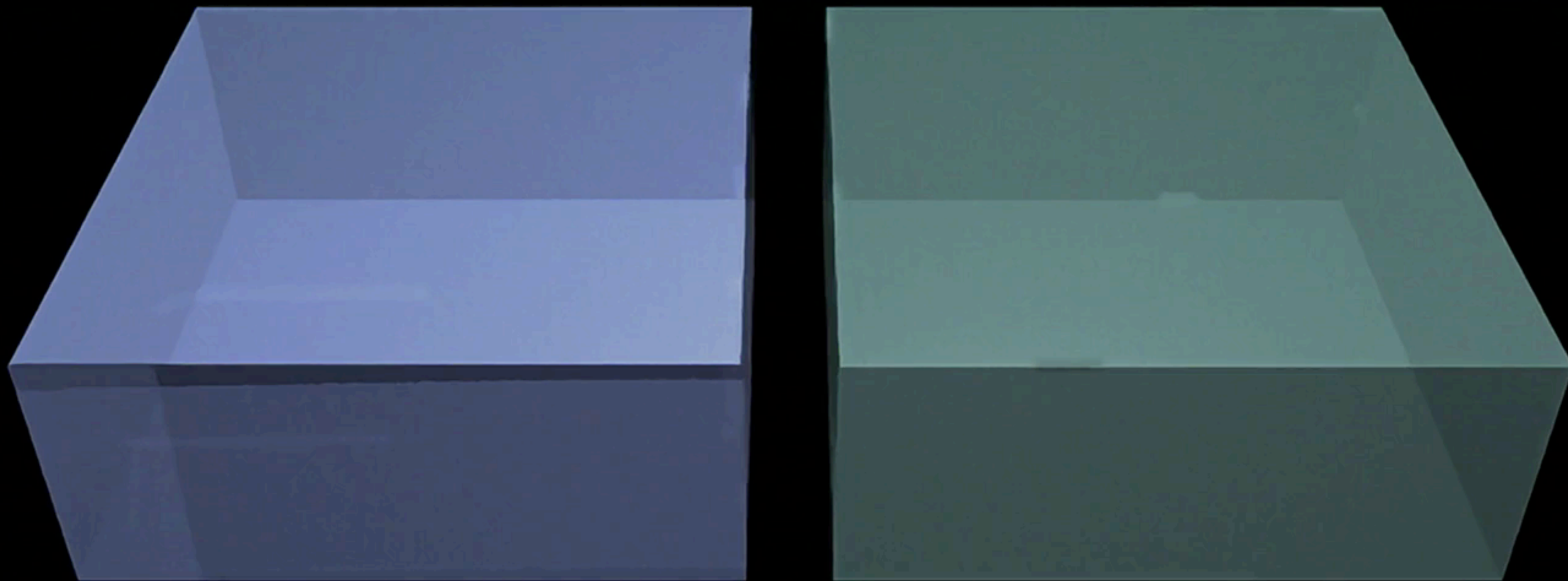


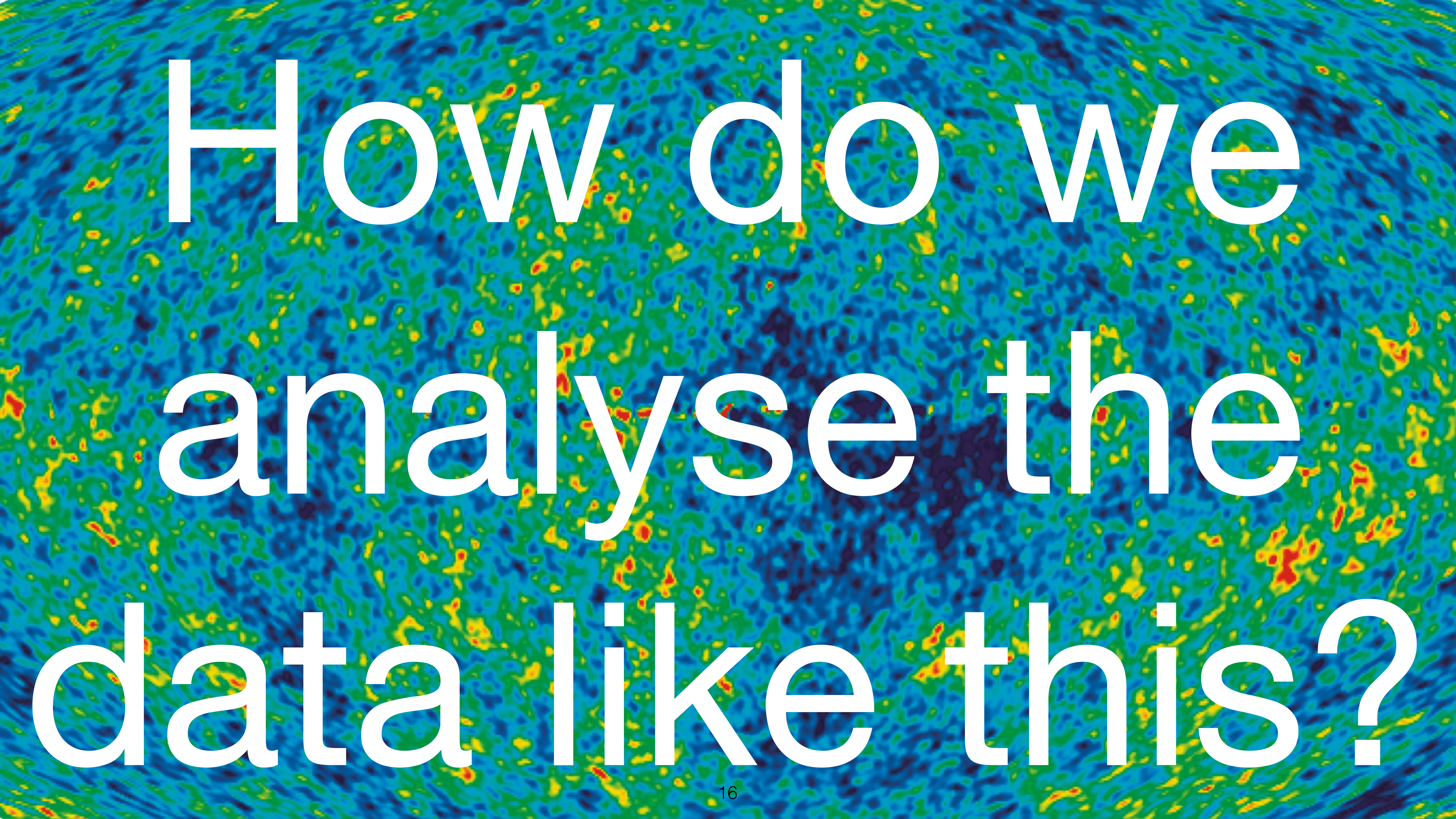


Sopa de Missô Cósmica

- 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

Credit: WMAP Science Team

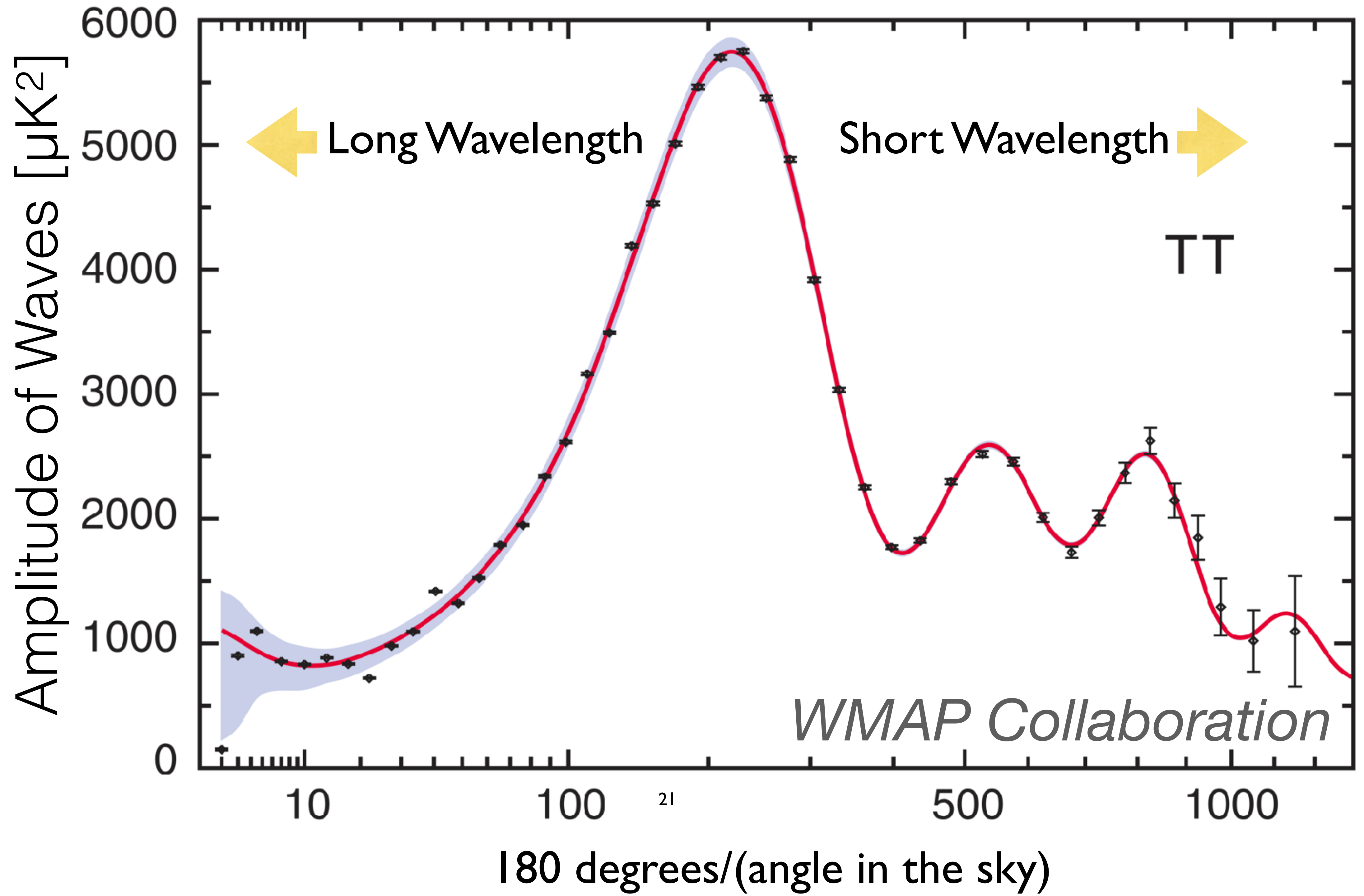


The background of the slide is a Cosmic Microwave Background (CMB) fluctuation map. It shows a complex pattern of temperature variations across the sky, with colors ranging from dark blue (cooler) to red and yellow (warmer). The pattern consists of numerous small, irregular patches and larger-scale structures, representing the primordial density fluctuations in the early universe.

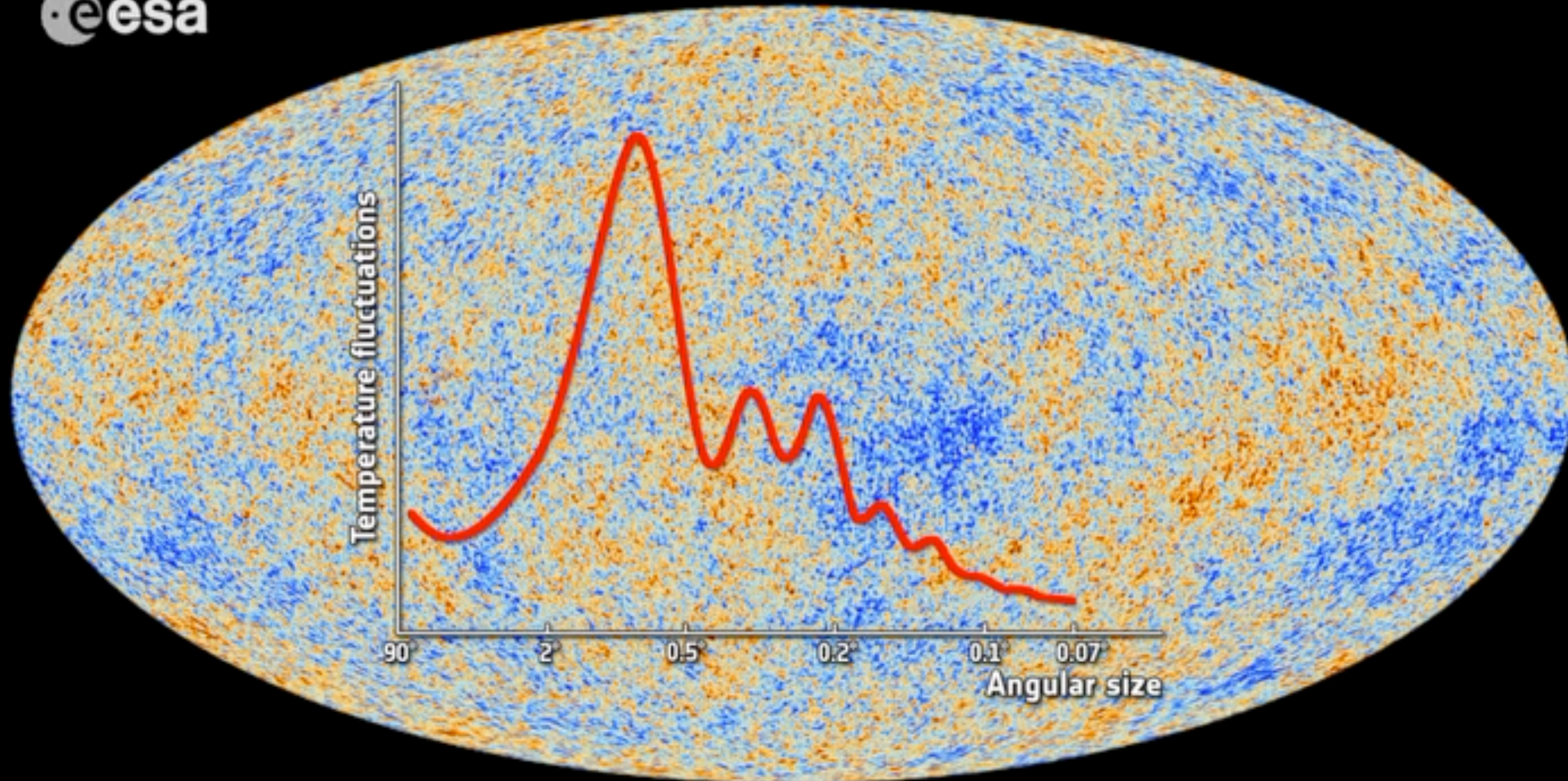
How do we
analyse the
data like this?

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**



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"

James Peebles Facts

Sound waves in the fireball Universe, predicted in 1970



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

THE ASTROPHYSICAL JOURNAL, 162:815–836, December 1970

© 1970 The University of Chicago All rights reserved Printed in U S.A.

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



Sound waves in the fireball Universe, predicted in 1970

Astrophysics and Space Science 7 (1970) 3–19. All Rights Reserved
Copyright © 1970 by D. Reidel Publishing Company, Dordrecht-Holland

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)

The Franklin Institute
of Physics



and told me that I am lazy.



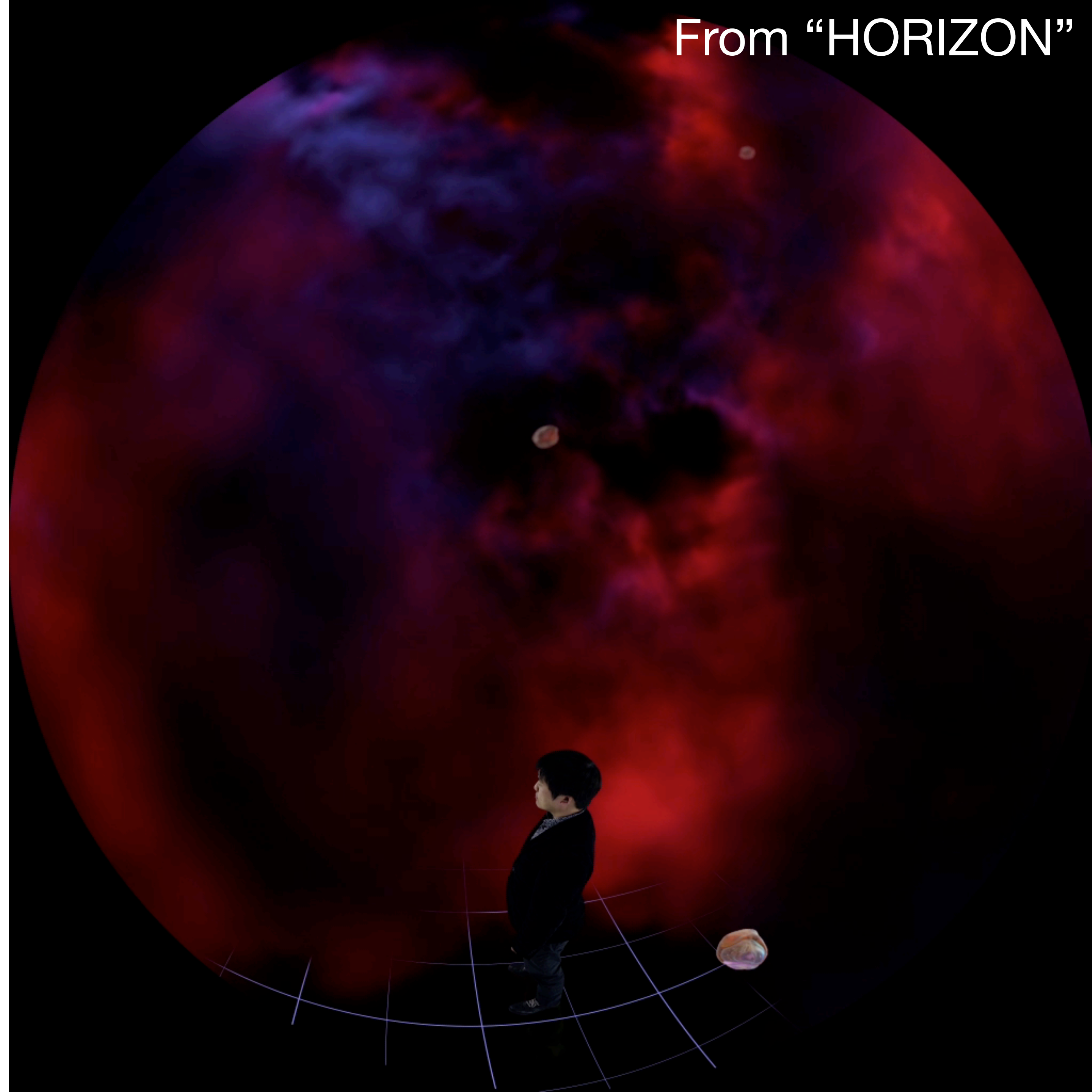
Determine the composition of the Universe

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!**



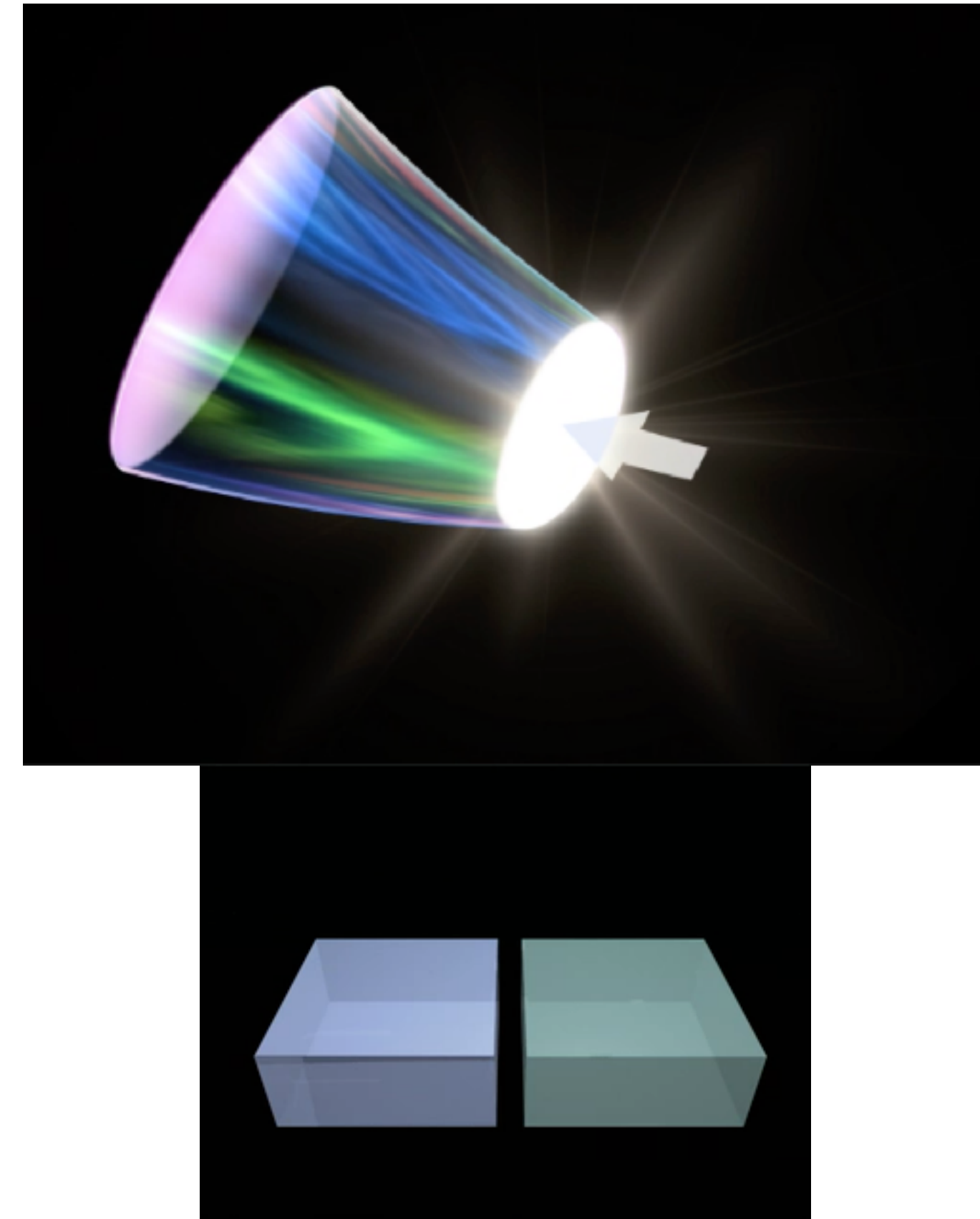
“Let’s give some impact to the beginning of this model”

- 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?**



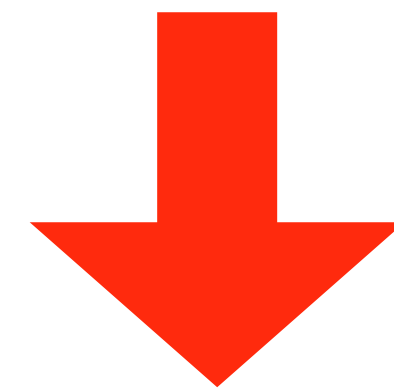
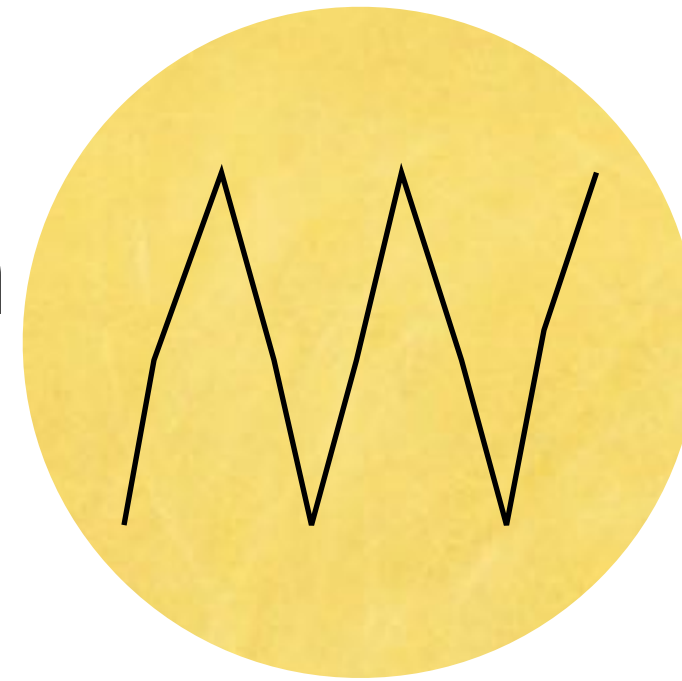
Gravity + Quantum

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

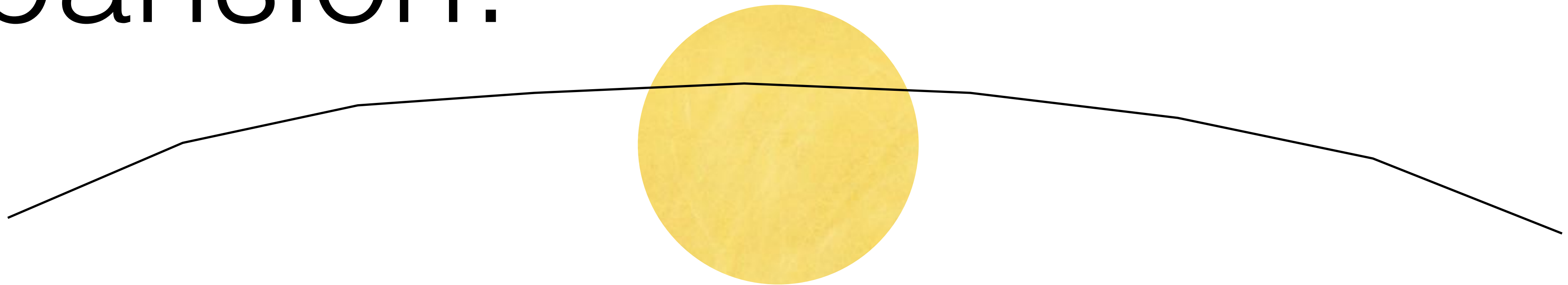
Starobinsky (1980); Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

Quantum mechanical fluctuation
on microscopic scales



Exponential
Expansion!



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

**What? How can we believe such
a statement?**

We have accumulated very good evidence so far

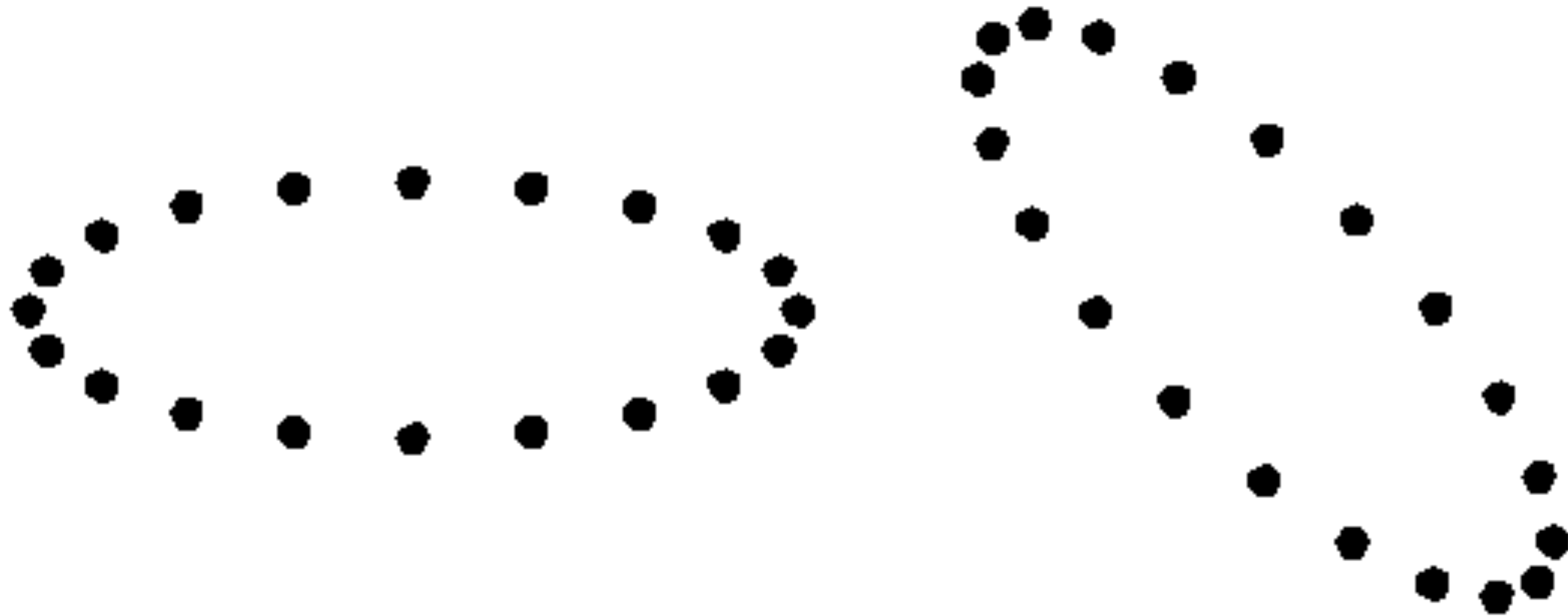
The next step: Primordial Gravitational Waves

- Since the first discovery of the CMB temperature fluctuation by COBE in 1992, we have made a tremendous progress in making much more detailed measurements of the CMB over the last three decades.
- Three space missions, COBE (NASA) -> WMAP (NASA) -> Planck (ESA), as well as a host of ground-based and balloon-borne experiments. **Truly the global community effort!**
- What more do we want? **Primordial gravitational waves.** (Starobinsky 1979)
- Why more evidence? Because “*the extraordinary claim requires extraordinary evidence*” (Carl Sagan)

**Let's talk about the gravitational
waves (tensor modes)**

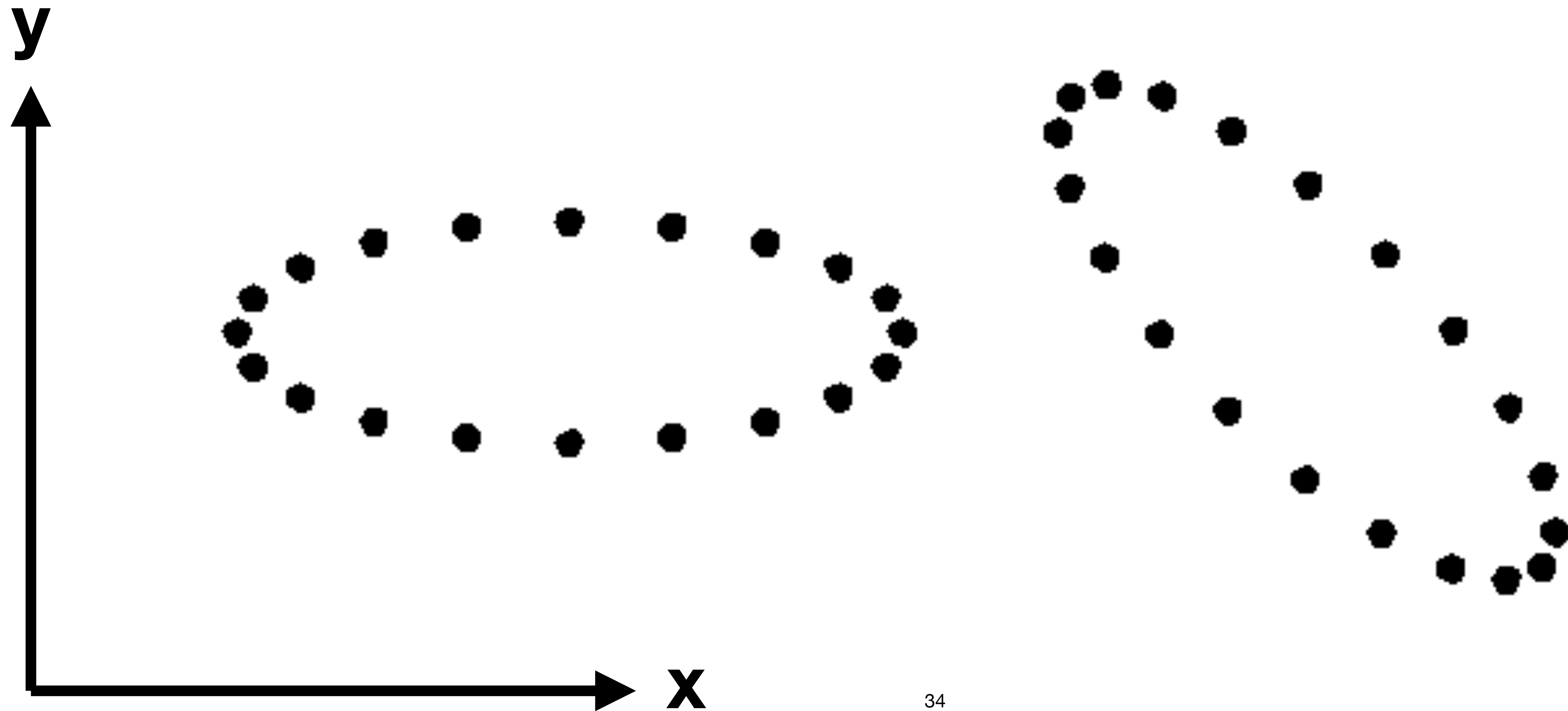
Gravitational waves are coming towards you!

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

- Compact notation using Kronecker's delta symbol:

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

$x = (x, y, z)$

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

- To include distortion in space,

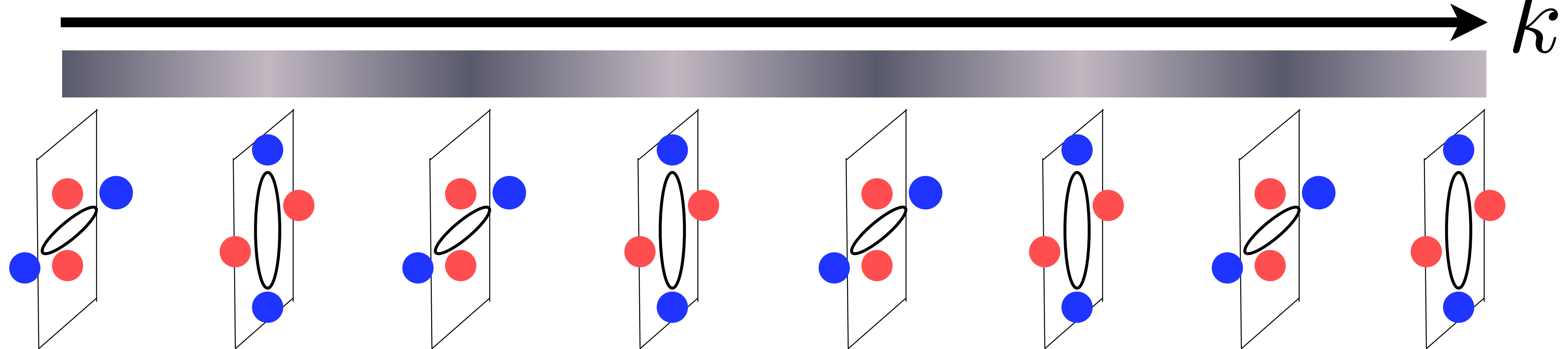
$$ds^2 = a^2 \sum_{i=1}^3 \sum_{j=1}^3 (\delta_{ij} + \boxed{h_{ij}}) dx^i dx^j$$

Distortion in space!

Four conditions for gravitational waves

- The gravitational wave shall be transverse.

- The direction of distortion is perpendicular to the propagation direction \vec{k}



Thus,

$$\sum_{i=1}^3 k^i h_{ij} = 0$$

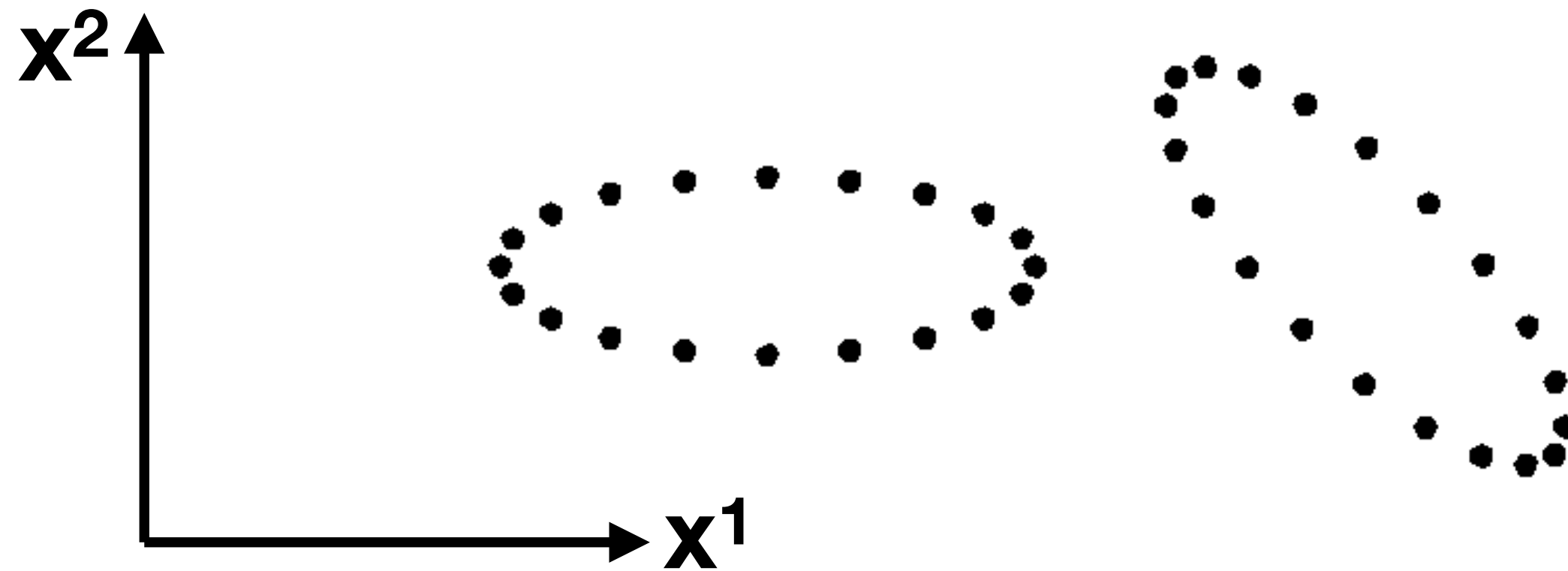
3 conditions for h_{ij}

Four conditions for gravitational waves

- The gravitational wave shall not change the area

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

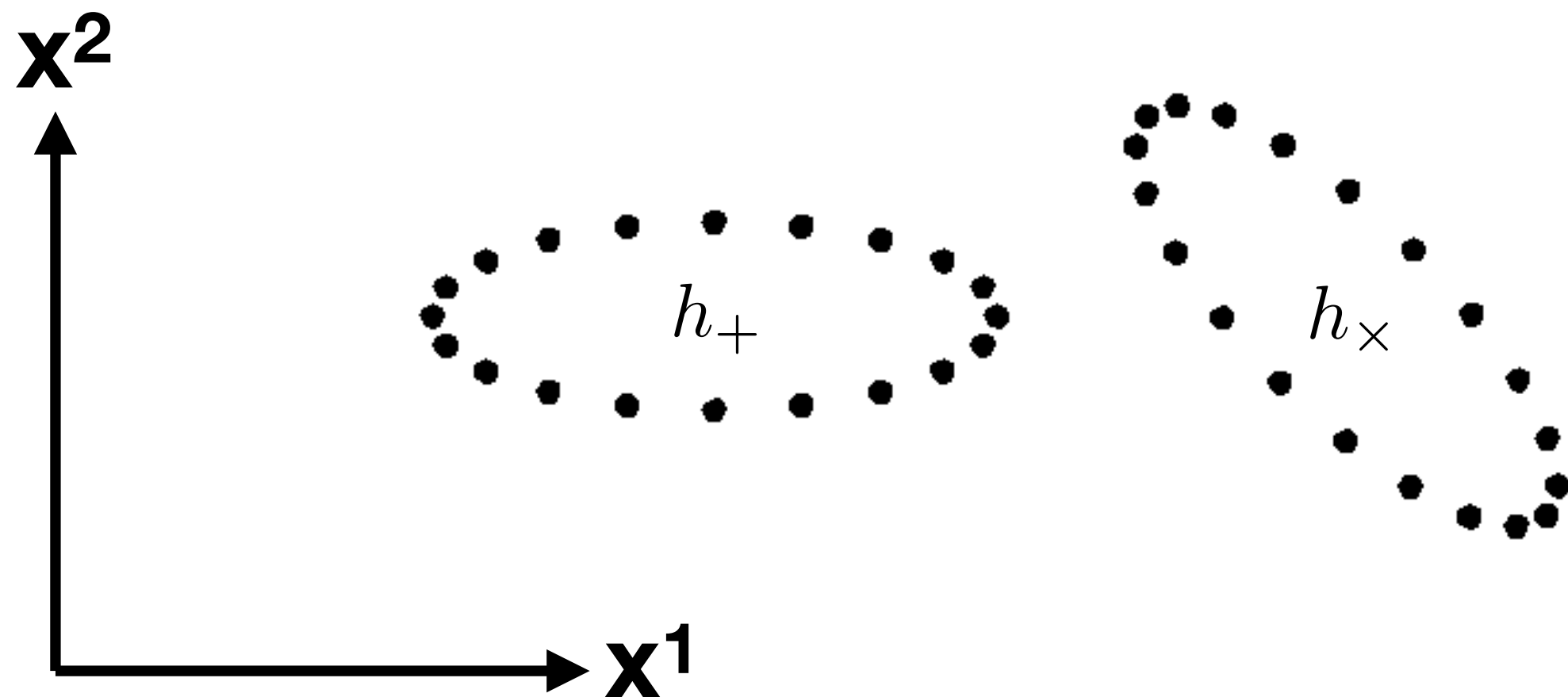
1 condition for h_{ij}

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

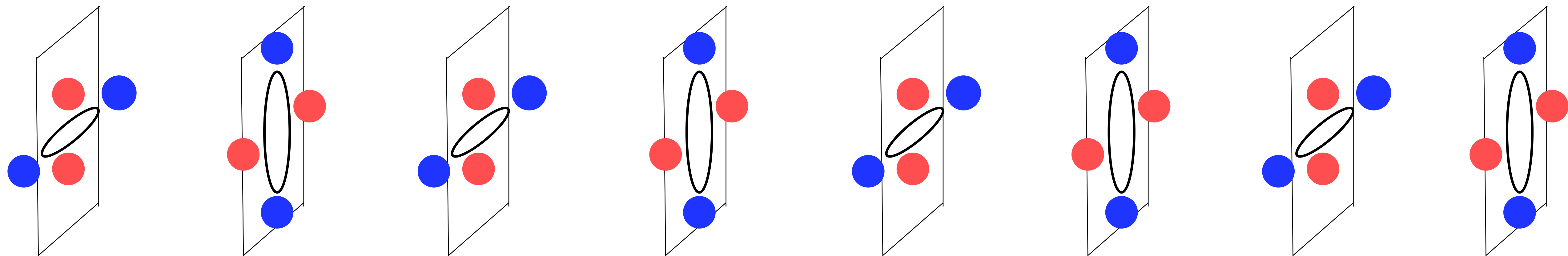
$$h_{ij} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



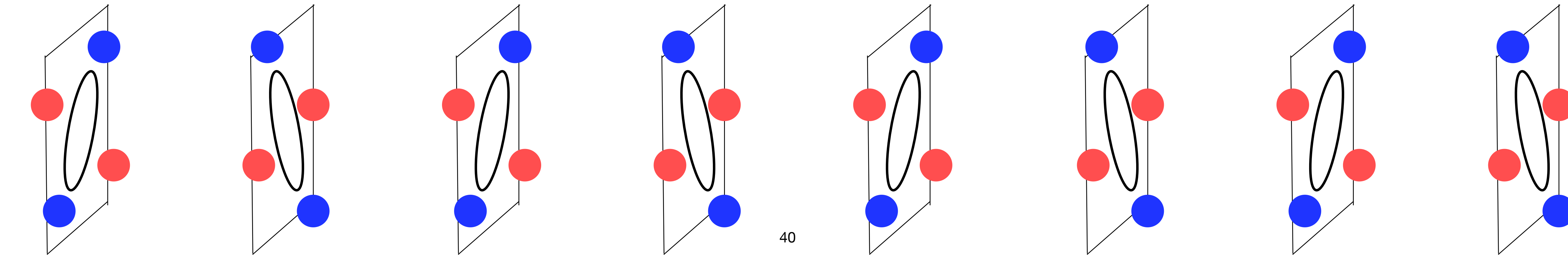
Propagation direction of GW \vec{k}



$h_+ = \cos(kz)$

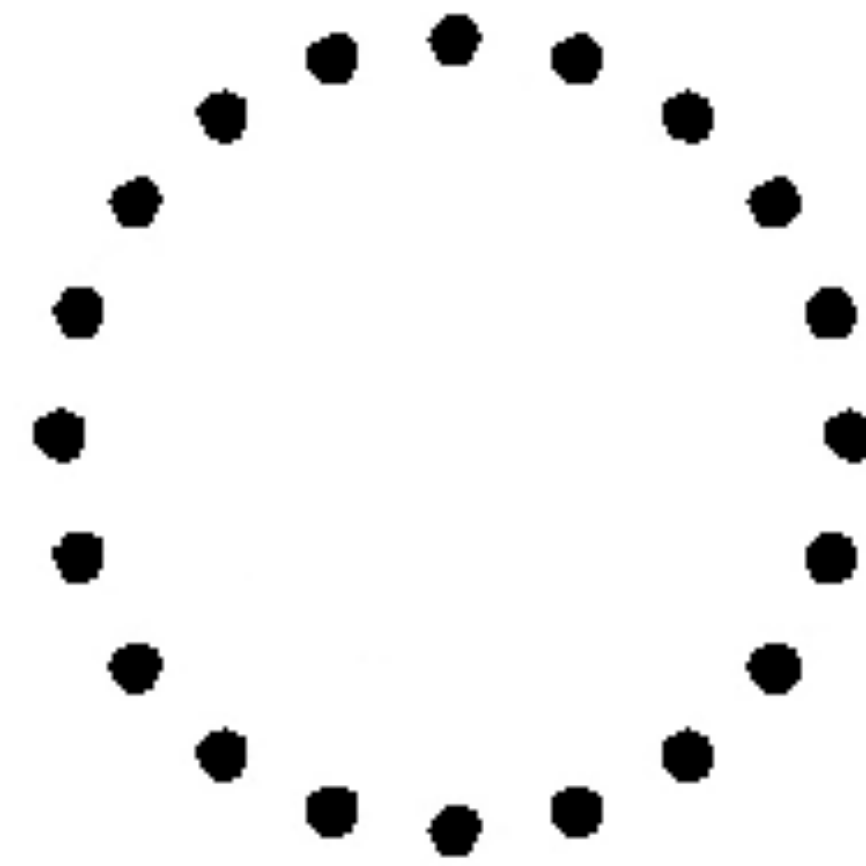
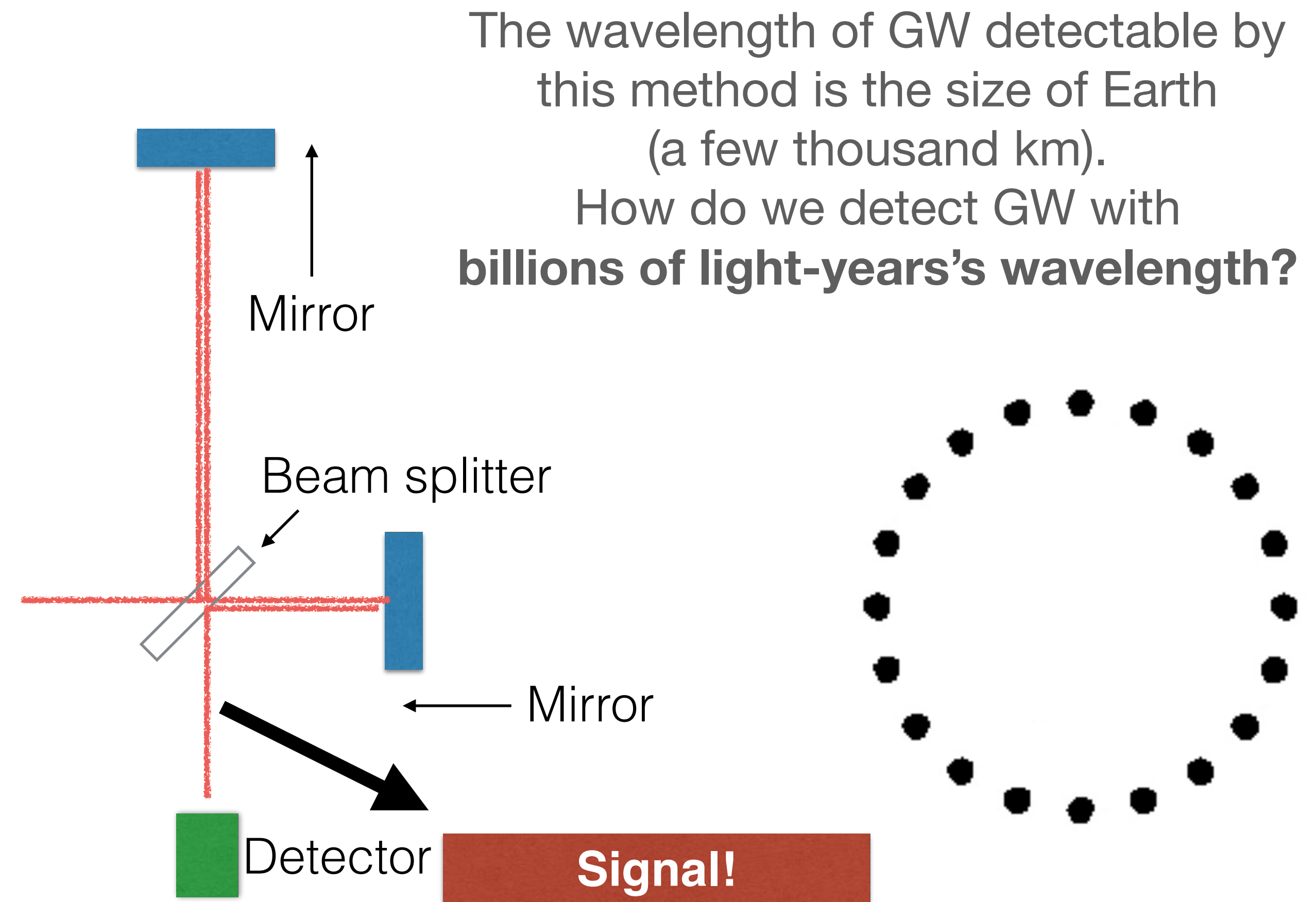
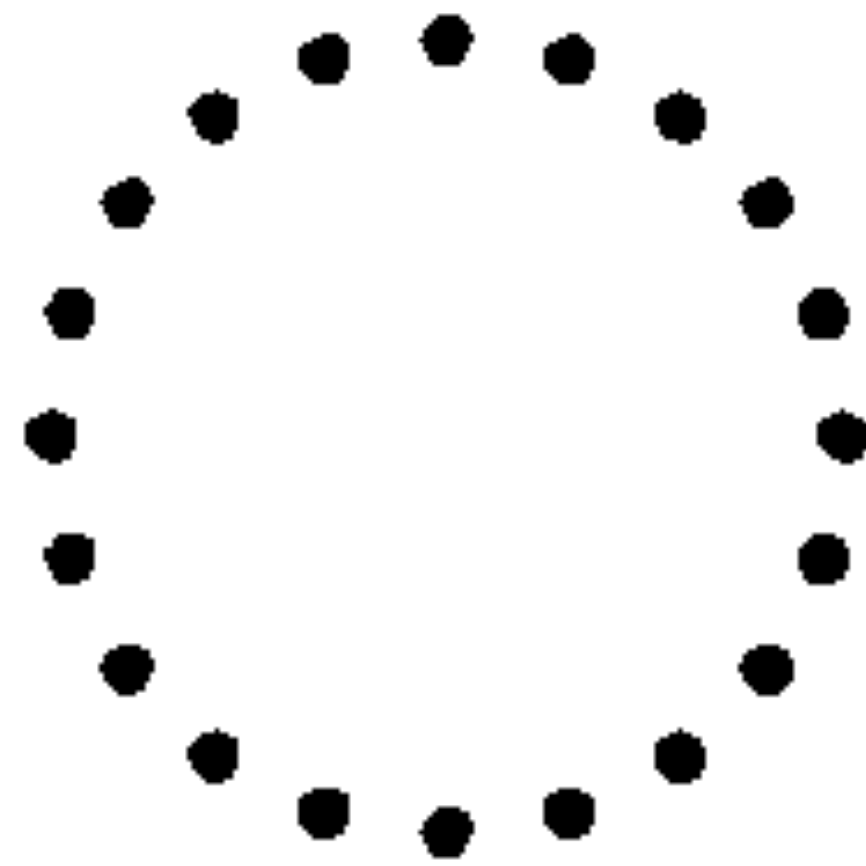
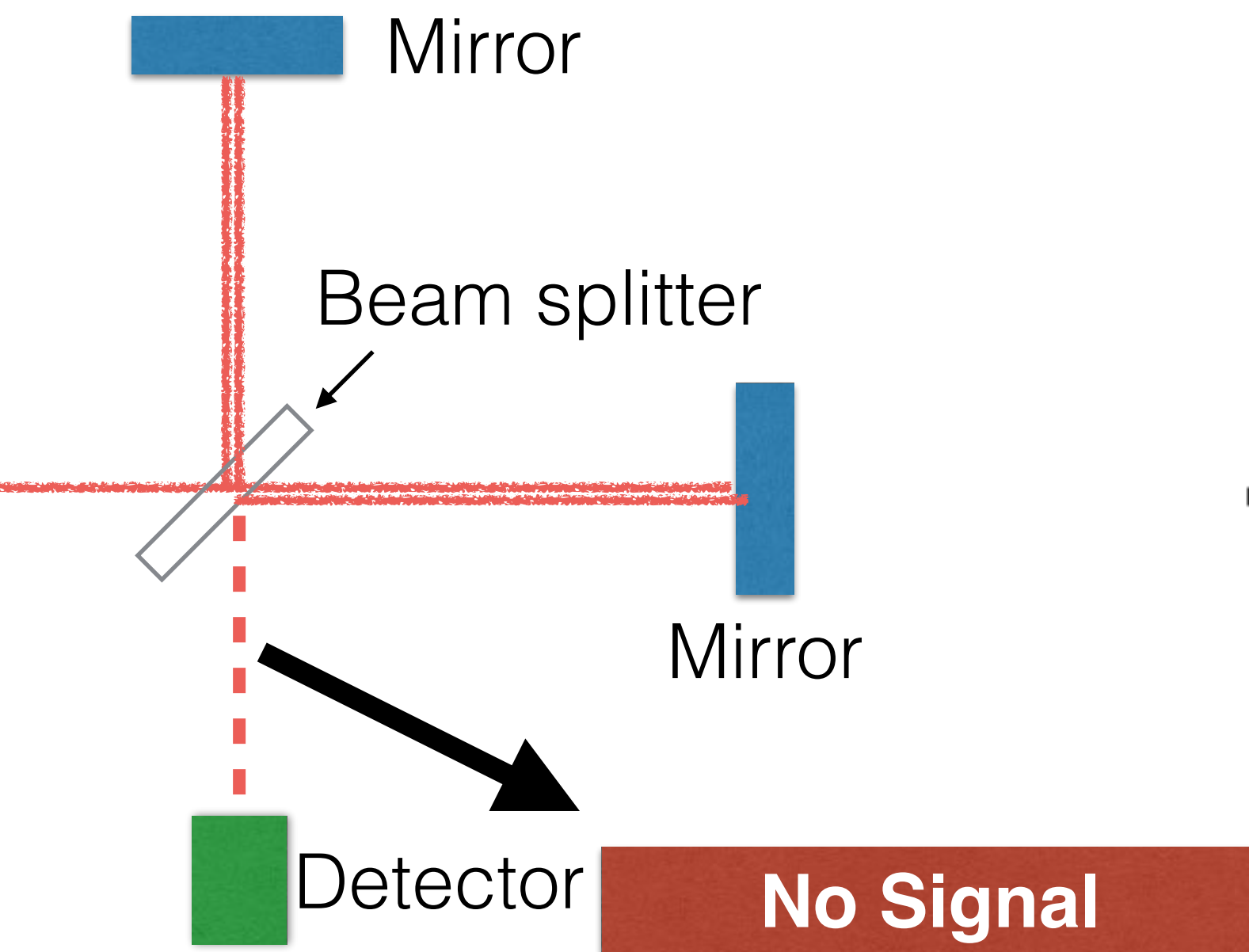


$h_x = \cos(kz)$



How to detect GW?

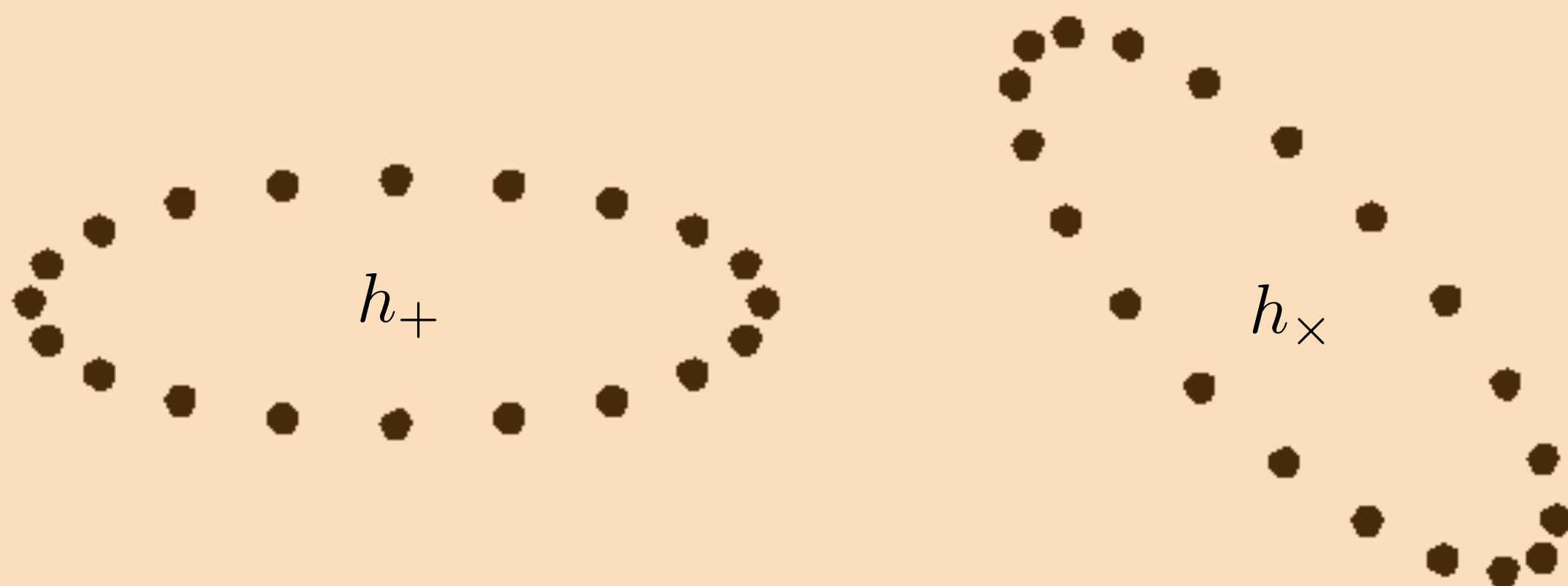
Laser interferometer technique, used by LIGO and VIRGO



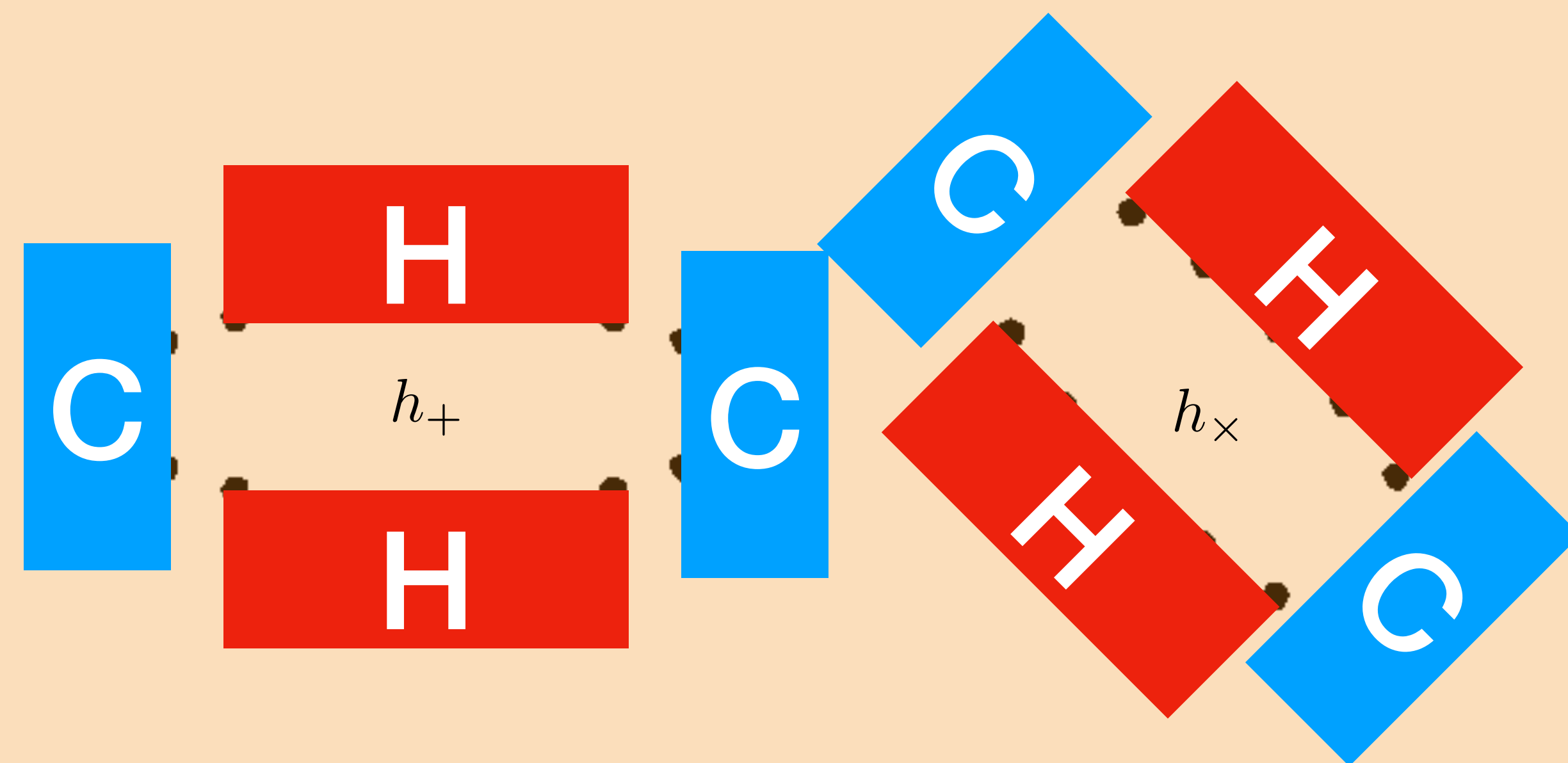
Detecting GW by CMB

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

Isotropic radiation field (CMB)



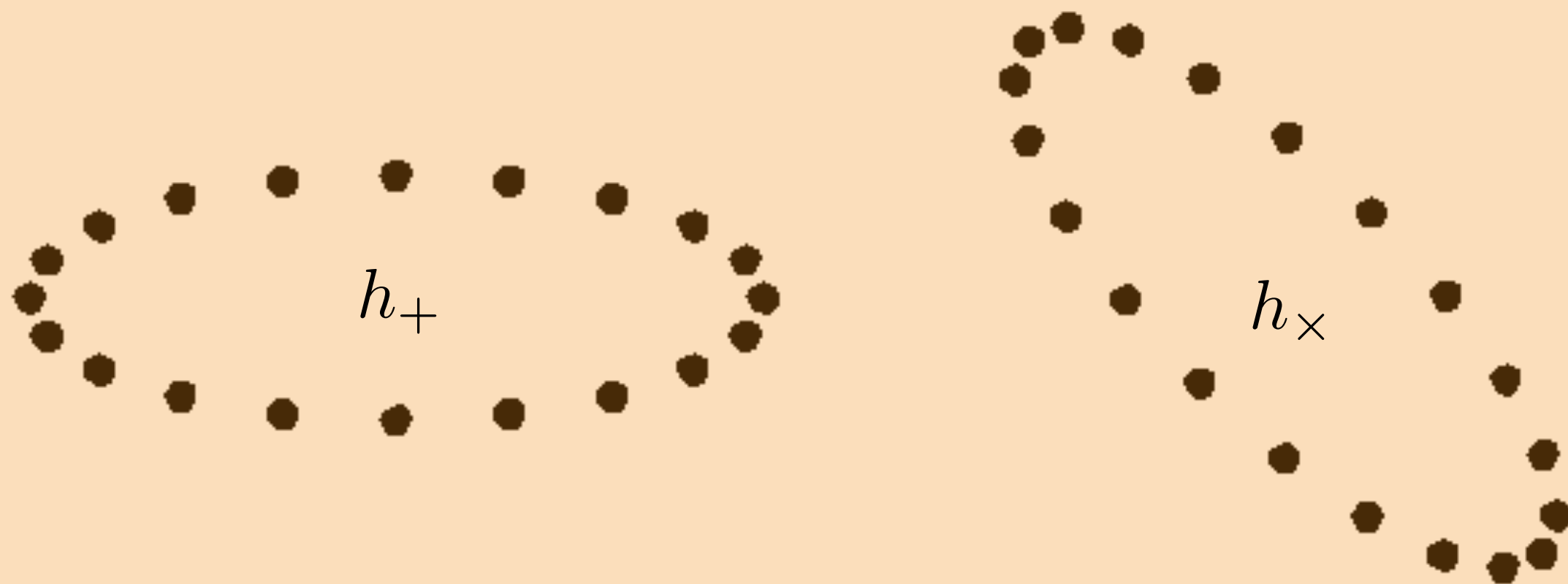
Isotropic radiation field (CMB)



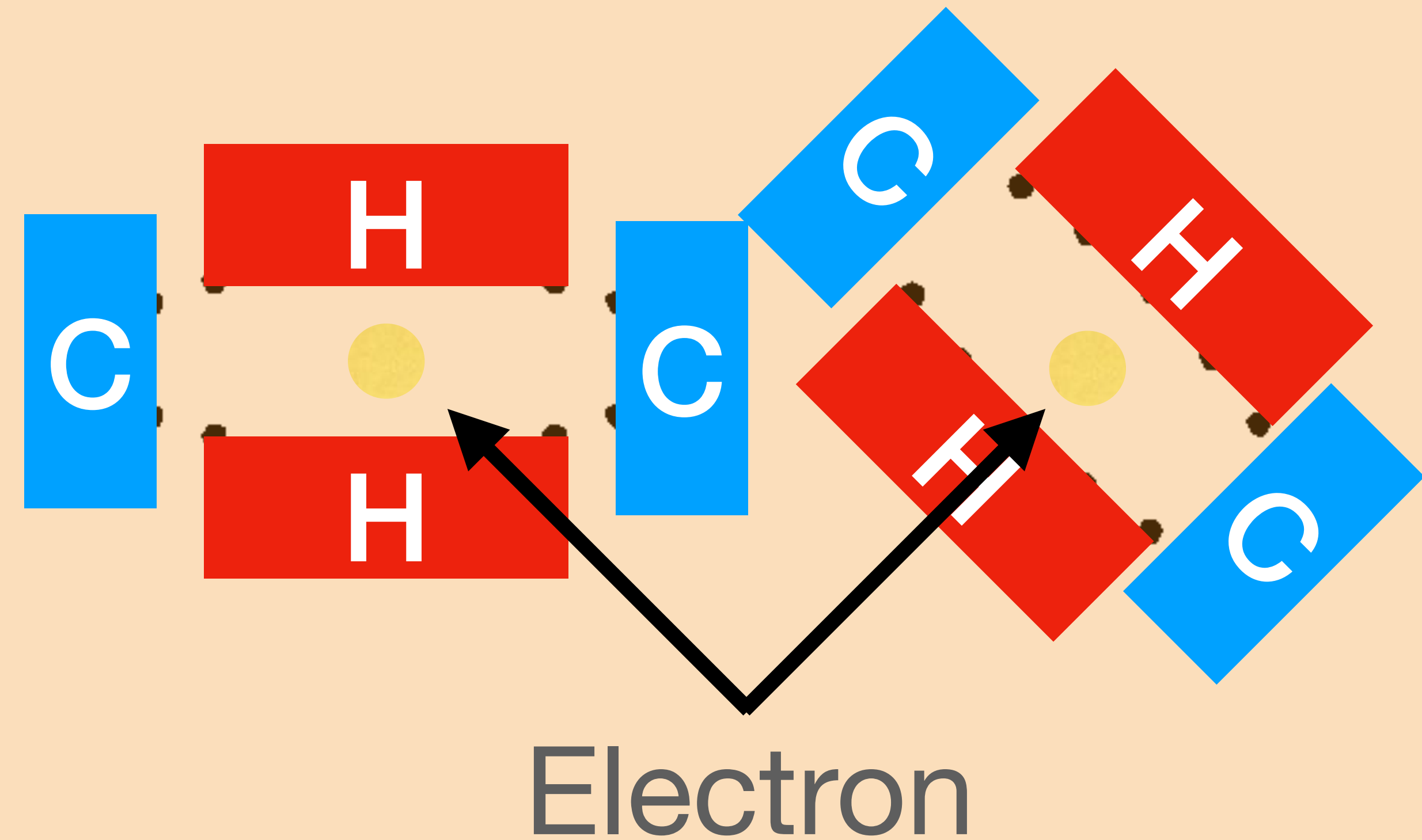
Detecting GW by CMB

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

Isotropic radiation field (CMB)



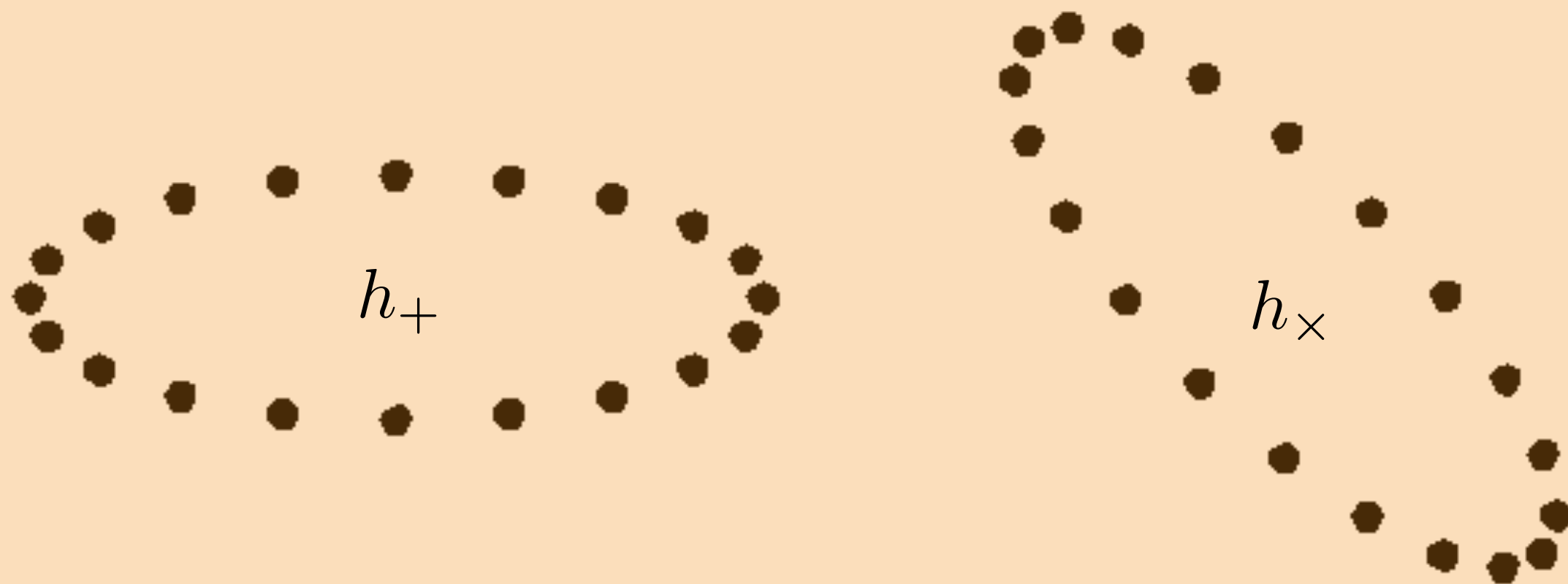
Isotropic radiation field (CMB)



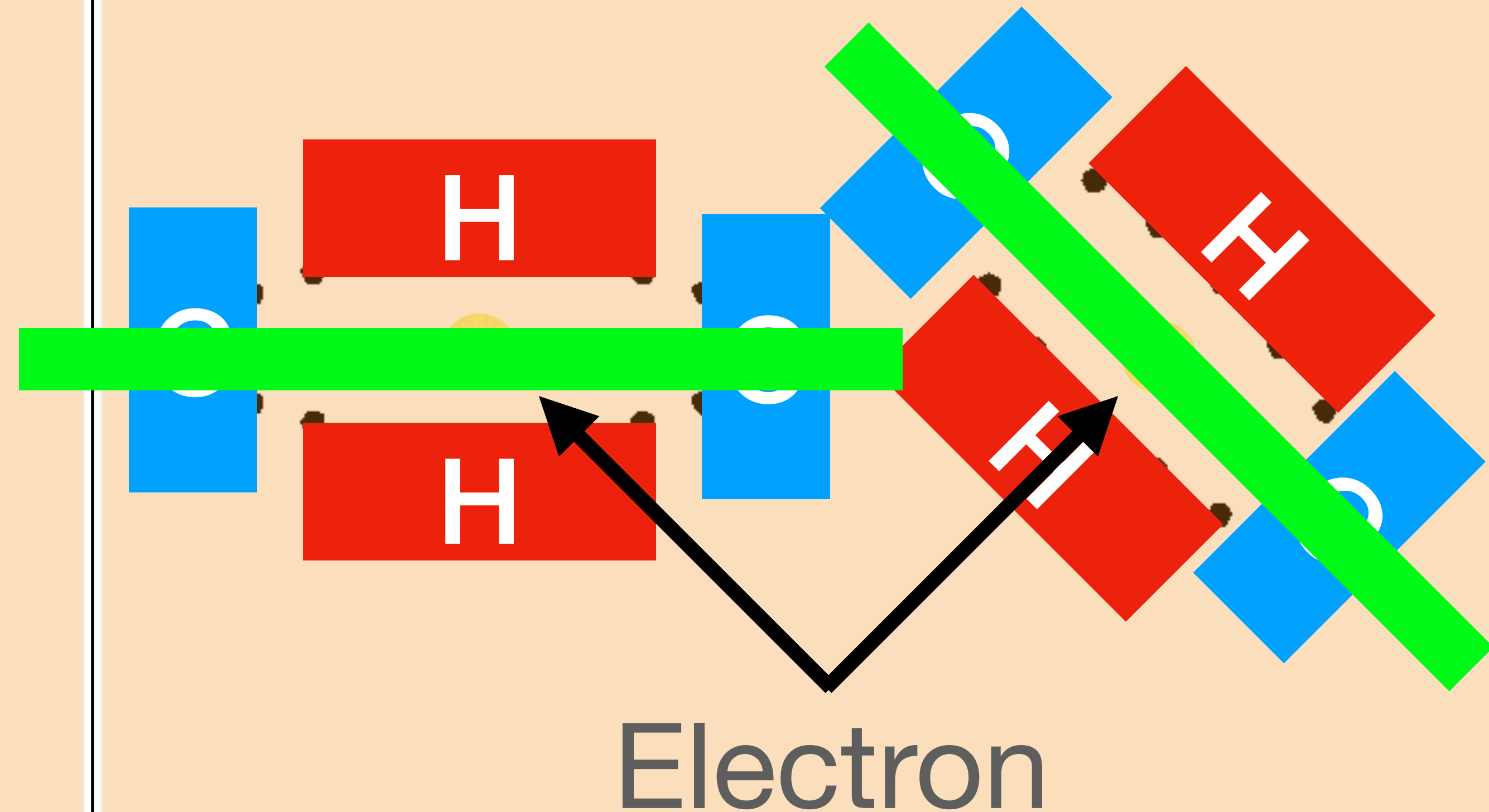
Detecting GW by CMB *Polarisation*

Quadrupole temperature anisotropy scattered by an electron

Isotropic radiation field (CMB)



Isotropic radiation field (CMB)



Credit: TALEX

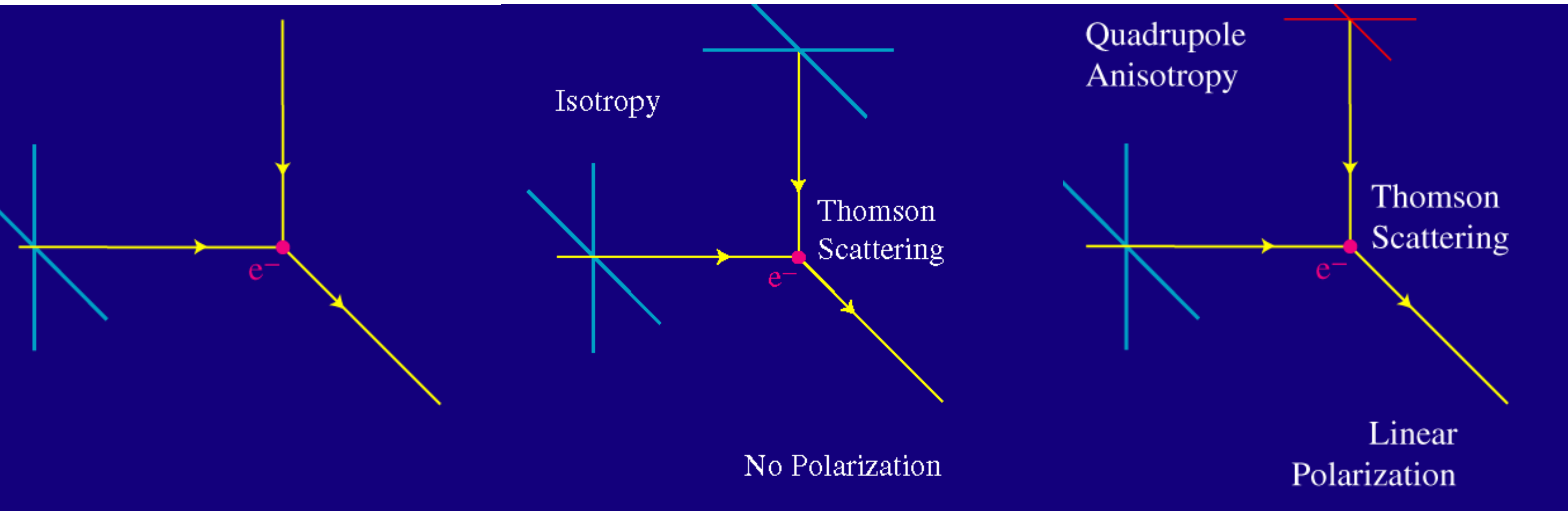


Credit: TALEX

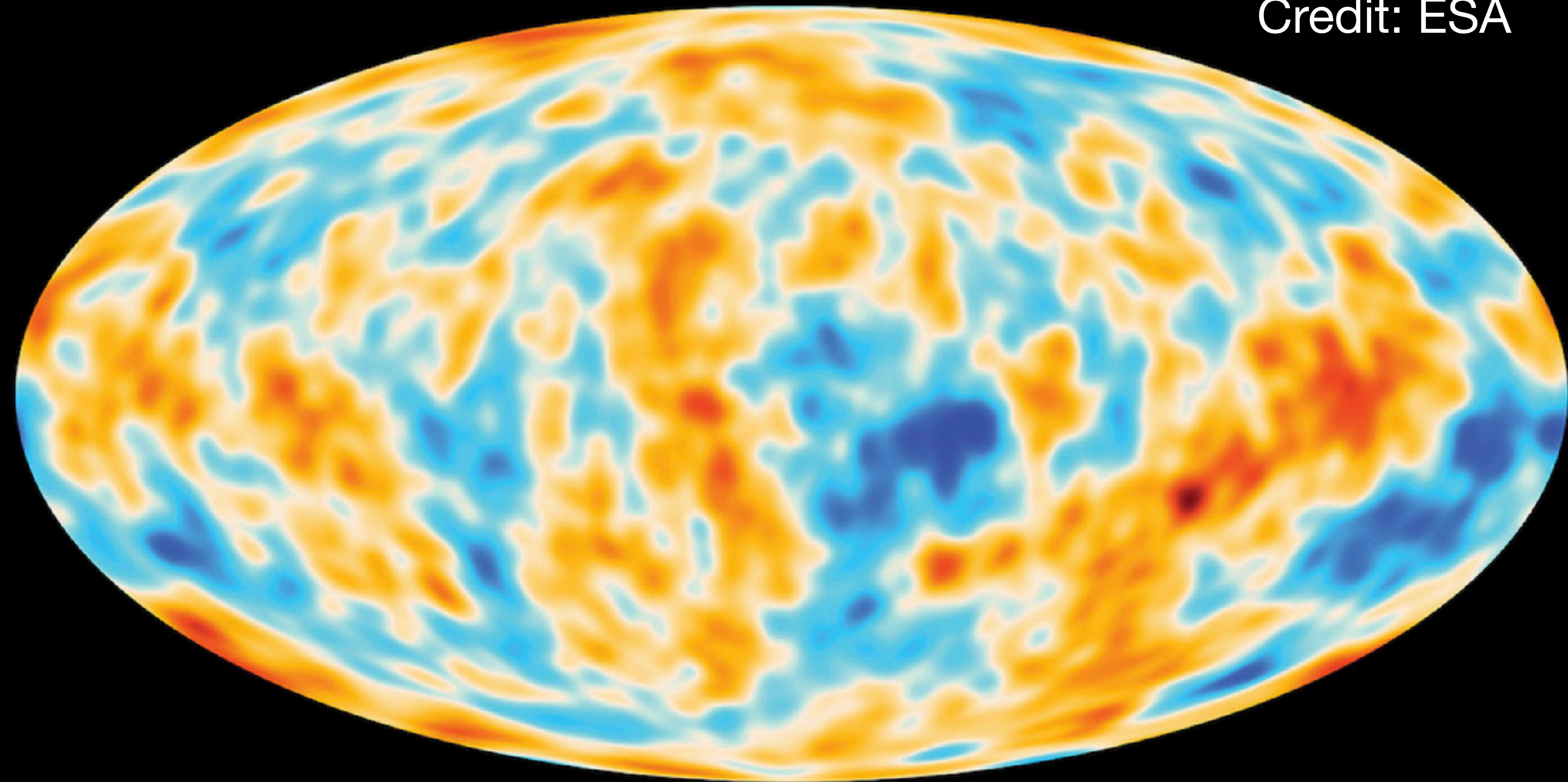


Physics of CMB Polarisation

Necessary and sufficient condition: Scattering and Quadrupole Anisotropy

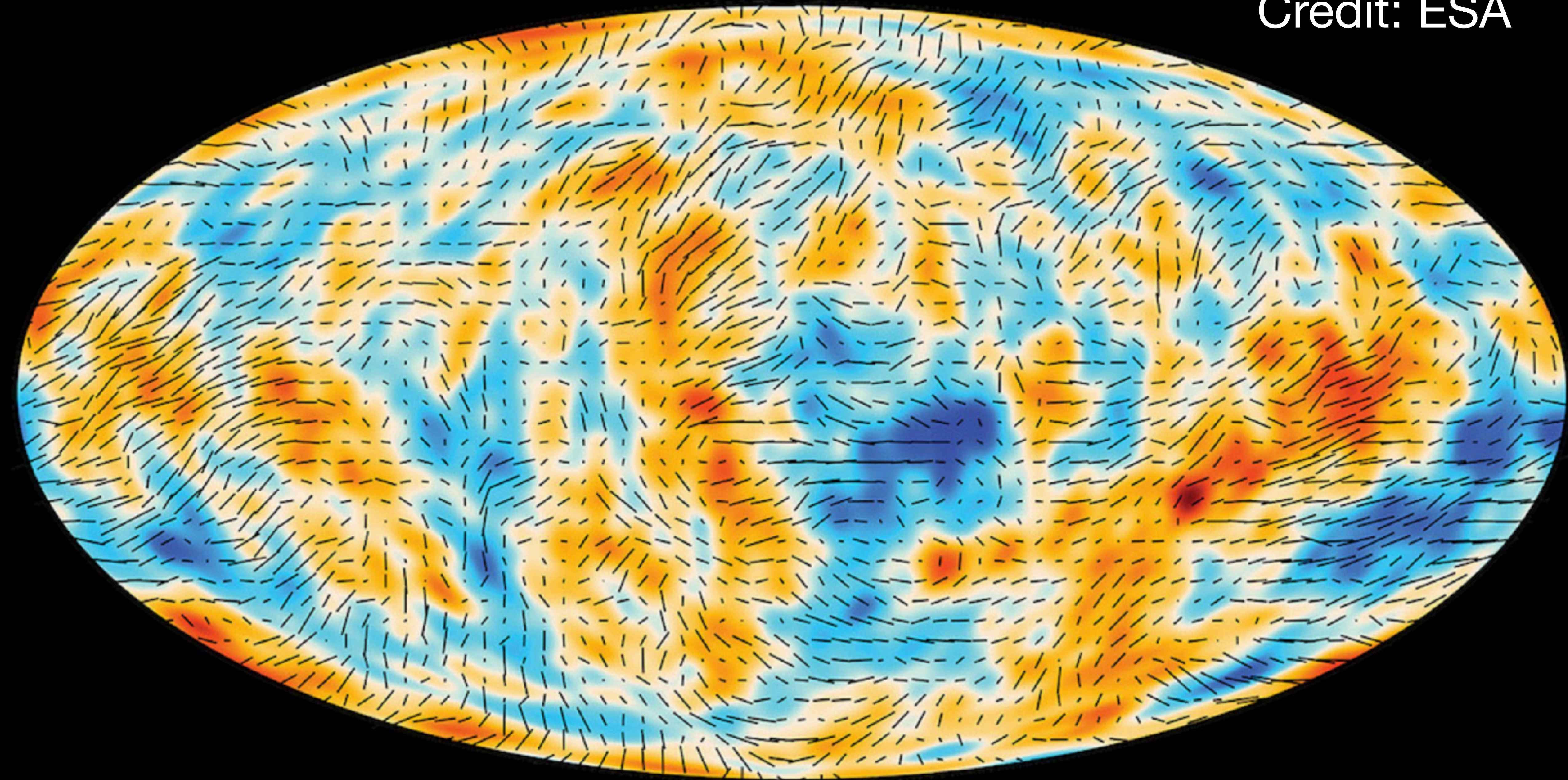


Credit: ESA



Temperature (smoothed)

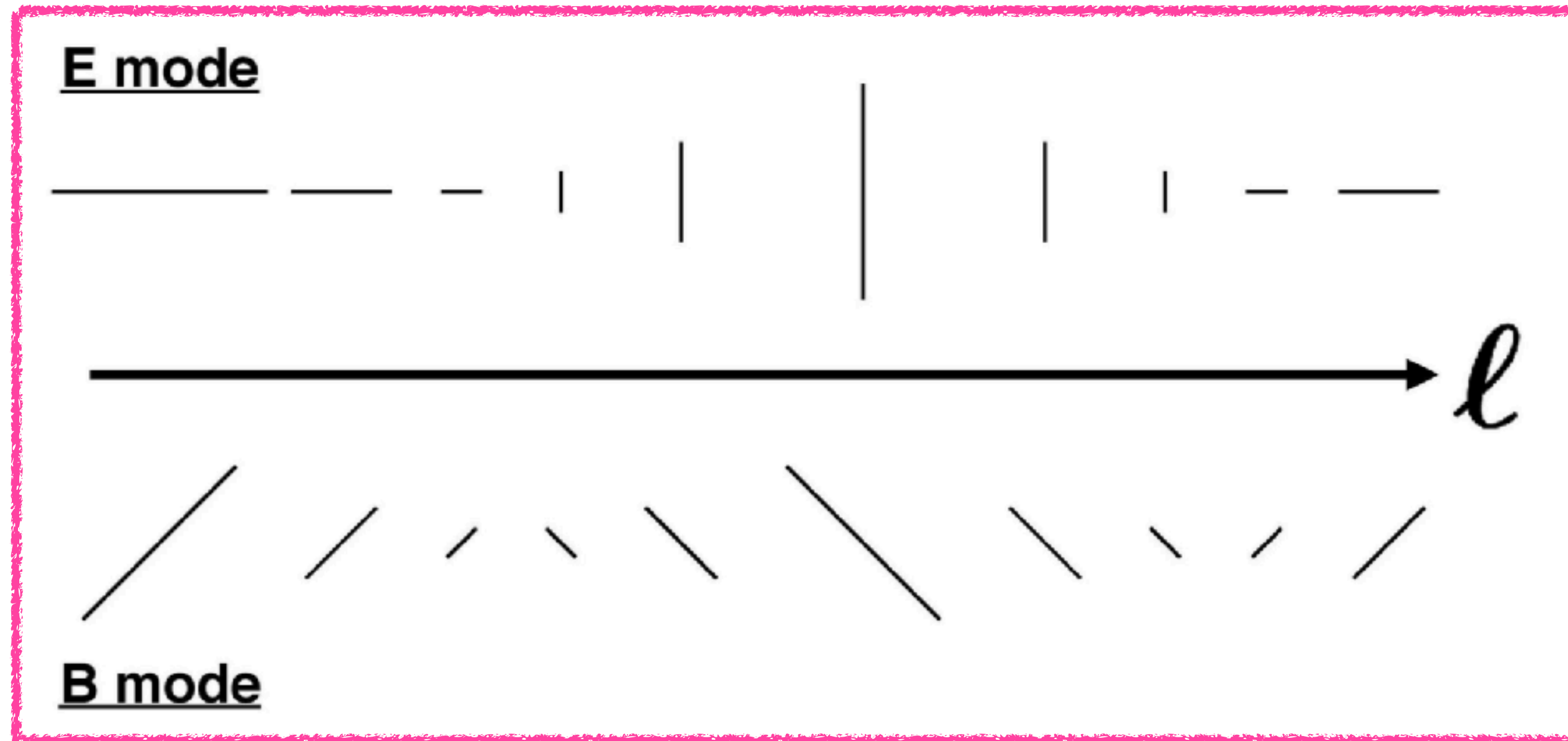
Credit: ESA



Temperature (smoothed) + Polarisation

E- and B-mode decomposition

Concept defined in Fourier space



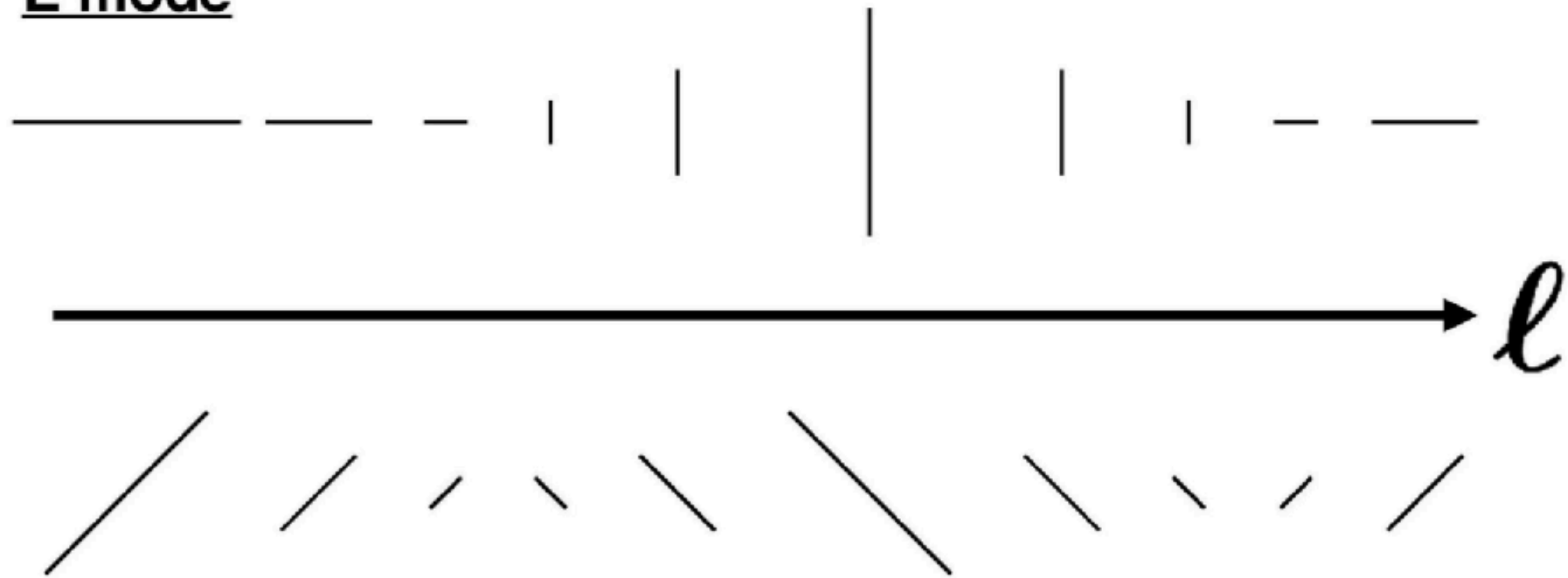
Direction of the Fourier
wavenumber vector

- **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

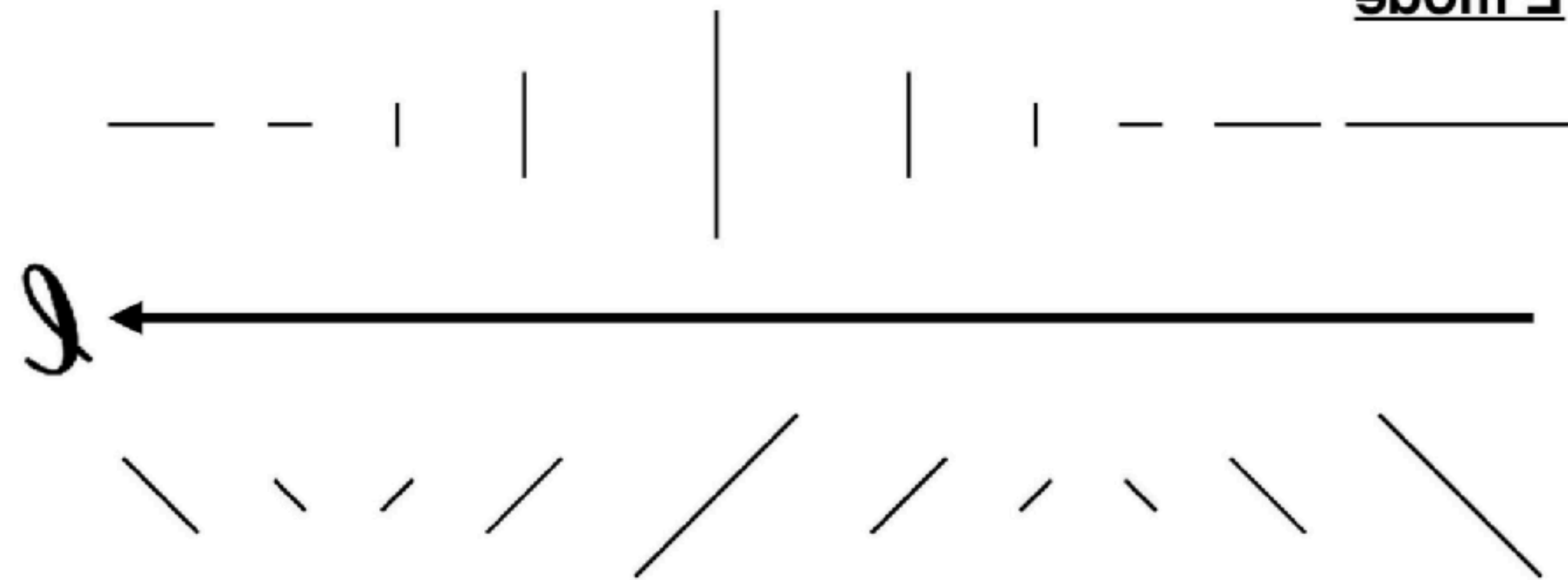
E-mode remains the same, whereas B-mode changes the sign

E mode



B mode

E mode



B mode

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

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

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

$$\langle T_{\ell} E_{\ell'}^* \rangle = \langle T_{\ell}^* E_{\ell'} \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{TE}$$

- The other combinations $\langle TB \rangle$ and $\langle EB \rangle$ are not invariant under the parity flip.

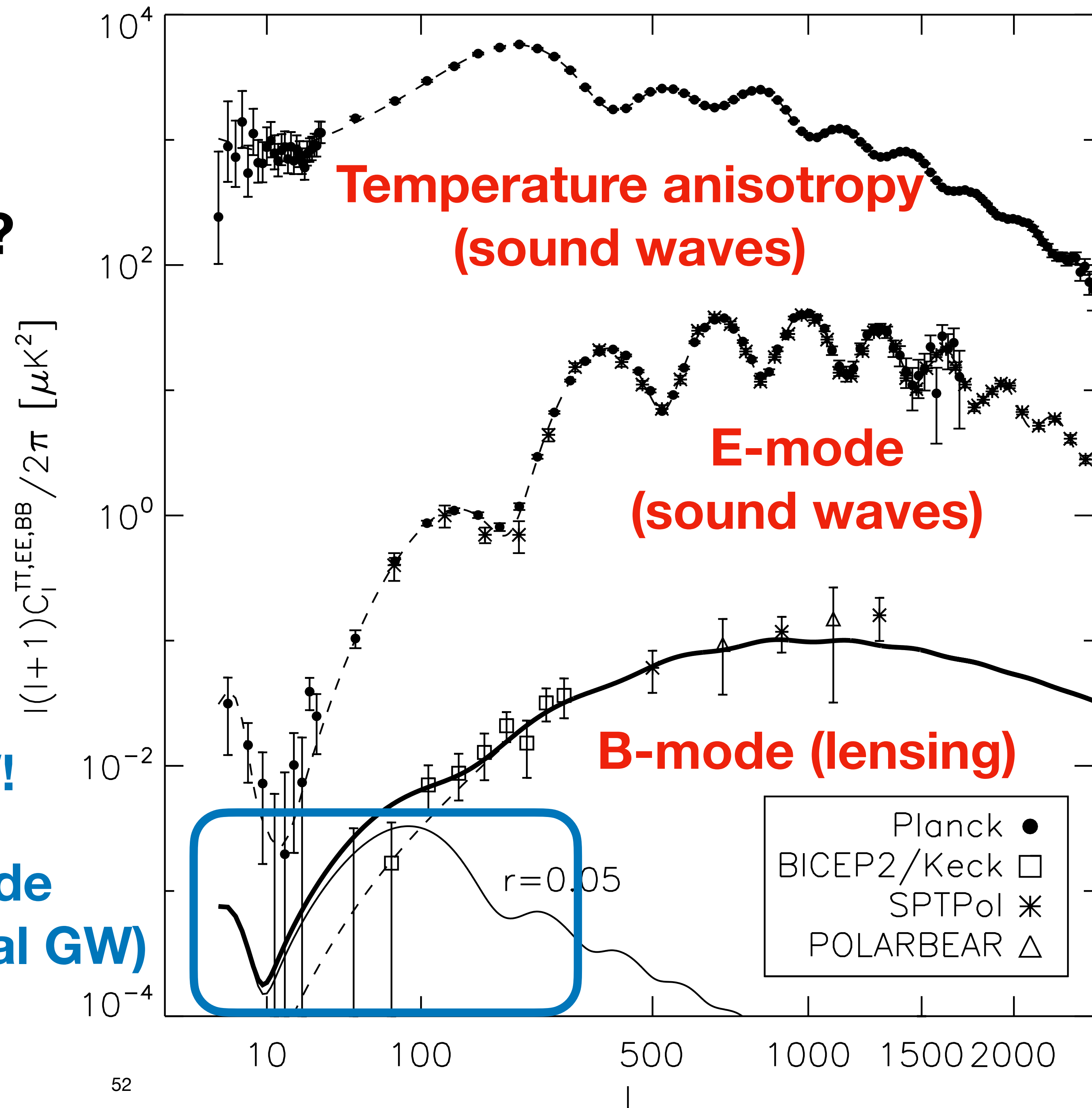
- [Side Note]** We can use these combinations to probe parity-violating physics (e.g., axions)

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!**

**B-mode
(Primordial GW)**



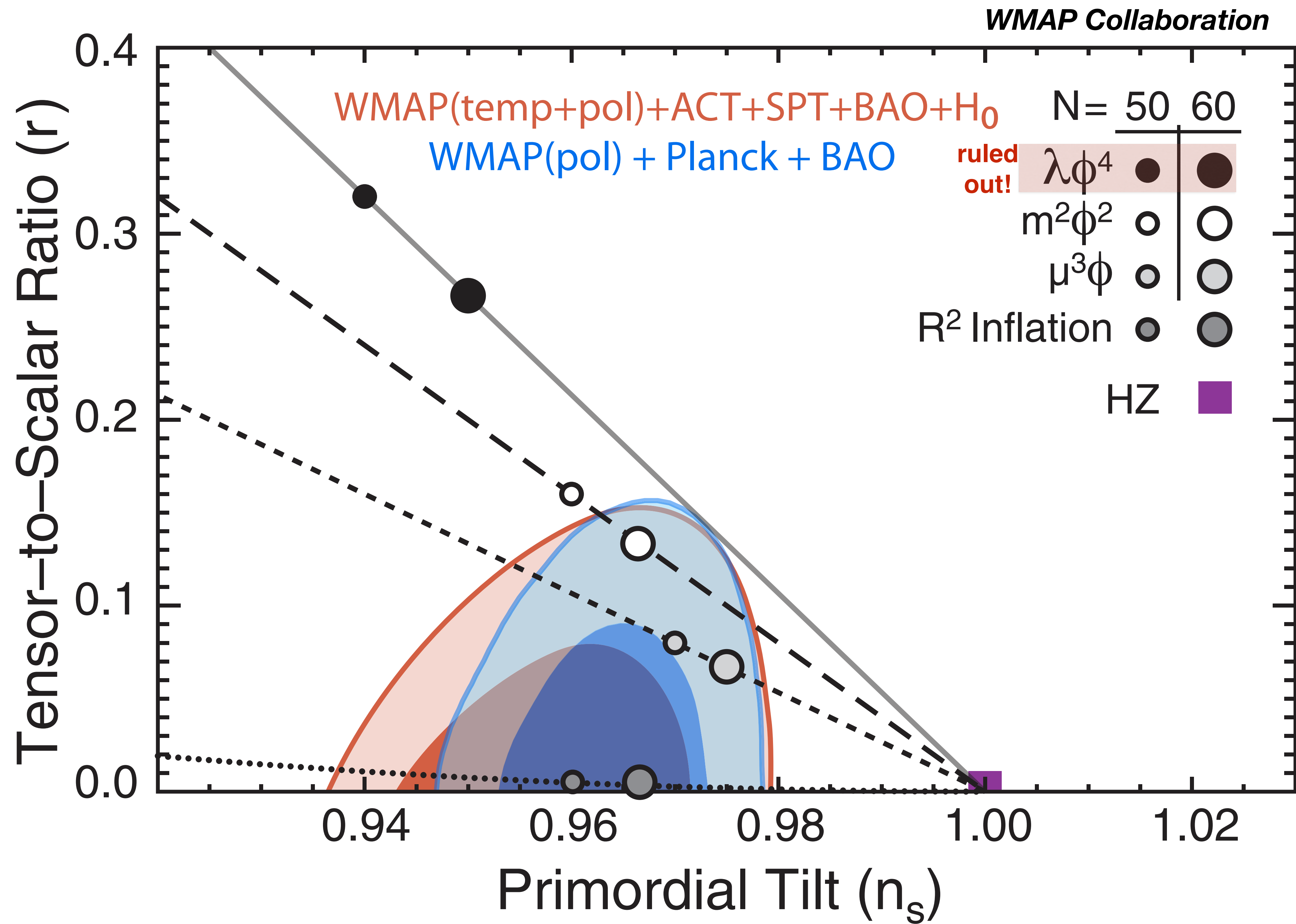
Tensor-to-scalar Ratio

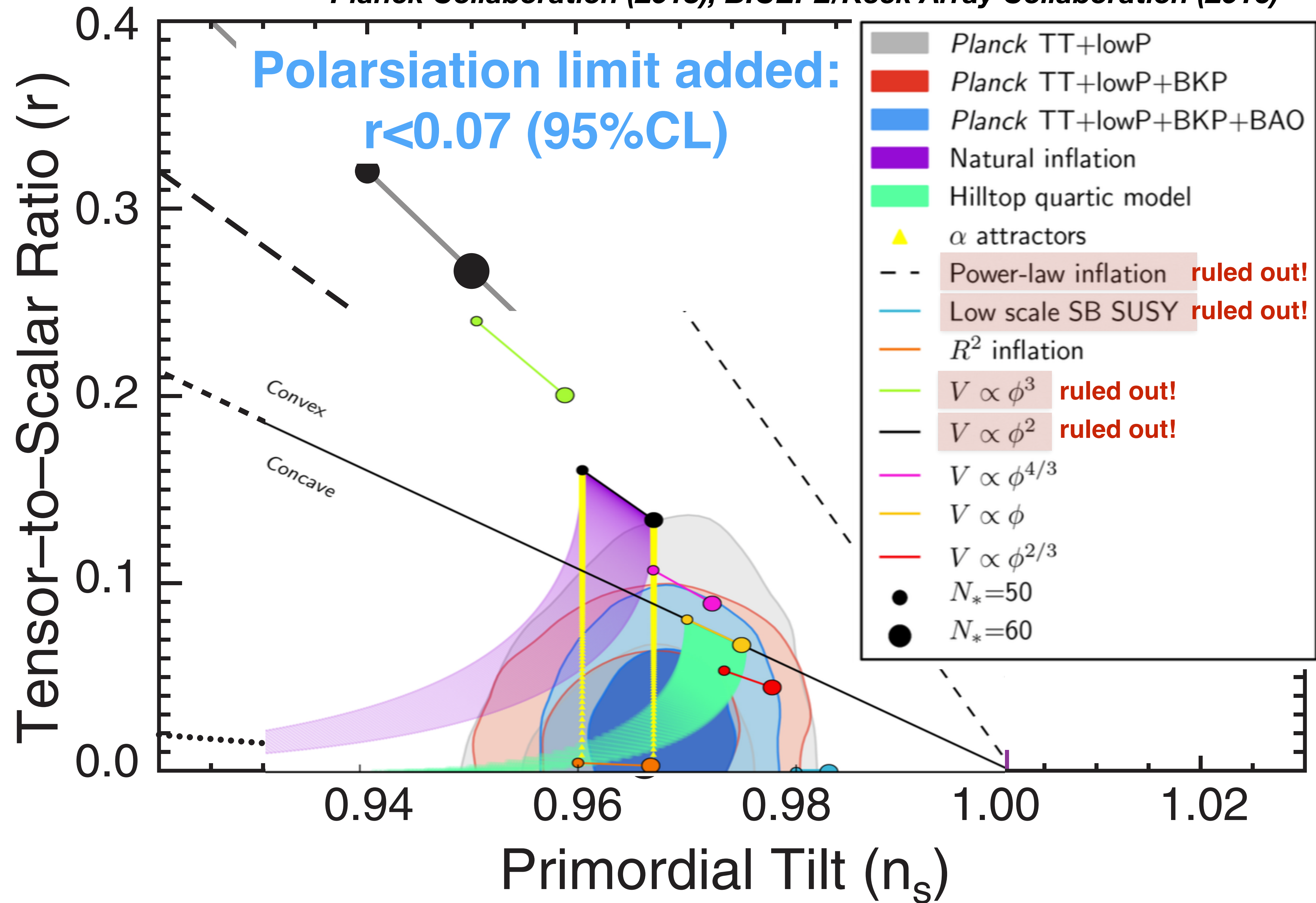
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

Scalar mode

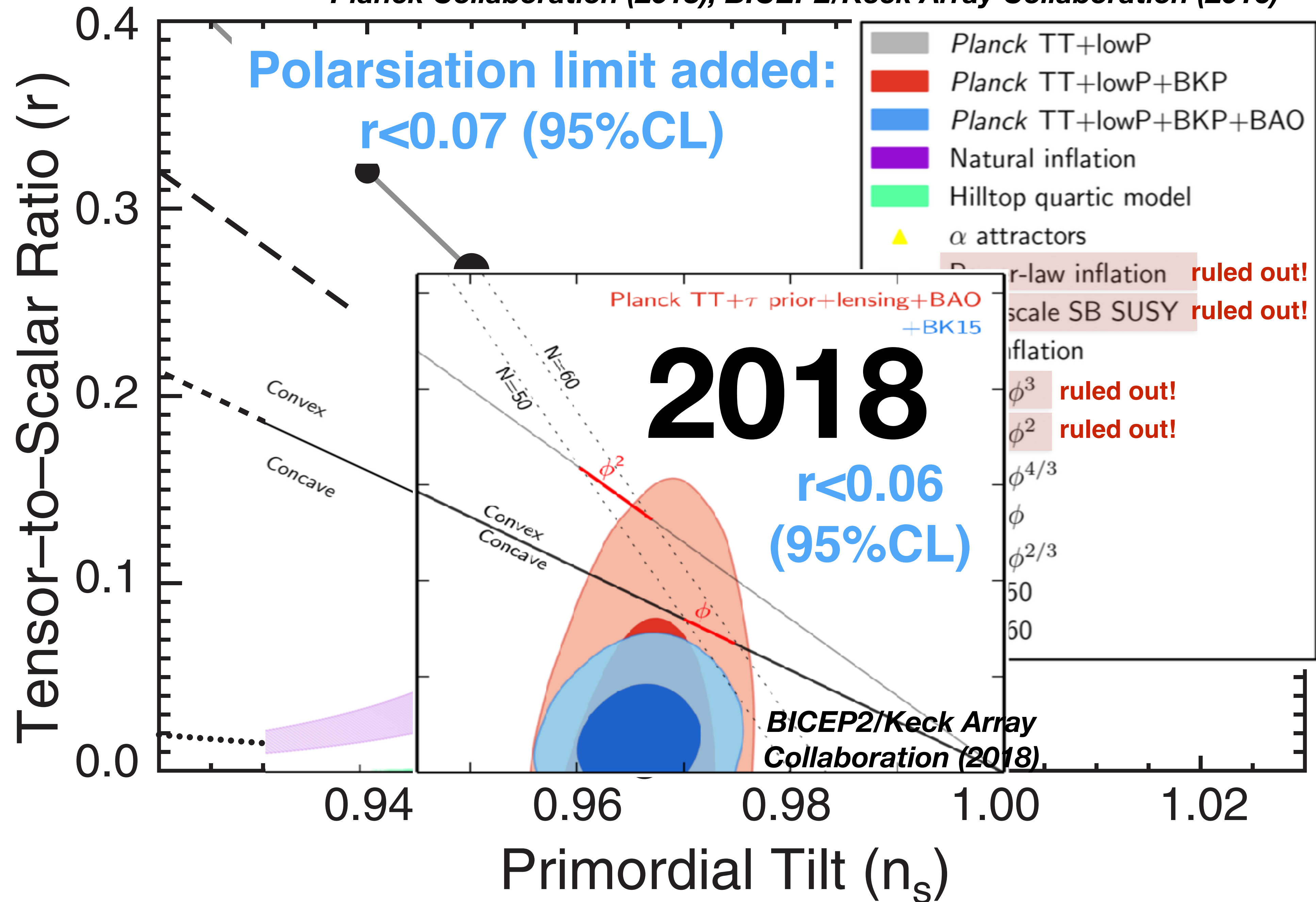
- We really want to find this! The current upper bound is **$r < 0.06$** (95%CL)

BICEP2/Keck Array Collaboration (2018)





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



But, wait a minute...

Are GWs from vacuum fluctuation in spacetime, or from sources?

$$\square h_{ij} = -16\pi G \pi_{ij}$$

- **Homogeneous solution:** “GWs from vacuum fluctuation”
- **Inhomogeneous solution:** “GWs from sources”
 - Scalar and vector fields cannot source tensor fluctuations at linear order (possible at non-linear level)
Many papers by Sorbo, Peloso, and others
 - SU(2) gauge field can!

Maleknejad & Sheikh-Jabbari (2013); Dimastrogiovanni & Peloso (2013);
Adshead, Martinec & Wyman (2013); Obata & Soda (2016); ...

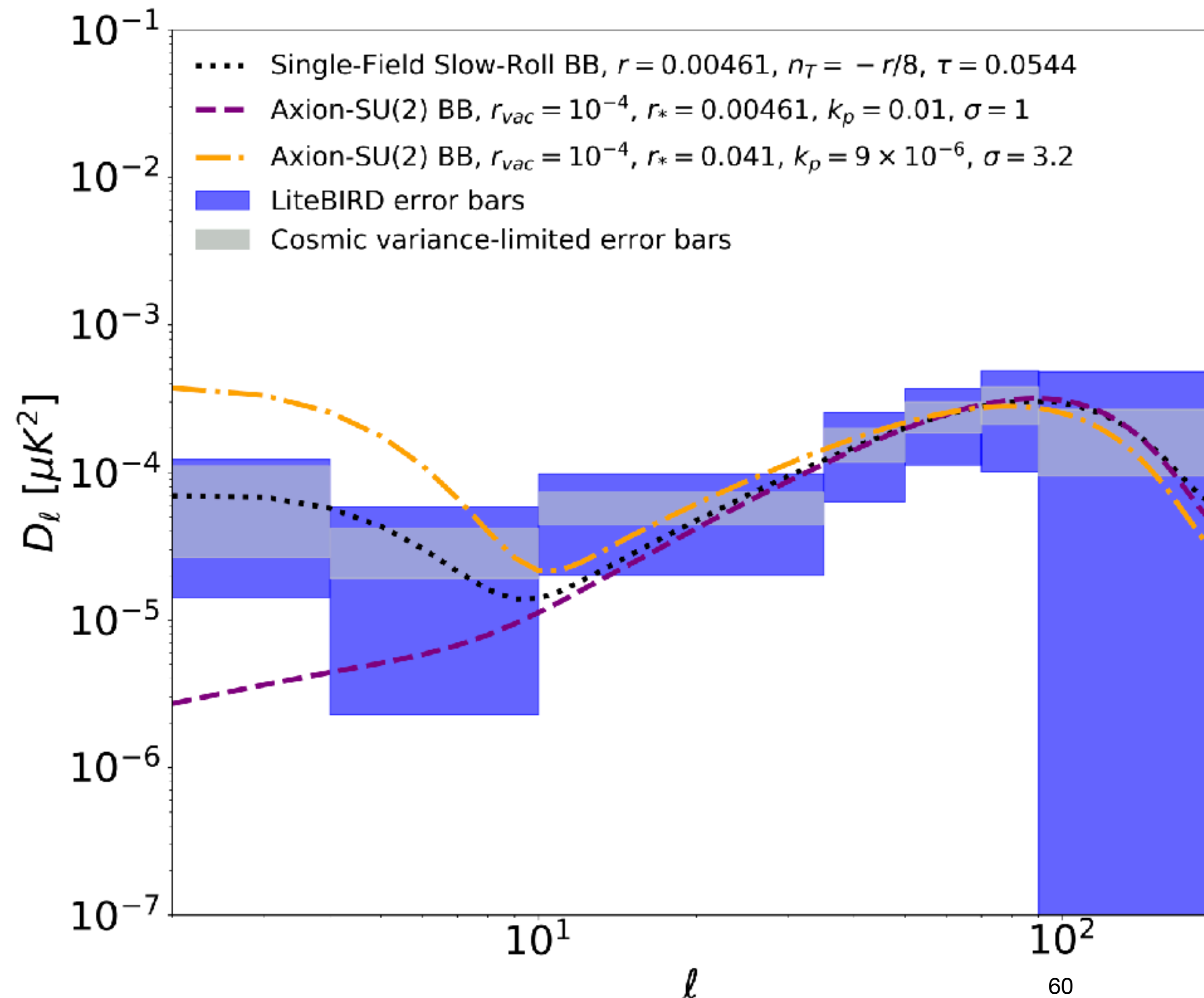
Important Message

$$\square h_{ij} = -16\pi G \pi_{ij}$$

- Do not take it for granted if someone told you that detection of the primordial gravitational waves would be a signature of “quantum gravity”!
- Only the homogeneous solution corresponds to the vacuum tensor metric perturbation. **There is no *a priori* reason to neglect an inhomogeneous solution!**
- Contrary, we have several examples in which detectable B-modes are generated by **sources** [U(1) and SU(2)]

B-mode power spectrum

Vacuum fluctuation versus the Gauge field contribution



- **Dotted:** Vacuum fluctuation in spacetime (homogeneous solution)
- **Other curves:** the Gauge field contributions (inhomogeneous solution) for two representative cases
- **Message:** we need to measure both low and high multipoles!

Experimental Strategy

Commonly Assumed So Far

1. Detect CMB polarisation in multiple frequencies, to make sure that it is from the CMB (i.e., Planck spectrum)
2. Check for scale invariance: Consistent with a scale invariant spectrum?
 - Yes => Announce discovery of the vacuum fluctuation in spacetime
 - No => WTF?

New Experimental Strategy: New Standard!

1. Detect CMB polarisation in multiple frequencies, to make sure that it is from the CMB (i.e., Planck spectrum)
 2. Check for scale invariance: Consistent with a scale invariant spectrum?
 3. Parity violating correlations consistent with zero?
 4. Consistent with Gaussianity?
- If, and **ONLY IF** Yes to **all** => Announce discovery of the vacuum fluctuation in spacetime

If not, you may have just
discovered new physics
during inflation!

1. De
ma

rum)

2. Check for scale invariance: Consistent with a scale invariant spectrum?

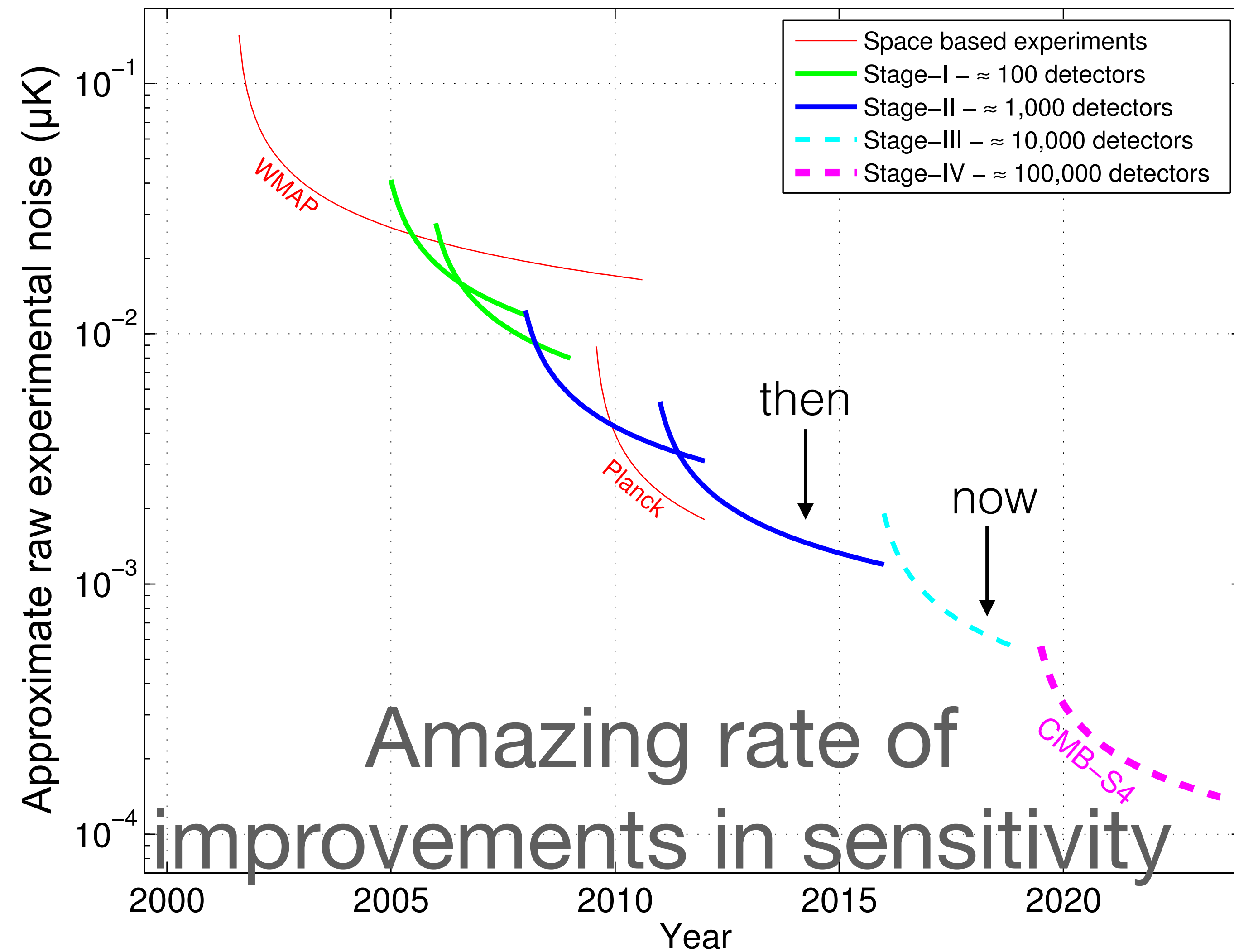
3. Parity violating correlations consistent with zero?

4. Consistent with Gaussianity?

- If, and **ONLY IF** Yes to **all** => Announce discovery of the vacuum fluctuation in spacetime

Experimental Landscape

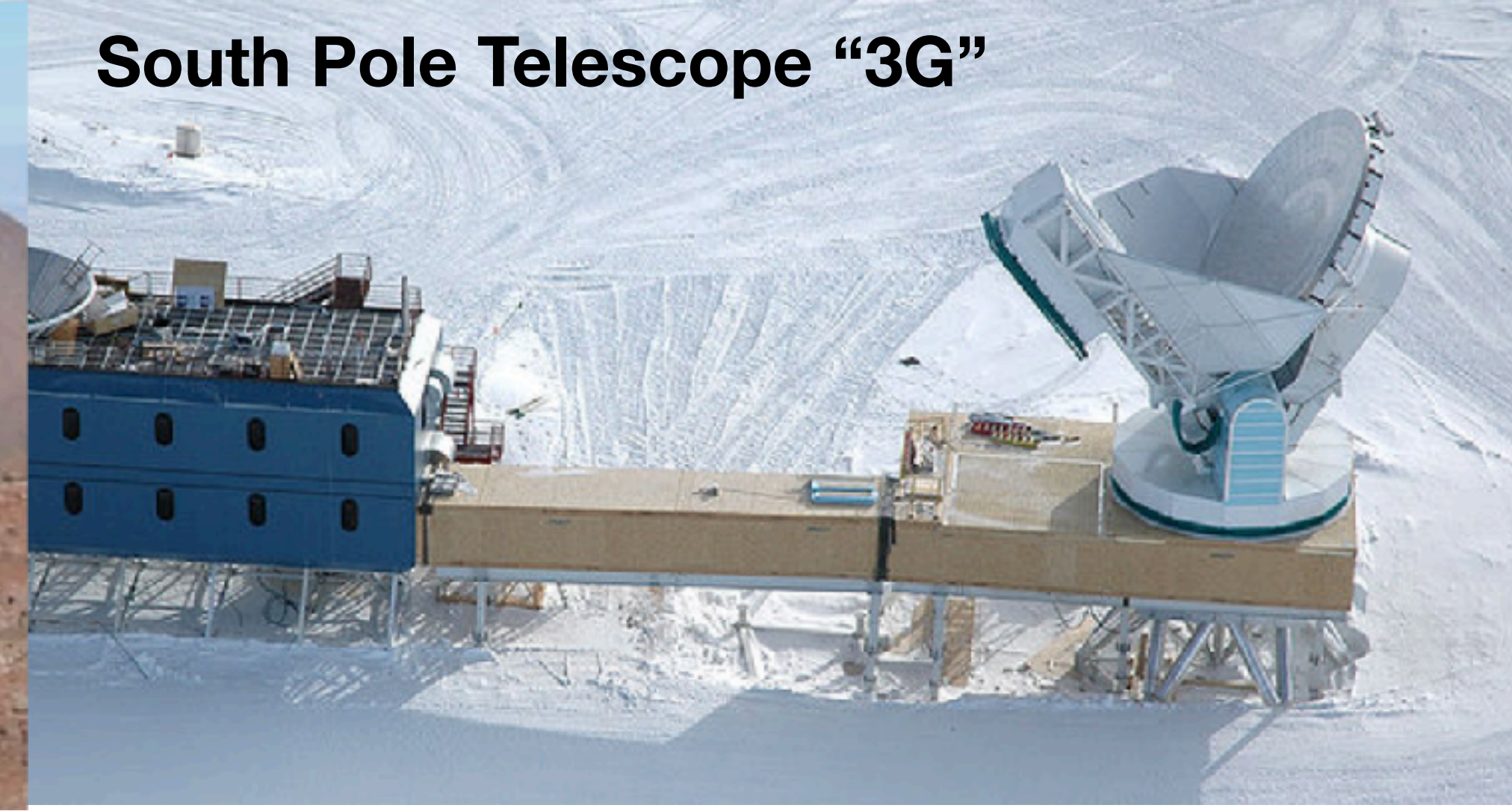
CMB Stages



**Advanced Atacama
Cosmology Telescope**

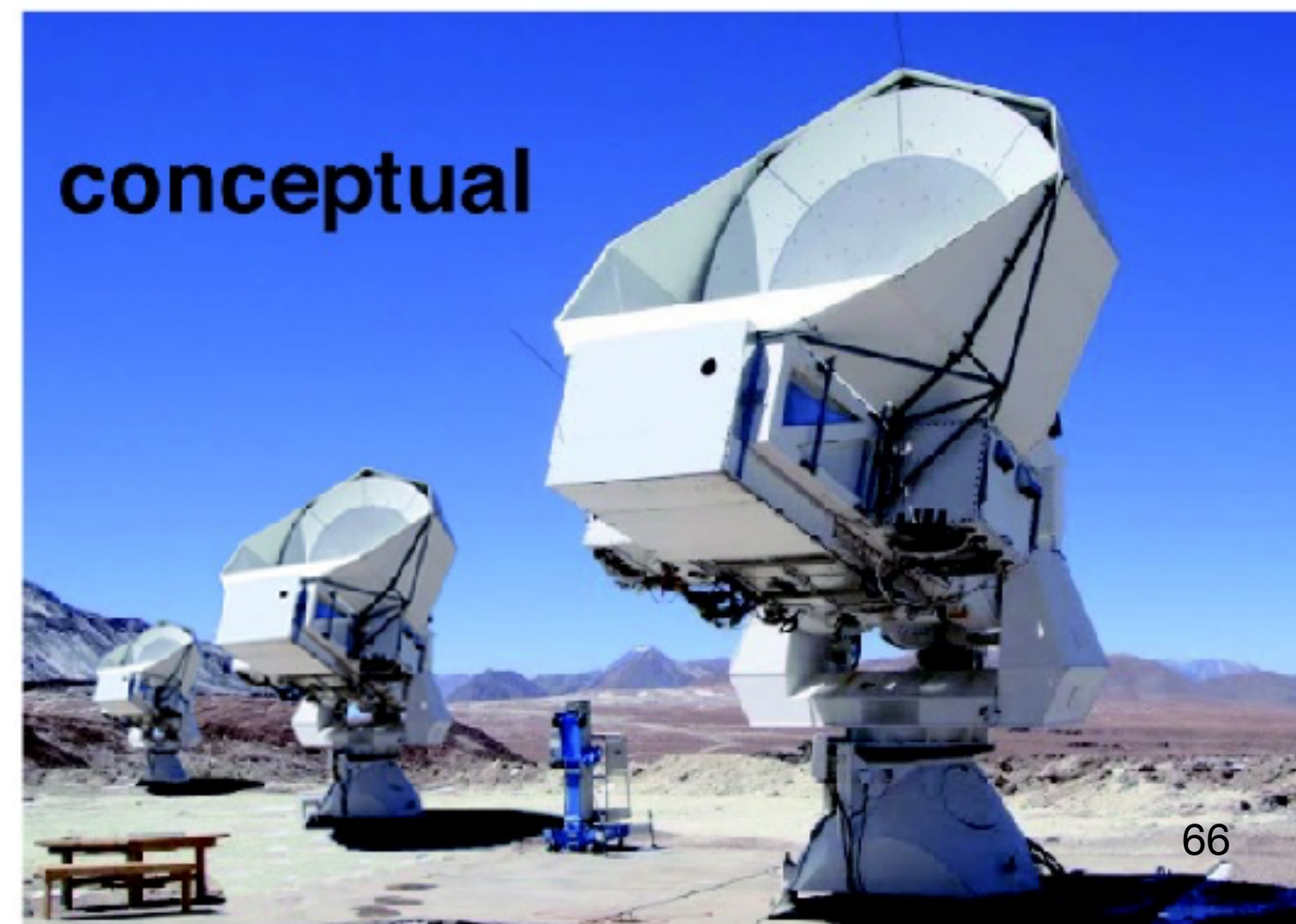


South Pole Telescope “3G”



On-going Ground-based Experiments

The Simons Array

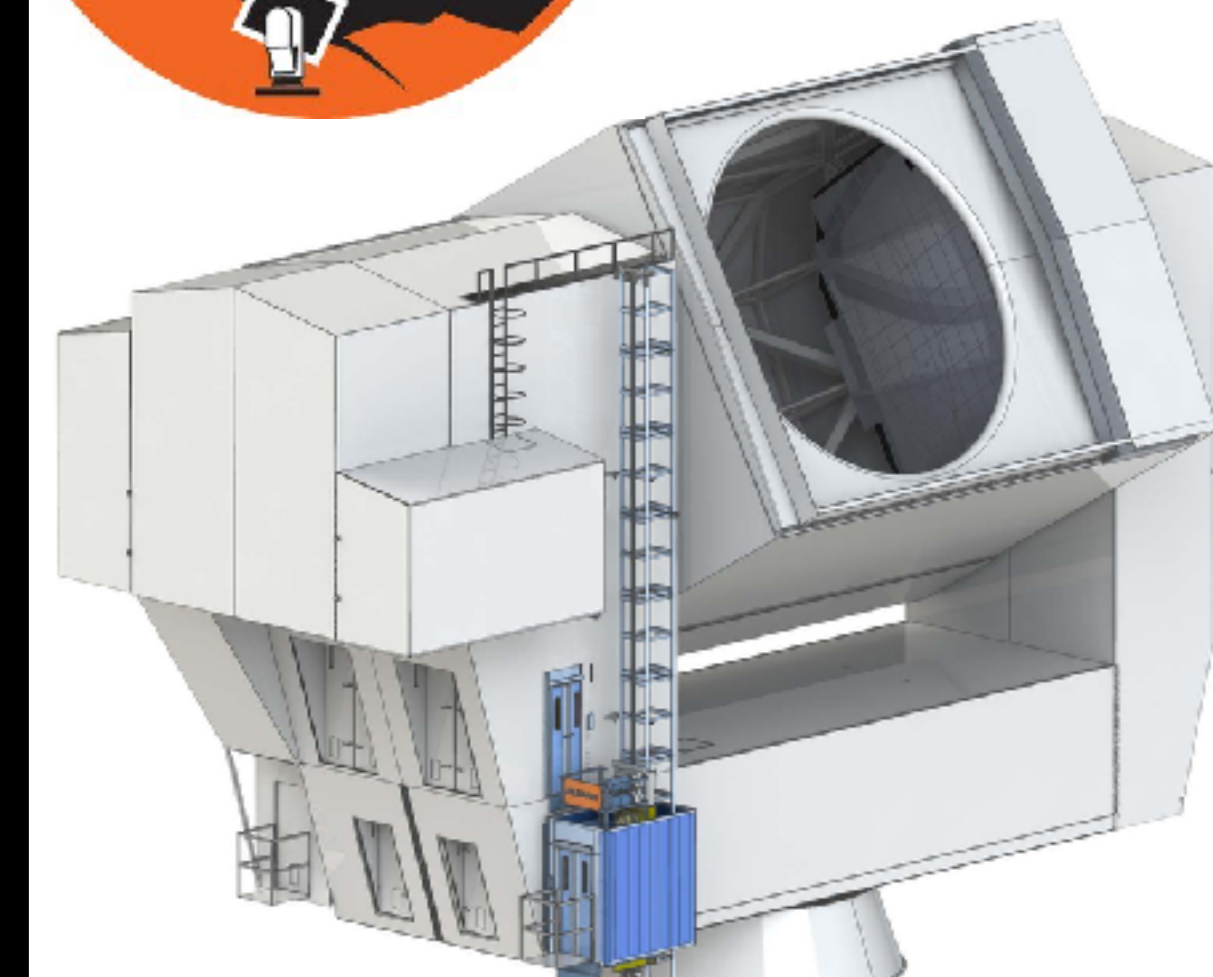


BICEP/Keck Array



CLASS





Early 2020s
~\$100M



**Advanced Atacama
Cosmology Telescope**



The Simons Array



conceptual



South Pole Telescope "3G"



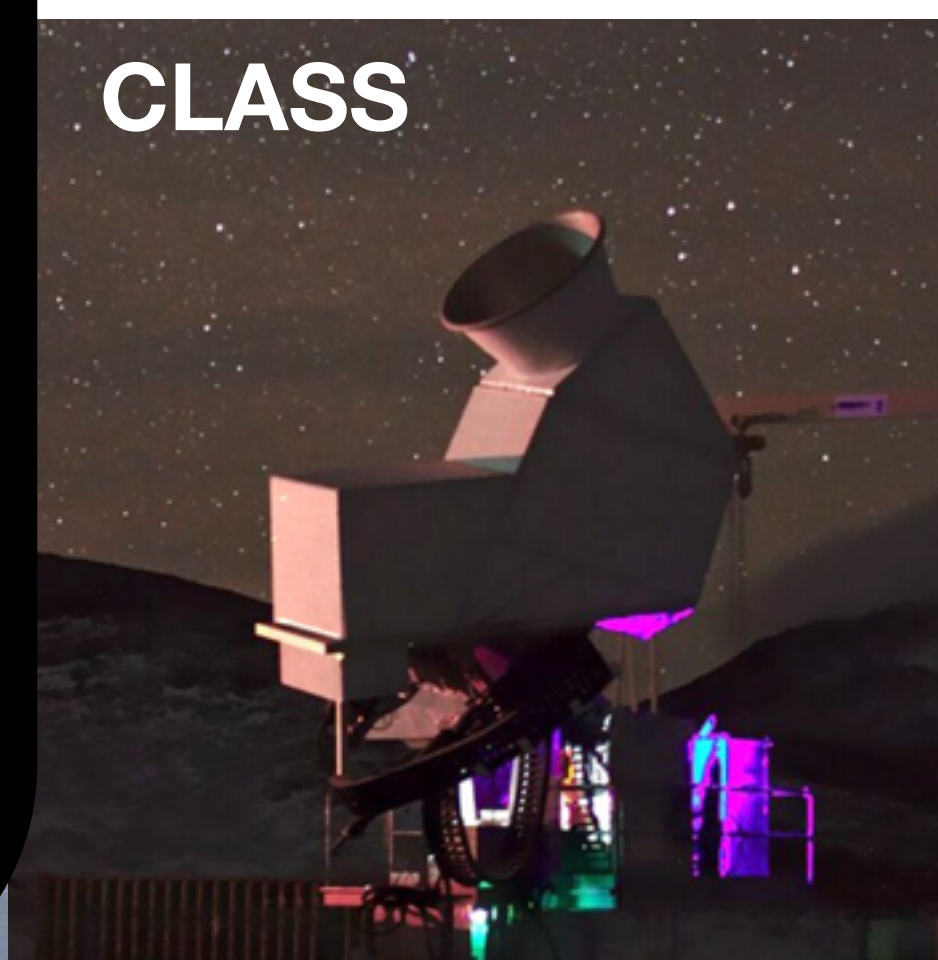
**The South Pole
Observatory**

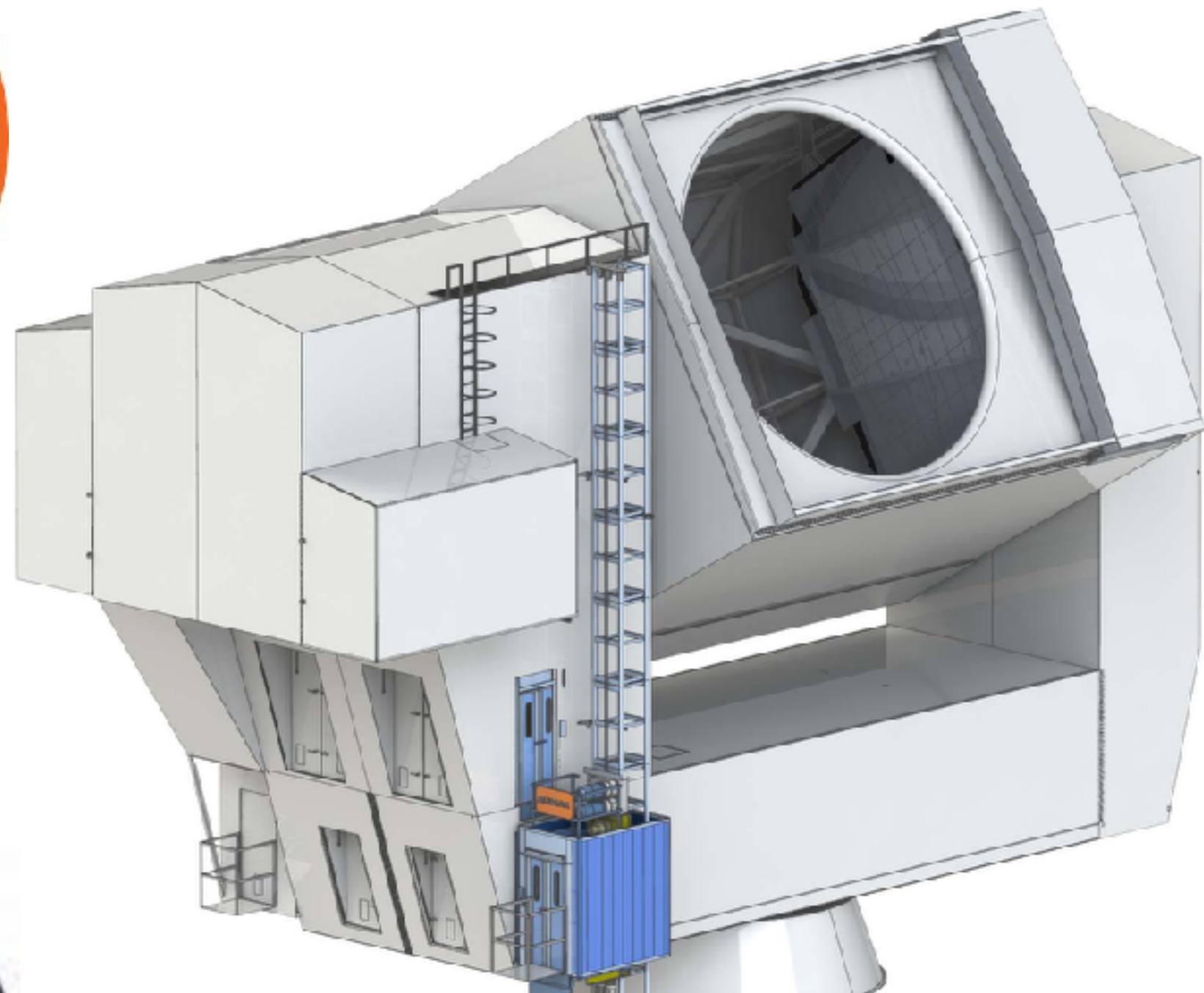


BICEP/Keck Array

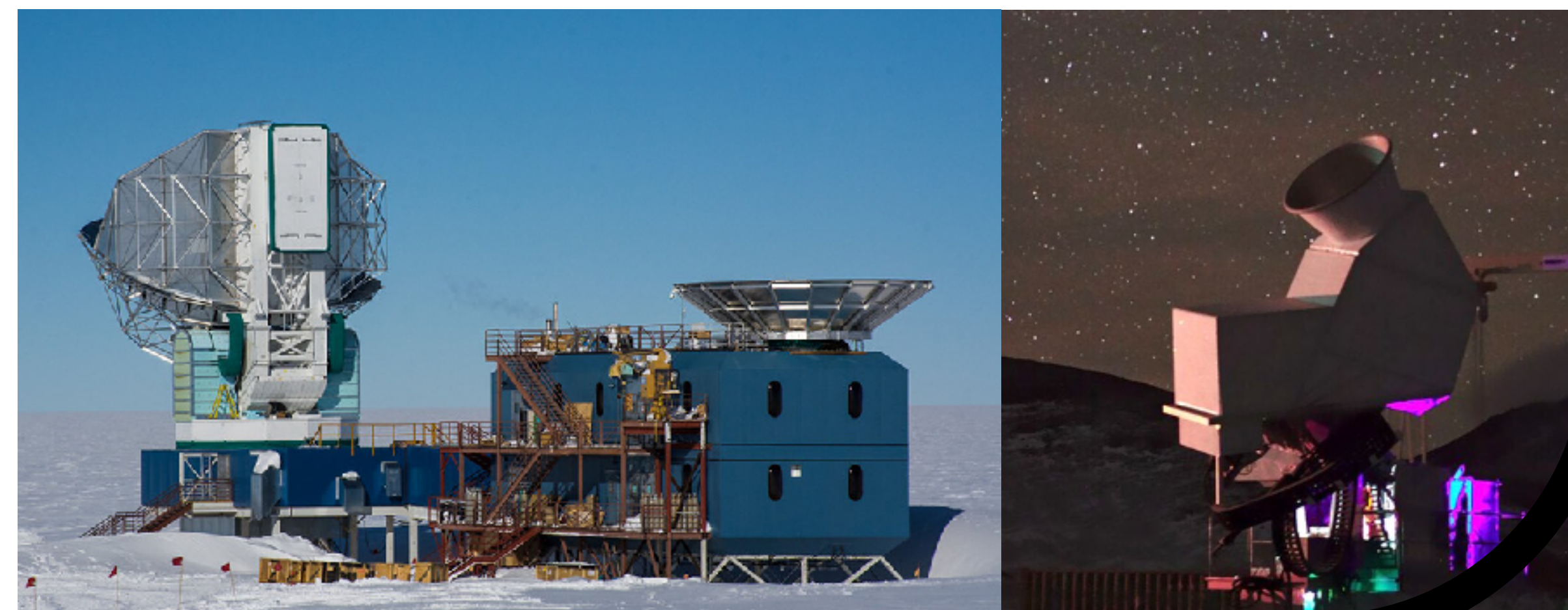


CLASS





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



2029– LiteBIRD



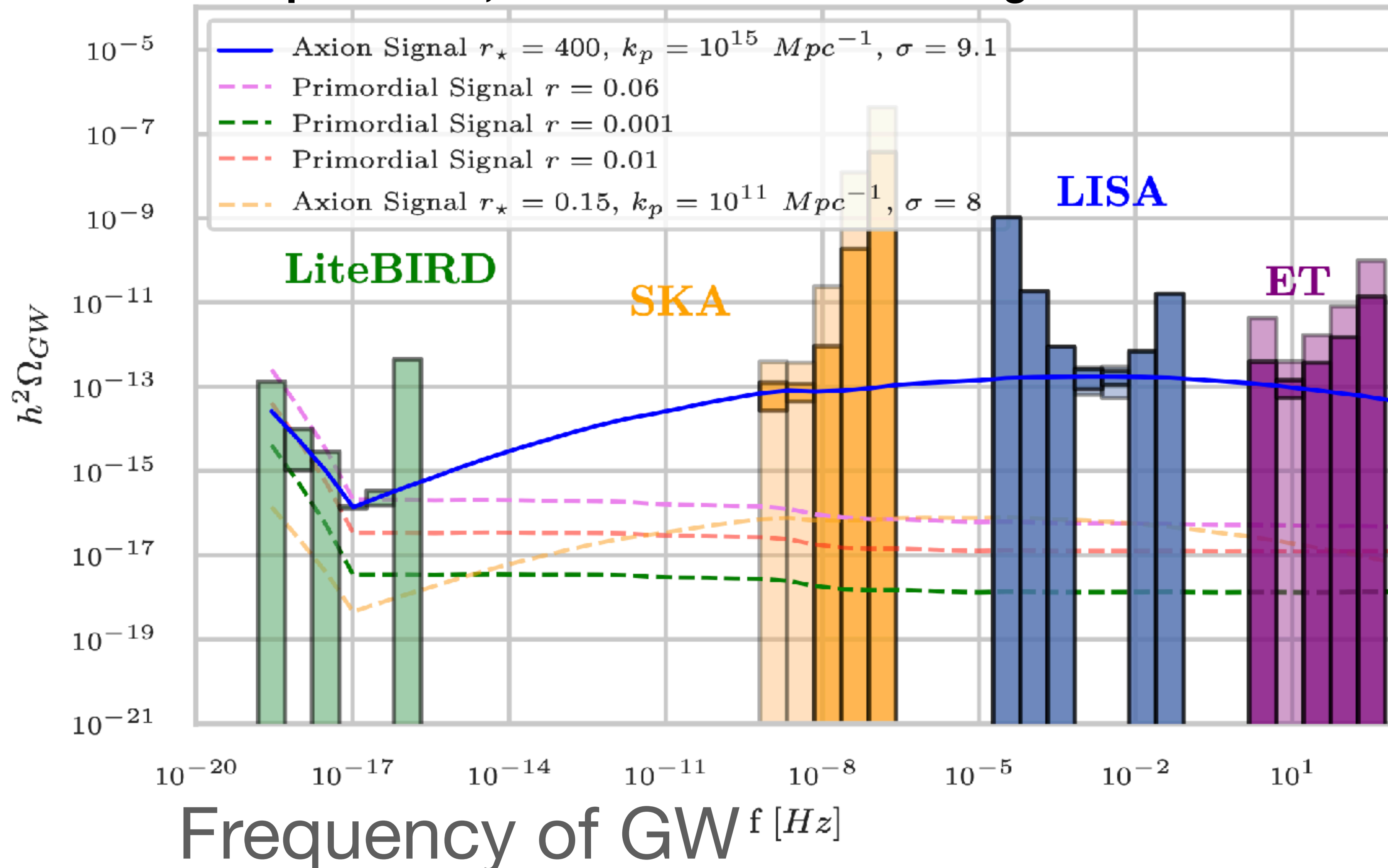
**JAXA
+ NASA
+ CSA
+ Europe**

**A few thousand super-conducting
microwave sensors in space.
Selected by JAXA to fly to L2!**

Not just CMB!

With direct detection experiments, we cover 21 orders of magnitude in the GW frequency

Energy Density of GW
today



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.