Finding Gravitational Waves from the Early Universe

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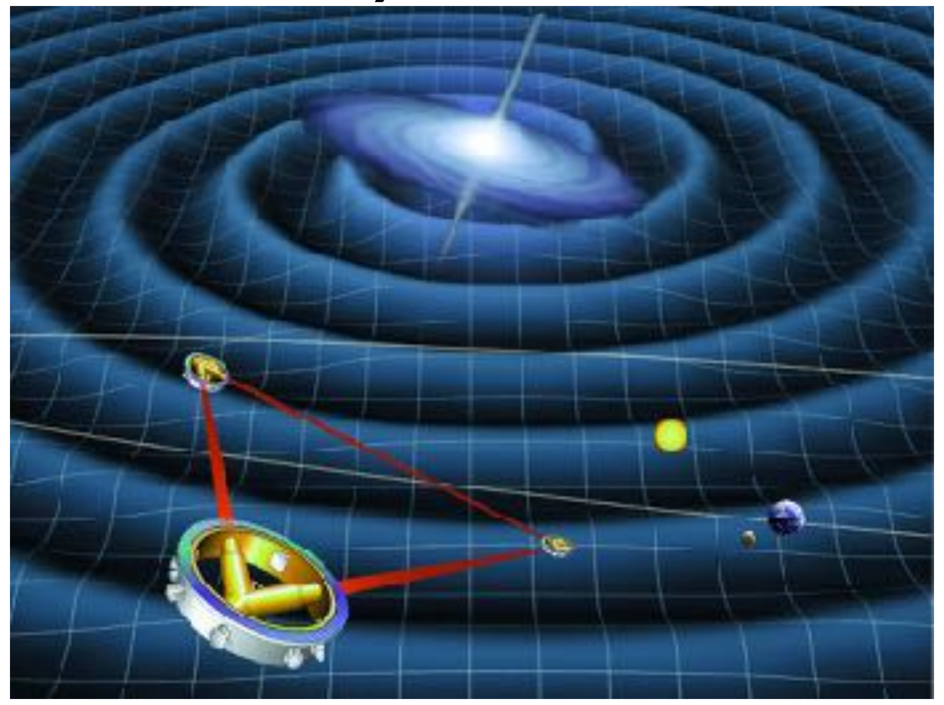
Monthly Research Colloquia, Agenzia Spaziale Italiana (MoRe-ASI), May 17, 2021

Let’s find Gravitational Waves (GW)!

But how? The detection method depends on the GW frequency.

- **Laser interferometers** on the ground: **deca- to kilo Hz** (*LIGO*, *VIRGO*, *…*, *ET*)
    - The wavelength ~ the size of Earth

- **Laser interferometers** in space: **milli Hz** (*LISA*), deci Hz (future mission?)
    - The wavelength ~ Astronomical Unit



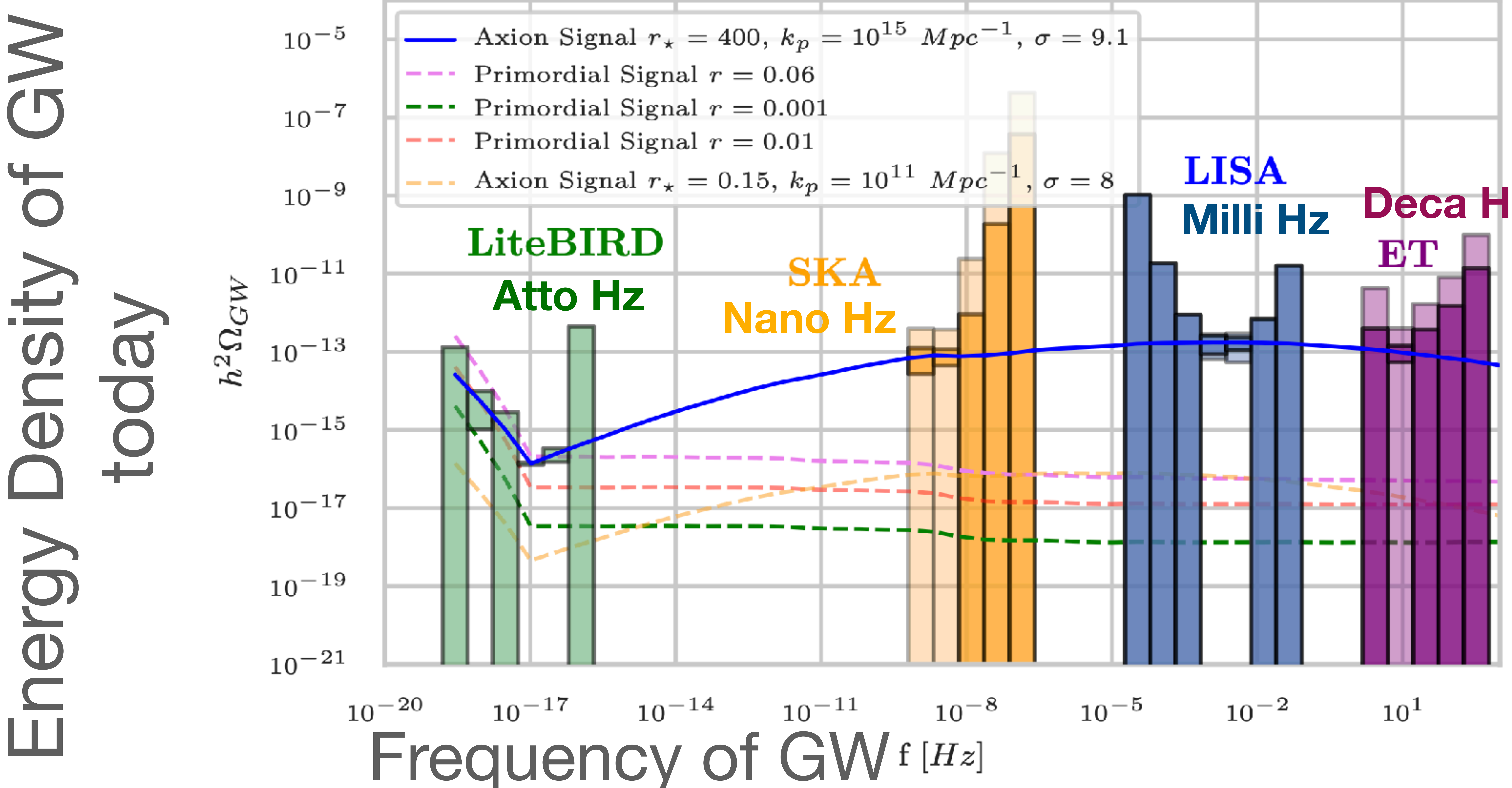
- **Pulsar timing arrays**: **nano Hz** (*EPTA*, *SKA*)
    - The wavelength ~ the size of the Milky Way

- **Cosmic microwave background**: **atto Hz** (*WMAP*, *Planck*, ***LiteBIRD***)
    - The wavelength ~ **billions of light years!**

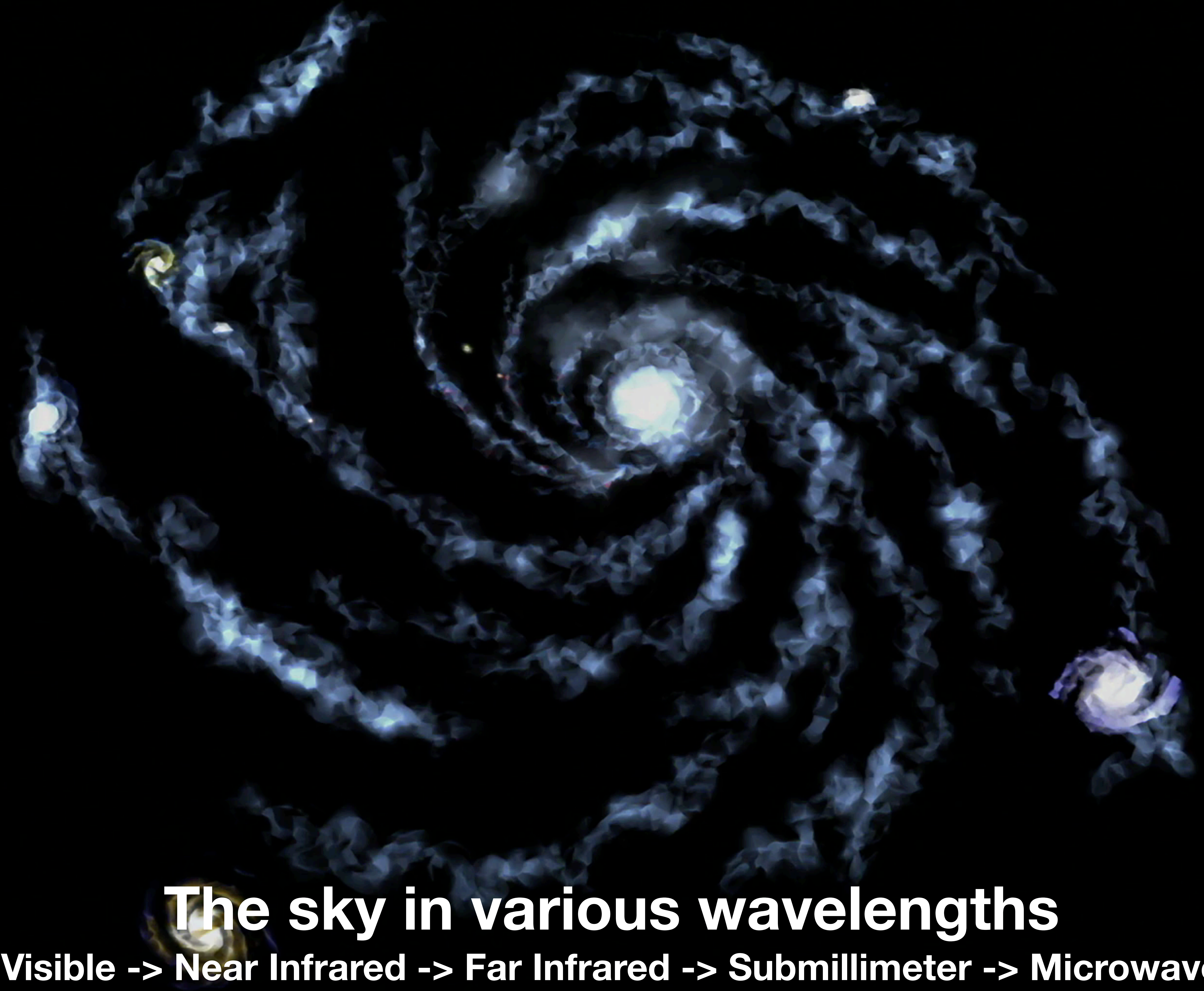
Campeti, EK, Poletti, Baccigalupi (2021)

GWs from the early Universe are everywhere!

We can measure it across 21 orders of magnitude in the GW frequency



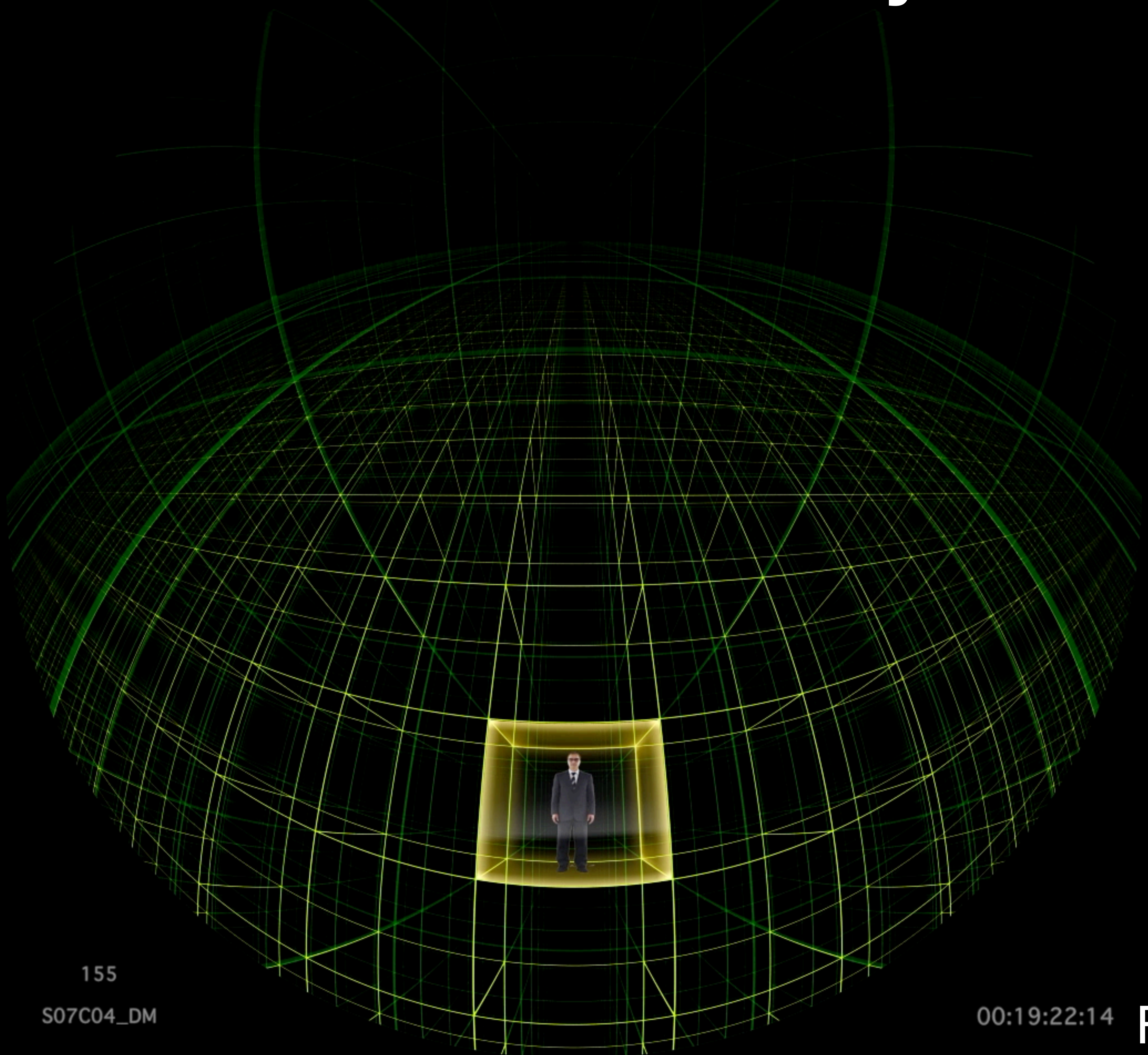
Credit: WMAP Science Team



The sky in various wavelengths

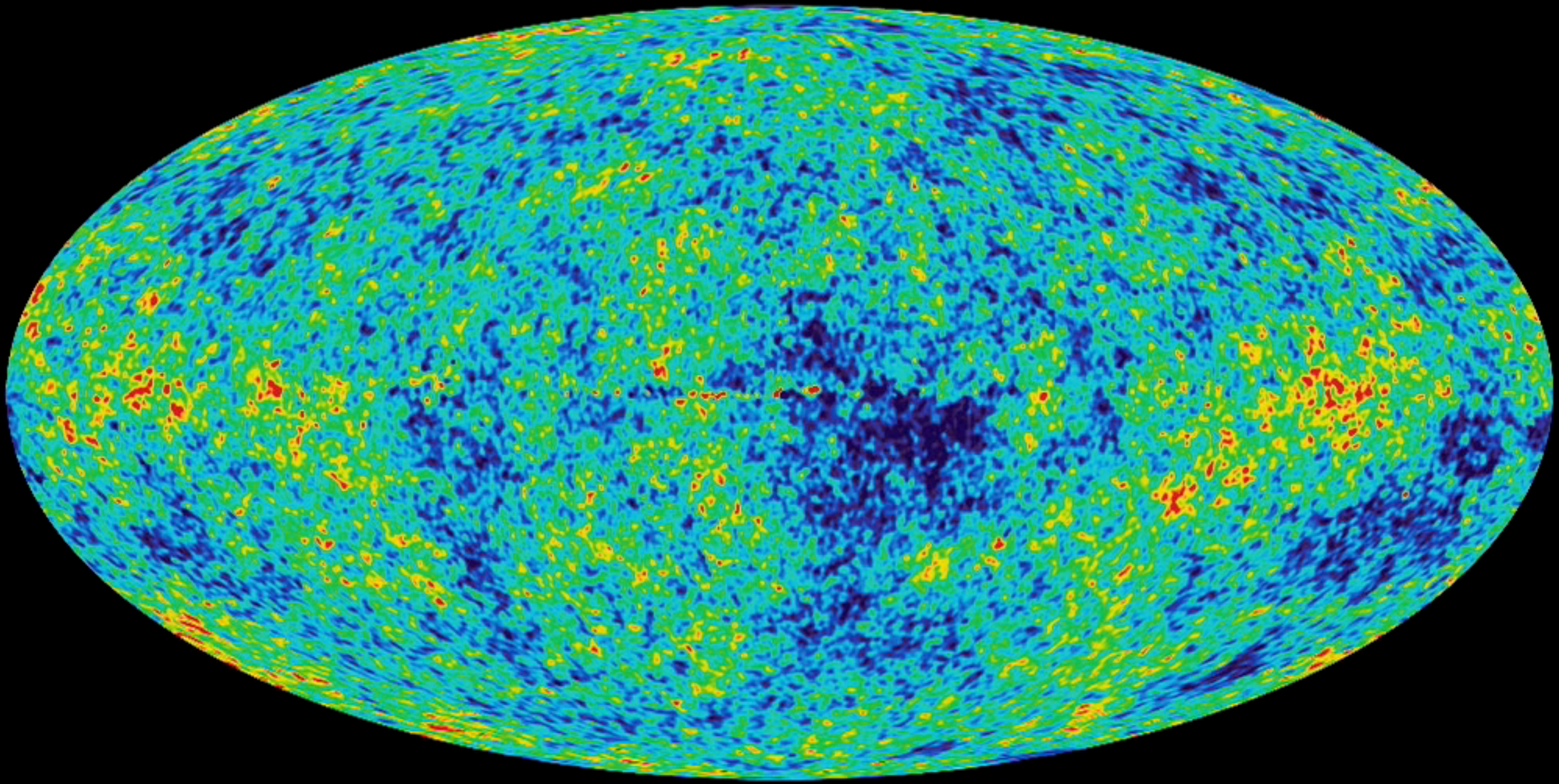
Visible -> Near Infrared -> Far Infrared -> Submillimeter -> Microwave

Where did the CMB we see today come from?



From “HORIZON”

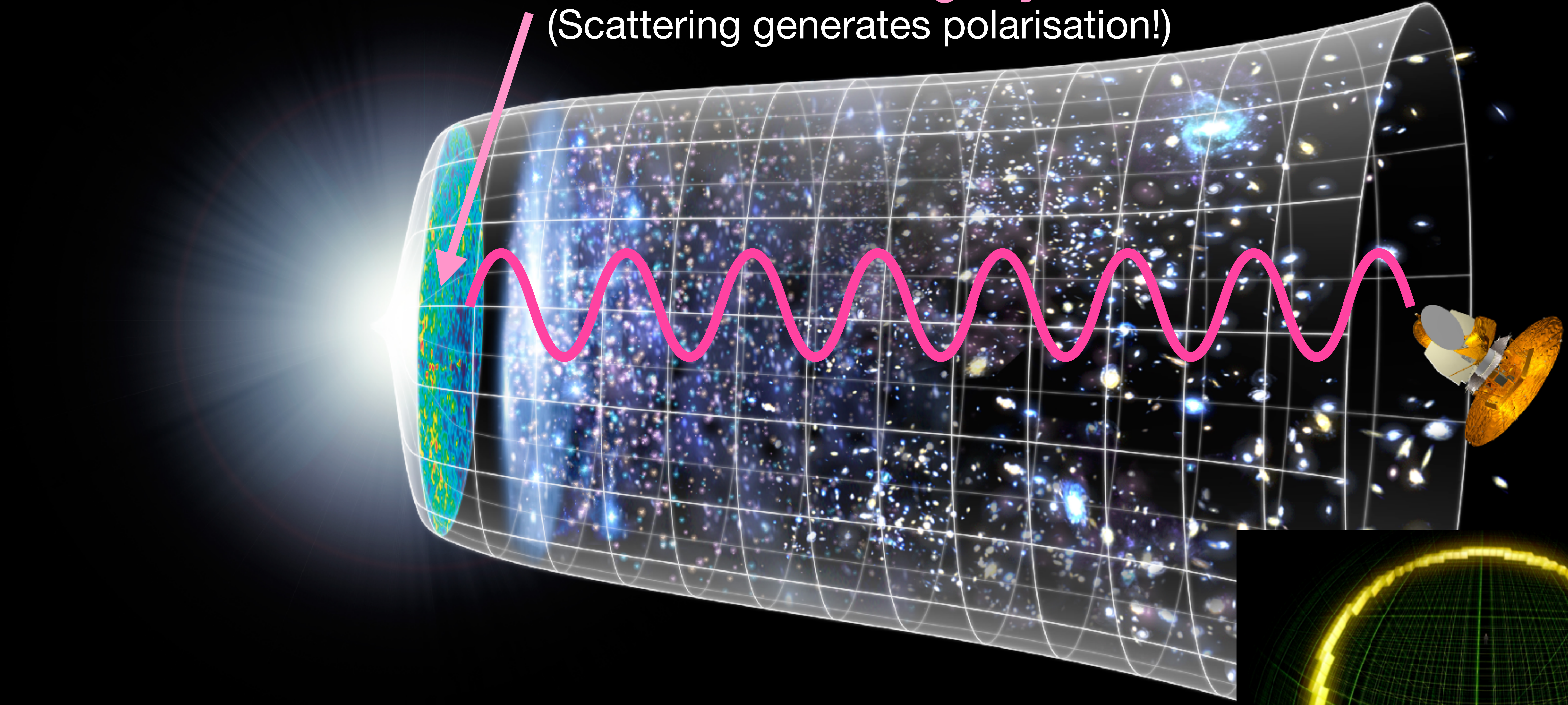
Credit: WMAP Science Team

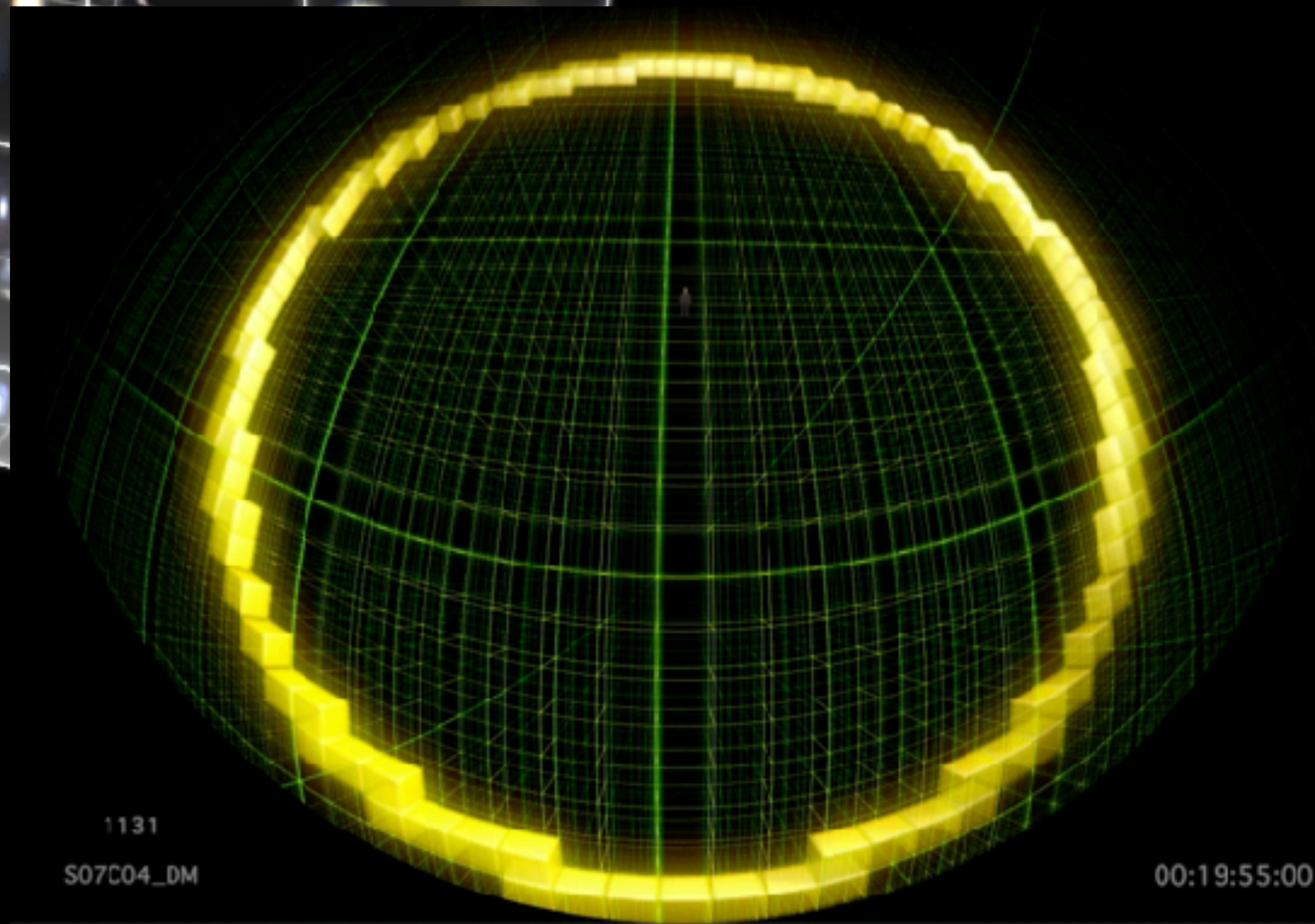


Credit: WMAP Science Team

The surface of "last scattering" by electrons

(Scattering generates polarisation!)





Not 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!*

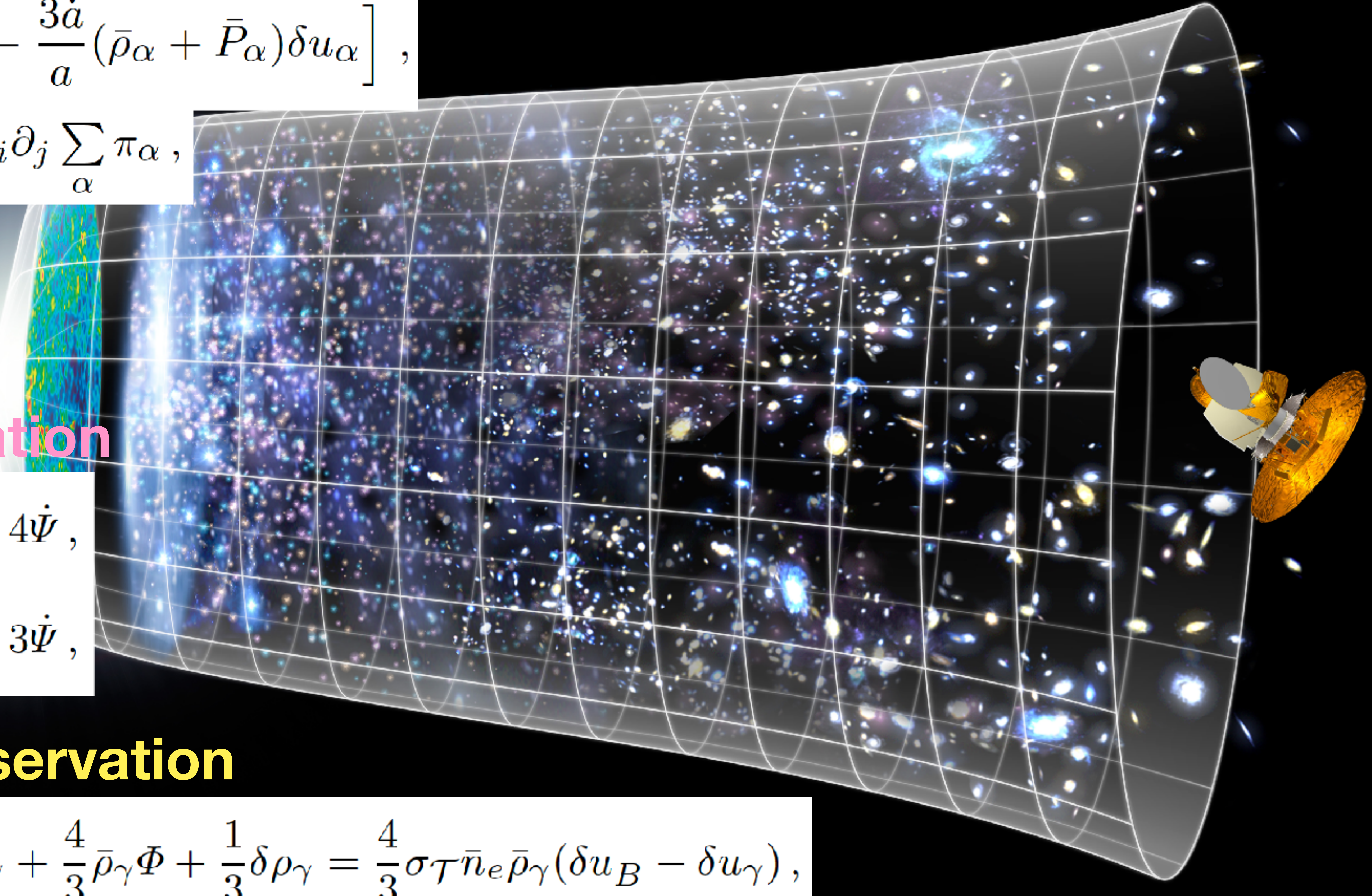
Before we talk about the GW, let's talk about the sound waves (scalar modes)

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

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

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

Laws of physics!

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”

Gravitational Field Equations

+

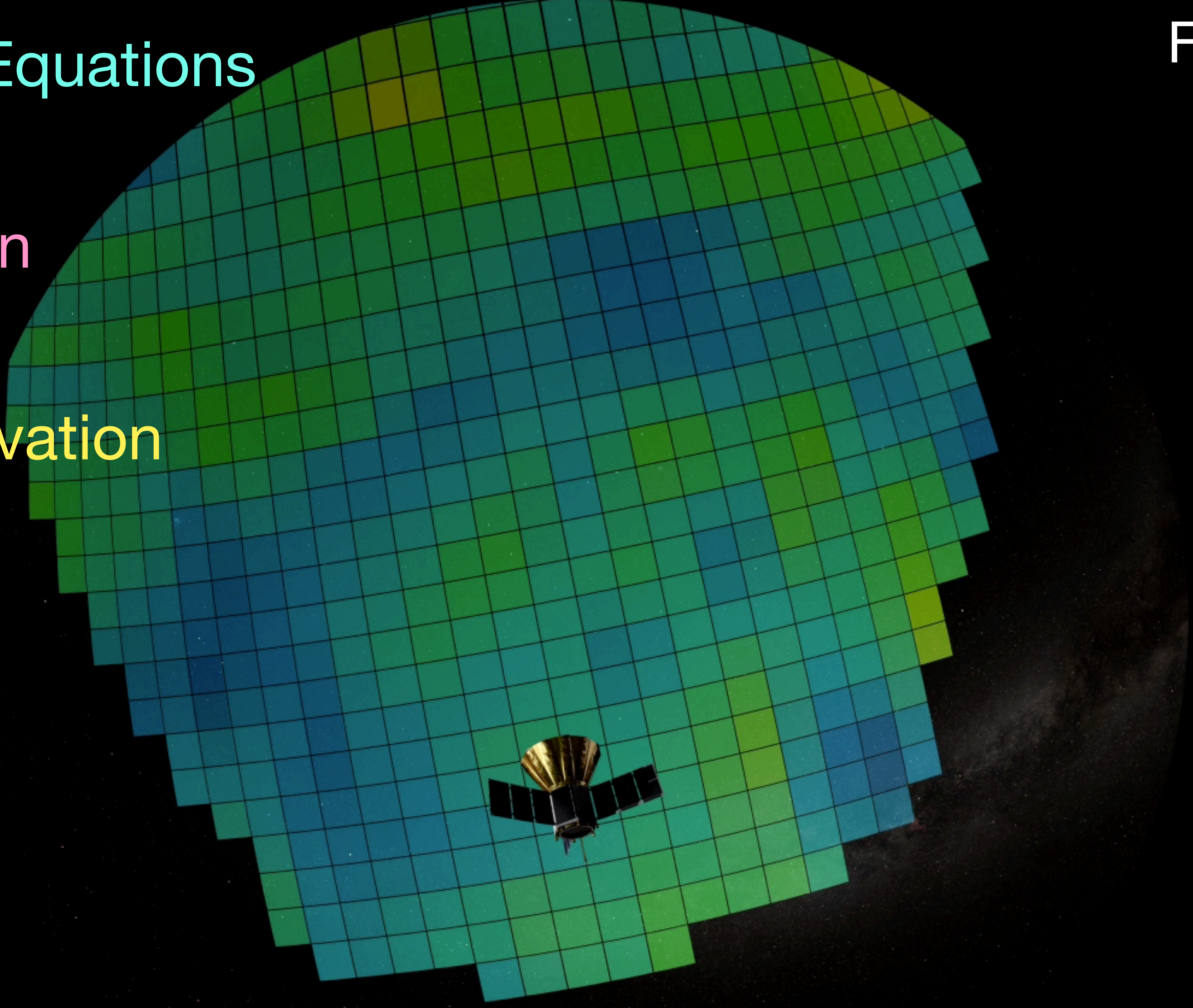
Energy Conservation

+

Momentum Conservation

=

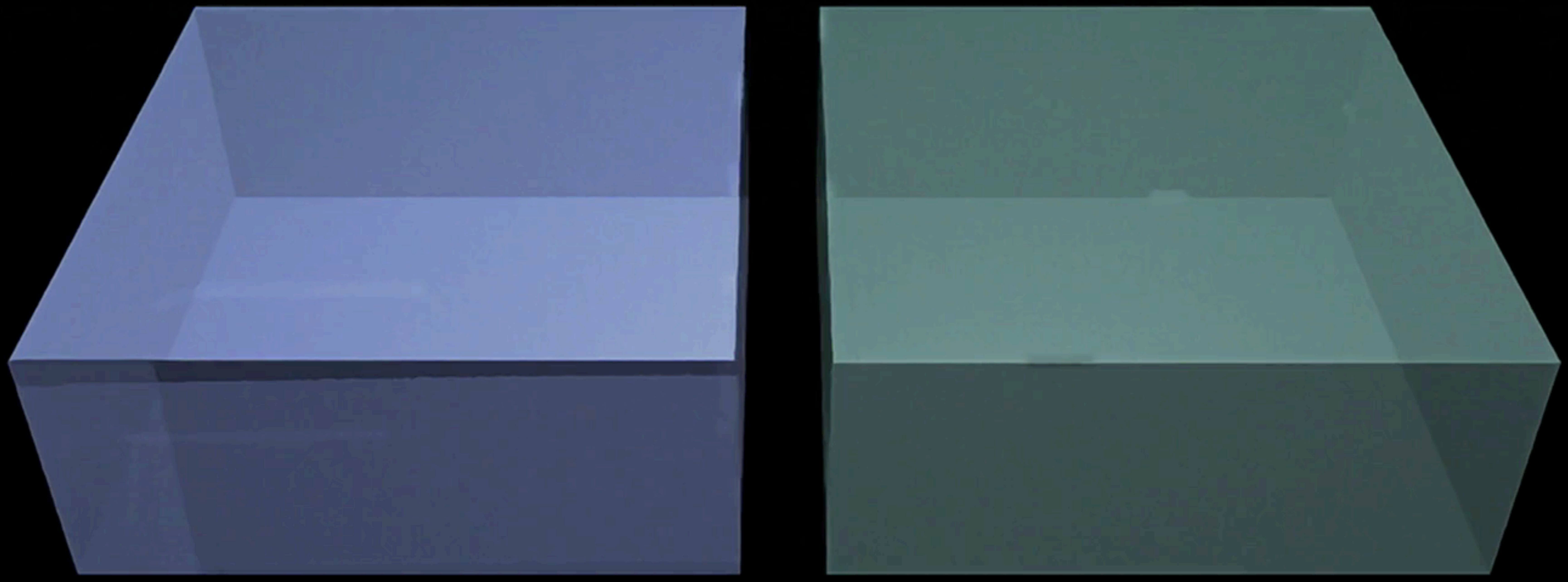
Sound Waves!



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

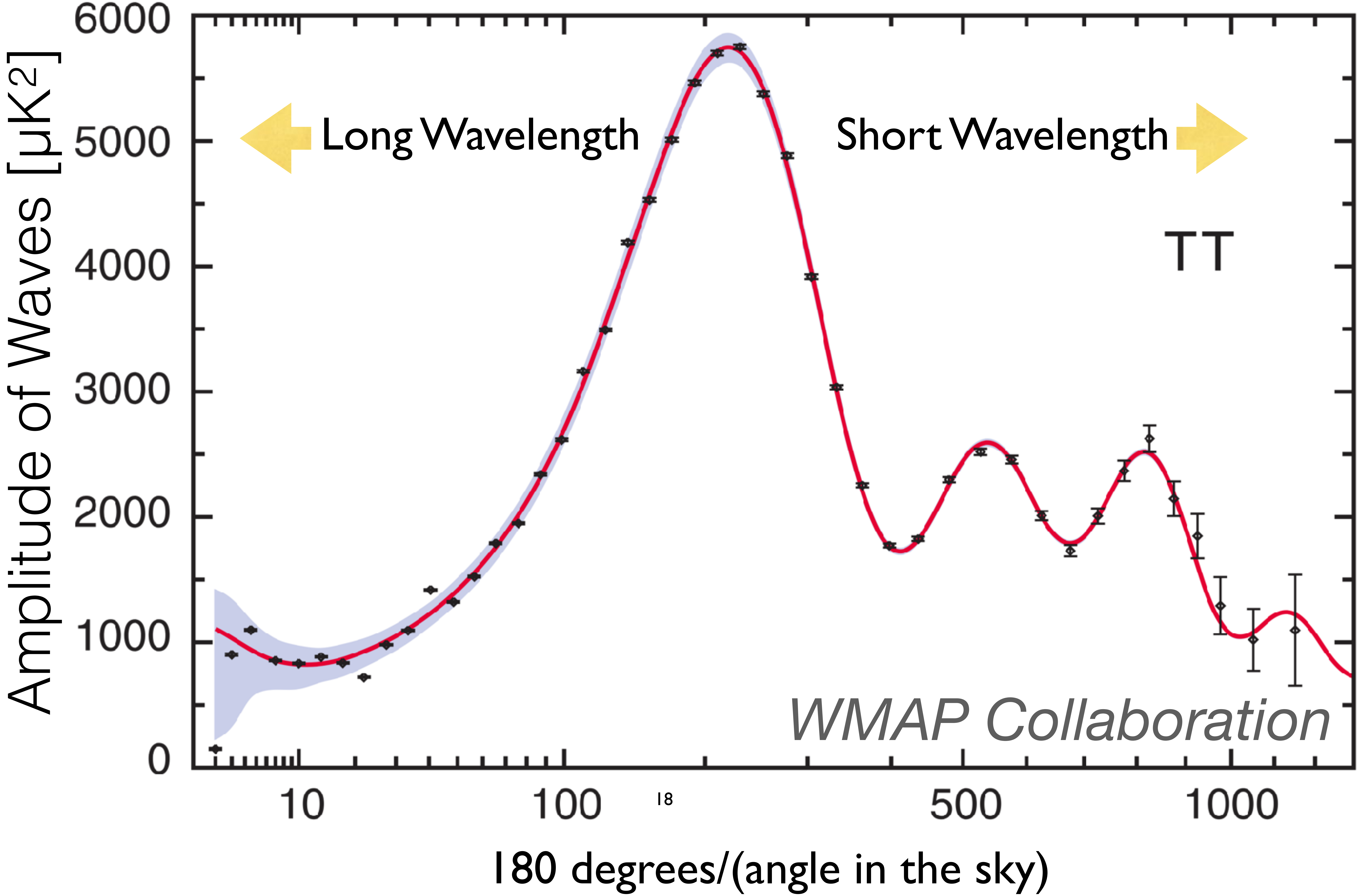
Credit: WMAP Science Team



How do we analyse the data like this?

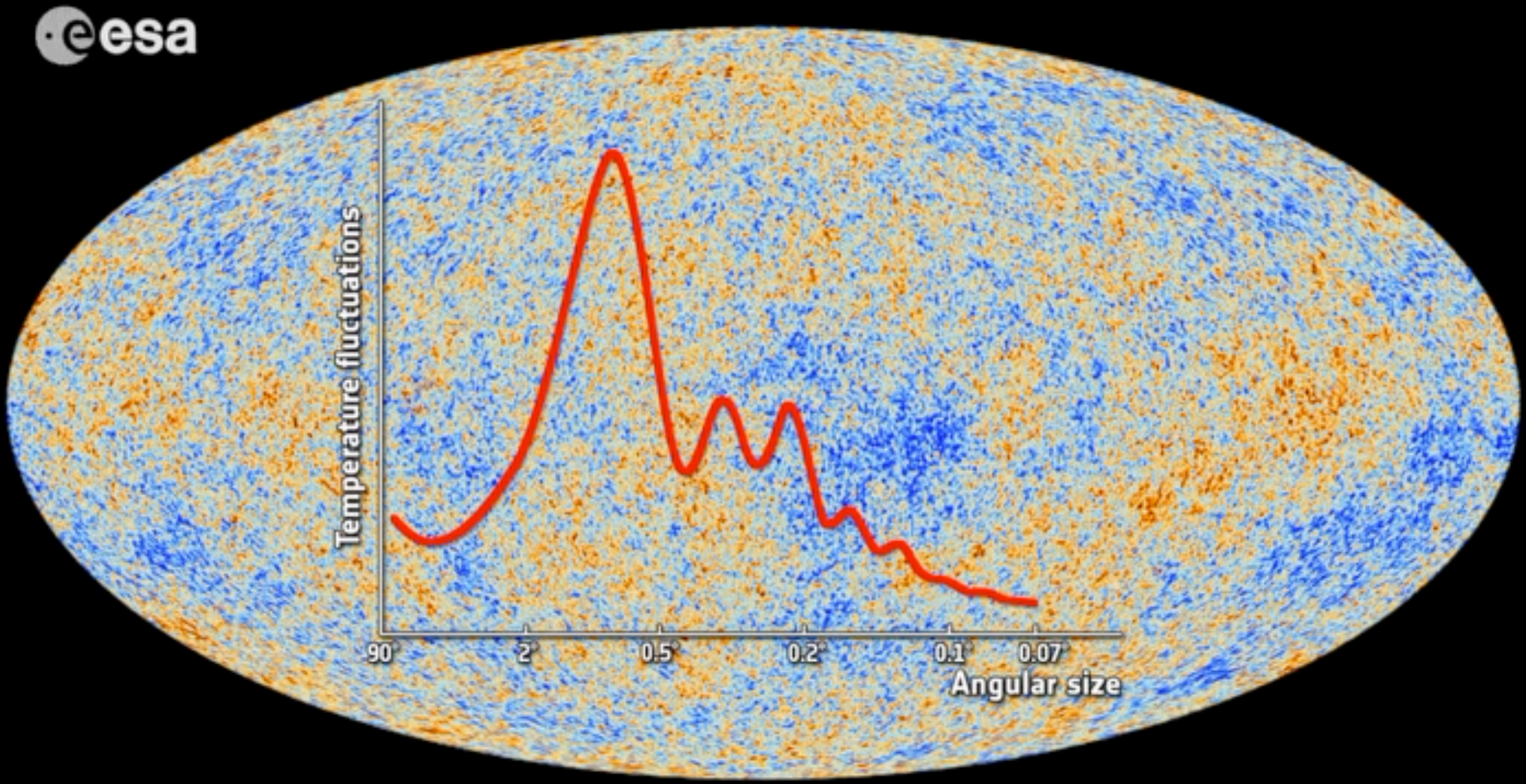
Data Analysis

- 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



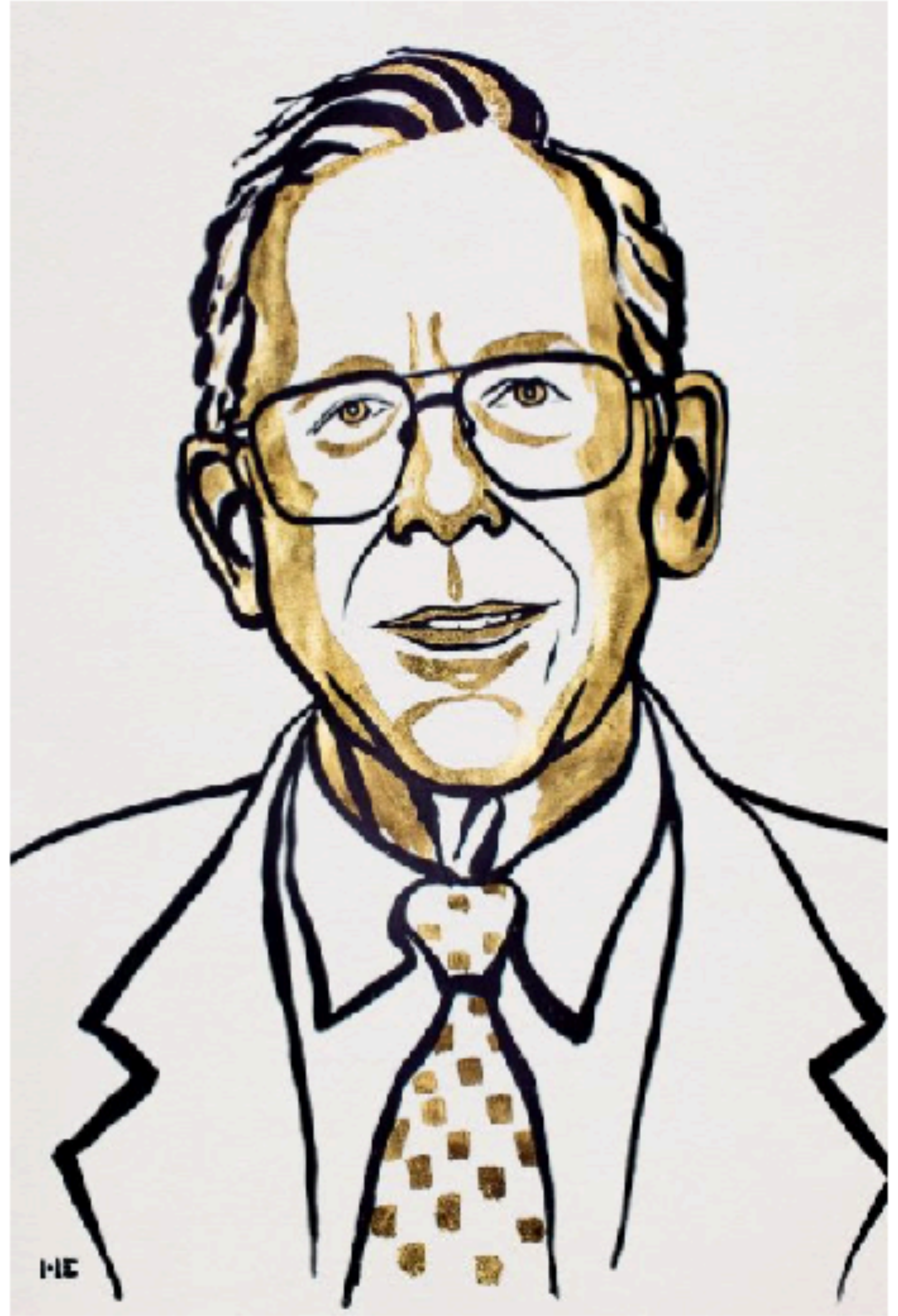
The Royal Swedish Academy of Sciences has decided to award the 2019 Nobel Prize in Physics to

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

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

https://www.nobelprize.org

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

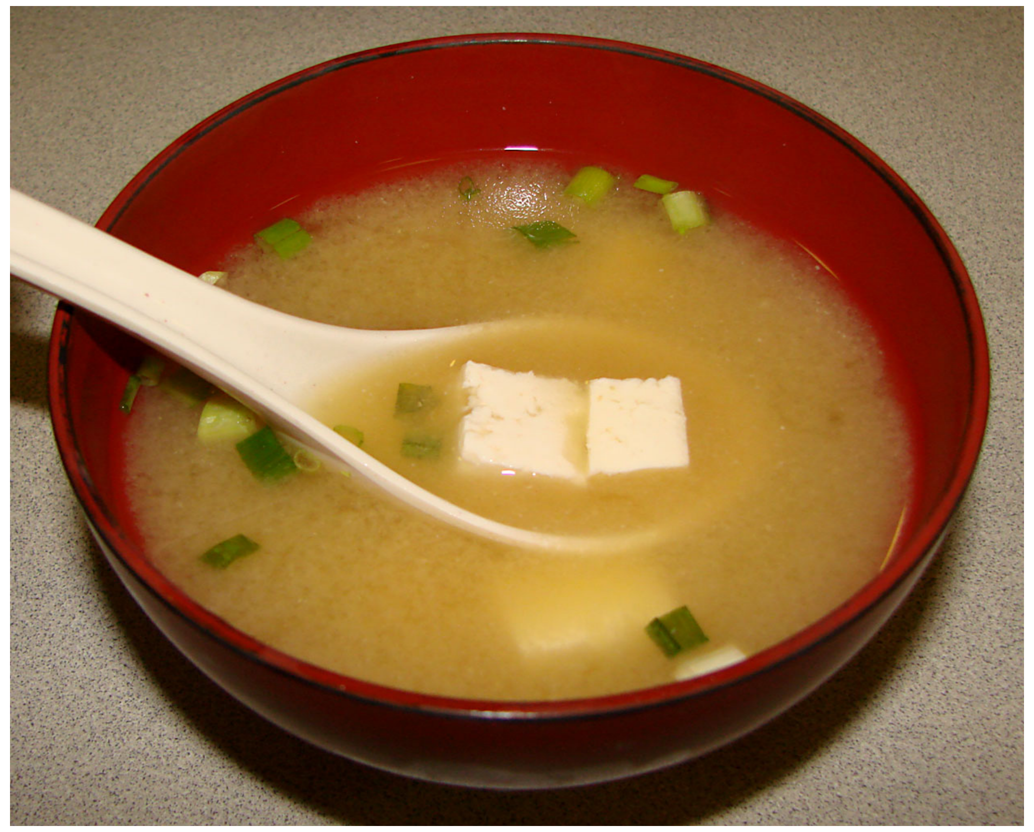
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)

Determine the composition of the Universe

The Universe as a "hot soup"

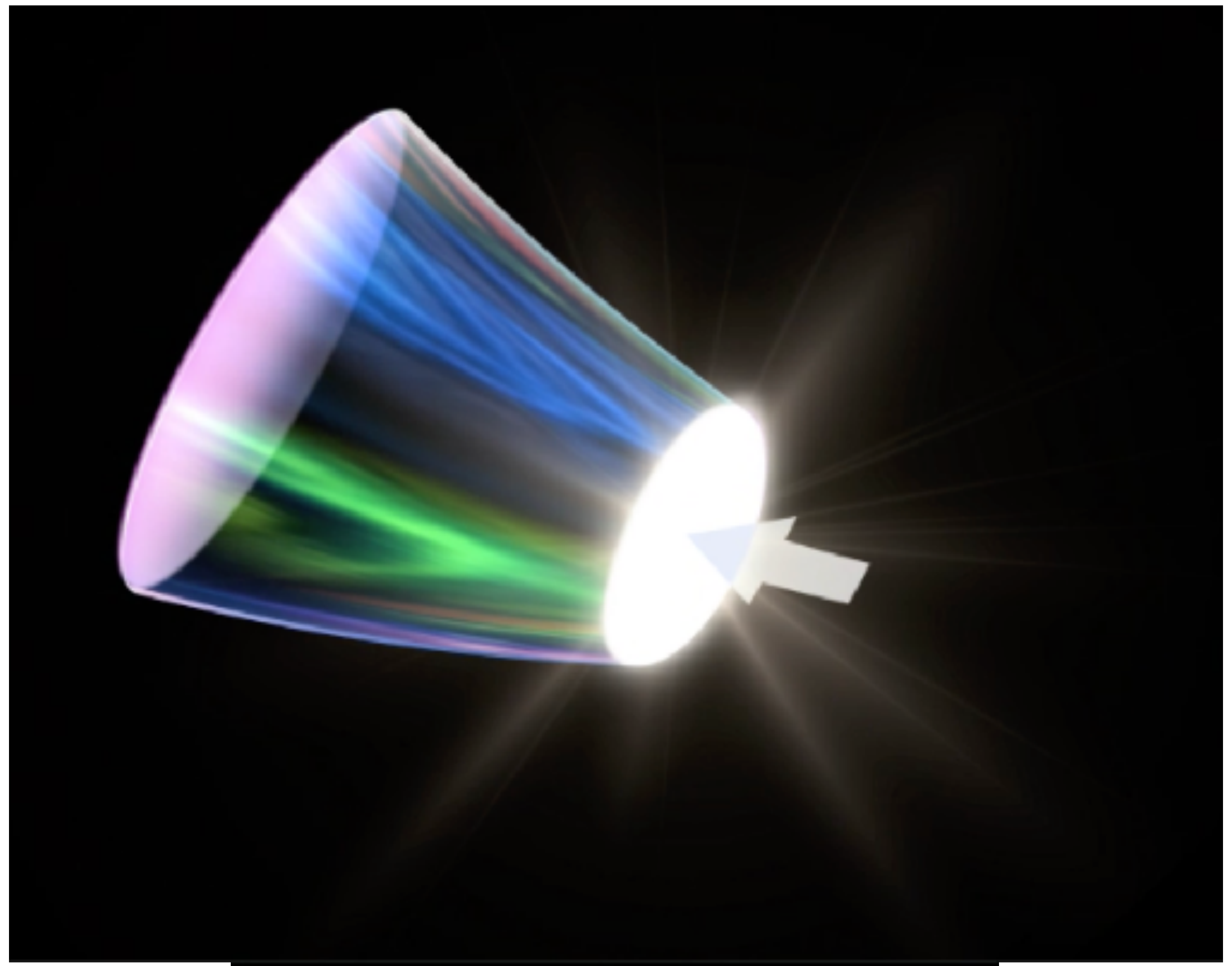
- The power spectrum allows us to determine the composition of the Universe, such as the density of atoms, dark matter, and dark energy.



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

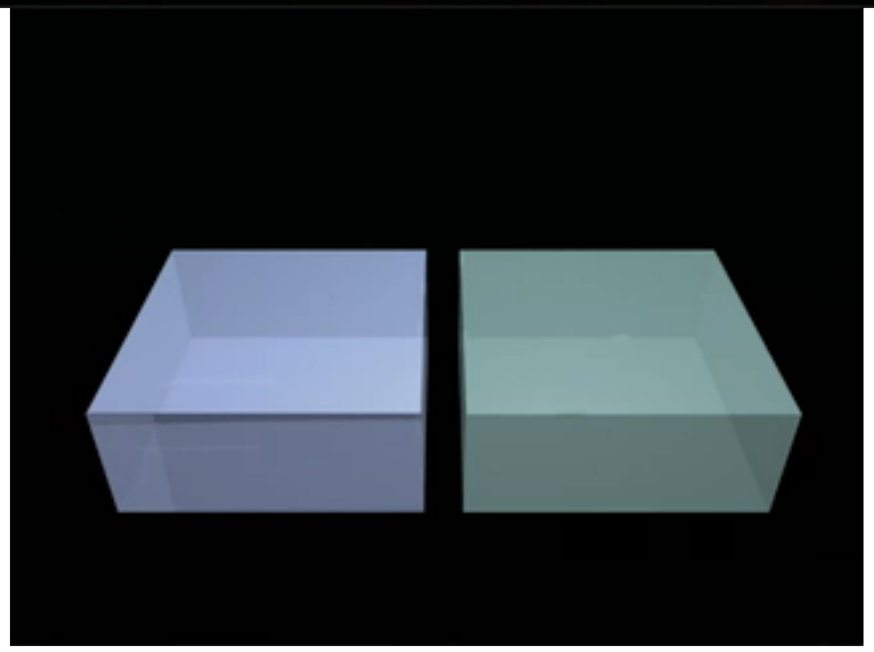
"Let's give some impact to the beginning of this model"

- 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?**

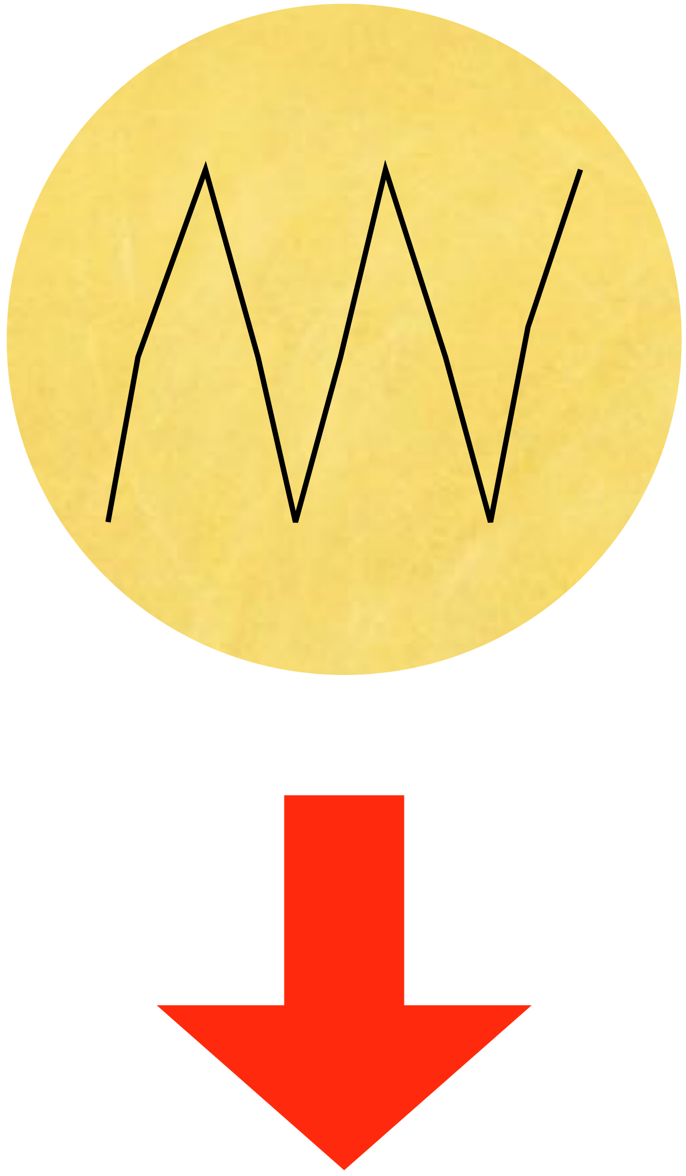
Gravity + Quantum

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

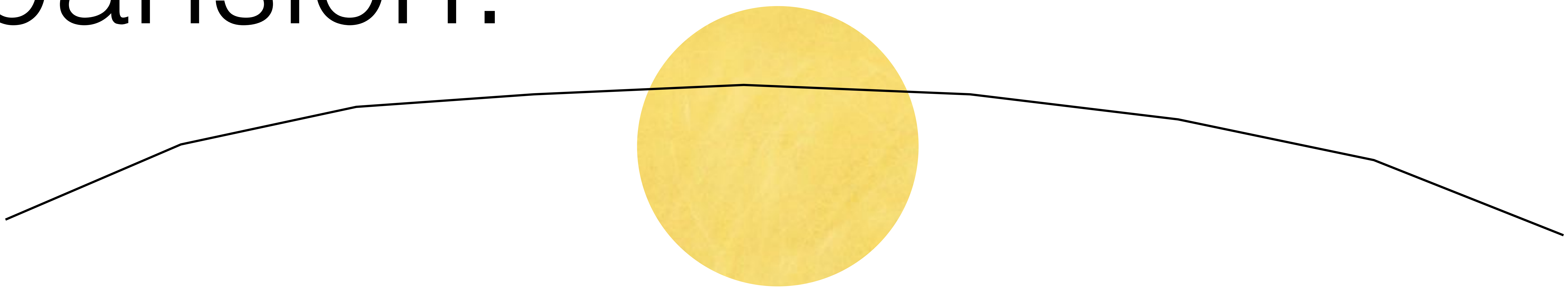
Starobinsky (1980); Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

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

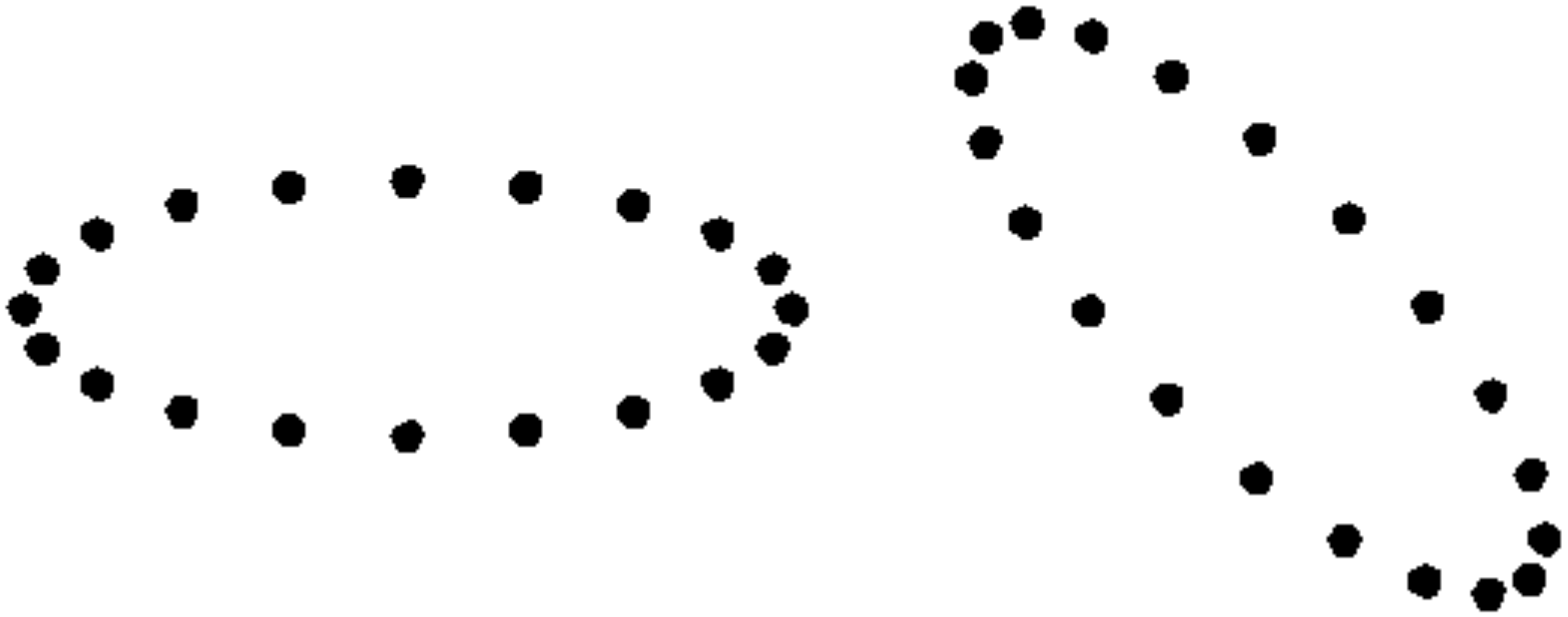
The next step: Primordial Gravitational Waves

- 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 GW (tensor modes)

Gravitational waves are coming towards you!

To visualise the waves, watch motion of test particles.



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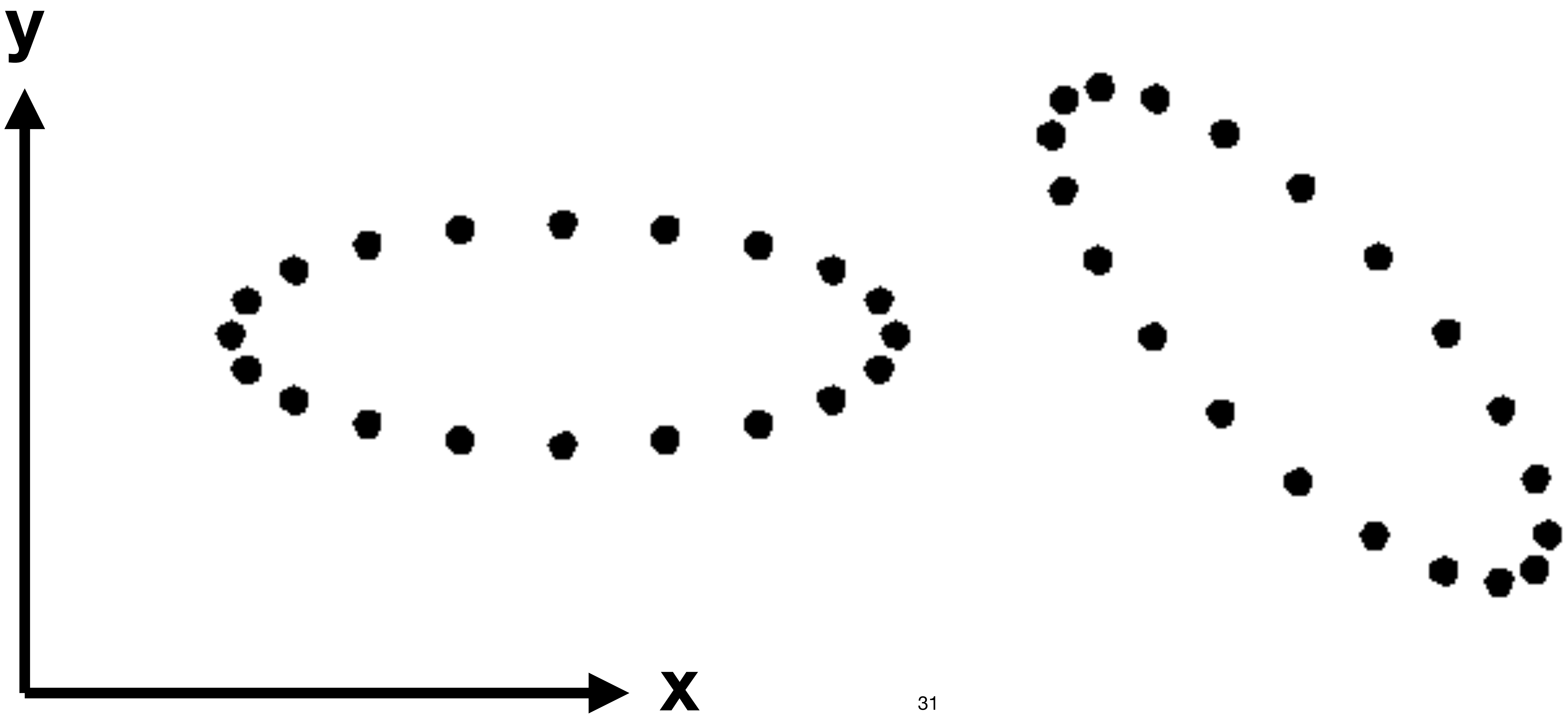


Distance between two points

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

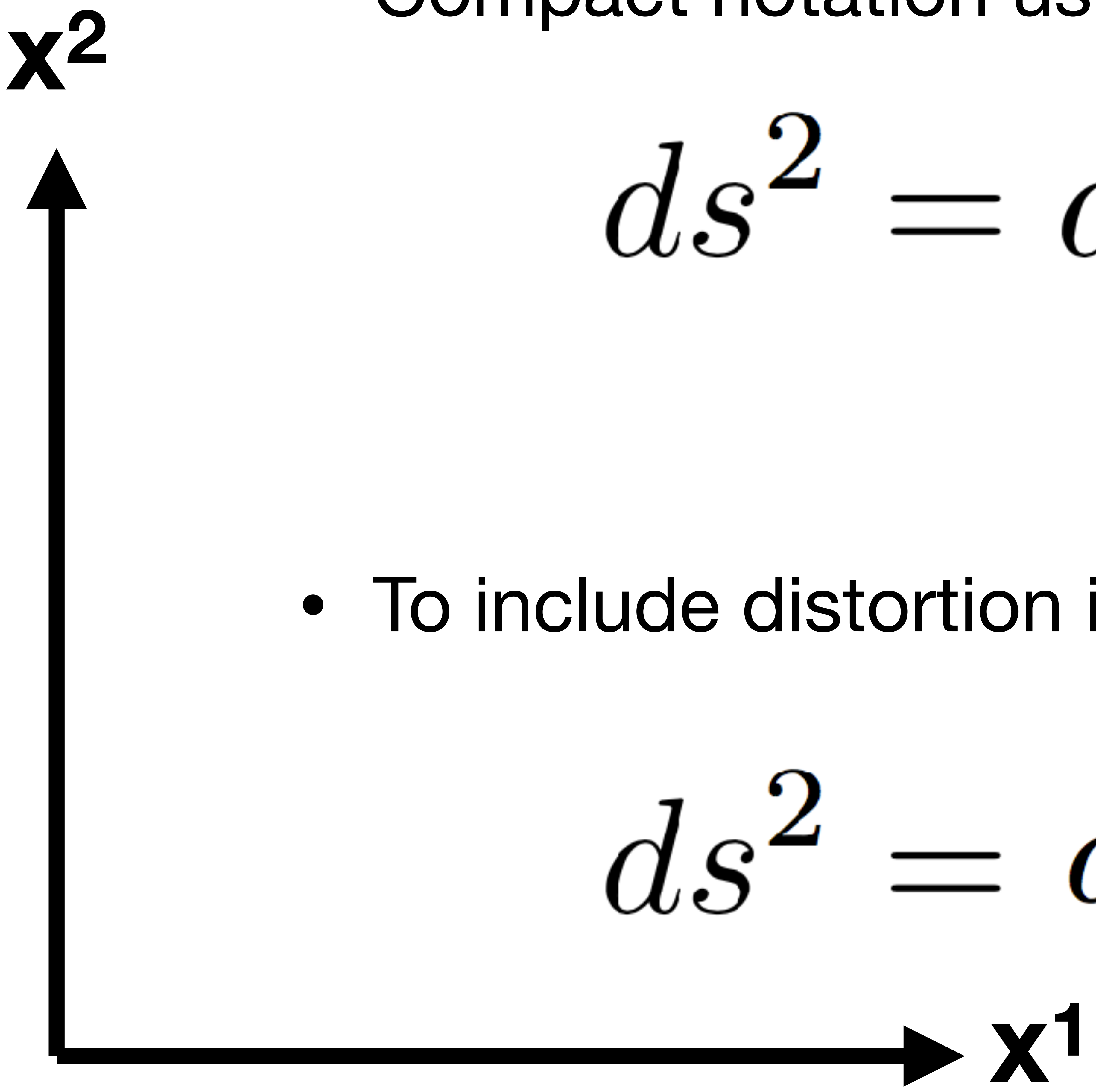
$$ds^2 = dx^2 + dy^2 + dz^2$$

- 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

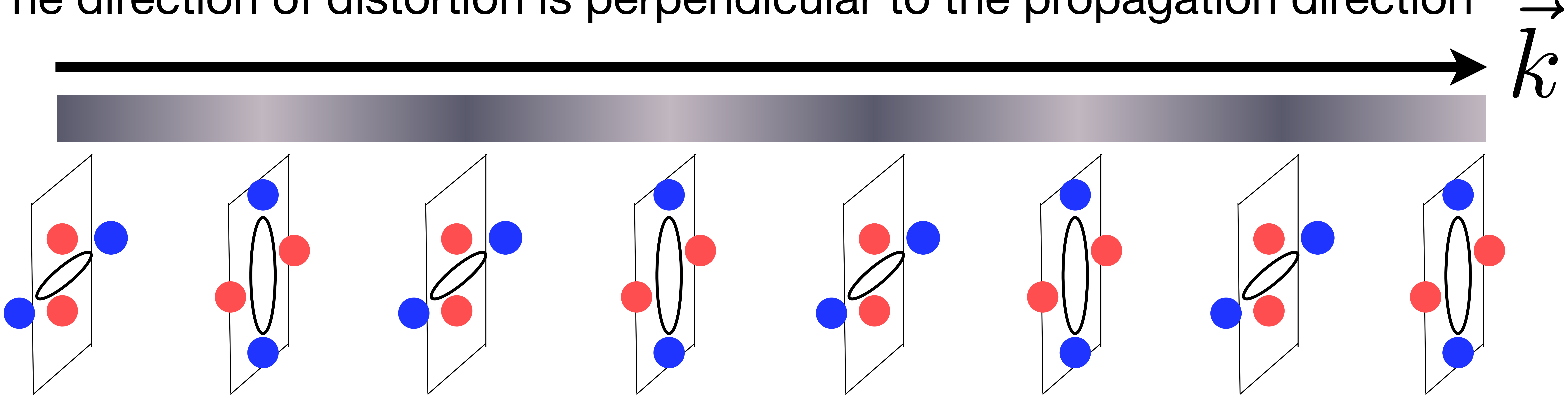
- To include distortion in space,

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

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



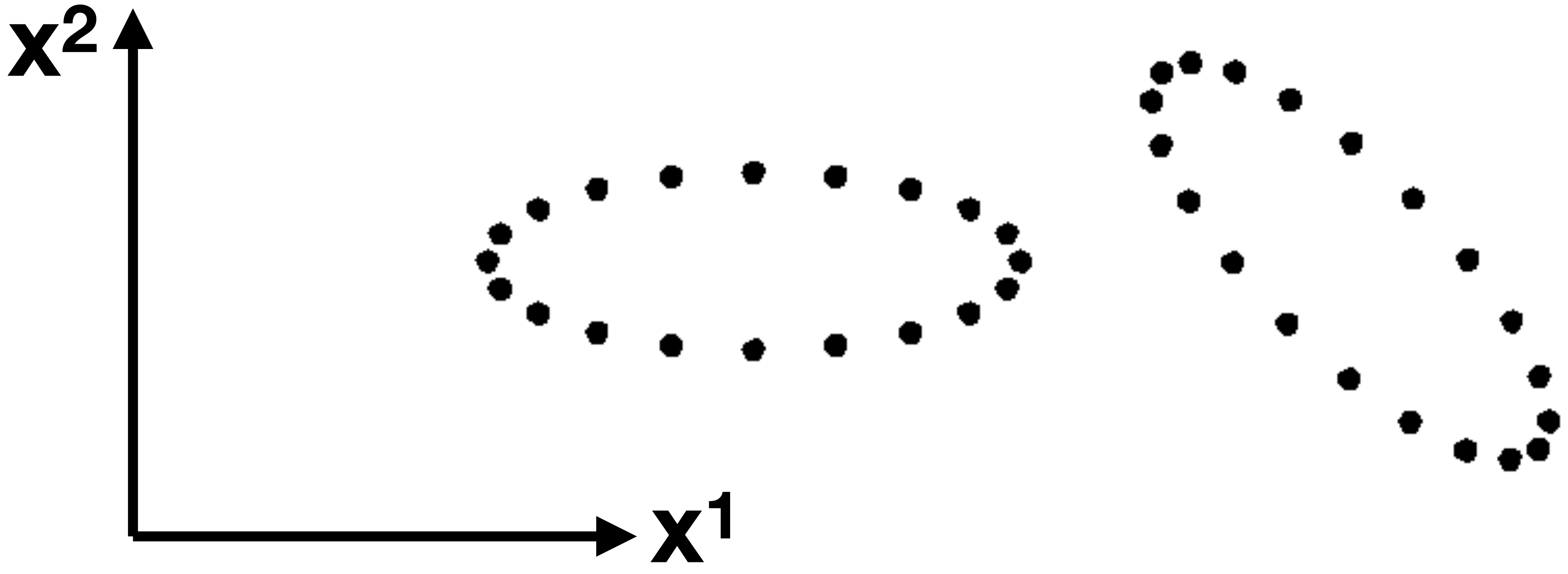
Thus, $$\sum_{i=1}^{3} k^i h_{ij} = 0$$

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

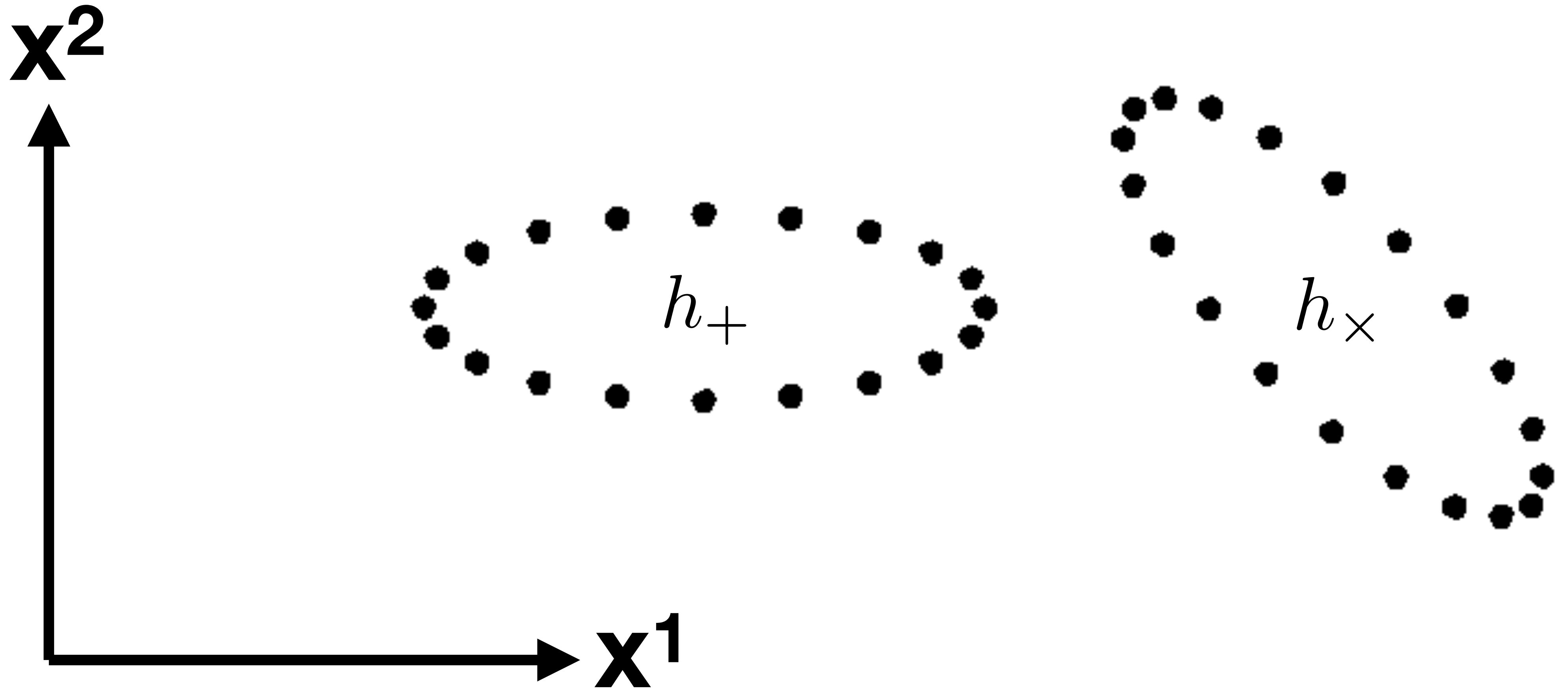
1 condition for h_{ij}

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

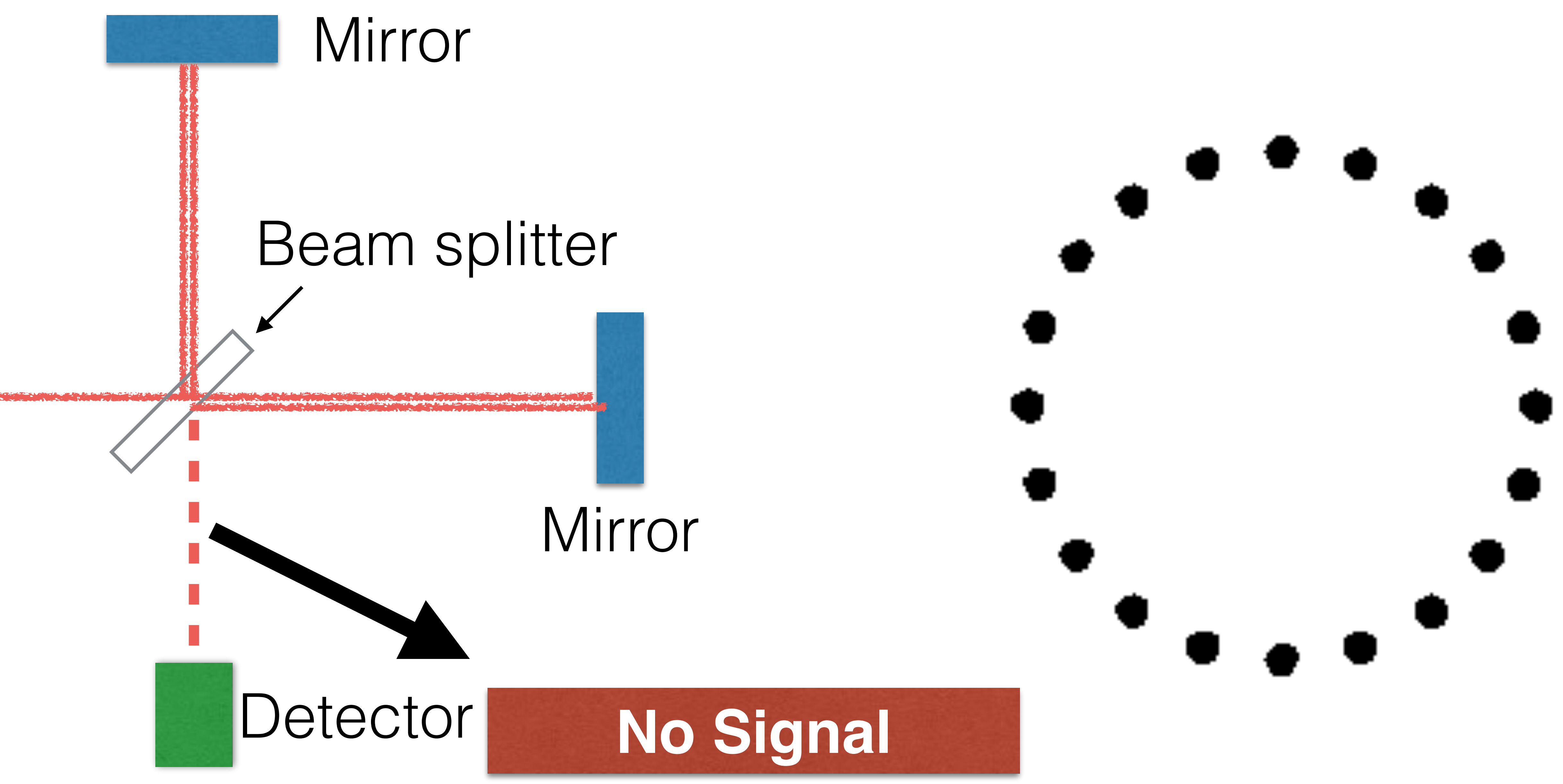
$$h_{ij} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



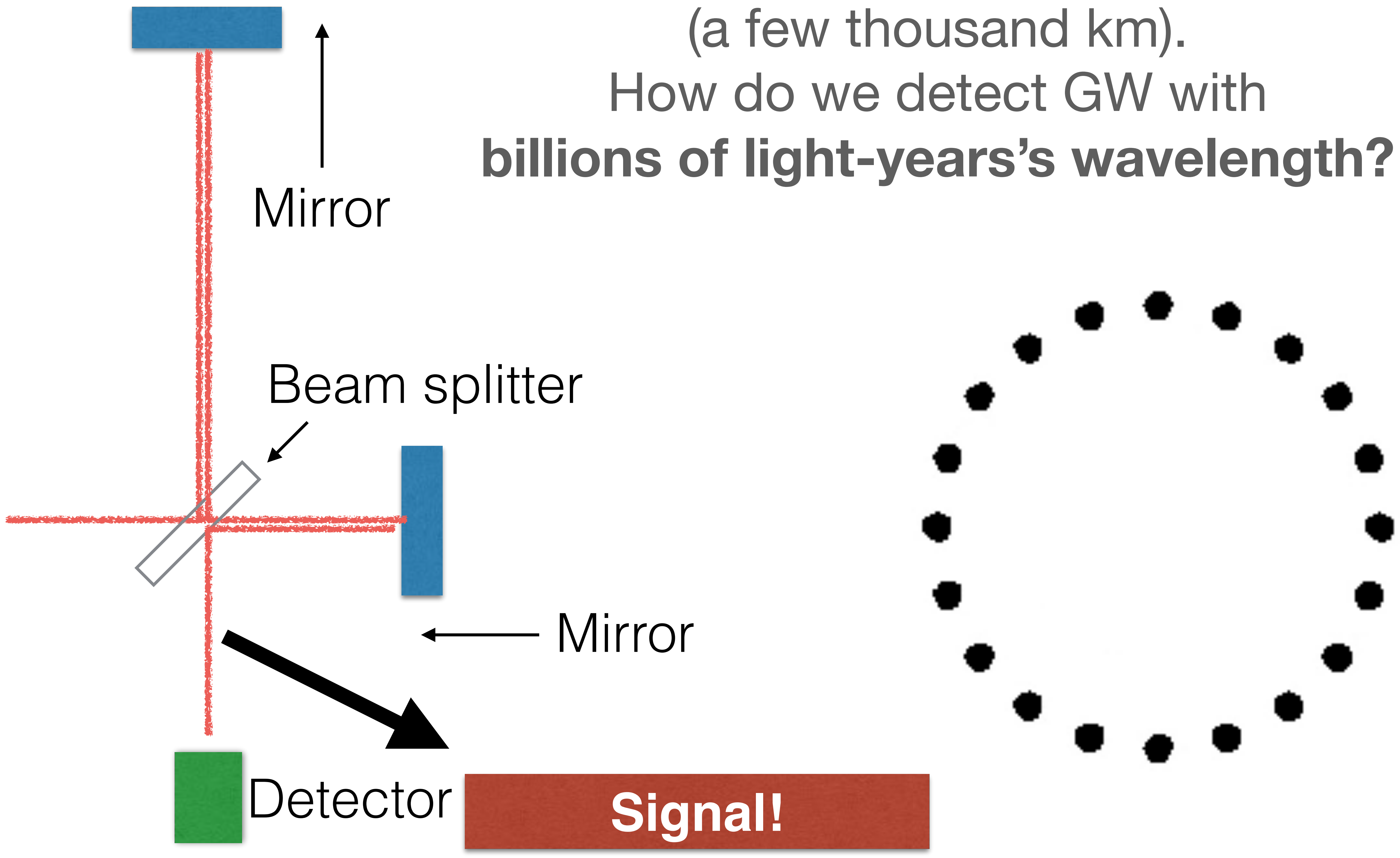

Propagation direction of GW $\vec{k}$
z
h+=cos(kz)
hx=cos(kz)

How to detect GW?

Laser interferometer technique, used by LIGO and VIRGO

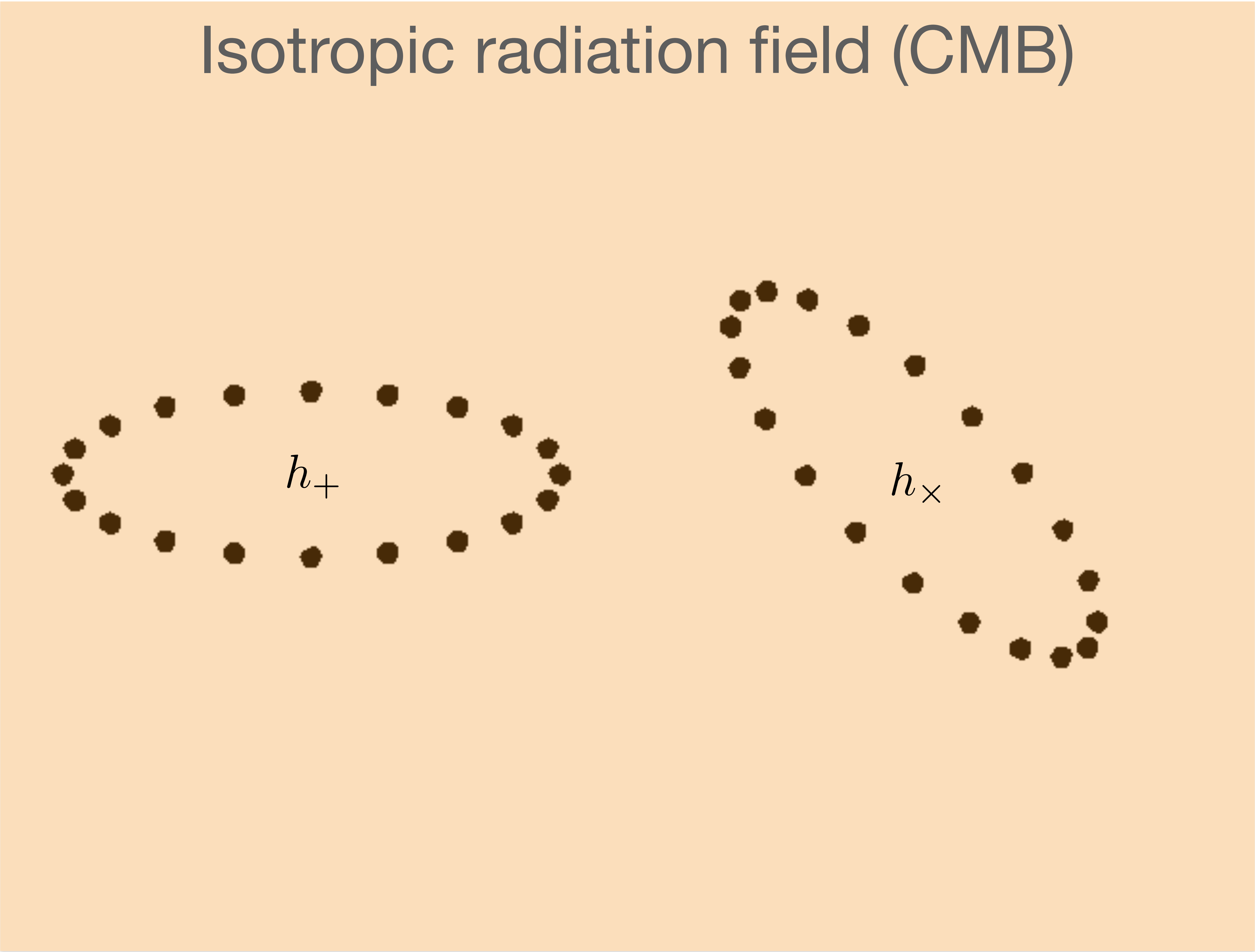


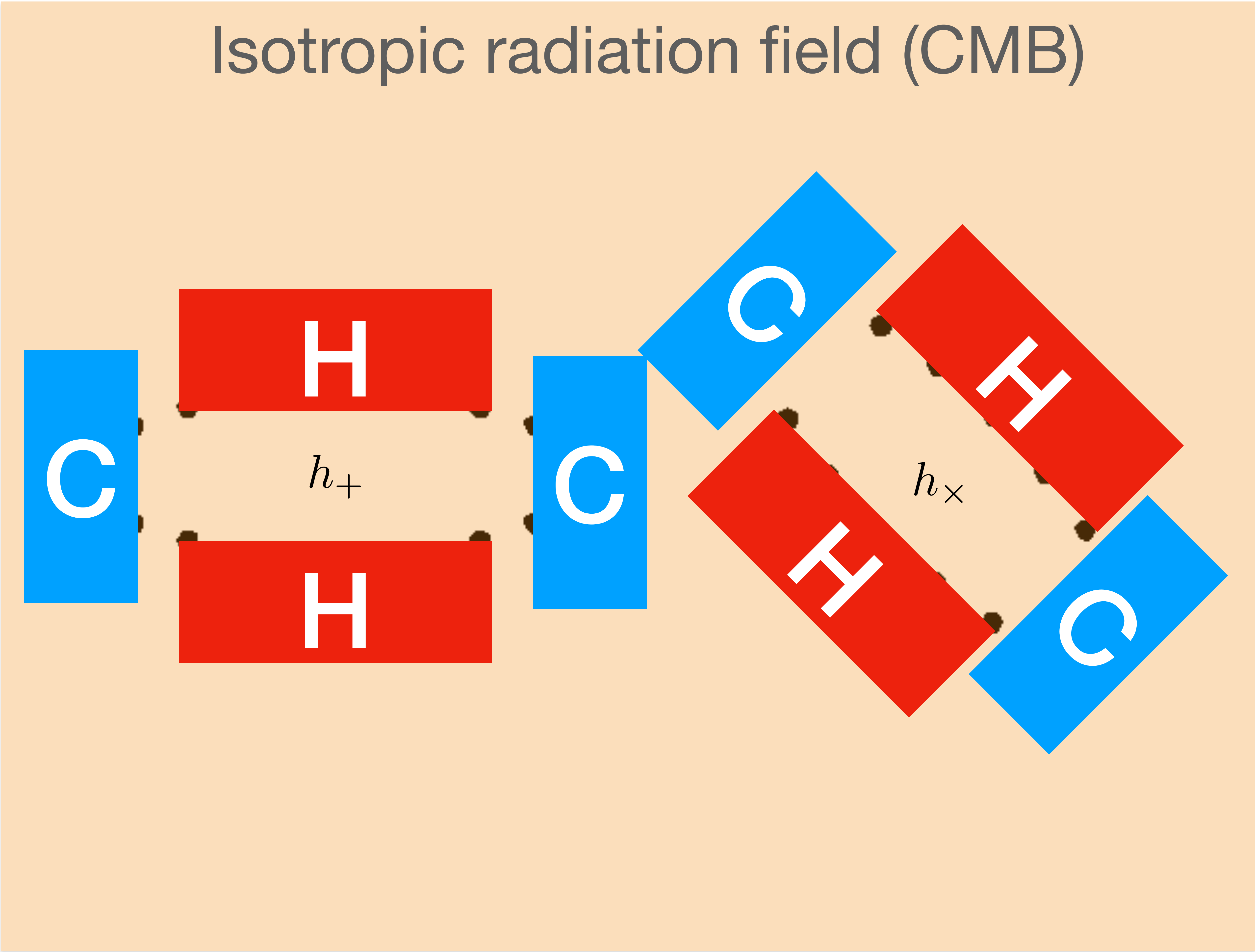
The wavelength of GW detectable by this method is the size of Earth (a few thousand km).
How do we detect GW with **billions of light-years's wavelength?**



Detecting GW by CMB

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





Detecting GW by CMB

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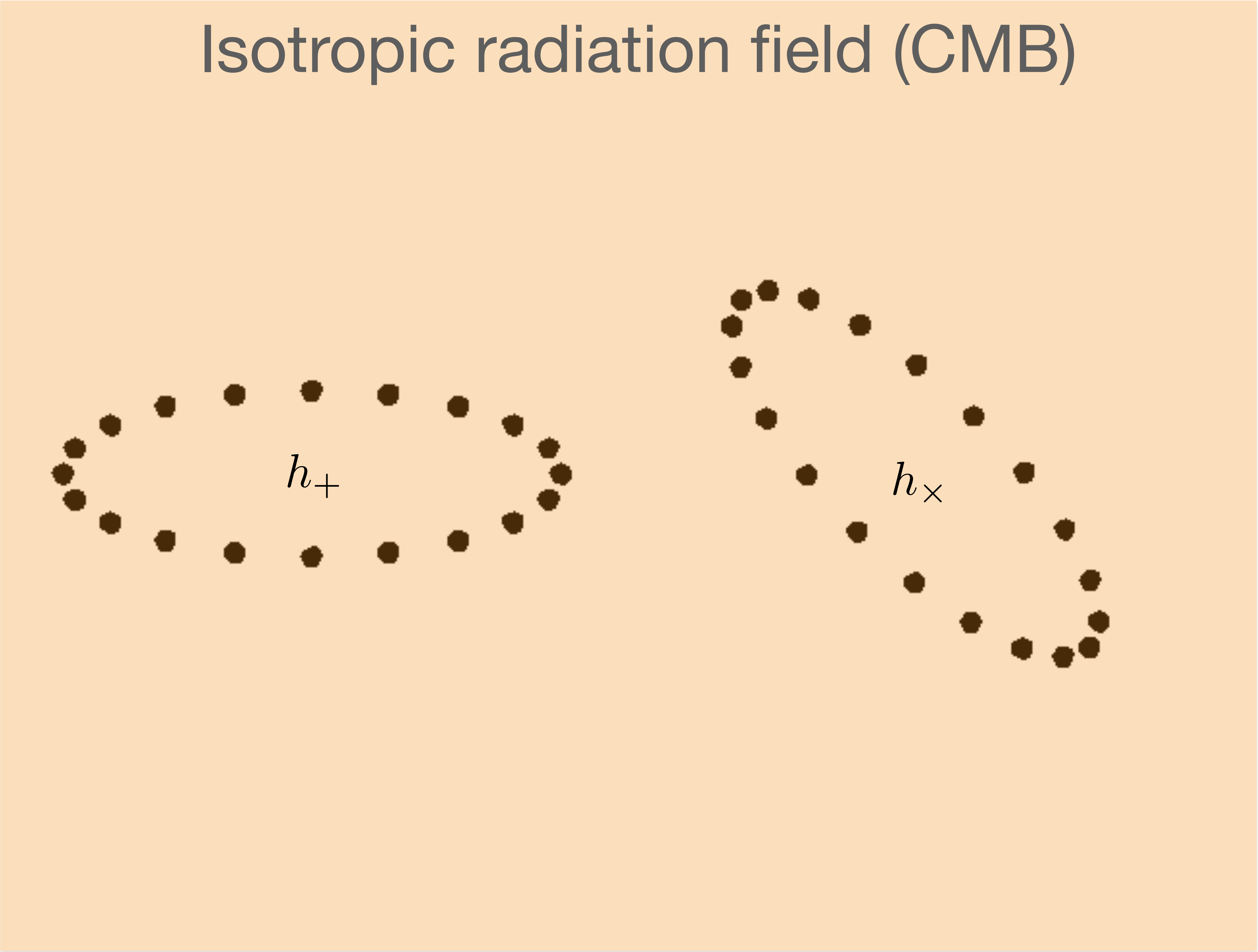
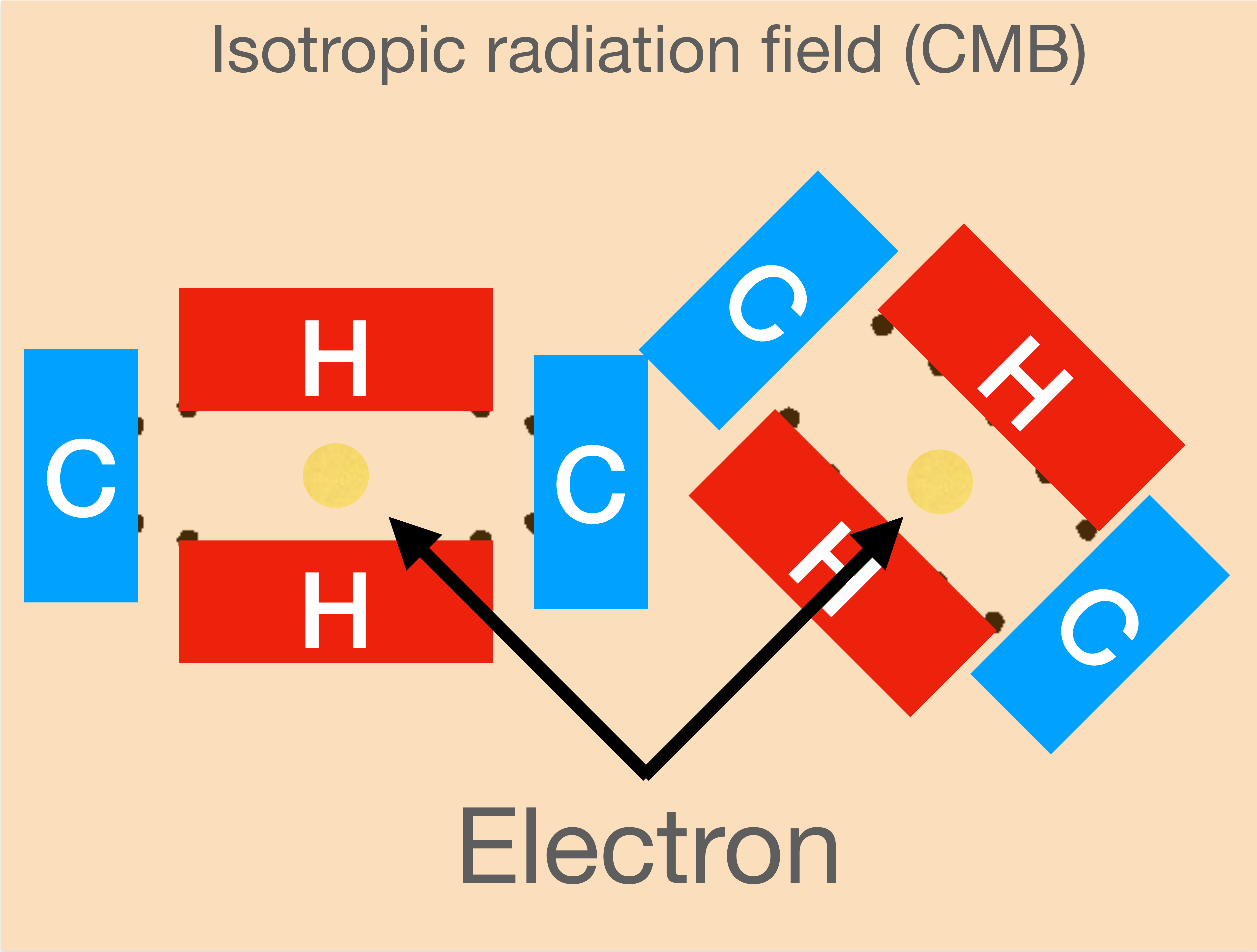
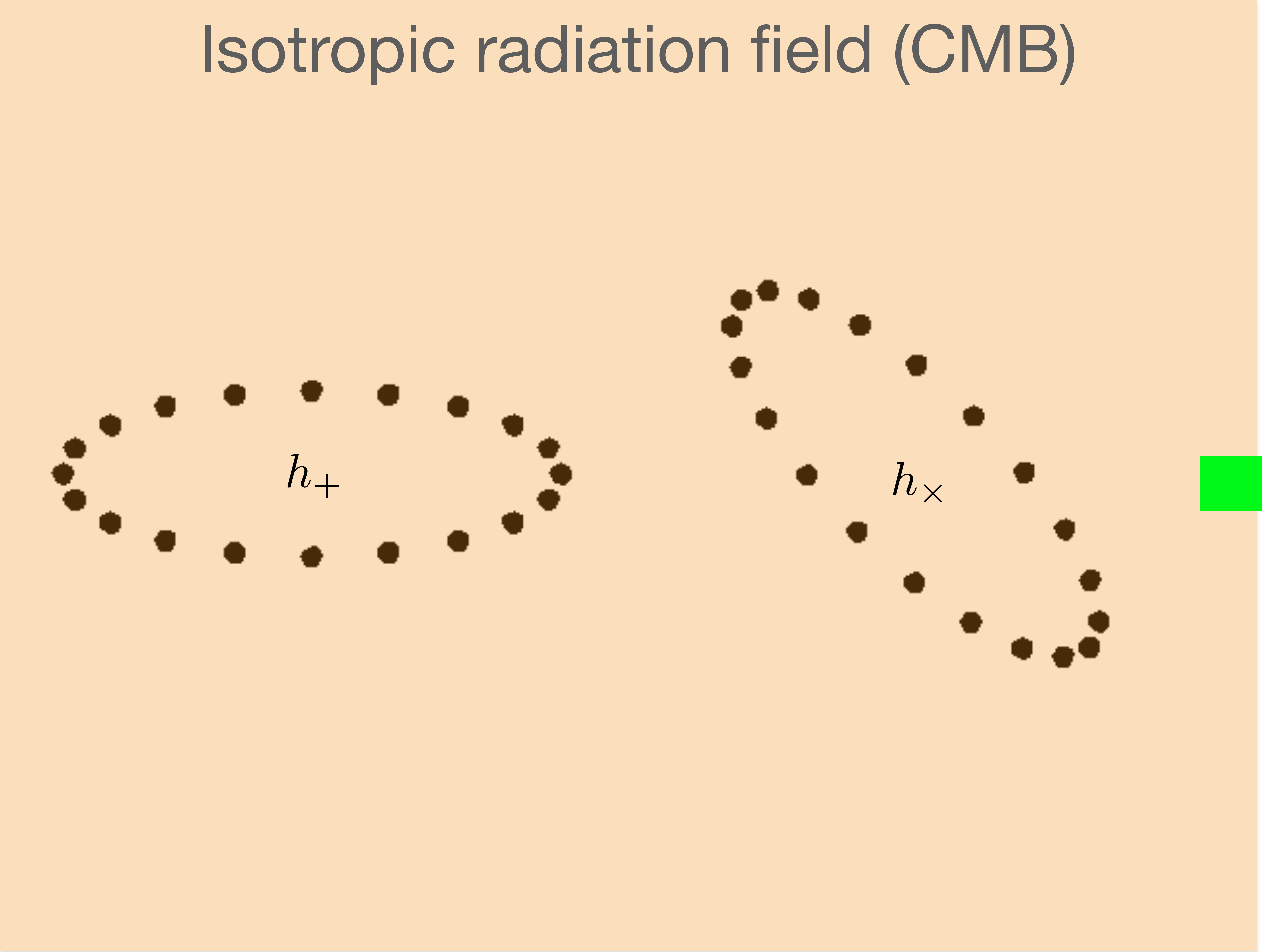
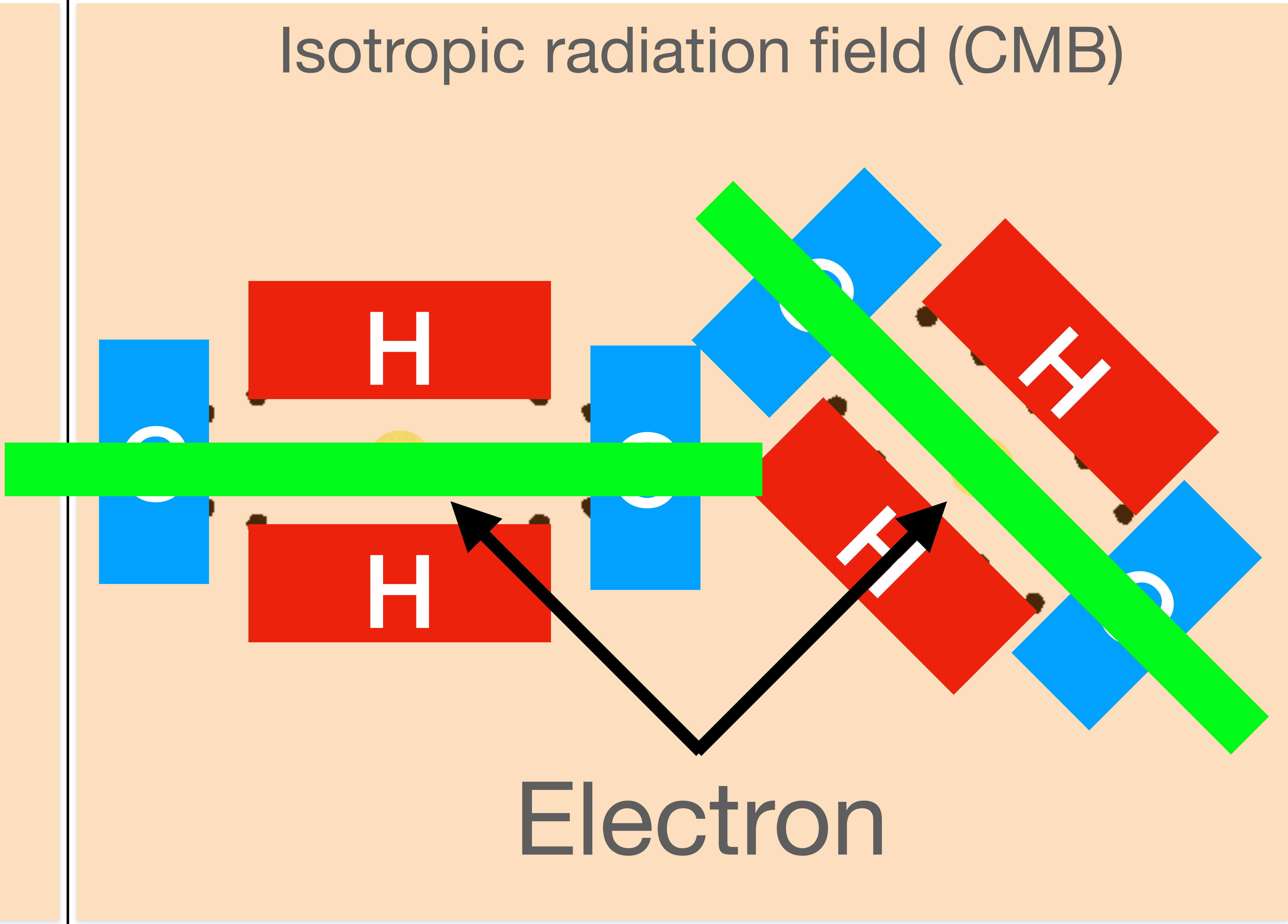




Detecting GW by CMB *Polarisation*

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

Credit: ESA

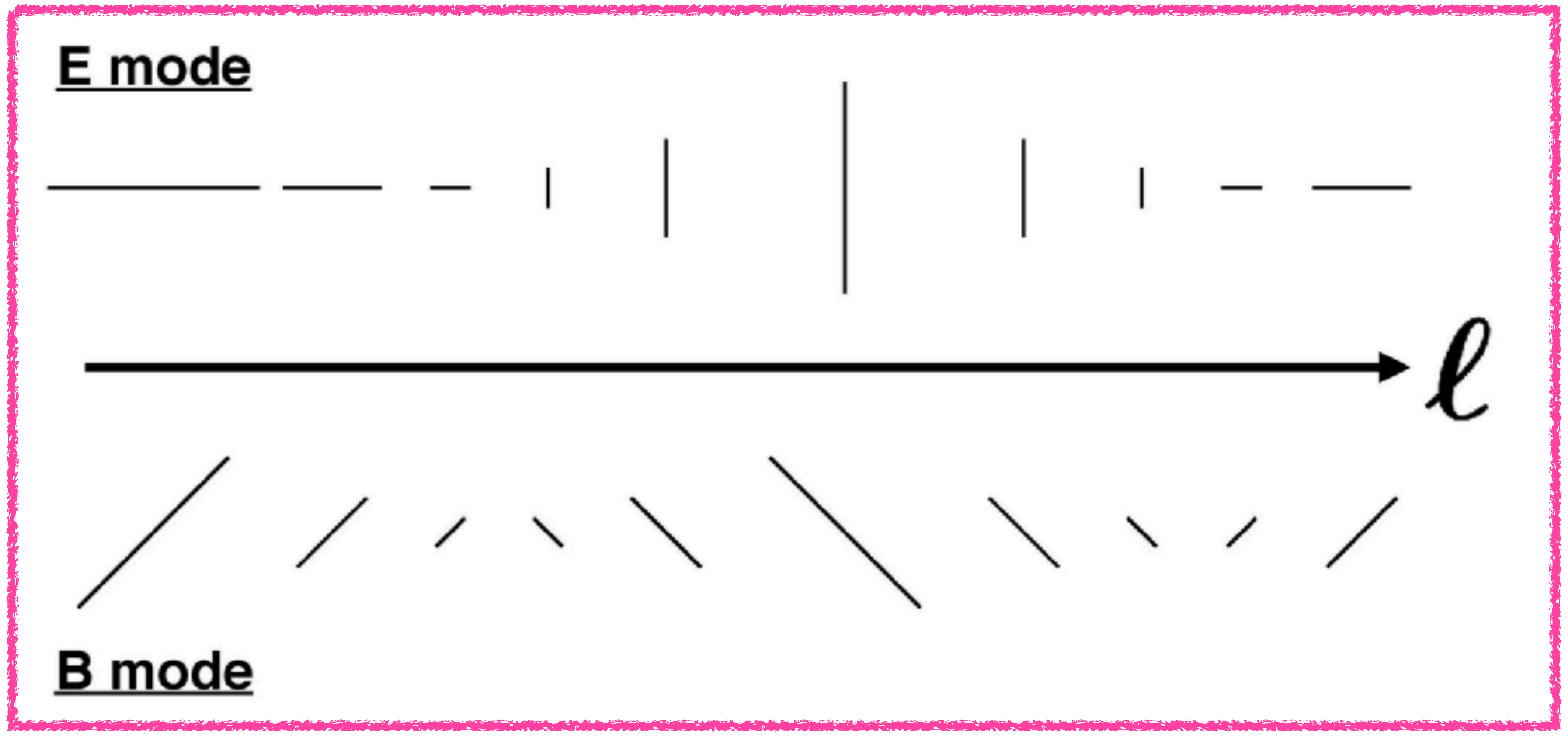
Temperature (smoothed)

Temperature (smoothed) + Polarisation

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

E- and B-mode decomposition

Concept defined in Fourier space

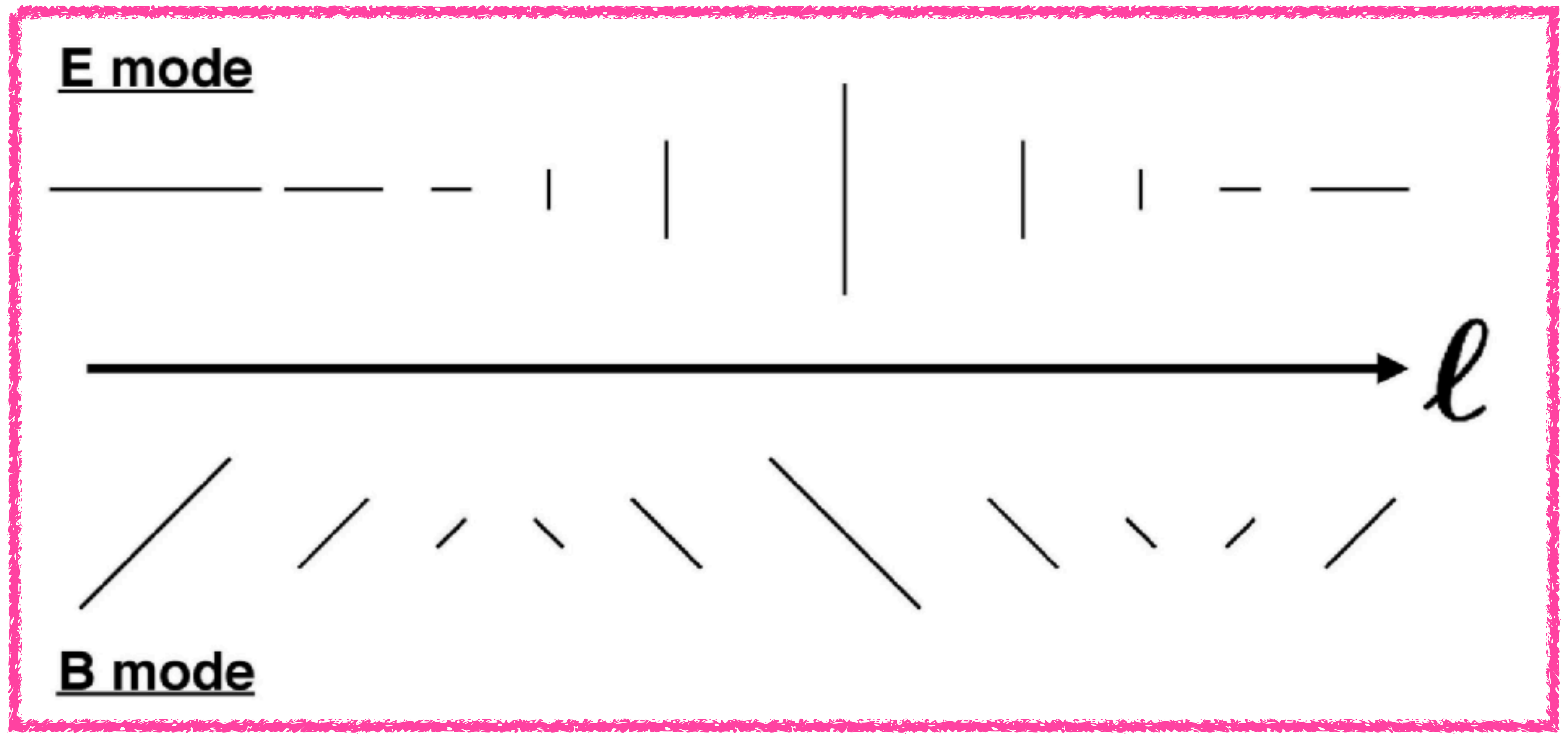


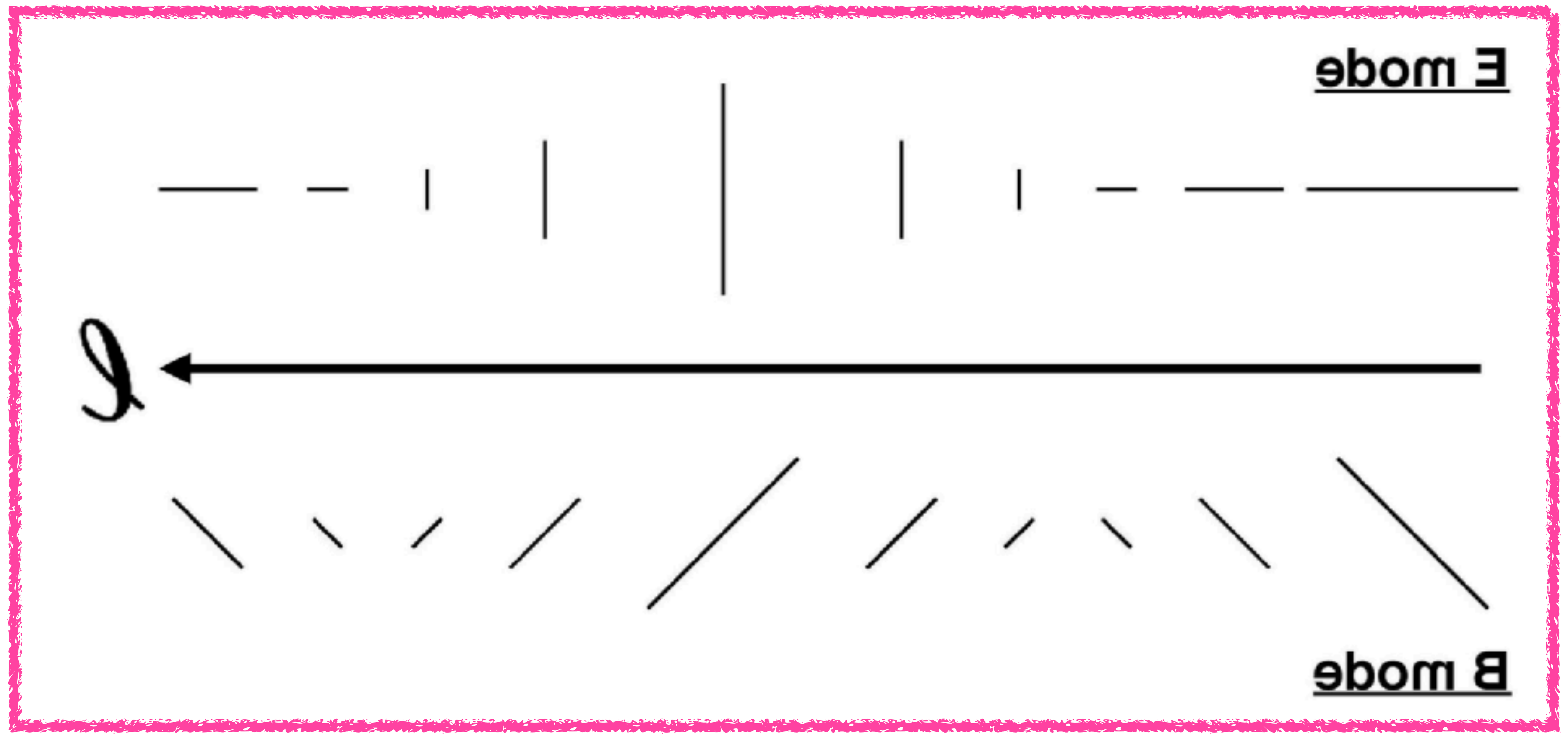
Direction of the Fourier wavenumber vector

- **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

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

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

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

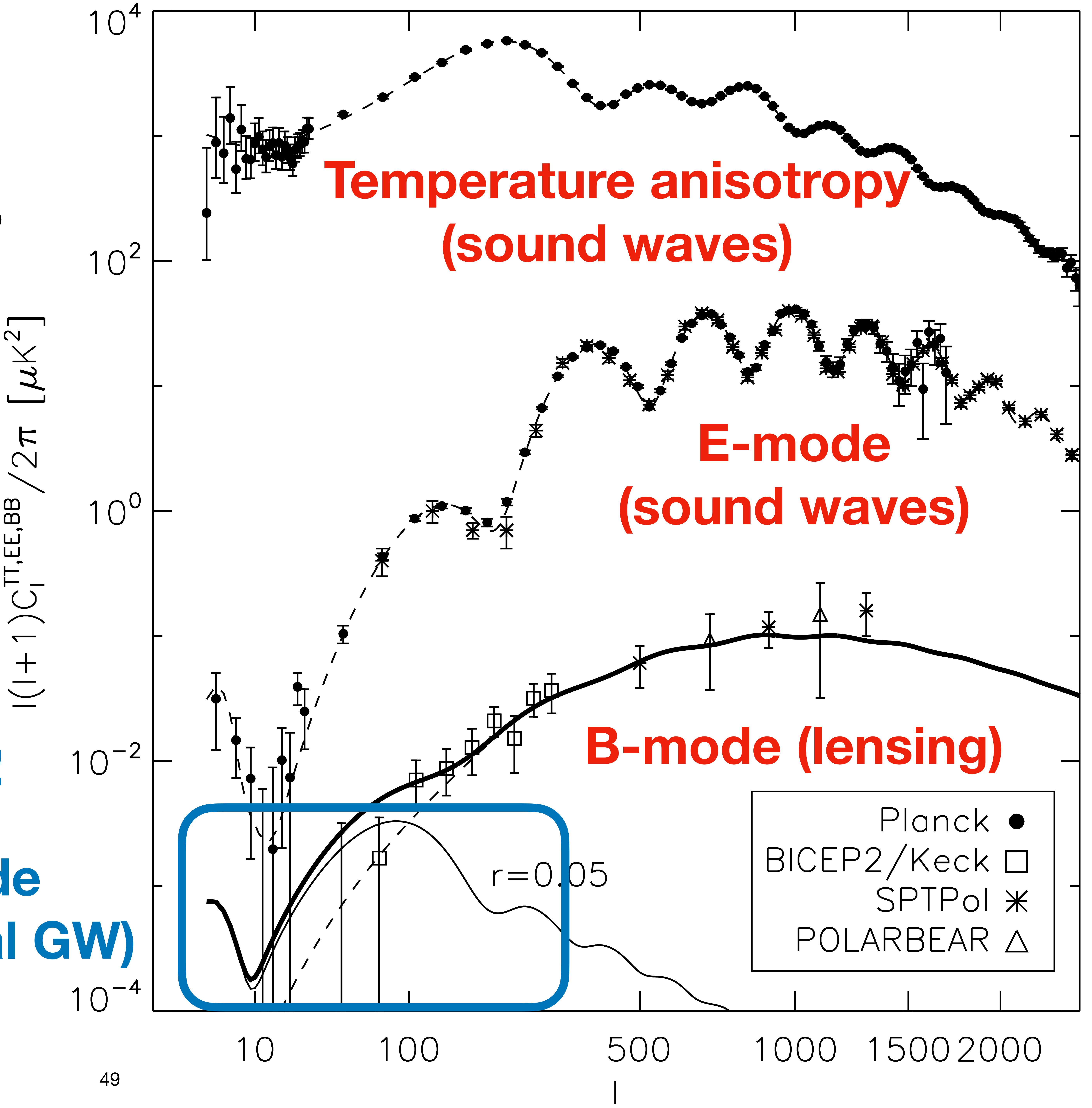
- The other combinations <TB> and <EB> are not invariant under the parity flip.
  - **[Side Note] We can use these combinations to probe parity-violating physics (e.g., axions)**

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)



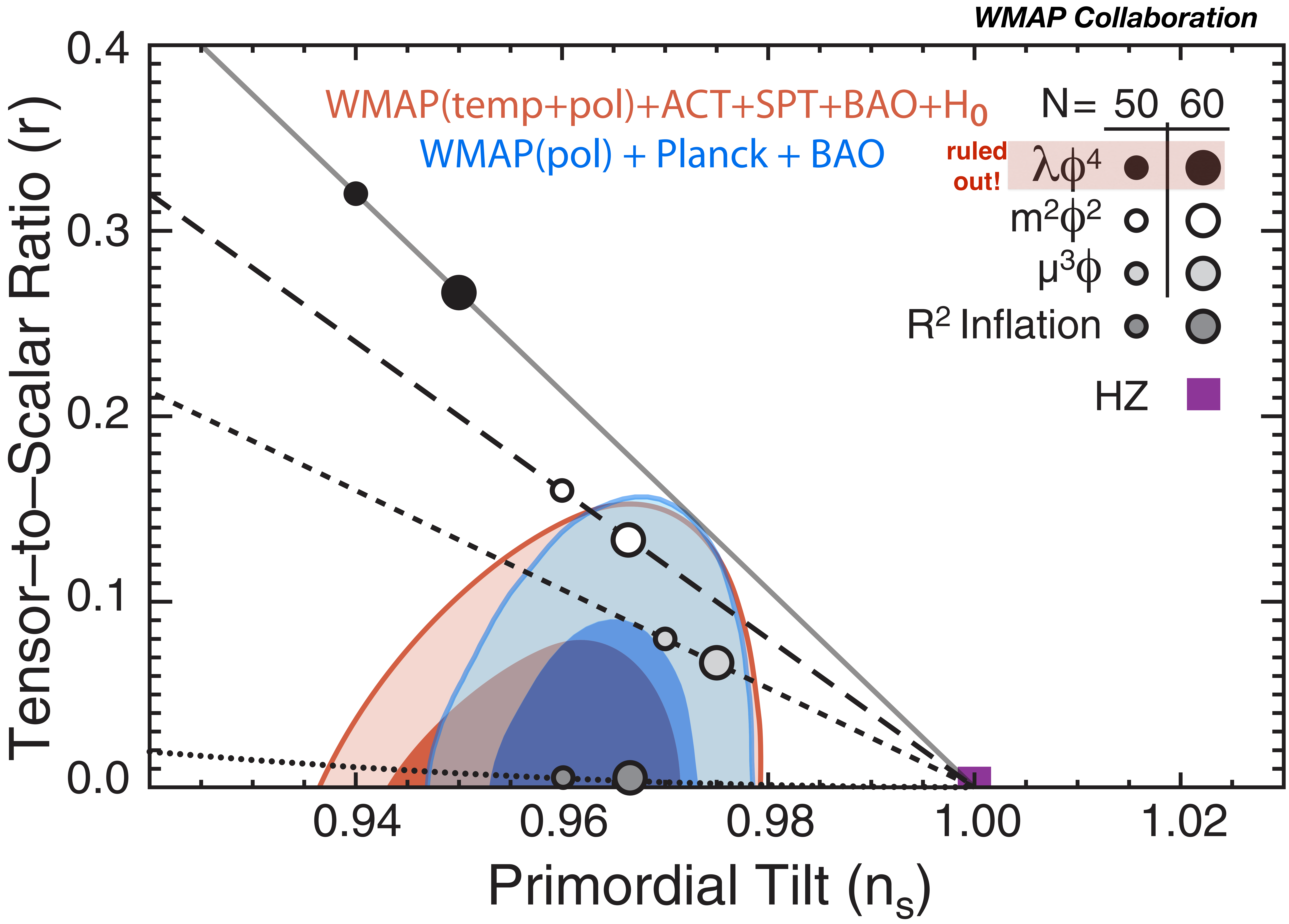
Tensor-to-scalar Ratio

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

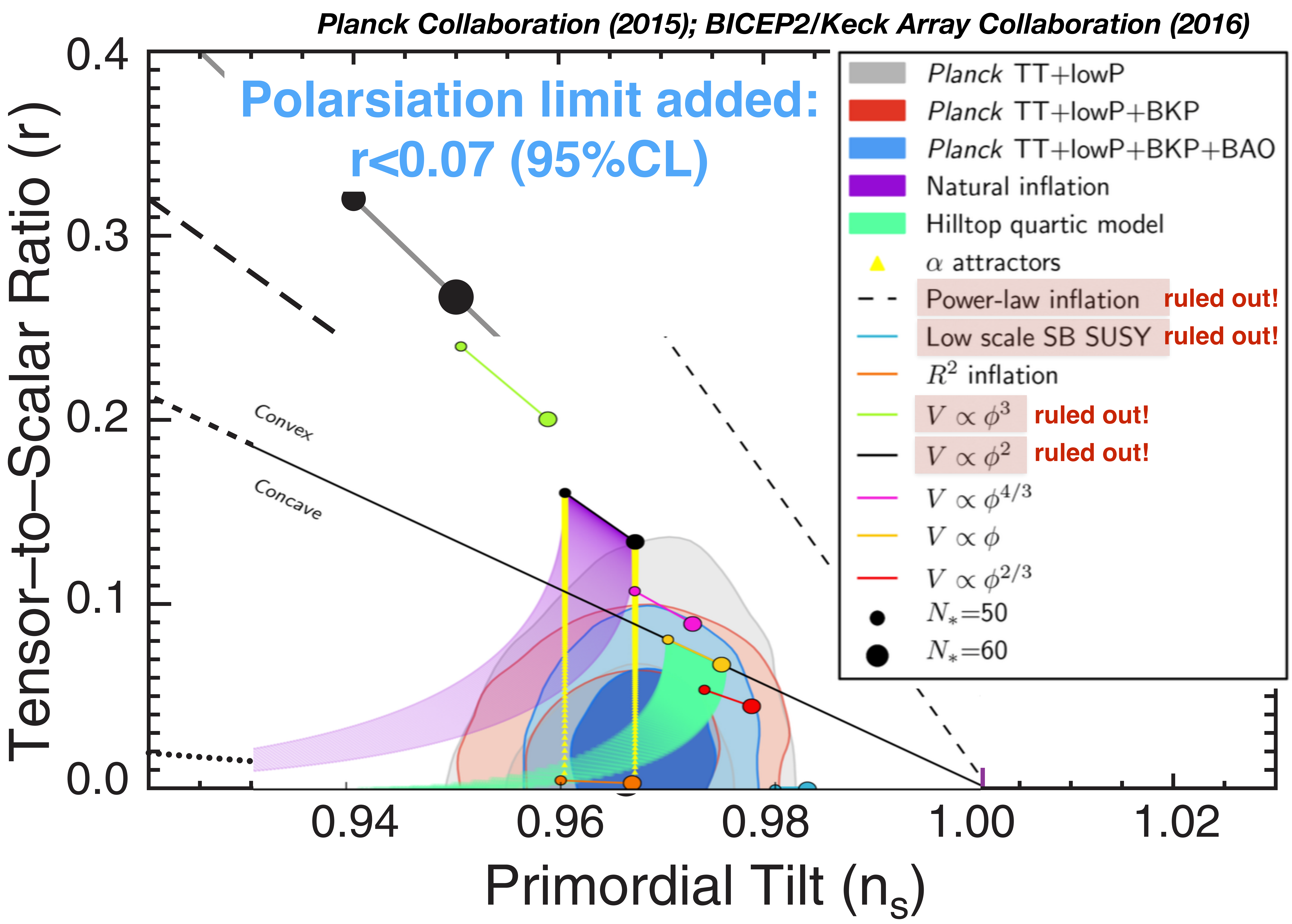
Scalar mode

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

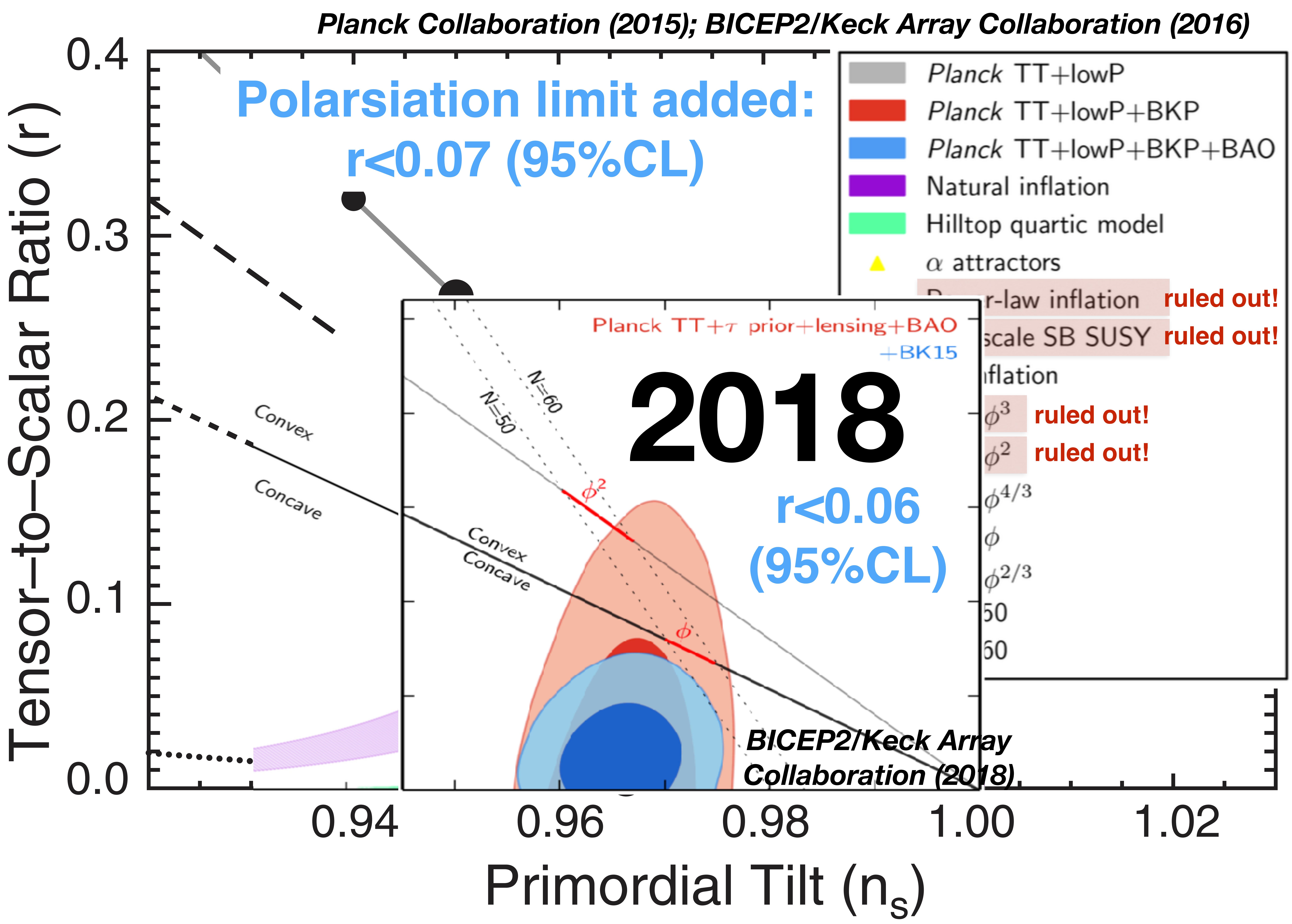
BICEP2/Keck Array Collaboration (2018)



WMAP Collaboration
WMAP(temp+pol)+ACT+SPT+BAO+H_0
WMAP(pol) + Planck + BAO
N= 50 60
ruled out!
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
R^2 Inflation
HZ
Tensor-to-Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)



Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
Tensor-to-Scalar Ratio (r)
Primordial Tilt (n_s)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Convex
Concave
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation ruled out!
Low scale SB SUSY ruled out!
R^2 inflation
$V \propto \phi^3$ ruled out!
$V \propto \phi^2$ ruled out!
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
$N_*=50$
$N_*=60$



Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
Tensor-to-Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)
Convex
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Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
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α attractors
r-law inflation ruled out!
scale SB SUSY ruled out!
flation
ϕ^3 ruled out!
ϕ^2 ruled out!
$\phi^{4/3}$
ϕ
$\phi^{2/3}$
50
60
Planck TT+τ prior+lensing+BAO
+BK15
2018
r<0.06
(95%CL)
N=60
N=50
ϕ^2
ϕ
BICEP2/Keck Array
Collaboration (2018)

Experimental Landscape

CMB-S4

Next Generation CMB Experiment

CMB Stages

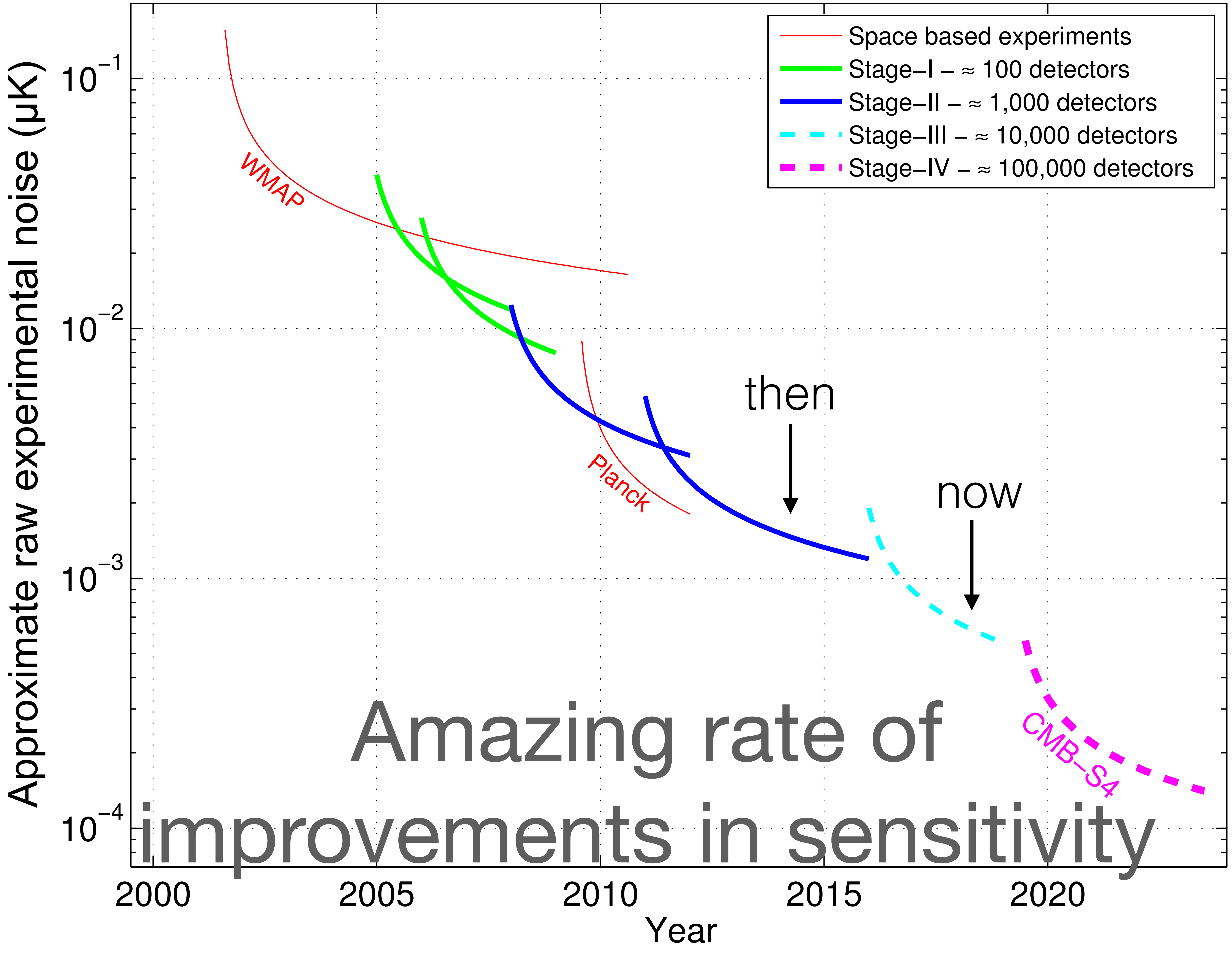
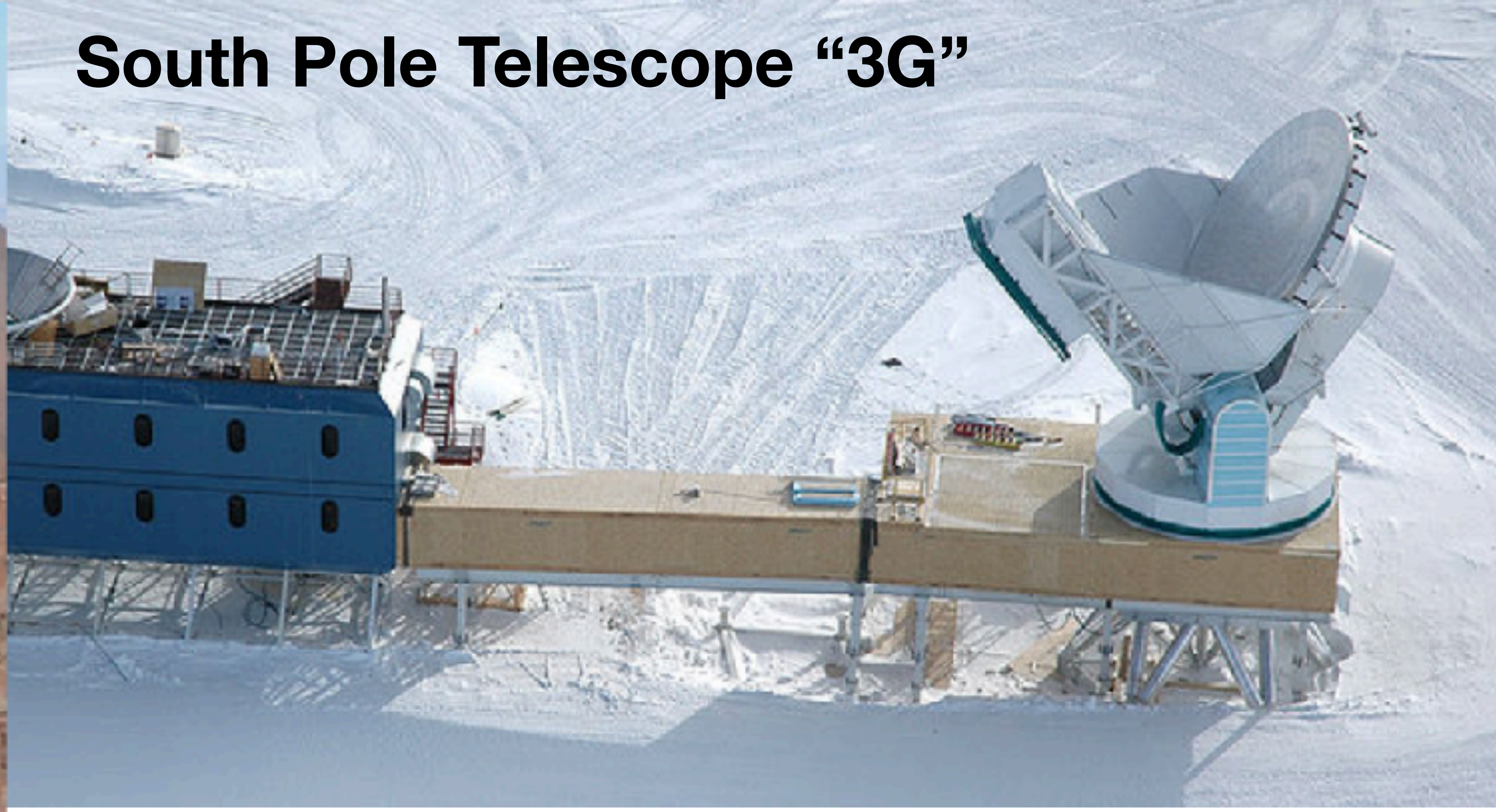
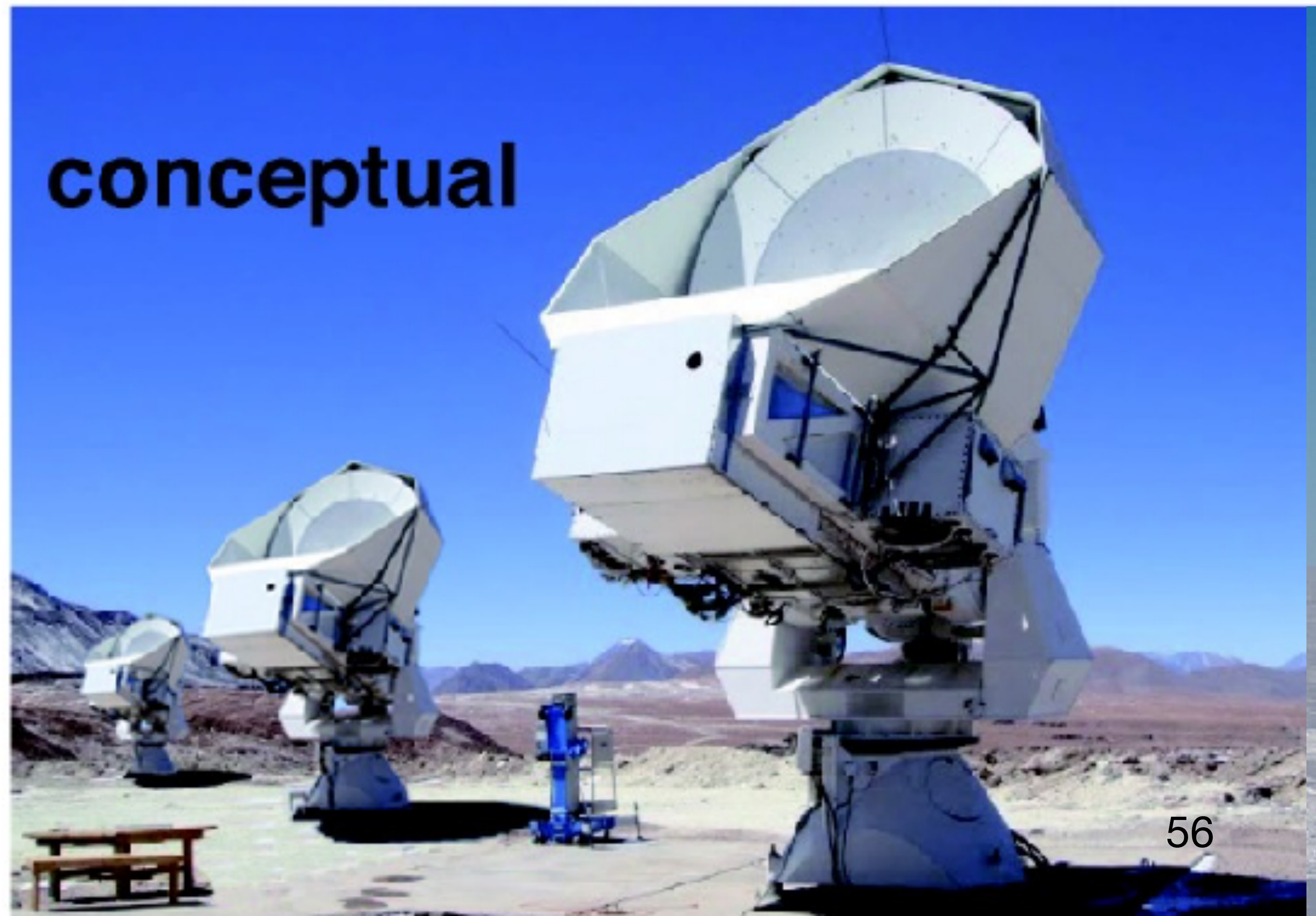


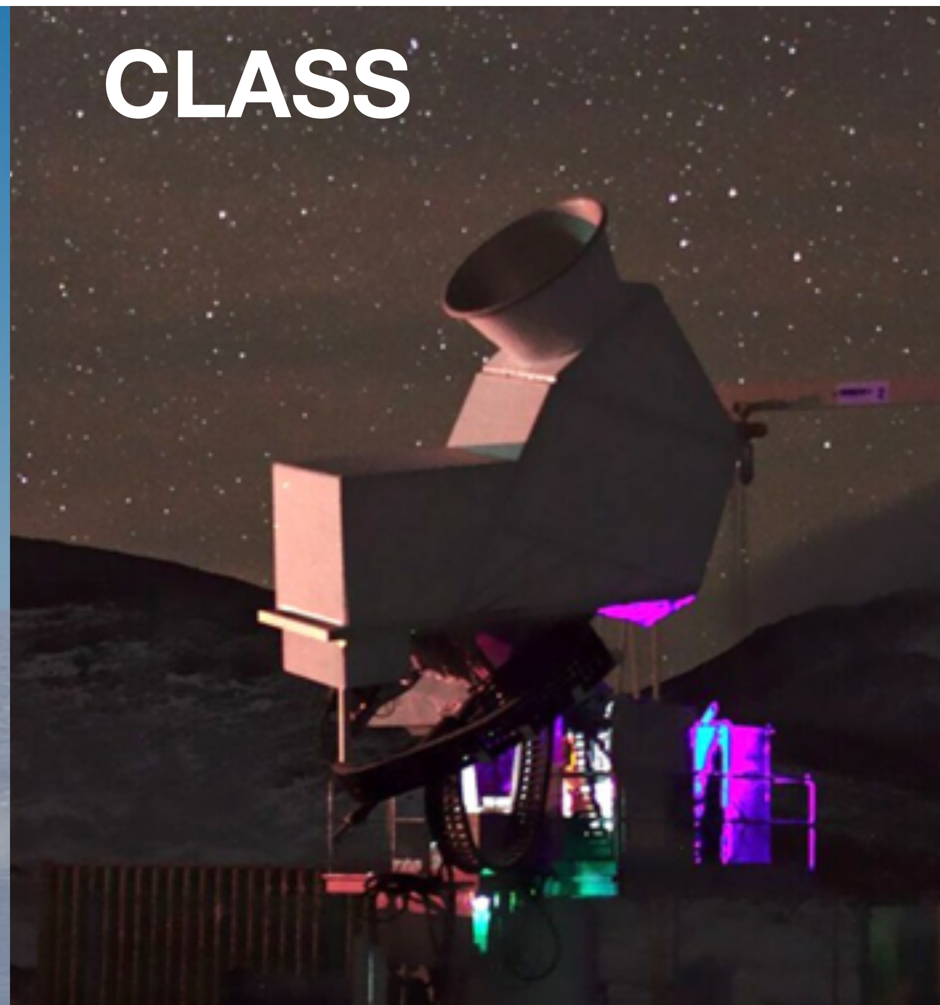
Figure by Clem Pryke for 2013 Snowmass documents



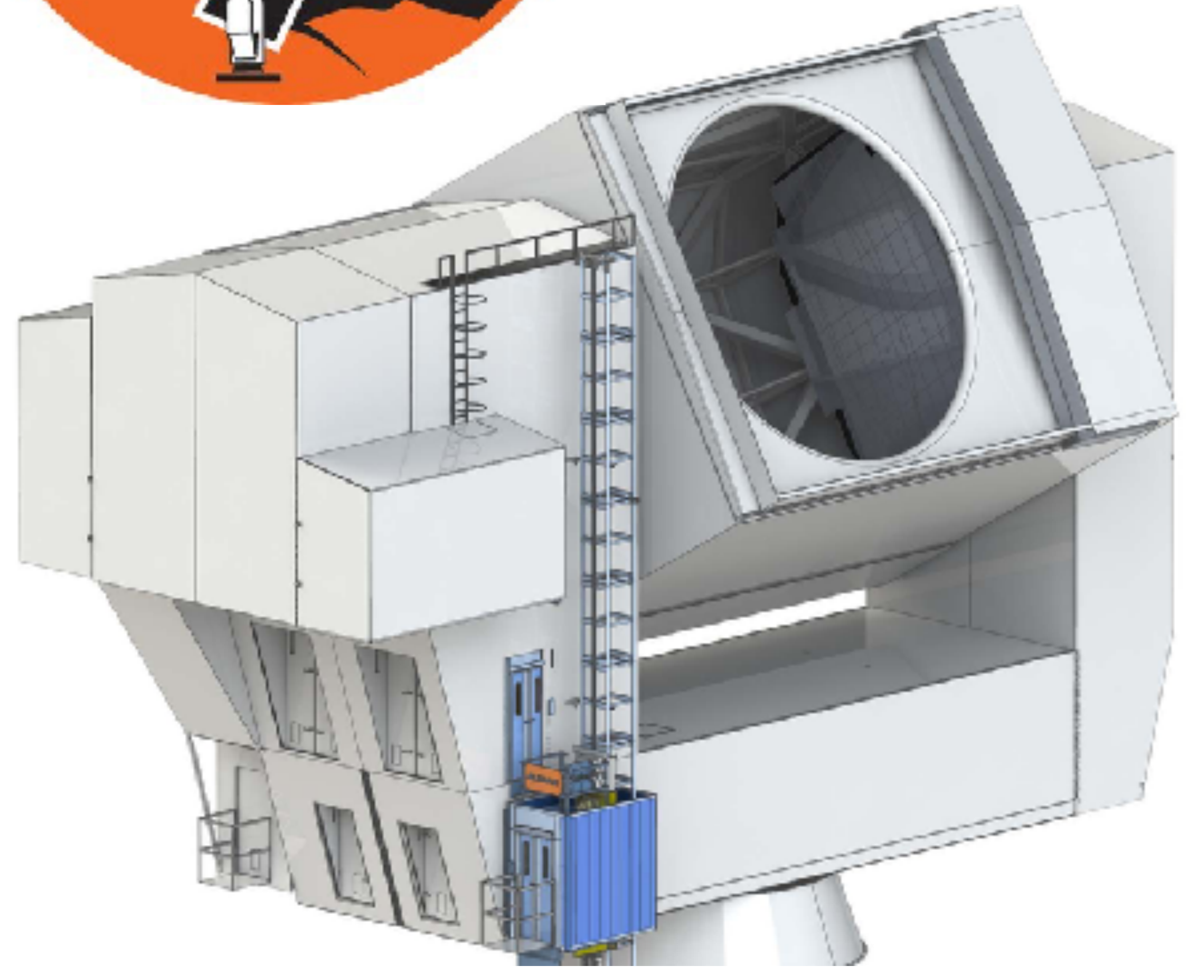
On-going Ground-based Experiments

The Simons Array





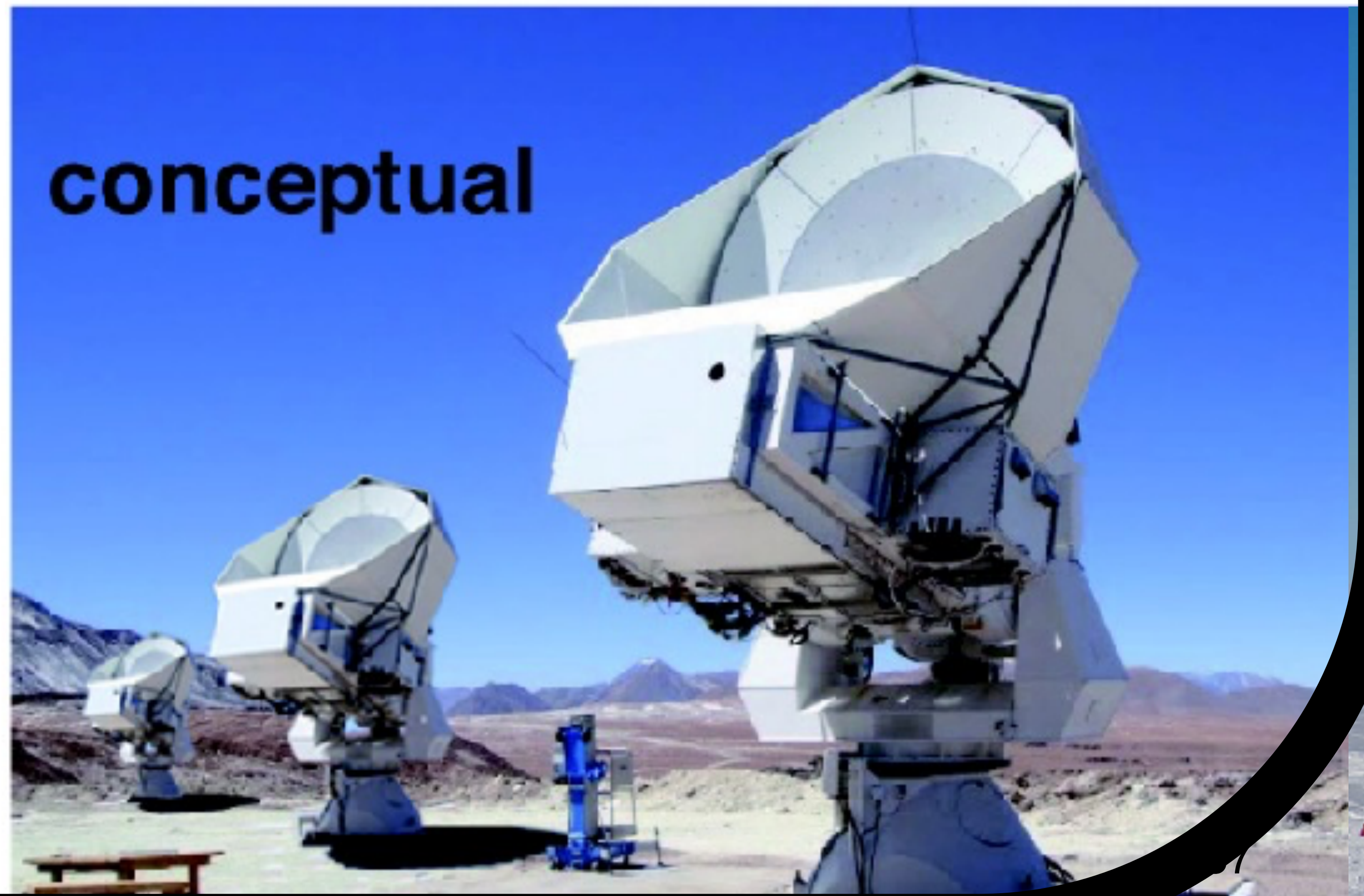
SIMONS OBSERVATORY



Early 2020s

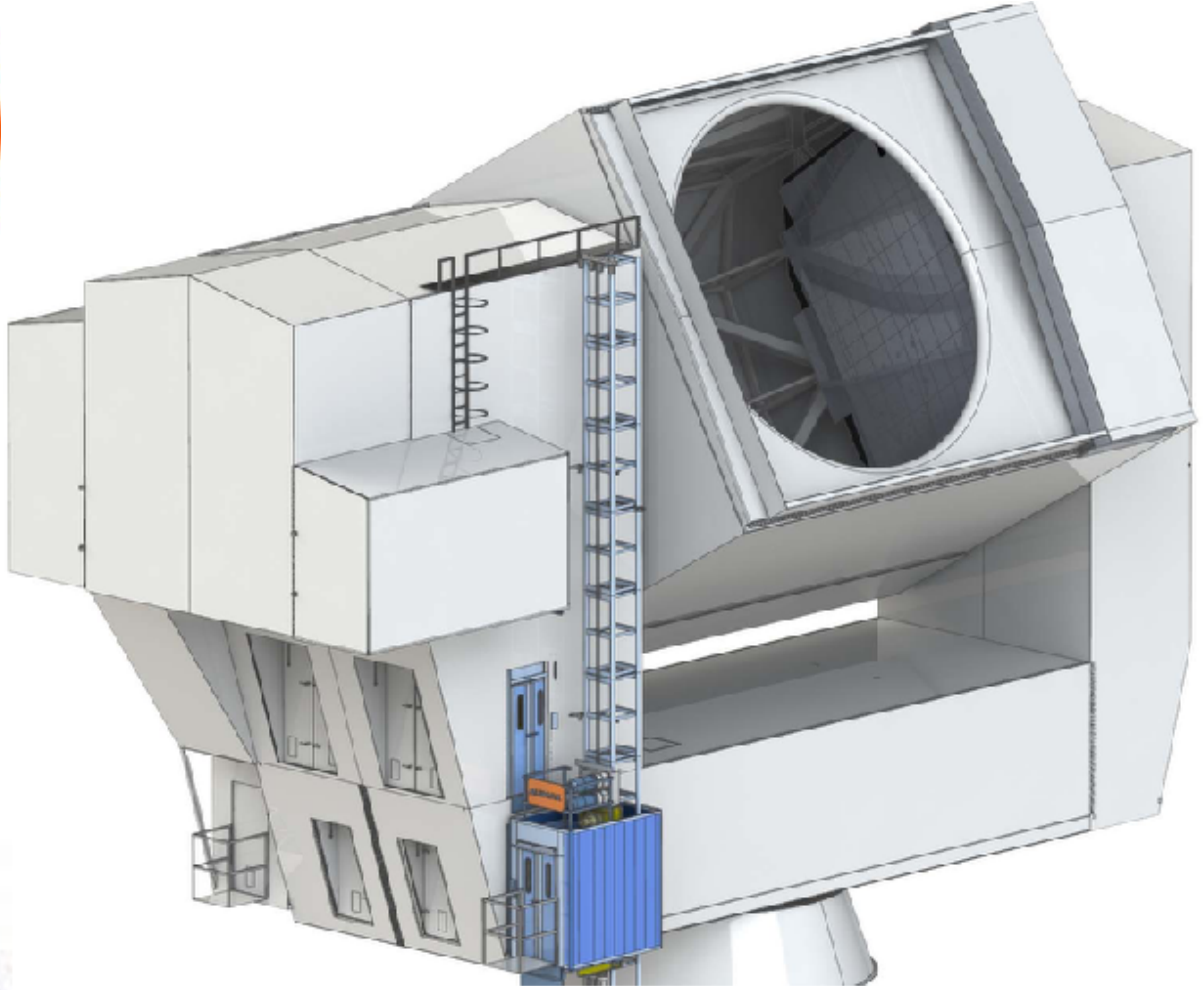
~$100M

The Simons Array



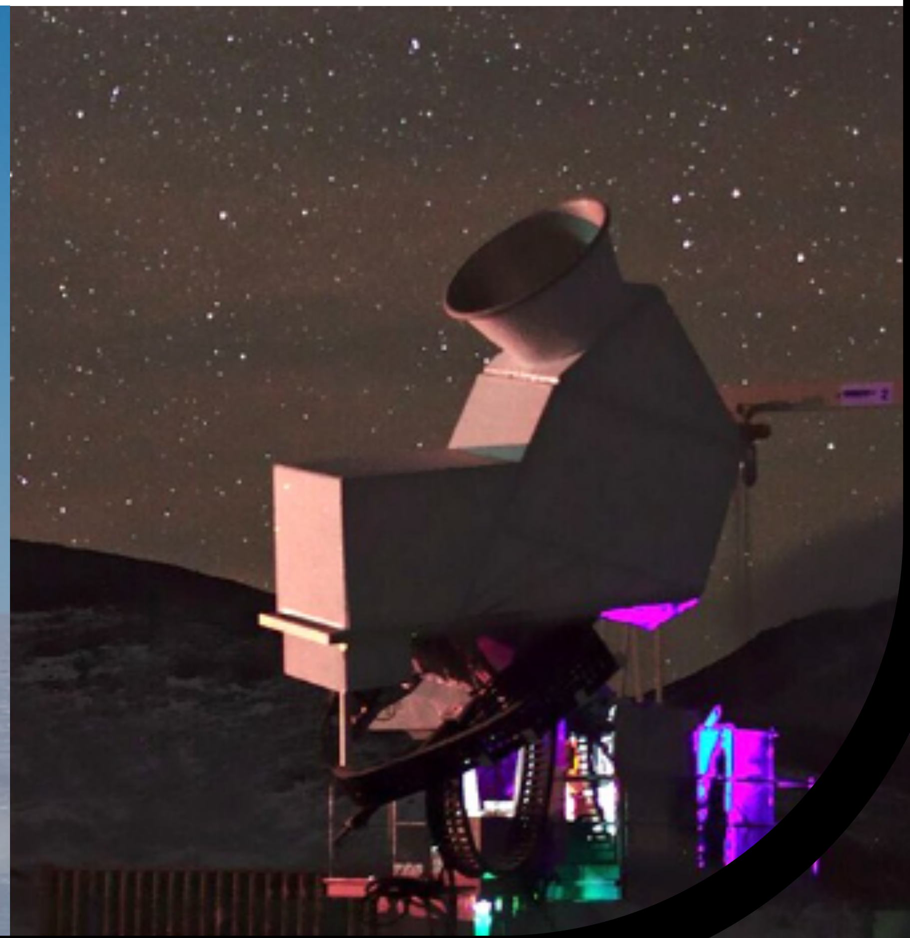
The South Pole Observatory

SIMONS OBSERVATORY



CCAT-p

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

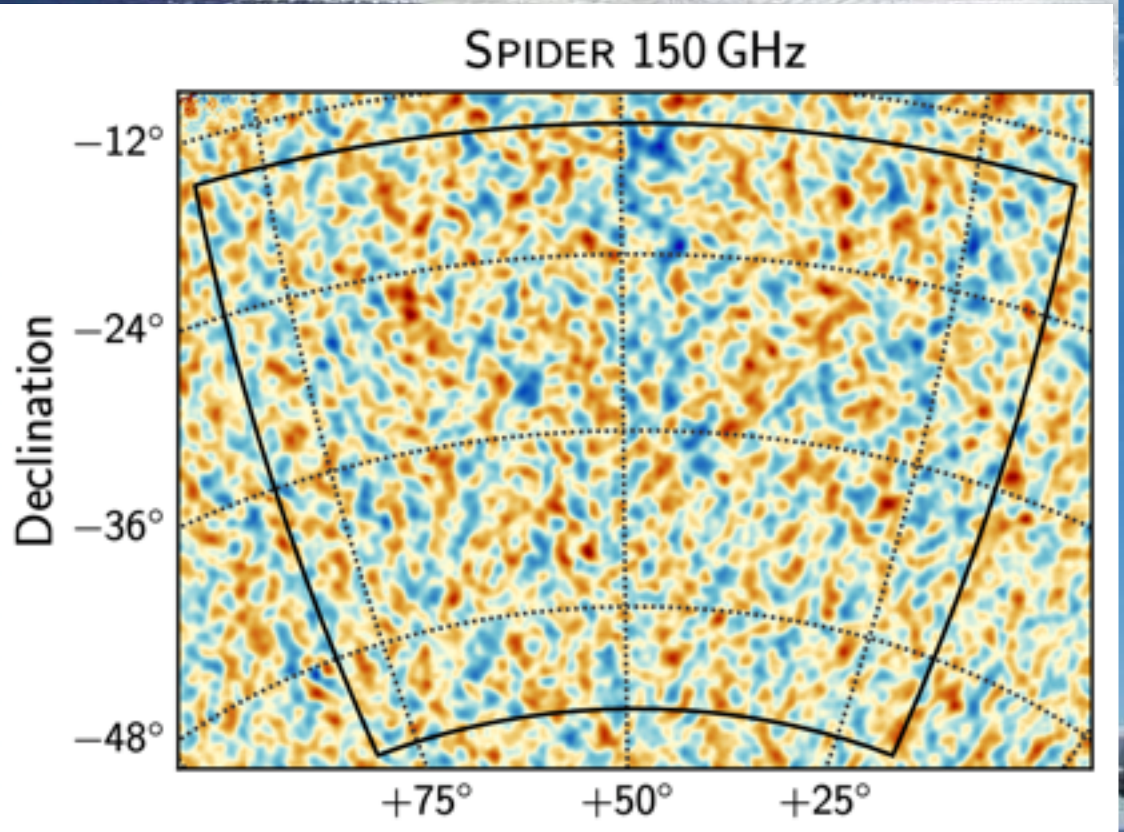


Balloons!

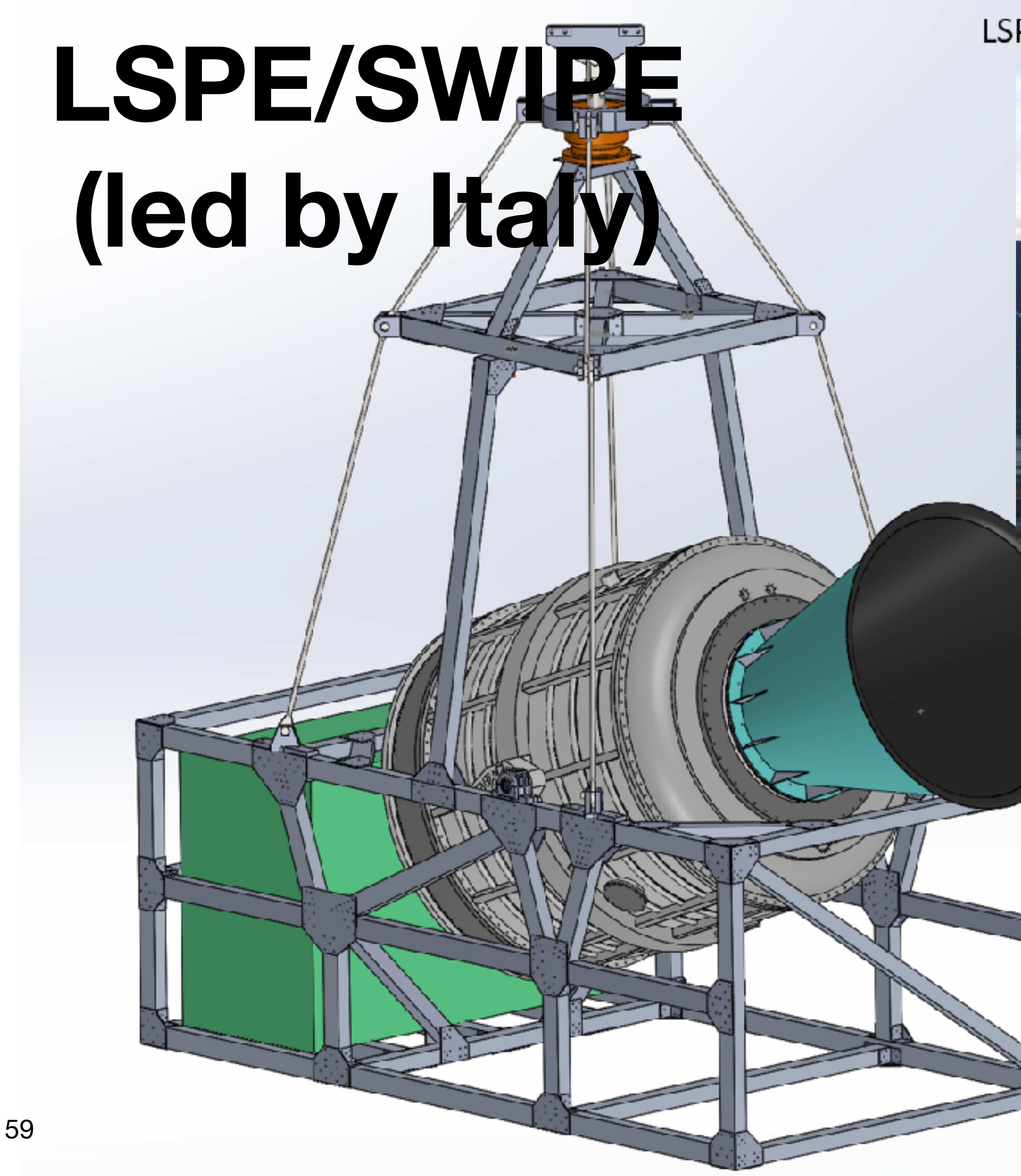
“Almost space”

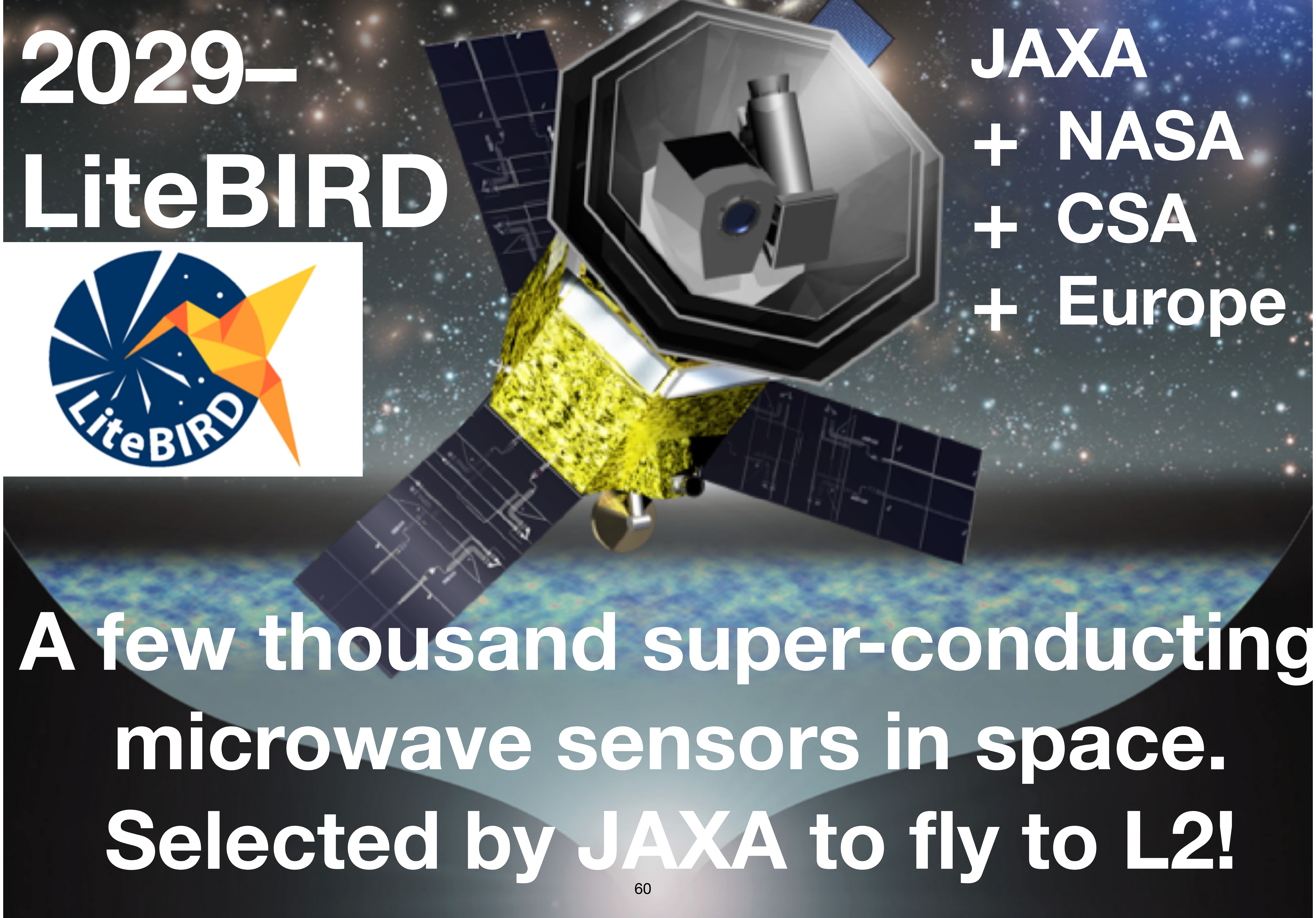
SPIDER
(led by USA)

First B-mode result: arXiv:2103.13334



LSPE/SWIPE
(led by Italy)





2029– LiteBIRD

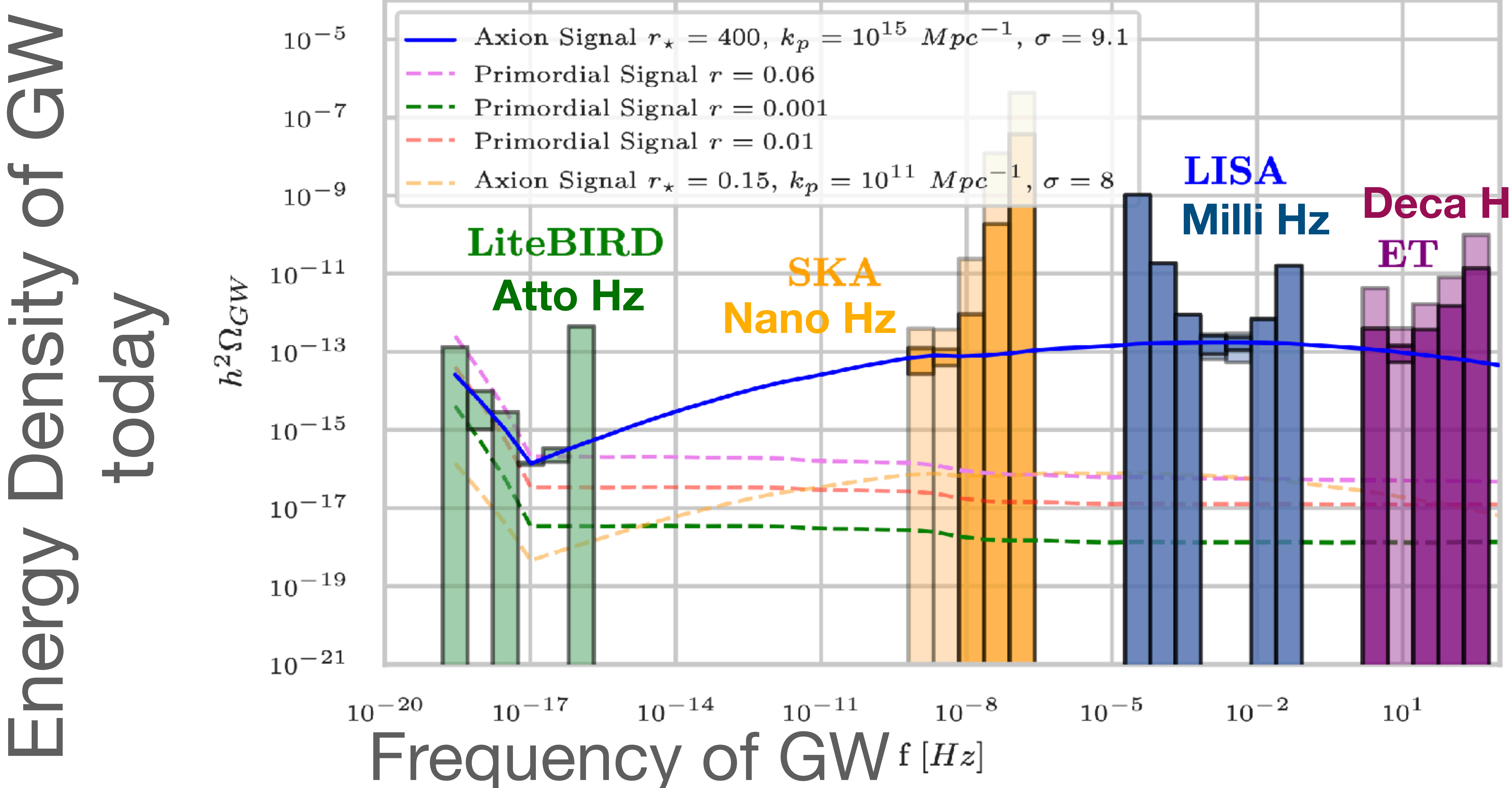
JAXA
\+ NASA
\+ CSA
\+ Europe

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

Campeti, EK, Poletti, Baccigalupi (2021)

But let's recall again: not just CMB!

We can measure it across 21 orders of magnitude in the GW frequency



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 and balloon-borne experiments within the next 10 years.
  - Then, the definitive measurement will come from **LiteBIRD** in early 2030s.