Finding Cosmic Inflation

Eiichiro Komatsu
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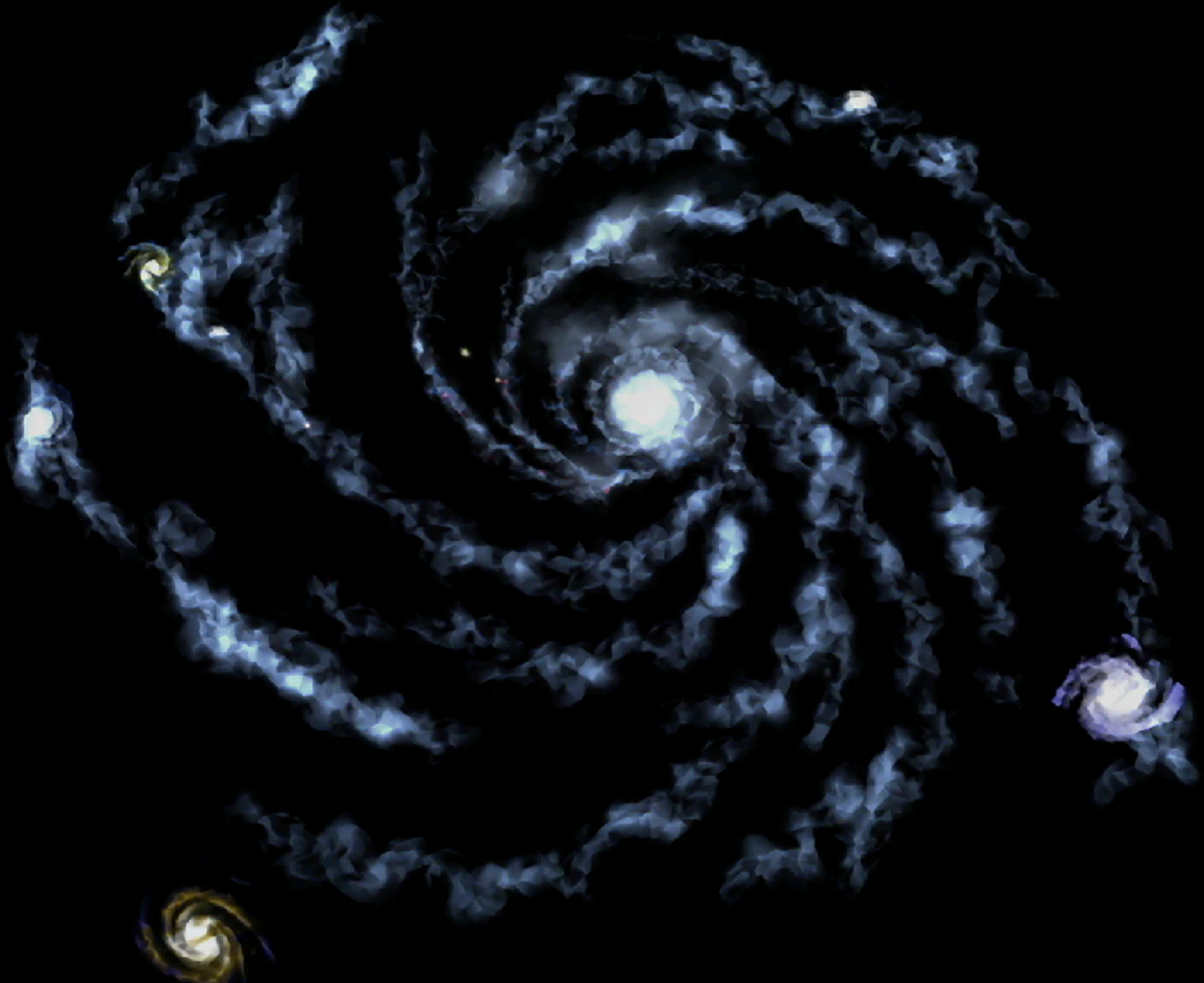
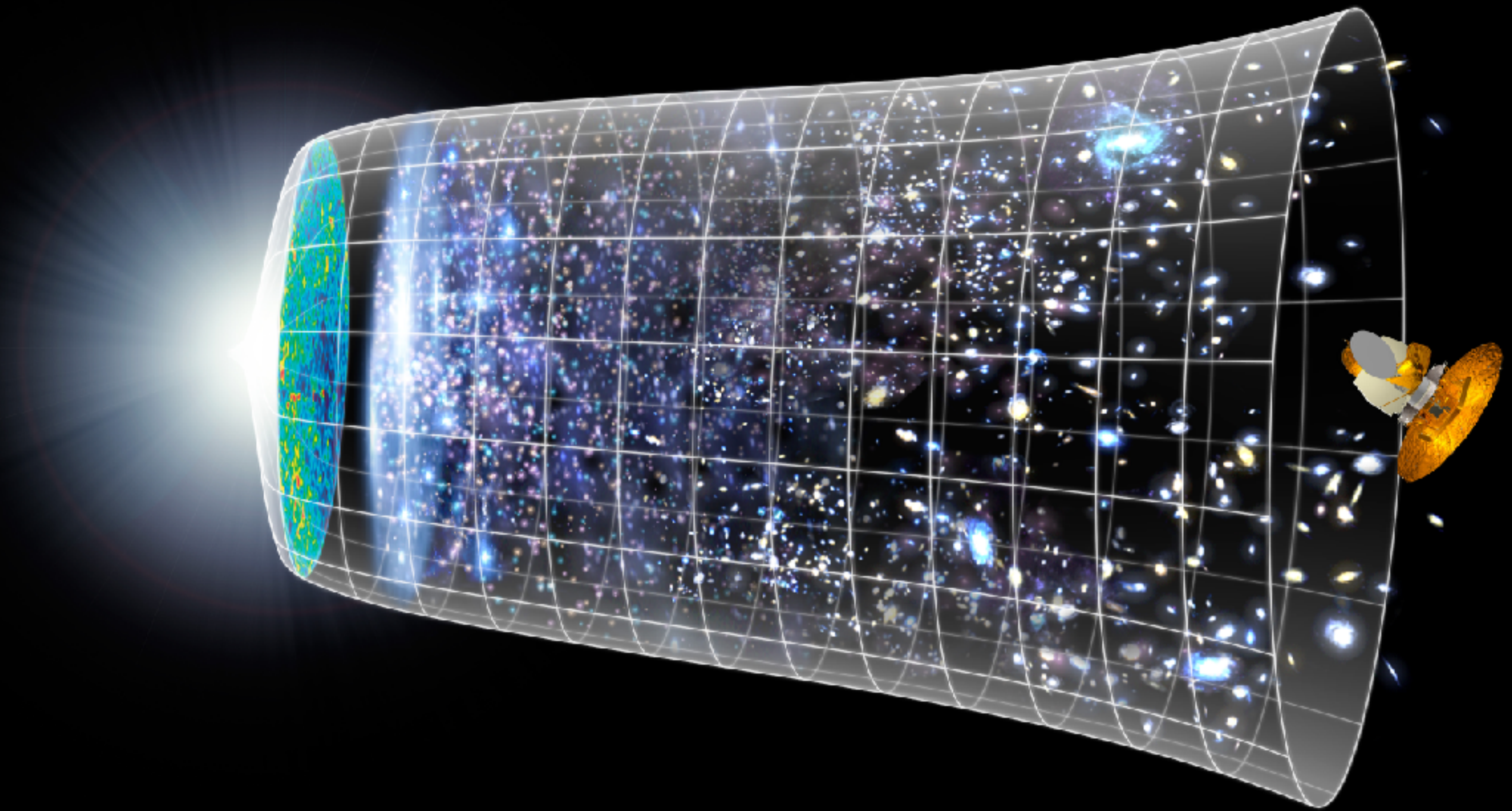
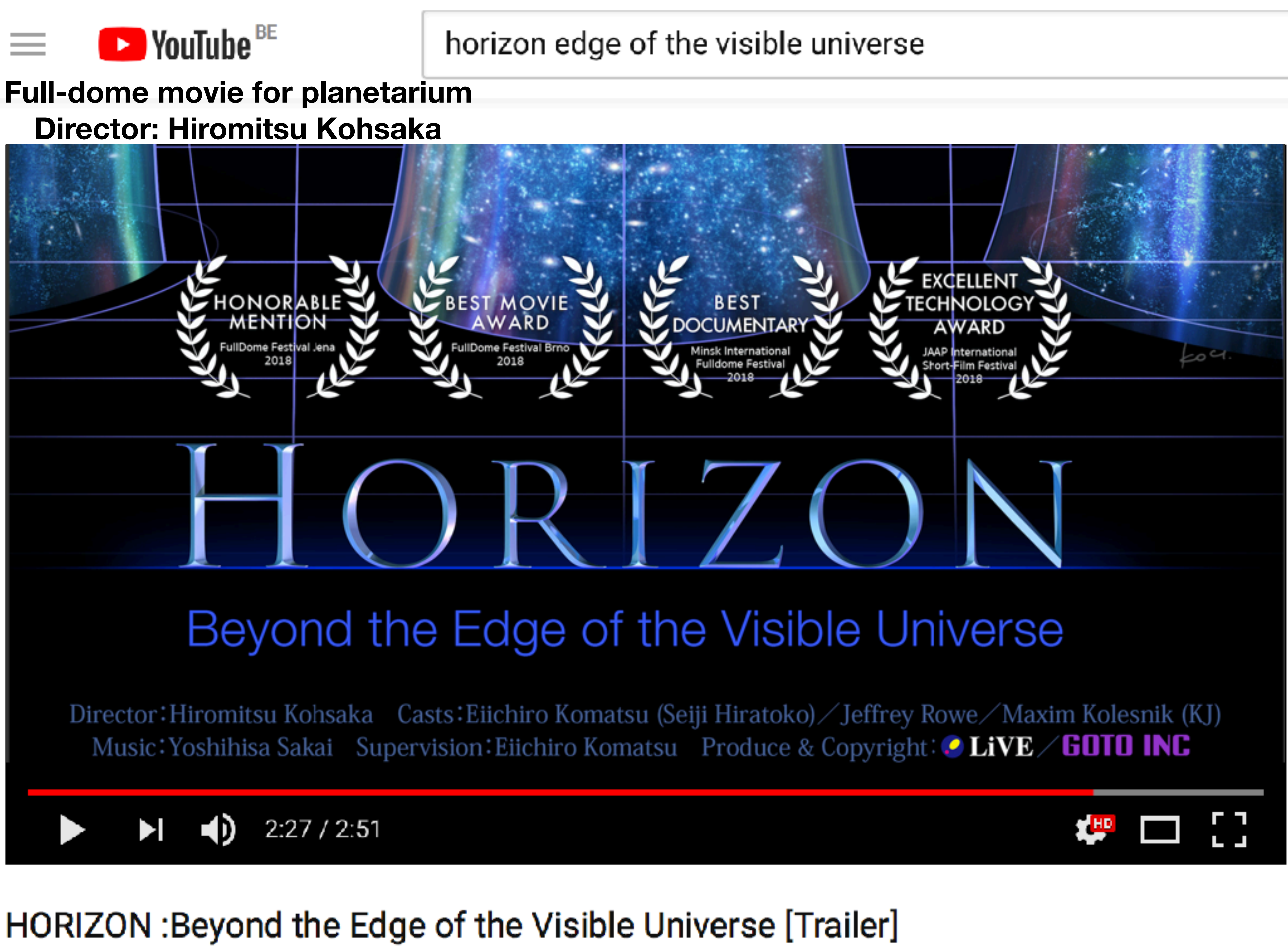
Séminaire du DAp, CEA Paris-Saclay
September 24, 2019





Full-dome movie for planetarium

Director: Hiromitsu Kohsaka



horizon edge of the visible universe

HONORABLE MENTION
FullDome Festival Jena
2018

BEST MOVIE AWARD
FullDome Festival Brno
2018

BEST DOCUMENTARY
Minsk International Fulldome Festival
2018

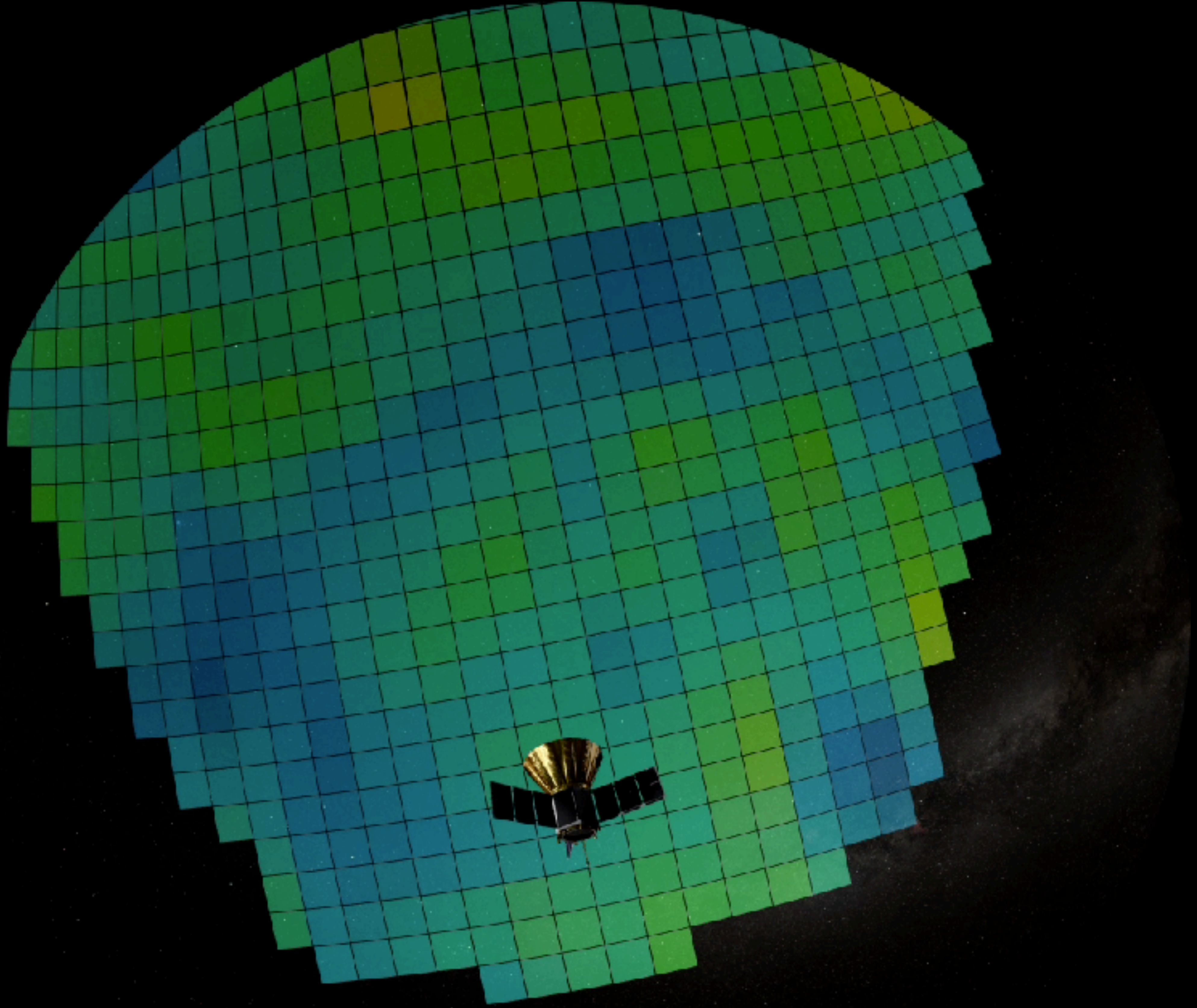
EXCELLENT TECHNOLOGY AWARD
JAAP International Short-Film Festival
2018

HORIZON

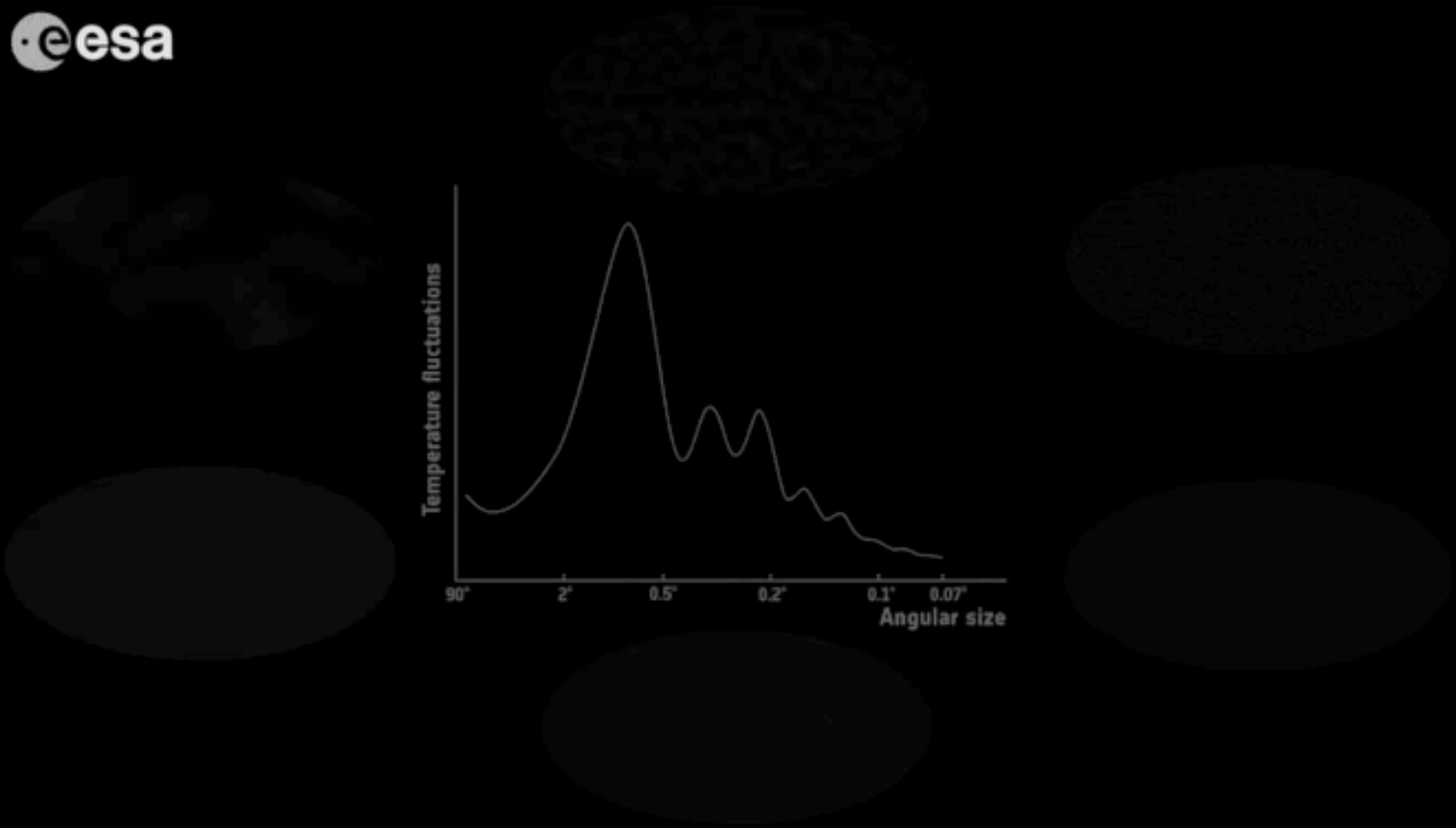
Beyond the Edge of the Visible Universe

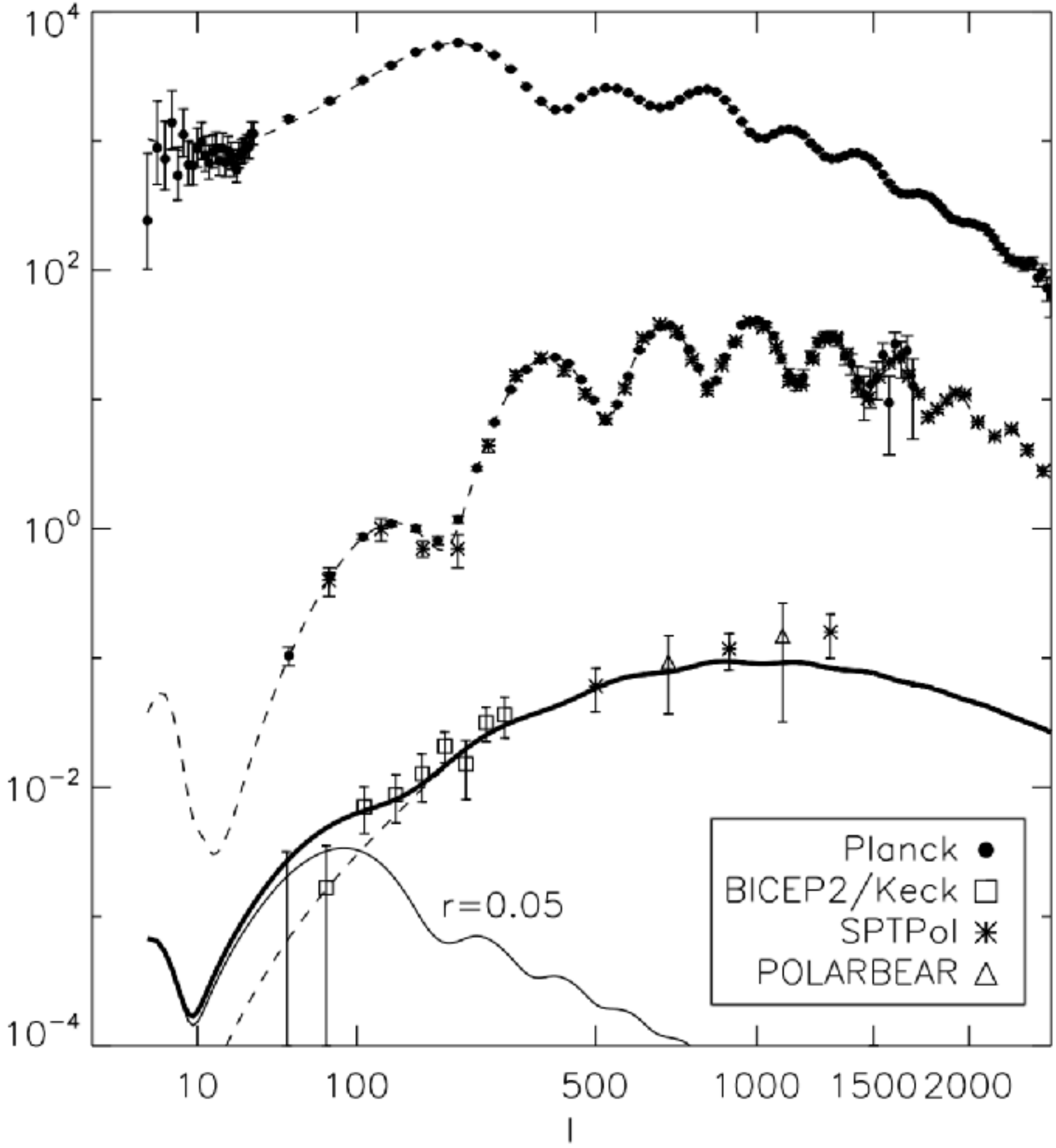
Director:Hiromitsu Kohsaka Casts:Eiichiro Komatsu (Seiji Hiratoko)／Jeffrey Rowe／Maxim Kolesnik (KJ)
Music:Yoshihisa Sakai Supervision:Eiichiro Komatsu Produce & Copyright:LiVE／GOTO INC

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

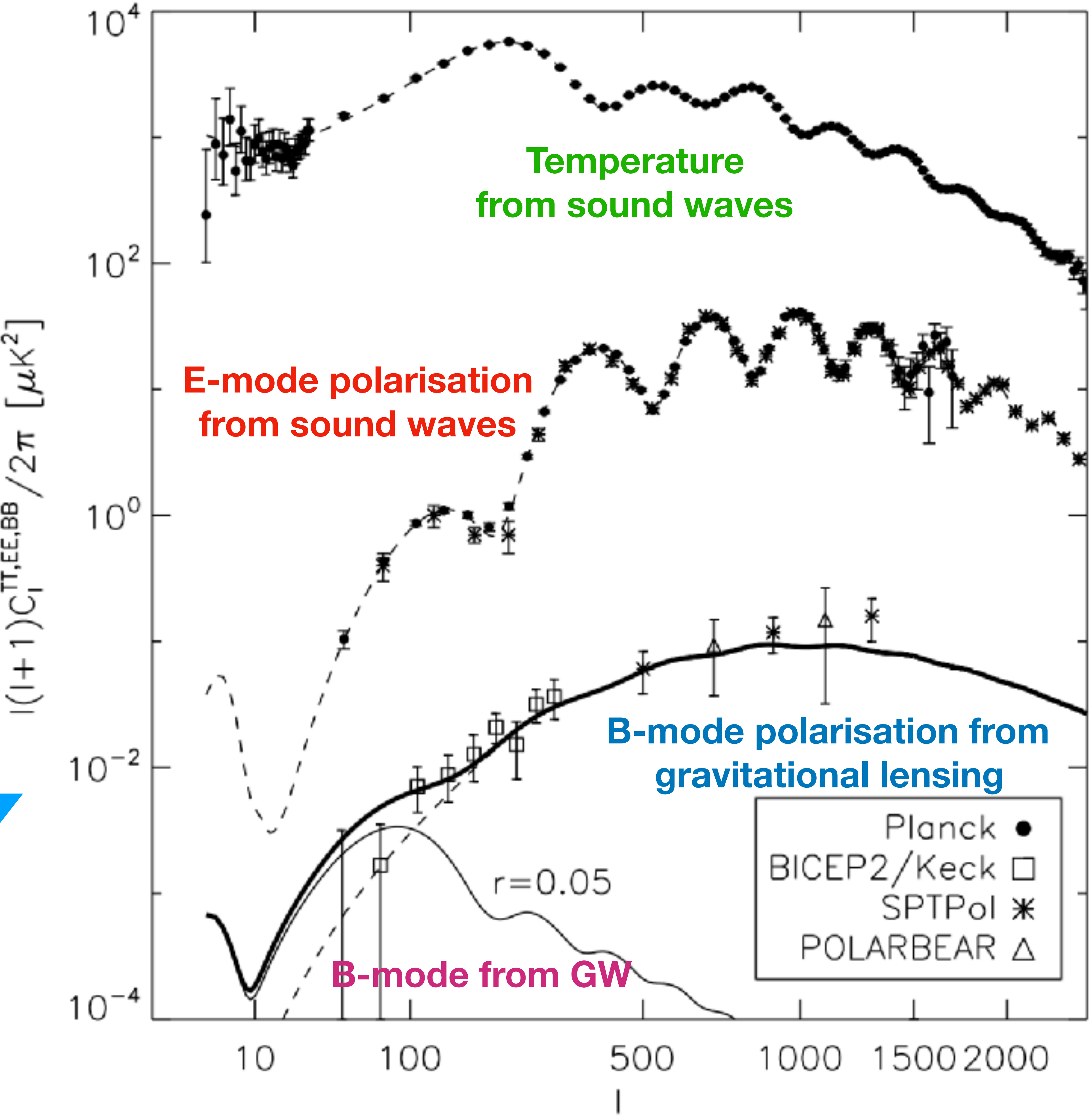


Power spectrum, explained




10^4
10^2
10^0
10^{-2}
10^{-4}
$l(l+1)C_l^{TT,EE,BB}/2\pi\ [\mu K^2]$
10
100
500
1000
1500
2000
l
r=0.05
Planck ●
BICEP2/Keck □
SPTPol ✳
POLARBEAR △

Seven orders of magnitude in power in “just” 25 years



CMB-S4
Next Generation CMB Experiment

CMB Stages

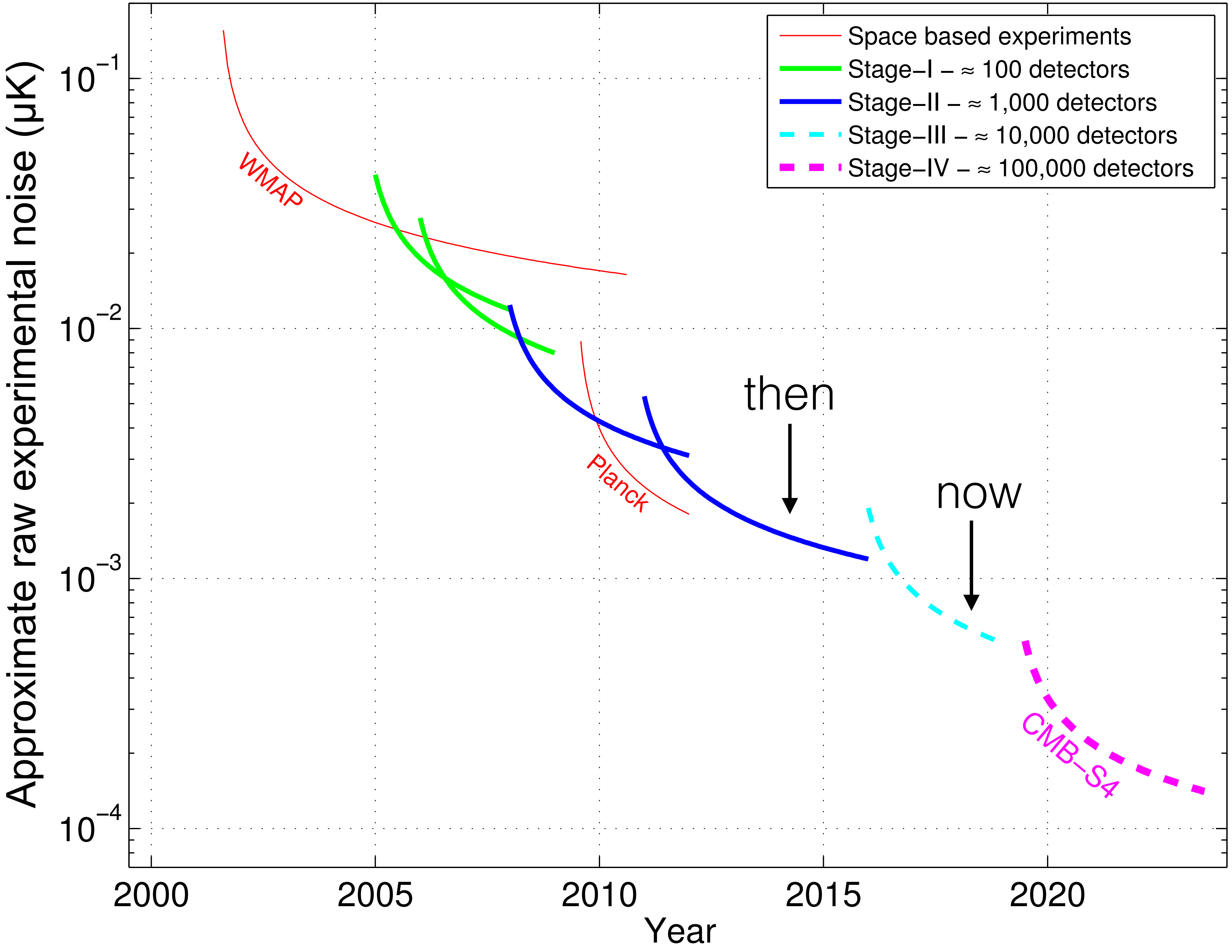
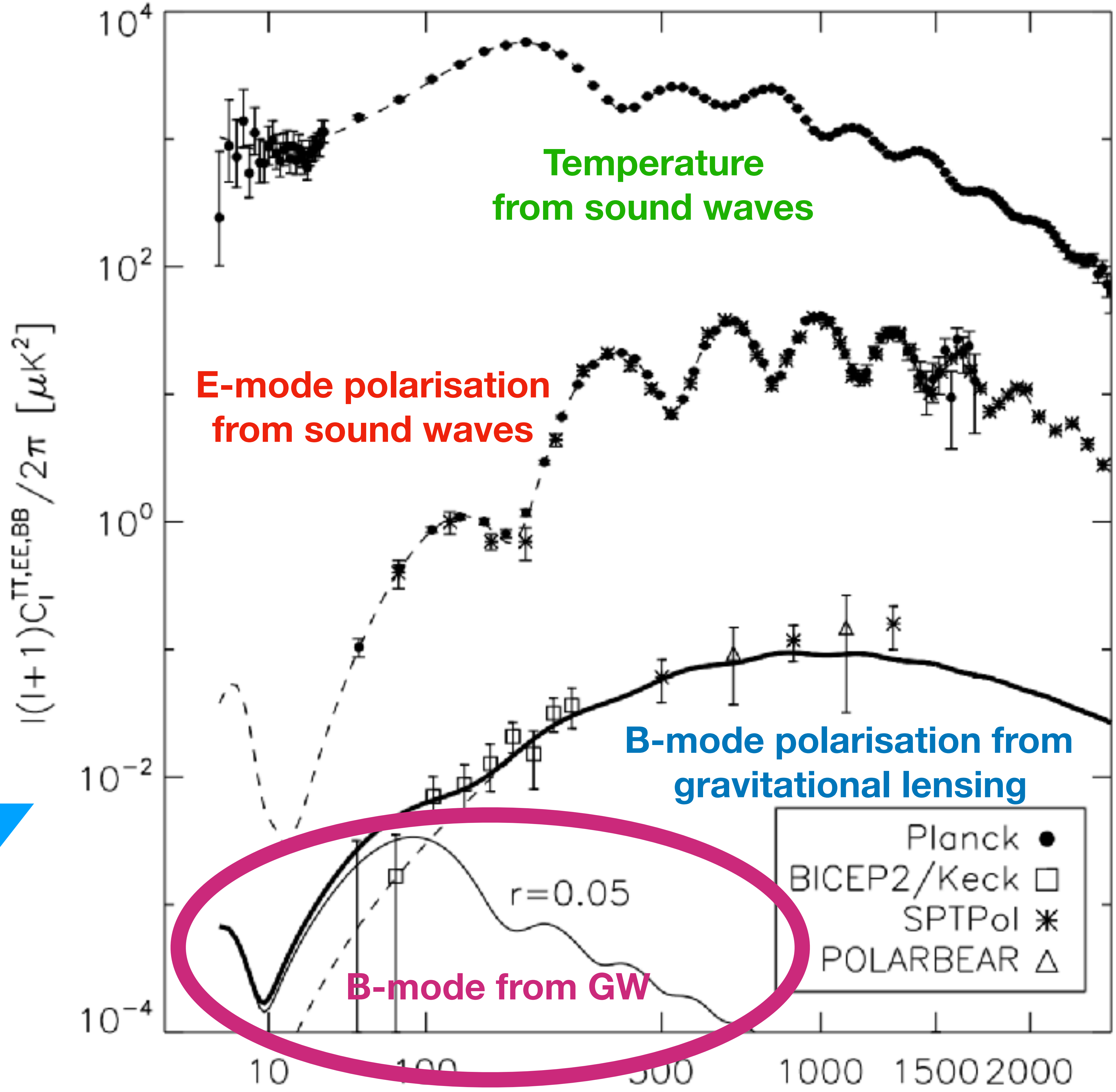


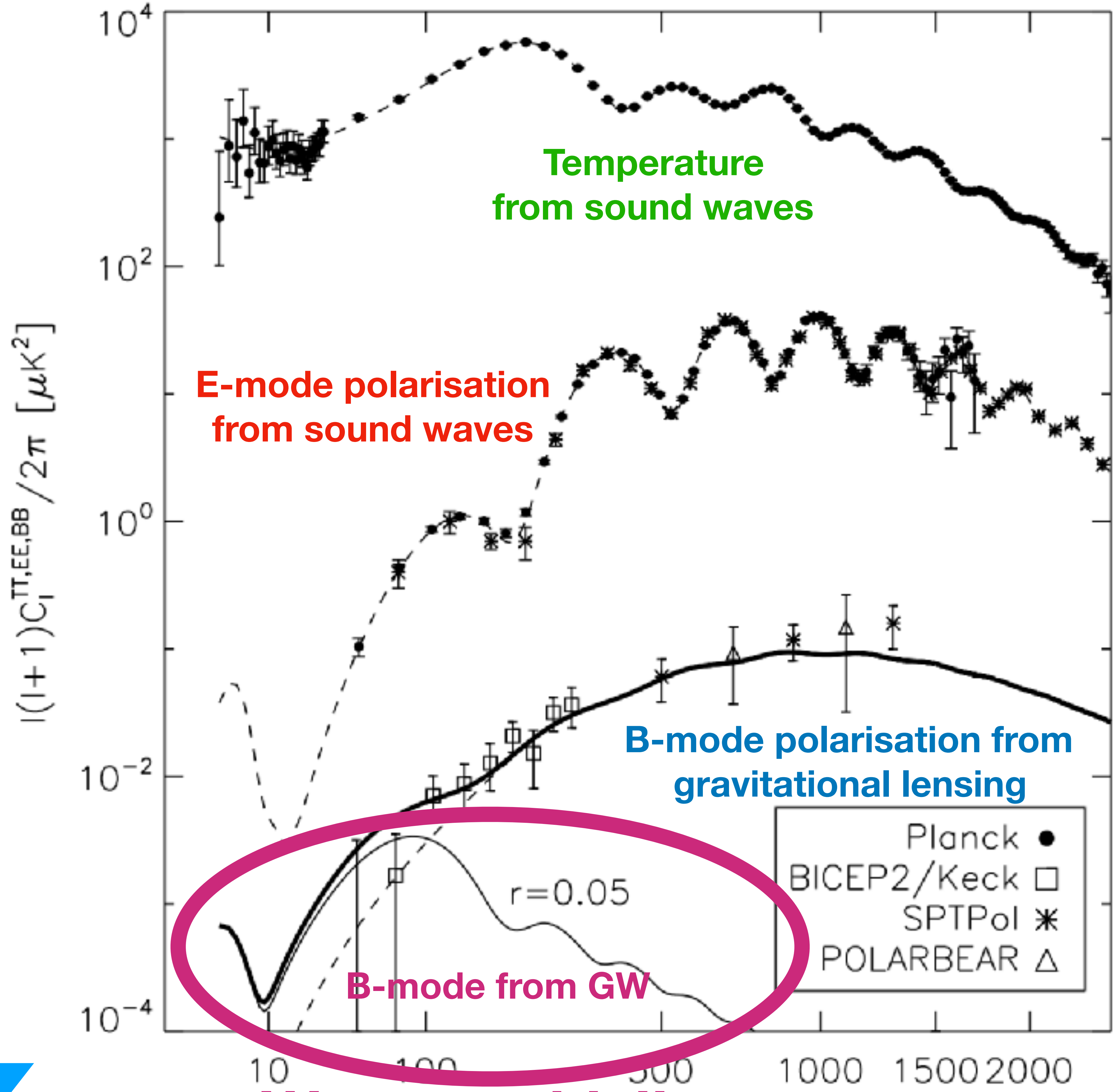
Figure by Clem Pryke for 2013 Snowmass documents

Seven orders of magnitude in power in "just" 25 years



We want this!!

Another two orders of magnitude in the next 10–15 years



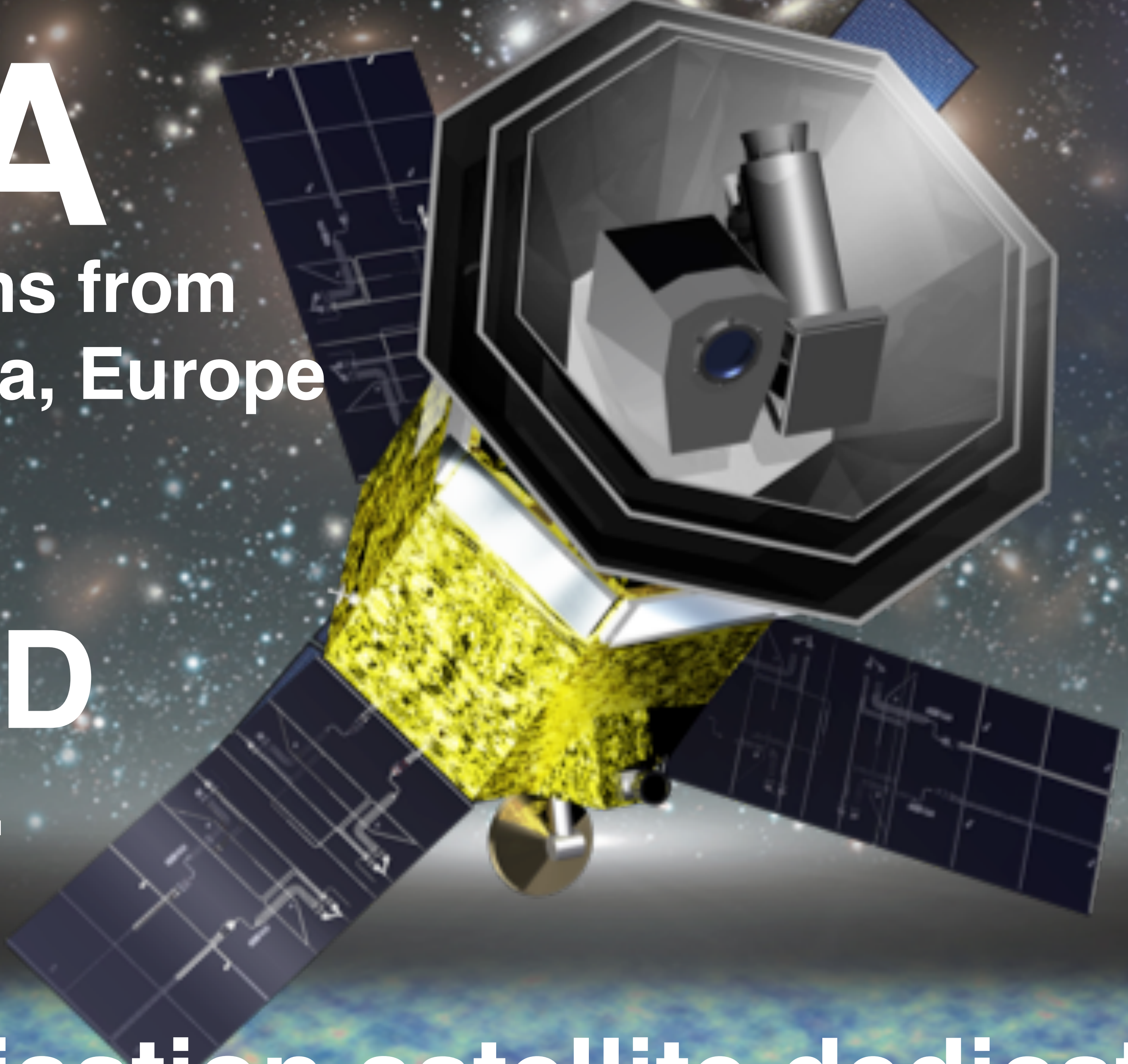
Temperature from sound waves

E-mode polarisation from sound waves

B-mode polarisation from gravitational lensing

B-mode from GW

We want this!!



JAXA

+ participations from
USA, Canada, Europe

LiteBIRD
2028–

Polarisation satellite dedicated to measure CMB polarisation from primordial GW, with a few thousand TES bolometers in space

JAXA

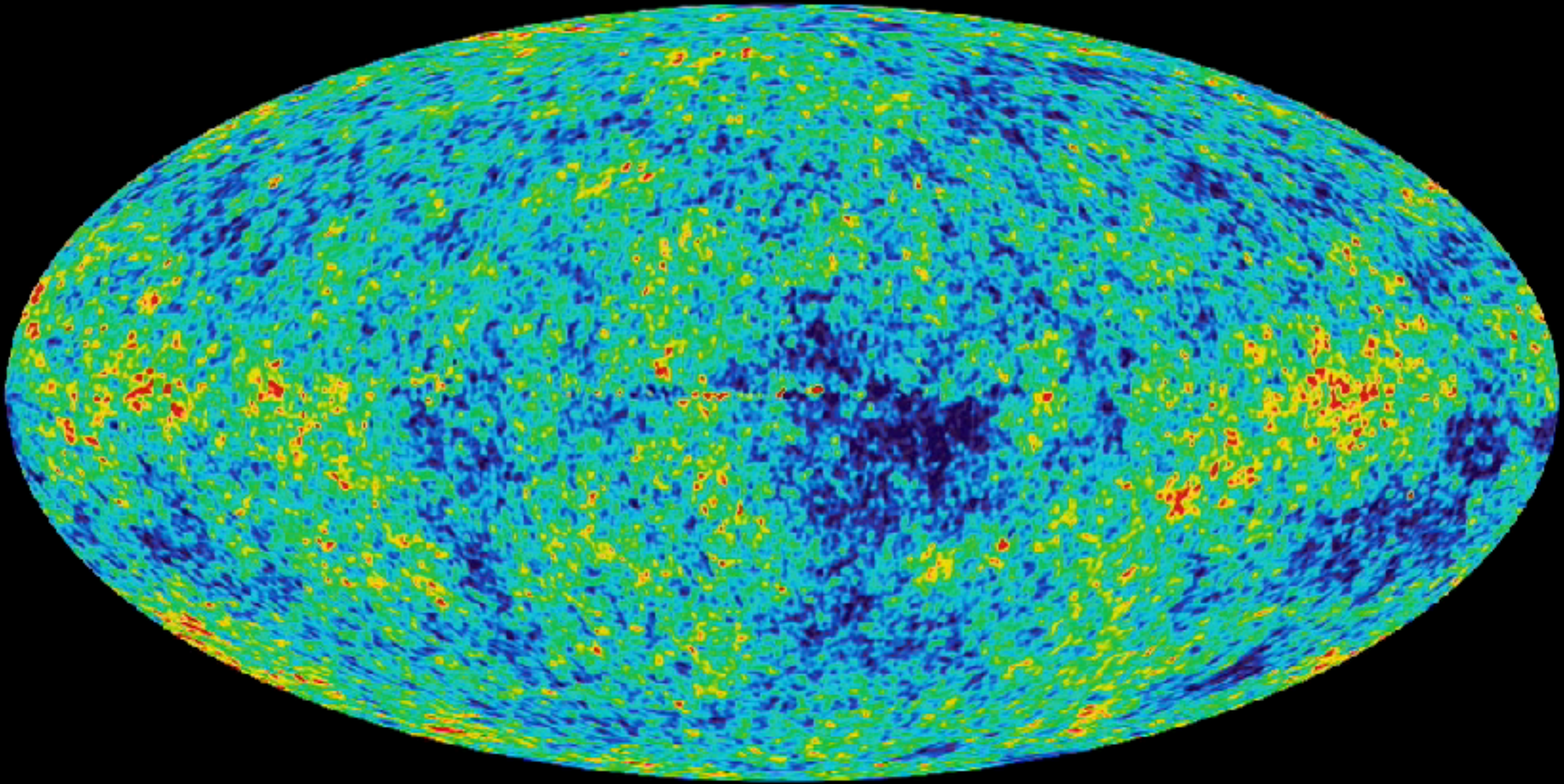
+ participations from
USA, Canada, Europe

LiteBIRD
2028–

Selected!

May 21: JAXA has chosen LiteBIRD as the strategic large-class mission.

We will go to L2!



A Remarkable Story

- Observations of the cosmic microwave background and their interpretation taught us that **galaxies, stars, planets, and ourselves originated from tiny fluctuations in the early Universe**

- *But,* ***what generated the initial fluctuations?***

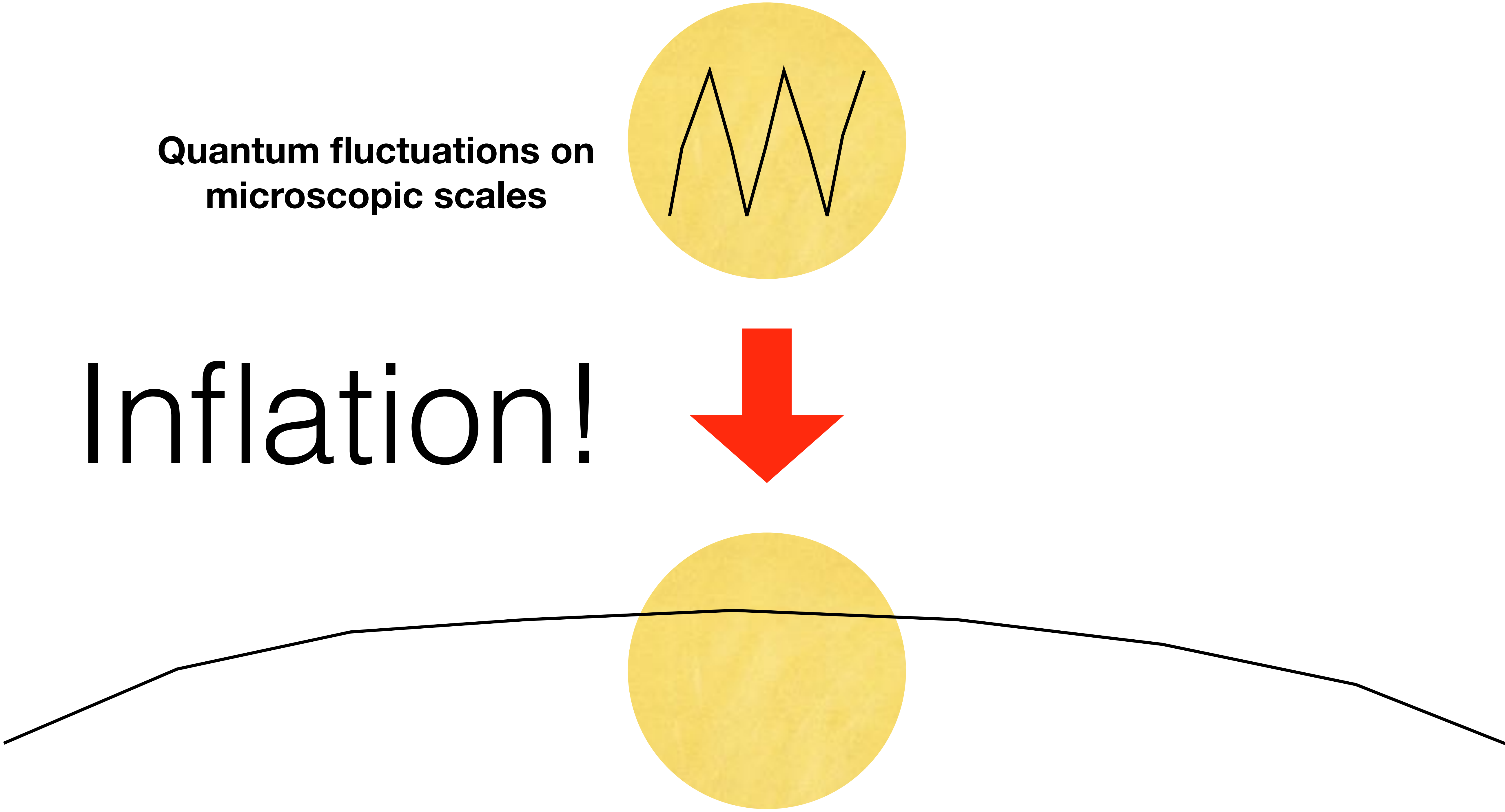
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

Leading Idea

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

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

Cosmic Inflation



Quantum fluctuations on microscopic scales

Inflation!

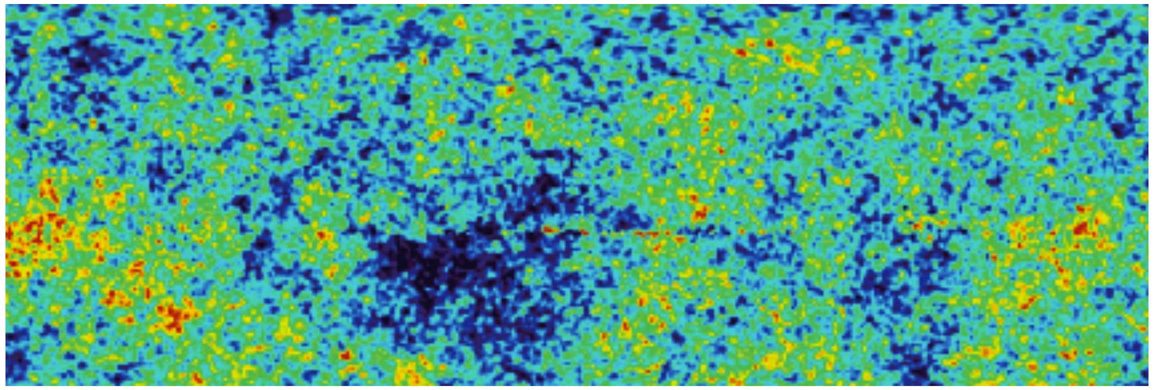
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

Key Predictions

ζ

scalar mode

- Fluctuations we observe today in CMB and the matter distribution originate from quantum fluctuations during inflation



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

h_{ij}

tensor mode

- There should also be *ultra long-wavelength* gravitational waves generated during inflation

Grishchuk (1974)
Starobinsky (1979)

We measure distortions in space

- A distance between two points in space

$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

- $\boldsymbol{\zeta}$: “curvature perturbation” (scalar mode)
  - Perturbation to the determinant of the spatial metric
- $\mathbf{h}_{ij}$: “gravitational waves” (tensor mode)
  - Perturbation that does not alter the determinant

$$\sum_i h_{ii} = 0$$

We measure distortions in space

- A distance between two points in space

$$d\ell^2 = \boxed{a^2(t)}[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

scale factor

- **ζ** : "curvature perturbation" (scalar mode)
    - Perturbation to the determinant of the spatial metric
- **h$_{ij}$** : "gravitational waves" (tensor mode)
    - Perturbation that does not alter the determinant

$$\sum_i h_{ii} = 0$$

Finding Inflation

- Inflation is the accelerated, quasi-exponential expansion. Defining the Hubble expansion rate as **H(t)=dln(a)/dt**, we must find

$$\frac{\ddot{a}}{a} = \dot{H} + H^2 > 0 \quad \Longrightarrow \quad \epsilon \equiv -\frac{\dot{H}}{H^2} < 1$$

- For inflation to explain flatness of spatial geometry of our observable Universe, we need to have a **sustained** period of inflation. This implies $\varepsilon = O(N^{-1})$ or smaller, where N is the number of e-folds of expansion counted from the end of inflation:

$$N \equiv \ln \frac{a_{\rm end}}{a} = \int_t^{t_{\rm end}} dt' \; H(t') \approx 50$$

Have we found inflation?

- *Have we found ε << 1?*

$$\epsilon \equiv -\frac{\dot{H}}{H^2}$$

- To achieve this, we need to map out **H(t)**, and show that it does not change very much with time
  - **We need the “Hubble diagram” during inflation!**

Fluctuations are proportional to H

- **Both scalar (ζ) and tensor (h_{ij}) perturbations are proportional to H**
  - Consequence of the uncertainty principle
    - [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. **We can map H(t) by measuring CMB fluctuations over a wide range of angles**

Fluctuations are proportional to H

- **We can map H(t) by measuring CMB fluctuations over a wide range of angles**

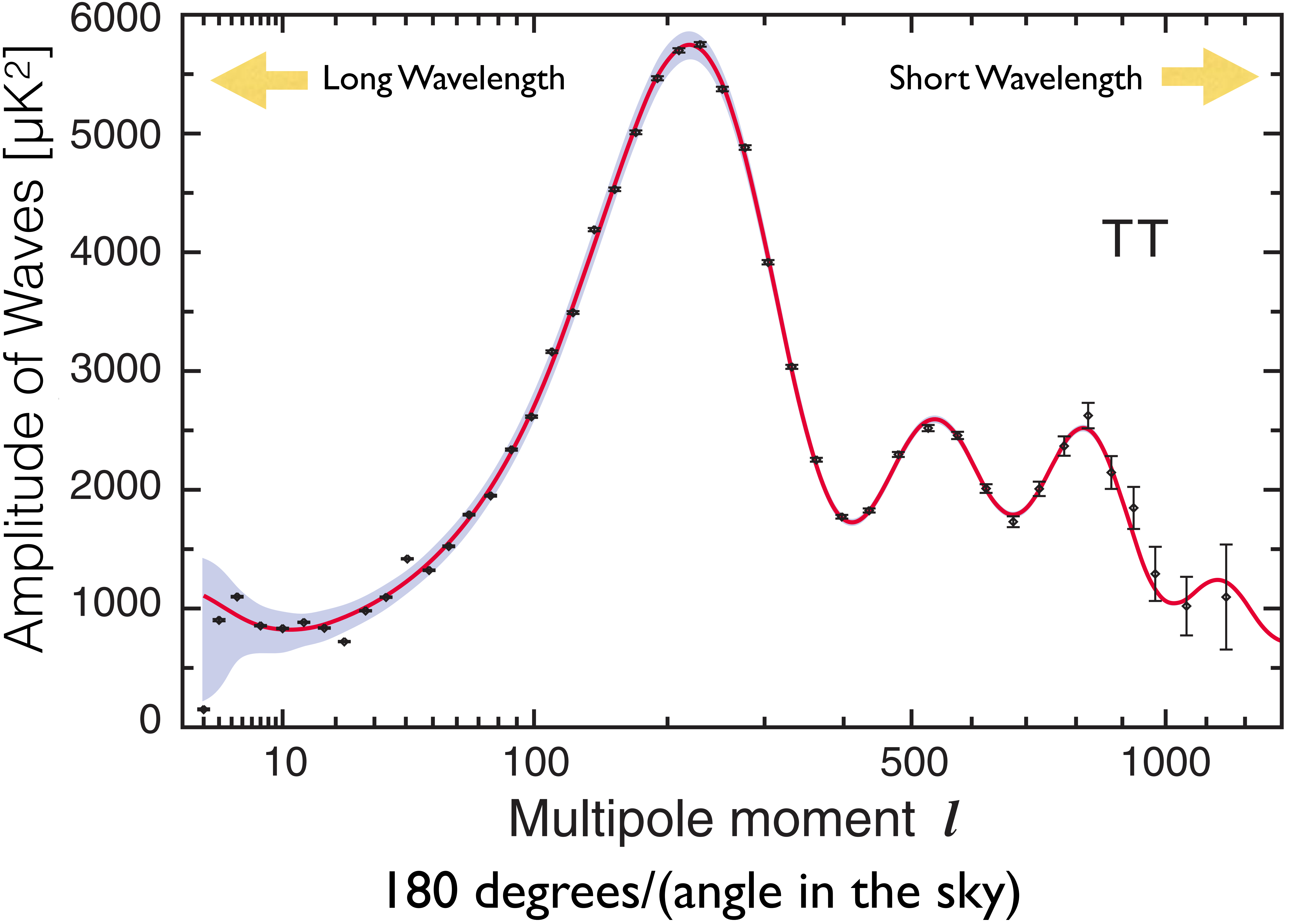
1. We want to show that the amplitude of CMB fluctuations does not depend very much on angles

2. Moreover, since inflation must end, H would be a decreasing function of time. It would be fantastic to show that the amplitude of CMB fluctuations actually DOES depend on angles such that the small scale has ***slightly*** smaller power

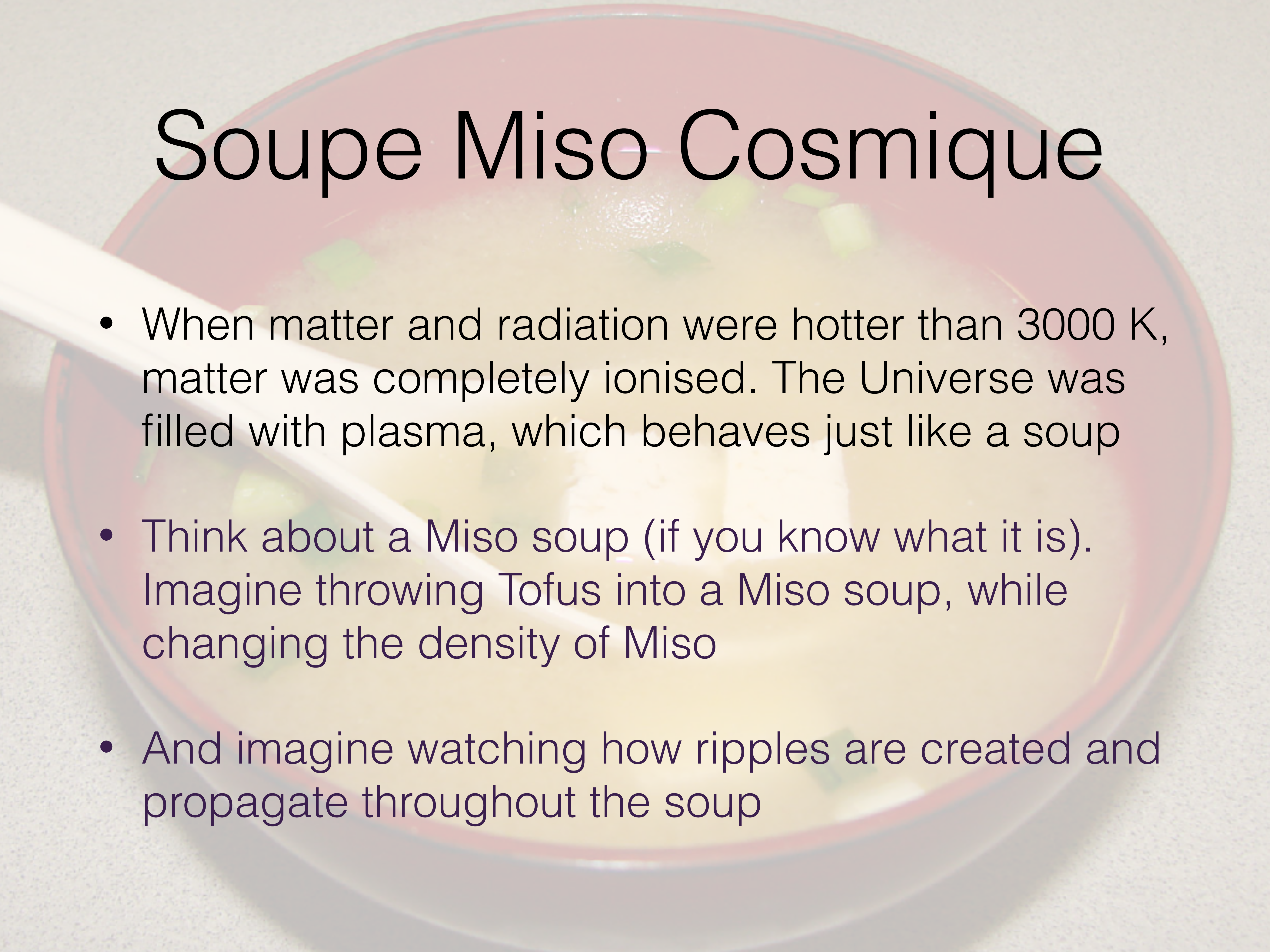
Data Analysis

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

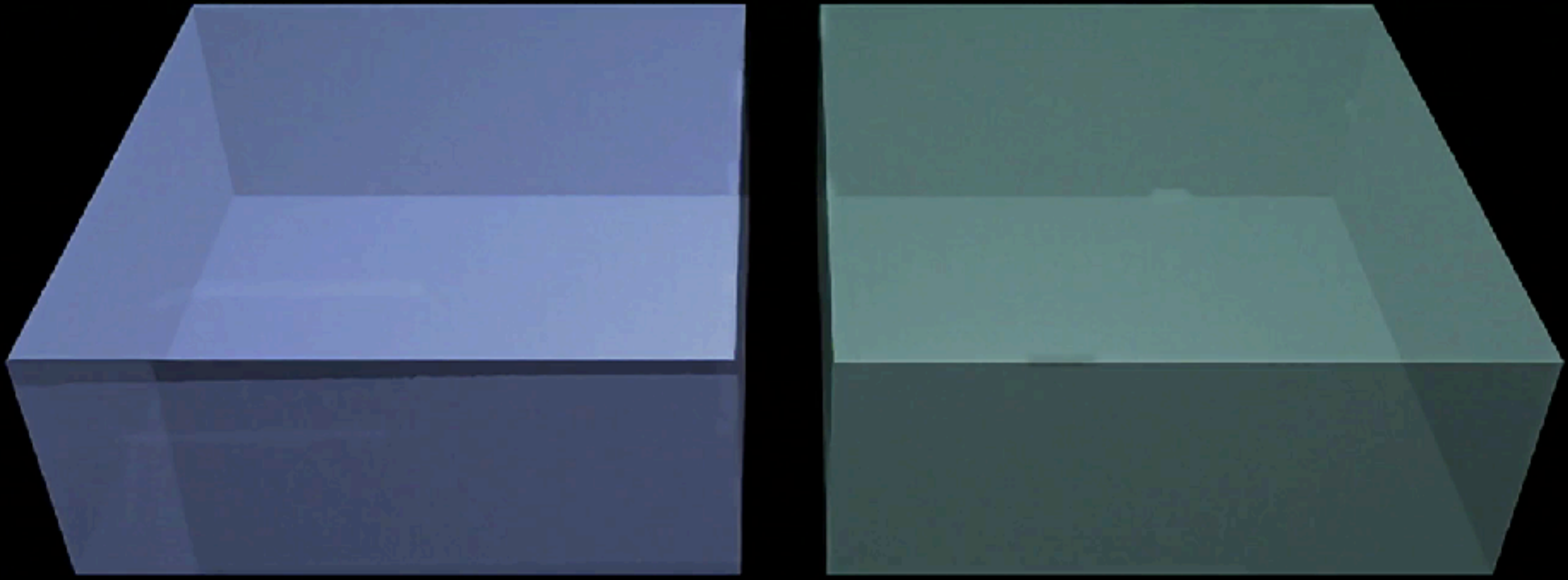
WMAP Collaboration



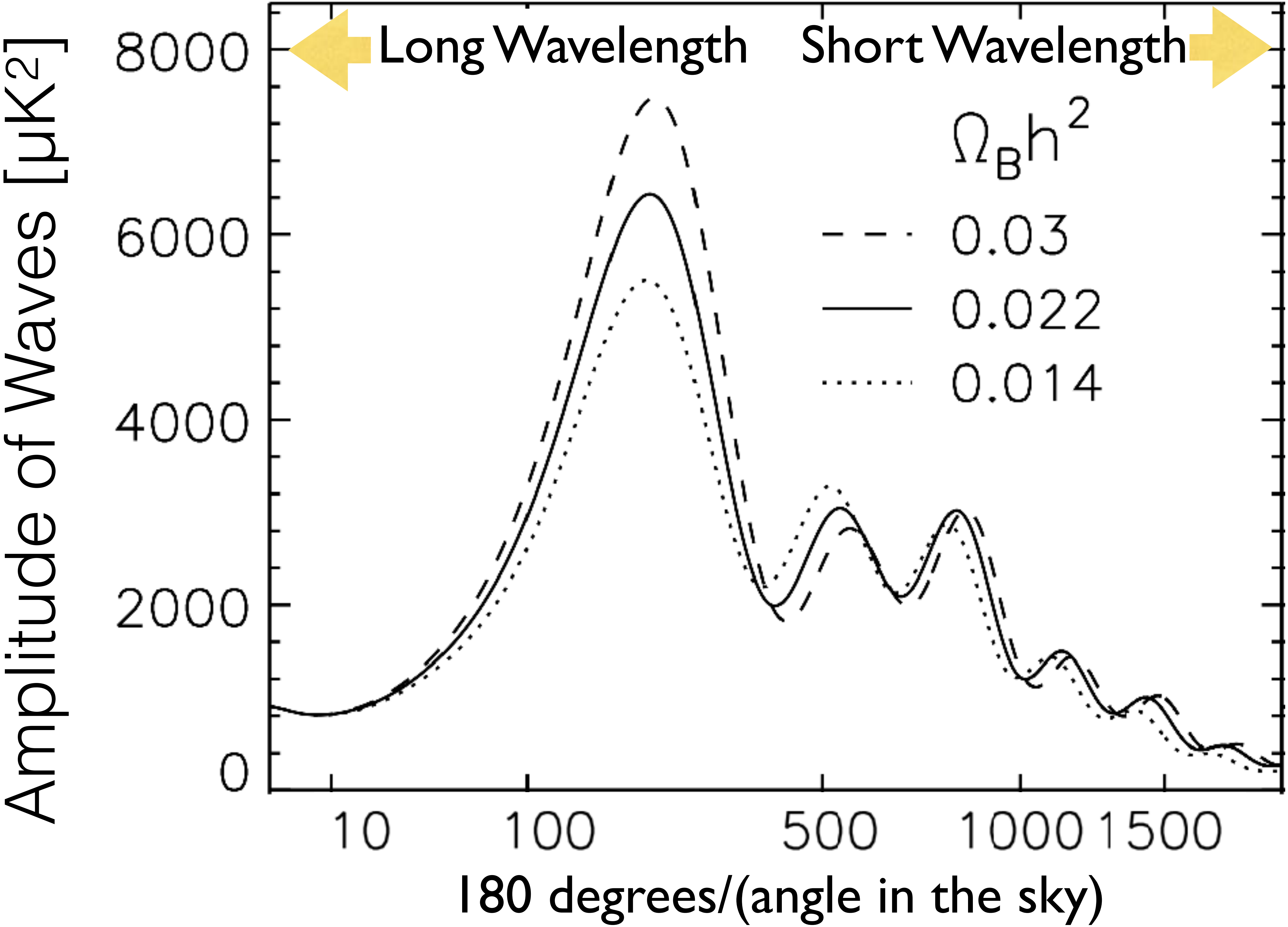
Soupe Miso Cosmique



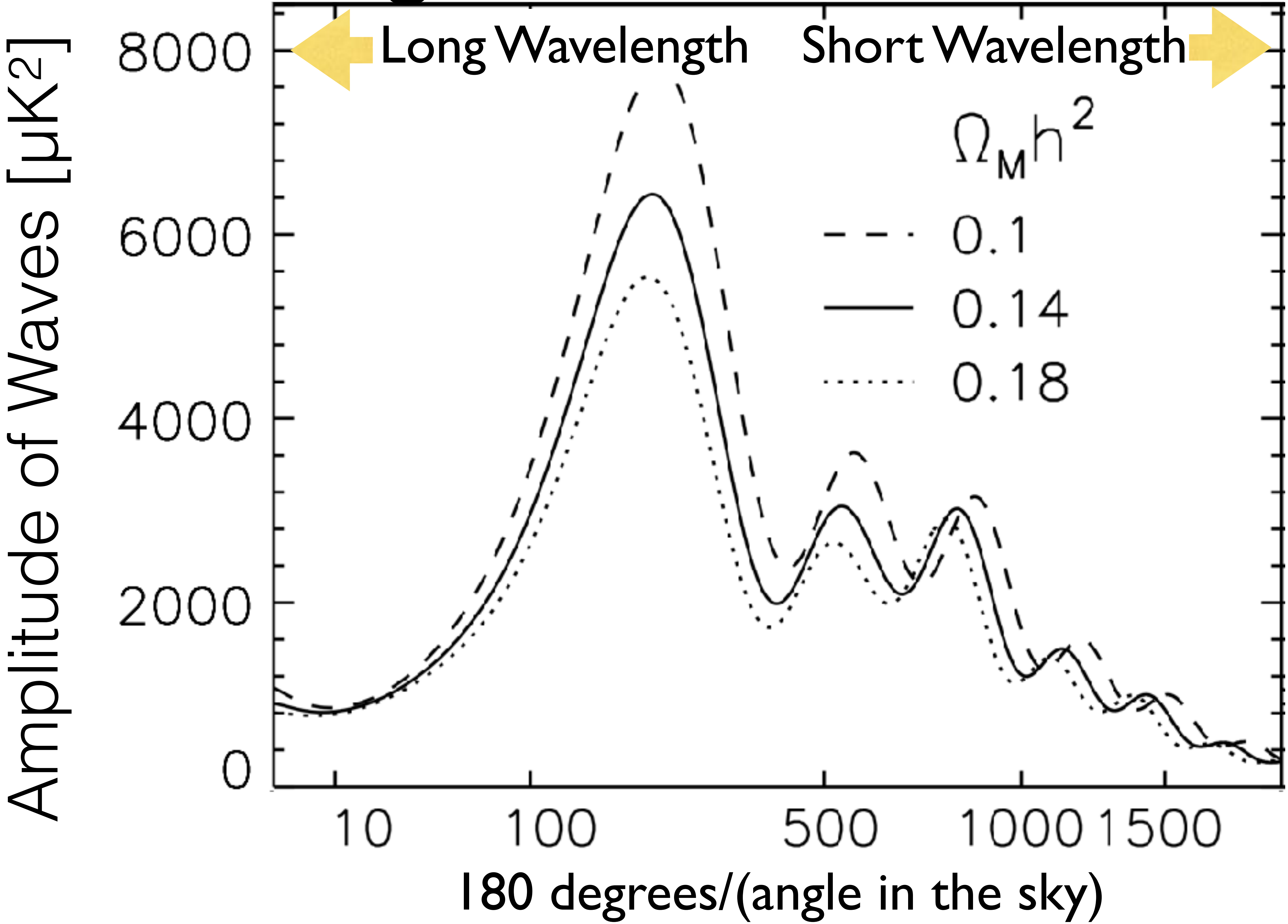
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching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



Measuring Abundance of H&He

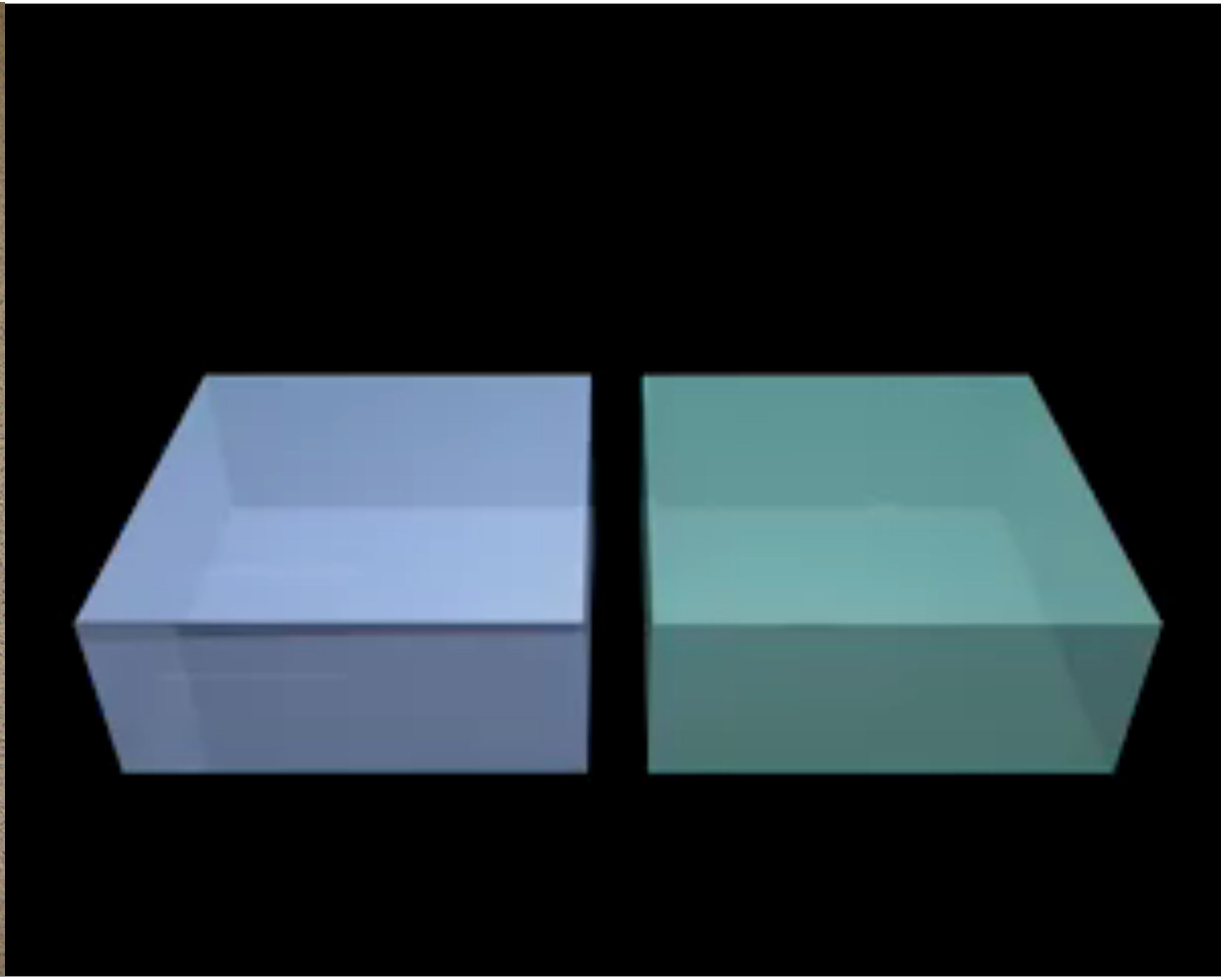


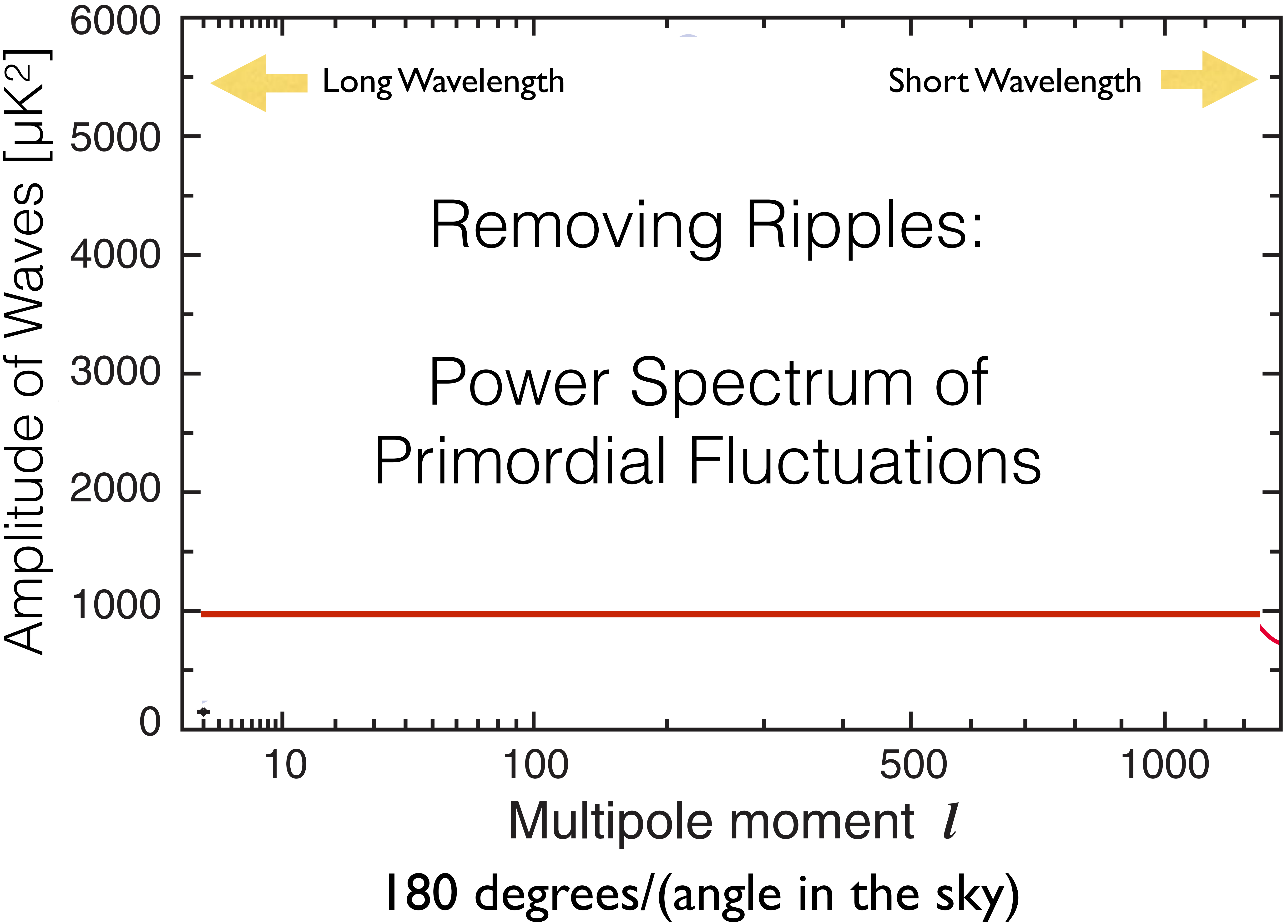
Measuring Total Matter Density



Origin of Fluctuations

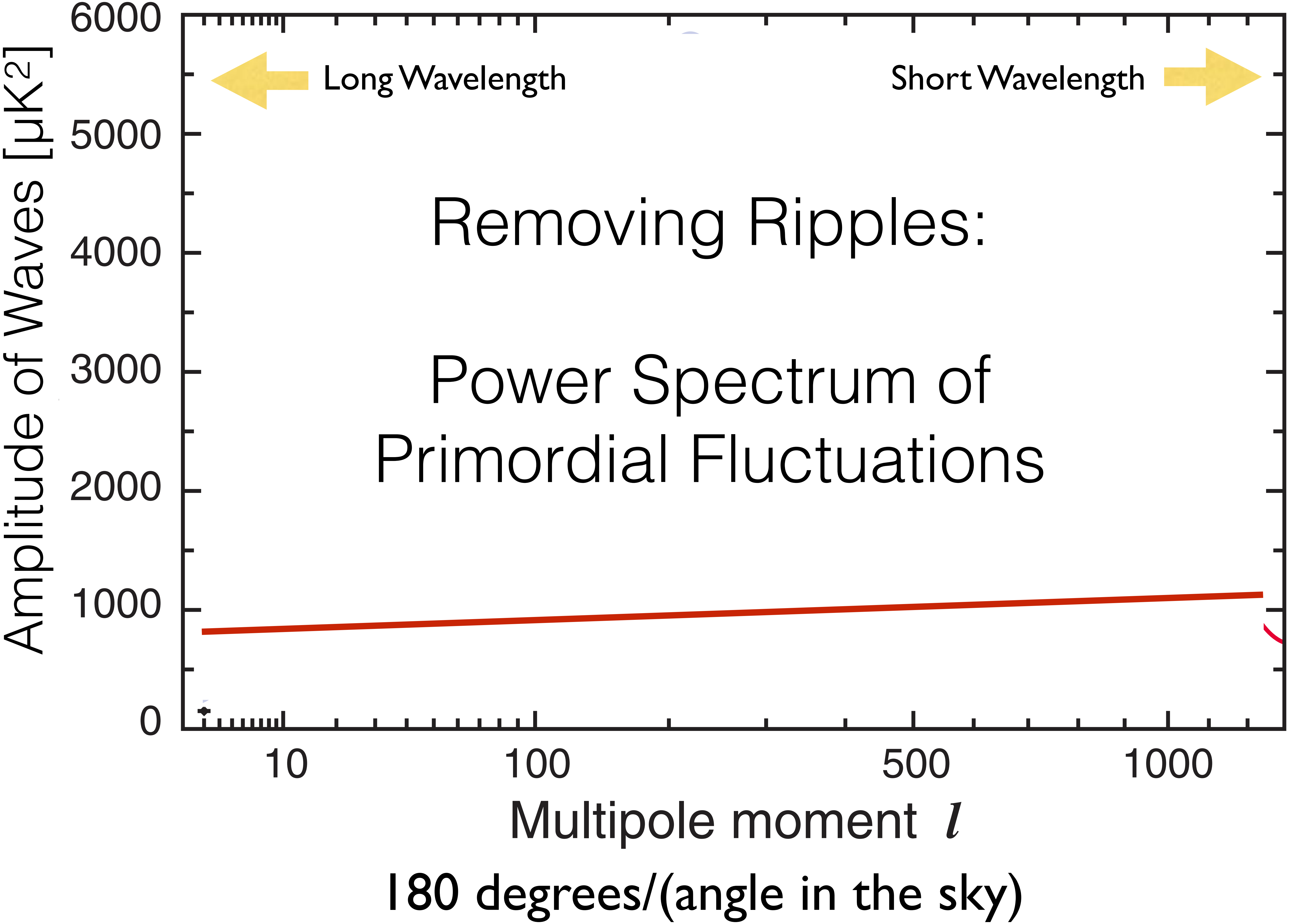
- Who dropped those Tofus into the cosmic Miso soup?





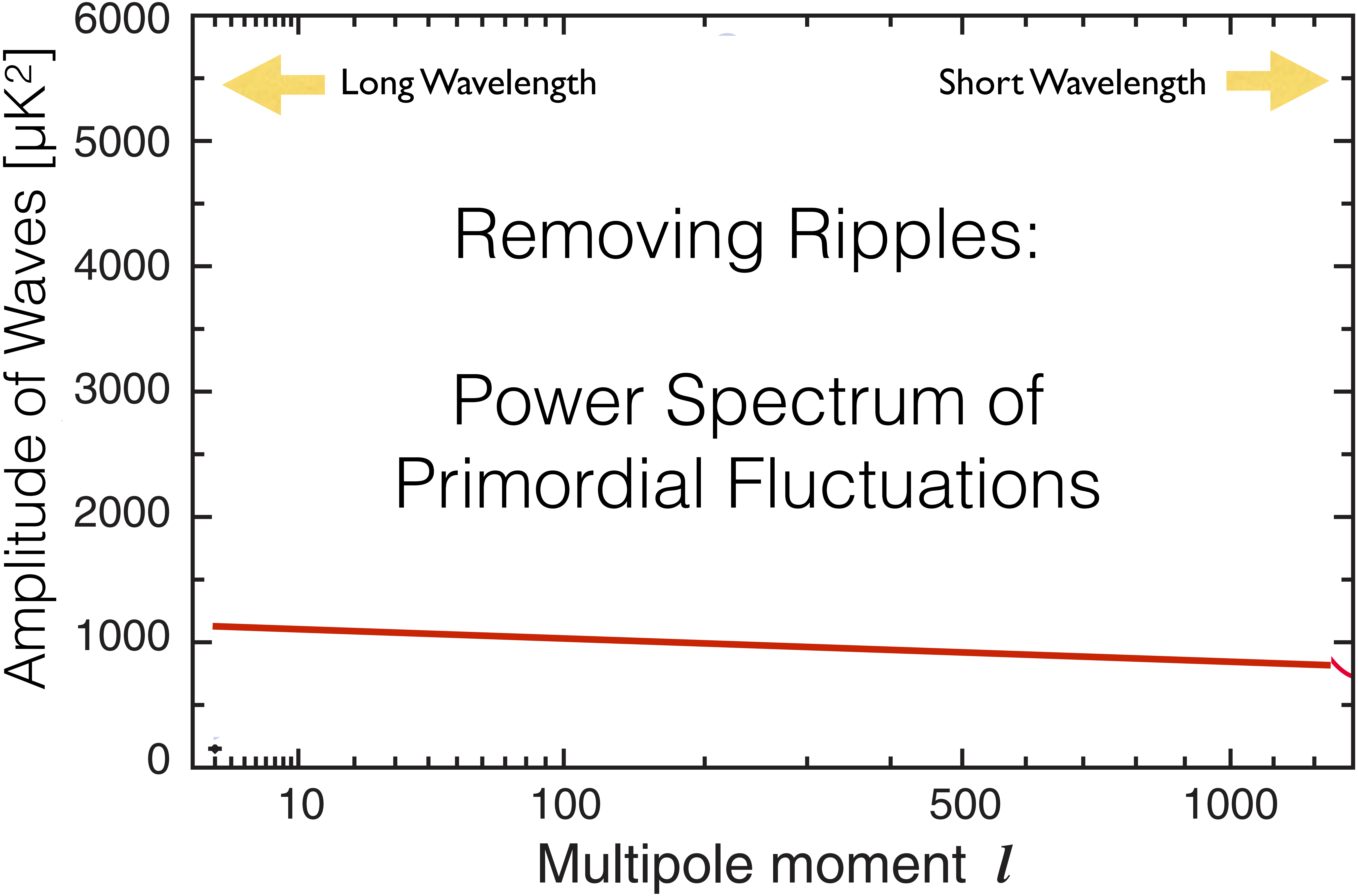
Removing Ripples:

Power Spectrum of Primordial Fluctuations



Removing Ripples:

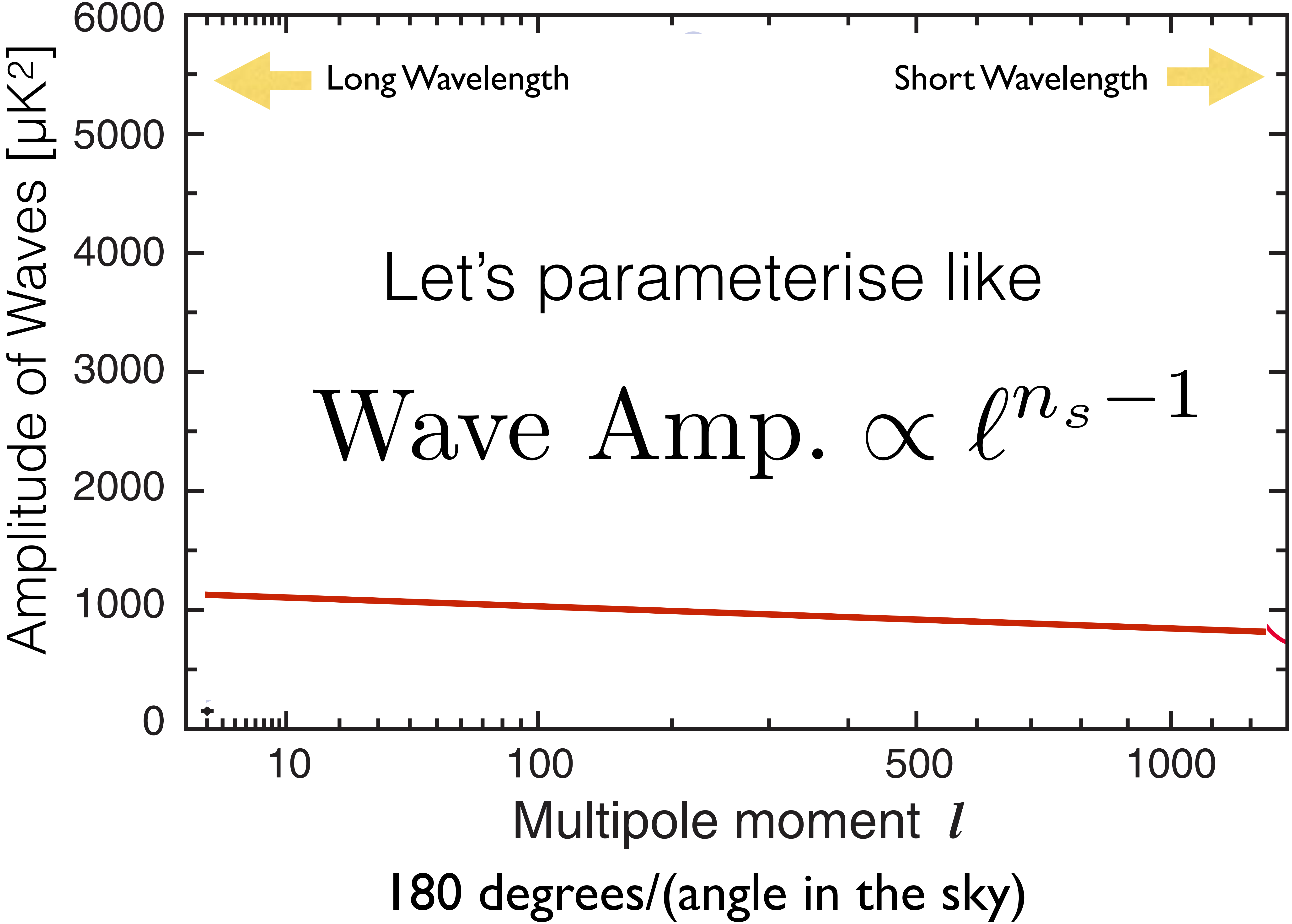
Power Spectrum of Primordial Fluctuations



Removing Ripples:

Power Spectrum of Primordial Fluctuations

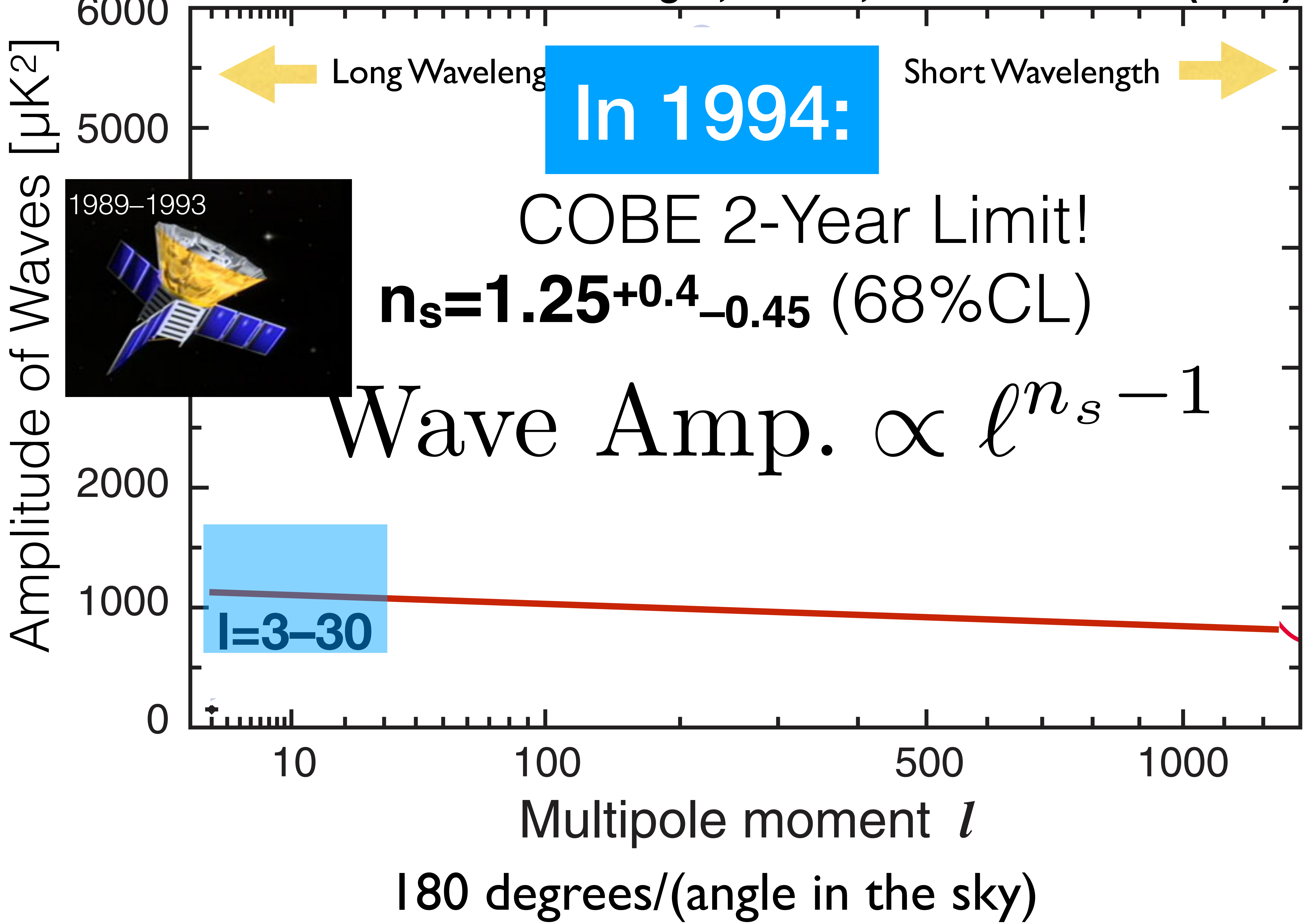
180 degrees/(angle in the sky)



Let's parameterise like

$$\text{Wave Amp.} \propto \ell^{n_s - 1}$$

Wright, Smoot, Bennett & Lubin (1994)



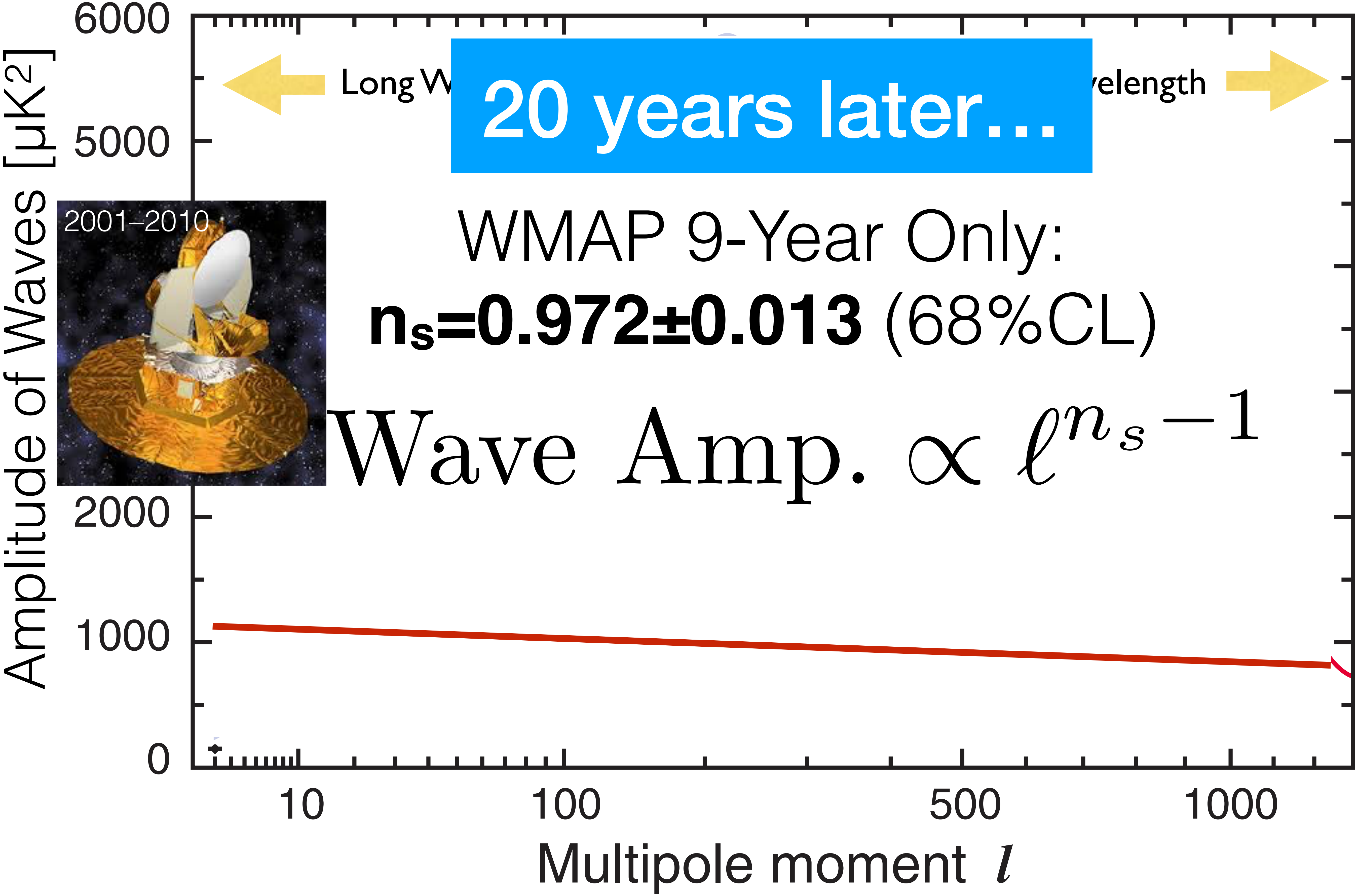
In 1994:

COBE 2-Year Limit!

$n_s=1.25^{+0.4}_{-0.45}$ (68%CL)

$$\text{Wave Amp.} \propto \ell^{n_s-1}$$

WMAP Collaboration



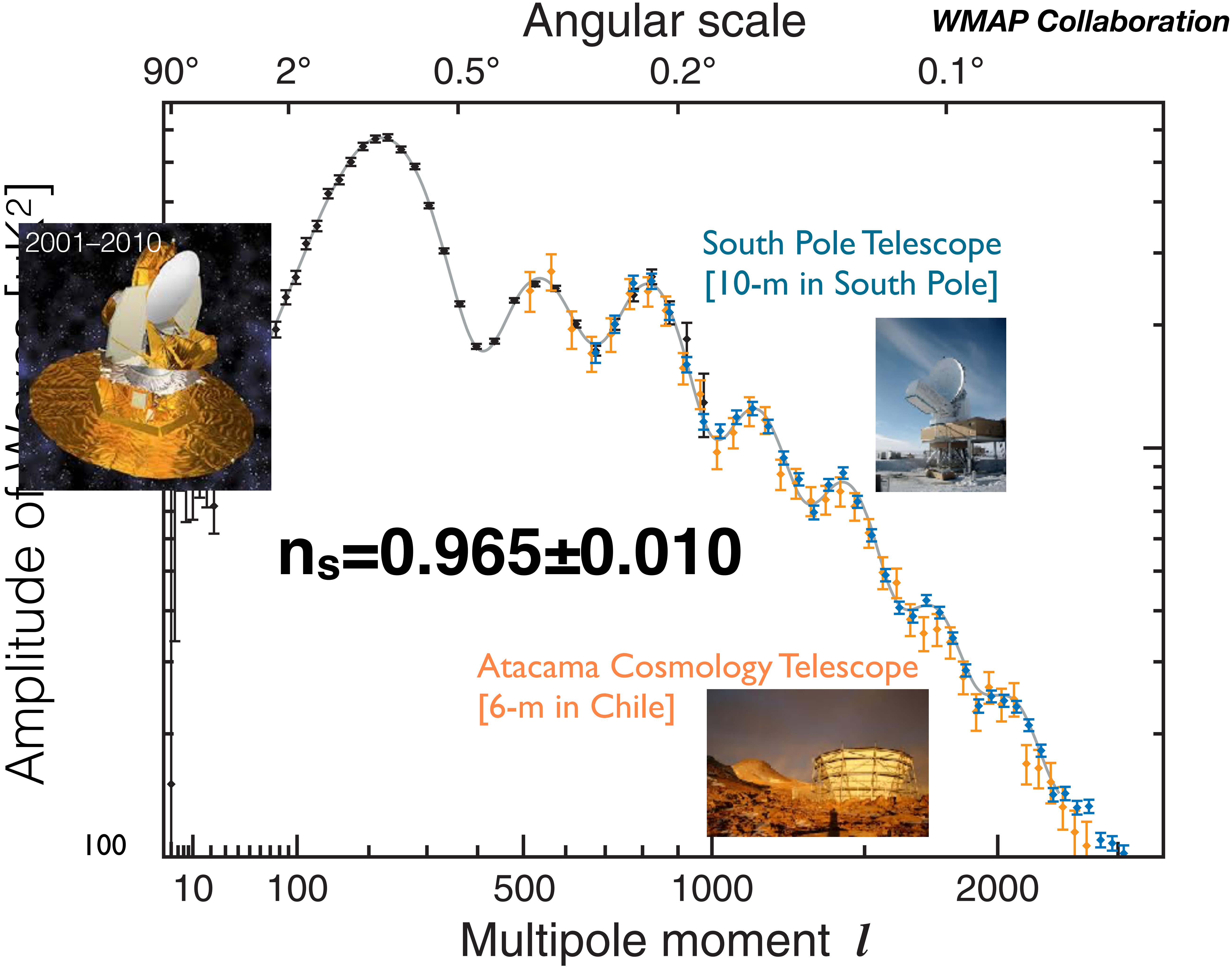
20 years later…

WMAP 9-Year Only:

n_s=0.972±0.013 (68%CL)

$$\text{Wave Amp.} \propto \ell^{n_s-1}$$

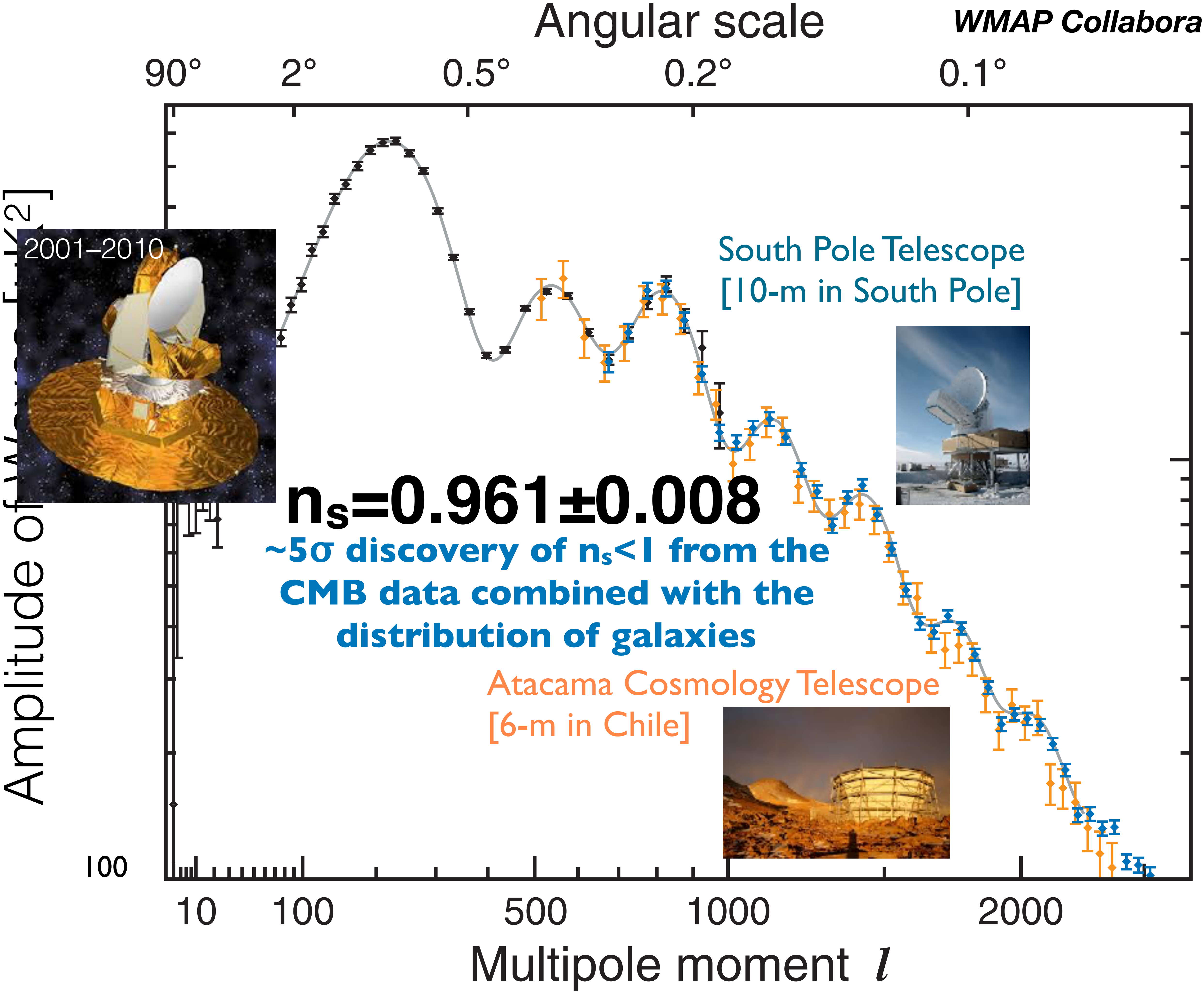
180 degrees/(angle in the sky)



$n_s=0.965\pm0.010$

WMAP Collaboration

WMAP Collaboration



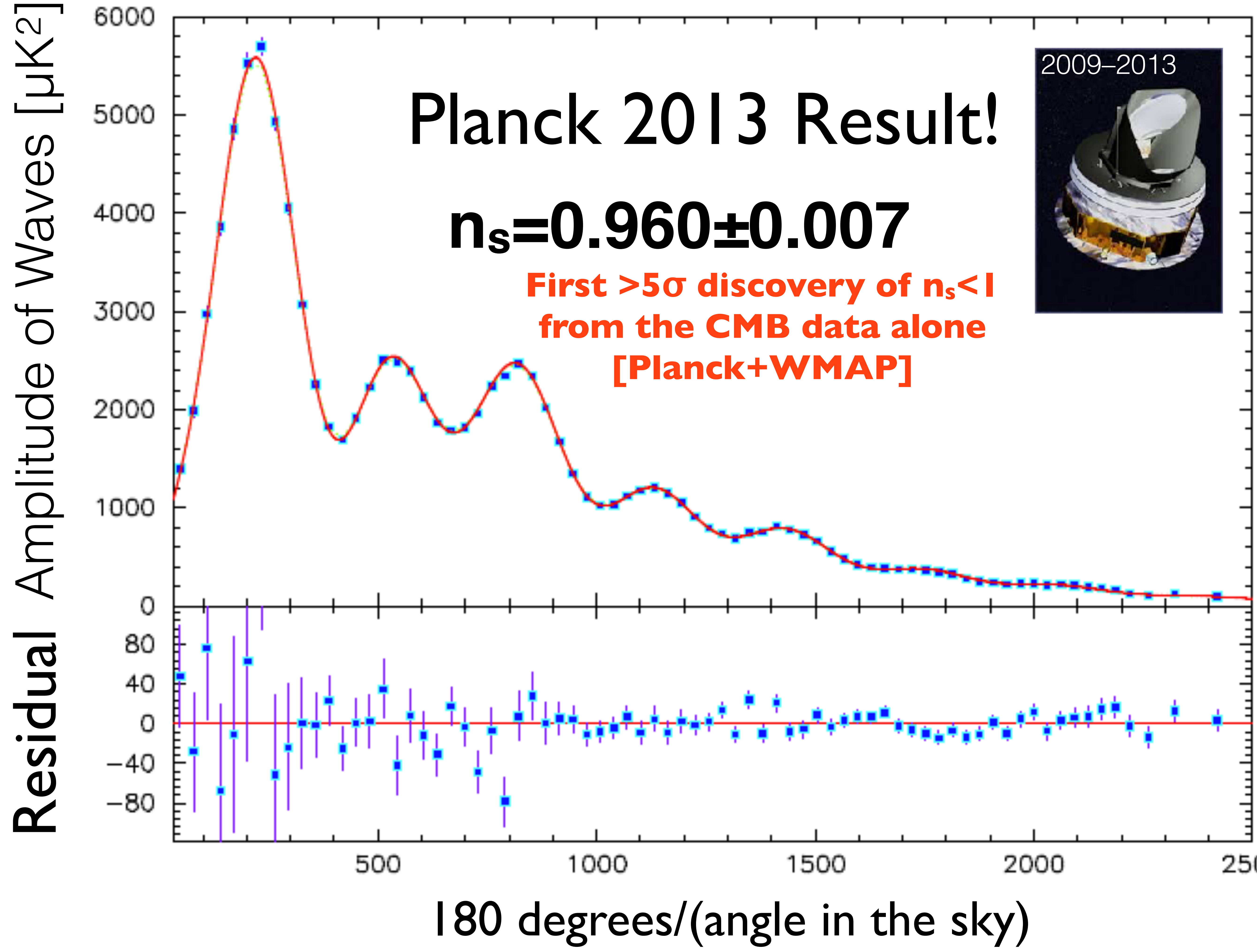
South Pole Telescope
[10-m in South Pole]

Atacama Cosmology Telescope
[6-m in Chile]

n_s=0.961±0.008

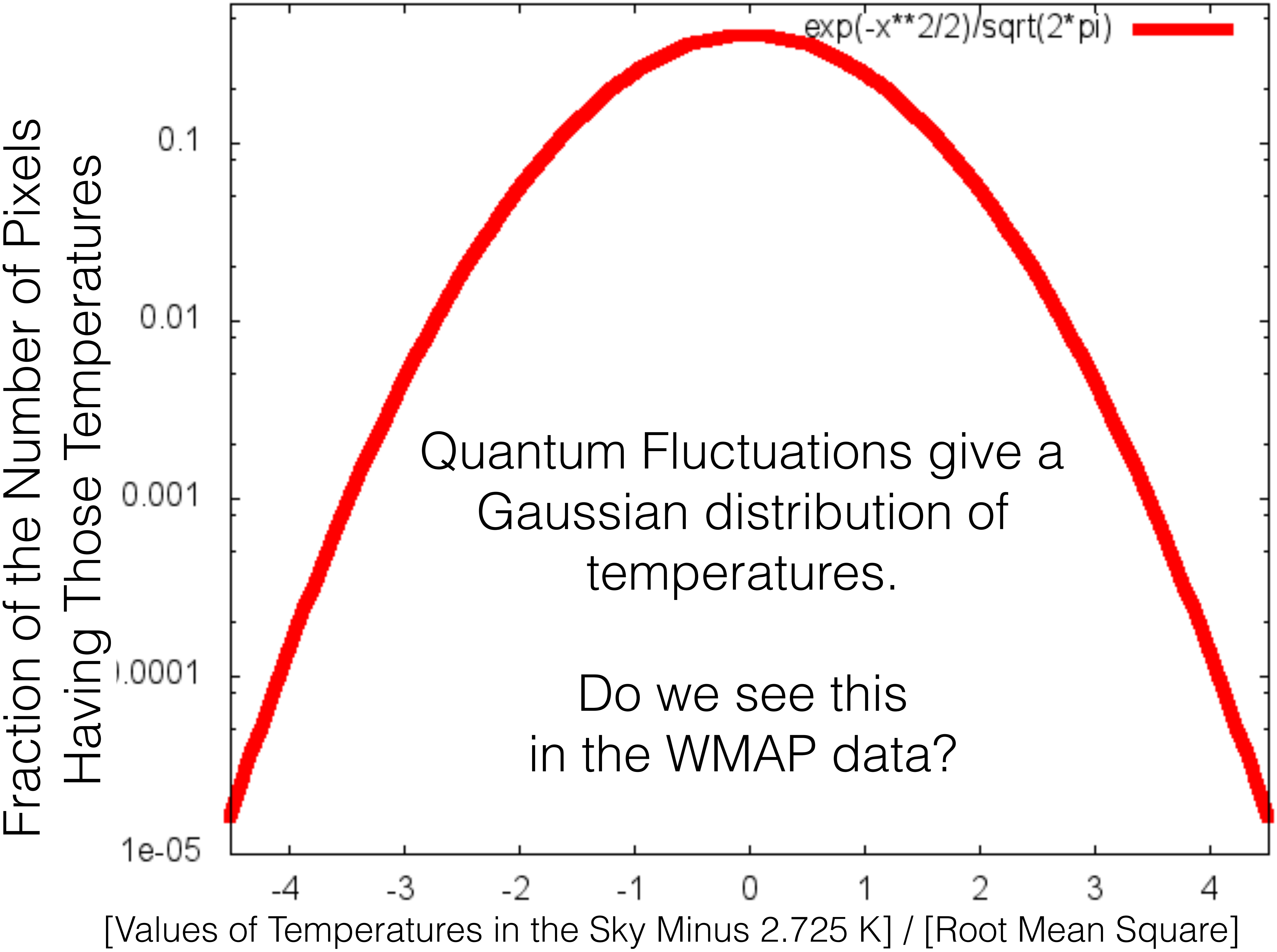
~5σ discovery of $n_s<1$ from the CMB data combined with the distribution of galaxies

Planck 2013 Result!



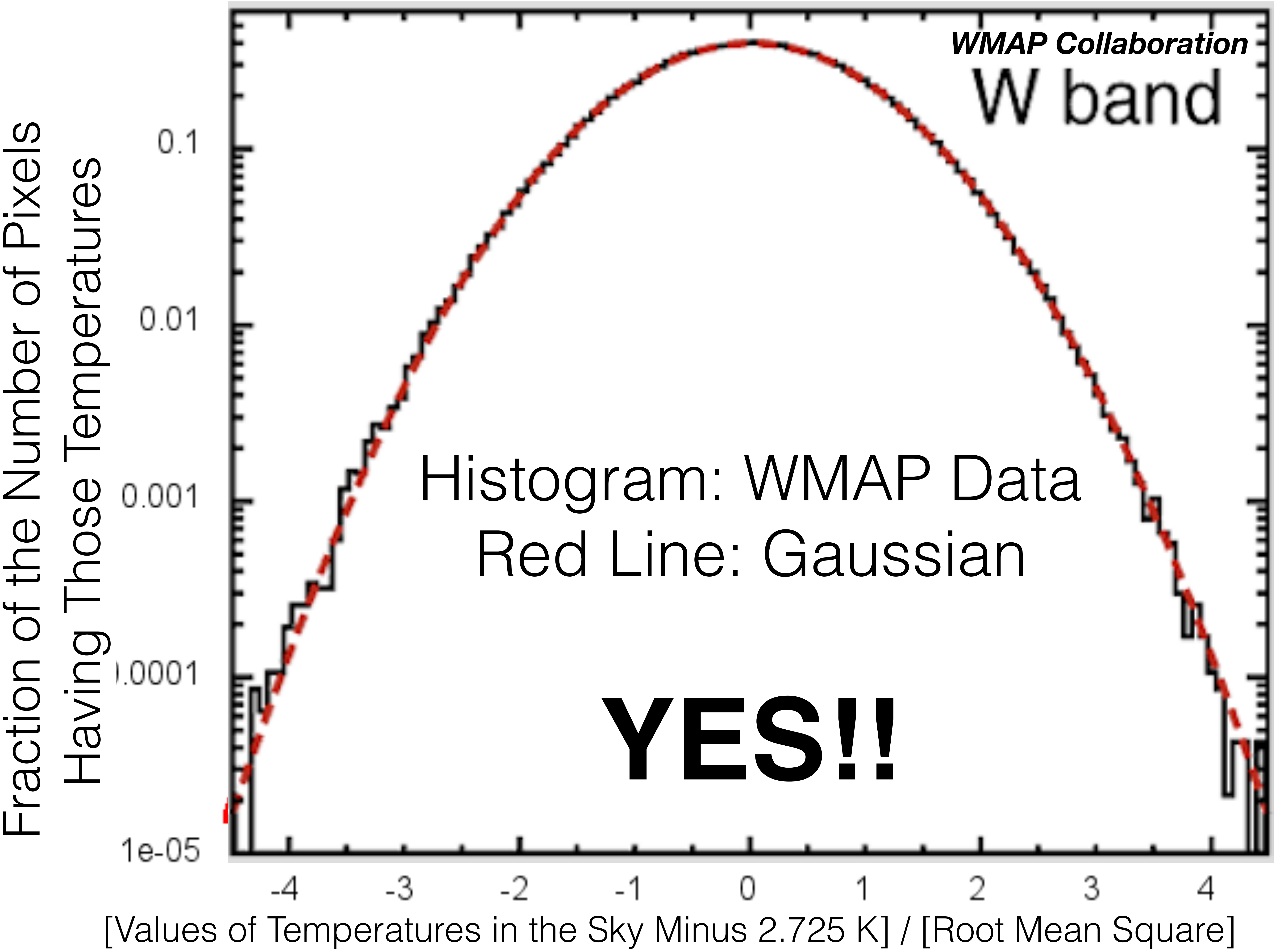
n_s=0.960±0.007

First >5σ discovery of n_s<1 from the CMB data alone [Planck+WMAP]



Quantum Fluctuations give a
Gaussian distribution of
temperatures.

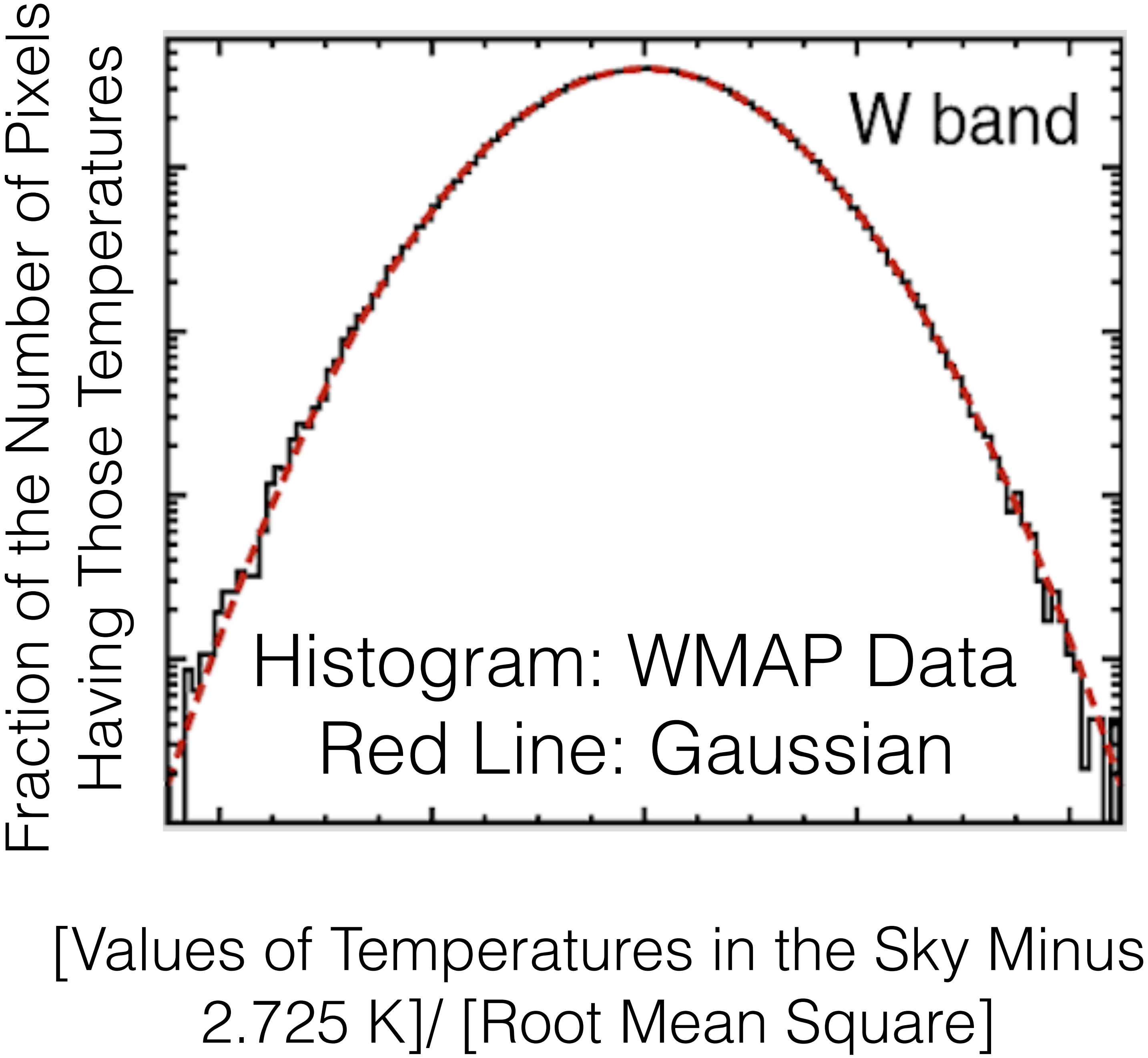
Do we see this
in the WMAP data?



Histogram: WMAP Data
Red Line: Gaussian

YES!!

Testing Gaussianity



Histogram: WMAP Data
Red Line: Gaussian

- Since a Gauss distribution is symmetric, it must yield a vanishing **3-point function**

$$\langle \delta T^3 \rangle \equiv \int_{-\infty}^{\infty} d\delta T \; P(\delta T) \delta T^3$$

- More specifically, we measure this by averaging the product of temperatures at three different locations in the sky

$$\langle \delta T(\hat{n}_1) \delta T(\hat{n}_2) \delta T(\hat{n}_3) \rangle$$

Lack of non-Gaussianity

- The WMAP data show that the distribution of temperature fluctuations of CMB is very precisely Gaussian
  - with an upper bound on a deviation of **0.2%** (95%CL)

$$\zeta(\mathbf{x}) = \zeta_{\rm gaus}(\mathbf{x}) + \frac{3}{5} f_{\rm NL} \zeta^2_{\rm gaus}(\mathbf{x}) \quad \textbf{with} \quad f_{\rm NL} = 37 \pm 20 \ (68\% \ {\rm CL})$$

WMAP 9-year Result

- The Planck data improved the upper bound by an order of magnitude: deviation is <**0.03%** (95%CL)

$$f_{\rm NL} = 0.8 \pm 5.0 \ (68\% \ {\rm CL})$$

Planck 2015 Result

So, have we found inflation?

- Single-field slow-roll inflation looks remarkably good:
  - **Super-horizon fluctuation**
  - **Adiabaticity**
  - **Gaussianity**
  - **n_s<1**
- What more do we want? **Gravitational waves**. Why?
  - Because the "*extraordinary claim requires extraordinary evidence*"

Grishchuk (1974); Starobinsky (1979)

Gravitational waves as the quantum vacuum fluctuation in spacetime

- Quantising the gravitational waves in de Sitter space in **vacuum**

$$\Box h_{ij} = 0$$

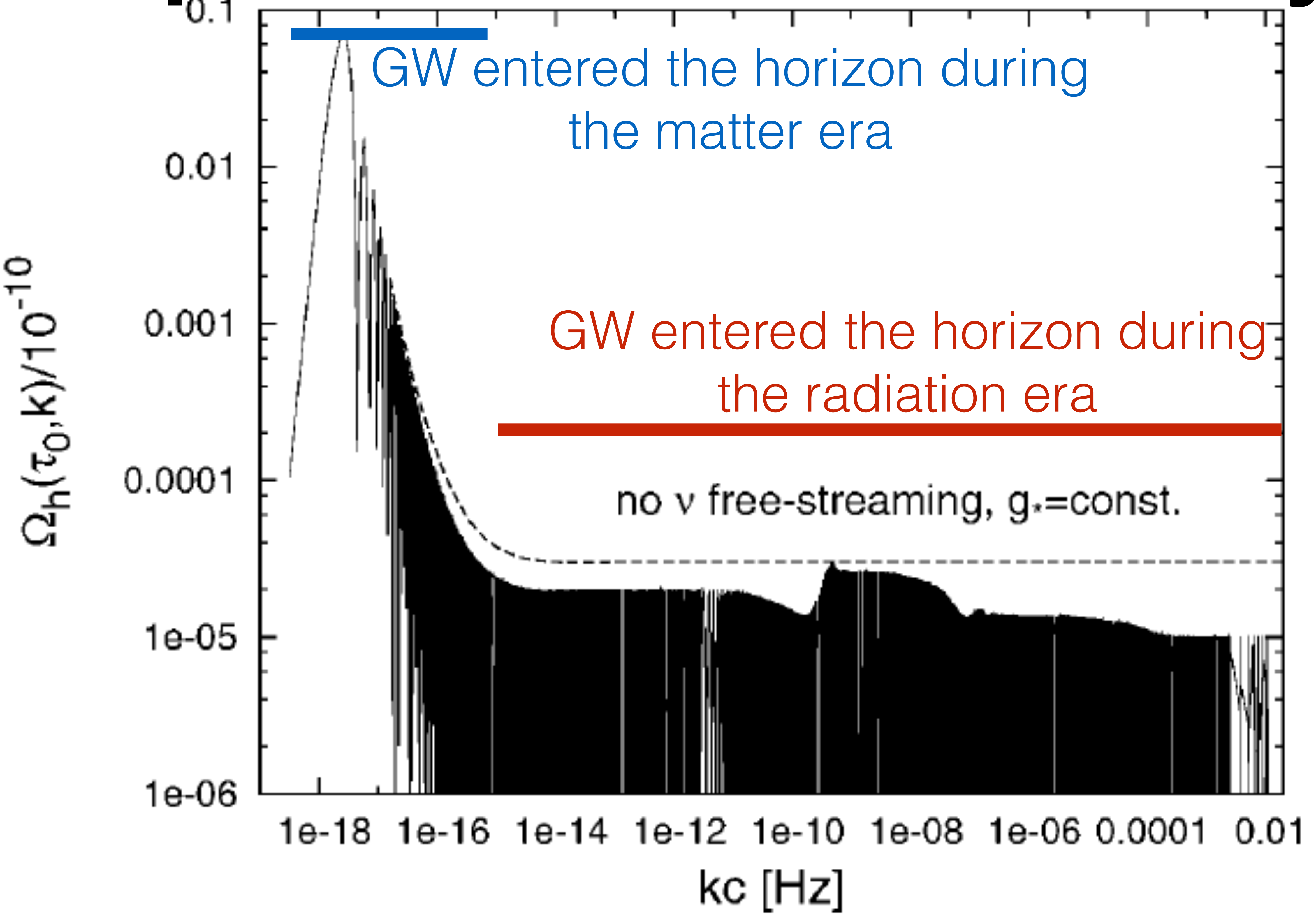
gives

scale-invariant spectrum

$$k^3 \langle h_{ij}(\mathbf{k}) h^{ij*}(\mathbf{k}') \rangle = (2\pi)^3 \delta_D(\mathbf{k} - \mathbf{k}') \boxed{\frac{8}{M_{\rm pl}^2} \left(\frac{H}{2\pi} \right)^2}$$

Watanabe & EK (2006)

Theoretical energy density
Spectrum of GW today



Watanabe & EK (2006)

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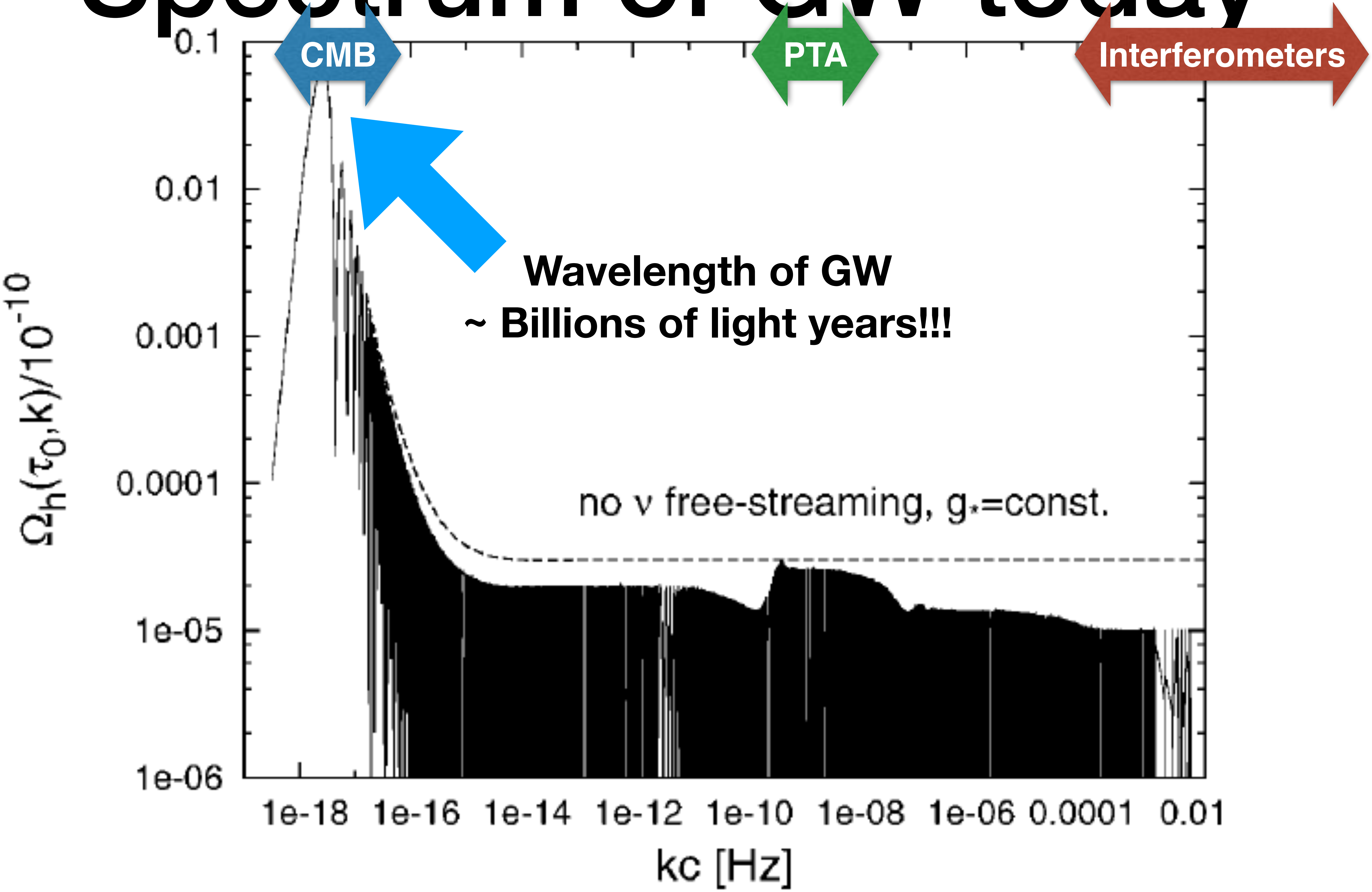


Wavelength of GW
~ Billions of light years!!!

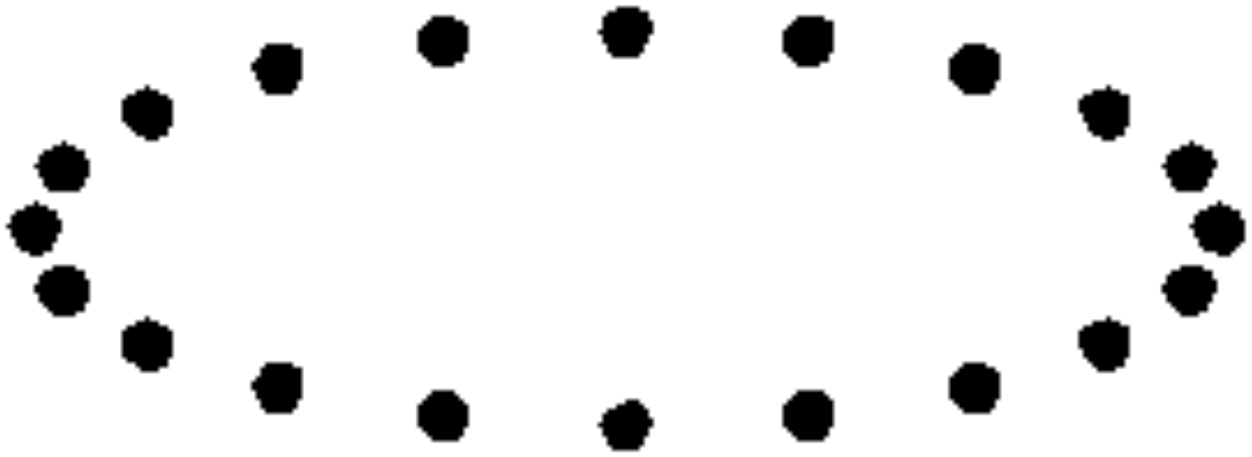
Measuring GW

- GW changes distances between two points

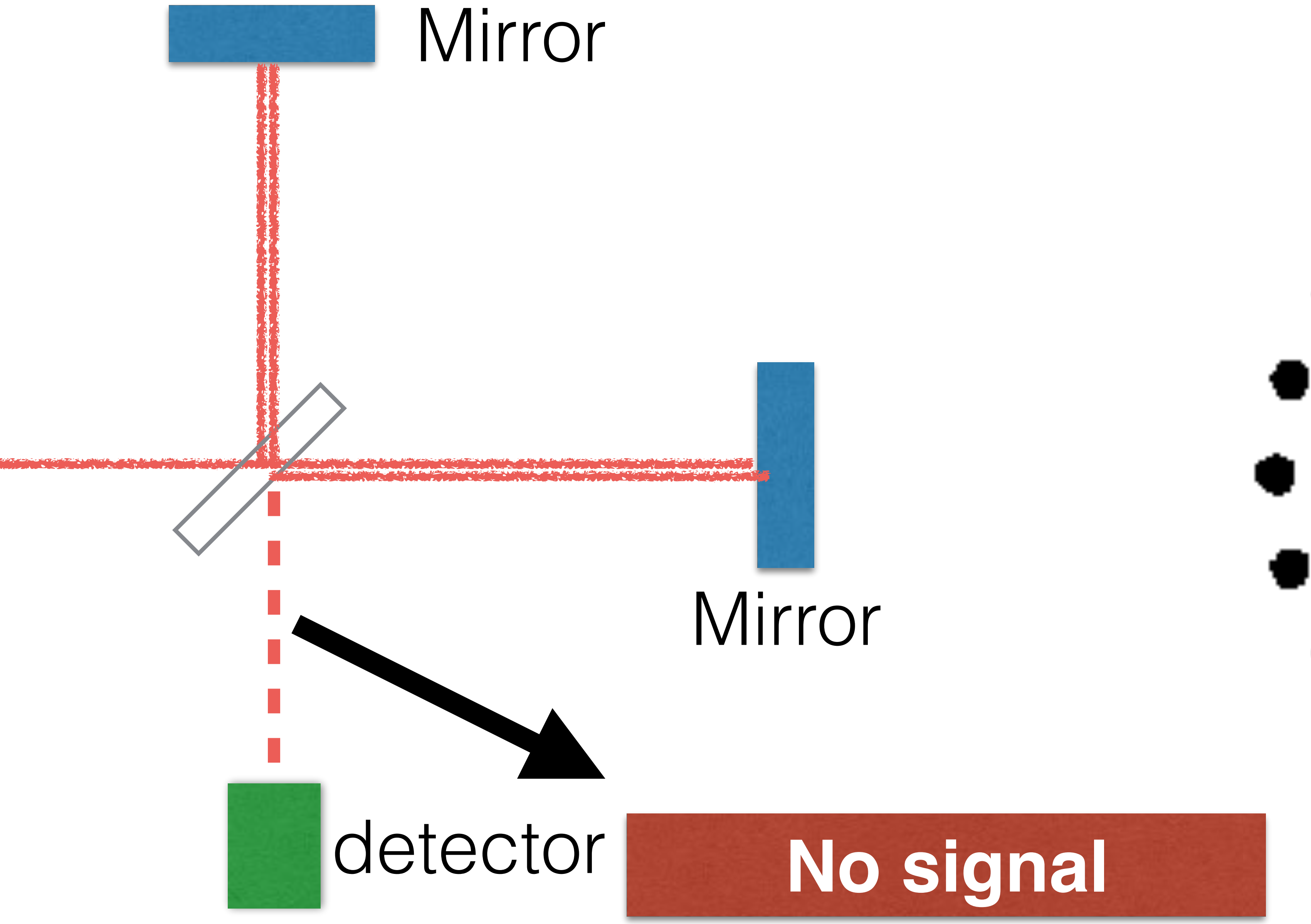
$$d\ell^2 = d\mathbf{x}^2 = \sum_{ij} \delta_{ij} dx^i dx^j$$

$$\Downarrow$$

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



Laser Interferometer

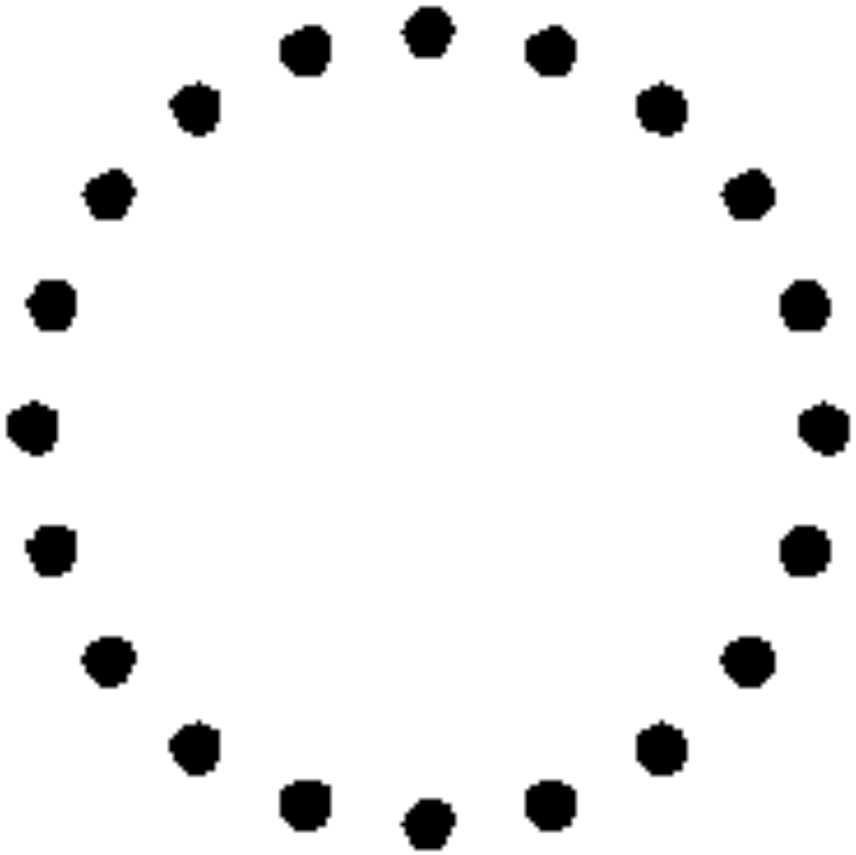


Mirror

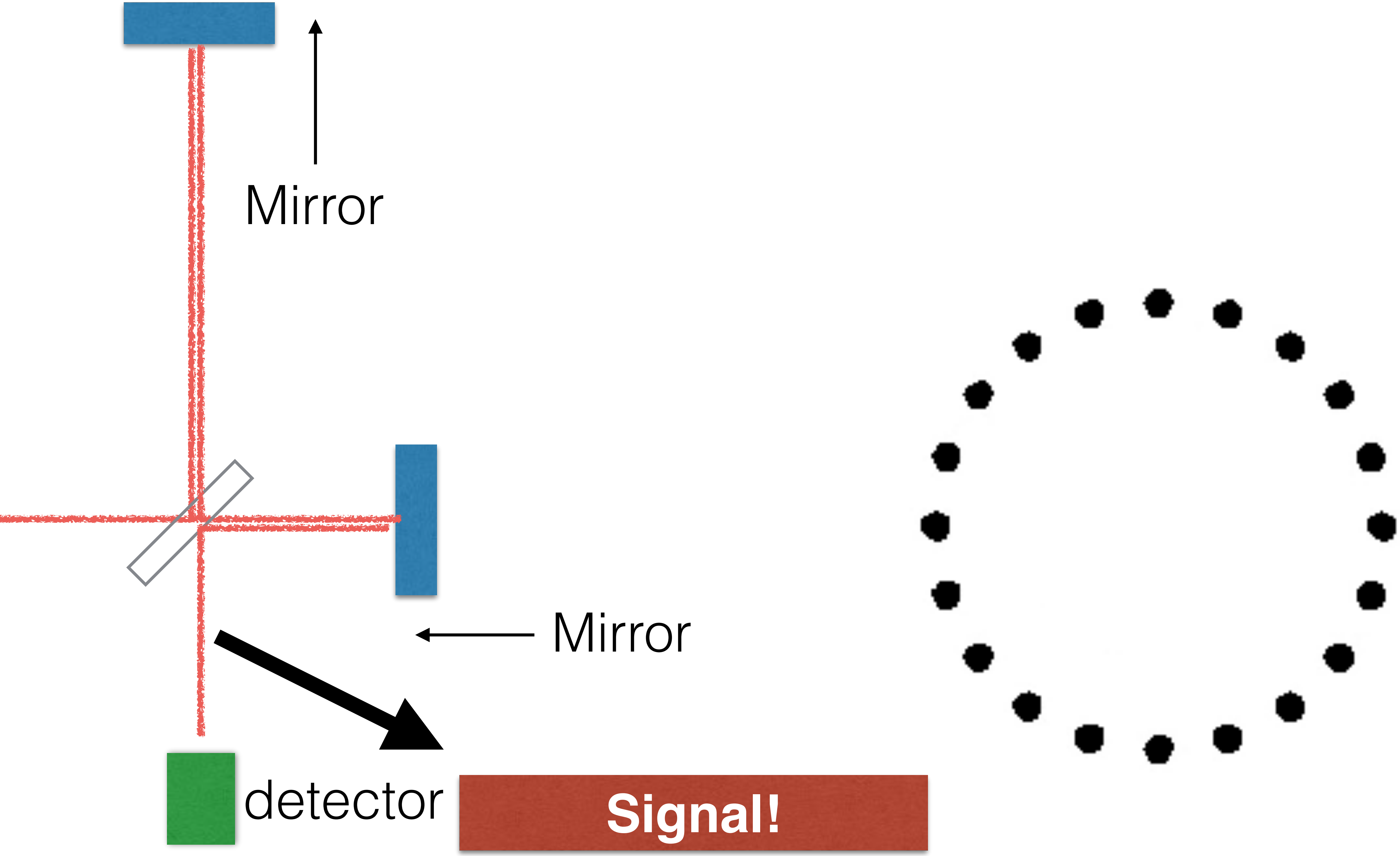
Mirror

detector

No signal



Laser Interferometer



Mirror

Mirror

detector

Signal!

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

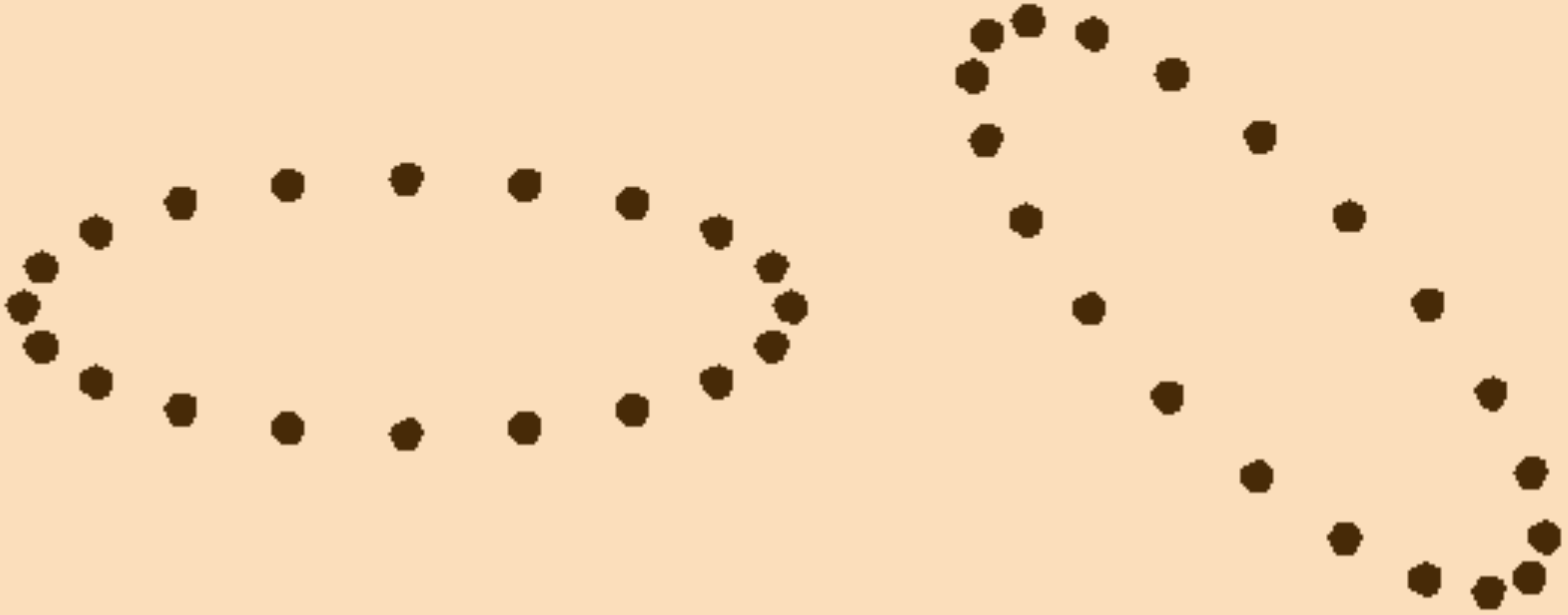
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

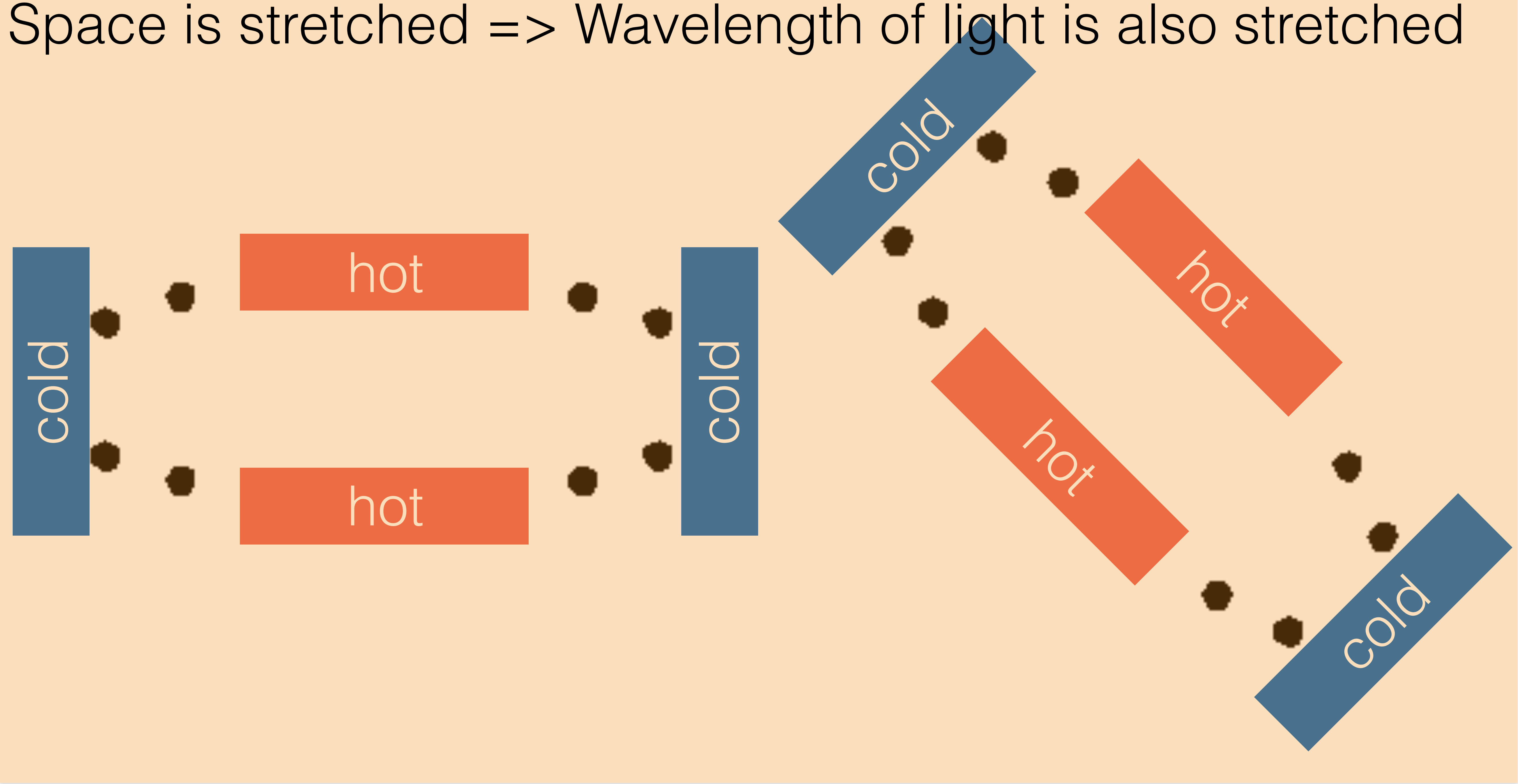
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



Detecting GW by CMB

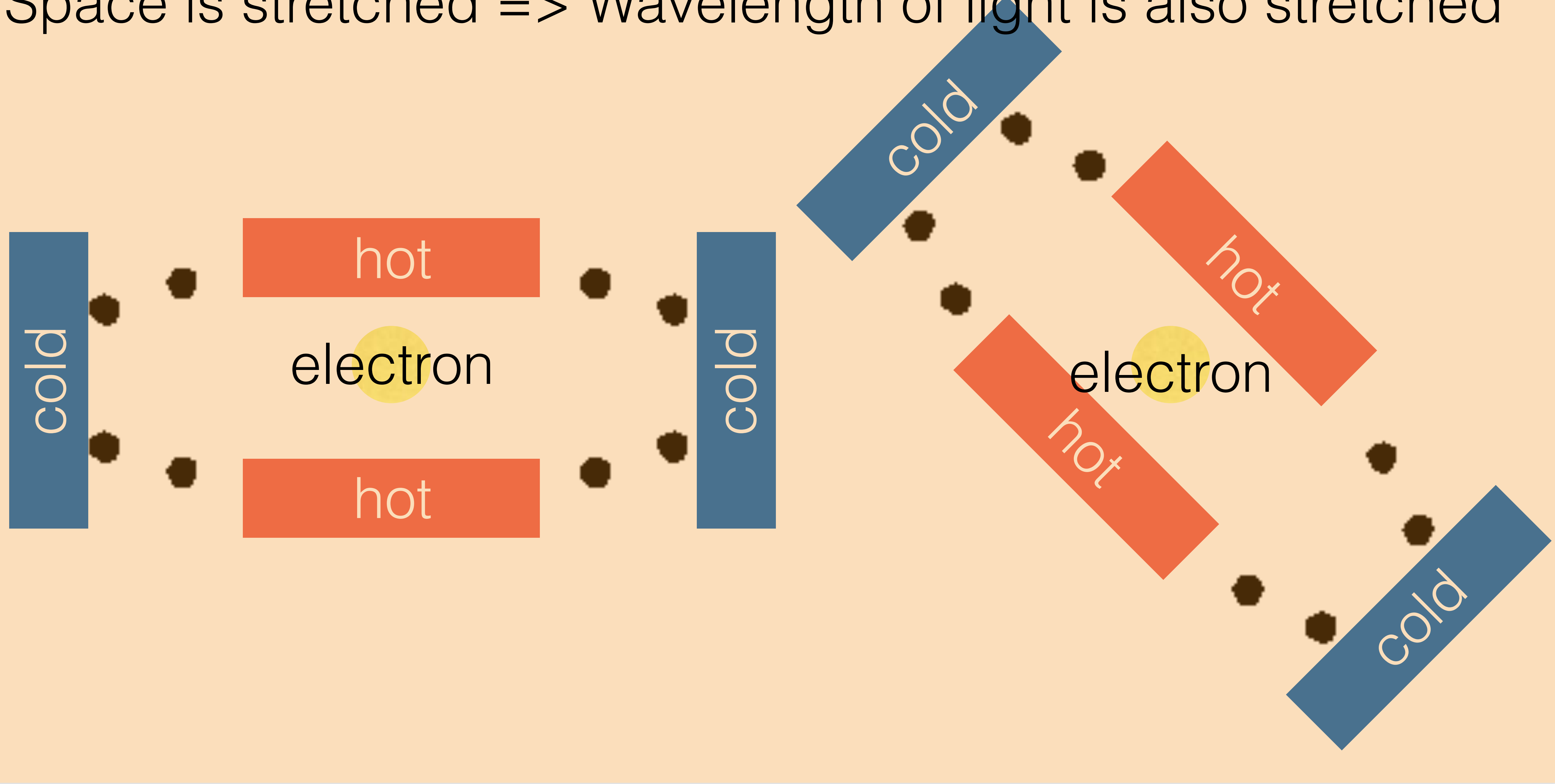
Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB

Polarisation

Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB
Polarisation

Space is stretched => Wavelength of light is also stretched

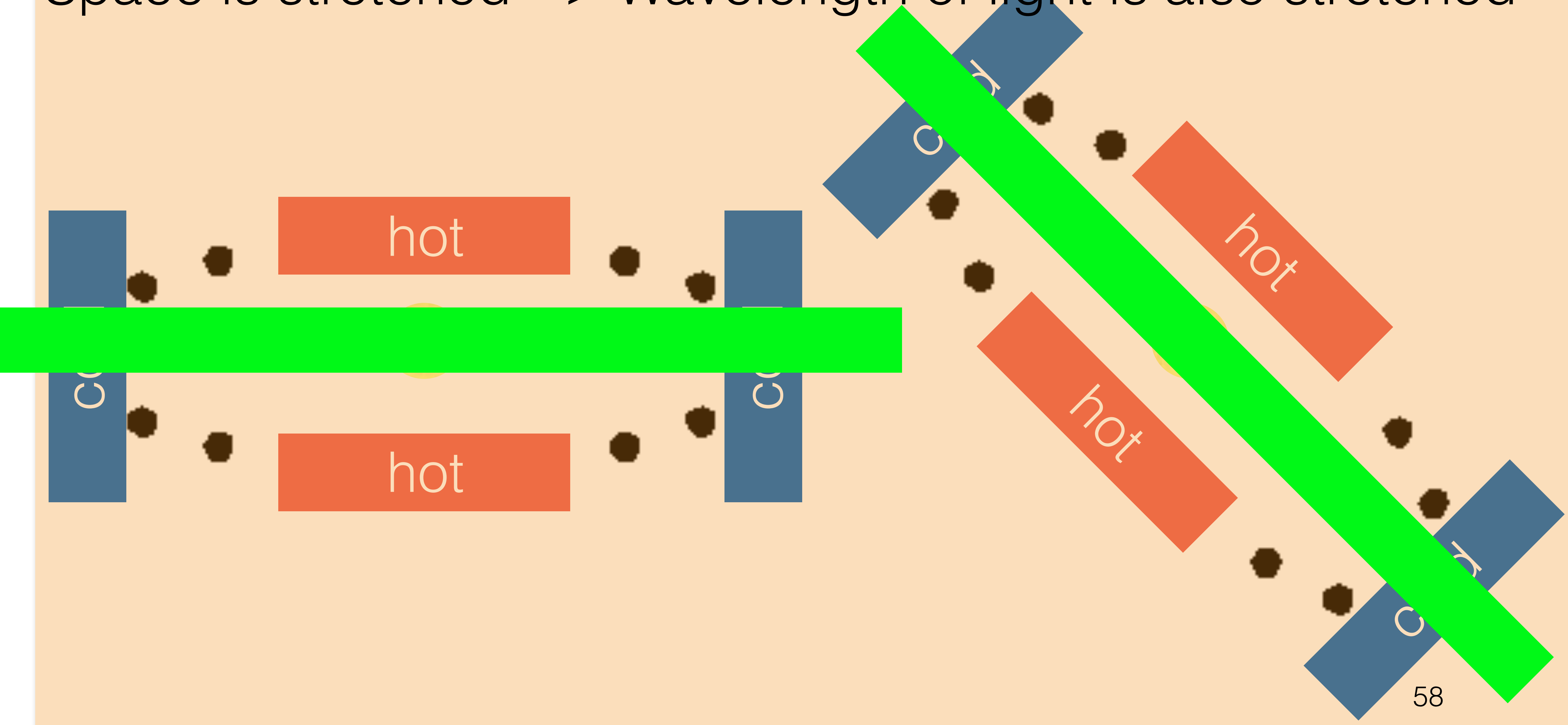



Photo Credit: TALEX

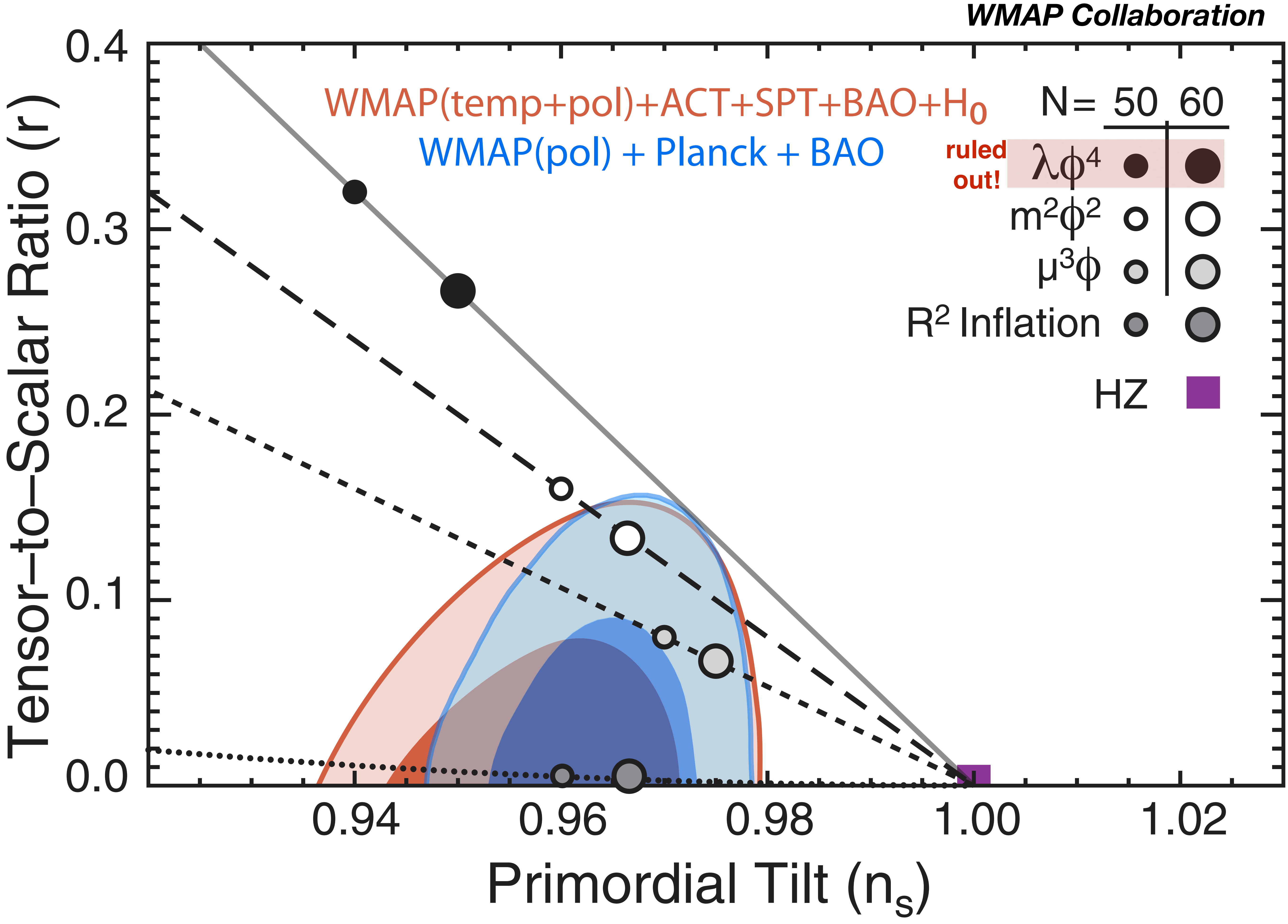
Photo Credit: TALEX

Tensor-to-scalar Ratio

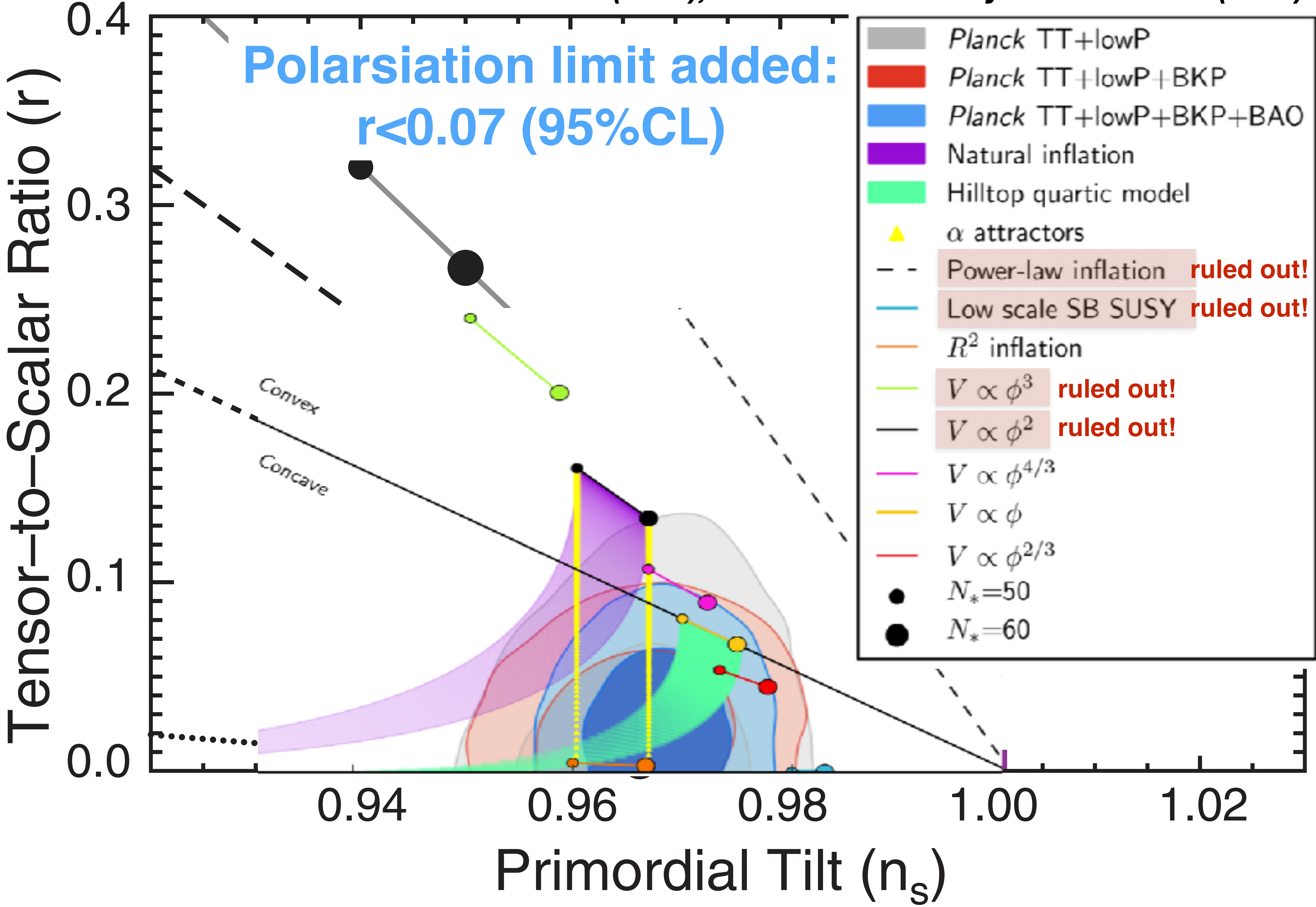
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

- 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+H0
WMAP(pol) + Planck + BAO
N= 50 60
ruled out!
λφ4
m2φ2
μ3φ
R2 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 (ns)

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



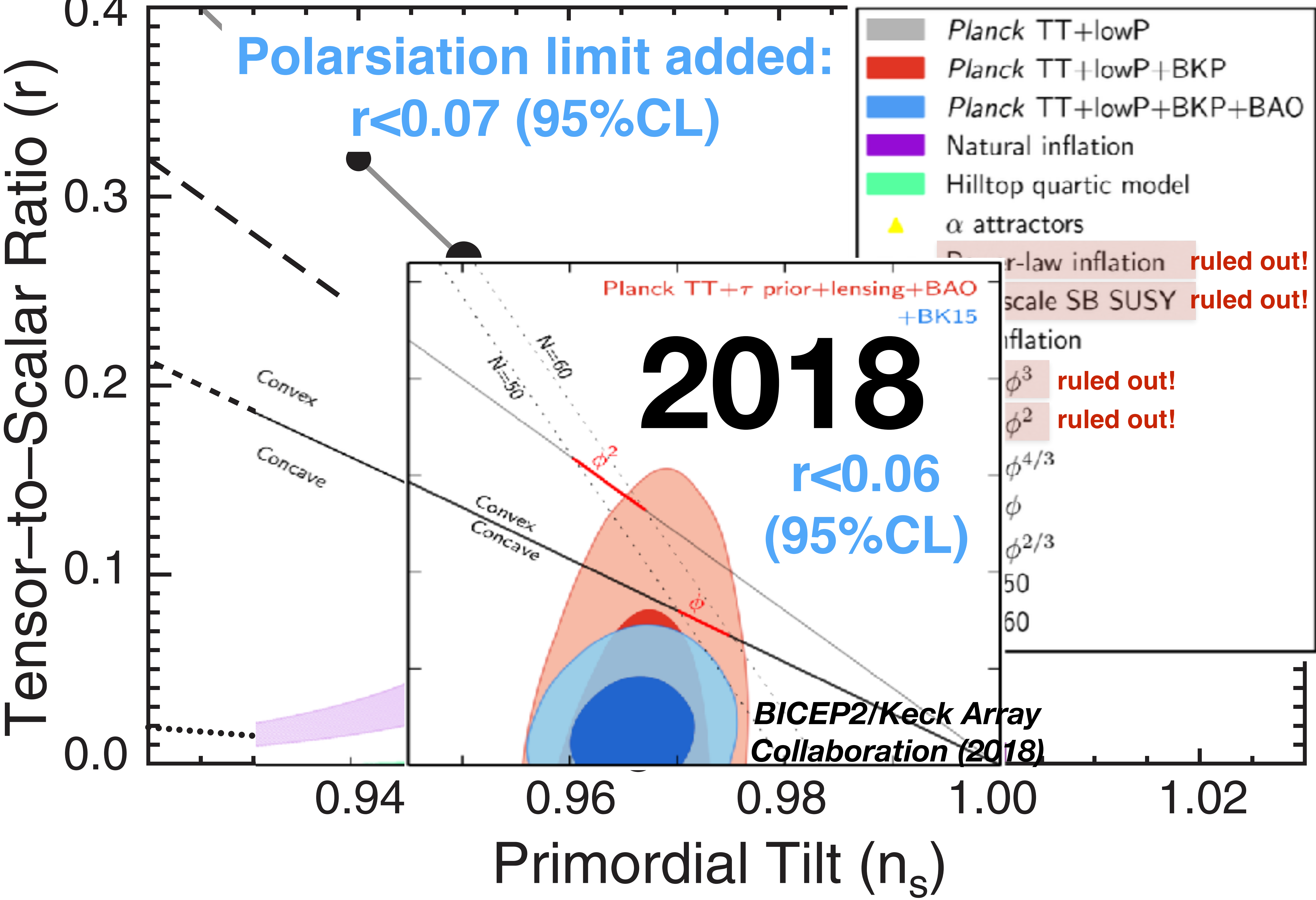
Polarsiation limit added: $r<0.07$ (95%CL)

Power-law inflation **ruled out!**

Low scale SB SUSY **ruled out!**

$V \propto \phi^3$ **ruled out!**

$V \propto \phi^2$ **ruled out!**



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

Polarsiation limit added: $r<0.07$ (95%CL)

ruled out!

ruled out!

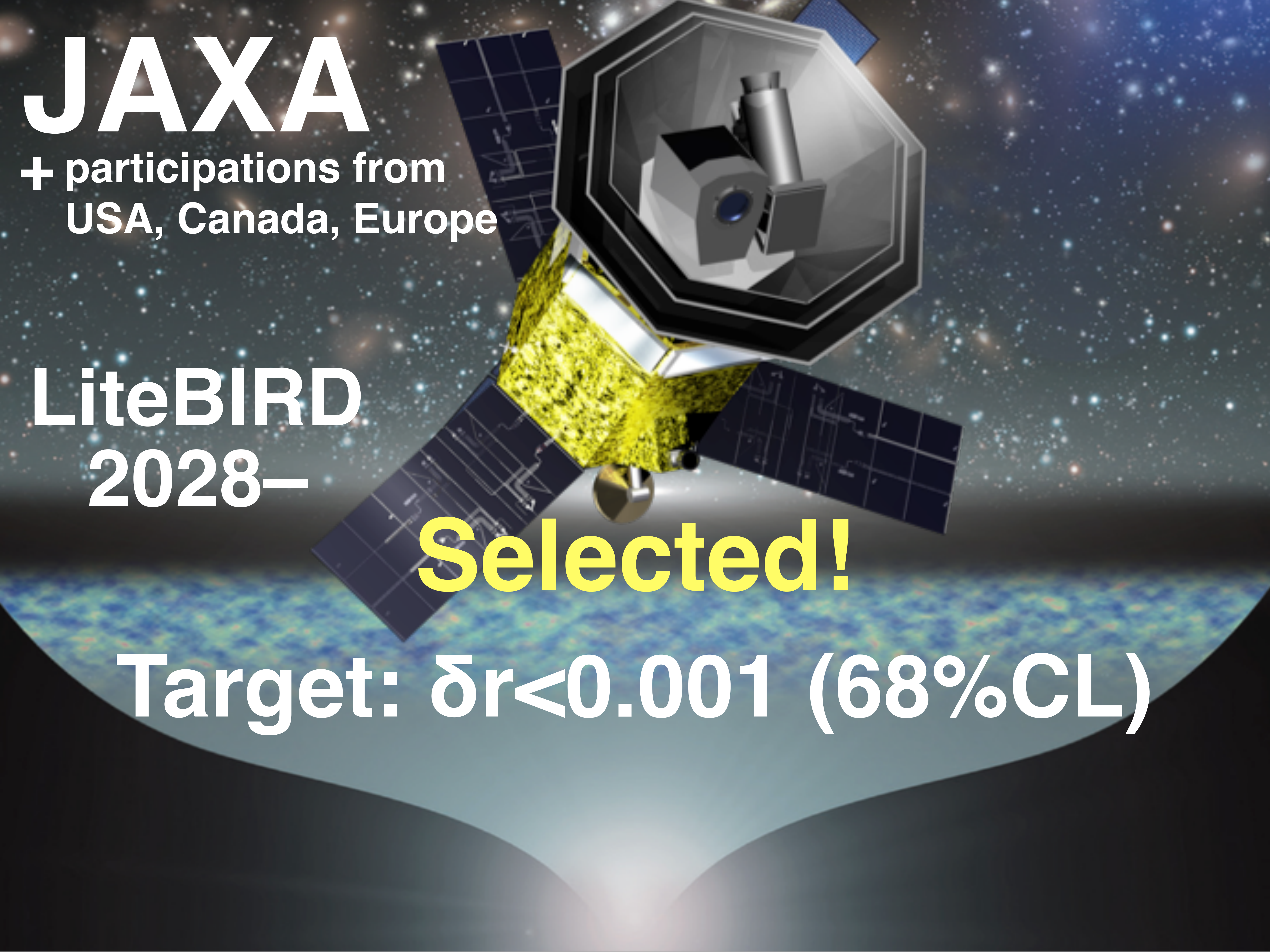
ruled out!

ruled out!

2018

$r<0.06$ (95%CL)

BICEP2/Keck Array Collaboration (2018)



JAXA

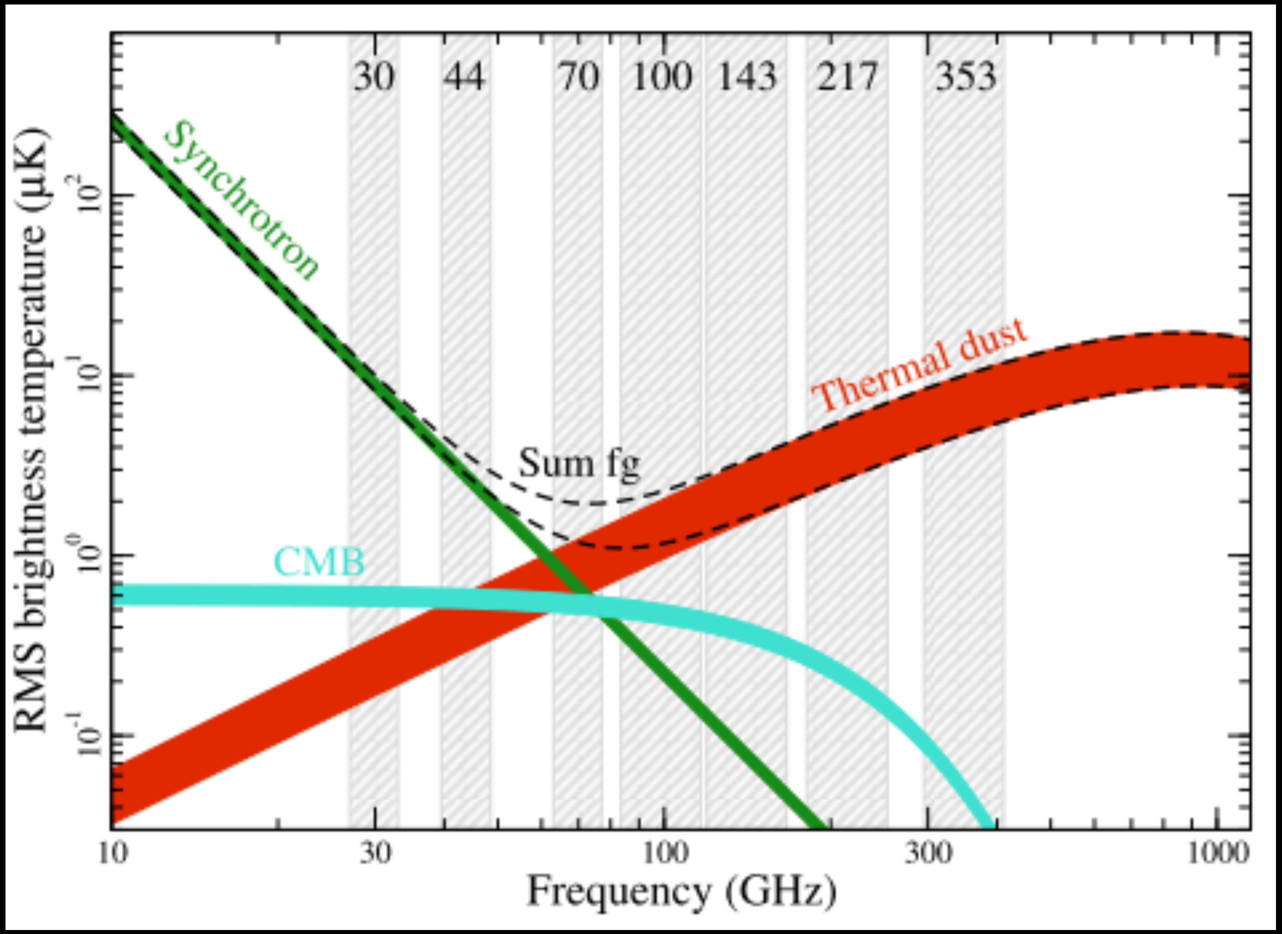
+ participations from
USA, Canada, Europe

LiteBIRD
2028–

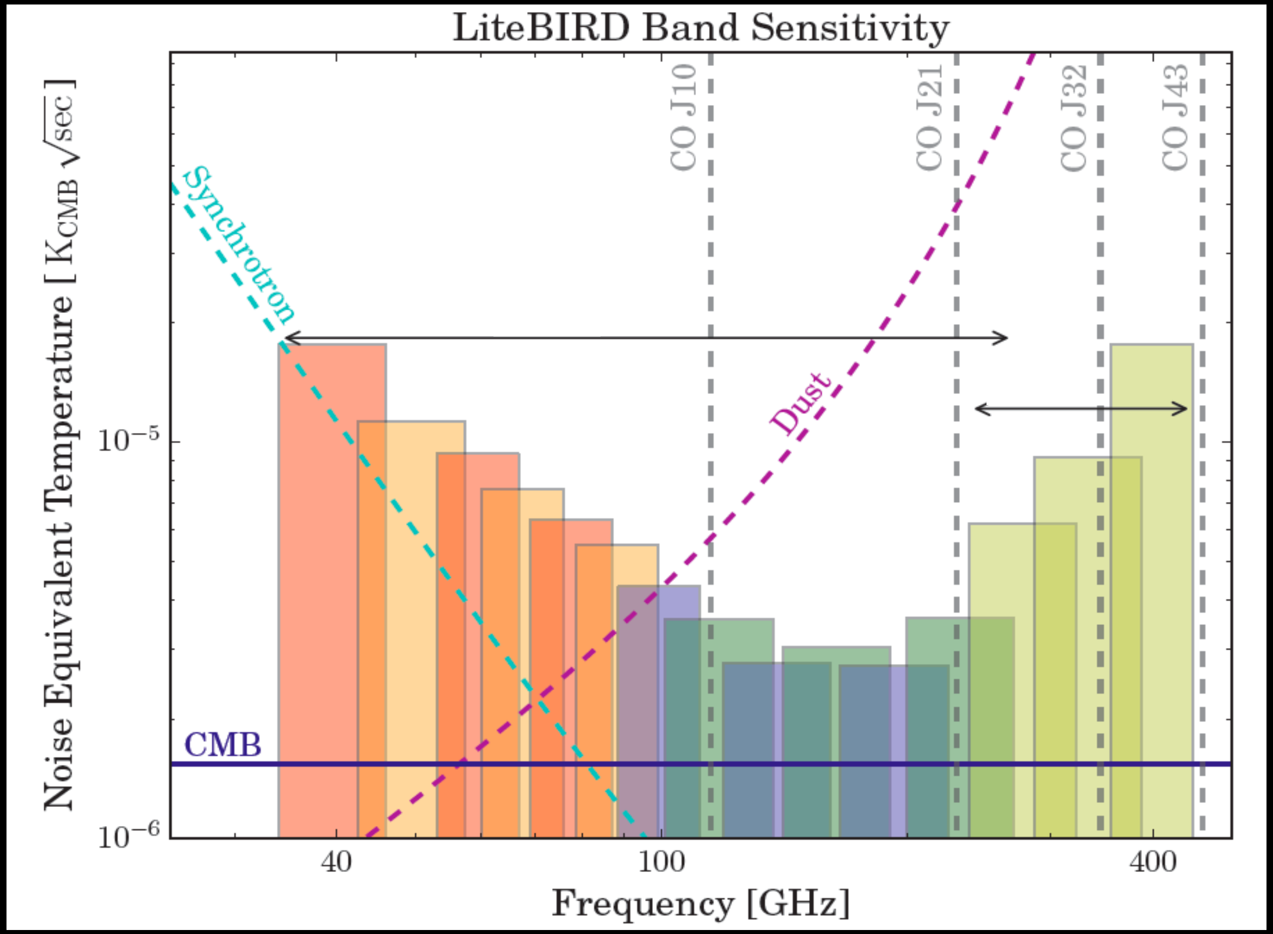
Selected!

Target: $\delta r < 0.001$ (68%CL)

Foreground Removal



Polarized galactic emission (Planck X)



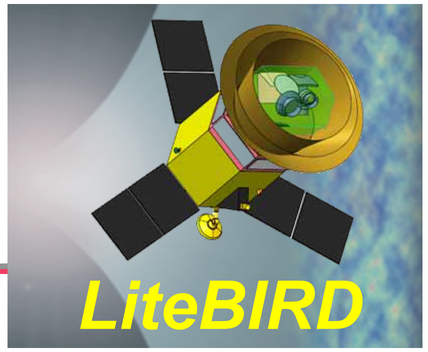
LiteBIRD: 15 frequency bands

- Polarized foregrounds
  - Synchrotron radiation and thermal emission from inter-galactic dust
  - Characterize and remove foregrounds
- 15 frequency bands between 40 GHz - 400 GHz
  - Split between Low Frequency Telescope (LFT) and High Frequency Telescope (HFT)
  - LFT: 40 GHz – 235 GHz
  - HFT: 280 GHz – 400 GHz

Slide courtesy Toki Suzuki (Berkeley)

Slide courtesy Yutaro Sekimoto (ISAS/JAXA)

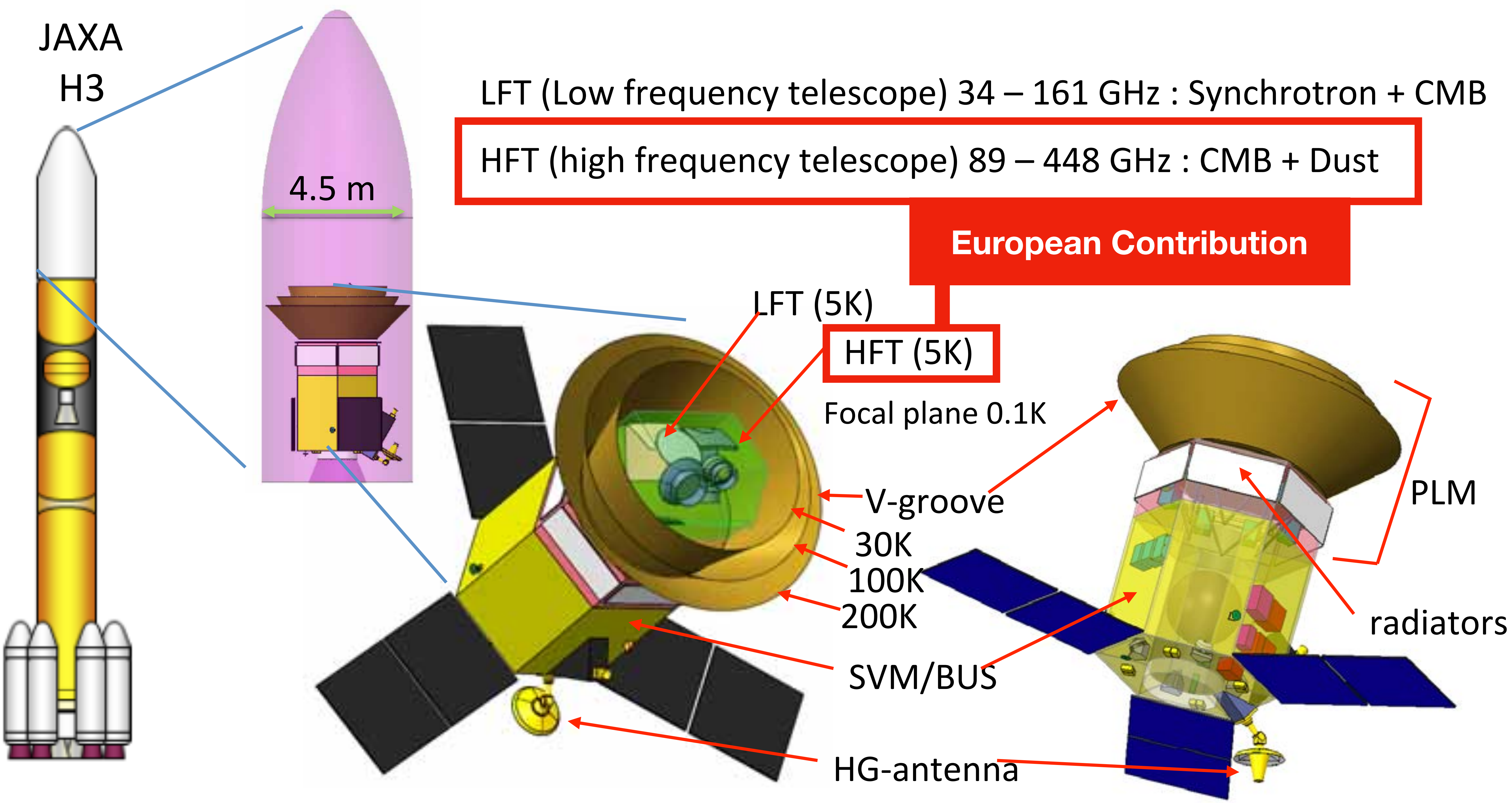
LiteBIRD Spacecraft



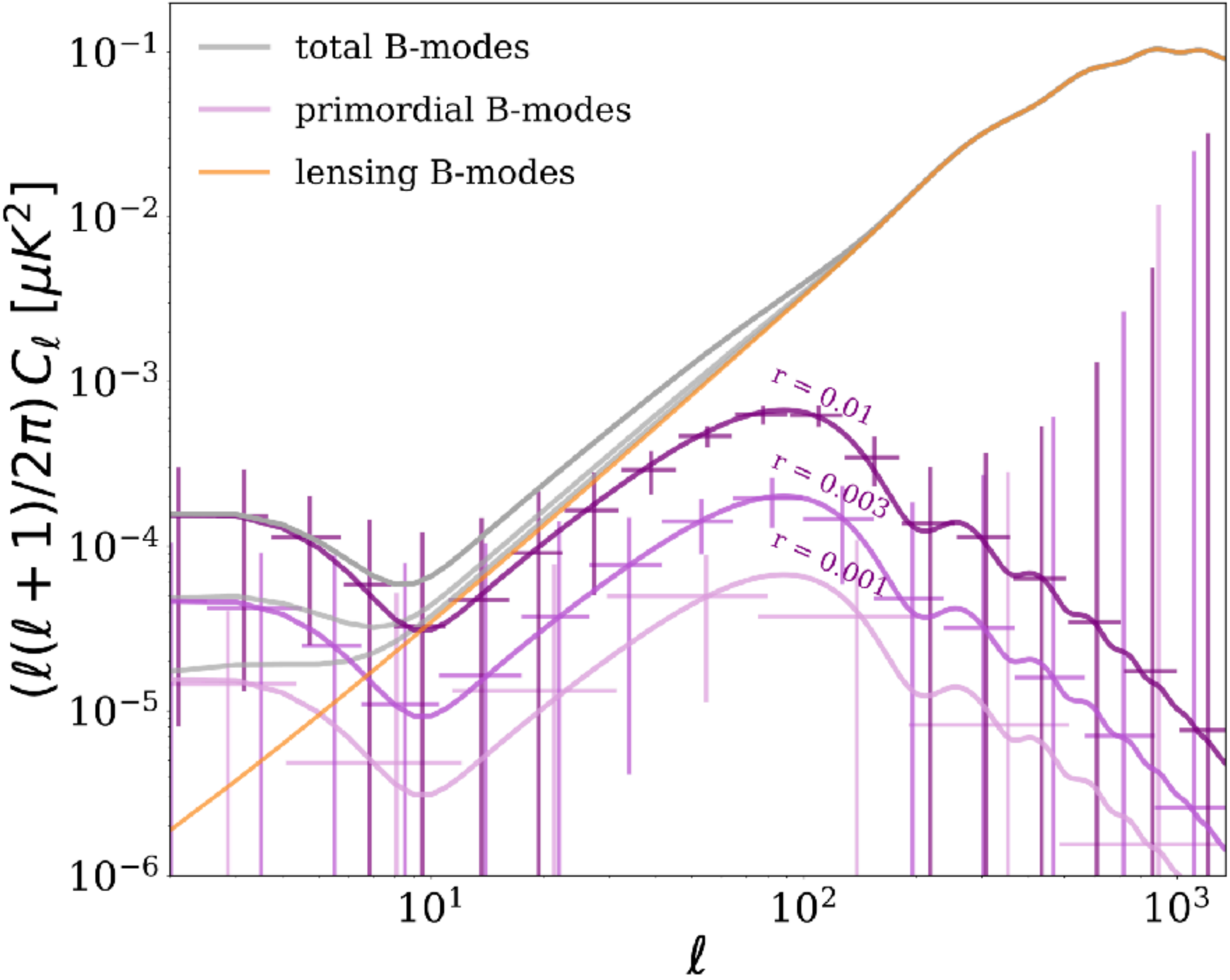
LFT (Low frequency telescope) 34 – 161 GHz : Synchrotron + CMB

HFT (high frequency telescope) 89 – 448 GHz : CMB + Dust

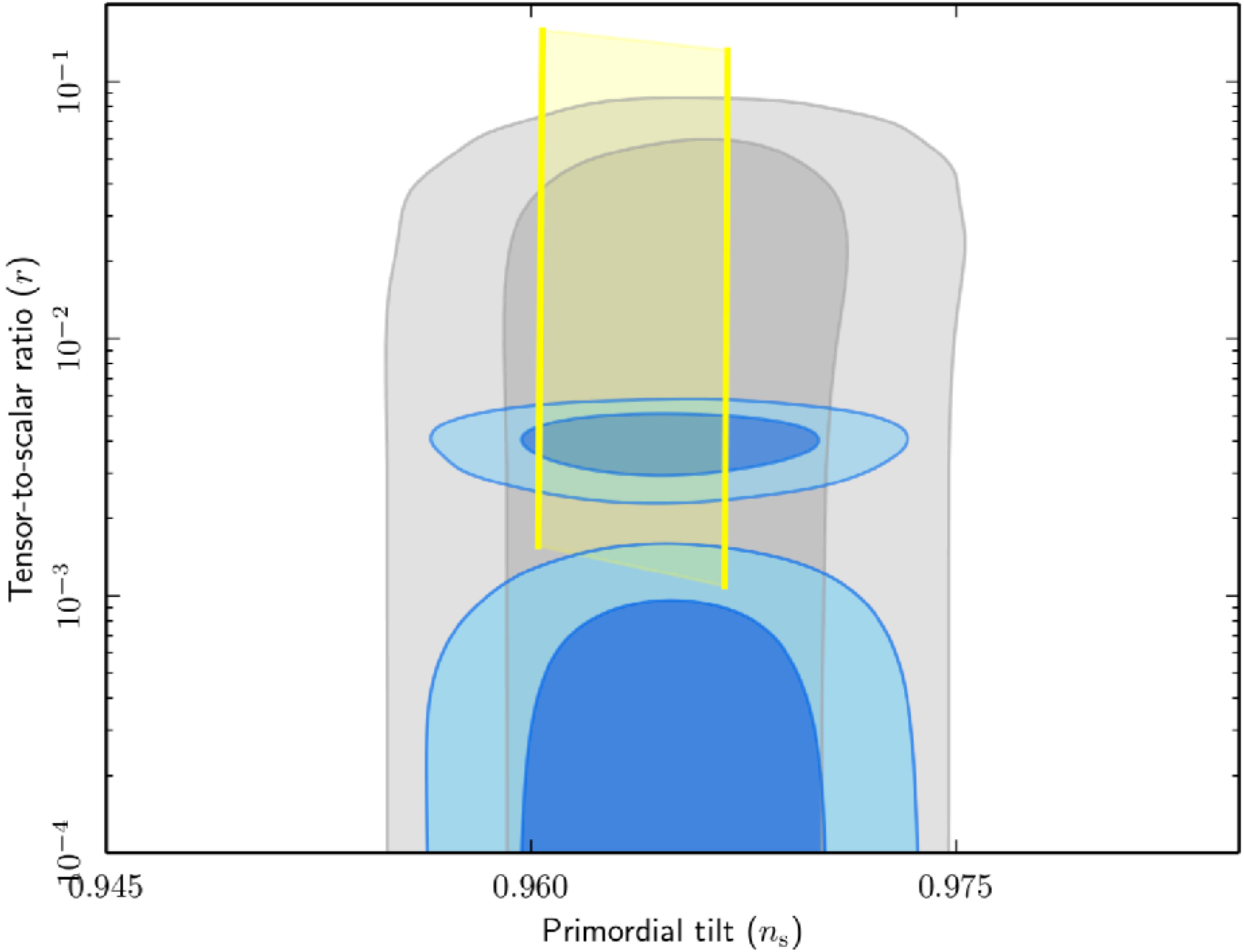
European Contribution



LiteBIRD Collaboration



LiteBIRD Collaboration

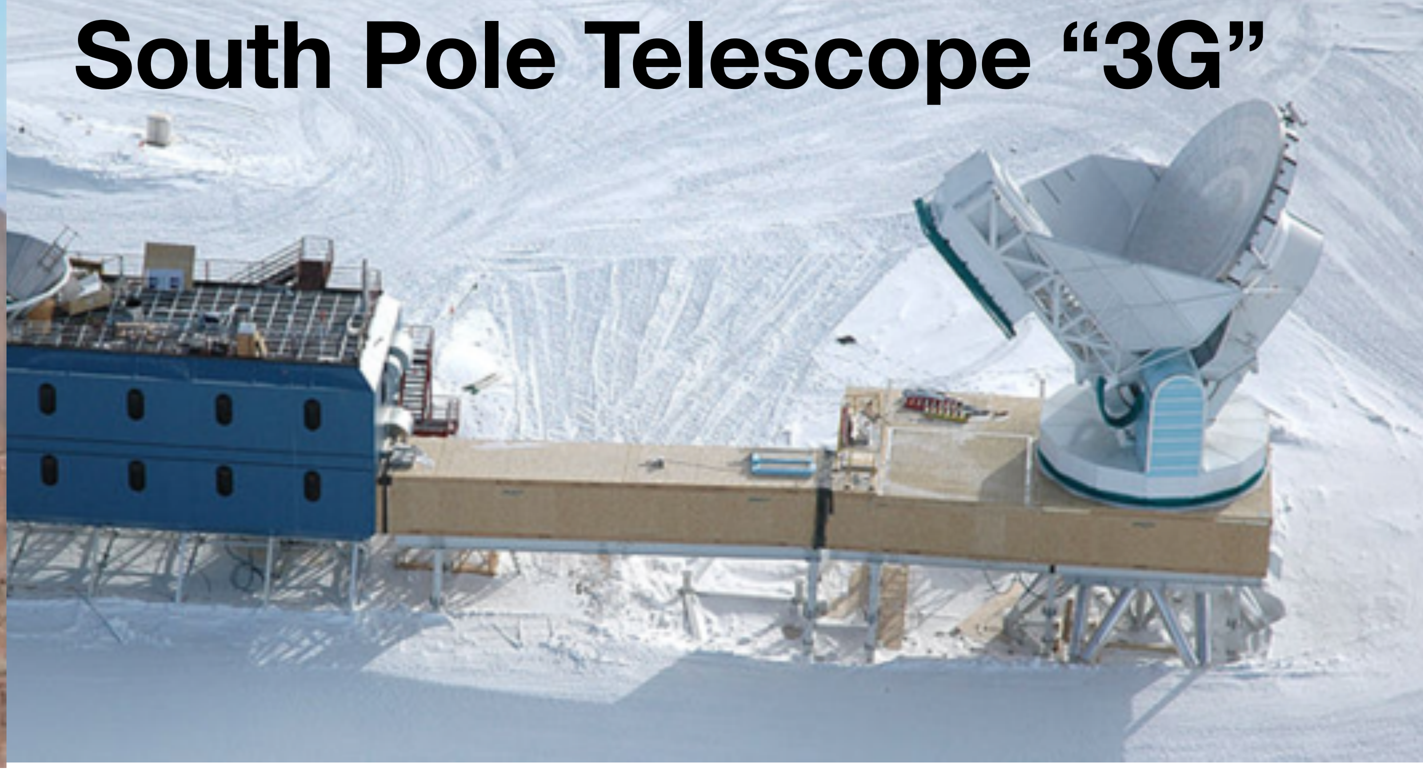


Summary

- Inflation looks pretty good: passed all the tests using the scalar (density) perturbation
- **Next frontier**: Using CMB polarisation to find GWs from inflation. **Critical test of the physics of inflation!**
  - With *LiteBIRD* we plan to reach $r \sim 10^{-3}$, i.e., 100 times better than the current bound

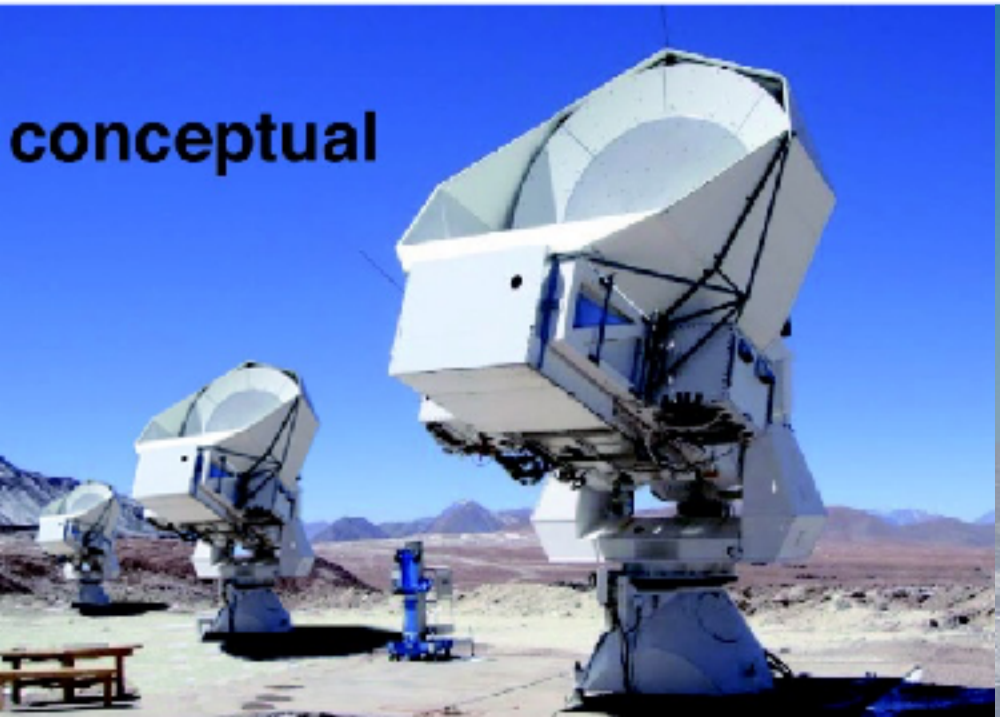
Ground-based Experiments


Advanced Atacama Cosmology Telescope

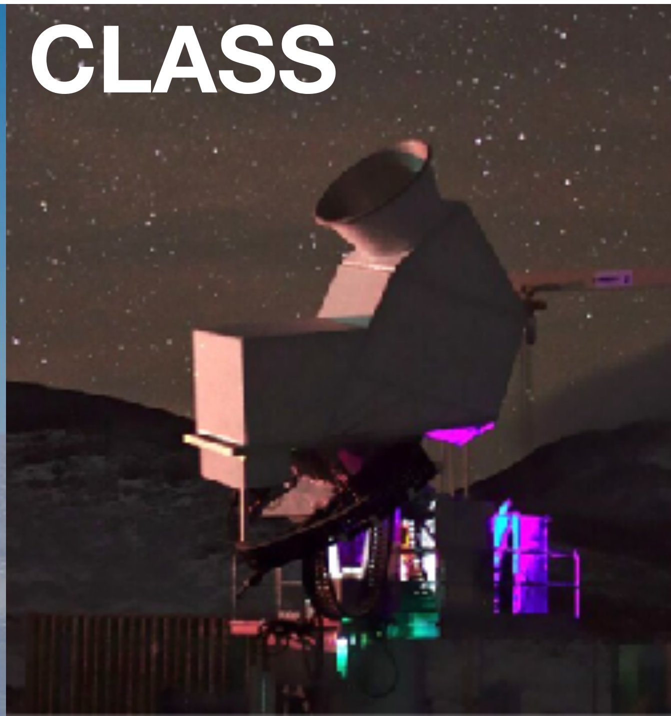

South Pole Telescope “3G”

What comes next?

The Simons Array


conceptual

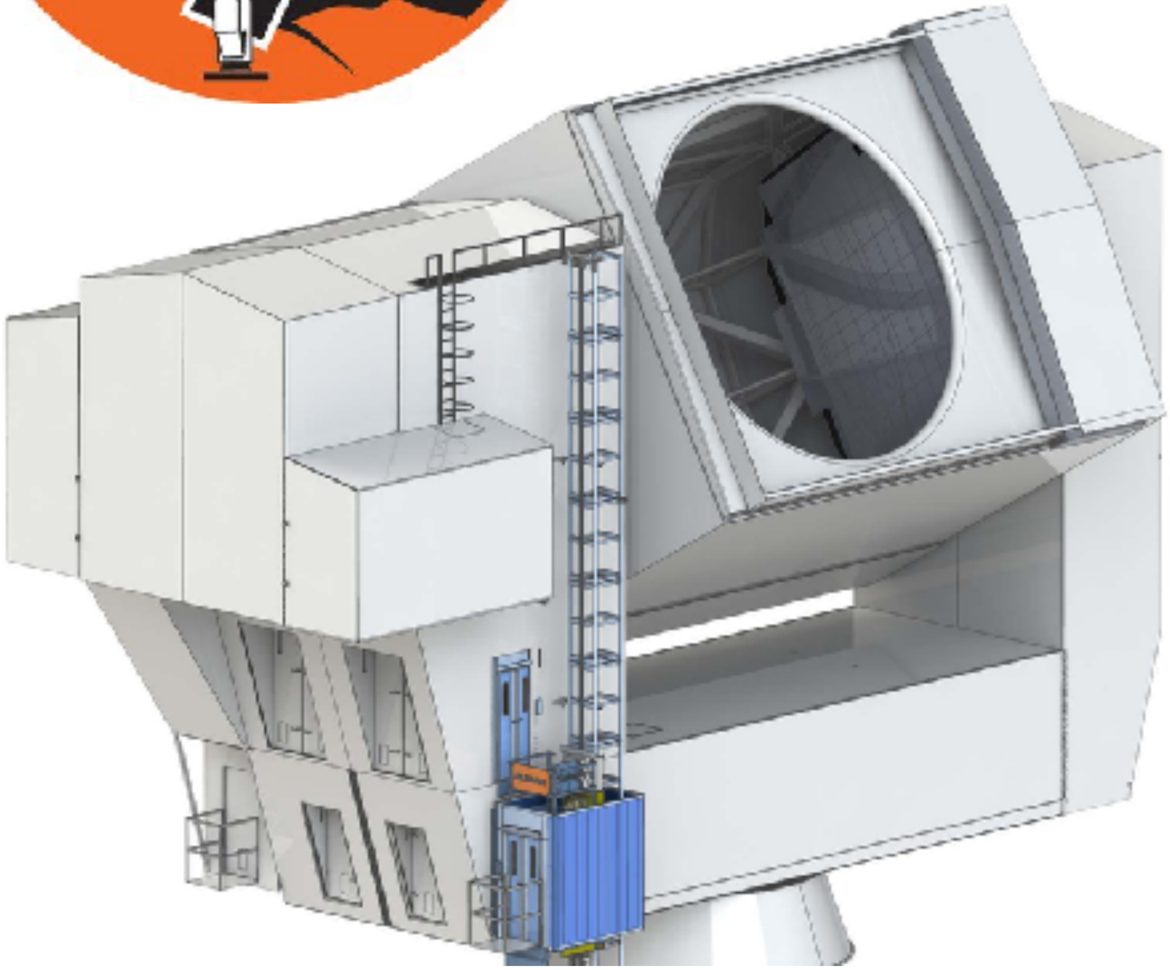

BICEP/Keck Array


CLASS

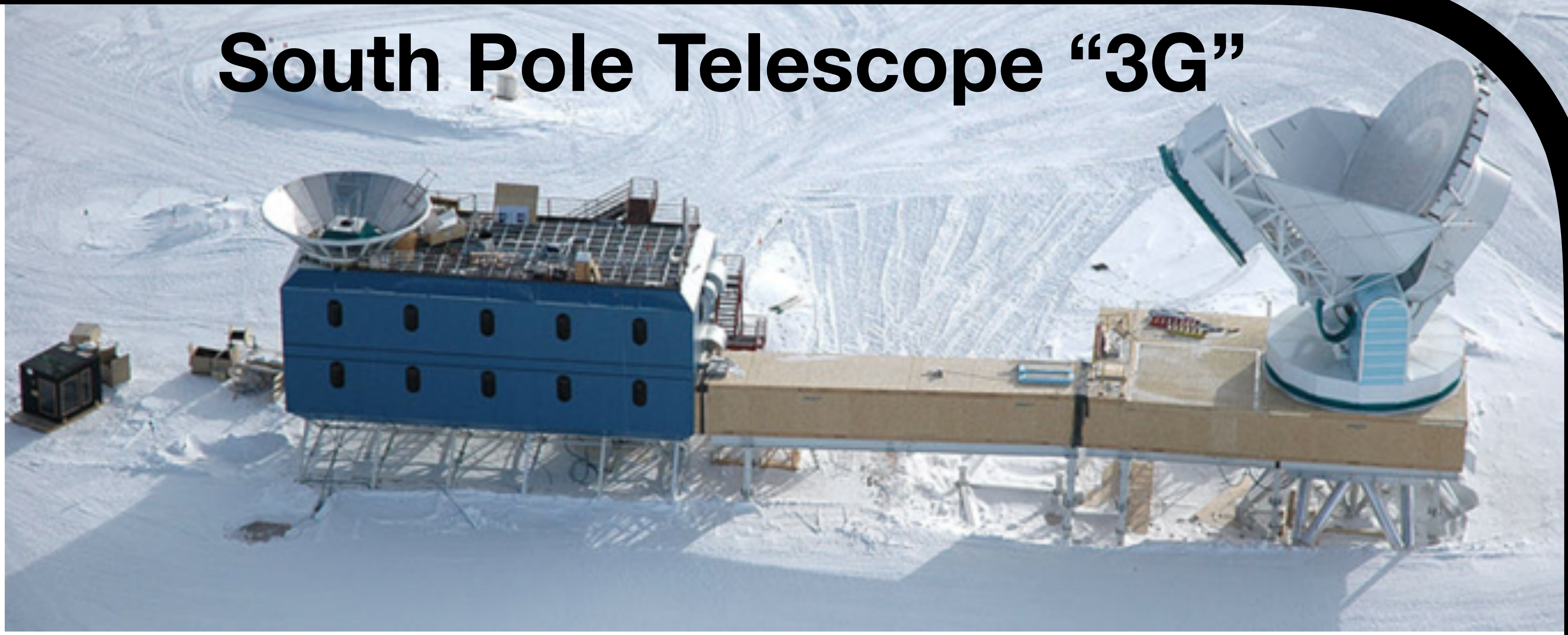
Advanced Atacama Cosmology Telescope

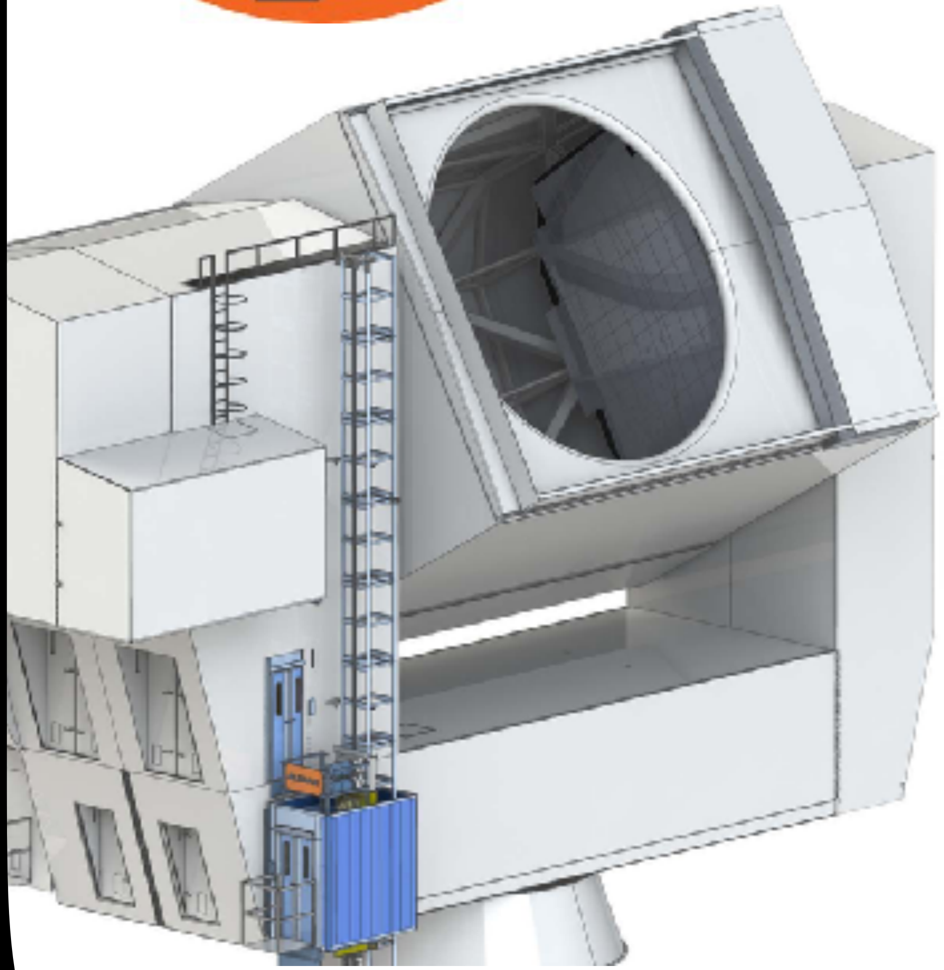
The Simons Array

SIMONS OBSERVATORY



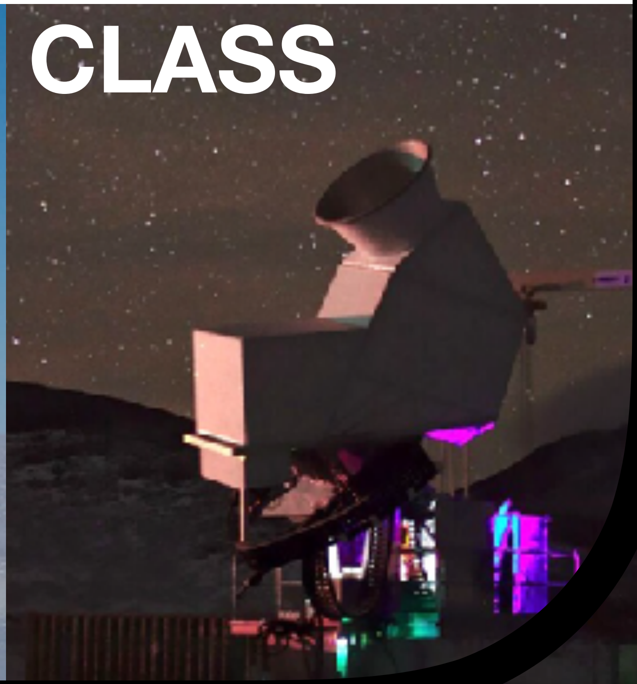
SIMONS
OBSERVATORY


South Pole Telescope “3G”



CMB-S4(?)


BICEP/Keck Array


CLASS

The Biggest Enemy: Polarised Dust Emission

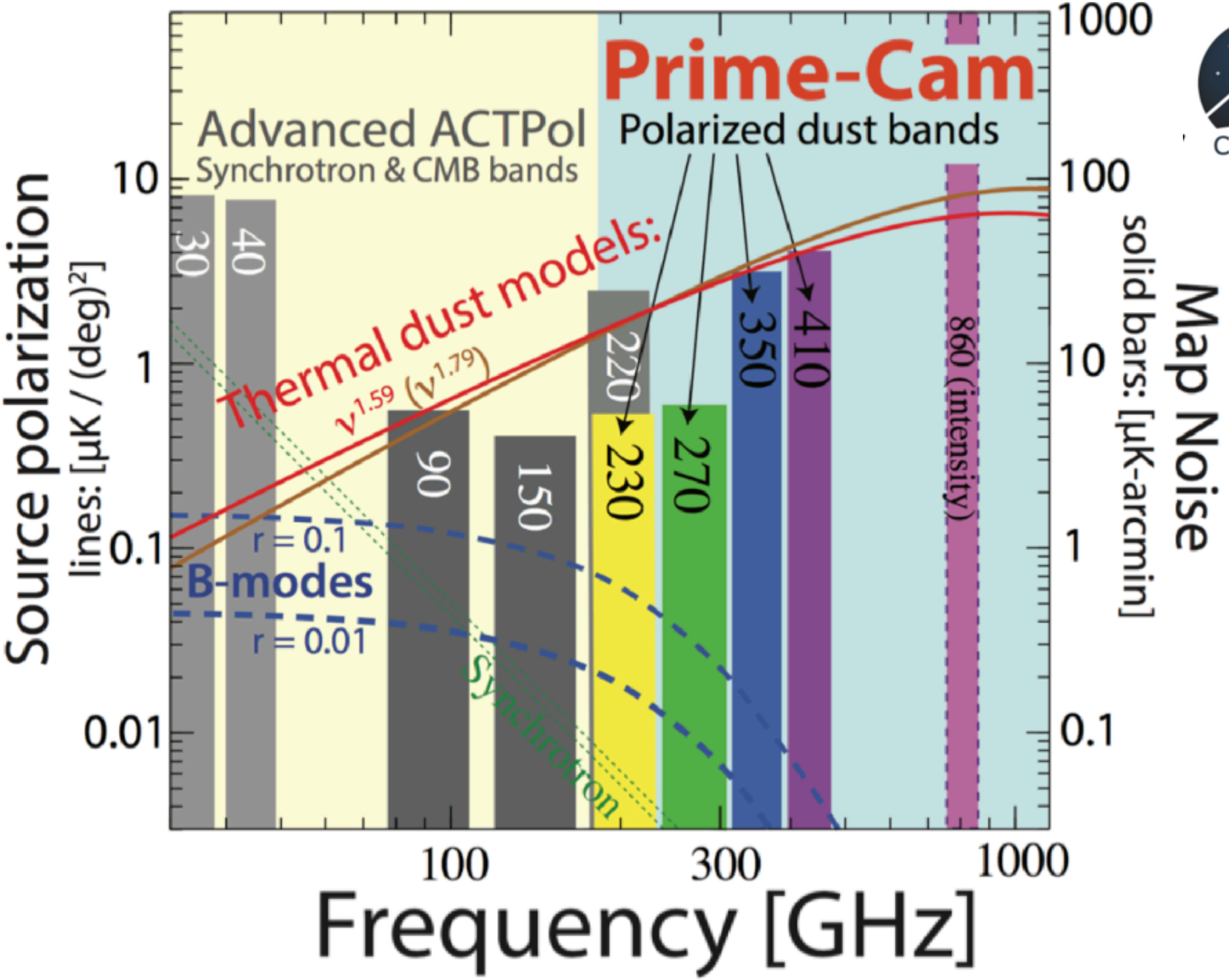
- The upcoming data will **NOT** be limited by statistics, but by systematic effects such as the Galactic contamination

- **Solution**: Observe the sky at multiple frequencies, especially at high frequencies (>300 GHz)

- This is challenging, unless we have a superb, high-altitude site with low water vapour

- CCAT-p!

CCAT-p Collaboration



CCAT-p

Frank Bertoldi's slide from the Florence meeting

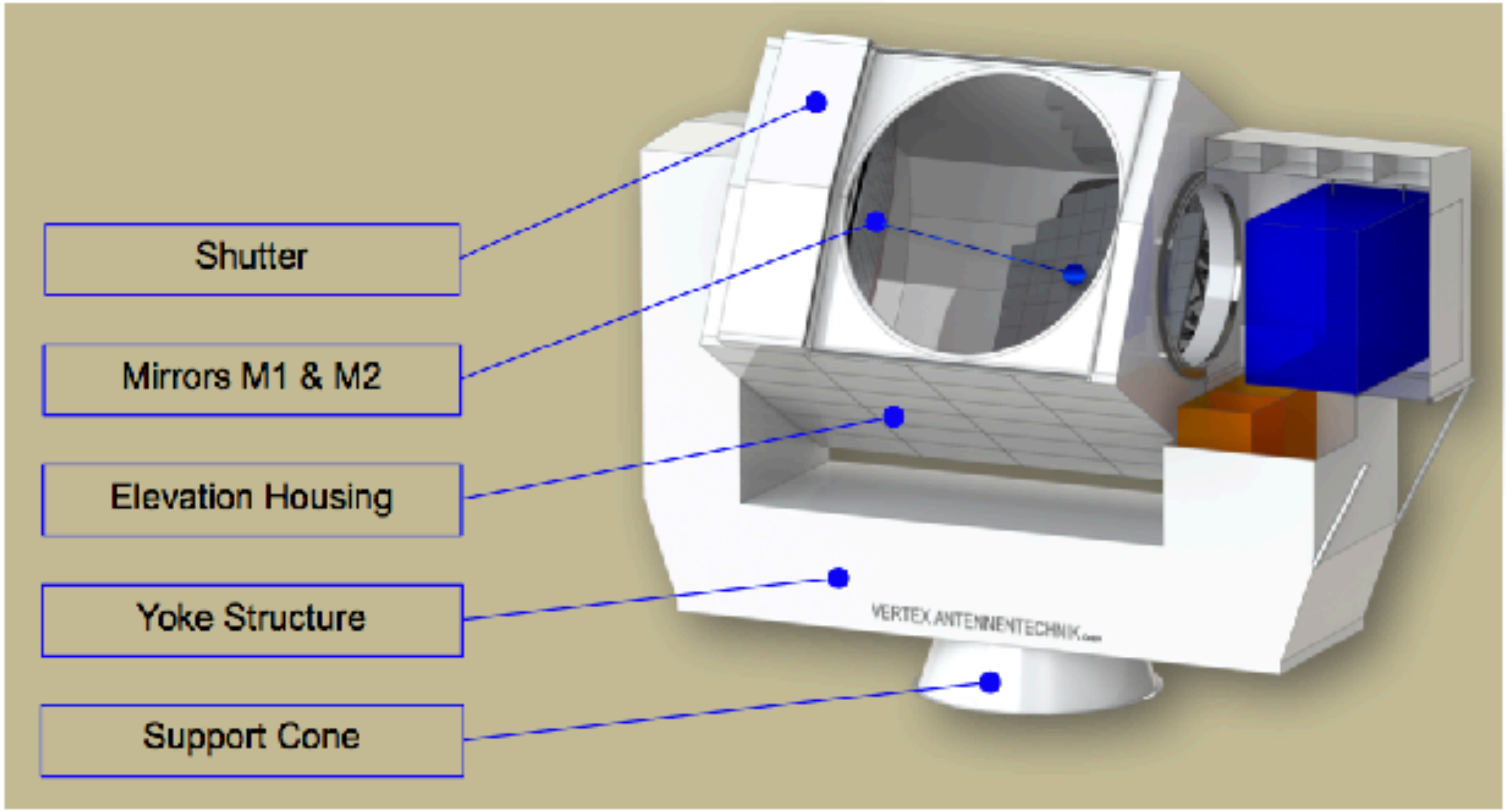
Where is CCAT-p?

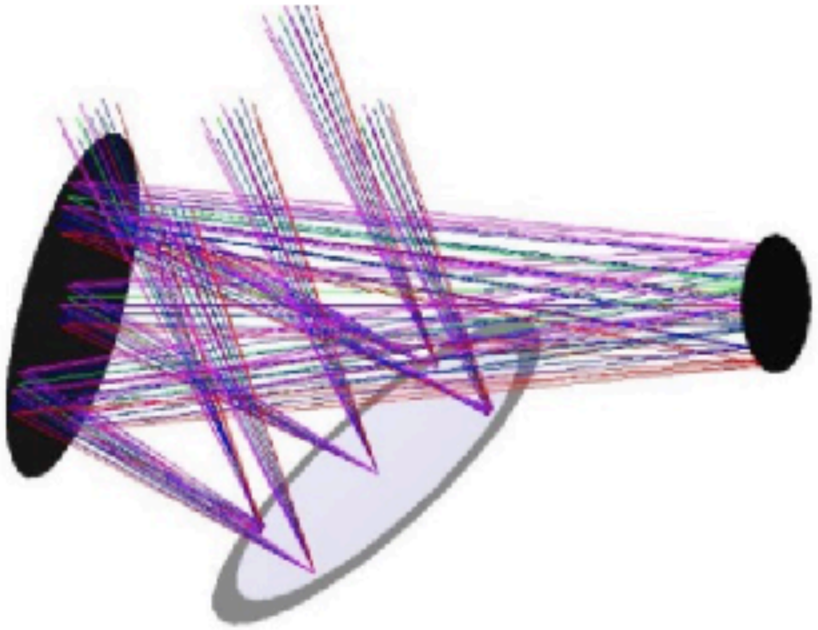
Cerro Chajnantor at 5600 m w/ TAO

Frank Bertoldi's slide from the Florence meeting

What is CCAT-p?

CCAT-prime is a high surface accuracy / throughput 6 m submm (0.3-3mm) telescope





Cornell U. + German consortium + Canadian consortium + …

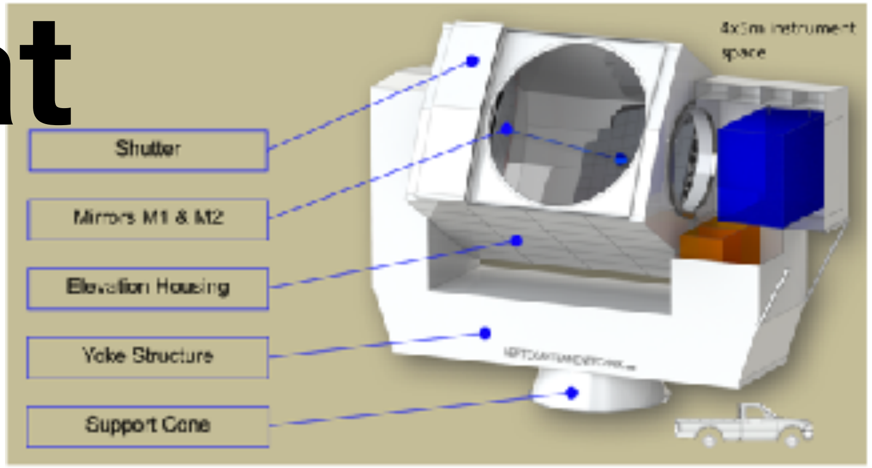
A Game Changer

- **CCAT-p**: 6-m, **Cross-dragone** design, on Cerro Chajnantor (5600 m)

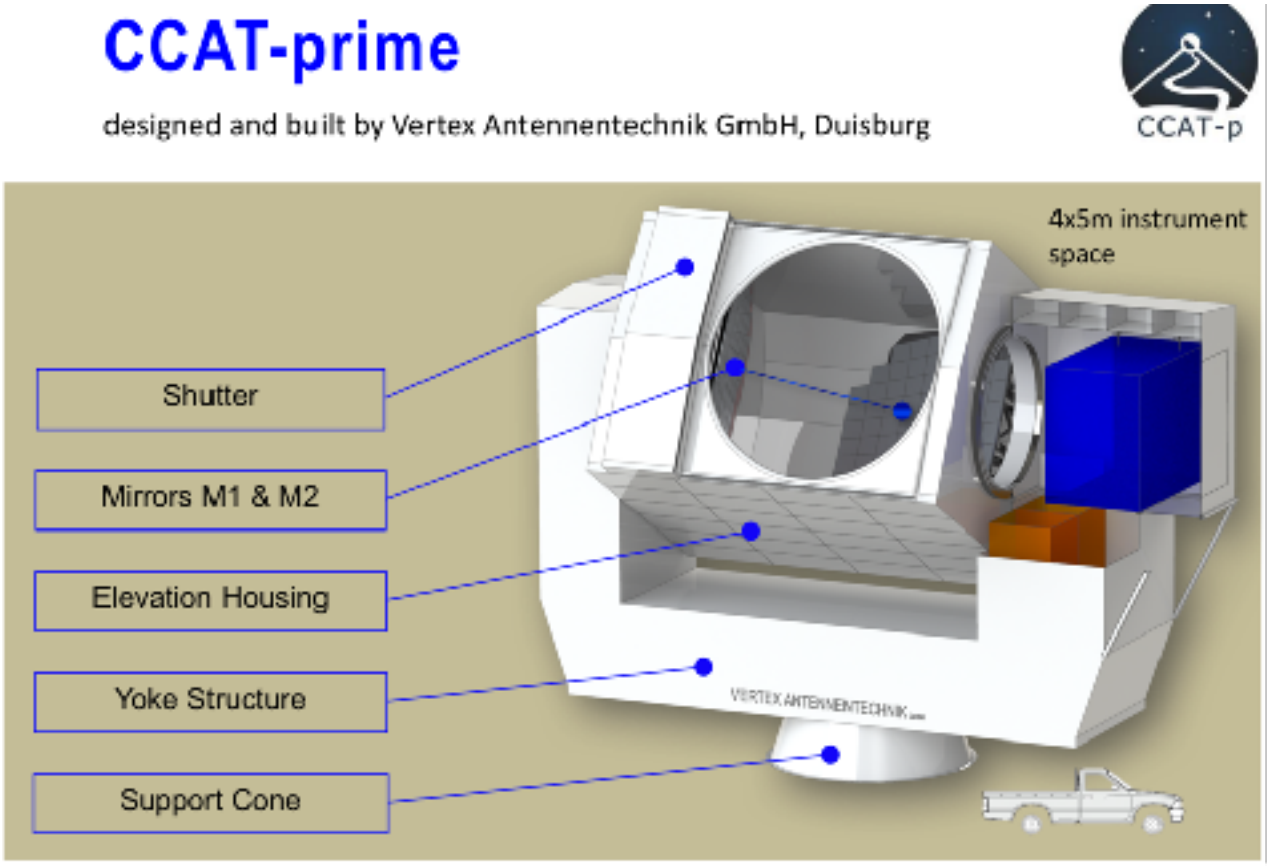
- **Germany makes great telescopes!**

CCAT-prime

designed and built by Vertex Antennentechnik GmbH, Duisburg

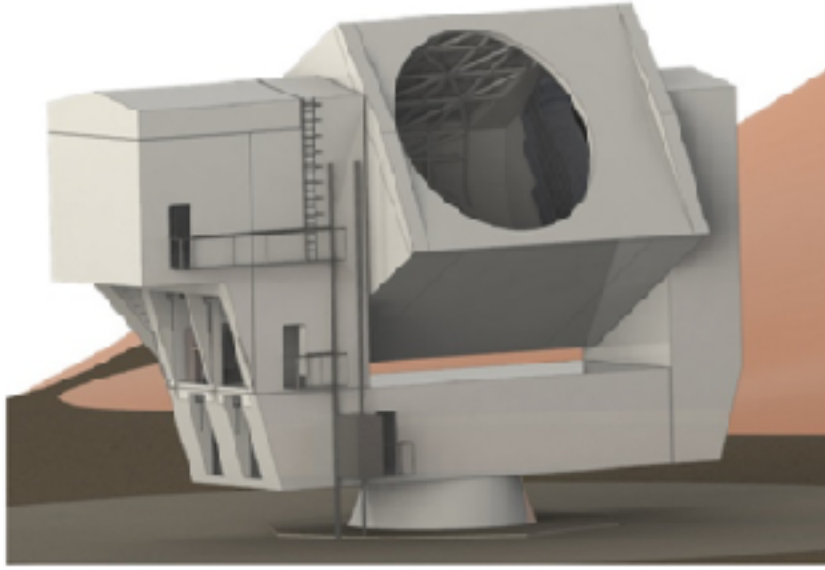


- Design study completed, and the contract has been signed by "VERTEX Antennentechnik GmbH"
  - CCAT-p is a great opportunity for Germany to make <u>significant contributions</u> towards the CMB S-4 landscape (both US and Europe) by providing telescope designs and the "lessons learned" with prototypes.



CCAT-prime

designed and built by Vertex Antennentechnik GmbH, Duisburg



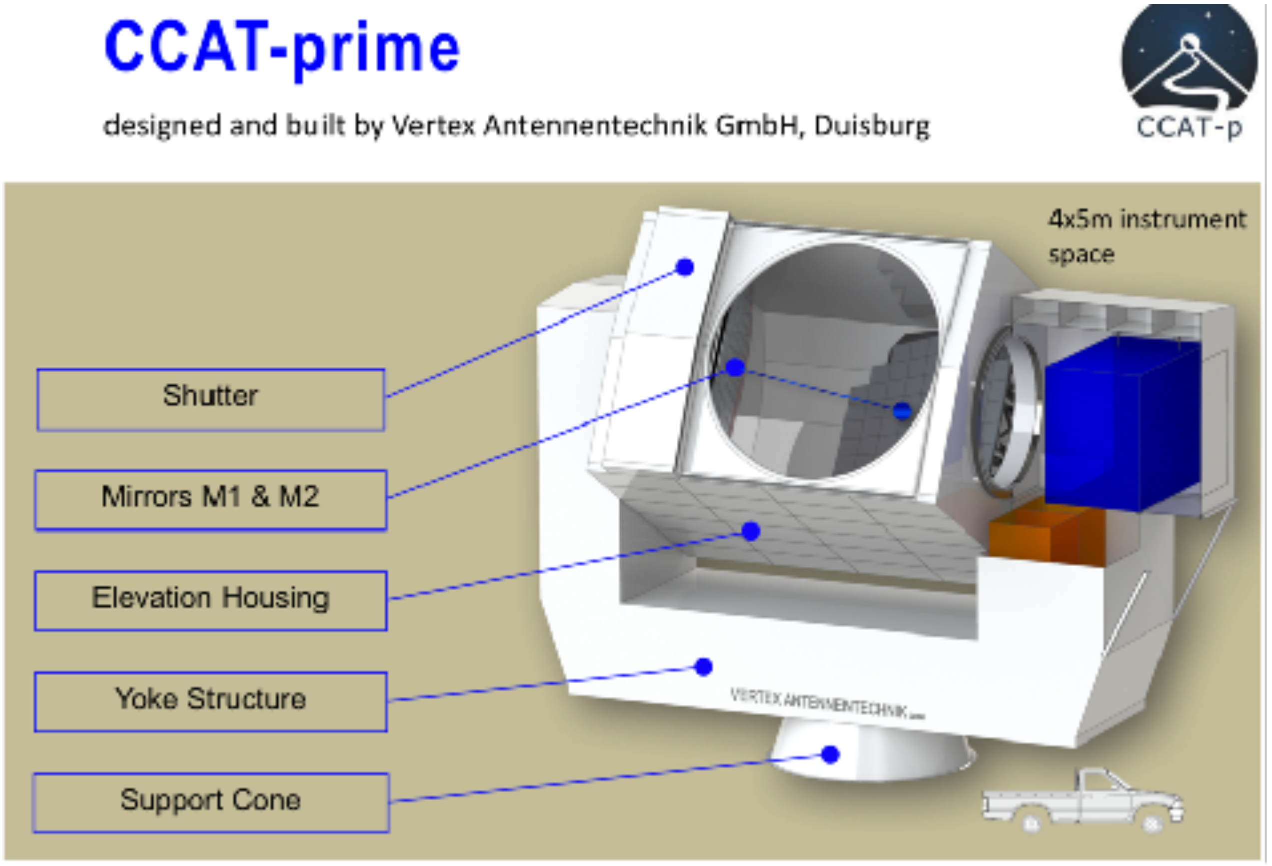
A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

Simons Observatory (USA)

in collaboration

South Pole?

This could be “CMB-S4”



CCAT-prime

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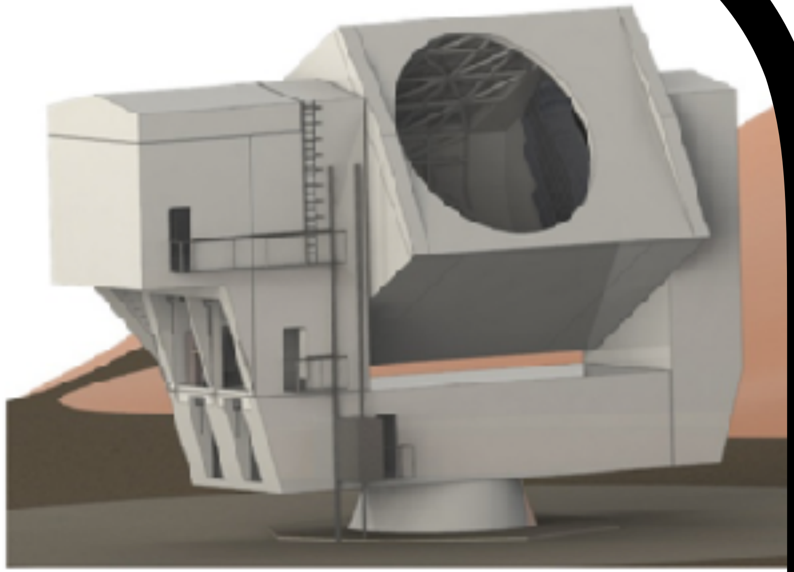

A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

Simons Observatory (USA)

in collaboration

South Pole?

But, wait a minute…

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

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

- **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); …

Final Remark

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

- We have ignored the source term during inflation, and considered only the vacuum fluctuation. Is this justified? **Maybe not!**

- *Further reading:*
  - B. Thorne et al., Phys. Rev. D, 97, 043506 (2018), arXiv: 1707.03240
  - A. Agrawal et al., Phys. Rev. D, 97, 103526 (2018), arXiv: 1707.03023
  - A. Maleknejad & E. Komatsu, JHEP, 05, 174 (2019), arXiv: 1808.09076

Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Effect of π_{ij}