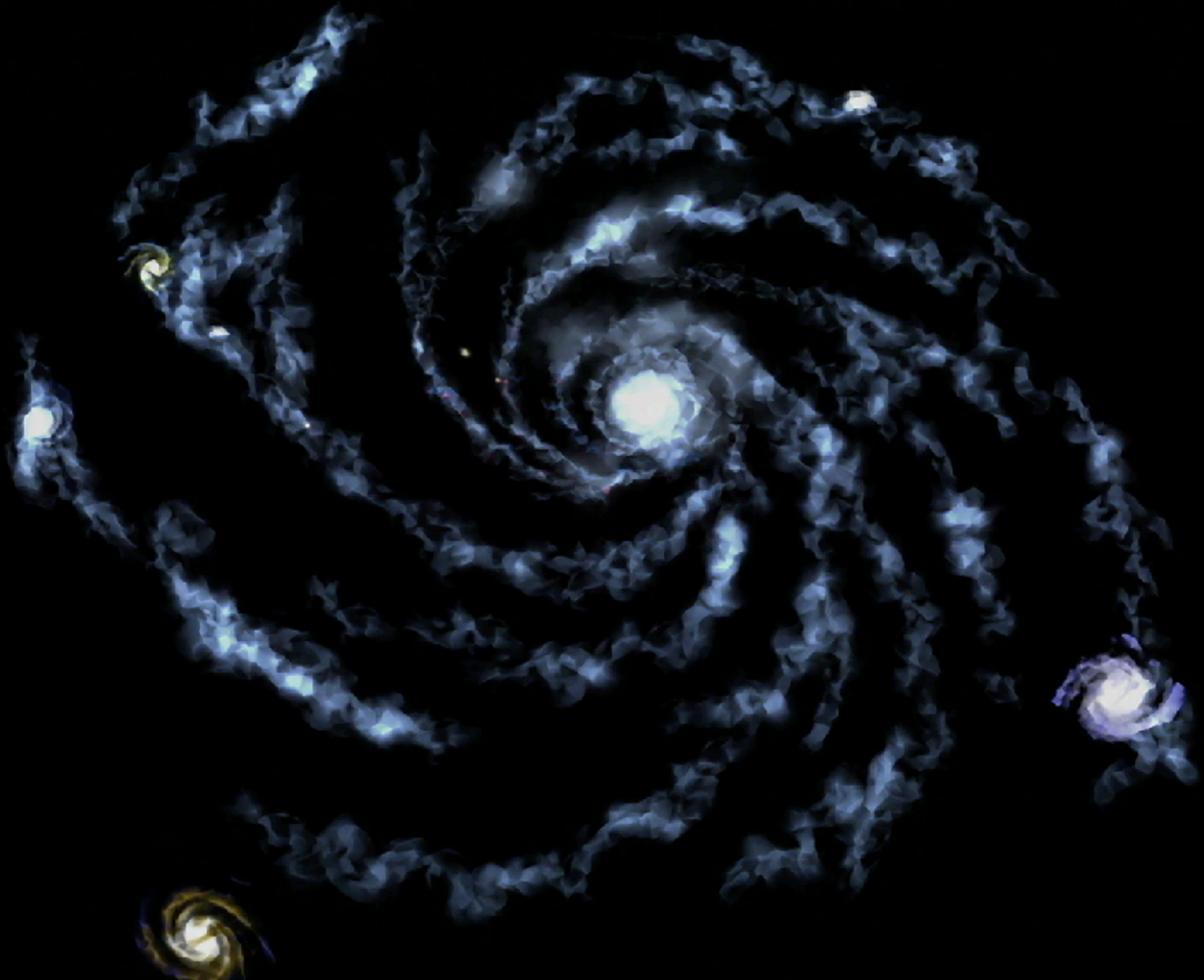
Finding Cosmic Inflation

Eiichiro Komatsu (MPI für Astrophysik)

100 Year Anniversary of the MPI für Physik

October 10, 2017



One-page Summary of My Talk

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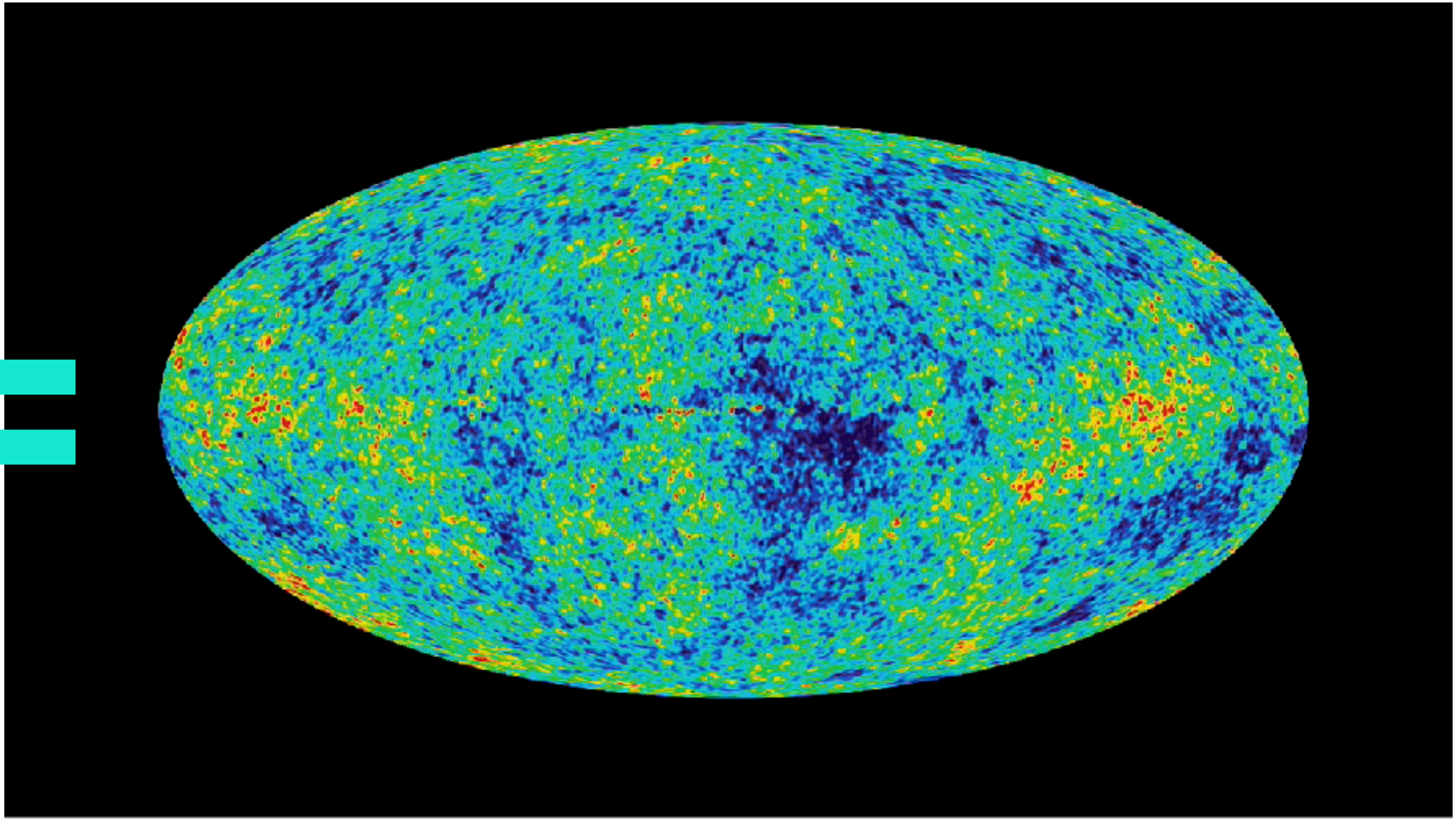


A Remarkable Story

- 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?***

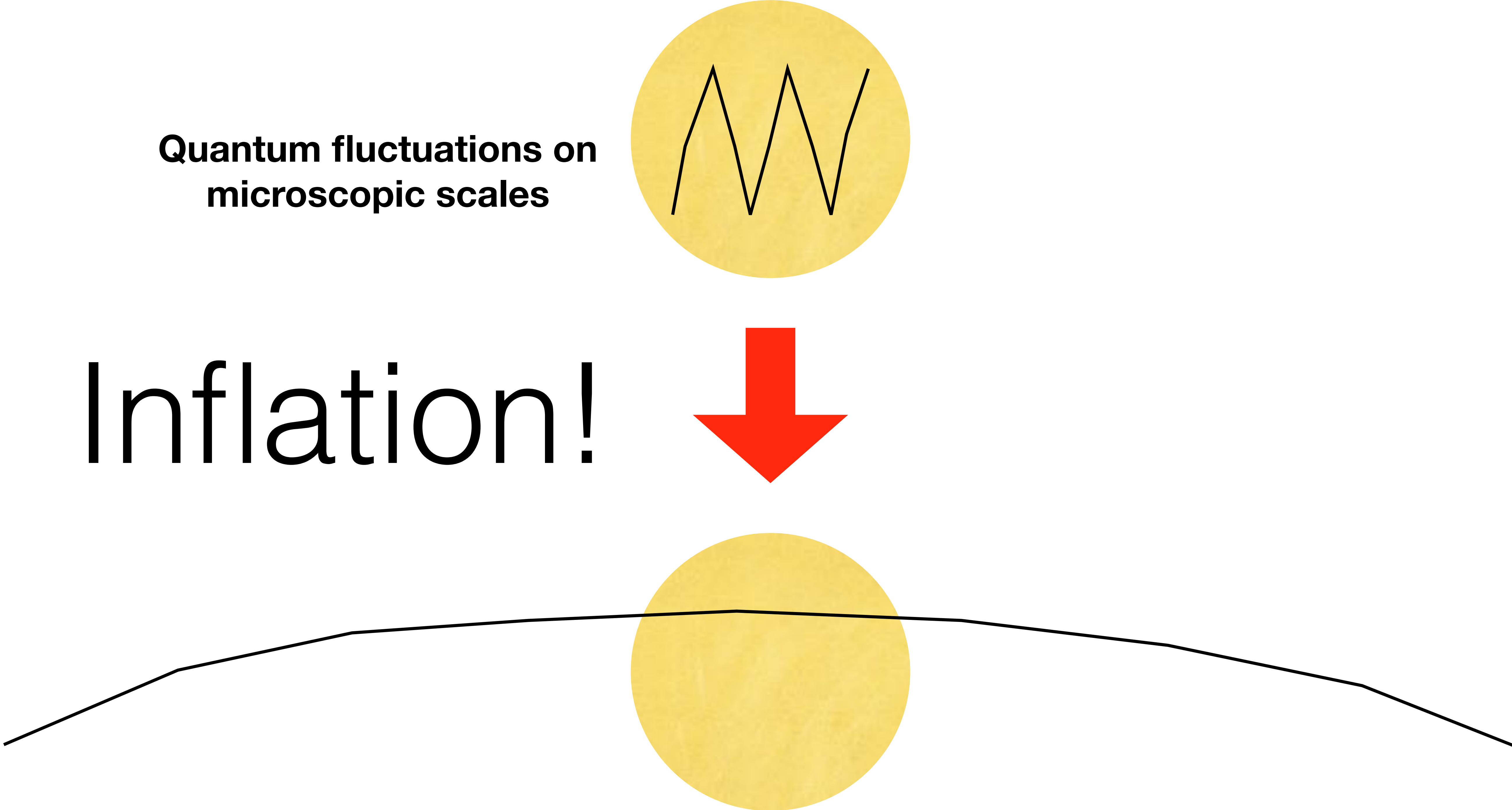
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

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?

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

Cosmic Inflation



Quantum fluctuations on microscopic scales

Inflation!

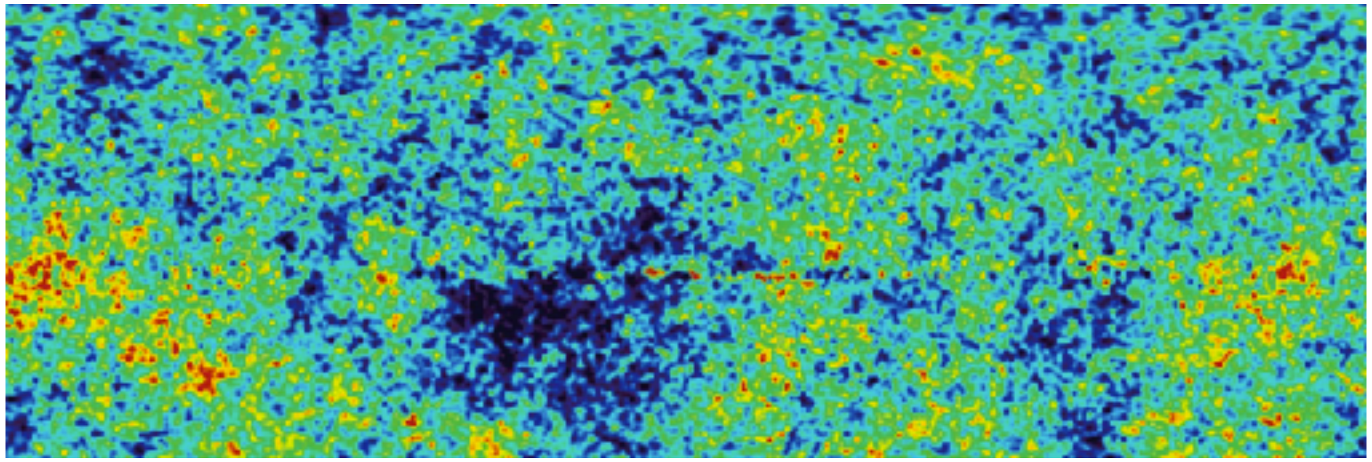
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

Key Predictions

ζ

scalar mode

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



h_{ij}

tensor mode

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

Starobinsky (1979)

We measure distortions in space

- A distance between two points in space

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

- **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

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

We measure distortions in space

- A distance between two points in space

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

- **ζ** : “curvature perturbation” (scalar mode)
  - Perturbation to the determinant of the spatial metric
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  - 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 **$H(t)=d\ln(a)/dt$**, 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**

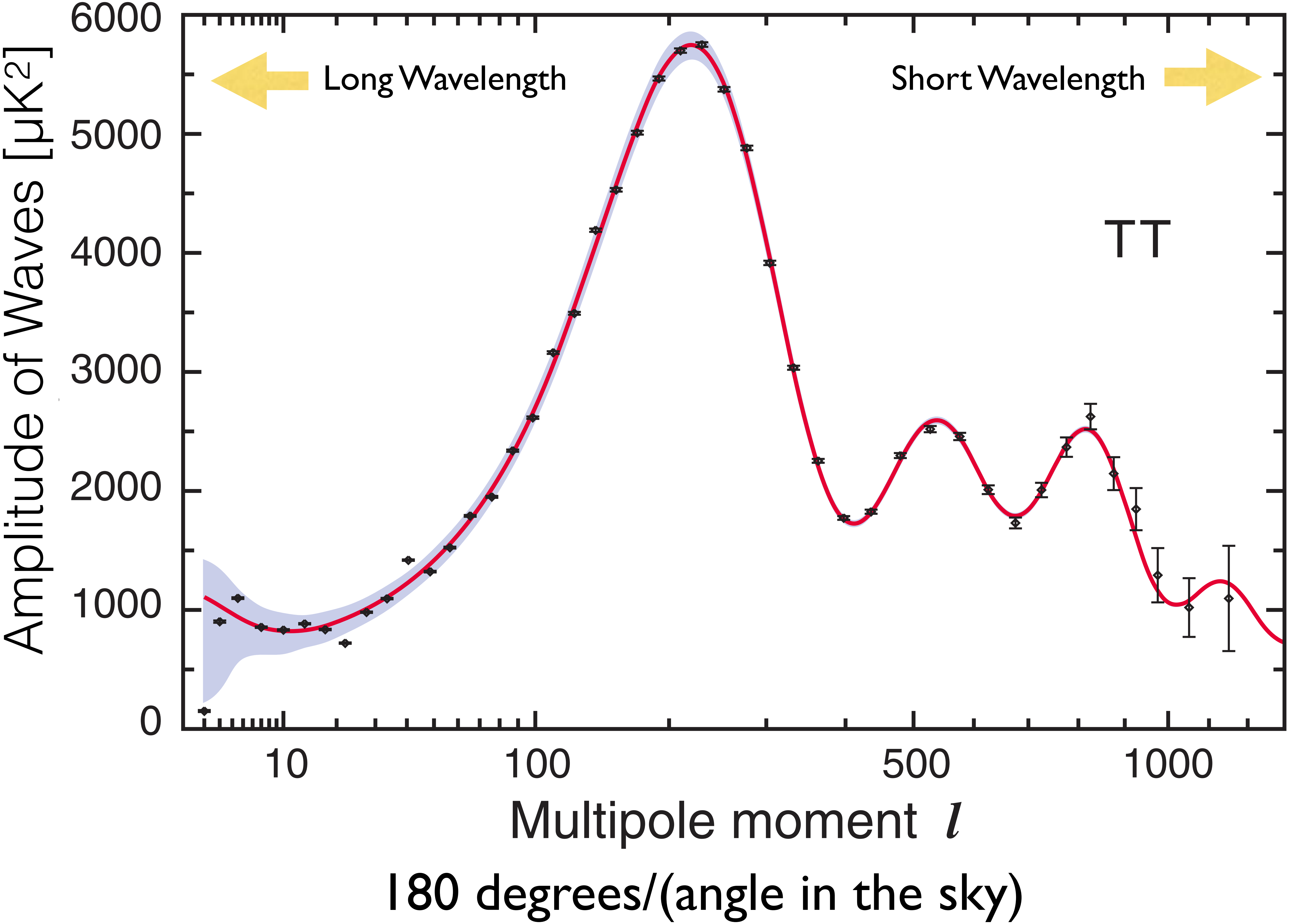
    1. We want to show that the amplitude of CMB fluctuations does not depend very much on angles

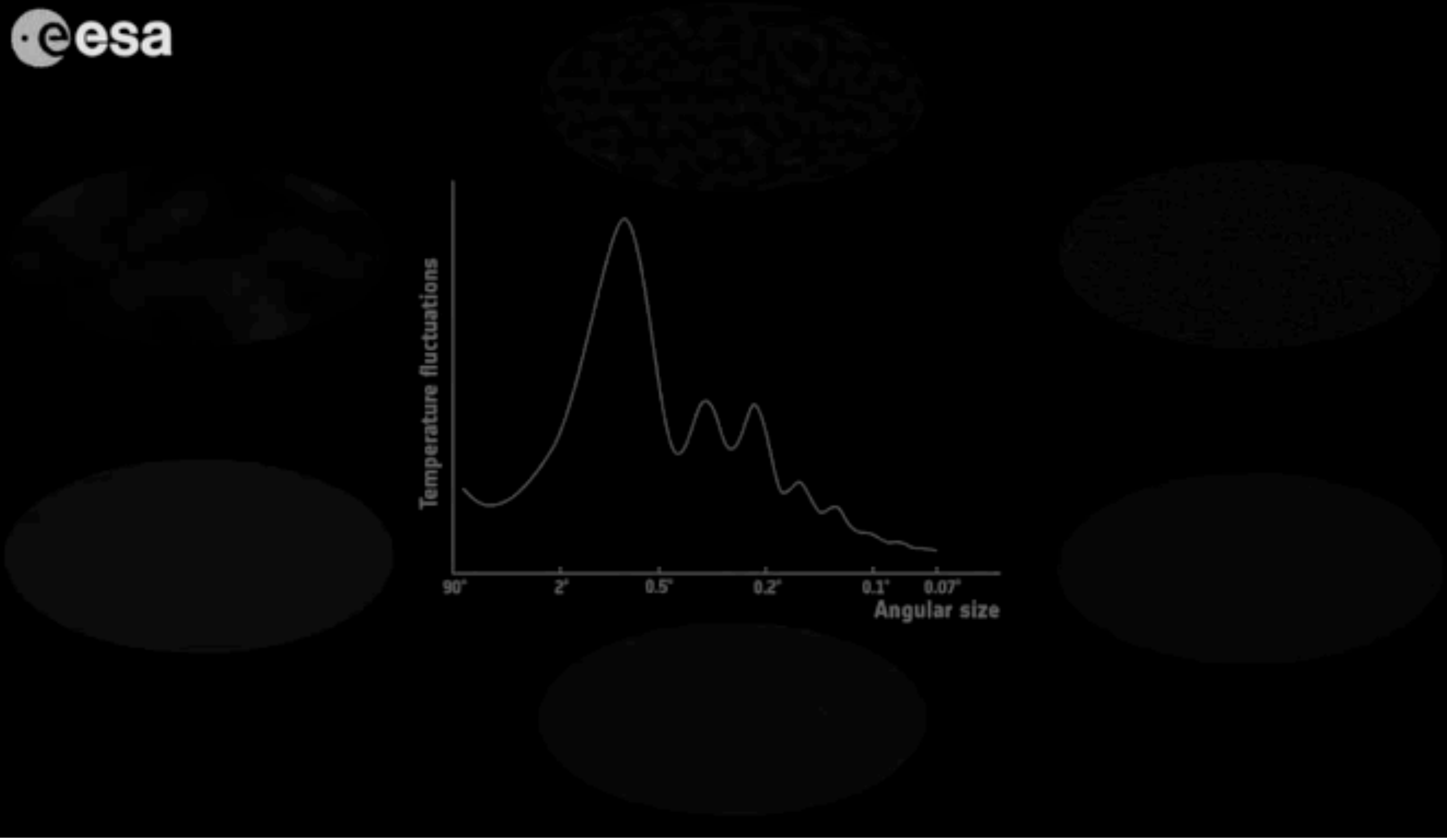
    2. Moreover, since inflation must end, H would be a decreasing function of time. It would be fantastic to show that the amplitude of CMB fluctuations actually DOES depend on angles such that the small scale has ***slightly*** smaller power

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

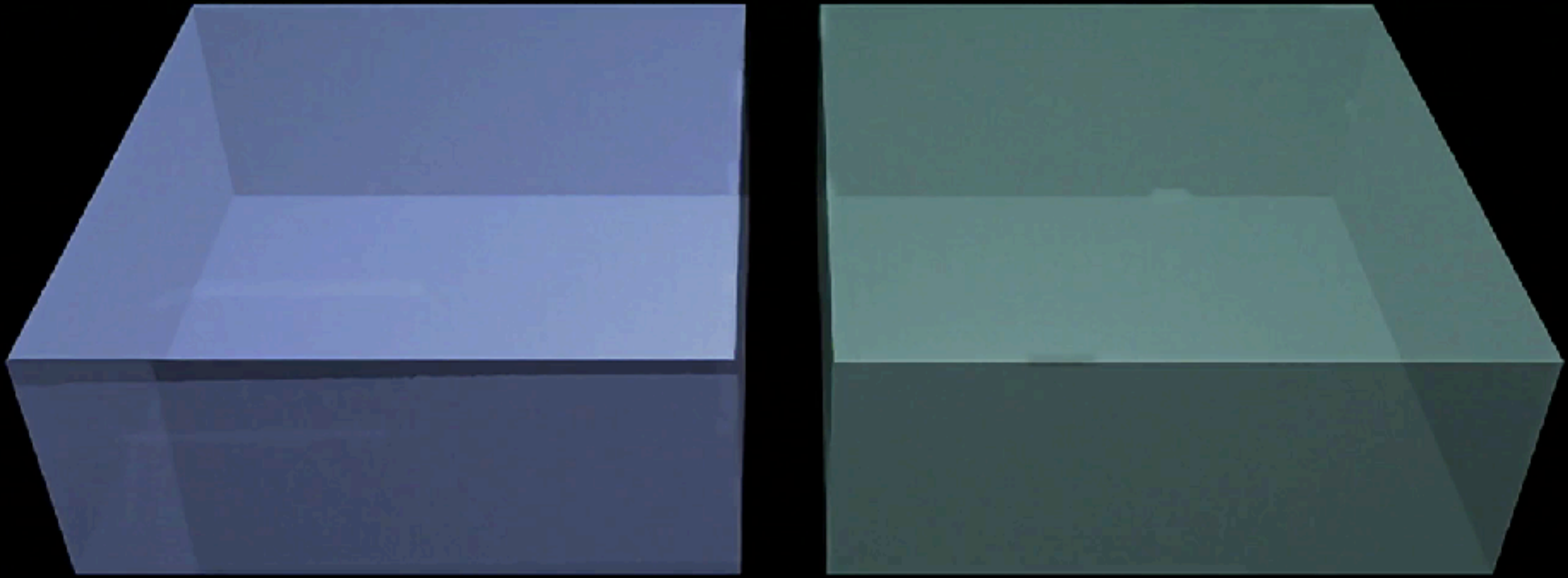
WMAP Collaboration



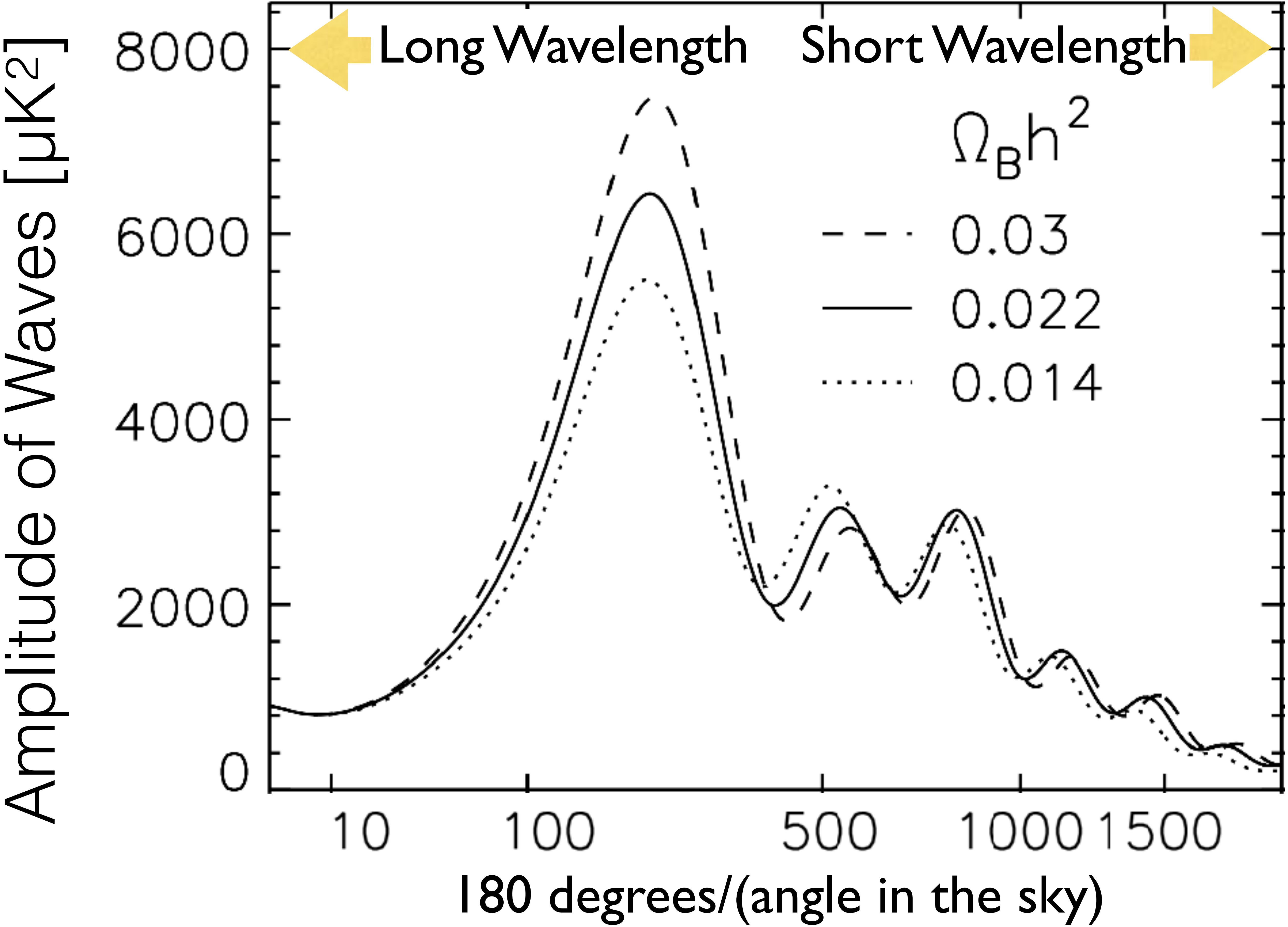

Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size

Kosmische Miso Suppe

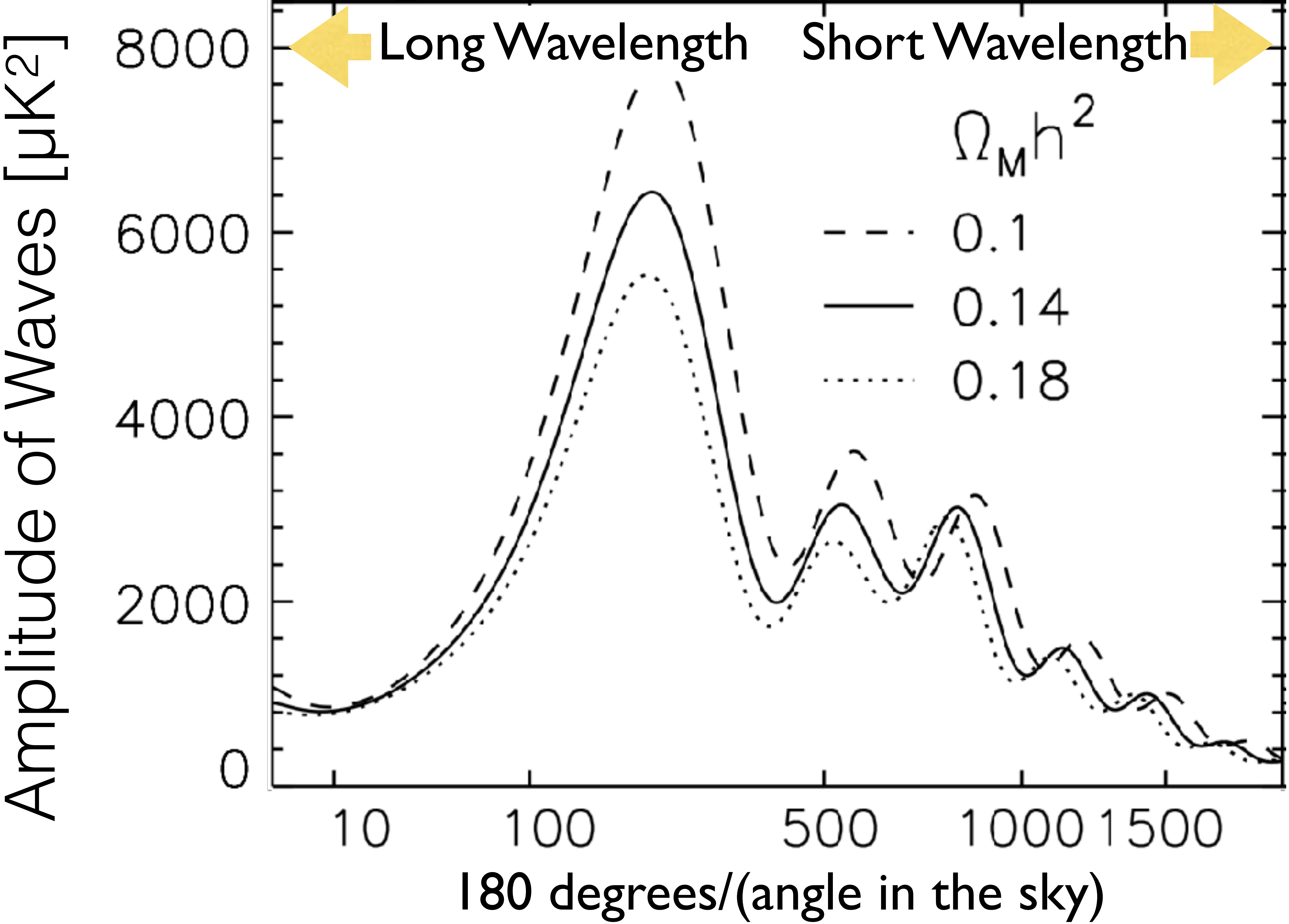
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching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



Measuring Abundance of H&He

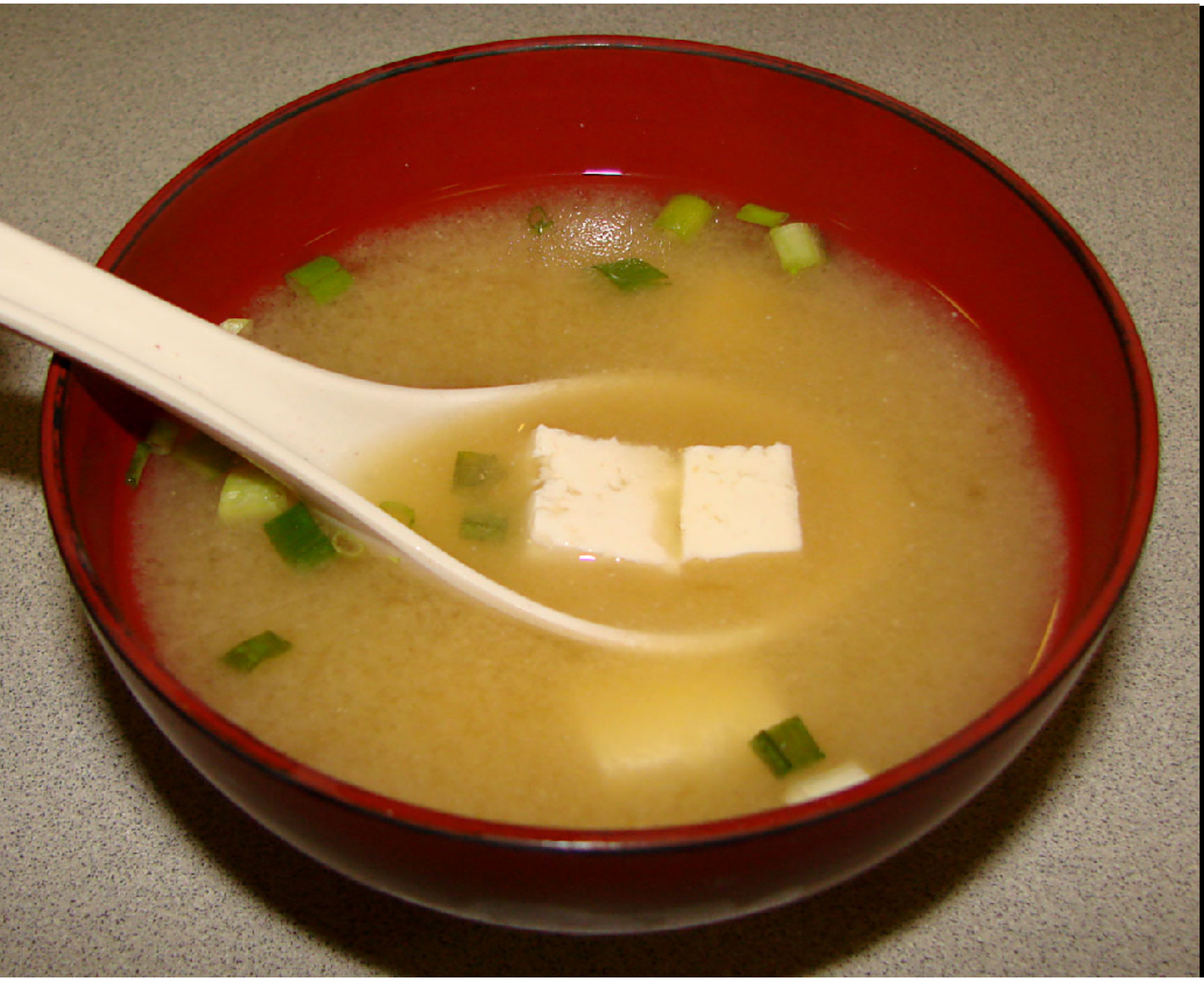


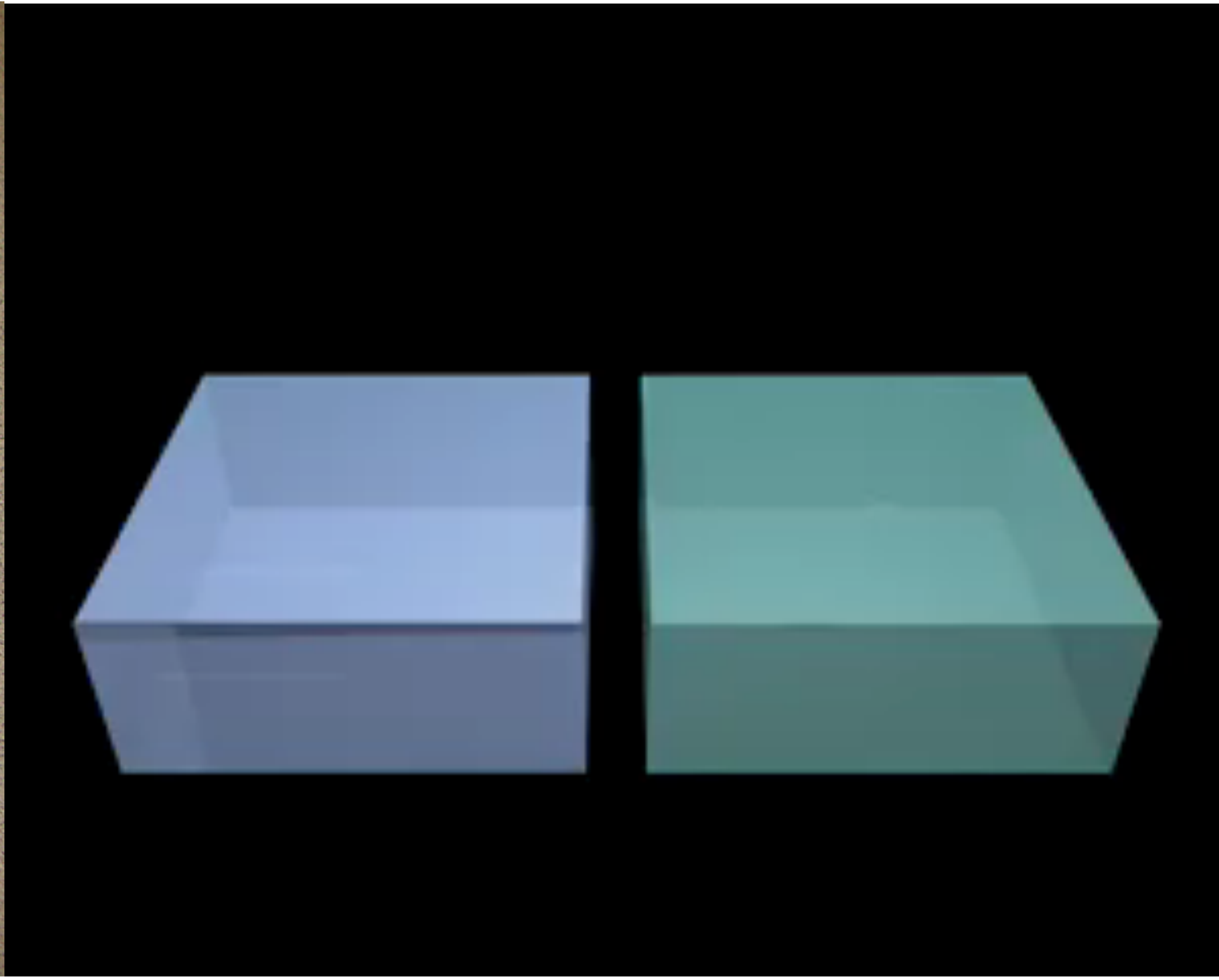
Measuring Total Matter Density

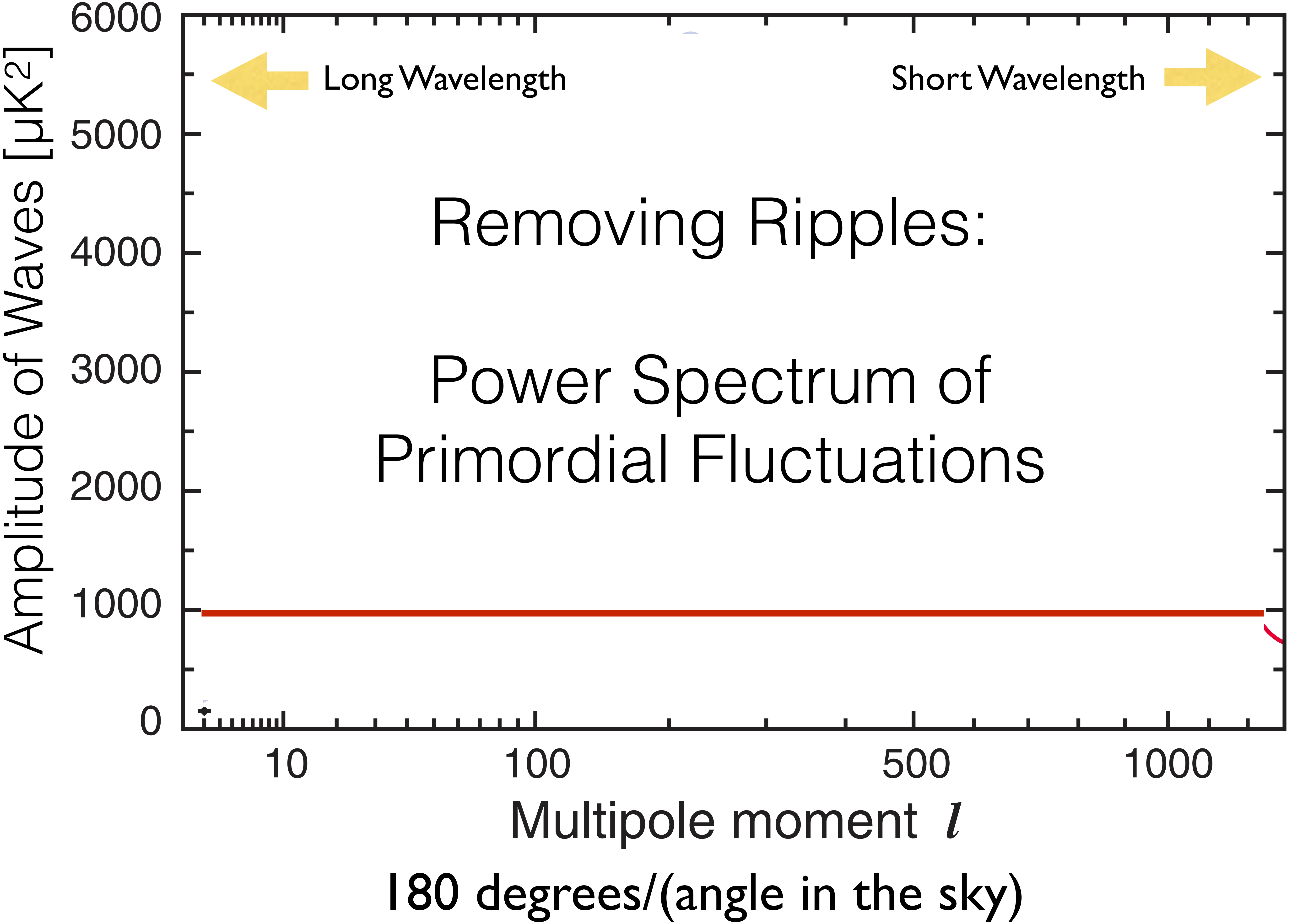


Origin of Fluctuations

- Who dropped those Tofus into the cosmic Miso soup?

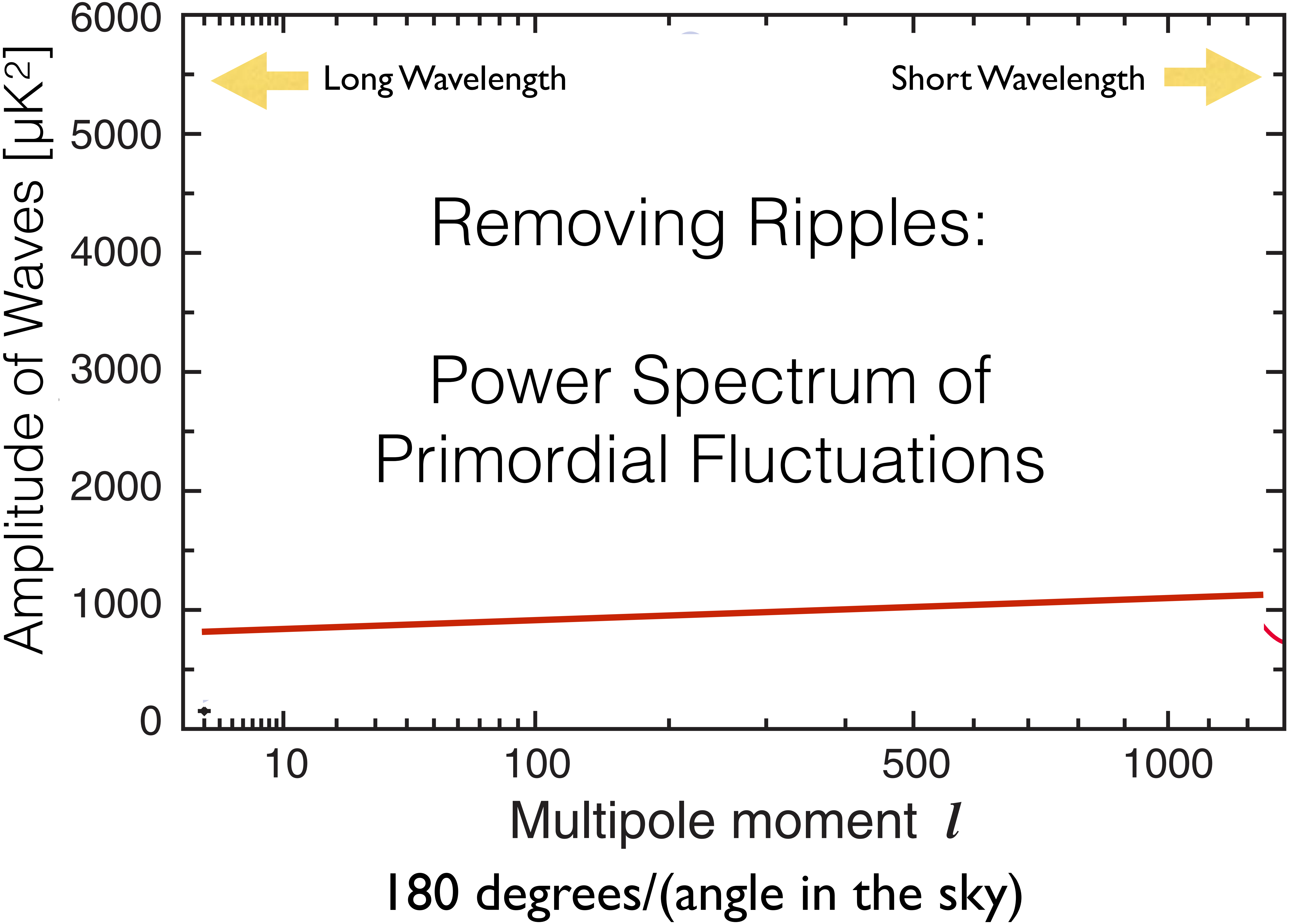






Removing Ripples:

Power Spectrum of Primordial Fluctuations



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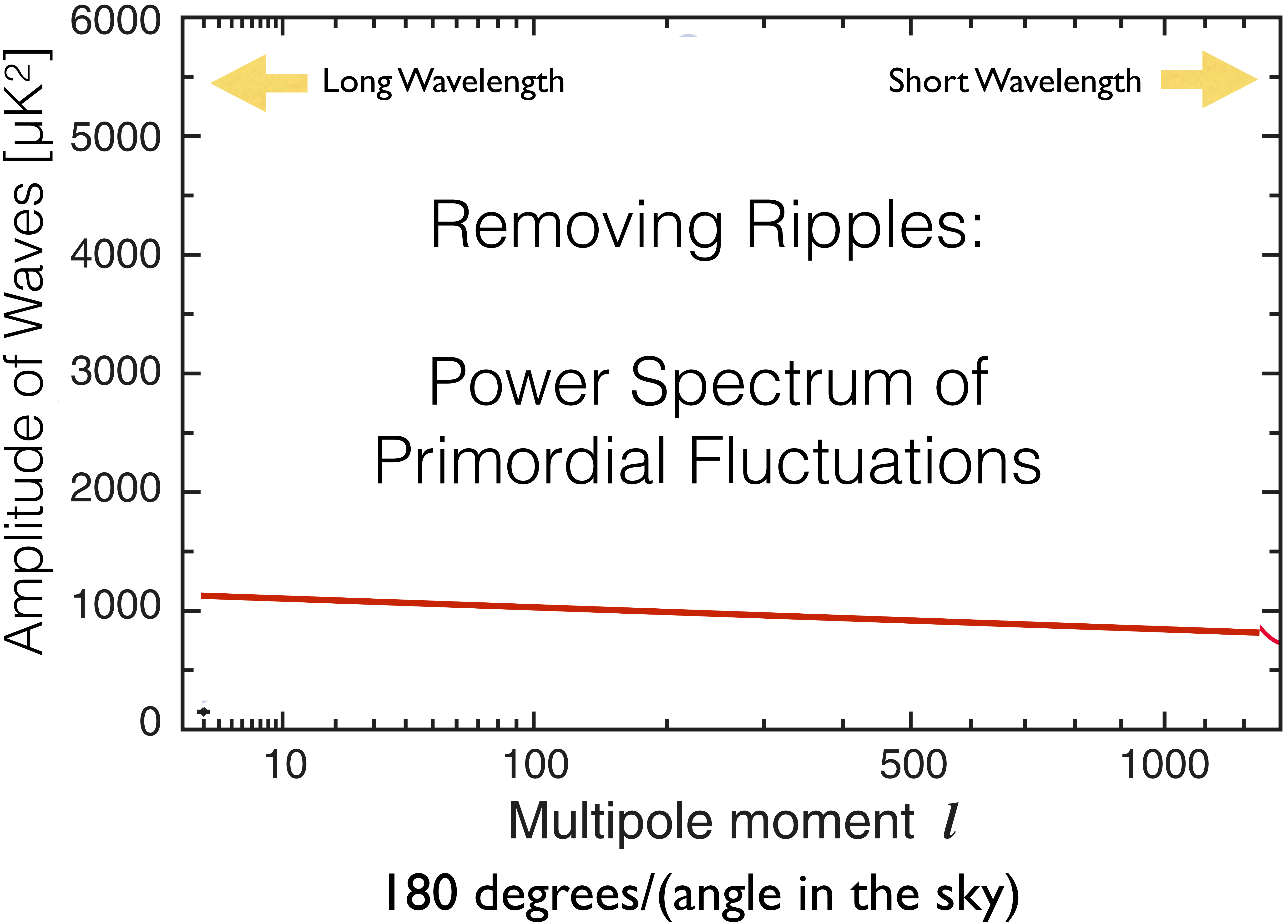

Removing Ripples:

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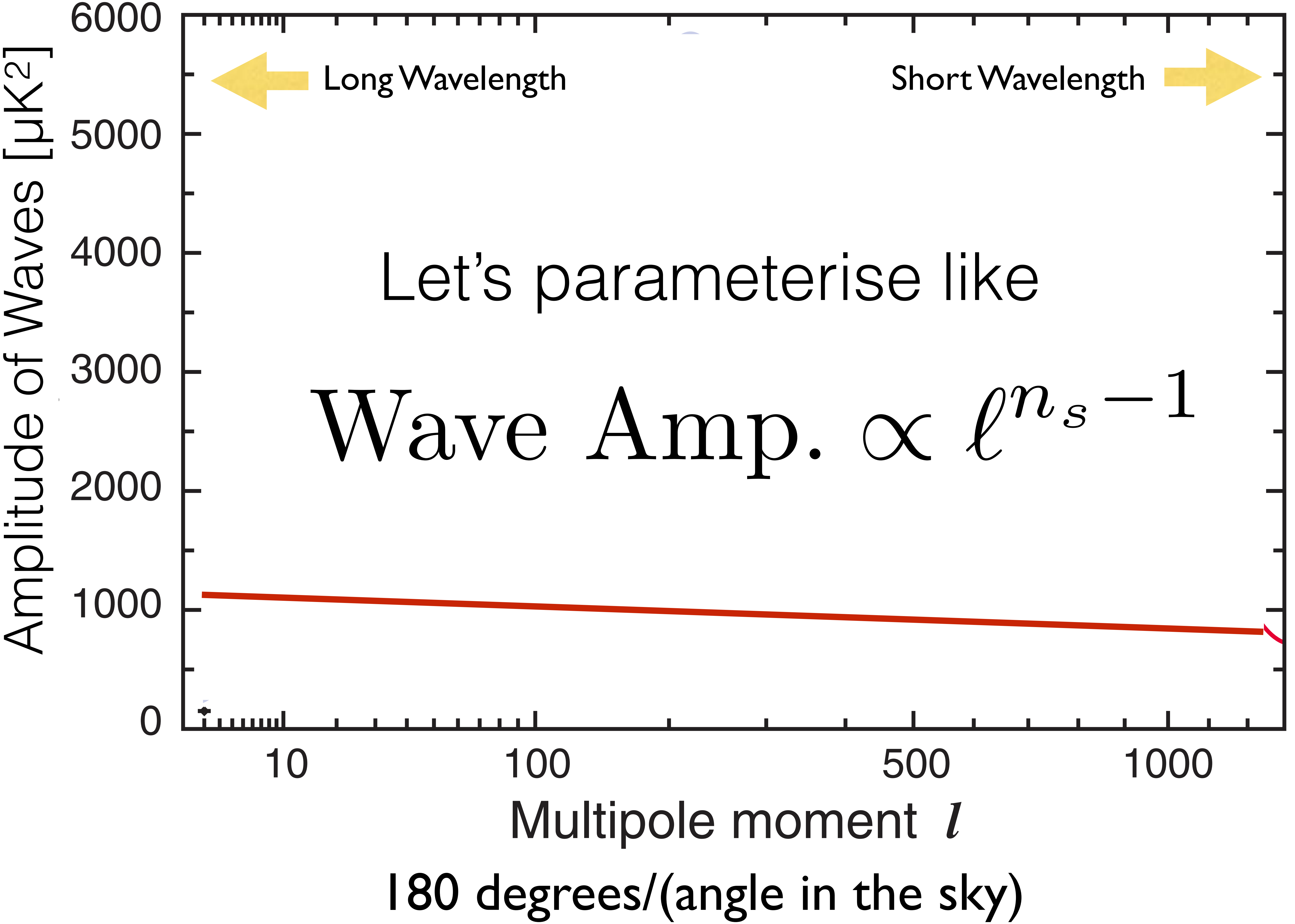
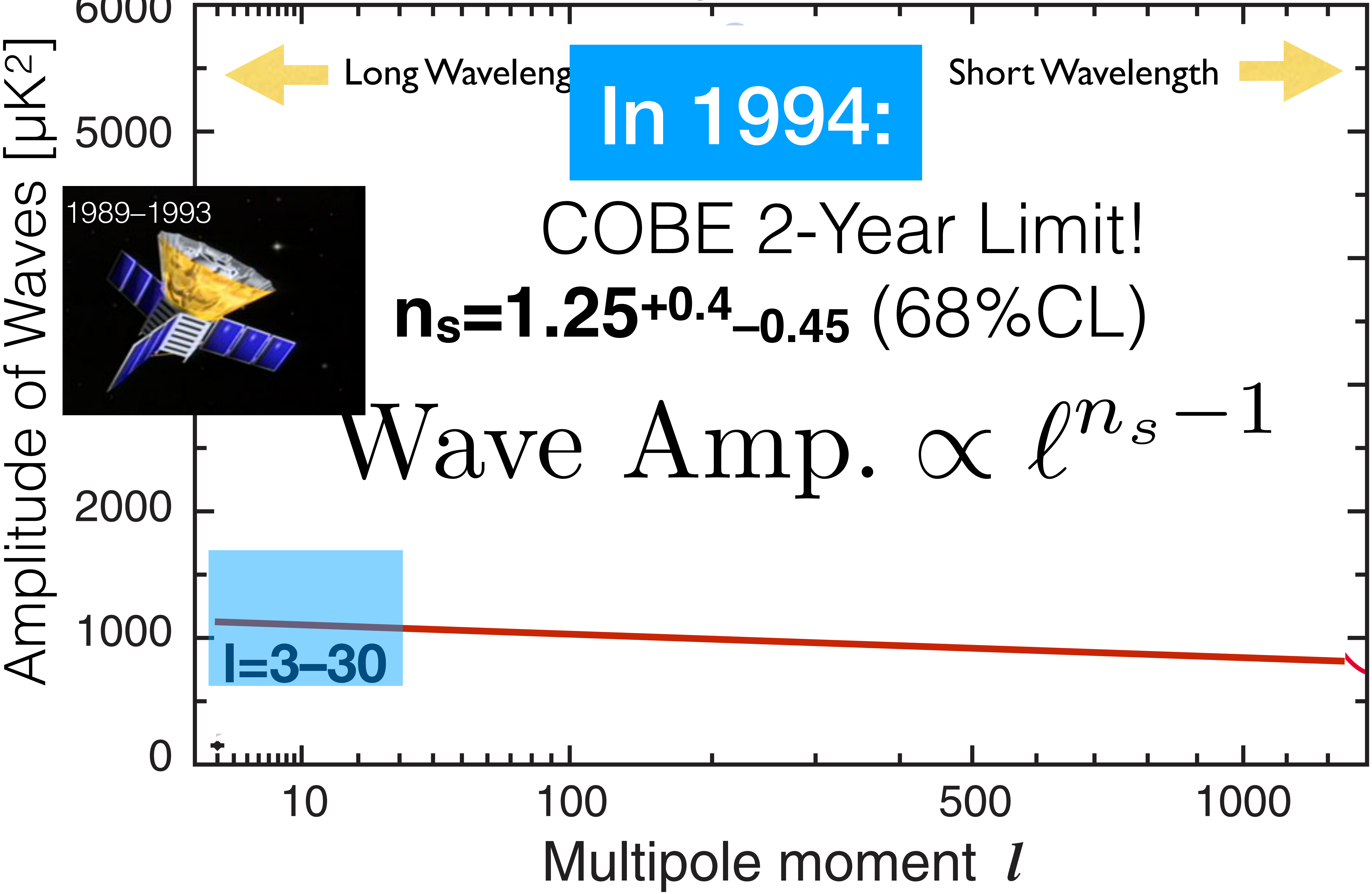


Let's parameterise like

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

Wright, Smoot, Bennett & Lubin (1994)



In 1994:

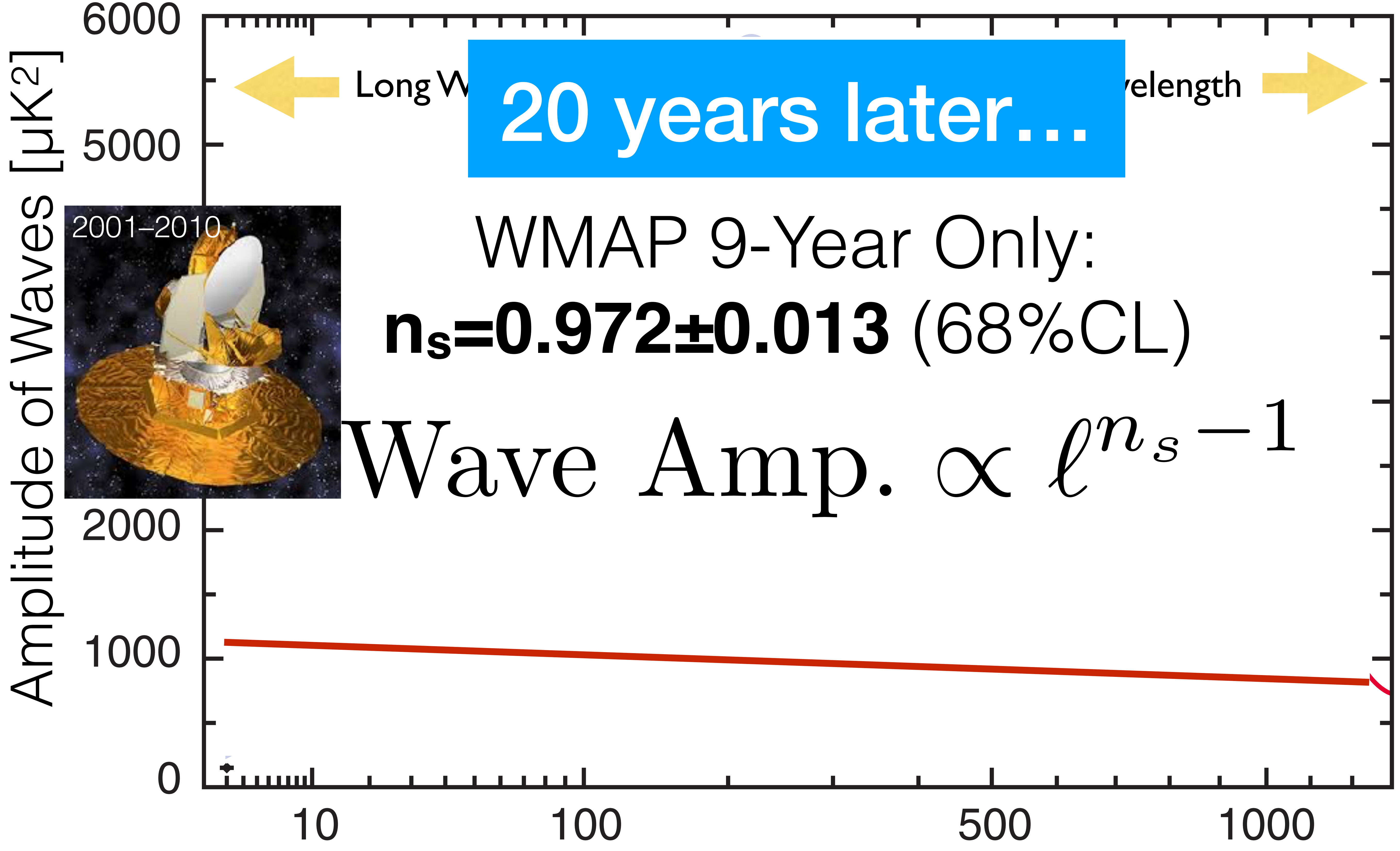
COBE 2-Year Limit!

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

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

180 degrees/(angle in the sky)

WMAP Collaboration



180 degrees/(angle in the sky)

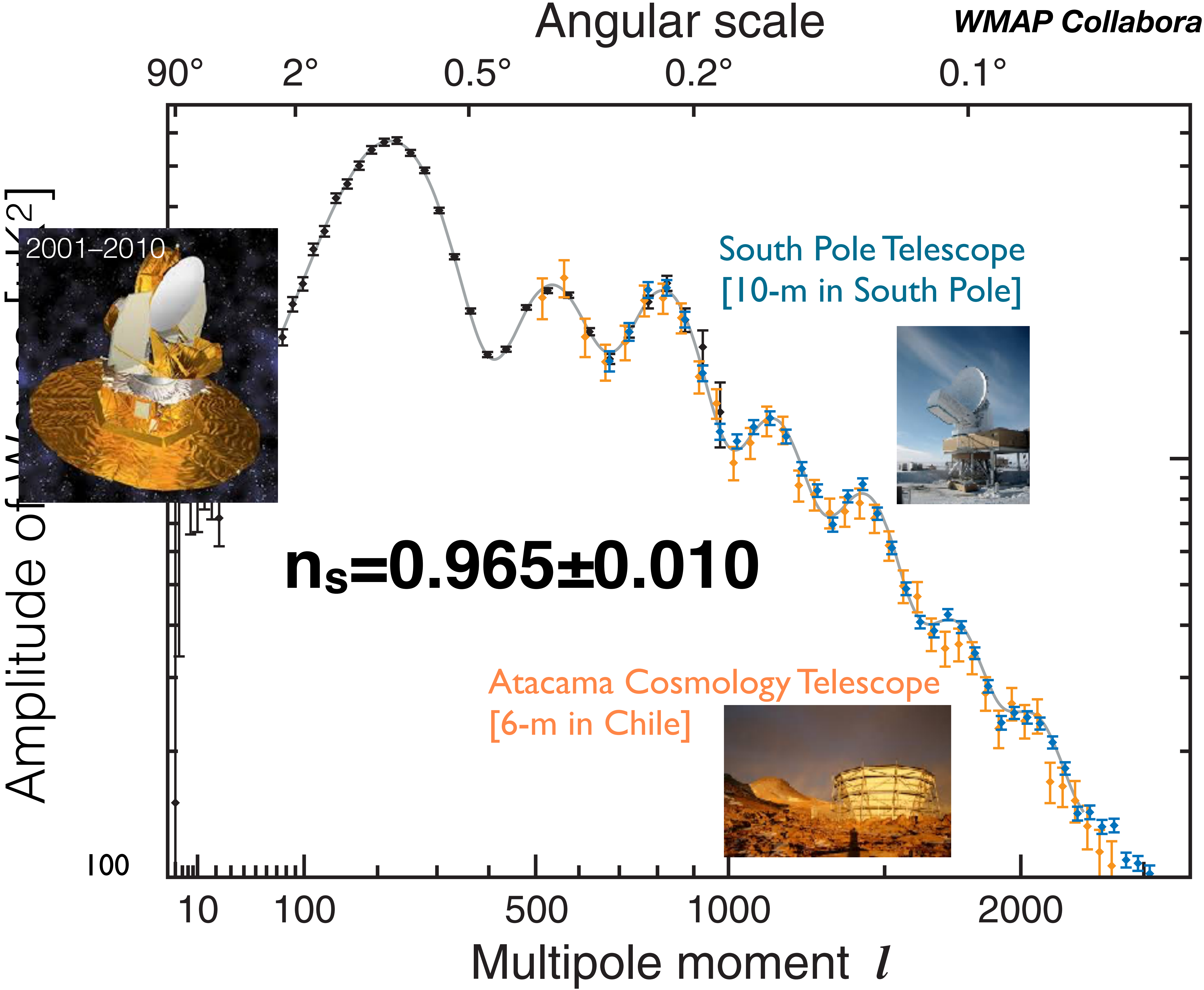
20 years later…

WMAP 9-Year Only:

n_s=0.972±0.013 (68%CL)

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

WMAP Collaboration

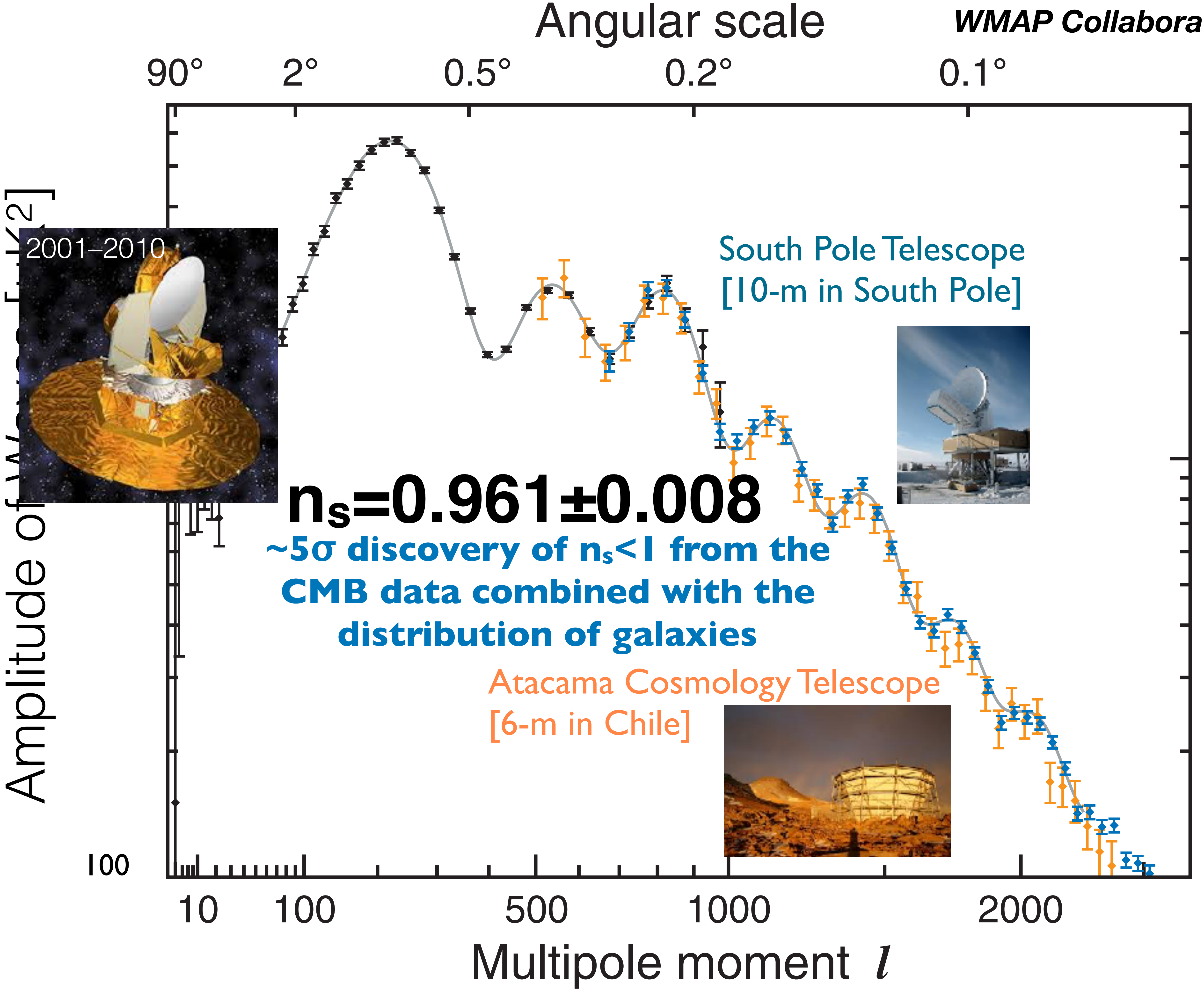


South Pole Telescope
[10-m in South Pole]

Atacama Cosmology Telescope
[6-m in Chile]

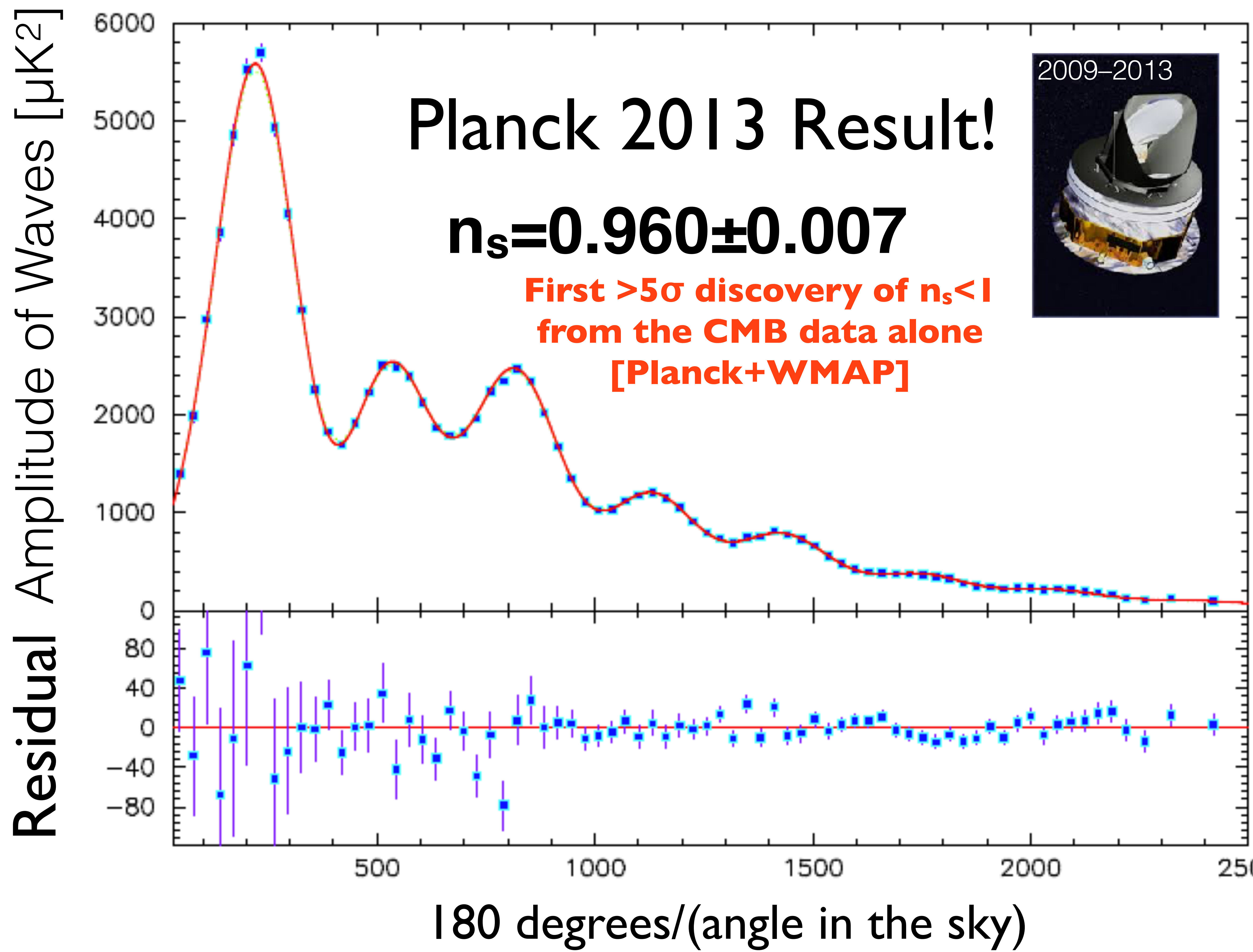
$n_s=0.965\pm0.010$

WMAP Collaboration



$n_s = 0.961 \pm 0.008$

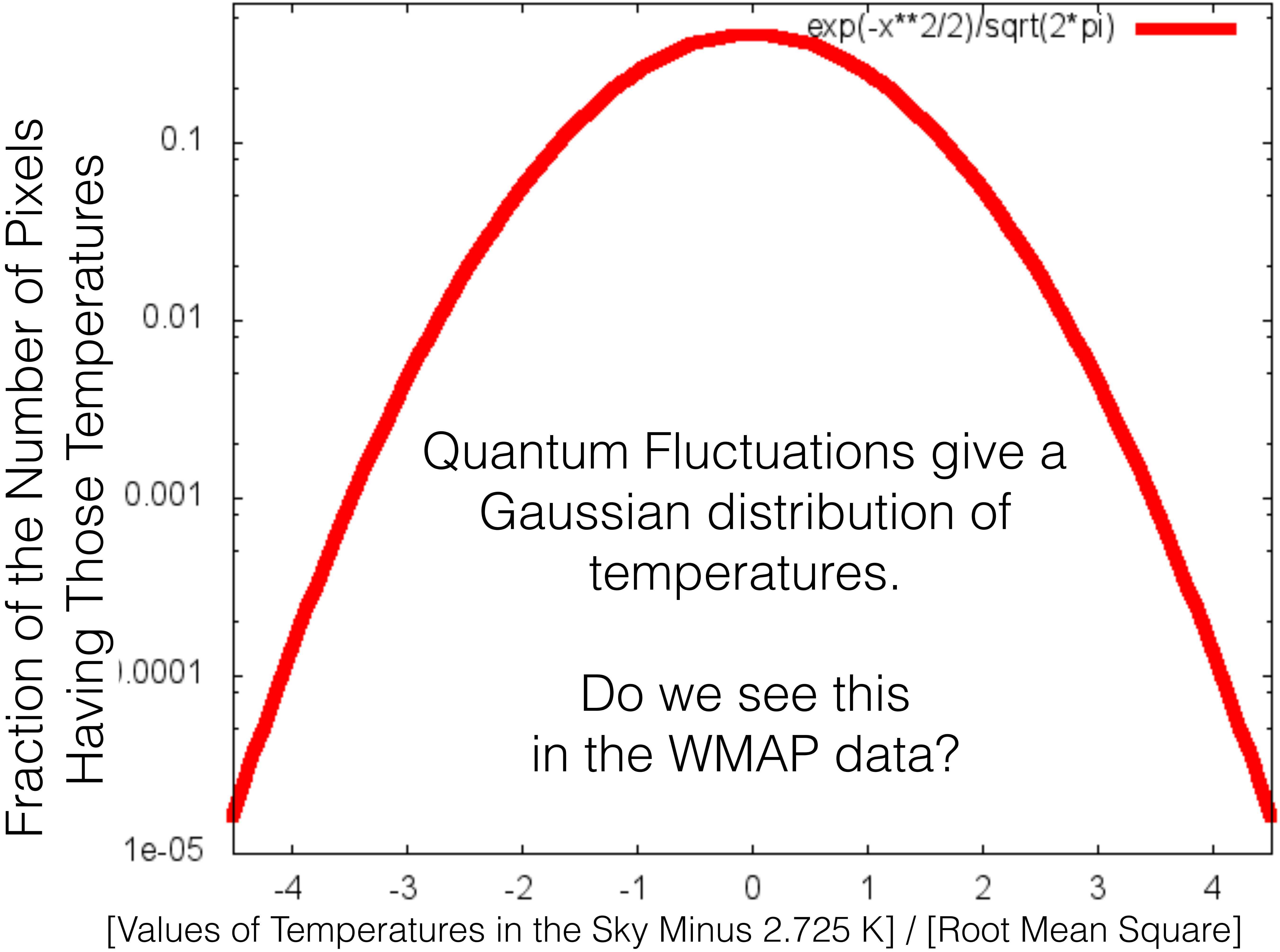
~5σ discovery of $n_s < 1$ from the CMB data combined with the distribution of galaxies



Planck 2013 Result!

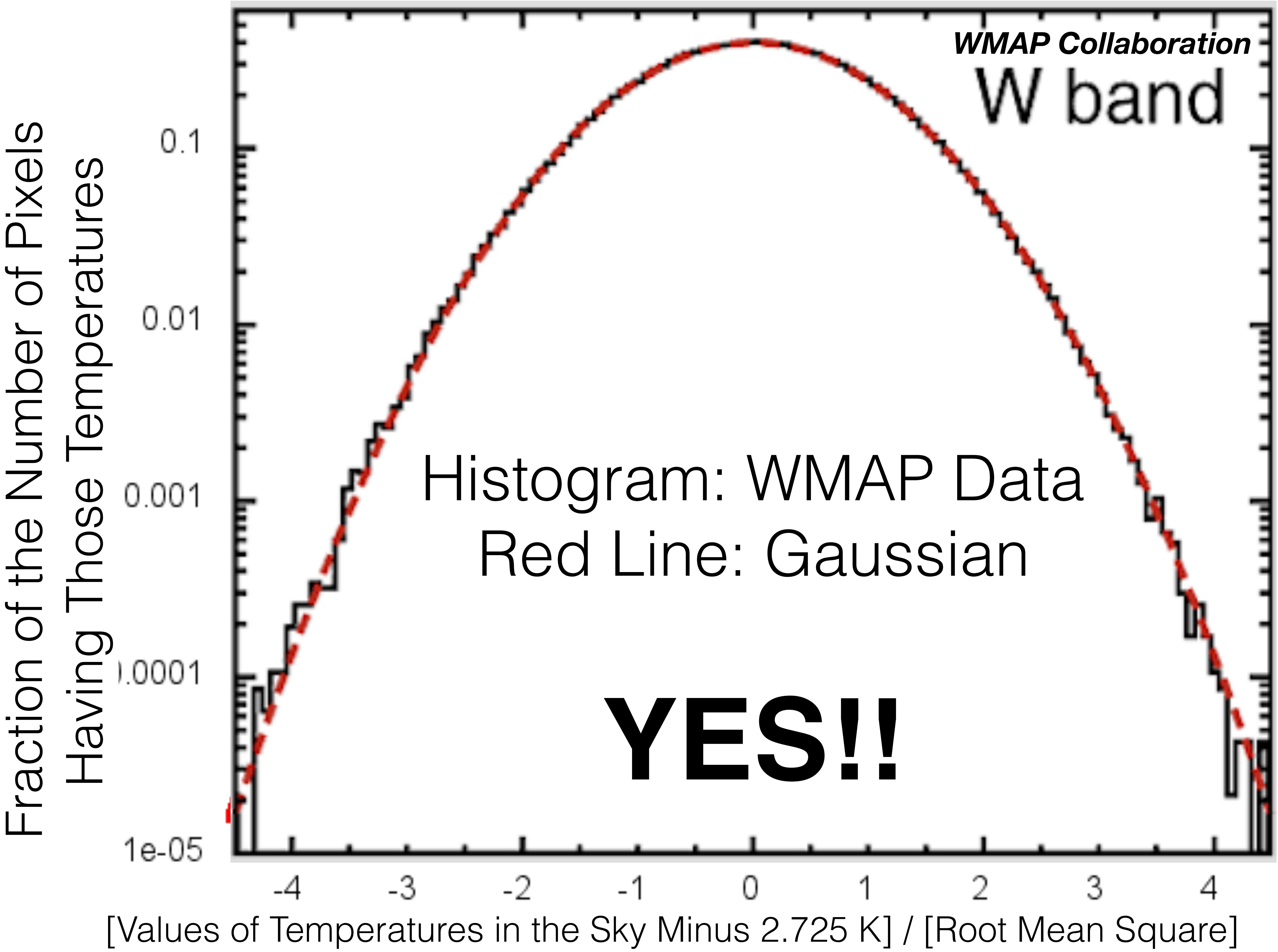
n_s=0.960±0.007

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?

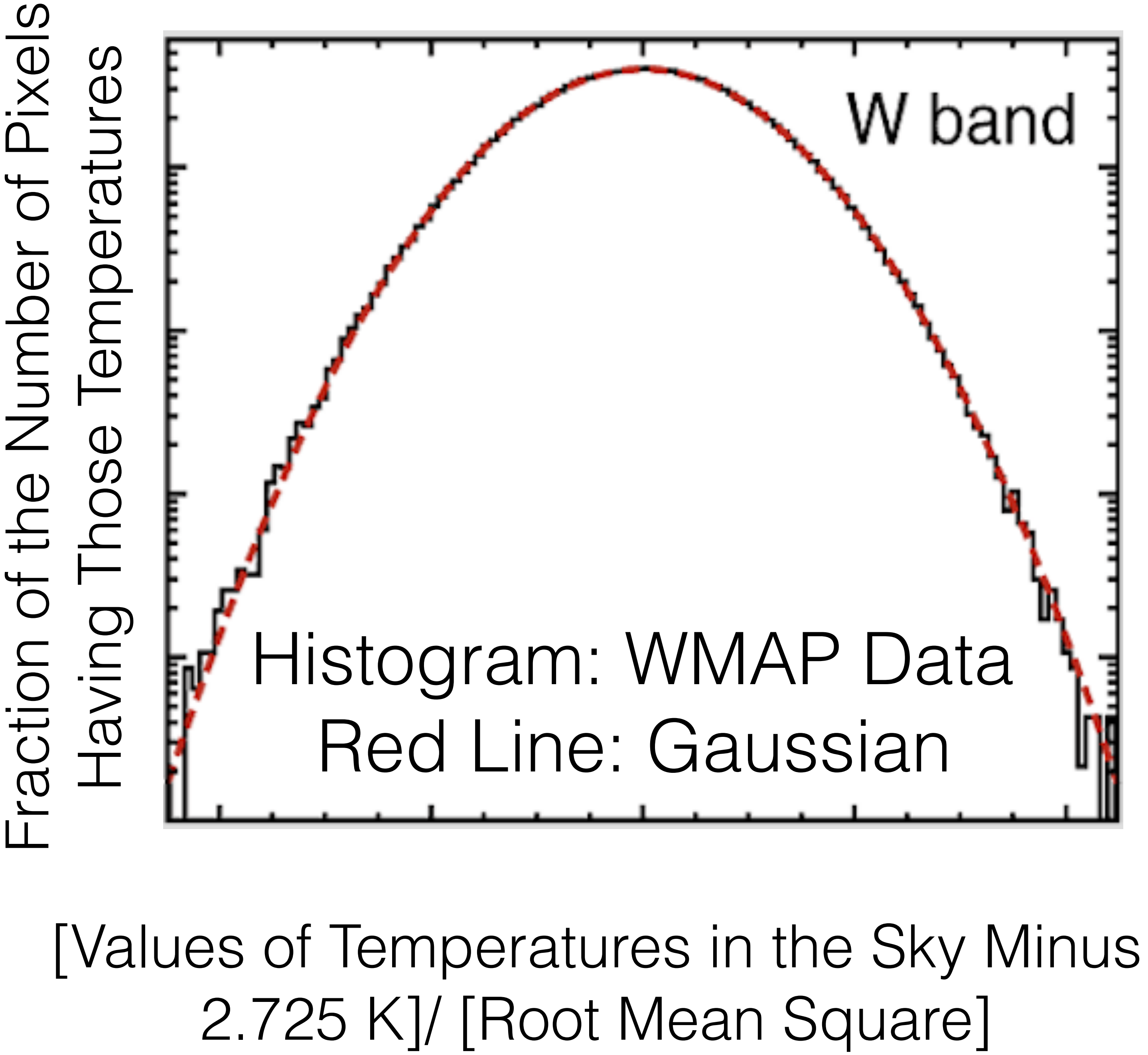


WMAP Collaboration

Histogram: WMAP Data
Red Line: Gaussian

YES!!

Testing Gaussianity



- 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)

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

WMAP 9-year Result

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

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

Planck 2015 Result

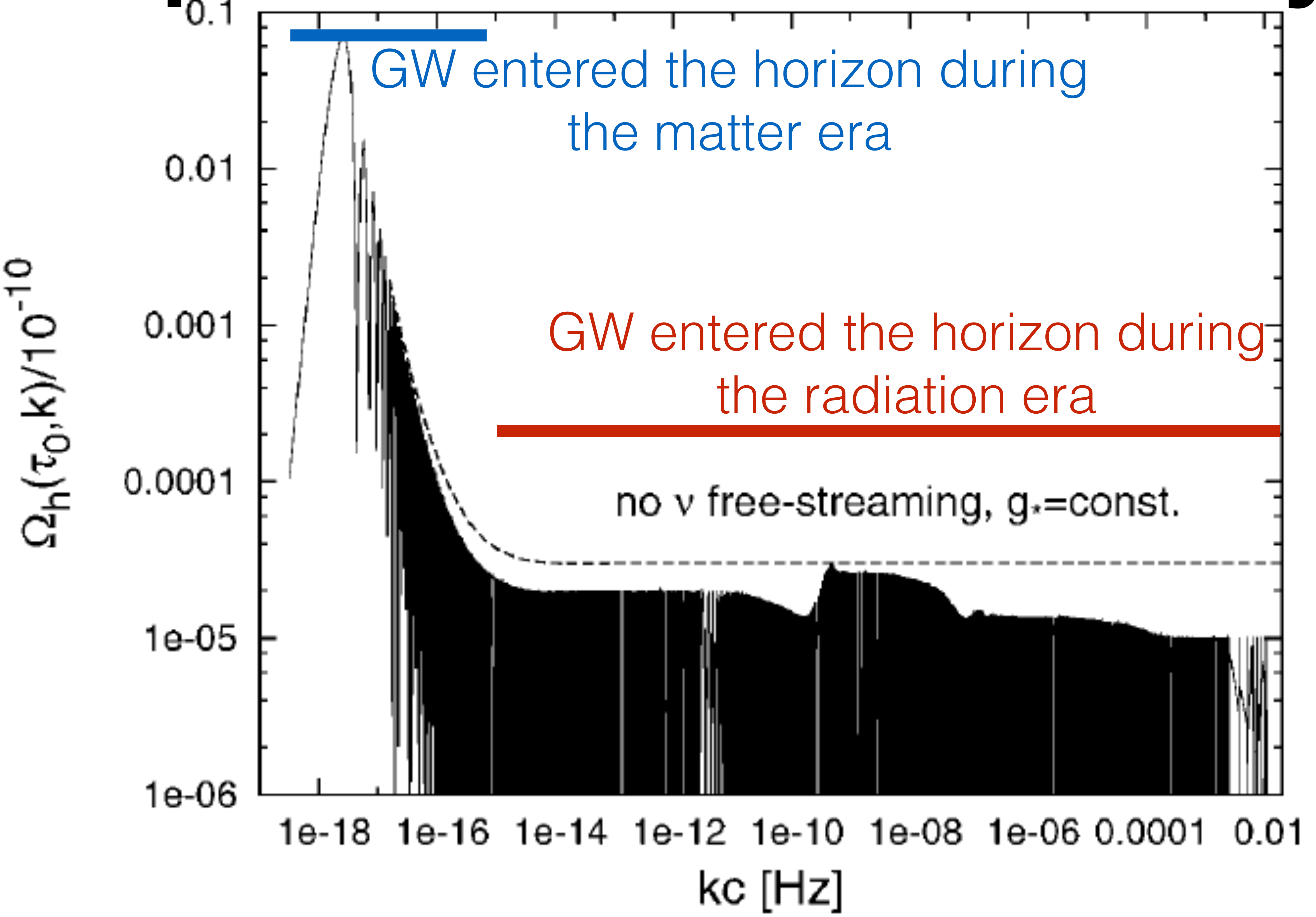
So, have we found inflation?

- 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*"

Watanabe & EK (2006)

Theoretical energy density

Spectrum of GW today



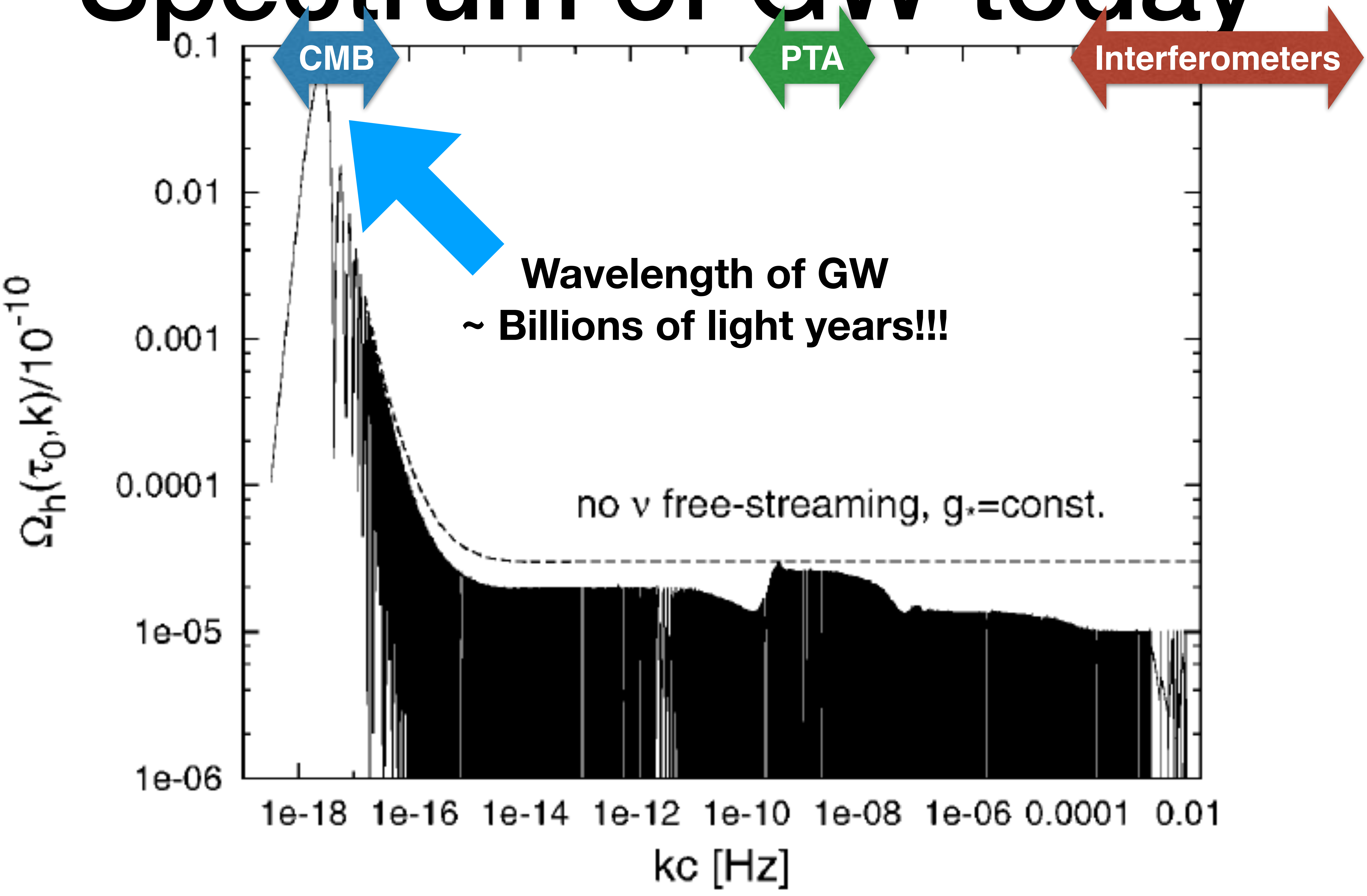
GW entered the horizon during the matter era

GW entered the horizon during the radiation era

Watanabe & EK (2006)

Theoretical energy density

Spectrum of GW today



Wavelength of GW
~ Billions of light years!!!

Finding Signatures of Gravitational Waves in the CMB

- **Next frontier in the CMB research**

1. Find evidence for nearly scale-invariant gravitational waves

New Research Area!

2. Once found, test Gaussianity to make sure (or not!) that the signal comes from vacuum fluctuation

3. Constrain inflation models

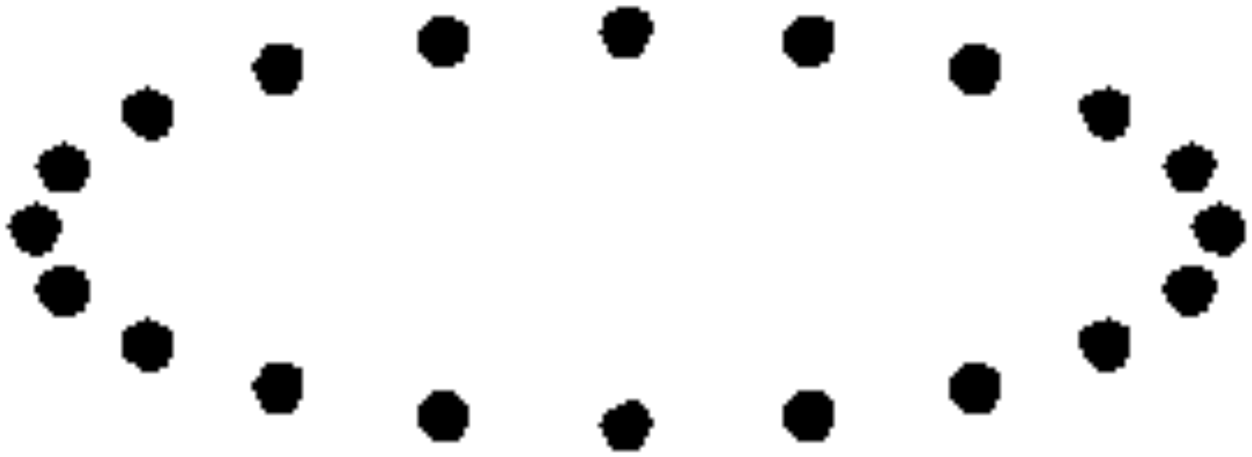
Measuring GW

- GW changes distances between two points

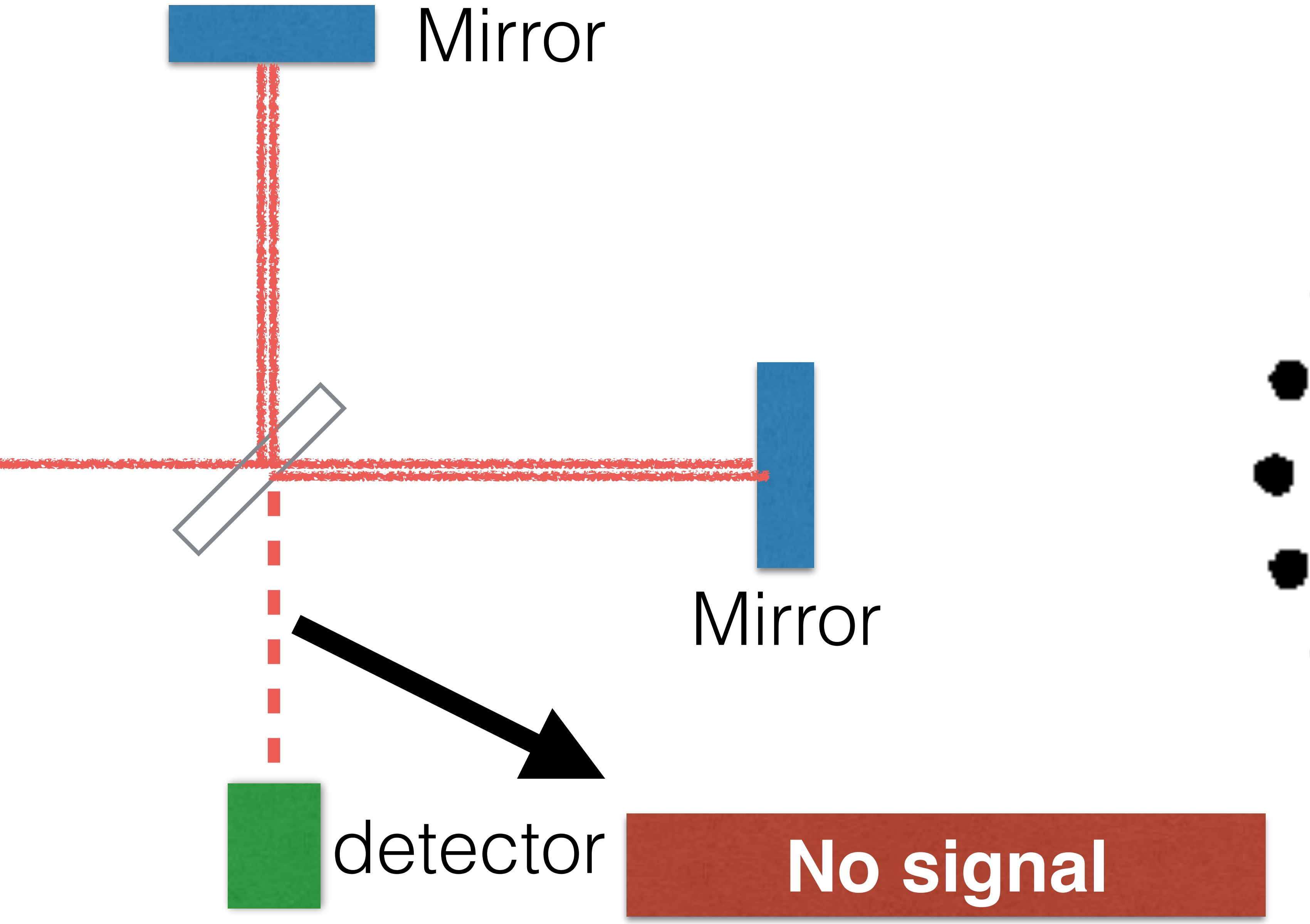
$$d\ell^2 = d\mathbf{x}^2 = \sum_{ij} \delta_{ij} dx^i dx^j$$

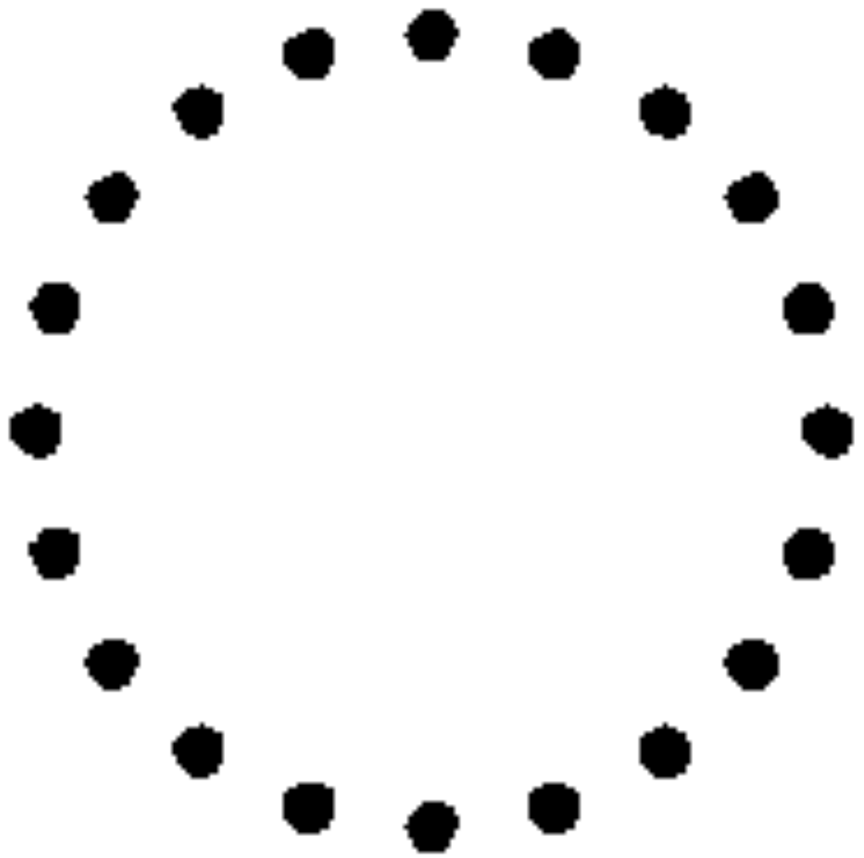
⬇

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

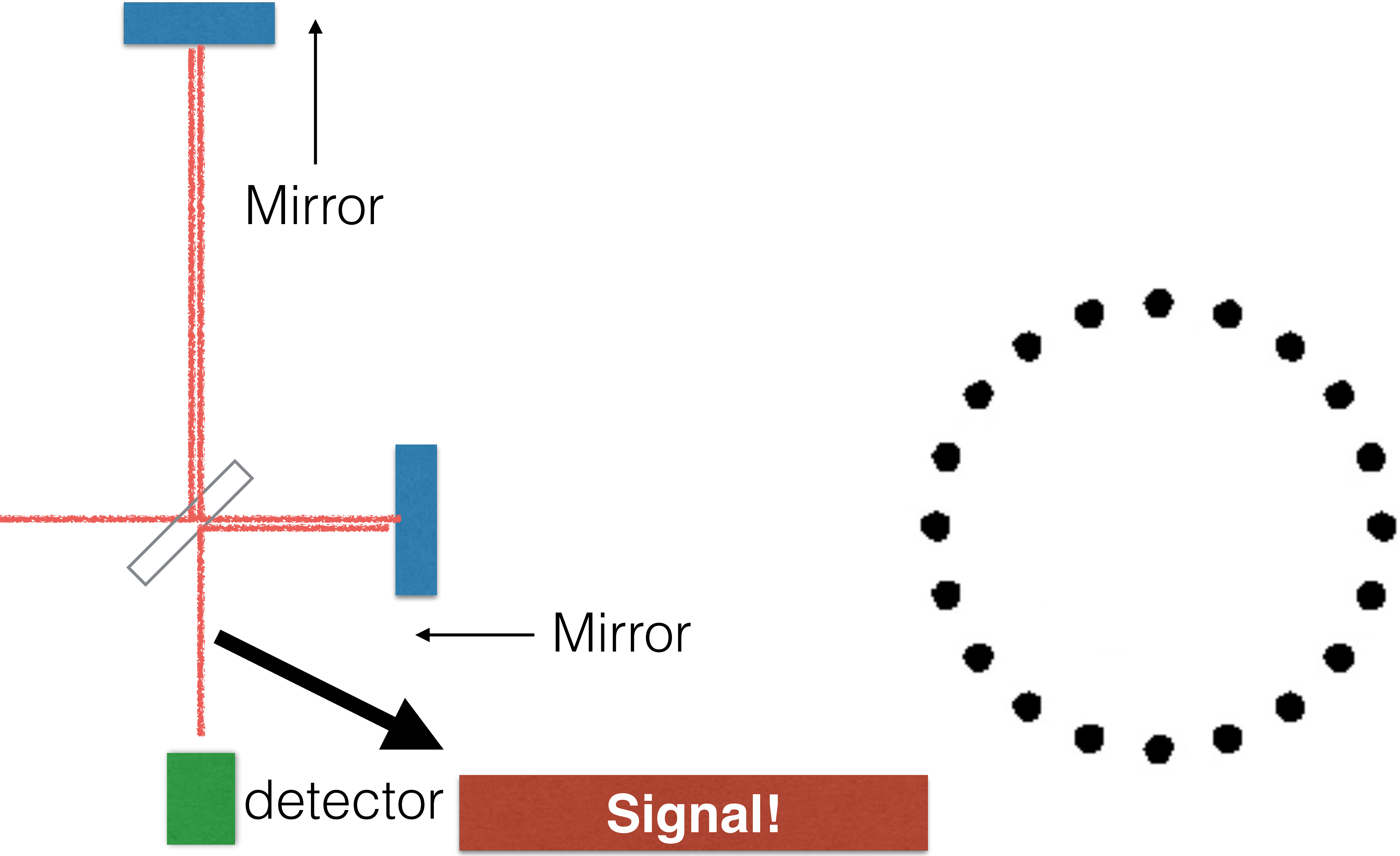


Laser Interferometer





Laser Interferometer



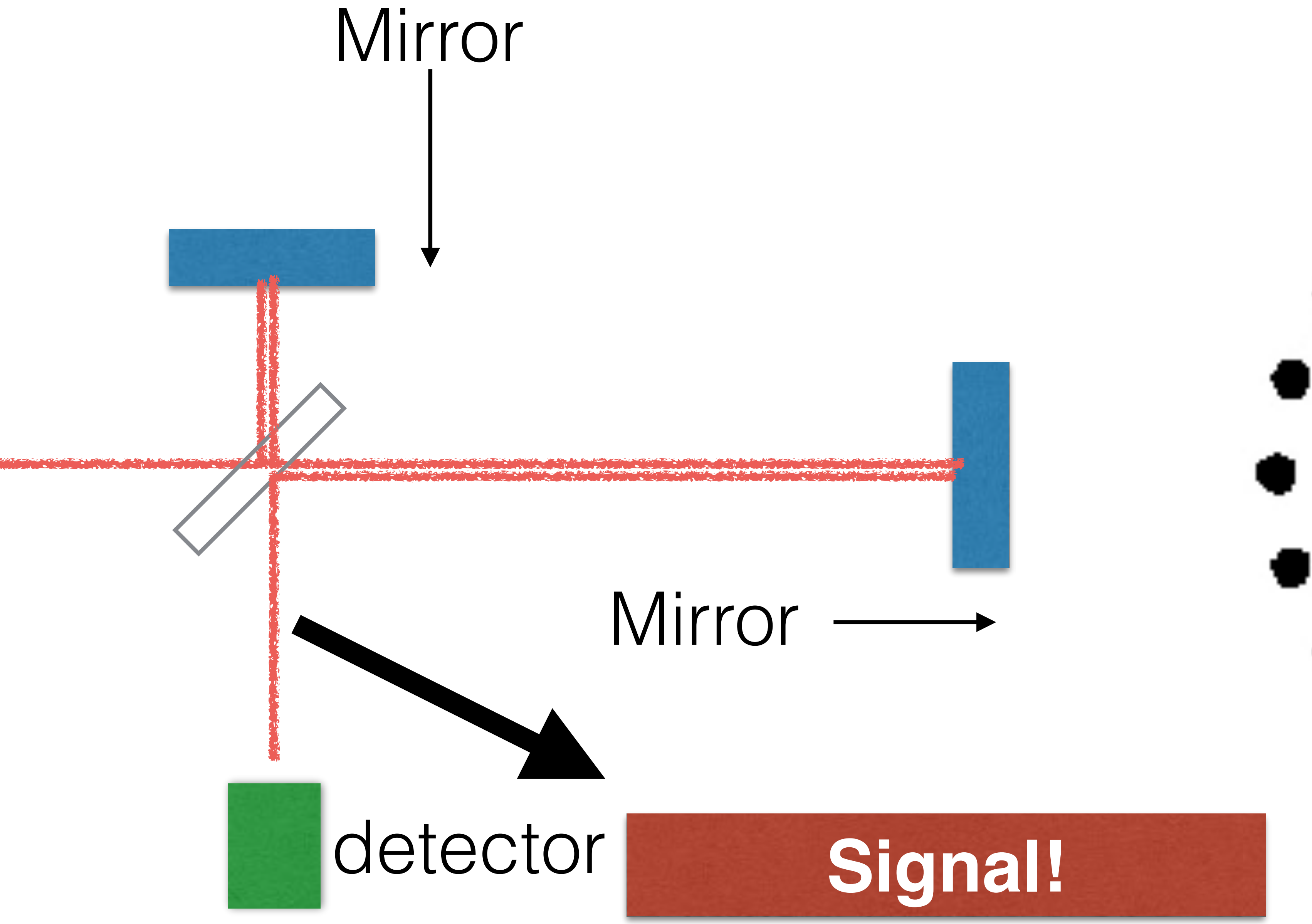
Mirror

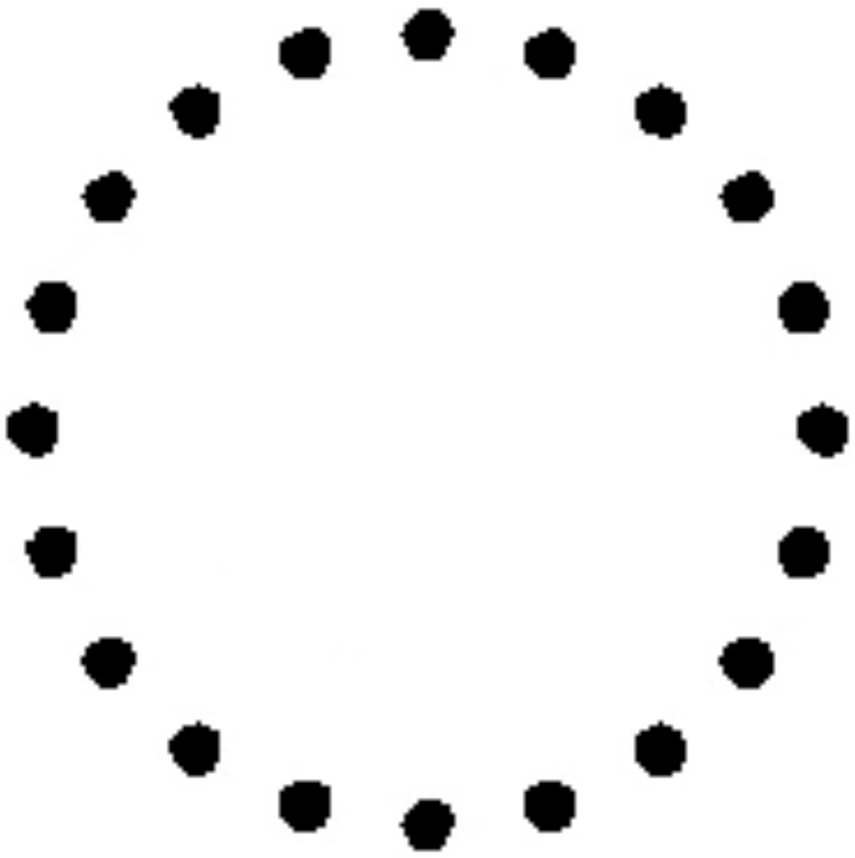
Mirror

detector

Signal!

Laser Interferometer





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

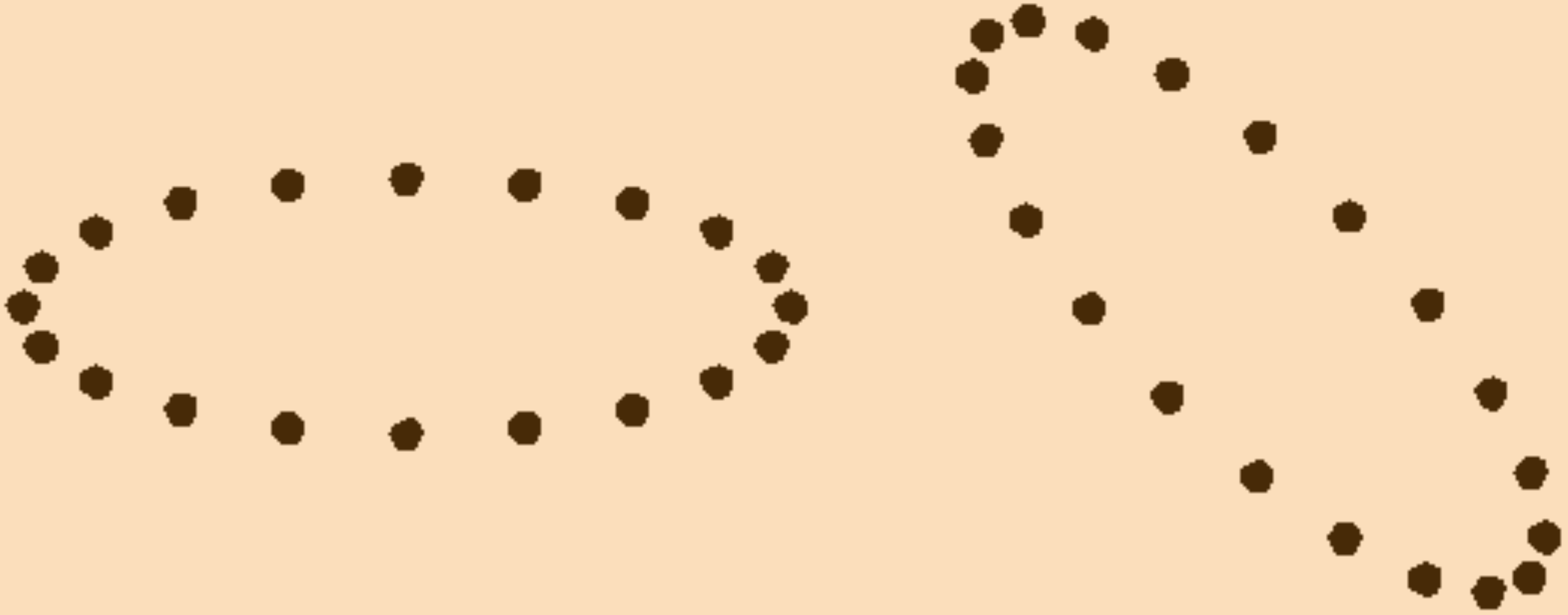
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

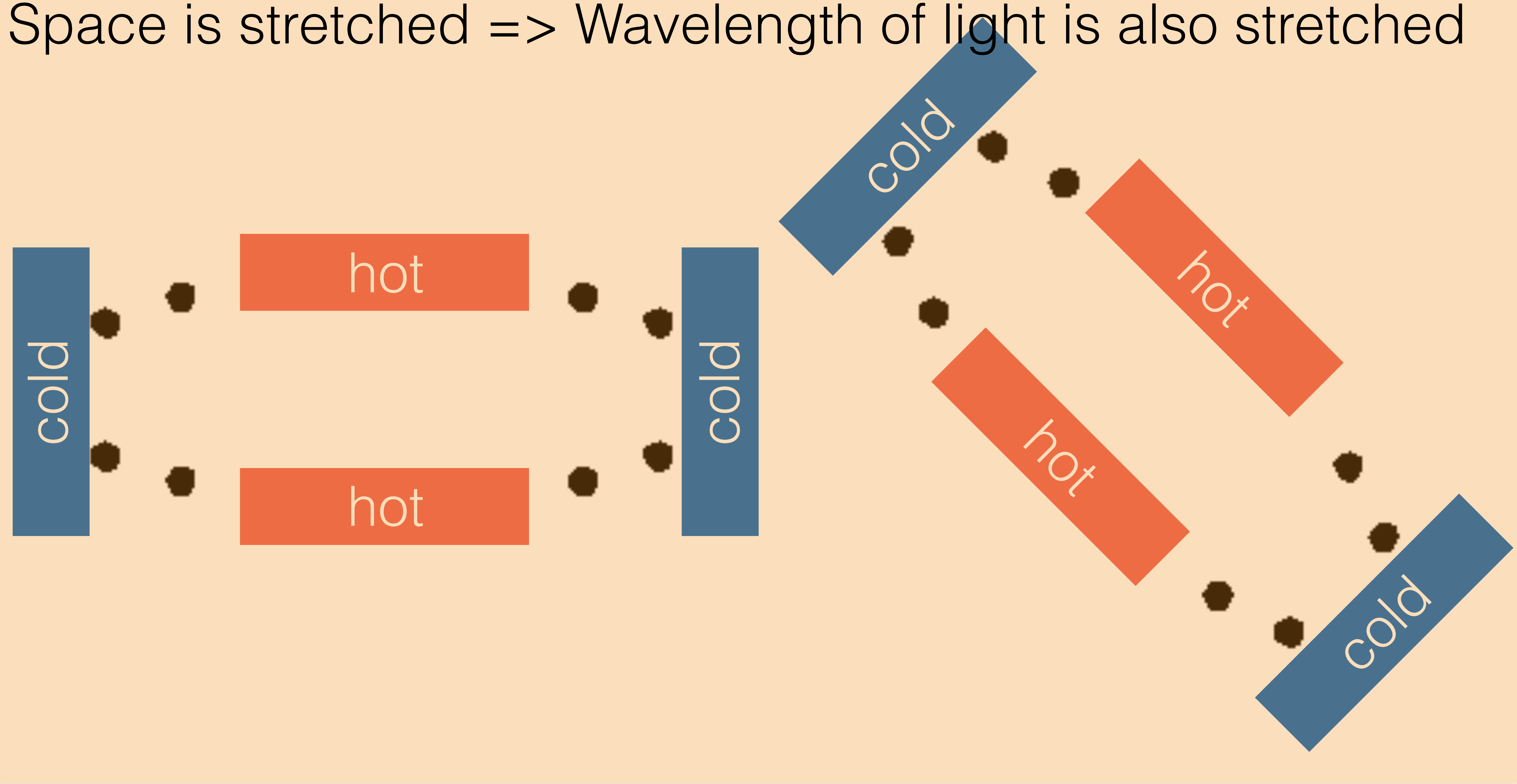
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



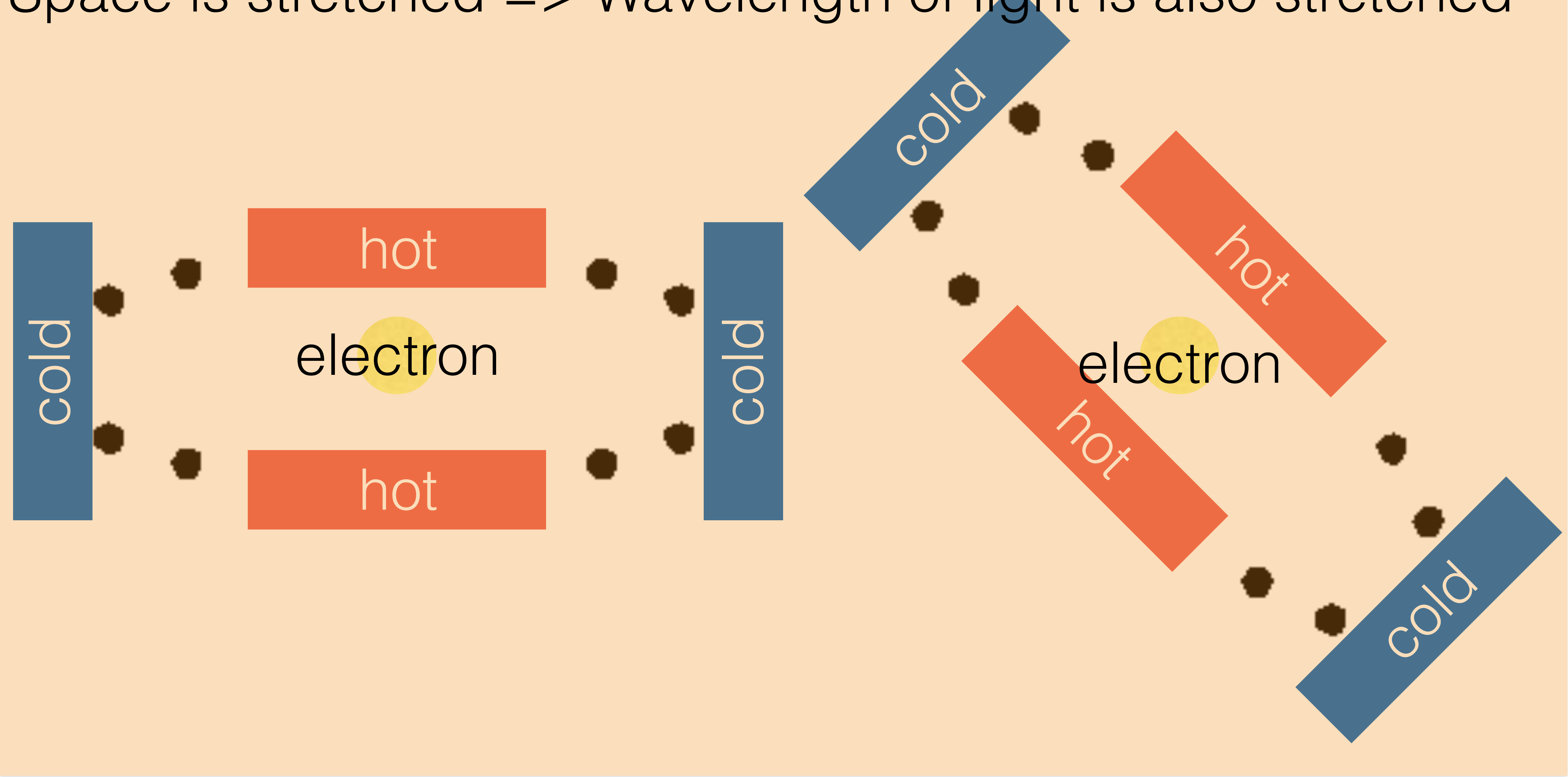
Detecting GW by CMB

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

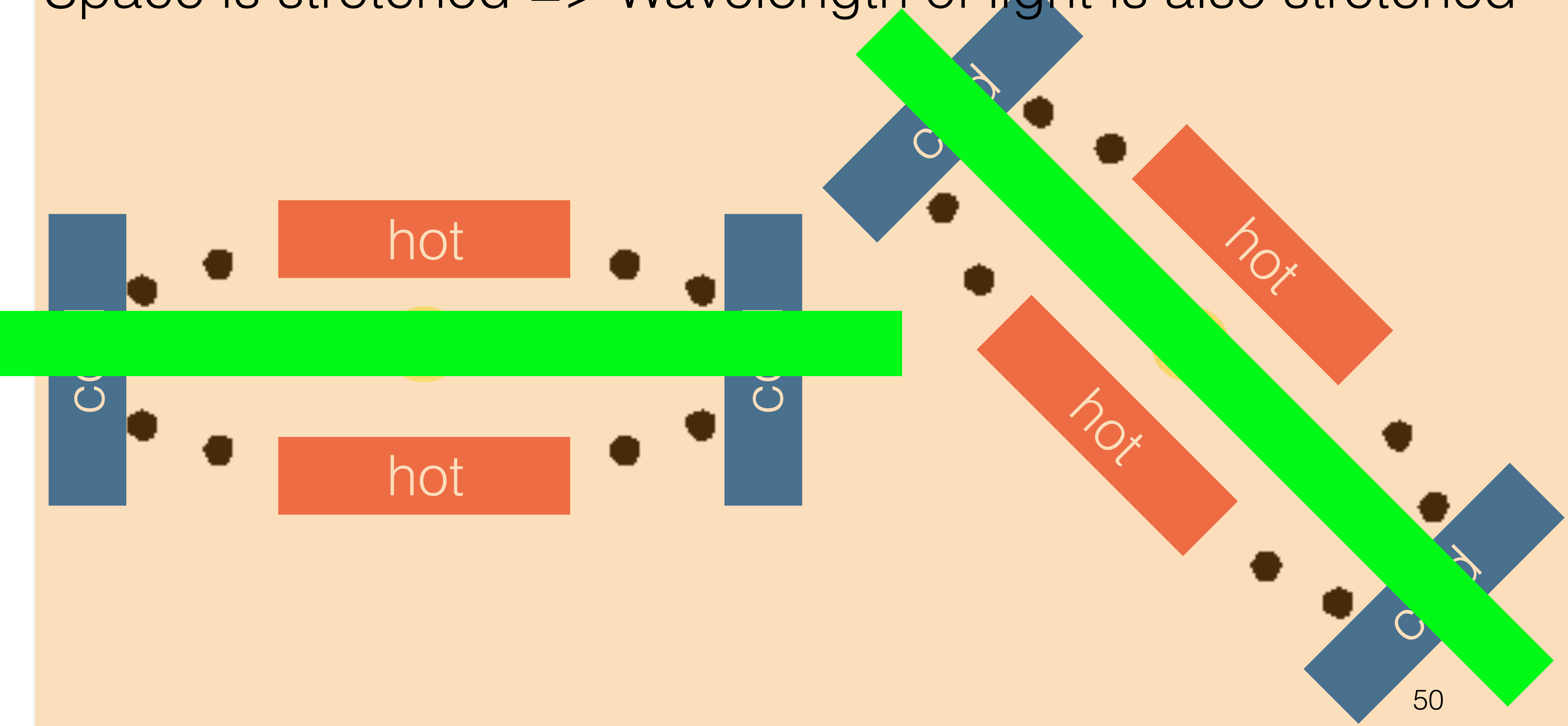


Photo Credit: TALEX

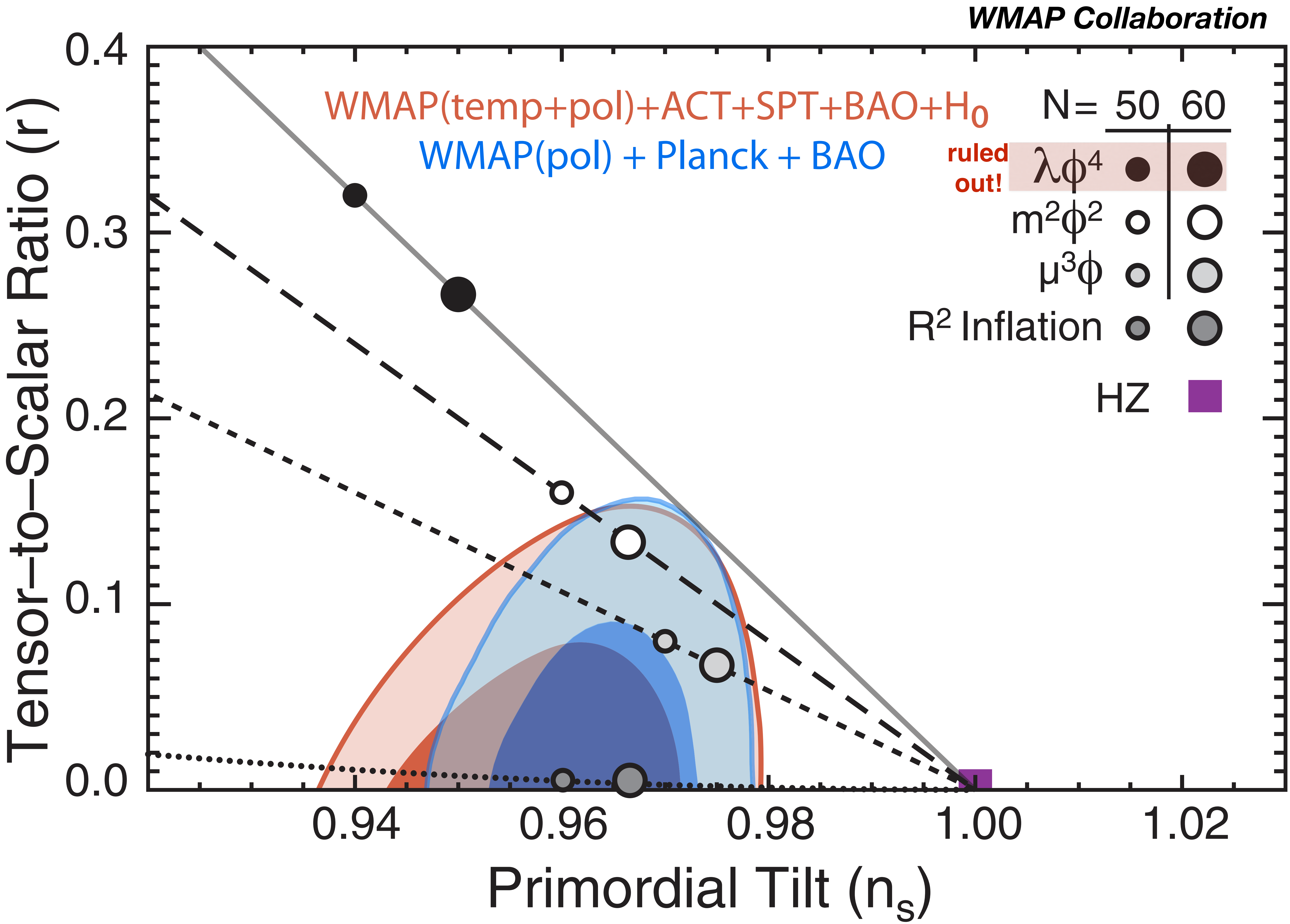
Photo Credit: TALEX

Tensor-to-scalar Ratio

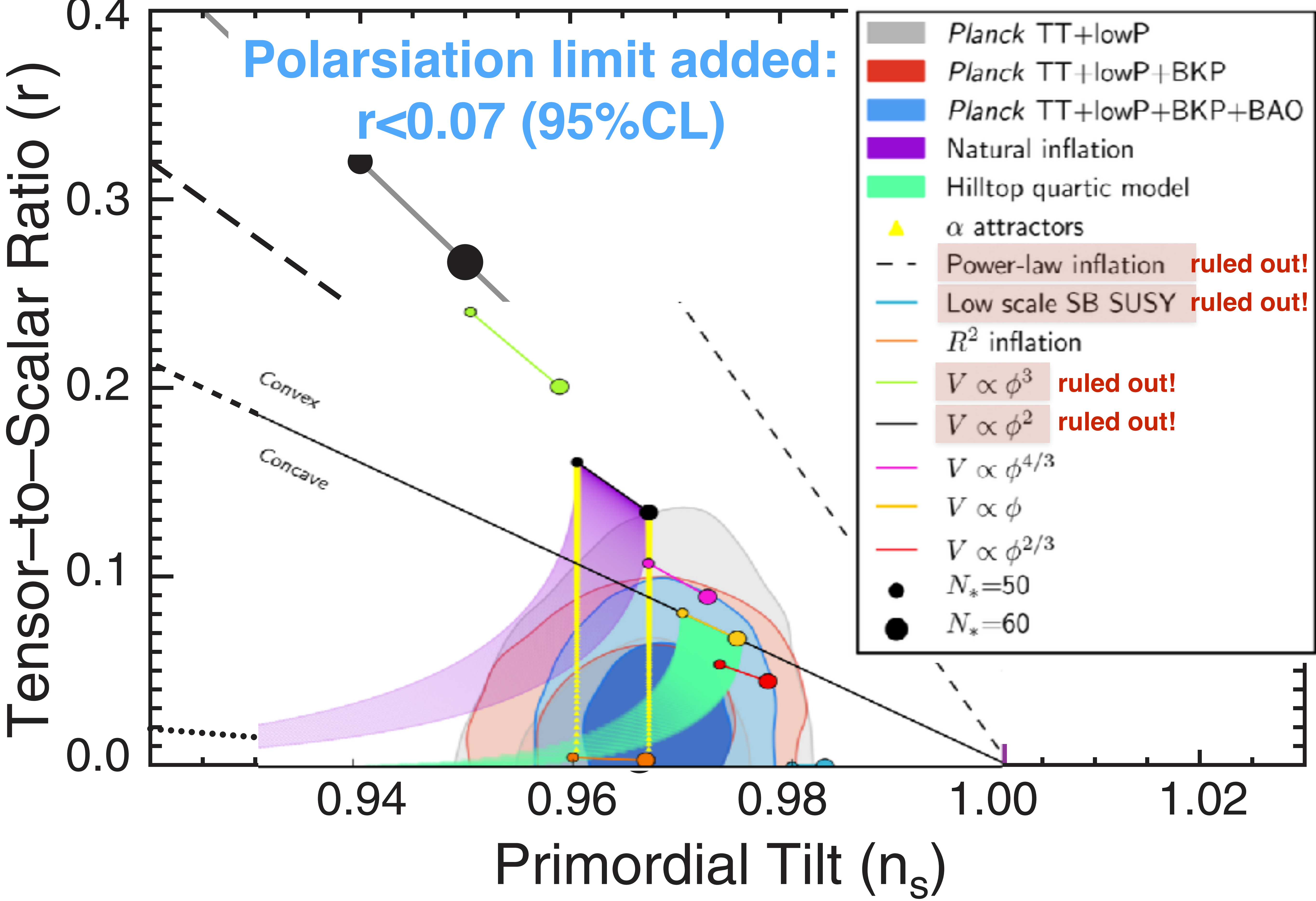
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

- We really want to find this! The current upper bound is **r<0.07** (95%CL)

  BICEP2/Keck Array Collaboration (2016)


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)

ruled out!
ruled out!
ruled out!
ruled out!

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
    - SU(2) gauge field can!

Maleknejad & Sheikh-Jabbari (2013); Dimastrogiovanni & Peloso (2013); Adshead, Martinec & Wyman (2013)

Important Message

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

- **Do not take it for granted if someone told you that detection of the B-mode polarisation 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)]

Experimental Strategy Commonly Assumed So Far

1. Detect B-mode polarisation in multiple frequencies, to make sure that it is the B-mode of the CMB

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 B-mode polarisation in multiple frequencies, to make sure that it is the B-mode of the CMB

2. Consistent with a scale invariant spectrum?

3. Parity violating correlations (TB and EB) 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!

2. Consistent with a scale invariant spectrum?
3. Parity violating correlations (TB and EB) consistent with zero?
4. Consistent with Gaussianity?

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

Further Remarks

- "*Guys, you are complicating things too much!*"
- **No.** These sources (eg., gauge fields) should be ubiquitous in a high-energy universe. They have every right to produce GWs if they are around
- Sourced GWs with r>>0.001 can be phenomenologically more attractive than the vacuum GW from the large-field inflation [requiring super-Planckian field excursion]. Better radiative stability, etc
- Rich[er] phenomenology: Better integration with the Standard Model; reheating; baryon synthesis via leptogenesis, etc. **Testable using many more probes!**

Dimastrogiovanni, Fasielo & Fujita (2017)

GW from Axion-SU(2) Dynamics

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_\phi + \mathcal{L}_\chi - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \frac{\lambda\,\chi}{4f} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

- ϕ: inflaton field
- χ: pseudo-scalar “axion” field. Spectator field (i.e., negligible energy density compared to the inflaton)
- Field strength of an SU(2) field A^a_ν :

$$F^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g\epsilon^{abc} A^b_\mu A^c_\nu$$

Scenario

- The SU(2) field contains tensor, vector, and scalar components
- The tensor components are amplified strongly by a coupling to the axion field
    - But, **only one helicity is amplified** => GW is **chiral** (well-known result)
- Brand-new result: **GWs sourced by this mechanism are strongly non-Gaussian!**

Agrawal, Fujita & EK (2017)

Agrawal, Fujita & EK (2017)

Large bispectrum in GW from SU(2) fields

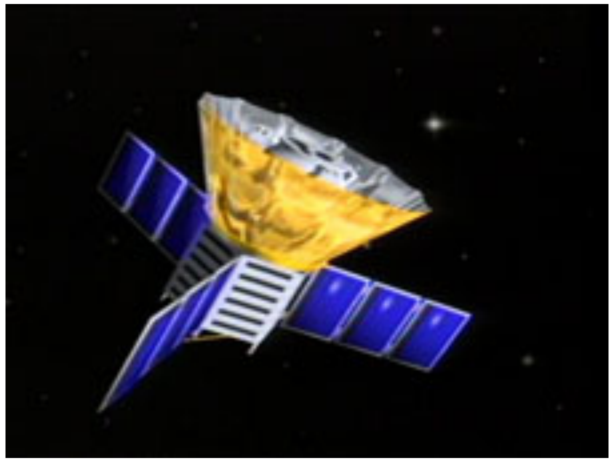
$$\frac{B_h^{RRR}(k,k,k)}{P_h^2(k)} \approx \frac{25}{\Omega_A}$$

- $\Omega_A << 1$ is the energy density fraction of the gauge field
- B_h/P_h^2 is of order unity for the vacuum contribution
- ***Gaussianity offers a powerful test of whether the detected GW comes from the vacuum fluctuation or from sources***

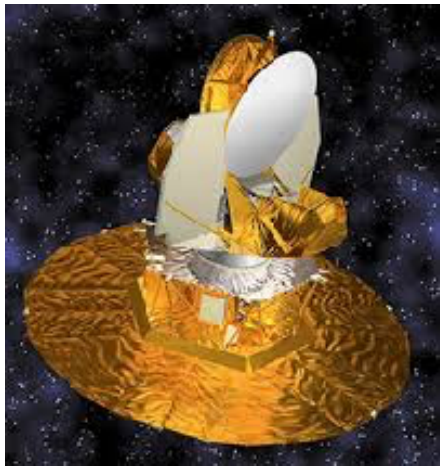
Current Situation

- No detection of polarisation from primordial GW yet
- Many ground-based and balloon-borne experiments are taking data now

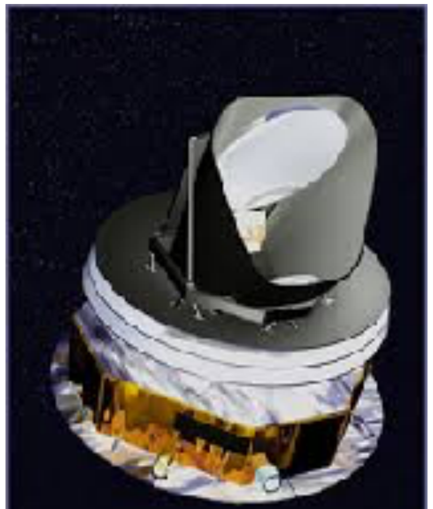
The search continues!!



1989–1993

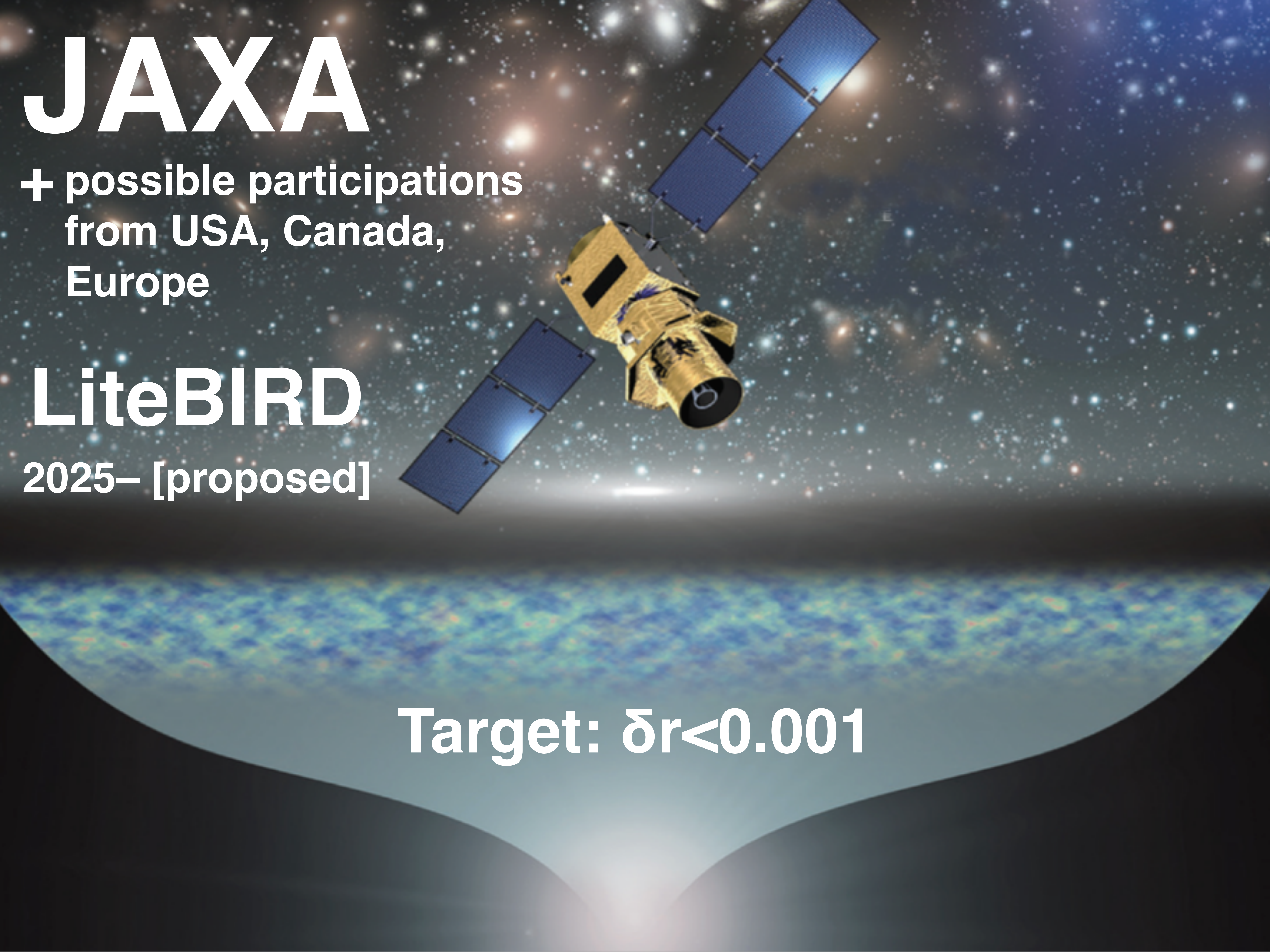


2001–2010



2009–2013

202X–



JAXA

+ possible participations
from USA, Canada,
Europe

LiteBIRD

2025– [proposed]

Target: $\delta r < 0.001$

JAXA

+ possible participations
from USA, Canada,
Europe

LiteBIRD

2025– [proposed]

Polarisation satellite dedicated to measure CMB polarisation from primordial GW, with a few thousand super-conducting detectors in space

JAXA

+ possible participations
from USA, Canada,
Europe

LiteBIRD

2025– [proposed]

Down-selected by JAXA as one of the two missions competing for a launch in mid 2020's

Summary

- Single-field inflation looks good: all the CMB data support it
- **<u>Next frontier</u>**: Using CMB polarisation to find GWs from inflation. **Definitive evidence for inflation!**
  - With LiteBIRD we plan to reach $r \sim 10^{-3}$, i.e., 100 times better than the current bound
  - GW from vacuum or sources? An exciting window to new physics

B-mode power spectrum measurements

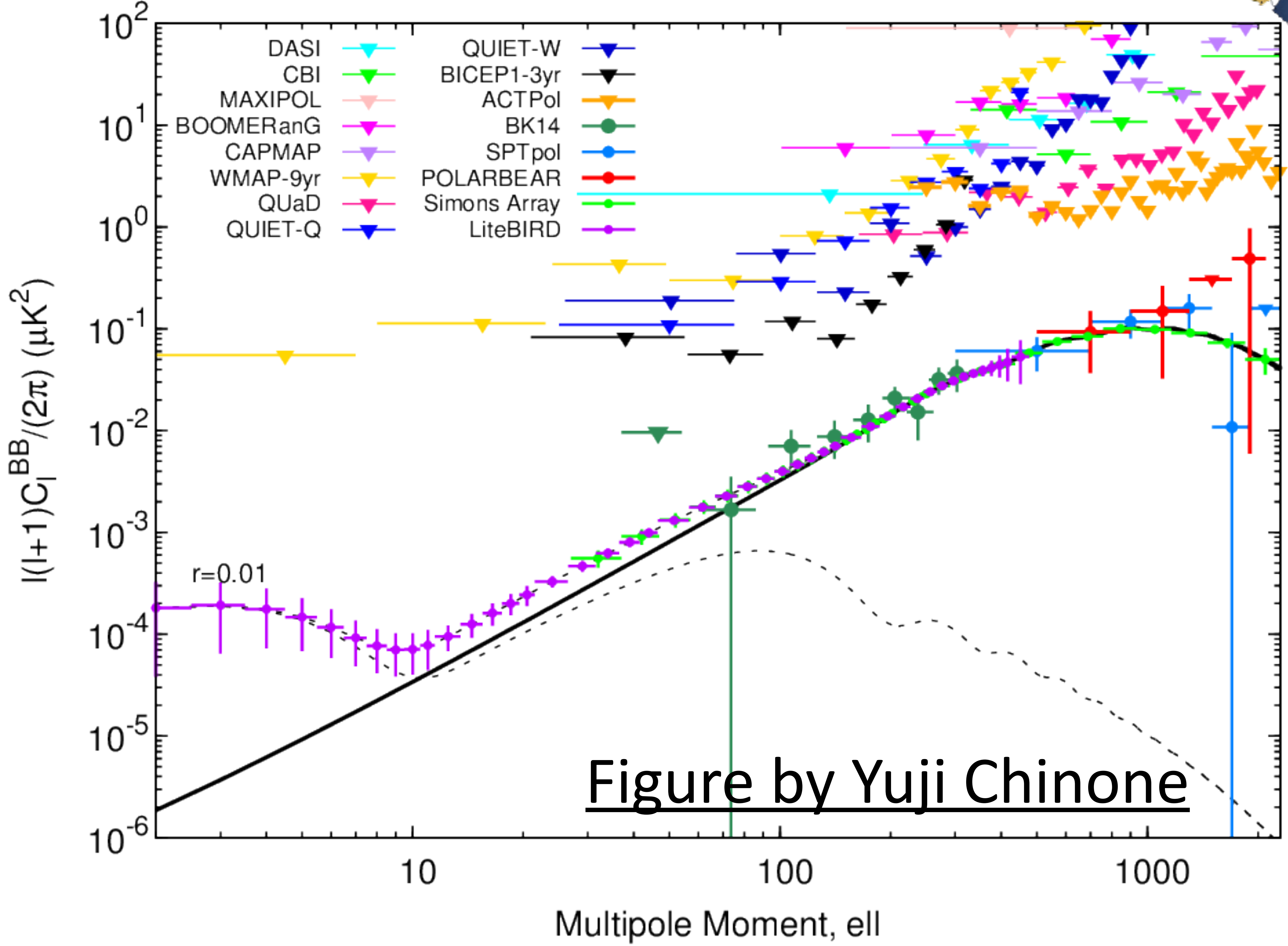


Figure by Yuji Chinone

LiteBIRD working group

152 members, international and interdisciplinary (as of July 2017)

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E. Linder
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C.-L. Kuo
D. Li
T. Namikawa
K. L. Thompson

Satellite

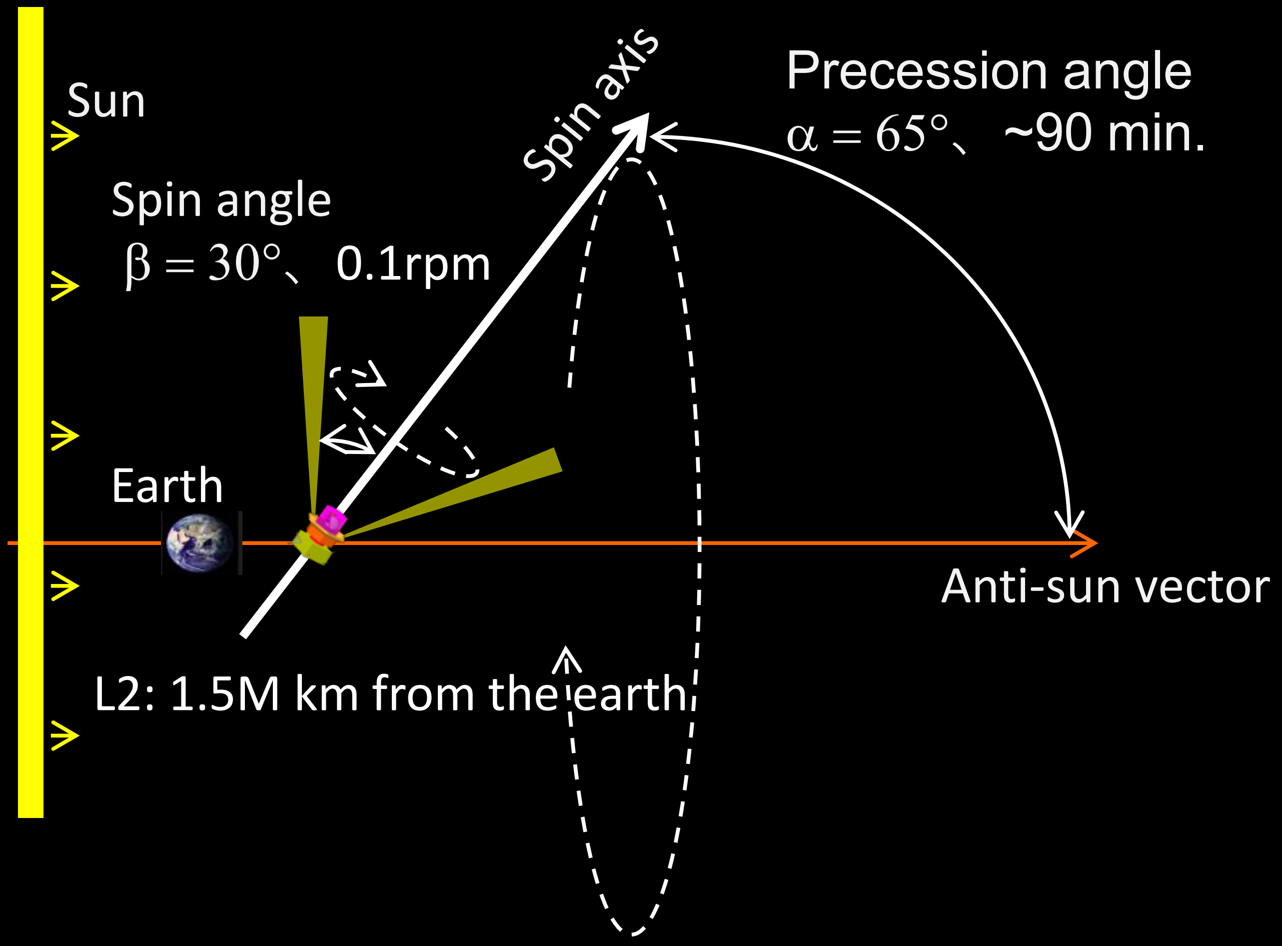
X-ray

Infrared

CMB

Observation Strategy

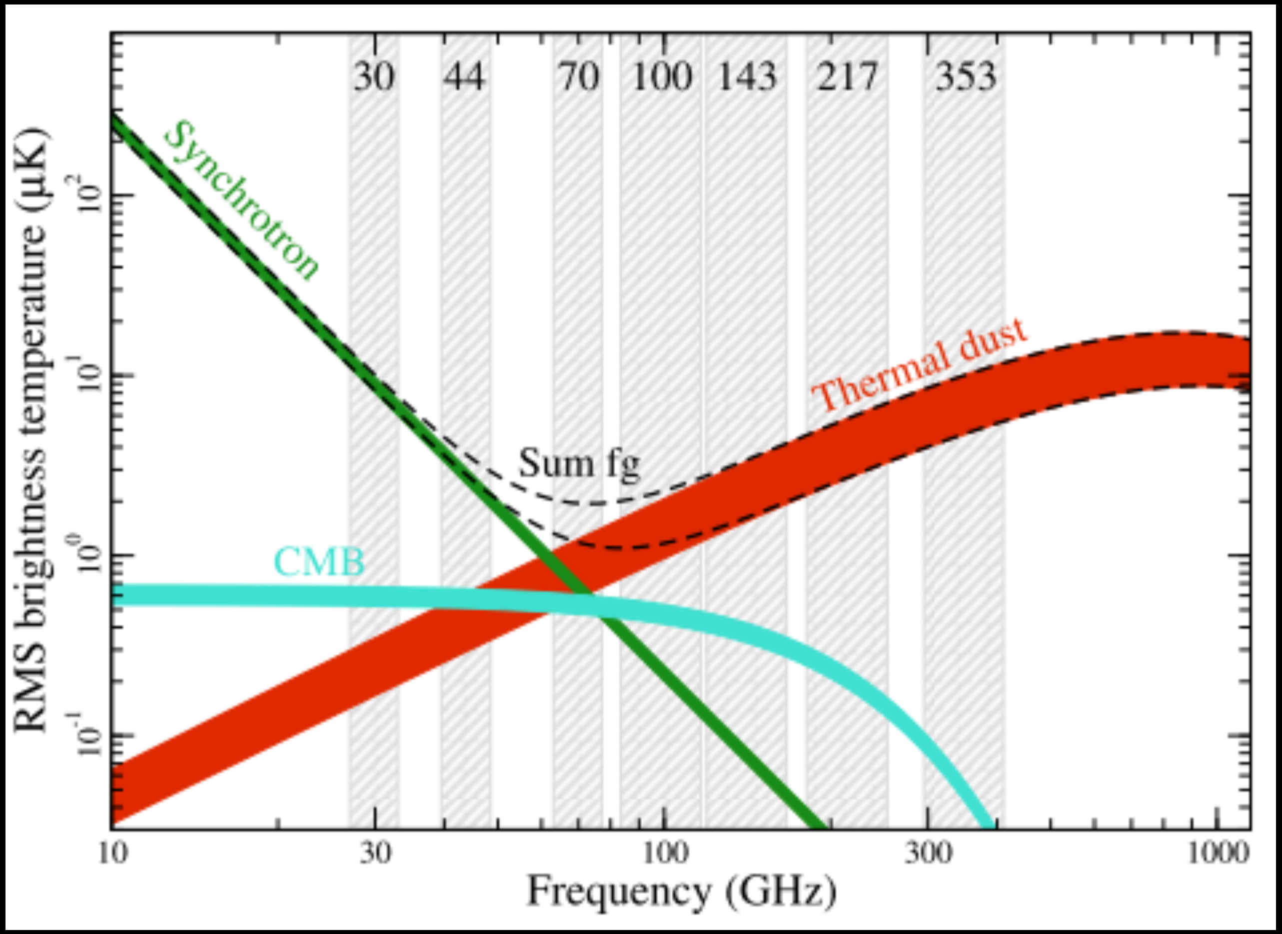
JAXA H3 Launch Vehicle (JAXA)



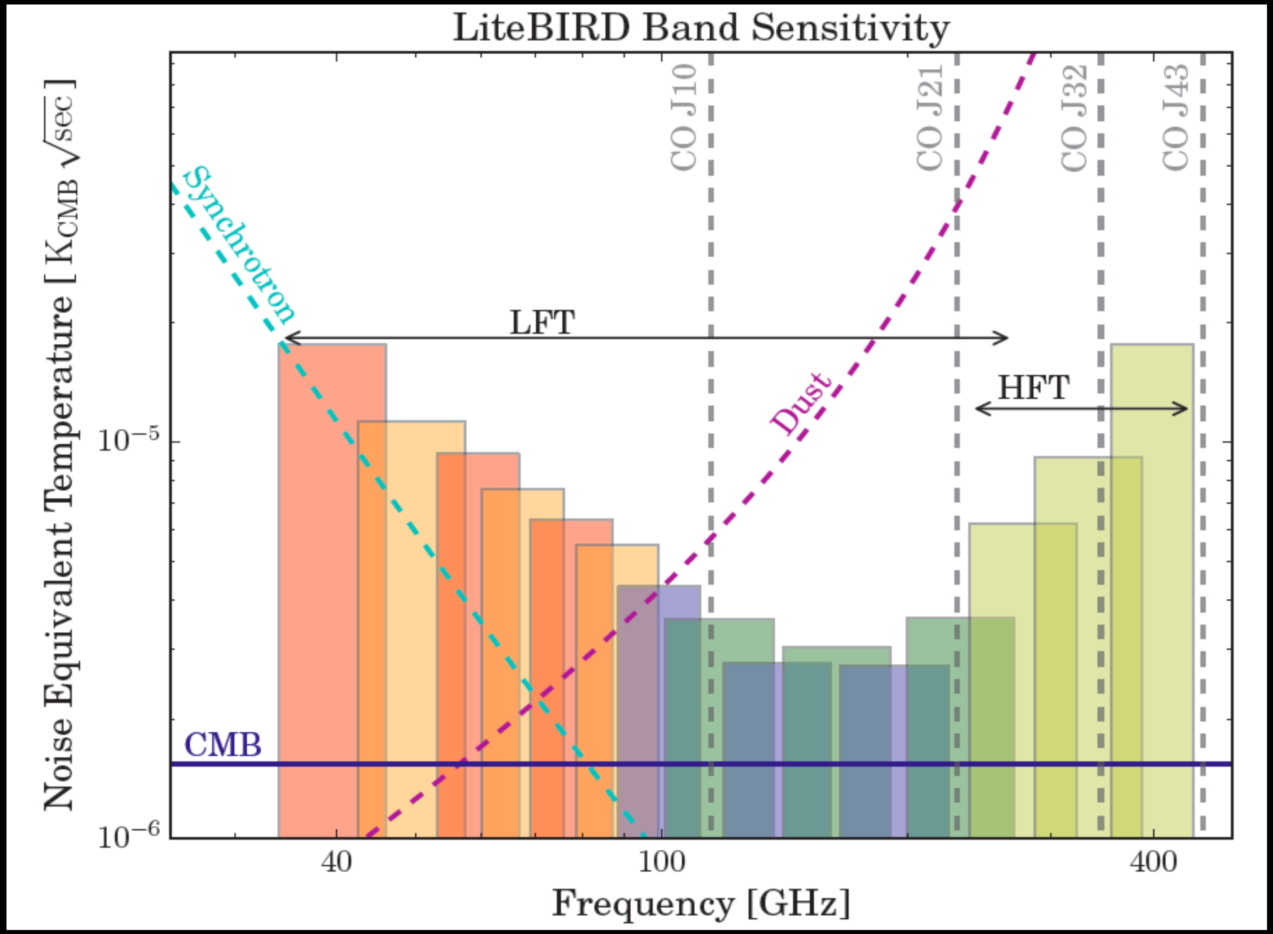
- Launch vehicle: JAXA H3
- Observation location: Second Lagrangian point (L2)
- Scan strategy: Spin and precession, full sky
- Observation duration: 3-years
- Proposed launch date: Mid 2020's

Slide courtesy Toki Suzuki (Berkeley)

Foreground Removal



Polarized galactic emission (Planck X)



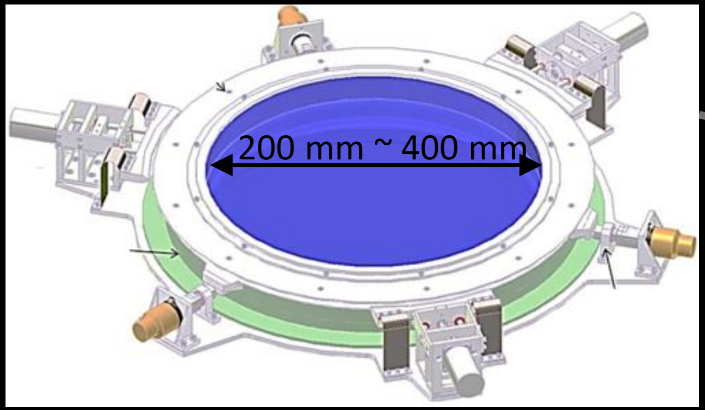
LiteBIRD: 15 frequency bands

- 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

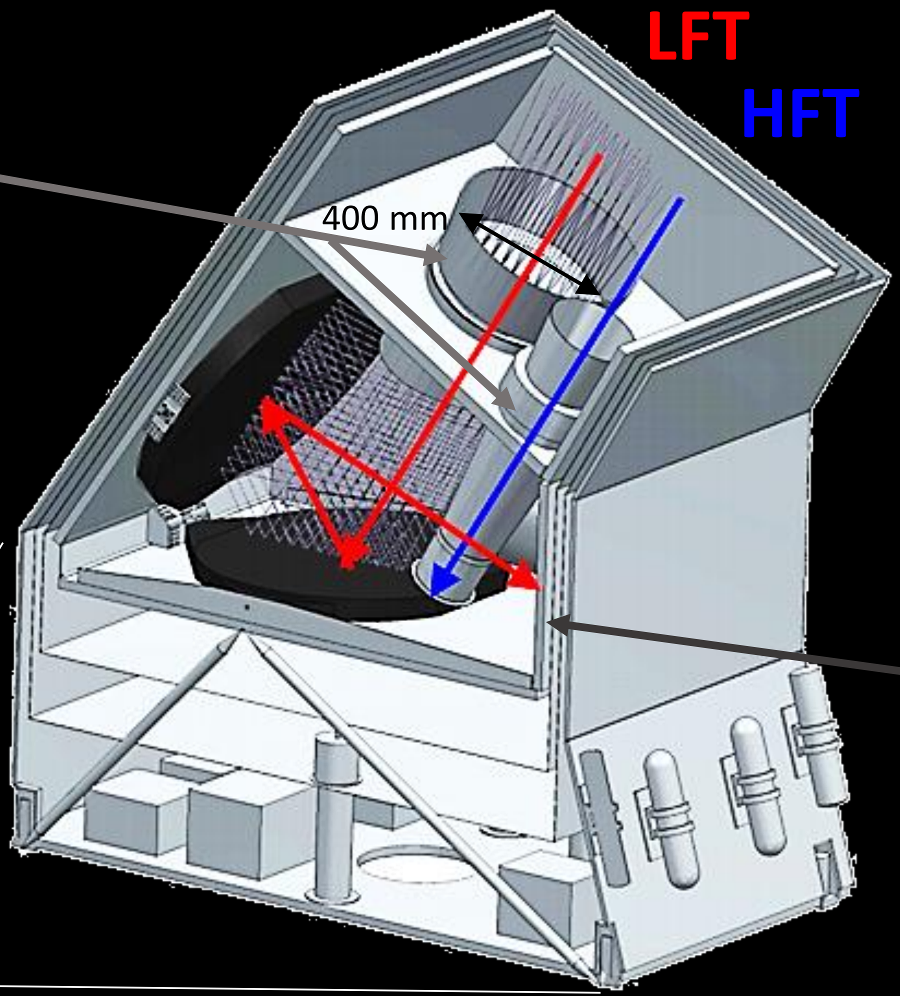
Slide courtesy Toki Suzuki (Berkeley)

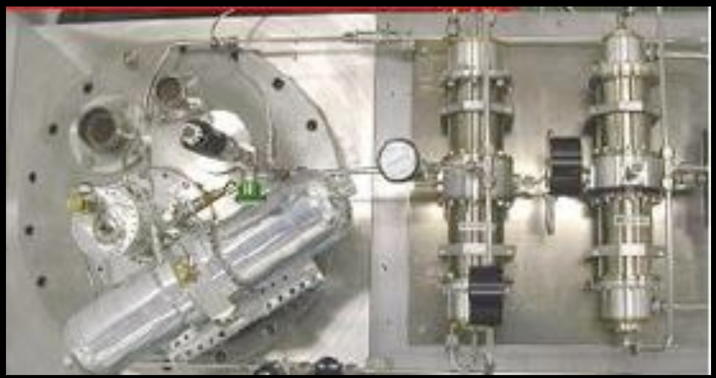
Instrument Overview

Slide courtesy Toki Suzuki (Berkeley)

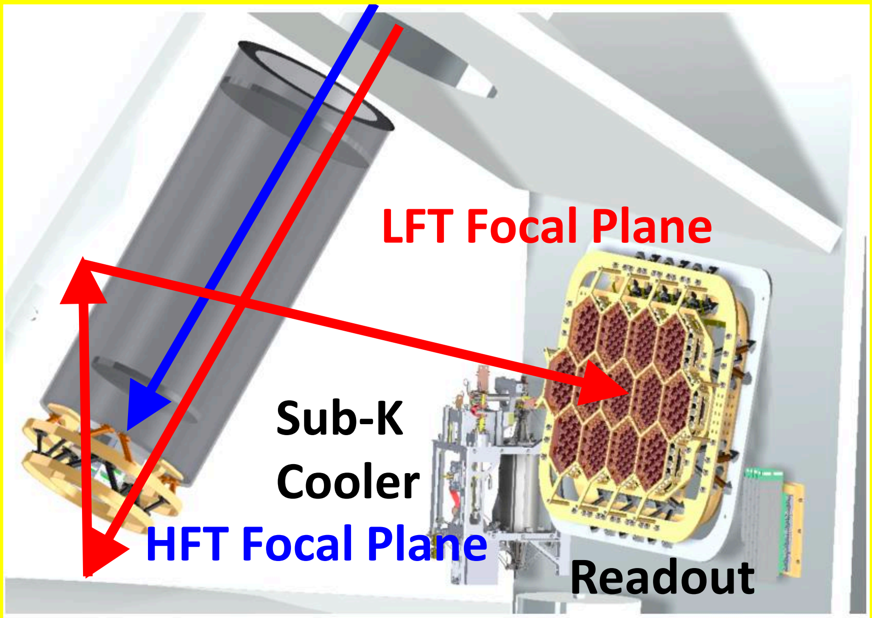


Half-wave plate

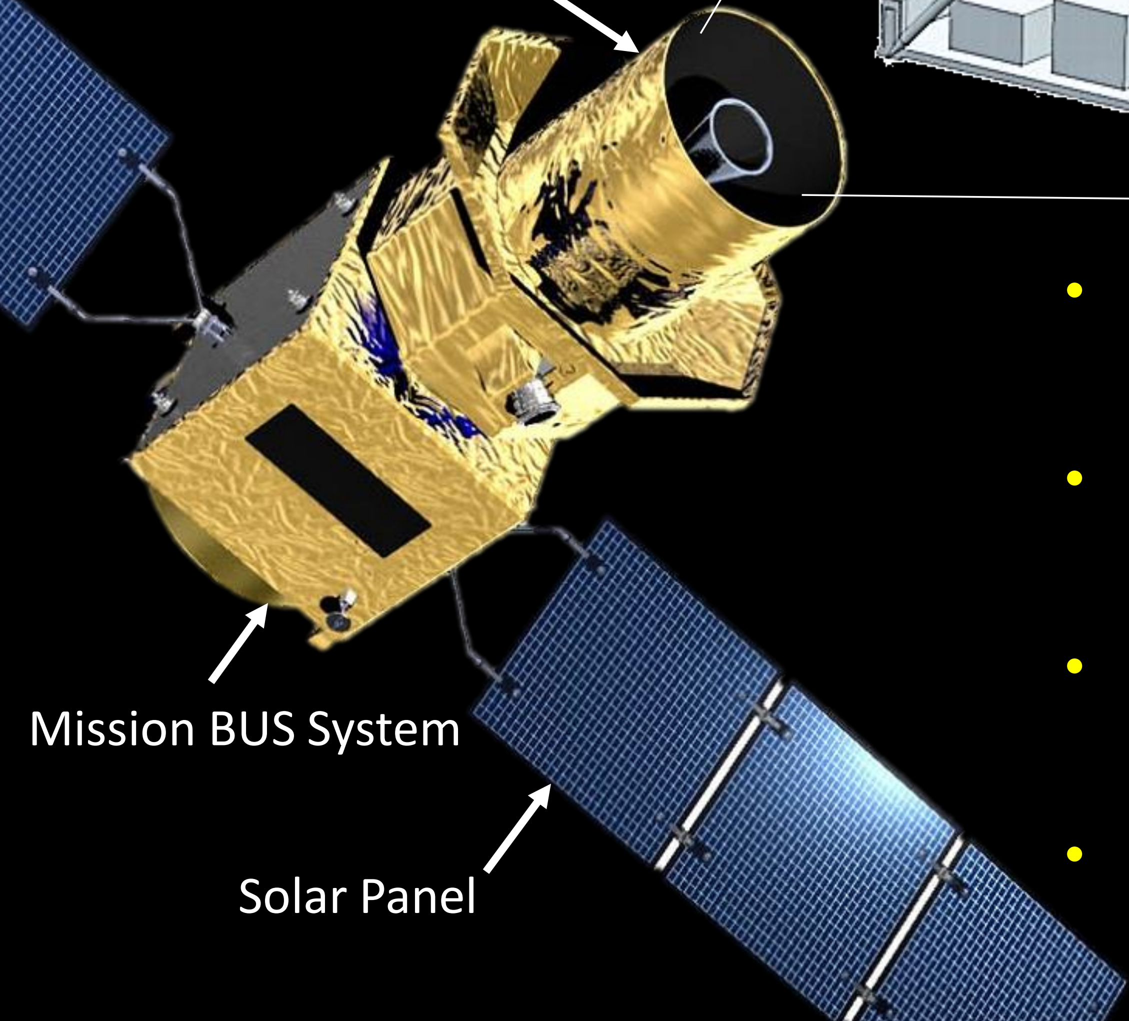




Stirling & Joule Thomson Coolers



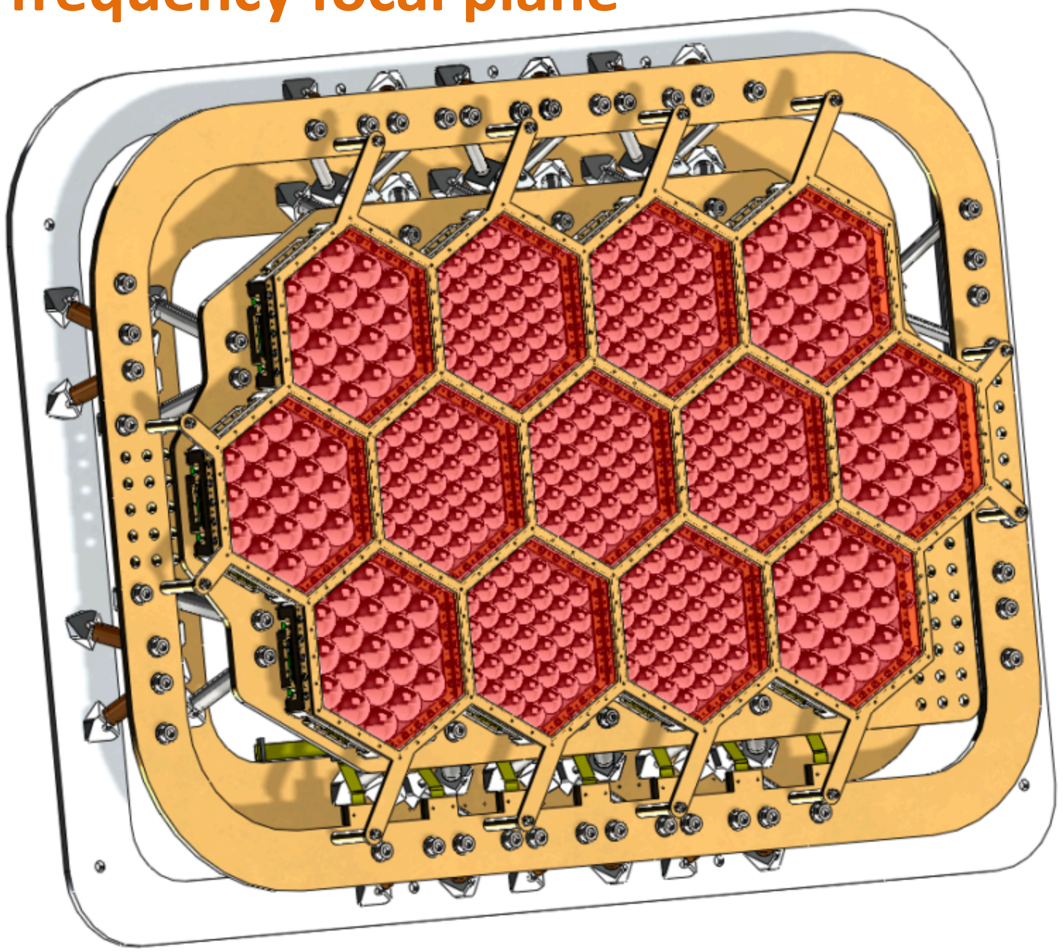
Sub-Kelvin Instrument

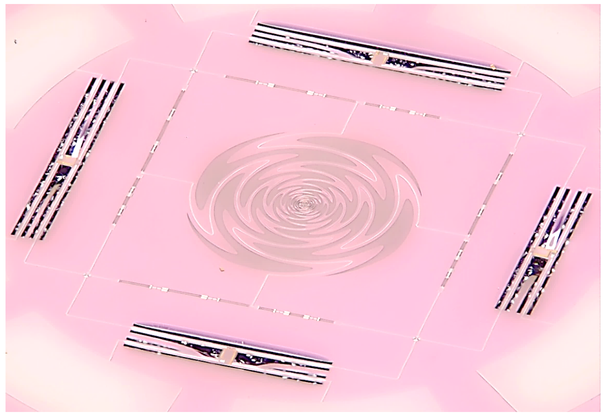


- Two telescopes
  - Crossed-Dragone (LFT) & on-axis refractor (HFT)
- Cryogenic rotating achromatic half-wave plate
  - Modulates polarization signal
- Stirling & Joule Thomson coolers
  - Provide cooling power above 2 Kelvin
- Sub-Kelvin Instrument
  - Detectors, readout electronics, and a sub-kelvin cooler

LFT and HFT focal plane units using TES

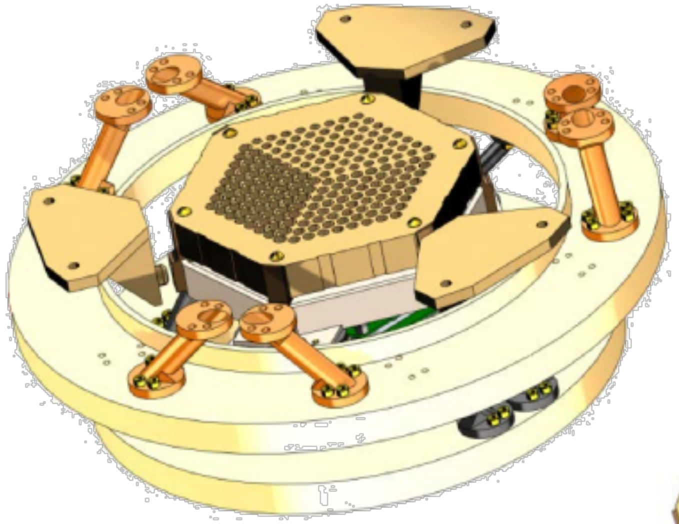
Low frequency focal plane



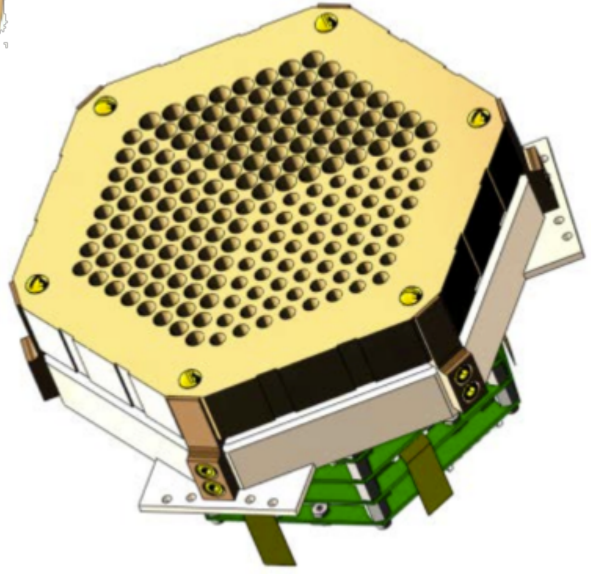


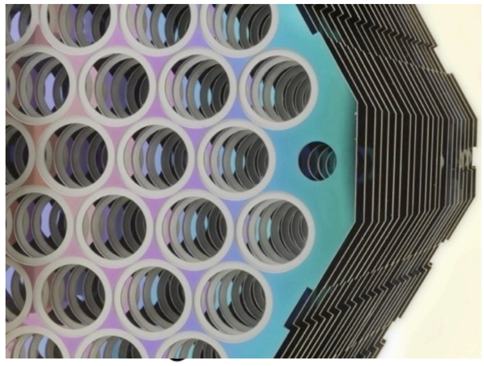
Three colors per pixel
with a lenslet coupling.

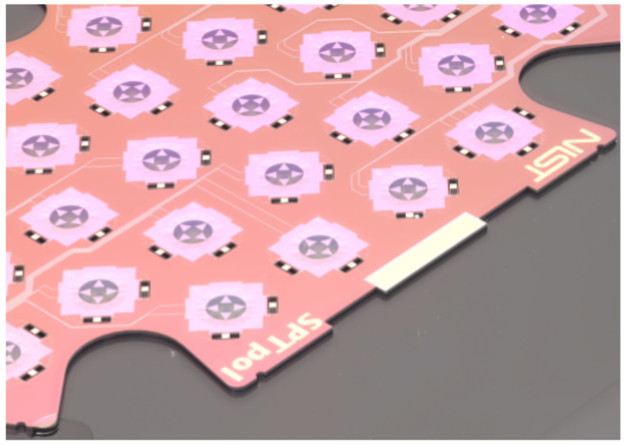
High frequency focal plane

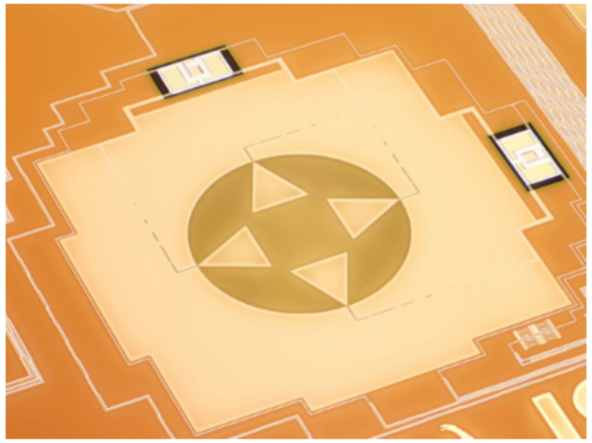


Each color per feed,
and three colors within
one focal plane.





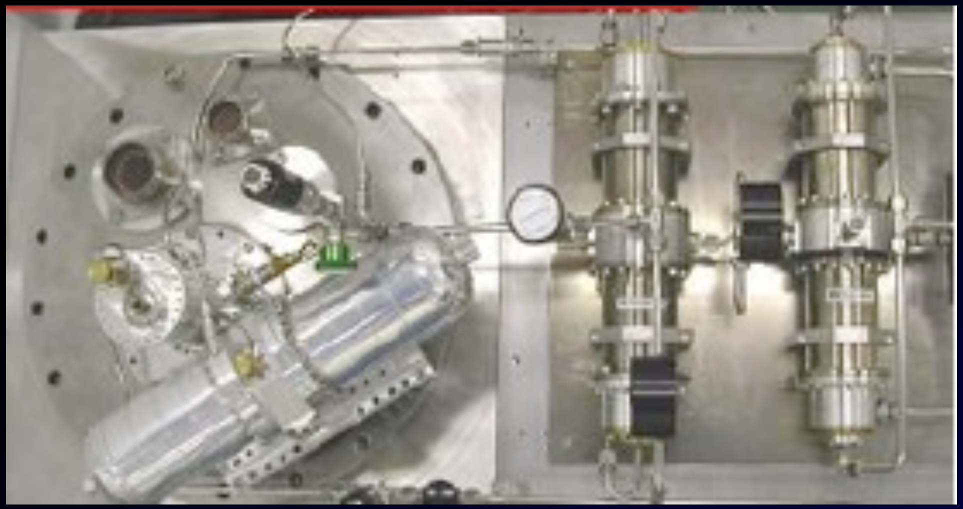




- The current baseline design uses a single ADR to cool the both focal planes.
- The LF focal plane has ** TESs and the HF focal plane has ** TESs.
- The TES is read by SQUID together with the readout electronics is based on the digital frequency multiplexing system.
- The effect of the cosmic ray is evaluated by building a model. The irradiation test is in plan.

Slide courtesy Tomo Matsumura (Kavli IPMU)

Cooling system



SHI/JAXA

Cryogenics

- Warm launch
- 3 years of observations
- 4 K for the mission instruments (optical system)
- 100 mK for the focal plane

Mechanical cooler

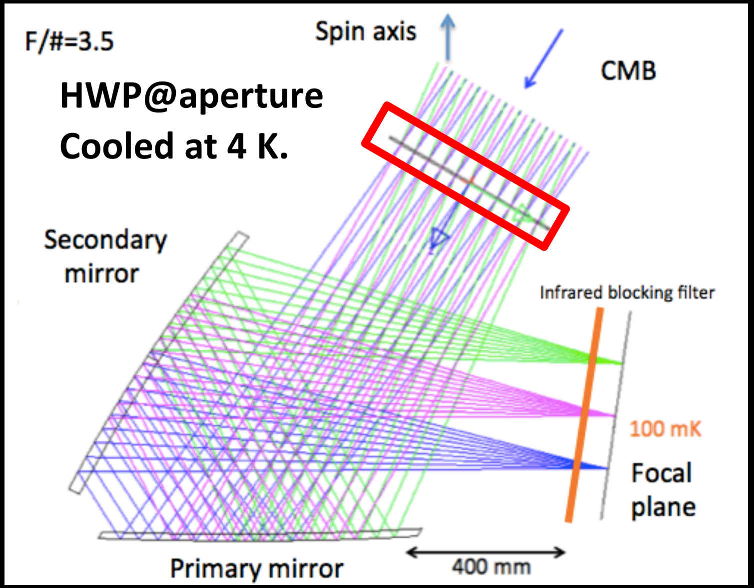
- The 2-stage Stirling cooler and 4K-JT cooler from the heritage of the JAXA satellites, Akari (Astro-F), JEM-SMILES and Astro-H.
- The 1K-JT provides the 1.7 K interface to the sub-Kelvin stage.

Sub-Kelvin cooler

- ADR has a high-TRL and extensive development toward Astro-H, SPICA, and Athena.
- Closed dilution with the Planck heritage is also under development.

Slide courtesy Tomo Matsumura (Kavli IPMU)

Polarization modulator



Note: we also employ the polarization modulator for HFT.

- Due to our focus on the primordial signal at low ell, we employ the continuously rotating achromatic half-wave plate (HWP).
- The HWP modulator suffices mitigating the 1/f noise and the differential systematics.

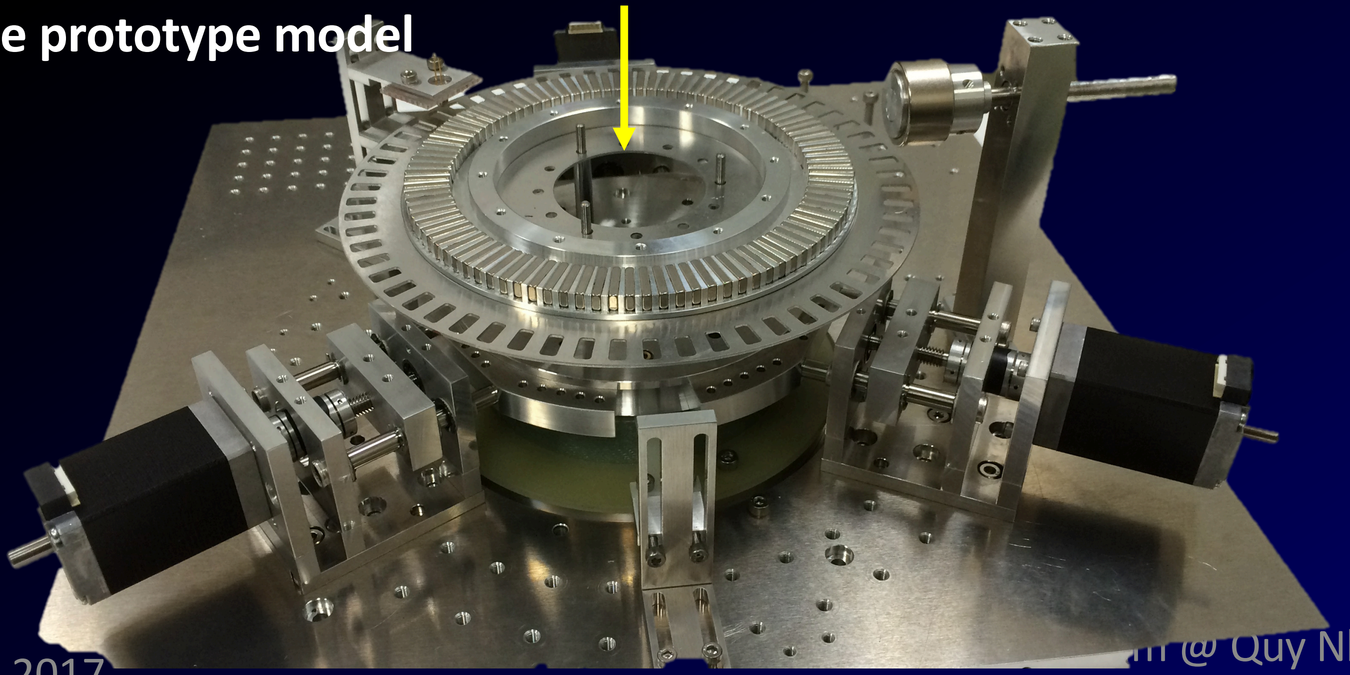
Broadband coverage

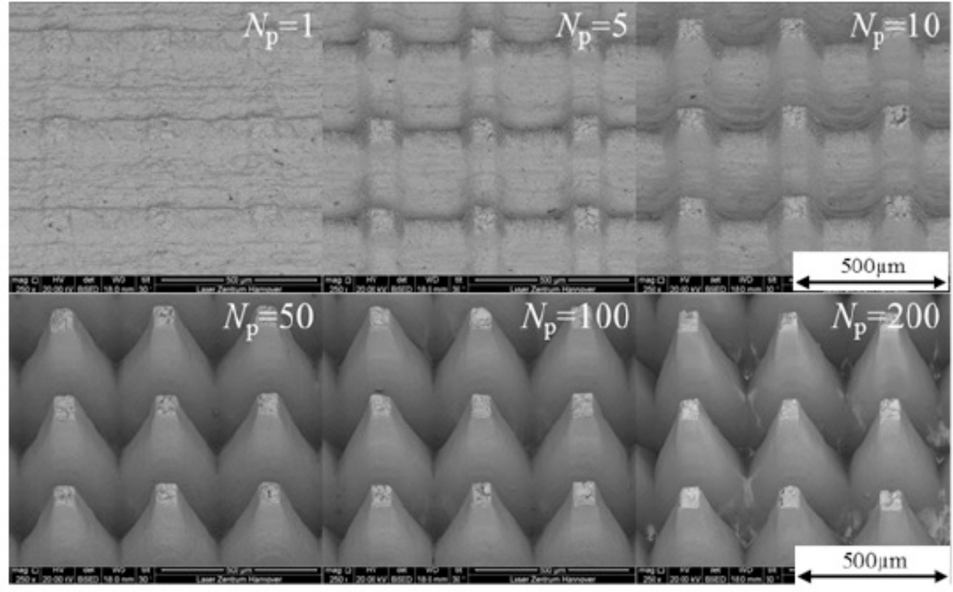
- The broadband coverage is done by the sub-wavelength anti-reflection structure.
- The broadband modulation efficiency is achieved by using 9-layer achromatic HWP.

Rotational mechanism

The continuous rotation is achieved by employing the superconducting magnetic bearing. This system has a heritage from EBEX. The prototype system has built and test the kinetic and thermal feasibility.

The 1/9 scale prototype model





The proton irradiation test is conducted to key components, including sapphire, YBCO, and magnets. We have not found the no-go results. And the further test is in progress.

Slide courtesy Tomo Matsumura (Kavli IPMU)