Critical Tests of Theory of the Early Universe using the Cosmic Microwave Background

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Breakthrough in Cosmological Research

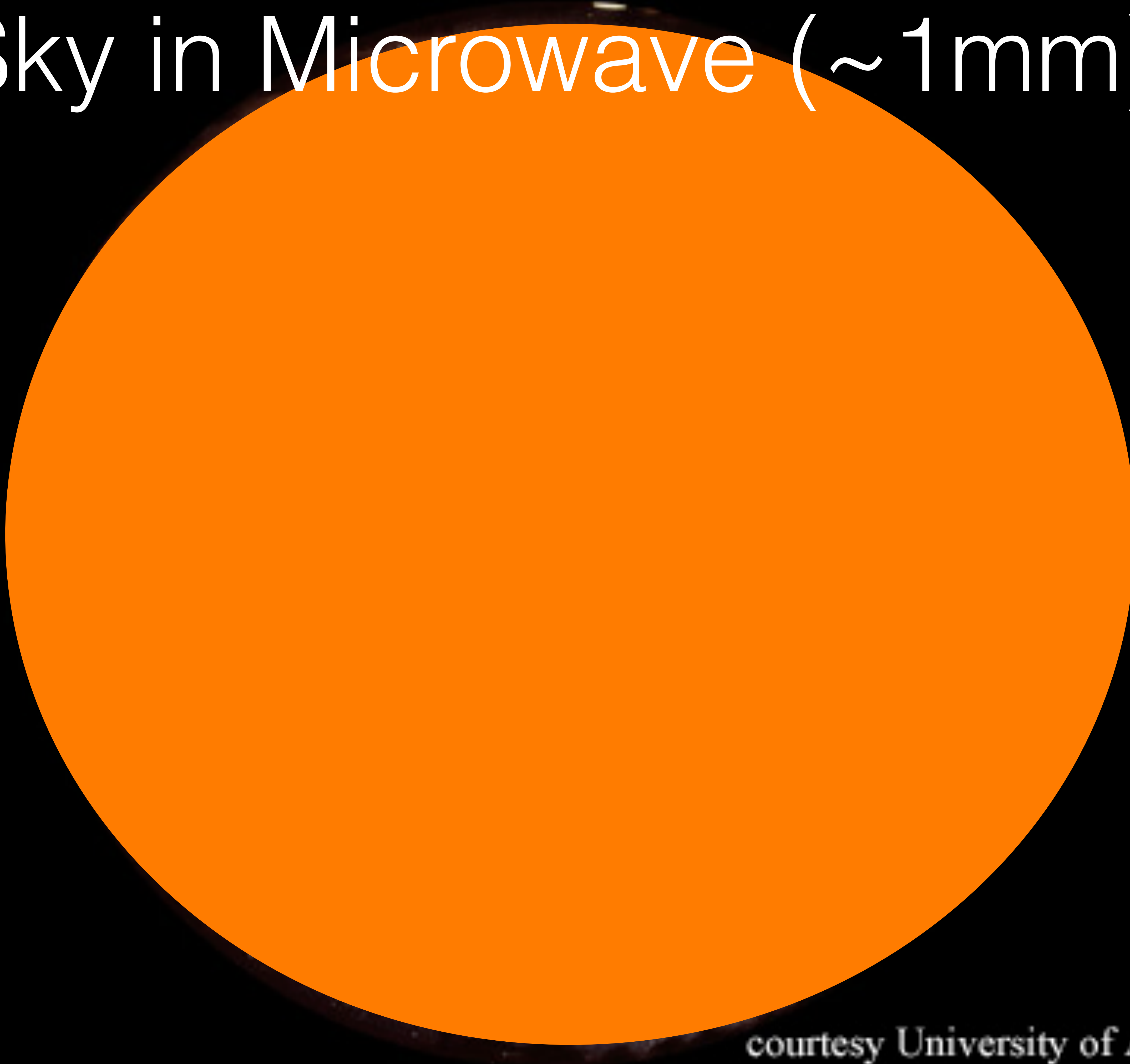
- We can actually **see** the physical condition of the universe when it was very young


From “Cosmic Voyage”

Sky in Optical (~0.5μm)

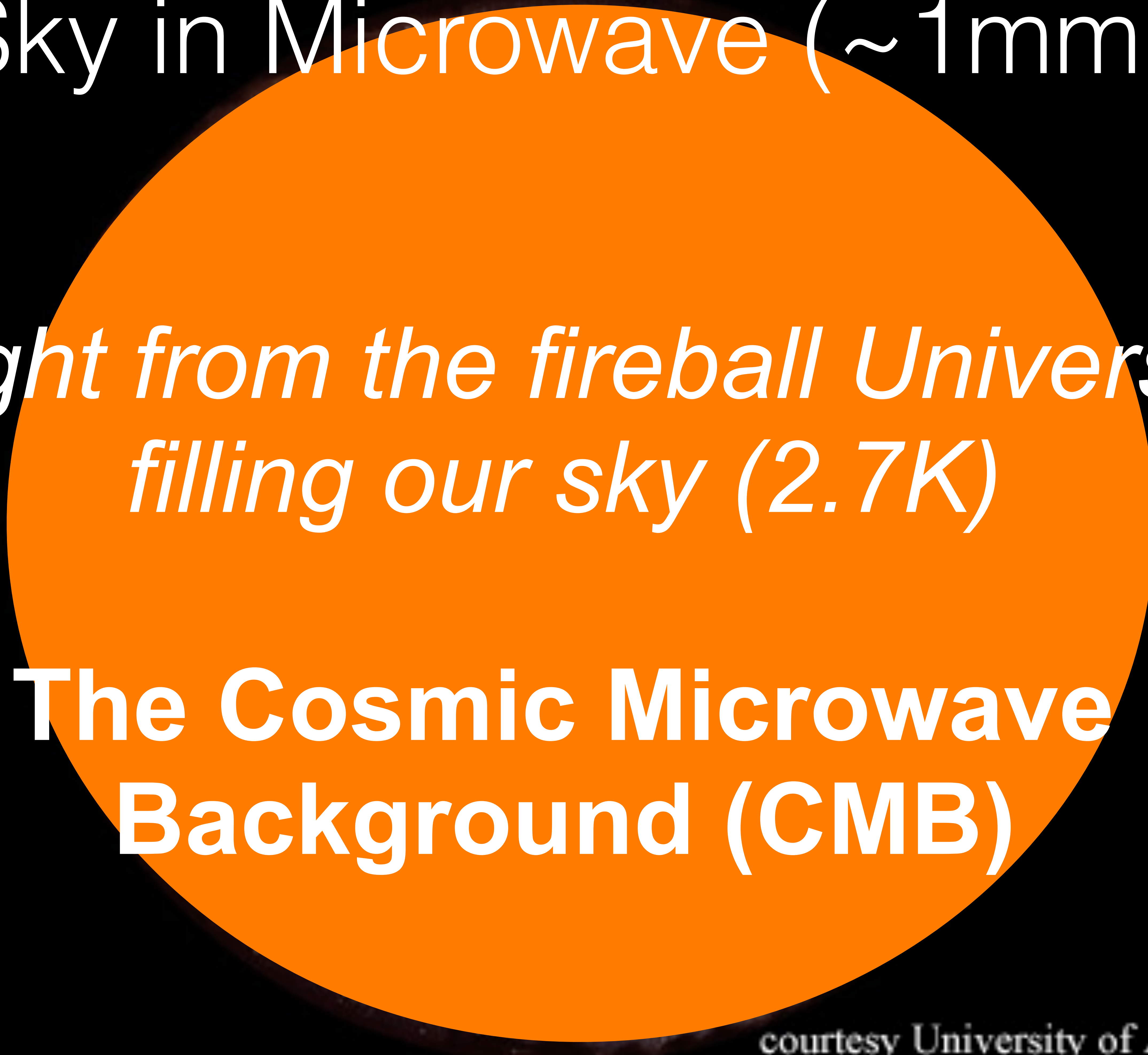
courtesy University of Arizona

Sky in Microwave (~1mm)



courtesy University of Arizona

Sky in Microwave (~1mm)



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

The Cosmic Microwave Background (CMB)

courtesy University of Arizona

410 photons

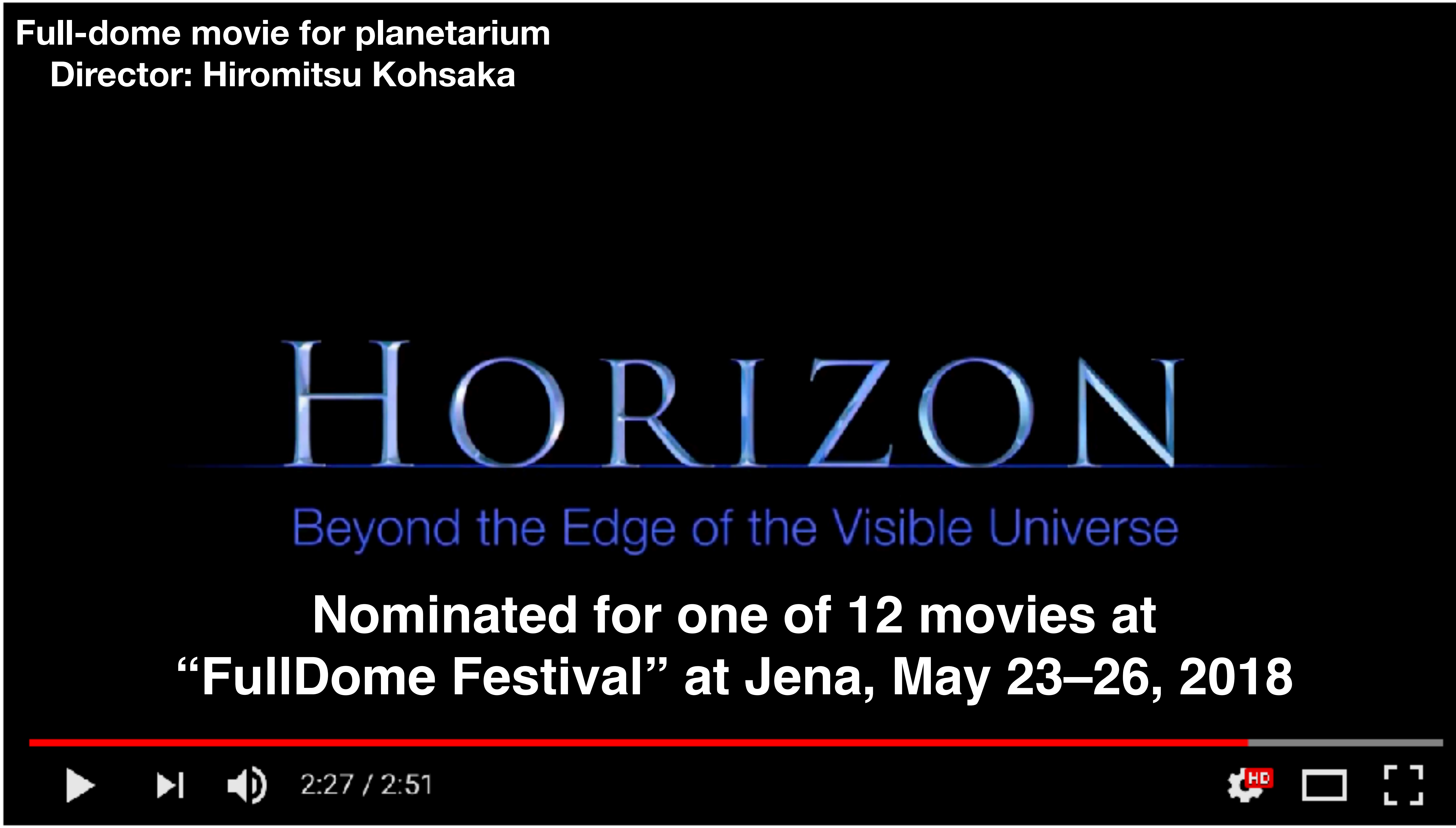
per

cubic centimeter!!

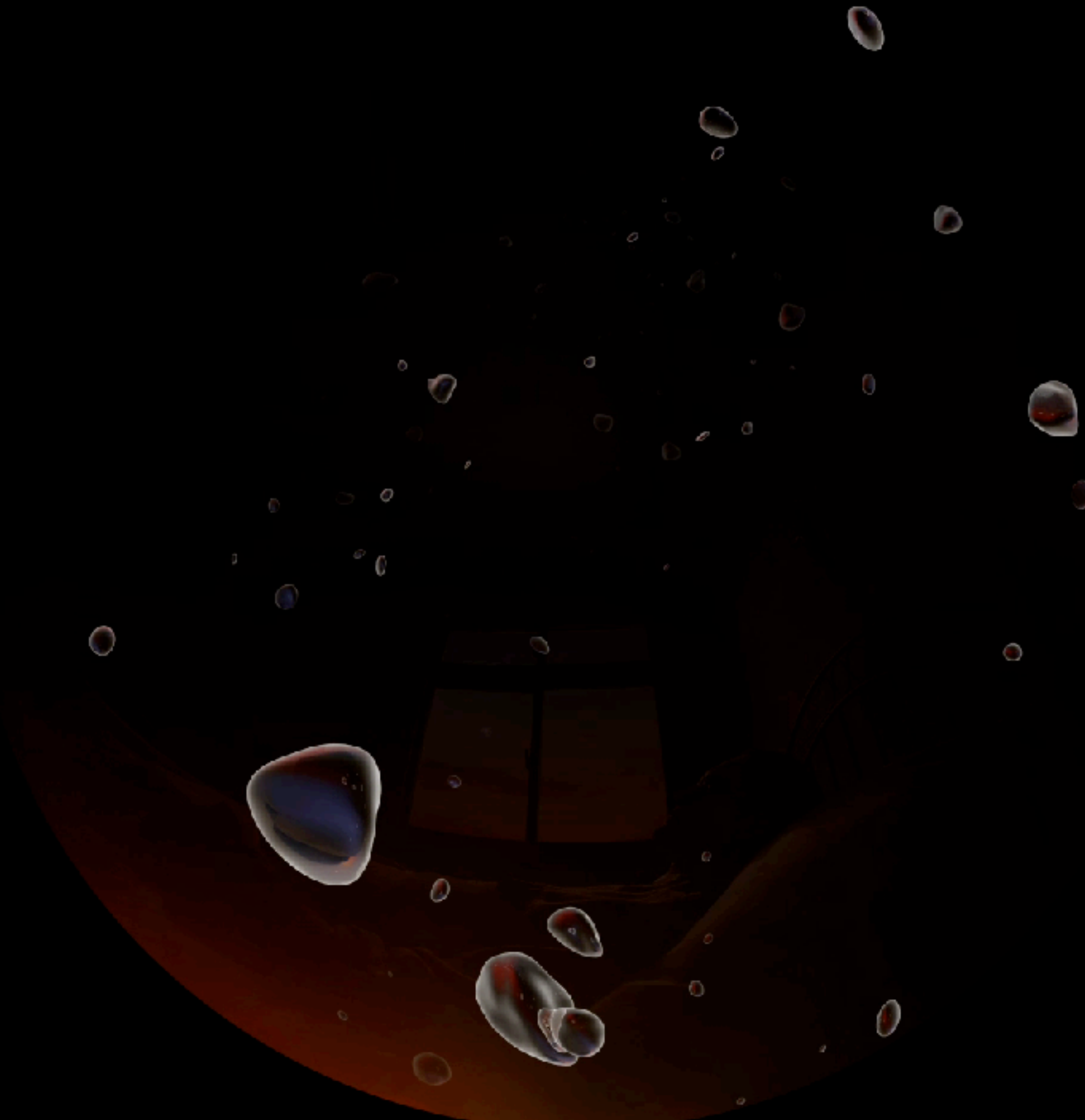
courtesy University of Arizona

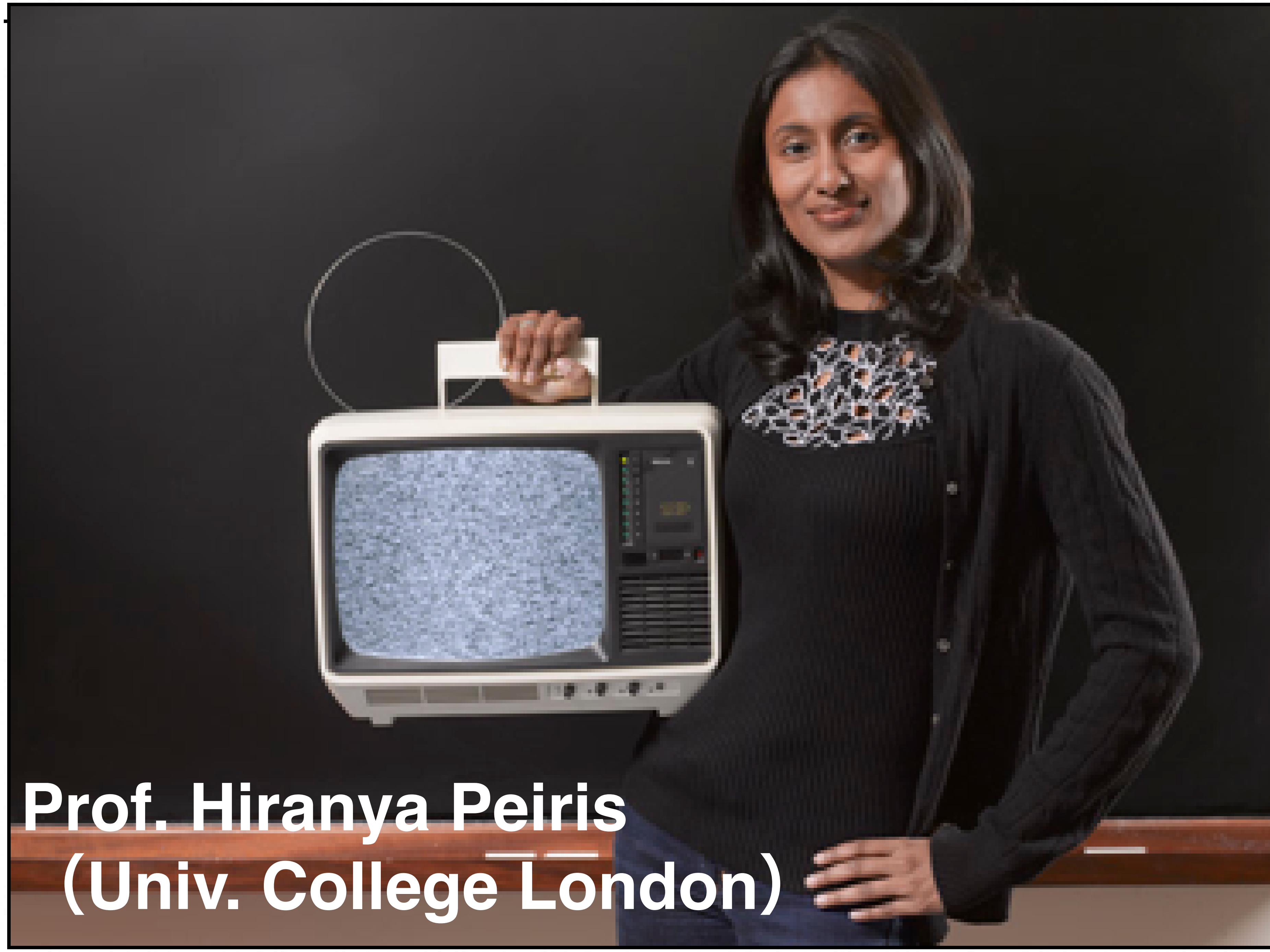
YouTube BE

horizon edge of the visible universe



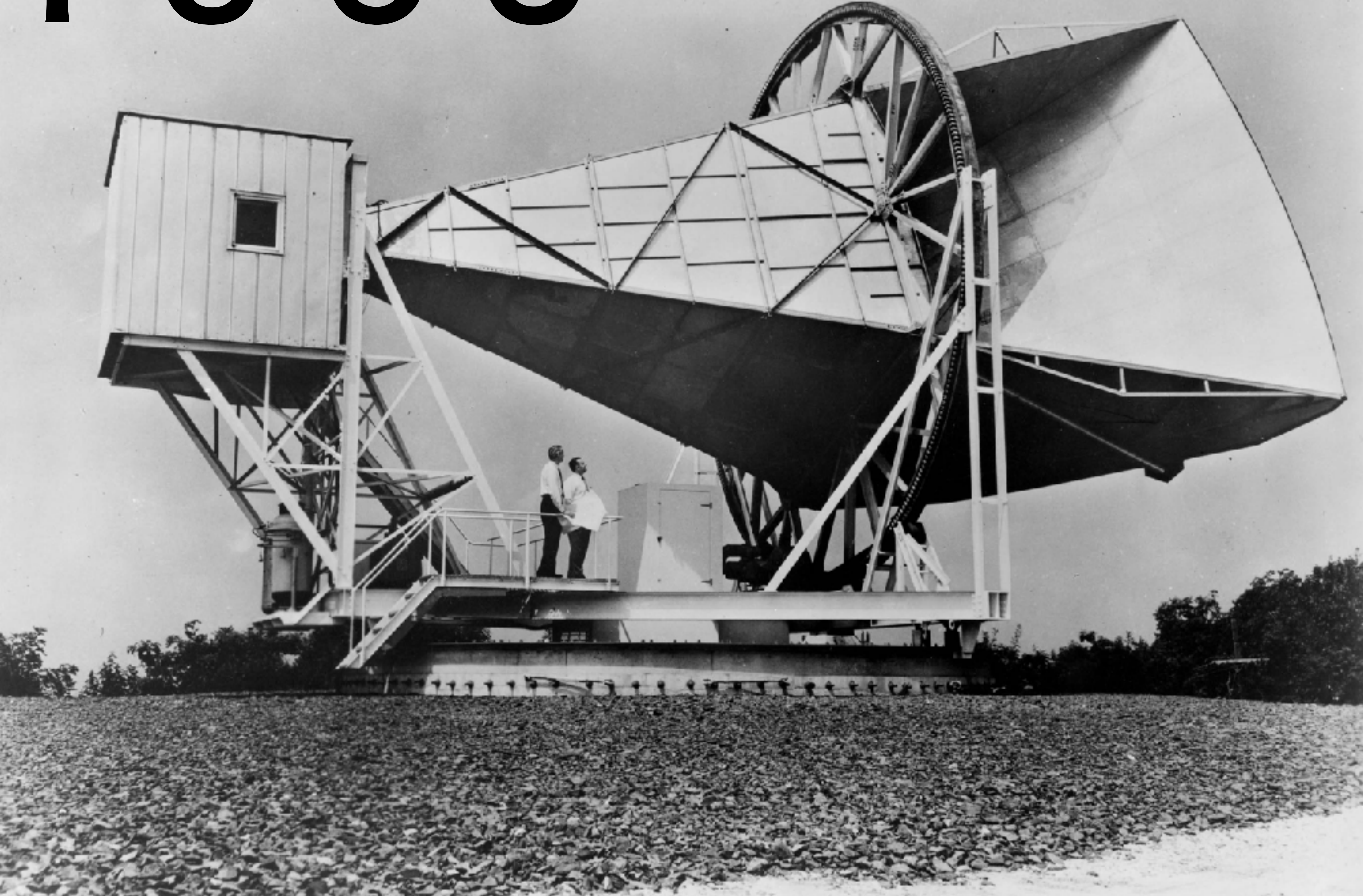
HORIZON :Beyond the Edge of the Visible Universe [Trailer]



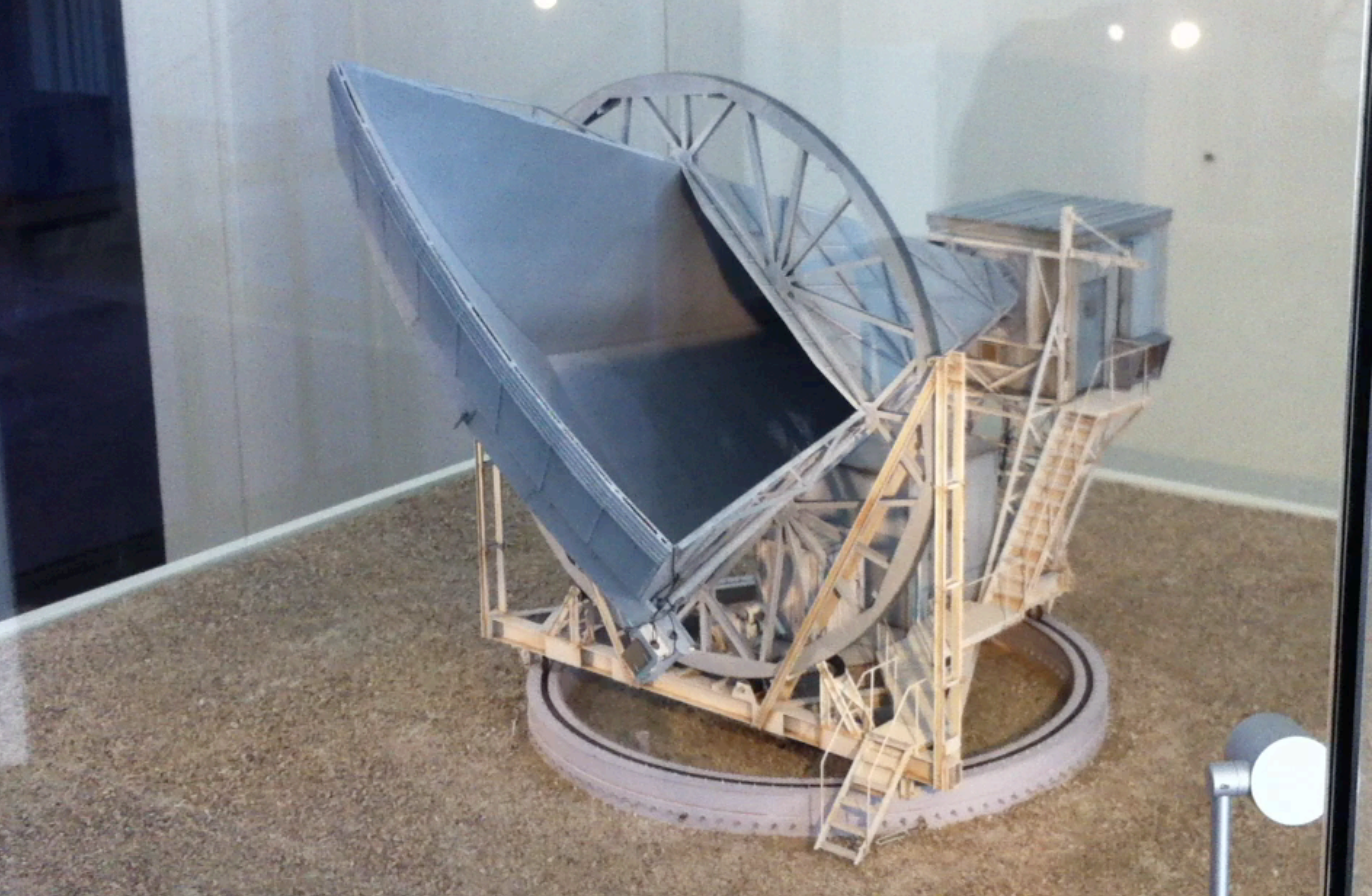


All you need to do is to detect radio waves. For example, 1% of noise on the TV is from the fireball Universe

1965

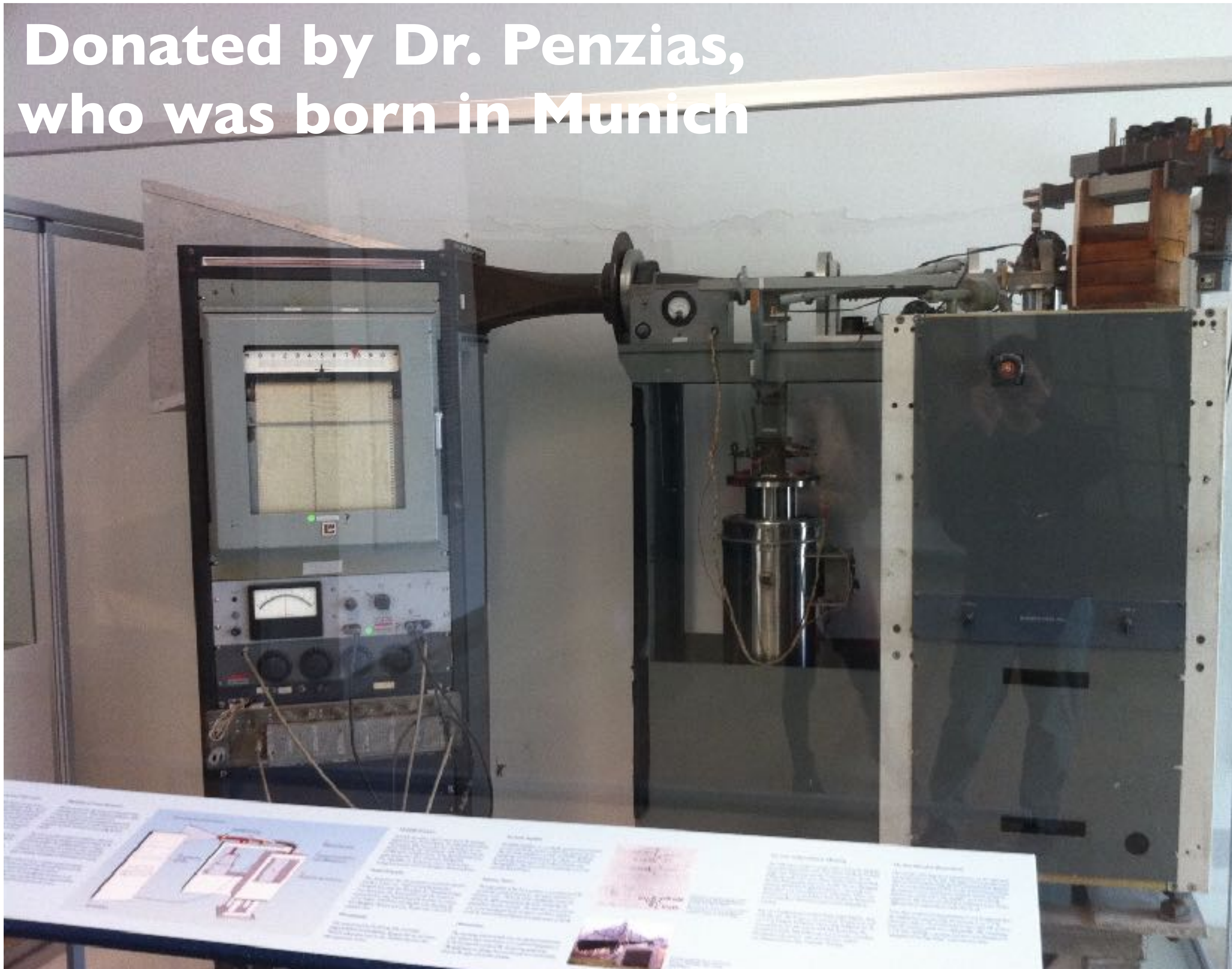


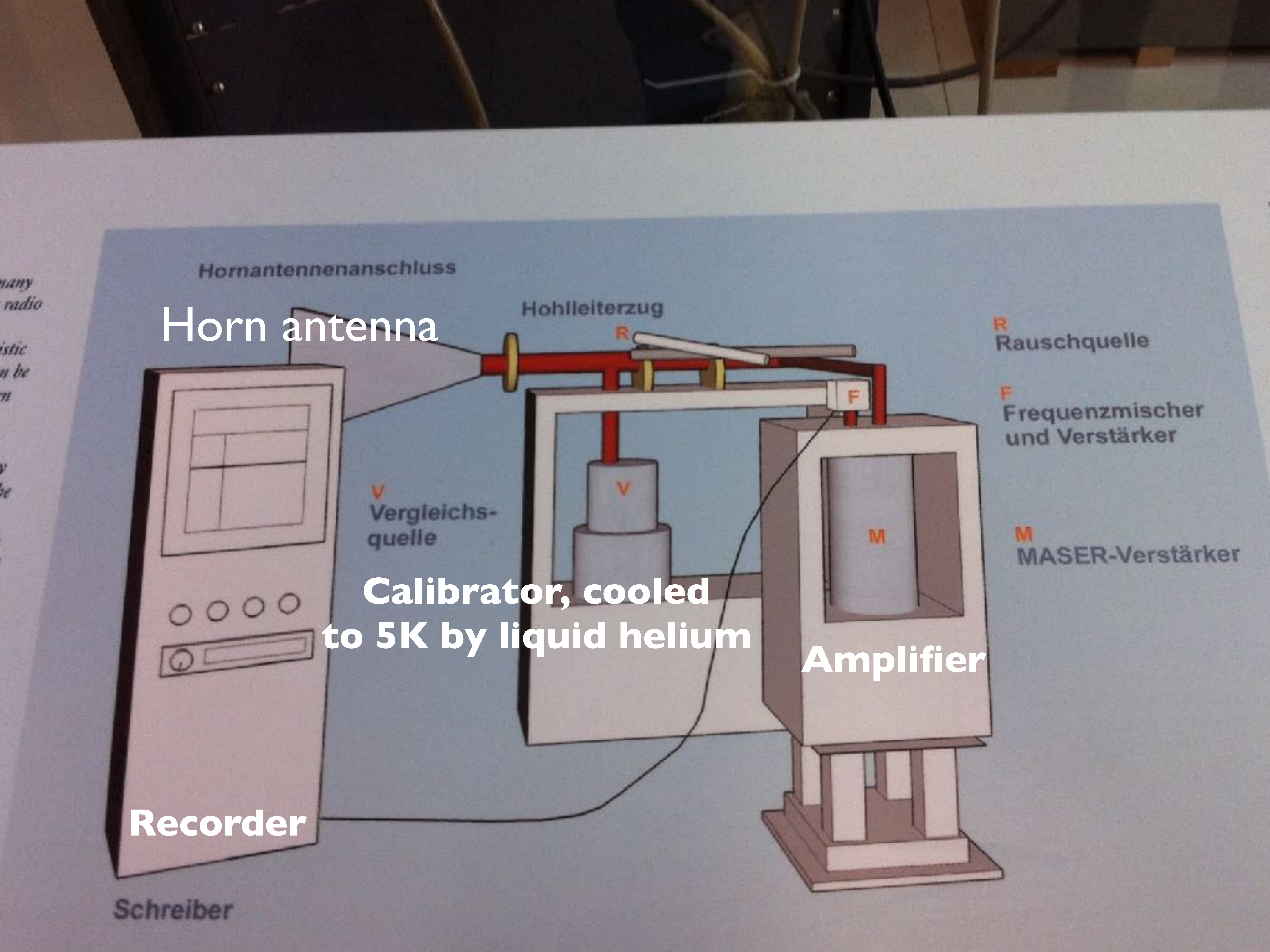
I:25 model of the antenna at Bell Lab
The 3rd floor of Deutsches Museum



The real detector system used by Penzias & Wilson
The 3rd floor of Deutsches Museum

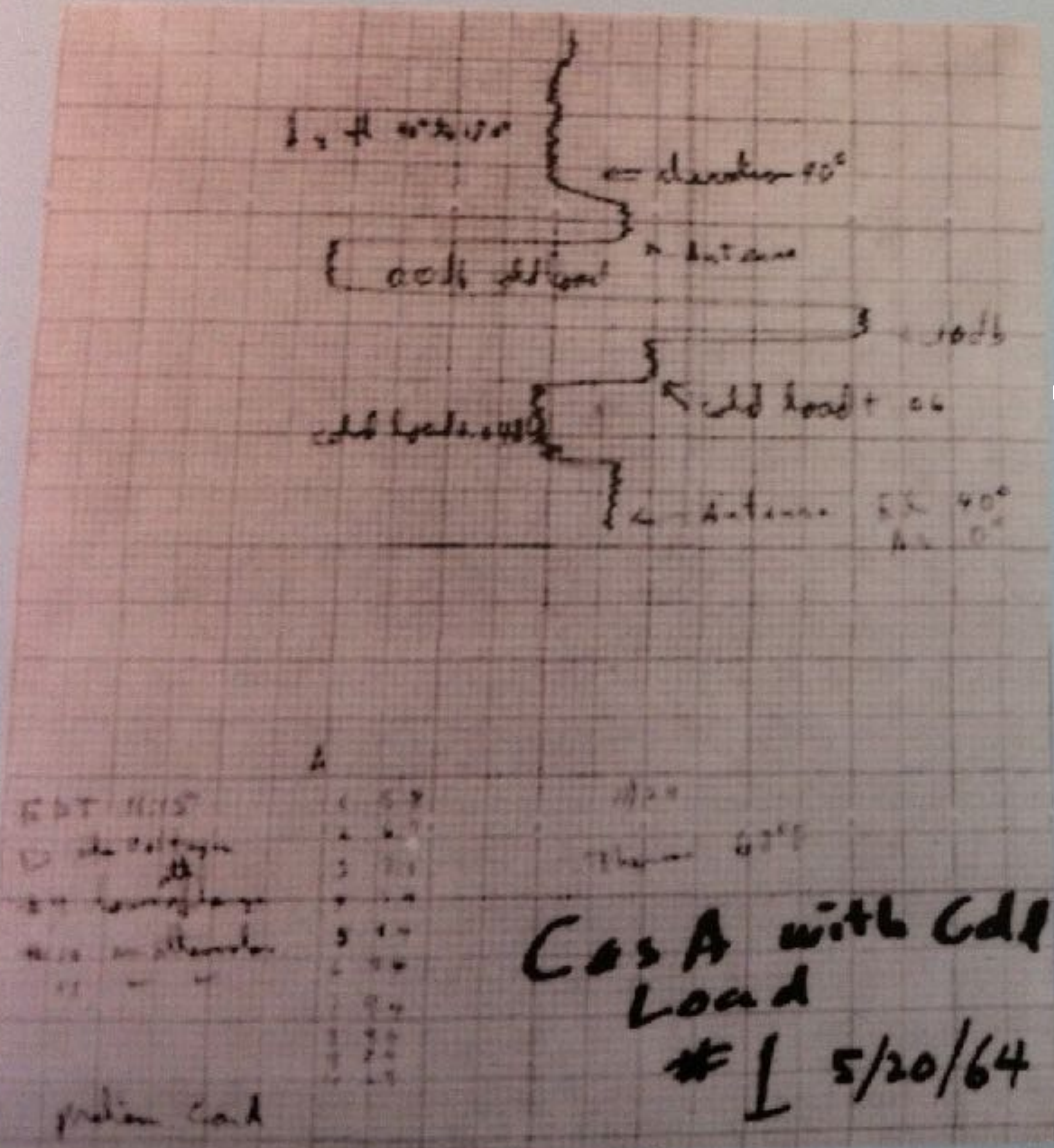

Arno Penzias


Donated by Dr. Penzias, who was born in Munich


Hornantennenanschluss
Horn antenna
Hohlleiterzug
R
R
Rauschquelle
F
F
Frequenzmischer
und Verstärker
V
Vergleichs-
quelle
V
M
M
MASER-Verstärker
Calibrator, cooled
to 5K by liquid helium
Amplifier
Recorder
Schreiber

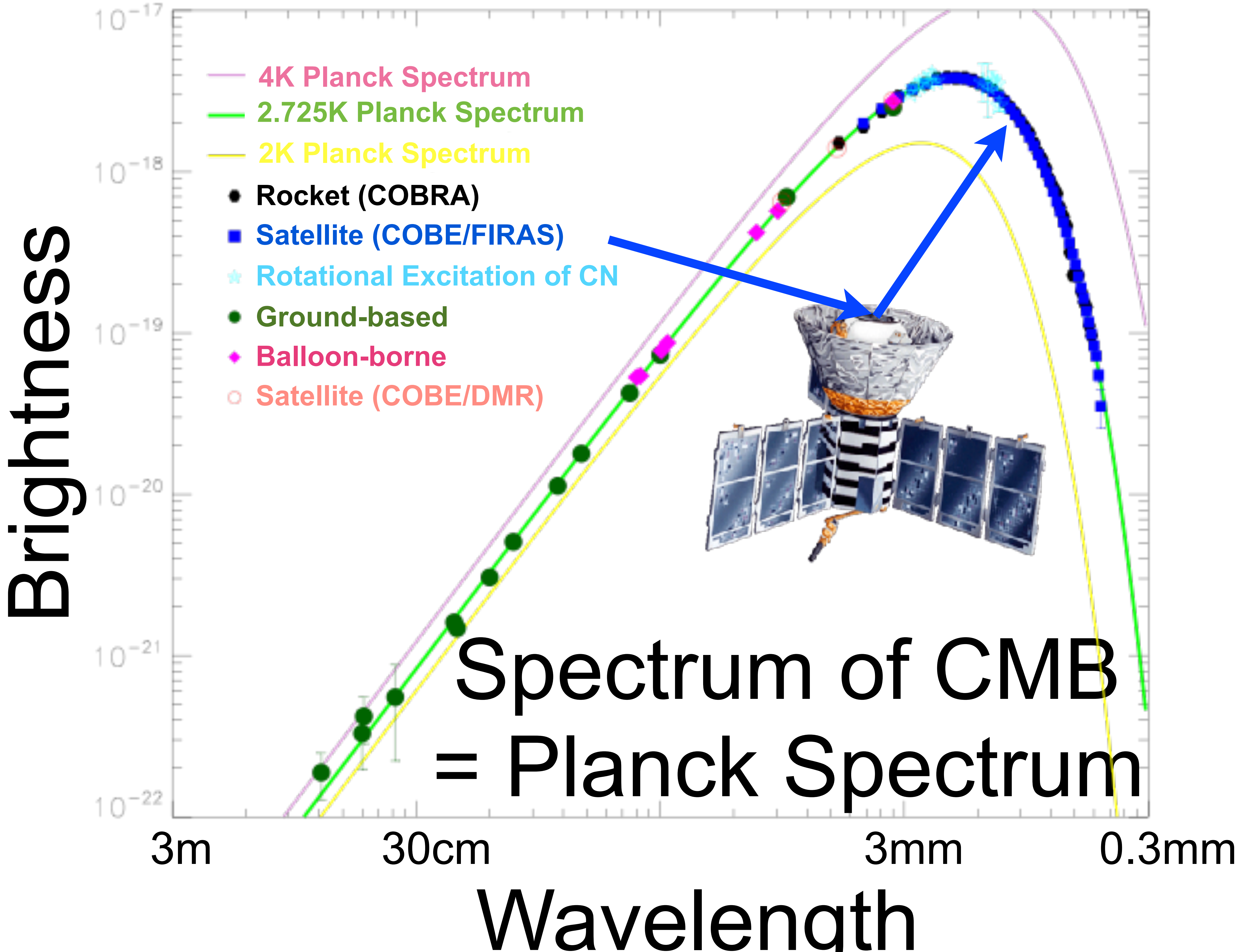
May 20, 1964
CMB
Discovered

6.7–2.3–0.8–0.1
= 3.5±1.0 K

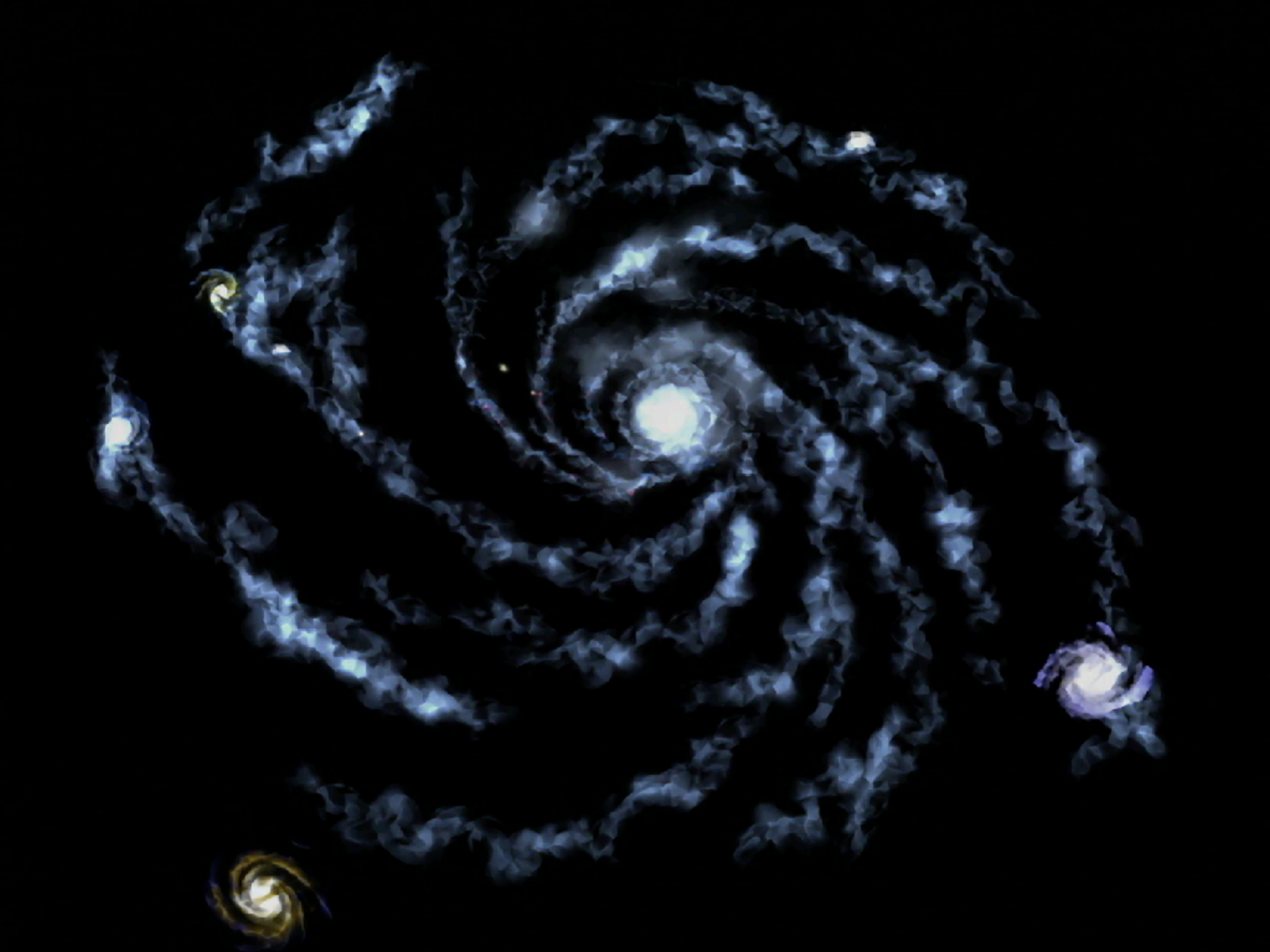


Schreiberaufzeichnung der ersten Messung des Mikrowellenhintergrundes am 20.5.1964

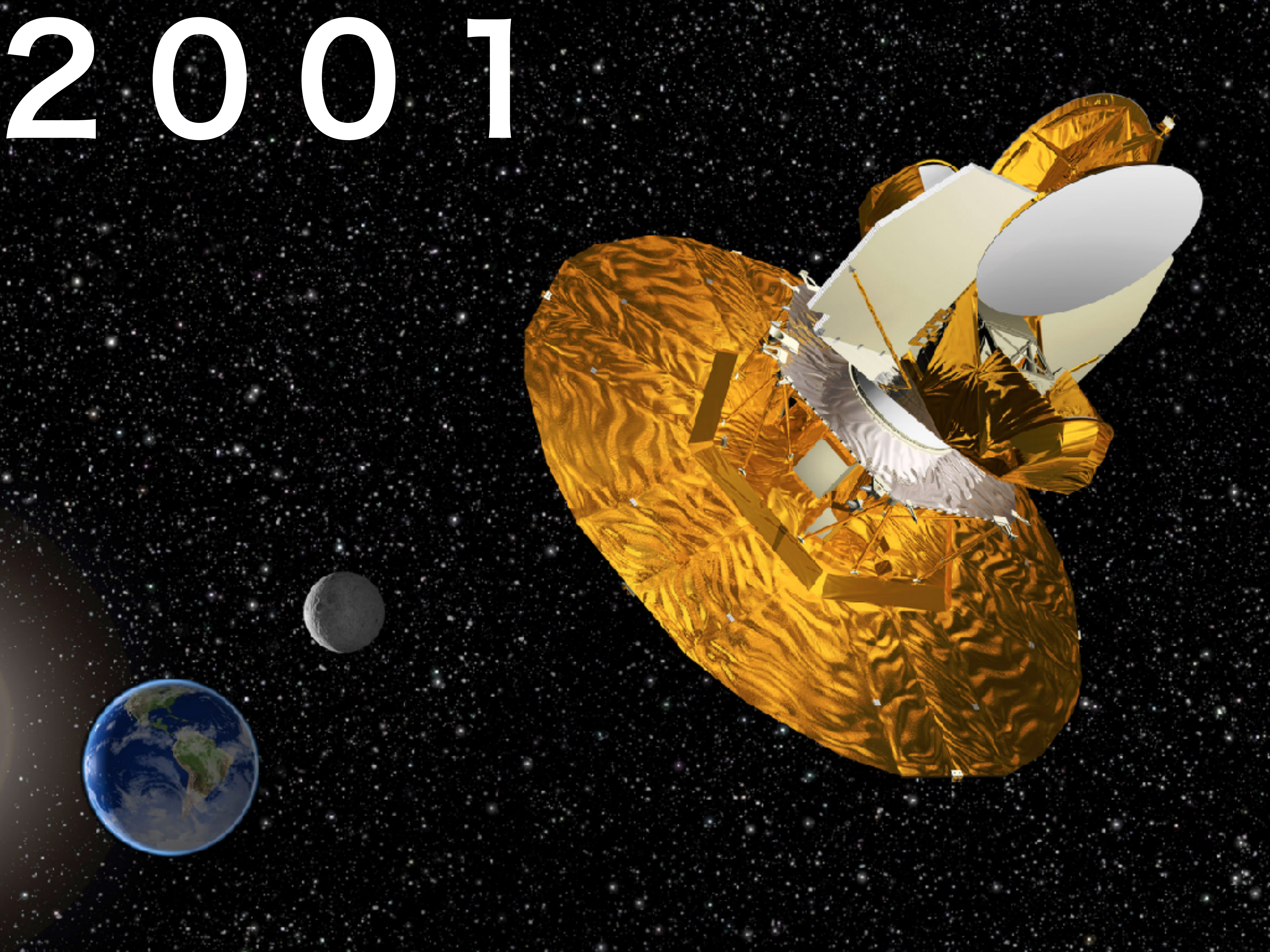
Recording of the first measurement of cosmic microwave background radiation taken on 5/20/1964.



4K Planck Spectrum
2.725K Planck Spectrum
2K Planck Spectrum
Rocket (COBRA)
Satellite (COBE/FIRAS)
Rotational Excitation of CN
Ground-based
Balloon-borne
Satellite (COBE/DMR)
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
Brightness
3m
30cm
3mm
0.3mm
Wavelength
Spectrum of CMB
= Planck Spectrum

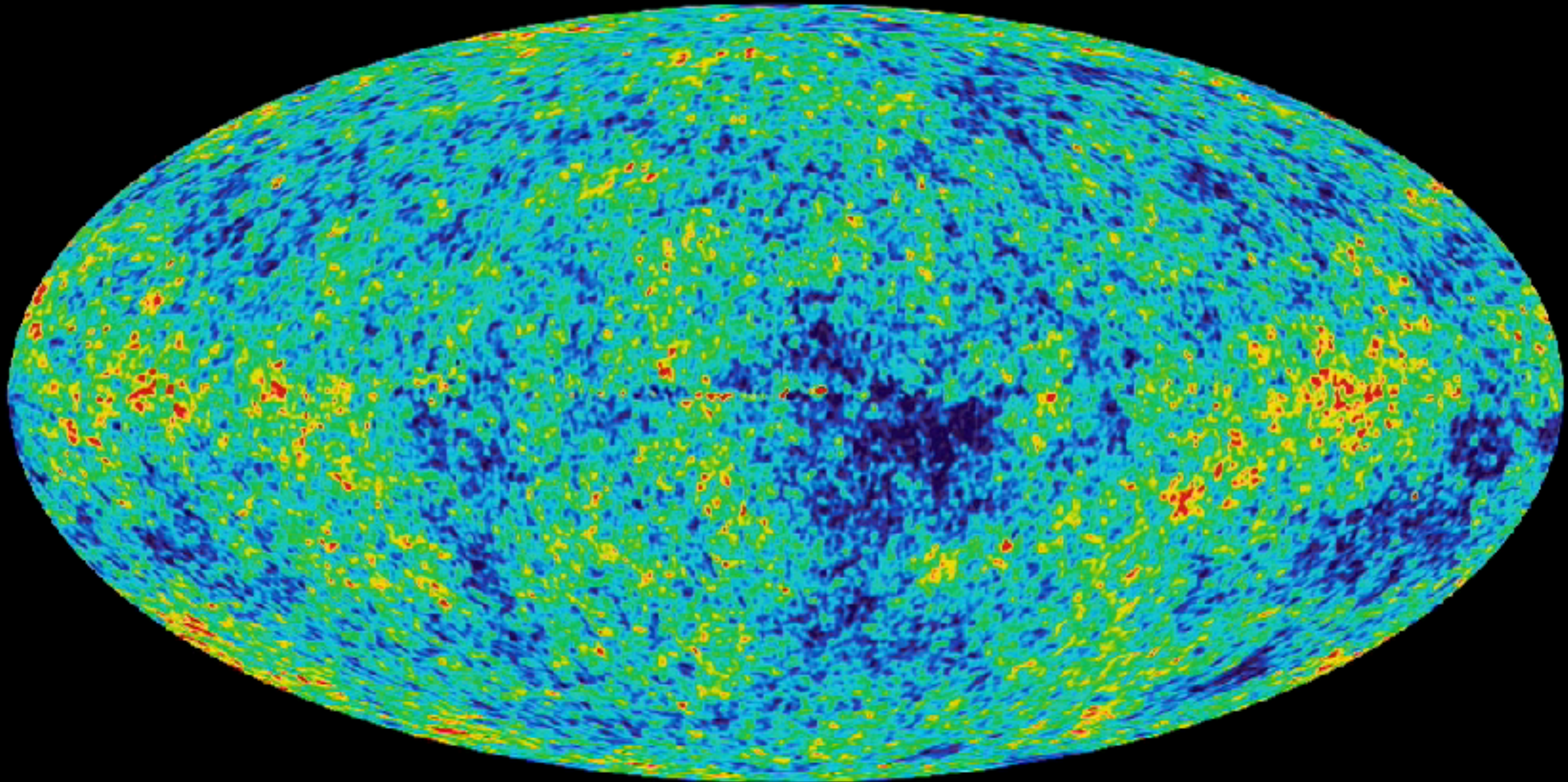


2001



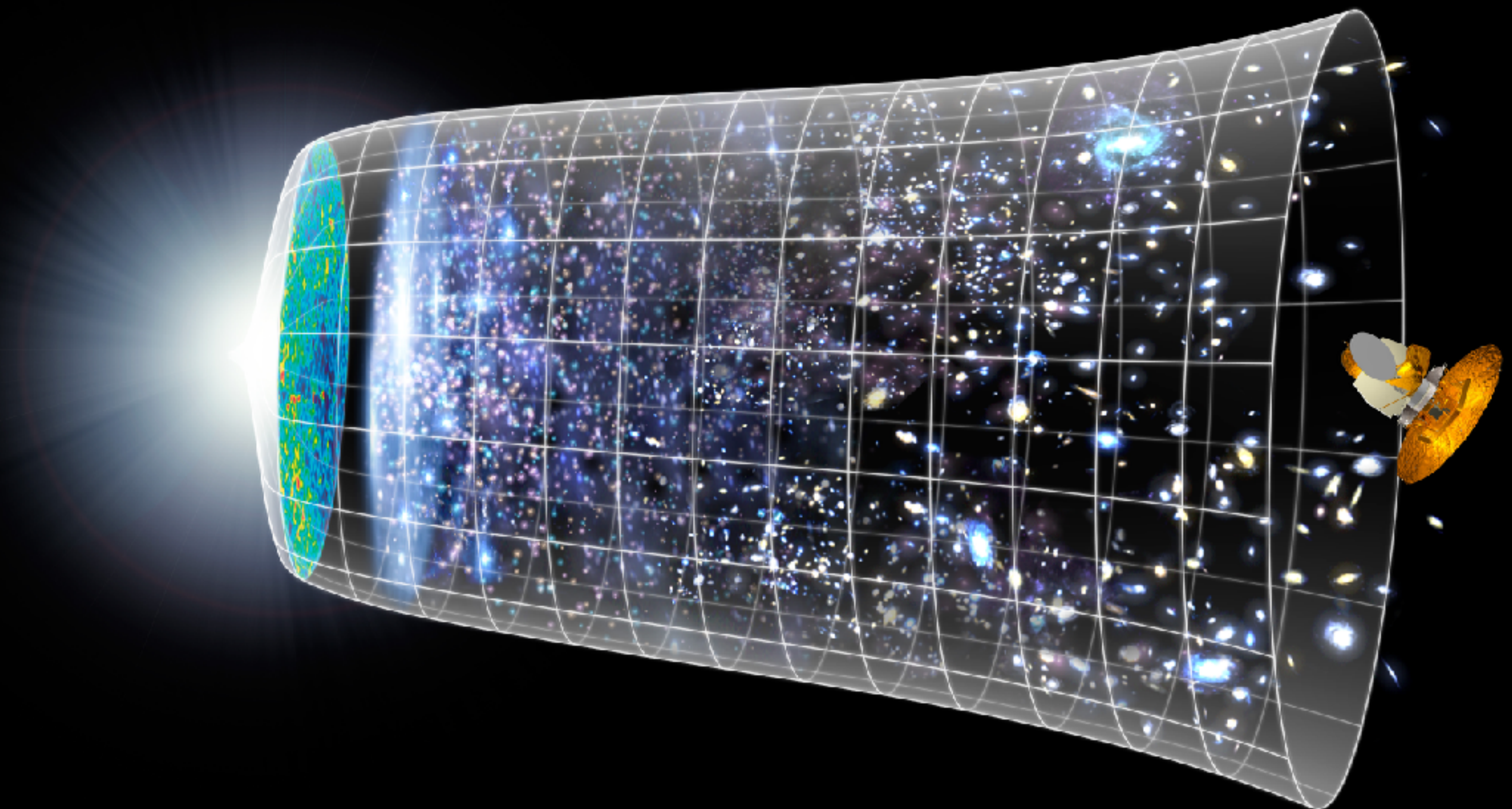
WMAP Science Team
July 19, 2002

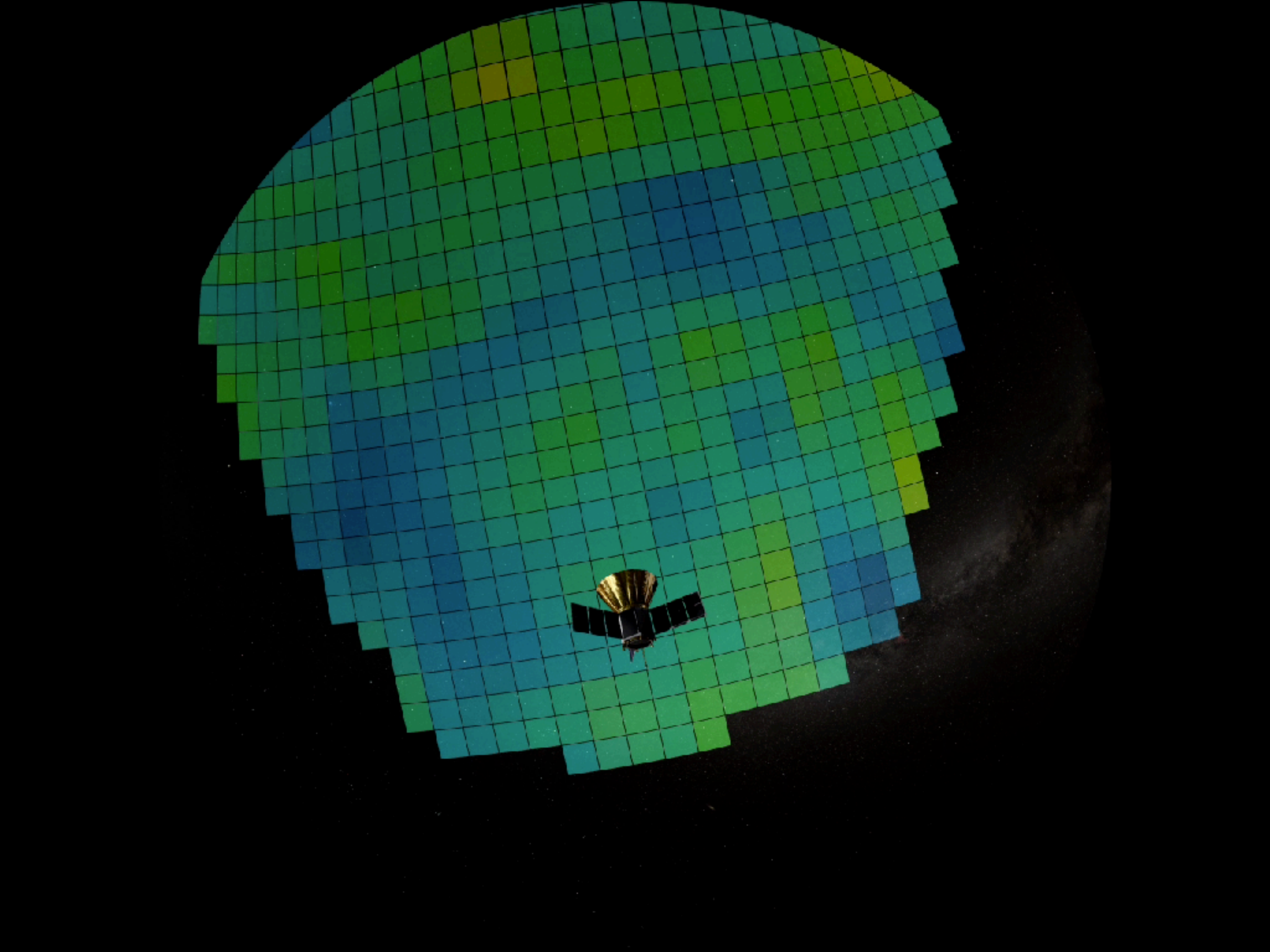
- WMAP was launched on June 30, 2001
- The WMAP mission ended after 9 years of operation



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?***





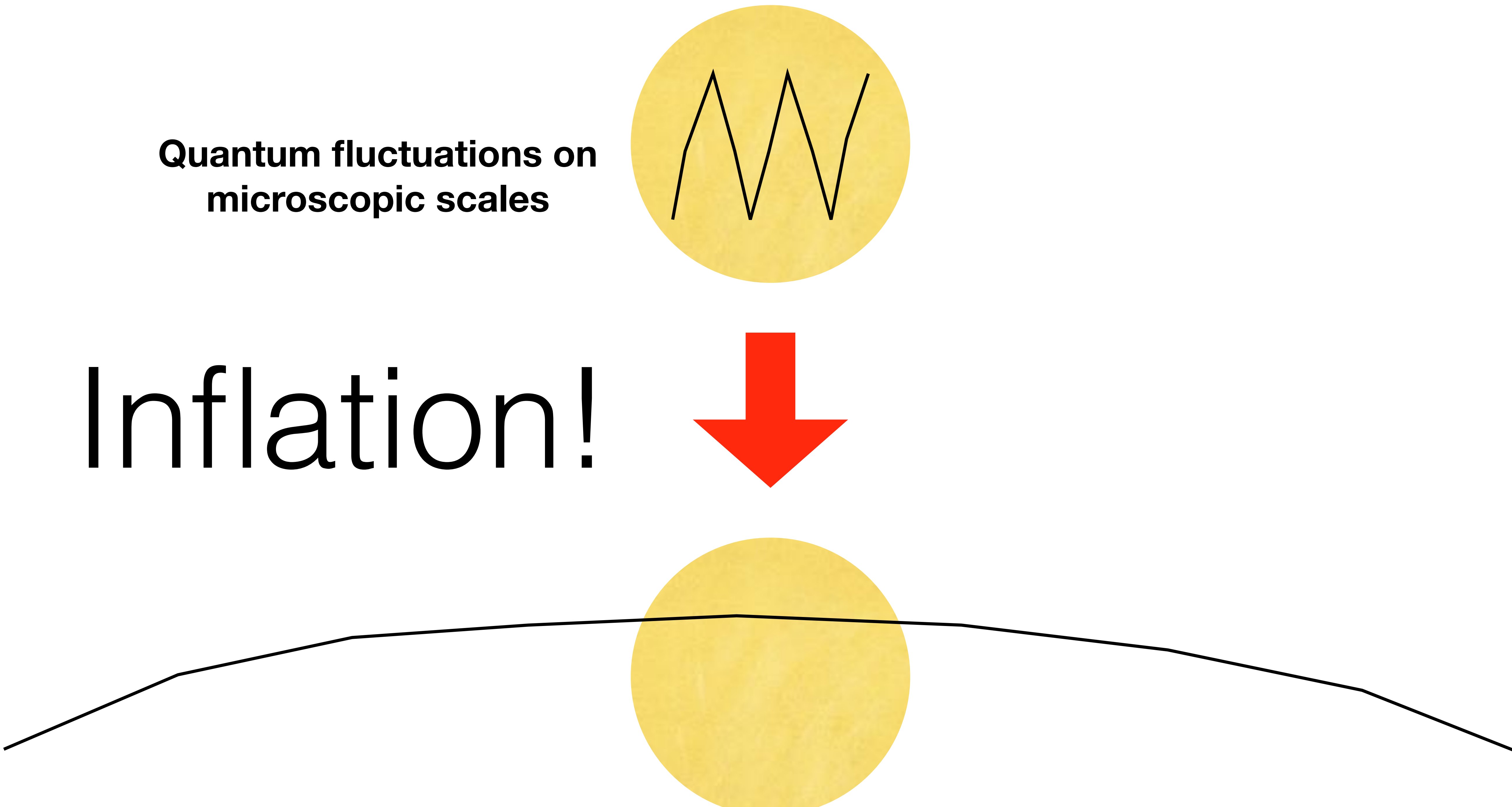
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

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



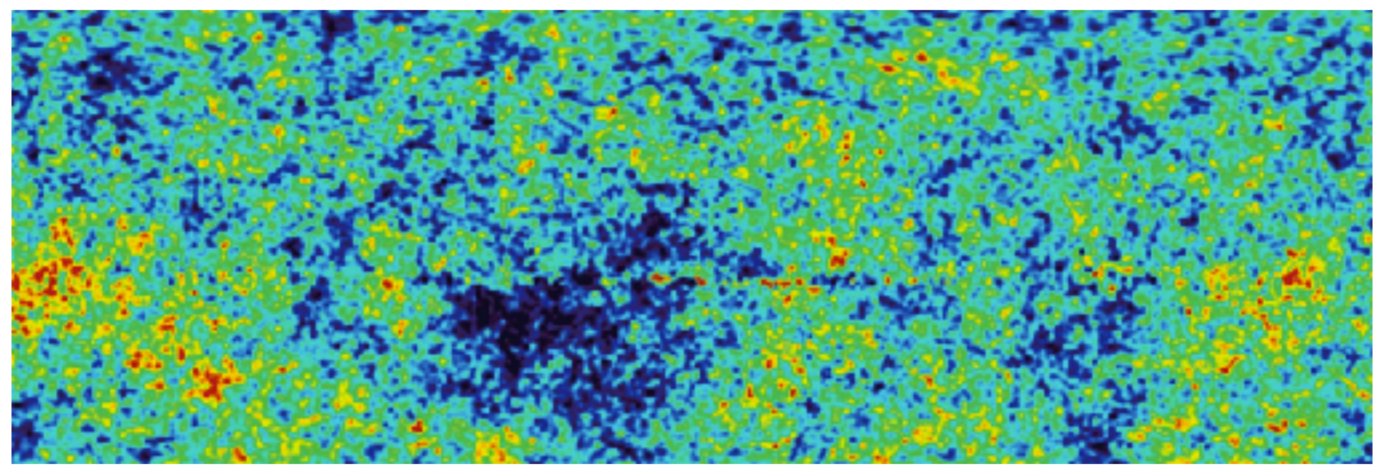
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

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

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

- **ζ** : “curvature perturbation” (scalar mode)
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$$\sum_i h_{ii} = 0$$

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?

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

- *Have we found ε << 1?*
- To achieve this, we need to map out **H(t)**, and show that it does not change very much with time

Fluctuations are proportional to H

- **Both scalar (ζ) and tensor (h_{ij}) perturbations are proportional to H**

  - Consequence of the uncertainty principle

    - $\boxed{\text{[energy you can borrow]} \sim \text{[time you borrow]}^{-1} \sim H}$

  - **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

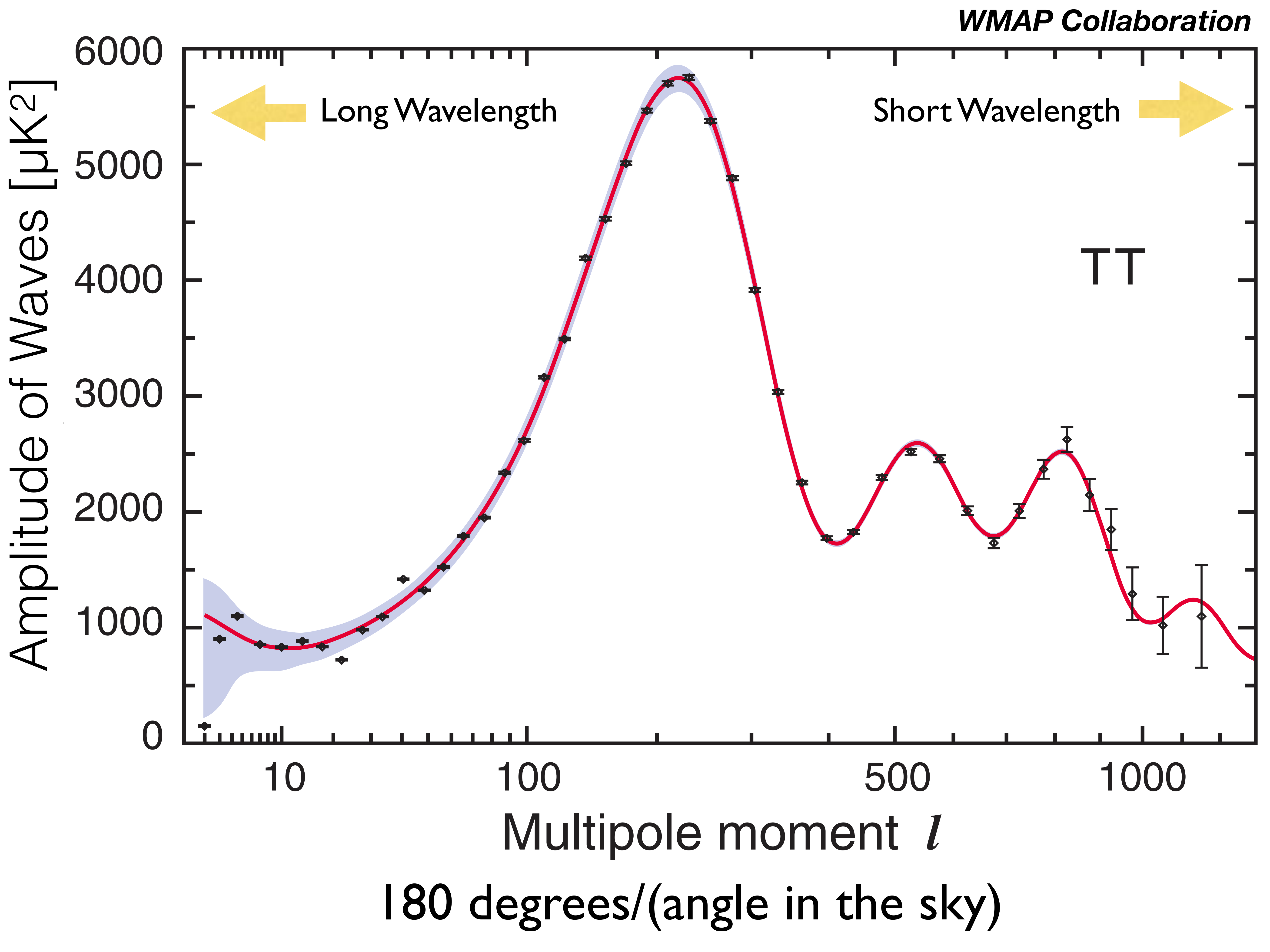
- **We can map H(t) by measuring CMB fluctuations over a wide range of angles**

1. We want to show that the amplitude of CMB fluctuations does not depend very much on angles (i.e., $\varepsilon << 1$)

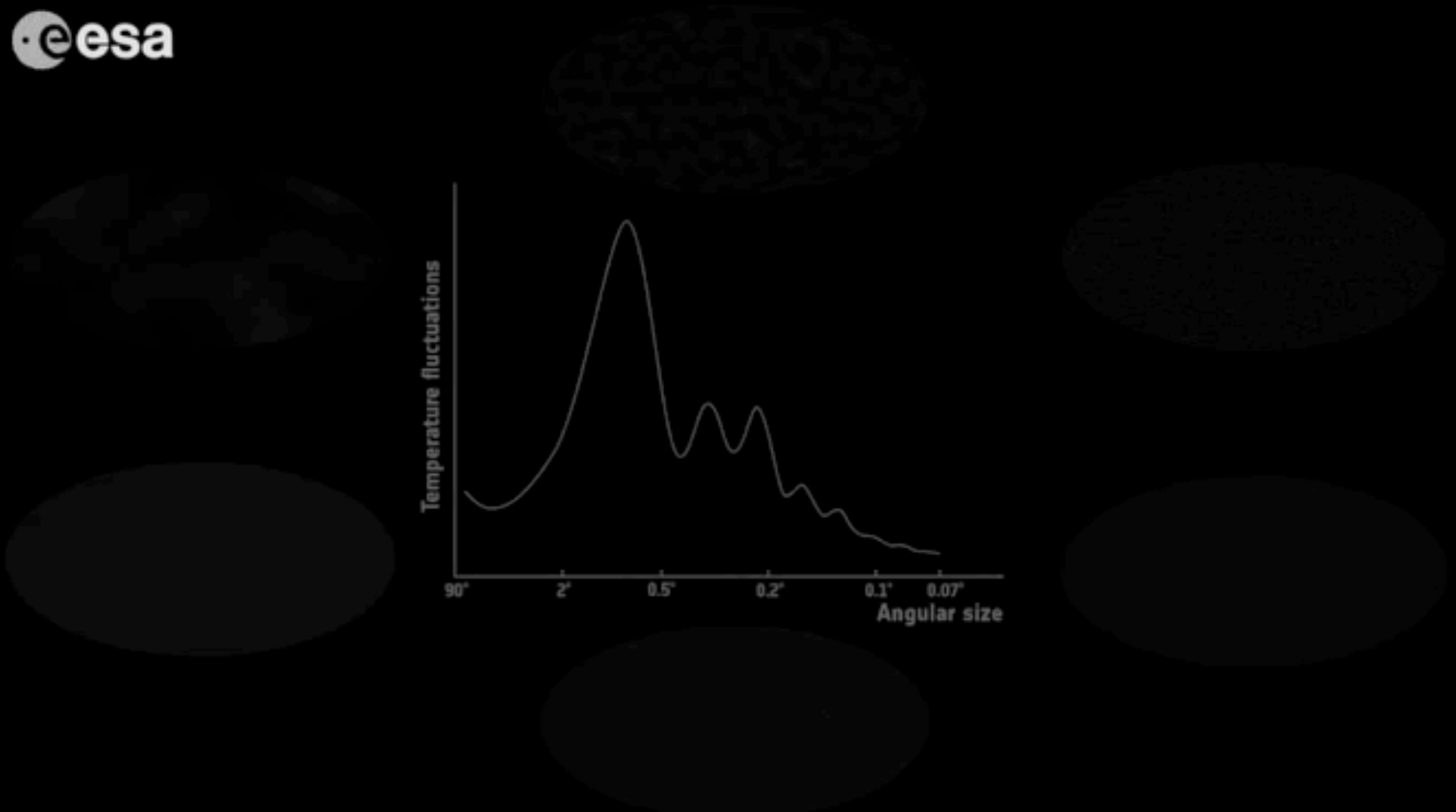
2. Moreover, since inflation must end, H would be a decreasing function of time. It would be fantastic to show that the amplitude of CMB fluctuations actually DOES depend on angles such that the small scale has ***slightly*** smaller power

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

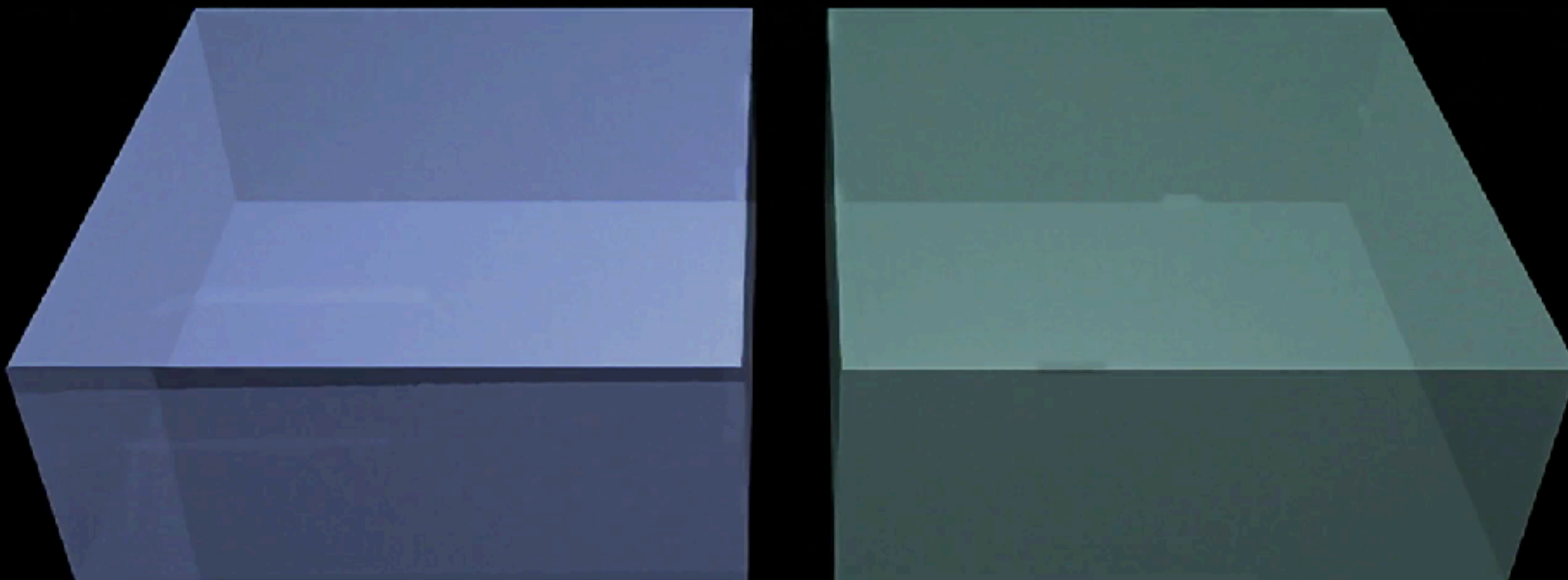

WMAP Collaboration
Long Wavelength
Short Wavelength
TT
Amplitude of Waves [μK²]
0
1000
2000
3000
4000
5000
6000
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

Power spectrum, explained

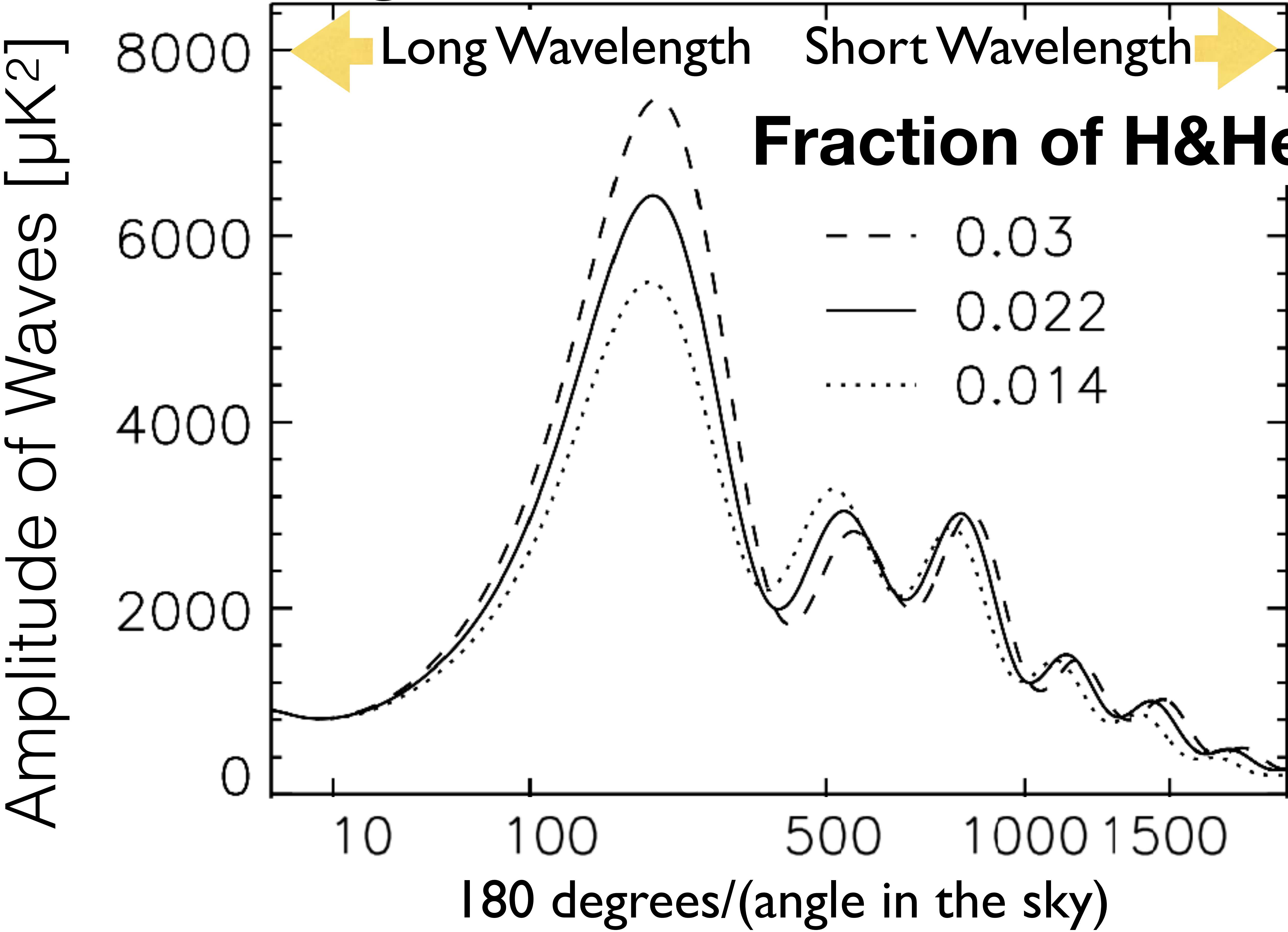


Kosmische Miso Suppe

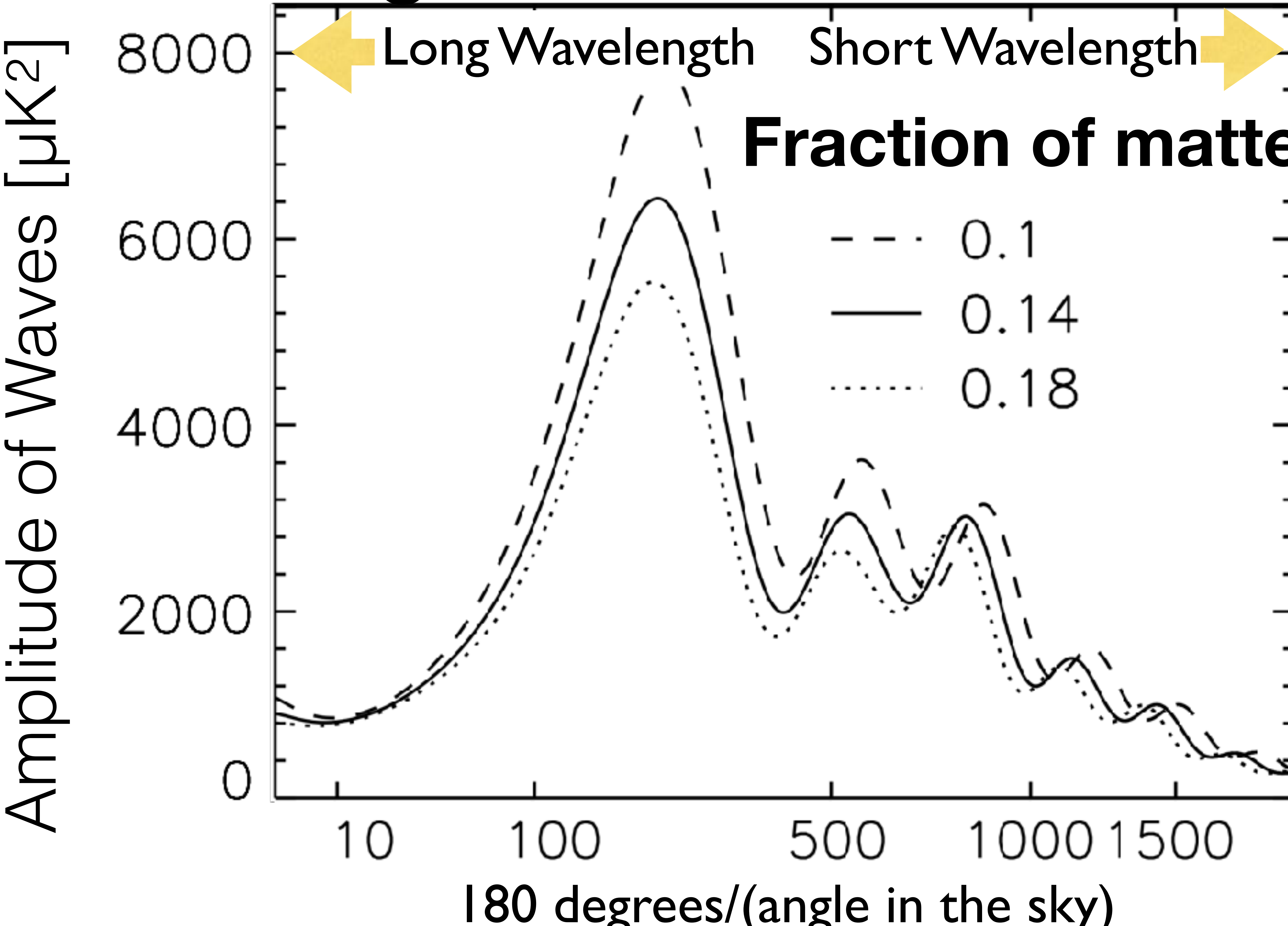
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching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



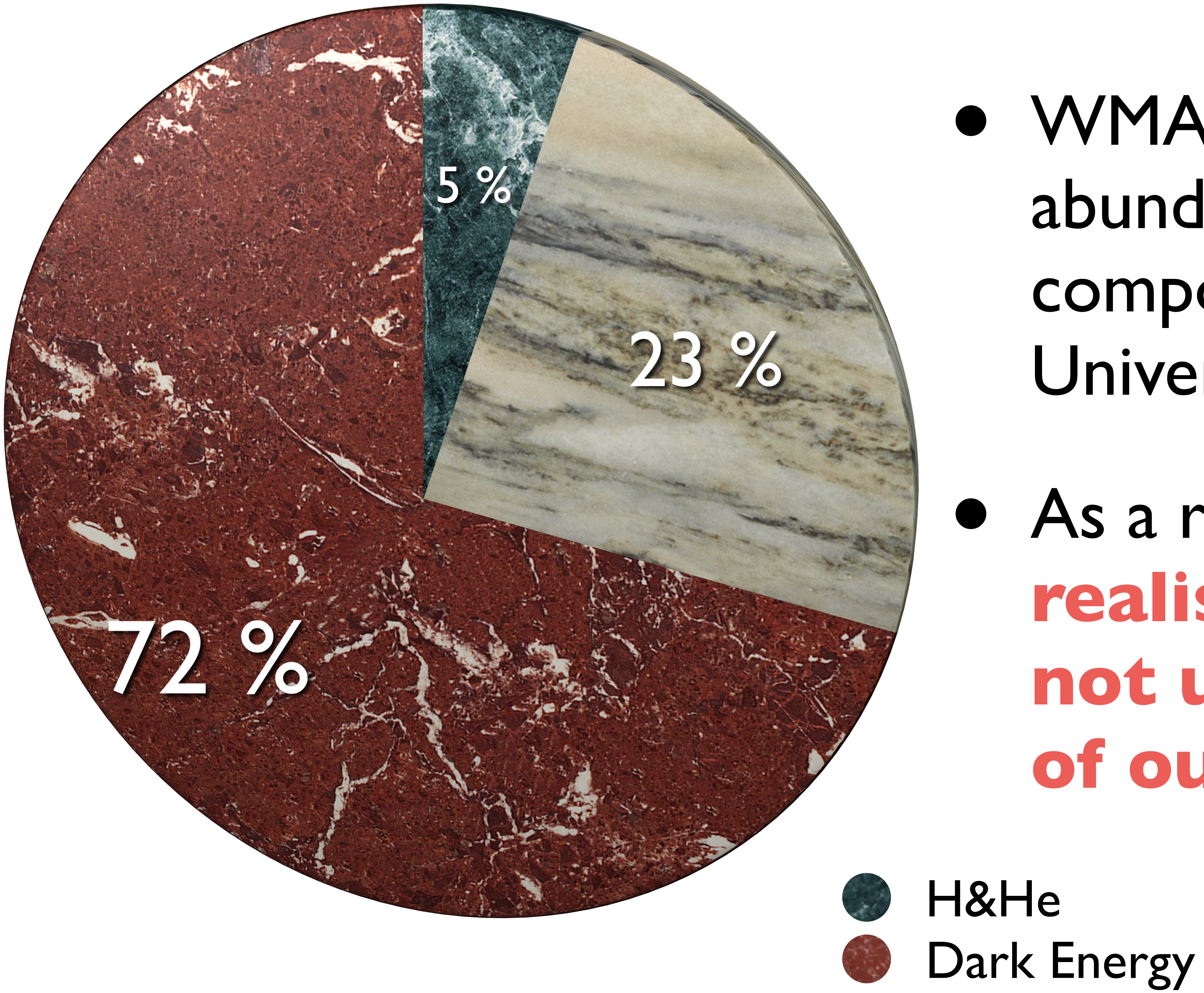
Measuring Abundance of H&He



Measuring ***Total*** Matter Density



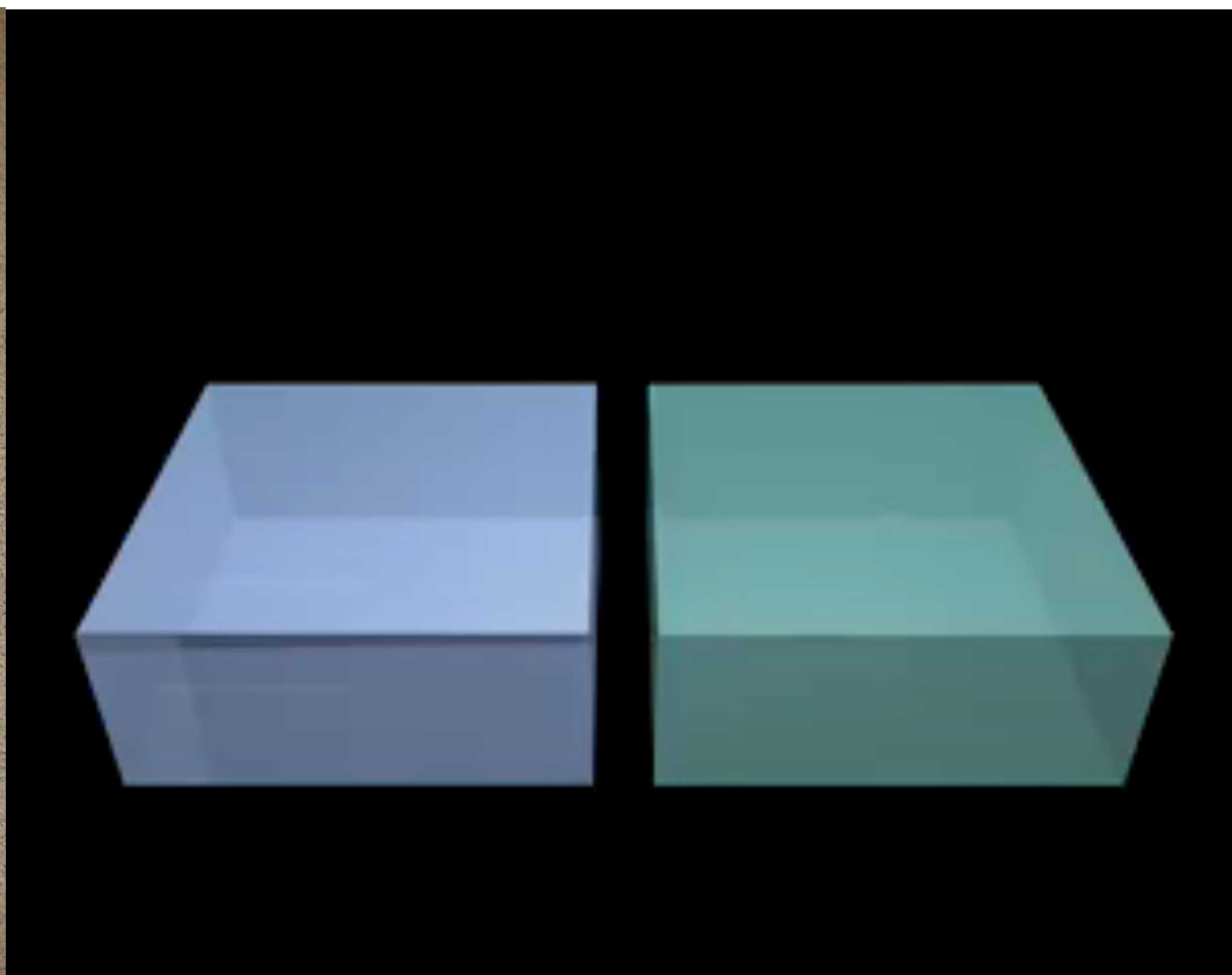
Cosmic Pie Chart

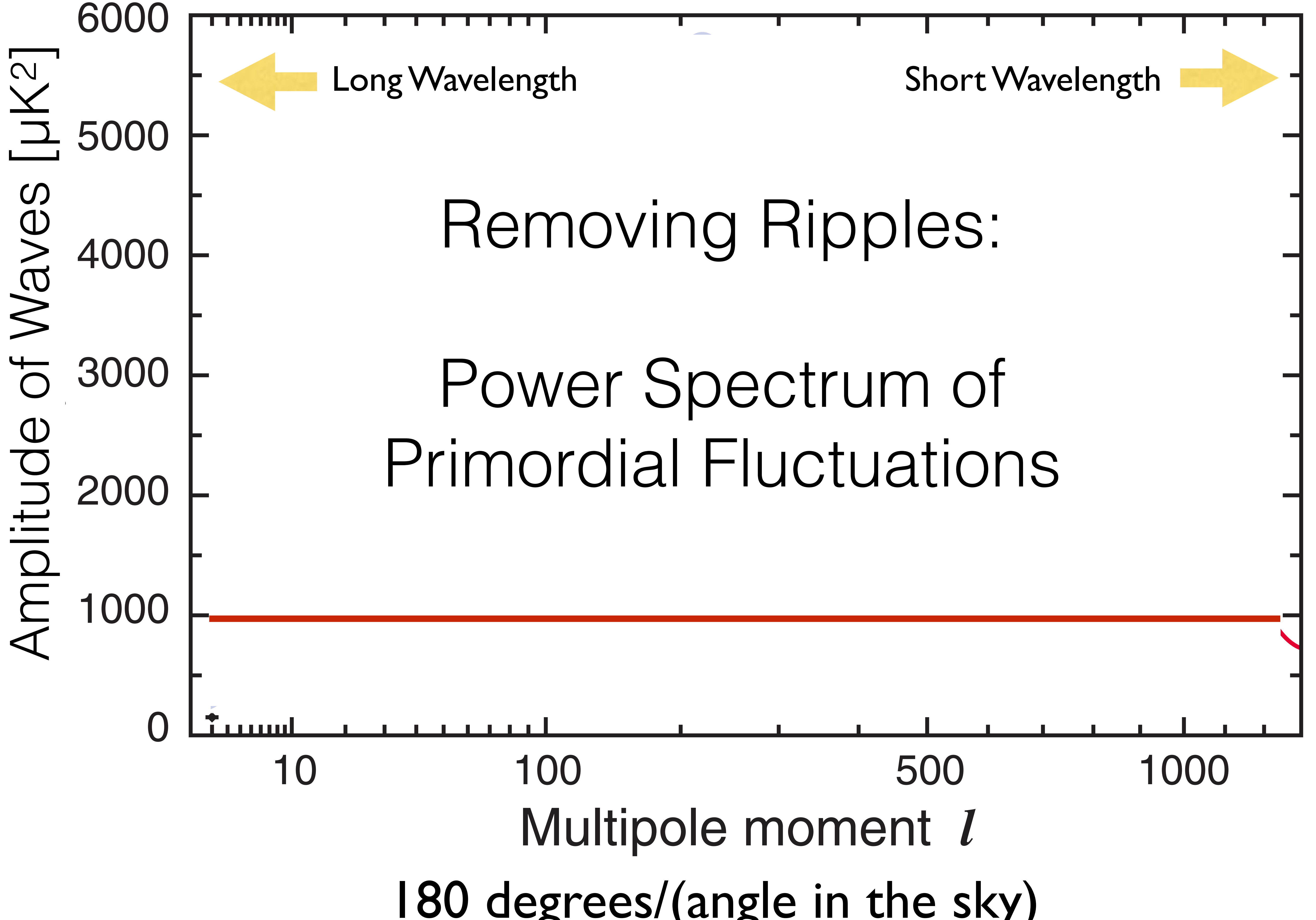


- WMAP determined the abundance of various components in the Universe
- As a result, **we came to realise that we do not understand 95% of our Universe...**

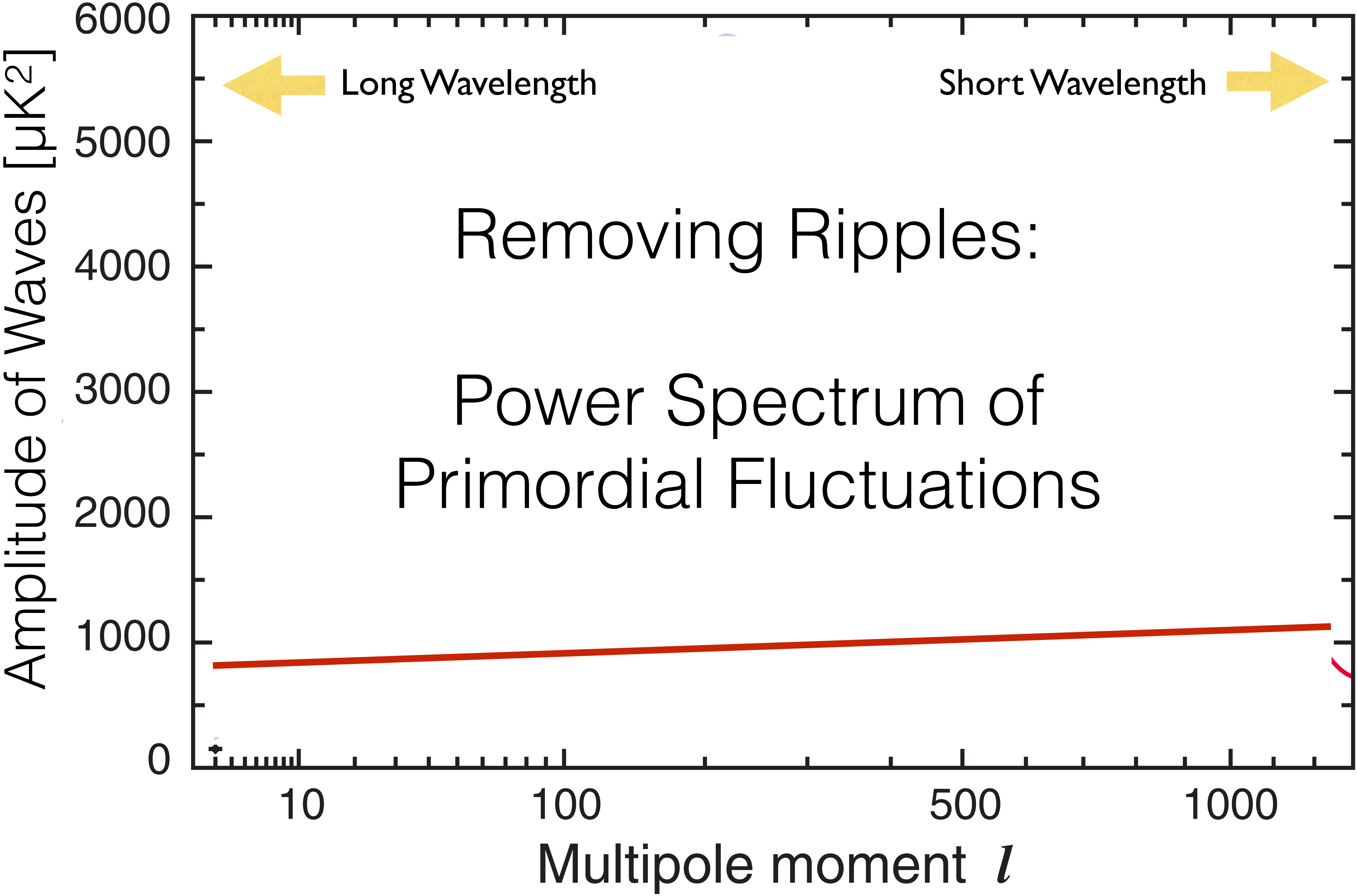
Origin of Fluctuations

- Who dropped those Tofus into the cosmic Miso soup?

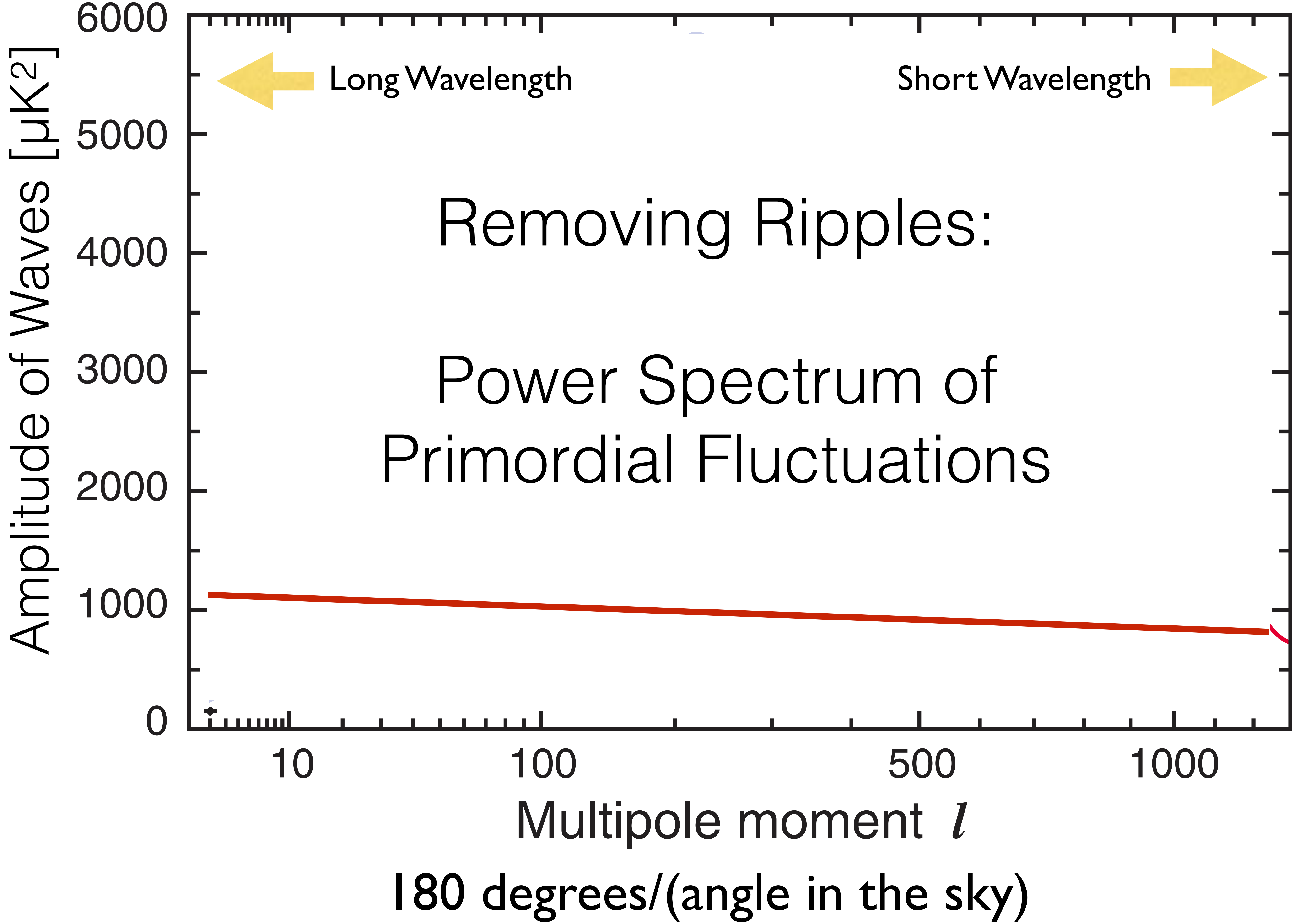




Removing Ripples:
Power Spectrum of Primordial Fluctuations
Long Wavelength
Short Wavelength
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



180 degrees/(angle in the sky)


Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of Primordial Fluctuations
Amplitude of Waves [μK²]
6000
5000
4000
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Multipole moment l
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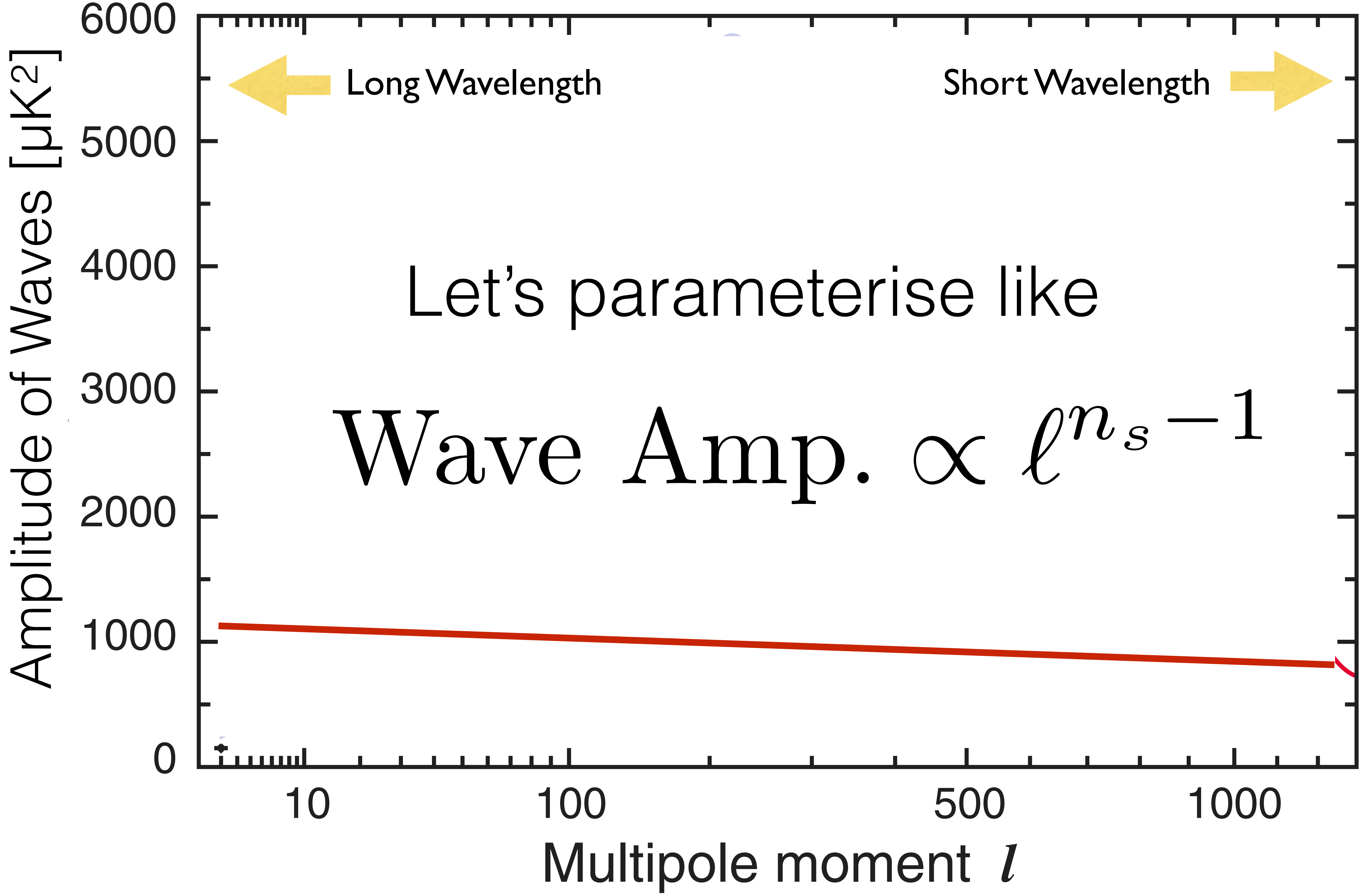
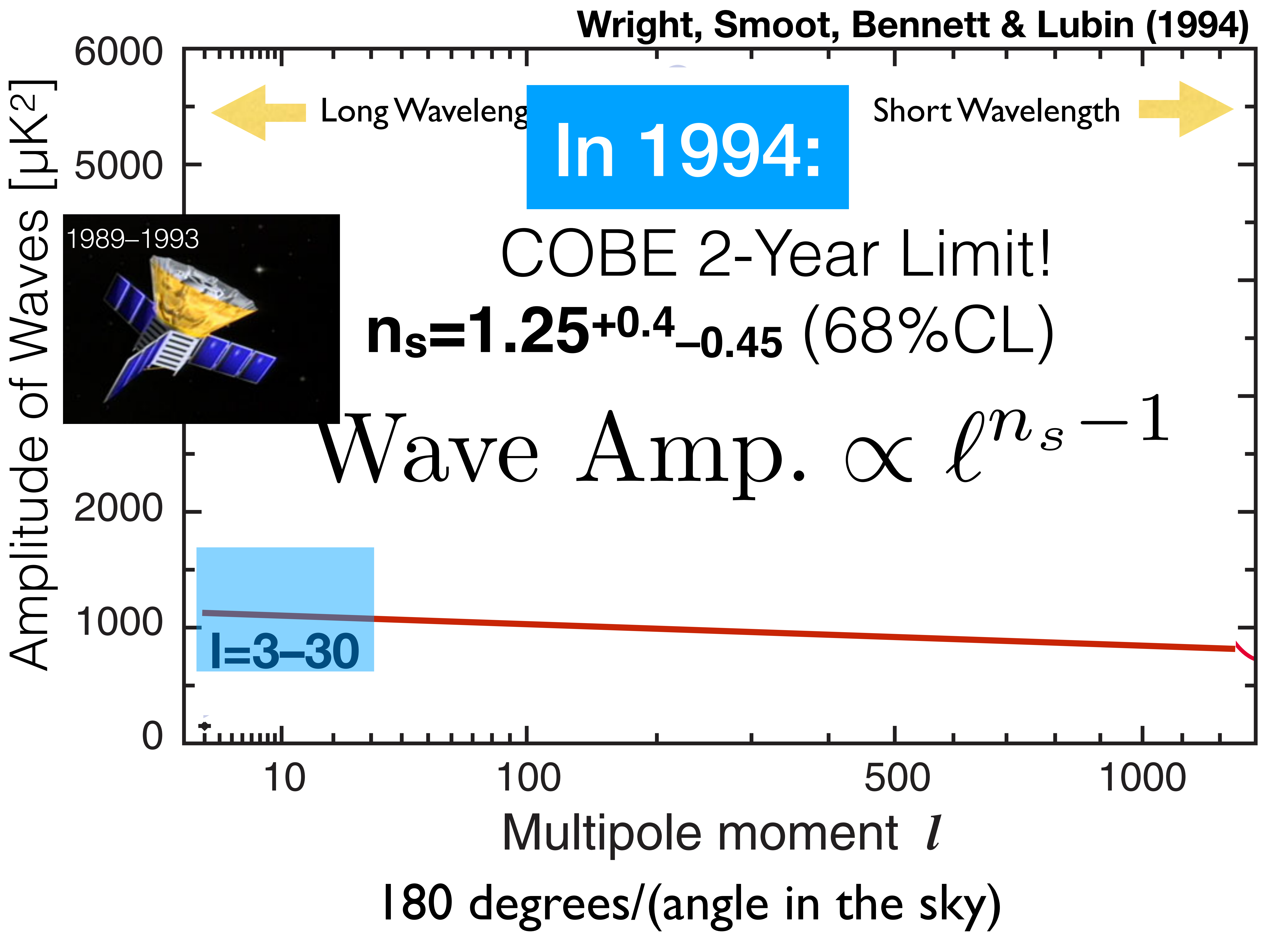
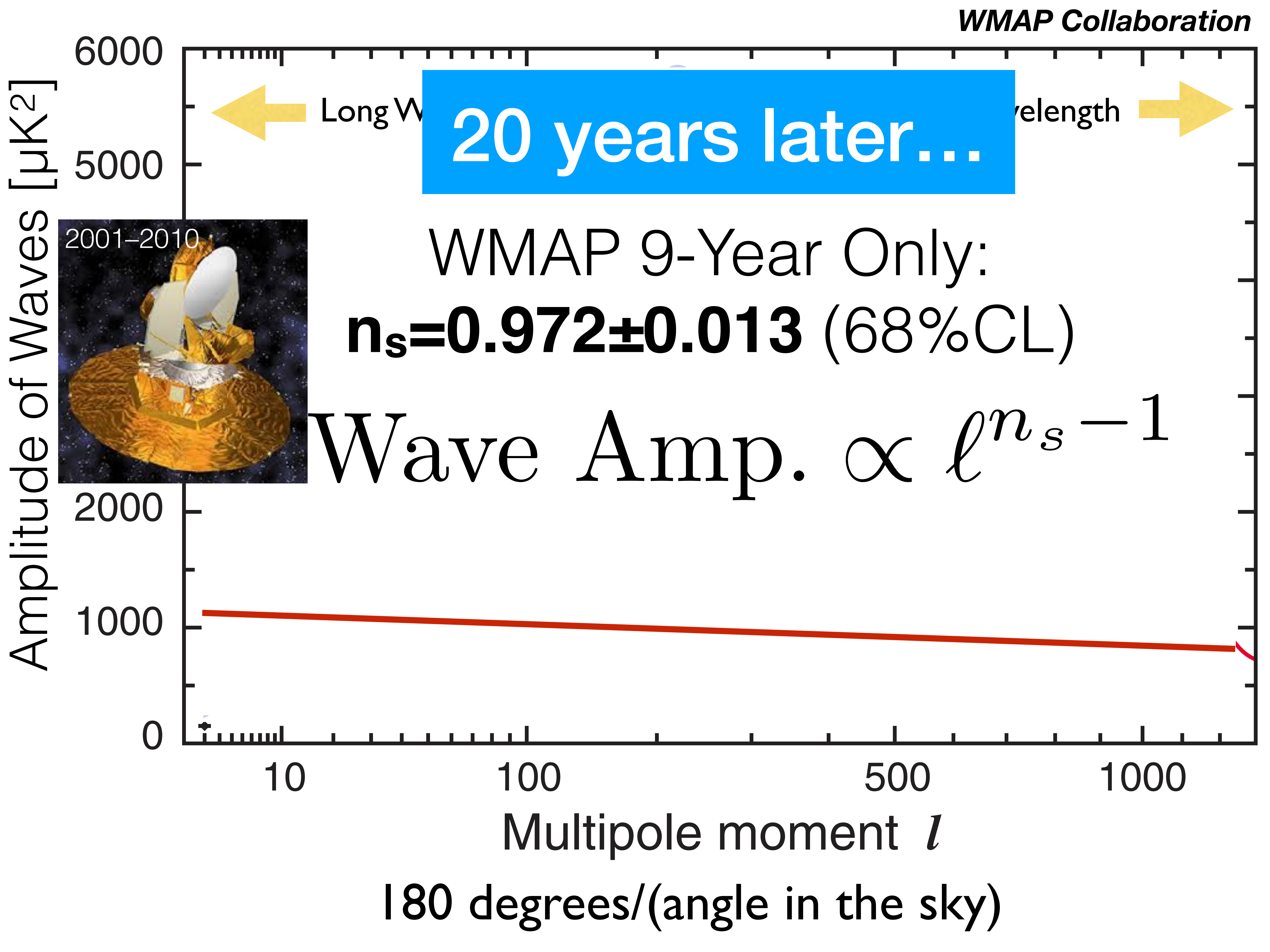


Let's parameterise like

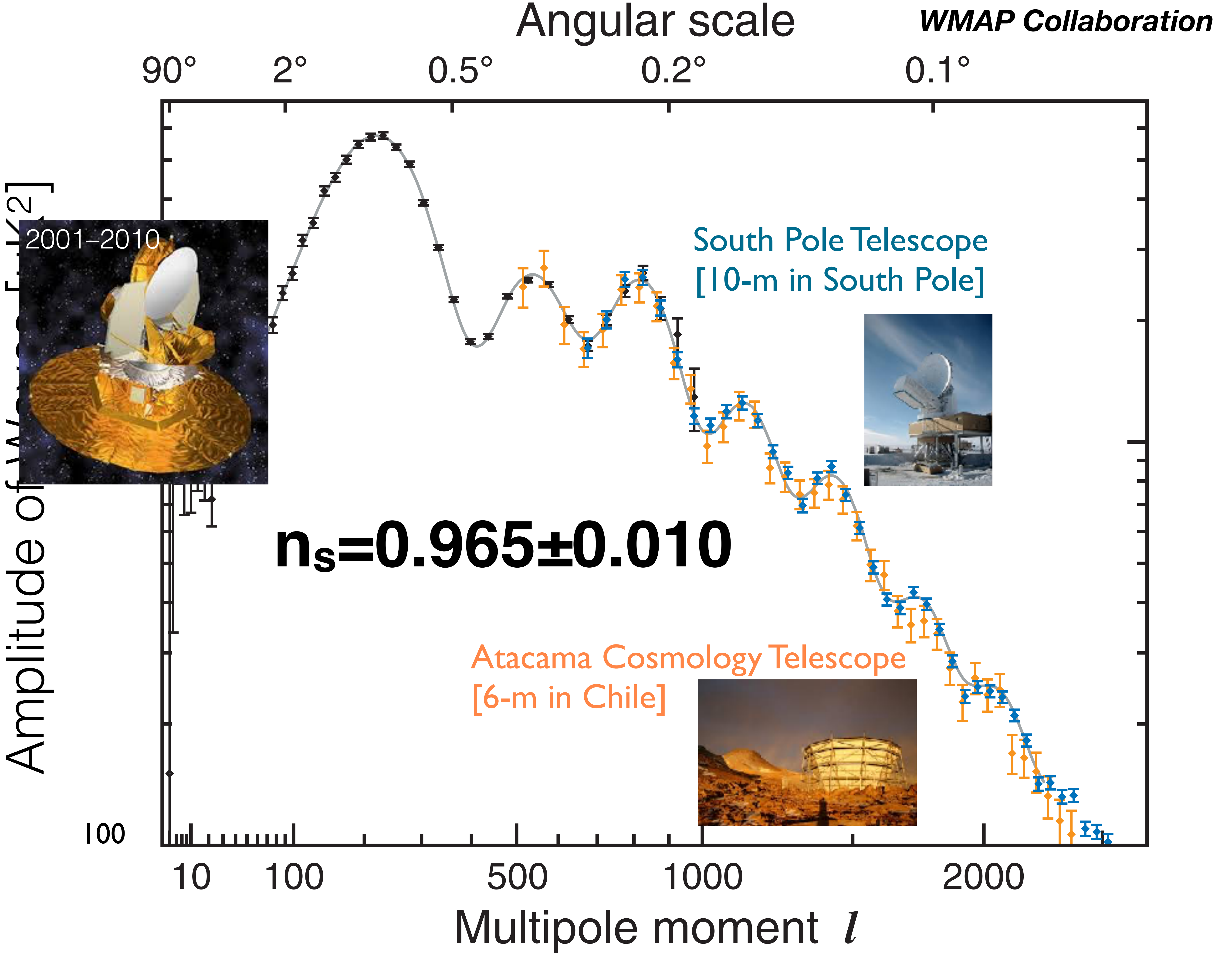
$$\text{Wave Amp.} \propto \ell^{n_s - 1}$$

180 degrees/(angle in the sky)

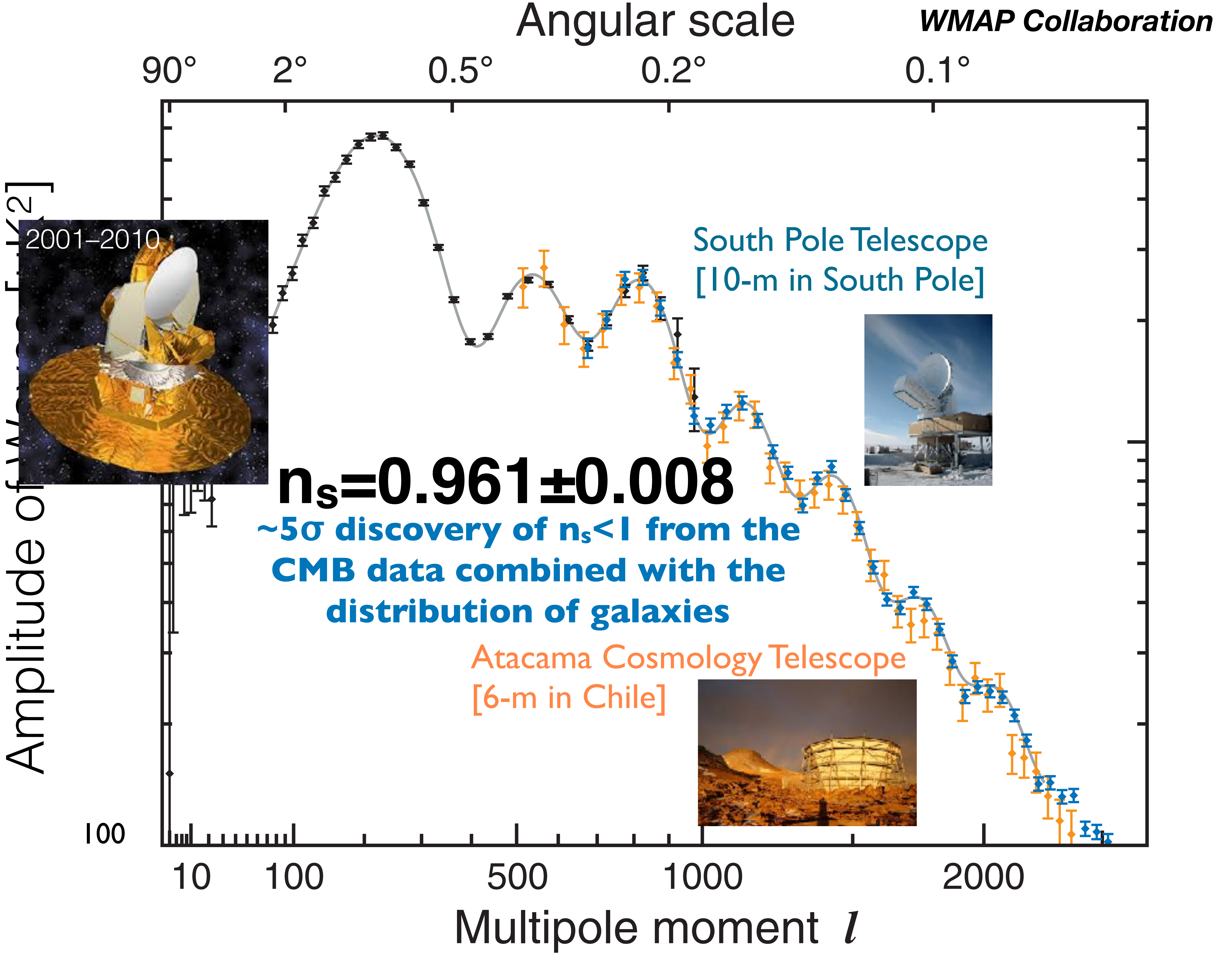

Wright, Smoot, Bennett & Lubin (1994)
In 1994:
COBE 2-Year Limit!
$n_s = 1.25^{+0.4}_{-0.45}$ (68%CL)
$\text{Wave Amp.} \propto \ell^{n_s - 1}$
Long Waveleng
Short Wavelength
1989–1993
l=3–30
Amplitude of Waves [μK²]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



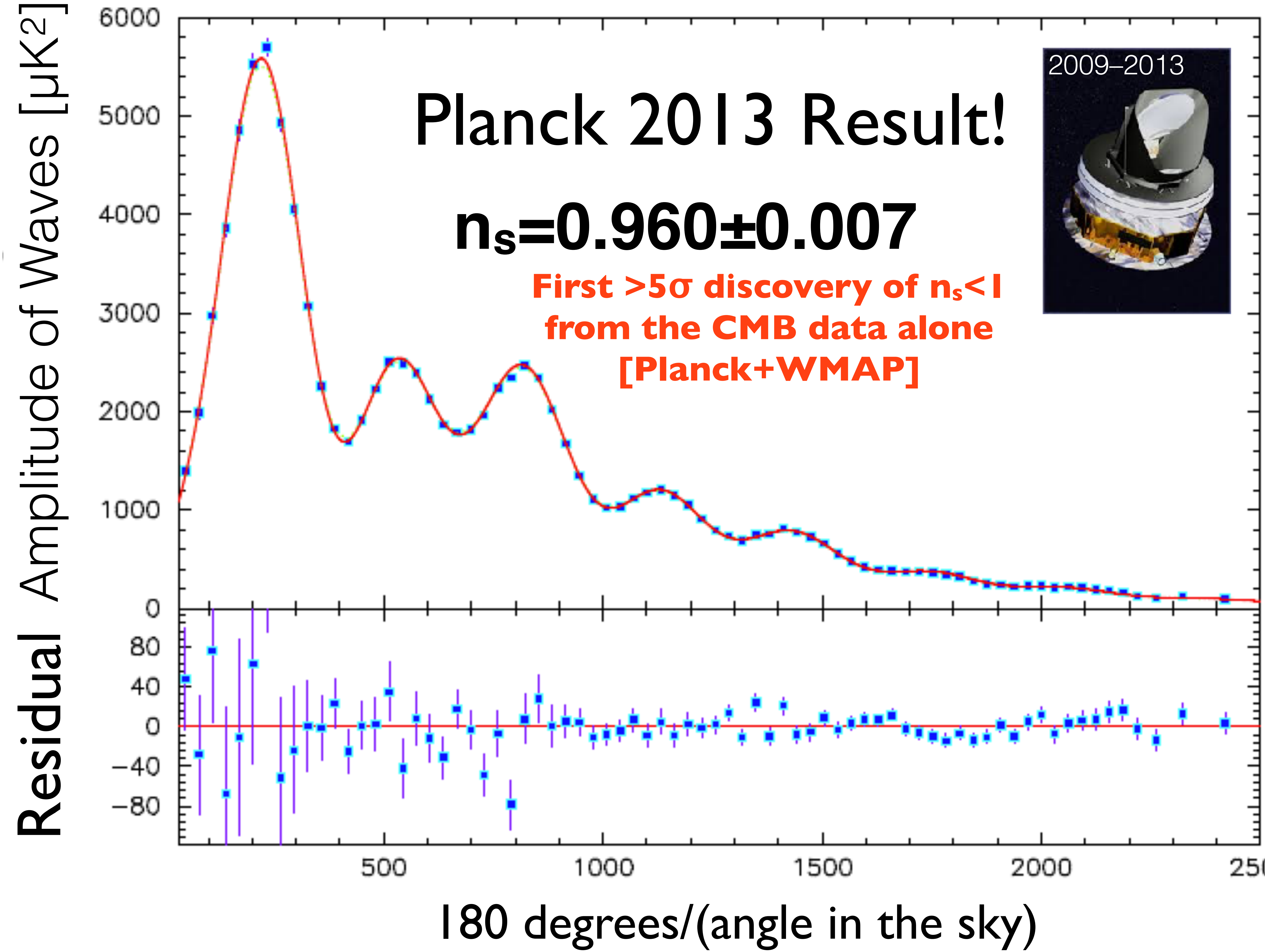
WMAP Collaboration
20 years later...
2001–2010
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
$$\text{Wave Amp.} \propto \ell^{n_s-1}$$
Long W
velength
Amplitude of Waves [μK^2]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



Angular scale
WMAP Collaboration
90°
2°
0.5°
0.2°
0.1°
2001–2010
South Pole Telescope
[10-m in South Pole]
n_s=0.965±0.010
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment l

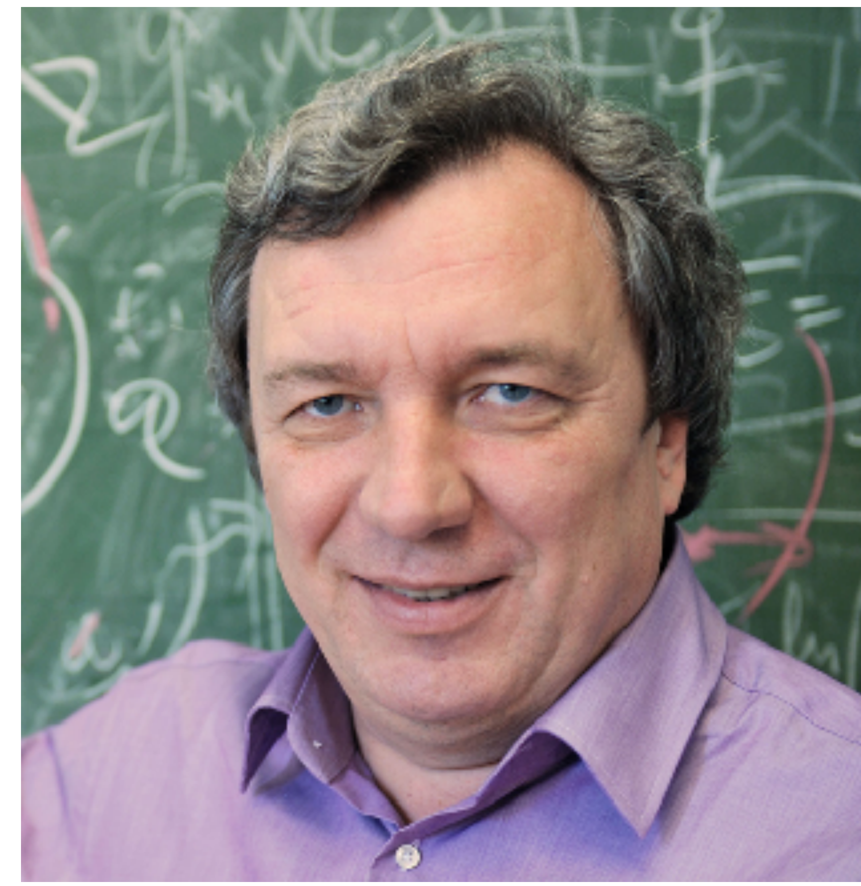


WMAP Collaboration
Angular scale
90°
2°
0.5°
0.2°
0.1°
Amplitude of Waves [μK^2]
2001–2010
South Pole Telescope
[10-m in South Pole]
n_s=0.961±0.008
~5σ discovery of n_s<1 from the
CMB data combined with the
distribution of galaxies
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment l

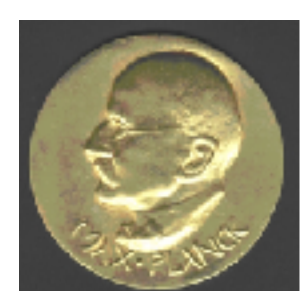

Planck 2013 Result!
n_s=0.960±0.007
First >5σ discovery of n_s<1
from the CMB data alone
[Planck+WMAP]
2009–2013
Amplitude of Waves [μK²]
Residual
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
180 degrees/(angle in the sky)

Predicted in 1981.
Finally discovered in 2013
by WMAP and Planck

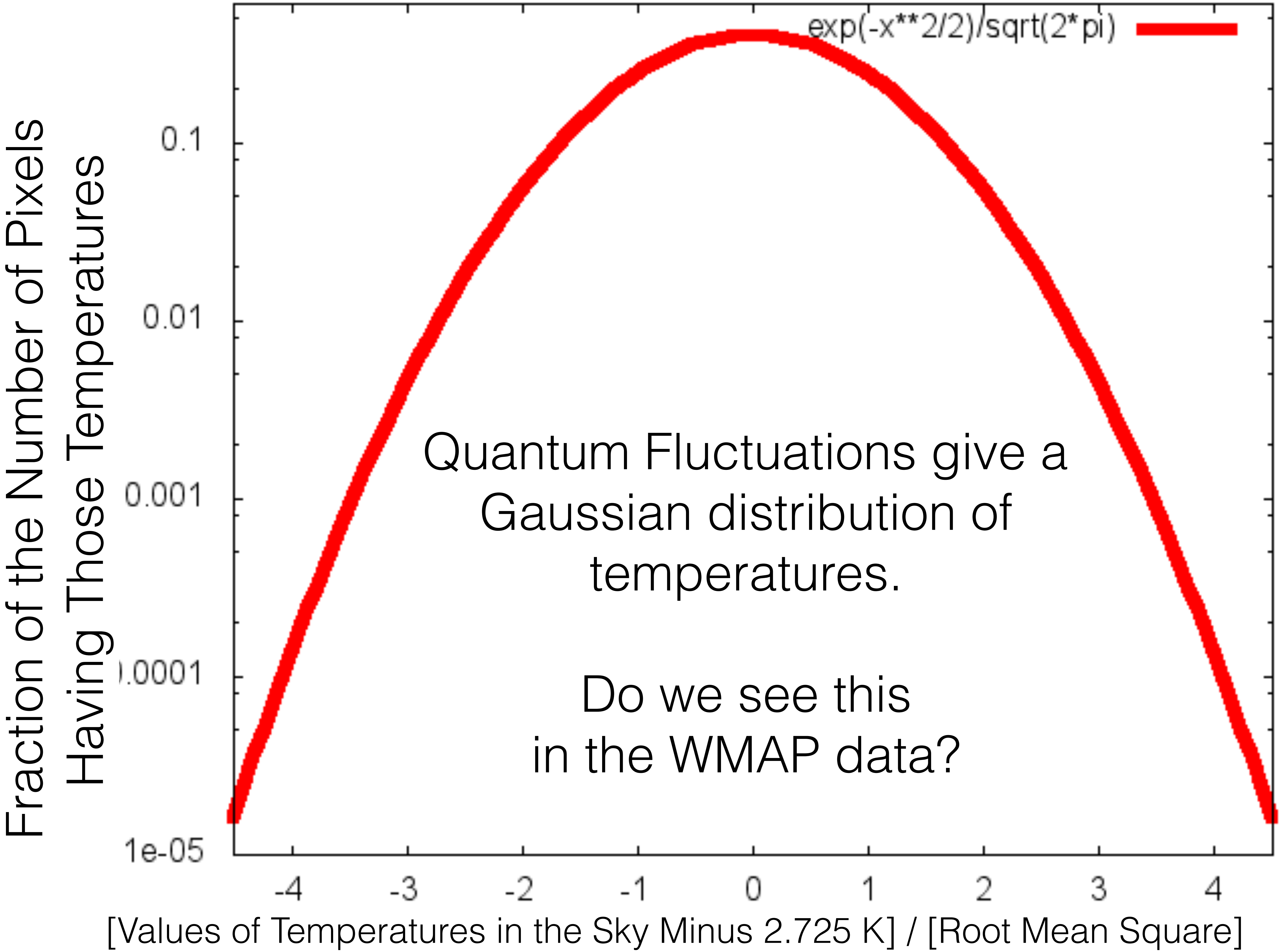
- Inflation must end
- Inflation predicts $n_s \sim 1$, but not exactly equal to 1. Usually $n_s < 1$ is expected
- **The discovery of $n_s < 1$ has been the dream of cosmologists since 1992,** when the CMB anisotropy was first discovered and $n_s \sim 1(\pm 0.4)$ was indicated

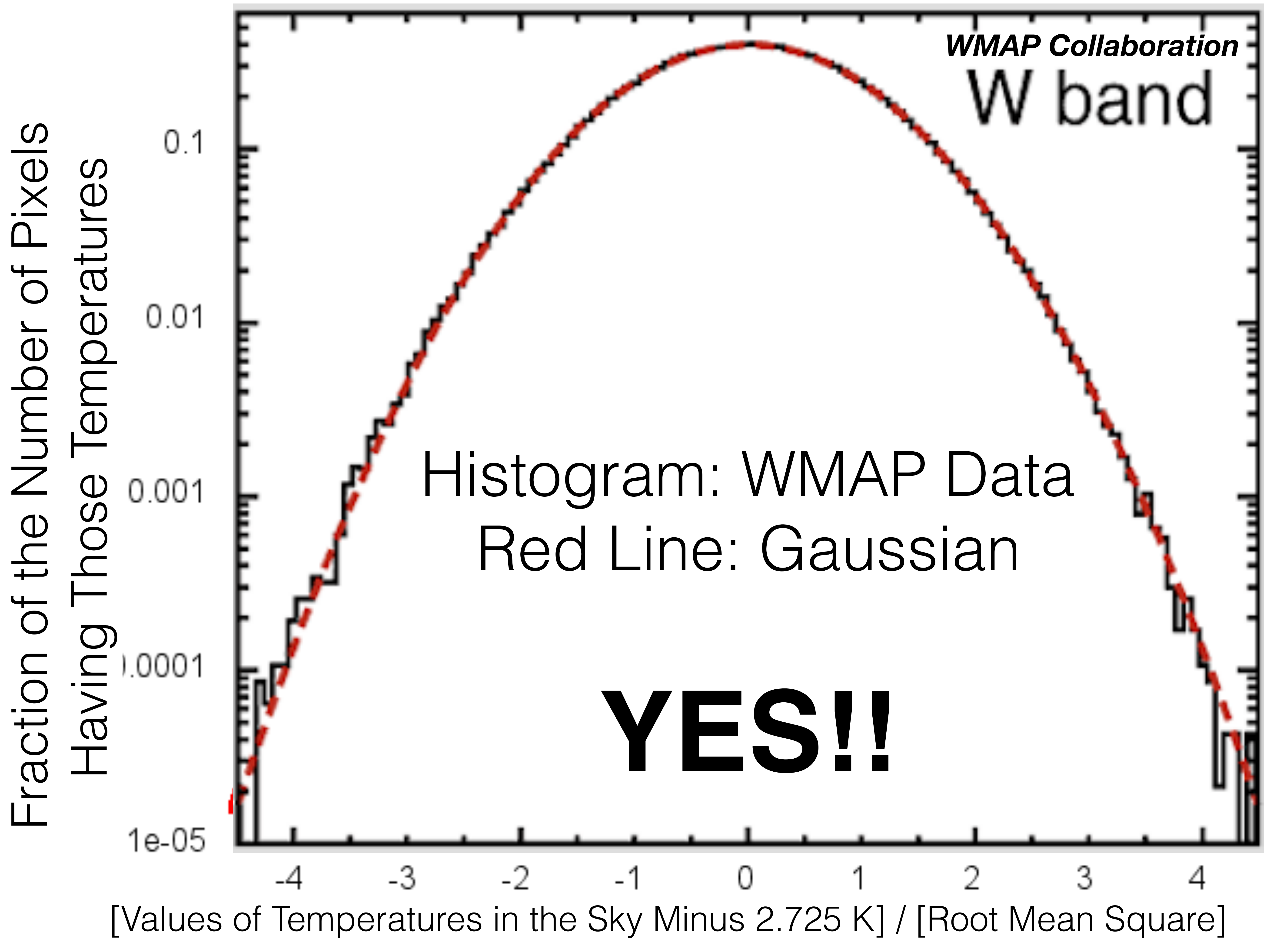


Slava Mukhanov (LMU) said in his 1981 paper that n_s should be less than 1



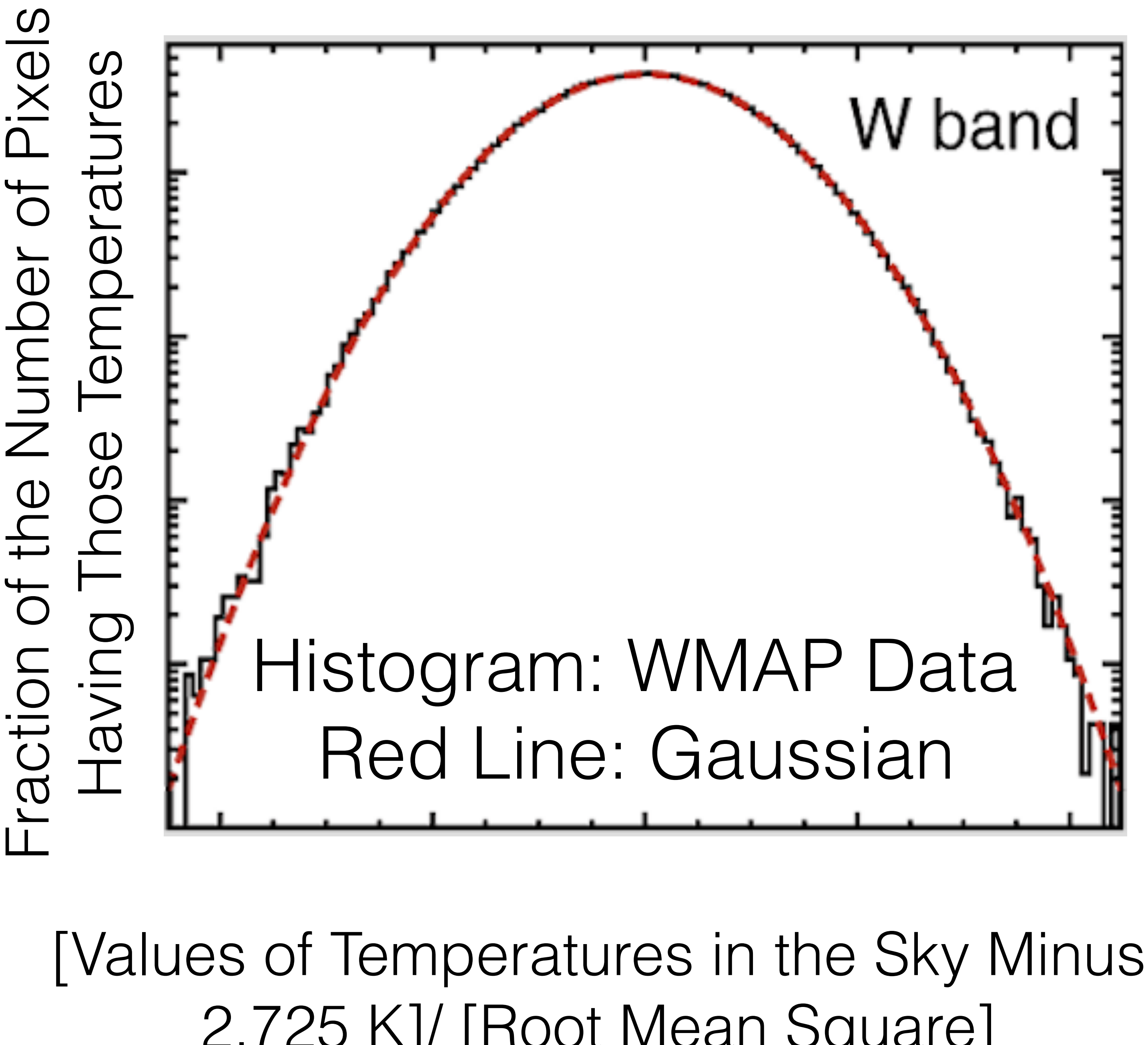
He was awarded
Max Planck Medal in 2015


exp(-x**2/2)/sqrt(2*pi)
0.1
0.01
0.001
0.0001
1e-05
-4
-3
-2
-1
0
1
2
3
4
Fraction of the Number of Pixels
Having Those Temperatures
[Values of Temperatures in the Sky Minus 2.725 K] / [Root Mean Square]
Quantum Fluctuations give a
Gaussian distribution of
temperatures.
Do we see this
in the WMAP data?



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

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)

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

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

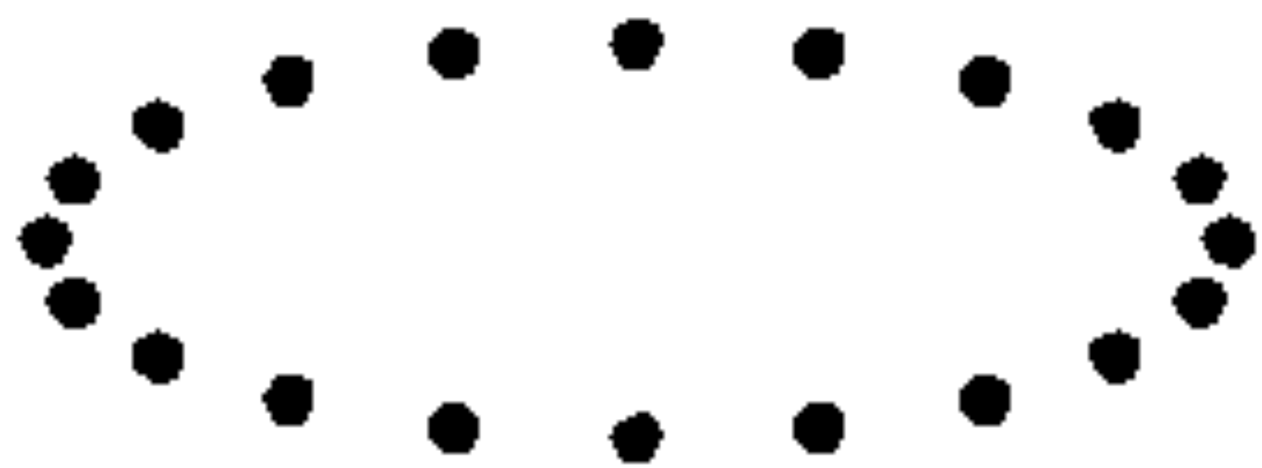
So, have we found inflation?

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

Measuring GW

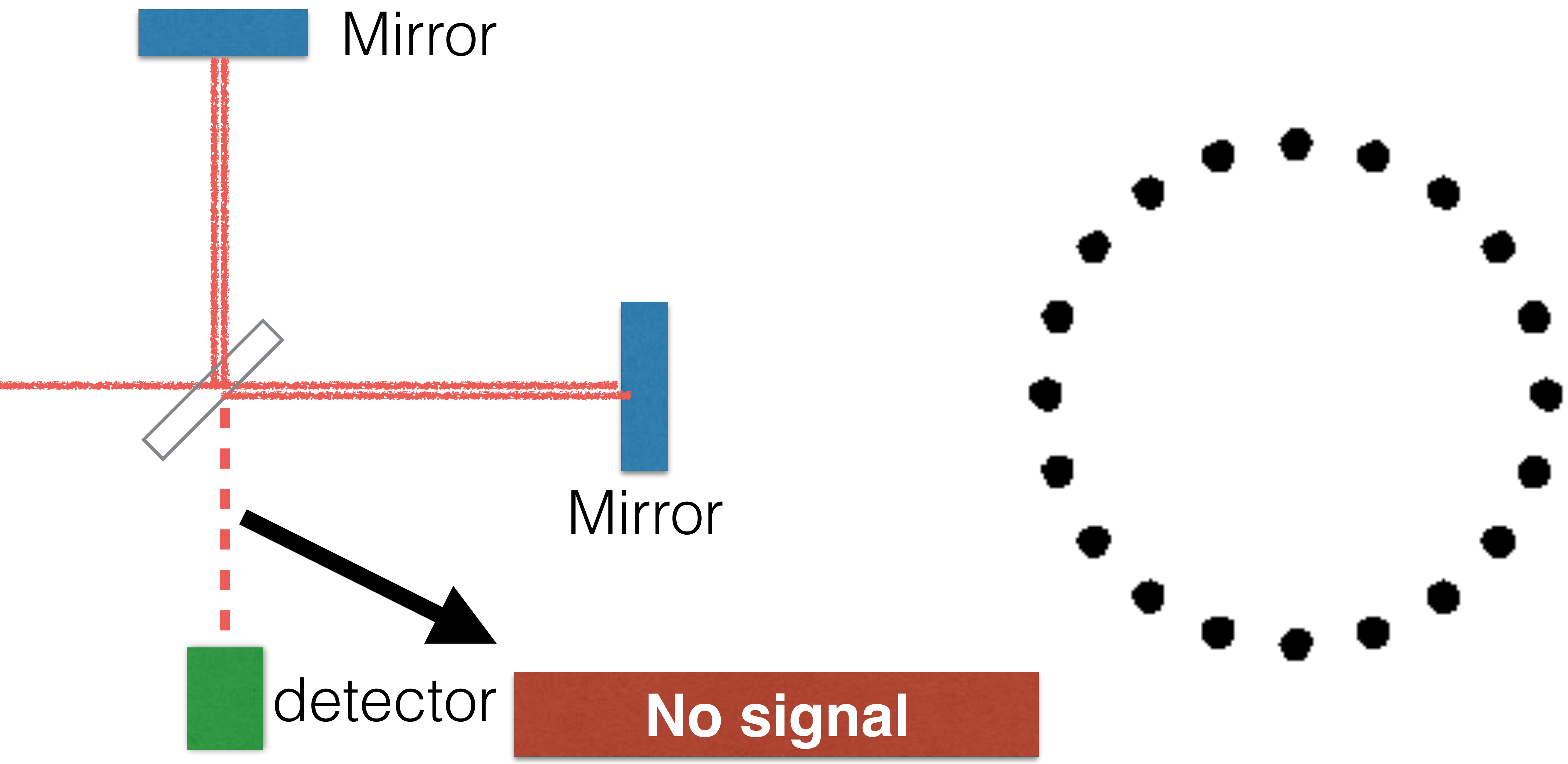
- GW changes distances between two points

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

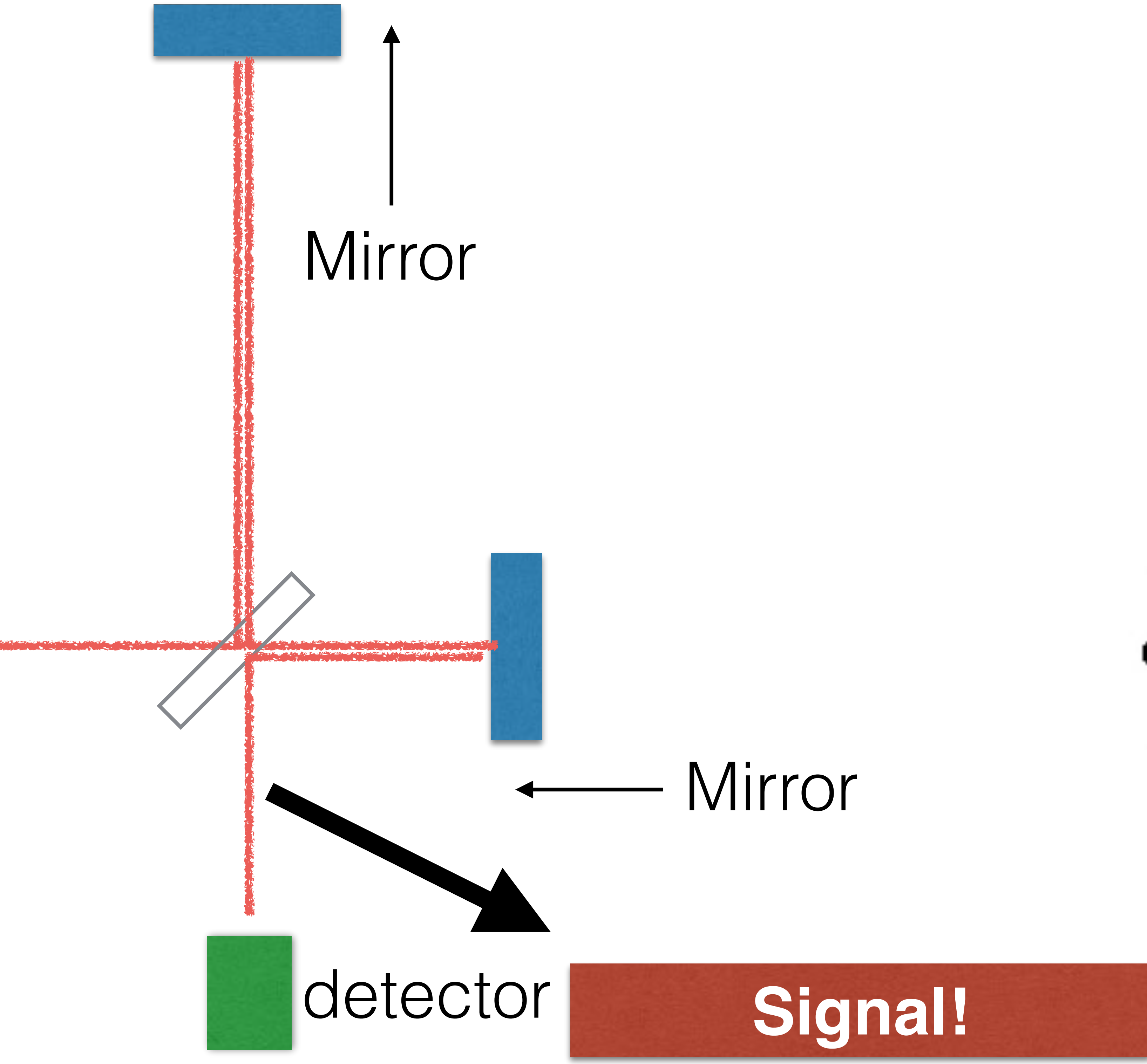


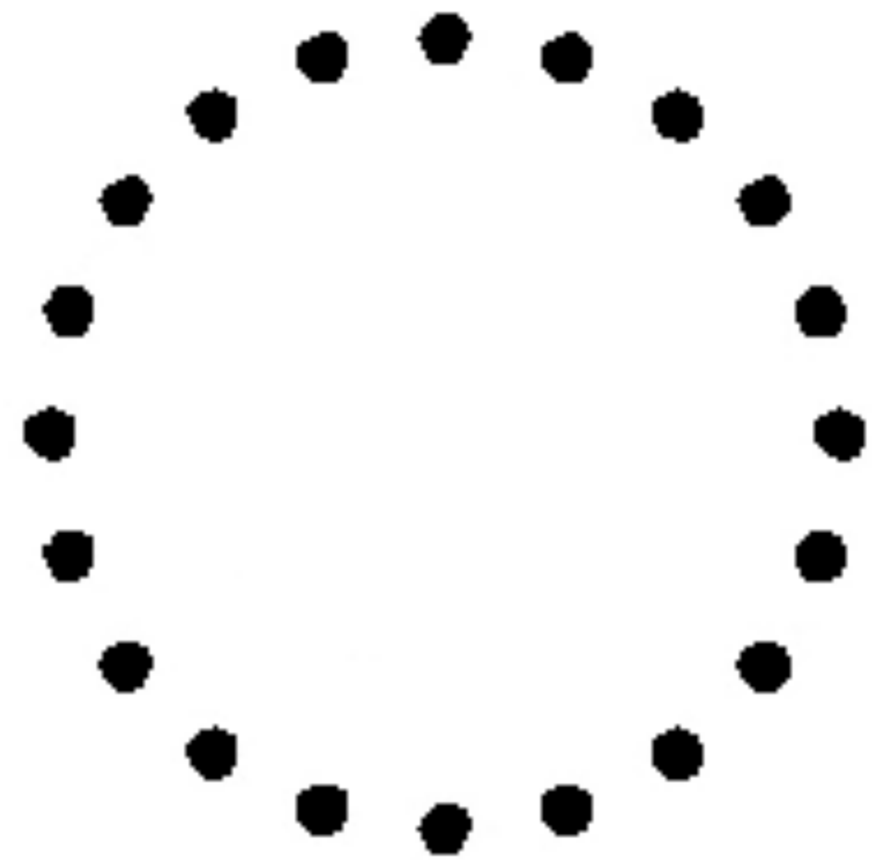
$$d\ell^2 = \sum_{ij} (\delta_{ij} + \underline{h_{ij}}) dx^i dx^j$$

Laser Interferometer

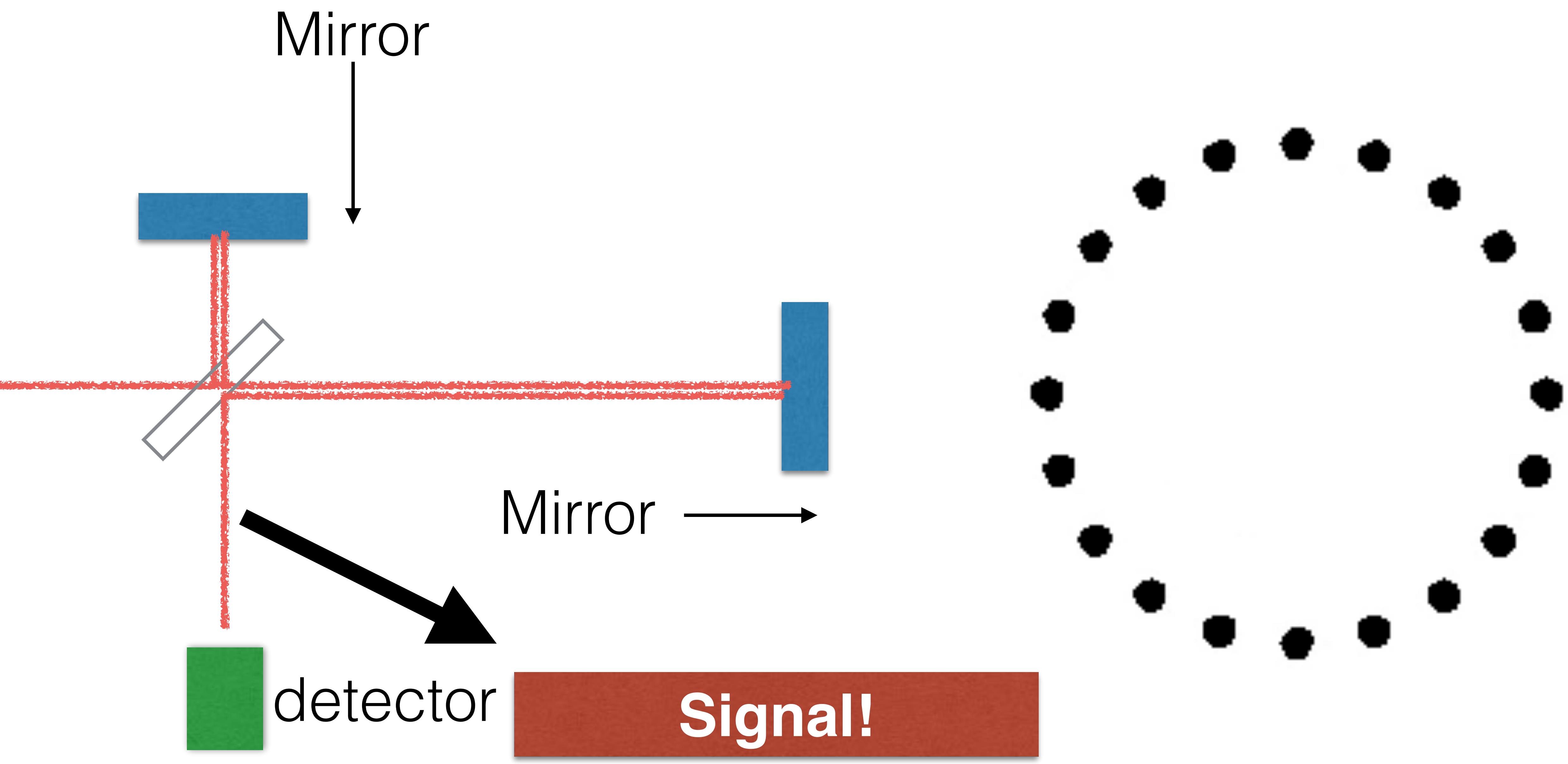


Laser Interferometer





Laser Interferometer



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

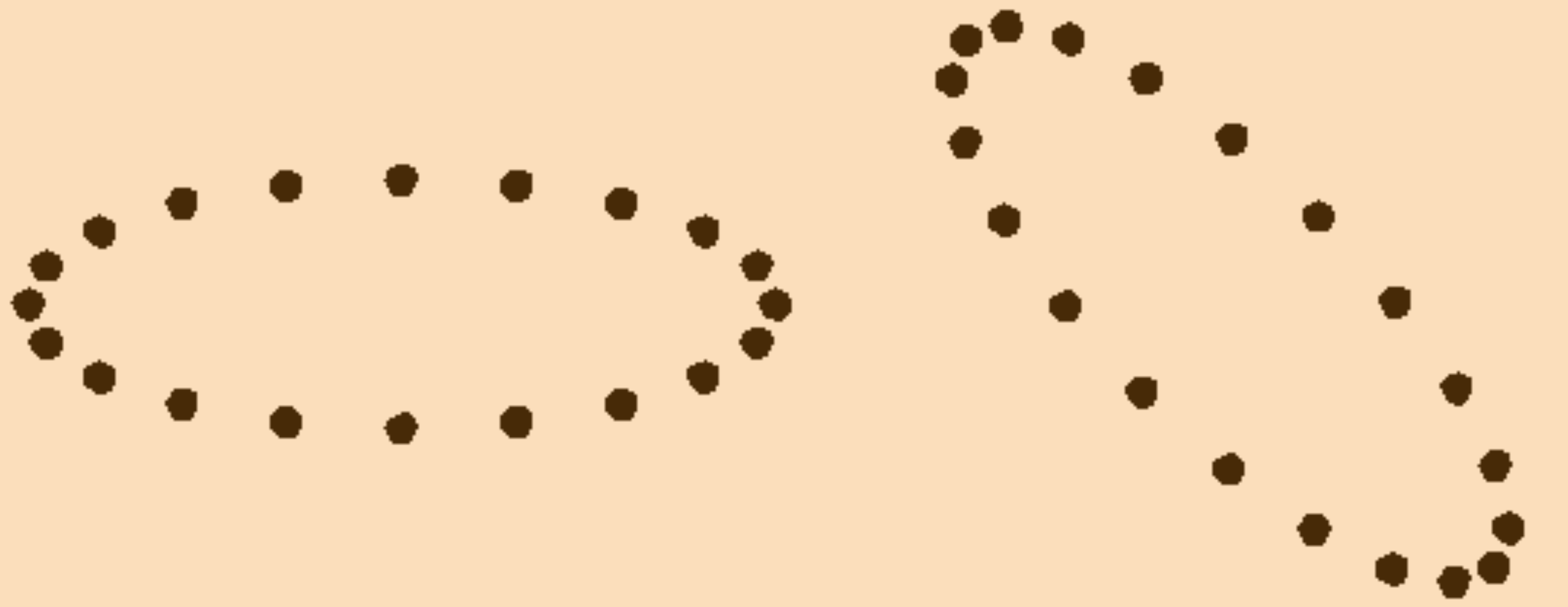
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

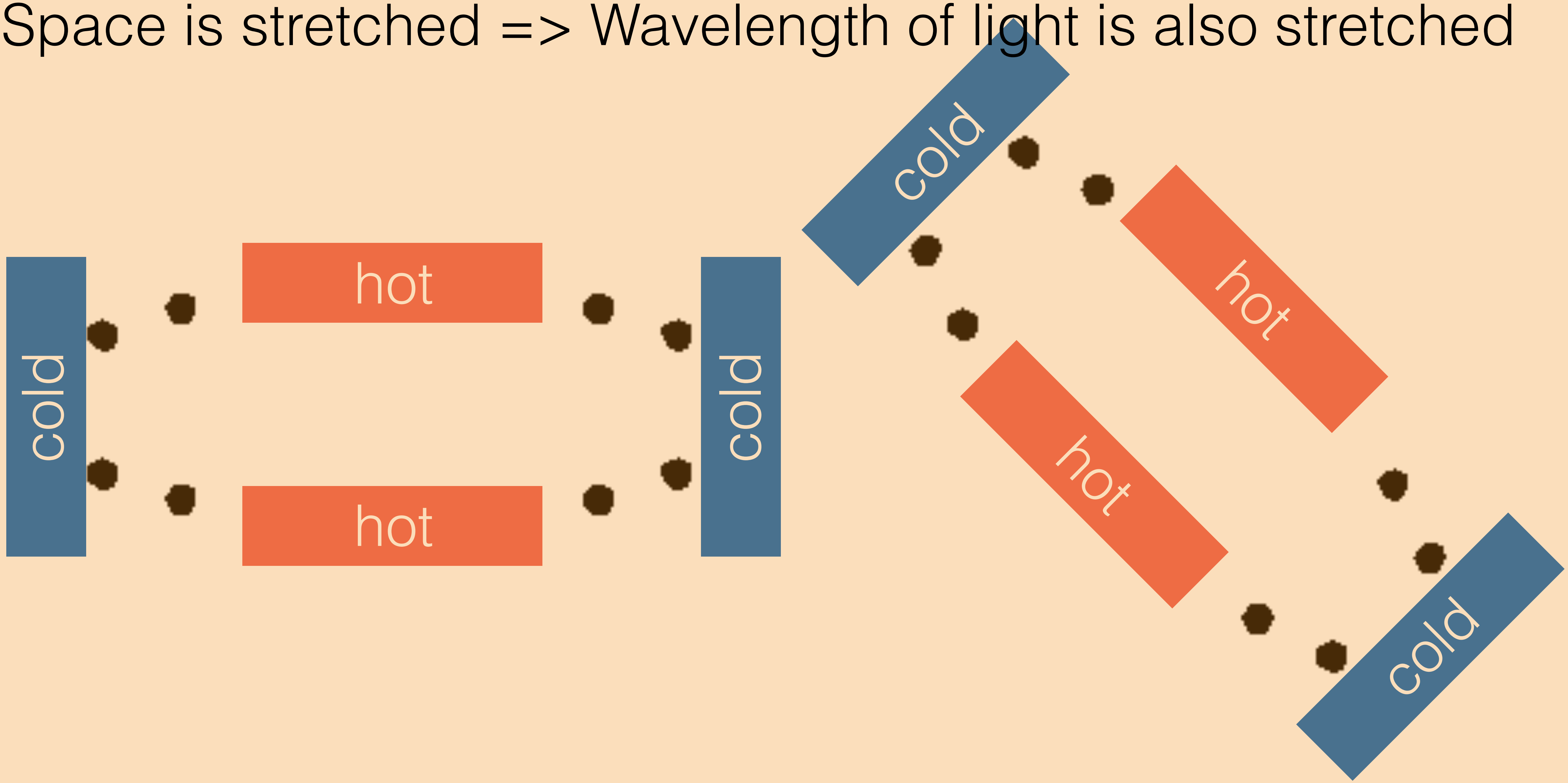
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



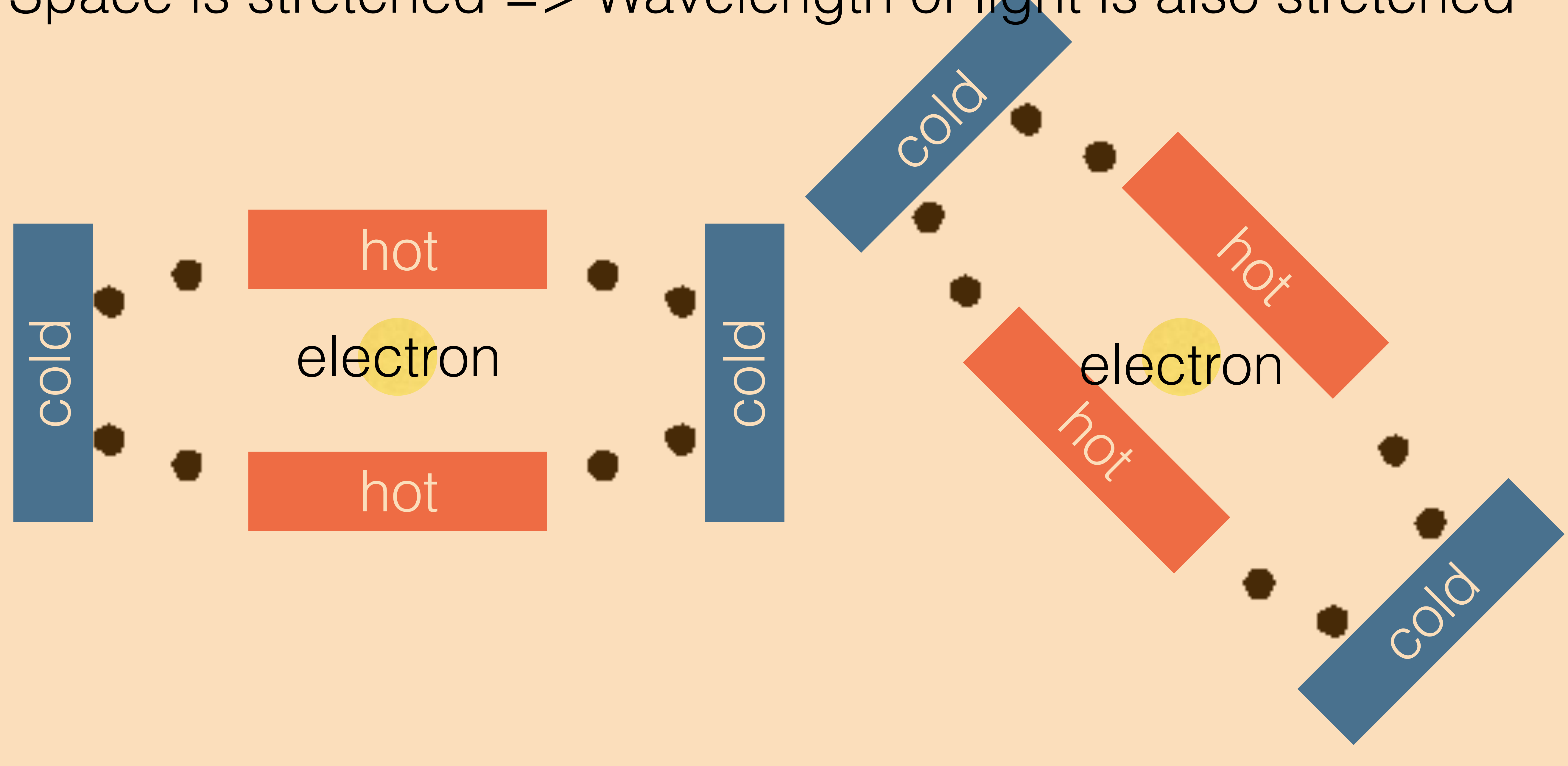
Detecting GW by CMB

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

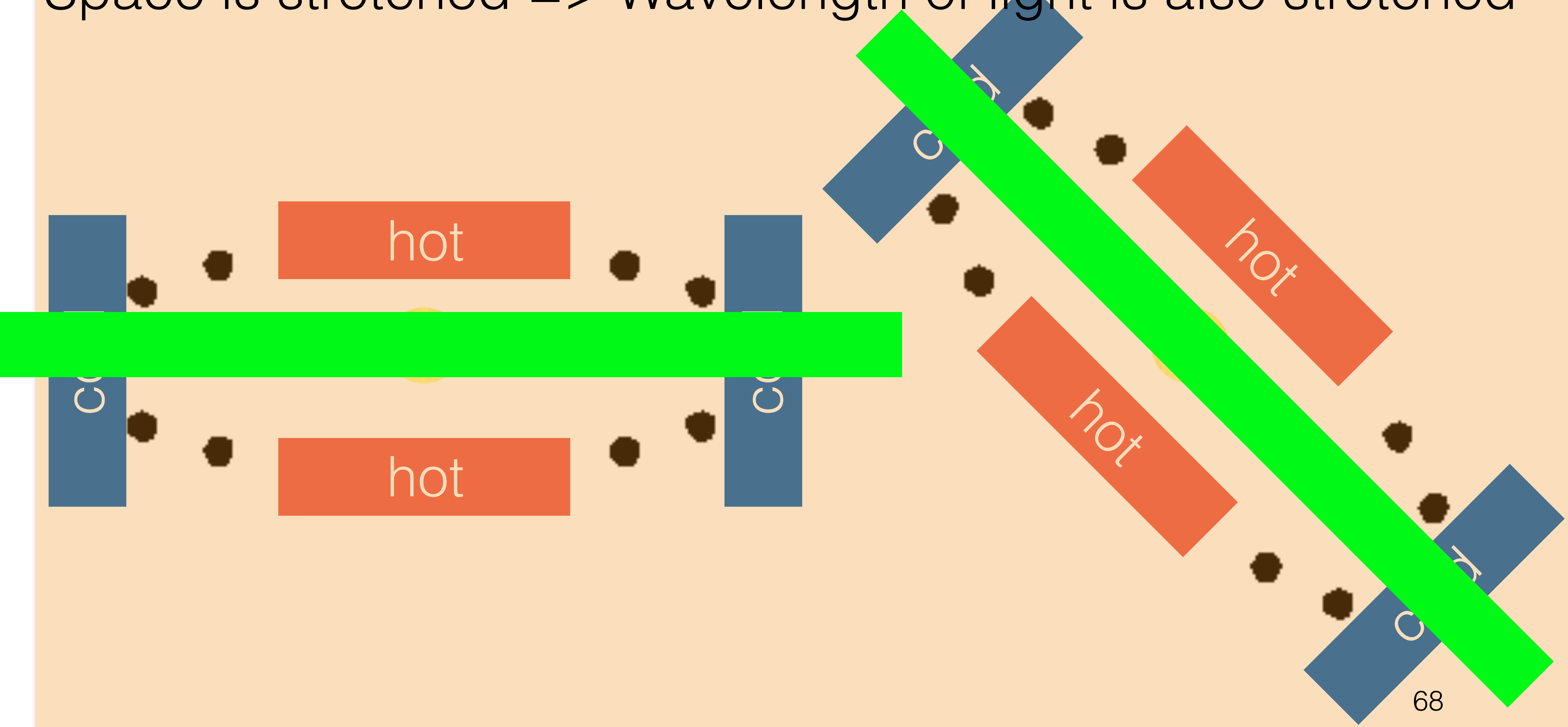



Photo Credit: TALEX
horizontally polarised

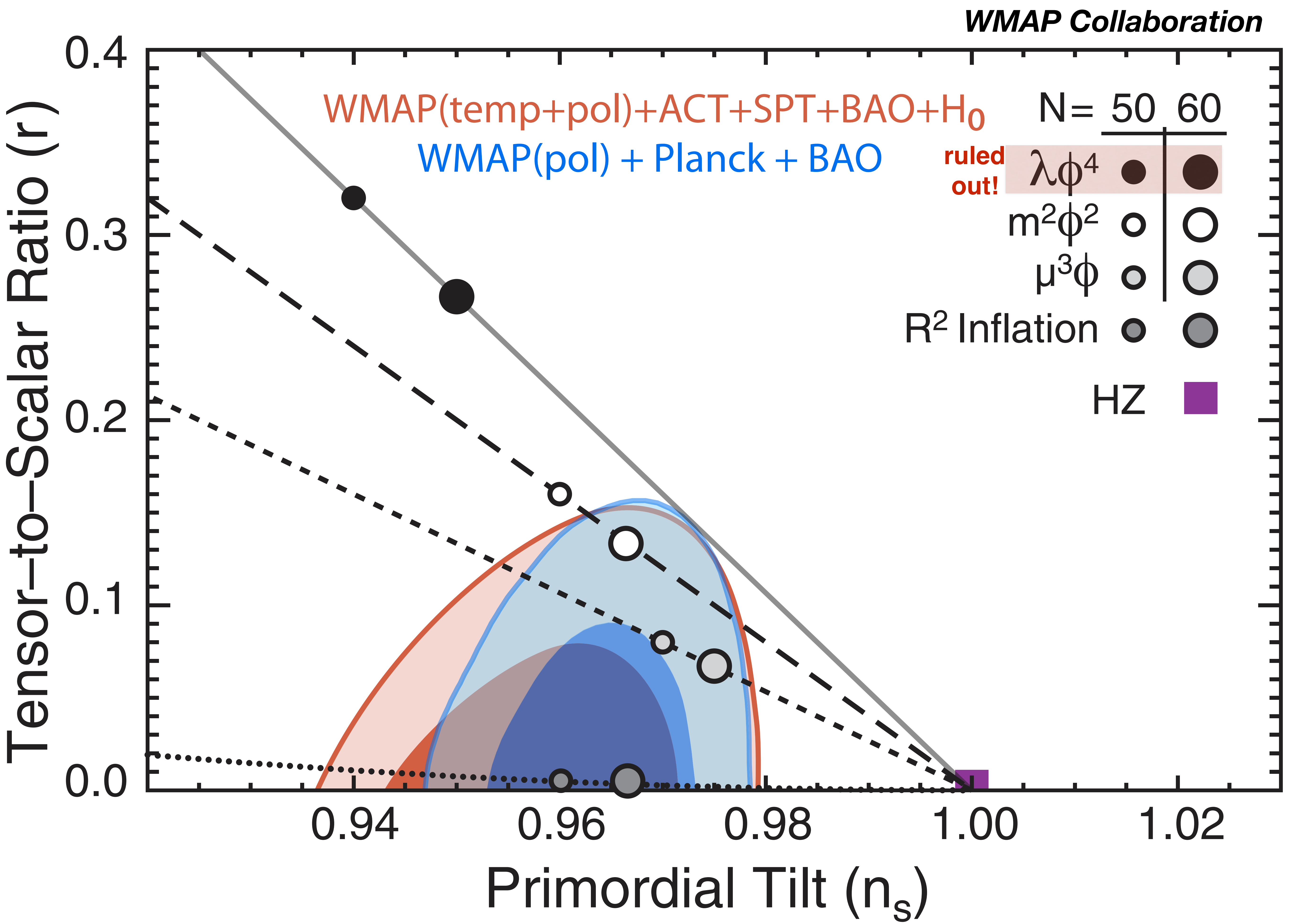

Photo Credit: TALEX

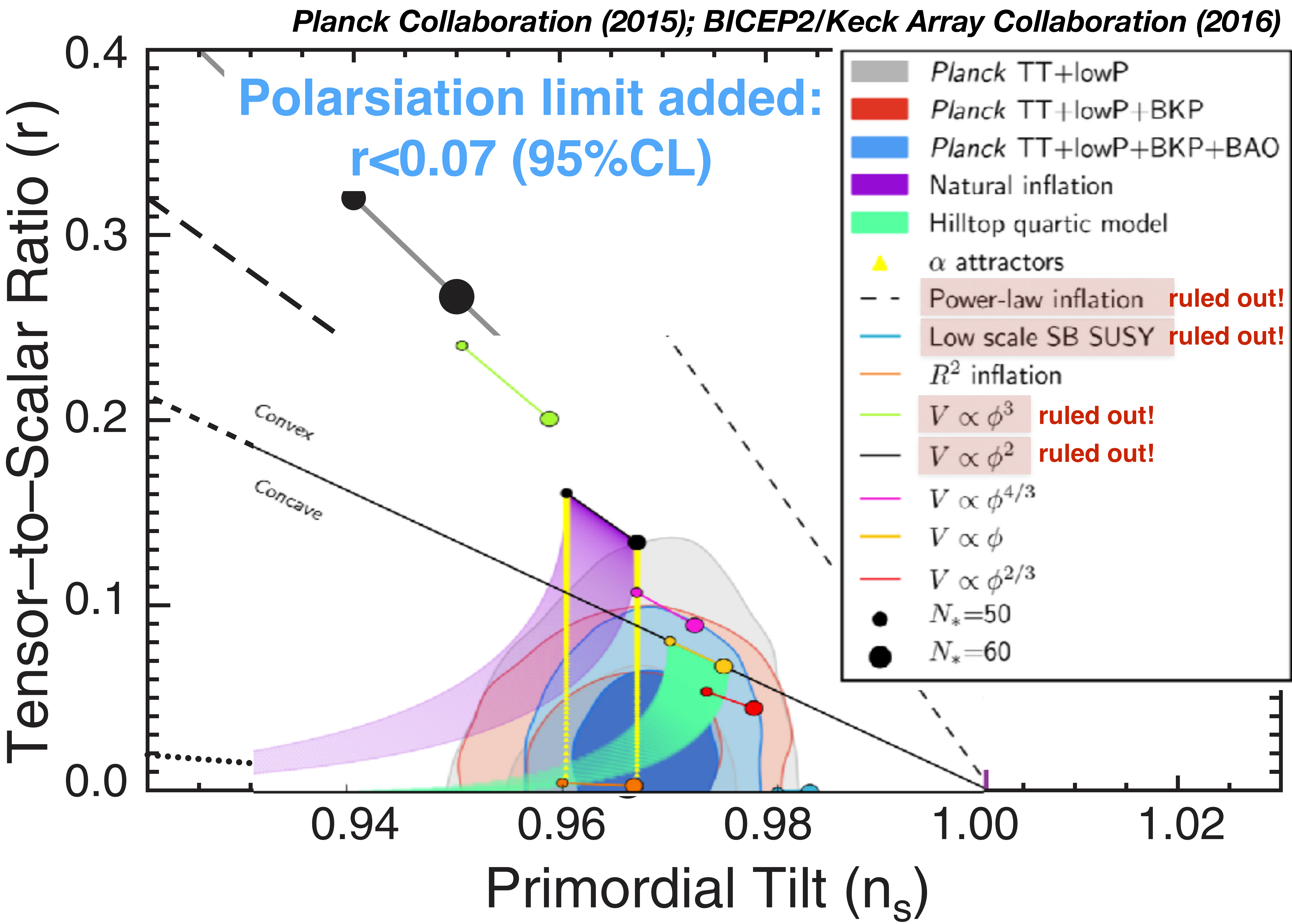
Tensor-to-scalar Ratio

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

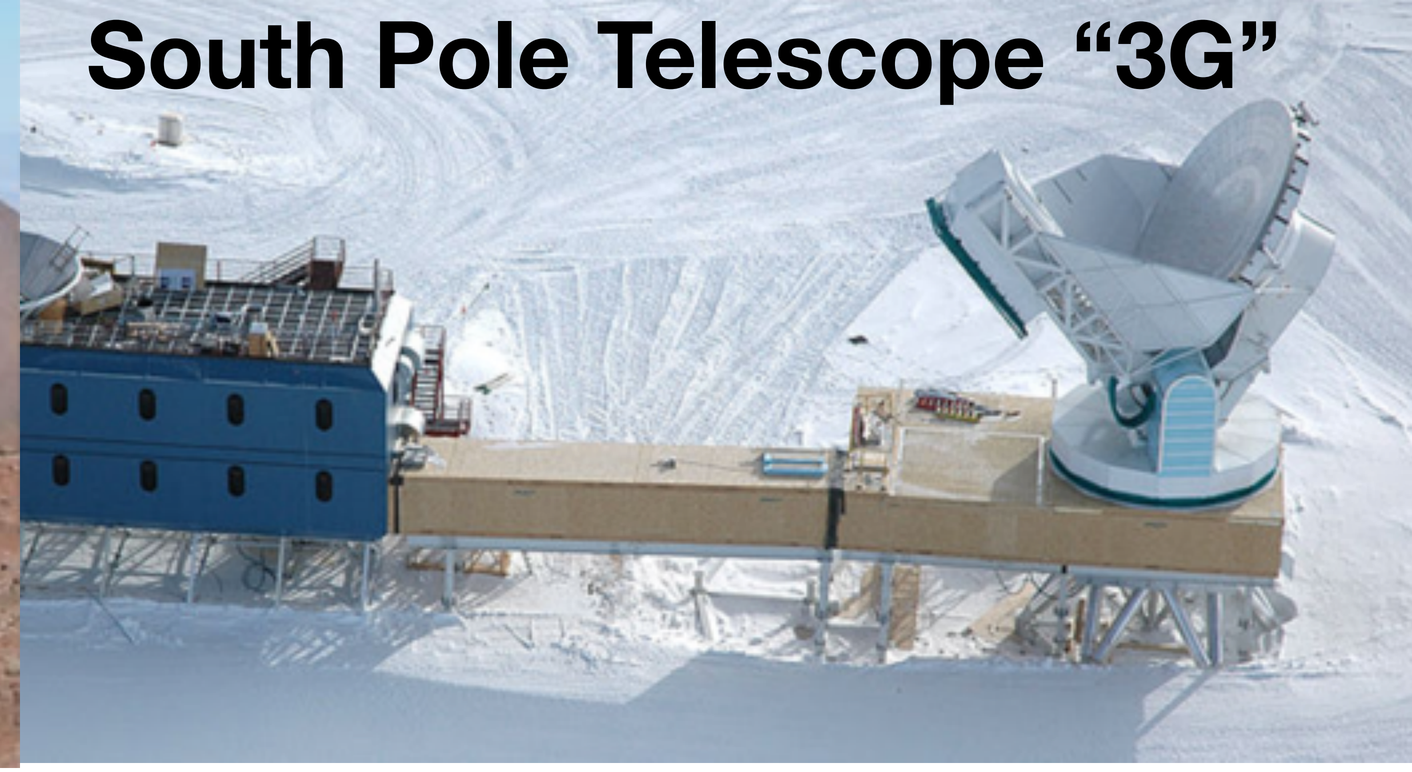
- We really want to find this! The current upper bound is **r<0.07** (95%CL)

BICEP2/Keck Array Collaboration (2016)


WMAP Collaboration
WMAP(temp+pol)+ACT+SPT+BAO+H0
WMAP(pol) + Planck + BAO
N= 50 60
ruled out!
λφ4
m2φ2
μ3φ
R2 Inflation
HZ
Tensor–to–Scalar Ratio (r)
0.0
0.1
0.2
0.3
0.4
Primordial Tilt (ns)
0.94
0.96
0.98
1.00
1.02

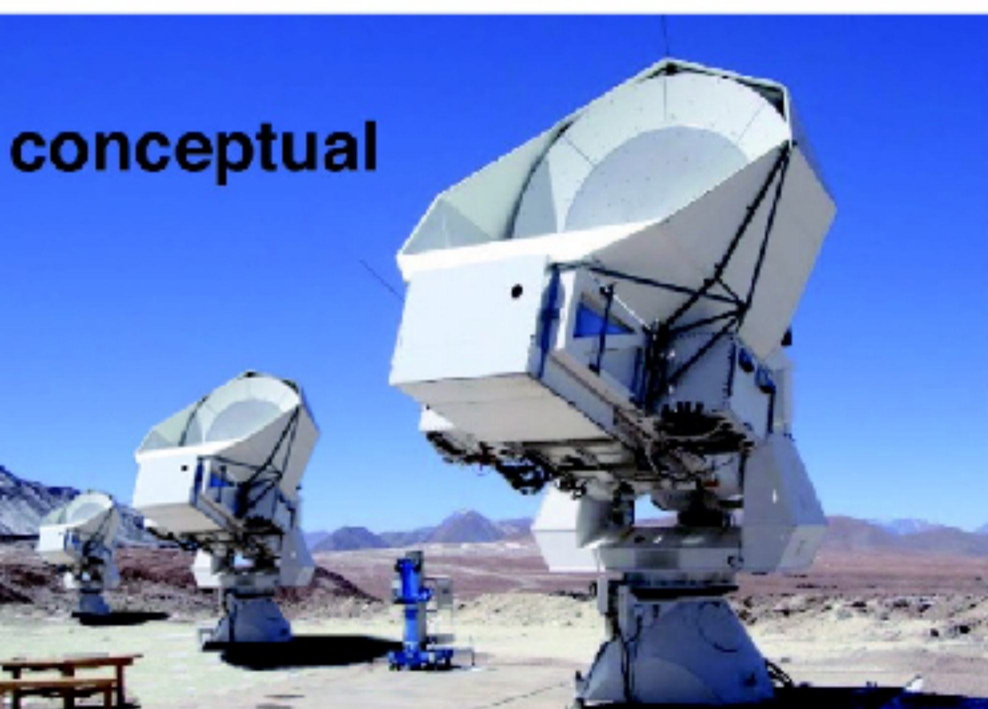

Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
ruled out!
Low scale SB SUSY
ruled out!
R^2 inflation
$V \propto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

What comes next?



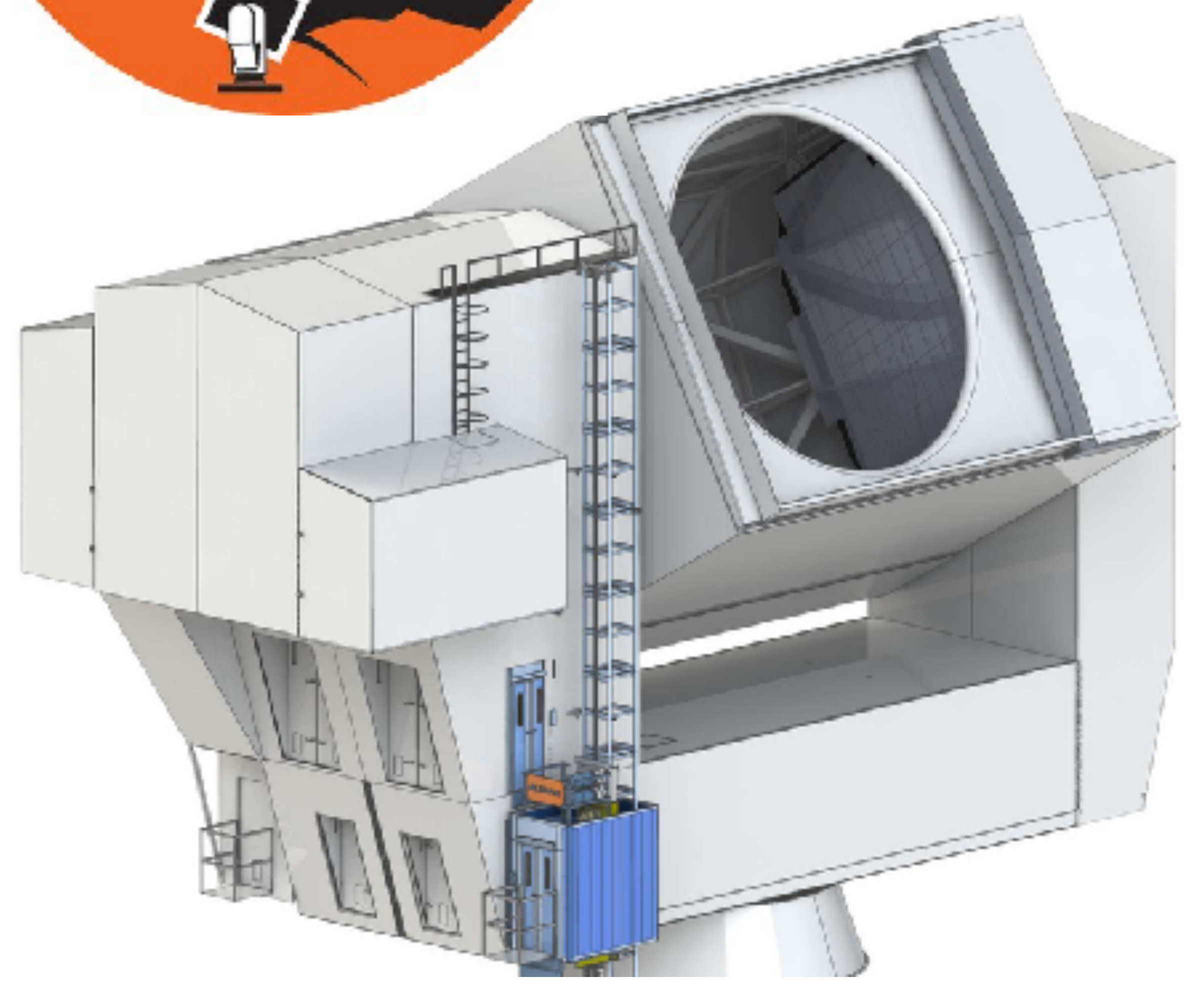
What comes next?

The Simons Array

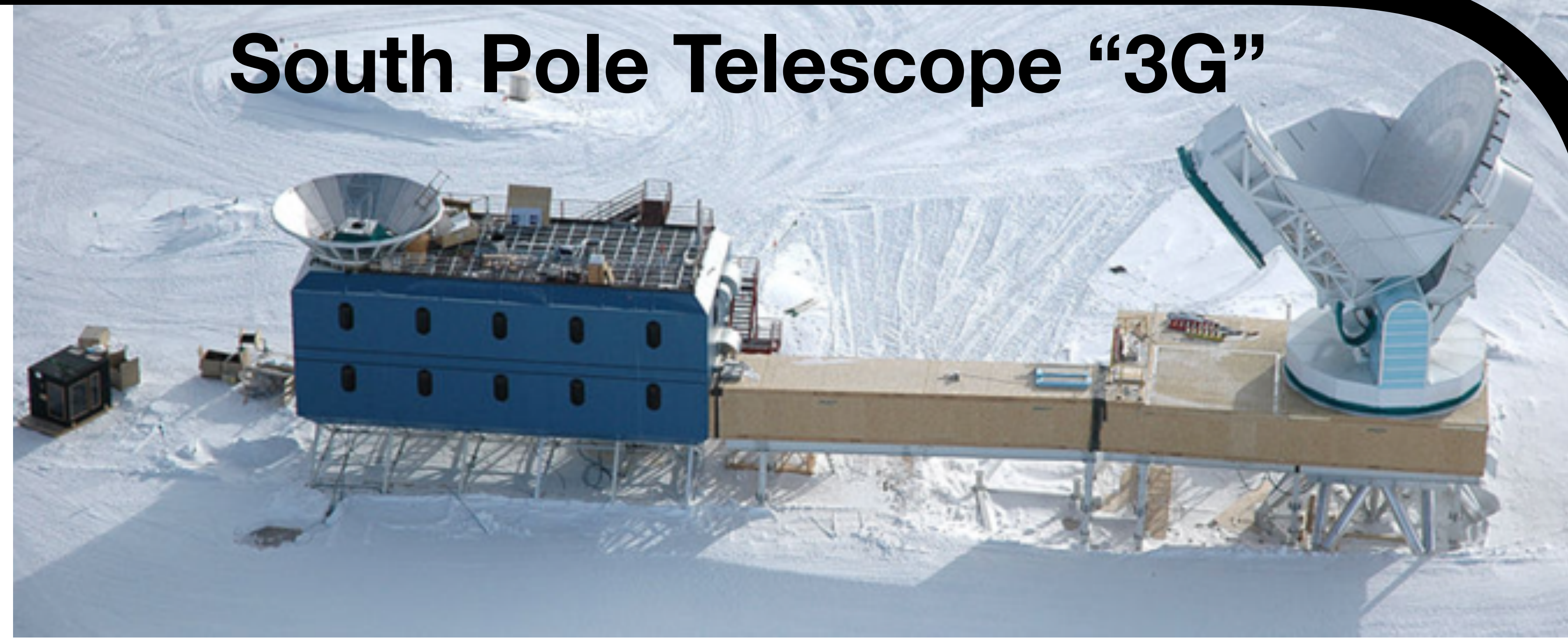


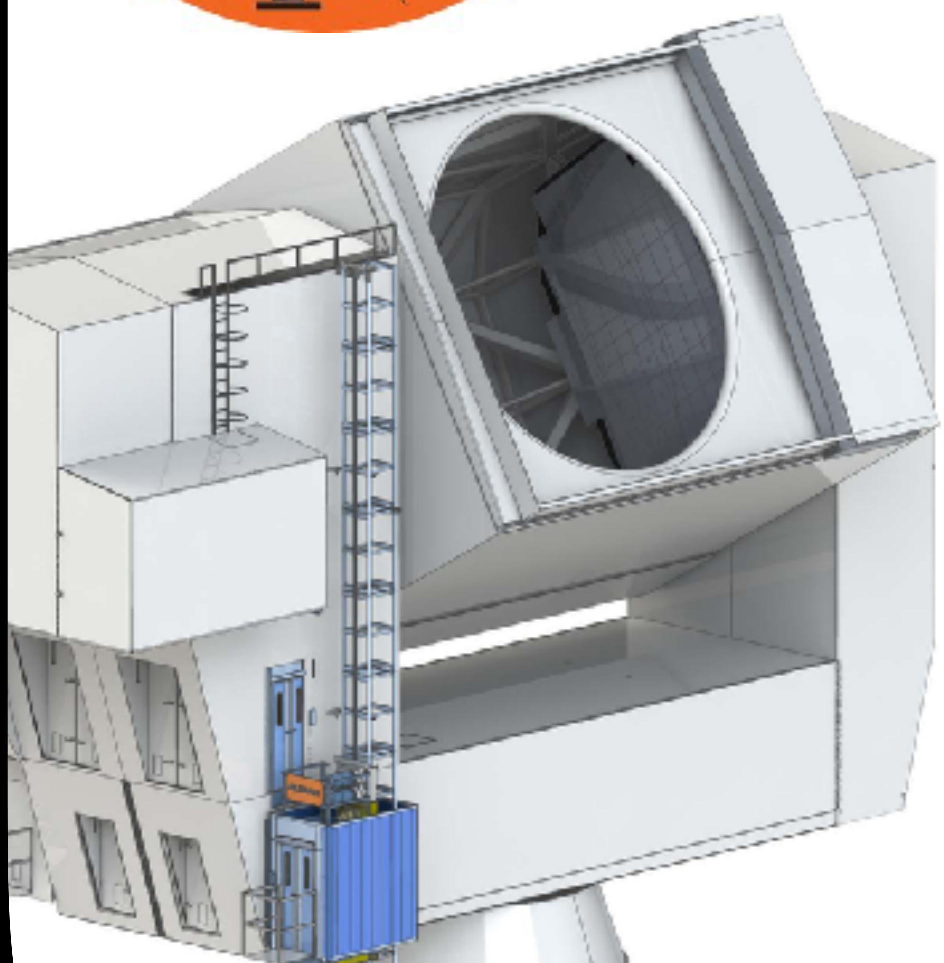
SIMONS
OBSERVATORY

The Simons Array



SIMONS OBSERVATORY





CMB-S4(?)

CMB-S4
Next Generation CMB Experiment

CMB Stages

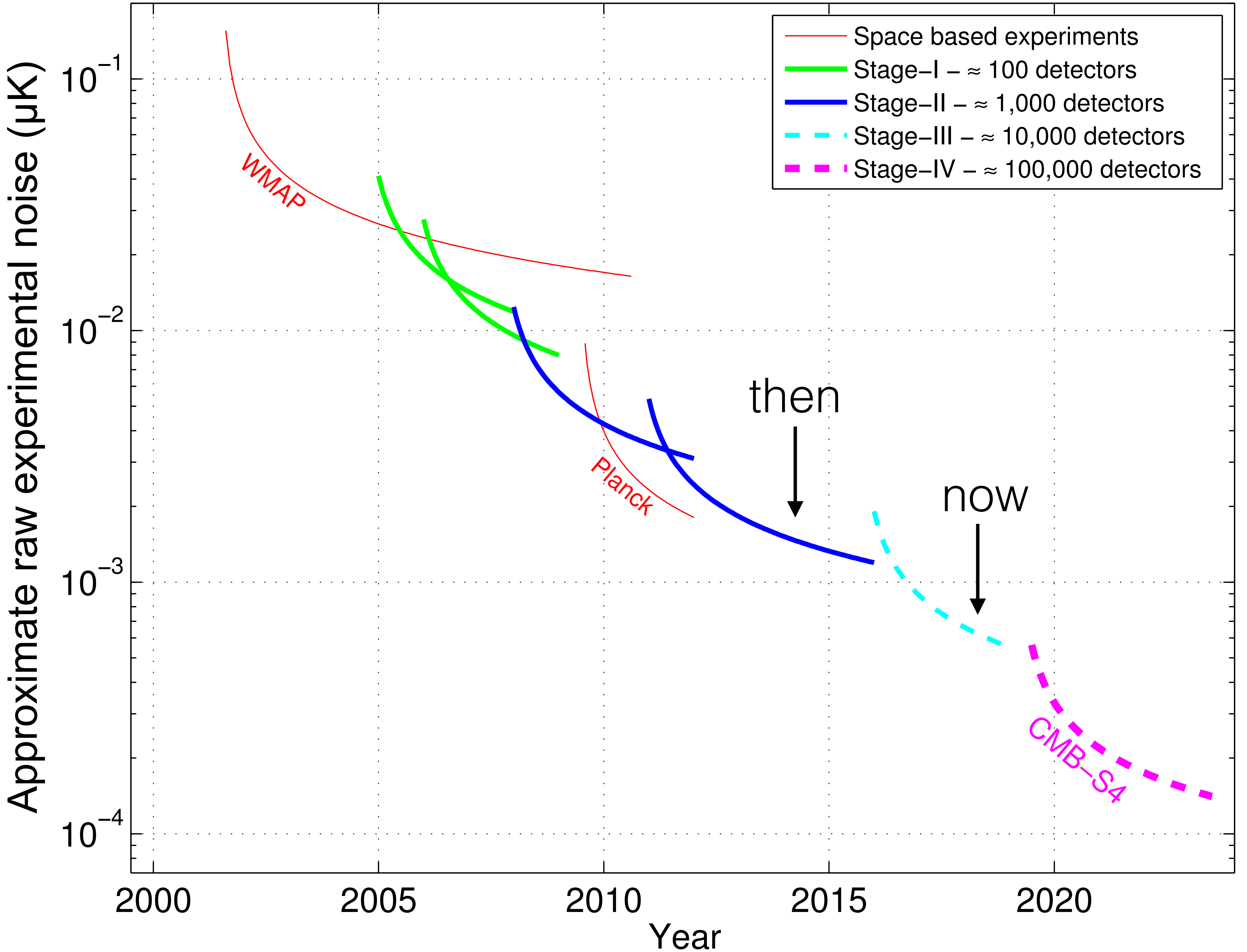


Figure by Clem Pryke for 2013 Snowmass documents

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

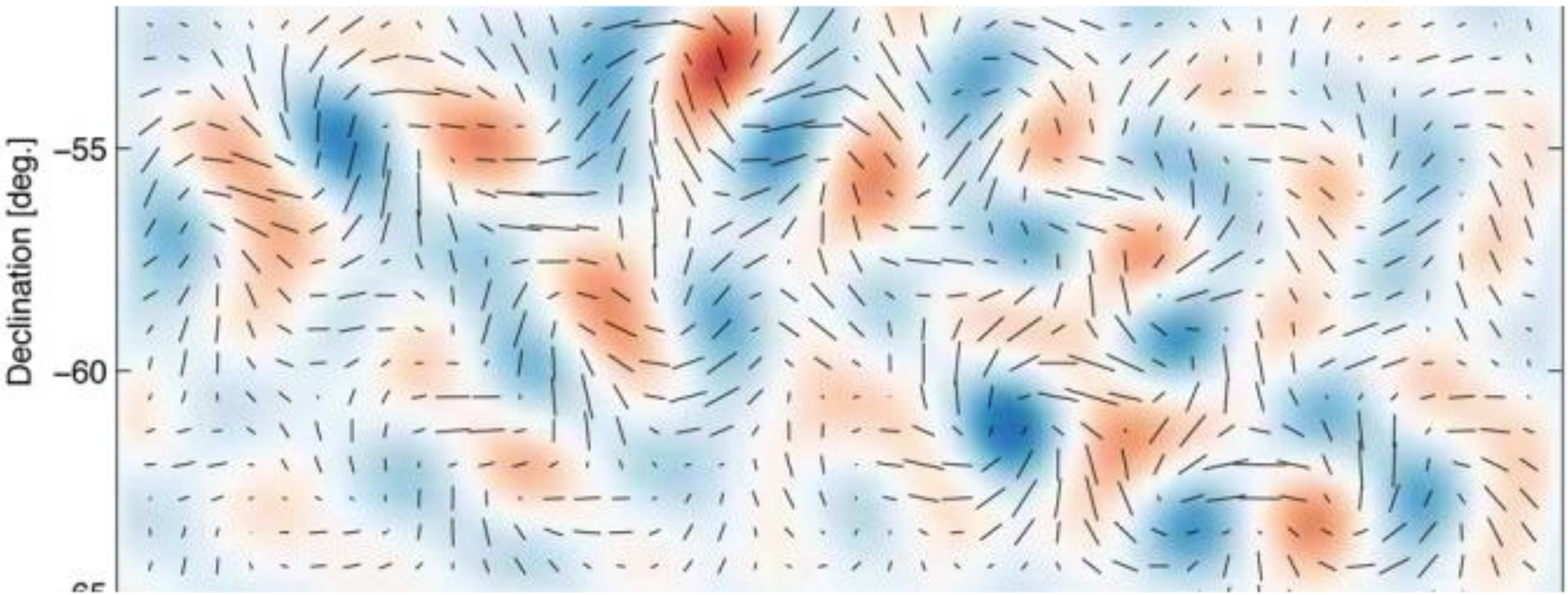
- CCAT-p!

March 17, 2014

BICEP2's announcement

First Direct Evidence of Cosmic Inflation

Release No.: 2014-05
For Release: Monday, March 17, 2014 - 10:45am



Cambridge, MA - Almost 14 billion years ago, the universe we inhabit burst into existence in an extraordinary event that initiated the Big Bang. In the first fleeting fraction of a second, the universe expanded exponentially, stretching far beyond the view of our best telescopes. All this, of course, was just theory.

SPACE & COSMOS

The New York Times

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

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17 March 2014 Last updated at 14:46 GMT

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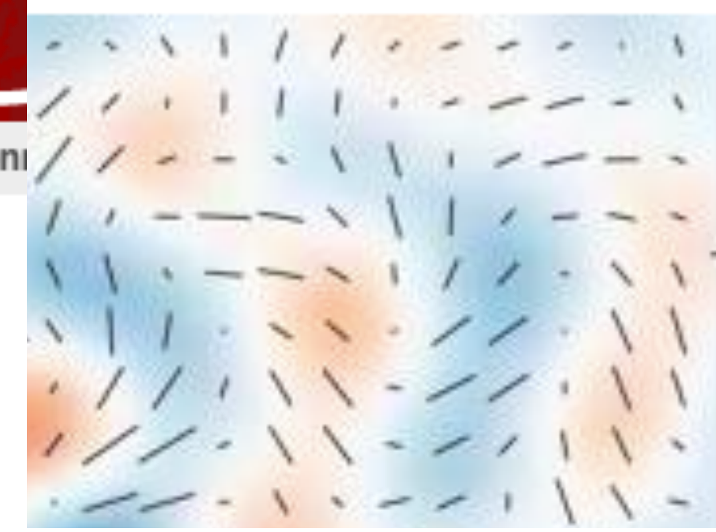
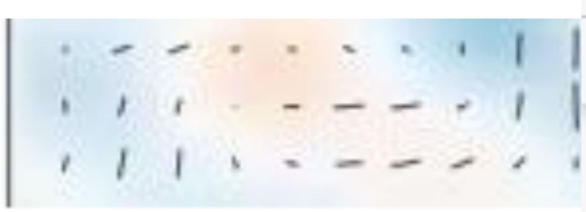


Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos
Science correspondent, BBC News



Cambridge, MA - Almost 14 billic
that initiated the Big Bang. In the
far beyond the view of our best tel

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Hir

17. März 2014, 17:34 Gravitationswellen

Signale aus der Geburtsstunde des Universums

Von Patrick Illinger

January 30, 2015

Joint Analysis of BICEP2 data and Planck data

SCIENCE

The New York Times

Speck of Interstellar Dust Obscures Glimpse of Big Bang

By DENNIS OVERBYE JAN. 30, 2015

BBC

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30 January 2015 Last updated at 20:54 GMT

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Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos
Science correspondent, BBC News

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Home > Wissen > Kosmologie - Urknall-Forscher gestehen Irrtum ein

Süddeutsche.de als Startseite einrichten

1. Februar 2015, 22:19 Kosmologie

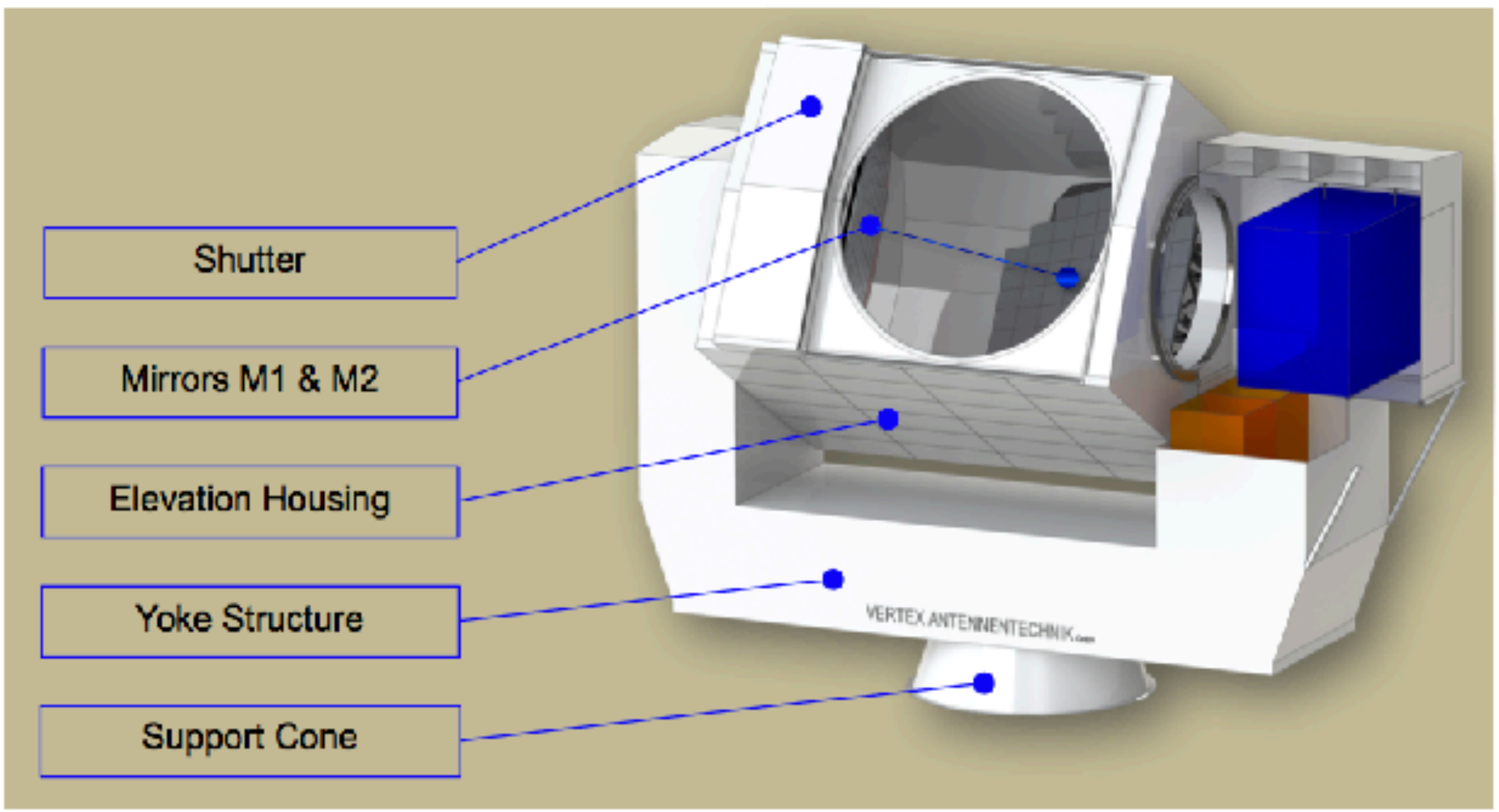
Urknall-Forscher gestehen Irrtum ein

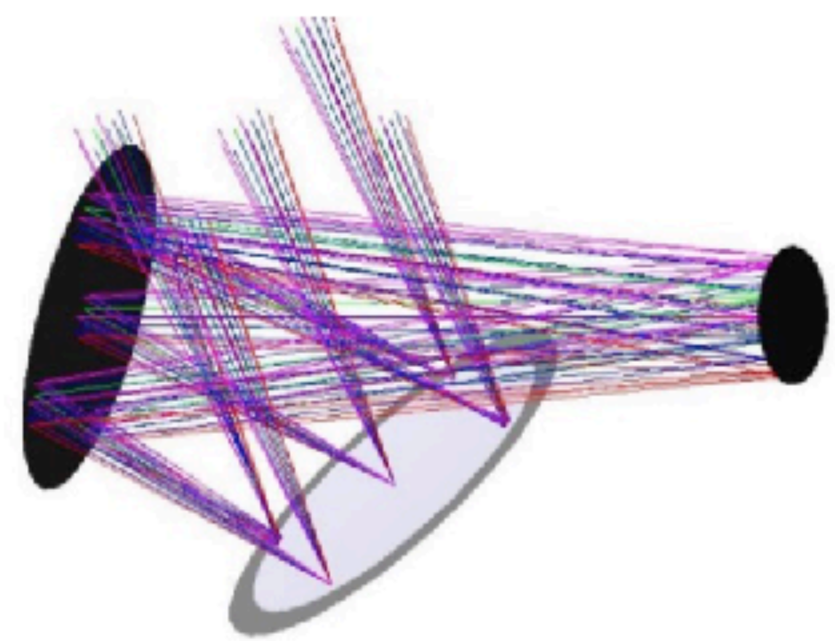
Von Marlene Weiß

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 + …

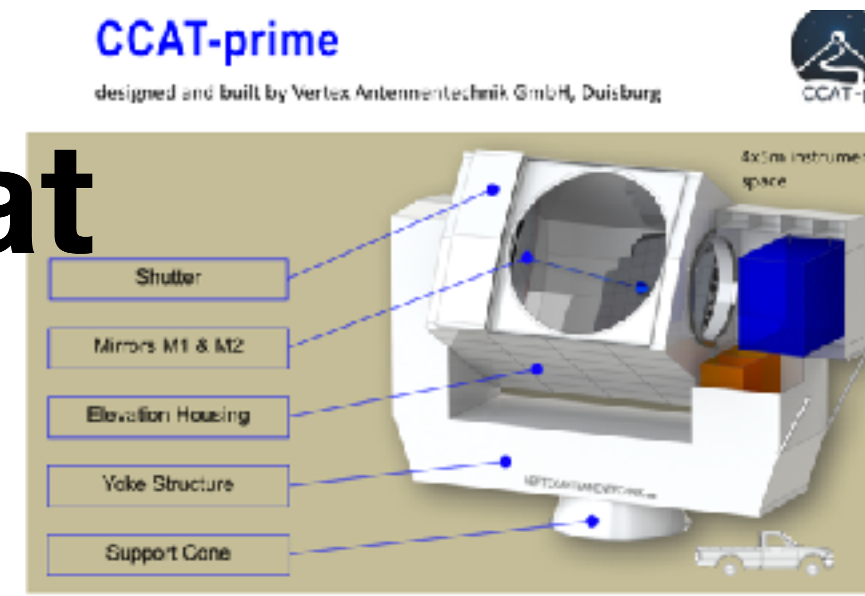
Frank Bertoldi's slide from the Florence meeting

Where is CCAT-p?

Cerro Chajnantor at 5600 m w/ TAO

A Game Changer

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

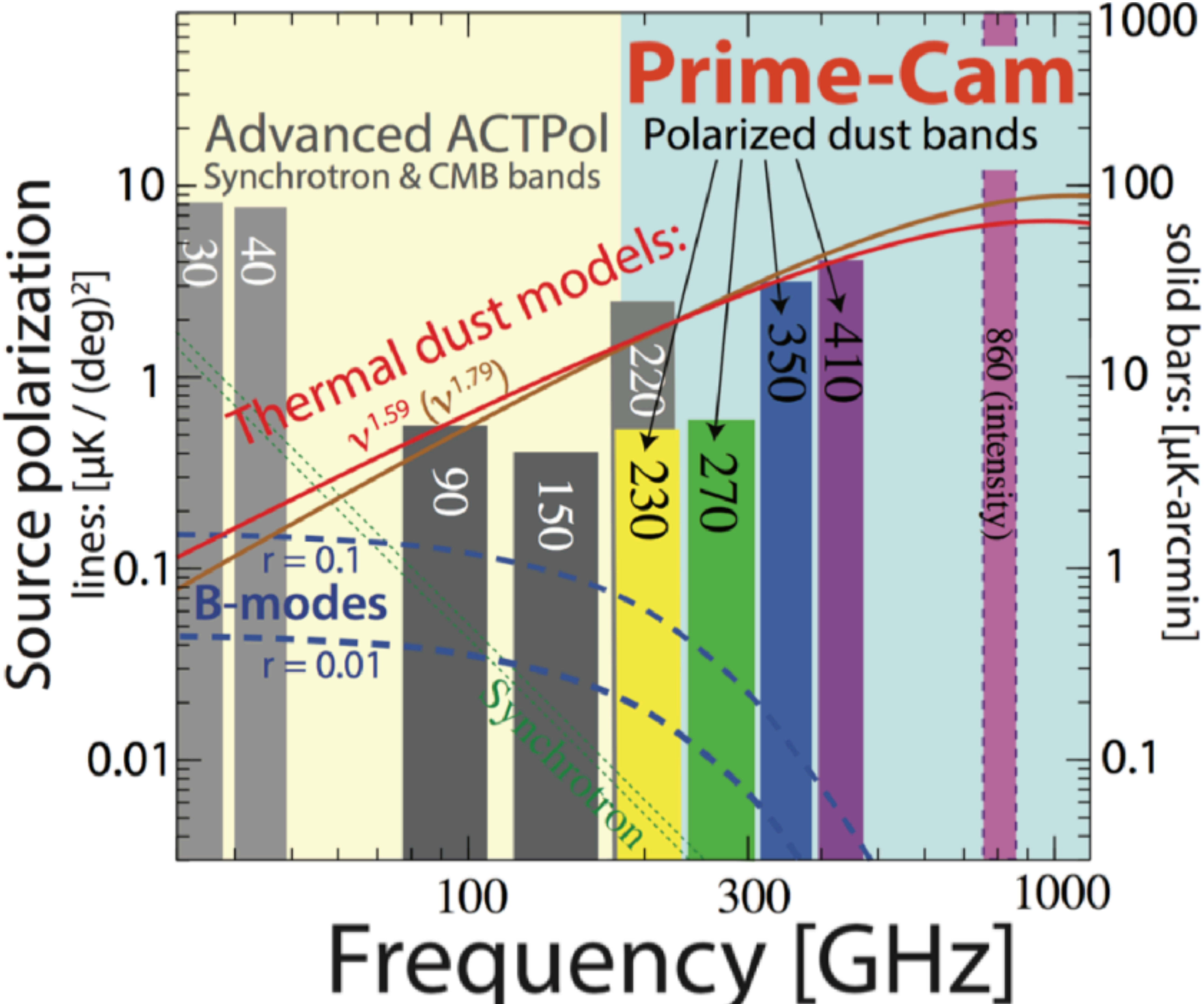


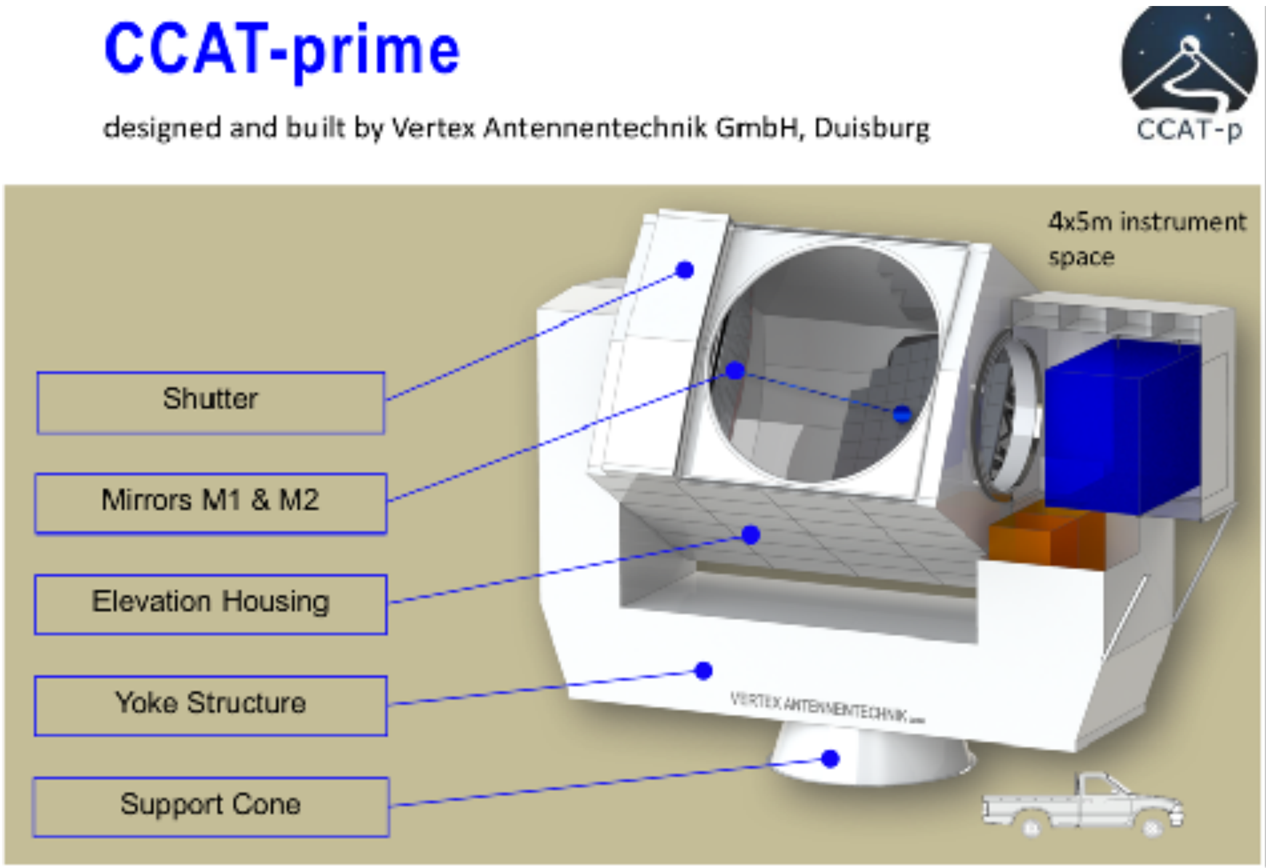
- **Germany makes great telescopes!**

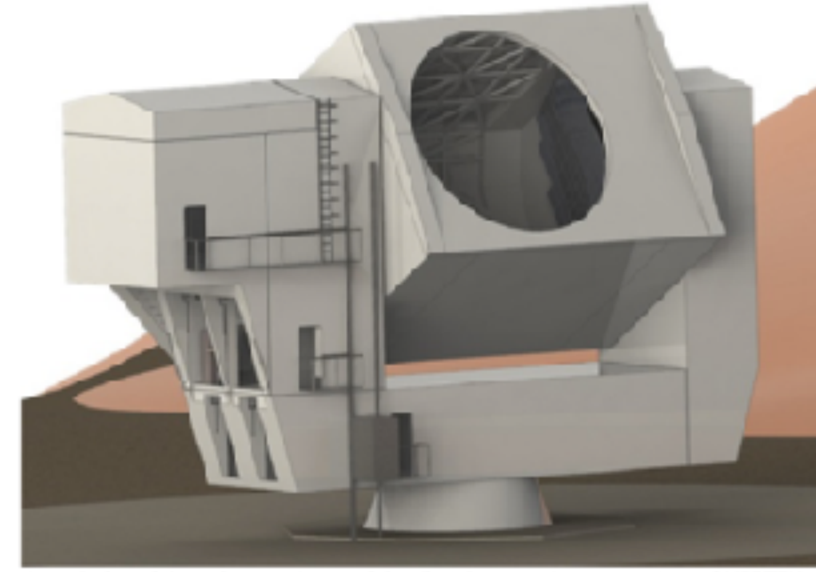
- Design study completed, and the contract has been signed by "VERTEX Antennentechnik GmbH"

    - 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-p Collaboration







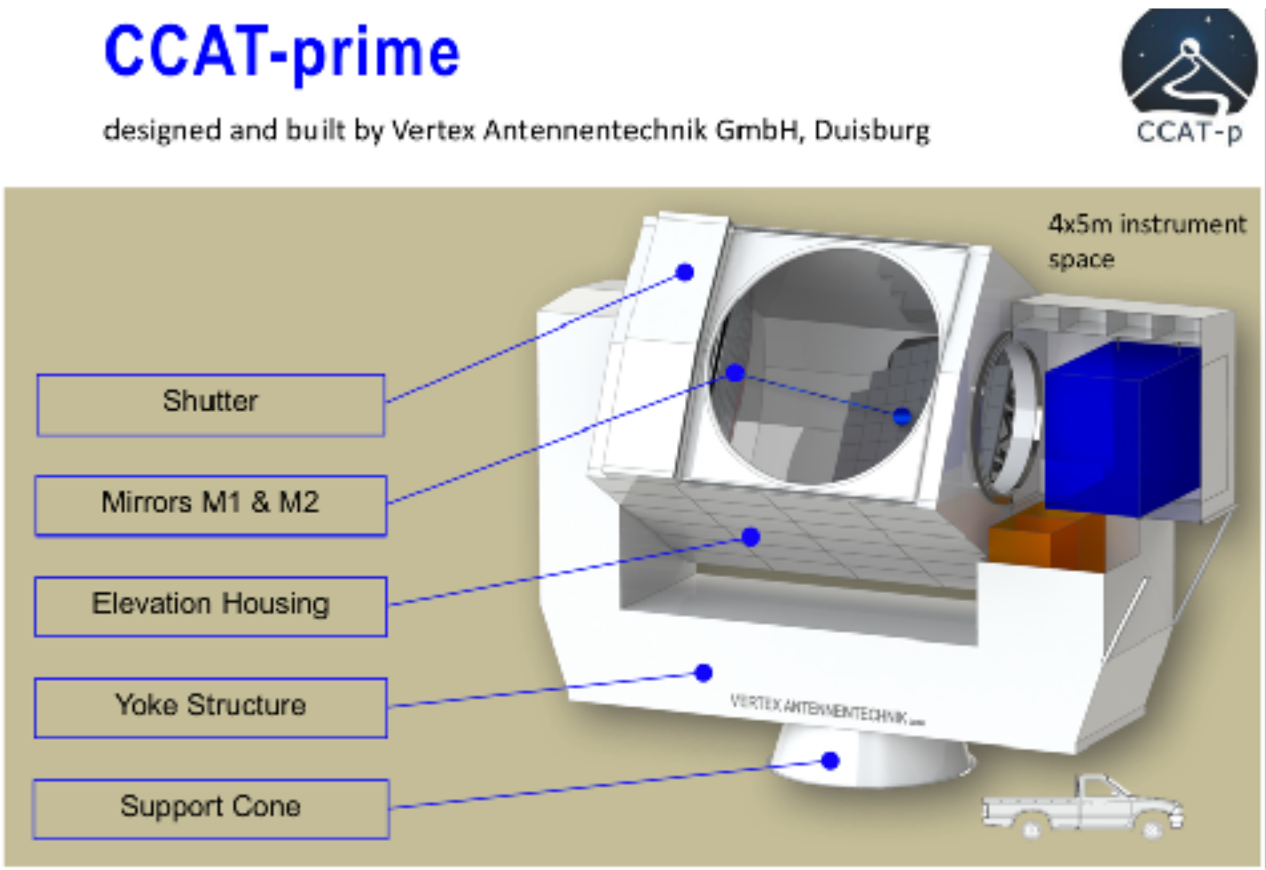
A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

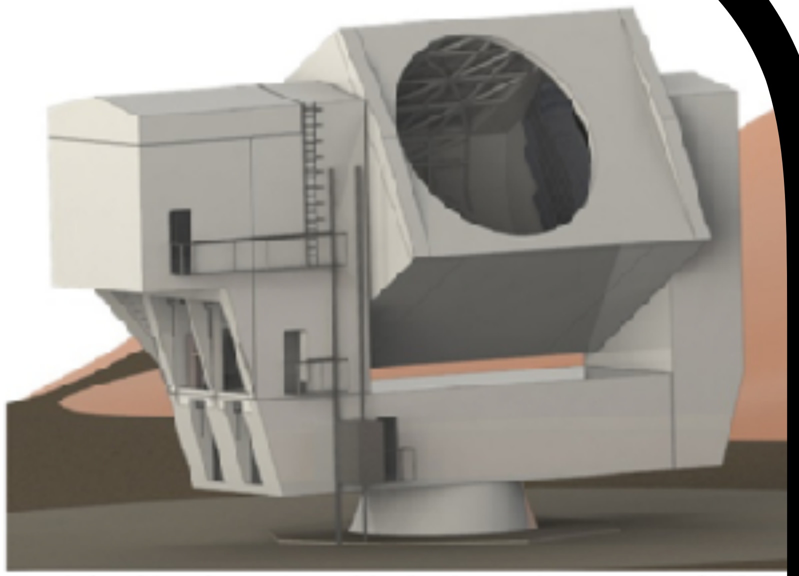
Simons Observatory (USA)

in collaboration

South Pole?

This could be "CMB-S4"





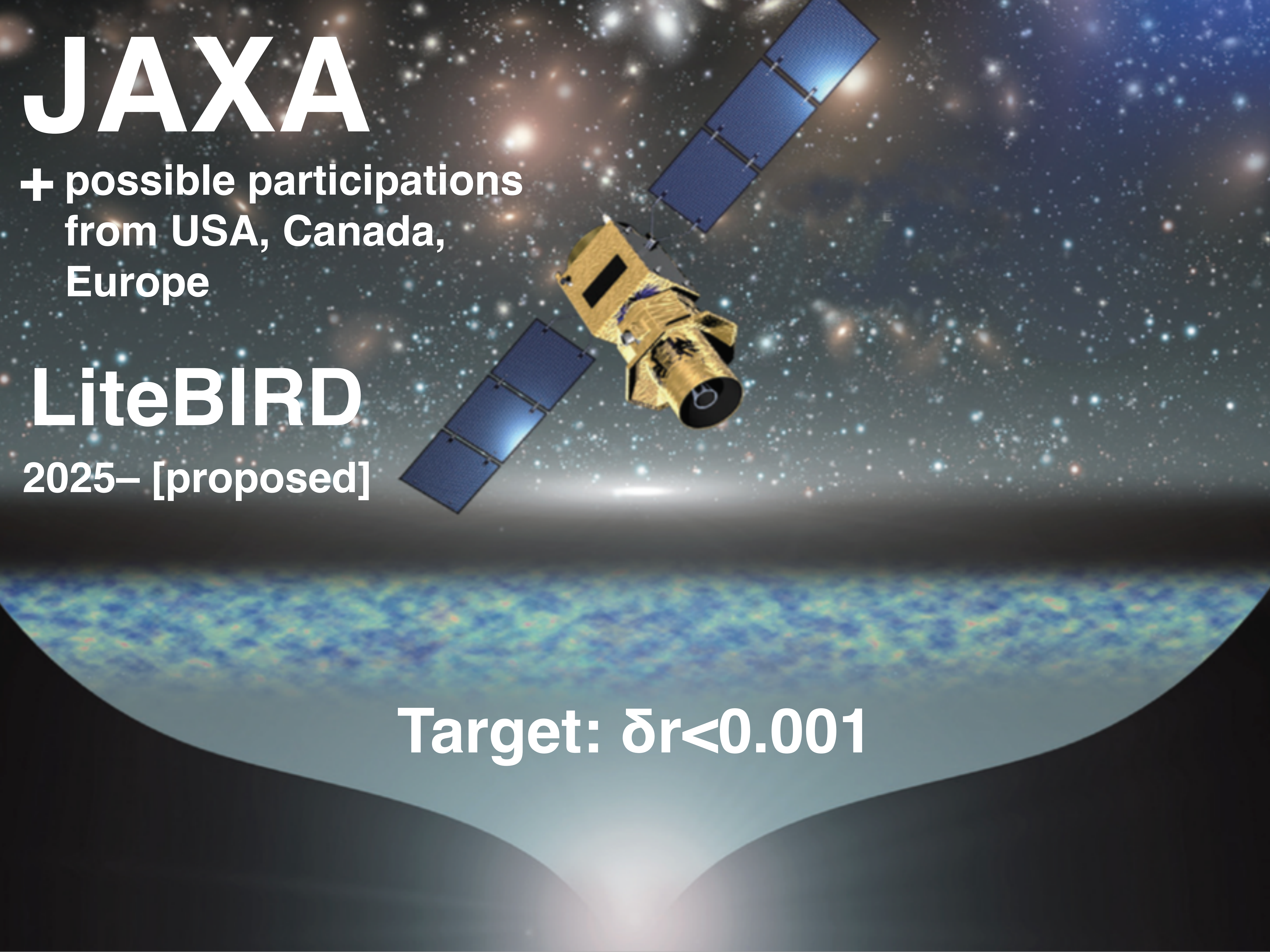
A rendering of the unique and powerful radio telescope. Image courtesy of VERTEX ANTENNENTECHNIK.

Simons Observatory (USA)

in collaboration

South Pole?

To have even more frequency coverage…


JAXA
+ possible participations from USA, Canada, Europe
LiteBIRD
2025– [proposed]
Target: δr<0.001

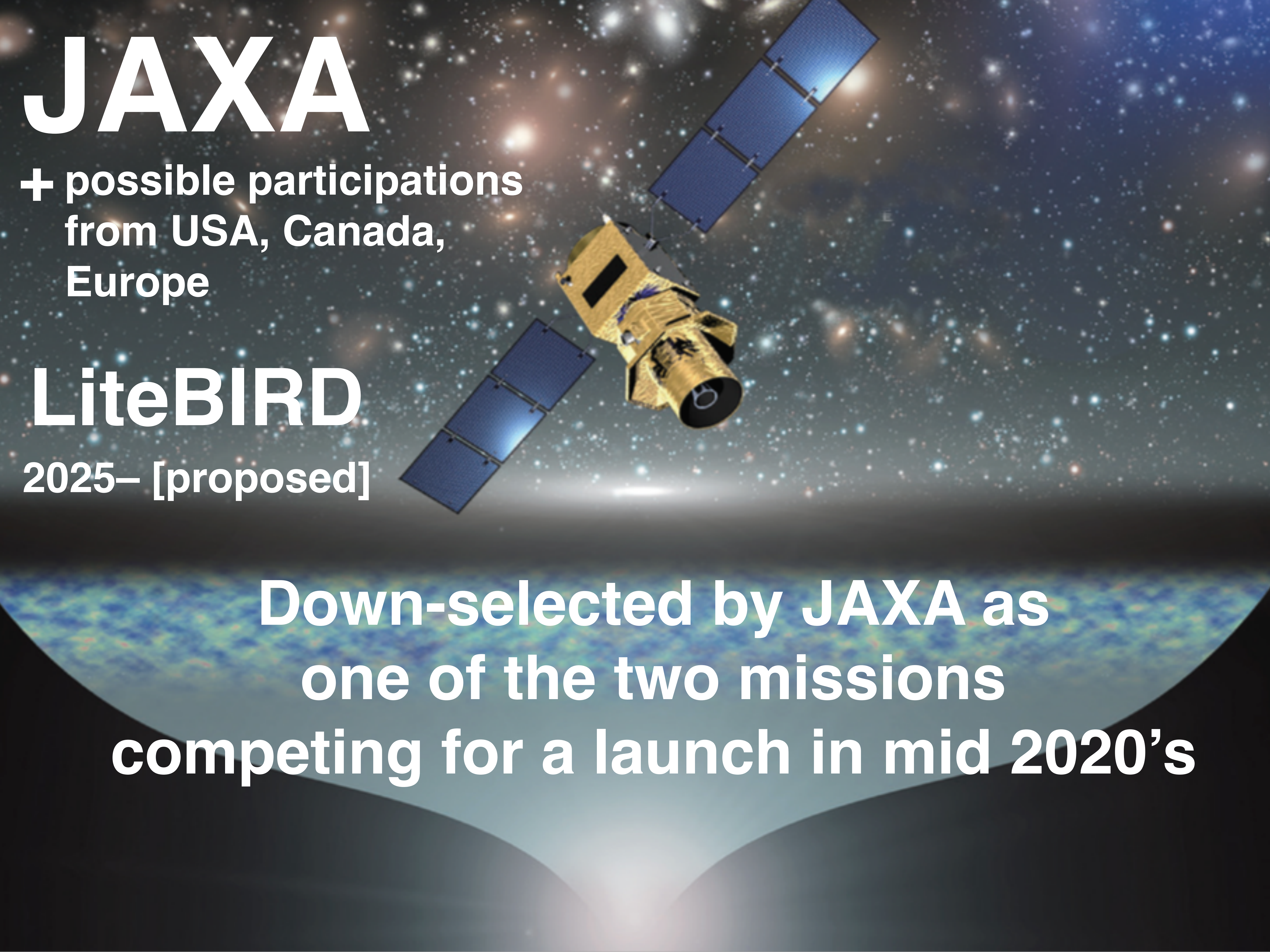
JAXA

+ possible participations from USA, Canada, Europe

LiteBIRD

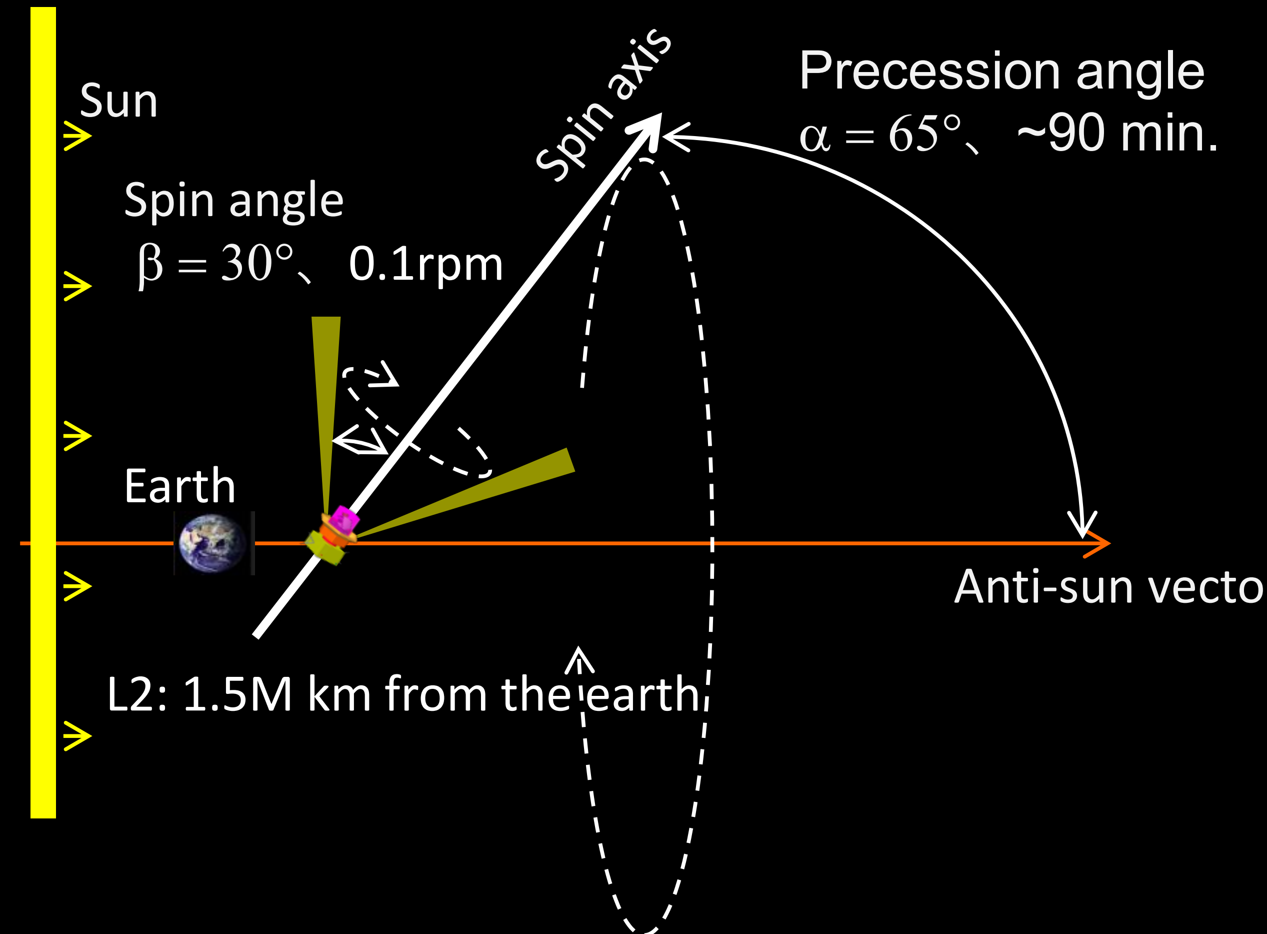
2025– [proposed]

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

Observation Strategy

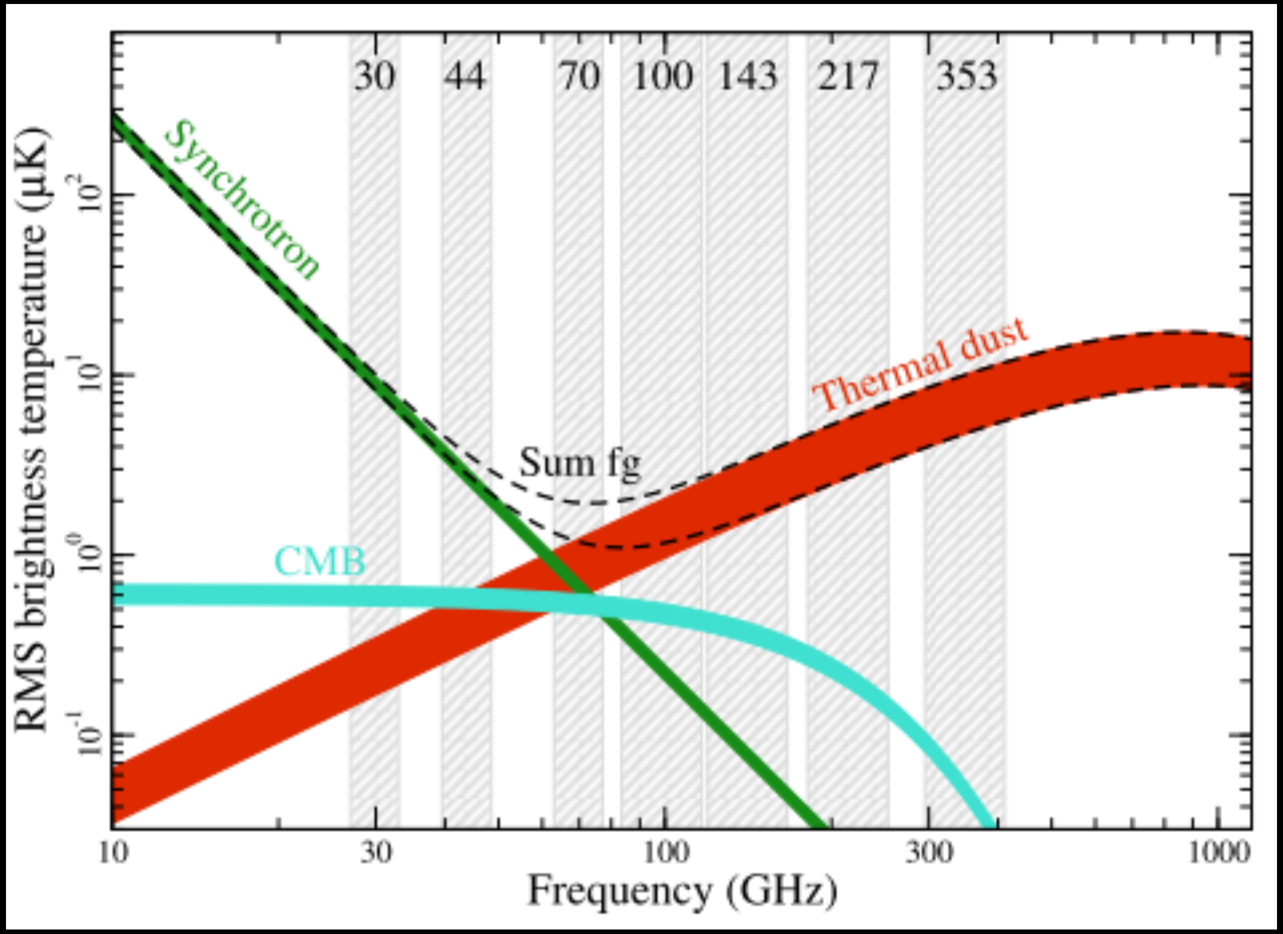
JAXA H3 Launch Vehicle (JAXA)



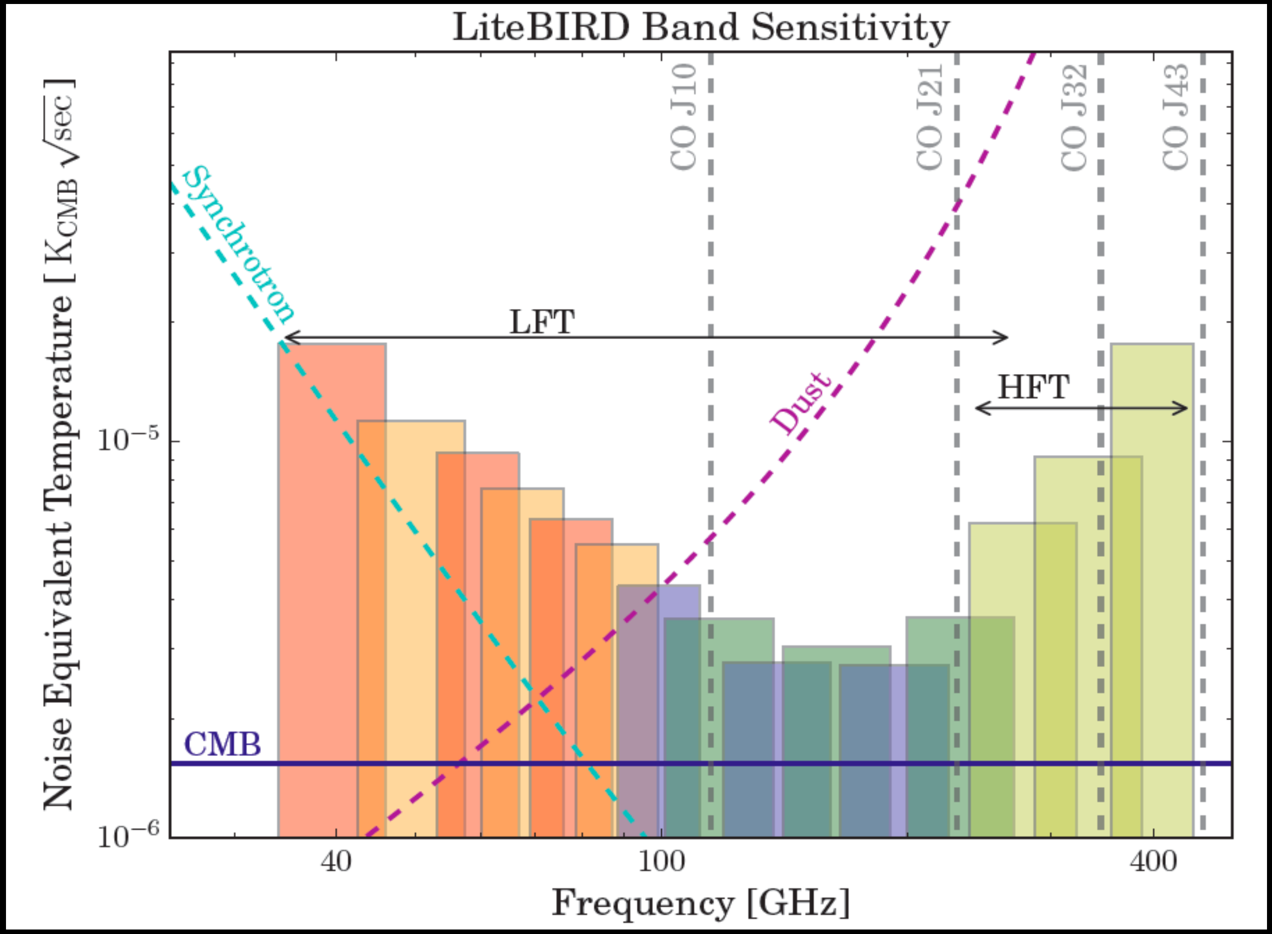
- Launch vehicle: JAXA H3
- Observation location: Second Lagrangian point (L2)
- Scan strategy: Spin and precession, full sky
- Observation duration: 3-years
- Proposed launch date: Mid 2020's

Slide courtesy Toki Suzuki (Berkeley)

Foreground Removal



Polarized galactic emission (Planck X)



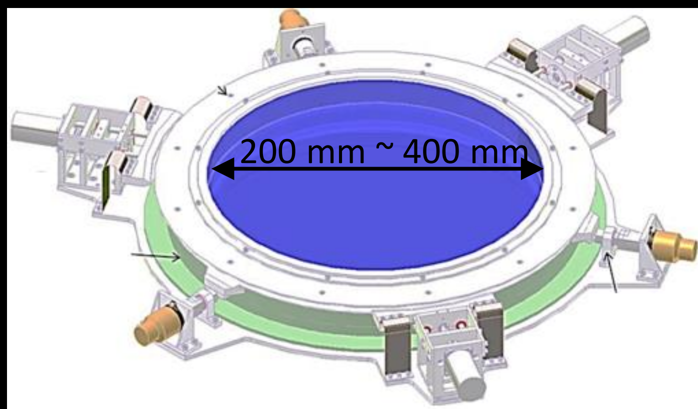
LiteBIRD: 15 frequency bands

- 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

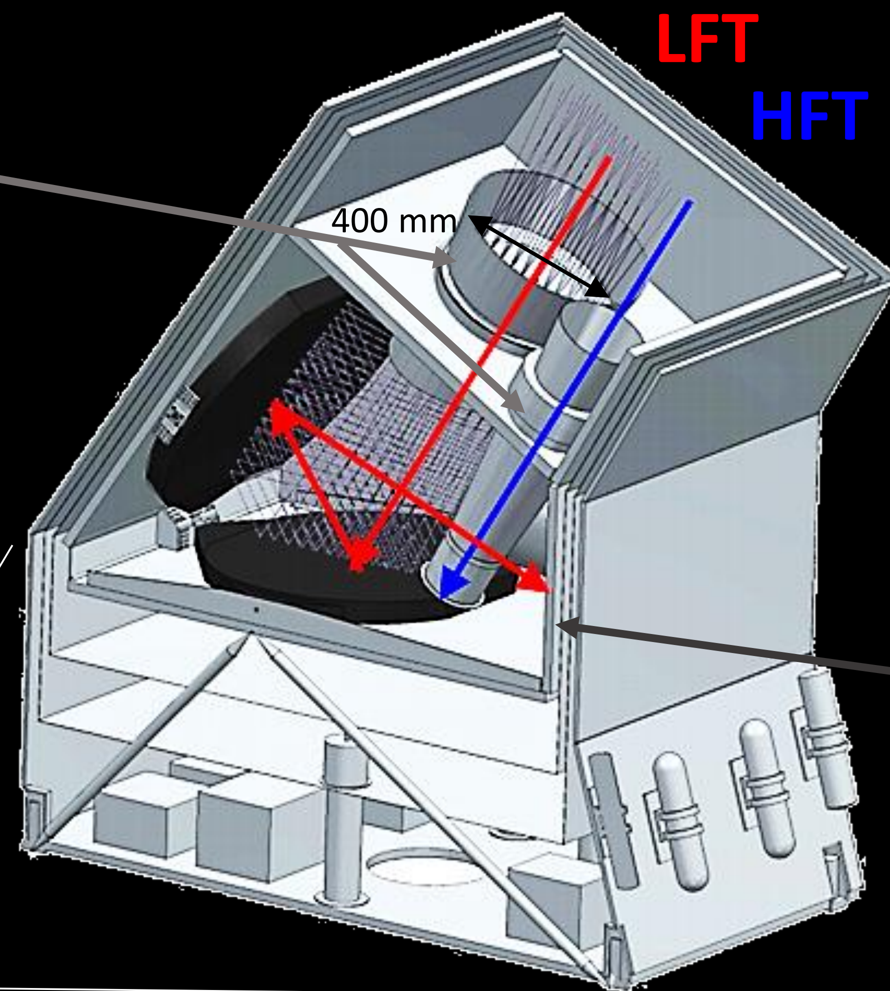
Slide courtesy Toki Suzuki (Berkeley)

Instrument Overview

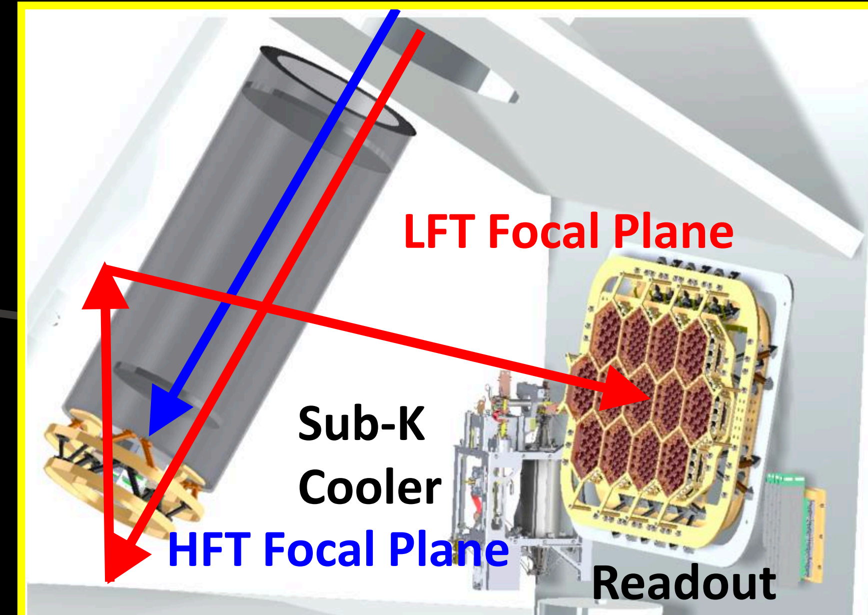
Slide courtesy Toki Suzuki (Berkeley)



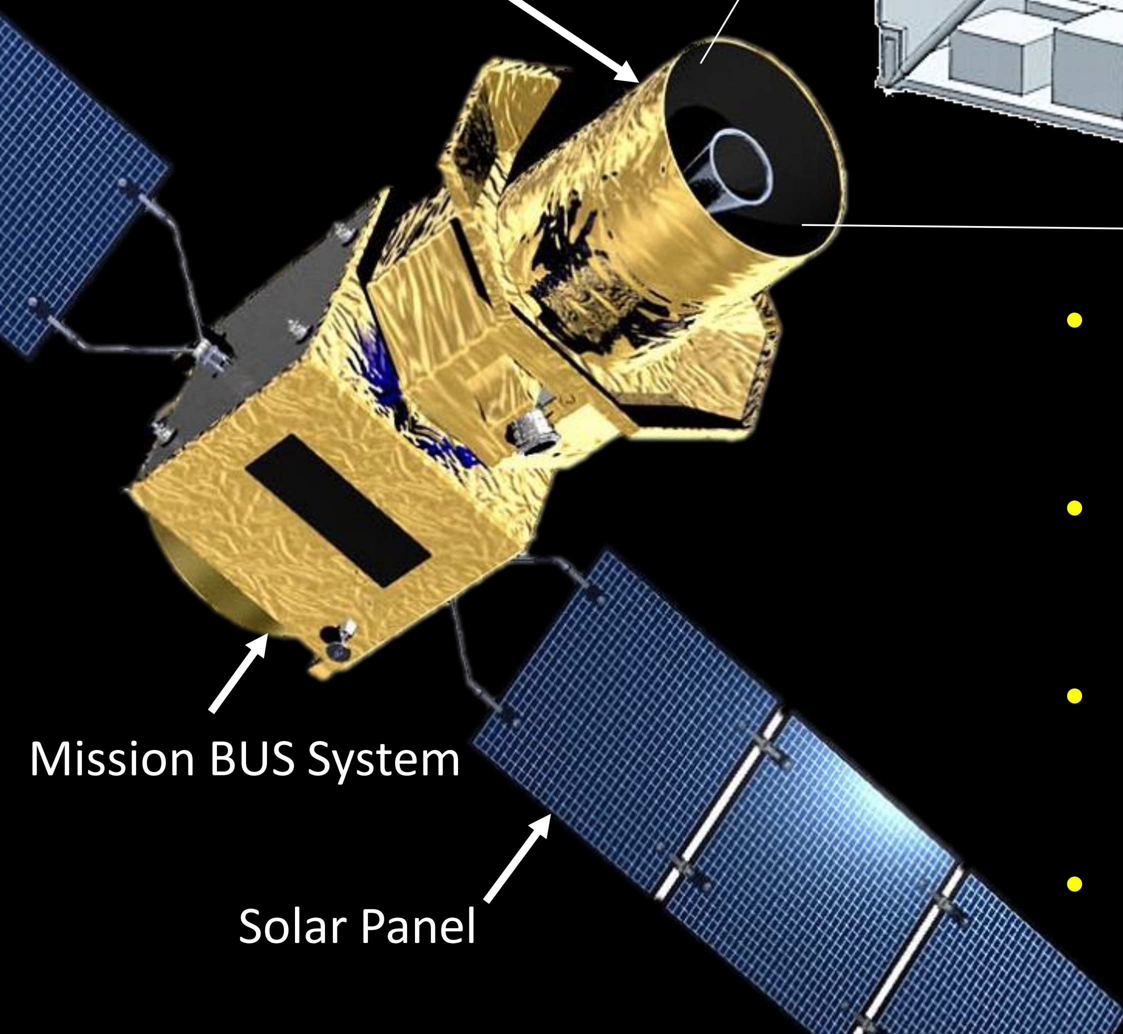
Half-wave plate



Stirling & Joule Thomson Coolers



Sub-Kelvin Instrument



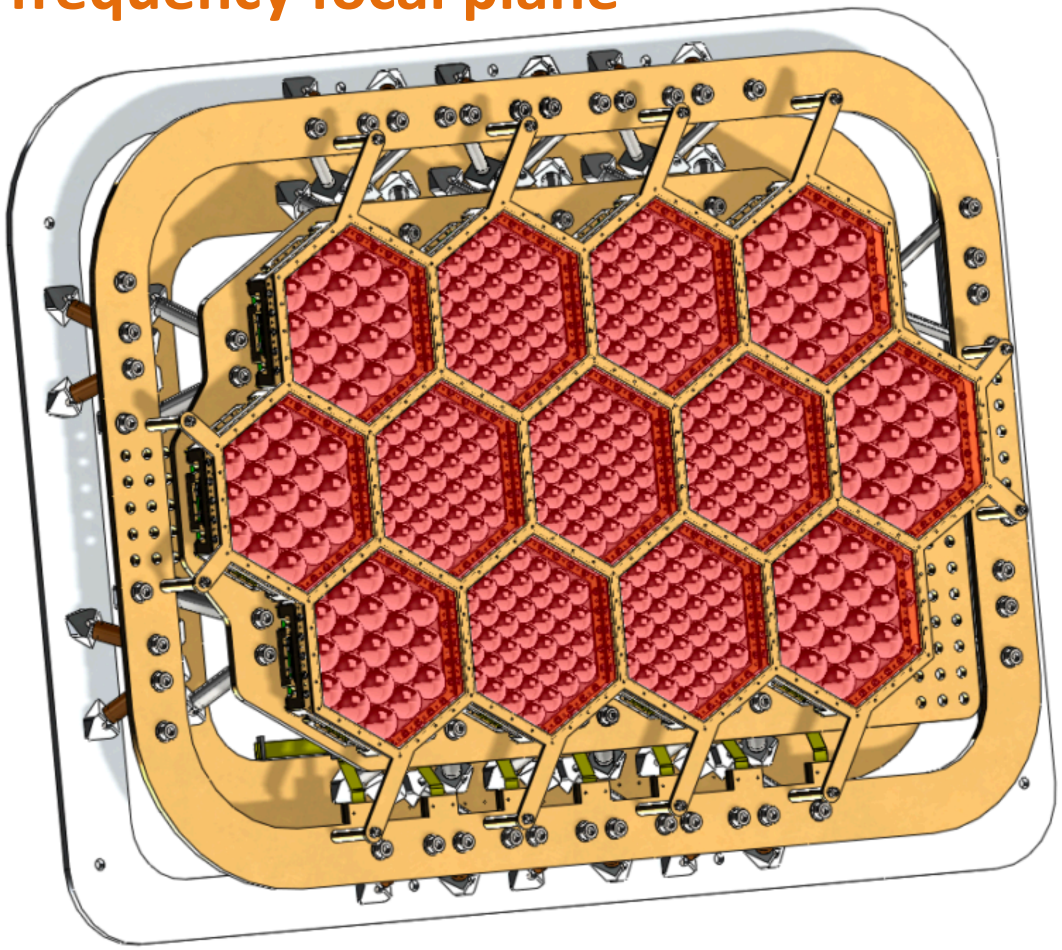
- Two telescopes
  - Crossed-Dragone (LFT) & on-axis refractor (HFT)
- Cryogenic rotating achromatic half-wave plate
  - Modulates polarization signal
- Stirling & Joule Thomson coolers
  - Provide cooling power above 2 Kelvin
- Sub-Kelvin Instrument
  - Detectors, readout electronics, and a sub-kelvin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

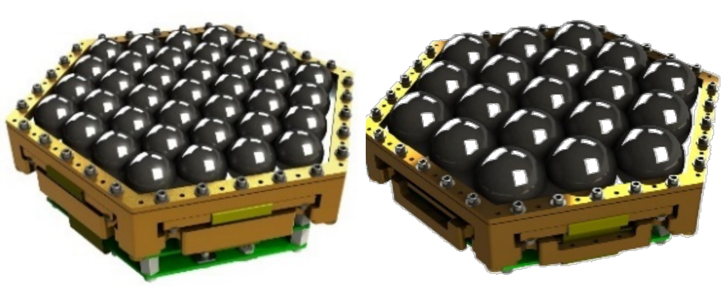
Summary

- Inflation looks good: all the CMB data support it
- **Next frontier**: Using CMB polarisation to find GWs from inflation. **Definitive evidence for inflation!**
  - With CCAT-p we can remove the dust polarisation to reach $r \sim 10^{-2}$ **reliably**, i.e., 10 times better than the current bound
  - With LiteBIRD we plan to reach $r \sim 10^{-3}$, i.e., 100 times better than the current bound

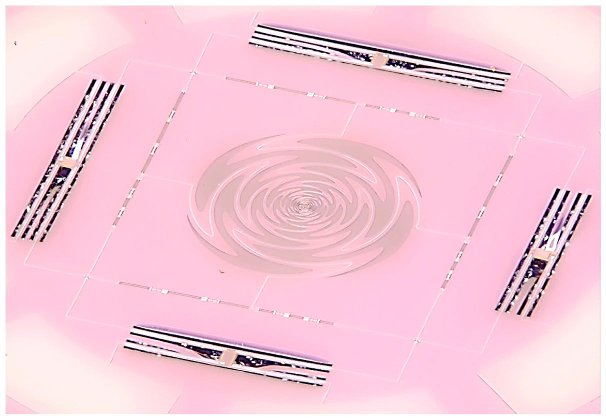
LFT and HFT focal plane units using TES

Low frequency focal plane

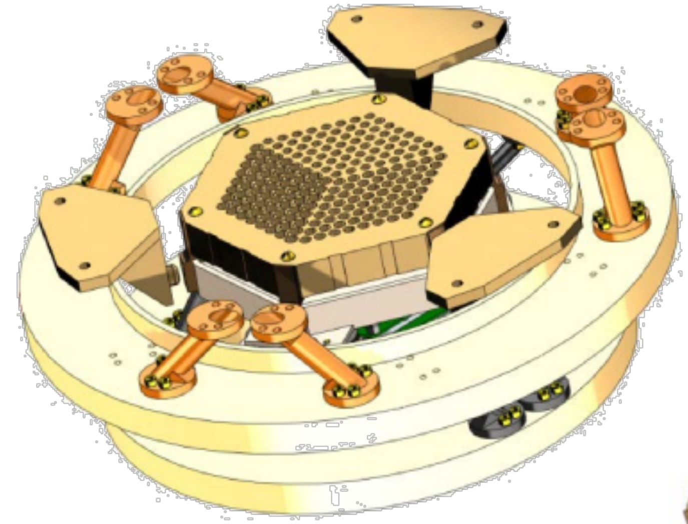




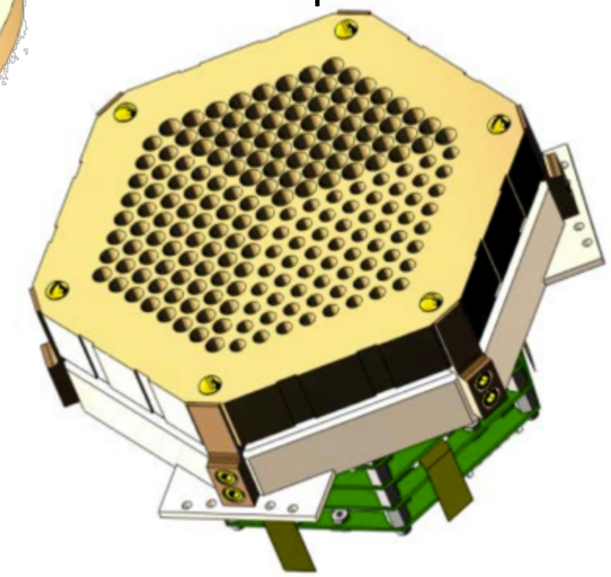
Three colors per pixel with a lenslet coupling.

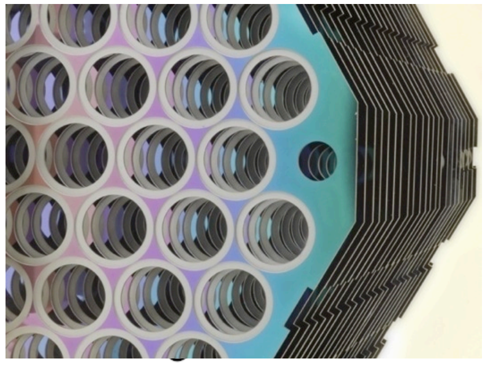


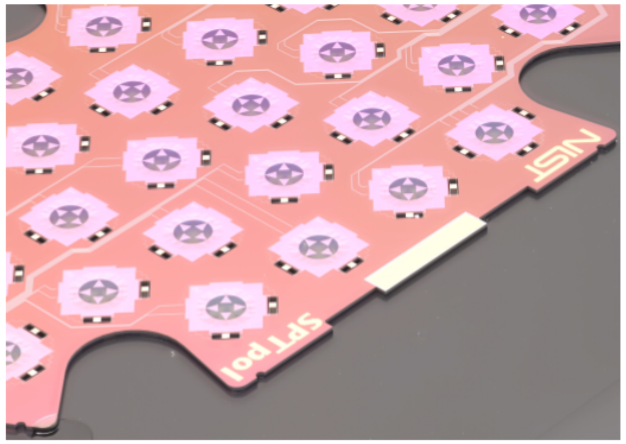
High frequency focal plane

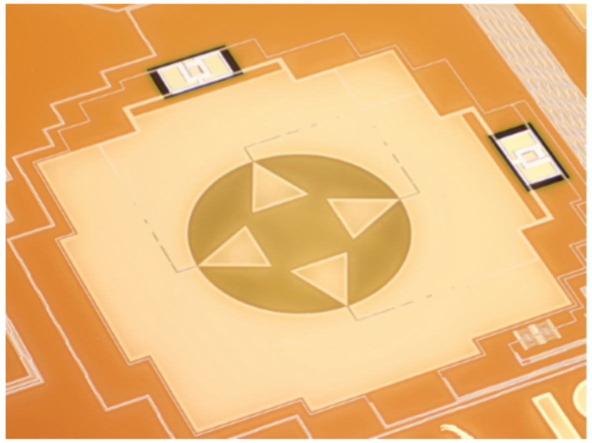


Each color per feed, and three colors within one focal plane.





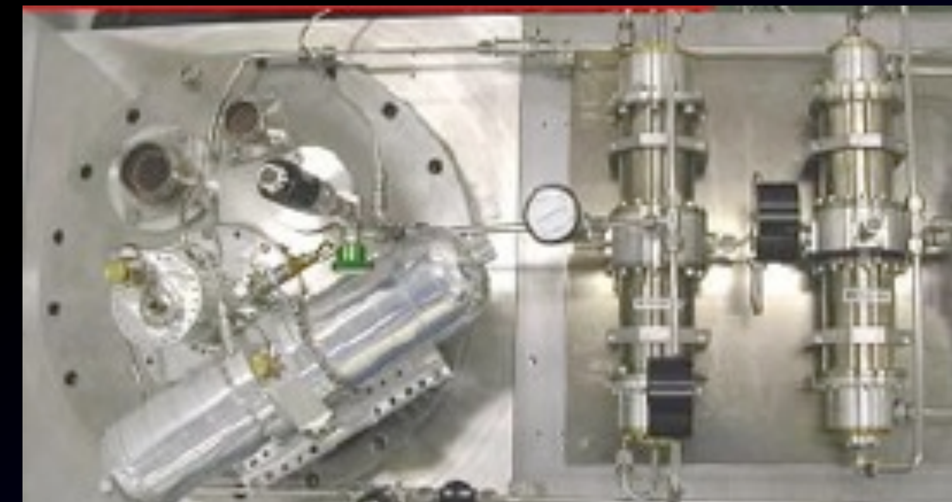




- The current baseline design uses a single ADR to cool the both focal planes.
- The LF focal plane has ** TESs and the HF focal plane has ** TESs.
- The TES is read by SQUID together with the readout electronics is based on the digital frequency multiplexing system.
- The effect of the cosmic ray is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

Slide courtesy Tomo Matsumura (Kavli IPMU)

Cooling system



SHI/JAXA

Cryogenics

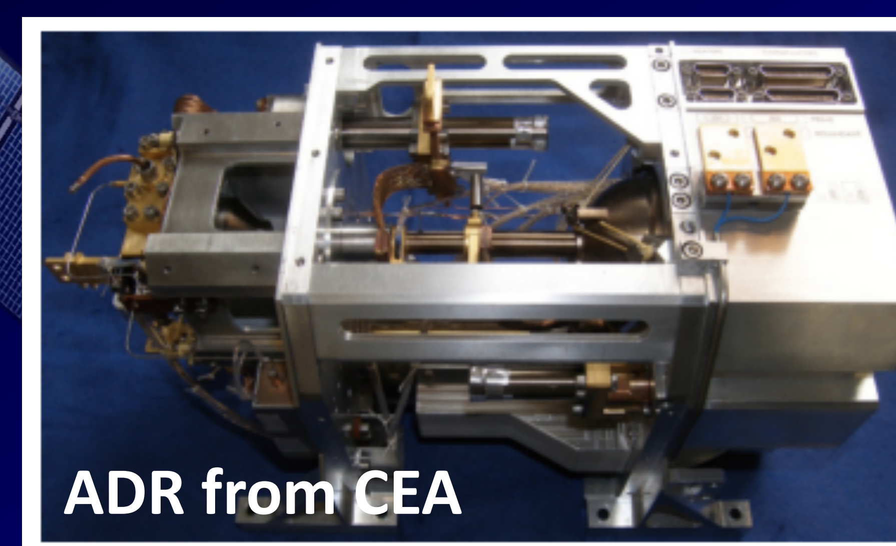
- Warm launch
- 3 years of observations
- 4 K for the mission instruments (optical system)
- 100 mK for the focal plane

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

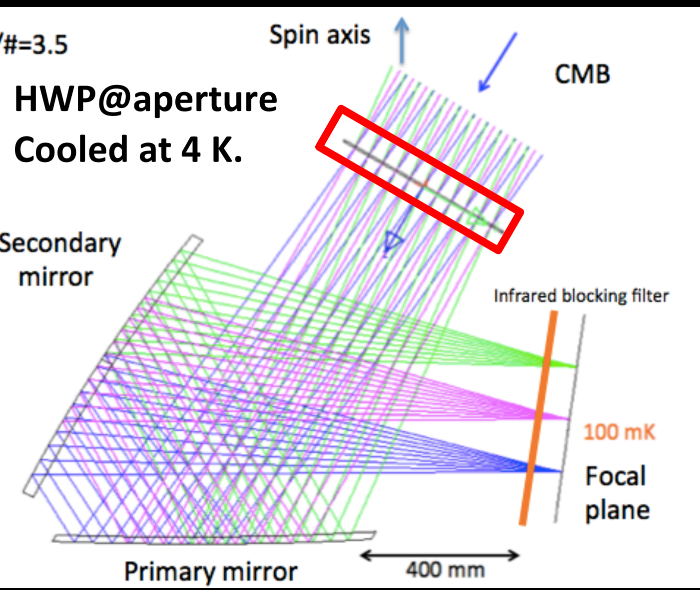
- ADR has a high-TRL and extensive development toward Astro-H, SPICA, and Athena.
- Closed dilution with the Planck heritage is also under development.



ADR from CEA

Slide courtesy Tomo Matsumura (Kavli IPMU)

Polarization modulator



ote: we also employ the
olarization 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.

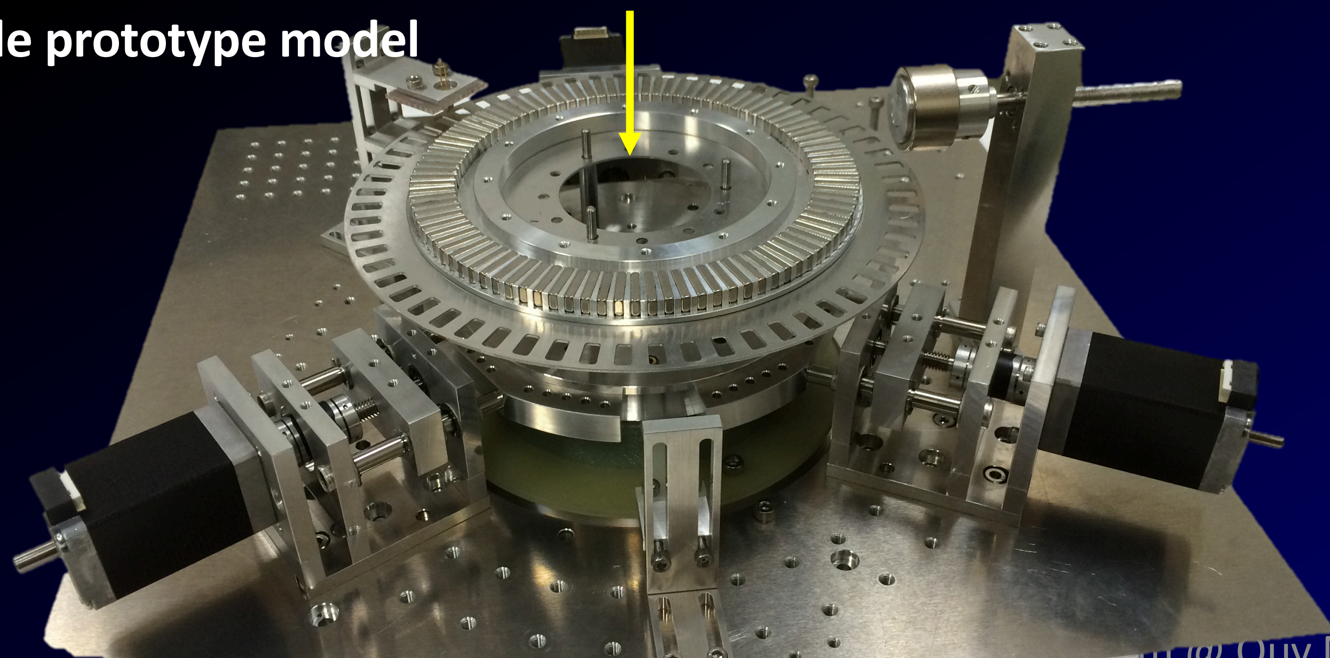
Broadband coverage

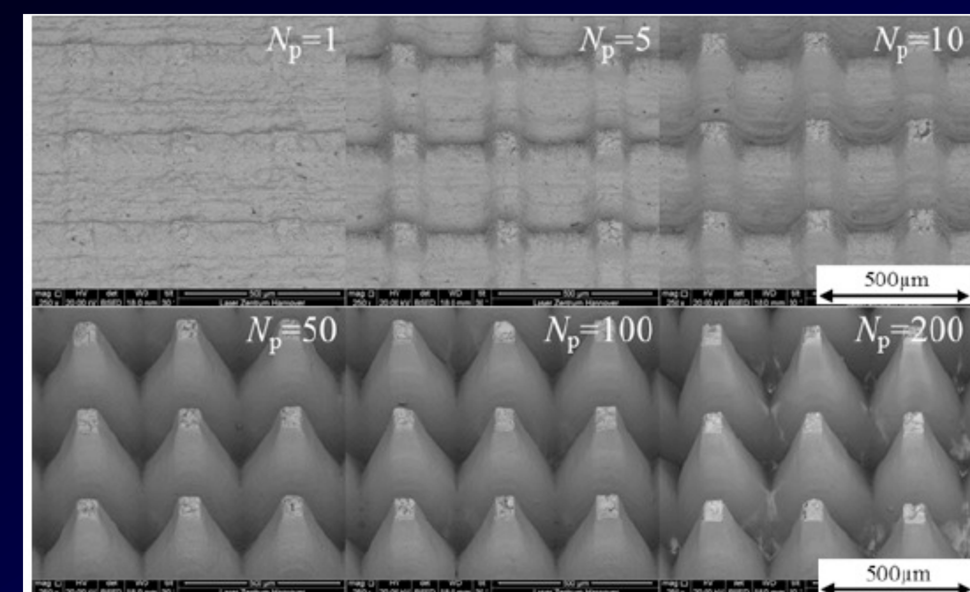
- The broadband coverage is done by the sub-wavelength anti-reflection structure.
- The broadband modulation efficiency is achieved by using 9-layer achromatic HWP.

otational mechanism

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

he 1/9 scale prototype model



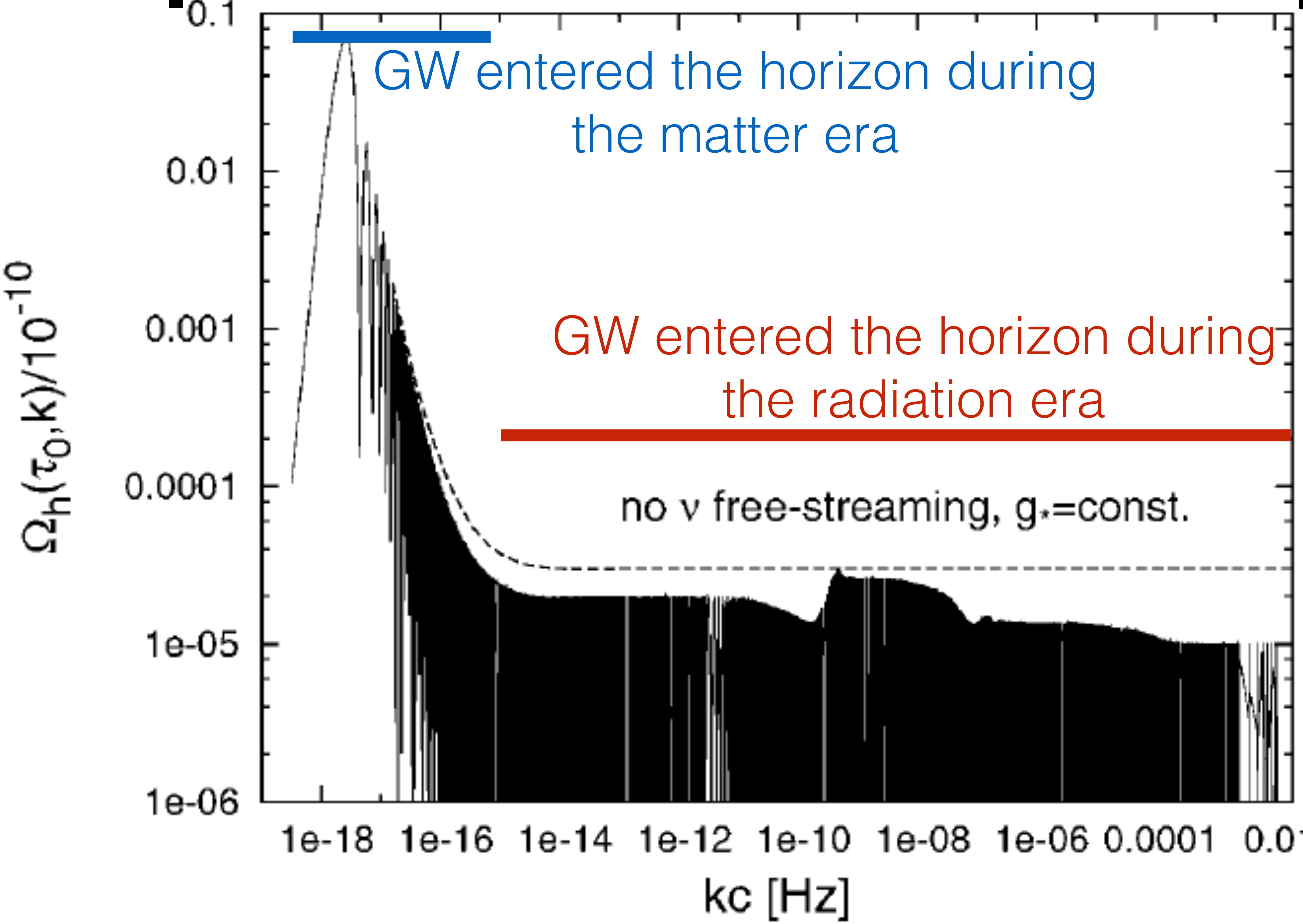


The proton irradiation test is conducted to key components, including sapphire, YBCO, and magnets. We have not found the no-go results. And the further test is in progress.

Slide courtesy Tomo Matsumura (Kavli IPMU)

Watanabe & EK (2006)

Theoretical energy density
Spectrum of GW today



Watanabe & EK (2006)

Theoretical energy density

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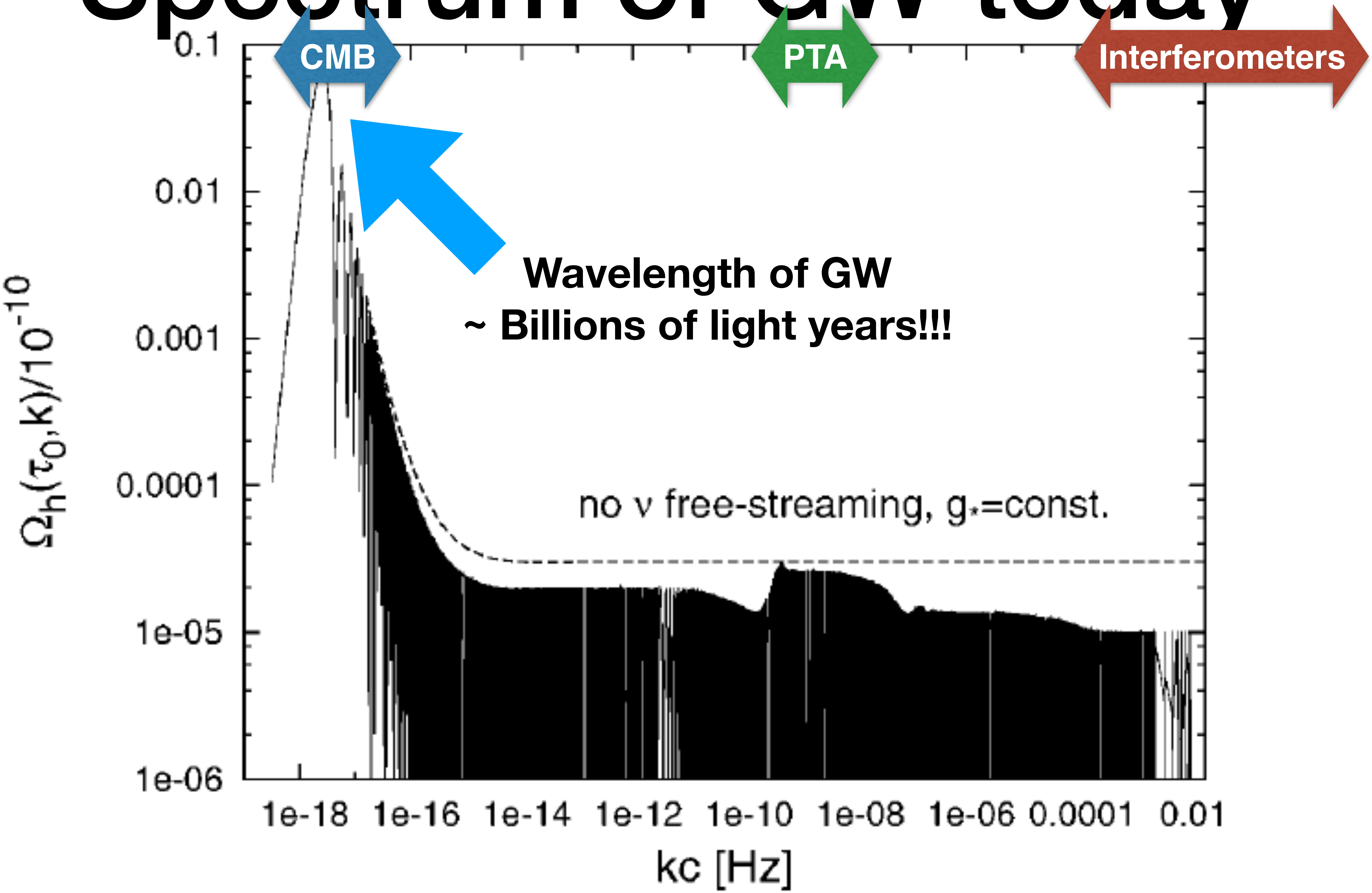


Finding Signatures of Gravitational Waves in the CMB

- **Next frontier in the CMB research**

1. Find evidence for nearly scale-invariant gravitational waves

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

3. Constrain inflation models

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)
    - SU(2) gauge field can!

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

Important Message

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

- **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)]

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. 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!

2. Consistent with a scale invariant spectrum?

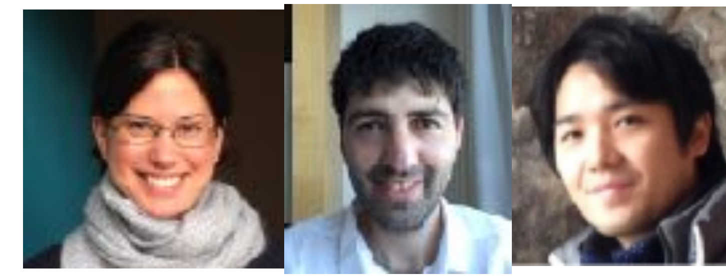
3. Parity violating correlations consistent with zero?

4. Consistent with Gaussianity?

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

Dimastrogiovanni, Fasielo & Fujita (2017)

GW from Axion-SU(2) Dynamics

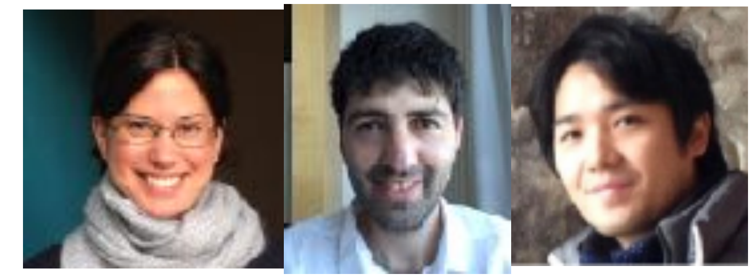


$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_\phi + \mathcal{L}_\chi - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \frac{\lambda\,\chi}{4f} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

- ϕ: inflaton field => Just provides quasi-de Sitter background
- 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 :

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

Dimastrogiovanni, Fasielo & Fujita (2017)



Background and Perturbation

- In an inflating background, the SU(2) field has a background solution:

$$A_i^a = [\text{scale factor}] \times Q \times \delta_i^a$$

$$Q \equiv (-f\partial_\chi U/3g\lambda H)^{1/3}$$

U: axion potential

- Perturbations contain a tensor mode (as well as S&V)

$$\delta A_i^a = t_{ai} + \cdots$$

$$t_{ii} = \partial_a t_{ai} = \partial_i t_{ai} = 0$$

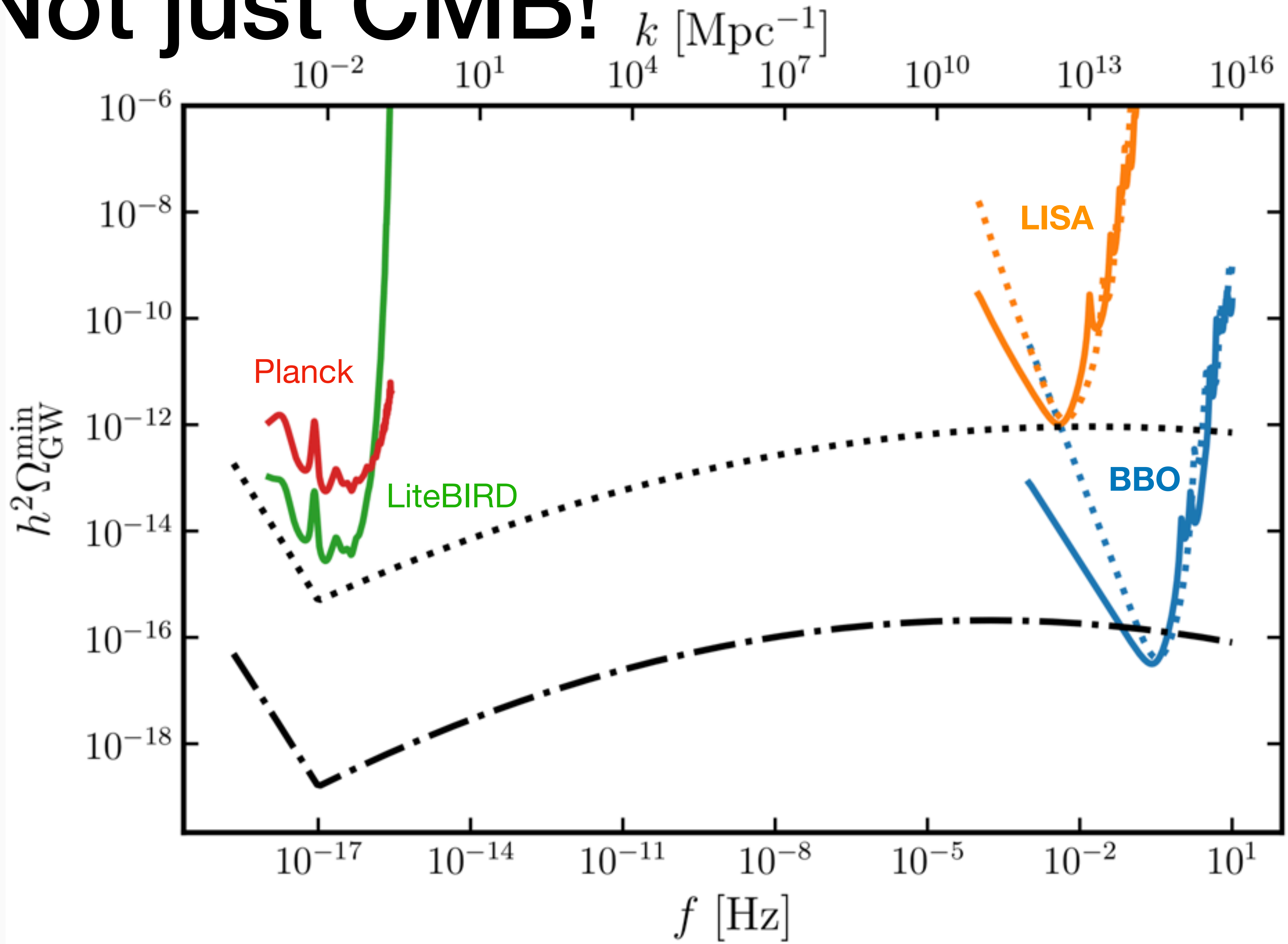
Scenario

- 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)

Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, arXiv:1707.03240

Not just CMB!



Agrawal, Fujita & EK, arXiv:1707.03023

Large bispectrum in GW from SU(2) fields

Aniket Agrawal
(MPA)

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

Tomo Fujita
(Kyoto)

$$\langle \hat{h}_R(\boldsymbol{k}_1)\hat{h}_R(\boldsymbol{k}_2)\hat{h}_R(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta\left(\sum_{i=1}^{3}\boldsymbol{k}_i\right) B_h^{RRR}(k_1,k_2,k_3)$$

- Ω_A << 1 is the energy density fraction of the gauge field
- **B_h/P_h^2 is of order unity for the vacuum contribution**

[Maldacena (2003); Maldacena & Pimentel (2011)]

- ***Gaussianity offers a powerful test of whether the detected GW comes from the vacuum or sources***

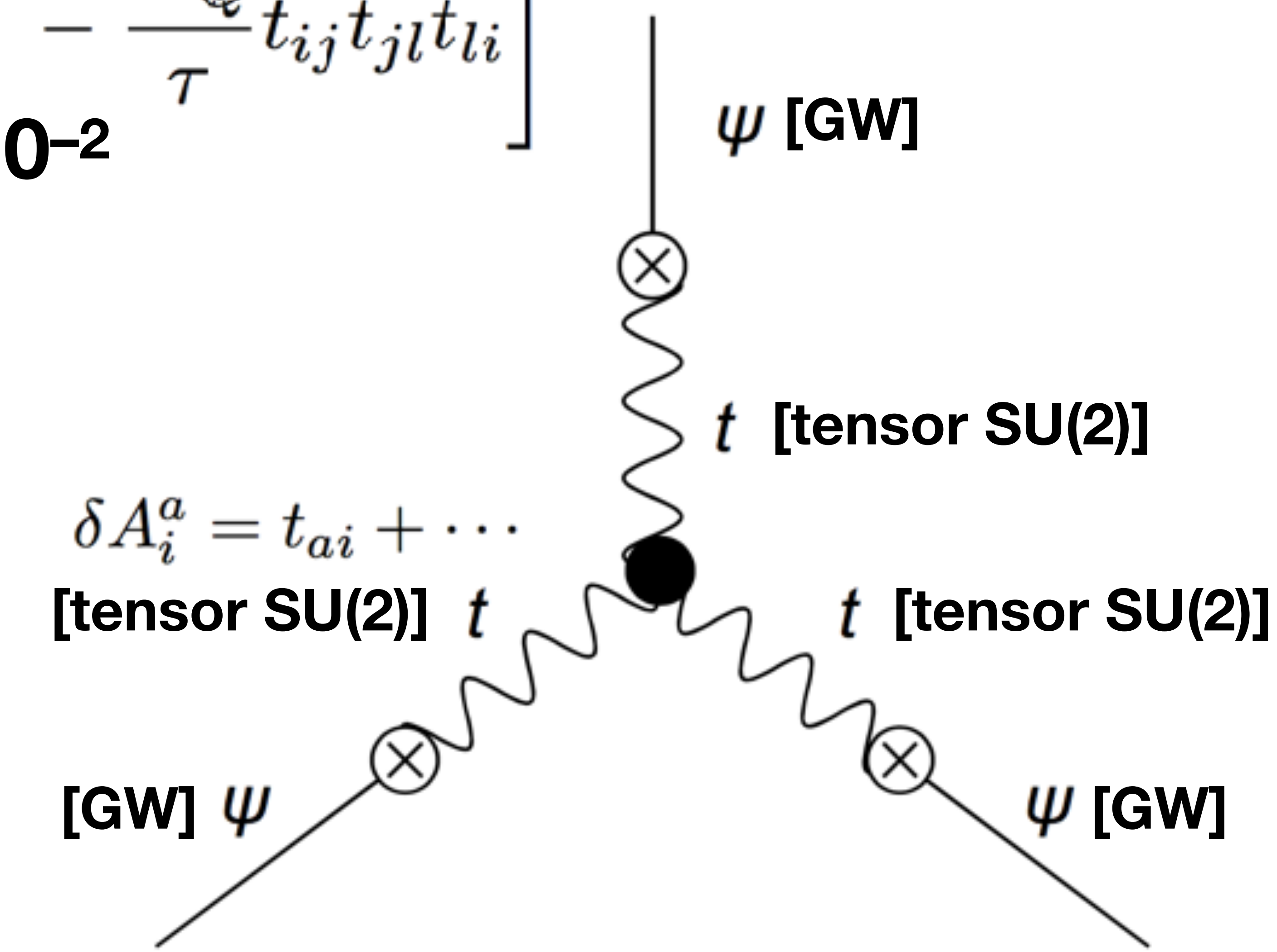
NG generated at the tree level

$$L_3^{(i)} = c^{(i)} \left[\epsilon^{abc} t_{ai} t_{bj} \left(\partial_i t_{cj} - \frac{m_Q^2 + 1}{3 m_Q \tau} \epsilon^{ijk} t_{ck} \right) - \frac{m_Q}{\tau} t_{ij} t_{jl} t_{li} \right]$$

$$c^{(i)} = g = m_Q^2 H / \sqrt{\epsilon_B} M_{\rm Pl}$$ **~10^{-2}**

$$\epsilon_B \equiv \frac{g^2 Q^4}{H^2 M_{\rm Pl}^2} \simeq \frac{2\Omega_A}{1 + m_Q^{-2}} \ll 1$$

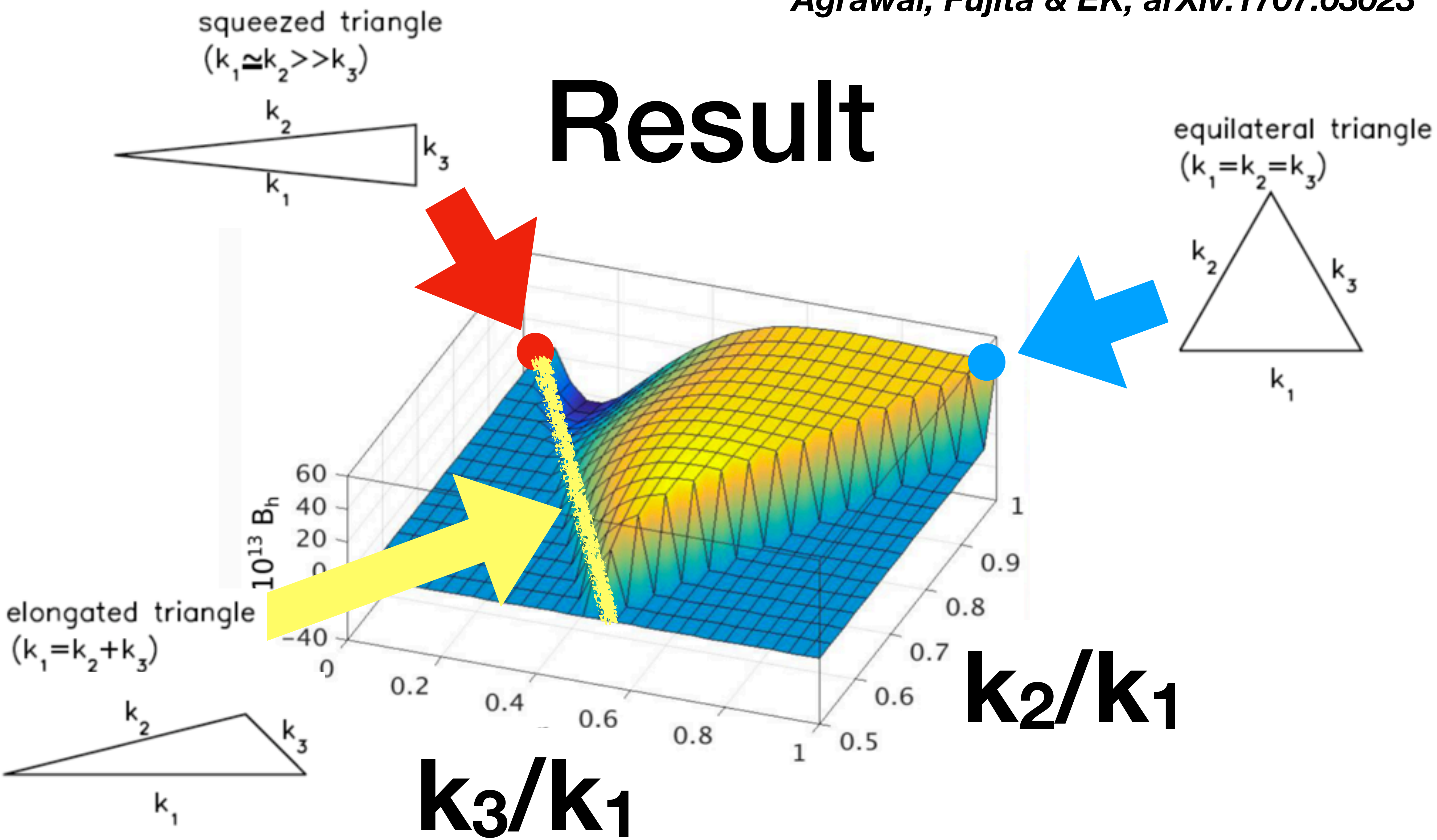
$m_Q \equiv gQ/H$ **[m_Q ~ a few]**



- This diagram generates second-order equation of motion for GW

Agrawal, Fujita & EK, arXiv:1707.03023

Result



- This shape is similar to, but not exactly the same as, what was used by the Planck team to look for tensor bispectrum

Planck Collaboration (2015)

Current Limit on Tensor NG

- The Planck team reported a limit on the tensor bispectrum in the following form:

$$f_{\rm NL}^{\rm tens} \equiv \frac{B_h^{+++}(k,k,k)}{F_{\rm scalar}^{\rm equil.}(k,k,k)}$$

- The denominator is the **scalar** equilateral bispectrum template, giving $F_{\rm scalar}^{\rm equil.}(k,k,k) = (18/5)P_{\rm scalar}^2(k)$

- The current 68%CL constraint is $f_{\rm NL}^{\rm tens} = 400 \pm 1500$

Agrawal, Fujita & EK, arXiv:1707.03023

SU(2), confronted

- The SU(2) model of Dimastrogiovanni et al. predicts:

$$f_{\rm NL}^{\rm tens} \approx \frac{125}{18\sqrt{2}}\frac{r^2}{\epsilon_B} \approx 2.5\frac{r^2}{\Omega_A}$$

- The current 68%CL constraint is $f_{\rm NL}^{\rm tens} = 400 \pm 1500$
  - This is already constraining!

Courtesy of Maresuke Shiraishi

LiteBIRD would nail it!