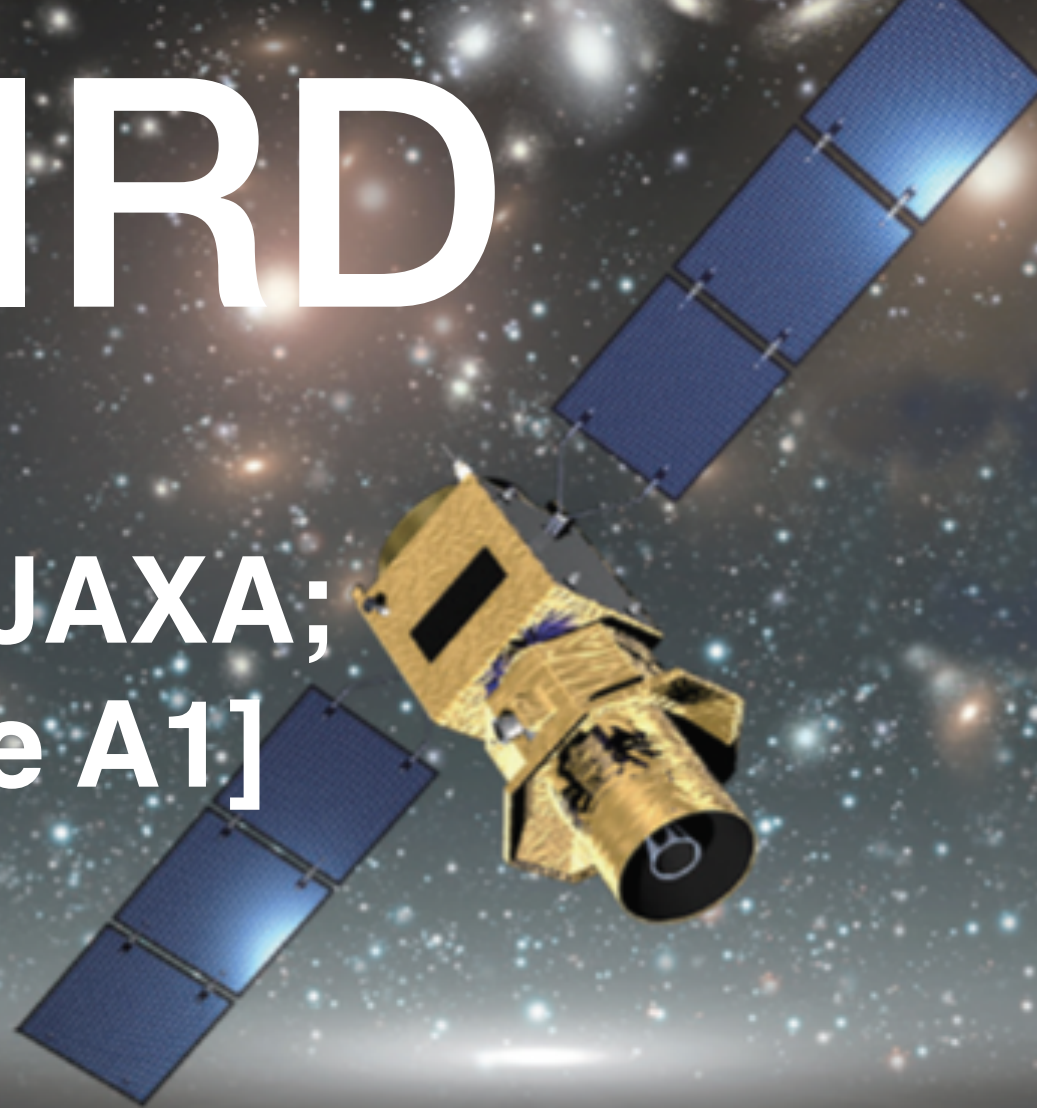


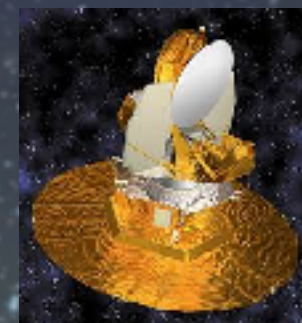
LiteBIRD

2025–

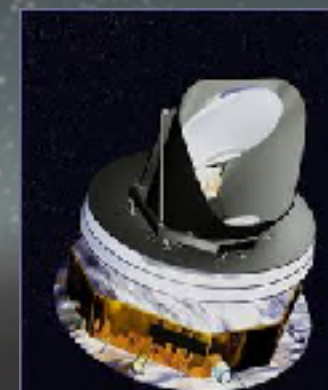
[proposed to JAXA;
now in Phase A1]



1989–1993



2001–2010

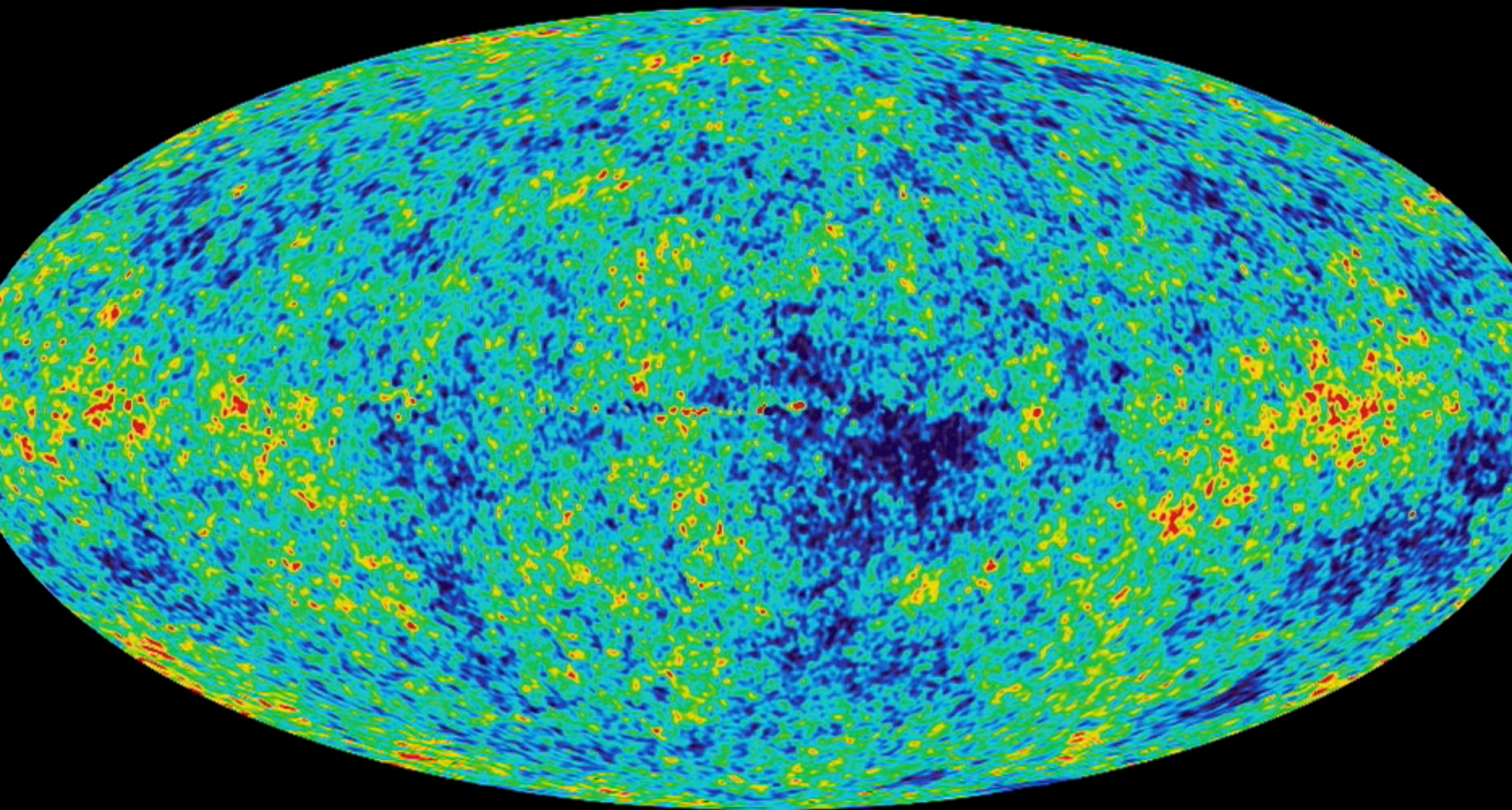


2009–2013

Eiichiro Komatsu
(Max-Planck-Institut für Astrophysik)
Nedfest 2017, UCLA, August 26, 2017

Part I:

**What do we know about inflation,
and how do we know it?**



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?

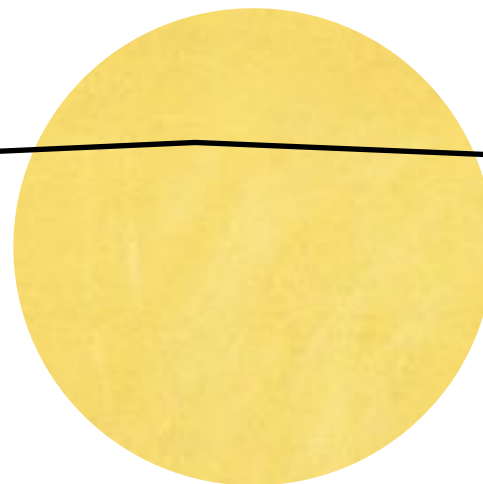
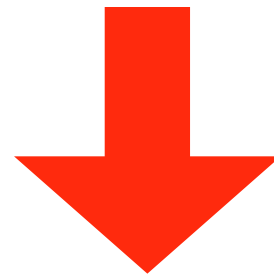
Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

Quantum fluctuations on
microscopic scales



Inflation!



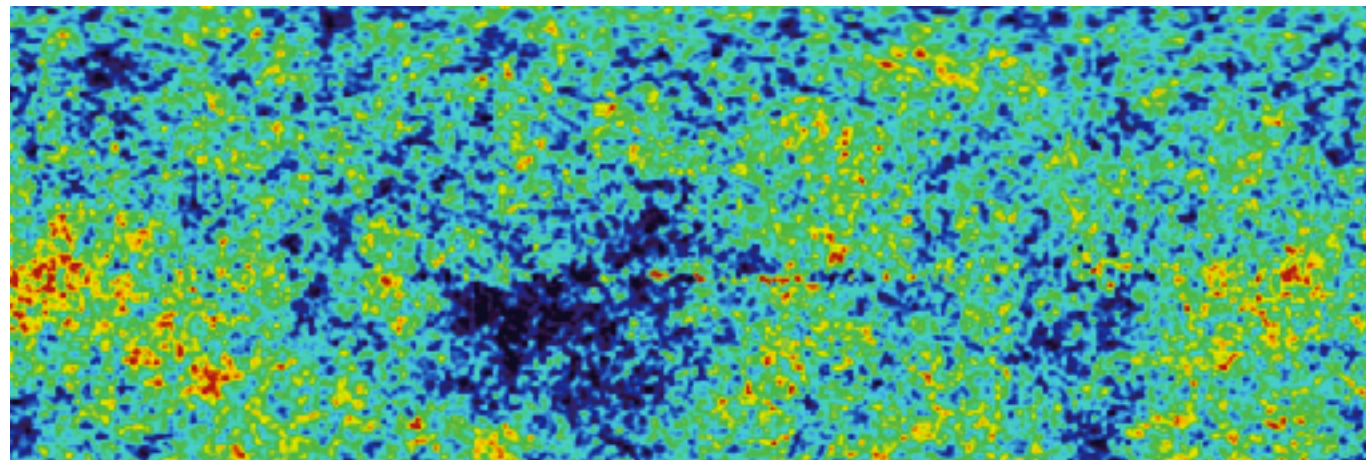
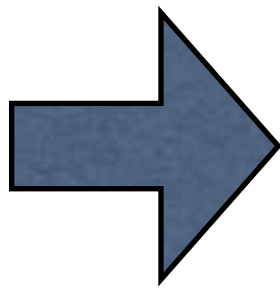
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

Key Predictions

 ζ

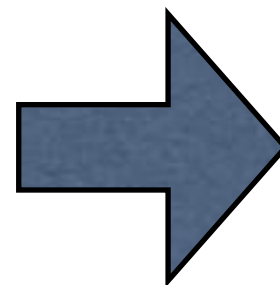
scalar
mode

- 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



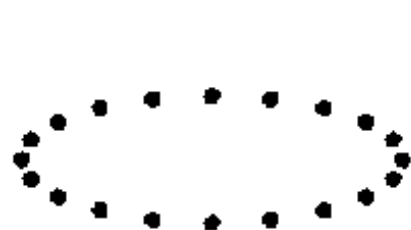
Starobinsky (1979)

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



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

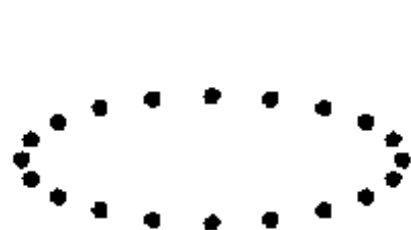
We measure distortions in space

- A distance between two points in space

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

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 $H(t) = d \ln(a) / dt$, 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 $\epsilon = O(N^{-1})$ or smaller, where N is the number of e-folds of expansion counted from the end of inflation:

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

Have we found inflation?

- *Have we found $\varepsilon \ll 1$?*

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

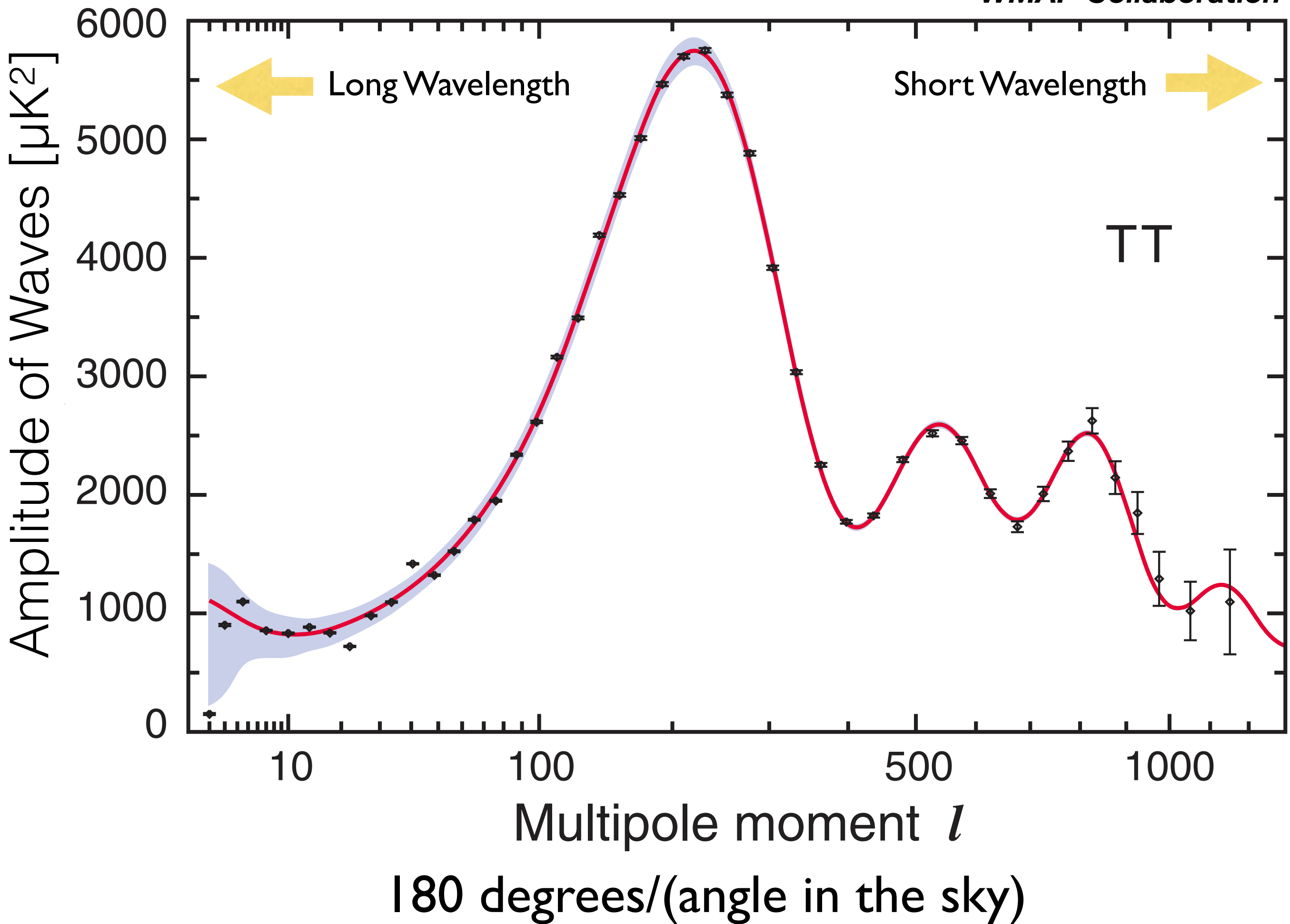
- To achieve this, we need to map out **H(t)**, and show that it does not change very much with time
 - **We need the “Hubble diagram” during inflation!**

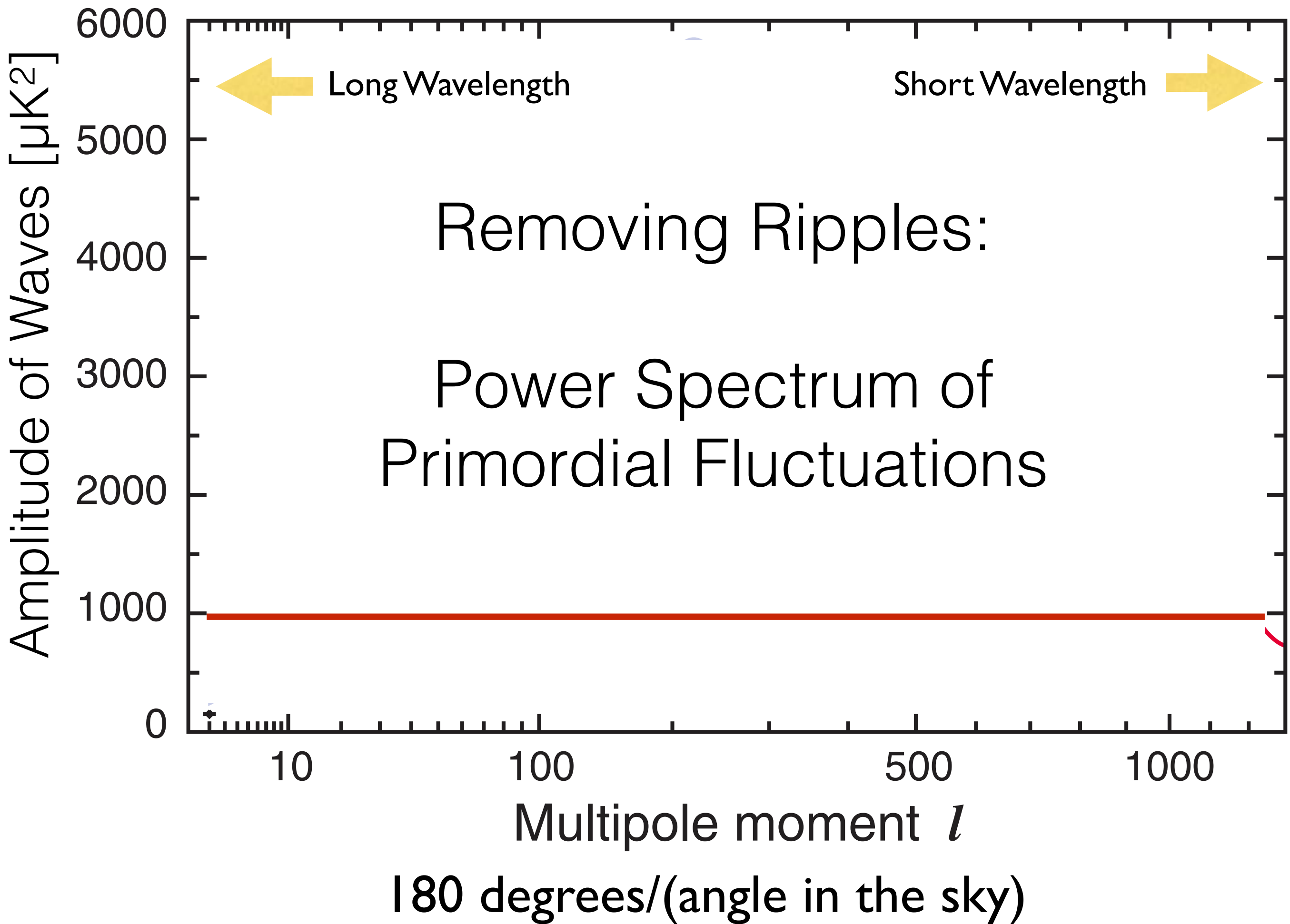
Fluctuations are proportional to H

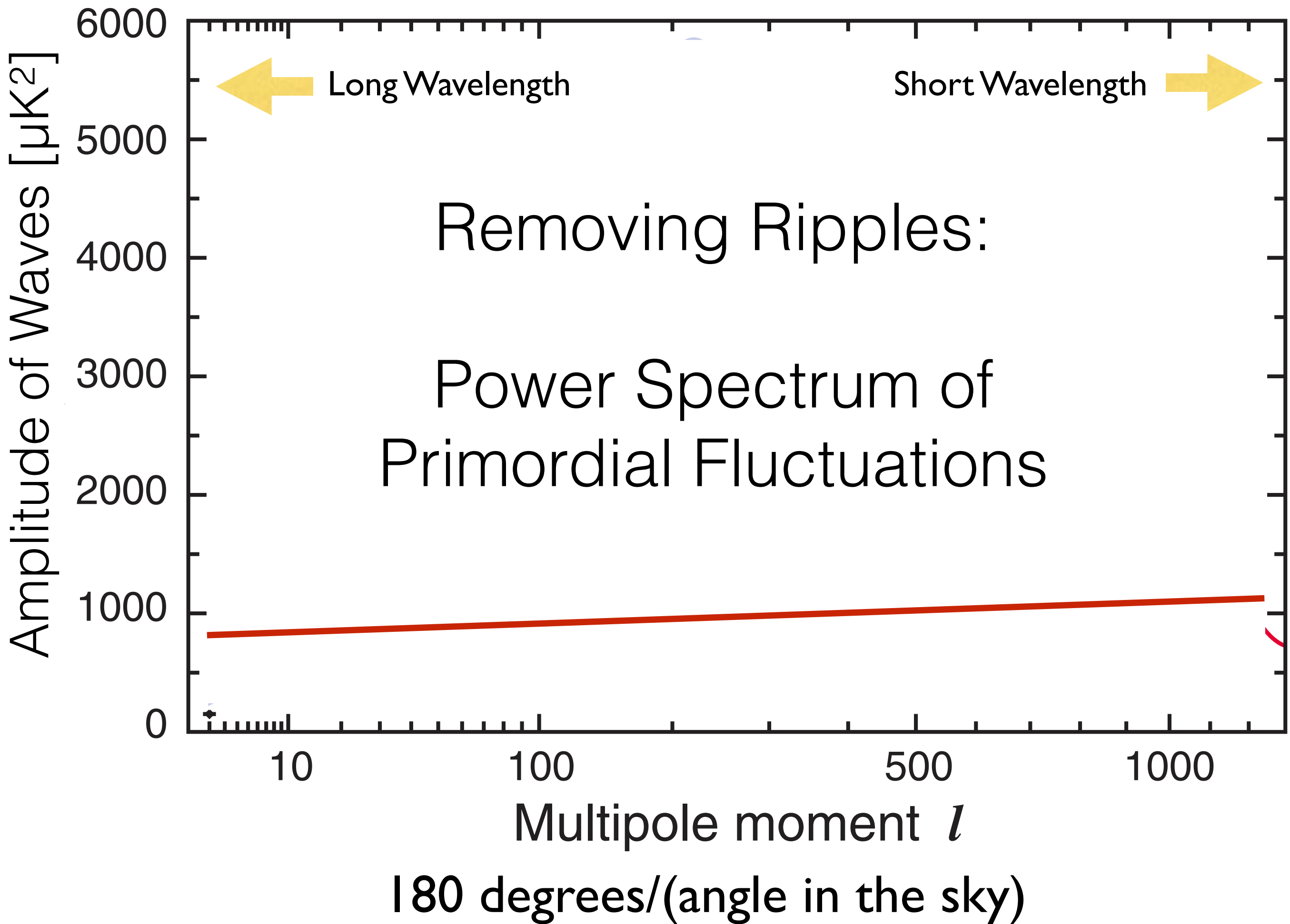
- Both scalar (ζ) and tensor (h_{ij}) perturbations are proportional to H
 - Consequence of the uncertainty principle
 - [energy you can borrow] $\sim$ [time you borrow] $^{-1} \sim H$
 - **KEY:** The earlier the fluctuations are generated, the more its wavelength is stretched, and thus the bigger the angles they subtend in the sky. **We can map $H(t)$ by measuring CMB fluctuations over a wide range of angles**

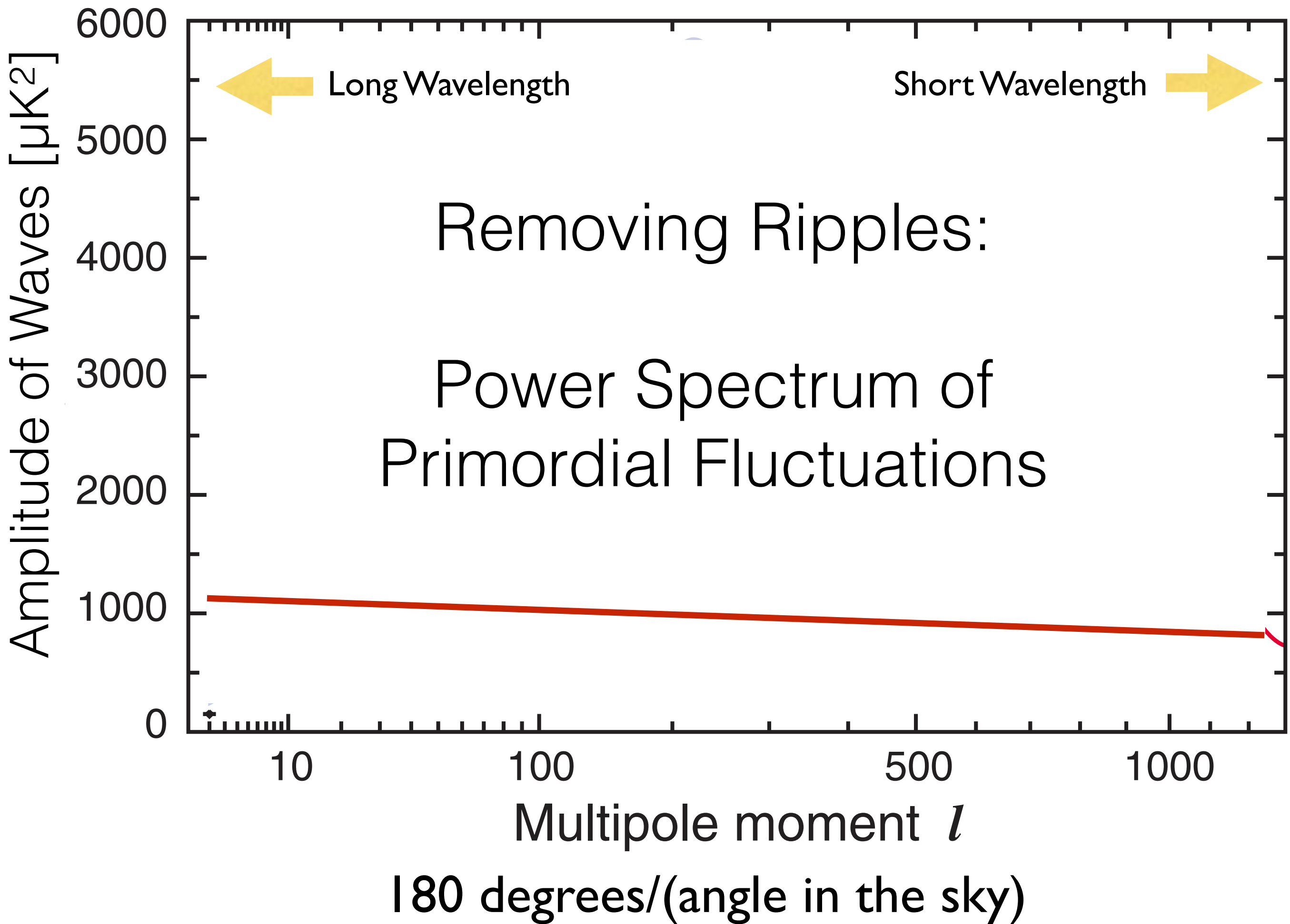
Fluctuations are proportional to H

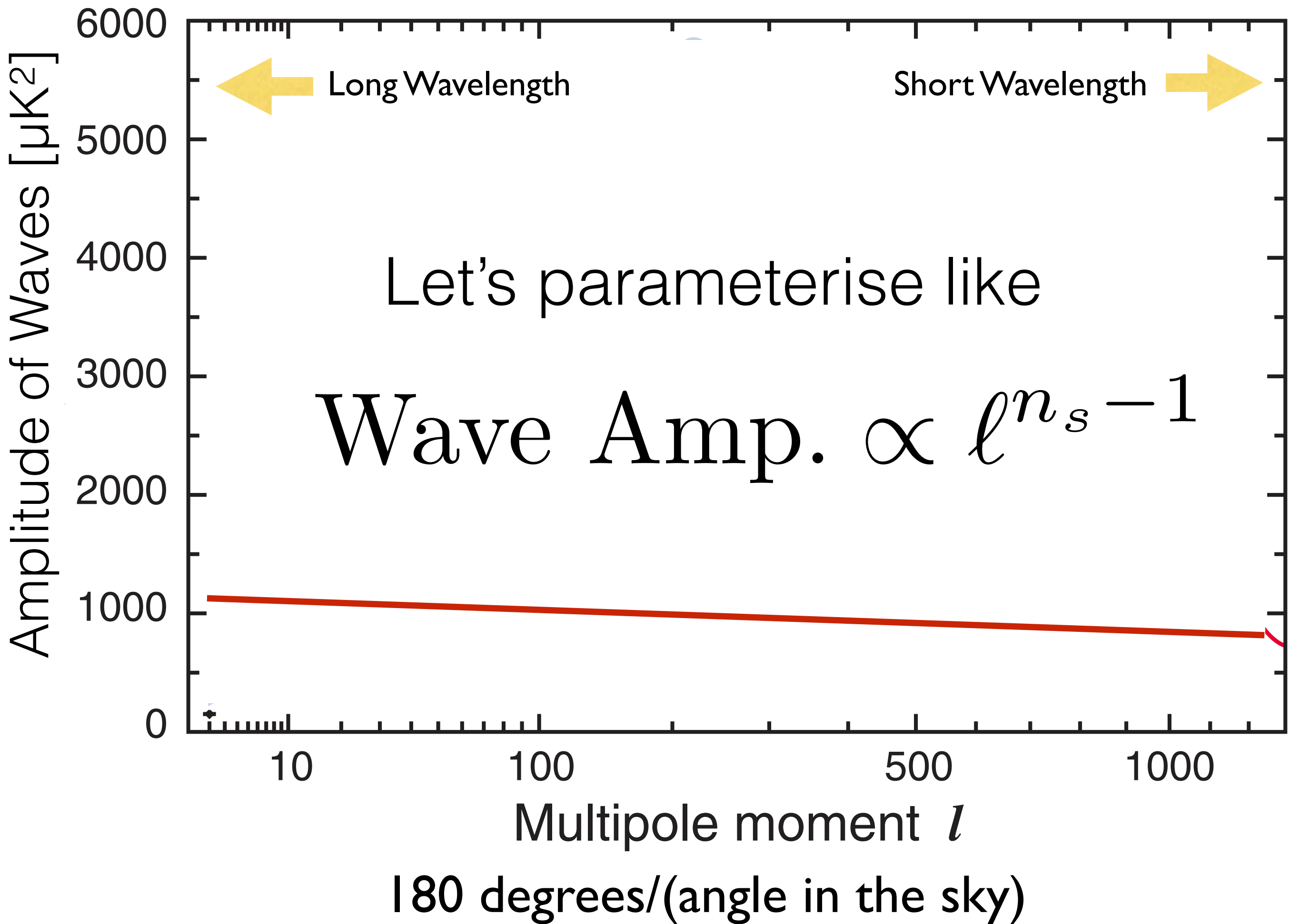
- We can map $H(t)$ by measuring CMB fluctuations over a wide range of angles
 1. We want to show that the amplitude of CMB fluctuations does not depend very much on angles
 2. Moreover, since inflation must end, H would be a decreasing function of time. It would be fantastic to show that the amplitude of CMB fluctuations actually DOES depend on angles such that the small scale has *slightly* smaller power











Wright, Smoot, Bennett & Lubin (1994)

In 1994:

COBE 2-Year Limit!

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

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

Amplitude of Waves [μK^2]

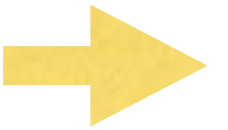
6000
5000

1989–1993



Wavelength

Short Wavelength



2000
1000
0

$l=3-30$

10

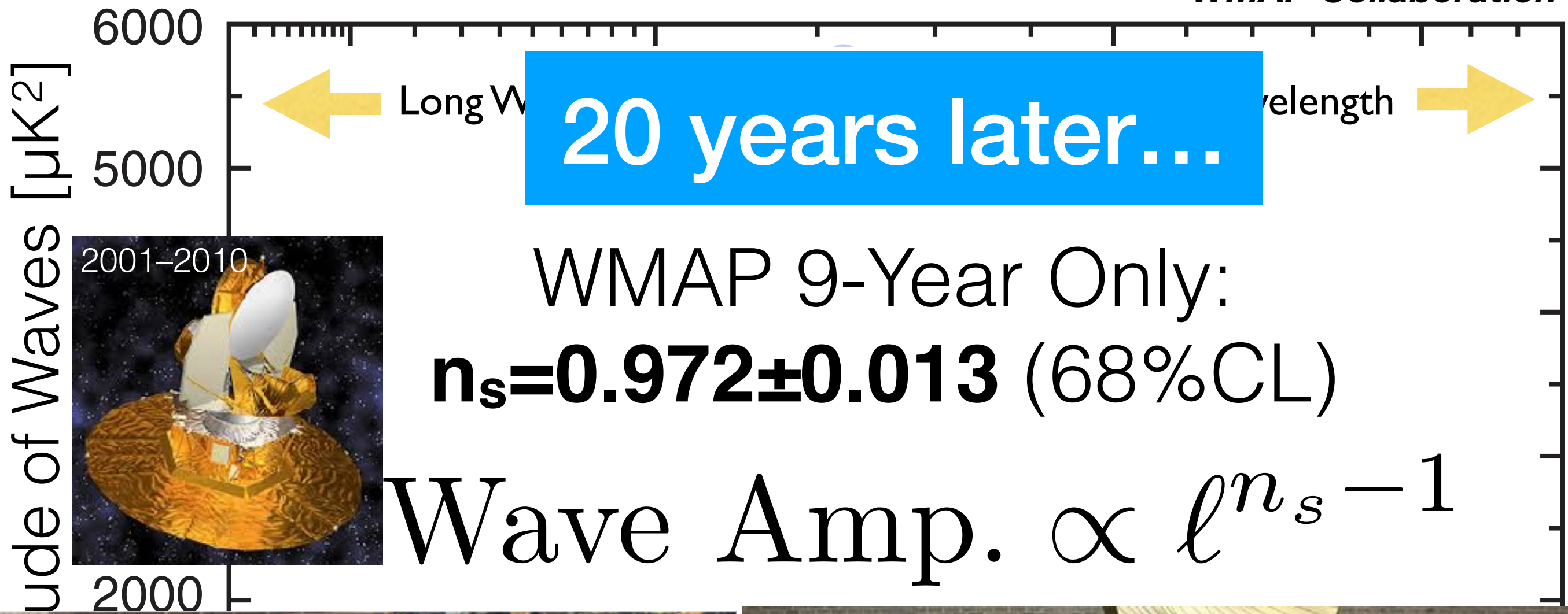
100

500

1000

Multipole moment l

$l \approx 180 \text{ degrees}/(\text{angle in the sky})$



Angular scale

WMAP Collaboration

90°

2°

0.5°

0.2°

0.1°

Amplitude of ΔC_{ℓ}^2

2001–2010

South Pole Telescope
[10-m in South Pole]

$$n_s = 0.965 \pm 0.010$$

Atacama Cosmology Telescope
[6-m in Chile]

100

10

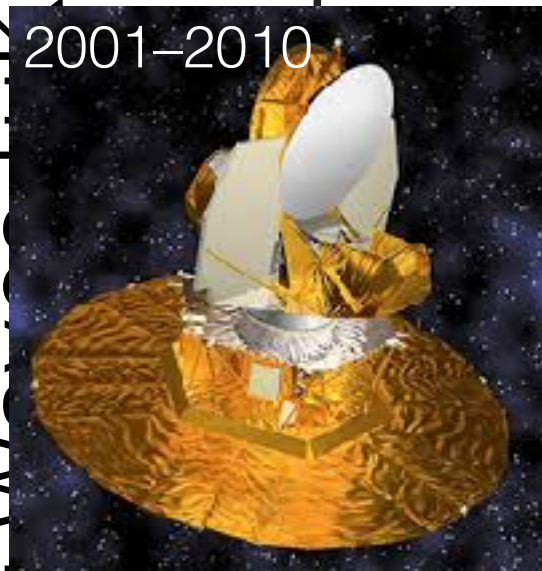
100

500

1000

2000

Multipole moment l



Angular scale

WMAP Collaboration

90°

2°

0.5°

0.2°

0.1°

Amplitude of ΔT_{CMB}^2

2001–2010

South Pole Telescope
[10-m in South Pole]

$n_s = 0.961 \pm 0.008$

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

Atacama Cosmology Telescope
[6-m in Chile]

100

10

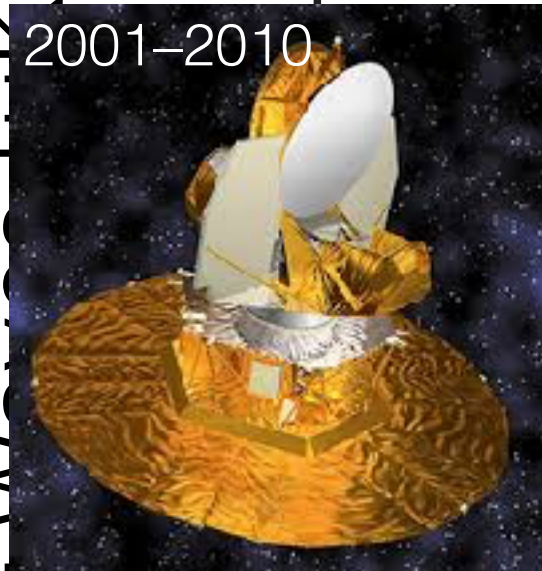
100

500

1000

2000

Multipole moment l



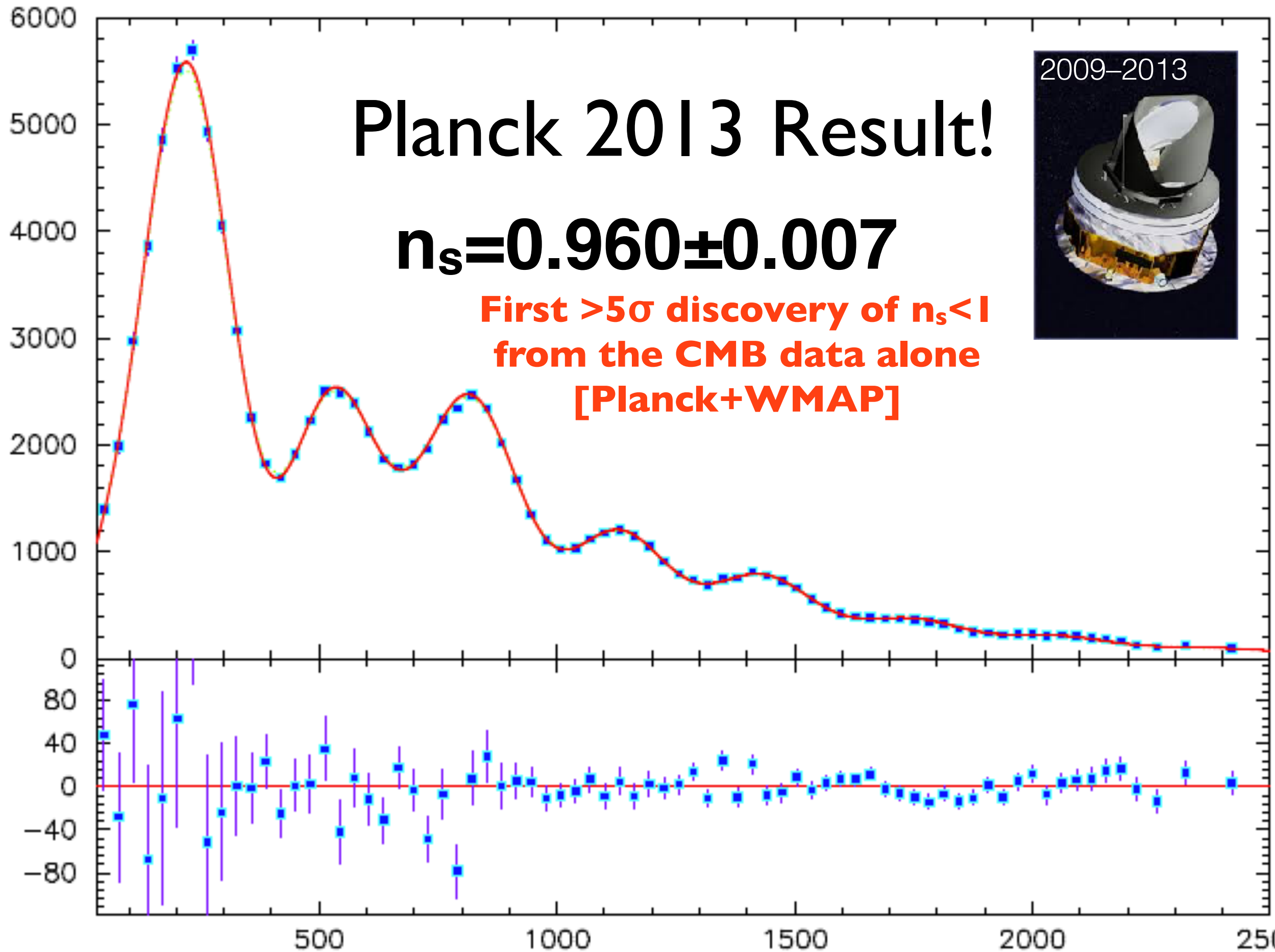
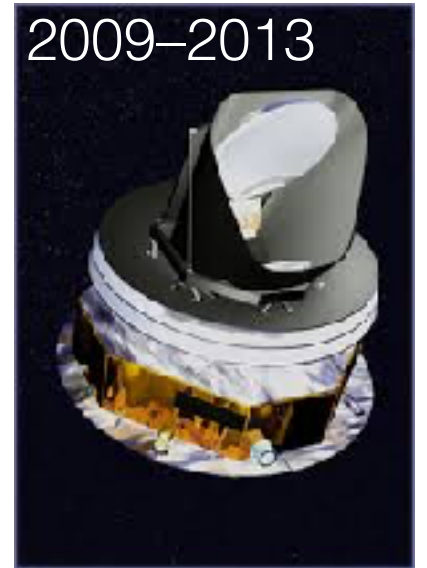
Residual Amplitude of Waves [μK^2]

Planck 2013 Result!

$$n_s = 0.960 \pm 0.007$$

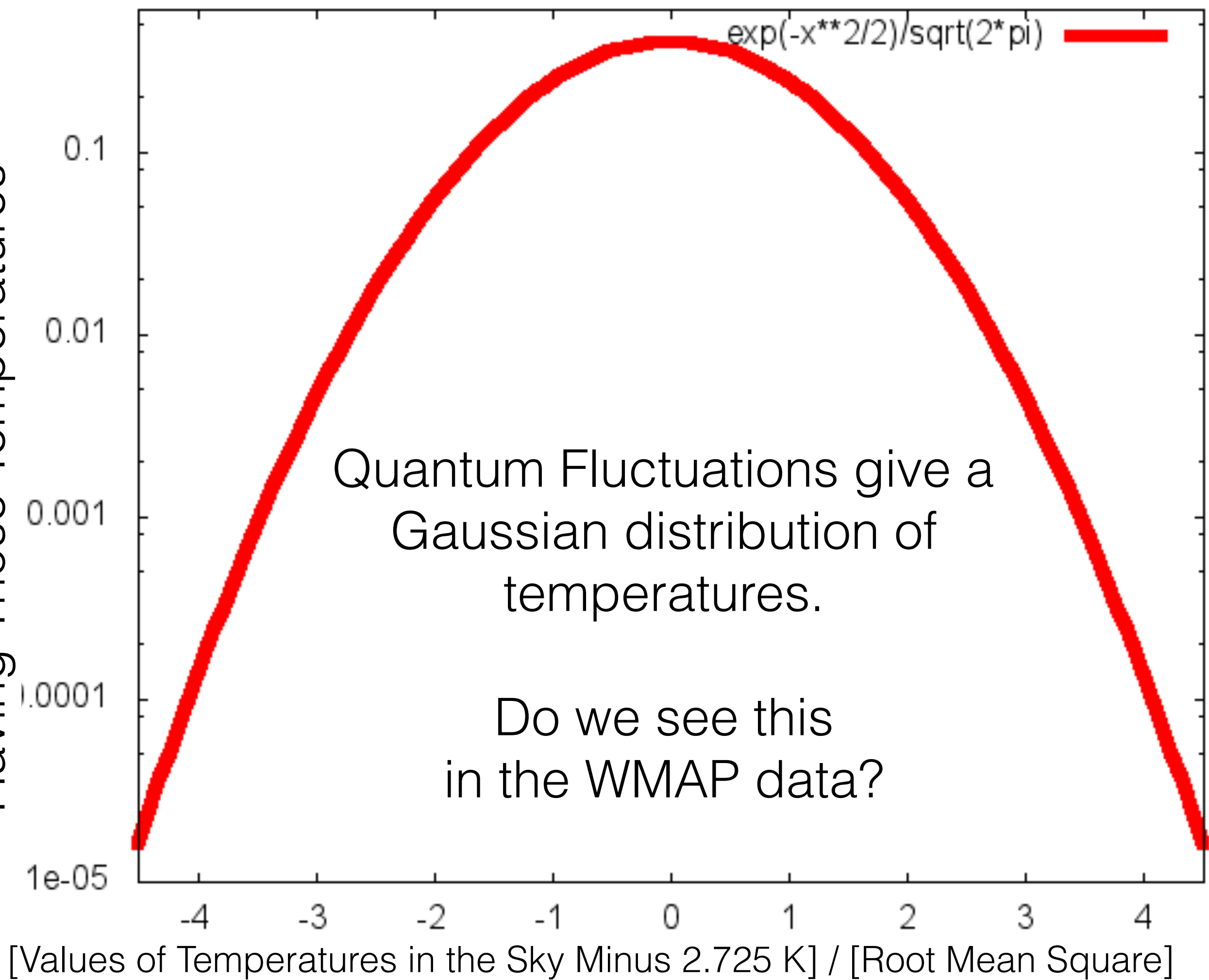
**First $>5\sigma$ discovery of $n_s < 1$
from the CMB data alone
[Planck+WMAP]**

2009–2013



l 80 degrees/(angle in the sky)

Fraction of the Number of Pixels
Having Those Temperatures



Fraction of the Number of Pixels
Having Those Temperatures

WMAP Collaboration

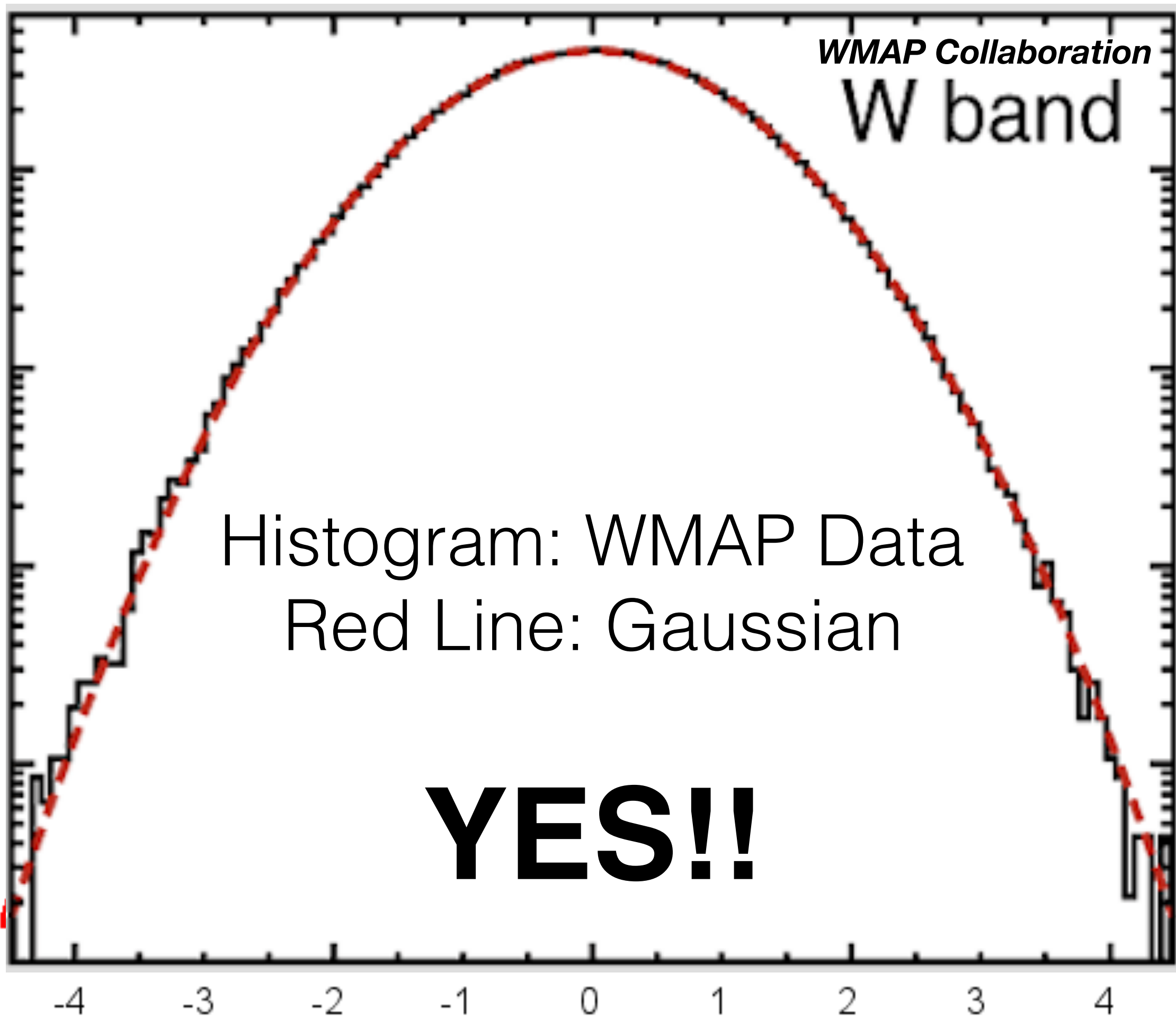
W band

0.1
0.01
0.001
0.0001
1e-05

Histogram: WMAP Data
Red Line: Gaussian

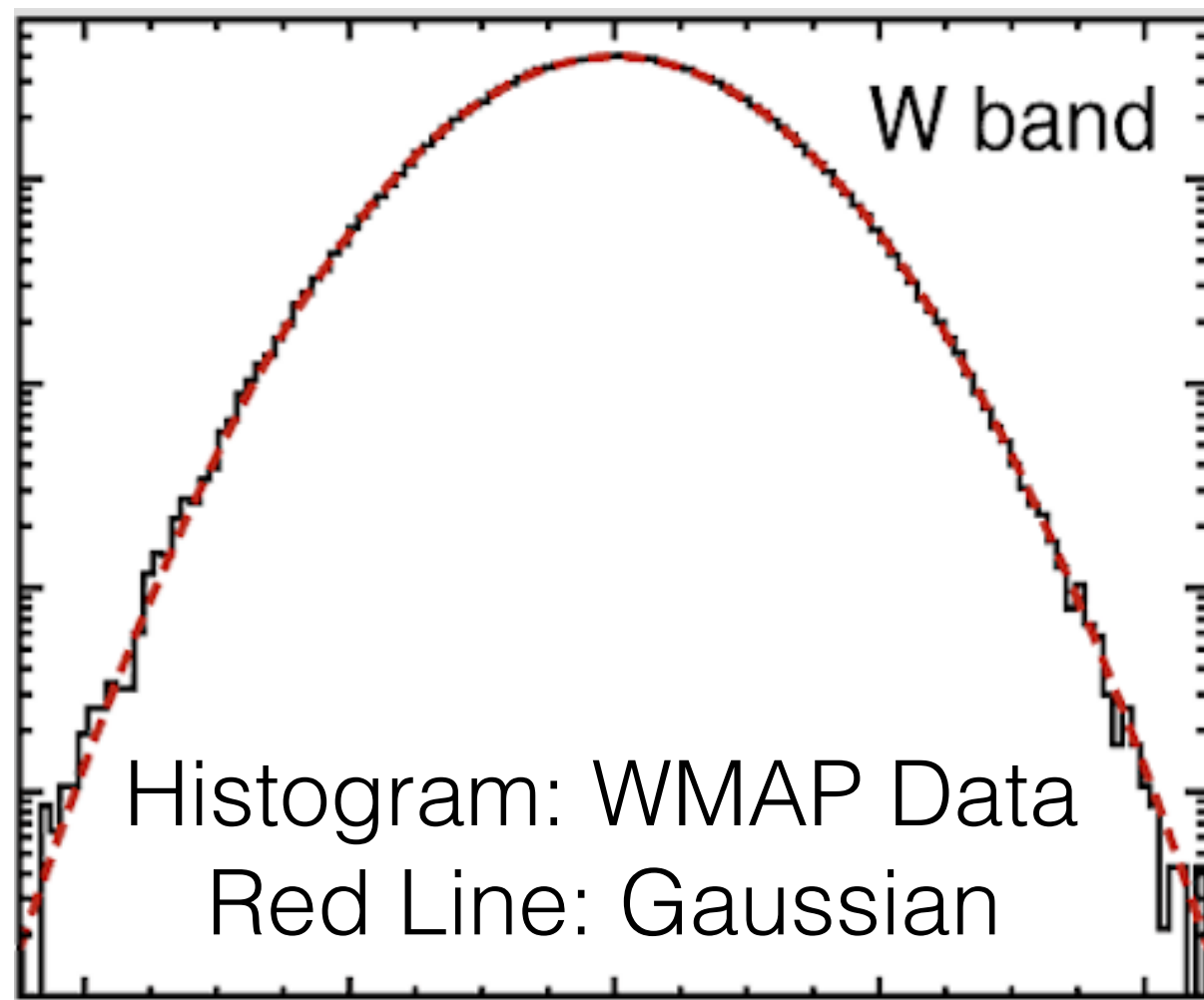
YES!!

[Values of Temperatures in the Sky Minus 2.725 K] / [Root Mean Square]



Testing Gaussianity

Fraction of the Number of Pixels
Having Those Temperatures



[Values of Temperatures in the Sky Minus
2.725 K]/ [Root Mean Square]

- 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)

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

WMAP 9-year Result

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

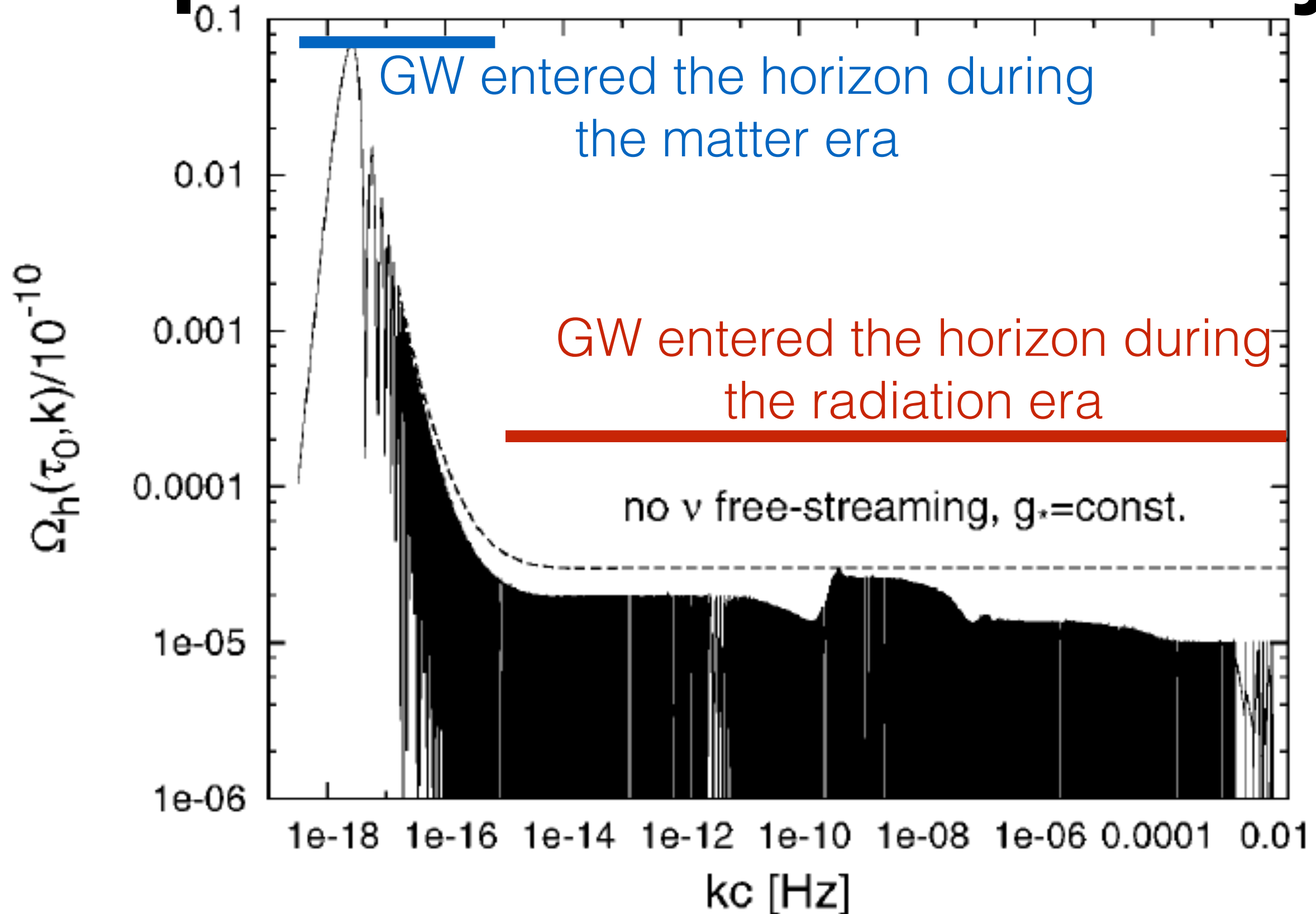
$$f_{\text{NL}} = 0.8 \pm 5.0 \text{ (68\% CL)}$$

Planck 2015 Result

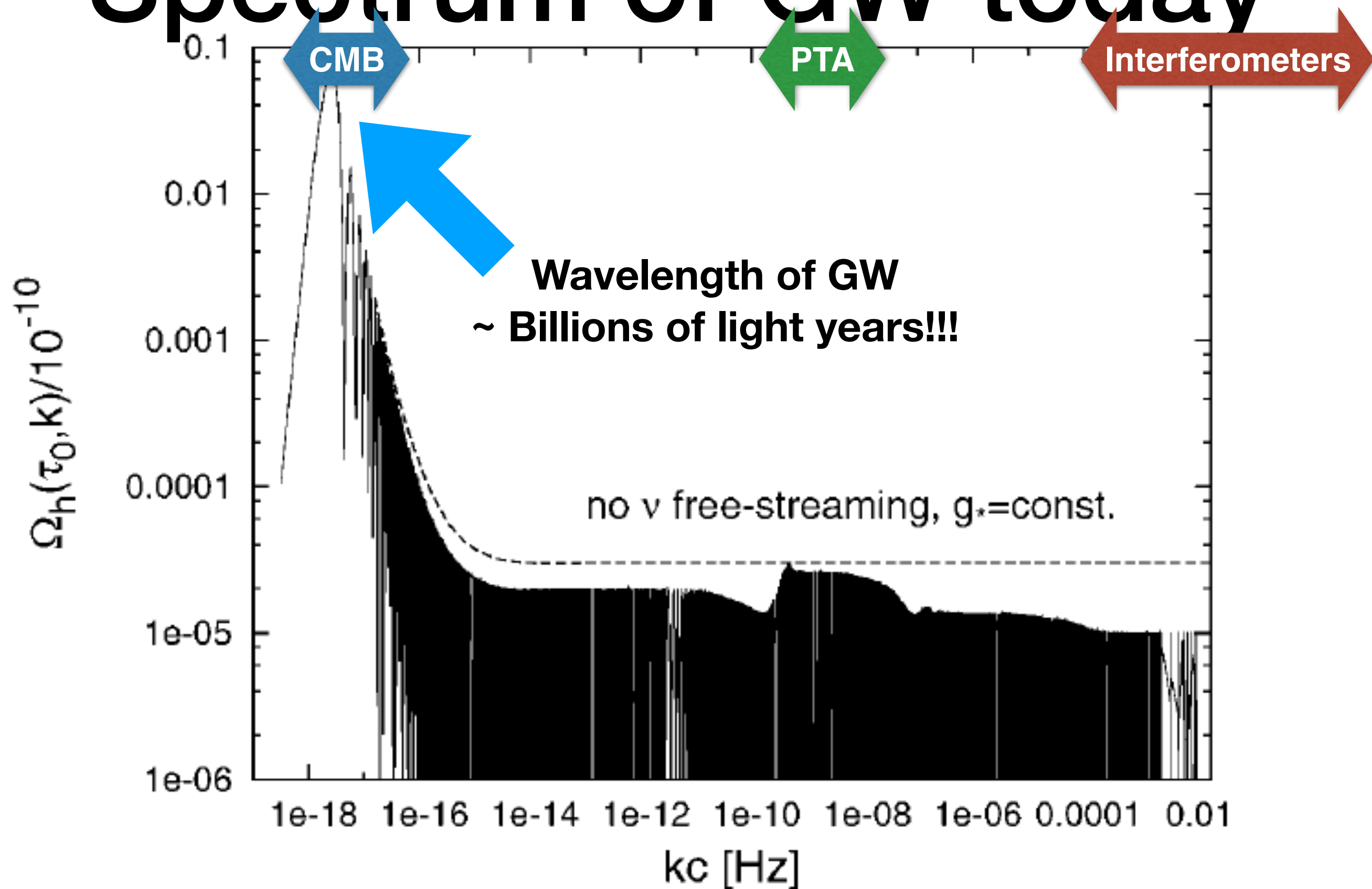
So, have we found inflation?

- 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*”

Theoretical energy density Spectrum of GW today



Theoretical energy density Spectrum of GW today



Finding Signatures of Gravitational Waves in the CMB

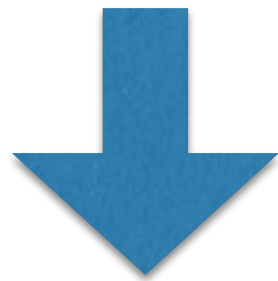
- **Next frontier in the CMB research**
 1. Find evidence for nearly scale-invariant gravitational waves
 2. Once found, test Gaussianity to make sure (or not!) that the signal comes from vacuum fluctuation
 3. Constrain inflation models

New
Research
Area!

Measuring GW

- GW changes distances between two points

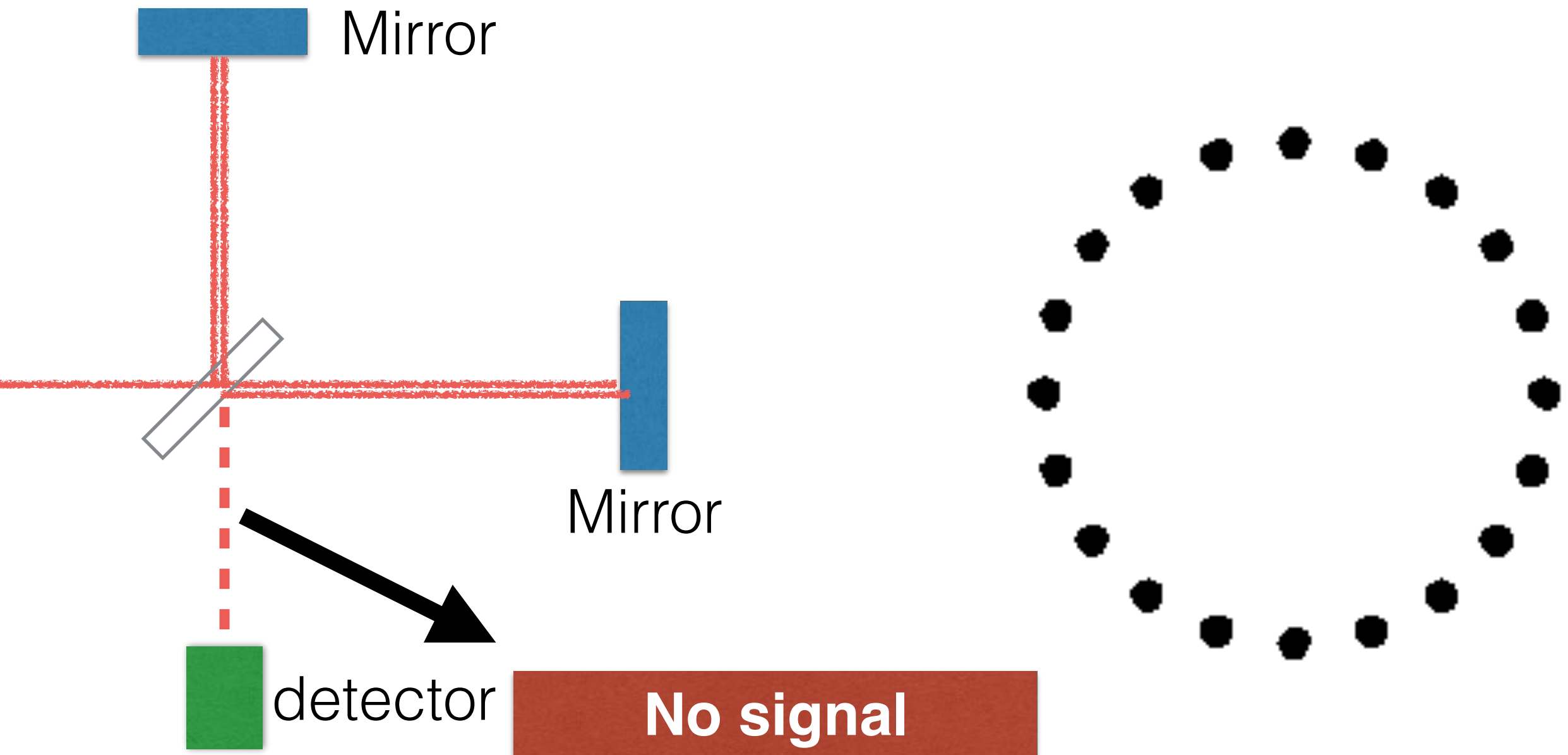
$$d\ell^2 = d\mathbf{x}^2 = \sum_{ij} \delta_{ij} dx^i dx^j$$



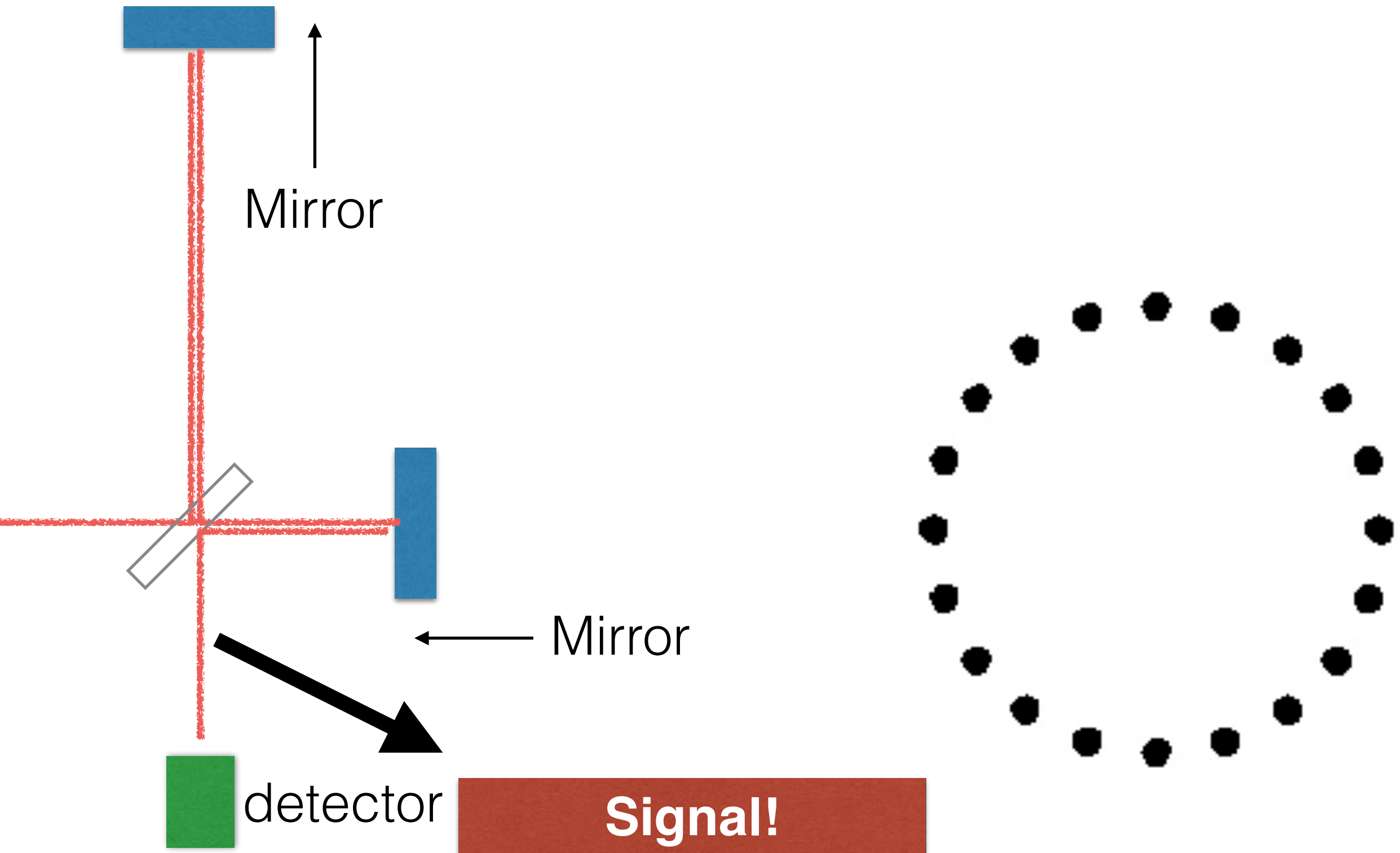
$$d\ell^2 = \sum_{ij} (\delta_{ij} + \text{perturbation}) dx^i dx^j$$



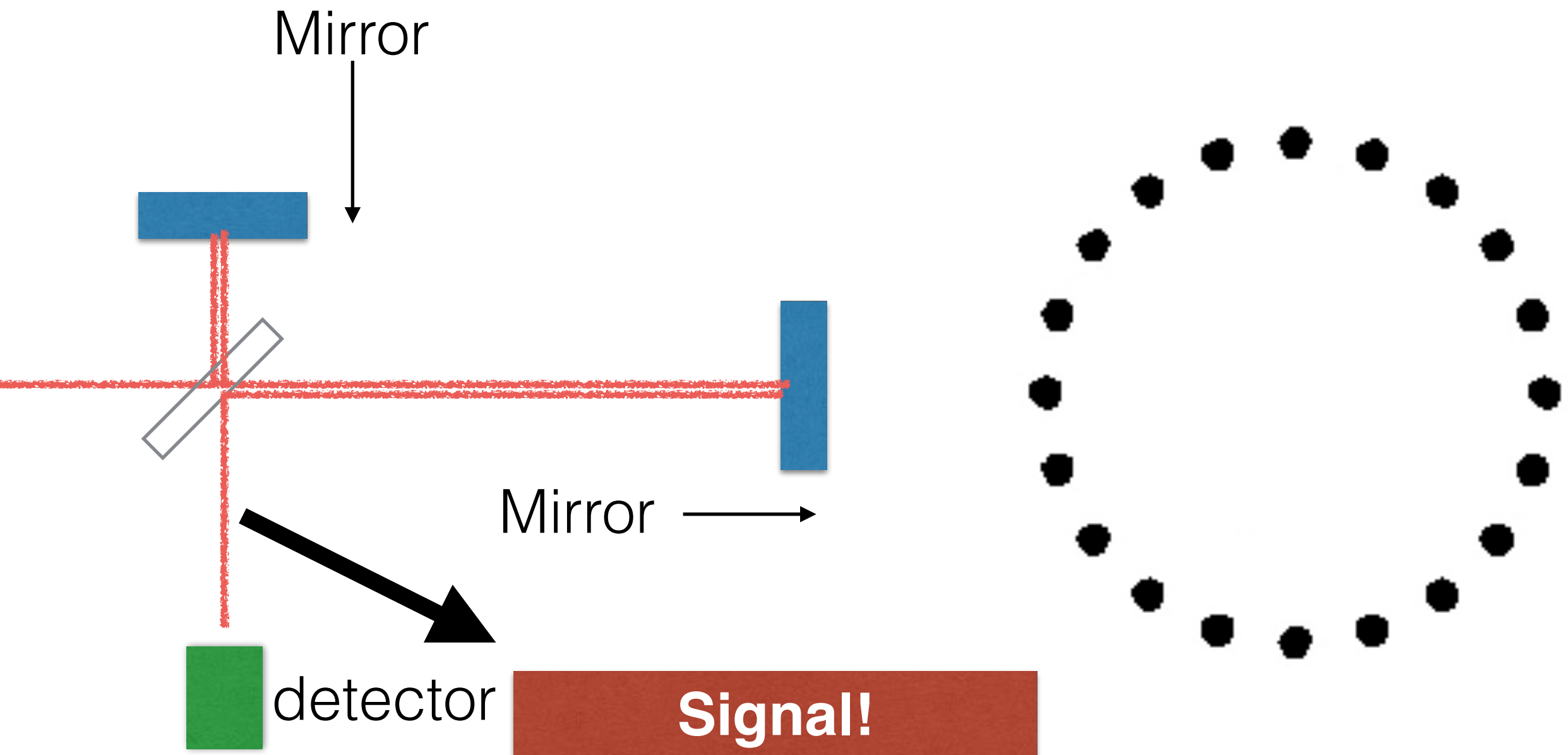
Laser Interferometer



Laser Interferometer



Laser Interferometer



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

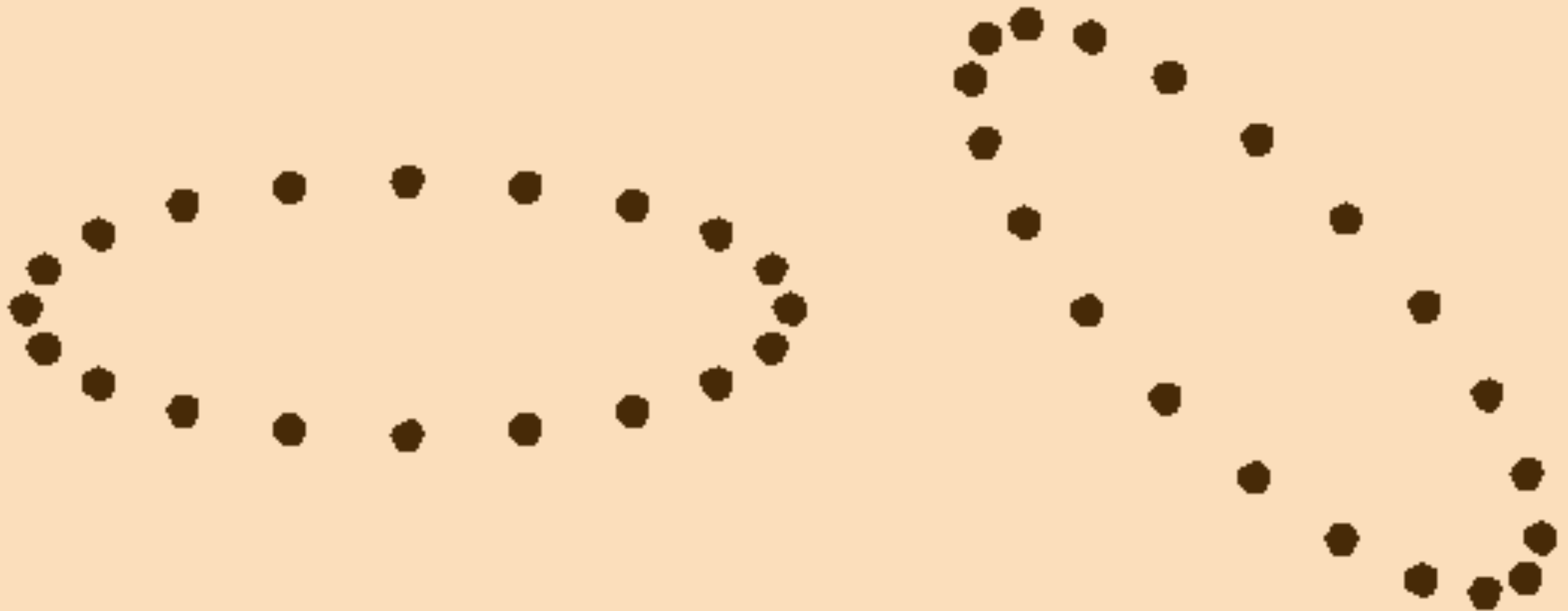
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years!!** How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

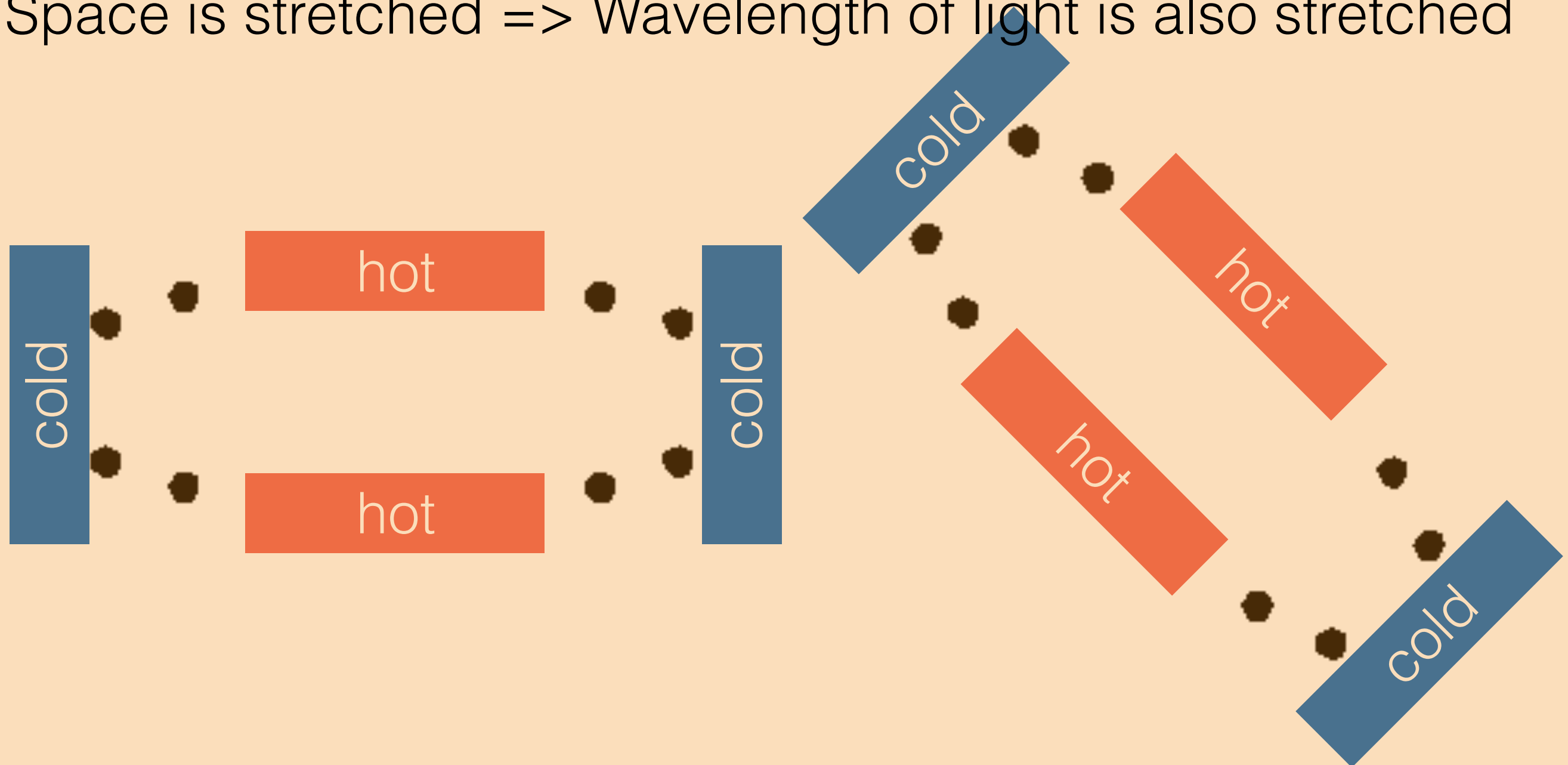
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



Detecting GW by CMB

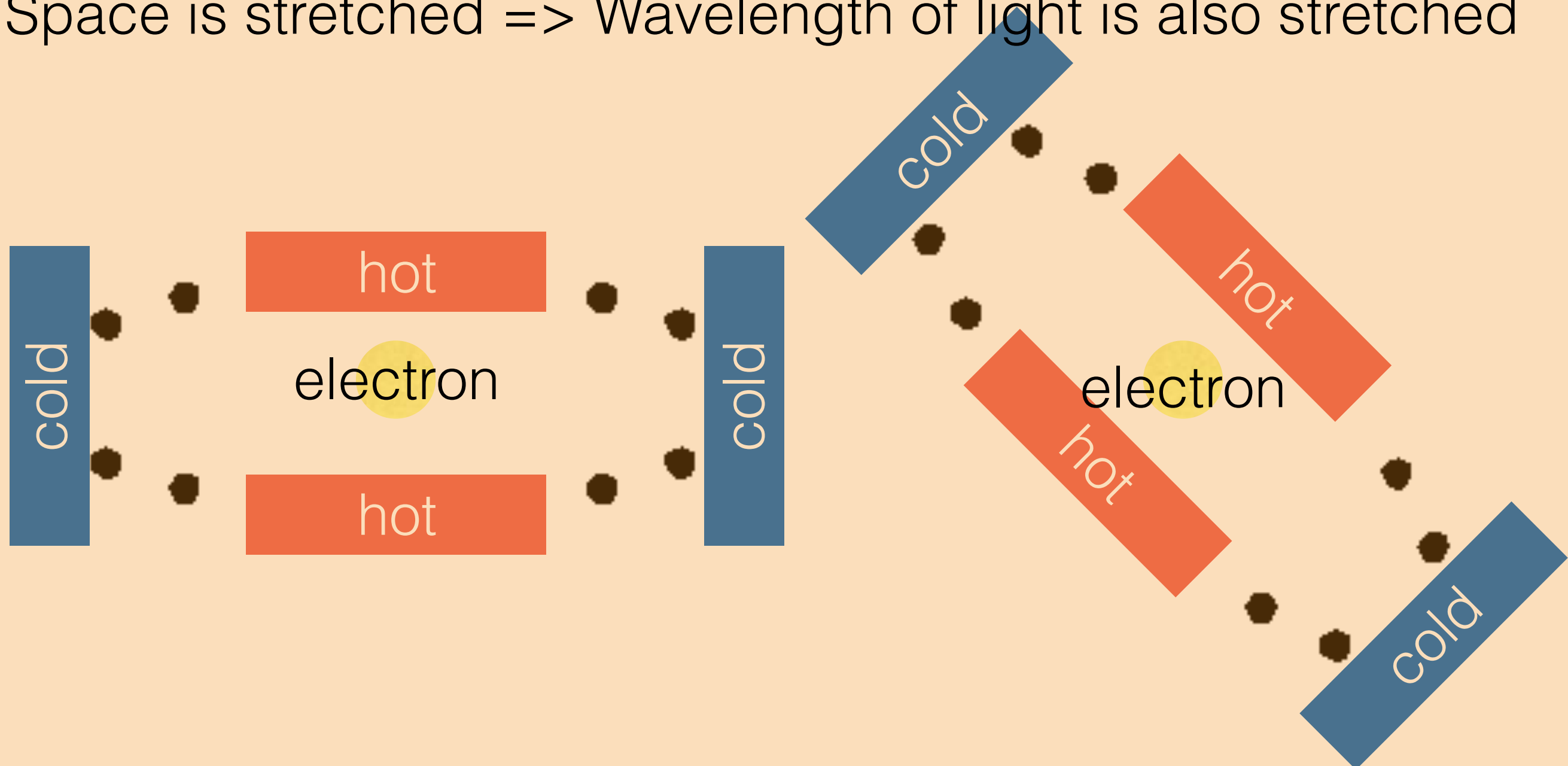
Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB

Polarisation

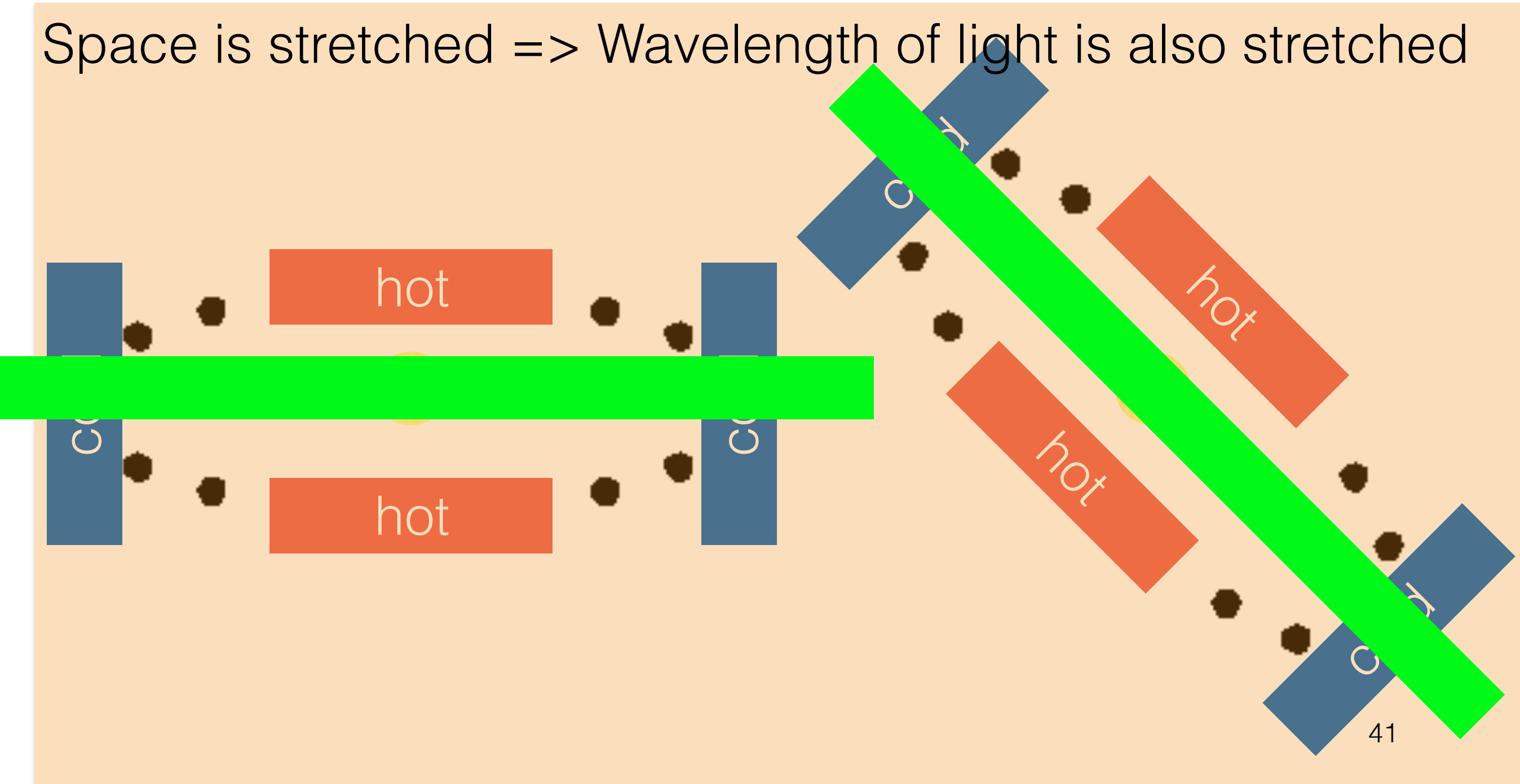
Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB

Polarisation

Space is stretched => Wavelength of light is also stretched

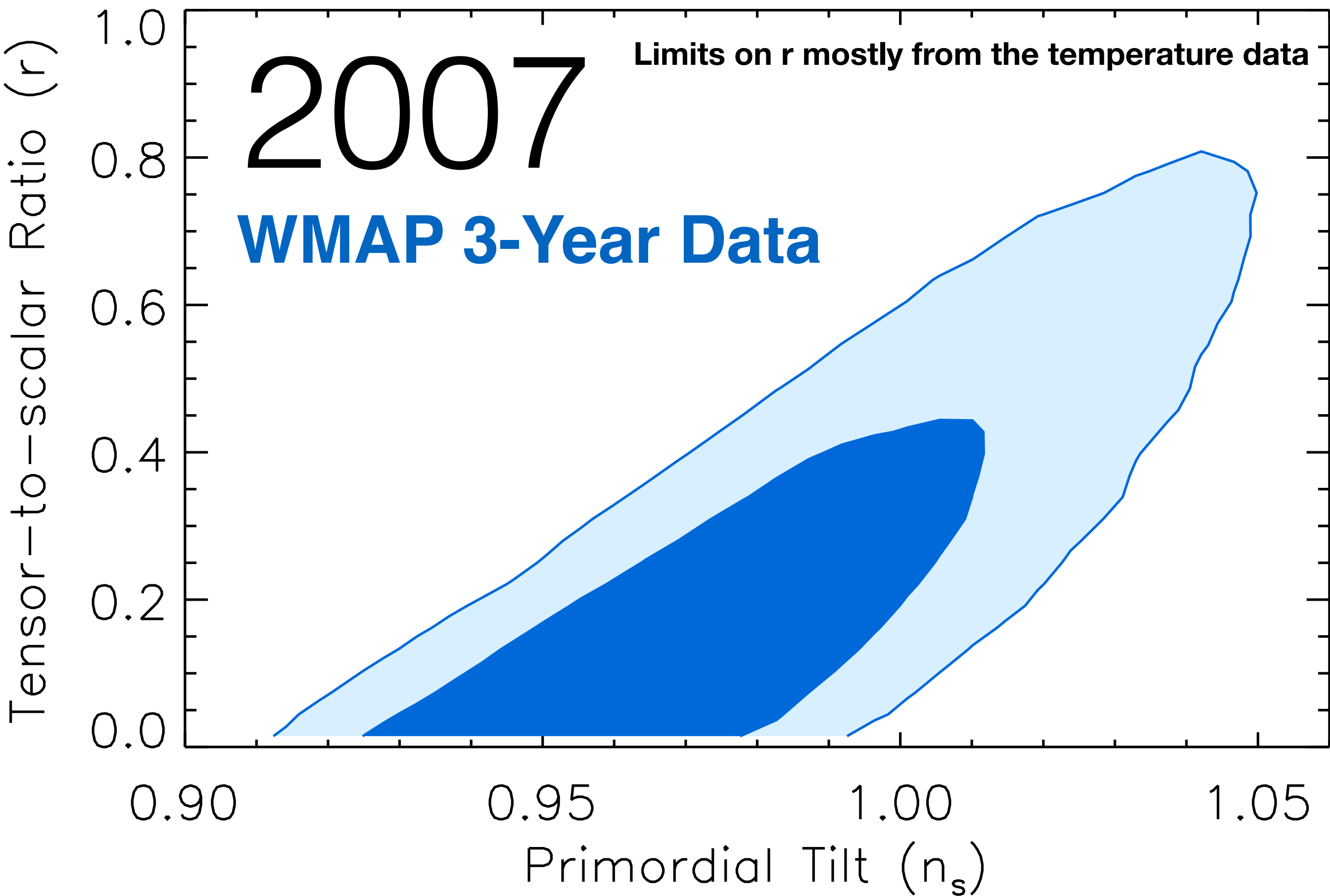


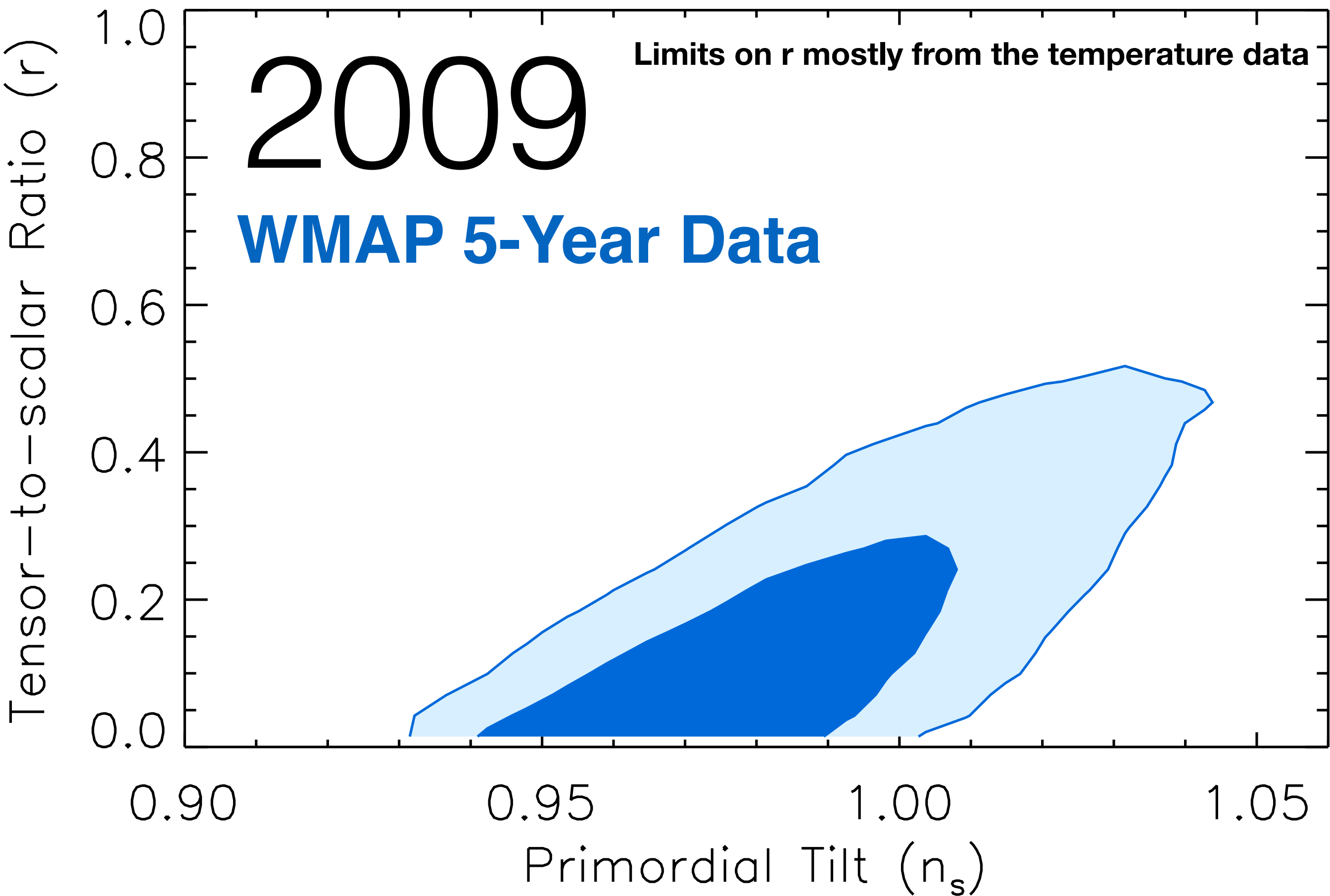
Tensor-to-scalar Ratio

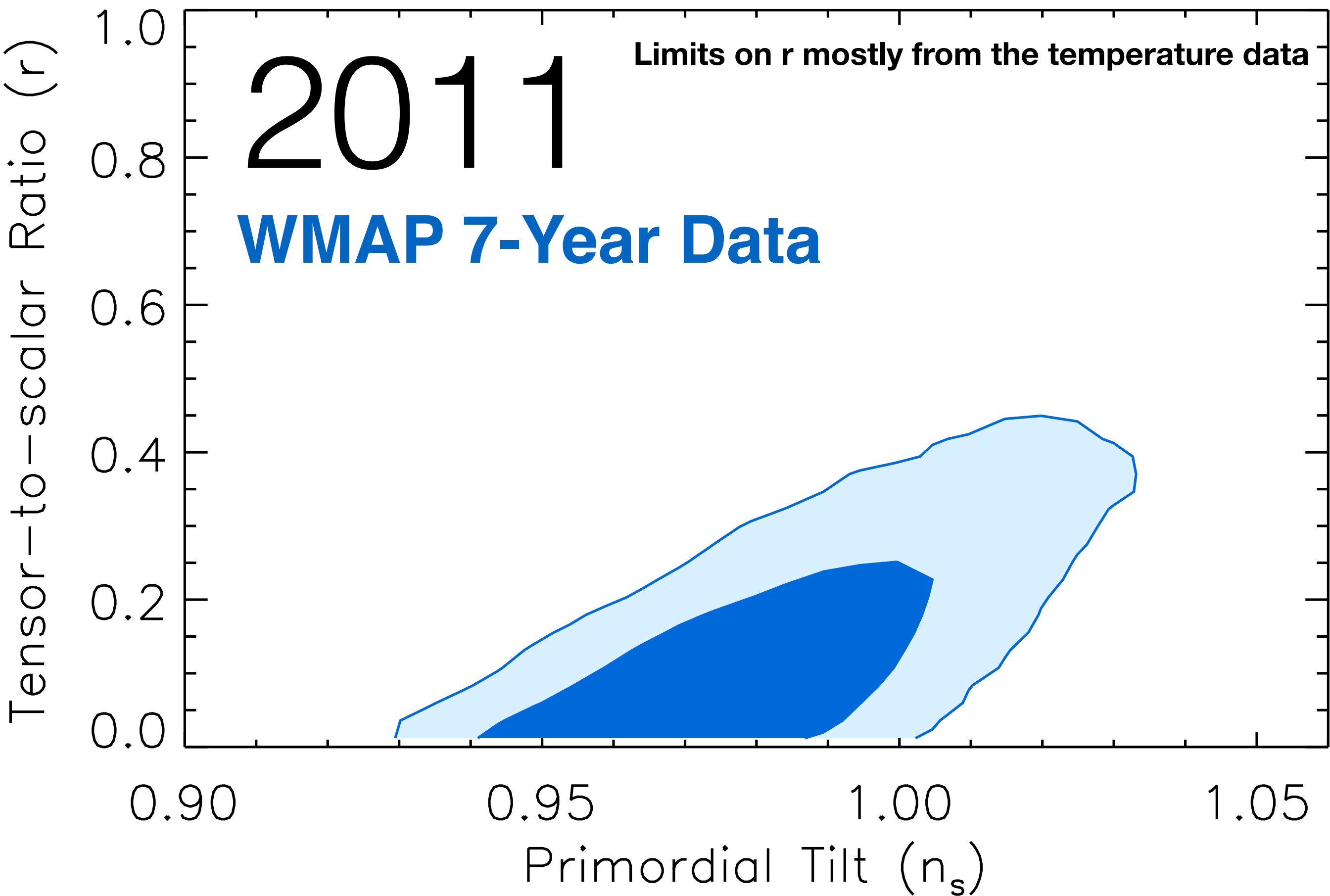
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

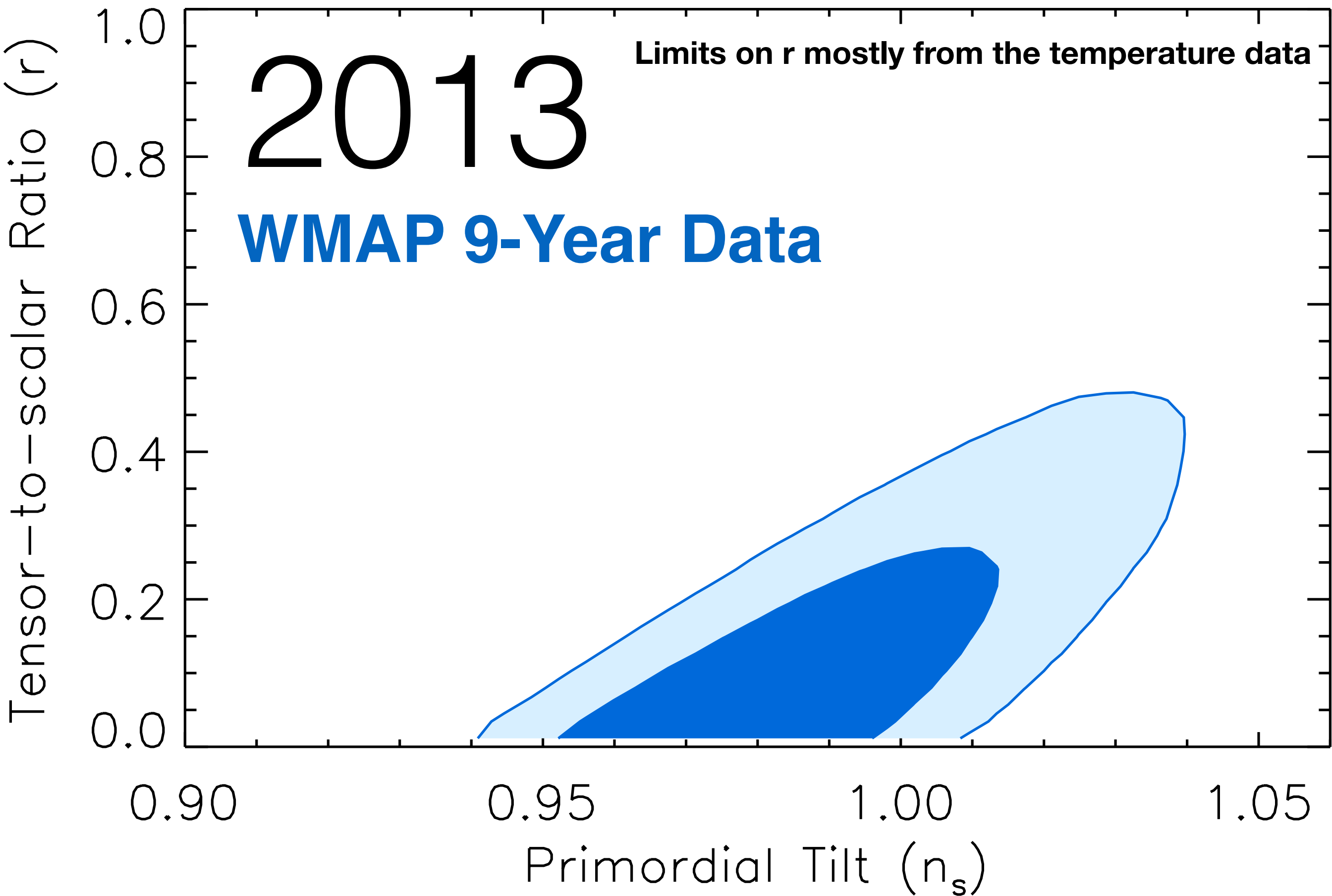
- We really want to find this! The current upper bound is **$r < 0.07$** (95%CL)

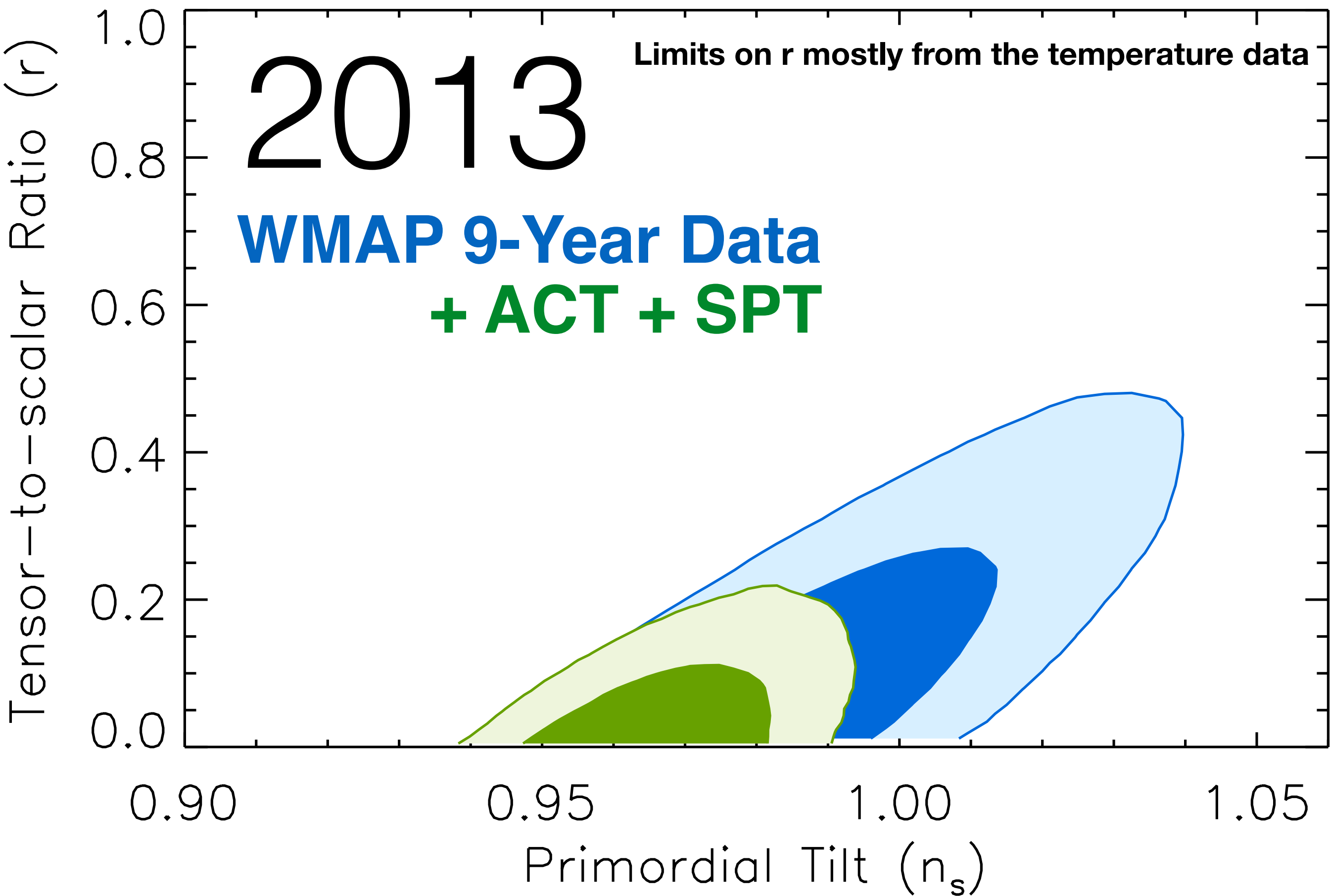
BICEP2/Keck Array Collaboration (2016)

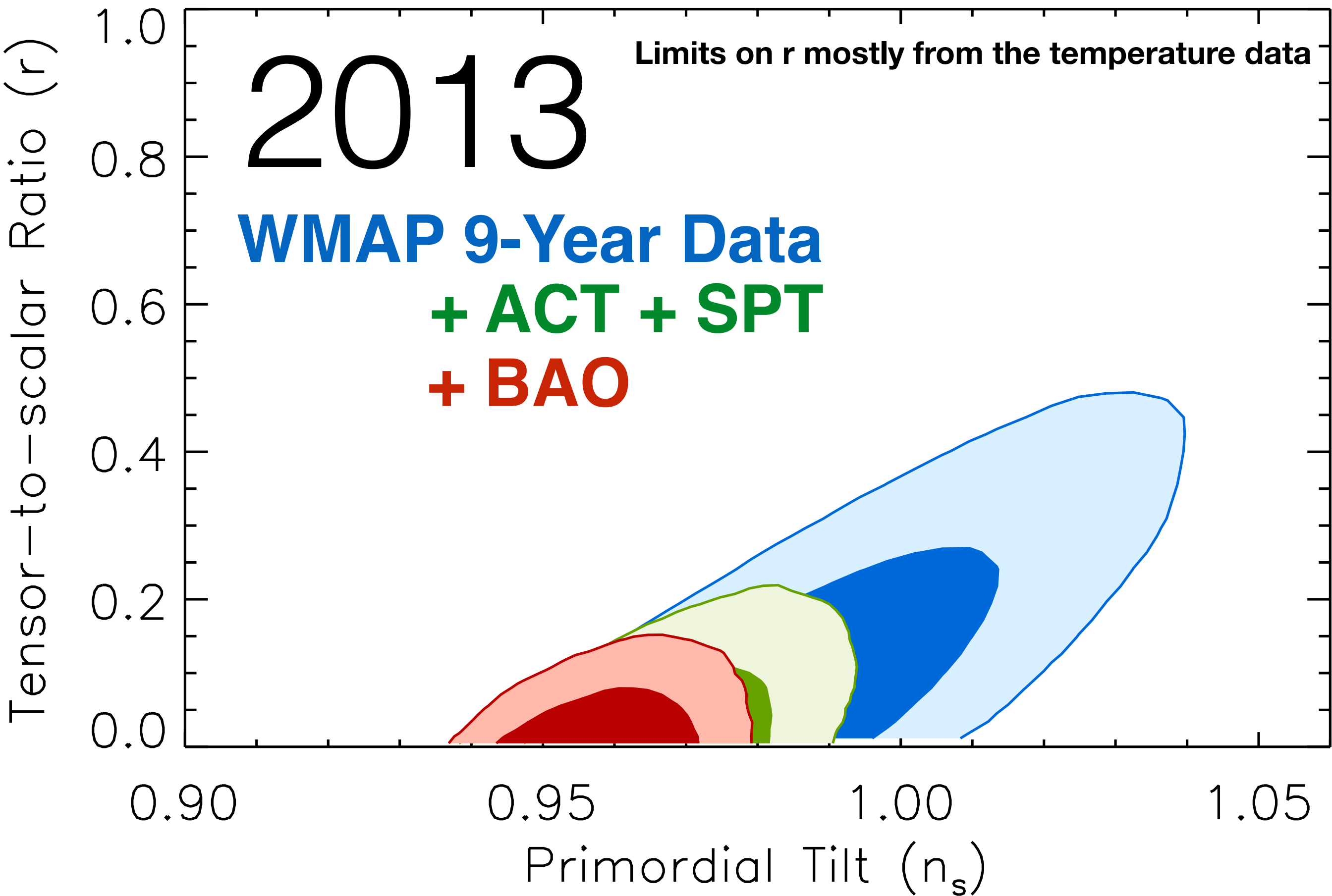


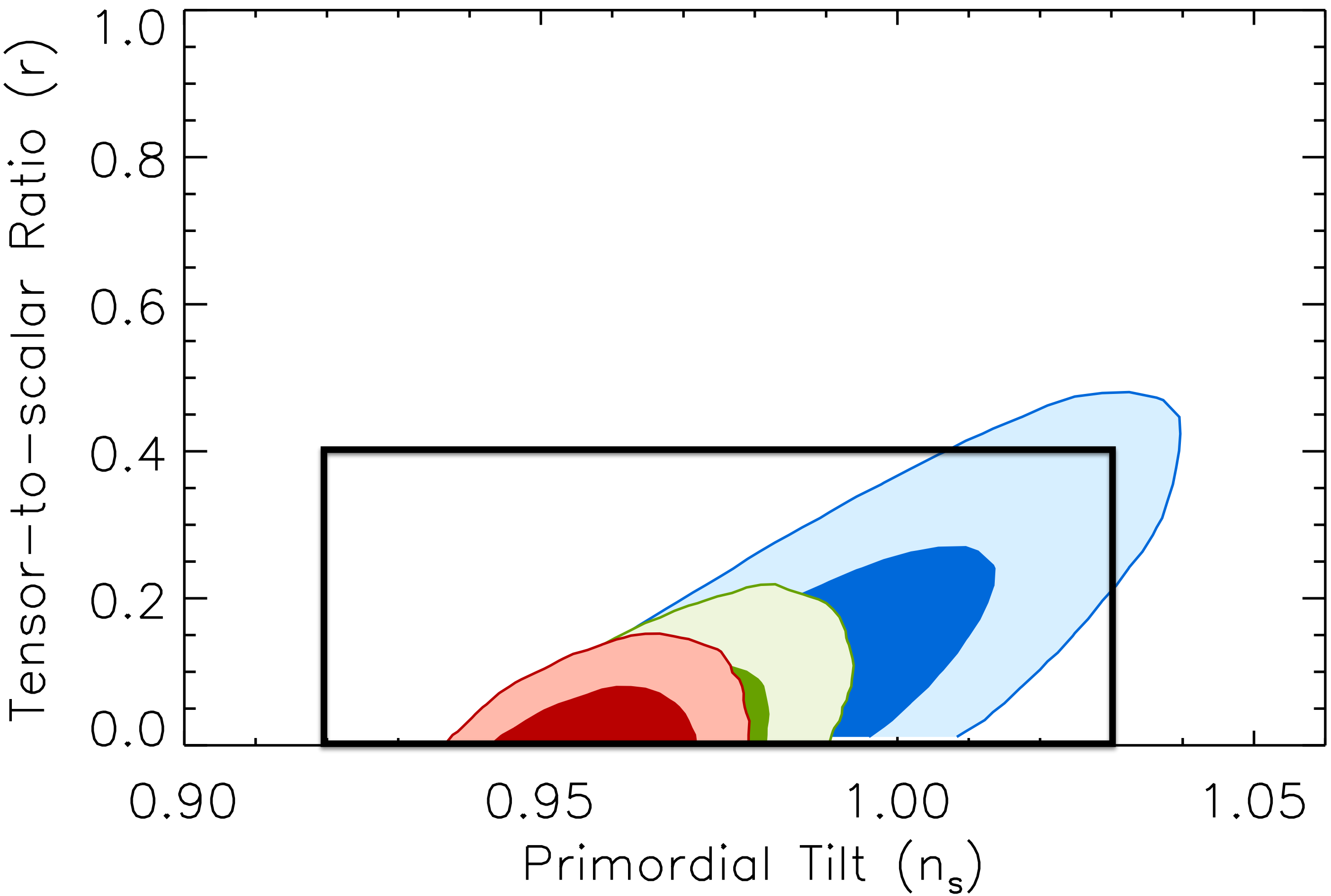


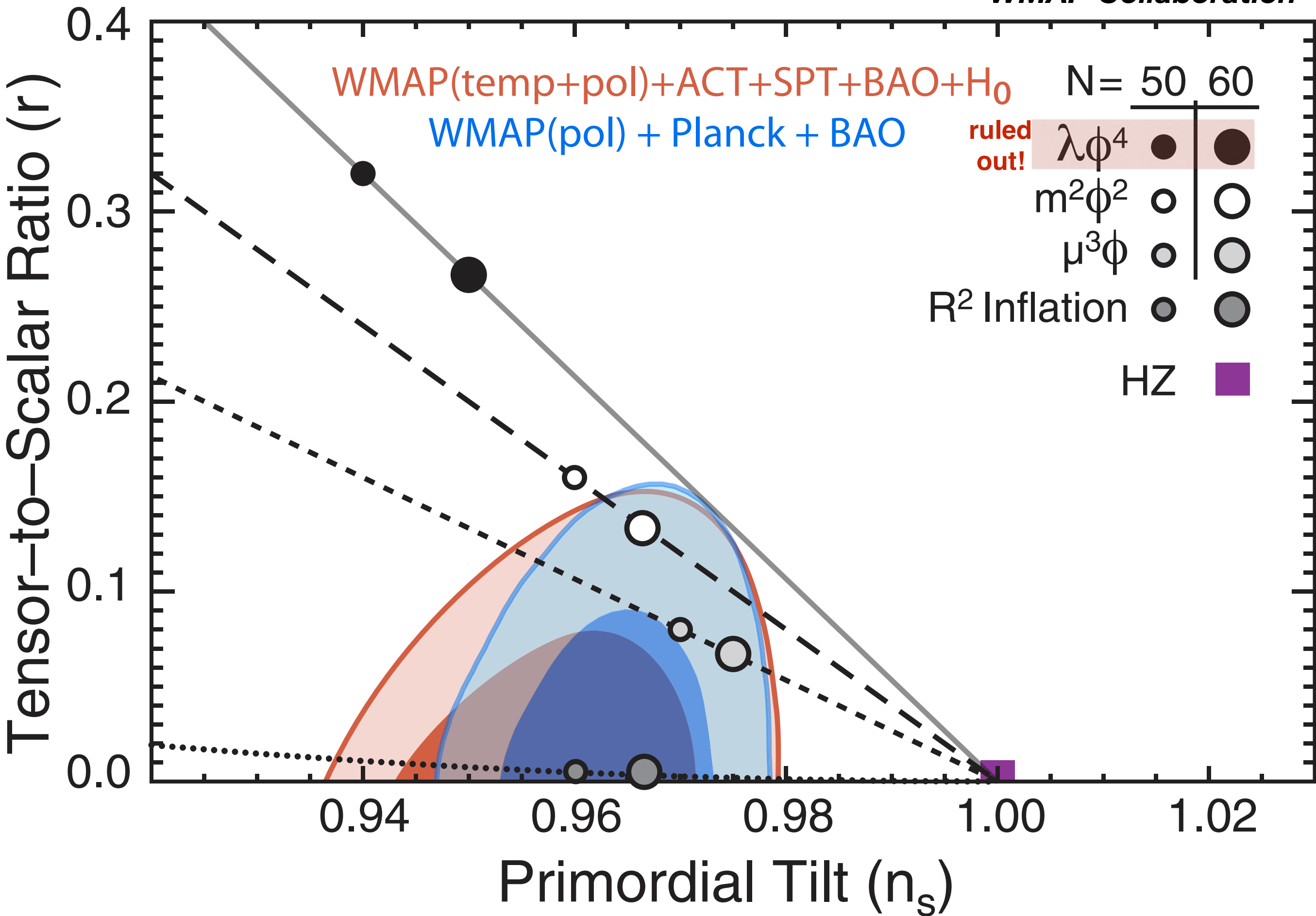






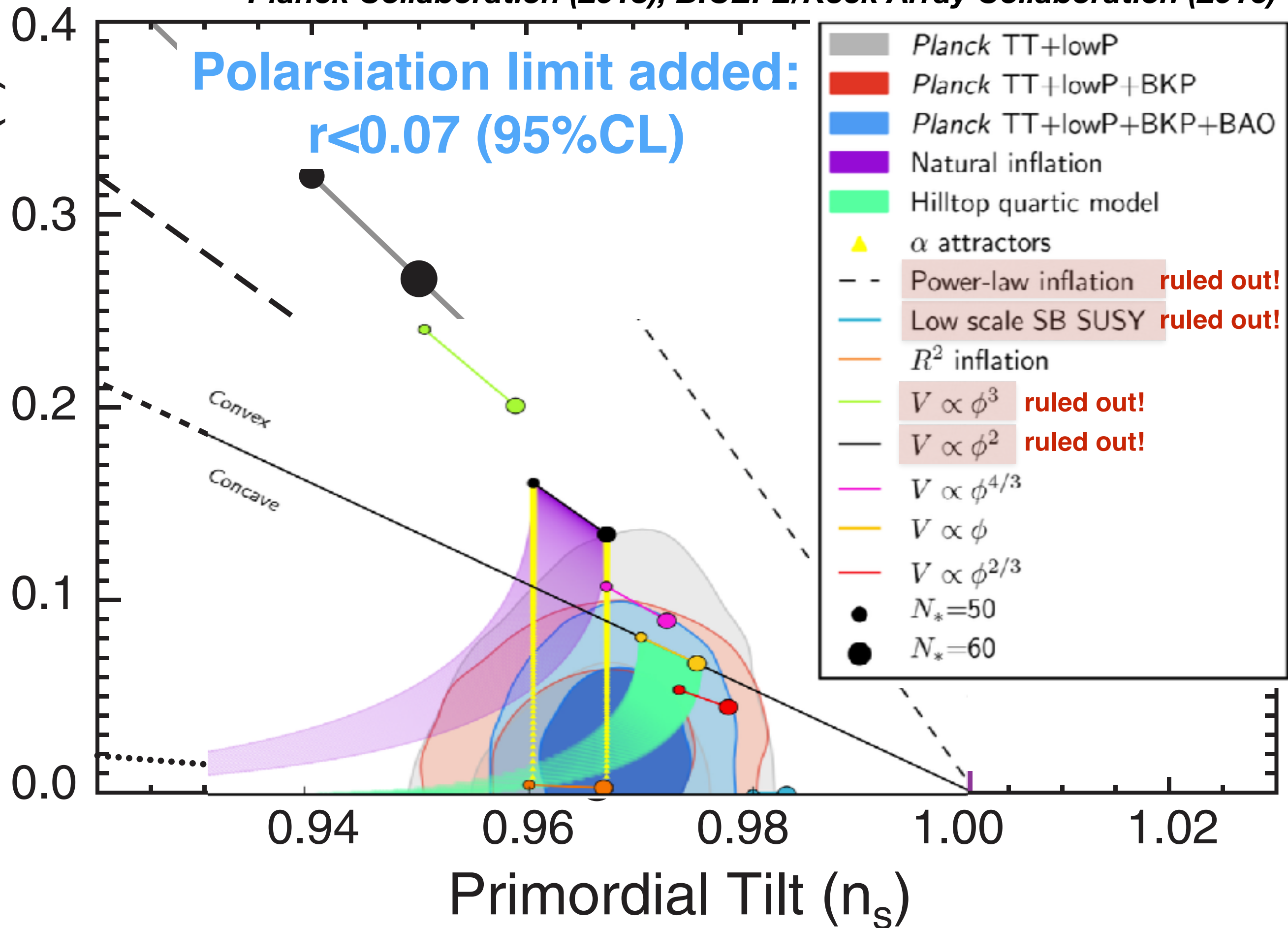






Tensor-to-Scalar Ratio (r)

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



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

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

- **Homogeneous solution:** “GWs from vacuum fluctuation”
- **Inhomogeneous solution:** “GWs from sources”
 - Scalar and vector fields cannot source tensor fluctuations at linear order
 - SU(2) gauge field can!

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

GW from Axion-SU(2) Dynamics

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

- 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_ν^a :

$$F_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g\epsilon^{abc} A_\mu^b A_\nu^c$$

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 $\Rightarrow$ GW is **chiral** (well-known result)
- Brand-new result: **GWs sourced by this mechanism are strongly non-Gaussian!**

Agrawal, Fujita & EK (2017)

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
(Stanford->Kyoto)

- $\Omega_A \ll 1$ 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

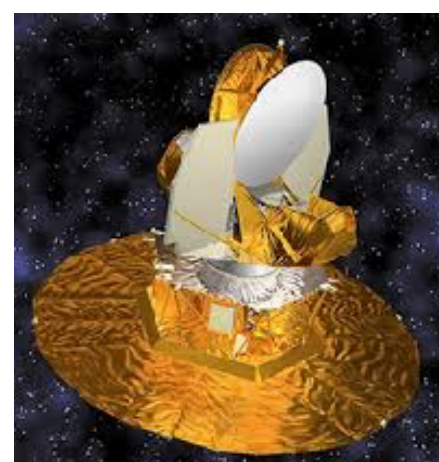
- No detection of polarisation from primordial GW yet
- Many ground-based and balloon-borne experiments are taking data now



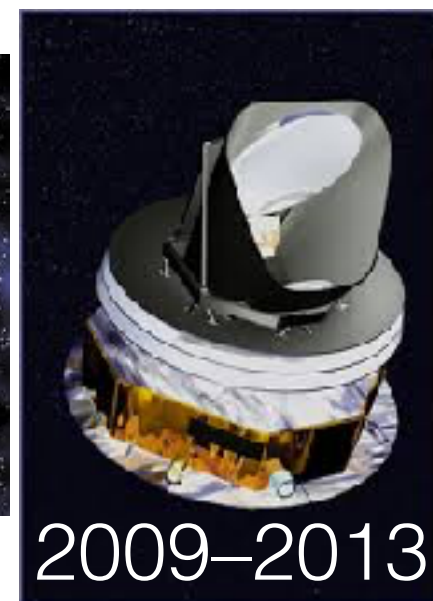
The search continues!!



1989–1993



2001–2010



2009–2013



202X–

Part II:

LiteBIRD Proposal

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

LiteBIRD working group

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

JAXA

T. Dotani
H. Fuke
H. Imada
I. Kawano
H. Matsuhara
K. Mitsuda
T. Nishibori
K. Nishijo
A. Noda
A. Okamoto
S. Sakai
Y. Sato
K. Shinozaki
H. Sugita
Y. Takei
H. Tomida
T. Wada
R. Yamamoto
N. Yamasaki
T. Yoshida
K. Yotsumoto

Osaka U.

M. Nakajima
K. Takano

Osaka Pref. U.

M. Inoue
K. Kimura
H. Ogawa
N. Okada

Okayama U.

T. Funaki
N. Hidehira
H. Ishino
A. Kibayashi
Y. Kida
K. Komatsu
S. Uozumi
Y. Yamada

NIFS

S. Takada

Kavli IPMU

A. Ducout
T. Iida
D. Kaneko
N. Katayama
T. Matsumura
Y. Sakurai
H. Sugai
B. Thorne
S. Utsunomiya

KEK

M. Hazumi (PI)
M. Hasegawa
Y. Inoue
N. Kimura
K. Kohri
M. Maki
Y. Minami
T. Nagasaki
R. Nagata
H. Nishino
T. Okamura
N. Sato
J. Suzuki
T. Suzuki
S. Takakura
O. Tajima
T. Tomaru
M. Yoshida

SOKENDAI

Y. Akiba
Y. Inoue
H. Ishitsuka
Y. Segawa
S. Takatori
D. Tanabe
H. Watanabe

NAOJ

A. Dominjon
T. Hasebe
J. Inatani
K. Karatsu
S. Kashima
M. Nagai
T. Noguchi
Y. Sekimoto
M. Sekine

Kitazato U.

T. Kawasaki

Saitama U.

M. Naruse

NICT

Y. Uzawa

Konan U.

I. Ohta

Kansei Gakuin U.

S. Matsuura

AIST

K. Hattori

U. Tokyo

A. Kusaka
S. Sekiguchi
T. Shimizu
S. Shu
N. Tomita

Tohoku U.

M. Hattori
T. Morishima

Nagoya U.

K. Ichiki

Yokohama Natl. U.

T. Fujino
F. Irie
S. Nakamura
K. Natsume
R. Takaku
T. Yamashita

RIKEN

S. Mima
S. Oguri
C. Otani

TIT

S. Matsuoka

APC Paris

R. Stompor

Cardiff U.

G. Pisano

Paris ILP

J. Errard

CU Boulder

N. Halverson

McGill U.

M. Dobbs

MPA

E. Komatsu

NIST

G. Hilton
J. Hubmayr

UC San Diego

K. Arnold
T. Elleot
B. Keating
G. Rebeiz

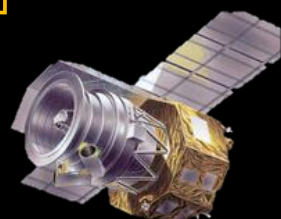
UC Berkeley / LBNL

D. Barron
J. Borrill
Y. Chinone
A. Cukierman
D. Curtis
T. de Haan
L. Hayes
J. Fisher
N. Goeckner-wald
C. Hill
O. Jeong
R. Keskitalo
T. Kisner
A. Kusaka
A. Lee(US PI)
E. Linder
D. Meilhan
P. Richards
E. Taylor
U. Seljak
B. Sherwin
A. Suzuki
P. Turin
B. Westbrook
M. Willer
N. Whitehorn

Satellite



X-ray



Infrared



CMB

Stanford U.

S. Cho
K. Irwin
S. Kernasovskiy
C.-L. Kuo
D. Li
T. Namikawa
K. L. Thompson

LiteBIRD working group

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

JAXA

T. Dotani
H. Fuke
H. Imada
I. Kawano
H. Matsuhara
K. Mitsuda
T. Nishibori
K. Nishijo
A. Noda
A. Okamoto
S. Sakai
Y. Sato
K. Shinozaki
H. Sugita
Y. Takei
H. Tomida
T. Wada
R. Yamamoto
N. Yamasaki
T. Yoshida
K. Yotsumoto

Osaka U.

M. Nakajima
K. Takano

Osaka Pref. U.

M. Inoue
K. Kimura
H. Ogawa
N. Okada

Okayama

T. Funaki
N. Hidehiko
H. Ishino
A. Kibayama
Y. Kida
K. Komatsu
S. Uozumi
Y. Yamada

NIFS

S. Takada

Kavli IPMU

A. Ducouret
T. Iida
D. Kaneko
N. Katayama
T. Matsumura
Y. Sakurai
H. Sugai
B. Thorne
S. Utsunori

KEK

M. Hazumi (PI)

NAOJ

A. Dominjon

U. Tokyo

A. Kusaka

TIT

S. Matsuoka

UC Berkeley / LBNL

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K. L. Thompson

Satellite

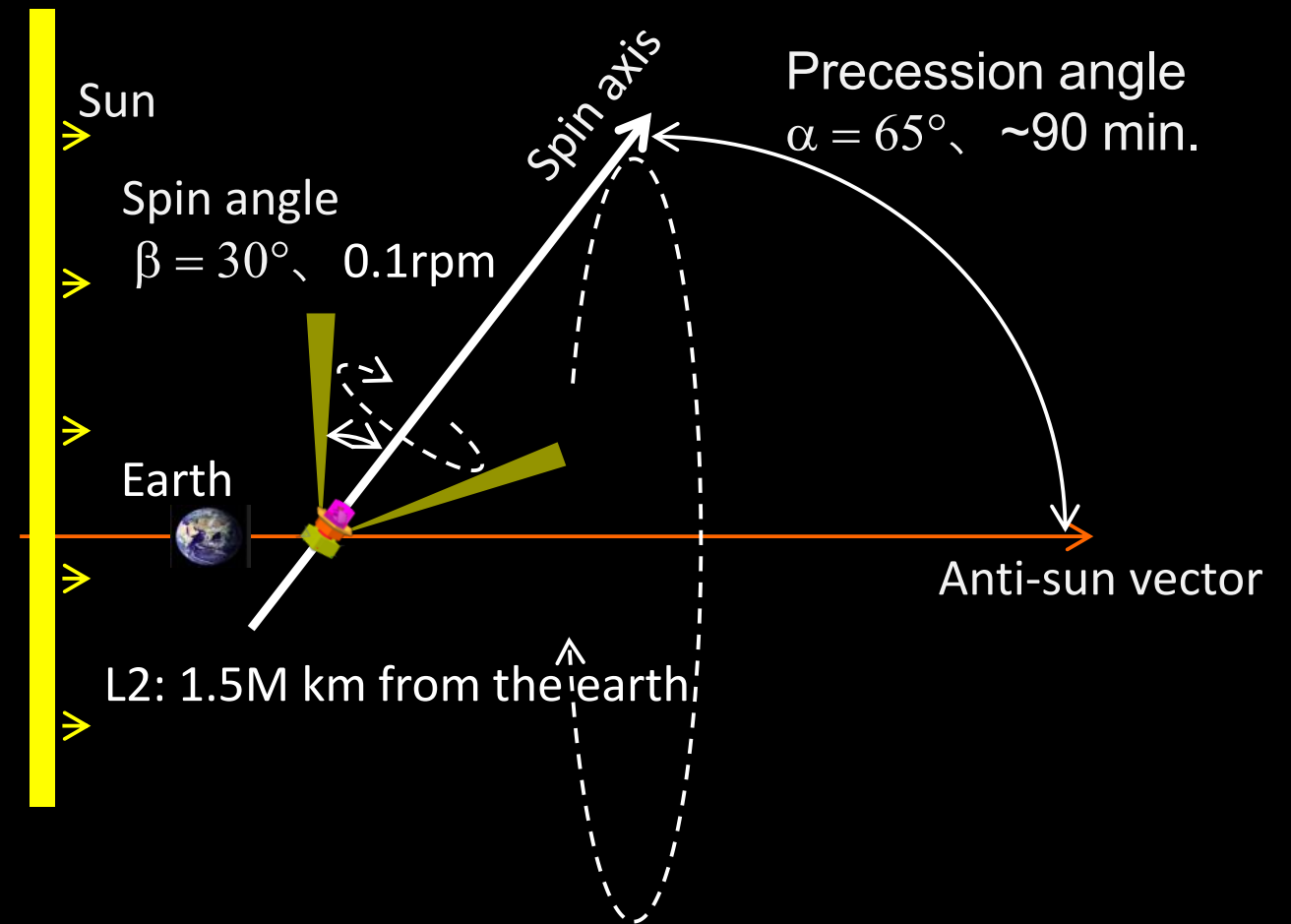
PI: Masashi Hazumi
(KEK / Kavli IPMU / SOKENDAI / JAXA)



Observation Strategy



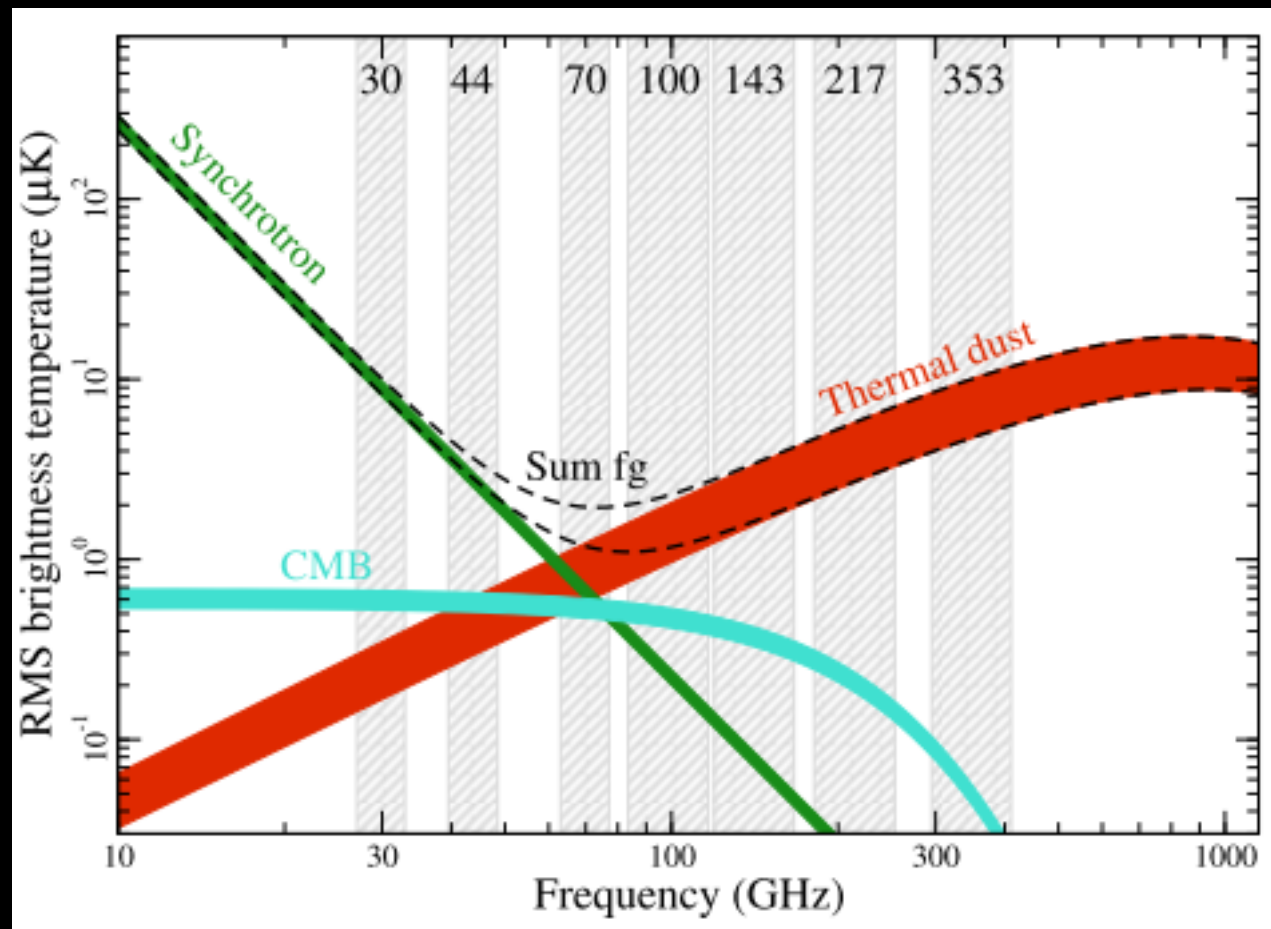
JAXA H3 Launch Vehicle (JAXA)



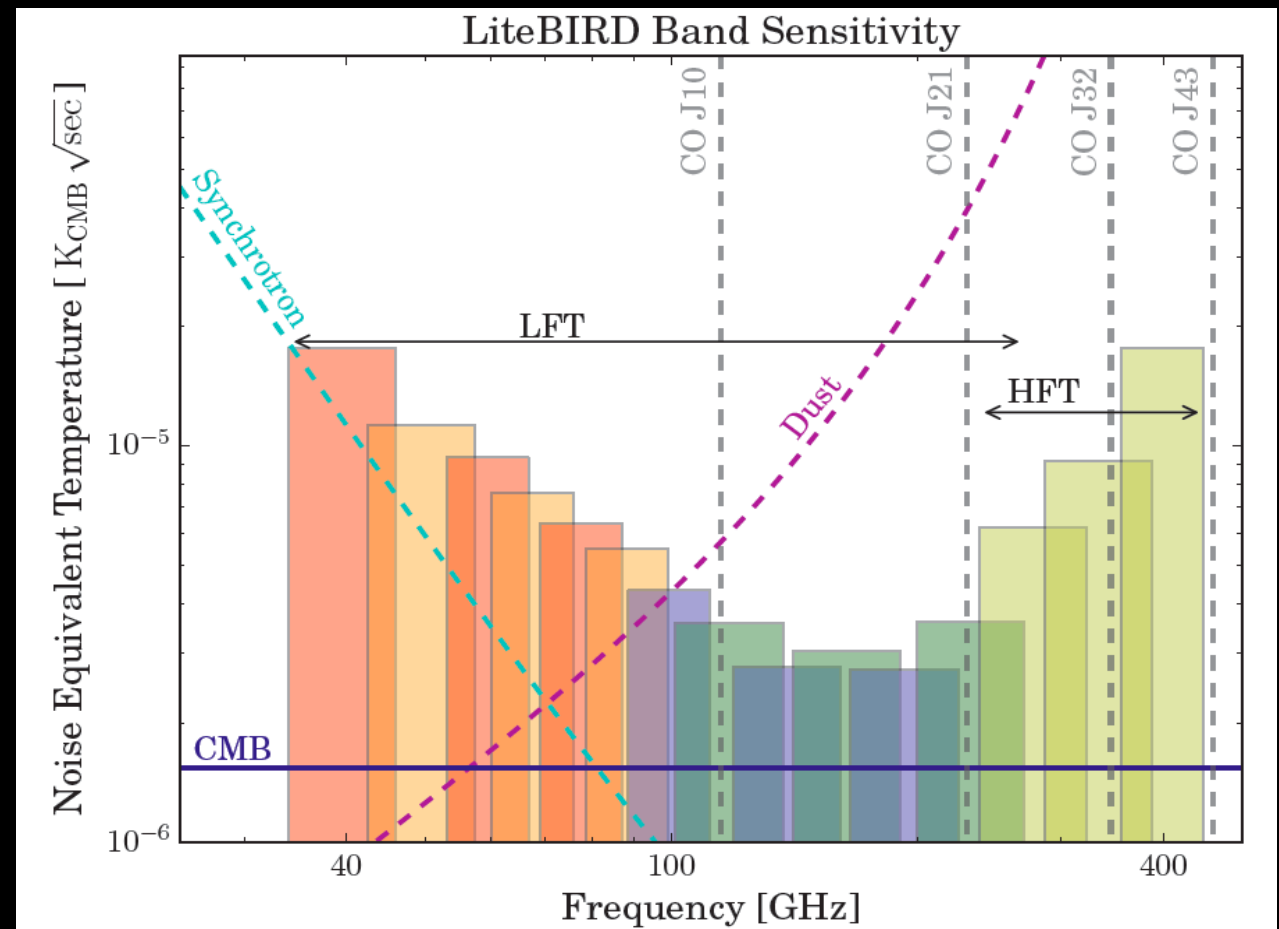
- Launch vehicle: **JAXA H3**
- Observation location: Second Lagrangian point (**L2**)
- Scan strategy: **Spin and precession, full sky**
- Observation duration: **3-years**
- Proposed launch date: **Mid 2020's**

Slide courtesy Toki Suzuki (Berkeley)

Foreground Removal



Polarized galactic emission (Planck X)



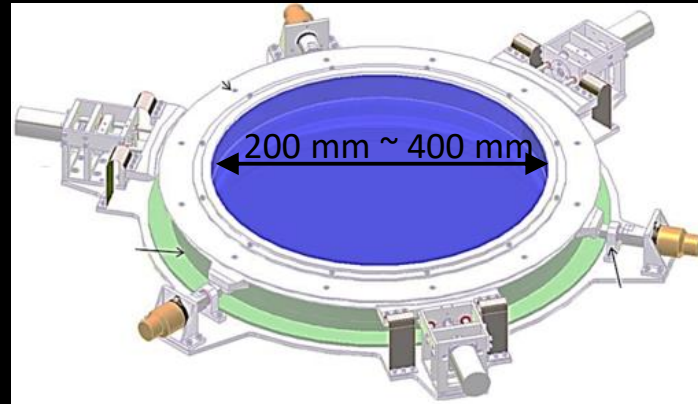
LiteBIRD: 15 frequency bands

- 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

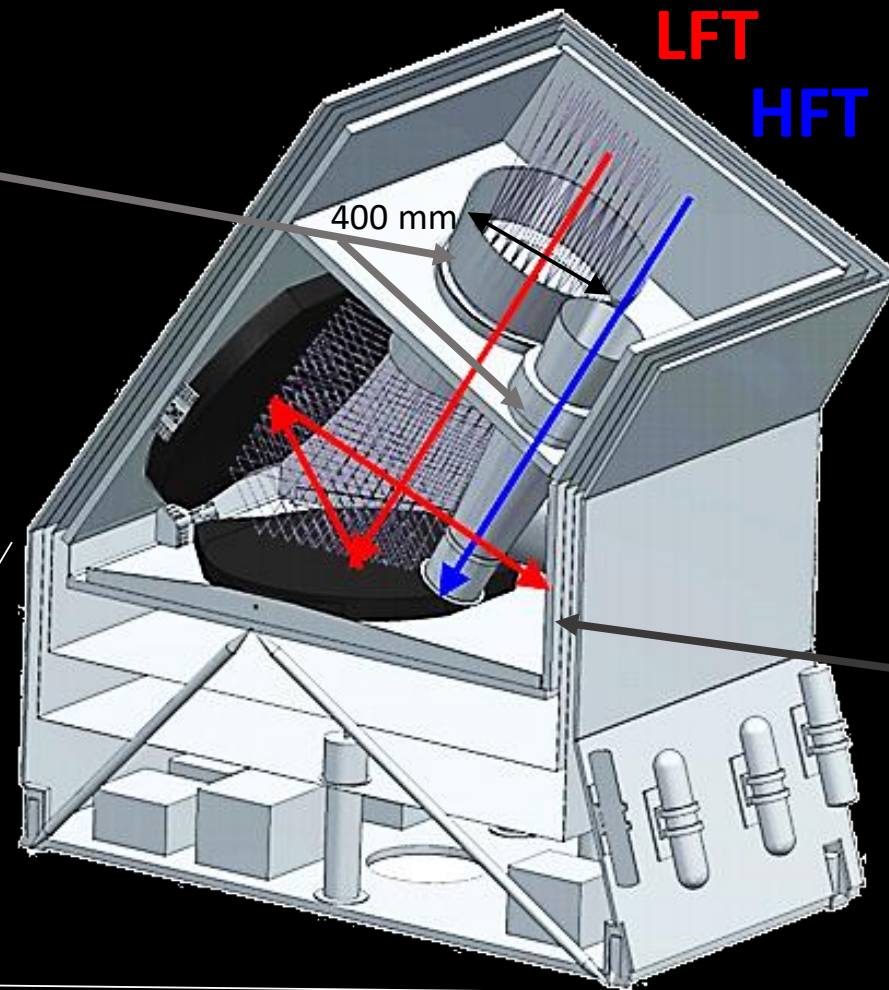
Slide courtesy Toki Suzuki (Berkeley)

Instrument Overview

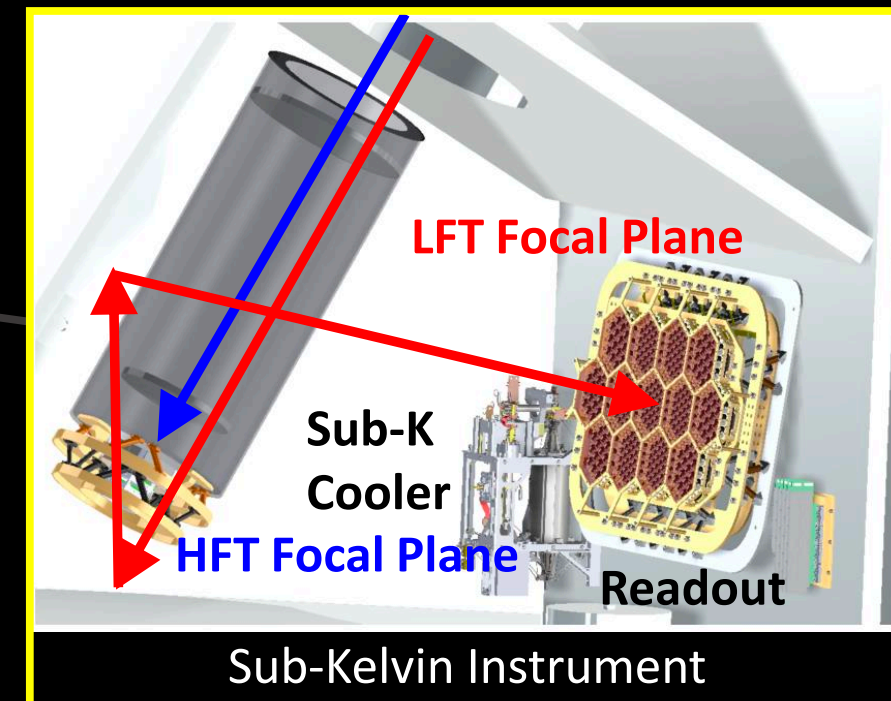
Slide courtesy Toki Suzuki (Berkeley)



Half-wave plate

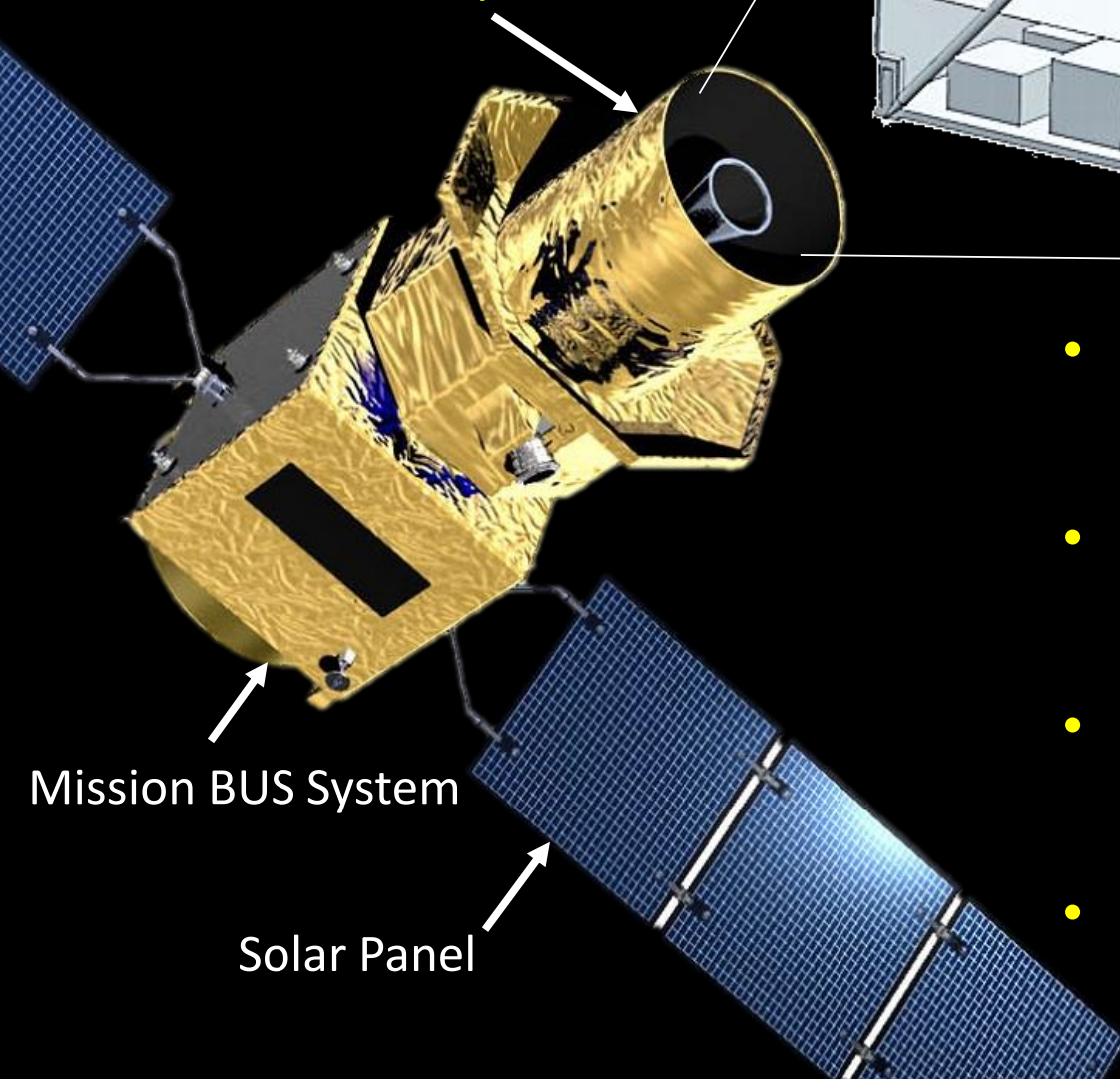


Stirling & Joule Thomson Coolers



Sub-Kelvin Instrument

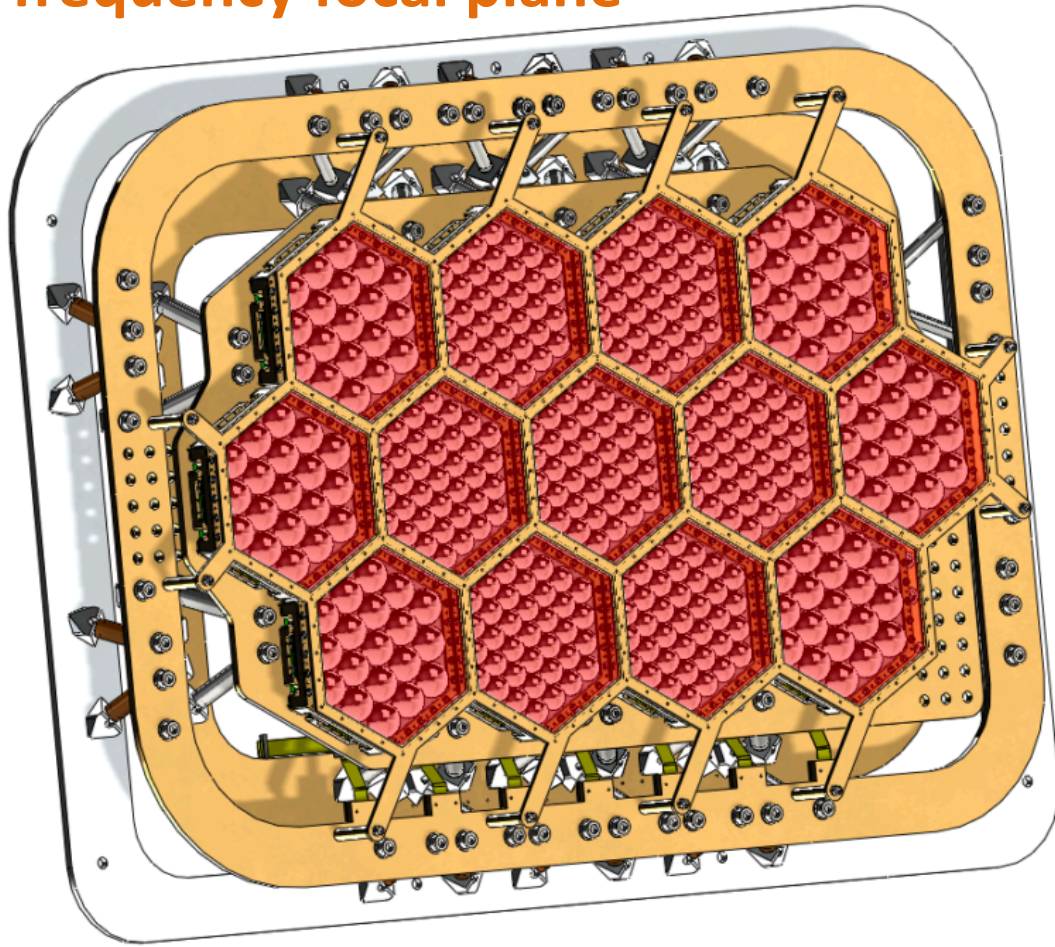
Cold Mission System



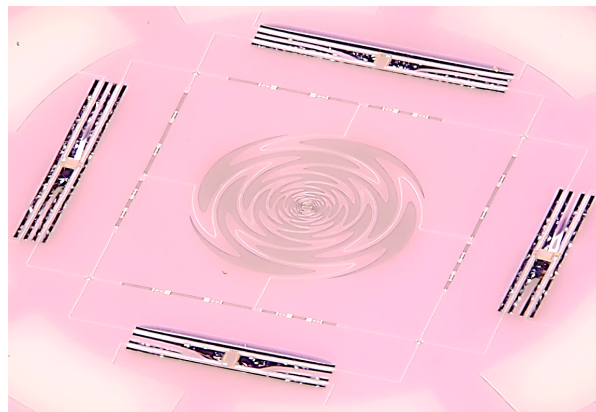
- Two telescopes
 - Crossed-Dragone (LFT) & on-axis refractor (HFT)
- Cryogenic rotating achromatic half-wave plate
 - Modulates polarization signal
- Stirling & Joule Thomson coolers
 - Provide cooling power above 2 Kelvin
- Sub-Kelvin Instrument
 - Detectors, readout electronics, and a sub-kelvin cooler

LFT and HFT focal plane units using TES

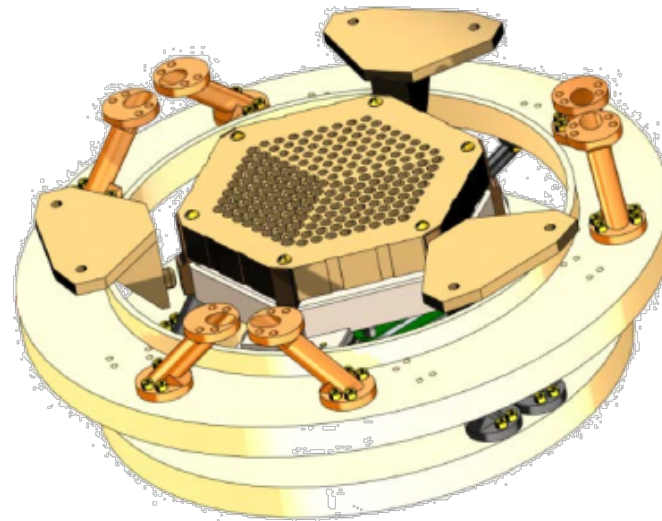
Low frequency focal plane



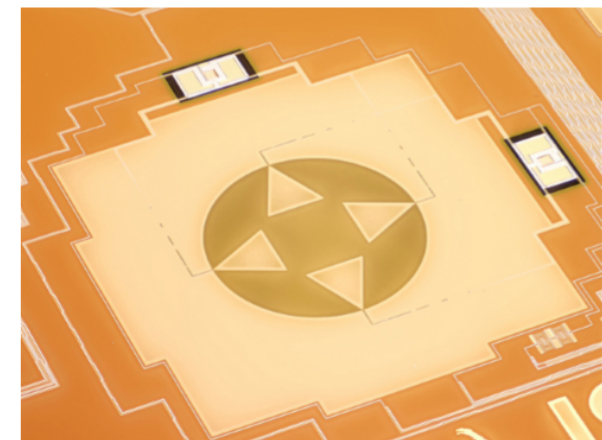
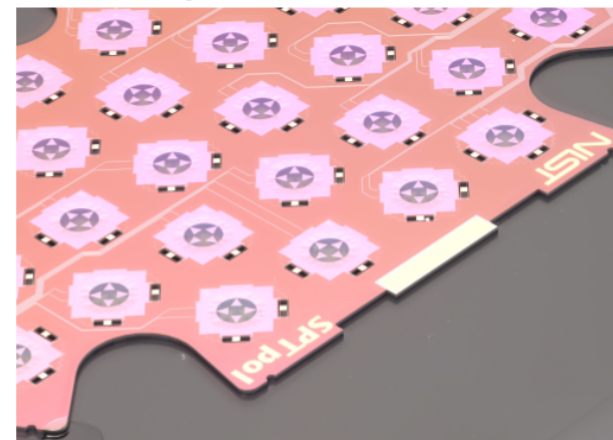
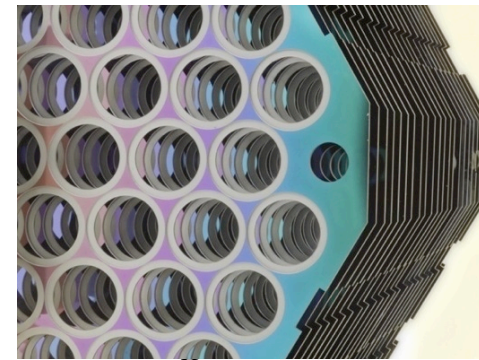
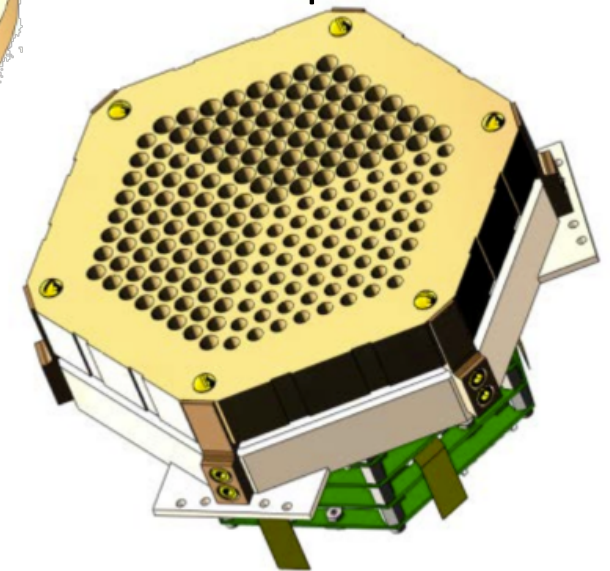
Three colors per pixel with a lenslet coupling.



High frequency focal plane



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



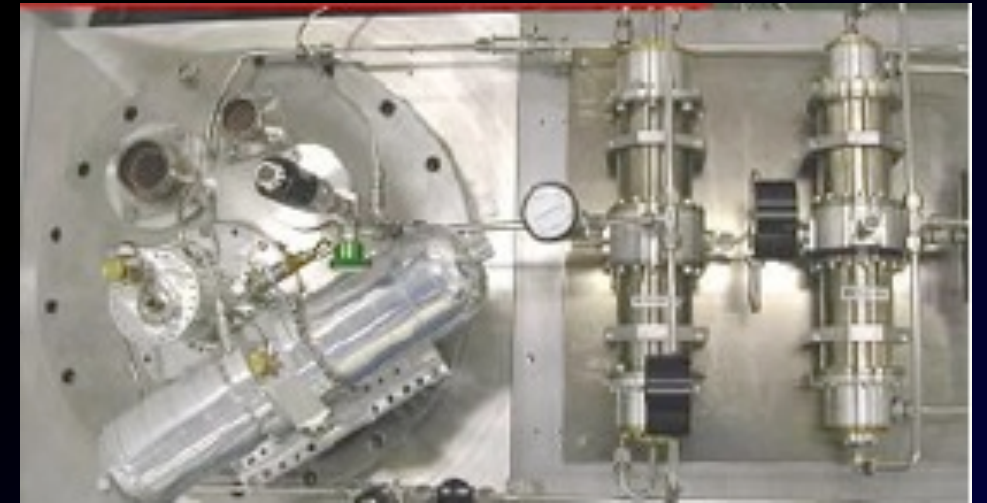
- The current baseline design uses a single ADR to cool the both focal planes.
- The LF focal plane has ** TESs and the HF focal plane has ** TESs.
- The TES is read by SQUID together with the readout electronics is based on the digital frequency multiplexing system.
- The effect of the cosmic ray is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

Slide courtesy Tomo Matsumura (Kavli IPMU)

Cooling system

Cryogenics

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



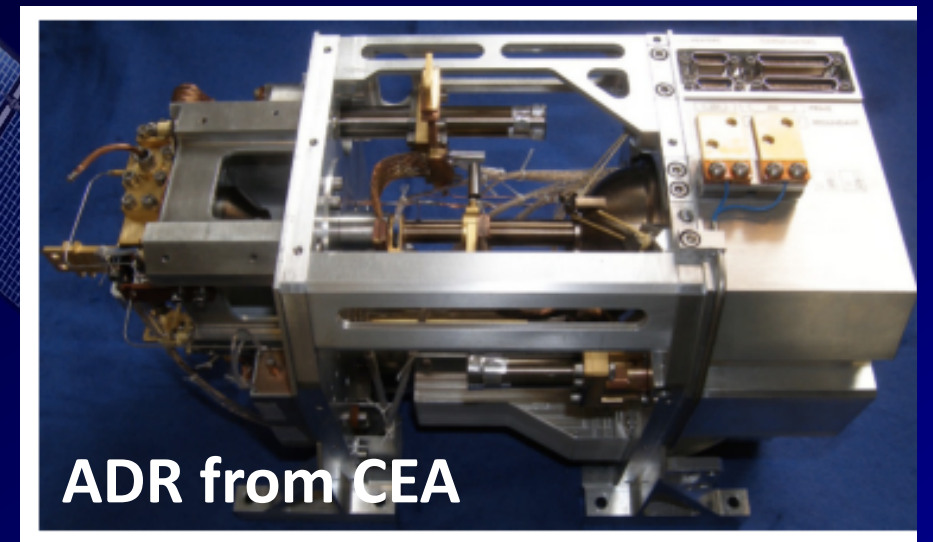
SHI/JAXA

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

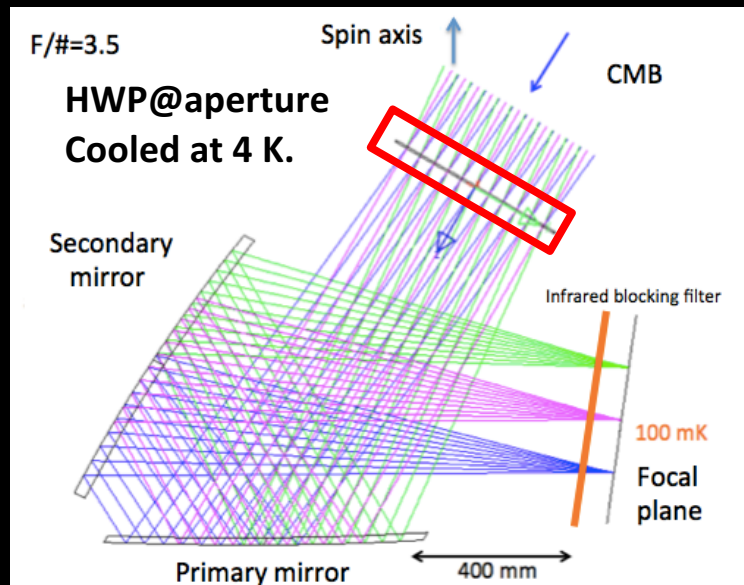
- ADR has a high-TRL and extensive development toward **Astro-H**, **SPICA**, and **Athena**.
- Closed dilution with the Planck heritage is also under development.



ADR from CEA

Slide courtesy Tomo Matsumura (Kavli IPMU)

Polarization modulator



- Due to our focus on the primordial signal at low ℓ , 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

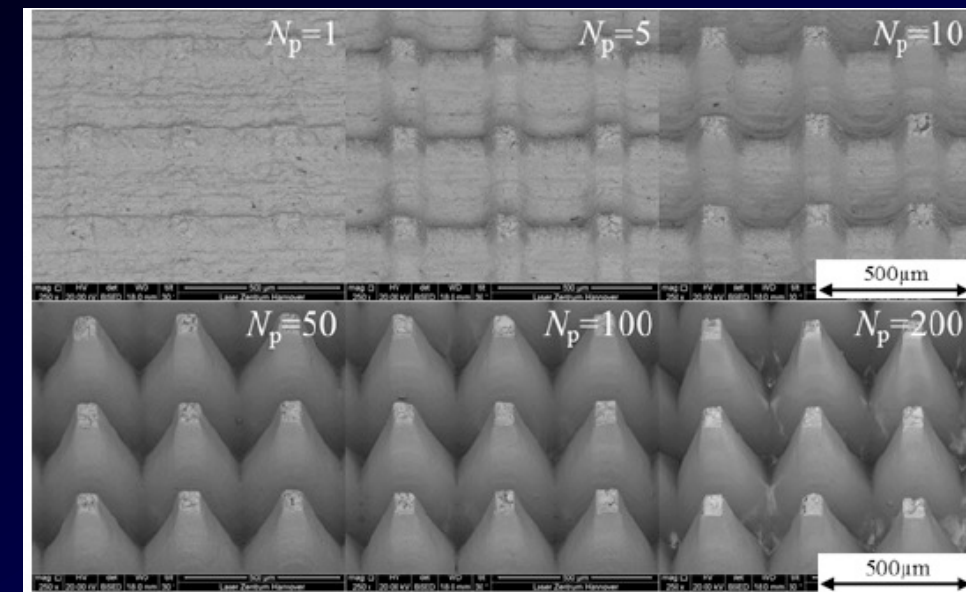
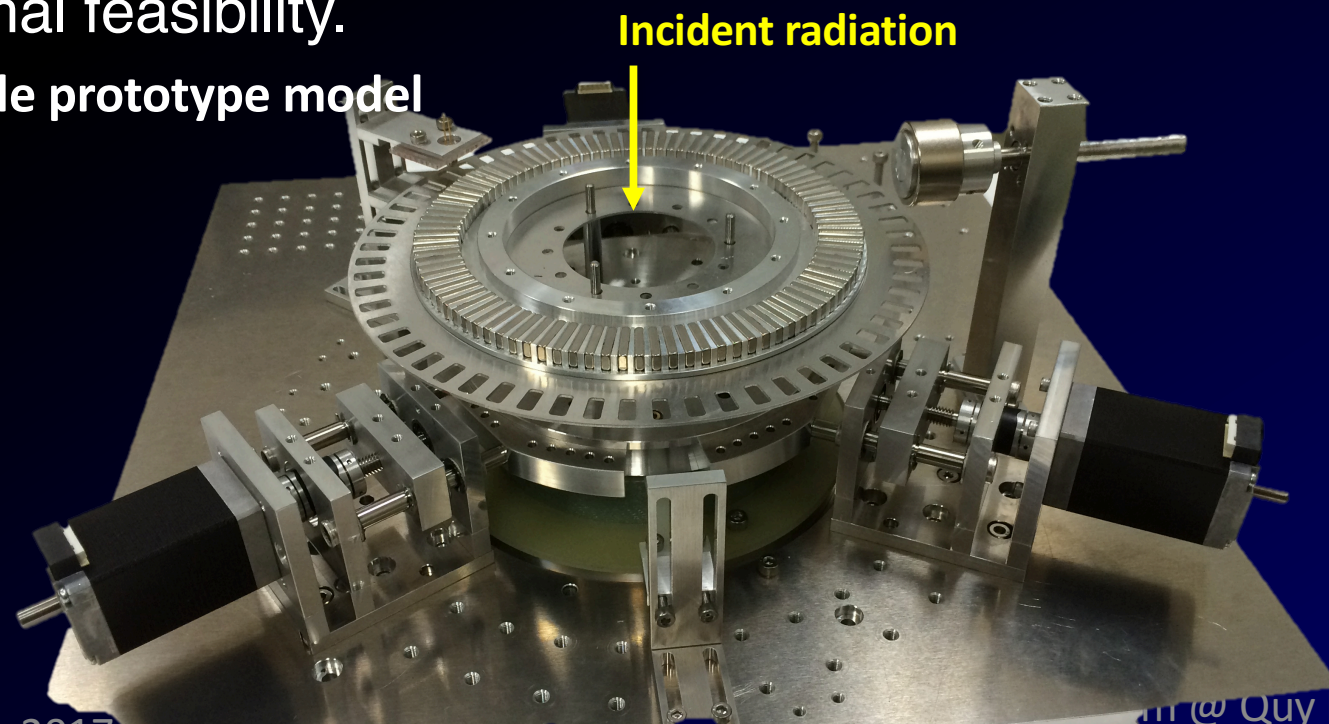
- The broadband coverage is done by the sub-wavelength anti-reflection structure.
- The broadband modulation efficiency is achieved by using 9-layer achromatic HWP.

Note: we also employ the polarization modulator for HFT.

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.



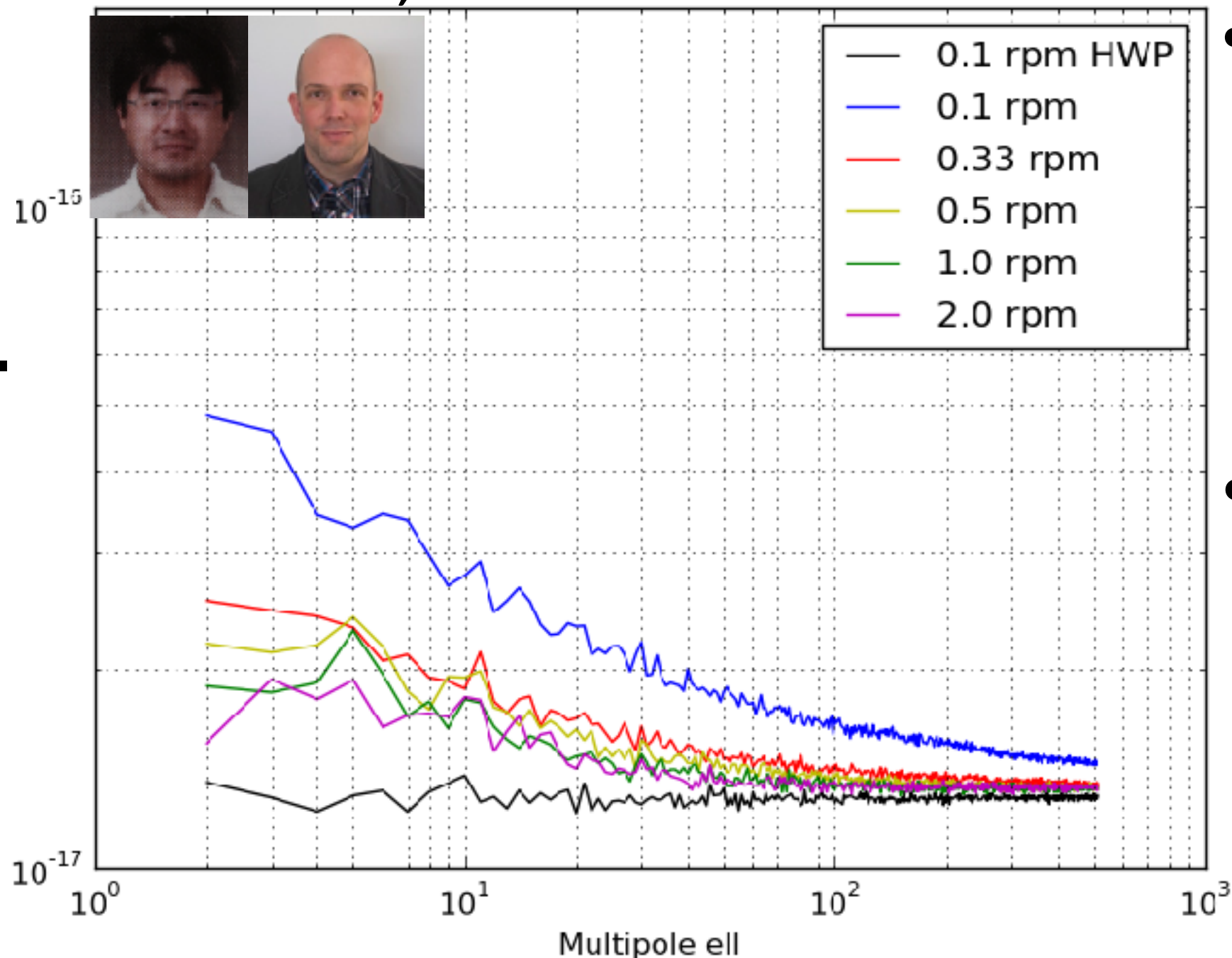
**MOVING
PARTS??!!**

You are a moron...

We need it for a critical reason: mitigation of $1/f$ noise

S. Uozumi, T. Kisner

BB Power Spectrum

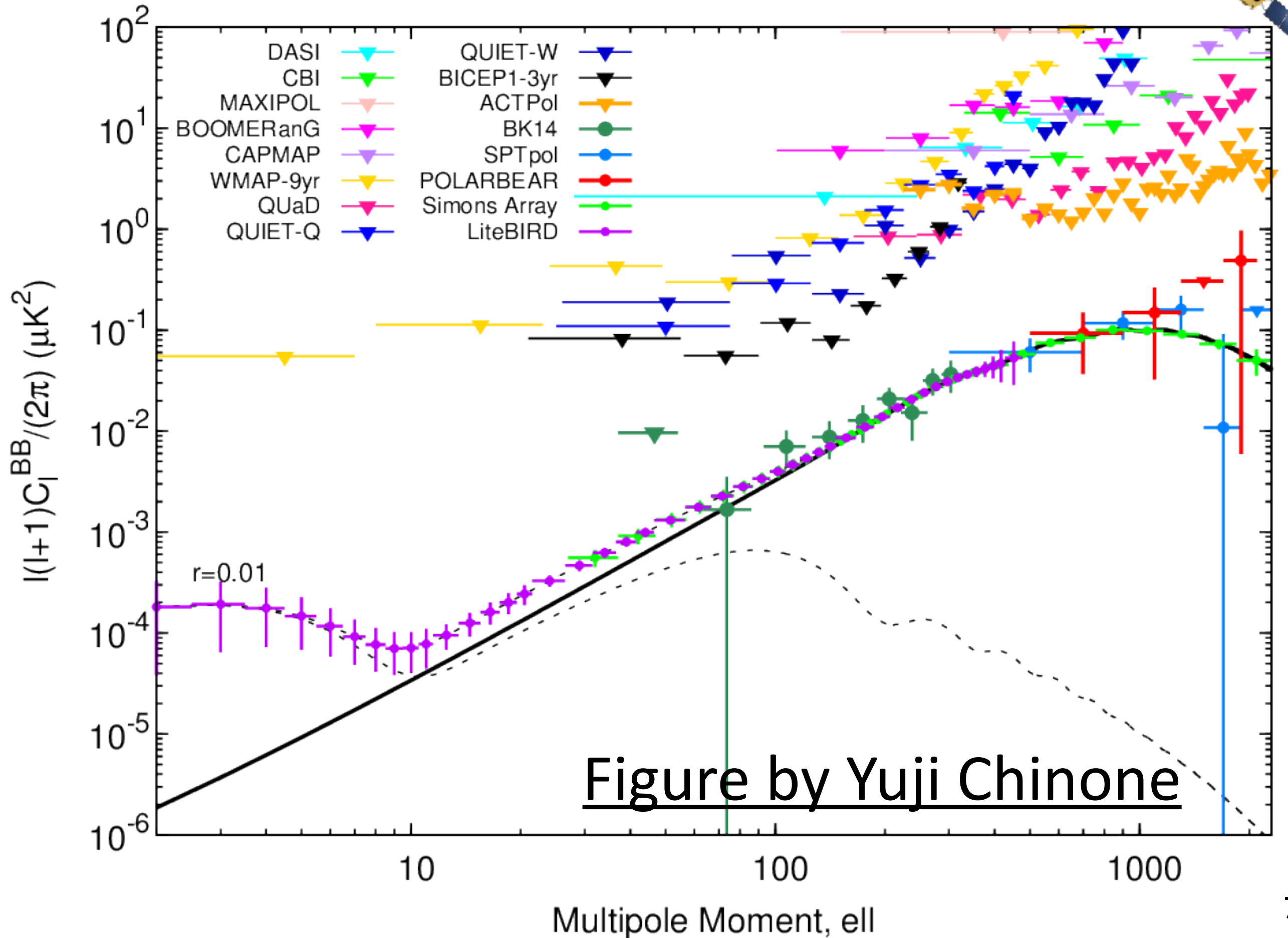
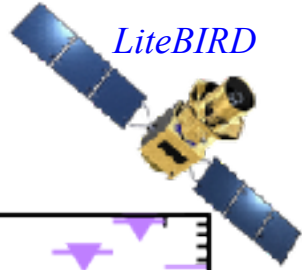


- Scan only cannot reduce the $1/f$ noise to a sufficient level
- We really need a rotating HWP to modulate the input sky signal to a higher frequency

Summary

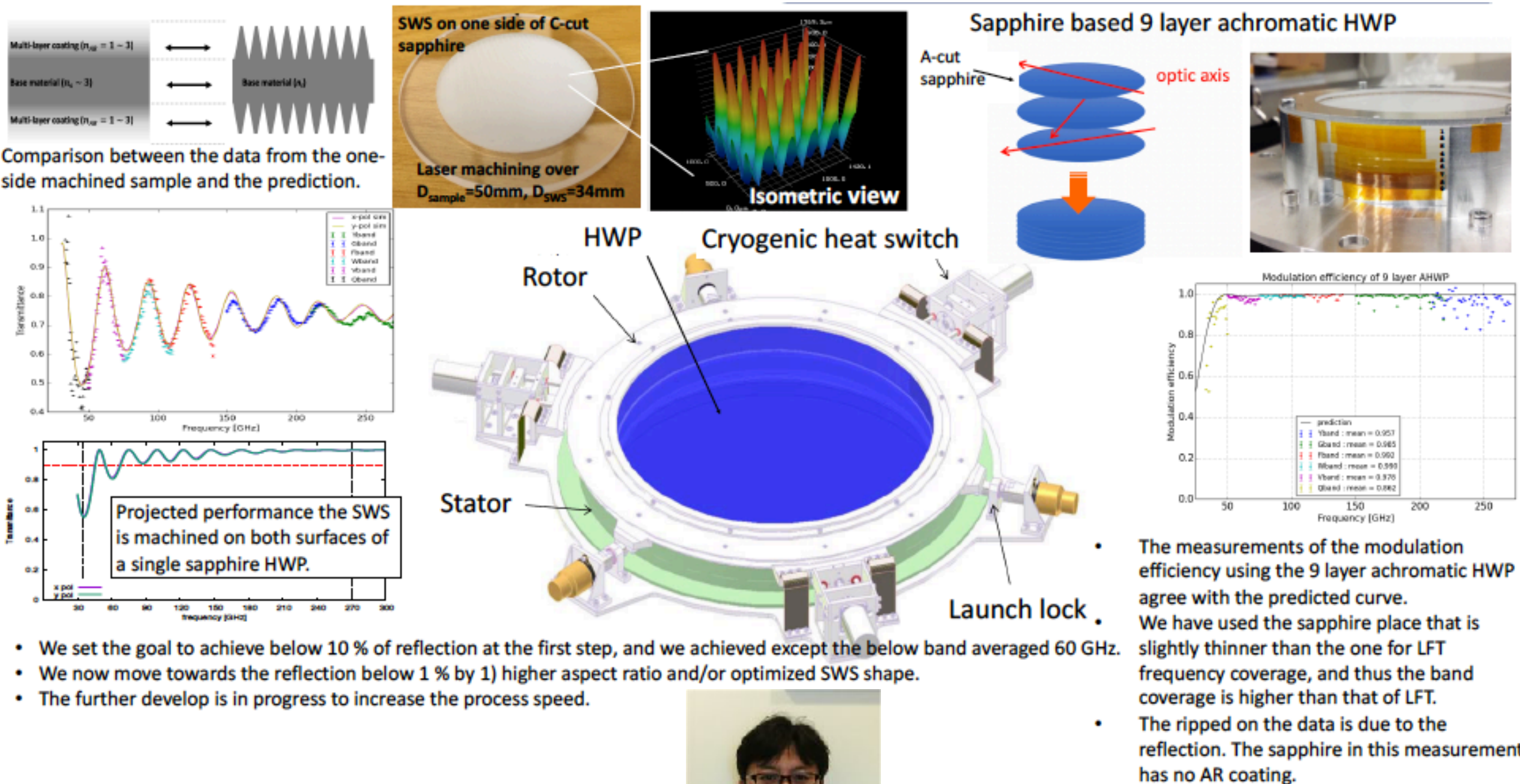
- Single-field inflation looks good: all the CMB data support it
- **Next frontier**: Using CMB polarisation to find GWs from inflation. **Definitive evidence for inflation!**
- With LiteBIRD we plan to reach $r \sim 10^{-3}$, i.e., 100 times better than the current bound
- GW from vacuum or sources?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

B-mode power spectrum measurements



Polarization Modulator

broadband AR coating and polarization modulation efficiency



from LTD17 poster (T. Matsumura et al.)

