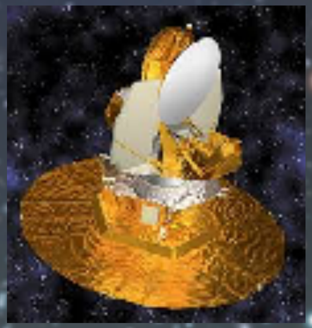
LiteBIRD

2025–

[proposed to JAXA; now in Phase A1]

1989–1993



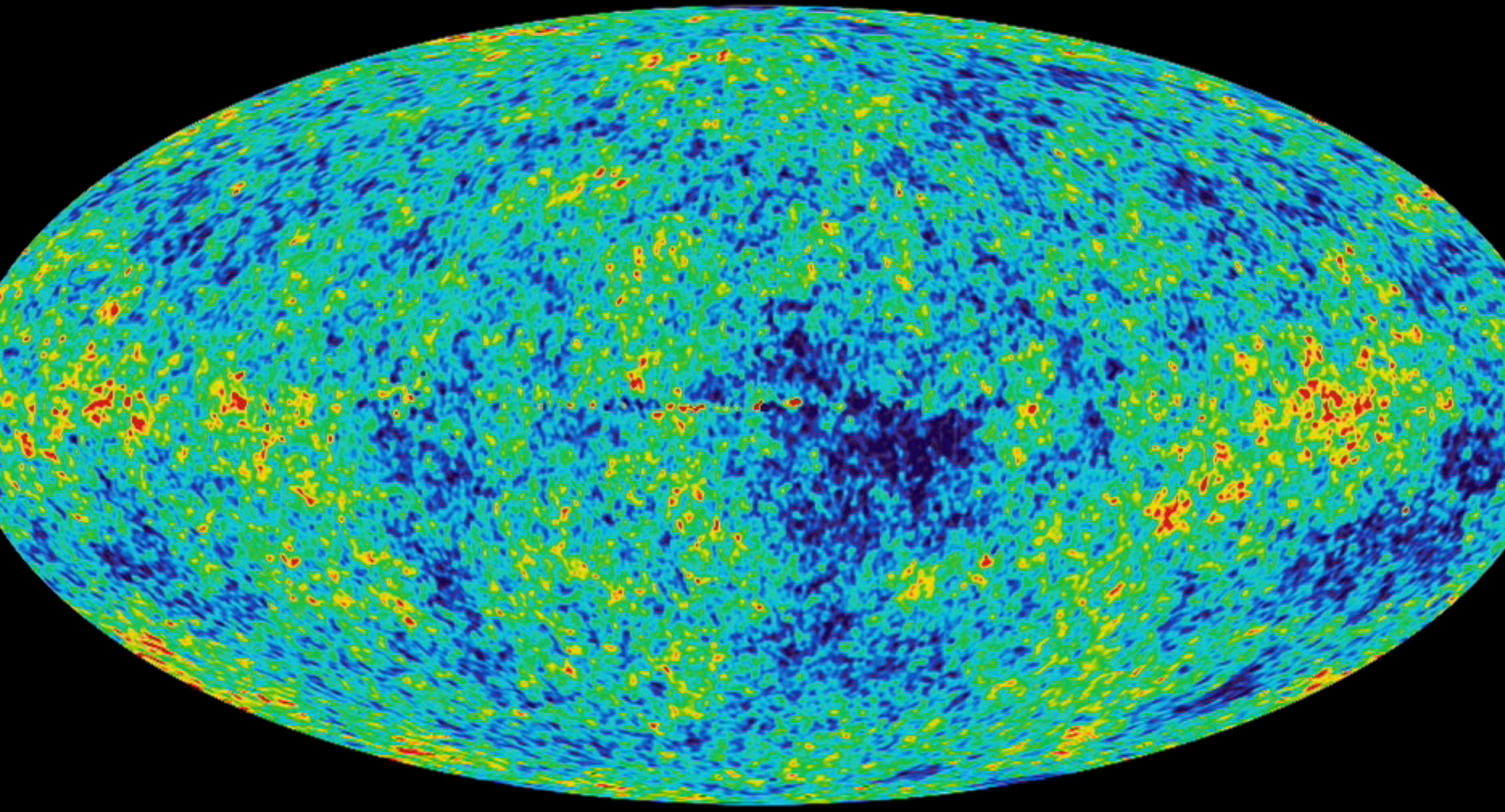
2001–2010

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

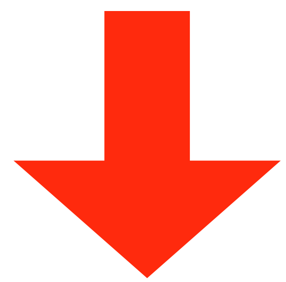
- Quantum mechanics at work in the early Universe
  - "*We all came from quantum fluctuations*"
- But, how did quantum fluctuations on the *microscopic* scales become *macroscopic* fluctuations over large distances?
  - What is the **missing link** between small and large scales?

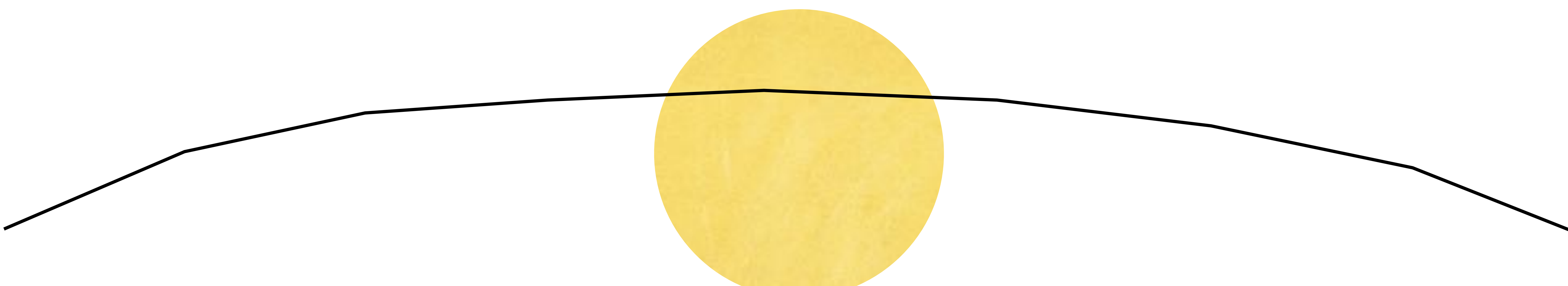
Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

Quantum fluctuations on microscopic scales

Inflation!





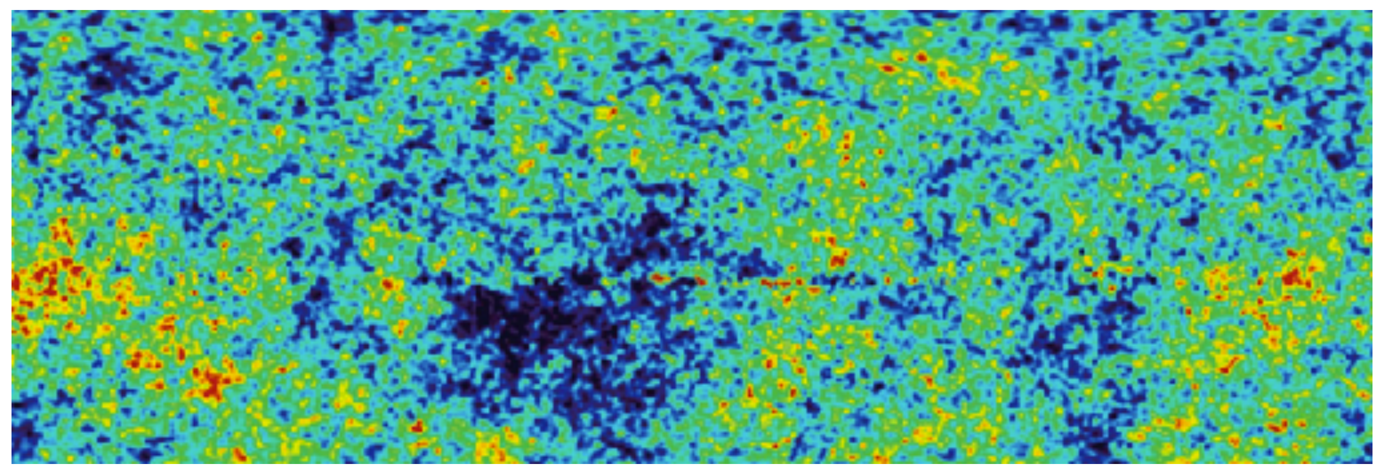
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

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

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

scale factor

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

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

Finding Inflation

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

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

- 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

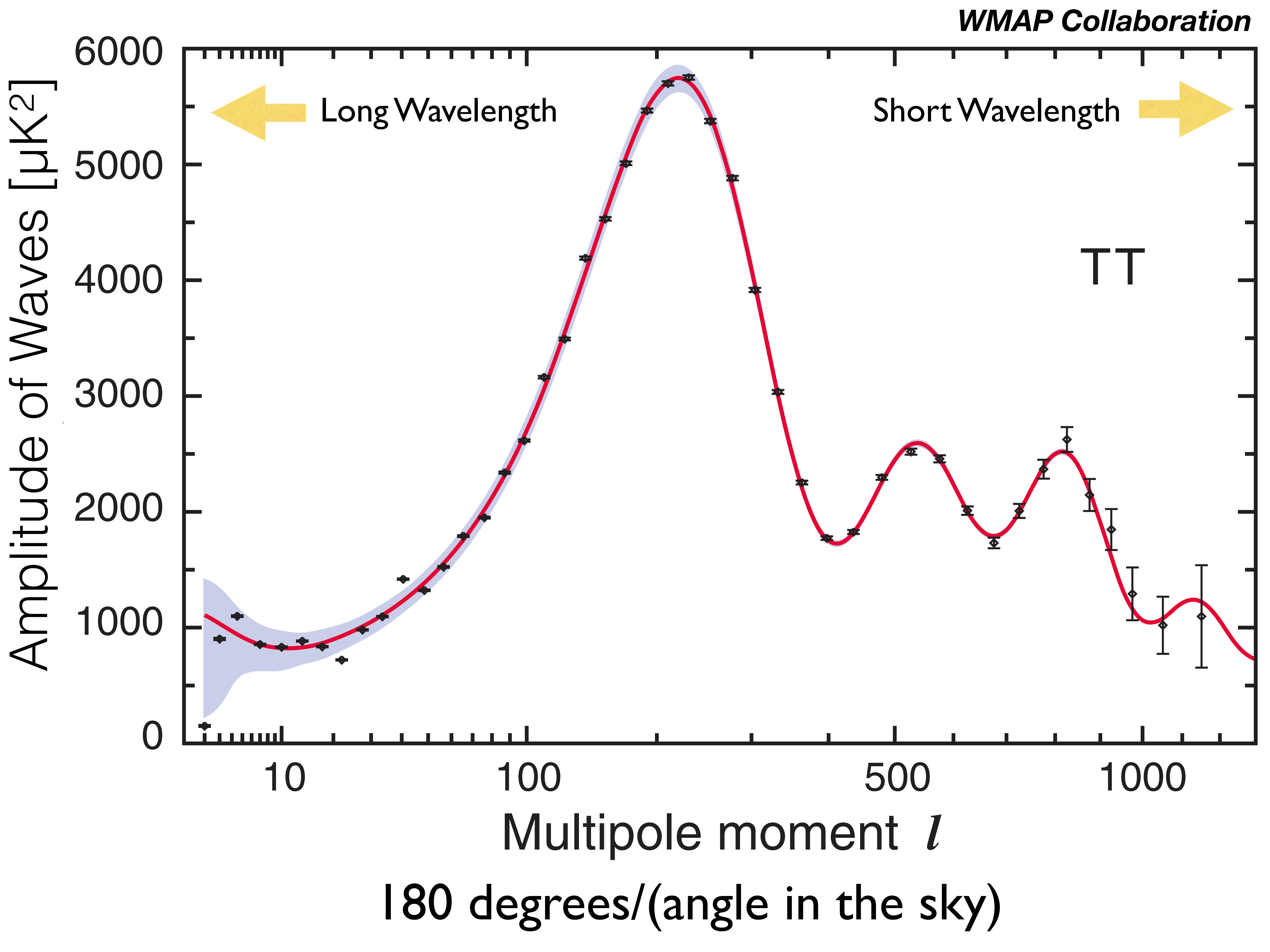
- **Both scalar (ζ) and tensor (h_{ij}) perturbations are proportional to H**
  - Consequence of the uncertainty principle
  - [energy you can borrow] ~ [time you borrow]$^{-1}$ ~ H
  - **KEY**: The earlier the fluctuations are generated, the more its wavelength is stretched, and thus the bigger the 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

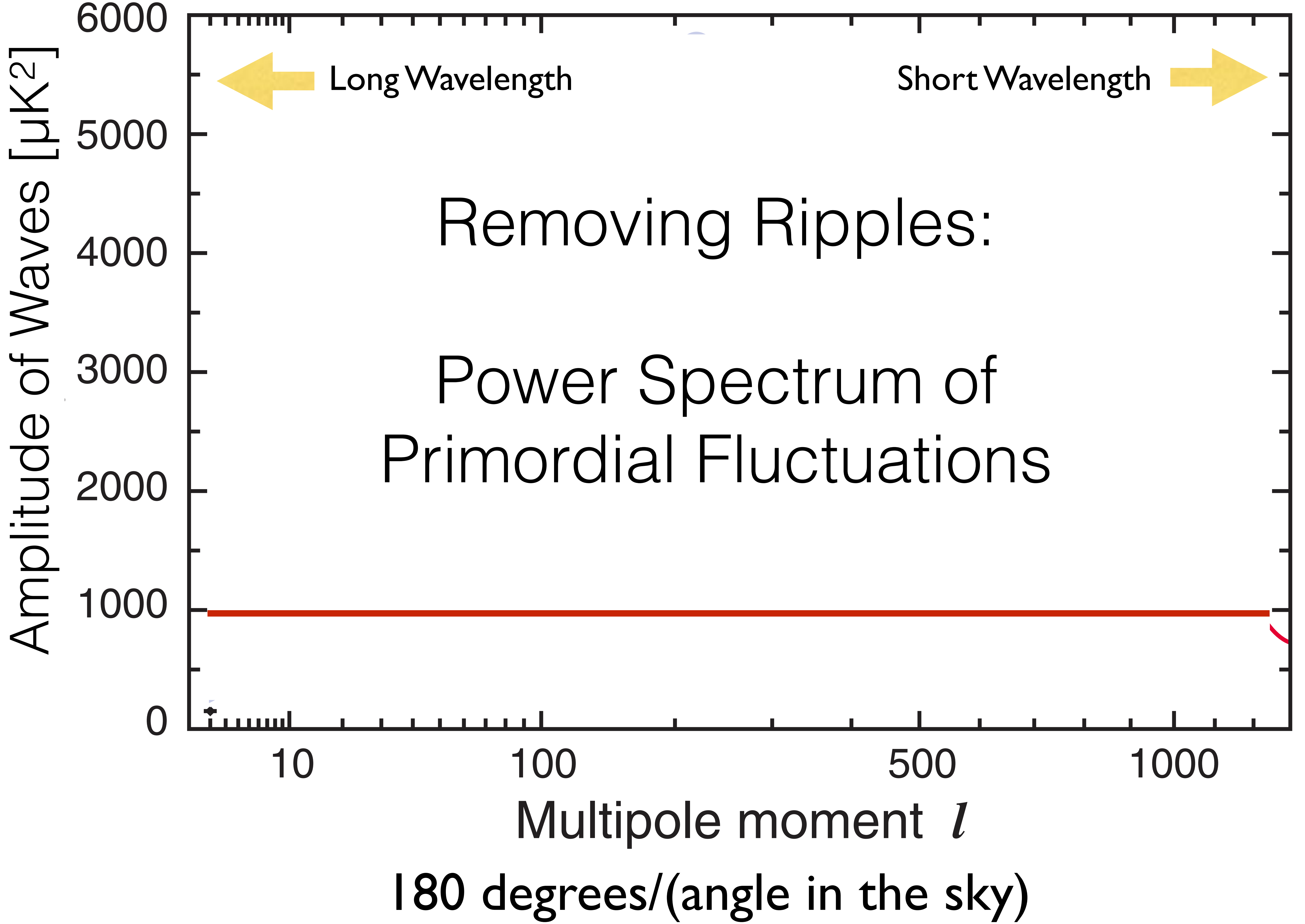
- **We can map H(t) by measuring CMB fluctuations over a wide range of angles**

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

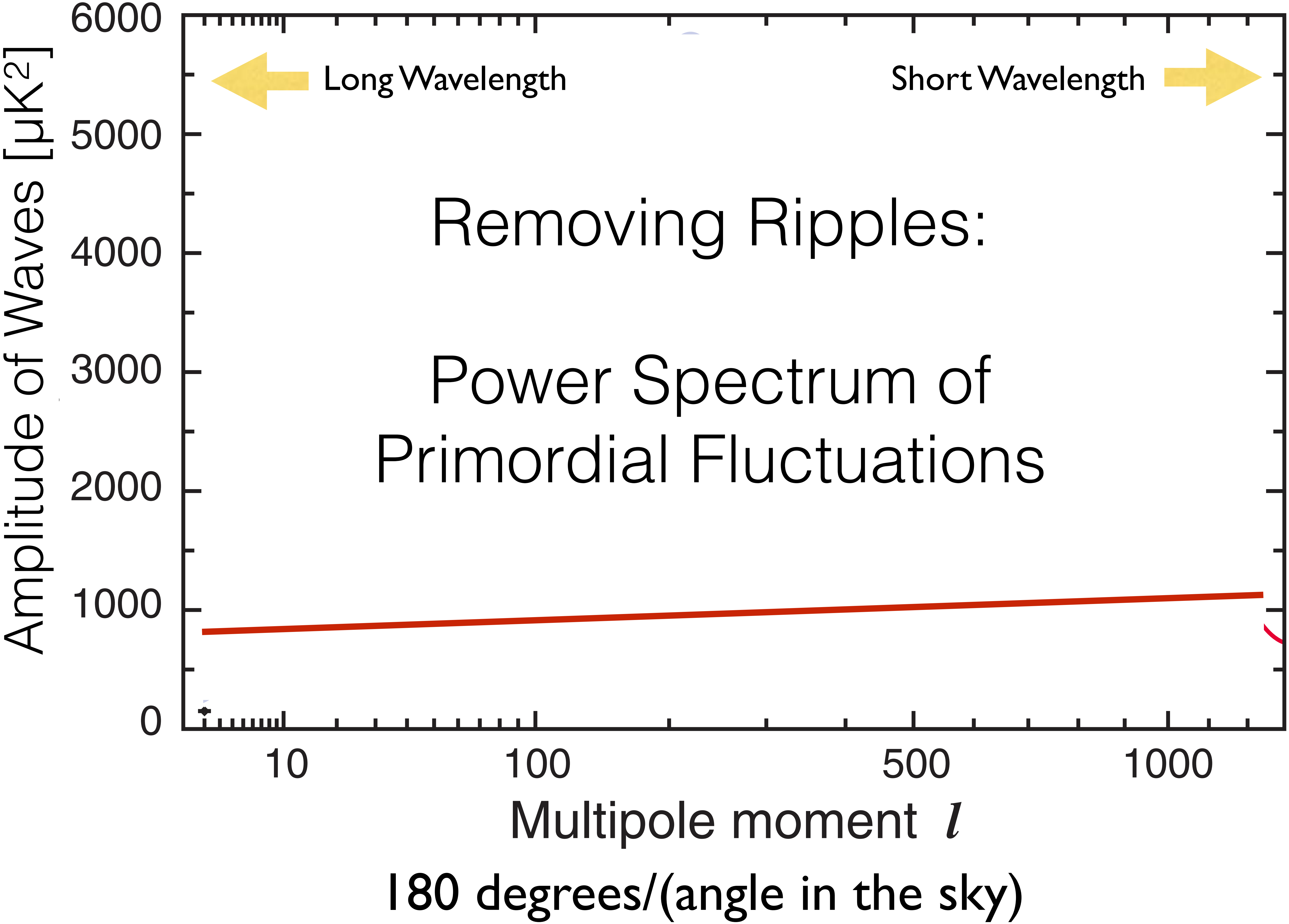
2. Moreover, since inflation must end, H would be a decreasing function of time. It would be fantastic to show that the amplitude of CMB fluctuations actually DOES depend on angles such that the small scale has ***slightly*** smaller power



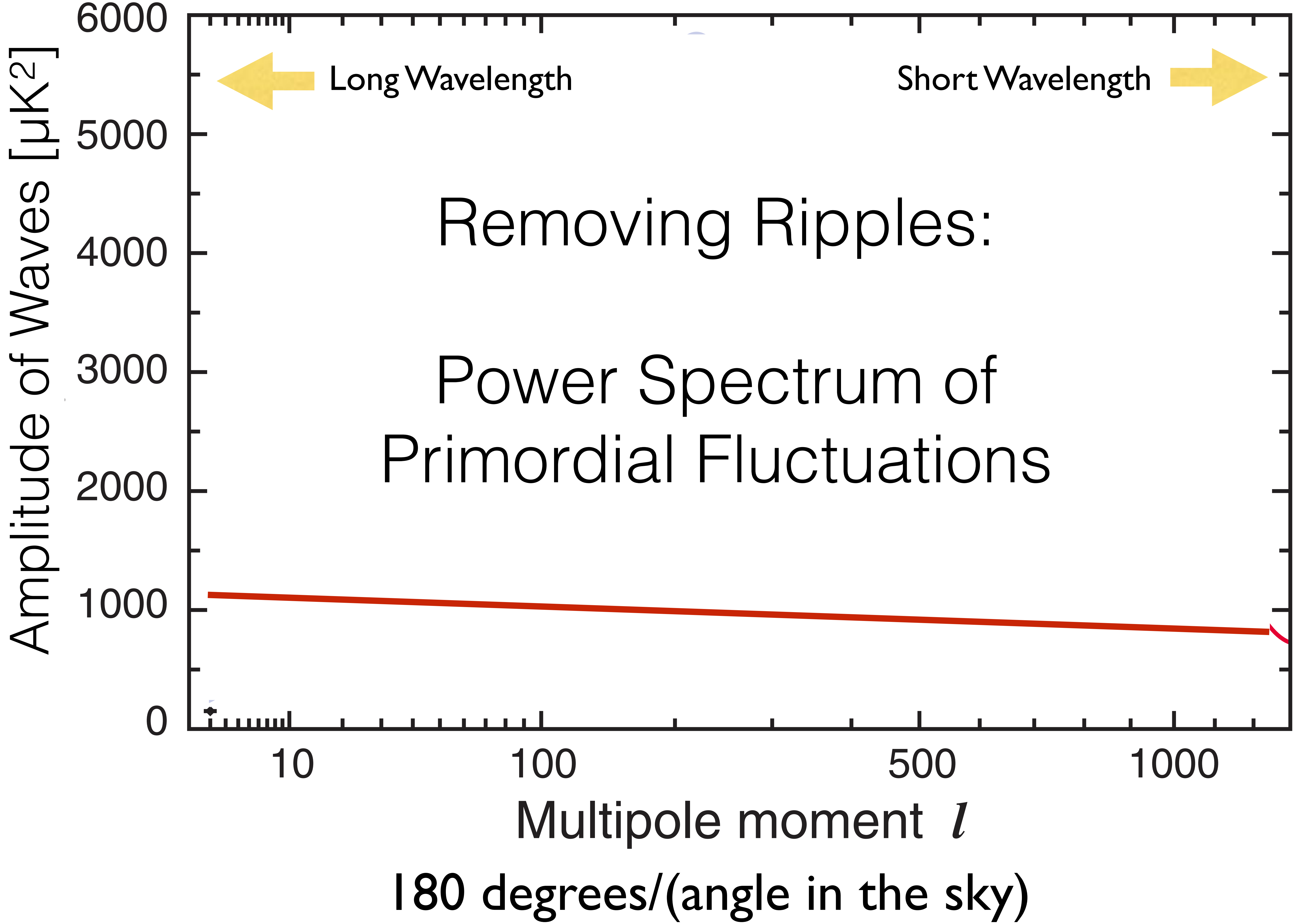
WMAP Collaboration
Long Wavelength
Short Wavelength
TT
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



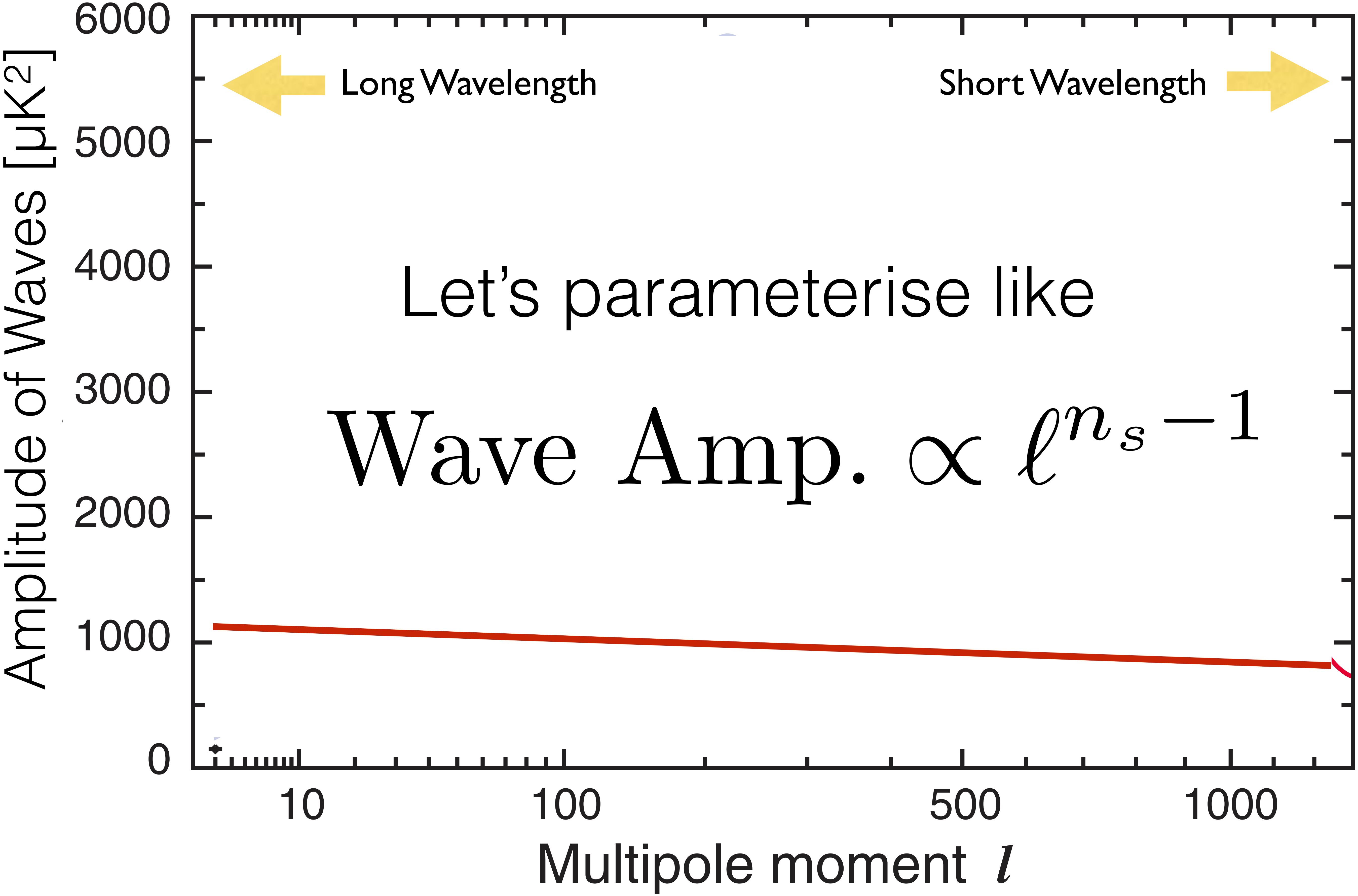
Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



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)



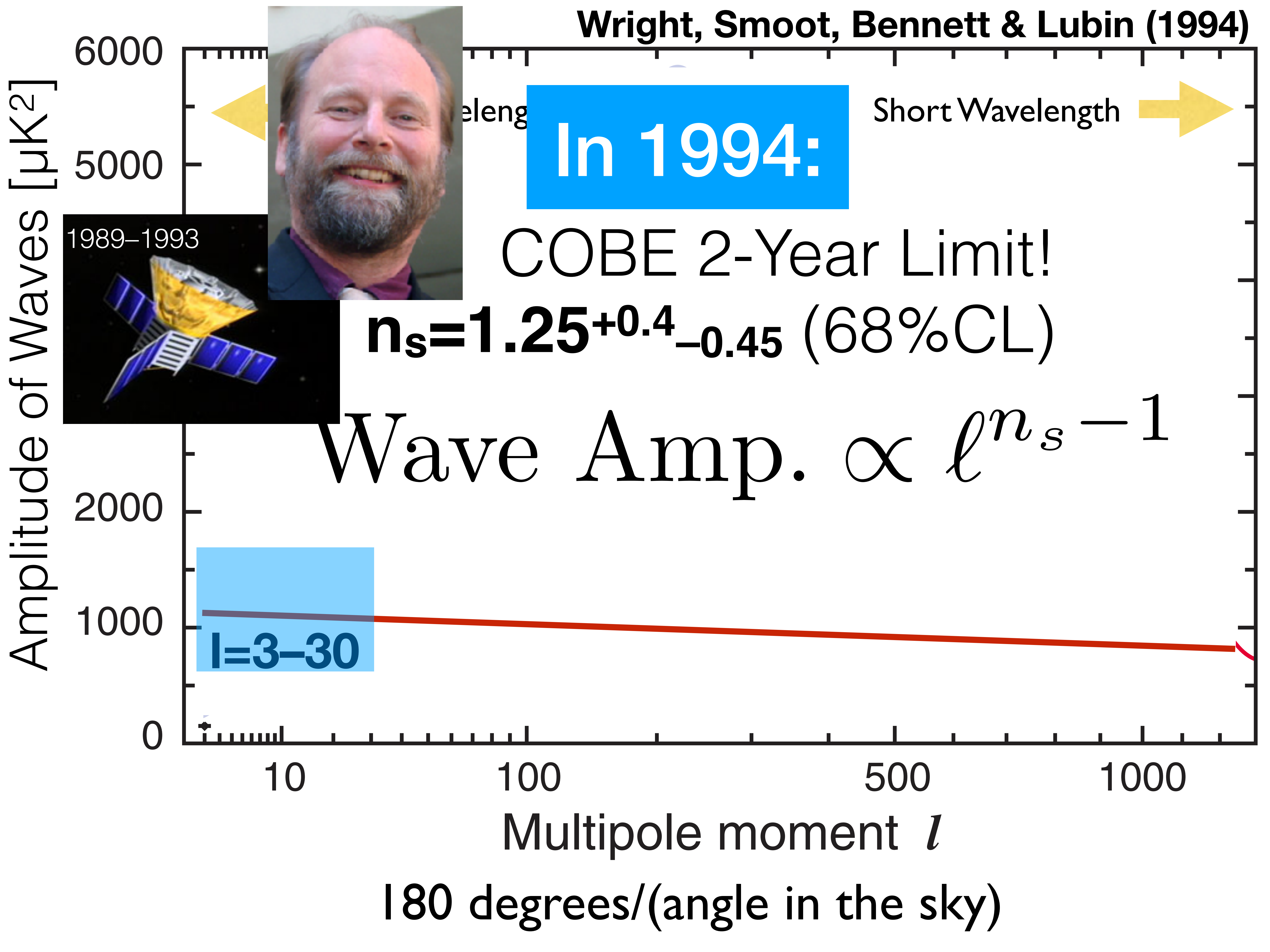
Removing Ripples:
Power Spectrum of Primordial Fluctuations
Long Wavelength
Short Wavelength
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

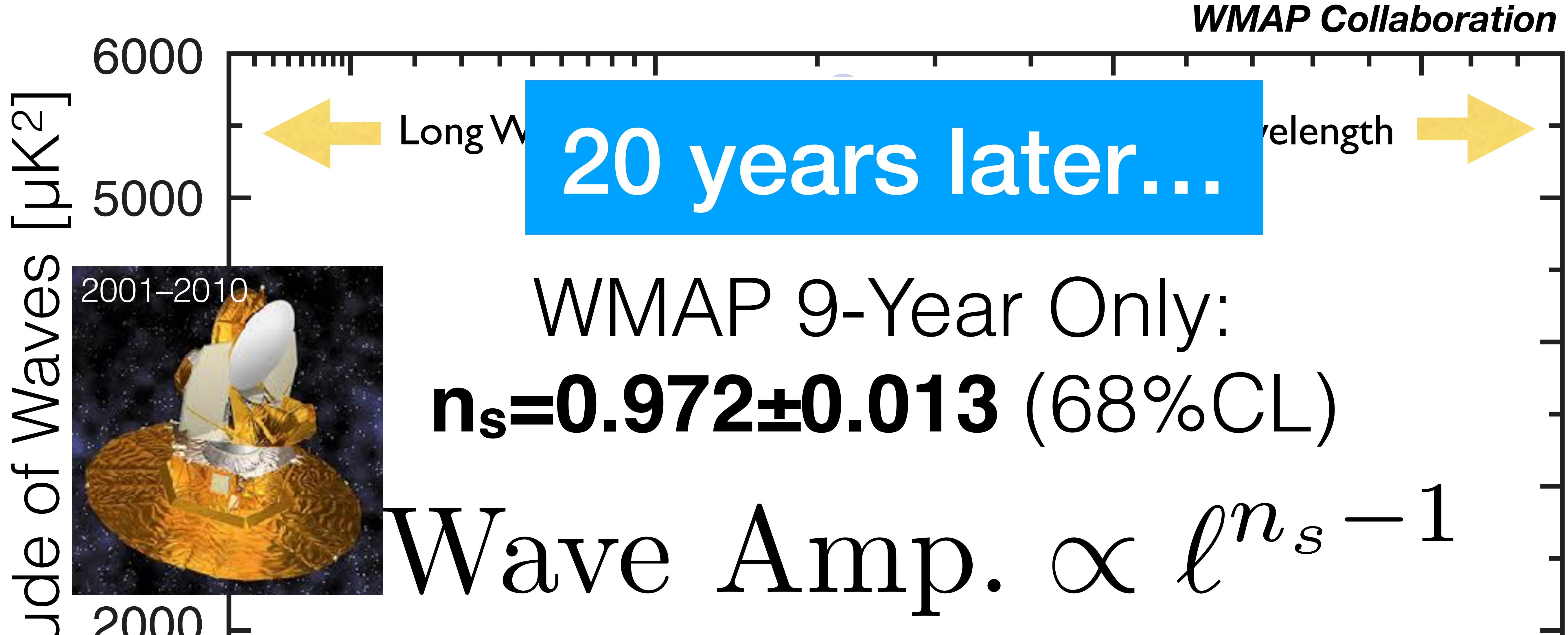


Let's parameterise like

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

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)
$\text{Wave Amp.} \propto \ell^{n_s-1}$
1989–1993
Short Wavelength
l=3–30
6000
5000
2000
1000
0
Amplitude of Waves [μK²]
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

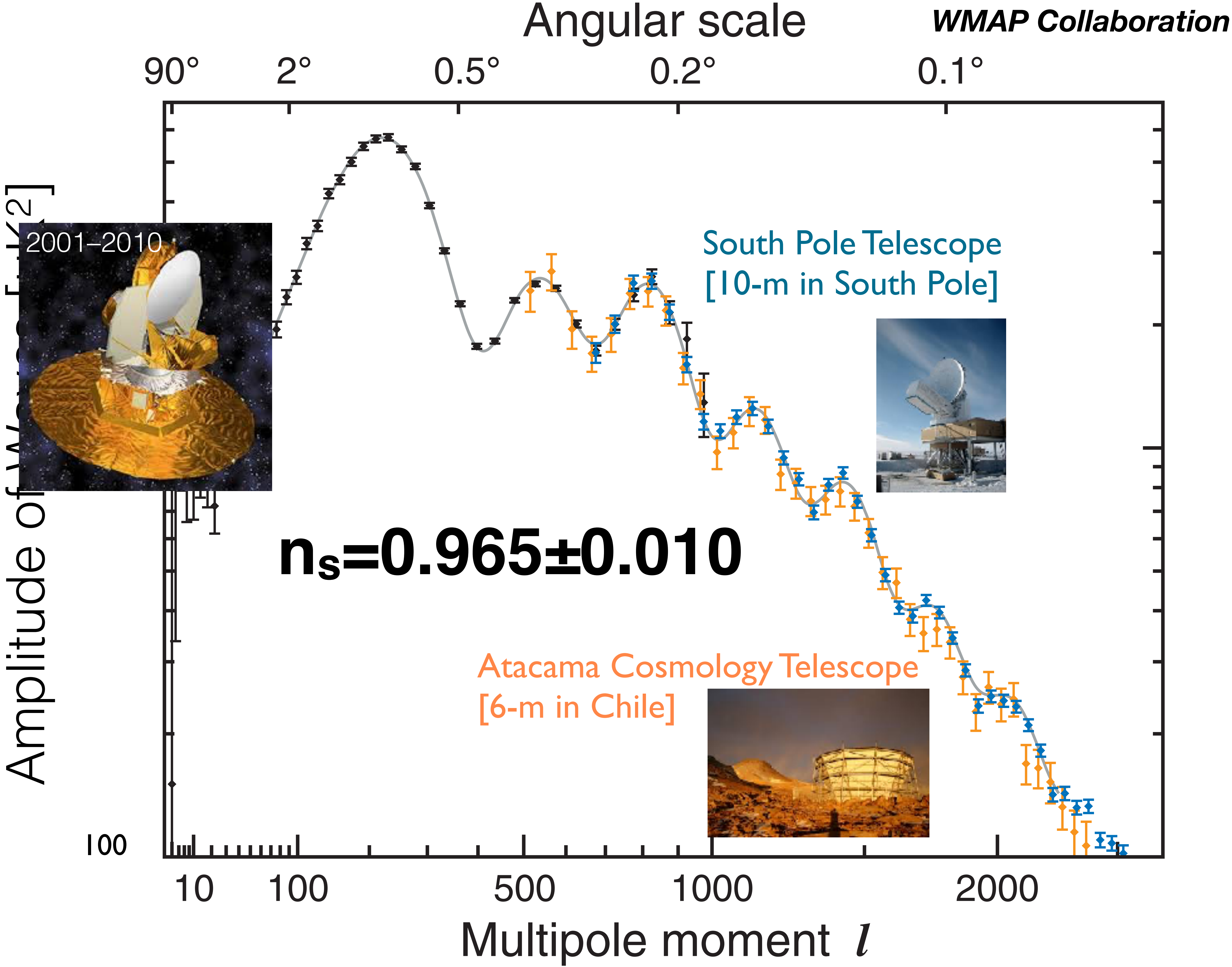


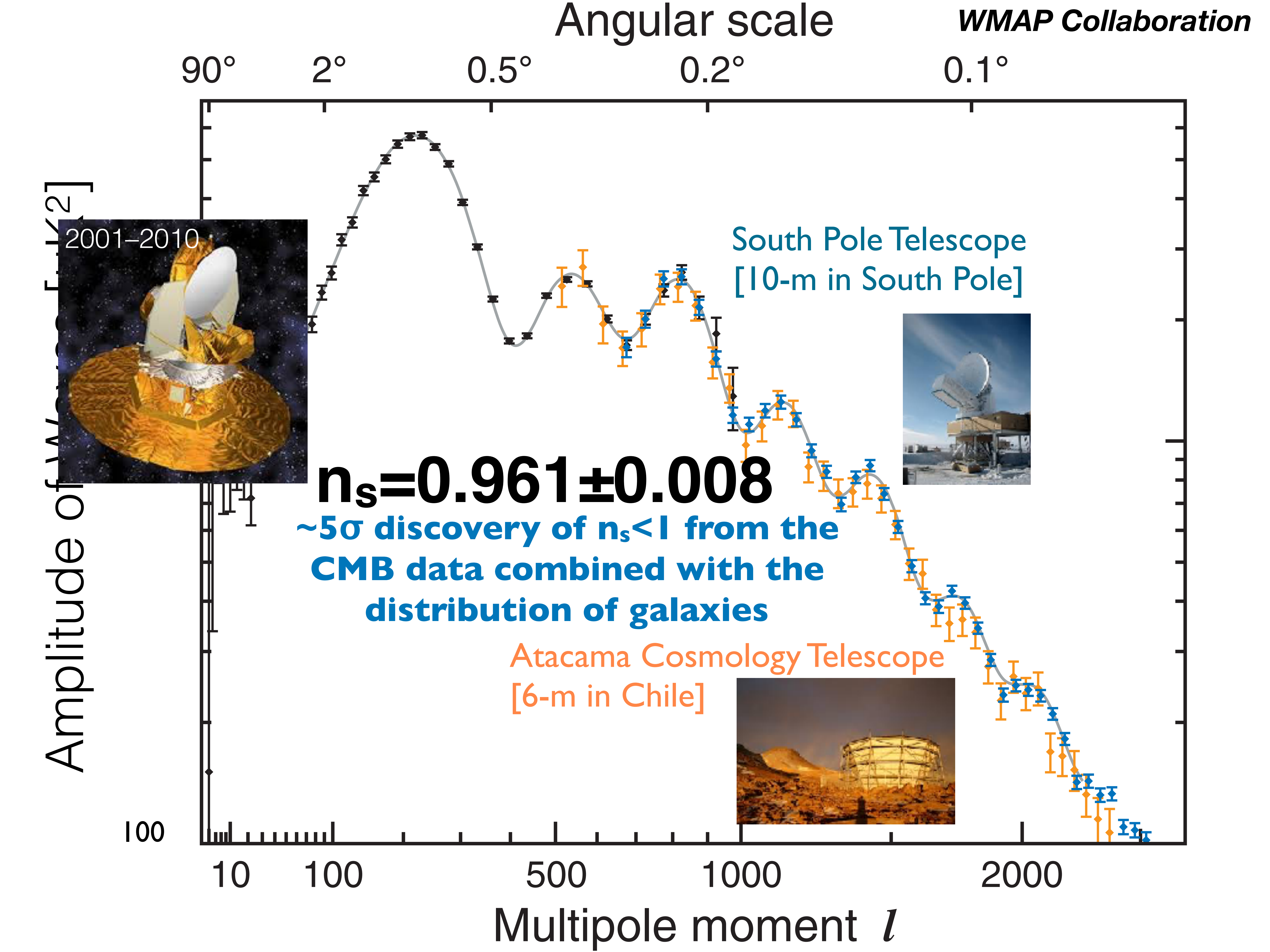
20 years later…

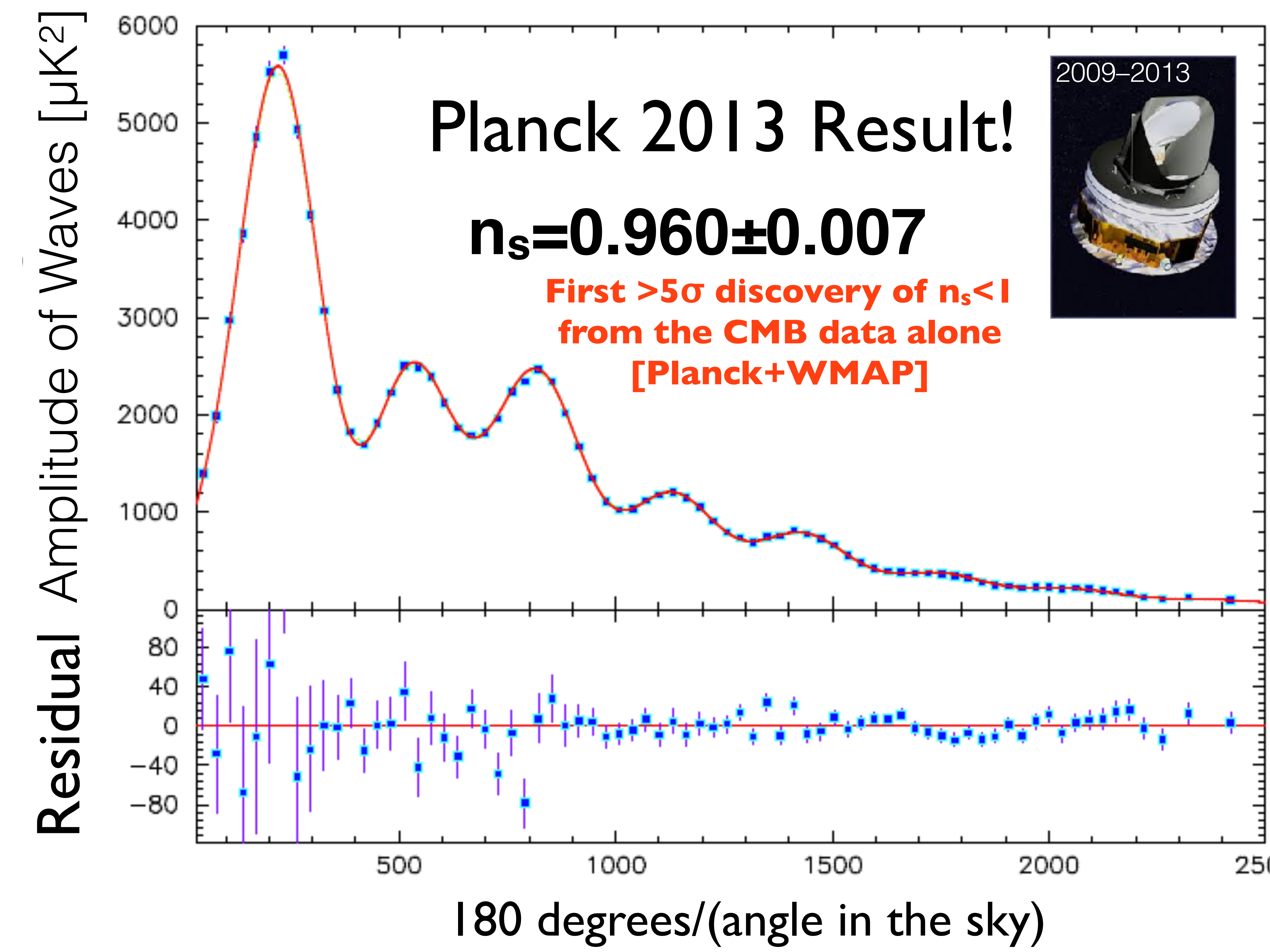
WMAP 9-Year Only:

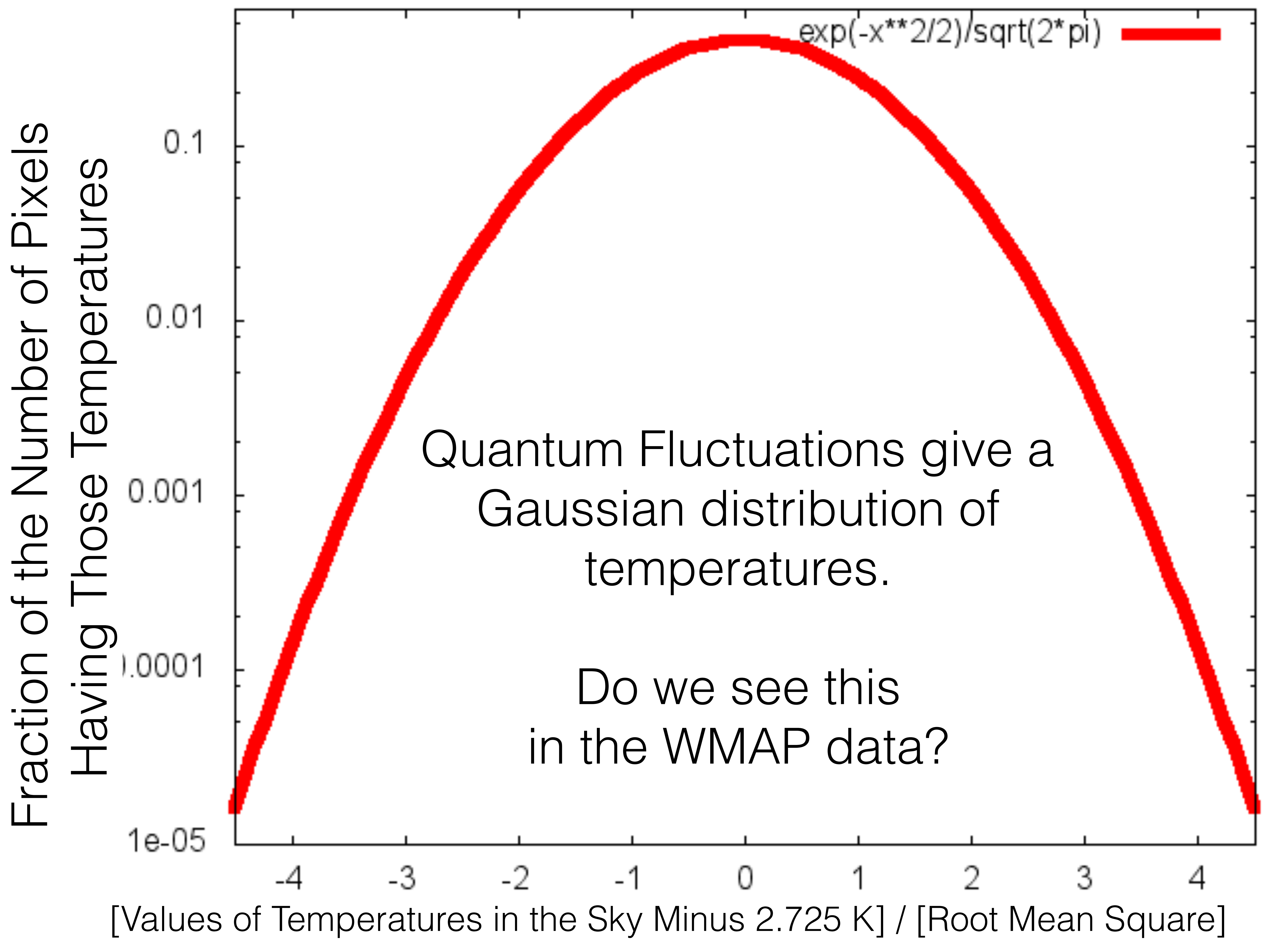
n_s=0.972±0.013 (68%CL)

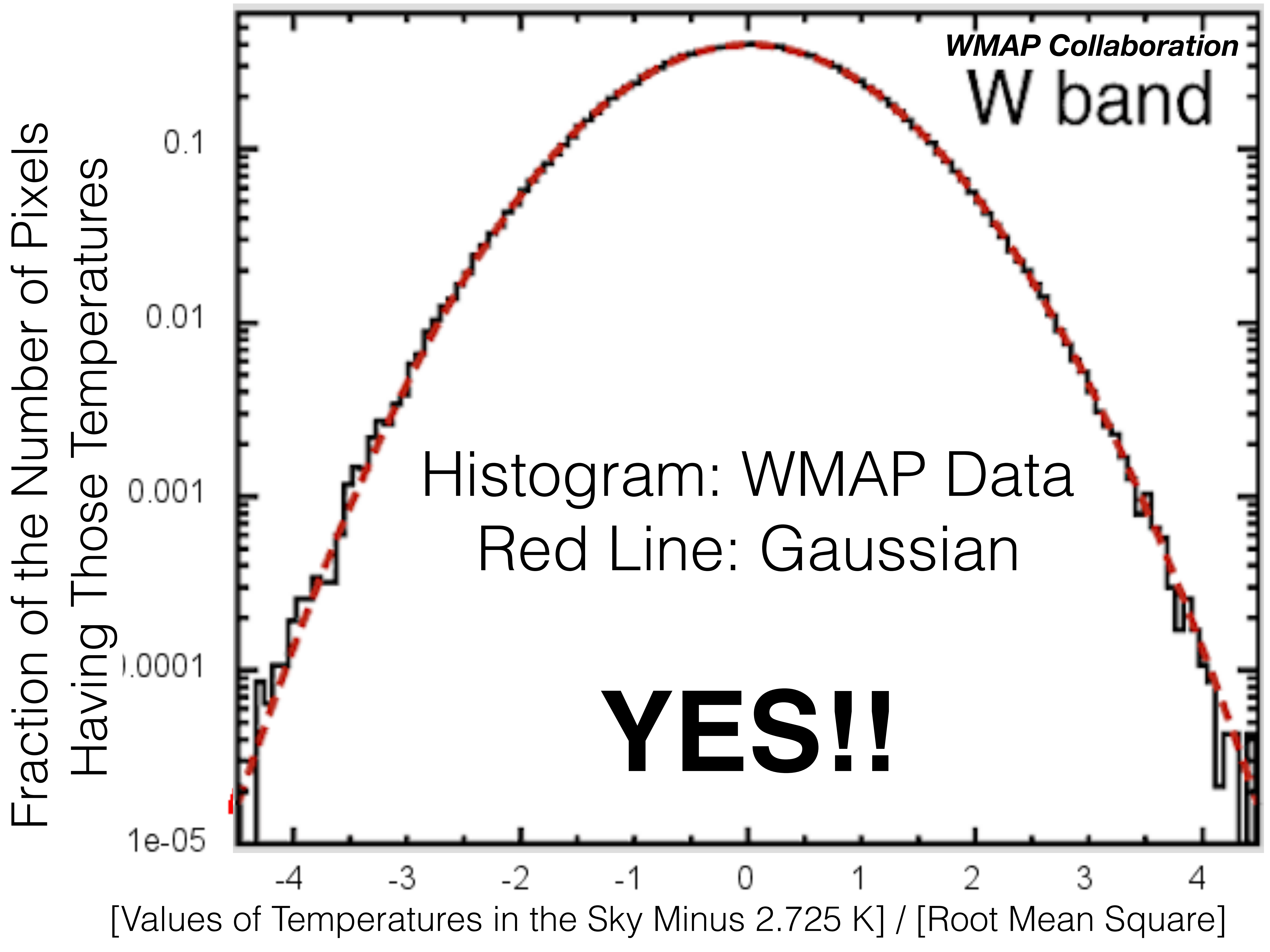
$$\text{Wave Amp.} \propto \ell^{n_s-1}$$


WMAP Collaboration
Angular scale
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]
Amplitude of
100
10
100
500
1000
2000
Multipole moment l

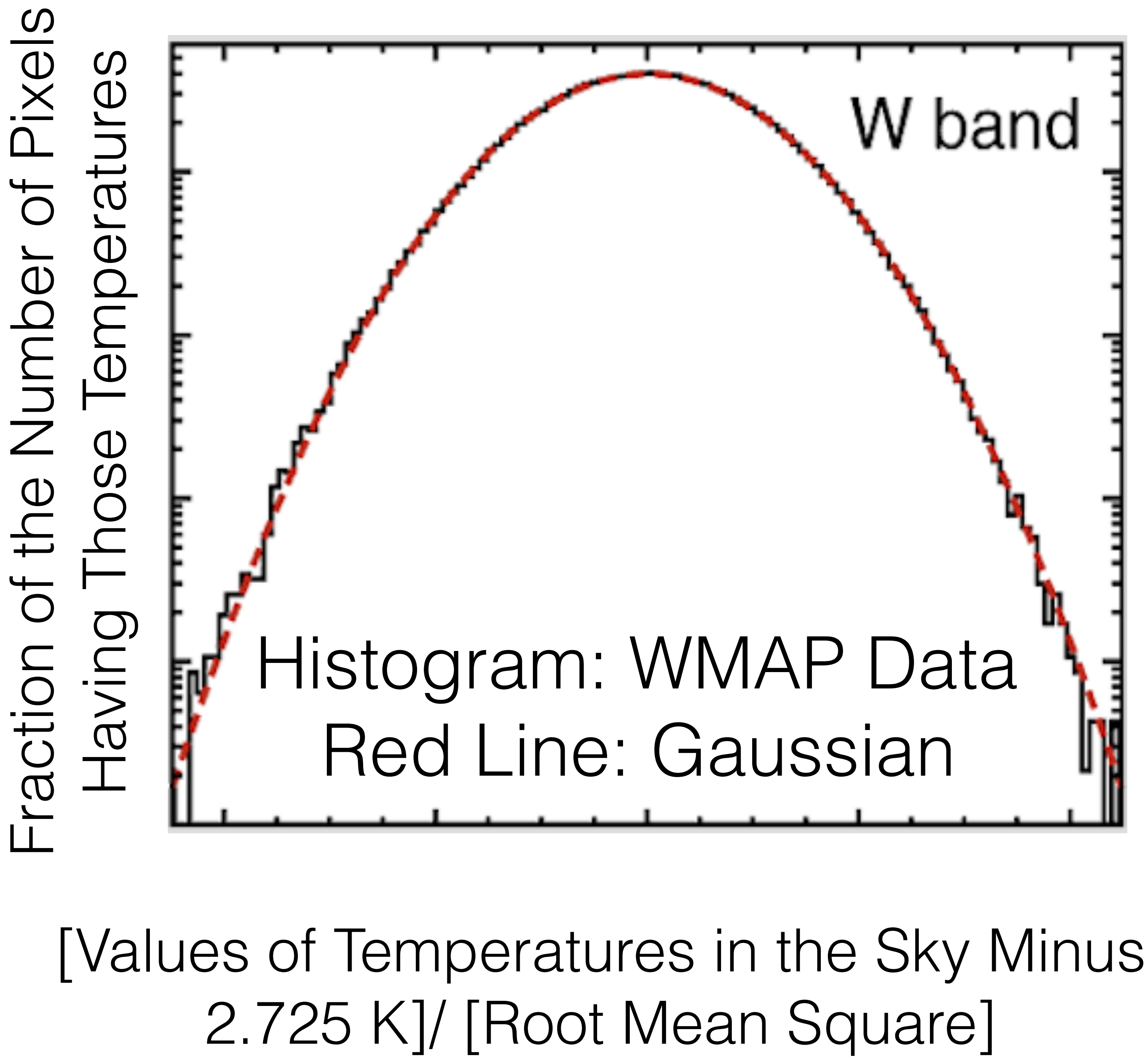

WMAP Collaboration
Angular scale
90°
2°
0.5°
0.2°
0.1°
Amplitude of
2001–2010
South Pole Telescope
[10-m in South Pole]
n_s=0.961±0.008
~5σ discovery of n_s<1 from the CMB data combined with the distribution of galaxies
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment 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 [μK^2]
Residual
180 degrees/(angle in the sky)
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
250


exp(-x**2/2)/sqrt(2*pi)
Fraction of the Number of Pixels
Having Those Temperatures
0.1
0.01
0.001
0.0001
1e-05
-4
-3
-2
-1
0
1
2
3
4
[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)

$$\zeta(\mathbf{x}) = \zeta_{\rm gaus}(\mathbf{x}) + \frac{3}{5} f_{\rm NL} \zeta^2_{\rm gaus}(\mathbf{x})$$ **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

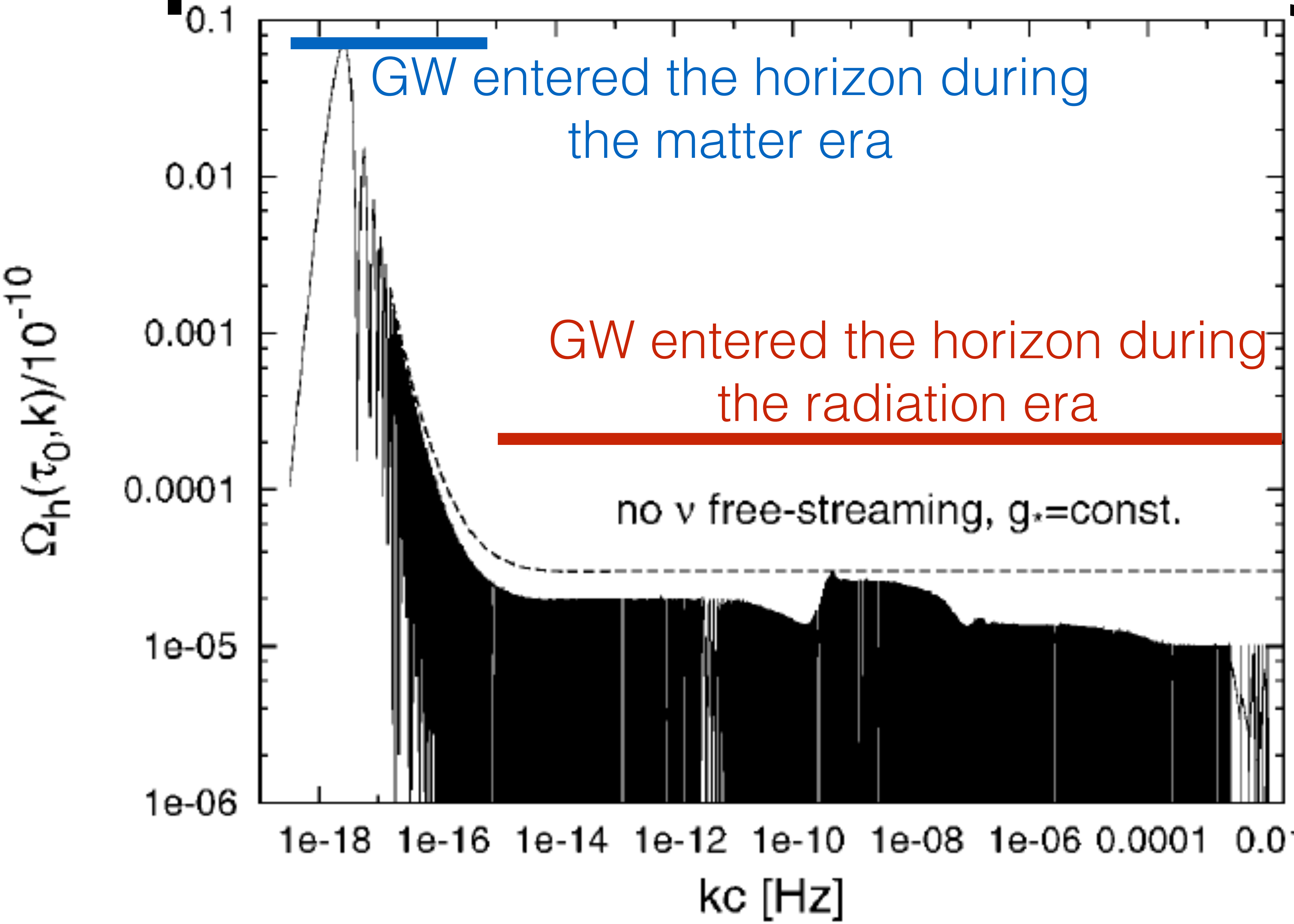
So, have we found inflation?

- 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

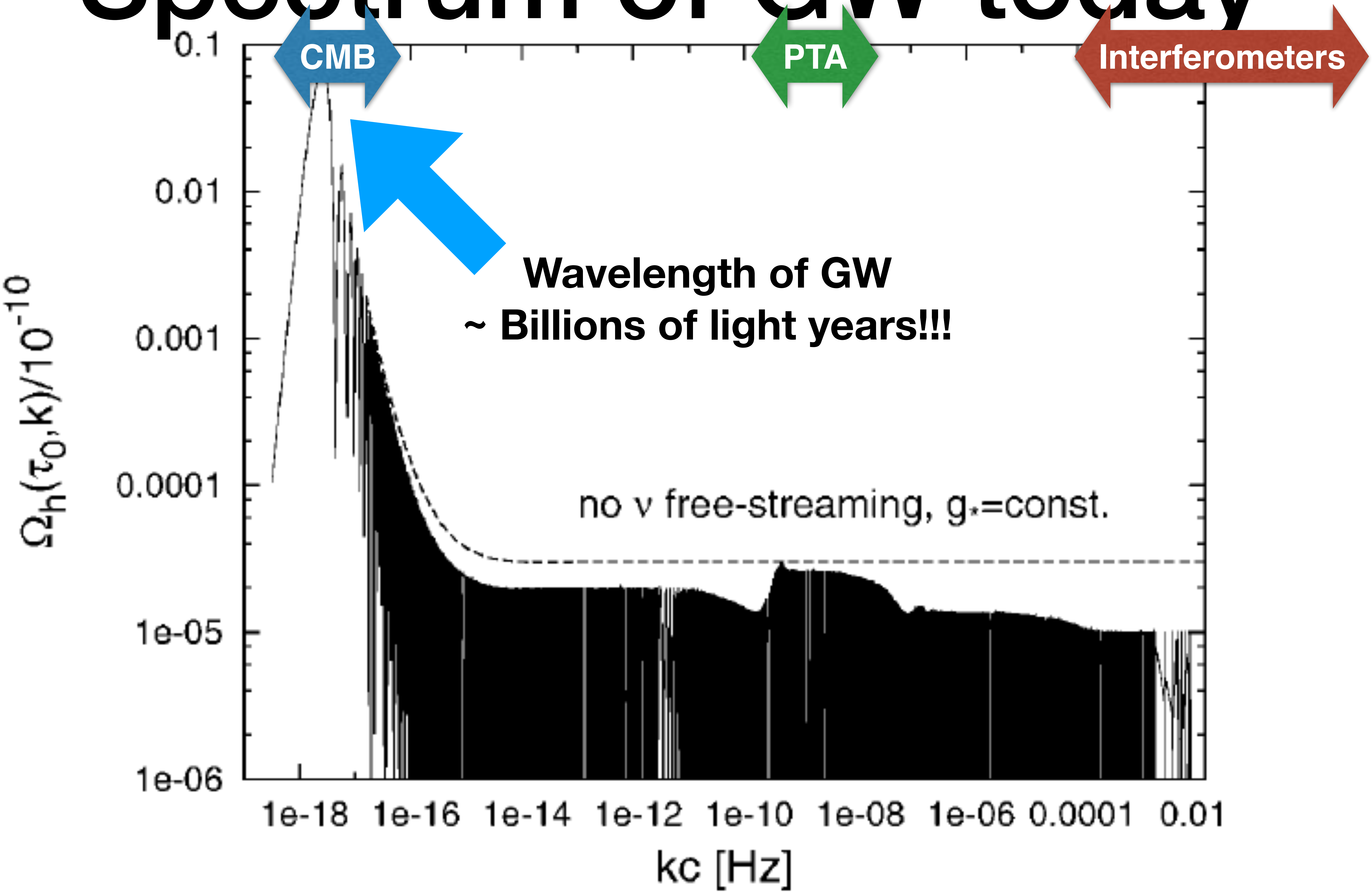
Spectrum of GW today



Watanabe & EK (2006)

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

New Research Area!

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

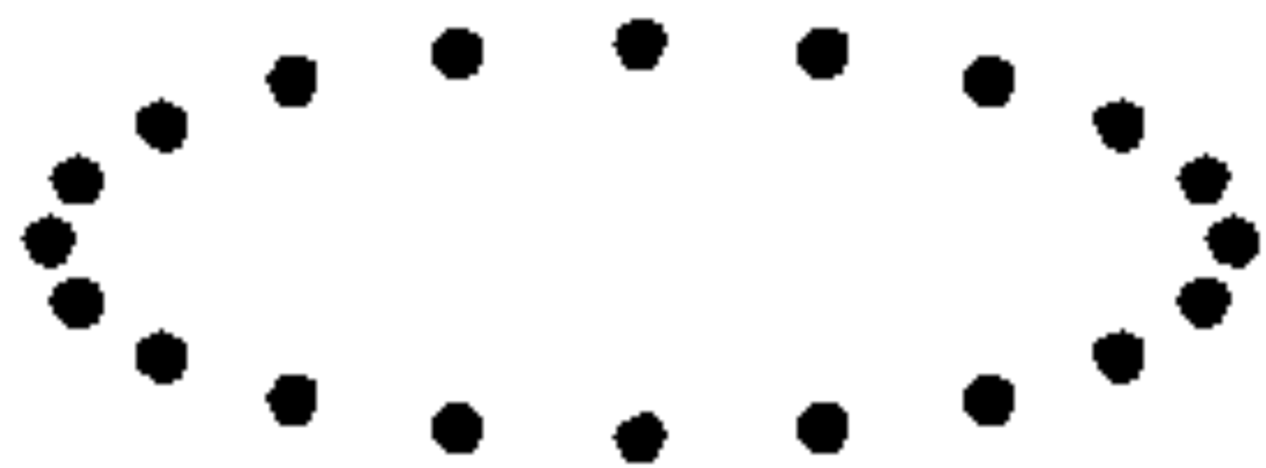
3. Constrain inflation models

Measuring GW

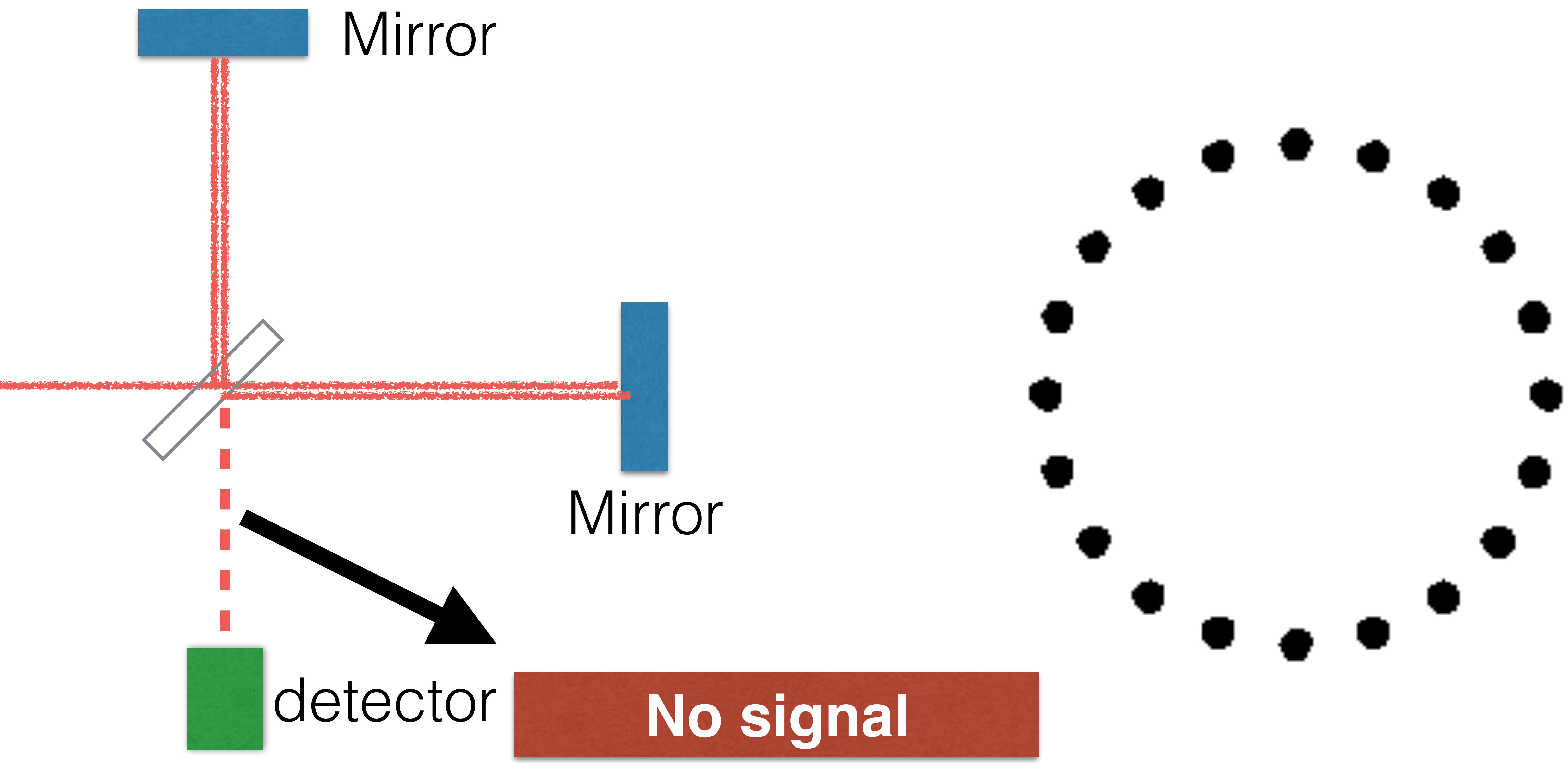
- GW changes distances between two points

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

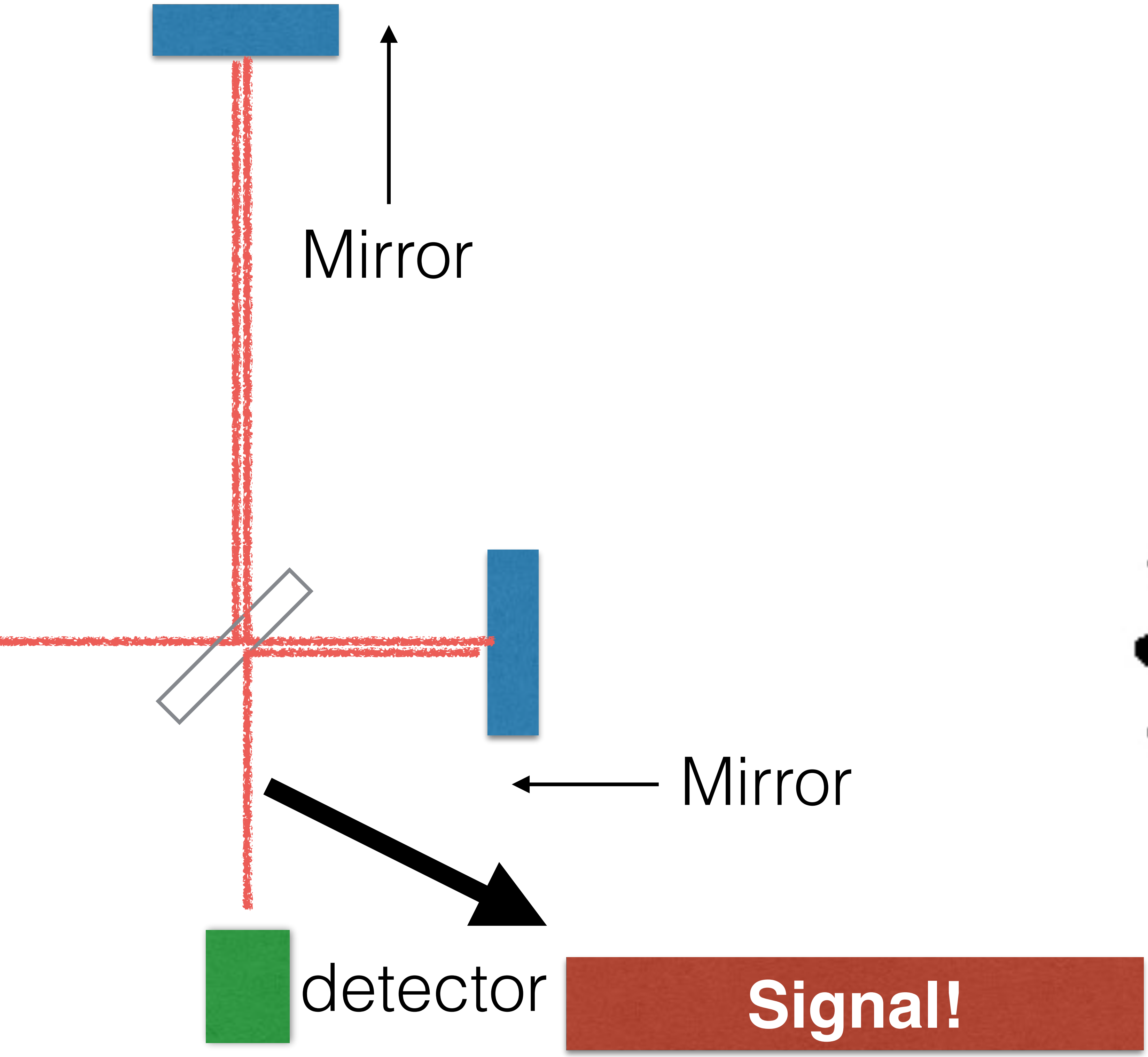
$$d\ell^2 = \sum_{ij} (\delta_{ij} + h_{ij}) dx^i dx^j$$

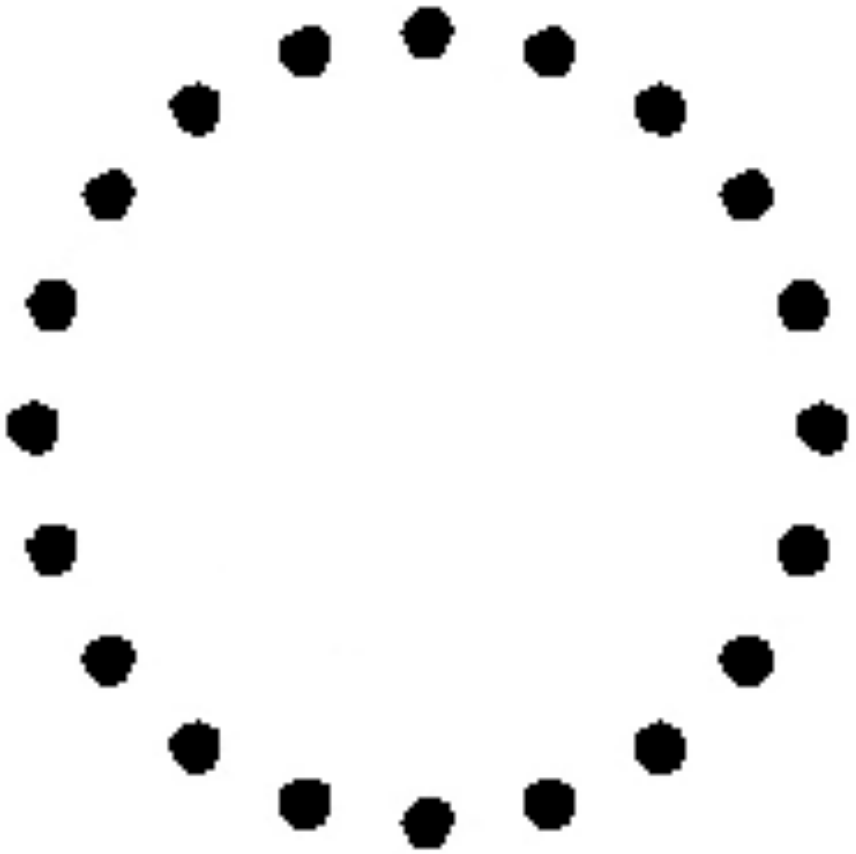


Laser Interferometer

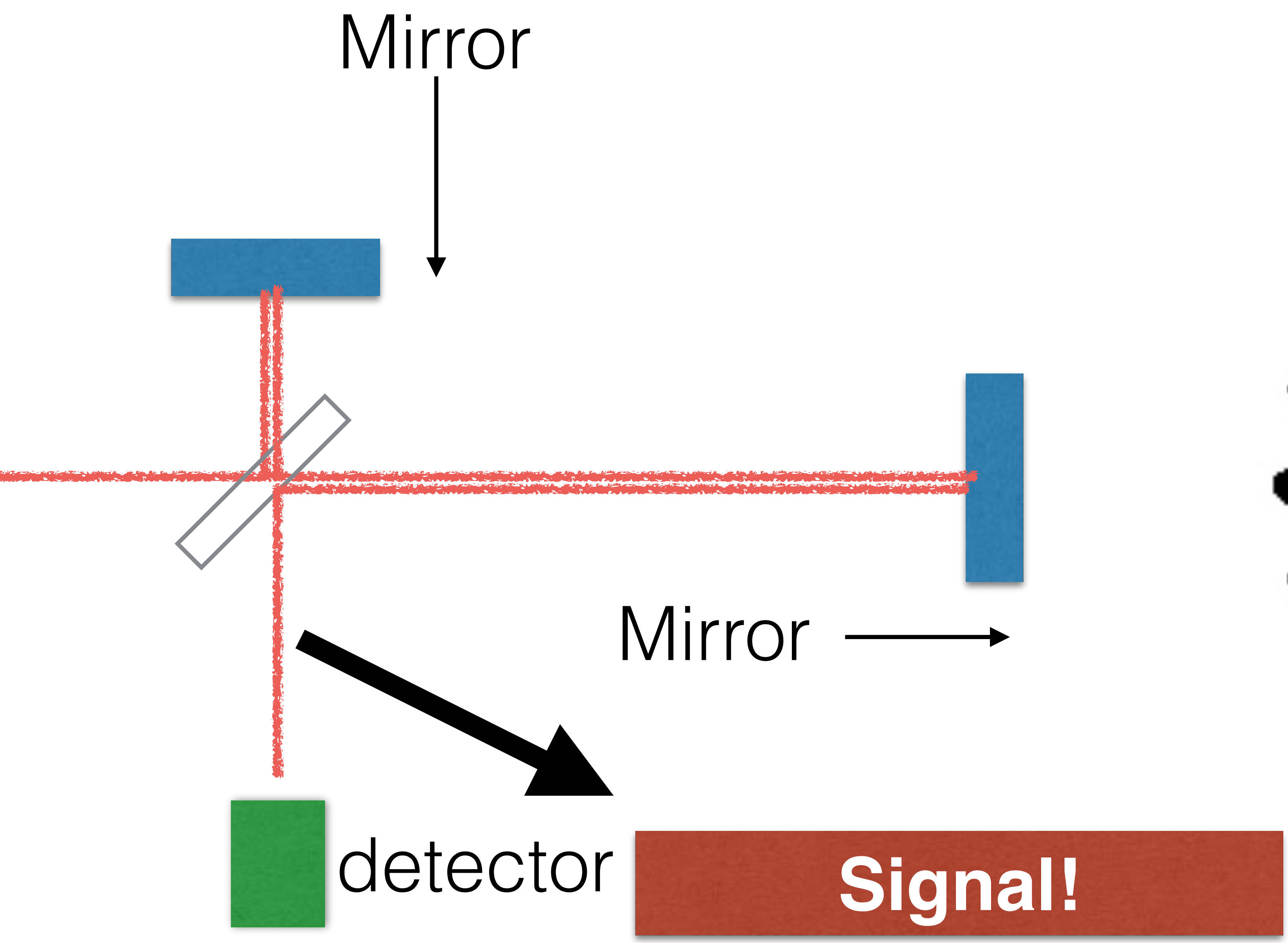


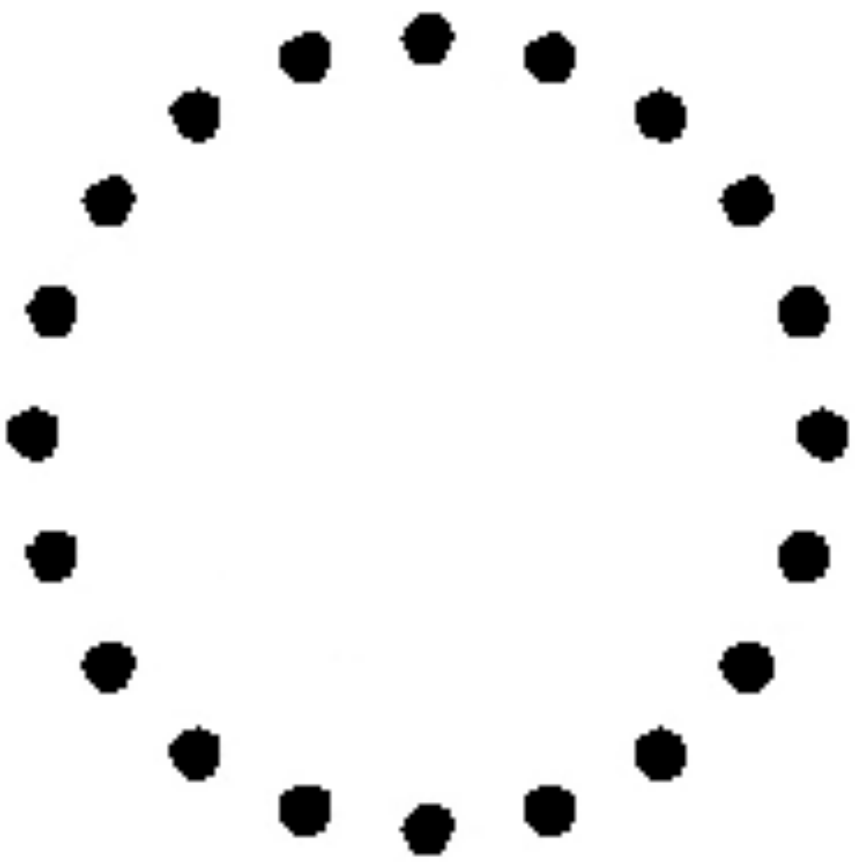
Laser Interferometer





Laser Interferometer





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

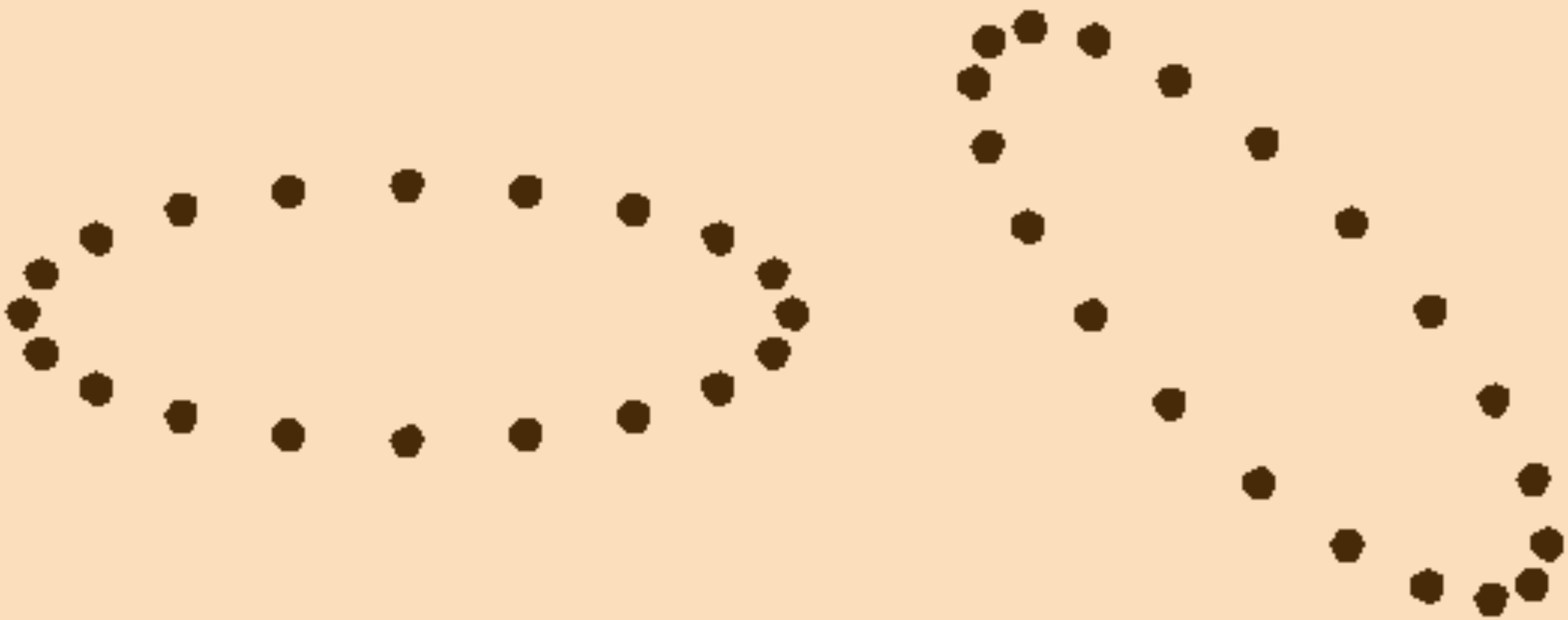
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

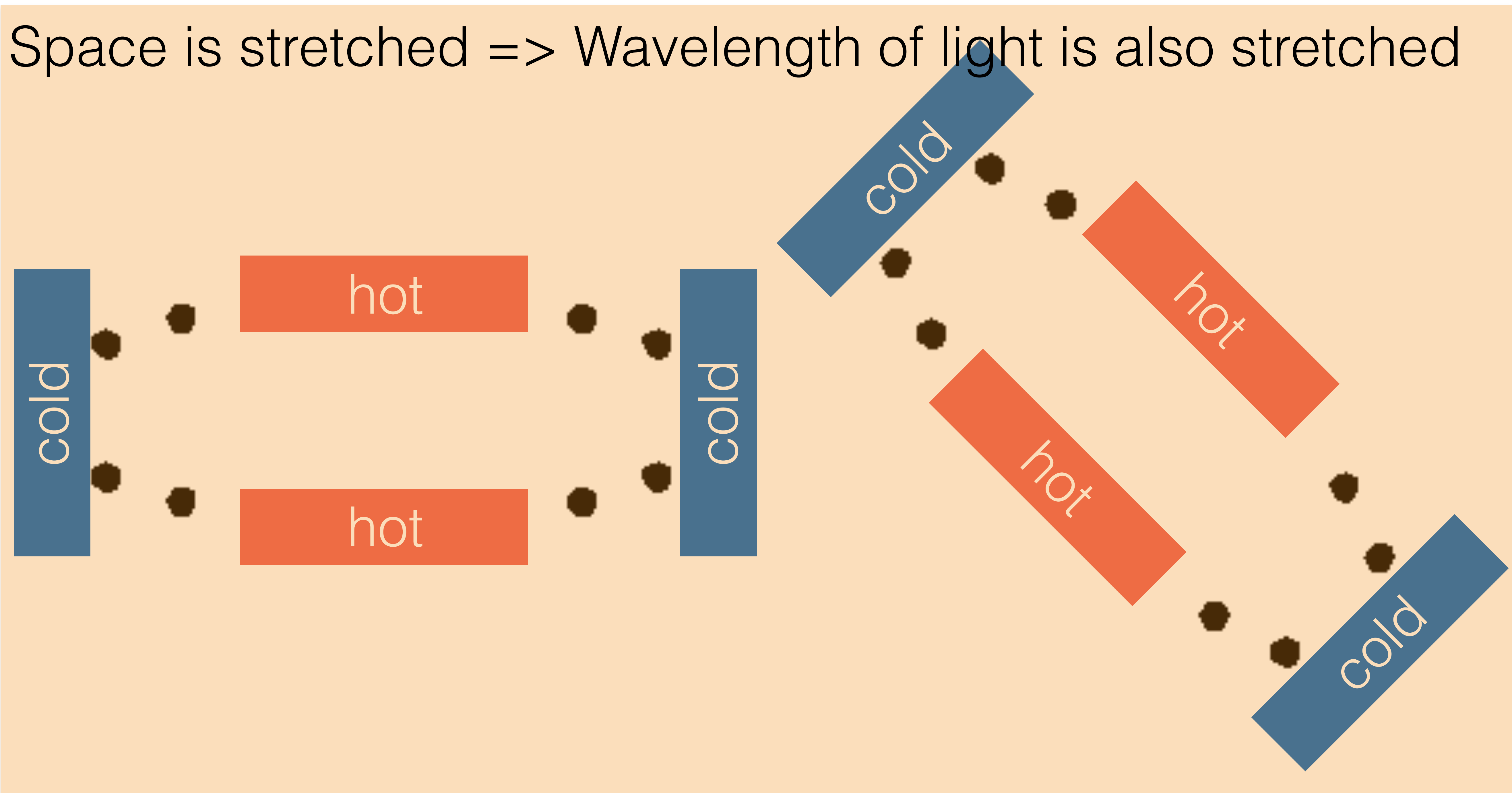
Isotropic electro-magnetic fields

Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields

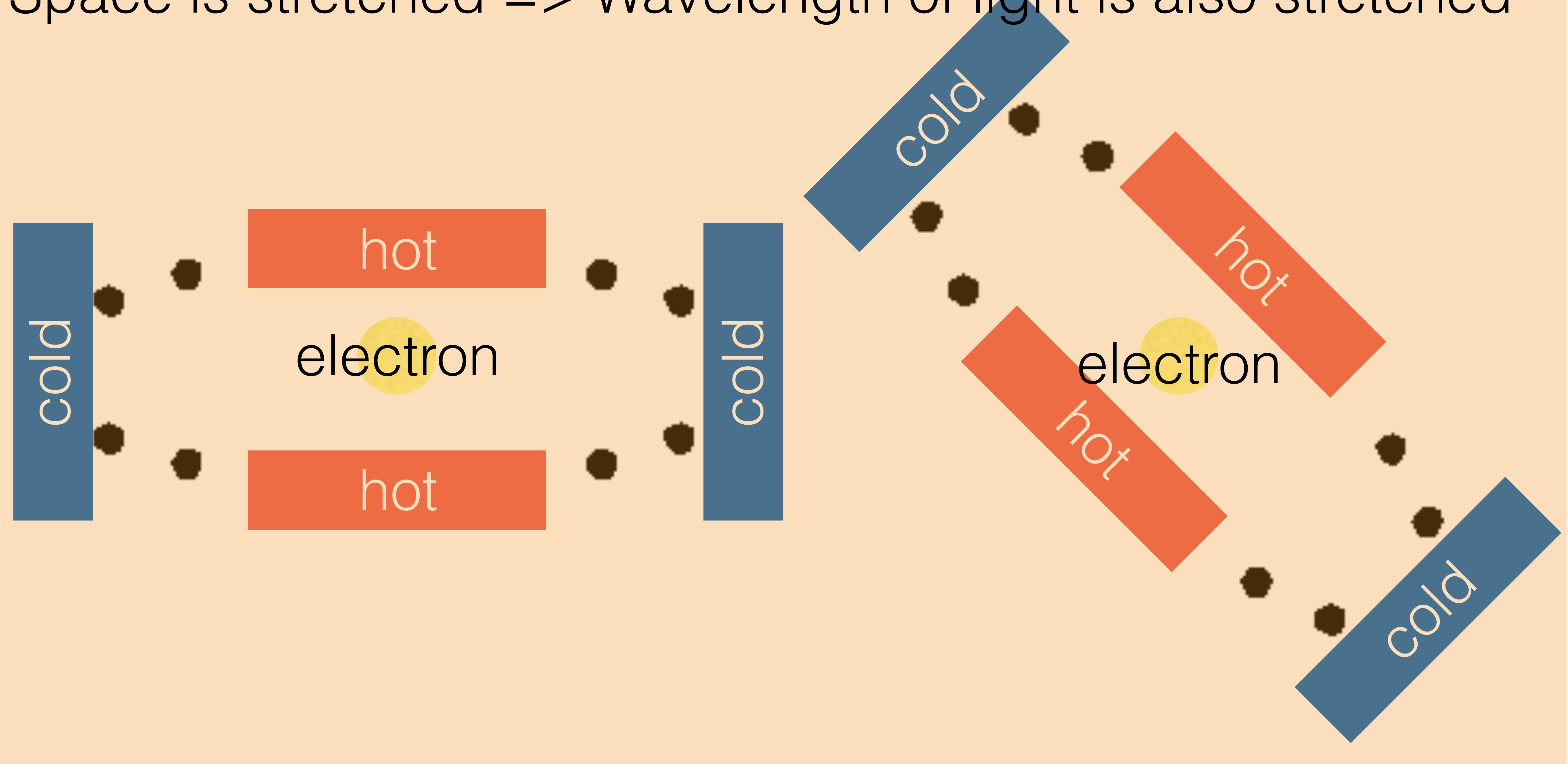


Detecting GW by CMB



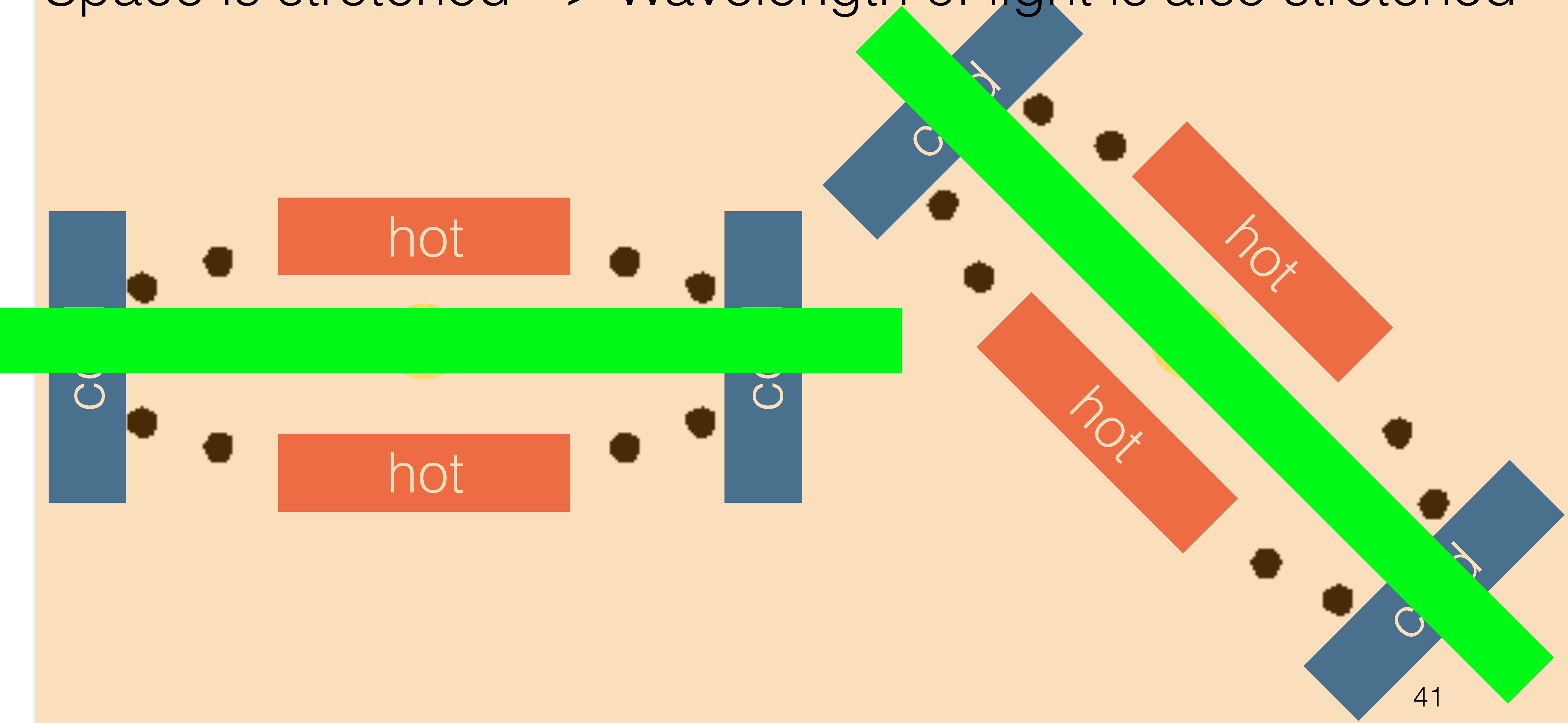
Detecting GW by CMB
Polarisation

Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB
Polarisation

Space is stretched => Wavelength of light is also stretched

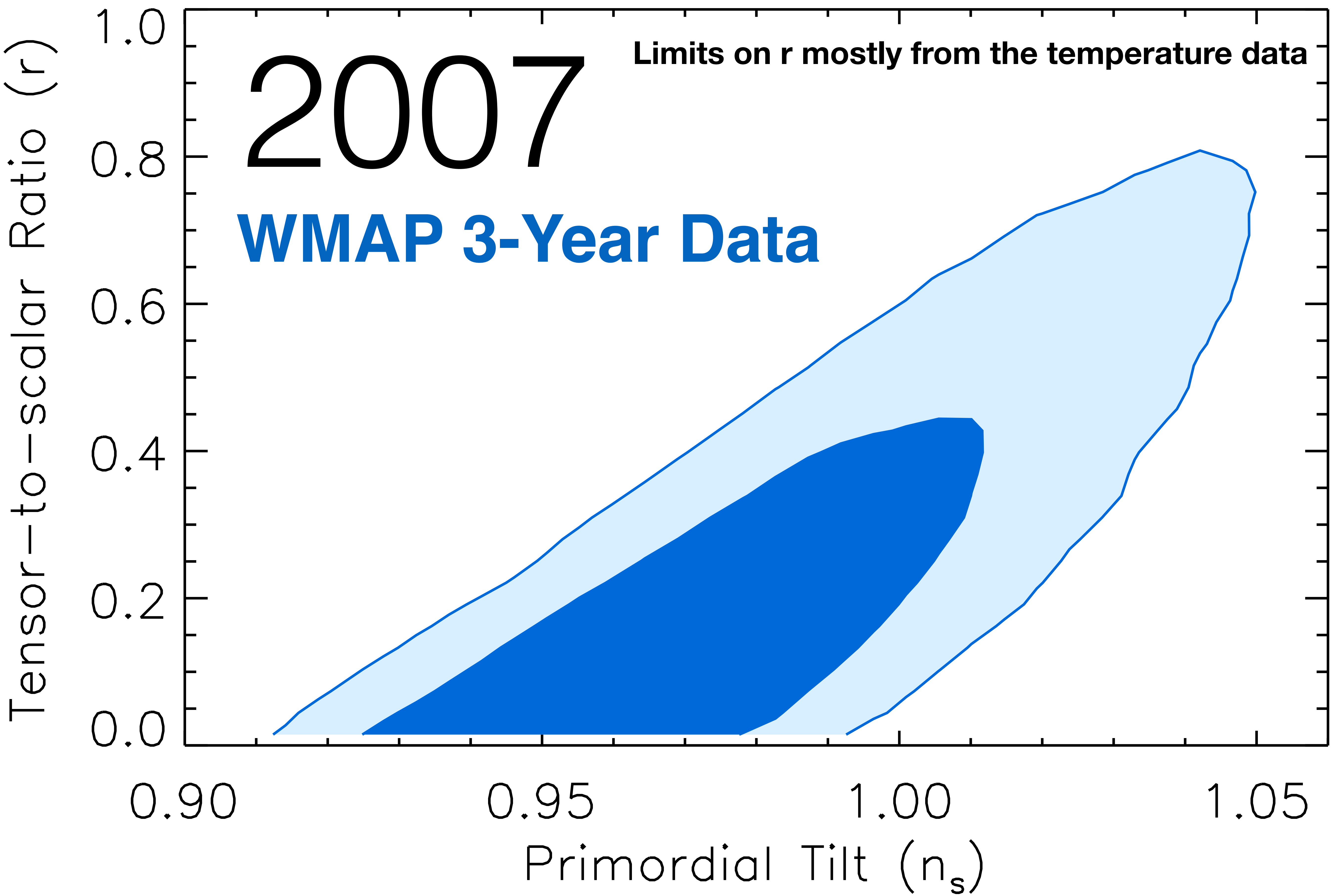


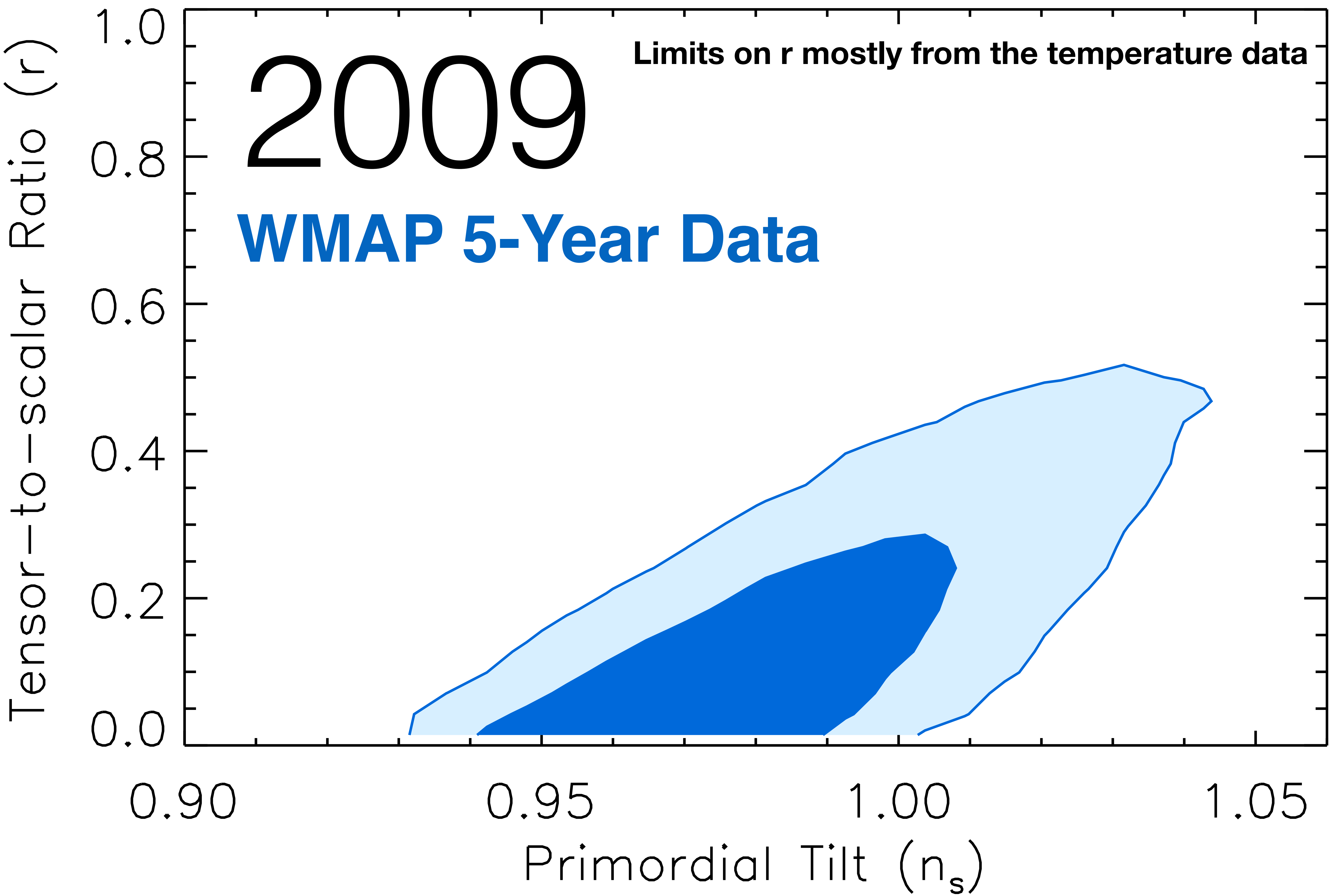
Tensor-to-scalar Ratio

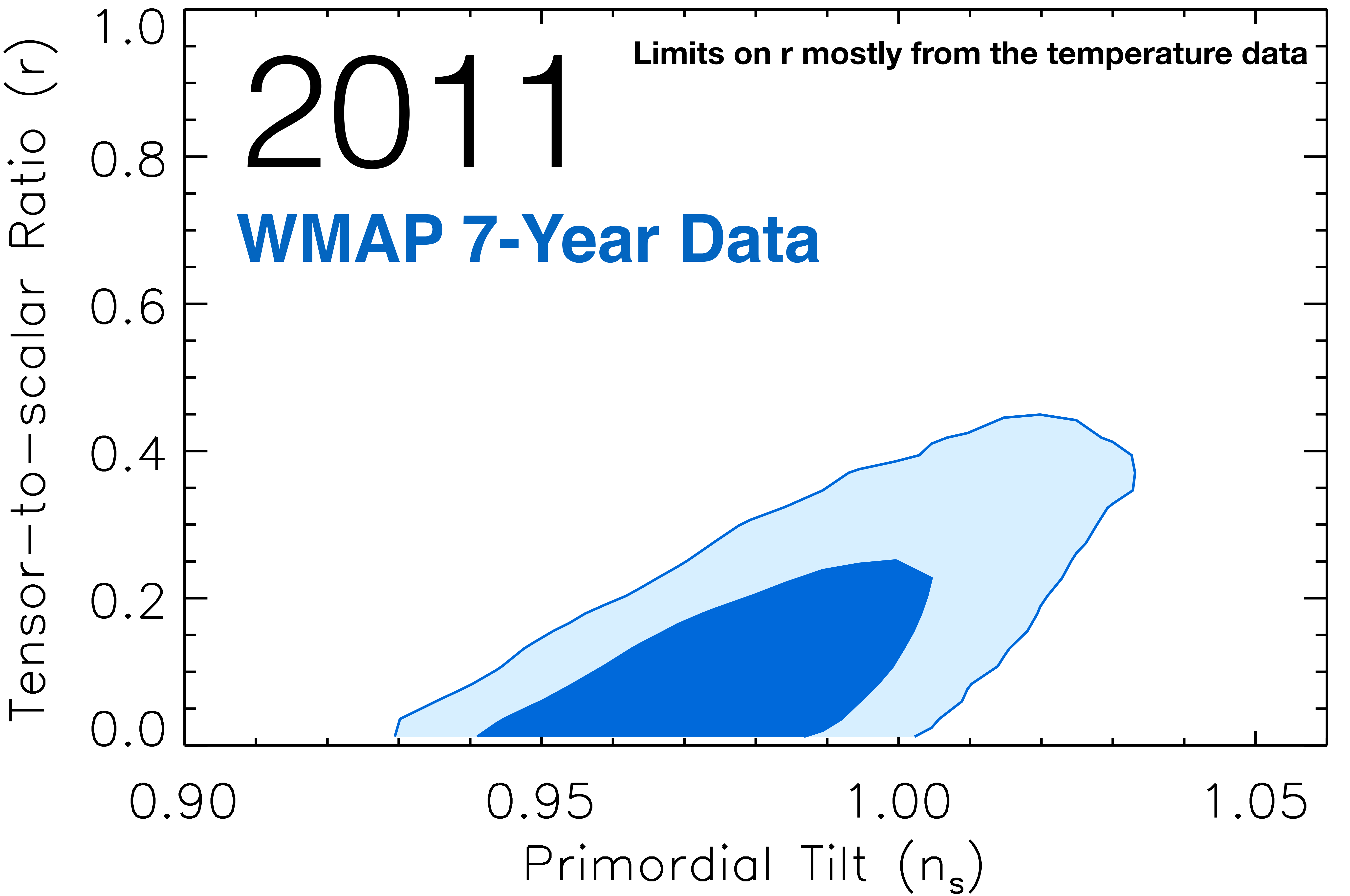
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

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

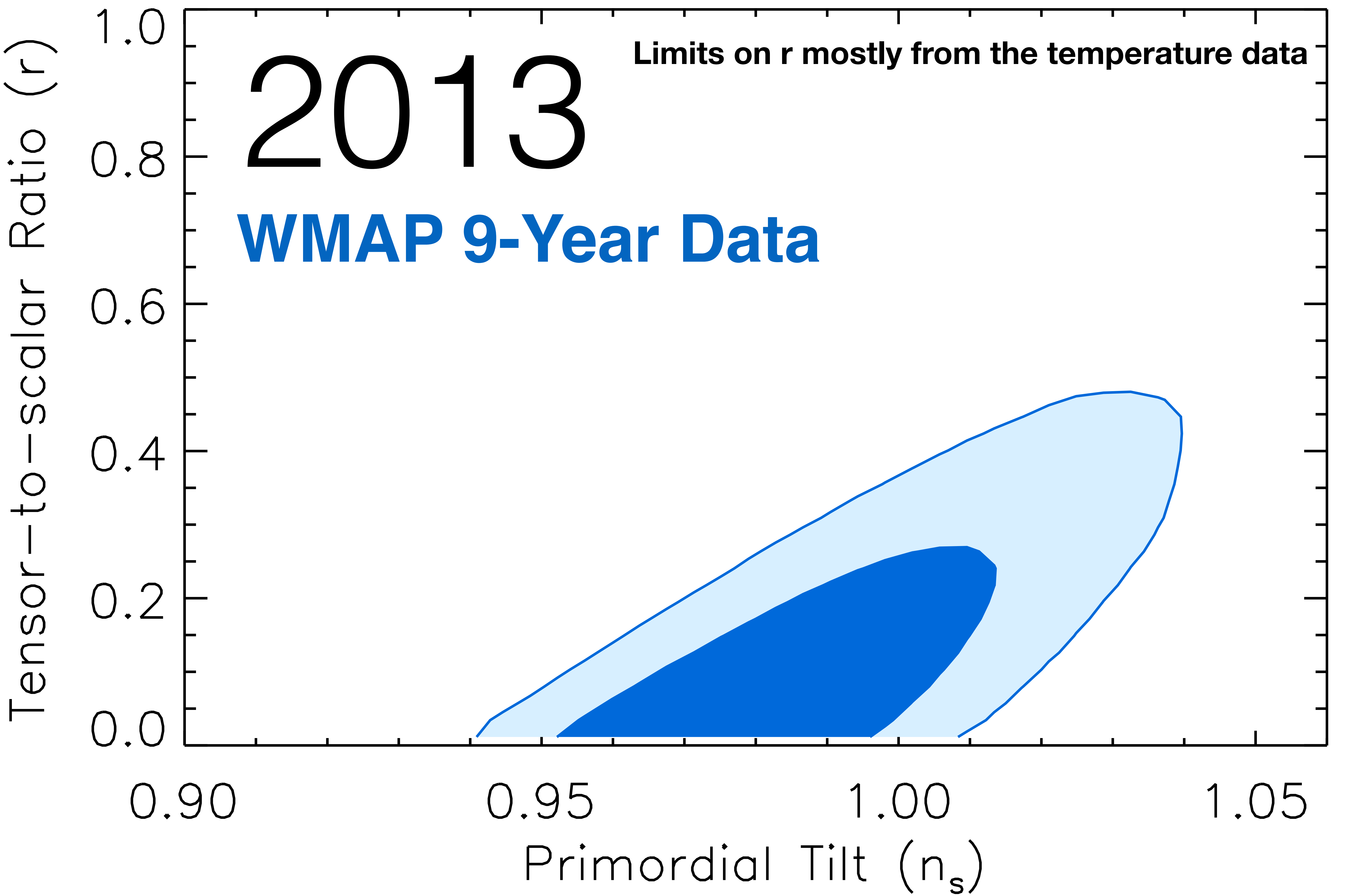
BICEP2/Keck Array Collaboration (2016)


Limits on r mostly from the temperature data
2007
WMAP 3-Year Data
Tensor-to-scalar Ratio (r)
1.0
0.8
0.6
0.4
0.2
0.0
0.90
0.95
1.00
1.05
Primordial Tilt (n_s)

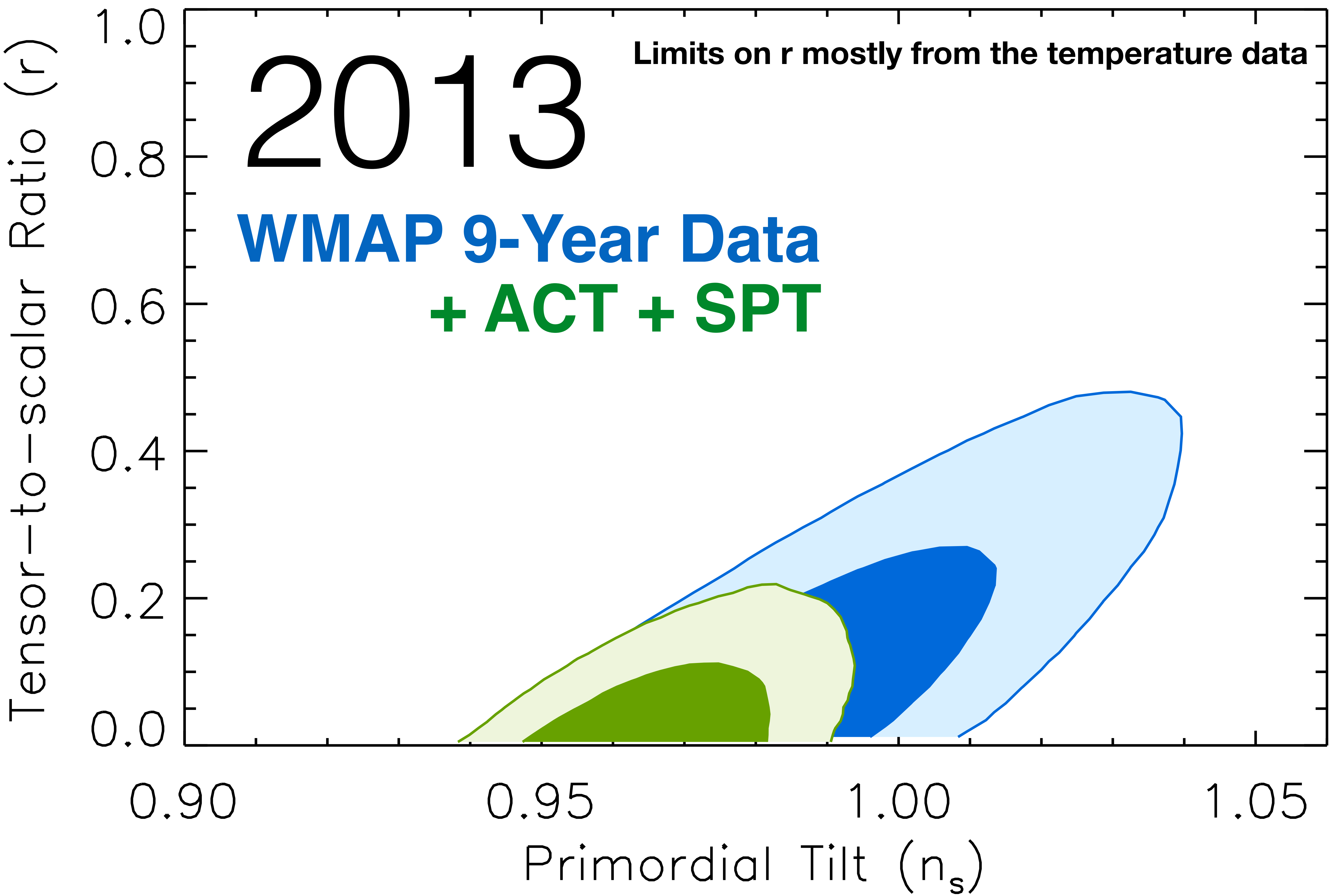

Limits on r mostly from the temperature data
2009
WMAP 5-Year Data
Tensor-to-scalar Ratio (r)
1.0
0.8
0.6
0.4
0.2
0.0
0.90
0.95
1.00
1.05
Primordial Tilt (n_s)



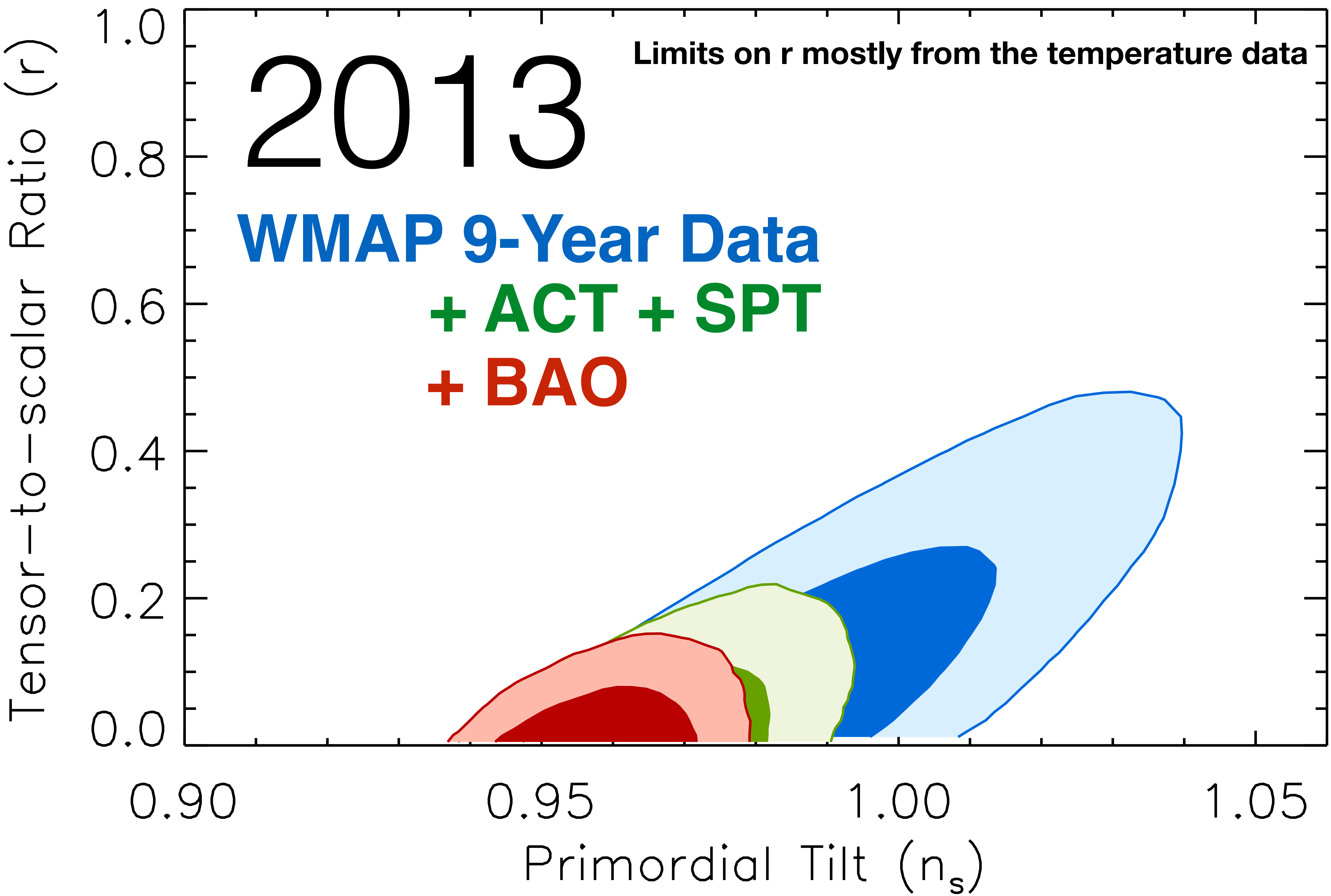
2011
WMAP 7-Year Data
Limits on r mostly from the temperature data
Tensor-to-scalar Ratio (r)
Primordial Tilt (n_s)
1.0
0.8
0.6
0.4
0.2
0.0
0.90
0.95
1.00
1.05



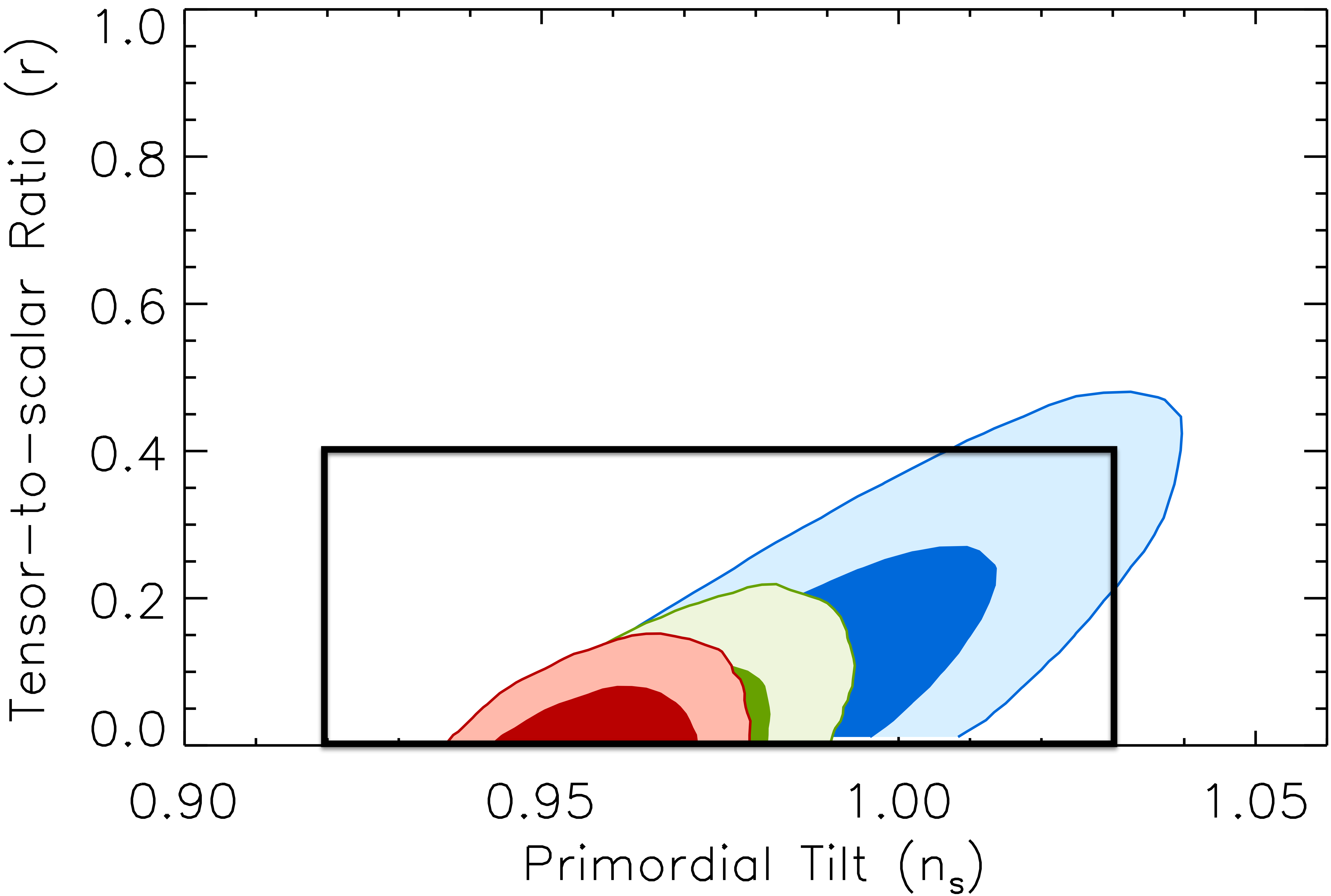
Limits on r mostly from the temperature data
2013
WMAP 9-Year Data
Tensor-to-scalar Ratio (r)
1.0
0.8
0.6
0.4
0.2
0.0
0.90
0.95
1.00
1.05
Primordial Tilt (n_s)

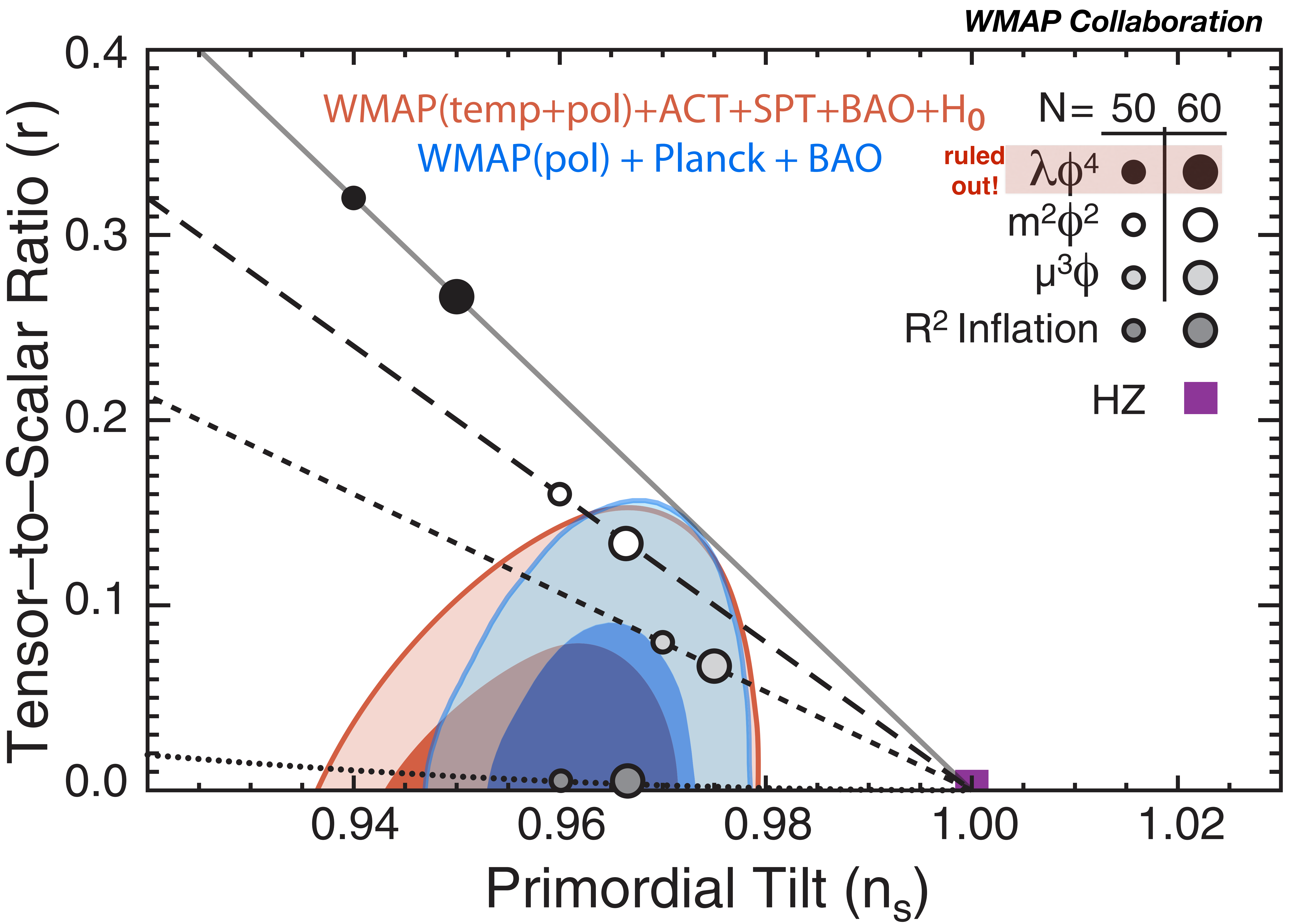


Limits on r mostly from the temperature data
2013
WMAP 9-Year Data
+ ACT + SPT
Tensor-to-scalar Ratio (r)
1.0
0.8
0.6
0.4
0.2
0.0
0.90
0.95
1.00
1.05
Primordial Tilt (n_s)

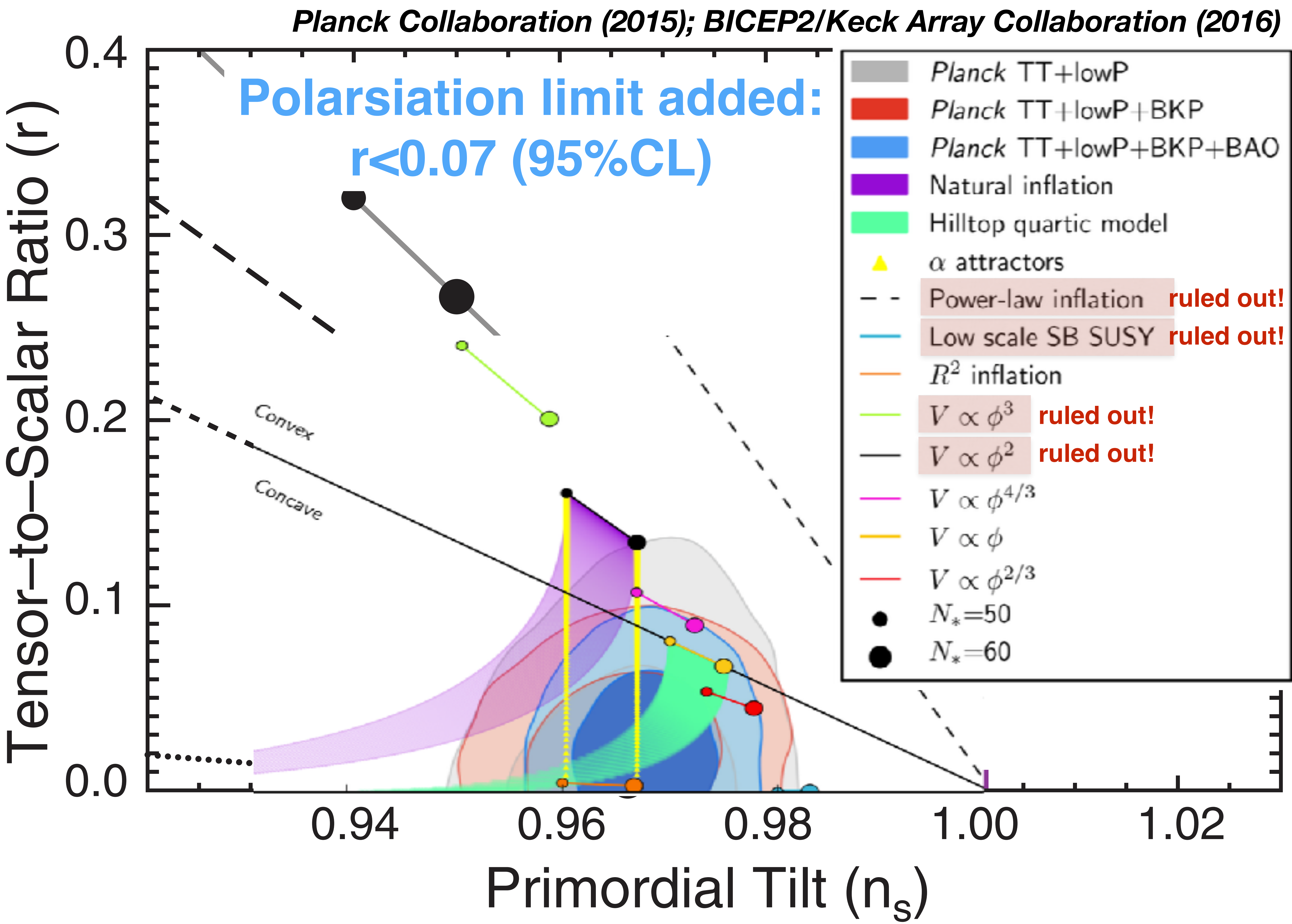


1.0
0.8
0.6
0.4
0.2
0.0
Tensor-to-scalar Ratio (r)
2013
Limits on r mostly from the temperature data
WMAP 9-Year Data
+ ACT + SPT
+ BAO
0.90
0.95
1.00
1.05
Primordial Tilt (n_s)


Tensor-to-scalar Ratio (r)
1.0
0.8
0.6
0.4
0.2
0.0
0.90
0.95
1.00
1.05
Primordial Tilt (n_s)



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


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

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

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

- **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)

Dimastrogiovanni, Fasielo & Fujita (2017)

GW from Axion-SU(2) Dynamics

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

- 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

Aniket Agrawal
(MPA)

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

Tomo Fujita
(Stanford->Kyoto)

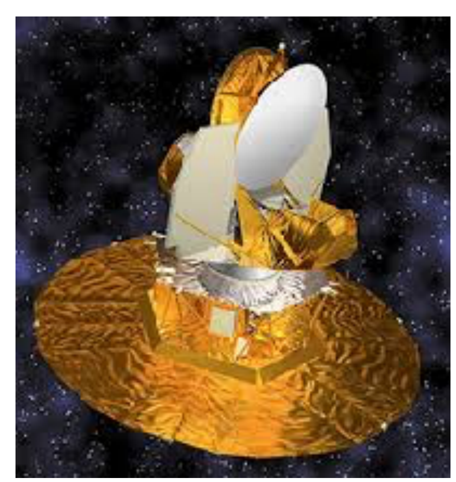
- Ω_A << 1 is the energy density fraction of the gauge field
- B_h/P_h^2 is of order unity for the vacuum contribution
- ***Gaussianity offers a powerful test of whether the detected GW comes from the vacuum fluctuation or from sources***

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: 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

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
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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

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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

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M. Hattori
T. Morishima

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K. Ichiki

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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

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E. Komatsu

NIST
G. Hilton
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UC San Diego
K. Arnold
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B. Keating
G. Rebeiz

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J. Borrill
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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

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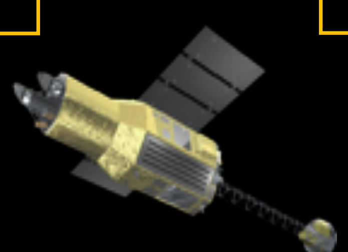
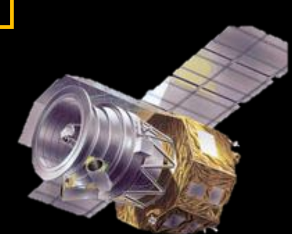
K. Irwin
S. Kernasovskiy
C.-L. Kuo
D. Li
T. Namikawa
K. L. Thompson

Satellite



X-ray



Infrared

CMB

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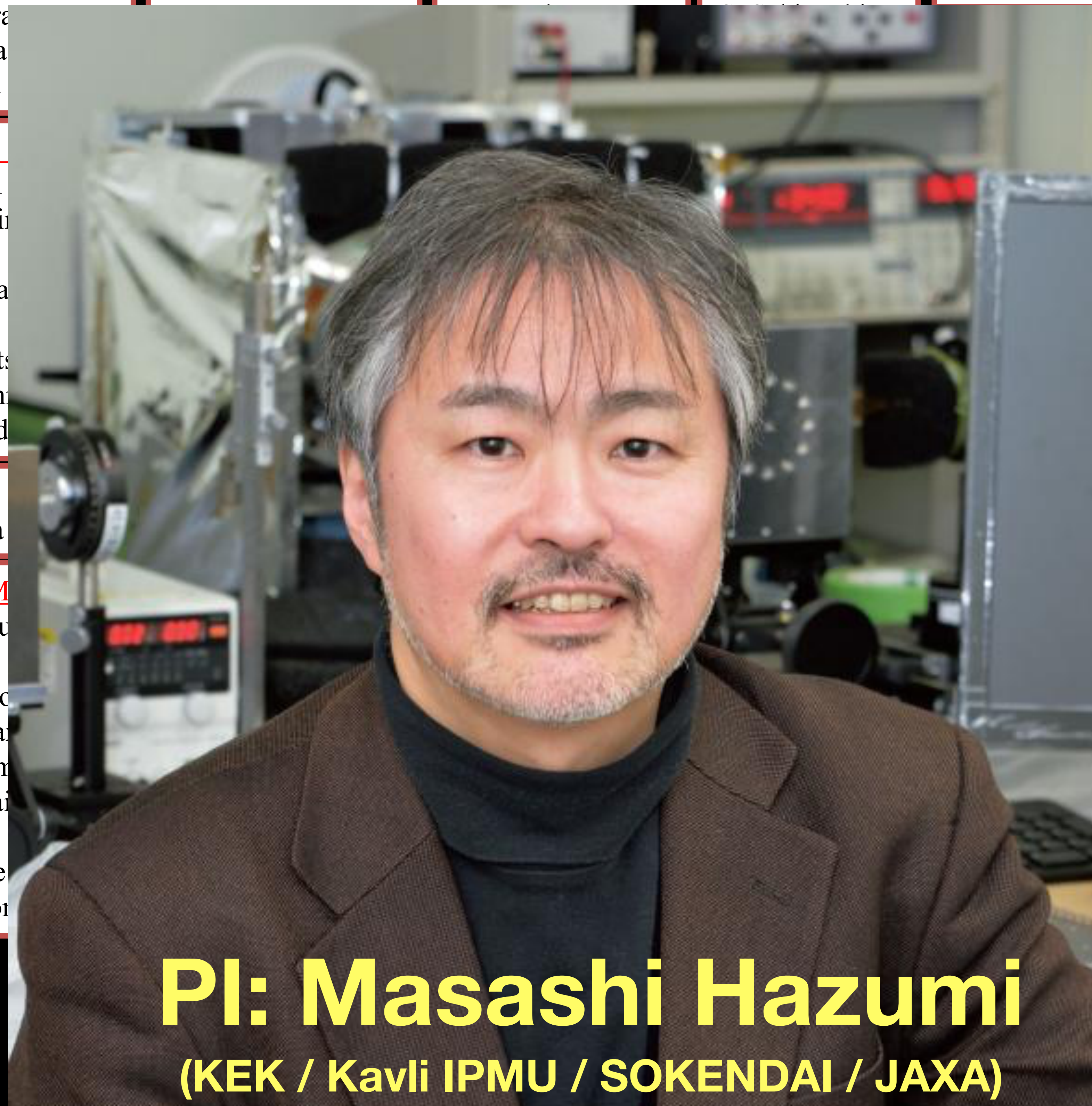

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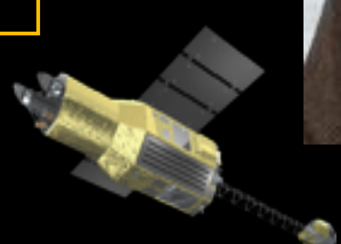
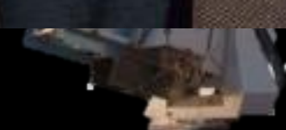
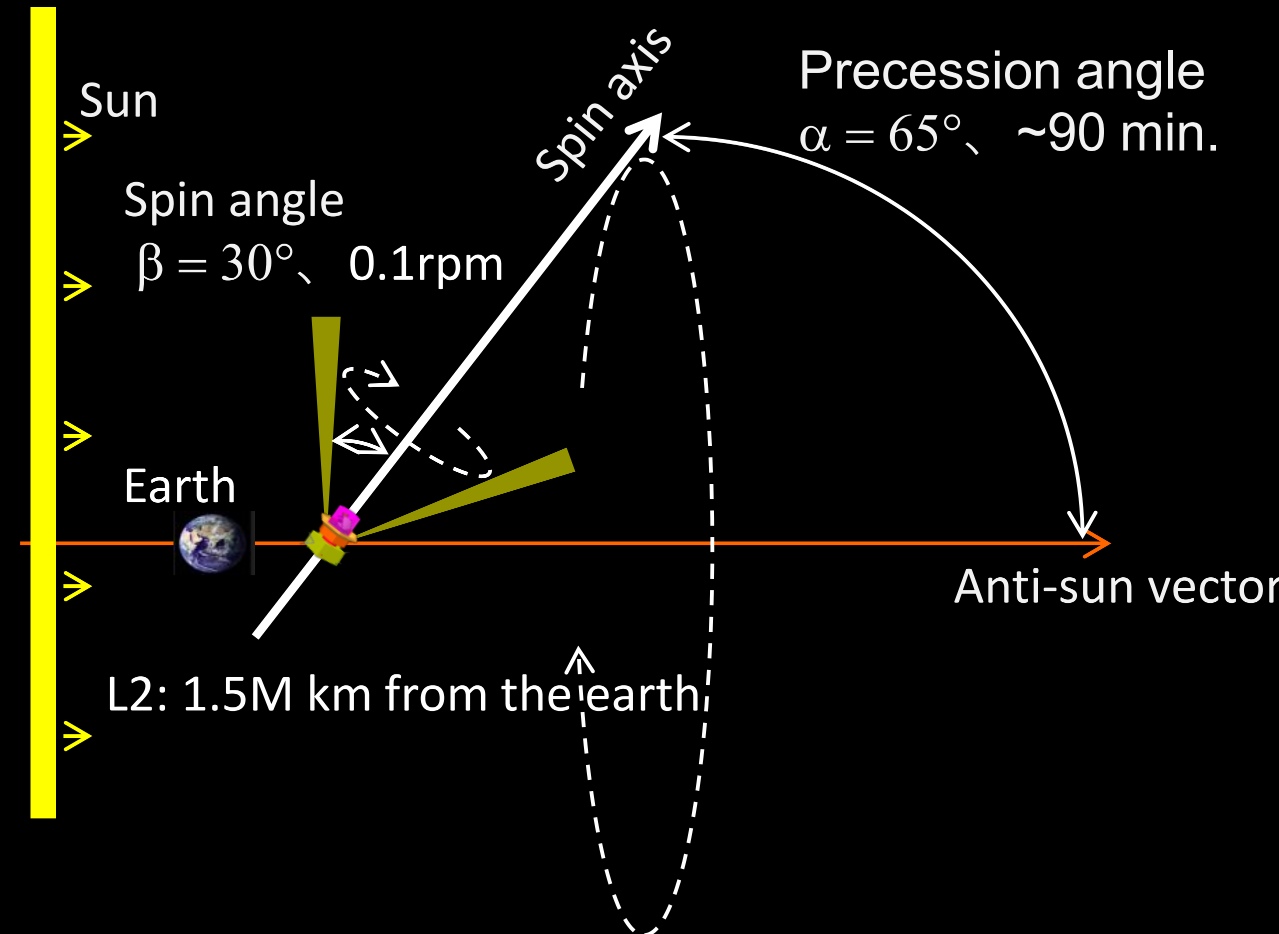




Observation Strategy

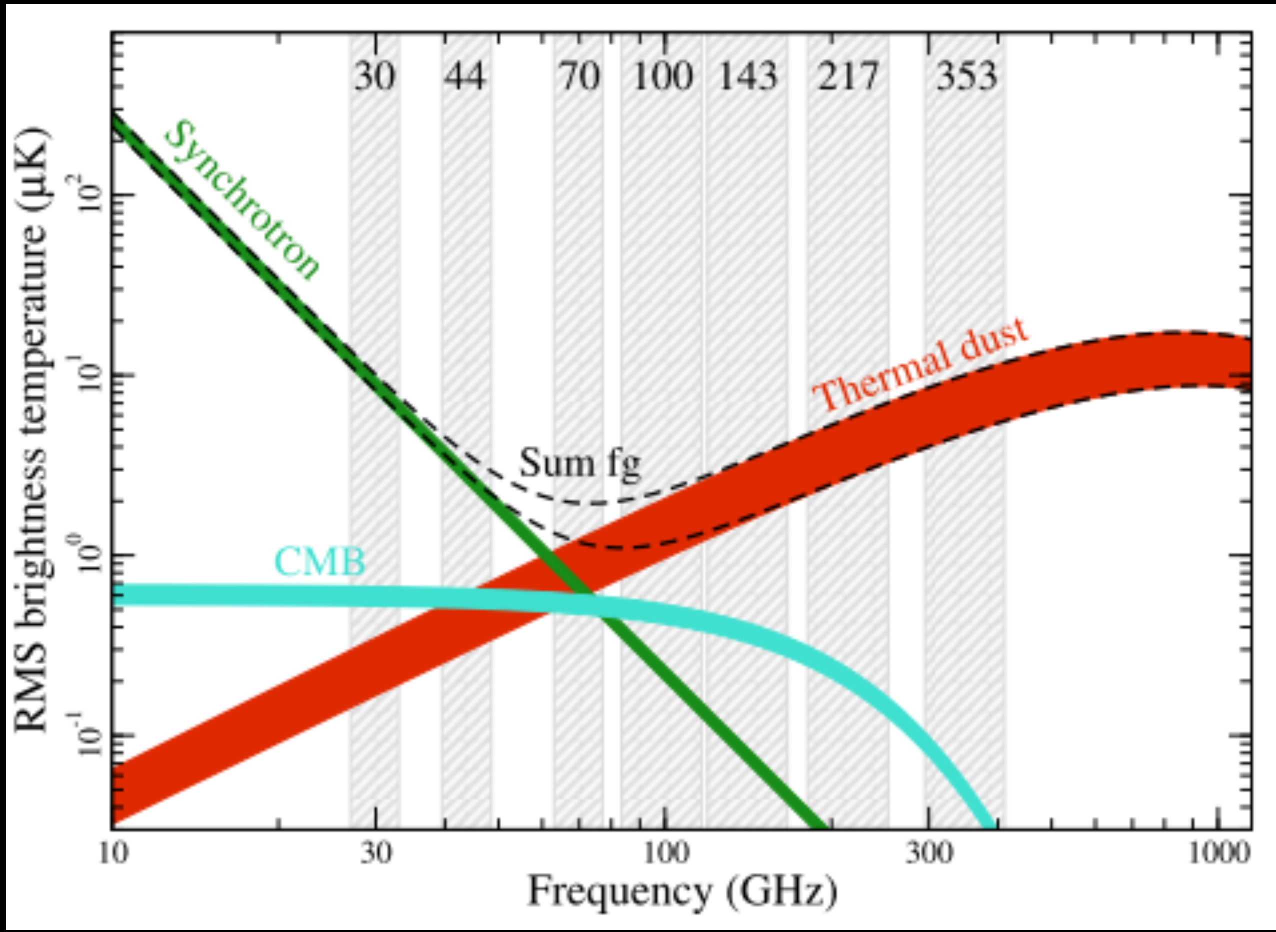
JAXA H3 Launch Vehicle (JAXA)



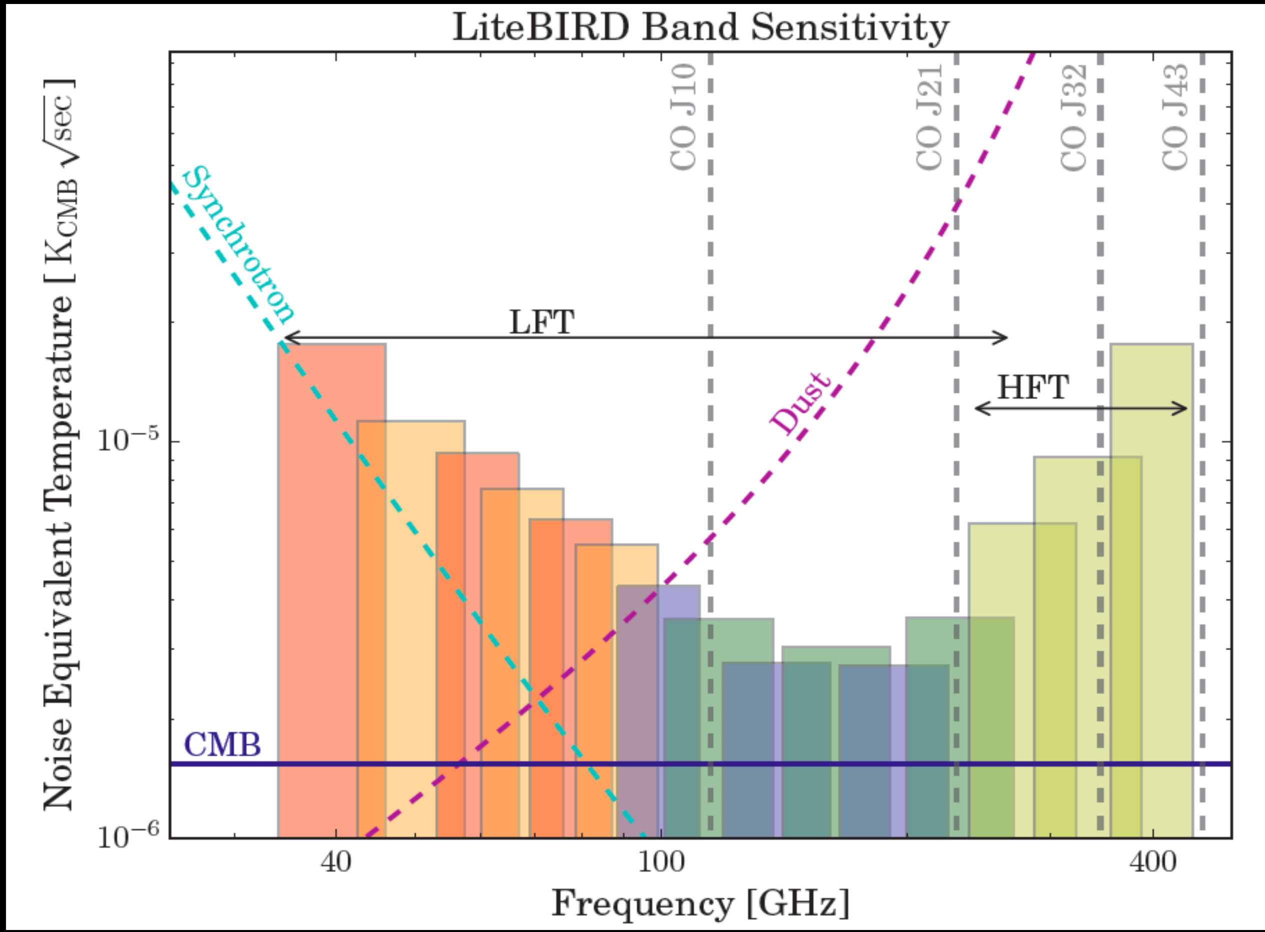
- Launch vehicle: JAXA H3
- Observation location: Second Lagrangian point (L2)
- Scan strategy: Spin and precession, full sky
- Observation duration: 3-years
- Proposed launch date: Mid 2020’s

Slide courtesy Toki Suzuki (Berkeley)

Foreground Removal



Polarized galactic emission (Planck X)



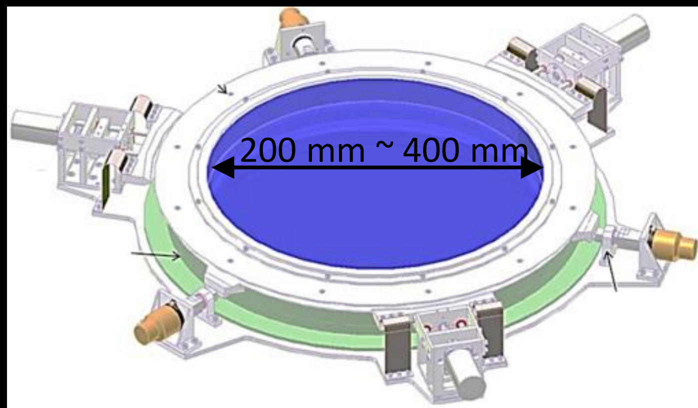
LiteBIRD: 15 frequency bands

- 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

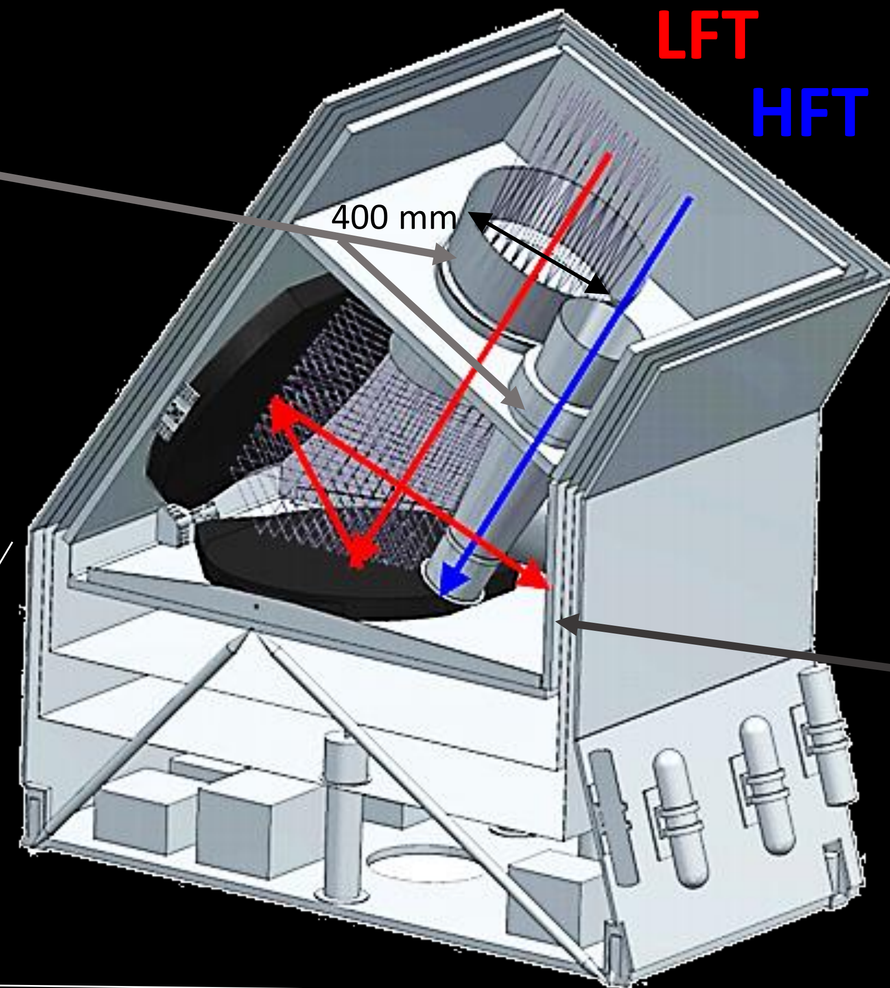
Slide courtesy Toki Suzuki (Berkeley)

Instrument Overview

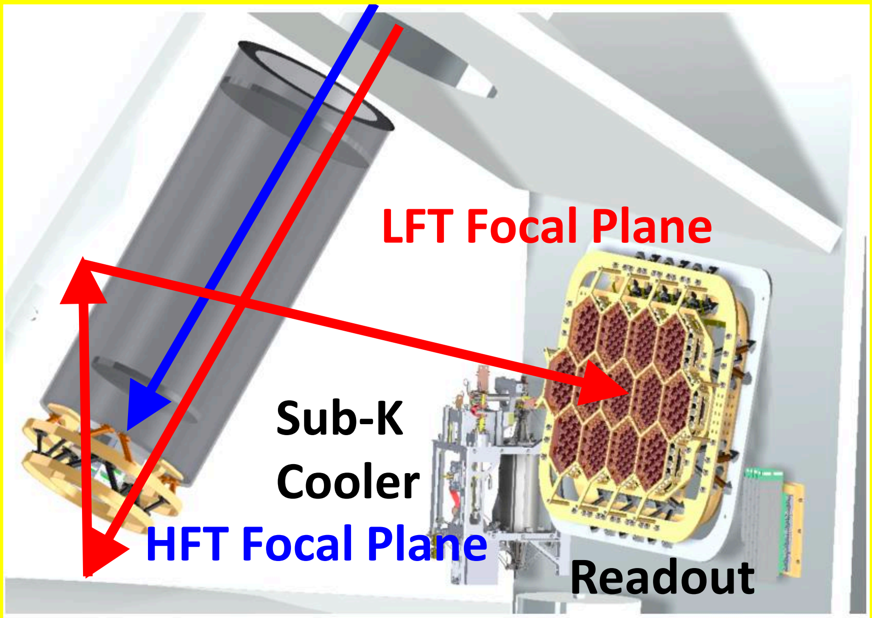
Slide courtesy Toki Suzuki (Berkeley)



Half-wave plate



Stirling & Joule Thomson Coolers

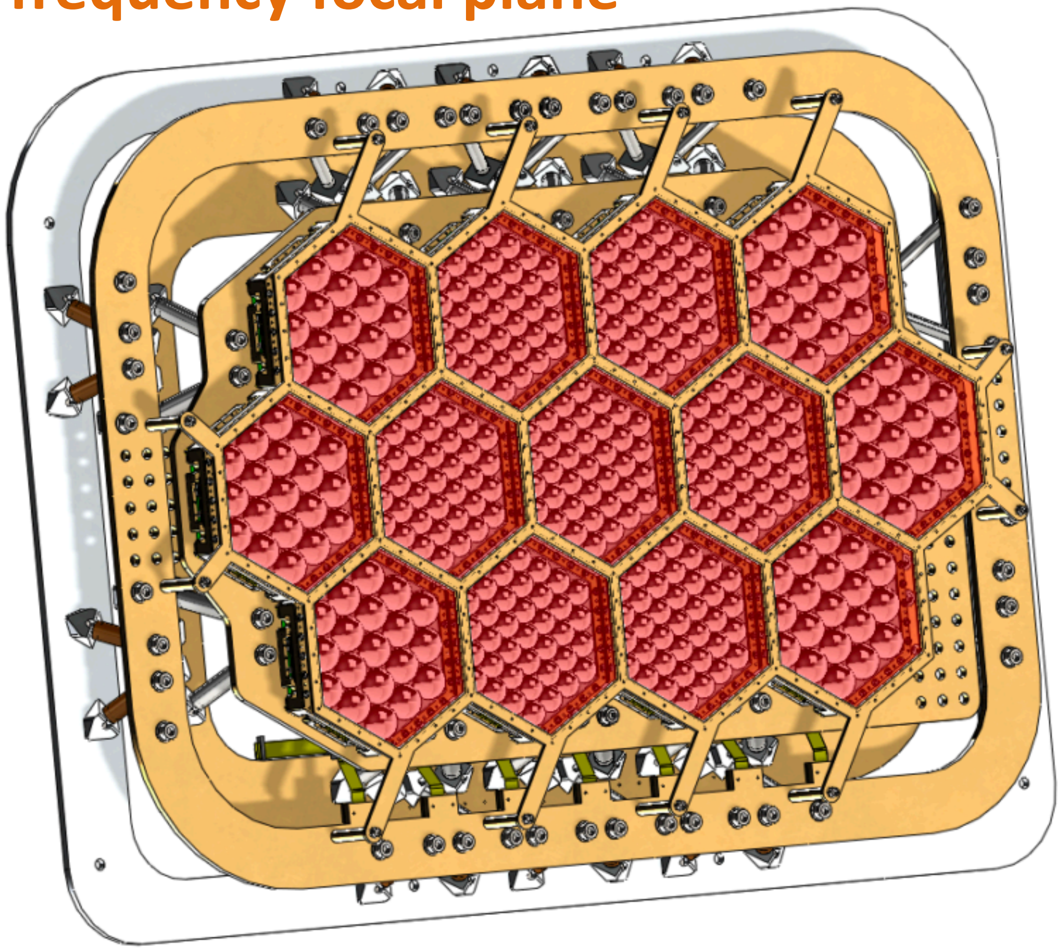


Sub-Kelvin Instrument

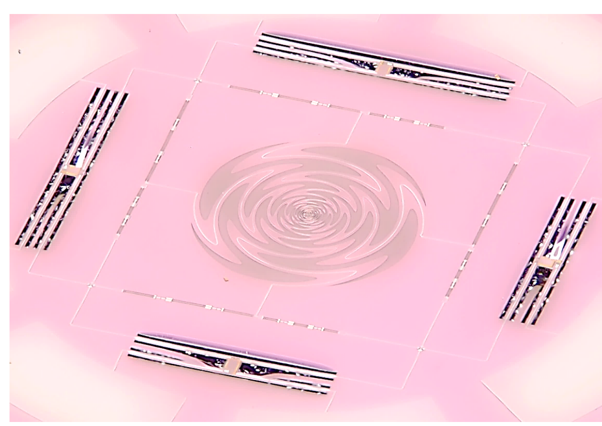
- Two telescopes
  - Crossed-Dragone (LFT) & on-axis refractor (HFT)
- Cryogenic rotating achromatic half-wave plate
  - Modulates polarization signal
- Stirling & Joule Thomson coolers
  - Provide cooling power above 2 Kelvin
- Sub-Kelvin Instrument
  - Detectors, readout electronics, and a sub-kelvin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

LFT and HFT focal plane units using TES

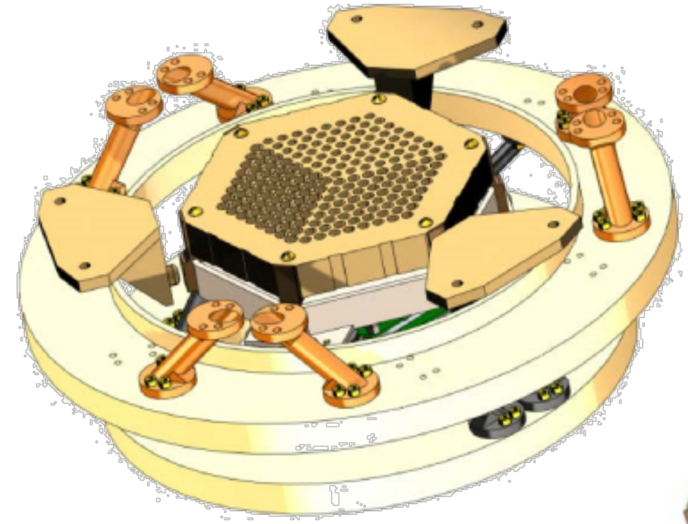
Low frequency focal plane



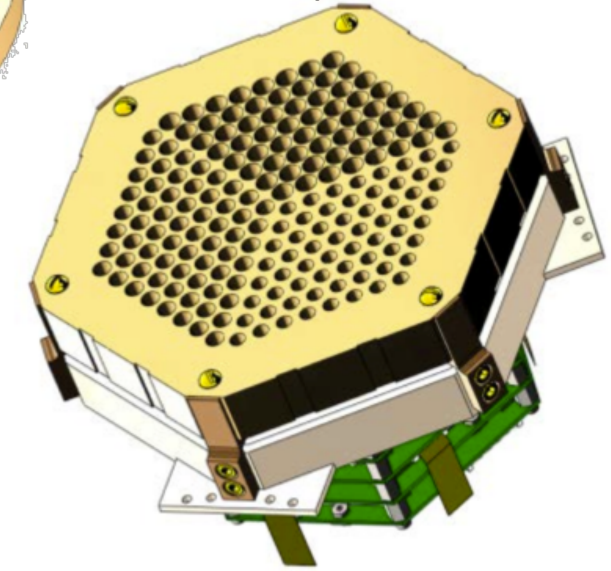
Three colors per pixel with a lenslet coupling.

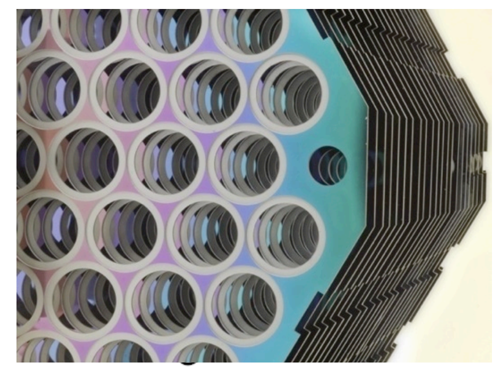


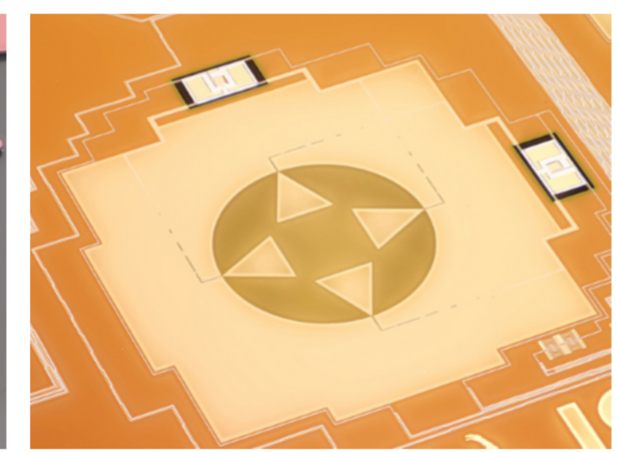
High frequency focal plane



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



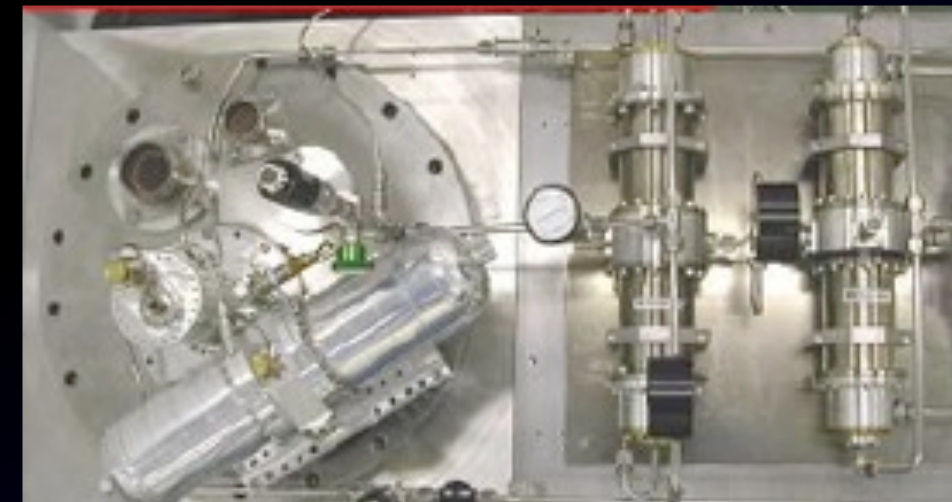




- The current baseline design uses a single ADR to cool the both focal planes.
- The LF focal plane has ** TESs and the HF focal plane has ** TESs.
- The TES is read by SQUID together with the readout electronics is based on the digital frequency multiplexing system.
- The effect of the cosmic ray is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

Slide courtesy Tomo Matsumura (Kavli IPMU)

Cooling system



SHI/JAXA

Cryogenics

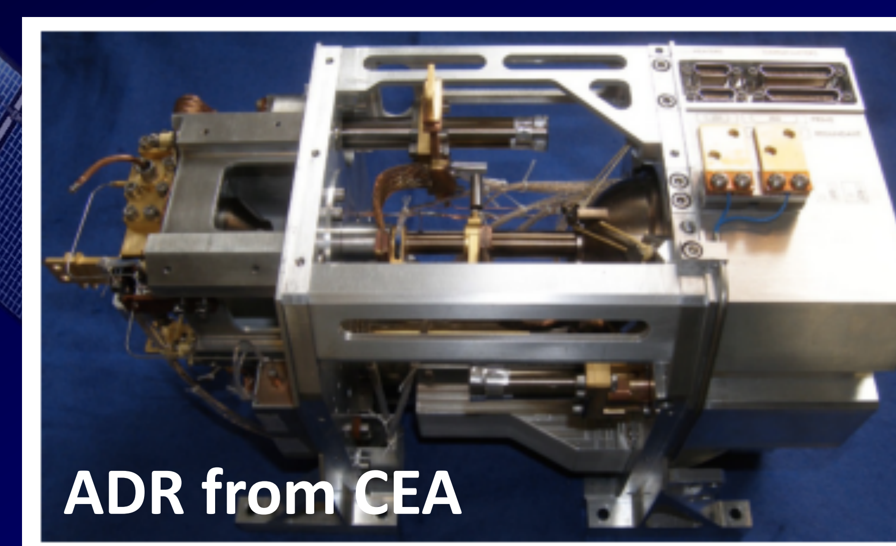
- Warm launch
- 3 years of observations
- 4 K for the mission instruments (optical system)
- 100 mK for the focal plane

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.

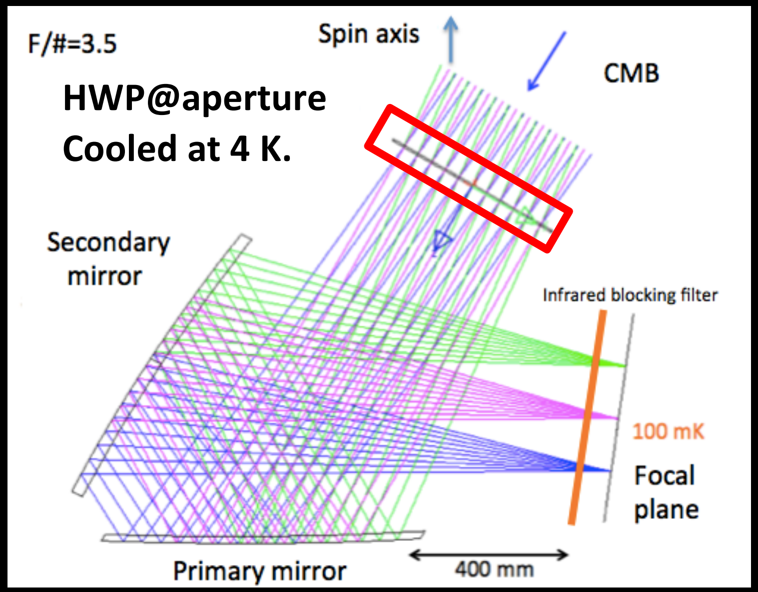
Sub-Kelvin cooler

- 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

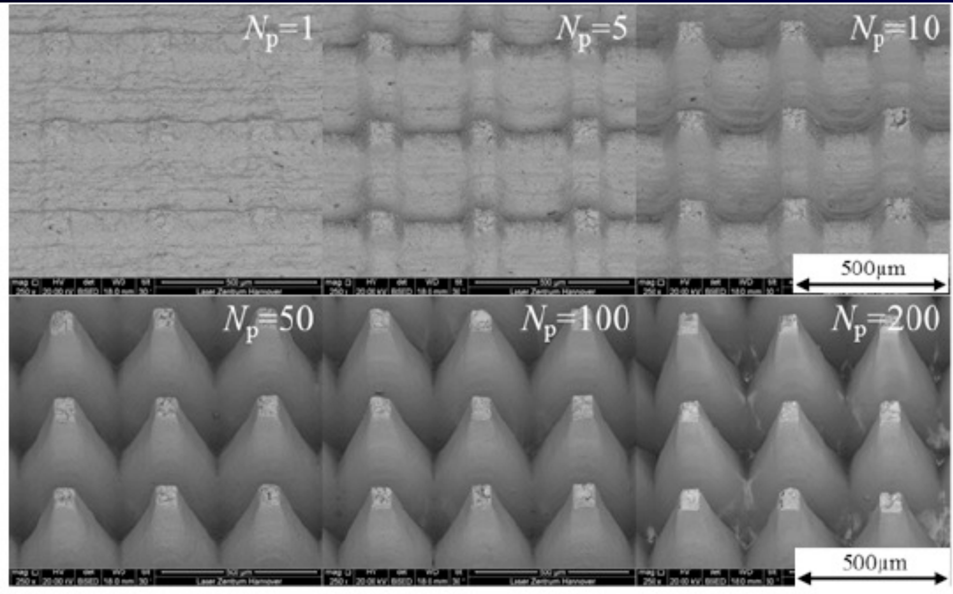


Note: we also employ the polarization modulator for HFT.

- 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

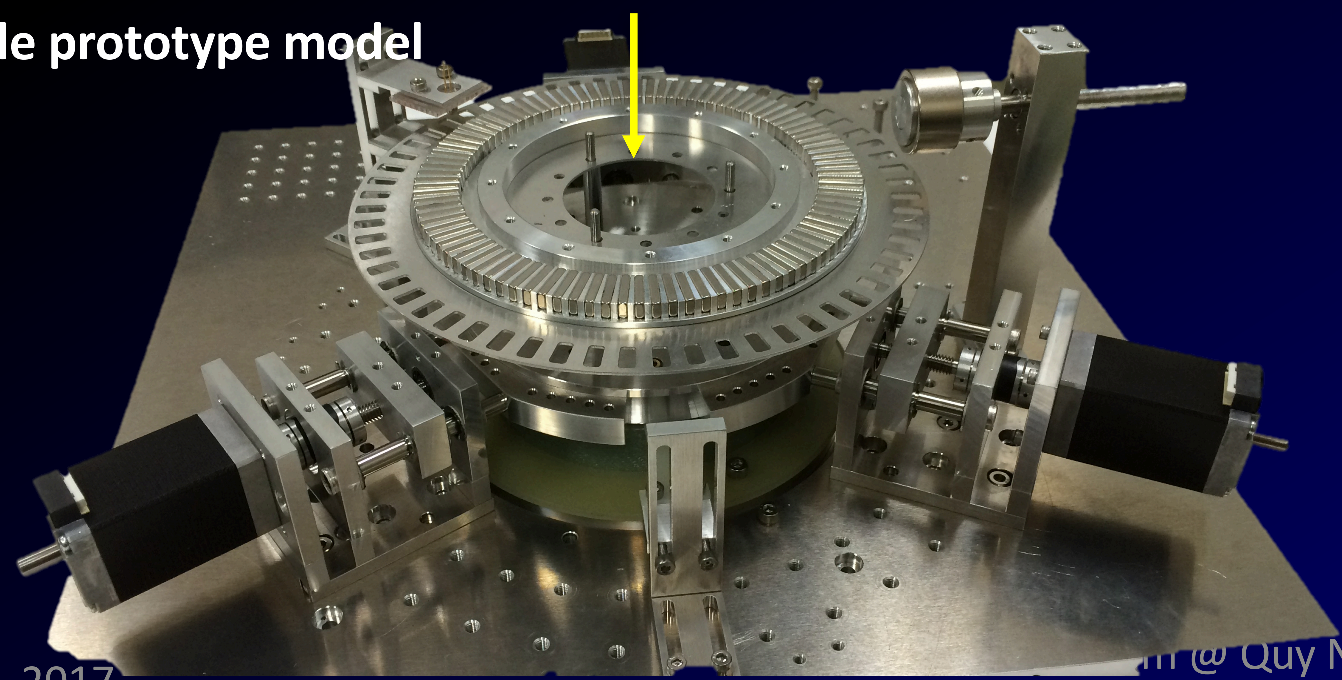
- The broadband coverage is done by the sub-wavelength anti-reflection structure.
- The broadband modulation efficiency is achieved by using 9-layer achromatic HWP.



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.

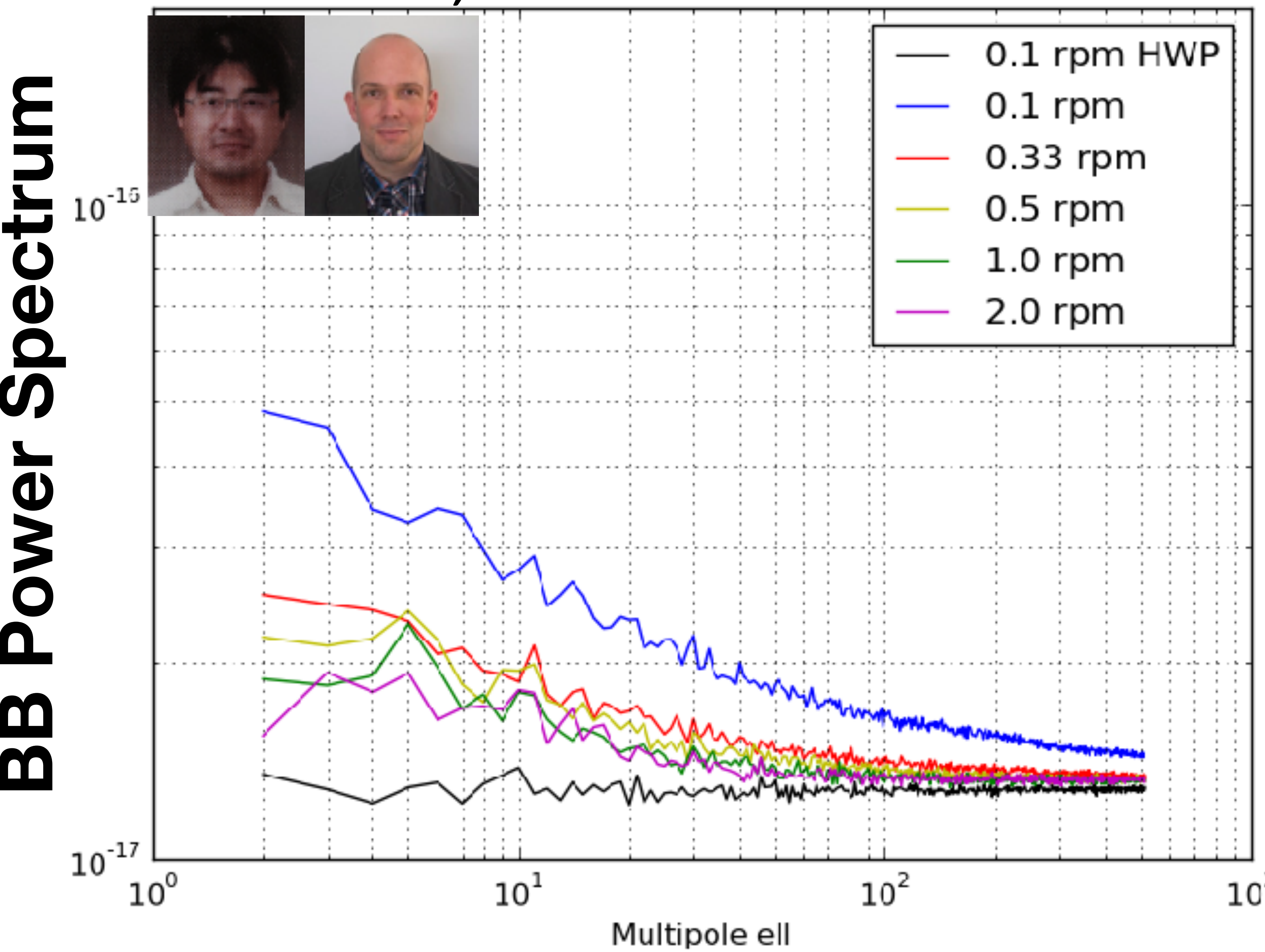
Slide courtesy Tomo Matsumura (Kavli IPMU)

MOVING PARTS??!!

You are a moron…

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

S. Uozumi, T. Kisner



- 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

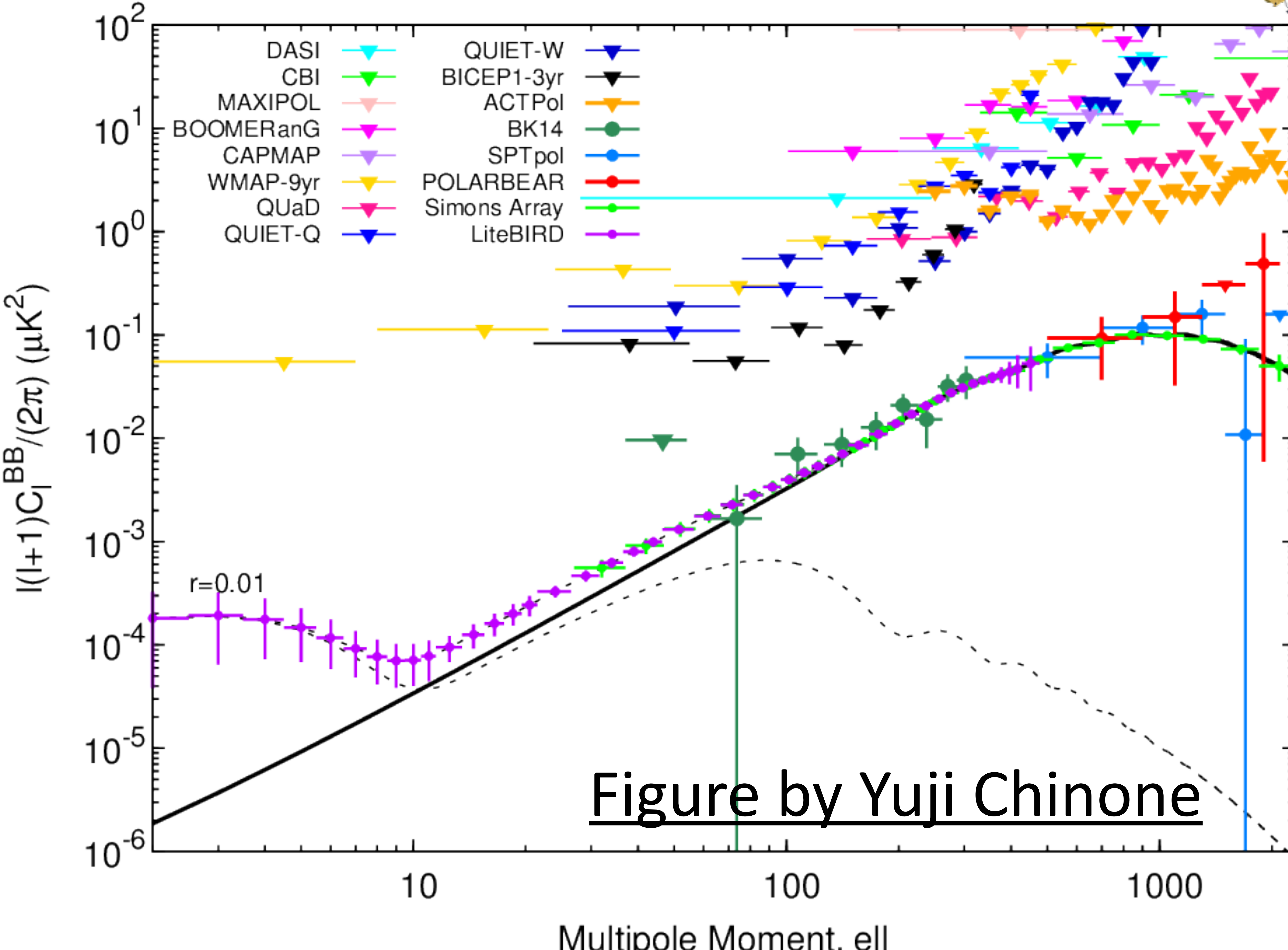
- Single-field inflation looks good: all the CMB data support it

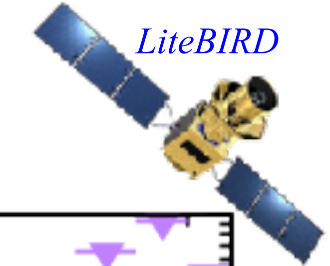
- **Next frontier**: Using CMB polarisation to find GWs from inflation. **Definitive evidence for inflation!**

    - 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

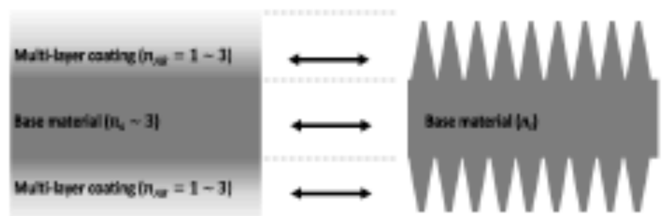
B-mode power spectrum measurements



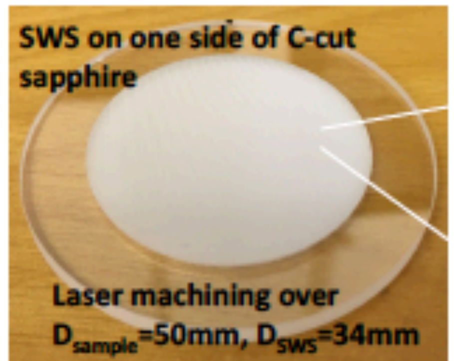


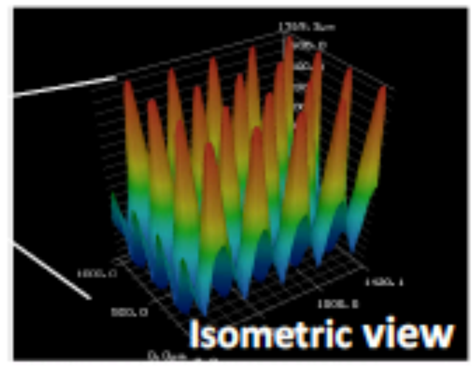
Polarization Modulator

broadband AR coating and polarization modulation efficiency

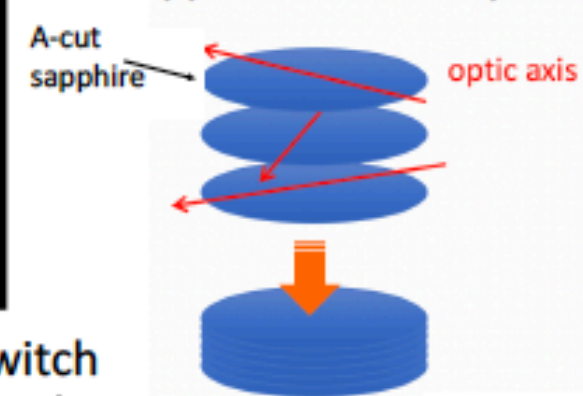


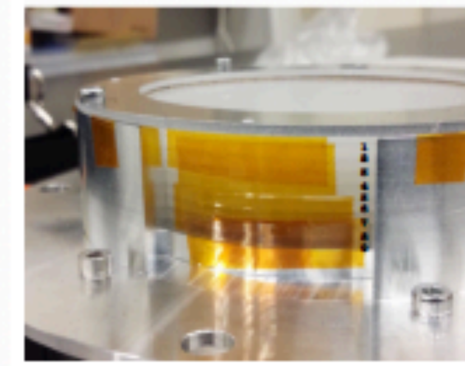
Comparison between the data from the one-side machined sample and the prediction.

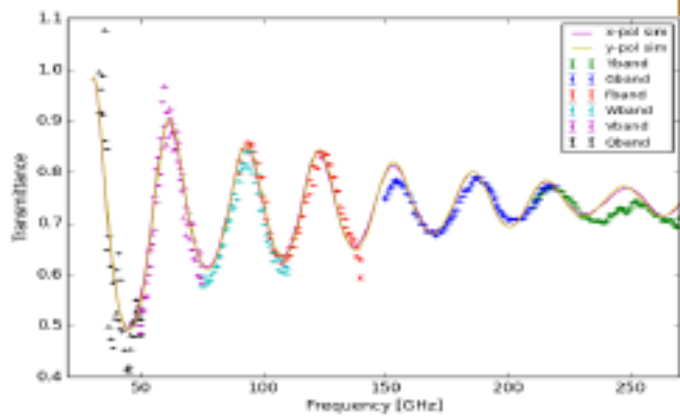


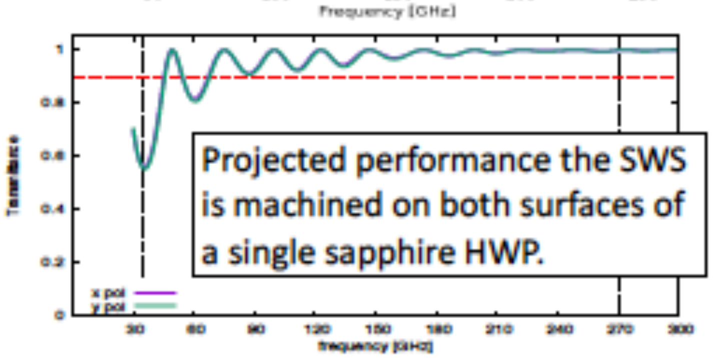


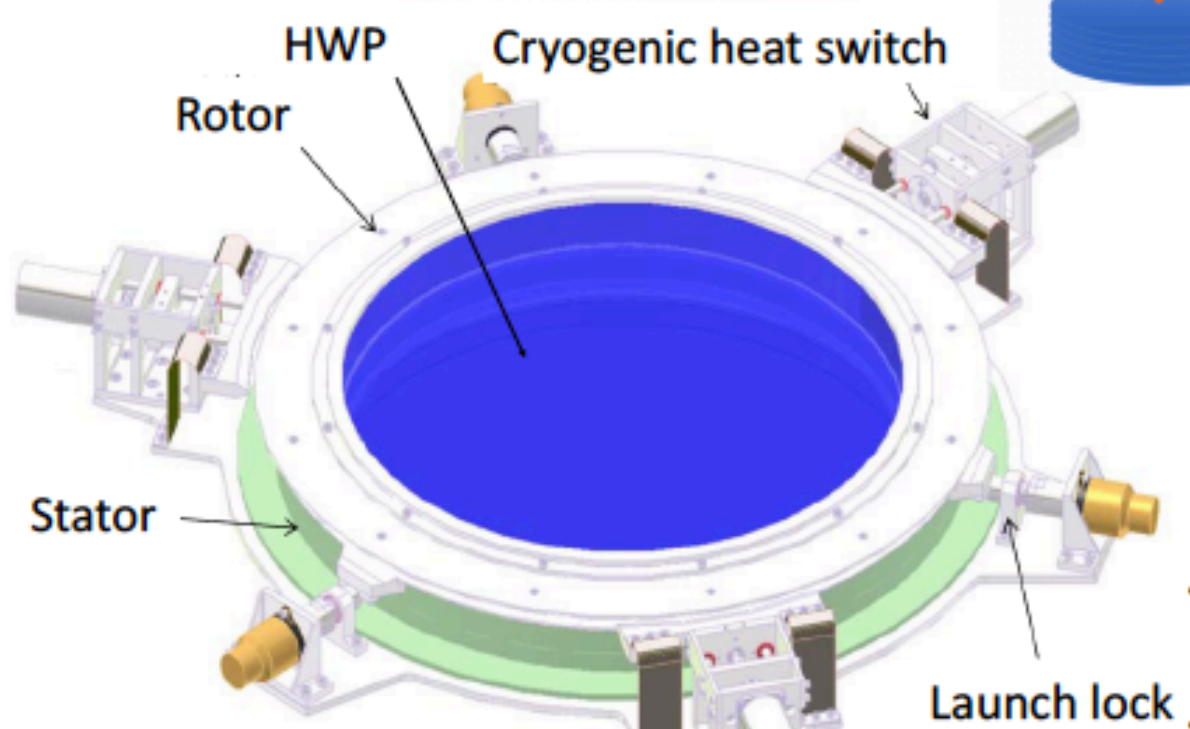
Sapphire based 9 layer achromatic HWP

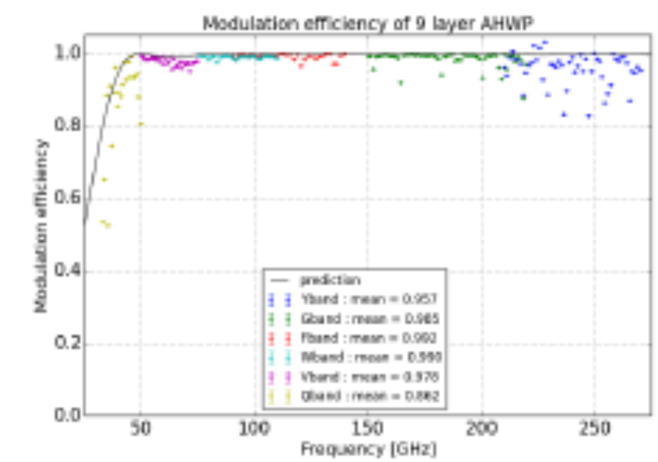












- The measurements of the modulation efficiency using the 9 layer achromatic HWP agree with the predicted curve.
- We have used the sapphire place that is slightly thinner than the one for LFT frequency coverage, and thus the band coverage is higher than that of LFT.
- The ripped on the data is due to the reflection. The sapphire in this measurement has no AR coating.

- We set the goal to achieve below 10 % of reflection at the first step, and we achieved except the below band averaged 60 GHz.
- We now move towards the reflection below 1 % by 1) higher aspect ratio and/or optimized SWS shape.
- The further develop is in progress to increase the process speed.

from LTD17 poster (T. Matsumura et al.)