Finding Cosmic Inflation

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YKIS 2018 “*General Relativity: The Next Generation*”
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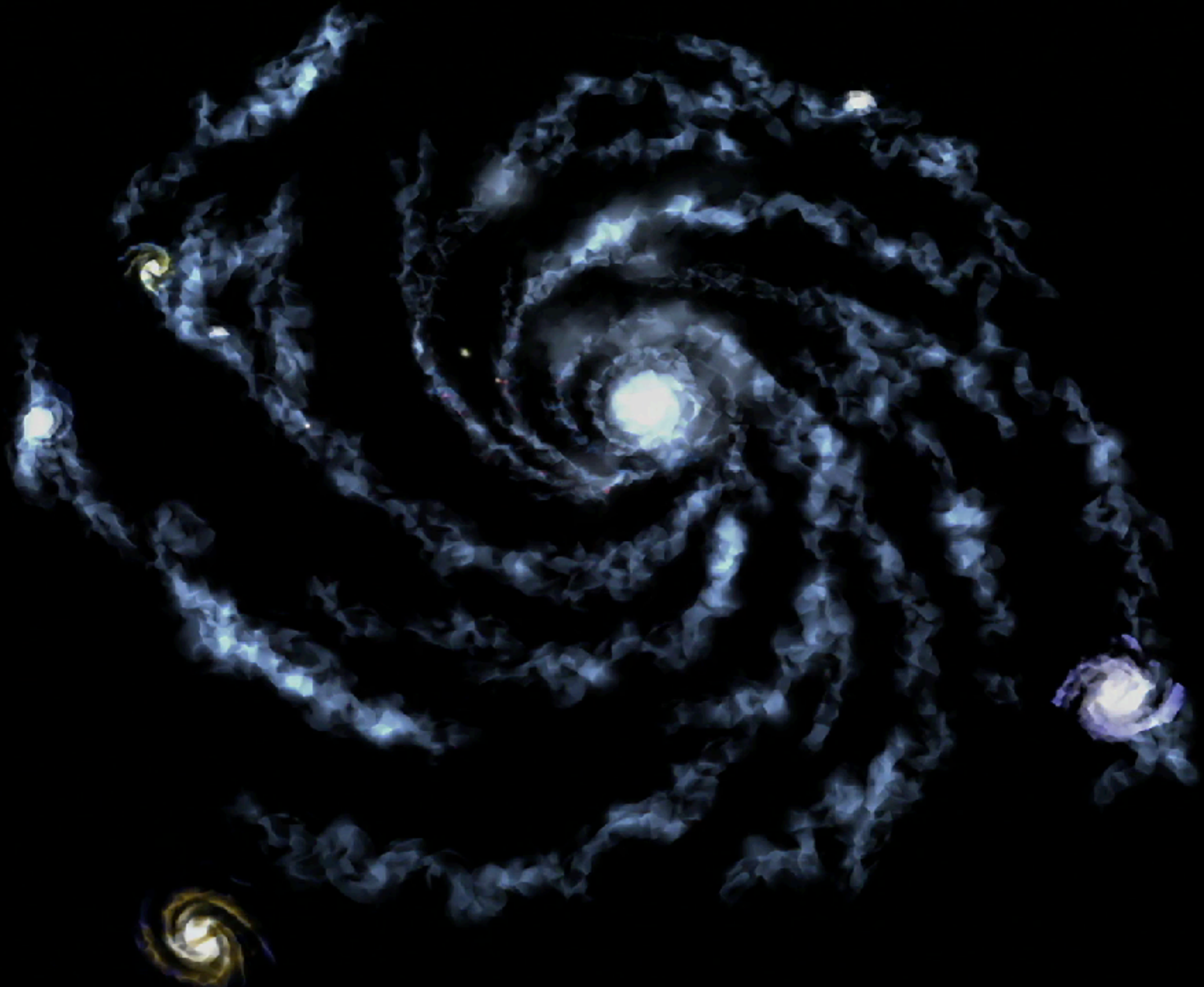
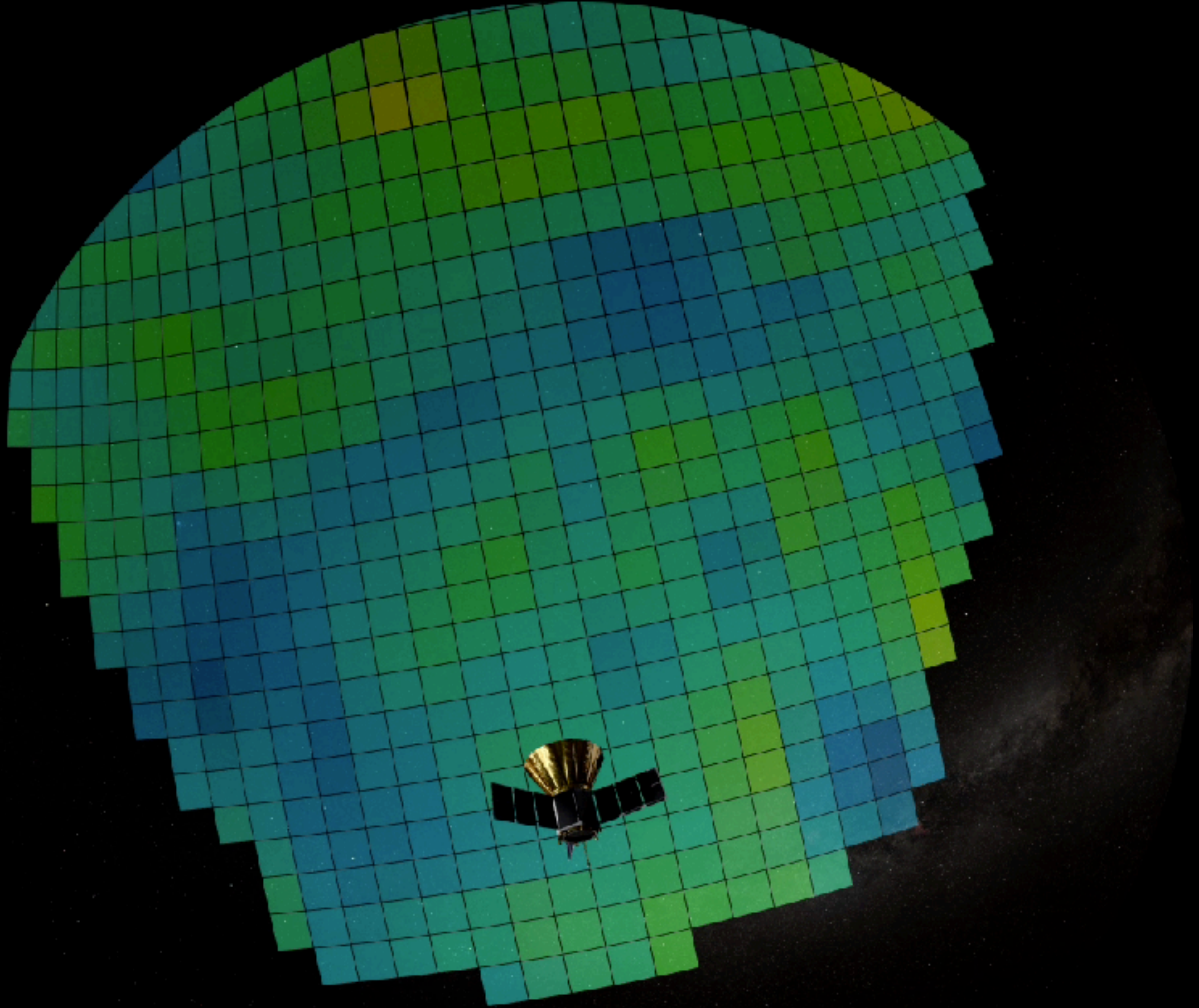


Full-dome movie for planetarium
Director: Hiromitsu Kohsaka

日本語バージョン
「HORIZON～宇宙の果てにあるもの～」
多摩六都科学館（西東京市）
仙台市天文台（仙台市）
鹿児島市立科学館（鹿児島市）
他、で上映中・上映予定

HORIZON
Beyond the Edge of the Visible Universe

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



A Remarkable Story

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

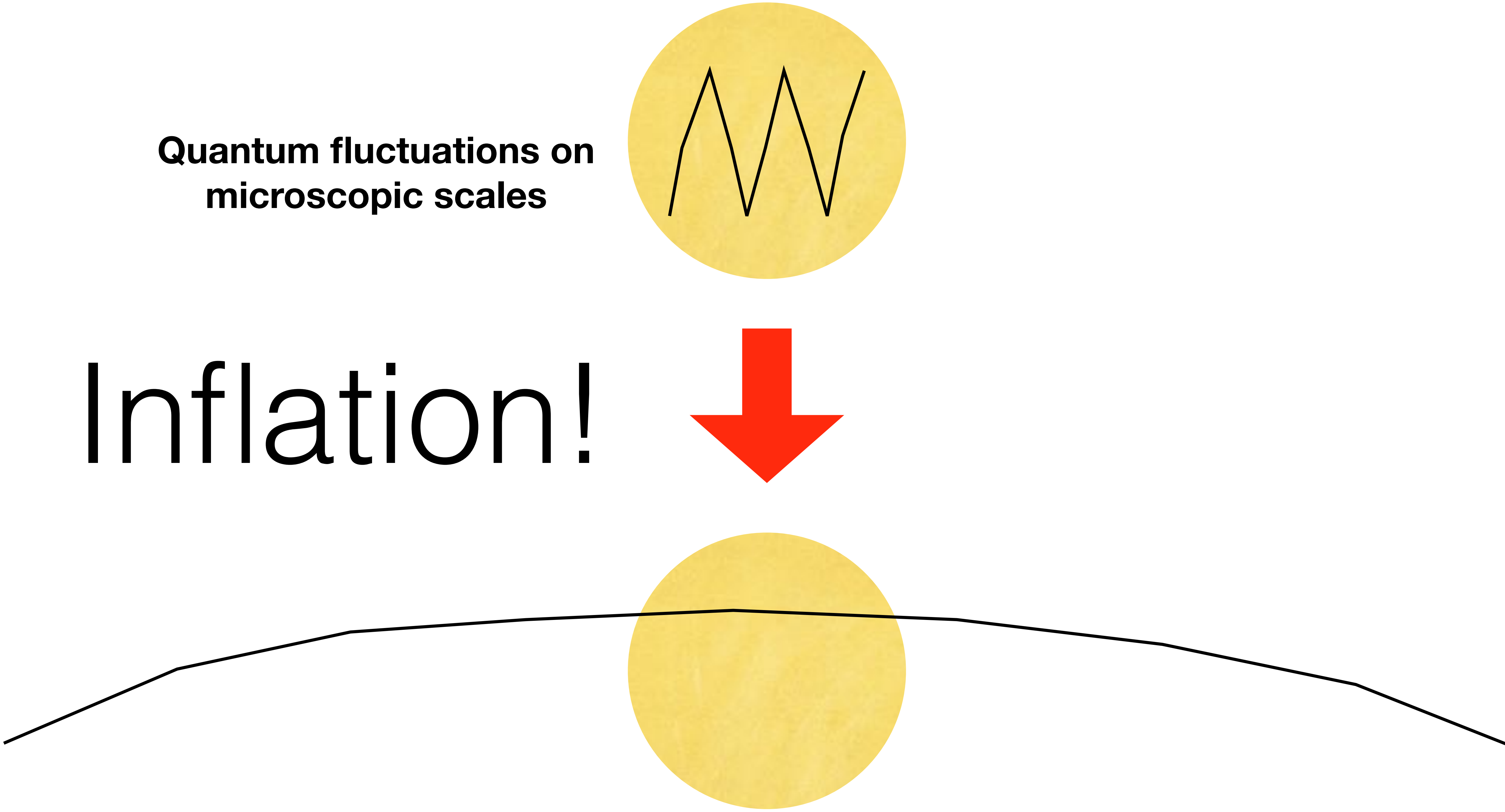
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

Leading Idea

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

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

Cosmic Inflation



Quantum fluctuations on microscopic scales

Inflation!

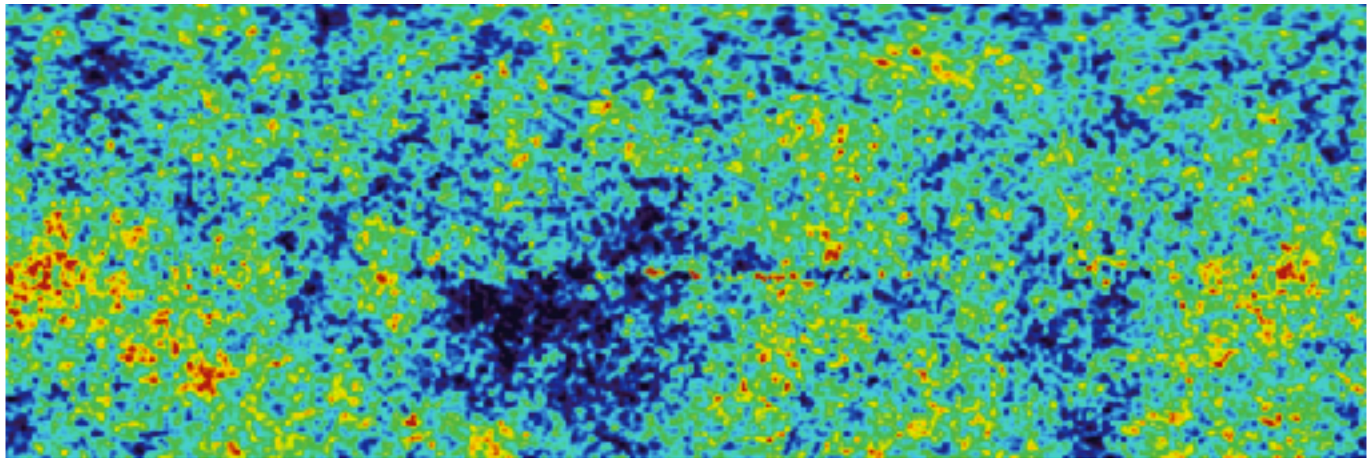
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

Key Predictions

ζ

scalar mode

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



h_{ij}

tensor mode

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

Starobinsky (1979)

We measure distortions in space

- A distance between two points in space

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

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

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

We measure distortions in space

- A distance between two points in space

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

- **ζ** : “curvature perturbation” (scalar mode)
  - Perturbation to the determinant of the spatial metric
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$$\sum_i h_{ii} = 0$$

Finding Inflation

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

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

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

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

Have we found inflation?

- *Have we found ε << 1?*

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

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

Fluctuations are proportional to H

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

Fluctuations are proportional to H

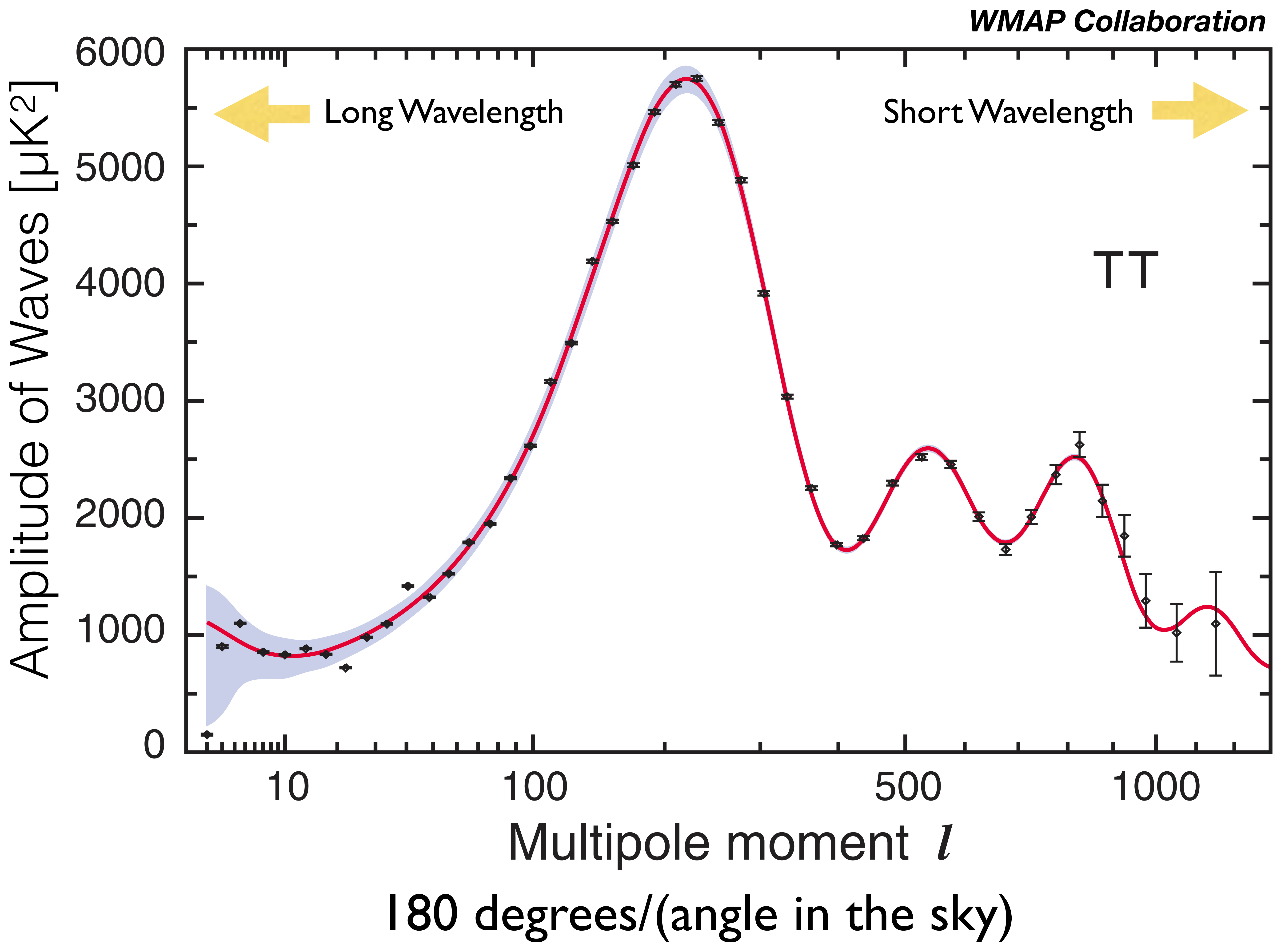
- **We can map H(t) by measuring CMB fluctuations over a wide range of angles**

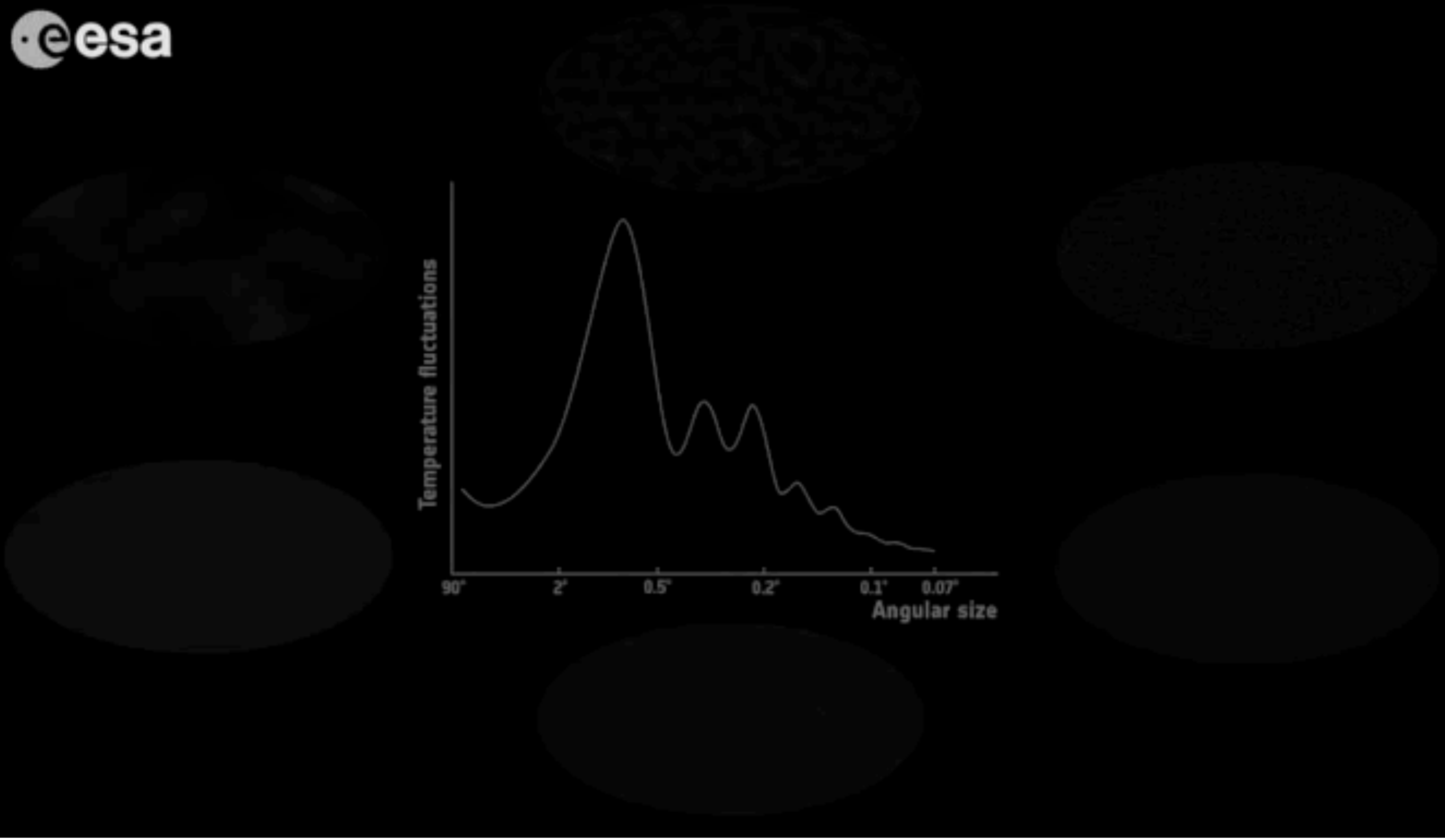
  1. We want to show that the amplitude of CMB fluctuations does not depend very much on angles

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

Data Analysis

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


WMAP Collaboration
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)

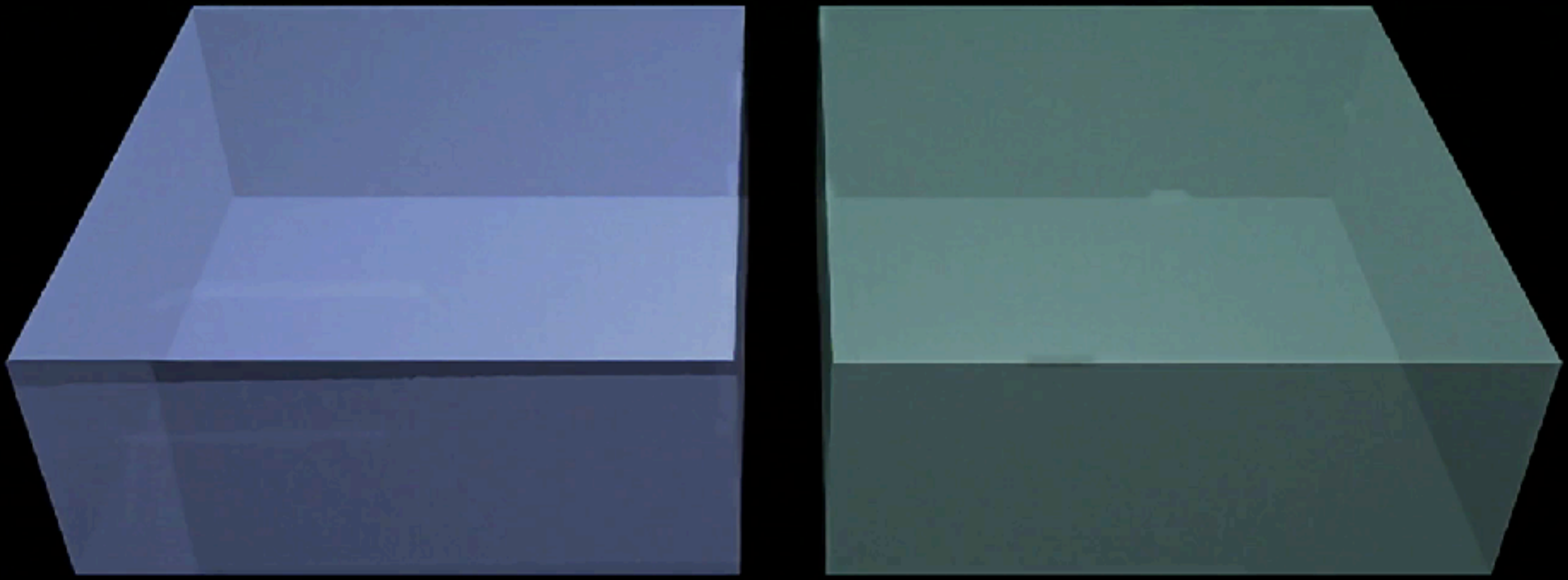

Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size

Cosmic Miso Soup

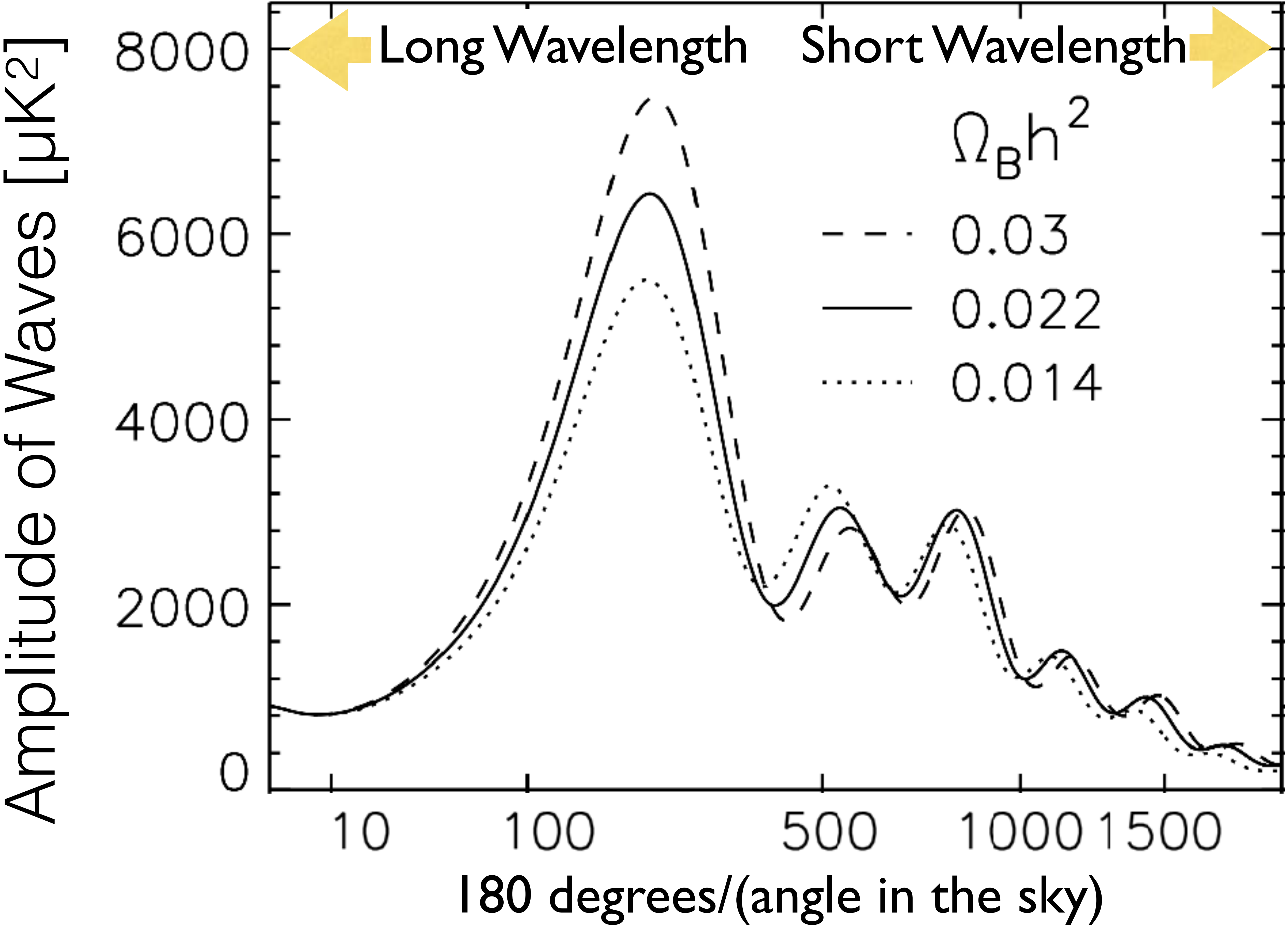
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup

- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso

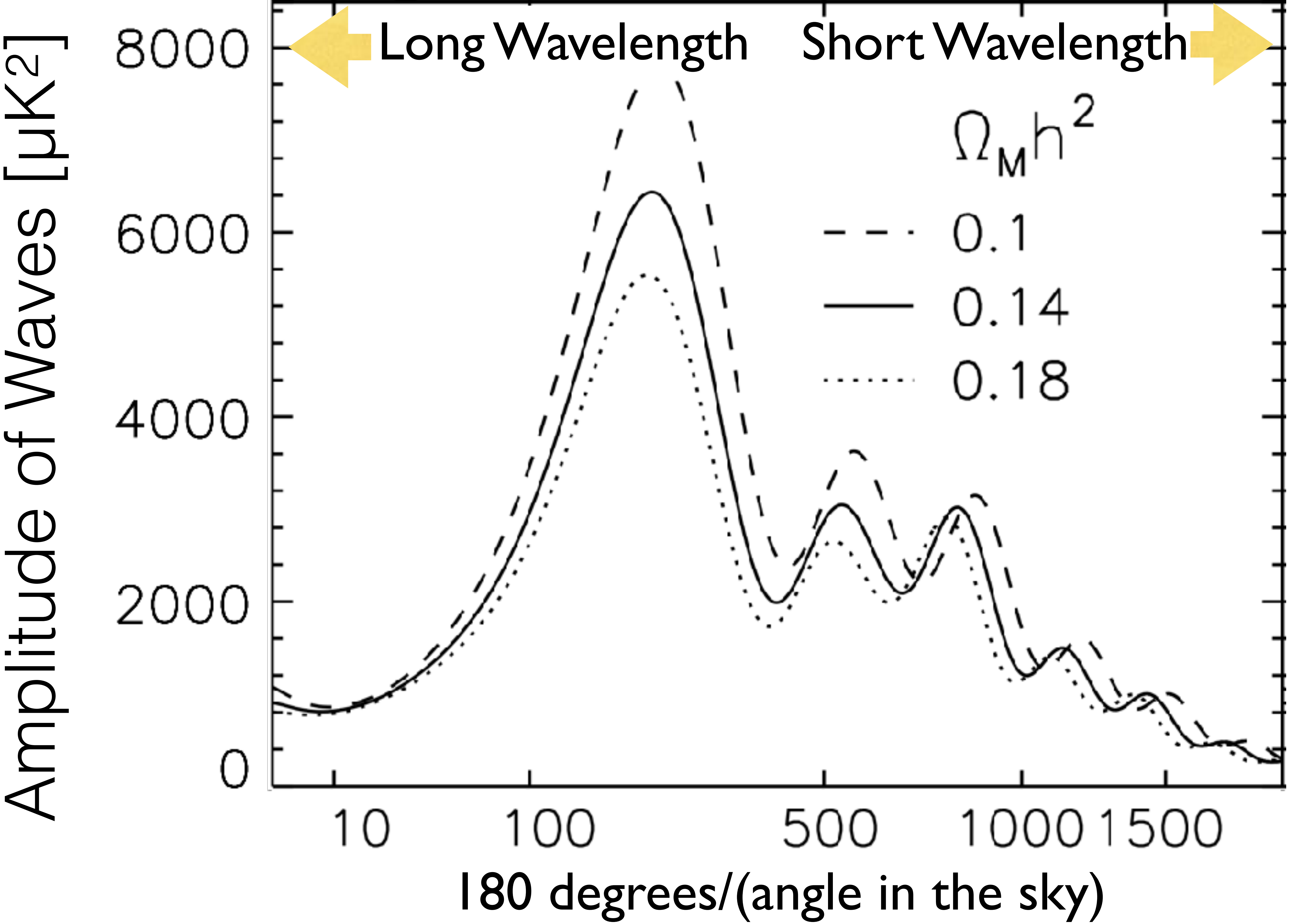
- And imagine watching how ripples are created and propagate throughout the soup



Measuring Abundance of H&He

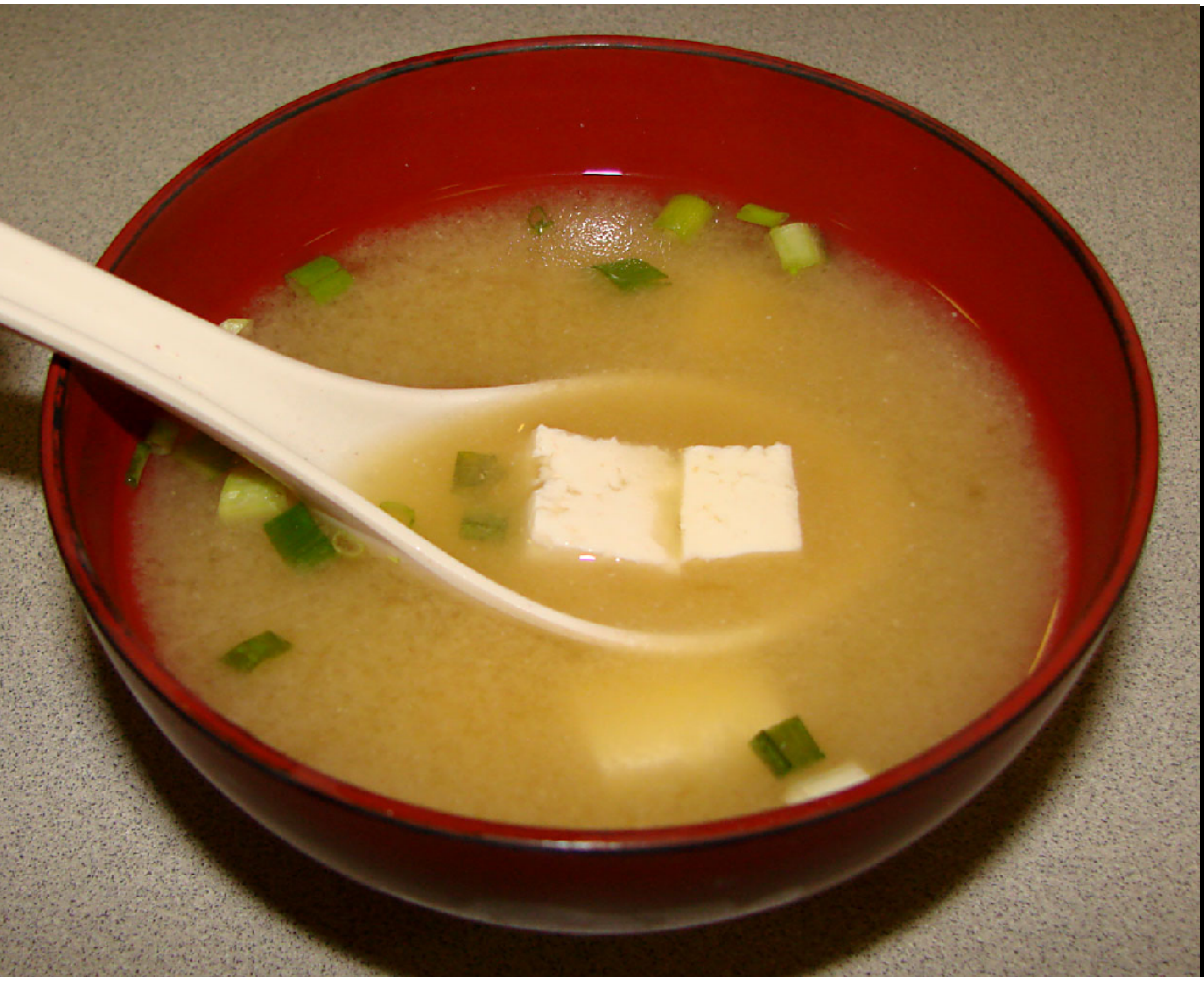


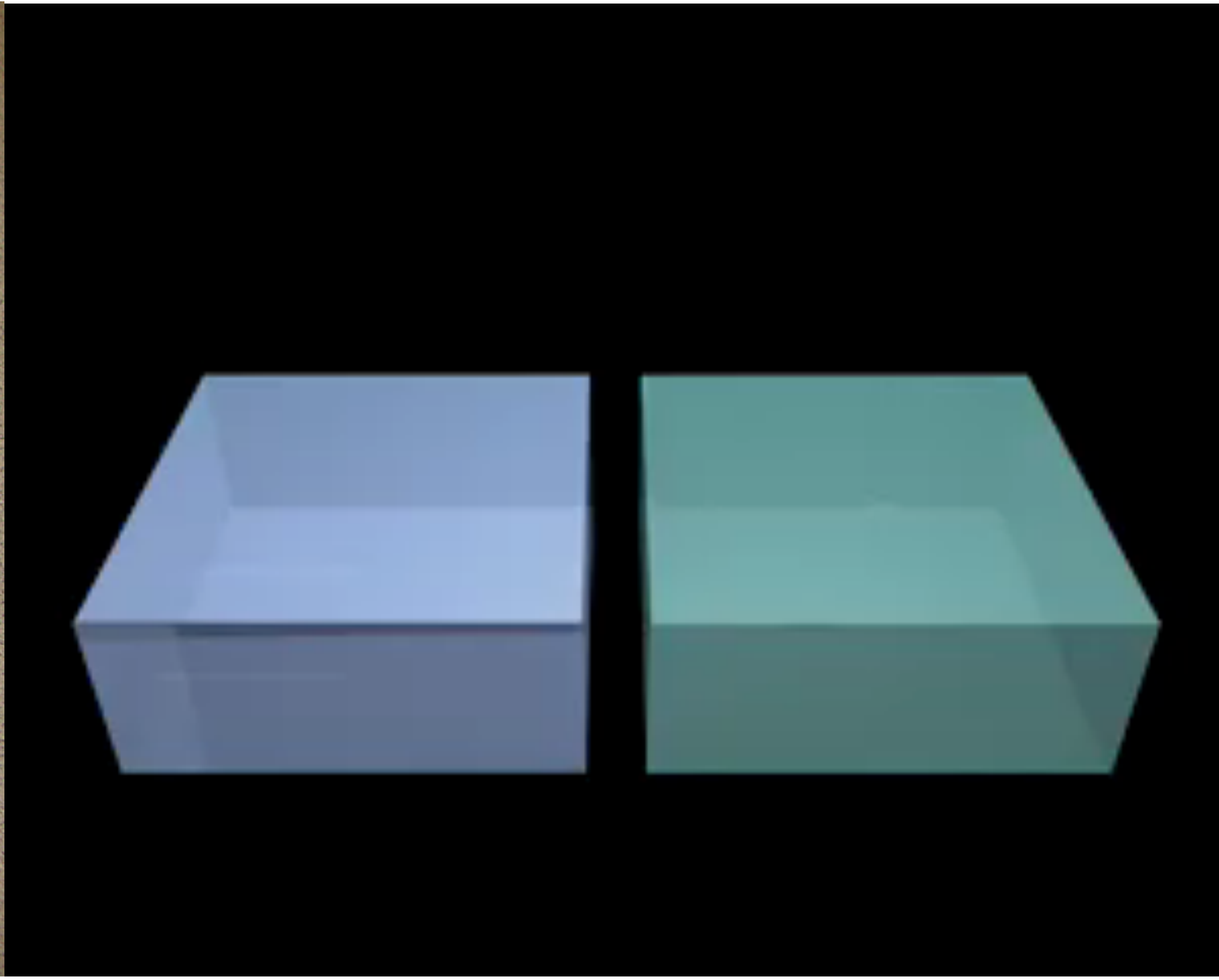
Measuring Total Matter Density



Origin of Fluctuations

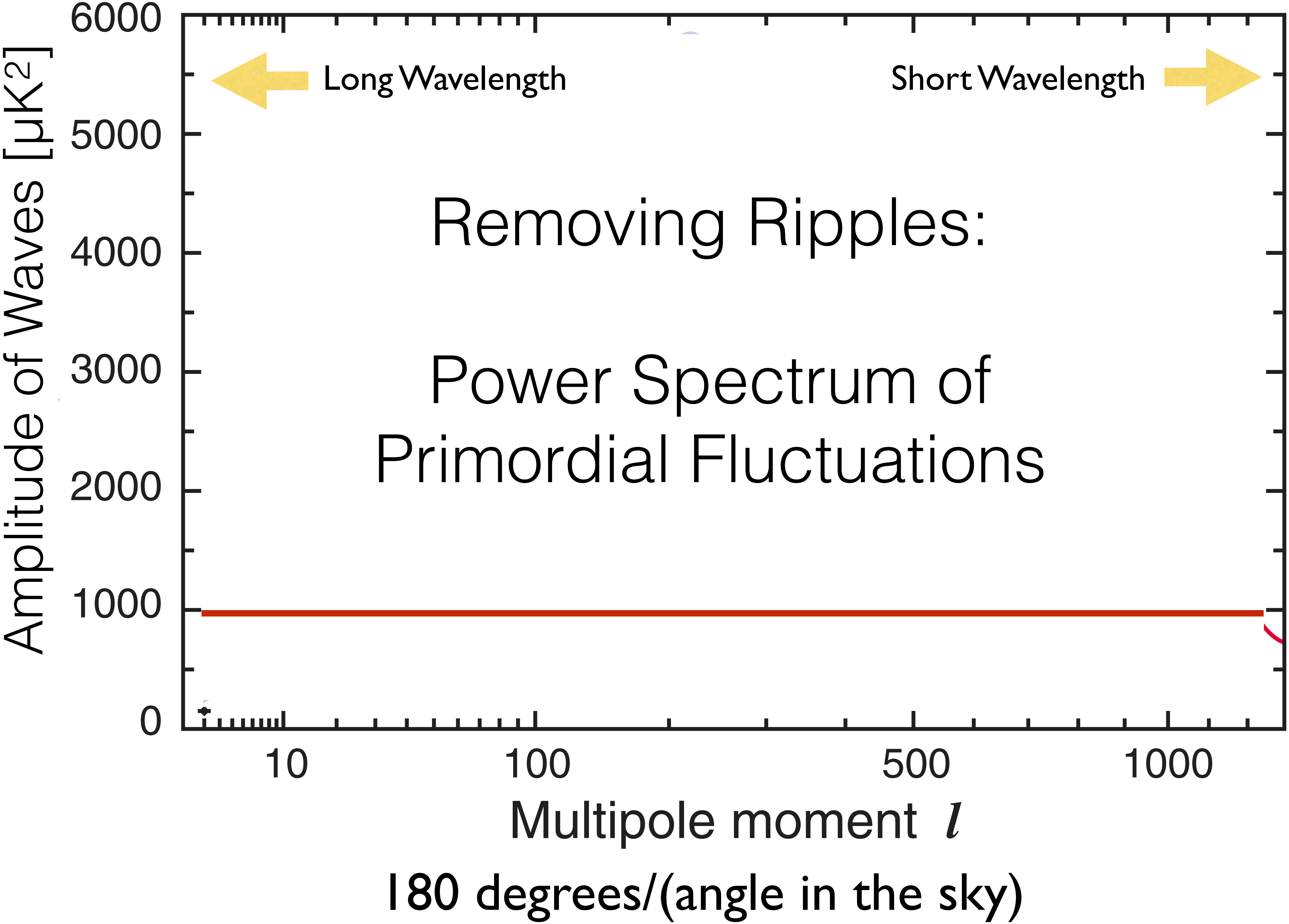
- Who dropped those Tofus into the cosmic Miso soup?

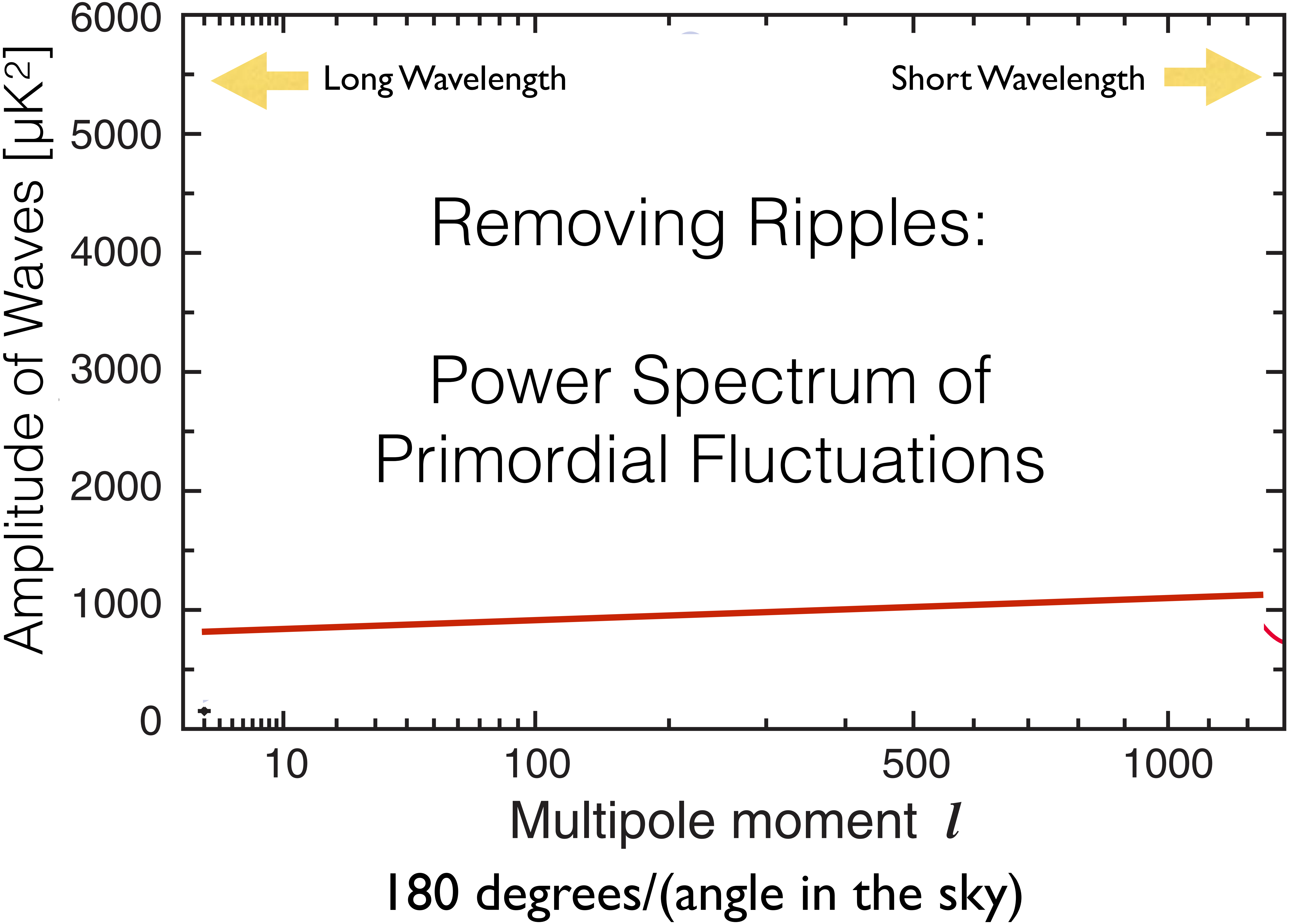




Removing Ripples:

Power Spectrum of Primordial Fluctuations





Removing Ripples:

Power Spectrum of Primordial Fluctuations

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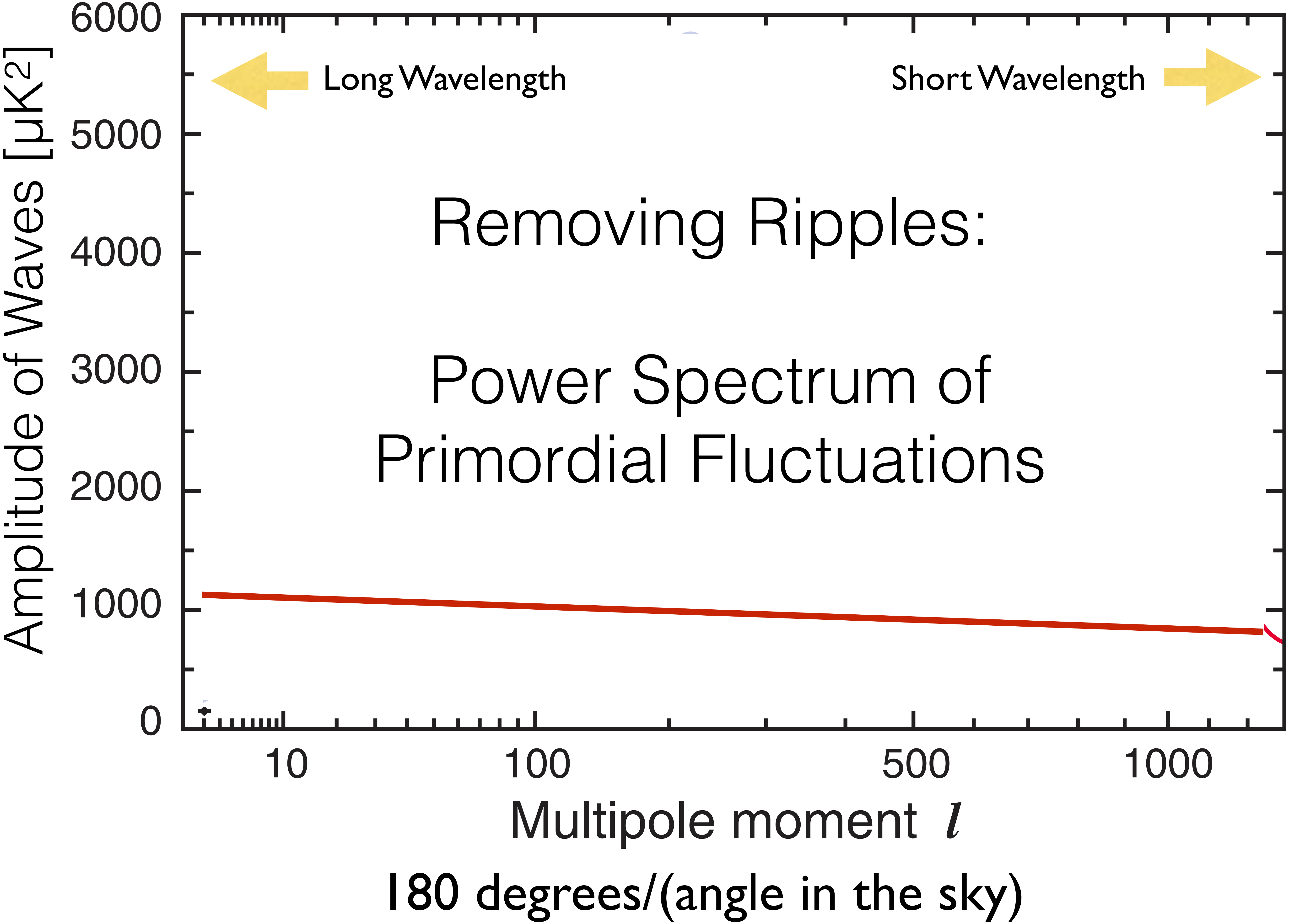
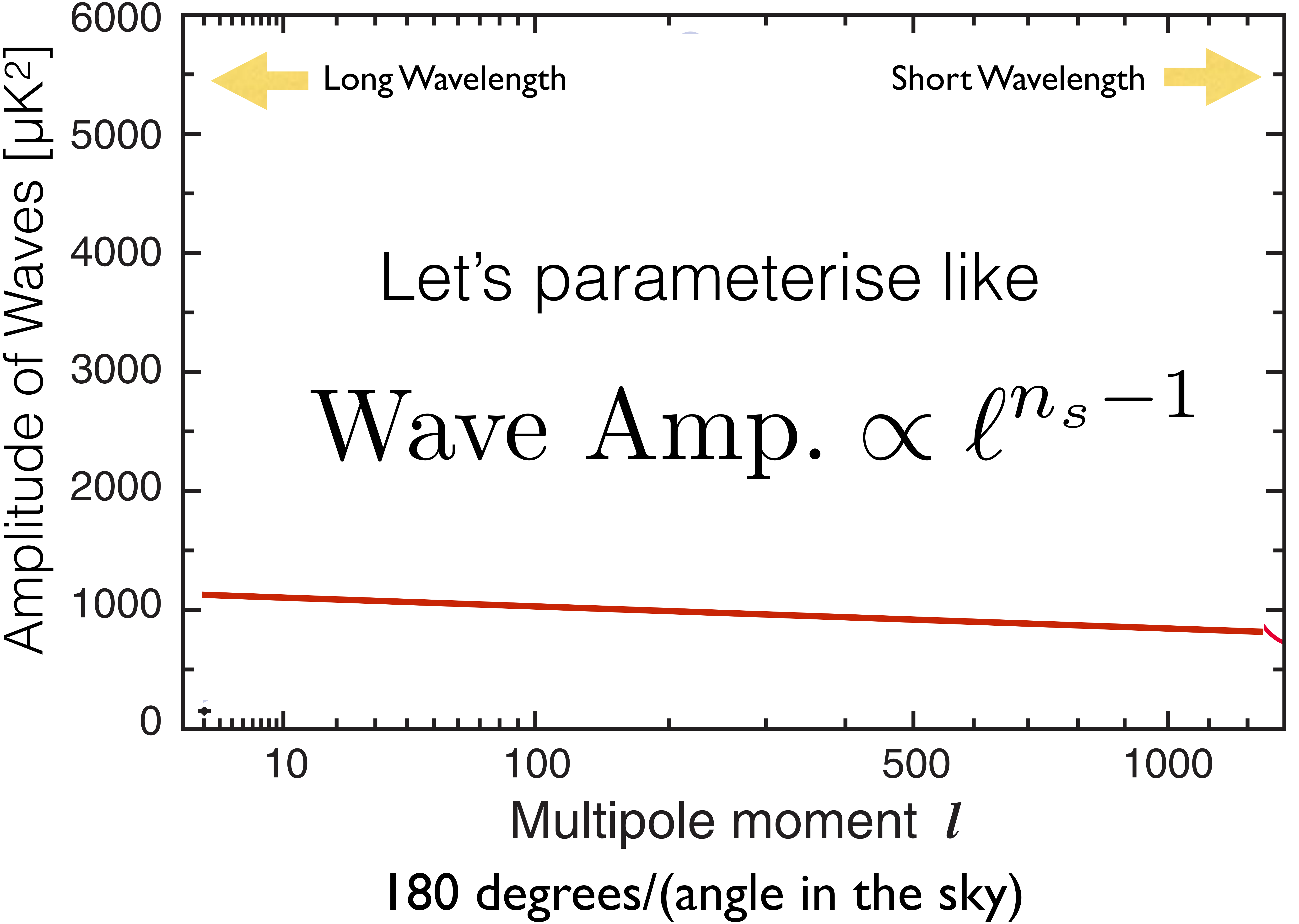
Power Spectrum of Primordial Fluctuations

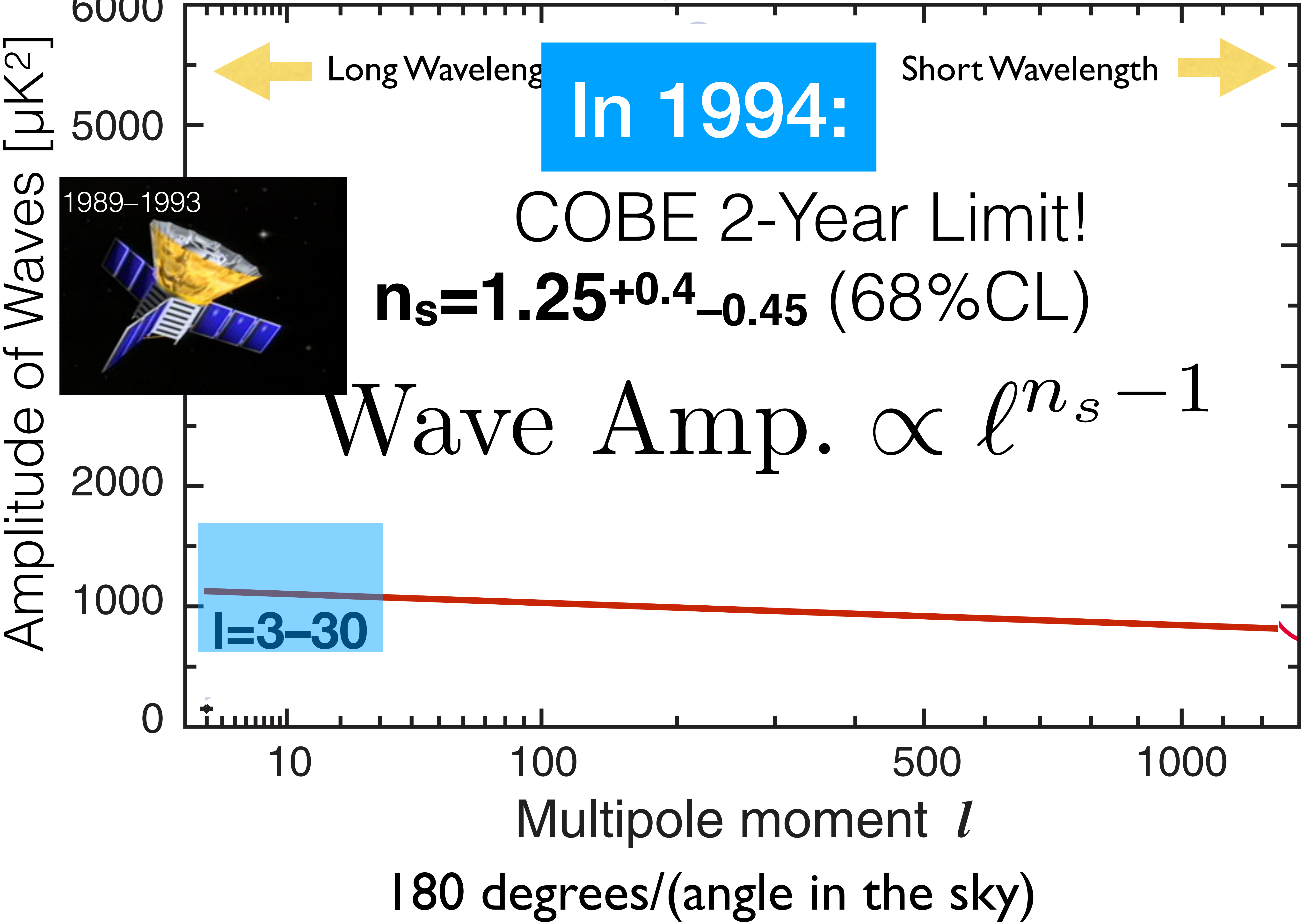




Let's parameterise like

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

Wright, Smoot, Bennett & Lubin (1994)

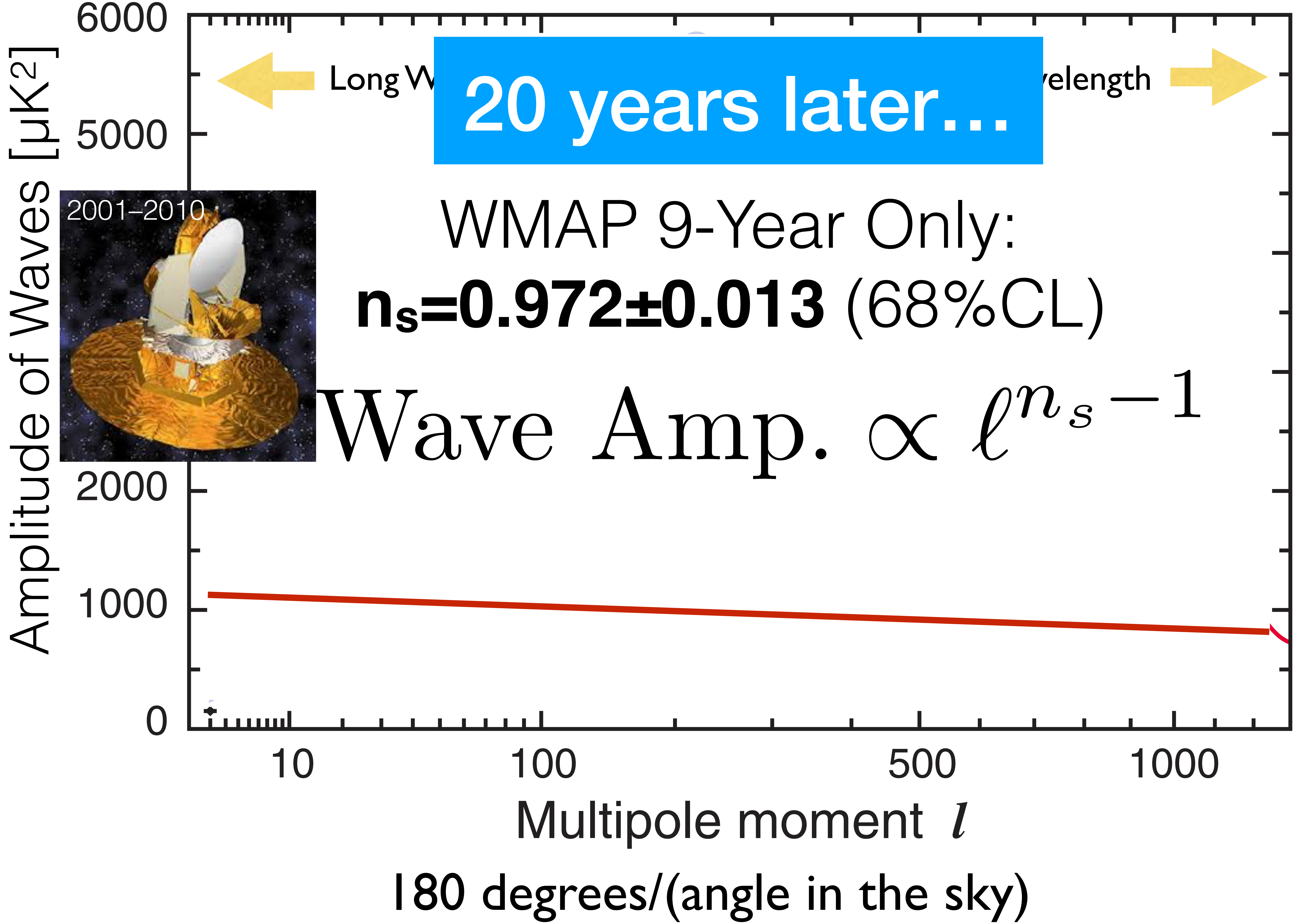


In 1994:

COBE 2-Year Limit!

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

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



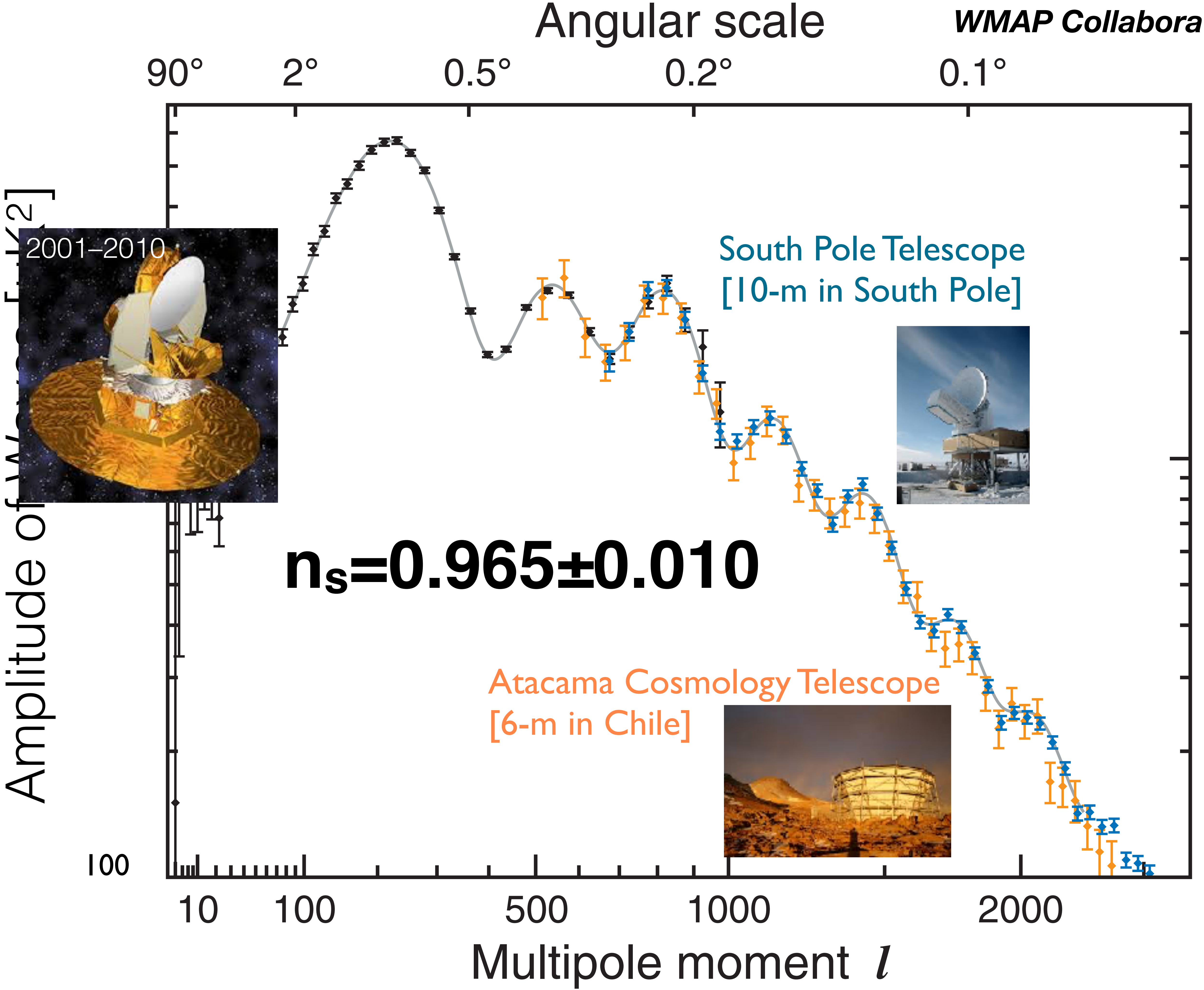
20 years later…

WMAP 9-Year Only:

n_s=0.972±0.013 (68%CL)

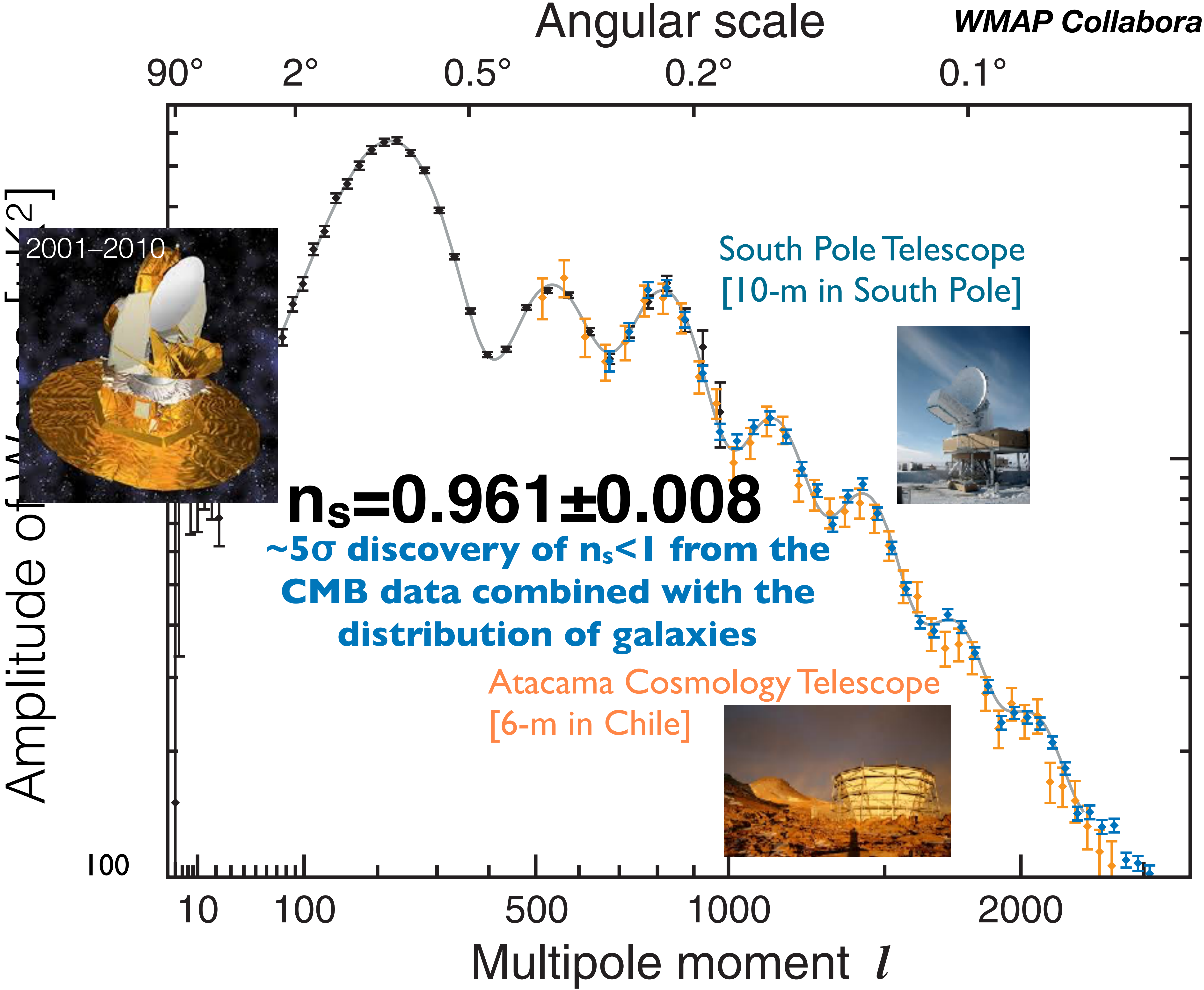
$$\text{Wave Amp.} \propto \ell^{n_s-1}$$

WMAP Collaboration



n_s=0.965±0.010

WMAP Collaboration



n_s=0.961±0.008

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

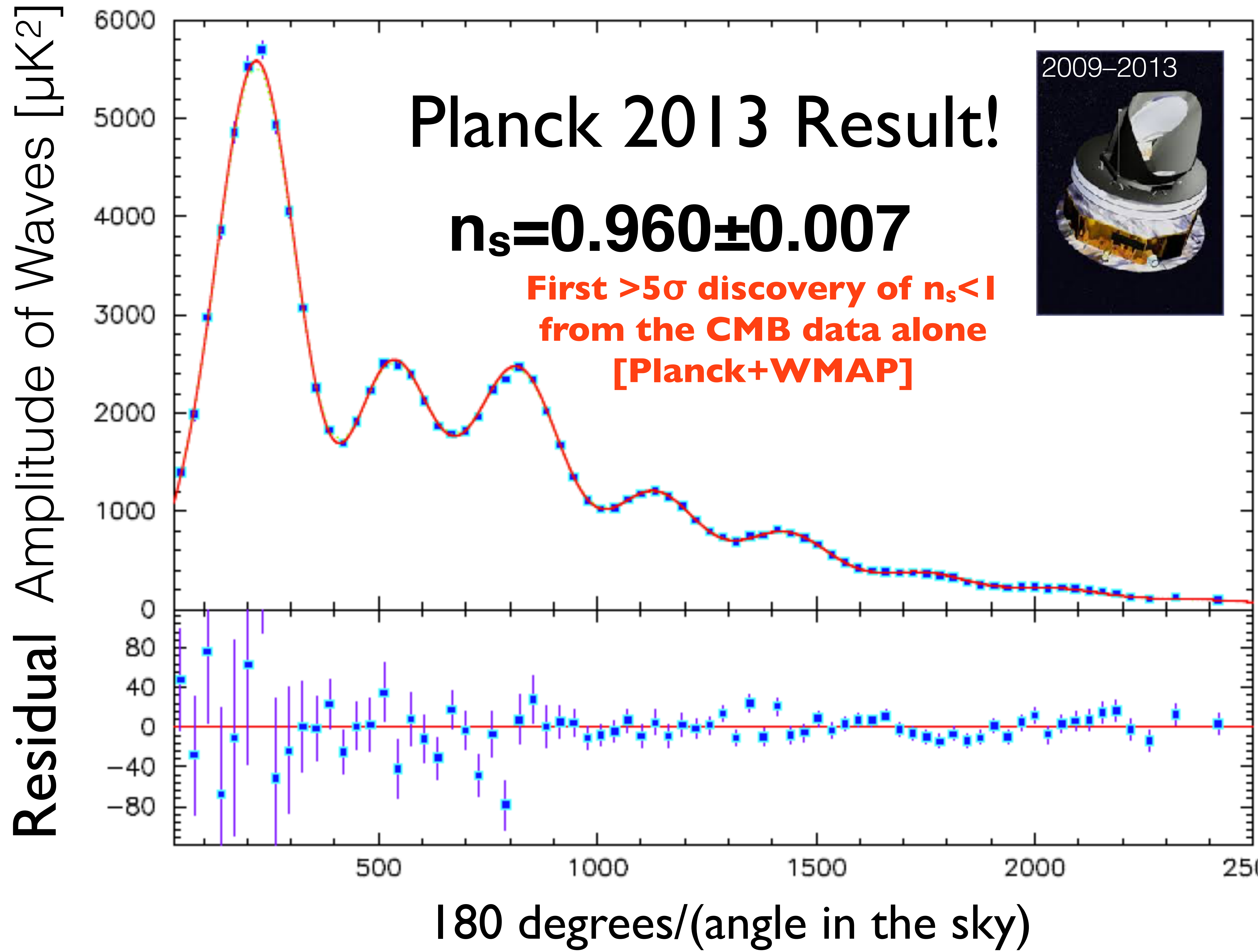
South Pole Telescope
[10-m in South Pole]

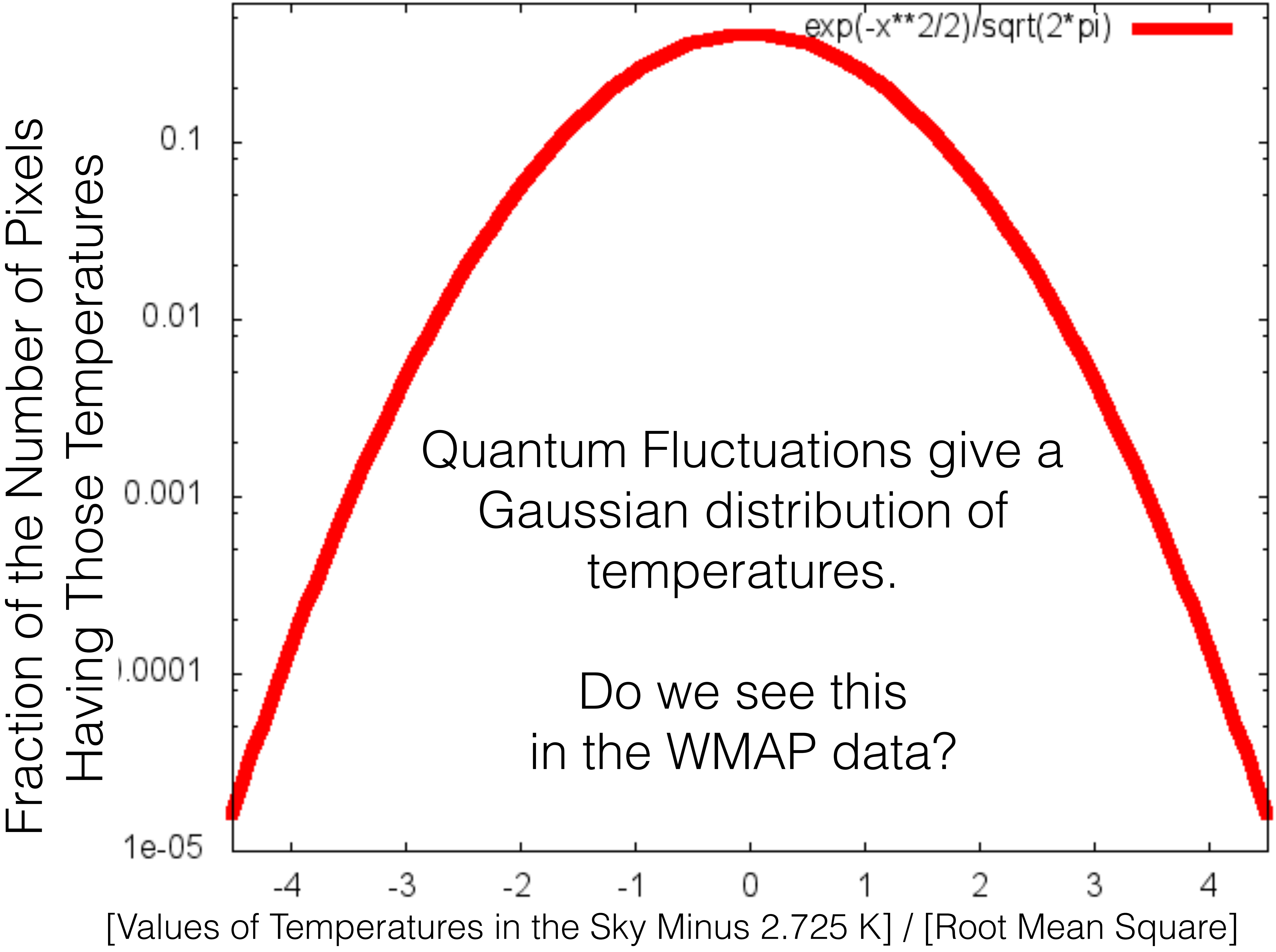
Atacama Cosmology Telescope
[6-m in Chile]

Planck 2013 Result!

$n_s=0.960\pm0.007$

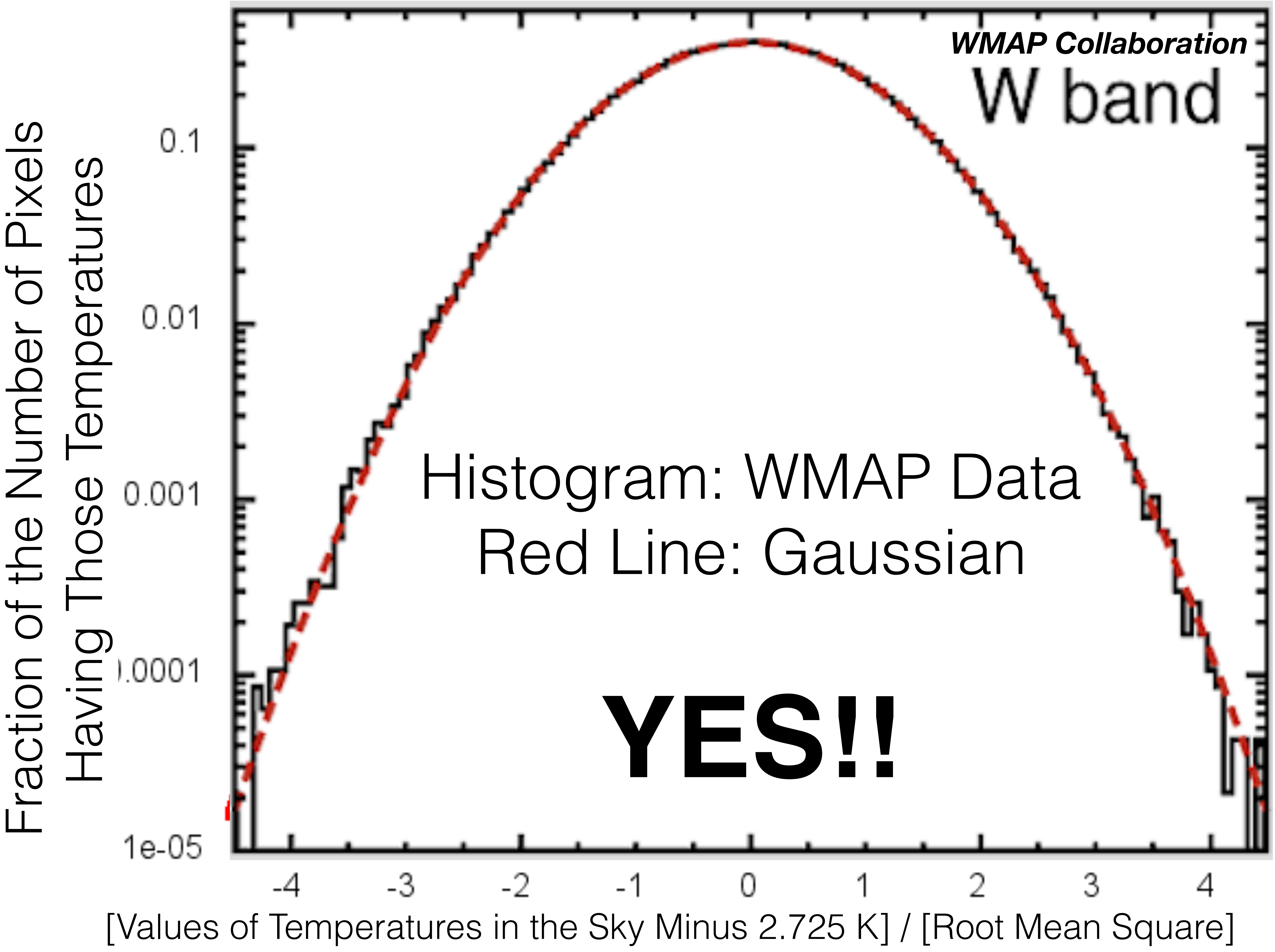
First >5σ discovery of $n_s<1$ from the CMB data alone [Planck+WMAP]





Quantum Fluctuations give a Gaussian distribution of temperatures.

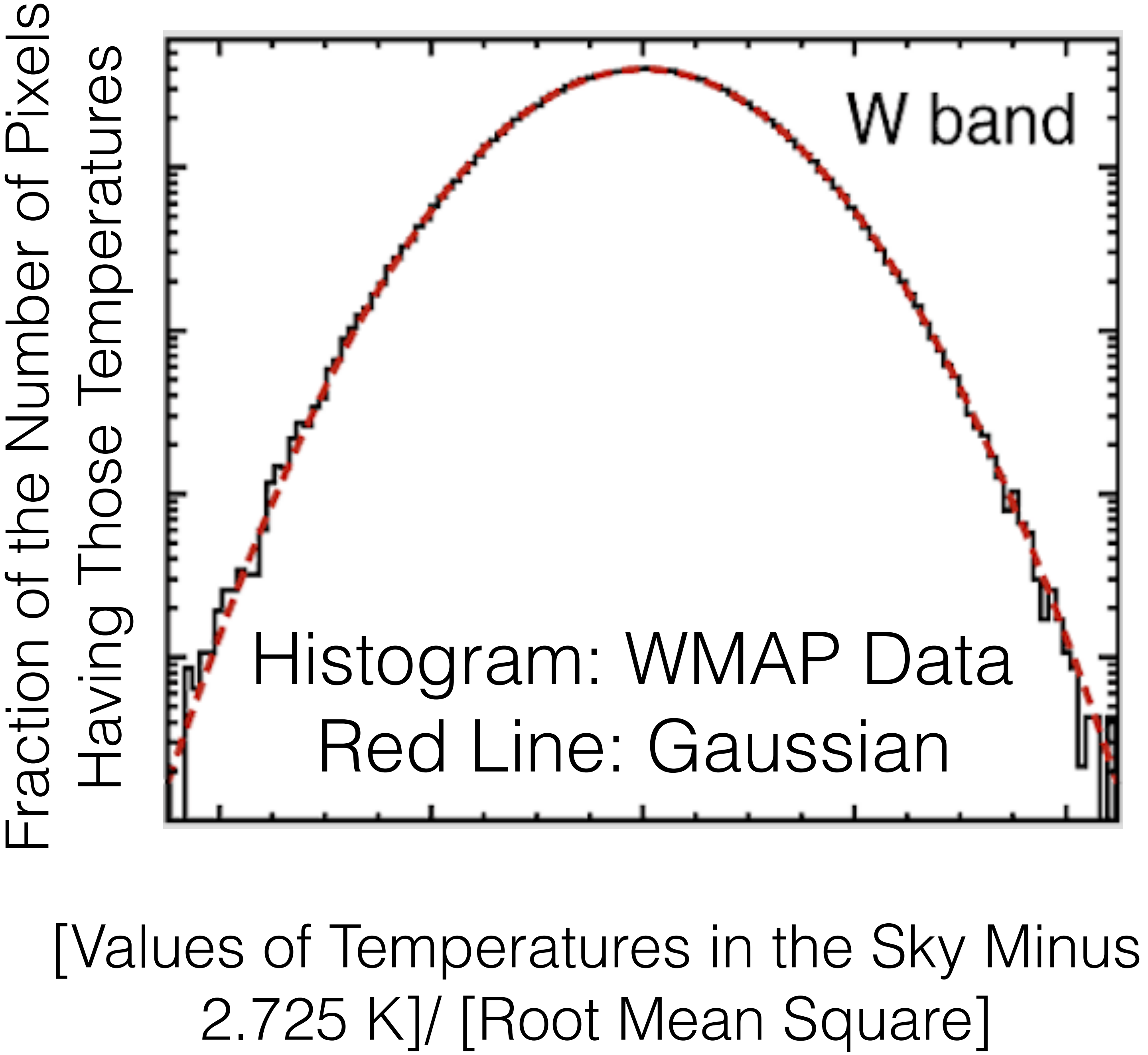
Do we see this in the WMAP data?



Histogram: WMAP Data
Red Line: Gaussian

YES!!

Testing Gaussianity



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

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

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

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

Lack of non-Gaussianity

- The WMAP data show that the distribution of temperature fluctuations of CMB is very precisely Gaussian

  - with an upper bound on a deviation of **0.2%** (95%CL)

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

WMAP 9-year Result

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

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

Planck 2015 Result

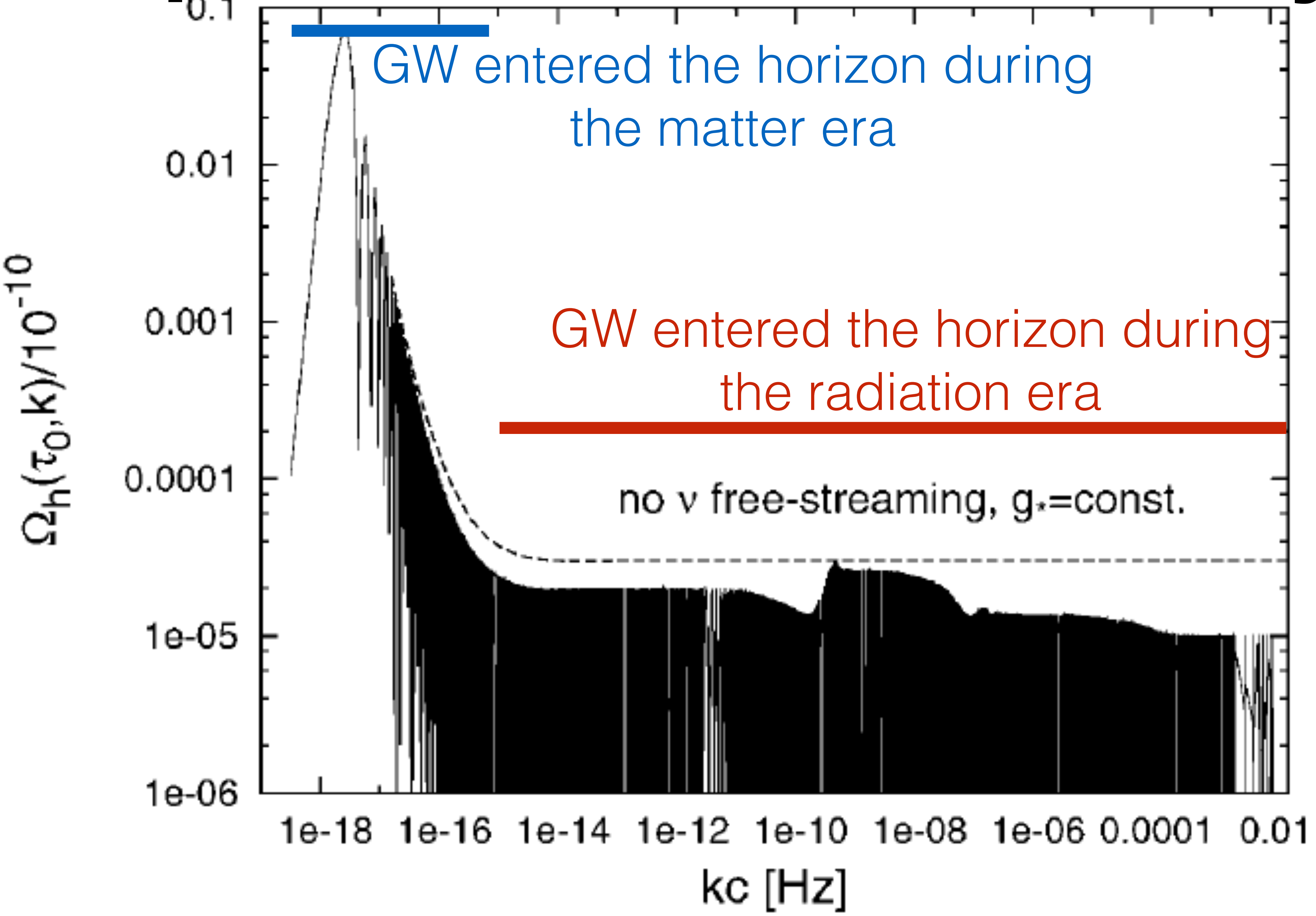
So, have we found inflation?

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

Watanabe & EK (2006)

Theoretical energy density

Spectrum of GW today



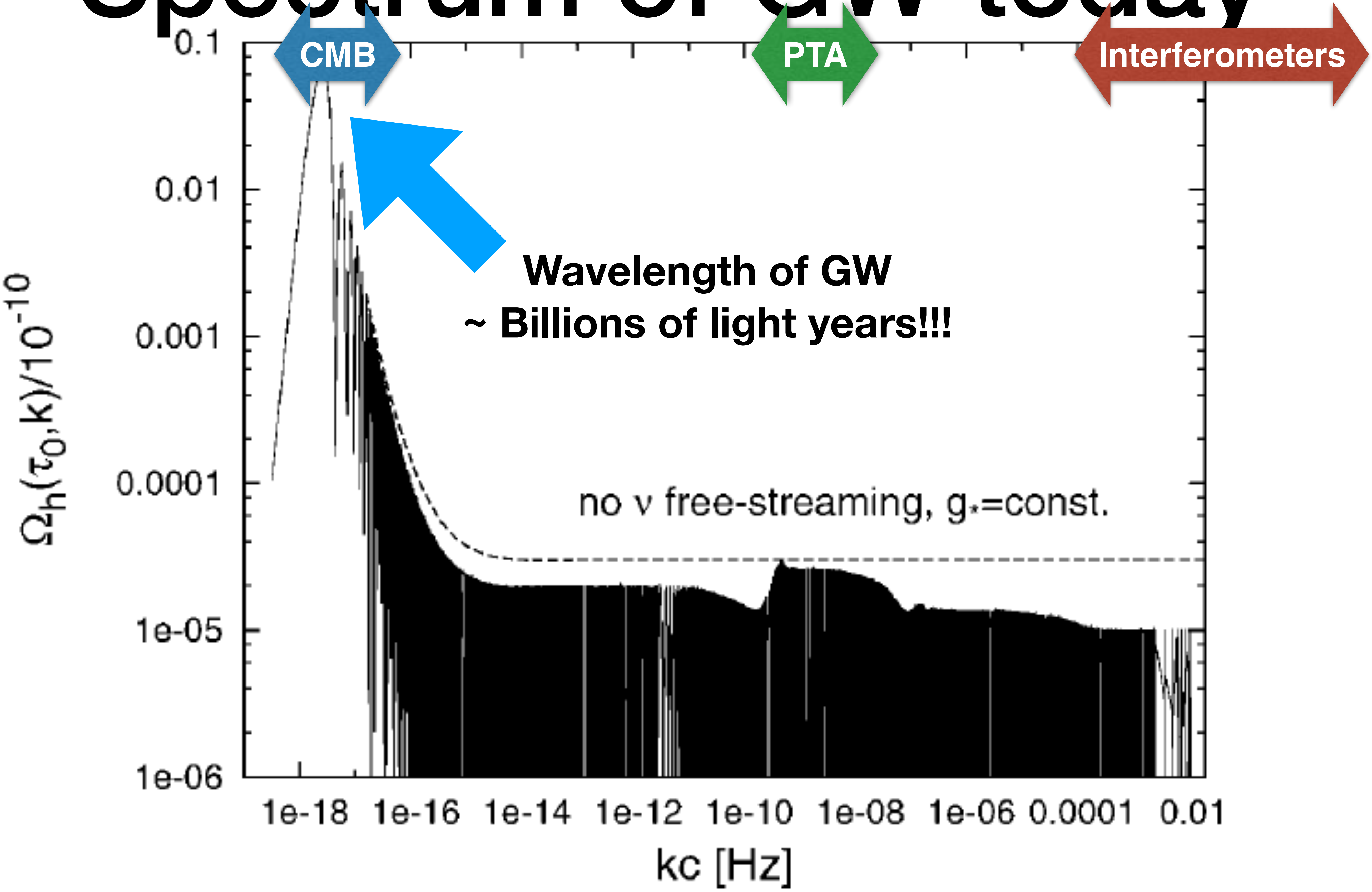
GW entered the horizon during the matter era

GW entered the horizon during the radiation era

Watanabe & EK (2006)

Theoretical energy density

Spectrum of GW today



Wavelength of GW

~ Billions of light years!!!

Finding Signatures of Gravitational Waves in the CMB

- **Next frontier in the CMB research**

1. Find evidence for nearly scale-invariant gravitational waves

New Research Area!

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

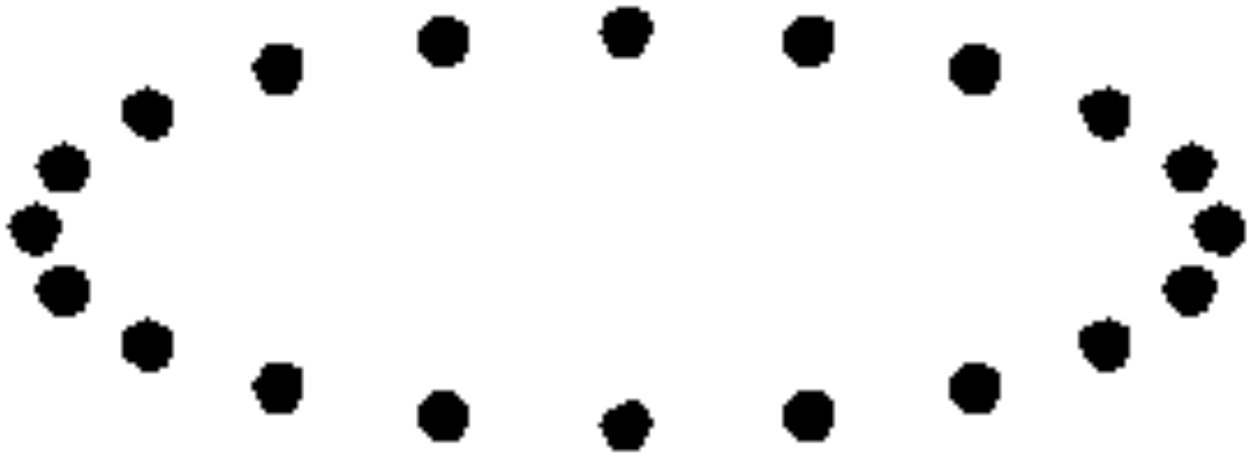
3. Constrain inflation models

Measuring GW

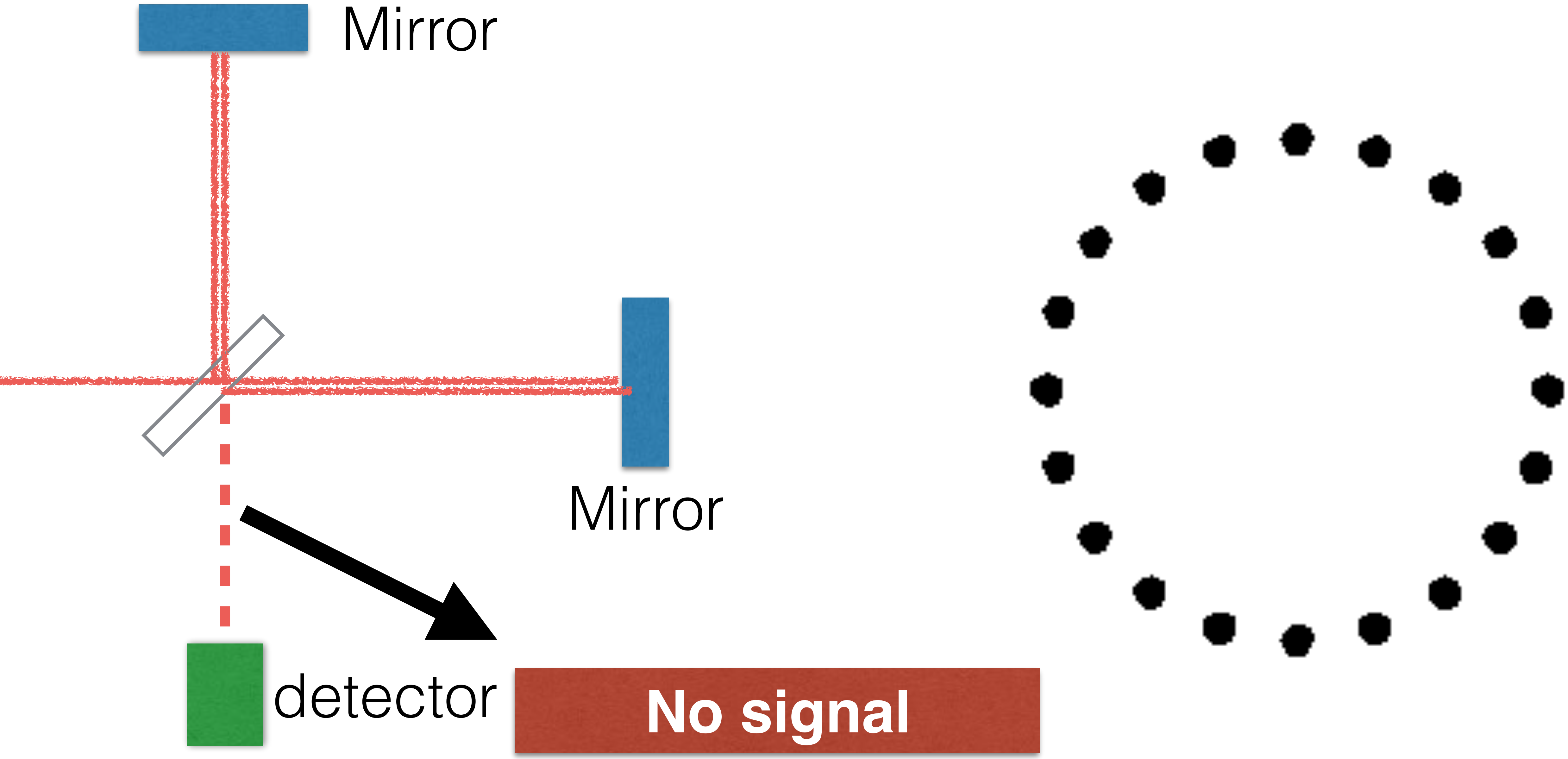
- GW changes distances between two points

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

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

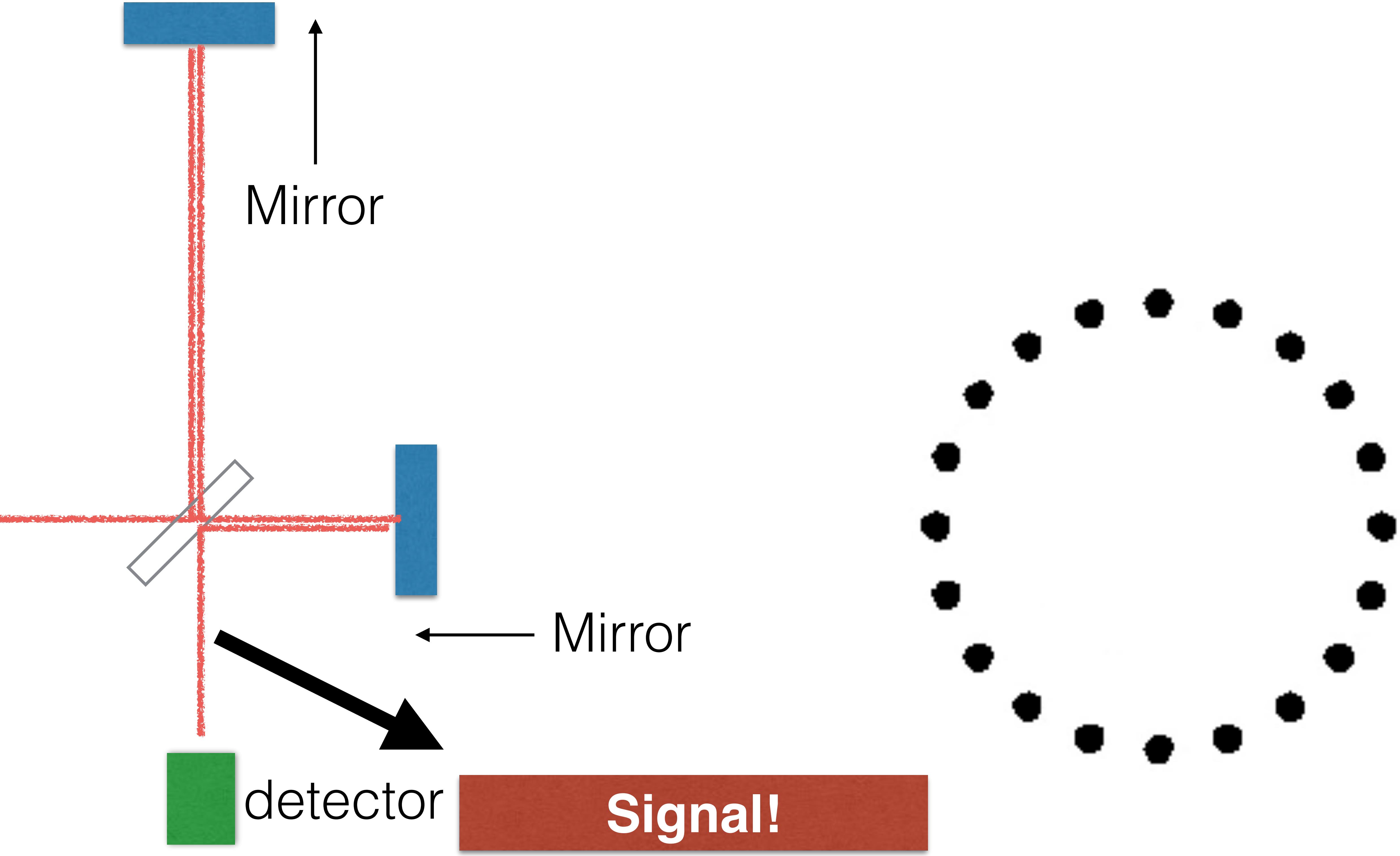


Laser Interferometer



No signal

Laser Interferometer



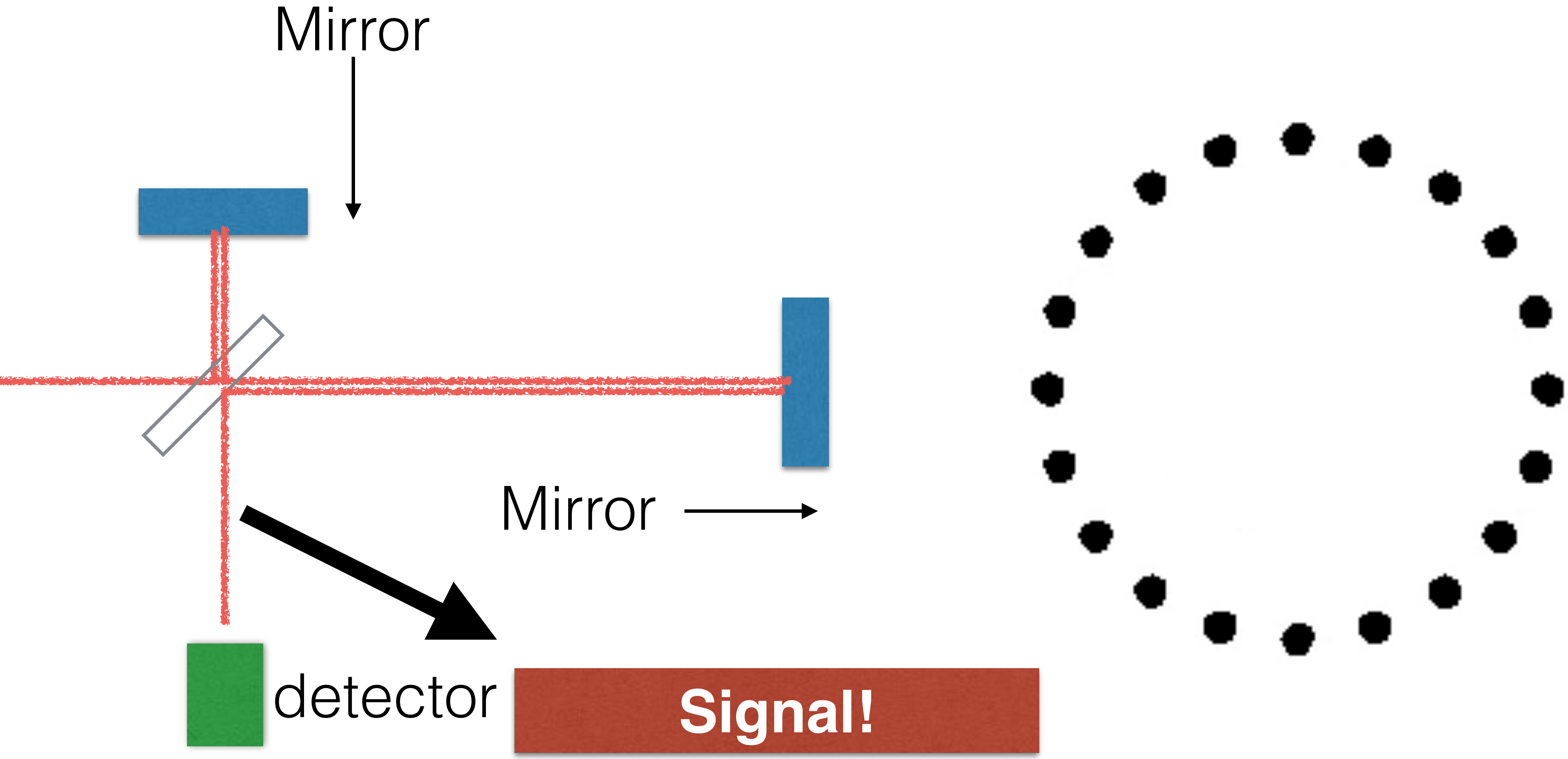
Mirror

Mirror

detector

Signal!

Laser Interferometer



Mirror

Mirror

detector

Signal!

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

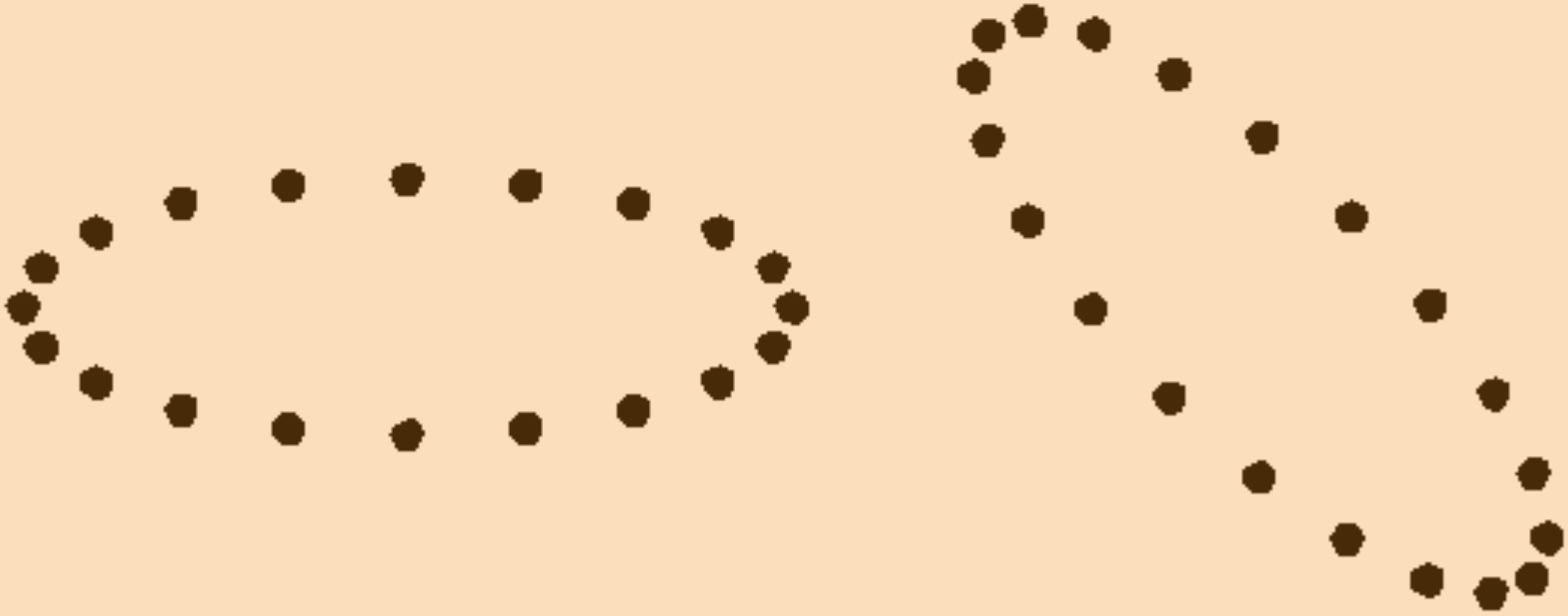
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

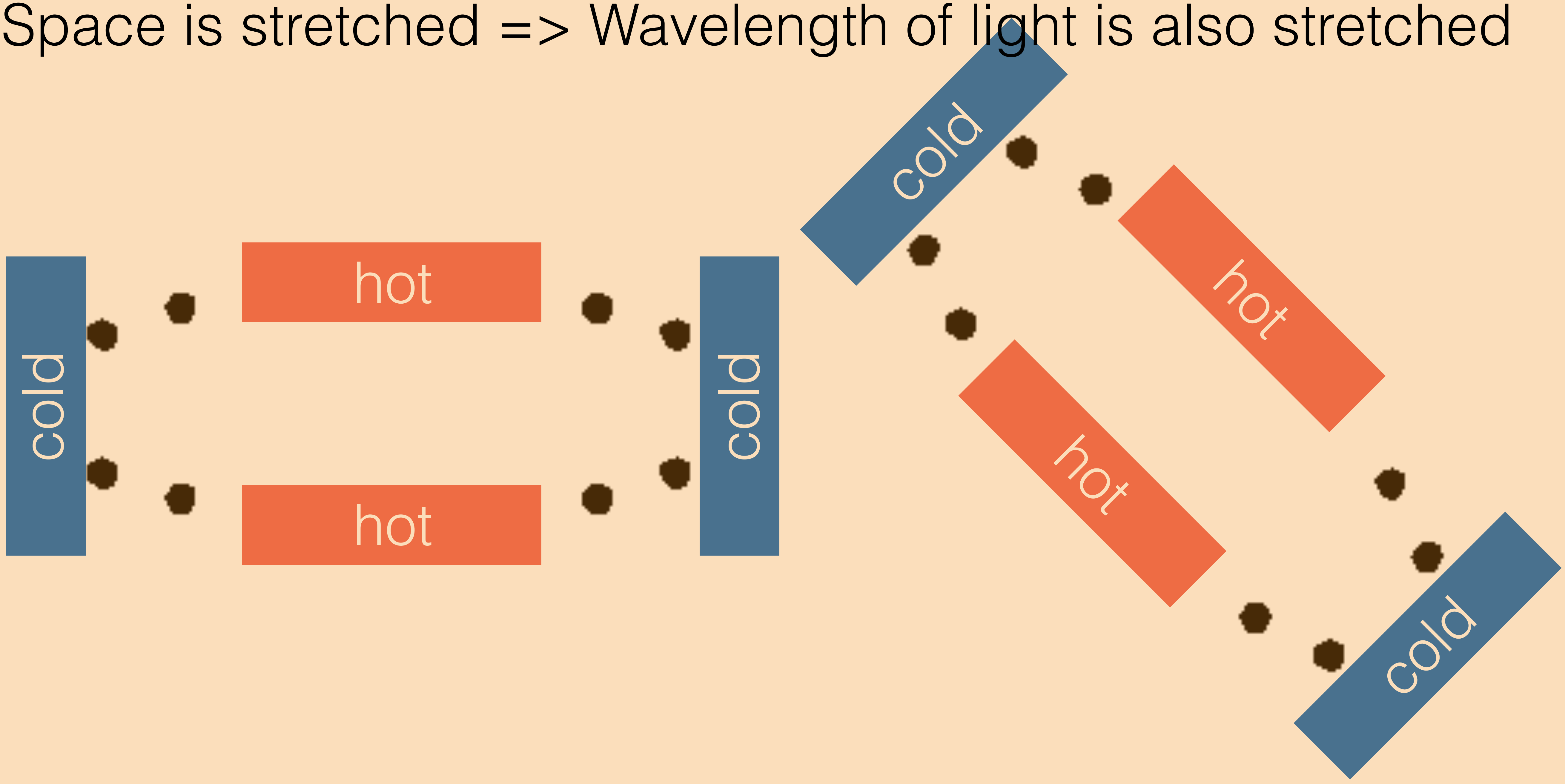
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



Detecting GW by CMB

Space is stretched => Wavelength of light is also stretched



Detecting GW by CMB

Polarisation

Space is stretched => Wavelength of light is also stretched

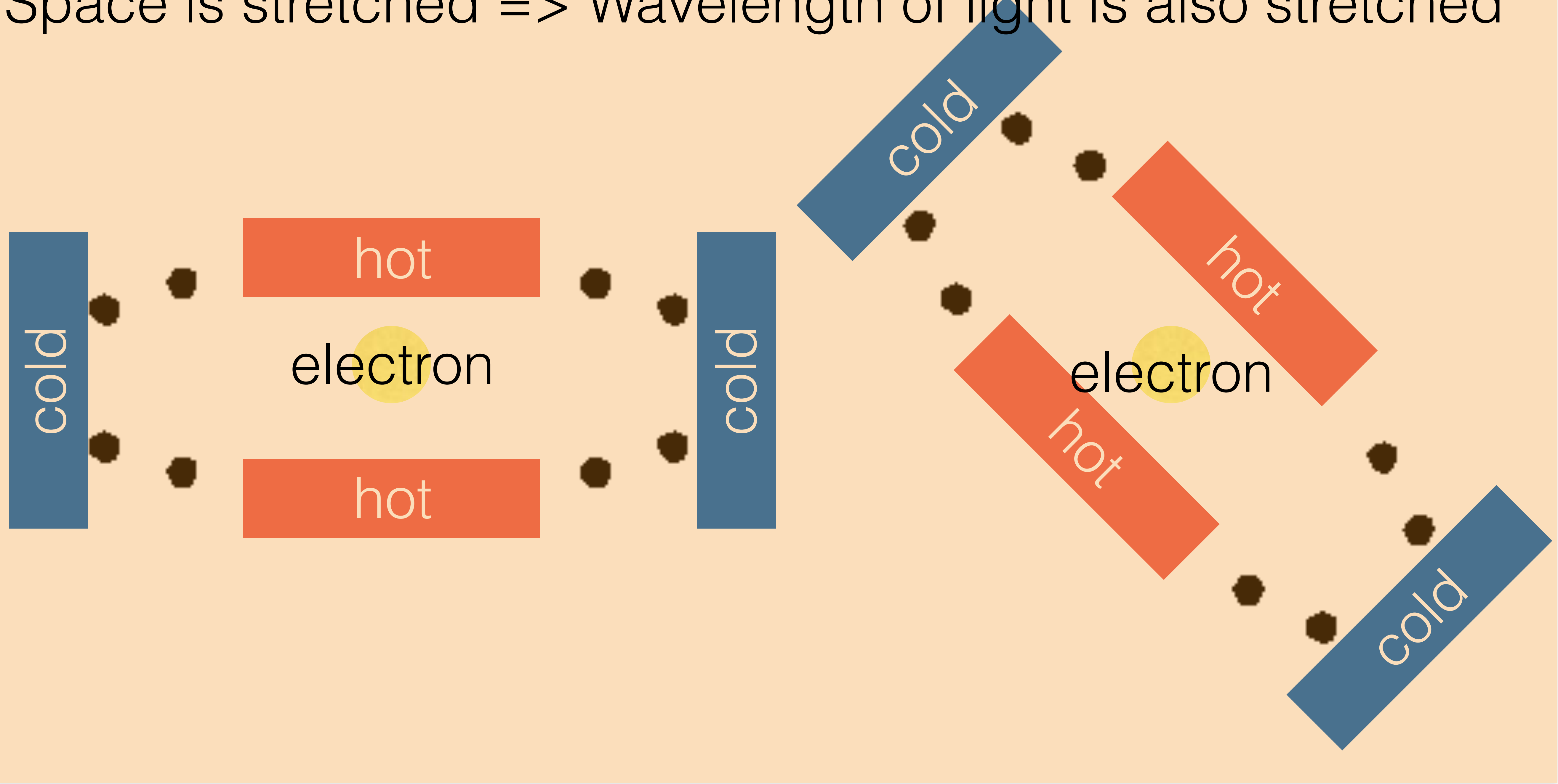


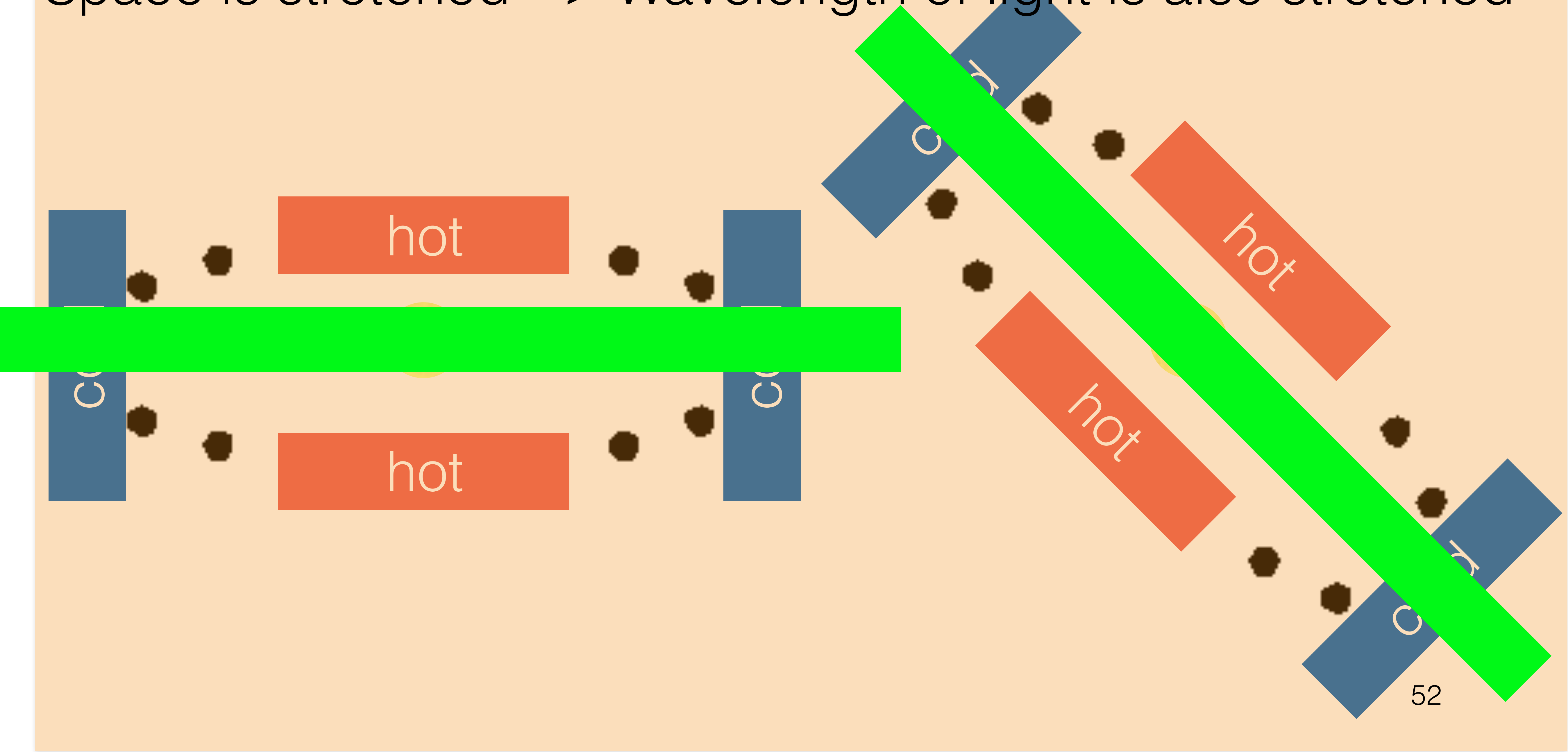
Photo Credit: TALEX

horizontally polarised

Photo Credit: TALEX

Detecting GW by CMB
Polarisation

Space is stretched => Wavelength of light is also stretched

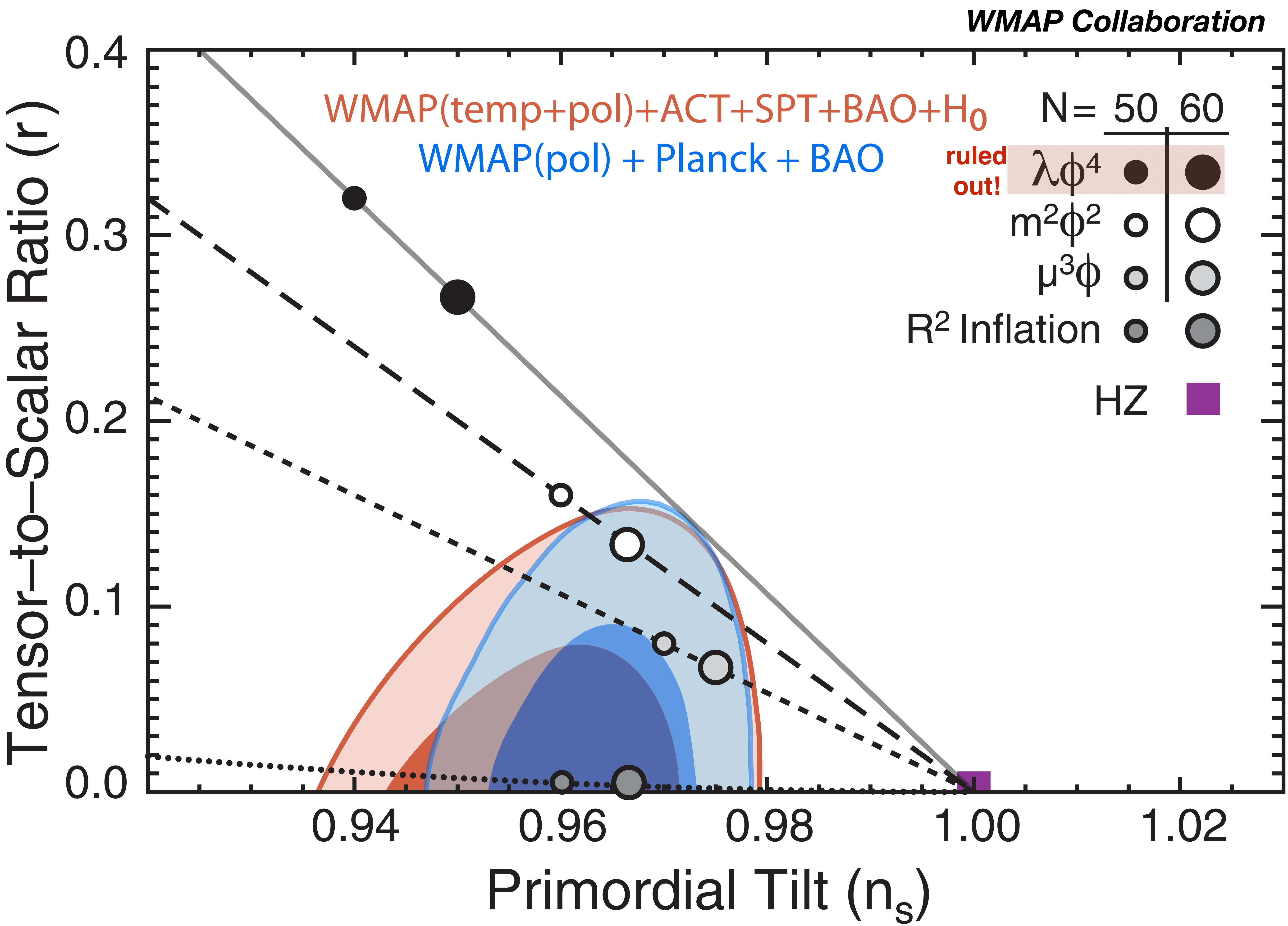


Tensor-to-scalar Ratio

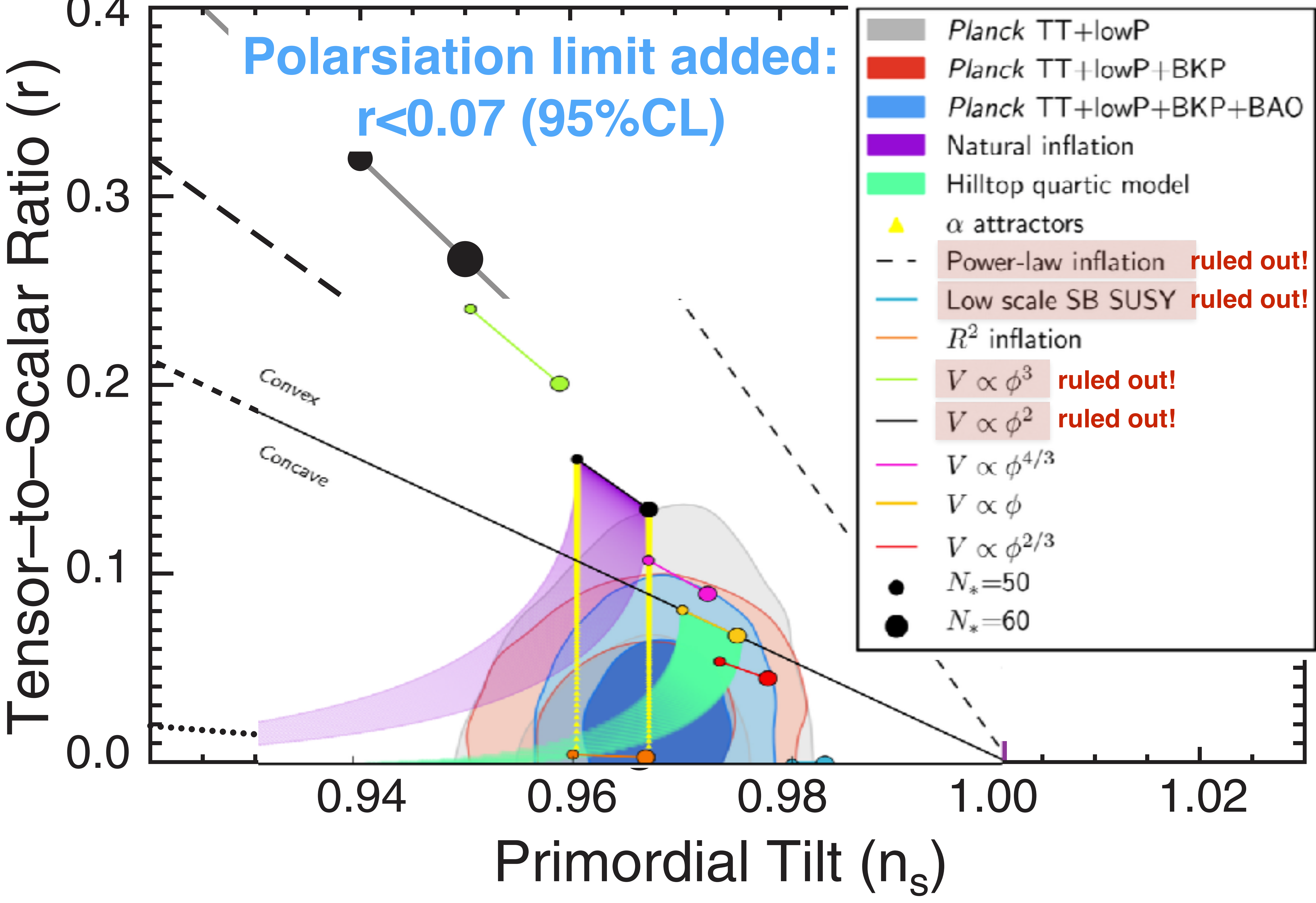
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

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

BICEP2/Keck Array Collaboration (2016)


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

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



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

Power-law inflation **ruled out!**

Low scale SB SUSY **ruled out!**

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

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

But, wait a minute…

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

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

- **Homogeneous solution**: “GWs from vacuum fluctuation”

- **Inhomogeneous solution**: “GWs from sources”

    - Scalar and vector fields cannot source tensor fluctuations at linear order (possible at non-linear level)

    - SU(2) gauge field can!

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

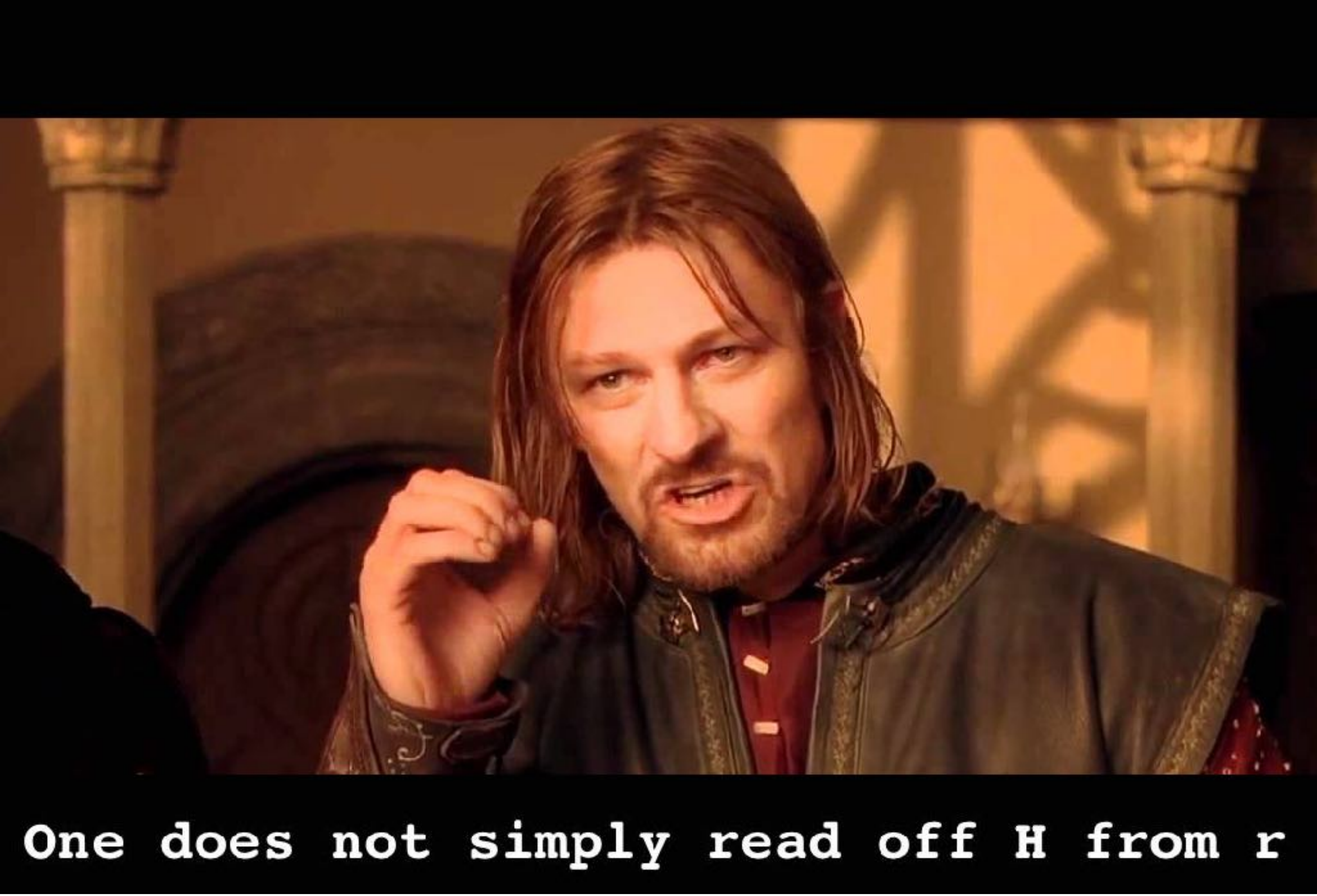
Important Message

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

- **Do not take it for granted if someone told you that detection of the B-mode polarisation would be a signature of "quantum gravity"!**
    - Only the homogeneous solution corresponds to the vacuum tensor metric perturbation. **There is no *a priori* reason to neglect an inhomogeneous solution!**
    - Contrary, we have several examples in which detectable B-modes are generated by **sources** [U(1) and SU(2)]

A New Paradigm

- We must **not** assume that detection of gravitational waves (GWs) from inflation immediately implies that GWs are from the vacuum fluctuation in tensor metric perturbation
  - The homogeneous solution is related to H(t) (or the inflaton field excursion; “Lyth bound”) during inflation, but the inhomogeneous solution is **not.**
  - **Detection of B-mode polarisation ≠ Vacuum fluctuation in metric**



From Matteo Fasiello

Experimental Strategy Commonly Assumed So Far

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

2. Check for scale invariance: Consistent with a scale invariant spectrum?

   - Yes => Announce discovery of the vacuum fluctuation in spacetime

   - No => WTF?

New Experimental Strategy: New Standard!

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

2. Consistent with a scale invariant spectrum?

3. Parity violating correlations (TB and EB) consistent with zero?

4. Consistent with Gaussianity?

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

If not, you may have just discovered new physics during inflation!

2. Consistent with a scale invariant spectrum?

3. Parity violating correlations (TB and EB) consistent with zero?

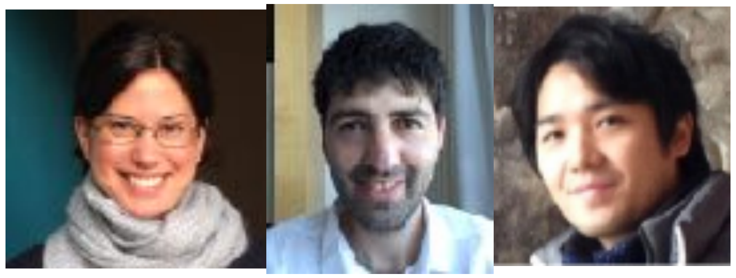
4. Consistent with Gaussianity?

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

Further Remarks

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

Dimastrogiovanni, Fasielo & Fujita (2017)



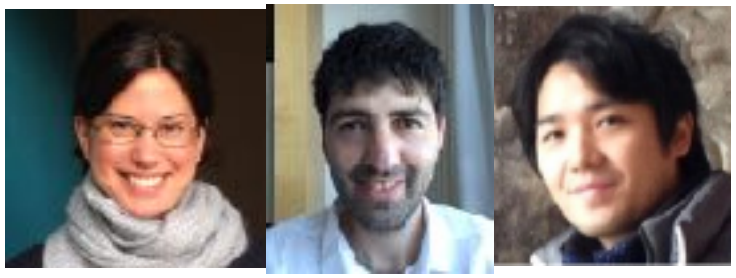
GW from Axion-SU(2) Dynamics

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

- ϕ: inflaton field => 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

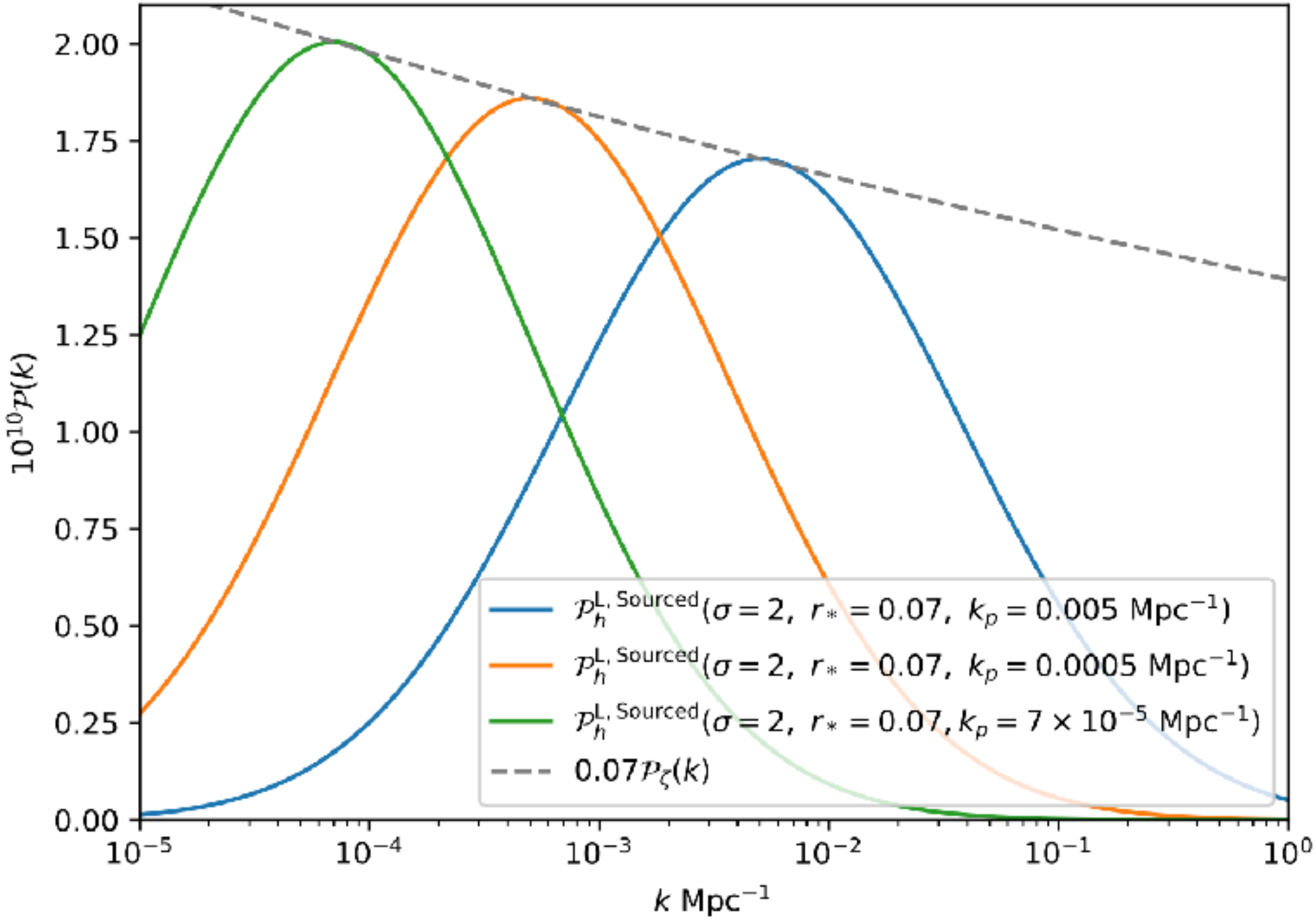
- The SU(2) field contains tensor, vector, and scalar components
- The tensor components are amplified strongly by a coupling to the axion field
  - But, **only one helicity is amplified** => GW is **chiral** (well-known result)
- Brand-new result: **GWs sourced by this mechanism are strongly non-Gaussian!**

Agrawal, Fujita & EK (2017)

Dimastrogiovanni, Fasiello & Fujita (2017)

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

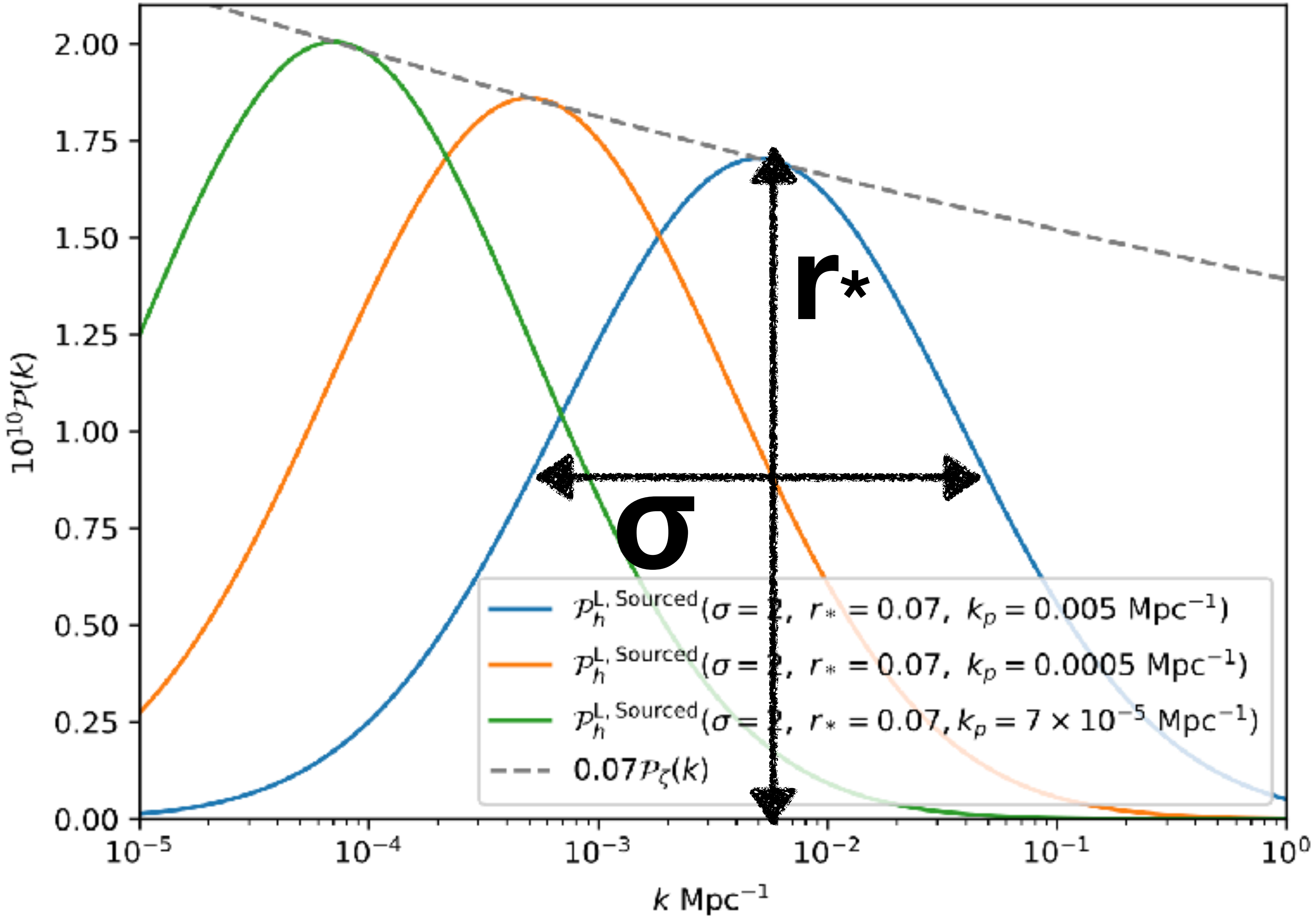
Example Tensor Spectra



- Sourced tensor spectrum can be close to scale invariant, but can also be bumpy

Dimastrogiovanni, Fasiello & Fujita (2017)
Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, arXiv:1707.03240

Example Tensor Spectra



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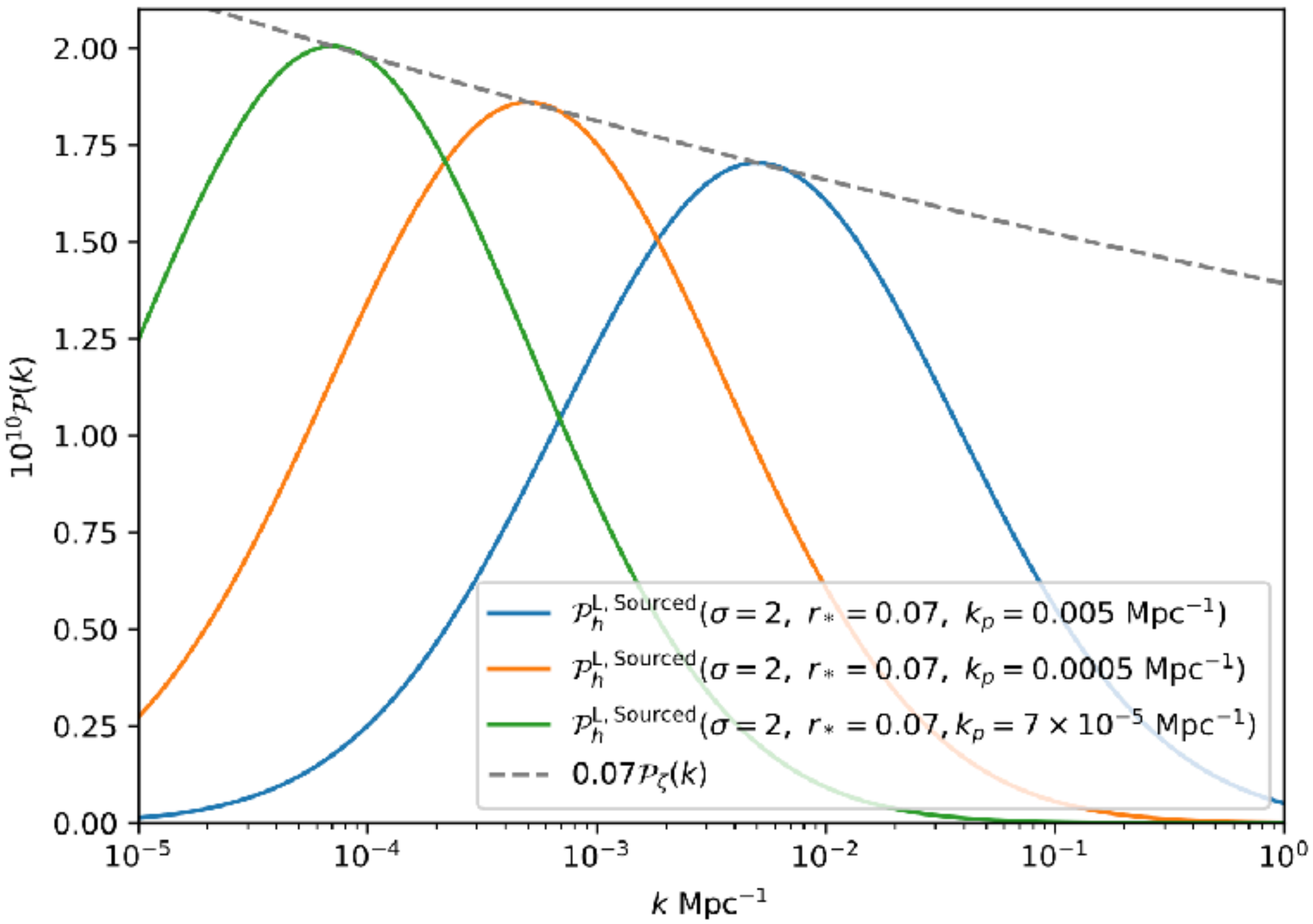
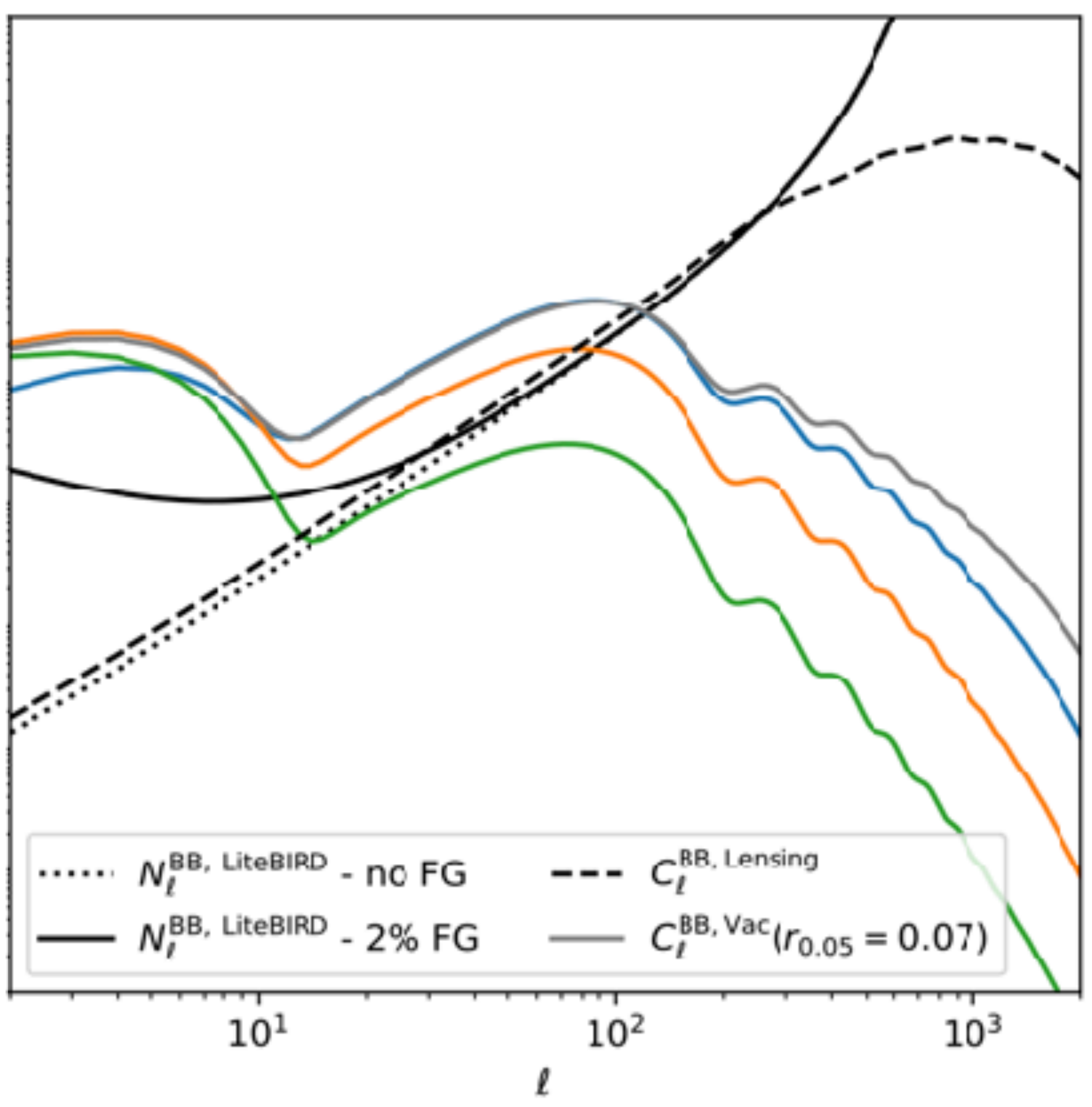
Dimastrogiovanni, Fasiello & Fujita (2017)
Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, arXiv:1707.03240

Example Tensor Spectra

Tensor Power Spectrum, P(k)



B-mode CMB spectrum, C_l^{BB}



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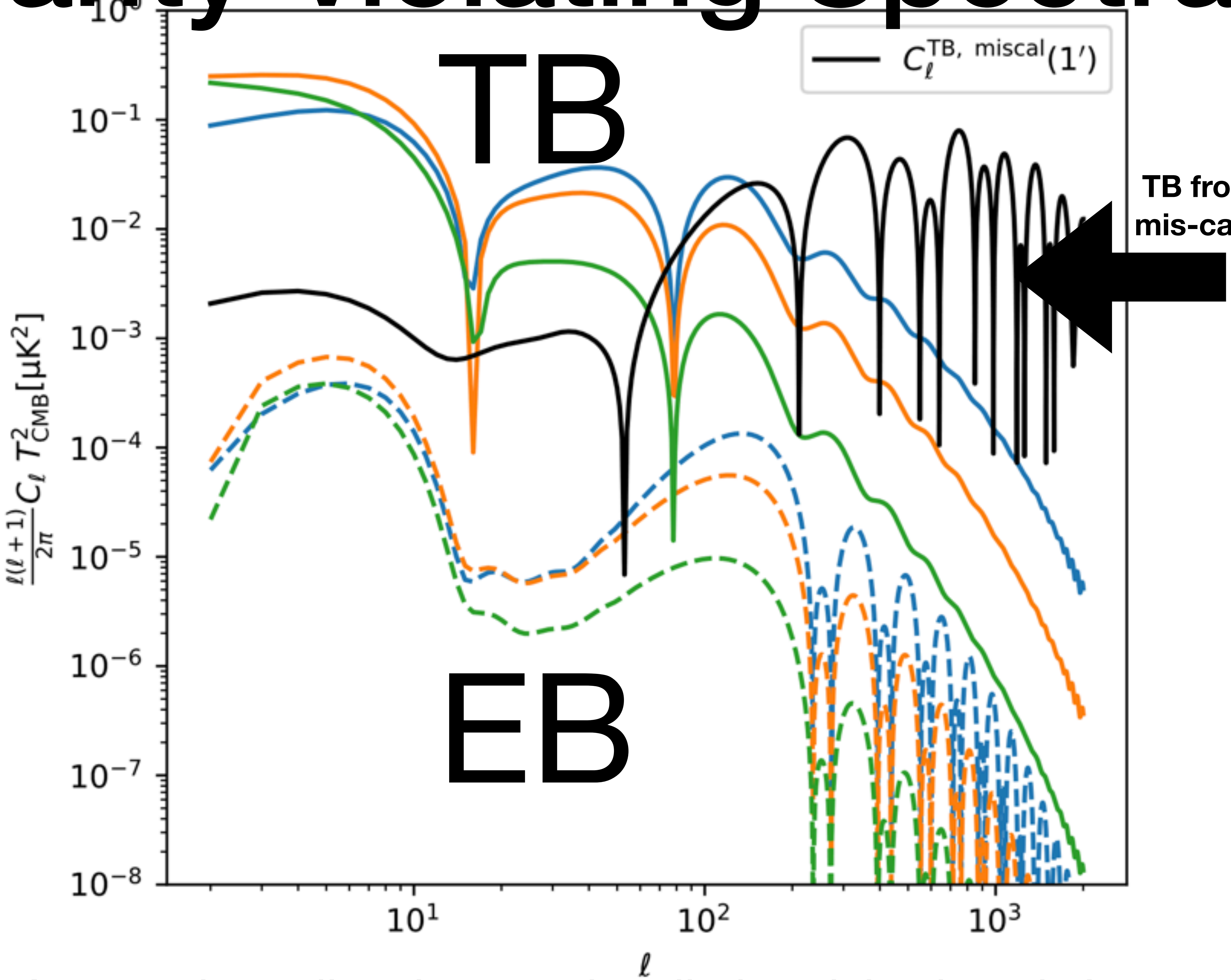
Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, arXiv:1707.03240

Parity-violating Spectra

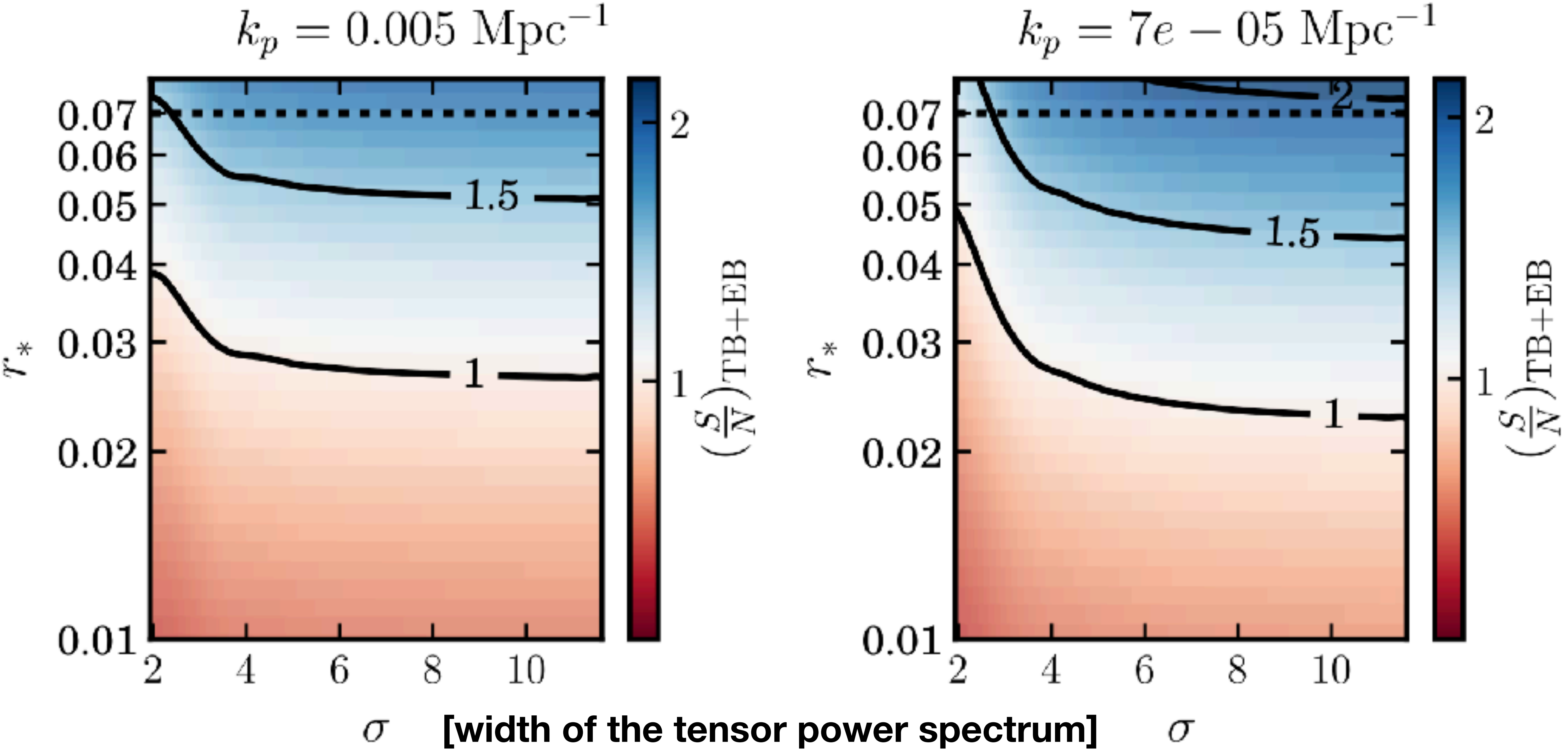


TB from angle mis-calibration

- Angle mis-calibration can be distinguished easily!

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

Signal-to-noise [LiteBIRD]

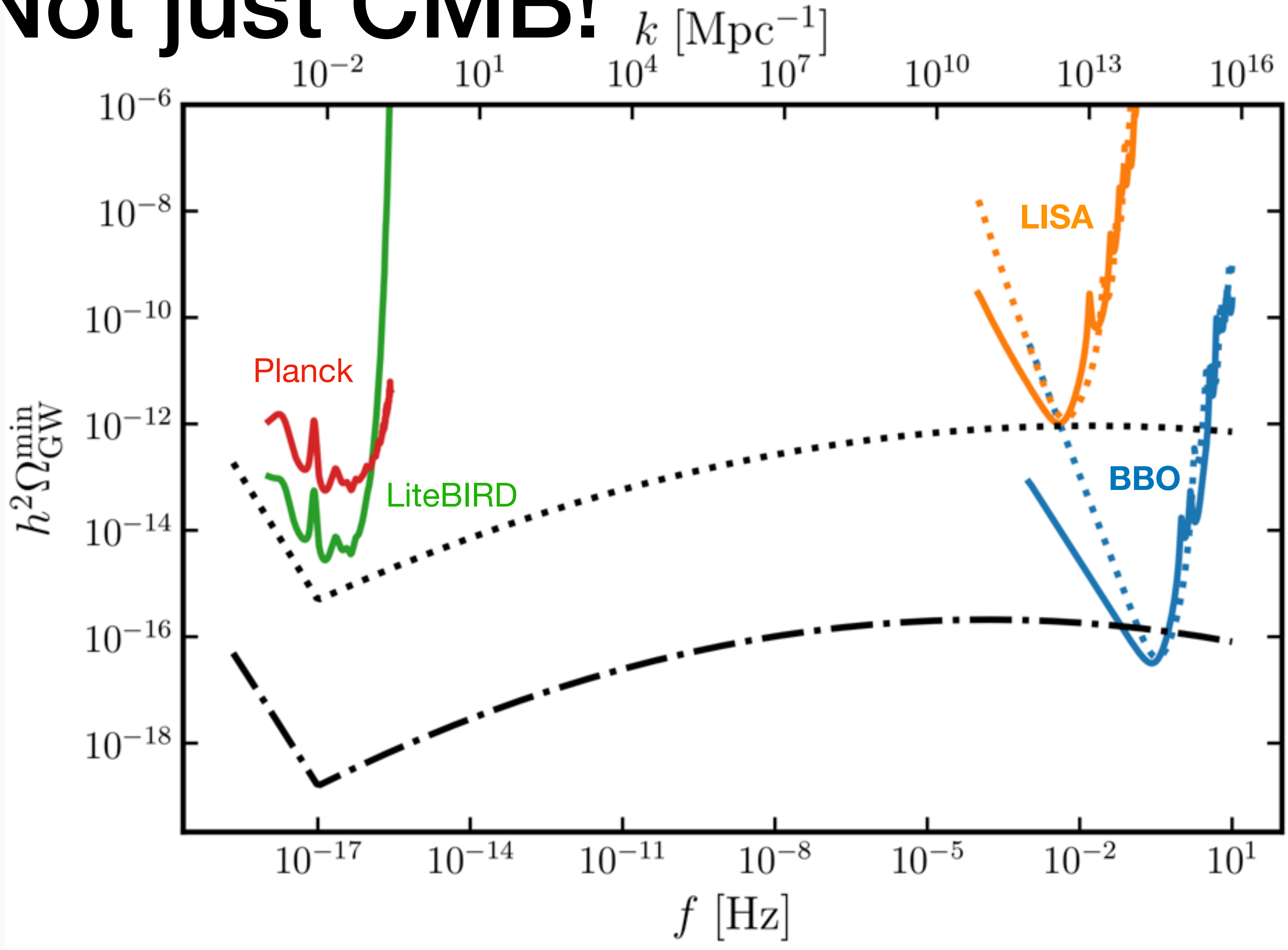


[width of the tensor power spectrum]

- S/N ~ a couple for the peak r_* of 0.07. It's something!

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)

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

- $\Omega_A << 1$ is the energy density fraction of the gauge field

- **B_h/P_h^2 is of order unity for the vacuum contribution**

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

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

Agrawal, Fujita & EK, arXiv:1707.03023

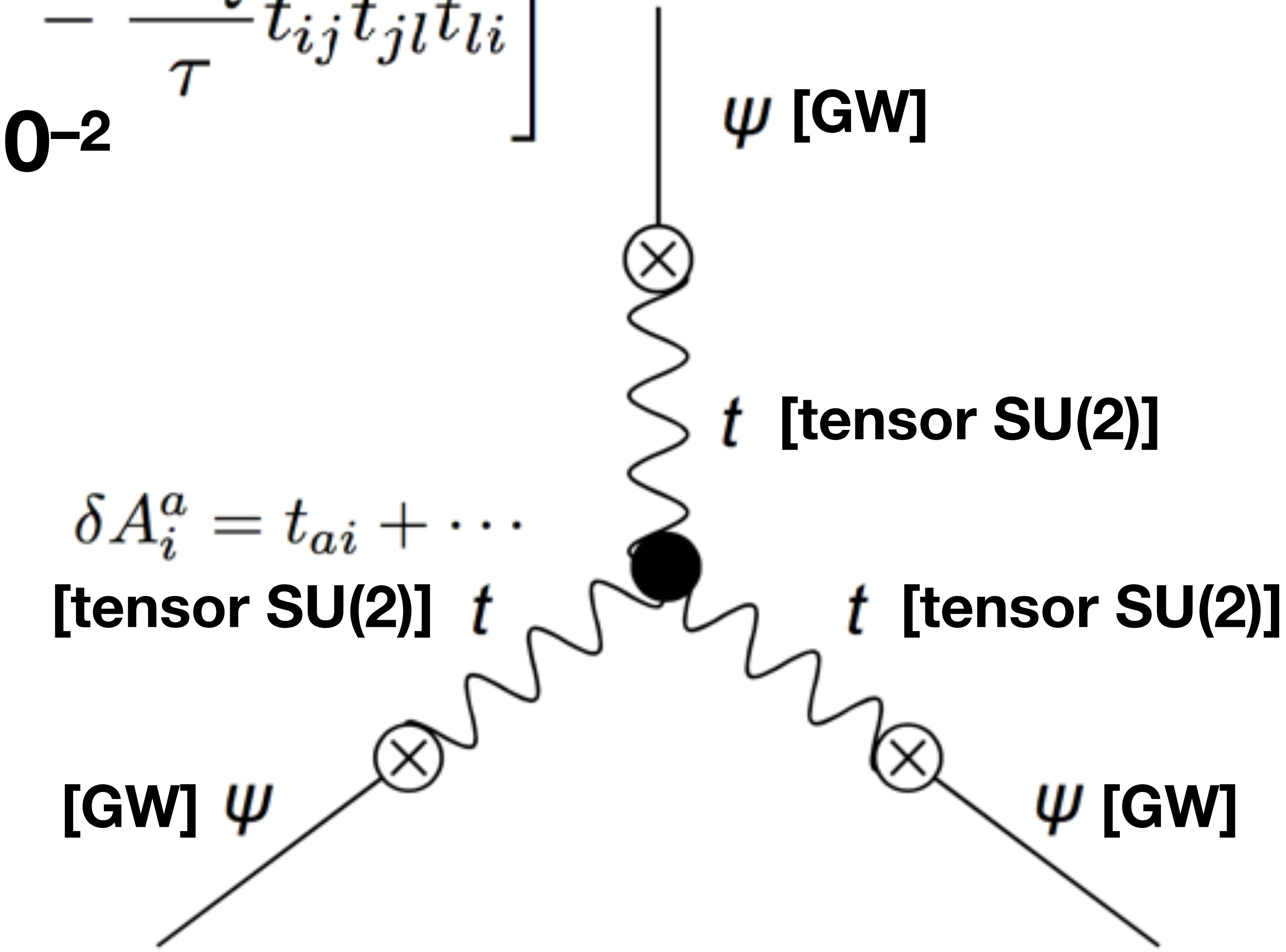
NG generated at the tree level

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

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

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

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



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

Agrawal, Fujita & EK, arXiv:1707.03023

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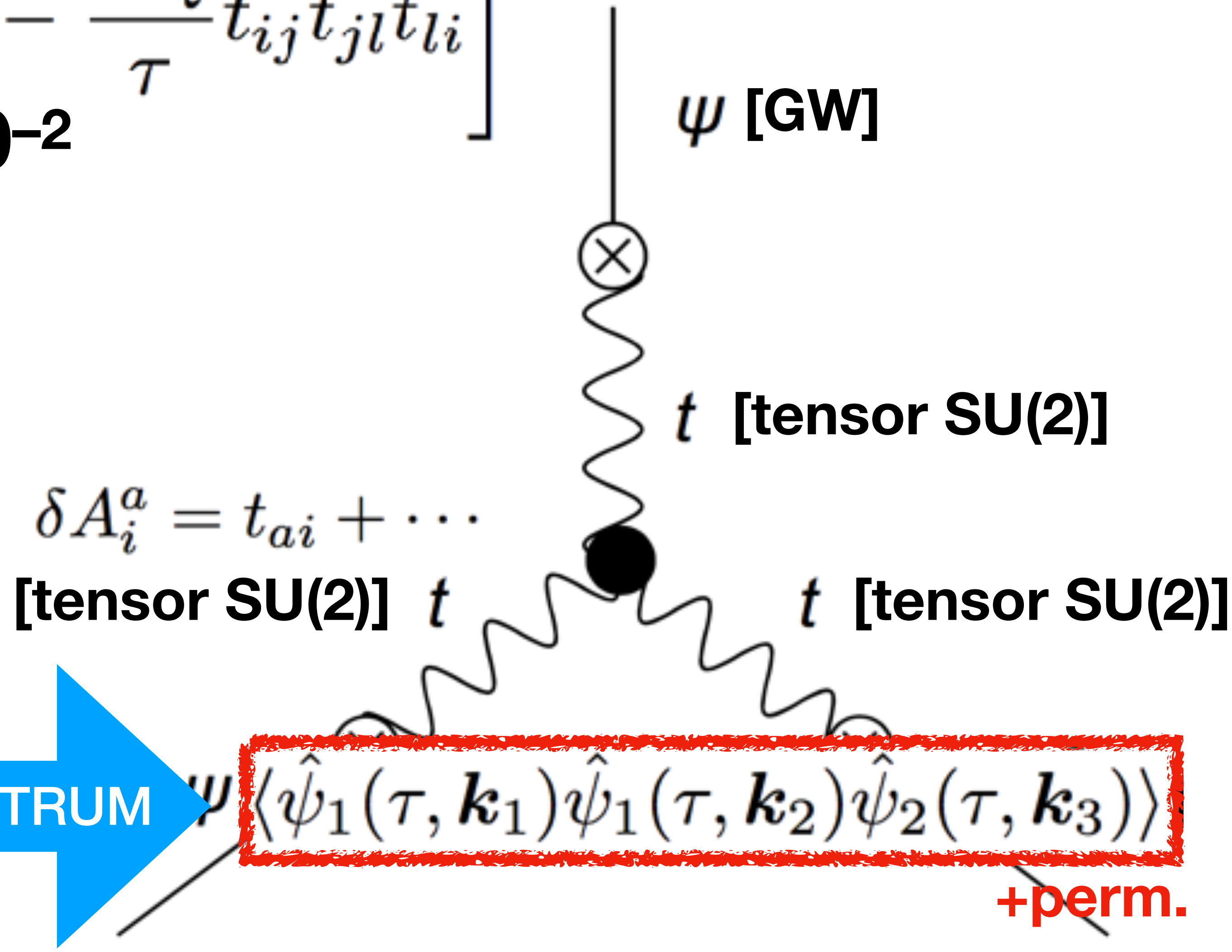


- This diagram generates second-order equation of motion for GW

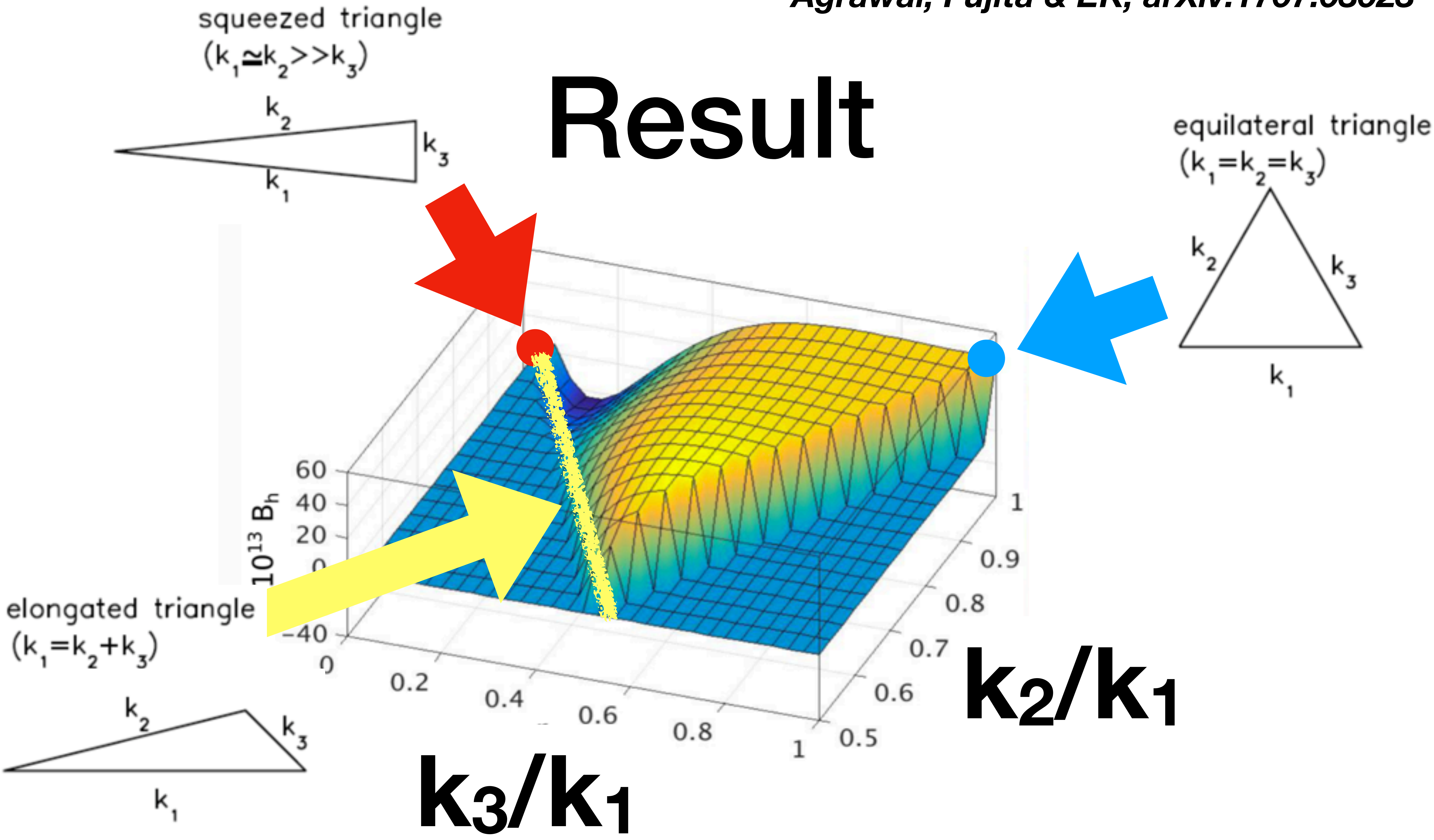
BISPECTRUM

$\langle \hat{\psi}_1(\tau, \boldsymbol{k}_1)\hat{\psi}_1(\tau, \boldsymbol{k}_2)\hat{\psi}_2(\tau, \boldsymbol{k}_3)\rangle$

+perm.

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

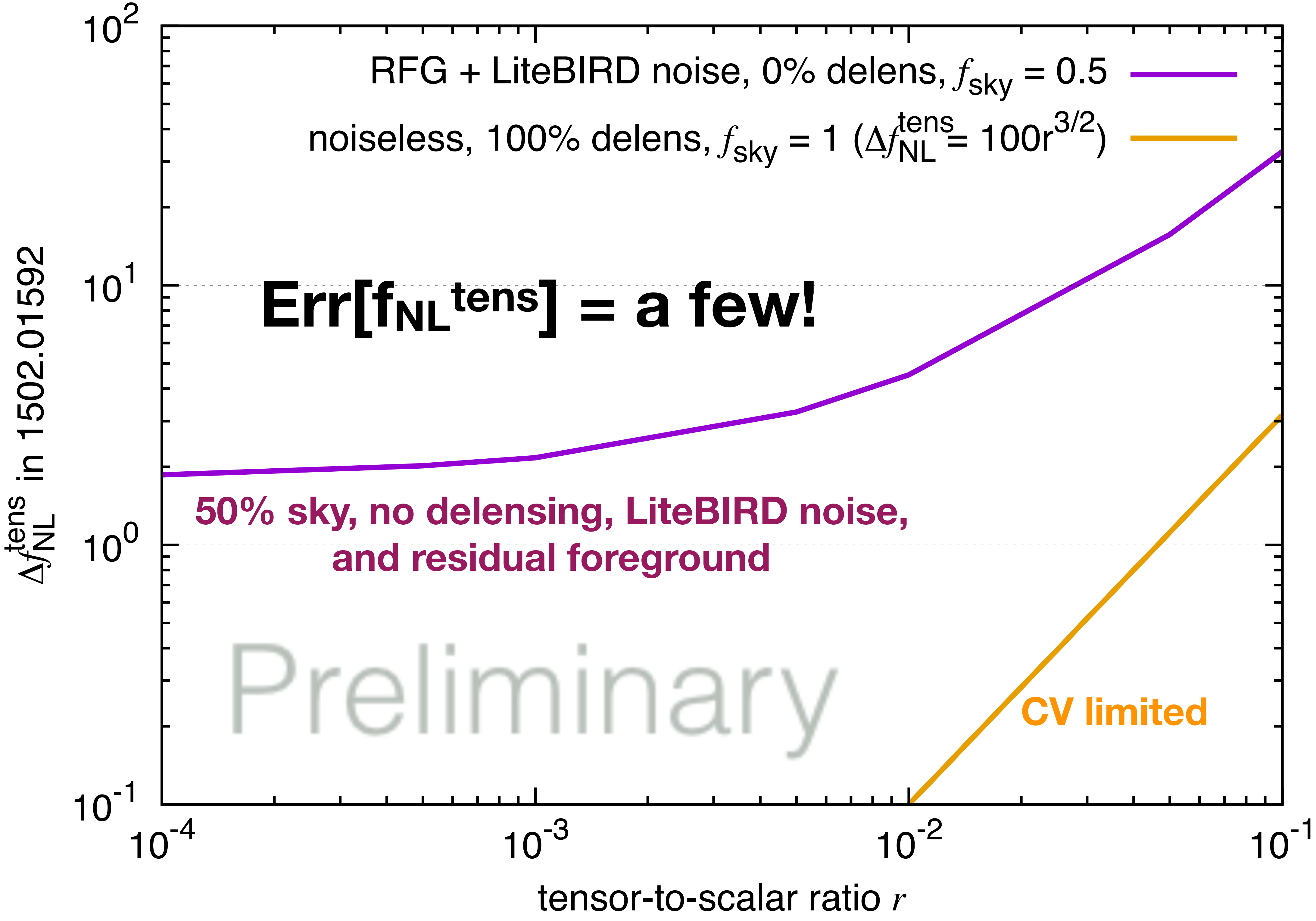
- The SU(2) model of Dimastrogiovanni et al. predicts:

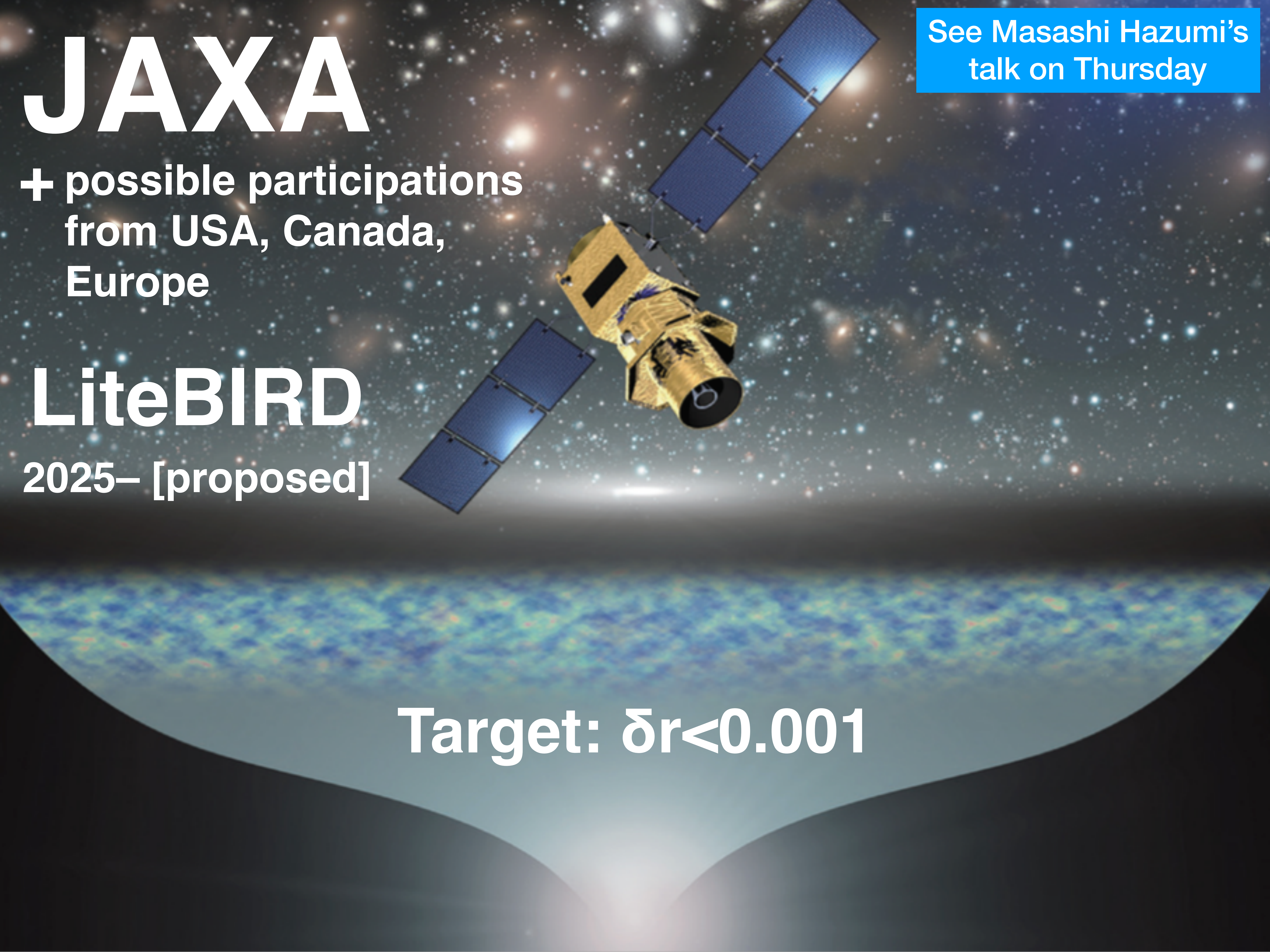
$$f_{\rm NL}^{\rm tens} \approx \frac{125}{18\sqrt{2}}\frac{r^2}{\epsilon_B} \approx 2.5\frac{r^2}{\Omega_A}$$

- 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!





JAXA

\+ possible participations from USA, Canada, Europe

LiteBIRD

2025– [proposed]

See Masashi Hazumi’s talk on Thursday

Target: $\delta r<0.001$

JAXA

+ possible participations from USA, Canada, Europe

See Masashi Hazumi’s talk on Thursday

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

See Masashi Hazumi's talk on Thursday

LiteBIRD

2025– [proposed]

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

Summary

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