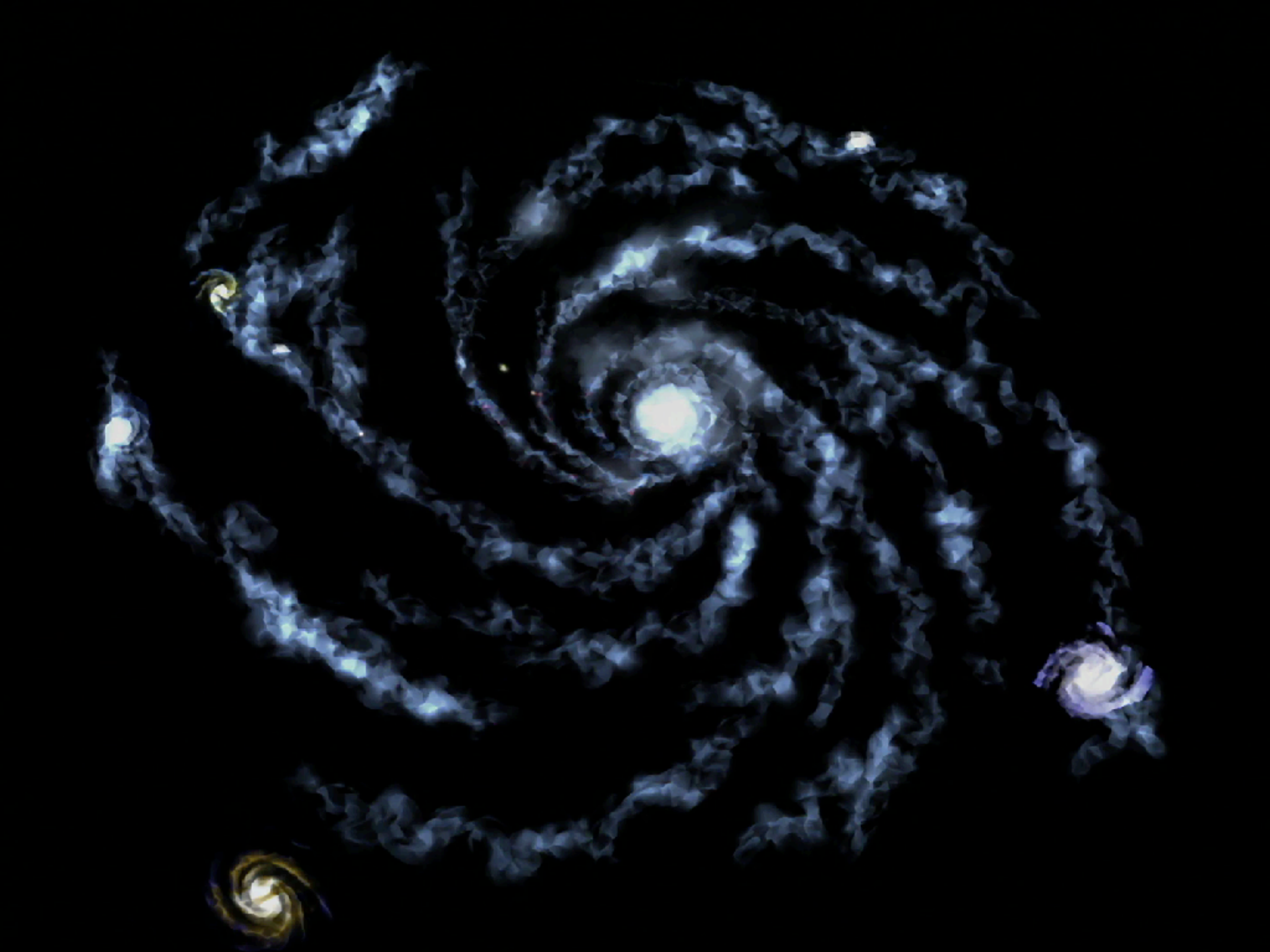
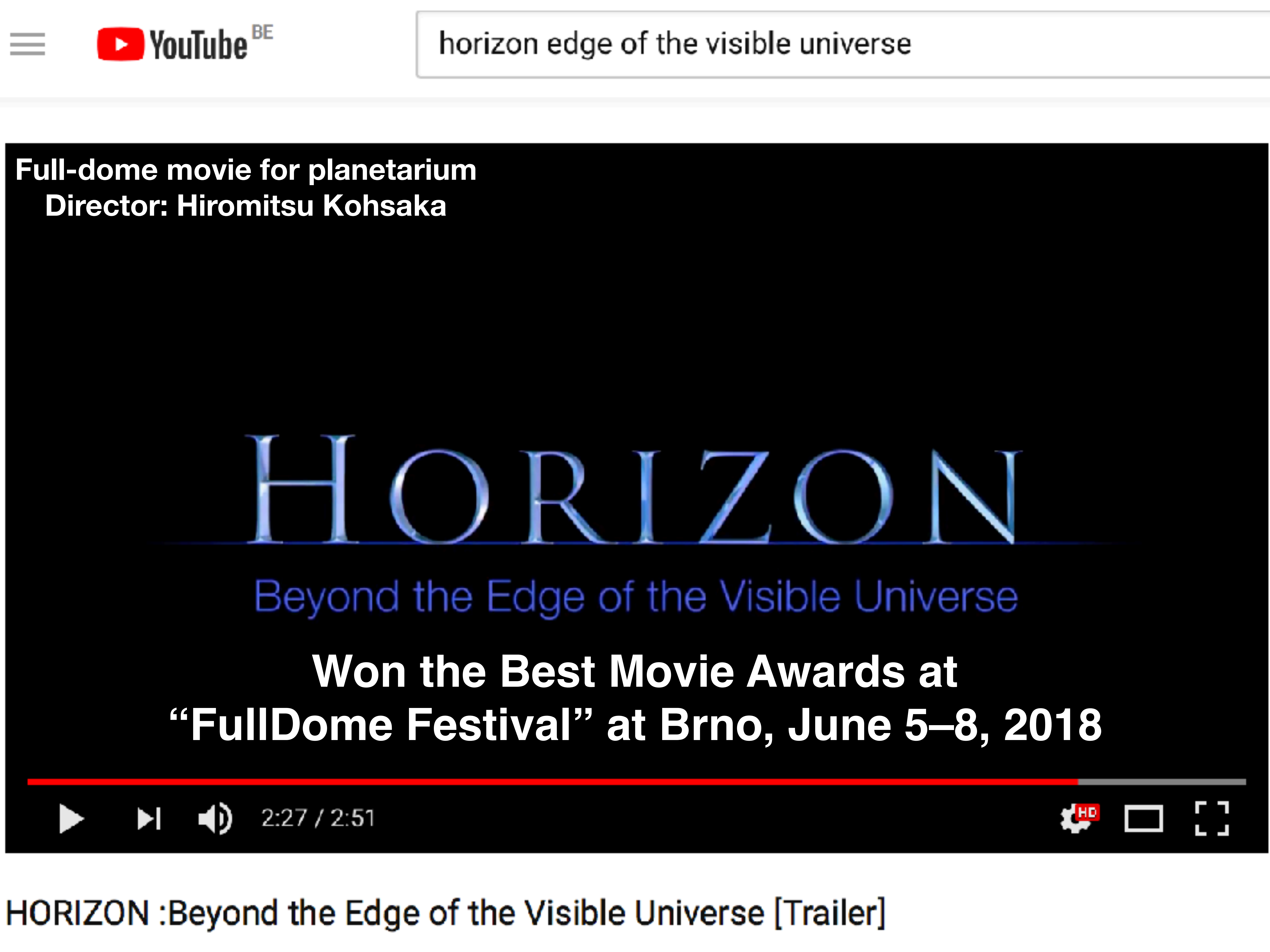
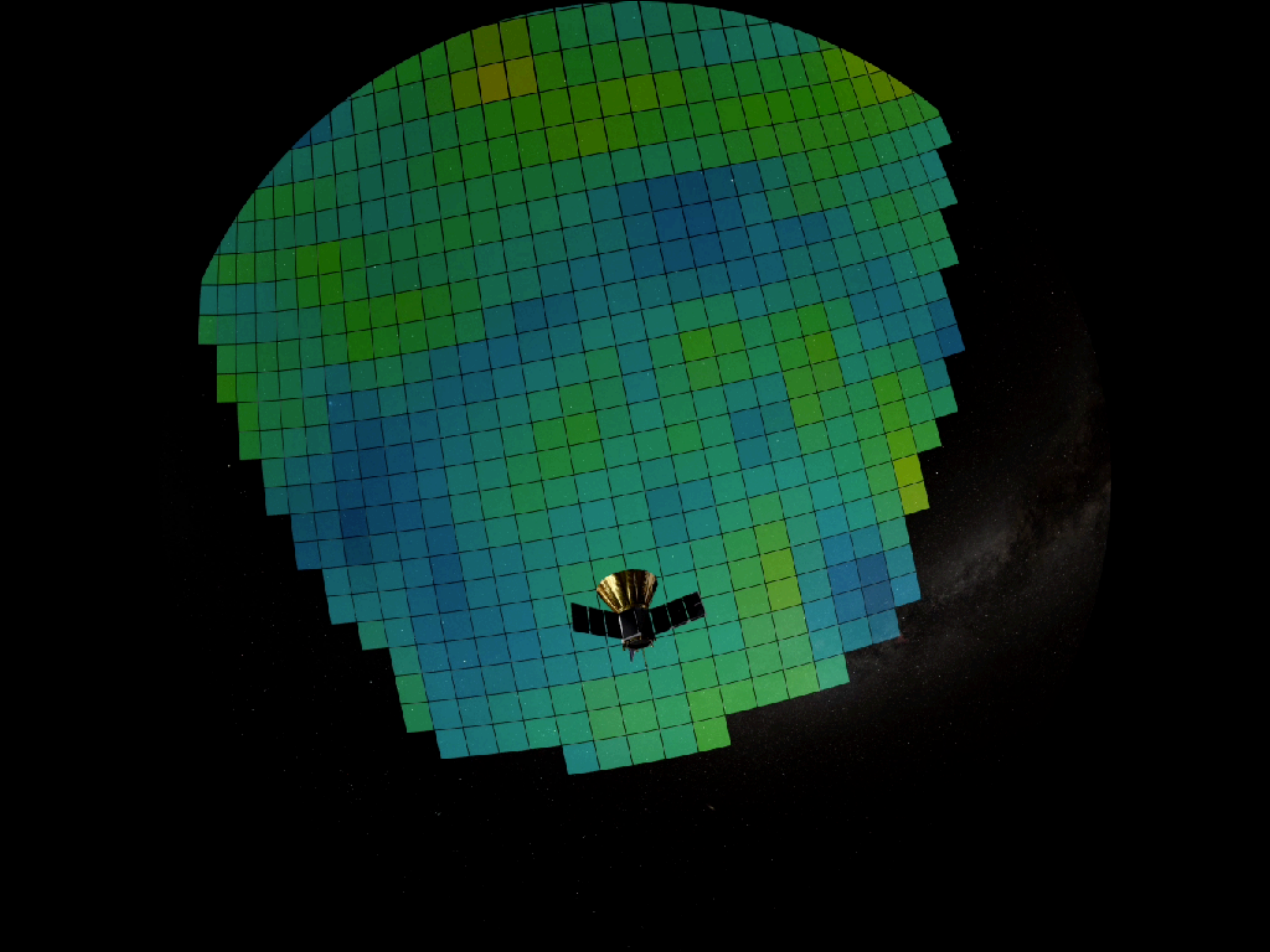
Finding Cosmic Inflation

Eiichiro Komatsu
[MPI für Astrophysik]
HEP Theorie-Seminar, RWTH Aachen
July 12, 2018




YouTube BE
horizon edge of the visible universe
Full-dome movie for planetarium
Director: Hiromitsu Kohsaka
HORIZON
Beyond the Edge of the Visible Universe
Won the Best Movie Awards at
“FullDome Festival” at Brno, June 5–8, 2018
2:27 / 2:51
HD
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?***

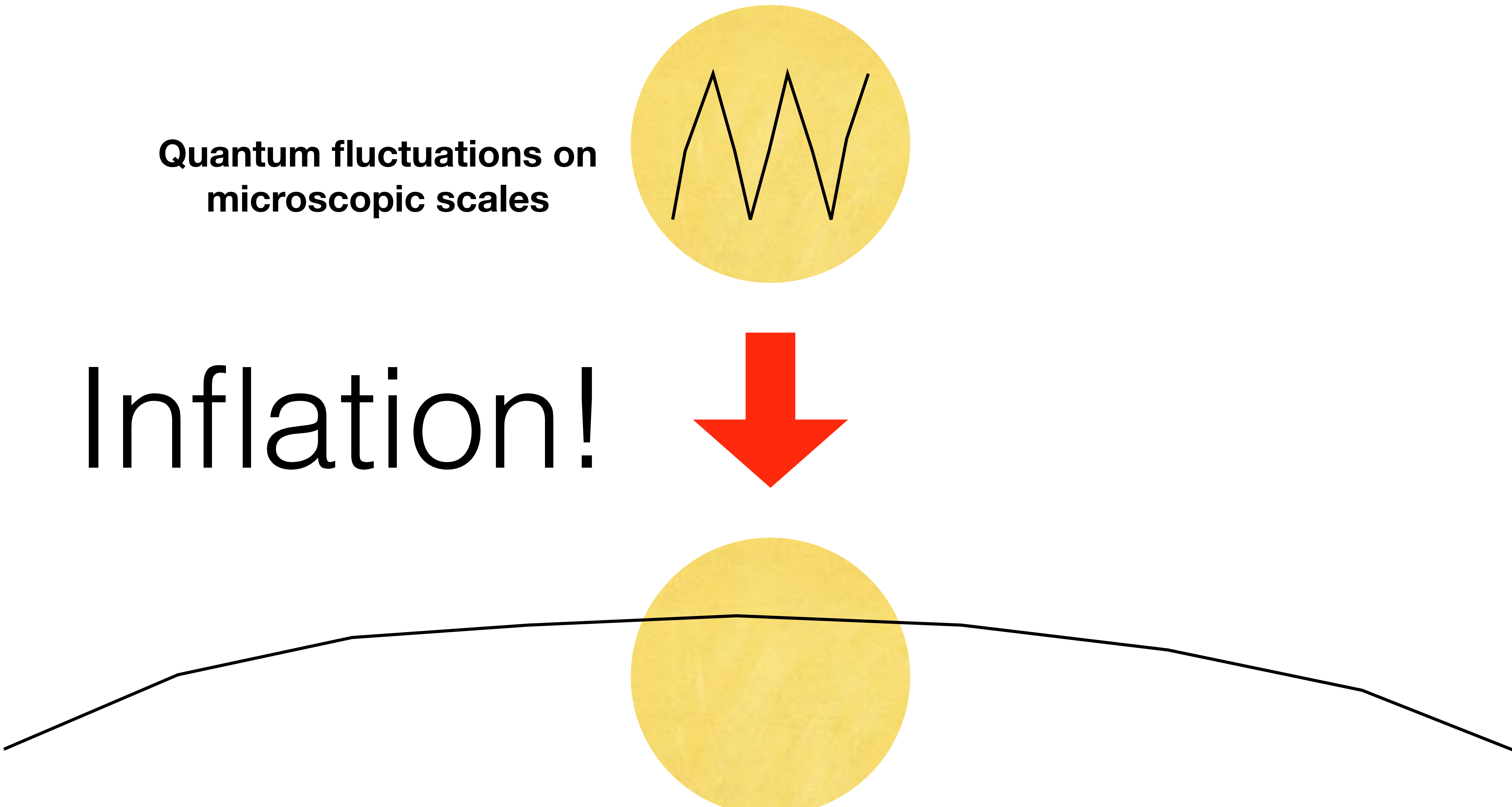
Mukhanov & Chibisov (1981); Hawking (1982); Starobinsky (1982); Guth & Pi (1982); Bardeen, Turner & Steinhardt (1983)

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



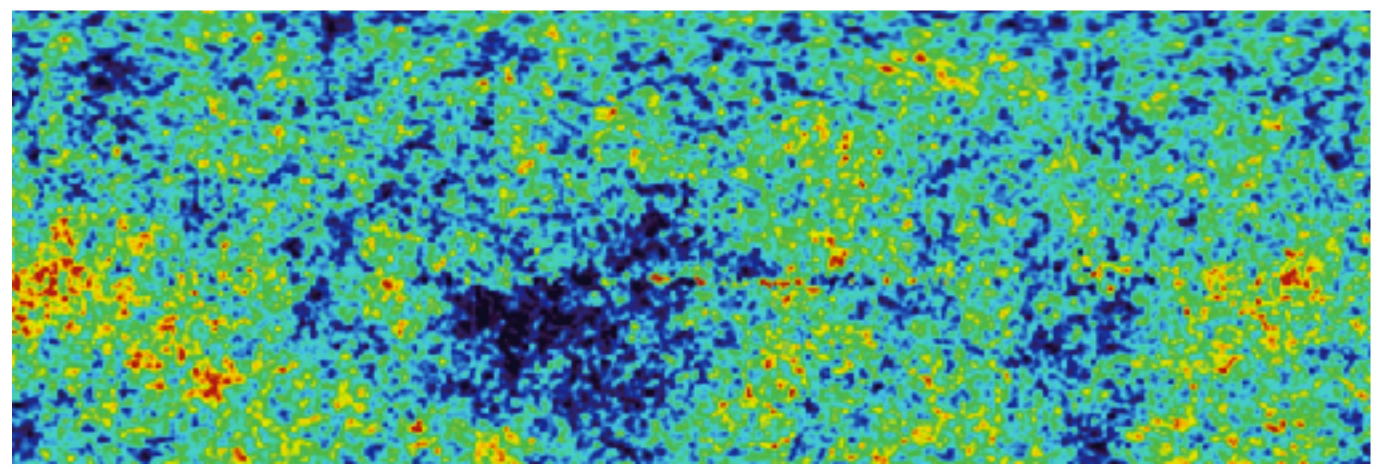
- Exponential expansion (inflation) stretches the wavelength of quantum fluctuations to cosmological scales

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
- $\mathbf{h_{ij}}$: “gravitational waves” (tensor mode)
  - Perturbation that does not alter the determinant

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

We measure distortions in space

- A distance between two points in space

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

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

Finding Inflation

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

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

- 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

  - **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

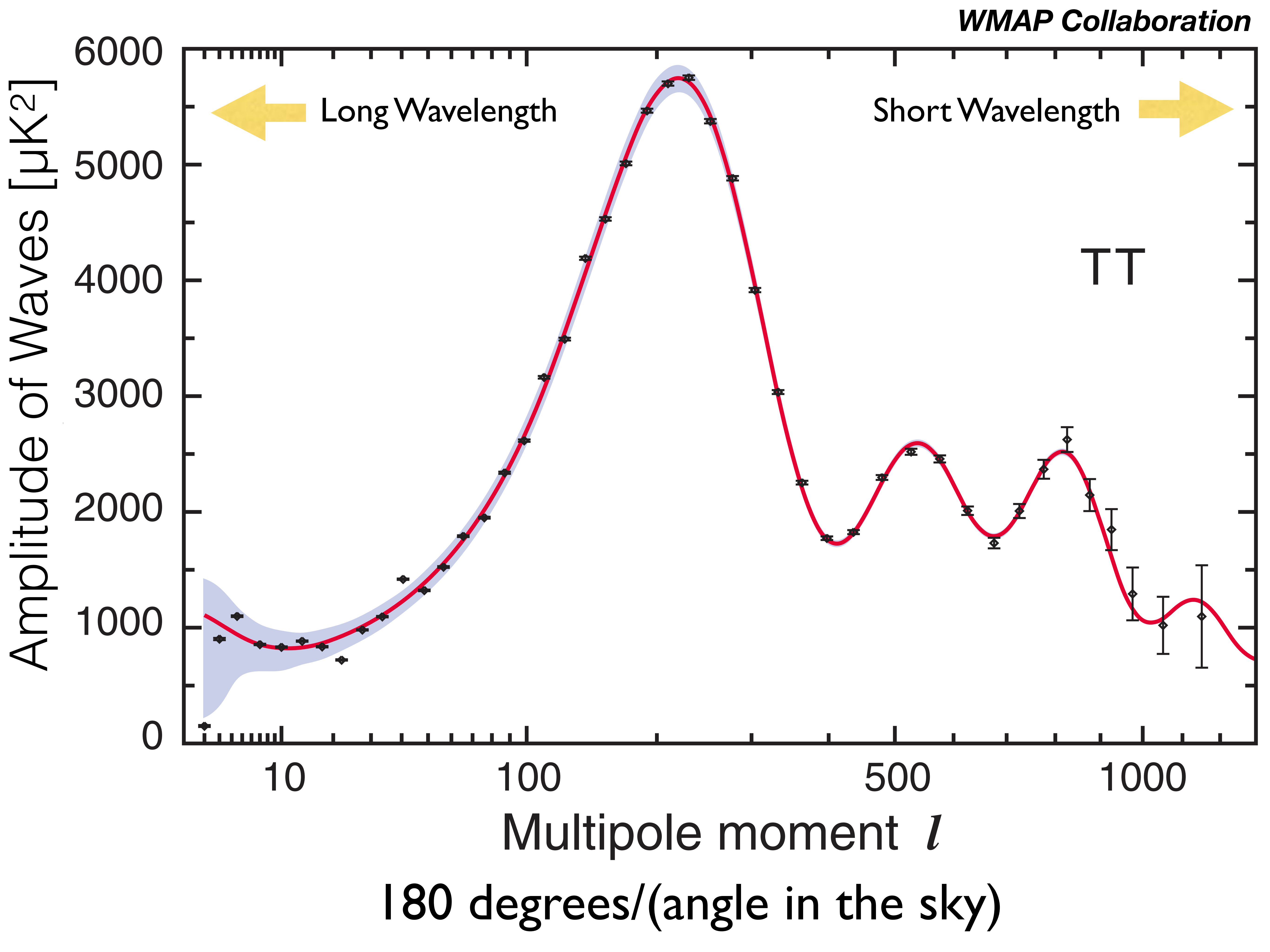
- **We can map H(t) by measuring CMB fluctuations over a wide range of angles**

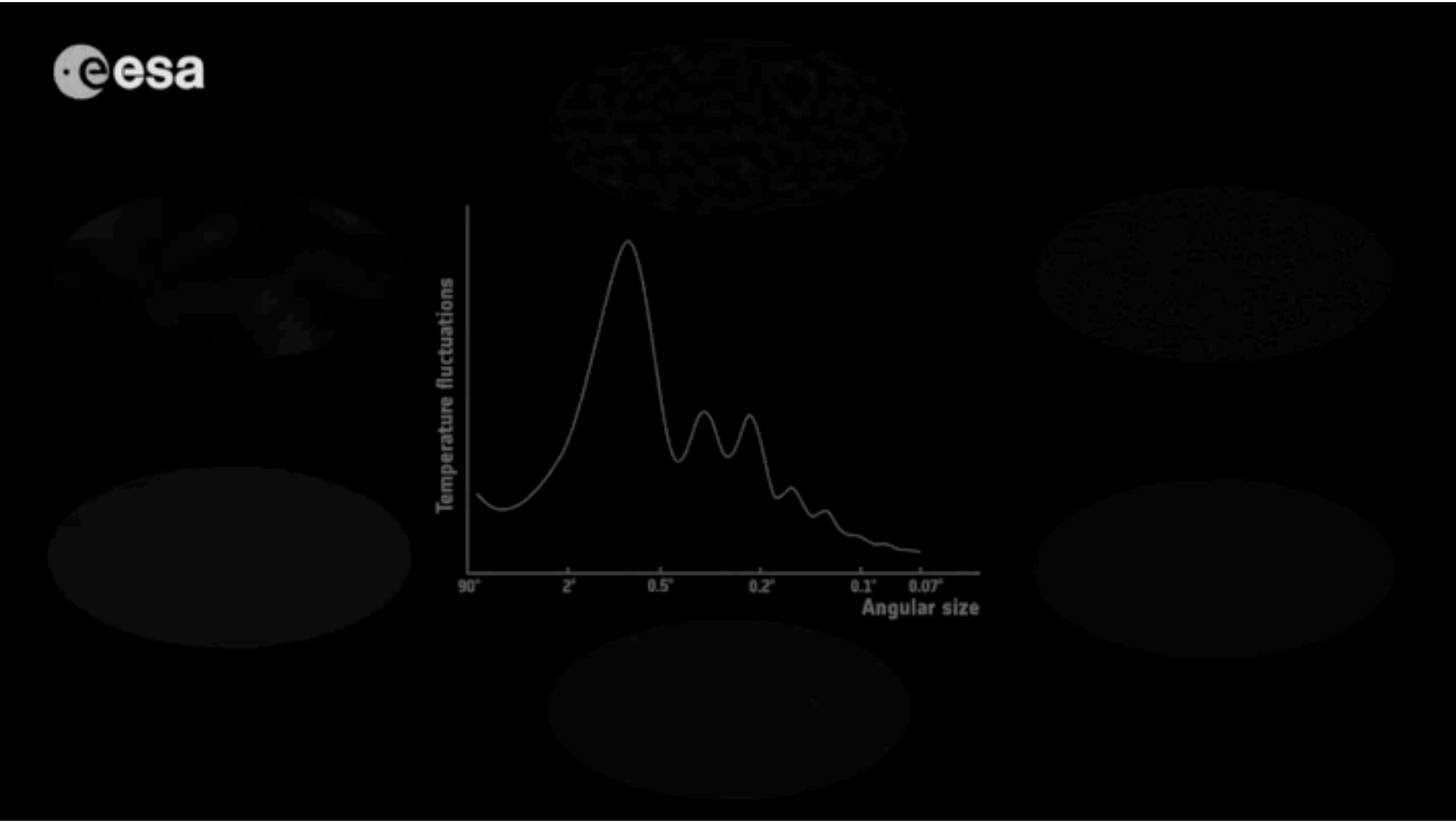
1. We want to show that the amplitude of CMB fluctuations does not depend very much on angles

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

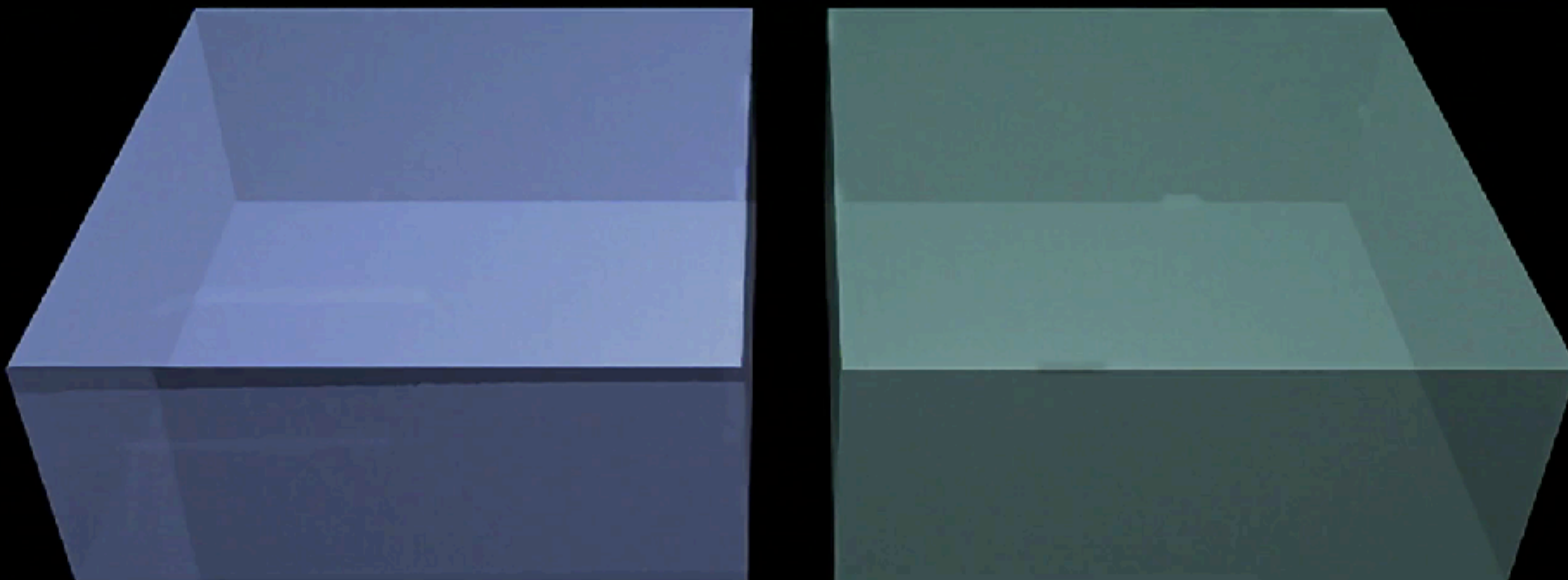

esa
Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size

Cosmic Miso Soup

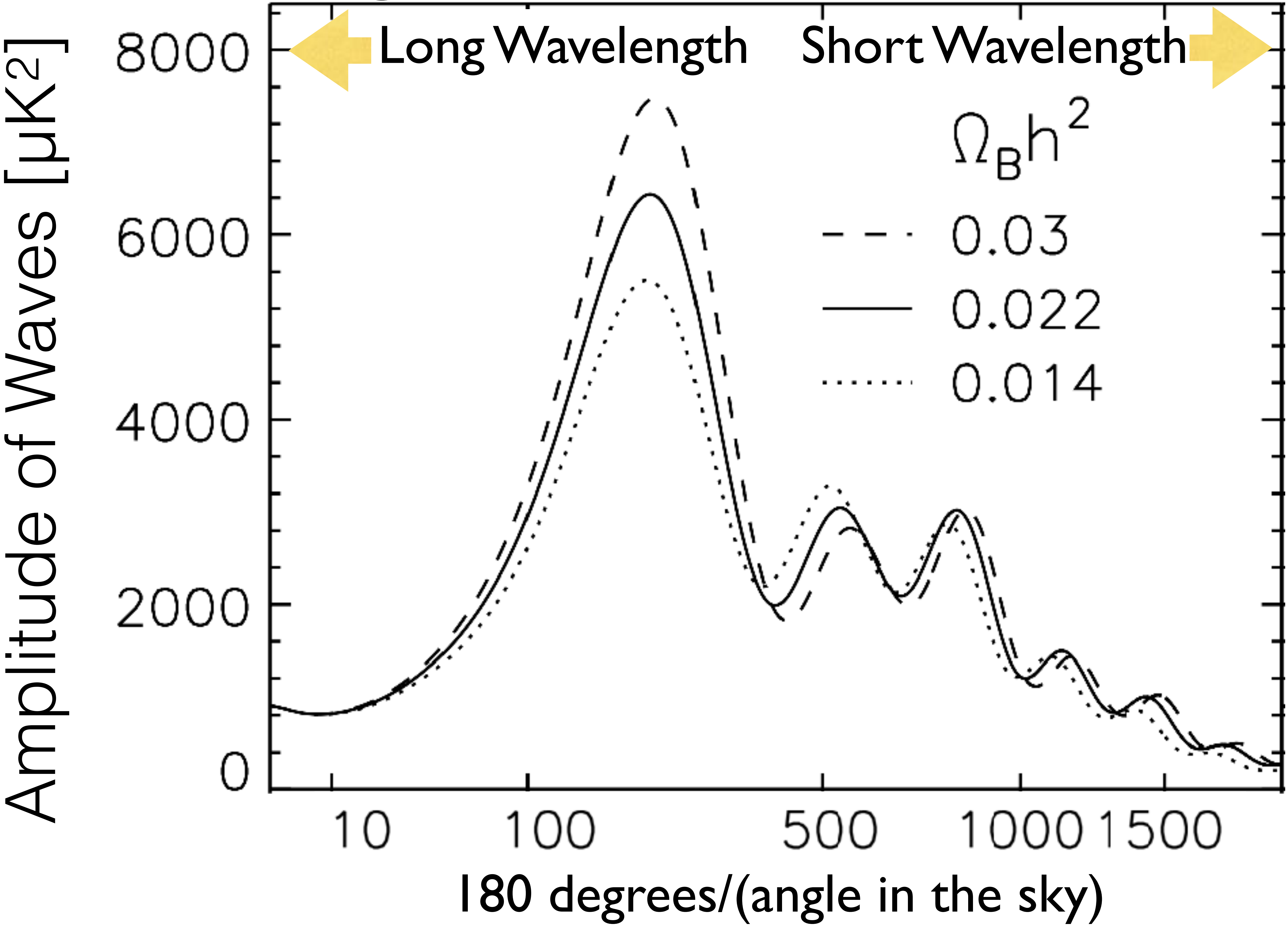
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup

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

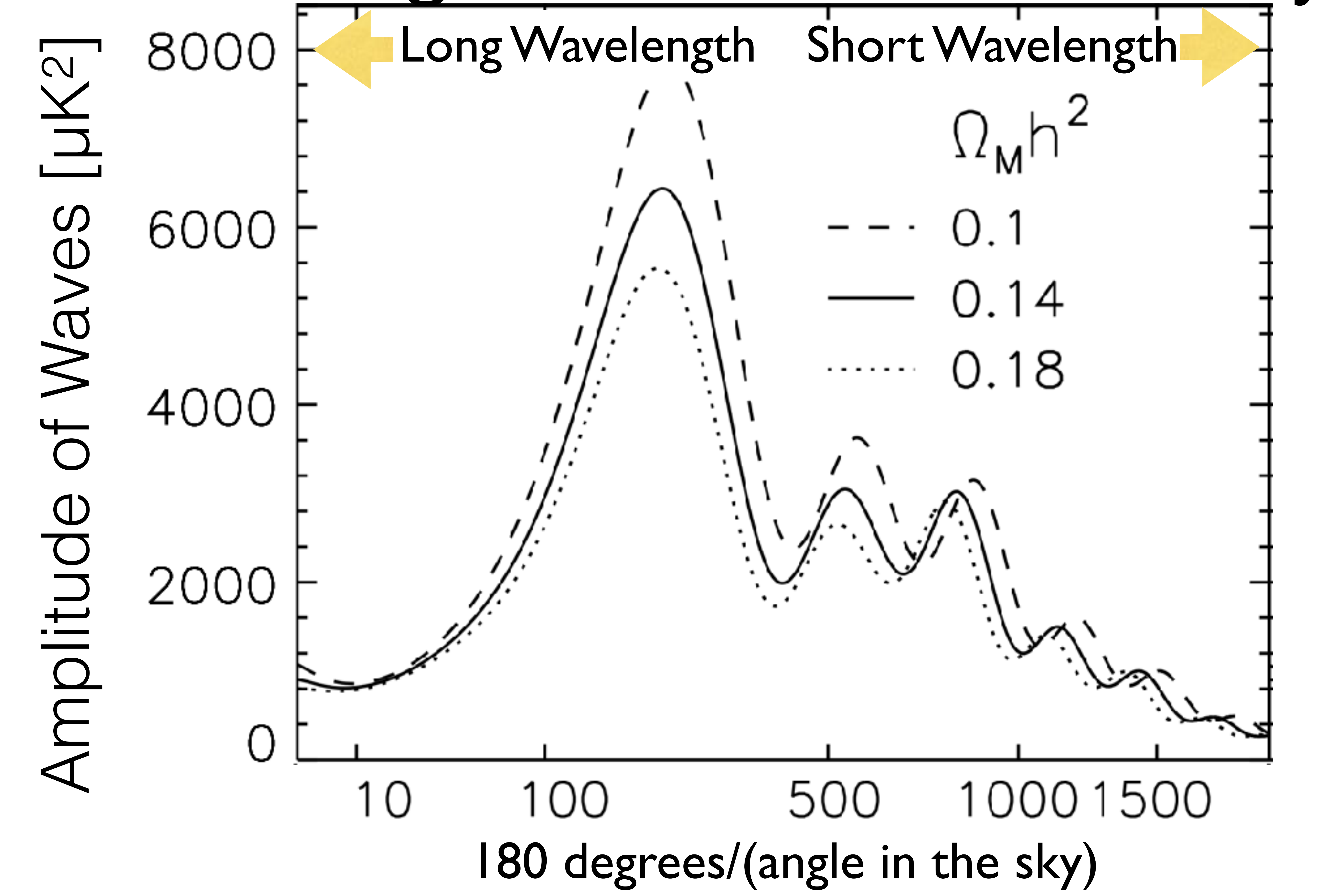
- And imagine watching how ripples are created and propagate throughout the soup



Measuring Abundance of H&He

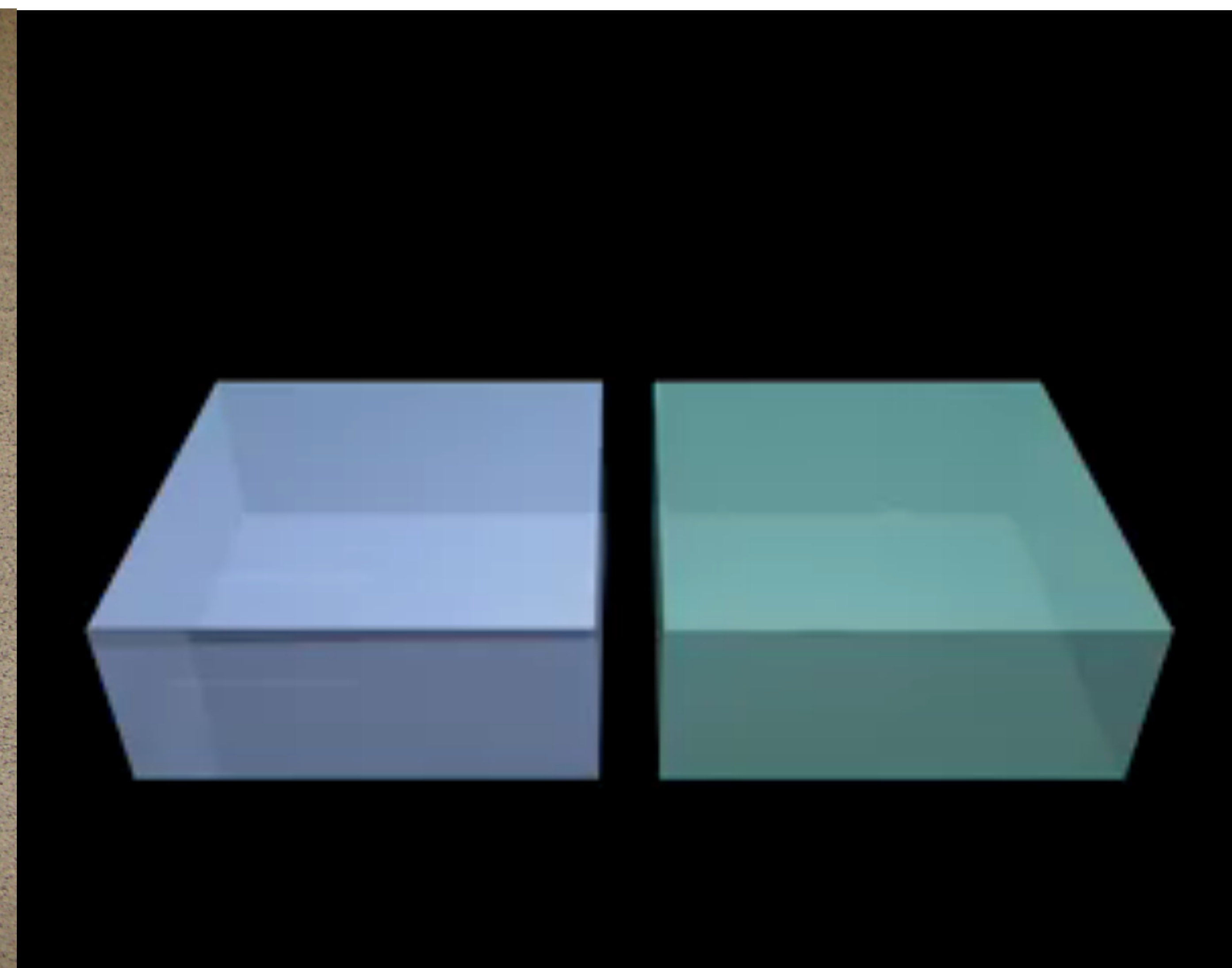


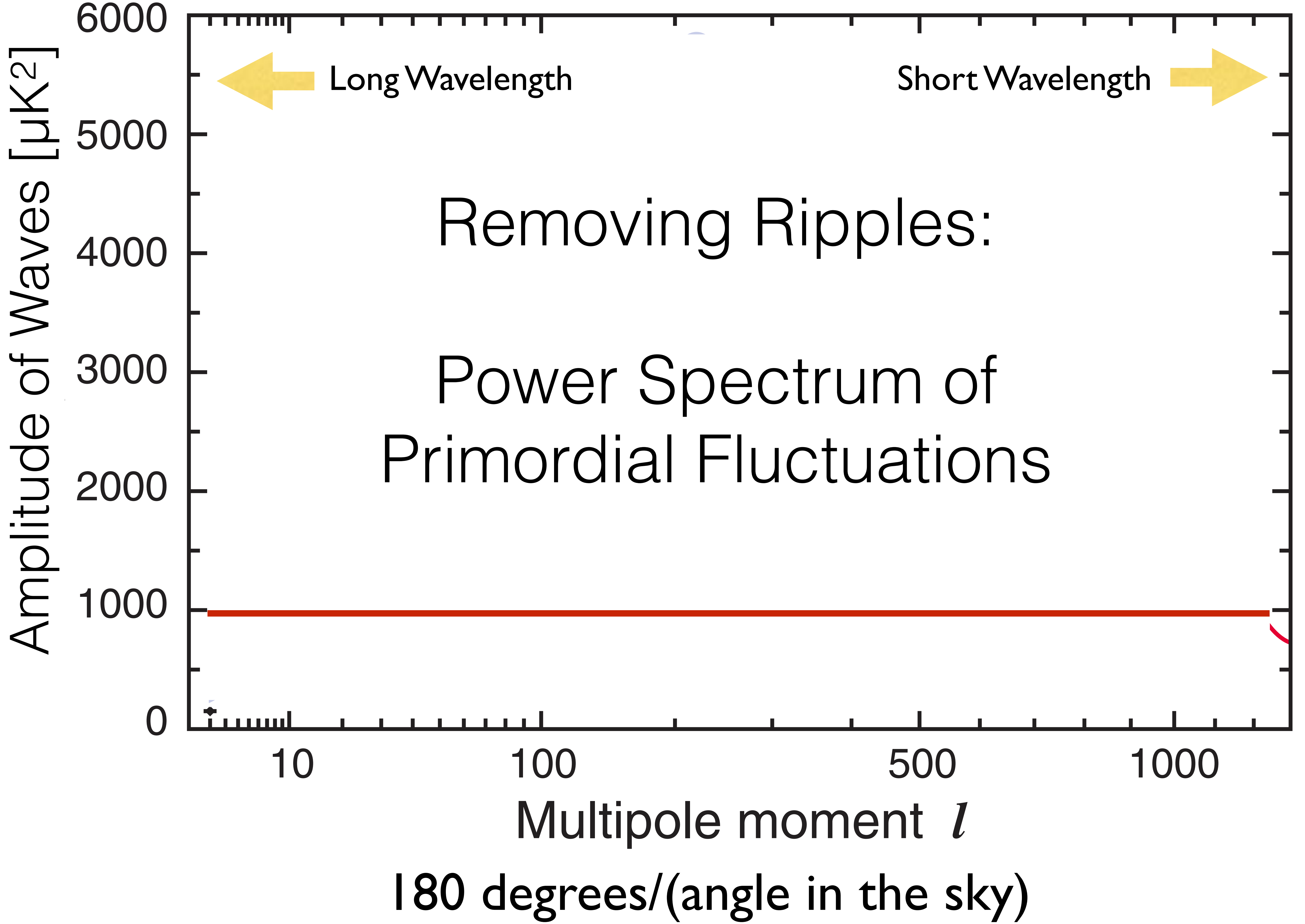
Measuring Total Matter Density



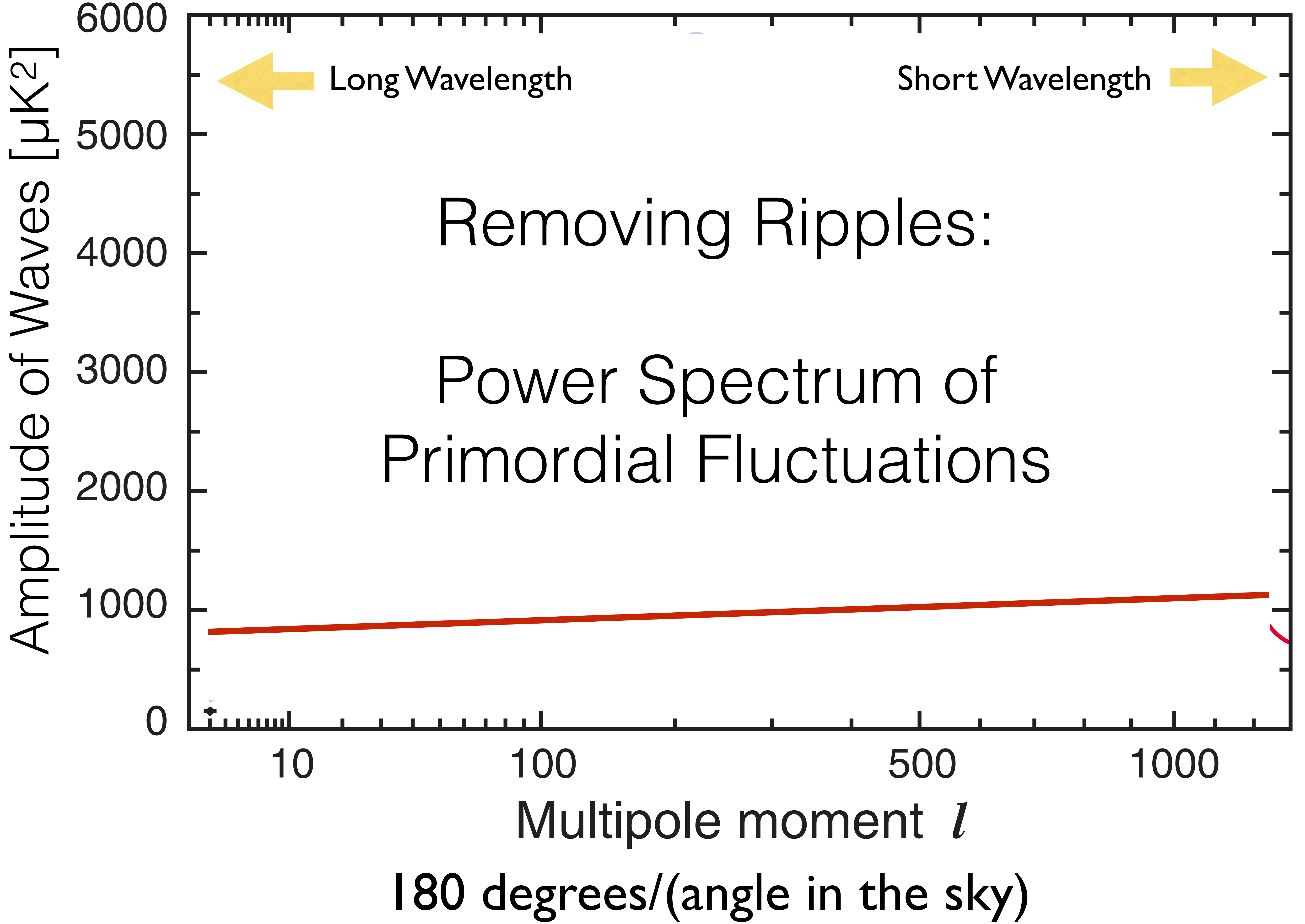
Origin of Fluctuations

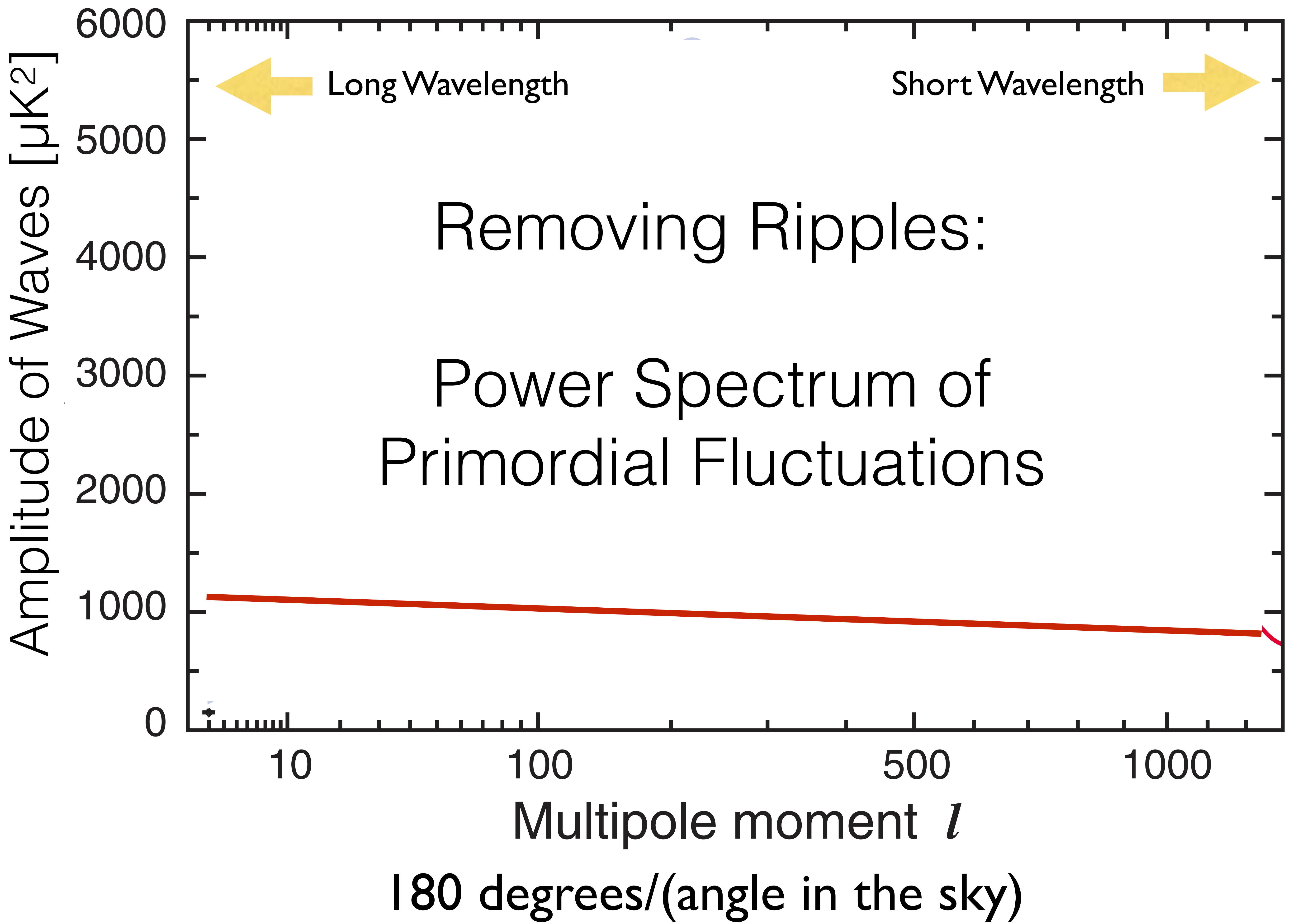
- Who dropped those Tofus into the cosmic Miso soup?

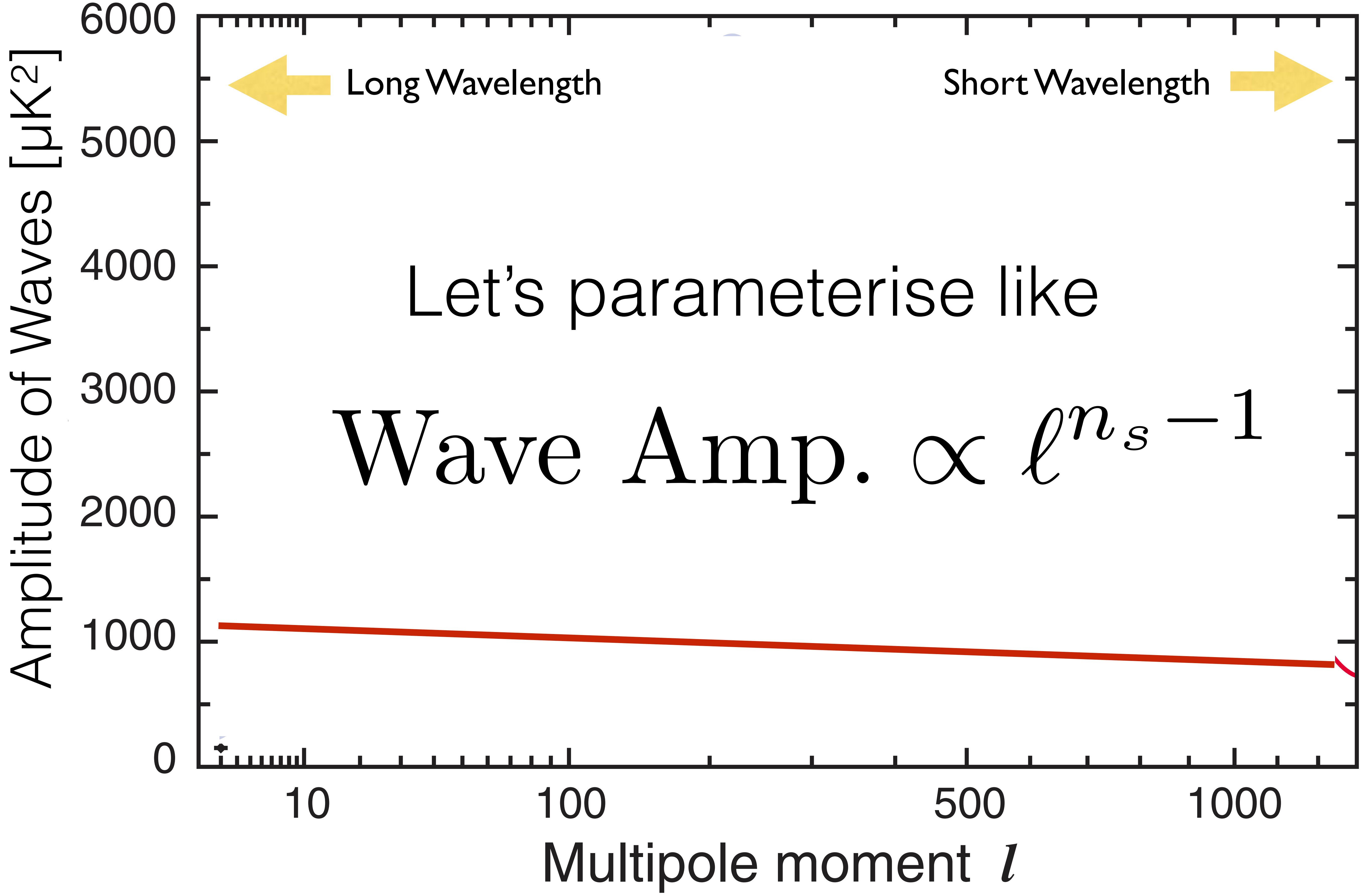




Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
Amplitude of Waves [μK2]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)


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)

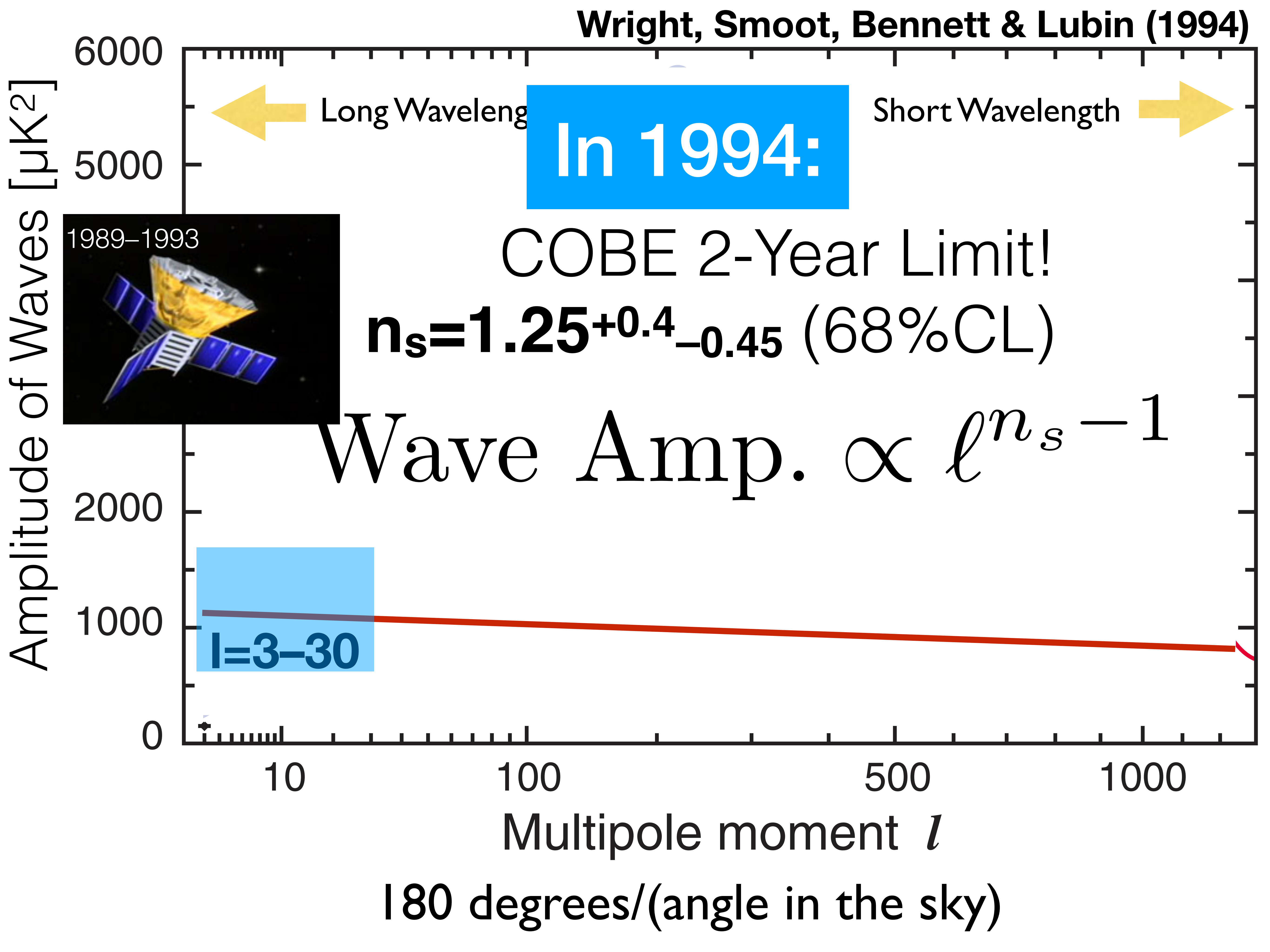

6000
5000
4000
3000
2000
1000
0
Amplitude of Waves [μK²]
Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

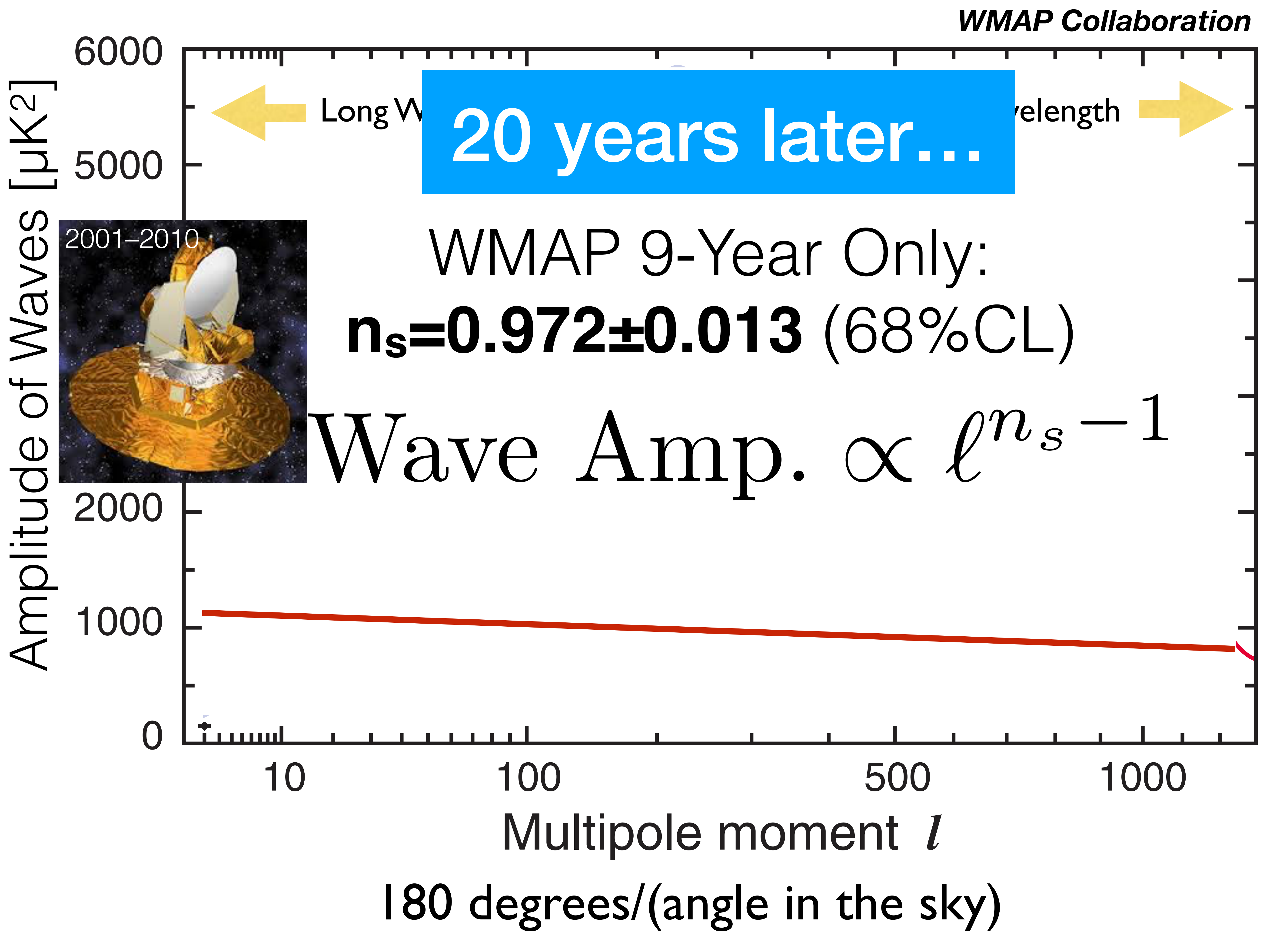


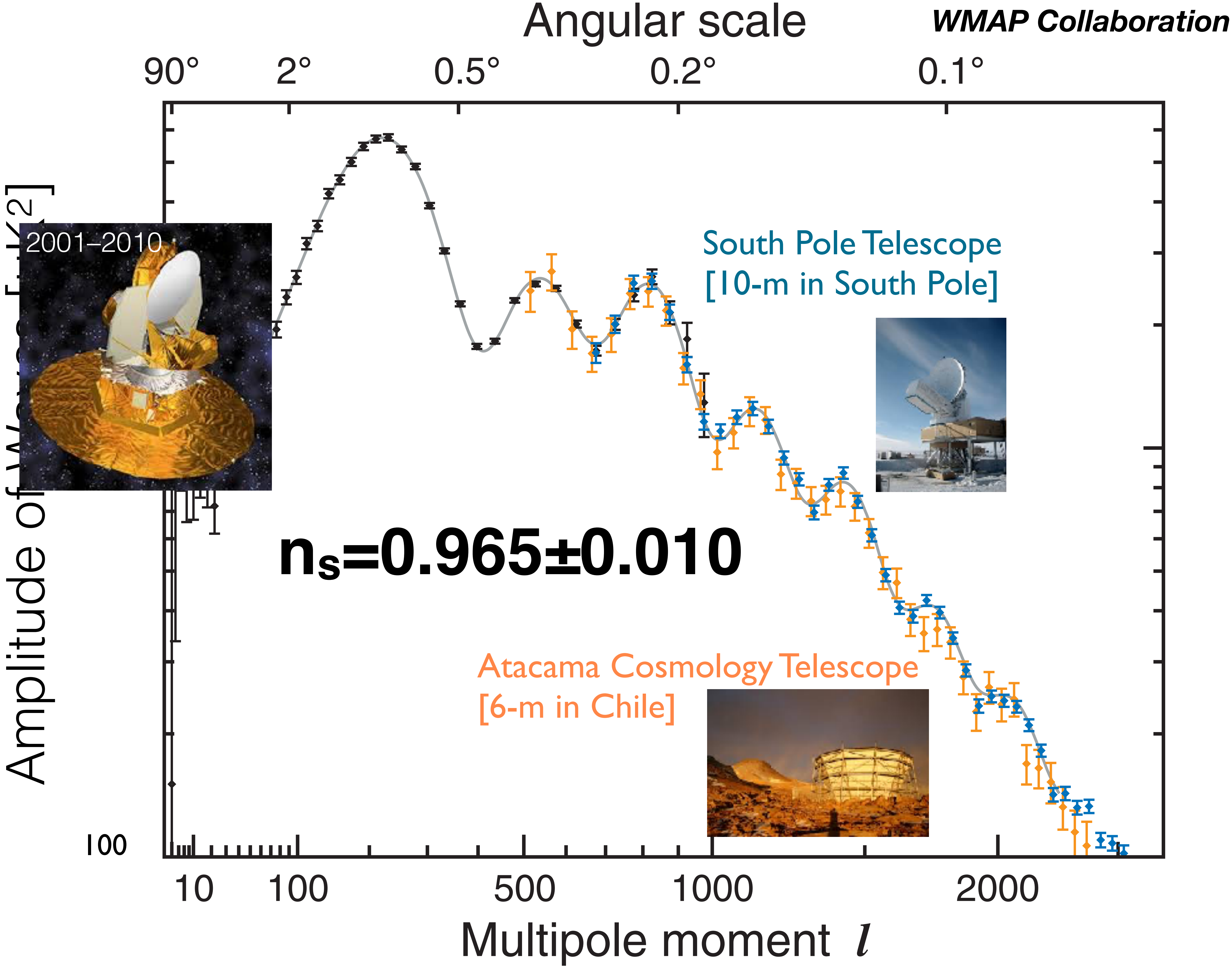
Let's parameterise like

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

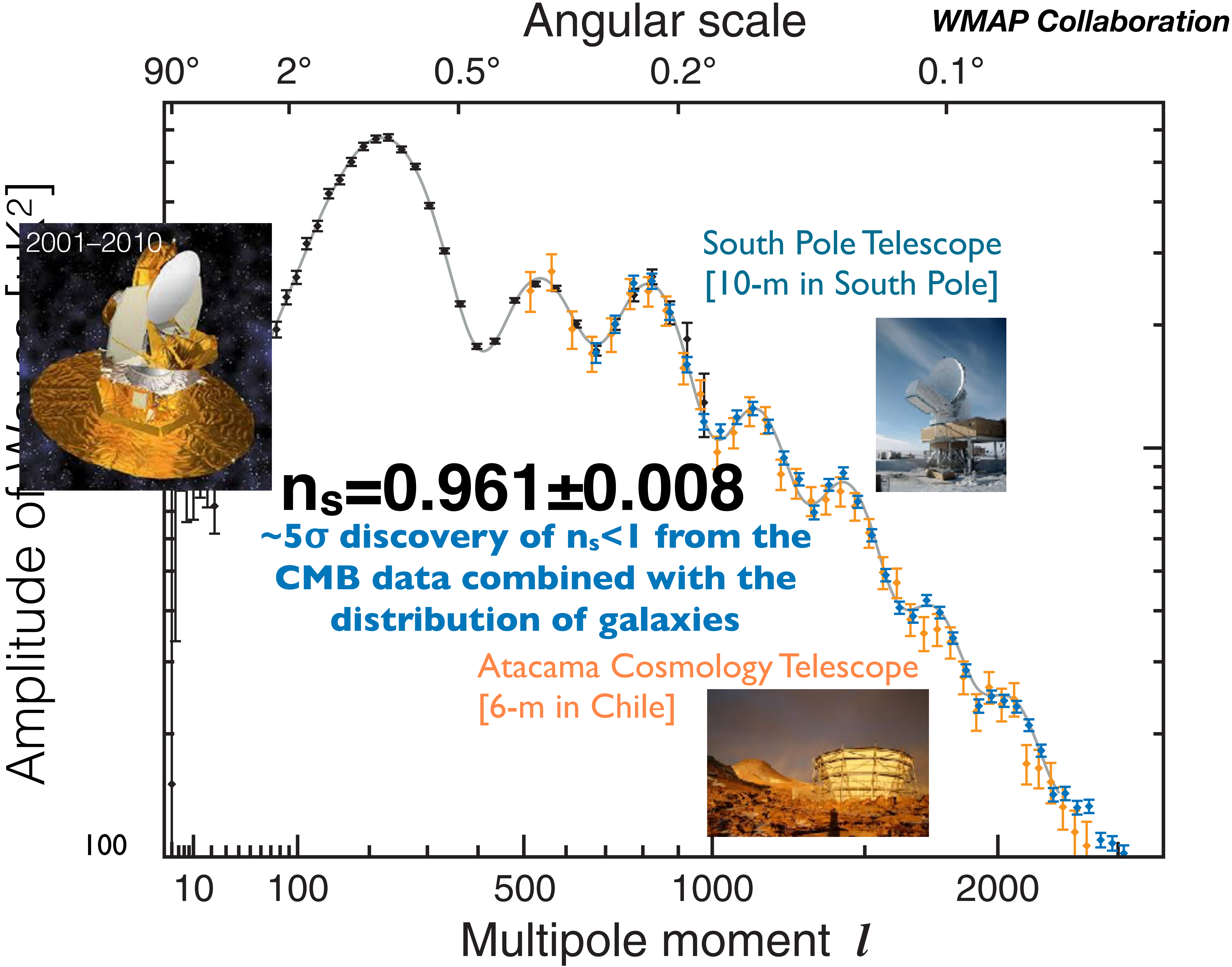
180 degrees/(angle in the sky)

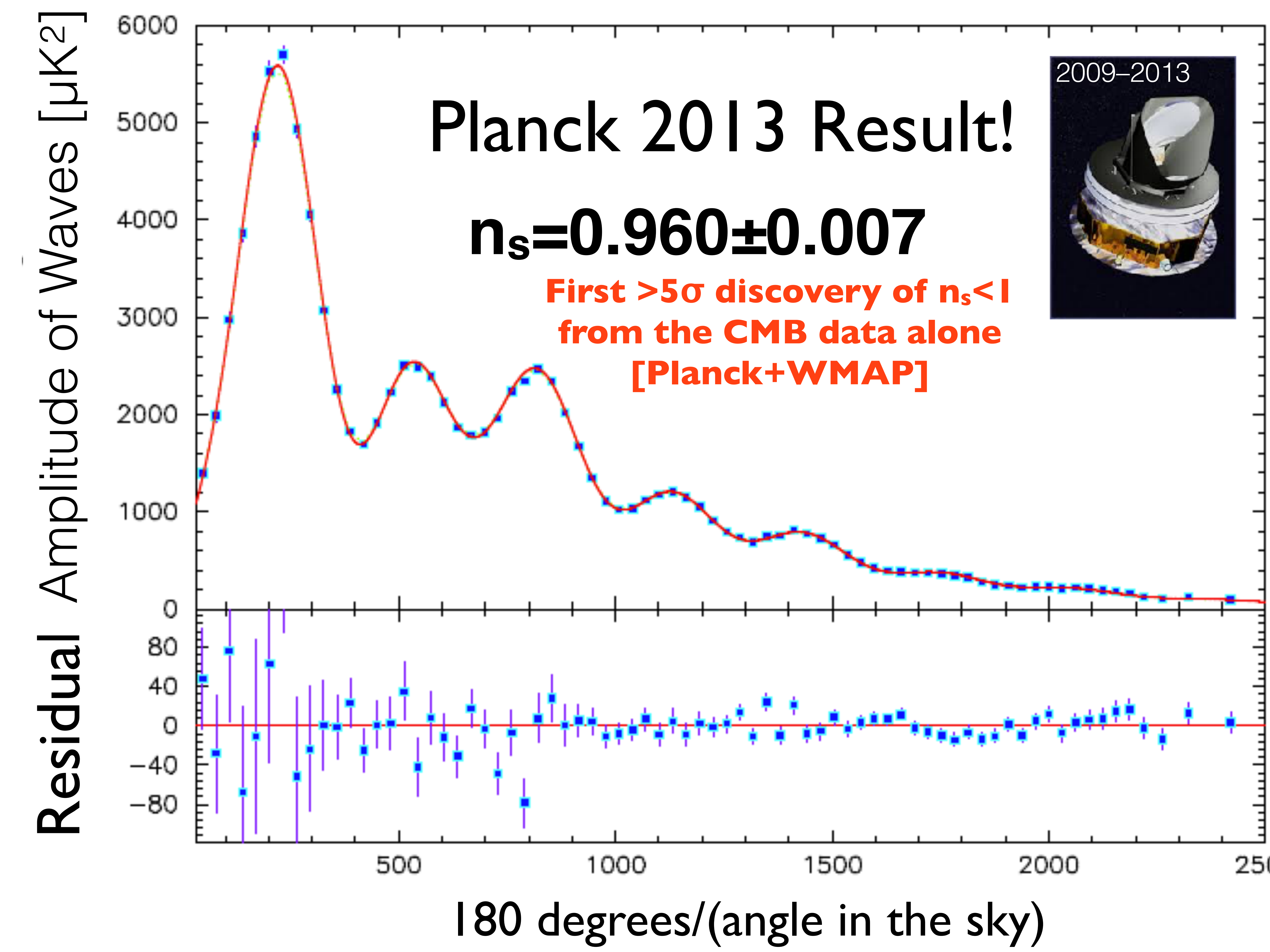

Wright, Smoot, Bennett & Lubin (1994)
In 1994:
COBE 2-Year Limit!
$n_s = 1.25^{+0.4}_{-0.45}$ (68%CL)
Wave Amp. $\propto \ell^{n_s - 1}$
1989–1993
Long Wavelength
Short Wavelength
l=3–30
Amplitude of Waves [μK²]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

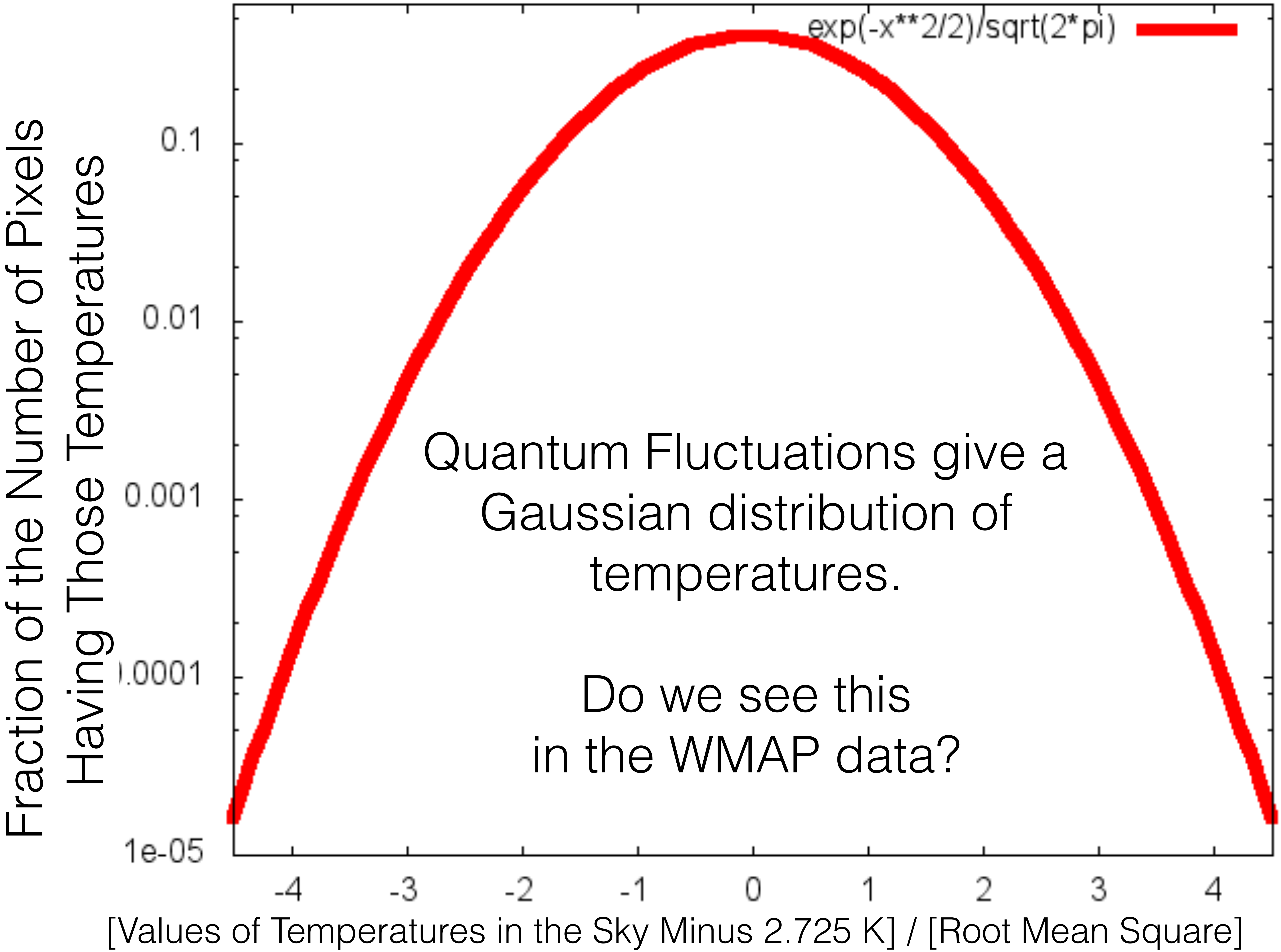

WMAP Collaboration
20 years later...
Long W
velength
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
$$\text{Wave Amp.} \propto \ell^{n_s-1}$$
2001–2010
Amplitude of Waves [μK²]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



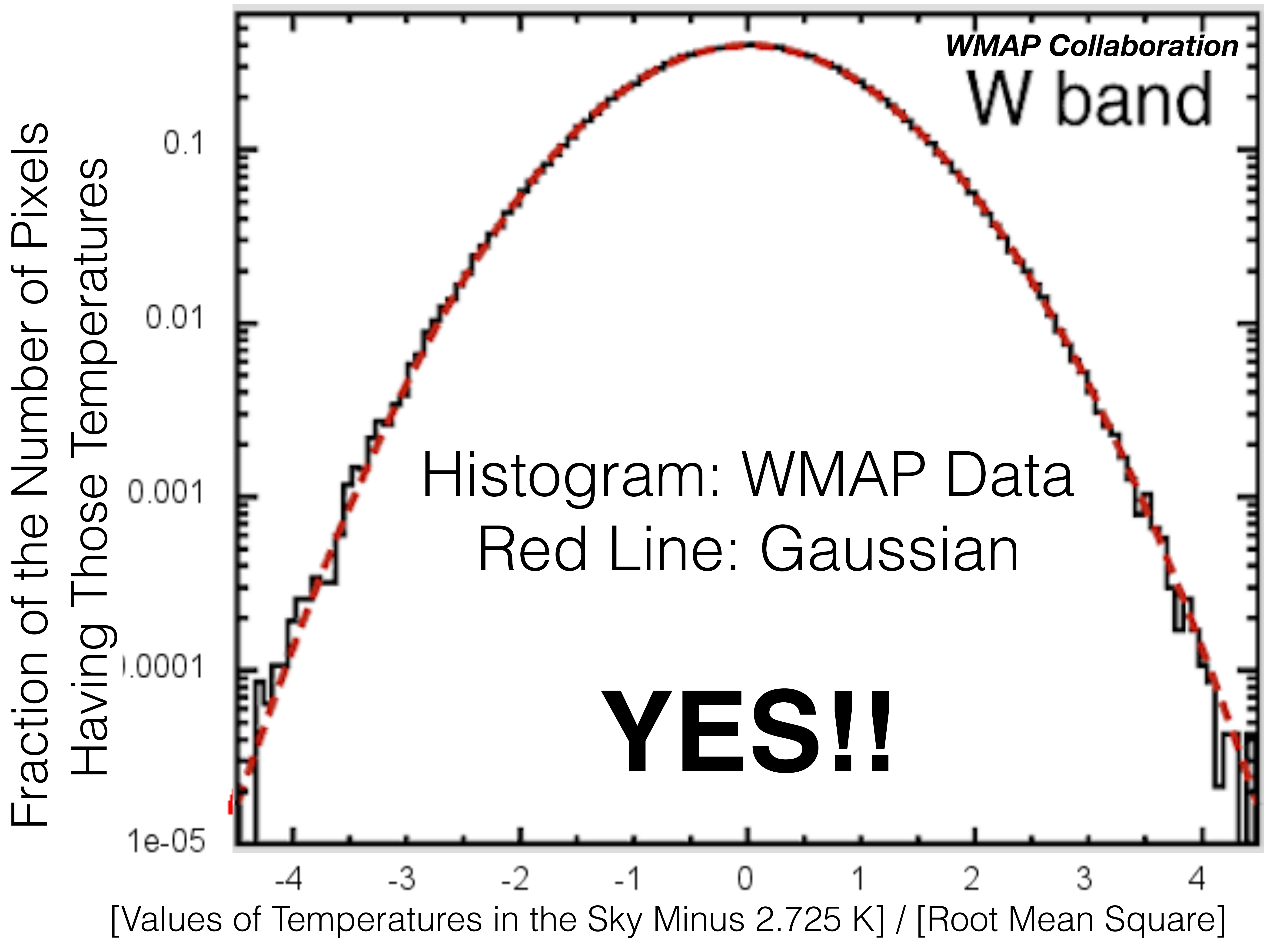
WMAP Collaboration
Angular scale
90°
2°
0.5°
0.2°
0.1°
Amplitude of Waves [μK^2]
2001–2010
South Pole Telescope
[10-m in South Pole]
n_s=0.965±0.010
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment l


WMAP Collaboration
Angular scale
90°
2°
0.5°
0.2°
0.1°
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!
2009–2013
n_s=0.960±0.007
First >5σ discovery of n_s<1
from the CMB data alone
[Planck+WMAP]
Amplitude of Waves [μK²]
Residual
180 degrees/(angle in the sky)
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000



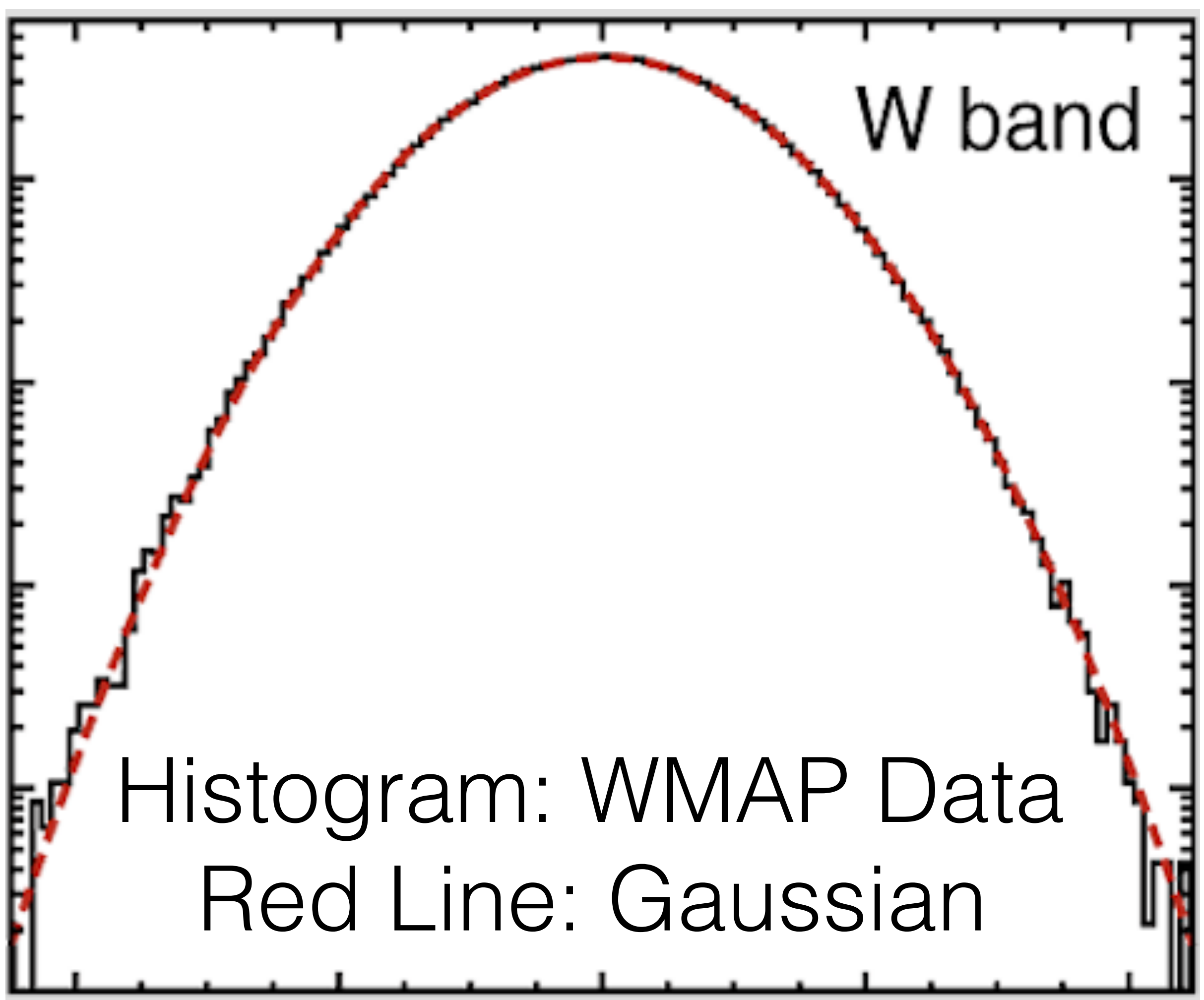
exp(-x**2/2)/sqrt(2*pi)
0.1
0.01
0.001
0.0001
1e-05
-4
-3
-2
-1
0
1
2
3
4
Fraction of the Number of Pixels
Having Those Temperatures
[Values of Temperatures in the Sky Minus 2.725 K] / [Root Mean Square]
Quantum Fluctuations give a
Gaussian distribution of
temperatures.
Do we see this
in the WMAP data?



WMAP Collaboration
W band
Histogram: WMAP Data
Red Line: Gaussian
YES!!
Fraction of the Number of Pixels
Having Those Temperatures
0.1
0.01
0.001
.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]

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)

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

WMAP 9-year Result

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

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

Planck 2015 Result

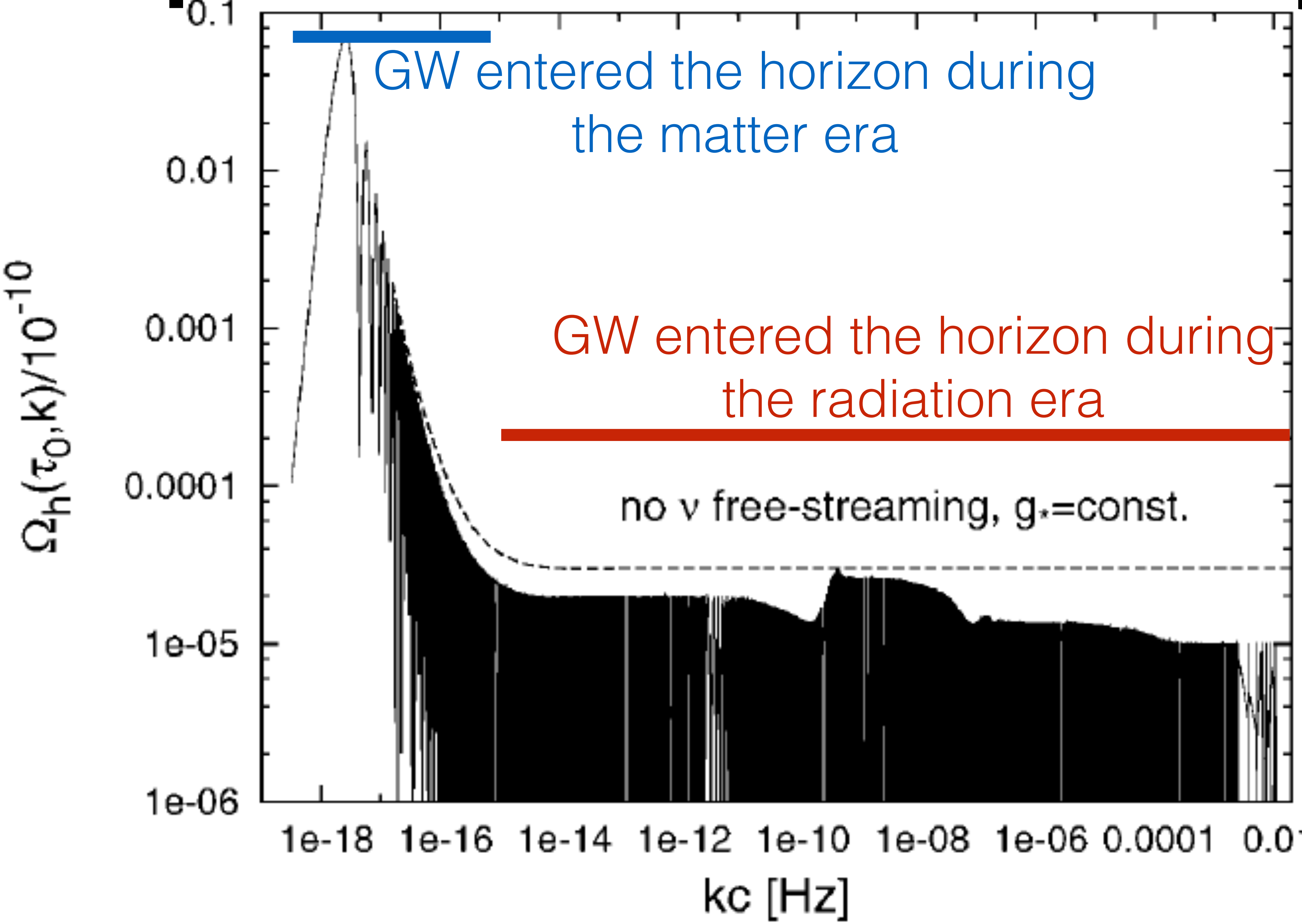
So, have we found inflation?

- Single-field slow-roll inflation looks remarkably good:
  - **Super-horizon fluctuation**
  - **Adiabaticity**
  - **Gaussianity**
  - $\mathbf{n_s<1}$
- 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

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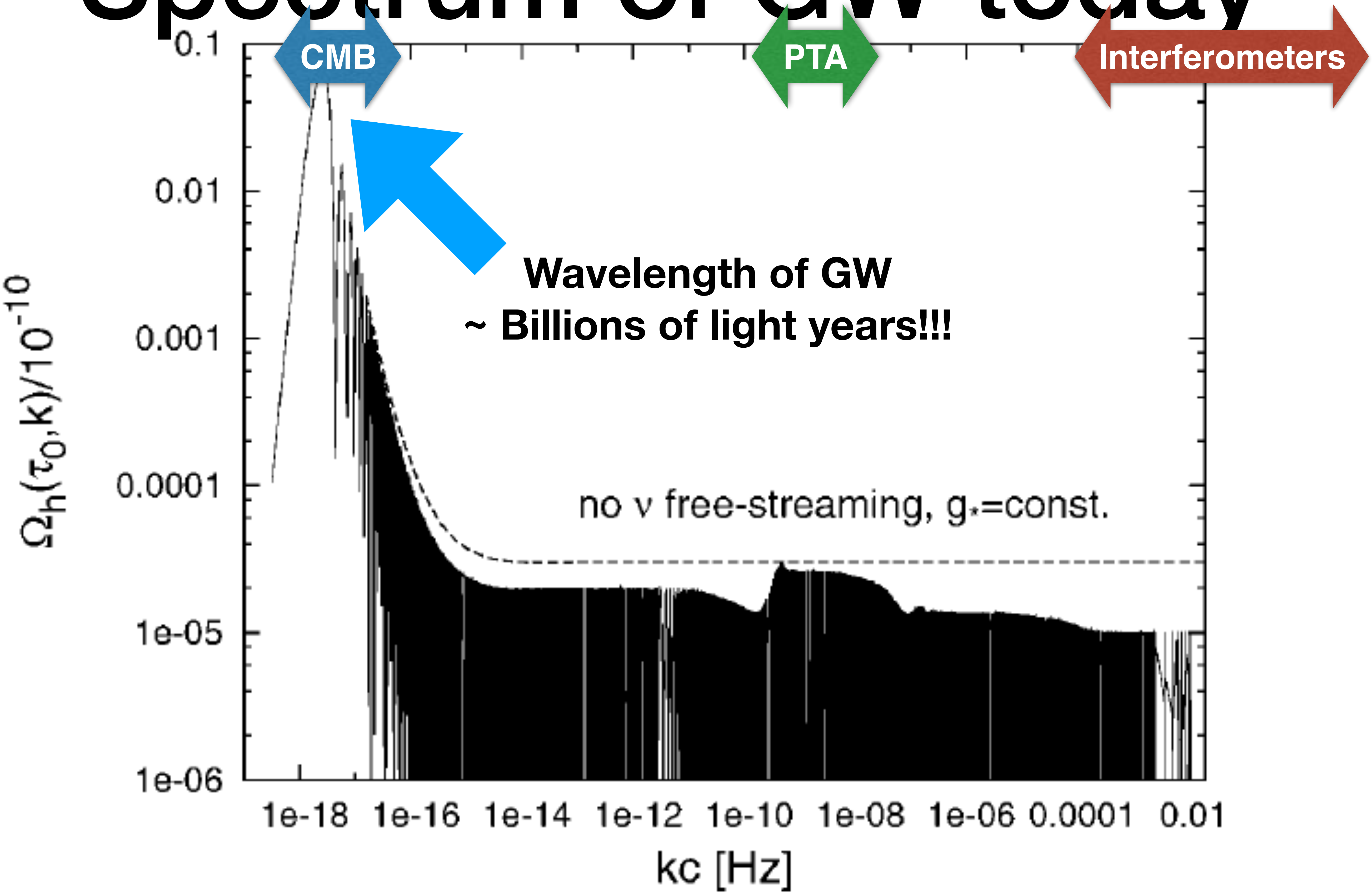


Finding Signatures of Gravitational Waves in the CMB

- **Next frontier in the CMB research**

1. Find evidence for nearly scale-invariant gravitational waves

New Research Area!

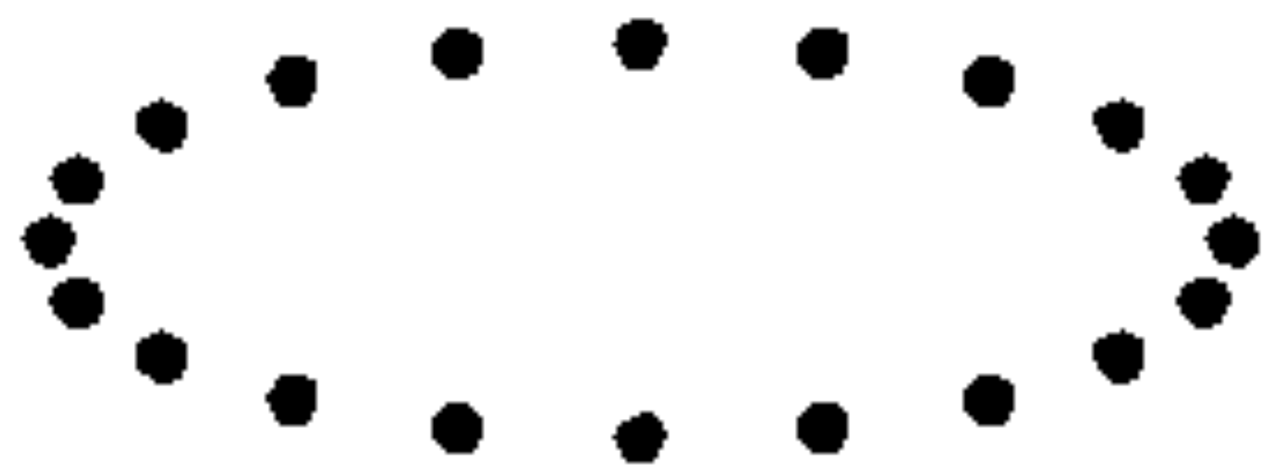
2. Once found, test Gaussianity to make sure (or not!) that the signal comes from vacuum fluctuation

3. Constrain inflation models

Measuring GW

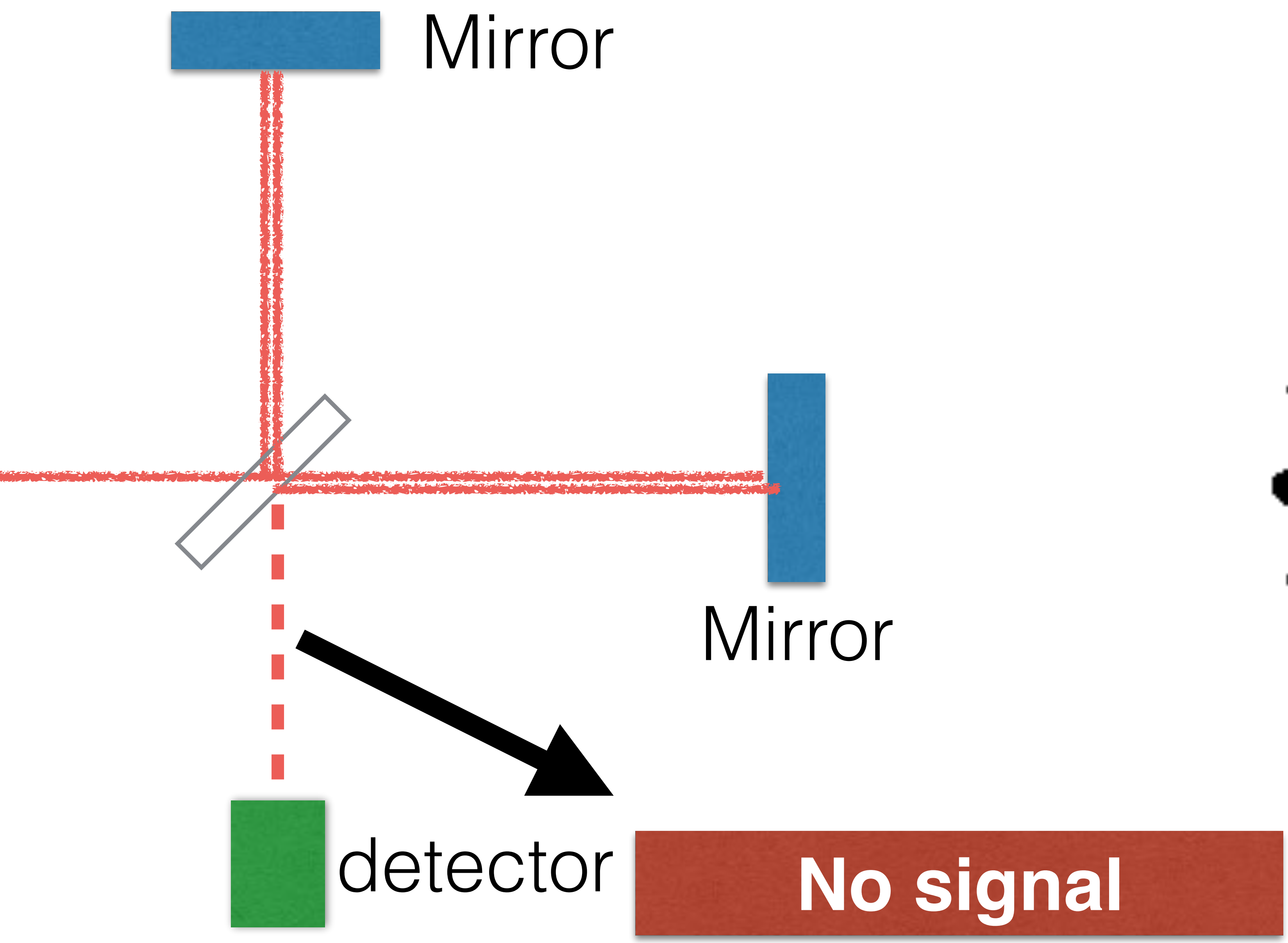
- GW changes distances between two points

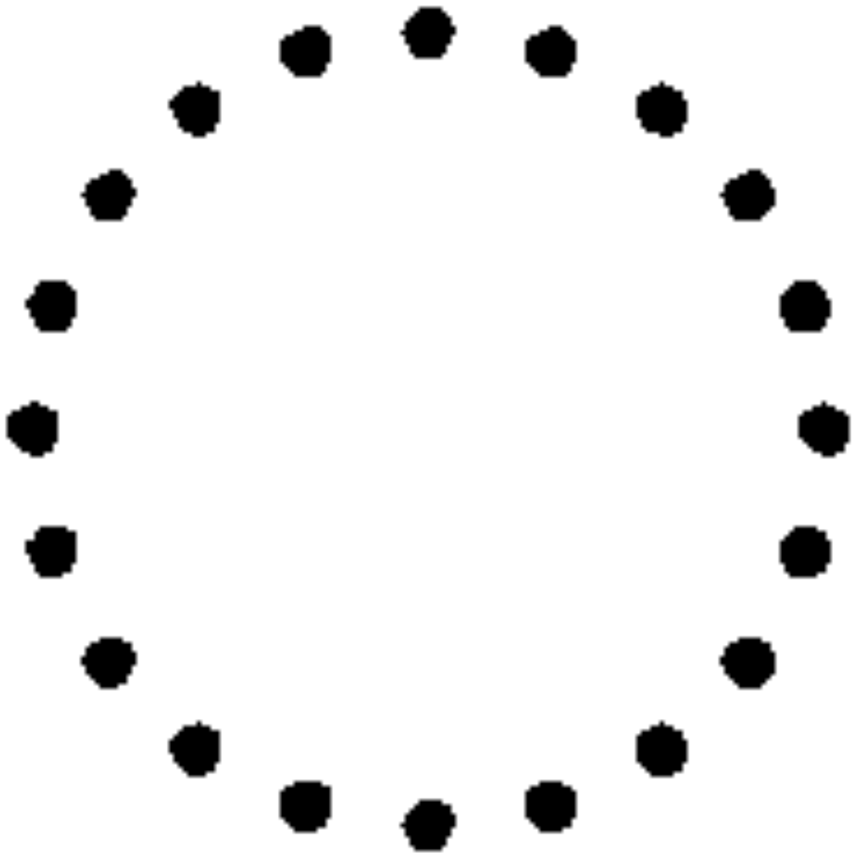
$$d\ell^2 = d\mathbf{x}^2 = \sum_{ij} \delta_{ij} dx^i dx^j$$



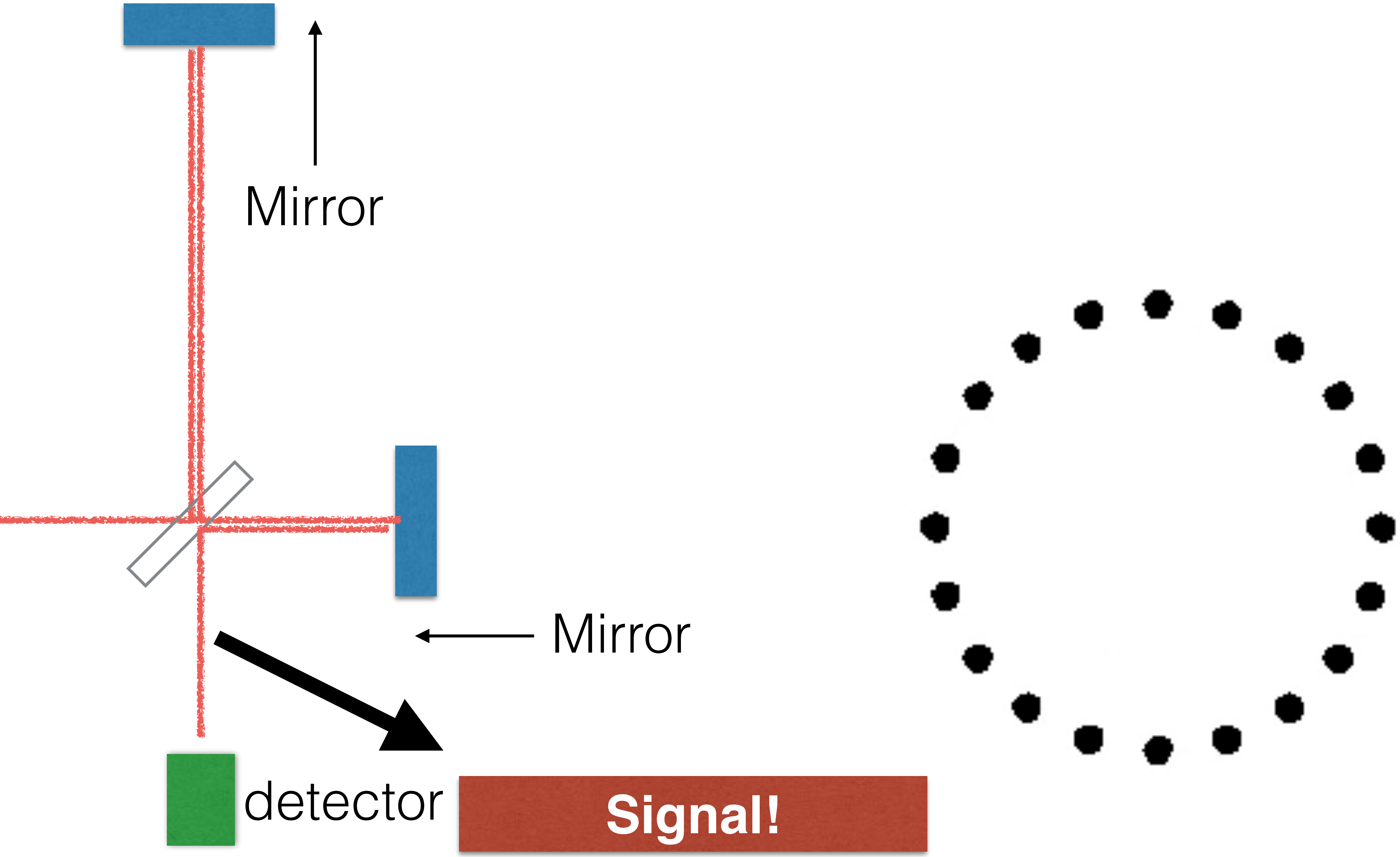
$$d\ell^2 = \sum_{ij} (\delta_{ij} + \underline{h_{ij}}) dx^i dx^j$$

Laser Interferometer

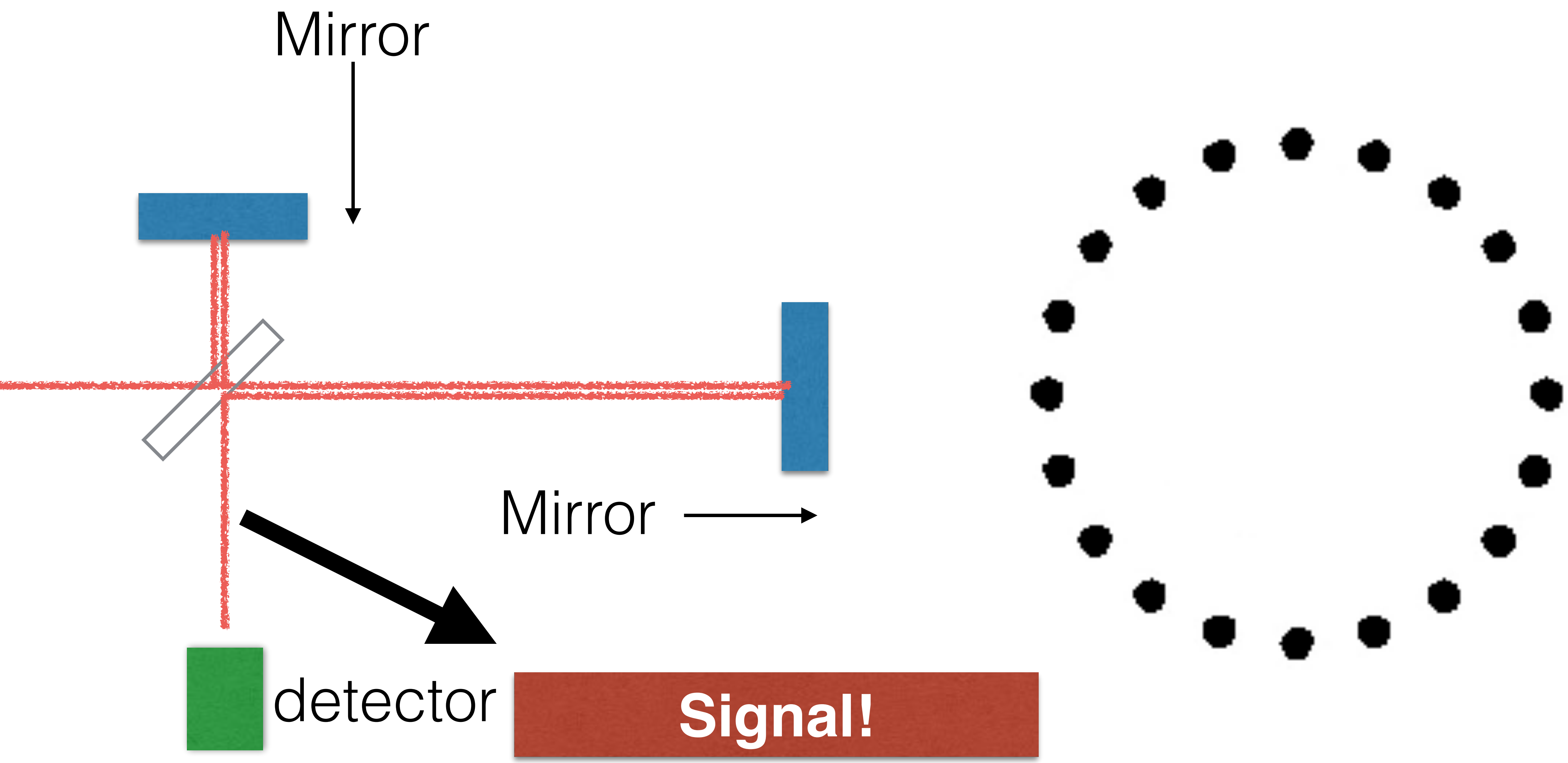




Laser Interferometer



Laser Interferometer



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

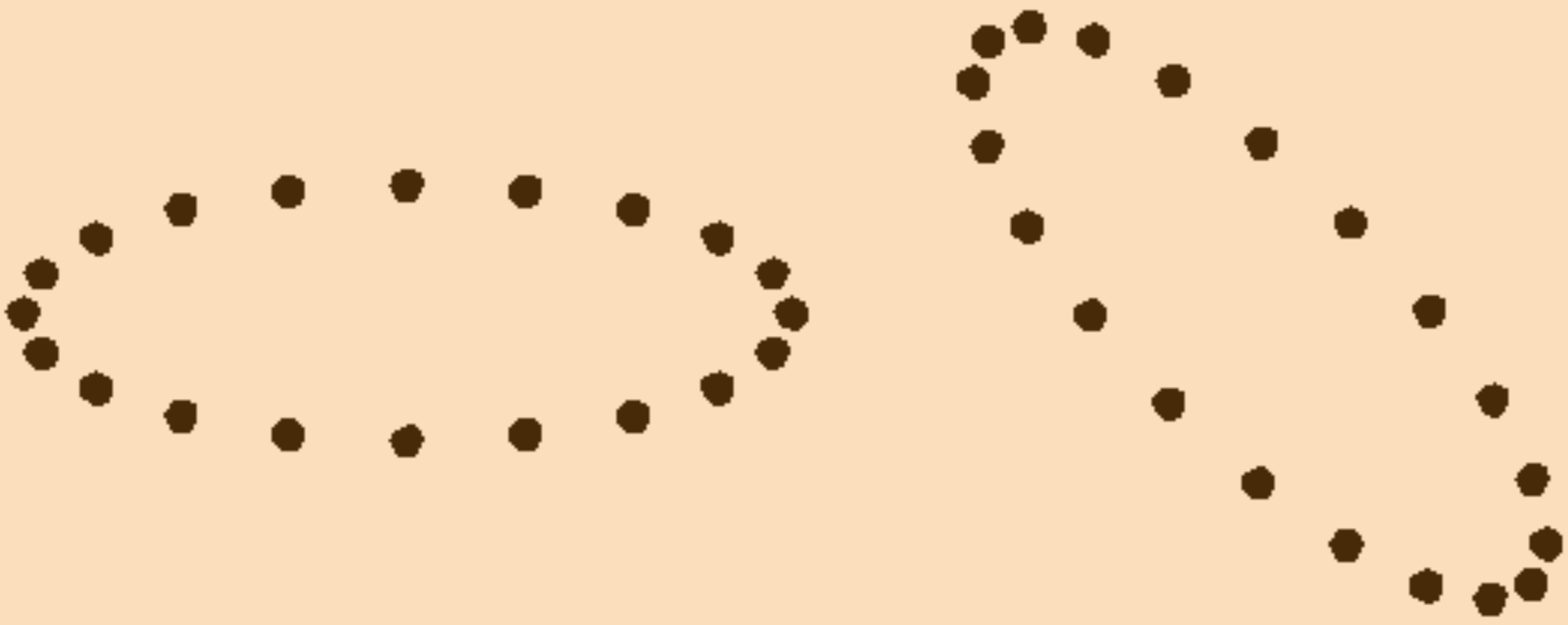
But, the primordial GW affecting the CMB has a wavelength of **billions of light-years**!! How do we find it?

Detecting GW by CMB

Isotropic electro-magnetic fields

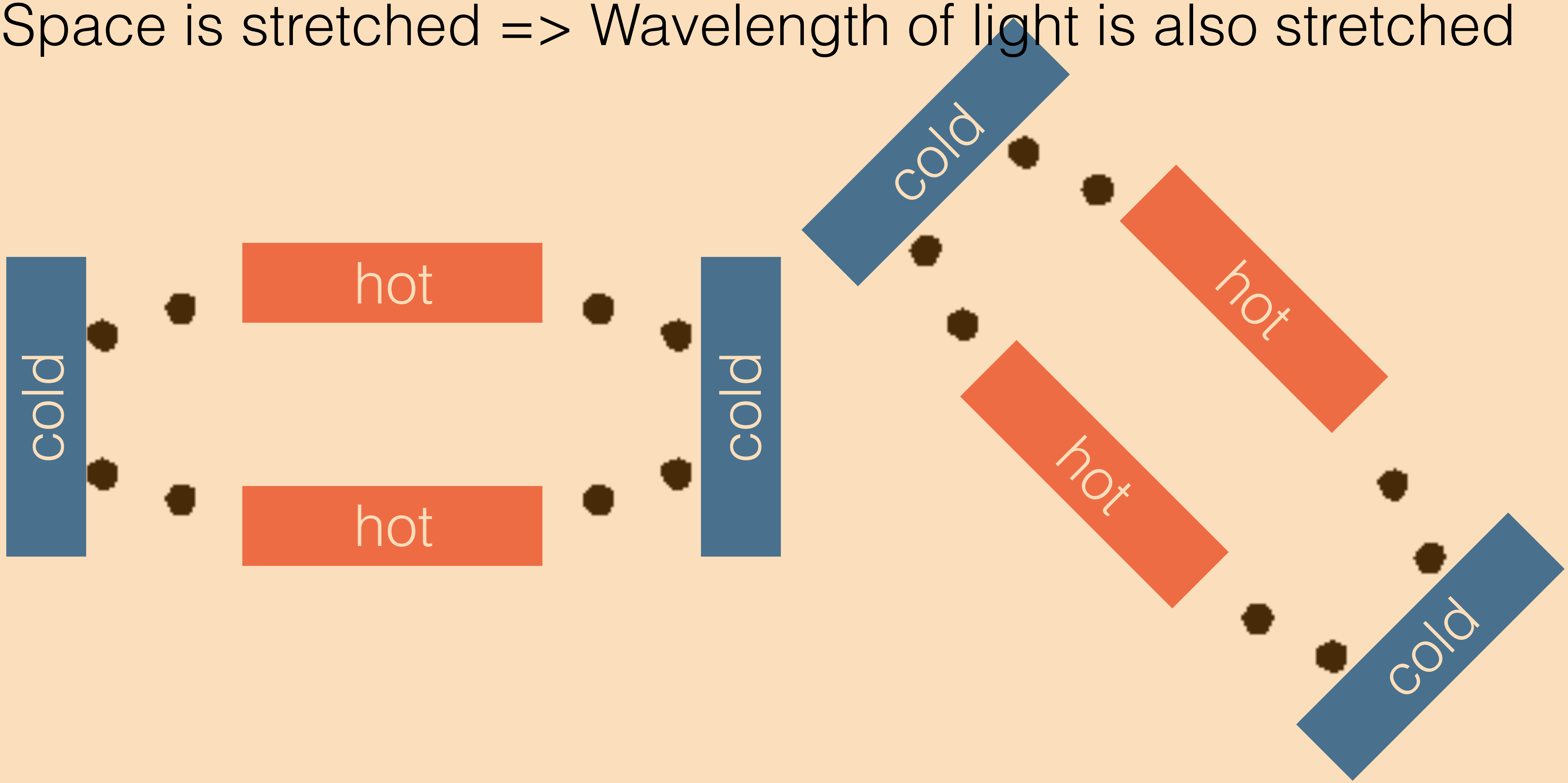
Detecting GW by CMB

GW propagating in isotropic electro-magnetic fields



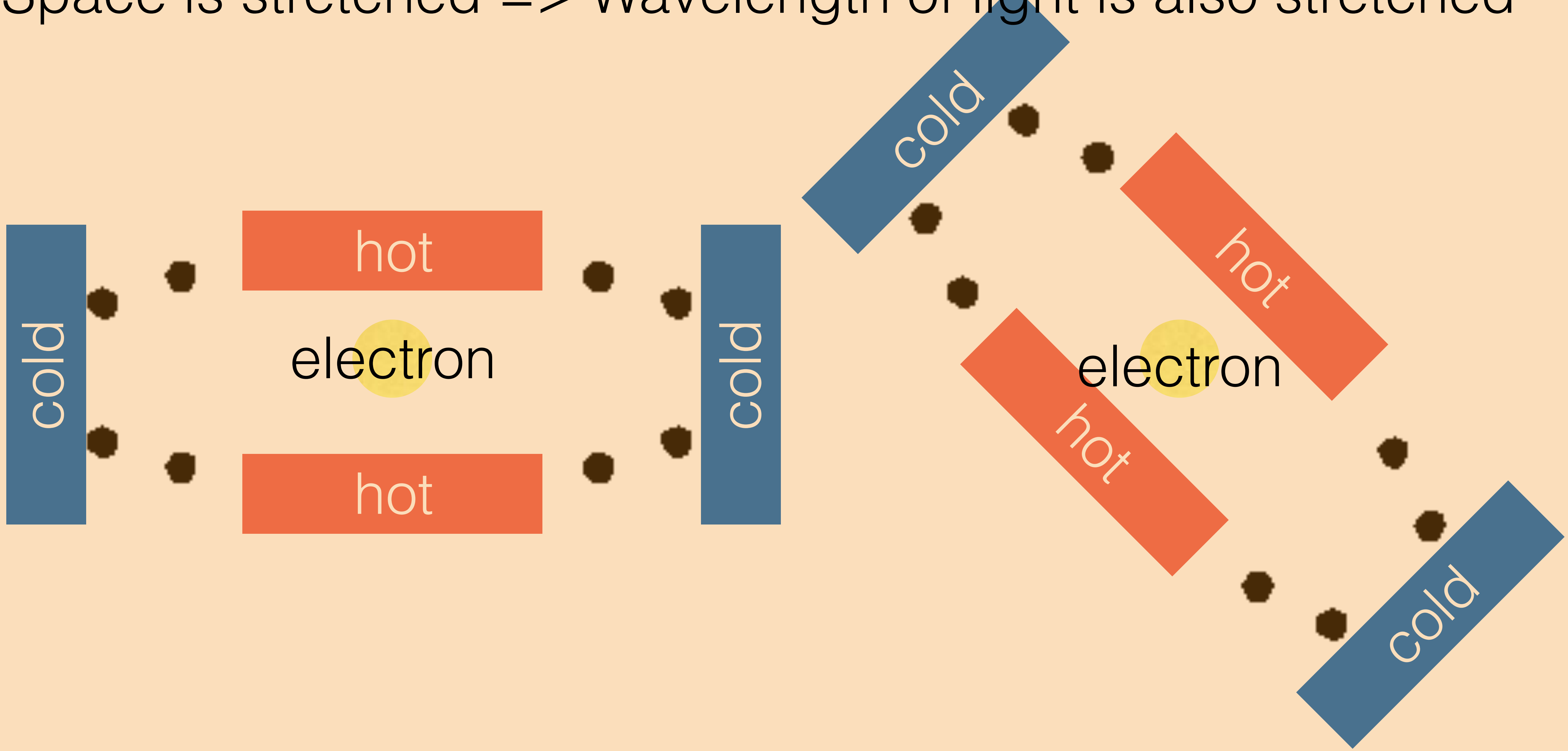
Detecting GW by CMB

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**

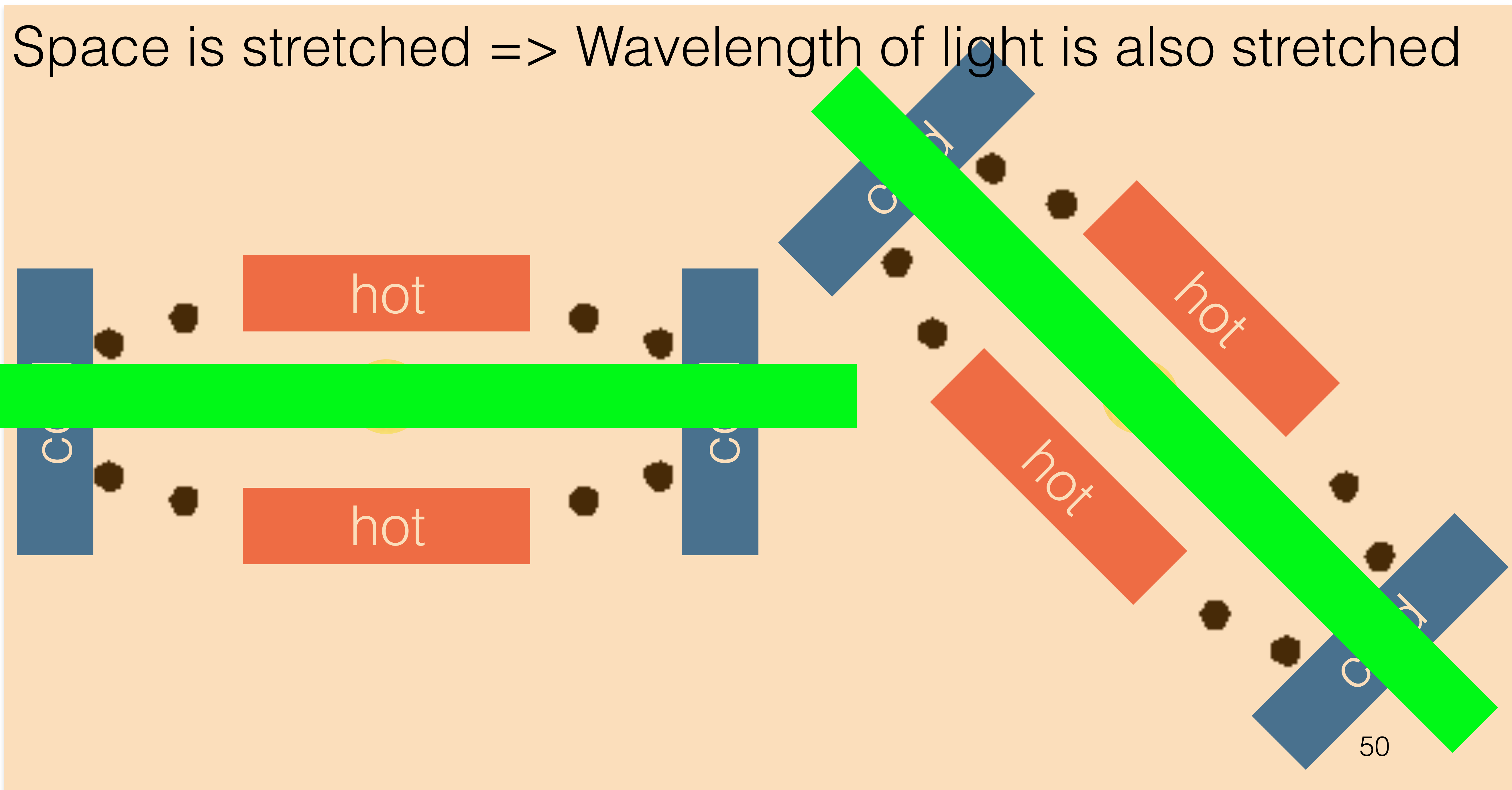



Photo Credit: TALEX
horizontally polarised

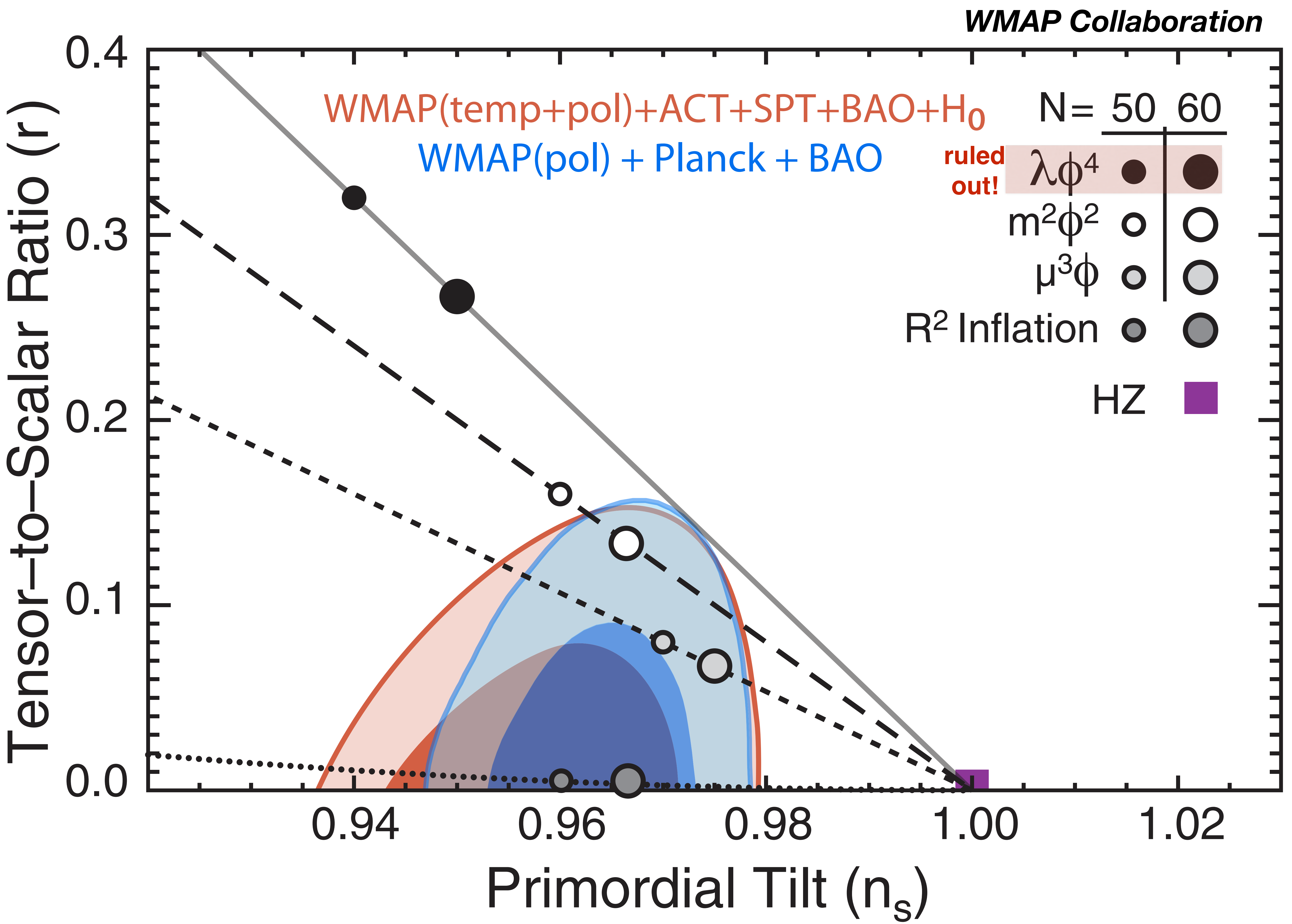

Photo Credit: TALEX

Tensor-to-scalar Ratio

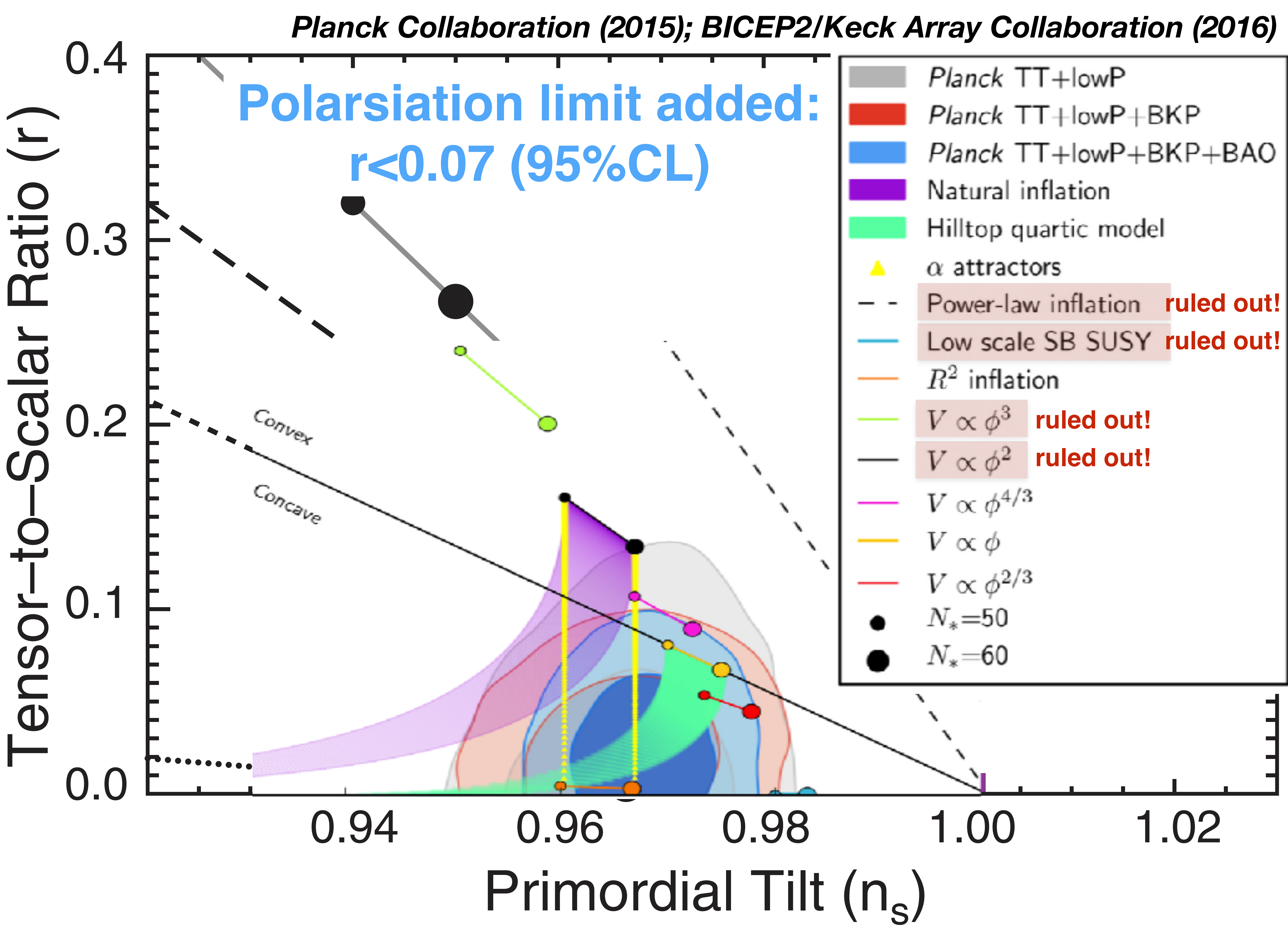
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

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

BICEP2/Keck Array Collaboration (2016)

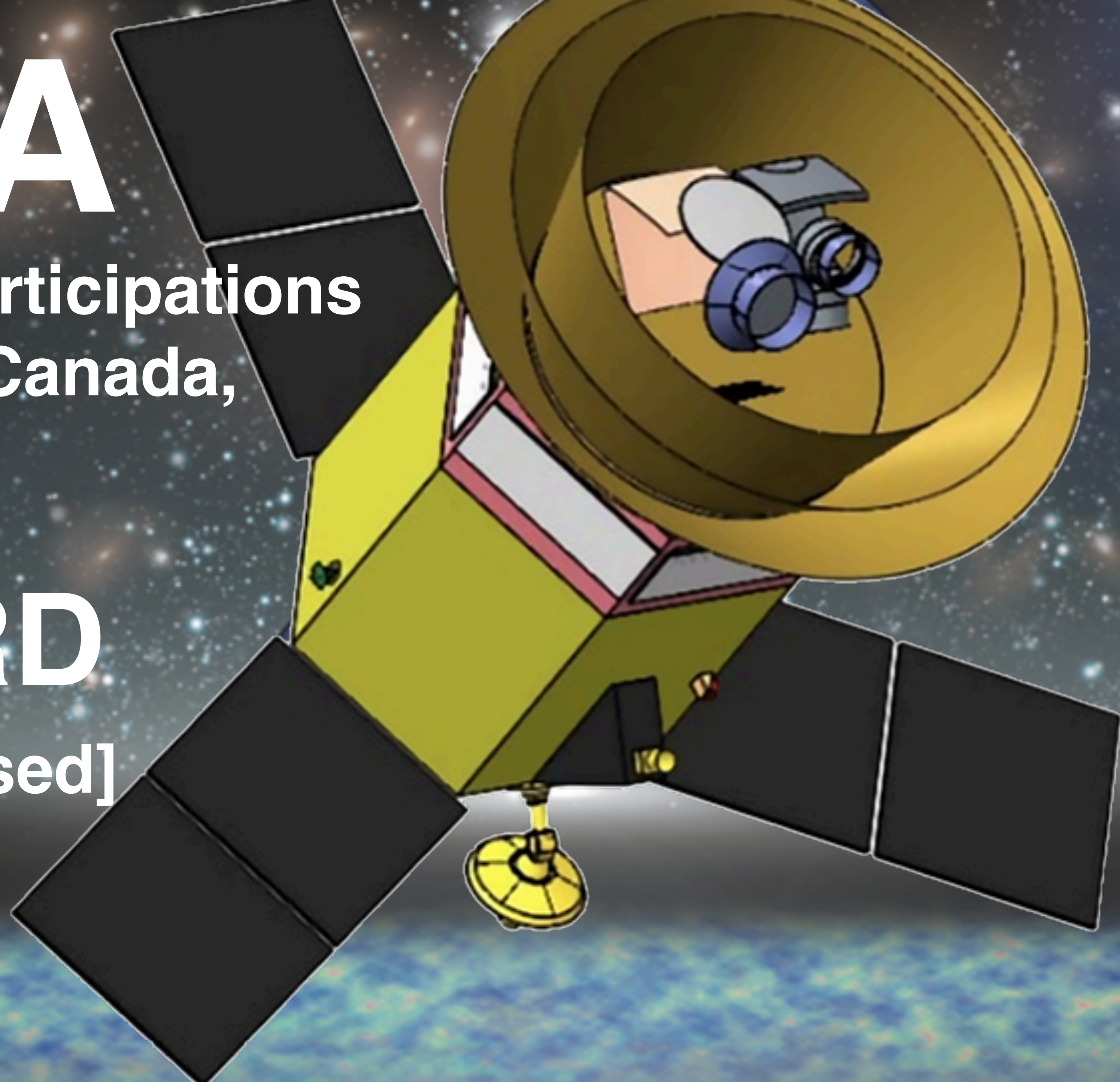


WMAP Collaboration
WMAP(temp+pol)+ACT+SPT+BAO+H0
WMAP(pol) + Planck + BAO
N= 50 60
ruled out!
λφ4
m2φ2
μ3φ
R2 Inflation
HZ
Tensor–to–Scalar Ratio (r)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (ns)


Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
Tensor–to–Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
Convex
Concave
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)
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!
R² inflation
V ∝ φ³
ruled out!
V ∝ φ²
ruled out!
V ∝ φ^{4/3}
V ∝ φ
V ∝ φ^{2/3}
N*=50
N*=60

JAXA

+ possible participations from USA, Canada, Europe



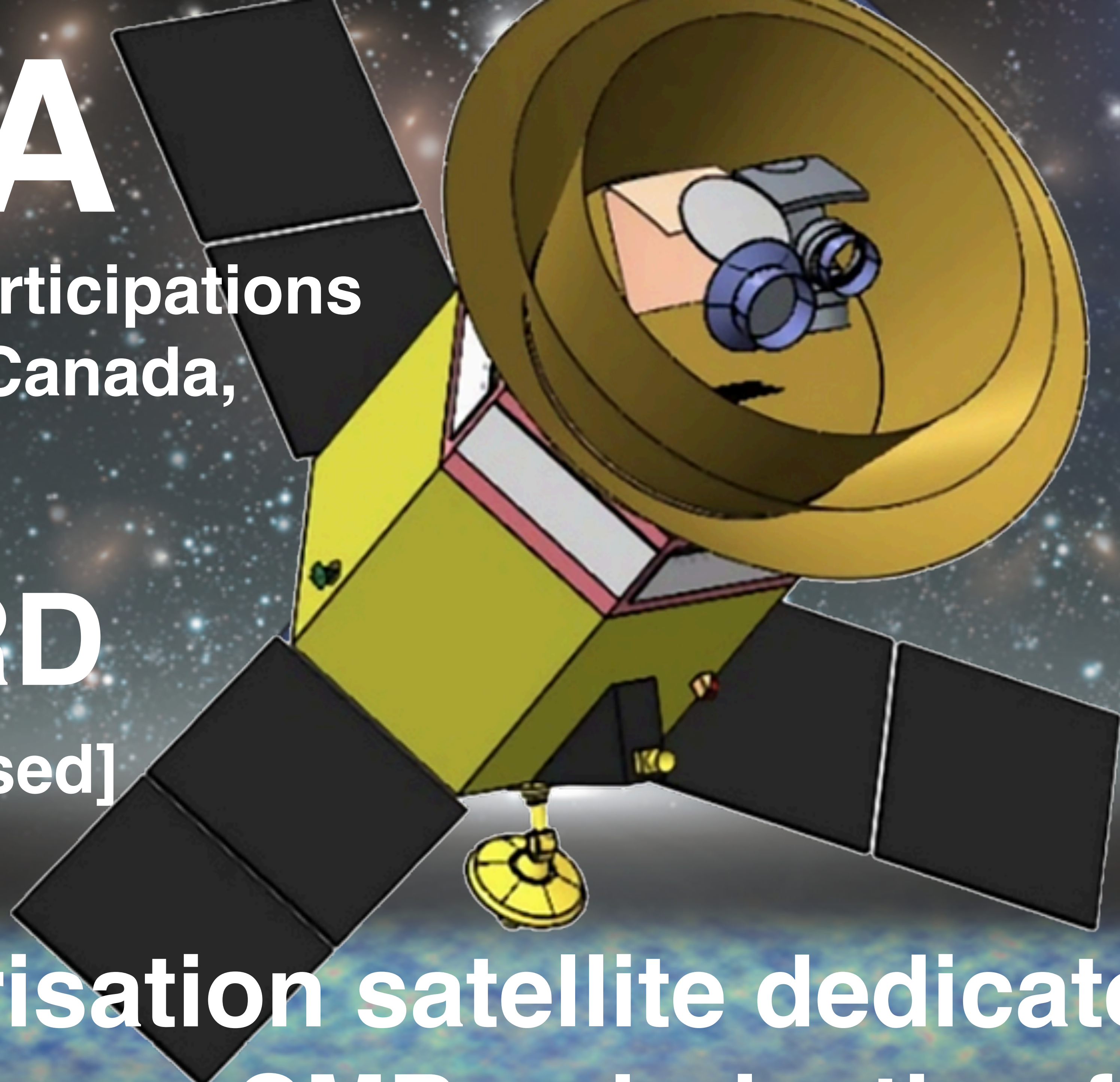
LiteBIRD

2025– [proposed]

Target: $\delta r<0.001$ (68%CL)

JAXA

+ possible participations from USA, Canada, Europe



LiteBIRD

2025– [proposed]

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

JAXA

+ possible participations from USA, Canada, Europe

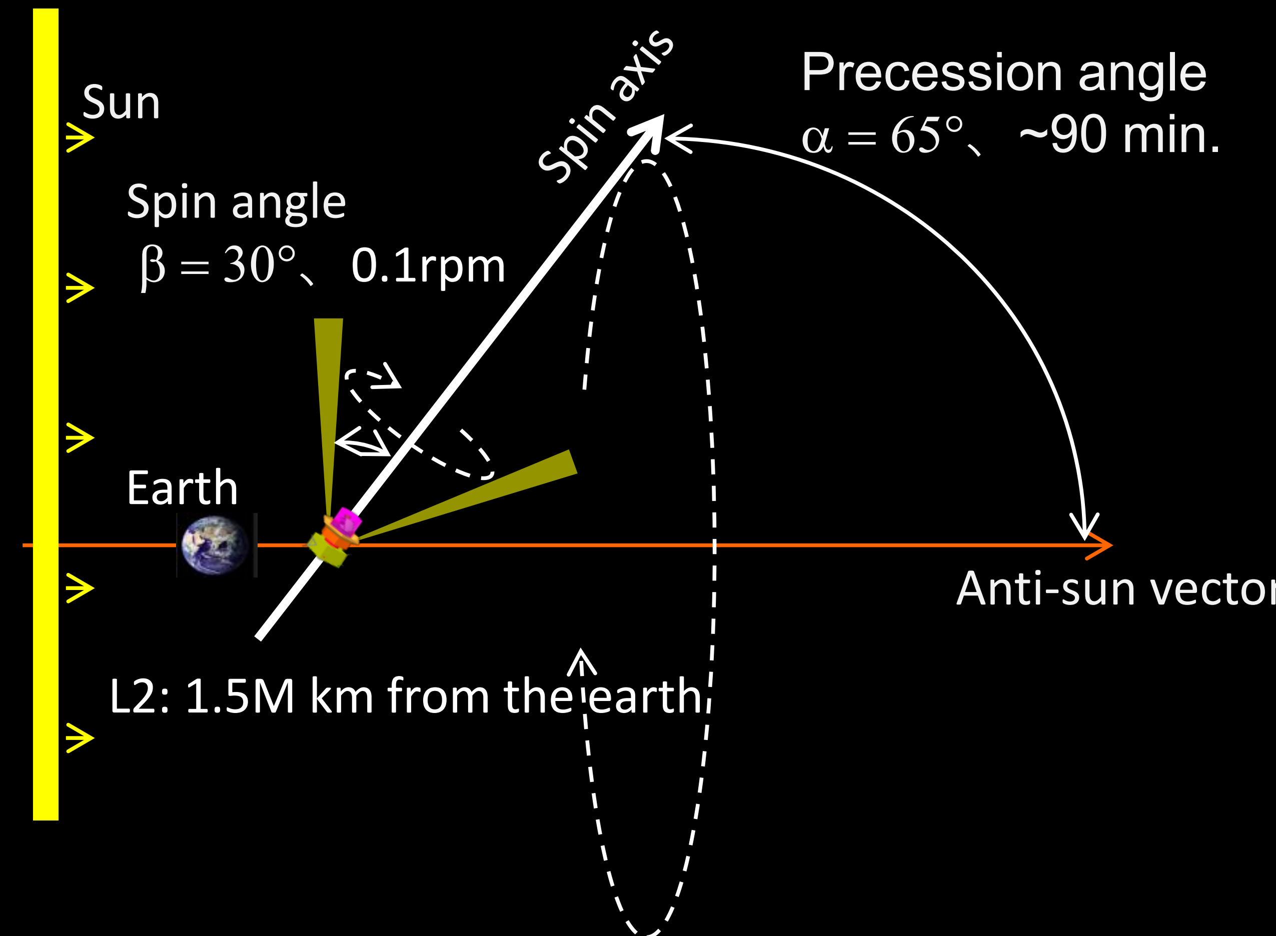
LiteBIRD

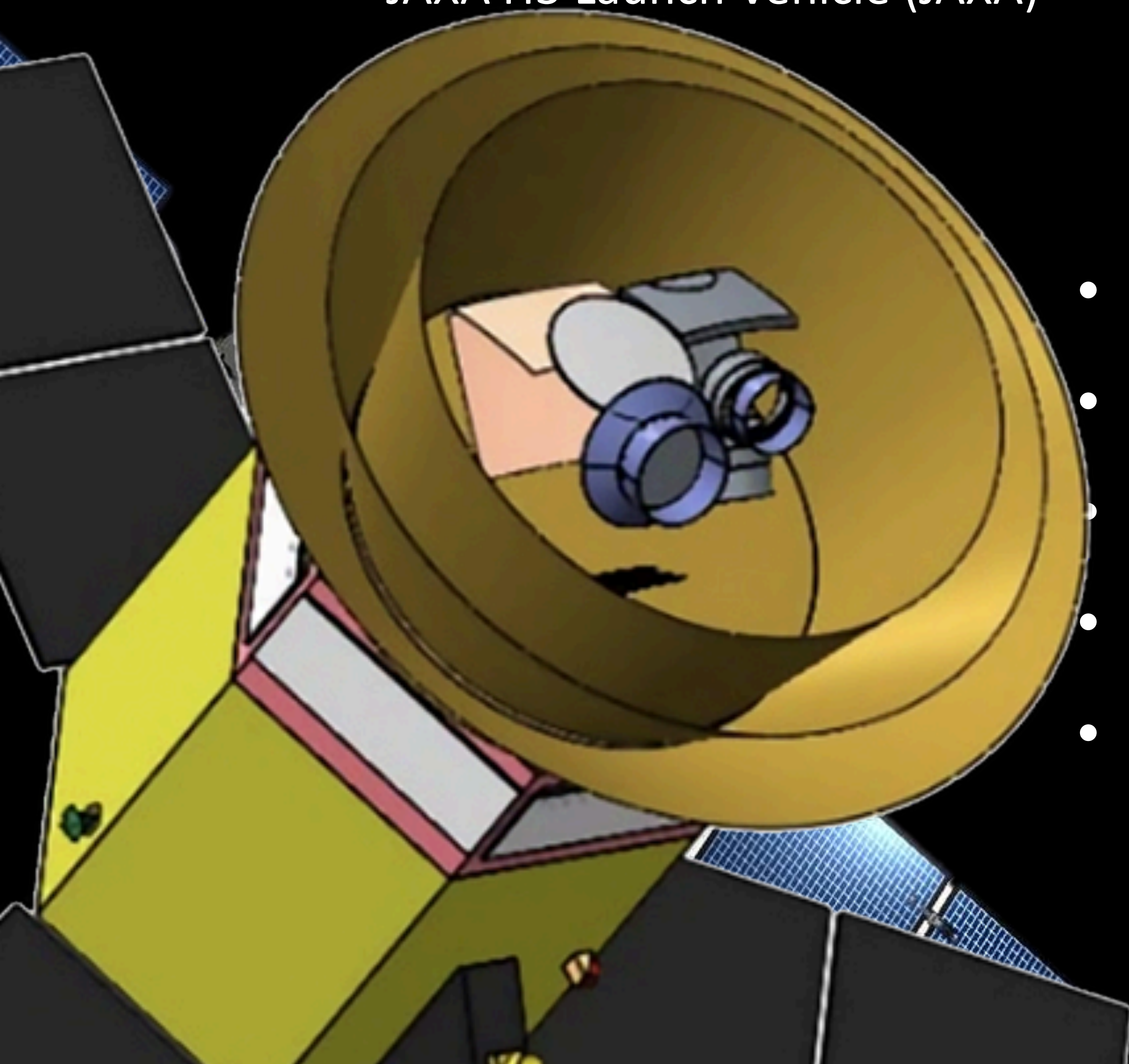
2025– [proposed]

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

Observation Strategy

JAXA H3 Launch Vehicle (JAXA)

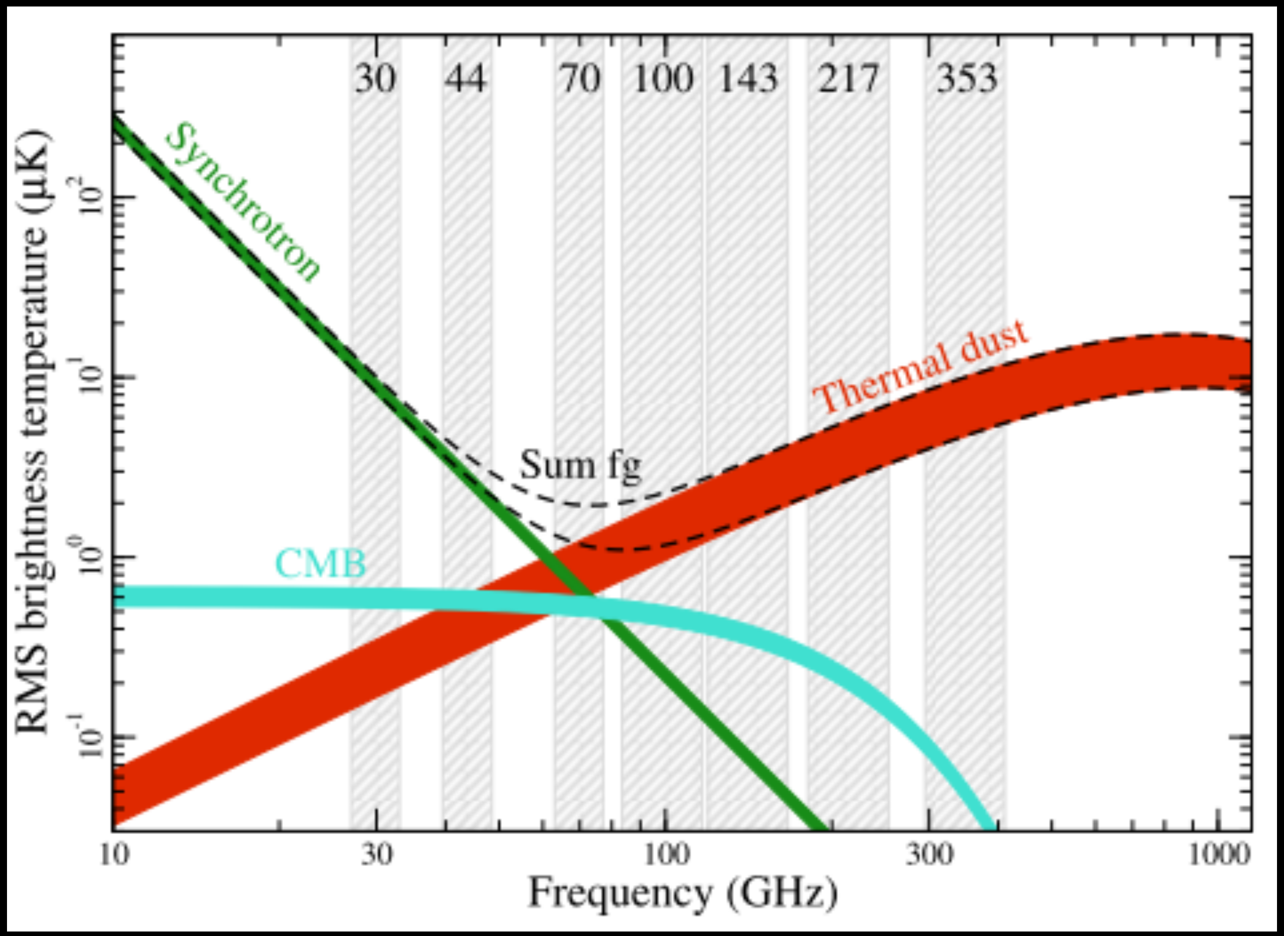




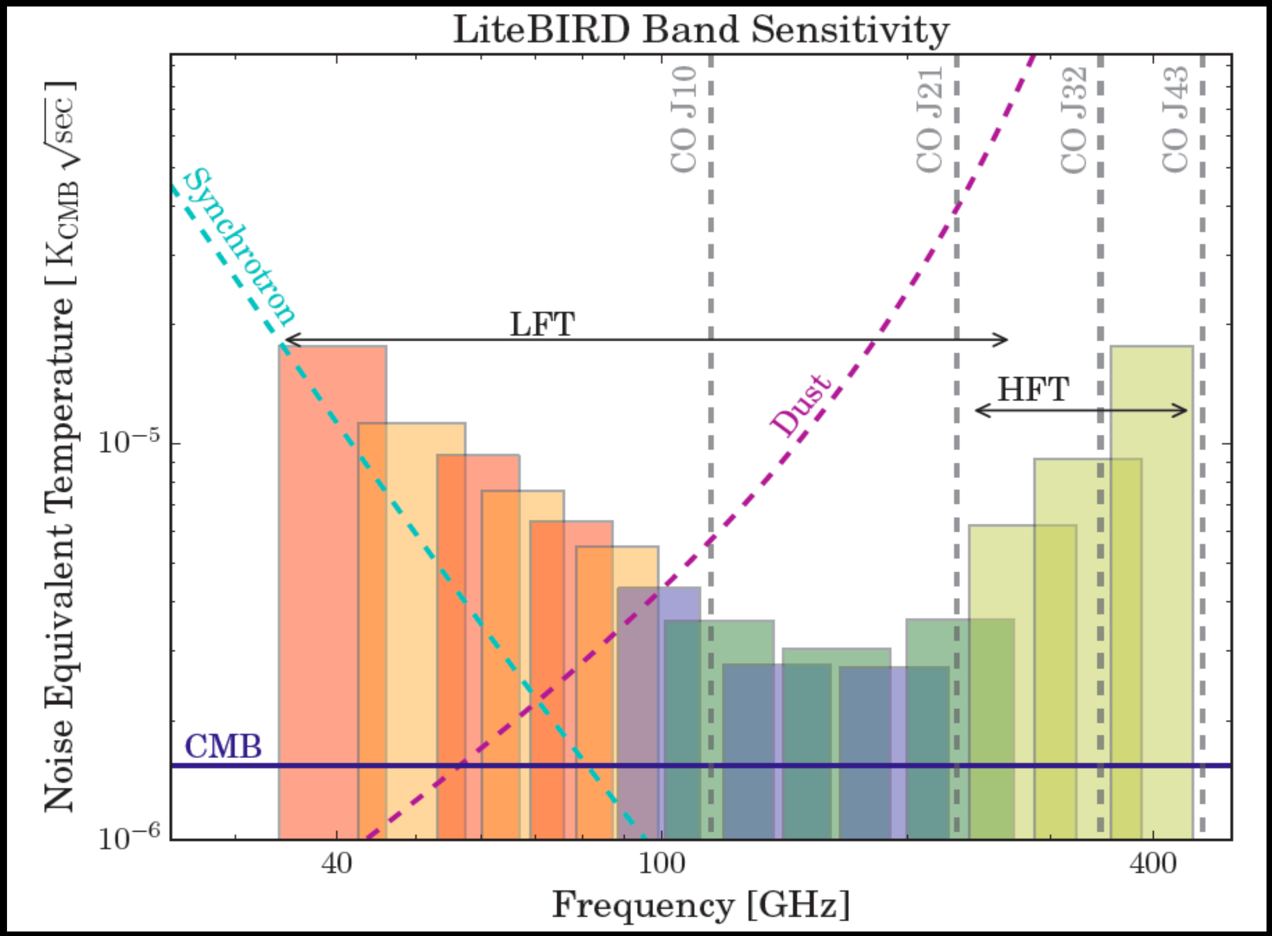
- Launch vehicle: JAXA H3
- Observation location: Second Lagrangian point (L2)
- Scan strategy: Spin and precession, full sky
- Observation duration: 3-years
- Proposed launch date: Mid 2020's

Slide courtesy Toki Suzuki (Berkeley)

Foreground Removal



Polarized galactic emission (Planck X)



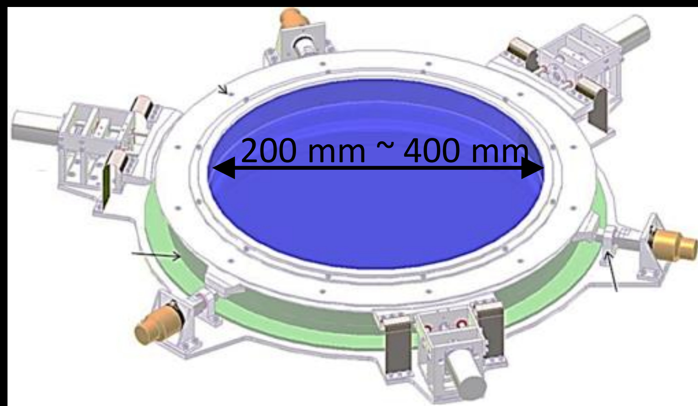
LiteBIRD: 15 frequency bands

- Polarized foregrounds
  - Synchrotron radiation and thermal emission from inter-galactic dust
  - Characterize and remove foregrounds
- 15 frequency bands between 40 GHz - 400 GHz
  - Split between Low Frequency Telescope (LFT) and High Frequency Telescope (HFT)
  - LFT: 40 GHz – 235 GHz
  - HFT: 280 GHz – 400 GHz

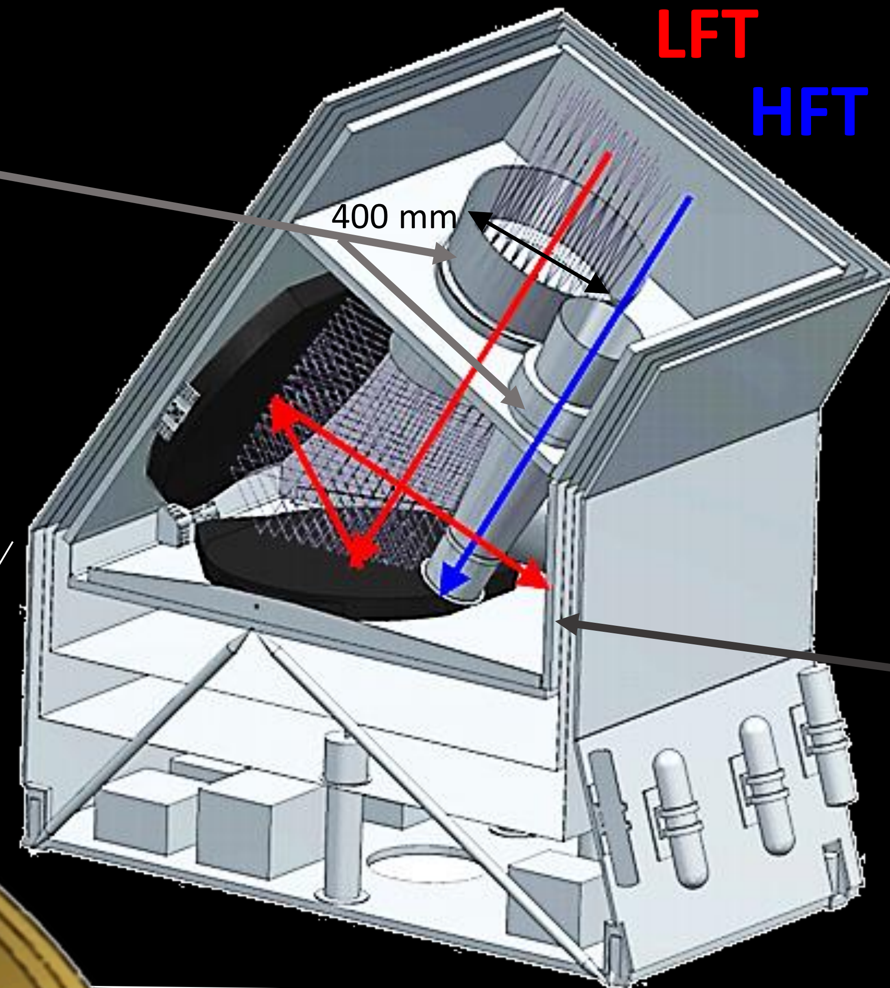
Slide courtesy Toki Suzuki (Berkeley)

Instrument Overview

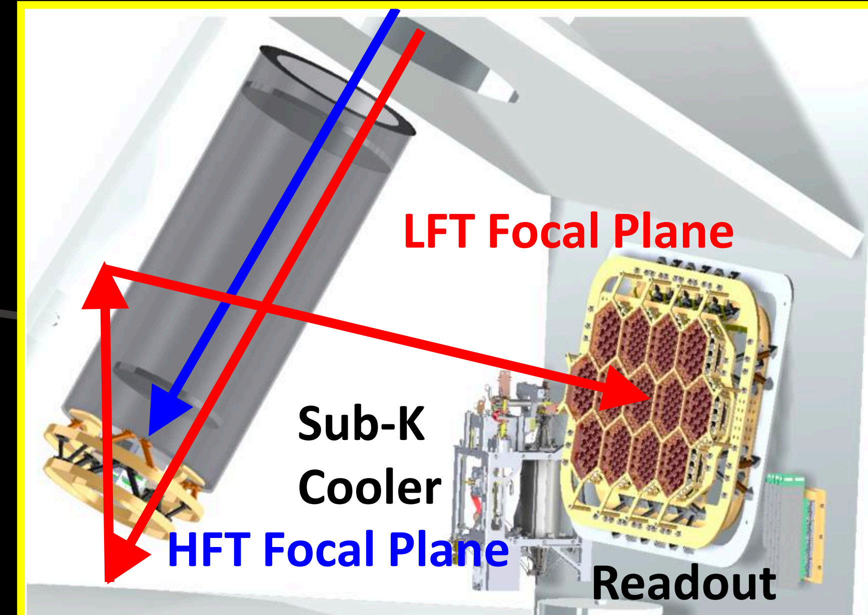
Slide courtesy Toki Suzuki (Berkeley)



Half-wave plate

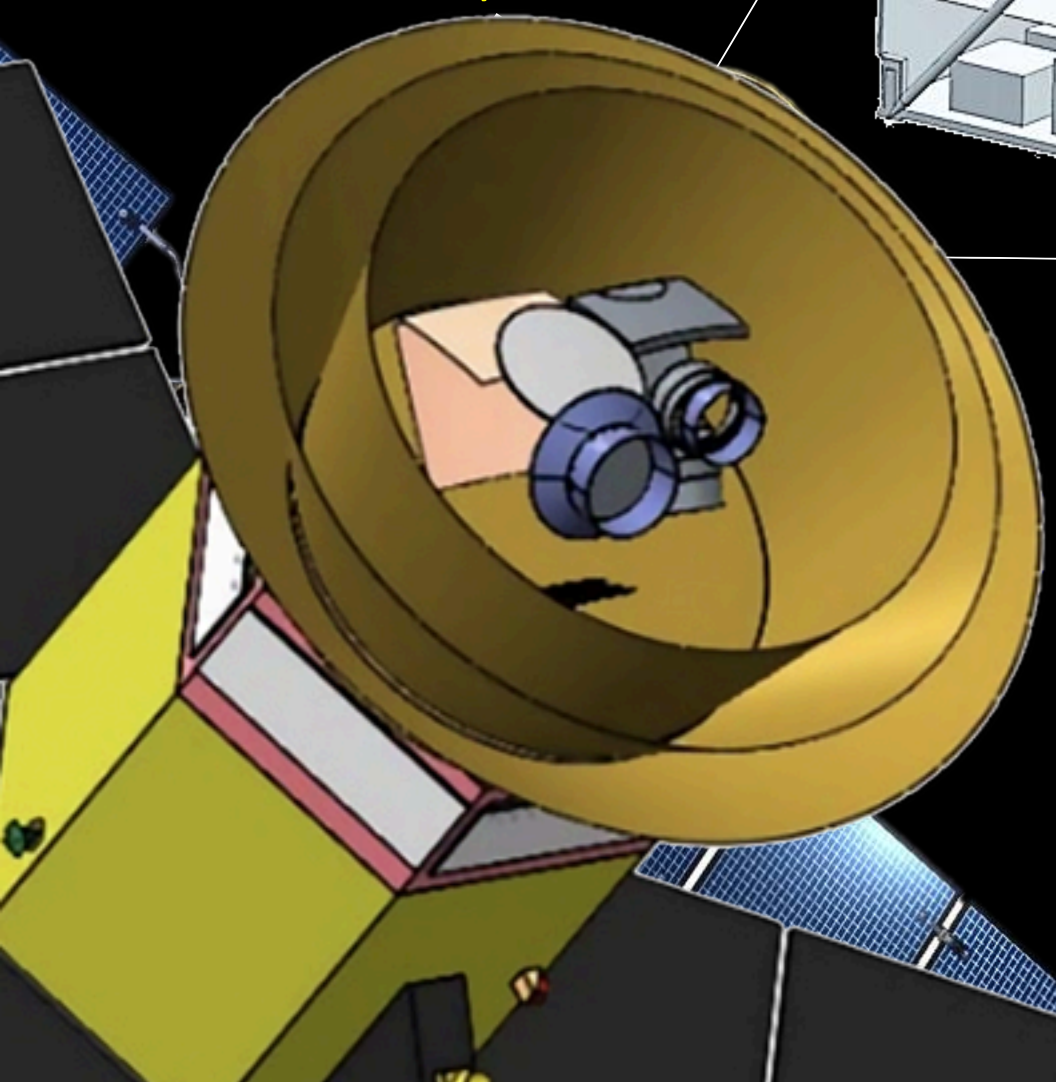


Stirling & Joule Thomson Coolers



Sub-Kelvin Instrument

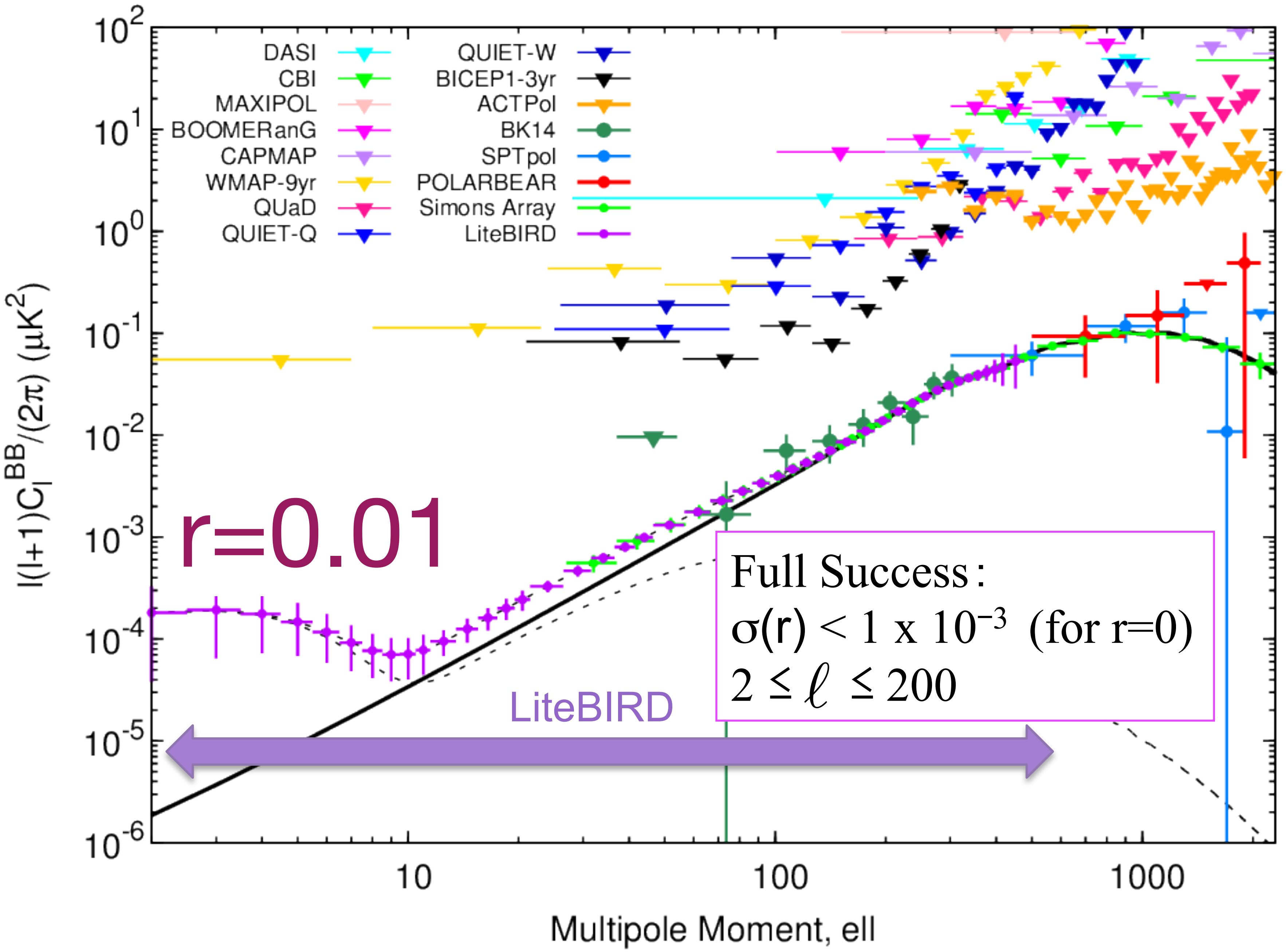
Cold Mission System



- 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

The Quest of the Primordial Gravitational Waves

LiteBIRD Expectation



LiteBIRD only (without de-lensing)

Slide courtesy Ludovic Montier

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 primordial gravitational waves would be a signature of "quantum gravity"!**

  - Only the homogeneous solution corresponds to the vacuum tensor metric perturbation. **There is no *a priori* reason to neglect an inhomogeneous solution!**

  - Contrary, we have several examples in which detectable B-modes are generated by **sources** [U(1) and SU(2)]

Experimental Strategy Commonly Assumed So Far

1. Detect CMB polarisation in multiple frequencies, to make sure that it is from the CMB (i.e., Planck spectrum)

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

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

    - No => WTF?

New Experimental Strategy: New Standard!

1. Detect CMB polarisation in multiple frequencies, to make sure that it is from the CMB (i.e., Planck spectrum)

2. Consistent with a scale invariant spectrum?

3. Parity violating correlations consistent with zero?

4. Consistent with Gaussianity?

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

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

2. Consistent with a scale invariant spectrum?

3. Parity violating correlations consistent with zero?

4. Consistent with Gaussianity?

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

Further Remarks

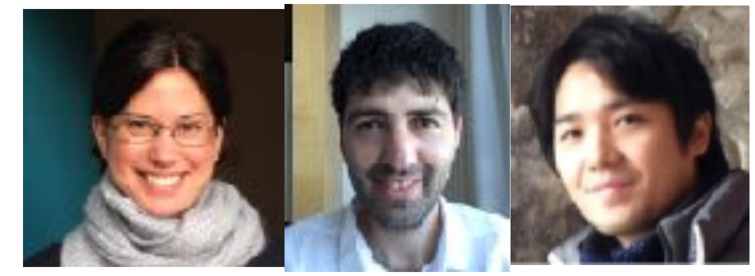
- "*Guys, you are complicating things too much!*"

- **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

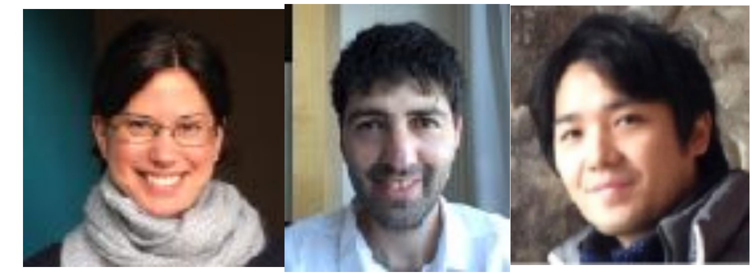
$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_\phi + \mathcal{L}_\chi - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \frac{\lambda\,\chi}{4f} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

- 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
    - **<u>Only one helicity is amplified</u>** => GW is **chiral** (well-known result)
- Brand-new result: **GWs sourced by this mechanism are strongly non-Gaussian!**

Agrawal, Fujita & EK, PRD, 97, 103526 (2018)

Dimastrogiovanni, Fasielo & Fujita (2017)

Gravitational Waves

- Defining canonically-normalised circular polarisation modes as

$$\psi_{L,R} \equiv (aM_{\rm Pl}/2)(h_+ \pm i h_\times)$$

- The equations of motion for L and R modes are ($x \equiv k/aH$)

$$\partial_x^2 \psi_{R,L} + \left(1 - \frac{2}{x^2}\right)\psi_{R,L} = \frac{2\sqrt{\epsilon_E}}{x}\partial_x t_{R,L} + \frac{2\sqrt{\epsilon_B}}{x^2}(m_Q \mp x)\, t_{R,L}$$

$$\left(\begin{array}{l} m_Q \equiv gQ/H \ \text{ = a few} \\ \epsilon_B \equiv g^2Q^4/(HM_{\rm Pl})^2 \ \ll 1 \\ \epsilon_E \equiv (HQ + \dot{Q})^2/(HM_{\rm Pl})^2 \ \ll 1 \end{array}\right.$$

Dimastrogiovanni, Fasielo & Fujita (2017)

Spin-2 Field from SU(2)

- The equations of motion for L and R modes of SU(2) are

$$\partial_x^2 t_{R,L} + \left[1 + \frac{2}{x^2}\left(m_Q\,\xi \boxed{\mp} x(m_Q + \xi)\right)\right] t_{R,L}$$

the minus sign gives an instability -> exponential amplification of t_R!

$$= -\frac{2\sqrt{\epsilon_E}}{x}\partial_x \psi_{R,L} + \frac{2}{x^2}\left[(m_Q \mp x)\sqrt{\epsilon_B} + \sqrt{\epsilon_E}\right]\psi_{R,L}$$

$$\xi \equiv \frac{\lambda}{2fH}\dot{\chi} \simeq m_Q + \frac{1}{m_Q}$$

$$m_Q \equiv gQ/H \quad = \text{a few}$$

$$\epsilon_B \equiv g^2 Q^4/(HM_{\rm Pl})^2 \ll 1$$

$$\epsilon_E \equiv (HQ + \dot{Q})^2/(HM_{\rm Pl})^2 \ll 1$$

Dimastrogiovanni, Fasielo & Fujita (2017)

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- **The produced gravitational waves are totally chiral!**

- The solution (when all the parameters are constant and the terms on the right hand side are ignored):

$$t_R(x) = \frac{1}{\sqrt{2k}} i^\beta\, W_{\beta,\alpha}(-2ix) \quad \left(\begin{array}{l}\alpha \equiv -i\sqrt{2m_Q\xi - 1/4} \\ \beta \equiv -i(m_Q + \xi)\end{array}\right.$$

[Whittaker function]

Dimastrogiovanni, Fasielo & Fujita (2017)

Gravitational Waves

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- Inhomogeneous solution:

$$\lim_{x\to 0}\psi_R^{(s)}(x) = \frac{1}{\sqrt{2kx}}\left[\mathcal{F}_E\sqrt{\epsilon_E} + \mathcal{F}_B\sqrt{\epsilon_B}\right]$$

F_E, F_B: some complicated functions

Dimastrogiovanni, Fasiello & Fujita (2017)

Power Spectrum!

$$\mathcal{P}_h^{(s)}(k) = \frac{H^2}{\pi^2 M_{\rm Pl}^2} \left| \sqrt{2k}x \lim_{x\to 0} \psi_R^{(s)}(x) \right|^2 = \frac{\epsilon_B H^2}{\pi^2 M_{\rm Pl}^2} \mathcal{F}^2$$

$$\boxed{\mathcal{F}^2 \equiv \left| \mathcal{F}_B + \sqrt{\epsilon_E/\epsilon_B}\mathcal{F}_E \right|^2 \approx \exp(3.6 m_Q)}$$

- This exponential dependence on m_Q makes it possible to have $P_{\text{sourced}} >> P_{\text{vacuum}}$
- **New Paradigm**

Phenomenology

$$\partial_x^2 t_{R,L} + \left[1 + \frac{2}{x^2}\left(m_Q\,\xi \boxed{\mp} x(m_Q + \xi)\right)\right] t_{R,L} = \ldots$$

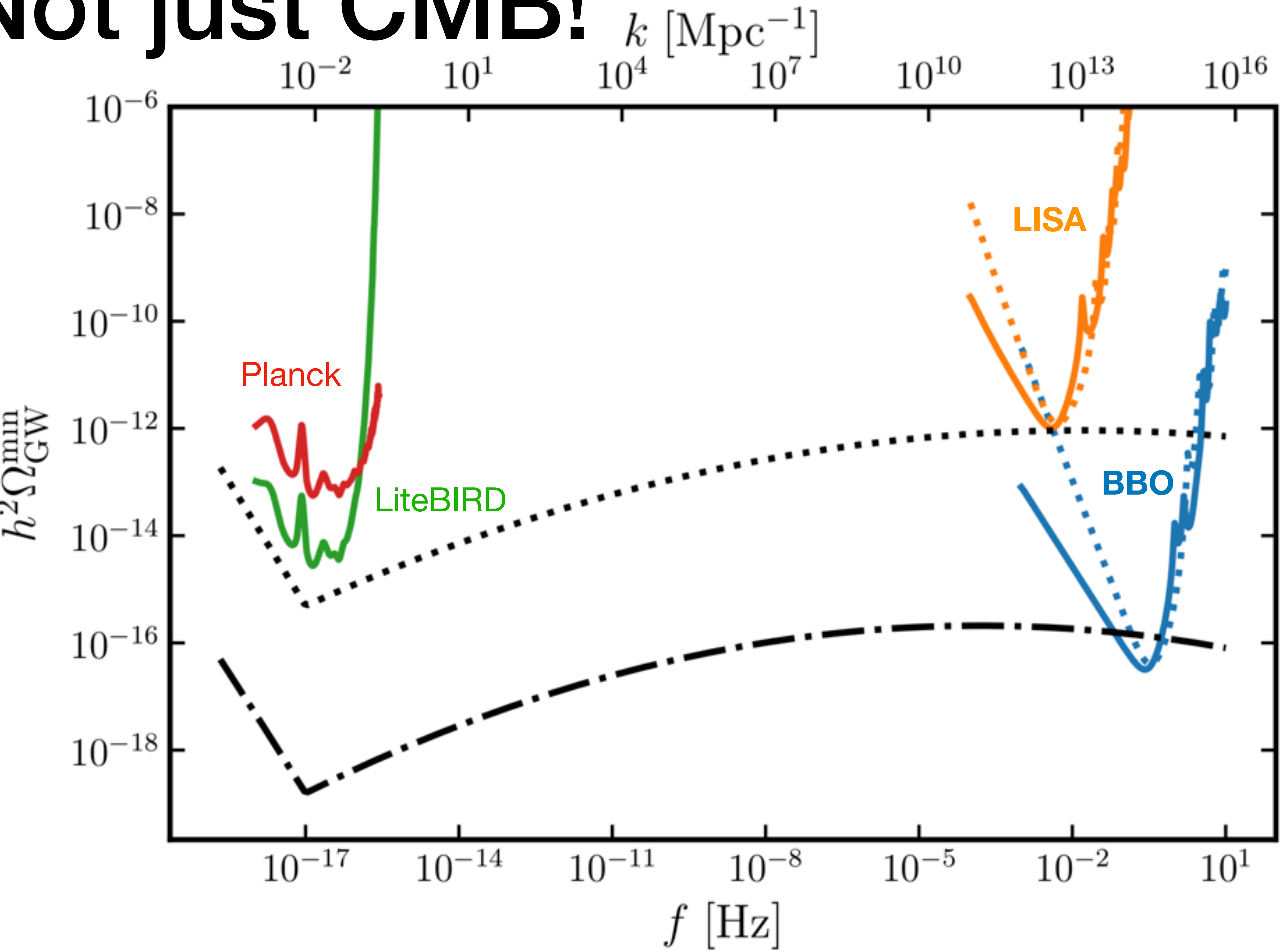
the minus sign gives an instability -> exponential amplification of t_R!

$$\left(\begin{array}{l} \xi \equiv \dfrac{\lambda}{2fH}\dot{\chi} \simeq m_Q + \dfrac{1}{m_Q} \\ m_Q \equiv gQ/H \quad = \text{a few} \end{array}\right.$$

- The scale-dependence of the produced tensor modes is determined by how m_Q changes with time
- E.g., Axion rolling faster towards the end of inflation: BLUE TILTED power spectrum! Therefore…

Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

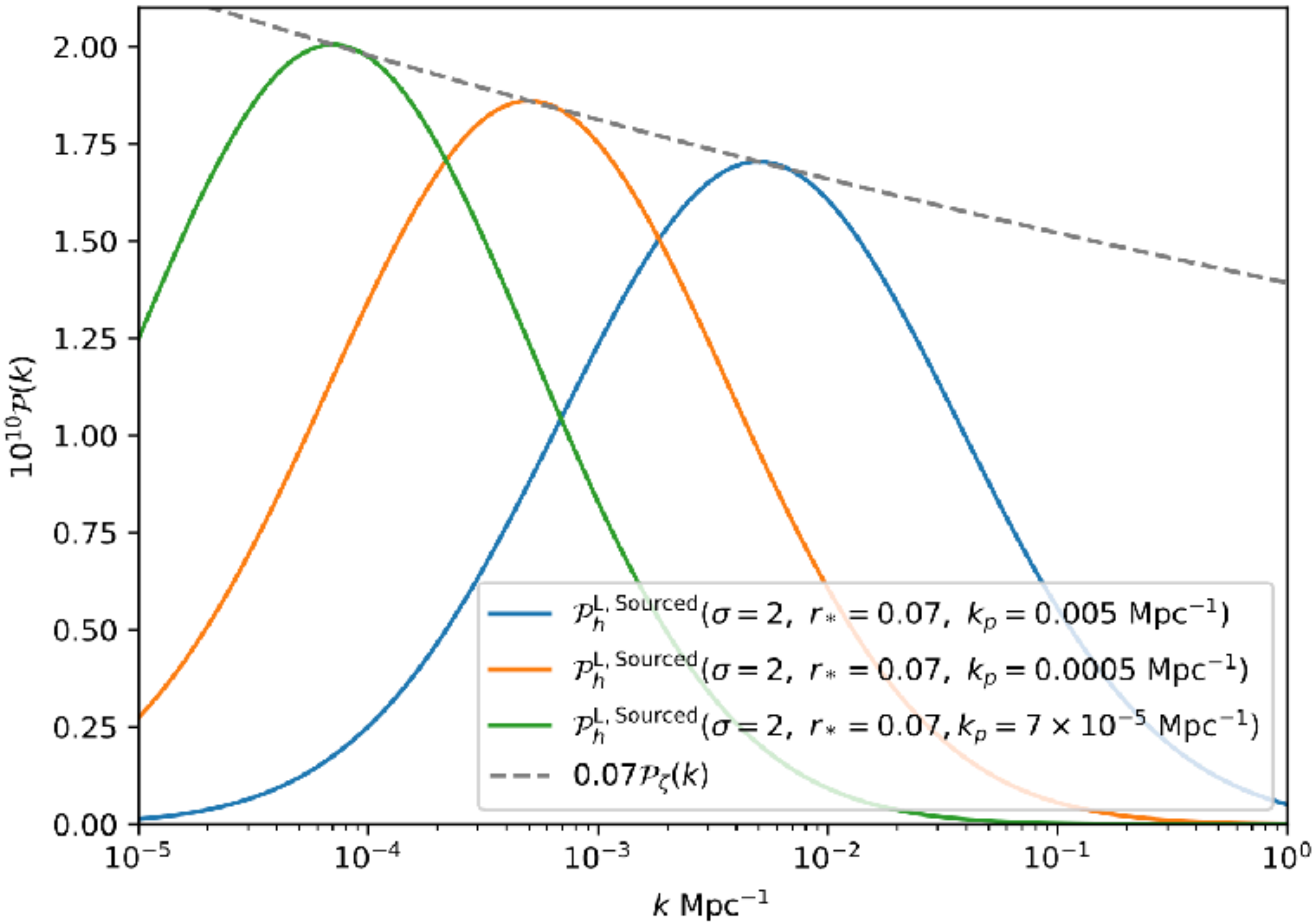
Not just CMB!



Dimastrogiovanni, Fasiello & Fujita (2017)

Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Example Tensor Spectra

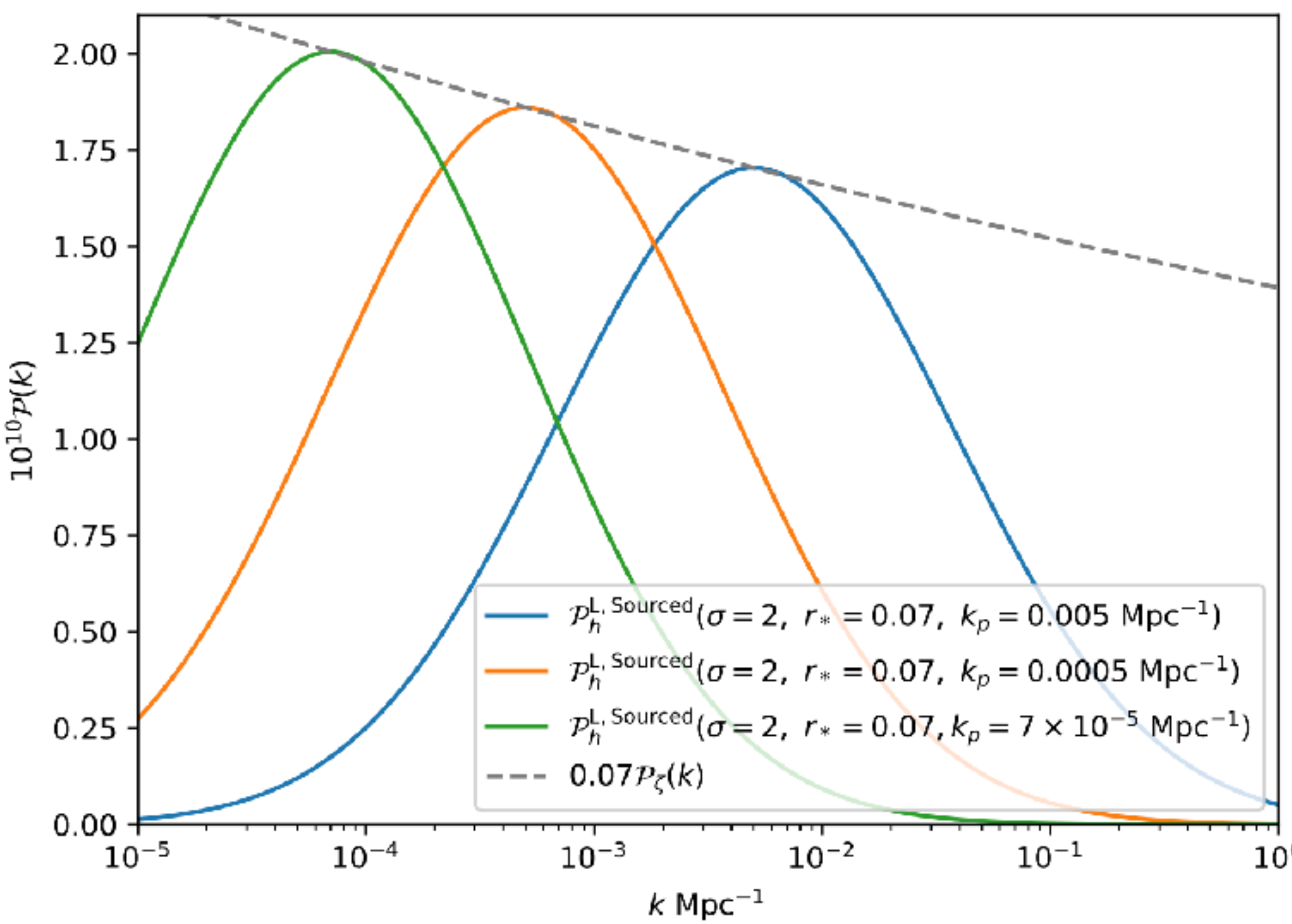


- Sourced tensor spectrum can also be bumpy

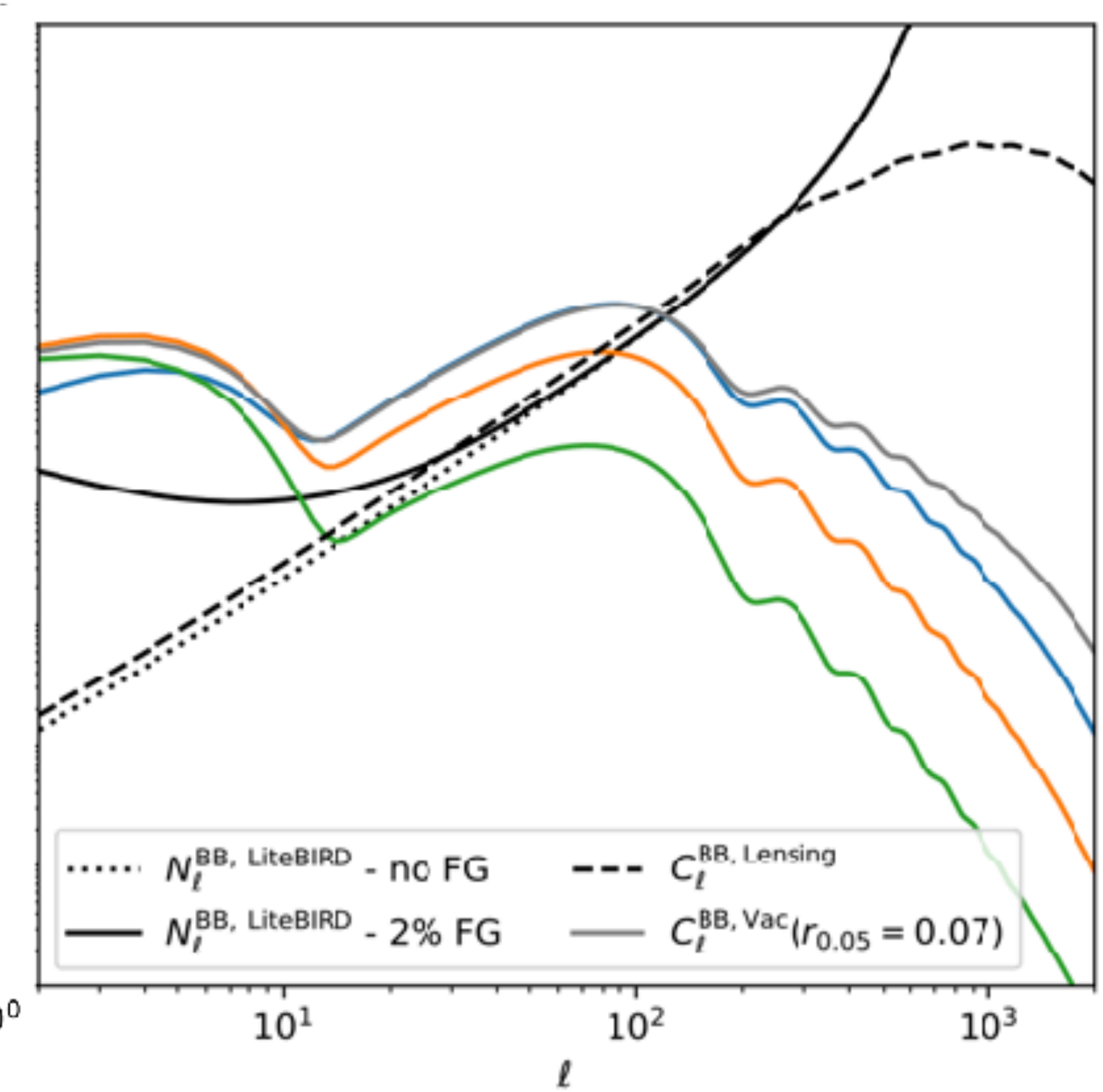
Dimastrogiovanni, Fasiello & Fujita (2017)
Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Example Tensor Spectra

Tensor Power Spectrum, P(k)



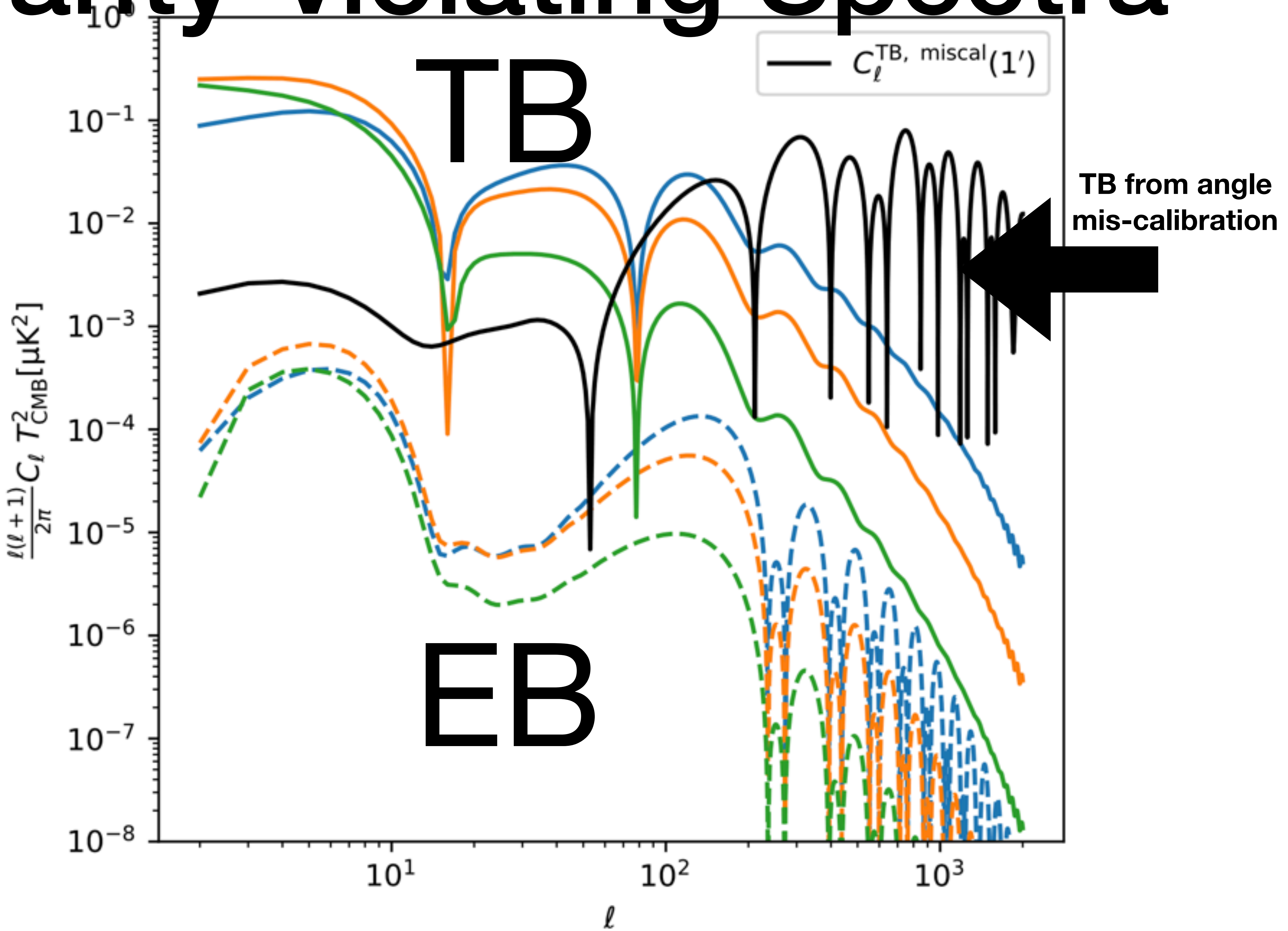
B-mode CMB spectrum, C_l^{BB}



- The B-mode power spectrum still looks rather normal

Thorne, Fujita, Hazumi, Katayama, EK & Shiraishi, PRD, 97, 043506 (2018)

Parity-violating Spectra



- Angle mis-calibration can be distinguished easily!

Agrawal, Fujita & EK, PRD, 97, 103526 (2018)

Large bispectrum in GW from SU(2) fields

Aniket Agrawal
(MPA)

Tomo Fujita
(Kyoto)

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

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

- $\Omega_A << 1$ 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, PRD, 97, 103526 (2018)

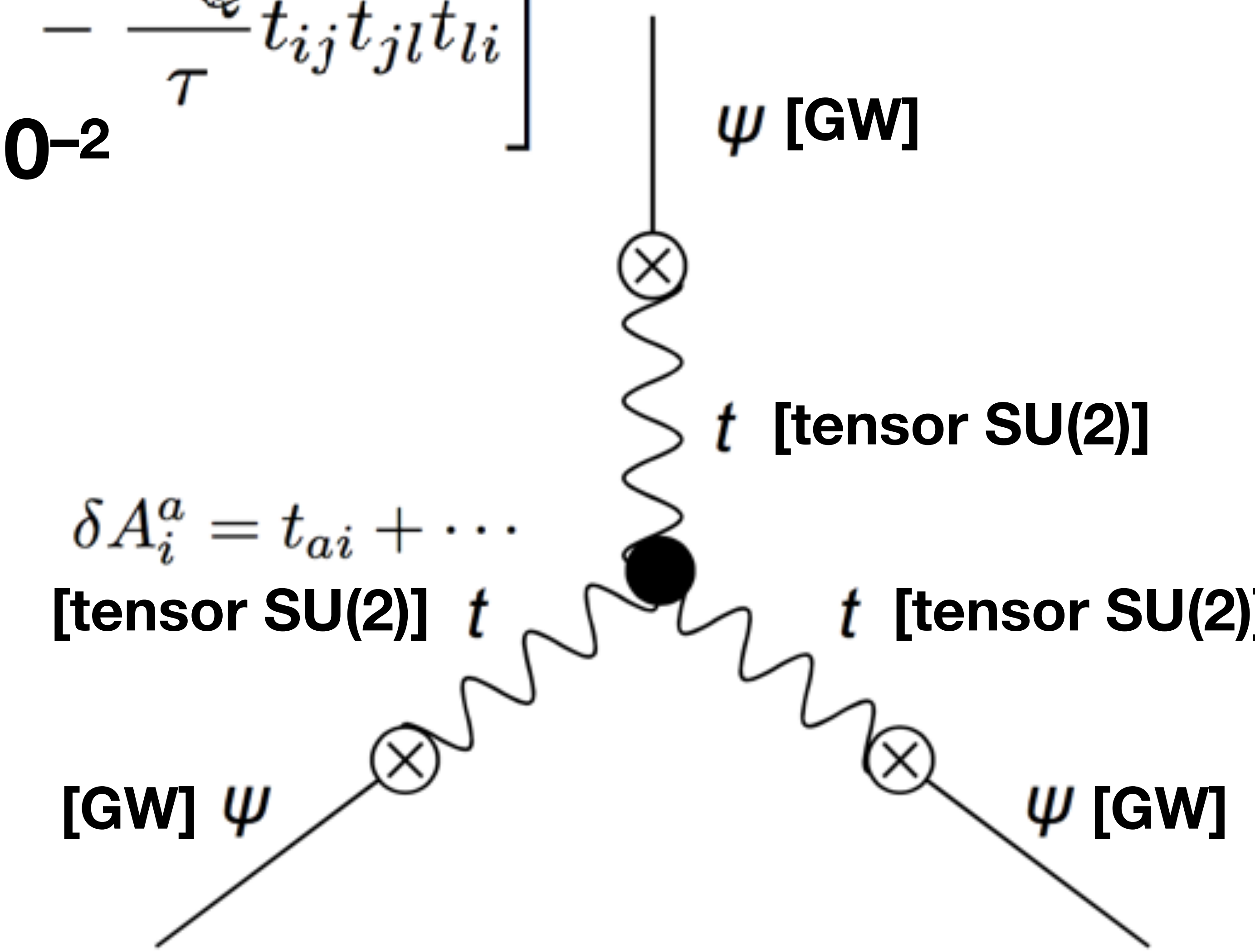
NG generated at the tree level

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

$$c^{(i)} = g = m_Q^2 H/\sqrt{\epsilon_B} M_{\rm Pl}$$ **~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, PRD, 97, 103526 (2018)

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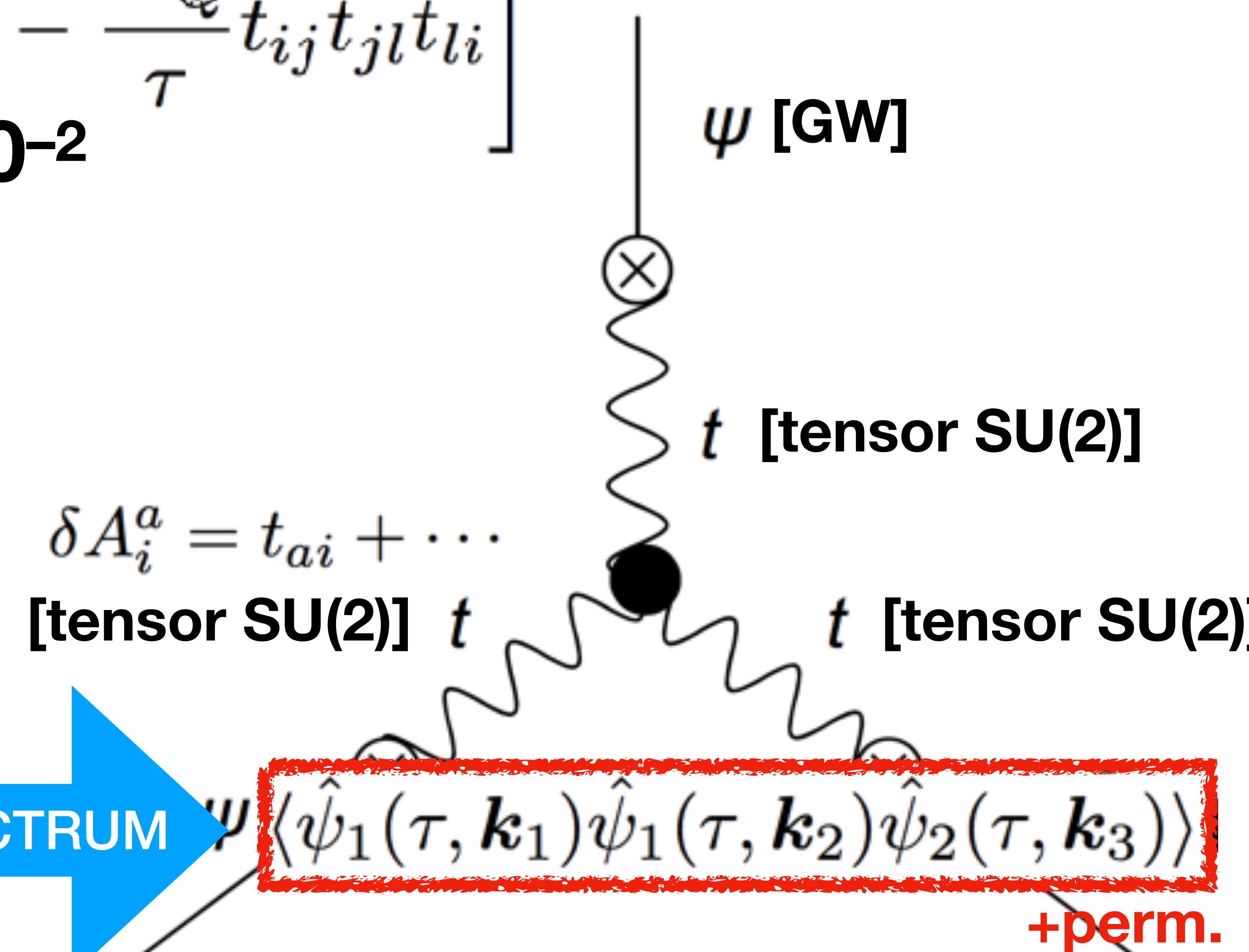
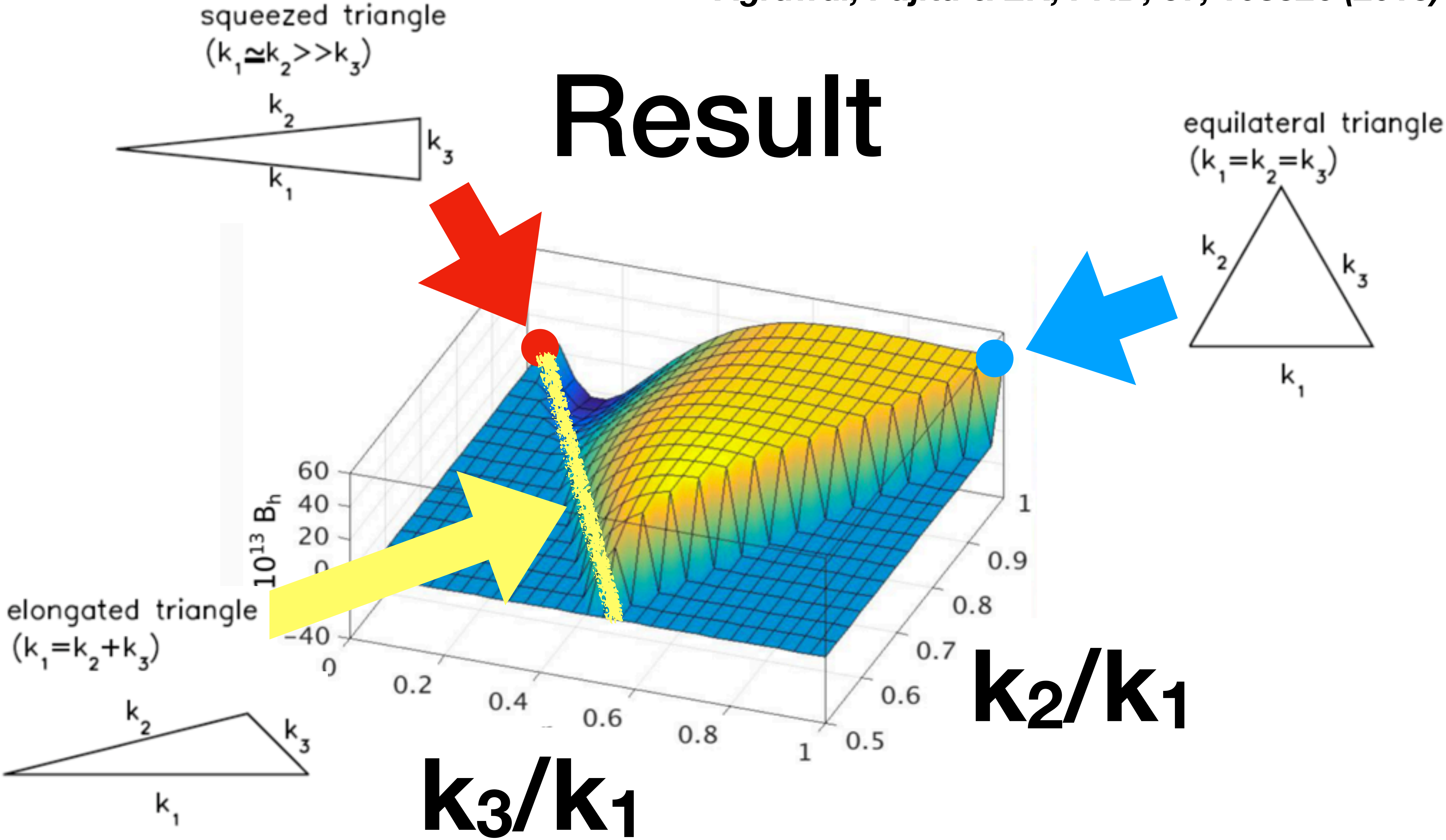


- This diagram generates second-order equation of motion for GW

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, PRD, 97, 103526 (2018)

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 $f_{\rm NL}^{\rm tens} = 400 \pm 1500$

SU(2), confronted

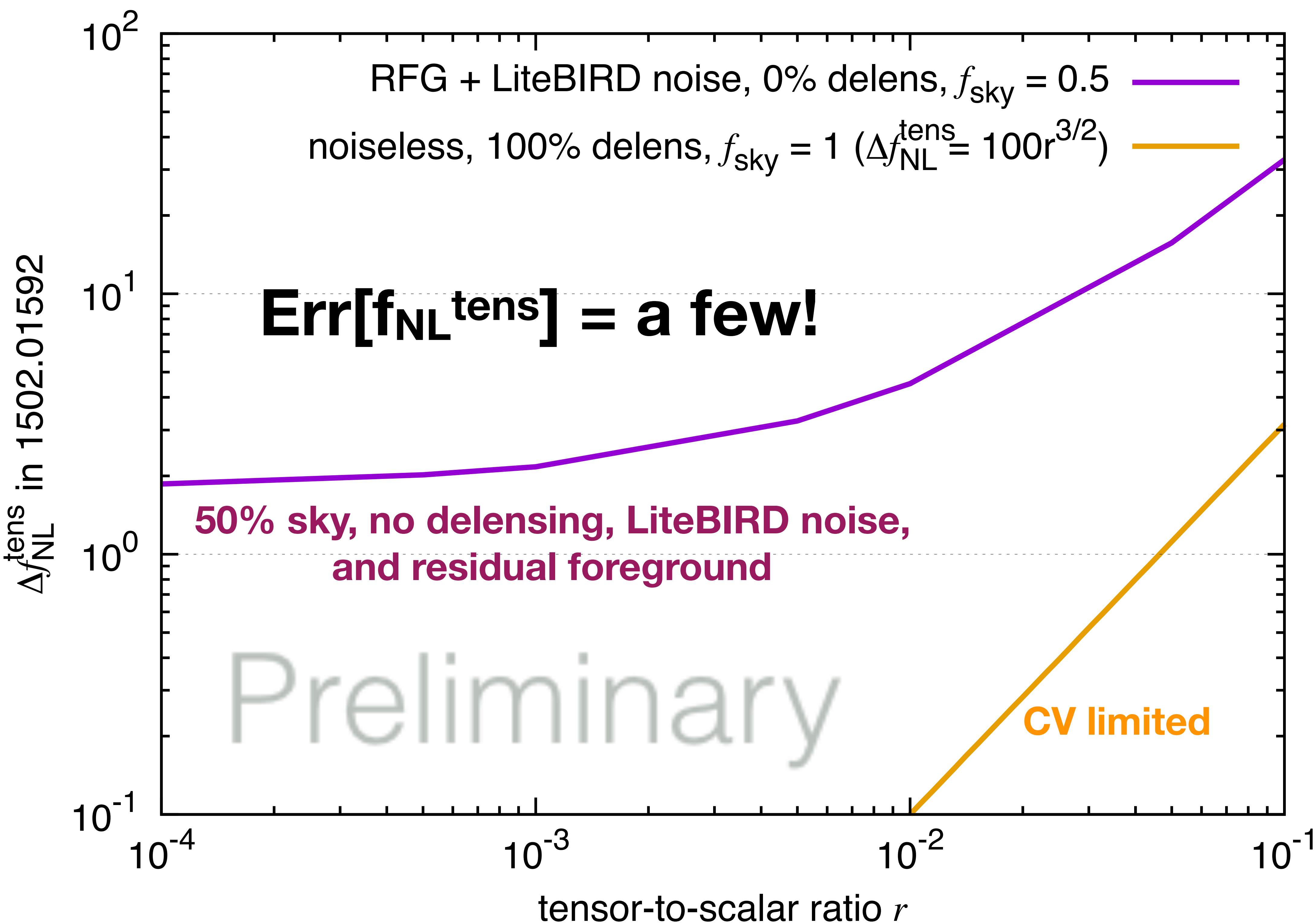
- The SU(2) model of Dimastrogiovanni et al. predicts:

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

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

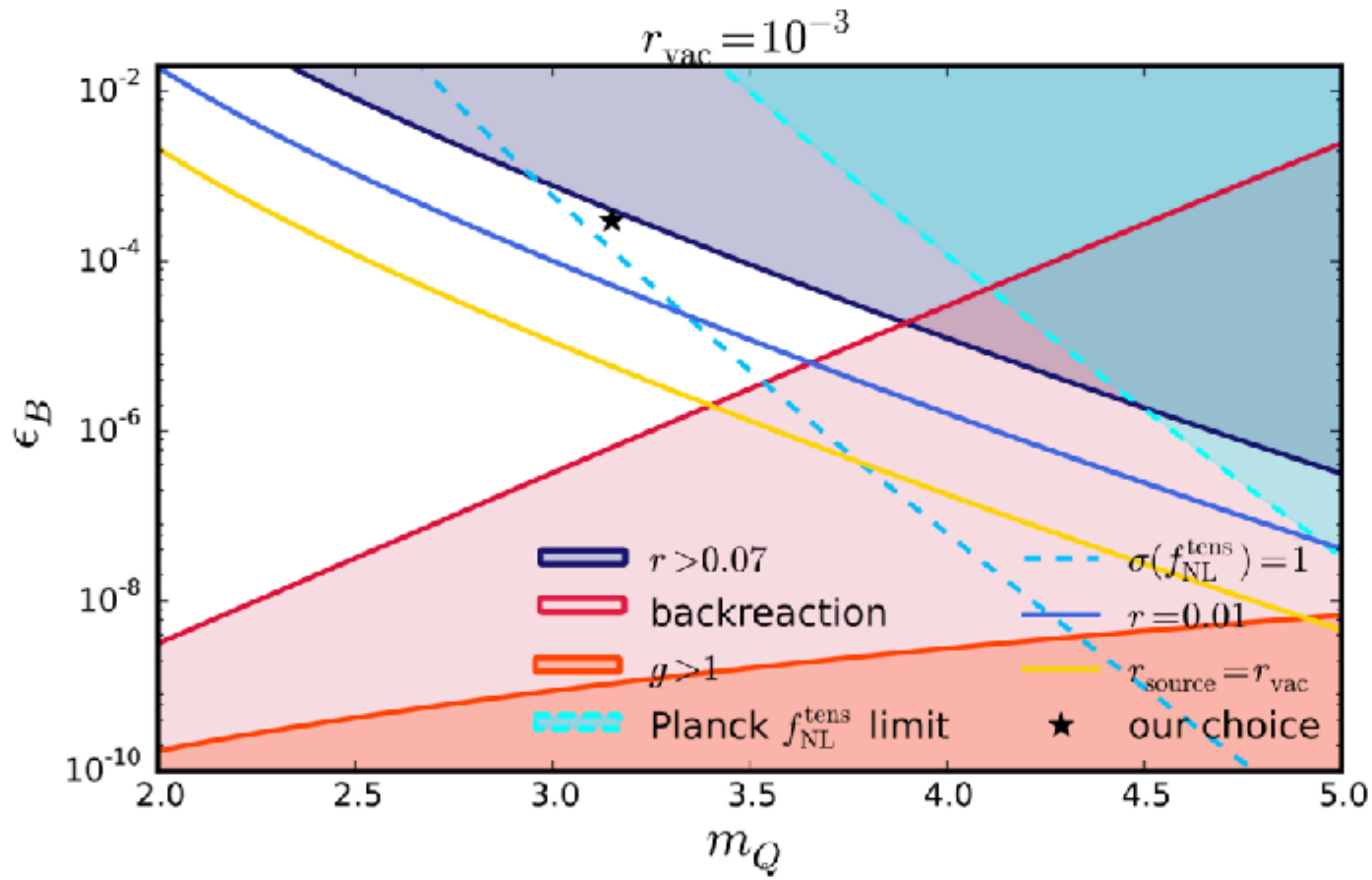
Courtesy of Maresuke Shiraishi

LiteBIRD would nail it!



Agrawal, Fujita & EK, JCAP, 97, 103526 (2018)

Parameter Scan

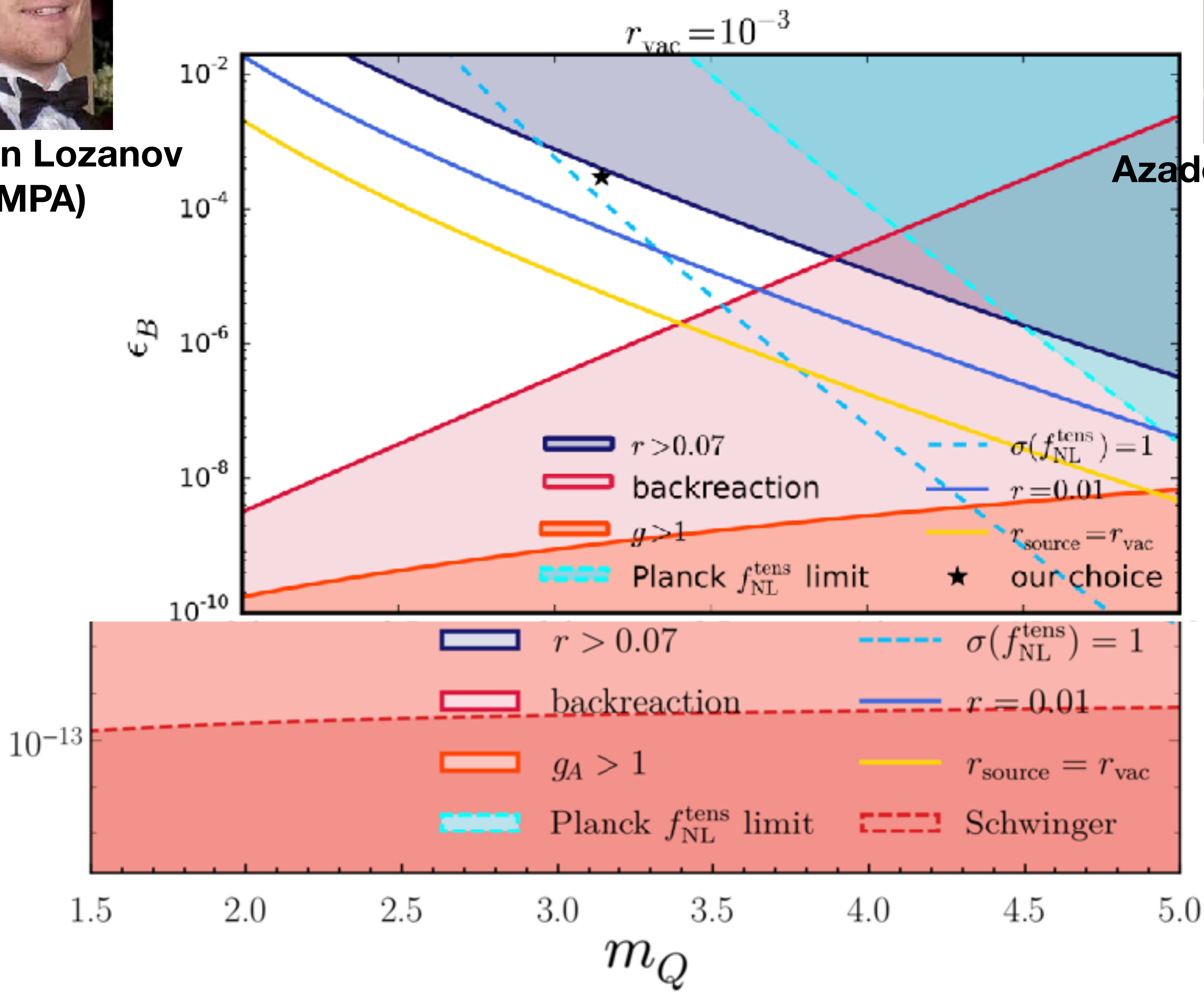


Lozanov, Maleknejad & EK, arXiv:1805.09318

Schwinger Effect

Kaloian Lozanov
(MPA)

Azadeh Maleknejad
(MPA)



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