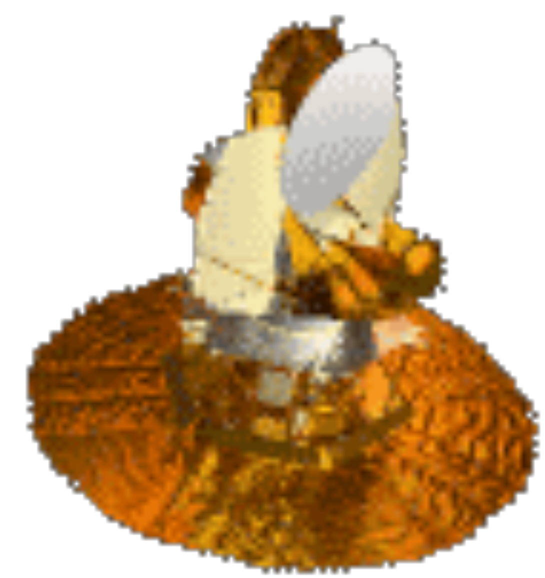
CMB Polarisation: Toward an Observational Proof of Cosmic Inflation

Eiichiro Komatsu, Max-Planck-Institut für Astrophysik
Colloquium, Max-Planck-Institut für Radioastronomie
October 16, 2015



March 17, 2014

BICEP2's announcement

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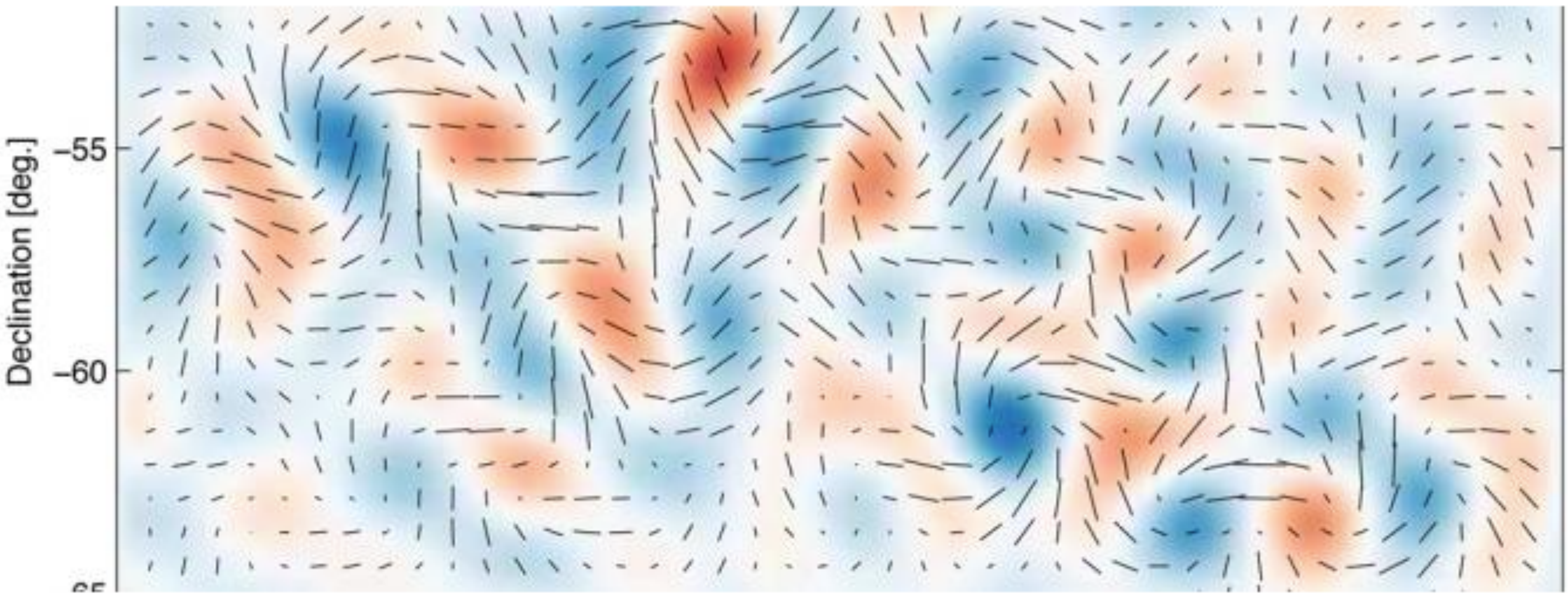
First Direct Evidence of Cosmic Inflation

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



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

SPACE & COSMOS

The New York Times

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

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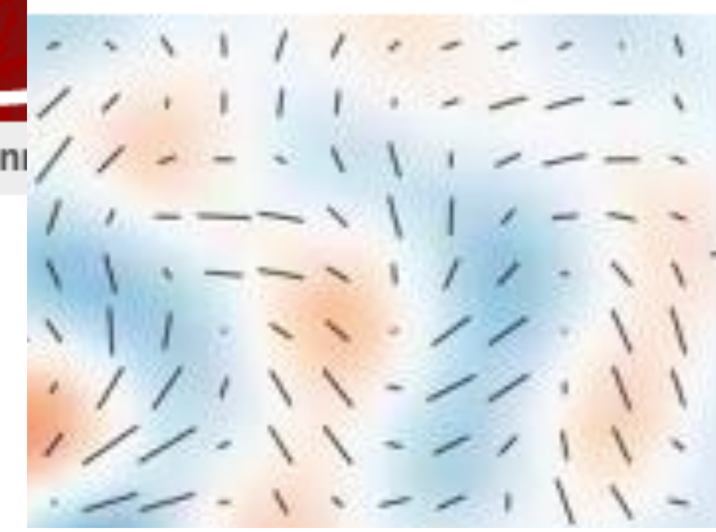

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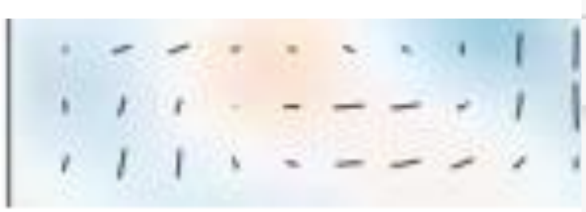
Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos
Science correspondent, BBC News



Cambridge, MA - Almost 14 billic
that initiated the Big Bang. In the
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17. März 2014, 17:34 Gravitationswellen

Signale aus der Geburtsstunde des Universums

Von Patrick Illinger

January 30, 2015

Joint Analysis of BICEP2 data and Planck data

SCIENCE

The New York Times

Speck of Interstellar Dust Obscures Glimpse of Big Bang

By DENNIS OVERBYE JAN. 30, 2015

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Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos
Science correspondent, BBC News

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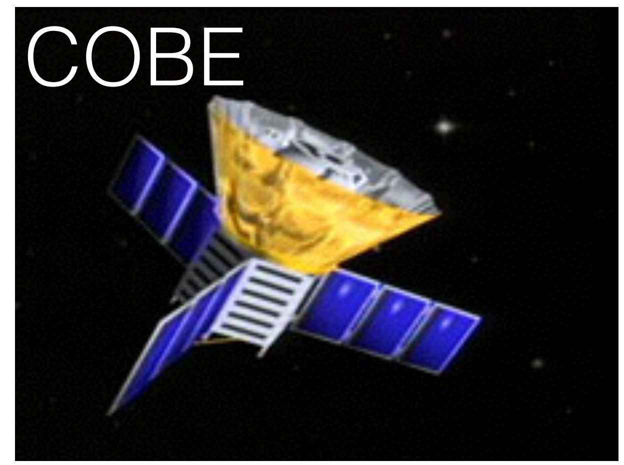
1. Februar 2015, 22:19 Kosmologie

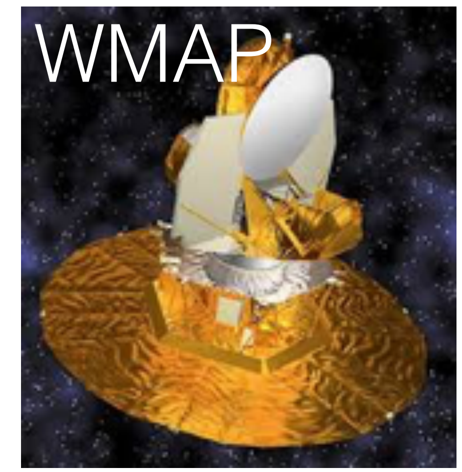
Urknall-Forscher gestehen Irrtum ein

Von Marlene Weiß

The search continues!!



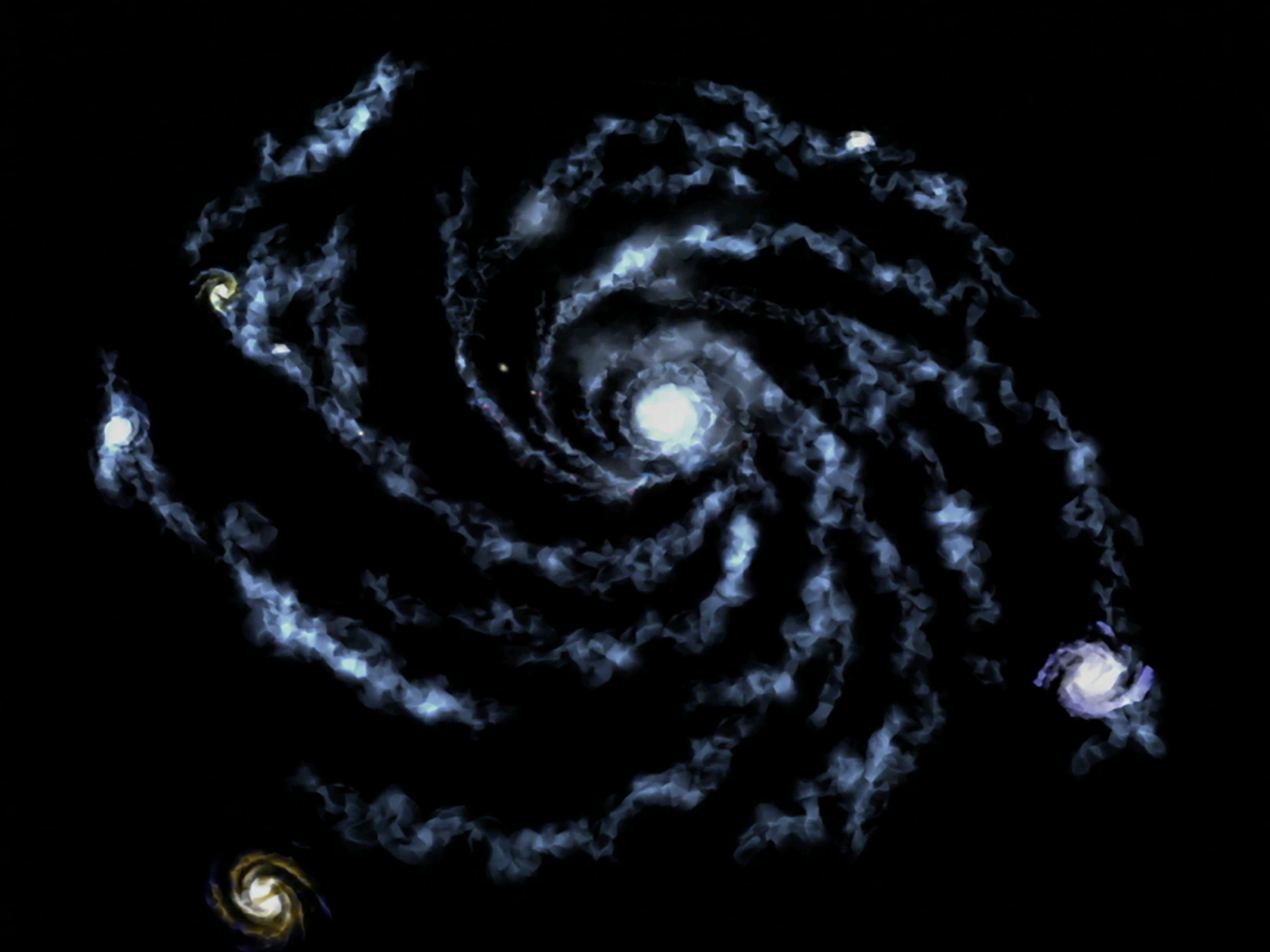
1989–1993

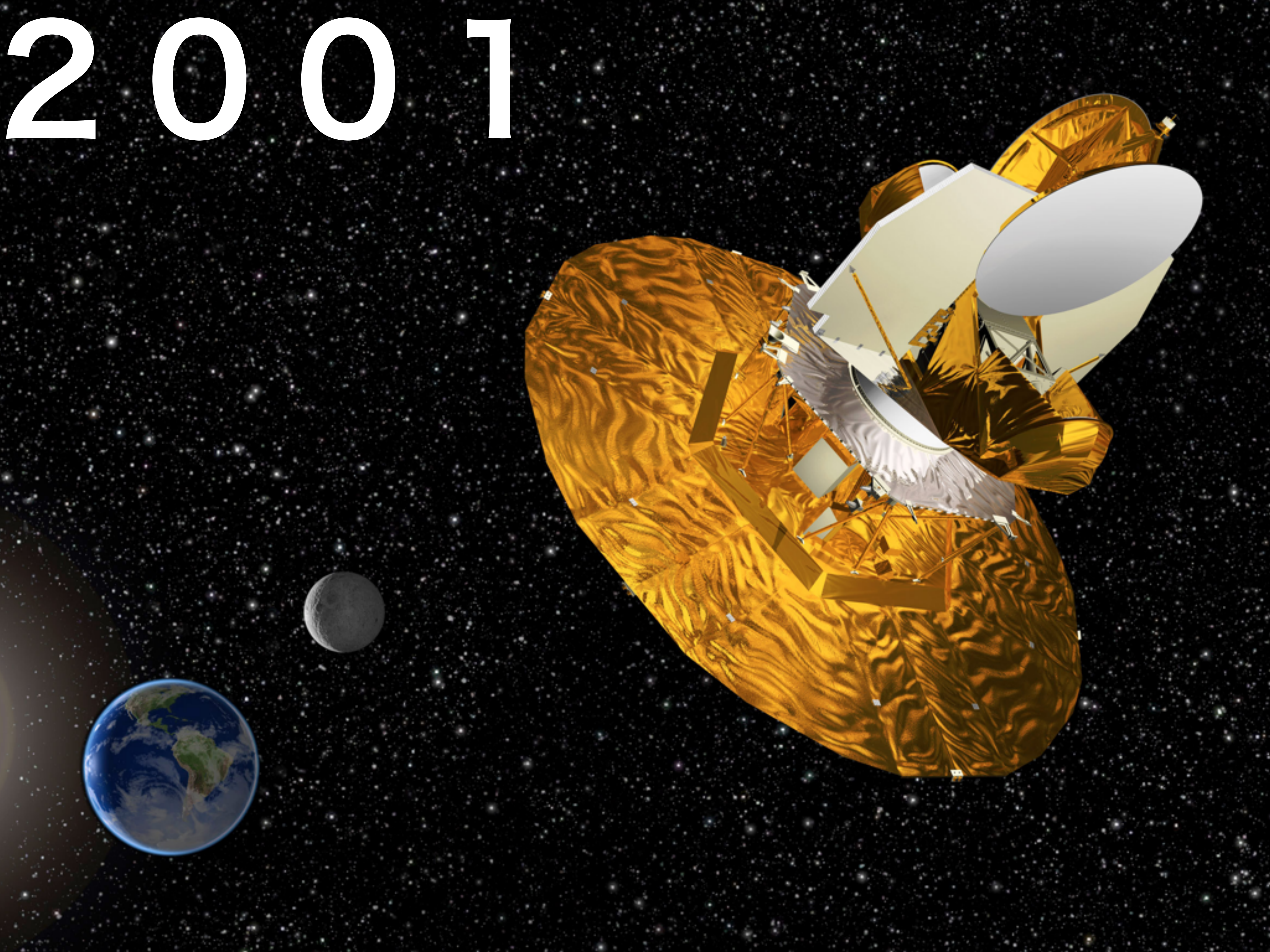


2001–2010

?

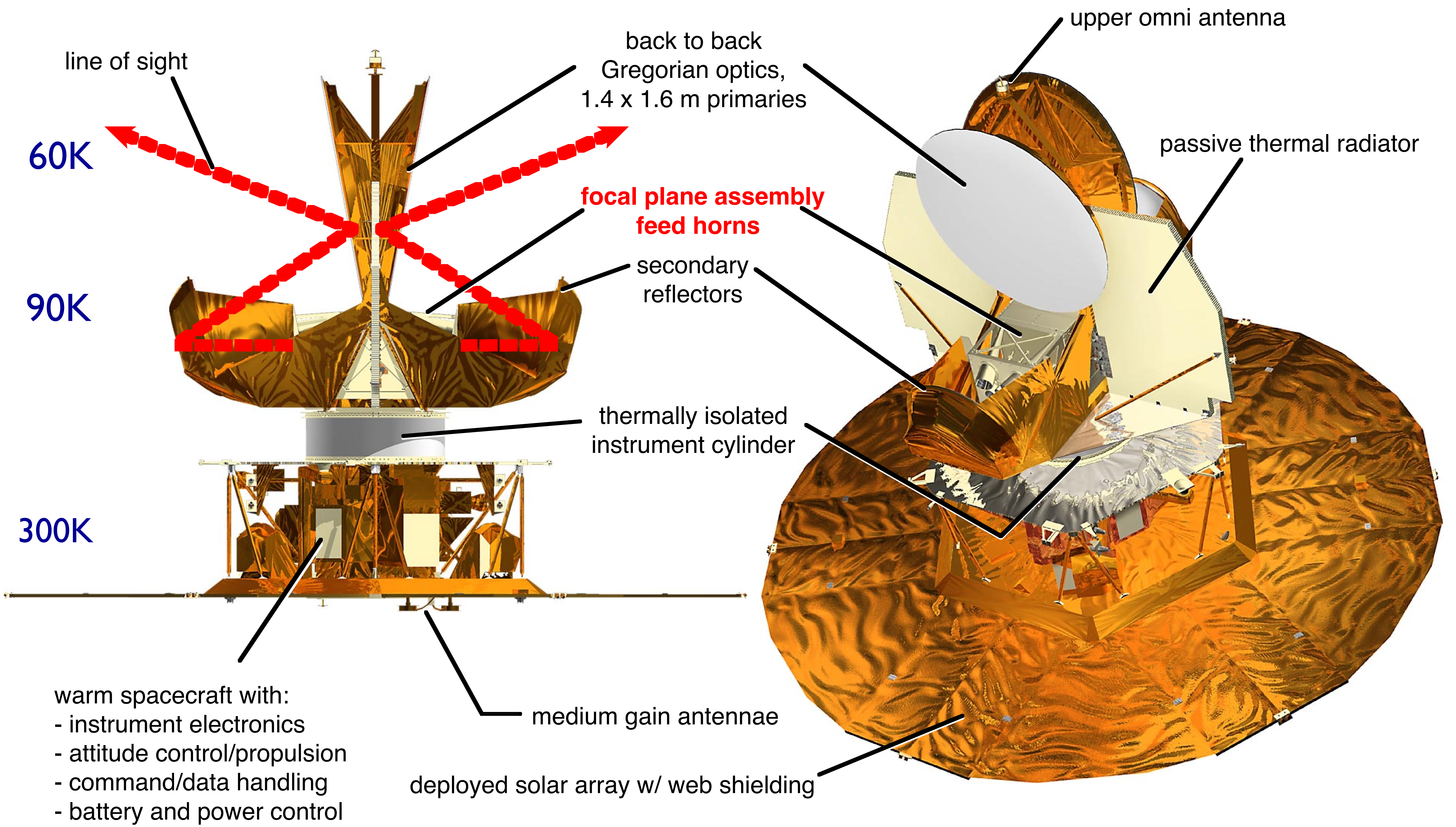
202X–




2001

WMAP Spacecraft

Radiative Cooling: No Cryogenic System



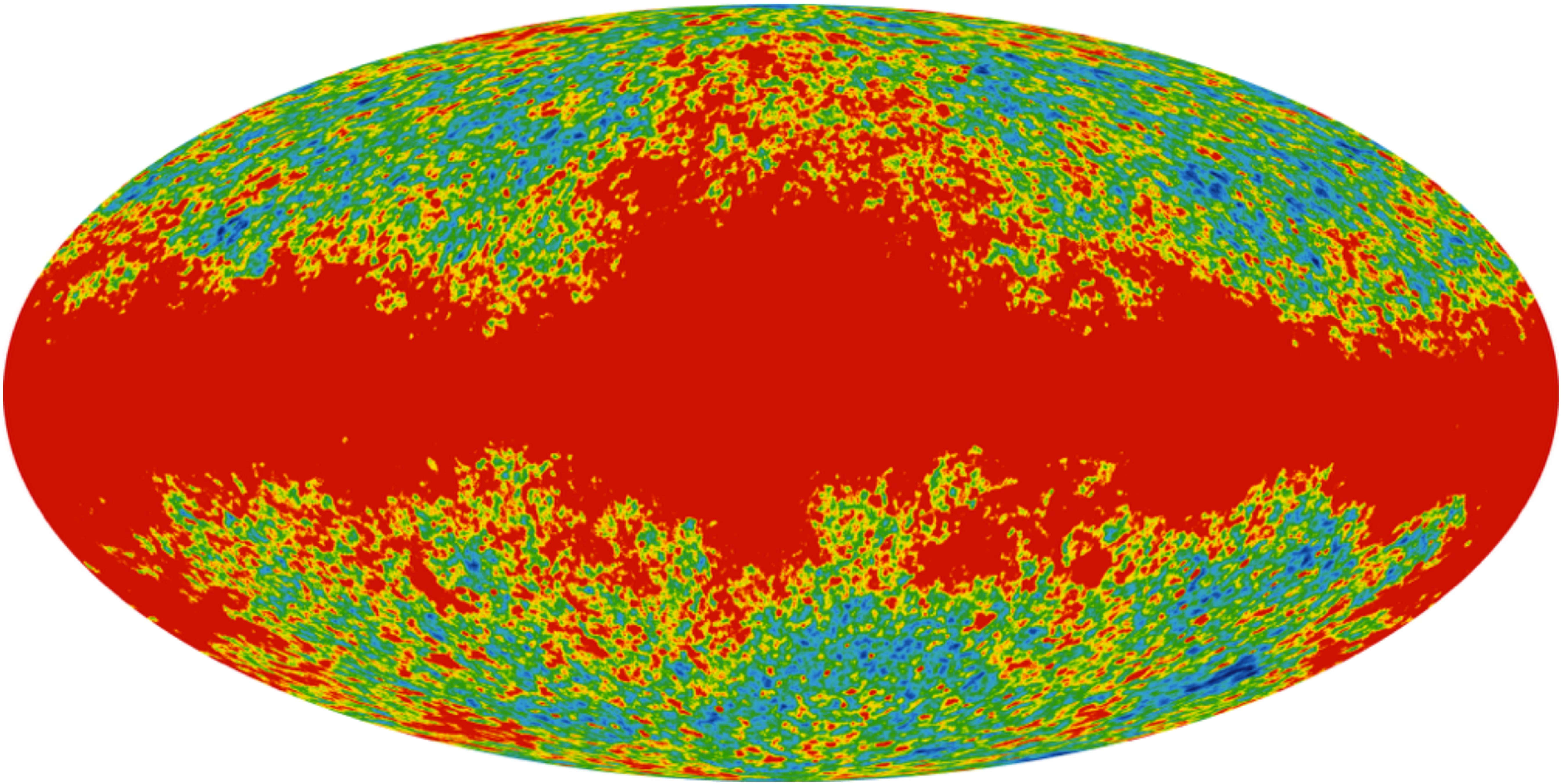
MAP990422

WMAP Science Team
July 19, 2002

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

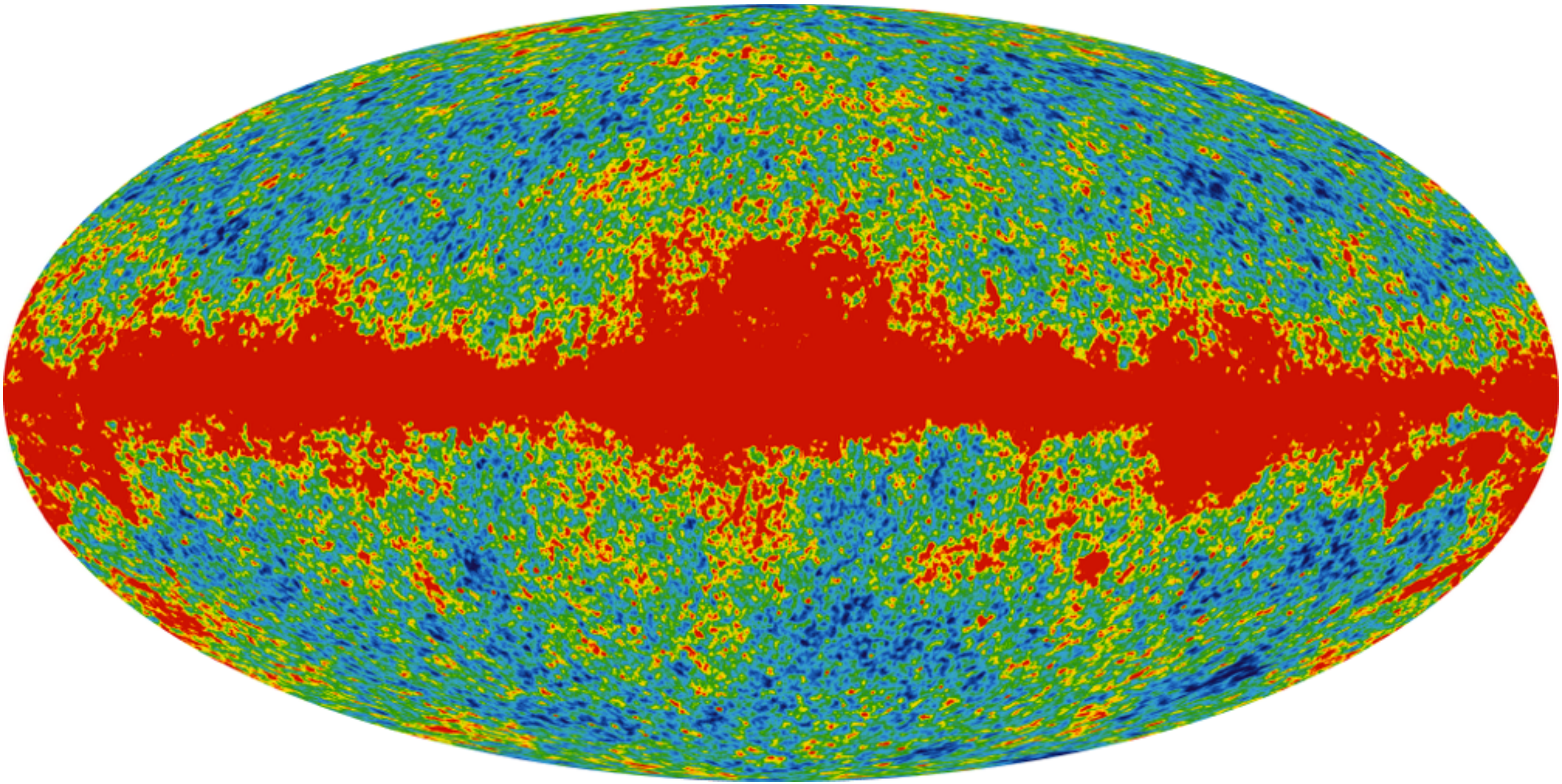
WMAP Collaboration

23 GHz



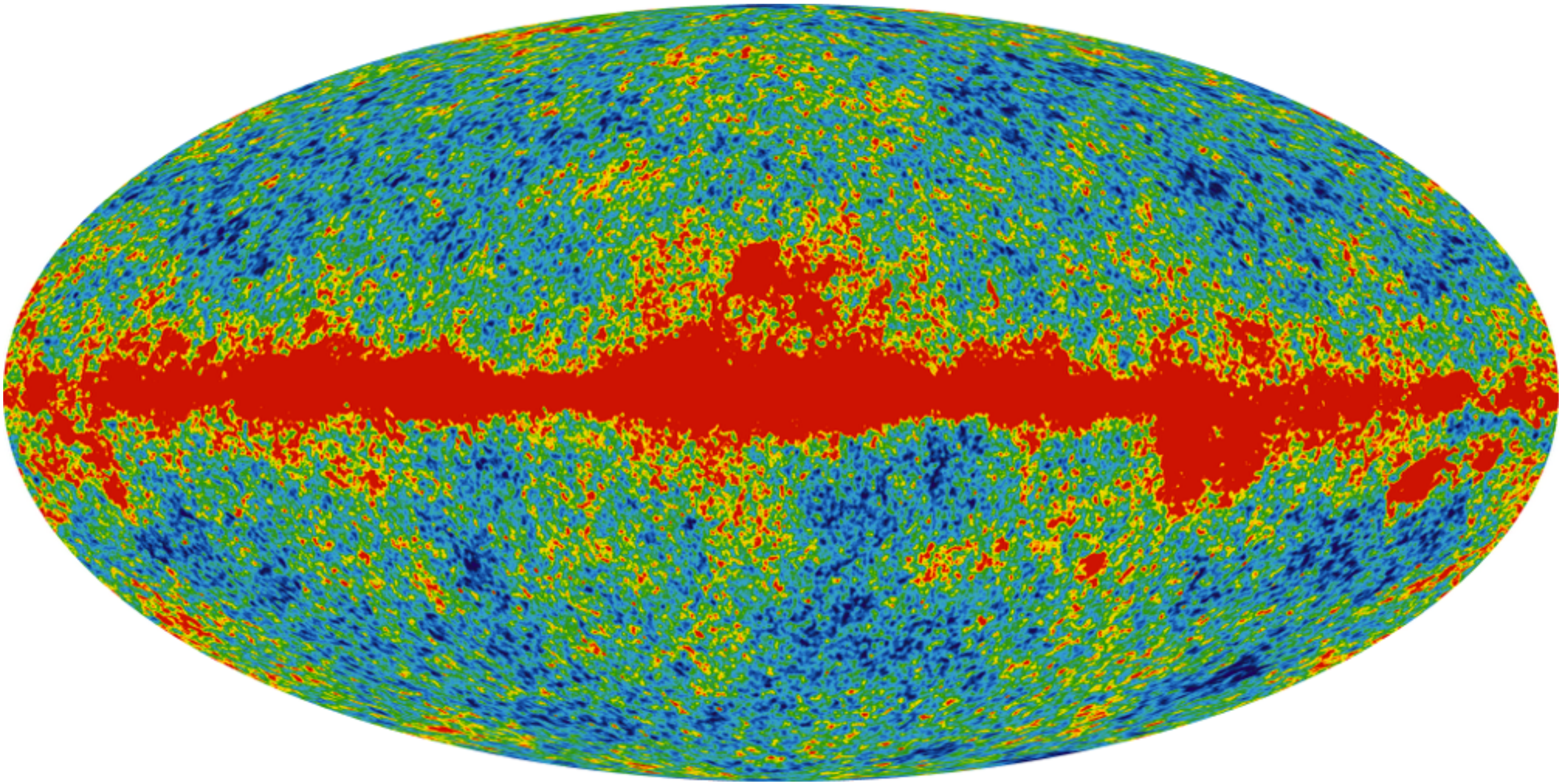
WMAP Collaboration

33 GHz



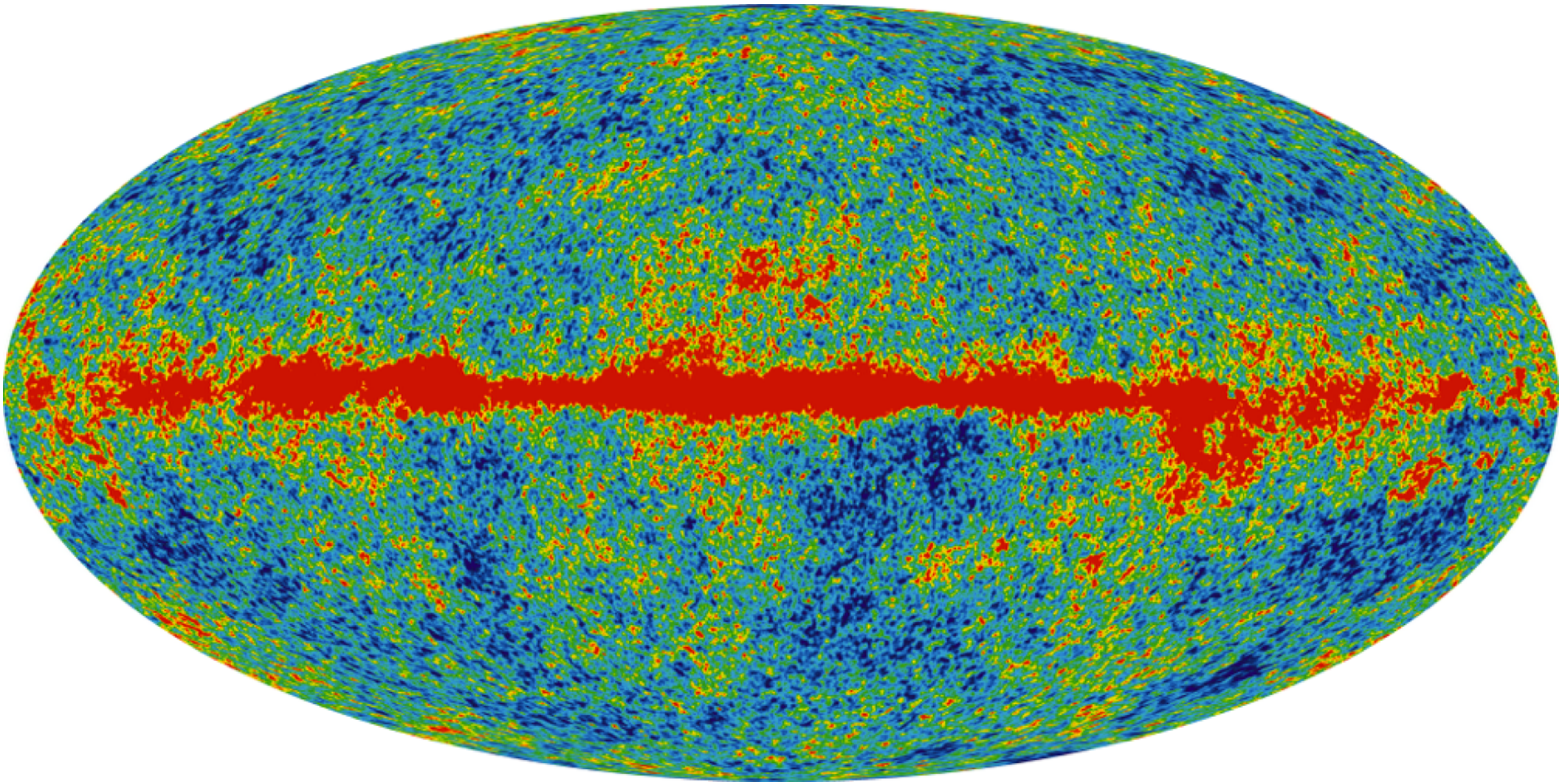
WMAP Collaboration

41 GHz



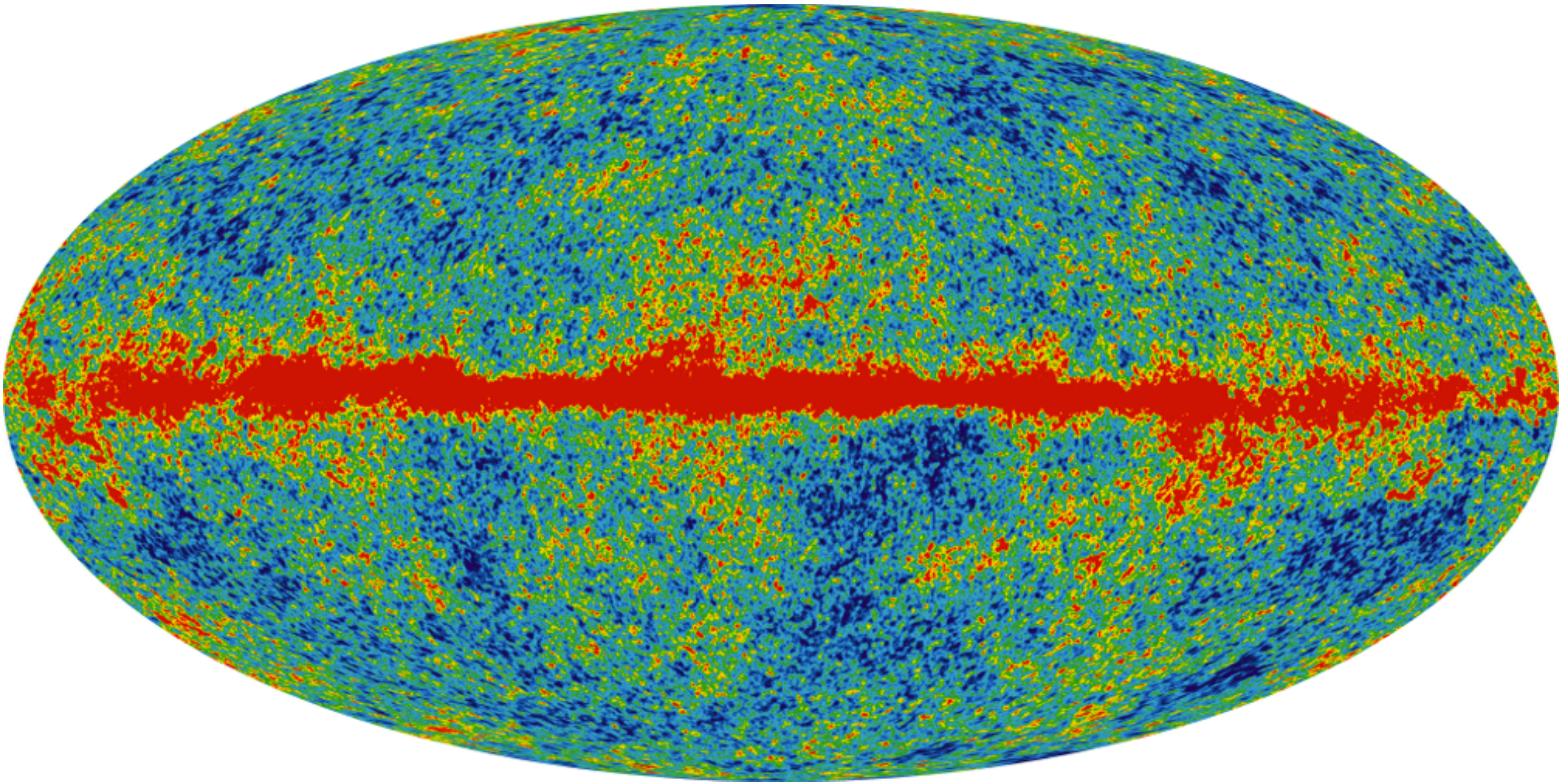
WMAP Collaboration

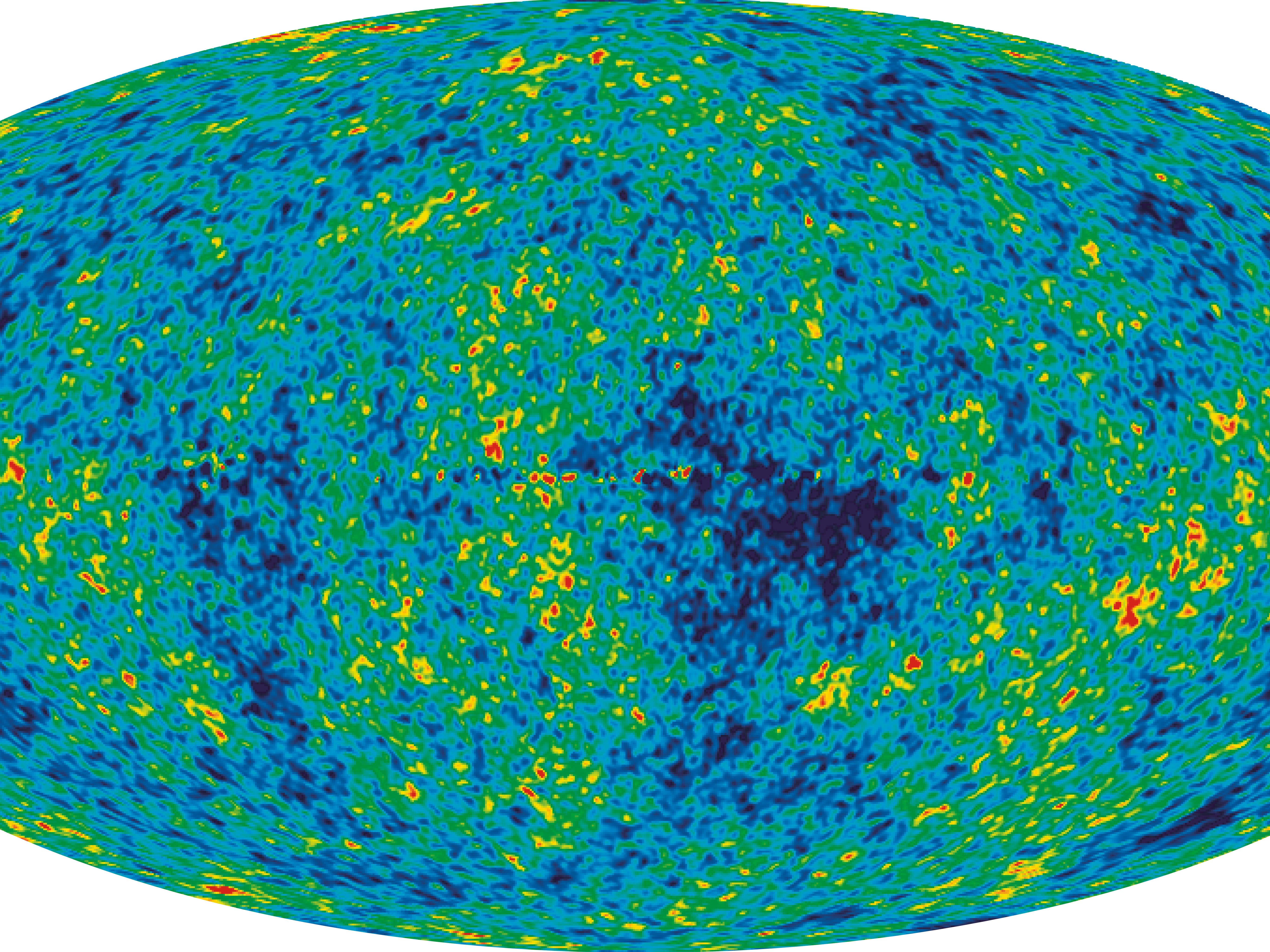
61 GHz



WMAP Collaboration

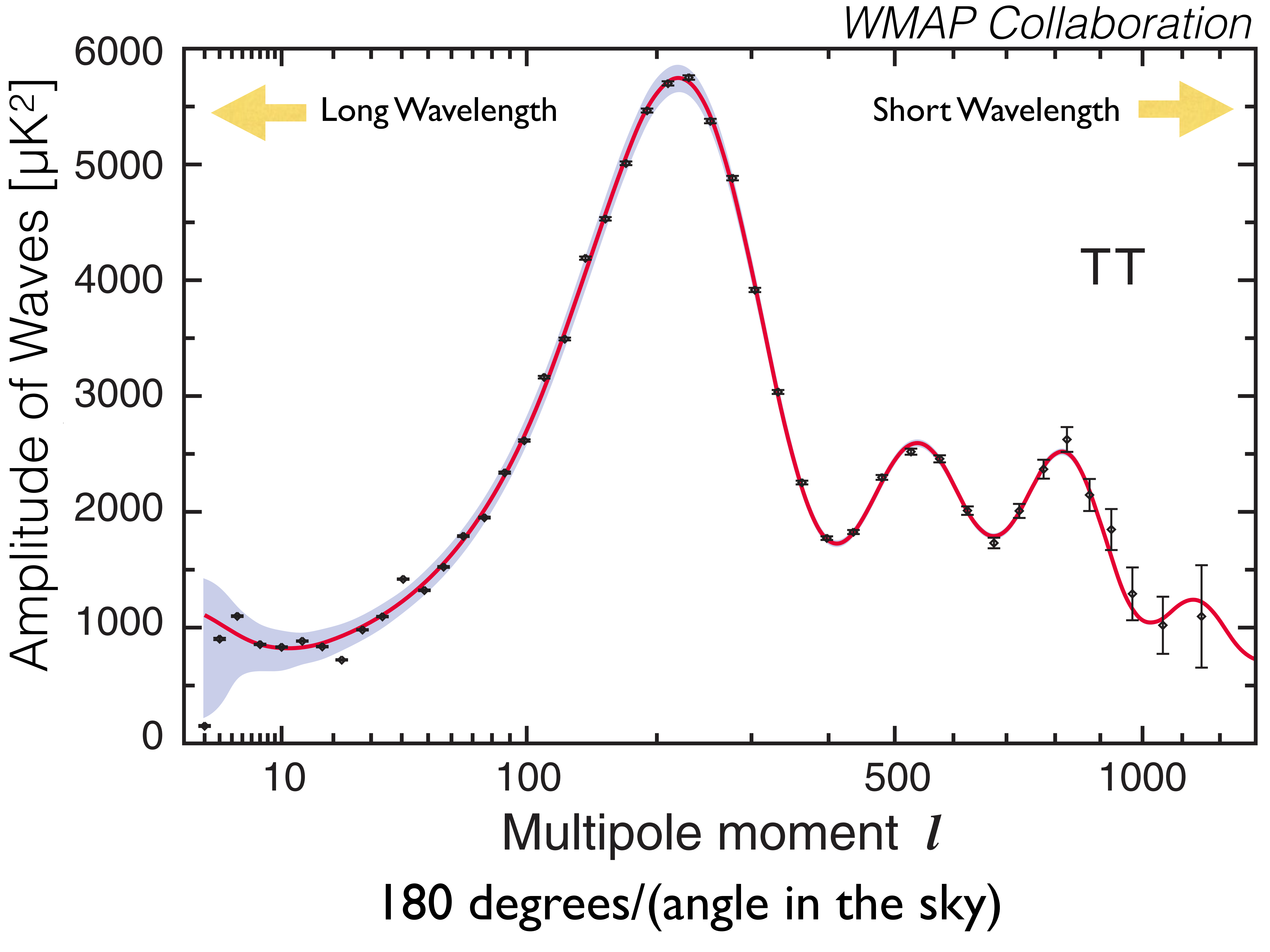
94 GHz





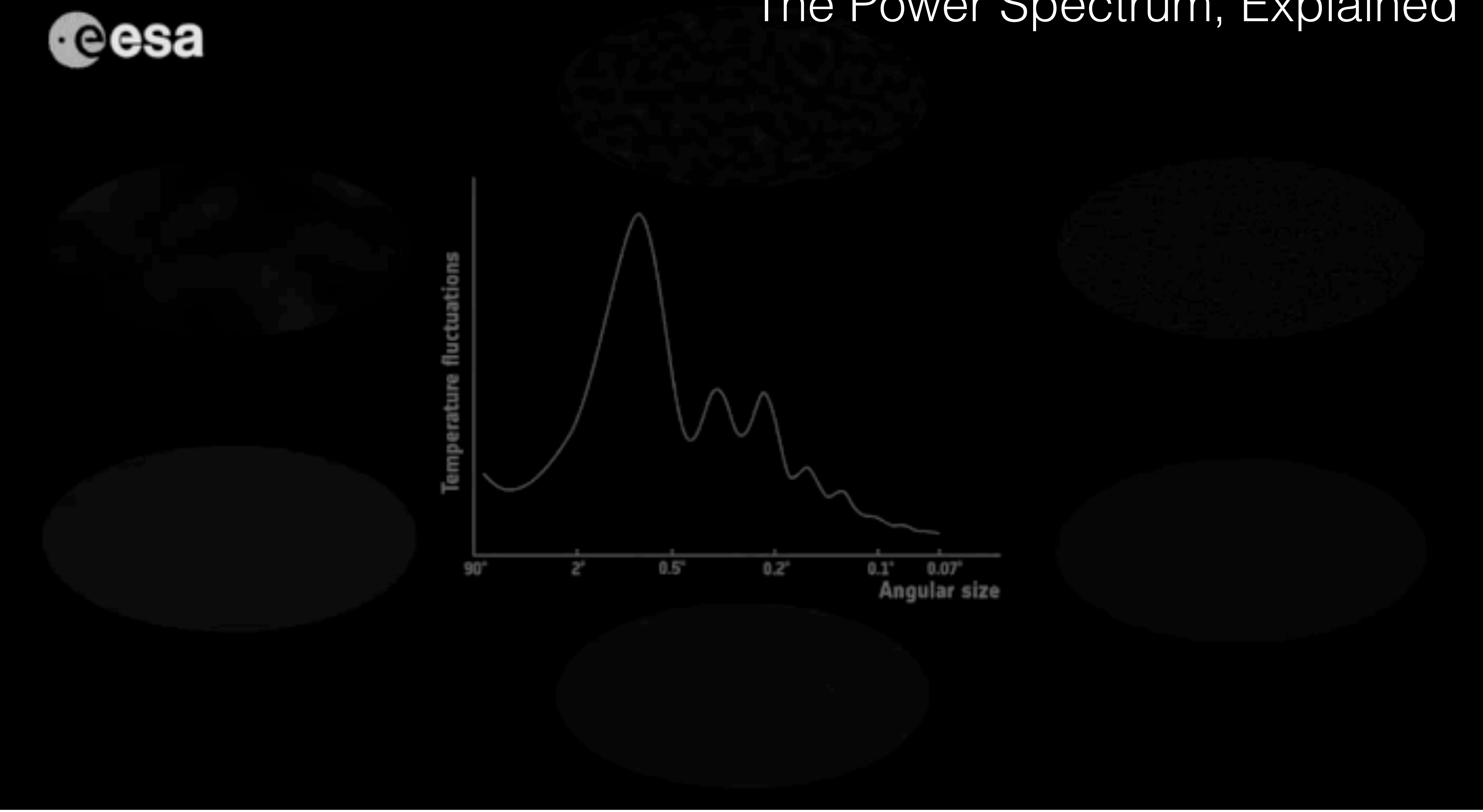
Data Analysis

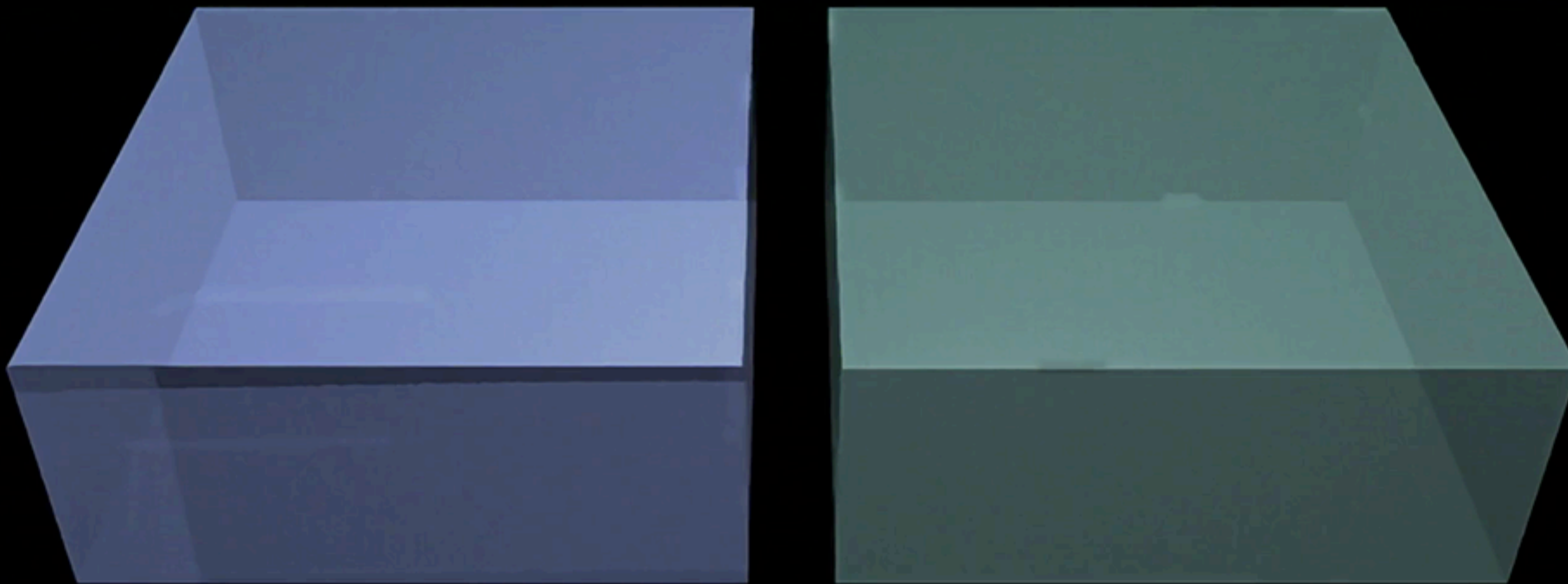
- Decompose temperature fluctuations in the sky into a set of waves with various wavelengths
- Make a diagram showing the strength of each wavelength



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)

The Power Spectrum, Explained





Outstanding Questions

- Where does anisotropy in CMB temperature come from?
    - This is the origin of galaxies, stars, planets, and everything else we see around us, including ourselves
- The leading idea: **quantum fluctuations in vacuum, stretched to cosmological length scales** by a rapid exponential expansion of the universe called "*cosmic inflation*" in the very early universe

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

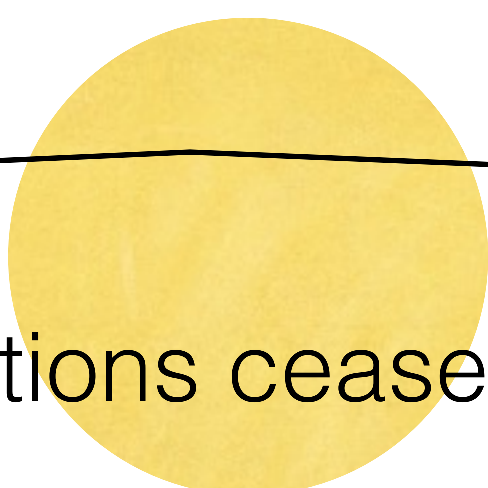
Cosmic Inflation

- In a tiny fraction of a second, the size of an atomic nucleus became the size of the Solar System
    - In 10^{-36} second, space was stretched by at least a factor of 10^{26}

Stretching Micro to Macro

Quantum fluctuations on microscopic scales

Inflation!



- Quantum fluctuations cease to be quantum
- Become macroscopic, classical fluctuations

Scalar and Tensor Modes

- 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 change the determinant (area)

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

Heisenberg's Uncertainty Principle

- You can borrow energy from vacuum, if you promise to return it immediately

- [Energy you can borrow] x [Time you borrow] = constant

Heisenberg's Uncertainty Principle

- [Energy you can borrow] x [Time you borrow] = constant

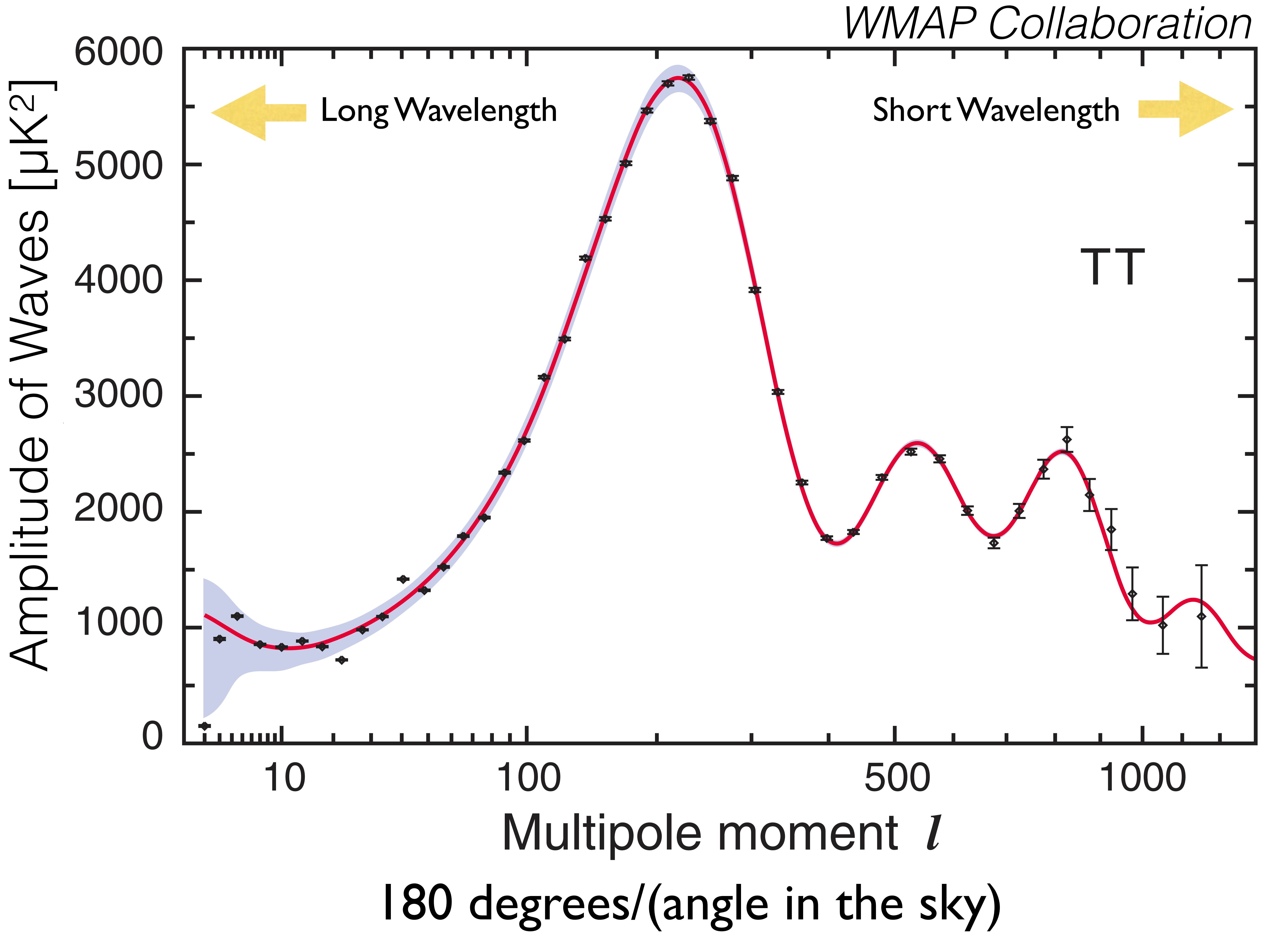
- Suppose that the distance between two points increases in proportion to **a(t)** [which is called the scale factor] by the expansion of the universe

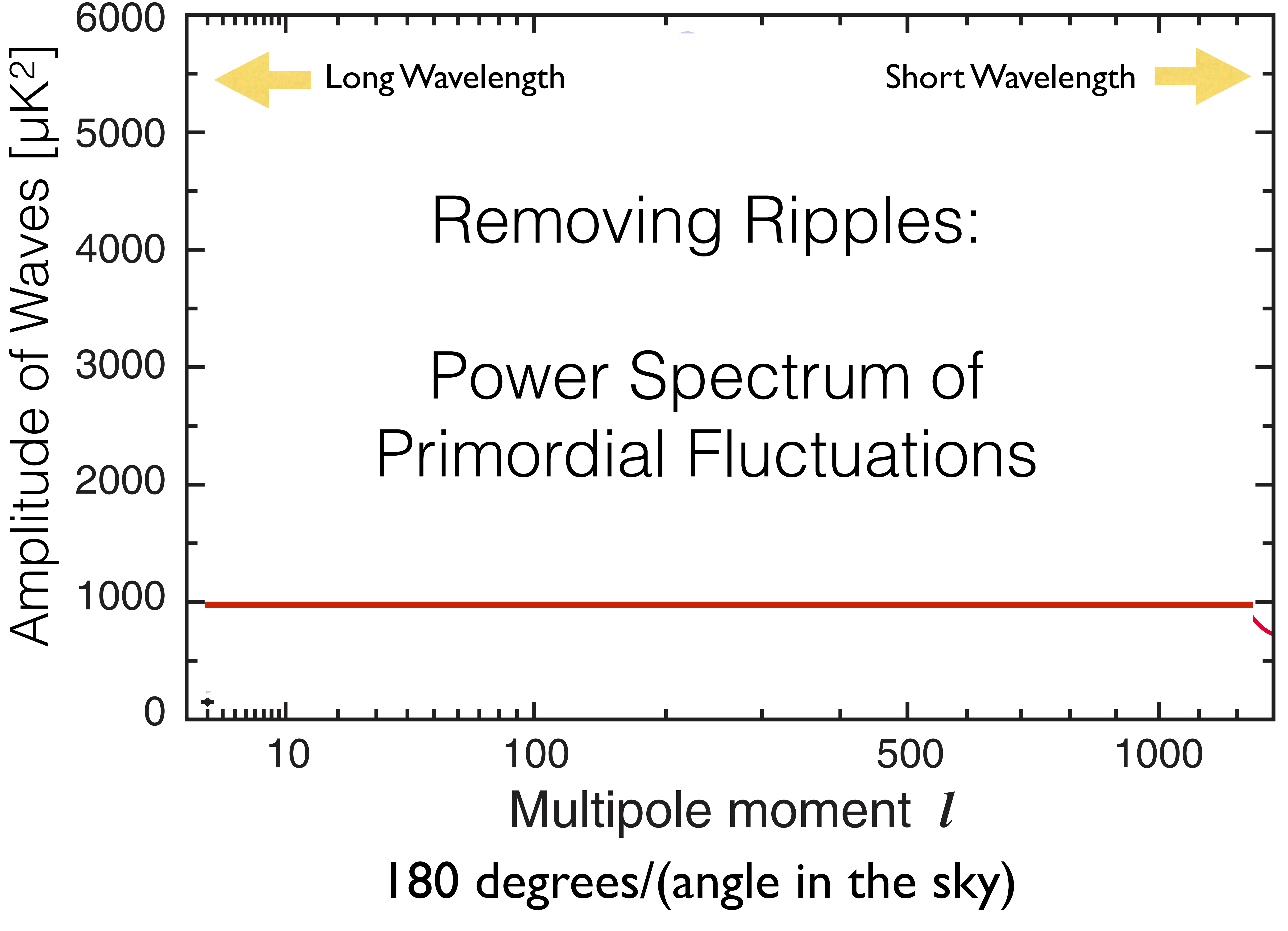
- Define the "expansion rate of the universe" as

$$H \equiv \frac{\dot{a}}{a}$$ [This has units of 1/time]

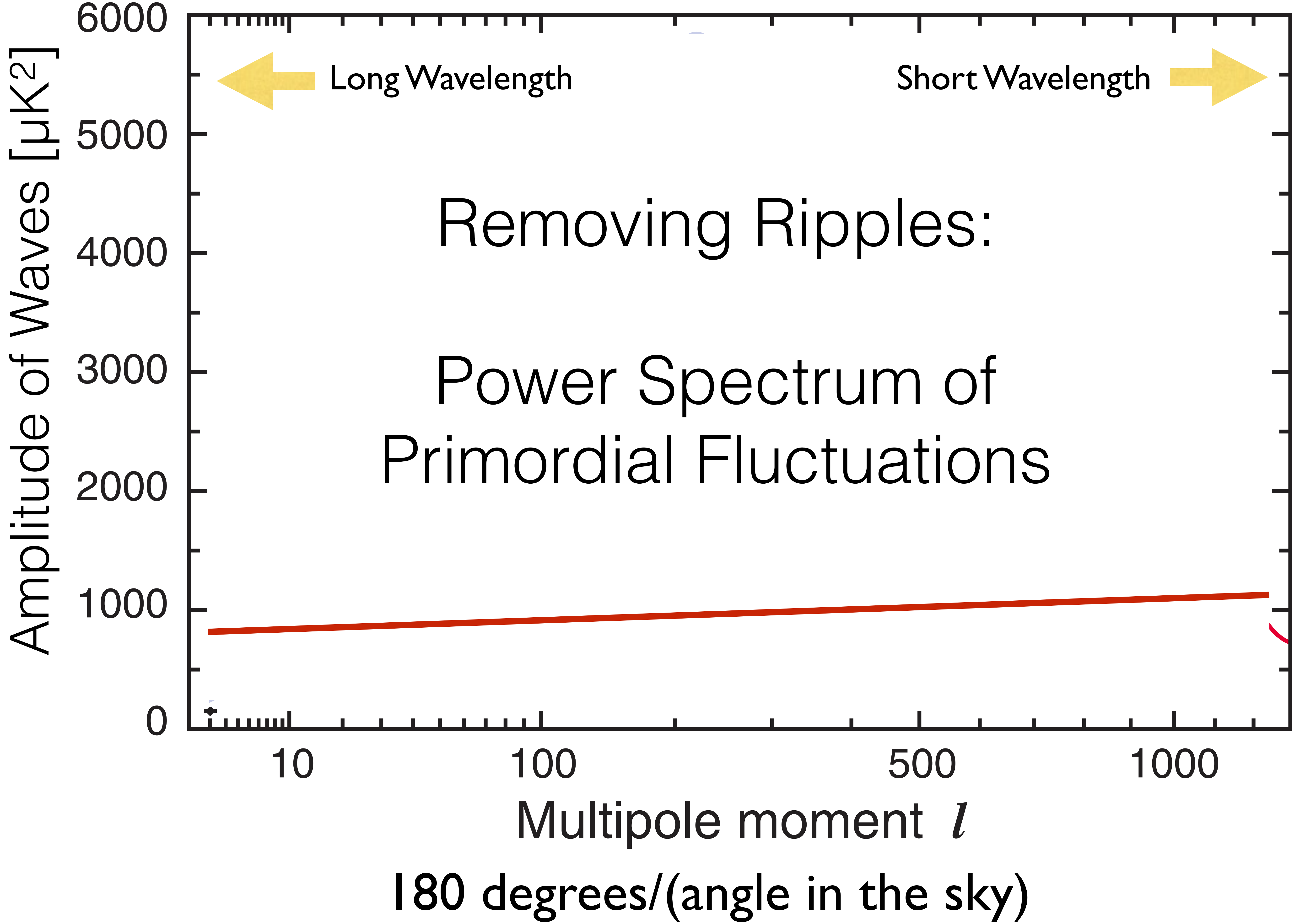
Fluctuations are proportional to H

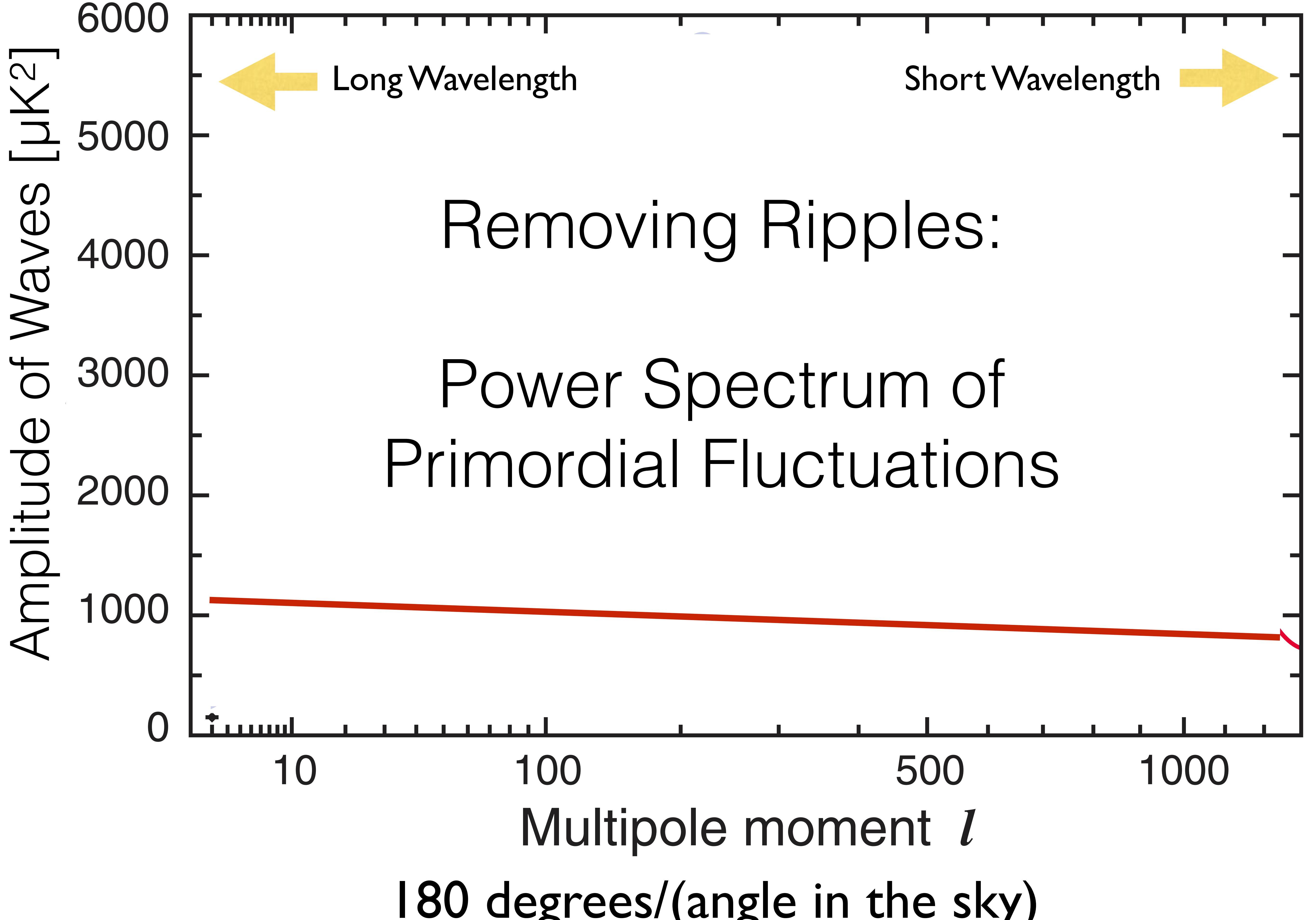
- [Energy you can borrow] x [Time you borrow] = constant
- $H \equiv \frac{\dot{a}}{a}$ [This has units of 1/time]
- Then, **both ζ and h_{ij} are proportional to H**
- Inflation occurs in 10^{-36} second - this is such a short period of time that you can borrow a lot of energy! **H during inflation in energy units is 10^{14} GeV**

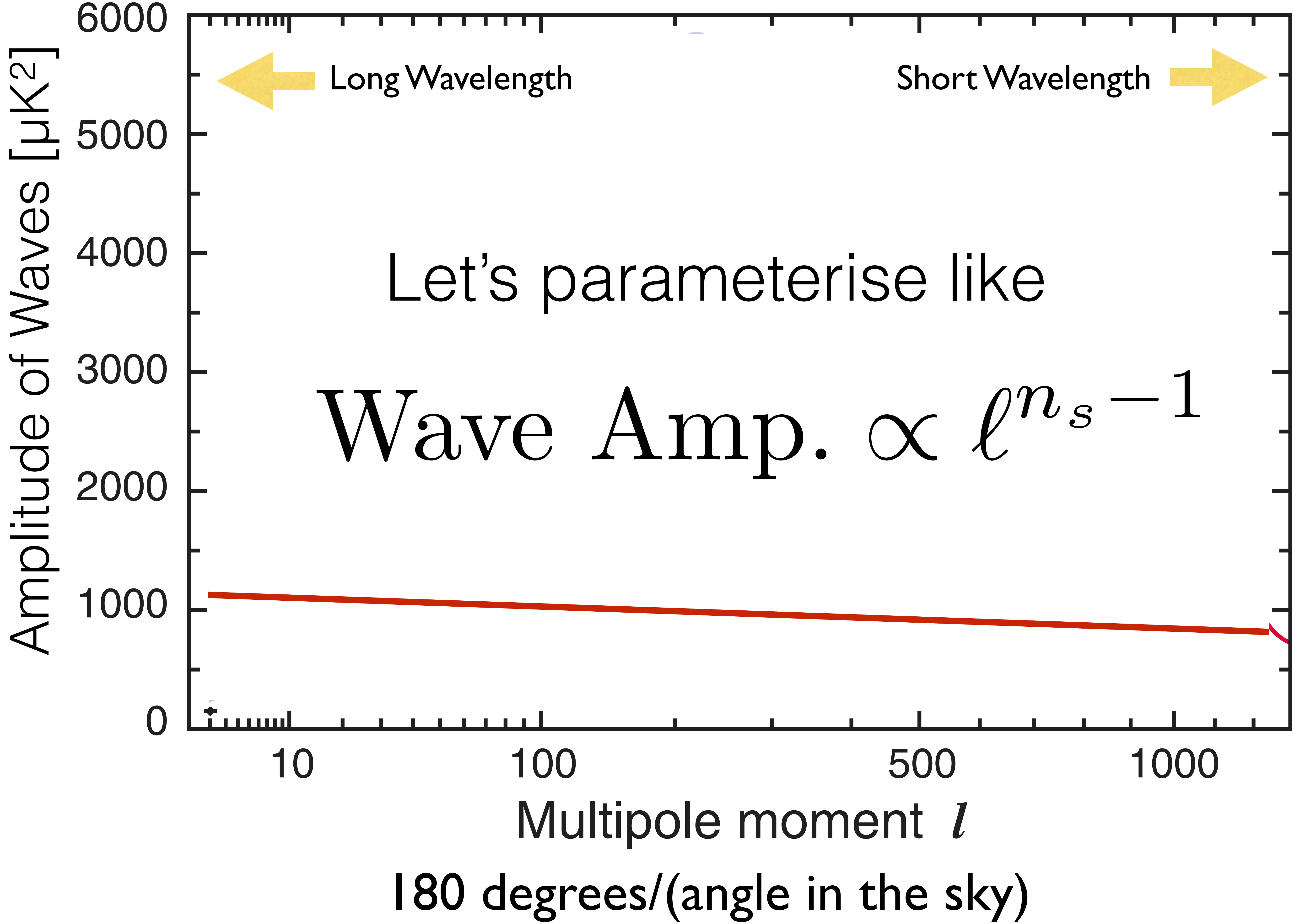

WMAP Collaboration
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
Short Wavelength
TT
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

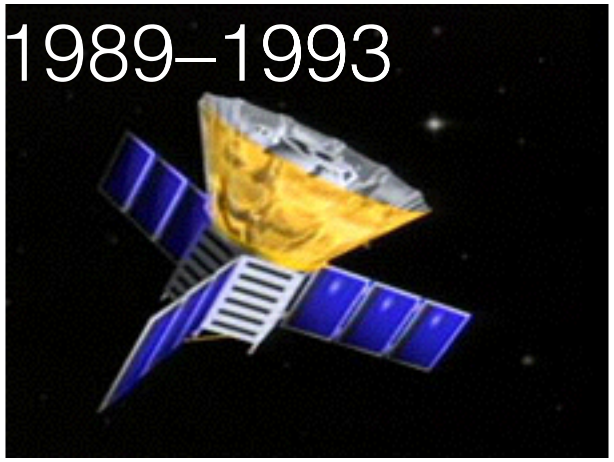


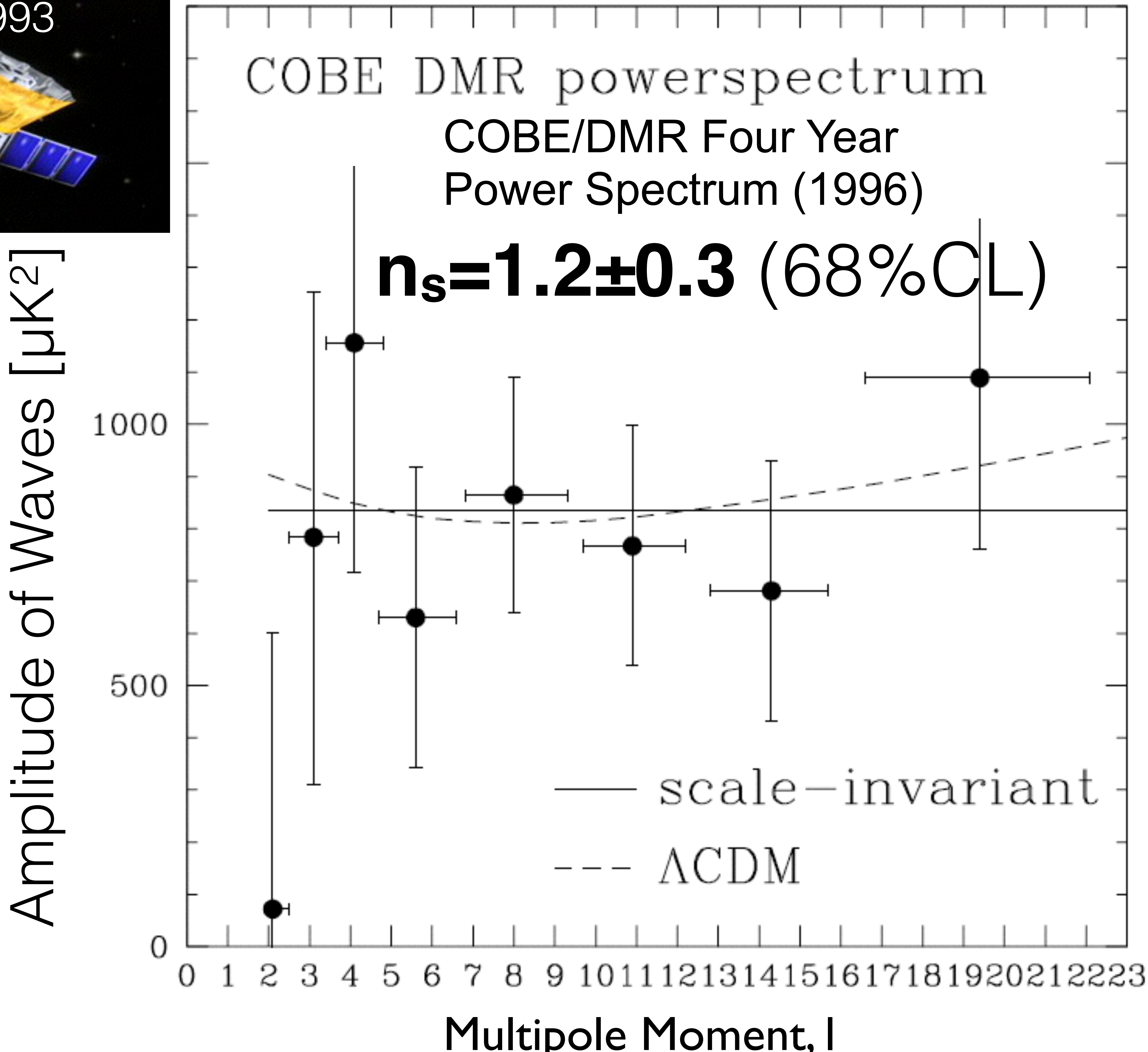
Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of Primordial Fluctuations
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

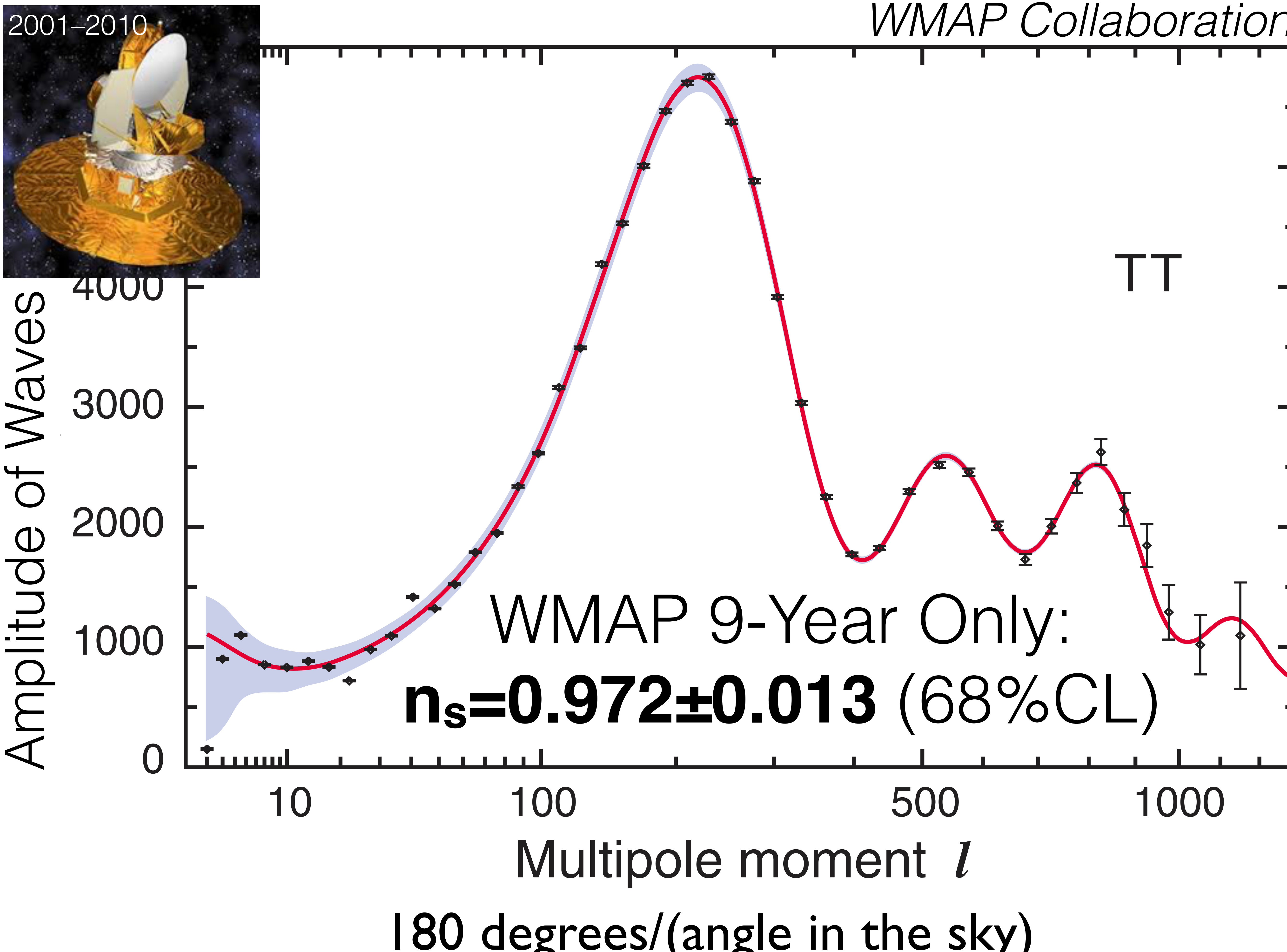

Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)


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)

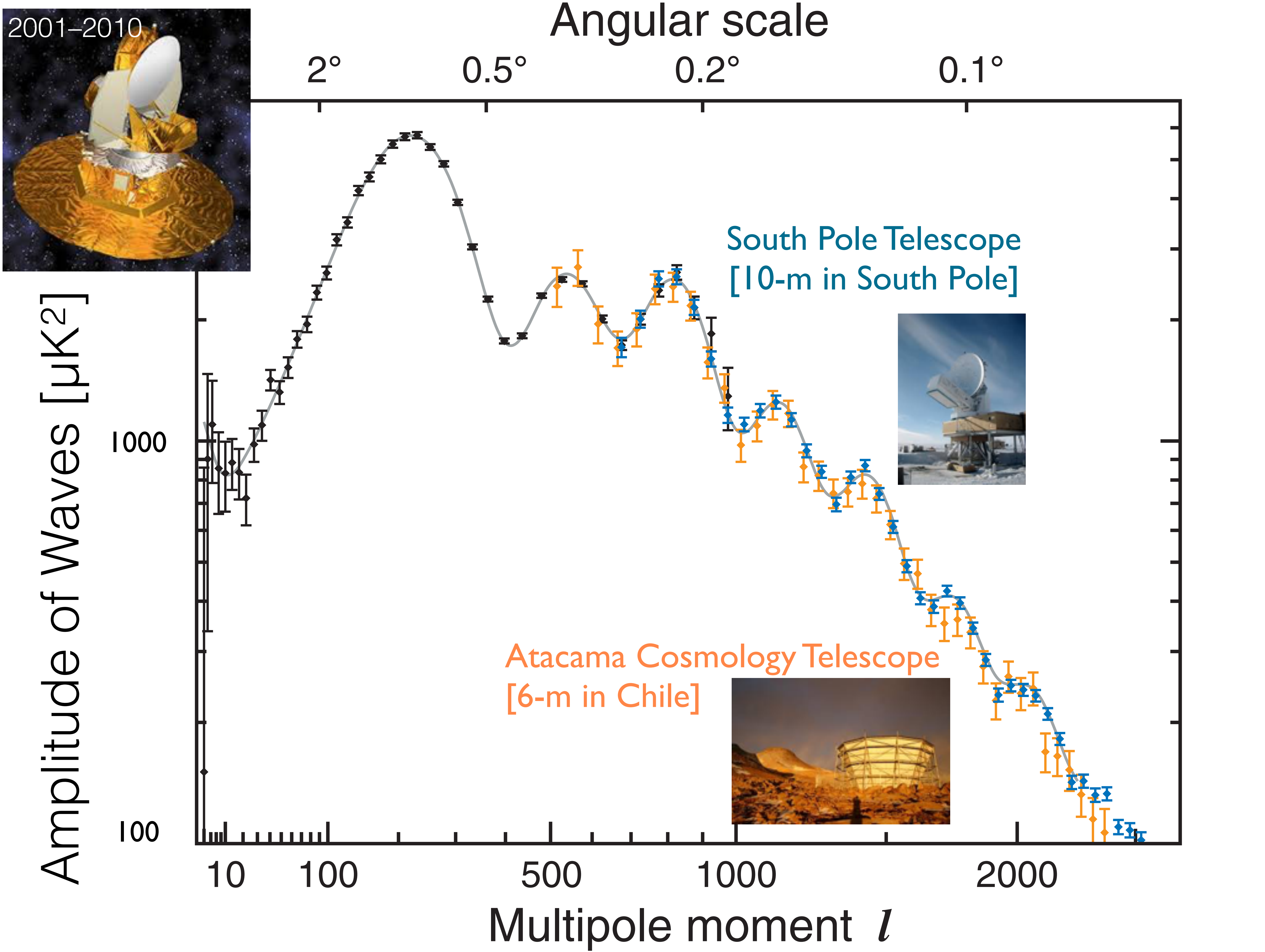

6000
5000
4000
3000
2000
1000
0
Amplitude of Waves [μK^2]
Long Wavelength
Short Wavelength
Let's parameterise like
$\text{Wave Amp.} \propto \ell^{n_s - 1}$
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

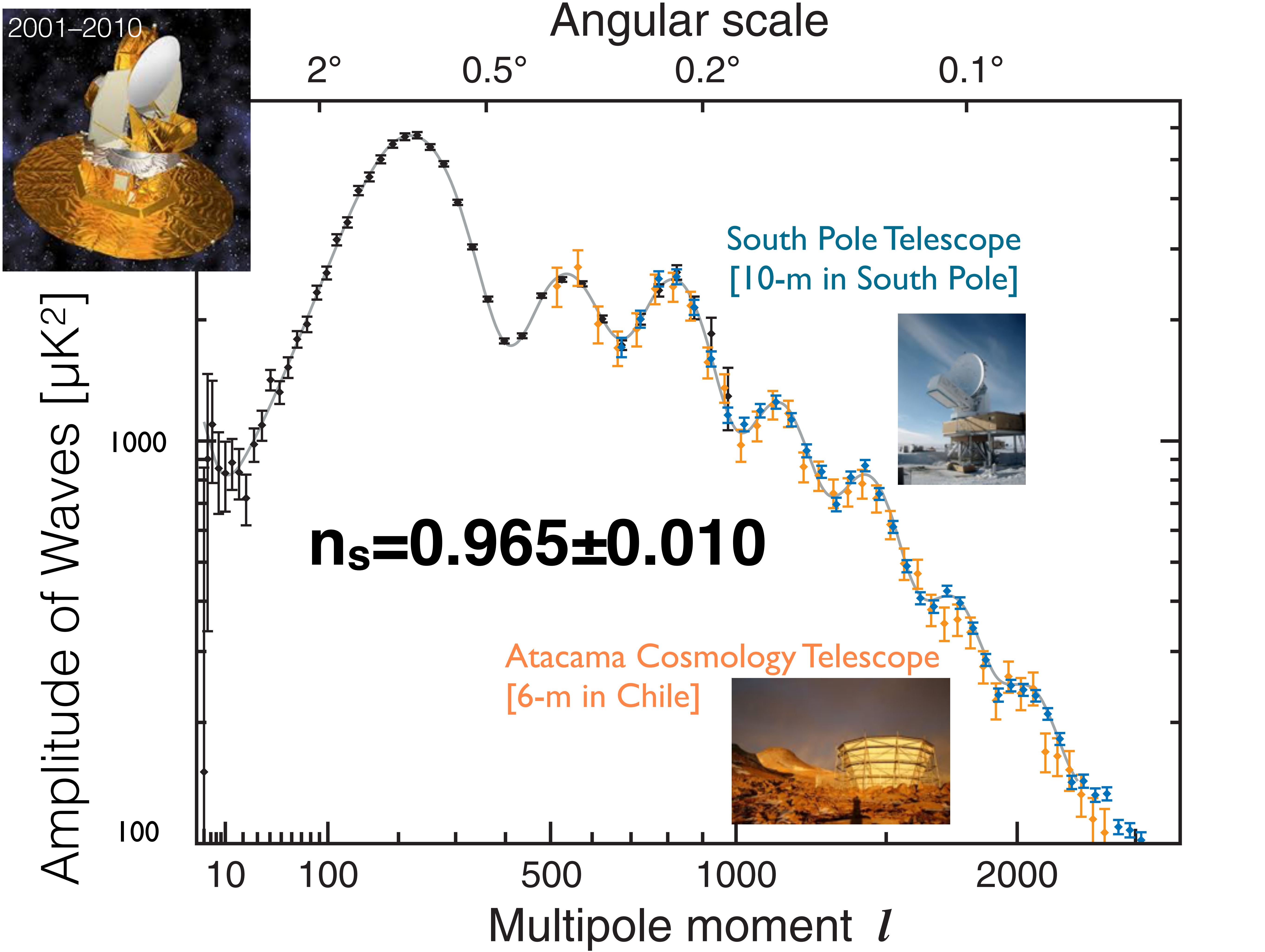

1989–1993


COBE DMR powerspectrum
COBE/DMR Four Year Power Spectrum (1996)
n_s=1.2±0.3 (68%CL)
Amplitude of Waves [μK²]
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
scale-invariant
ΛCDM
Multipole Moment, l

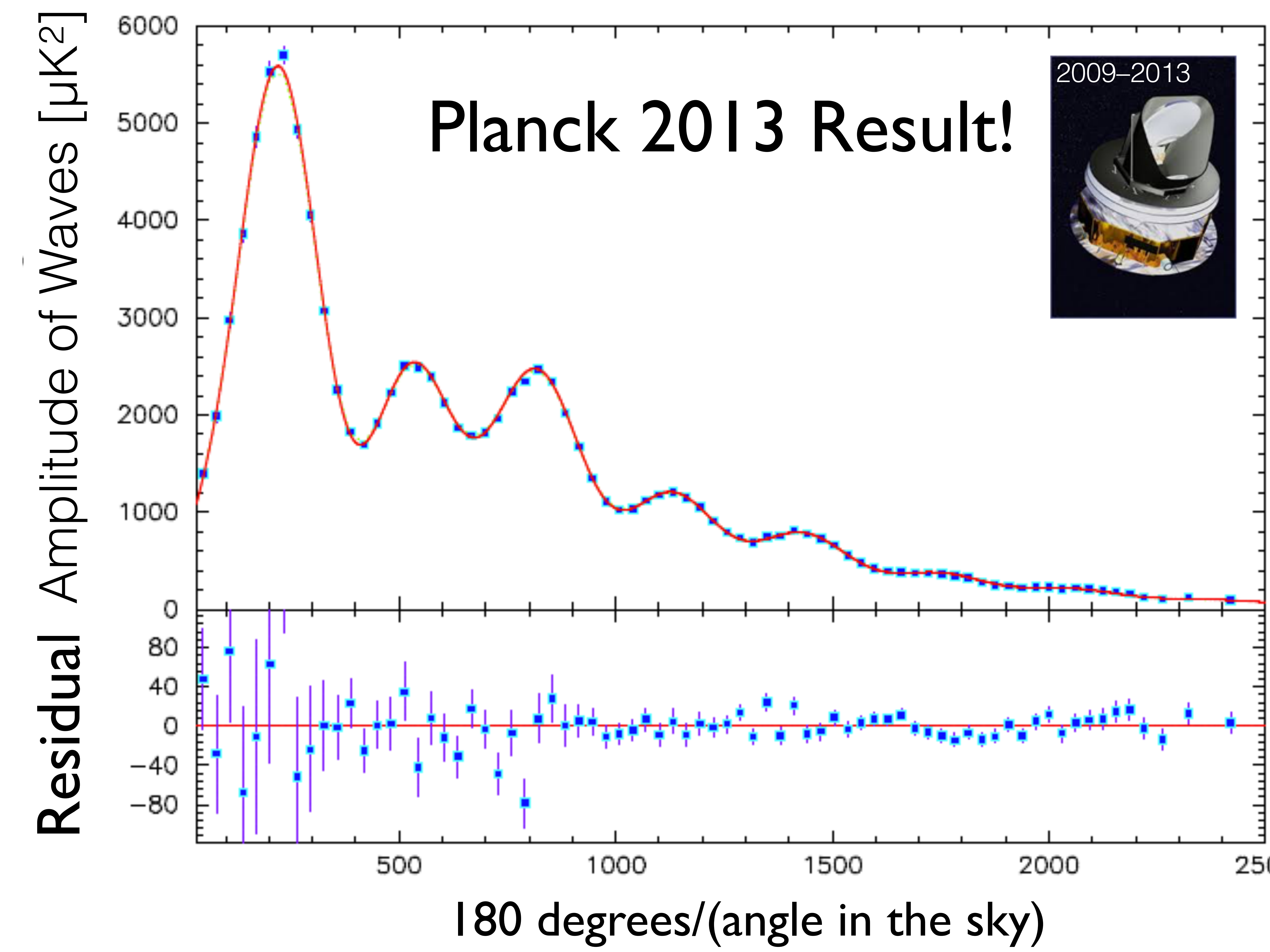


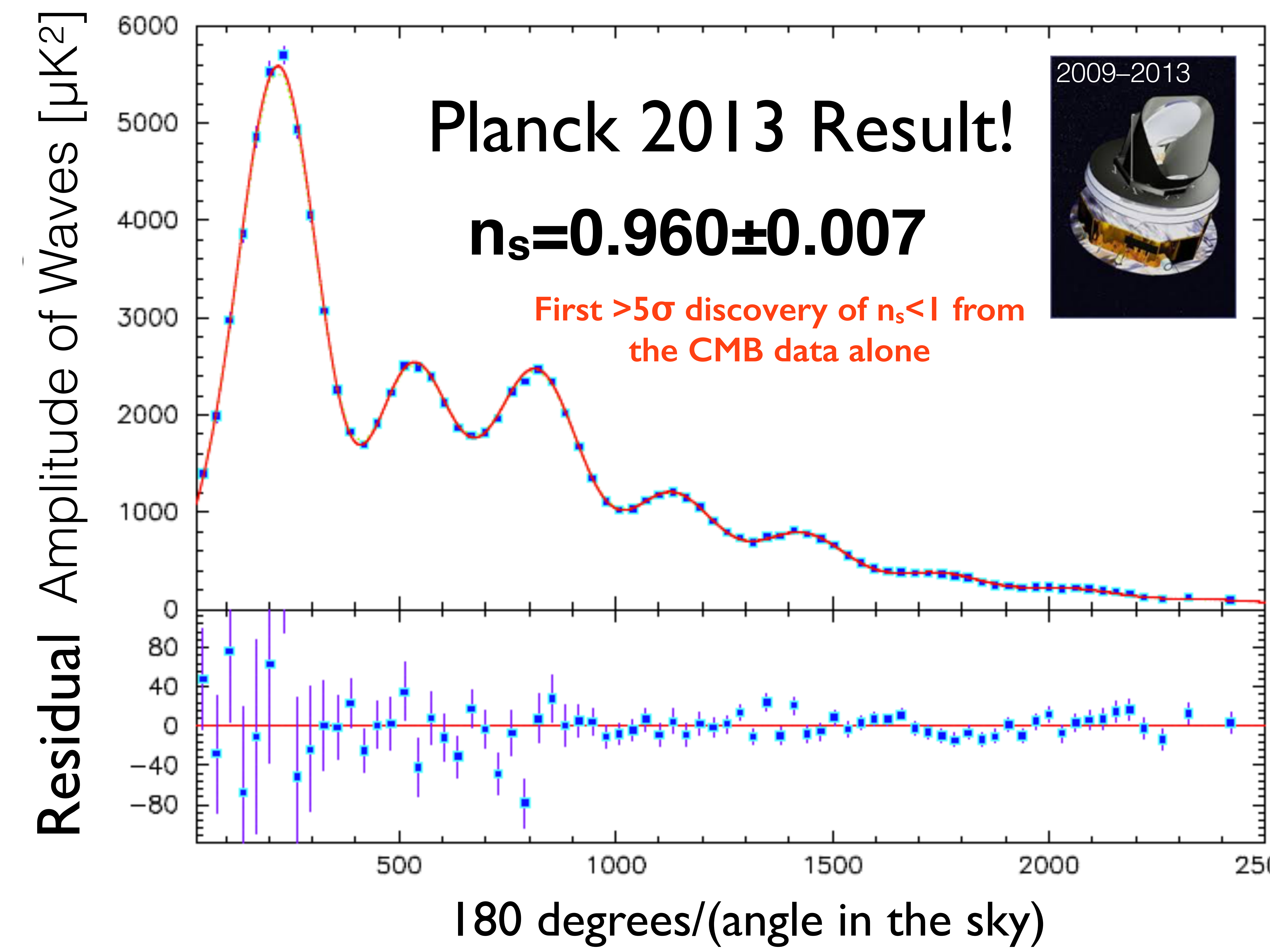
2001–2010
WMAP Collaboration
TT
Amplitude of Waves
0
1000
2000
3000
4000
10
100
500
1000
WMAP 9-Year Only:
ns=0.972±0.013 (68%CL)
Multipole moment l
180 degrees/(angle in the sky)


2001–2010
Angular scale
2°
0.5°
0.2°
0.1°
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
Amplitude of Waves [μK²]
1000
100
10
100
500
1000
2000
Multipole moment l



2001–2010
Angular scale
2°
0.5°
0.2°
0.1°
South Pole Telescope
[10-m in South Pole]
Amplitude of Waves [μK²]
1000
100
n_s=0.965±0.010
Atacama Cosmology Telescope
[6-m in Chile]
10
100
500
1000
2000
Multipole moment l


Planck 2013 Result!
2009–2013
Amplitude of Waves [μK²]
Residual
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
250
180 degrees/(angle in the sky)

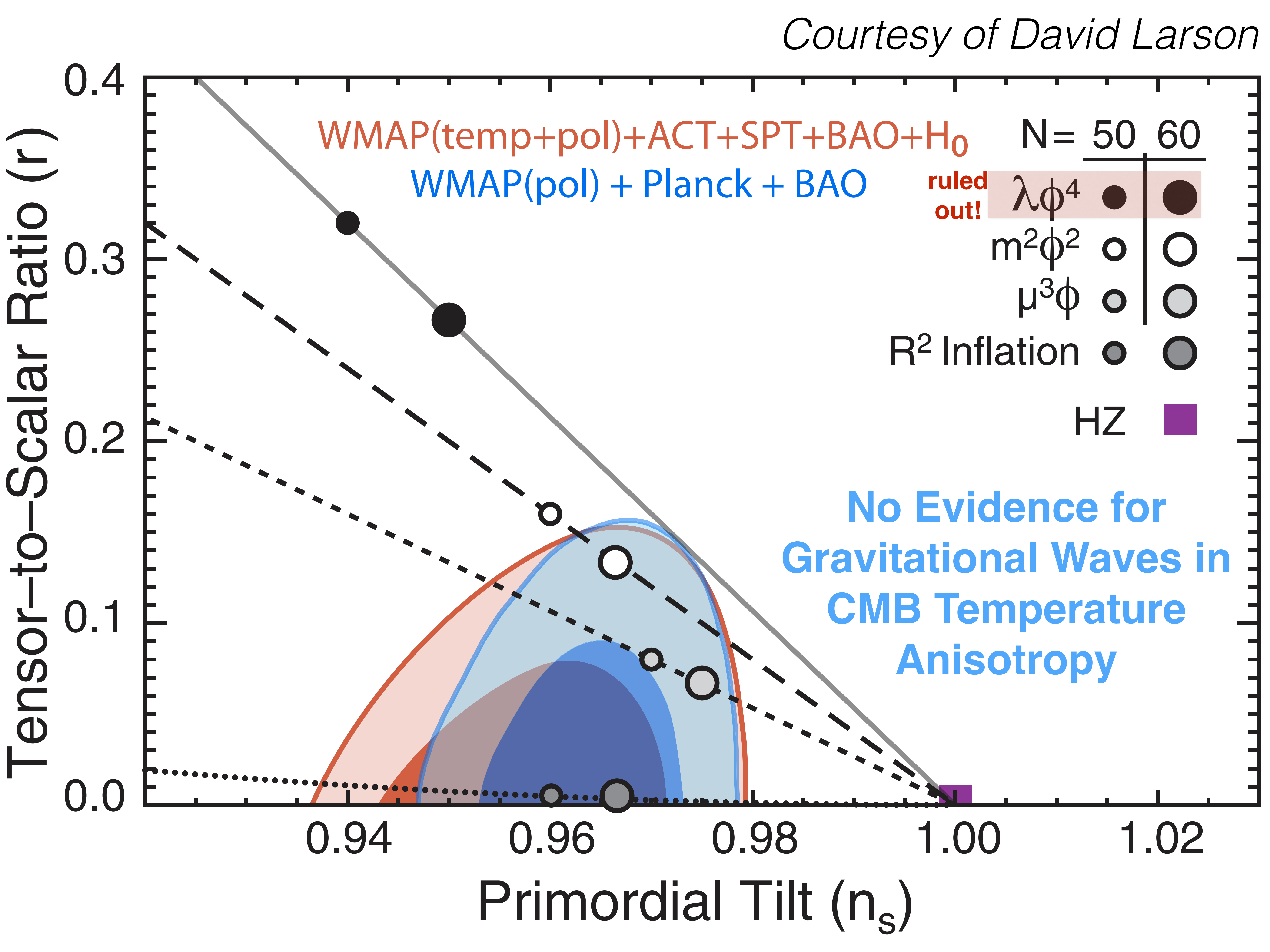


Planck 2013 Result!
n_s=0.960±0.007
First >5σ discovery of n_s<1 from the CMB data alone
2009–2013
Amplitude of Waves [μK²]
Residual
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
180 degrees/(angle in the sky)

Expectations

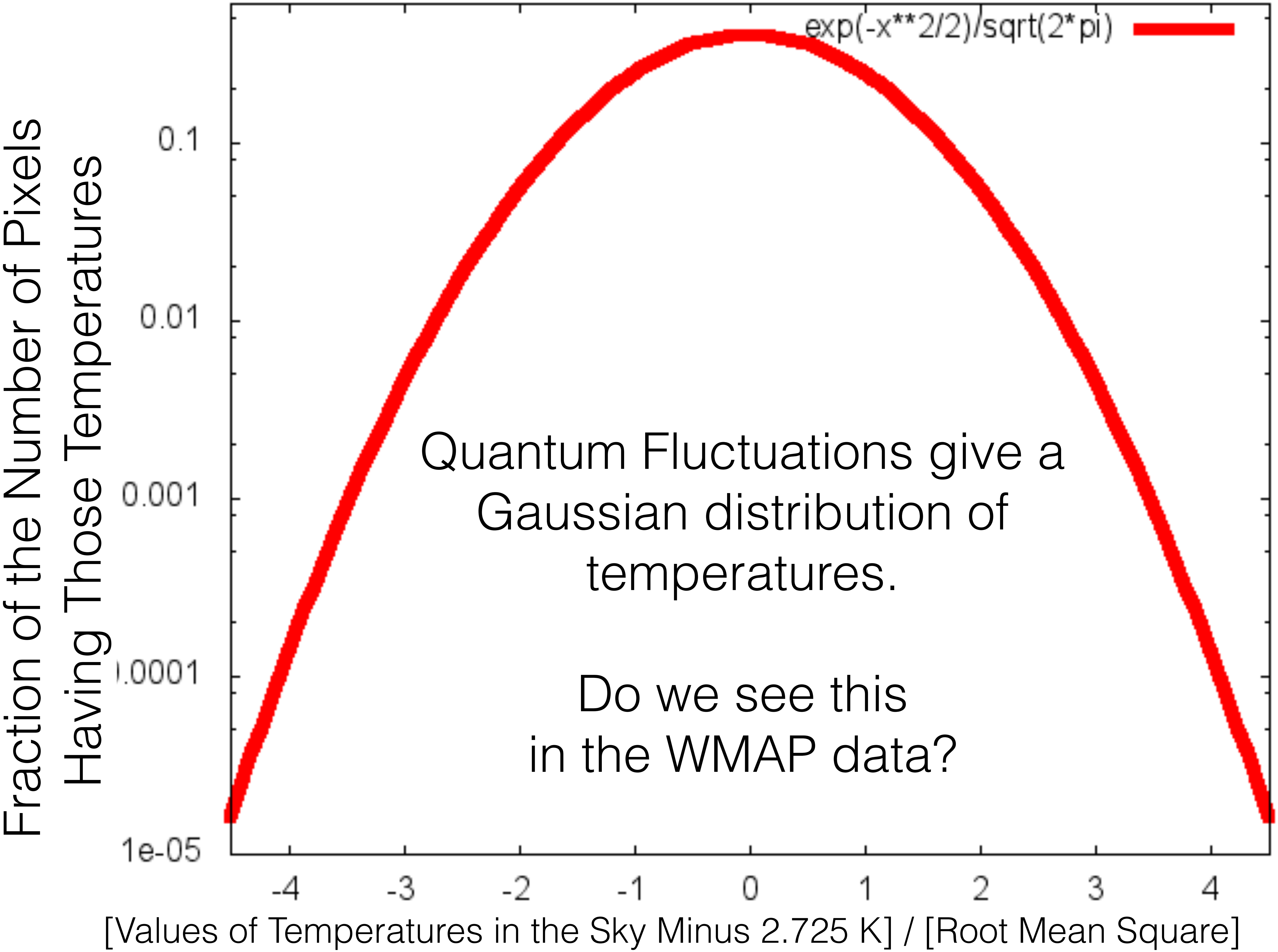
- Inflation must end
- Inflation predicts $n_s \sim 1$, but not exactly equal to 1. Usually $n_s < 1$ is expected
- **The discovery of $n_s<1$ has been the dream of cosmologists since 1992,** when the CMB anisotropy was discovered and $n_s \sim 1$ (to within 30%) was indicated

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



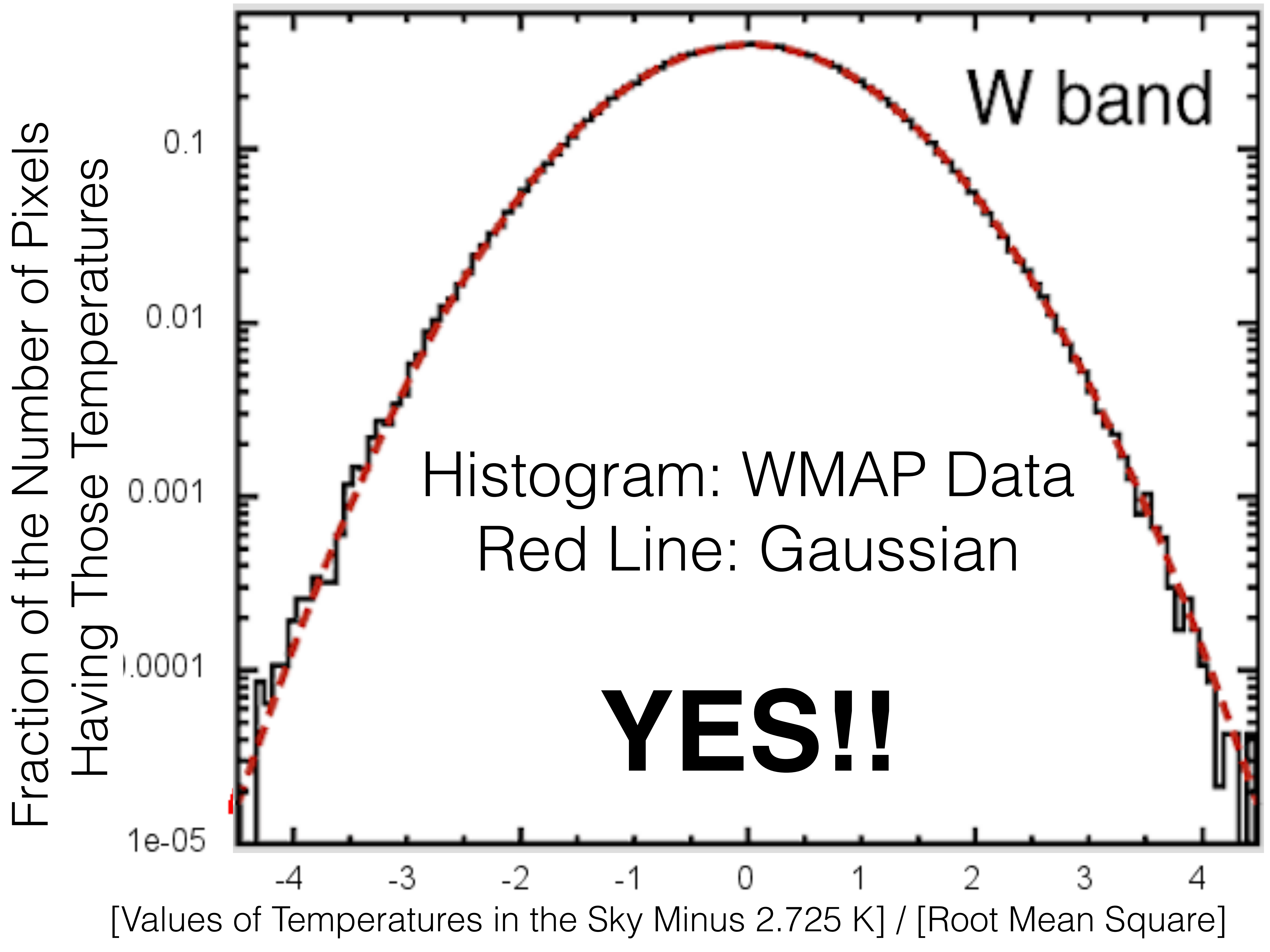
Courtesy of David Larson
WMAP(temp+pol)+ACT+SPT+BAO+H0
WMAP(pol) + Planck + BAO
N= 50 60
ruled out!
λφ4
m2φ2
μ3φ
R2 Inflation
HZ
No Evidence for Gravitational Waves in CMB Temperature Anisotropy
Tensor–to–Scalar Ratio (r)
Primordial Tilt (ns)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02

How do we know that primordial fluctuations were of *quantum mechanical origin*?



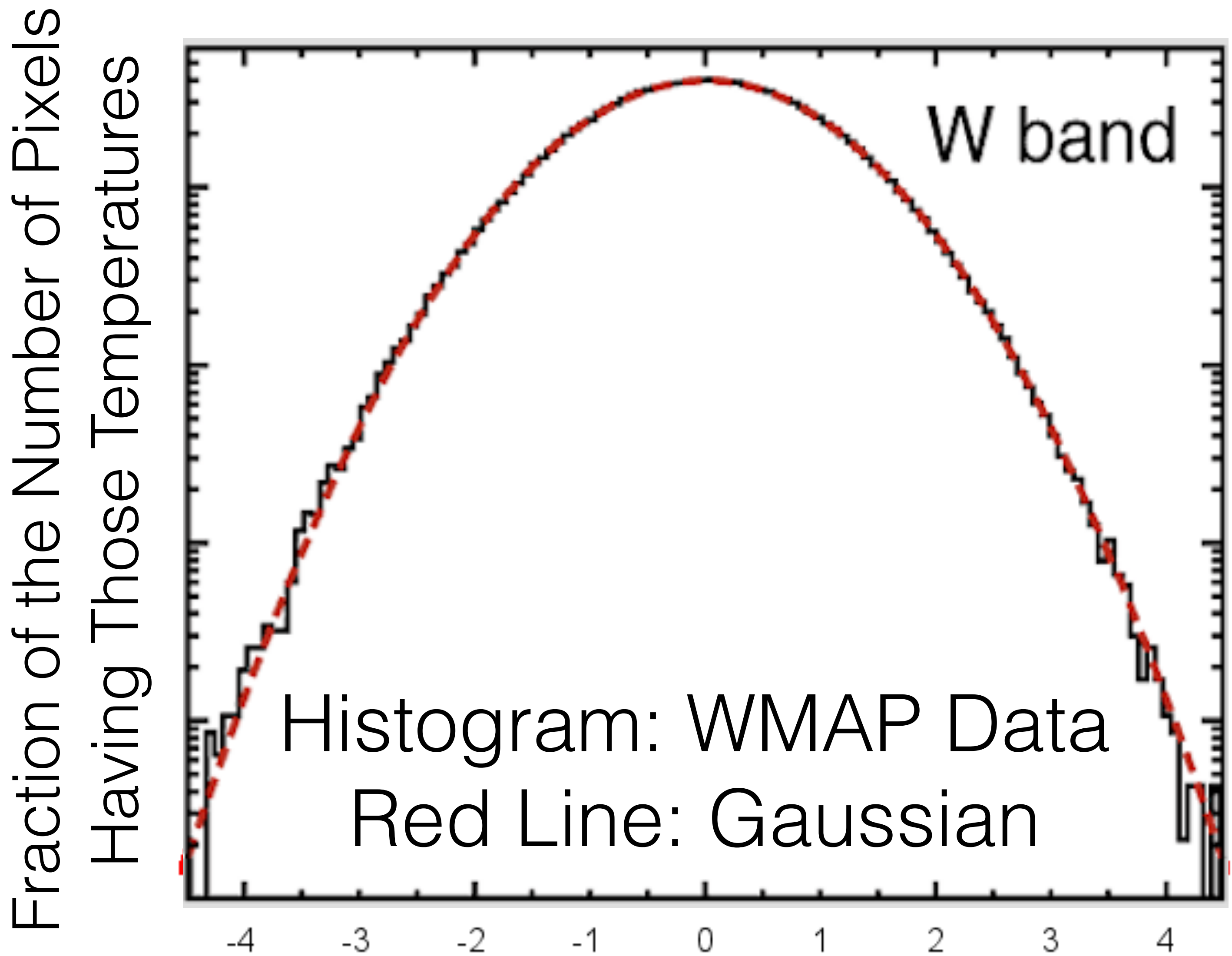
Quantum Fluctuations give a Gaussian distribution of temperatures.

Do we see this in the WMAP data?



W band
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]
Histogram: WMAP Data
Red Line: Gaussian
YES!!

Testing Gaussianity



[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 using temperatures at three different locations and average:

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

Non-Gaussianity:

A Powerful Test of Quantum Fluctuations

- 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%**
- With improved data provided by the Planck mission, the upper bound is now **0.03%**

CMB Research: Next Frontier

Primordial Gravitational Waves

Extraordinary claims require extraordinary evidence.
The same quantum fluctuations could also generate gravitational waves, and we wish to find them

Quantum fluctuations and gravitational waves

- Quantum fluctuations generated during inflation are proportional to the Hubble expansion rate during inflation, **H**

- Variance of gravitational waves is then proportional to **H²**:

$$\langle h_{ij} h^{ij} \rangle \propto H^2$$

Tensor-to-scalar Ratio

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

- We really want to find this quantity!
- **The upper bound from the temperature anisotropy data: r<0.1** [WMAP & Planck]

Energy Scale of Inflation

$$\langle h_{ij} h^{ij} \rangle \propto H^2$$

- Then, the Friedmann equation relates H^2 to the energy density (or potential) of a scalar field driving inflation:

$$H^2 = \frac{V(\phi)}{3M_{\rm pl}^2}$$

- For example r=0.2 implies

$$V^{1/4} = 2 \times 10^{16} \left(\frac{r}{0.2} \right)^{1/4} \ \mathrm{GeV}$$

Has Inflation Occurred?

- We must see [near] scale invariance of the gravitational wave power spectrum:

$$\langle h_{ij}(\mathbf{k}) h^{ij,*}(\mathbf{k}) \rangle \propto k^{n_t}$$

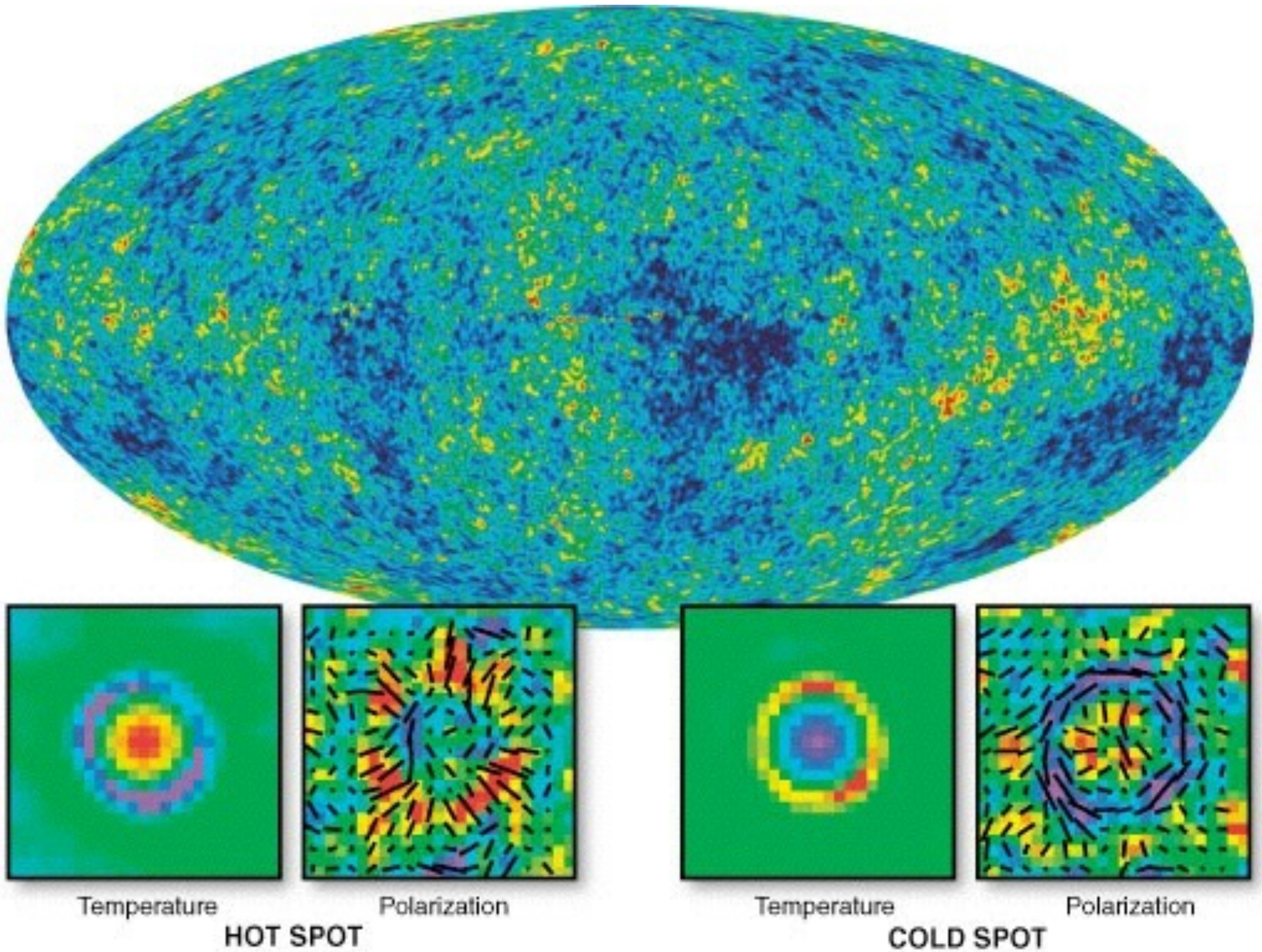
with

$$n_t = \mathcal{O}(10^{-2})$$

Inflation, defined

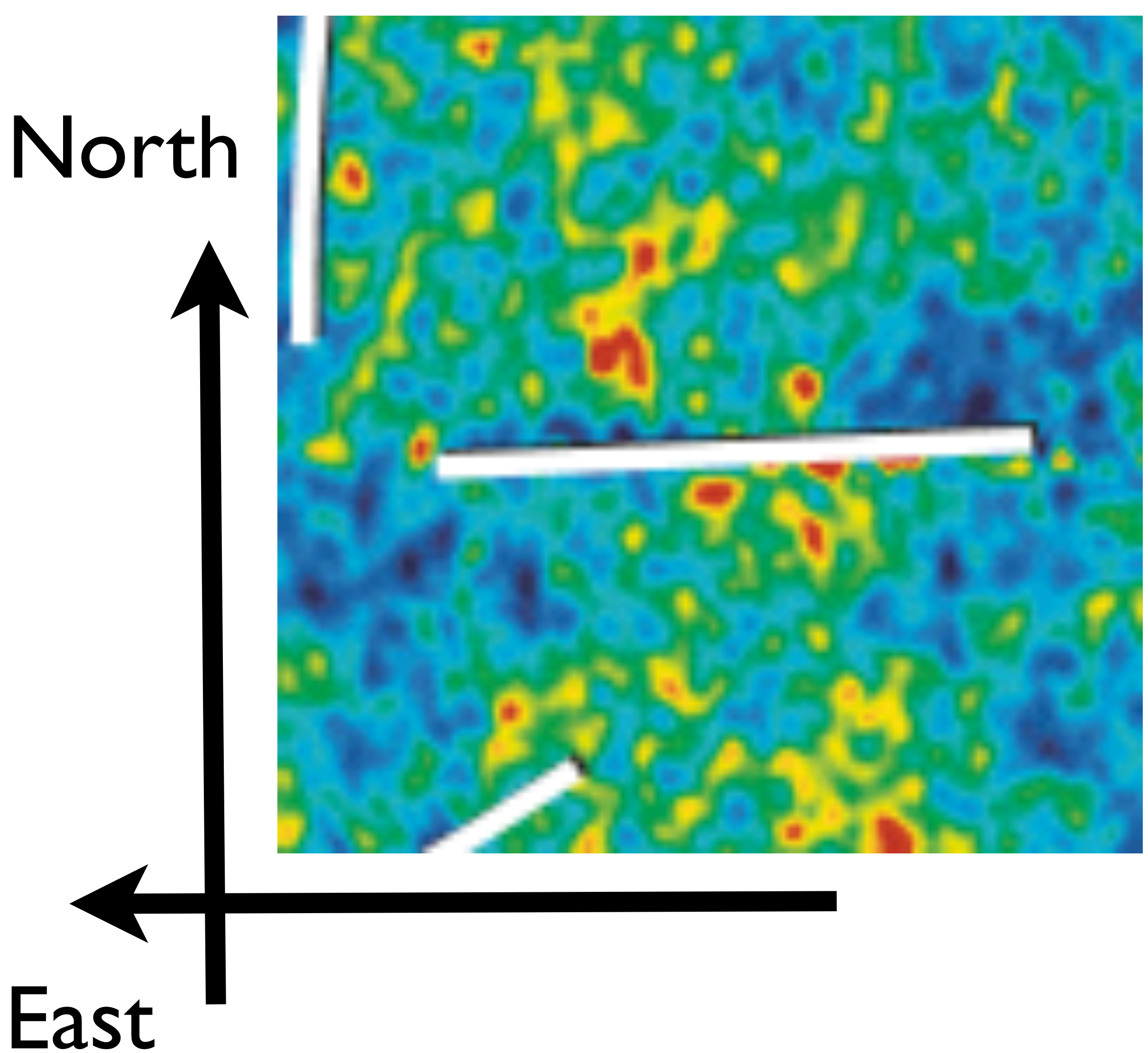
- Necessary and sufficient condition for inflation = sustained accelerated expansion in the early universe
- Expansion rate: $H=(da/dt)/a$
- Accelerated expansion: $(d^2a/dt^2)/a = dH/dt + H^2 > 0$
- Thus, **$-(dH/dt)/H^2 < 1$**
- In other words:
    - The rate of change of H must be slow [$n_t \sim 0$]
    - [and H usually decreases slowly, giving $n_t < 0$]

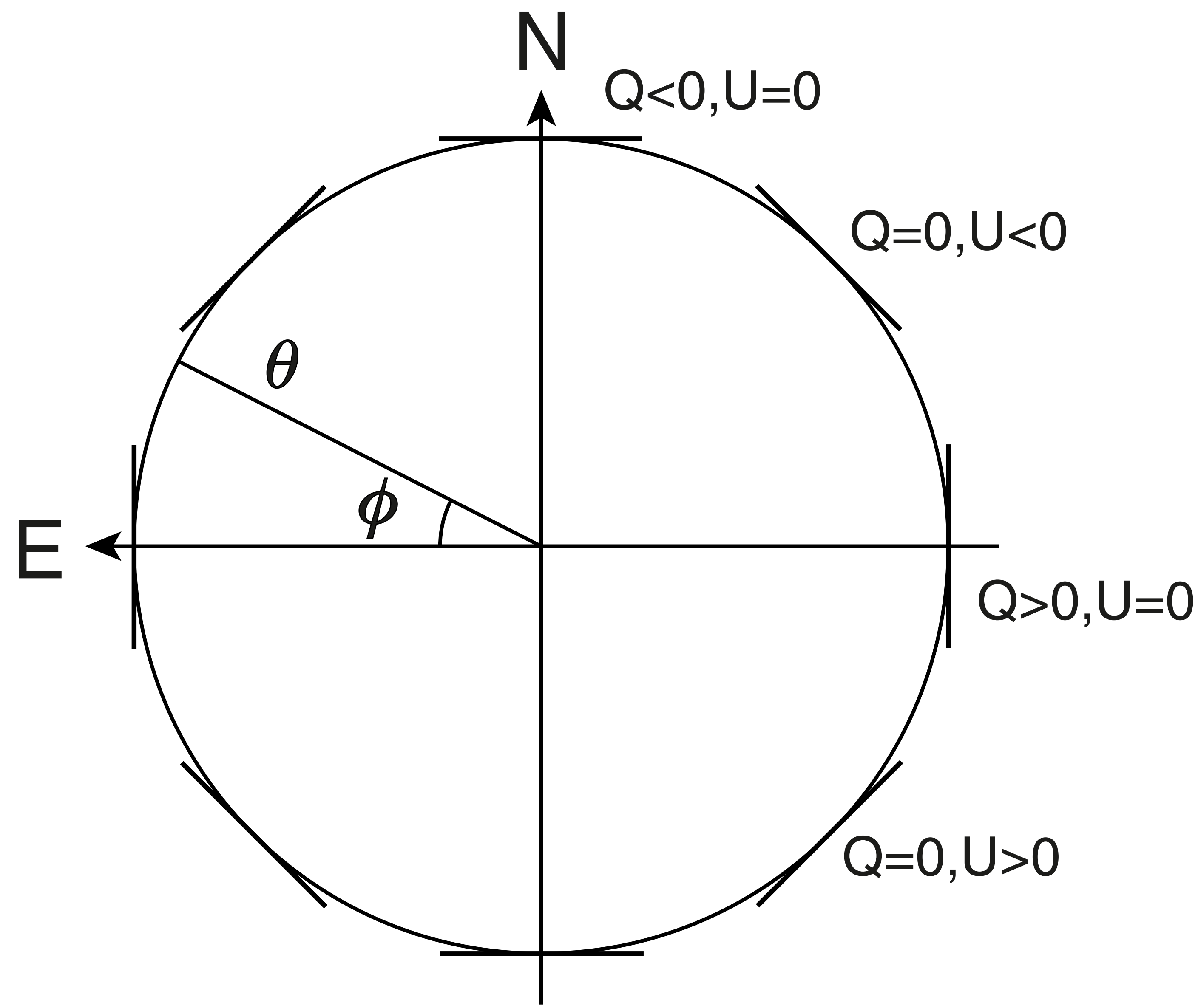
CMB Polarisation



- CMB is [weakly] polarised!

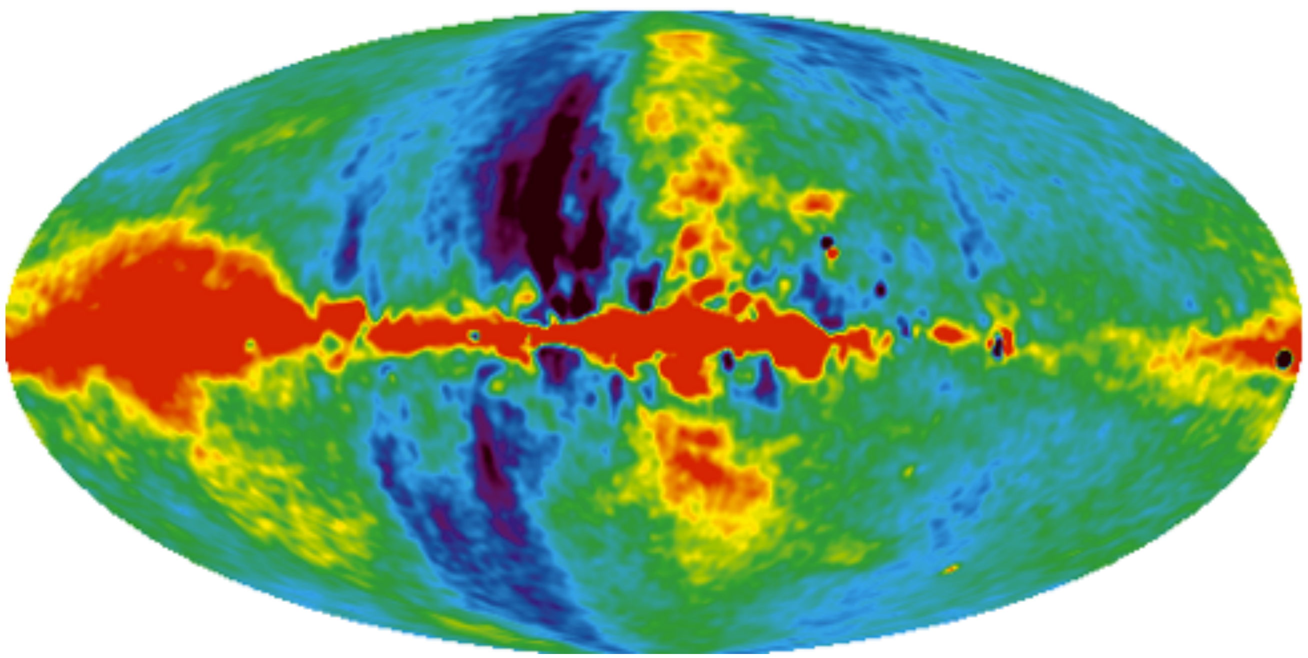
Stokes Parameters



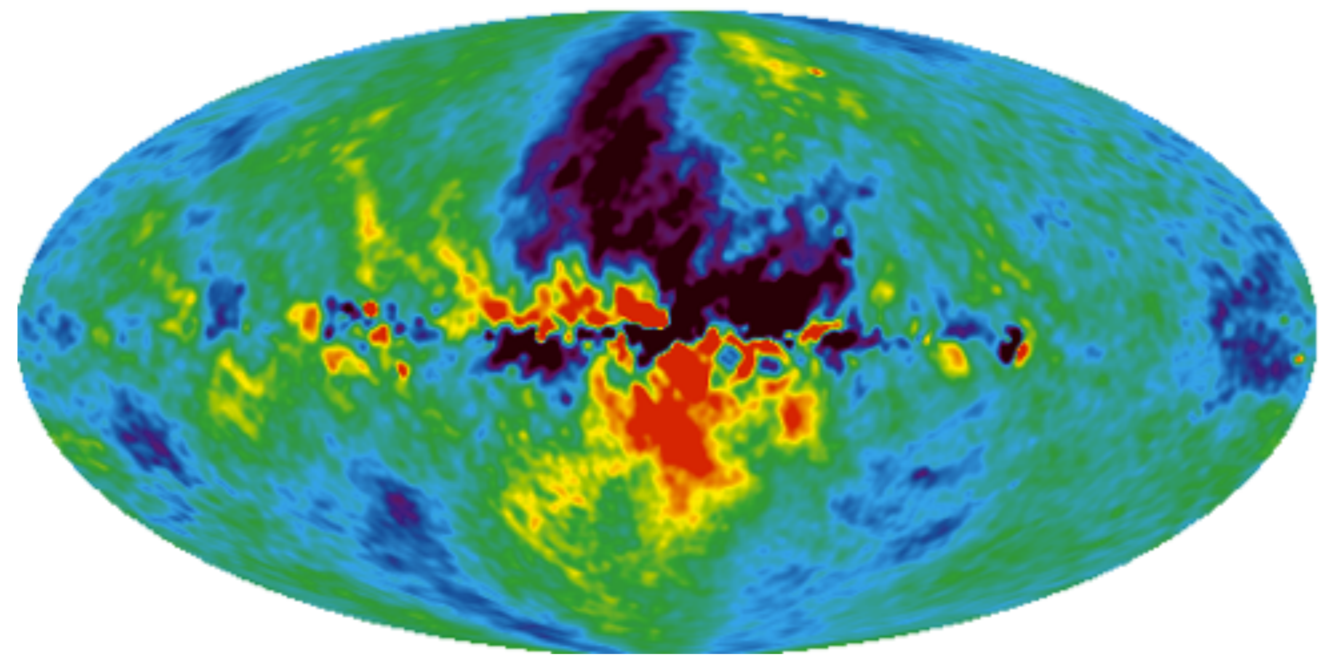


WMAP Collaboration

23 GHz



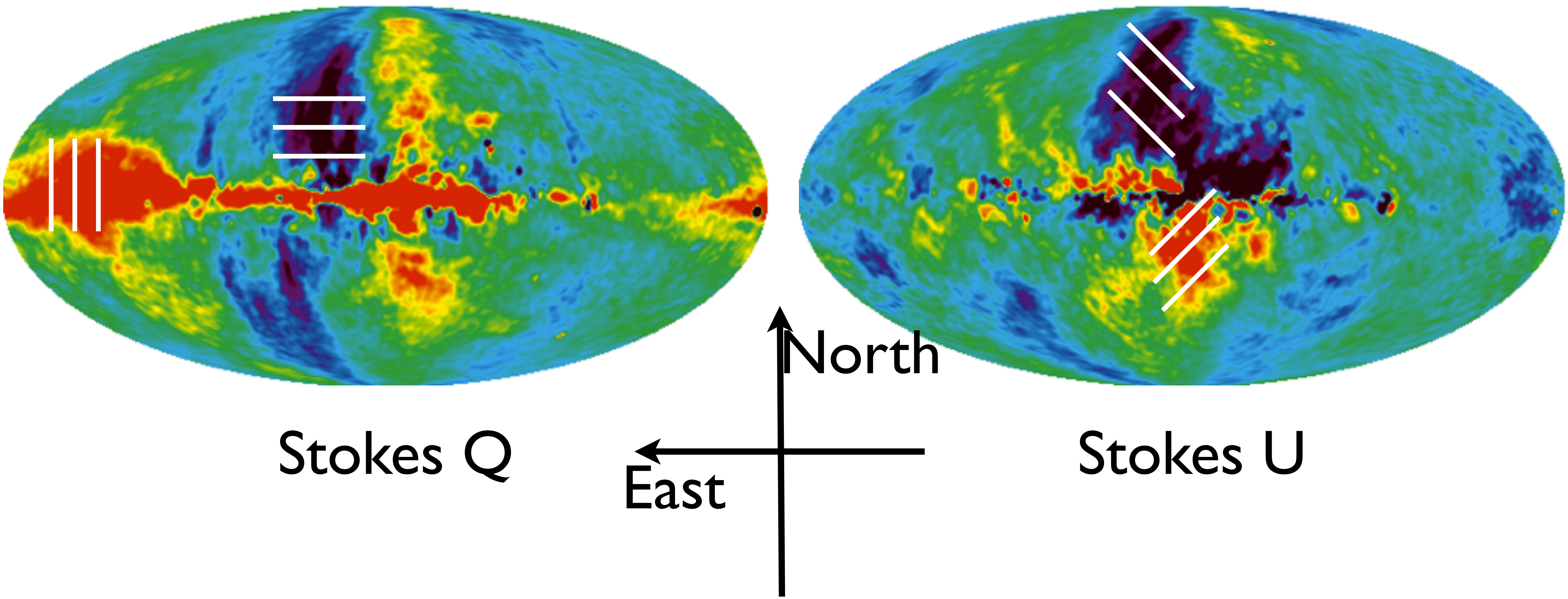
Stokes Q



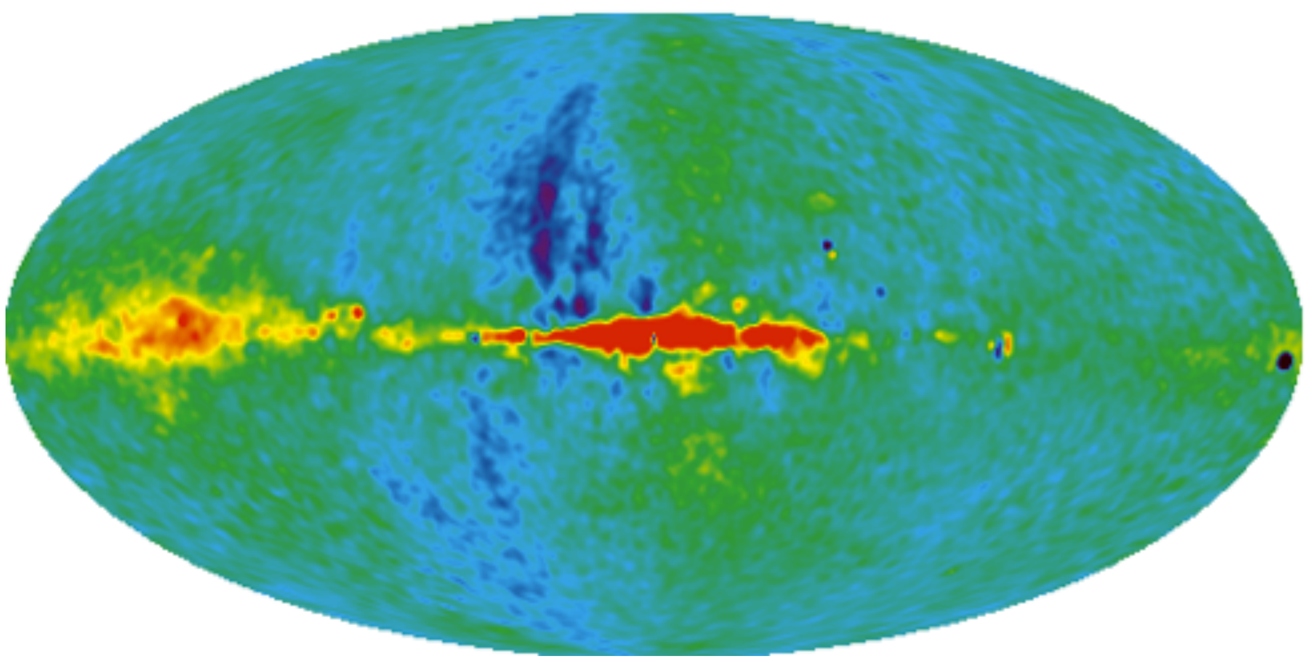
Stokes U

WMAP Collaboration

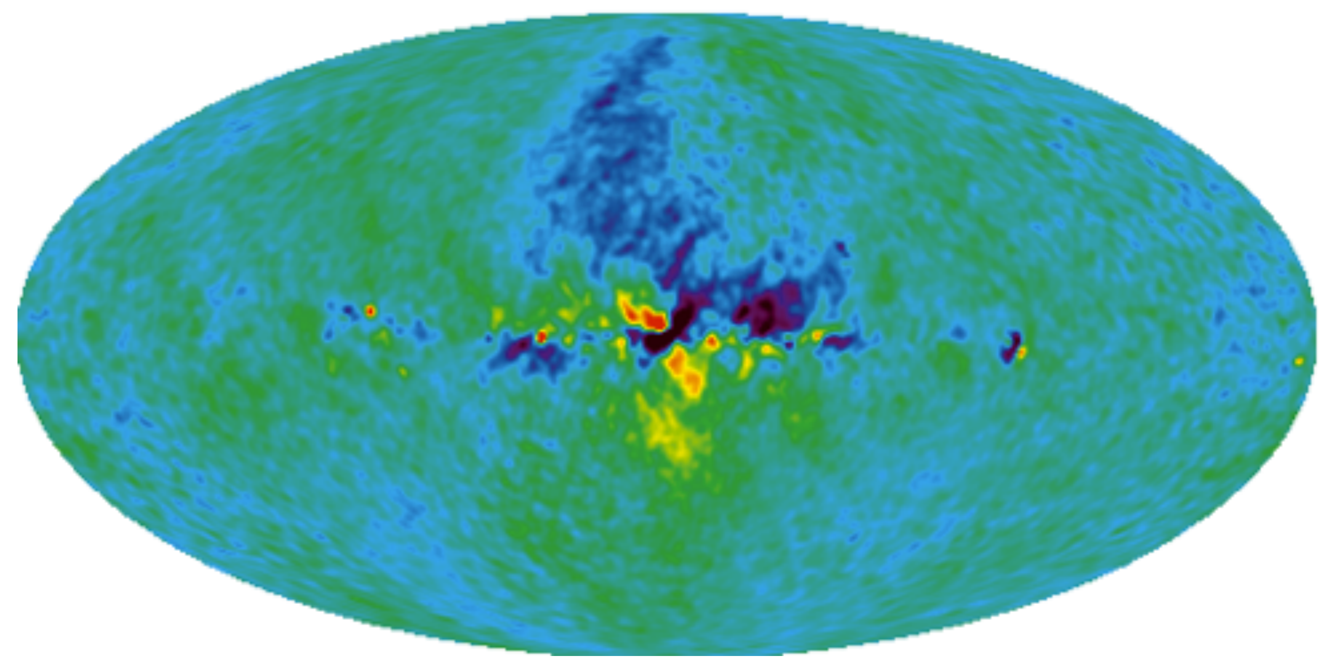
23 GHz



33 GHz



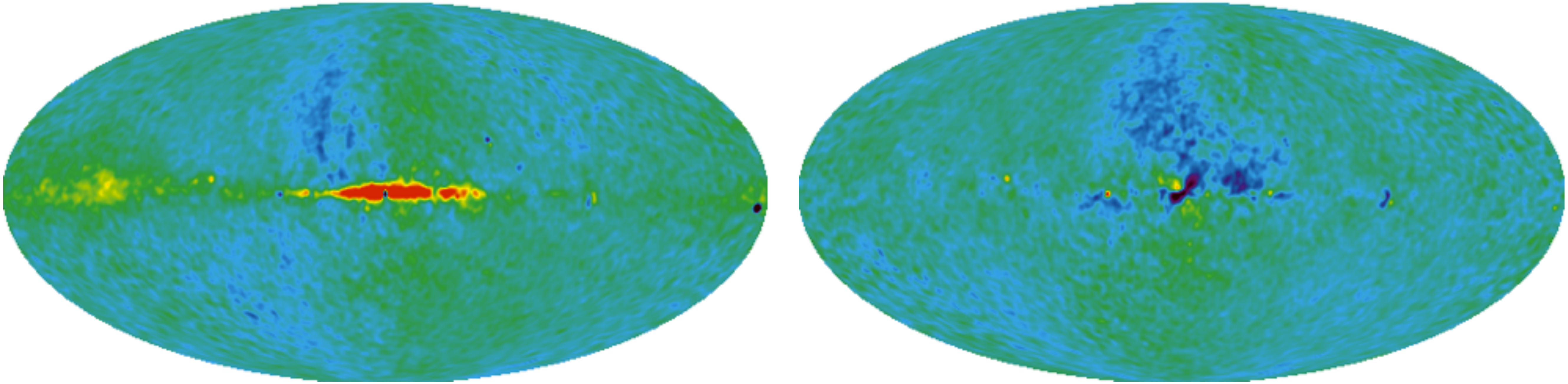
Stokes Q



Stokes U

WMAP Collaboration

41 GHz

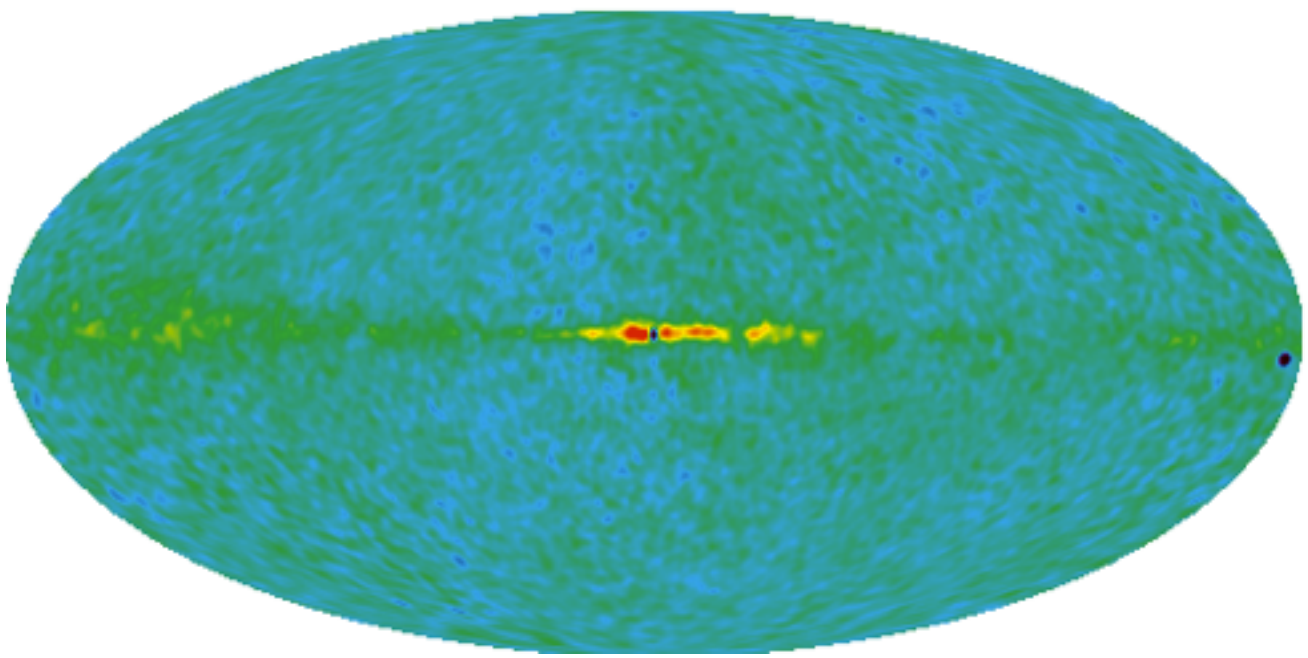


Stokes Q

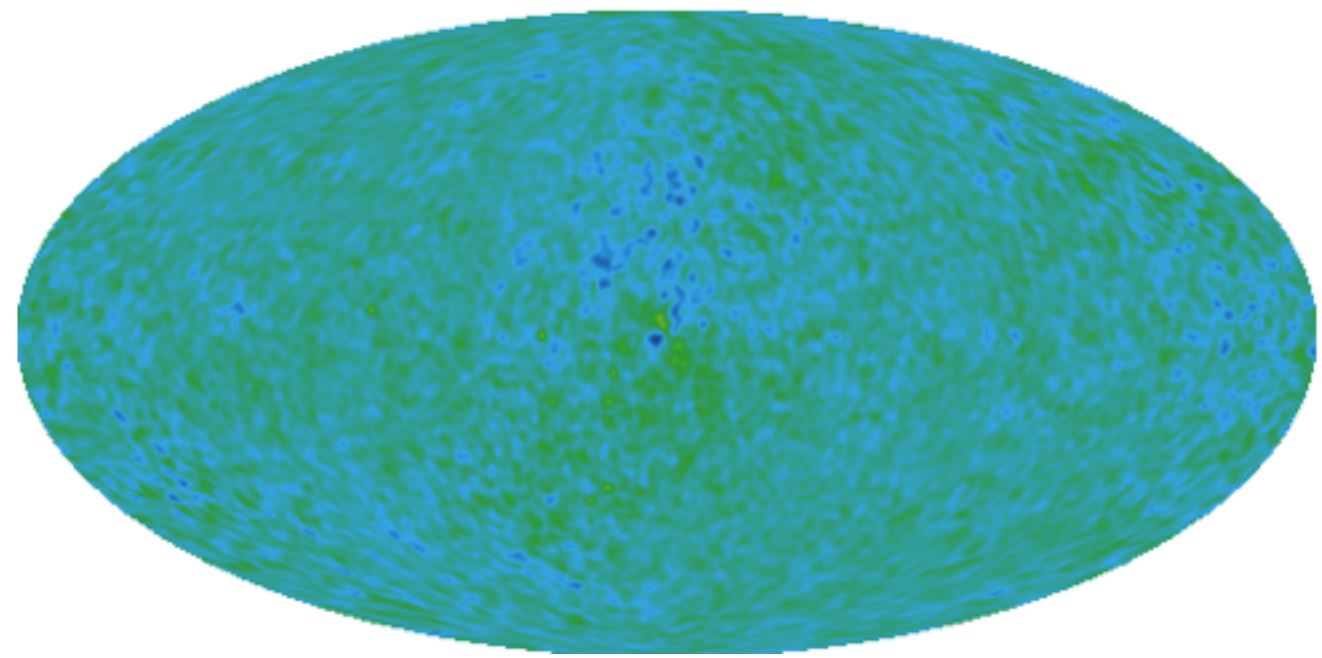
Stokes U

WMAP Collaboration

61 GHz



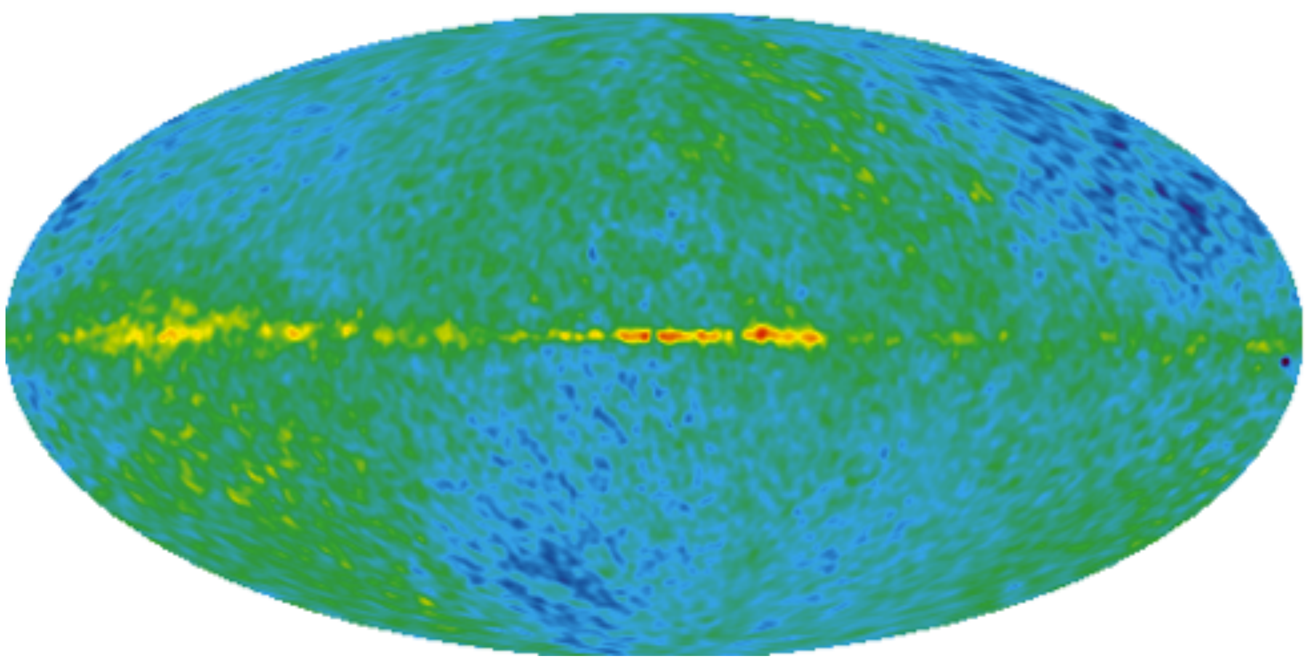
Stokes Q



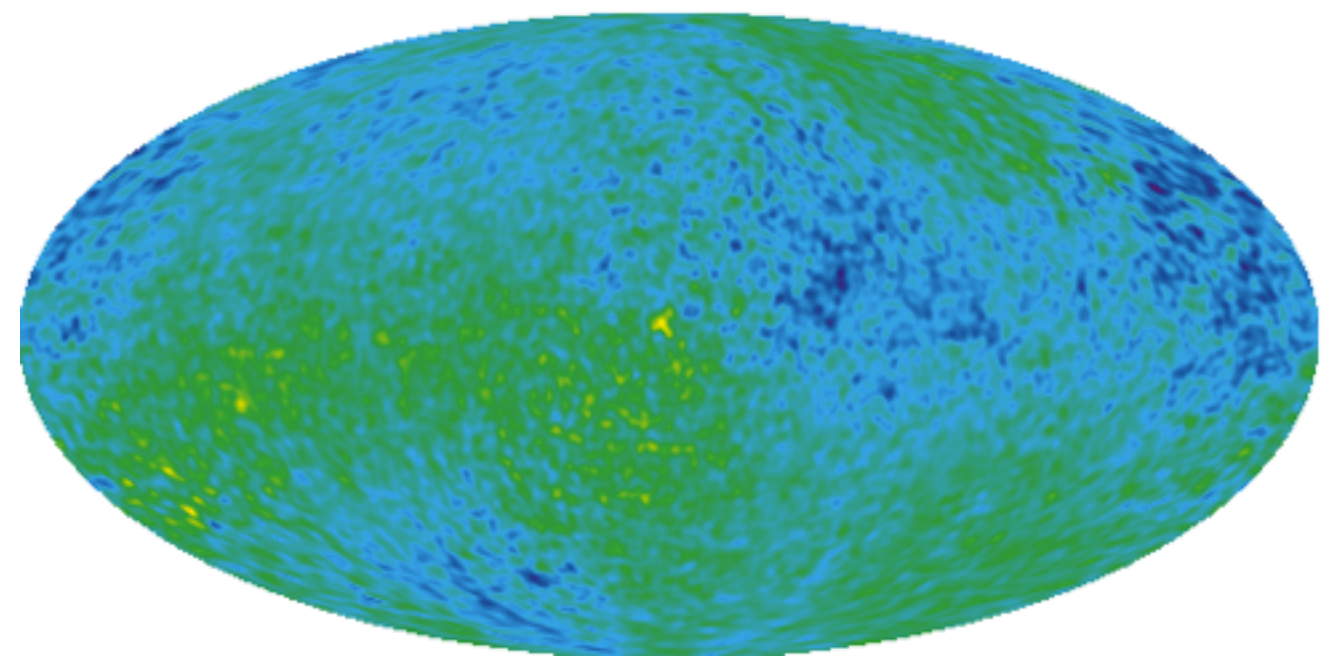
Stokes U

WMAP Collaboration

94 GHz



Stokes Q



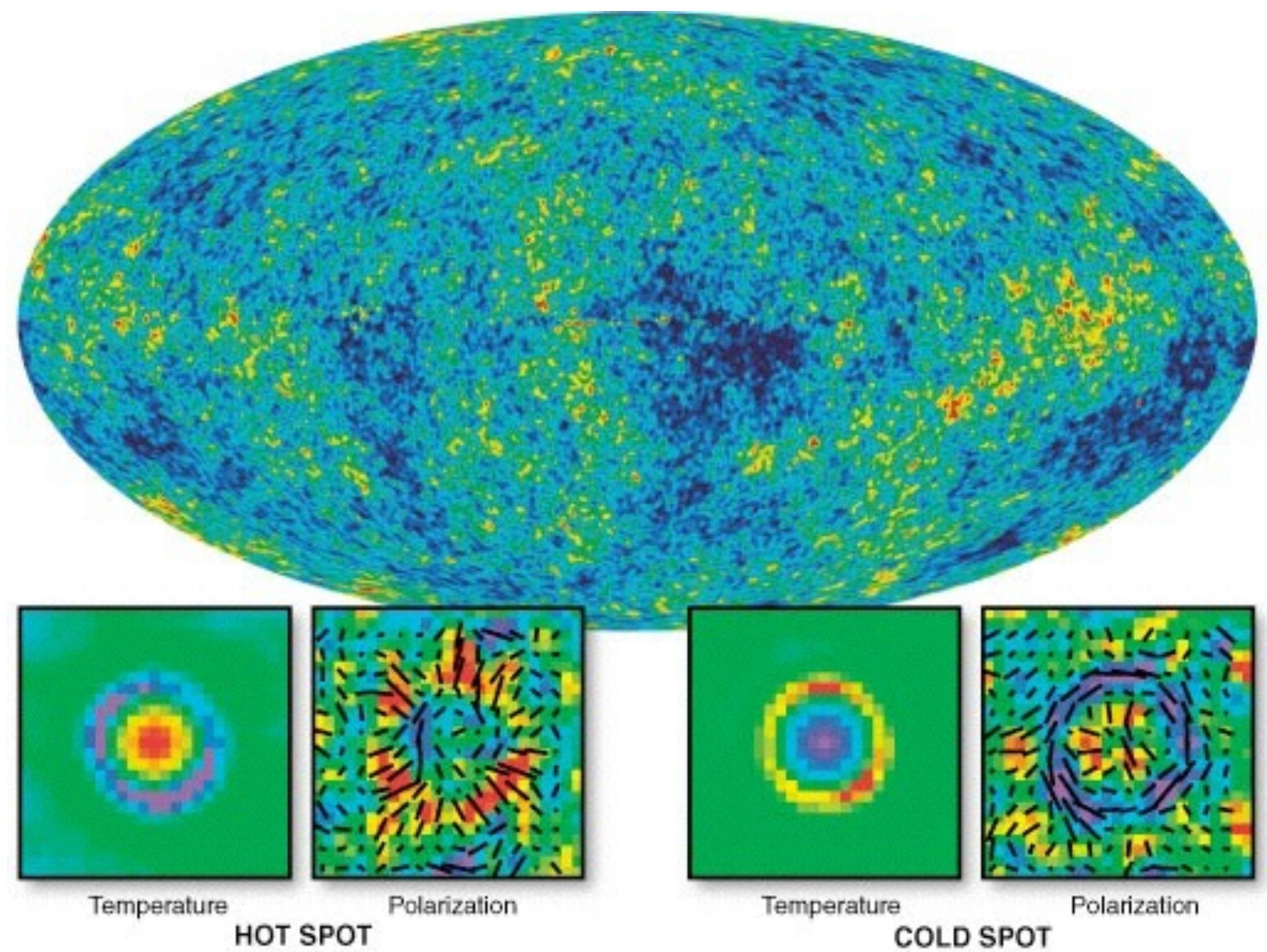
Stokes U

How many components?

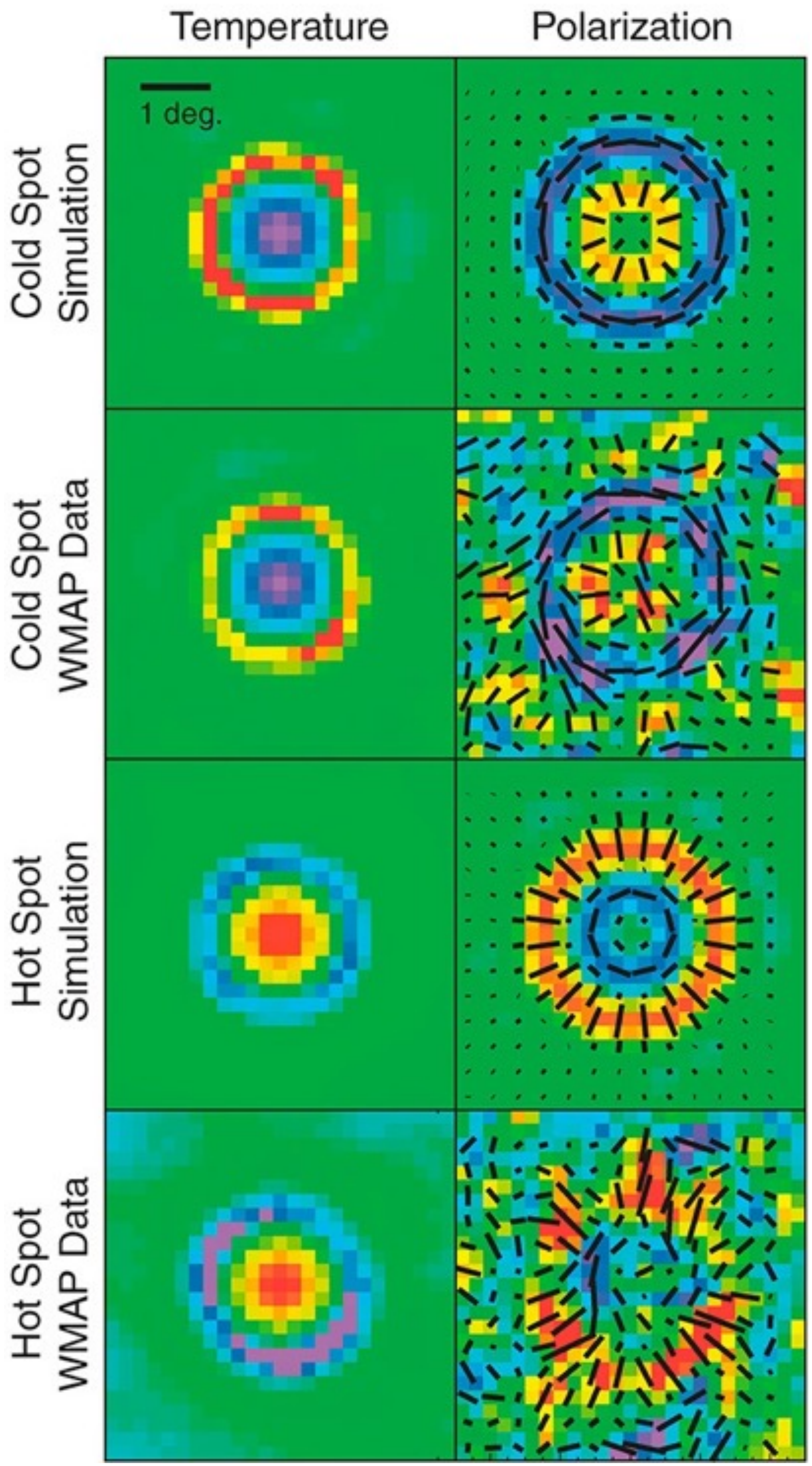
- CMB: $T_\nu \sim \nu^0$
- Synchrotron: $T_\nu \sim \nu^{-3}$
- Dust: $T_\nu \sim \nu^2$
- Therefore, we need **at least** 3 frequencies to separate them

Seeing polarisation in the WMAP data

- Average polarisation data around cold and hot temperature spots
- Outside of the Galaxy mask [not shown], there are 11536 hot spots and 11752 cold spots
- Averaging them beats the noise down



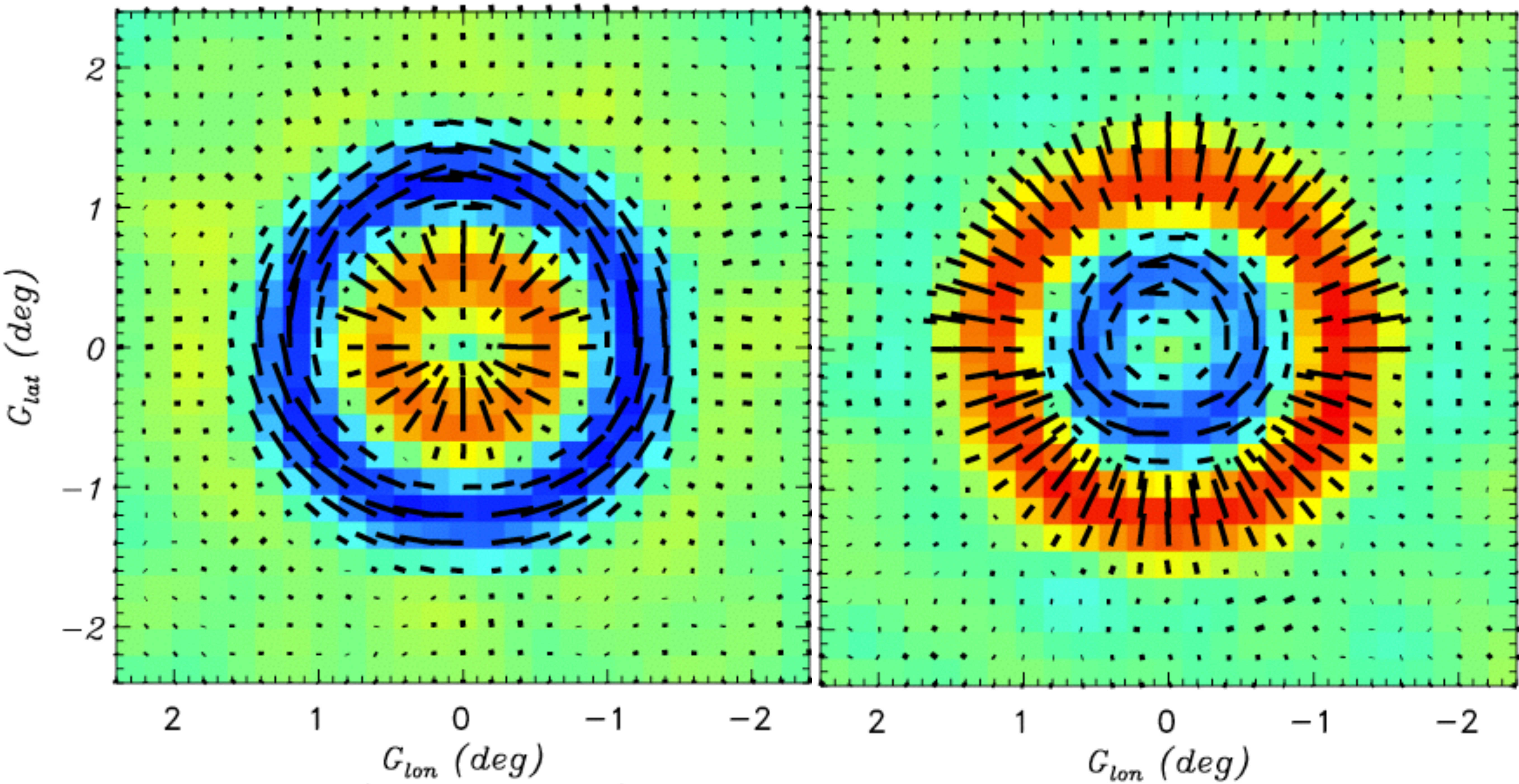
WMAP Collaboration



Radial and tangential polarisation around temperature spots

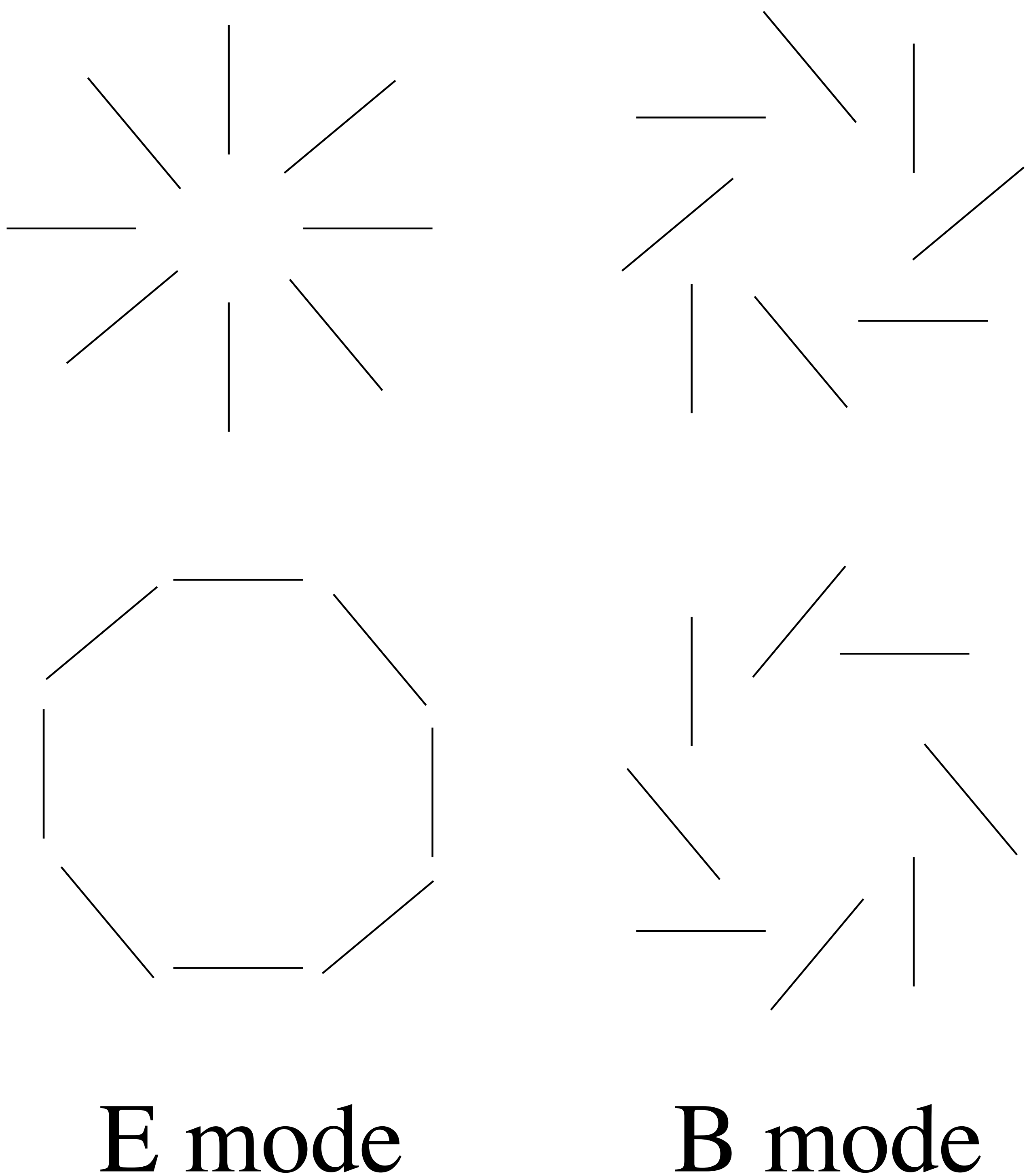
- This shows polarisation generated by the plasma flowing into gravitational potentials
- Signatures of the "scalar mode" fluctuations in polarisation
- These patterns are called "**E modes**"

Planck Data!



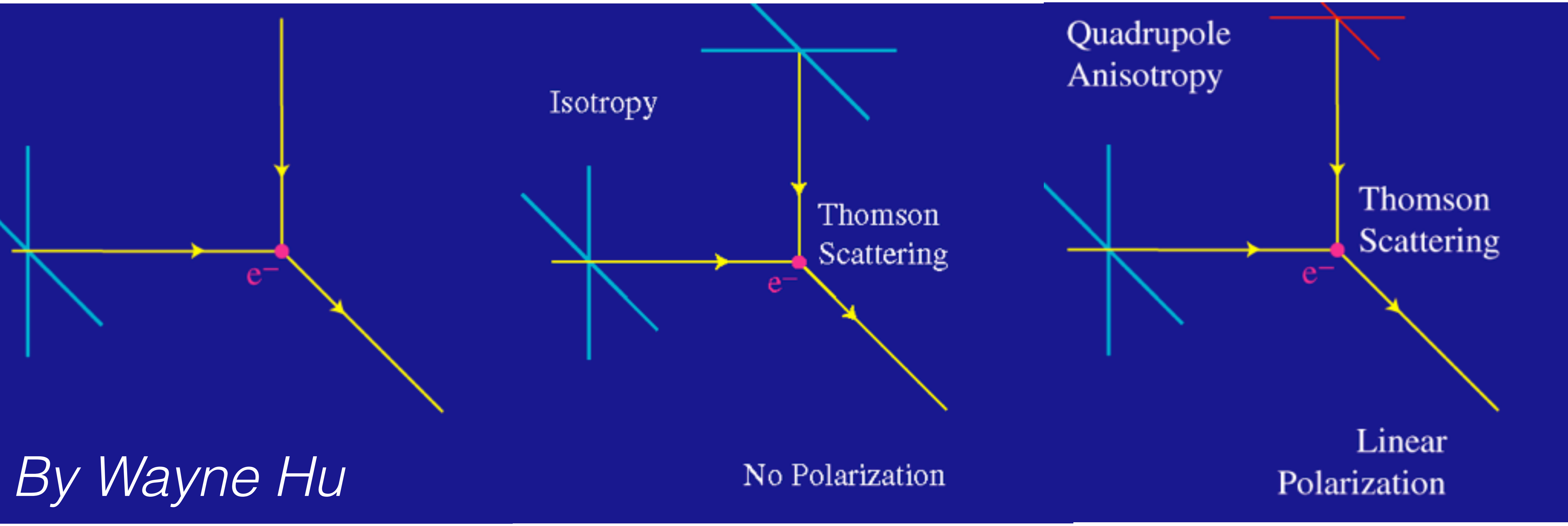
Q_r (cold spots) Q_r (hot spots)

E and B modes



- Density fluctuations [scalar modes] can only generate E modes
- Gravitational waves can generate both E and B modes

Physics of CMB Polarisation

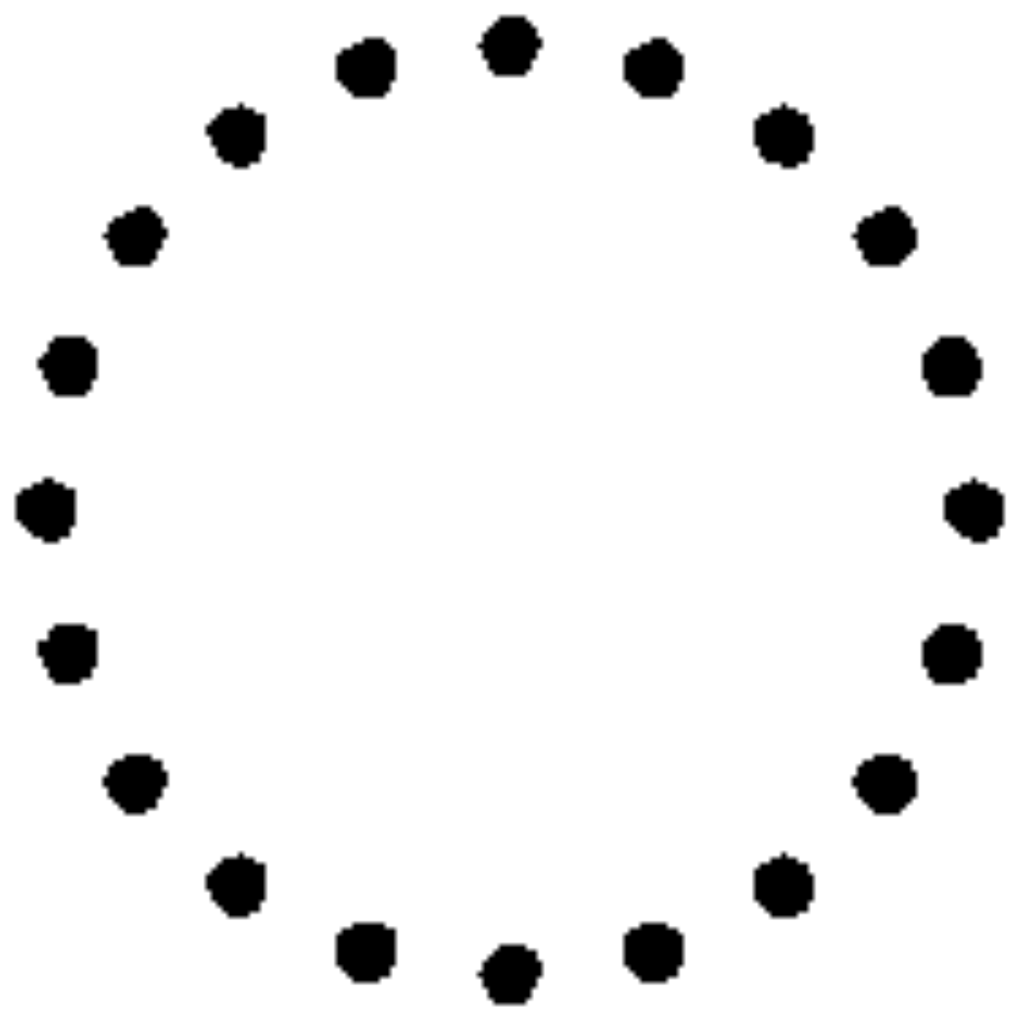


- Necessary and sufficient conditions for generating polarisation in CMB:
  - Thomson scattering
  - Quadrupolar temperature anisotropy around an electron

Origin of Quadrupole

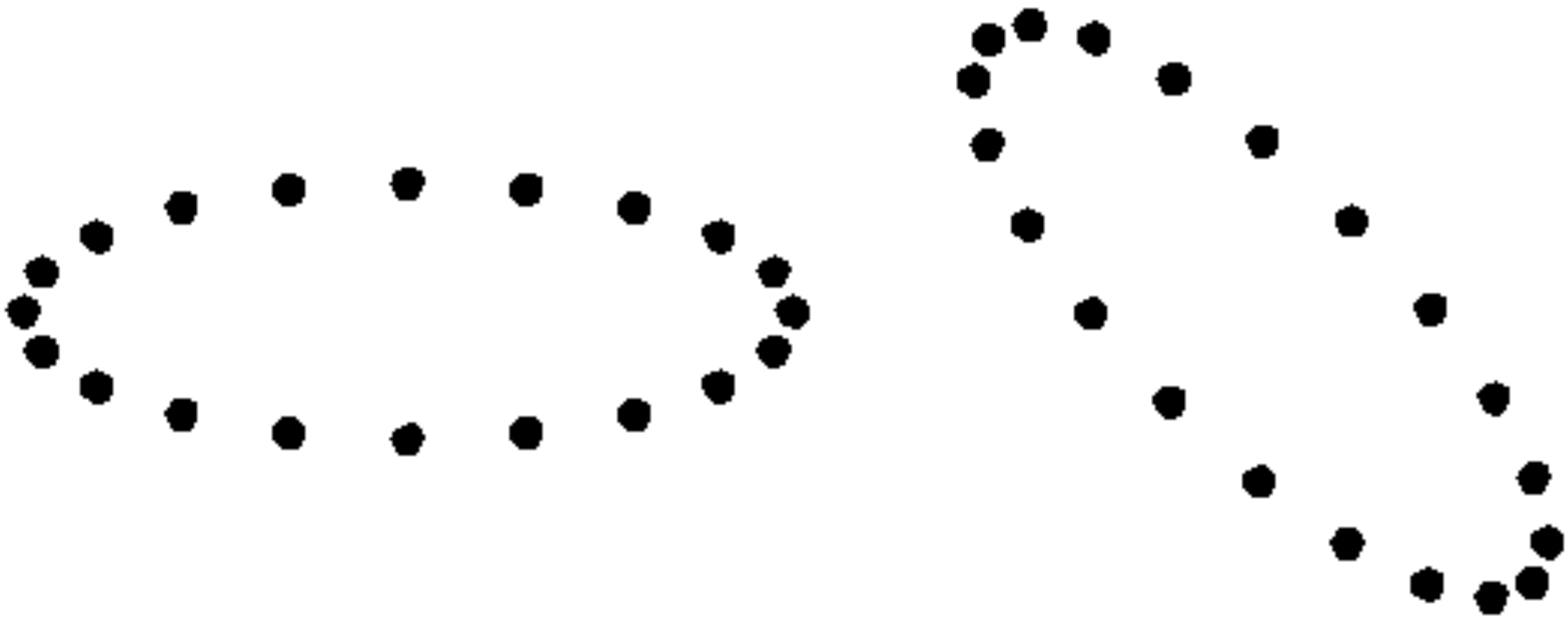
- **Scalar perturbations**: motion of electrons with respect to photons
- **Tensor perturbations**: gravitational waves

Gravitational waves are coming toward you!



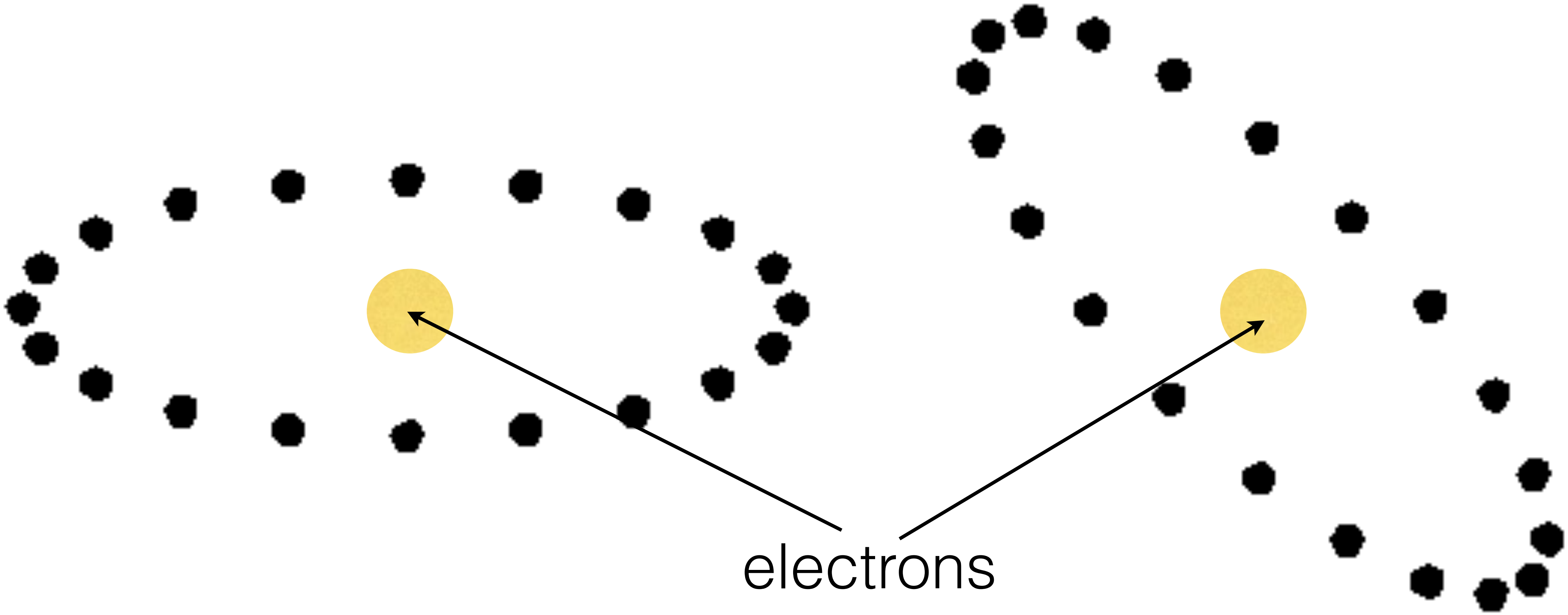
- What do they do to the distance between particles?

Two GW modes

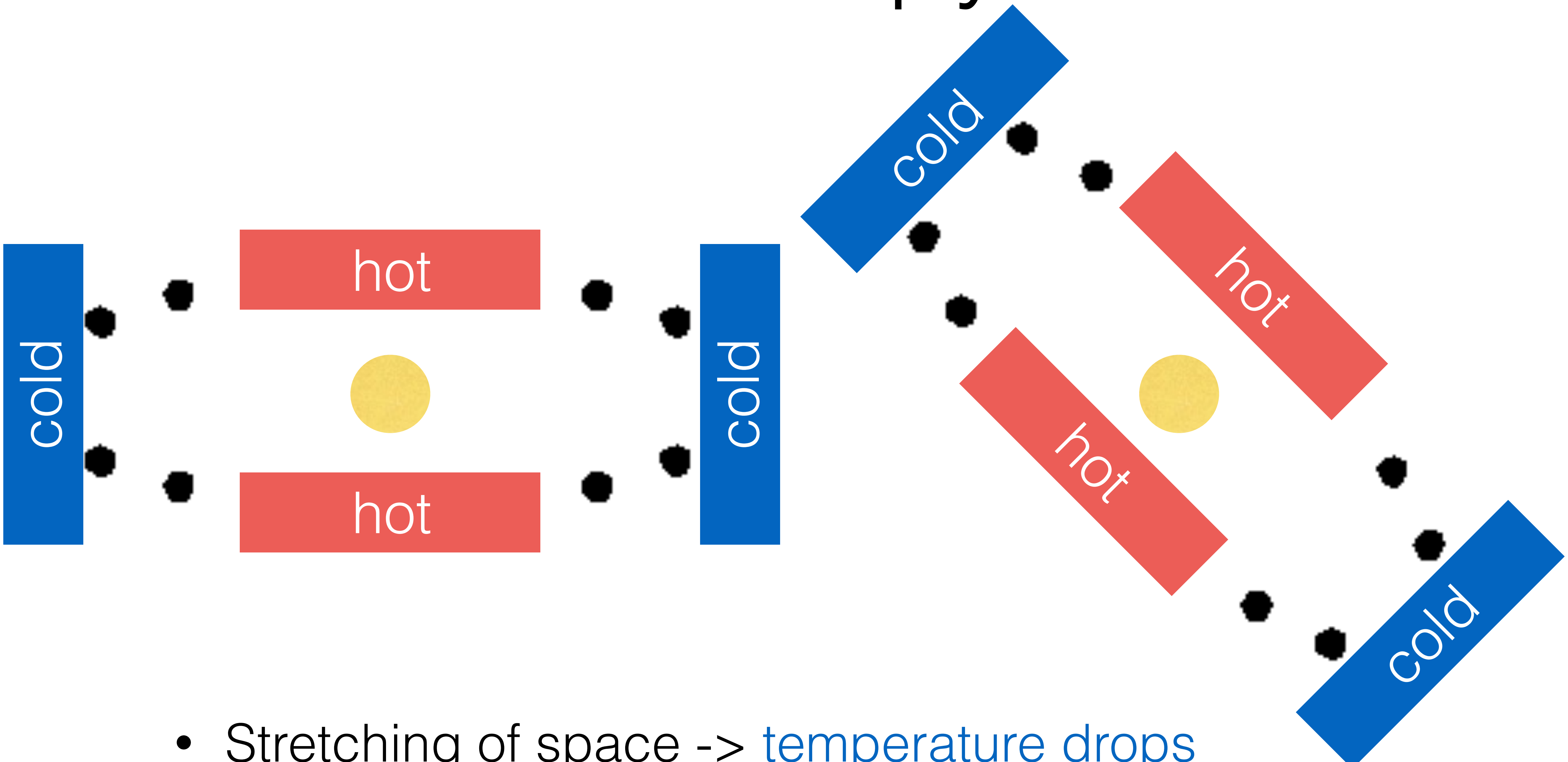


- Anisotropic stretching of space generates quadrupole temperature anisotropy. How?

GW to temperature anisotropy

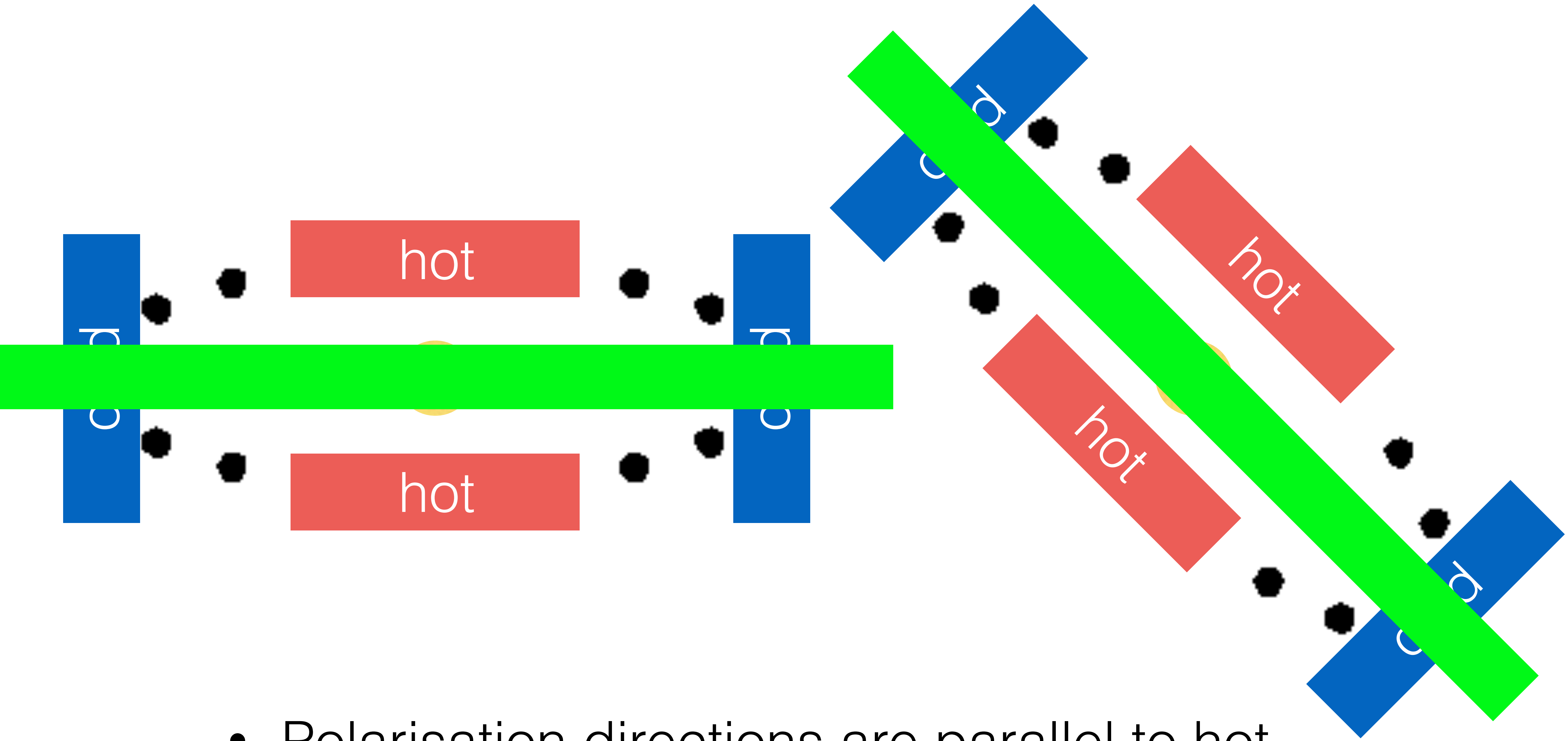


GW to temperature anisotropy

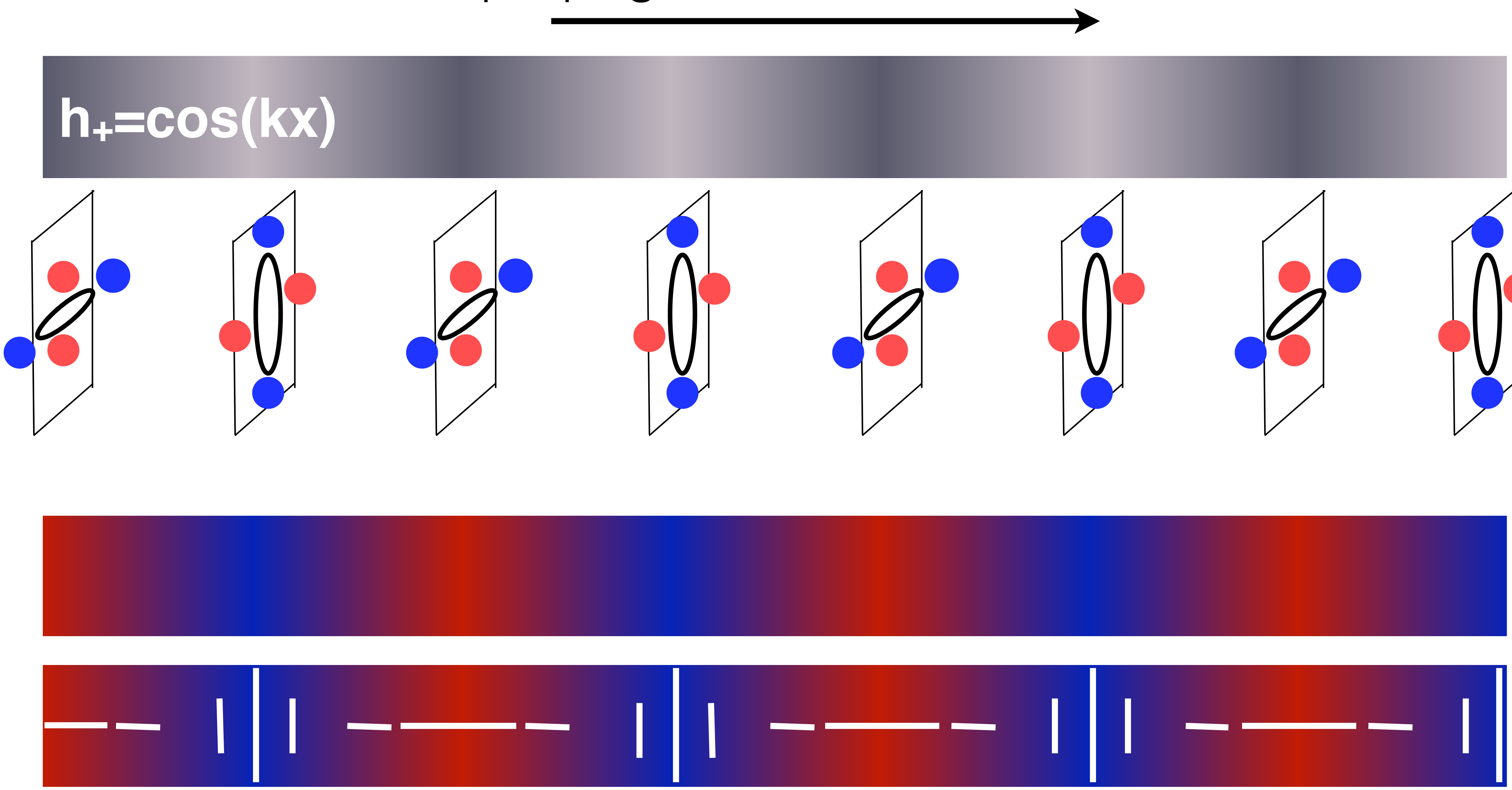


- Stretching of space -> temperature drops
- Contraction of space -> temperature rises

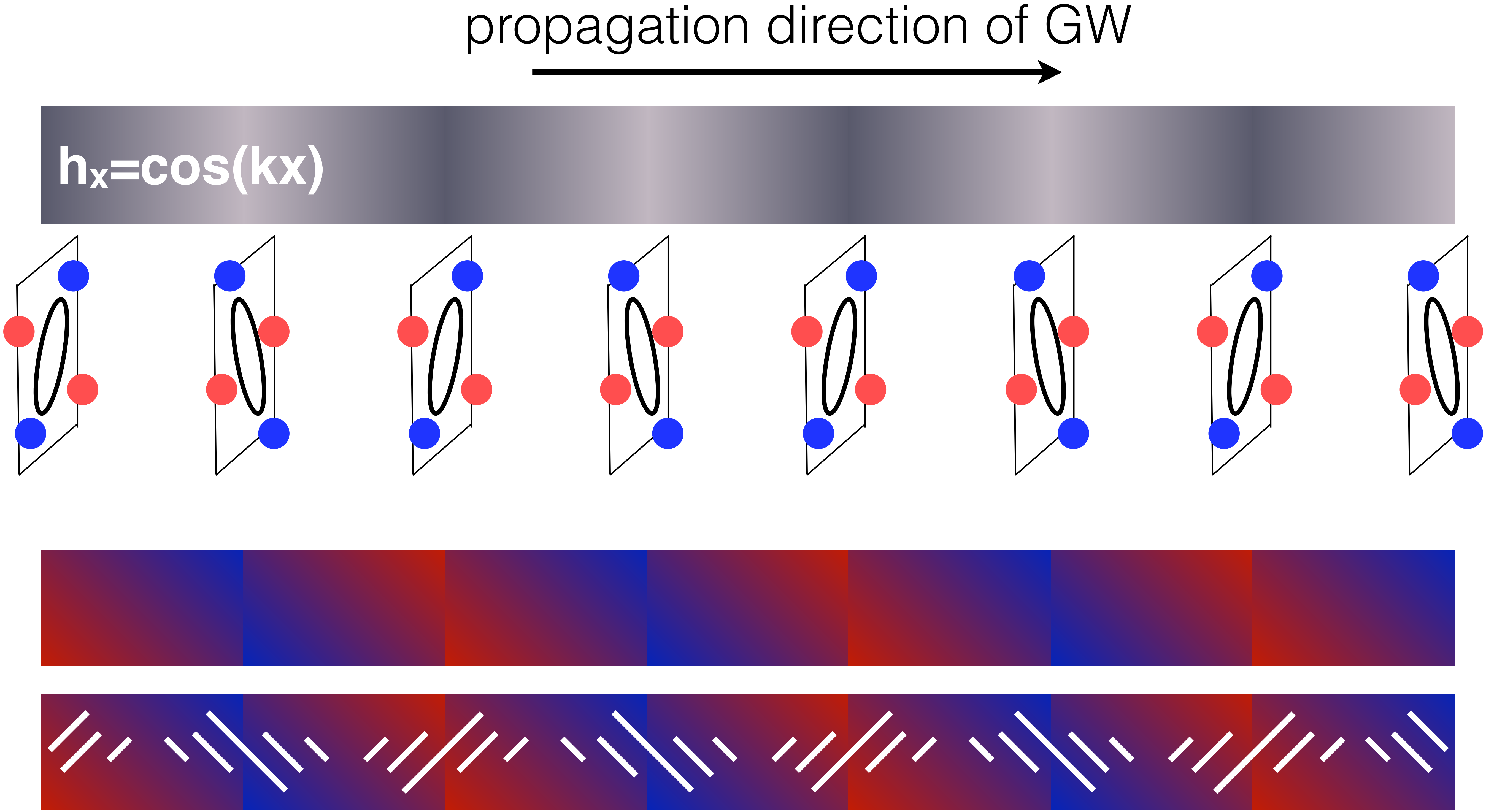
Then to polarisation!



- Polarisation directions are parallel to hot regions propagation direction of GW



Polarisation directions perpendicular/parallel to the wavenumber vector -> **E mode polarisation**



Polarisation directions 45 degrees tilted from to the wavenumber vector -> **B mode polarisation**

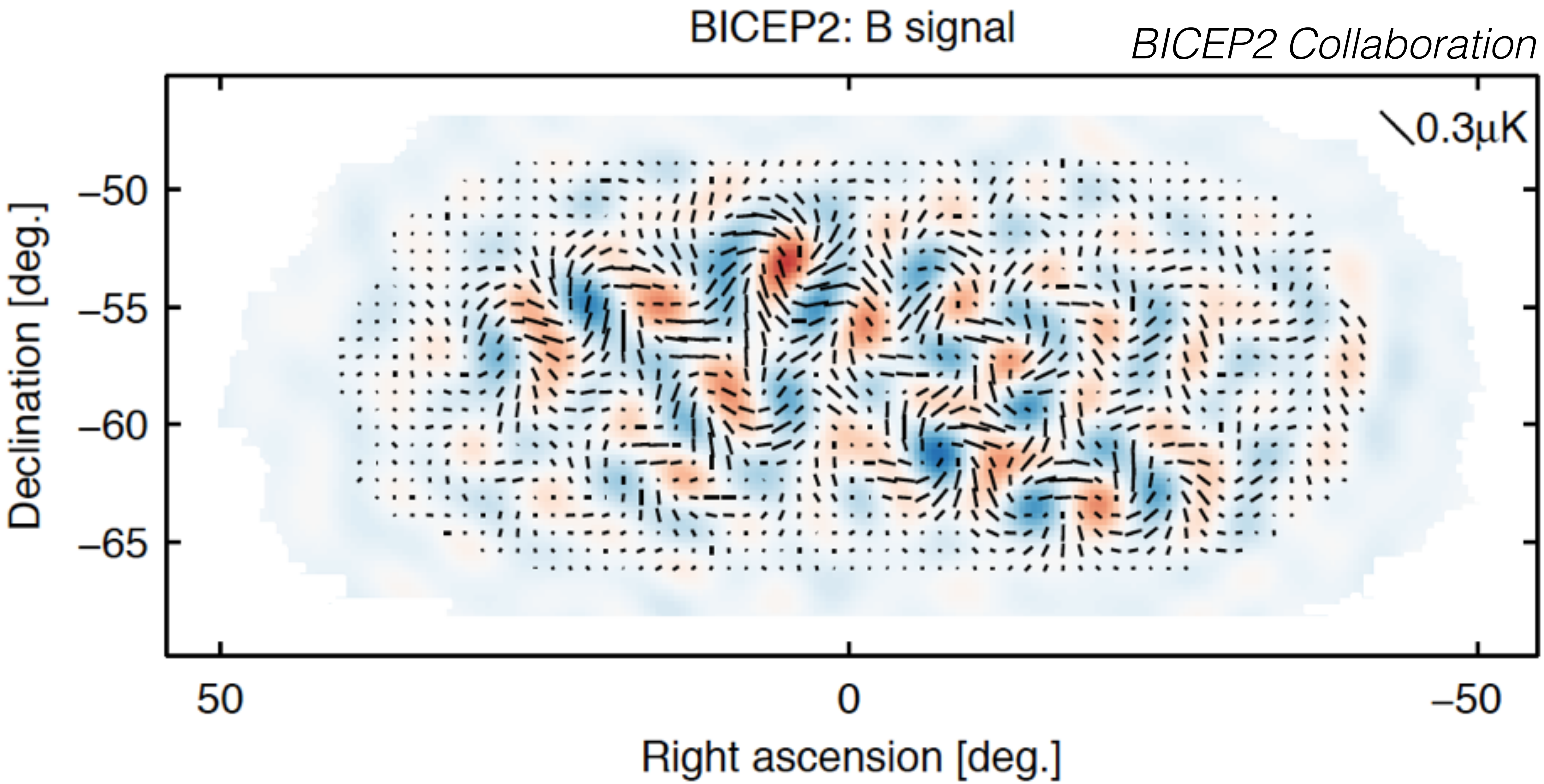
Important note:

- Definition of h_+ and $h_\times$ depends on coordinates, but definition of E- and B-mode polarisation does not depend on coordinates

- Therefore, h_+ does not always give E; $h_\times$ does not always give B

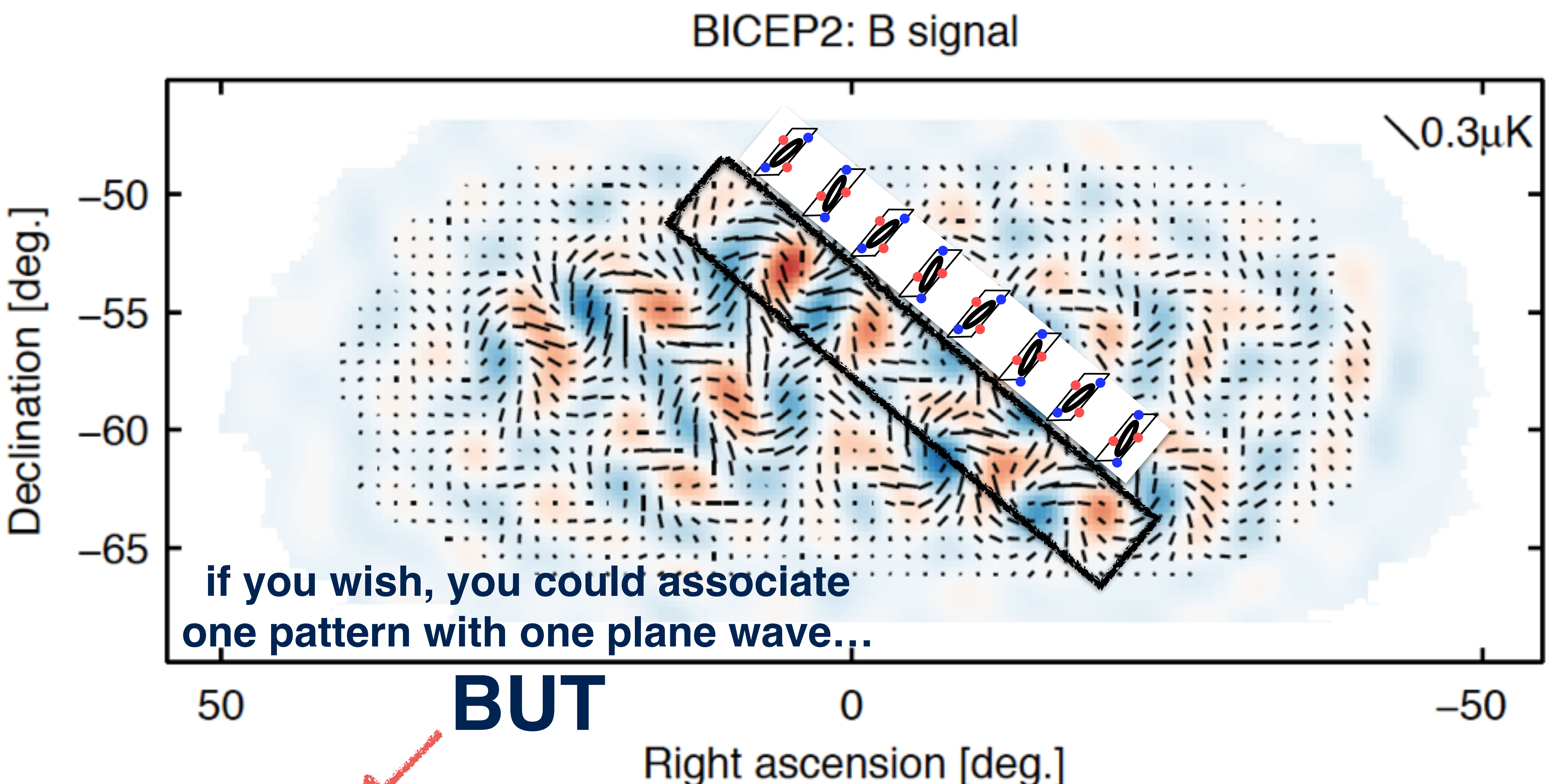
  - The important point is that **h_+ and $h_\times$ always coexist**. When a linear combination of h_+ and $h_\times$ produces E, another combination produces B

Signature of gravitational waves in the sky [?]



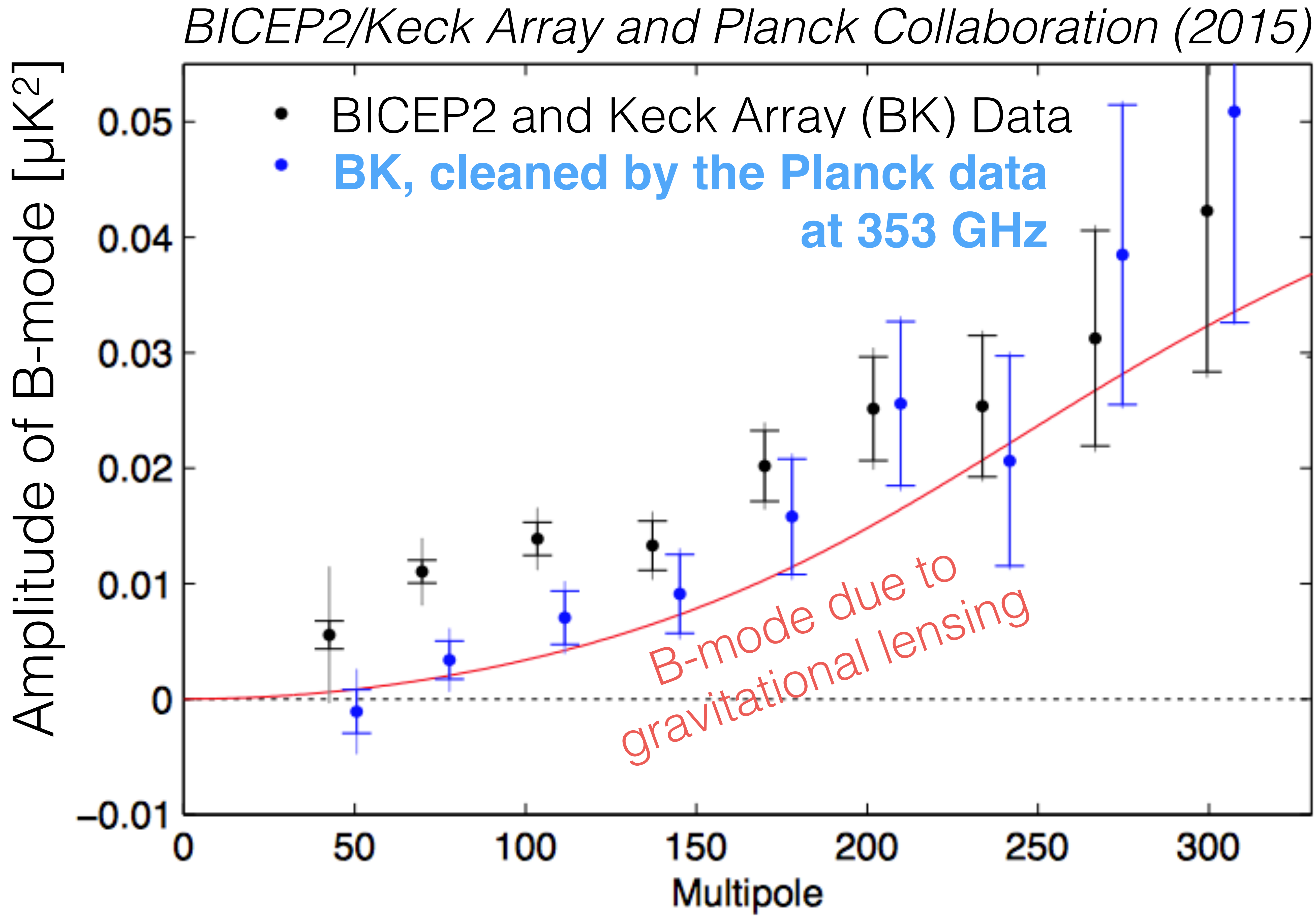
<u>CAUTION</u>: we are NOT seeing a single plane wave propagating perpendicular to our line of sight

Signature of gravitational waves in the sky [?]

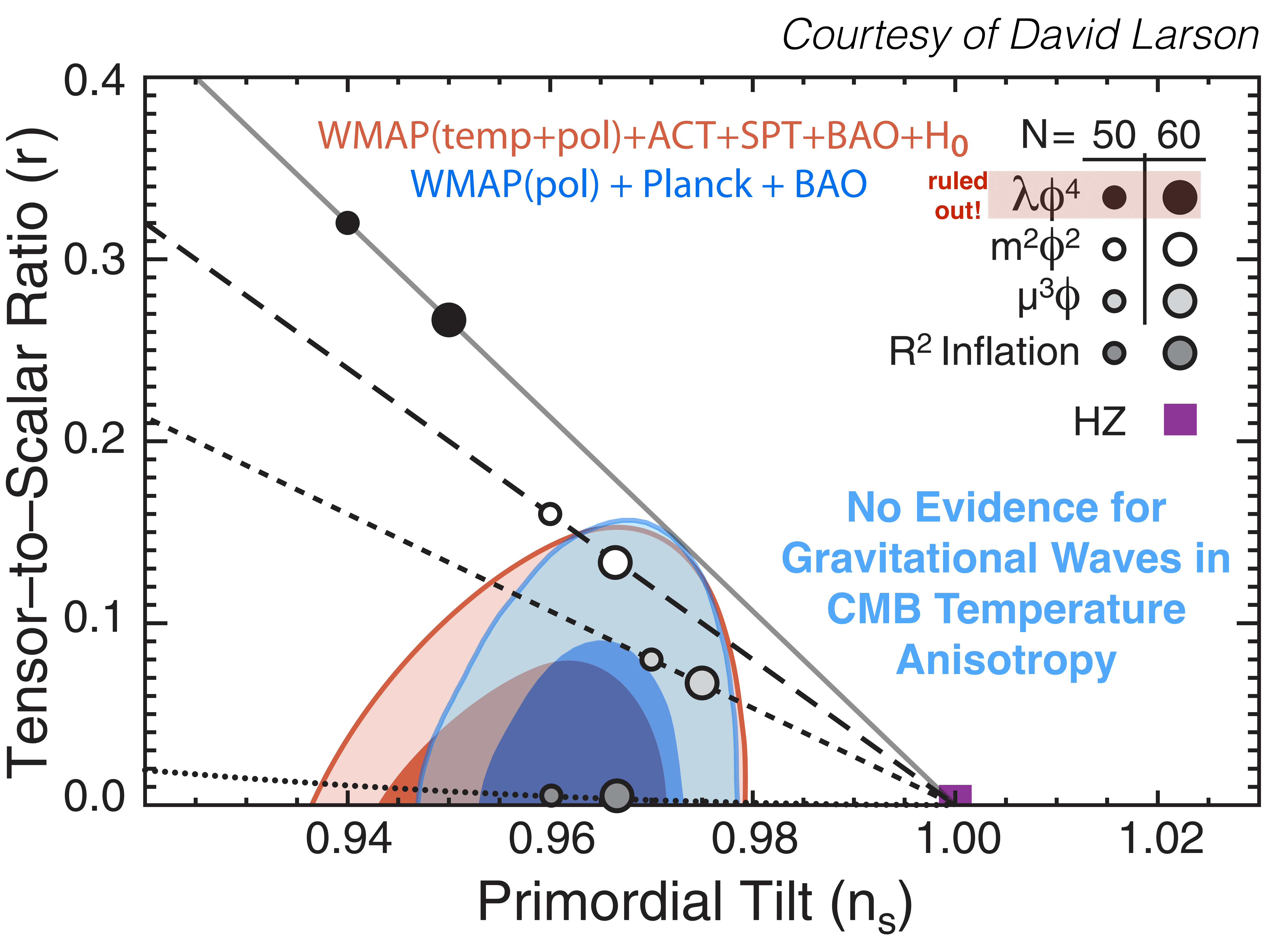


BUT

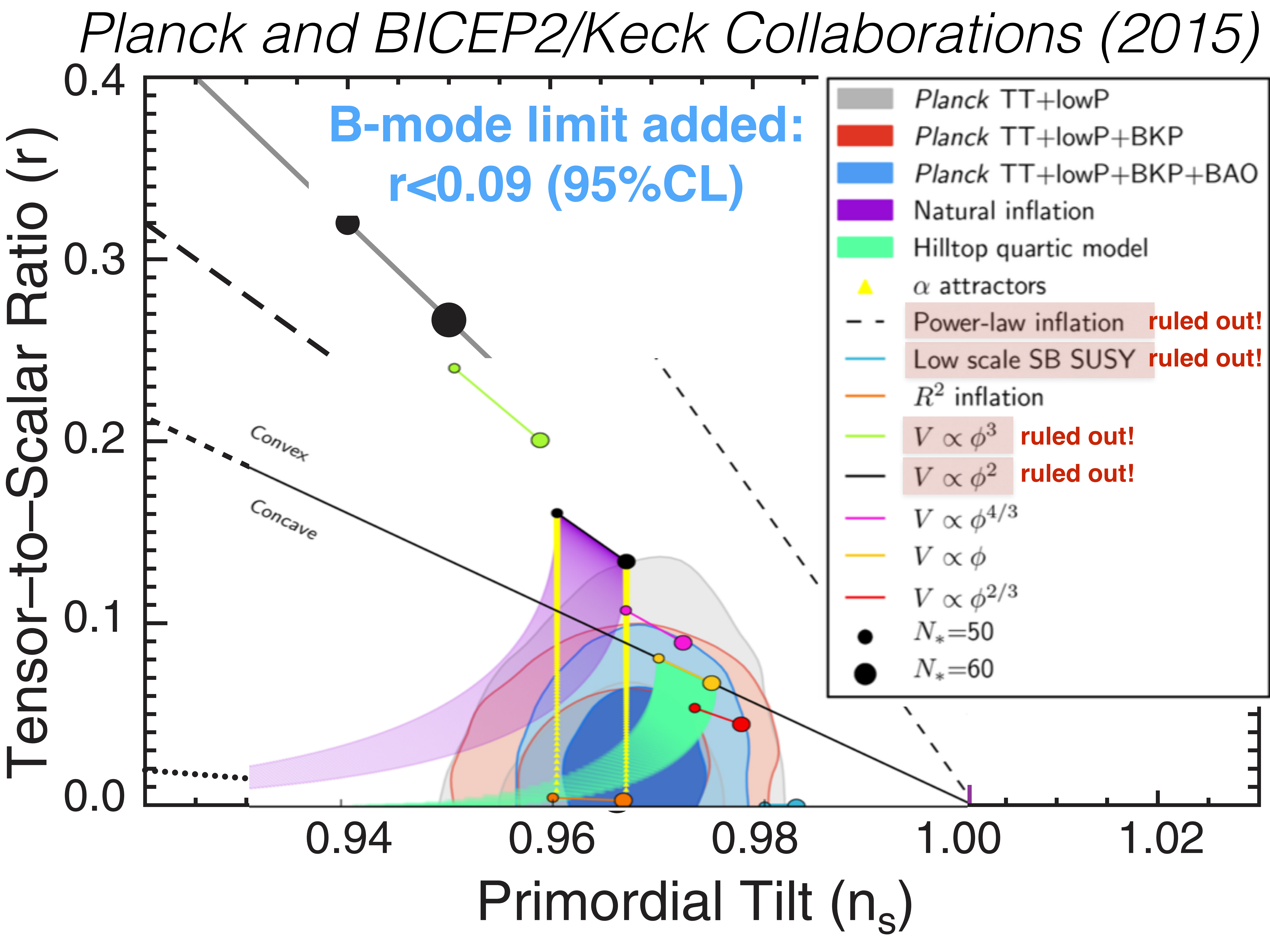
<u>CAUTION</u>: we are NOT seeing a single plane wave propagating perpendicular to our line of sight



BICEP2/Keck Array and Planck Collaboration (2015)
Amplitude of B-mode [μK²]
BICEP2 and Keck Array (BK) Data
BK, cleaned by the Planck data
at 353 GHz
B-mode due to
gravitational lensing
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300
Multipole



Courtesy of David Larson
WMAP(temp+pol)+ACT+SPT+BAO+H0
WMAP(pol) + Planck + BAO
N= 50 60
ruled out!
λφ4
m2φ2
μ3φ
R2 Inflation
HZ
No Evidence for Gravitational Waves in CMB Temperature Anisotropy
Tensor–to–Scalar Ratio (r)
Primordial Tilt (ns)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02



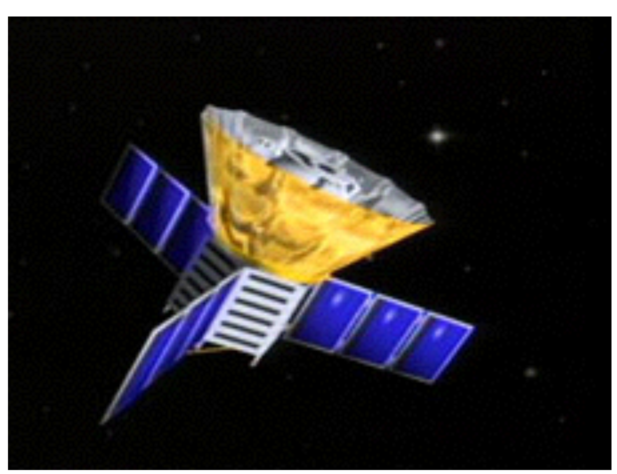
Planck and BICEP2/Keck Collaborations (2015)
B-mode limit added:
r<0.09 (95%CL)
Tensor–to–Scalar Ratio (r)
Primordial Tilt (n_s)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
Convex
Concave
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
ruled out!
Low scale SB SUSY
ruled out!
R² inflation
V ∝ φ³
ruled out!
V ∝ φ²
ruled out!
V ∝ φ^{4/3}
V ∝ φ
V ∝ φ^{2/3}
N*=50
N*=60

Current Situation

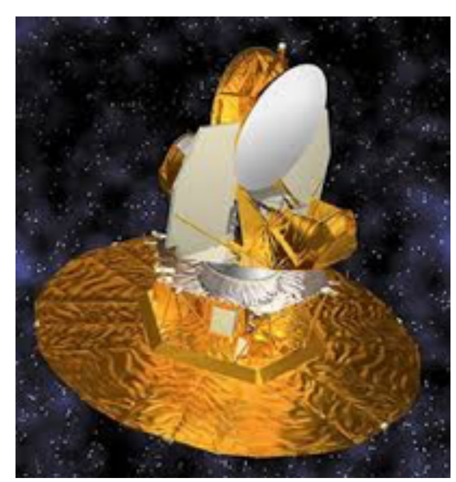
- Planck shows the evidence that the signal detected by BICEP2 is not cosmological, but is due to dust

- No strong evidence that the detected signal is cosmological

The search continues!!



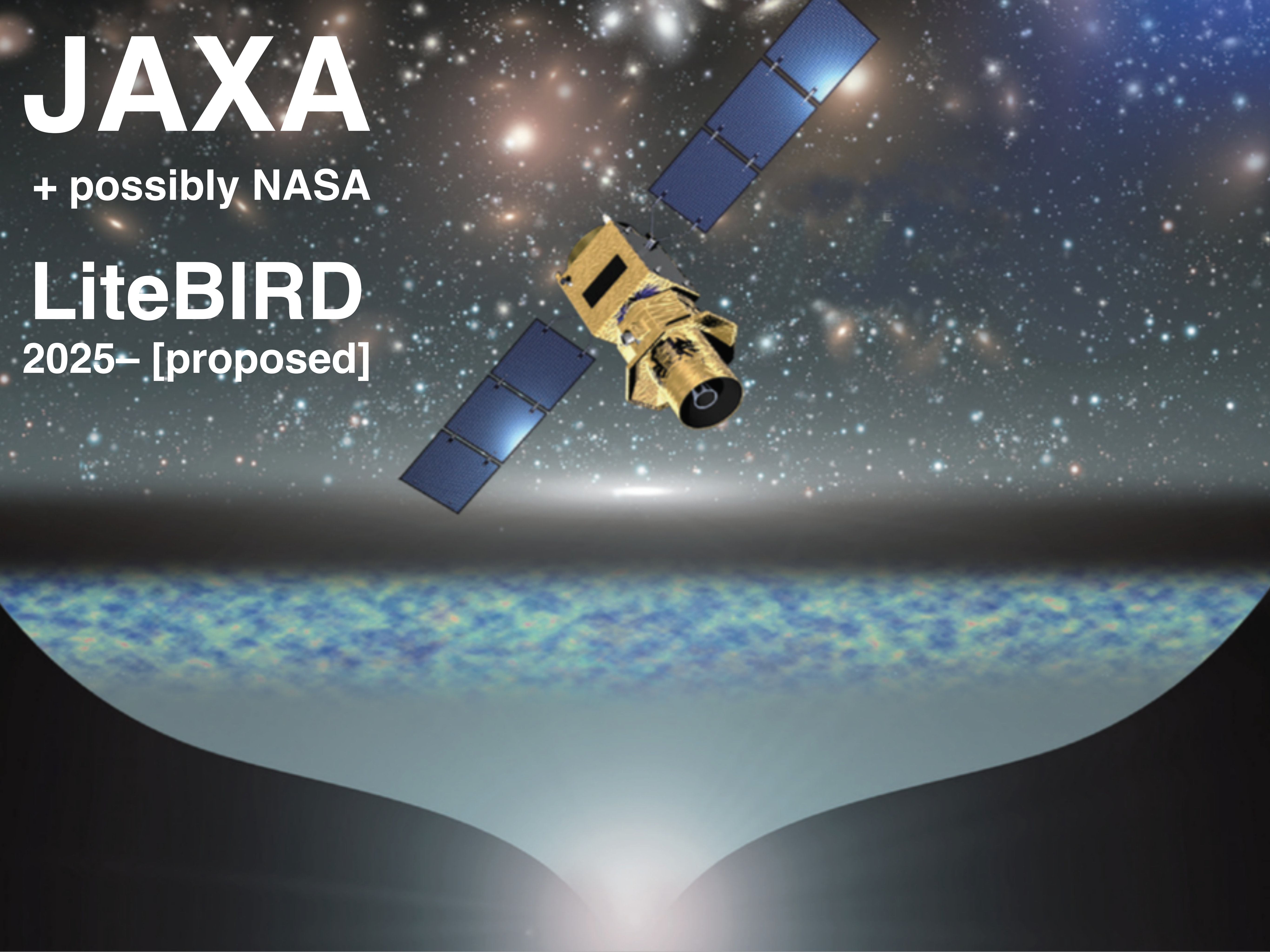
1989–1993

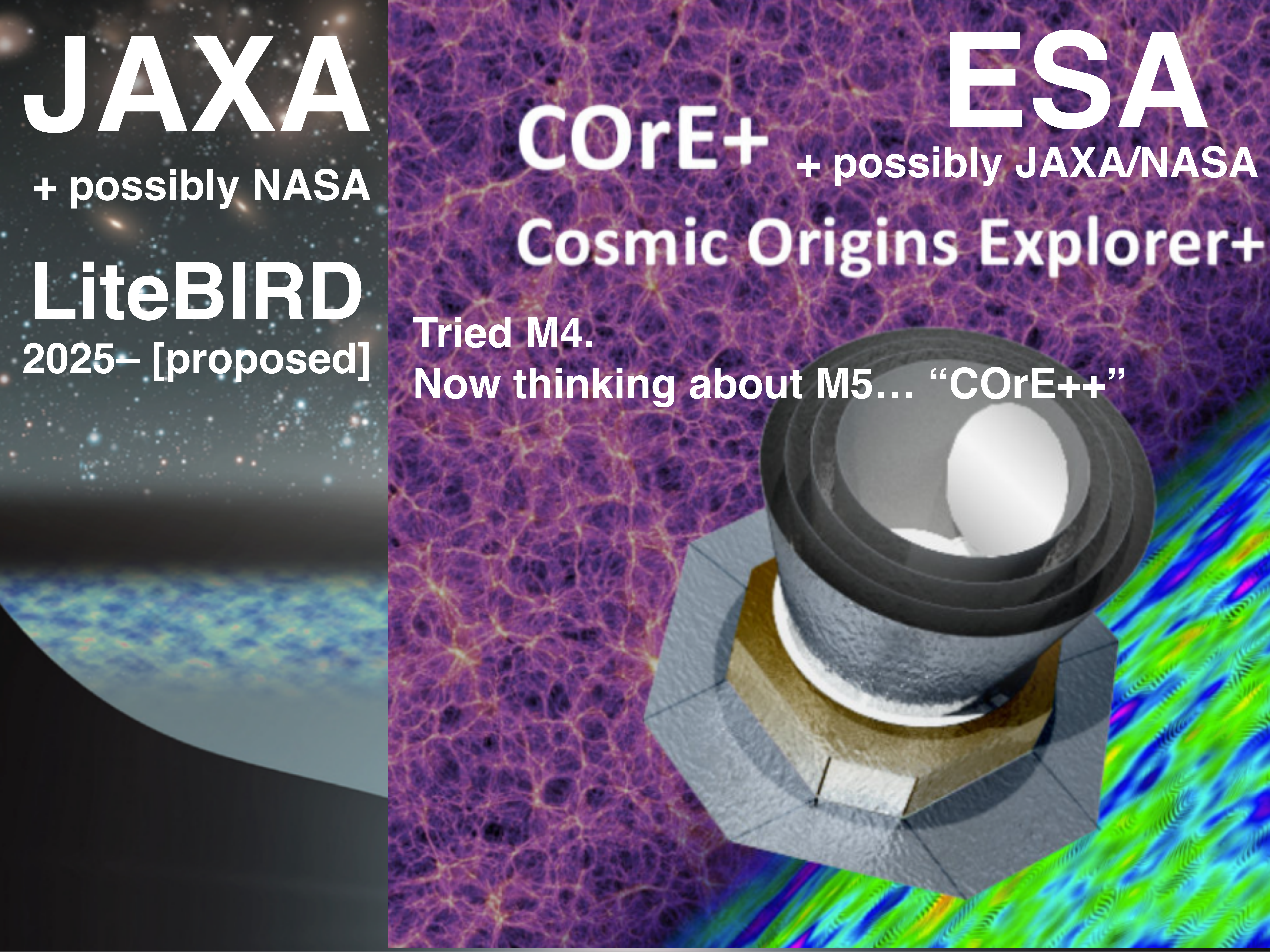


2001–2010

2009–2013

202X–


JAXA
+ possibly NASA
LiteBIRD
2025– [proposed]


JAXA
+ possibly NASA
LiteBIRD
2025– [proposed]
ESA
COrE+
+ possibly JAXA/NASA
Cosmic Origins Explorer+
Tried M4.
Now thinking about M5… “COrE++”

Conclusion

- The WMAP and Planck's temperature data provide **strong evidence for the quantum origin of structures in the universe**

- The next goal: **definitive evidence** for inflation by an unambiguous measurement of the primordial B-mode polarisation power spectrum

- **LiteBIRD** proposal to JAXA: a focused, primordial B-mode CMB polarisation satellite in 2025

- **COrE++** proposal to ESA's M5 call