Why B-mode?

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- …because we wish to find **definitive** evidence for cosmic inflation by detecting and characterising the **primordial gravitational waves**

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- Haven't we found already definitive evidence for it?

Yes!

Let's take a look…




$H \equiv \frac{\dot{a}}{a}$ [a is the scale factor]

Inflation, defined

- **Accelerated expansion during the early universe**

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

- For inflation to explain flatness of our observable universe, a **sustained** period of acceleration is required

- This implies $\varepsilon = O(N^{-1})$ [or smaller], where N is the number of e-fold 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?

- I.e., *have we found ε << 1?*
- To show ε << 1, **we need to map H(t)**
  - In other words, we need to draw the "Hubble diagram" during inflation

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

We measure distortions in space

- A distance between two points in space

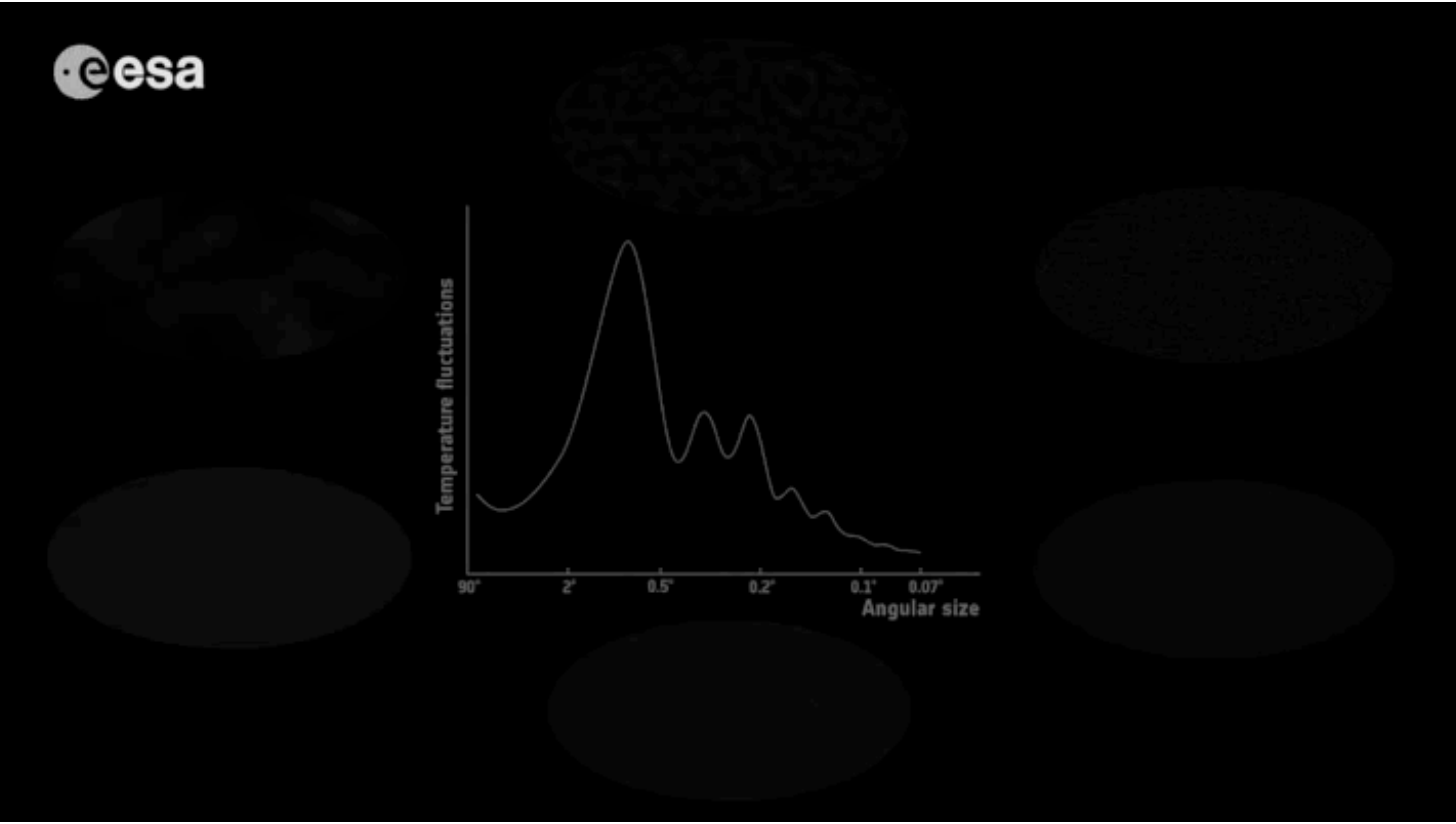
$$d\ell^2 = a^2(t)[1+2\zeta(\mathbf{x},t)][\delta_{ij}+h_{ij}(\mathbf{x},t)]dx^i dx^j$$

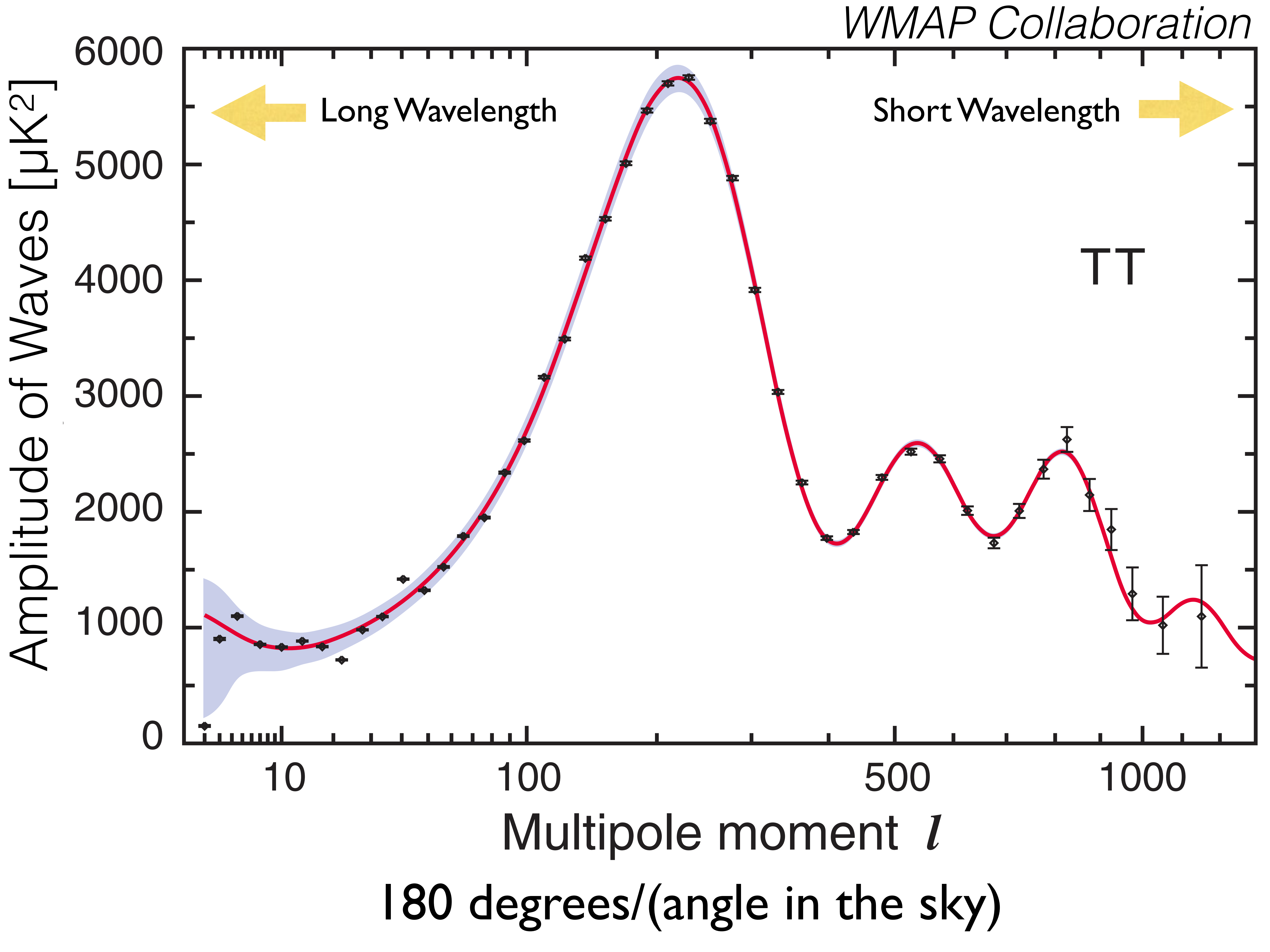
- ζ: “curvature perturbation” (scalar mode)
    - Perturbation to the determinant of the spatial metric
- h_{ij}: “gravitational waves” (tensor mode)
    - Perturbation that does not change the determinant (area)

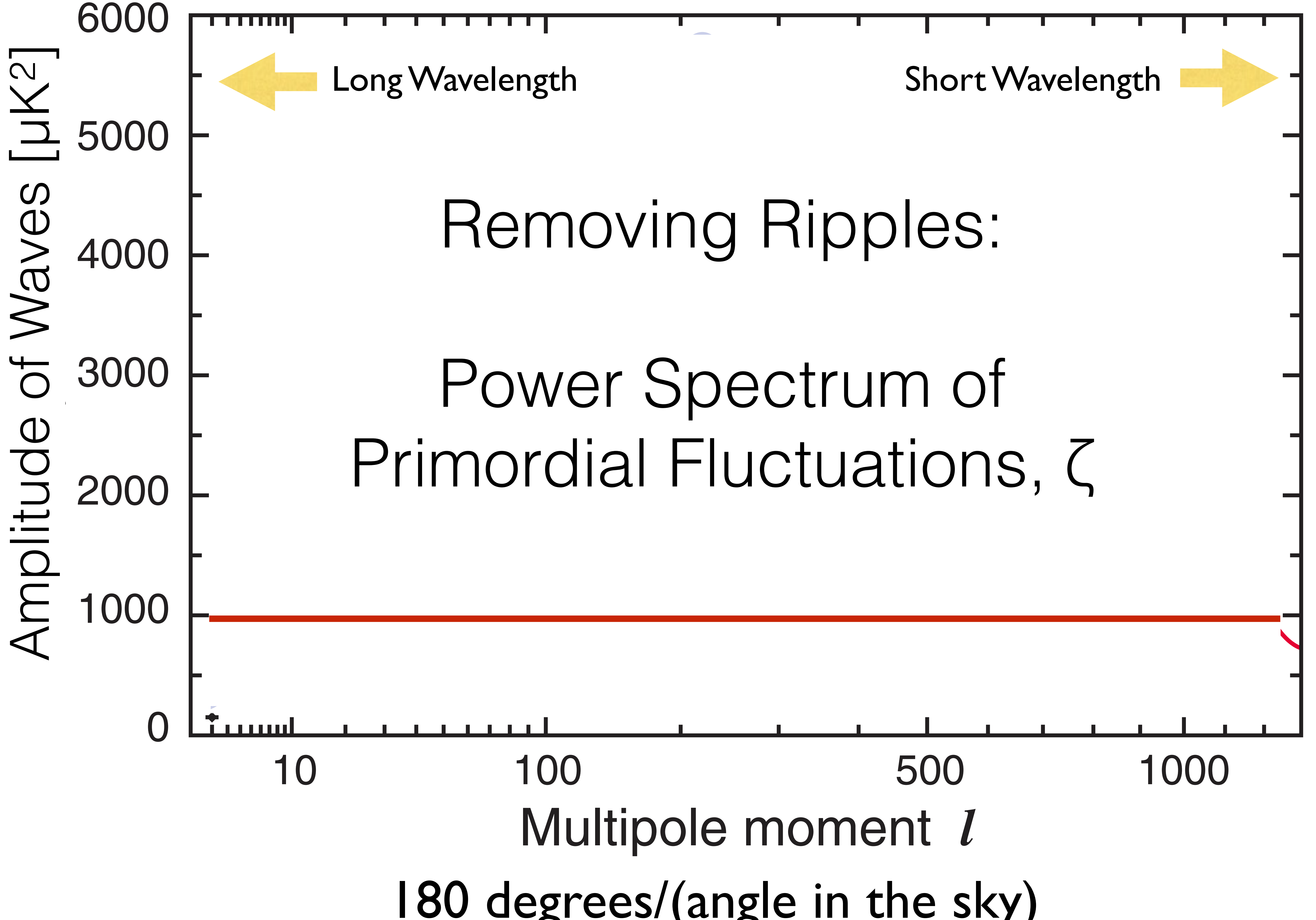
$$\sum_i h_{ii} = 0$$

Fluctuations are proportional to H

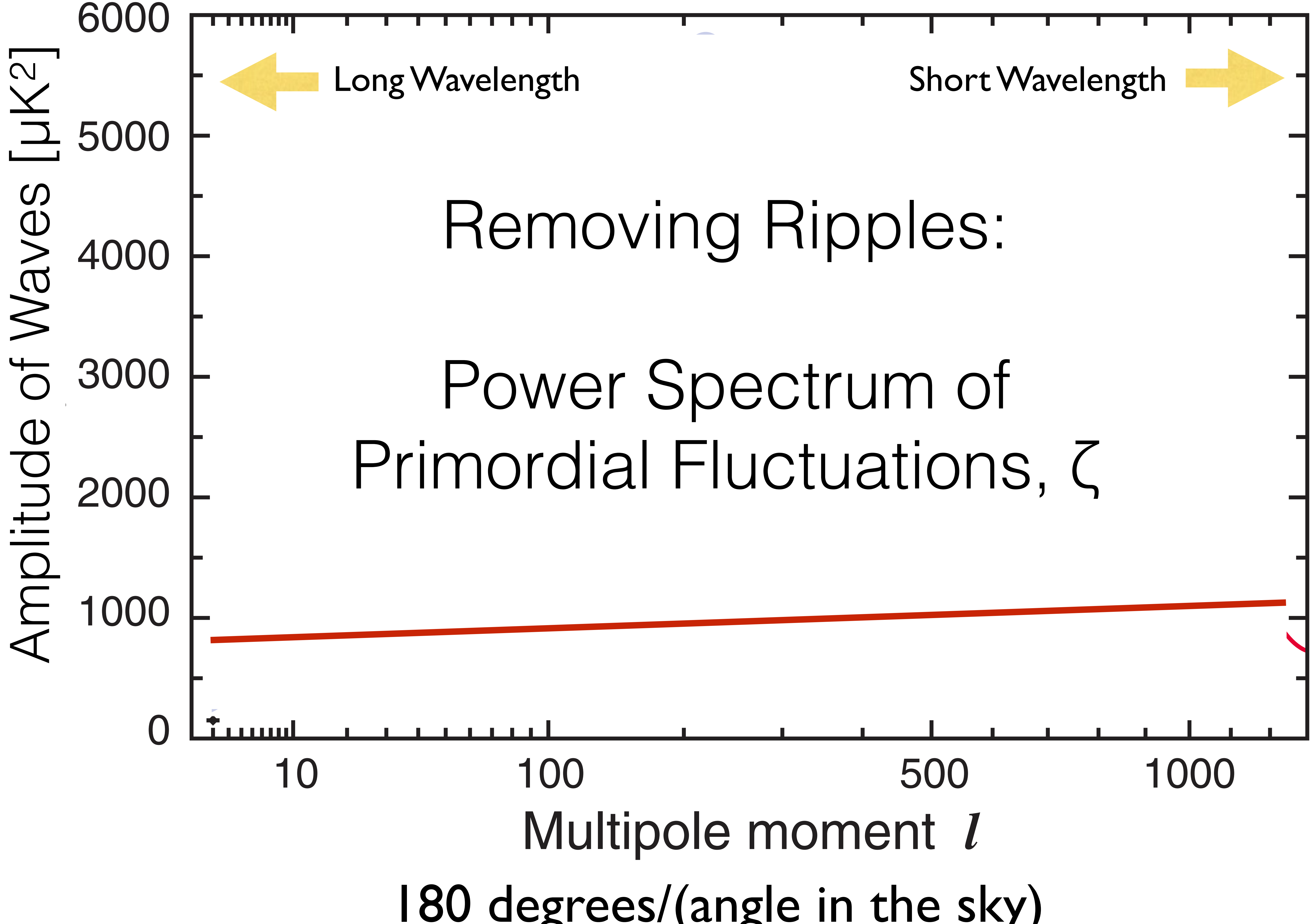
- Uncertainty Principle:
    - [*Energy you can borrow*] x [*Time you borrow*] = constant
- $H \equiv \frac{\dot{a}}{a}$ [This has units of 1/time]
- Then, **both ζ and h_{ij} are proportional to H**
- Earlier the fluctuations are generated, the bigger the angles they subtend in the sky. **We can map H(t) by measuring fluctuations over a wide range of angles**


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


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



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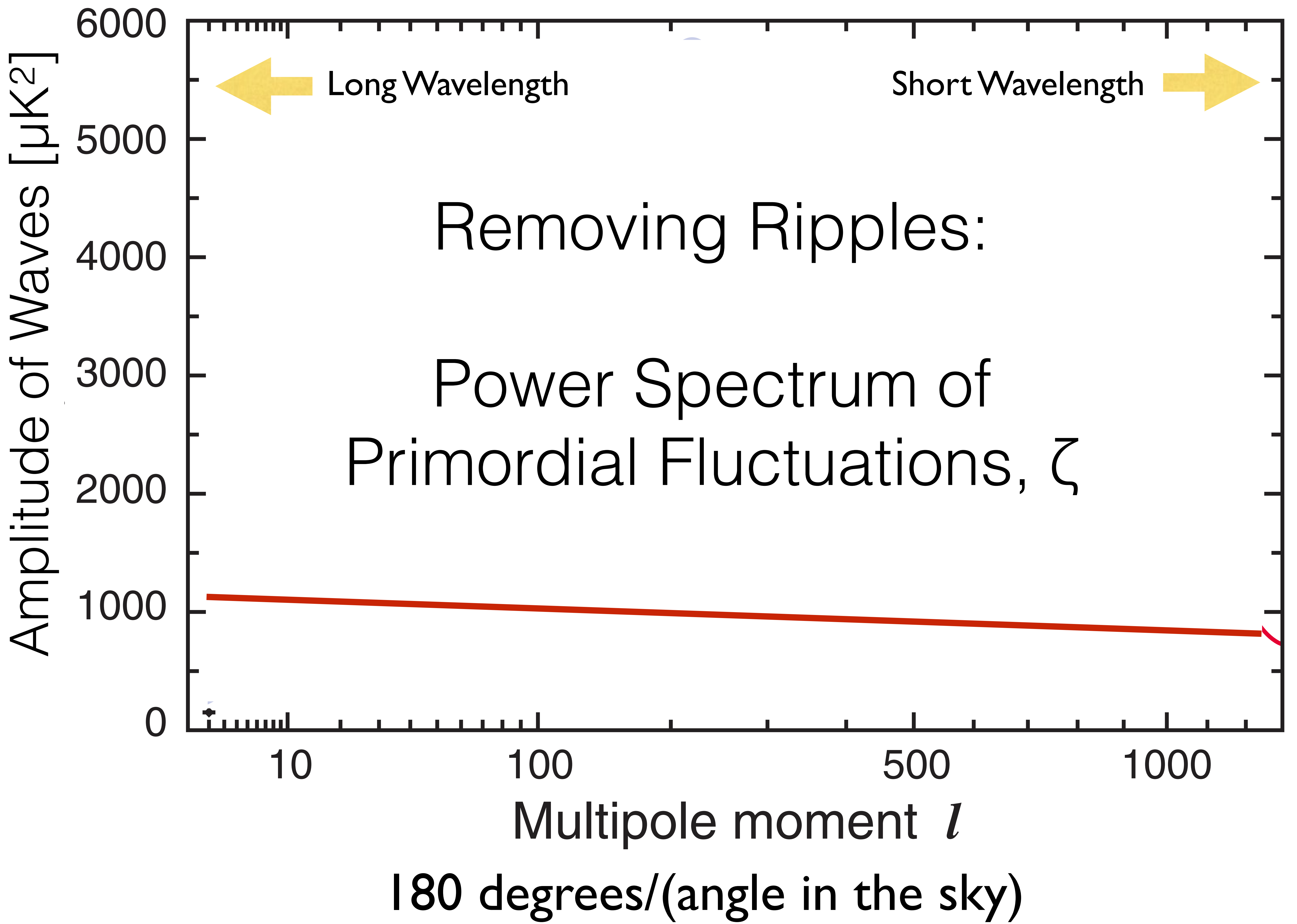

Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of
Primordial Fluctuations, ζ
Amplitude of Waves [μK²]
6000
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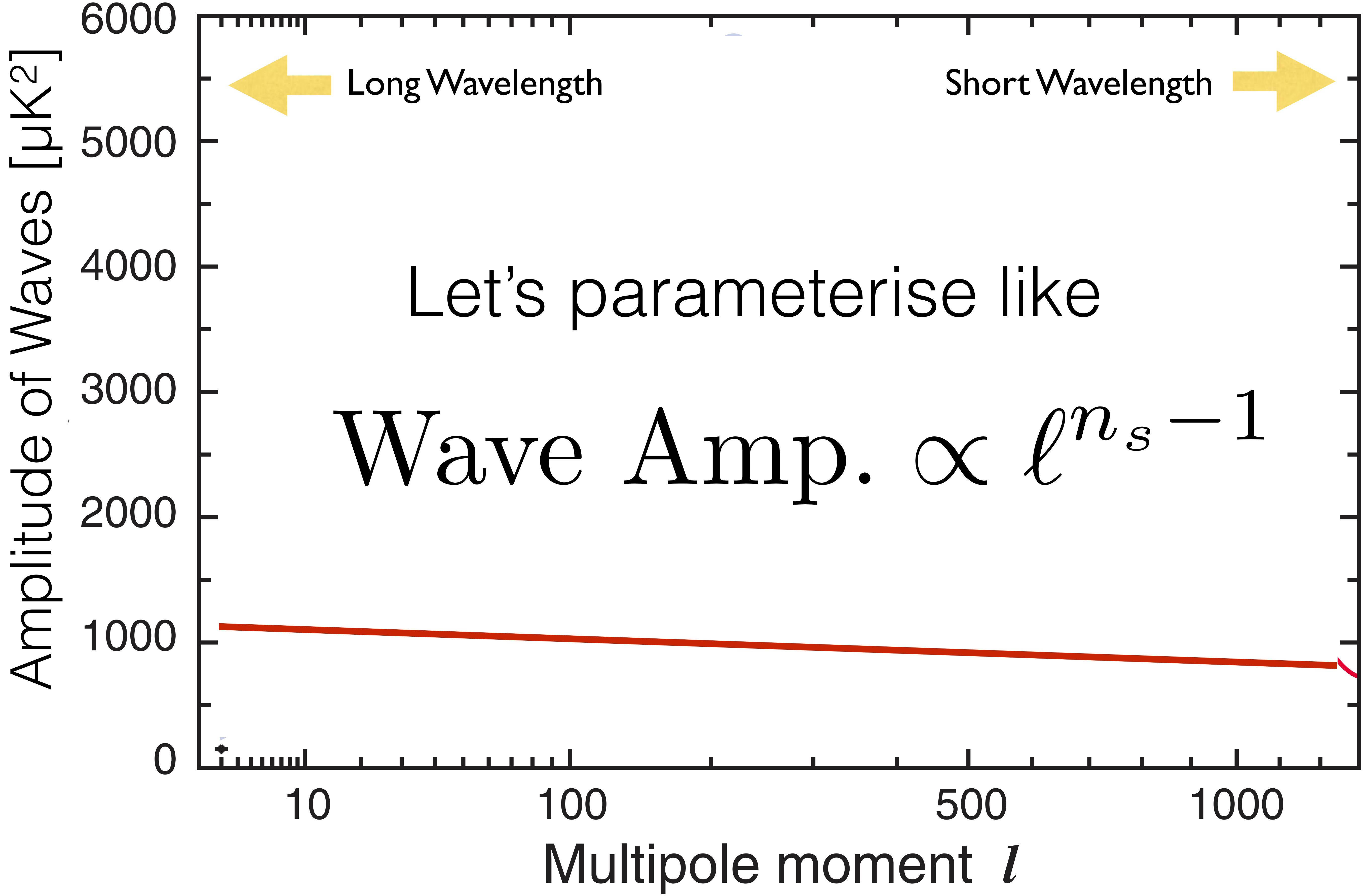
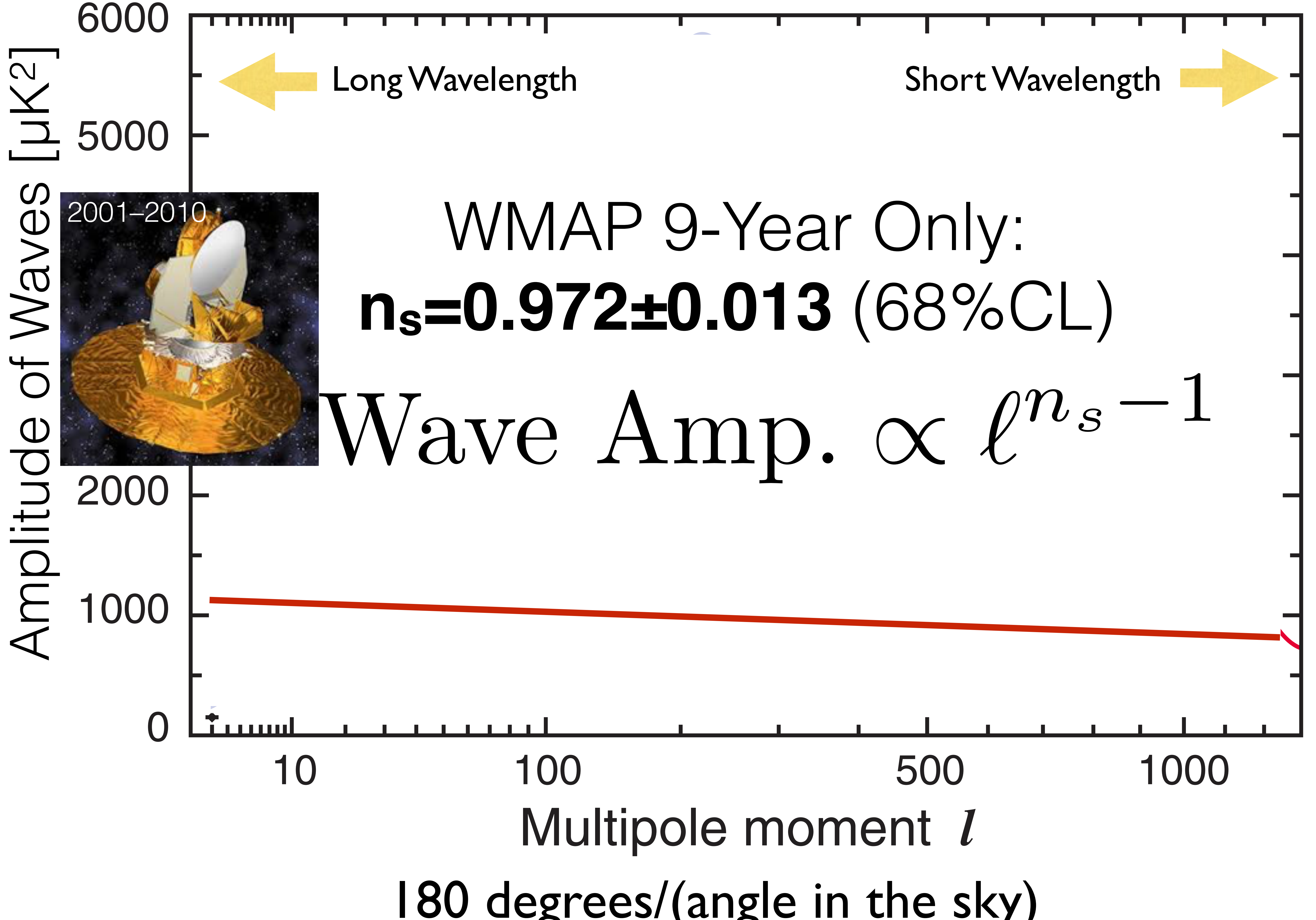
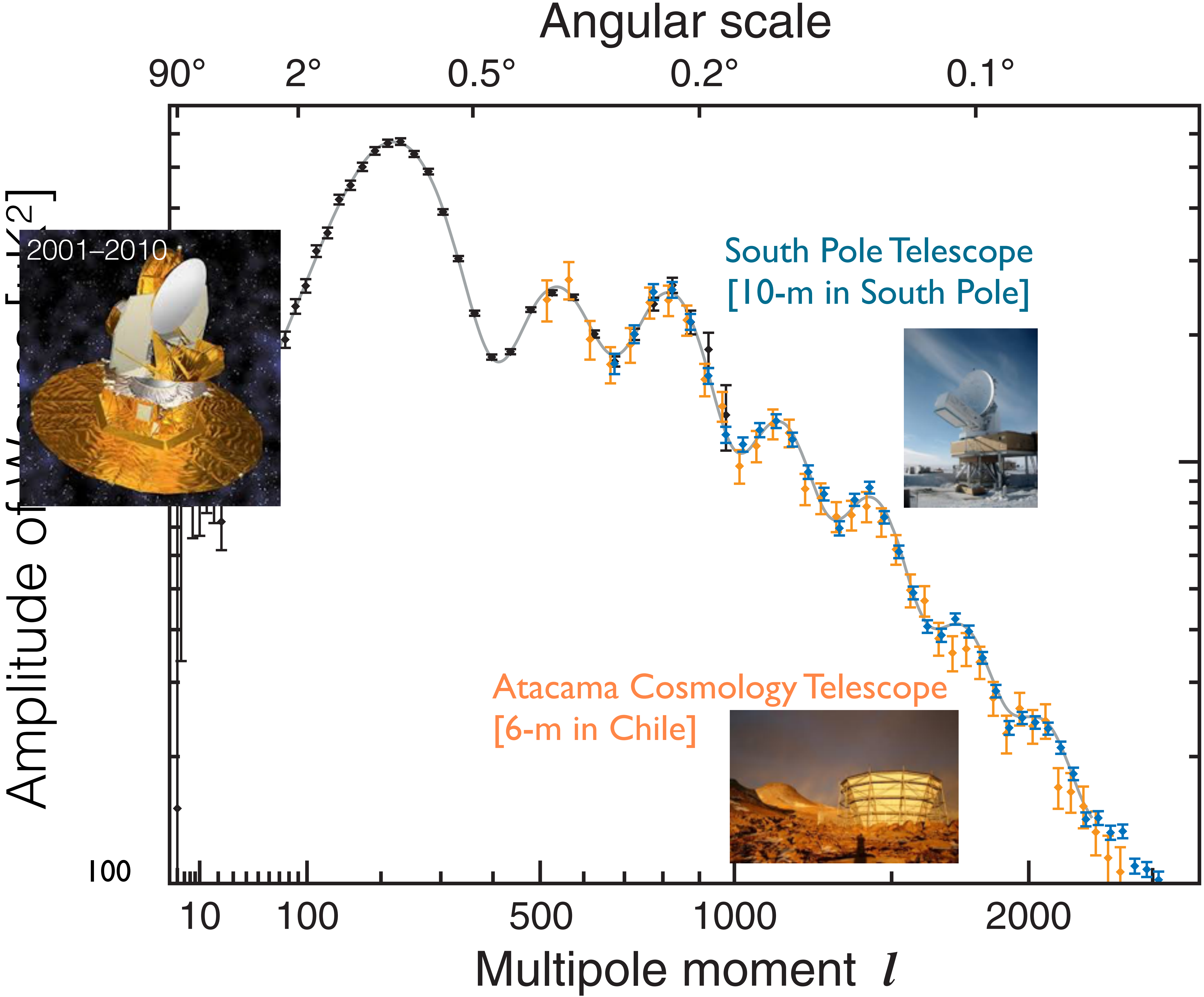
500
1000
Multipole moment l
180 degrees/(angle in the sky)

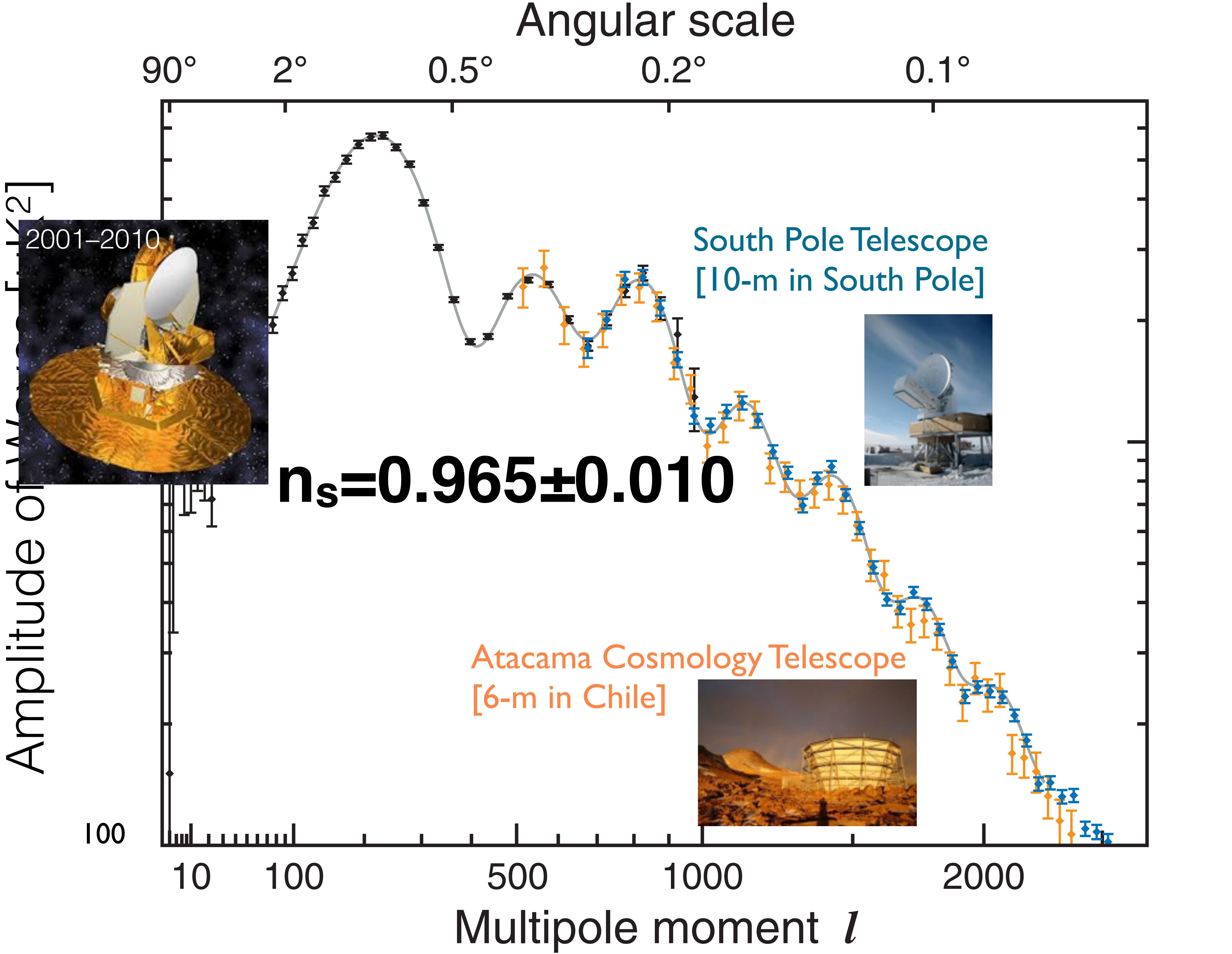


180 degrees/(angle in the sky)

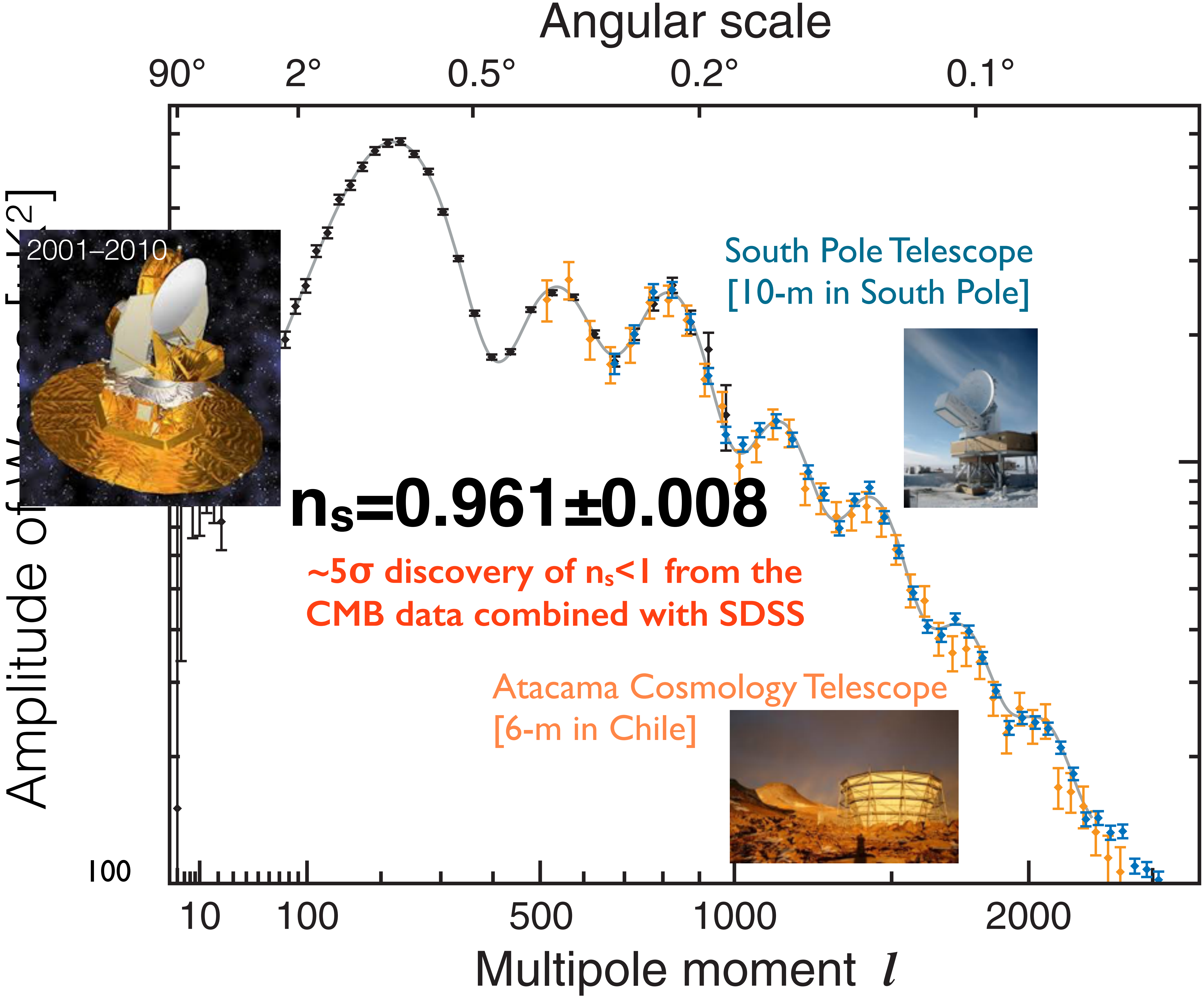


Long Wavelength
Short Wavelength
2001–2010
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
Wave Amp. $\propto \ell^{n_s-1}$
Amplitude of Waves [μK²]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

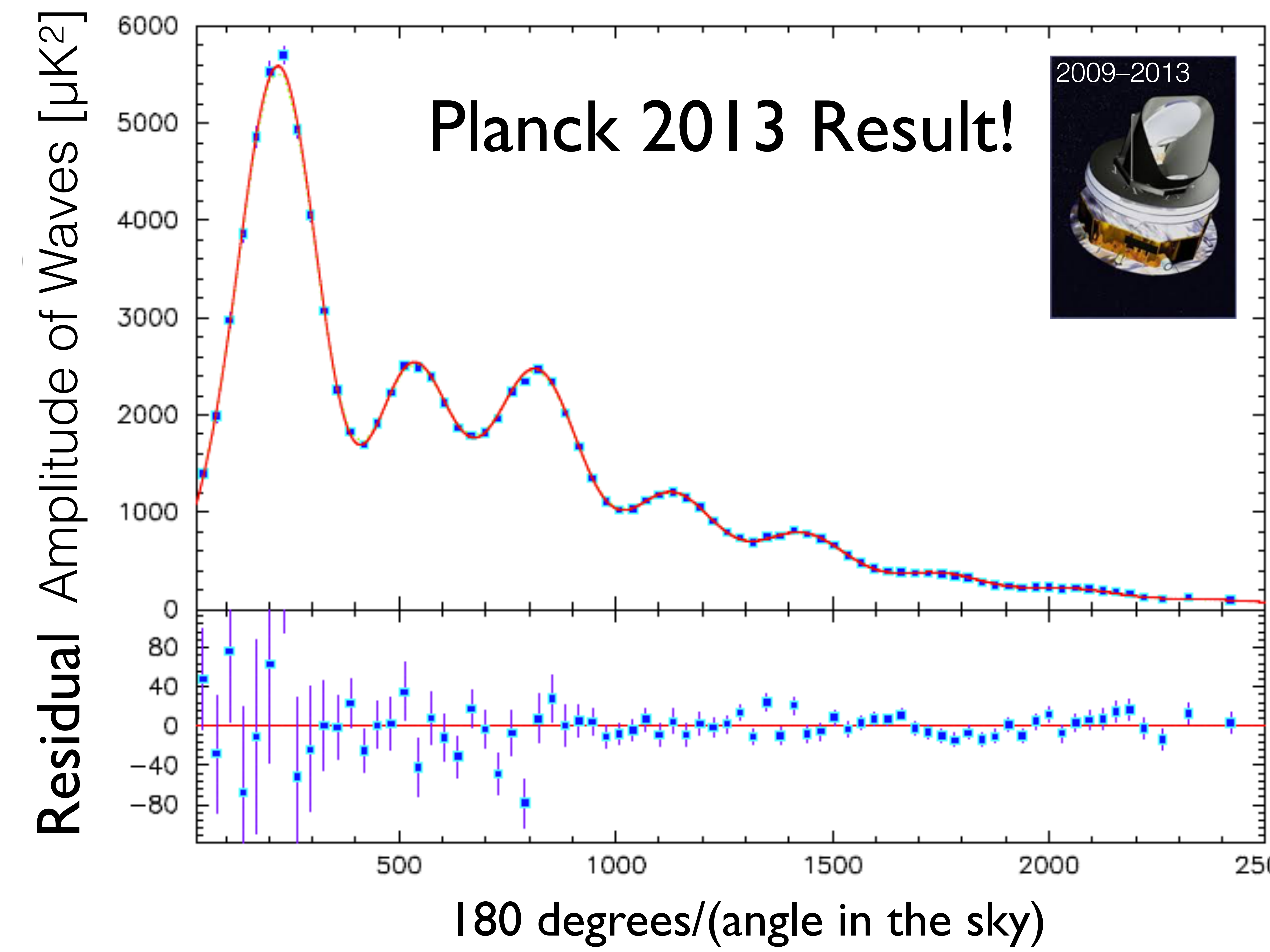

Angular scale
90°
2°
0.5°
0.2°
0.1°
Amplitude of Waves [μK²]
2001–2010
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment l



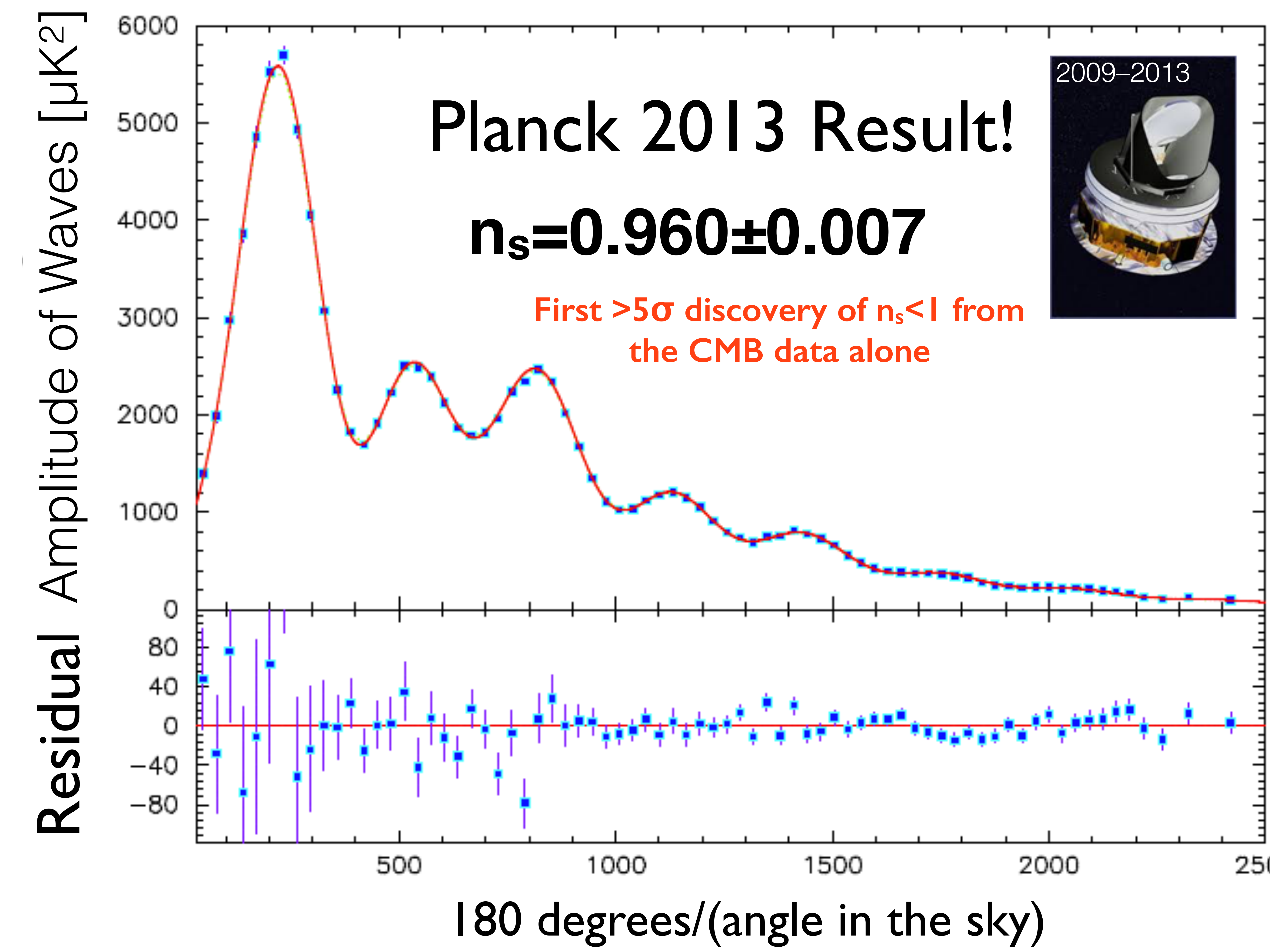
Angular scale
90°
2°
0.5°
0.2°
0.1°
2001–2010
South Pole Telescope
[10-m in South Pole]
n_s=0.965±0.010
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment l



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 SDSS
Atacama Cosmology Telescope
[6-m in Chile]
100
10
100
500
1000
2000
Multipole moment l
Amplitude of



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
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
180 degrees/(angle in the sky)
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000

Garriga & Mukhanov (1999)

$1 - n_s \ll 1$: Have we seen $\varepsilon \ll 1$?

- **Not quite**. ζ is basically proportional to H, but the pre-factor can depend on time. If there was only one dominant field in the early universe:

$$\zeta = (2\epsilon \underbrace{c_s}_{\text{propagation speed of a scalar field}})^{-1/2} \times H$$

- Even if H(t) varies rapidly, $n_s \sim 1$ can still be achieved if ε or c_s or both also vary, canceling the variation in H(t). **ζ does not give H(t) directly**

In general:

- ζ does not probe the expansion history during inflation directly because **its behaviour depends very much on properties of matter** present in the universe

- The connection to H(t) can be more complicated for multi-field (multi-matter) models

- We need a probe which maps H(t) **more directly**

Starobinsky (1979)

Here comes gravitational waves

- Gravitational waves are not coupled to (scalar) matter. Thus, it directly probes H(t) via

$$h_{ij}^{\text{prim}} = \frac{\sqrt{2}e_{ij}}{M_{\text{Pl}}} \times H$$

independent of time!

Has Inflation Occurred?

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

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

with

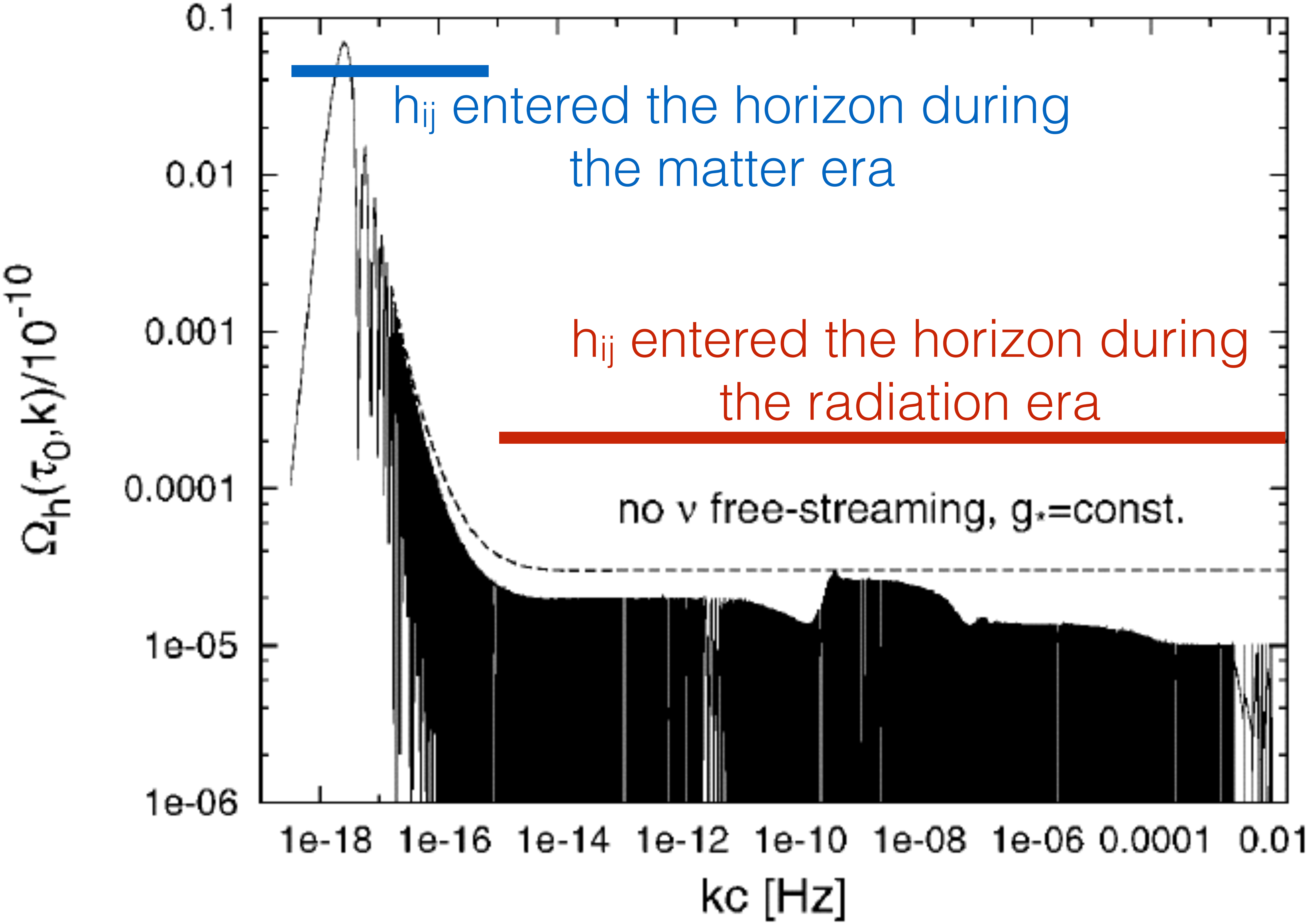
$$|n_t| \ll 1$$

In most models,
$n_t = -2\epsilon < 0$

Theoretical

Watanabe & Komatsu (2006)

Spectrum of GW today for $n_t=0$



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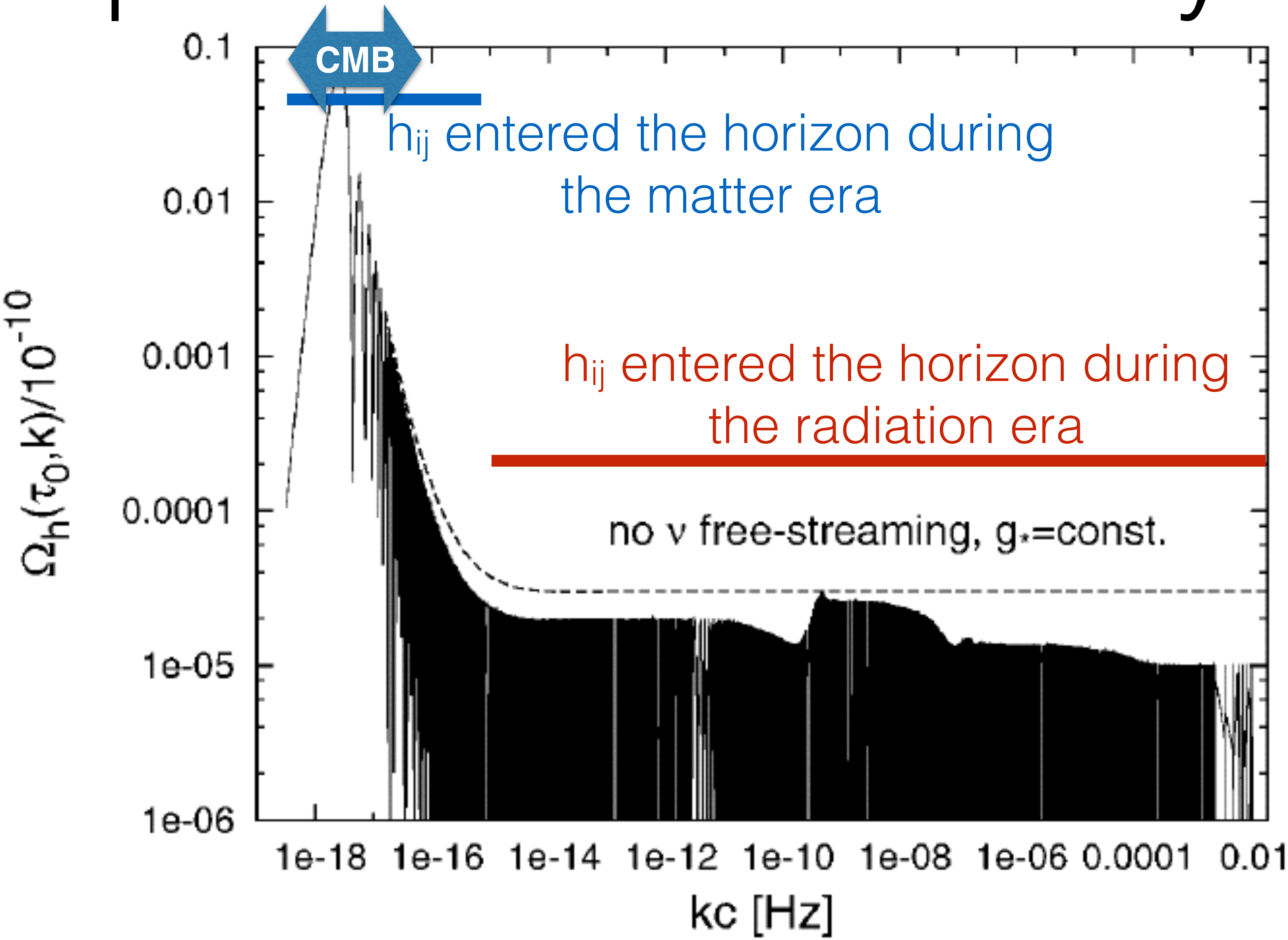

Theoretical

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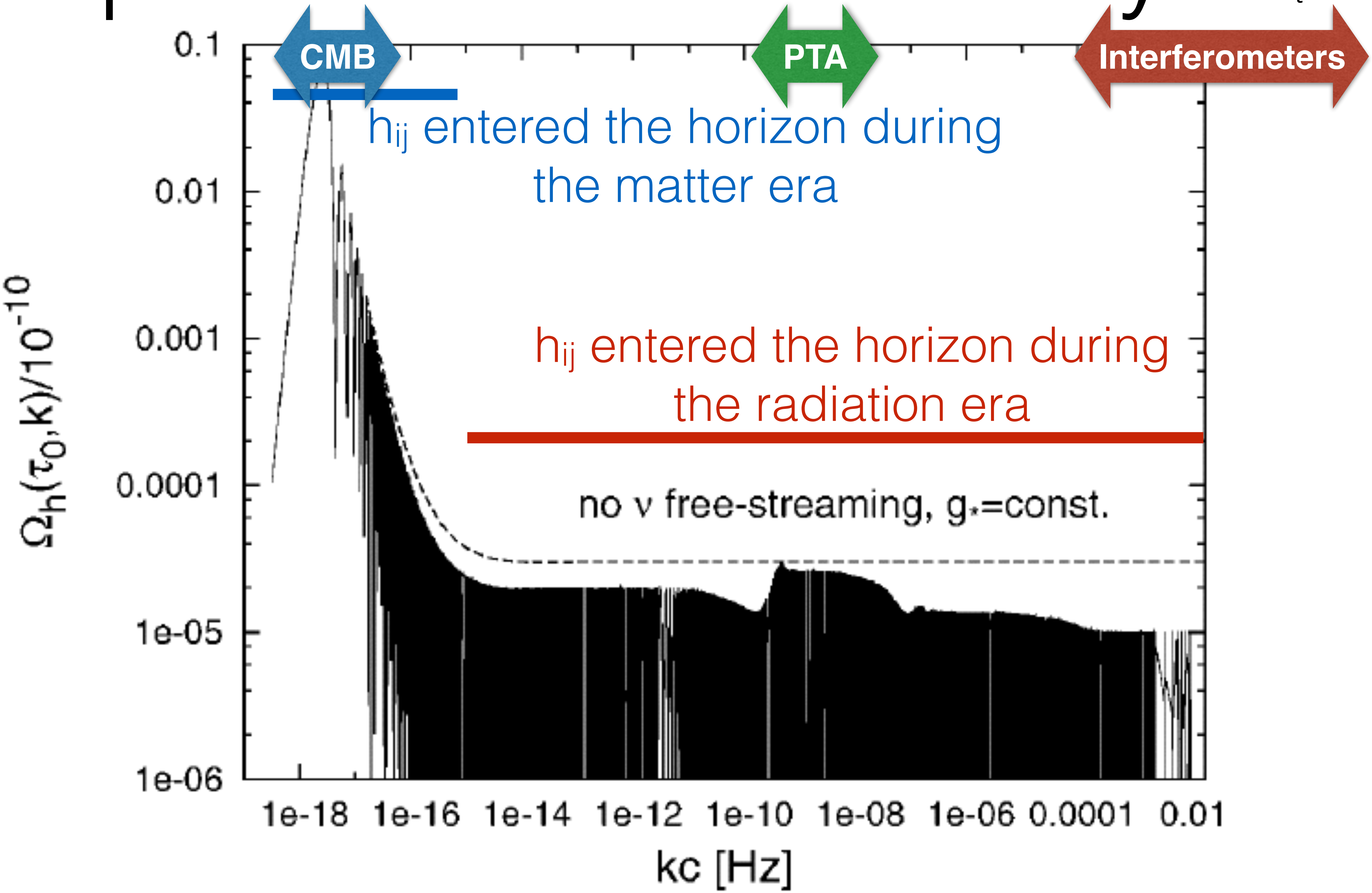
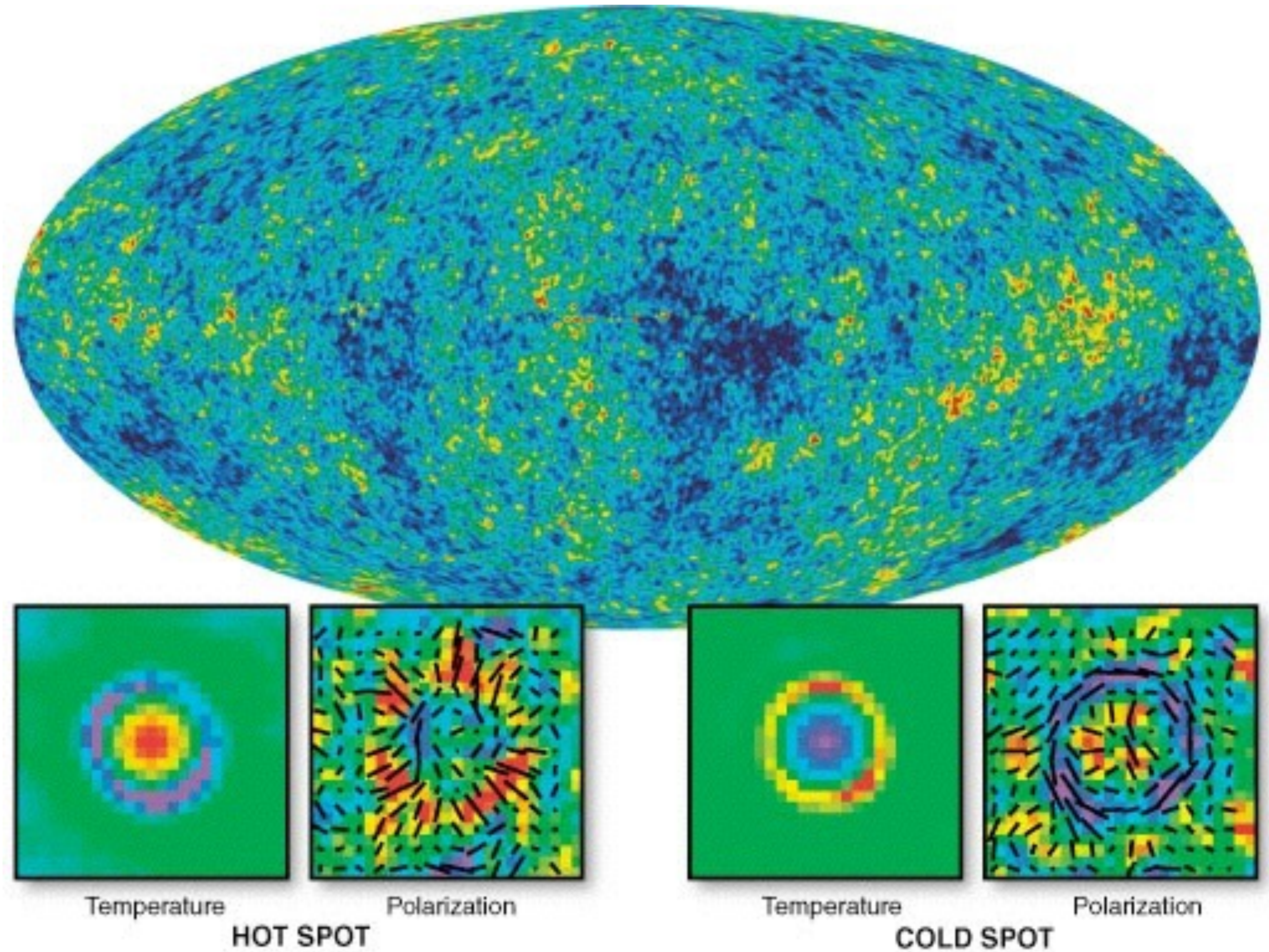
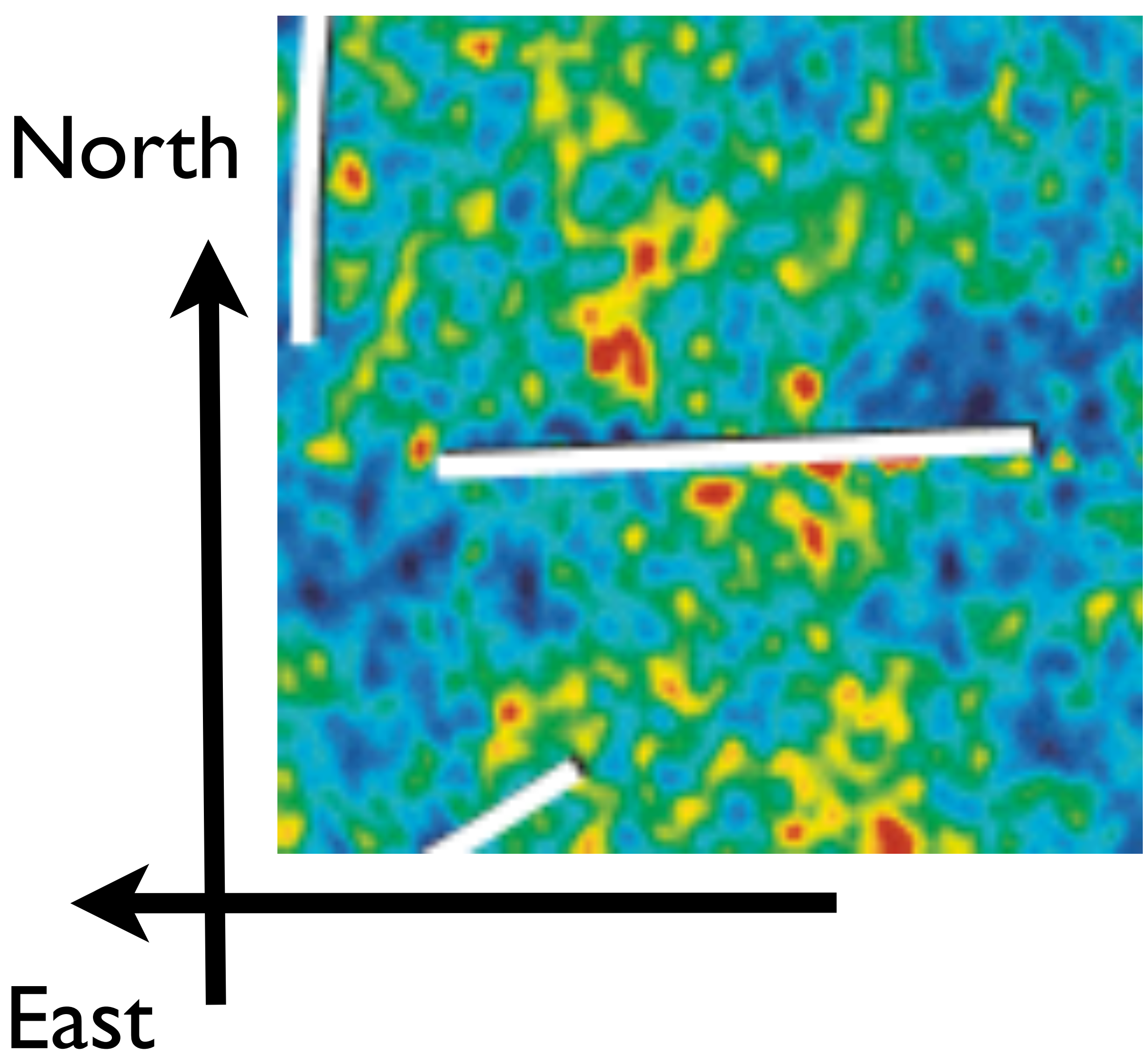


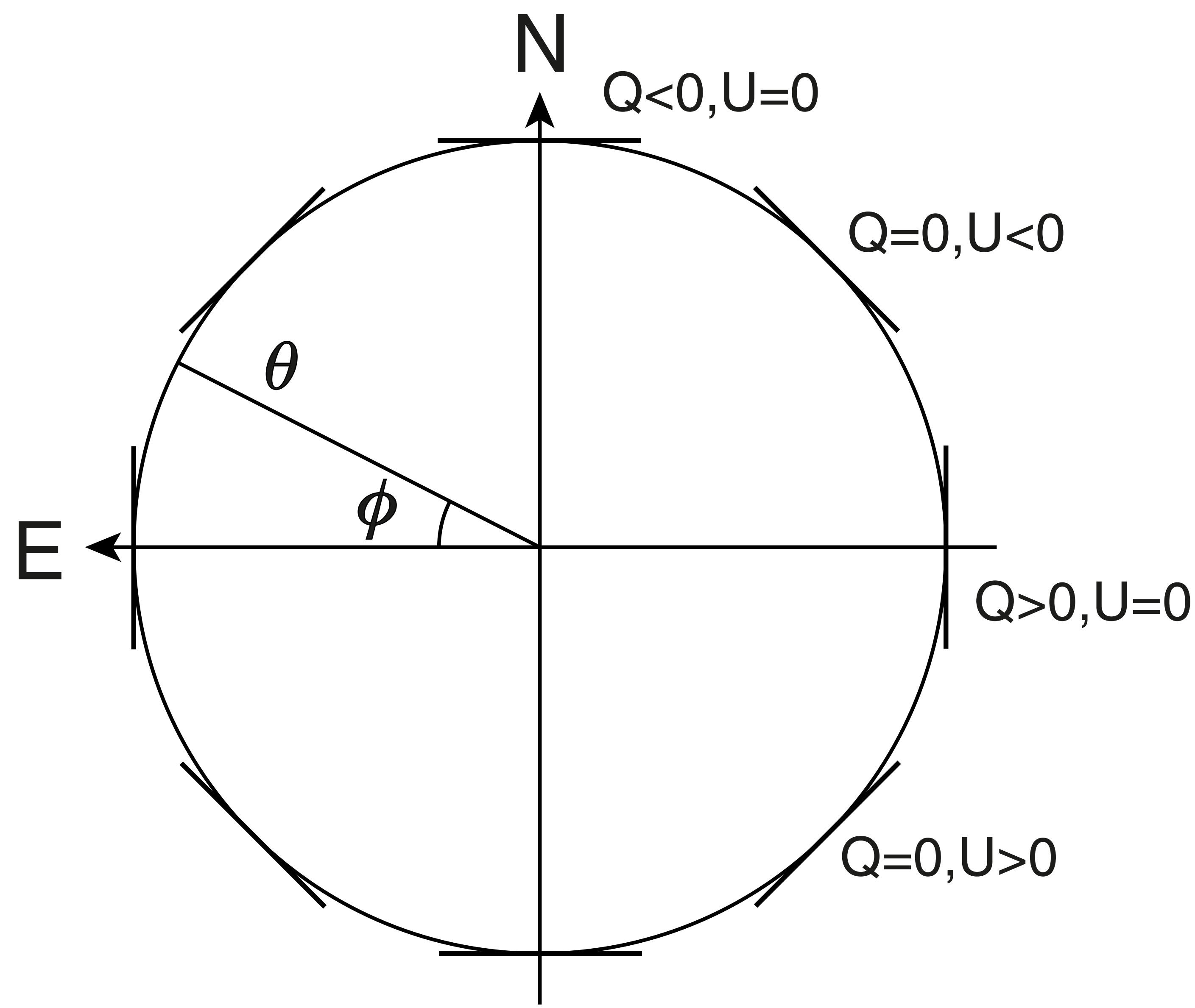
CMB Polarisation



- CMB is [weakly] polarised!

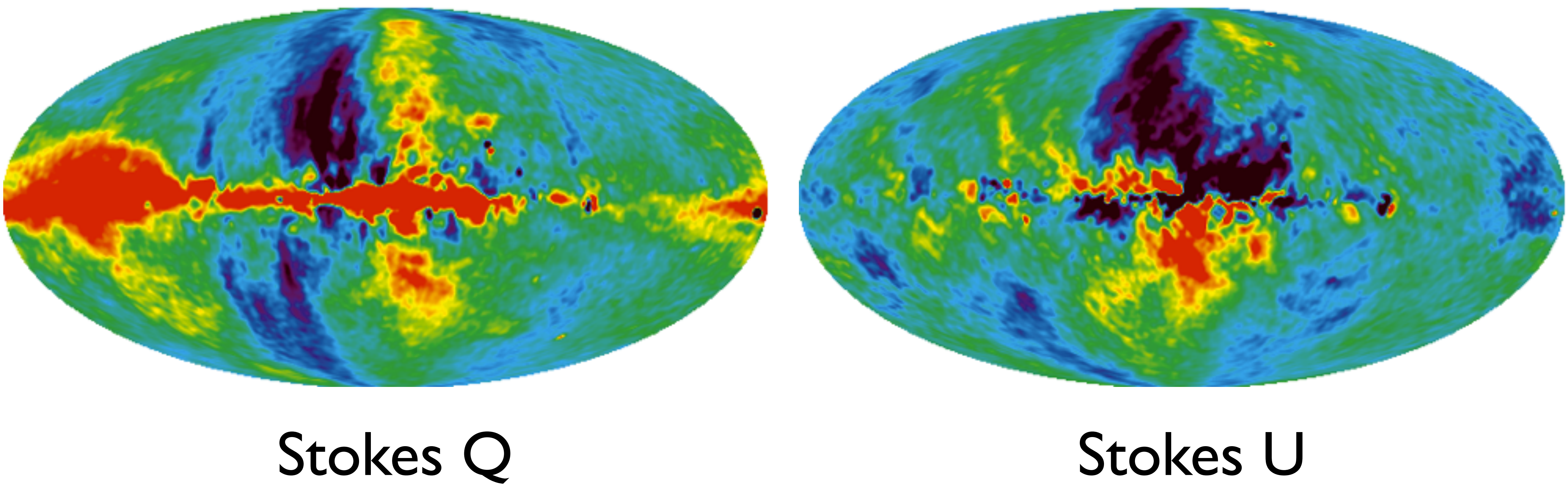
Stokes Parameters



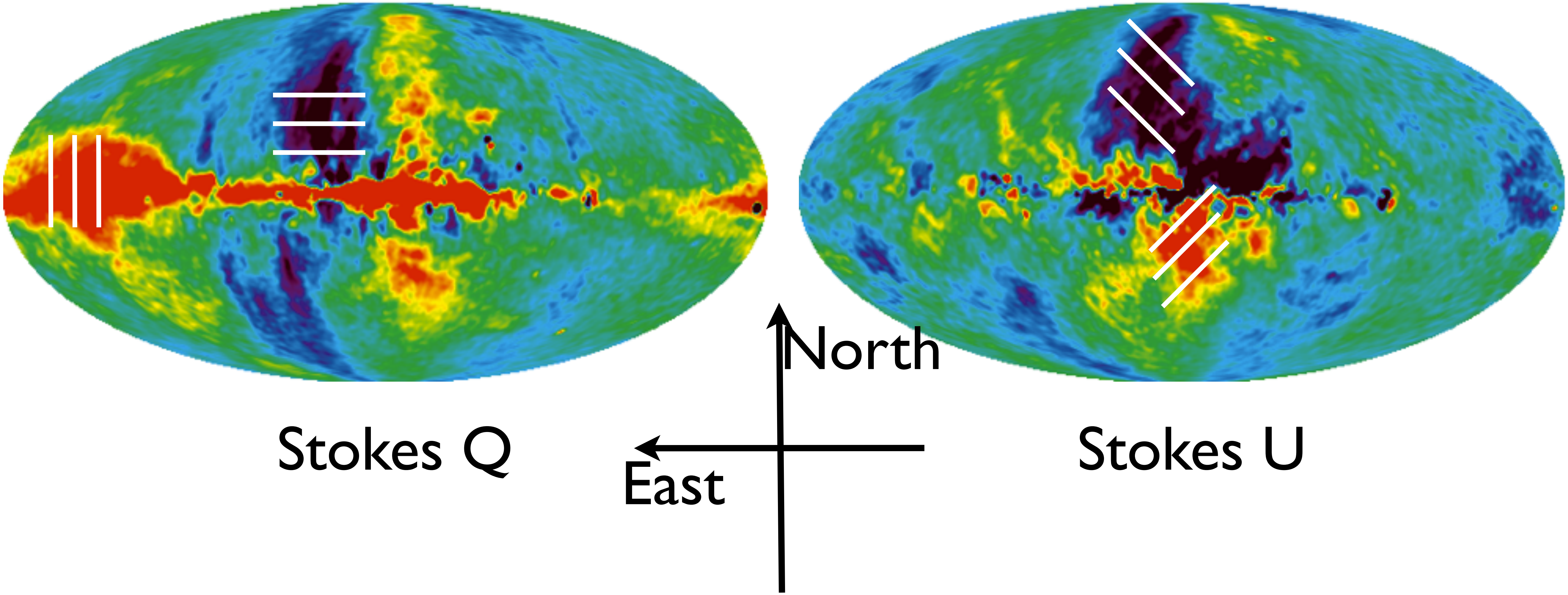


WMAP Collaboration

23 GHz

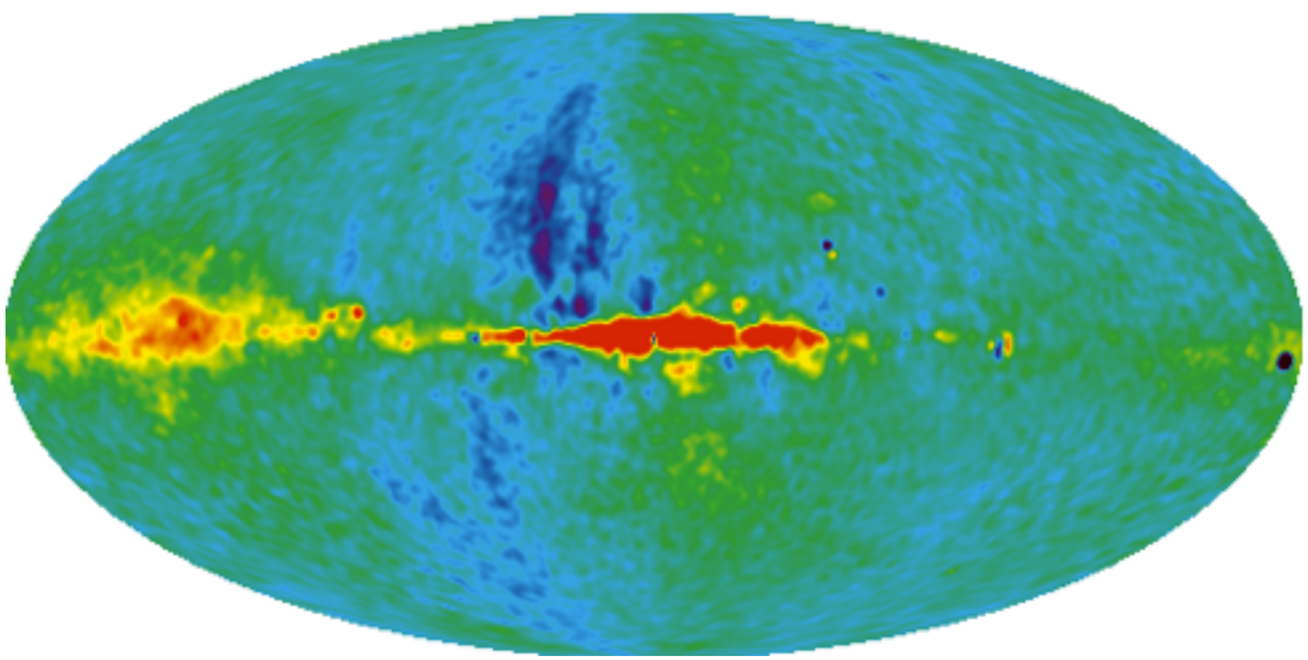


23 GHz

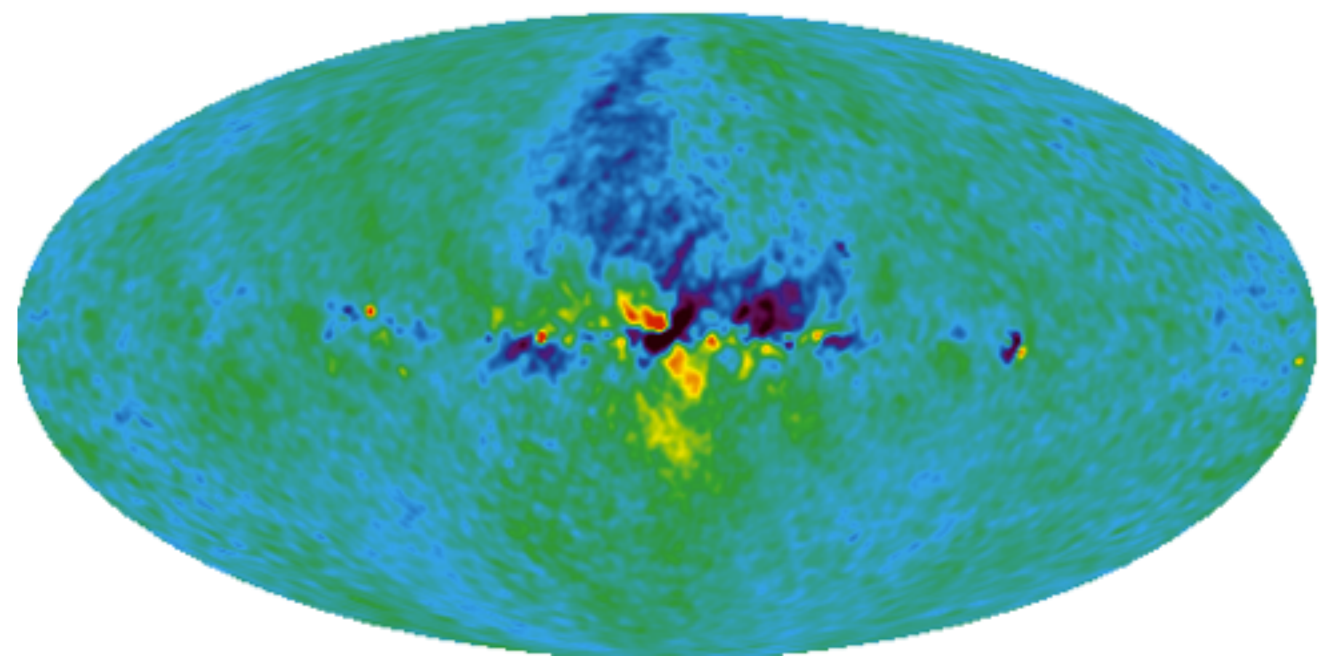


WMAP Collaboration

33 GHz



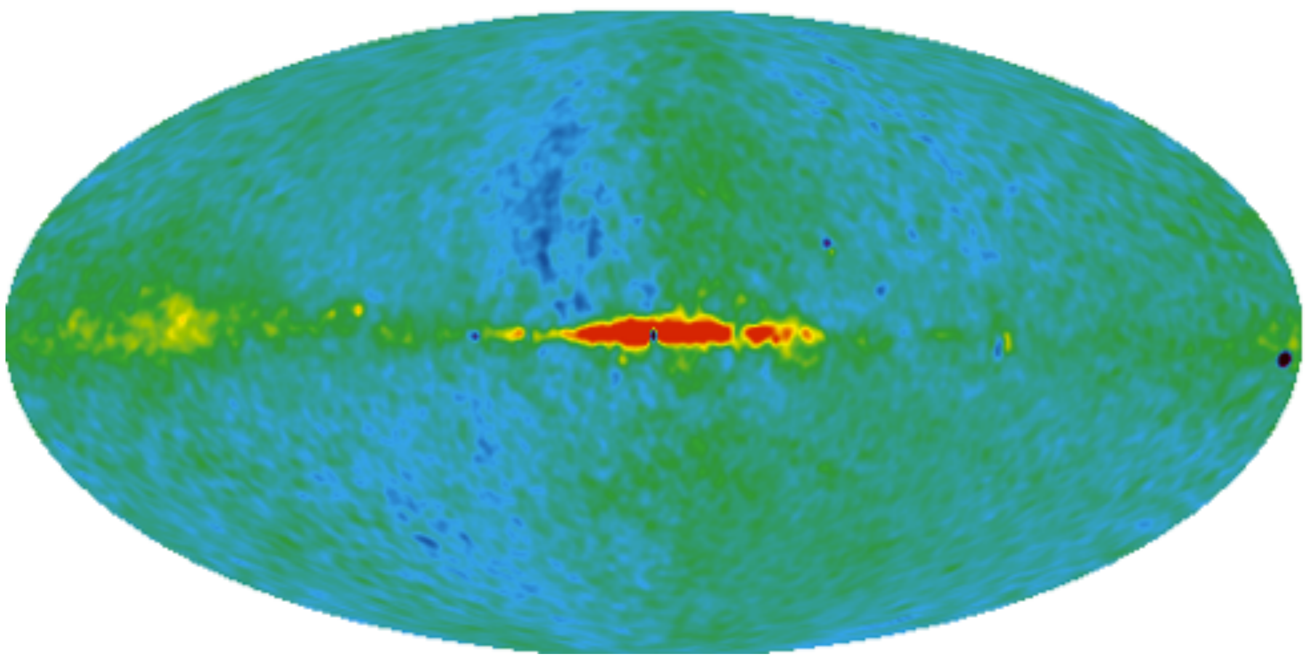
Stokes Q



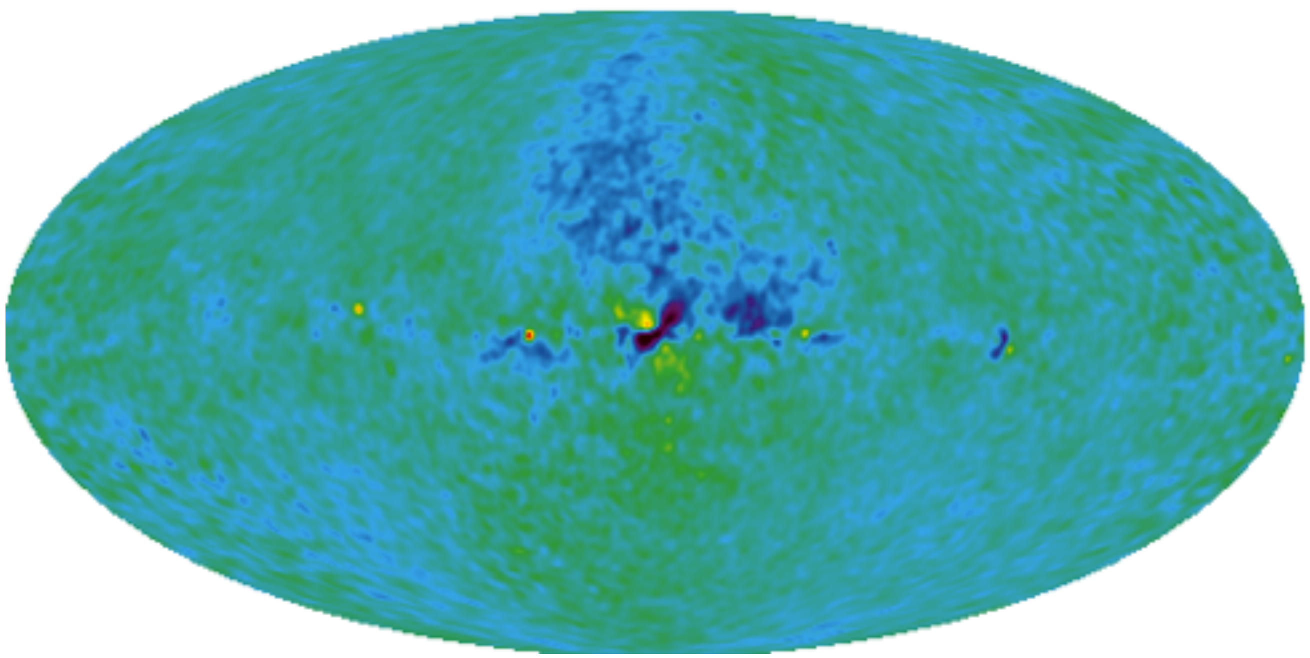
Stokes U

WMAP Collaboration

41 GHz



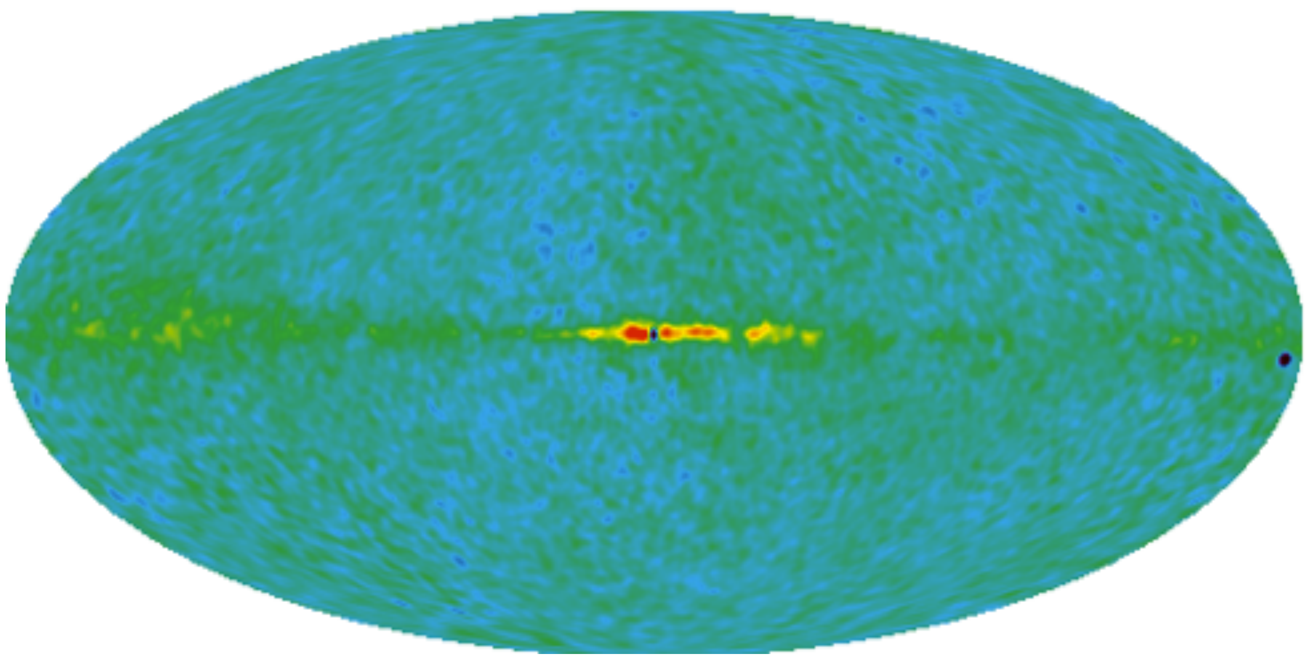
Stokes Q



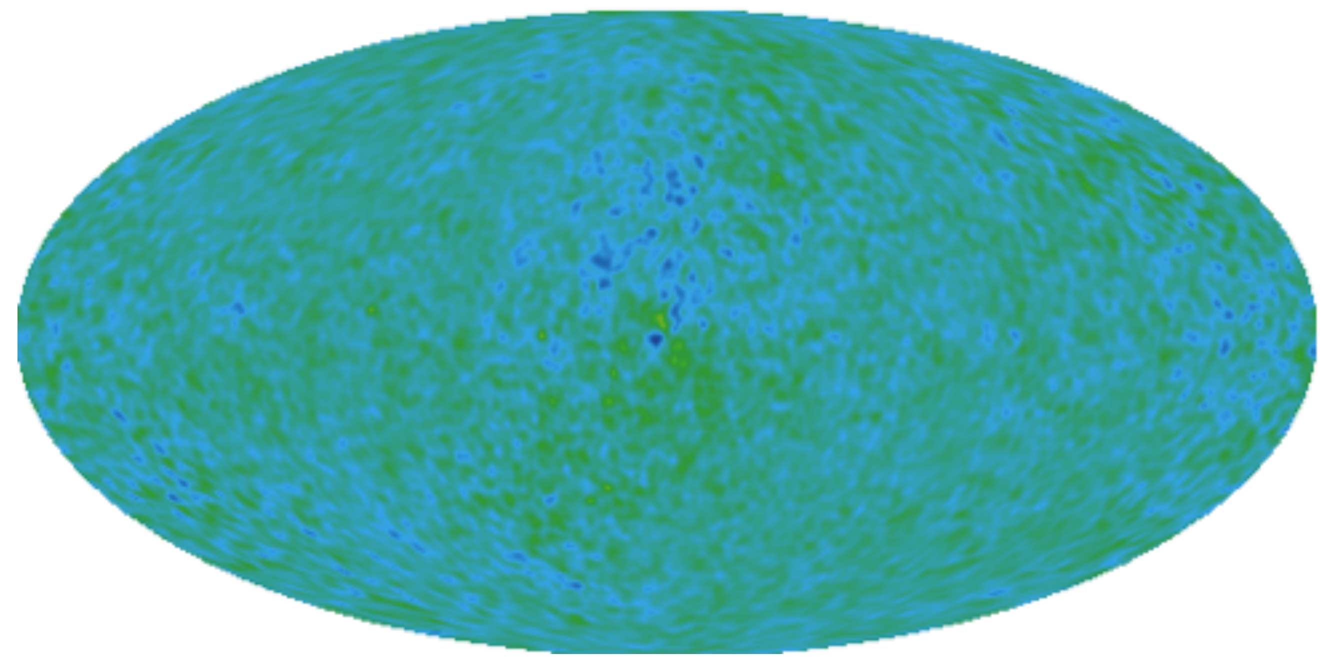
Stokes U

WMAP Collaboration

61 GHz



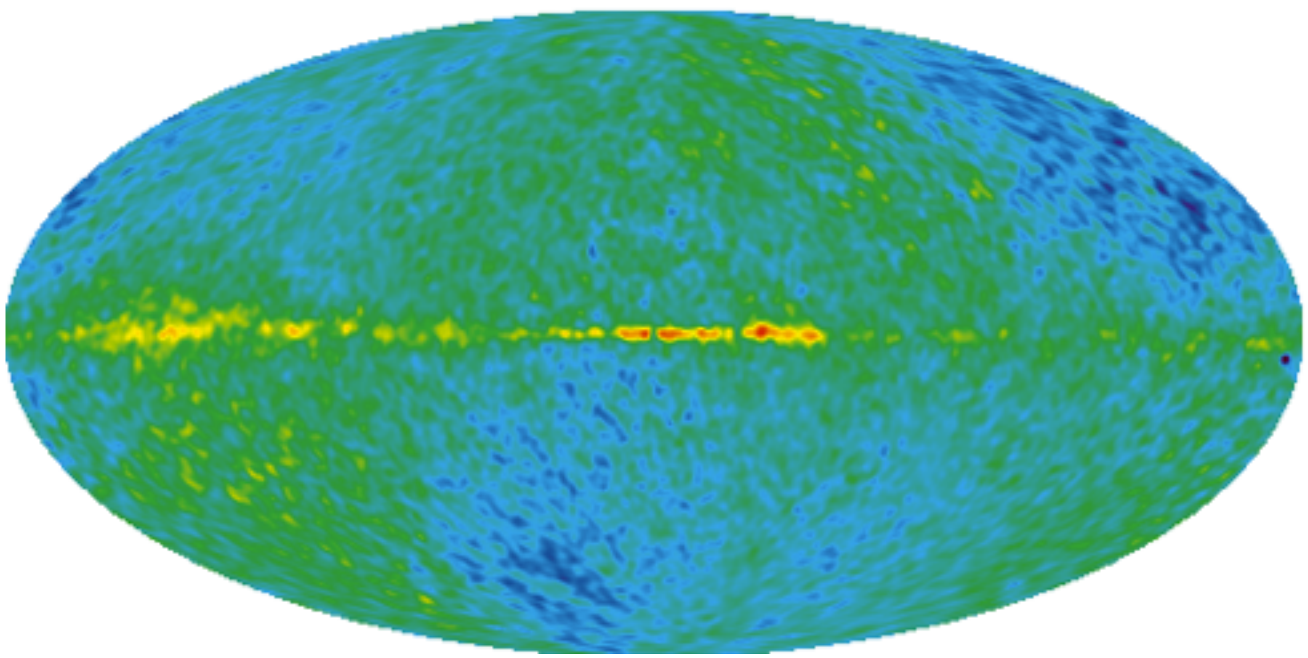
Stokes Q



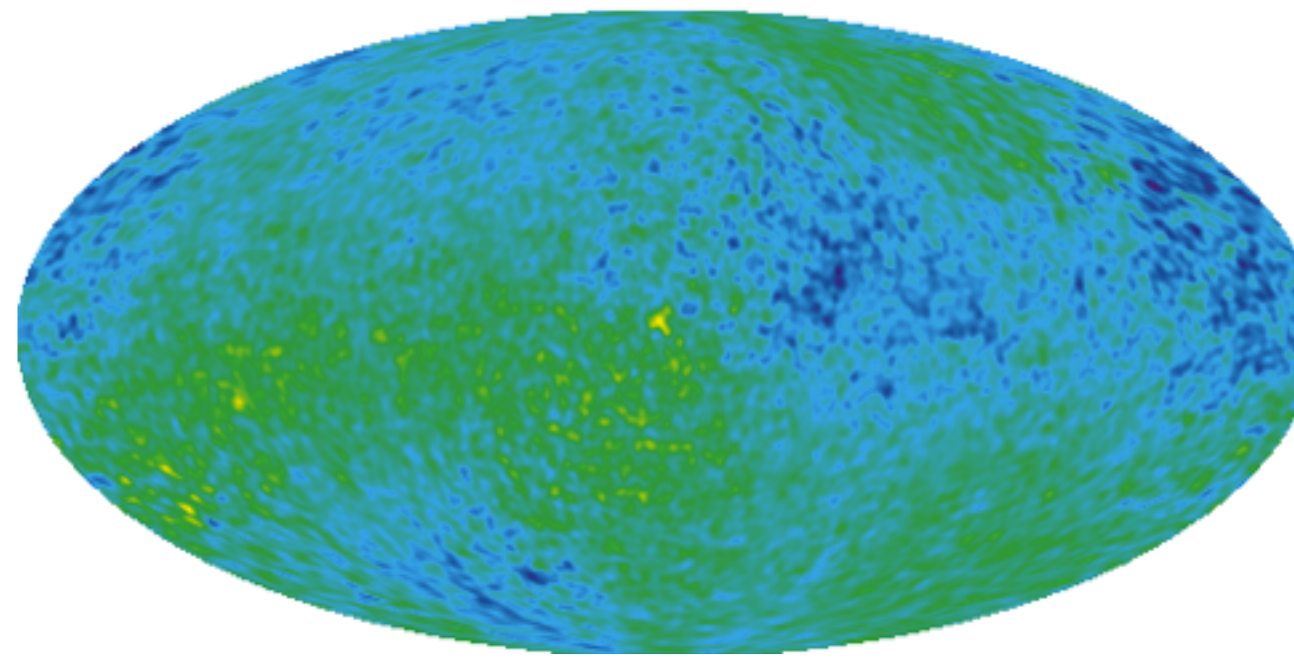
Stokes U

WMAP Collaboration

94 GHz



Stokes Q



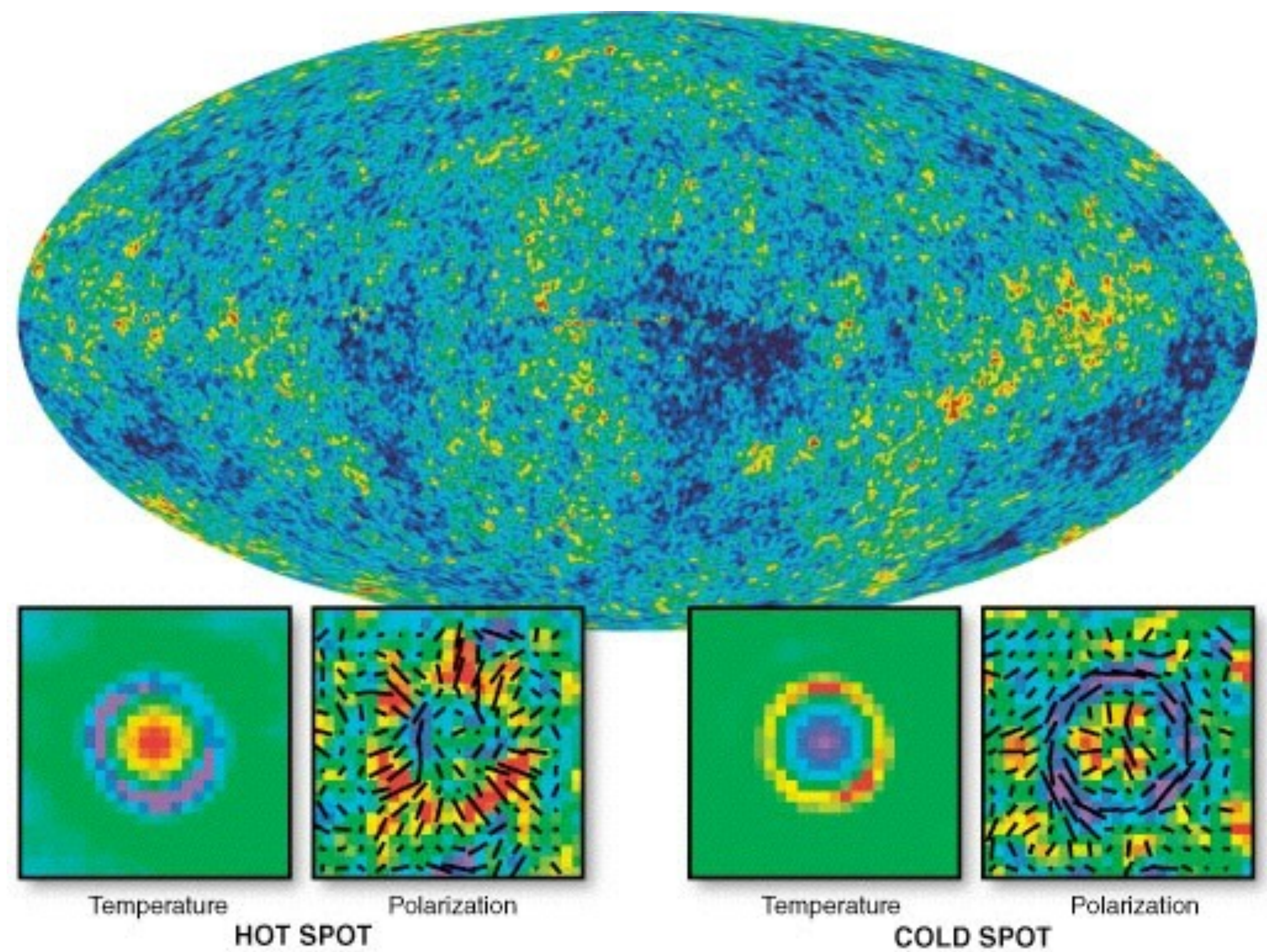
Stokes U

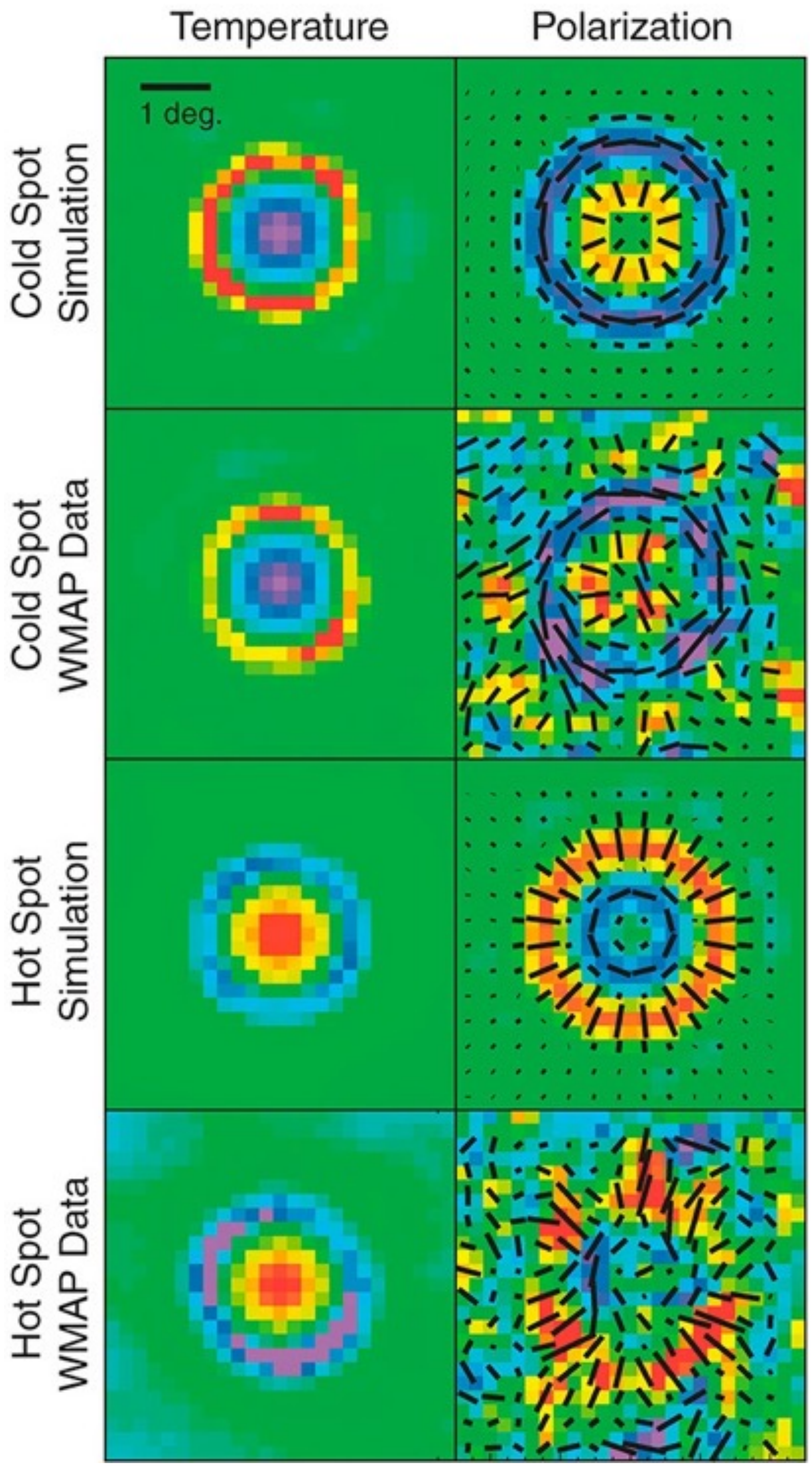
How many components?

- 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



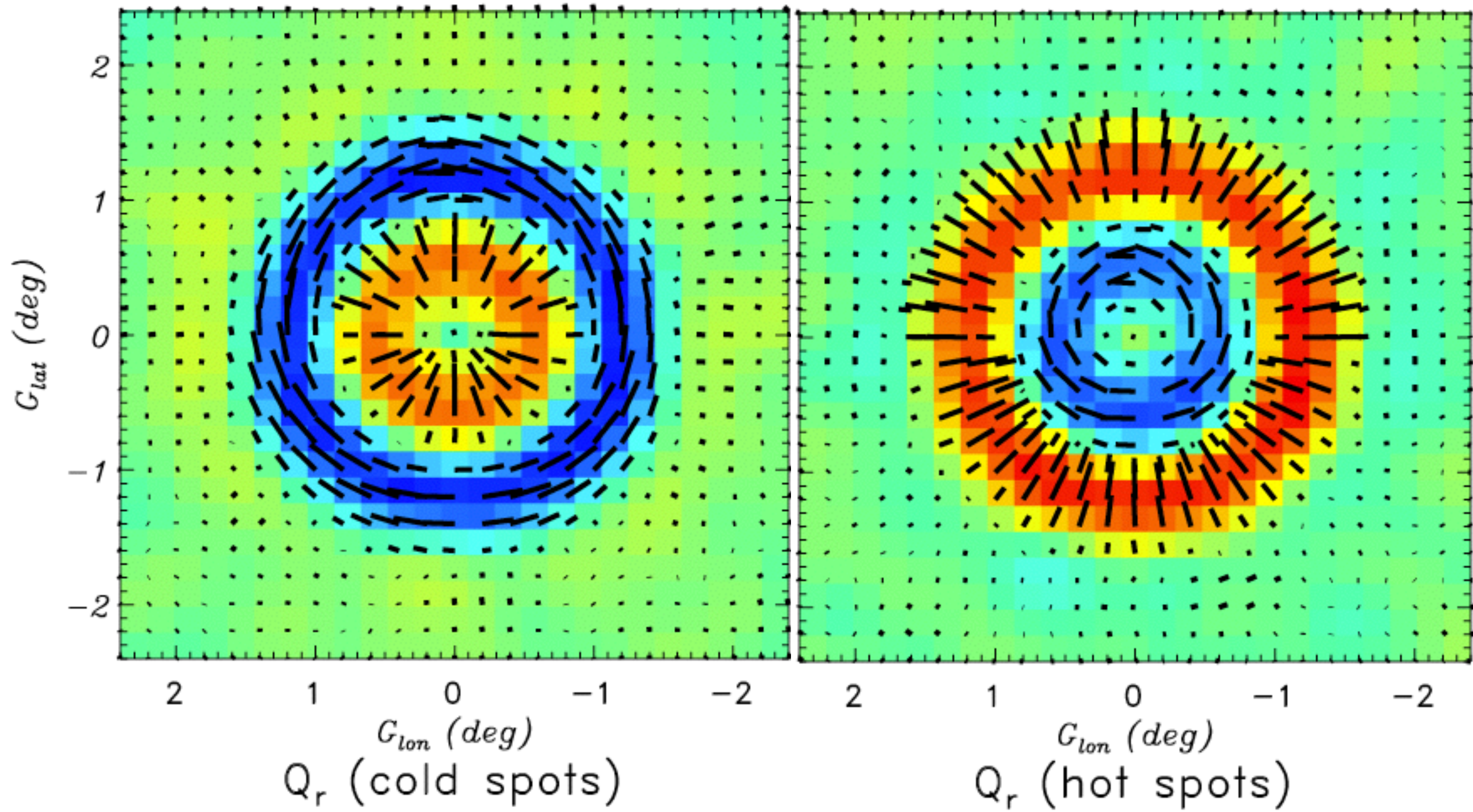


WMAP Collaboration

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**”

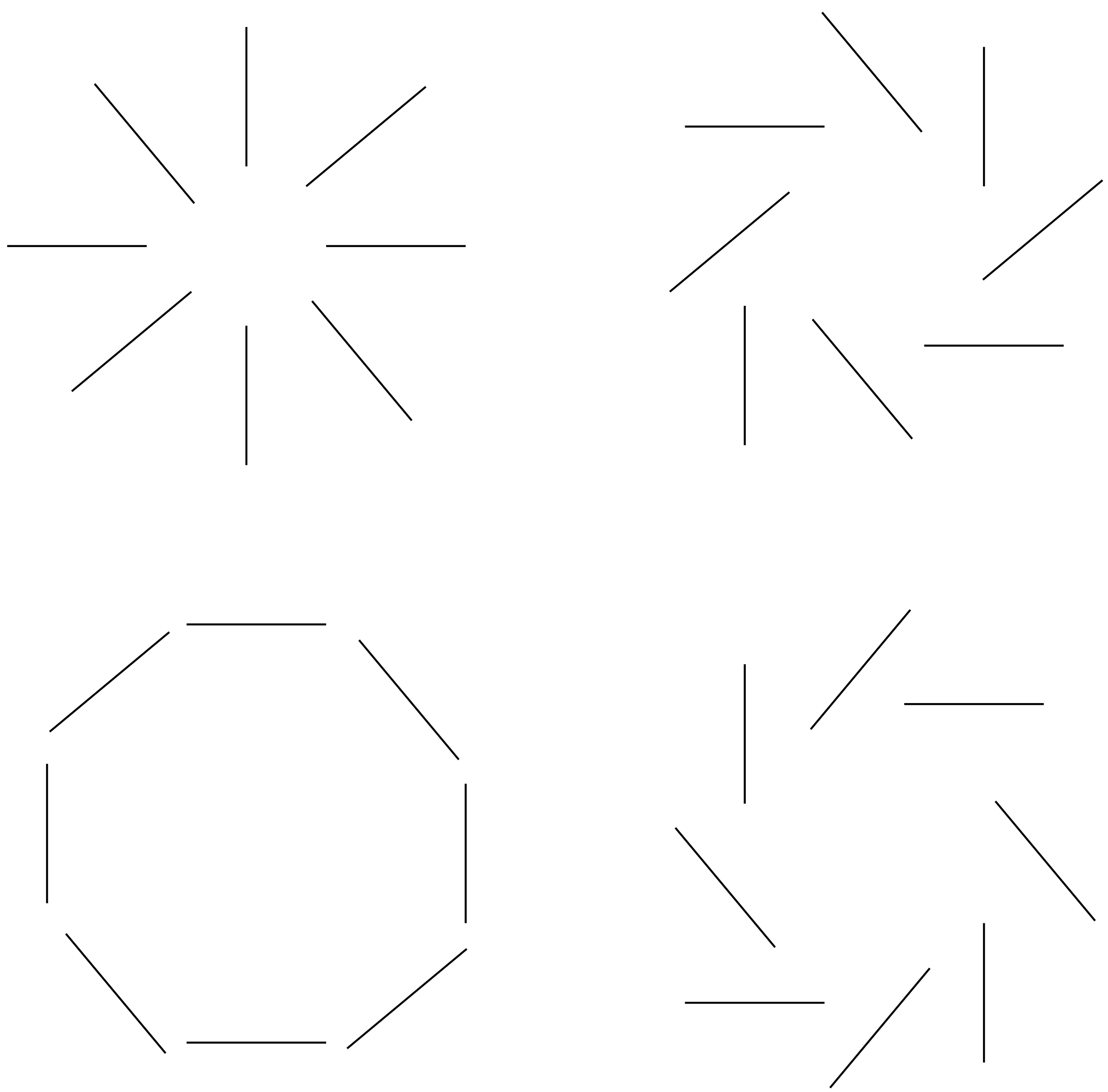
Planck Data!



2
1
0
−1
−2
G_{lat} (deg)
2
1
0
−1
−2
G_{lon} (deg)
Q_r (cold spots)
2
1
0
−1
−2
G_{lon} (deg)
Q_r (hot spots)

Seljak & Zaldarriaga (1997); Kamionkowski et al. (1997)

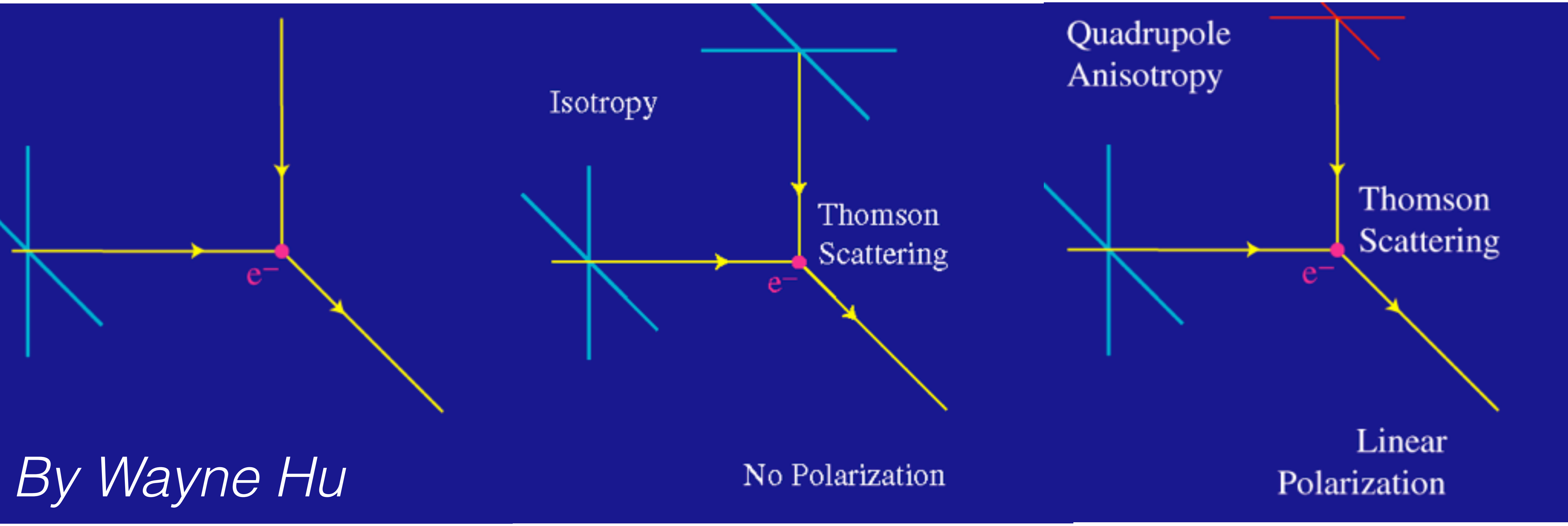
E and B modes



E mode B mode

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

Physics of CMB Polarisation

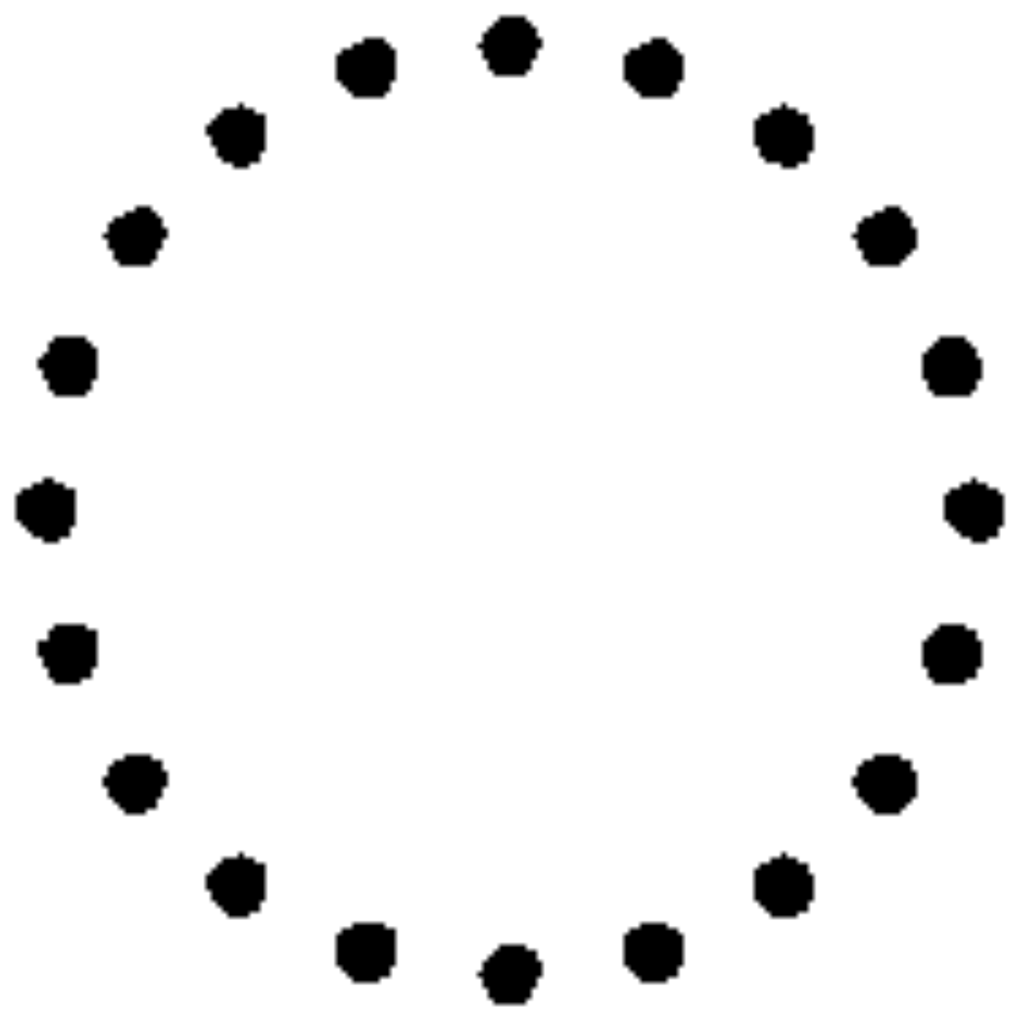


- Necessary and sufficient conditions for generating polarisation in CMB:
    - Thomson scattering
    - Quadrupolar temperature anisotropy around an electron

Origin of Quadrupole

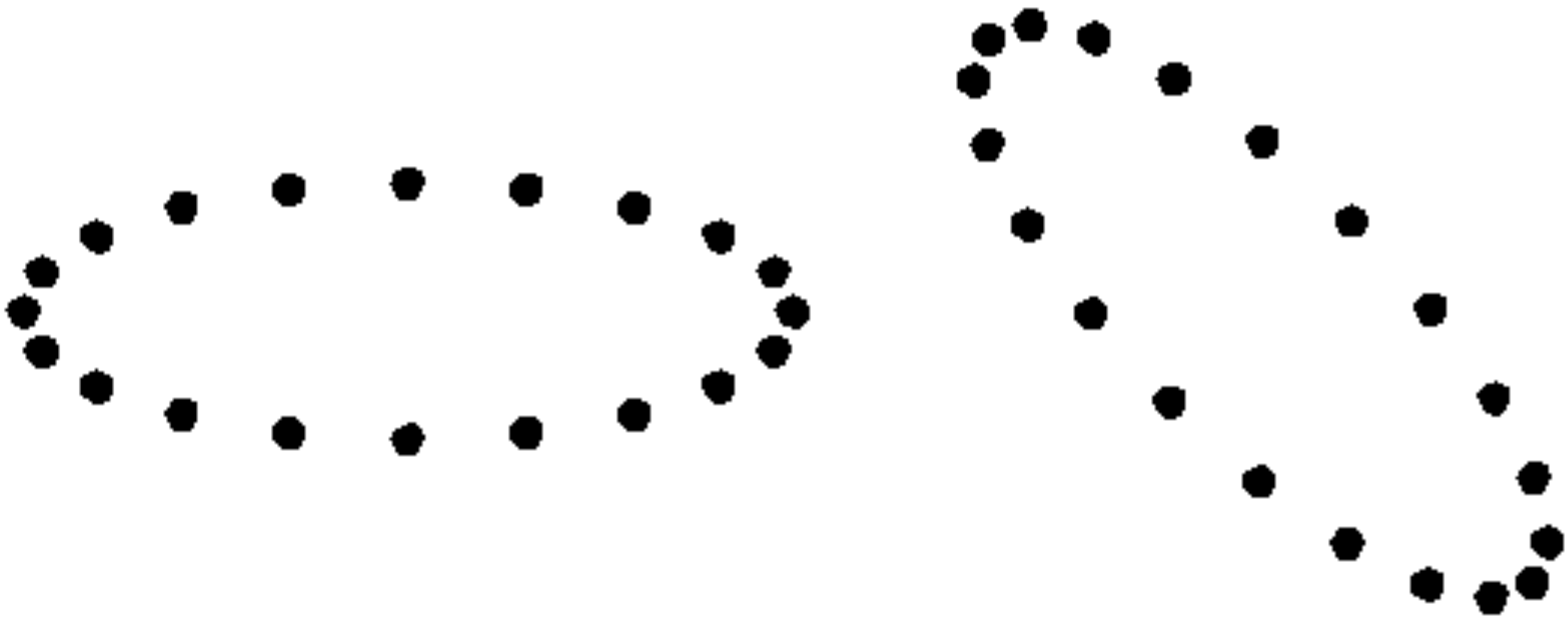
- **Scalar perturbations**: motion of electrons with respect to photons
- **Tensor perturbations**: gravitational waves

Gravitational waves are coming toward you!



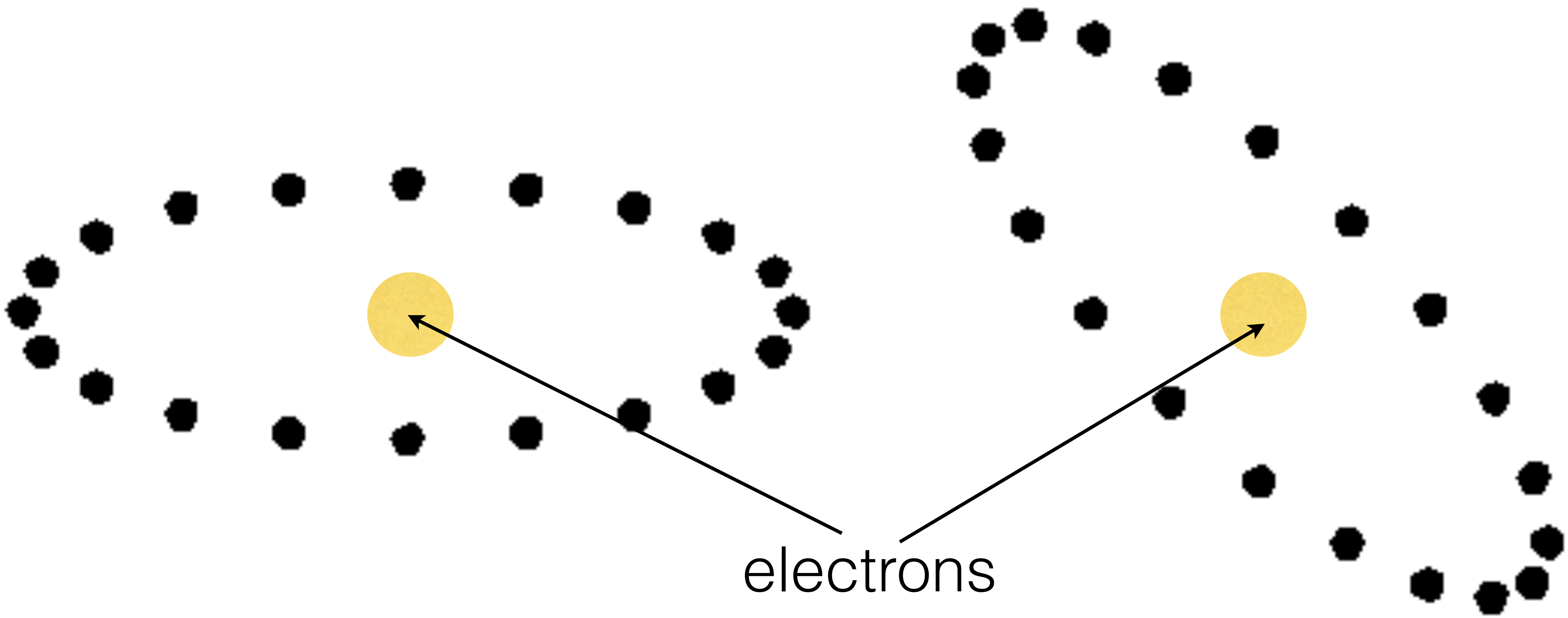
- What do they do to the distance between particles?

Two GW modes

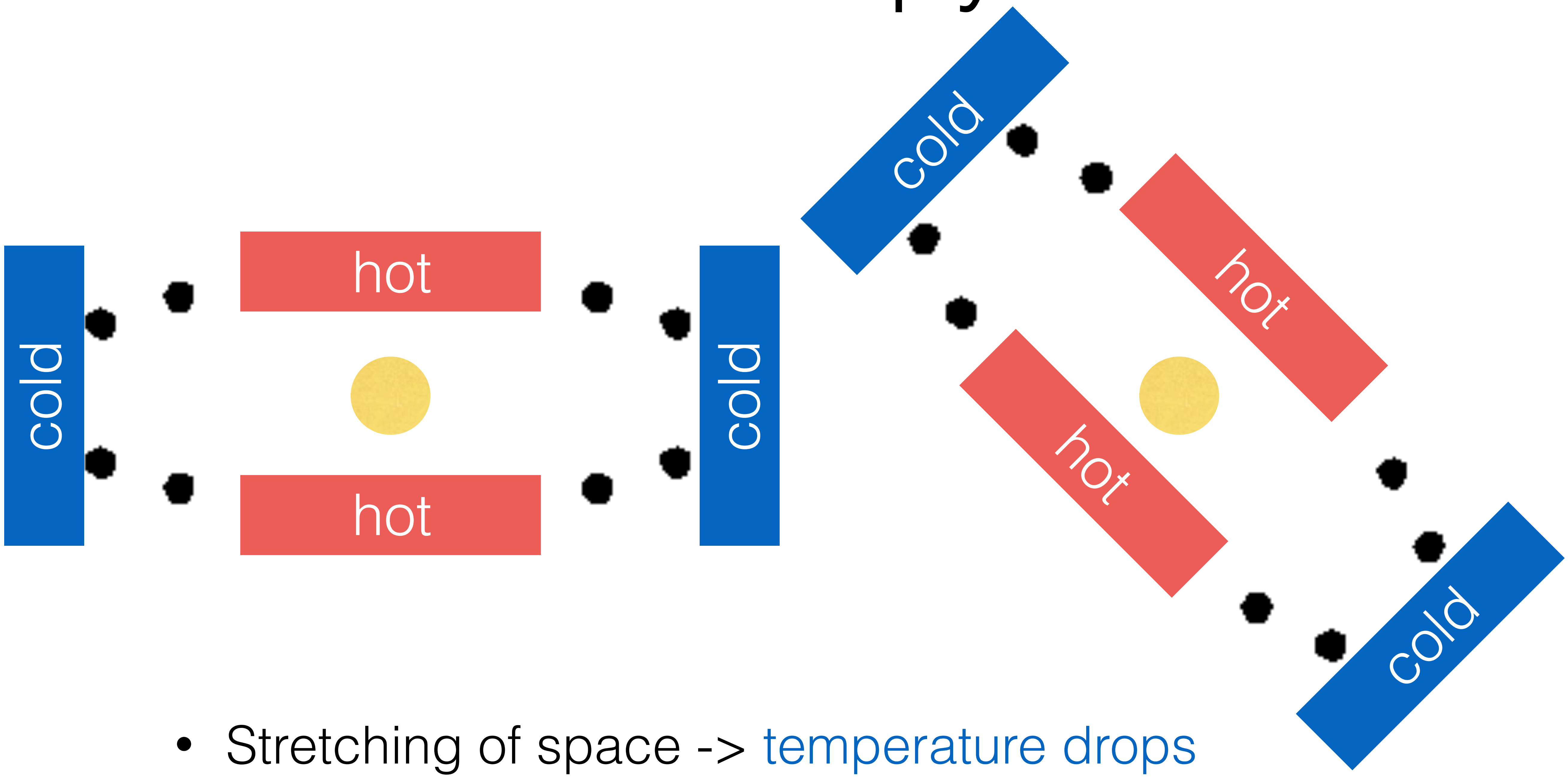


- Anisotropic stretching of space generates quadrupole temperature anisotropy. How?

GW to temperature anisotropy

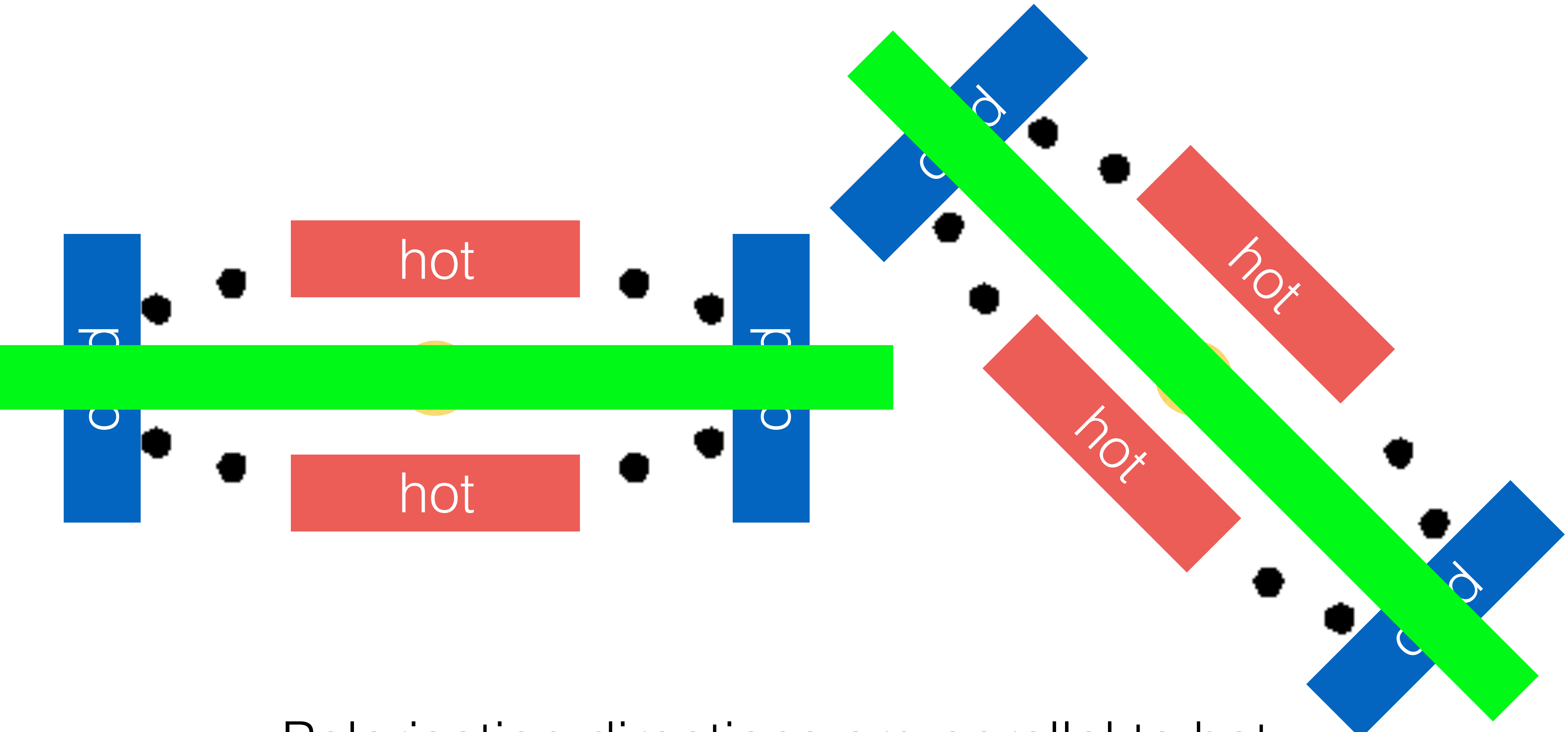


GW to temperature anisotropy



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

Then to polarisation!



- Polarisation directions are parallel to hot regions

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

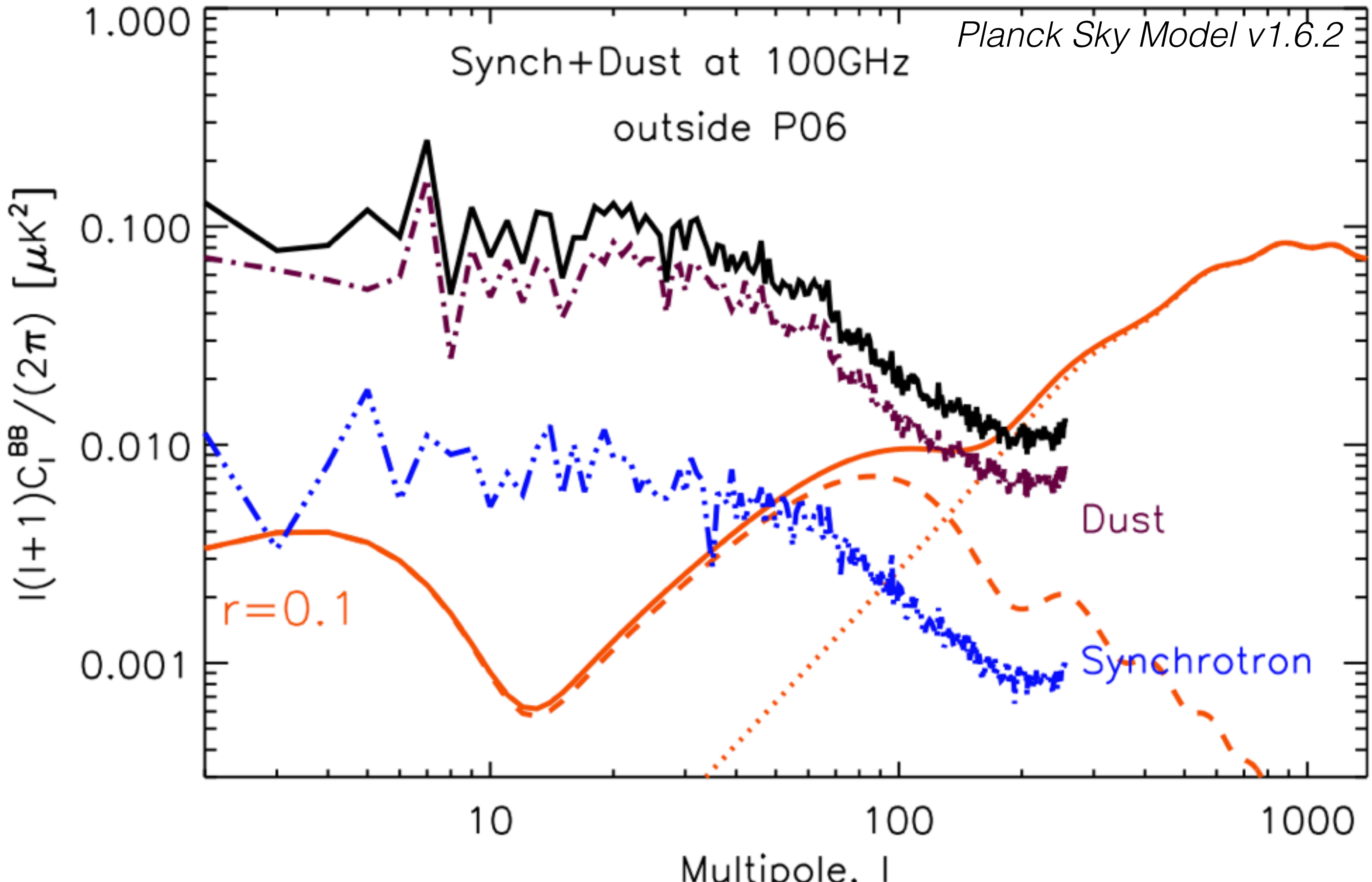
  - The important point is that **h_+ and $h_\times$ always coexist**. When a linear combination of h_+ and $h_\times$ produces E, another combination produces B

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]

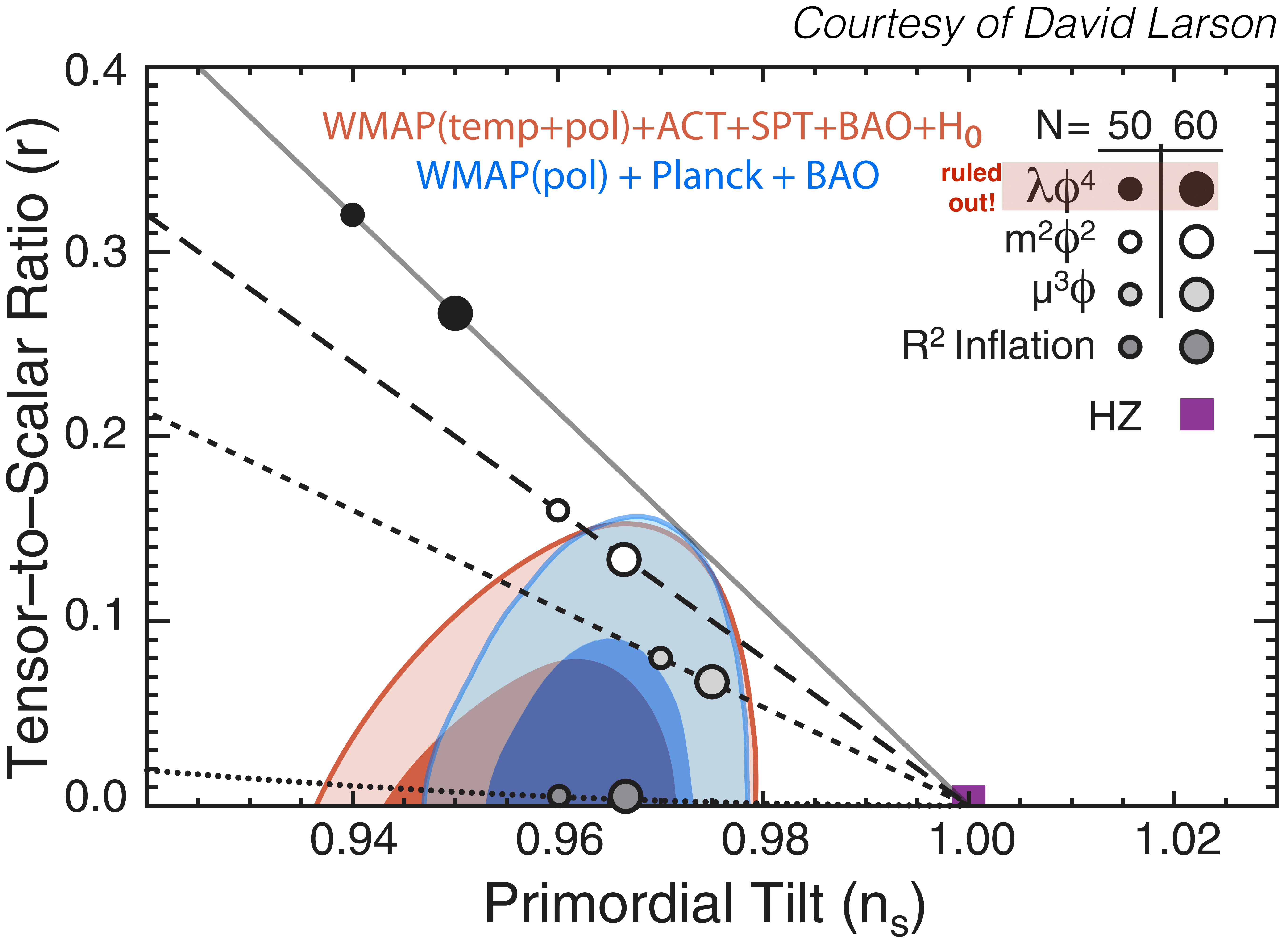
Katayama & Komatsu (2011)



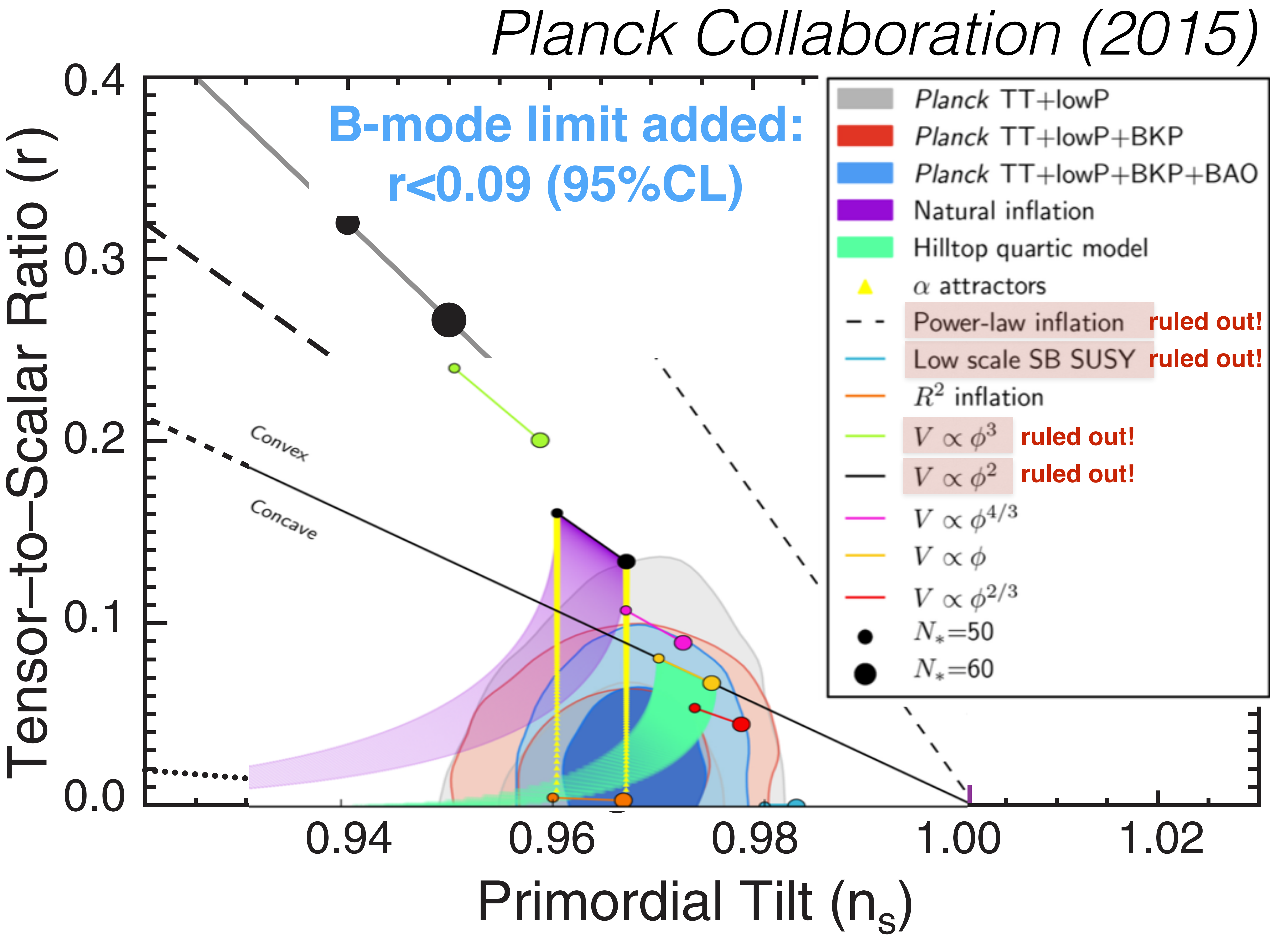
- At 100 GHz, the total foreground emission is a couple of orders of magnitude bigger in power at l<10

If B-mode is found…

- Then what?
- The next step is to nail the specific model of inflation



Courtesy of David Larson
WMAP(temp+pol)+ACT+SPT+BAO+H_0
WMAP(pol) + Planck + BAO
N= 50 60
ruled out!
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
R^2 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 (n_s)



Planck Collaboration (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!
R^2 inflation
$V \propto \phi^3$ ruled out!
$V \propto \phi^2$ ruled out!
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
N_*=50
N_*=60

Summary

- *Why B-mode?*
  - Definitive evidence for inflation by showing *dH/dt* is small, hence **the accelerating universe!**
- We must show that the primordial gravitational waves have a **near scale-invariant power spectrum**
- Of course we need to find it first. **Challenges: systematics, foreground, & lensing.** All topics will be discussed extensively throughout this workshop!