Critical Tests of Theory of the Early Universe using the Cosmic Microwave Background

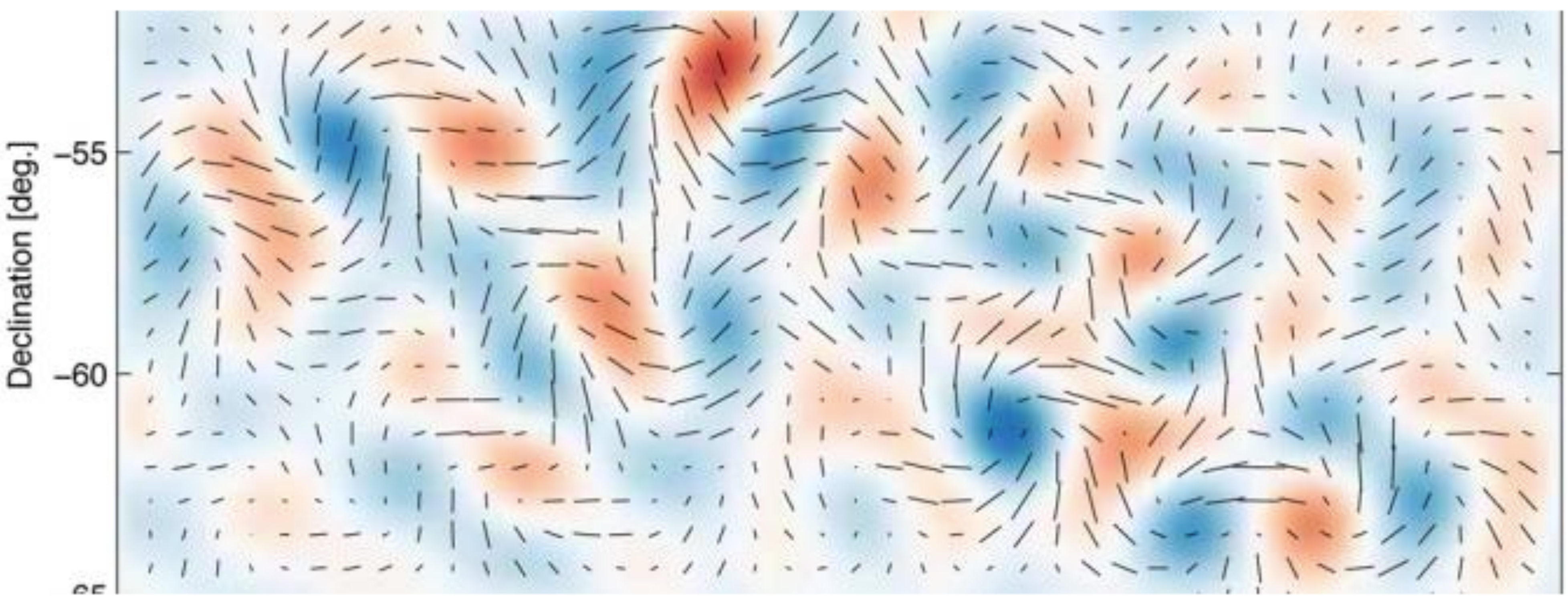
Eiichiro Komatsu, Max-Planck-Institut für Astrophysik
Kavli IPMU–RIKEN–Osaka Symposium
November 6, 2014

March 17, 2014

BICEP2’s announcement

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.

Researchers from the BICEP2 collaboration today announced the first direct evidence for this cosmic inflation. Their data also represent the first images of gravitational waves, or ripples in space-time. These waves have been described as the "first tremors of the Big Bang." Finally, the data confirm a deep connection between quantum mechanics and general relativity.

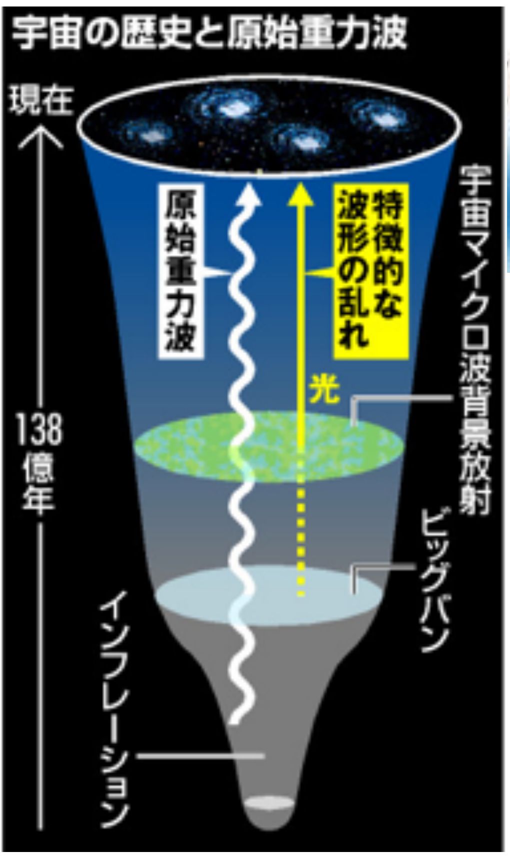
"Detecting this signal is one of the most important goals in cosmology today. A lot of work by a lot of people has led up to this point," said John Kovac (Harvard-Smithsonian Center for Astrophysics), leader of the BICEP2 collaboration.

HARVARD-SMITHSONIAN
CENTER FOR AS

About Research Education &

First Direct Evidence of Cosmic

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



BBC News Sport Weather Capital Future Shop

NEWS SCIENCE & ENVIRONMENT

Home | UK | Africa | Asia | Europe | Latin America | Mid-East | US & Canada | Business | Health | Sci/Environ

17 March 2014 Last updated at 14:46 GMT

Share

Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos
Science correspondent, BBC News

The New York Times

SPACE & COSMOS

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

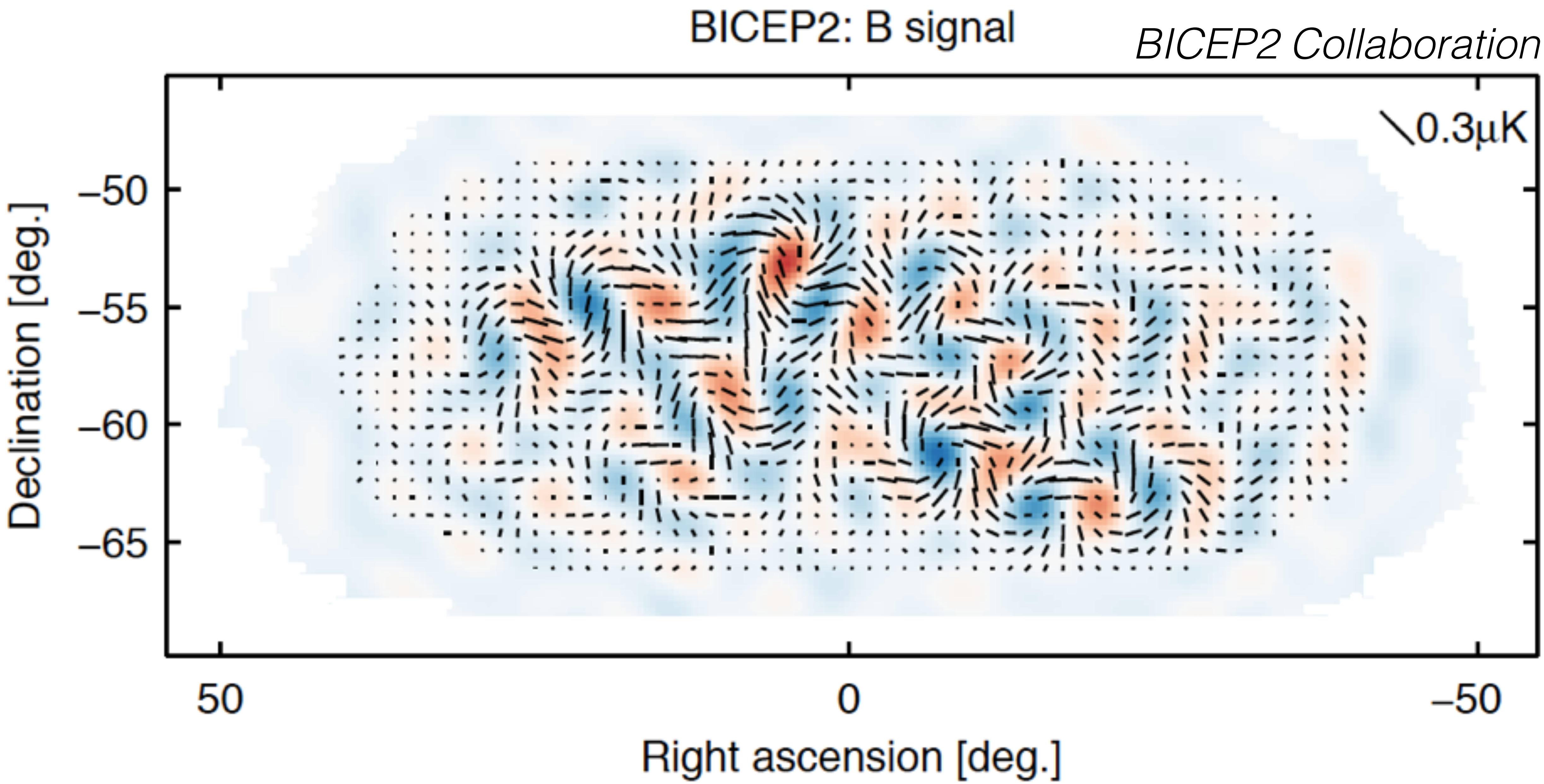
the first fleeting fraction of a second, the universe expanded exponentially, stretching
telescopes. All this, of course, was just theory.

朝日新聞 DIGITAL

宇宙誕生直後の瞬間膨張、インフレーション初観測　米チーム

2014年3月18日05時00分

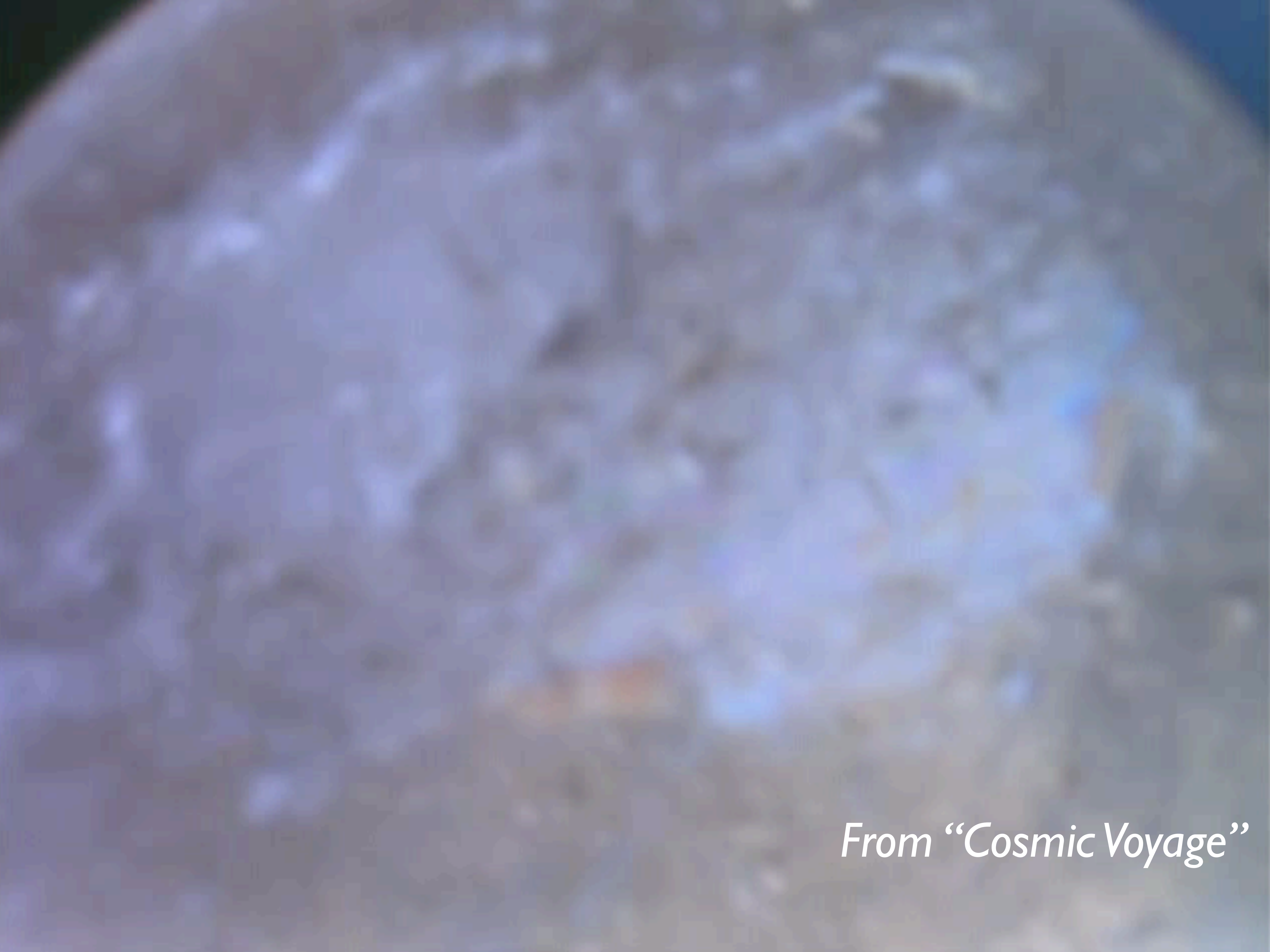
Signature of Cosmic Inflation in the Sky [?]



One of the goals of this presentation is to help you understand what this figure is actually showing

Breakthroughs in Cosmological Research Over the Last Two Decades

- We can actually **see** the physical condition of the universe when it was very young

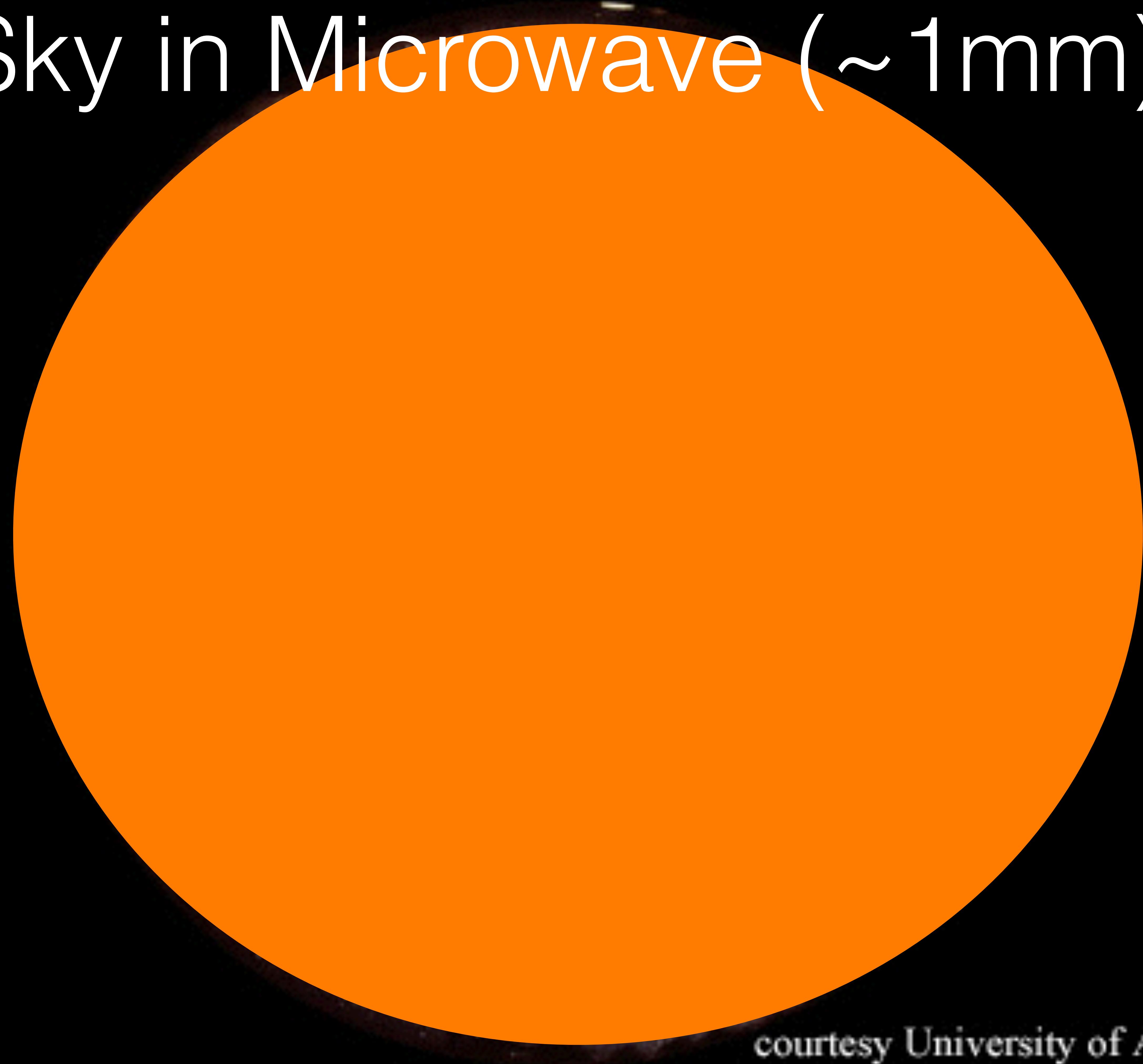


From “Cosmic Voyage”

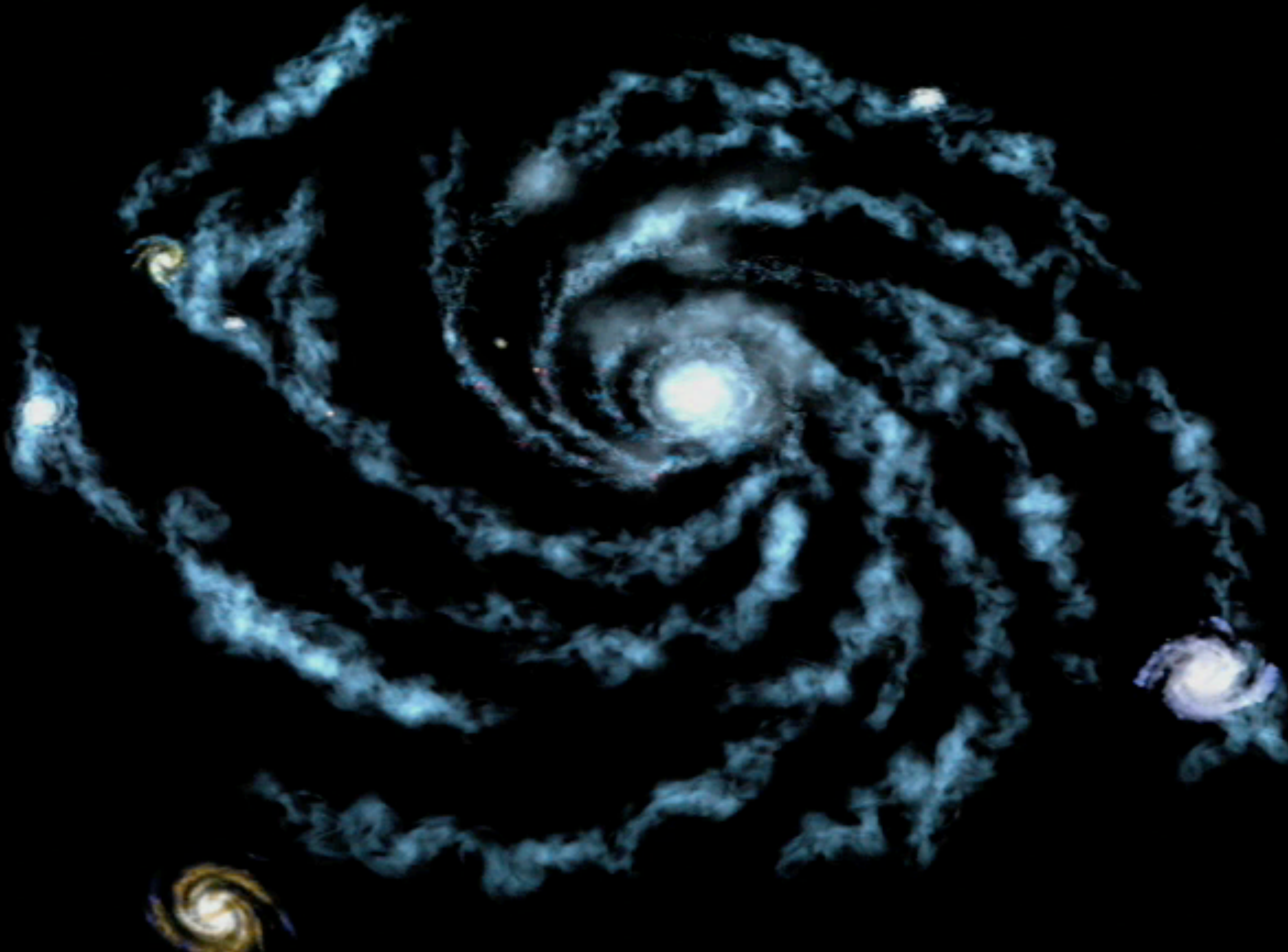
Sky in Optical (~0.5μm)

courtesy University of Arizona

Sky in Microwave (~1mm)

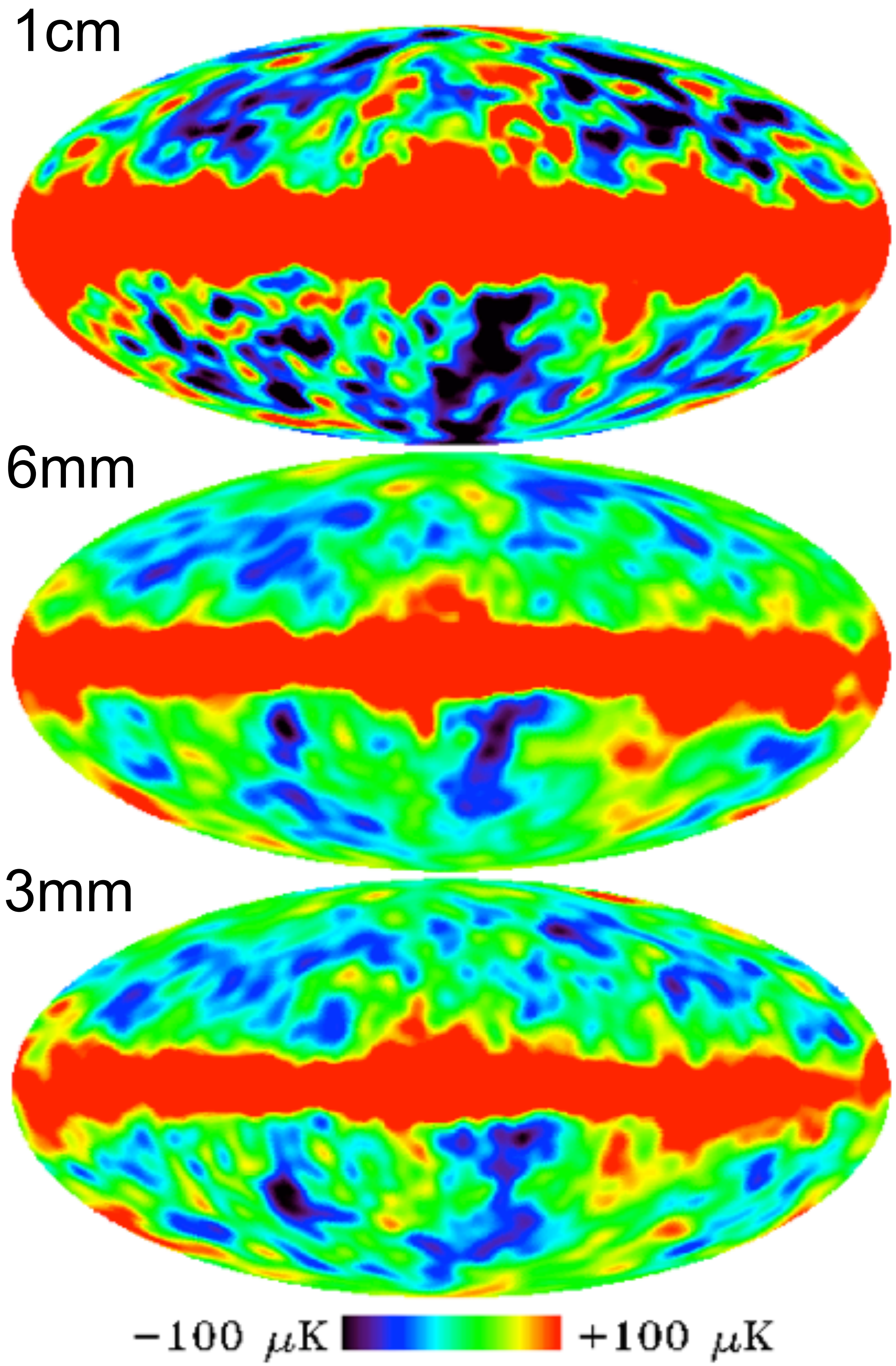


courtesy University of Arizona



Smoot et al. (1992)

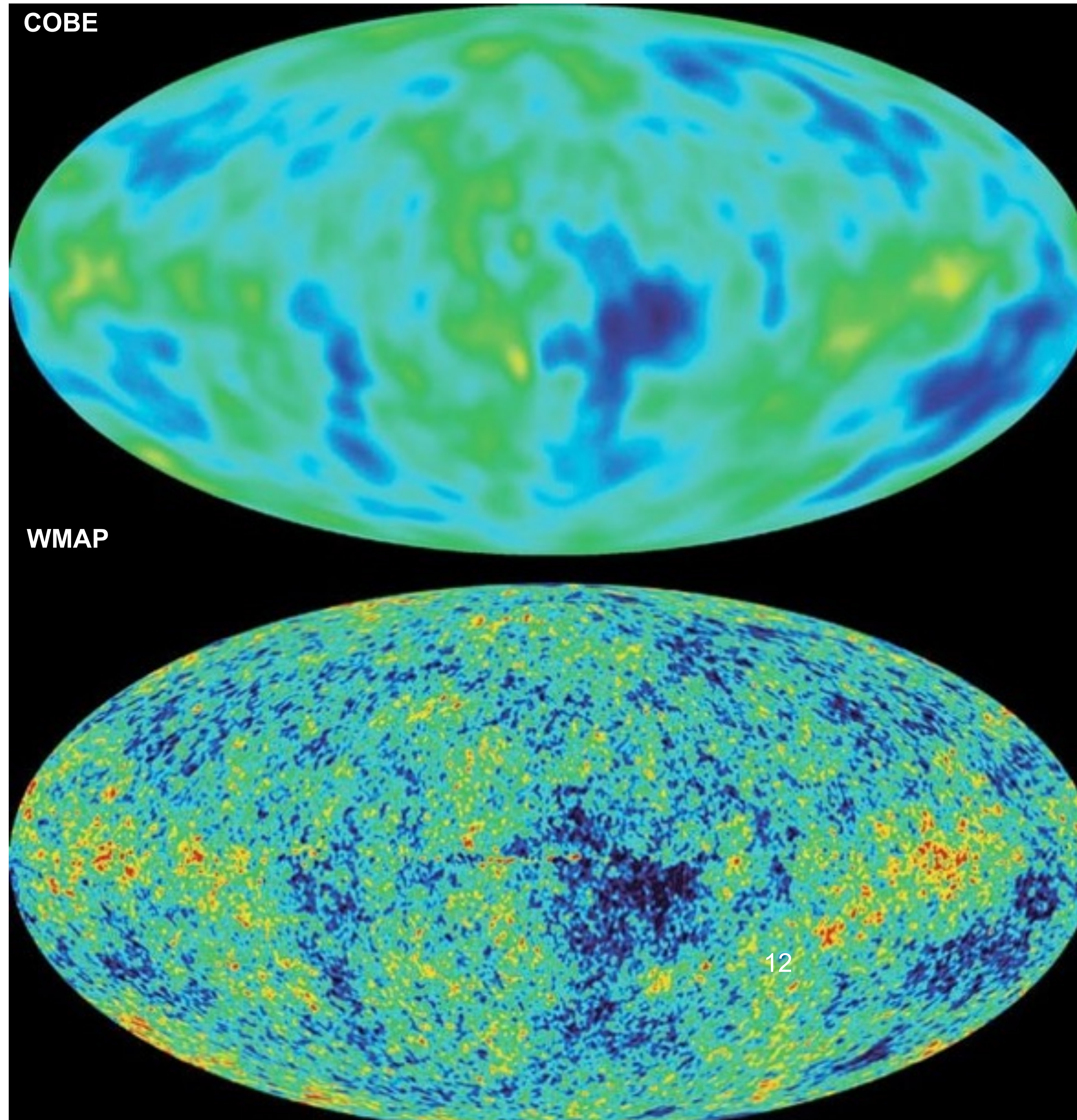
COBE/DMR, 1992



•CMB is anisotropic!
(at the 1/100,000 level)

COBE to WMAP

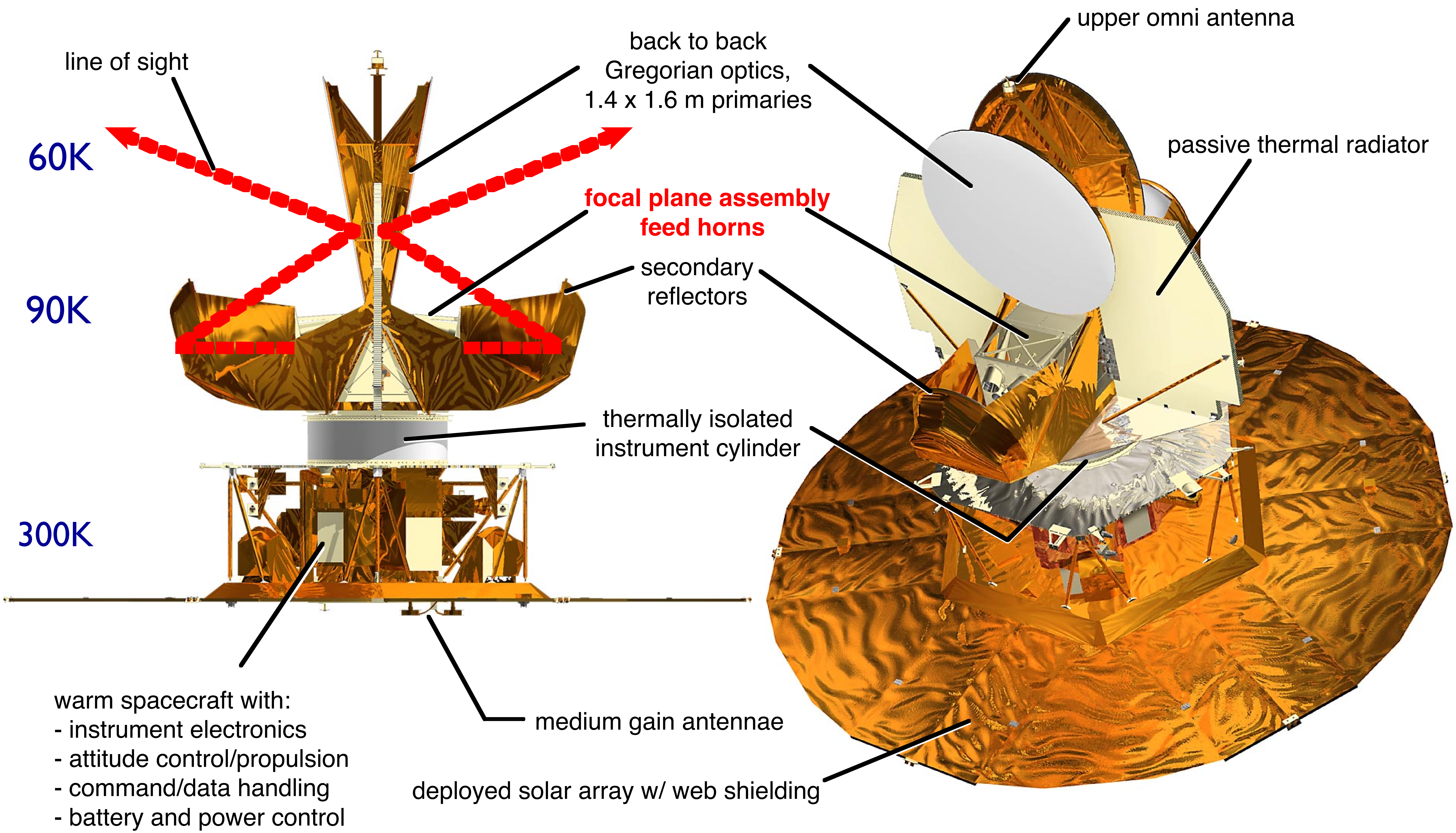
COBE
1989



WMAP
2001

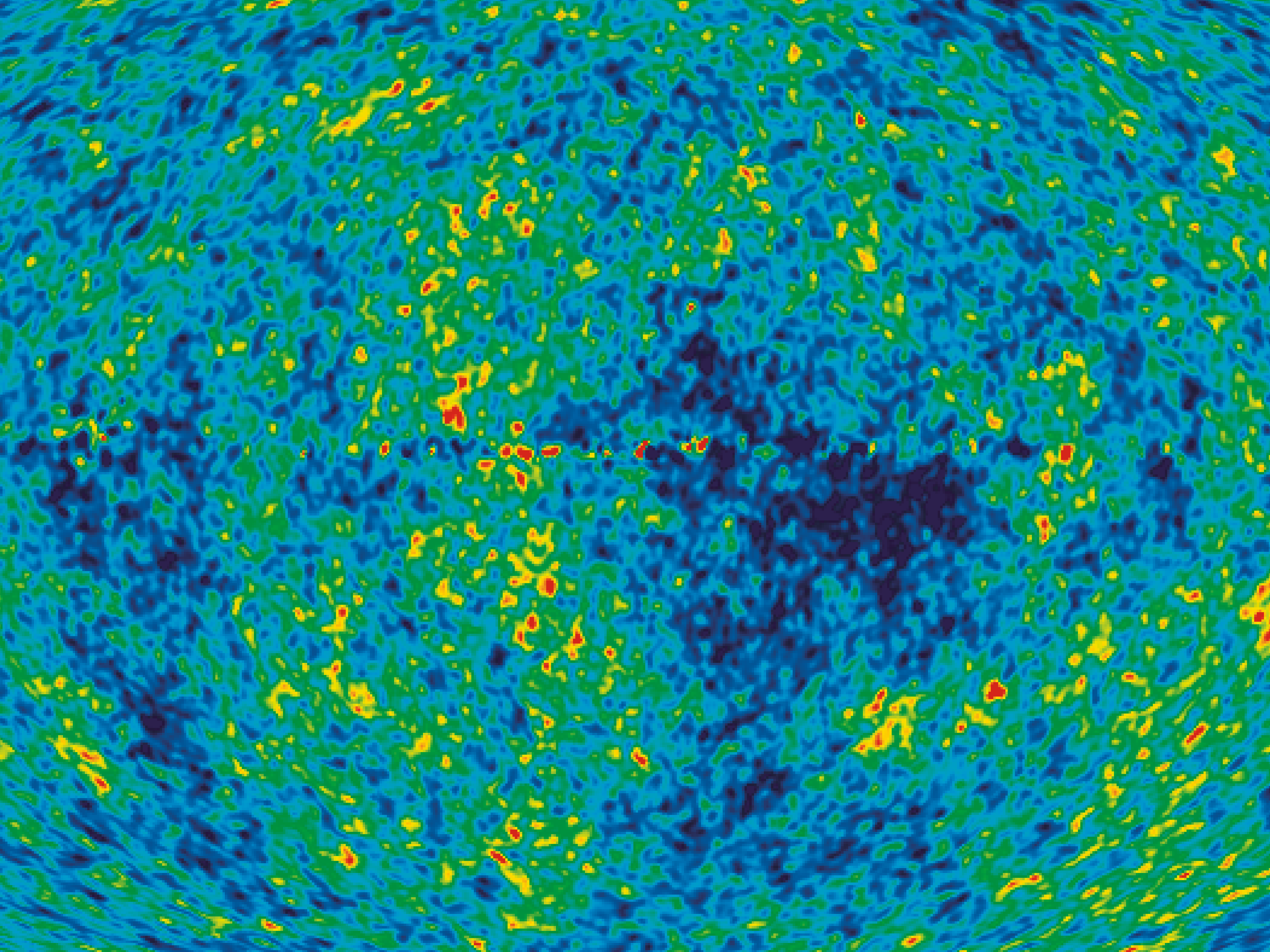
WMAP Spacecraft

Radiative Cooling: No Cryogenic System



AP990422

WMAP Science Team

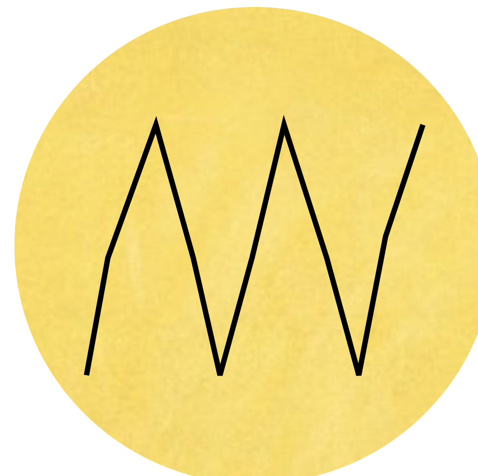


Outstanding Questions

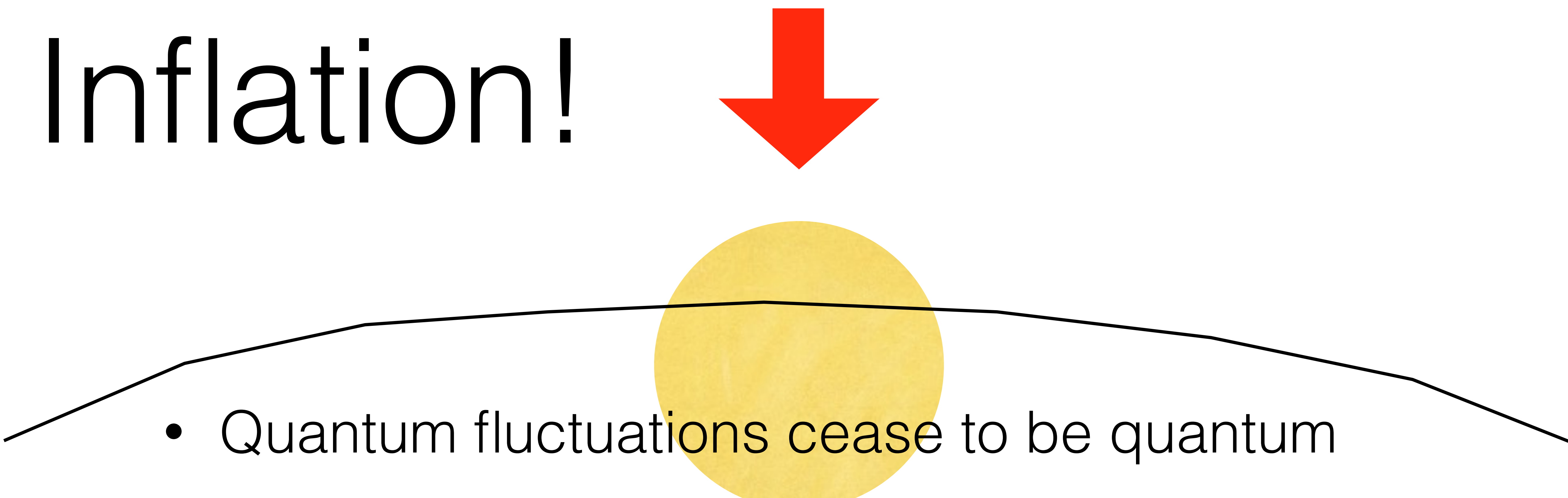
- Where does anisotropy in CMB temperature come from?
    - This is the origin of galaxies, stars, planets, and everything else we see around us, including ourselves
- The leading idea: **quantum fluctuations in vacuum, stretched to cosmological length scales** by a rapid exponential expansion of the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

Stretching Micro to Macro

Quantum fluctuations on microscopic scales



Inflation!



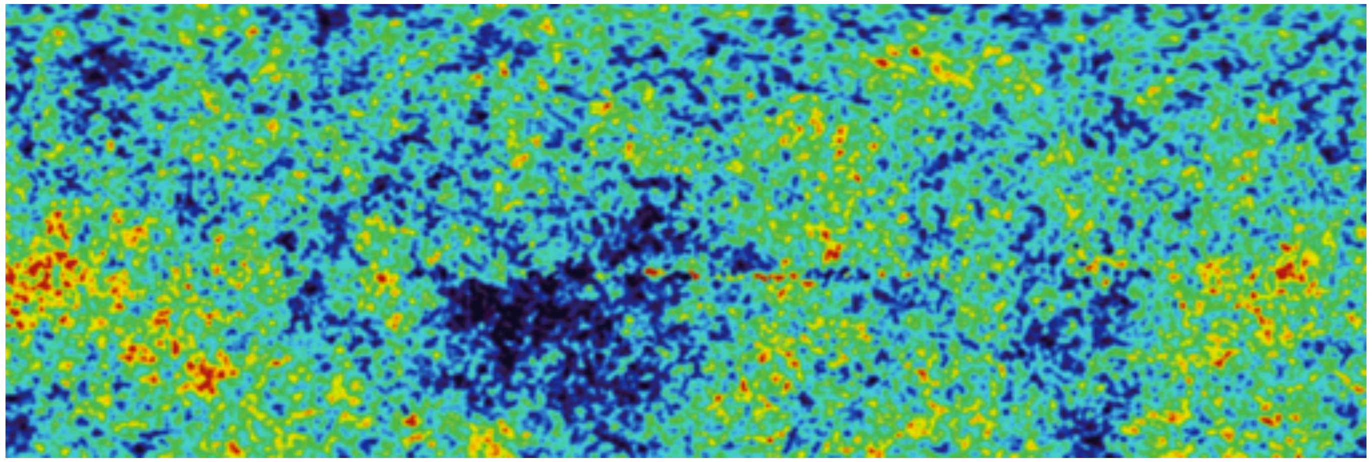
- Quantum fluctuations cease to be quantum
- Become macroscopic, classical fluctuations

Key Predictions of Inflation

ζ

scalar mode

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



h_{ij}

tensor mode

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

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)

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

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 current upper bound: r<0.1** [WMAP & Planck]

Fluctuations are proportional to H

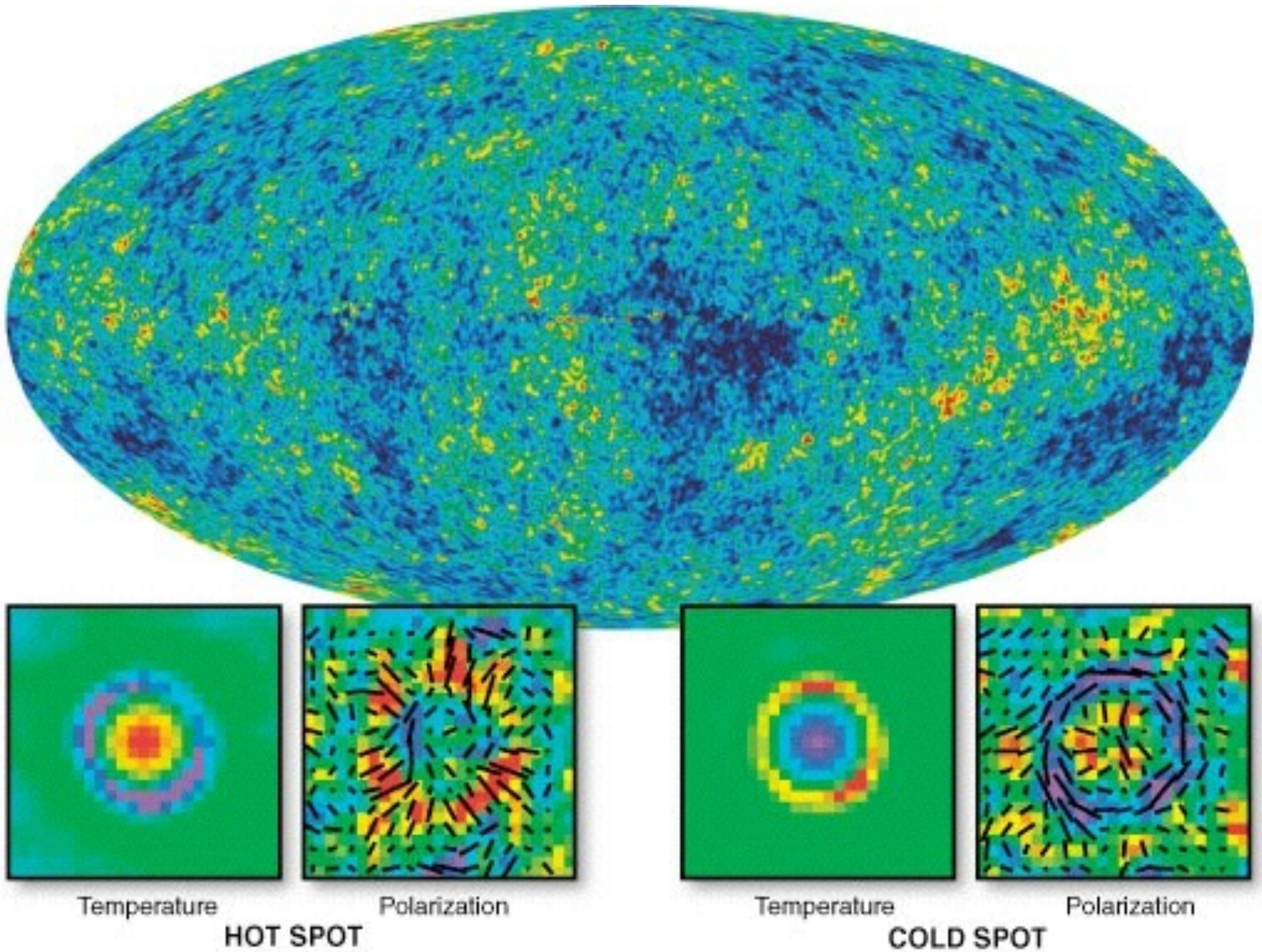
- [Energy you can borrow] x [Time you borrow] = constant
- $H \equiv \frac{\dot{a}}{a}$ [This has units of 1/time]
- Then, **both ζ and h_{ij} are proportional to H**
- Inflation occurs in 10^{-36} second - this is such a short period of time that you can borrow a lot of energy! **H during inflation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

*WMAP 9-year Results (2012) and Planck 2013 Results

Key Predictions of Inflation

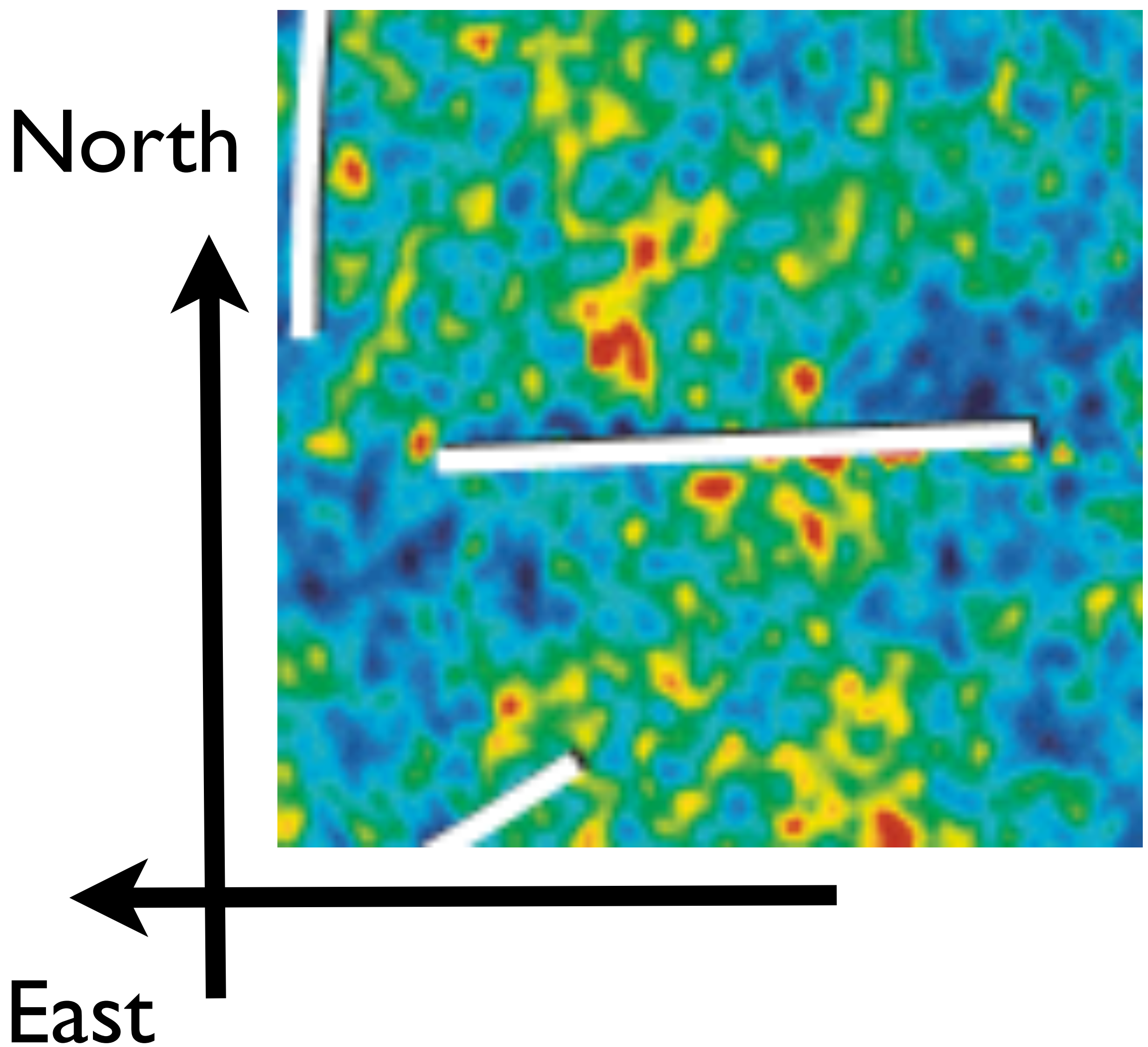
- Inflation must end; thus, H slowly decreases with time
  - This means that the amplitude of fluctuations on larger scales is bigger than those on smaller scales. **This has now been observed***
- The origin of fluctuations is quantum. The wave function of vacuum fluctuations of a free field is a Gaussian. **CMB anisotropy is Gaussian to better than 0.1% precision***
- There exist ultra long-wavelength primordial gravitational waves. **This is yet to be found. How can we find this?**

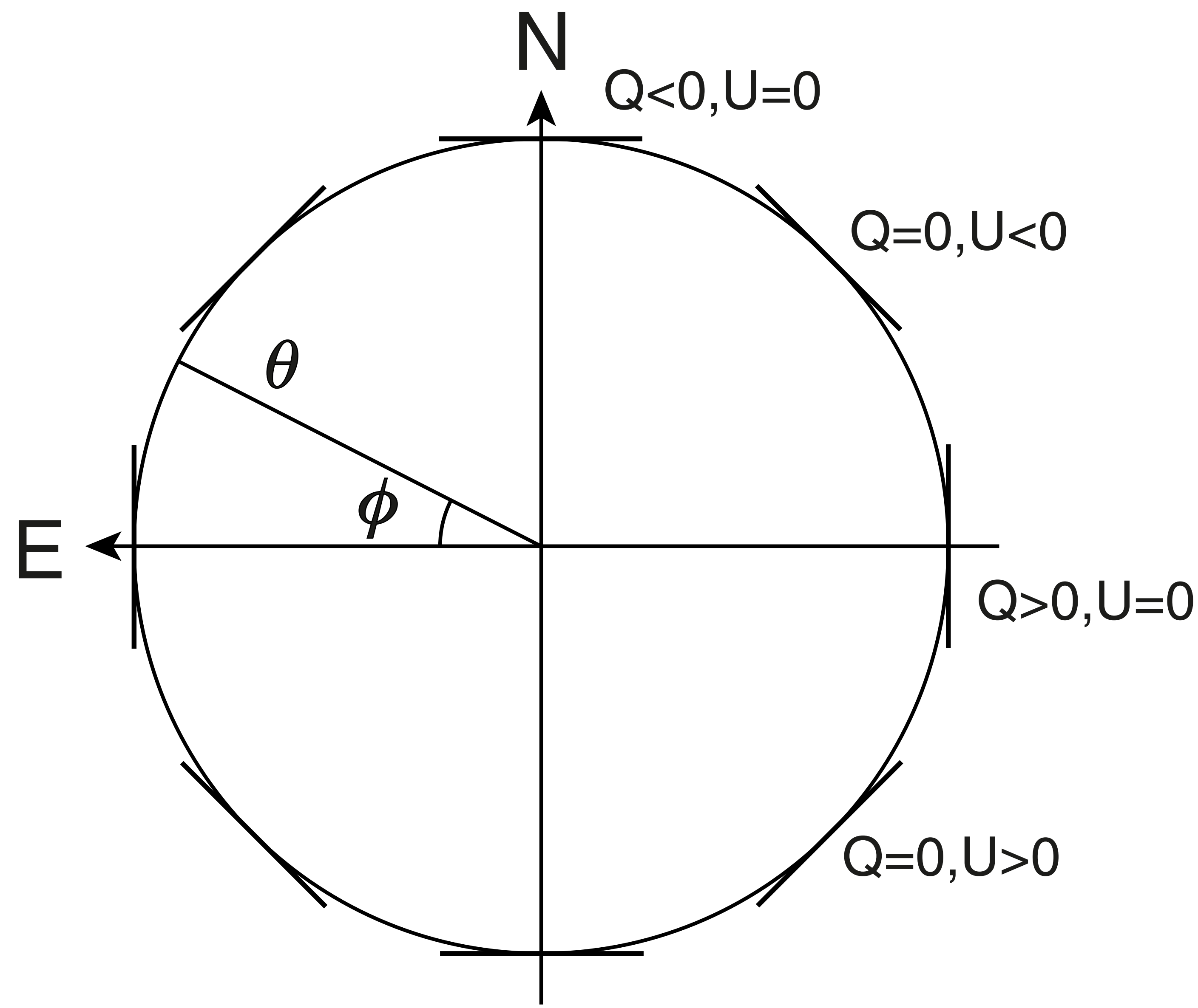
CMB Polarisation



- CMB is [weakly] polarised!

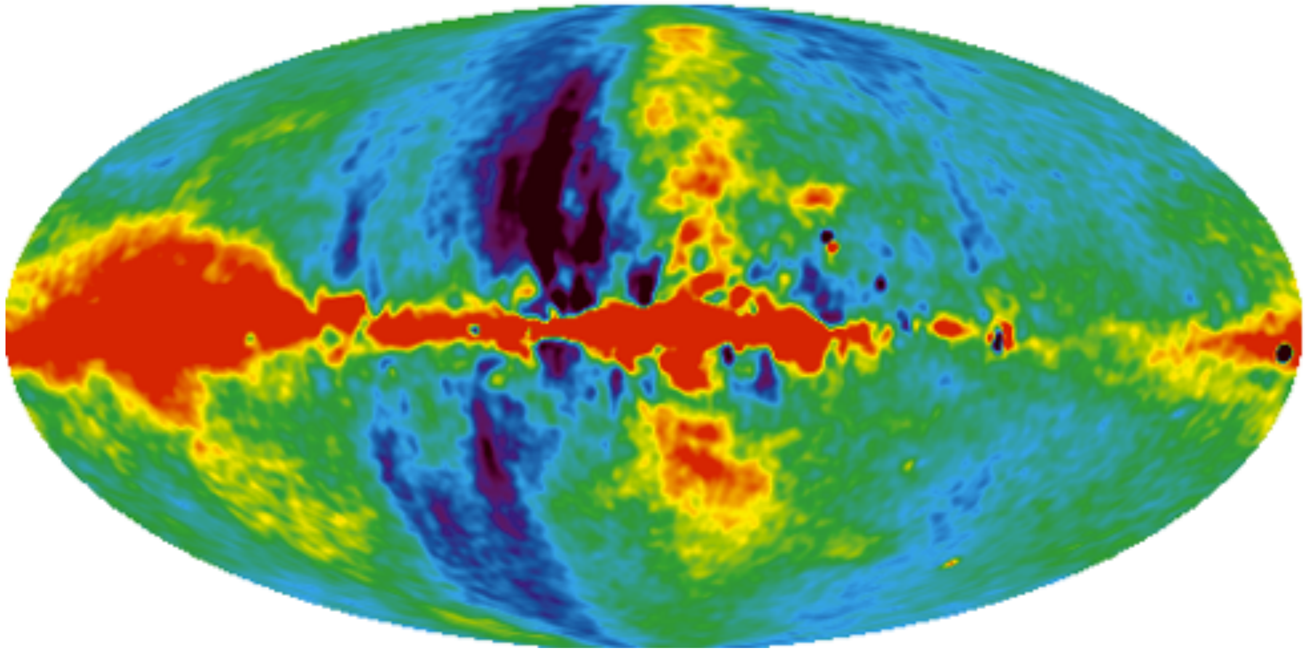
Stokes Parameters



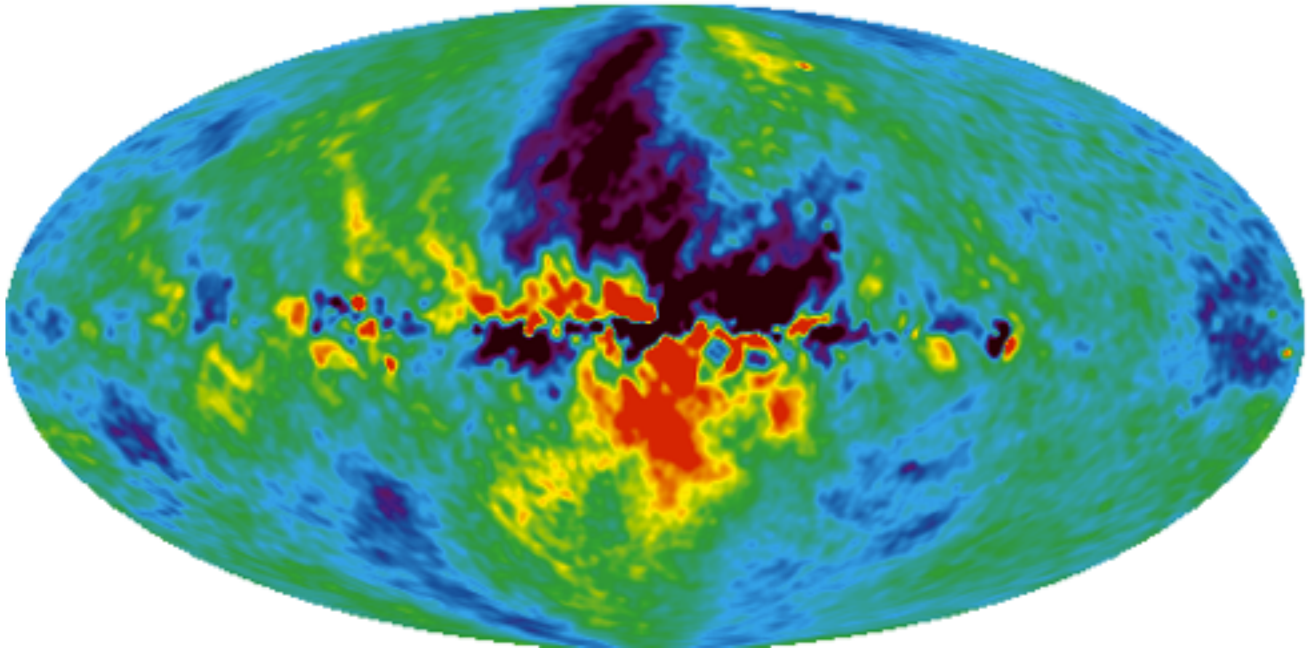


WMAP Collaboration

23 GHz

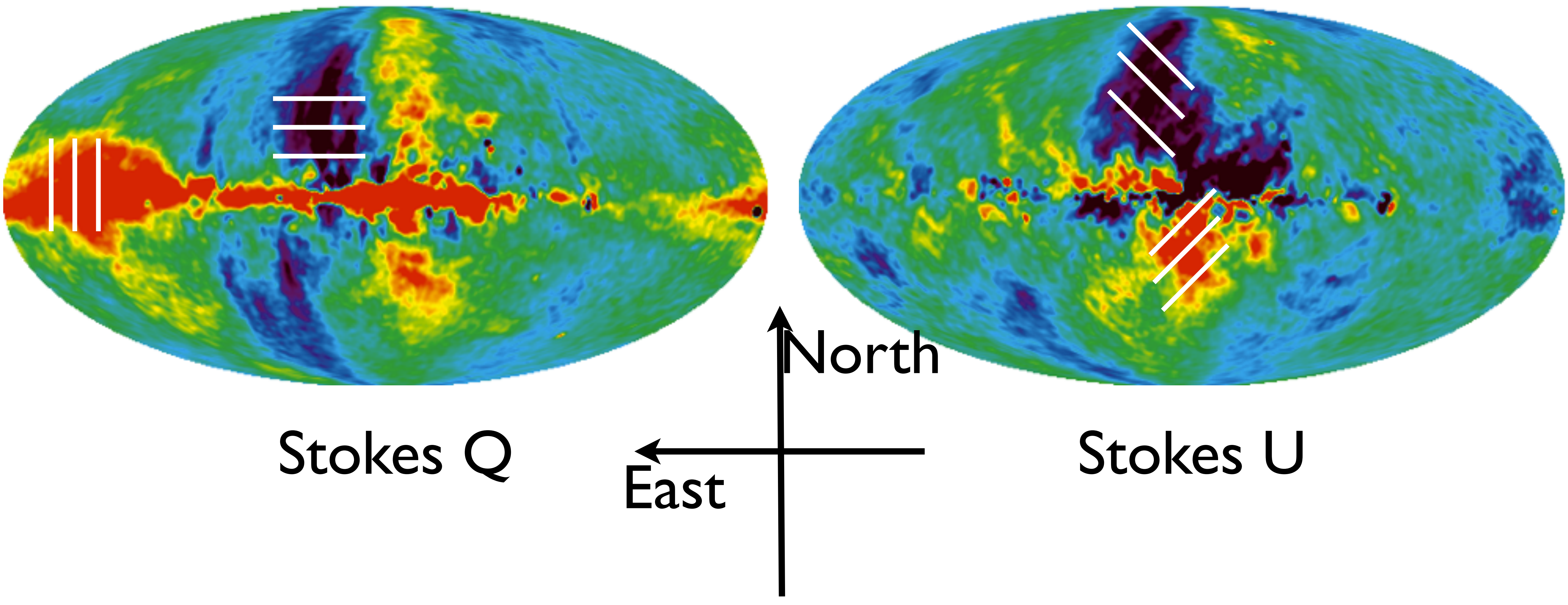


Stokes Q



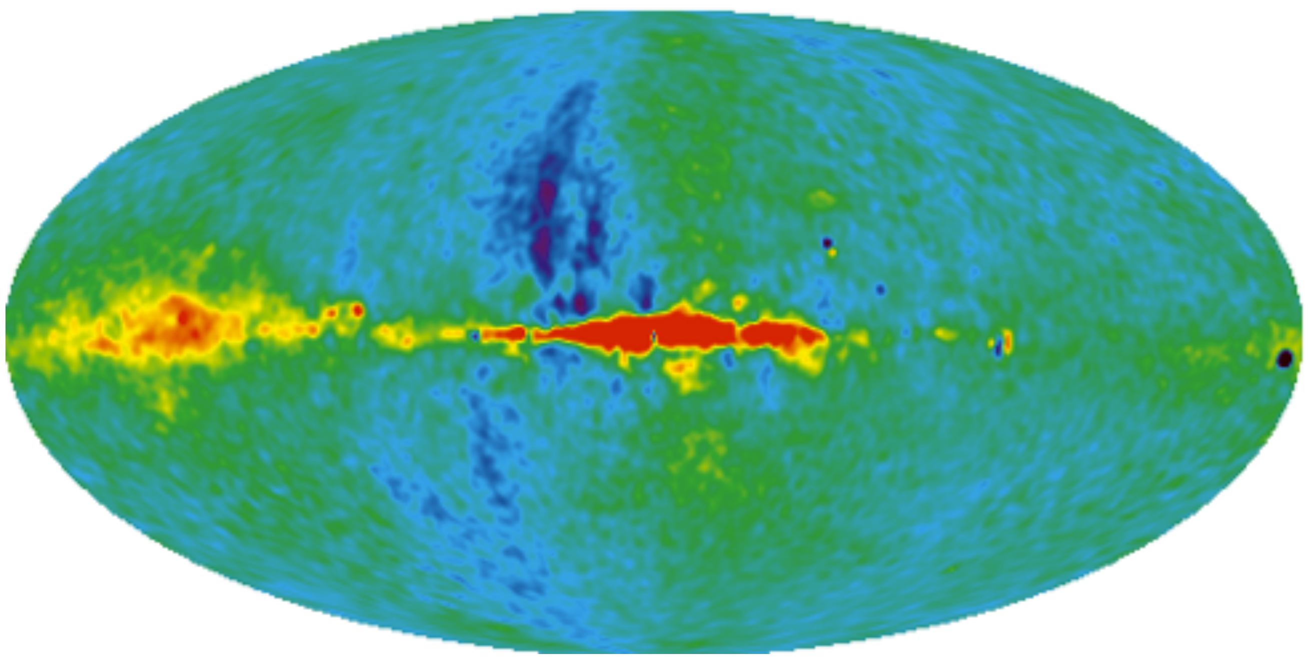
Stokes U

23 GHz [13 mm]

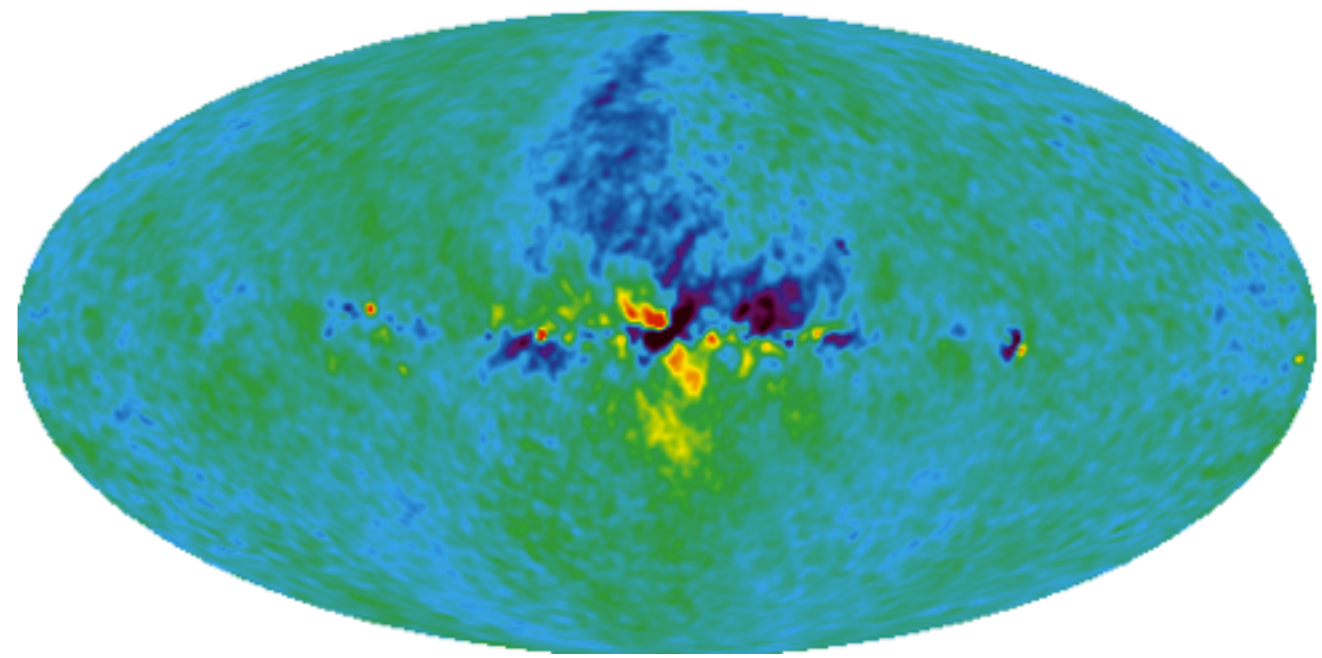


WMAP Collaboration

33 GHz [9.1 mm]



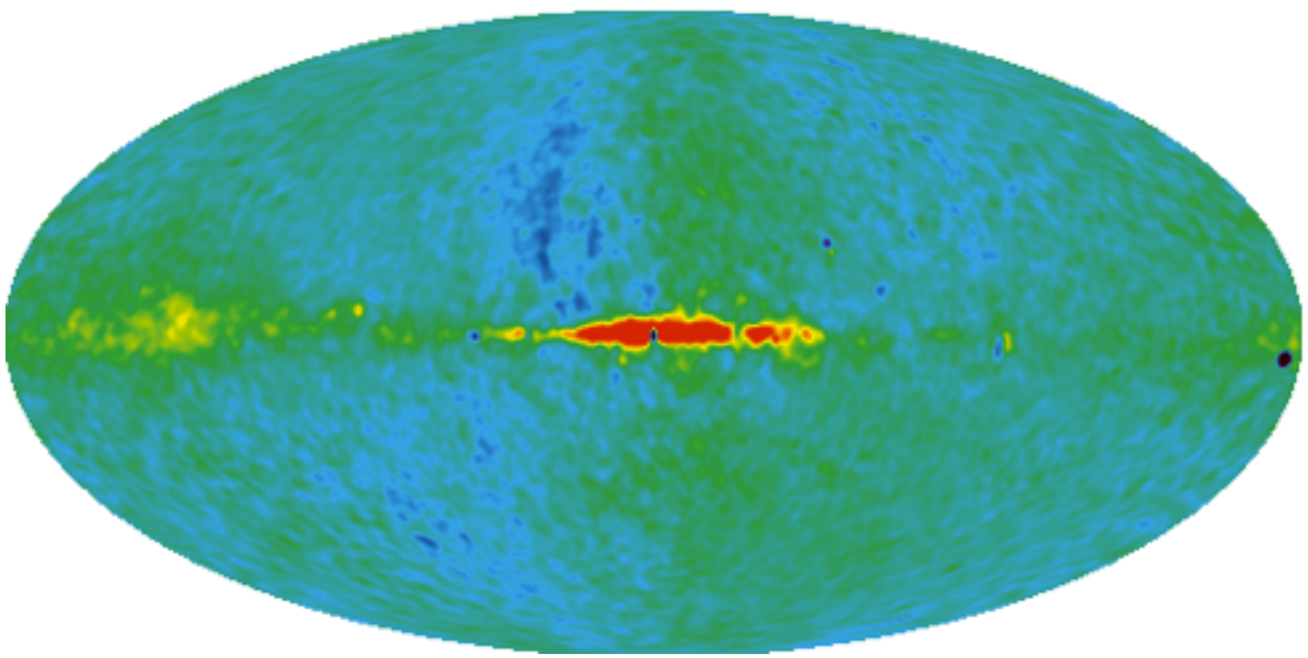
Stokes Q



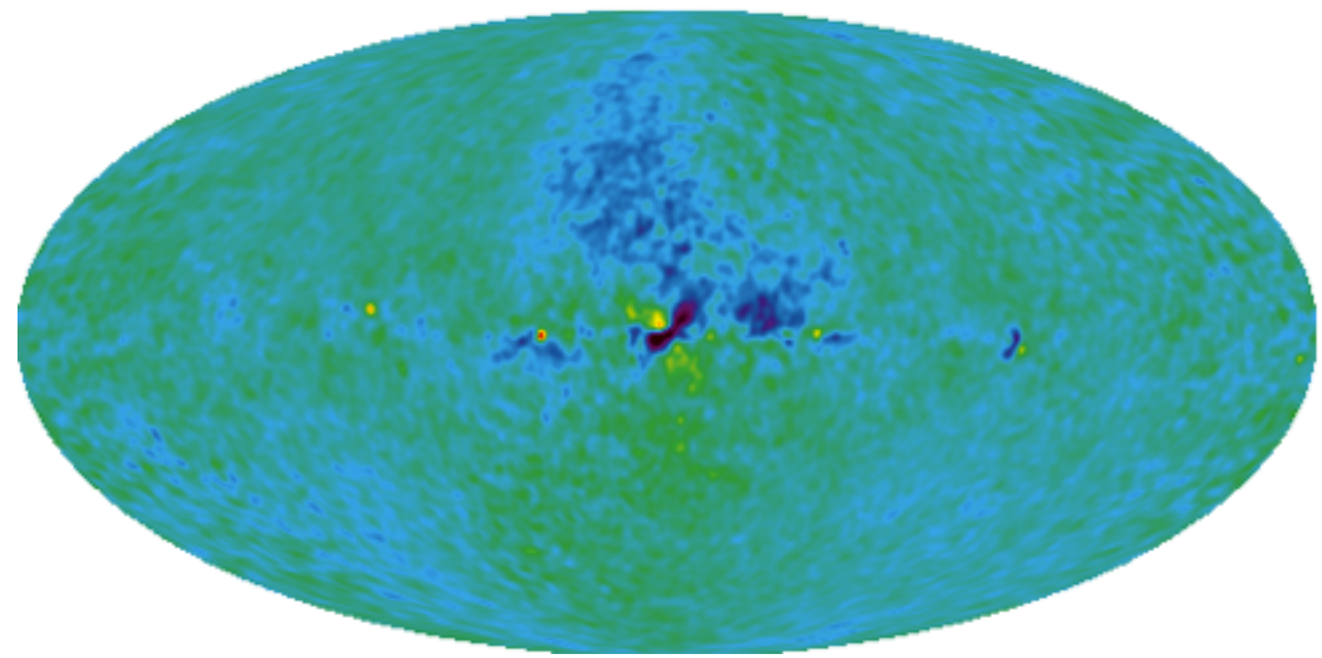
Stokes U

WMAP Collaboration

41 GHz [7.3 mm]



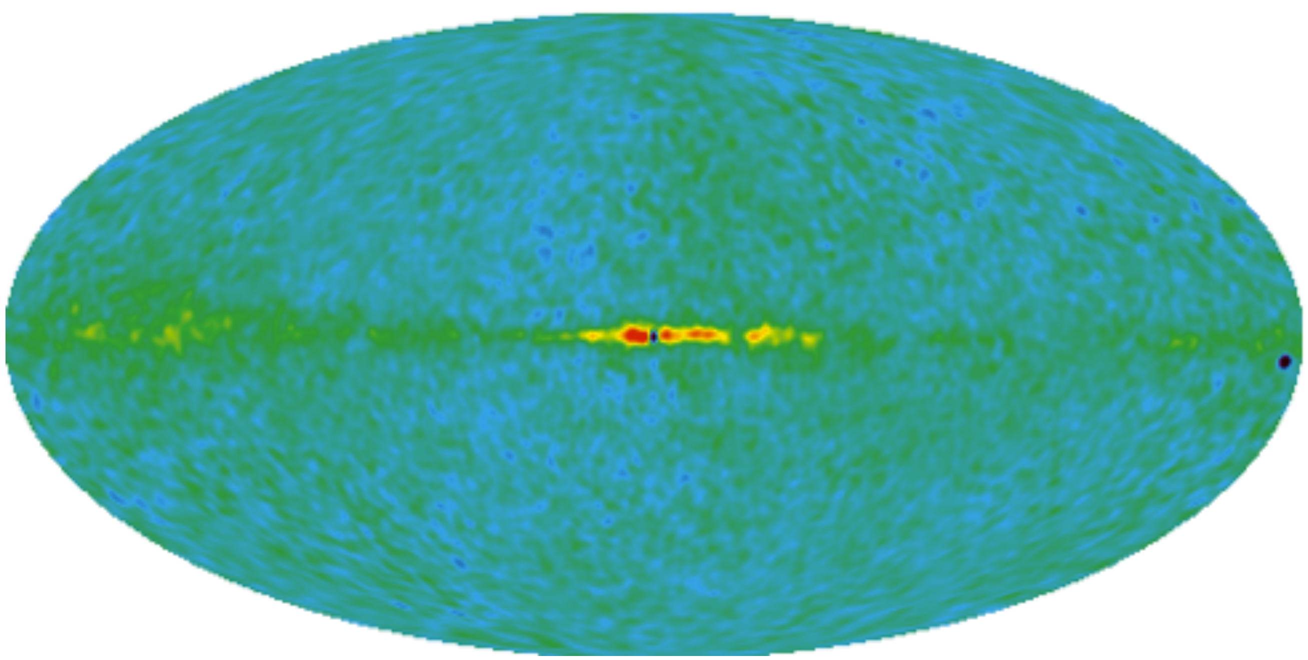
Stokes Q



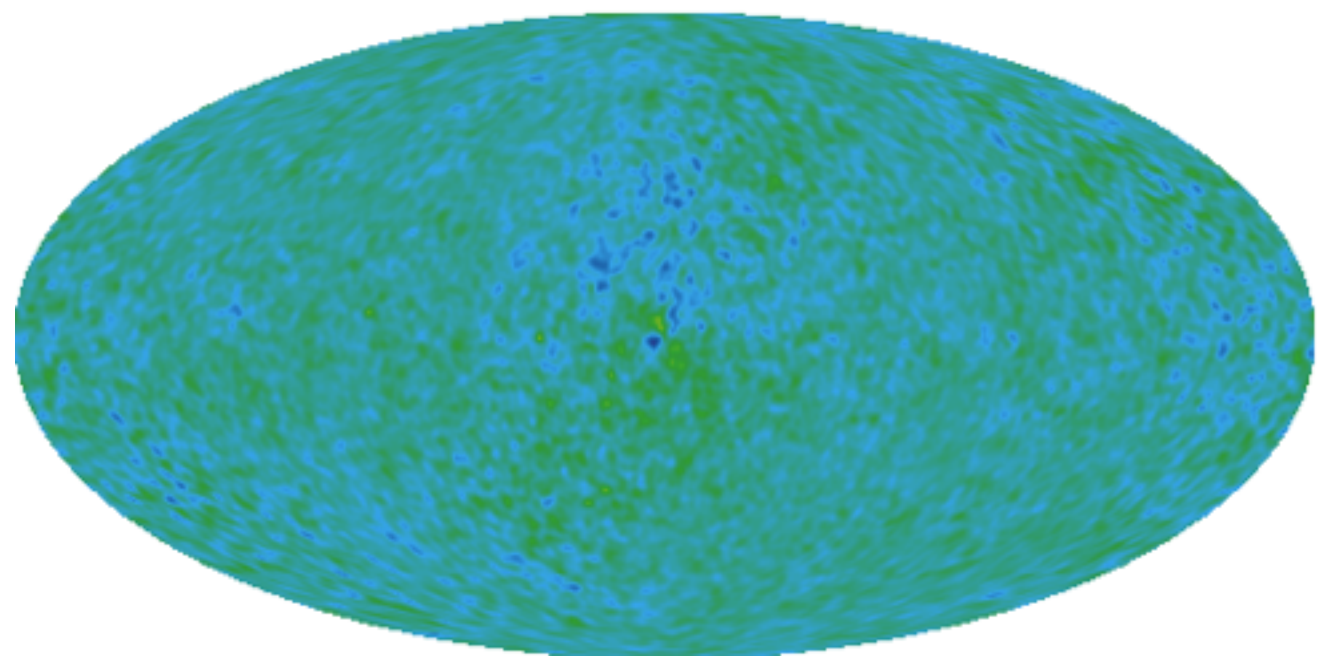
Stokes U

WMAP Collaboration

61 GHz [4.9 mm]



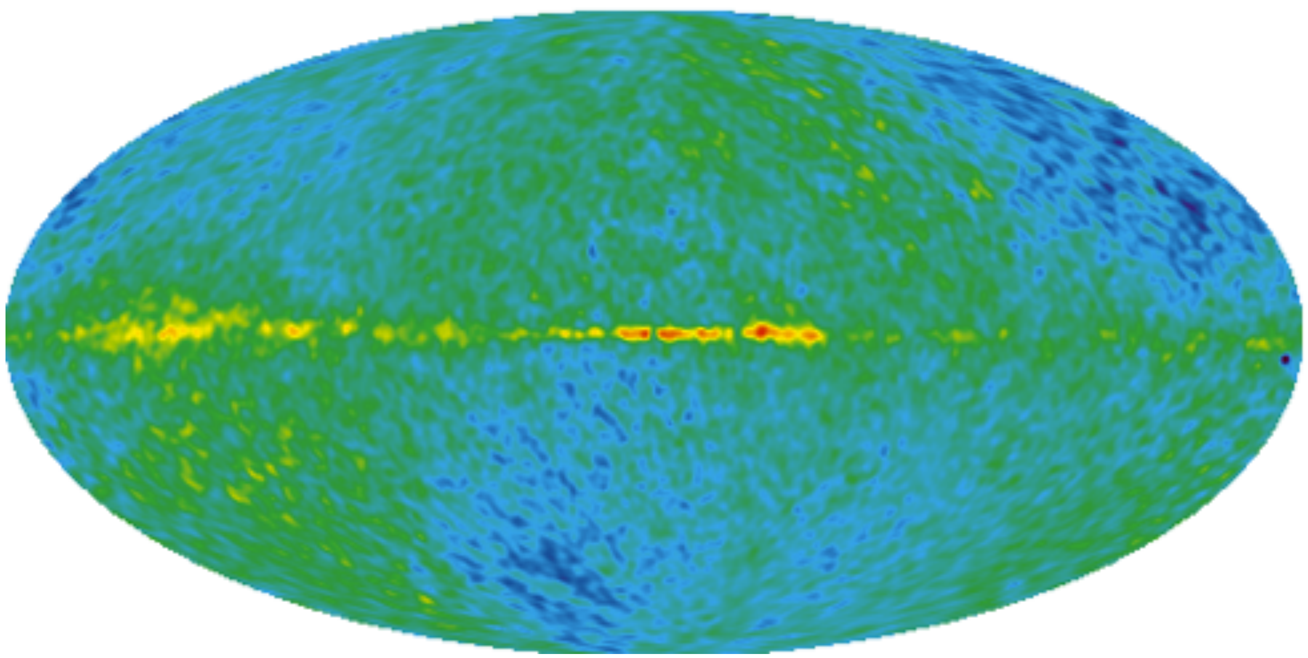
Stokes Q



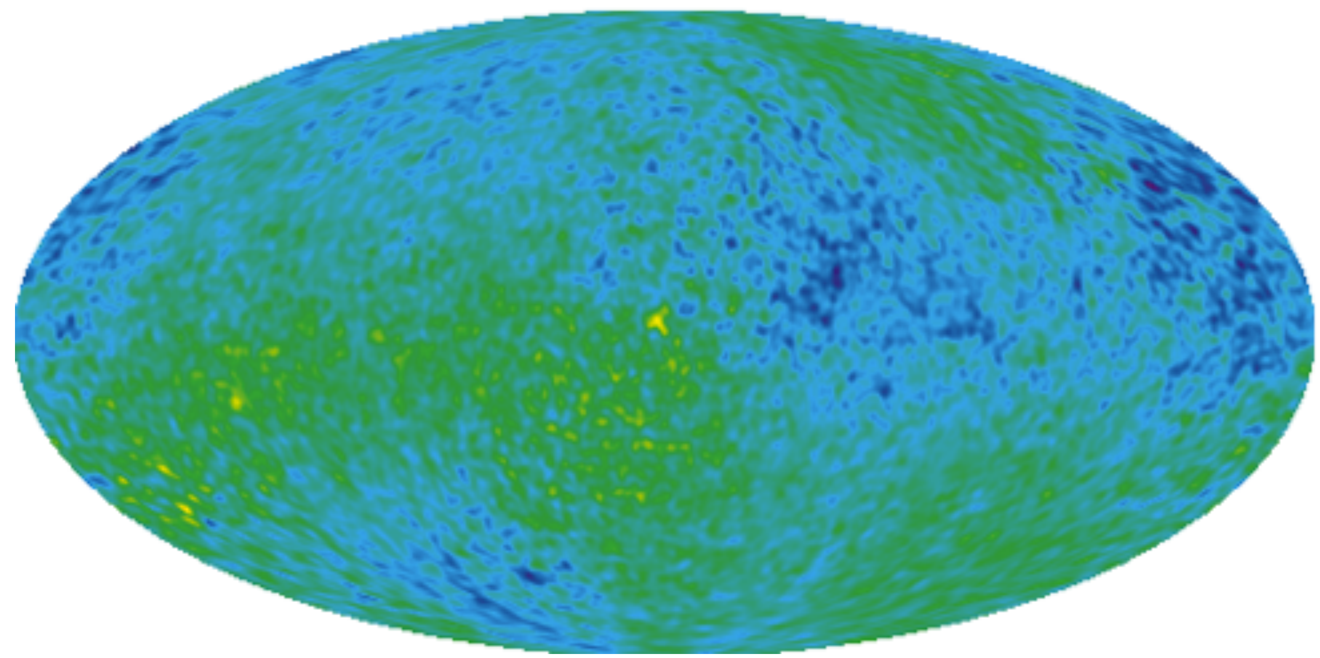
Stokes U

WMAP Collaboration

94 GHz [3.2 mm]



Stokes Q



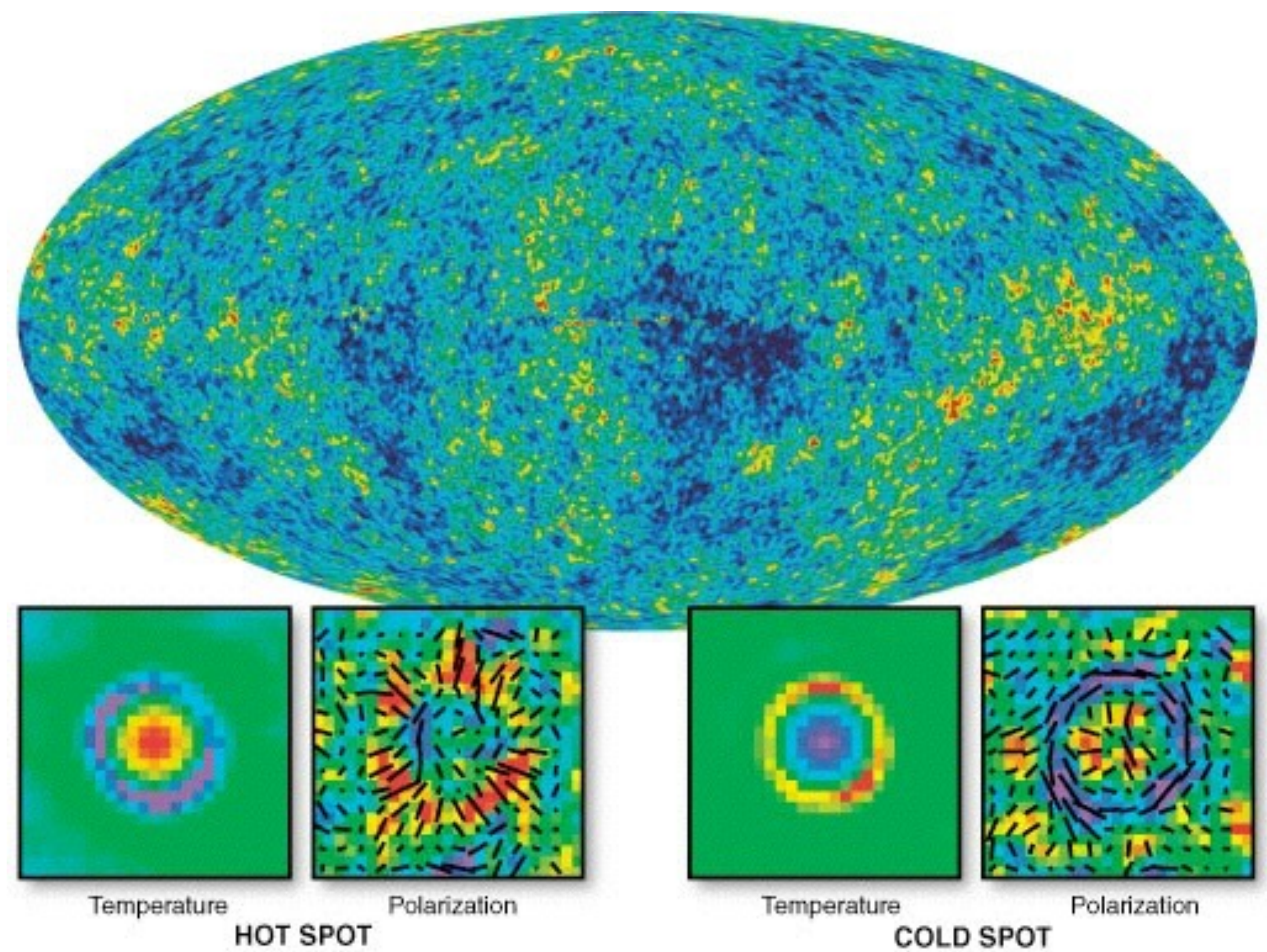
Stokes U

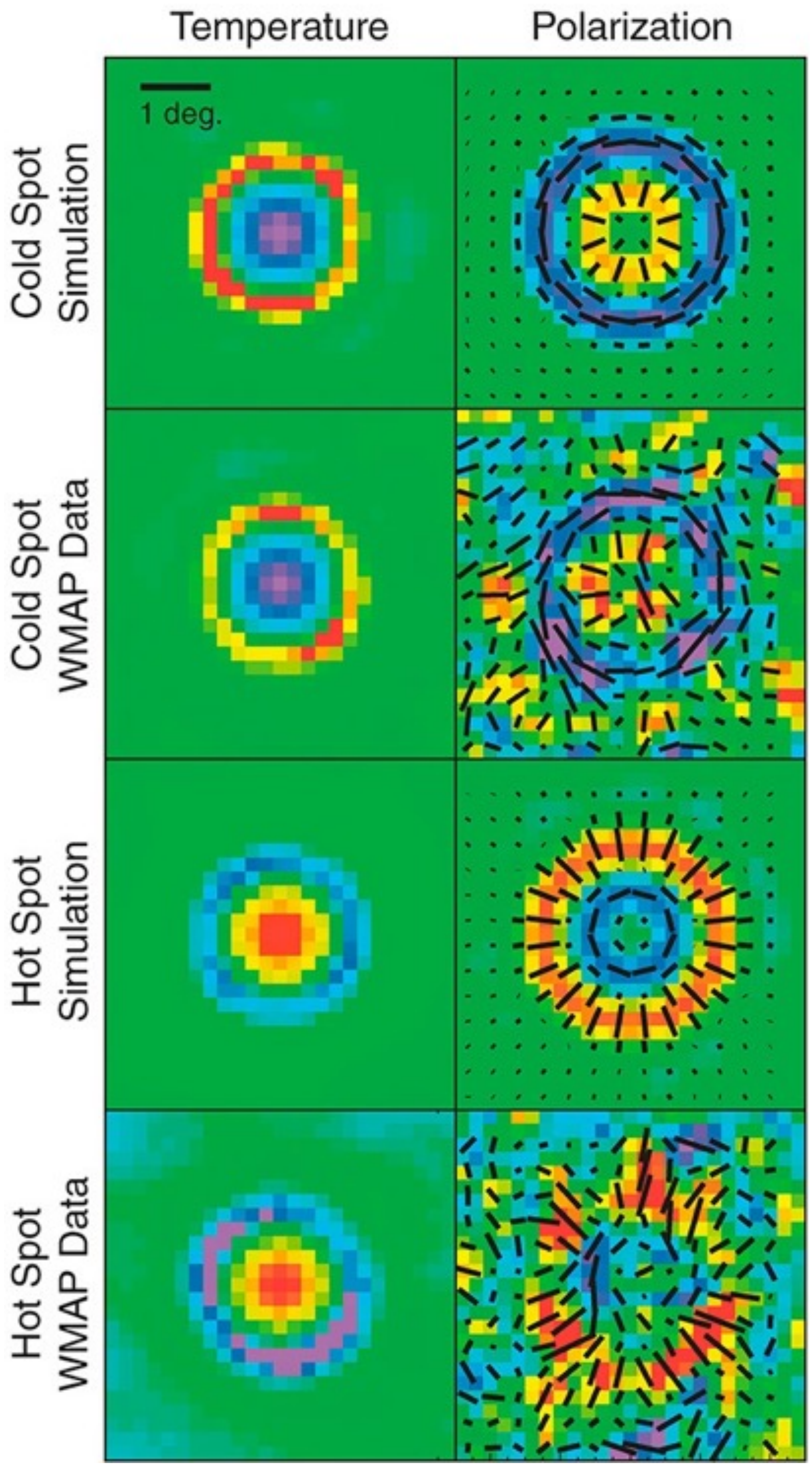
How many components?

- 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





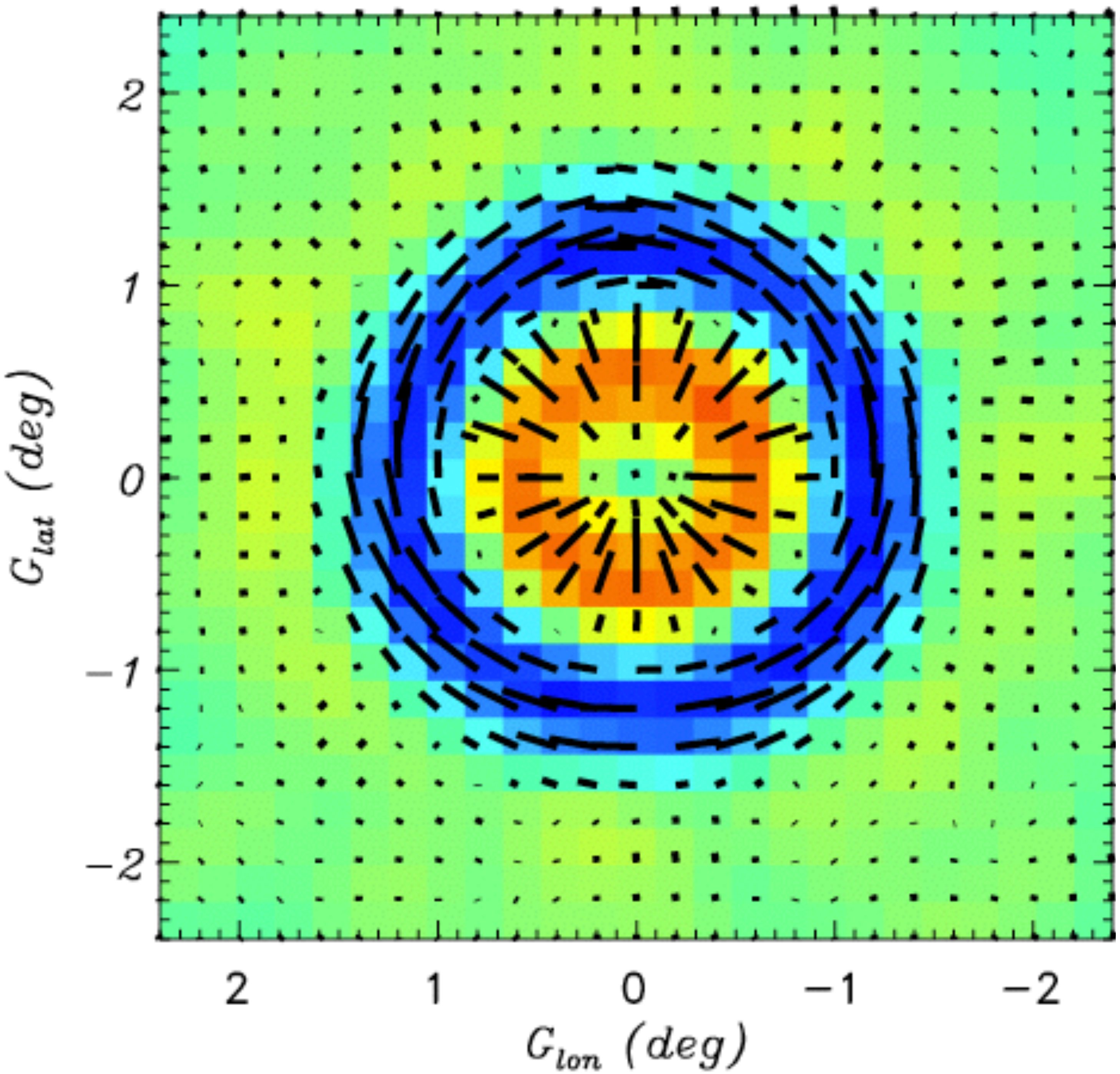
WMAP Collaboration

Radial and tangential polarisation around temperature spots

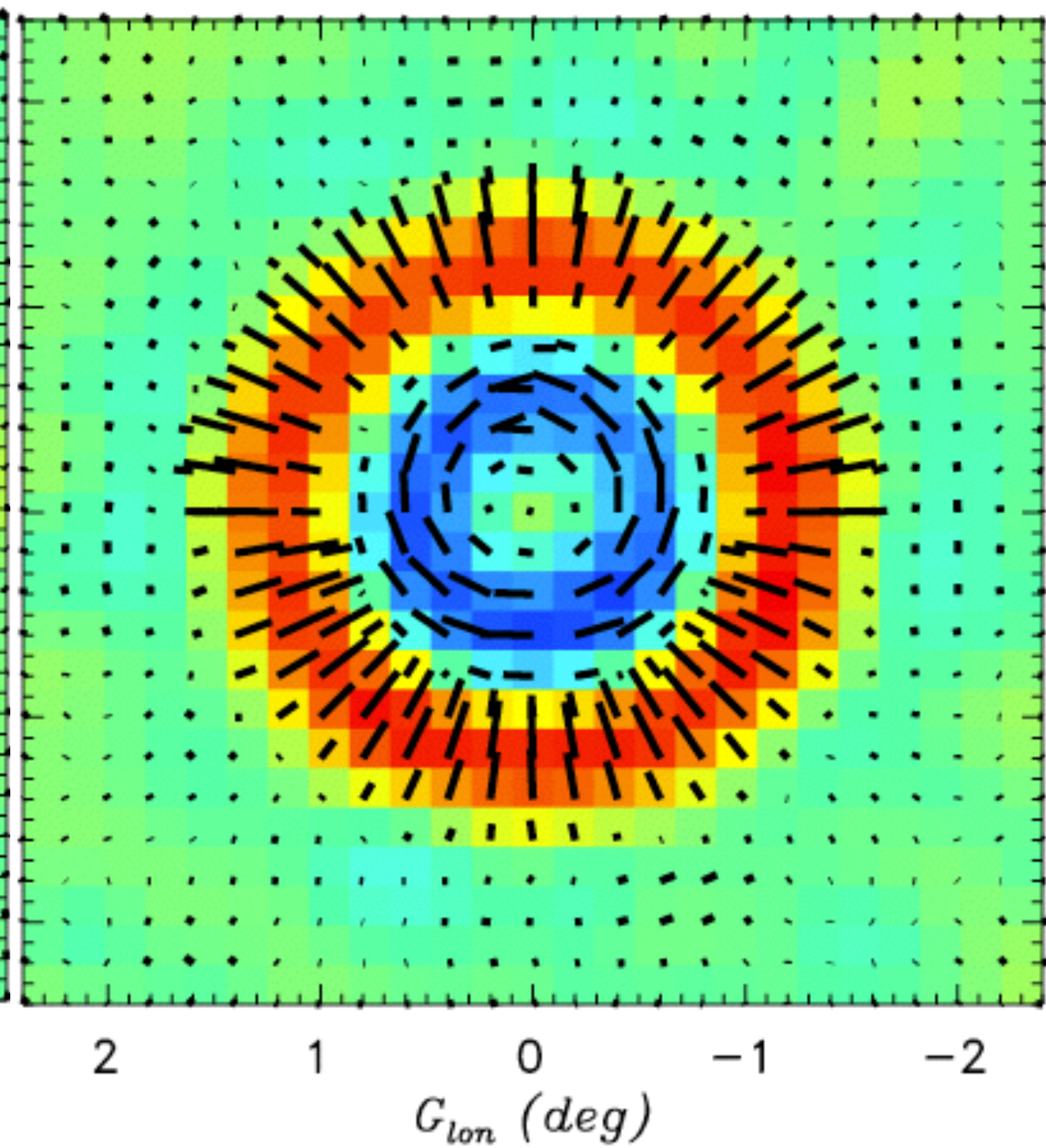
- This shows polarisation generated by the plasma flowing into gravitational potentials
- Signatures of the "scalar mode" fluctuations in polarisation
- These patterns are called "**E modes**"

Planck Collaboration

Planck Data!



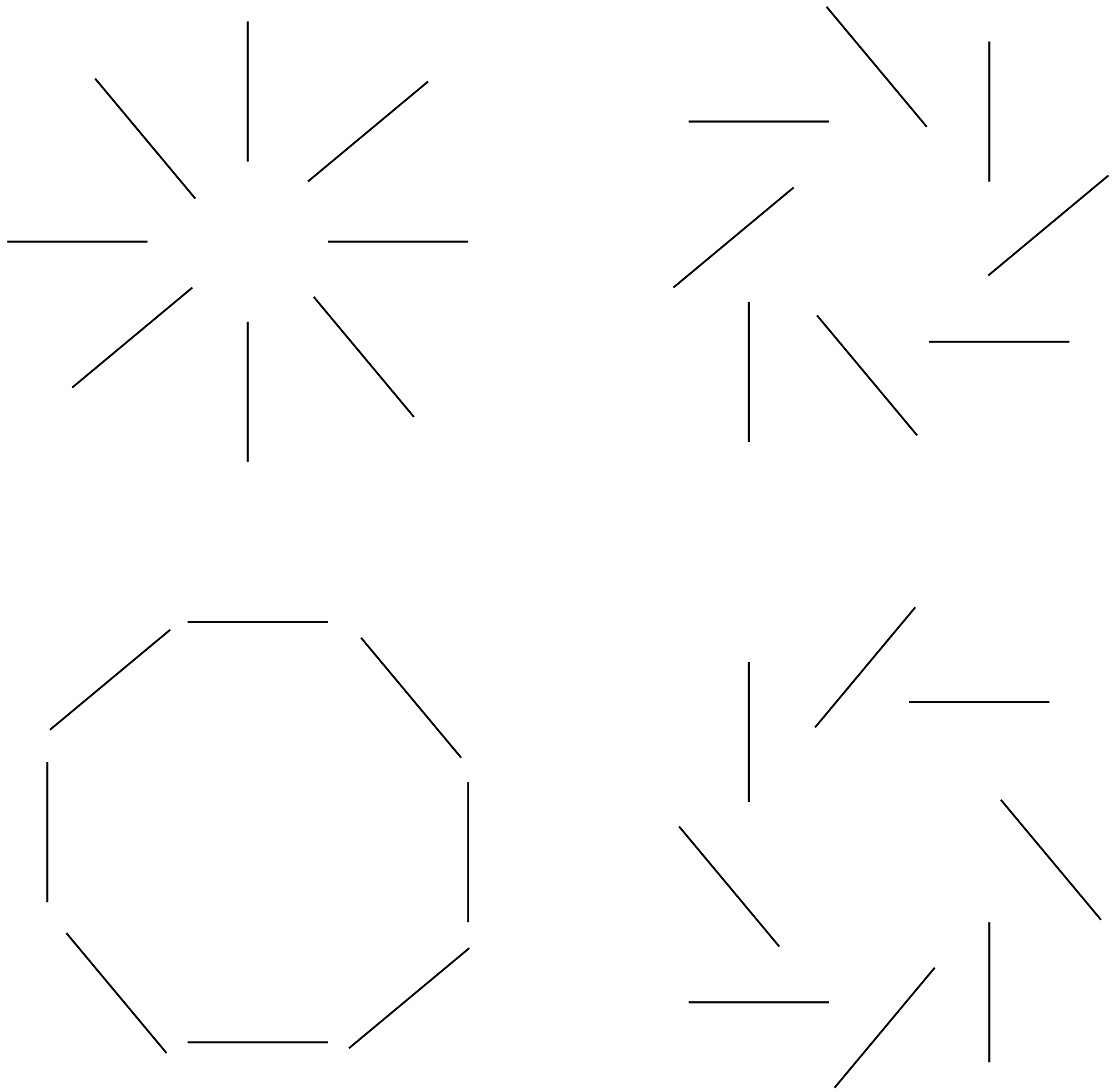
Q_r (cold spots)



Q_r (hot spots)

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

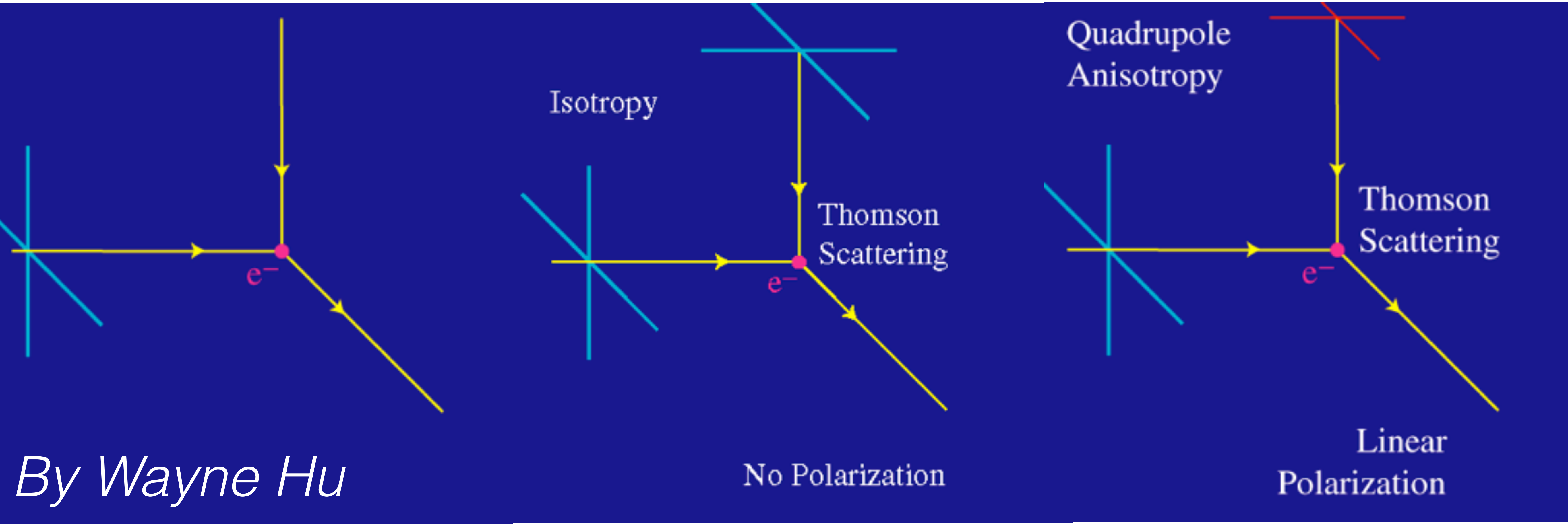
E and B modes



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

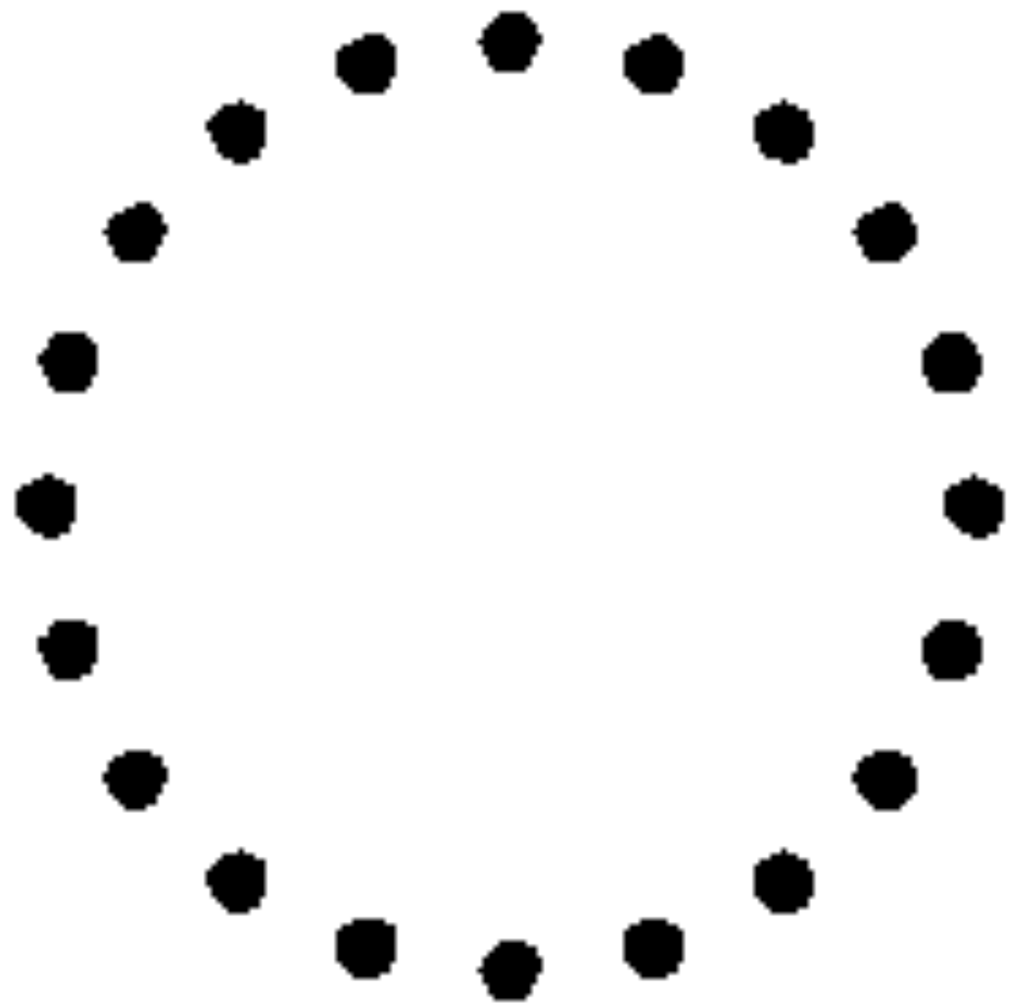


- Necessary and sufficient conditions for generating polarisation in CMB:
    - Thomson scattering
    - Quadrupolar temperature anisotropy around an electron

Origin of Quadrupole

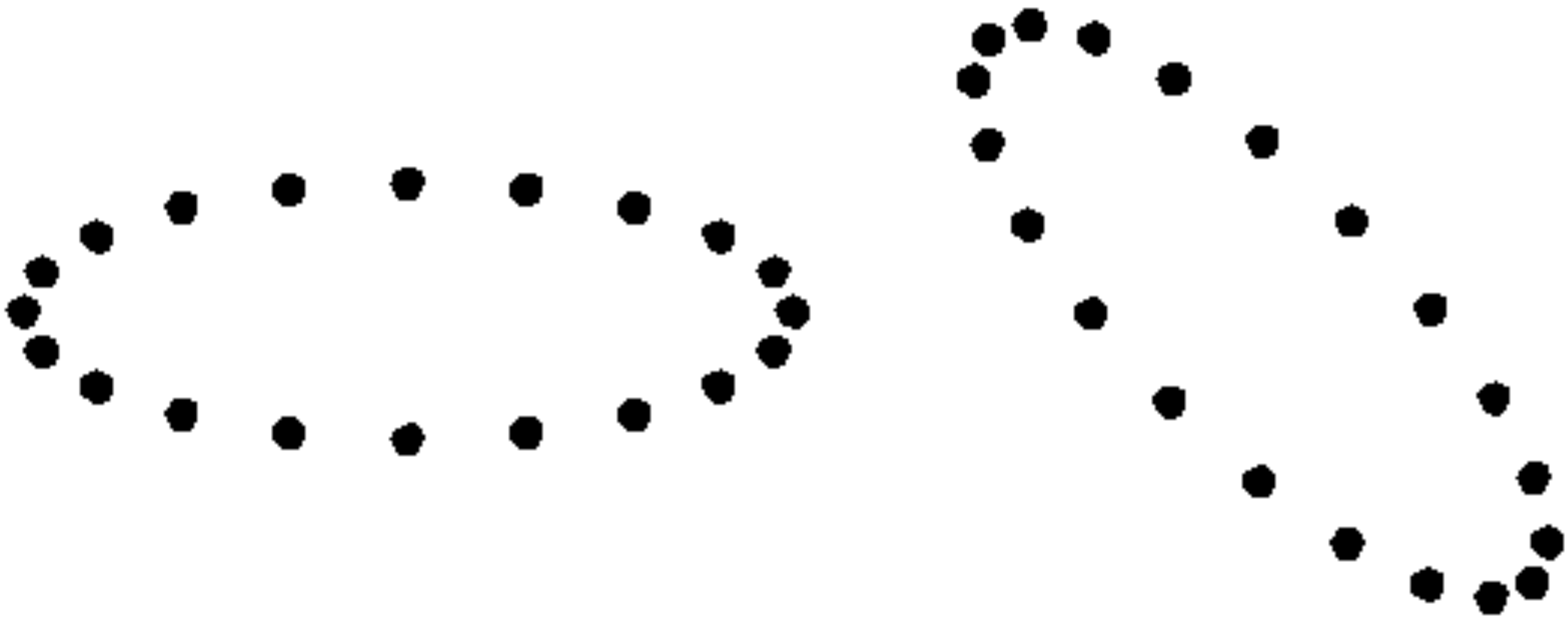
- **Scalar perturbations**: motion of electrons with respect to photons
- **Tensor perturbations**: gravitational waves

Gravitational waves are coming toward you!



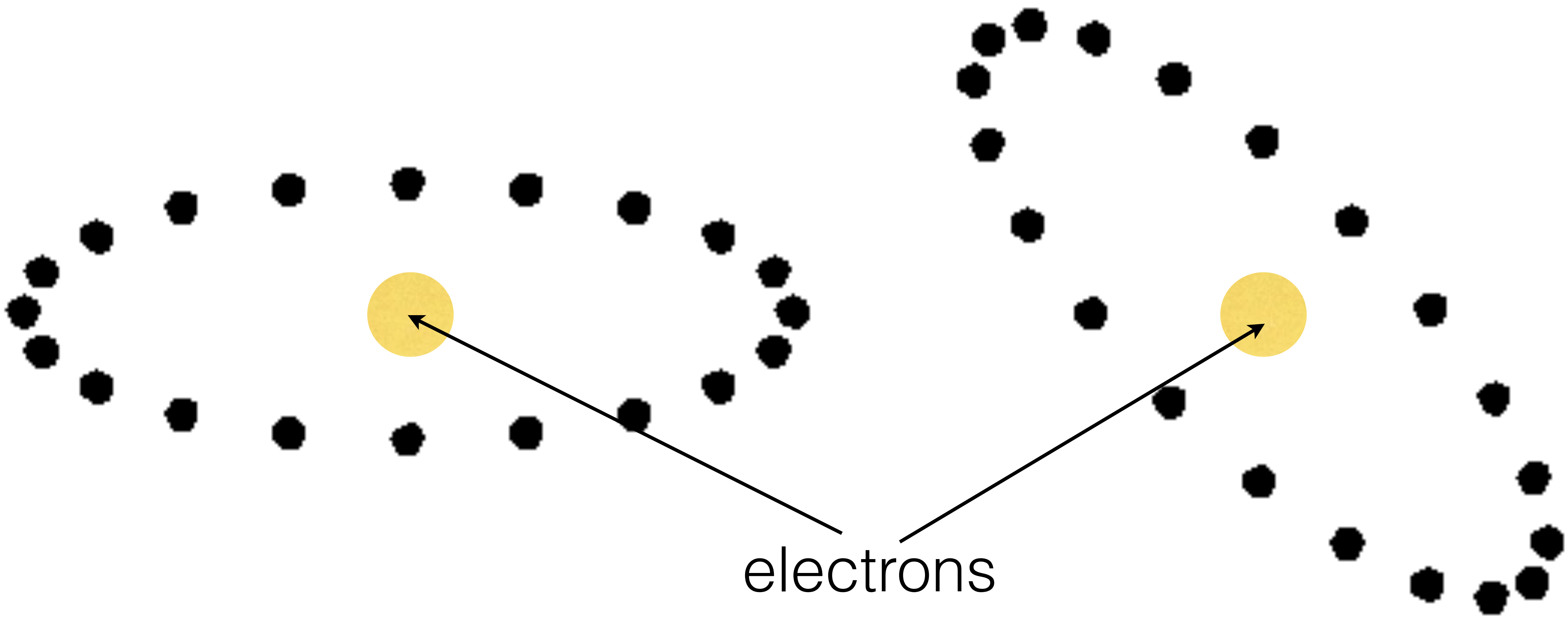
- What do they do to the distance between particles?

Two GW modes

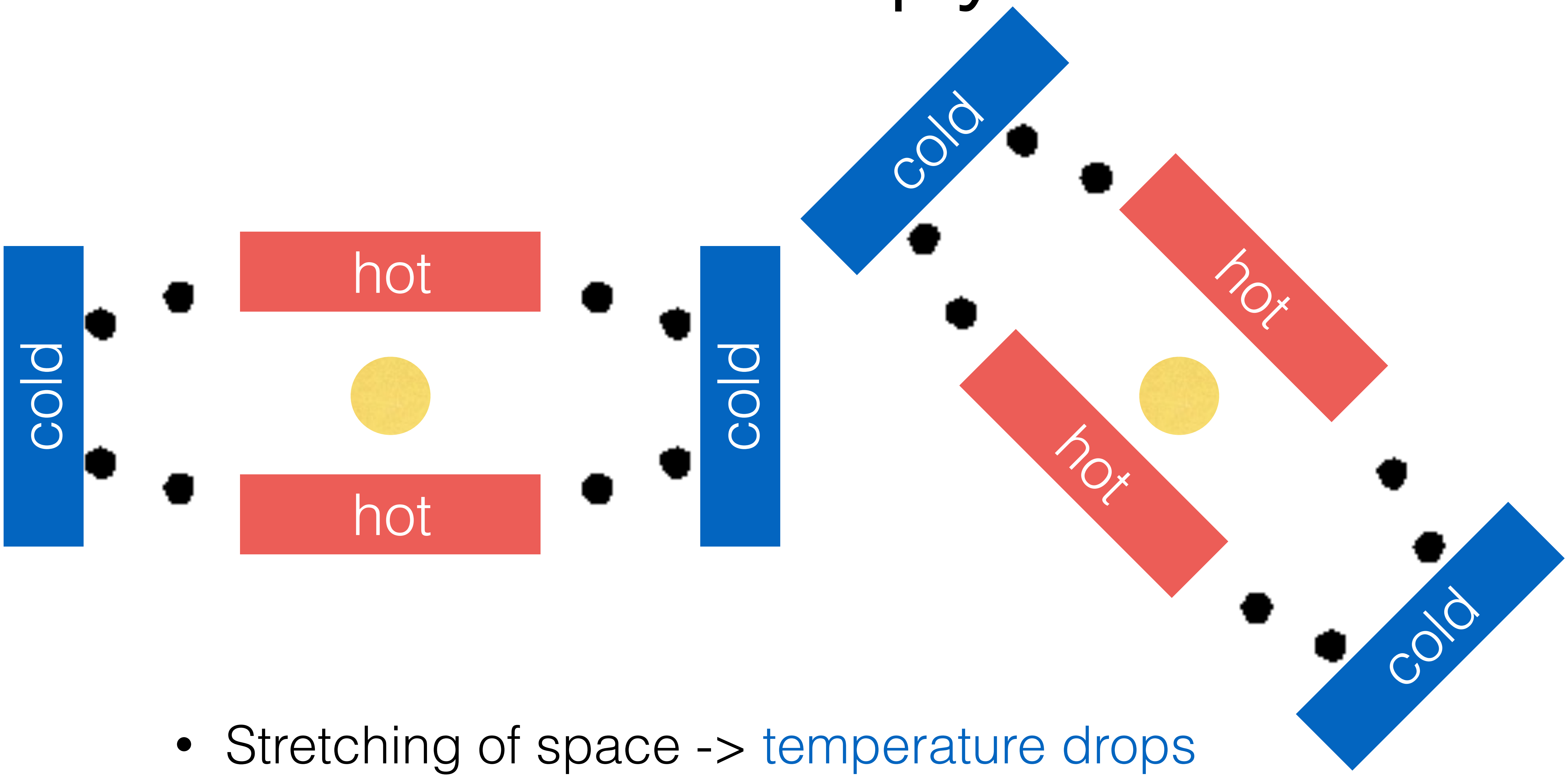


- Anisotropic stretching of space generates quadrupole temperature anisotropy. How?

GW to temperature anisotropy

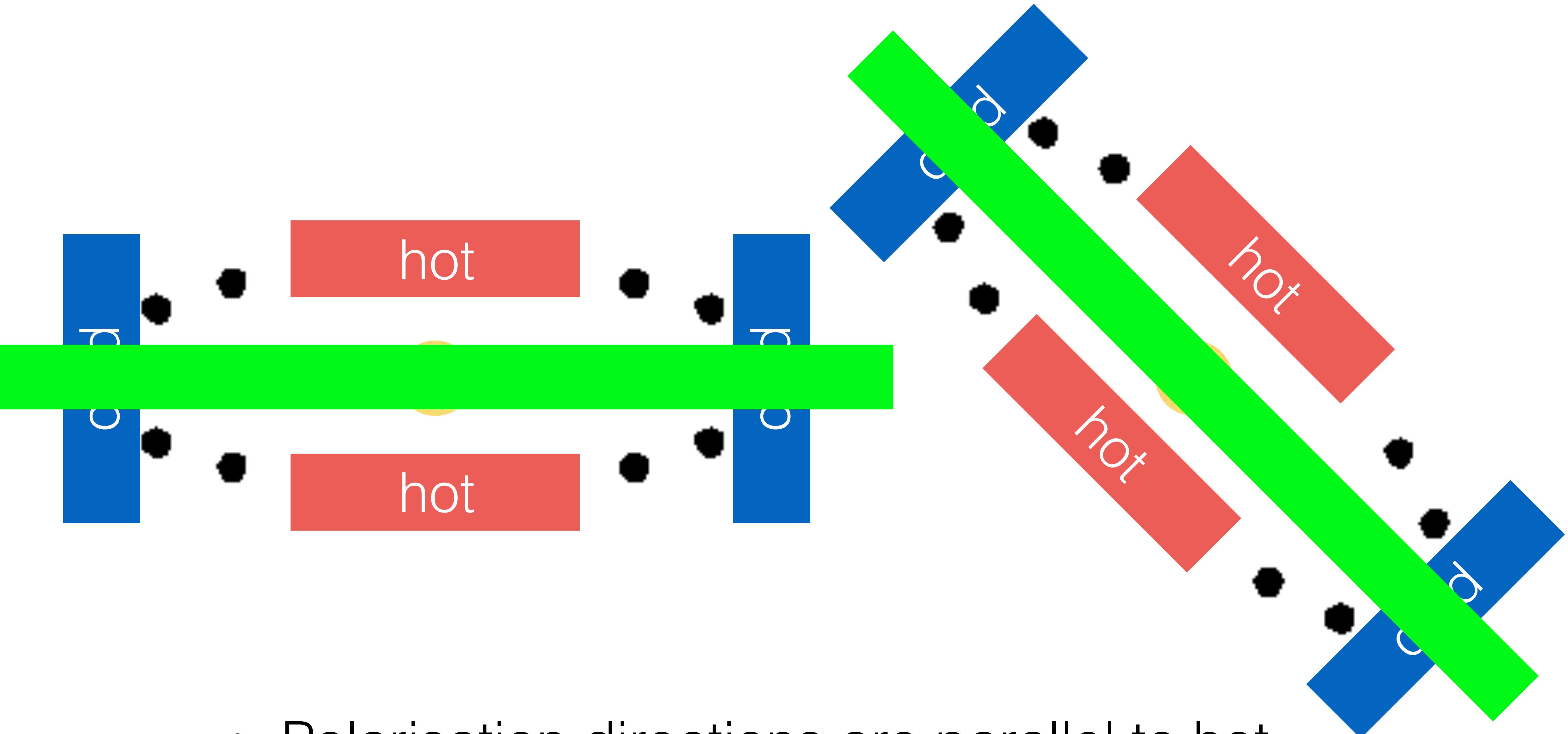


GW to temperature anisotropy

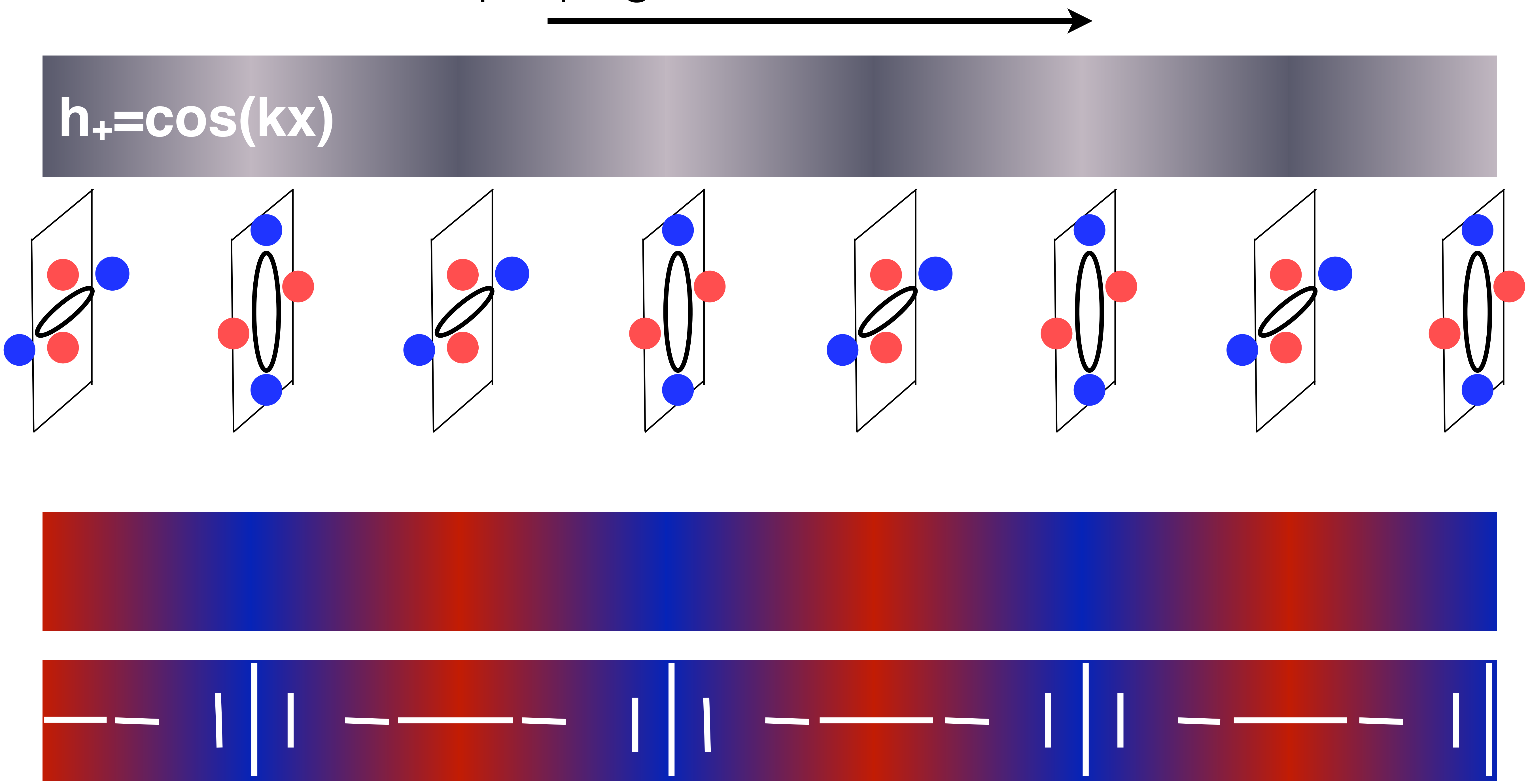


- Stretching of space -> temperature drops
- Contraction of space -> temperature rises

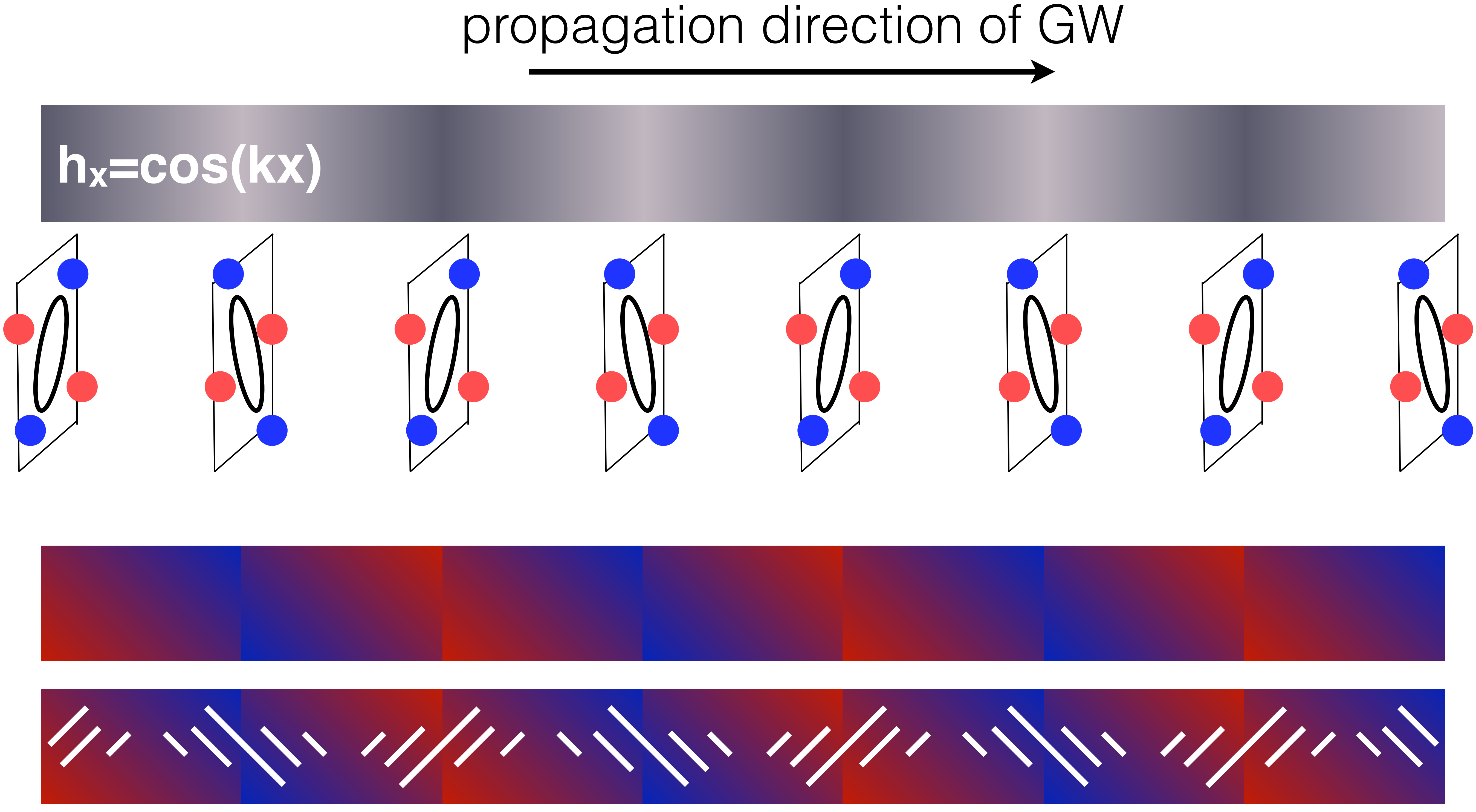
Then to polarisation!



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



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

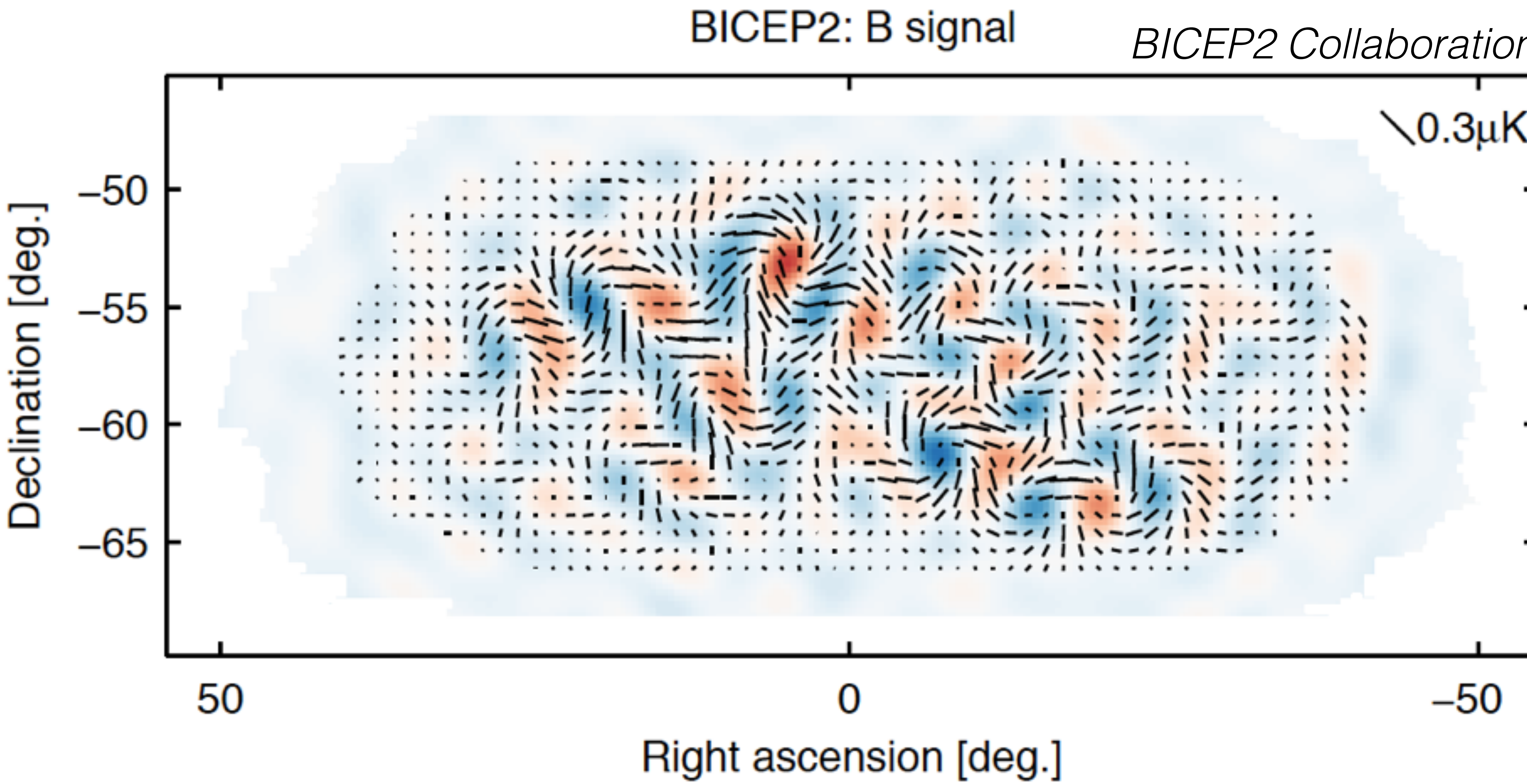


Polarisation directions 45 degrees tilted from to the wavenumber vector -> **B mode polarisation**

Important note:

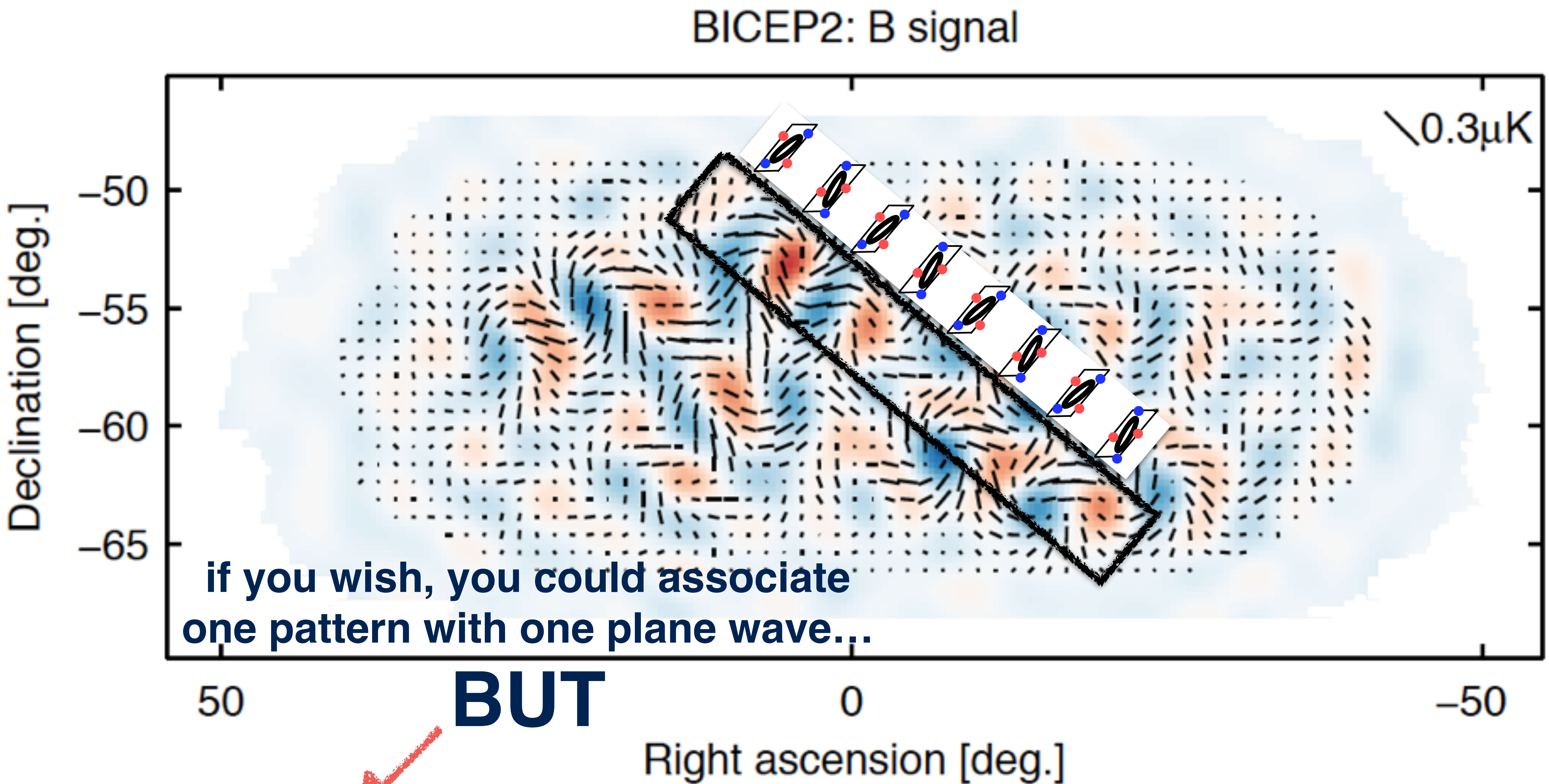
- Definition of h_+ and $h_\times$ depends on coordinates, but definition of E- and B-mode polarisation does not depend on coordinates
- Therefore, h_+ does not always give E; $h_\times$ does not always give B
    - The important point is that **h_+ and $h_\times$ always coexist**. When a linear combination 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

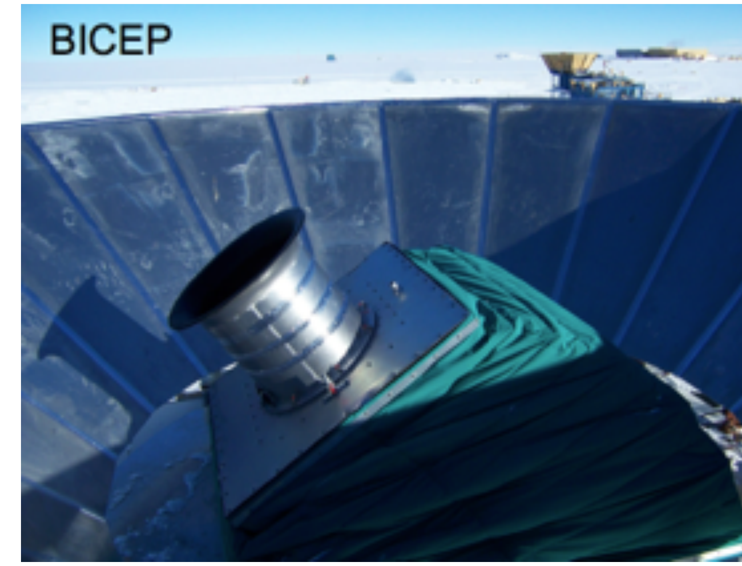
Signature of gravitational waves in the sky [?]



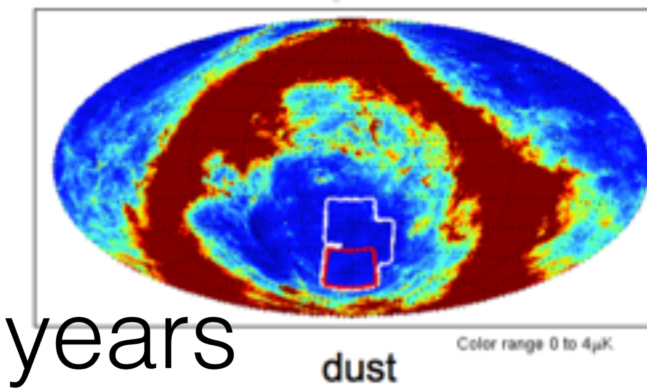
BUT

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

What is BICEP2?



- A small [26 cm] refractive telescope at South Pole
- 512 bolometers working at 150 GHz



- Observed 380 square degrees for three years [2010-2012]
- Previous: BICEP1 at 100 and 150 GHz [2006-2008]
- On-going: Keck Array = 5 x BICEP2 at 150 GHz [2011-2013] and additional detectors at 100 and 220 GHz [2014-]

Is the signal cosmological?

- Worries:
  - Is it from Galactic foreground emission, e.g., dust?
  - Is it from imperfections in the experiment, e.g., detector mismatches?

Eiichiro Komatsu

March 14 near Munich

If detection of the primordial B-modes were to be reported on Monday, I would like see:

[1] Detection (>3 sigma each) in more than one frequency, like 100 GHz and 150 GHz giving the same answers to within the error bars.

[2] Detection (could be a couple of sigmas each) in a few multipole bins, i.e., not in just one big multipole bin.

Then I will believe it!

facebook

Eiichiro Komatsu

March 14 near Munich

If detection of the primordial B-modes were to be reported on Monday, I would like see:

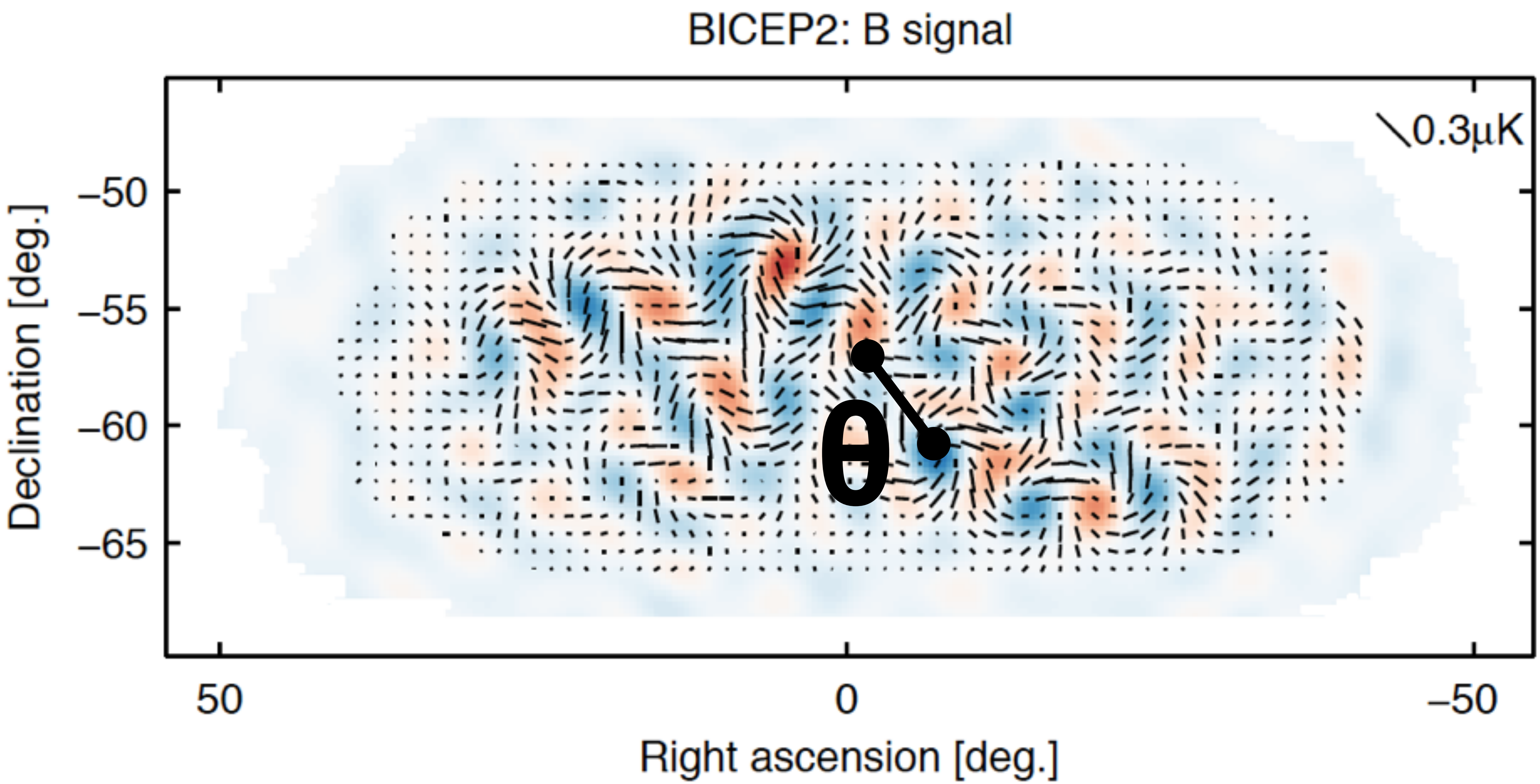
etection (>3 sigma each) in more than one frequency, like 100 GHz and Hz giving the same answers to within the error bars.

etection (could be a couple of sigmas each) in a few multipole bins, i.e., just one big multipole bin.

Then I will believe it!

facebook

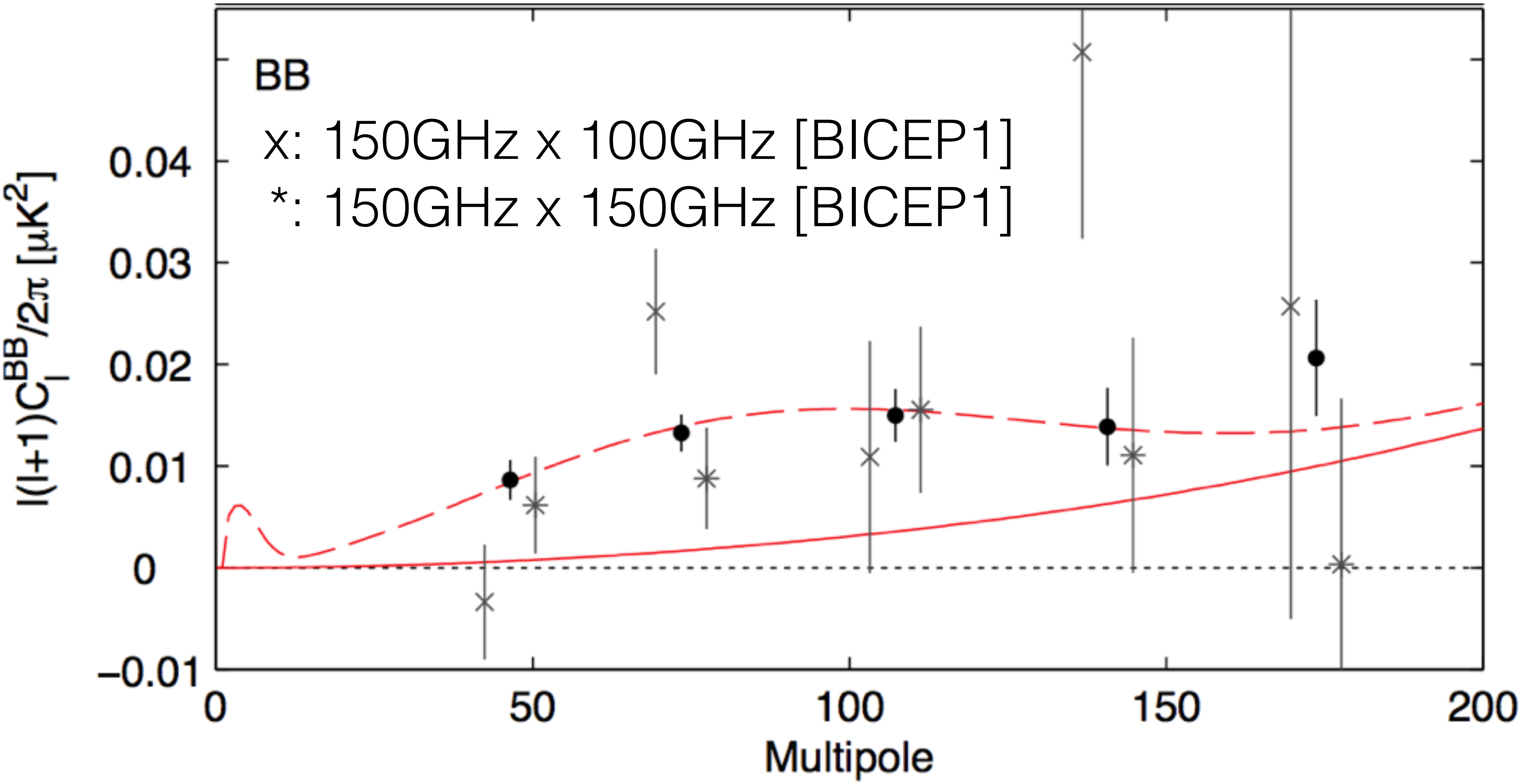
Analysis: Two-point Correlation Function



$$C(\theta) = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C_\ell P_\ell(\cos\theta)$$

C_ℓ is the "power spectrum" with

$$\ell \approx \frac{\pi}{\theta}$$



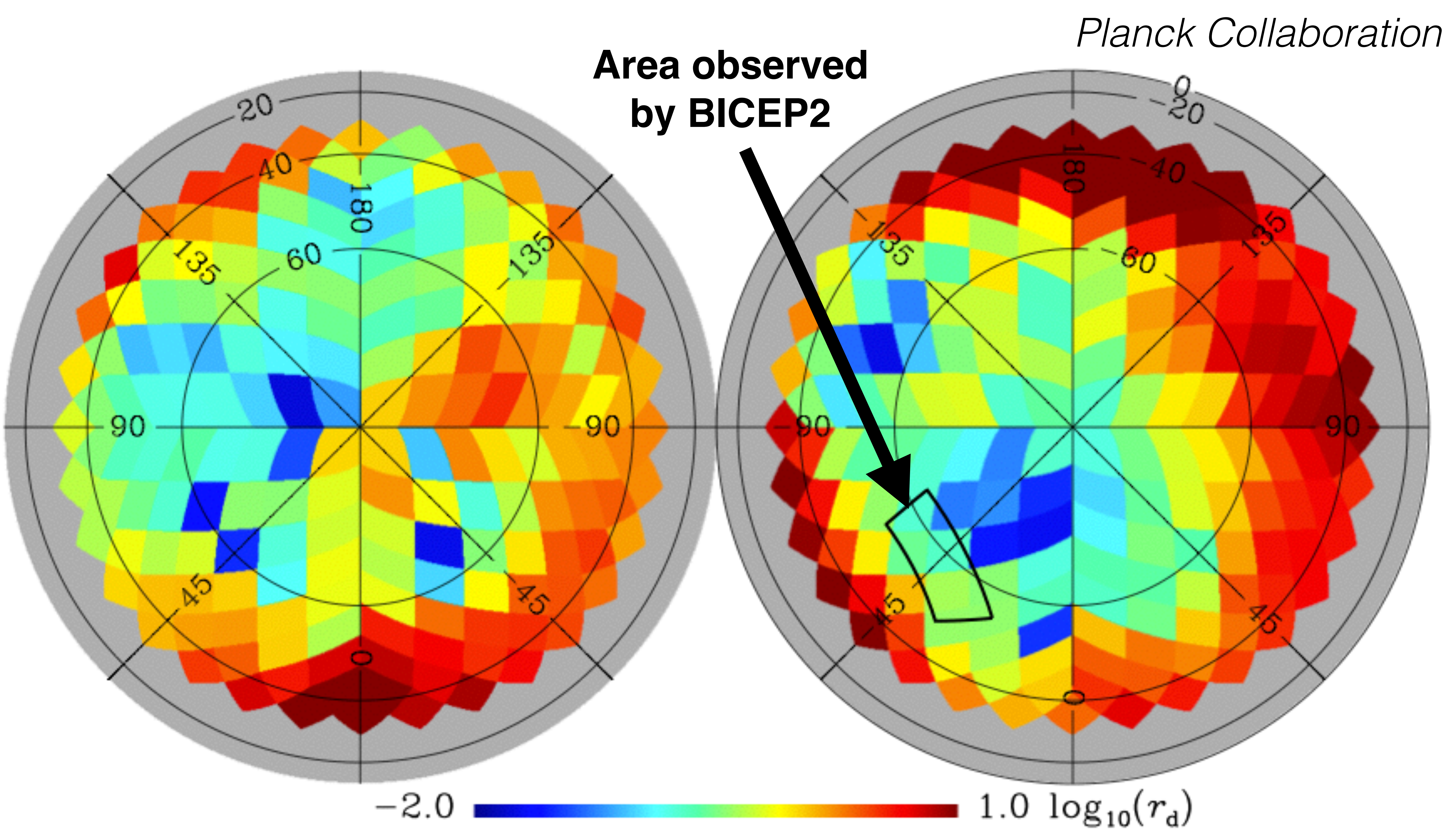
No 100 GHz x 100 GHz [yet]

Situation until a month ago

- No strong evidence that the detected signal is not cosmological
- No strong evidence that the detected signal is cosmological, either

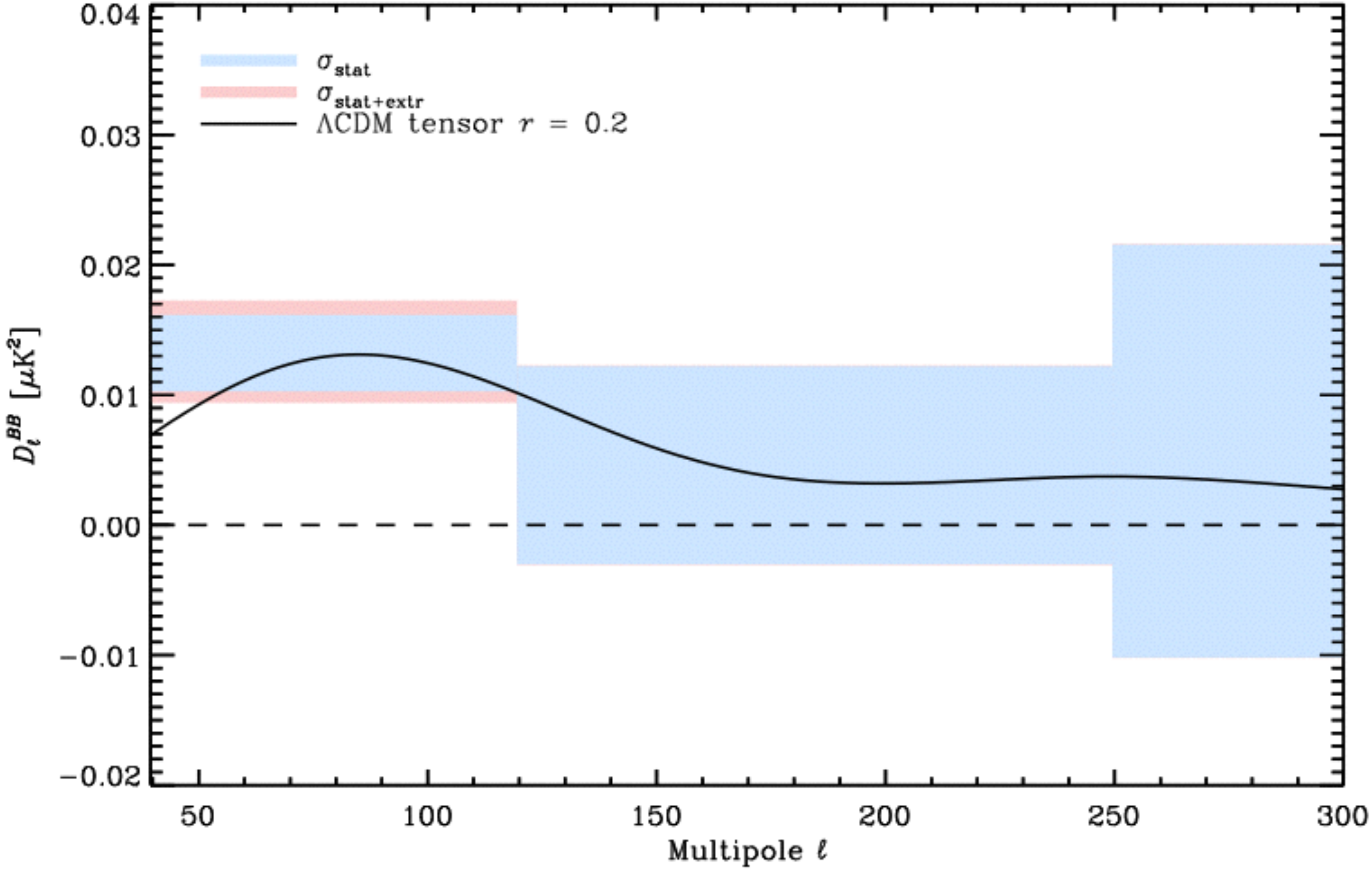
September 22, 2014

Planck’s Intermediate Paper on Dust



• Values of the “tensor-to-scalar ratio” equivalent to the B-mode power spectrum seen at various locations in the sky

Planck Collaboration



- Planck measured the B-mode power spectrum at 353 GHz well
- Extrapolating it down to 150 GHz appears to explain all of the signal seen by BICEP2…

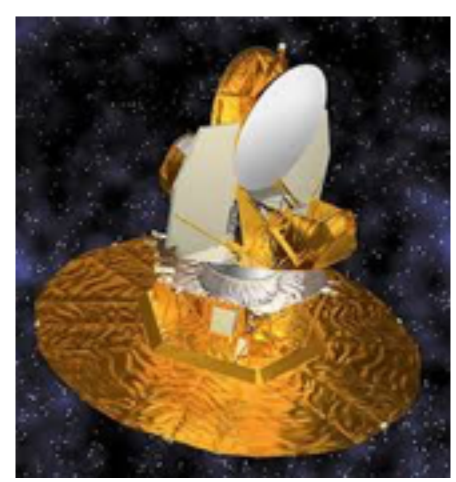
Current Situation

- Planck shows the evidence that the detected signal 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–

LiteBIRD

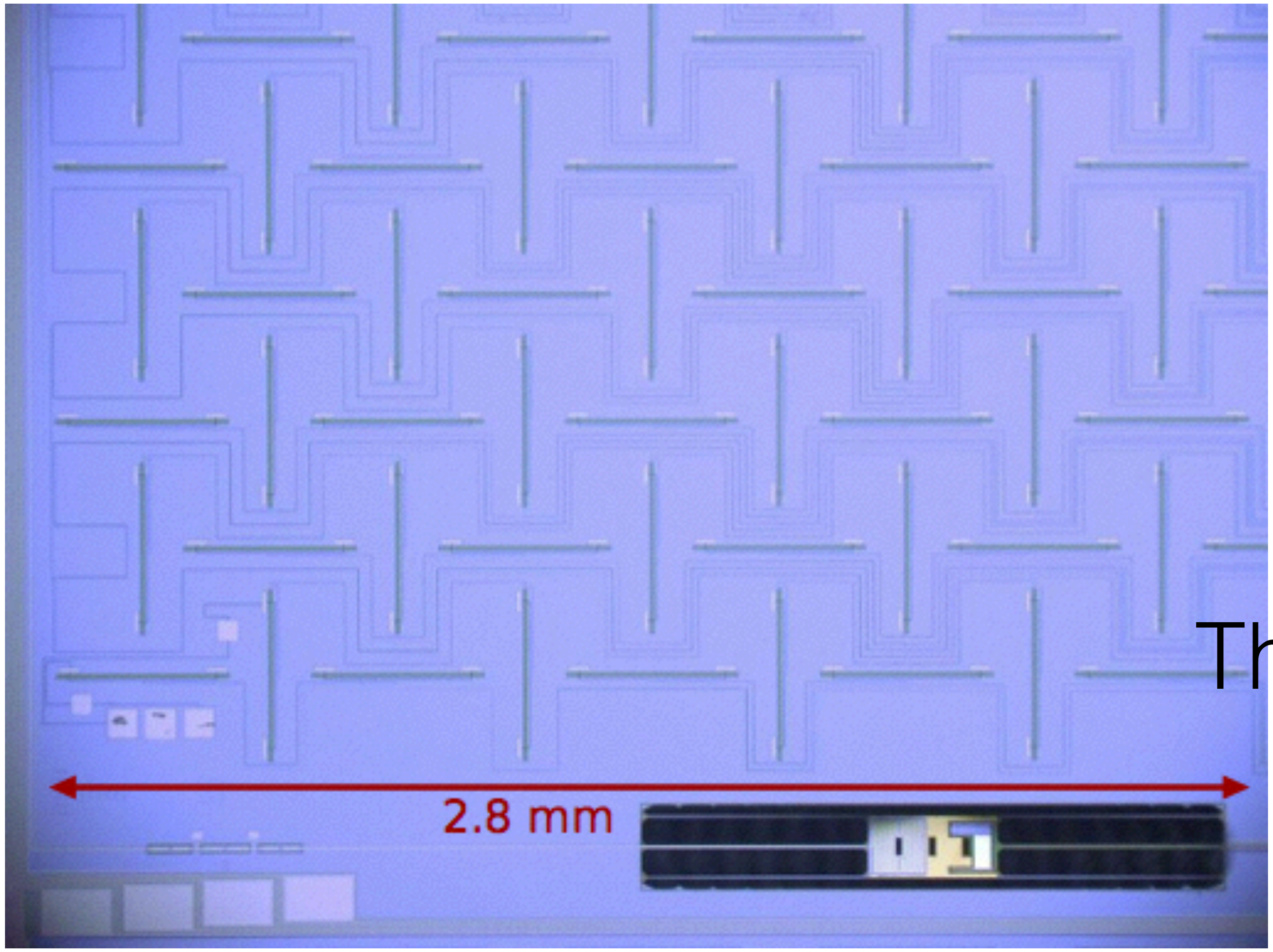
- Next-generation polarisation-sensitive microwave experiment. Target launch date: early 2020
- Led by Prof. Masashi Hazumi (KEK); a collaboration of ~70 scientists in Japan, USA, Canada, and Germany
- **Singular goal**: measurement of the primordial B-mode power spectrum with **Err[r]=0.001**
- **6 frequency bands** between 50 and 320 GHz

Conclusion

- The WMAP and Planck’s temperature data provide **strong evidence for the quantum origin of structures in the universe**
- The next goal: unambiguous measurement of the primordial B-mode polarisation power spectrum
- **LiteBIRD** proposal: a B-mode CMB polarisation satellite in early 2020

How does BICEP2 measure polarisation?

- By taking the difference between two detectors (A&B), measuring two orthogonal polarisation states

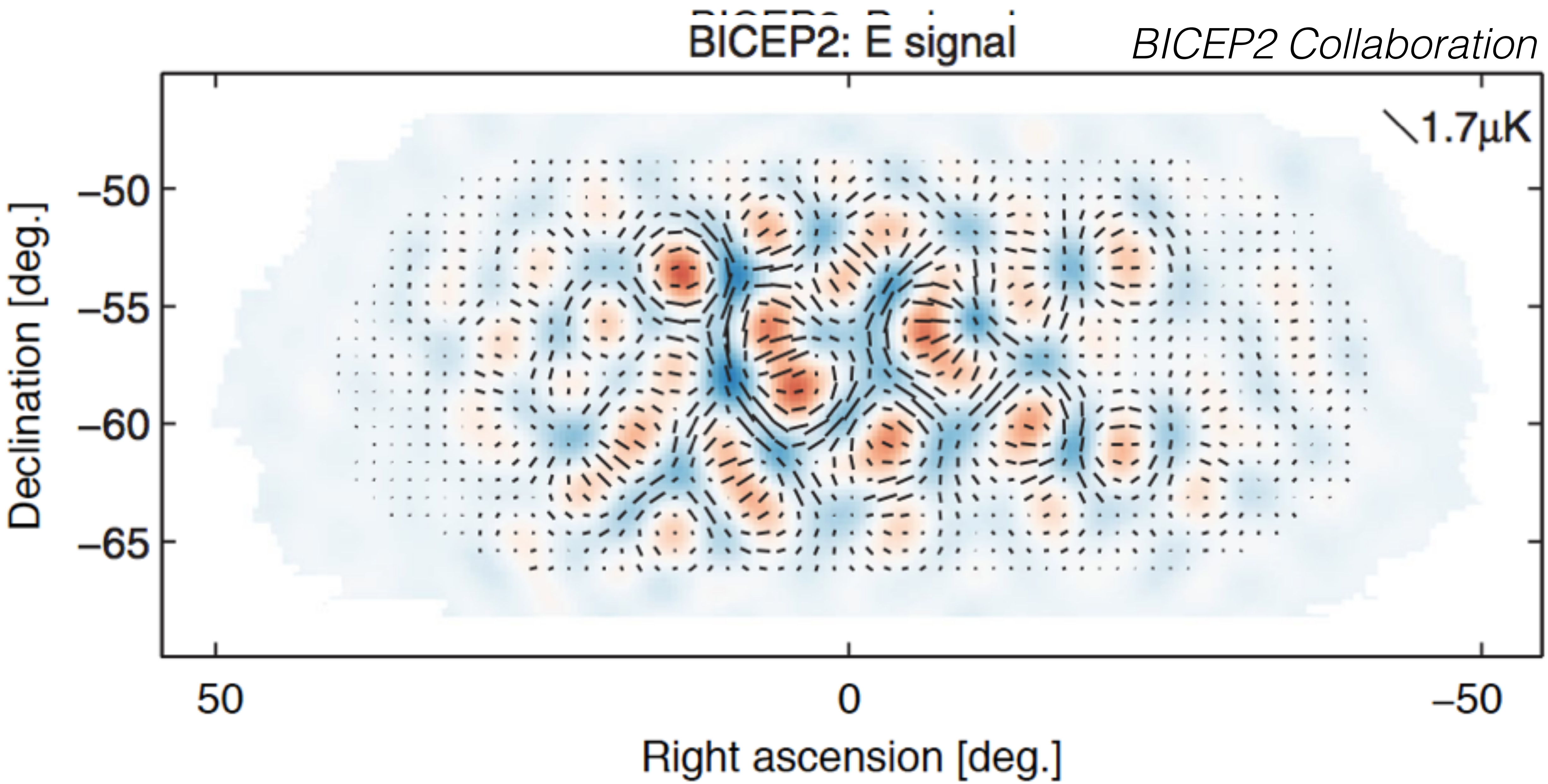


Horizontal slots
-> A detector

Vertical slots
-> B detector

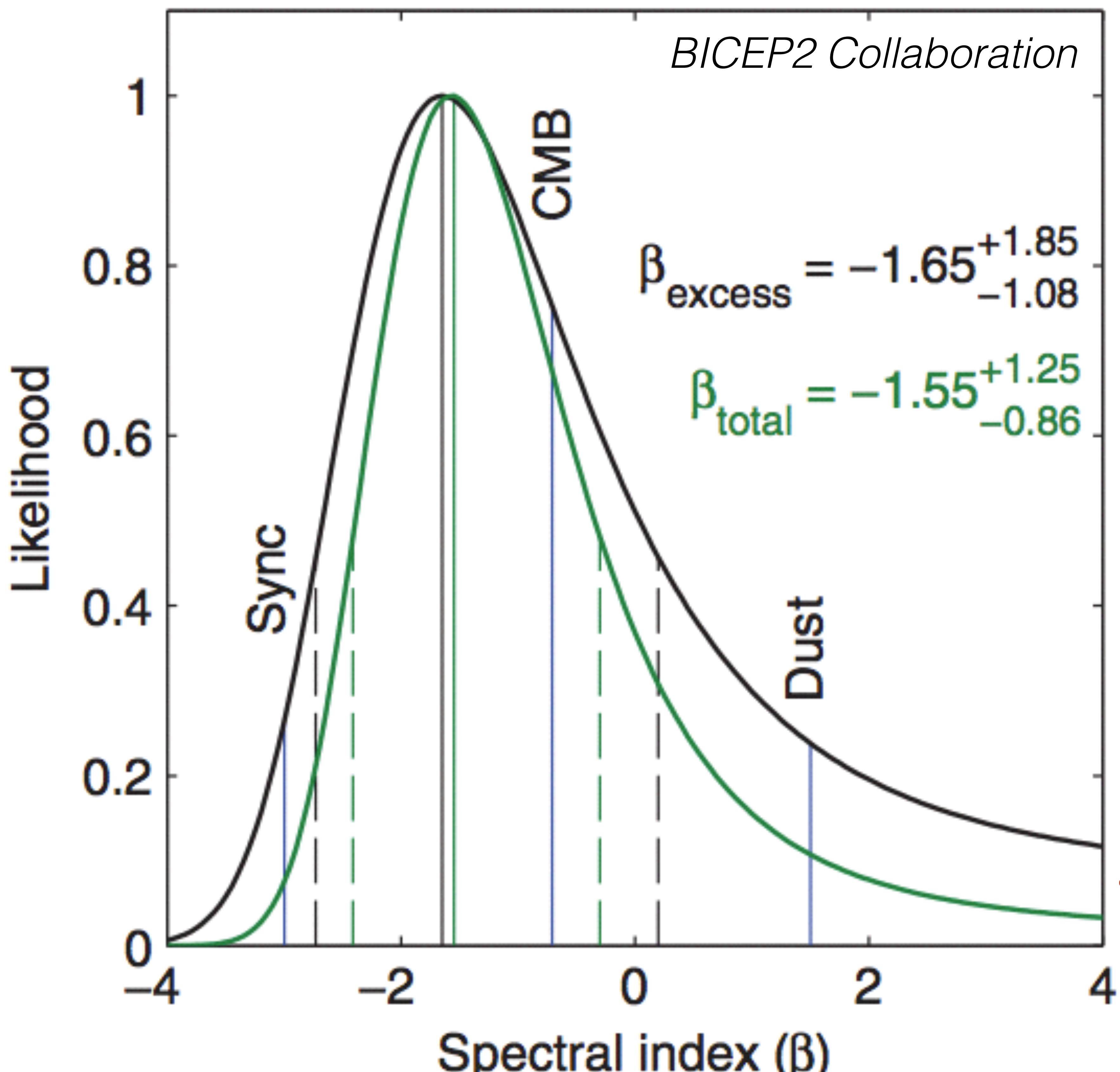
These slots are co-located, so they look at approximately same positions in the sky

There are E modes in the sky as well



The E-mode polarisation is totally dominated by the scalar-mode fluctuations [density waves]

Can we rule out synchrotron or dust?



- **The answer is No**