CMB Polarisation: Toward an Observational Proof of Cosmic Inflation

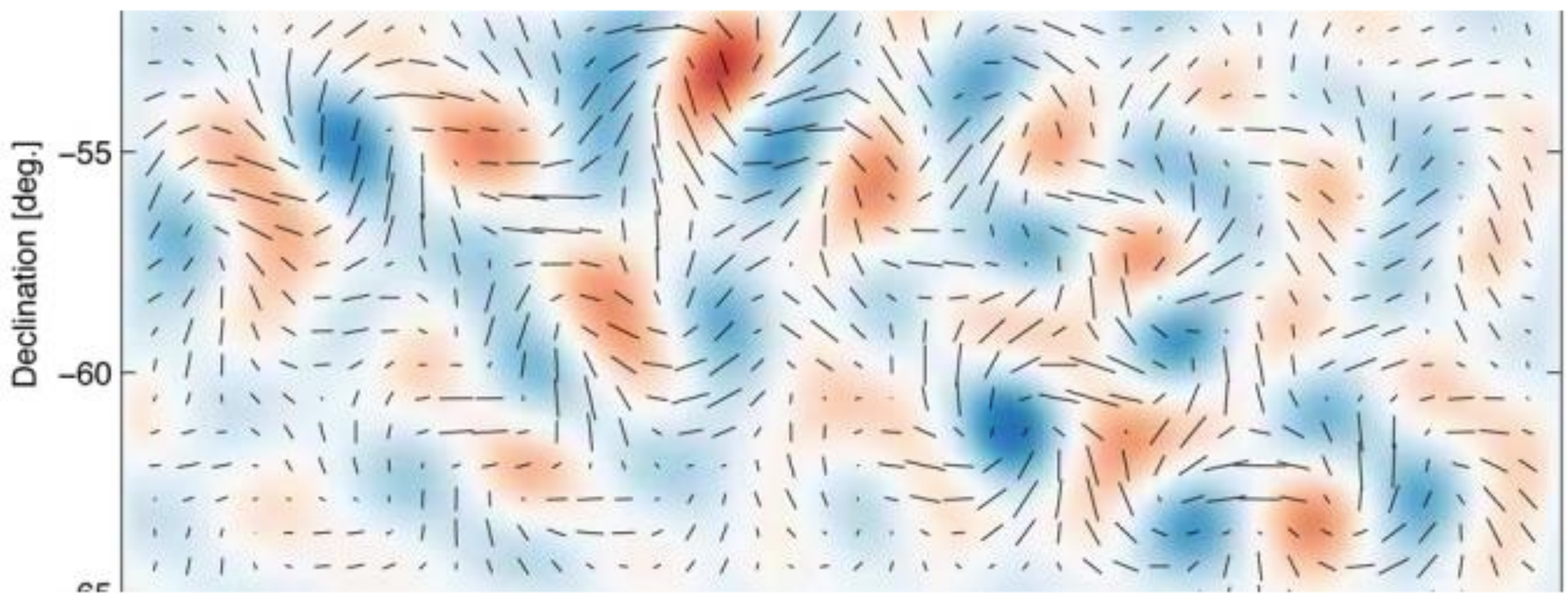
Eiichiro Komatsu, Max-Planck-Institut für Astrophysik
Colloquium, ICTP, October 22, 2014

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.

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First Direct Evidence of Cosmic

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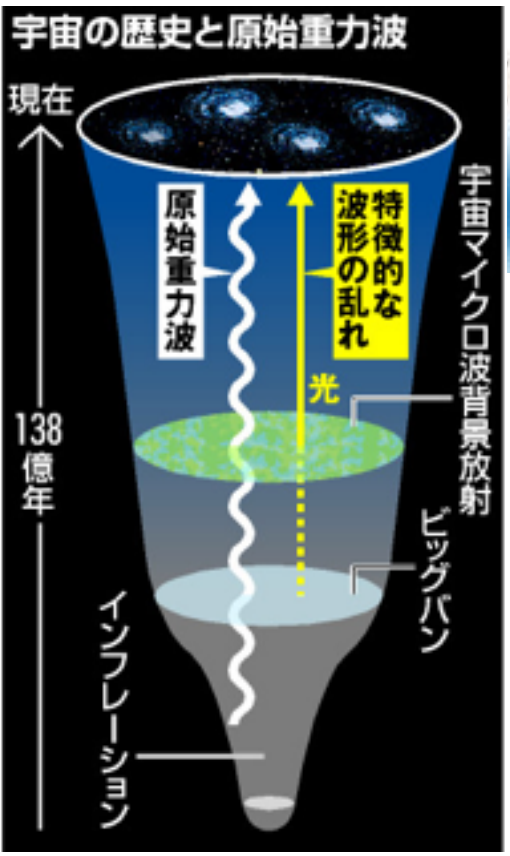

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Cosmic inflation: 'Spectacular' discovery hailed

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

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telescopes. All this, of course, was just theory.
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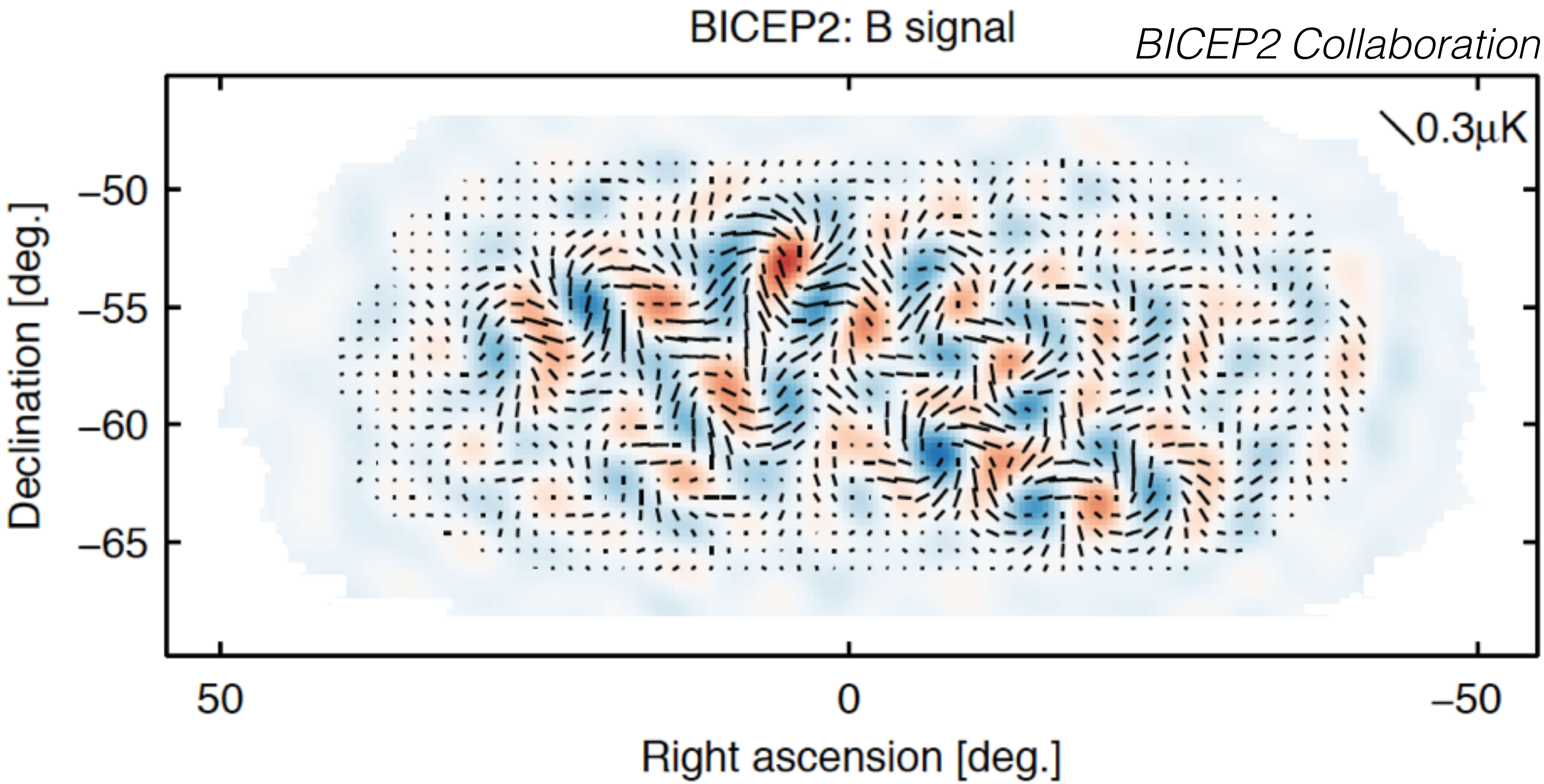
朝日新聞 DIGITAL

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 [?]

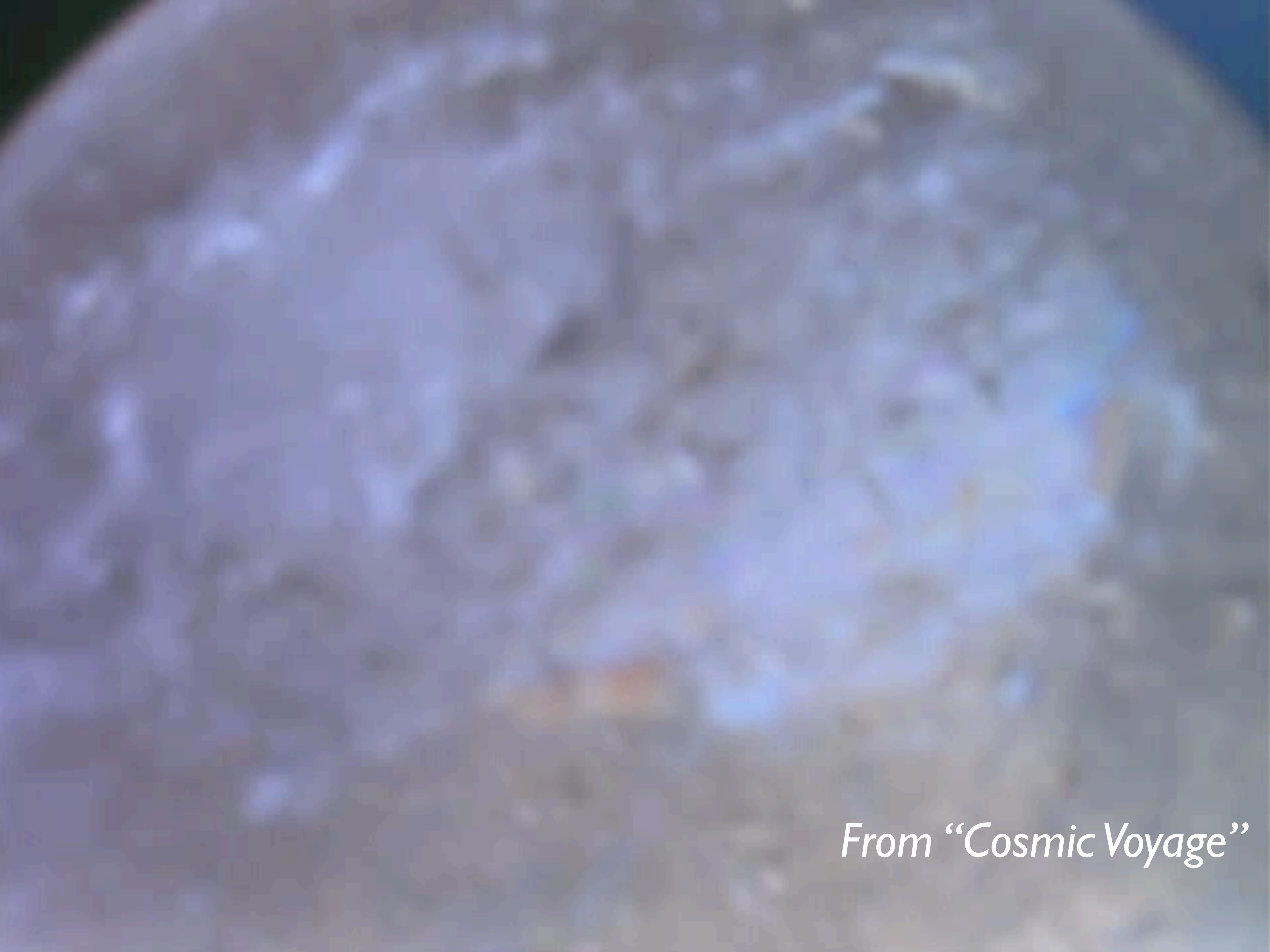
BICEP2 Collaboration



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

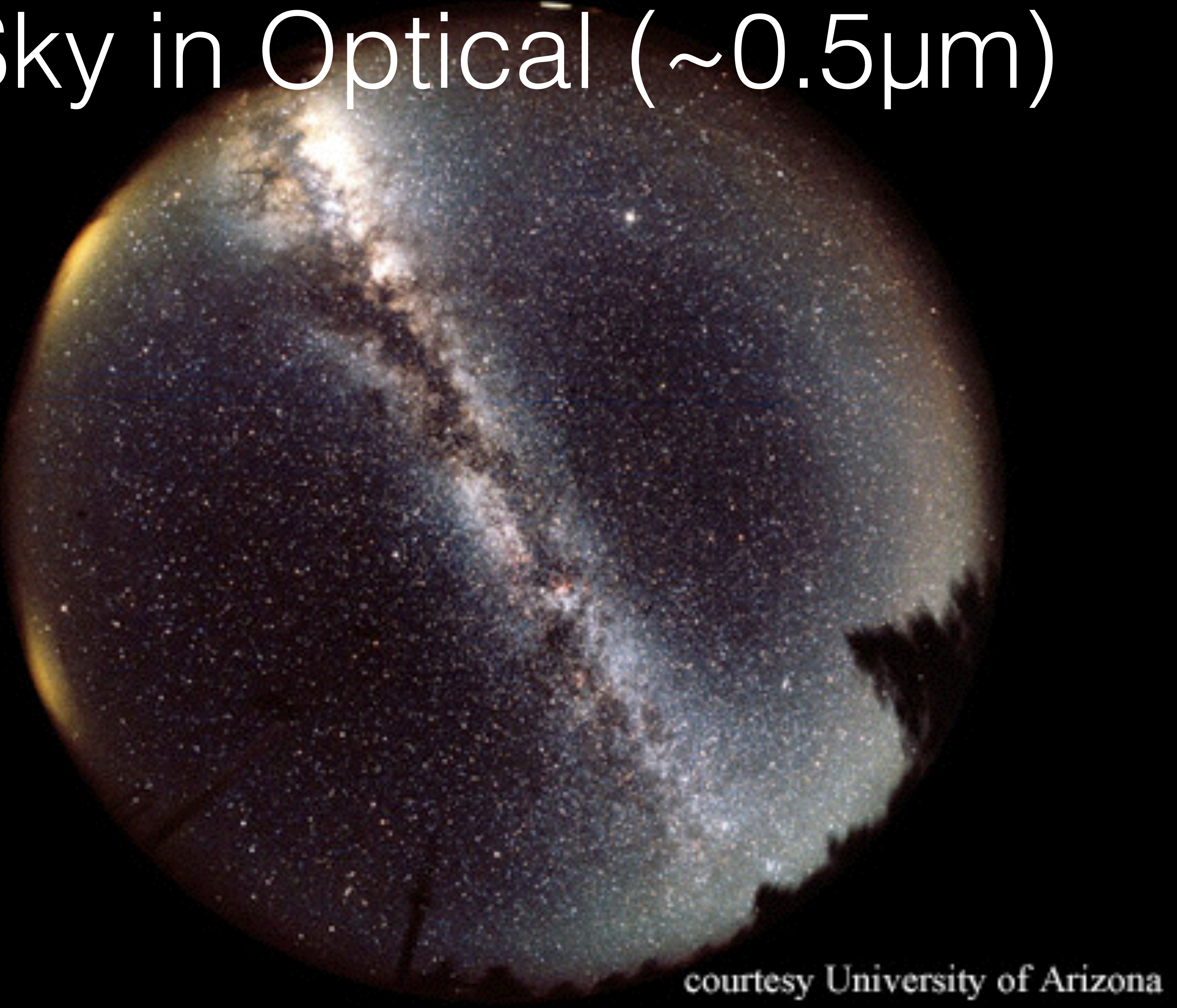
Breakthroughs in Cosmological Research Over the Last Two Decades

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

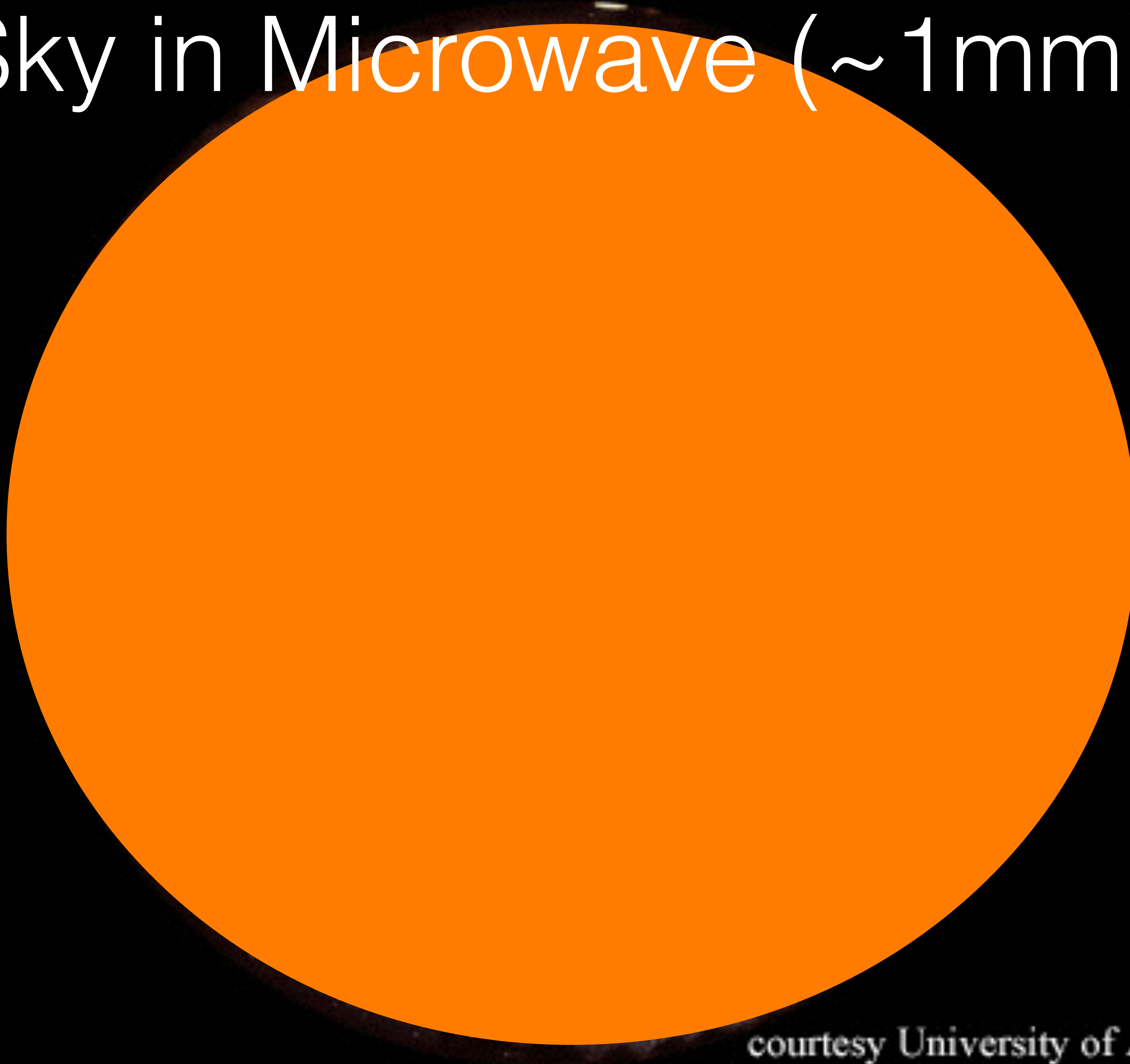


From "Cosmic Voyage"

Sky in Optical (~0.5μm)

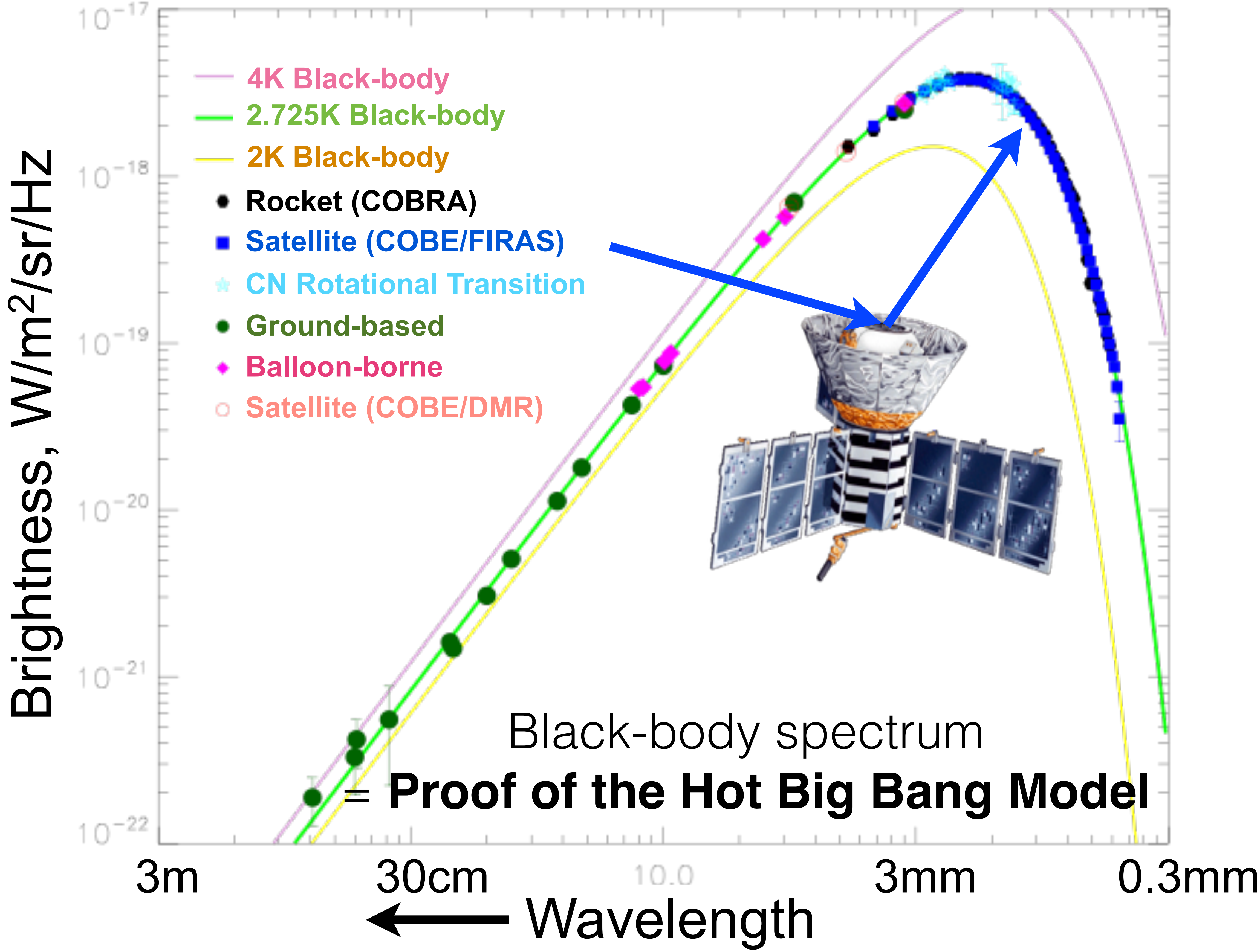


Sky in Microwave (~1mm)



courtesy University of Arizona

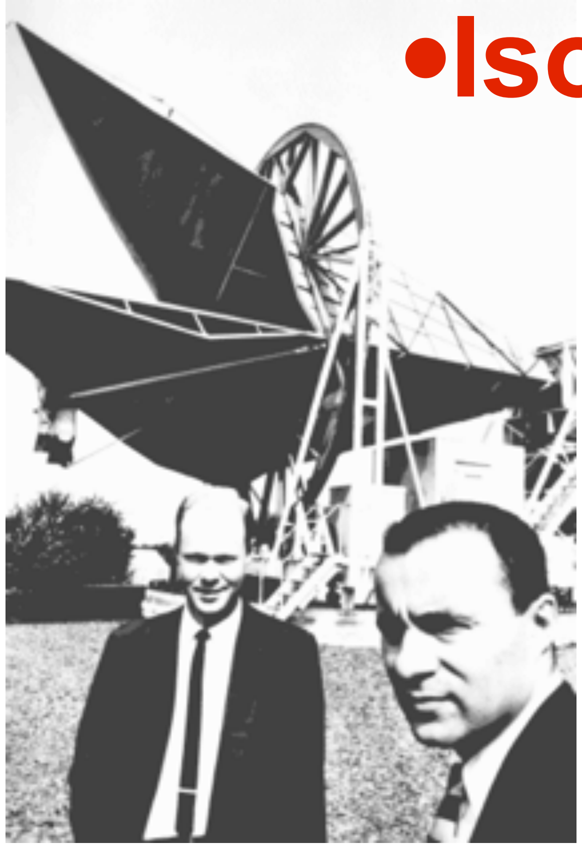
From Samtleben et al. (2007)



Arno Penzias & Robert Wilson, 1965

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

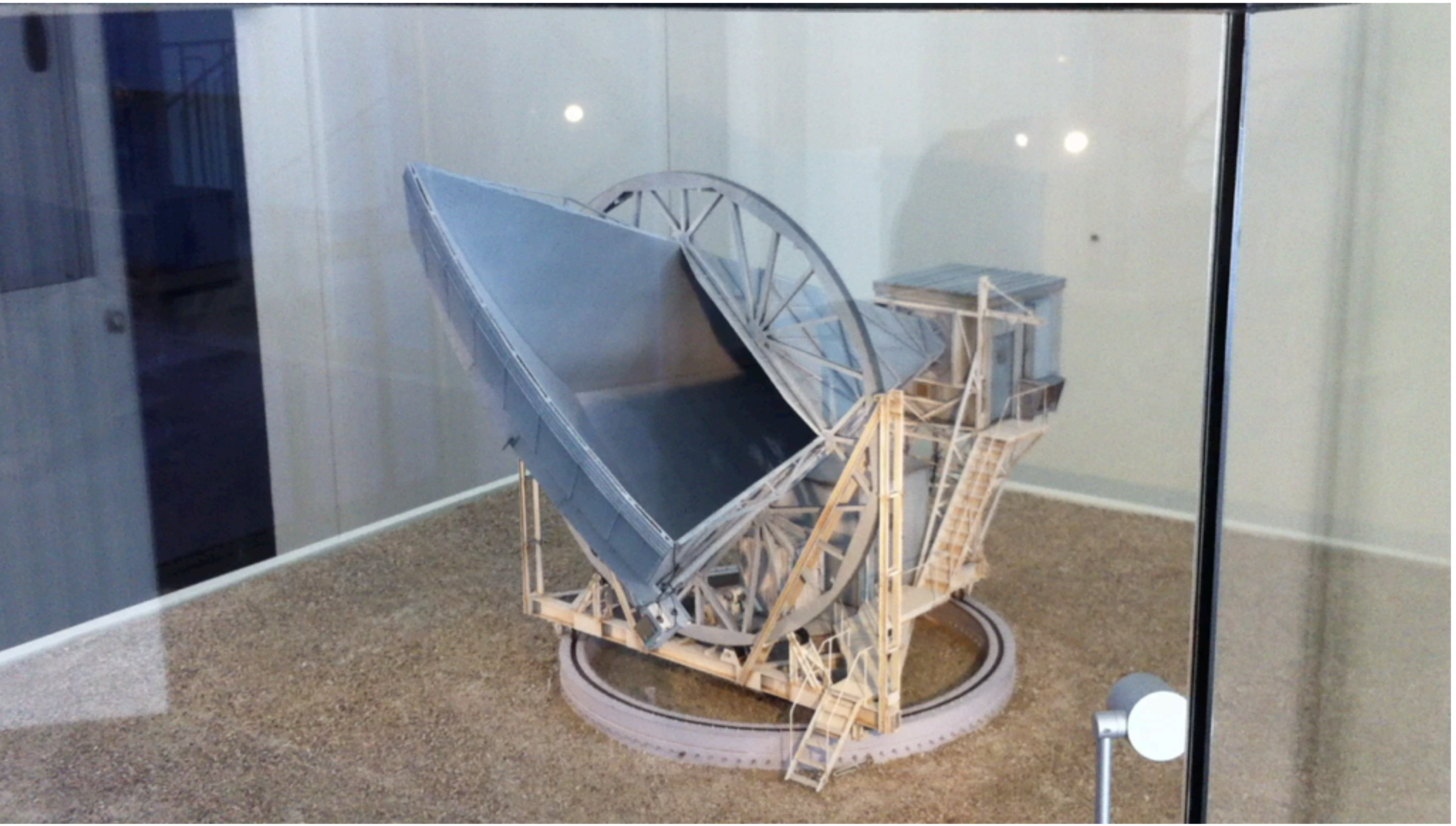


•Isotropic

A. A. PENZIAS
R. W. WILSON

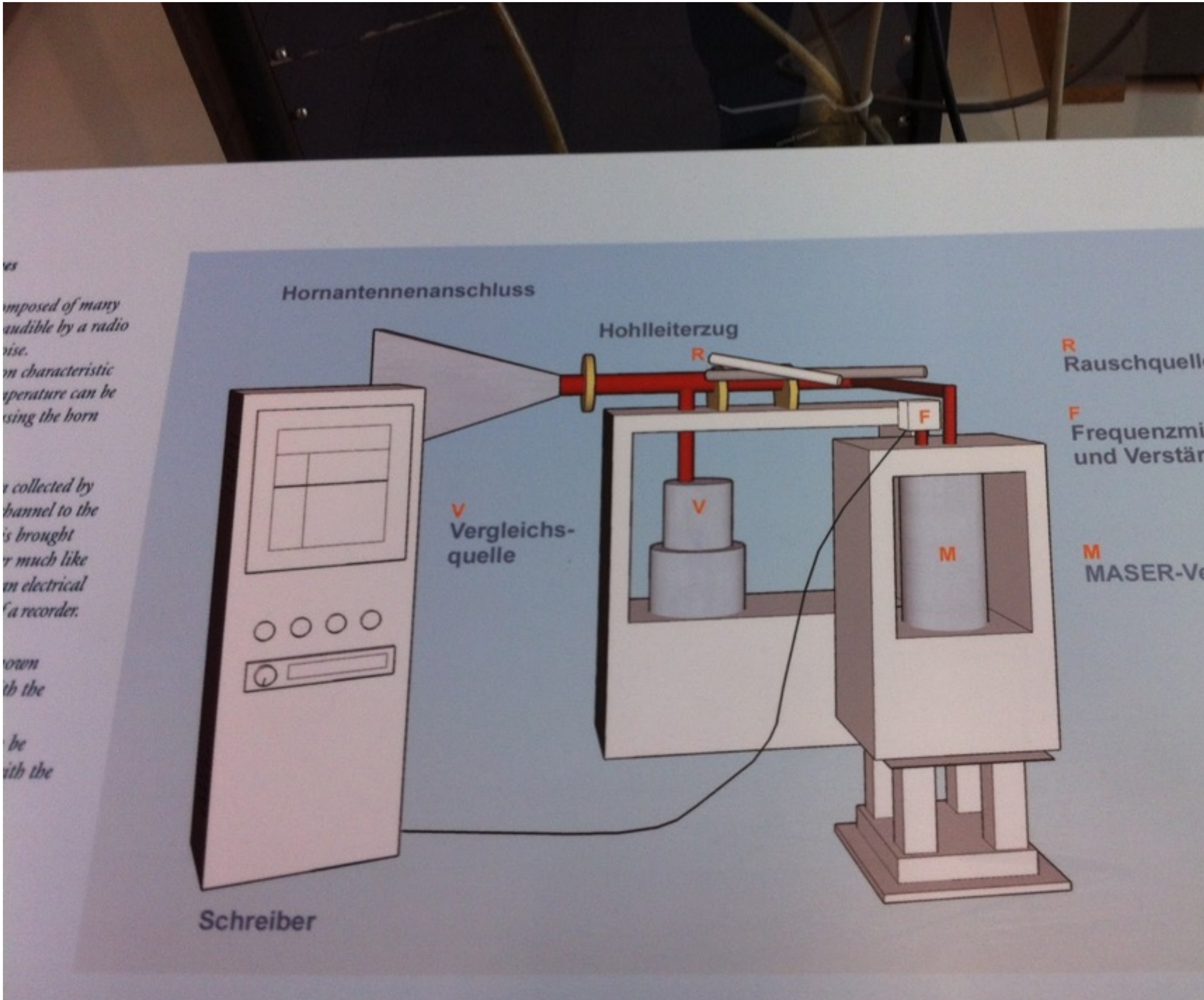
May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

1:25 model at Deutsches Museum



The REAL back-end system of the Penzias-Wilson experiment, exhibited at Deutsches Museum

Arno Penzias



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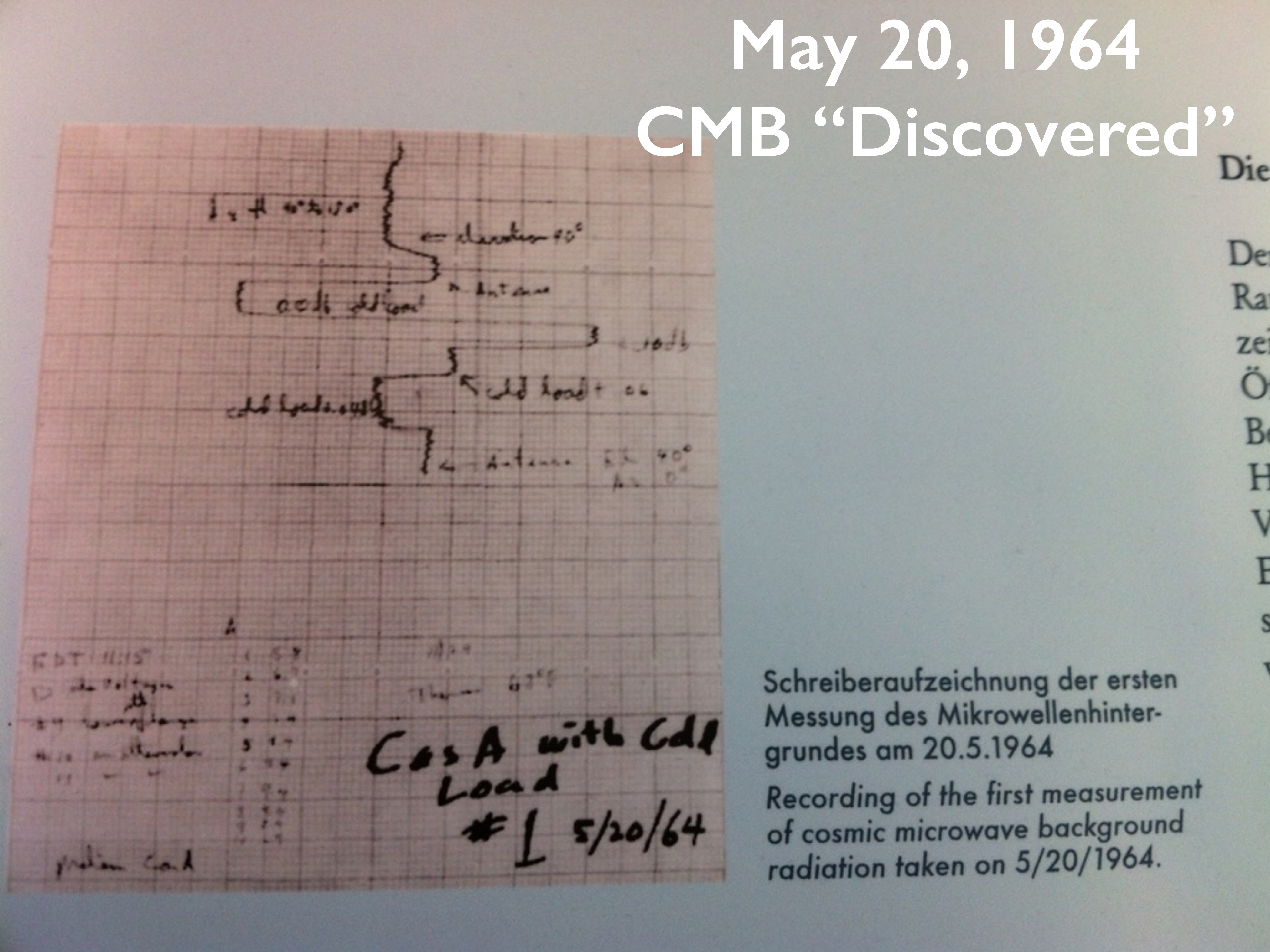
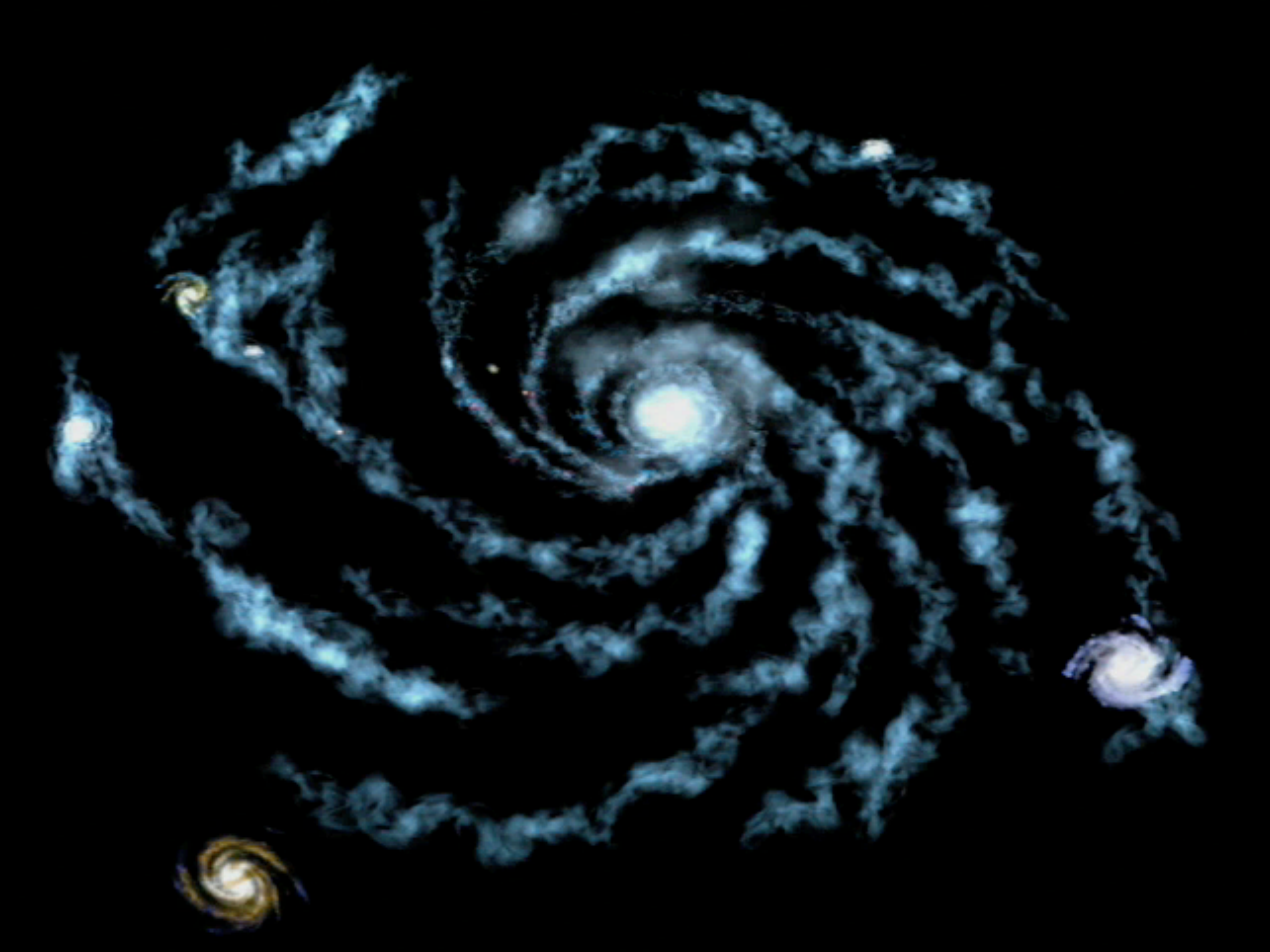
M
MASER-V
Schreiber

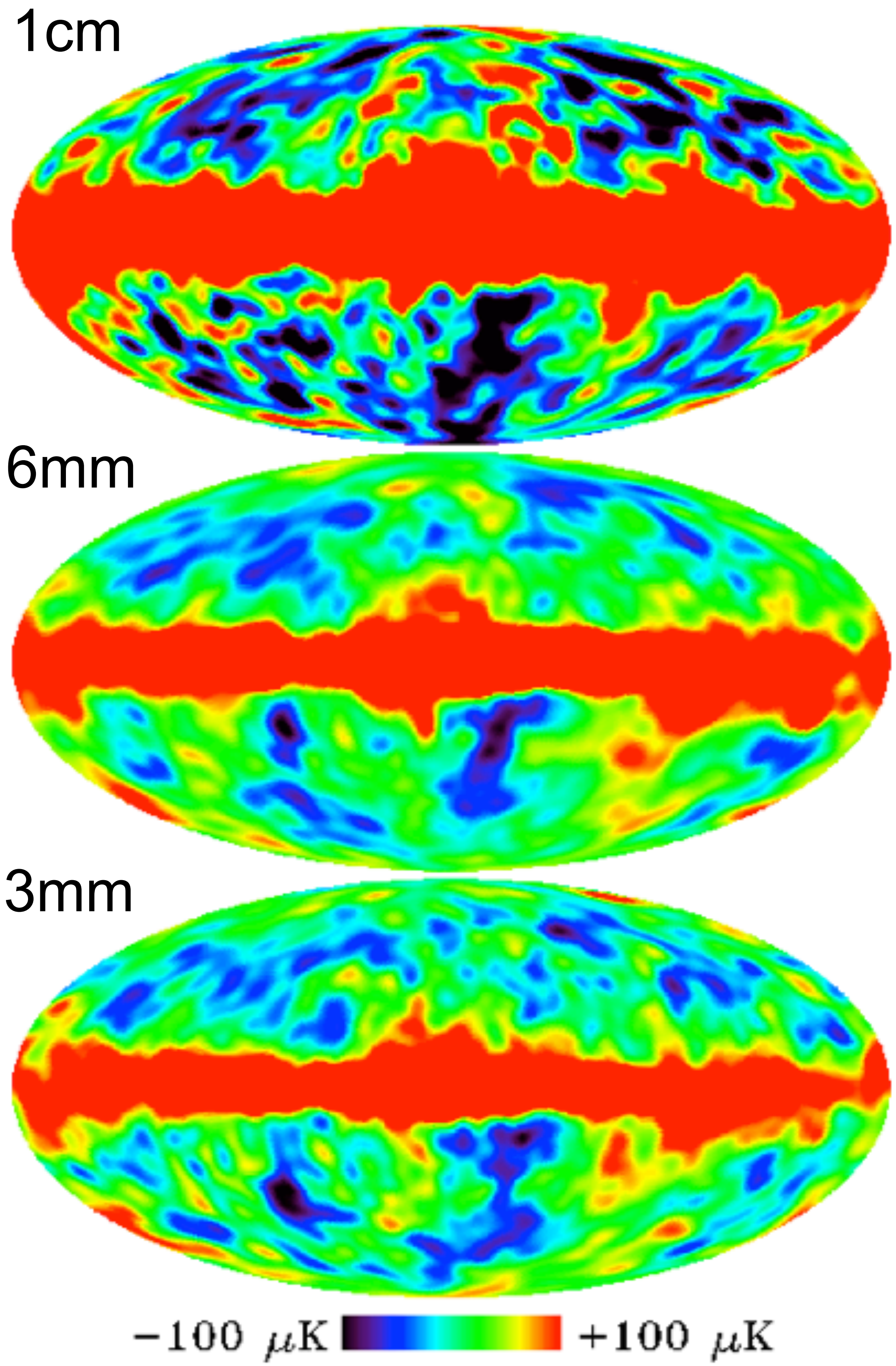
May 20, 1964
CMB "Discovered"





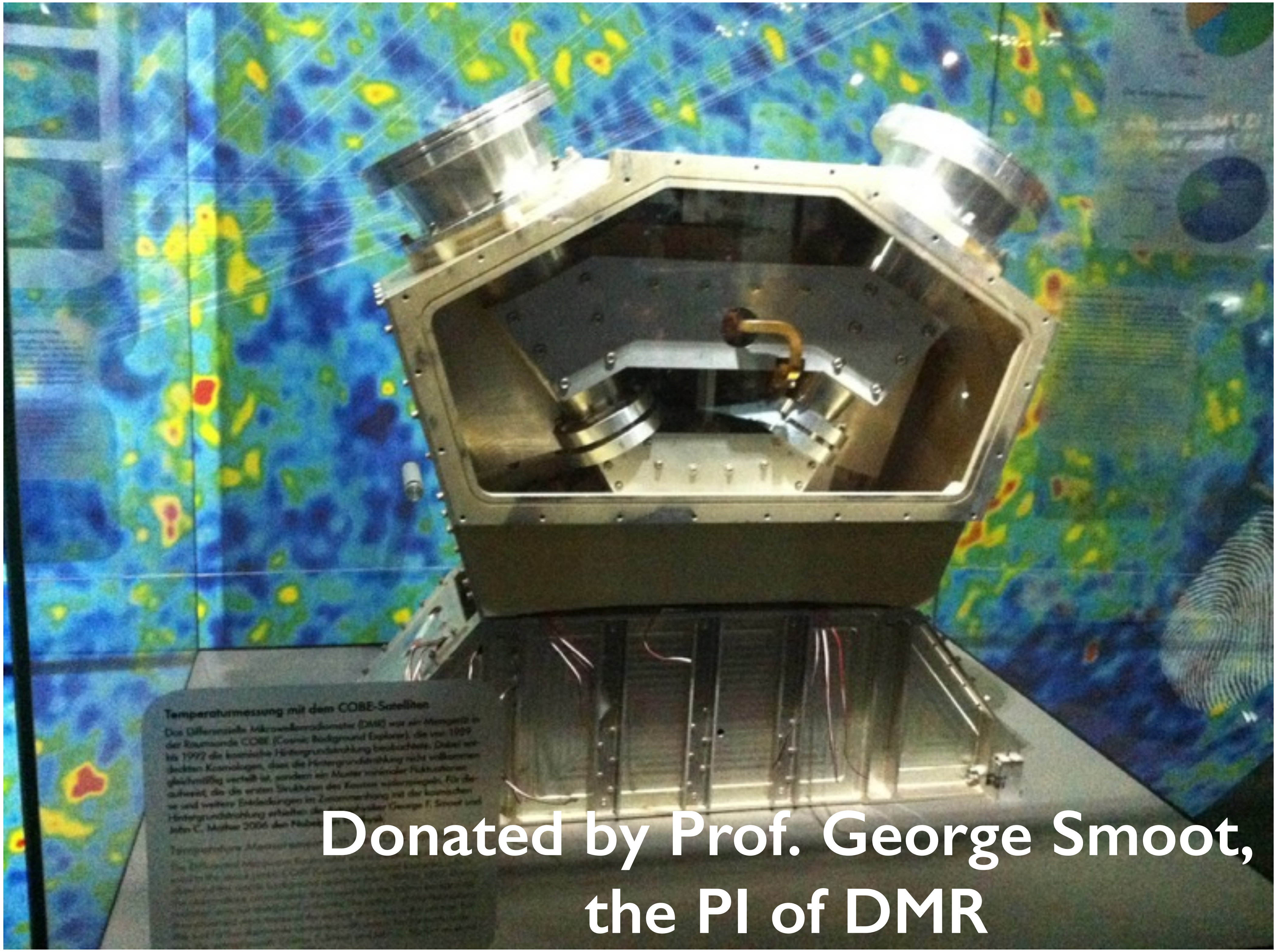
Smoot et al. (1992)

COBE/DMR, 1992



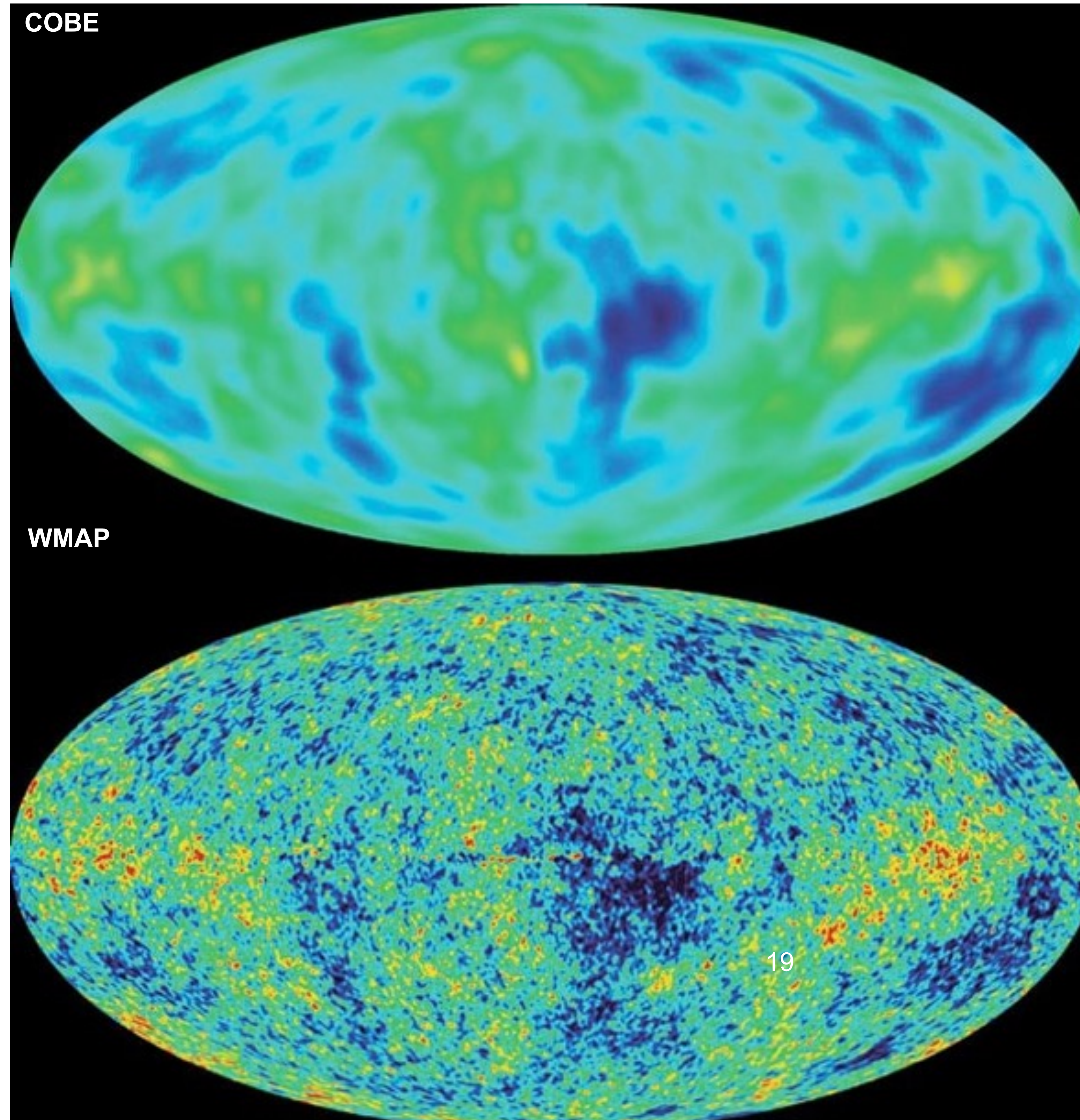
•CMB is anisotropic!
(at the 1/100,000 level)

A spare unit of COBE/DMR (λ=1cm)



COBE to WMAP

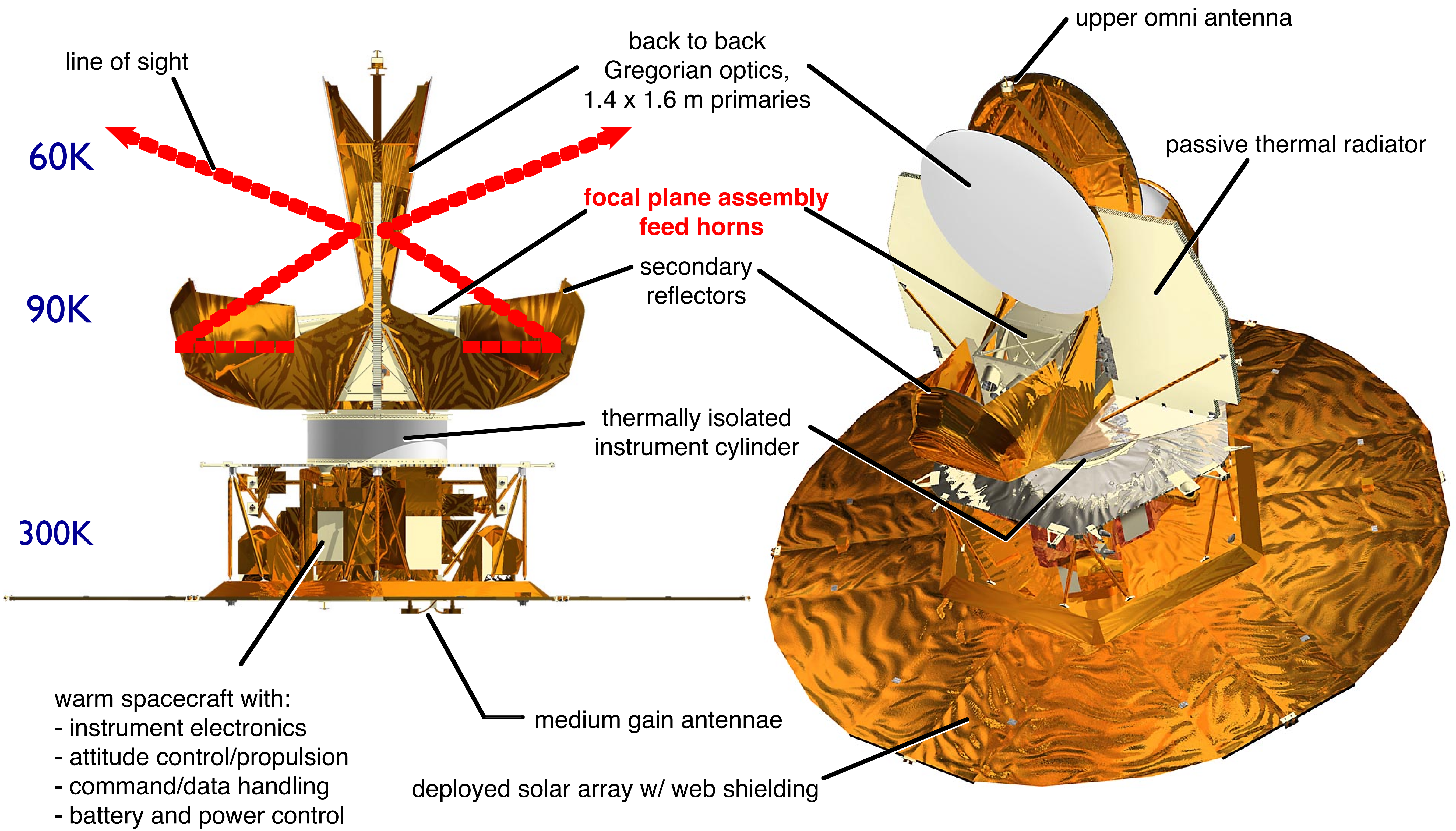
COBE
1989



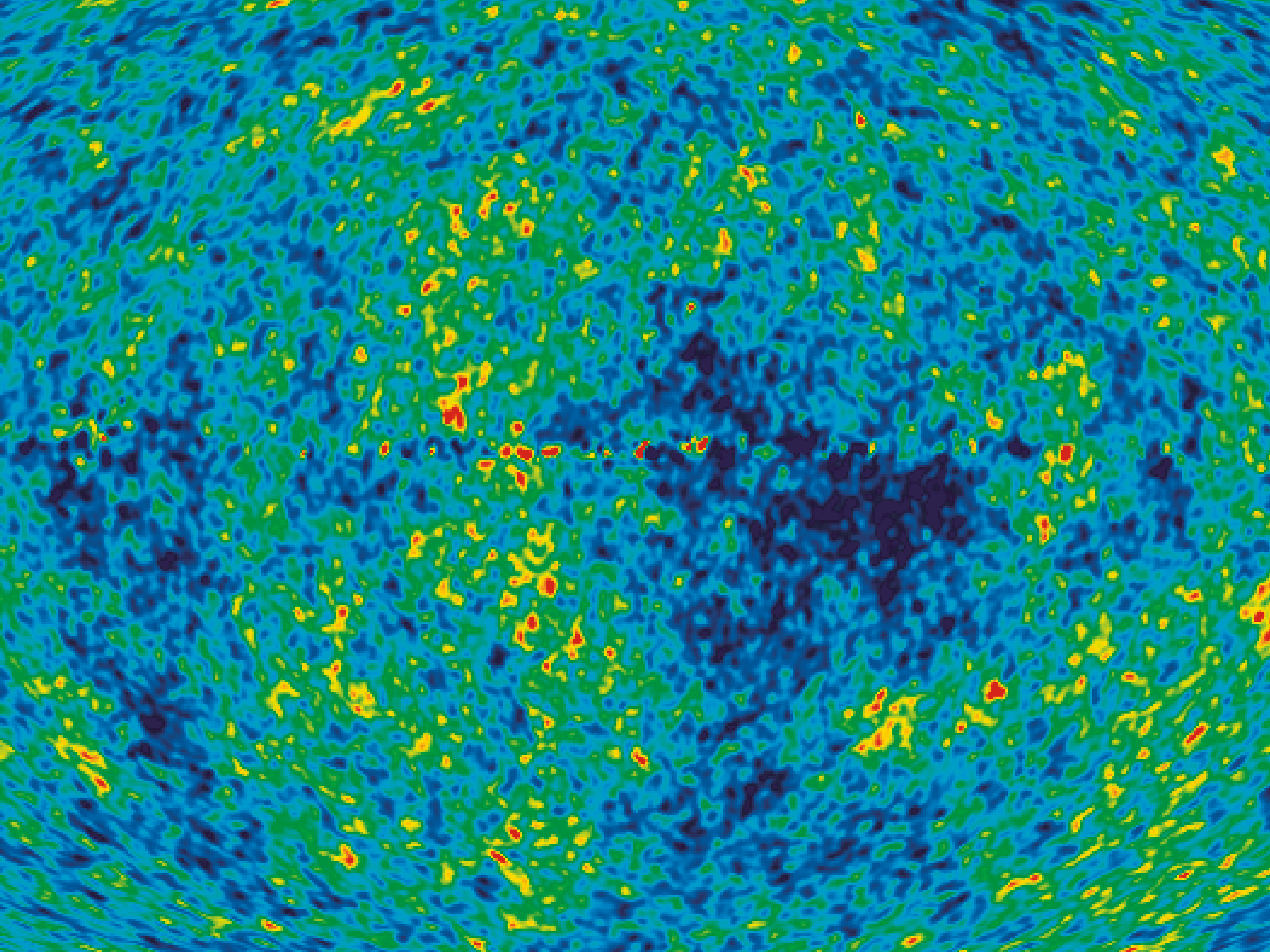
WMAP
2001

WMAP Spacecraft

Radiative Cooling: No Cryogenic System



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

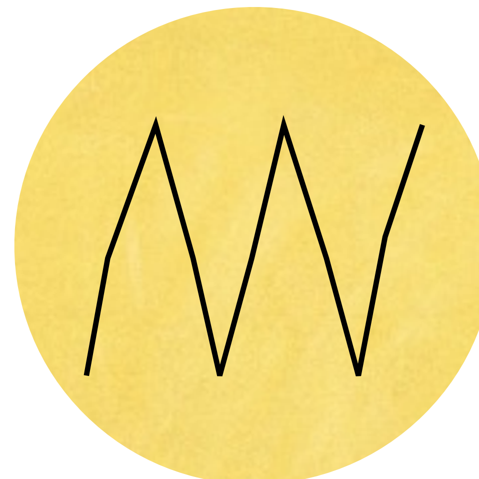
Starobinsky (1980); Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

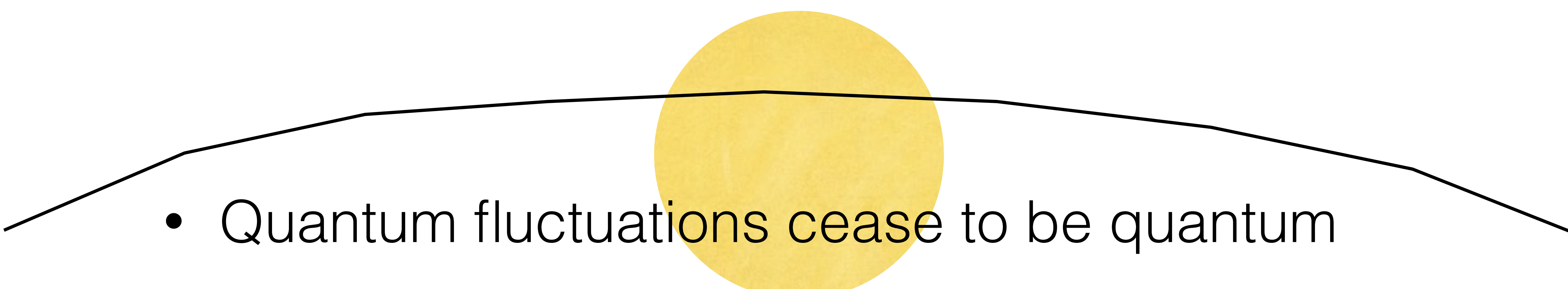
- In a tiny fraction of a second, the size of an atomic nucleus became the size of the Solar System
    - In 10^{-36} second, space was stretched by at least a factor of 10^{26}

Stretching Micro to Macro

Quantum fluctuations on microscopic scales



Inflation!



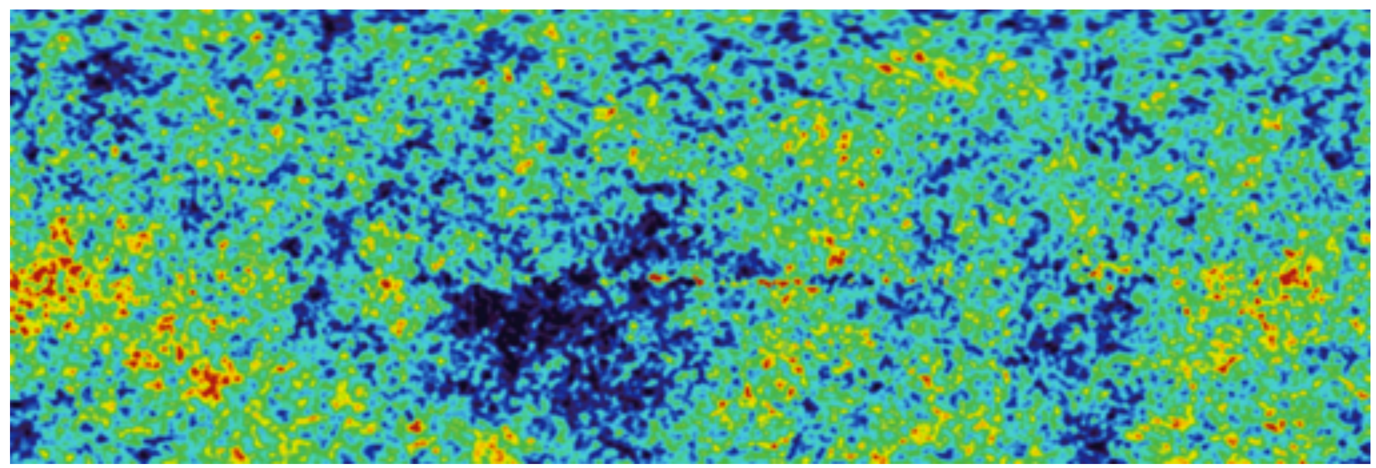
- Quantum fluctuations cease to be quantum
- Become macroscopic, classical fluctuations

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]

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

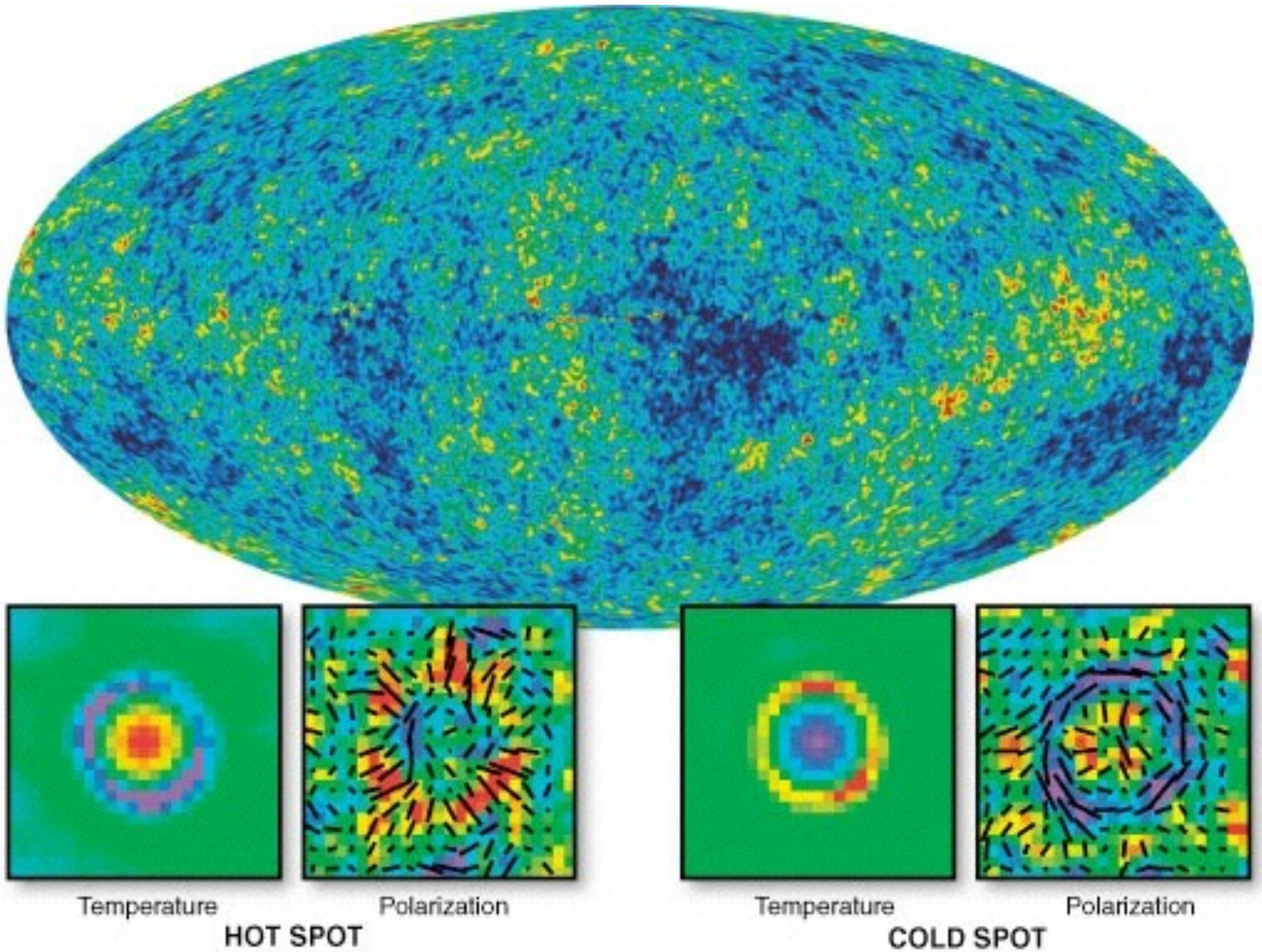
- [Energy you can borrow] x [Time you borrow] = constant
- $H \equiv \frac{\dot{a}}{a}$ [This has units of 1/time]
- Then, **both ζ and h_{ij} are proportional to H**
- Inflation occurs in 10^{-36} second - this is such a short period of time that you can borrow a lot of energy! **H during inflation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

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

Key Predictions of Inflation

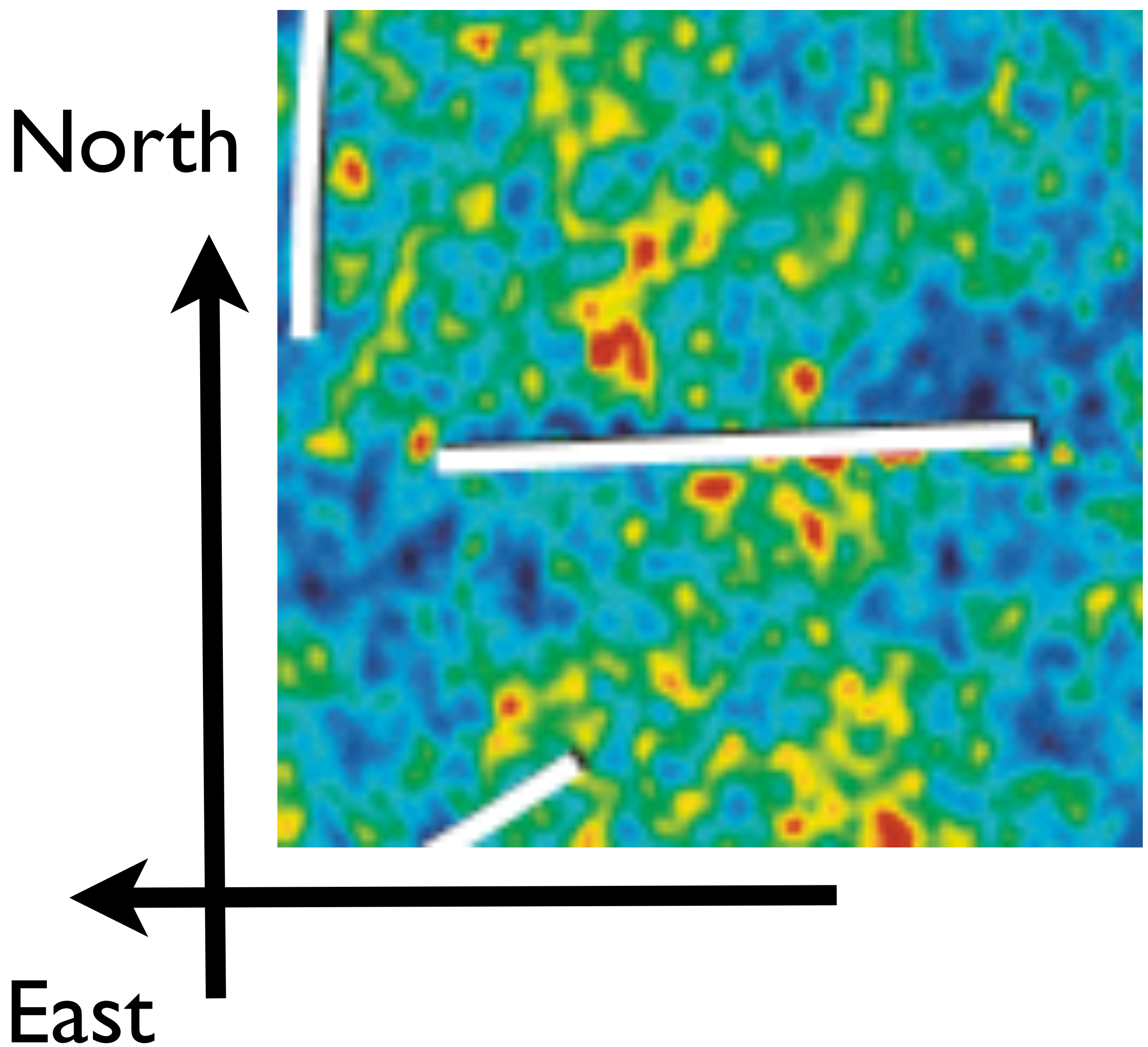
- Inflation must end; thus, H slowly decreases with time
  - This means that the amplitude of fluctuations on larger scales is bigger than those on smaller scales. **This has now been observed***
- The origin of fluctuations is quantum. The wave function of vacuum fluctuations of a free field is a Gaussian. **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?**

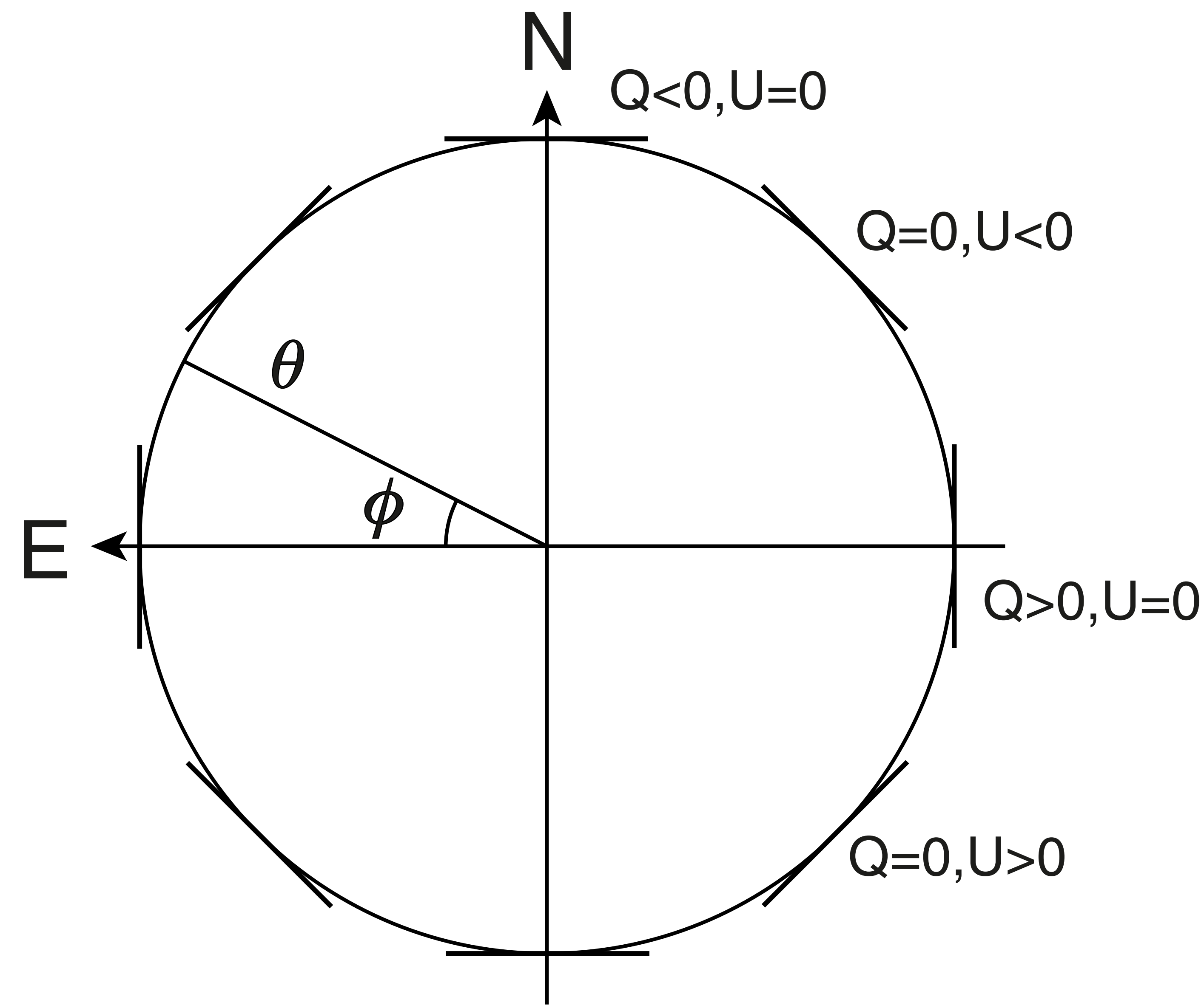
CMB Polarisation



- CMB is [weakly] polarised!

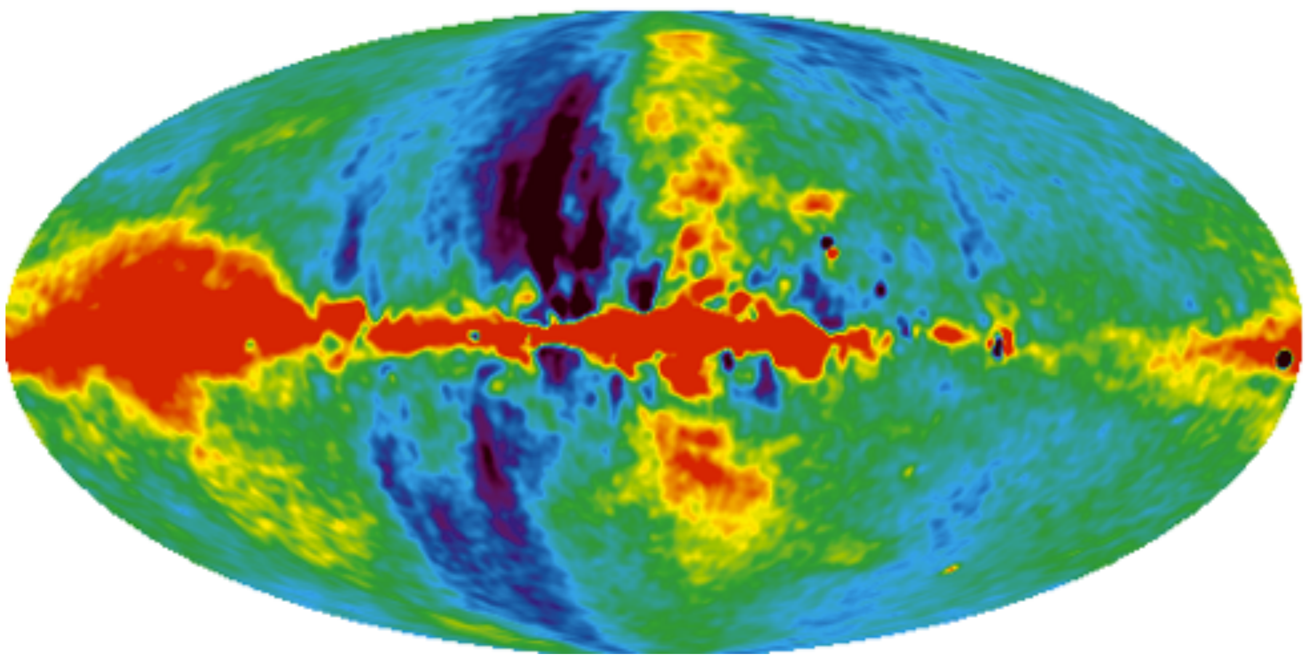
Stokes Parameters



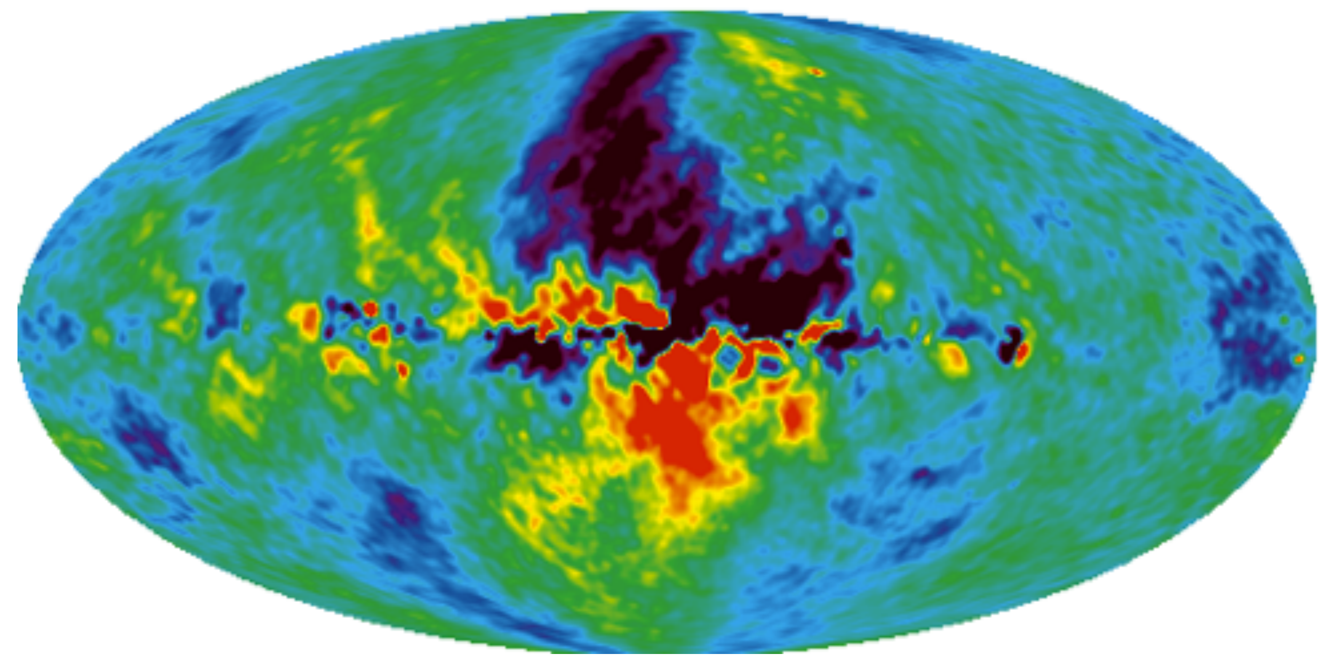


WMAP Collaboration

23 GHz



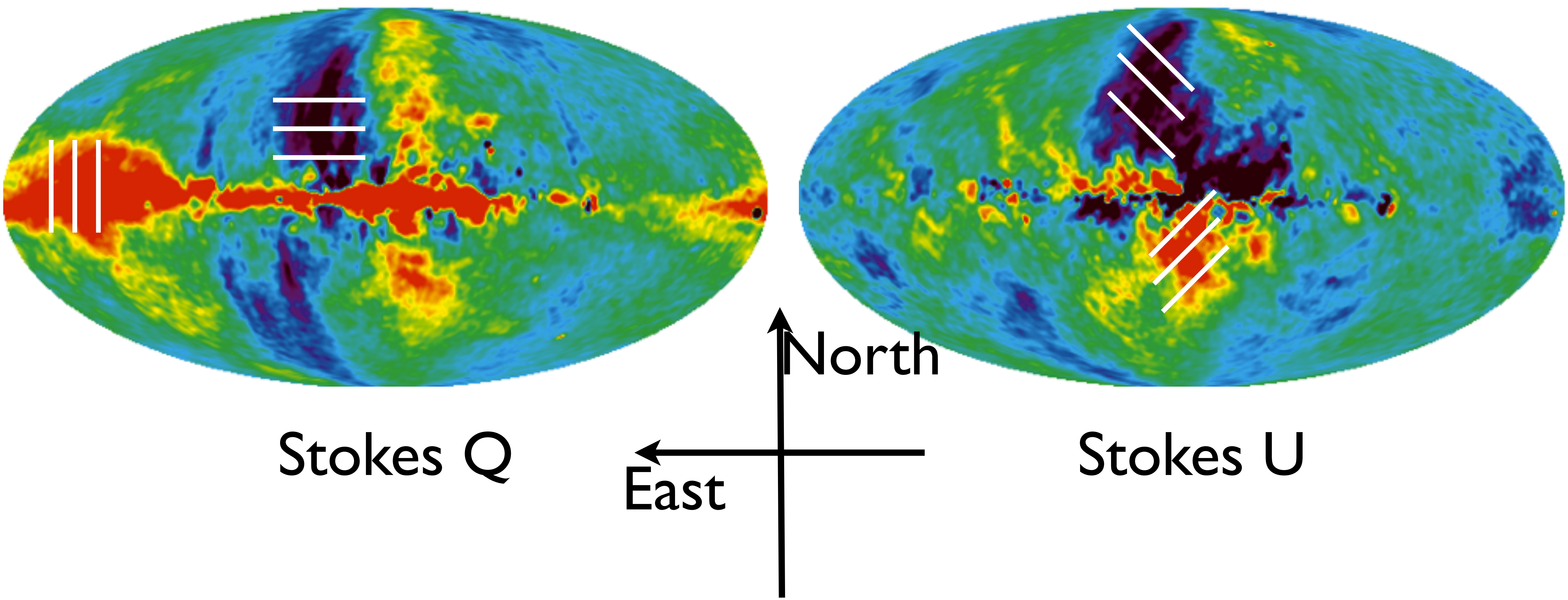
Stokes Q



Stokes U

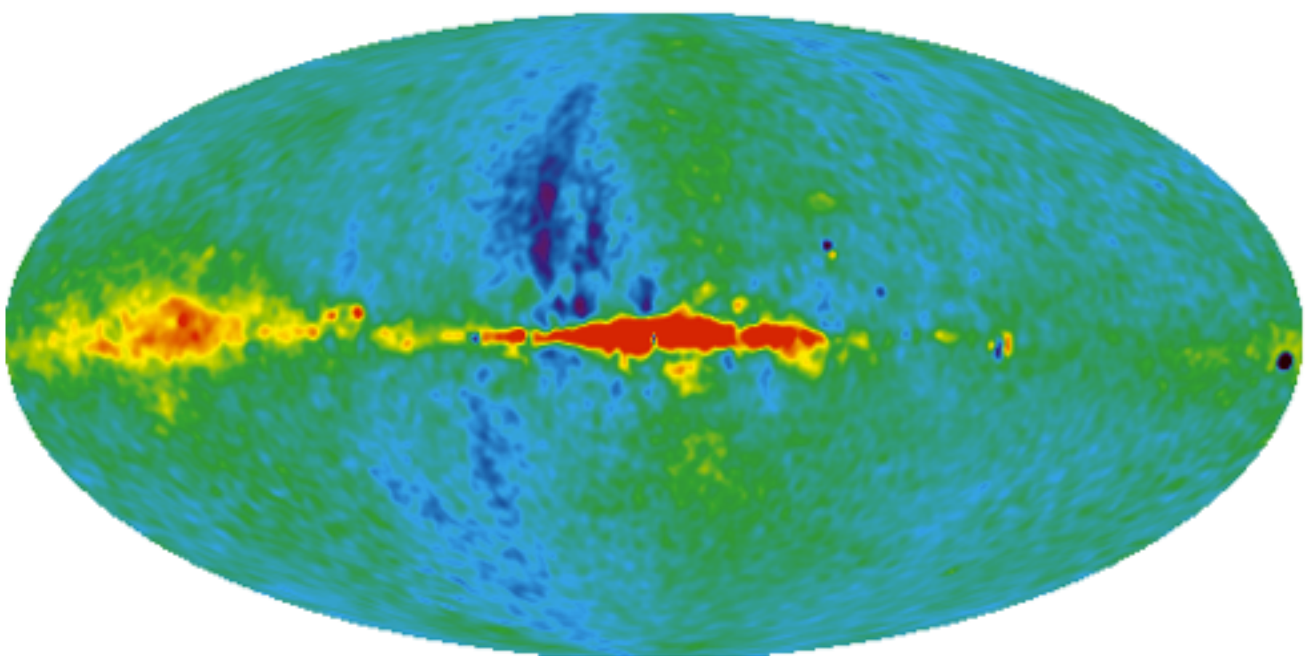
WMAP Collaboration

23 GHz [13 mm]

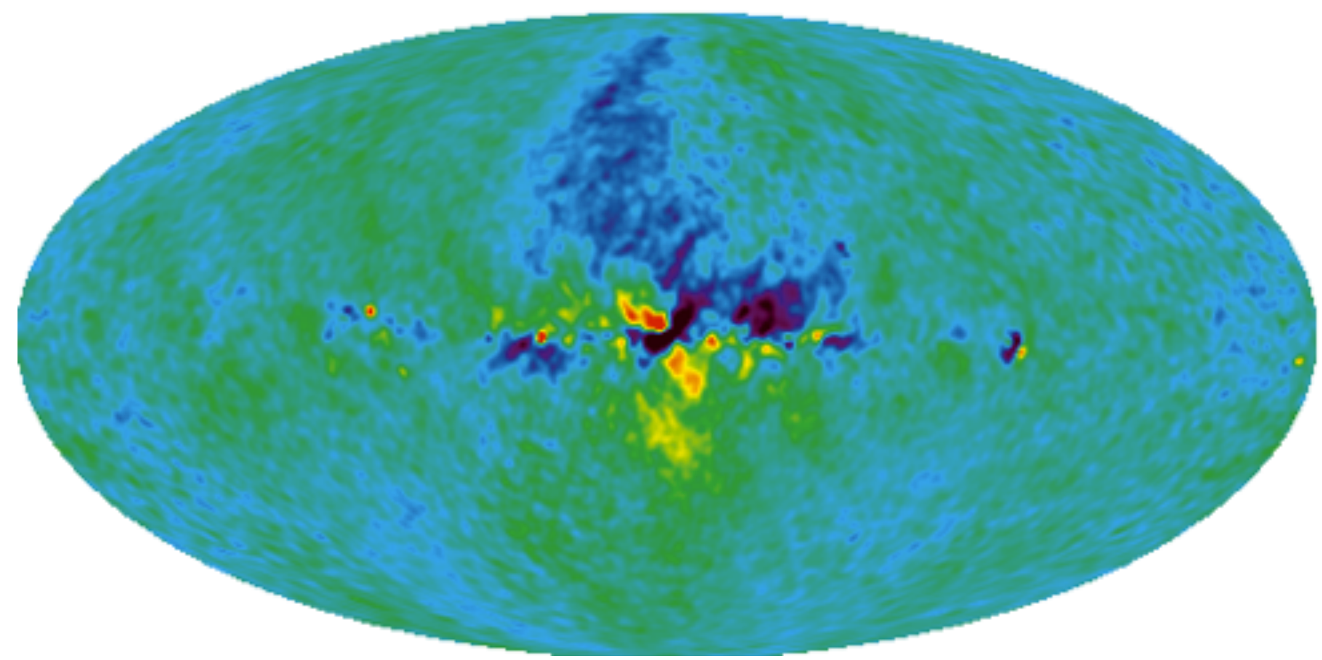


WMAP Collaboration

33 GHz [9.1 mm]



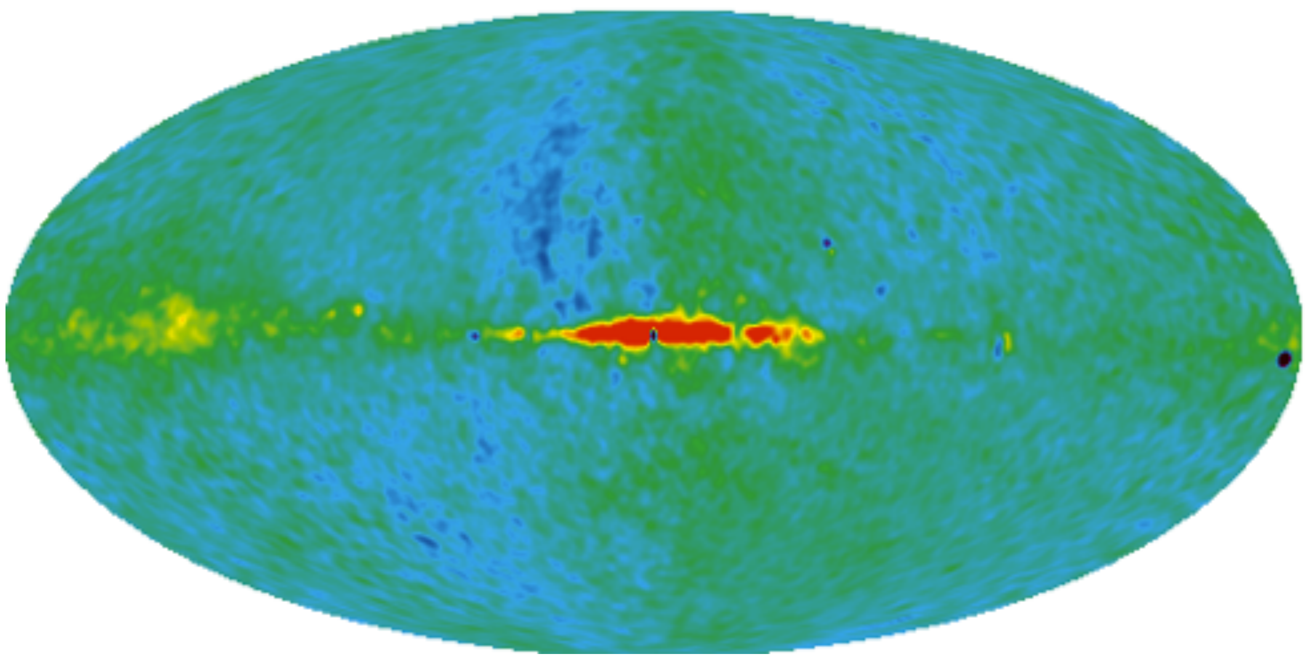
Stokes Q



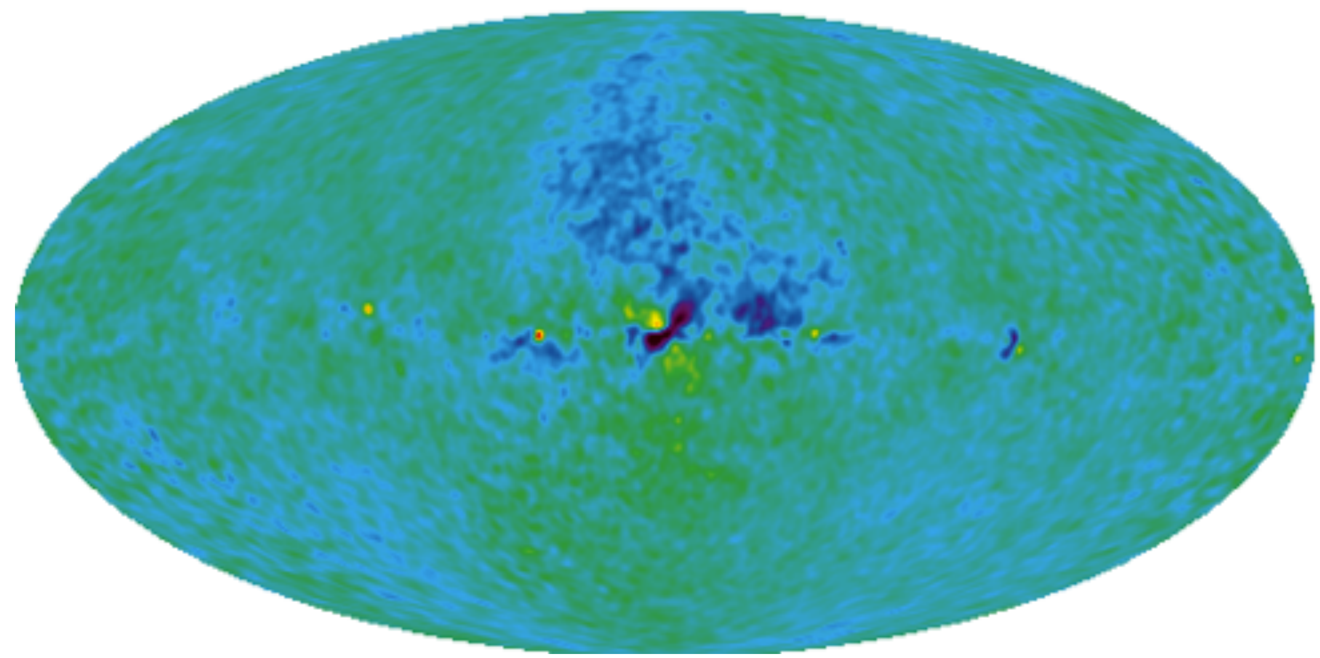
Stokes U

WMAP Collaboration

41 GHz [7.3 mm]



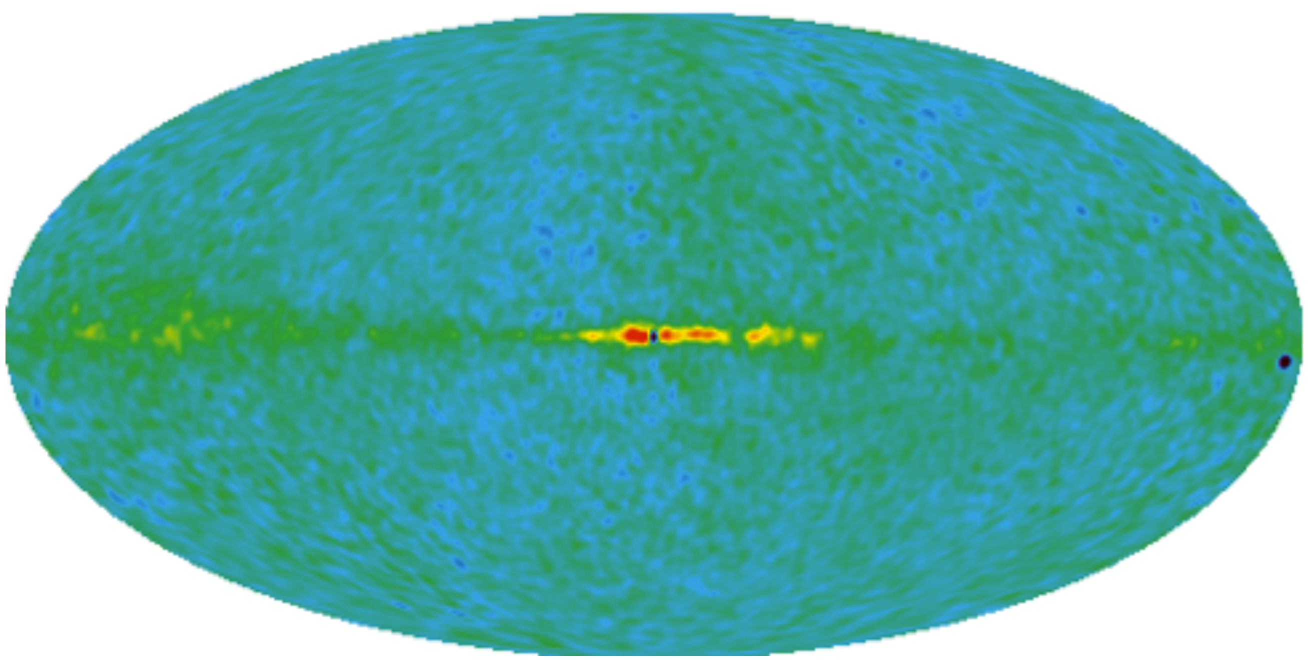
Stokes Q



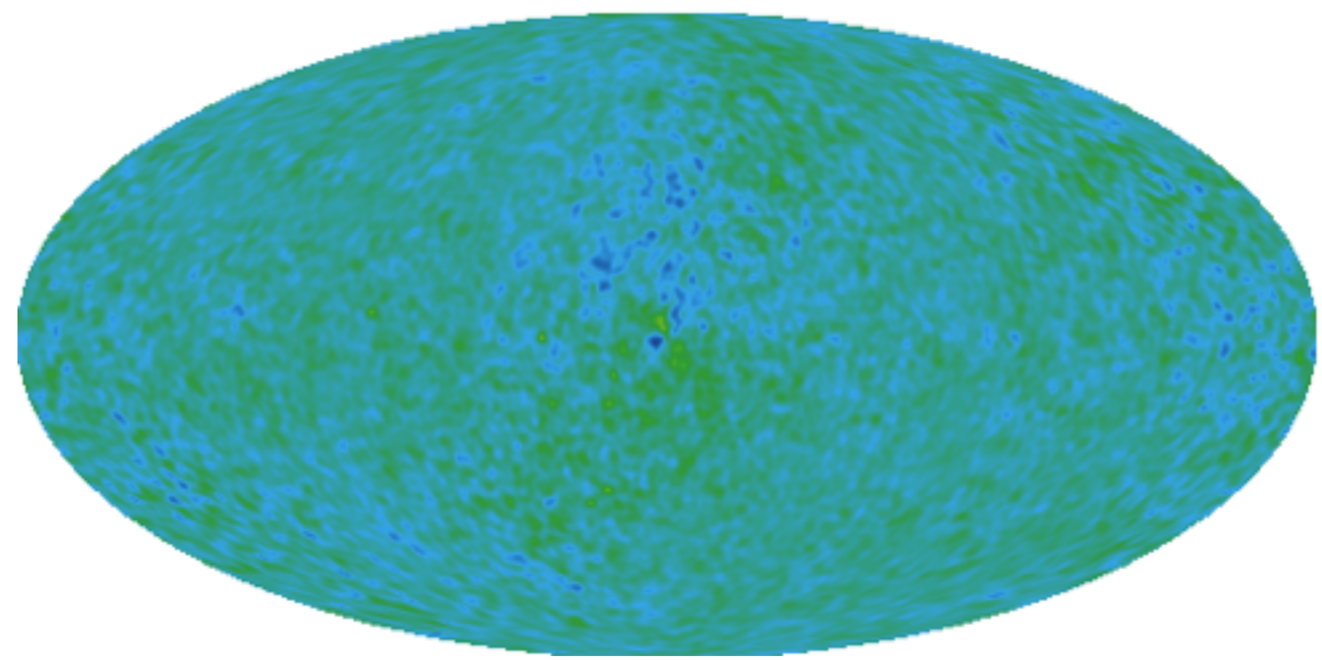
Stokes U

WMAP Collaboration

61 GHz [4.9 mm]



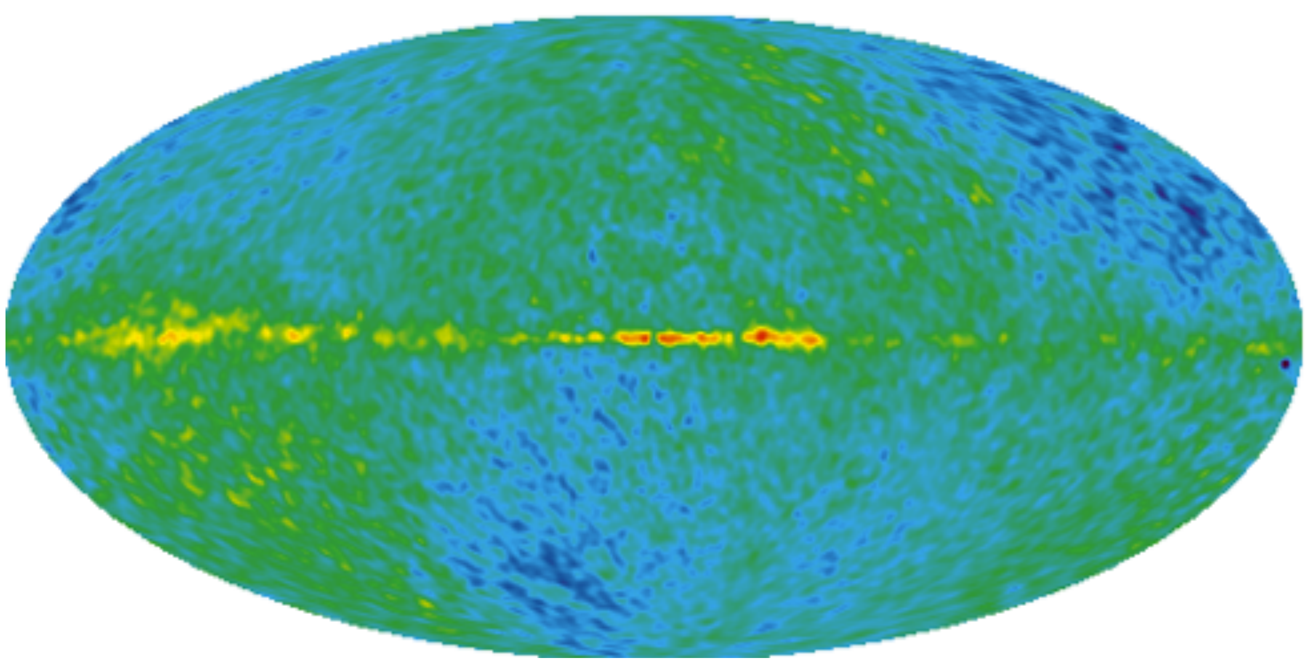
Stokes Q



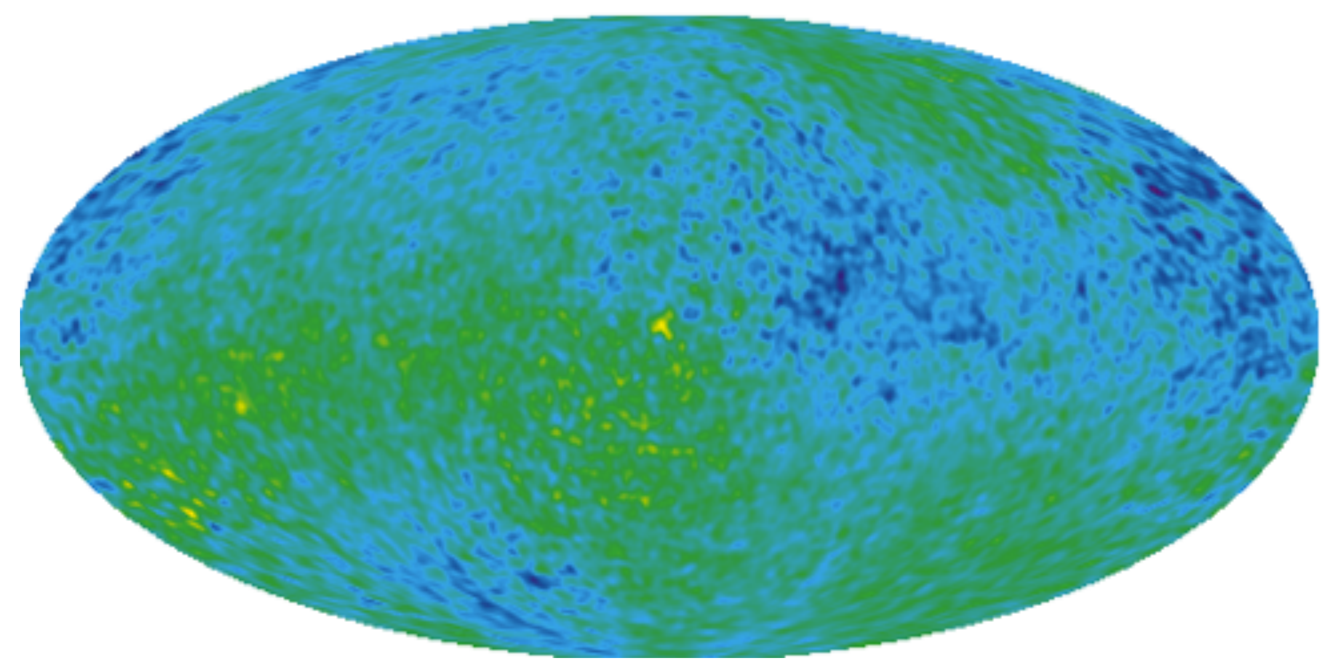
Stokes U

WMAP Collaboration

94 GHz [3.2 mm]



Stokes Q



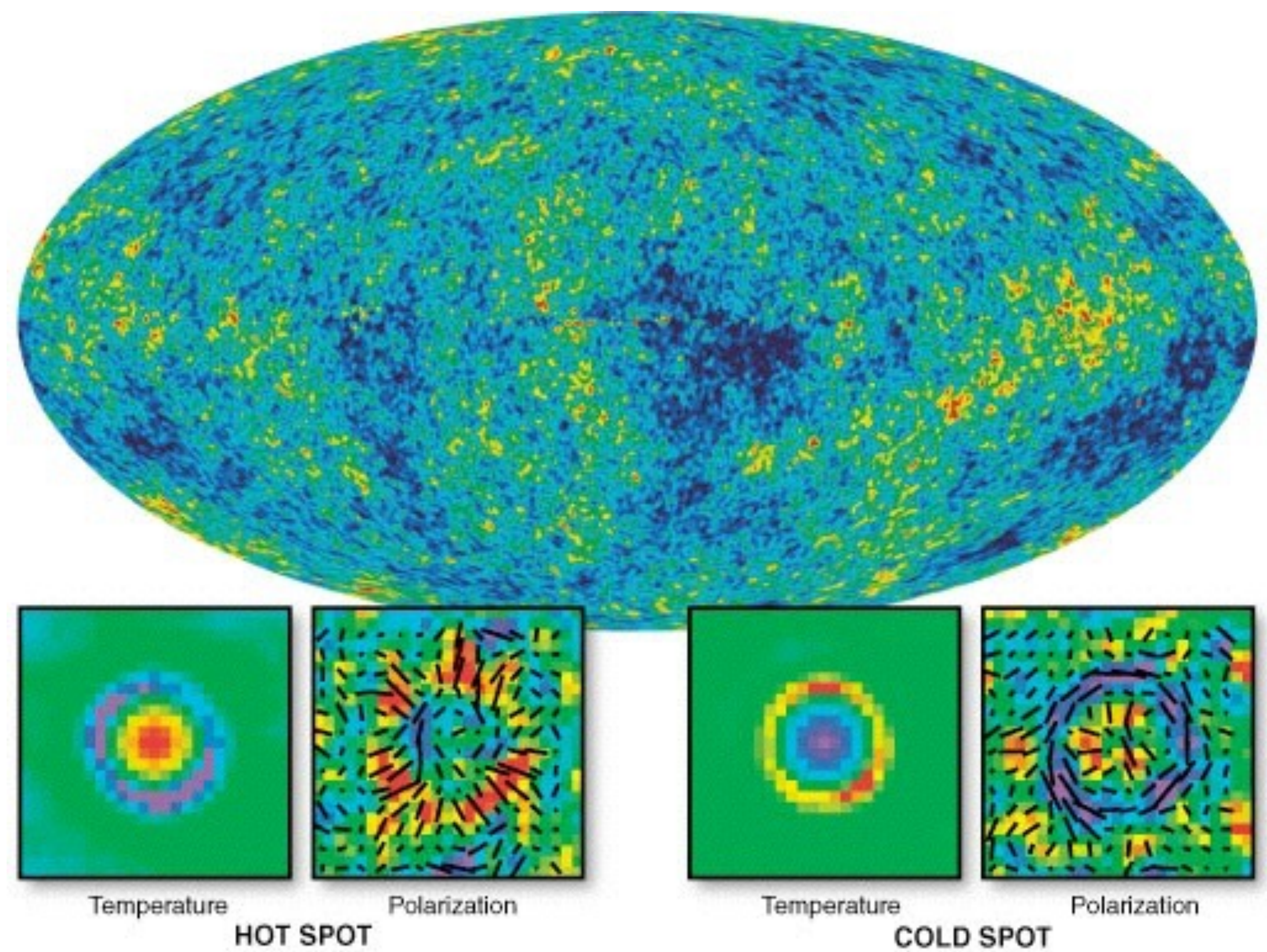
Stokes U

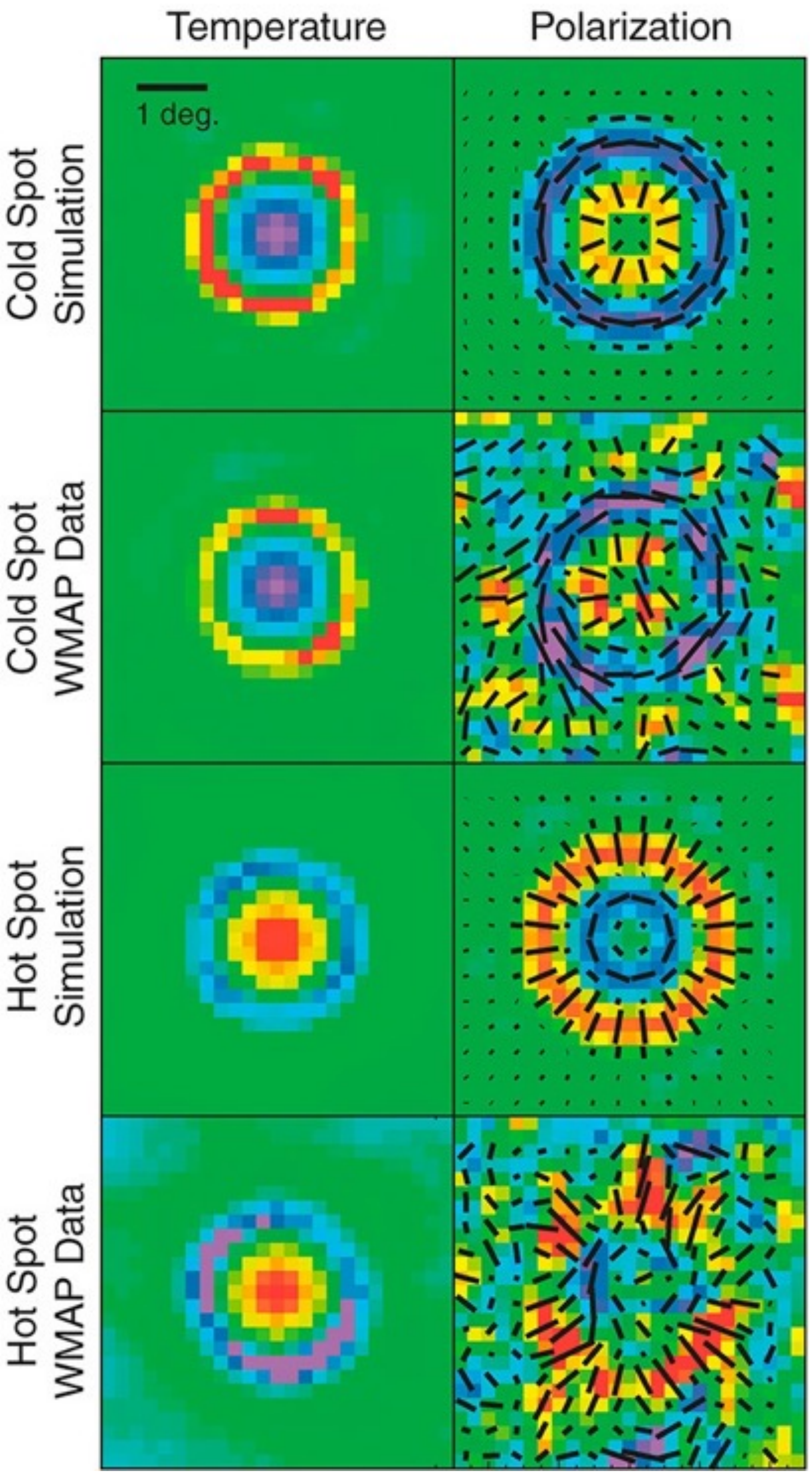
How many components?

- 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



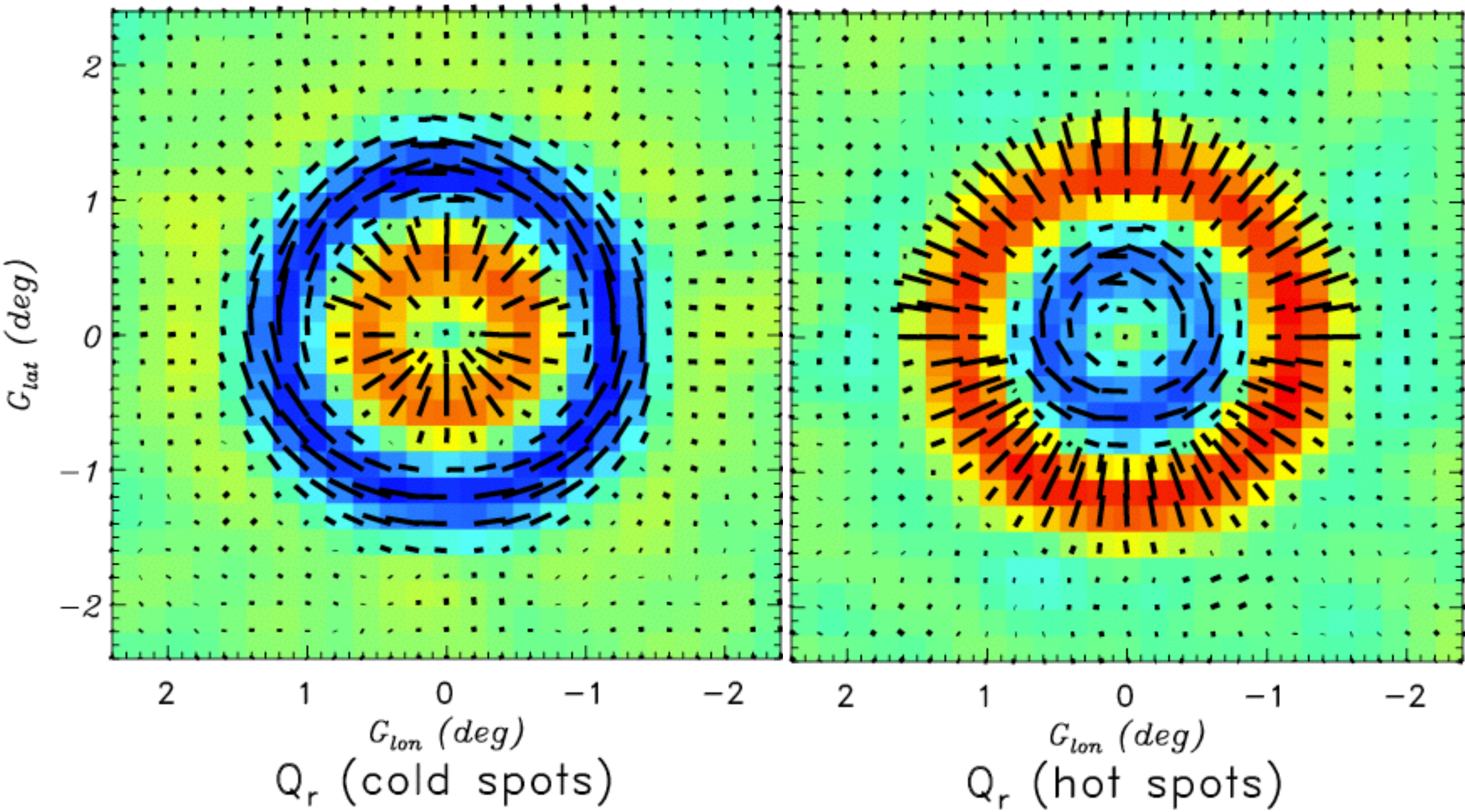


WMAP Collaboration

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**”

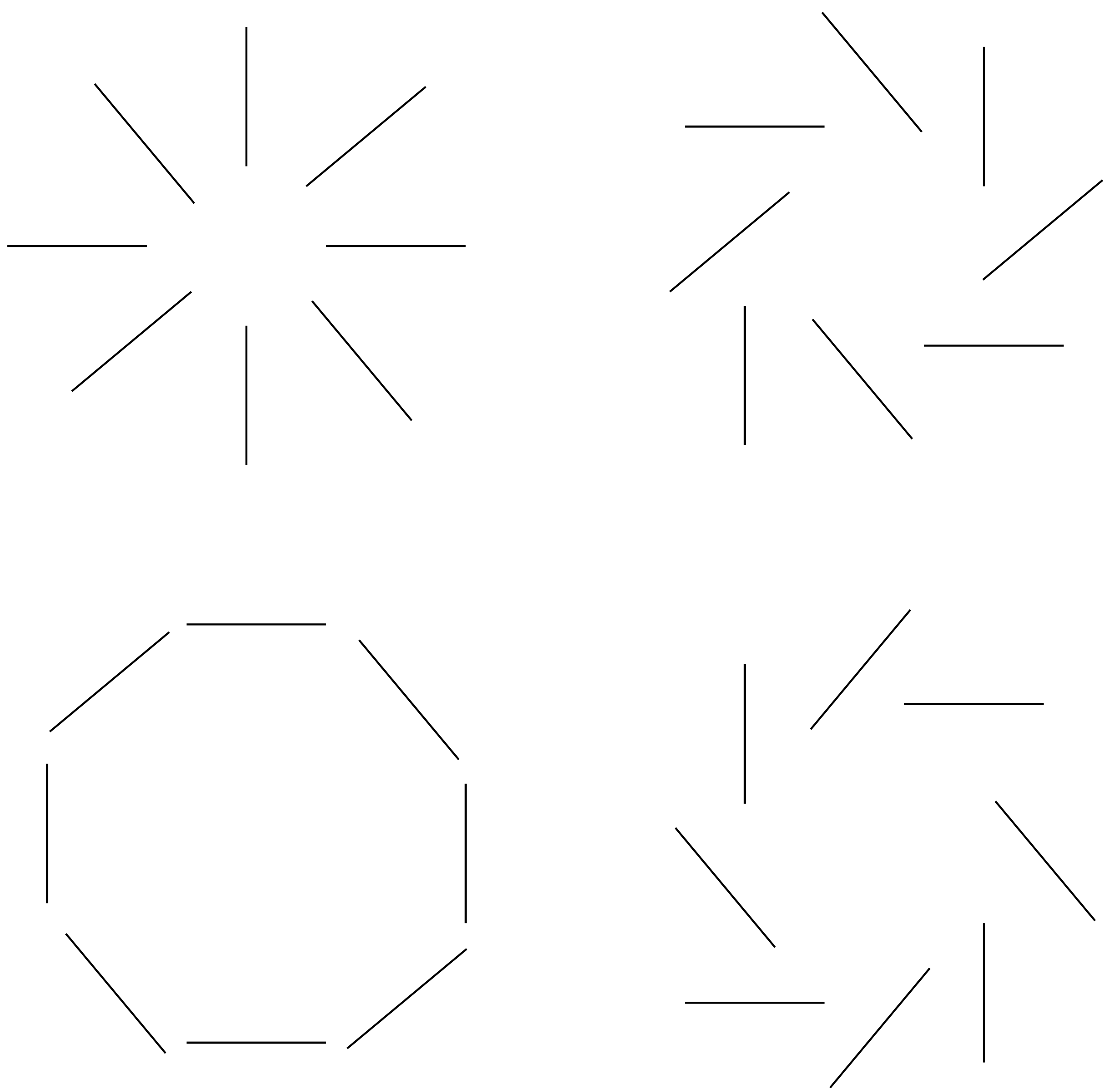
Planck Data!



G_{lat} (deg)
2
1
0
−1
−2
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)

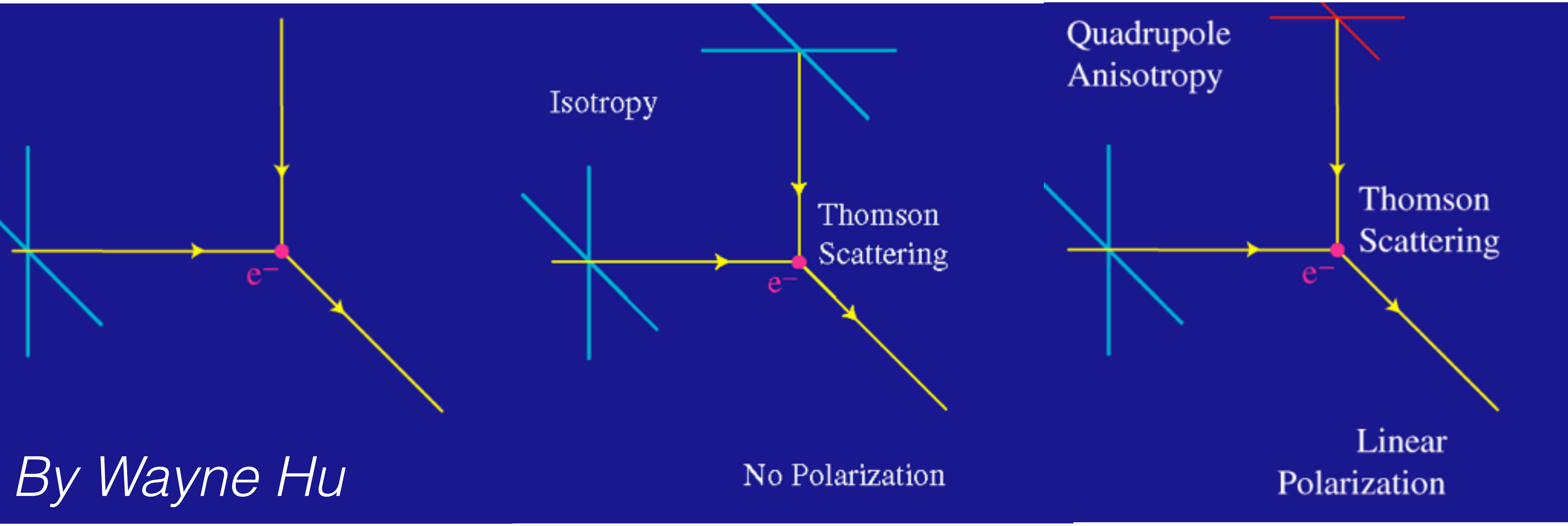
E and B modes



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

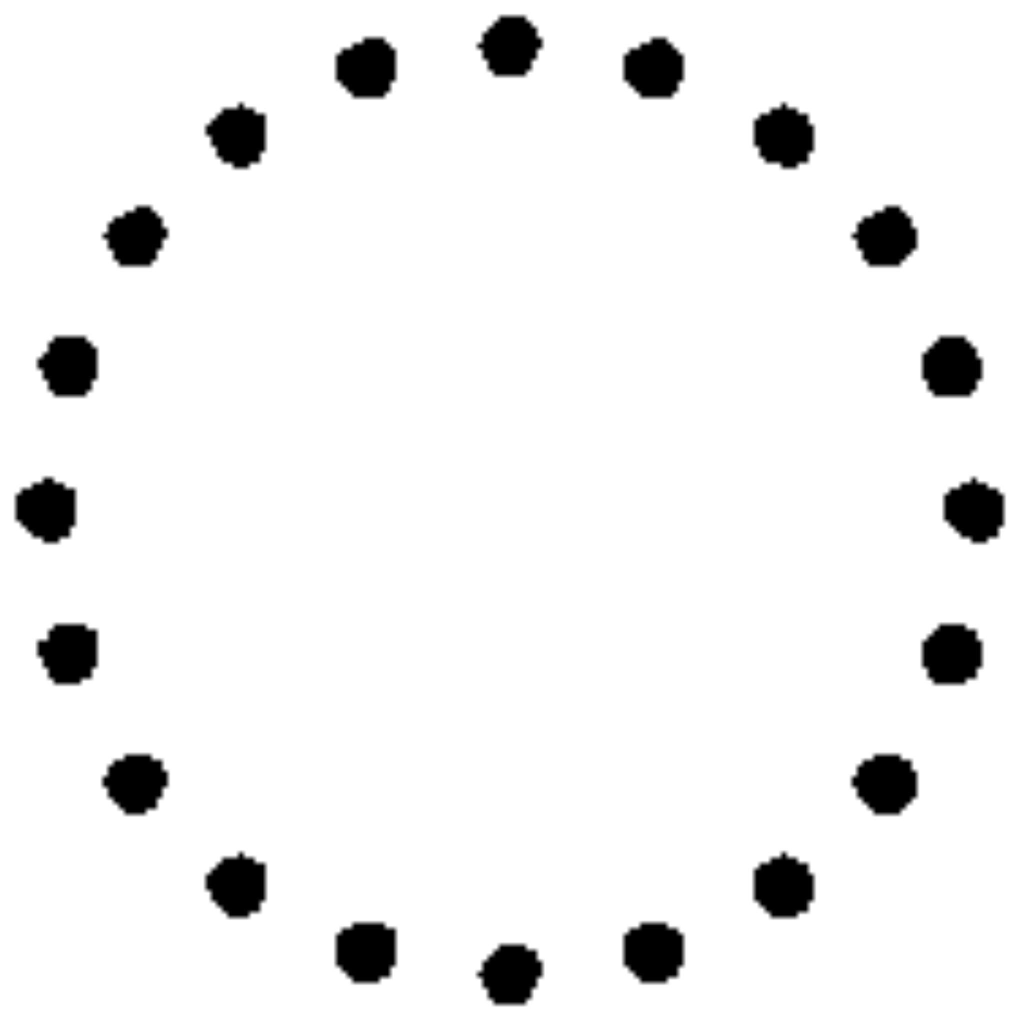


- Necessary and sufficient conditions for generating polarisation in CMB:
  - Thomson scattering
  - Quadrupolar temperature anisotropy around an electron

Origin of Quadrupole

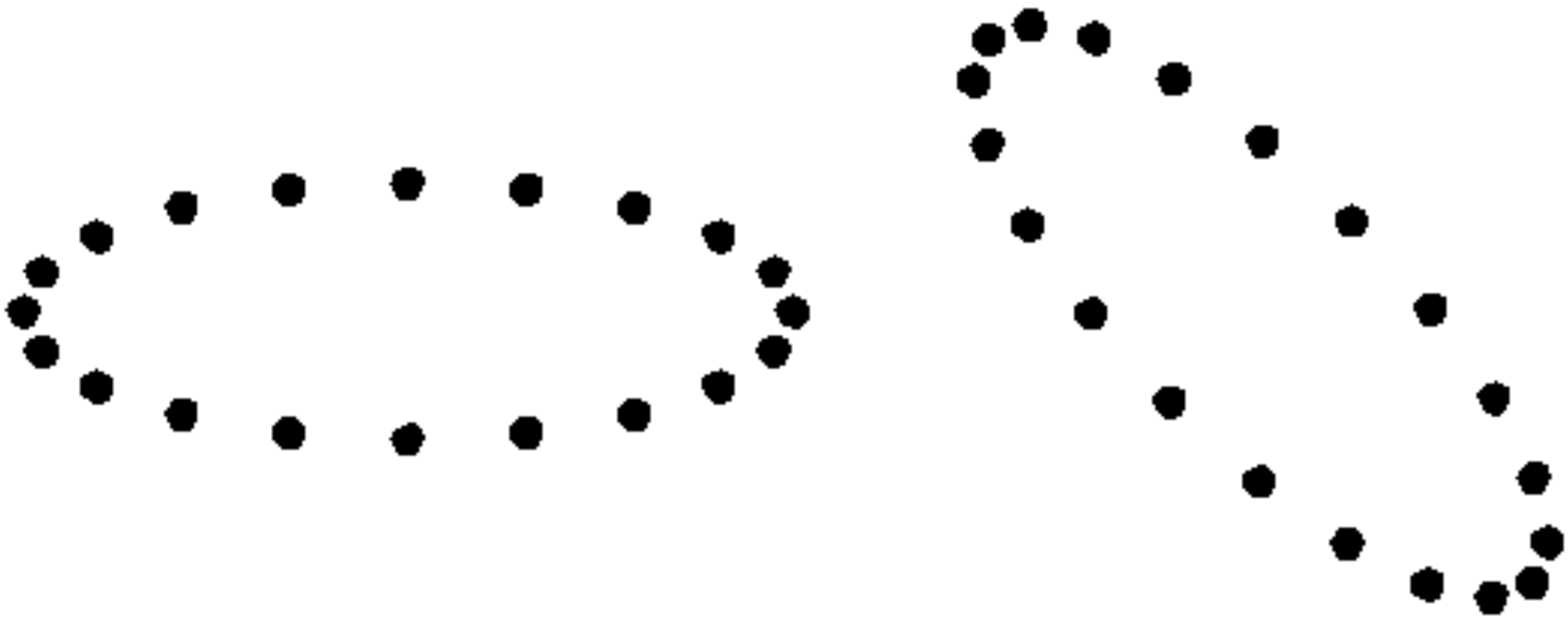
- **Scalar perturbations**: motion of electrons with respect to photons
- **Tensor perturbations**: gravitational waves

Gravitational waves are coming toward you!



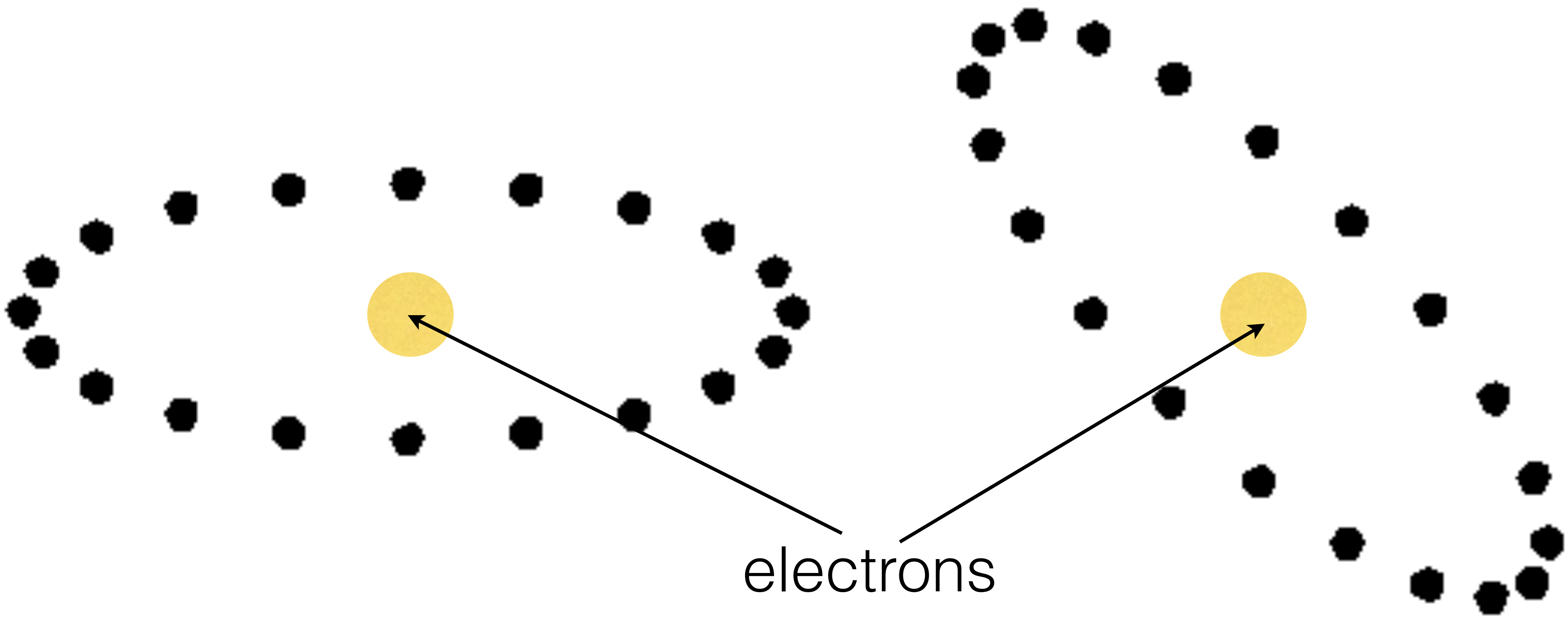
- What do they do to the distance between particles?

Two GW modes

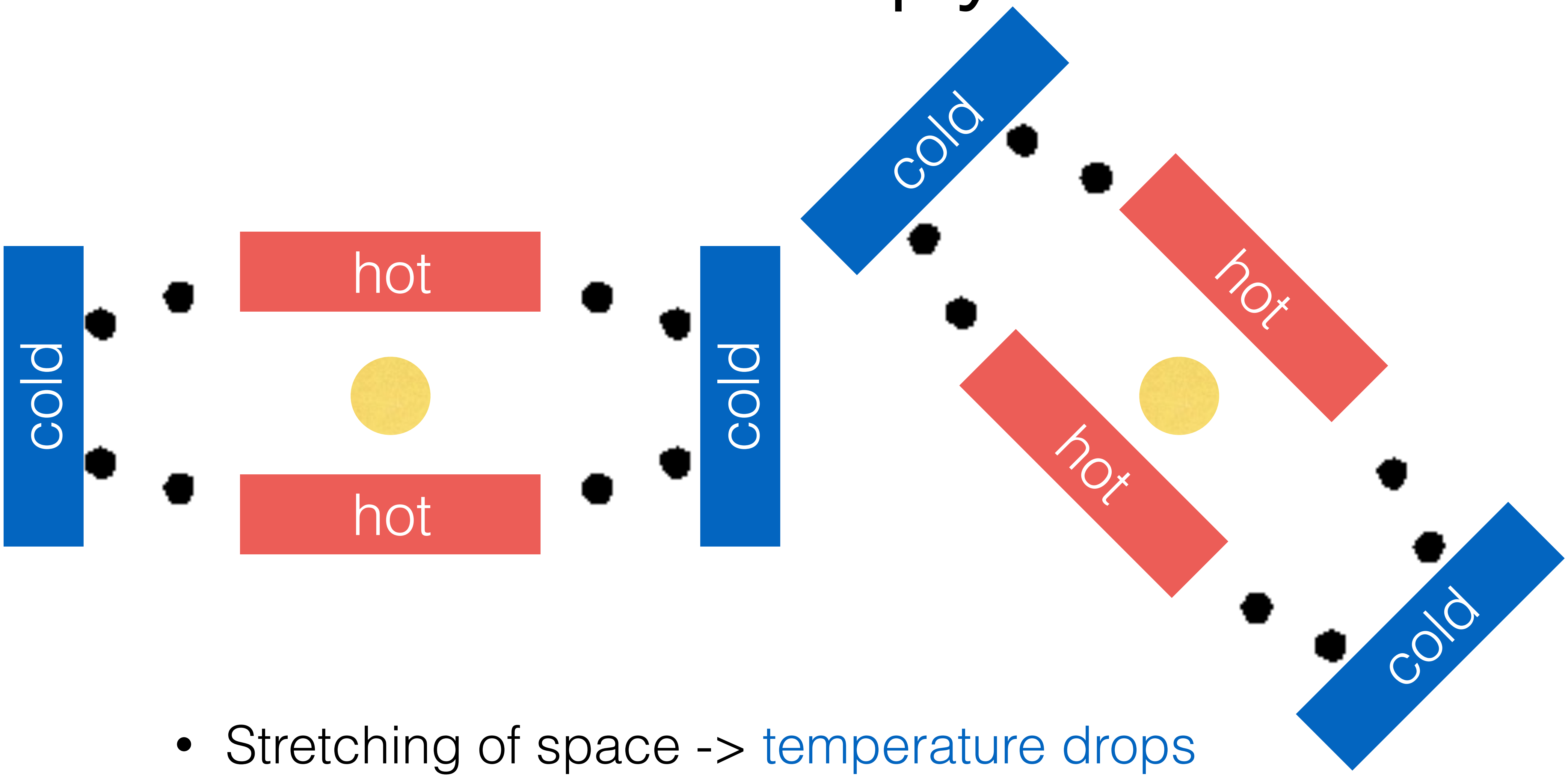


- Anisotropic stretching of space generates quadrupole temperature anisotropy. How?

GW to temperature anisotropy

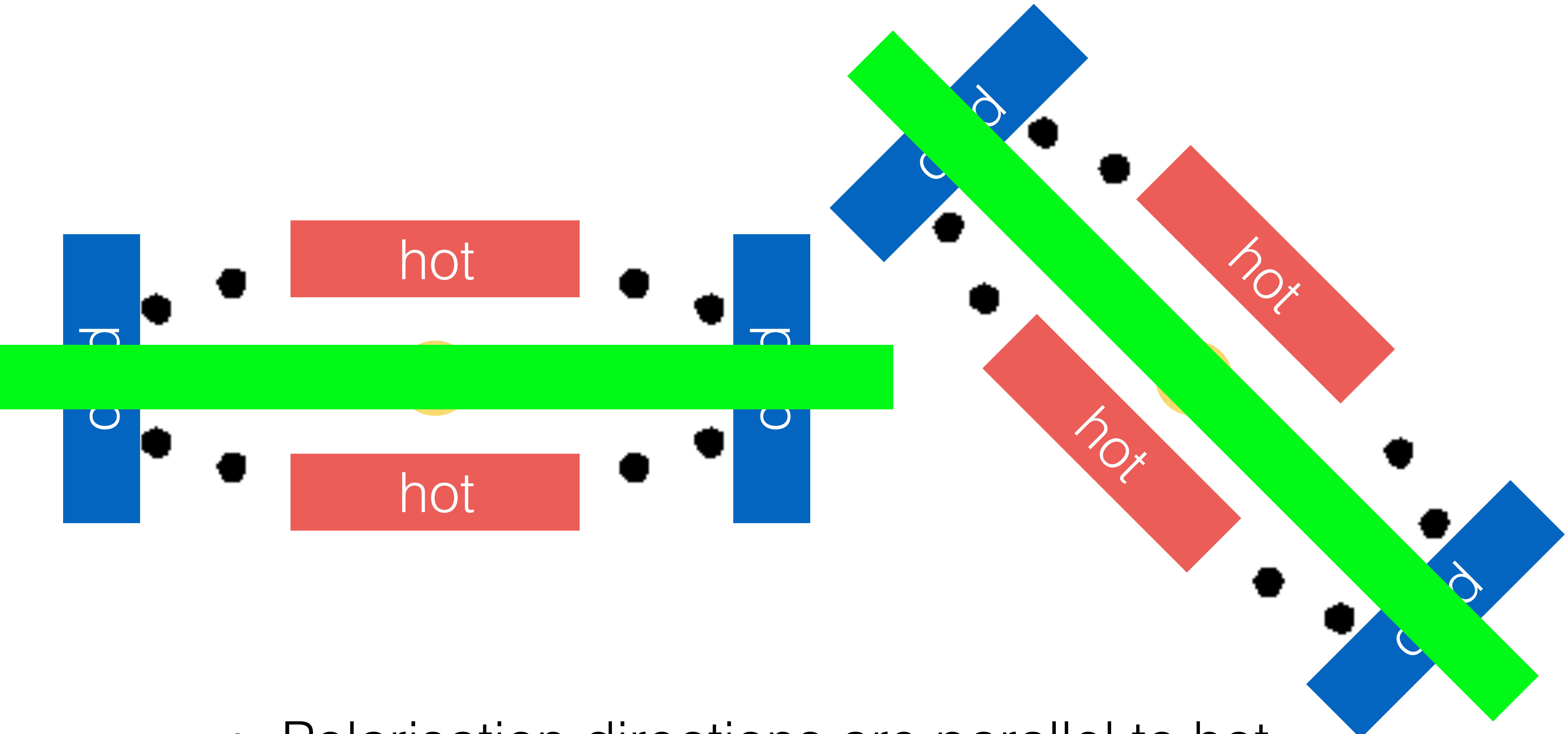


GW to temperature anisotropy

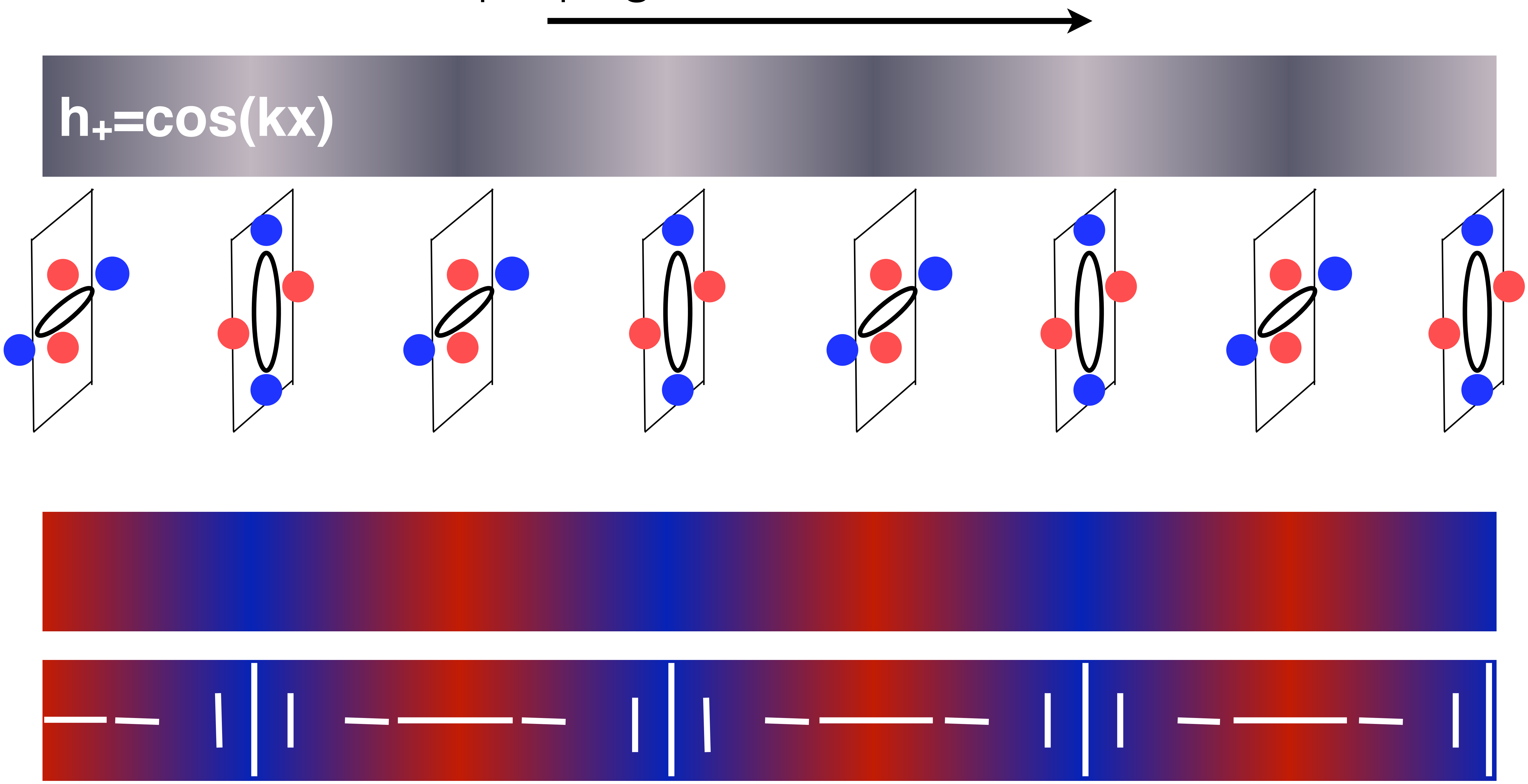


- Stretching of space -> temperature drops
- Contraction of space -> temperature rises

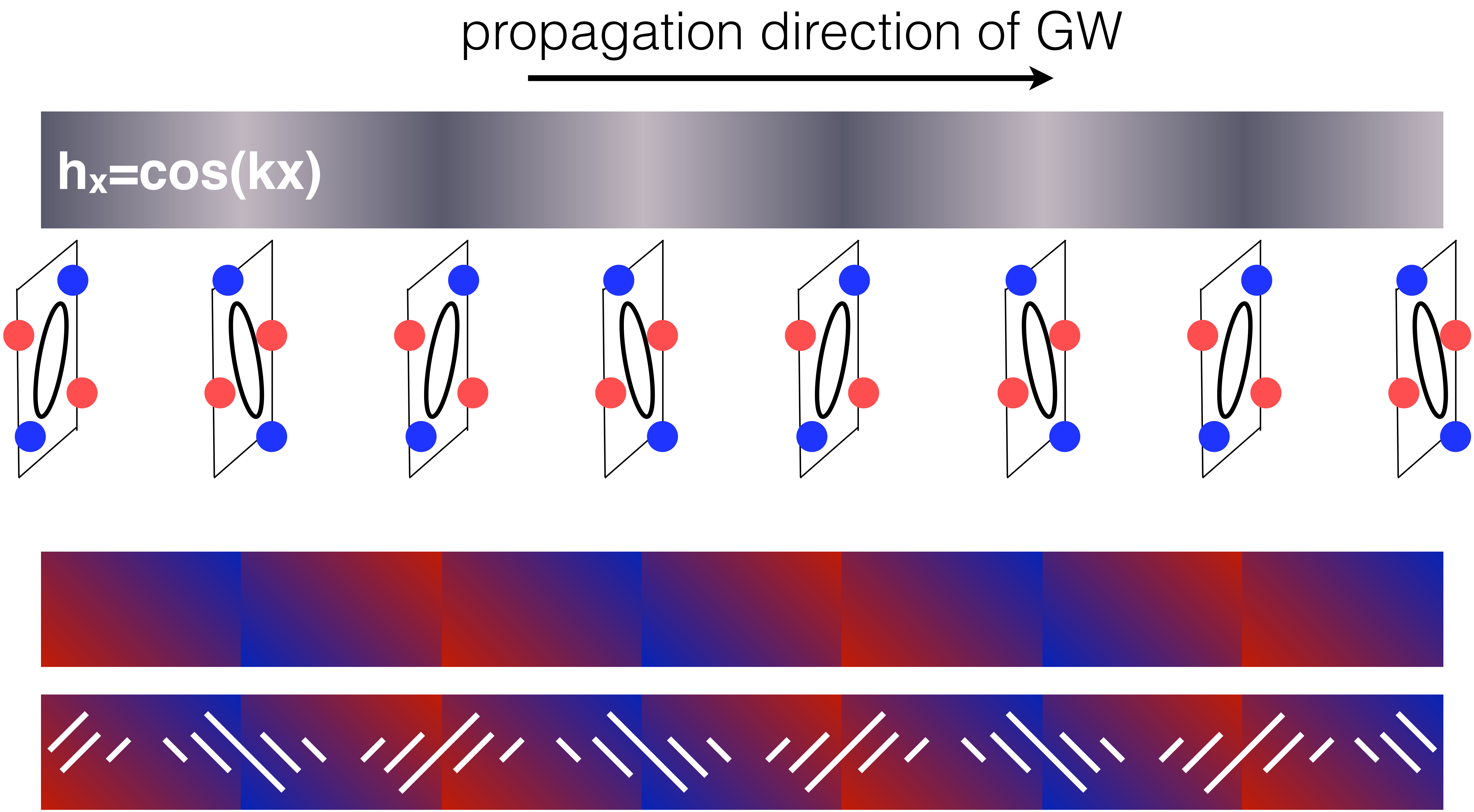
Then to polarisation!



- Polarisation directions are parallel to hot regions 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:

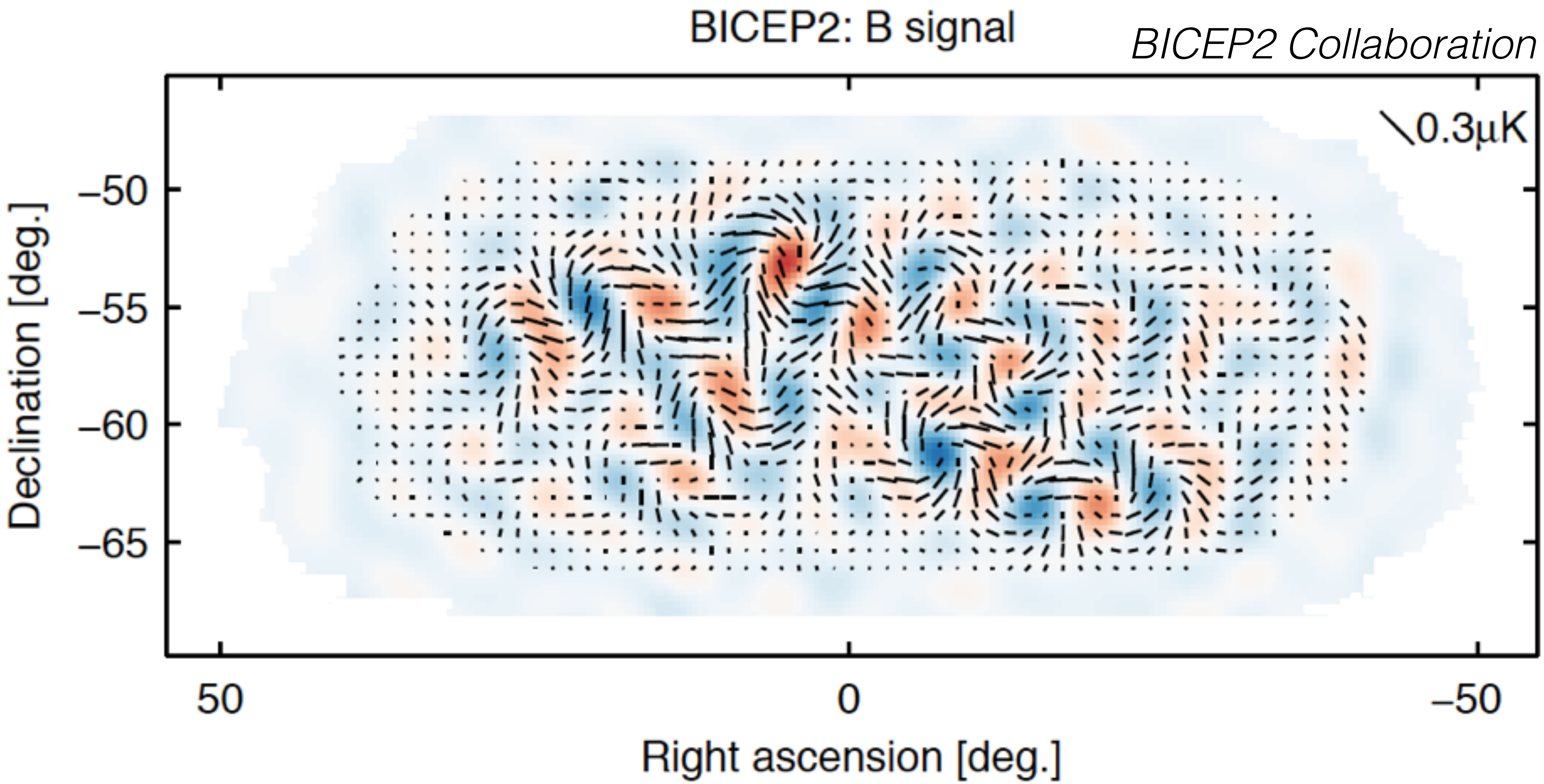
- Definition of h_+ and $h_\times$ depends on coordinates, but definition of E- and B-mode polarisation does not depend on coordinates

- 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

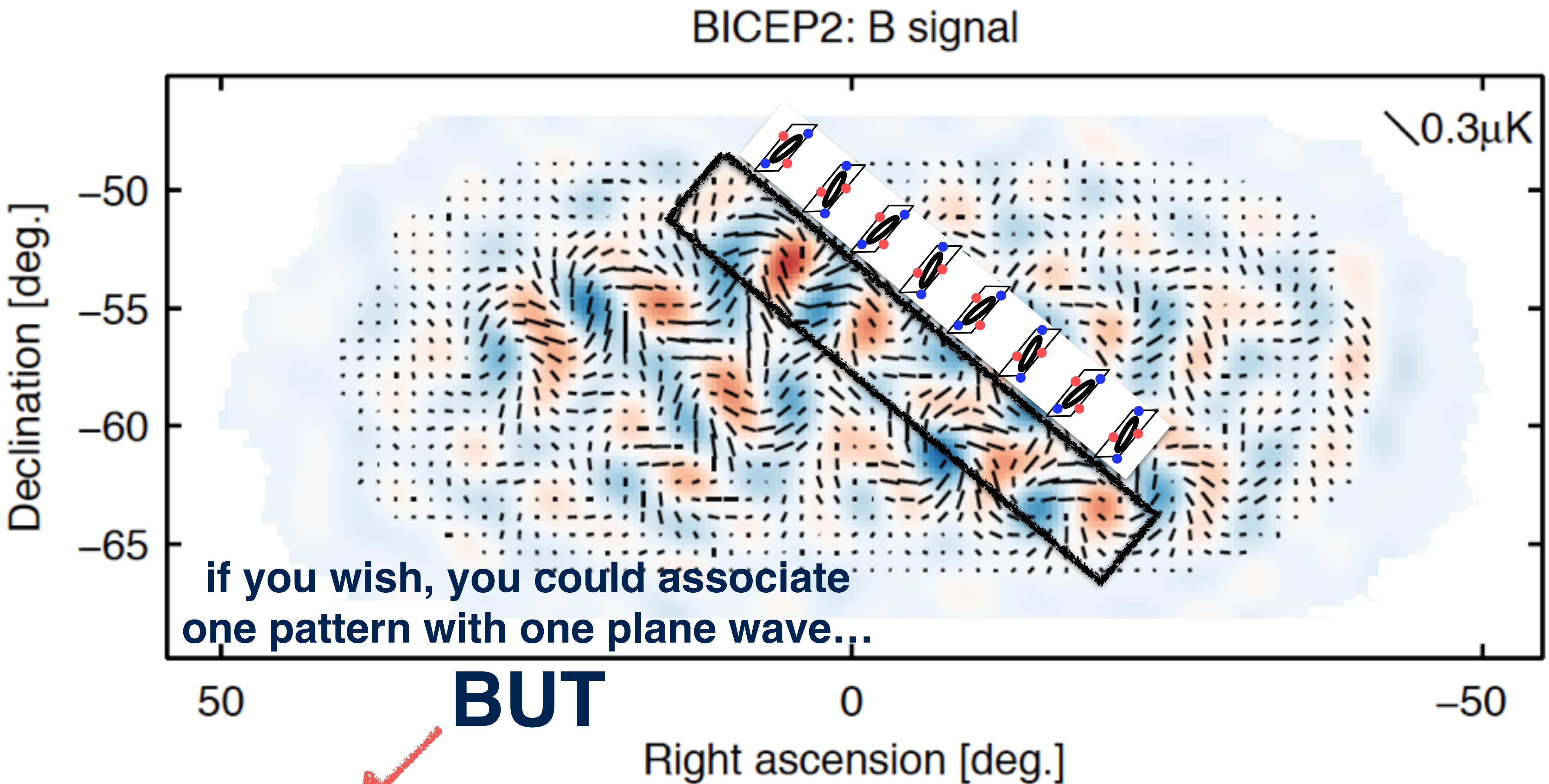
Signature of gravitational waves in the sky [?]

BICEP2 Collaboration



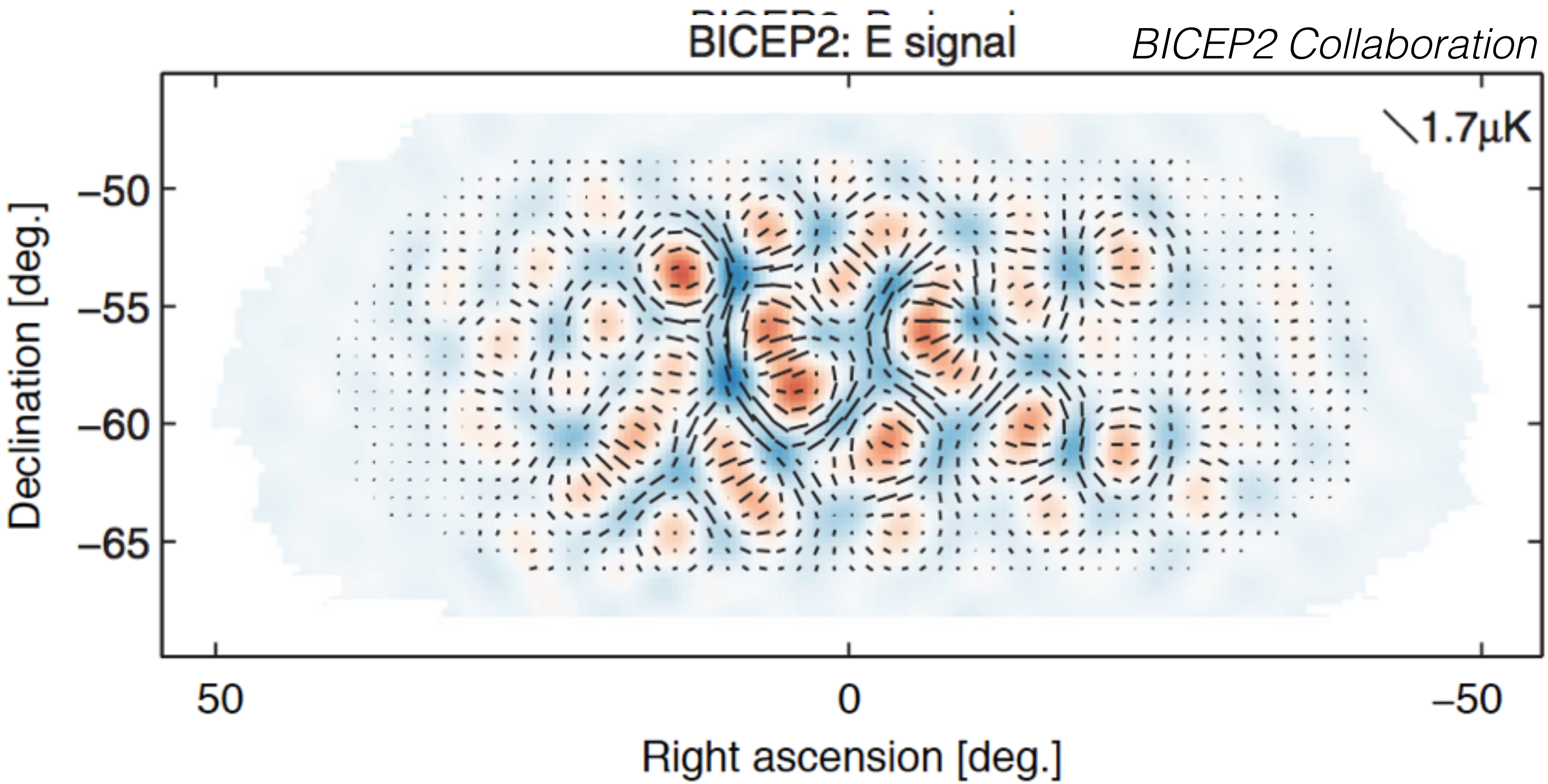
<u>CAUTION</u>: we are NOT seeing a single plane wave propagating perpendicular to our line of sight

Signature of gravitational waves in the sky [?]



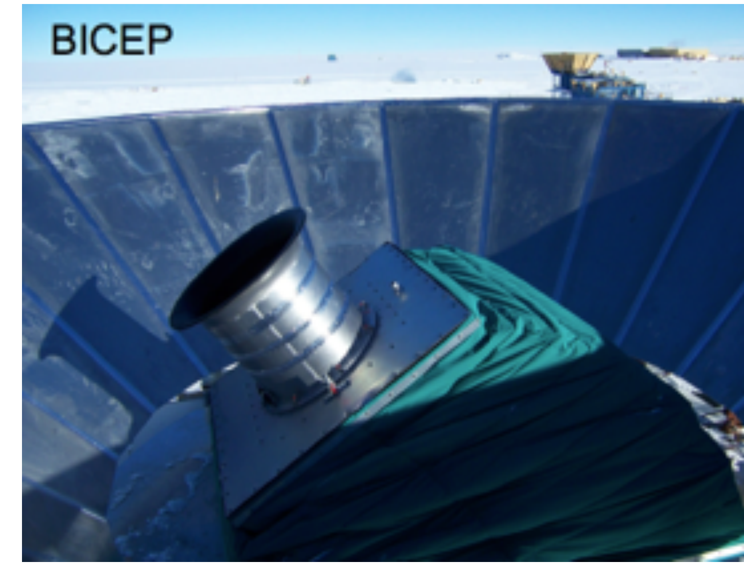
CAUTION: we are NOT seeing a single plane wave propagating perpendicular to our line of sight

There are E modes in the sky as well

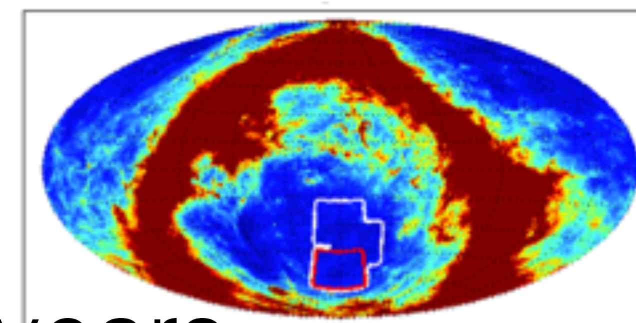


The E-mode polarisation is totally dominated by the scalar-mode fluctuations [density waves]

What is BICEP2?



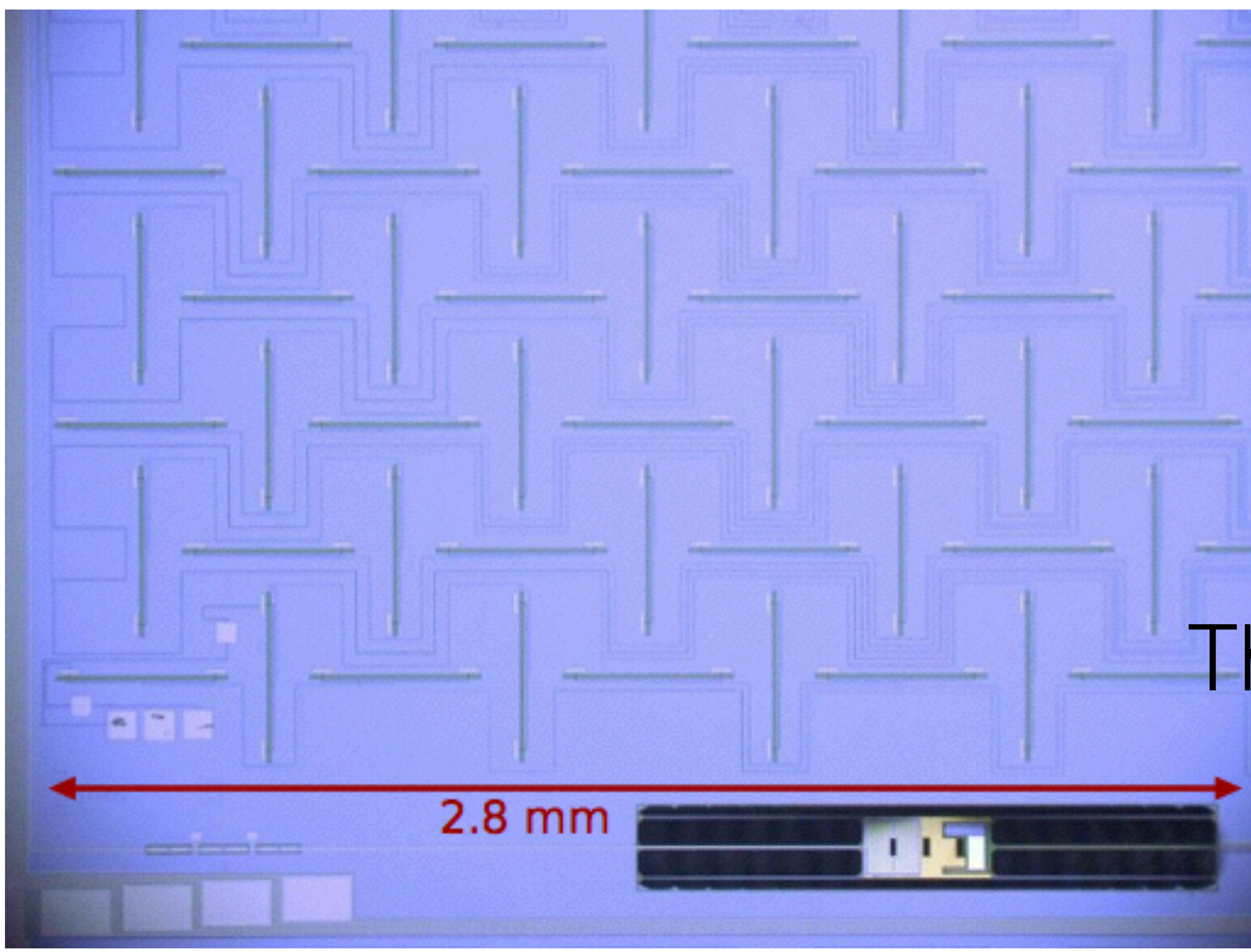
- A small [26 cm] refractive telescope at South Pole
- 512 bolometers working at 150 GHz



- 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-]

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

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

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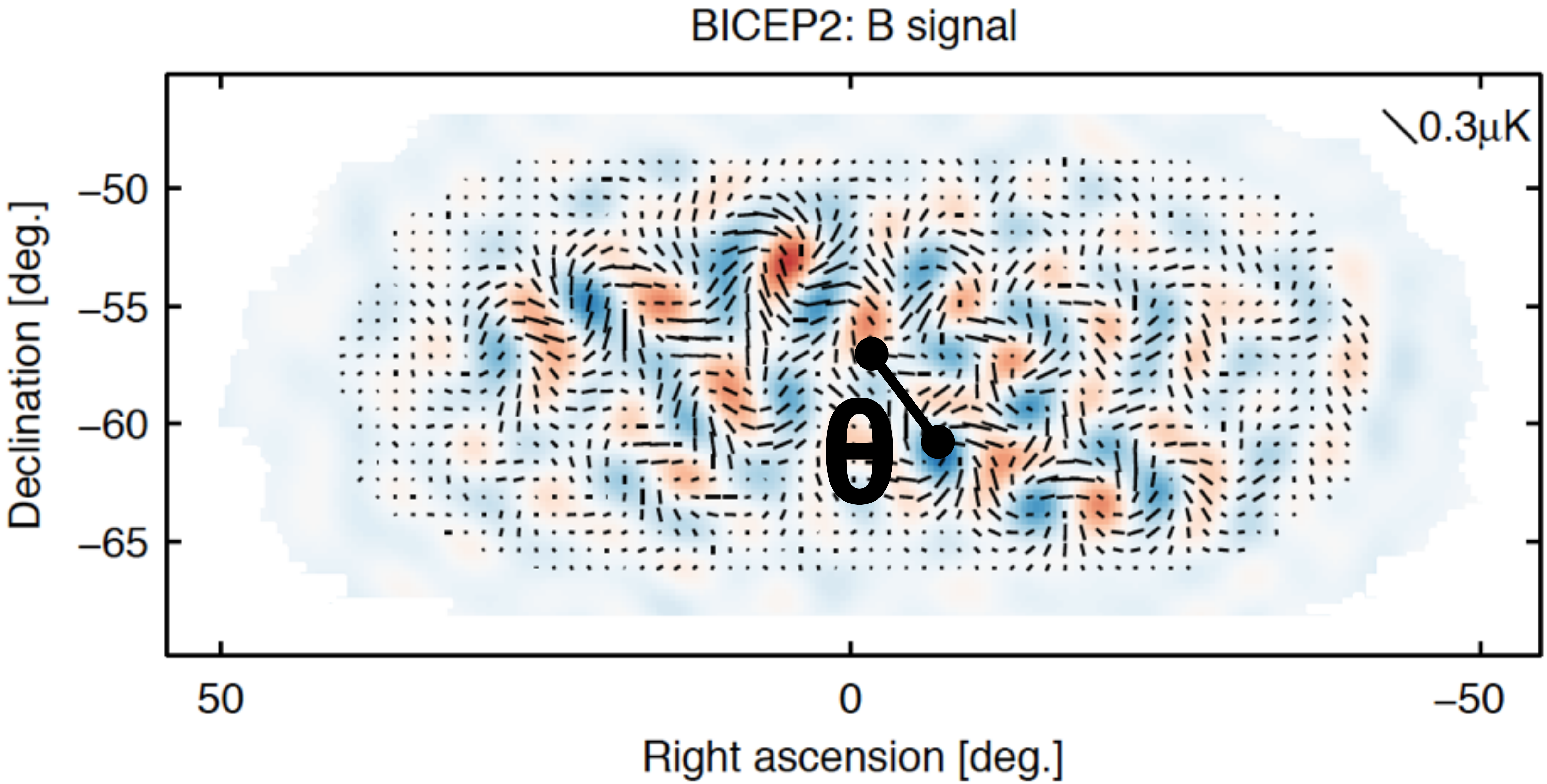
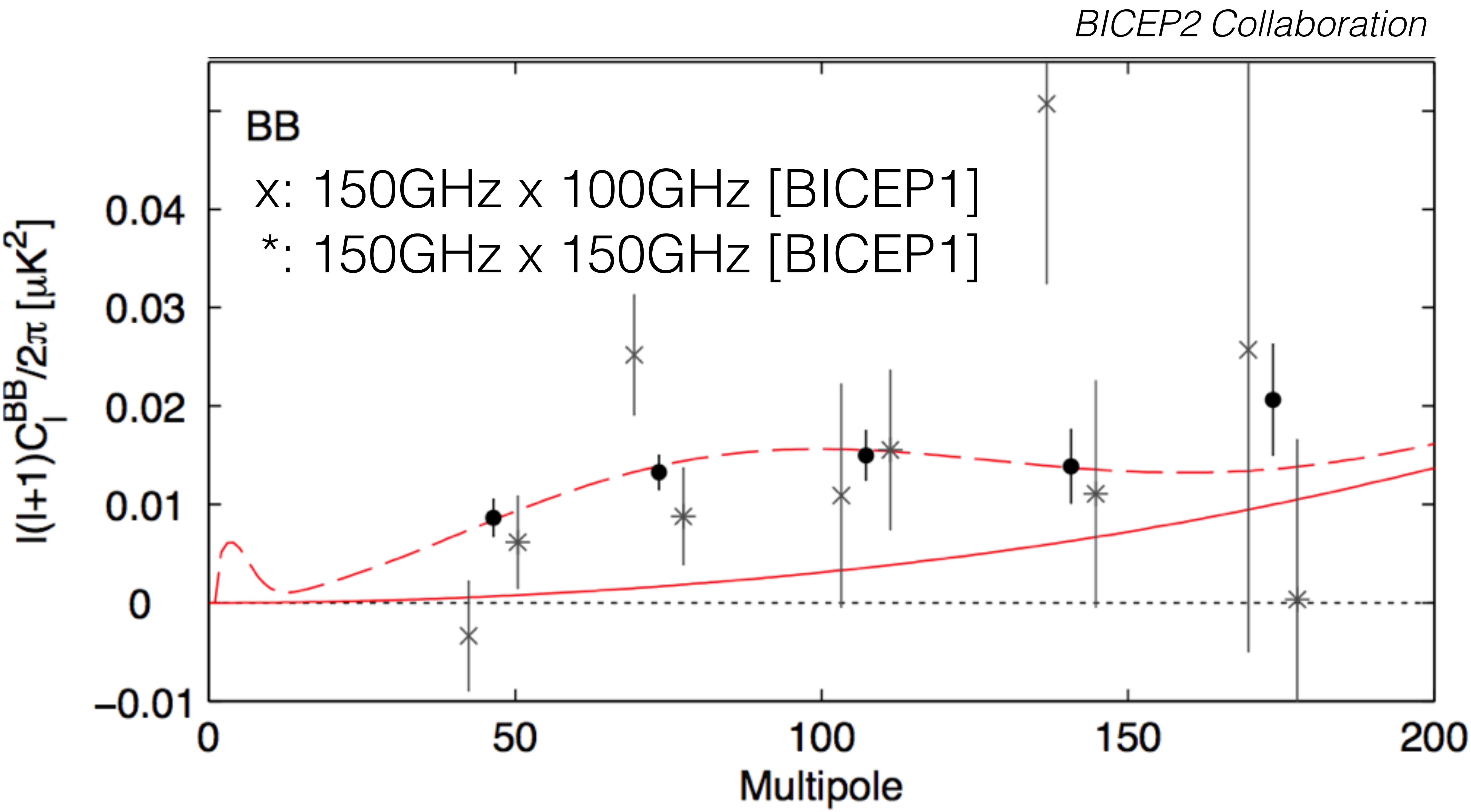
Analysis: Two-point Correlation Function



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

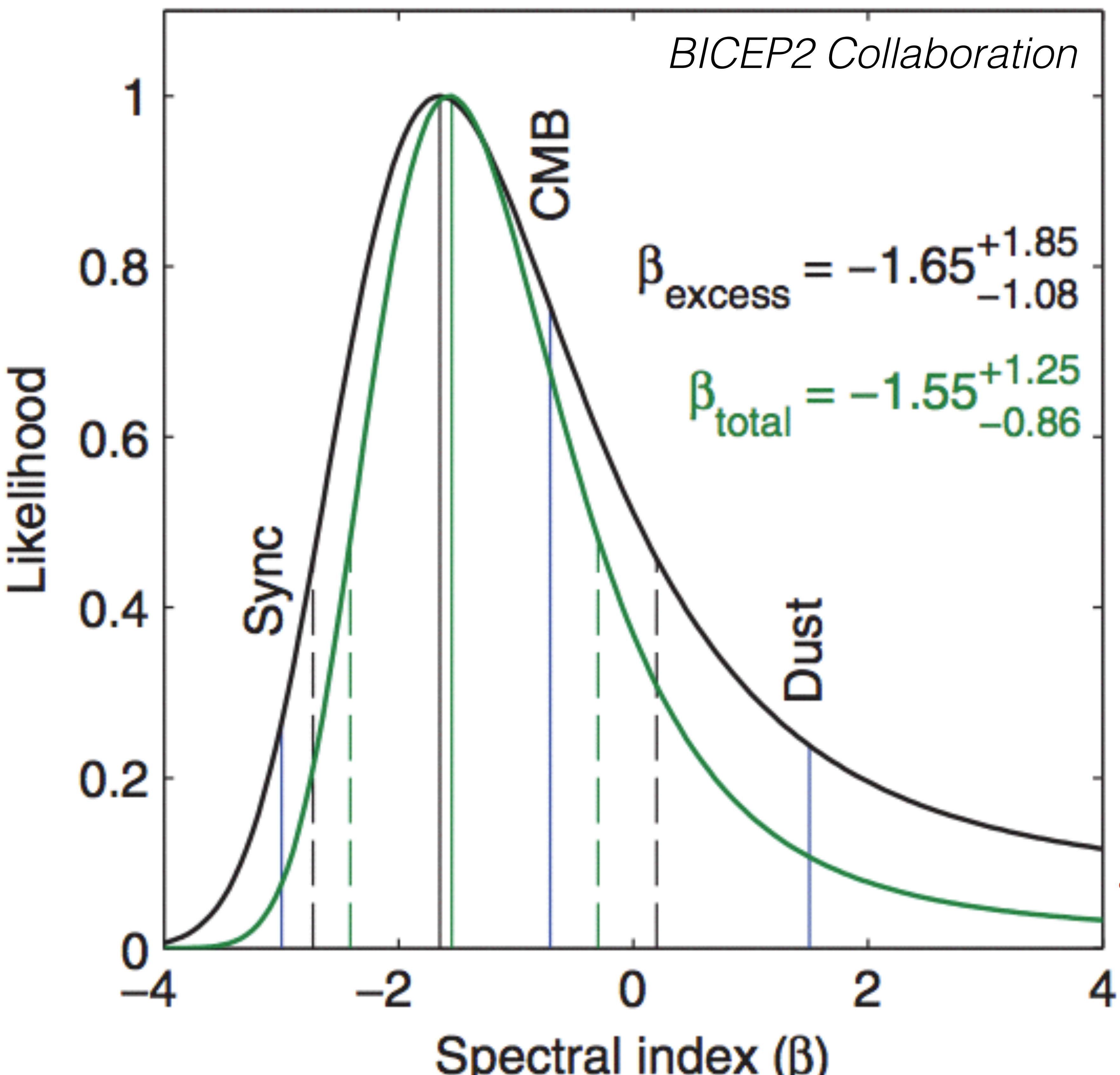
C_{ℓ} is the "power spectrum" with

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



No 100 GHz x 100 GHz [yet]

Can we rule out synchrotron or dust?



- **The answer is No**

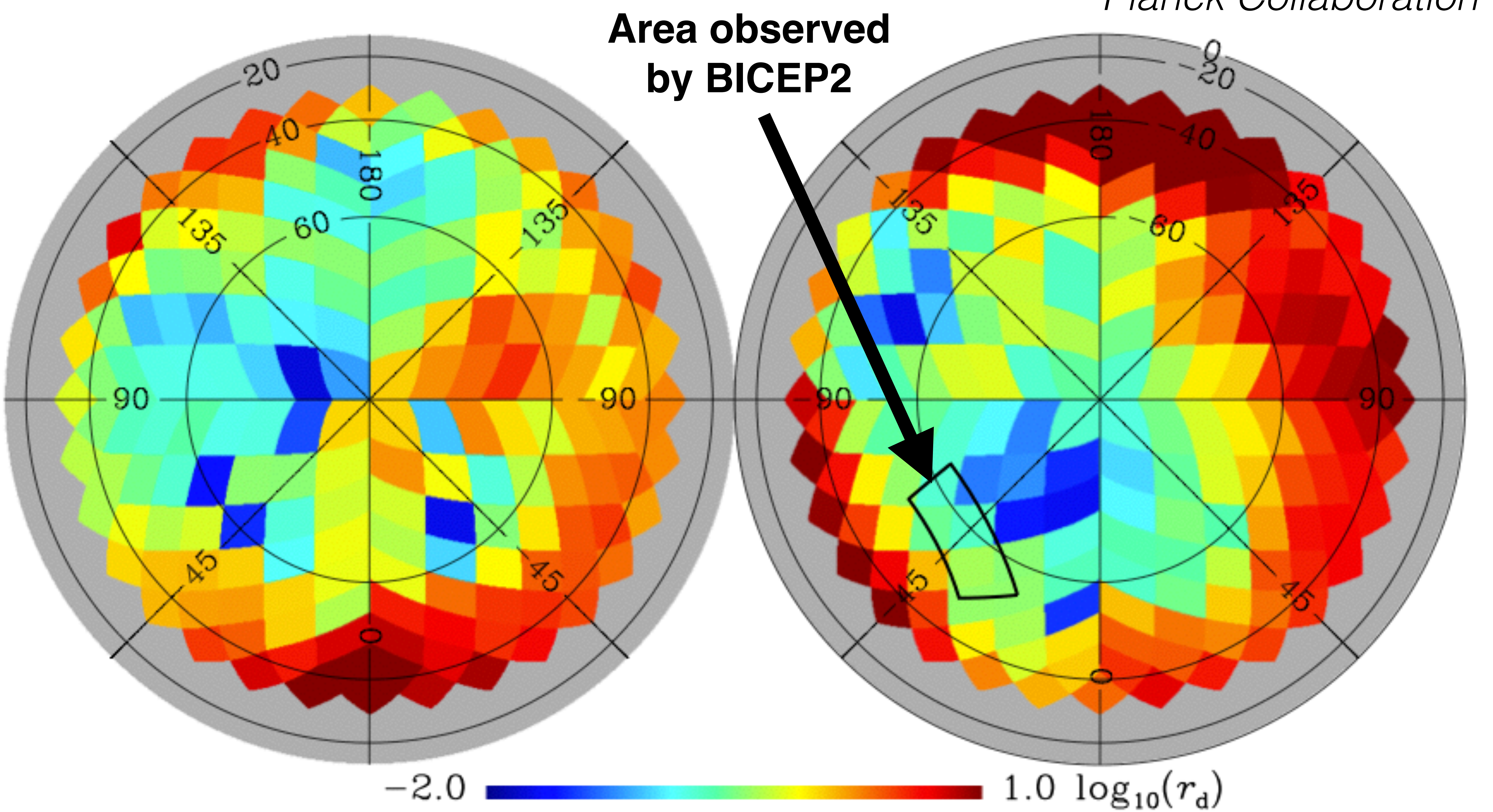
Situation until a month ago

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

September 22, 2014

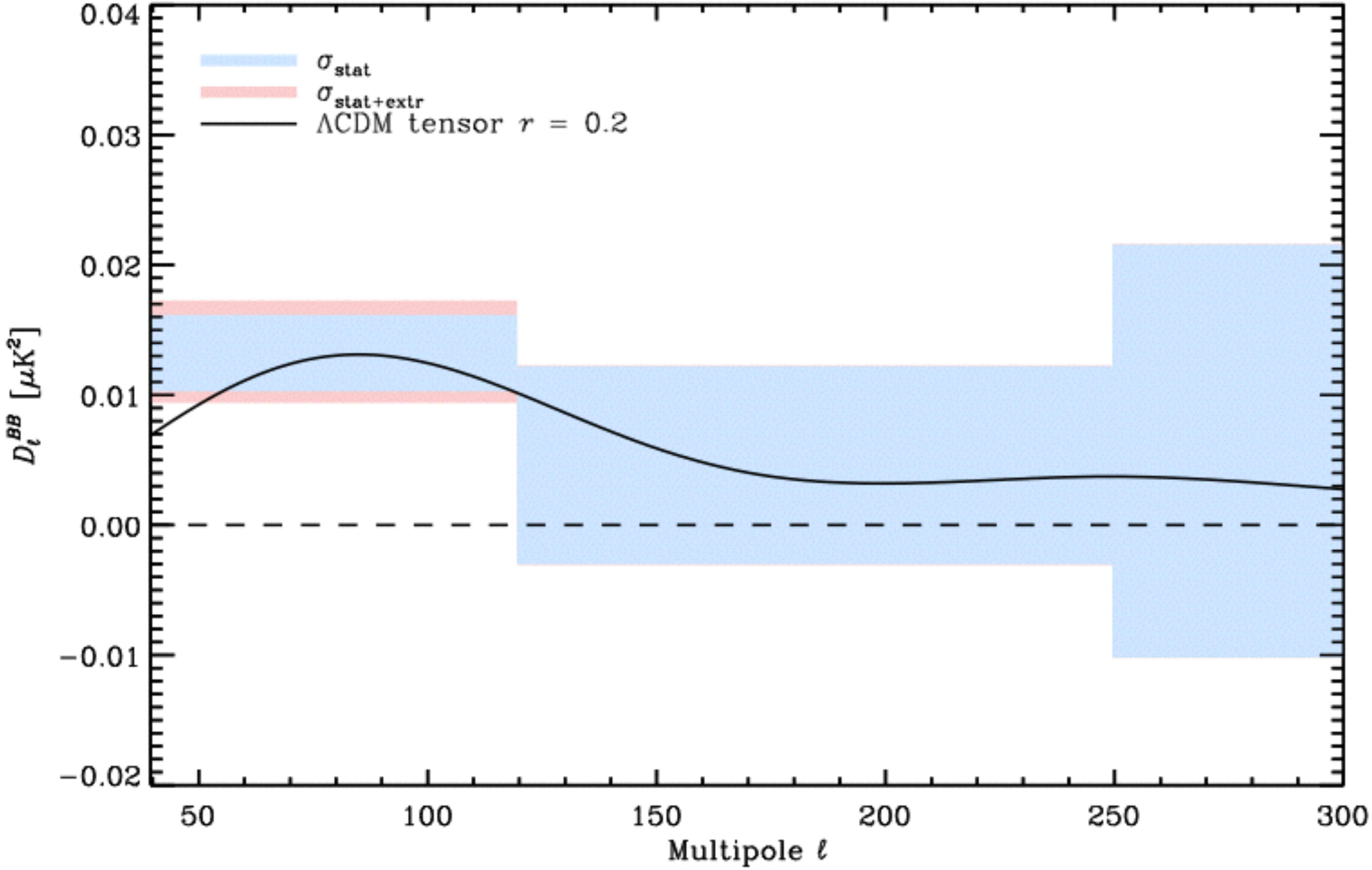
Planck’s Intermediate Paper on Dust

Planck Collaboration



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

Planck Collaboration



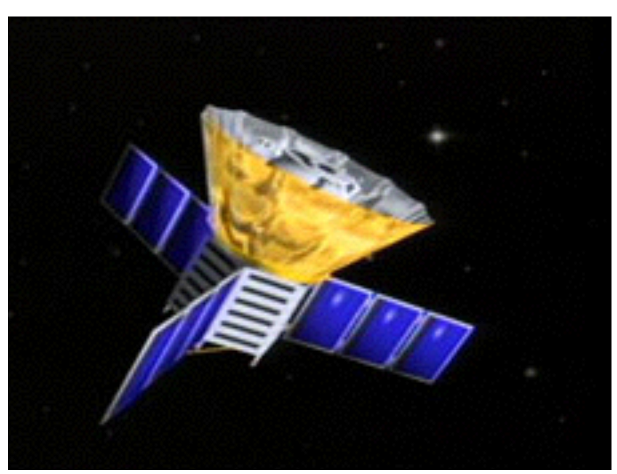
- Planck measured the B-mode power spectrum at 353 GHz well
- Extrapolating it down to 150 GHz appears to explain all of the signal seen by BICEP2…

Current Situation

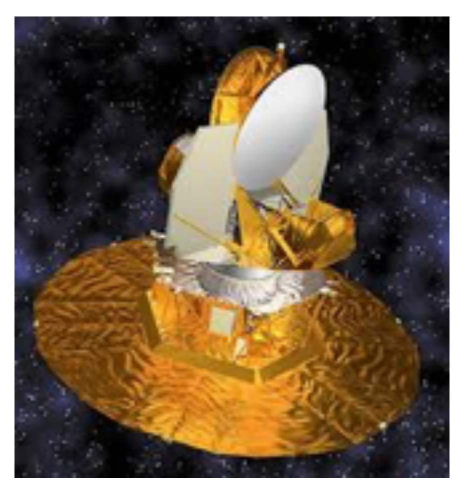
- Planck shows the evidence that the detected signal is not cosmological, but is due to dust

- No strong evidence that the detected signal is cosmological

The search continues!!



1989–1993



2001–2010

2009–2013

202X–

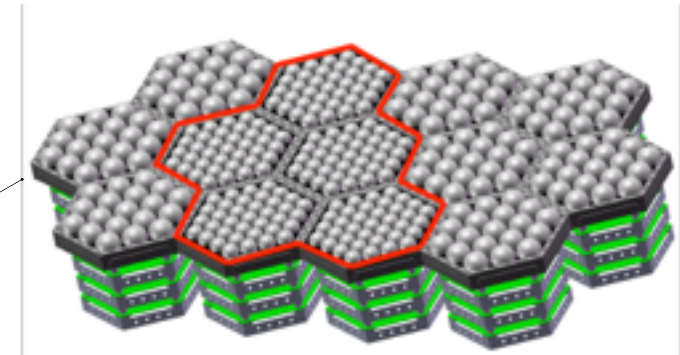
LiteBIRD

- 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

LiteBIRD

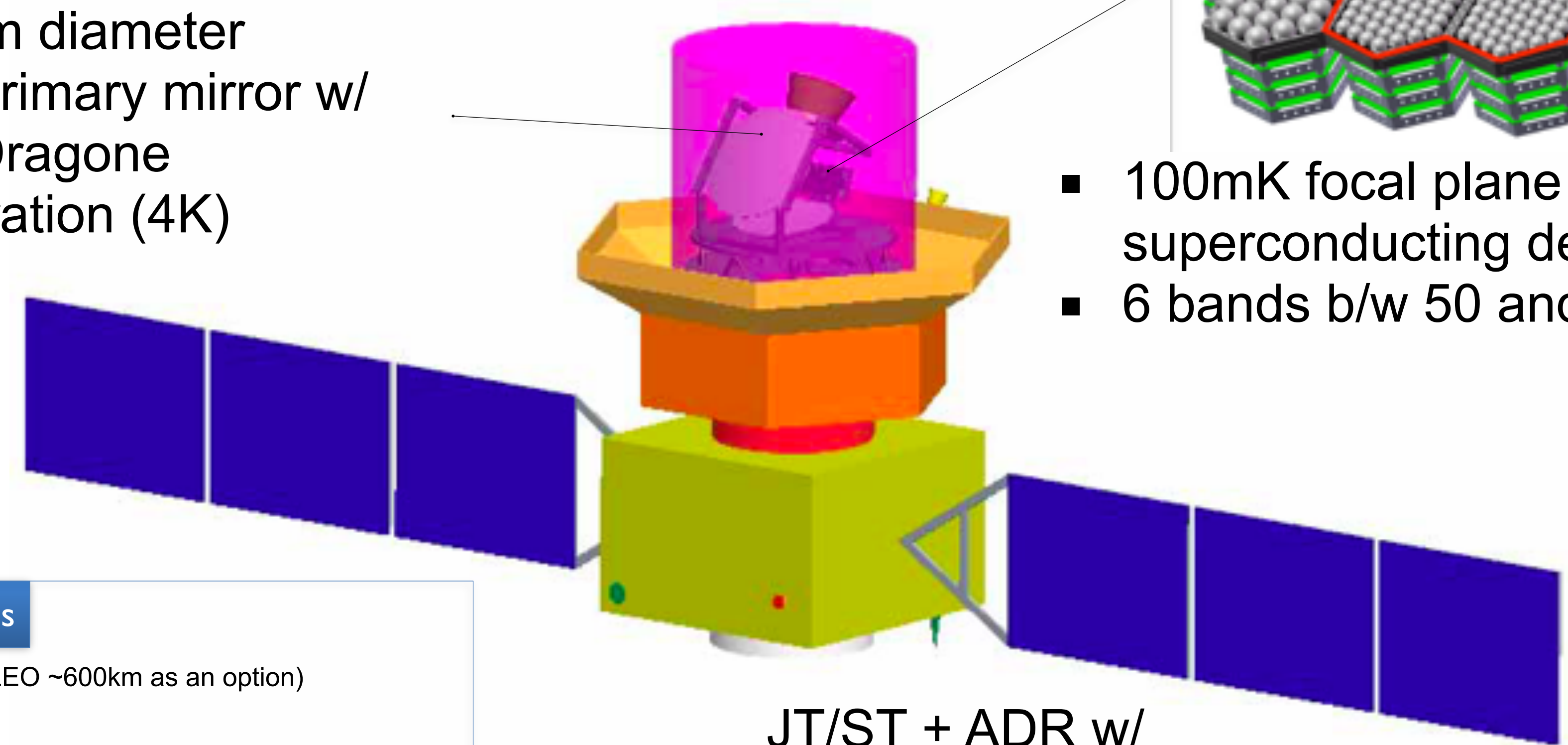
Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

- Candidate for JAXA's future missions on "fundamental physics"
- **Goal:** Search for primordial gravitational waves to the lower bound of well-motivated inflationary models
- **Full success:** $\delta r < 0.001$ (δr is the total uncertainties on tensor-to-scalar ratio, which is a fundamental cosmology parameter related to the power of primordial gravitational waves)



- 100mK focal plane w/ multi-chroic superconducting detector array
- 6 bands b/w 50 and 320 GHz

- Continuously-rotating HWP w/ 30 cm diameter
- 60 cm primary mirror w/ Cross-Dragone configuration (4K)



JT/ST + ADR w/ heritages of X-ray missions

Major specifications

- Orbit: L2 (Twilight LEO ~600km as an option)
- Weight: ~1300kg
- Power: ~2000W
- Observing time: > 2 years
- Spin rate: ~0.1rpm

ESA's M4 Call is Out [Target Launch in 2025]

- We are working on the COrE+ mission proposal
    - COrE = Cosmic Origins Explorer
    - Original version not selected by M3
- The letter of intent has been sent, and the proposal is due mid January 2015
- The effort led by Paolo de Bernardis, Jacques Delabrouille, and Francois Bouchet

COrE+: a sketch

- The previous definition of COrE+ is still being worked out. Heavily affected by BICEP2/Planck results, and a rather tight budget (450M Euro by ESA and perhaps 100M Euro by the European consortium) and weight limit (payload 800 kg)

- Still want **10x more sensitivity than Planck** with more frequency coverage, while maintaining comparable angular resolution

  - which means 5 times better angular resolution and many more frequencies than LiteBIRD

  - A near ultimate mission

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

- **COrE+ proposal**: more comprehensive (and last?) CMB satellite in late 2020