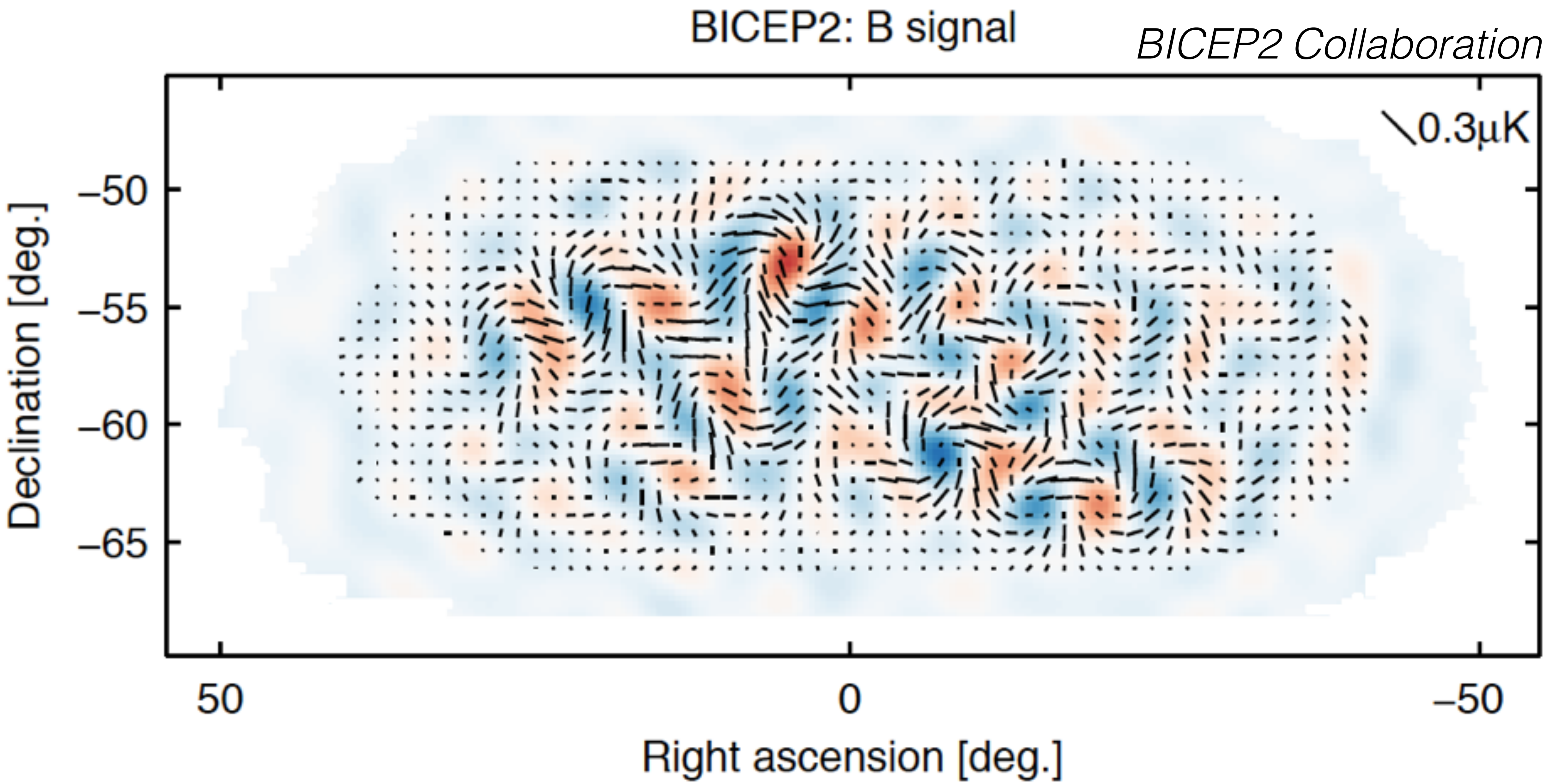
CMB Polarisation: Toward an Observational Proof of Cosmic Inflation

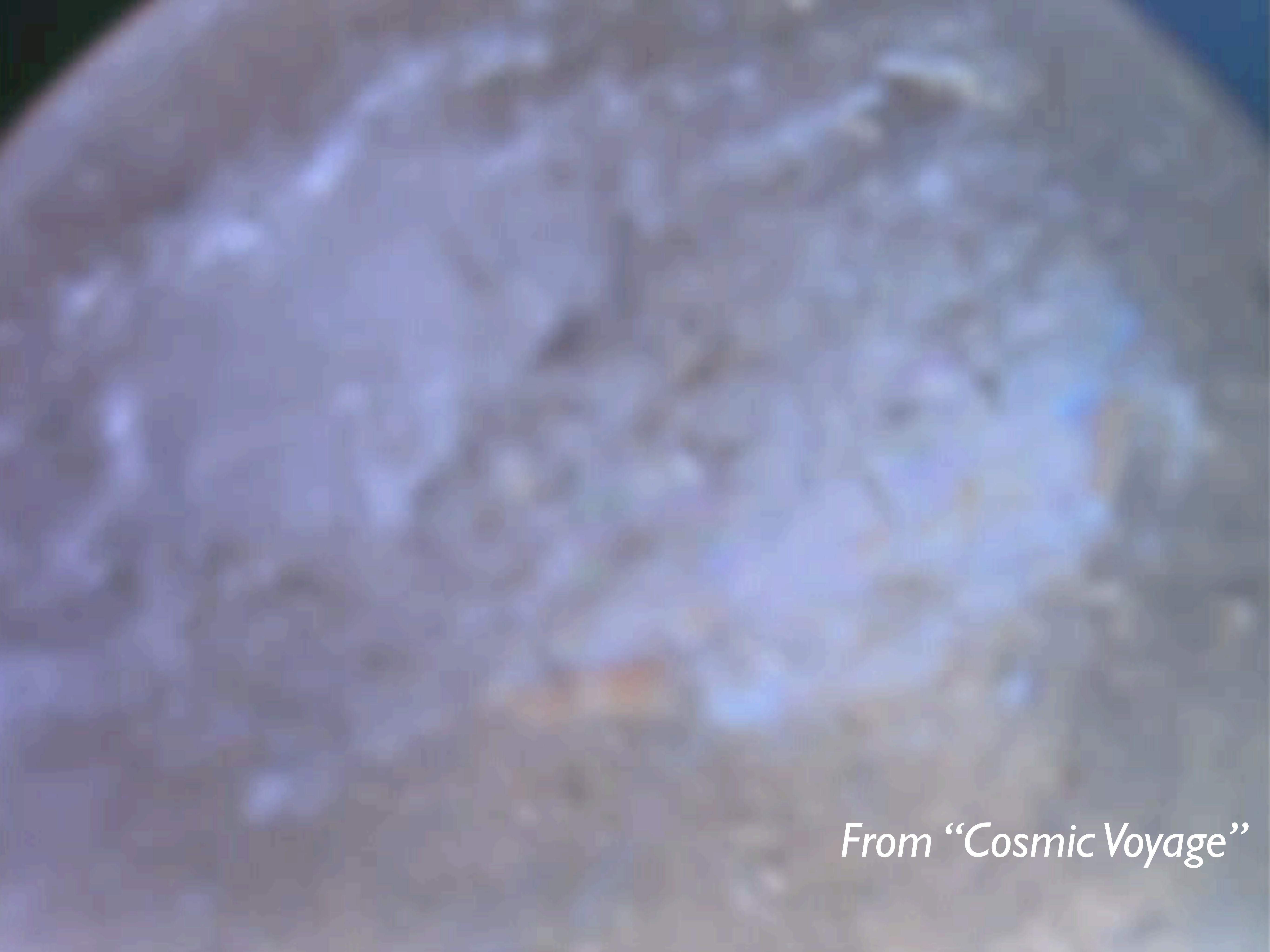
Eiichiro Komatsu, Max-Planck-Institut für Astrophysik
Seminar, LAPP, June 27, 2014

Signature of gravitational waves in the sky [?]



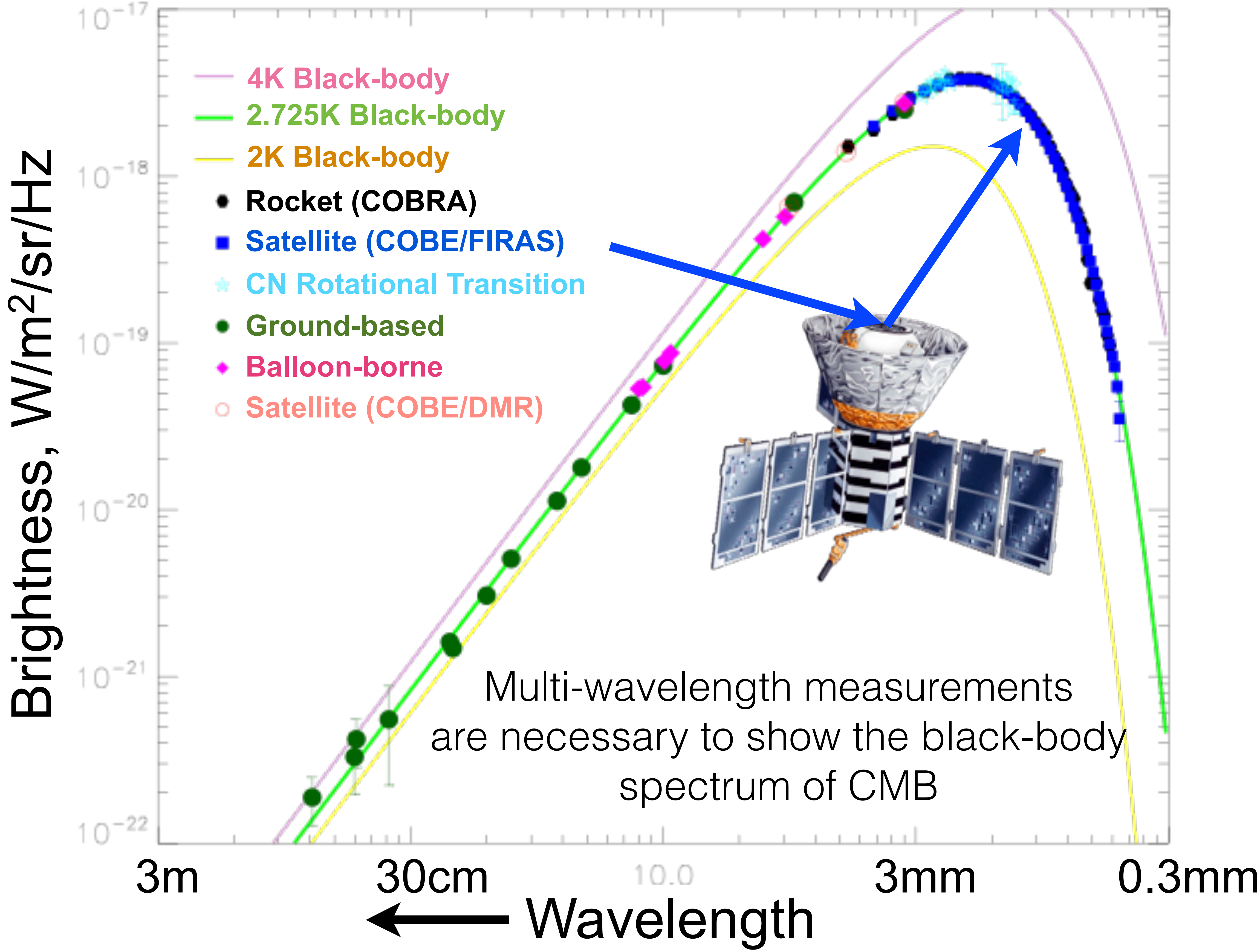
BICEP2 Collaboration

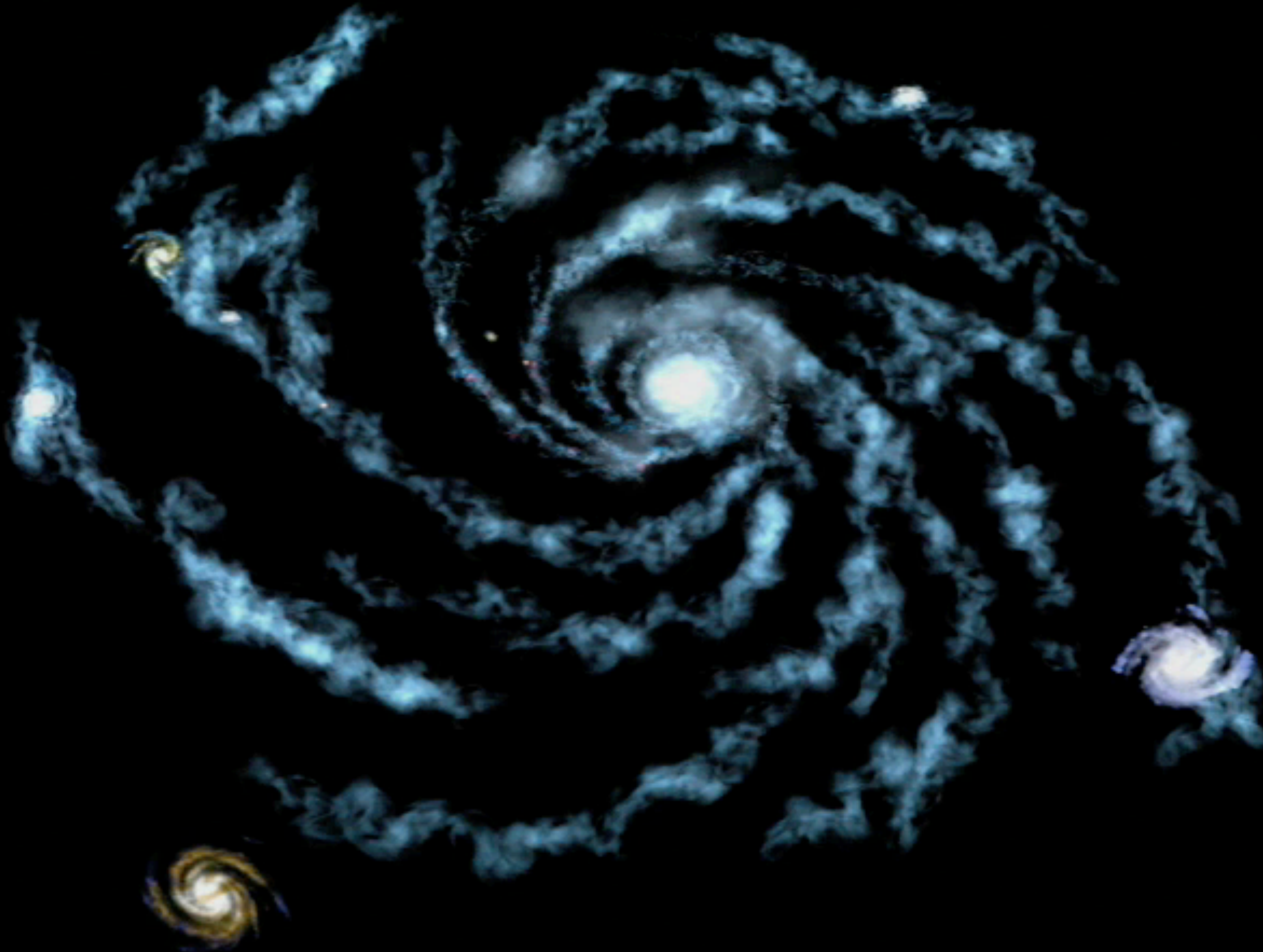
One of the goals of this presentation is to help you understand what this figure is actually showing



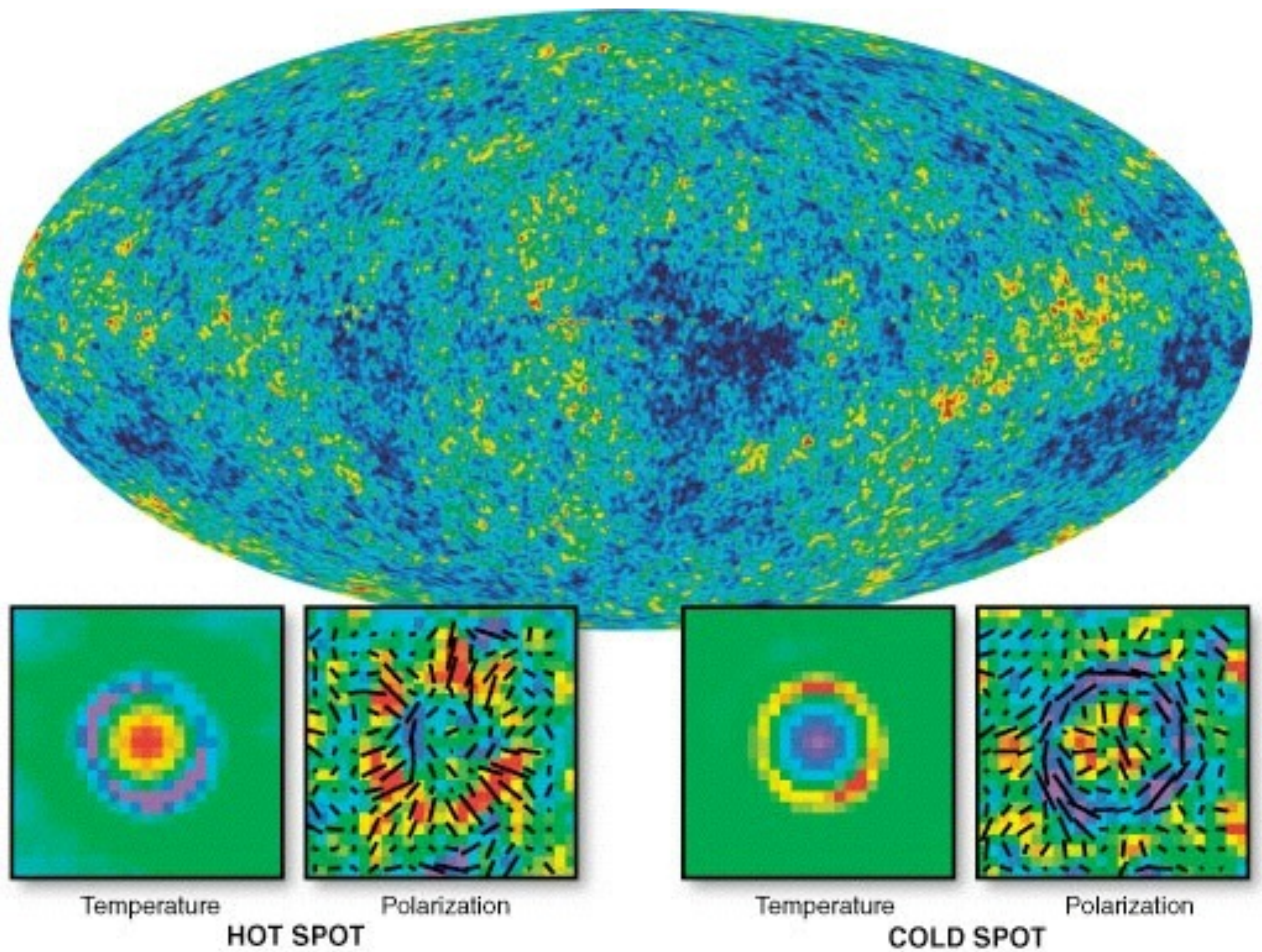
From “Cosmic Voyage”

From Samtleben et al. (2007)



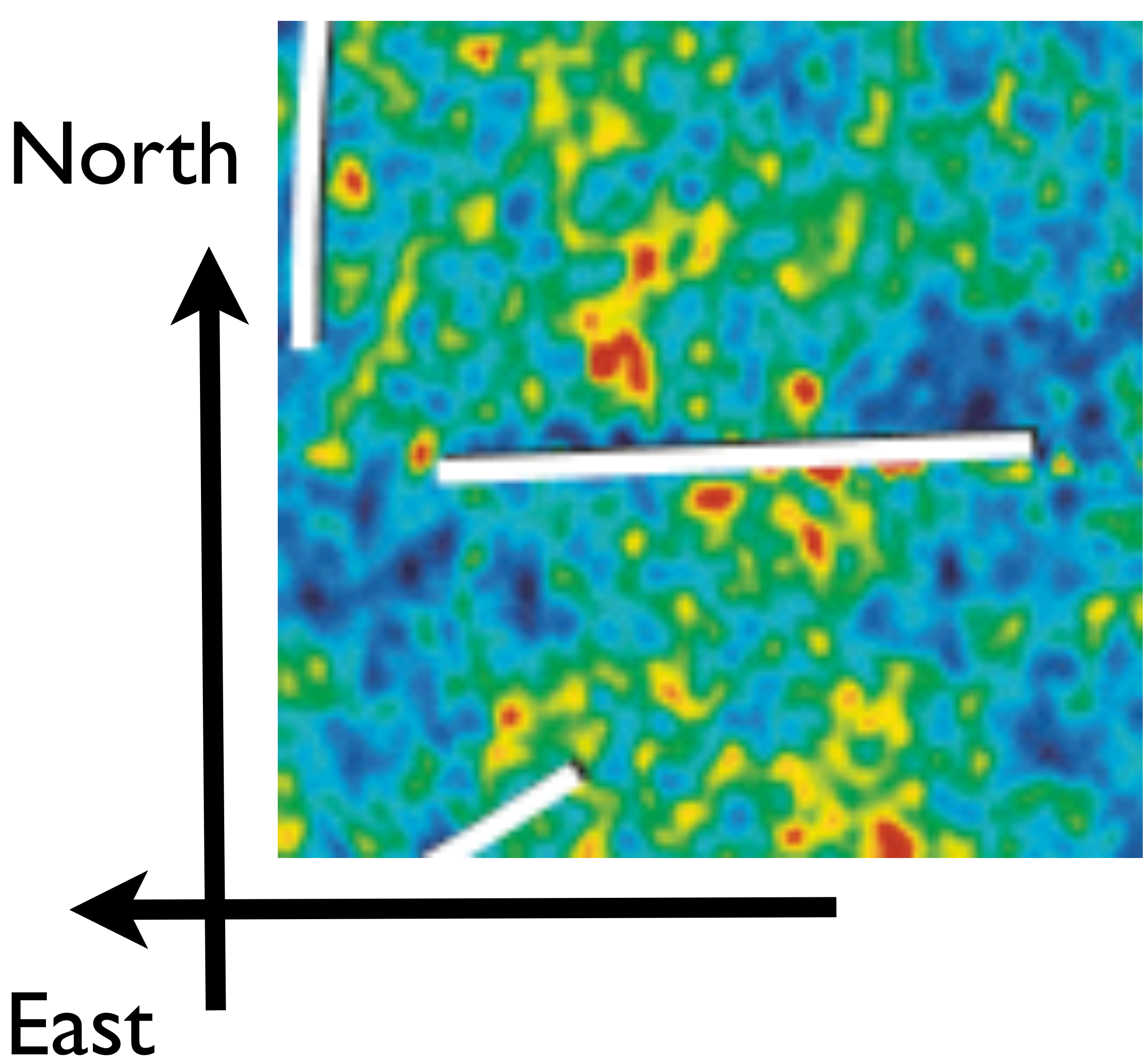


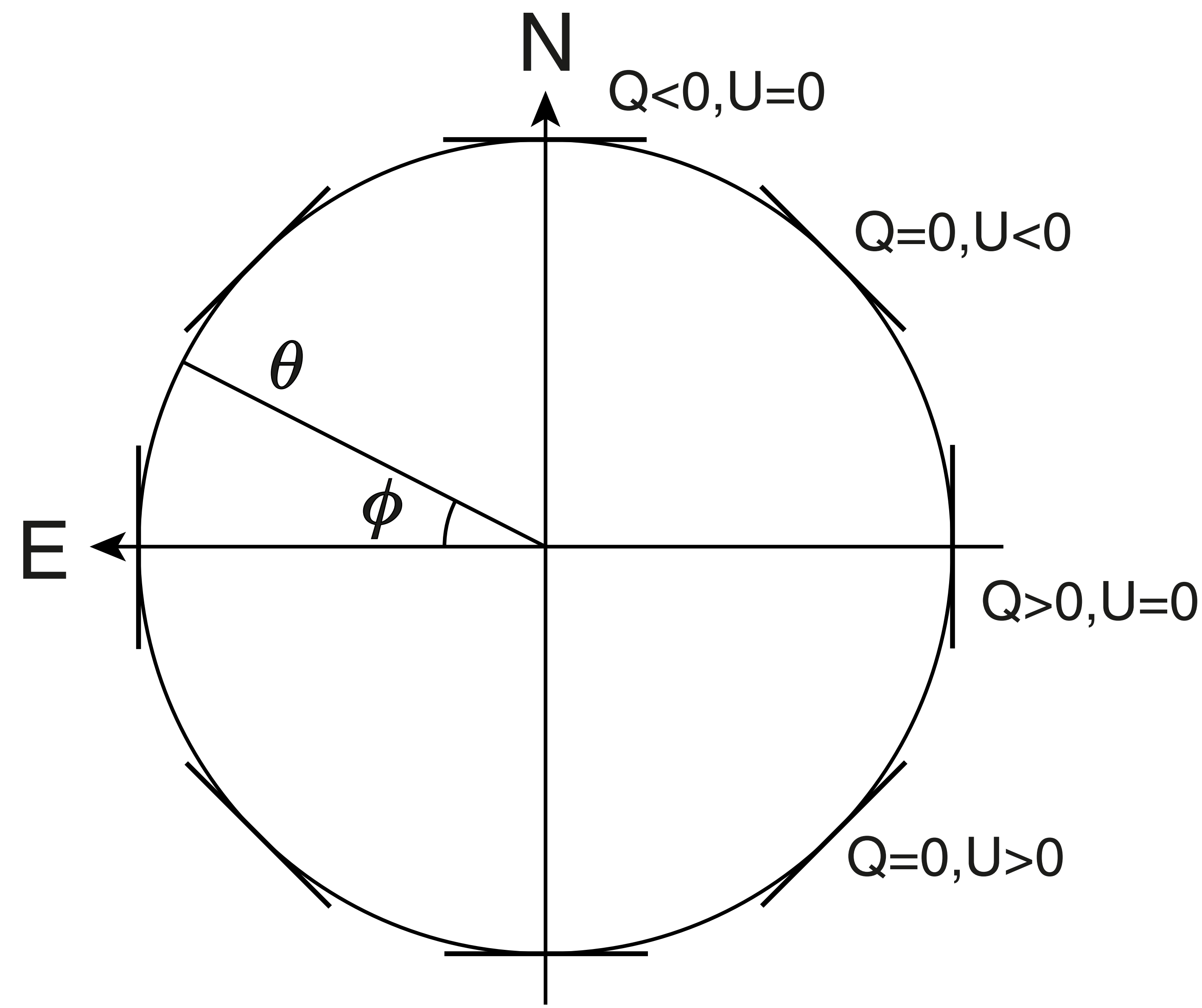
CMB Polarisation



- CMB is [weakly] polarised!

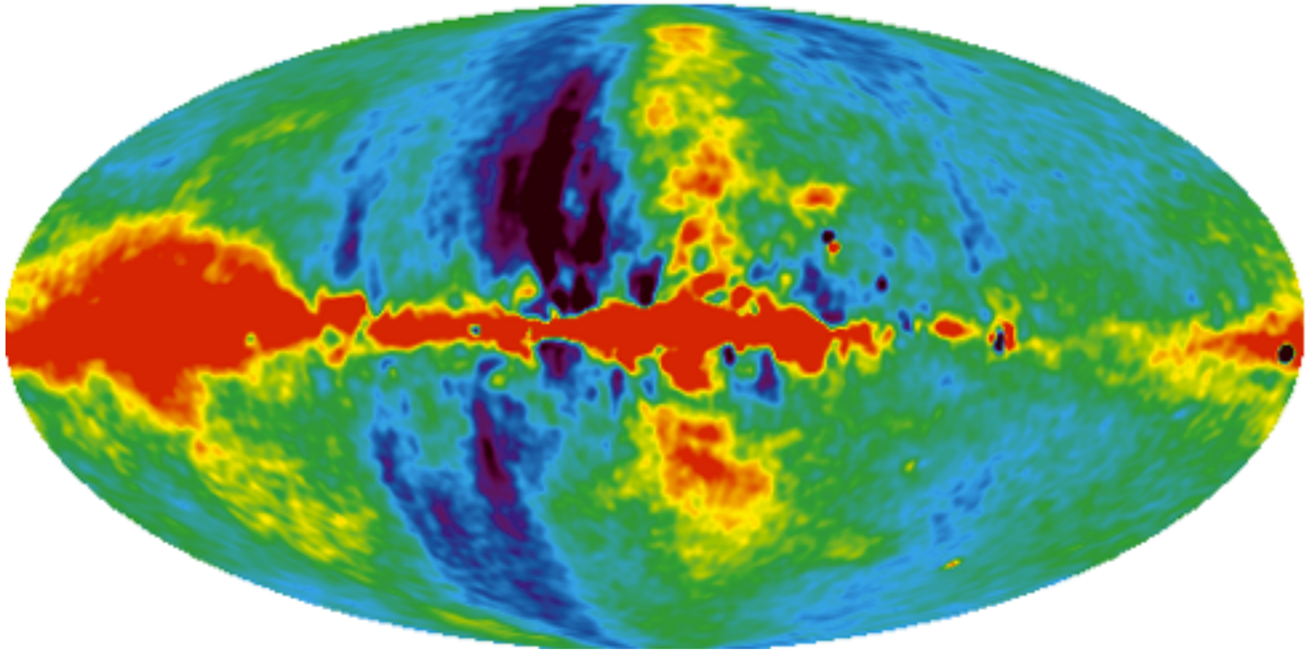
Stokes Parameters



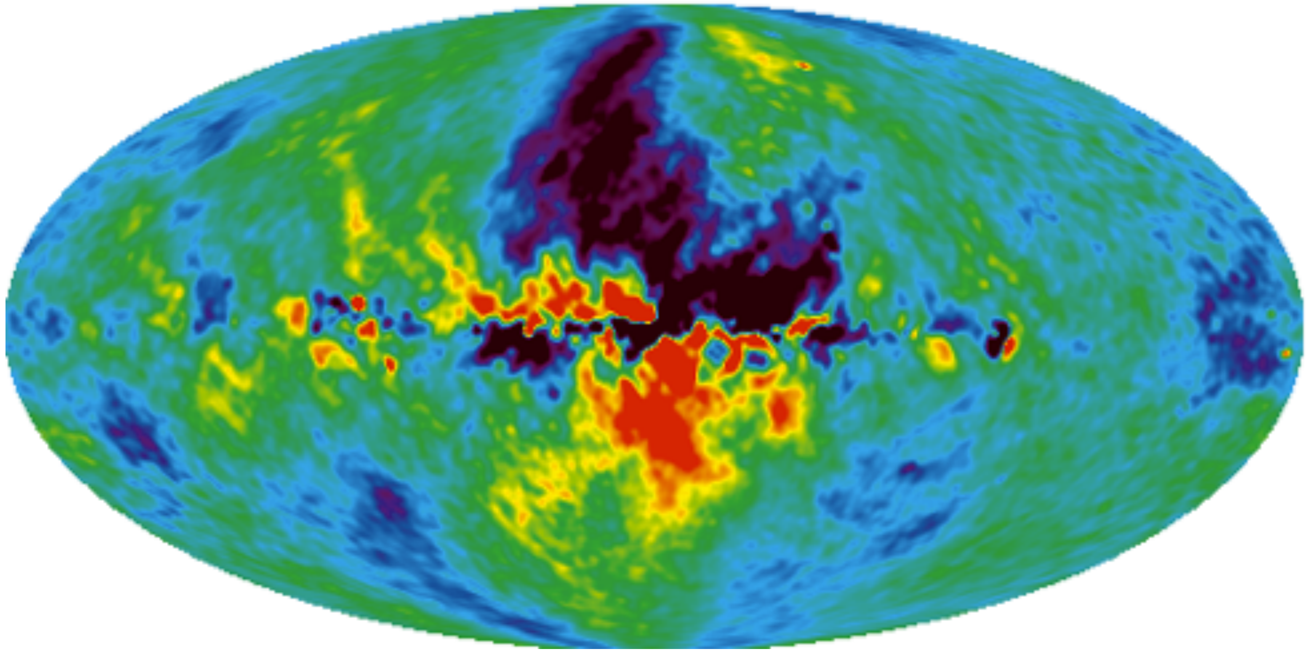


WMAP Collaboration

23 GHz



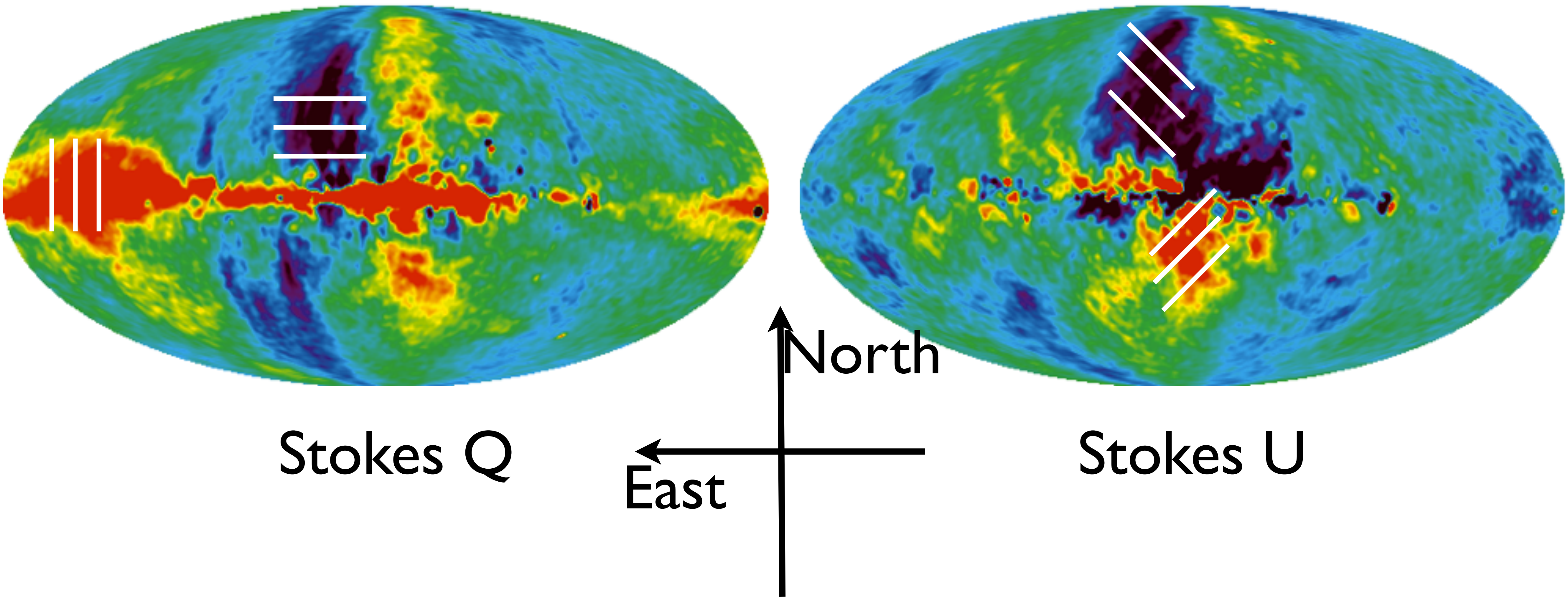
Stokes Q



Stokes U

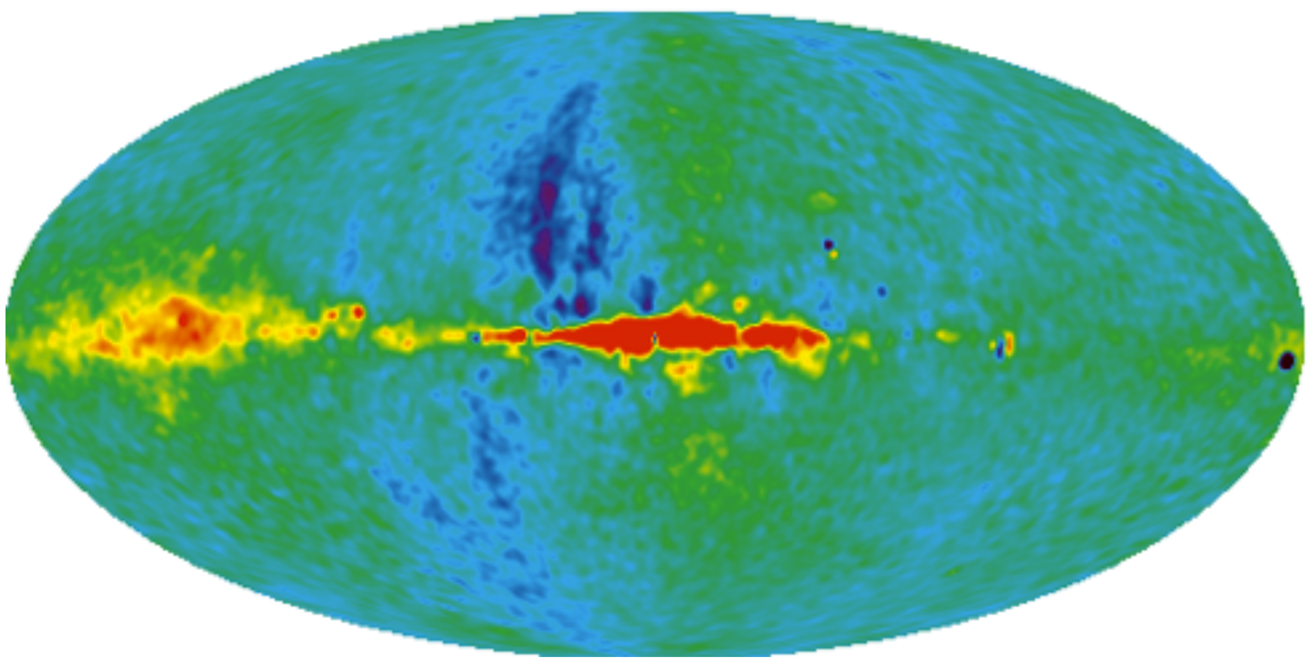
WMAP Collaboration

23 GHz [13 mm]

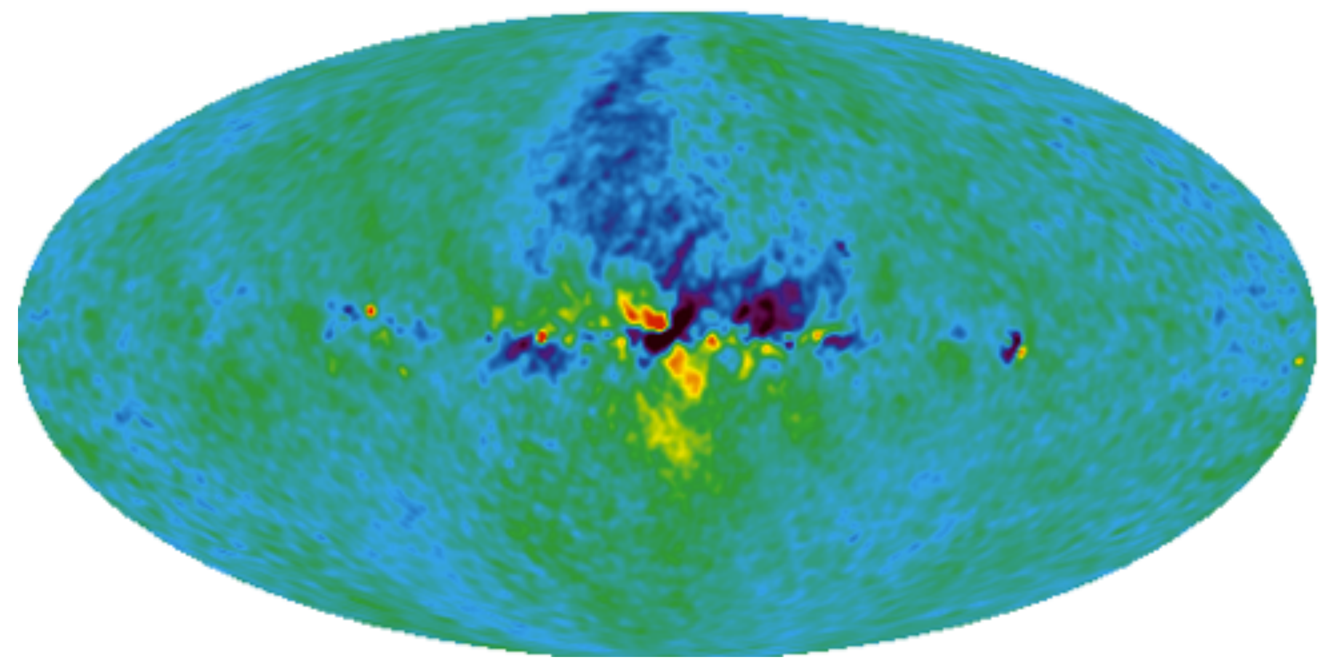


WMAP Collaboration

33 GHz [9.1 mm]

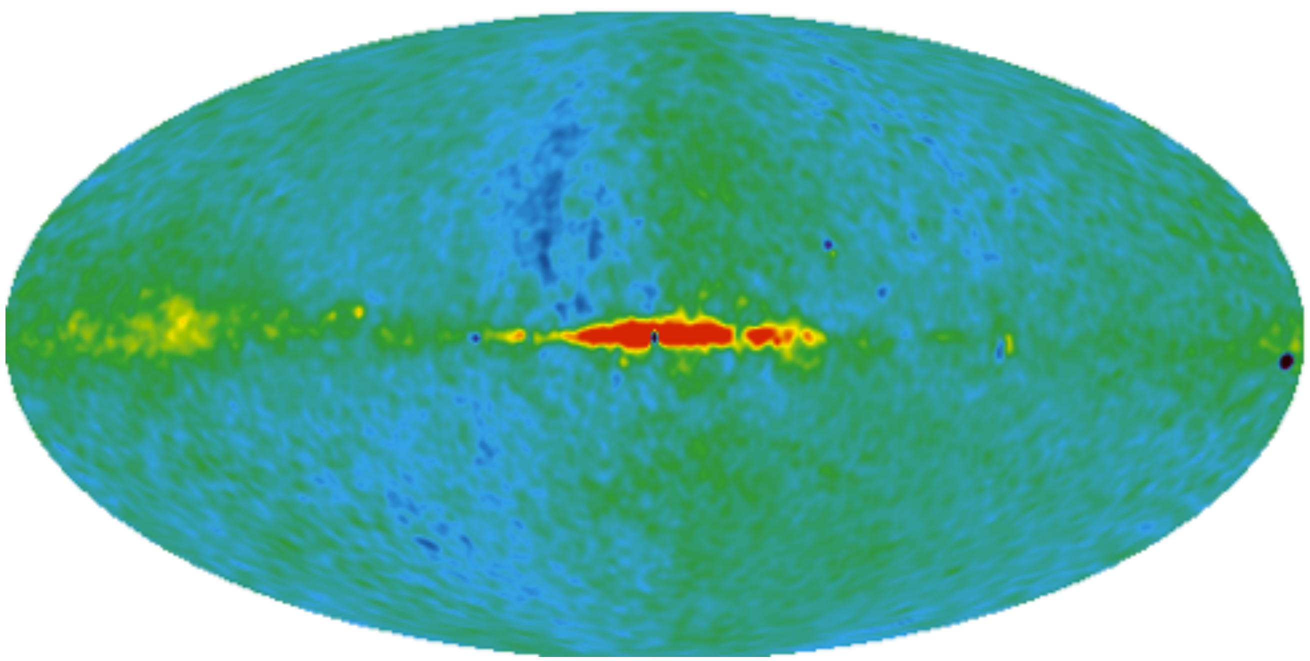


Stokes Q

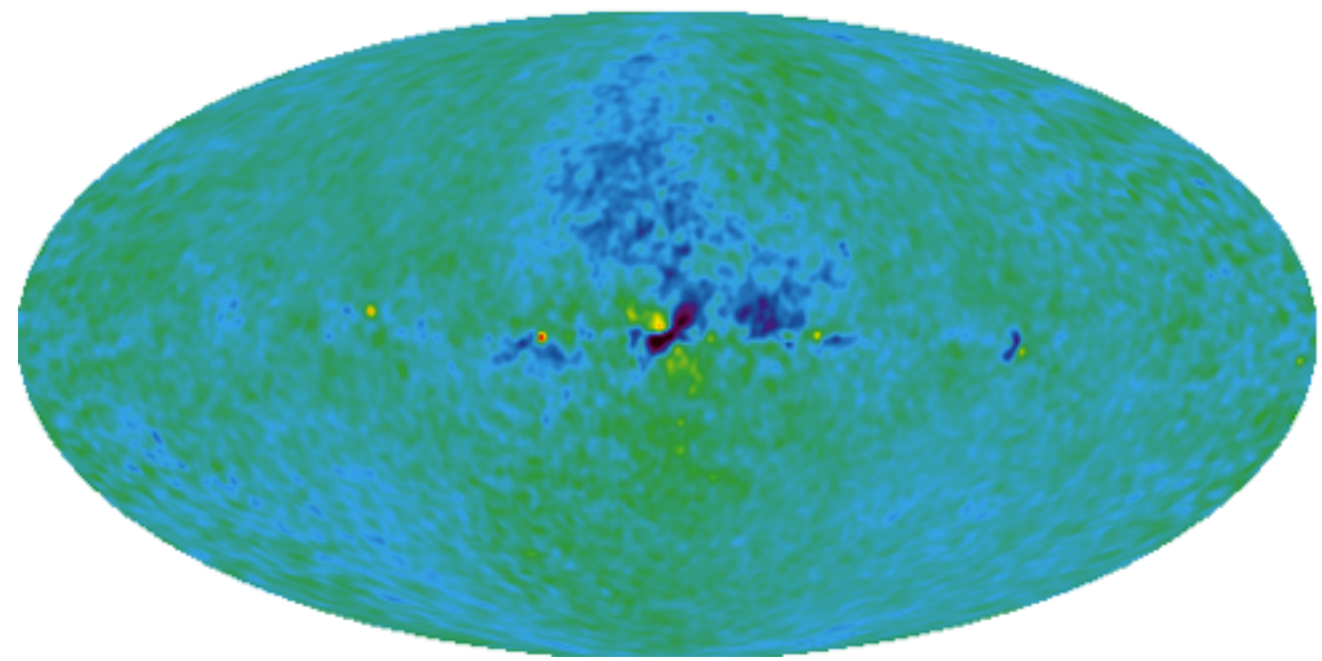


Stokes U

41 GHz [7.3 mm]



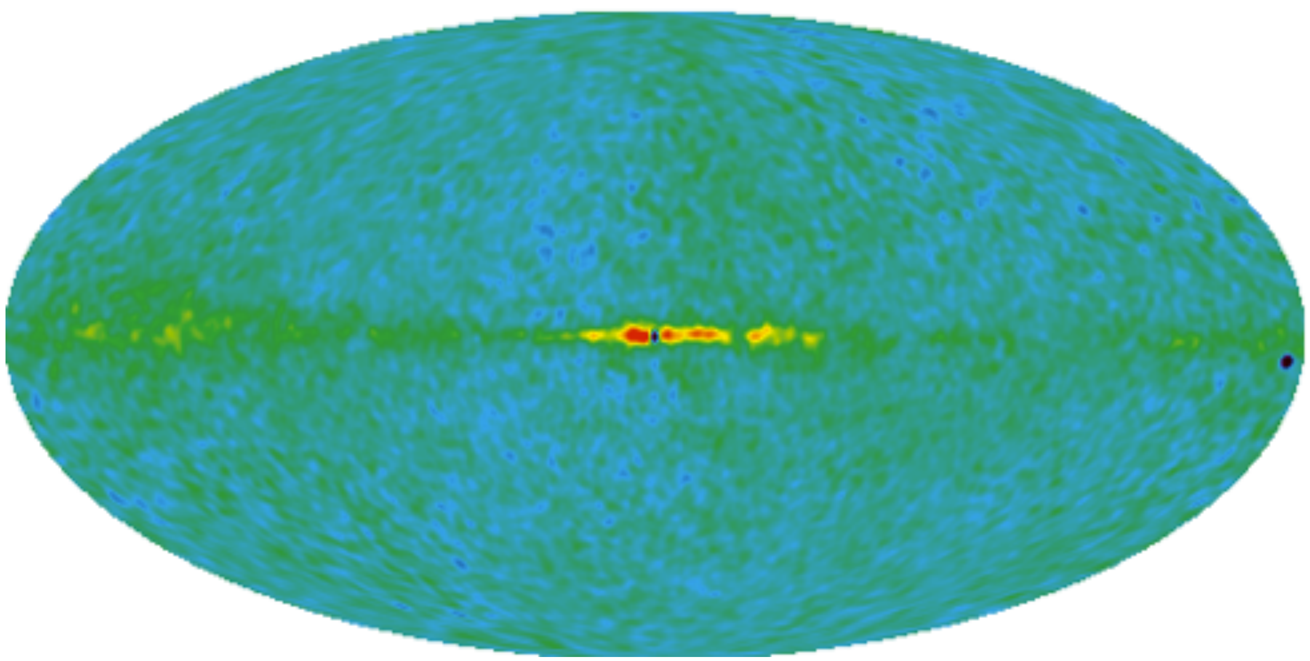
Stokes Q



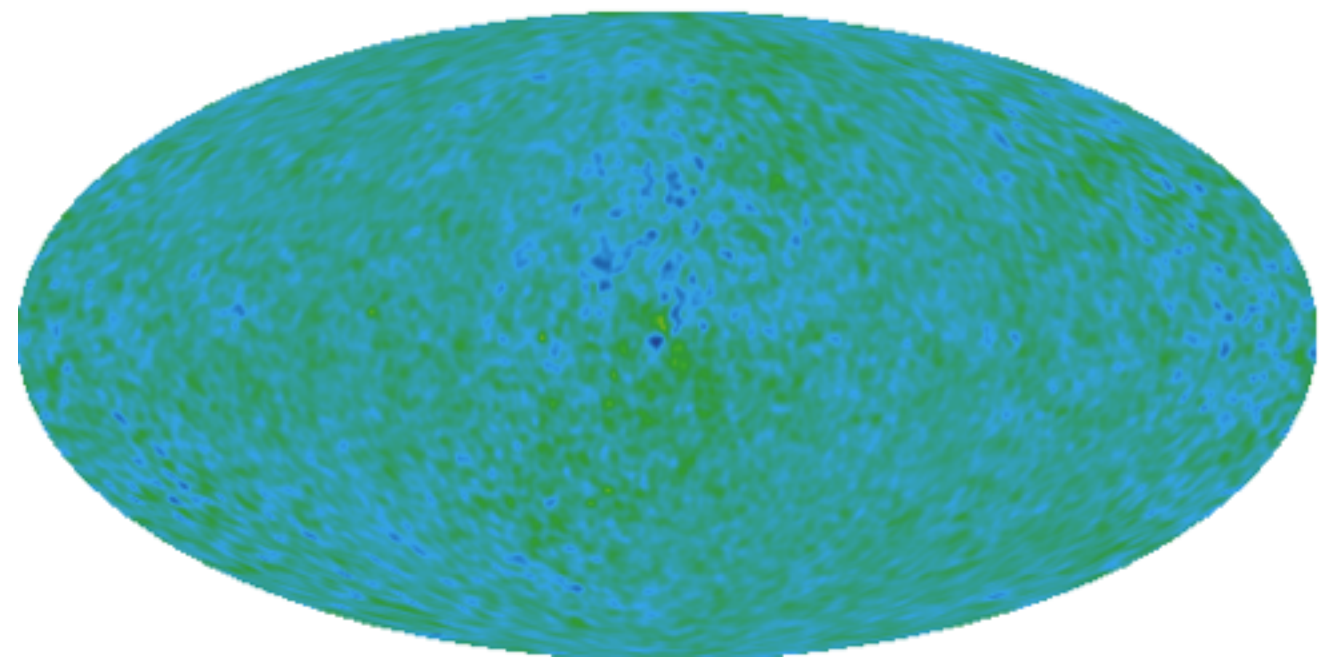
Stokes U

WMAP Collaboration

61 GHz [4.9 mm]

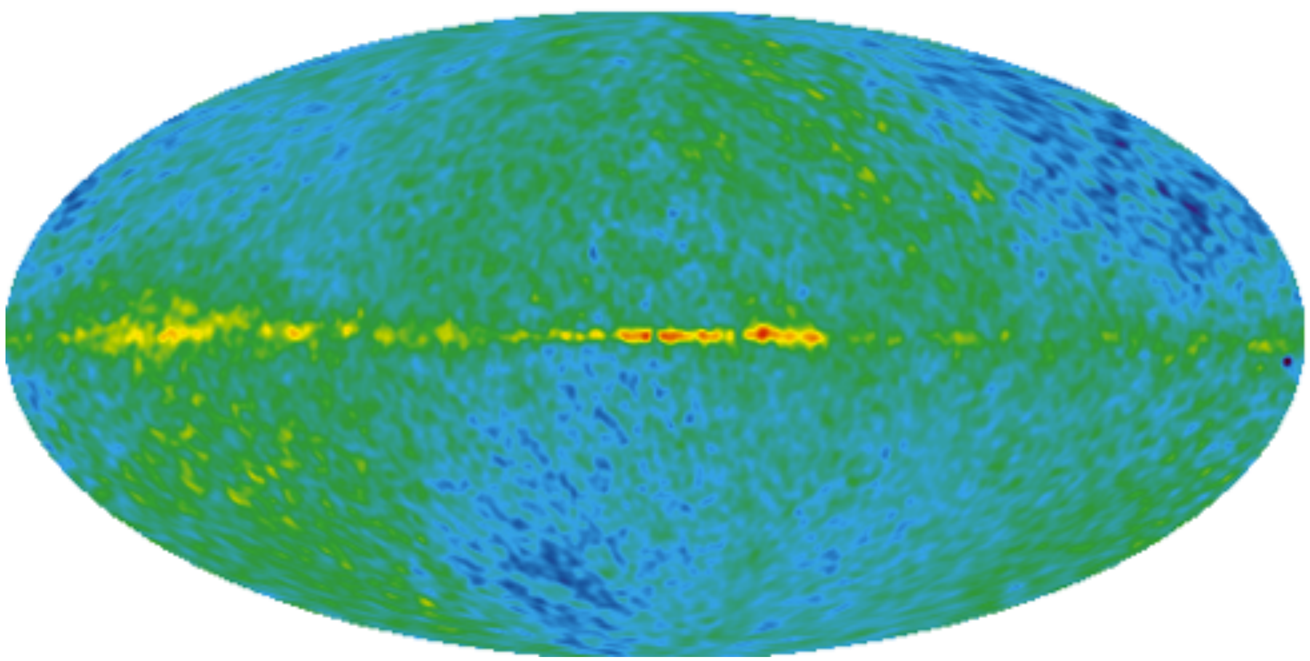


Stokes Q

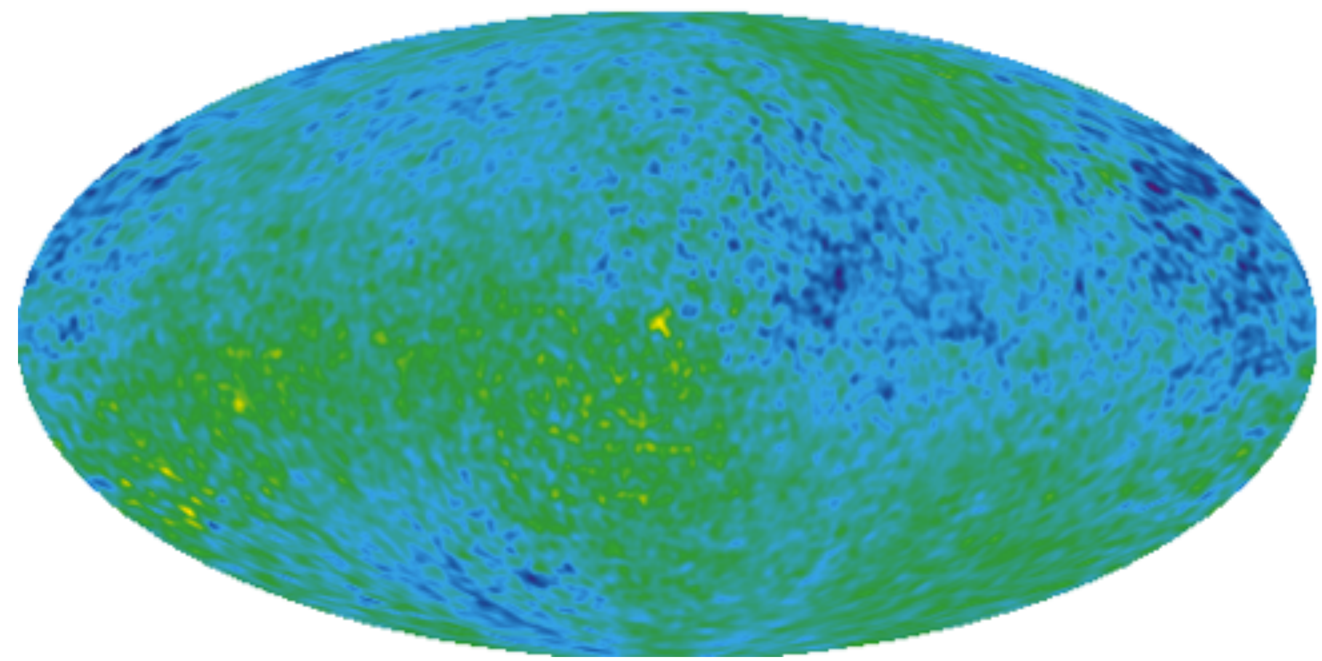


Stokes U

94 GHz [3.2 mm]



Stokes Q



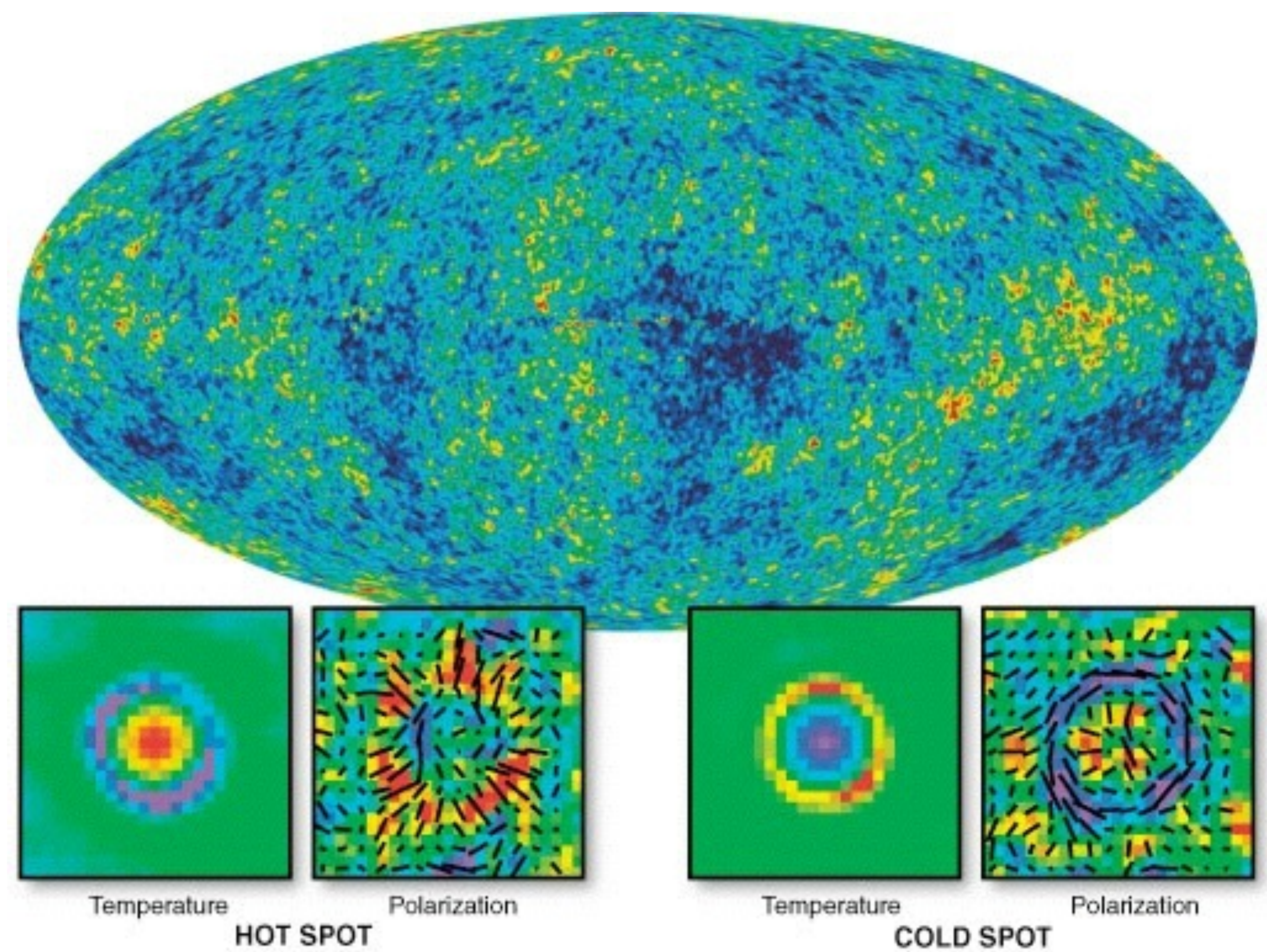
Stokes U

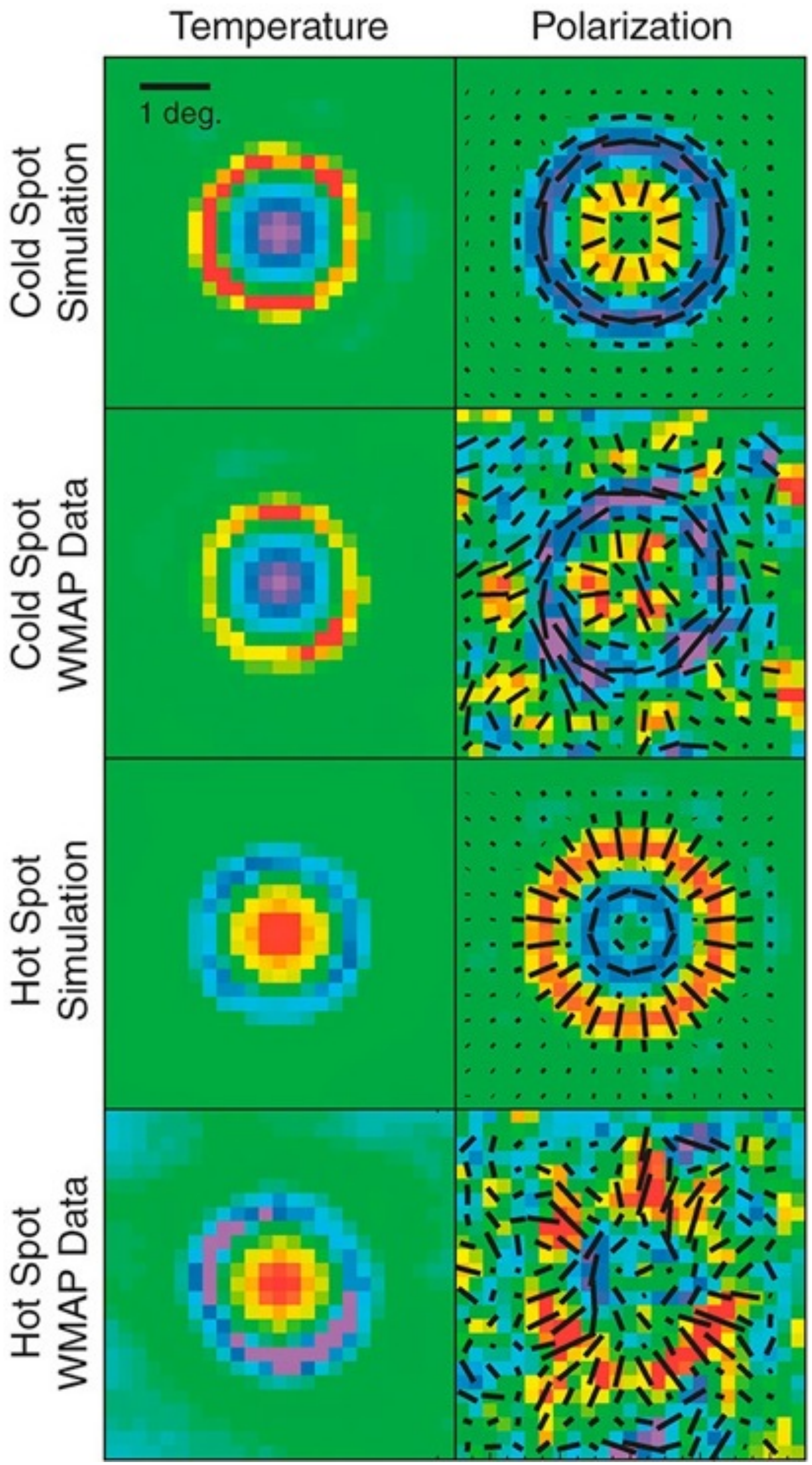
How many components?

- 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





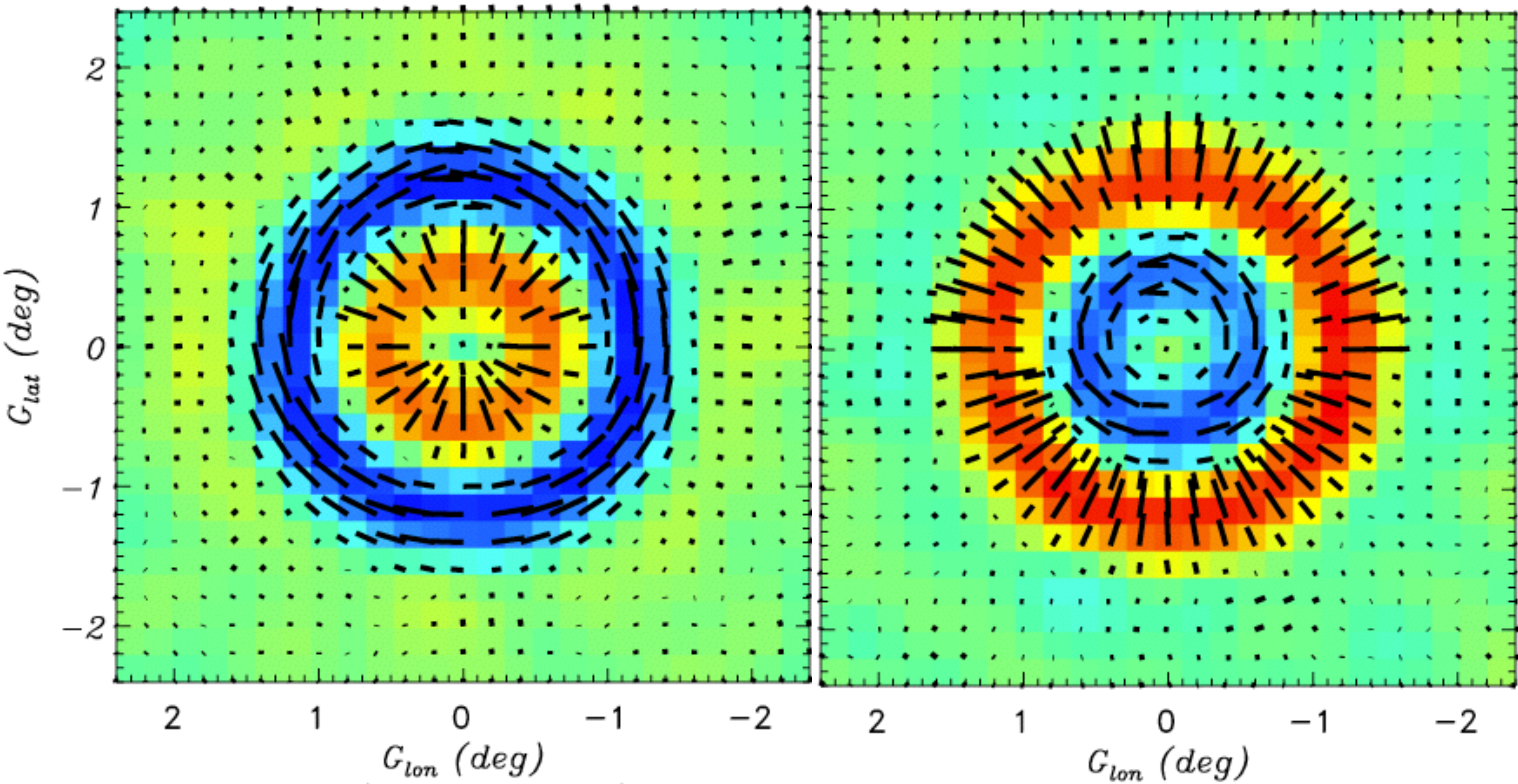
WMAP Collaboration

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

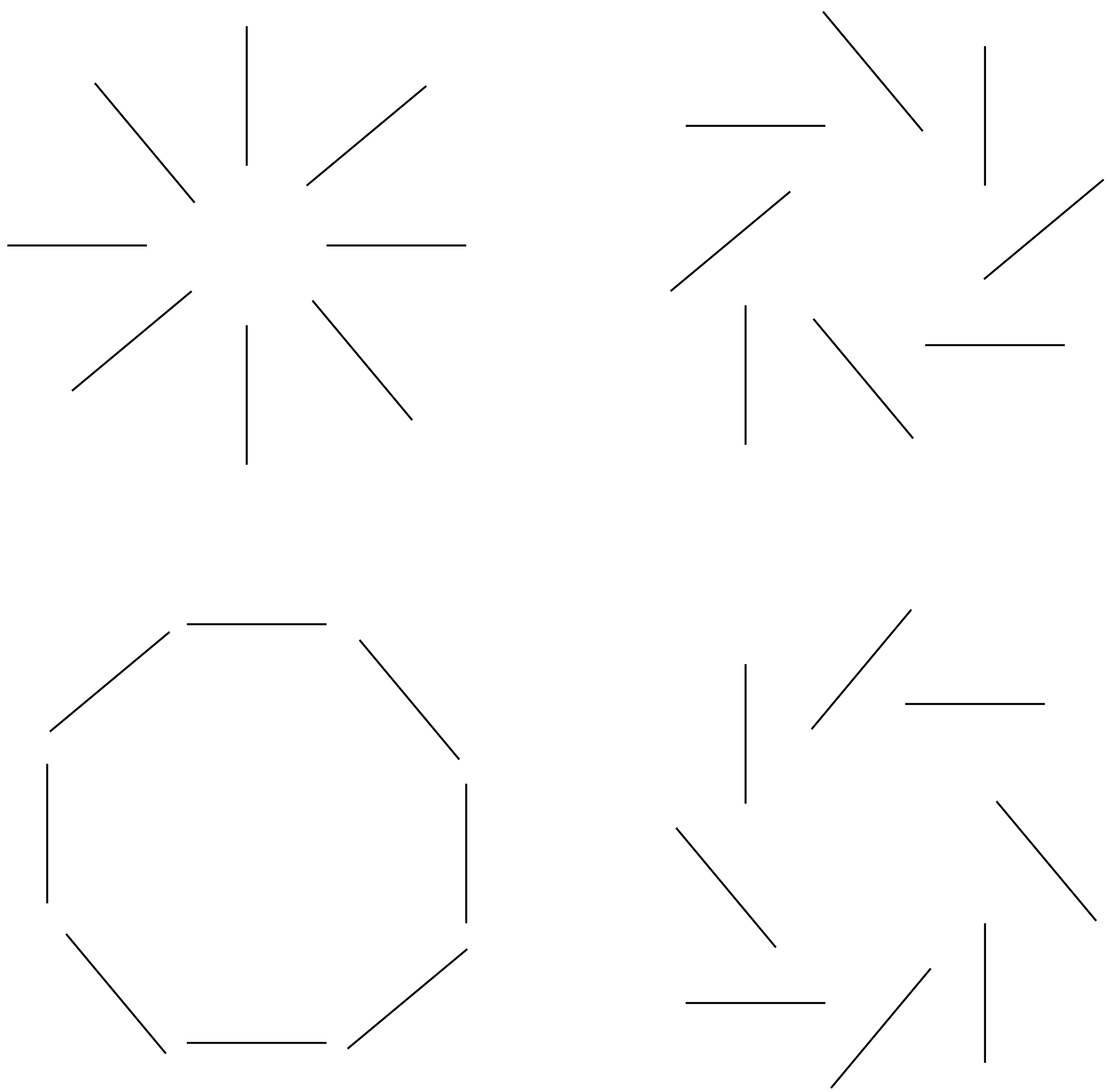
Planck Data!



Q_r (cold spots) Q_r (hot spots)

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

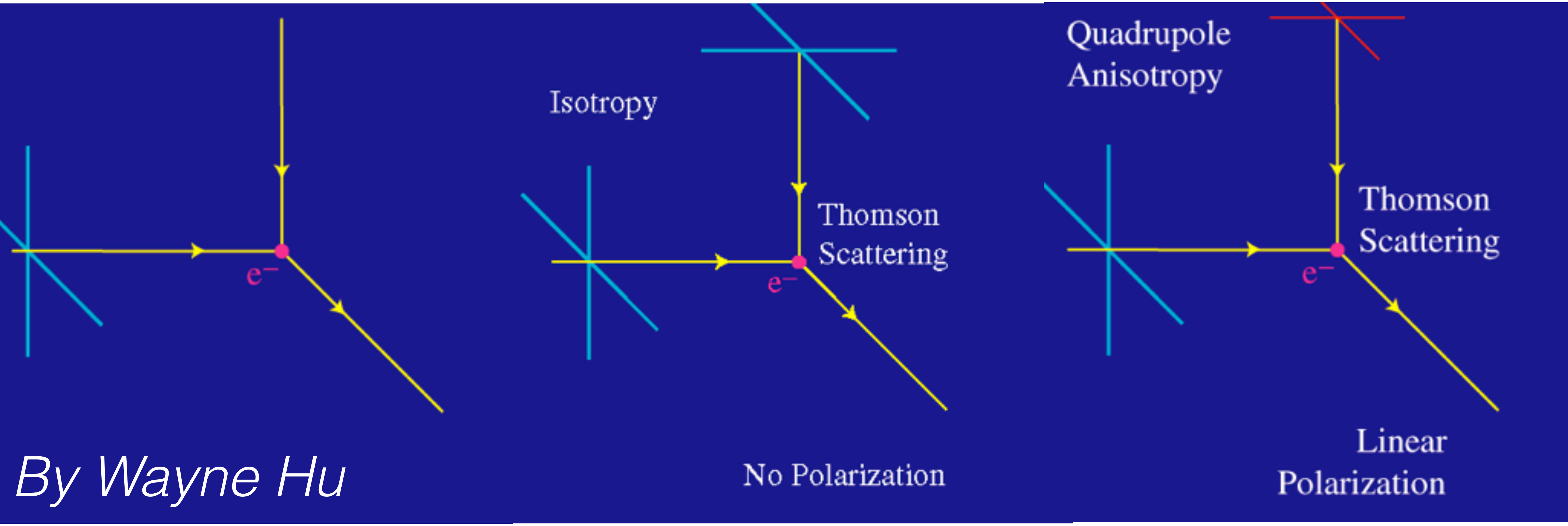
E and B modes



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

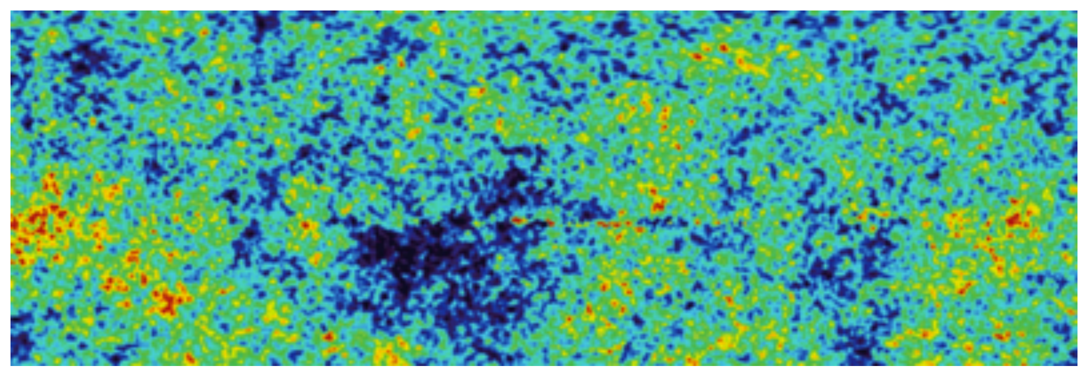
- **Scalar perturbations**: motion of electrons with respect to photons
- **Tensor perturbations**: gravitational waves

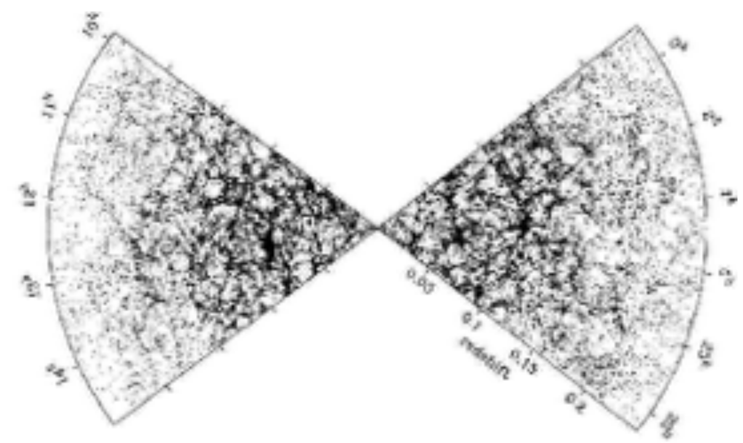
Key Predictions of Inflation

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

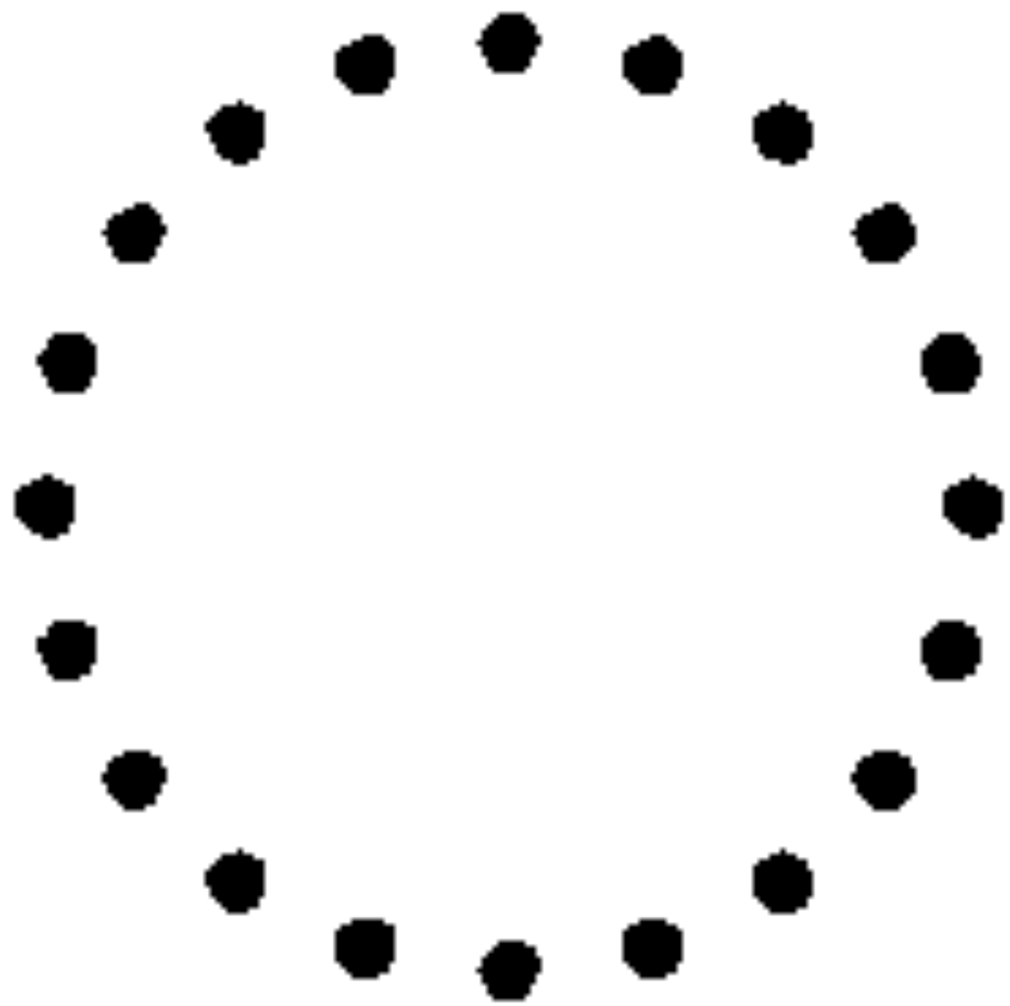
- A distance between two points in space

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

- 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)

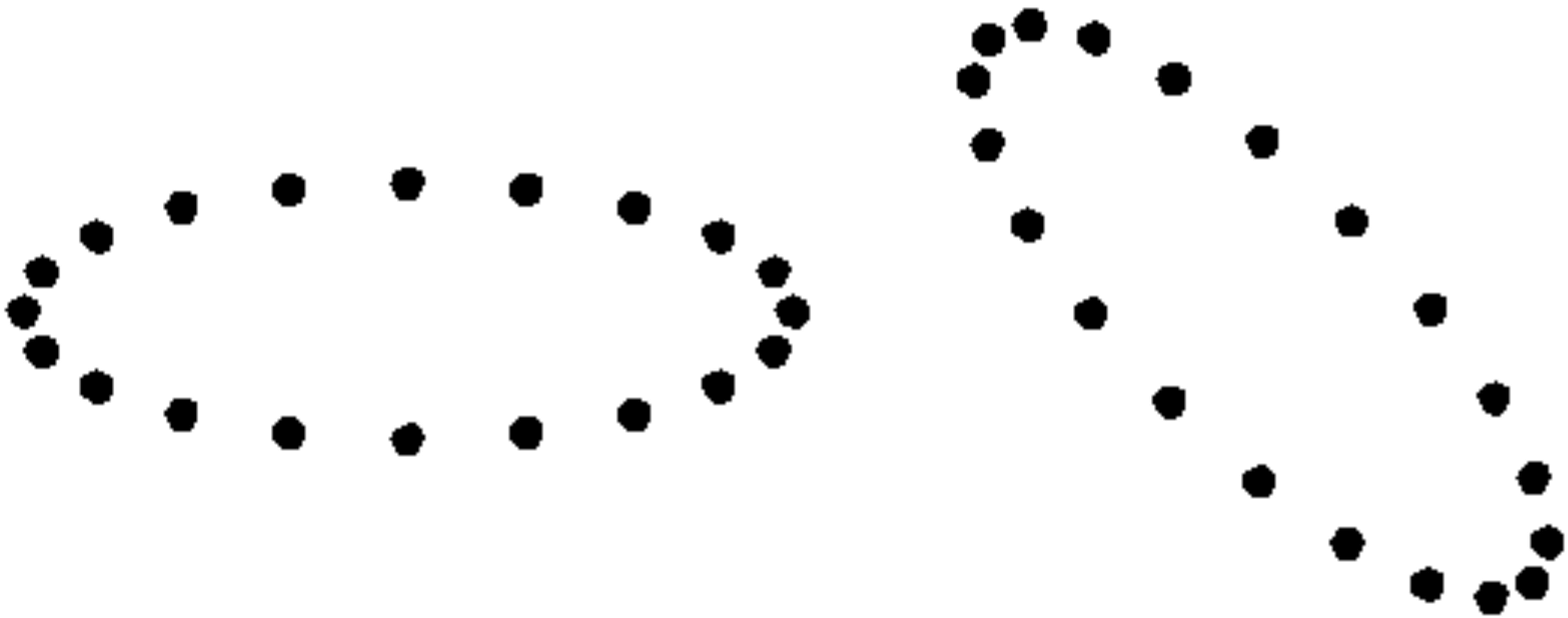
$$\sum_i h_{ii} = 0$$

Gravitational waves are coming toward you!



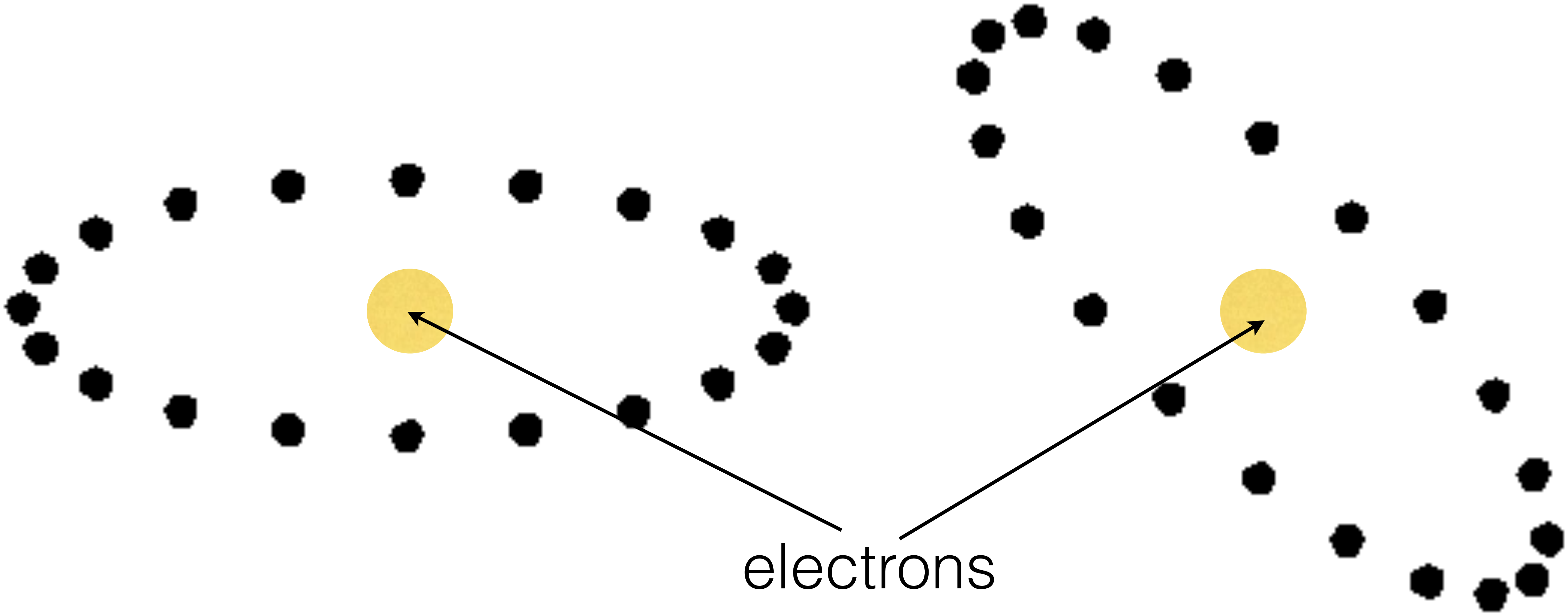
- What do they do to the distance between particles?

Two GW modes

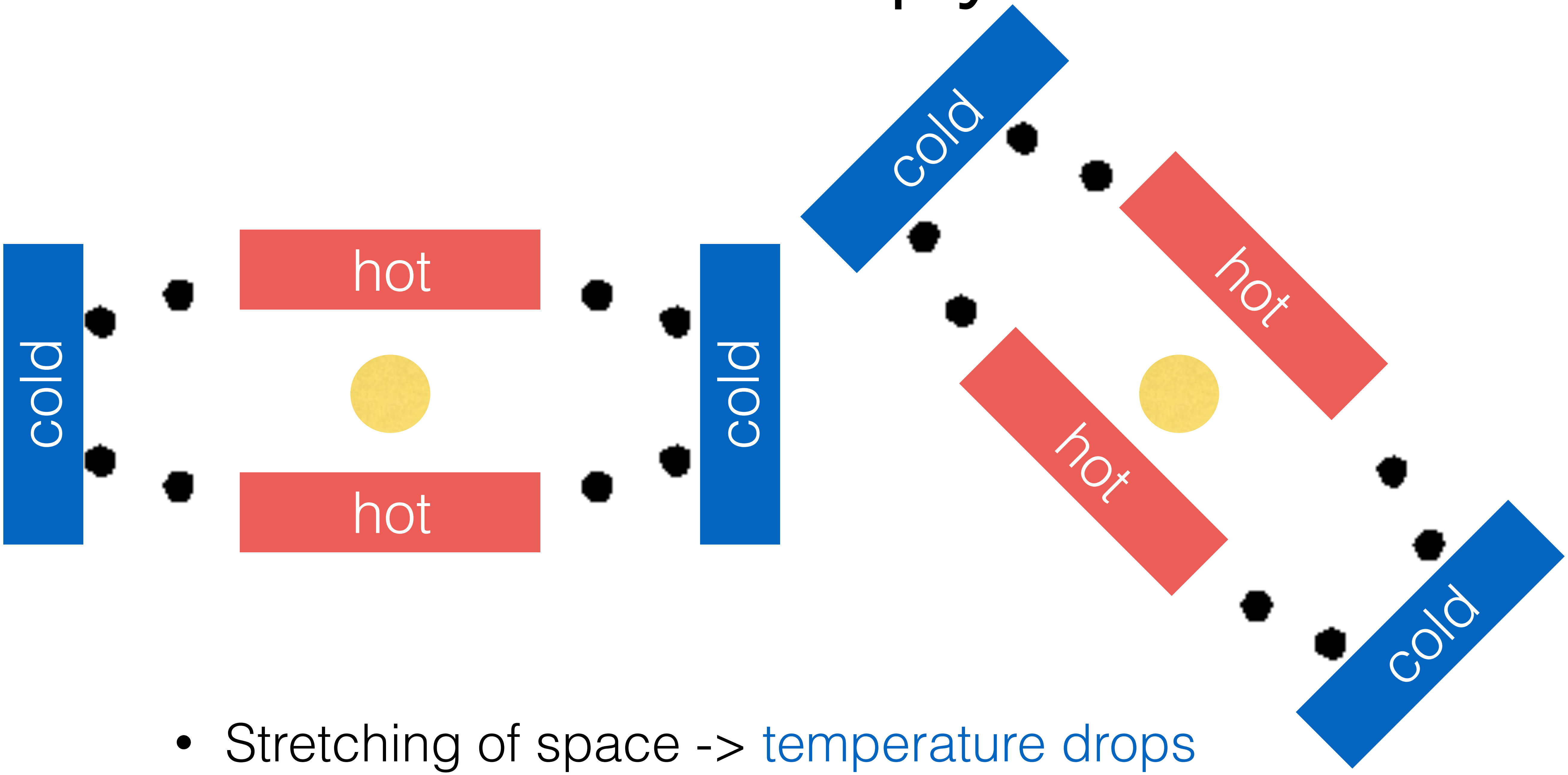


- Anisotropic stretching of space generates quadrupole temperature anisotropy. How?

GW to temperature anisotropy

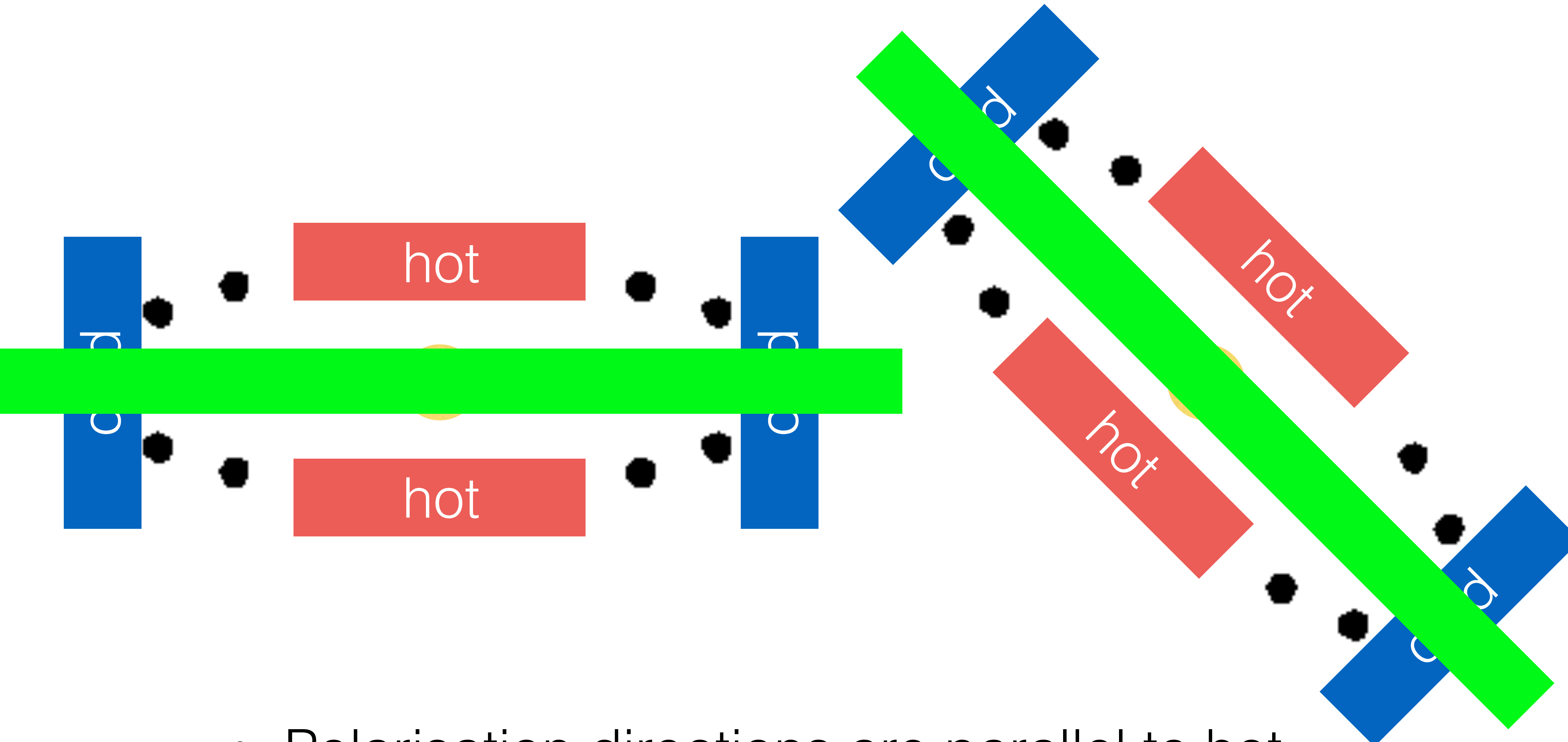


GW to temperature anisotropy

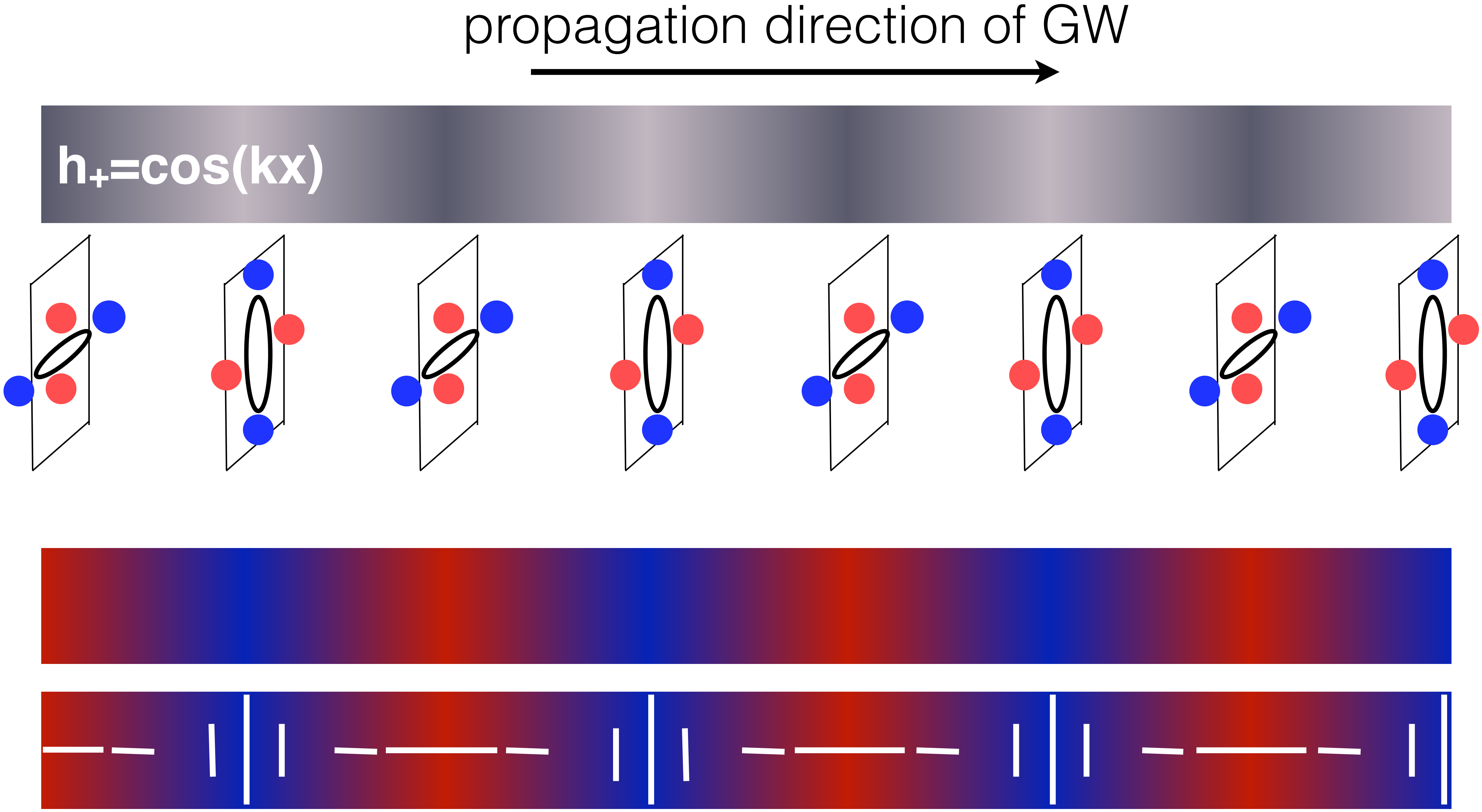


- Stretching of space -> temperature drops
- Contraction of space -> temperature rises

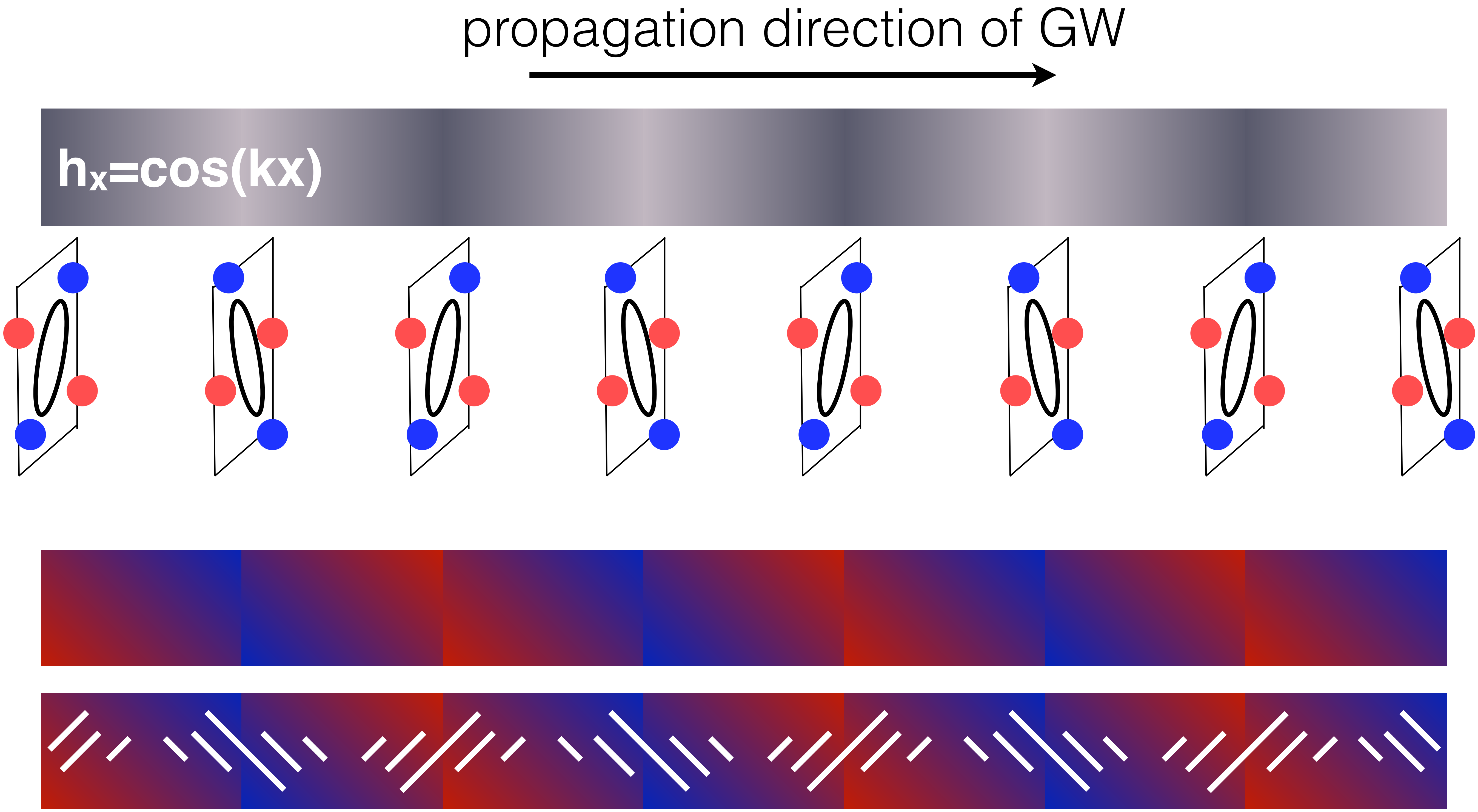
Then to polarisation!



- Polarisation directions are parallel to hot regions



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



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

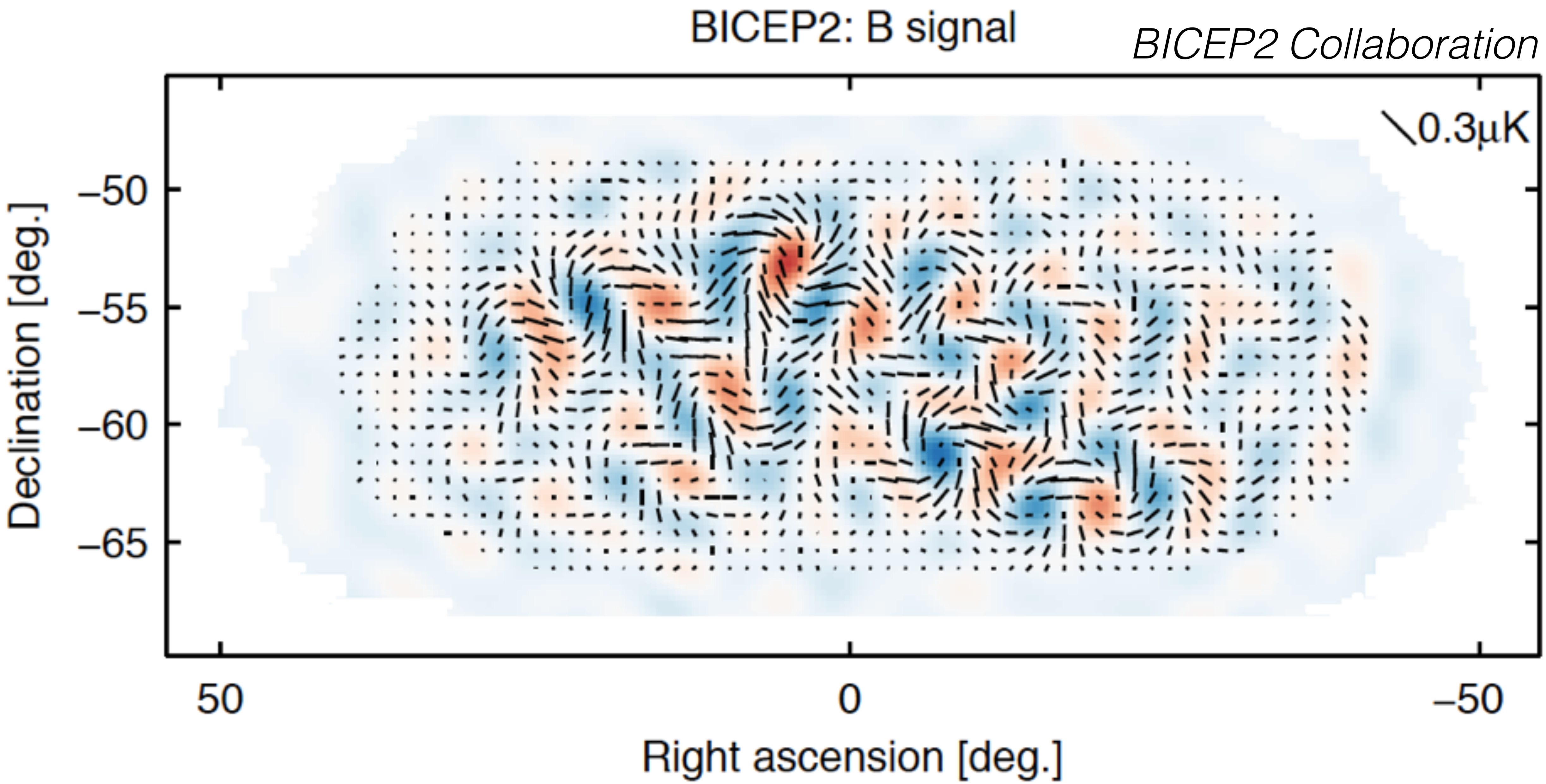
Important note:

- 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

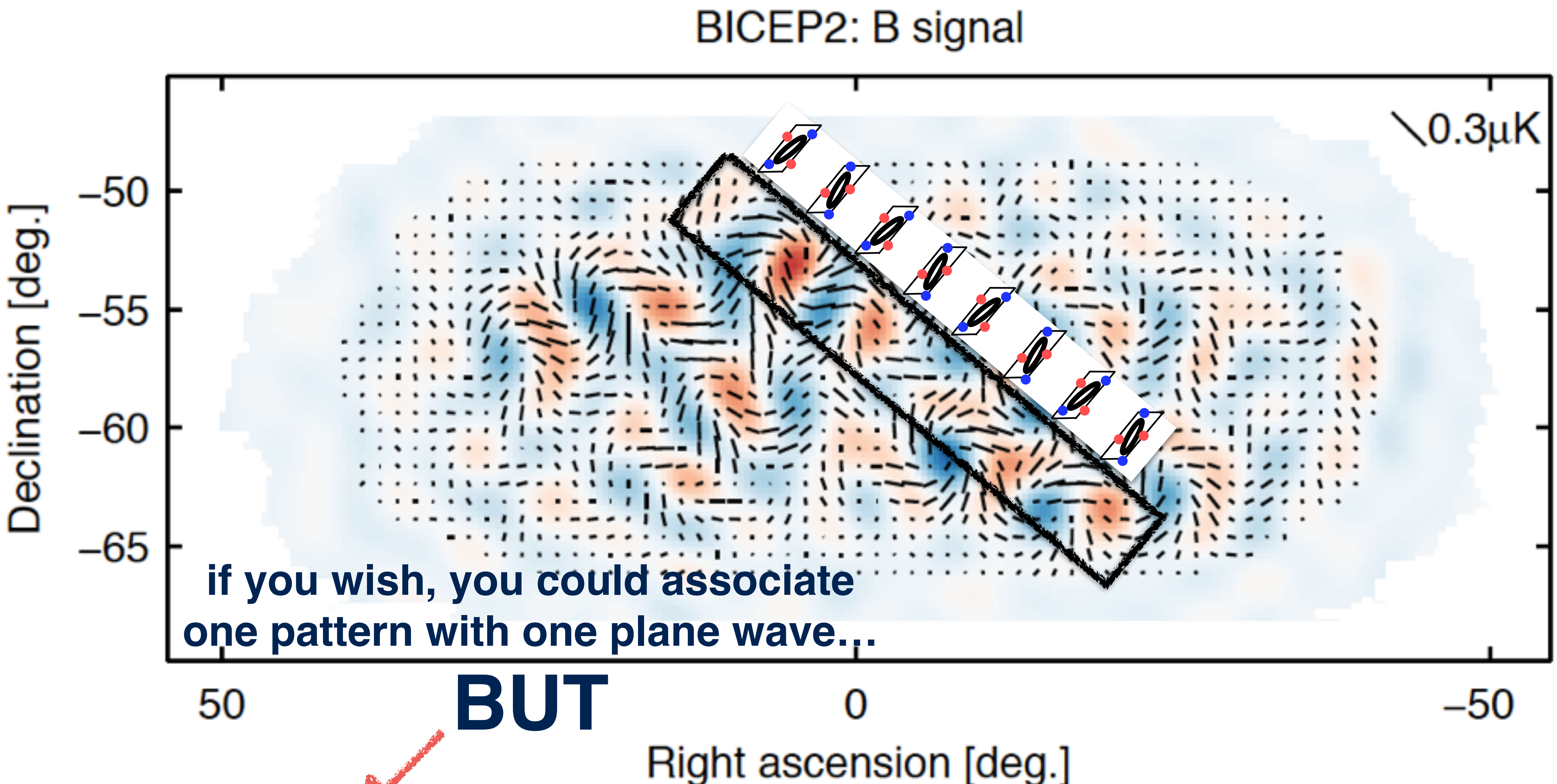
    - The important point is that **h_+ and $h_\times$ always coexist**. When a linear combination of h_+ and $h_\times$ produces E, another combination produces B

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

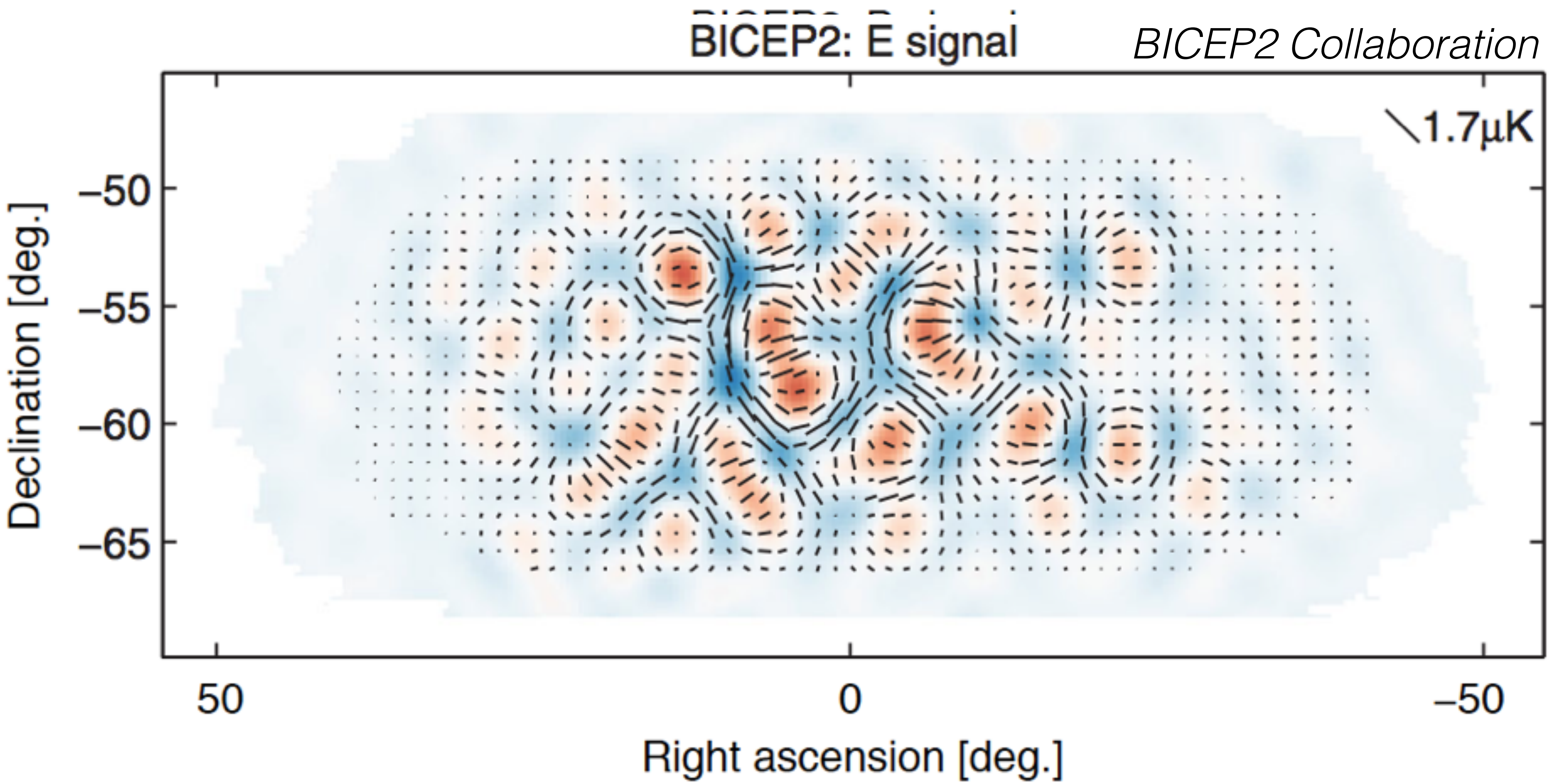
Signature of gravitational waves in the sky [?]



BUT

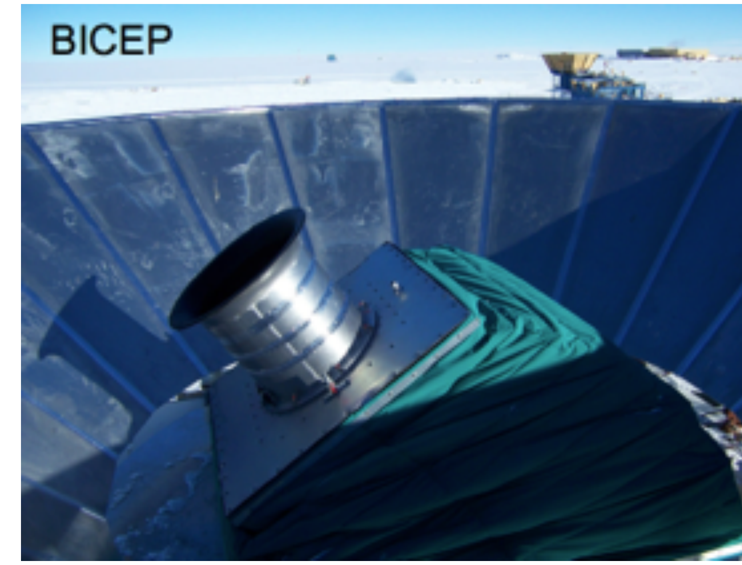
<u>CAUTION</u>: we are NOT seeing a single plane wave propagating perpendicular to our line of sight

There are E modes in the sky as well

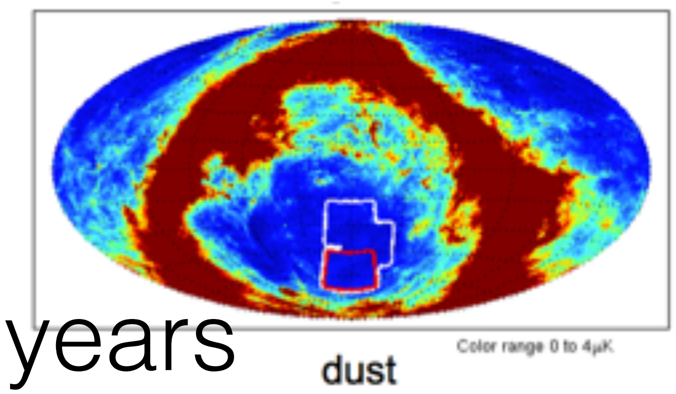


The E-mode polarisation is totally dominated by the scalar-mode fluctuations [density waves]

What is BICEP2?



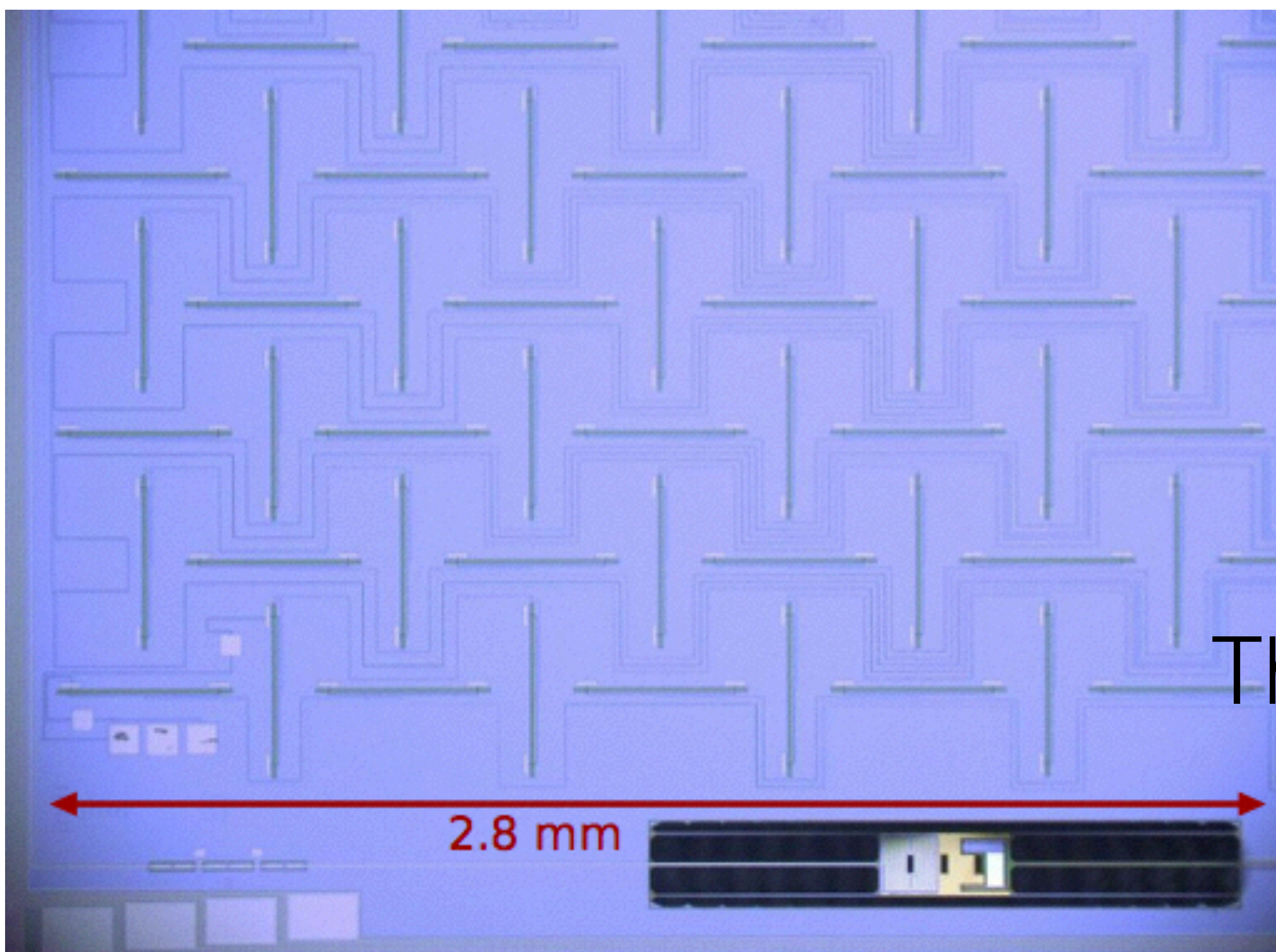
- A small [26 cm] refractive telescope at South Pole
- 512 bolometers working at 150 GHz



- 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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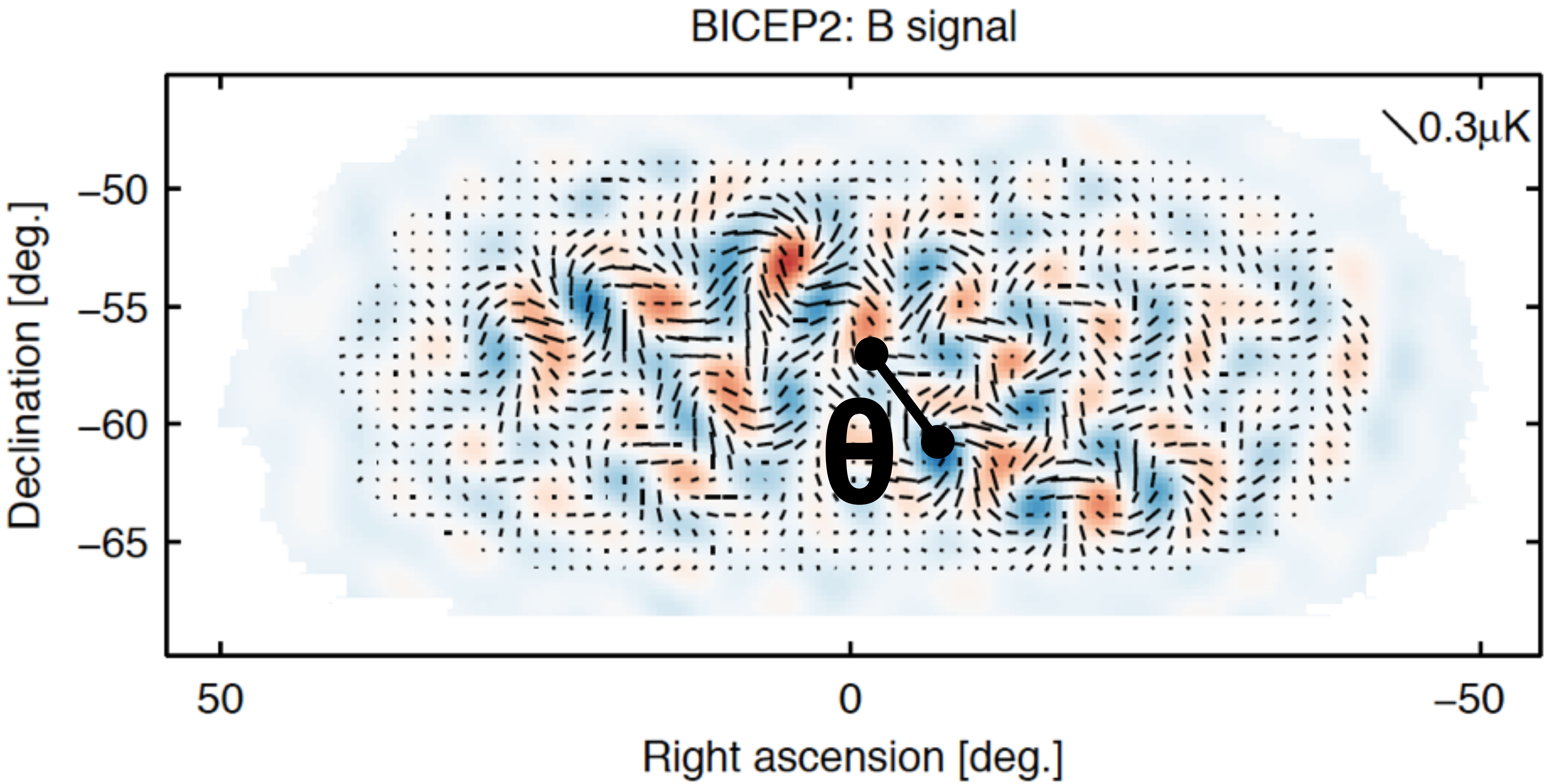
Analysis: Two-point Correlation Function

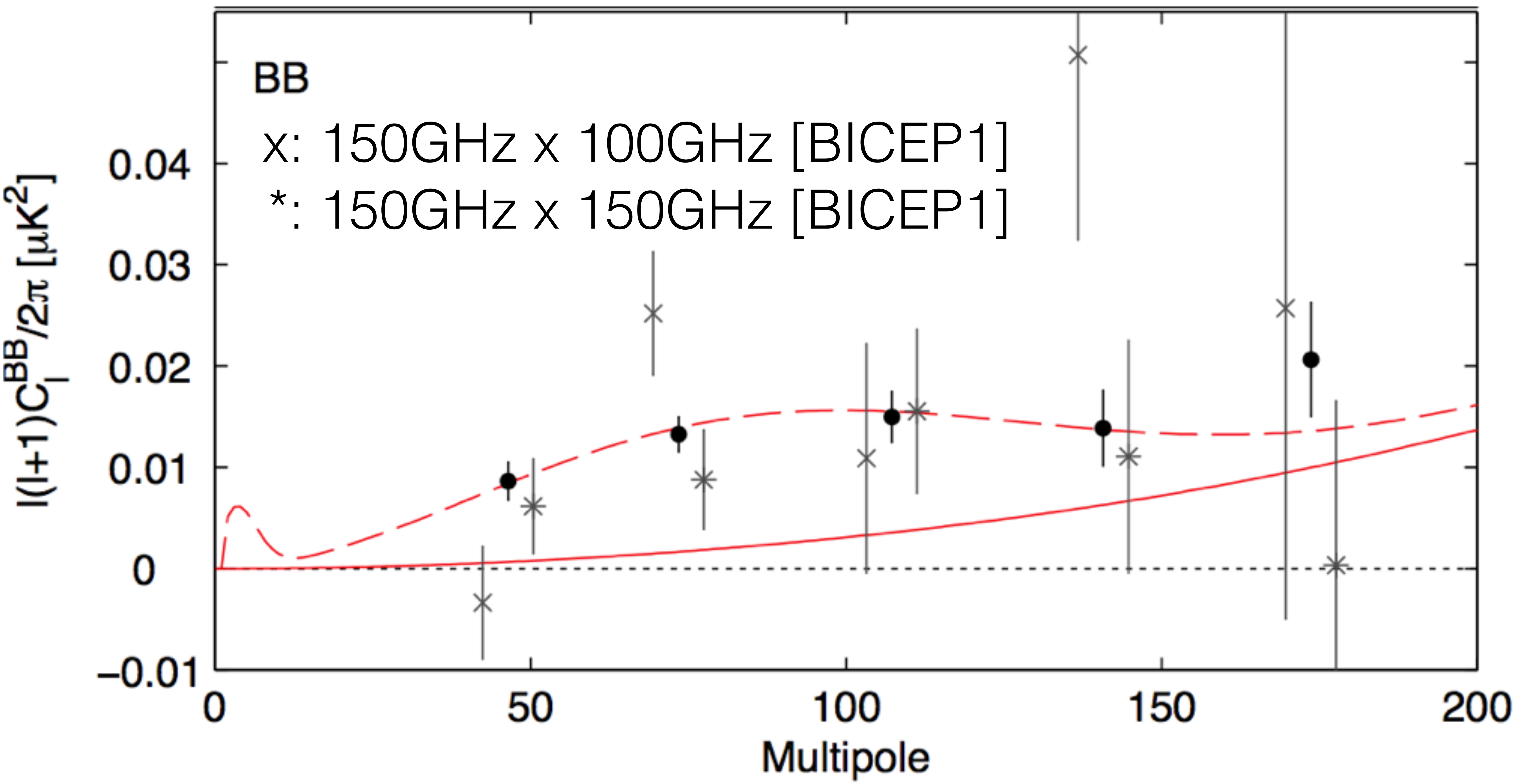


$$C(\theta) = \frac{1}{4\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\cos\theta)$$

C_ℓ is the "power spectrum" with

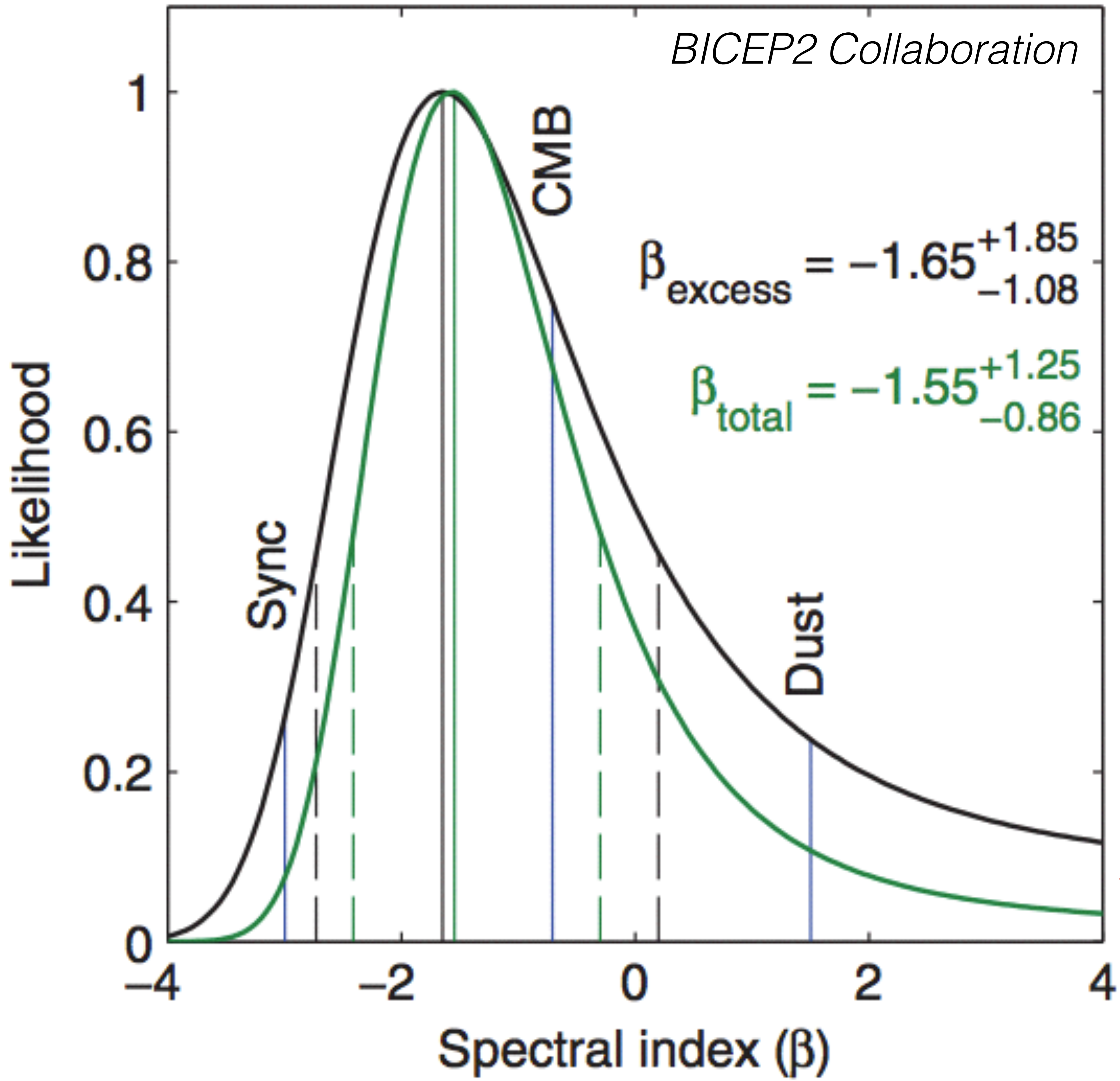
$$\ell \approx \frac{\pi}{\theta}$$

BICEP2 Collaboration



No 100 GHz x 100 GHz [yet]

Can we rule out synchrotron or dust?



- **The answer is No**

Current Situation

- No strong evidence that the detected signal is not cosmological
- No strong evidence that the detected signal is cosmological, either
- Nonetheless, if the detected signal is indeed cosmological, what are the implications?

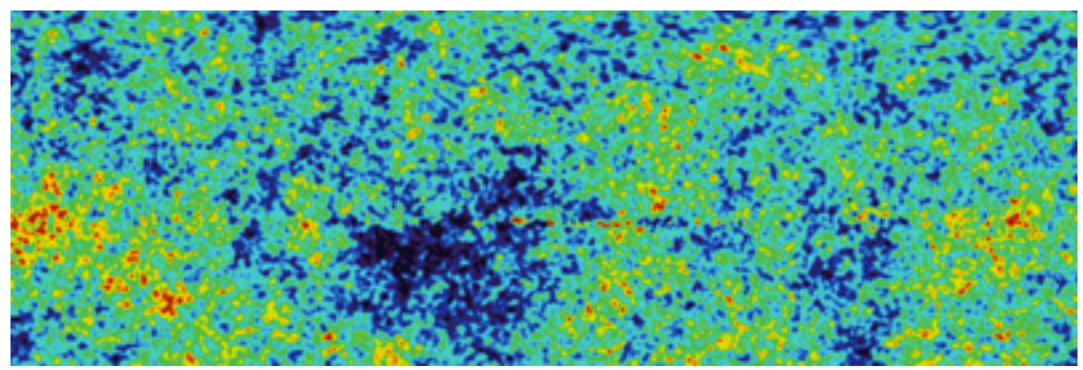
Recalling

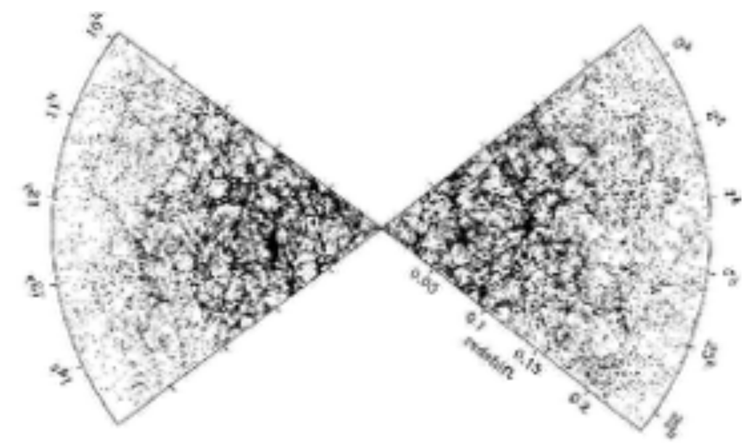
Key Predictions of Inflation

ζ

scalar mode

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

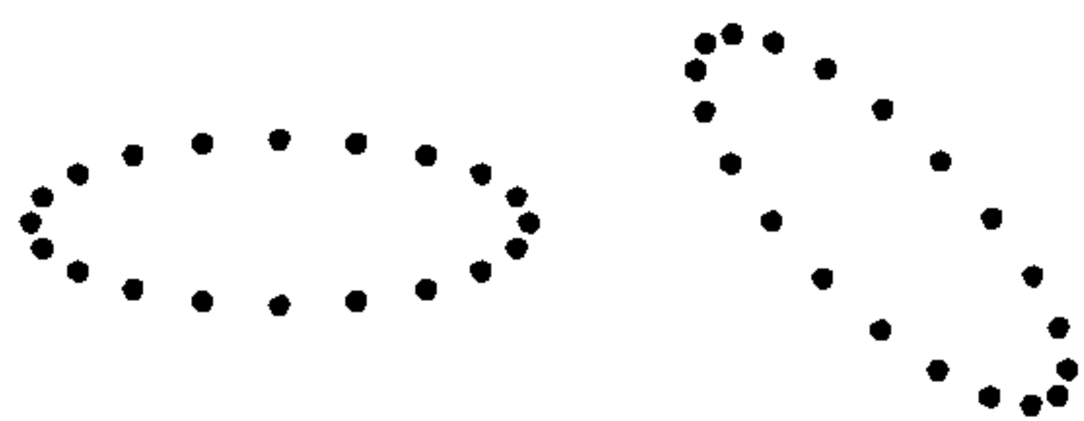




h_{ij}

tensor mode

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



Tensor-to-scalar Ratio

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

- The BICEP2 results suggest **r~0.2**, if we do not subtract any foregrounds

Quantum fluctuations and gravitational waves

- Quantum fluctuations generated during inflation are proportional to the Hubble expansion rate during inflation, **H**
    - Simply a consequence of Uncertainty Principle
- Variance of gravitational waves is then proportional to **H²**:

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

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:

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

- The BICEP2 result, 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

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

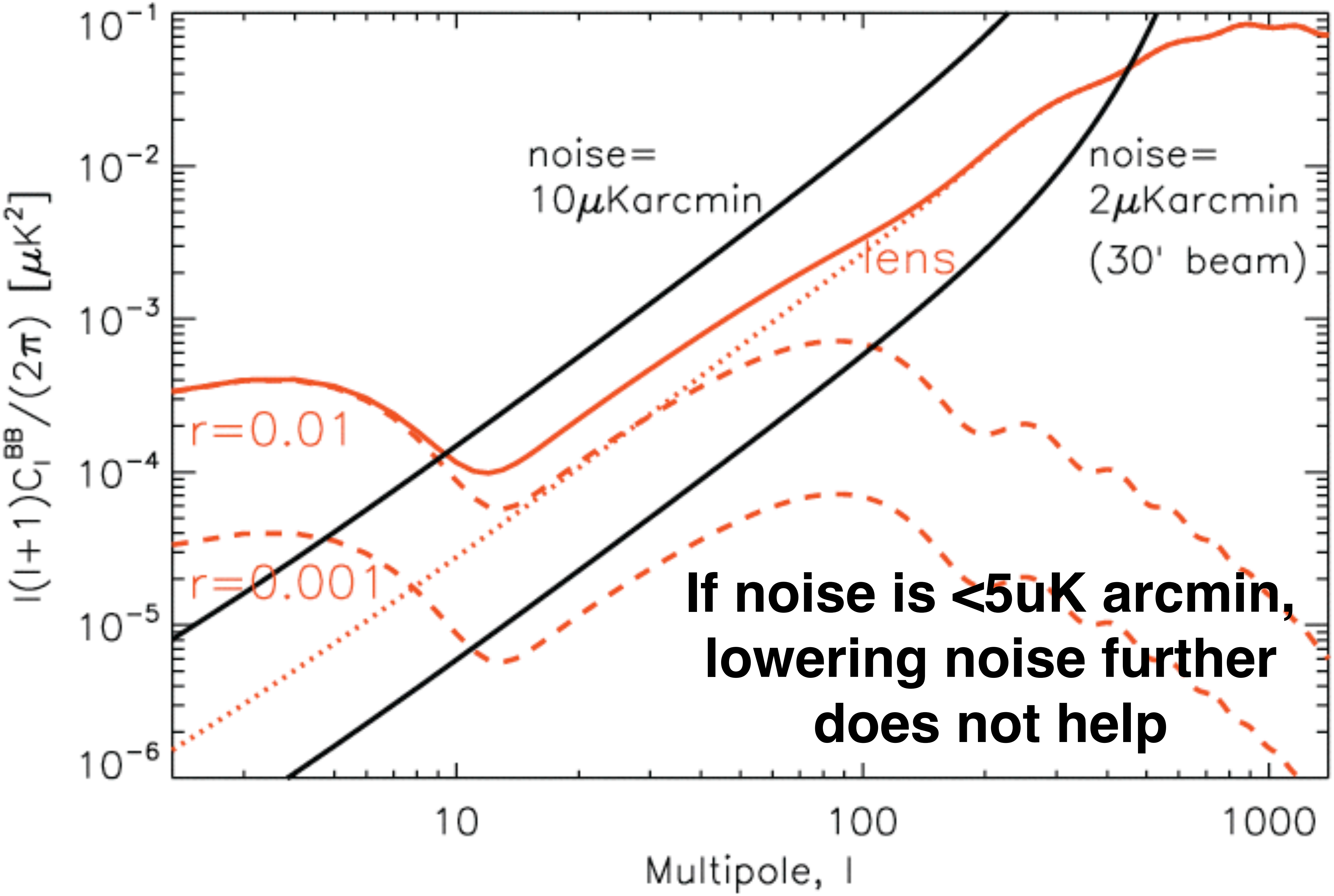
Inflation, defined

- 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 $n_t < 0$]

If BICEP2's discovery of the primordial B-modes is confirmed, what is next?

- Prove inflation by characterising the B-mode power spectrum precisely. Specifically:
  - We will find the existence of the predicted "reionisation bump" at $l<10$
  - We will determine the tensor tilt, n_t, to the precision of a few x 10^{-2}
    - [The exact scale invariance is $n_t=0$]

Lensing limits our ability to determine the tensor tilt

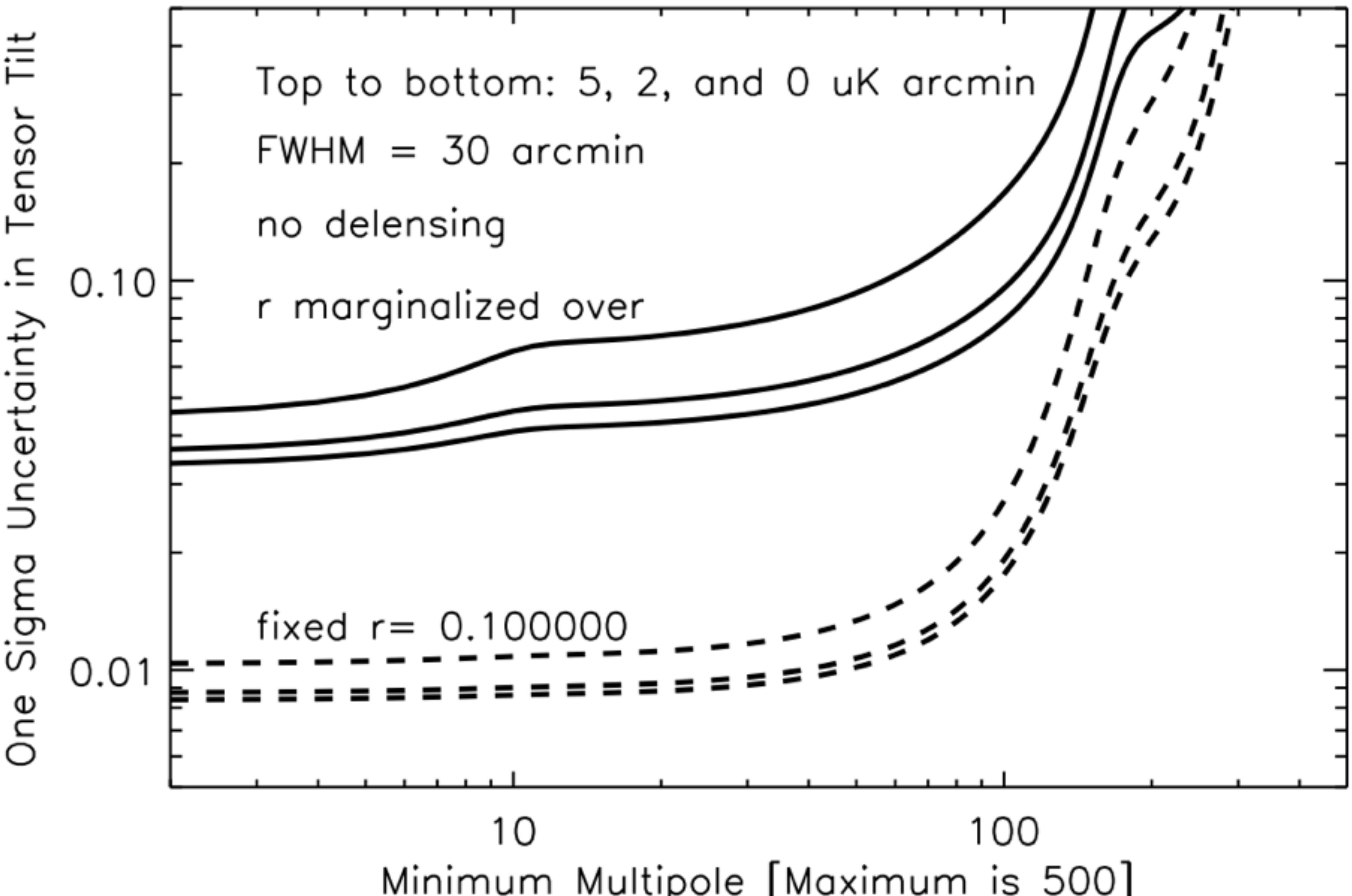


Tensor Tilt, n_t

- **In the best case scenario** without de-lensing, the uncertainty on n_t is **Err[n_t]~0.03 for r=0.1**, which is too large to test the single-field consistency relation, $n_t = -r/8 \sim -0.01(r/0.1)$
- De-lensing is crucial!

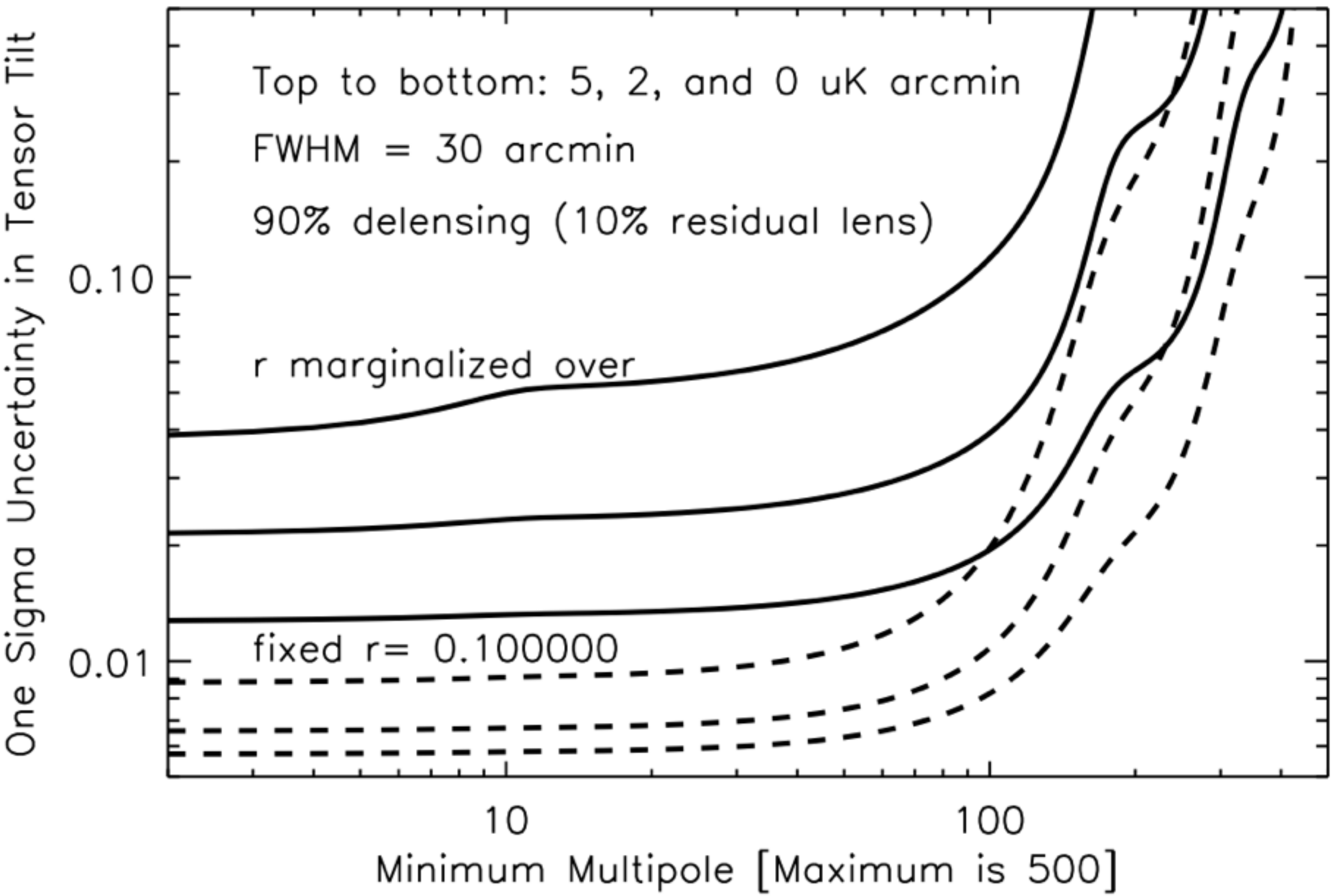
Most optimistic forecast [full sky, white noise, no foreground]

Without de-lensing [r=0.1]



Most optimistic forecast [full sky, white noise, no foreground]

90% de-lensing [r=0.1]



Why reionisation bump?

- Measuring the reionisation bump at $l<10$ would not improve the precision of the tensor tilt very much
- However, it is an important **qualitative** test of the prediction of inflation

Toward precision measurement of B-modes

- What experiment can we design to achieve this measurement?

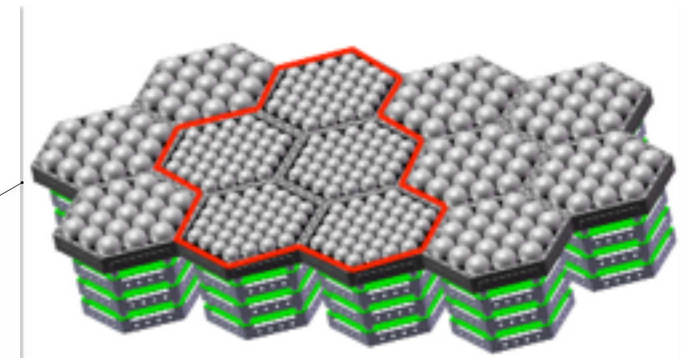
LiteBIRD

- 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

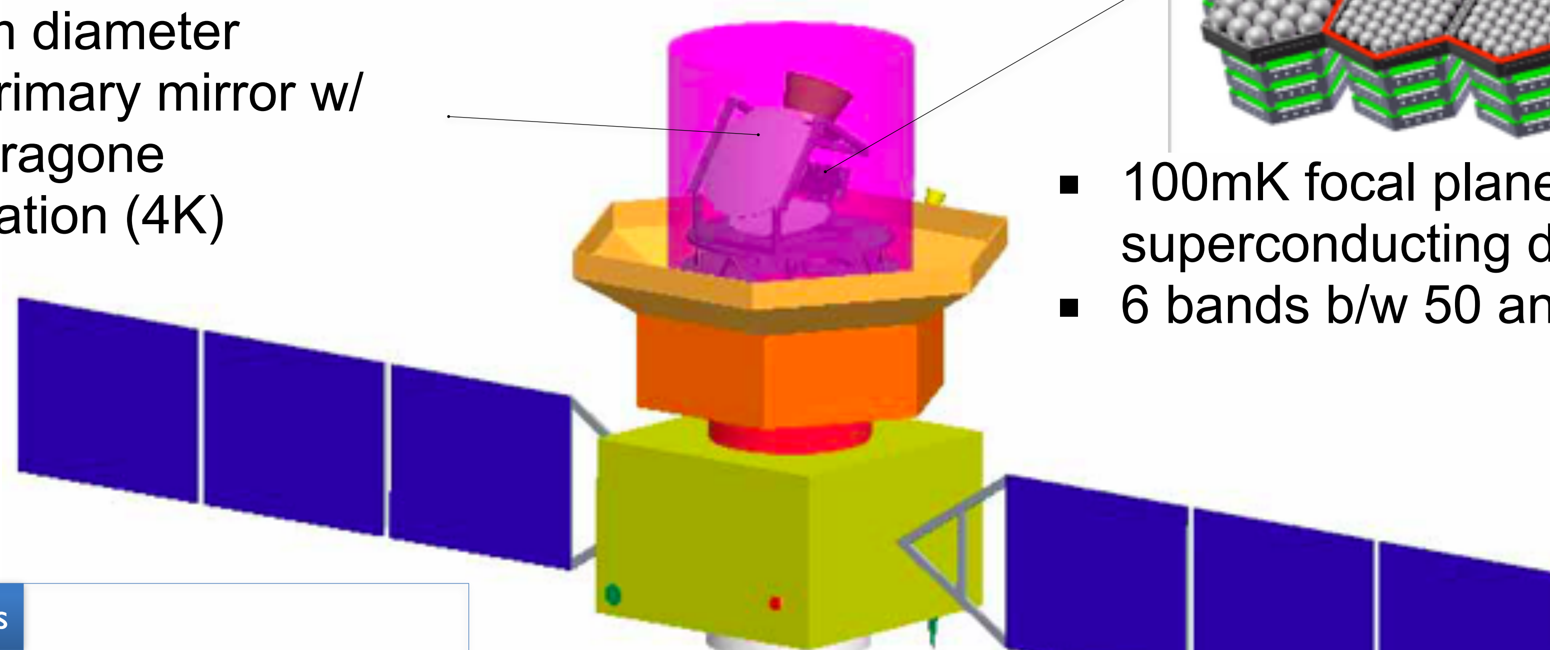
Lite (Light) Satellite for the Studies of **B**-mode Polarization and **I**nflation from Cosmic Background **R**adiation **D**etection

- 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

LiteBIRD working group

❖ 68 members (as of Nov. 21, 2013)

KEK
Y. Chinone
K. Hattori
M. Hazumi (PI)
M. Hasegawa
Y. Hori
N. Kimura
T. Matsumura
H. Morii
R. Nagata
S. Oguri
N. Sato
T. Suzuki
O. Tajima
T. Tomaru
H. Yamaguchi
M. Yoshida

JAXA
H. Fuke
I. Kawano
H. Matsuhara
K. Mitsuda
T. Nishibori
A. Noda
S. Sakai
Y. Sato
K. Shinozaki
H. Sugita
Y. Takei
T. Wada
N. Yamasaki
T. Yoshida
K. Yotsumoto

UC Berkeley
W. Holzapfel
A. Lee (US PI)
P. Richards
A. Suzuki

McGill U.
M. Dobbs

LBNL
J. Borrill

Tsukuba U.
M. Nagai

Kavli IPMU
N. Katayama
H. Nishino

Yokohama NU.
K. Mizukami
S. Nakamura
K. Natsume

Osaka Pref. U.
K. Kimura
M. Kozu
H. Ogawa

MPA
E. Komatsu

Tohoku U.
M. Hattori
K. Ishidoshiro
K. Morishima

Konan U.
I. Ohta

Saitama U.
M. Naruse

ATC/NAOJ
K. Karatsu
T. Noguchi
Y. Sekimoto
Y. Uzawa

RIKEN
K. Koga
S. Mima
C. Otani

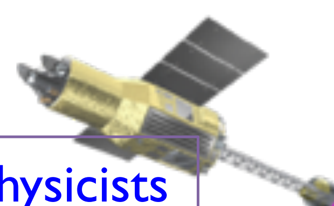
SOKENDAI
Y. Akiba
Y. Inoue
H. Ishitsuka
H. Watanabe

Osaka U.
S. Takakura

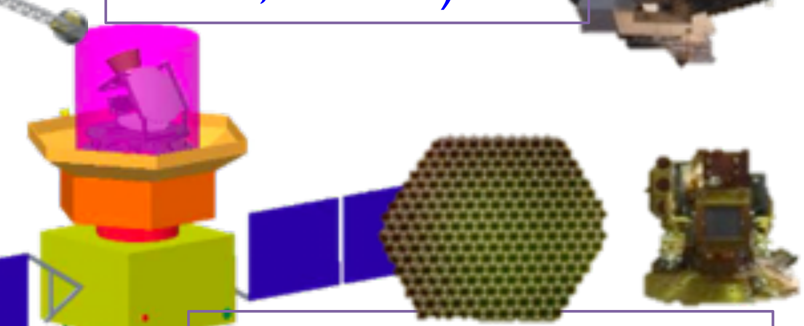
Okayama U.
H. Ishino
A. Kibayashi
Y. Kibe

NIFS
S. Takada

CMB experimenters (Berkeley, KEK, McGill, Eiichiro)



X-ray astrophysicists (JAXA)



Infrared astronomers (JAXA)

JAXA engineers, Mission Design Support Group, SE office

Superconducting Device (Berkeley, RIKEN, NAOJ, Okayama, KEK etc.)

LiteBIRD focal plane design

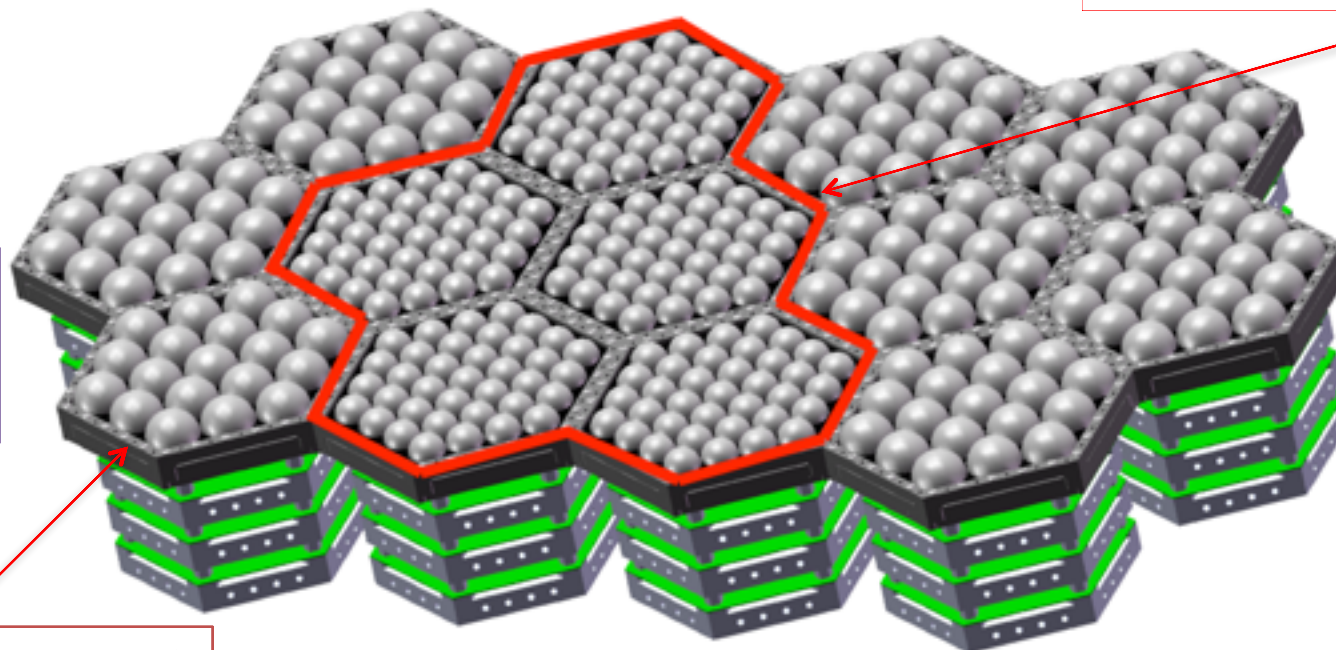
UC Berkeley TES option

2022 TES bolometers

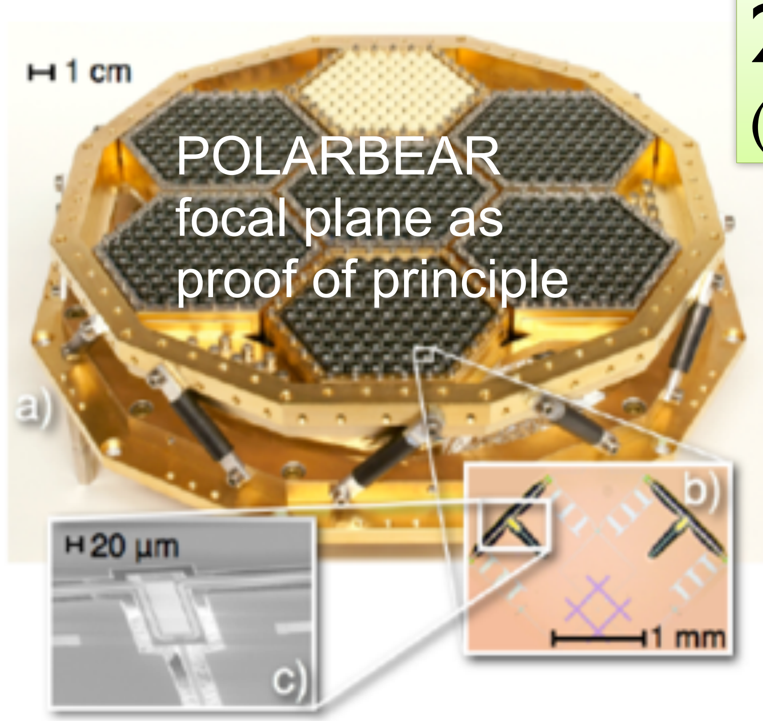
T_{bath} = 100mK

tri-chroic (140/195/280GHz)

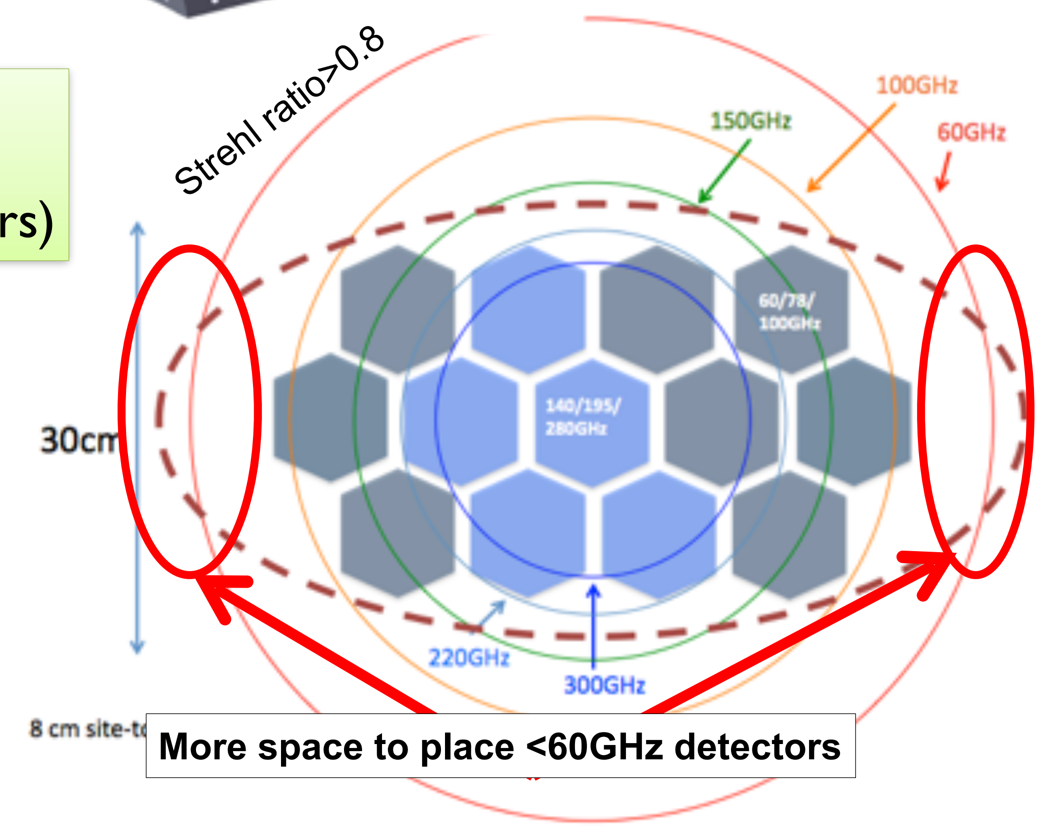
Band centers can be distributed to increase the effective number of bands



tri-chroic (60/78/100GHz)



2μKarcmin
(w/ 2 effective years)



LiteBIRD proposal milestones

- 2012 October - 2014 March
  Feasibility studies & cost estimation with MELCO and NEC
- 2013 April - 2014 April
  Review and recommendation from Science Council of Japan
- late 2014
  White Paper (will be published in *Progress of Theoretical and Experimental Physics (PTEP)*
- 2014 June - December
  Proposal and Mission Definition Review (MDR)
- 2015 ~
  Phase A

Conclusion

- If the signal detected by BICEP2 is cosmological, we are very close to proving that inflation did occur
- The next goal: unambiguous measurement of the primordial B-mode polarisation power spectrum, to determine the tensor tilt, n_t
  - **Err[n_t]~0.01** possible only with substantial de-lensing
- **LiteBIRD** proposal: a B-mode CMB polarisation satellite in early 2020