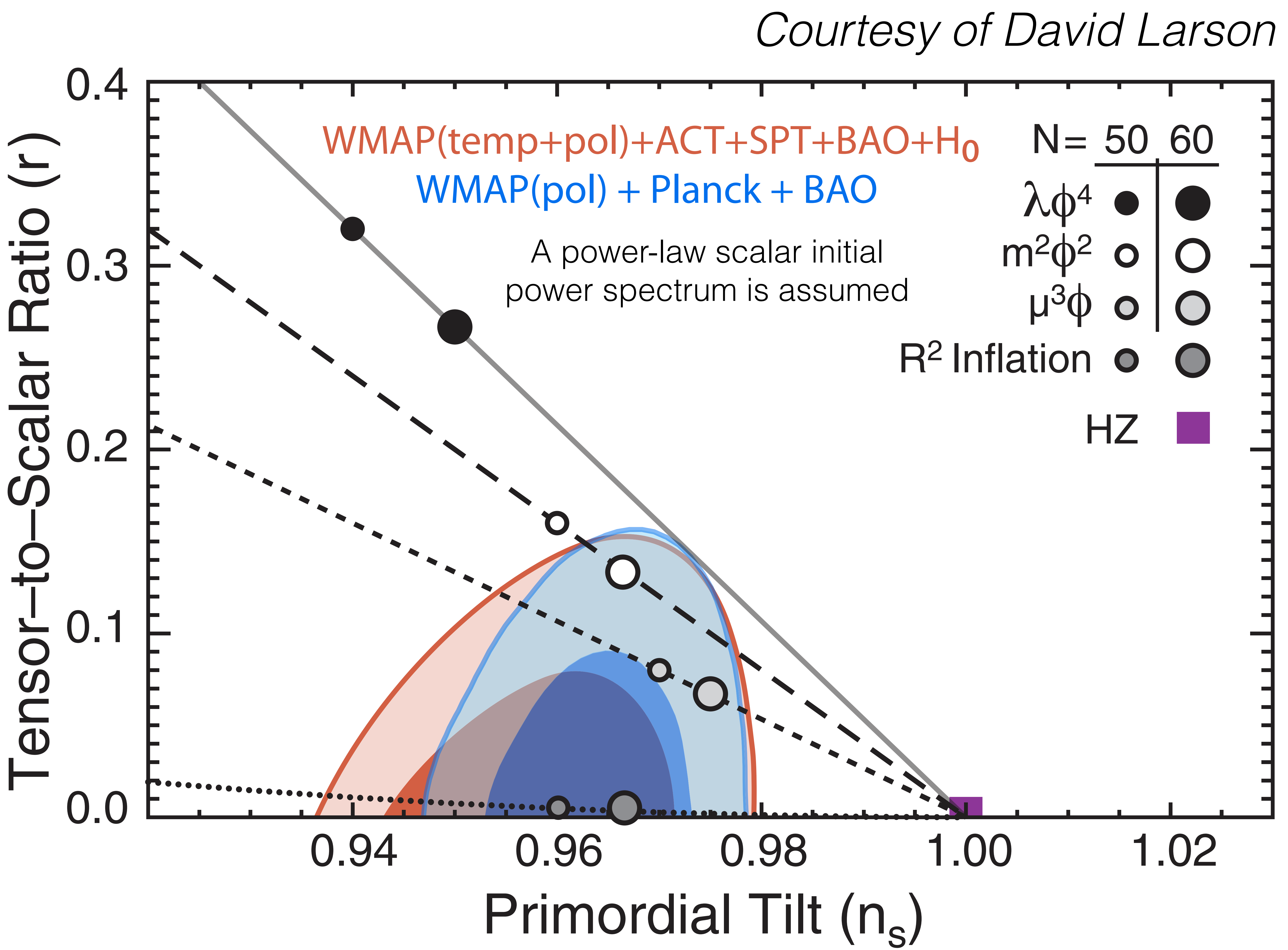
CMB Polarisation: Toward an Observational Proof of Cosmic Inflation

Eiichiro Komatsu, Max-Planck-Institut für Astrophysik
ITP Cosmology Seminar, Universität Heidelberg
September 26, 2014

Finding Inflation: Breakthroughs in 2012 and 2013

- *Discovery of broken scale invariance, $n_s<1$, with more than 5σ*
    - WMAP+ACT+SPT+BAO [December 2012]
    - WMAP+Planck [March 2013]
- *Remarkable degree of Gaussianity of primordial fluctuations*
    - Non-Gaussianity limited to <0.2% by WMAP and <0.04% by Planck [for the local form]
- These are important milestones: **strong evidence for the quantum origin of structures in the universe**



Courtesy of David Larson
Tensor–to–Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)
WMAP(temp+pol)+ACT+SPT+BAO+H_0
WMAP(pol) + Planck + BAO
A power-law scalar initial
power spectrum is assumed
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
R^2 Inflation
HZ

March 17, 2014

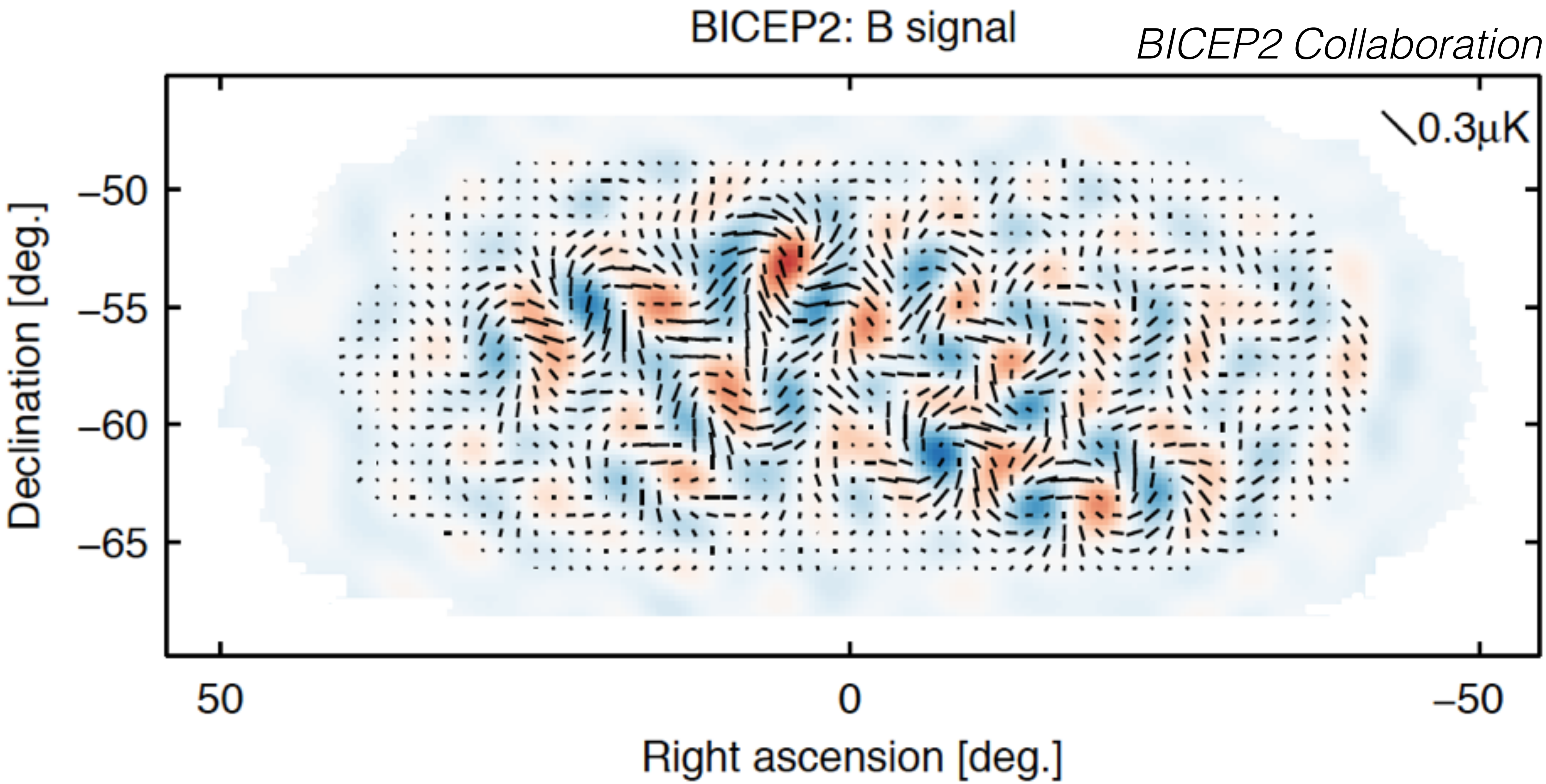
BICEP2's announcement

**yet to be confirmed*

Breakthrough* in 2014

- *Discovery of the primordial* B-modes with more than 5σ by BICEP2*
  - Detection of nearly scale-invariant tensor perturbations proves inflation
  - This requires precise characterisation of the B-mode power spectrum. How are we going to achieve this?

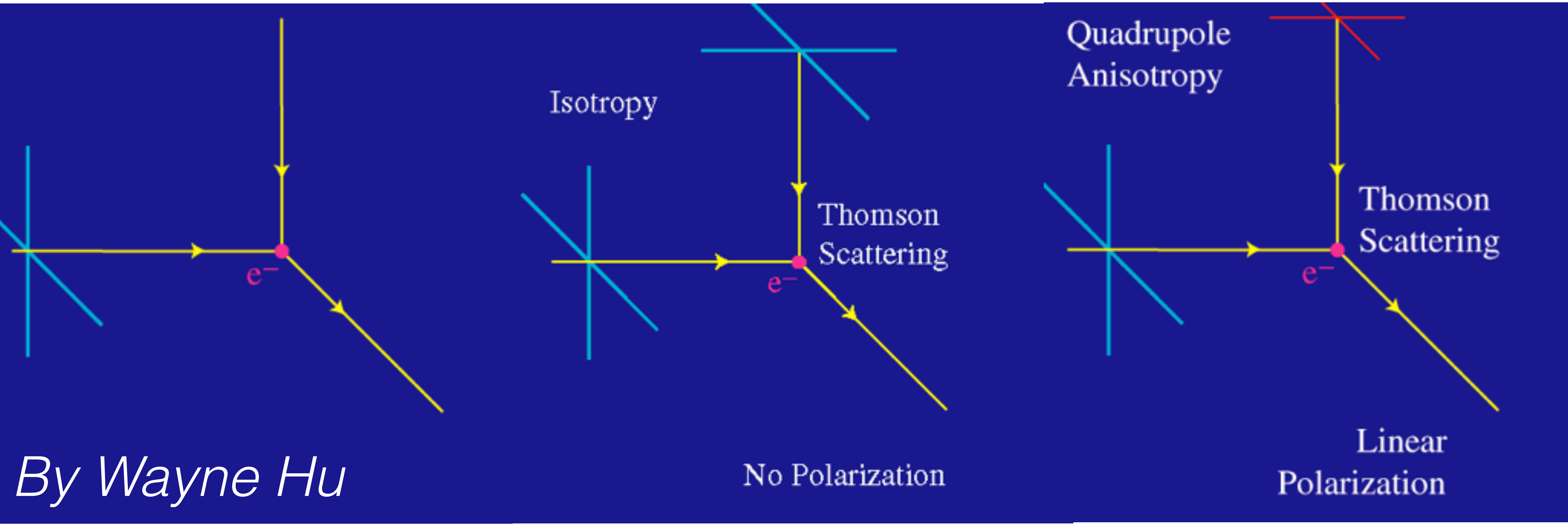
Signature of gravitational waves in the sky [?]



BICEP2 Collaboration

Let's try to understand what is shown in this plot, *assuming that it is due to gravitational waves*

Physics of CMB Polarisation



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

Origin of Quadrupole

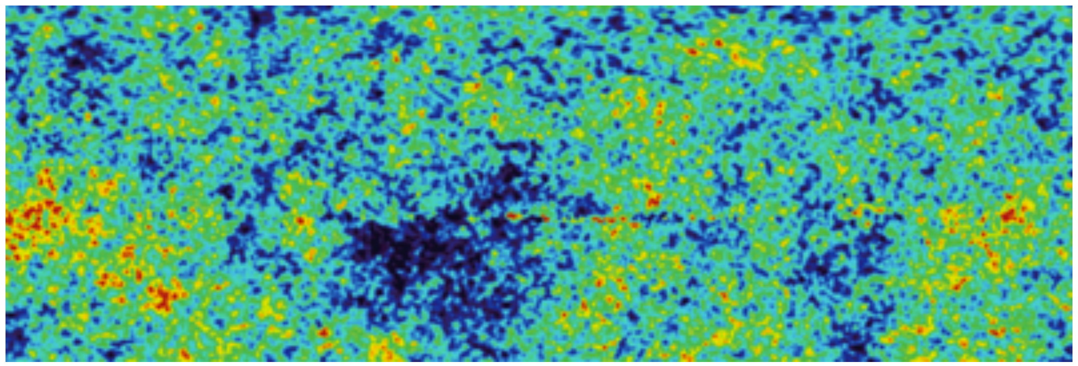
- **Scalar perturbations**: motion of electrons with respect to photons
- **Tensor perturbations**: gravitational waves

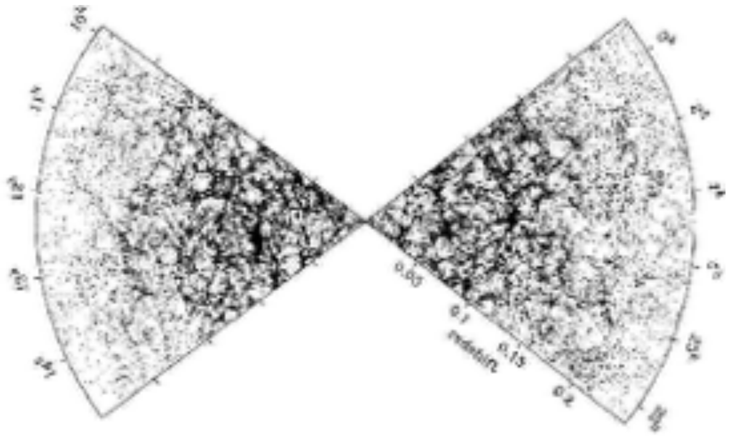
Key Predictions of Inflation

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)

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

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:

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

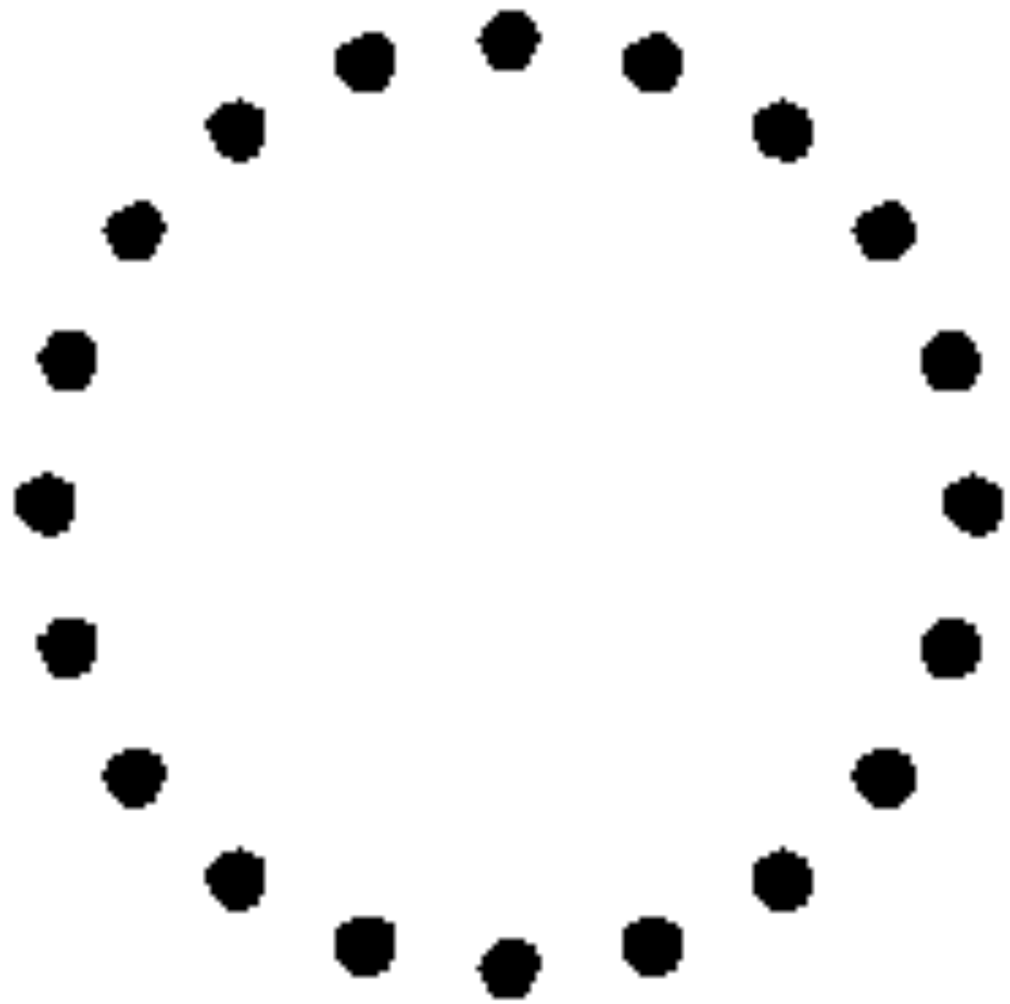
with

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

Inflation, defined

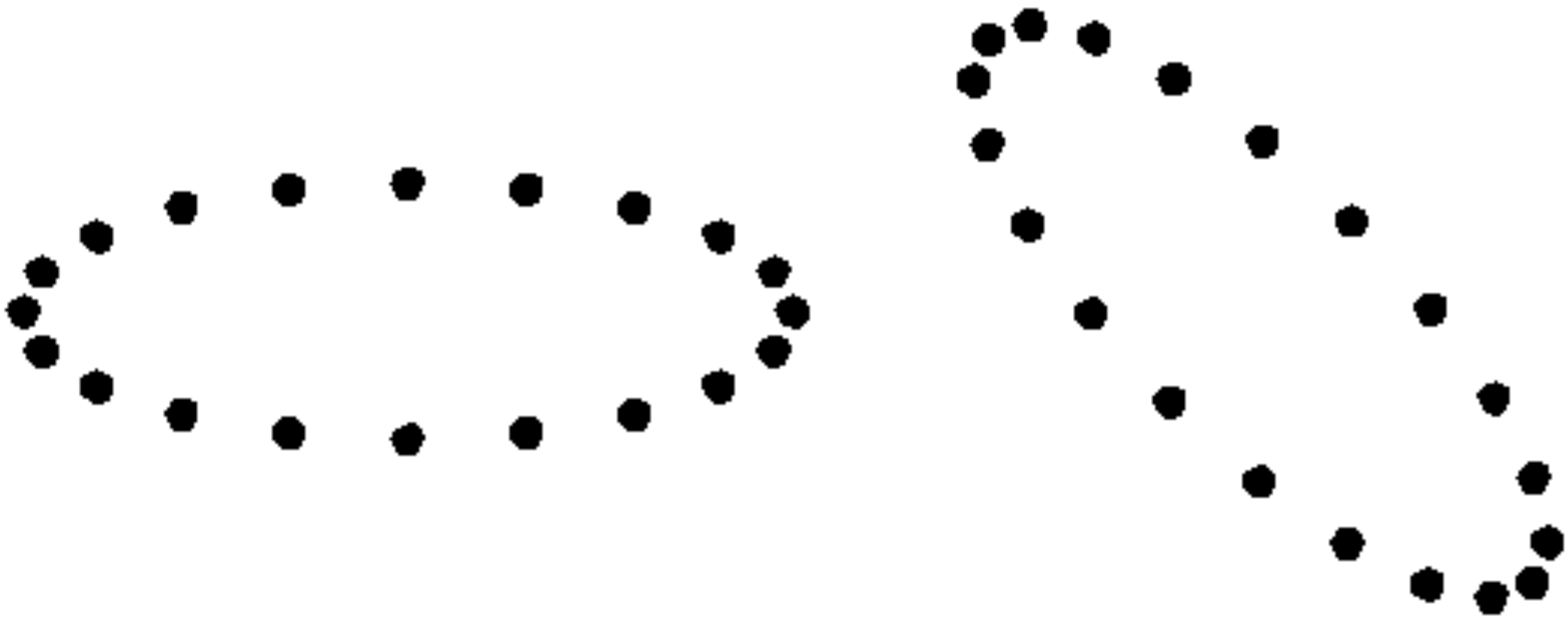
- Necessary and sufficient condition for inflation = sustained accelerated expansion in the early universe
- Expansion rate: $H=(da/dt)/a$
- Accelerated expansion: $(d^2a/dt^2)/a = dH/dt + H^2 > 0$
- Thus, $\boldsymbol{-(dH/dt)/H^2 < 1}$
- In other words:
  - The rate of change of H must be slow [$n_t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

Gravitational waves are coming toward you!



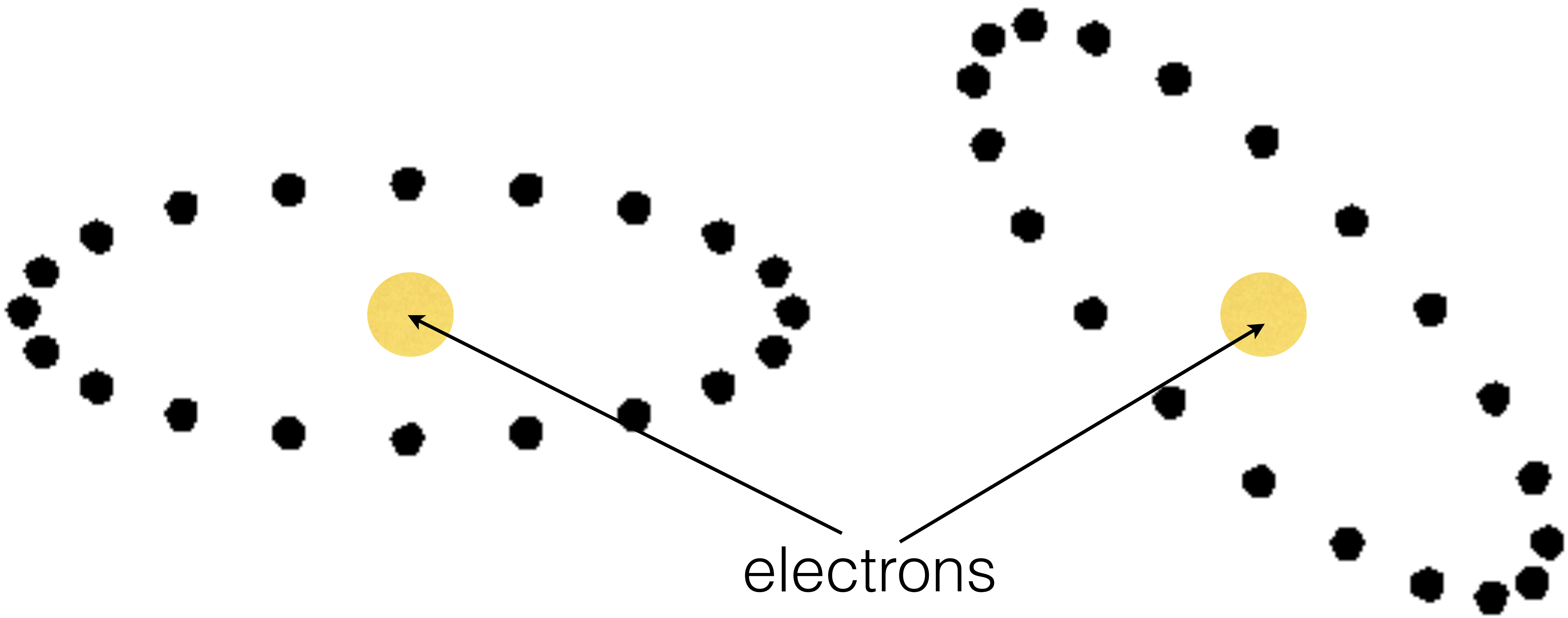
- What do they do to the distance between particles?

Two GW modes

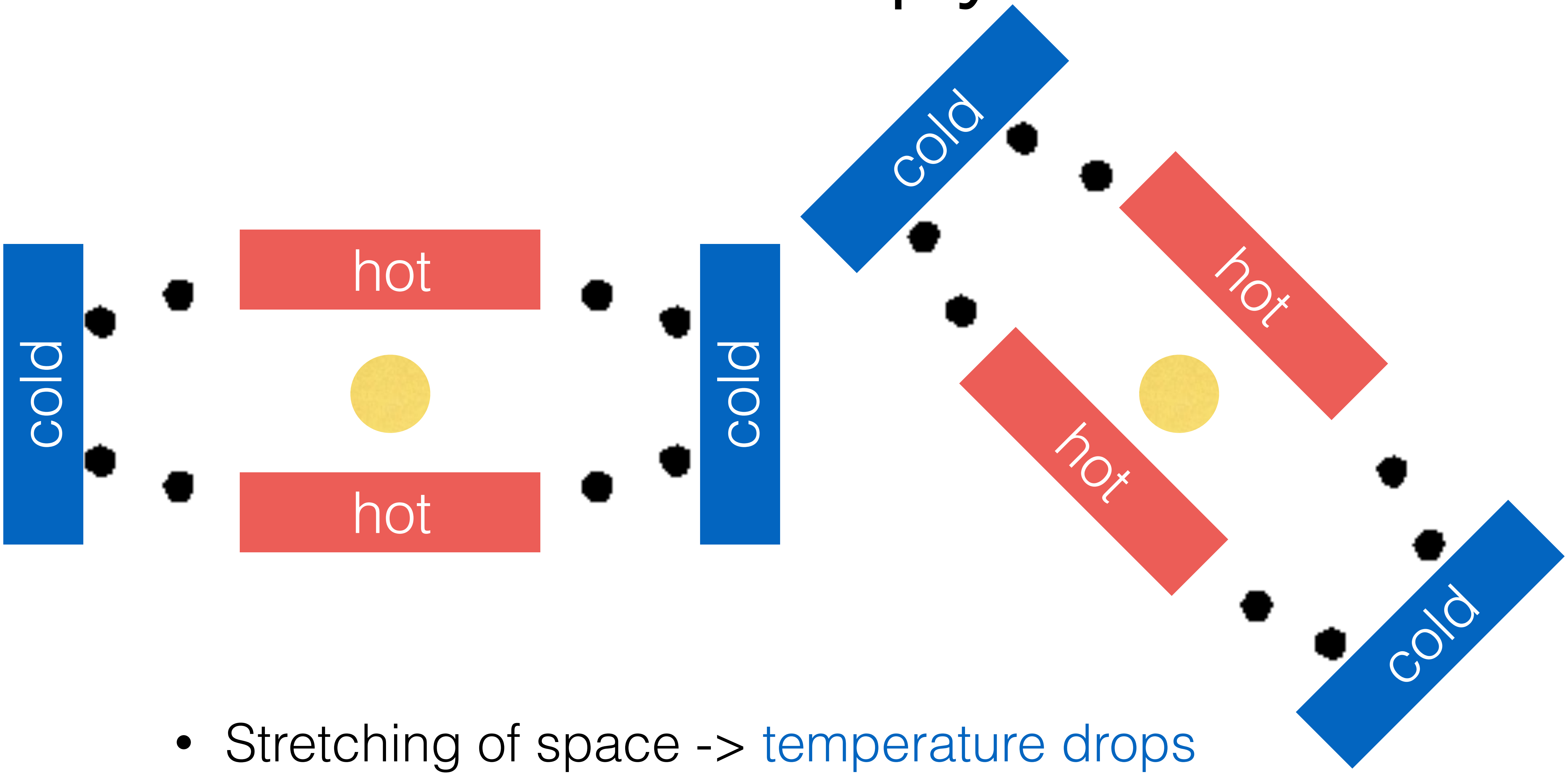


- Anisotropic stretching of space generates quadrupole temperature anisotropy. How?

GW to temperature anisotropy

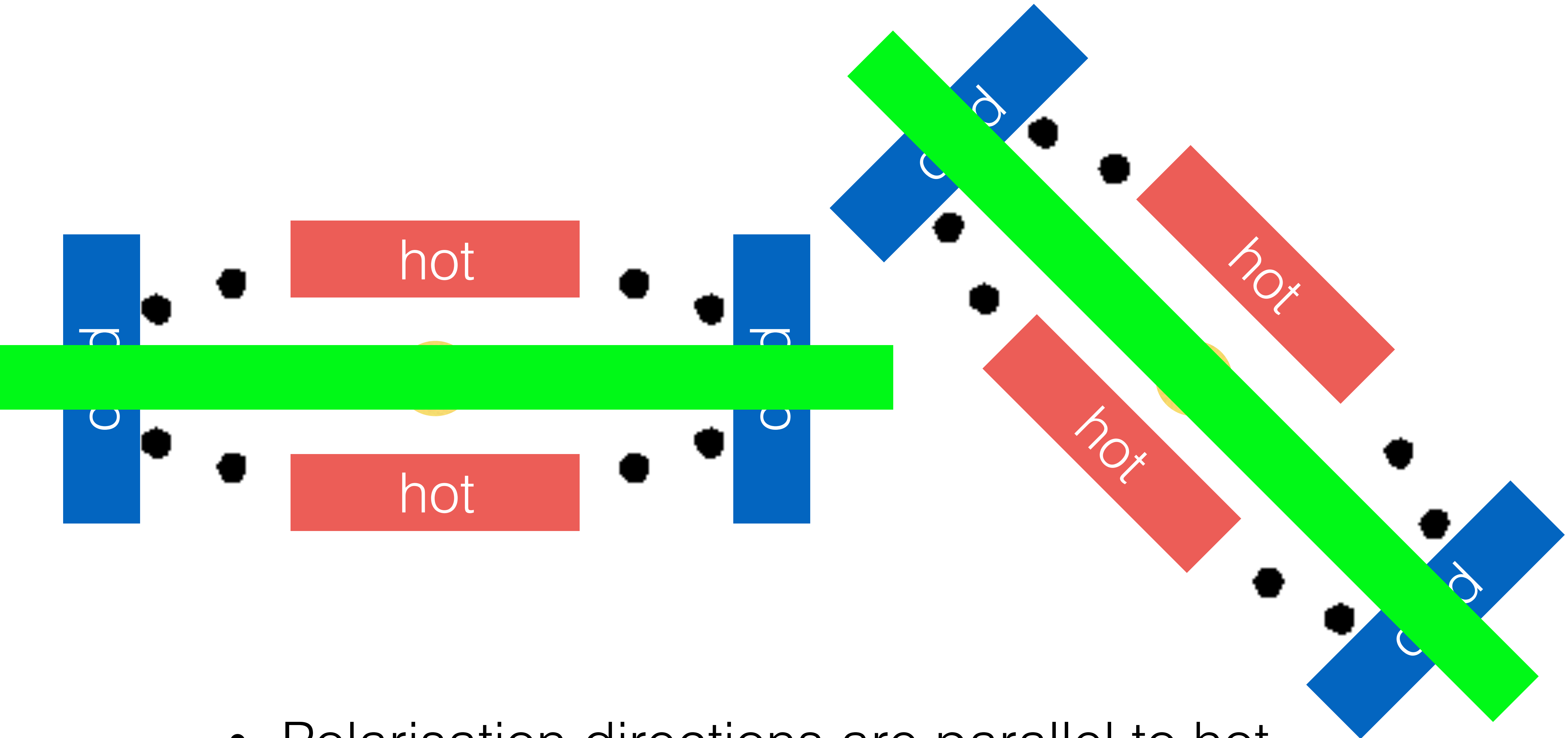


GW to temperature anisotropy

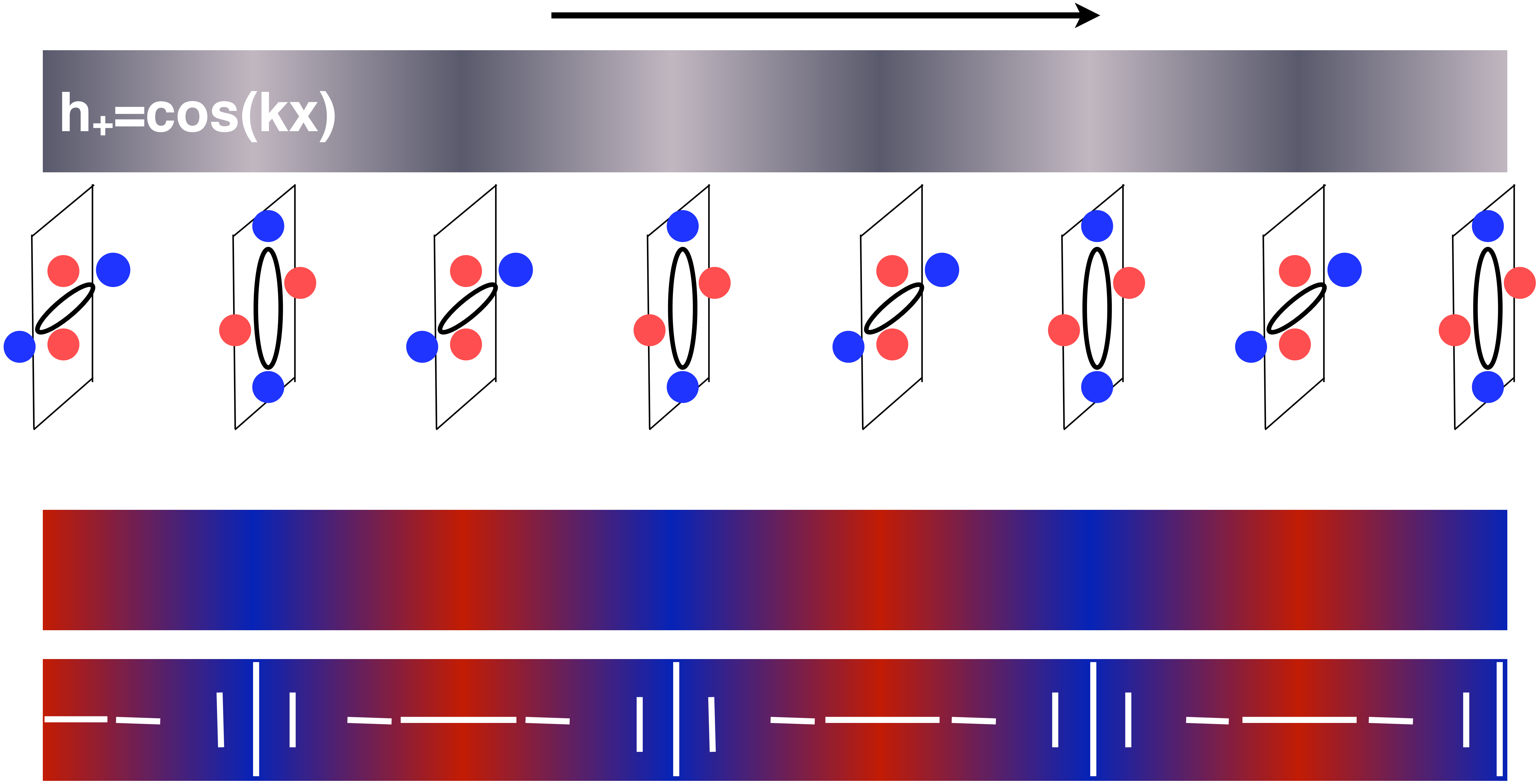


- Stretching of space -> temperature drops
- Contraction of space -> temperature rises

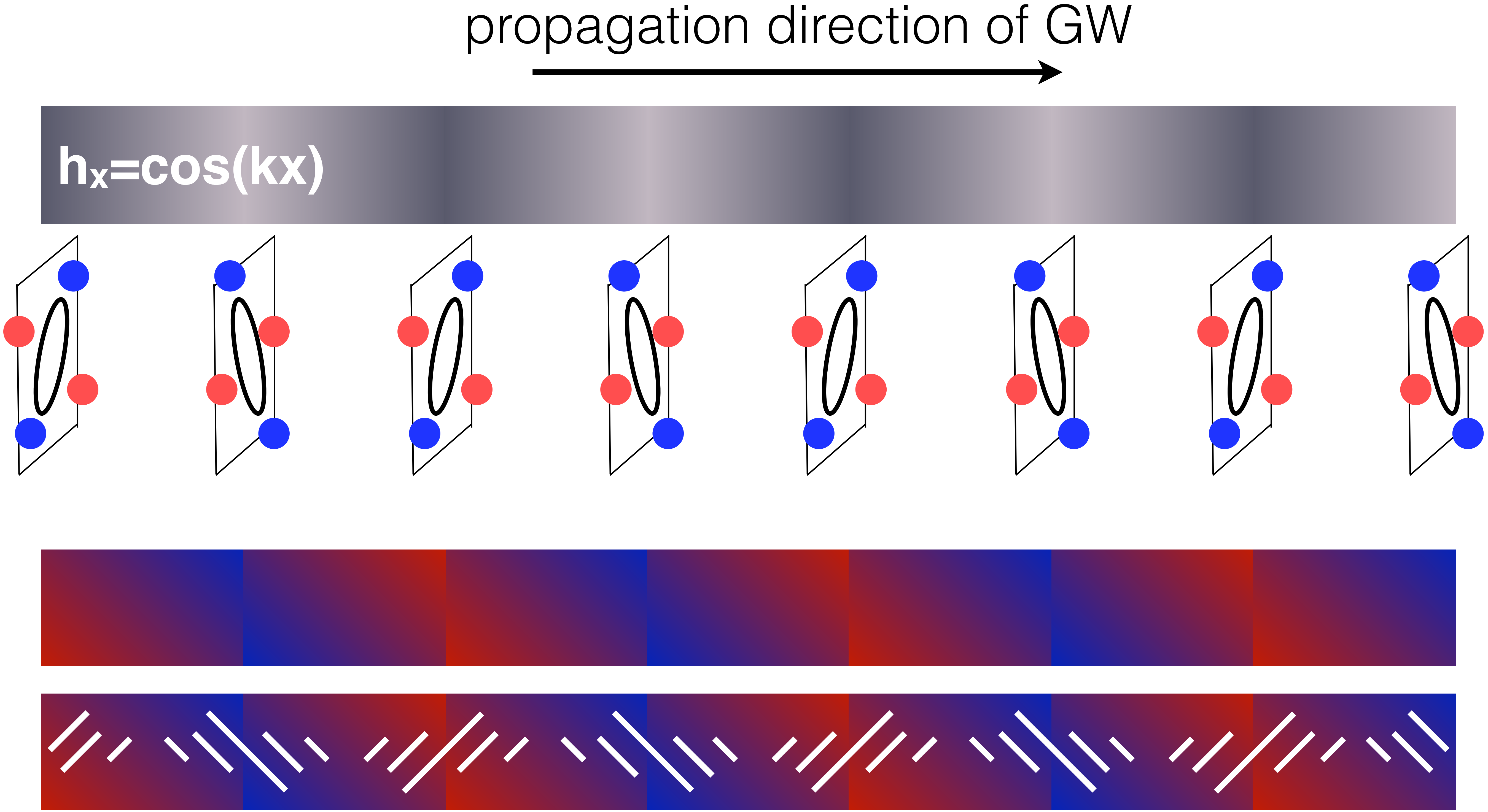
Then to polarisation!



- 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:

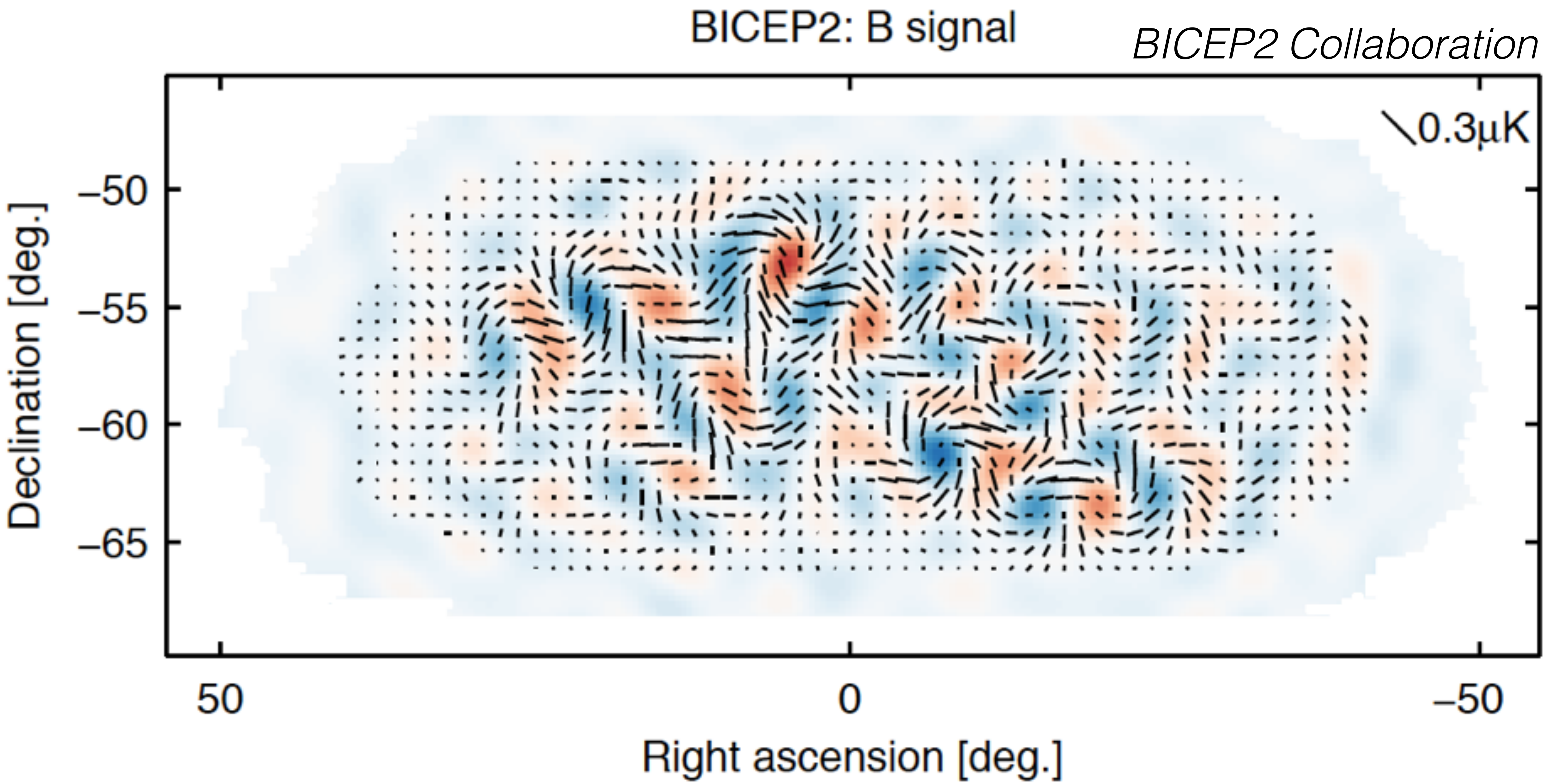
- Definition of h_+ and $h_\times$ depends on coordinates, but definition of E- and B-mode polarisation does not depend on coordinates

- 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

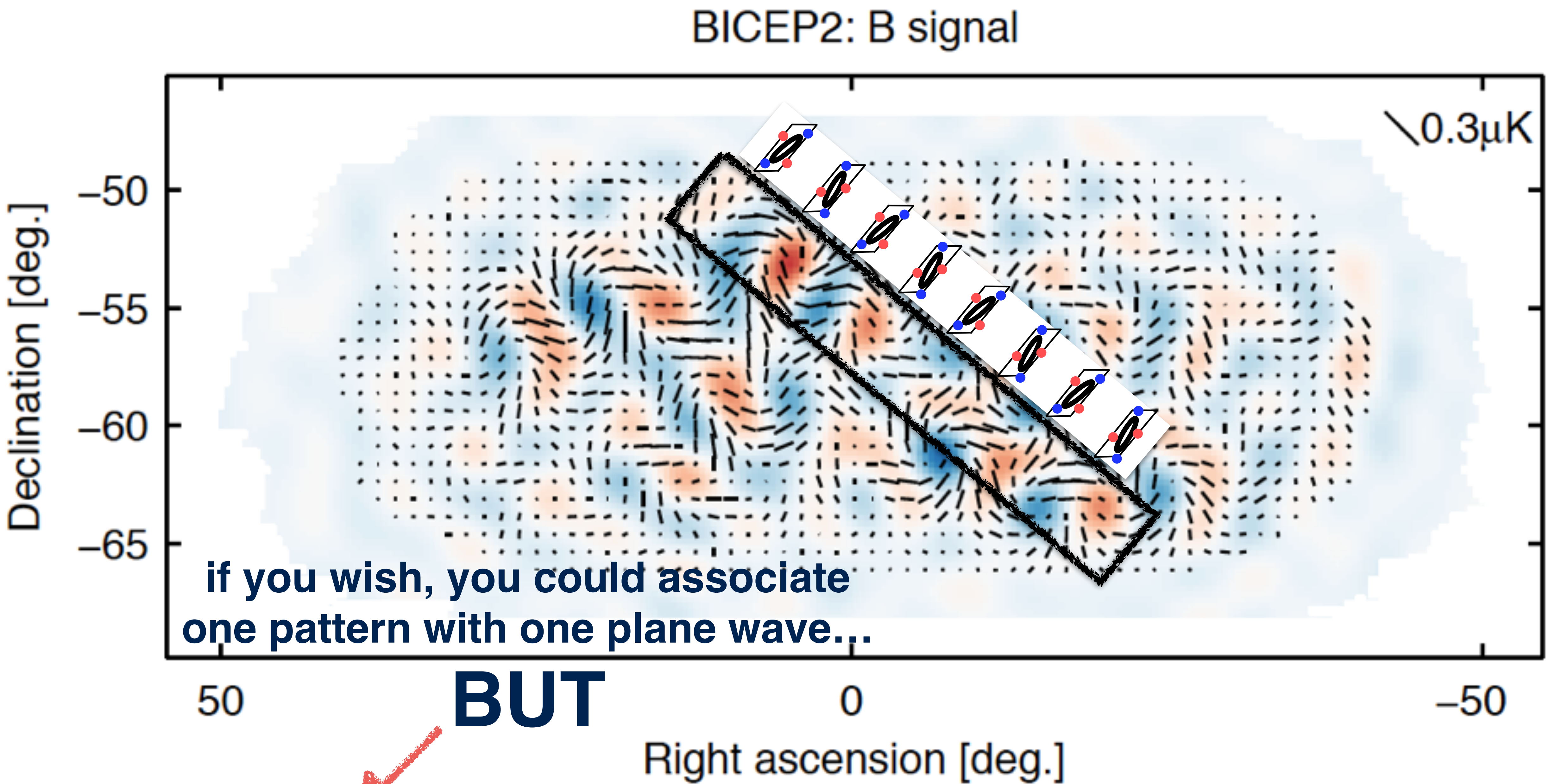
Signature of gravitational waves in the sky [?]

BICEP2 Collaboration



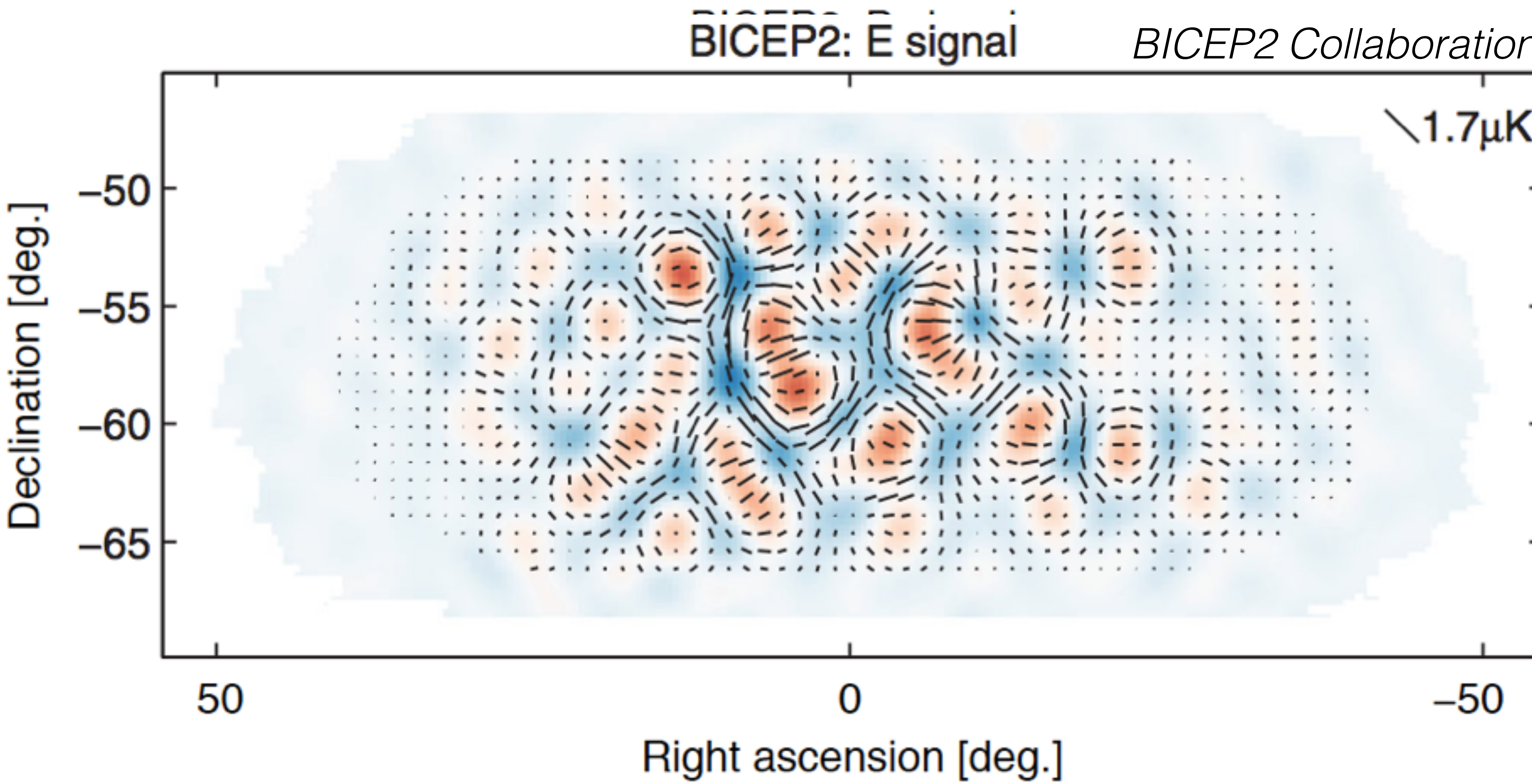
<u>CAUTION</u>: we are NOT seeing a single plane wave propagating perpendicular to our line of sight

Signature of gravitational waves in the sky [?]



<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]

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:

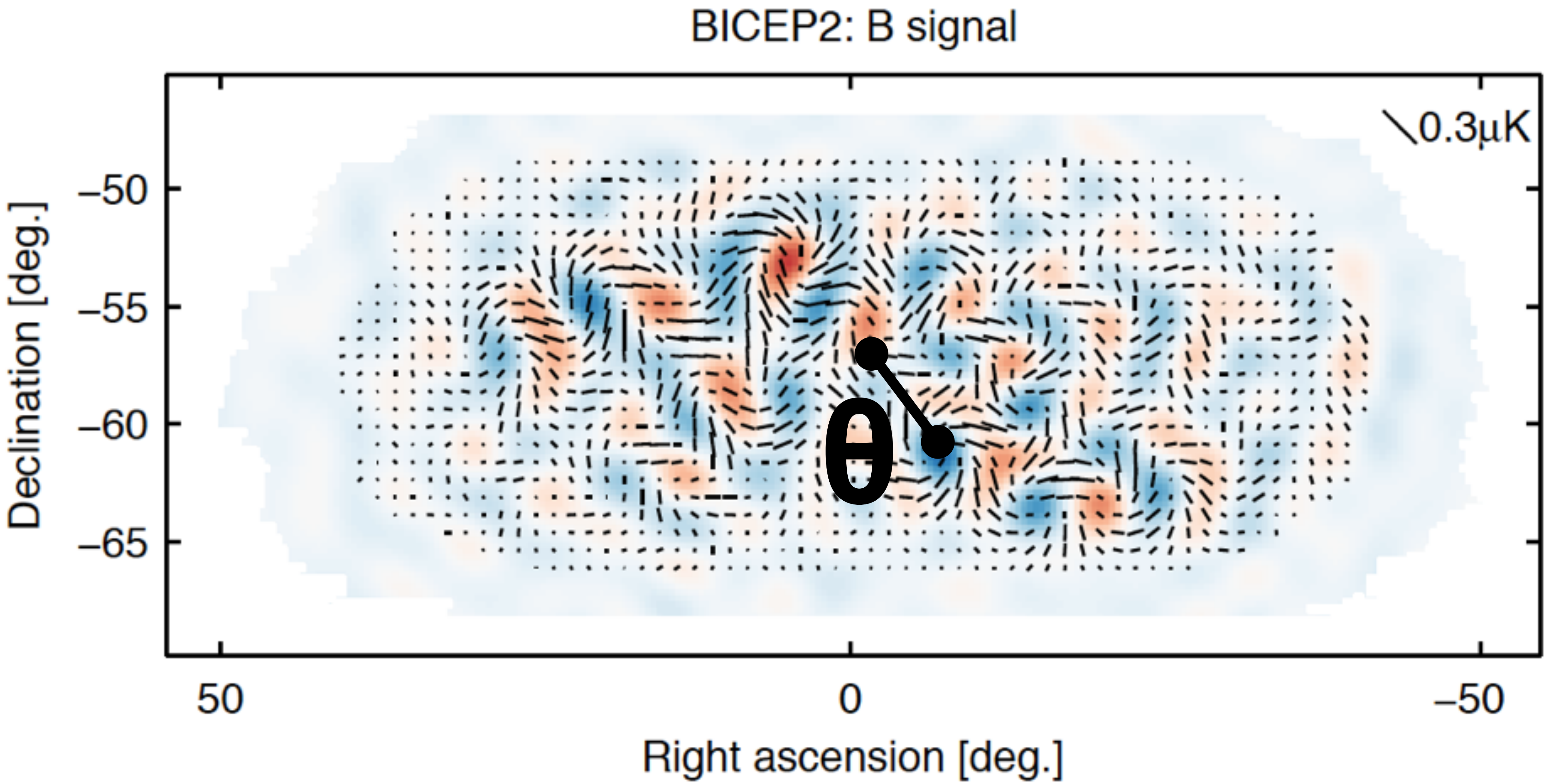
etection (>3 sigma each) in more than one frequency, like 100 GHz and
Hz giving the same answers to within the error bars.

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

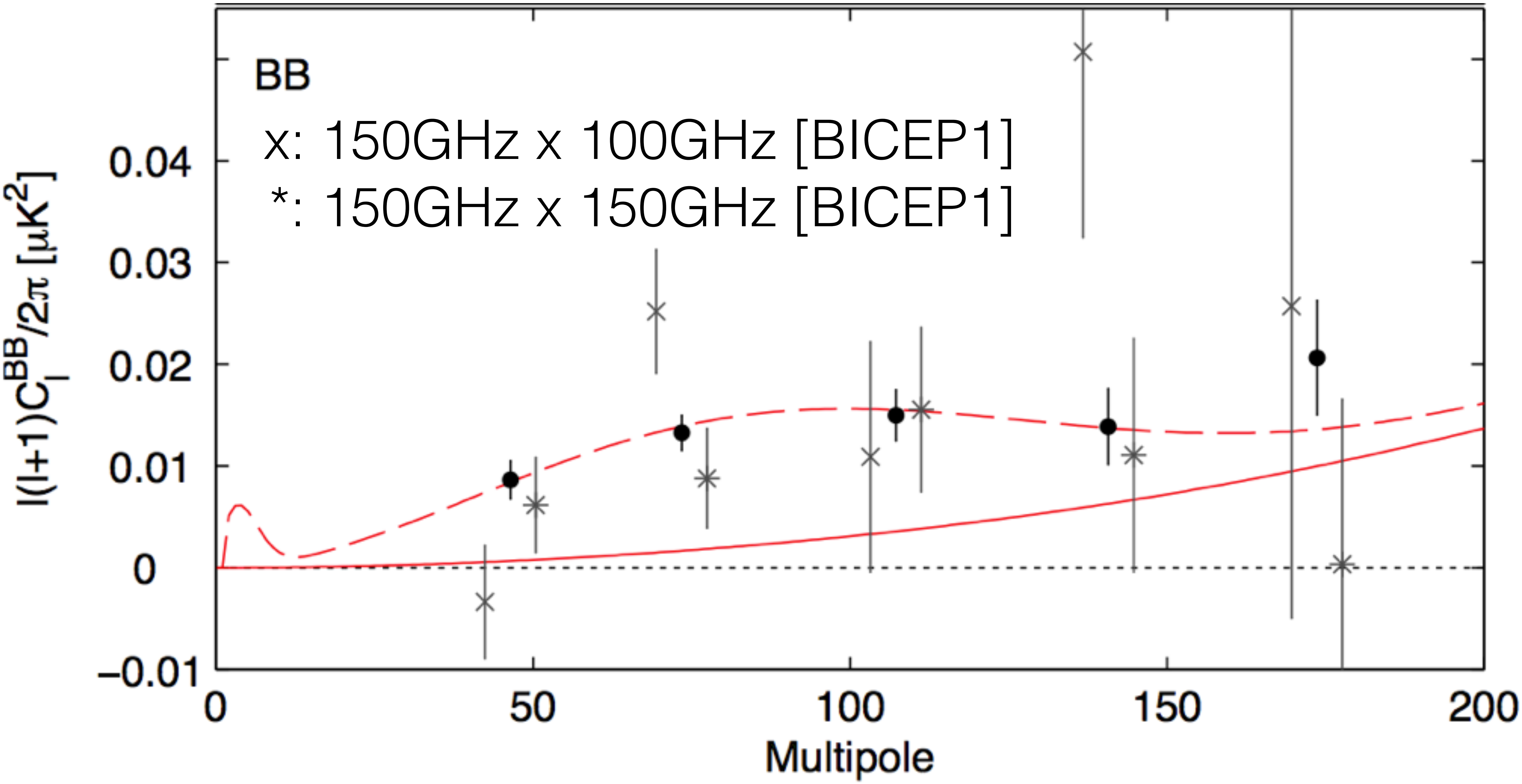


$$C(\theta) = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C_\ell P_\ell(\cos\theta)$$

C_ℓ is the "power spectrum" with

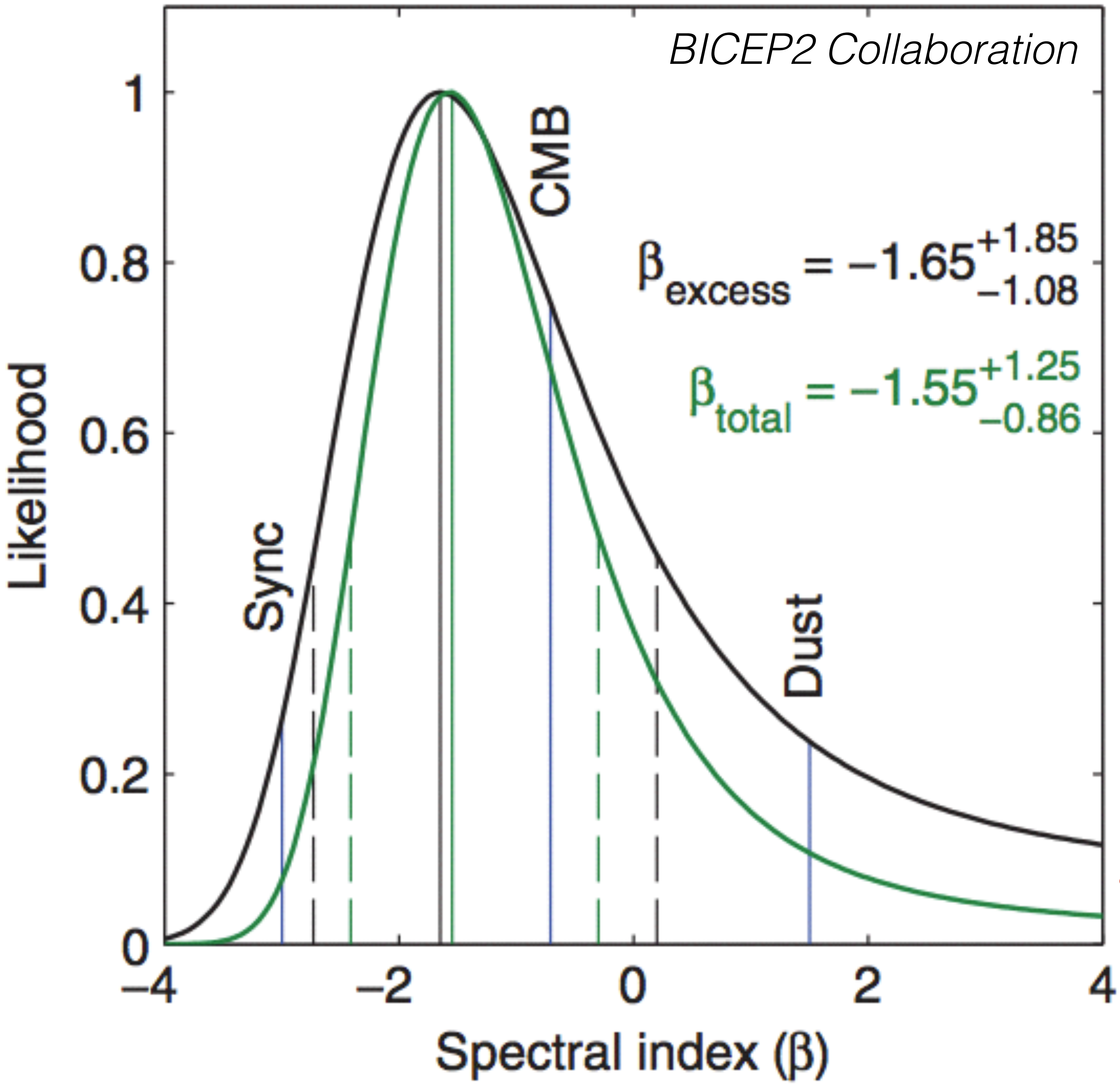
$$\ell \approx \frac{\pi}{\theta}$$

BICEP2 Collaboration



No 100 GHz x 100 GHz [yet]

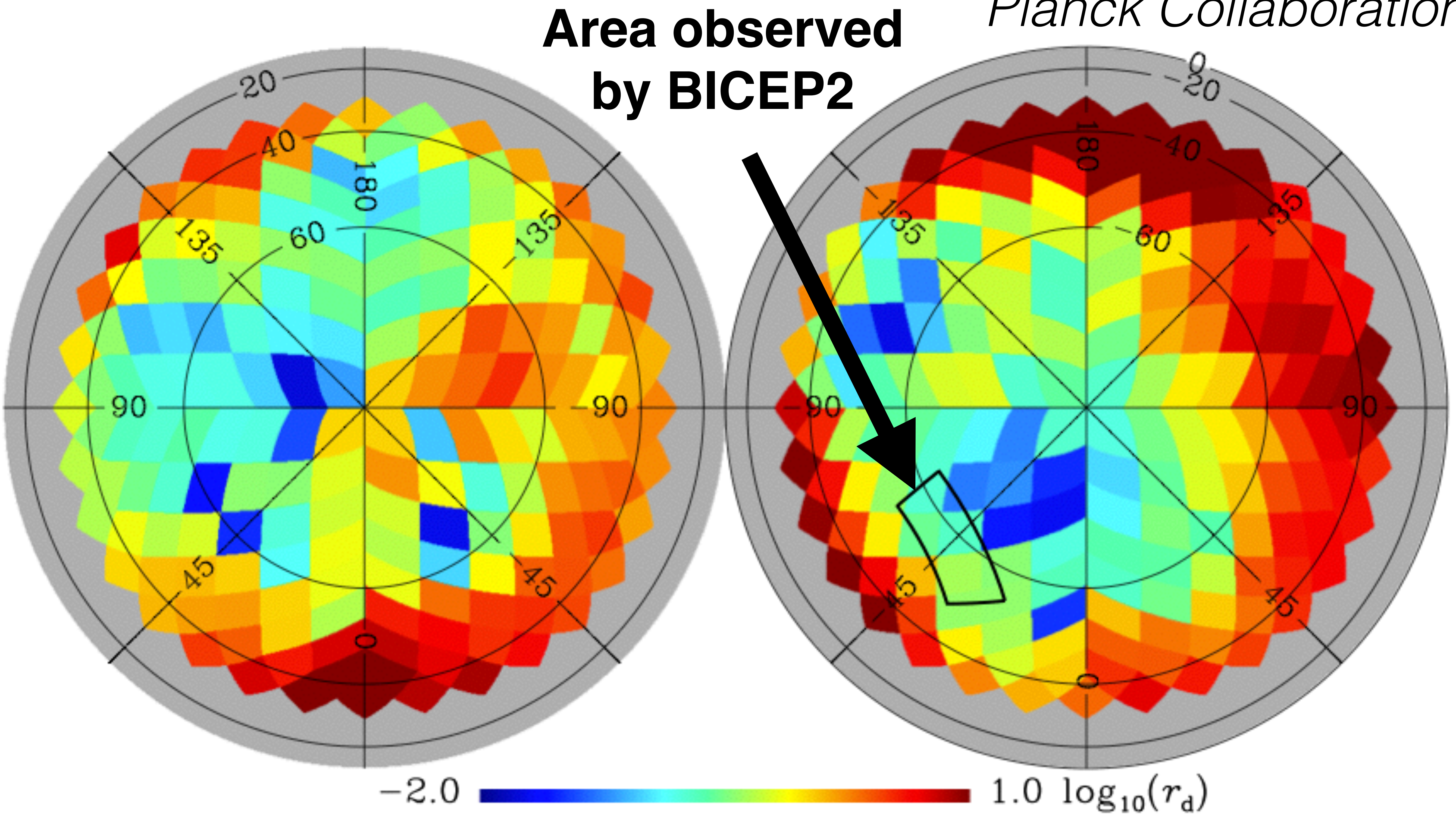
Can we rule out synchrotron or dust?



- **The answer is No**

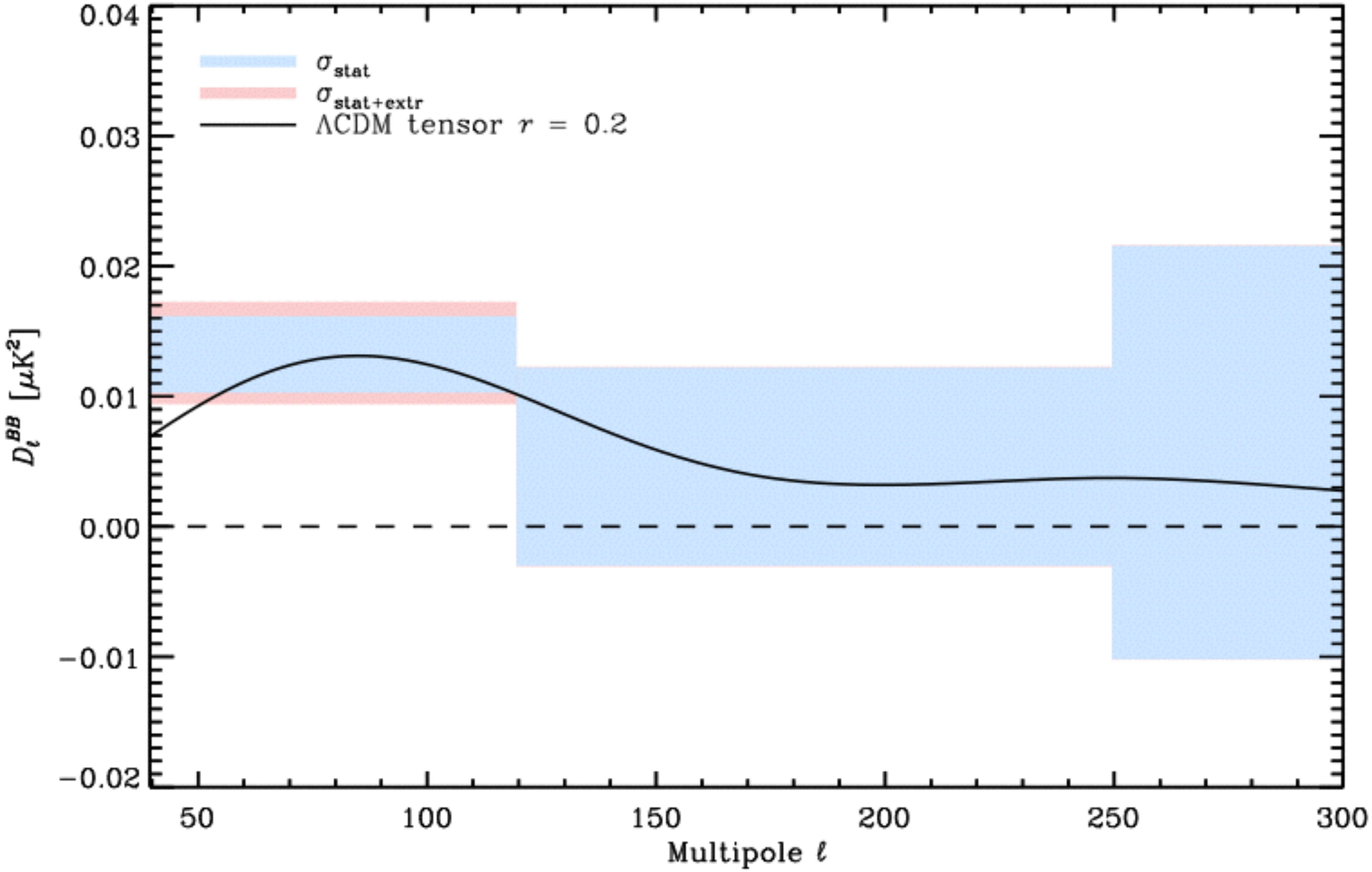
September 22, 2014

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…

Previous Situation [before Monday]

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

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

So, the search continues!

- We wish to “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 $n_t=0$]

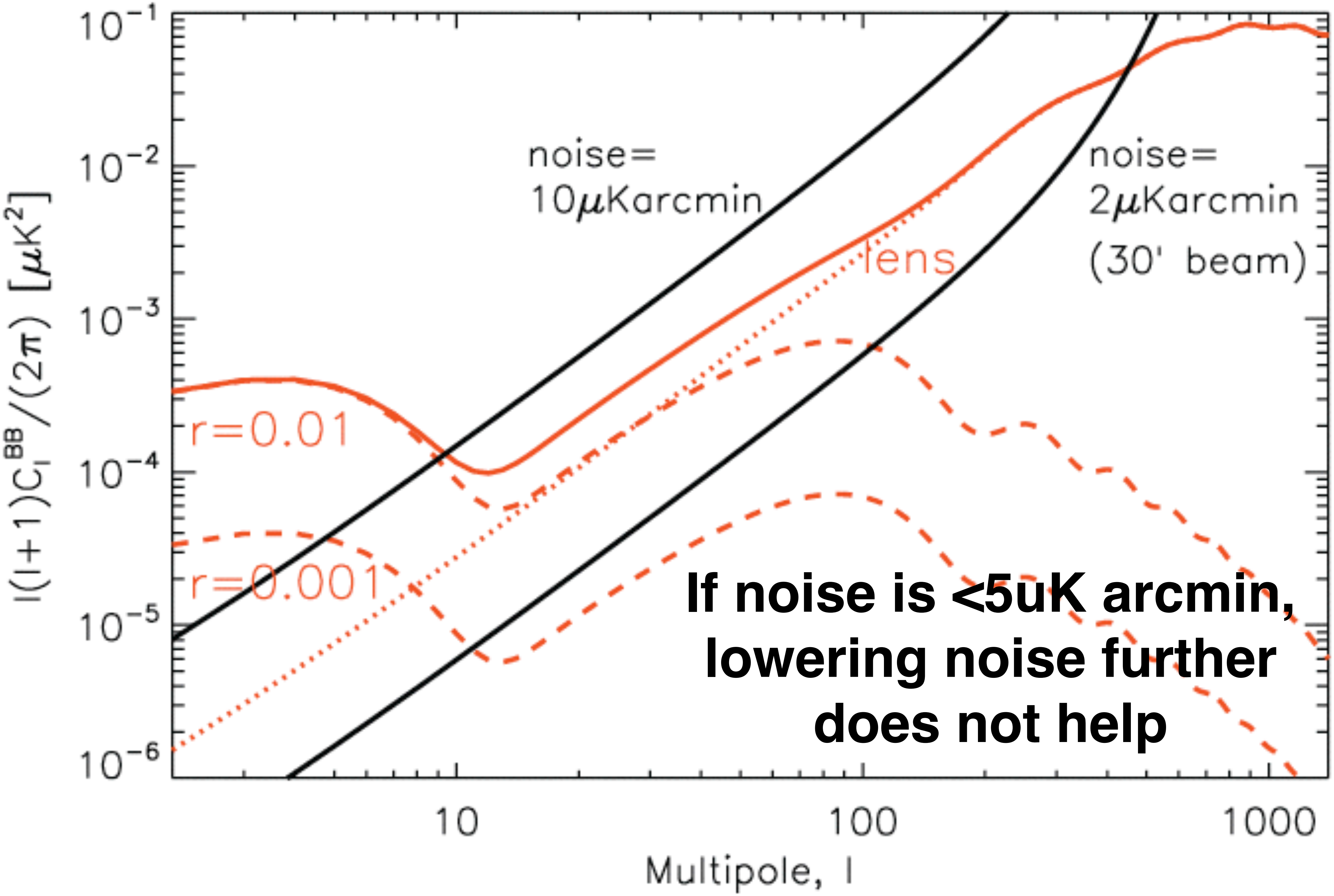
Tensor Tilt, n_t

- Unlike the scalar tilt, it is not easy to determine the tensor tilt because the lensing B-mode power spectrum reduces the number of usable modes for measuring the primordial B-mode power spectrum

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

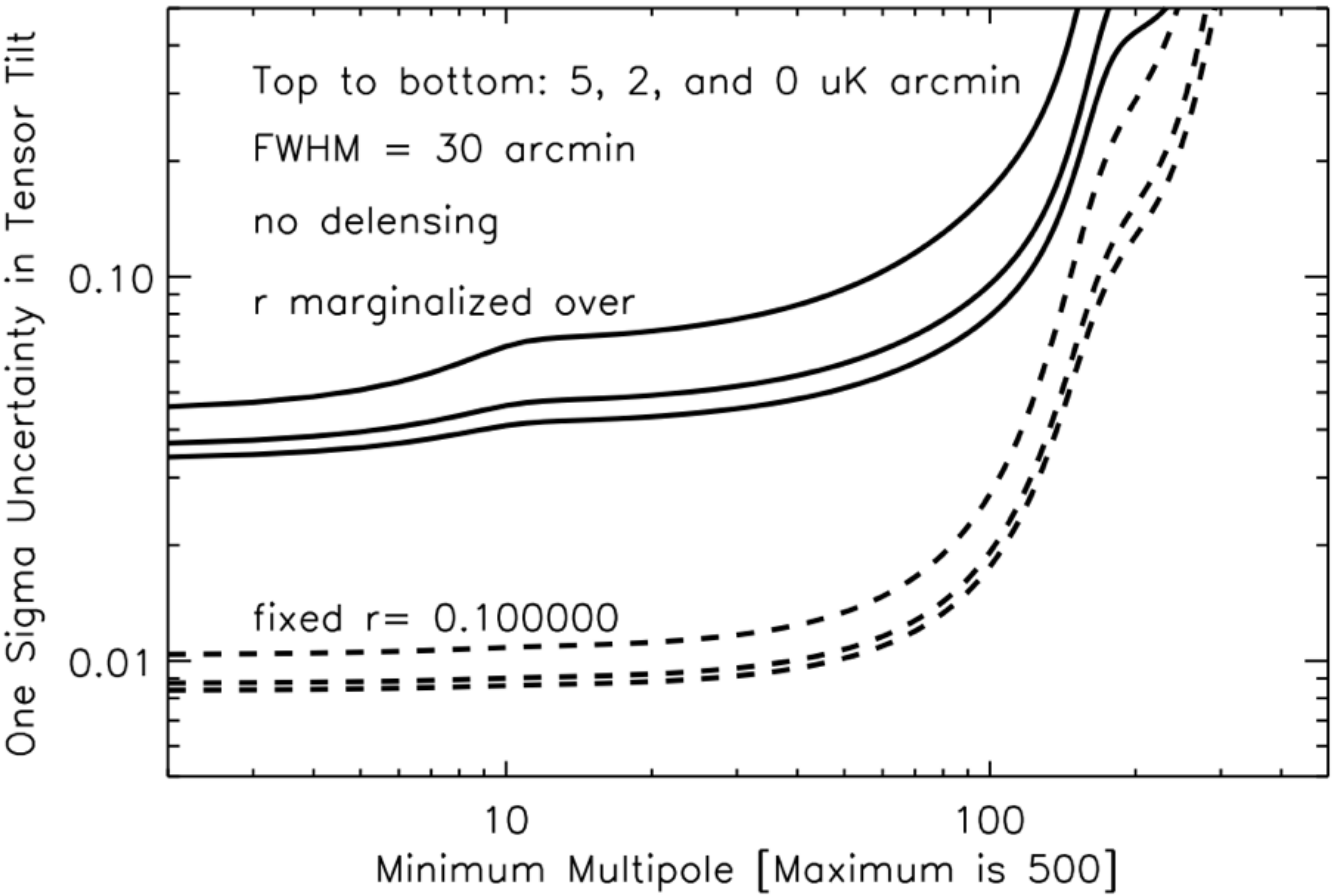
- De-lensing is crucial!

Lensing limits our ability to determine the tensor tilt



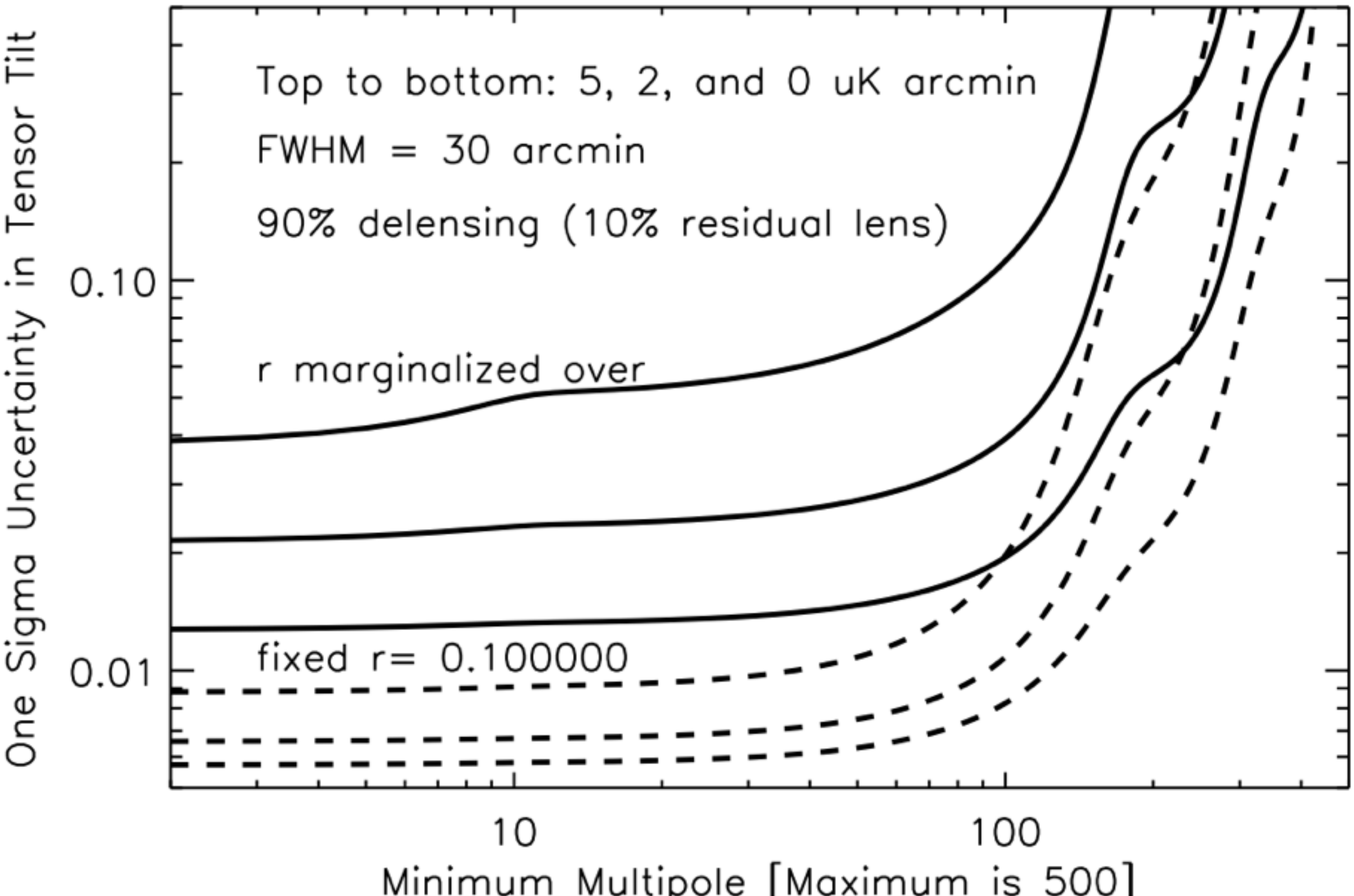
Most optimistic forecast [full sky, white noise, no foreground]

Without de-lensing [r=0.1]



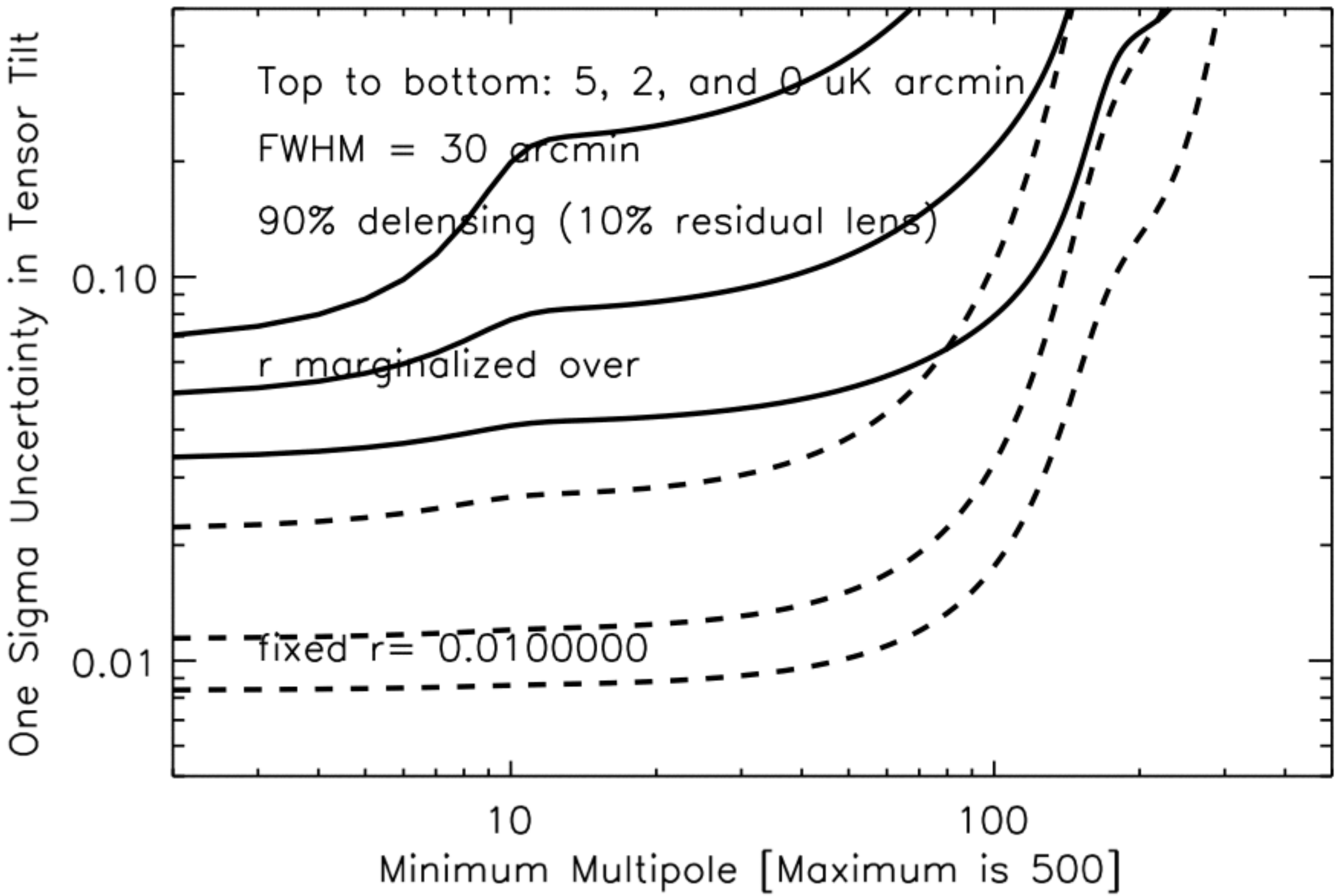
Most optimistic forecast [full sky, white noise, no foreground]

90% de-lensing [r=0.1]



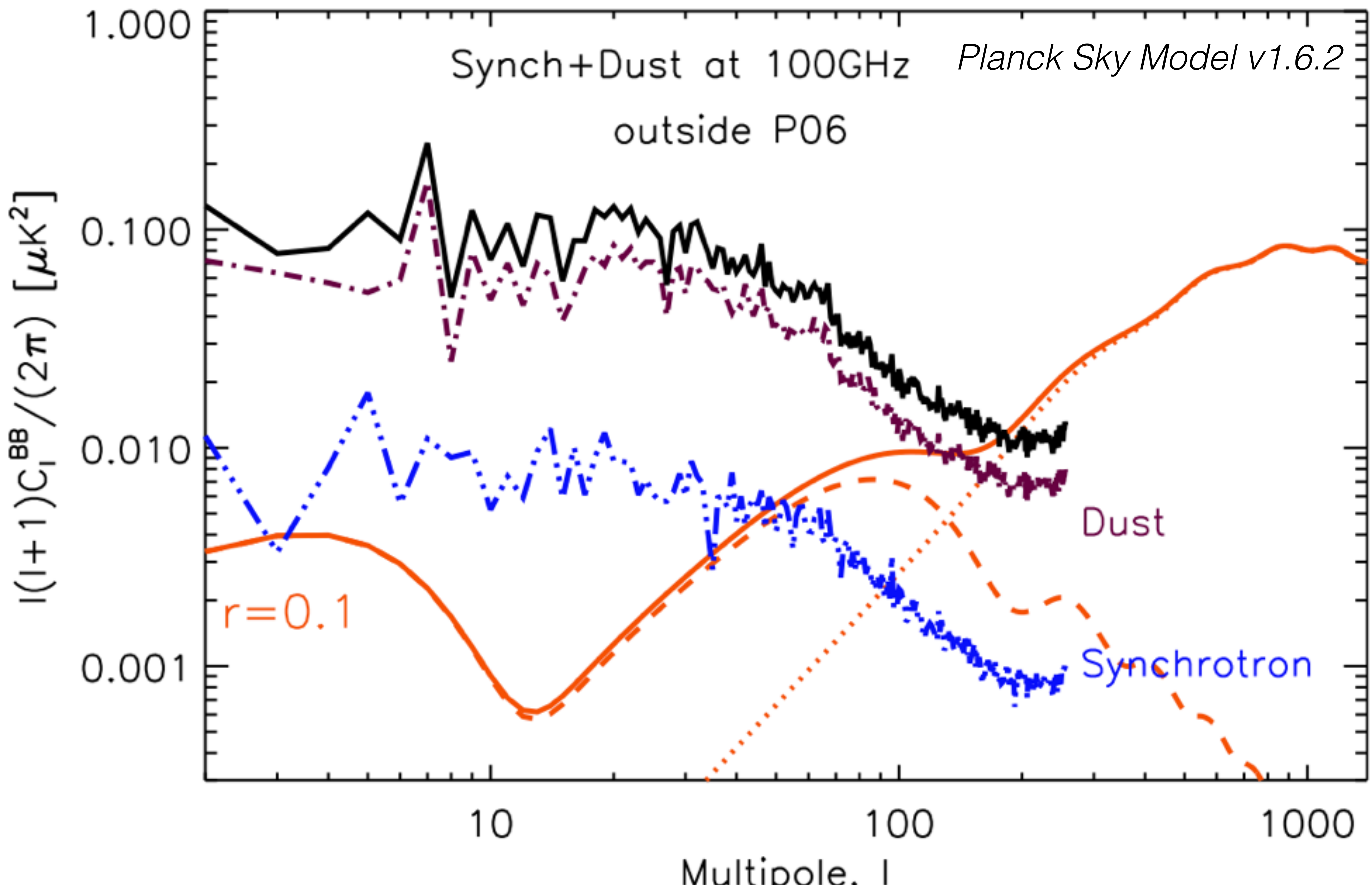
Most optimistic forecast [full sky, white noise, no foreground]

90% de-lensing [r=0.01]



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
- The measurement of the reionisation bump is a challenging task due to Galactic foreground



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

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

Gauss will help us

- The power spectrum captures only a fraction of information
- CMB is very close to Gaussian, while foreground is highly non-Gaussian
- CMB scientist's best friend is this equation:

$$-2\ln\mathcal{L} = ([\mathrm{data}]_i - [\mathrm{stuff}]_i)^t \underline{(C^{-1})}_{ij}([\mathrm{data}]_j - [\mathrm{stuff}]_j)$$

2-point function of
CMB plus noise

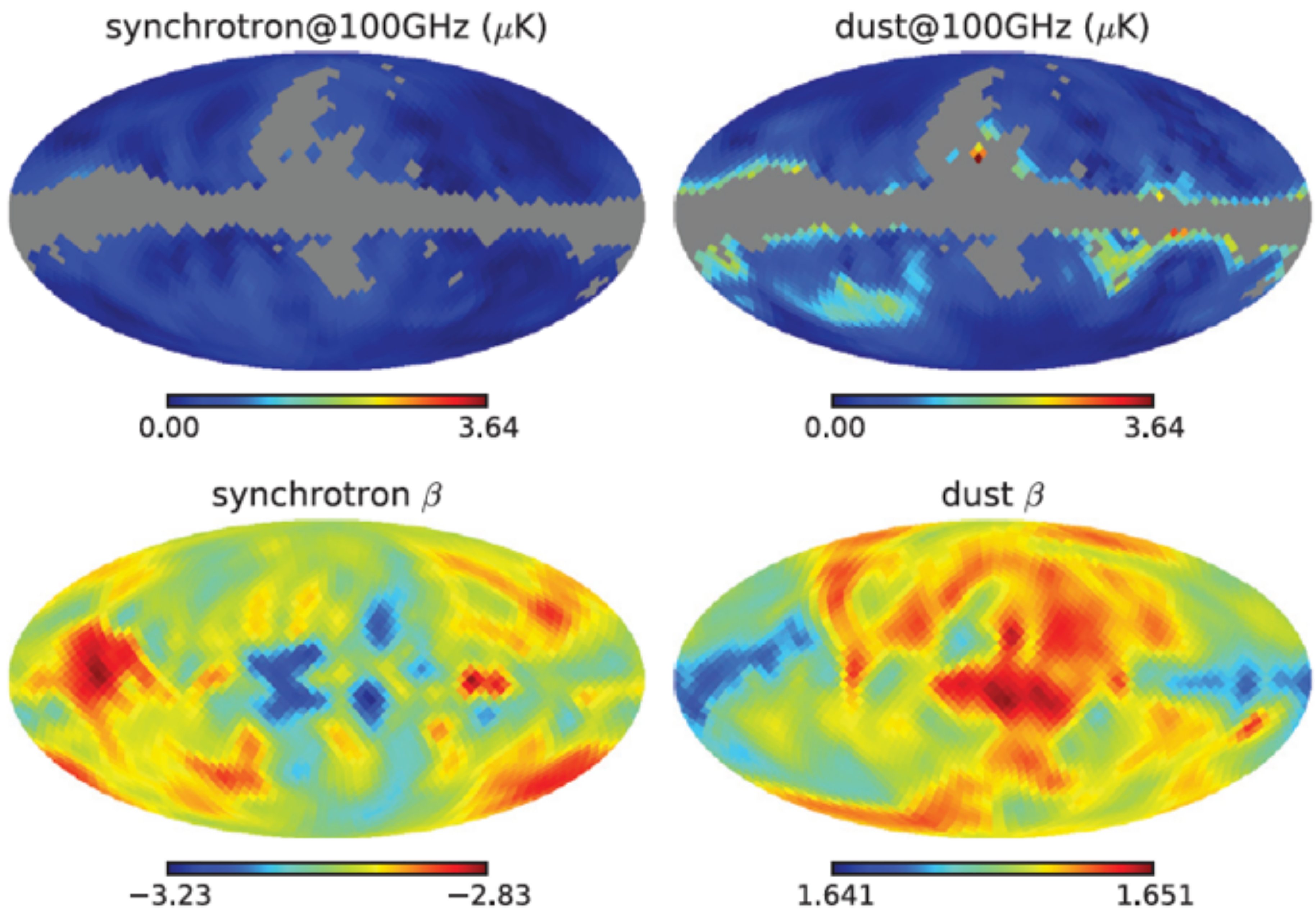
WMAP's Simple Approach

$$[Q', U'](\nu) = \frac{[Q, U](\nu) - \alpha_S(\nu)[Q, U](\nu = 23\,\mathrm{GHz})}{1 - \alpha_S(\nu)}$$

- Use the 23 GHz map as a tracer of synchrotron
- Fit the 23 GHz map to a map at another frequency with a single amplitude α_S, and subtract
- After correcting for the "CMB bias", this method removes synchrotron completely, **provided that**:
  - Spectral index [$T_\nu \sim \nu^\beta$; $\beta \sim -0.3$ for synchrotron] does not vary across the sky
- Residual foreground emission increases as the index variation increases

Limitation of the Simplest Approach

Planck Sky Model (ver 1.6.2)



- Synchrotron index **does** vary a lot across the sky

Going with the simplest

- While the synchrotron and dust indices do vary across the sky, let us go ahead with the simplest approach

- Obvious improvements are possible:

    - Fit multiple coefficients to different locations in the sky

    - Use more frequencies to constrain indices simultaneously

Methodology

We shall maximize the following likelihood function for estimating r, s, and α_i:

$$\mathcal{L}(r, s, \alpha_i) \propto \frac{\exp\left[-\frac{1}{2}\boldsymbol{x}'(\alpha_i)^T \boldsymbol{C}^{-1}(r, s, \alpha_i)\boldsymbol{x}'(\alpha_i)\right]}{\sqrt{|\boldsymbol{C}(r, s, \alpha_i)|}}, \quad (9)$$

where

$$\boldsymbol{x}' = \frac{[Q, U](\nu) - \sum_i \alpha_i(\nu)[Q, U]\left(\nu_i^{\text{template}}\right)}{1 - \sum_i \alpha_i(\nu)} \quad (10)$$

is a template-cleaned map. This is a generalization of Equation (6) for a multi-component case. In this paper, i takes on "S" and "D" for synchrotron and dust, respectively, unless noted otherwise. For definiteness, we shall choose

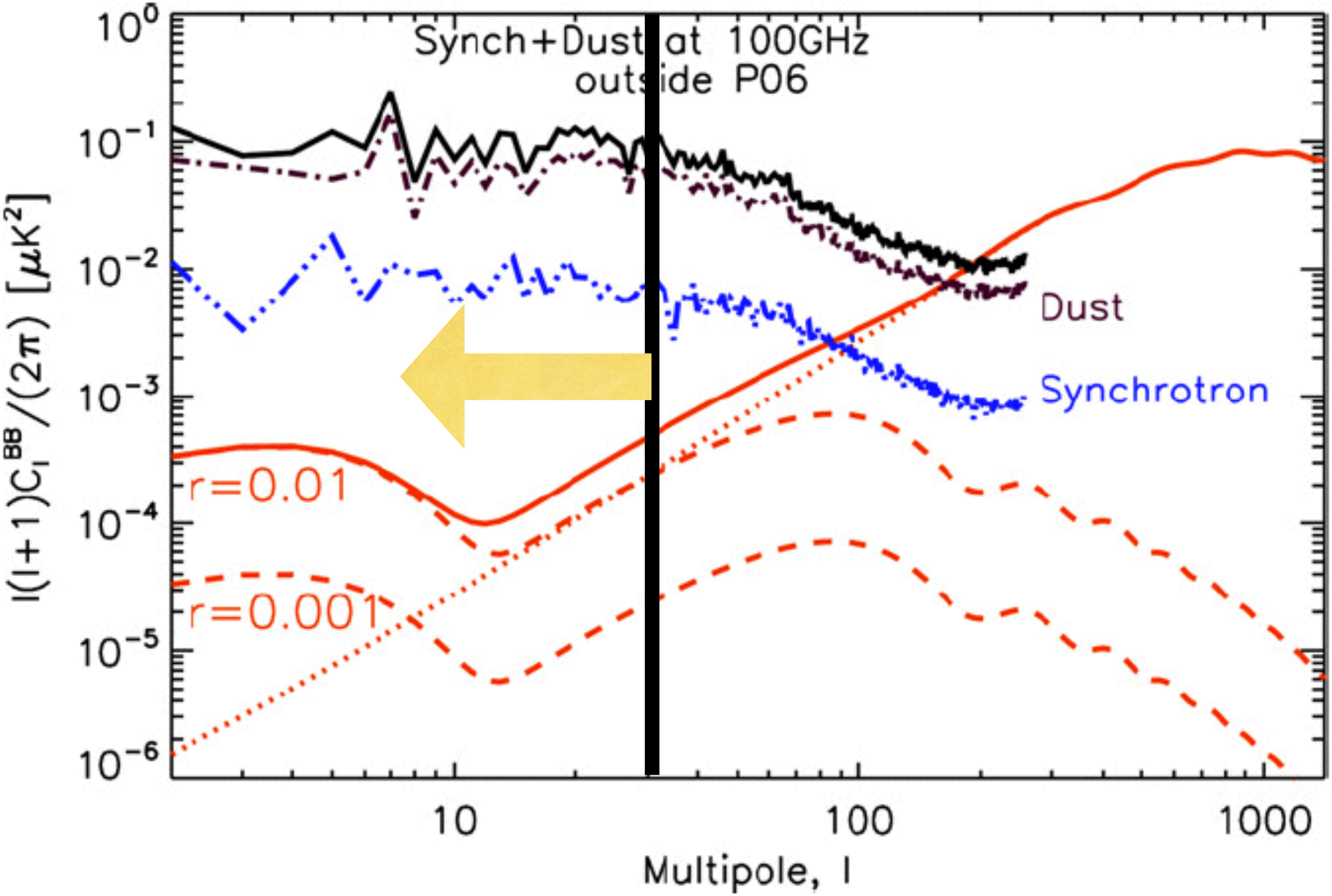
$$\begin{aligned} \nu &= 100\,\text{GHz}, \\ \nu_{\text{S}}^{\text{template}} &= 60\,\text{GHz}, \\ \nu_{\text{D}}^{\text{template}} &= 240\,\text{GHz}. \end{aligned}$$

$O(N^3)$

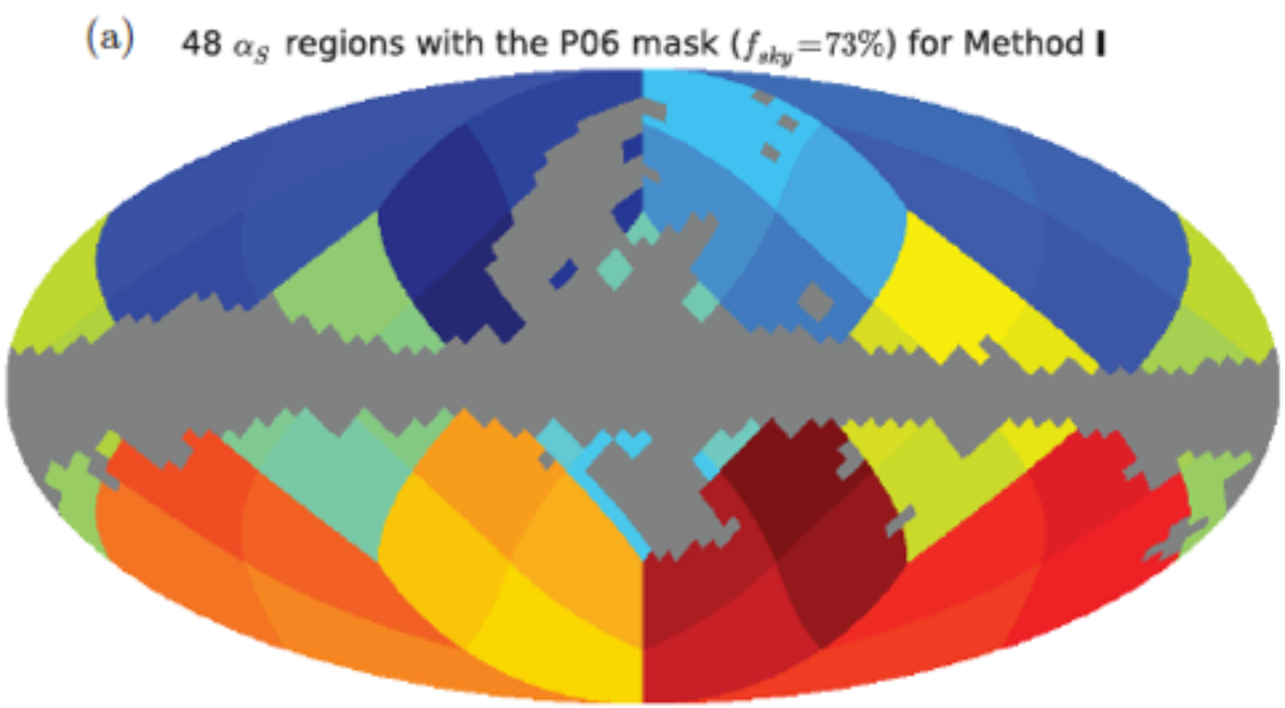
$$\mathcal{L}(r, s, \alpha_i) \propto \frac{\exp\left[-\frac{1}{2}\boldsymbol{x}'(\alpha_i)^T \boldsymbol{C}^{-1}(r, s, \alpha_i)\boldsymbol{x}'(\alpha_i)\right]}{\sqrt{|\boldsymbol{C}(r, s, \alpha_i)|}}$$

- Since we cannot invert the covariance matrix when the number of pixels is too large, we focus on low-resolution Q and U maps with 3072 pixels per map [N_{side}=16; 3.7-degree pixel]

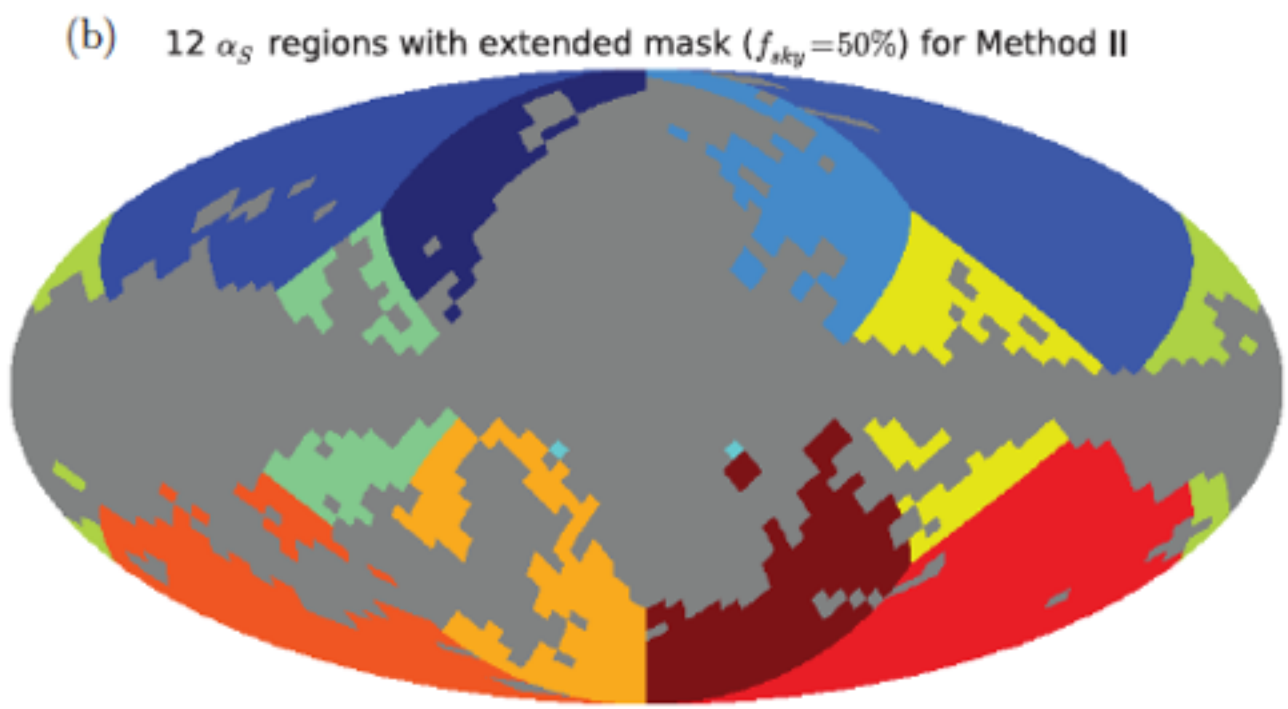
We target the reionisation bump



Two Masks and Choice of Regions for Synch. Index



Method I

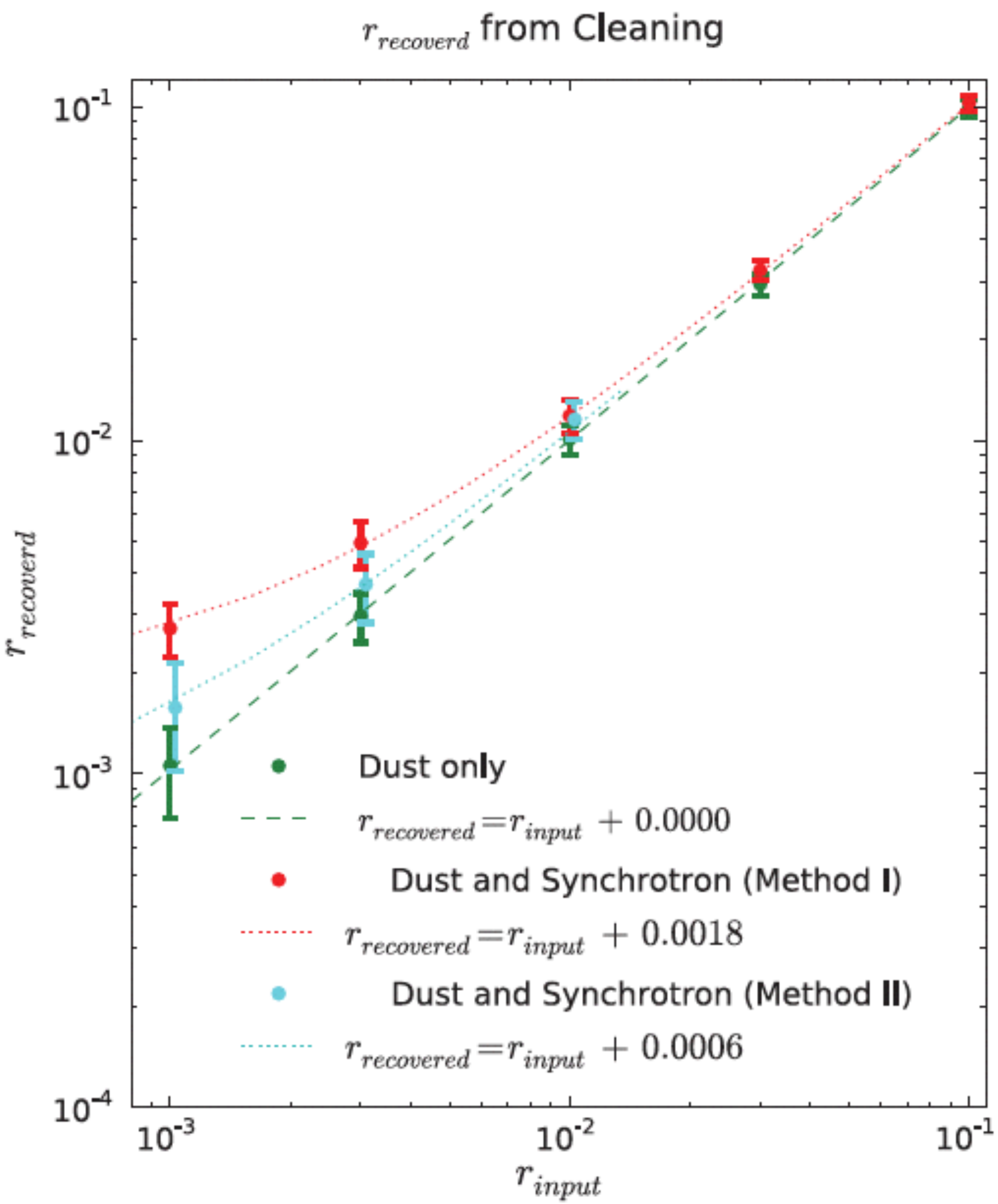


Method II

Katayama & Komatsu, ApJ, 737, 78 (2011)

Results

[3 frequency bands: 60, 100, 240 GHz]



- It works well!
- Method I: the bias is $\delta r = 2 \times 10^{-3}$
- Method II: the bias is $\delta r = 0.6 \times 10^{-3}$
- [This analysis needs to be re-done with the dust spectral index from Planck]

Toward precision measurement of B-modes

- $r \sim 10^{-3}$ seems totally possible, even in the presence of synchrotron and dust emissions
- 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

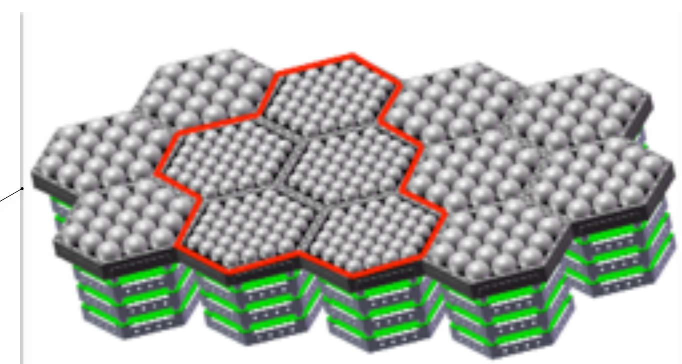
- **Singular goal**: measurement of the primordial B-mode power spectrum with **Err[r]=0.001**

- **6 frequency bands** between 50 and 320 GHz

LiteBIRD

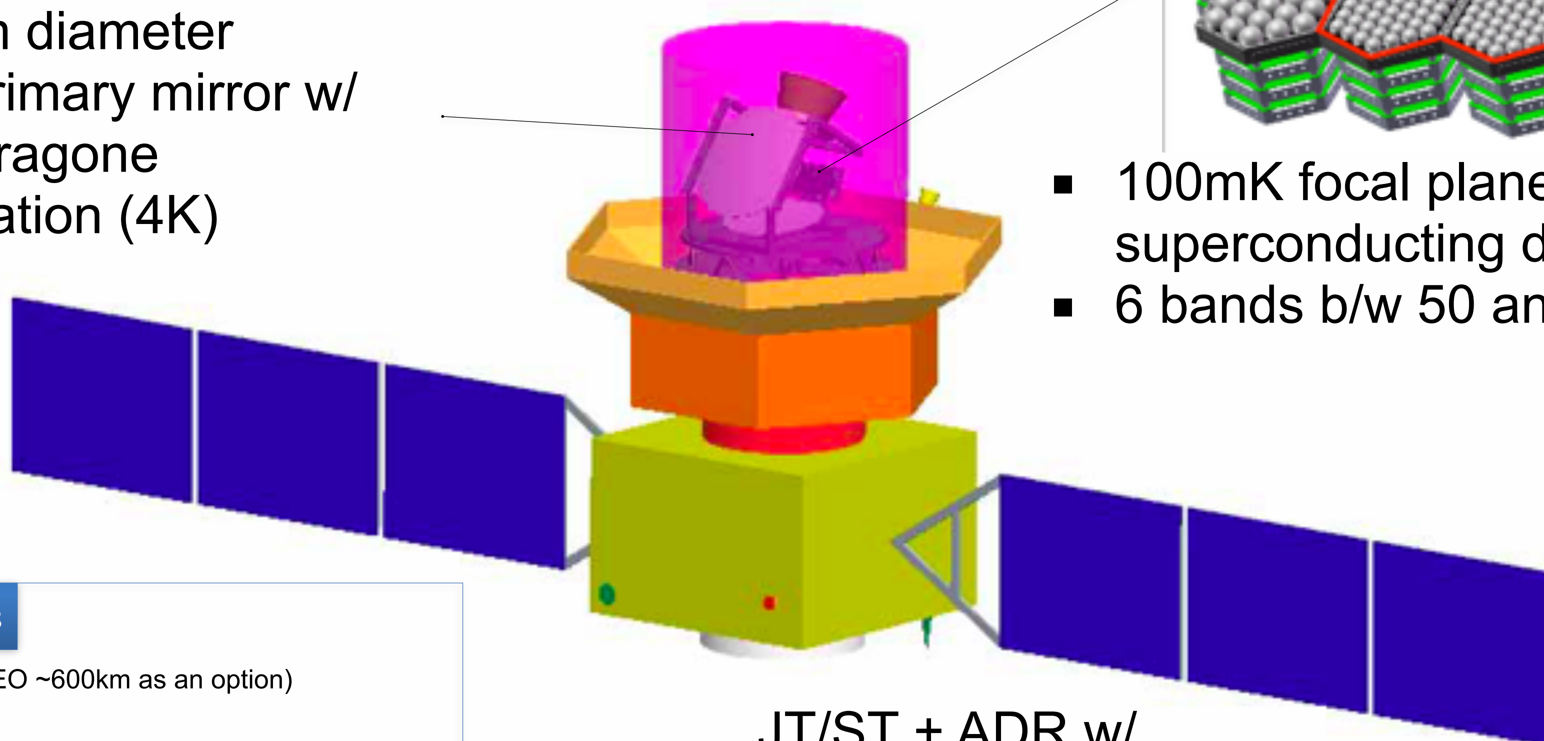
Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

- 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

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

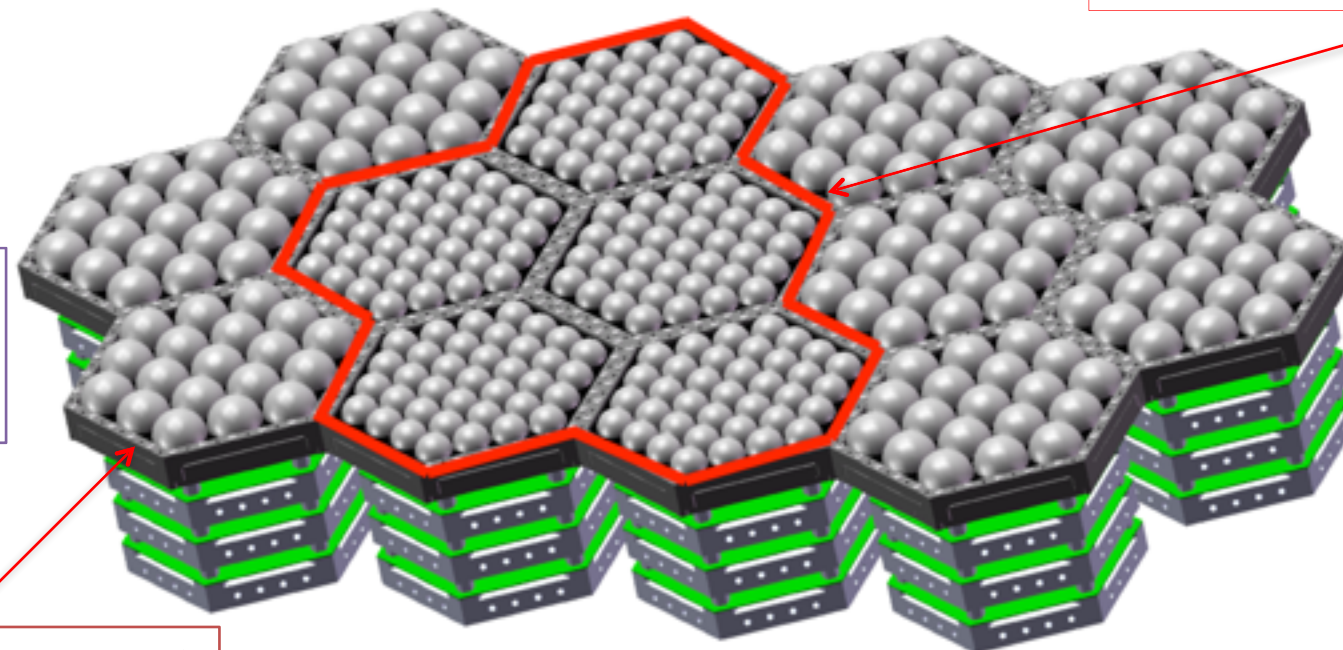
LiteBIRD focal plane design

UC Berkeley TES option

2022 TES bolometers

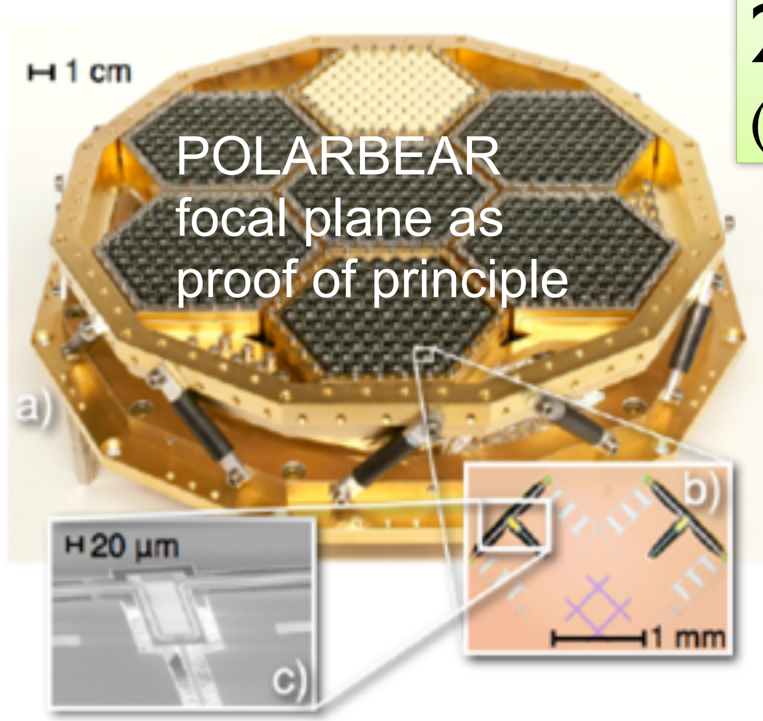
T_{bath} = 100mK

tri-chroic（140/195/280GHz）



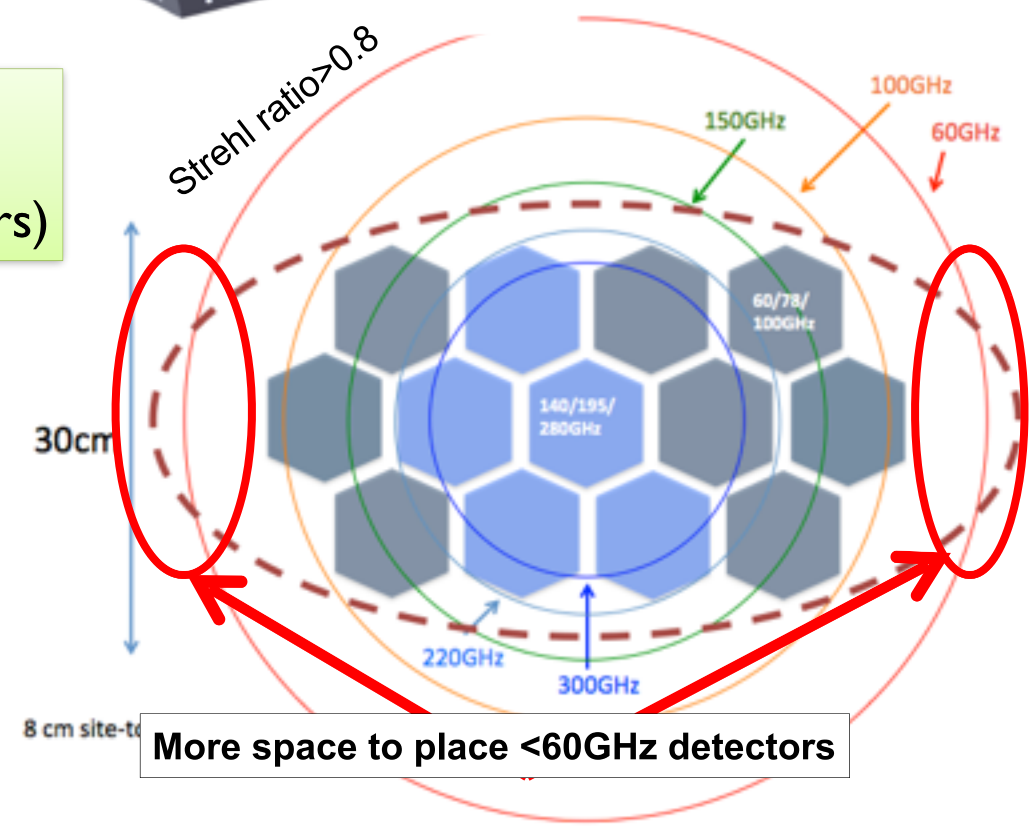
Band centers can be distributed to increase the effective number of bands

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
- 2014 March
  Recommendation from Science Council of Japan as one of the top 27 projects
- 2014 July
  Ranked highly in the "Roadmap 2014" of MEXT [Ministry of Education, Culture, Sports, Science & Technology 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

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
- German team [at the moment]: MPA, MPIfR, LMU, Aachen

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

- Important milestones for inflation have been achieved: **n_s<1 with 5σ**; remarkable Gaussianity
- The next goal: unambiguous measurement of the primordial B-mode polarisation power spectrum
- **Err[n_t]~0.01** possible only with substantial de-lensing
- Foreground cleaning with the simplest internal template method is promising, **limiting the bias in r to $<10^{-3}$**
- **LiteBIRD** proposal: a B-mode CMB polarisation satellite in early 2020
- **COrE+** proposal: a near ultime CMB polarisation satellite? M4 call - a target launch in 2025