CMB Polarization: Toward an **Observational** Proof of Cosmic Inflation

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
Colloquium, Yukawa Institute for Theoretical Physics
March 26, 2014

Has inflation happened?

- Yes, **if** the B-mode polarization detected by BICEP2 originates from primordial gravitational waves

Inflation, defined

- Necessary and sufficient condition for inflation = sustained accelerating expansion in the early universe
- Expansion rate: $H = (\mathrm{d}a/\mathrm{d}t)/a$
- Accelerating expansion: $(\mathrm{d}^2a/\mathrm{d}t^2)/a = \mathrm{d}H/\mathrm{d}t + H^2 > 0$
- Implying: $\boldsymbol{-(\mathrm{d}H/\mathrm{d}t)/H^2 < 1}$

- Therefore, we prove inflation by showing $\boldsymbol{-(\mathrm{d}H/\mathrm{d}t)/H^2 < 1}$

How to show $-(\mathrm{d}H/\mathrm{d}t)/H^2 < 1$

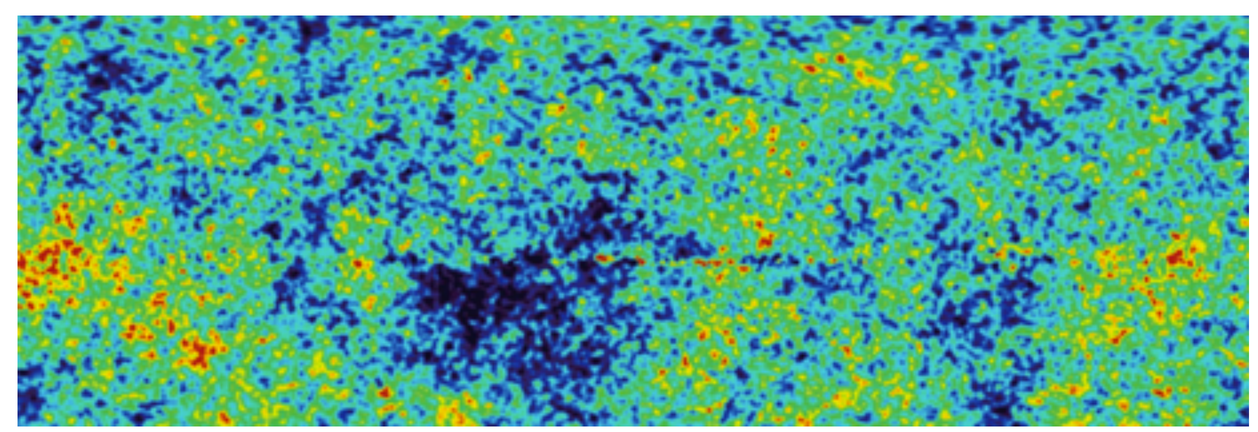
- *Detection of nearly scale-invariant gravitational waves!*
  - Gravitational waves (GW) are continuously created during inflation, **with the amplitude proportional to H**
  - Inflation then stretches the wavelength of GW to large scales
- GW created earlier = GW seen on large scales
- **Variation of the amplitudes of GW over length scales = Variation of H during inflation over time**

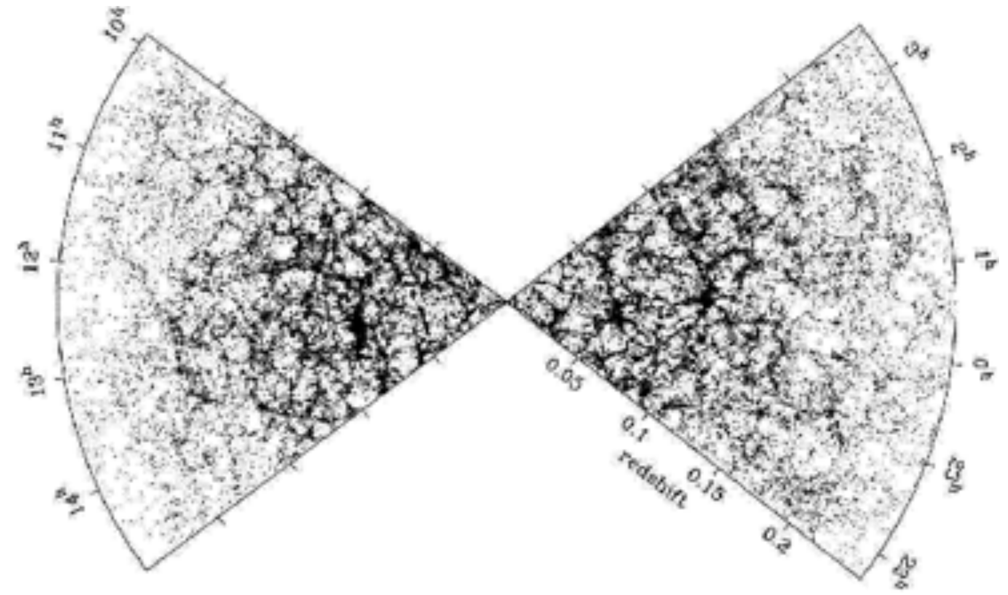
The Key Predictions of Inflation

ζ

scalar mode

- Fluctuations we observe today originated from quantum fluctuations generated during inflation





h_{ij}

tensor mode

- There should also be ultra-long-wavelength gravitational waves originated from quantum (or classical) fluctuations generated during inflation

We are measuring distortions in space

- A distance between two points in space
  - $$dl^2 = a^2(t)e^{2\zeta(x,t)}[e^h]_{ij}dx^idx^j$$
    $$= a^2(t)[1+2\underline{\zeta(x,t)}+\ldots][\delta_{ij}+\underline{h_{ij}(x,t)}+\ldots]dx^idx^j$$

- $\zeta(x,t)$: "curvature perturbation" (scalar mode)
- $h_{ij}(x,t)$: "gravitational waves" (tensor mode)
  - Area-conserving anisotropic stretching of space: $\det[e^h]=1$

We are measuring distortions in space

- A distance between two points in space
  - $dl^2 \;\; = a^2(t)e^{2\zeta(x,t)}[e^h]_{ij}dx^i dx^j$

    $= a^2(t)[1+2\zeta(x,t)+...][\delta_{ij}+h_{ij}(x,t)+...]dx^i dx^j$
- $\zeta(x,t)>0$: more (isotropic) stretching of space
  - More redshift -> colder photons
  - The Sachs-Wolfe formula gives $dT/T = -\zeta/5$

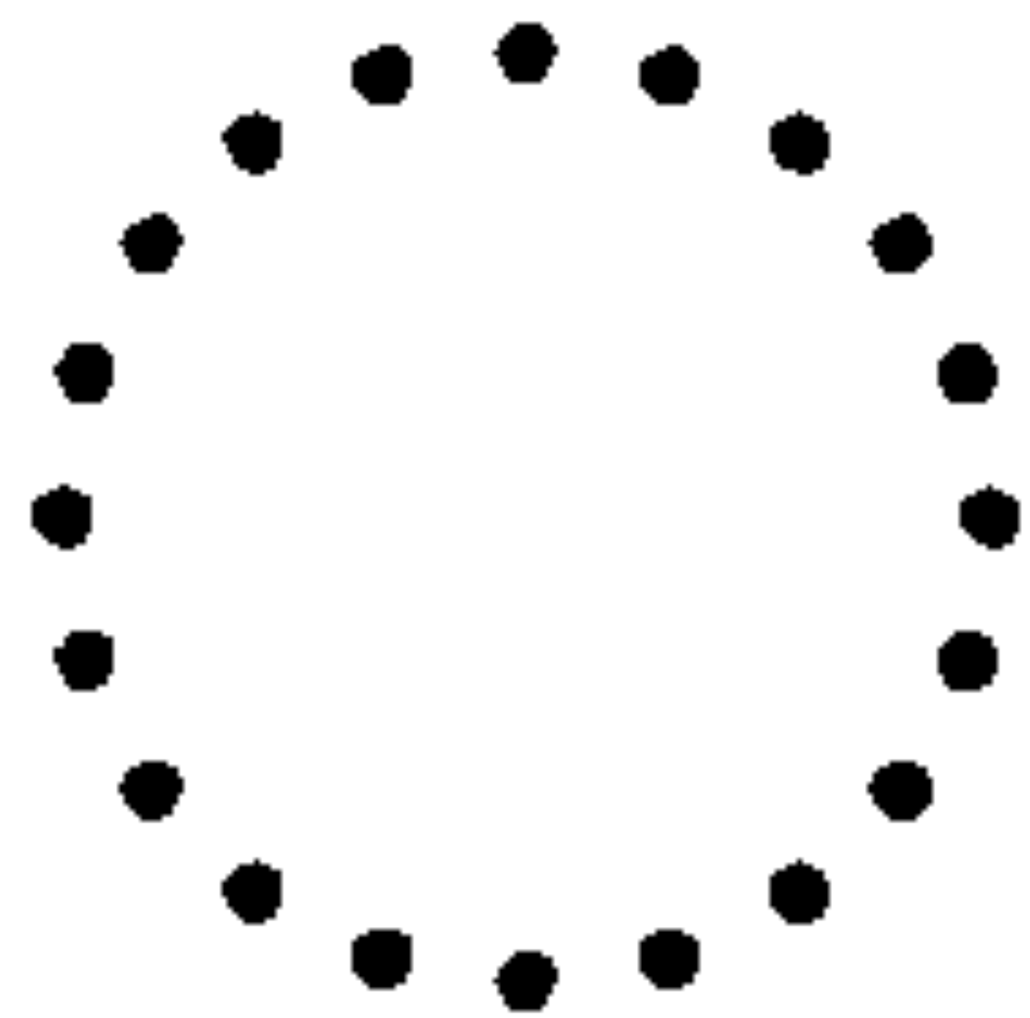
We are measuring distortions in space

- A distance between two points in space
  - $dl^2 \; = a^2(t)e^{2\zeta(x,t)}[e^h]_{ij}dx^i dx^j$

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

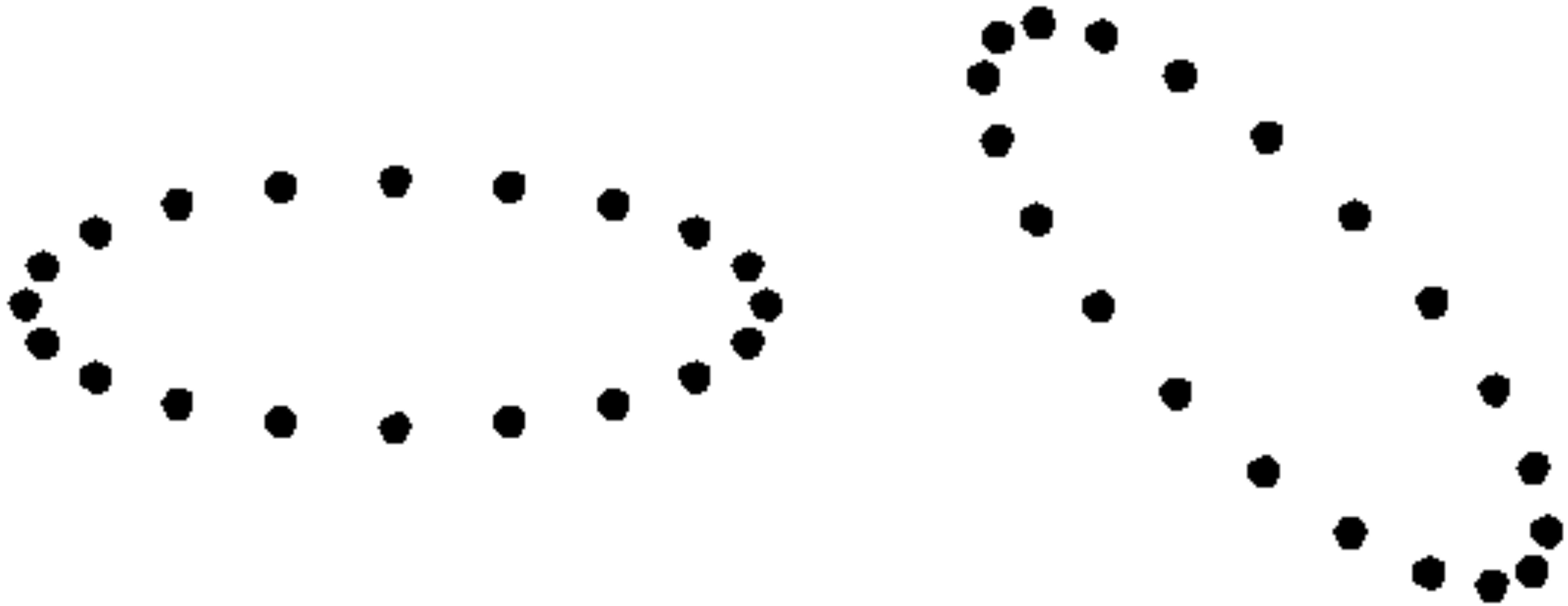
- $h_{ij}(x,t)$: ***anisotropic*** stretching of space

Gravitational waves are coming toward you... What do you do?



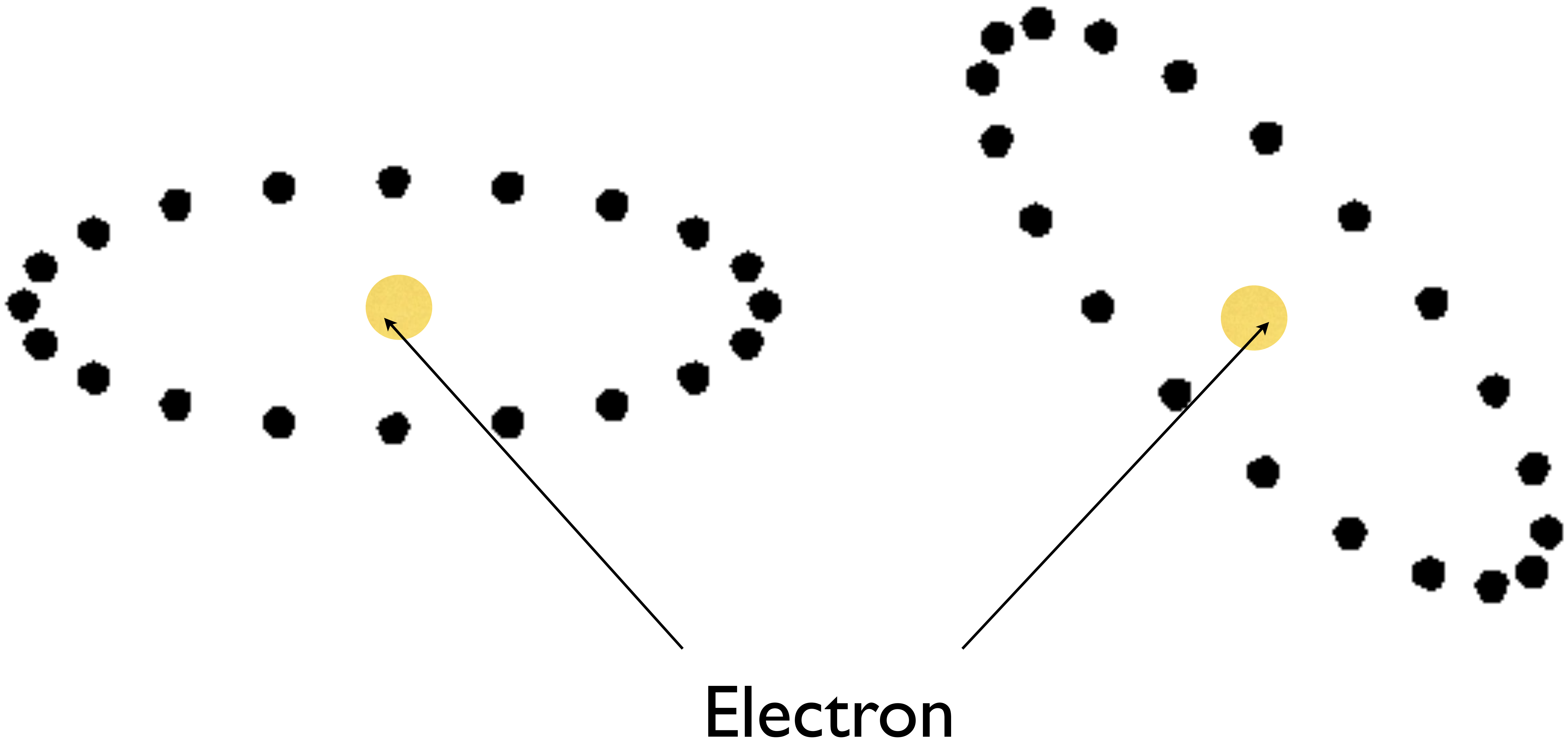
- Gravitational waves stretch space, causing particles to move.

Two Polarization States of GW

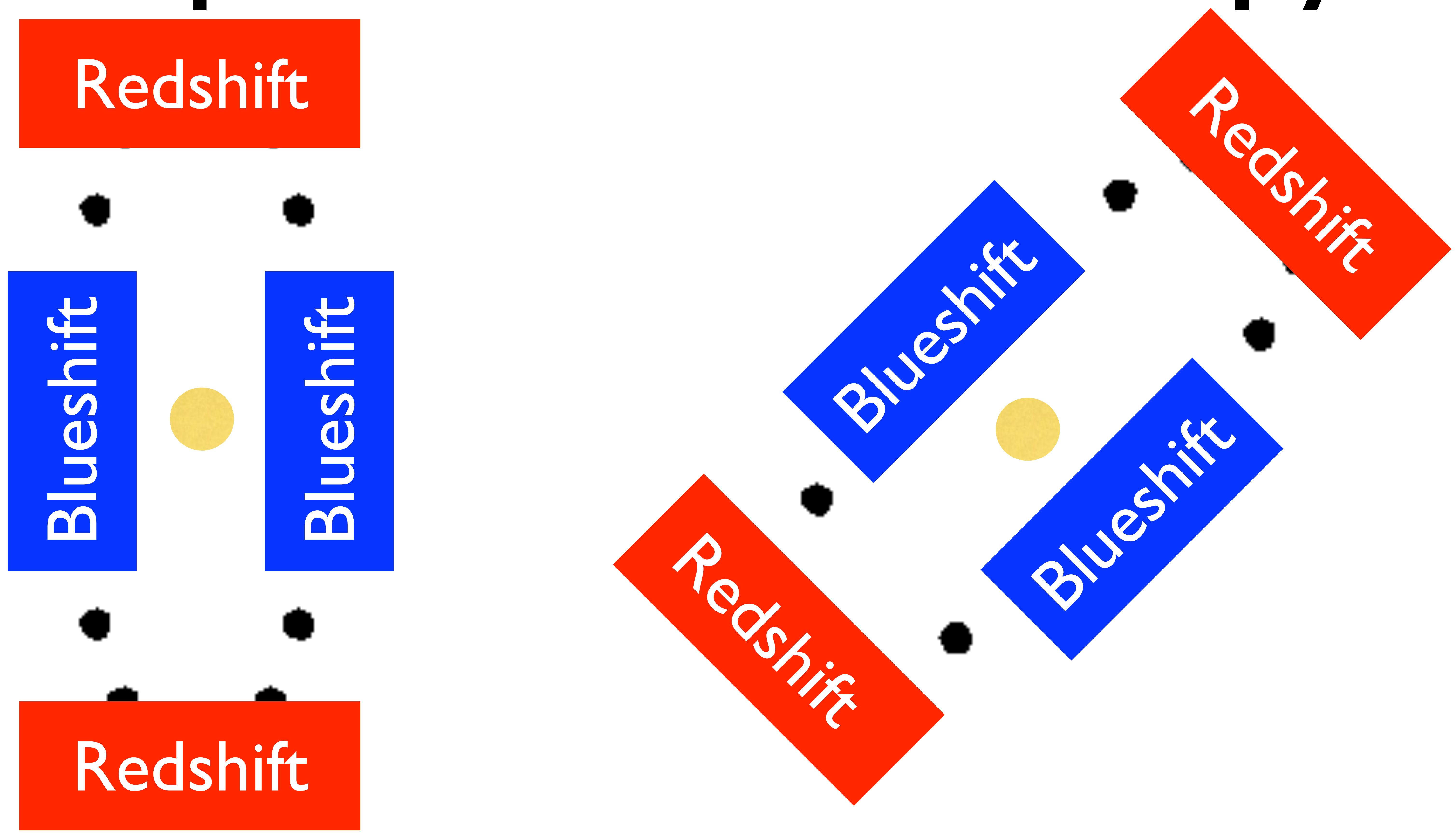


- This is great - this will automatically generate quadrupolar anisotropy around electrons!

From GW to temperature anisotropy



From GW to temperature anisotropy



Scalar Mode

- Inflation predicts "nearly scale-invariant spectrum"
  - which means, for $P_\zeta(k)=\langle|\zeta_k|^2\rangle \sim k^{ns-4}$, **$n_s$ is close to unity**
- Inflation predicts "nearly Gaussian fluctuations"
  - which means, for $f_{NL} \sim \langle\zeta_{k1}\zeta_{k2}\zeta_{k3}\rangle/[P_\zeta(k_1)P_\zeta(k_2)+\text{cyc.}]$, **$f_{NL}$ is much less than unity***

**for single-field canonical models*

Scalar Mode: Current Status

- $n_s<1$ is discovered at last (i.e., by more than 5σ!)
  - WMAP9+ACT+SPT+BAO: $n_s=0.958\pm0.008$ (68%CL)
  - Beautifully confirmed by Planck+WMAP9 polarization: $n_s=0.960\pm0.007$ (68%CL)
- Remarkably tight limit on $f_{NL}^{local} = 2.7\pm5.8$ (68%CL) by Planck
  - A massive (a factor of 3.4) improvement from WMAP9

Single-field, canonical inflation models agree with all the data:
$1-n_s \approx f_{NL} \approx O$[slow roll parameters] $= O(10^{-2})$

Yet

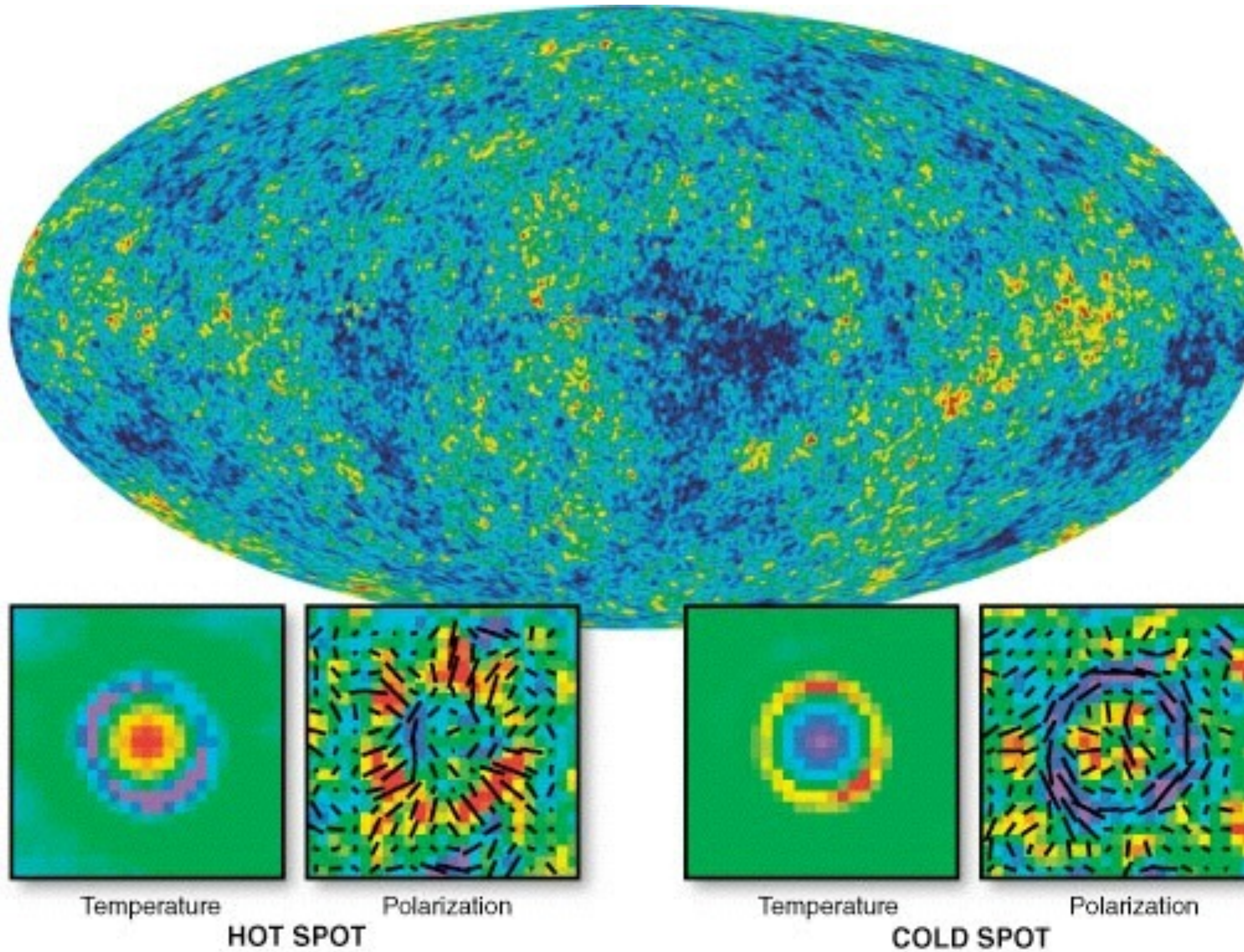
- Neither $n_s<1$ nor $f_{NL}<1$ proves that inflation happened!

- We need to detect long-wavelength, scale-invariant primordial gravitational waves to **definitively prove inflation observationally**

Tool

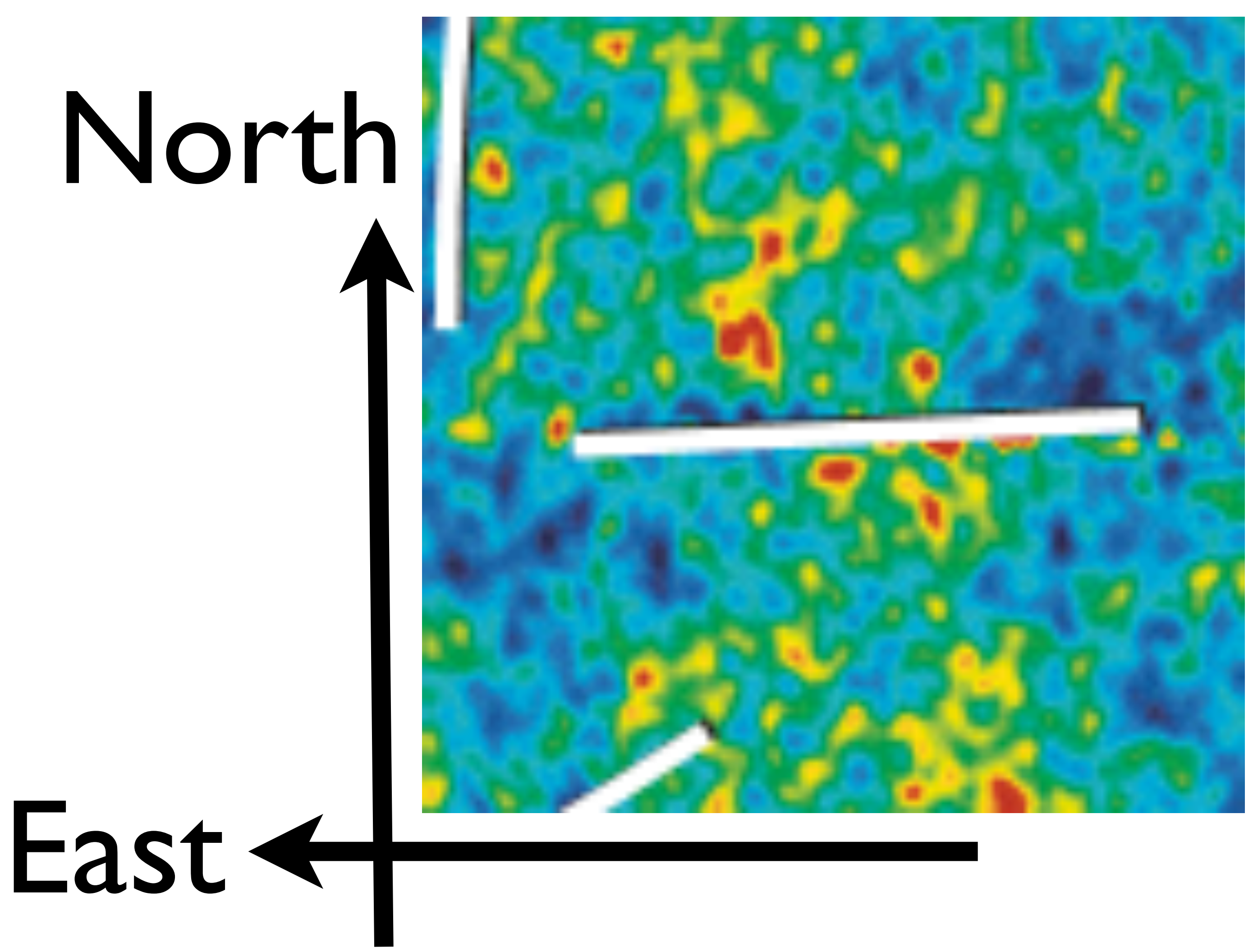
- CMB Polarization!

CMB Polarization

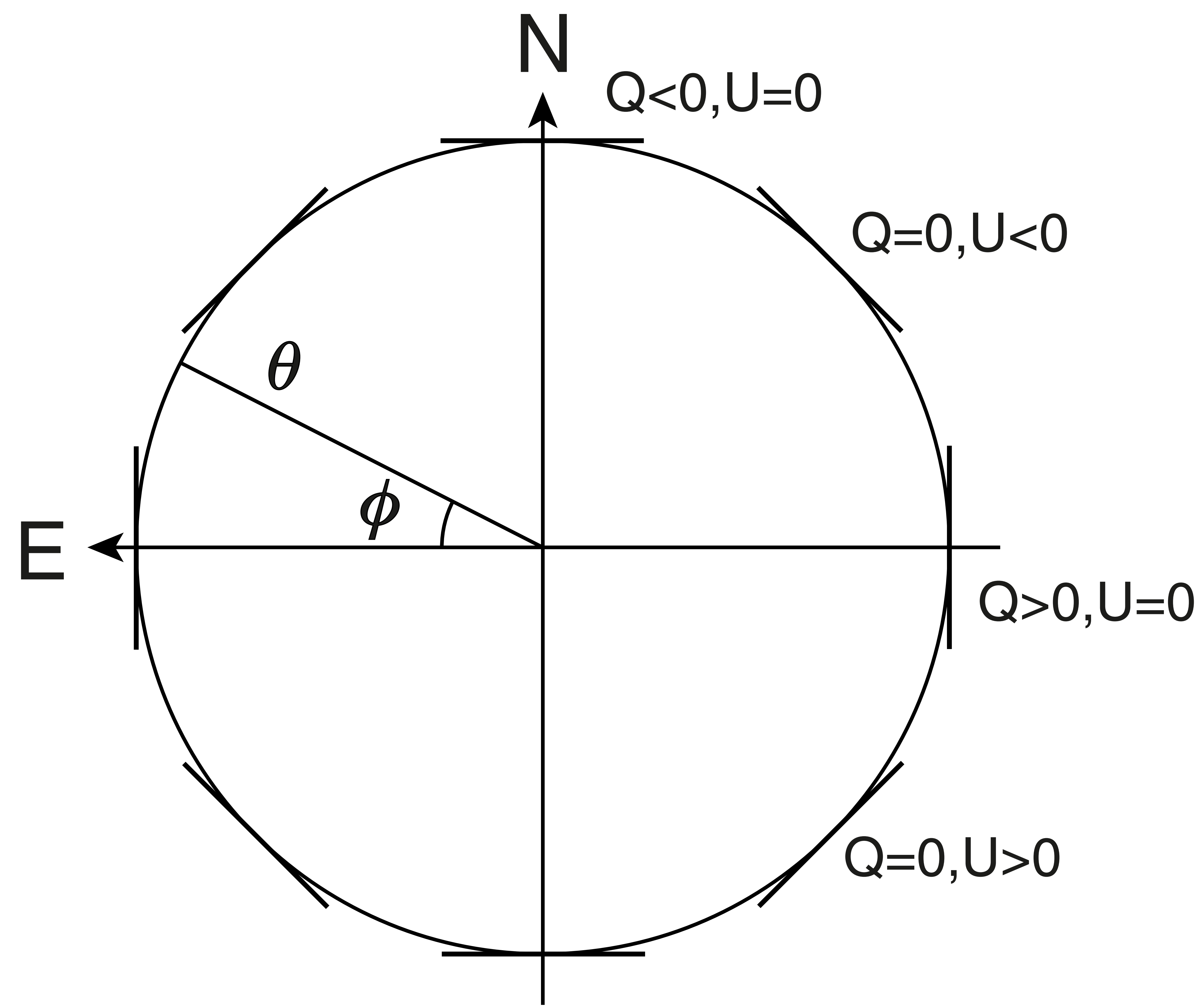


- *CMB is (very weakly) polarized*

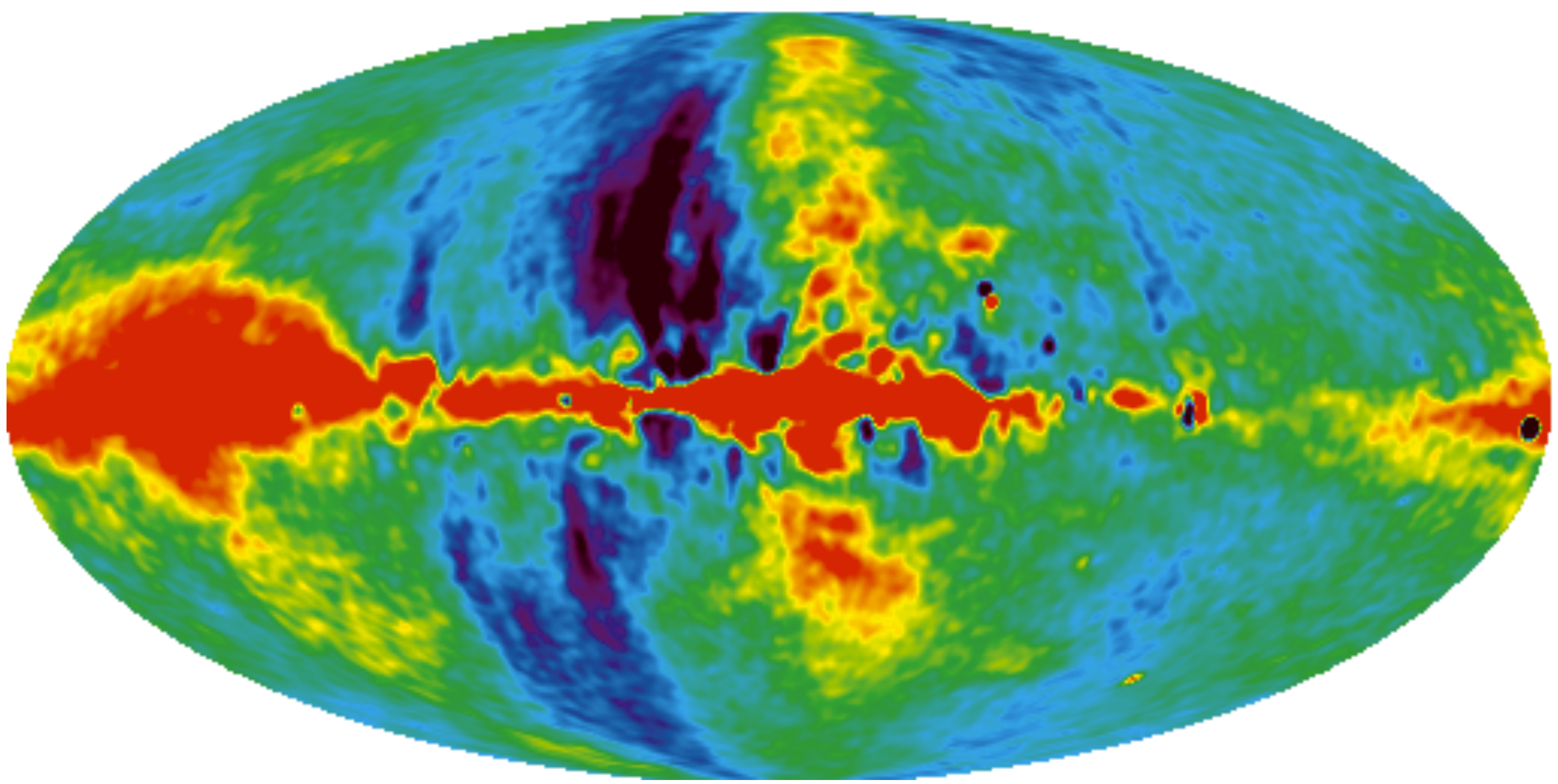
“Stokes Parameters”



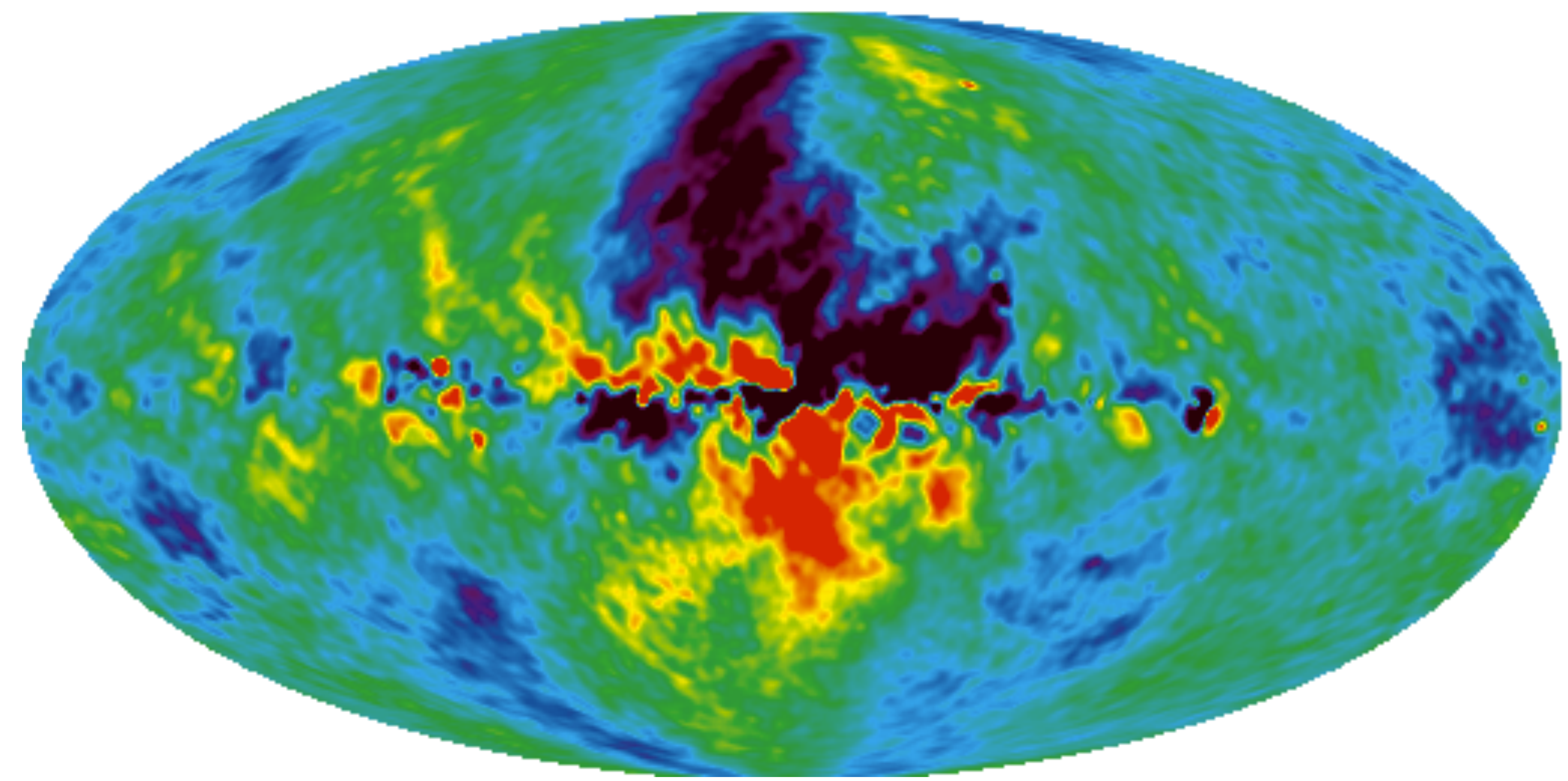
Q<0; U=0



23 GHz [polarized]

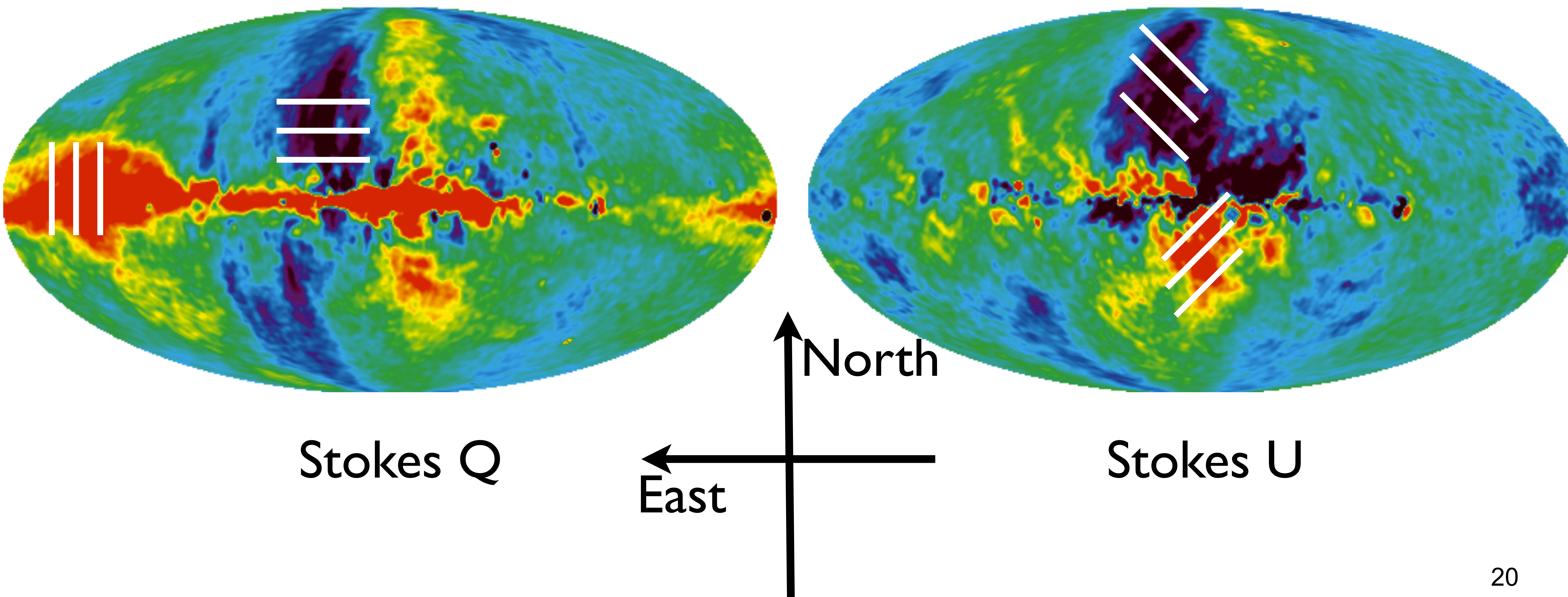


Stokes Q

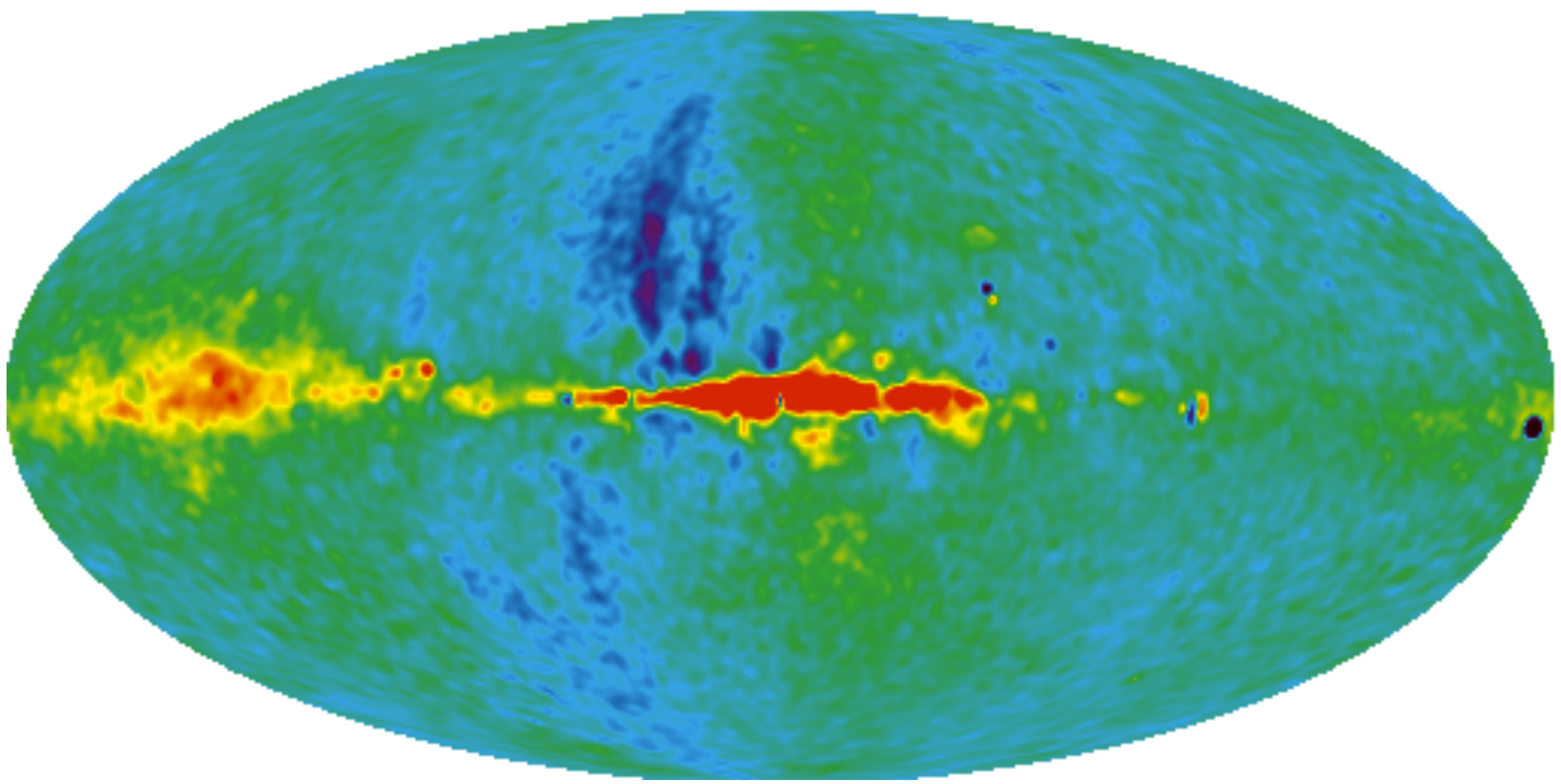


Stokes U

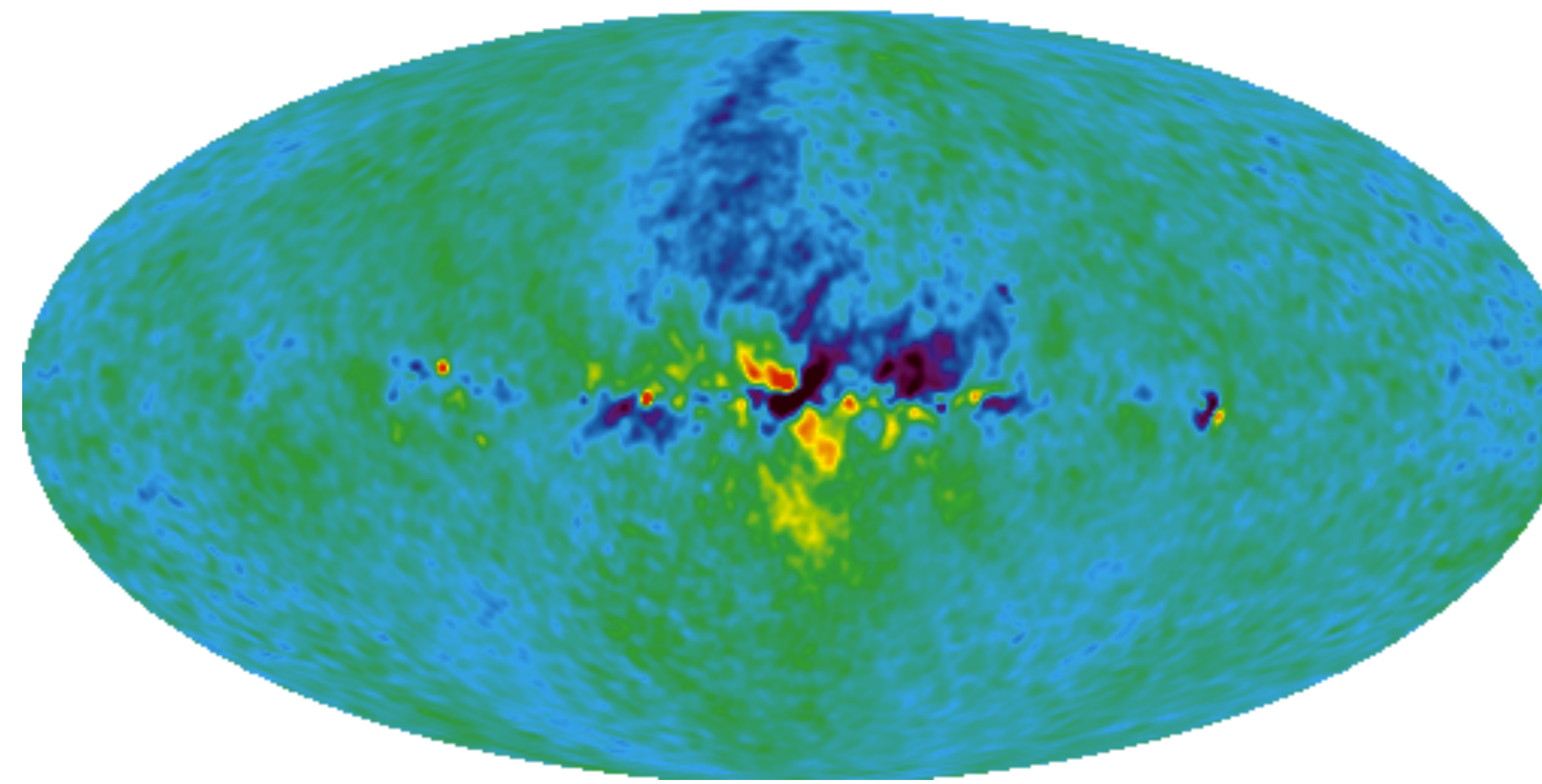
23 GHz [polarized]



33 GHz [polarized]

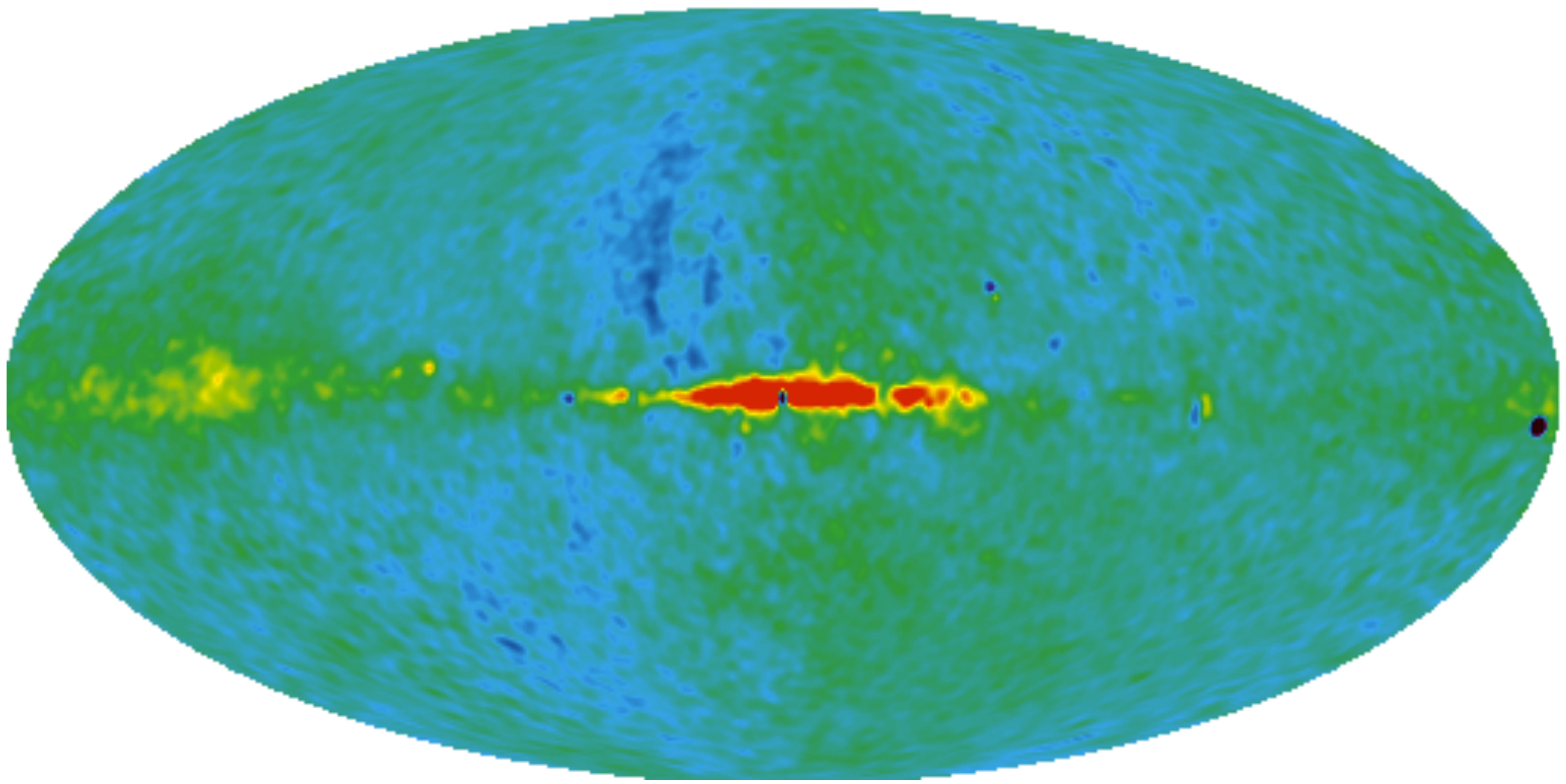


Stokes Q

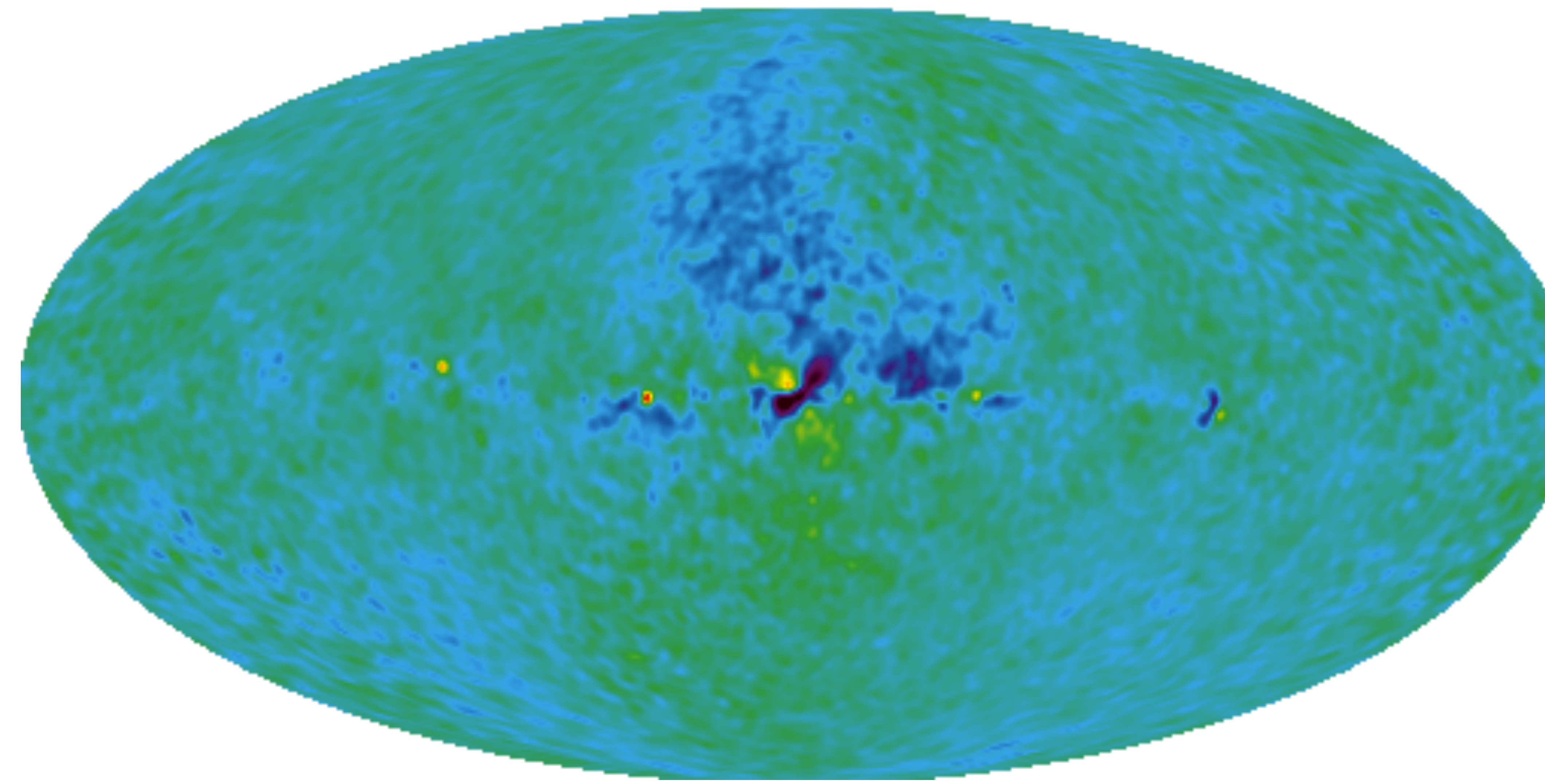


Stokes U

41 GHz [polarized]

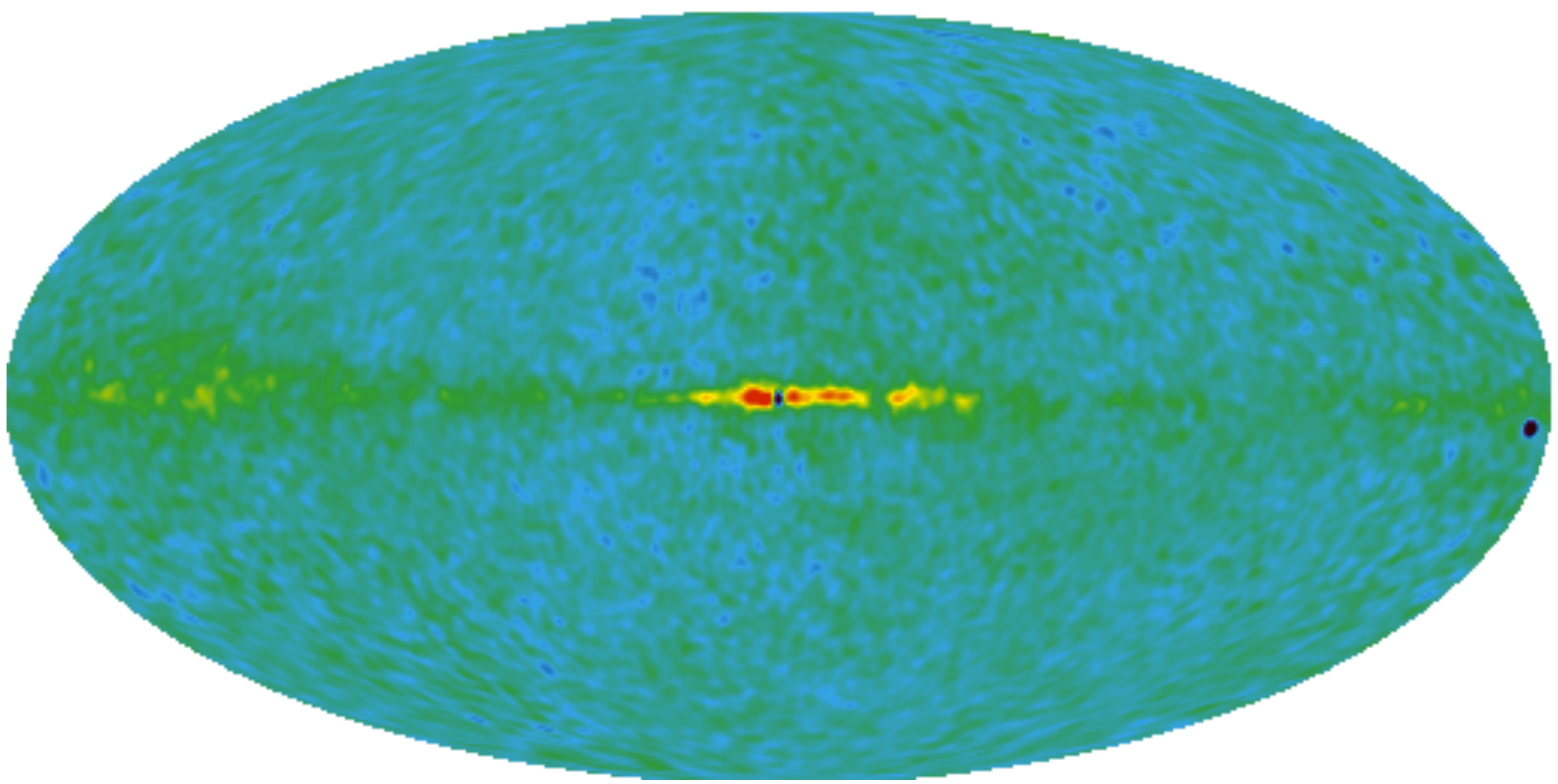


Stokes Q

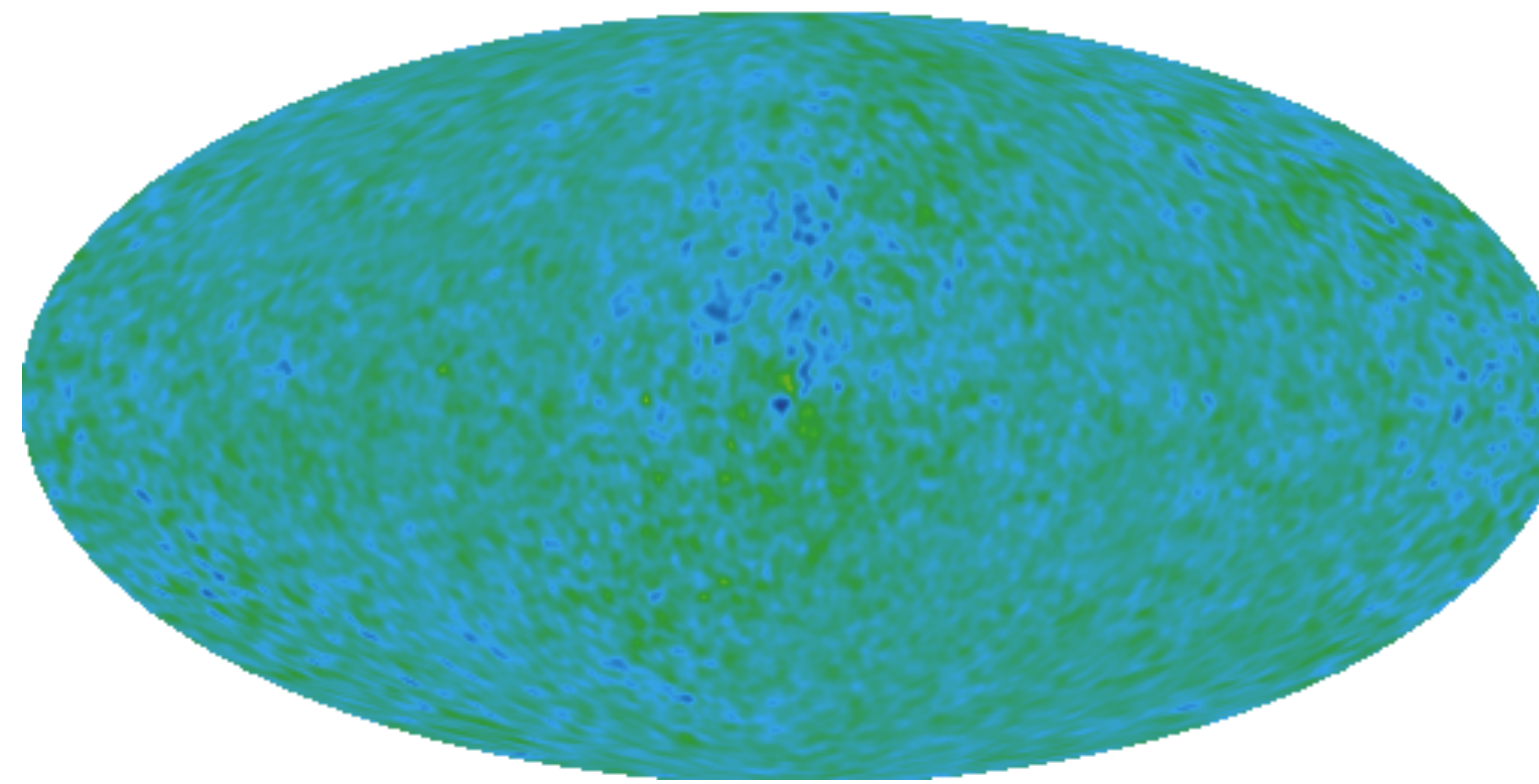


Stokes U

61 GHz [polarized]

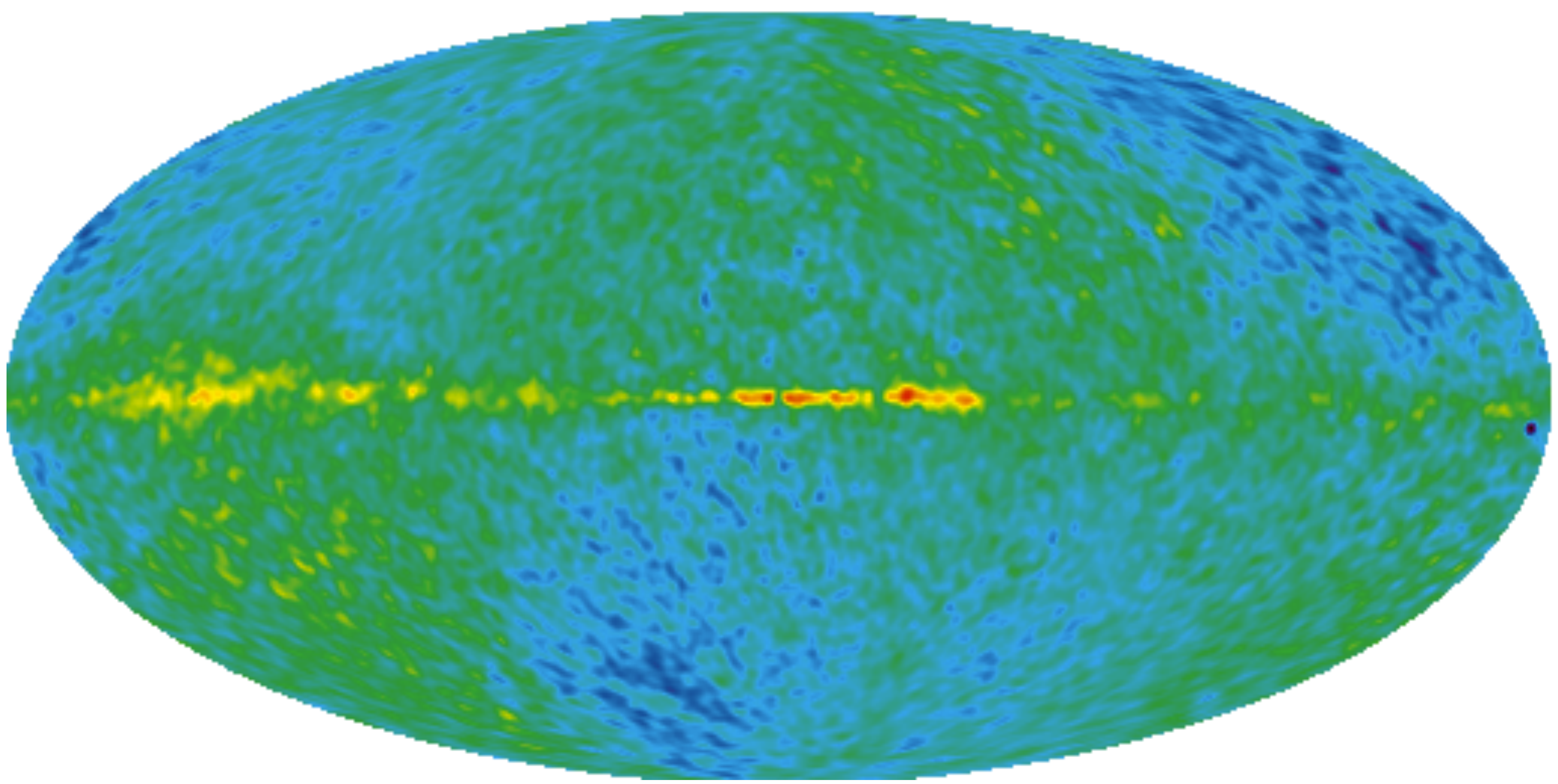


Stokes Q

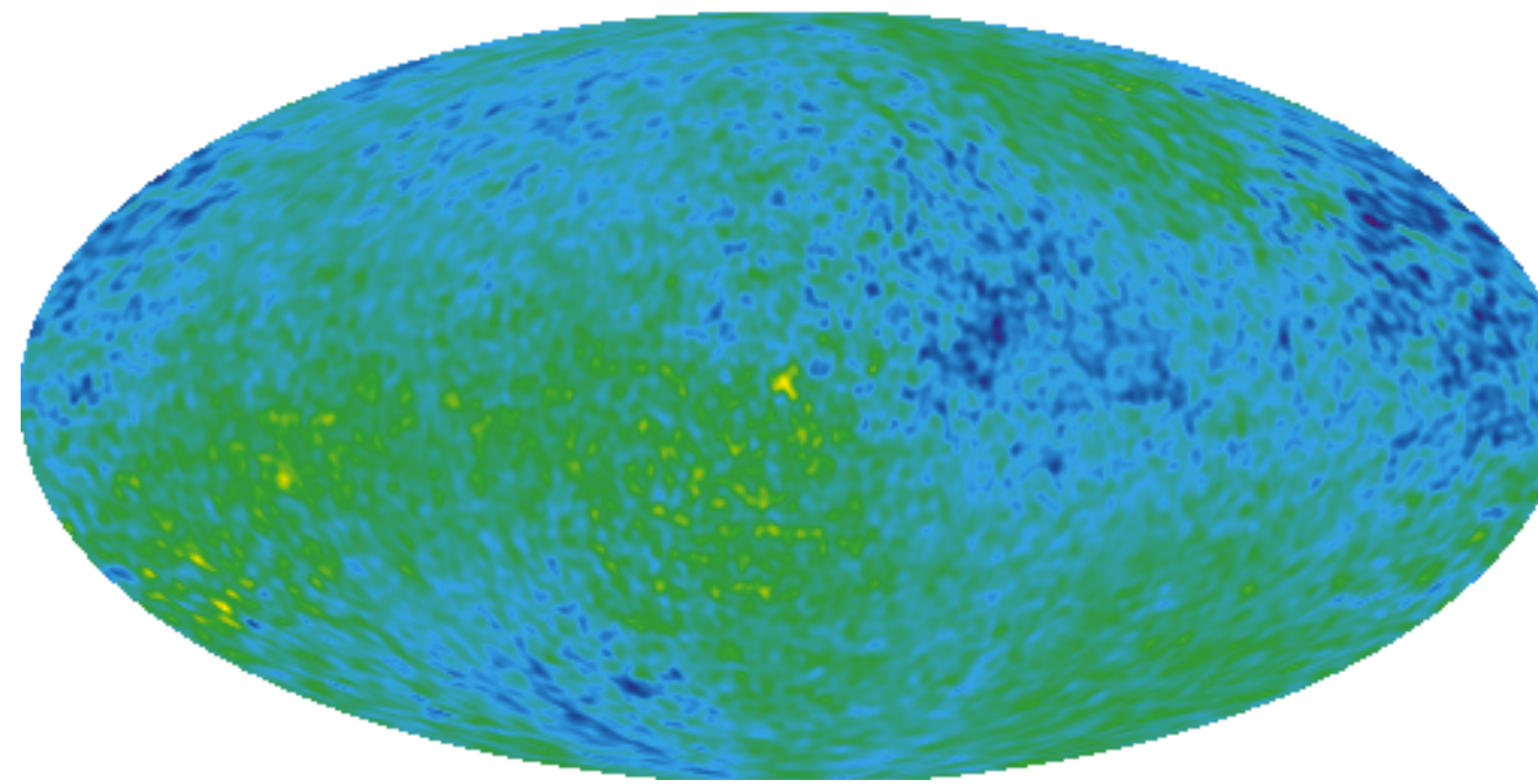


Stokes U

94 GHz [polarized]



Stokes Q



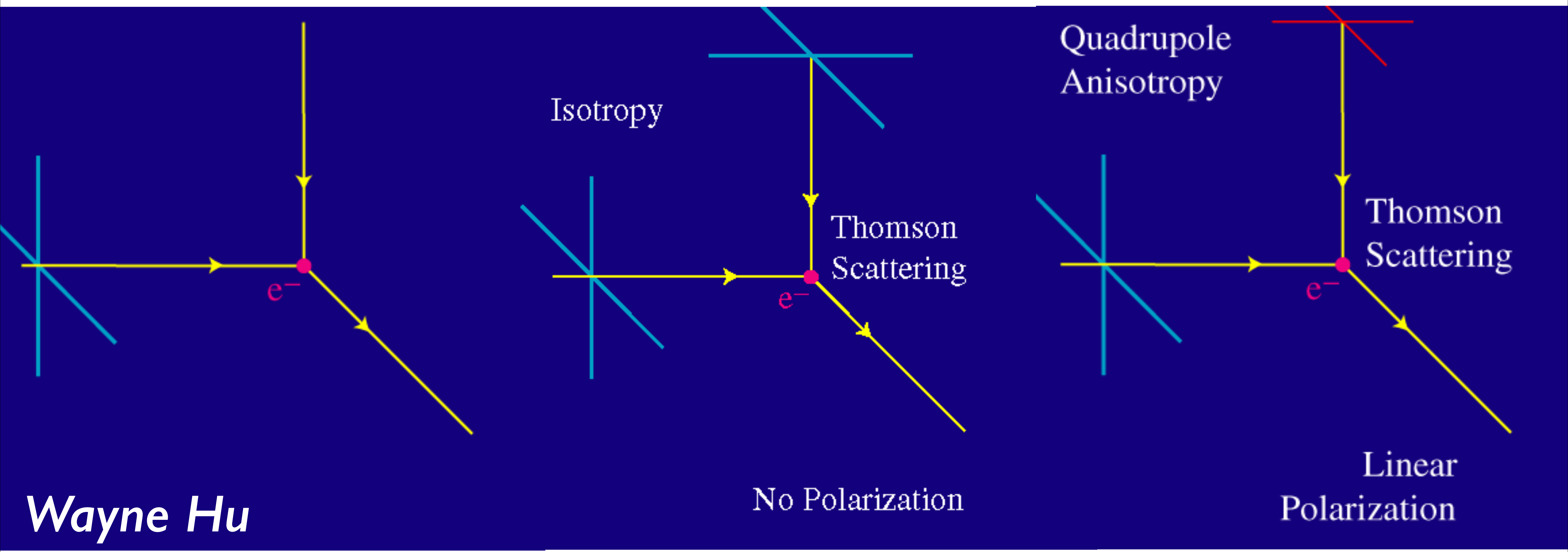
Stokes U

How many components?

1. **CMB**: $T_\nu \sim \nu^0$
2. **Synchrotron** (electrons going around magnetic fields): $T_\nu \sim \nu^{-3}$
3. **Dust** (heated dust emitting thermal emission): $T_\nu \sim \nu^2$

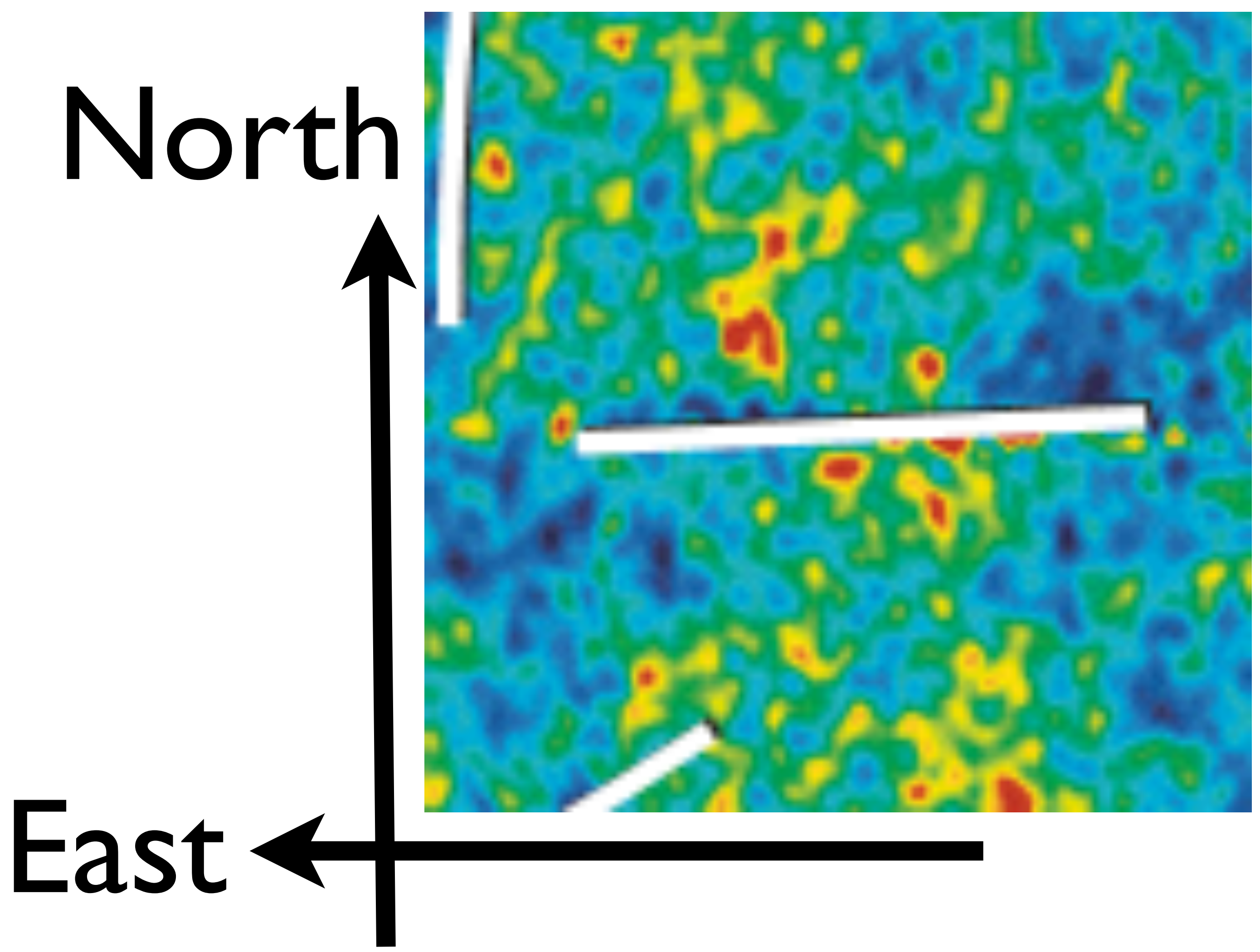
*You need at least **THREE** frequencies to separate them!*

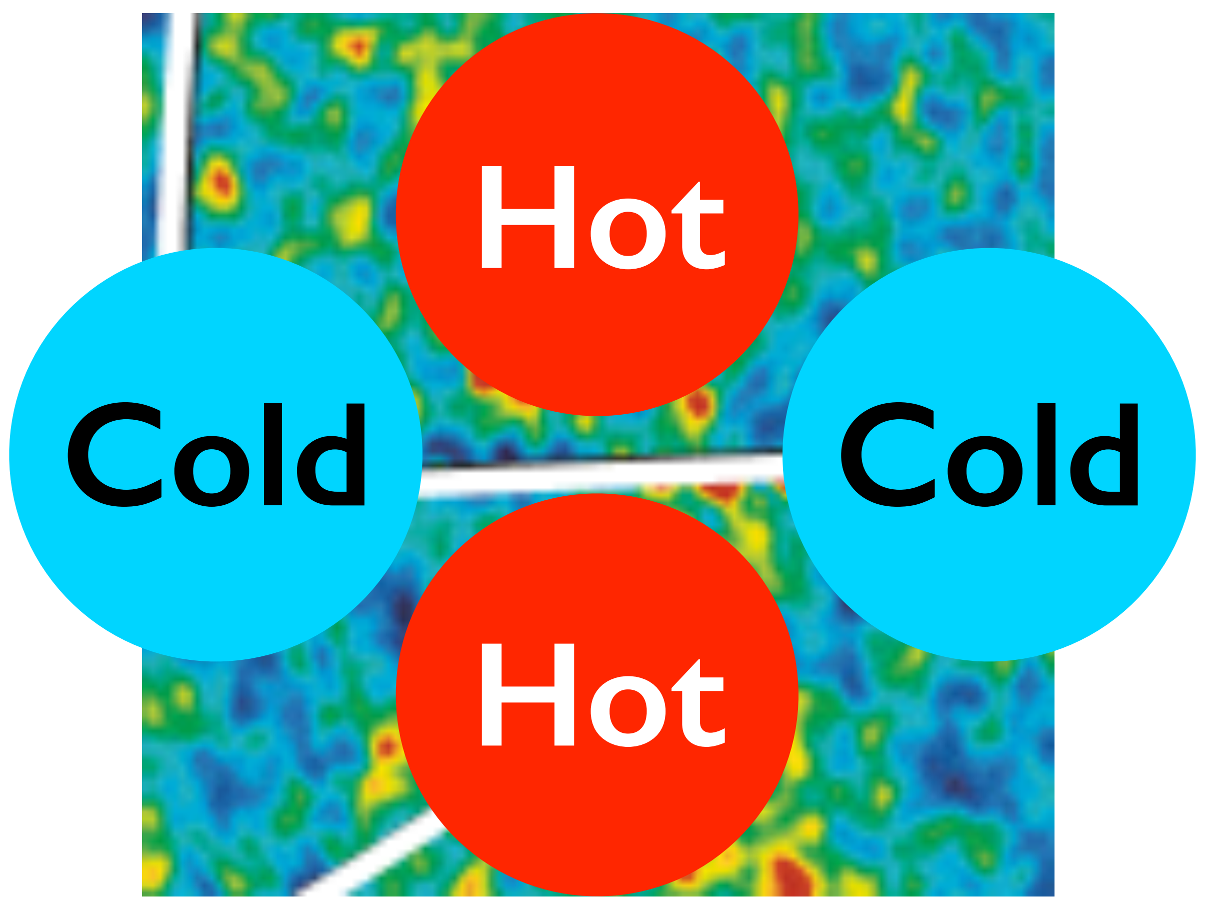
Physics of CMB Polarization



- CMB Polarization is created by a local temperature **quadrupole** anisotropy.

Principle



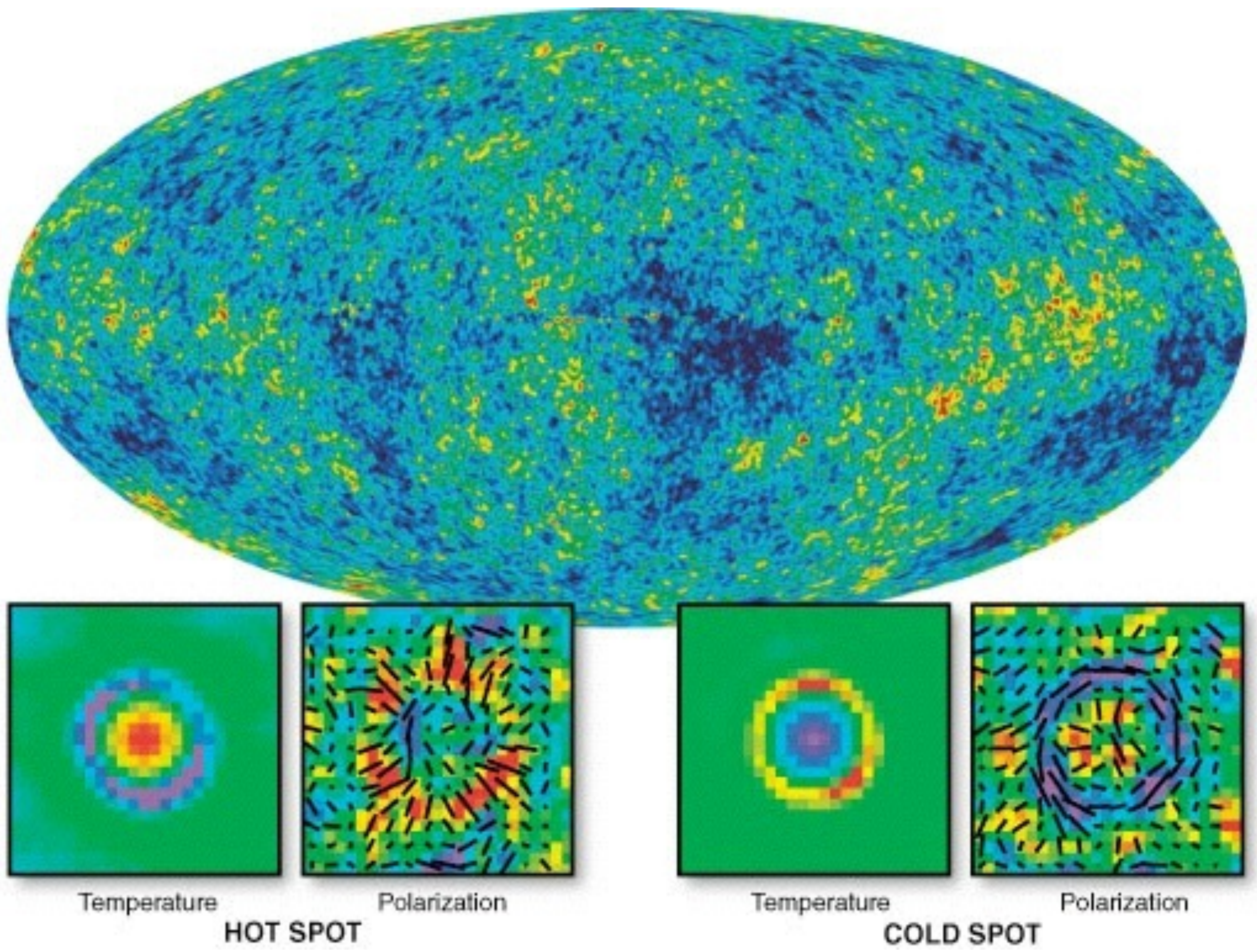


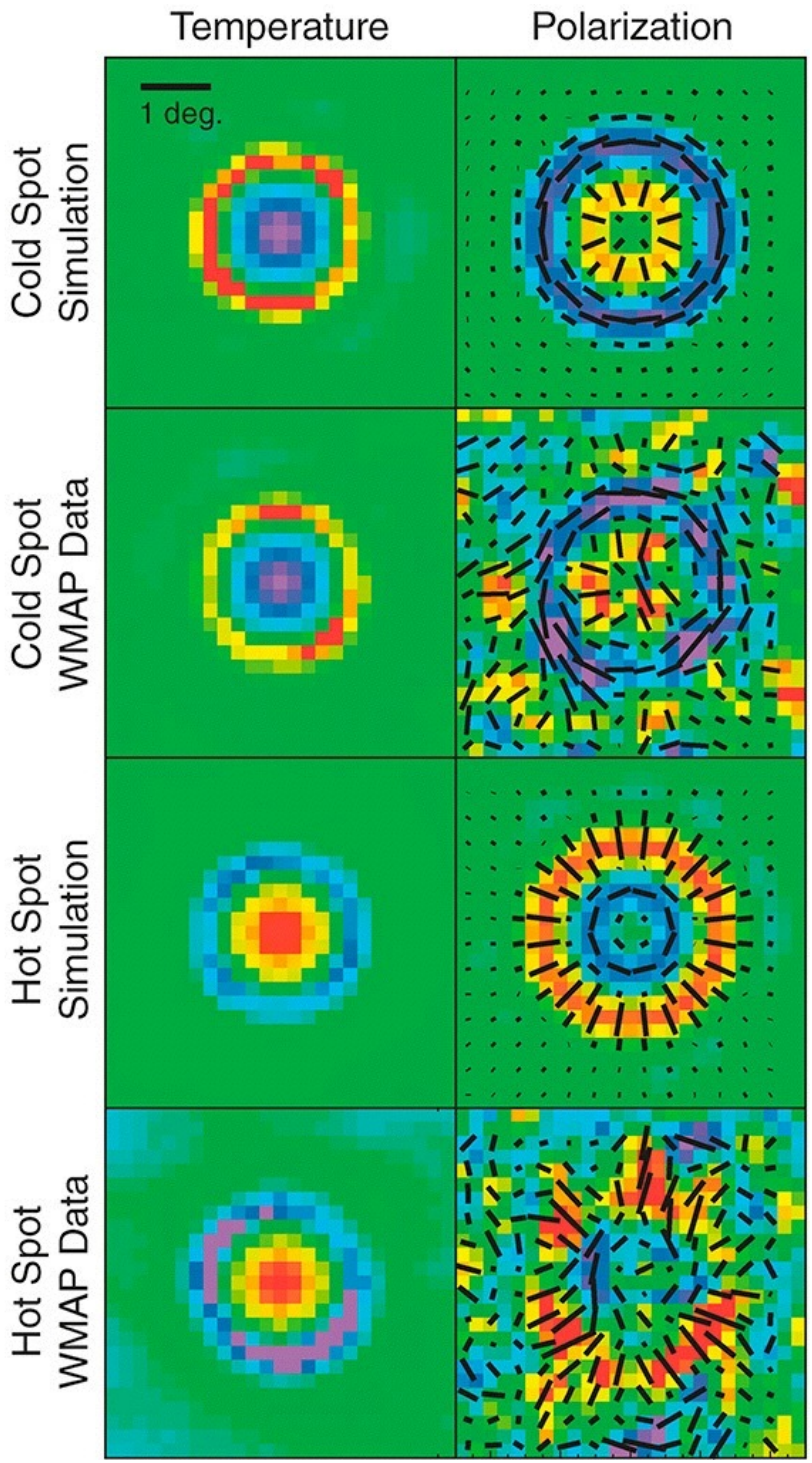
- **Polarization direction is parallel to "hot."**

Stacking Analysis

- Stack polarization images around temperature hot and cold spots.

- Outside of the Galaxy mask (not shown), there are 11536 hot spots and 11752 cold spots.



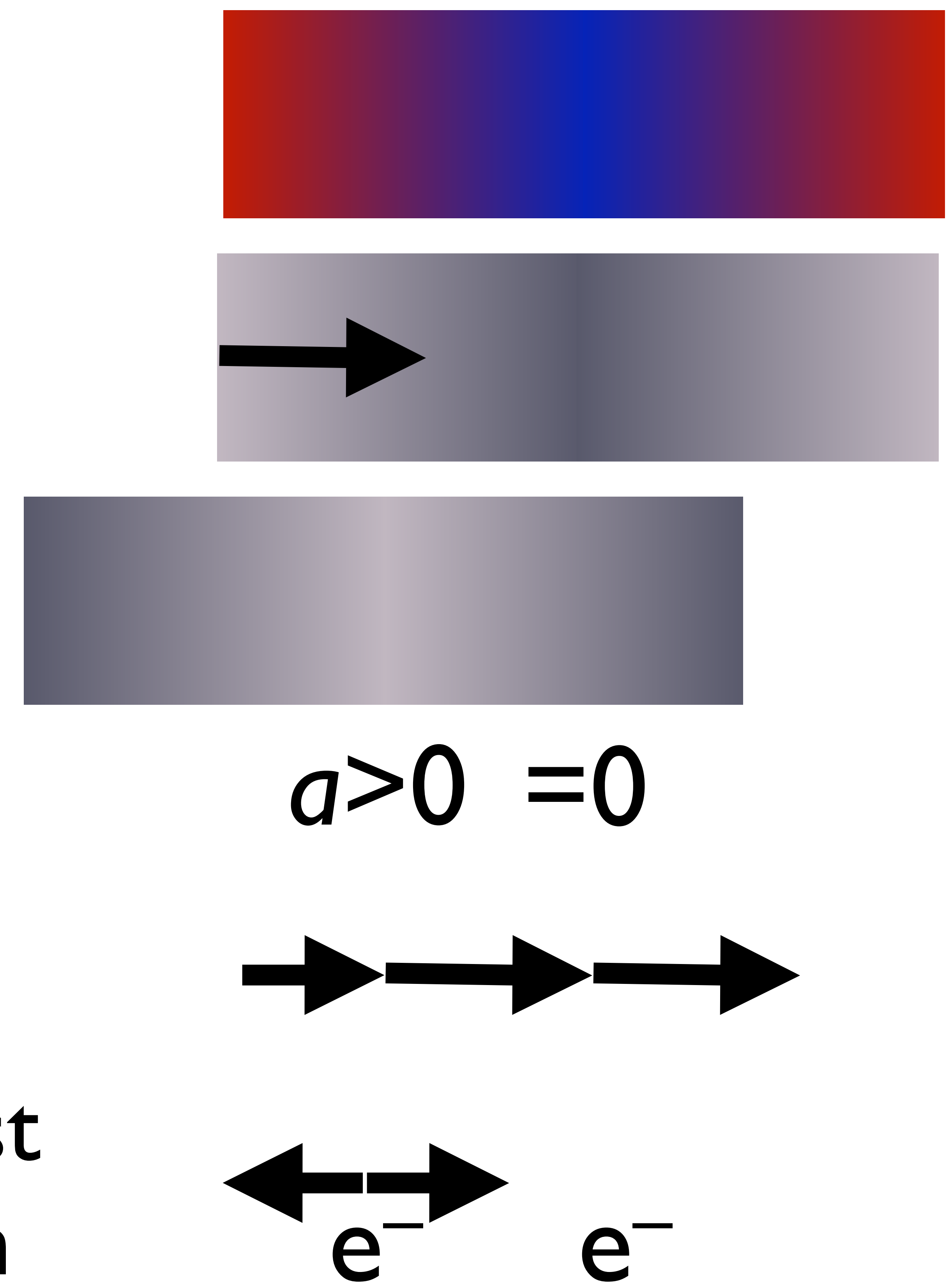


WMAP

Radial and Tangential Polarization Patterns around Temp. Spots

- All hot and cold spots are stacked
- “Compression phase” at θ=1.2 deg and “slow-down phase” at θ=0.6 deg are predicted to be there and we observe them!
- The 7-year overall significance level: 8σ

Quadrupole From Velocity Gradient (Large Scale)



ΔT — Sachs-Wolfe: $\Delta T/T=\Phi/3$

Potential Φ — Stuff flowing *in*

Acceleration $a=-\partial\Phi$

Velocity — Velocity gradient

Velocity in the rest frame of electron — The left electron sees colder photons along the plane wave

Polarization — Radial — None

Quadrupole From Velocity Gradient (Small Scale)

ΔT — Compression increases temperature

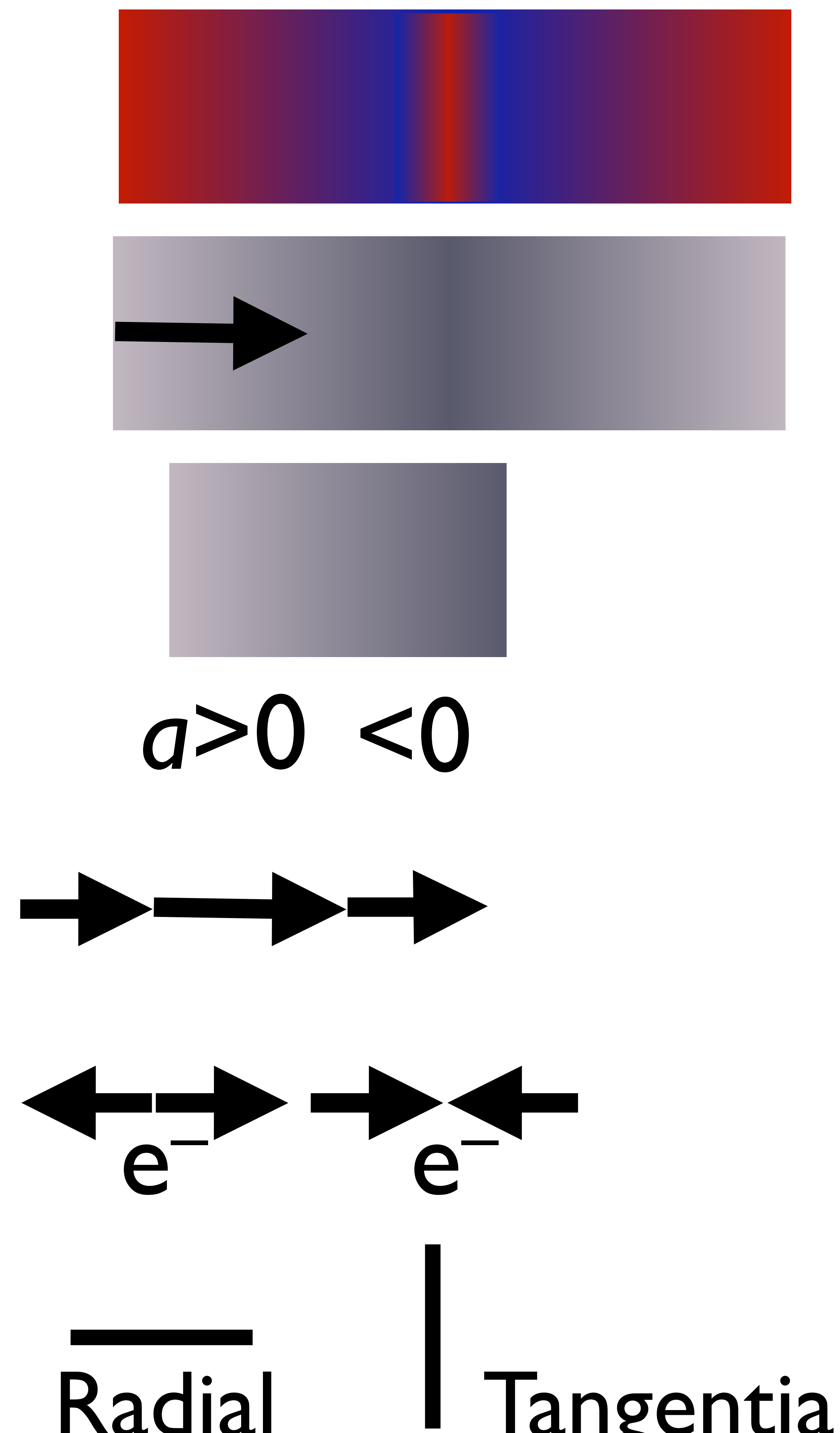
Potential Φ — Stuff flowing *in*

Acceleration $a = -\partial\Phi - \partial P$ — Pressure gradient slows down the flow

Velocity — Velocity gradient

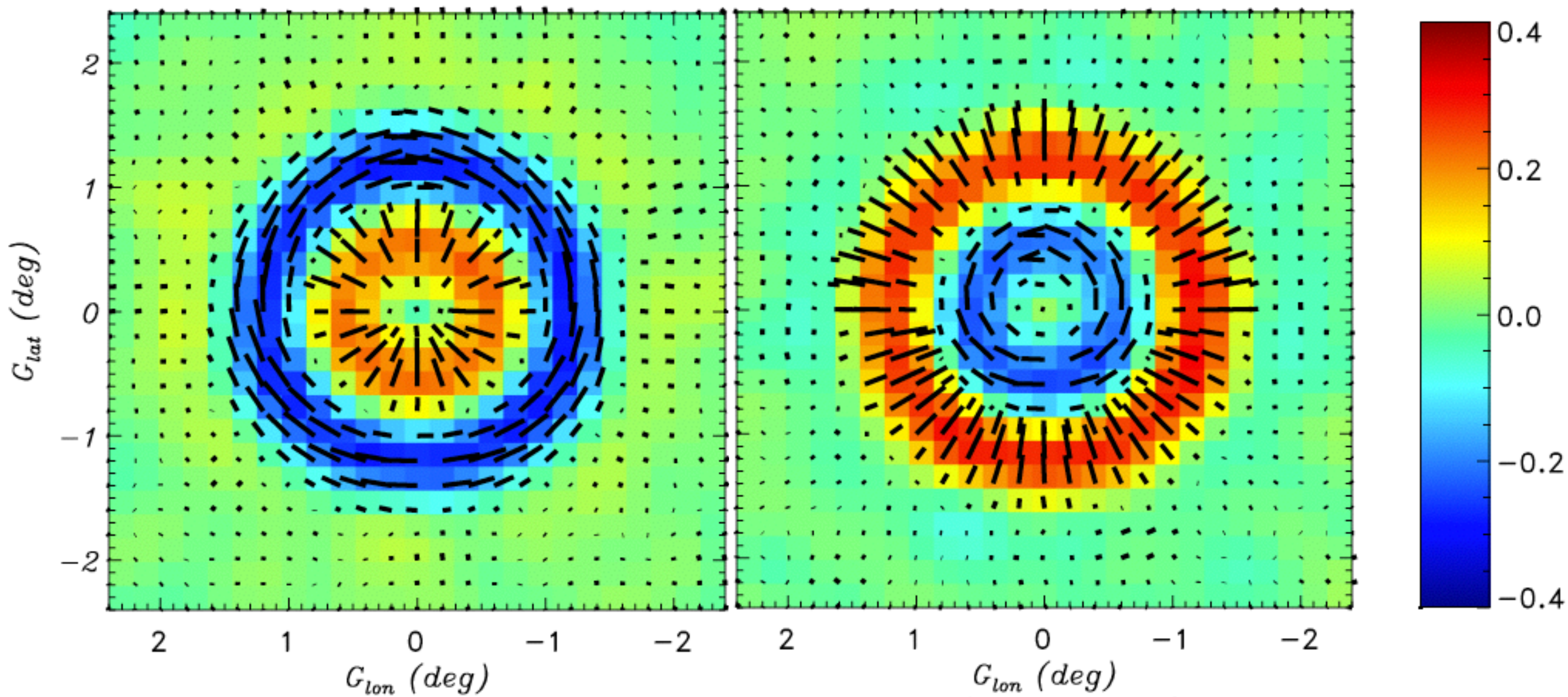
Velocity in the rest frame of electron

Polarization



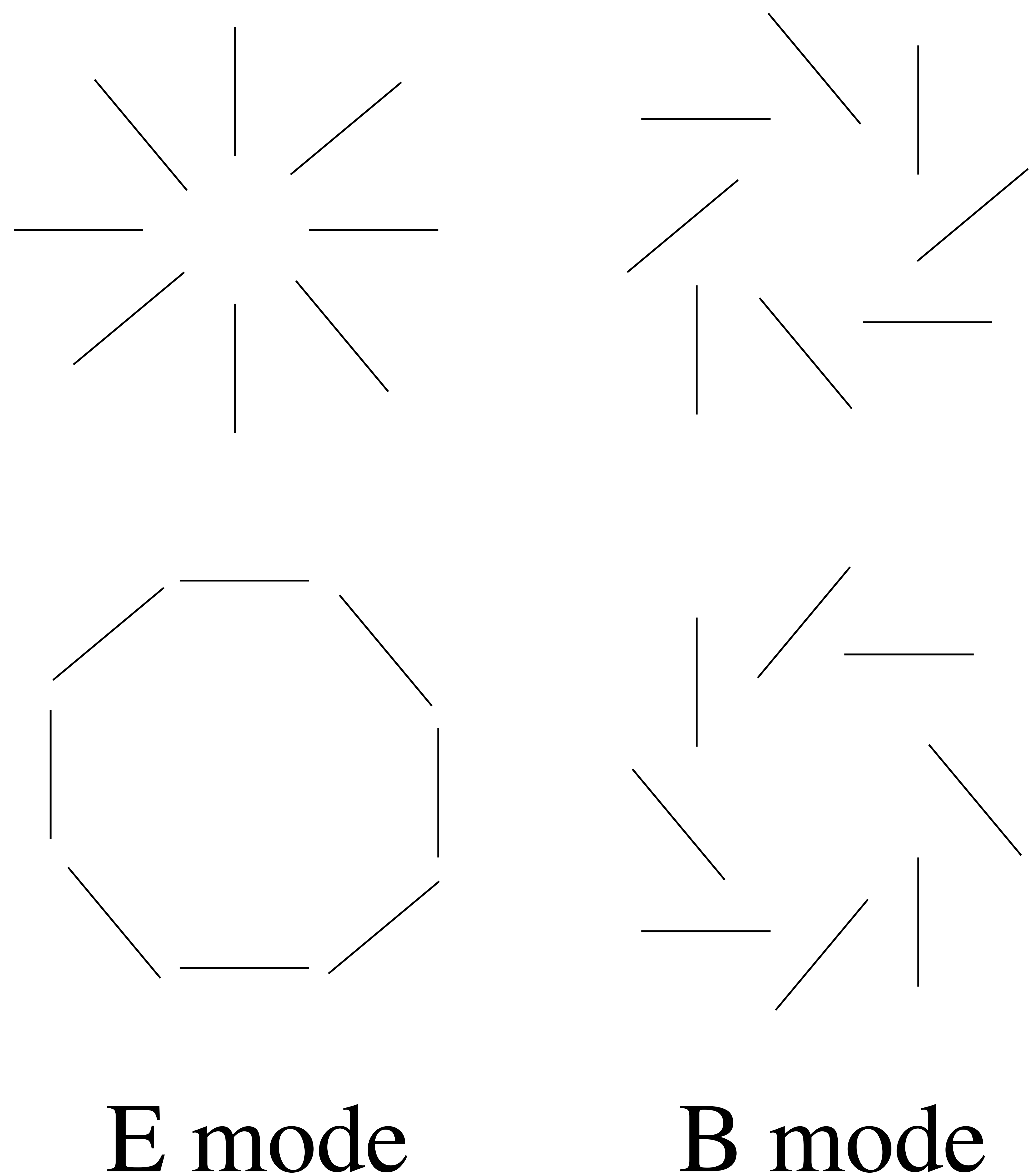
Planck Collaboration I (2013)

Planck Data!



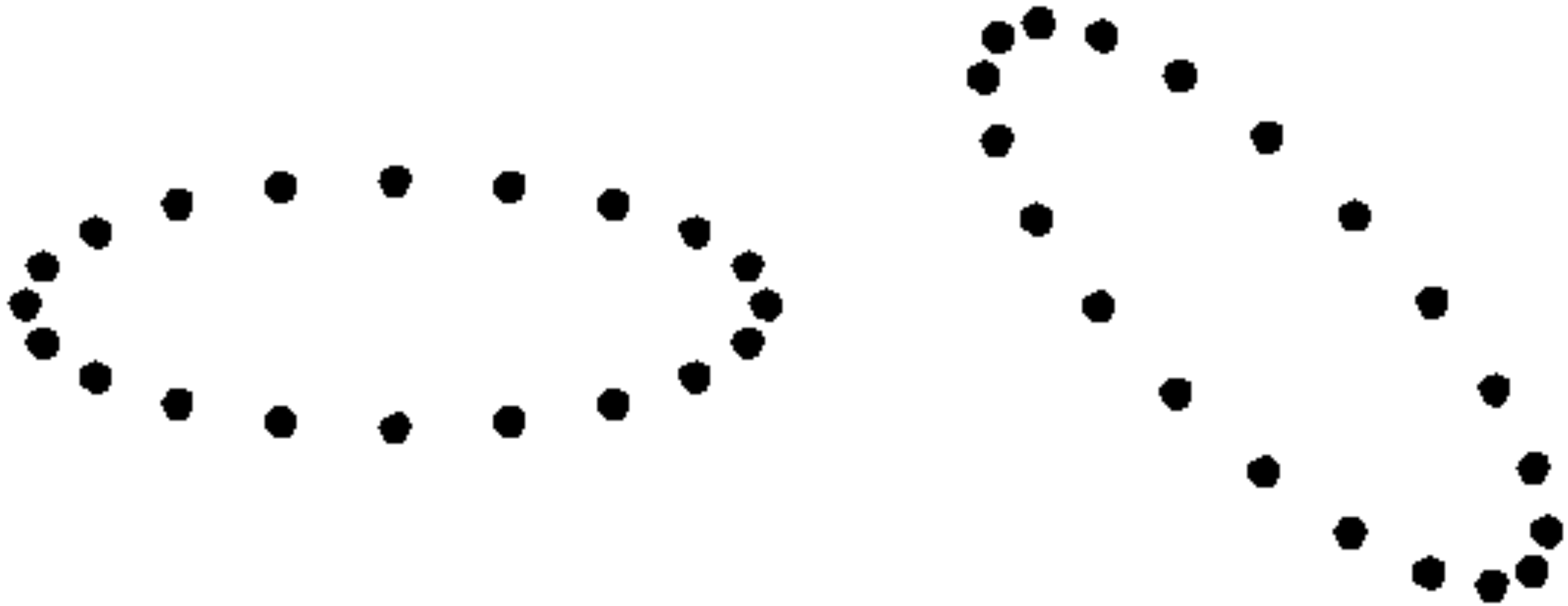
Q_r (cold spots) Q_r (hot spots)

E-mode and B-mode



- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

Two Polarization States of GW



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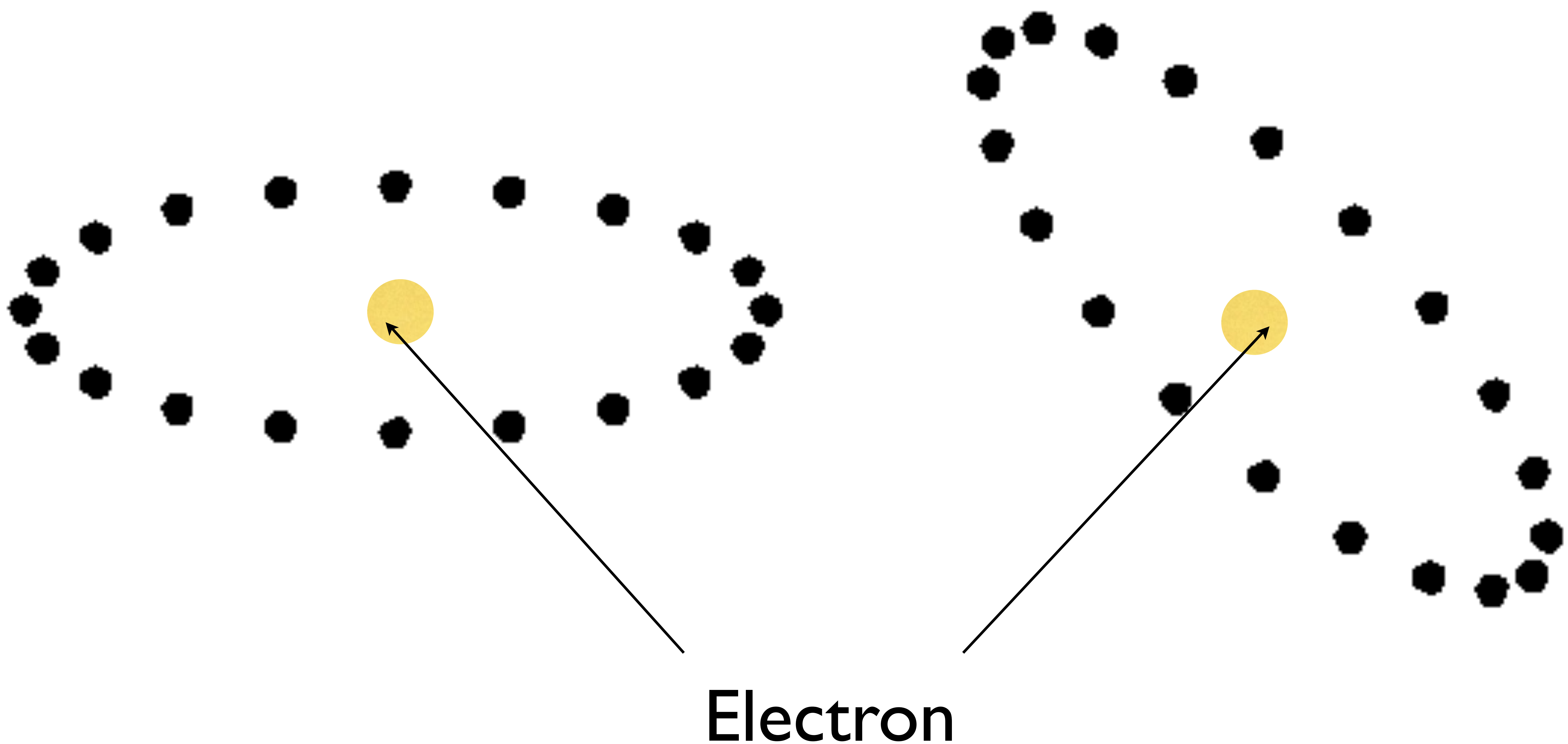
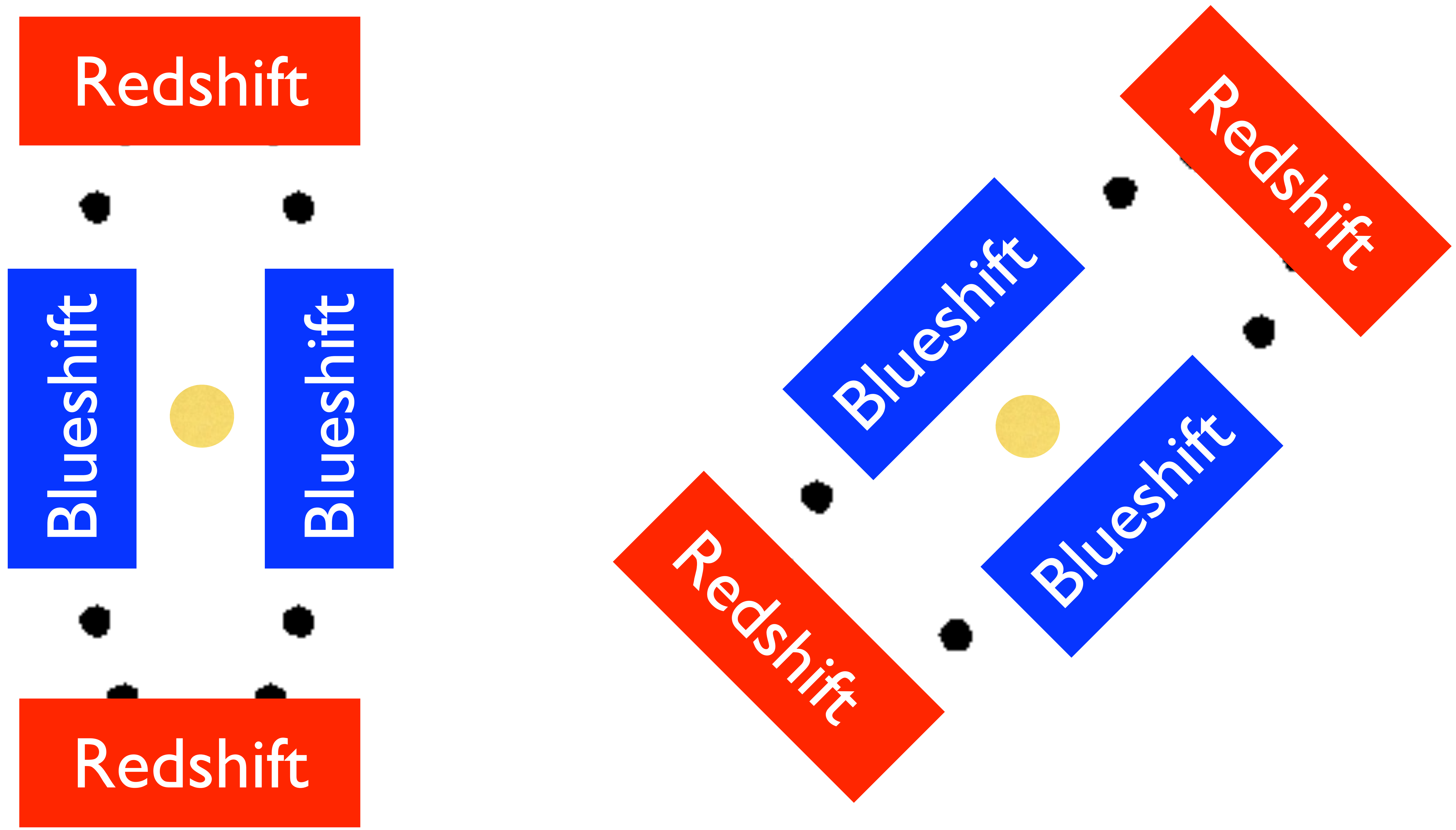
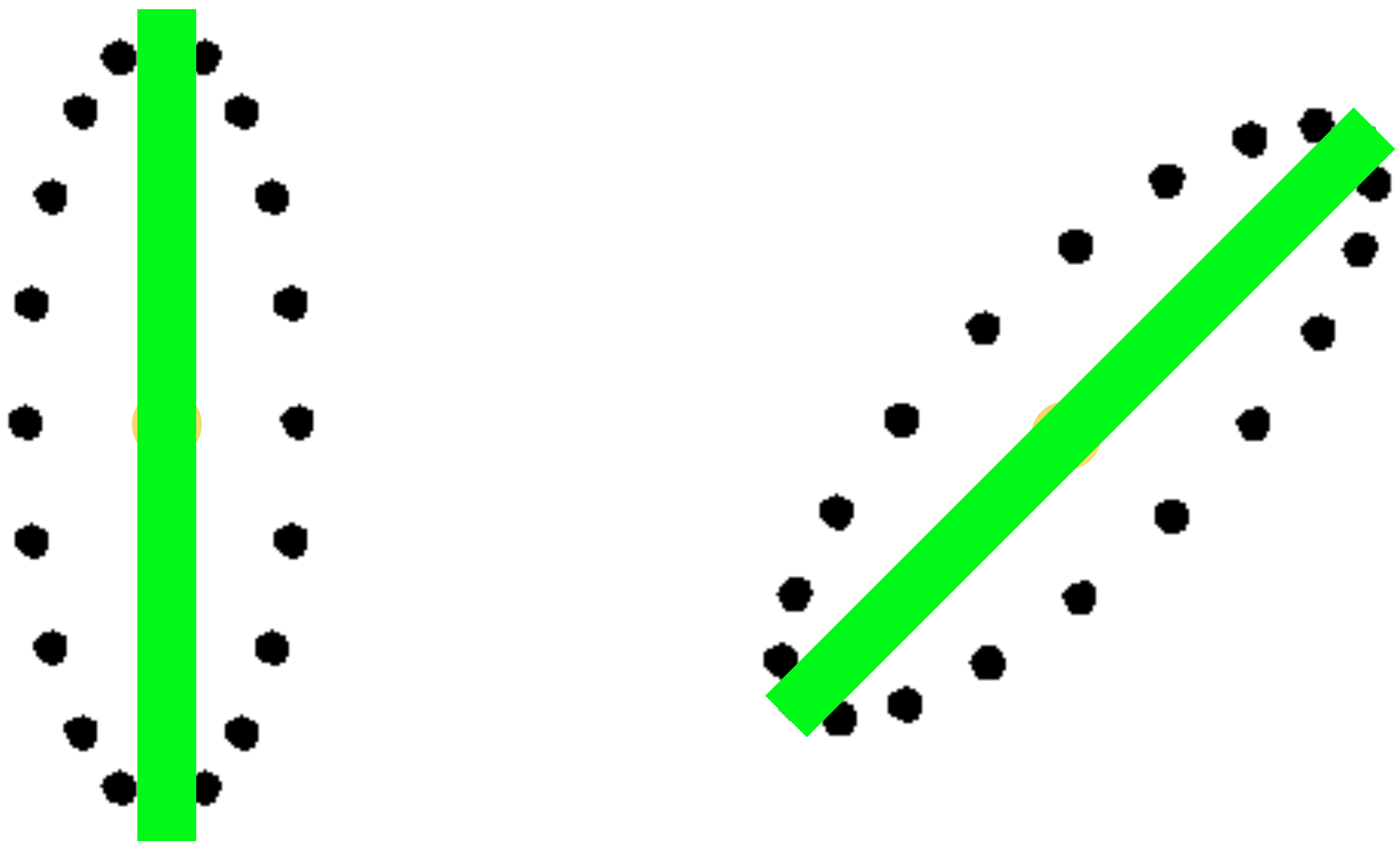
From GW to CMB Polarization



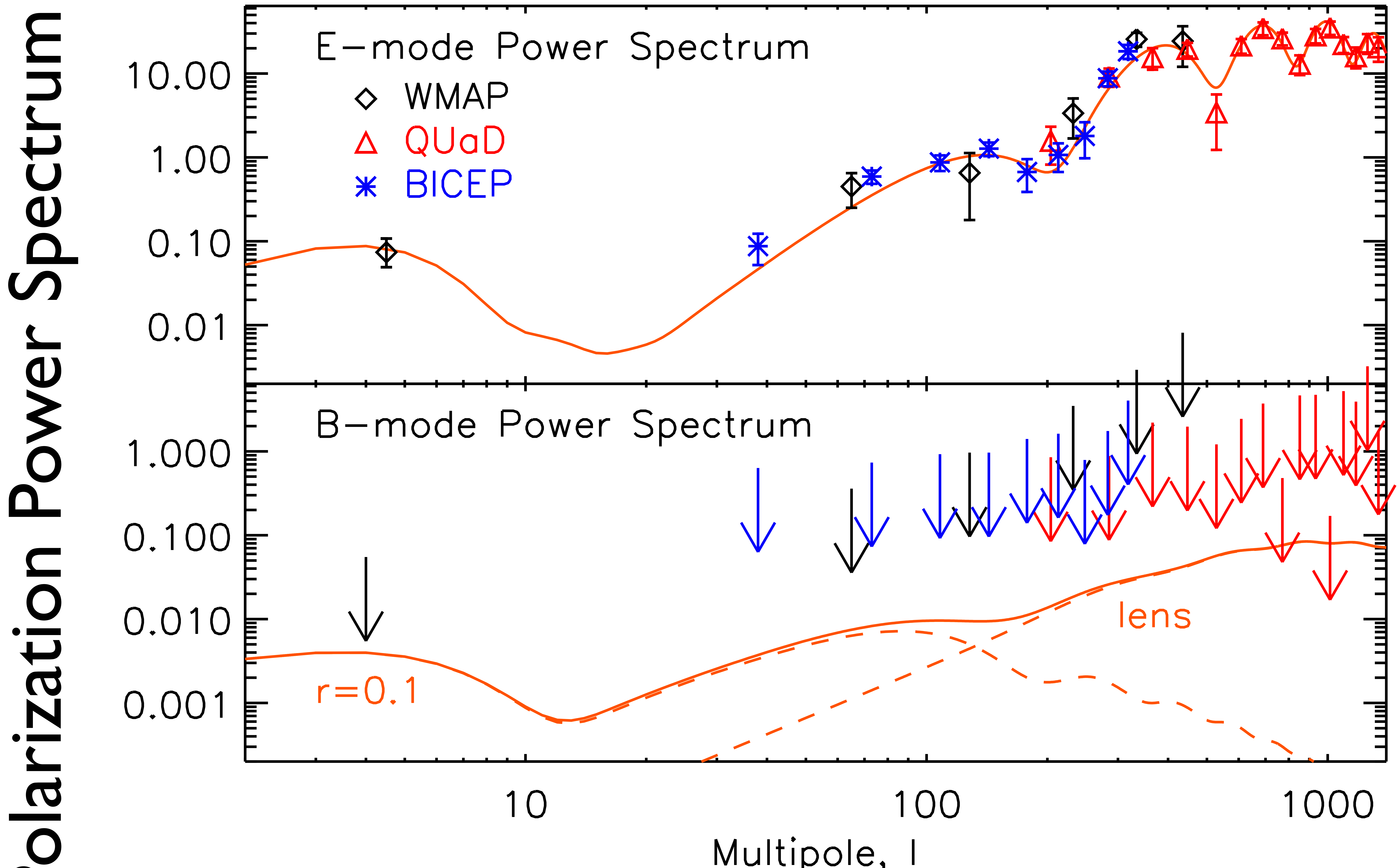
From GW to CMB Polarization



From GW to CMB Polarization



Gravitational waves can produce
both E- and B-mode polarization



- No detection of B-mode polarization at degree scales, *before March 17*

“Tensor-to-scalar Ratio,” r

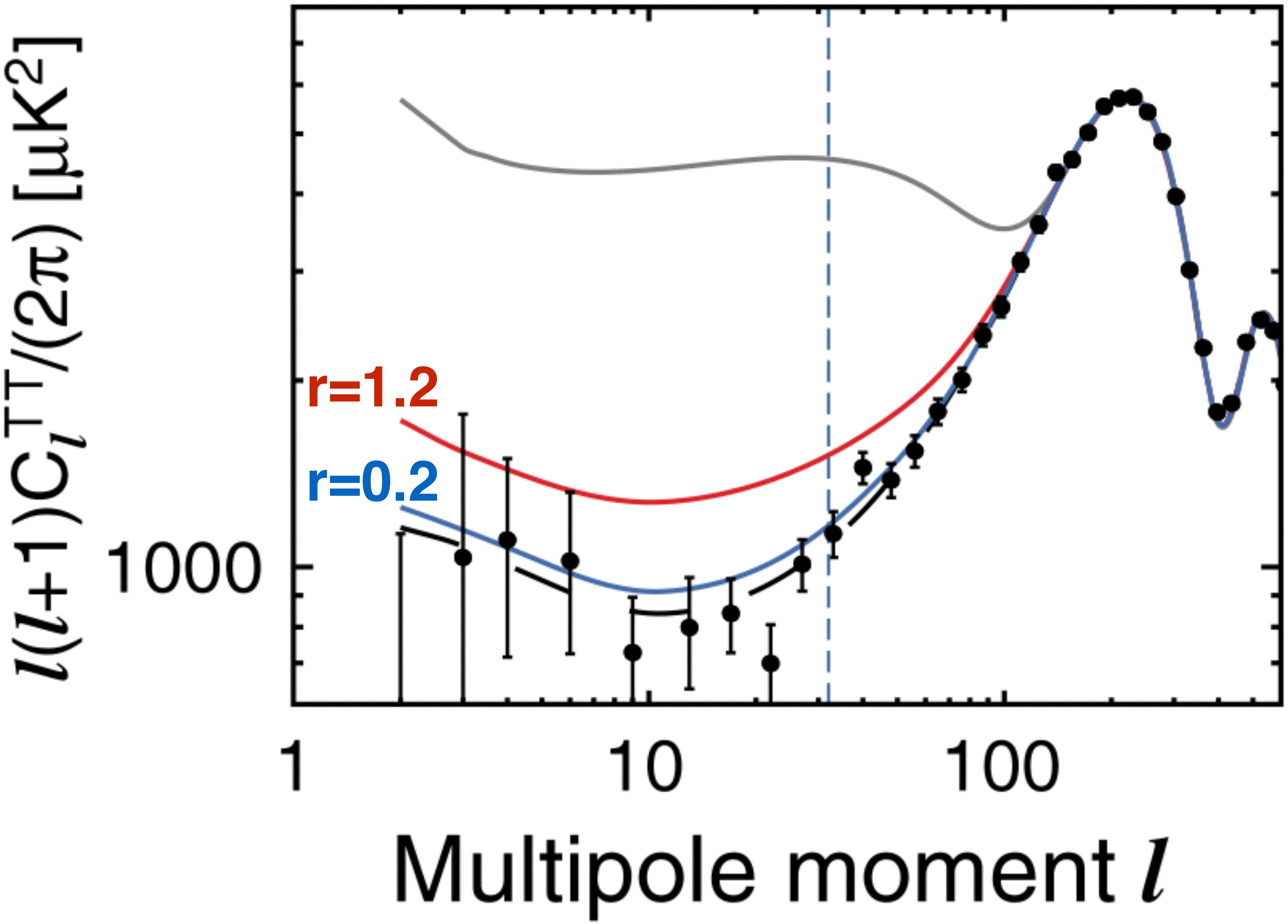
r = [Power in Gravitational Waves]

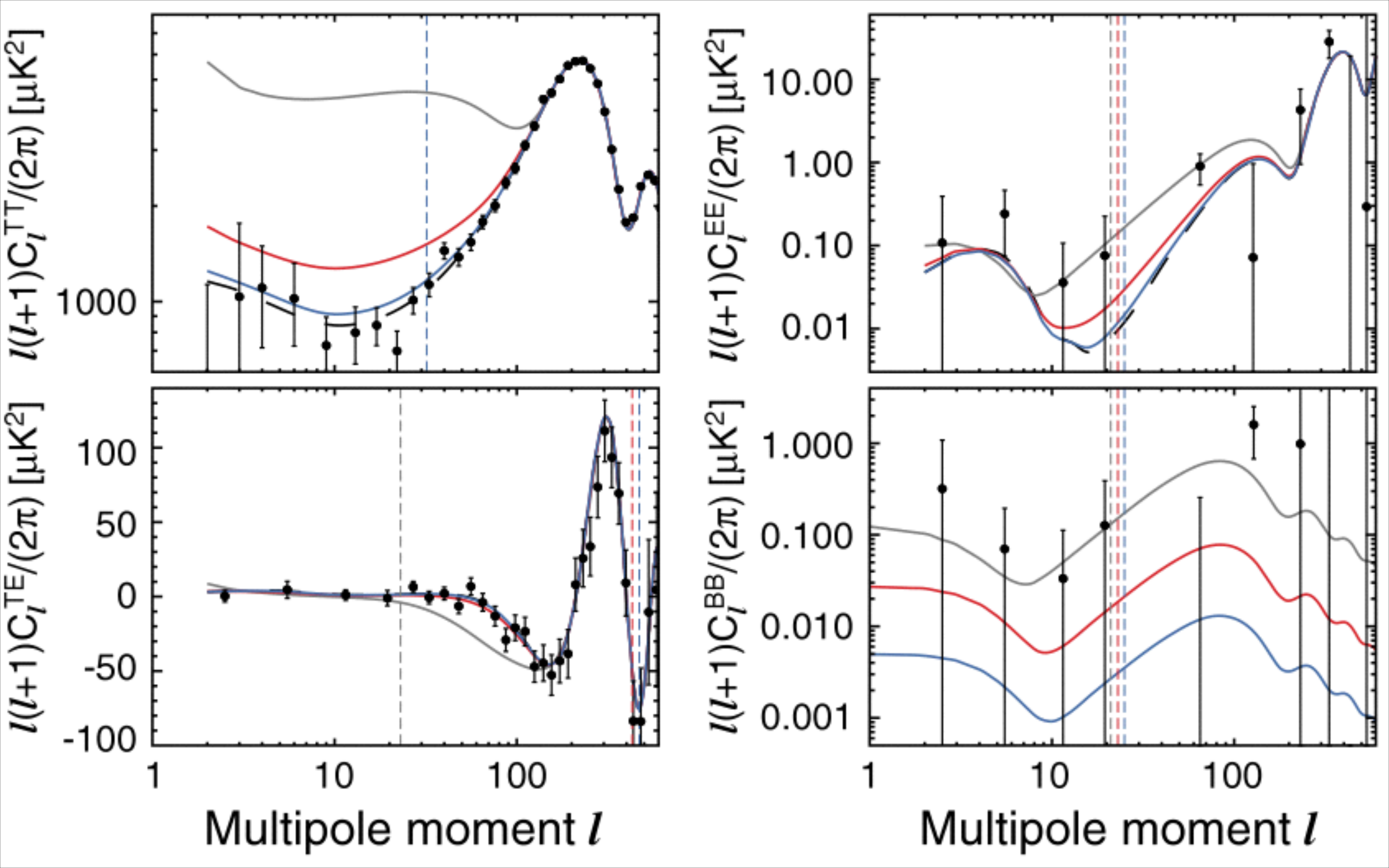
/ [Power in Curvature Perturbation]

$= \langle h_{ij,k0} h^{ij,k0*} \rangle / \langle |\zeta_{k0}|^2 \rangle$ at k_0=0.002 Mpc^{-1}

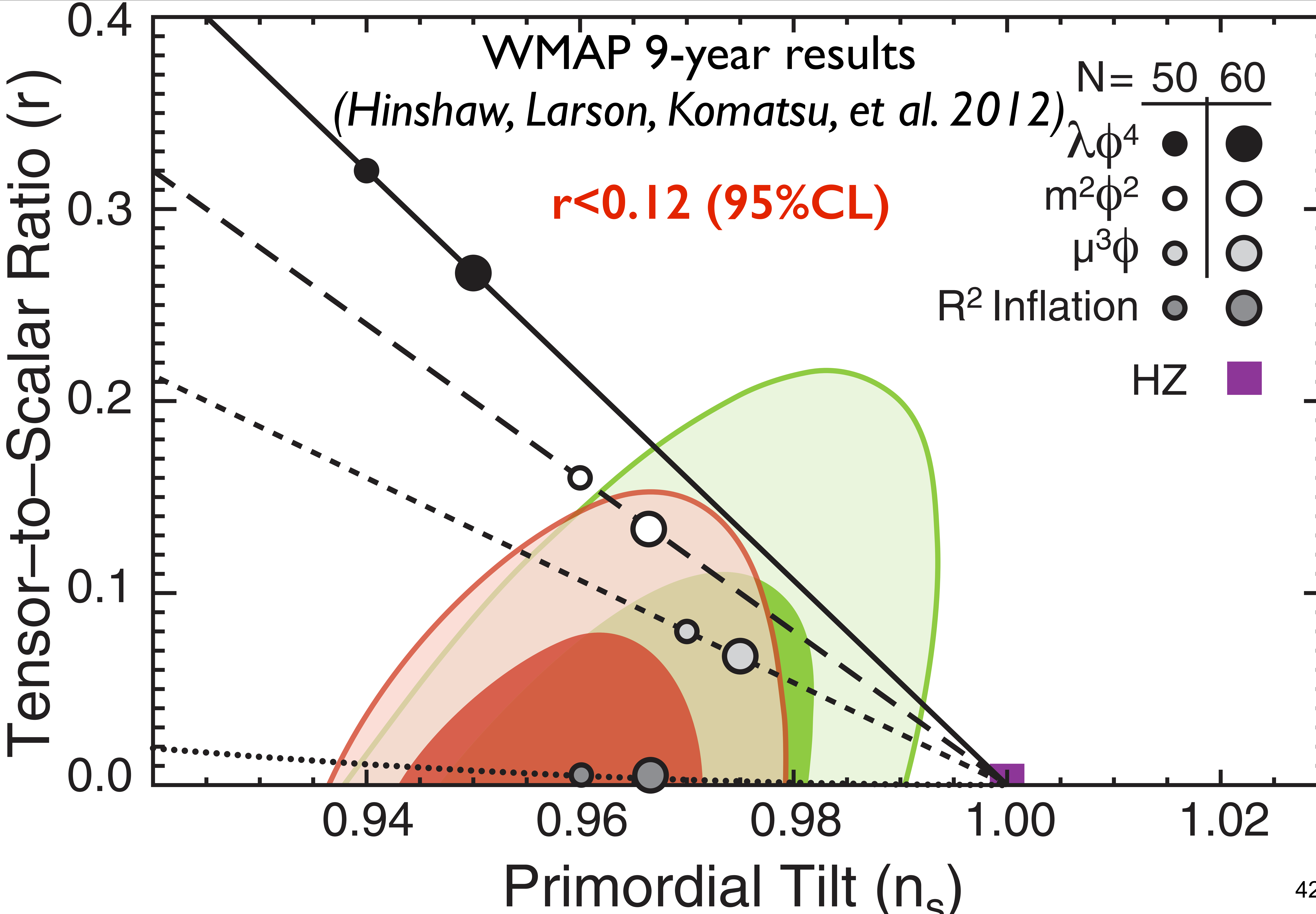
Inflation predicts r <~ 1

Limit from Temperature

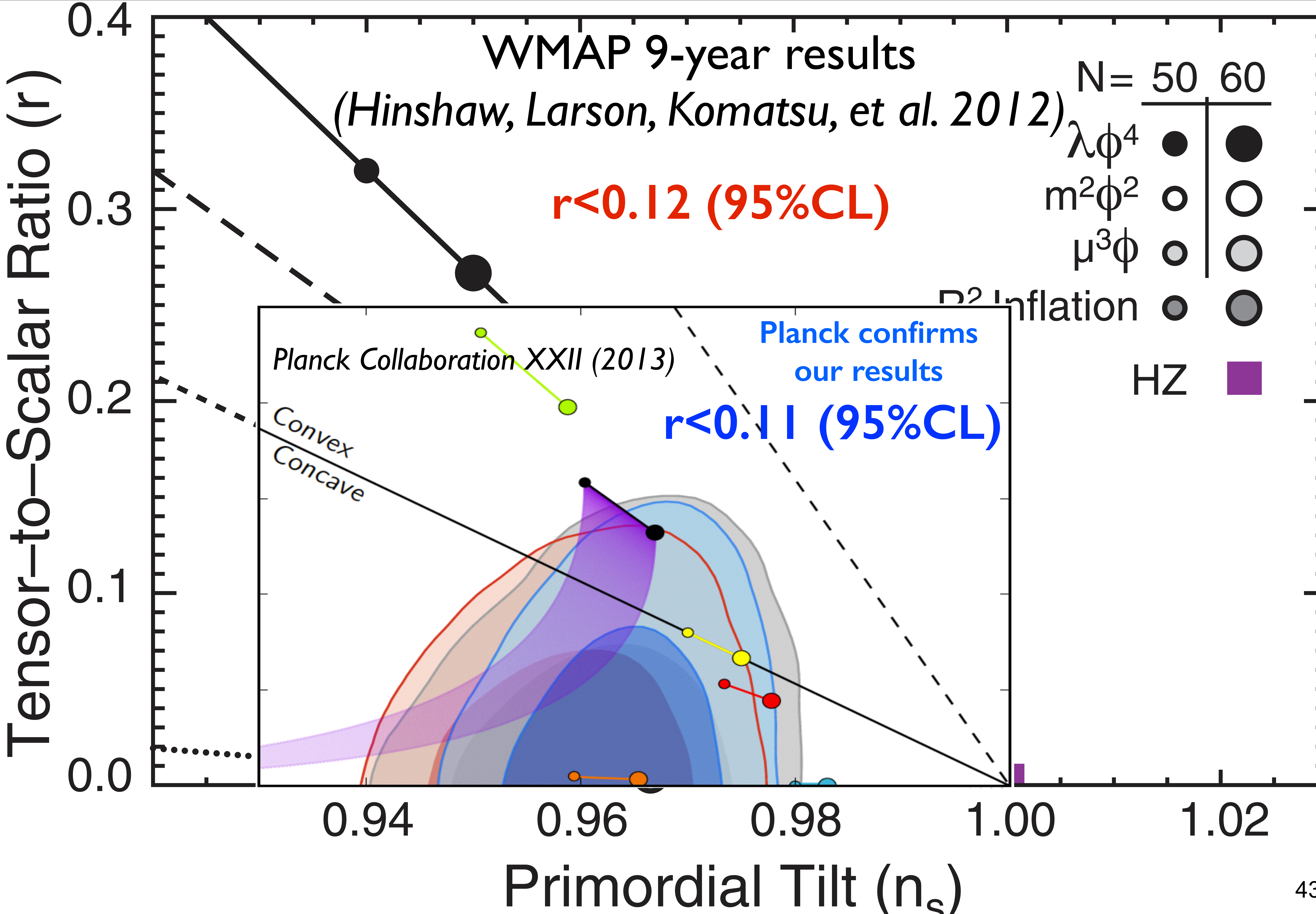




$l(l+1)C_l^{TT}/(2\pi)$ [μK^2]
1000
$l(l+1)C_l^{EE}/(2\pi)$ [μK^2]
10.00
1.00
0.10
0.01
$l(l+1)C_l^{TE}/(2\pi)$ [μK^2]
100
50
0
-50
-100
$l(l+1)C_l^{BB}/(2\pi)$ [μK^2]
1.000
0.100
0.010
0.001
1
10
100
Multipole moment l
1
10
100
Multipole moment l



WMAP 9-year results
(Hinshaw, Larson, Komatsu, et al. 2012)
r<0.12 (95%CL)
N= 50 60
λφ4
m2φ2
μ3φ
R2 Inflation
HZ
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 (ns)



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r<0.12 (95%CL)
N= 50 60
λφ4
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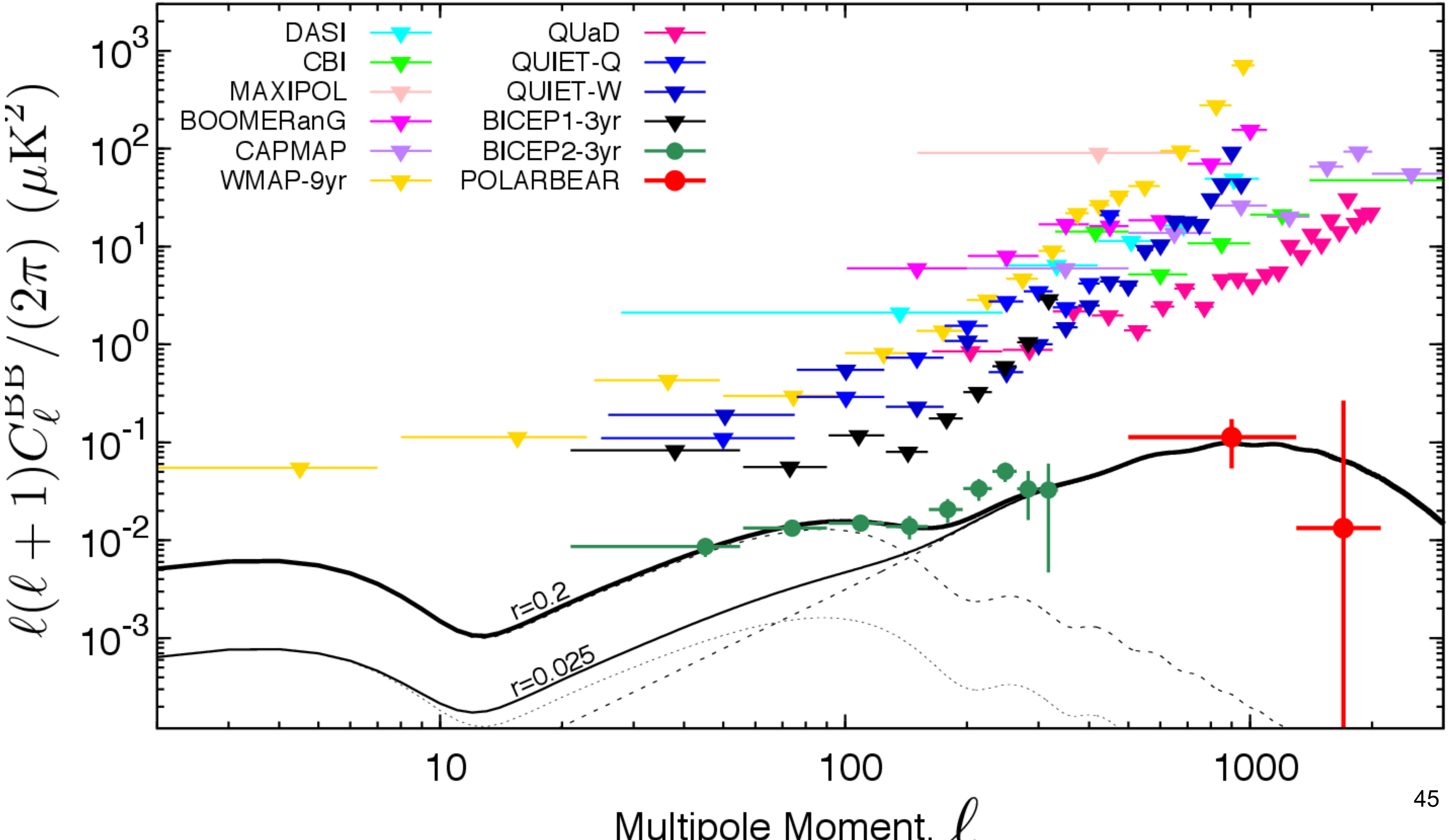
R2 Inflation
HZ
Planck Collaboration XXII (2013)
Planck confirms our results
r<0.11 (95%CL)
Convex
Concave
Tensor-to-Scalar Ratio (r)
Primordial Tilt (ns)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02

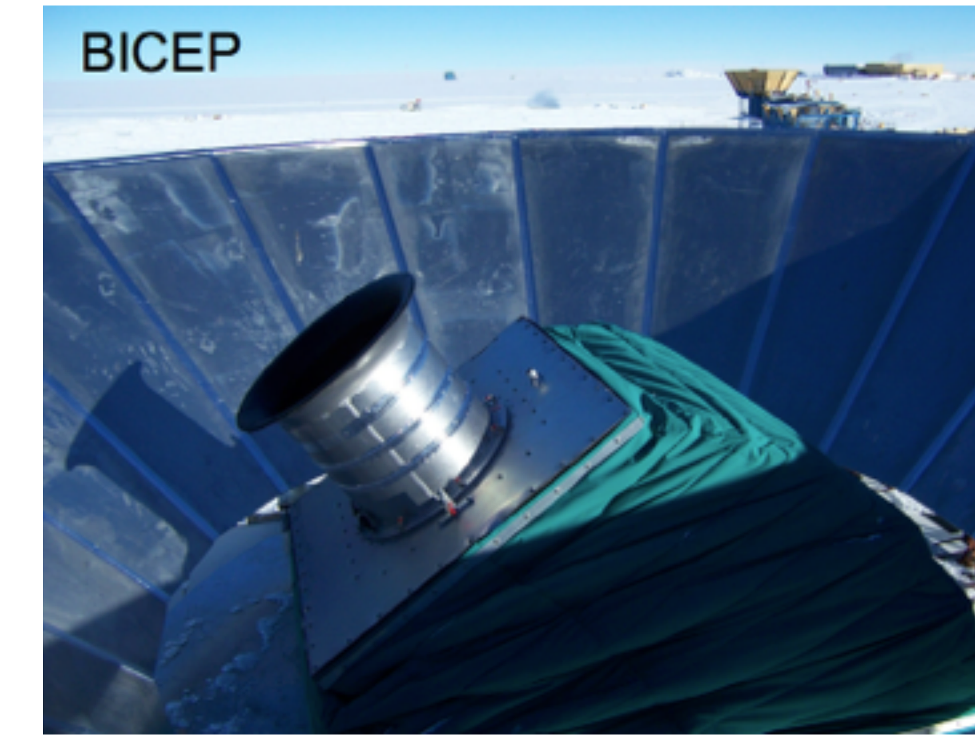
Then…

- 10:45 (Eastern Standard Time), March 17, 2014

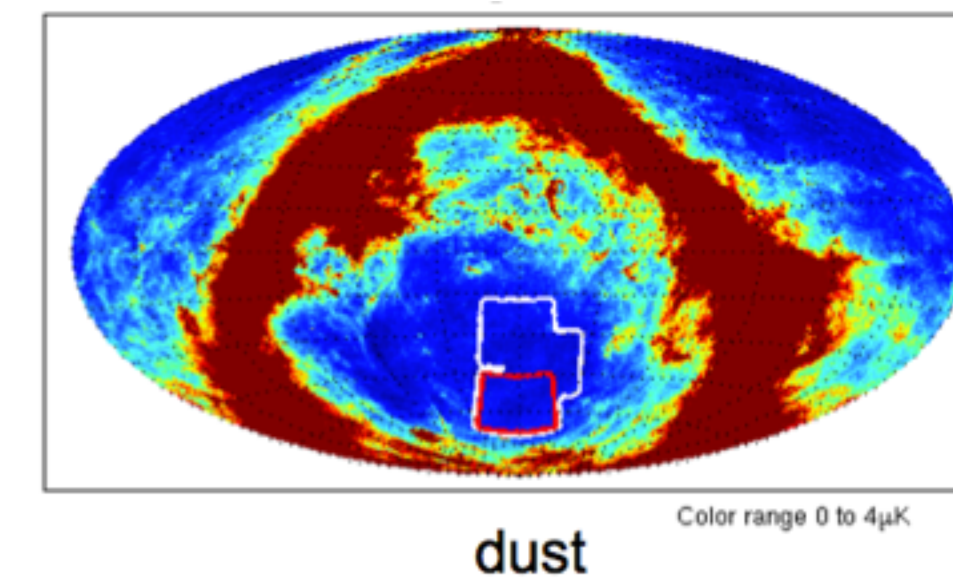
*Courtesy of Yuji Chinone, with the POLARBEAR data points



What is BICEP2?



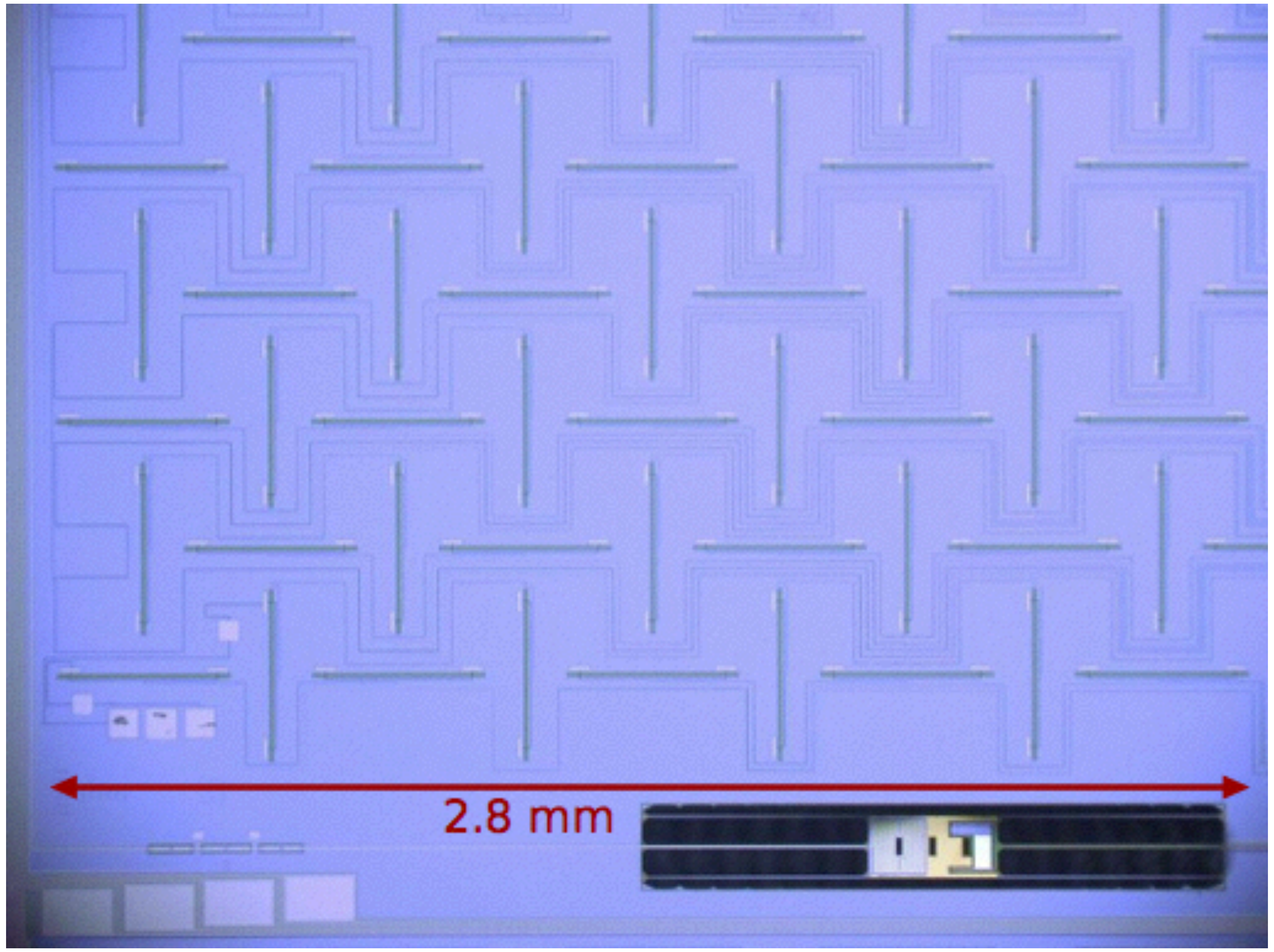
- A small [26 cm] refractive telescope at South Pole
- 512 bolometers working at 150 GHz
- Observed 380 square degrees for three years [2010-2012]



- 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 polarization?

- Taking the difference between two detectors (A&B), measuring two orthogonal polarization states



Horizontal slots
-> A detector

Vertical slots
-> B detector

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

Implication of the measured tensor-to-scalar ratio

- The measured r is directly connected to the potential energy of a field driving inflation.
- **r = 0.2 implies 2×10^{16} GeV**
  - Grand Unification Scale! Inflation is a phenomenon of the high[est] energy physics
- r = 0.2 also implies that a field driving inflation moved by ~ 5 x Planck Mass. A challenge to model building

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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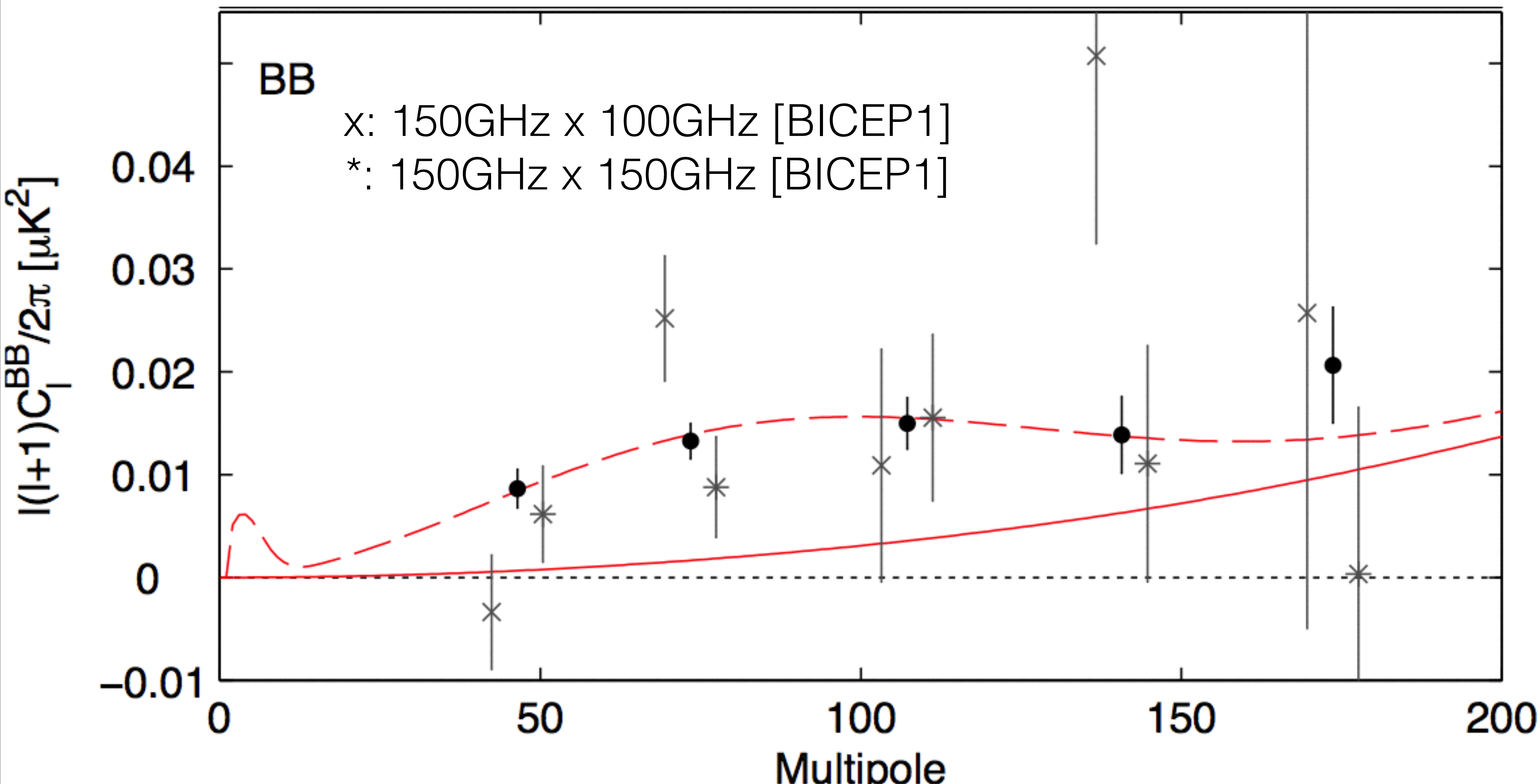
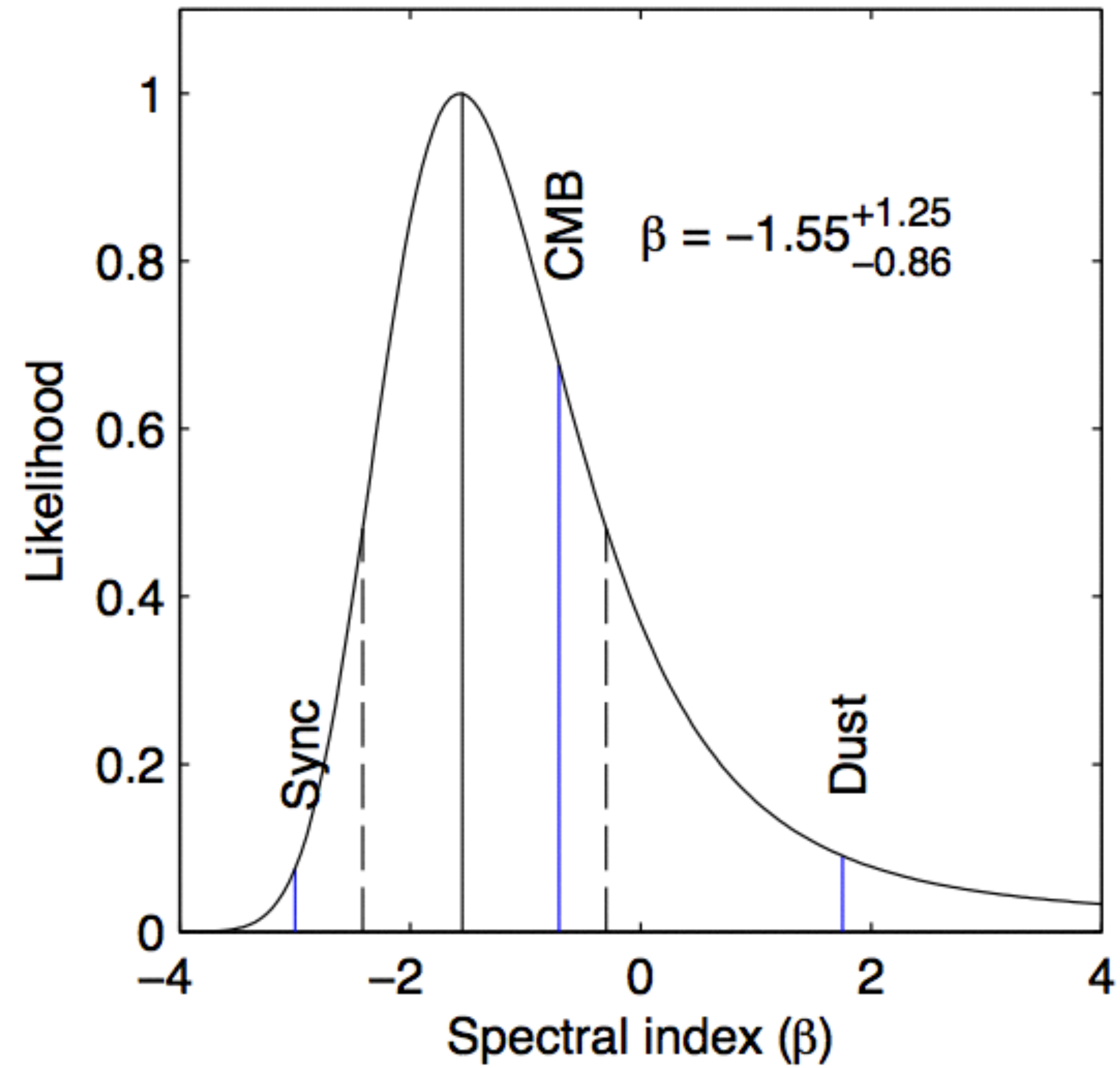


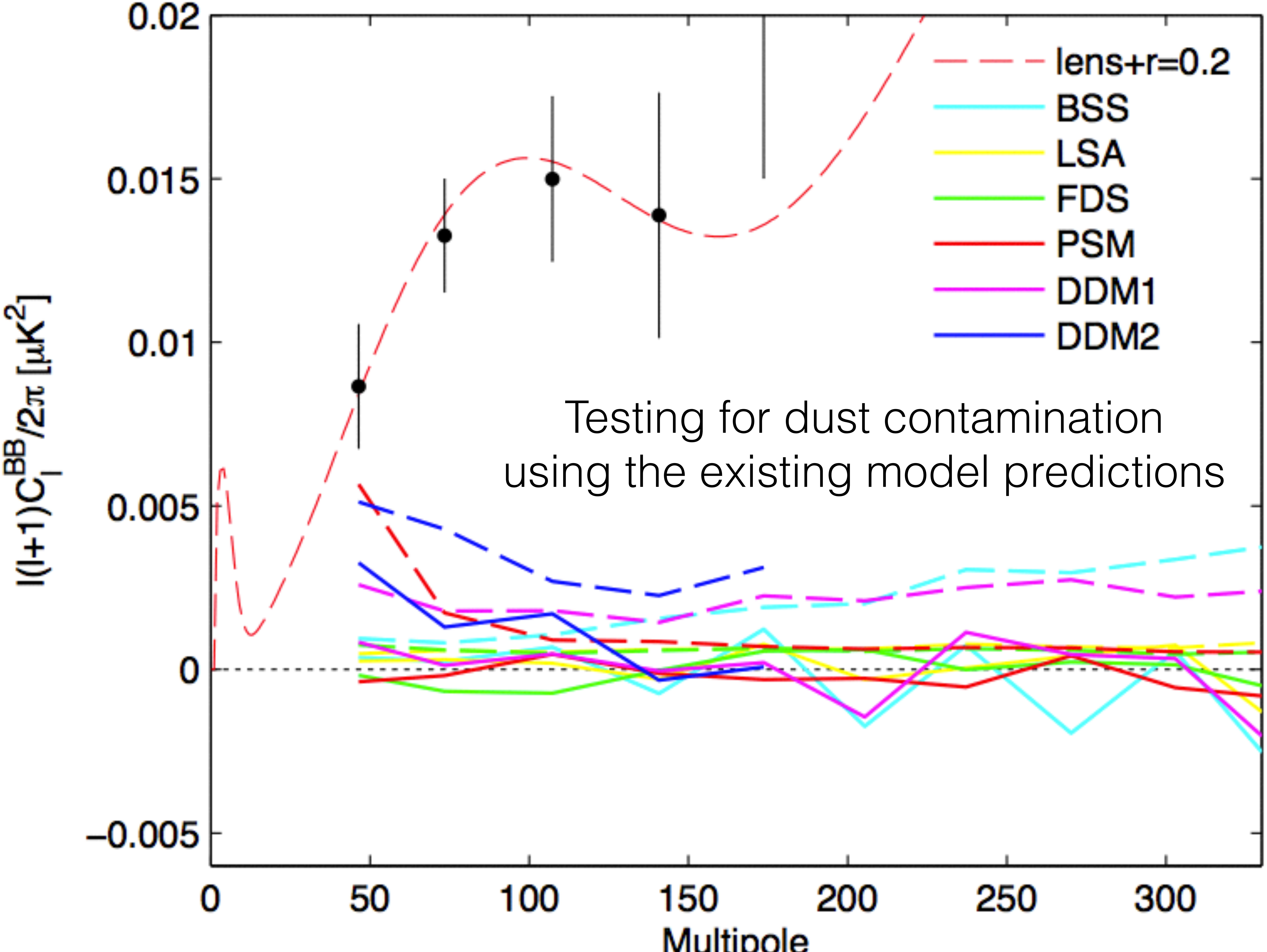
No 100 GHz x 100 GHz [yet]



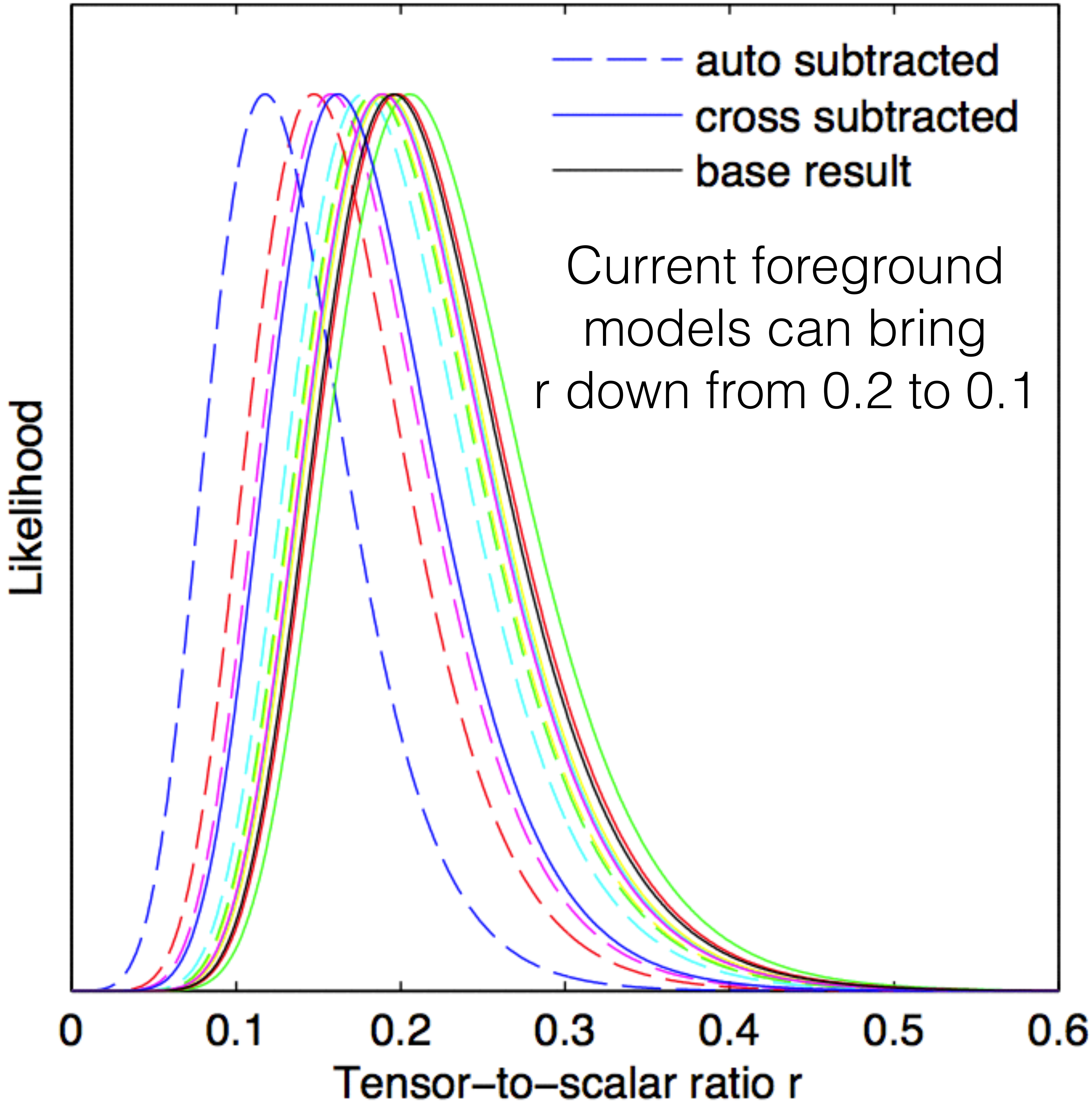
- Using the 100x150 GHz cross, they are able to "reject" representative spectra of synchrotron and dust at ~2 sigma level.
- In other words, **it is only ~2 sigma level that they can claim the cosmological origin of the signal.**

So, at this point

- I must conclude that:
  - "*There is no strong evidence that the detected B modes are not cosmological. However, there is no strong evidence that the detected B modes are cosmological, either.*"

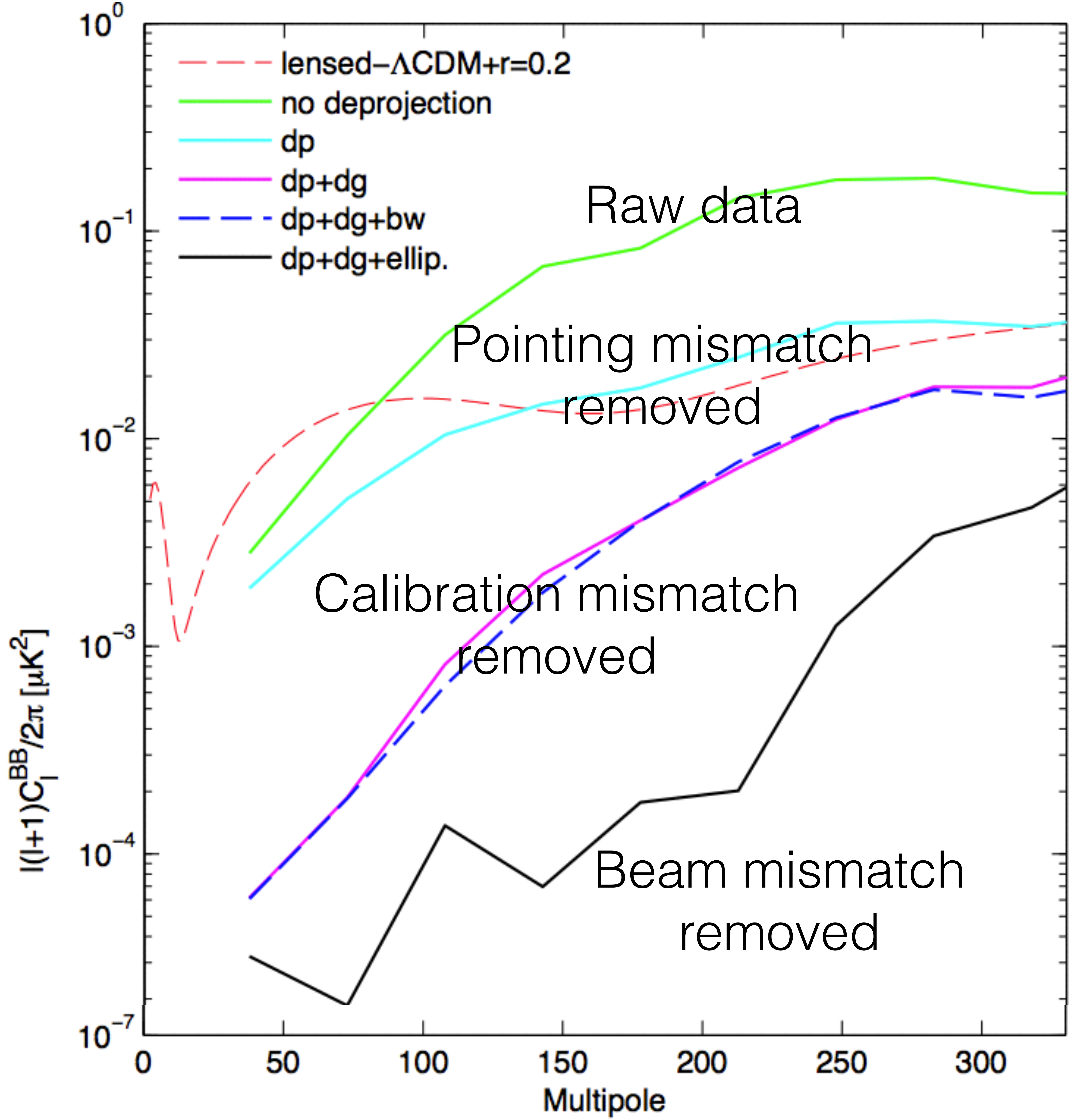


Testing for dust contamination
using the existing model predictions


auto subtracted
cross subtracted
base result
Current foreground
models can bring
r down from 0.2 to 0.1
Likelihood
0
0.1
0.2
0.3
0.4
0.5
0.6
Tensor–to–scalar ratio r

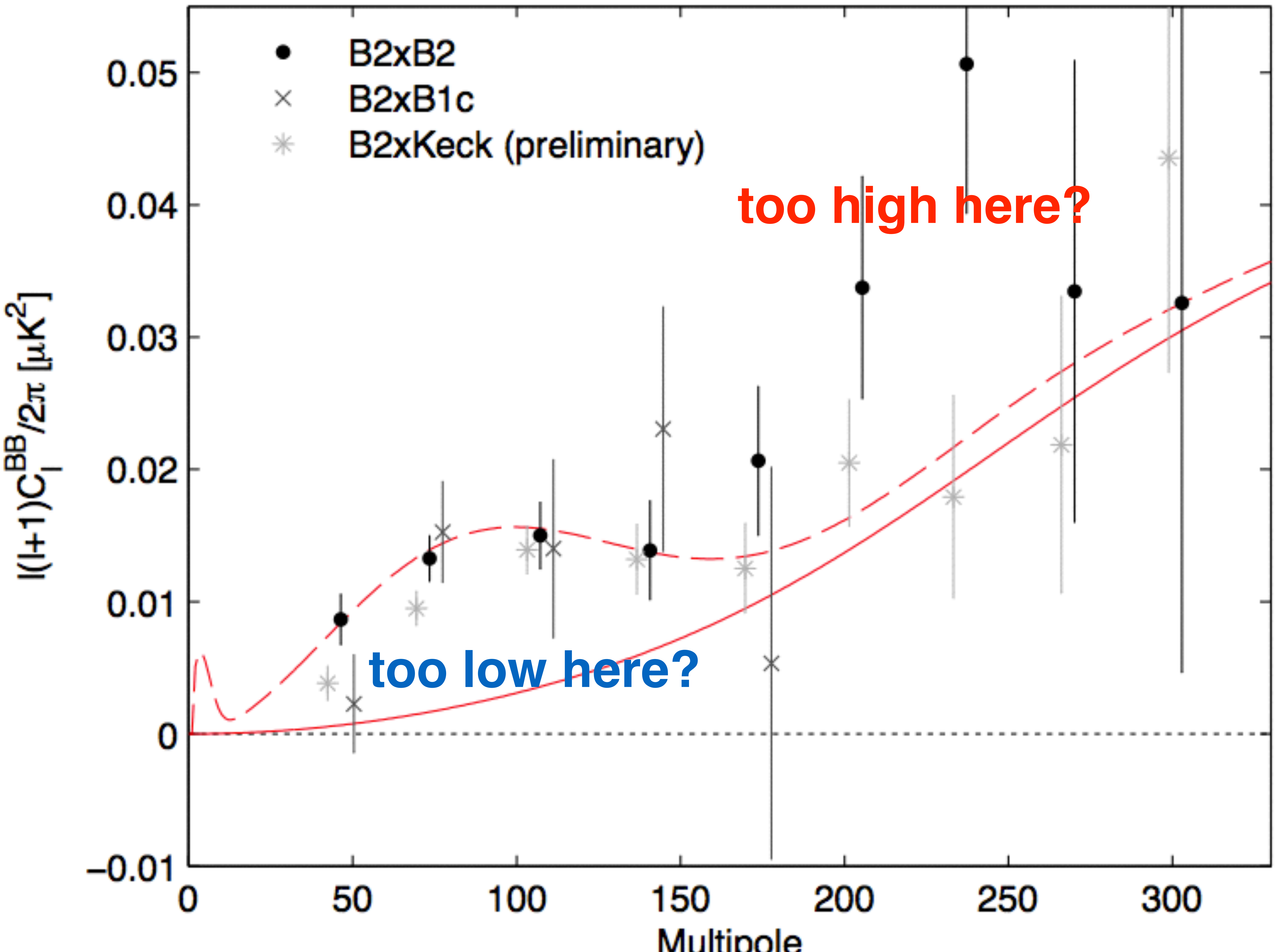
Instrumental Effects

- BICEP2 measures polarization by taking the outputs of two detectors
- If the properties of these detectors are different, the temperature-to-polarization leakage occurs
  - Two detectors seeing different locations in the sky
  - Two detectors receiving slightly different frequencies
  - Two detectors calibrated with a slight mis-calibration
  - Two detectors having different beams in the sky

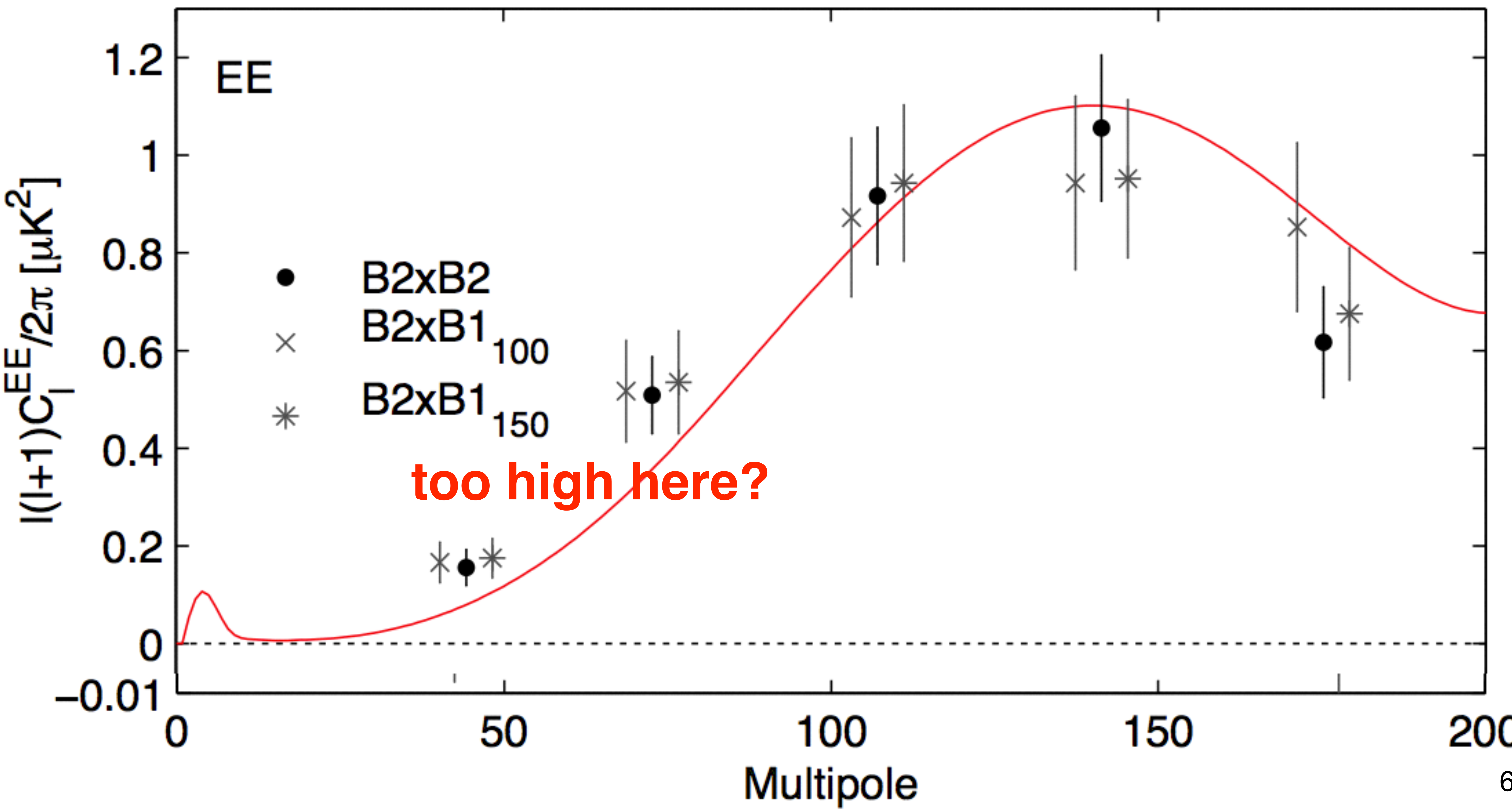


lensed−ΛCDM+r=0.2
no deprojection
dp
dp+dg
dp+dg+bw
dp+dg+ellip.
Raw data
Pointing mismatch removed
Calibration mismatch removed
Beam mismatch removed
l(l+1)C_l^BB/2π [μK²]
Multipole

Worries raised at FB so far



Worries raised at FB so far



“Reconciling” T and B

- The **Planck** temperature data suggest **r<0.11** [95%CL], assuming a power-law scalar power spectrum and adiabatic perturbations
- The **BICEP2** data suggest **r~0.1-0.2**
  - *The lower r values not a problem*
  - The higher r values would require a modification to the model:
    - Scale-dependent power-law scalar perturbation spectrum
    - A new perturbation source [anti]correlated with adiabatic perturbations, e.g., isocurvature
    - A cut-off of the scalar power at the largest scale -> a probe of the beginning of inflation?

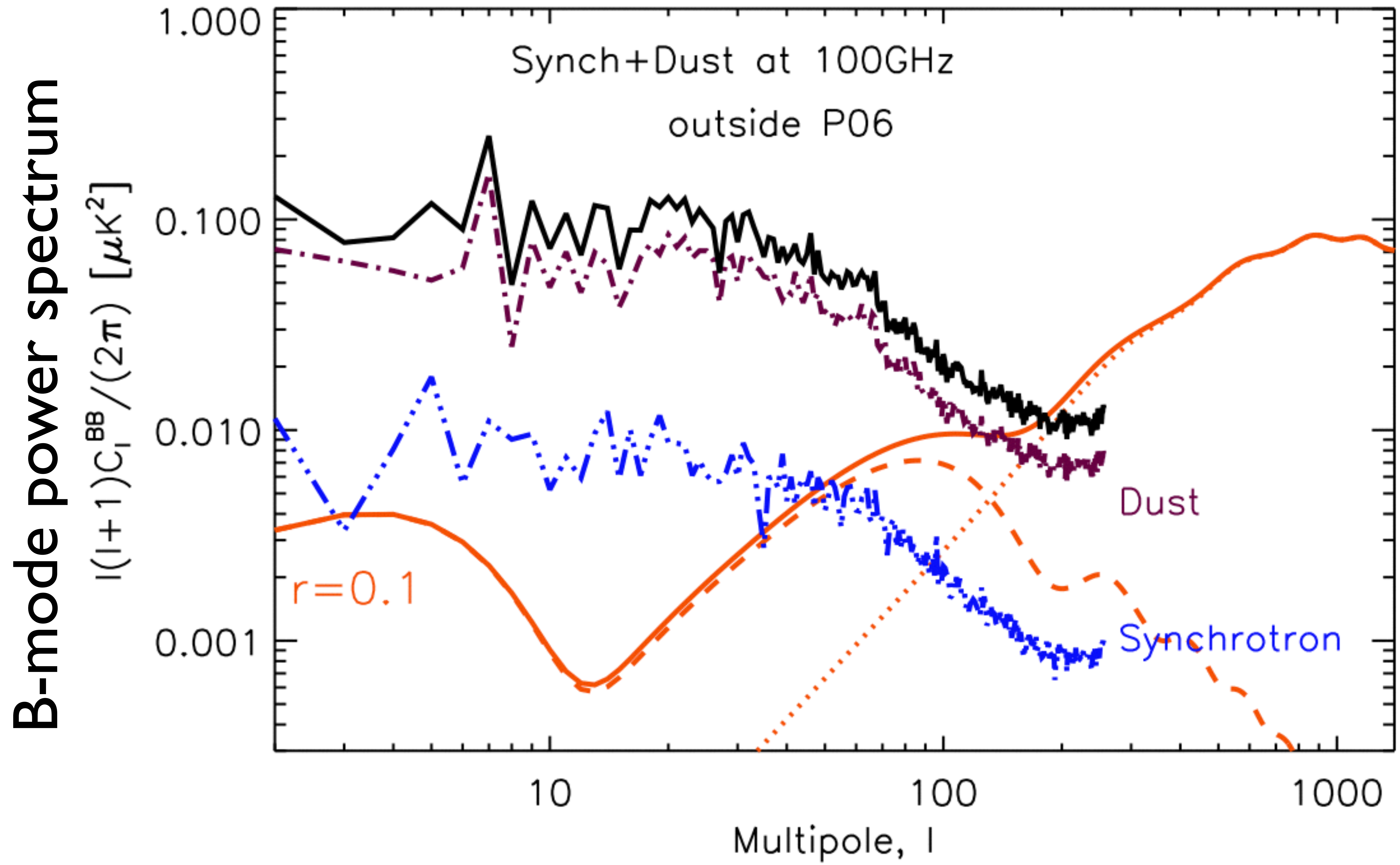
Next Step

- It is absolutely necessary to confirm BICEP2's claim at different frequencies
- Penzias & Wilson discovered the CMB at 7.3 cm, but the subsequent confirmation by Roll & Wilkinson at 3.2 cm played a crucial role in confirming a black-body spectrum of the signal
- We need this confirmation

If confirmed, then what's next?

- We must measure the "reionization bump" at l<10
- We then wish to determine the tensor tilt, n_t, to the precision of O(0.01)
  - The exact scale invariance is $n_t = 0$

Curse you, FG, I curse you...



- Even in the science channel (100GHz), foreground is a couple of orders of magnitude bigger in power at l<~10

Gauss will help you

- Don't be scared too much: the power spectrum captures only a fraction of information.
- Yes, CMB is very close to a Gaussian distribution. But, foreground is highly non-Gaussian.
- CMB scientist's best friend is this equation:

$$\boxed{-2\ln L = ([\text{data}]_i - [\text{stuff}]_i)^T (C^{-1})_{ij} ([\text{data}]_j - [\text{stuff}]_j)}$$

where "C_{ij}" describes the two-point correlation of CMB and noise

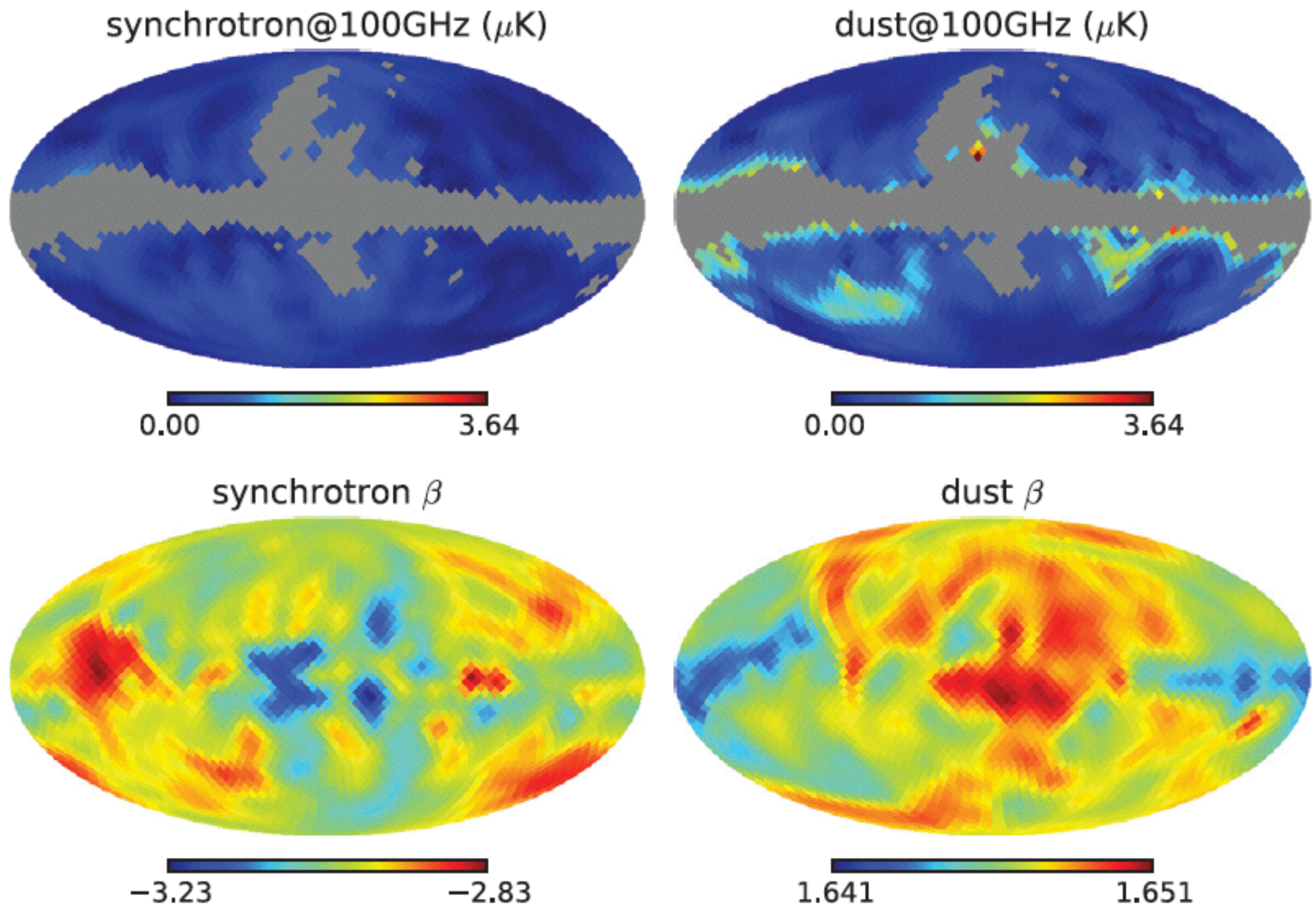
WMAP's Simple Approach

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

- 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 "CMB bias," this method removes foreground completely, provided that:
  - Spectral index ("β" of $T_\nu \sim \nu^\beta$; e.g., β~–3 for synchrotron) does not vary across the sky.

Limitation of the simplest approach

Planck Sky Model (ver 1.6.2)



- The index β <u>does</u> vary at lot for synchrotron!
- We don’t really know what β does for dust (just yet)

Nevertheless...

- Let's try and see how far we can go with the simplest approach. The biggest limitation of this method is a position-dependent index.

- And, obvious improvements are possible anyway:
  - Fit multiple coefficients to different locations in the sky
  - Use more frequencies to constrain the index

We describe the data (=CMB+noise+PSMv1.6.2) by

- Amplitude of the B-mode polarization: **r** [this is what we want to measure at the level of $r\sim10^{-3}$]
- Amplitude of the E-mode polarization from gravitational potential: **s** [which we wish to marginalize over]
- Amplitude of synchrotron: α_{Synch} [which we wish to marginalize over]
- Amplitude of dust: α_{Dust} [which we wish to marginalize over]

Methodology: we simply maximize the following likelihood function

estimating r, s, and α_i:

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

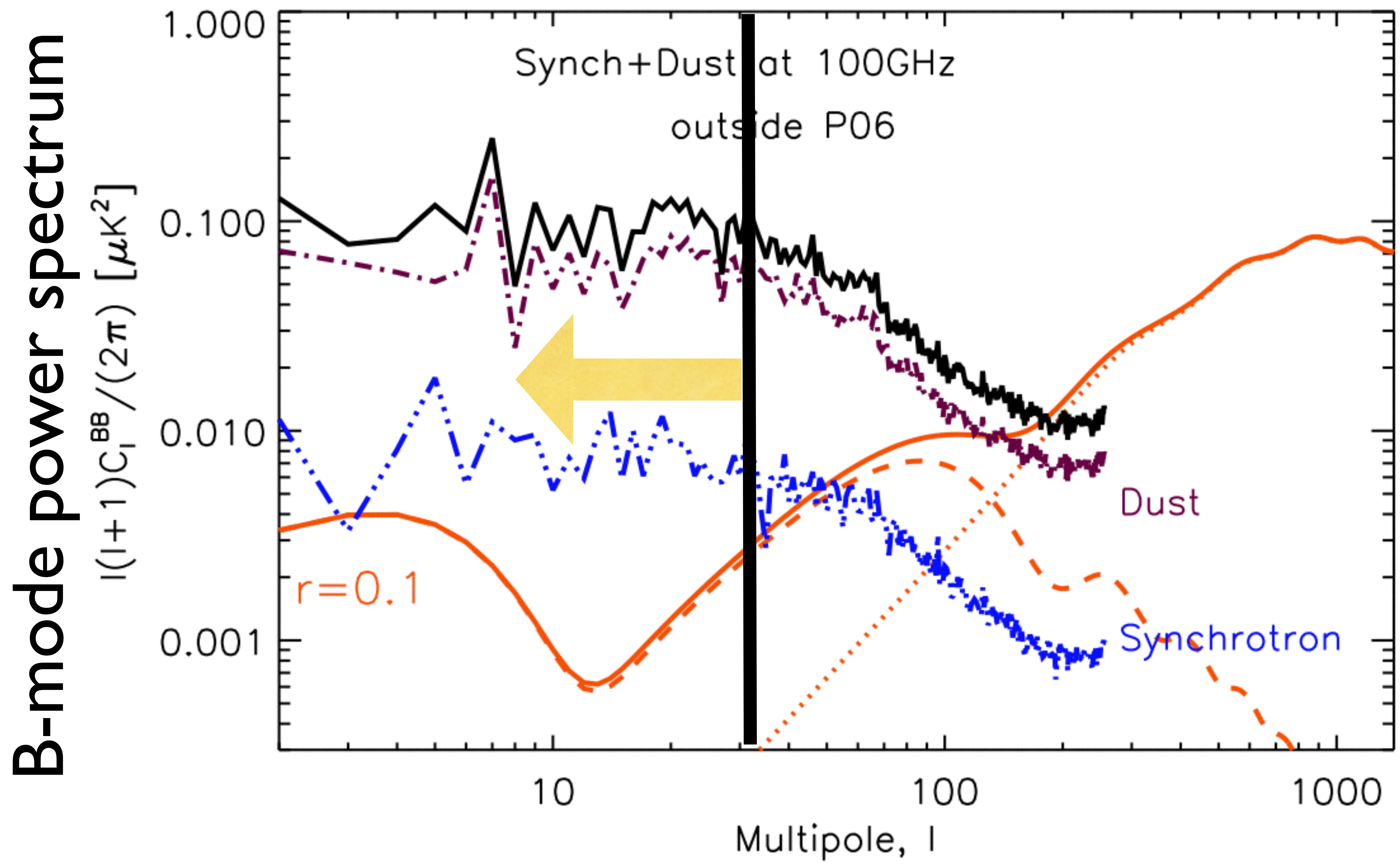
where

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

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

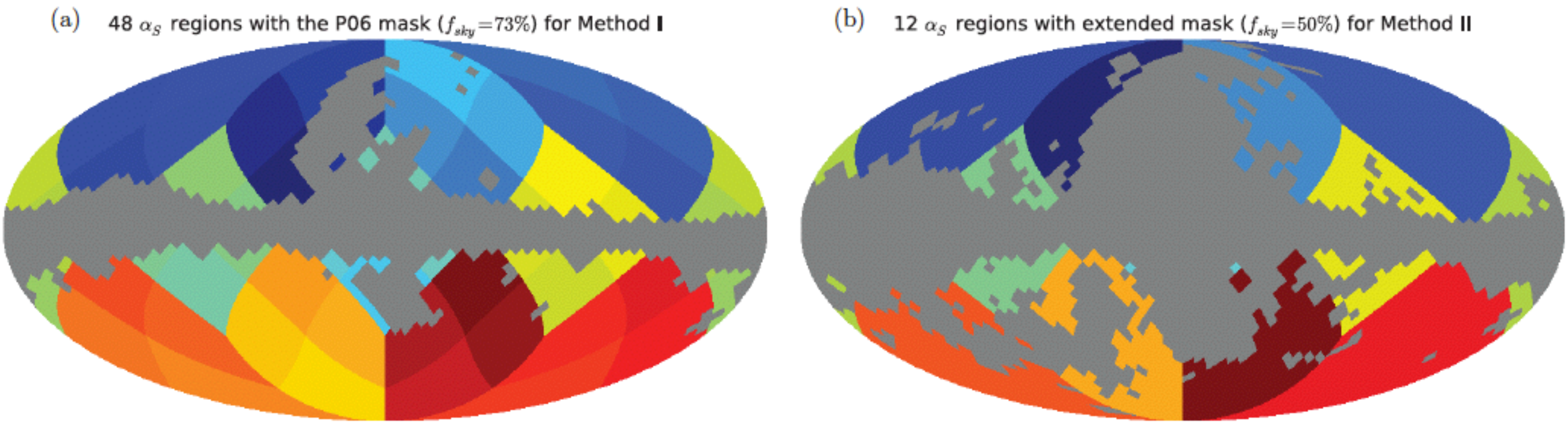
$$\begin{aligned} \nu &= 100\,\text{GHz}, \\ \nu_{\text{S}}^{\text{template}} &= 60\,\text{GHz}, \\ \nu_{\text{D}}^{\text{template}} &= 240\,\text{GHz}. \end{aligned}$$

We target the low-l bump



- This is a semi-realistic configuration for a future satellite mission targeting the B-modes from inflation.

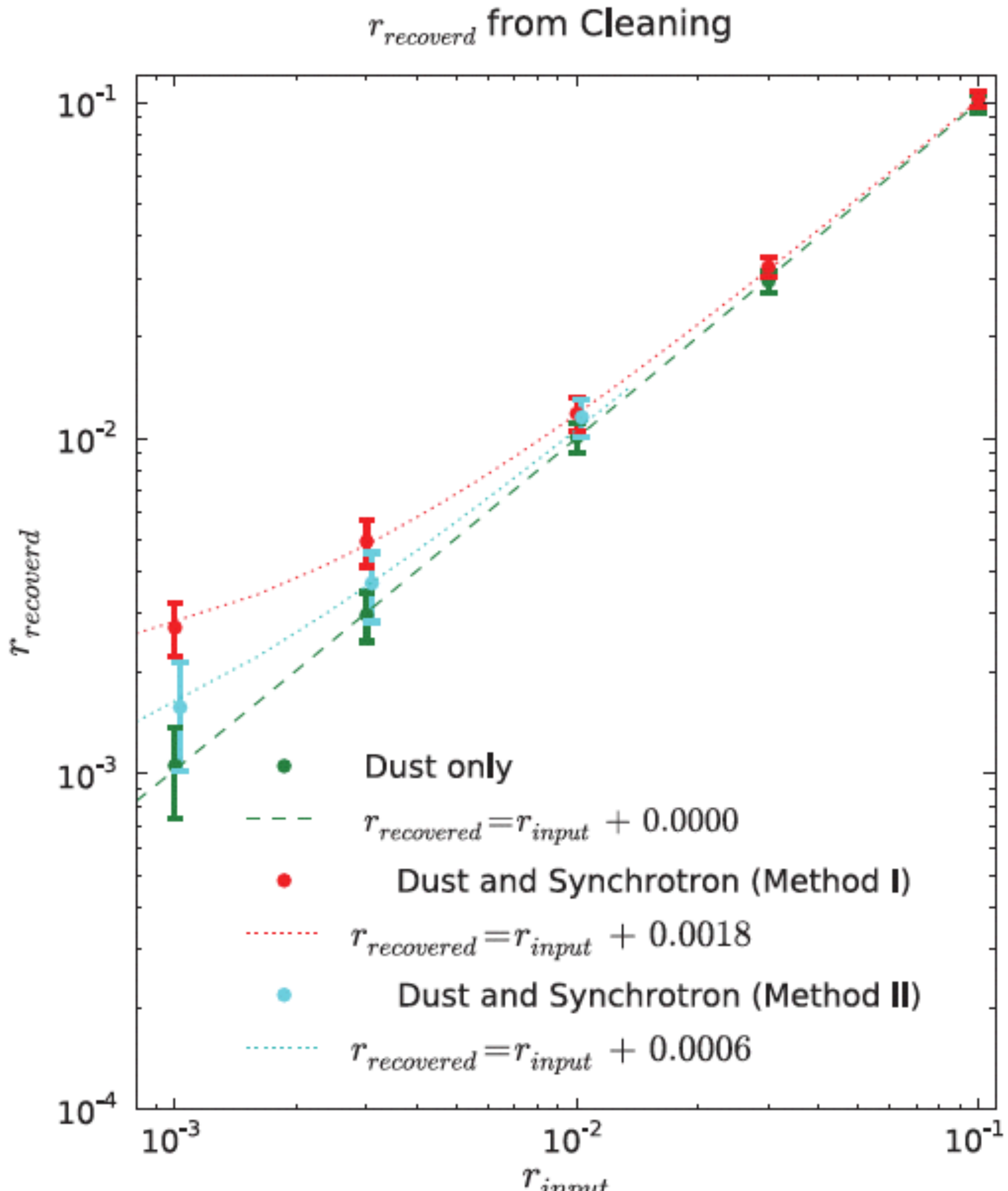
Two Masks and Choice of Regions for Synch Index



"Method I" "Method II"

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

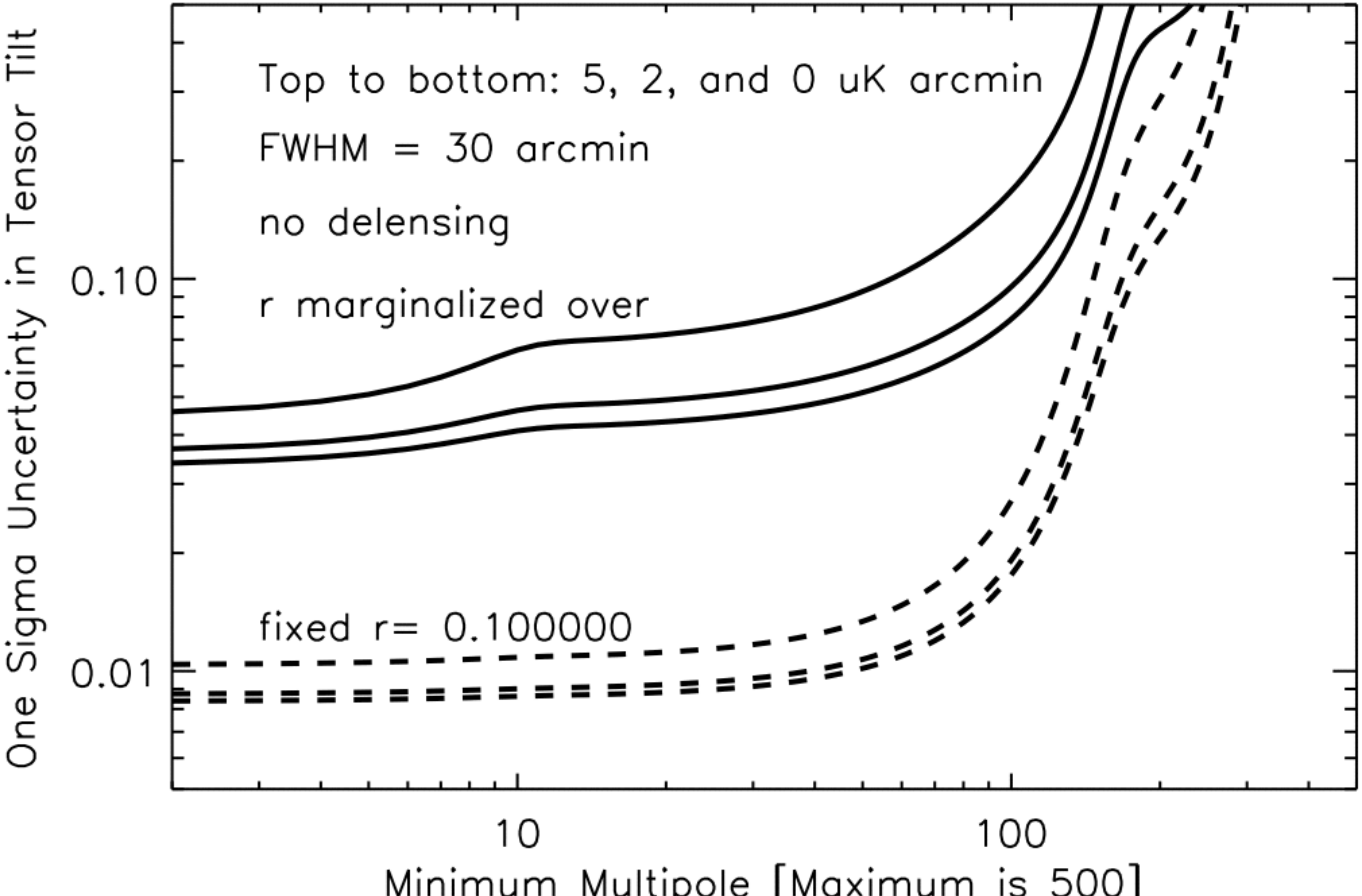
Results (3 frequency bands: 60, 100, 240 GHz)



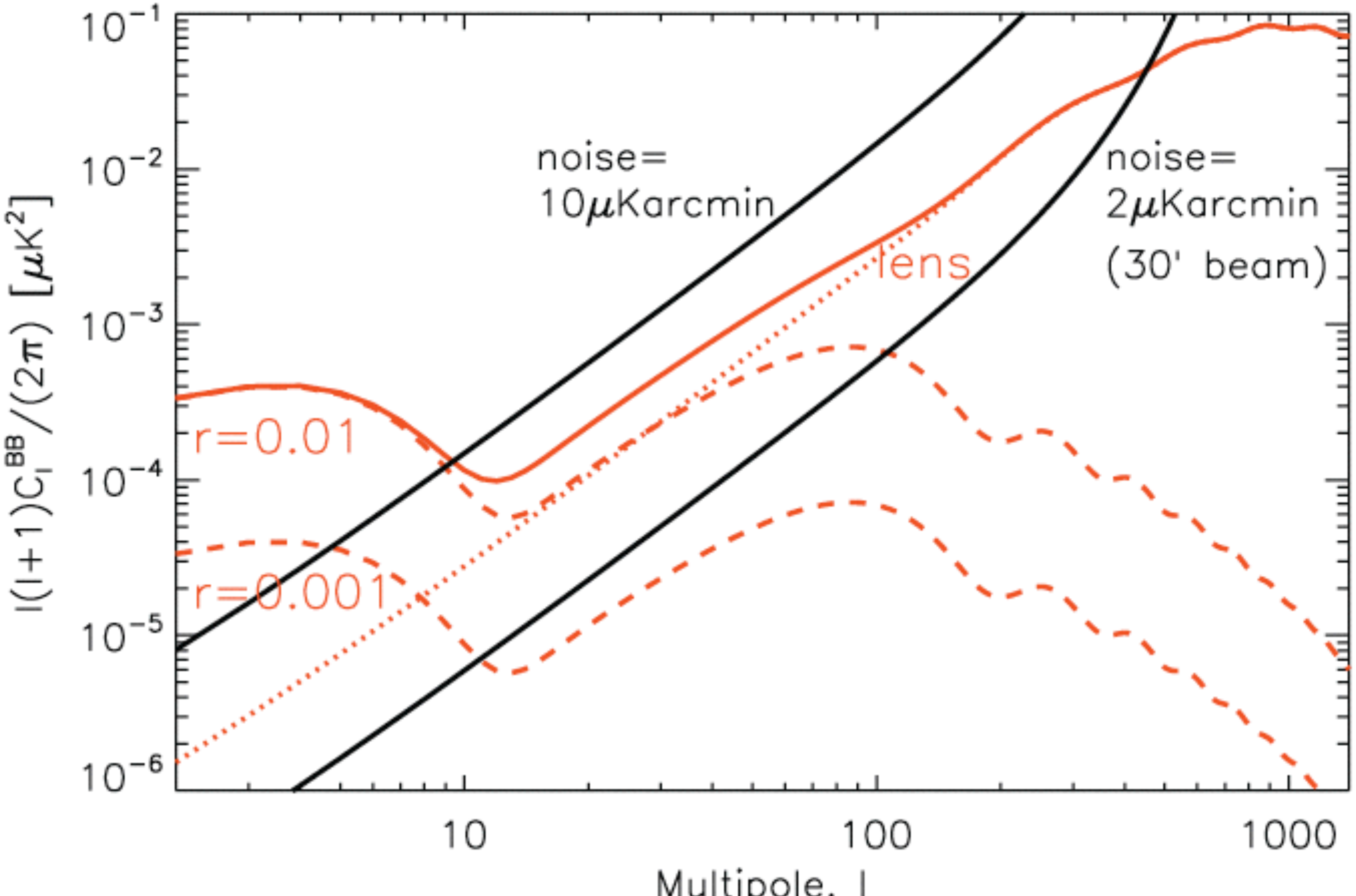
- It works quite well!
- For dust-only case (for which the index does not vary much): we observe ***no bias*** in the B-mode amplitude, as expected.
- For Method I (synch+dust), the bias is $\Delta r = 2\times10^{-3}$
- For Method II (synch+dust), the bias is $\Delta r = 0.6\times10^{-3}$

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

How about the tensor tilt?



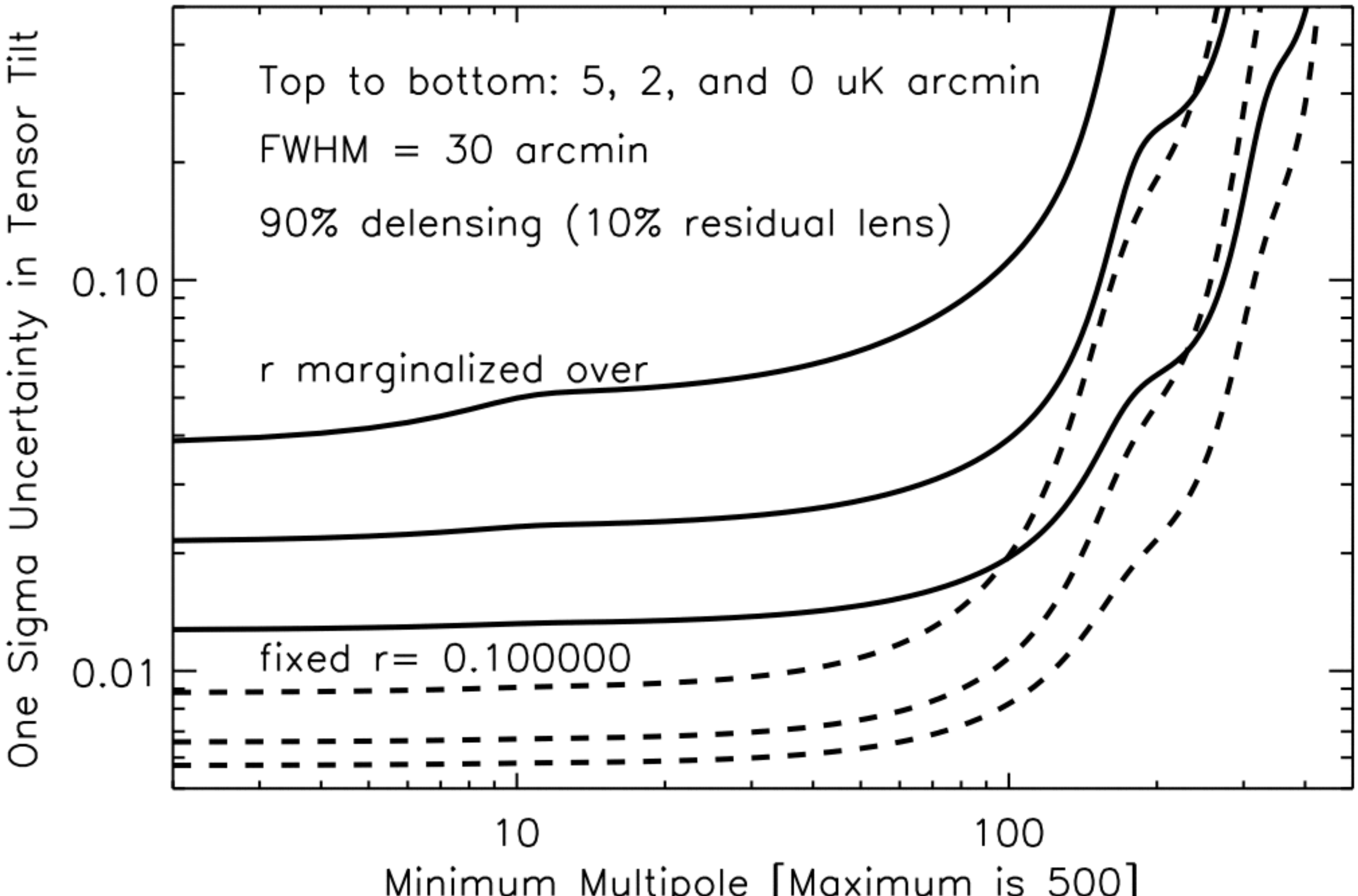
Lensing limits our ability to measure the tensor tilt



- Unless we "de-lens" maps, lowering noise to < 5uK arcmin does not help.
- We need de-lensing!

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

De-lensing is now crucial



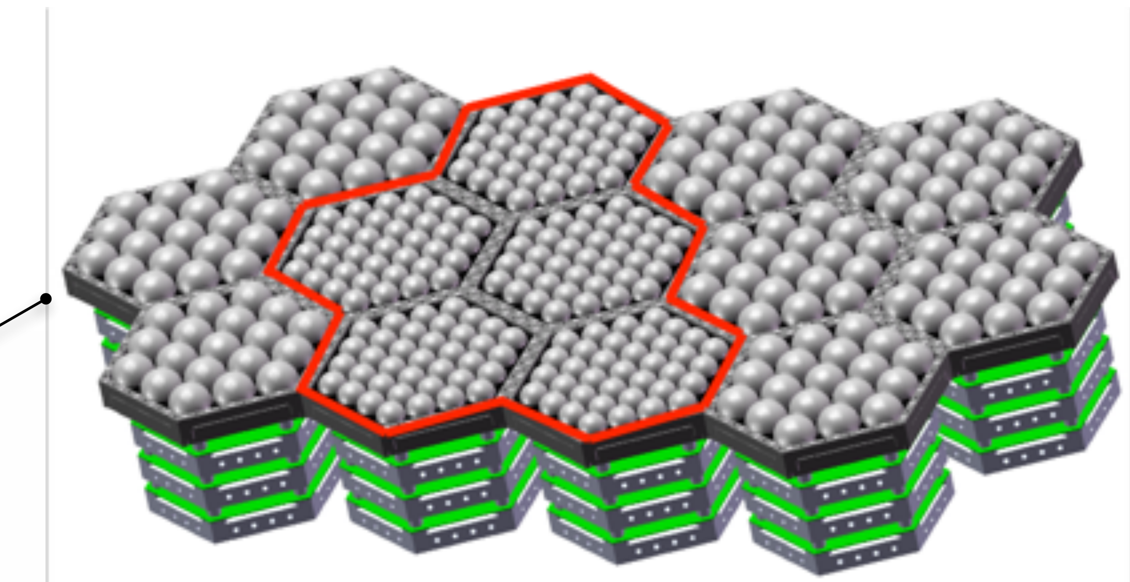
LiteBIRD

- Next-generation polarization-sensitive microwave experiment. Target launch date: ~2020
- Led by Prof. Masashi Hazumi (KEK); a collaboration of ~70 scientists in Japan, USA, Canada, and Germany
- We aim at measuring r with the precision of **Err[r]~0.001**
- **We need to study how well we can measure n_t**

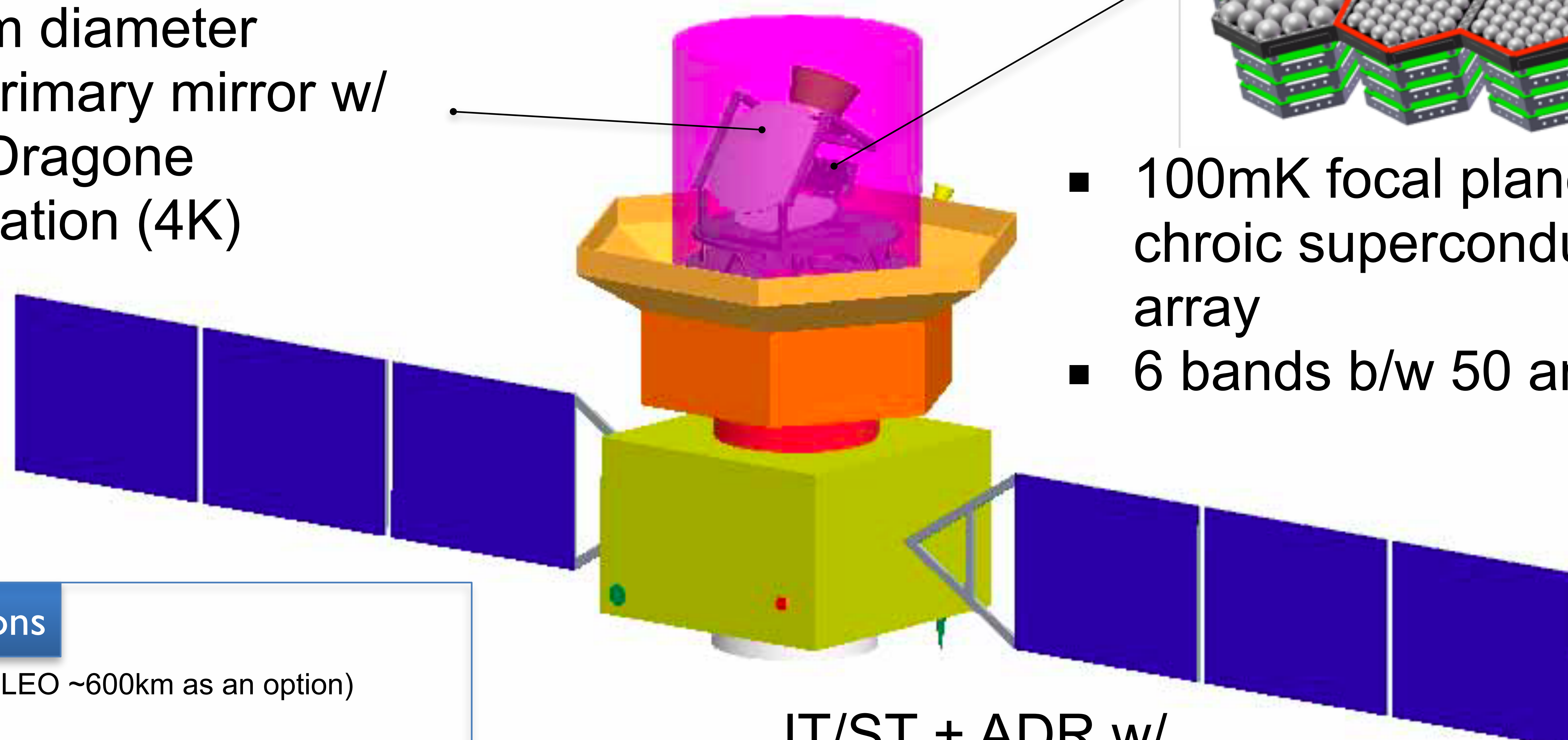
LiteBIRD

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:** δr < 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)



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



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

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

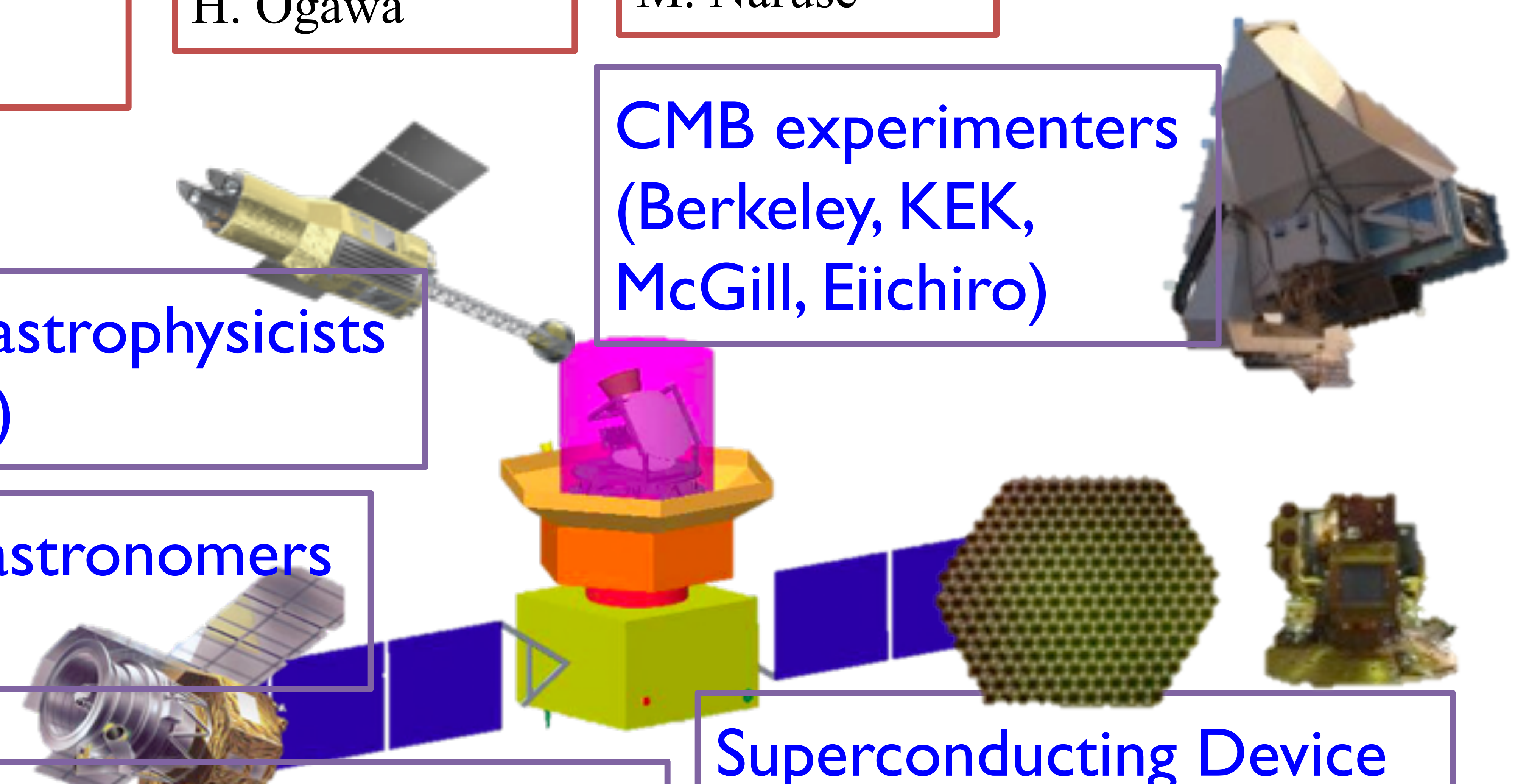
RIKEN
K. Koga
S. Mima
C. Otani

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

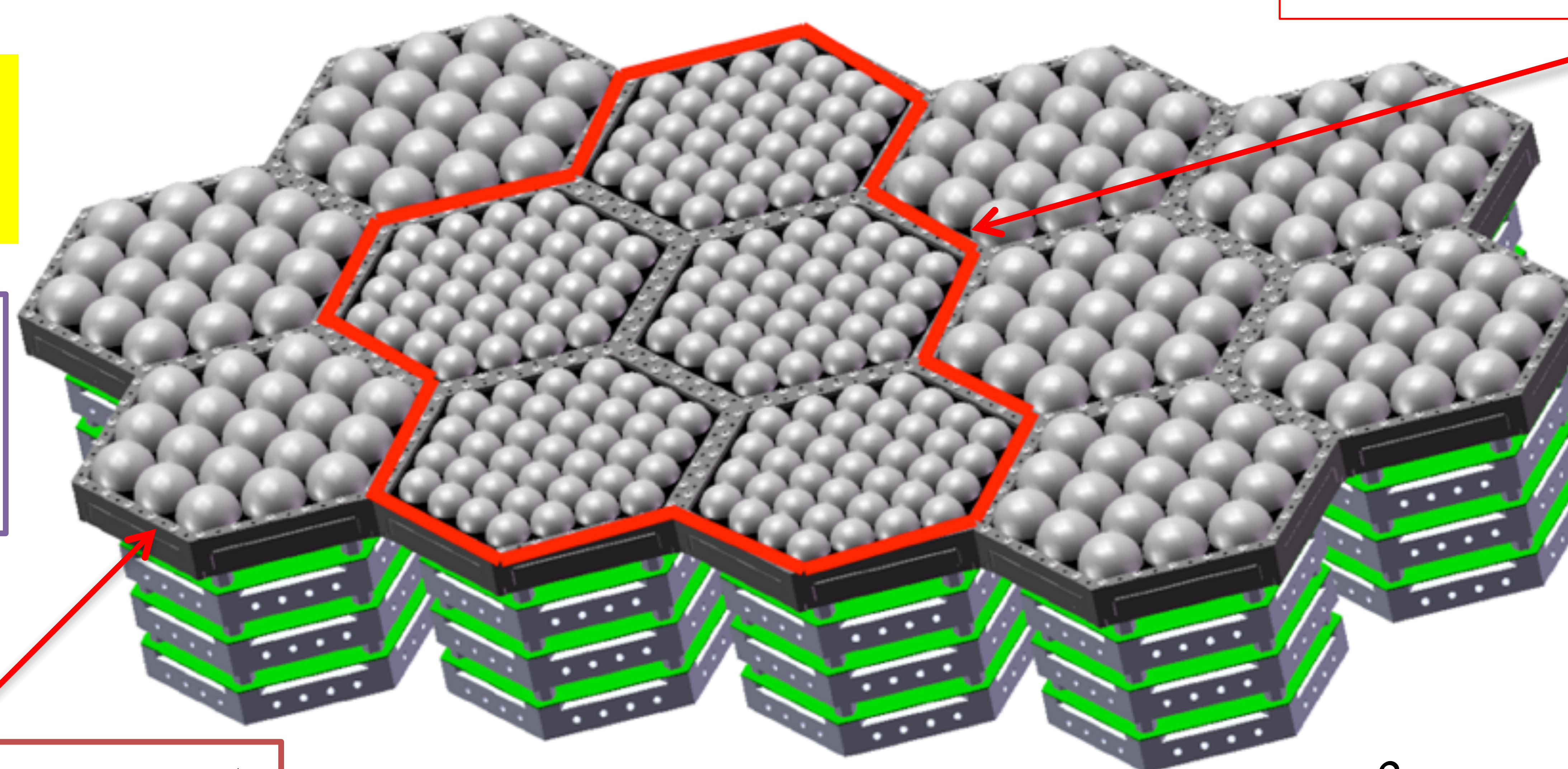
UC Berkeley TES option

2022 TES bolometers

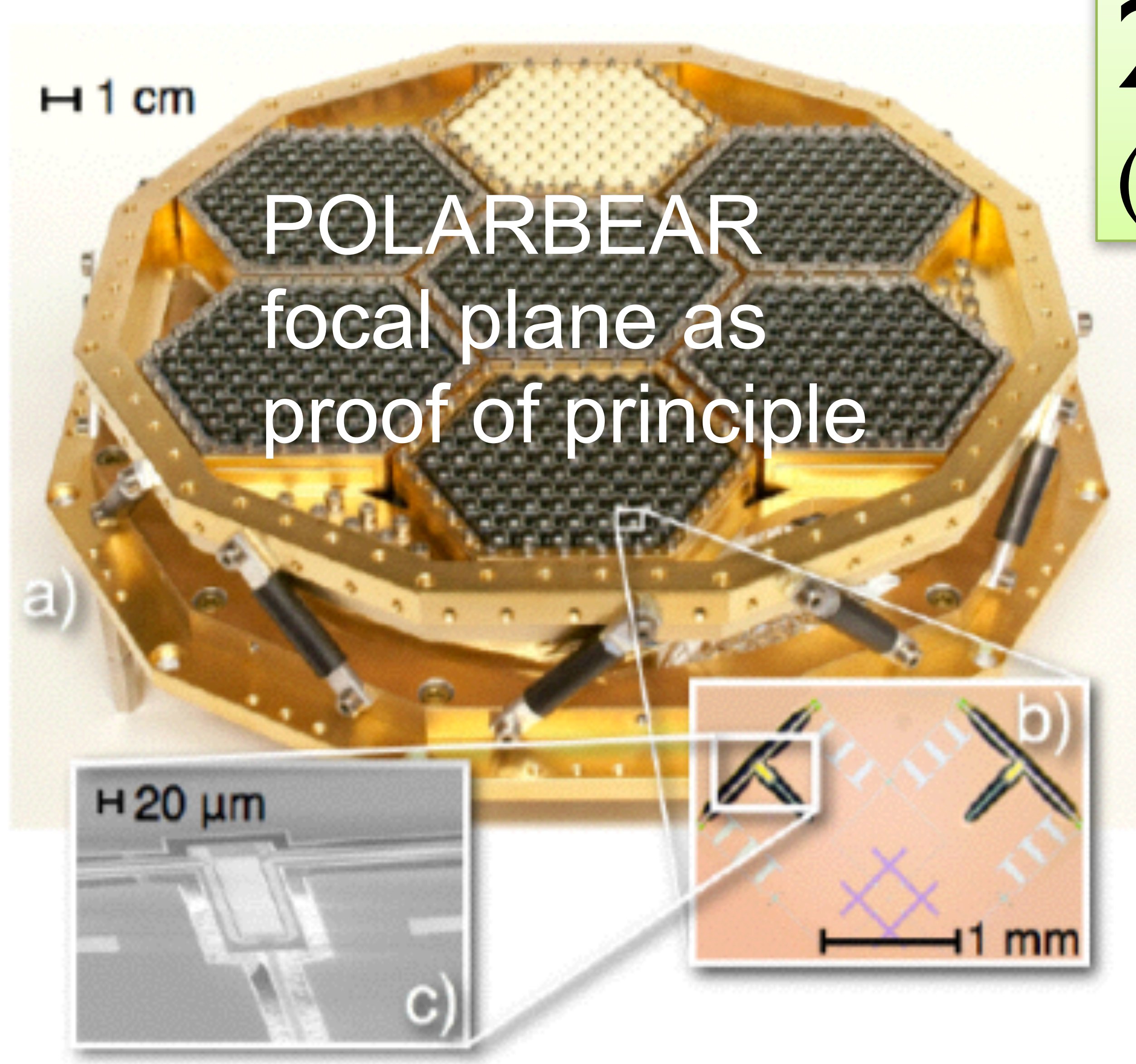
T_{bath} = 100mK

tri-chroic（140/195/280GHz）

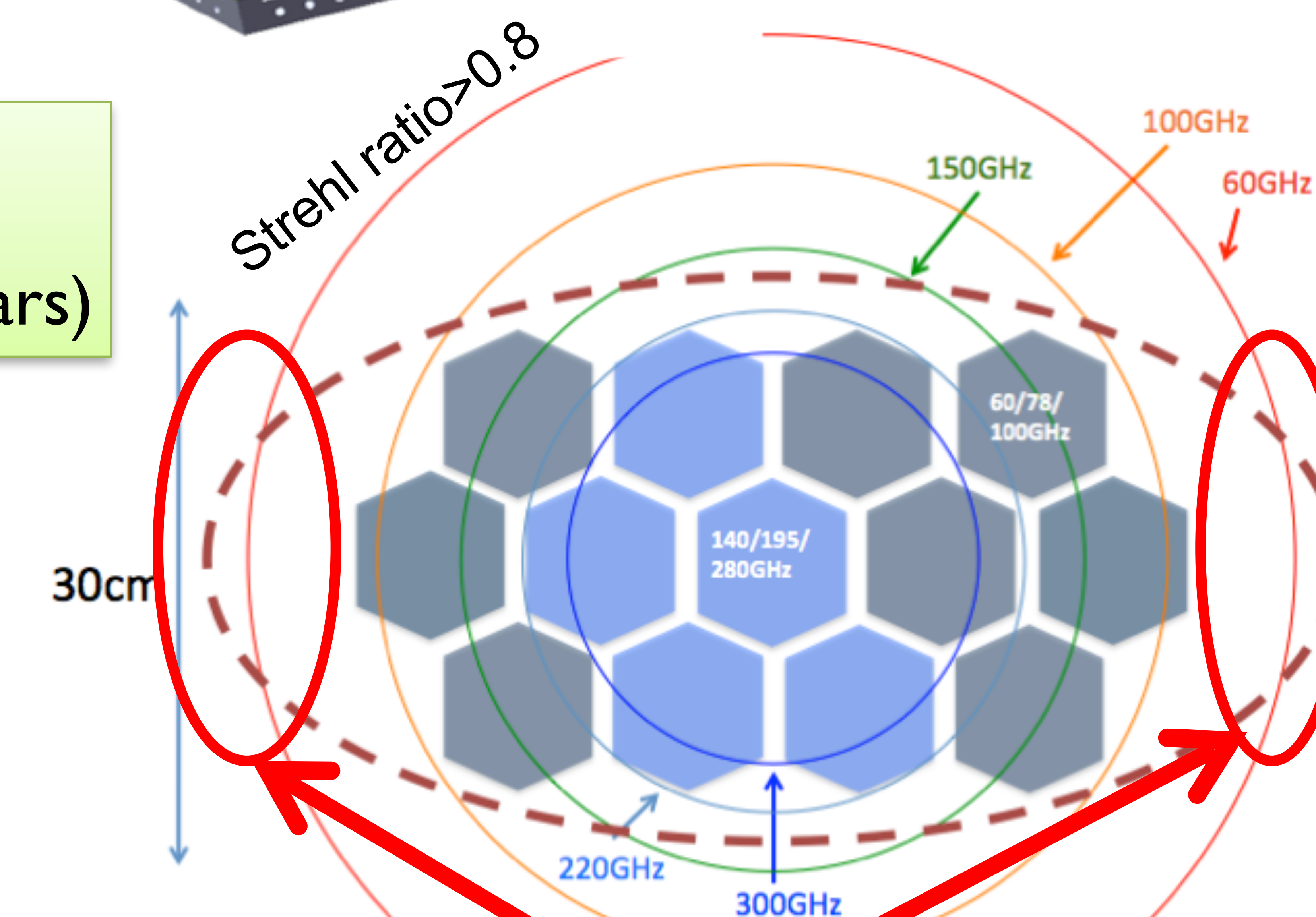
Band centers can be distributed to increase the effective number of bands



tri-chroic（60/78/100GHz）



2μKarcmin
(w/ 2 effective years)



More space to place <60GHz detectors

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
- 2014 May
  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

- BICEP2's finding is ground-breaking, if confirmed
  - **Current status**: "*There is no strong evidence that the detected B modes are not cosmological. However, there is no strong evidence that the detected B modes are cosmological, either.*"
- If confirmed, the next step is to measure the reionization bump at l<10 and measure the tensor tilt to O(0.01)