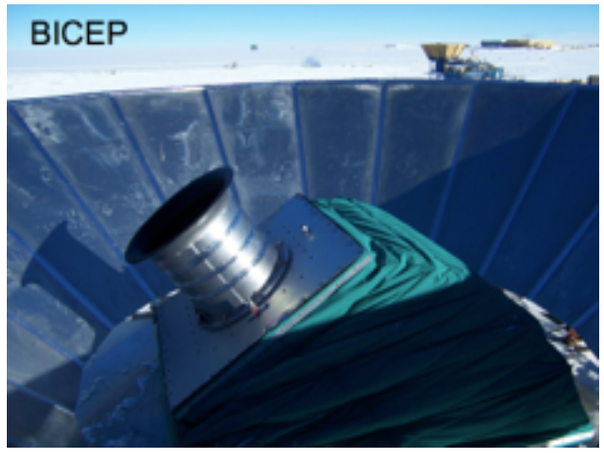
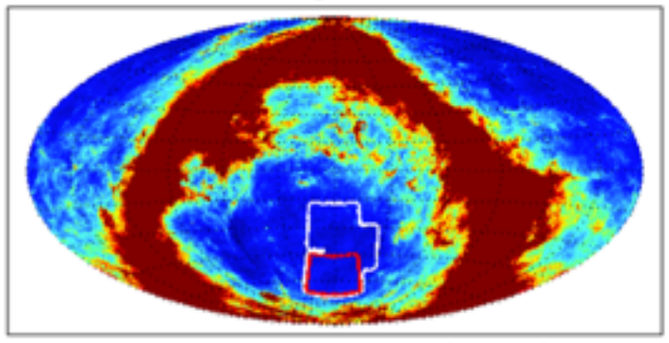
Discussion on BICEP2

March 20, 2014
Max-Planck-Institut für Astrophysik

What is BICEP2?

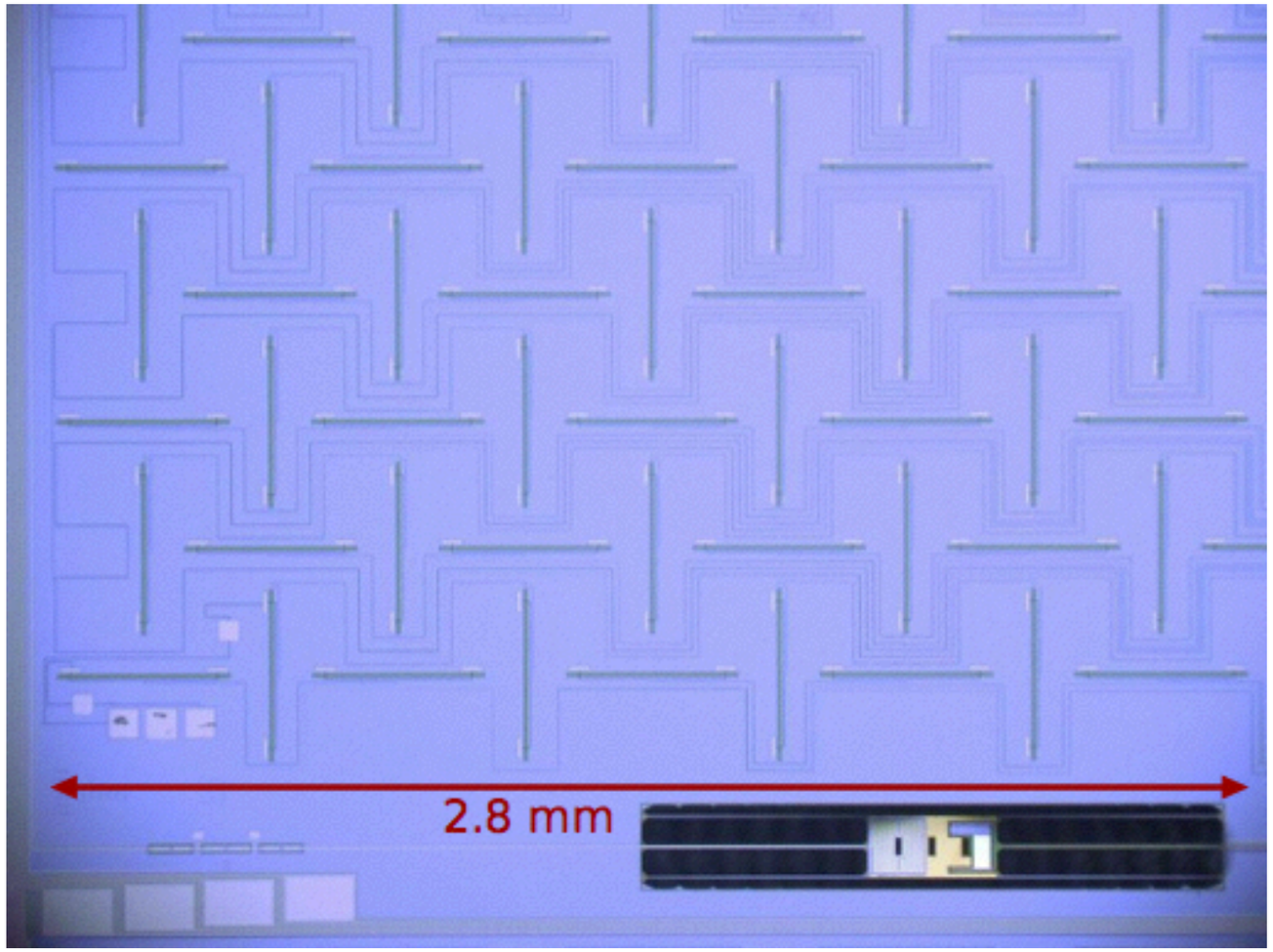


- A small [26 cm] refractive telescope at South Pole
- 512 bolometers working at 150 GHz
- Observed 380 square degrees for three years [2010-2012]
- Previous: BICEP1 at 100 and 150 GHz [2006-2008]
- On-going: Keck Array = 5 x BICEP2 at 150 GHz [2011-2013] and additional detectors at 100 and 220 GHz [2014-]



How does BICEP2 measure polarization?

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



Horizontal slots
-> A detector

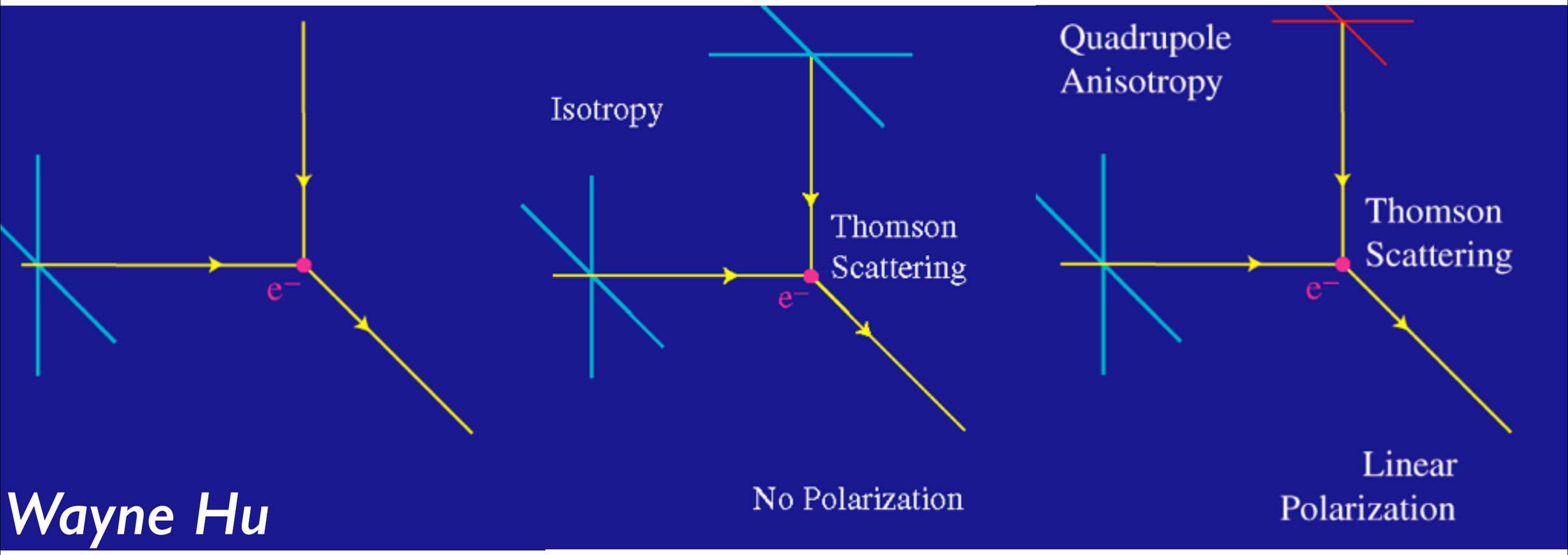
Vertical slots
-> B detector

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

CMB Polarization

- Necessary and sufficient conditions for producing polarization in CMB are:
  - CMB photons are scattered by electrons
  - An electron is surrounded by quadrupole temperature anisotropy

Physics of CMB Polarization



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

Origin of Quadrupole

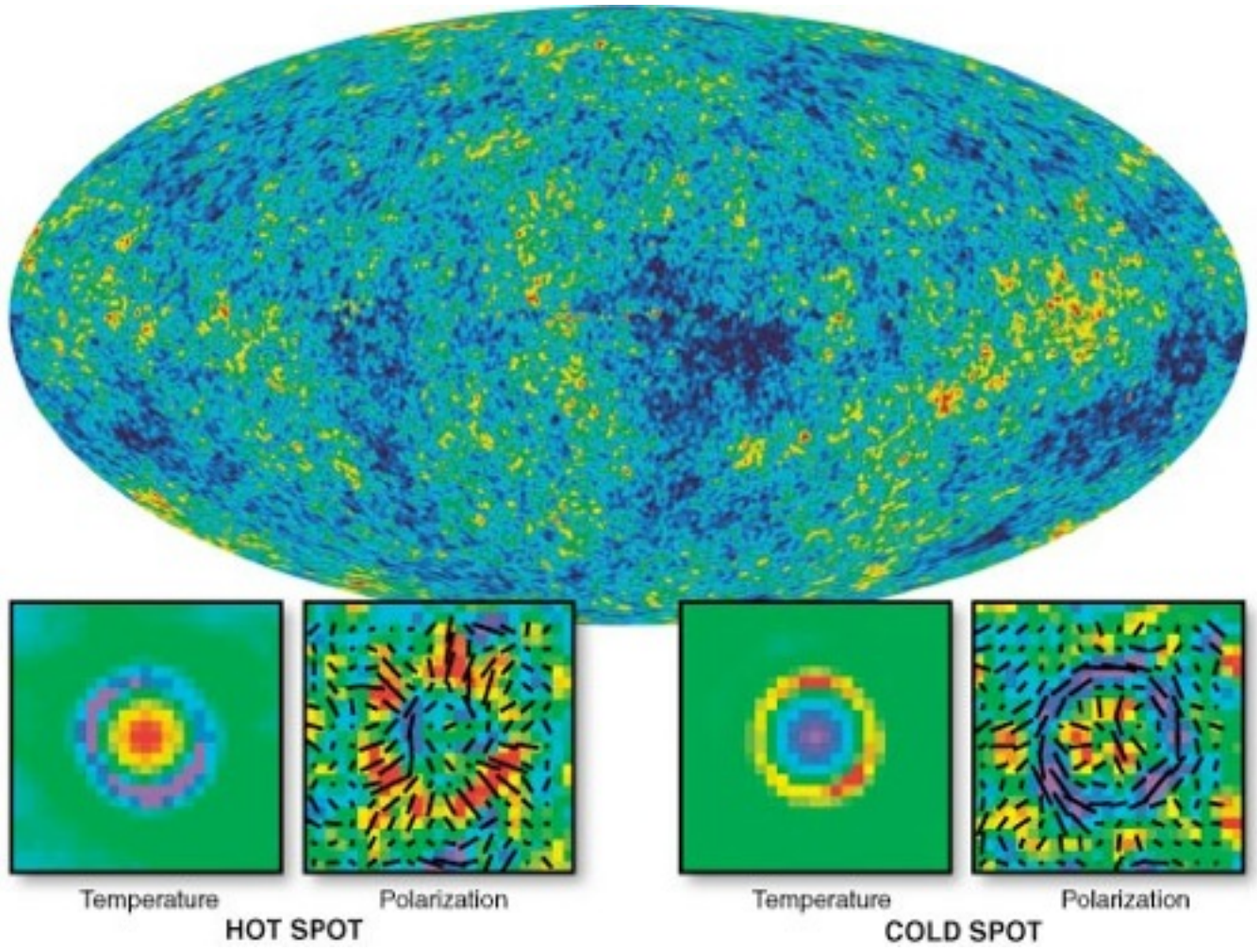
- Scalar perturbations: motion of electrons with respect to photons

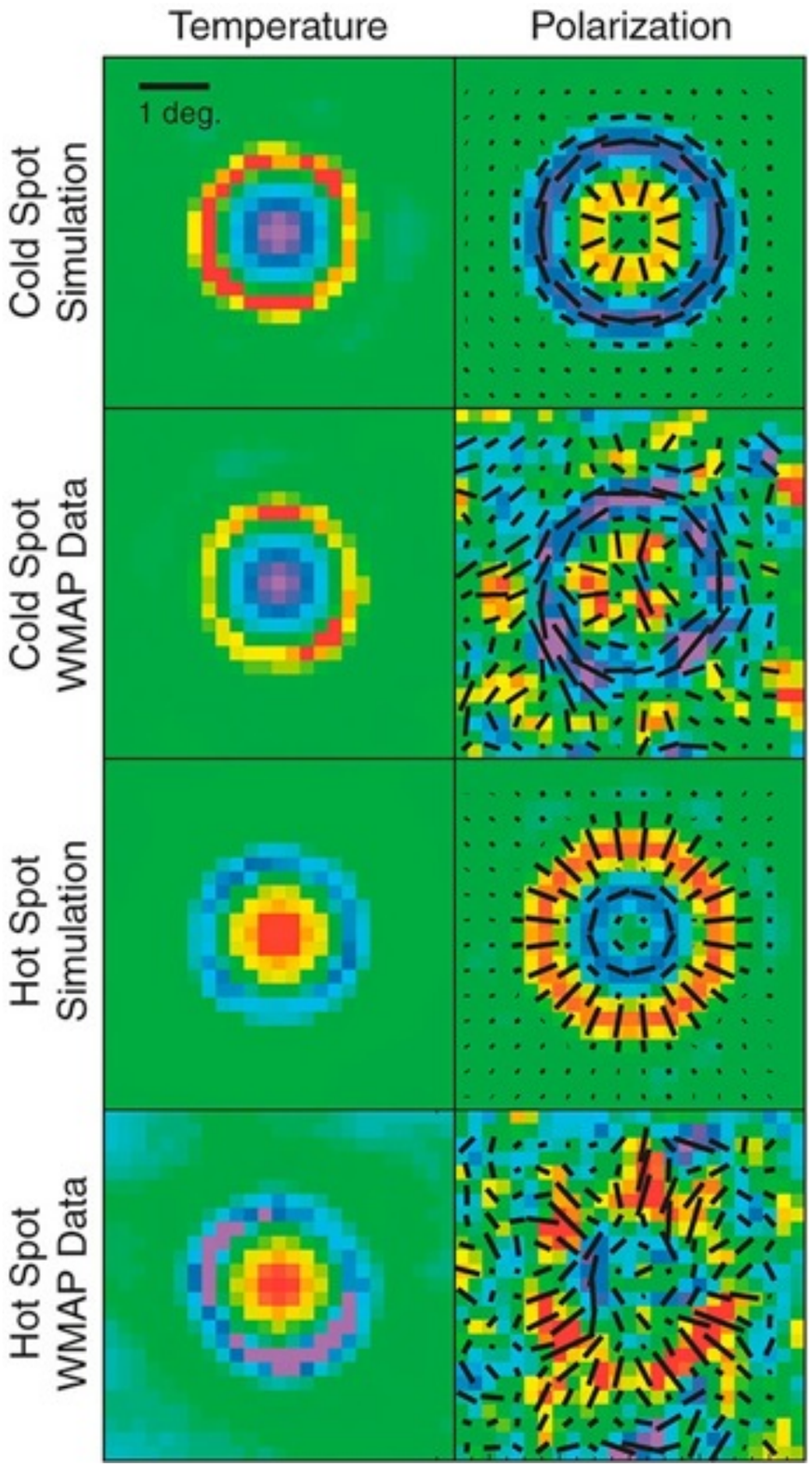
- Tensor perturbations: gravitational waves

Stacking Analysis

- Stack polarization images around temperature hot and cold spots in the WMAP data

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

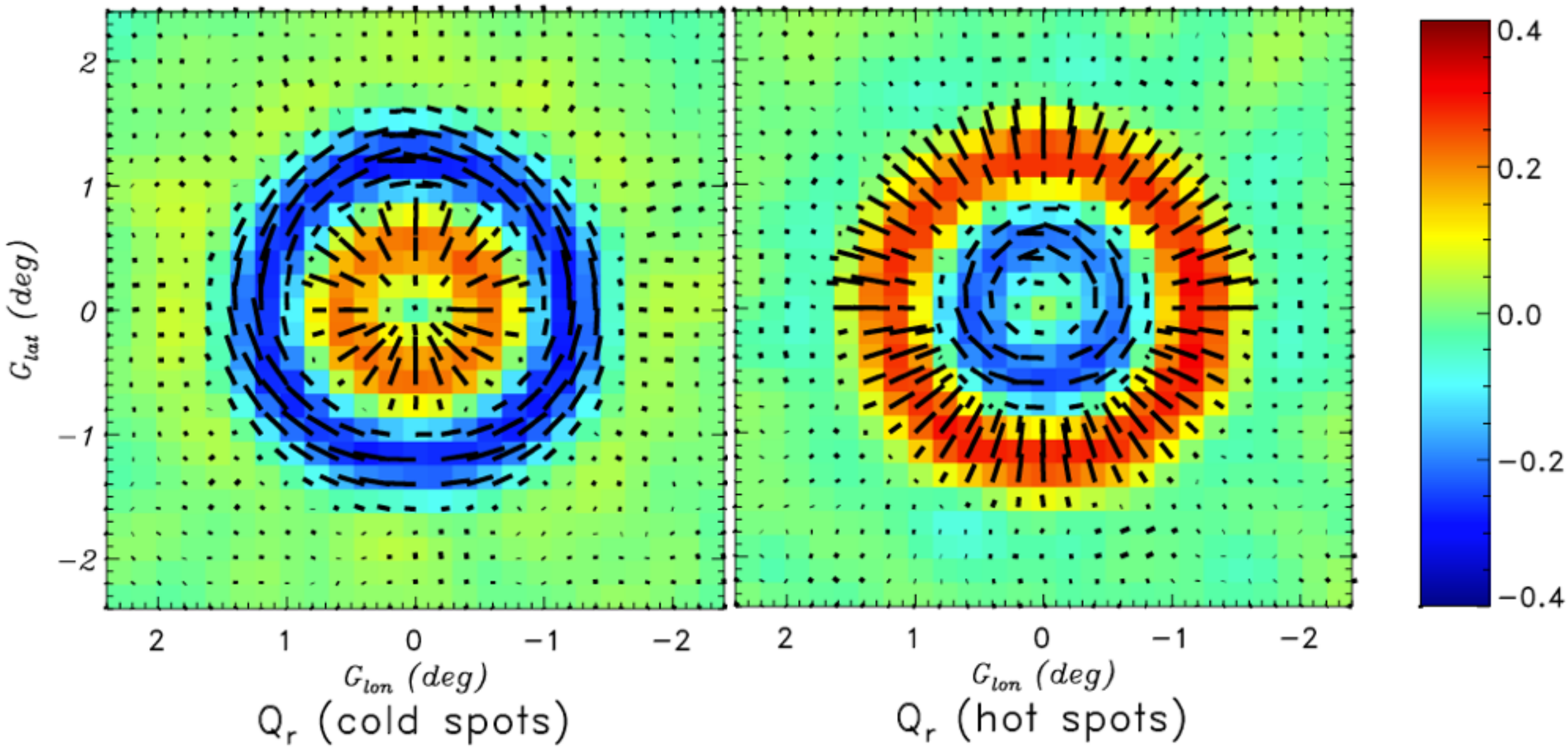




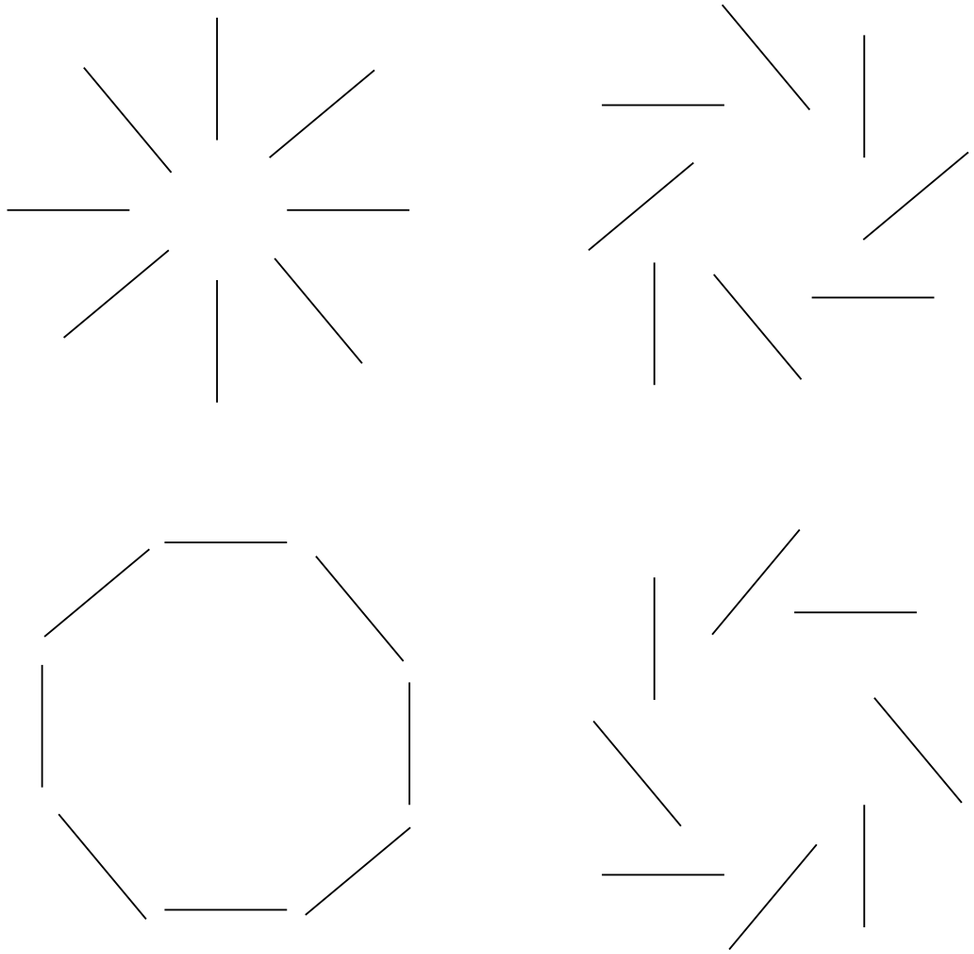
Radial and Tangential Polarization Patterns around Temp. Spots

- 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 WMAP 7-year overall significance level: 8σ

Planck Data!


2
1
0
−1
−2
G_{lat} (deg)
2
1
0
−1
−2
G_{lon} (deg)
Q$_r$ (cold spots)
2
1
0
−1
−2
G_{lon} (deg)
Q$_r$ (hot spots)
0.4
0.2
0.0
−0.2
−0.4

E-mode and B-mode

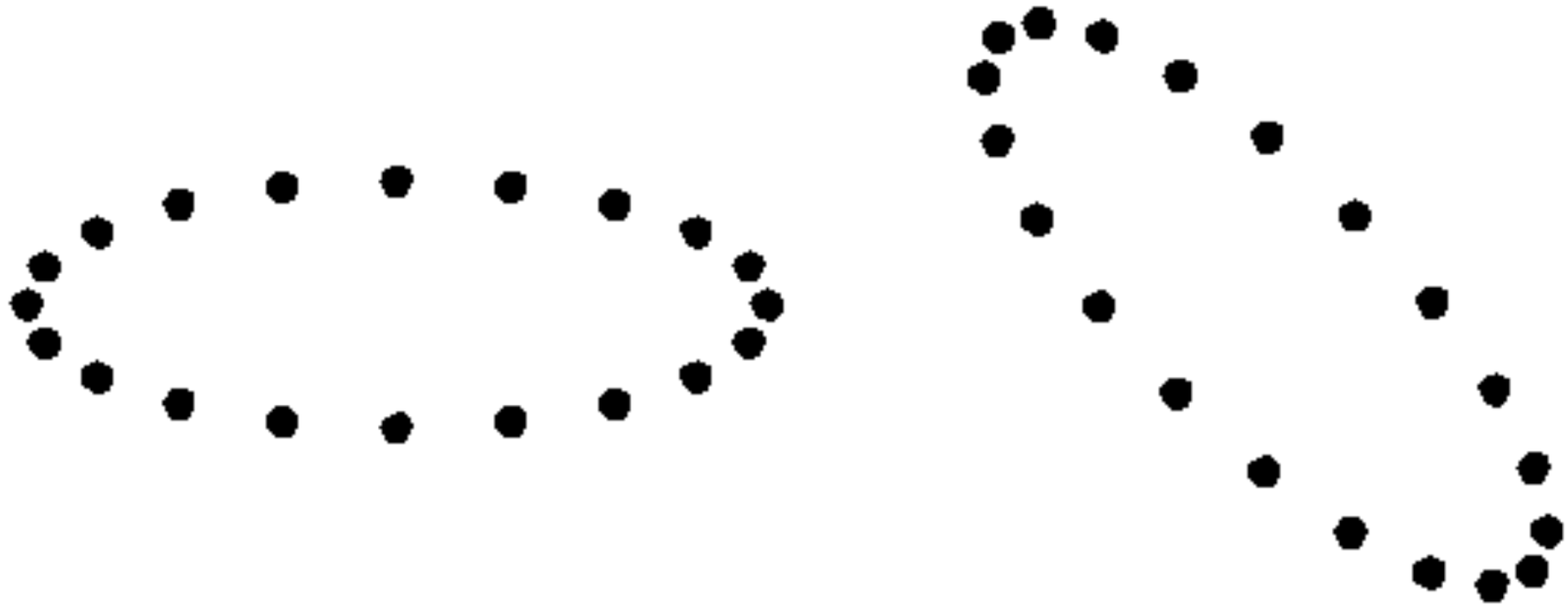


E mode B mode

- Gravitational potential can generate the E-mode polarization, but not B-modes.

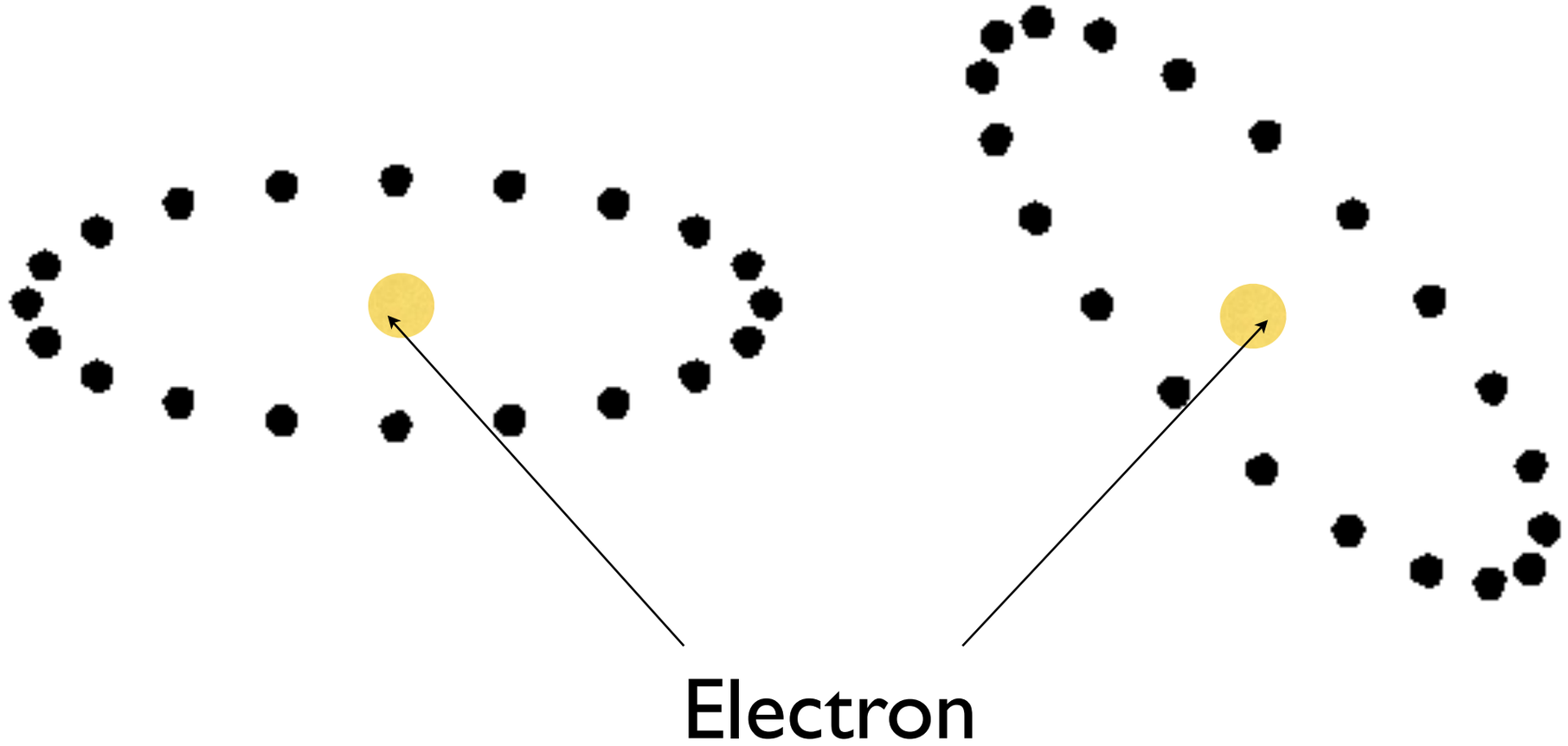
- **Gravitational waves** can generate both E- and B-modes!

Two Polarization States of GW

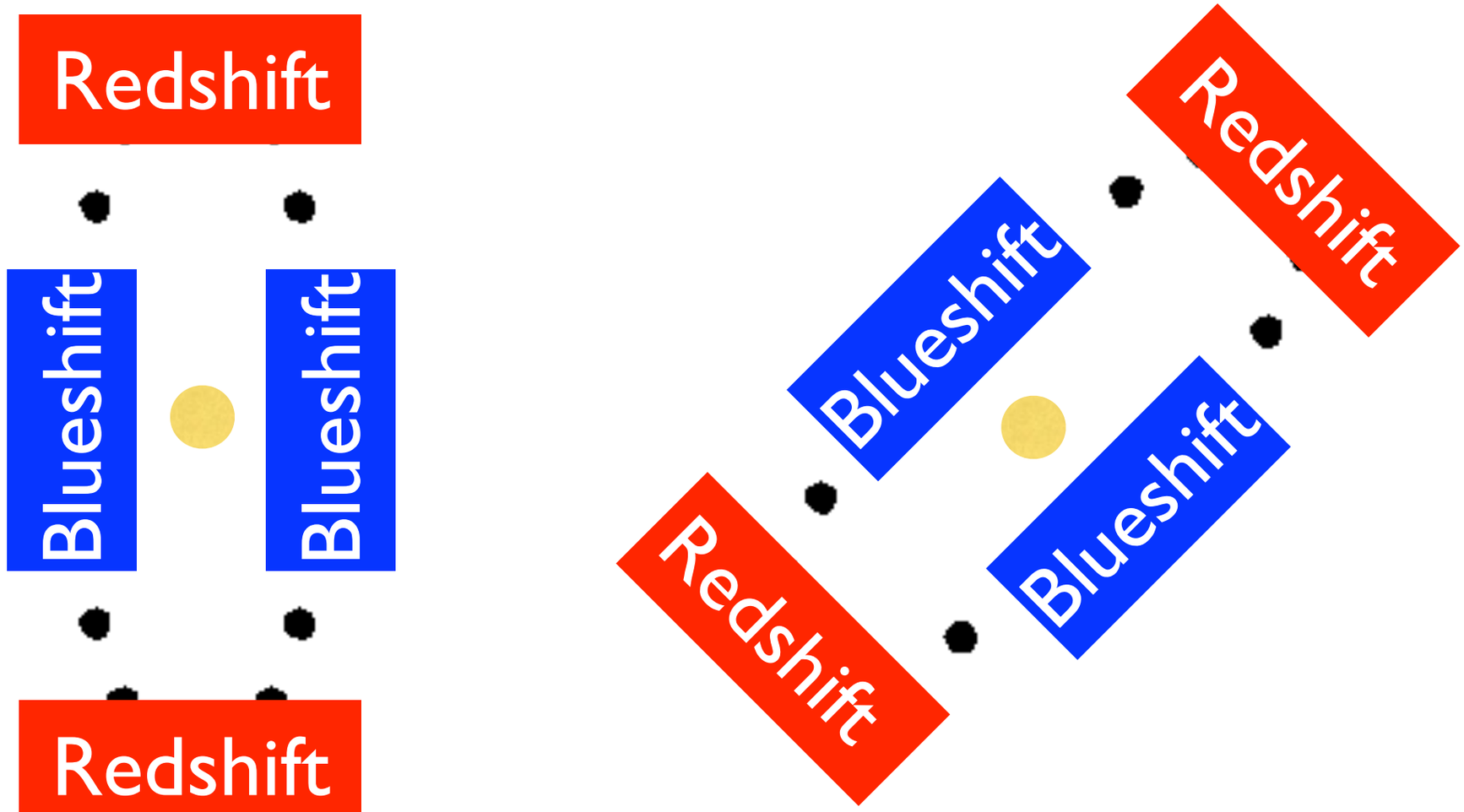


- This is great - this will automatically generate quadrupolar anisotropy around electrons!

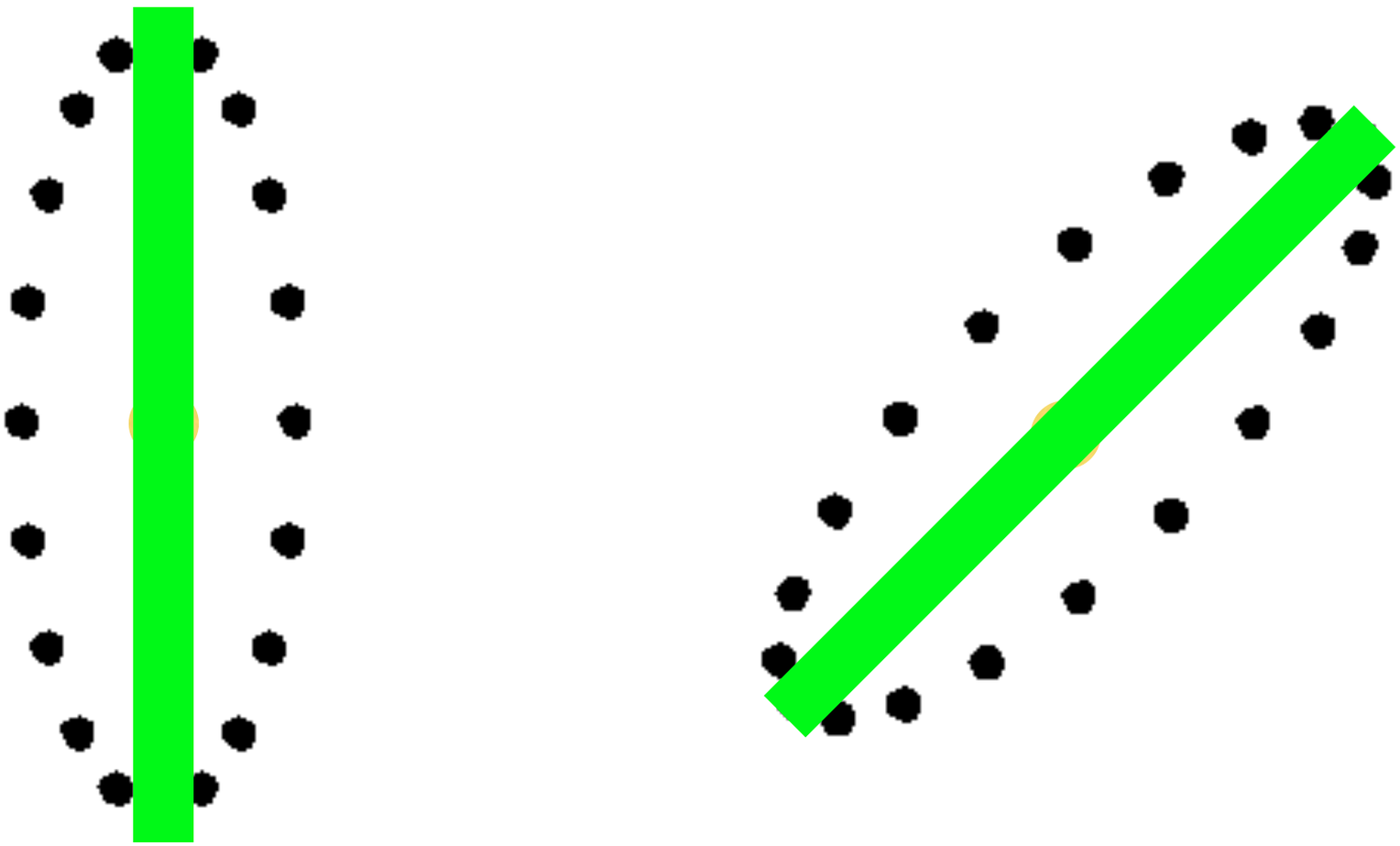
From GW to CMB Polarization



From GW to CMB Polarization



From GW to CMB Polarization



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

WMAP
QUaD
BICEP
QUIET
r=0.24
r=0.03
r=0.003
lens
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$l(l+1)C_l/(2\pi)$ [μK^2]
10
100
1000
Multipole, l

Tensor-to-scalar ratio, r

- r = [Power in tensor perturbation] / [Power in scalar perturbation]

- $r < 0.11$ [95% CL] from the temperature analysis of the Planck data assuming a power-law scalar perturbation power spectrum

BICEP2
BICEP1
QUAD
QUIET–Q
QUIET–W
CBI
Boomerang
DASI
WMAP
CAPMAP
r=0.2
lensing
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
Multipole
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3

Importance of B mode detection at degree scales

- If the detected B mode polarization is primordial [more later], and agrees with the prediction from a scale-invariant [but slightly red-tilted] gravitational wave spectrum, then:

- **It proves inflation**. Inflation generates these gravitational waves, whose wavelength has been stretched to cosmological scales. No astrophysics can do this.

- **This is a huge deal, if true**

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 ~10 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

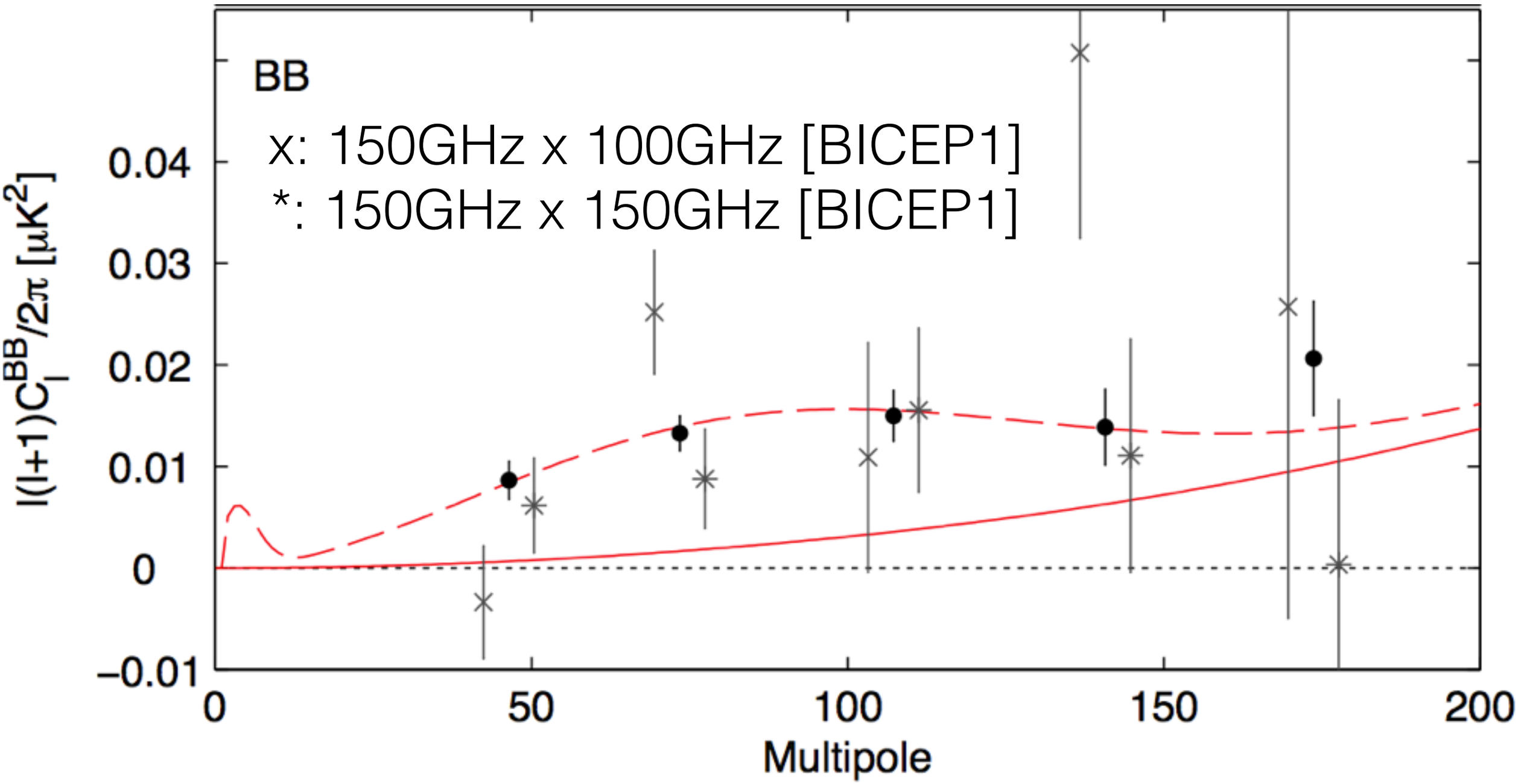
Eiichiro Komatsu
March 14 near Munich

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


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


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

Then I will believe it!



No 100 GHz x 100 GHz [yet]

B2xB2
B2xB1c
B2xKeck (preliminary)

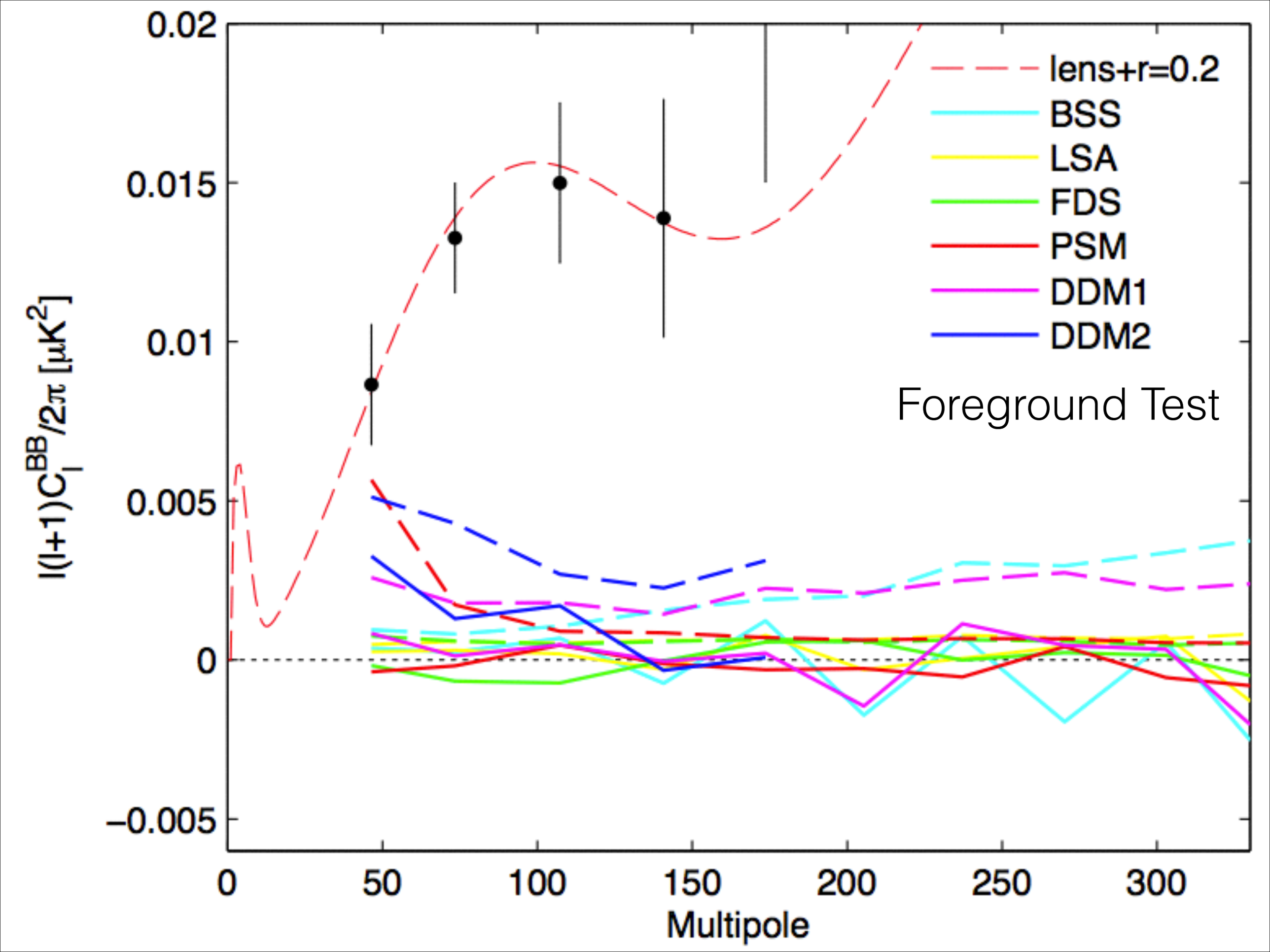
Correlations among different BICEP/Keck configurations

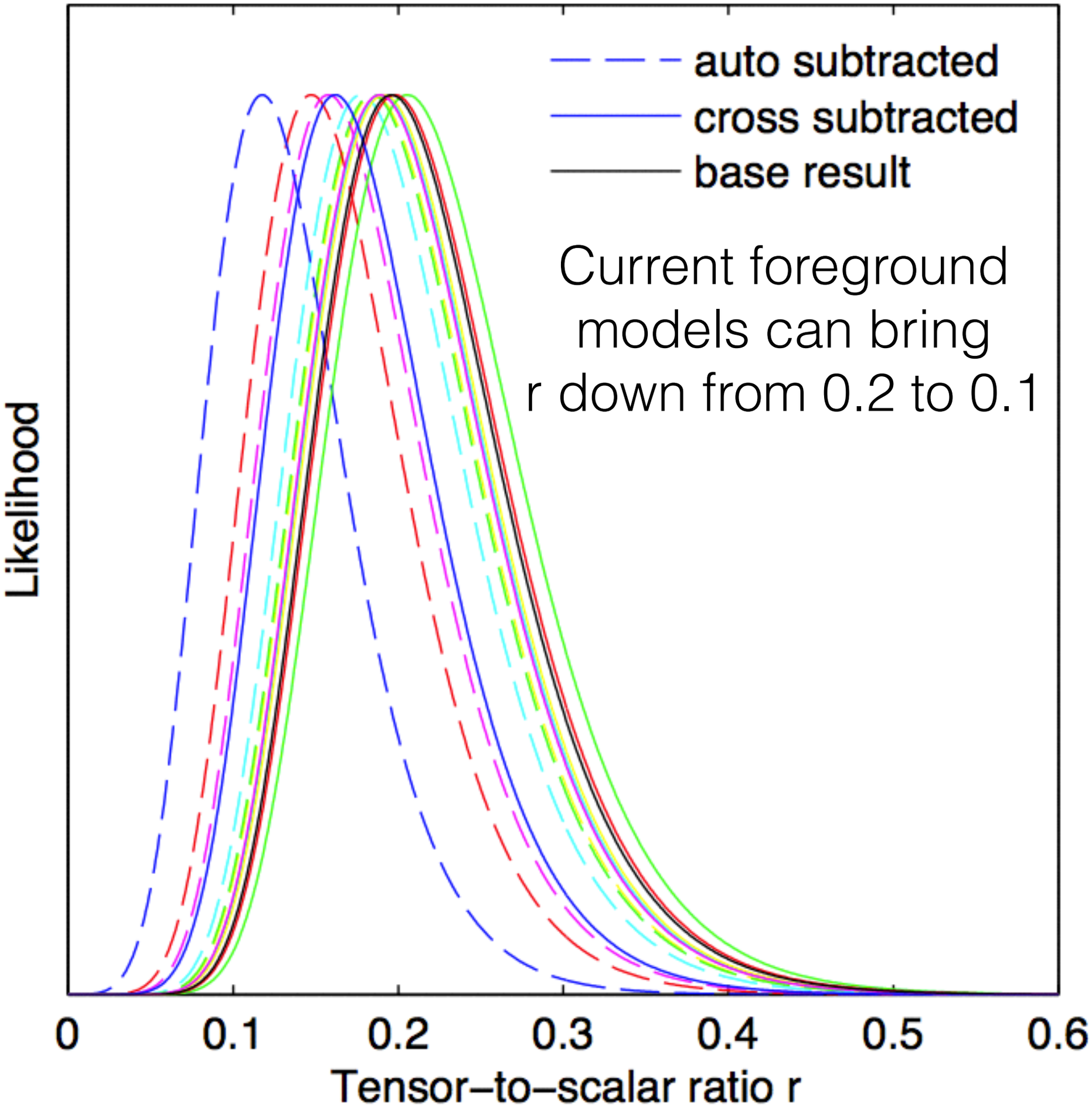
$l(l+1)C_l^{BB}/2\pi$ [μK^2]

0.05
0.04
0.03
0.02
0.01
0
−0.01

0
50
100
150
200
250
300

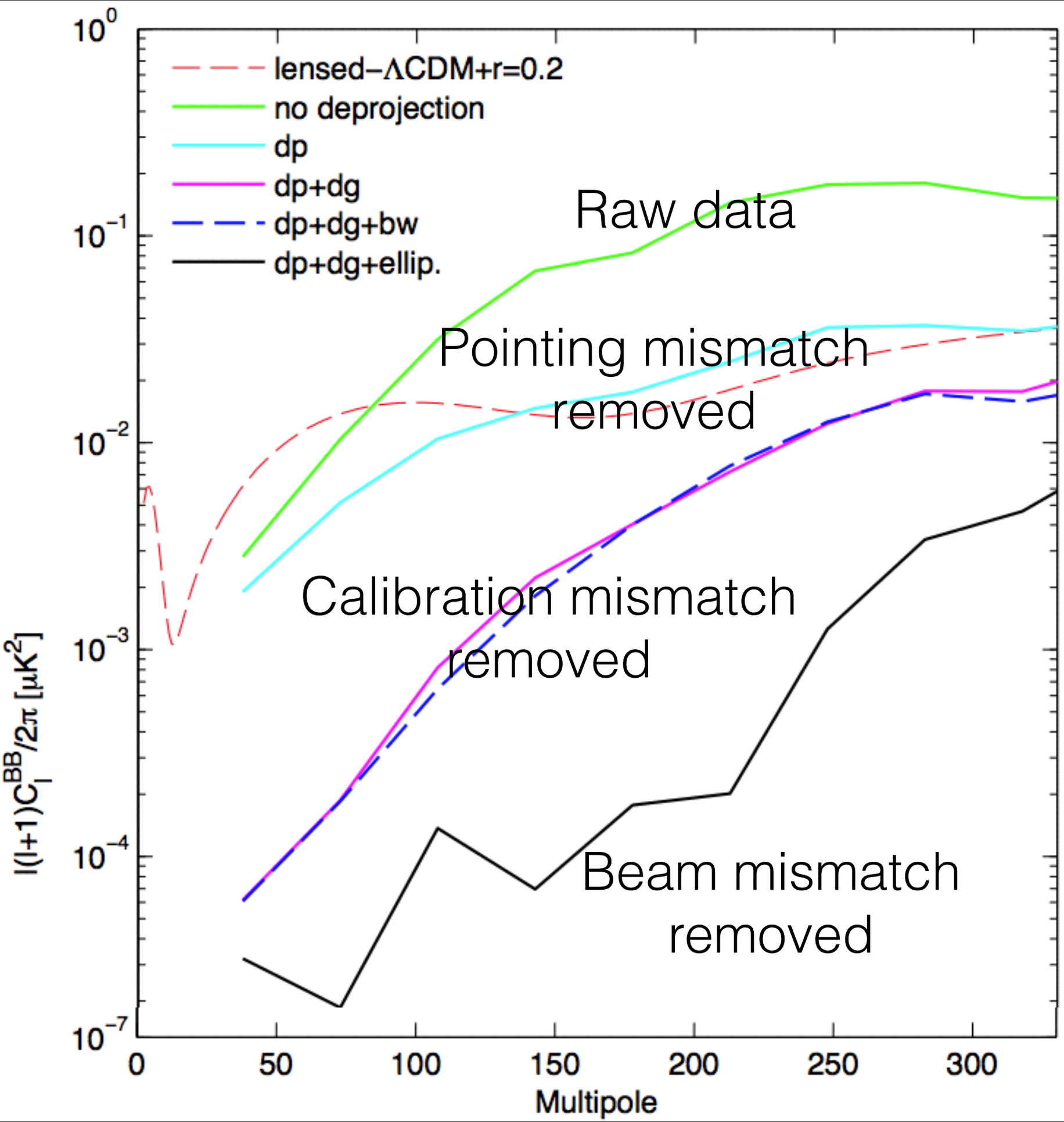
Multipole


0.02
0.015
0.01
0.005
0
−0.005
0
50
100
150
200
250
300
Multipole
l(l+1)C_l^BB/2π [μK^2]
lens+r=0.2
BSS
LSA
FDS
PSM
DDM1
DDM2
Foreground Test

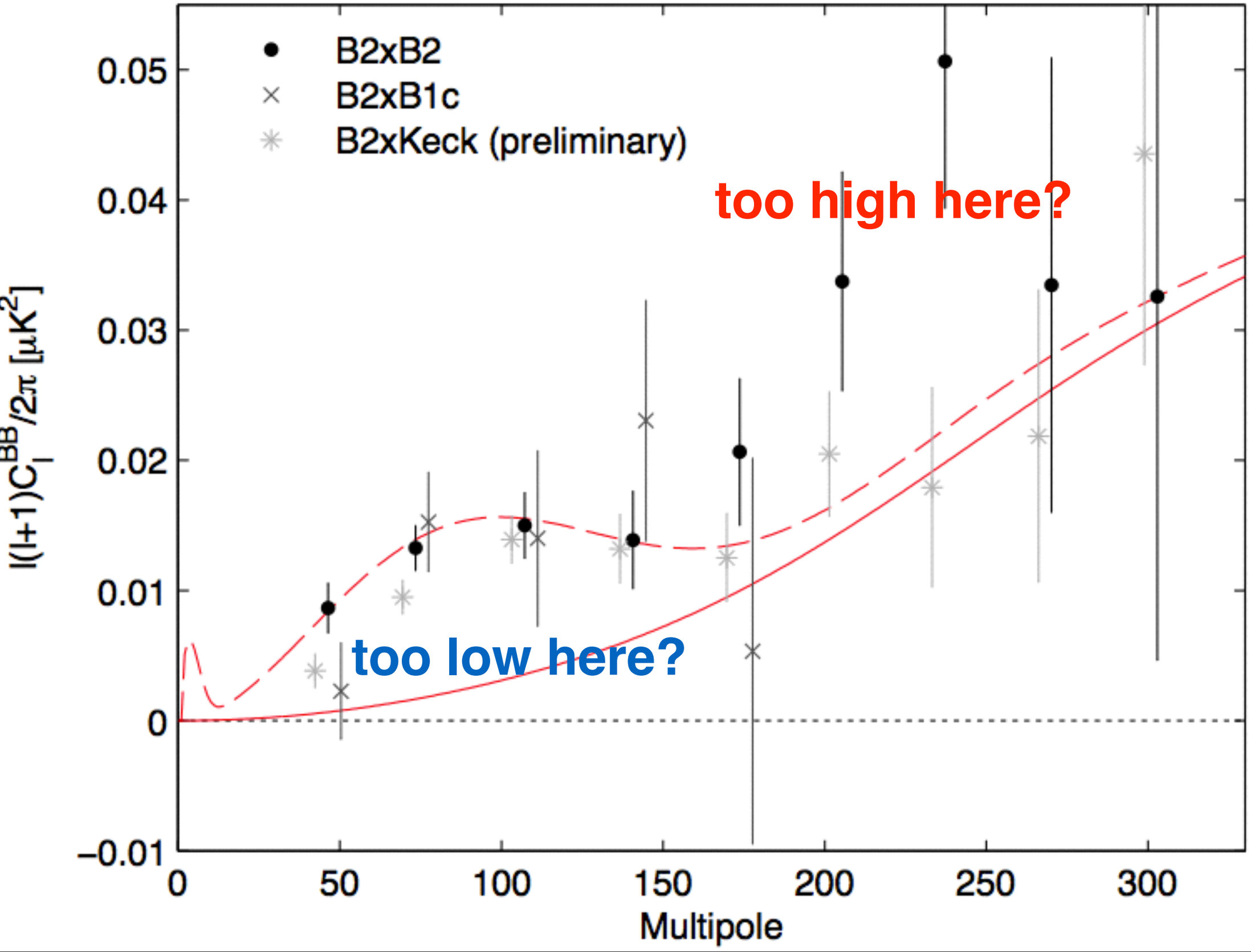

auto subtracted
cross subtracted
base result
Current foreground models can bring r down from 0.2 to 0.1
Likelihood
0
0.1
0.2
0.3
0.4
0.5
0.6
Tensor–to–scalar ratio r

Instrumental Effects

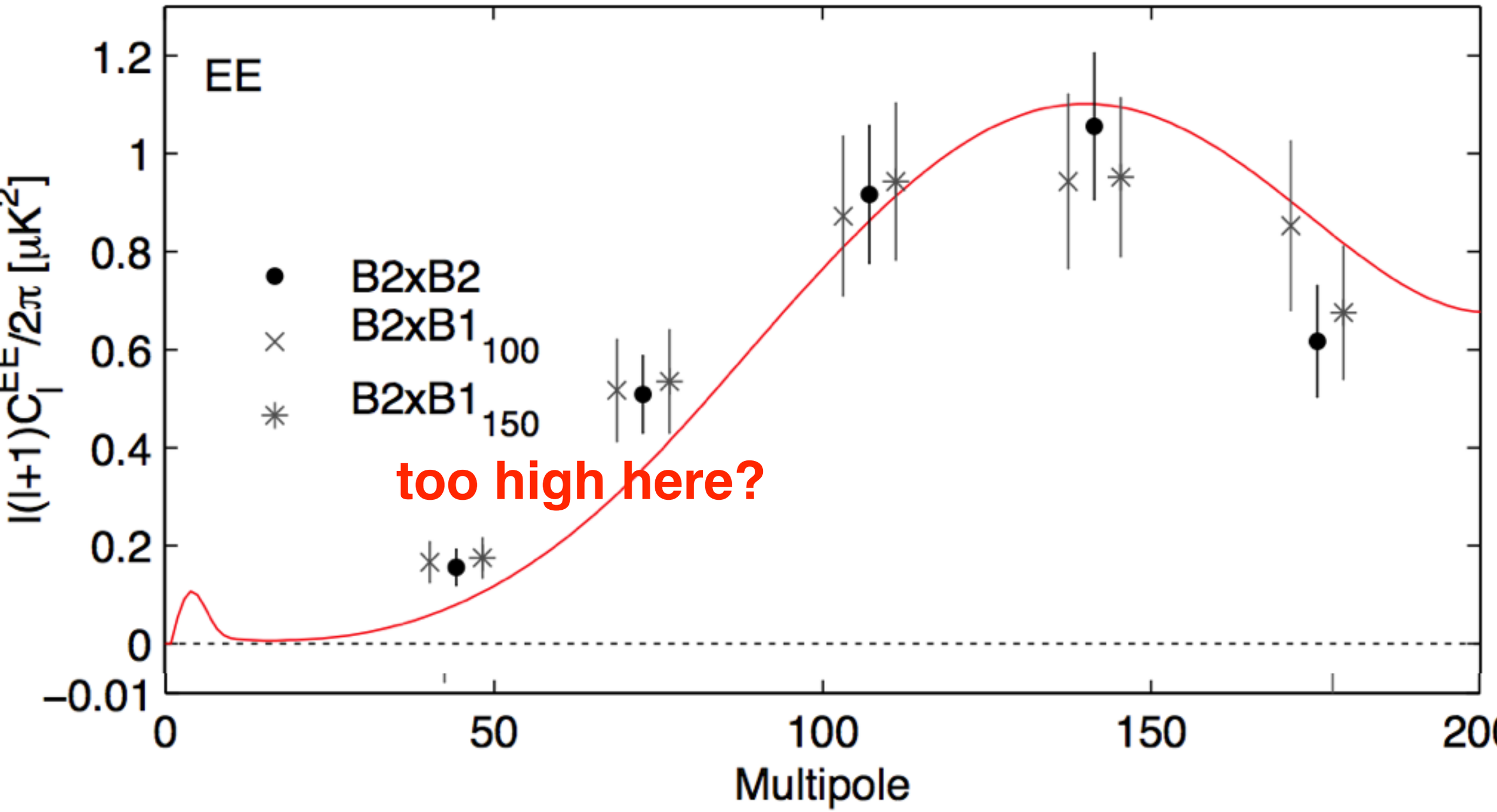
- BICEP2 measures polarization by taking the outputs of two detectors
- If the properties of these detectors are different, the temperature-to-polarization leakage occurs
  - Two detectors seeing different locations in the sky
  - Two detectors receiving slightly different frequencies
  - Two detectors 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
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-7}
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
0
50
100
150
200
250
300
Multipole

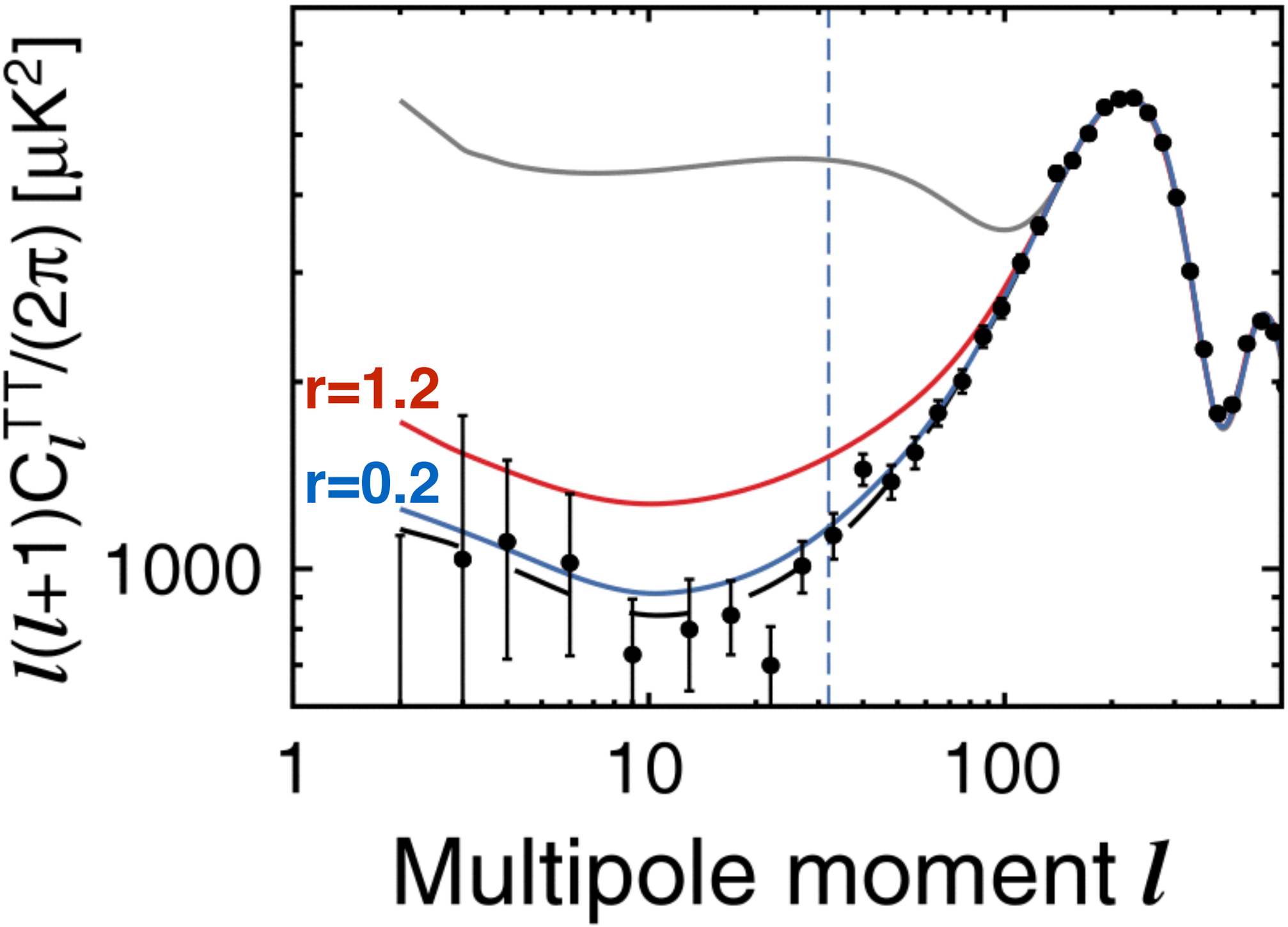
Worries raised at FB so far



Worries raised at FB so far



Limit from Temperature



“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?