Inflation Signatures
“To B or not to B”

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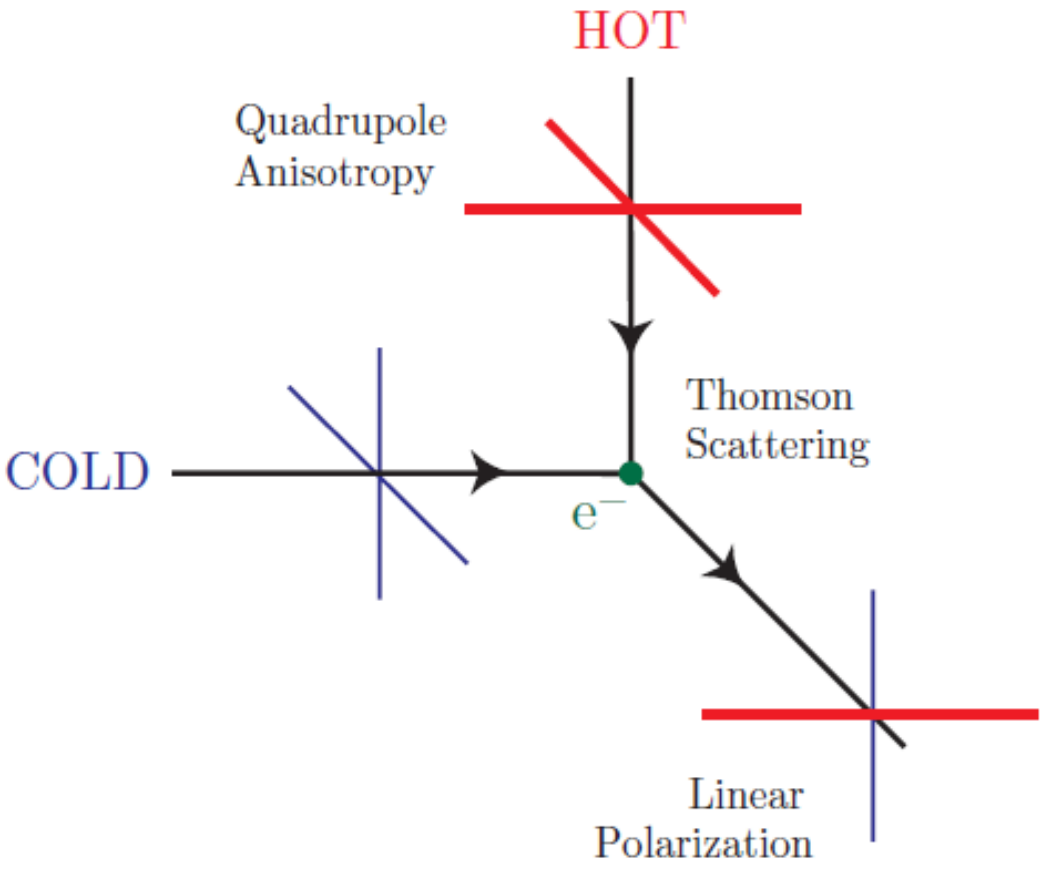
Creating Polarization in the CMB



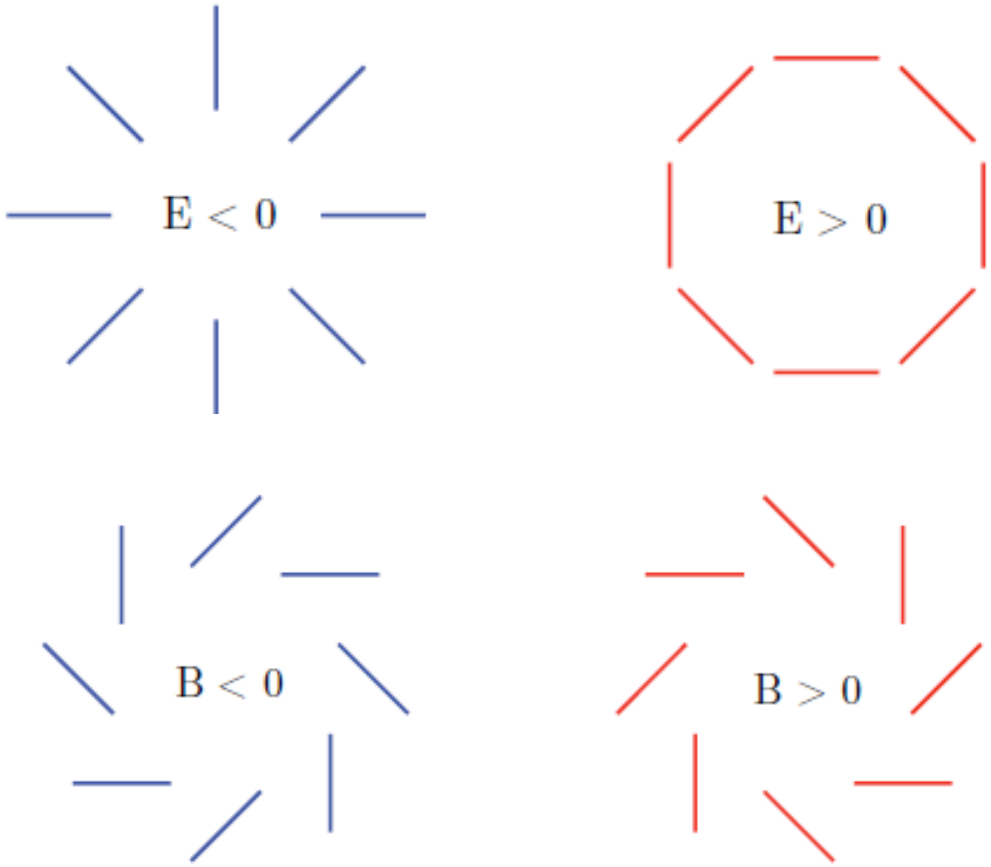
Nomenclature

$$(Q \pm iU)(\hat{n}) = \sum_{\ell,m} a_{\pm 2,\ell m}\, {}_{\pm 2}Y_{\ell m}(\hat{n})$$

$$a_{E,\ell m} \equiv -\frac{1}{2}\left(a_{2,\ell m} + a_{-2,\ell m}\right)$$

$$a_{B,\ell m} \equiv -\frac{1}{2i}\left(a_{2,\ell m} - a_{-2,\ell m}\right)$$

E and B Modes

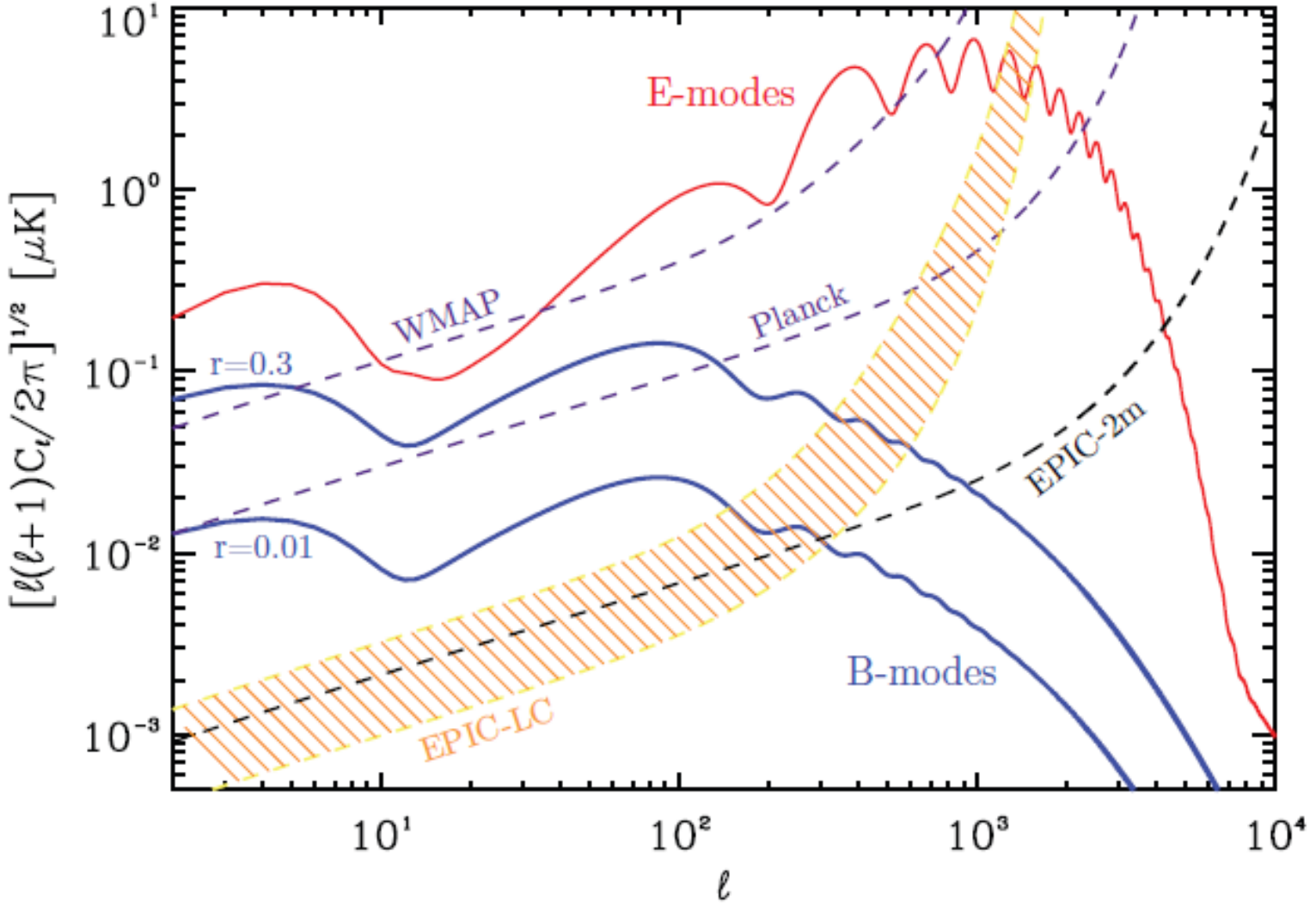


Power Spectra

$$C_\ell^{XY} \equiv \frac{1}{2\ell+1}\sum_m \langle a^*_{X,\ell m} a_{Y,\ell m}\rangle\,, \qquad X,Y = T,E,B$$

$$a_{X,\ell m} = 4\pi(-i)^\ell \int \frac{\mathrm{d}^3k}{(2\pi)^3}\,\Delta_{X\ell}(k)\,\{\zeta_{\vec{k}}, h_{\vec{k}}\}\,Y_{\ell m}(\hat{k})$$

$$C_\ell^{BB} = (4\pi)^2 \int k^2 \mathrm{d}k\, \underbrace{P_h(k)}_{\text{Inflation}}\, \Delta^2_{B\ell}(k)$$


E-modes
WMAP
Planck
r=0.3
r=0.01
EPIC-2m
EPIC-LC
B-modes
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ [μK]
ℓ
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
10^4

What do we learn

- No other known mechanism produces super horizon tensor fluctuation
- Inflation potential

$$V^{1/4} \sim \left(\frac{r}{0.01}\right)^{1/4} 10^{16}\,\mathrm{GeV}$$

- Super Planckian field variation

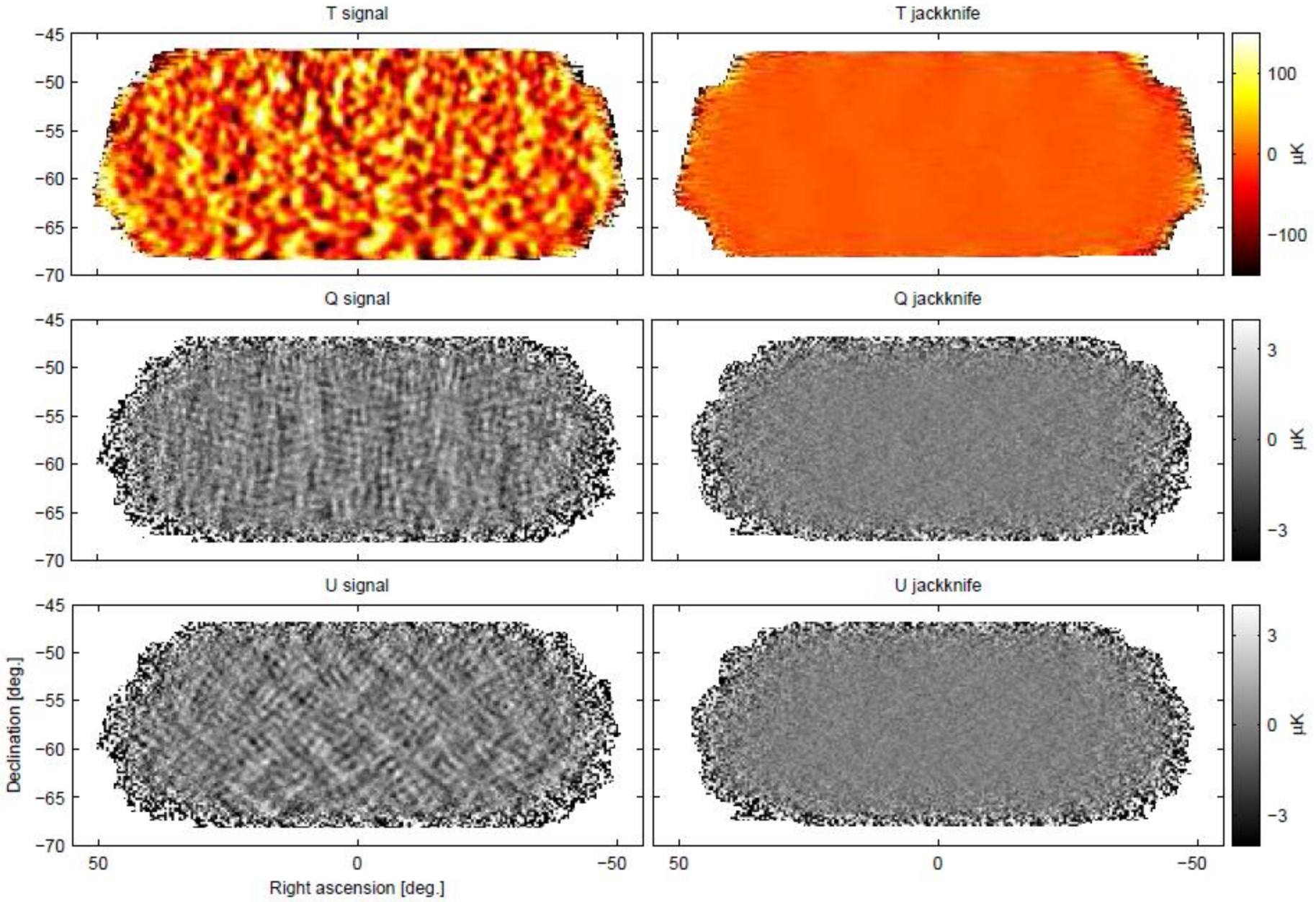
$$\frac{\Delta\phi}{M_{\mathrm{pl}}} = \mathcal{O}(1) \times \left(\frac{r}{0.01}\right)^{1/2}$$

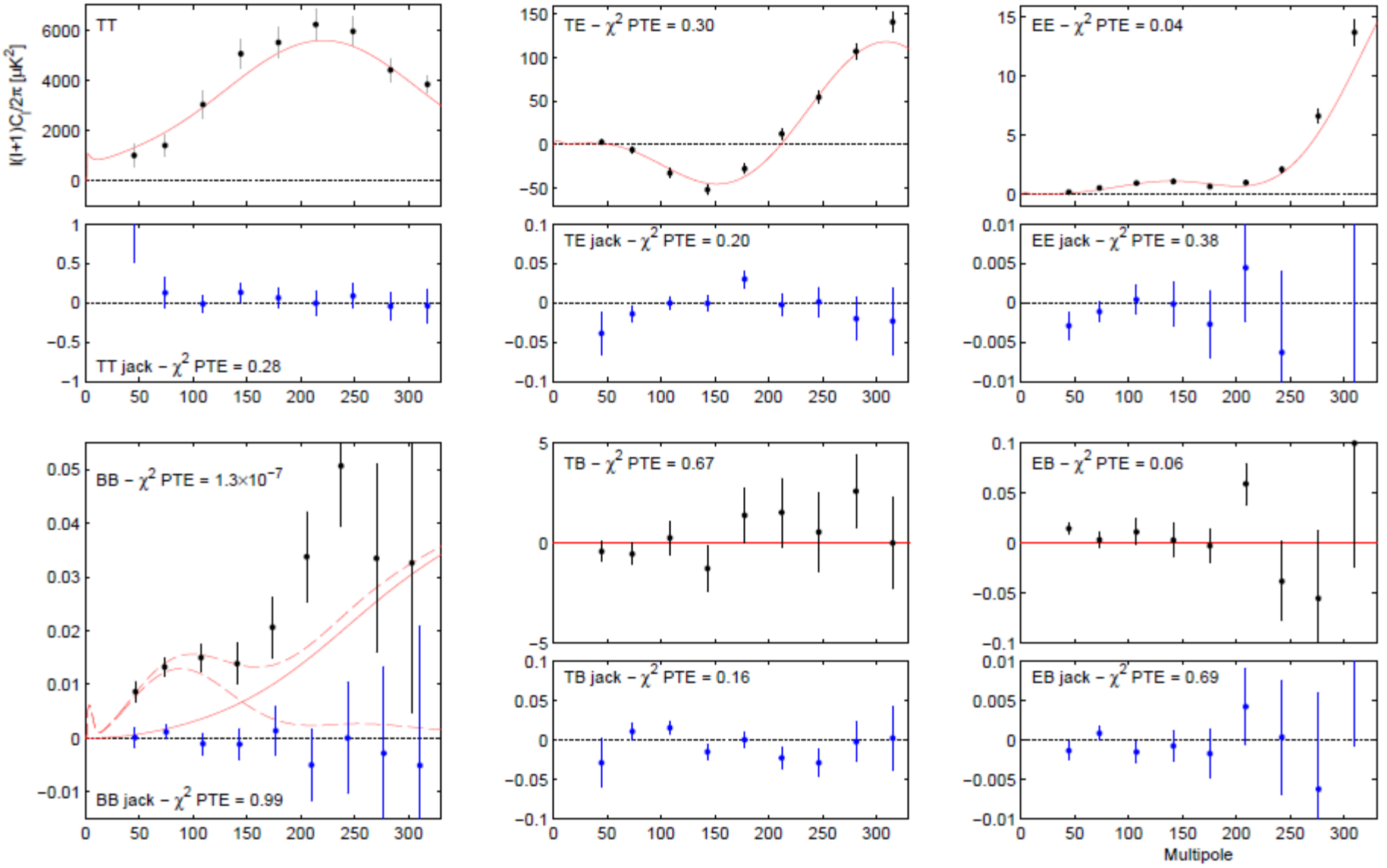
BiCEP 2 March 17 Results

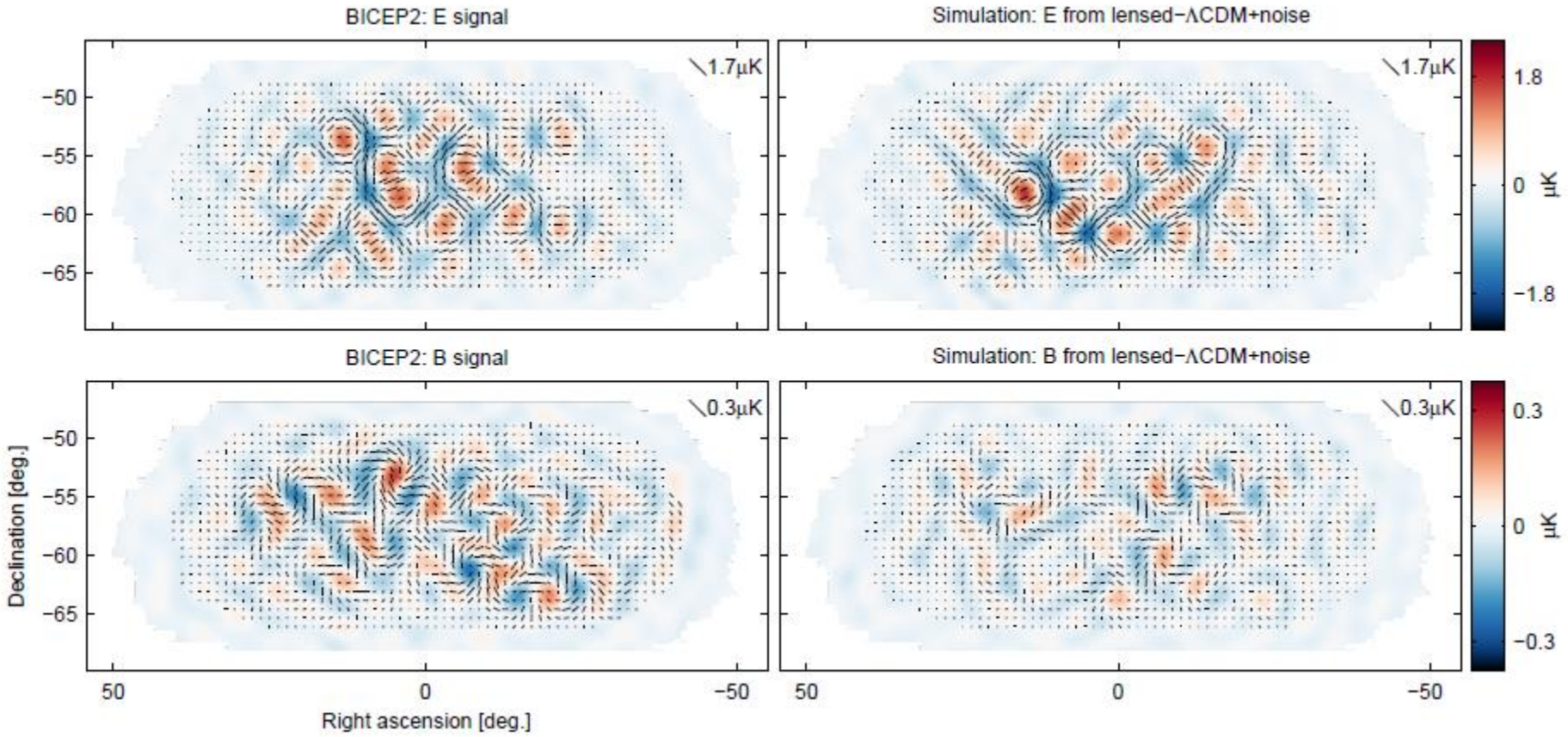
- Claim detection of r=0.2 +0.07, -0.05
- r=0 rejected at 7 sigma

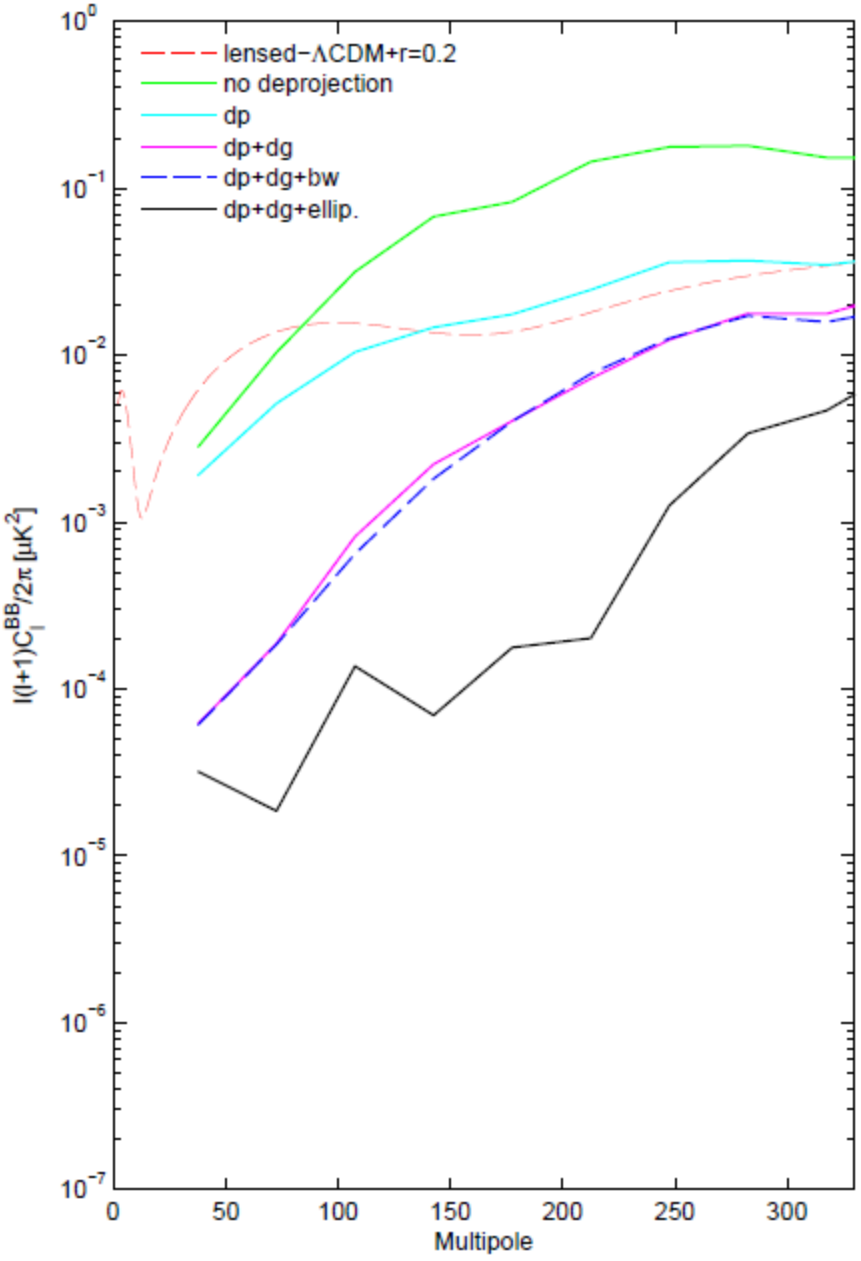
BiCEP B mode measurements

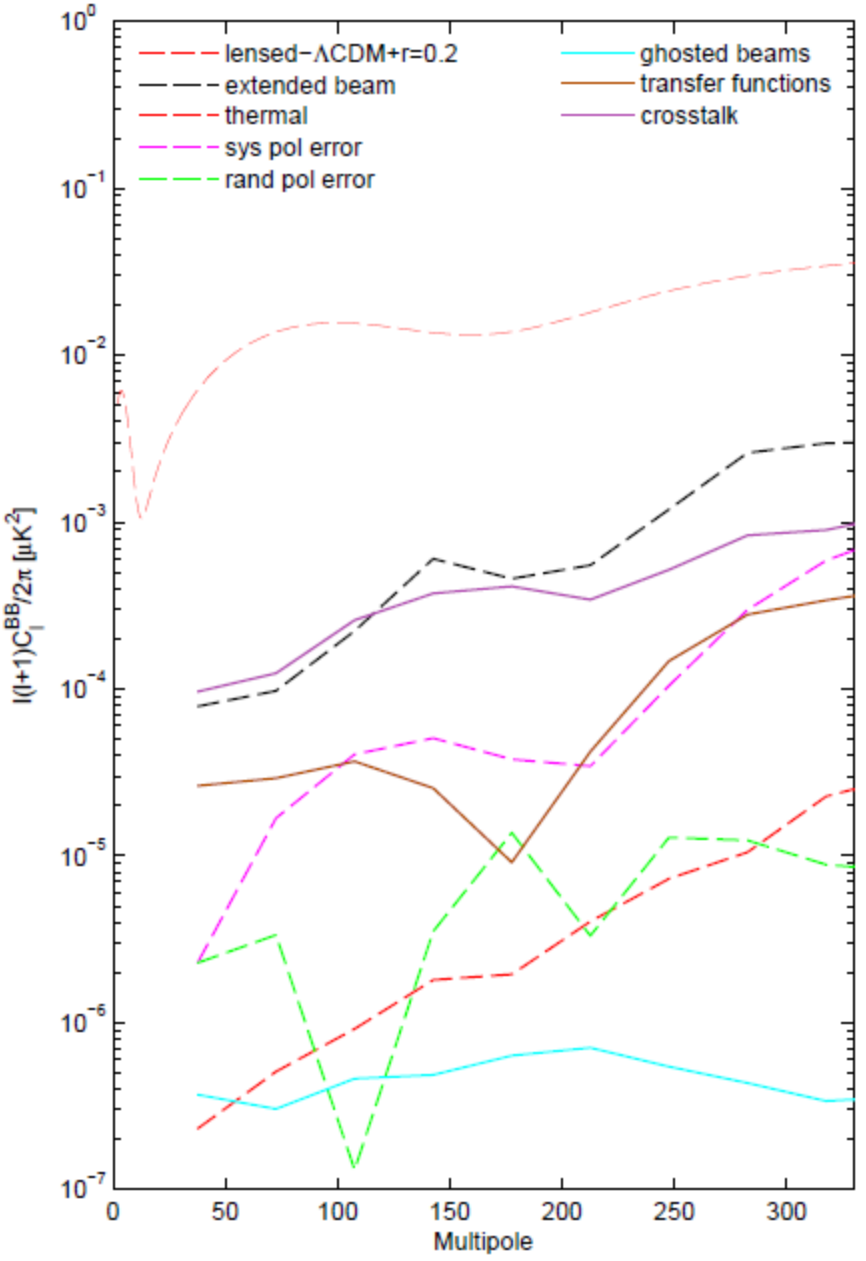
- Measure Tx and Ty with two orthogonal bolometers cooled to 270 mK – He3
- Optics are refractive - ~ 0.5 deg beam – cover ~ 1% sky
- One freq channel in BiCEP 2 – 150 Ghz – atmospheric window
- Measure Q and U linear polarization states
- Q = ½(Tx-Ty) – rotate 45 deg to get U
- V (circular pol) not measured
- Tx, Ty include instrument (few K), atmosphere (10K), gal (small in I, not in Q,U), CMB (~0.5K - Ta)
- 256 pairs of crossed bolo - ~ 300 micro K in 1 sec
- Integrate to get ~ 100 nK per 1 deg pixel
- MUST suppress/ understand all above (~10+K to 10^{-7} K level) this is 10^{8} rejection
- BiCEP is not a differential polarimeter - neither is Planck
- Systematic refection of all the above is critical

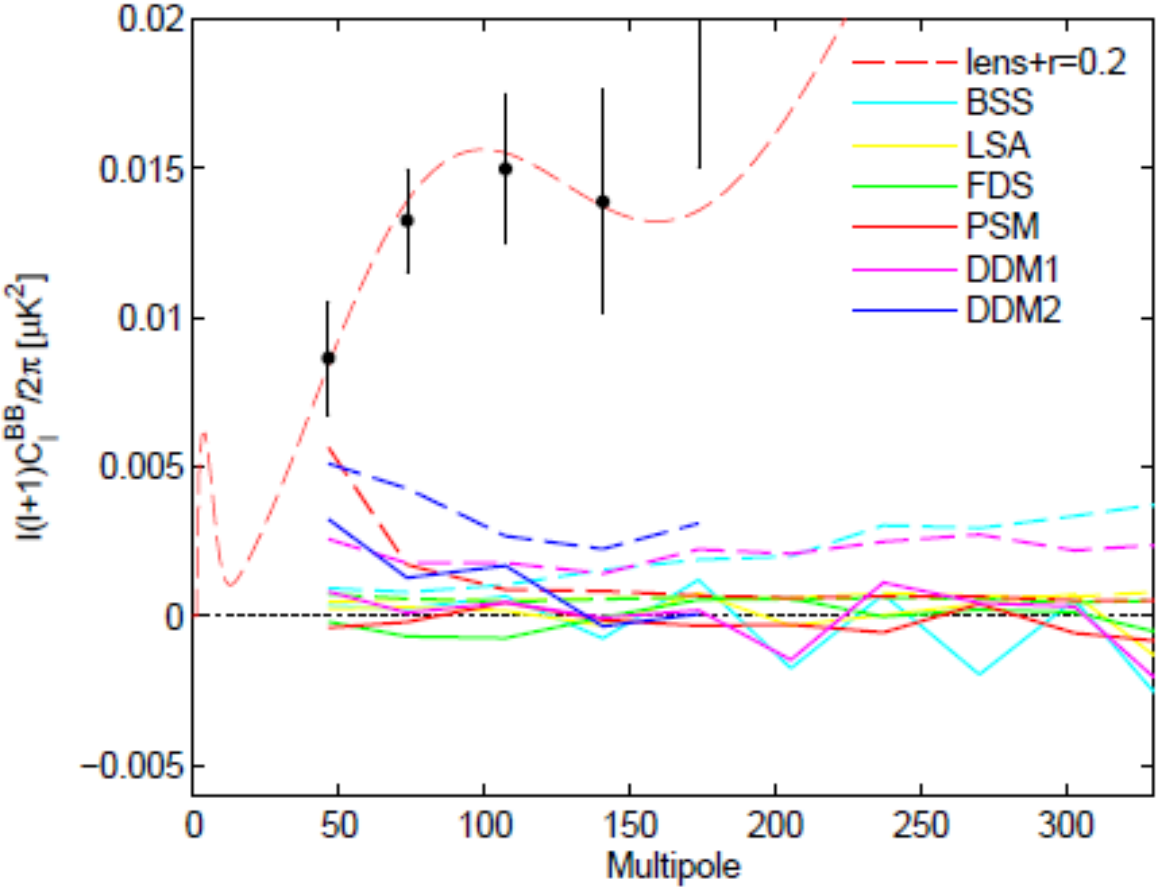

T signal
T jackknife
Q signal
Q jackknife
U signal
U jackknife
−45
−50
−55
−60
−65
−70
50
0
−50
Declination [deg.]
Right ascension [deg.]
100
0
−100
3
0
−3
μK

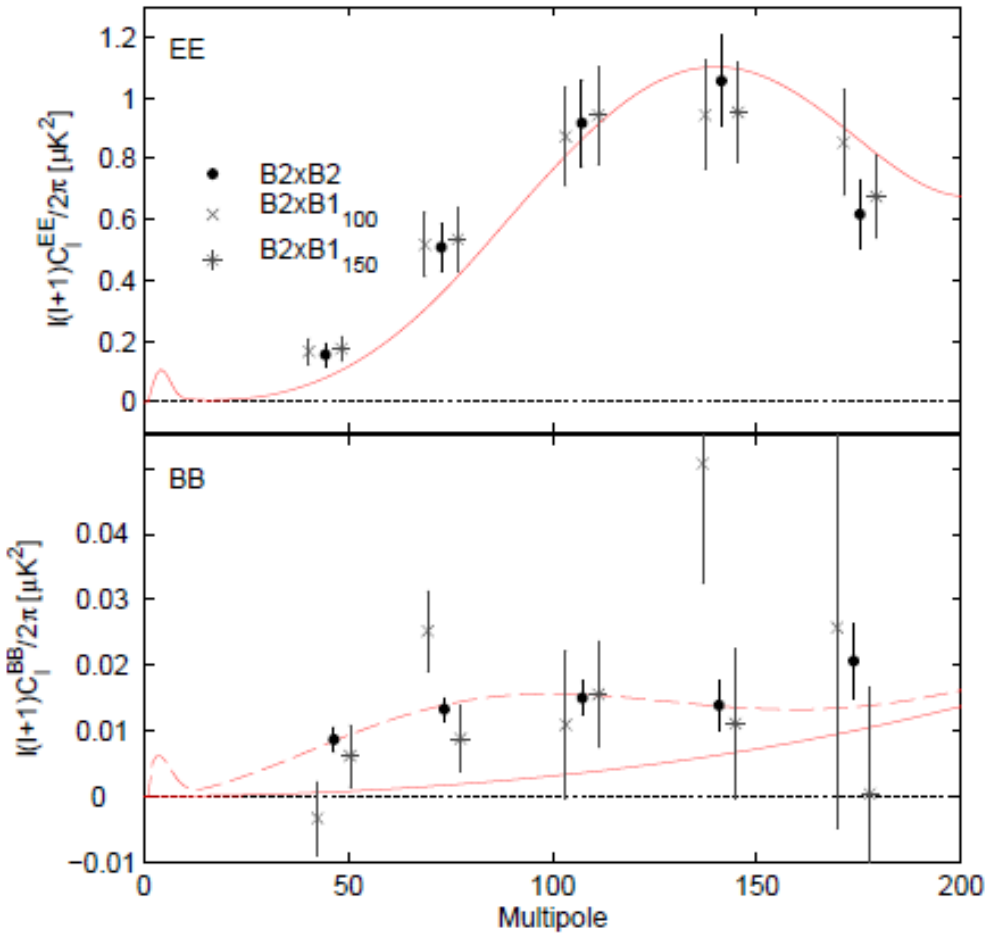

l(l+1)C_l/2π [μK^2]
TT
TT jack – χ^2 PTE = 0.28
TE – χ^2 PTE = 0.30
TE jack – χ^2 PTE = 0.20
EE – χ^2 PTE = 0.04
EE jack – χ^2 PTE = 0.38
BB – χ^2 PTE = 1.3×10^-7
BB jack – χ^2 PTE = 0.99
TB – χ^2 PTE = 0.67
TB jack – χ^2 PTE = 0.16
EB – χ^2 PTE = 0.06
EB jack – χ^2 PTE = 0.69
Multipole

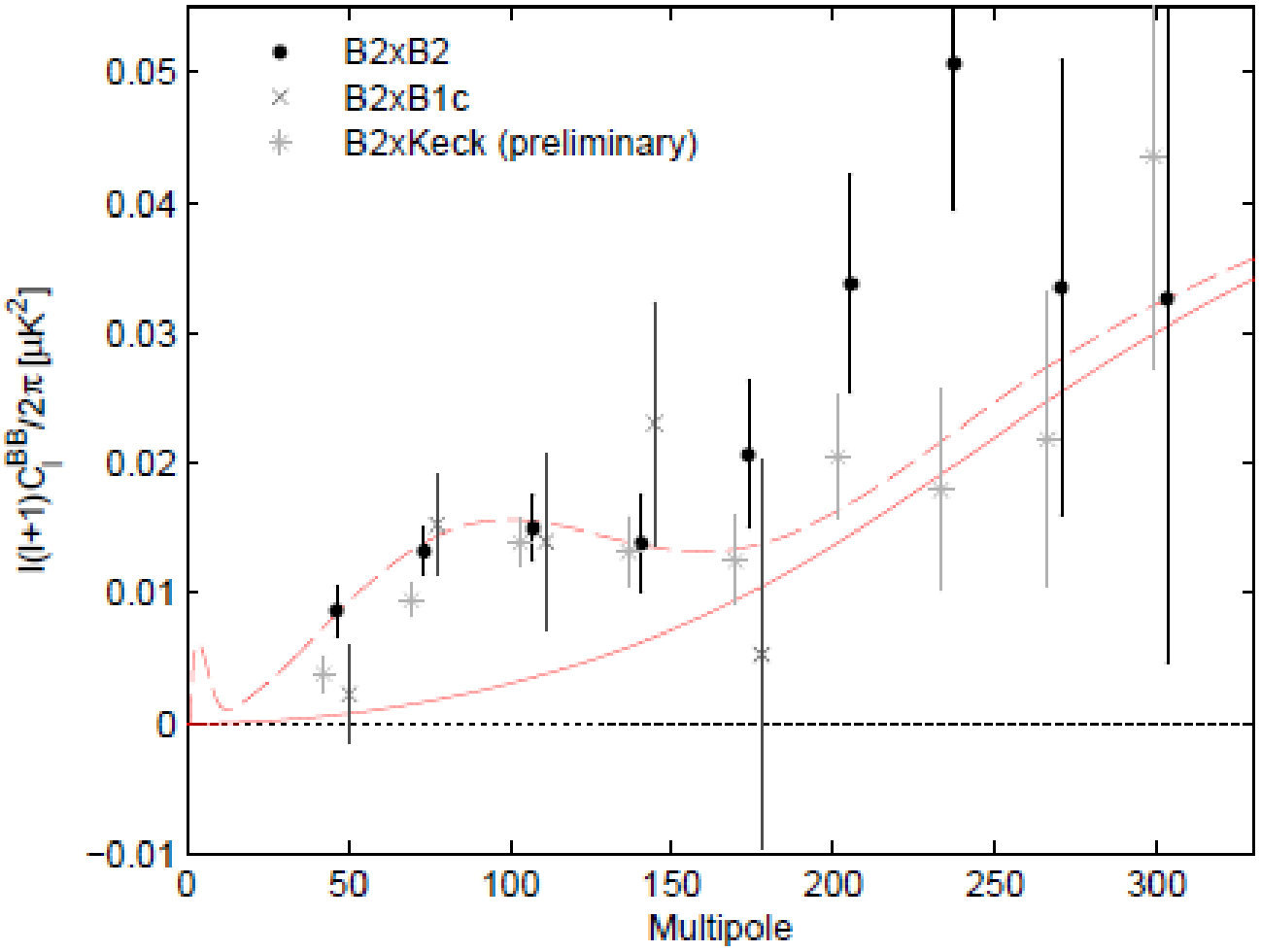

BICEP2: E signal
Simulation: E from lensed−ΛCDM+noise
BICEP2: B signal
Simulation: B from lensed−ΛCDM+noise
1.7μK
0.3μK
1.8
0
−1.8
μK
0.3
−0.3
−50
−55
−60
−65
50
0
−50
Declination [deg.]
Right ascension [deg.]

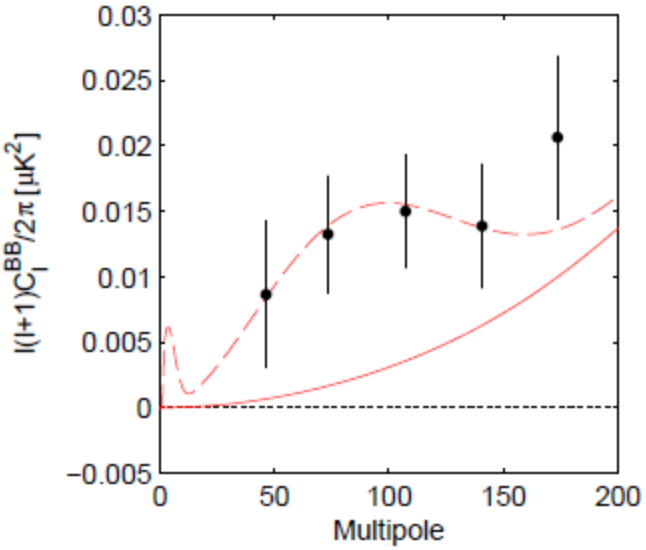

lensed−ΛCDM+r=0.2
no deprojection
dp
dp+dg
dp+dg+bw
dp+dg+ellip.
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole

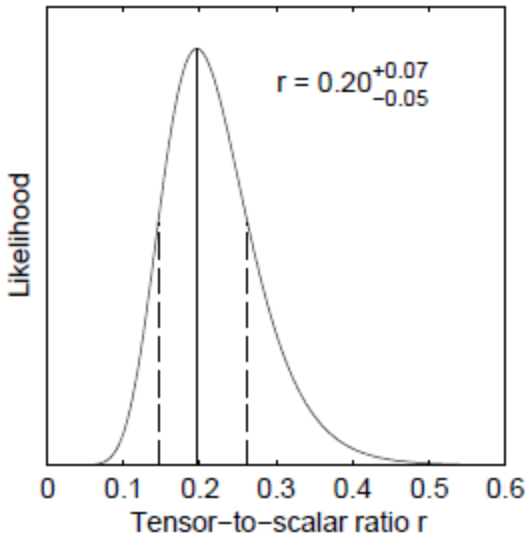

lensed−ΛCDM+r=0.2
extended beam
thermal
sys pol error
rand pol error
ghosted beams
transfer functions
crosstalk
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole

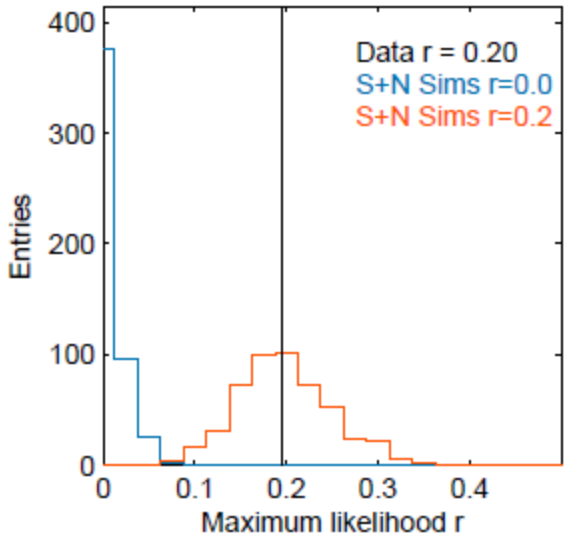

0.02
0.015
0.01
0.005
0
−0.005
0
50
100
150
200
250
300
Multipole
l(l+1)C_l^BB/2π [μK^2]
lens+r=0.2
BSS
LSA
FDS
PSM
DDM1
DDM2

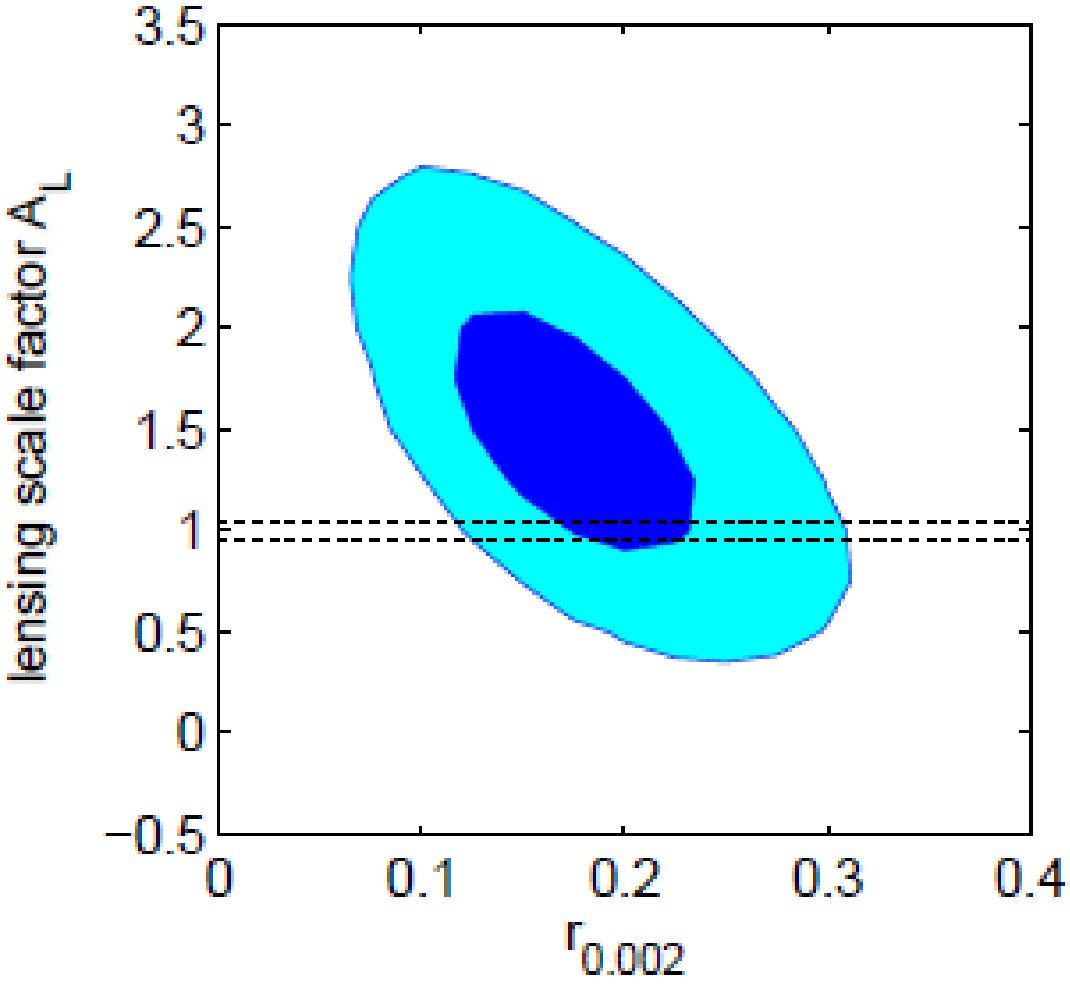

EE
BB
B2xB2
B2xB1100
B2xB150
l(l+1)C_l^EE/2π [μK^2]
l(l+1)C_l^BB/2π [μK^2]
Multipole
1.2
1
0.8
0.6
0.4
0.2
0
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200

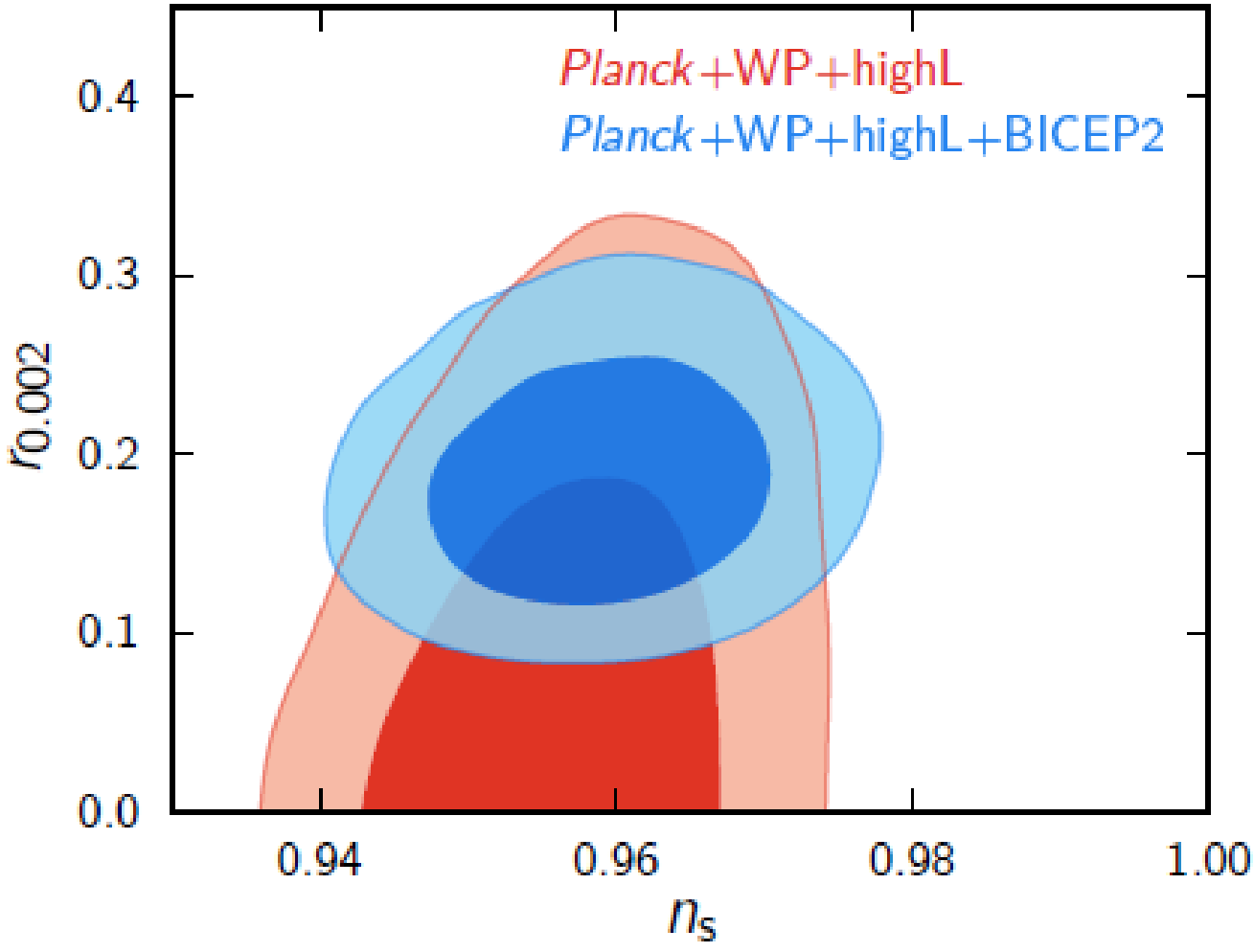

B2xB2
B2xB1c
B2xKeck (preliminary)
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300
Multipole
l(l+1)C_l^BB/2π [μK^2]

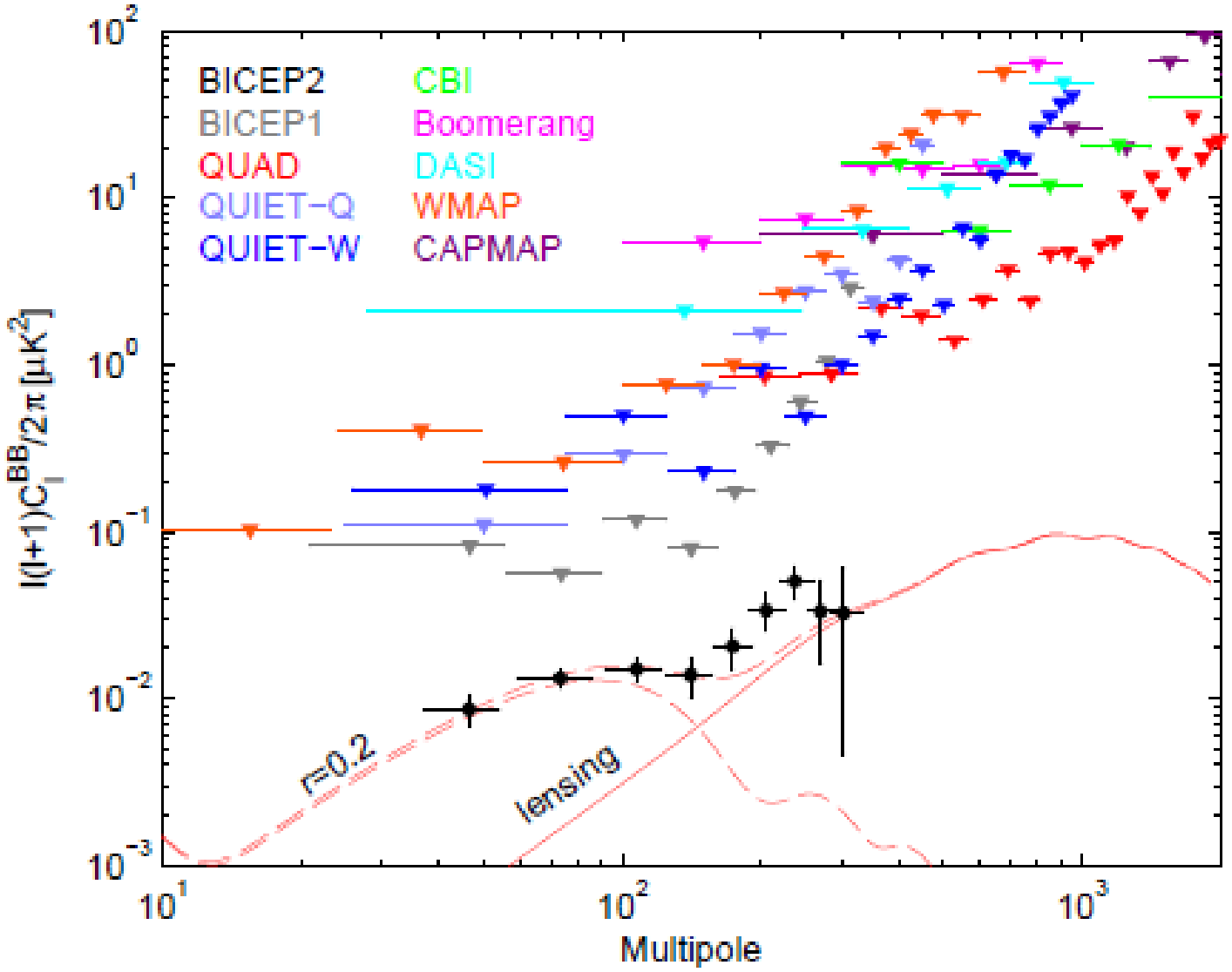

0.03
0.025
0.02
0.015
0.01
0.005
0
−0.005
0
50
100
150
200
Multipole
l(l+1)C_l^BB/2π [μK^2]


r = 0.20 +0.07 −0.05
Likelihood
0
0.1
0.2
0.3
0.4
0.5
0.6
Tensor−to−scalar ratio r


Data r = 0.20
S+N Sims r=0.0
S+N Sims r=0.2
400
300
200
100
0
Entries
0
0.1
0.2
0.3
0.4
Maximum likelihood r


lensing scale factor A_L
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
0
0.1
0.2
0.3
0.4
$r_{0.002}$


Planck+WP+highL
Planck+WP+highL+BICEP2
0.4
0.3
0.2
0.1
0.0
r0.002
0.94
0.96
0.98
1.00
ns


BICEP2
BICEP1
QUAD
QUIET−Q
QUIET−W
CBI
Boomerang
DASI
WMAP
CAPMAP
r=0.2
lensing
l(l+1)C_l^BB/2π [μK^2]
Multipole
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^1
10^2
10^3

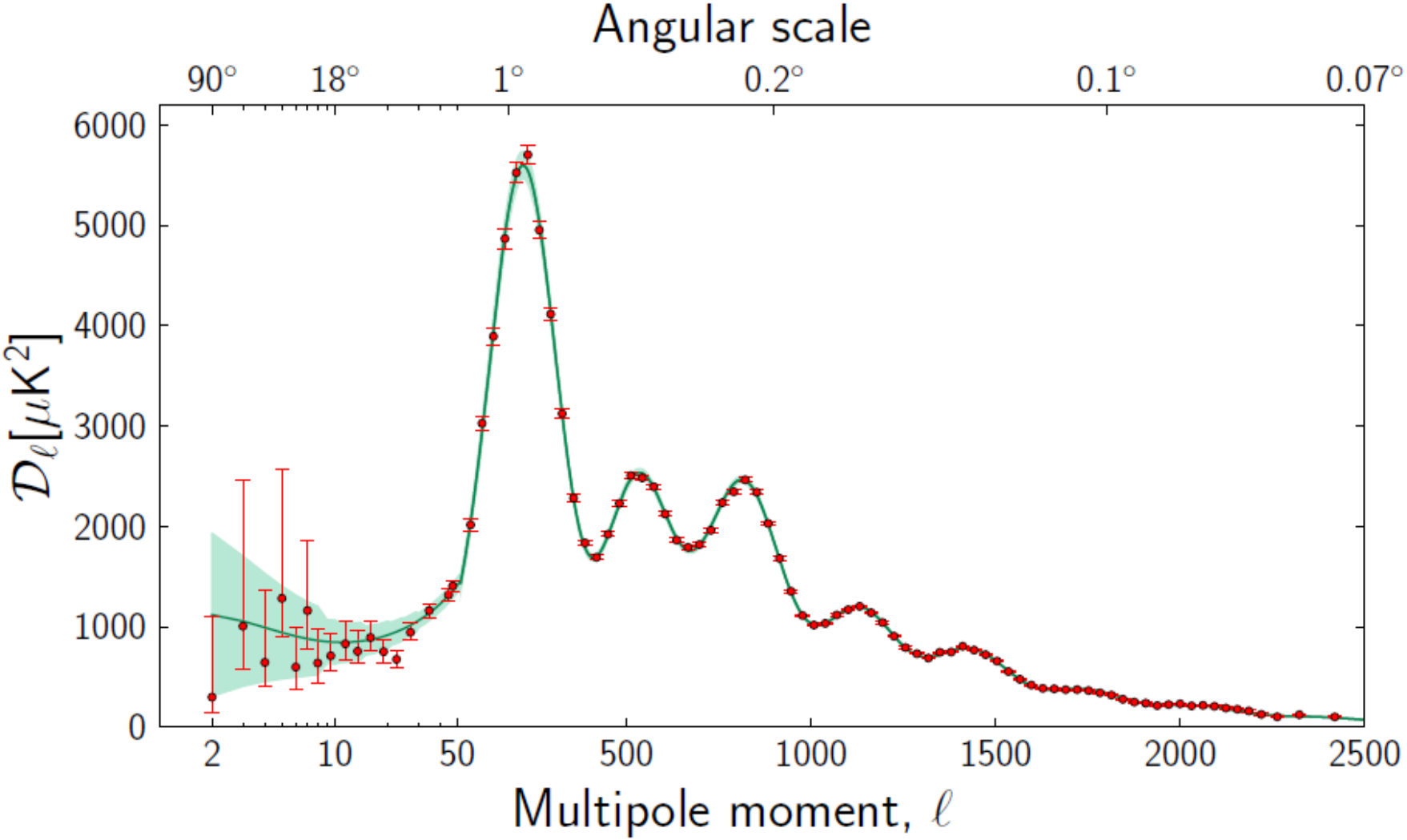
Planck Mission

- Planck mission data collecting 2009-2013 has ended
- Planck T (intensity) for about ½ mission released 2013
- Planck Q,U NOT released yet – 2014, 2015
- r ~ 0.05 (2 sigma) sensitivity possible at low l
- 30-1000 GHz freq coverage
- Full sky

TT Power Spectra – 7 peaks resolved

Error bars include SV and CV

Note low quadrupole



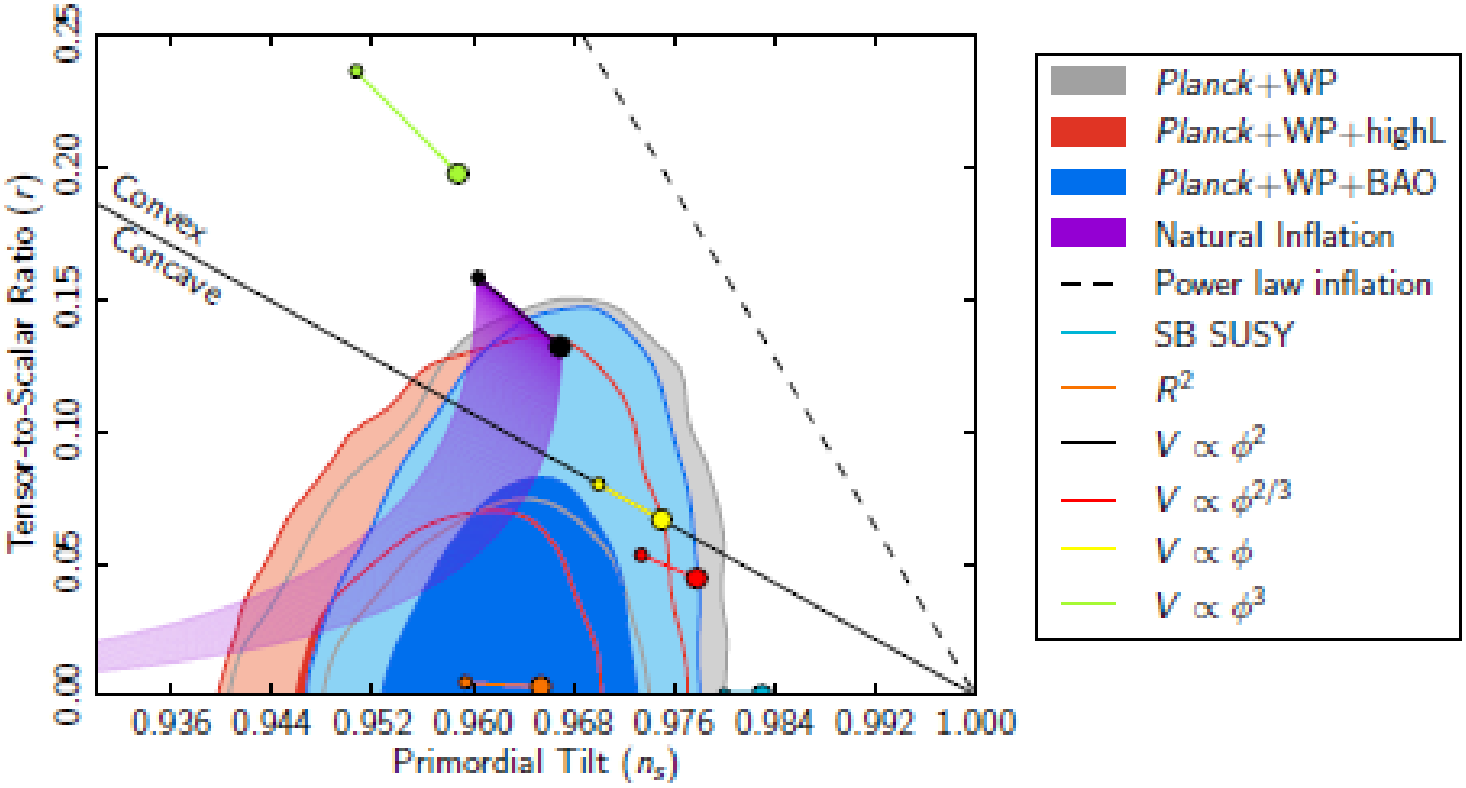
Marginalized n_s and r (1,2σ)

n_s does not equal 1

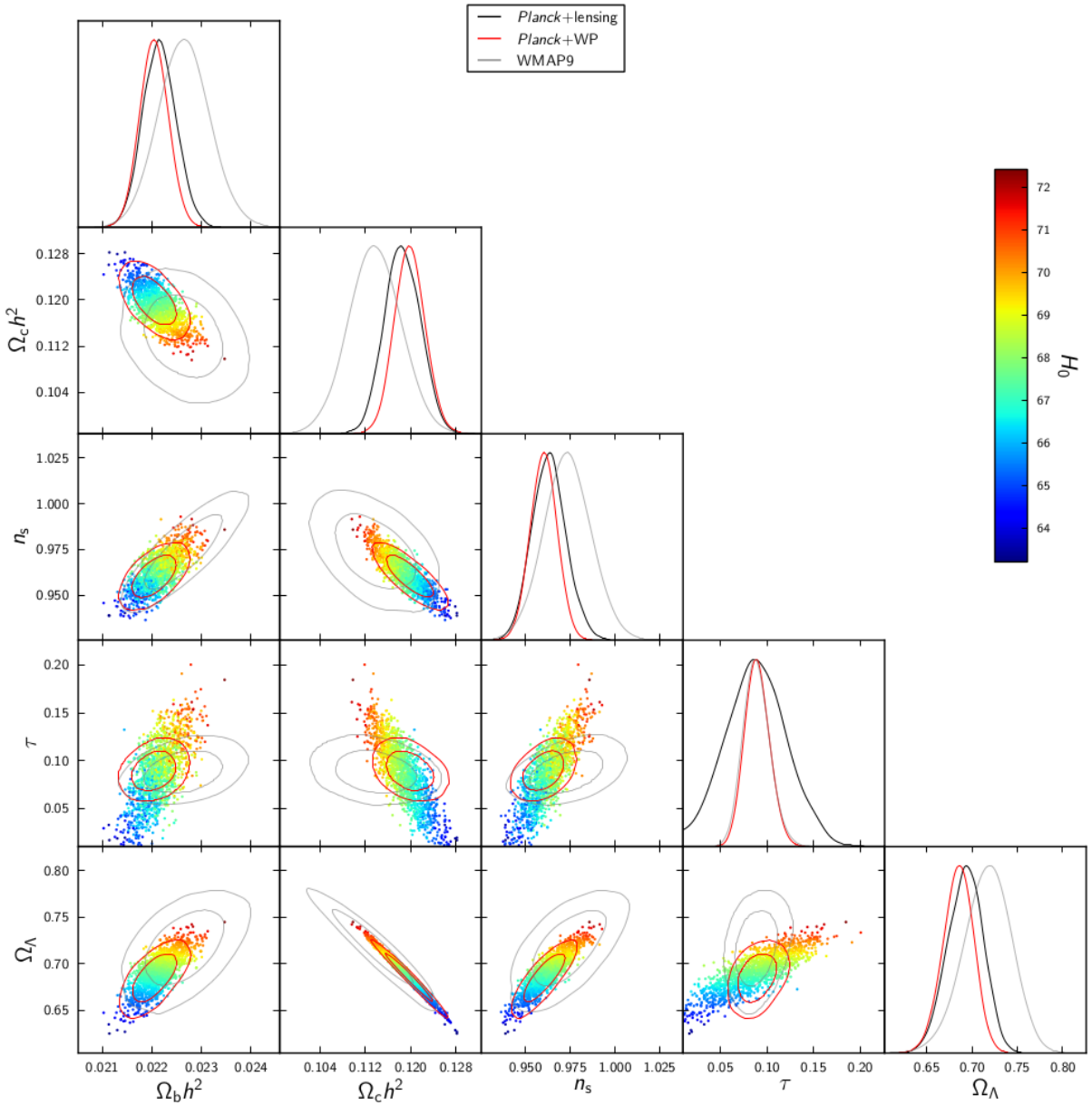
r<0.11 (2 σ) from T alone

Energy scale for "standard inflation" <1.9×10^{16} Gev (2 σ)

Planck polarization this year



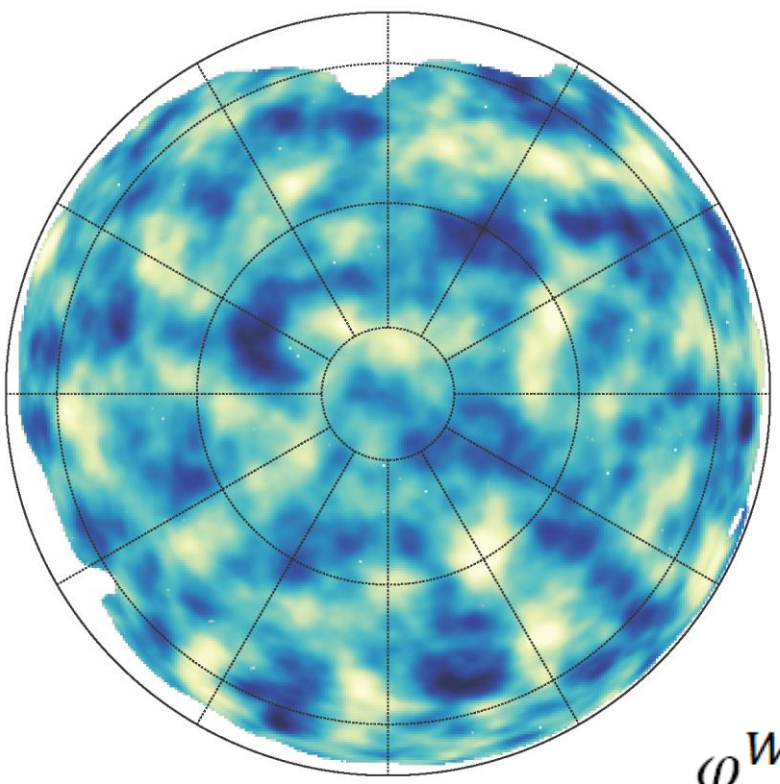
Selected parameters

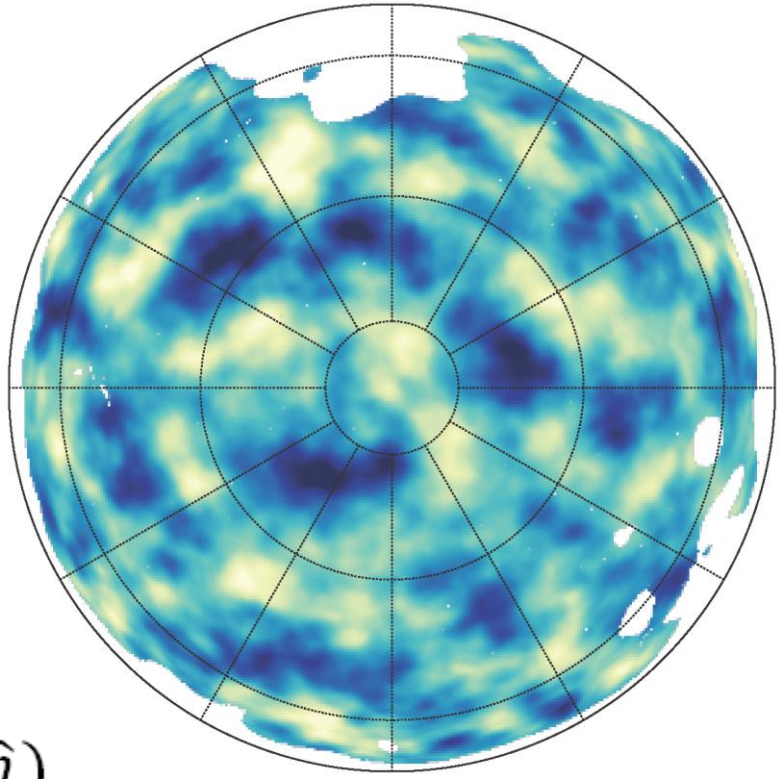


Lensing Potential Measured

High Significance (25 sigma)

Mode by mode SNR ~ 0.7 at L=30





$$\varphi^{WF}(\hat{n})$$

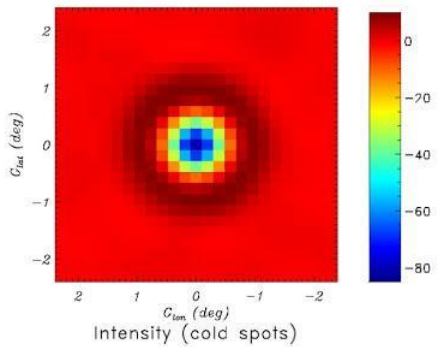
Galactic North

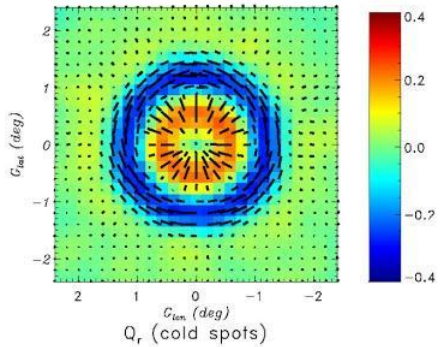
Galactic South

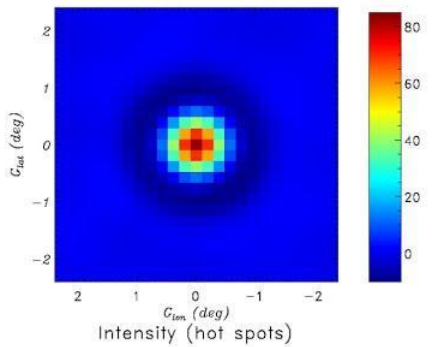
Planck polarization at Extrema T and Q

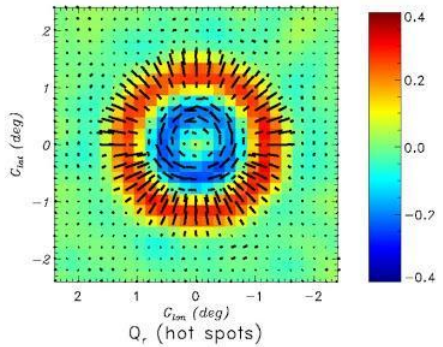
Left – cold spots , Right – hot spots

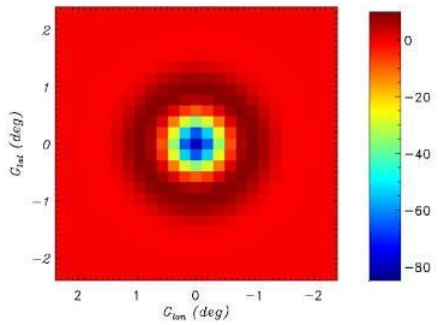
Top -data, bottom - Best fit model prediction

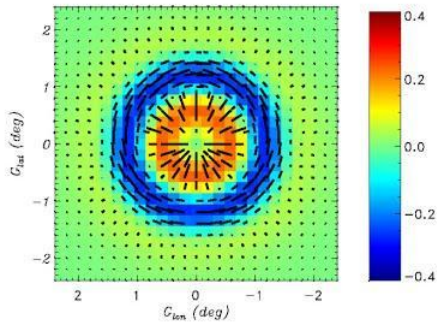


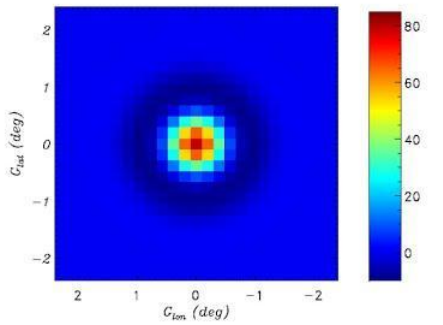


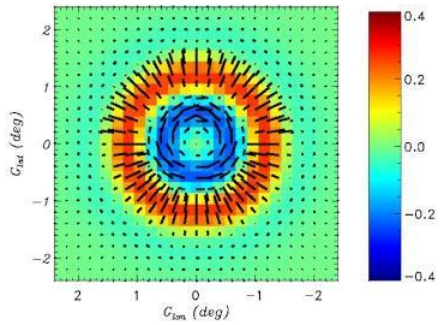


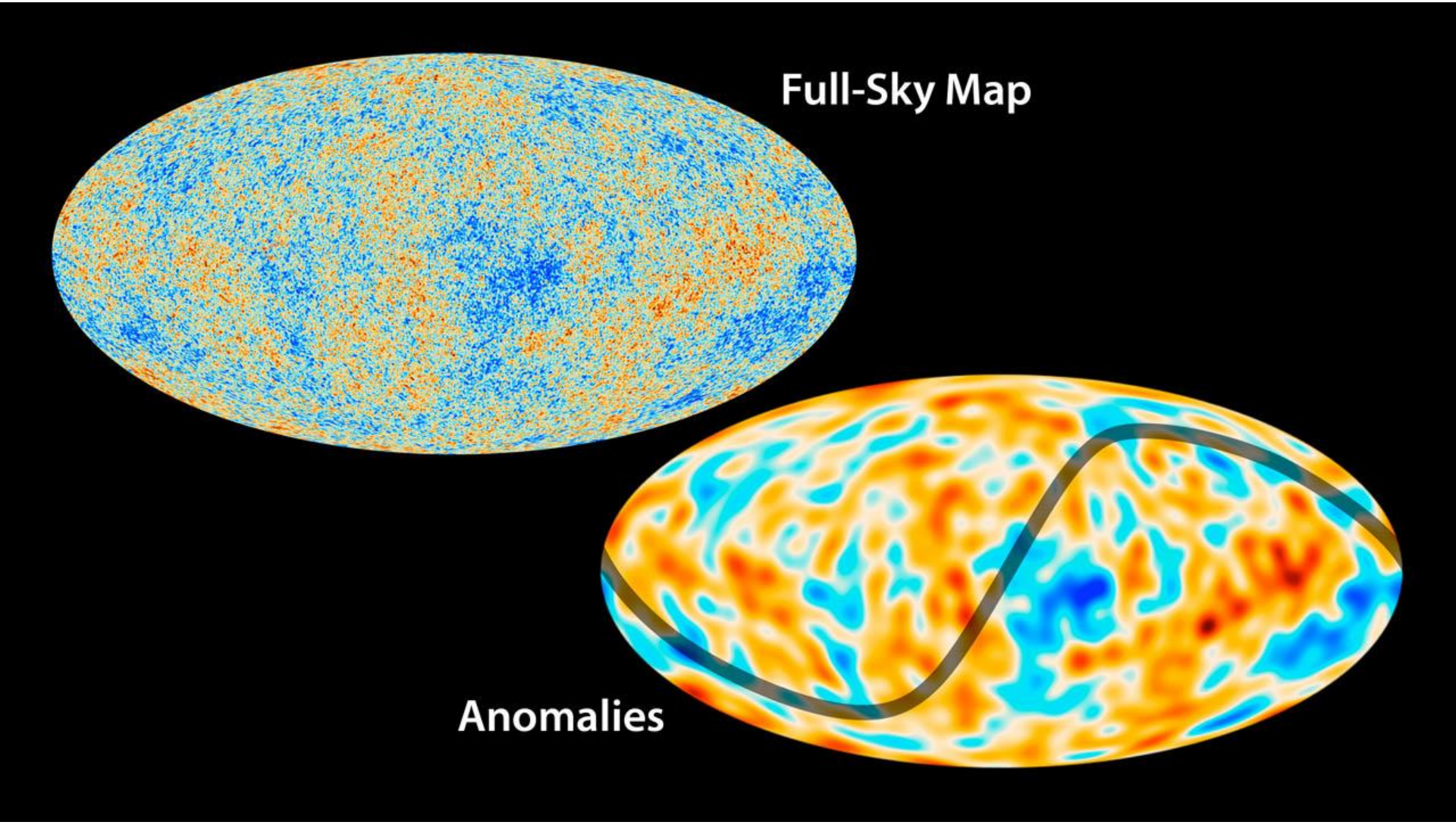








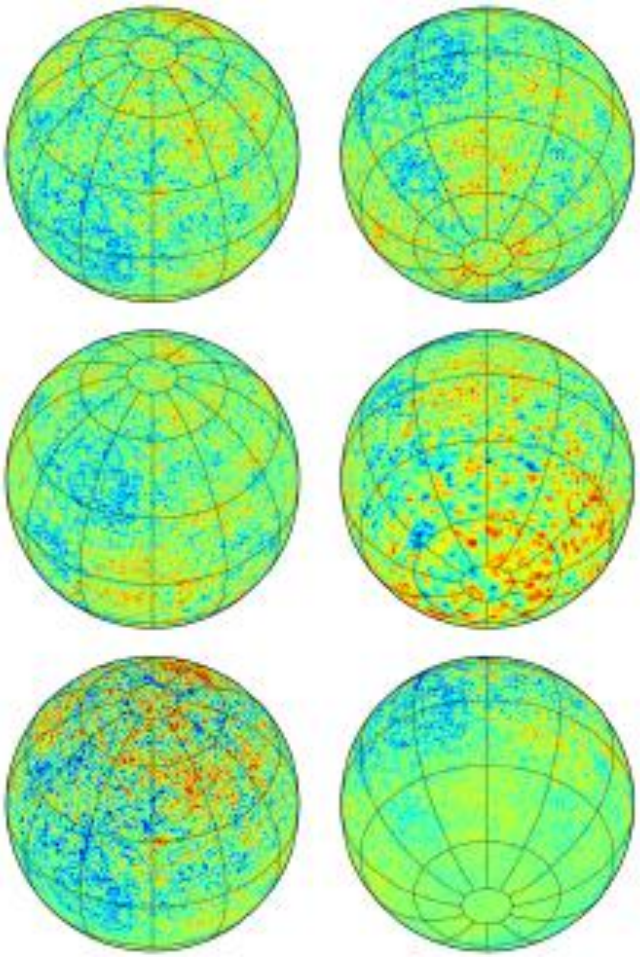



Full-Sky Map
Anomalies

Aberration of the CMB

Our motion shifts amplitude and angles
Expected effect is 10^{-3} of 10^{-5} = 10ppb!

- Left show exaggerated effect - 700x increase in our speed to 85% c.
- Our real speed relative to CMB is ~ 0.12% c
- We use this to look for the effect
- We know the direction and speed from CMB dipole
- Effects both amplitude and angles (~ 4')
- Angular effect is not trivial compared to lensing
- $\delta T(\hat{n}) = T0\ \hat{n} \cdot \beta + \delta T\ 1(\hat{n} - \nabla(\hat{n} \cdot \beta))(1 + \hat{n} \cdot \beta)$



Concerns

- r=0.2 is larger than recent Planck upper limit (r<0.11) BUT this assumed no running (no scale dependence) of spectral index
- BiCEP has less than 1% sky coverage
- BiCEP really has only 1 freq – 150 GHz
- Internal systematic concerns
- Foregrounds are a major worry in all B mode experiments – no good polarized dust model yet
- Planck will “weigh in” soon