Discovery of B mode polarization of the relic radiation and possible discovery of cosmological gravitational waves

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Fluctuations in the Universe

- Our Universe is isotropic and homogeneous, but tiny perturbations exist. Fluctuations are divided into three types: scalar perturbations (density perturbations), vector perturbations (rotational perturbations), and tensorial perturbations (cosmological gravitational waves) (Д.С.Горбунов, В.А.Рубаков, Введение в теорию ранней Вселенной. М.:КРАСАНД, 2010)

Spectrum of primordial fluctuations

- Zeldovich Ya. in 1972 put forward a hypothesis about the initial state of our Universe and its perturbation from very general assumptions.

Harrison-Zeldovich spectrum

- The paper MNRAS (1972), v.160, 1P Ya.B.Zeldovich predict a spectrum of fluctuation in our Universe which is called now Harrison-Zeldovich spectrum. 20 years later this magic prediction was confirmed by the observation of anisotropy of the CMBR. Hope that this spring it was also confirmed by the polarization observation of the CMBR.

Cosmological Gravitational Waves

- Grishchuk, L. 1974 – parametric mechanism of graviton creation
- Starobinsky, A. 1979 – graviton creation in the early Universe with f(R) gravitation
- Rubakov, V.; Sazhin, M.; Veryaskin A. 1982 – Graviton creation in the early Universe and Grand Unification Scale, Phys.Lett., **115B**, 189 (1982)

$$\frac{d^2 h(k,\eta)}{d\eta^2} + 2\frac{\dot{a}}{a}\frac{dh}{d\eta} + k^2 h = 0$$

solution of the equation is :

$$\mathrm{h}(\mathrm{k},\eta) =$$

$$= \frac{A(k)}{k} H_i \sin(k\eta_s + \phi) \qquad \eta_s \le \eta \le \eta_d$$

$$= \frac{3A(k)H_i}{k(k\eta)^2} \sin(k\eta_s + \phi)\left(\frac{\sin k\eta}{k\eta} - \cos k\eta\right) \qquad \eta \ge \eta_s$$

where

$$A(k) = \frac{1}{\pi M_{Pl}}\frac{2}{k}$$ is a zero fluctuation amplitude

$$h_{GW} \propto \frac{H_i}{M_{Pl}} \propto \frac{\sqrt{V(\phi)}}{M_{Pl}{}^2}$$

soon scalar mode amplitude was calculated

$$h_s \propto \frac{1}{M_{Pl}{}^2} \frac{H_i^2}{|H_i'(\phi)|}$$

Review : Copeland, Kolb, Liddle, Lidsey, Phys.Rev.D48, 2529, 1992

and referencies therein

Equation that describes the anisotropy of the CMBR

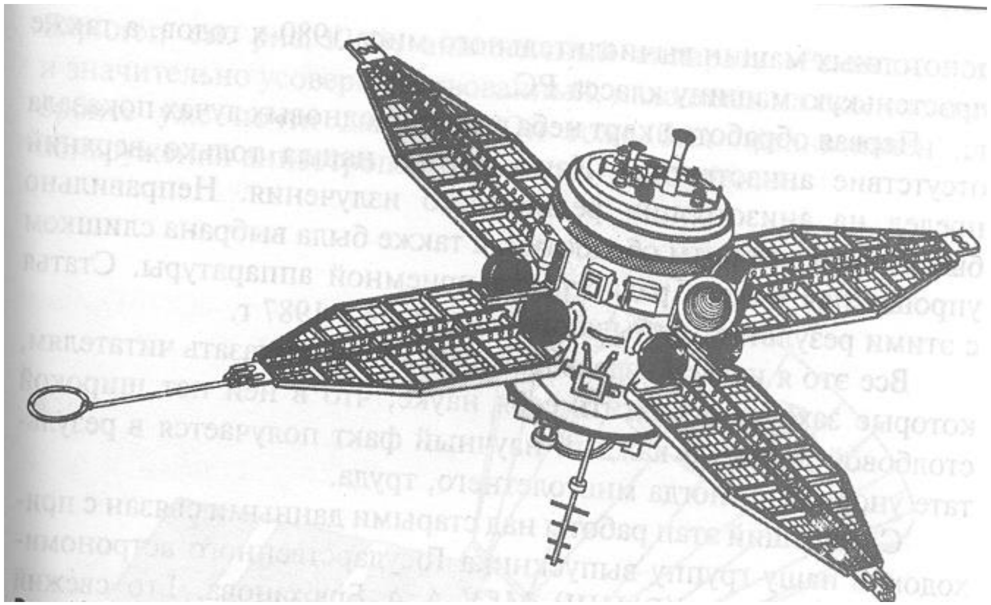
$$\frac{\delta T}{T} = -\frac{1}{2}\int \frac{\partial h_{ij}(t(\tau), x(\tau))}{\partial \tau} e^i e^j + \frac{1}{4}\frac{\delta \varepsilon_r}{\varepsilon} + \left(\frac{\vec{v}}{c}\vec{e}\right)_r$$

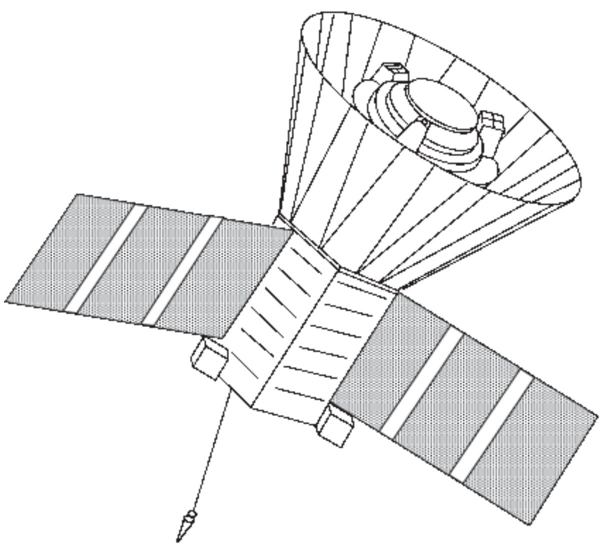
$$\frac{\delta T(\theta,\varphi)}{T} = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

$$c_l = \frac{1}{2l+1}\sum_{m=-l}^{l} a_{lm}{}^2$$

$$c_l = \frac{c_0}{l(l+1)}$$ - **HZ-spectrum**

5. Anisotropy of the CMBR

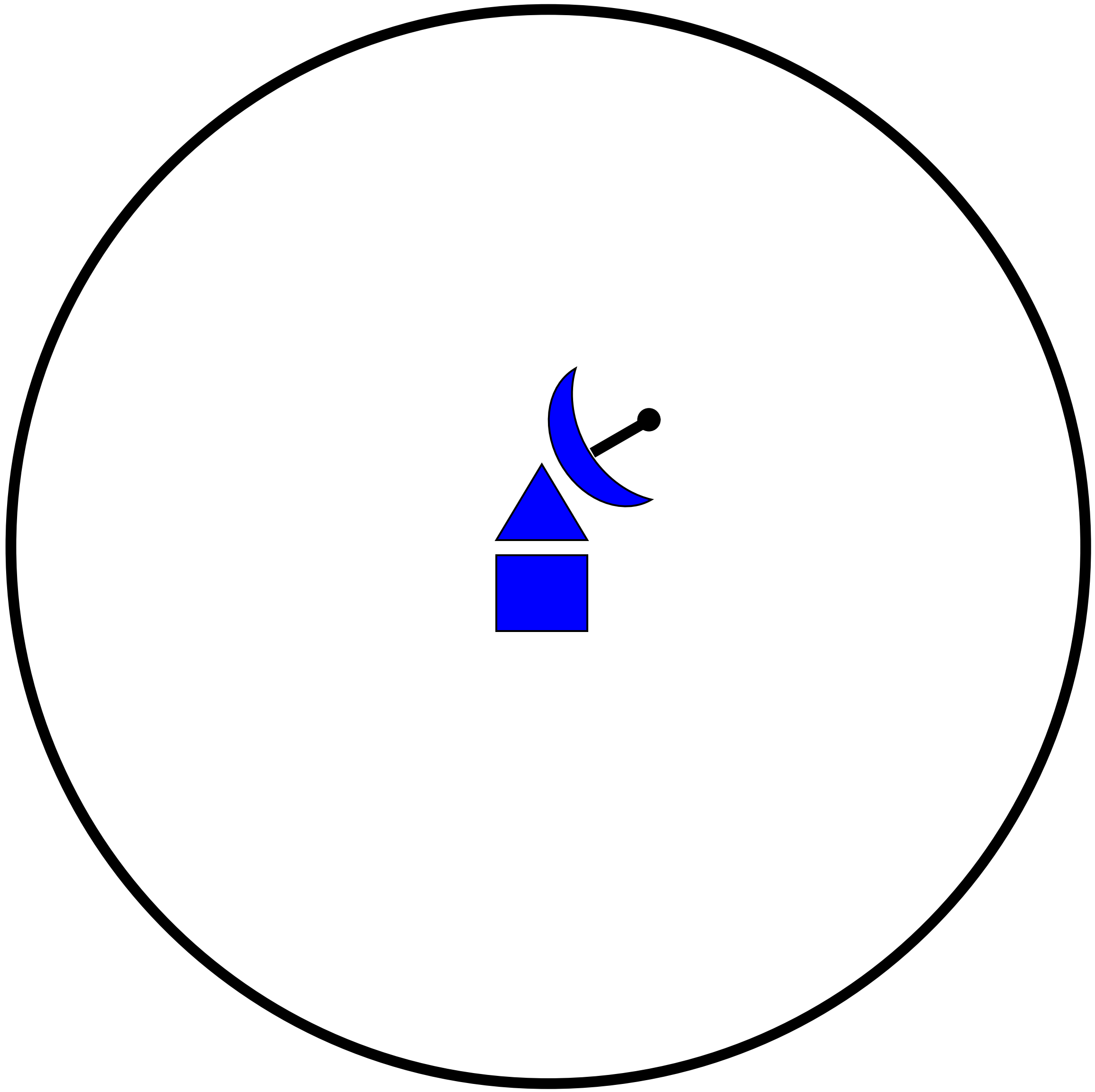


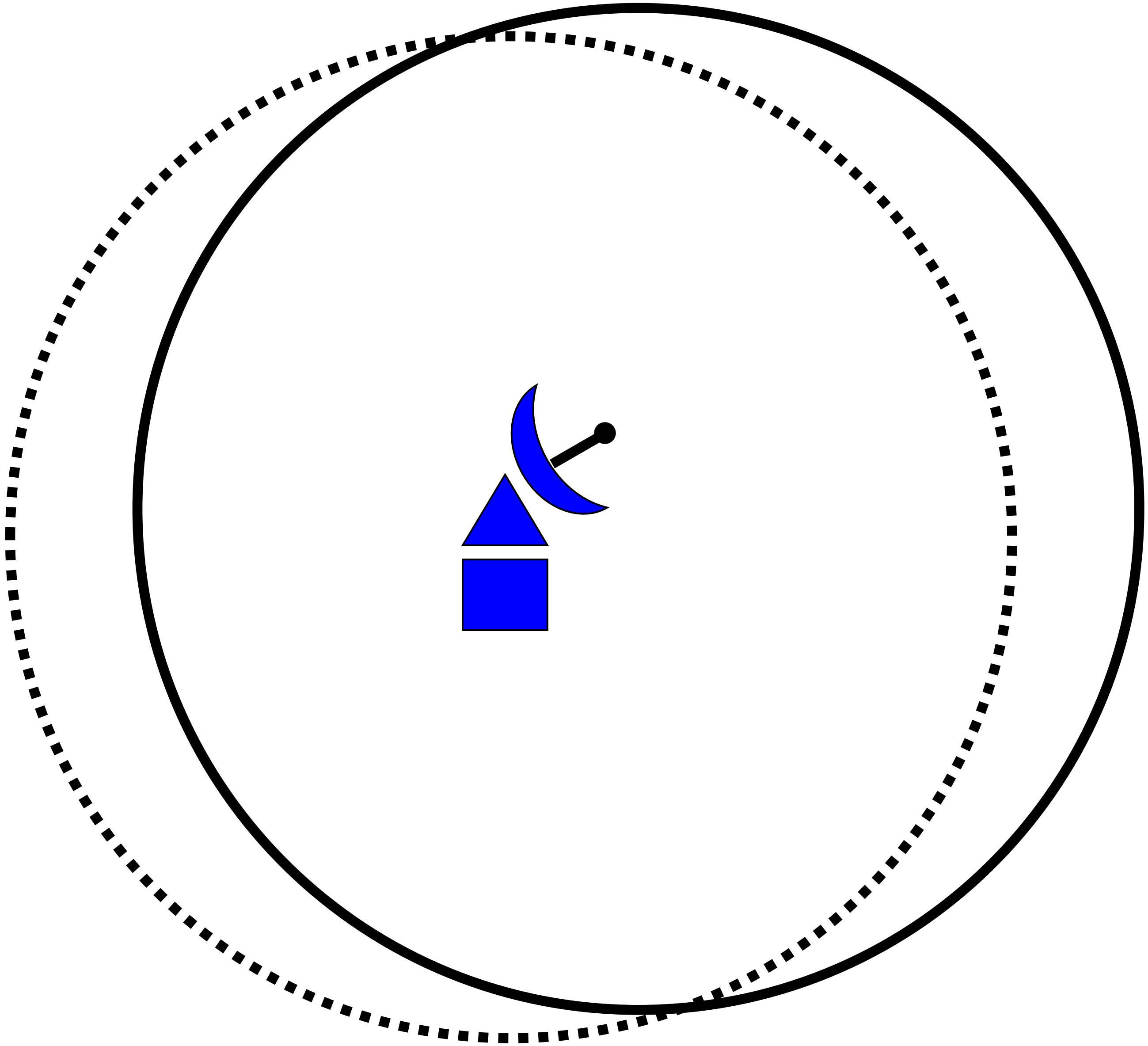


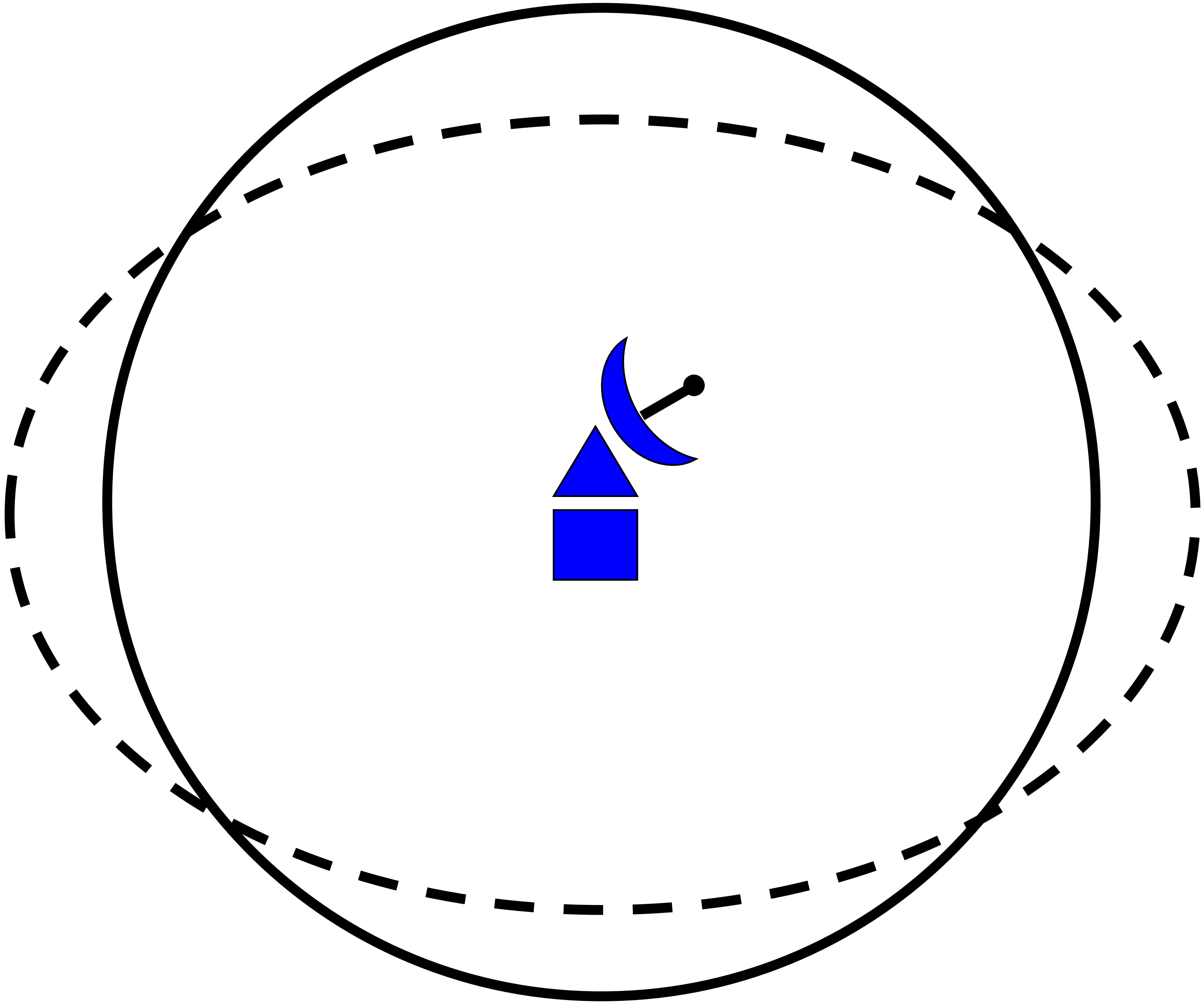
The last observational fact amoung the main is anisotropy of the CMBR.

The anisotropy was discovered in 1992.

Two groups announced the observation of the anisotropy signal. The first was the Relic group and the second was COBE.







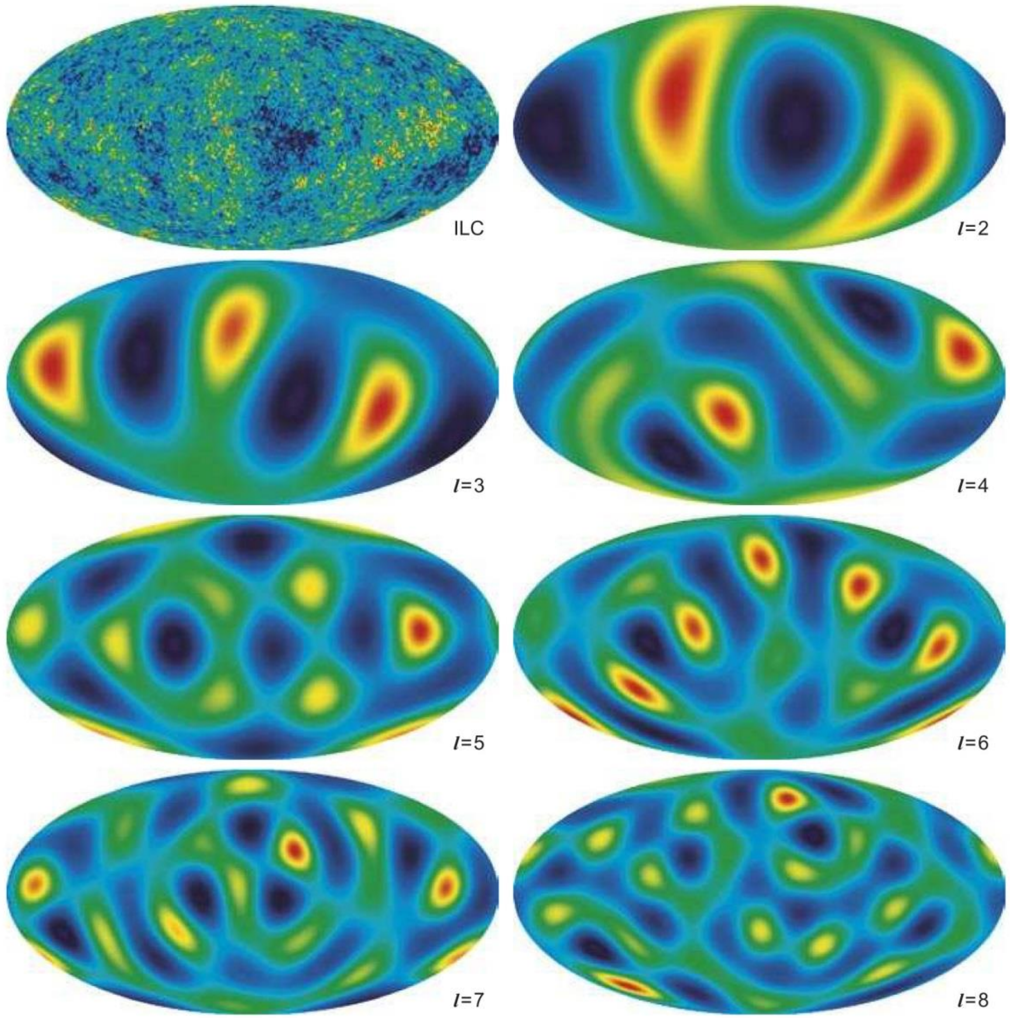


Fig. 14.— Maps of power spectrum modes $l = 2 - 8$ computed from full-sky fits to the ILC map, shown at top left. Many authors note peculiar patterns in the phase of these modes, and many claim that the behavior is inconsistent with Gaussian random-phase fluctuations, as predicted by inflation. For example, the $l = 5$ mode appears strikingly symmetric (a non-random distribution of power in m), while the $l = 2$ and 3 modes appear unusually aligned. The significance of these *a posteriori* observations is being actively debated. See §8 for a more detailed discussion.

Polarization of the CMBR

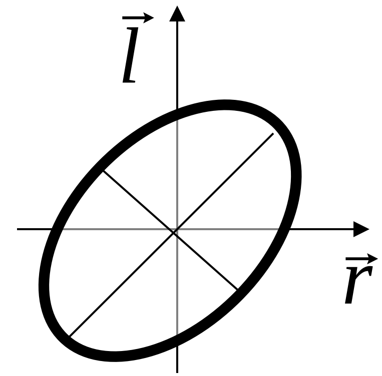
Stocks parameters:

$$I = I_l + I_r$$

$$Q = I_l - I_r$$

$$U = I_{12} + I_{21}$$

$$V = i\left(I_{21} - I_{12}\right)$$



$$I = \sum_{l,m} a_{lm} Y_{lm}(\theta, \varphi)$$

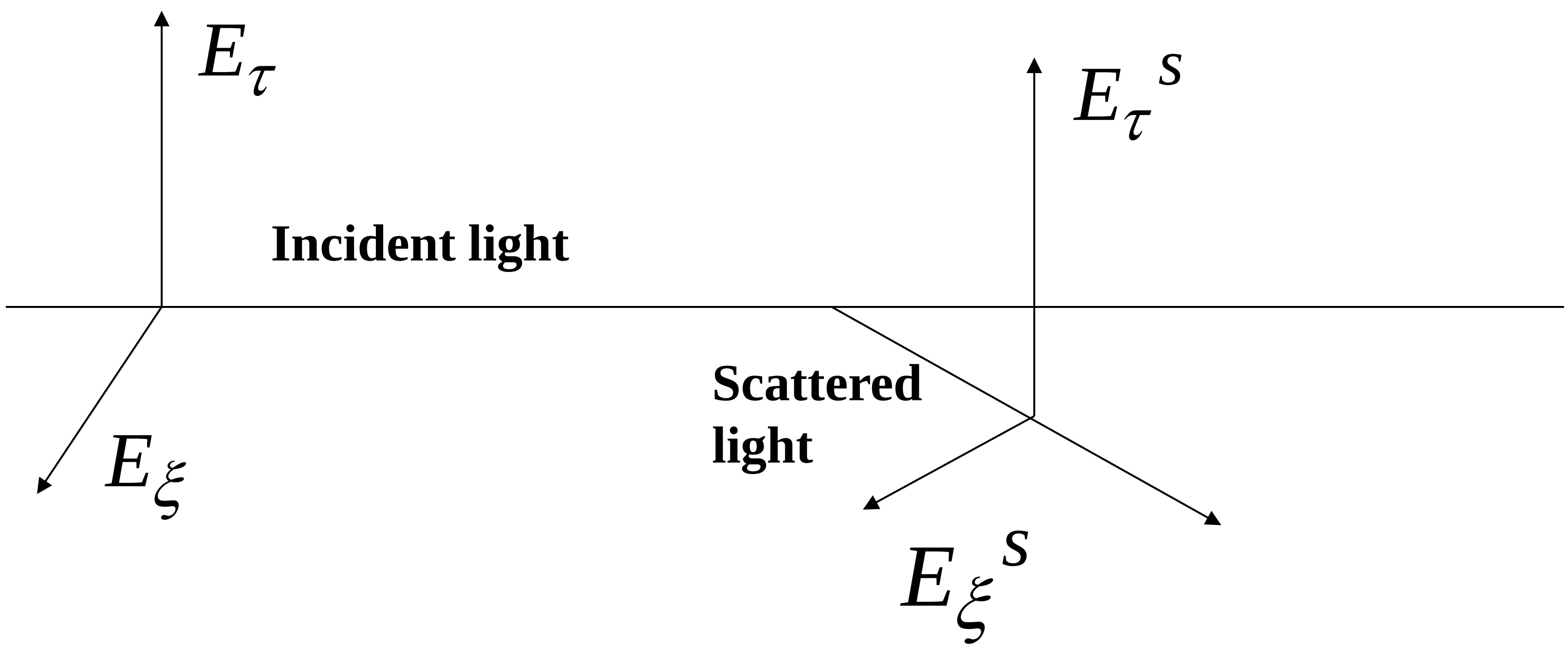
$$Q \pm iU = \sum_{l,m} a_{lm}{}^{\pm 2} Y_{lm}{}^{\pm 2}(\theta, \varphi)$$

$$a_{lm}{}^{E} = \frac{1}{2}\left(a_{lm}{}^{+2} + a_{lm}{}^{-2}\right)$$

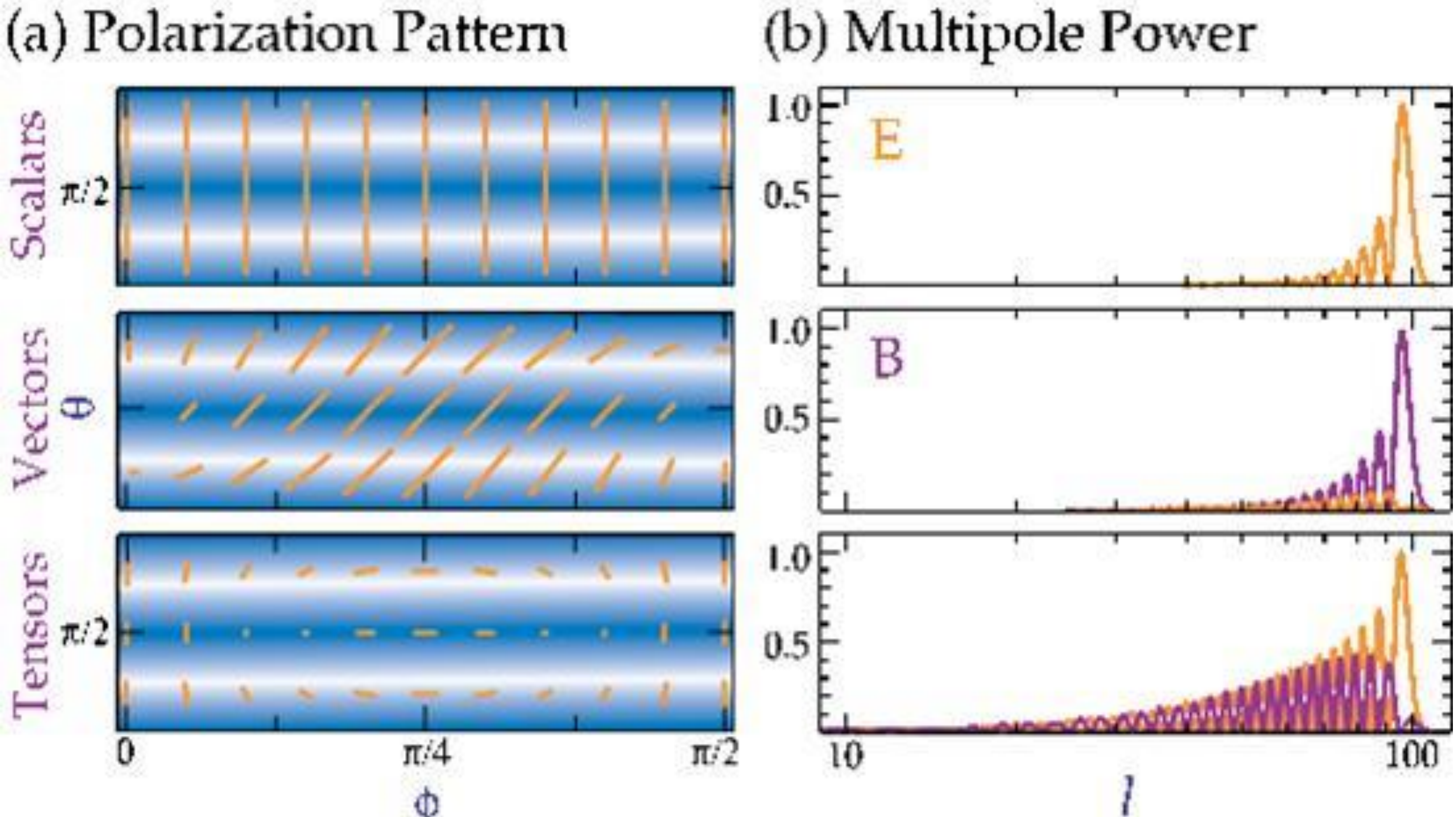
$$a_{lm}{}^{B} = \frac{i}{2}\left(a_{lm}{}^{+2} - a_{lm}{}^{-2}\right)$$

Polarization of the CMBR

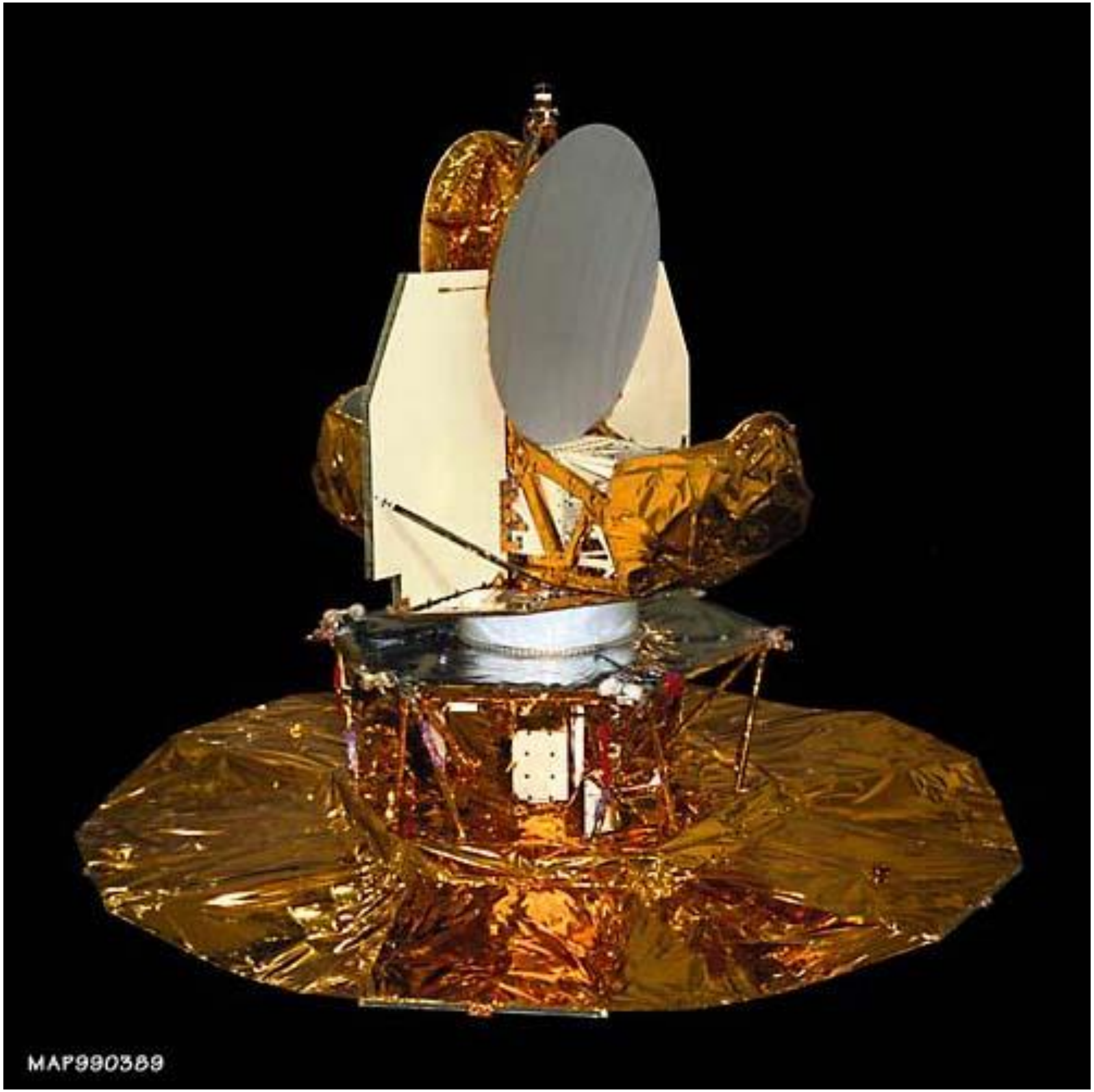
$$\frac{\partial\delta}{\partial\eta}+\frac{\partial\delta}{\partial x^{\alpha}}\cdot e^{\alpha}=\frac{1}{2}\frac{\partial h_{\alpha\beta}}{\partial\eta}e^{\alpha}e^{\beta}-\sigma_{T}N_{e}a(\eta)\times$$
$$\left(\delta-\oint P(\Omega,\Omega')\delta(\Omega')d\Omega'\right)$$



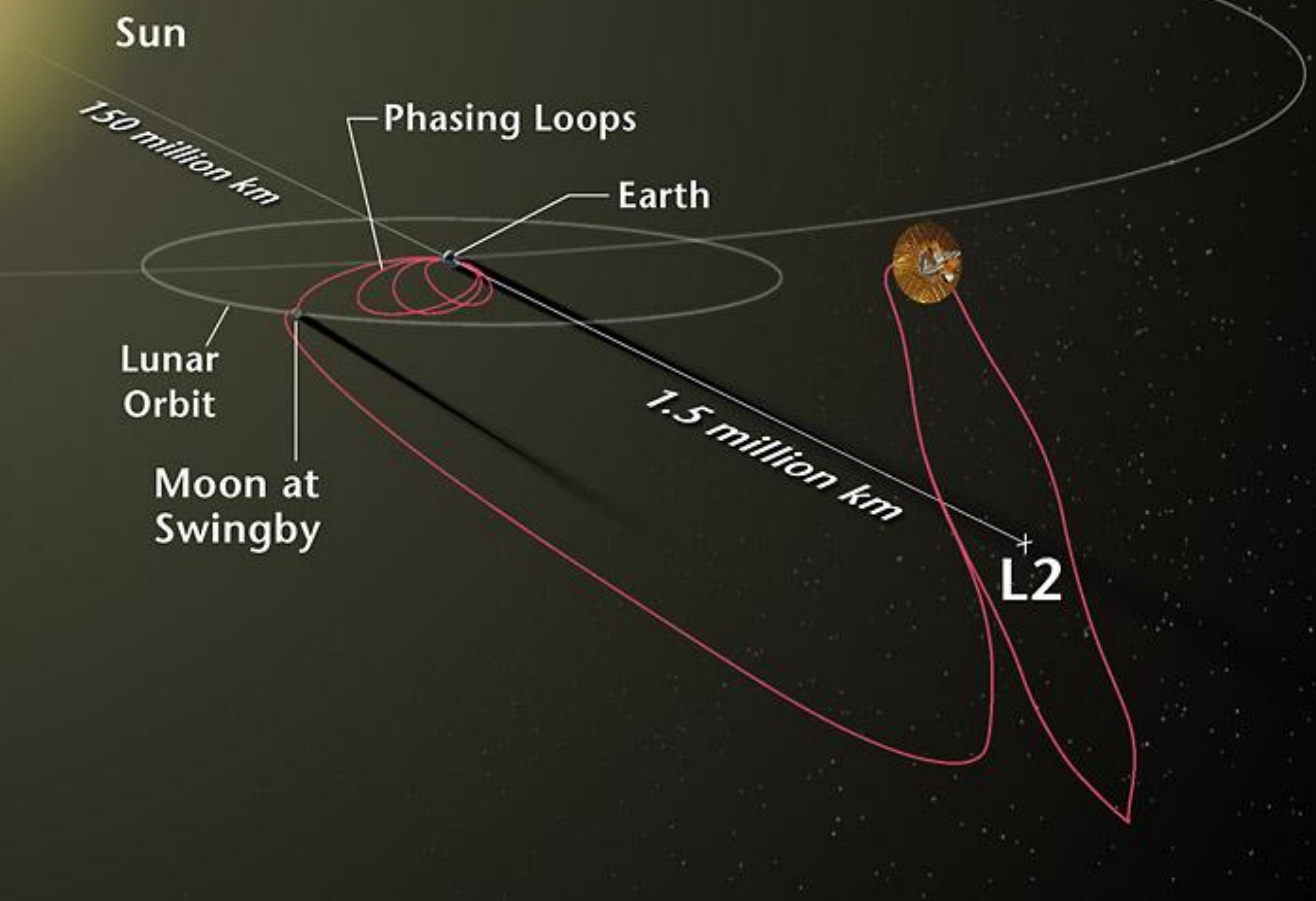
Basko, M., Polnarev A., 1980;


(a) Polarization Pattern
(b) Multipole Power
Scalars
Vectors
Tensors
θ
π/2
π/2
0
π/4
π/2
ϕ
1.0
0.5
E
1.0
0.5
B
1.0
0.5
10
100
l

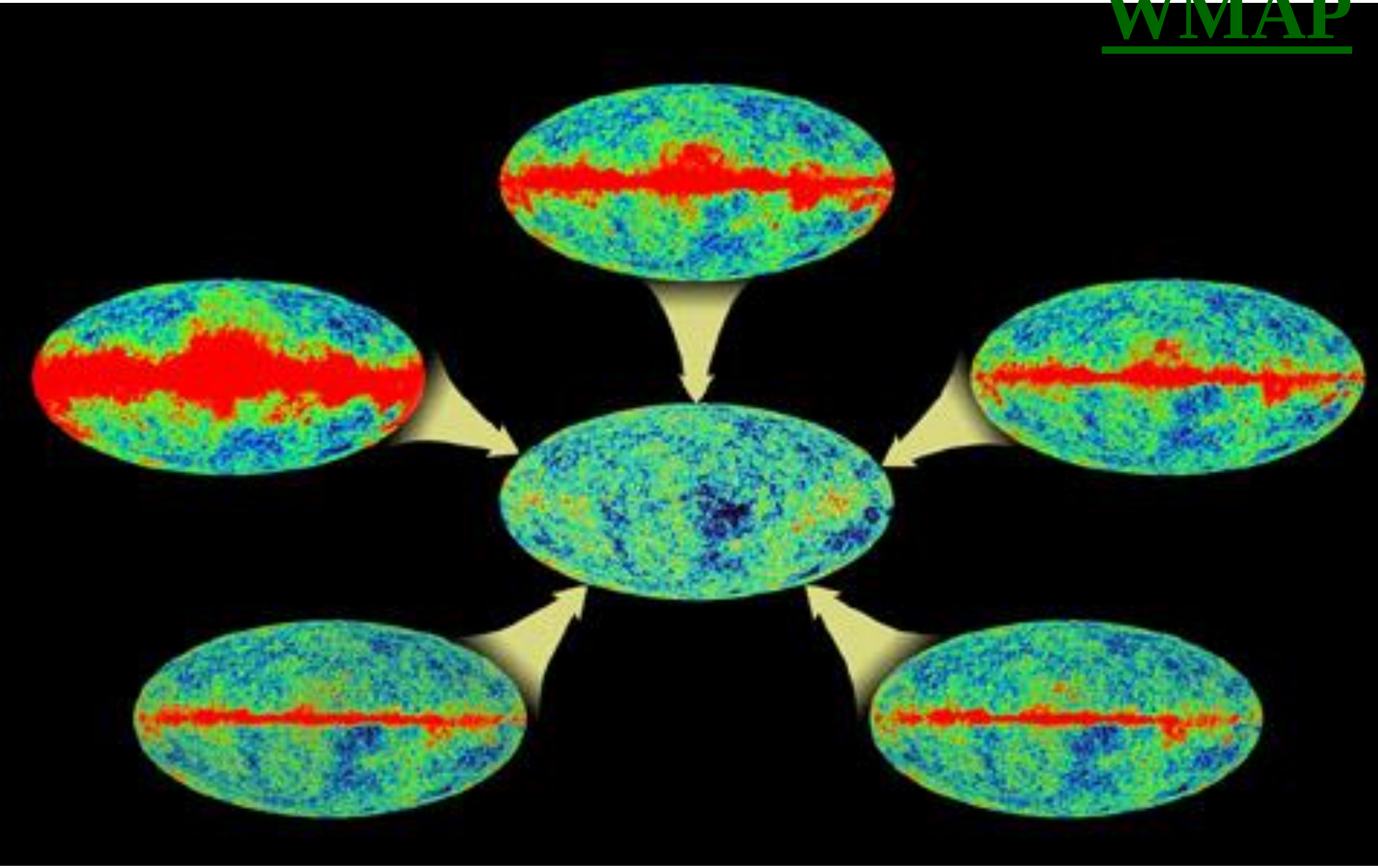
WMAP



WMAP

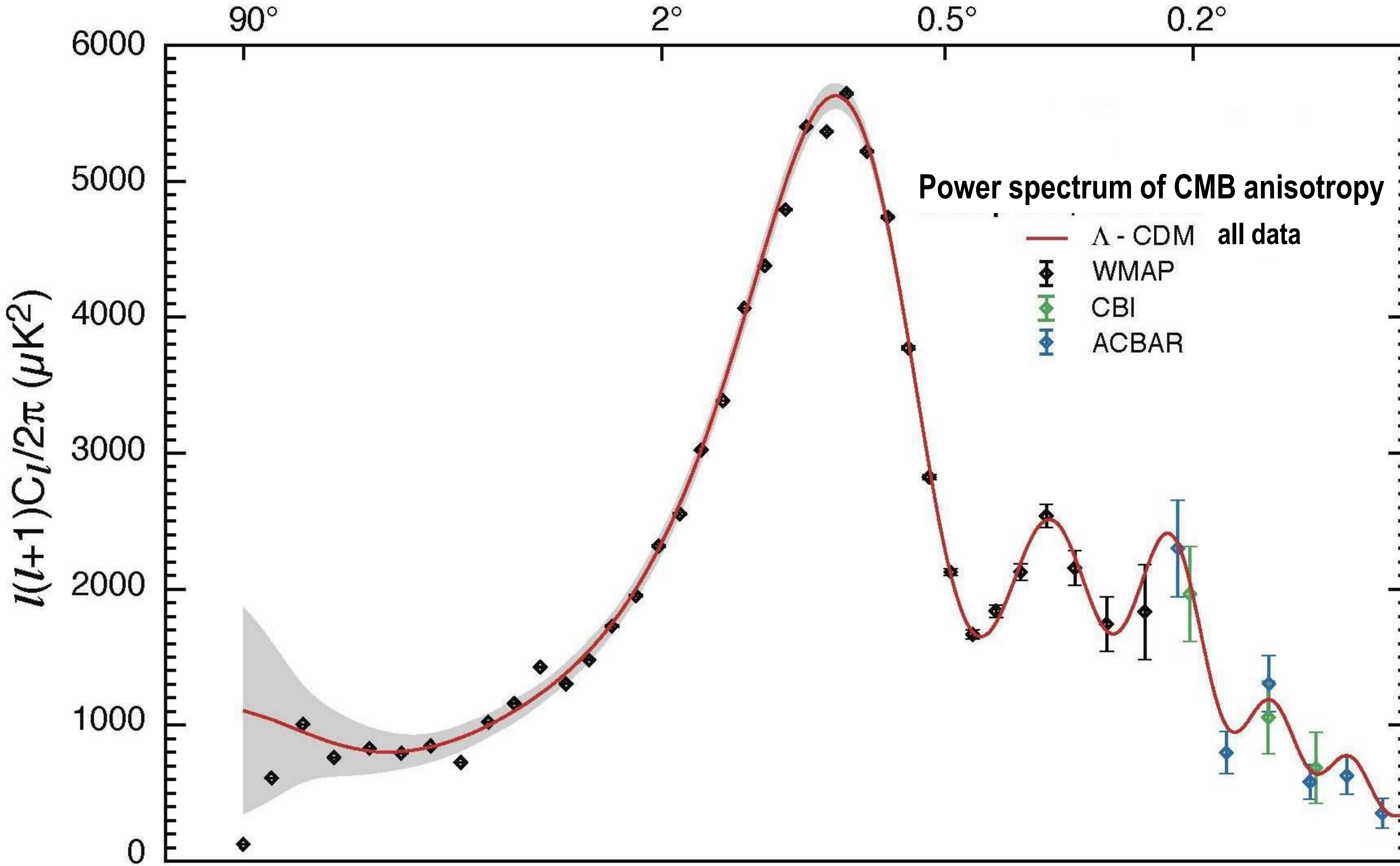

Sun
150 million km
Phasing Loops
Earth
Lunar
Orbit
Moon at
Swingby
1.5 million km
L2

WMAP

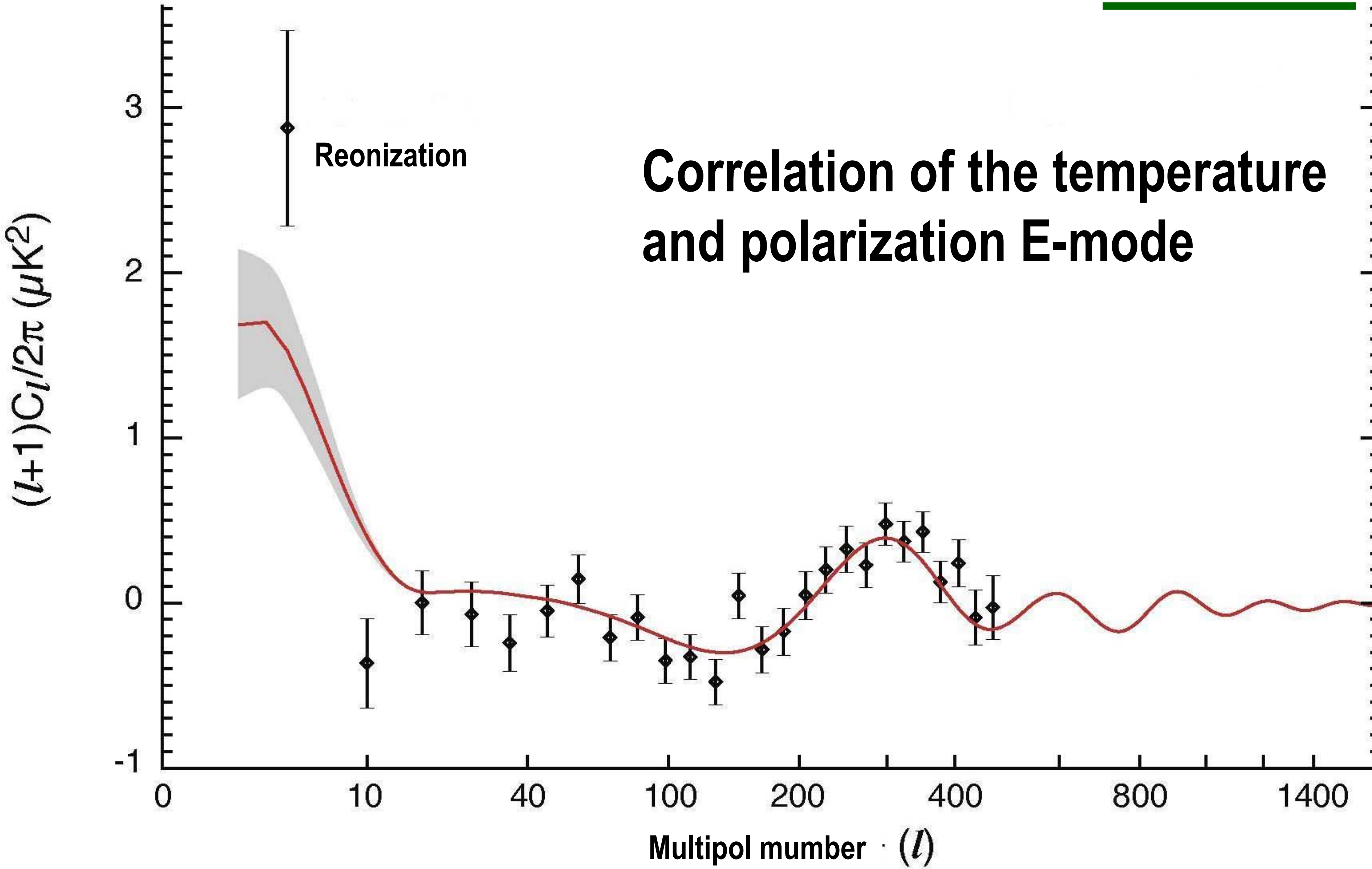


WMAP

Angular measure



WMAP


Reonization
Correlation of the temperature and polarization E-mode
$(l+1)C_l/2\pi\ (\mu K^2)$
3
2
1
0
-1
0
10
40
100
200
400
800
1400
Multipol mumber (l)

Anisotropy and Polarization

$$A = A(k)h_S \;+\; B(k)h_{GW}$$

$$P = C(k)h_S \;+\; D(k)h_{GW}$$

$$A(k)D(k) - C(k)B(k) \;\neq\; 0$$

Anisotropy and Polarization

- Therefore one may resolve this equations and obtains

h_S and h_{GW}

- Sazhin, M. 1984; Sazhin, M., Benitez, N. 1995;
- Sazhin, M., Toporensky, A., 1995,1996;
- Sazhin, M., Shulga, V., 1996.

Multipole expansion of Polarization

$$\frac{\delta T(\theta,\varphi)}{T}=\sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

$$I=\sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

$$Q \pm iU=\sum_{l,m} a_{lm}^{\pm 2} Y_{lm}^{\pm 2}(\theta,\varphi)$$

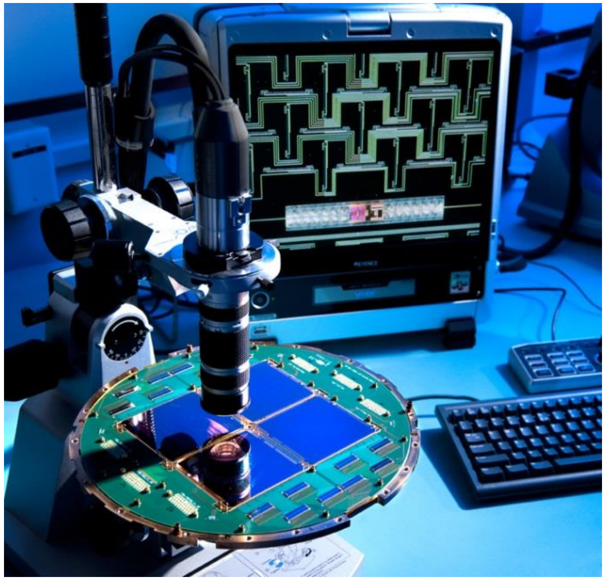
Sazhin, M., Shulga, V., 1996.

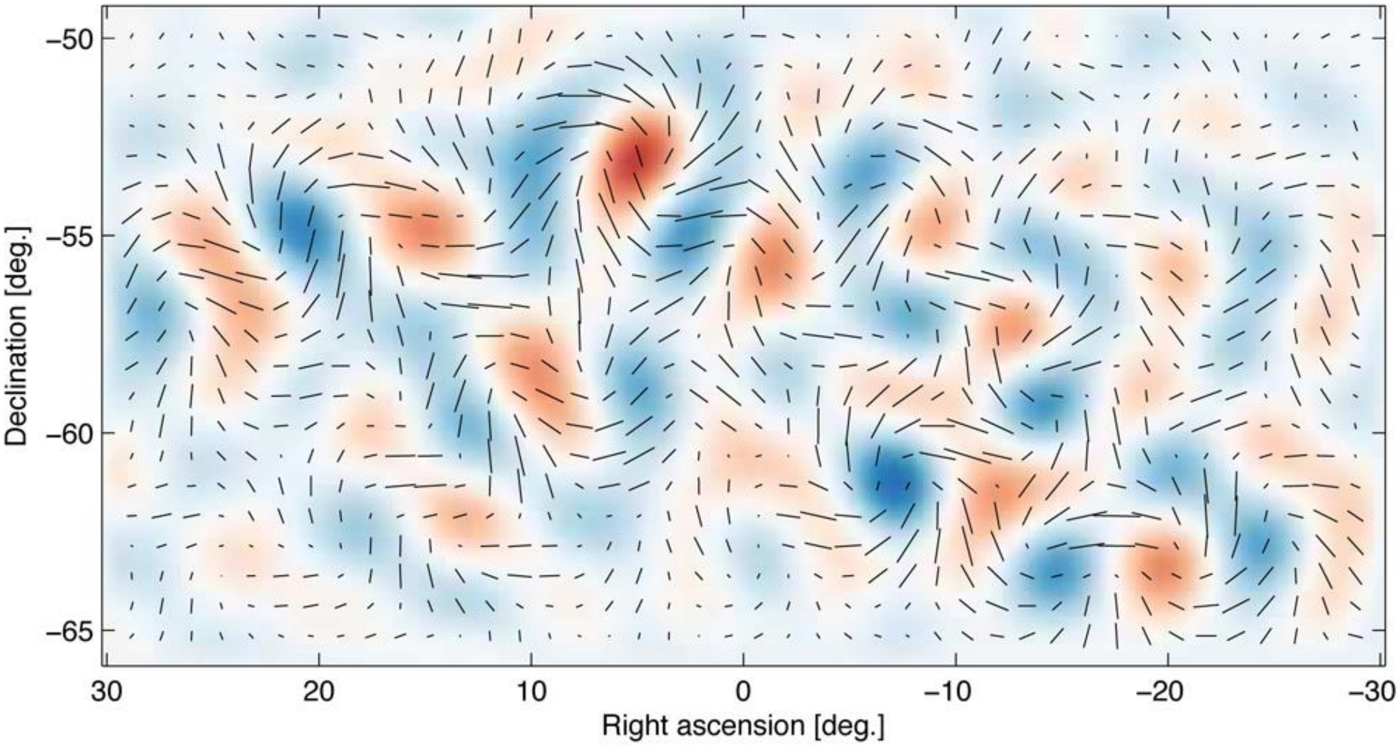
$$a_{lm}{}^{E} = \frac{1}{2}\left(a_{lm}{}^{+2} + a_{lm}{}^{-2}\right)$$

$$a_{lm}{}^{B} = \frac{i}{2}\left(a_{lm}{}^{+2} - a_{lm}{}^{-2}\right)$$

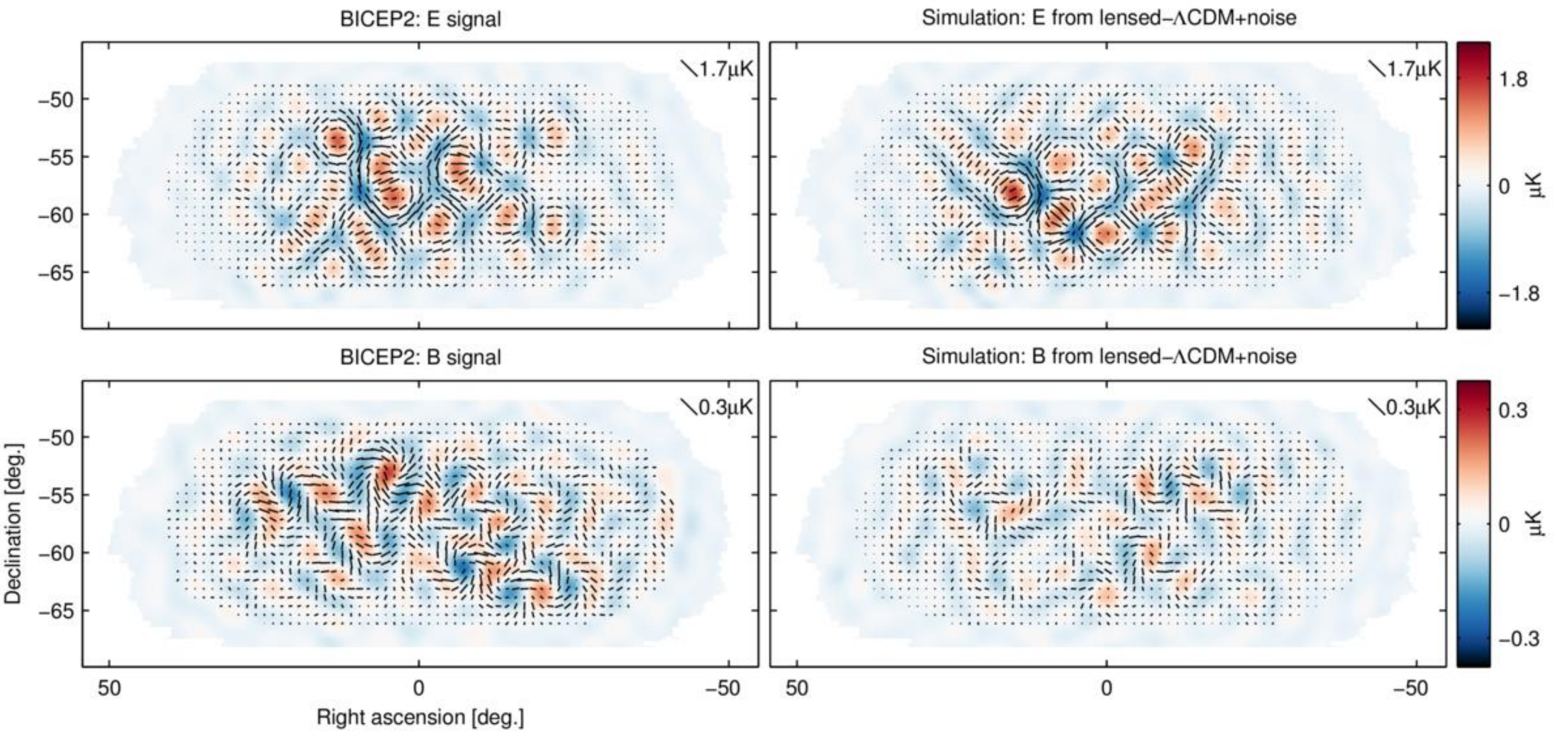
Seljiak , U., 1997; Scalar perturbations do not produce B mode of polarization

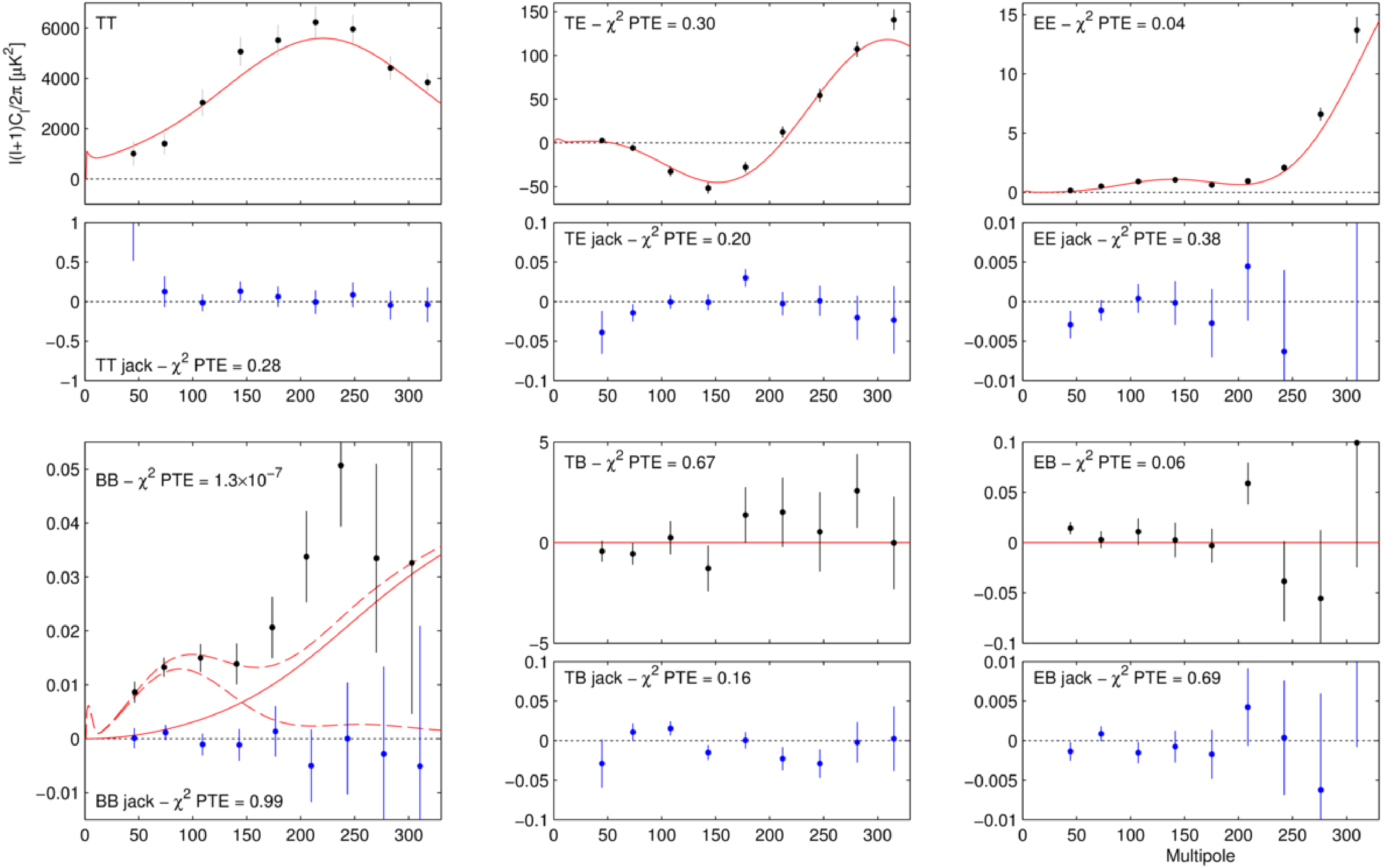
BICEP Experiment



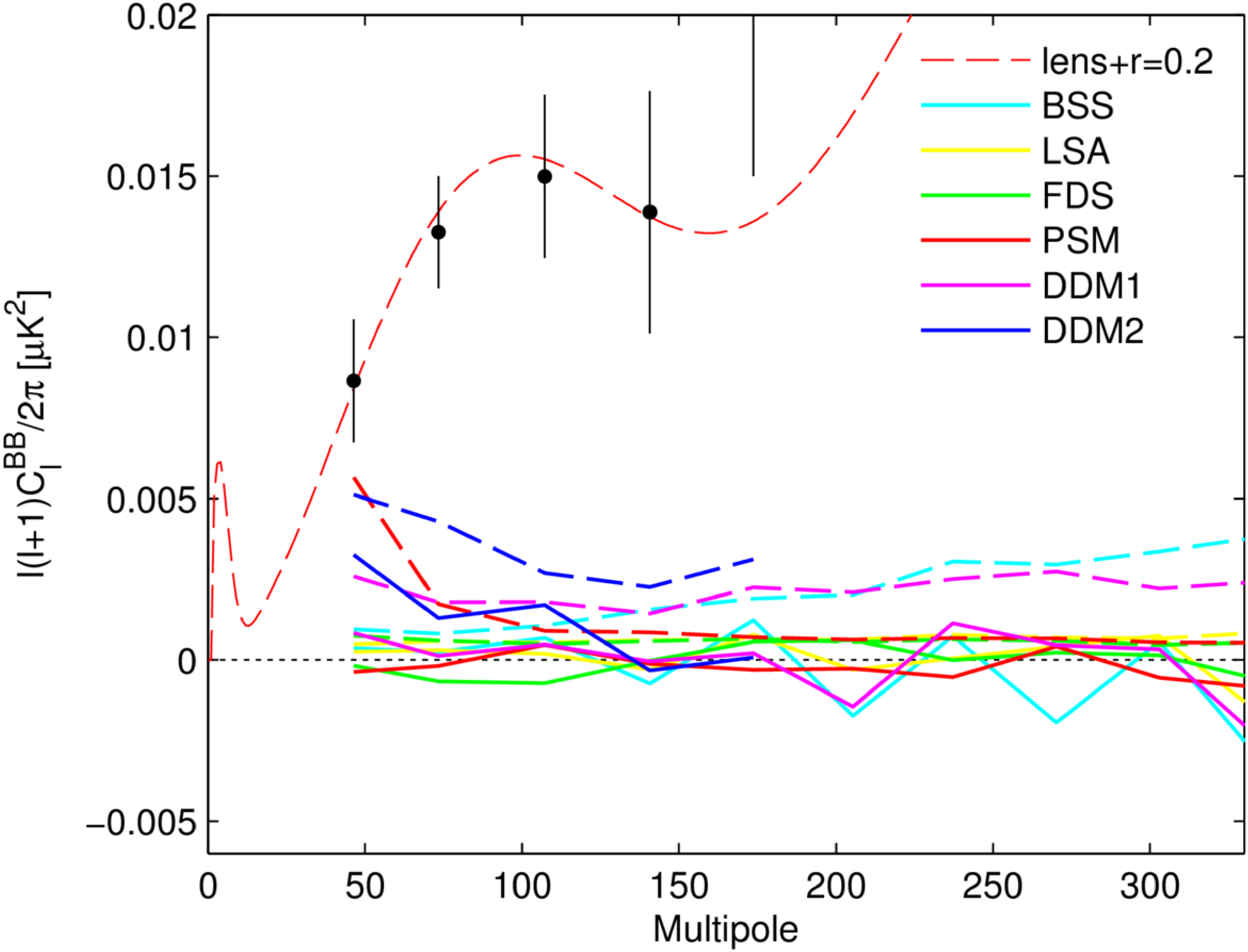


Gravitational waves from inflation generate a faint twisting pattern in the polarization of the cosmic microwave background, known as B-mode pattern. For the density fluctuations that generate most of the polarization of the CMB, this part of the primordial pattern is exactly zero.
Here is the actual B-mode pattern observed with the BICEP2 telescope, which is consistent with the pattern predicted for primordial gravitational waves.

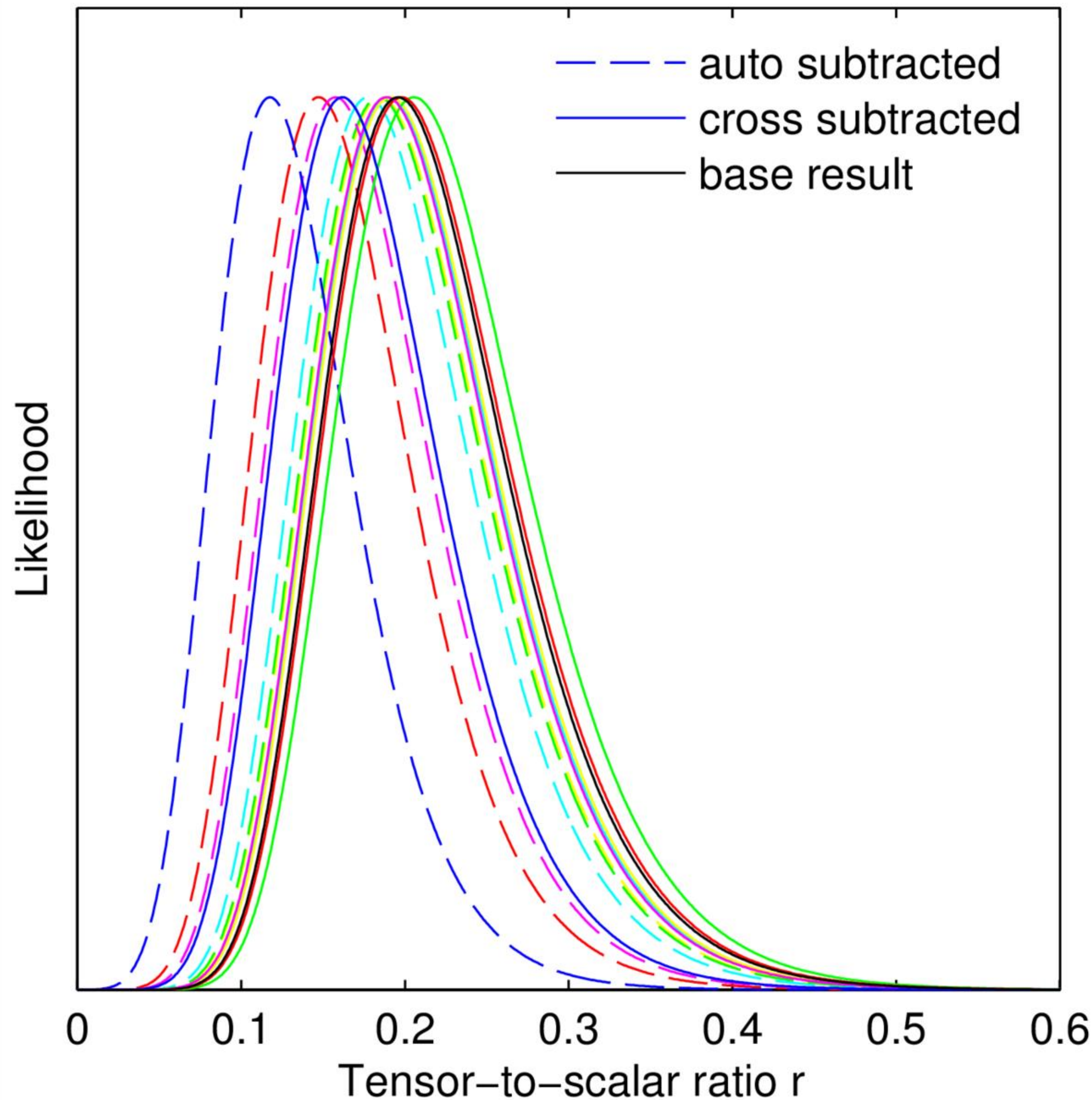

BICEP2: E signal
Simulation: E from lensed-ΛCDM+noise
BICEP2: B signal
Simulation: B from lensed-ΛCDM+noise
1.7μK
0.3μK
1.8
0
−1.8
0.3
−0.3
μK
Declination [deg.]
−50
−55
−60
−65
50
0
−50
Right ascension [deg.]

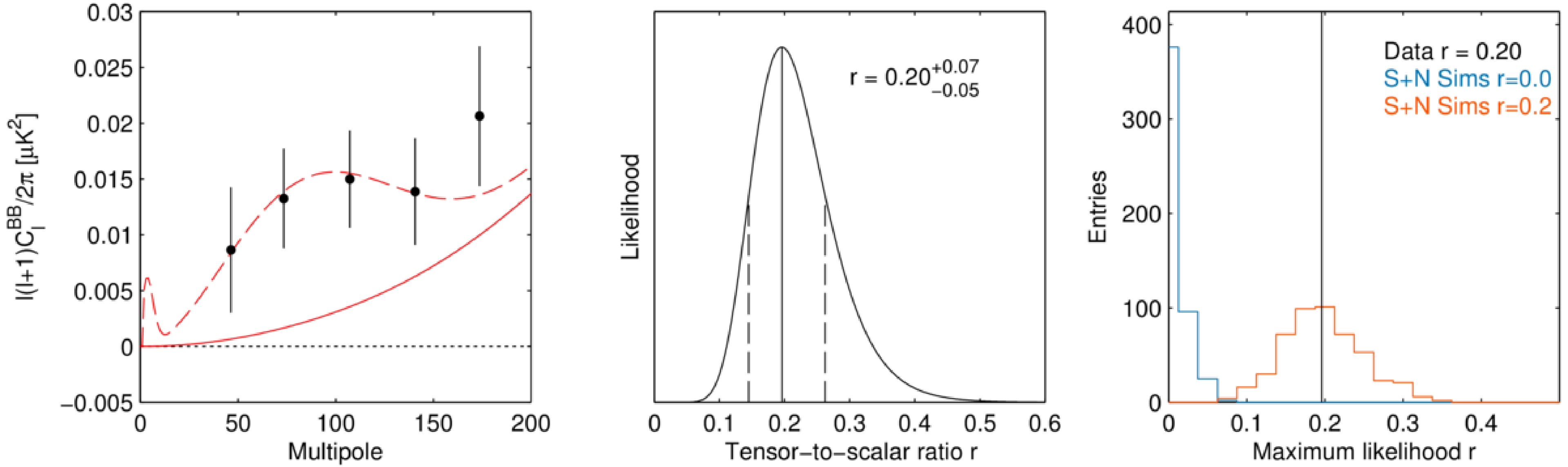


TT
$l(l+1)C_l/2\pi$ [μK^2]
TE – χ^2 PTE = 0.30
EE – χ^2 PTE = 0.04
TT jack – χ^2 PTE = 0.28
TE jack – χ^2 PTE = 0.20
EE jack – χ^2 PTE = 0.38
BB – χ^2 PTE = 1.3×10^{-7}
BB jack – χ^2 PTE = 0.99
TB – χ^2 PTE = 0.67
TB jack – χ^2 PTE = 0.16
EB – χ^2 PTE = 0.06
EB jack – χ^2 PTE = 0.69
Multipole

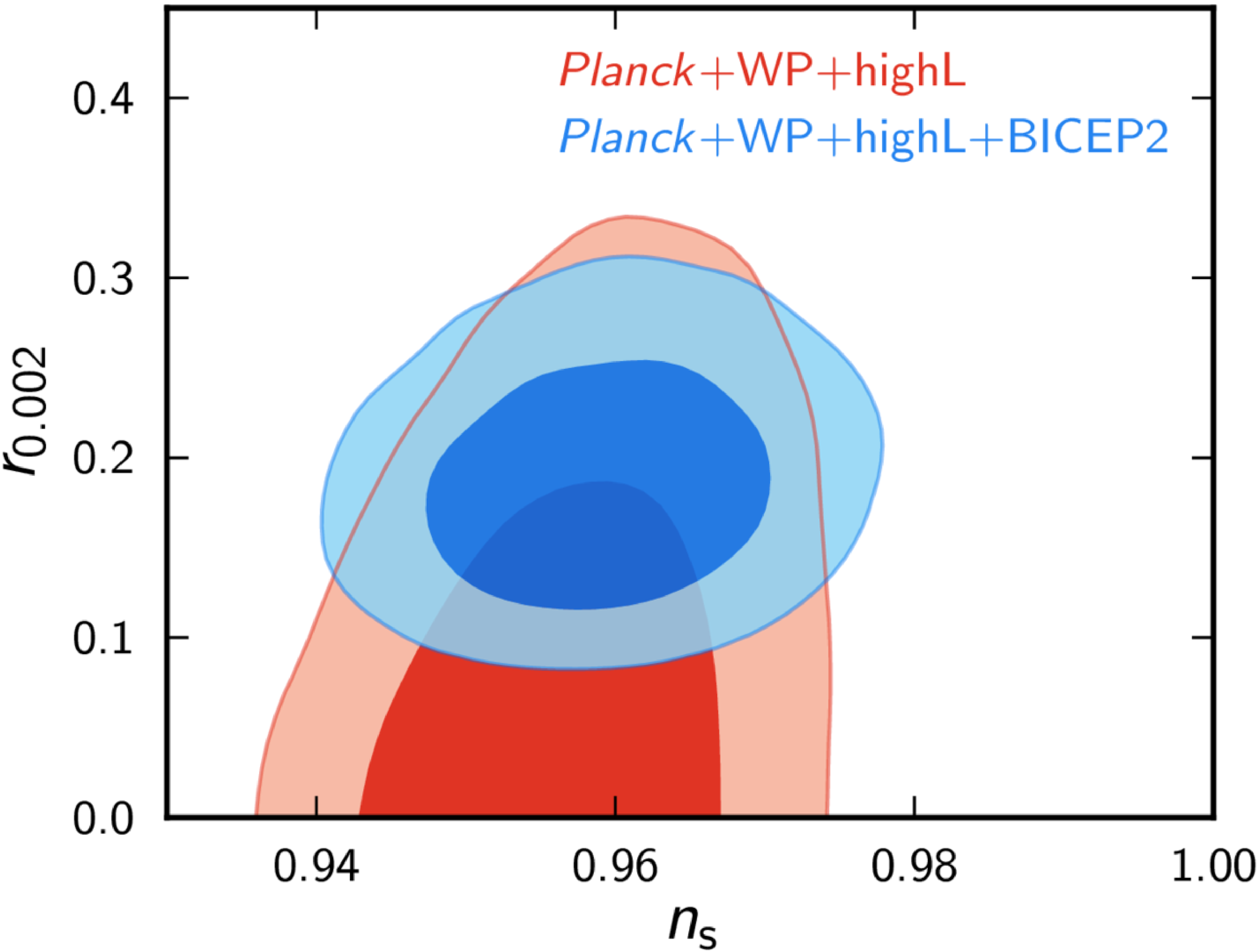


lens+r=0.2
BSS
LSA
FDS
PSM
DDM1
DDM2
0.02
0.015
0.01
0.005
0
−0.005
0
50
100
150
200
250
300
Multipole
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$

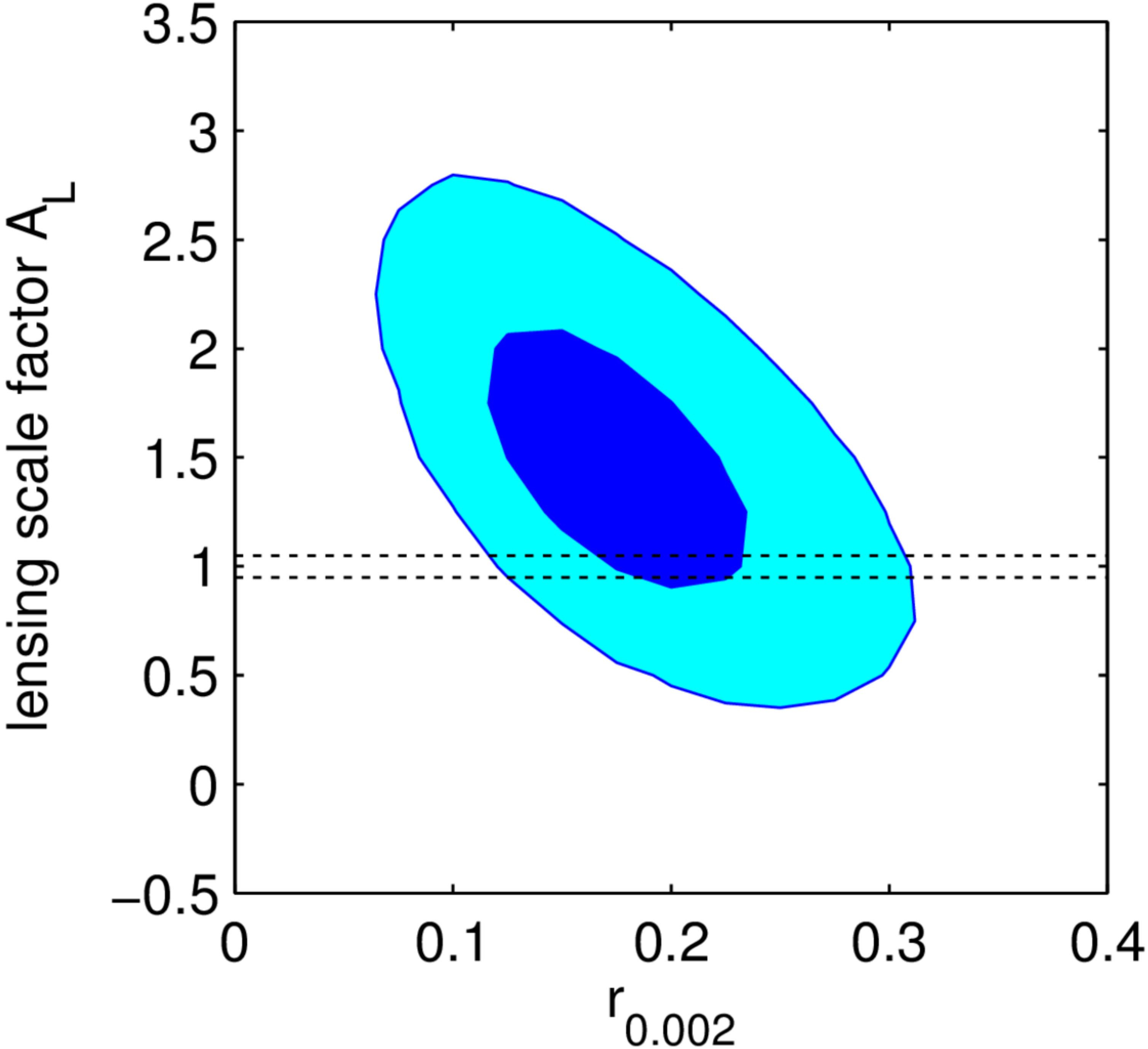

auto subtracted
cross subtracted
base result
Likelihood
0
0.1
0.2
0.3
0.4
0.5
0.6
Tensor−to−scalar ratio r

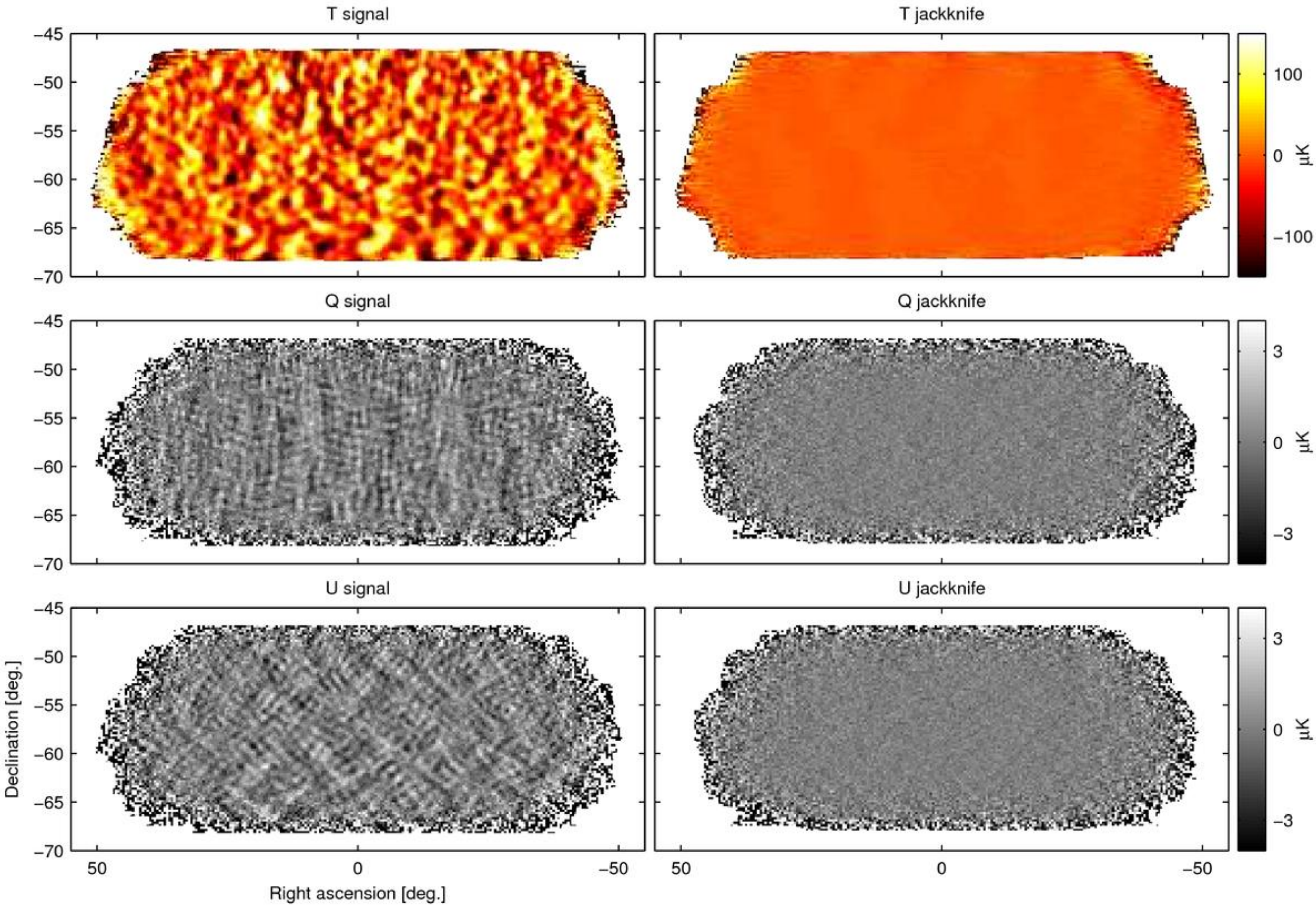


0.03
0.025
0.02
0.015
0.01
0.005
0
−0.005
l(l+1)C$_l^{BB}$/2π [μK^2]
0
50
100
150
200
Multipole
r = 0.20$^{+0.07}_{-0.05}$
Likelihood
0
0.1
0.2
0.3
0.4
0.5
0.6
Tensor−to−scalar ratio r
Data r = 0.20
S+N Sims r=0.0
S+N Sims r=0.2
400
300
200
100
0
Entries
0
0.1
0.2
0.3
0.4
Maximum likelihood r



Planck+WP+highL
Planck+WP+highL+BICEP2
0.4
0.3
0.2
0.1
0.0
$r_{0.002}$
0.94
0.96
0.98
1.00
n_s


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



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

Thank you
very much
for attention!