The lecture slides are available at
https://wwwmpa.mpa-garching.mpg.de/~komatsu/lectures--reviews.html

Lecture 9: CMB Polarisation from the Sound Waves

CMB is weakly polarised!

Credit: ESA

Temperature (smoothed) + Polarisation

Stokes Parameters change under coordinate rotation

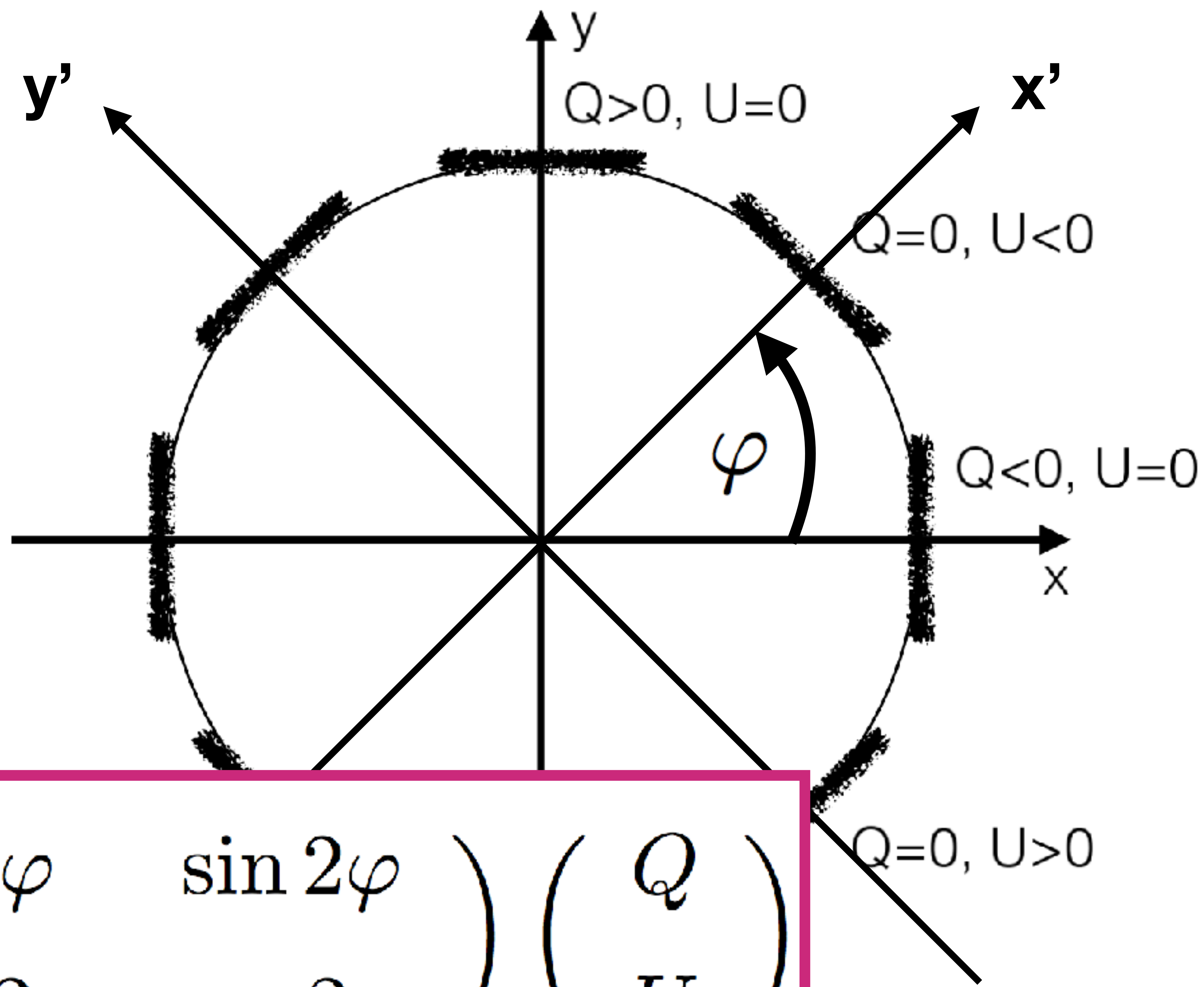
$$Q \propto E_x^2 - E_y^2$$

$$U \propto E_a^2 - E_b^2$$

Under (x,y) -> (x’,y’):

$$Q \longrightarrow \tilde{Q}$$

$$U \longrightarrow \tilde{U}$$



$$\begin{pmatrix} \tilde{Q} \\ \tilde{U} \end{pmatrix} = \begin{pmatrix} \cos 2\varphi & \sin 2\varphi \\ -\sin 2\varphi & \cos 2\varphi \end{pmatrix} \begin{pmatrix} Q \\ U \end{pmatrix}$$

Compact Expression

- Using an imaginary number, write $Q + iU$

Then, under the coordinate rotation we have

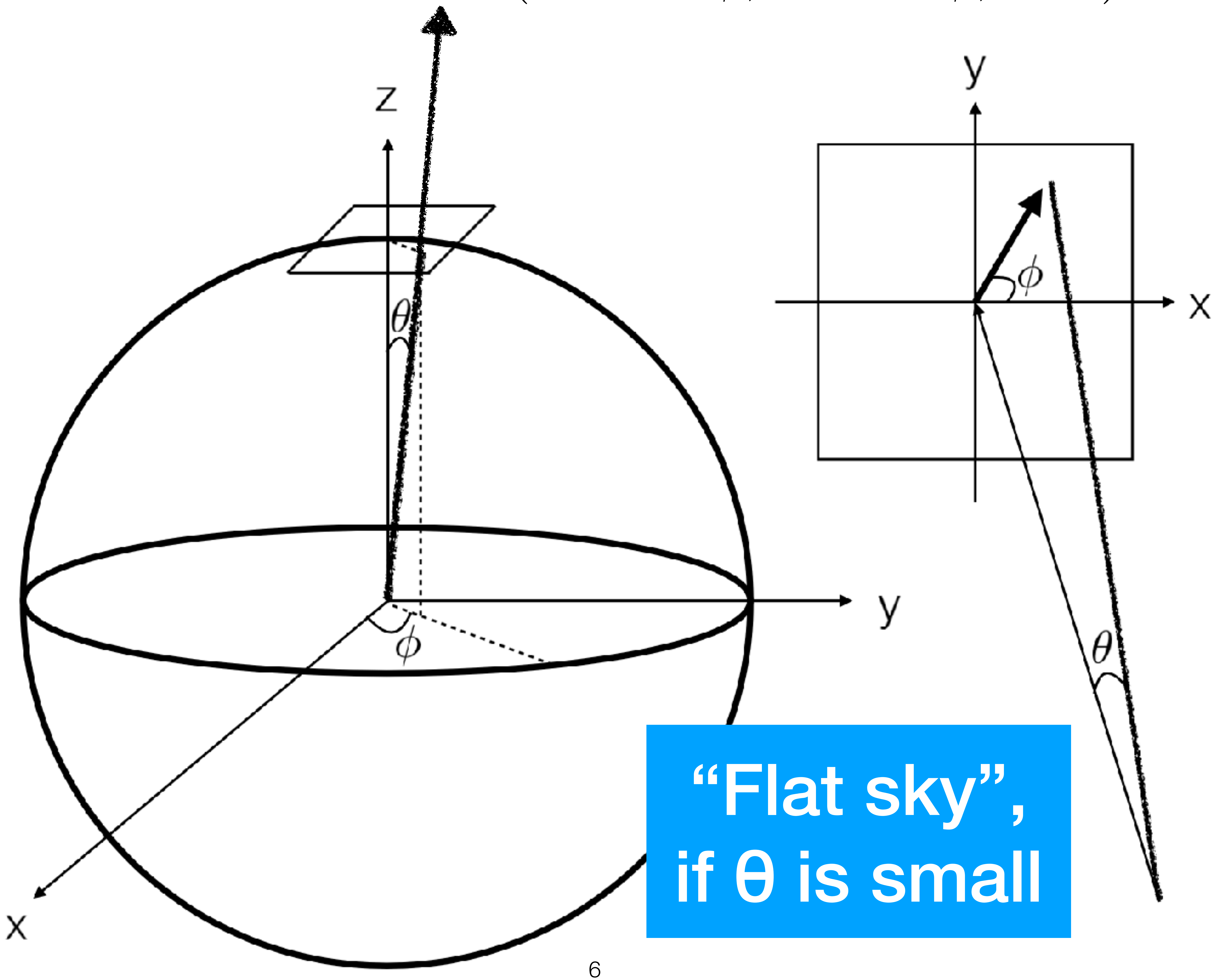
$$\tilde{Q} + i\tilde{U} = \exp(-2i\varphi)(Q + iU)$$

$$\tilde{Q} - i\tilde{U} = \exp(2i\varphi)(Q - iU)$$

C.f.
$$\begin{pmatrix} \tilde{Q} \\ \tilde{U} \end{pmatrix} = \begin{pmatrix} \cos 2\varphi & \sin 2\varphi \\ -\sin 2\varphi & \cos 2\varphi \end{pmatrix} \begin{pmatrix} Q \\ U \end{pmatrix}$$

Part I: E- and B-mode Polarisation

$$\hat{n} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$



"Flat sky", if θ is small

Fourier transform the Stokes Parameters?

$$Q(\boldsymbol{\theta}) + iU(\boldsymbol{\theta}) = \int \frac{d^2\ell}{(2\pi)^2}\; a_{\boldsymbol{\ell}} \exp(i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

where

$$\boldsymbol{\ell} = (\ell\cos\phi_\ell, \ell\sin\phi_\ell)$$

- As Q+iU changes under rotation, the Fourier coefficients $a_{\boldsymbol{\ell}}$ change as well
- So…

(*) Never mind the overall minus sign. This is just for convention.

Tweaking the Fourier Transform

$$Q(\boldsymbol{\theta}) + iU(\boldsymbol{\theta}) = \int \frac{d^2\ell}{(2\pi)^2}\, a_{\boldsymbol{\ell}} \exp(i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

where we write the coefficients as(*)

$$a_{\boldsymbol{\ell}} = -{}_2a_{\boldsymbol{\ell}} \exp(2i\phi_\ell)$$

- Under rotation, the azimuthal angle of a Fourier wavevector, ϕ_l, changes as $\phi_\ell \to \tilde{\phi}_\ell = \phi_\ell - \varphi$
- This cancels the factor in the left hand side:

$$\tilde{Q} + i\tilde{U} = \exp(-2i\varphi)(Q + iU)$$

Seljak (1997); Zaldarriaga & Seljak (1997); Kamionkowski, Kosowky, Stebbins (1997)

Tweaking Fourier Transform

- We thus write

$$Q(\boldsymbol{\theta}) \pm iU(\boldsymbol{\theta}) = -\int \frac{d^2\ell}{(2\pi)^2} \; {}_{\pm 2}a_{\boldsymbol{\ell}} \exp(\pm 2i\phi_\ell + i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

- And, defining ${}_{\pm 2}a_{\boldsymbol{\ell}} \equiv -(E_{\boldsymbol{\ell}} \pm iB_{\boldsymbol{\ell}})$

$$Q(\boldsymbol{\theta}) \pm iU(\boldsymbol{\theta}) = \int \frac{d^2\ell}{(2\pi)^2} \; (E_{\boldsymbol{\ell}} \pm iB_{\boldsymbol{\ell}}) \exp(\pm 2i\phi_\ell + i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

By construction E_l and B_l do not pick up a factor of exp(2iϕ) under coordinate rotation. That's great! What kind of polarisation patterns do these quantities represent?

Pure E, B Modes

- Q and U produced by E and B modes are given by

$$
\begin{aligned}
Q(\boldsymbol{\theta}) &= \int \frac{d^2\ell}{(2\pi)^2}(E_{\boldsymbol{\ell}} \cos 2\phi_\ell - B_{\boldsymbol{\ell}} \sin 2\phi_\ell) \exp(i\boldsymbol{\ell} \cdot \boldsymbol{\theta}) \\
U(\boldsymbol{\theta}) &= \int \frac{d^2\ell}{(2\pi)^2}(E_{\boldsymbol{\ell}} \sin 2\phi_\ell + B_{\boldsymbol{\ell}} \cos 2\phi_\ell) \exp(i\boldsymbol{\ell} \cdot \boldsymbol{\theta})
\end{aligned}
$$

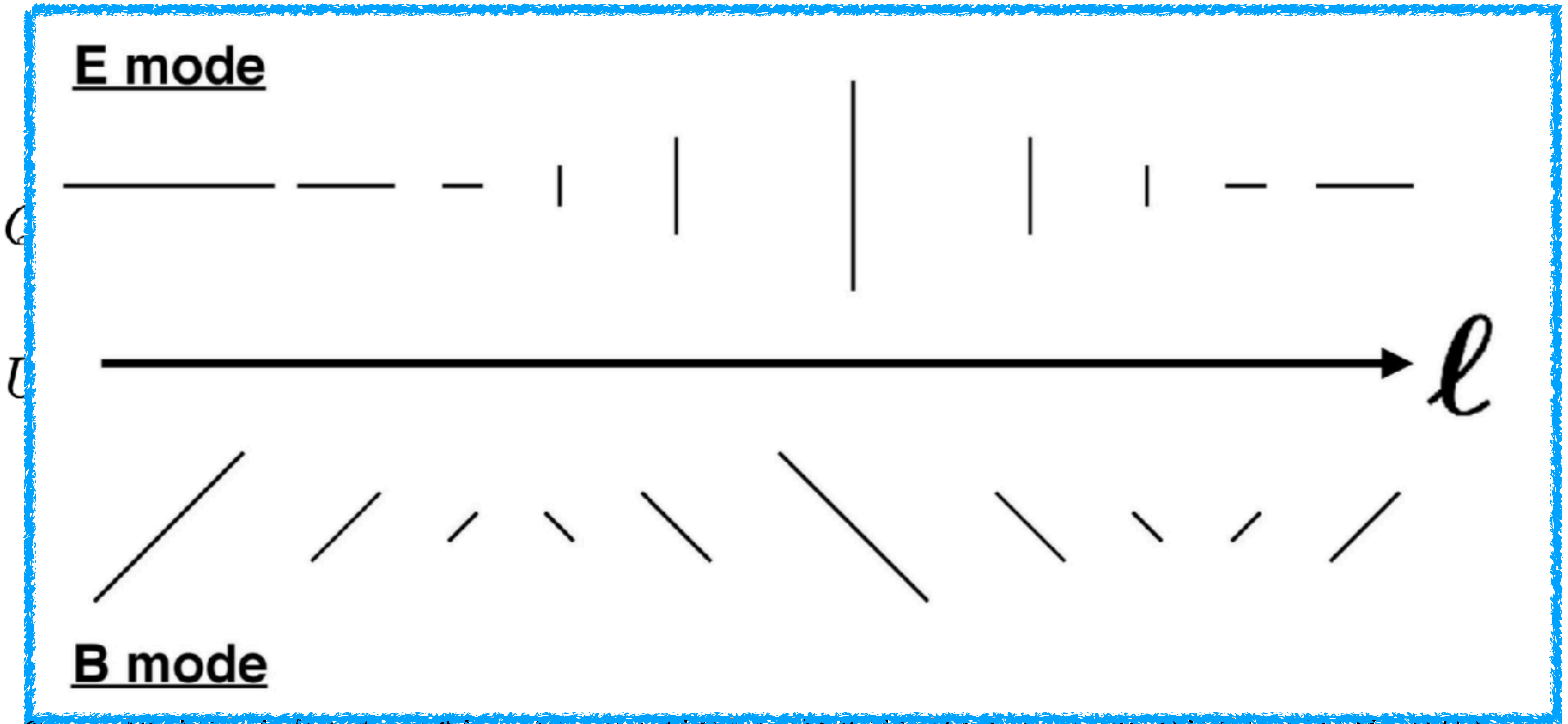
- Let's consider Q and U that are produced by a single Fourier mode

- Taking the x-axis to be the direction of a wavevector, we obtain

$$Q(\theta) = \Re\left[E_\ell \exp(i\ell\theta)\right]$$

$$U(\theta) = \Re\left[B_\ell \exp(i\ell\theta)\right]$$

Pure E, B Modes



- Taking the x-axis to be the direction of a wavevector, we obtain

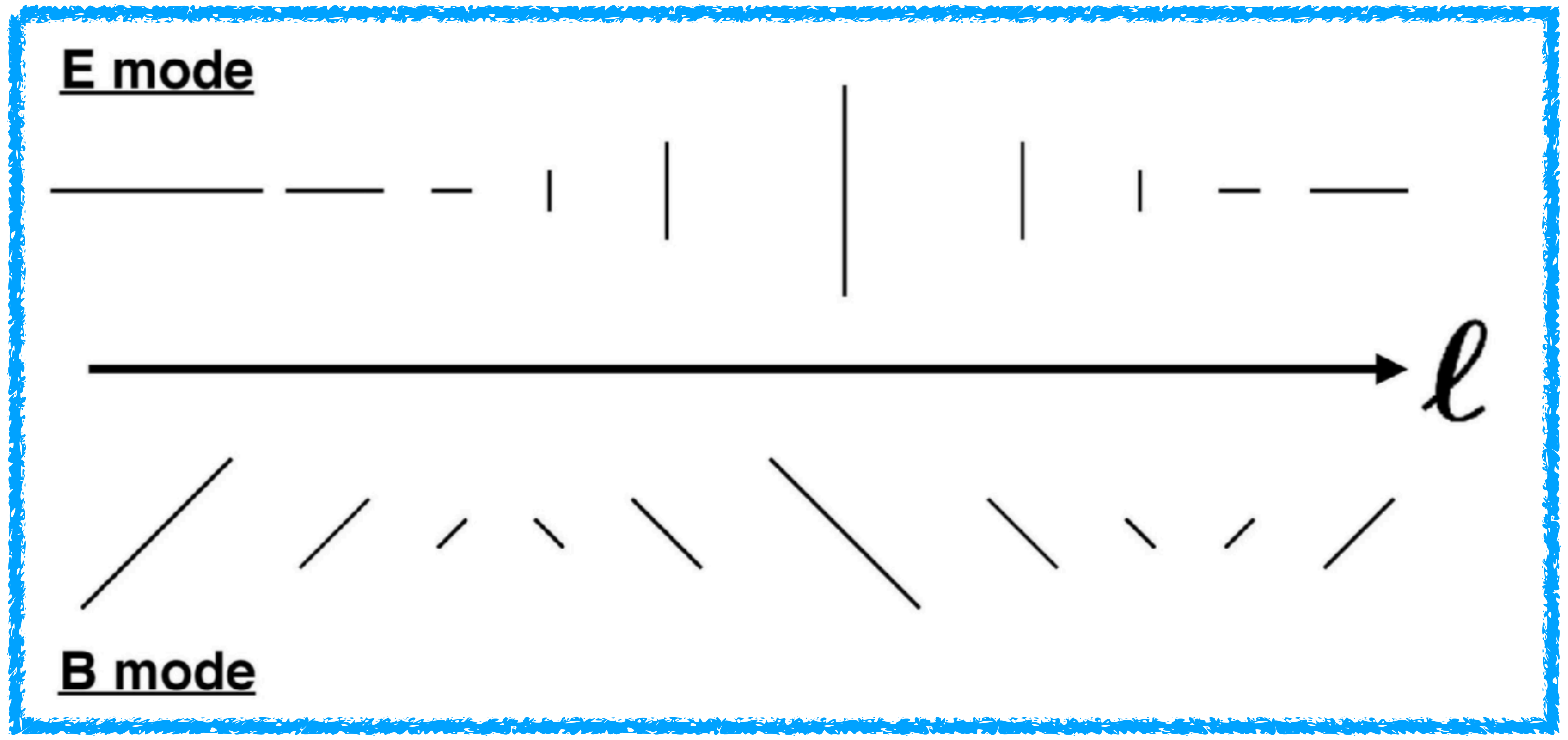
$$Q(\theta) = \Re\left[E_\ell \exp(i\ell\theta)\right]$$
$$U(\theta) = \Re\left[B_\ell \exp(i\ell\theta)\right]$$

CMB is weakly polarised!

Credit: ESA

Temperature (smoothed) + Polarisation

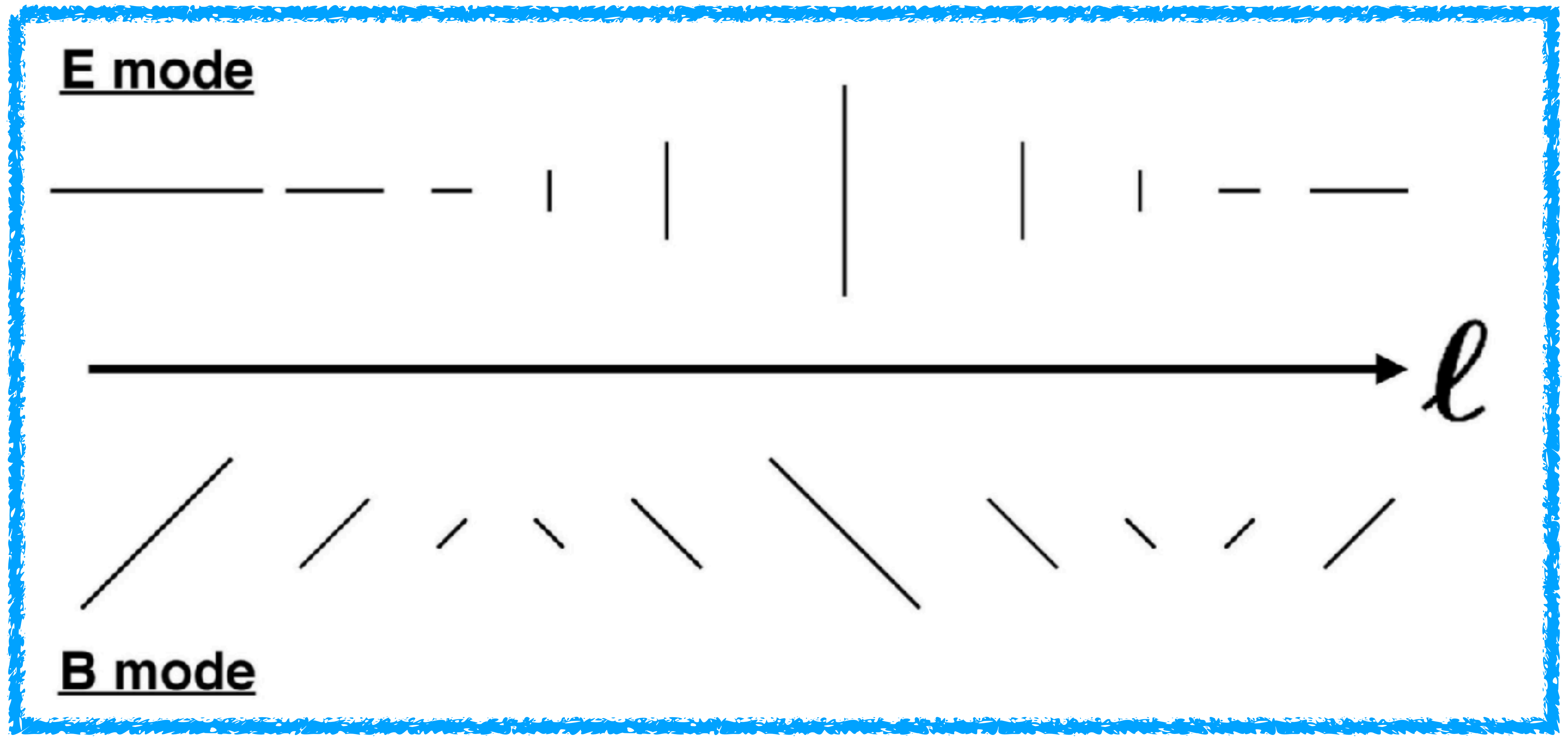
Geometric Meaning (1)

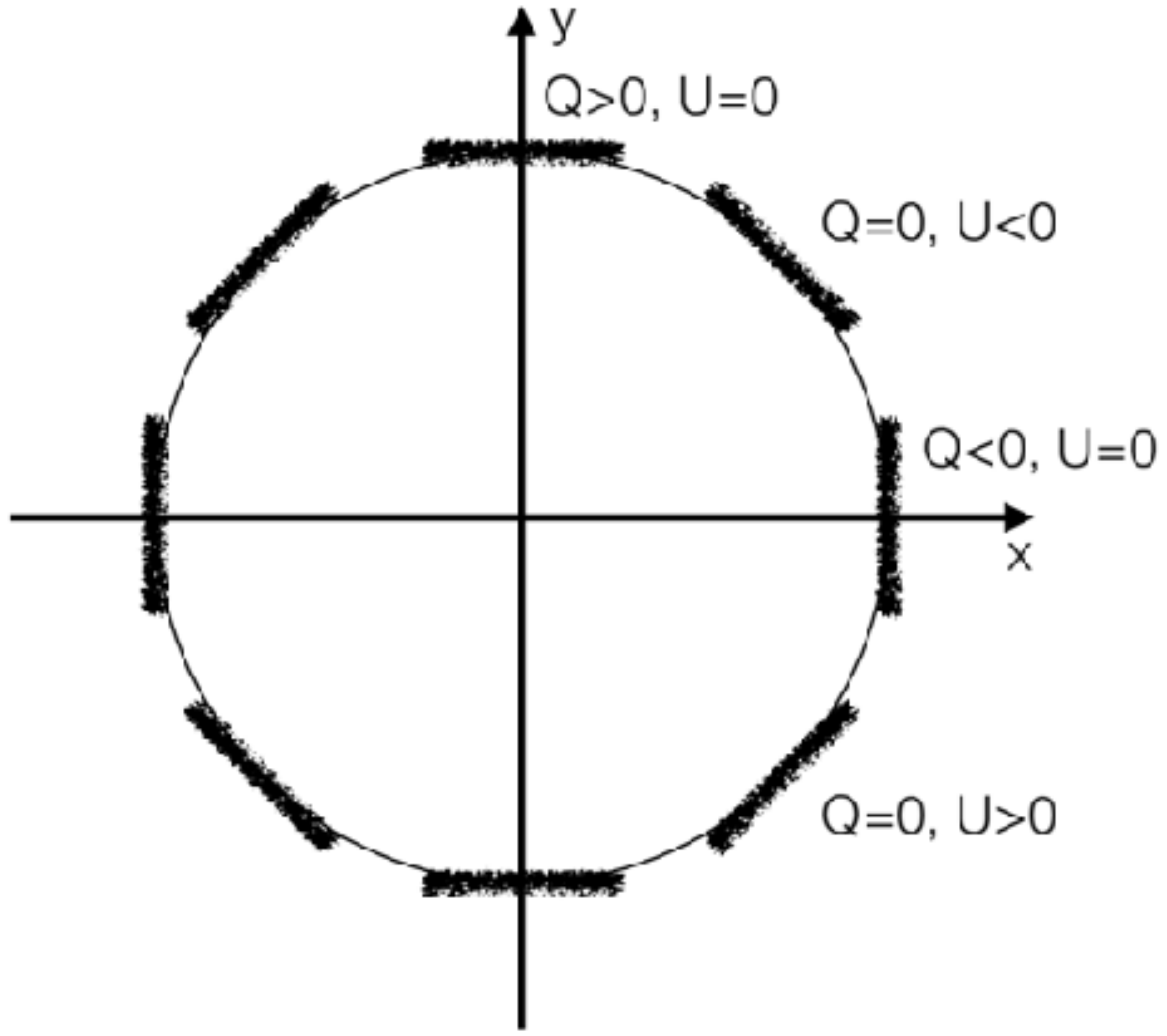


- **E mode**: Polarisation directions parallel or perpendicular to the wavevector

- **B mode**: Polarisation directions 45 degree tilted with respect to the wavevector

Geometric Meaning (2)

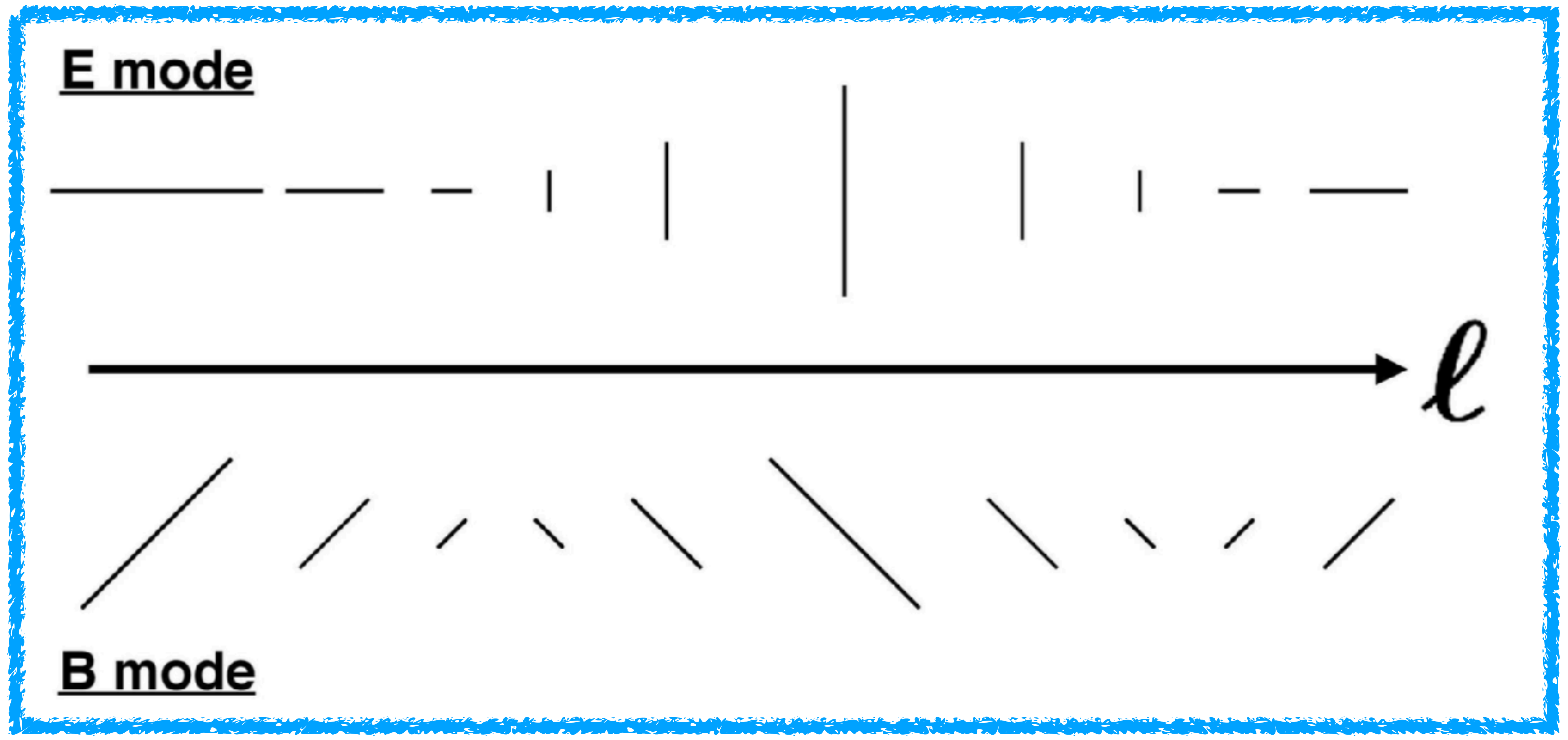


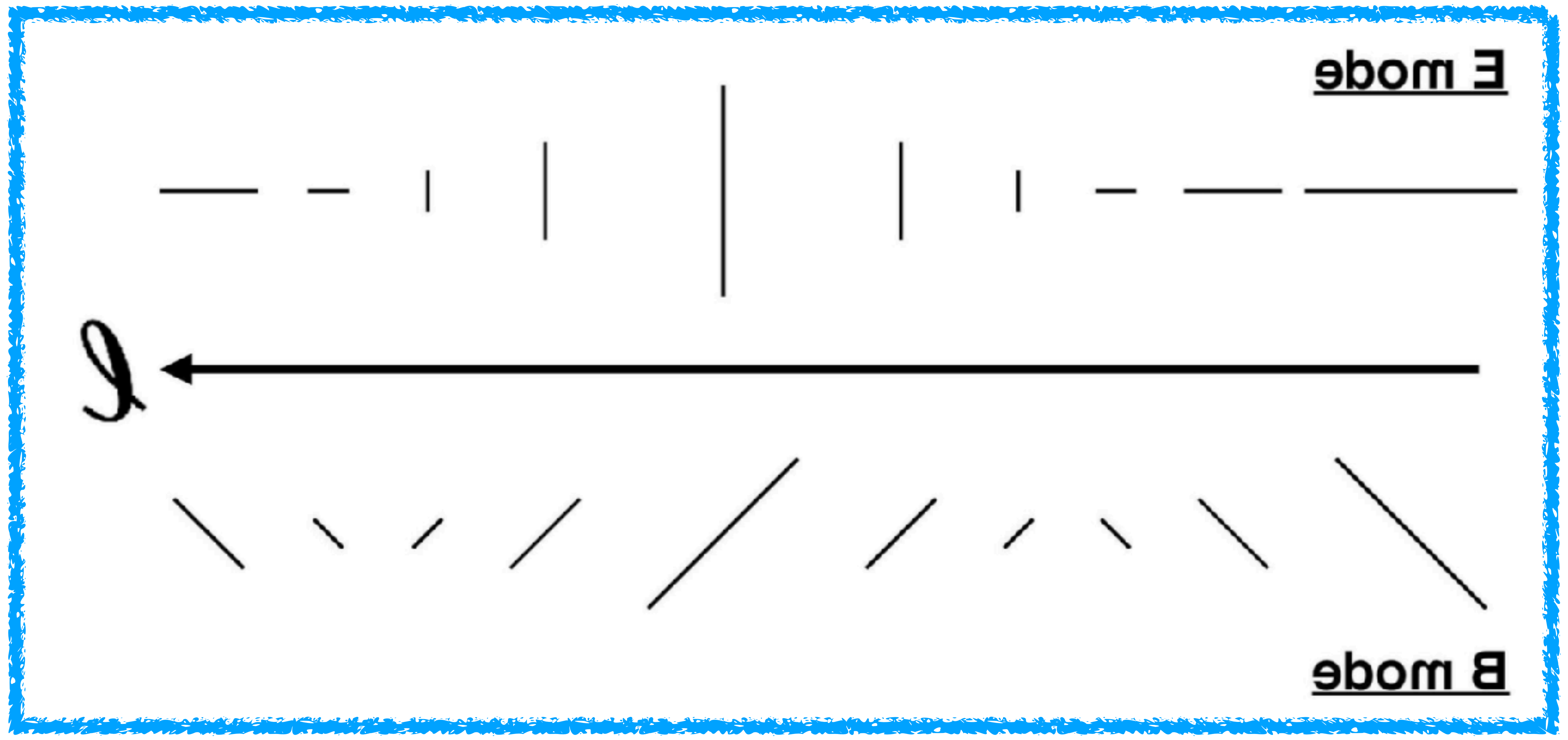


- **E mode**: Stokes Q, defined with respect to ℓ as the x-axis
- **B mode**: Stokes U, defined with respect to ℓ as the y-axis

IMPORTANT: These are all coordinate-independent statements

Parity





- **E mode**: Parity even
- **B mode**: Parity odd

Power Spectra

$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{BB}$$

$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

- However, <EB> and <TB> vanish for parity-preserving fluctuations because <EB> and <TB> change sign under parity flip.

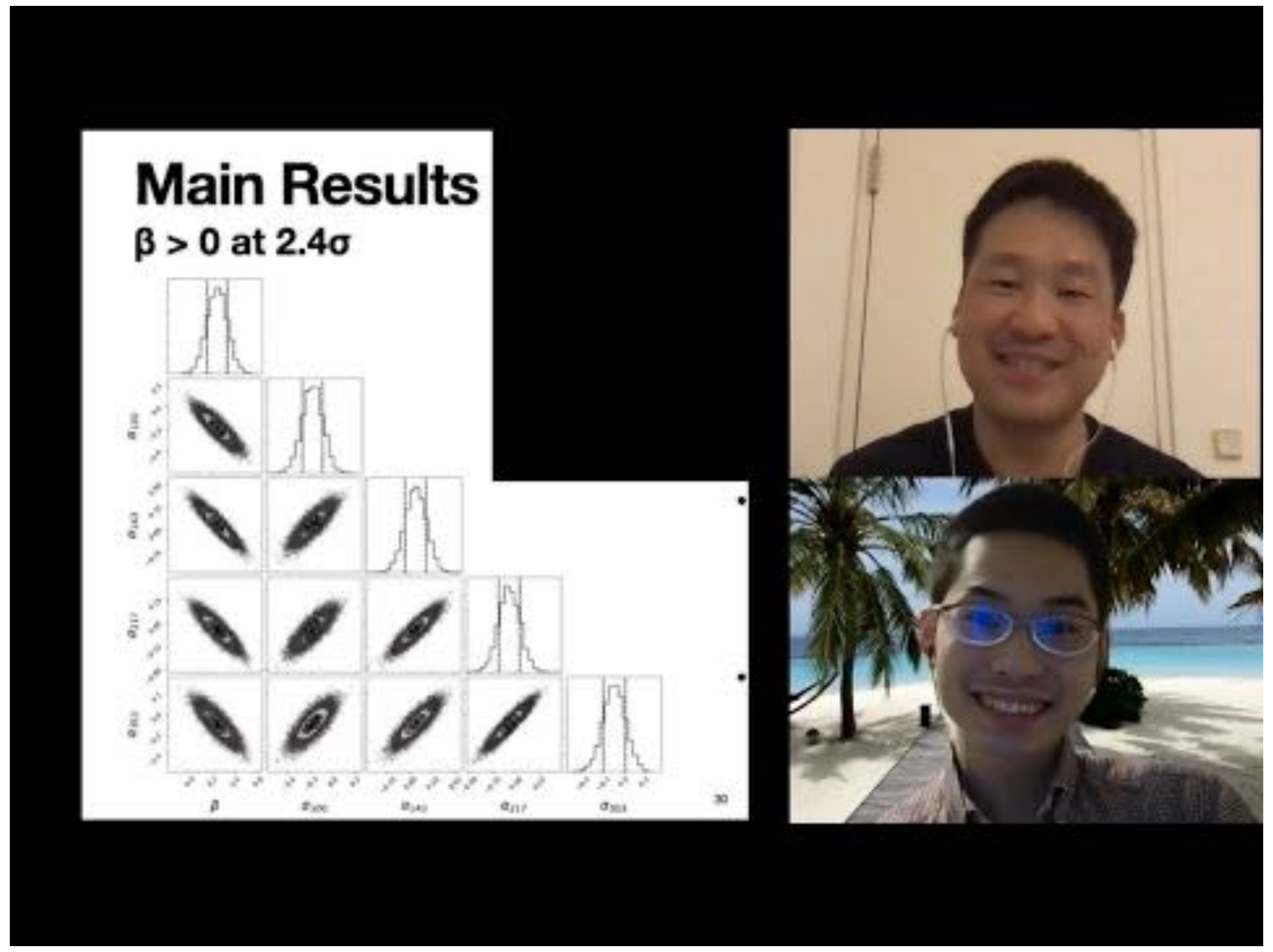
MPA Press Release (November 23, 2020)

A hint of <EB> correlation, pointing to new physics that violates parity?

Minami & Komatsu, PRL, **125**, 221301 (2020)

For explanation, see the YouTube video of "*Cosmology Talks*", hosted by Dr. Shaun Hotchkiss at the Univ. of Auckland.

https://youtu.be/9W9rDlEHg3c



https://www.mpa-garching.mpg.de/896049/news20201123

Contacts

Komatsu, Eiichiro
Director
2208
komatsu@...

Hämmerle, Hannelore
Press officer
3980
hanne@...

Original publication

1. *Yuto Minami, Eiichiro Komatsu*

New extraction of the cosmic birefringence from the Planck 2018 polarization data

Physical Review Letters, 23 November 2020

Source

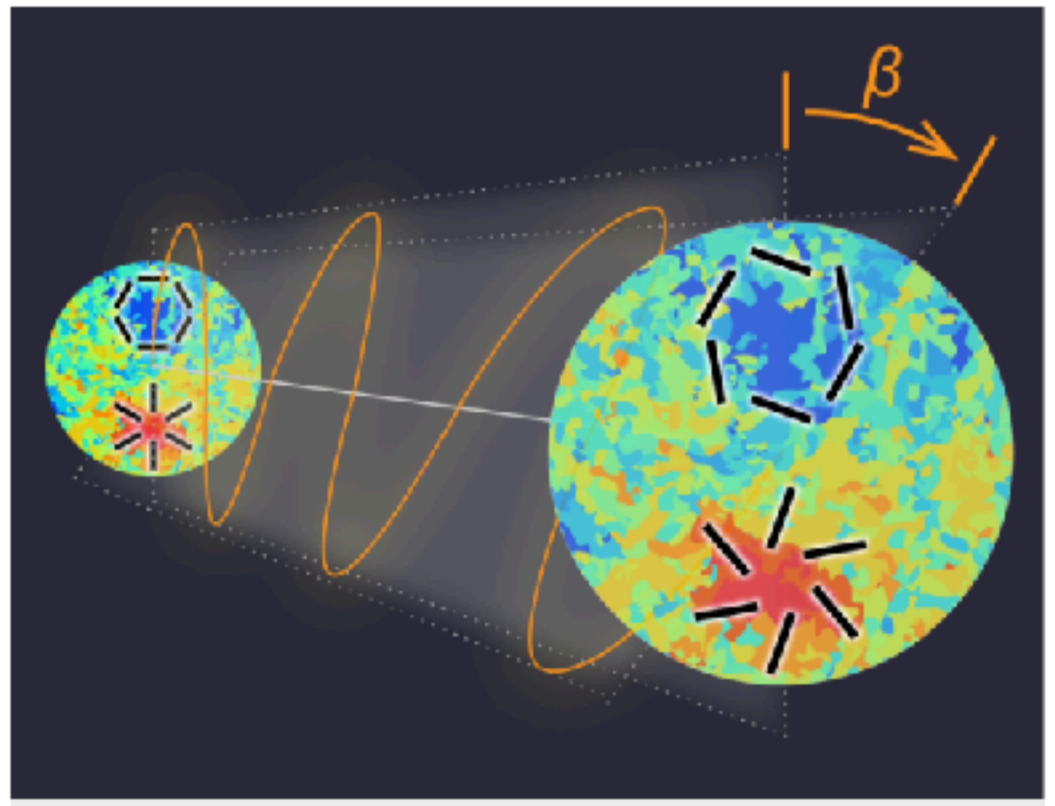
A hint of new physics in polarized radiation from the early Universe

NOVEMBER 23, 2020

Using Planck data from the cosmic microwave background radiation, an international team of researchers has observed a hint of new physics. The team developed a new method to measure the polarization angle of the ancient light by calibrating it with dust emission from our own Milky Way. While the signal is not detected with enough precision to draw definite conclusions, it may suggest that dark matter or dark energy causes a violation of the so-called "parity symmetry".

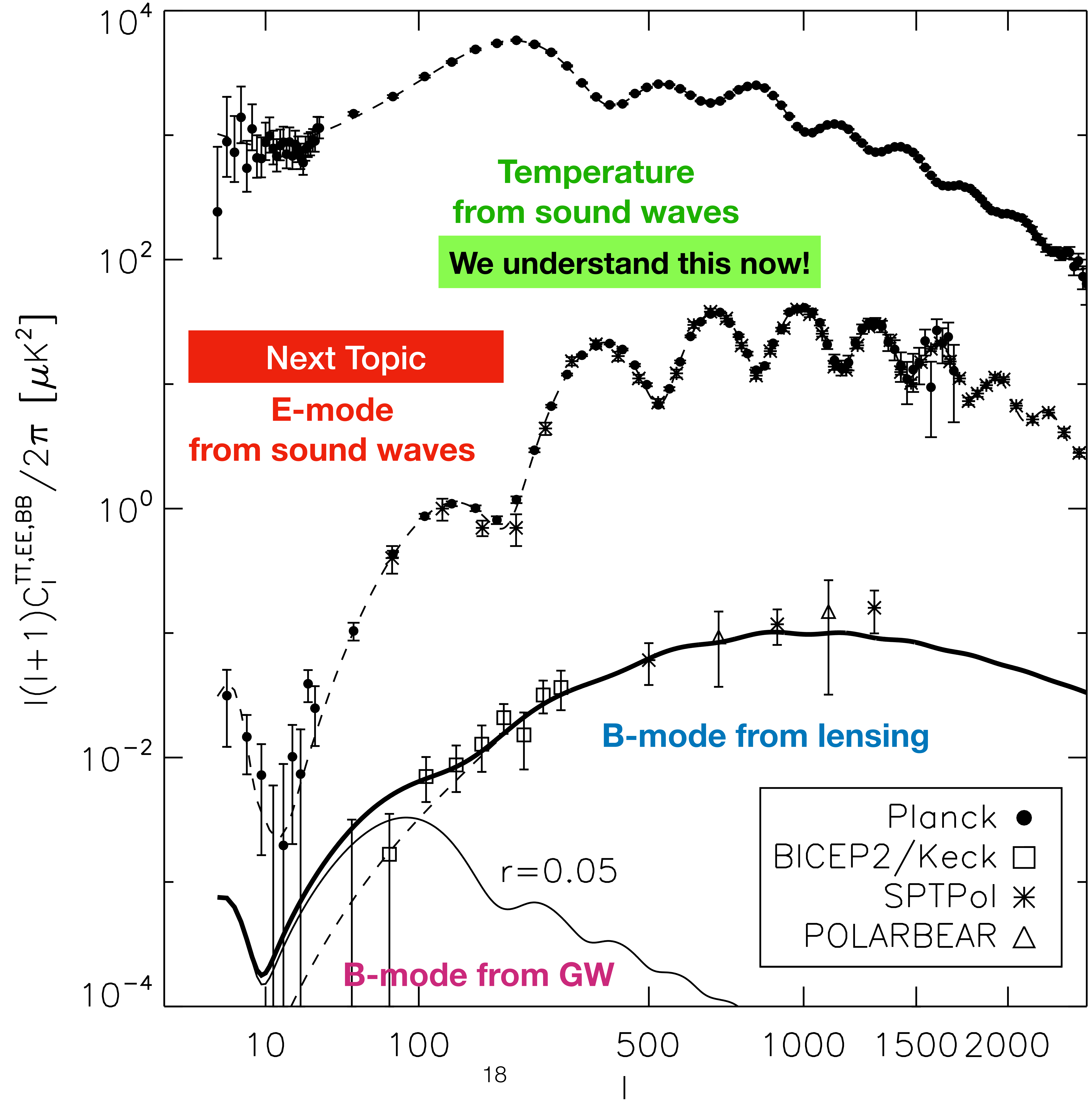
The laws of physics governing the Universe are thought not to change when flipped around in a mirror. For example, electromagnetism works the same regardless of whether you are in the original system, or in a mirrored system in which all spatial coordinates have been flipped. If this symmetry, called "parity," is violated, it may hold the key to understanding the elusive nature of dark matter and dark energy, which occupy 25 and 70 percent of the energy budget of the Universe today, respectively. While both dark, these two components have opposite effects on the evolution of the Universe: dark matter attracts, while dark energy causes the Universe to expand ever faster.

A new study, including researchers from the Institute of Particle and Nuclear Studies (IPNS) at the High Energy Accelerator Research Organization (KEK), the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) of the University of Tokyo, and the Max Planck Institute for Astrophysics (MPA), reports on a tantalizing hint of new physics—with 99.2 percent confidence level —which violates parity symmetry. Their findings were published in the journal *Physical Review Letters* on November 23, 2020; the paper was selected as the "Editors' Suggestion", judged by editors of the journal to be important, interesting, and well written.



As the light of the cosmic microwave background emitted 13.8 billion years ago (left image) travels

The hint to a violation of parity symmetry was found in the cosmic microwave background radiation, the remnant light of the Big Bang. The key is the polarized light of the cosmic microwave background. Light is a propagating electromagnetic wave. When it consists of waves oscillating in a preferred direction, physicists call it "polarized". The polarization arises when the light is scattered. Sunlight, for instance, consists of waves with all possible oscillating directions; thus, it is not polarized. The light of a rainbow, meanwhile, is polarized because the sunlight is scattered by water droplets in the atmosphere. Similarly, the light of the cosmic microwave background initially became polarized when scattered by electrons 400,000 years after the Big Bang. As this light traveled

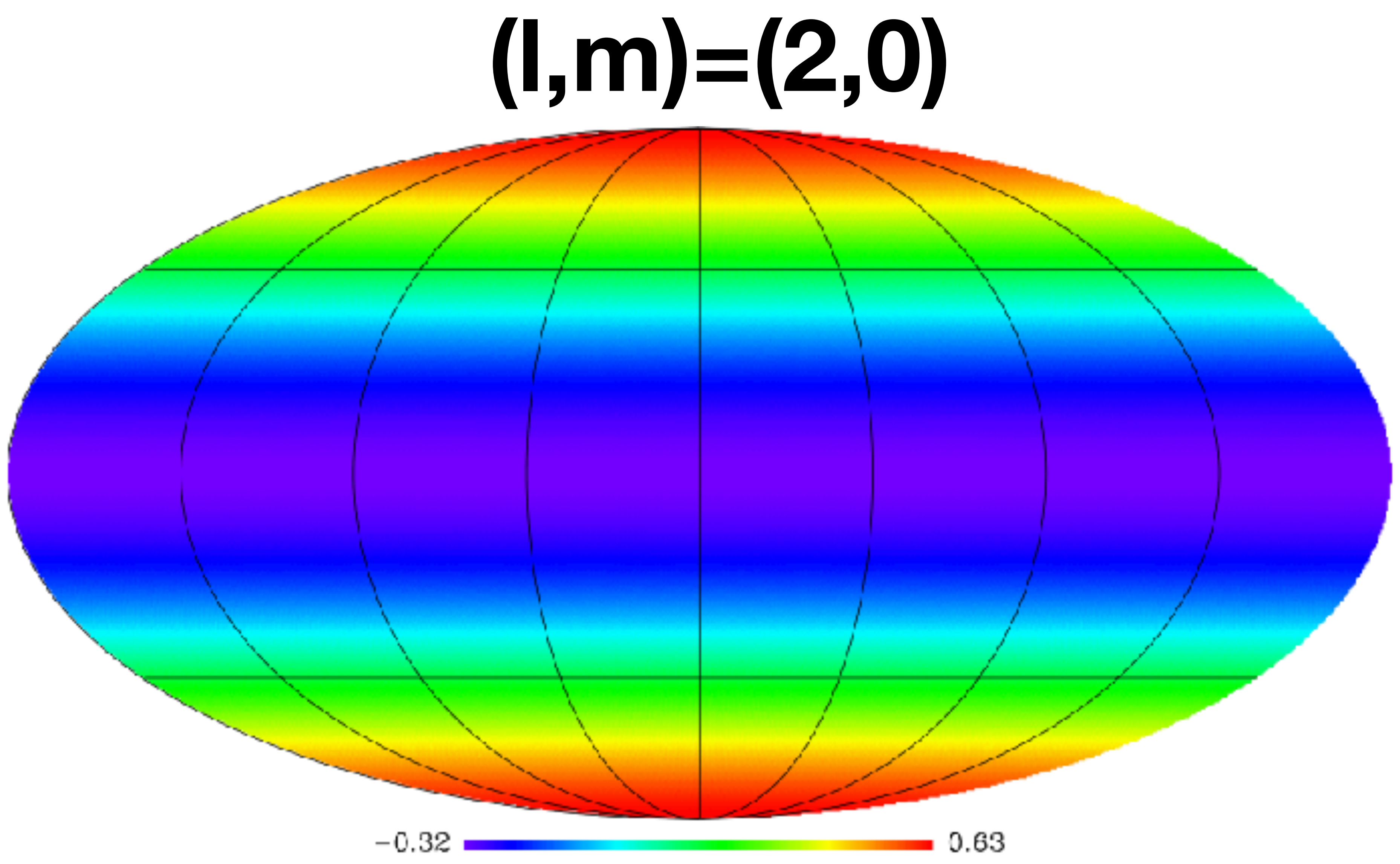


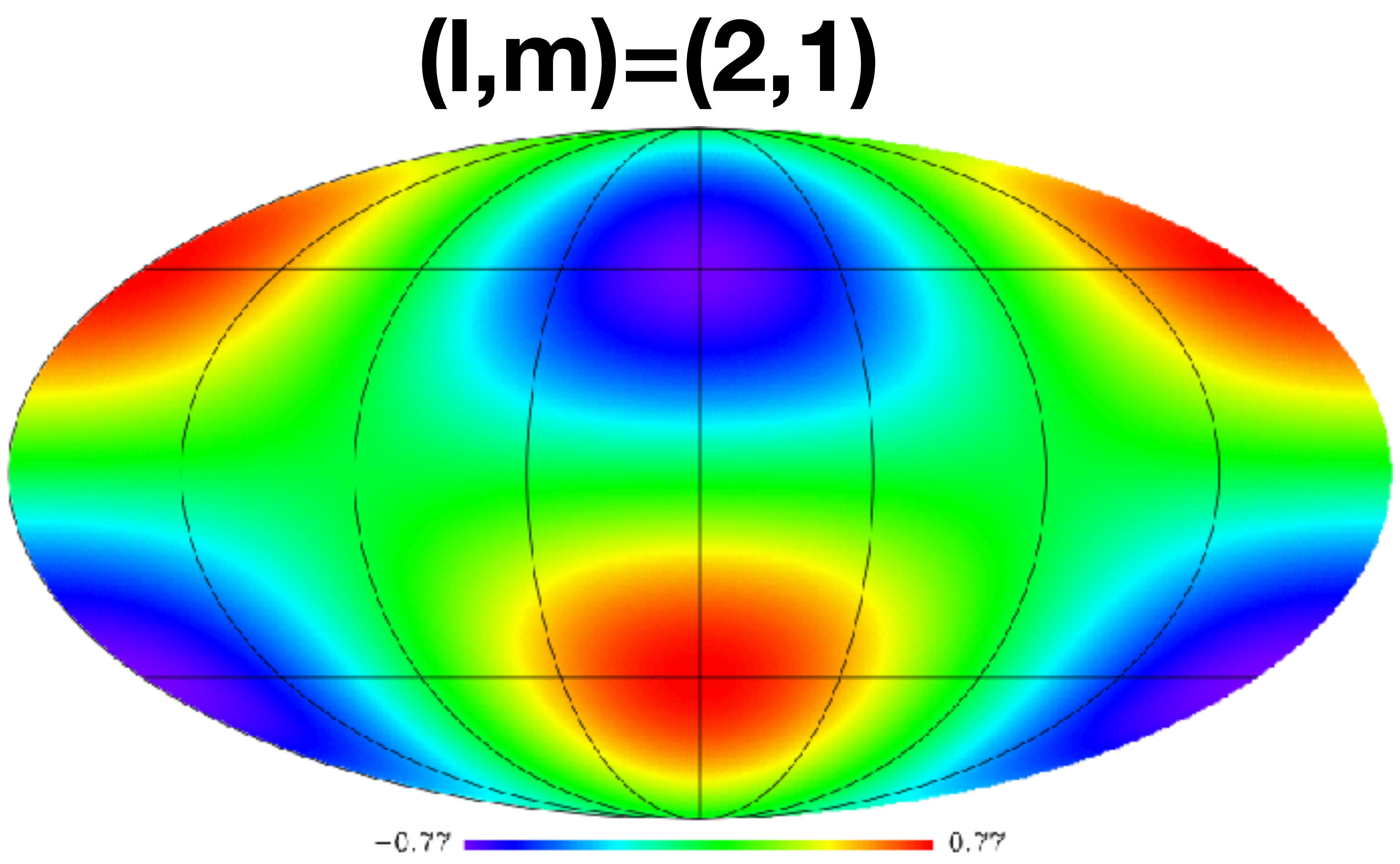
Temperature
from sound waves
We understand this now!
Next Topic
E-mode
from sound waves
B-mode from lensing
r=0.05
B-mode from GW
Planck
BICEP2/Keck
SPTPol
POLARBEAR
$l(l+1)C_l^{TT,EE,BB}/2\pi$ [μK^2]
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100
500
1000
1500
2000
l

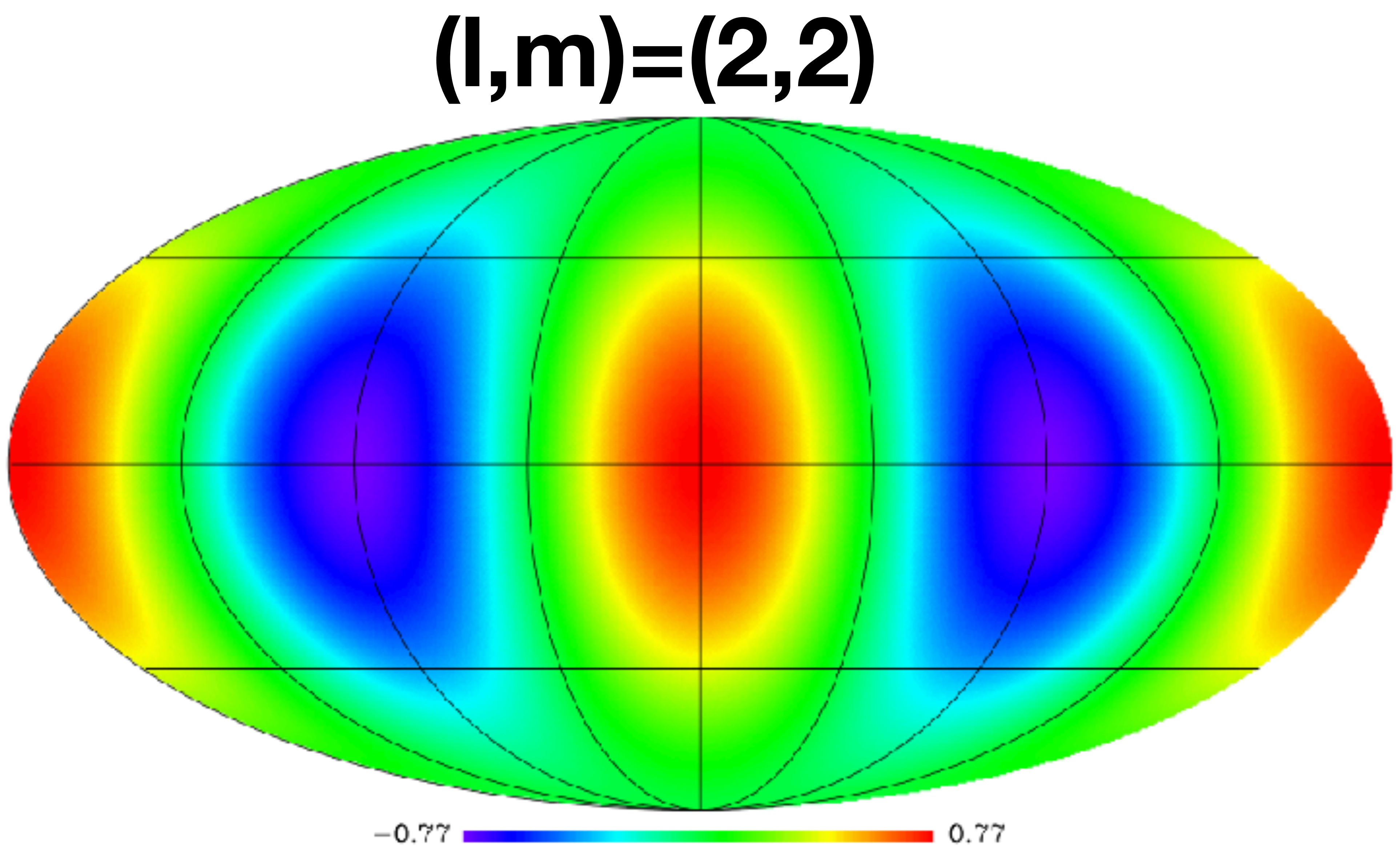
Part II: E-mode Polarisation from the Sound Waves

The Single Most Important Thing You Need to Remember

- Polarisation is generated by scattering of the local quadrupole temperature anisotropy, which is proportional to viscosity.

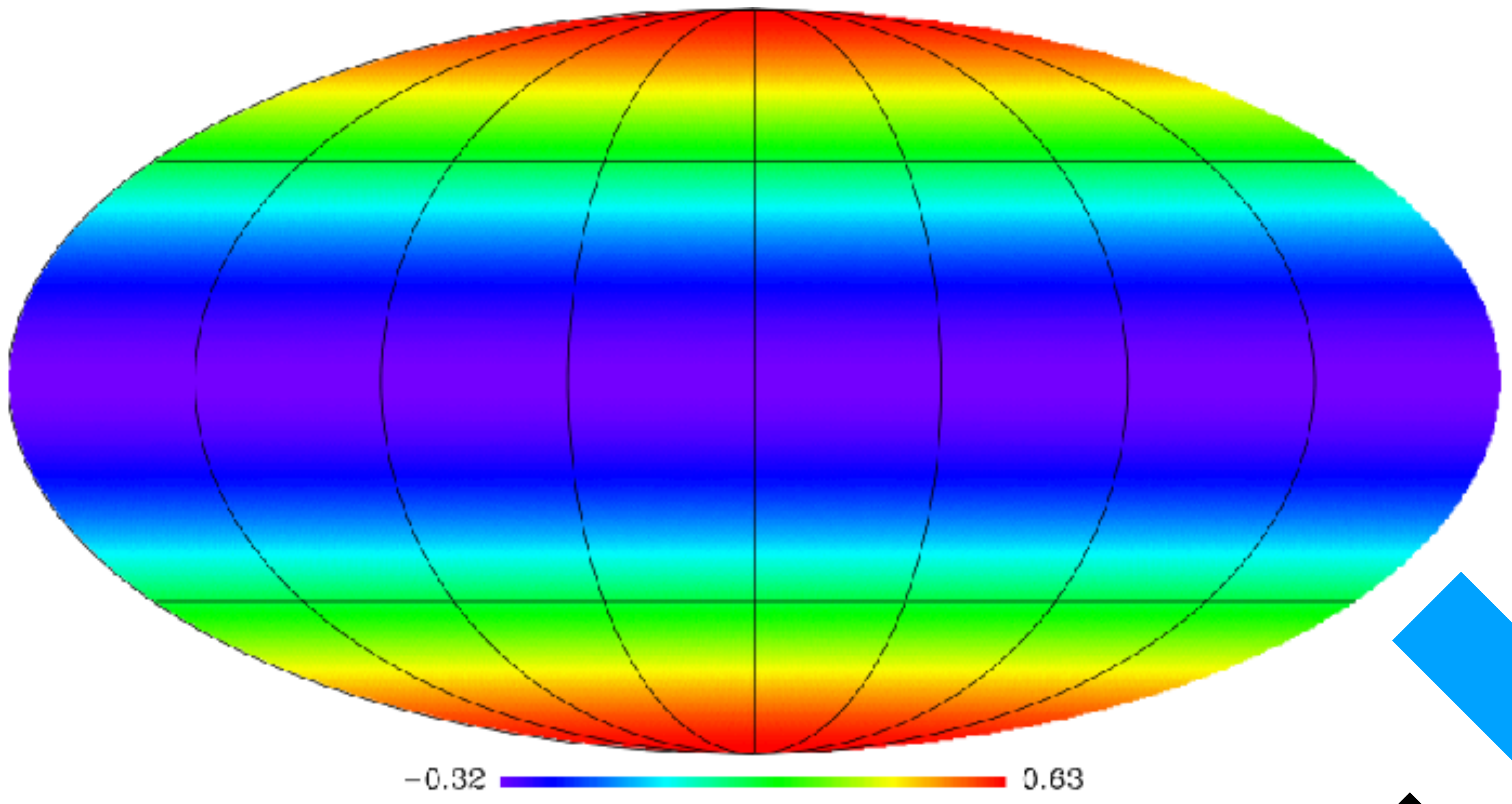




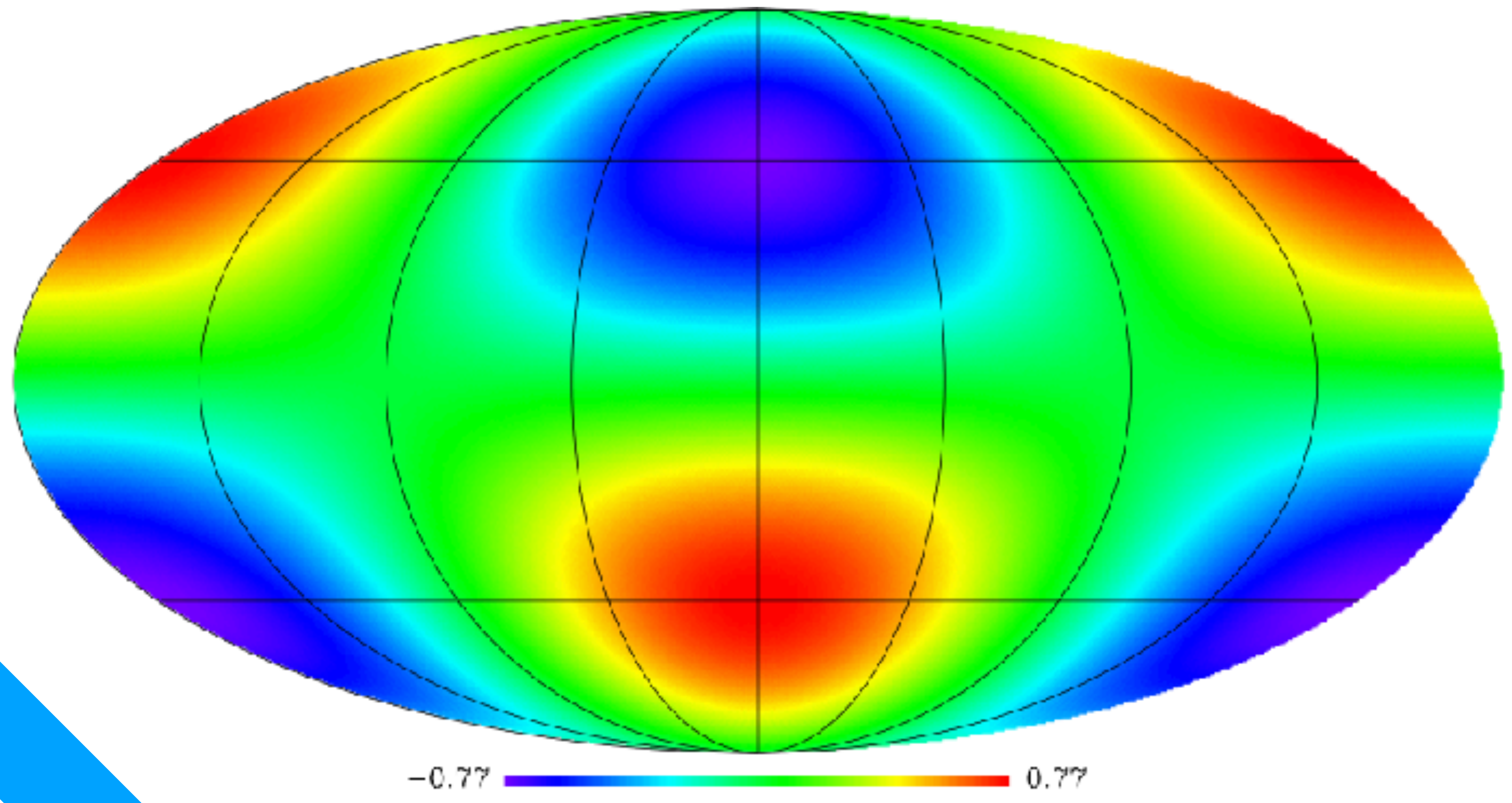


Local quadrupole temperature anisotropy seen from an electron

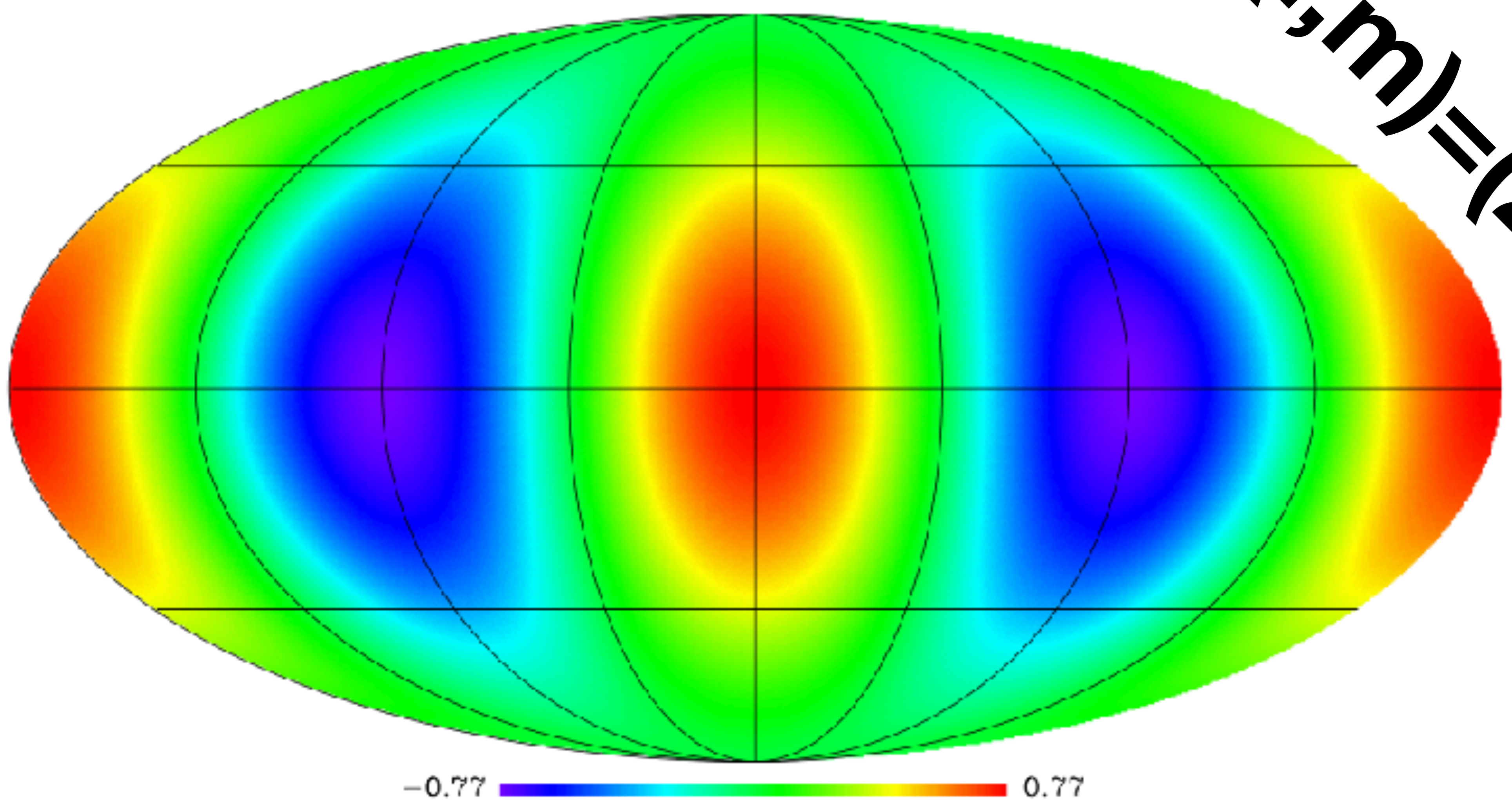
(l,m)=(2,0)



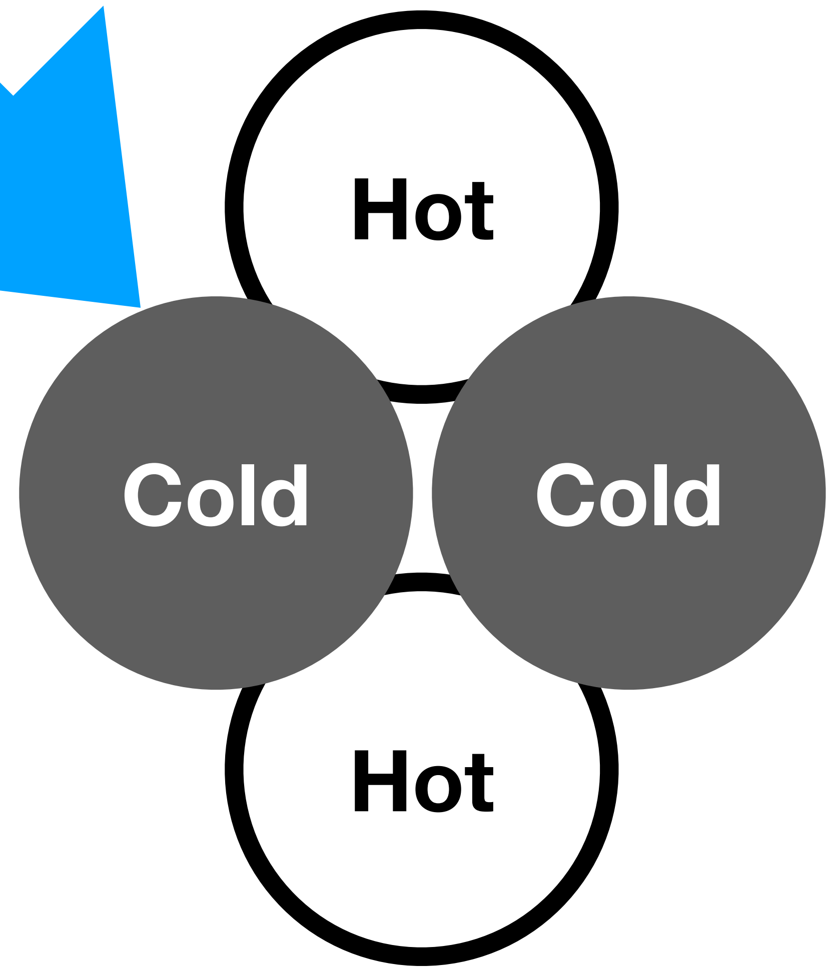
(l,m)=(2,1)



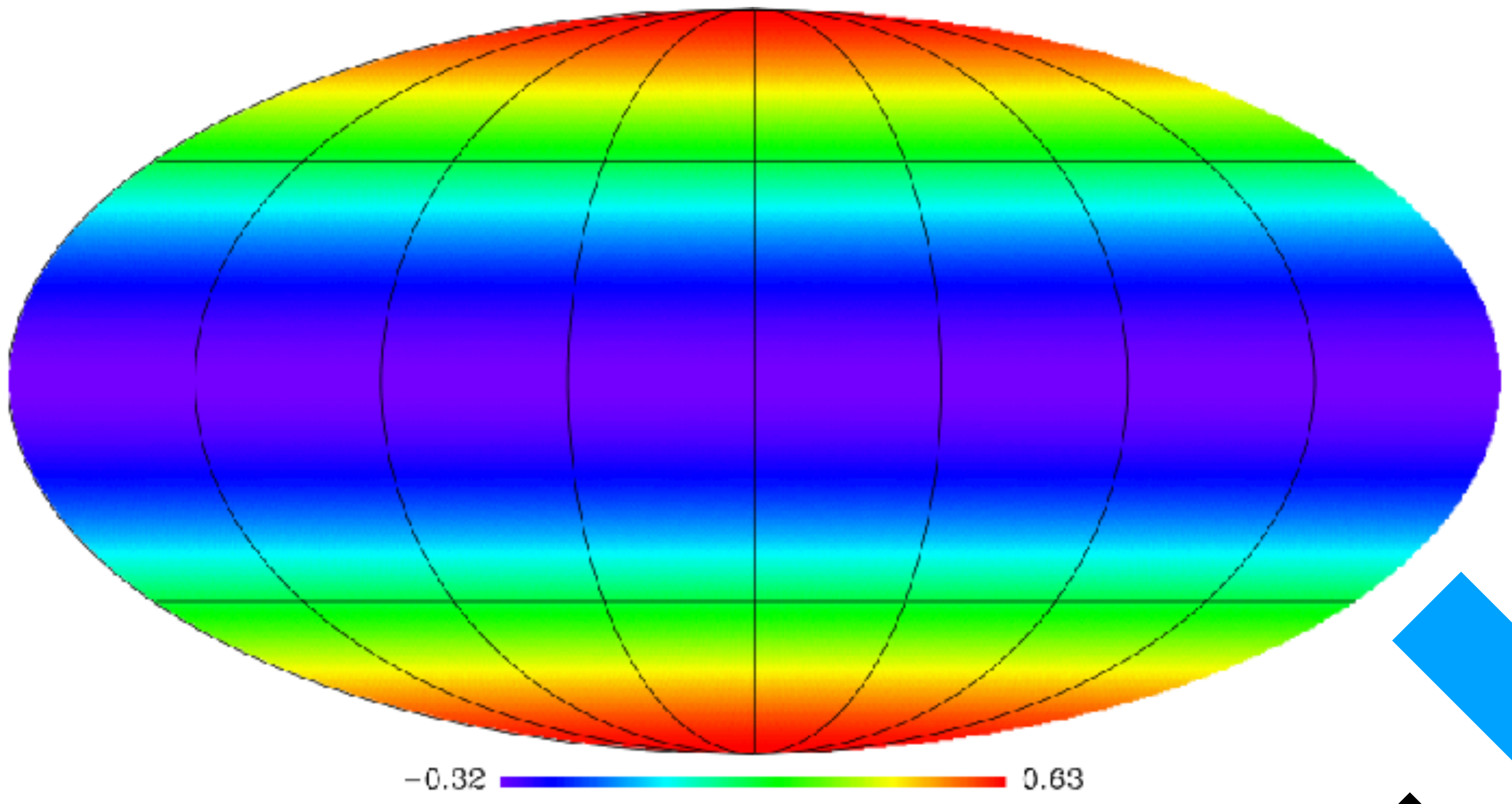
(l,m)=(2,2)



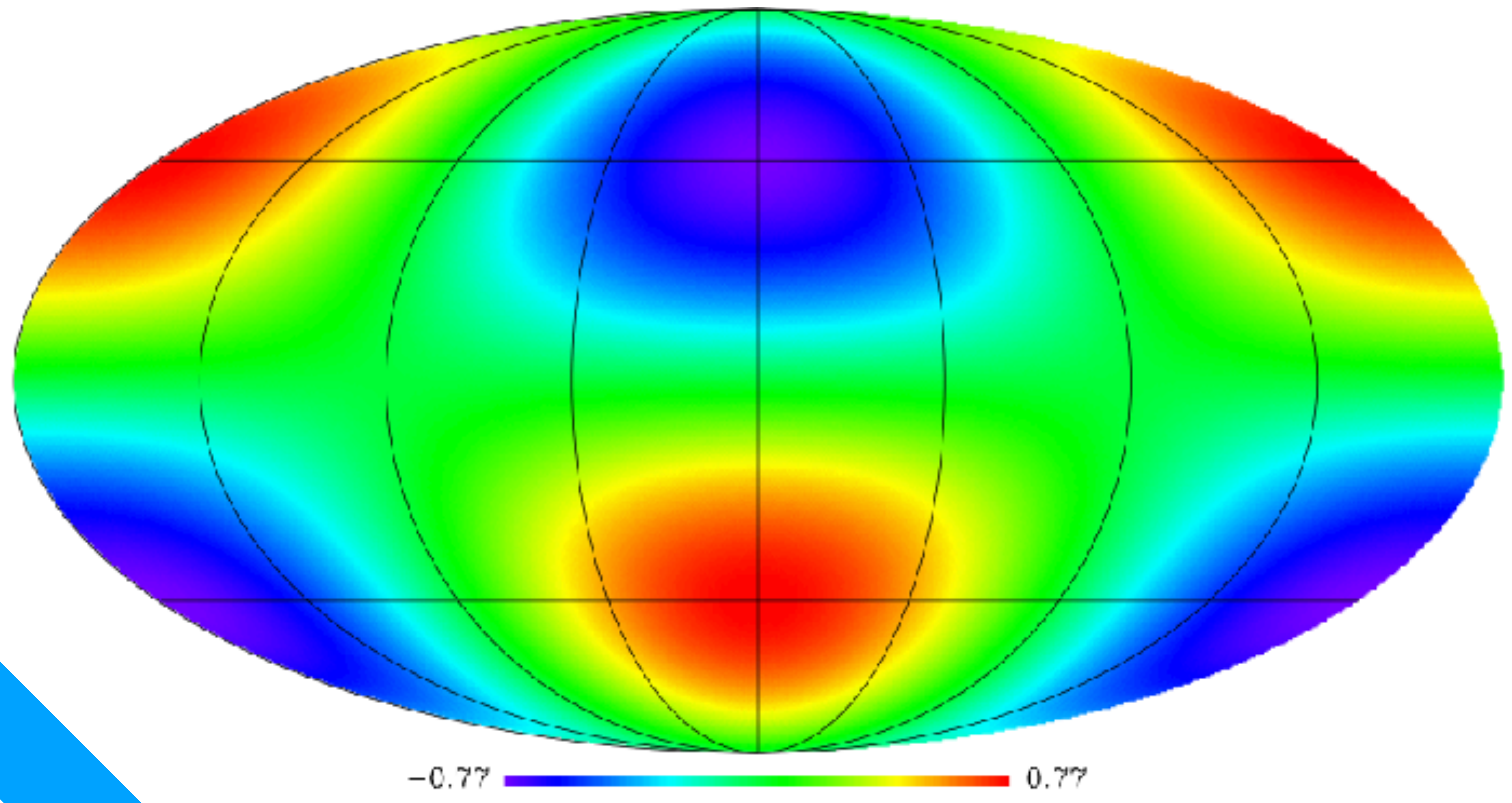
Let's symbolise (l,m)=(2,0) as



(l,m)=(2,0)



(l,m)=(2,1)



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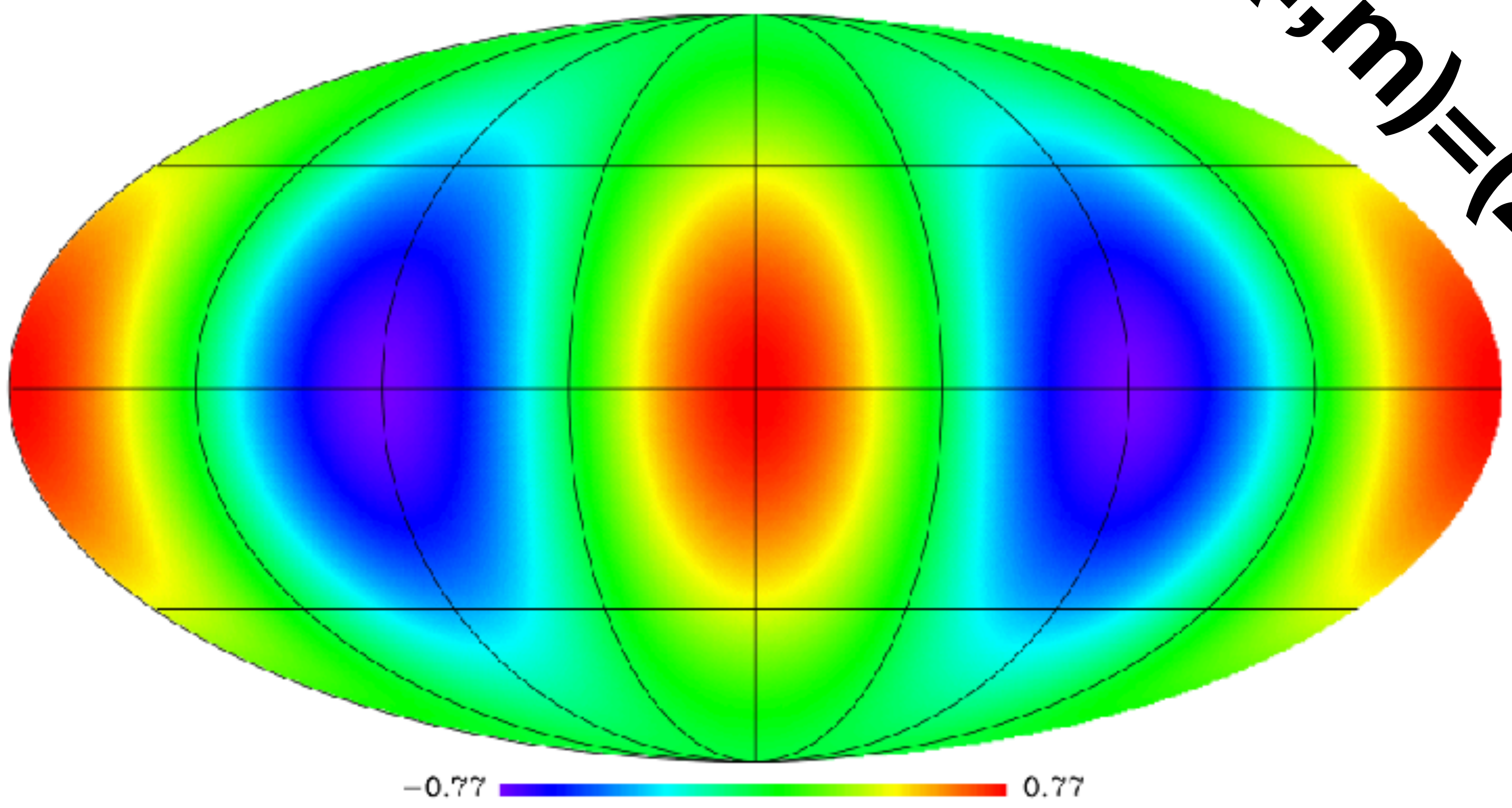

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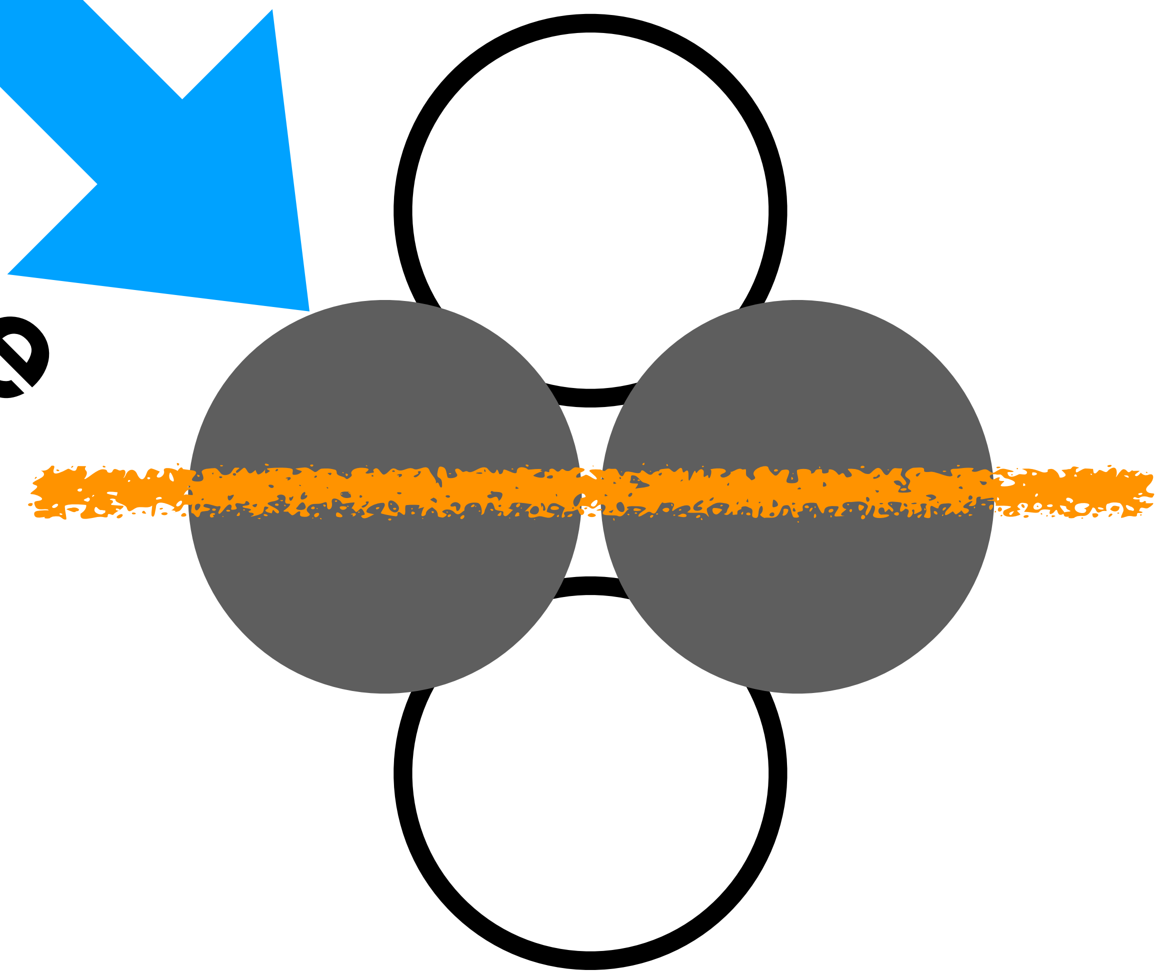
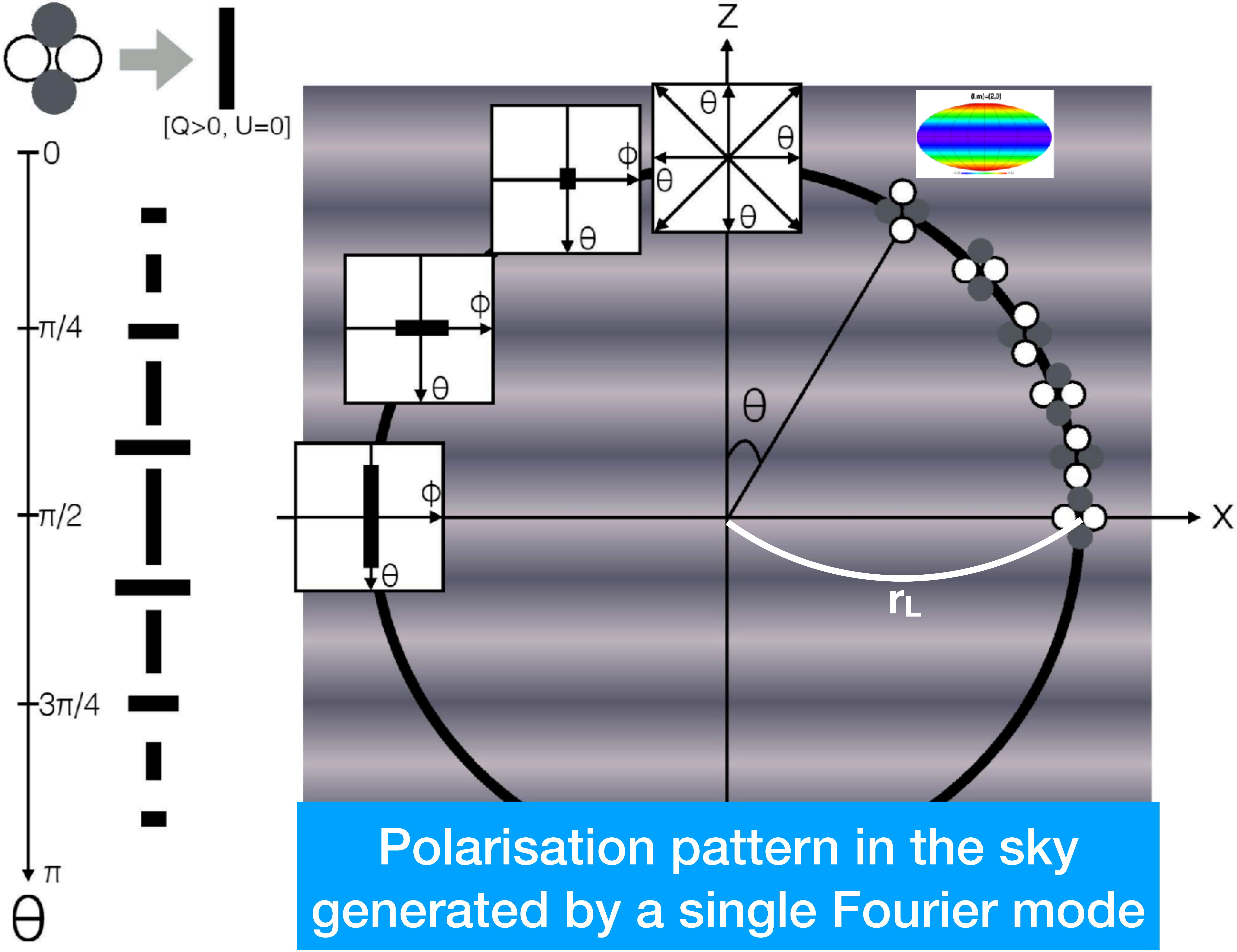
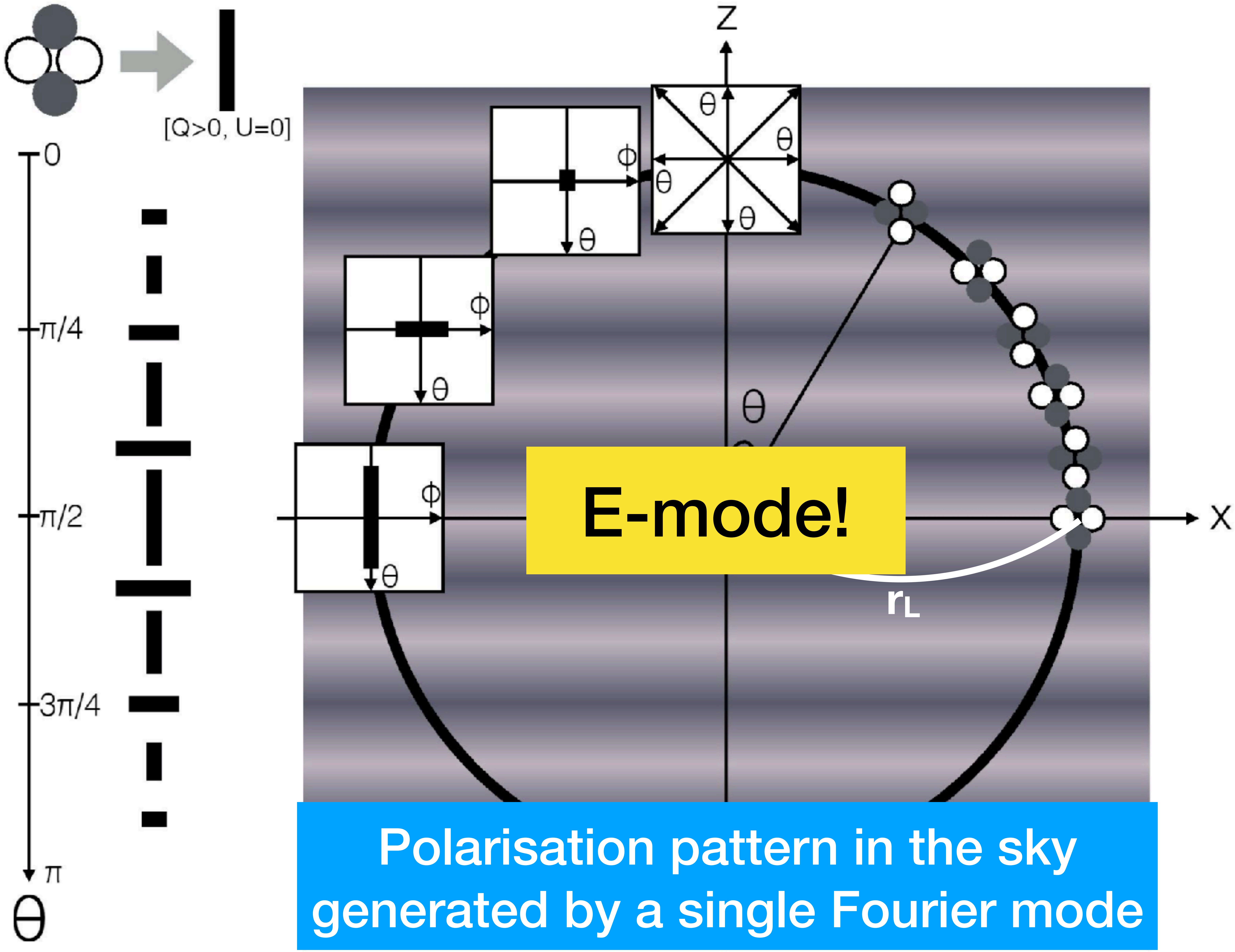


Polarisation pattern you will see



Polarisation pattern in the sky generated by a single Fourier mode



[Q>0, U=0]
0
π/4
π/2
3π/4
π
θ
Z
X
φ
θ
E-mode!
r_L
Polarisation pattern in the sky generated by a single Fourier mode

E-mode Power Spectrum

- Viscosity at the last-scattering surface is given by the **spatial gradient of the velocity**:

$$\Delta T_{ij} = a^2 \partial_i \partial_j \pi_\gamma$$

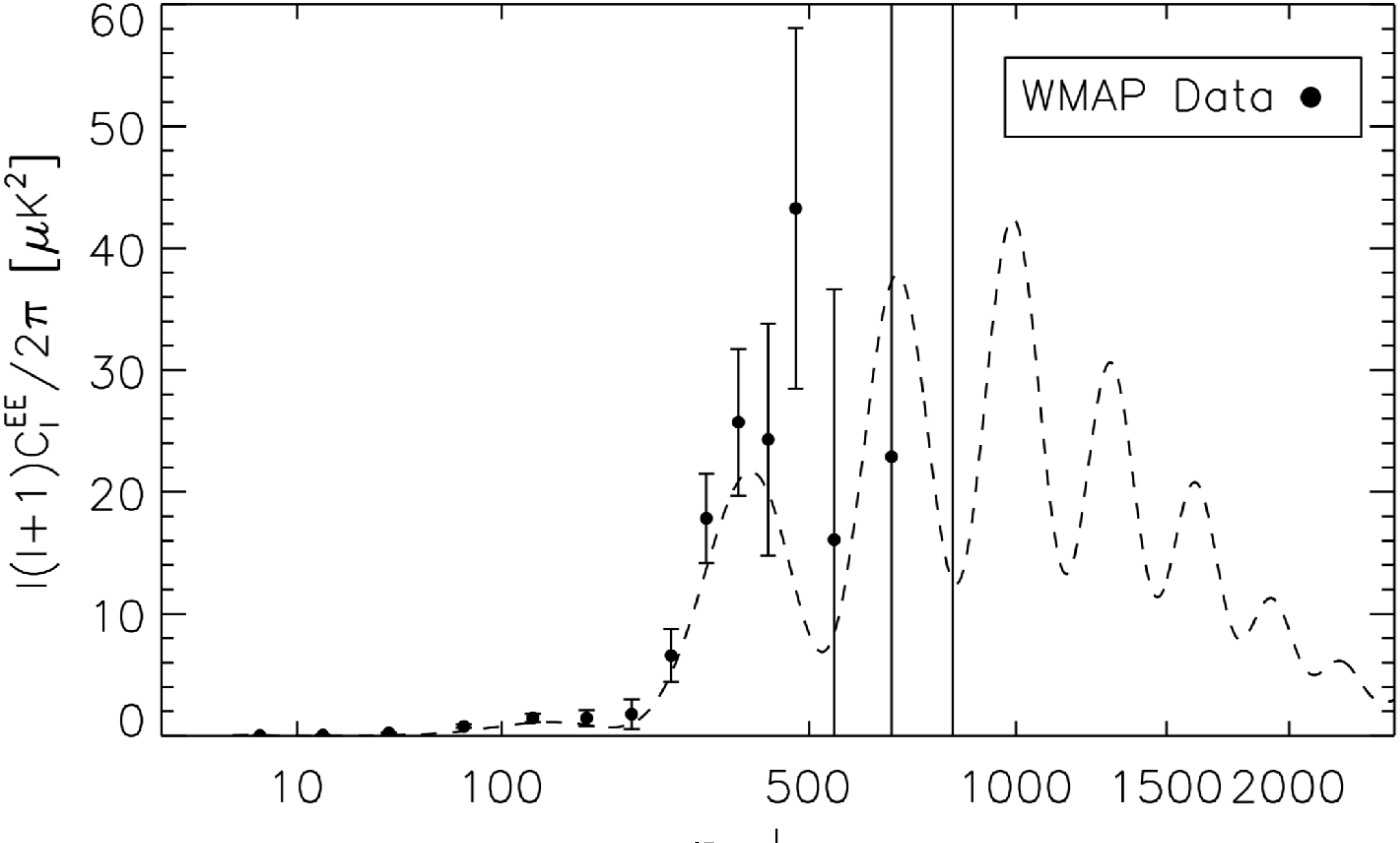
$$= -\frac{32}{45}\frac{\bar{\rho}_\gamma}{\sigma_{\mathcal{T}} \bar{n}_e} \partial_i \partial_j \delta u_\gamma$$

- Using the energy conservation, $\delta u_\gamma = (3a^2/q^2)\partial(\delta\rho_\gamma/4\bar{\rho}_\gamma)/\partial t$

- Velocity potential is $\mathrm{Sin}(qr_L)$, whereas the temperature power spectrum is predominantly $\mathrm{Cos}(qr_L)$

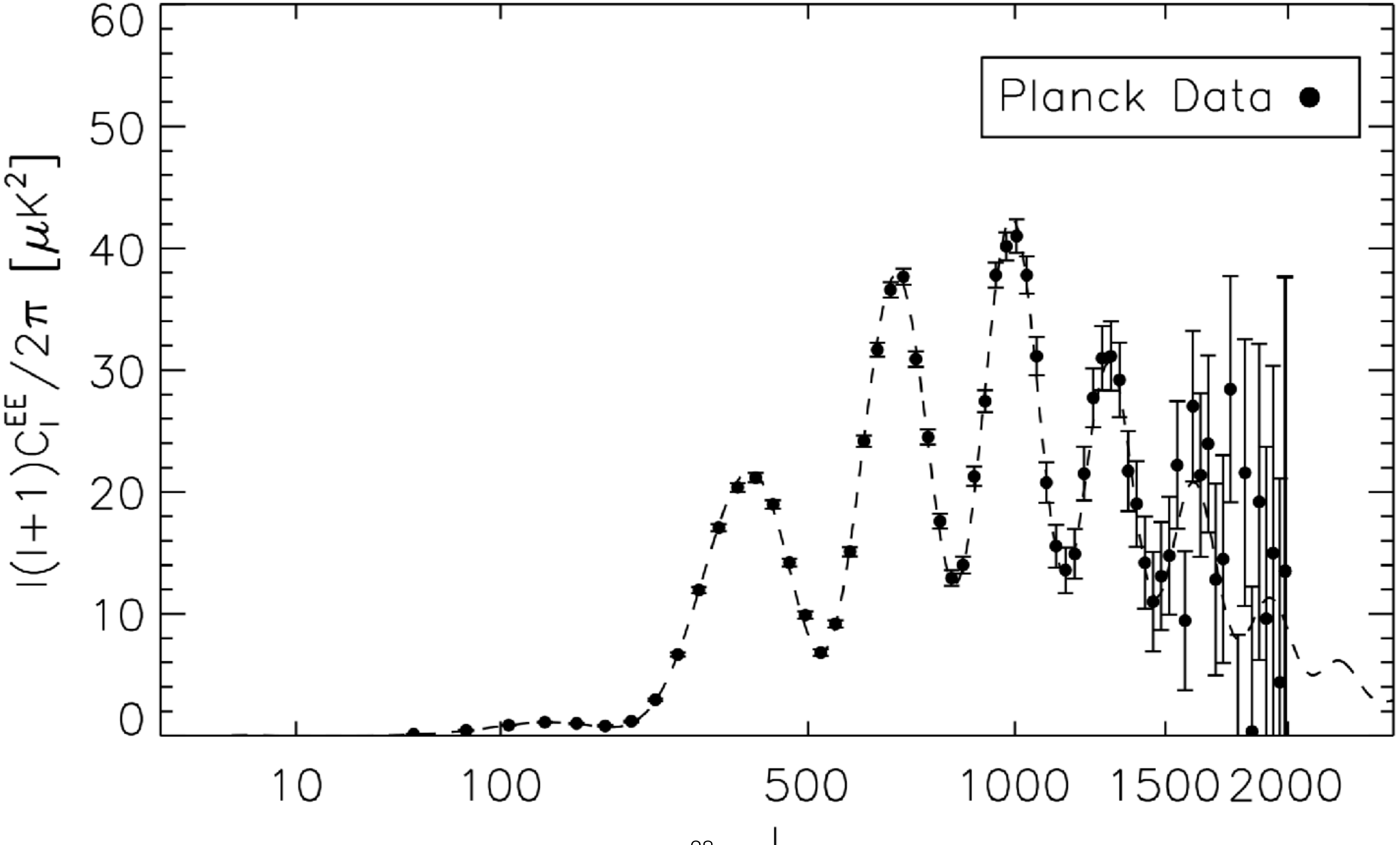
Bennett et al. (2013)

WMAP 9-year Power Spectrum



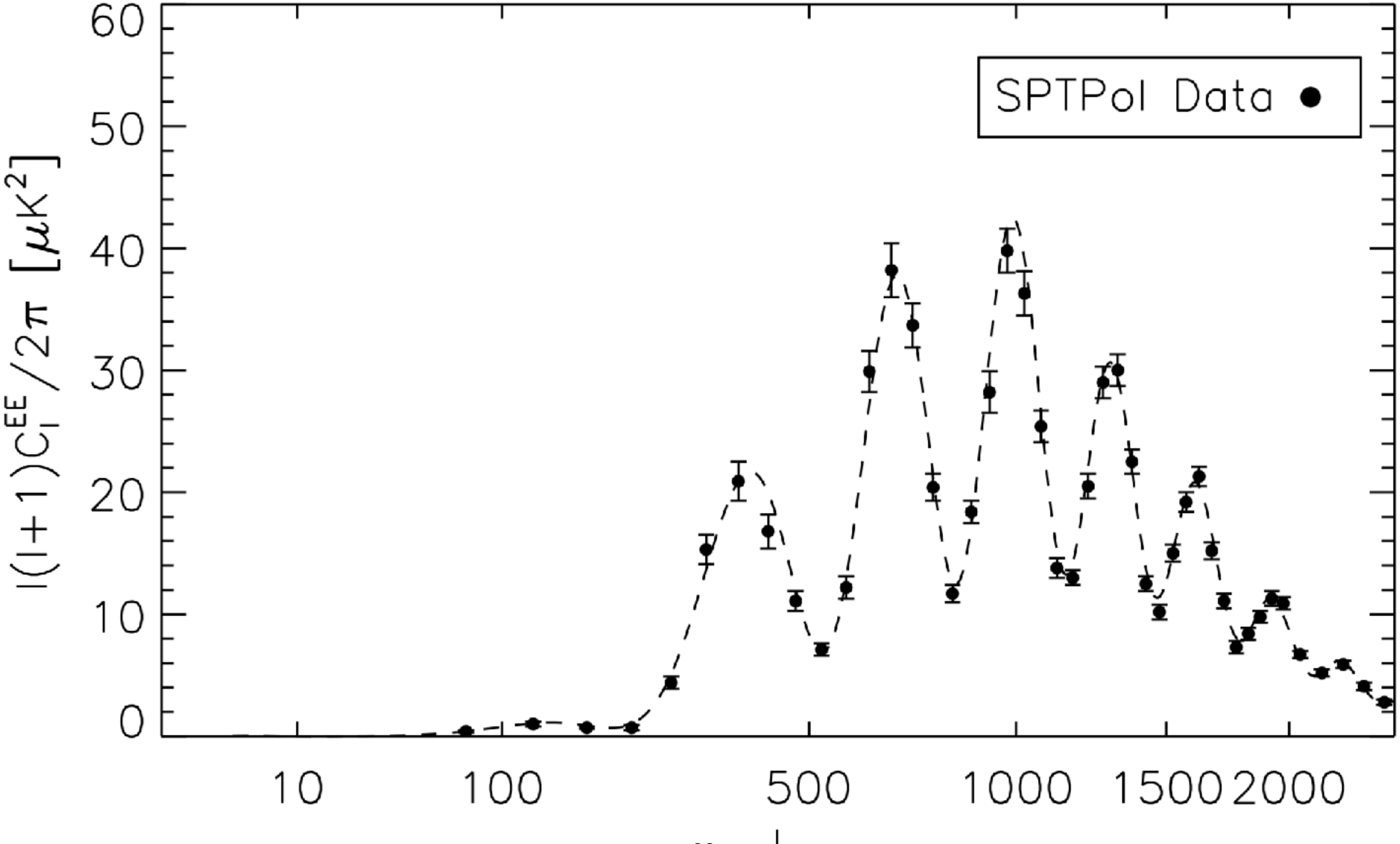
Planck Collaboration (2016)

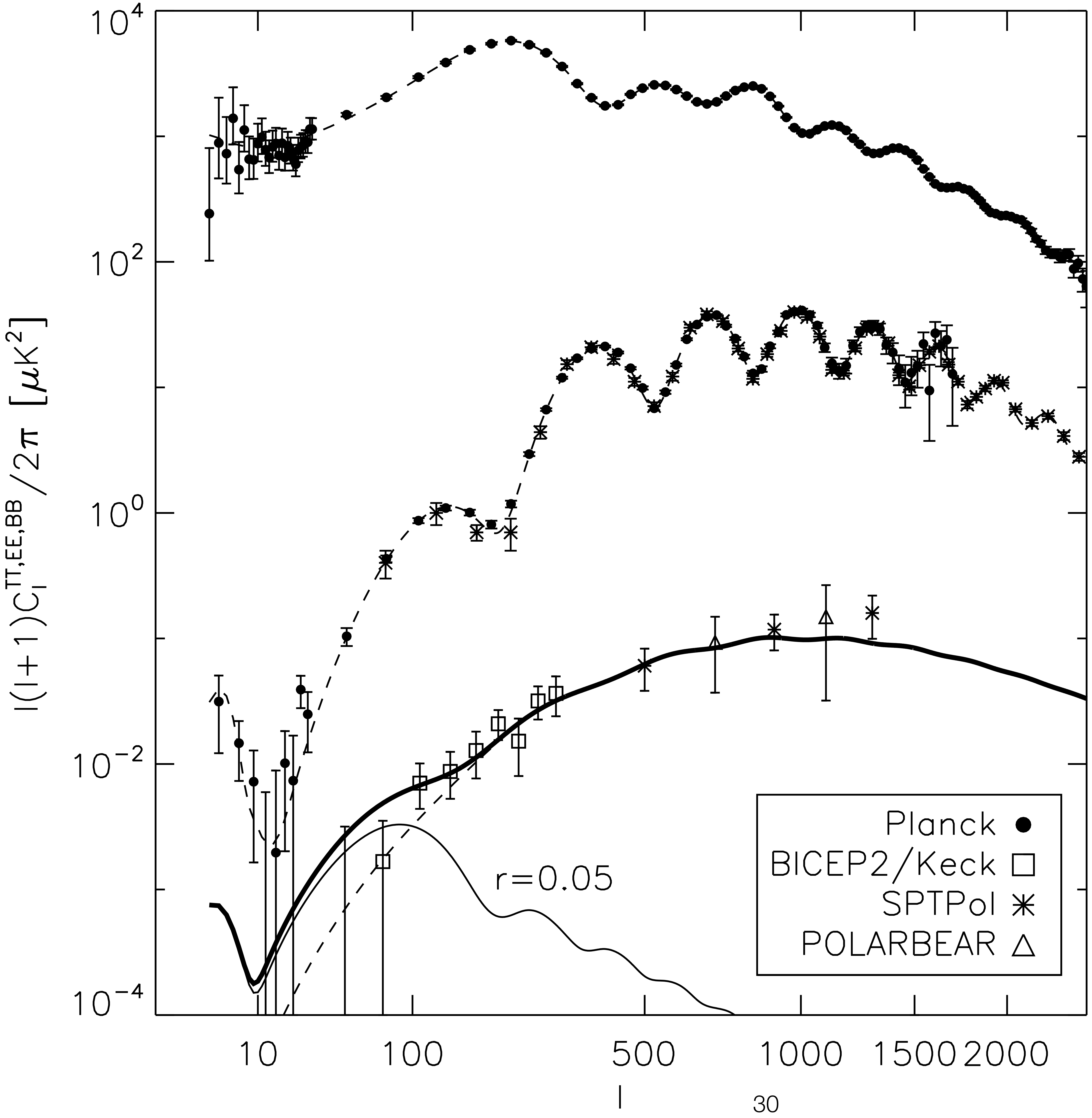
Planck 29-mo Power Spectrum



South Pole Telescope Collaboration (2018)

SPTPol Power Spectrum





[1] Troughs in T
-> Peaks in E

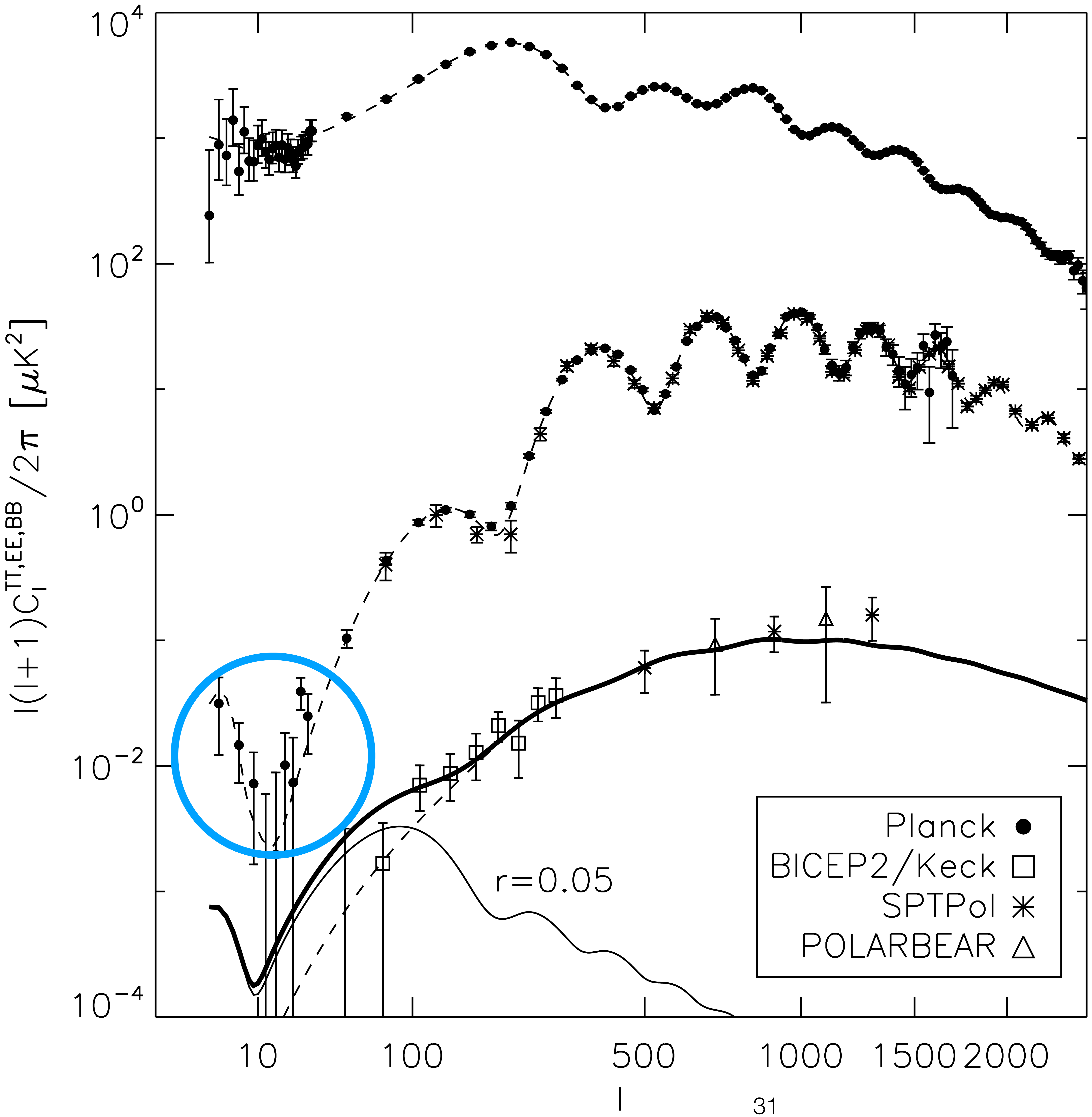
because $C_l^{TT} \sim \cos^2(qr_s)$
whereas $C_l^{EE} \sim \sin^2(qr_s)$

[2] T damps
-> E rises

because
T damps by viscosity,
whereas
E is created by viscosity.

[3] Peaks in E
are sharper

because C_l^{TT} is the sum of $\cos^2(qr_L)$ and the Doppler shift's $\sin^2(qr_L)$, whereas C_l^{EE} is just $\sin^2(qr_L)$



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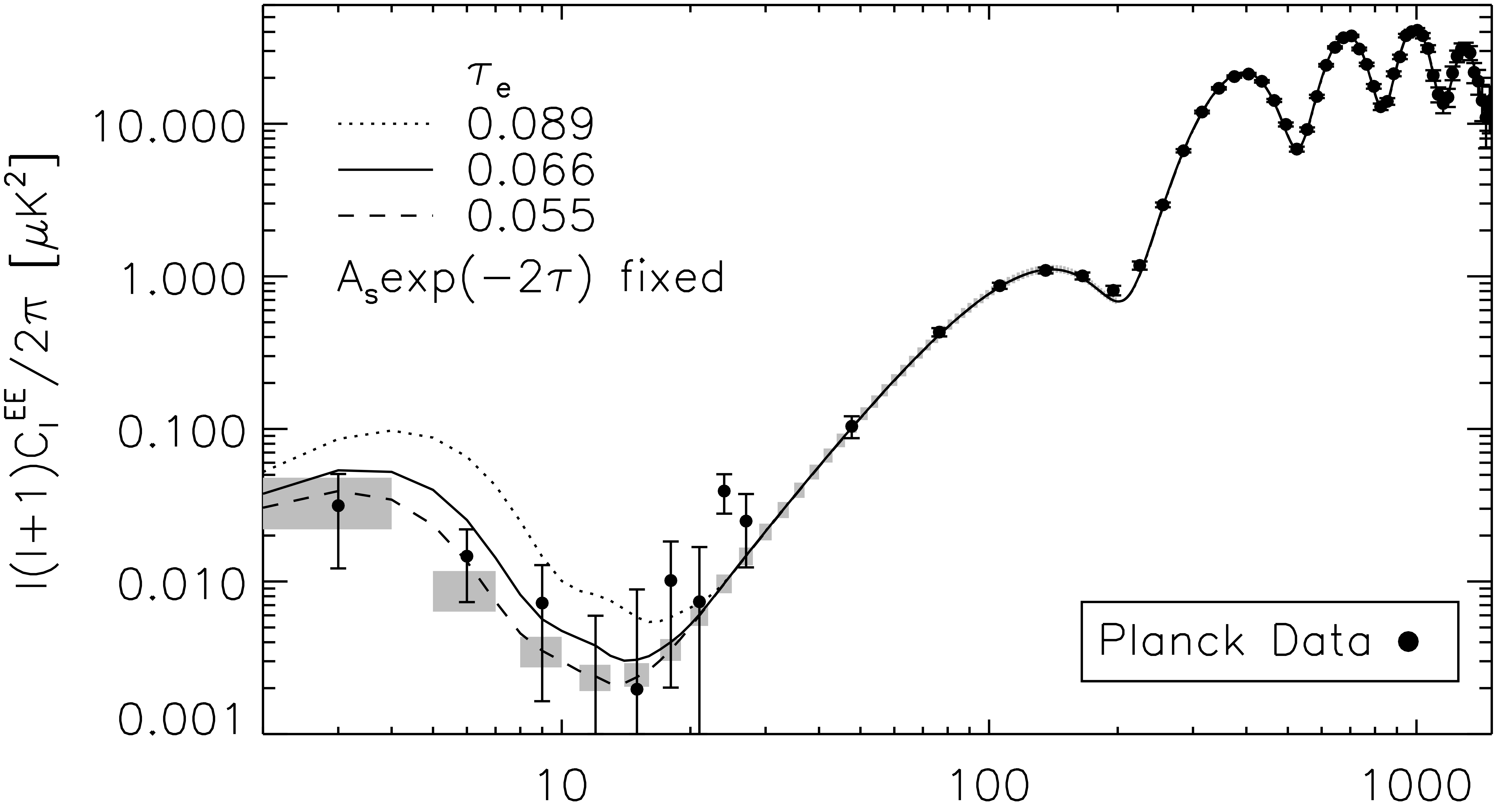
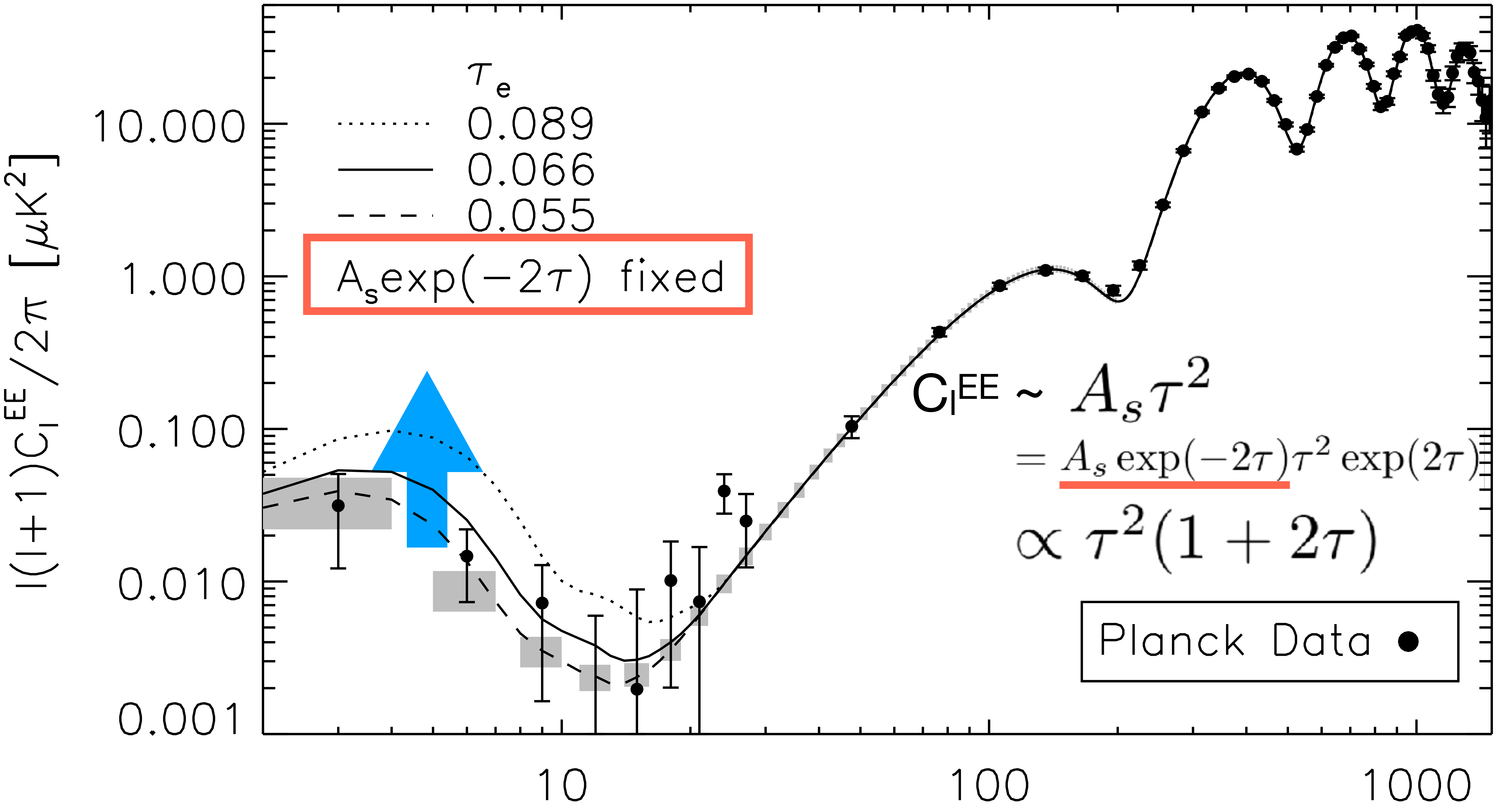
Polarisation from Re-ionisation



Polarisation from Re-ionisation



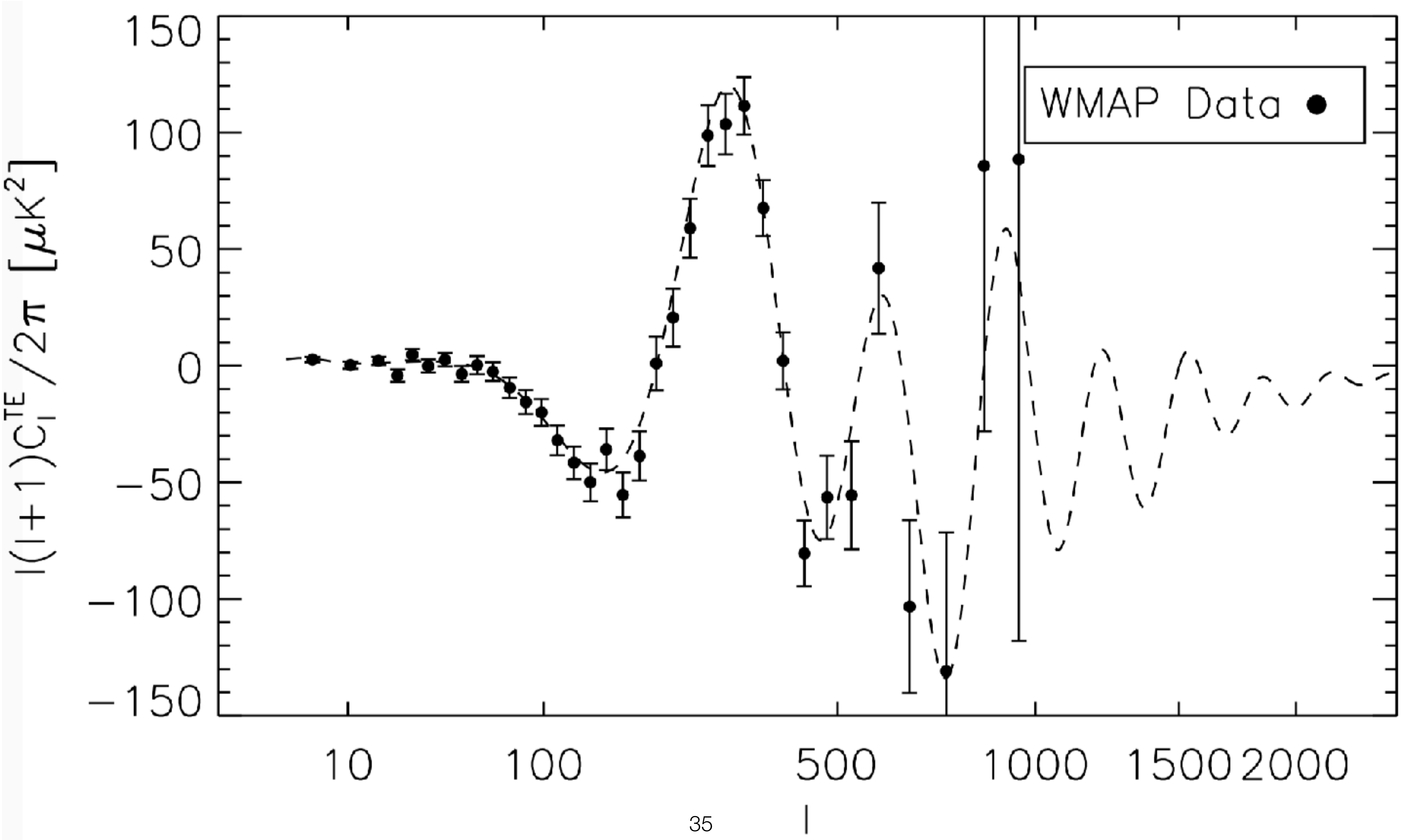
Cross-correlation between T and E

- Velocity potential is $\mathrm{Sin}(qr_L)$, whereas the temperature power spectrum is predominantly $\mathrm{Cos}(qr_L)$

- Thus, the TE correlation is $\mathrm{Sin}(qr_L)\mathrm{Cos}(qr_L)$ which can change sign

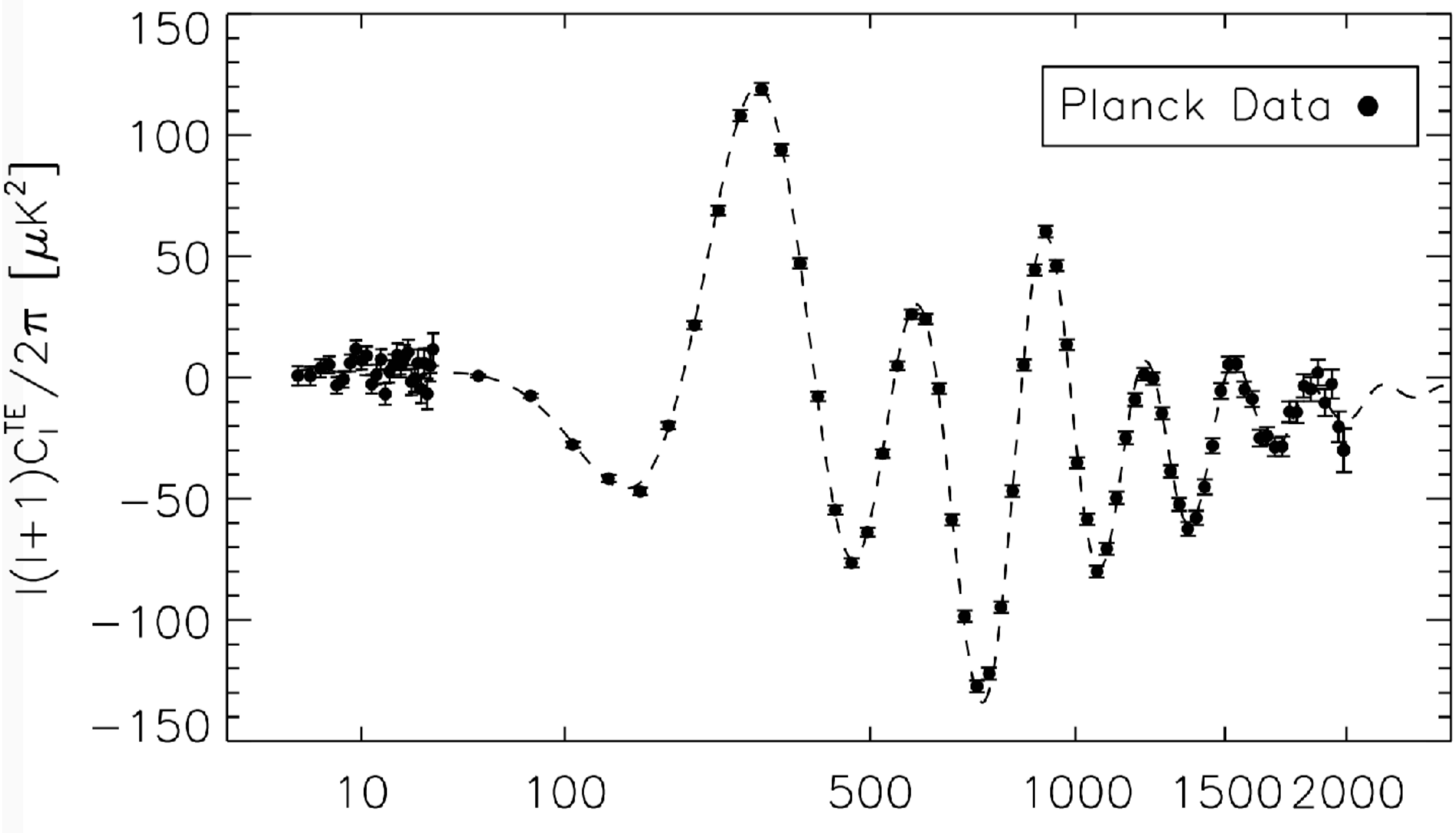
Bennett et al. (2013)

WMAP 9-year Power Spectrum



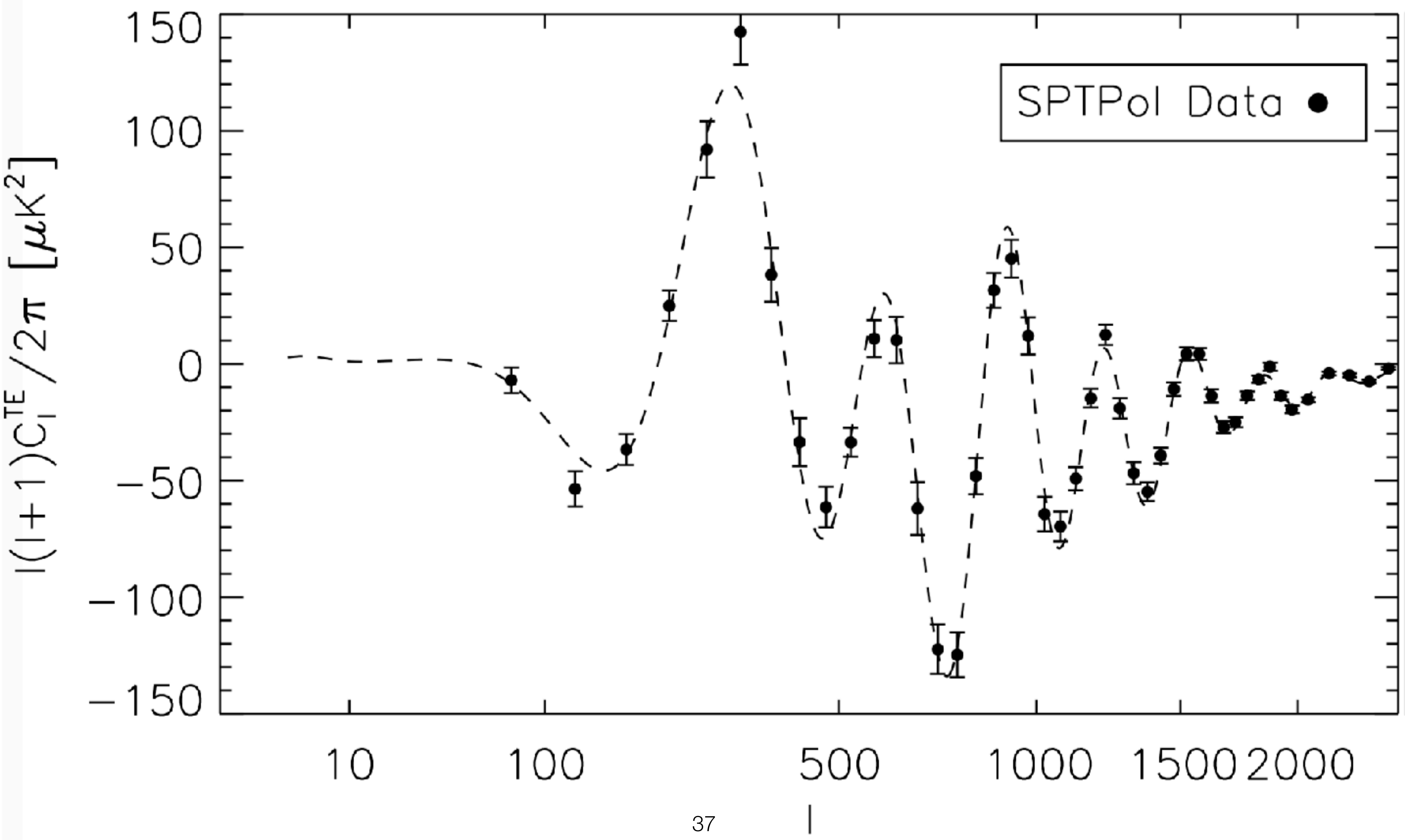
Planck Collaboration (2016)

Planck 29-mo Power Spectrum



South Pole Telescope Collaboration (2018)

SPTPol Power Spectrum



TE correlation is useful for understanding physics

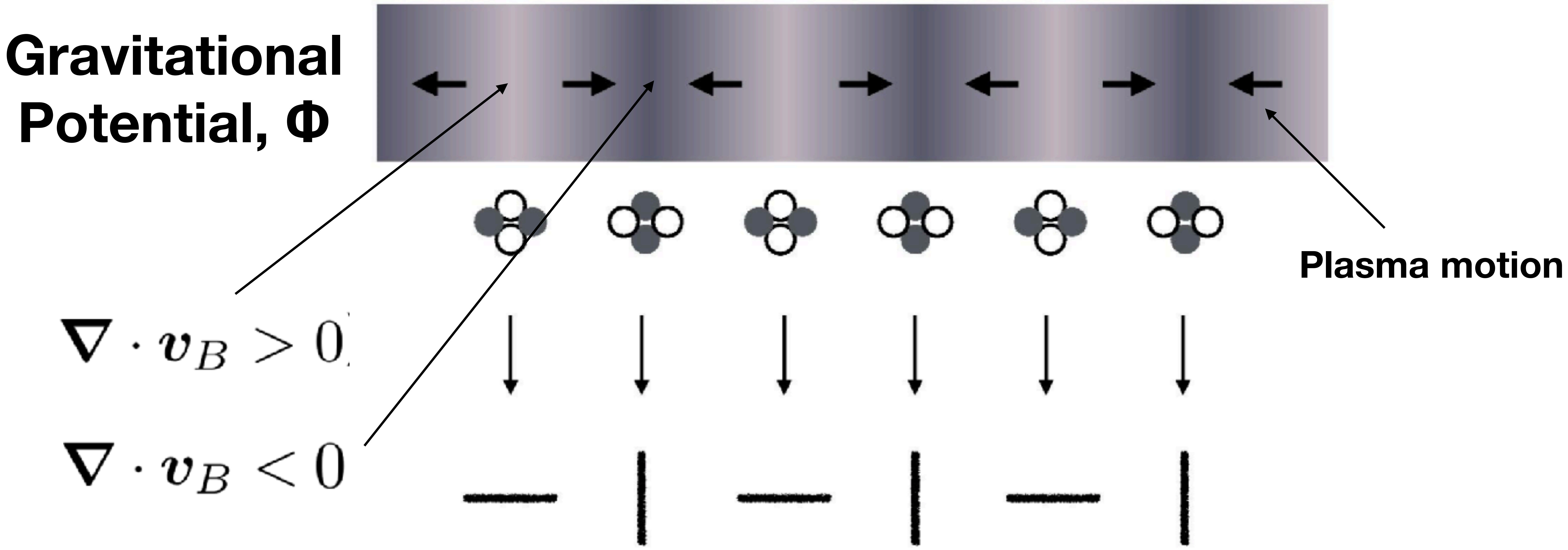
- T roughly traces gravitational potential, while E traces velocity

$$q^2\pi_\gamma \propto -q^2\delta u_\gamma \propto \boldsymbol{\nabla} \cdot \boldsymbol{v}_B$$

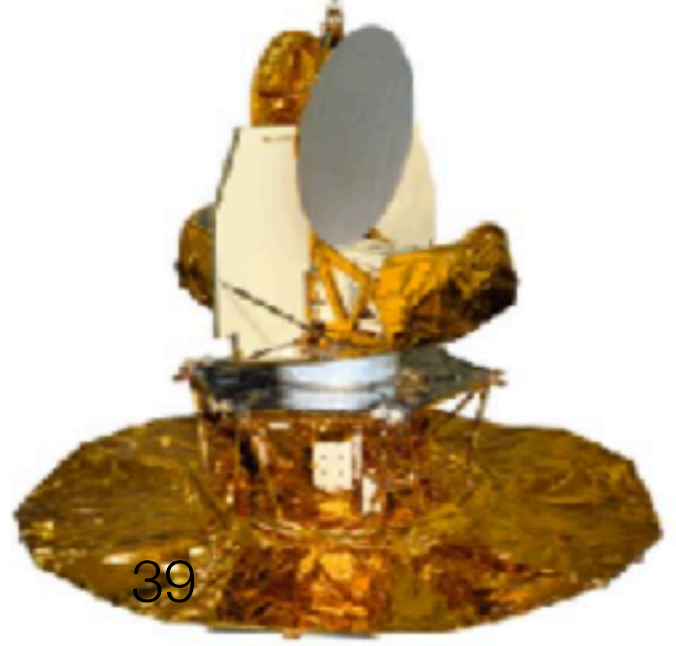
- With TE, we witness how plasma falls into gravitational potential wells!

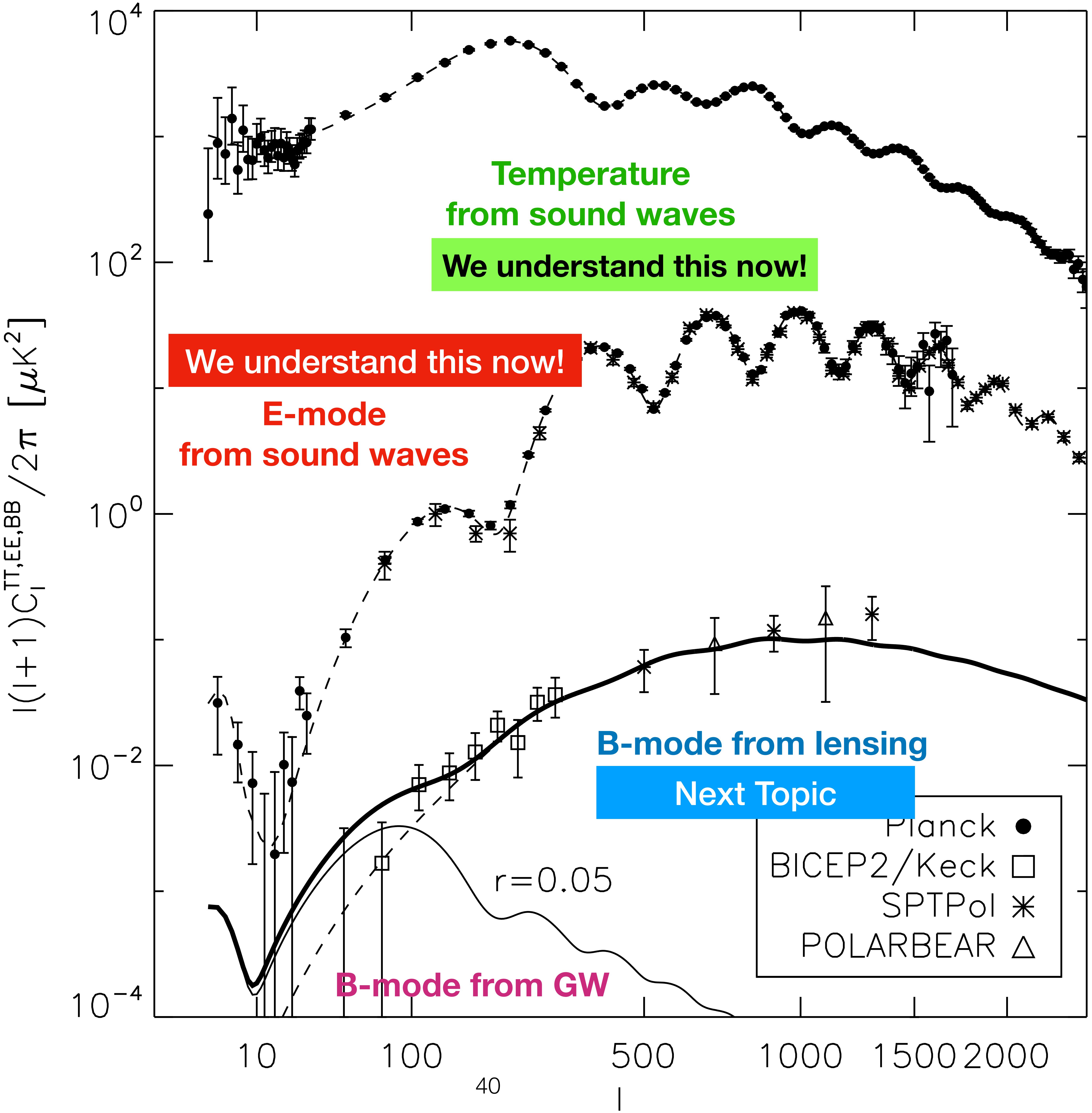
Coulson et al. (1994)

Example: Gravitational Effects



$$q^2 \pi_\gamma \propto -q^2 \delta u_\gamma \propto \nabla \cdot \boldsymbol{v}_B$$





Temperature
from sound waves
We understand this now!
We understand this now!
E-mode
from sound waves
B-mode from lensing
Next Topic
r=0.05
B-mode from GW
Planck
BICEP2/Keck
SPTPol
POLARBEAR
$l(l+1)C_l^{TT,EE,BB}/2\pi\ [\mu K^2]$
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100
500
1000
1500
2000
l

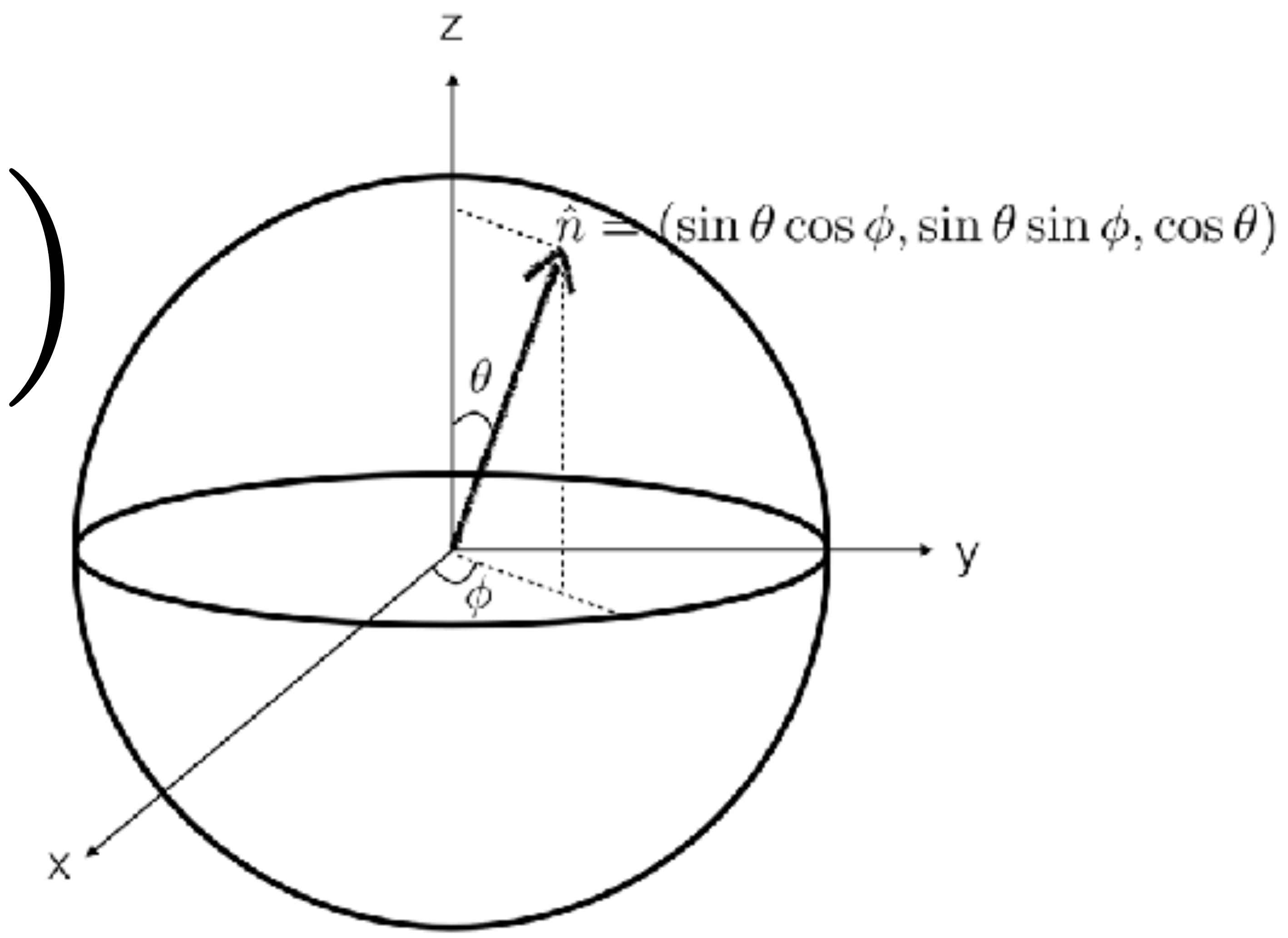
Part III: B-mode from Gravitational Lensing

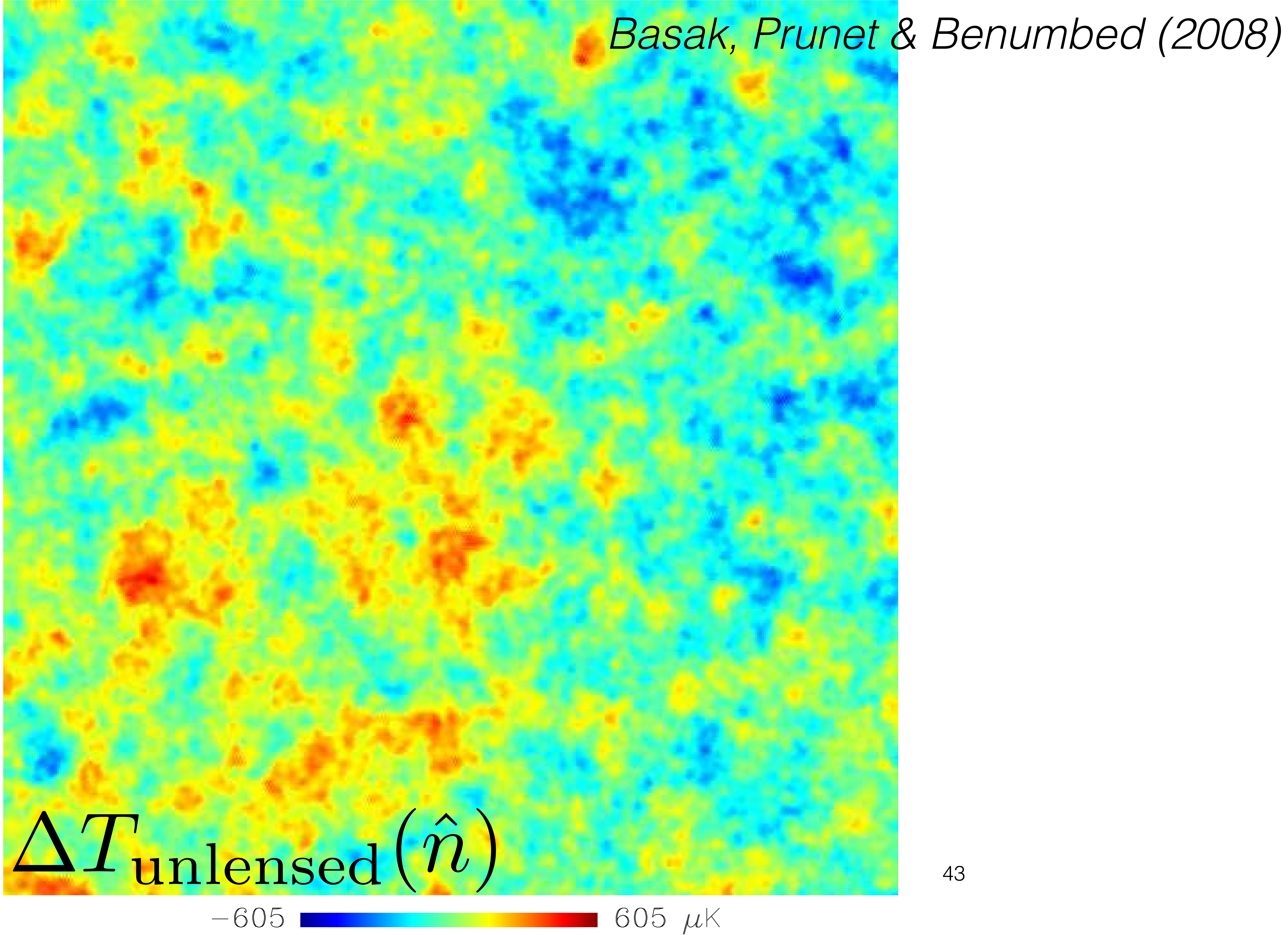
Gravitational lensing effect on the CMB

What does it do to CMB?

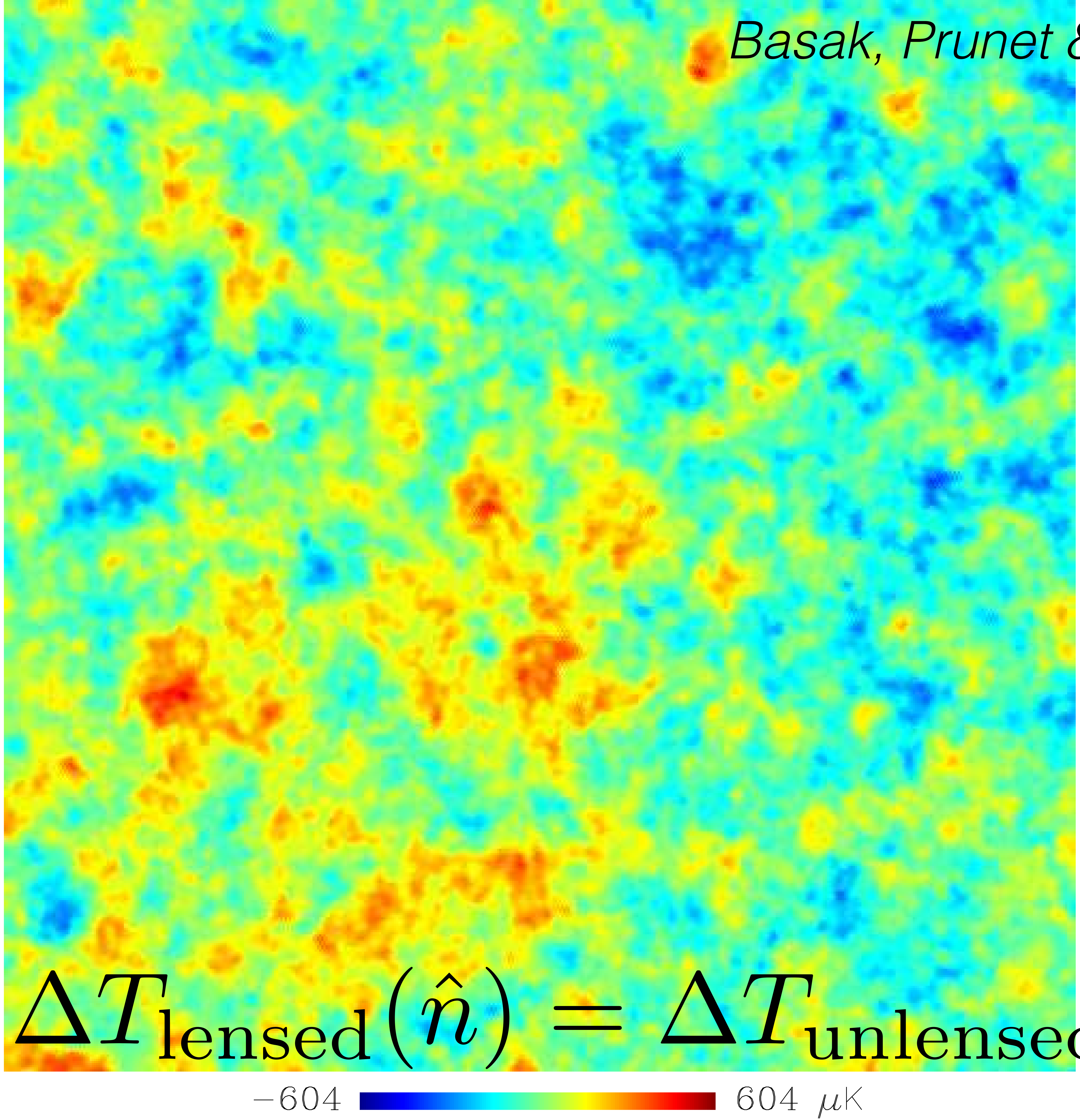
- The important fact: **the gravitational lensing effect does not change the surface brightness**.
- This means that the value of CMB temperature does not change by lensing; only the directions change.
- Only the **anisotropy** (and polarisation) is affected:

$$\Delta T_{\mathrm{lensed}}(\hat{n}) = \Delta T_{\mathrm{unlensed}}(\hat{n} + \mathbf{d})$$




Basak, Prunet & Benumbed (2008)
$\Delta T_{\mathrm{unlensed}}(\hat{n})$
−605
605 μK

Basak, Prunet & Benabed (2008)



$$\Delta T_{\rm lensed}(\hat{n}) = \Delta T_{\rm unlensed}(\hat{n} + \mathbf{d})$$

Gravitational lensing effect on the CMB

Deflection angle and the "lens potential"

$$\Delta T_{\rm lensed}(\hat{n}) = \Delta T_{\rm unlensed}(\hat{n} + \mathbf{d})$$

- The vector "**d**" is called the *deflection angle*. For the scalar perturbation, we can write **d** as a gradient of a scalar potential (like the electric field): $\mathbf{d} = \dfrac{\partial \psi}{\partial \hat{n}}$

  with

$$\psi(\hat{n}) = -\int_0^{r_L} dr \; \frac{r_L - r}{r_L r}(\Phi + \Psi)(r, \hat{n}r)$$

r_L: the comoving distance from the observer to the last scattering surface

E->B conversion due to lensing

“Mode Coupling”: Mixing of <u>different</u> Fourier wavenumbers

- In the flat-sky approximation, lensing affects the Stokes parameters as

$$(\tilde{Q} \pm i\tilde{U})(\boldsymbol{\theta}) = (Q \pm iU)(\boldsymbol{\theta} + \boldsymbol{d})$$

- Fourier-transforming both sides, we find

$$\tilde{E}_{\boldsymbol{\ell}} \pm i\tilde{B}_{\boldsymbol{\ell}} = \exp(\mp 2i\phi_{\ell}) \int d^2\theta \ \exp(-i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

$$\times \int \frac{d^2\ell'}{(2\pi)^2} \left(E_{\boldsymbol{\ell}'} \pm iB_{\boldsymbol{\ell}'}\right) \exp[\pm 2i\phi_{\ell'} + i\boldsymbol{\ell}'\cdot(\boldsymbol{\theta} + \boldsymbol{\nabla}\psi)]$$

Taylor-expand this

E->B conversion due to lensing

“Mode Coupling”: Mixing of different Fourier wavenumbers

- In the flat-sky approximation, lensing affects the Stokes parameters as

$$(\tilde{Q} \pm i\tilde{U})(\boldsymbol{\theta}) = (Q \pm iU)(\boldsymbol{\theta} + \boldsymbol{d})$$

- Fourier-transforming both sides, we find

$$\tilde{E}_{\boldsymbol{\ell}} \pm i\tilde{B}_{\boldsymbol{\ell}} = E_{\boldsymbol{\ell}} \pm iB_{\boldsymbol{\ell}} + \int \frac{d^2\ell'}{(2\pi)^2}\, \boldsymbol{\ell}' \cdot (\boldsymbol{\ell}' - \boldsymbol{\ell})(E_{\boldsymbol{\ell}'} \pm iB_{\boldsymbol{\ell}'})\psi_{\boldsymbol{\ell}-\boldsymbol{\ell}'} \exp[\pm 2i(\phi_{\ell'} - \phi_{\ell})]$$

Mode mixing!

E->B conversion due to lensing

“Mode Coupling”: Mixing of different Fourier wavenumbers

- The final results:

$$\tilde{E}_{\boldsymbol{\ell}} = E_{\boldsymbol{\ell}} + \int \frac{d^2\ell'}{(2\pi)^2}\, \boldsymbol{\ell}' \cdot (\boldsymbol{\ell}' - \boldsymbol{\ell})\psi_{\boldsymbol{\ell}-\boldsymbol{\ell}'}$$

$$\times \left\{ E_{\boldsymbol{\ell}'} \cos[2(\phi_{\ell'} - \phi_{\ell})] - B_{\boldsymbol{\ell}'} \sin[2(\phi_{\ell'} - \phi_{\ell})] \right\}$$

$$\tilde{B}_{\boldsymbol{\ell}} = B_{\boldsymbol{\ell}} + \int \frac{d^2\ell'}{(2\pi)^2}\, \boldsymbol{\ell}' \cdot (\boldsymbol{\ell}' - \boldsymbol{\ell})\psi_{\boldsymbol{\ell}-\boldsymbol{\ell}'}$$

$$\times \left\{ B_{\boldsymbol{\ell}'} \cos[2(\phi_{\ell'} - \phi_{\ell})] + E_{\boldsymbol{\ell}'} \sin[2(\phi_{\ell'} - \phi_{\ell})] \right\}$$

E->B conversion due to lensing

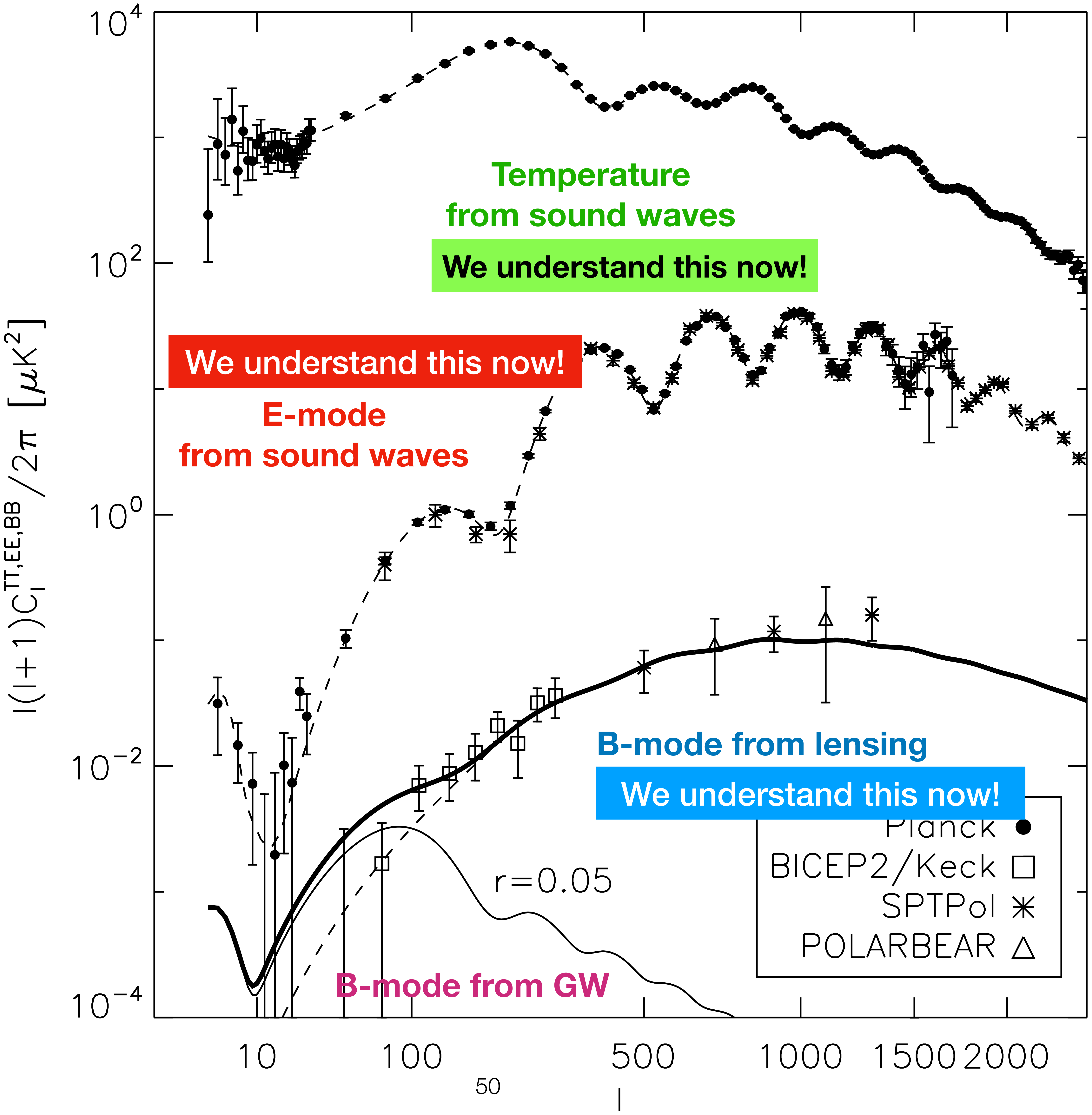
“Mode Coupling”: Mixing of different Fourier wavenumbers

- Even if there was no intrinsic B-mode polarisation at the last scattering surface:

$$\tilde{B}_{\boldsymbol{\ell}} = (2\pi)^{-2} \int d^2\ell' \ \boldsymbol{\ell}' \cdot (\boldsymbol{\ell}' - \boldsymbol{\ell}) \psi_{\boldsymbol{\ell}-\boldsymbol{\ell}'} E_{\boldsymbol{\ell}'} \sin[2(\phi_{\ell'} - \phi_{\ell})]$$

- Important: There is no monopole (l=0) for the lensing potential. **This means that E and B cannot be correlated at the same multipole: lensing does not violate parity globally.**

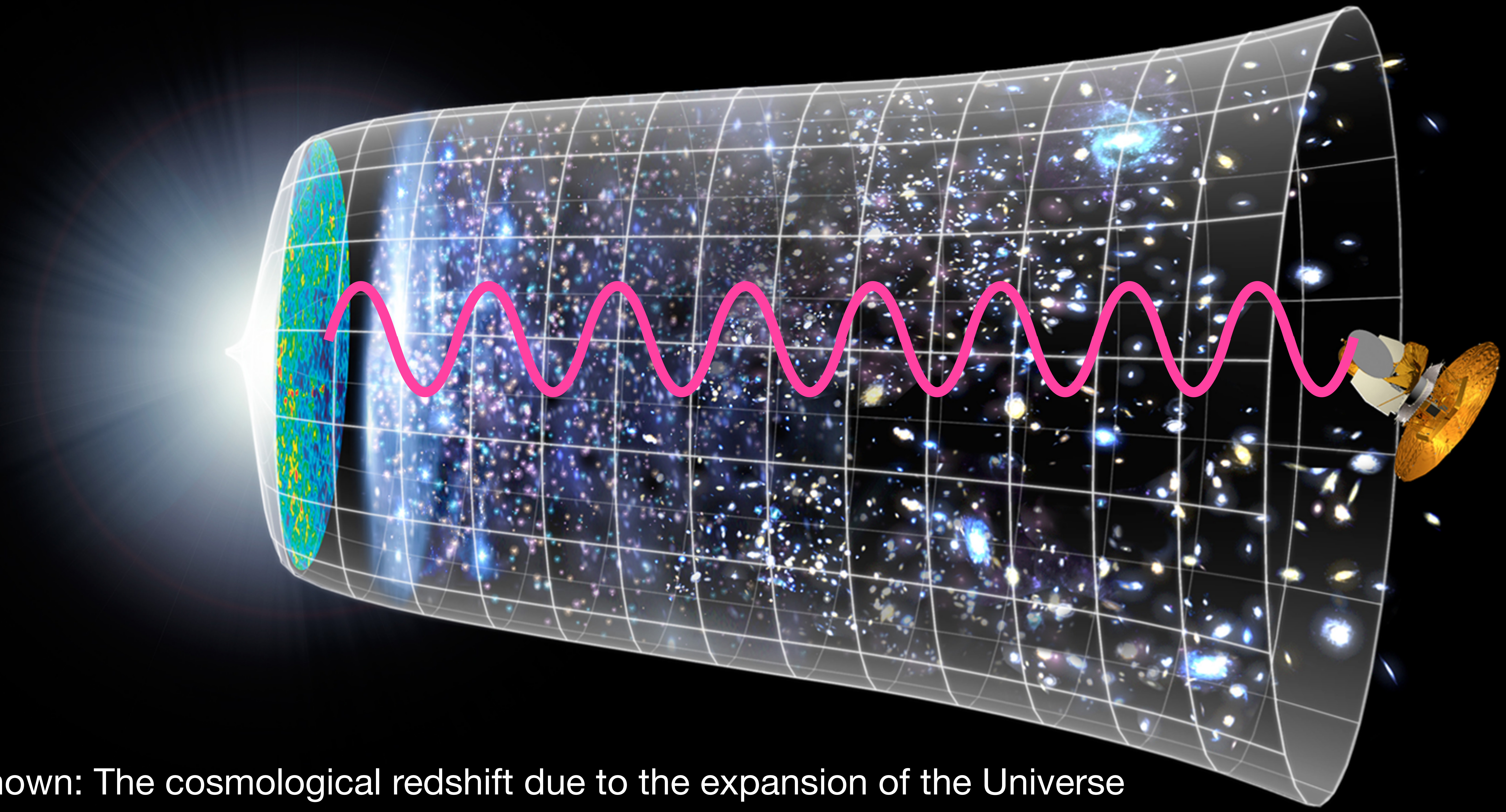
- The lensing effect is the convolution. As the lensing potential is “smooth” and does not contain the acoustic oscillation, convolution will smear out the acoustic oscillation in the E-mode polarisation.



Temperature
from sound waves
We understand this now!
We understand this now!
E-mode
from sound waves
B-mode from lensing
We understand this now!
r=0.05
B-mode from GW
Planck
BICEP2/Keck
SPTPol
POLARBEAR
$l(l+1)C_l^{TT,EE,BB}/2\pi$ [μK^2]
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100
500
1000
1500
2000
l

Part IV: EB Correlation: The Cosmic Birefringence

How does the electromagnetic wave of the CMB reach us?



Now shown: The cosmological redshift due to the expansion of the Universe

How does the electromagnetic wave of the CMB reach us?

Note: rotation of the polarisation plane is massively exaggerated!

Cosmic Birefringence

The Universe filled with a "birefringent material"

- If the Universe is filled with a pseudo-scalar field (e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta} \frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}} F_{\alpha\beta}$$

where g_a is a coupling constant of the order α, and the vacuum angle $\theta = \phi_a / f_a$ (ϕ_a = axion field). The equations

$$\sum_{\mu\nu} F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E})$$ **Parity Even**

$$\sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$ **Parity Odd**

- The axion field, θ, is a "pseudo scalar", which is parity odd; thus, the last term in Eq.3.7 is parity even as a whole.

Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998)

Cosmic Birefringence

The Universe filled with a “birefringent material”

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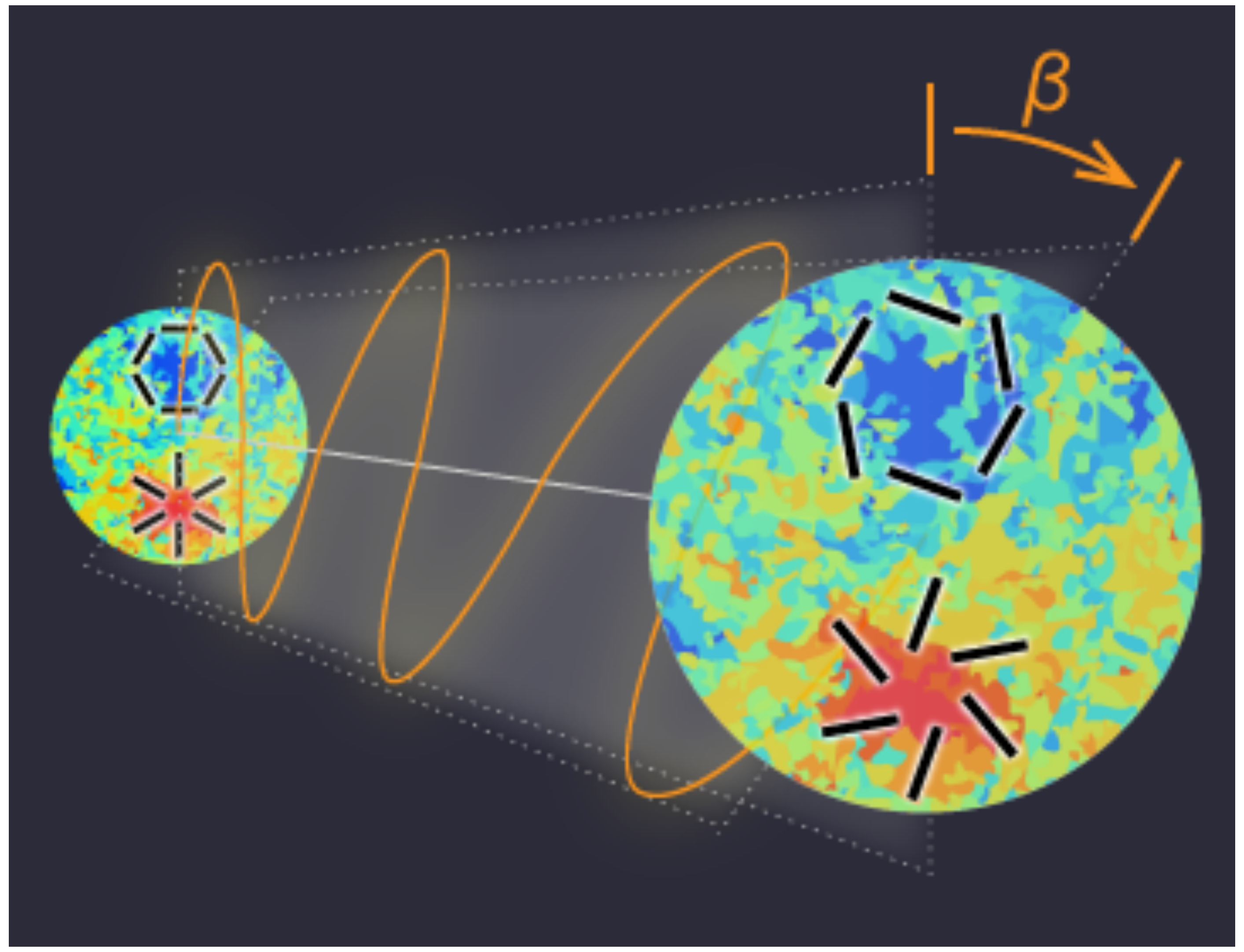


The “Cosmic Birefringence” (Carroll 1998)

This term makes the phase velocities of right- and left-handed polarisation states of photons different, leading to **rotation of the linear polarisation direction.**

Cosmic Birefringence

The effect accumulates over the distance

- If the Universe is filled with a pseudo-scalar field (e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

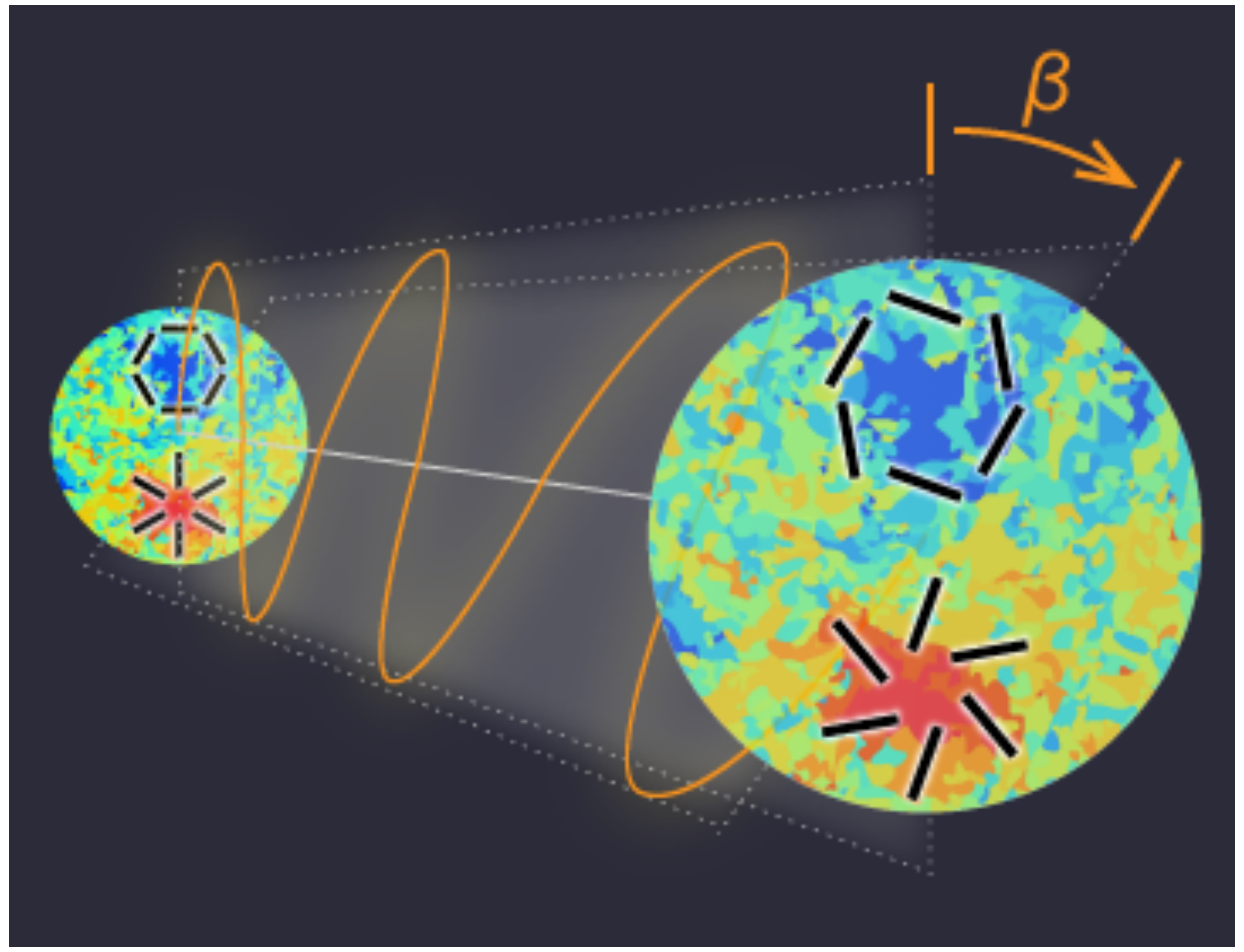
Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}, \qquad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta} \frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}} F_{\alpha\beta}$$

where g_a is a coupling constant of the order α, and the vacuum angle $\theta = \phi_a / f_a$ (ϕ_a = axion field). The equations

$$\beta = 2g_a \int_{t_{\rm emission}}^{t_{\rm observed}} dt\ \dot{\theta}$$



The larger the distance the photon travels, the larger the effect becomes.

Motivation

Why study the cosmic birefringence?

- The Universe’s energy budget is dominated by two dark components:
    - Dark Matter
    - Dark Energy
- Either or both of these can be an axion-like field!
    - See Marsh (2016) and Ferreira (2020) for reviews.
- Thus, detection of parity-violating physics in polarisation of the cosmic microwave background can transform our understanding of Dark Matter/ Energy.

(Simpler) Motivation

Why study the cosmic birefringence?

- We know that the weak interaction violates parity (Lee & Yang 1956; Wu et al. 1957).
  - Why should the laws of physics governing the Universe conserve parity?
- Let’s look!

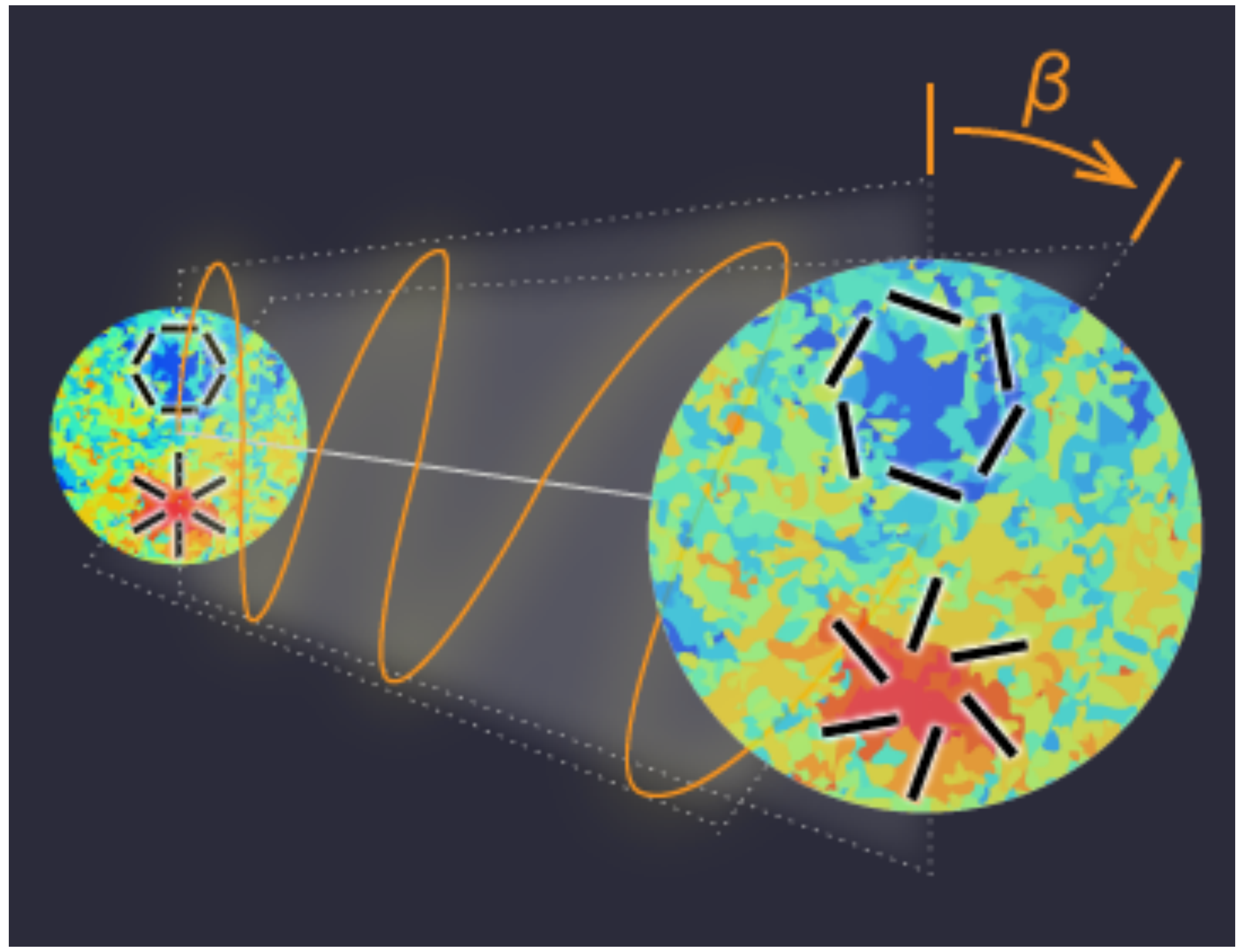
Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)

EB correlation from the cosmic birefringence

E <-> B conversion by rotation of the linear polarisation plane

- The intrinsic EE, BB, and EB power spectra 13.8 billion years ago would yield the observed EB as

$$C_\ell^{EB,\mathrm{obs}} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

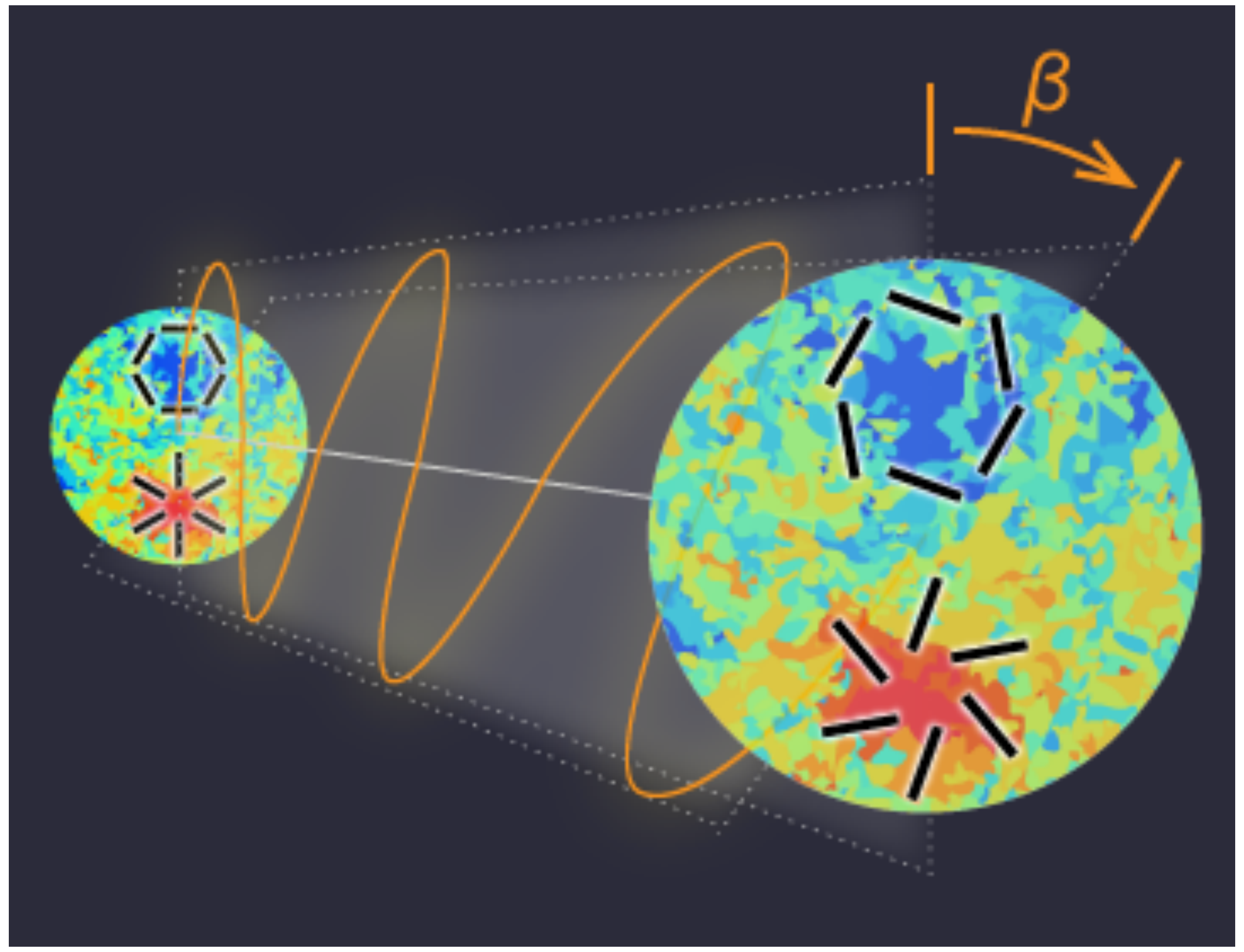


- **How do we infer β from the observational data?**

- Traditionally, one would find β by fitting $C_l^{EE,CMB} - C_l^{BB,CMB}$ to the observed $C_l^{EB,obs}$ using the best-fitting CMB model, and assuming the intrinsic EB to vanish, $C_l^{EB}=0$.

Searching for the birefringence

Improvement #1 (Zhao et al. 2015)



- If we look at how EE and BB spectra are also modified,

$$C_\ell^{EE,\mathrm{obs}} = C_\ell^{EE}\cos^2(2\beta) + C_\ell^{BB}\sin^2(2\beta) - C_\ell^{EB}\sin(4\beta)$$

$$C_\ell^{BB,\mathrm{obs}} = C_\ell^{EE}\sin^2(2\beta) + C_\ell^{BB}\cos^2(2\beta) + C_\ell^{EB}\sin(4\beta)$$

- We find

$$C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}} = (C_\ell^{EE} - C_\ell^{BB})\cos(4\beta) - 2C_\ell^{EB}\sin(4\beta)$$

- Thus,

$$C_\ell^{EB,\mathrm{obs}} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

$$= \frac{1}{2}\boxed{(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}})}\tan(4\beta) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

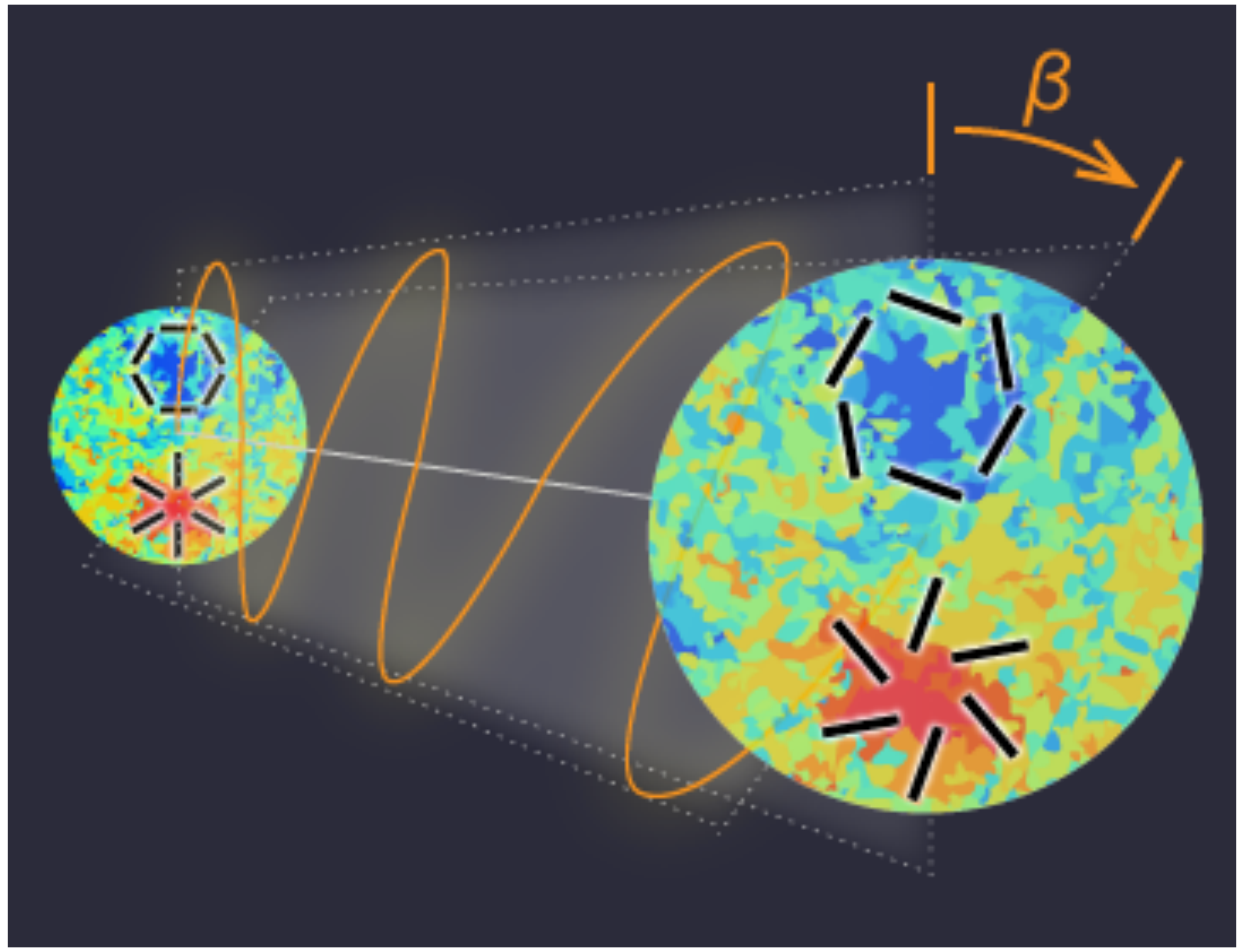
No need to assume a model

The Biggest Problem: Miscalibration of detectors

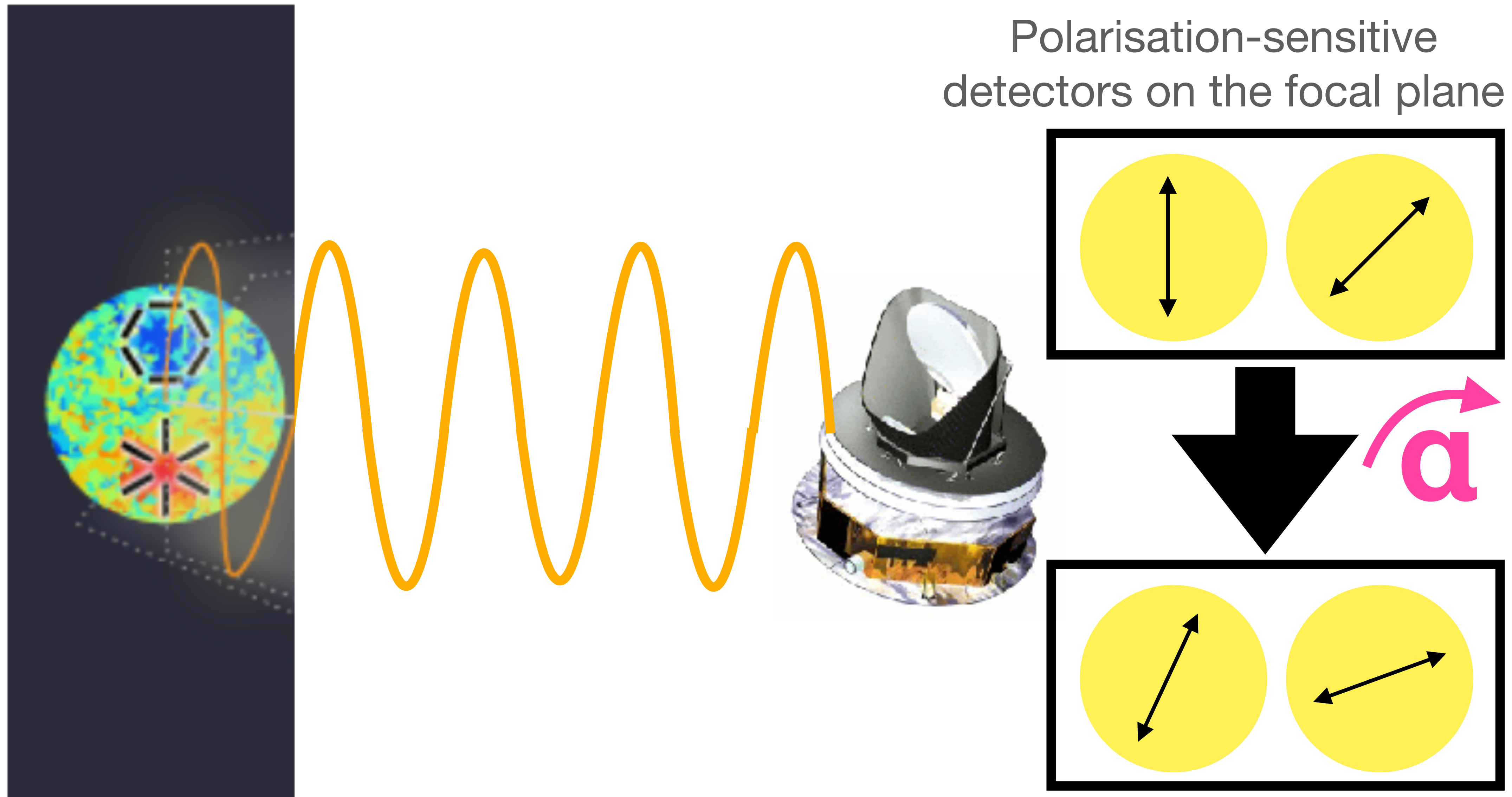
Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

Impact of miscalibration of polarisation angles

Cosmic or Instrumental?



OR



- Is the plane of linear polarisation rotated by the genuine cosmic birefringence effect, or simply because the polarisation-sensitive directions of detectors are rotated with respect to the sky coordinates (and we did not know it)?

- If the detectors are rotated by α, it seems that we can measure only the **sum α+β**.

The past measurements

The quoted uncertainties are all statistical only (68%CL)

- $\alpha+\beta = -6.0 \pm 4.0$ deg (Feng et al. 2006) first measurement
- $\alpha+\beta = -1.1 \pm 1.4$ deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- $\alpha+\beta = 0.55 \pm 0.82$ deg (QUaD Collaboration, Wu et al. 2009)
- …
- $\alpha+\beta = 0.31 \pm 0.05$ deg (Planck Collaboration 2016)
- $\alpha+\beta = -0.61 \pm 0.22$ deg (POLARBEAR Collaboration 2020)
- $\alpha+\beta = 0.63 \pm 0.04$ deg (SPT Collaboration, Bianchini et al. 2020)
- $\alpha+\beta = 0.12 \pm 0.06$ deg (ACT Collaboration, Namikawa et al. 2020)
- $\alpha+\beta = 0.09 \pm 0.09$ deg (ACT Collaboration, Choi et al. 2020)

Why not yet discovered?

The past measurements

Now including the estimated systematic errors on α

- β = –6.0 ± 4.0 ± **??** deg (Feng et al. 2006)
- β = –1.1 ± 1.4 ± **1.5** deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- β = 0.55 ± 0.82 ± **0.5** deg (QUaD Collaboration, Wu et al. 2009)
- …
- β = 0.31 ± 0.05 ± **0.28** deg (Planck Collaboration 2016)
- β = –0.61 ± 0.22 ± **??** deg (POLARBEAR Collaboration 2020)
- β = 0.63 ± 0.04 ± **??** deg (SPT Collaboration, Bianchini et al. 2020)
- β = 0.12 ± 0.06 ± **??** deg (ACT Collaboration, Namikawa et al. 2020)
- β = 0.09 ± 0.09 ± **??** deg (ACT Collaboration, Choi et al. 2020)

Uncertainty in the calibration of α has been the major limitation

The Key Idea: The polarised Galactic foreground emission as a calibrator


ESA's Planck

Credit: ESA

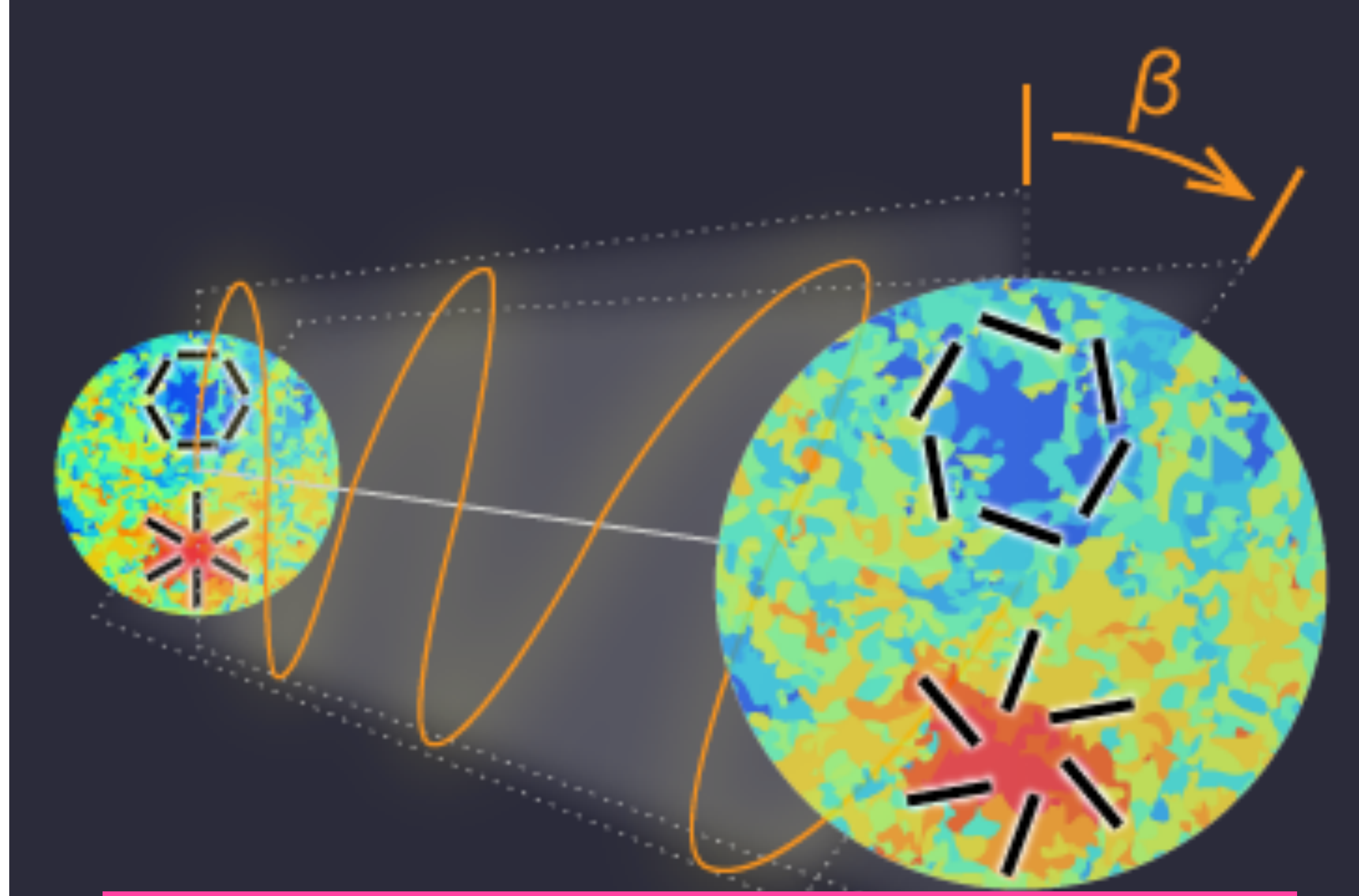
Polarised dust emission within our Milky Way!

Emitted "right there" - it would not be affected by the cosmic birefringence.

Directions of the magnetic field inferred from polarisation of the thermal dust emission in the Milky Way

Searching for the birefringence

Improvement #2 (Minami et al. 2019)



But the source of foreground is much closer!

- **<u>Idea:</u>** *Miscalibration of the polarization angle α rotates both the foreground and CMB, but β affects only the CMB.*

$$E^{\mathrm{o}}_{\ell,m} = E^{\mathrm{fg}}_{\ell,m}\cos(2\alpha) - B^{\mathrm{fg}}_{\ell,m}\sin(2\alpha) + E^{\mathrm{CMB}}_{\ell,m}\cos(2\alpha+2\beta) - B^{\mathrm{CMB}}_{\ell,m}\sin(2\alpha+2\beta) + E^{\mathrm{N}}_{\ell,m}$$

$$B^{\mathrm{o}}_{\ell,m} = E^{\mathrm{fg}}_{\ell,m}\sin(2\alpha) + B^{\mathrm{fg}}_{\ell,m}\cos(2\alpha) + E^{\mathrm{CMB}}_{\ell,m}\sin(2\alpha+2\beta) + B^{\mathrm{CMB}}_{\ell,m}\cos(2\alpha+2\beta) + B^{\mathrm{N}}_{\ell,m}$$

noise

- Thus,

$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)$$

measured — known accurately

$$+ \frac{1}{\cos(4\alpha)}\langle C_\ell^{EB,\mathrm{fg}}\rangle + \frac{\cos(4\beta)}{\cos(4\alpha)}\langle C_\ell^{EB,\mathrm{CMB}}\rangle\,.$$

Key: No explicit modelling of the foreground EE and BB is necessary

Assumption for the baseline result

What about the intrinsic EB correlation of the foreground emission?

$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)$$
$$+ \frac{1}{\cos(4\alpha)}\boxed{\langle C_\ell^{EB,\mathrm{fg}}\rangle} + \frac{\cos(4\beta)}{\cos(4\alpha)}\boxed{\langle C_\ell^{EB,\mathrm{CMB}}\rangle}.$$

- For the baseline result, we ignore the intrinsic EB correlations of the foreground $\langle C_\ell^{EB,\mathrm{fg}}\rangle$ and the CMB $\langle C_\ell^{EB,\mathrm{CMB}}\rangle$.
  - The latter is justifiable but the former is not. We will revisit this important issue at the end.

Minami et al. (2019)

Likelihood for the simplest case

Single-frequency case, full sky data

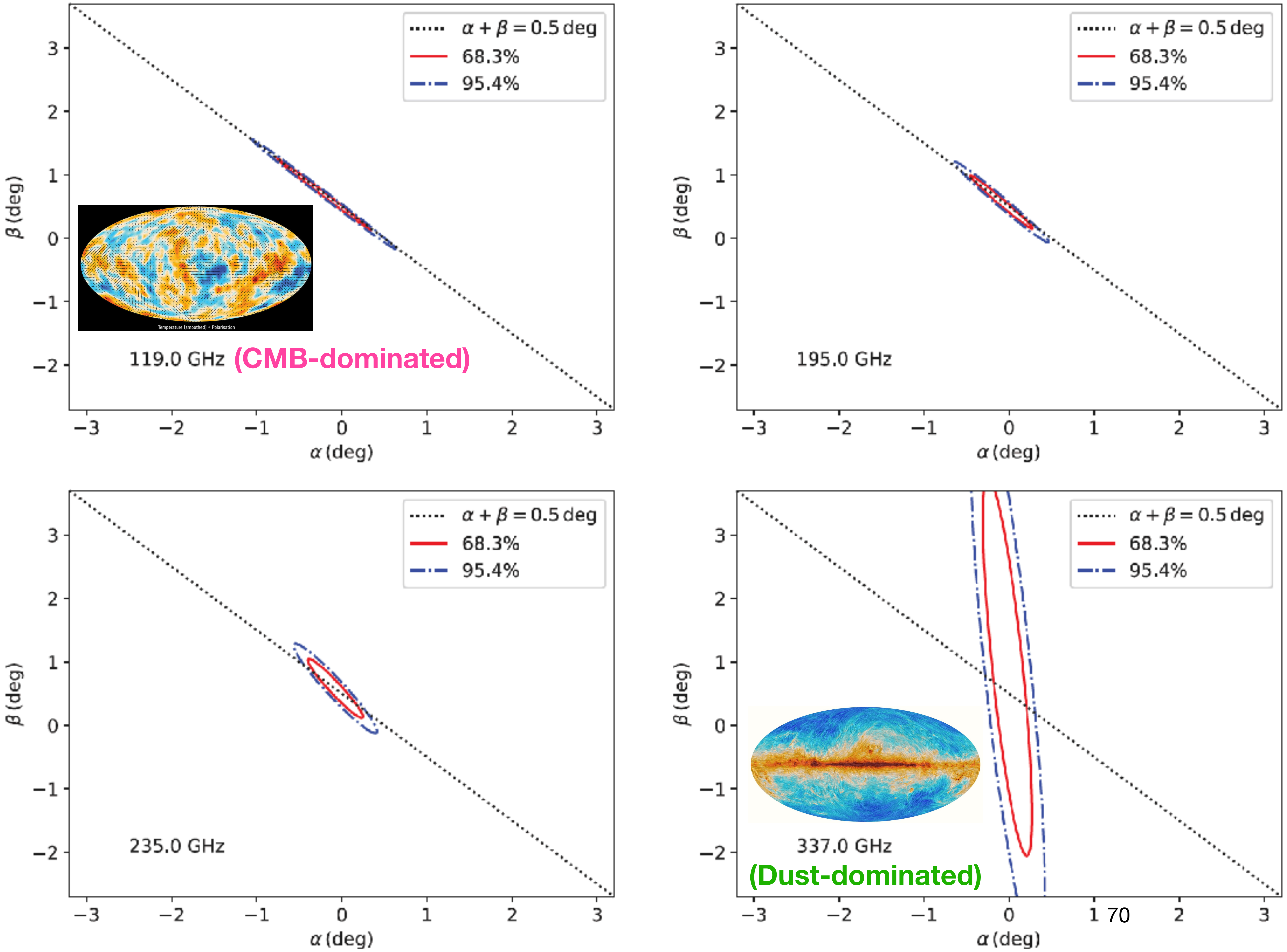
$$-2\ln\mathcal{L} = \sum_{\ell=2}^{\ell_{\max}} \frac{\left[C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right) - \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\mathrm{CMB}} - C_\ell^{BB,\mathrm{CMB}}\right)\right]^2}{\mathrm{Var}\left(C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)\right)}$$

- We determine α and β simultaneously from this likelihood.
- We first validate the algorithm using simulated data.
- For analysing the Planck data, we use the multi-frequency likelihood developed in Minami and Komatsu (2020a).

Minami et al. (2019)

How does it work?

Simulation of future CMB data (LiteBIRD)



- When the data are dominated by CMB, the sum of two angles, α+β, is determined precisely.
  - This is the diagonal line.
- The foreground determines α with some uncertainty, breaking the degeneracy. Then σ(β) ~ σ(α) because σ(α+β) << σ(α).
- When the data are dominated by the foreground, it can determine α but not β due to the lack of sensitivity to the CMB.

Minami & Komatsu (2020b)

Main Results

β > 0 at 2.4σ

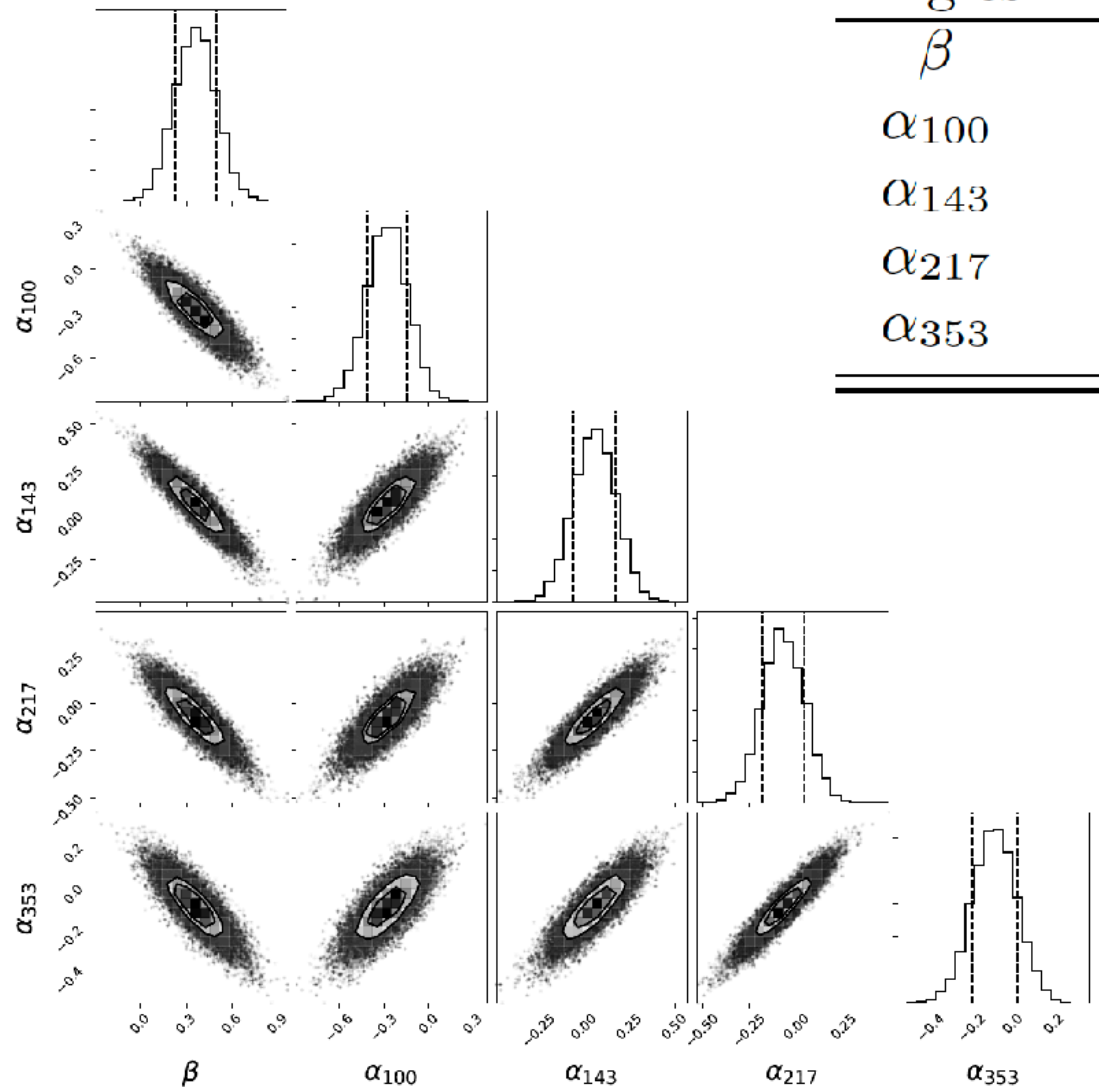
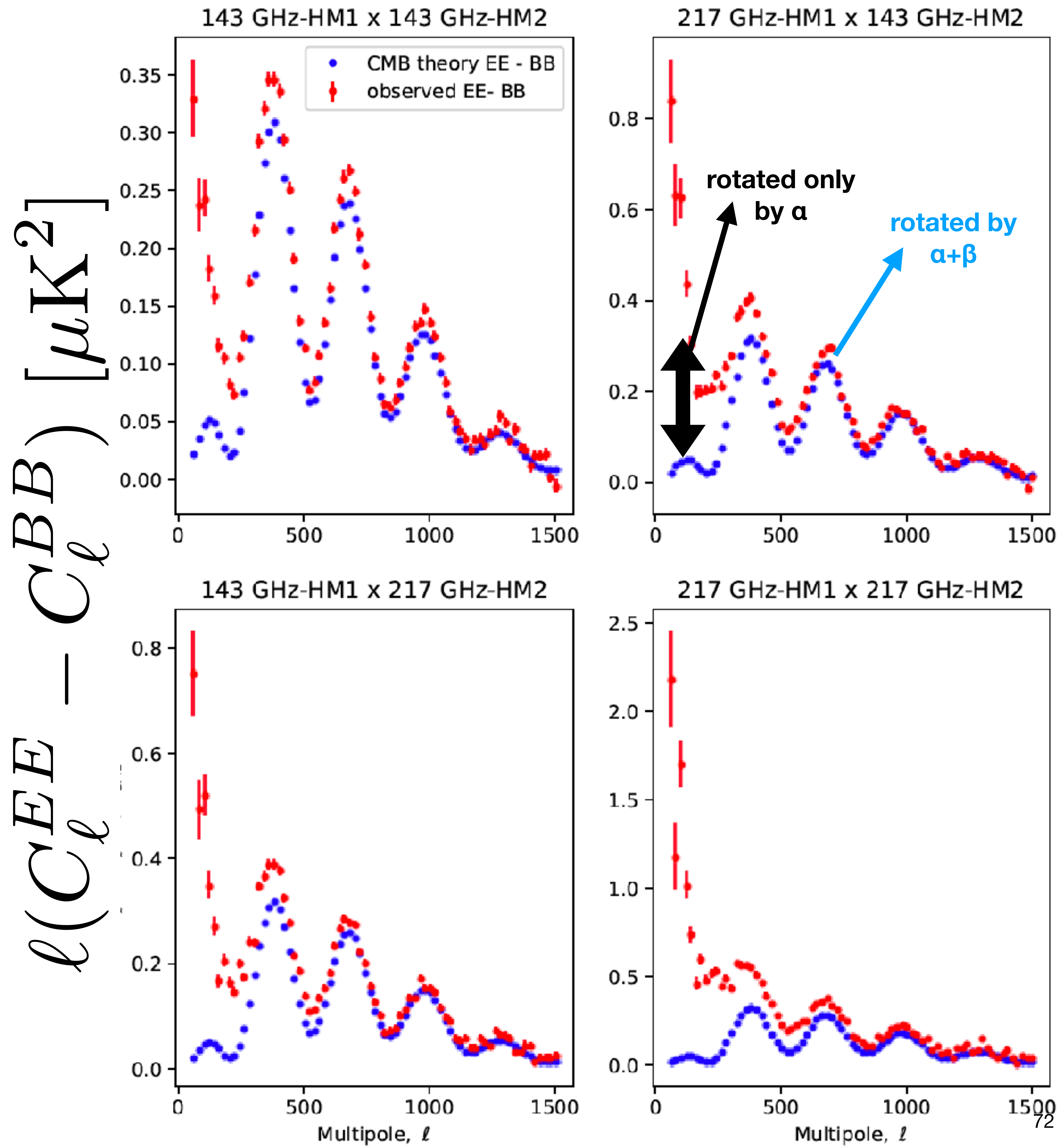


TABLE I. Cosmic birefringence and miscalibration angles from the Planck 2018 polarization data with 1σ (68%) uncertainties

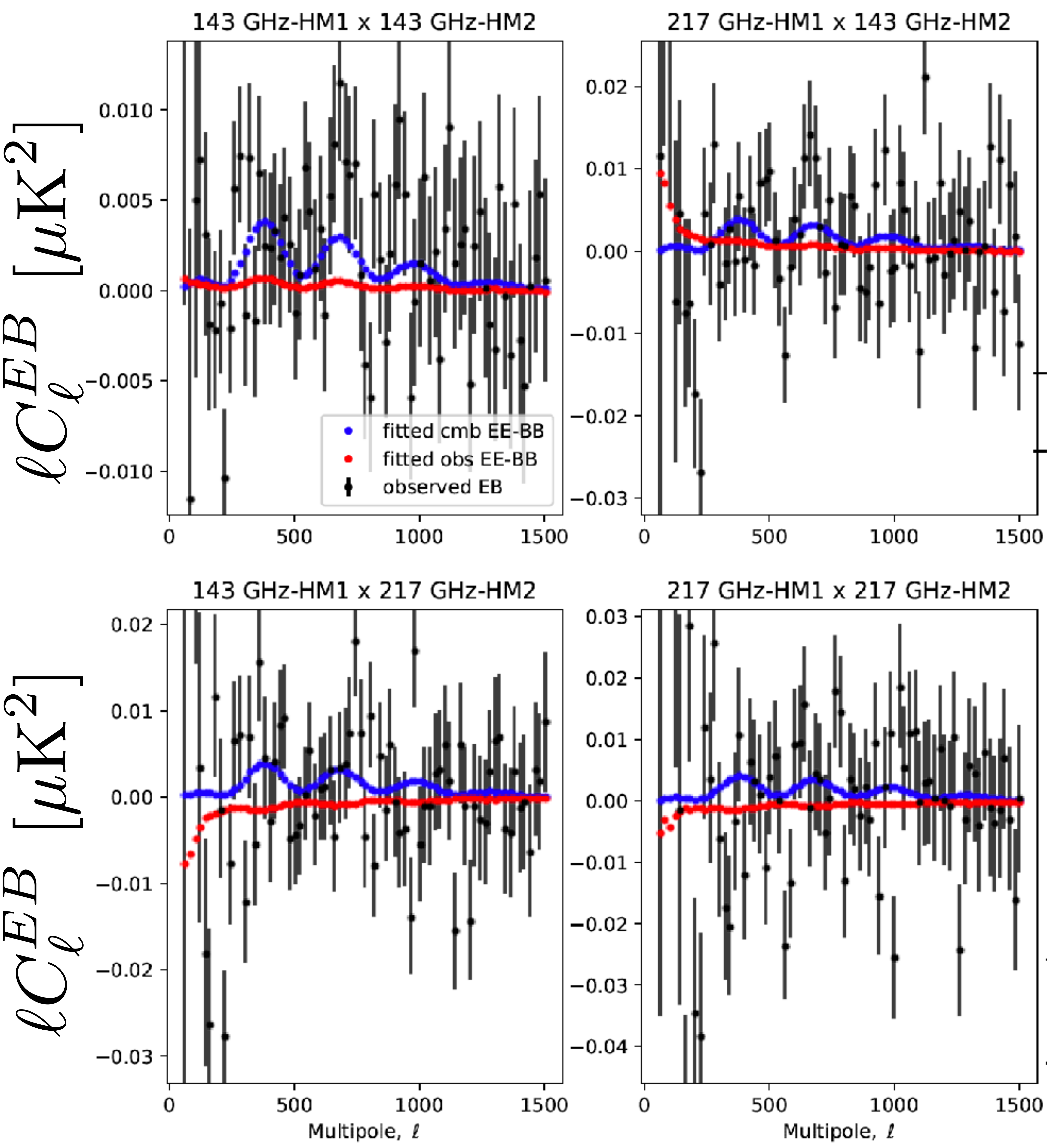
Angles	α_ν=0	Results (deg)
β	0.289 ± 0.048	0.35 ± 0.14
α_{100}		-0.28 ± 0.13
α_{143}		0.07 ± 0.12
α_{217}		-0.07 ± 0.11
α_{353}		-0.09 ± 0.11

- All α_ν's are consistent with zero either statistically, or within the ground calibration error of 0.28 deg.
  - Removing 100 GHz did not change β
- β=0.35 deg also agrees well with the Planck determination assuming α_ν=0:
  - β(α_ν=0) = 0.29 ± 0.05 (stat. from EB) ± 0.28 (syst.) [Planck Int. XLIX]



$$\langle C_\ell^{EB,o}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,o}\rangle - \langle C_\ell^{BB,o}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)$$

- Can we see β = 0.35 ± 0.14 deg by eyes?
- First, take a look at the observed EE–BB spectra.
  - Red: Total
  - Blue: The best-fitting CMB model
  - *The difference is due to the FG (and potentially systematics)*



Minami & Komatsu (2020b)

$$\langle C_\ell^{EB,o}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,o}\rangle - \langle C_\ell^{BB,o}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)$$

- Can we see β = 0.35 ± 0.14 deg by eyes?
  - Red: The signal attributed to the miscalibration angle, α_ν
  - Blue: The signal attributed to the cosmic birefringence, β
- Red + Blue is the best-fitting model for explaining the data points

How about the foreground EB?

- If the intrinsic foreground EB power spectrum exists, our method interprets it as a miscalibration angle α.
- Thus, α -> α+γ, where γ is the contribution from the intrinsic EB.
  - The sign of γ is the same as the sign of the foreground EB.
- From FG: α+γ. From CMB: α+β.
  - Thus, our method yields **β–γ = 0.35 ± 0.14 deg.**
- There is evidence for the dust-induced $TE_{dust} > 0$ and $TB_{dust} > 0$. Then, we'd expect $EB_{dust} > 0$ (Huffenberger et al. 2020), i.e., γ>0. If so, β increases further…

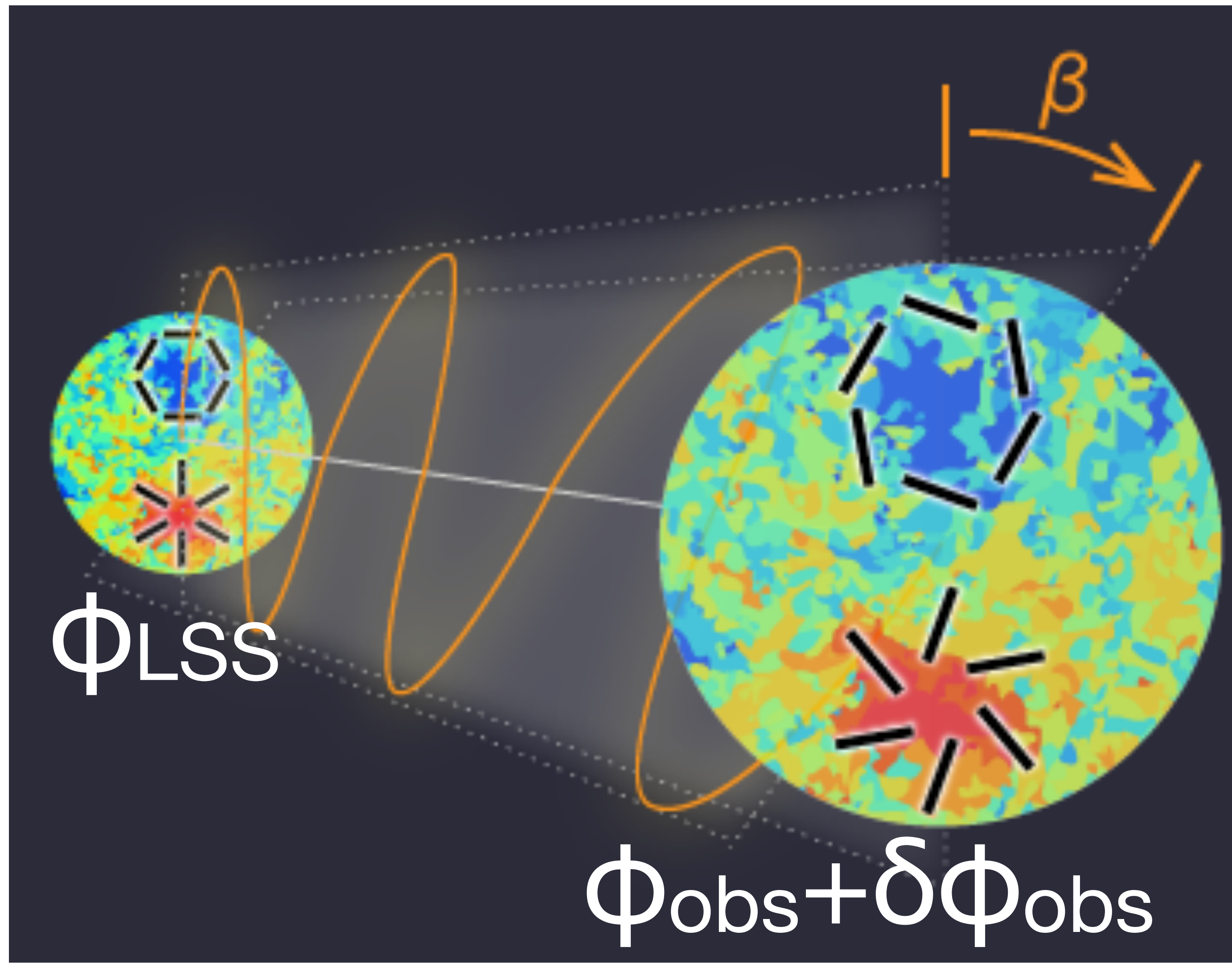
Minami & Komatsu (2020b)

Implications

What does it mean for your models of dark matter and energy?

- When the Lagrangian density includes a Chern-Simons coupling between a pseudo scalar field and the electromagnetic tensor given by

$$\mathcal{L} \supset \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

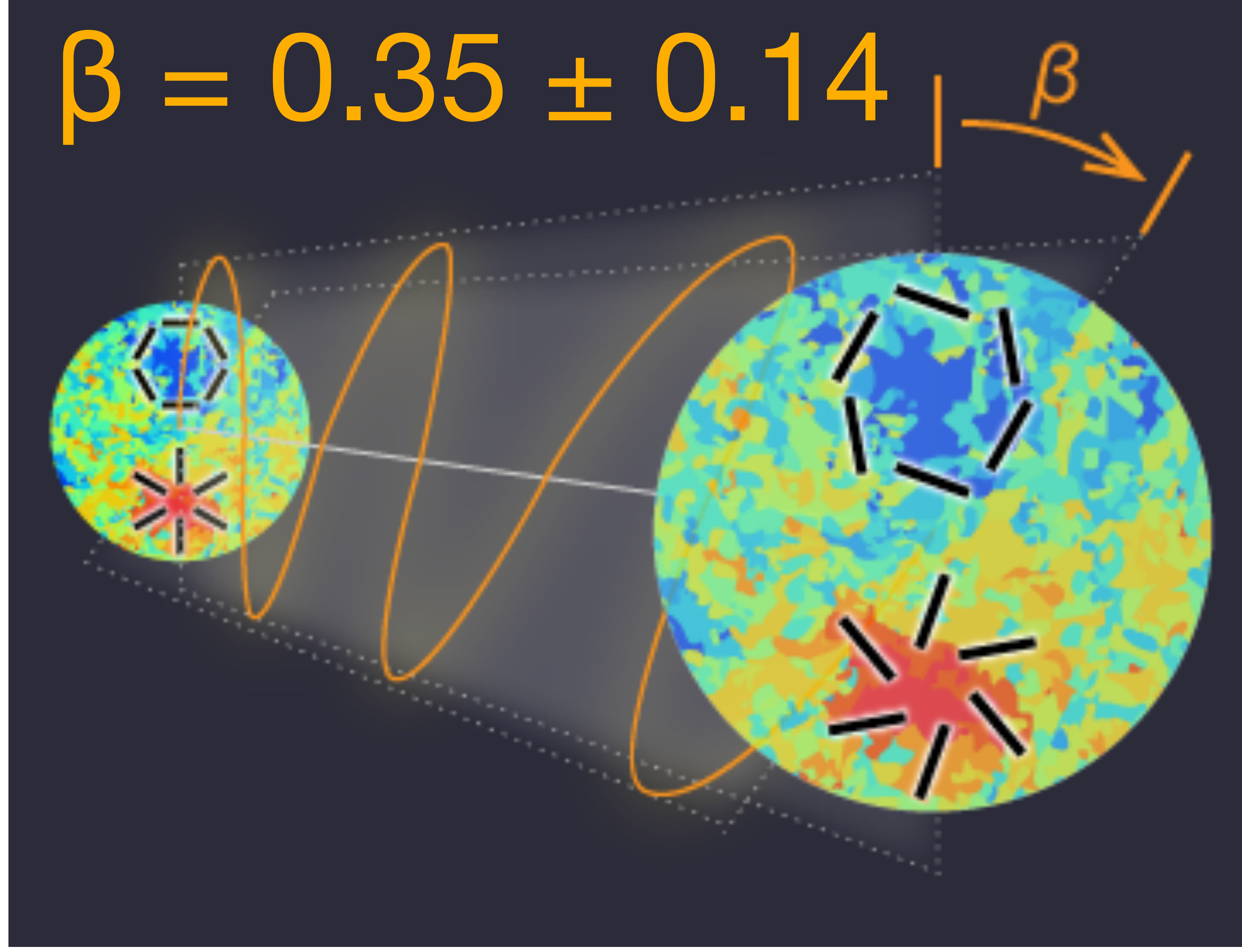


- The birefringence angle is

$$\beta = \frac{1}{2} g_{\phi\gamma} (\bar{\phi}_{\rm obs} - \bar{\phi}_{\rm LSS} + \delta\phi_{\rm obs})$$

- Our measurement yields

$$g_{\phi\gamma} (\bar{\phi}_{\rm obs} - \bar{\phi}_{\rm LSS} + \delta\phi_{\rm obs}) = (1.2 \pm 0.5) \times 10^{-2}\,{\rm rad}\,.$$



Summary of the Result

$\beta = 0.35 \pm 0.14$ (68%CL)

- We perfectly understand what 2.4σ means!
  - Higher statistical significance is need to confirm this signal.
- Our new method finally allowed us to make this “impossible” measurement, which may point to new physics.
  - Our method can be applied to any of the existing and future CMB experiments.
  - The confirmation (or otherwise) of the signal should be possible immediately.
- If confirmed, it would have important implications for dark matter/energy.