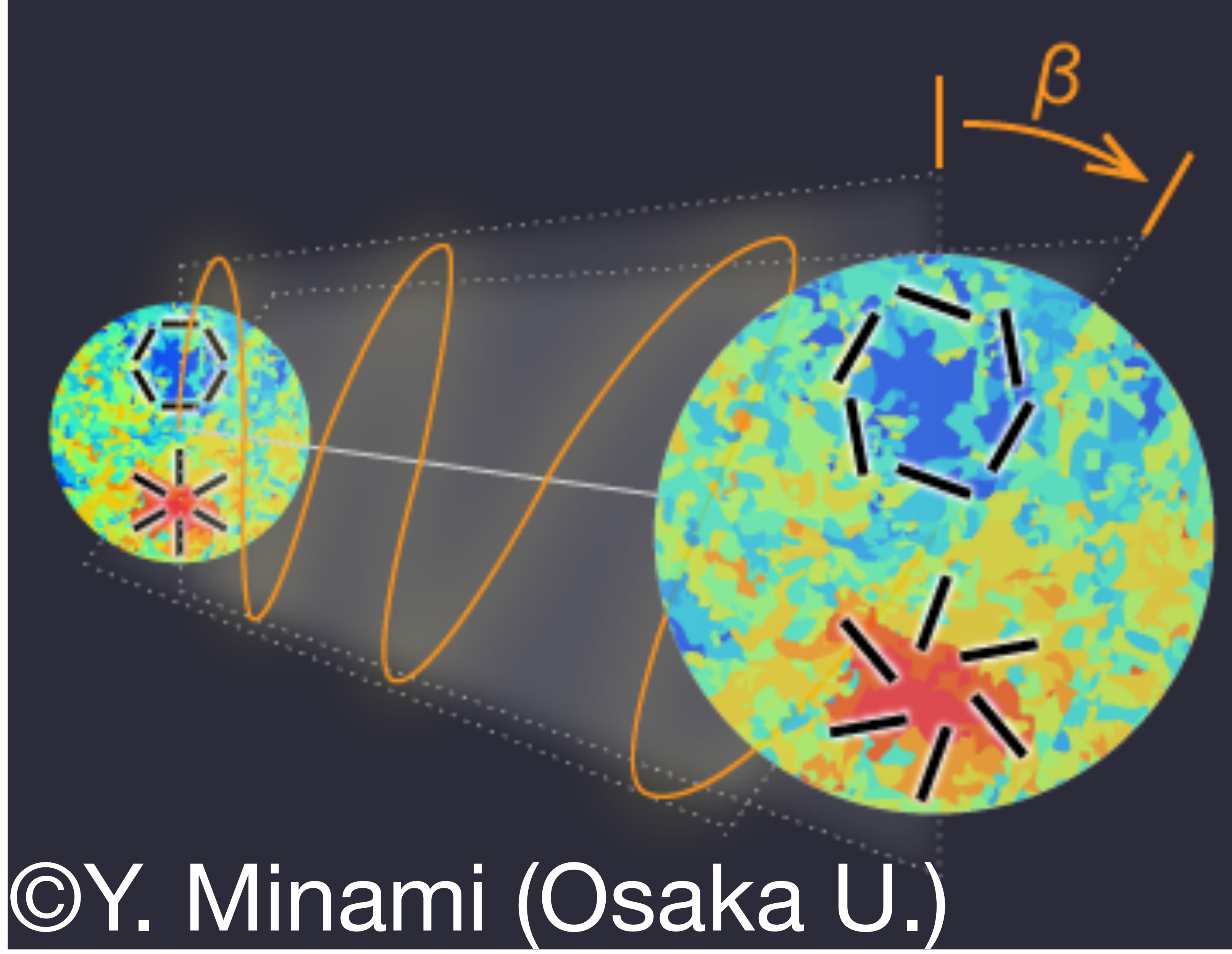


Cosmic Birefringence

A New Probe of Dark Matter and Dark Energy

based on

- *Minami & EK, PRL, 125, 221301 (2020)*
- *Diego-Palazuelos, Eskilt, Minami, et al., PRL, 128, 091302 (2022)*
- *EK, Nature Reviews Physics, 4 (2022)* [arXiv:2202.13919]

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)

Inaugural Conference, ICASU

May 19, 2022

MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK

い か す

ICASU
= “Stylish” in Japanese

nature reviews physics

Available also at arXiv:2202.13919

Published yesterday!

Review Article | Published: 18 May 2022

New physics from the polarized light of the cosmic microwave background

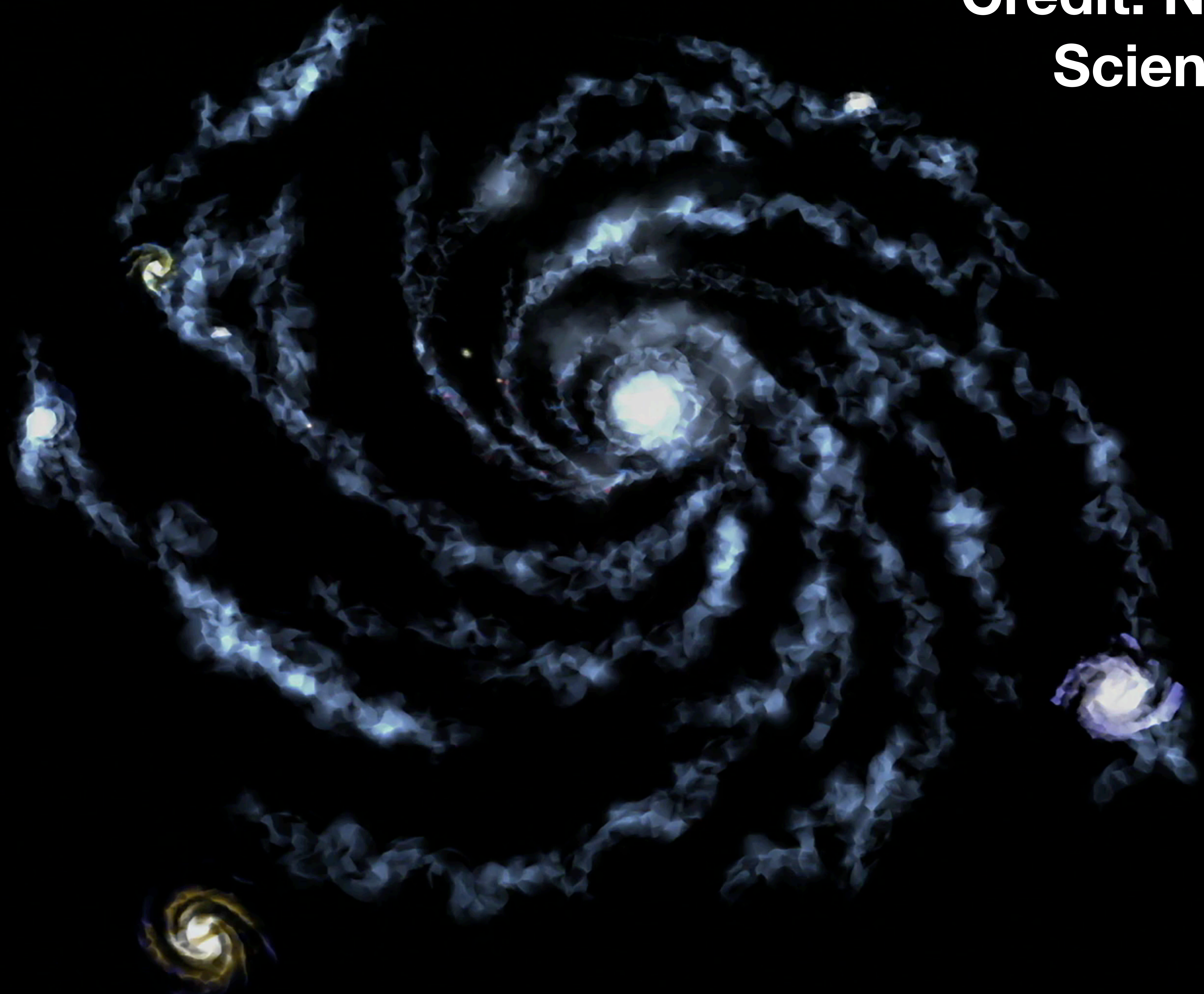
Eiichiro Komatsu

Nature Reviews Physics (2022) | Cite this article

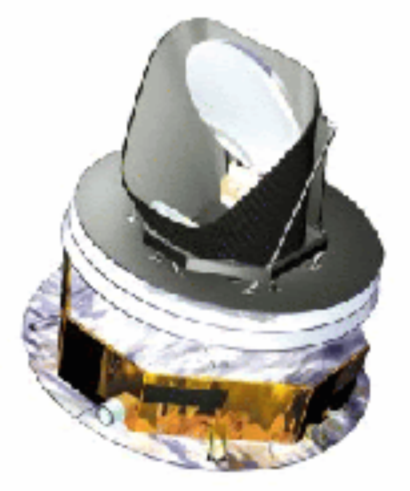
Metrics

Key Words:

1. Cosmic Microwave Background (CMB)
2. Polarization
3. Parity Symmetry



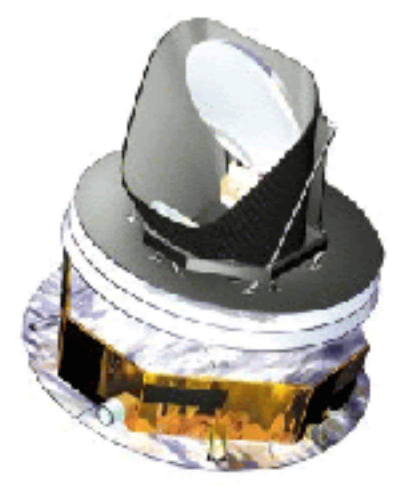
Credit: NASA/WMAP Science Team


ESA's Planck

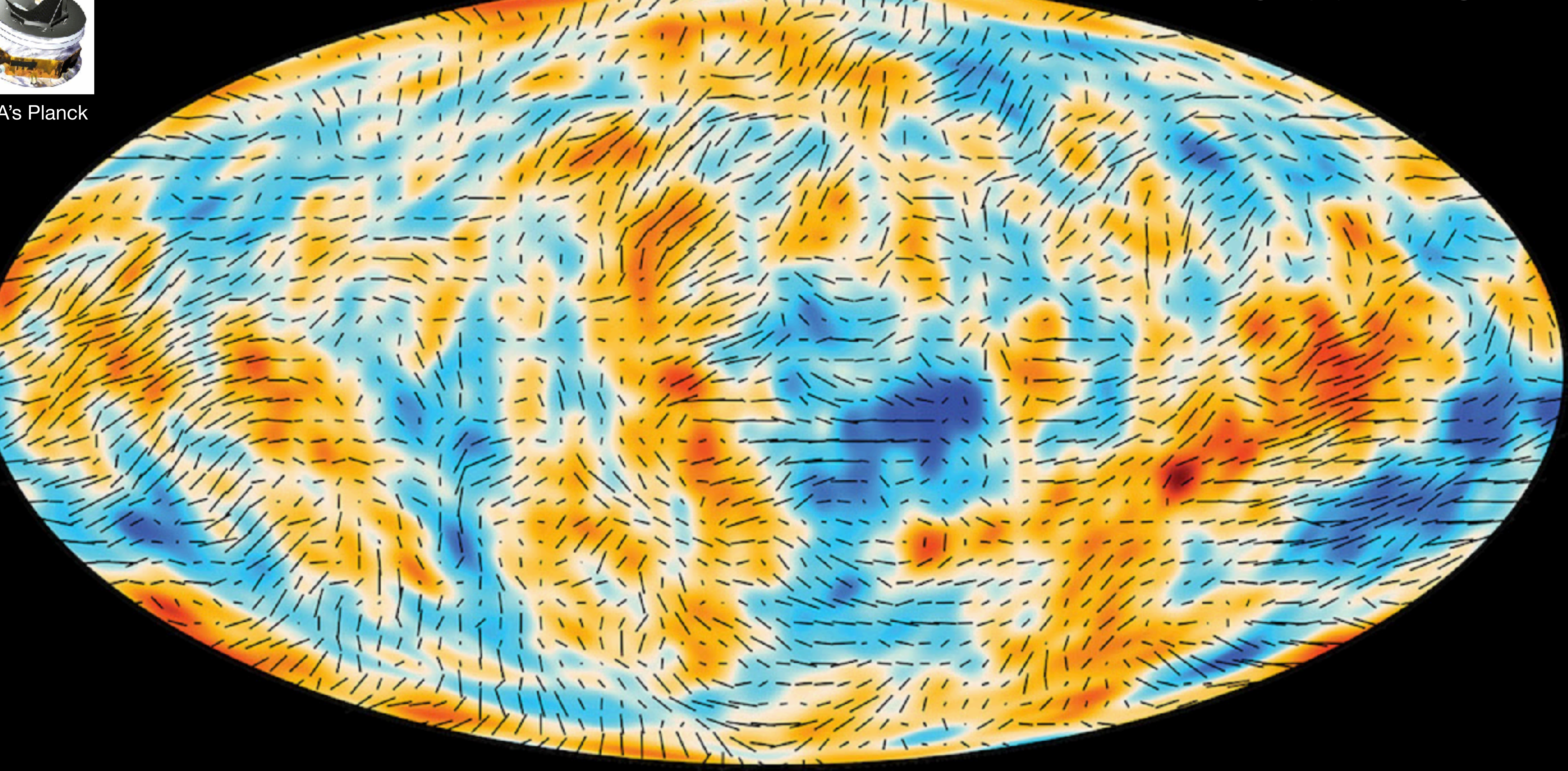
Credit: ESA

Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago


ESA's Planck

Credit: ESA



Emitted 13.8 billions years ago

Credit: TALEX

Why is CMB linearly polarised?

Credit: TALEX

Why is CMB linearly polarised?

Physics of CMB Polarisation

Necessary and sufficient condition: Scattering and Quadrupole Anisotropy

Credit：Wayne Hu

Standard Cosmological Model (ΛCDM) Requires New Physics

Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy (*Λ*)?

- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?

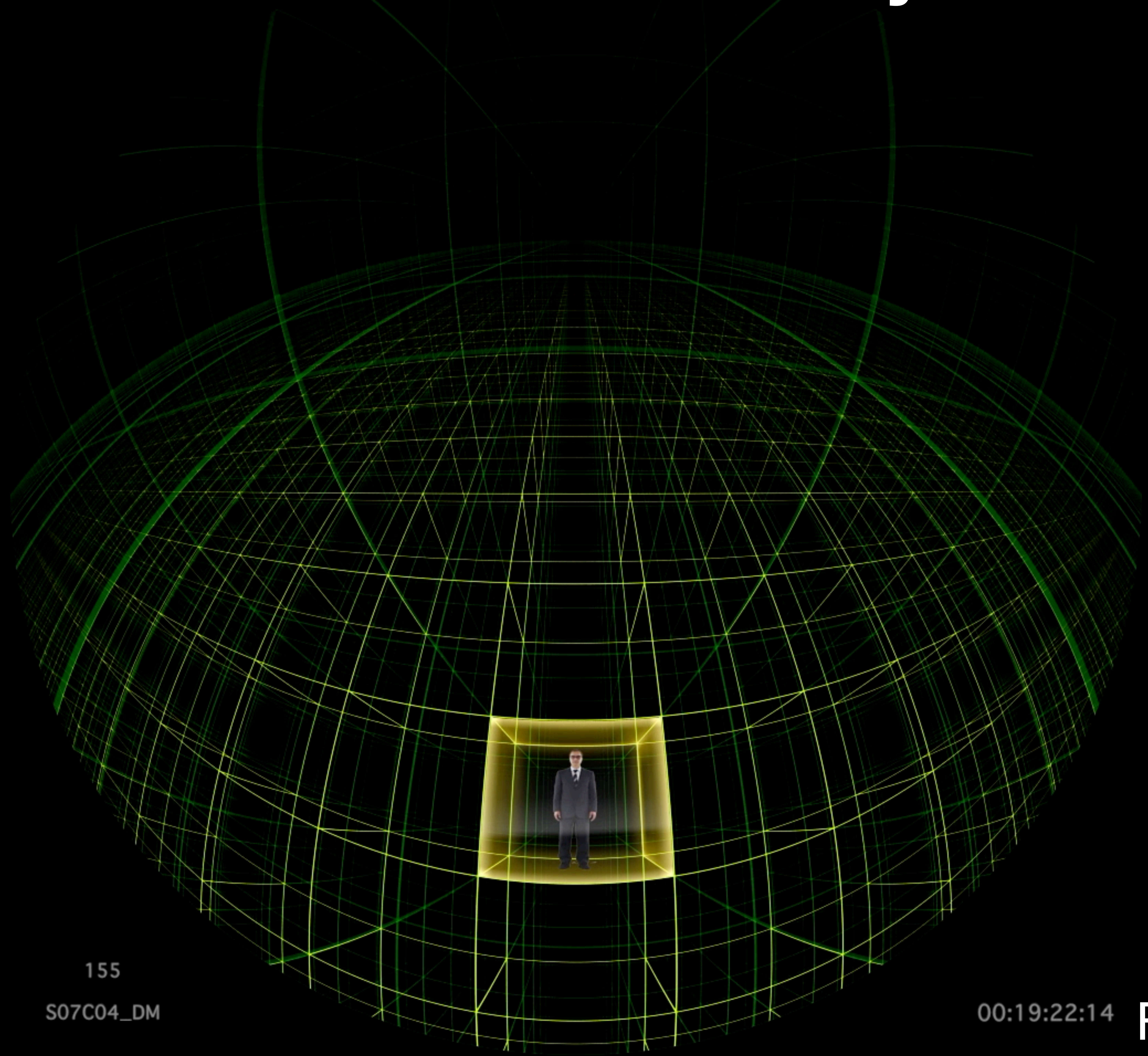
- *Polarisation* of the CMB may hold the key to the answers.

Standard Cosmological Model (ΛCDM) Requires New Physics

Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy (*Λ*)?
    - **Cosmic birefringence** in CMB polarisation
- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?
    - Imprint of **primordial gravitational waves** in CMB polarisation
- *Polarisation* of the CMB may hold the key to the answers.

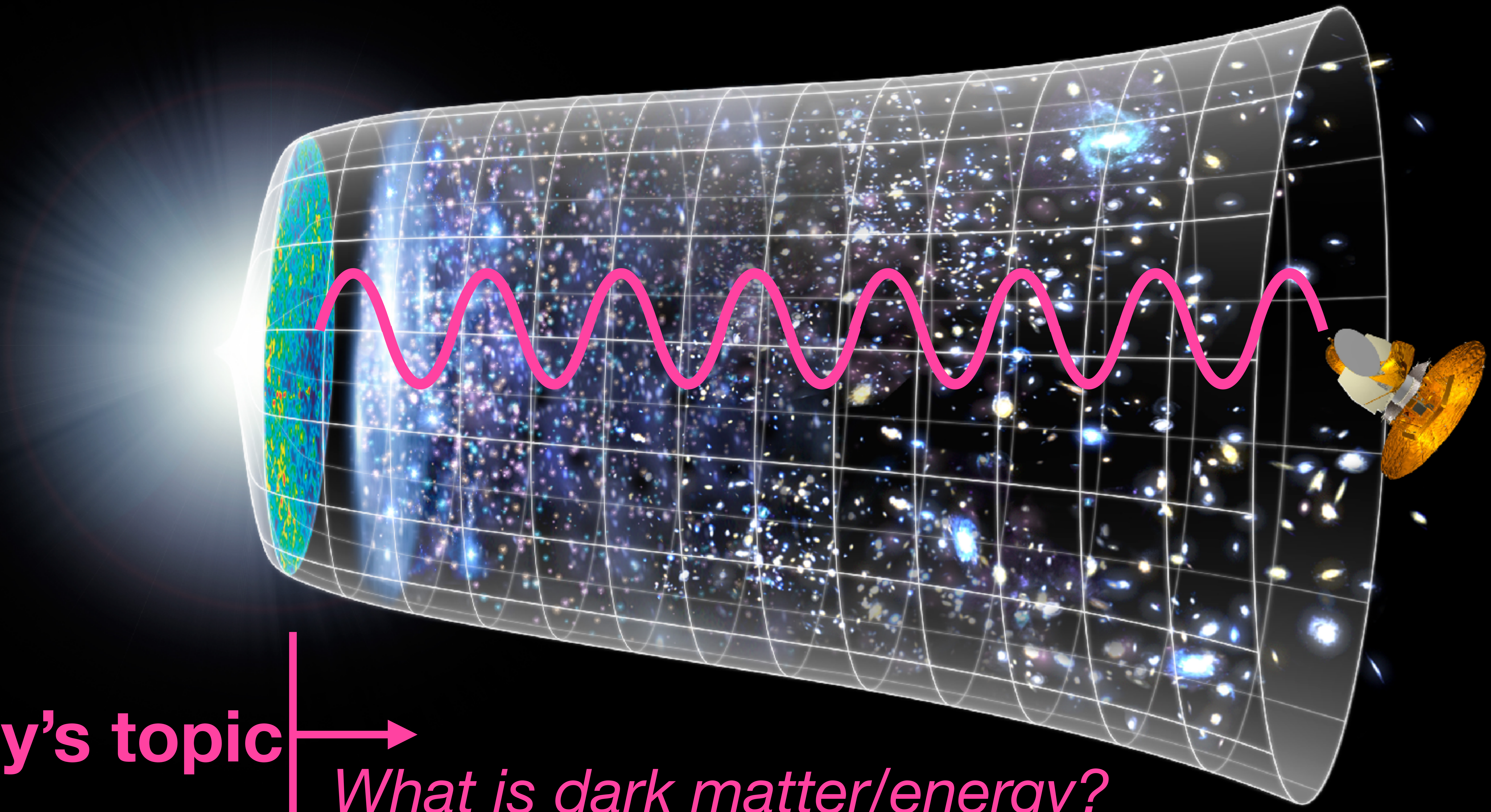
Where did the CMB we see today come from?



From "HORIZON"

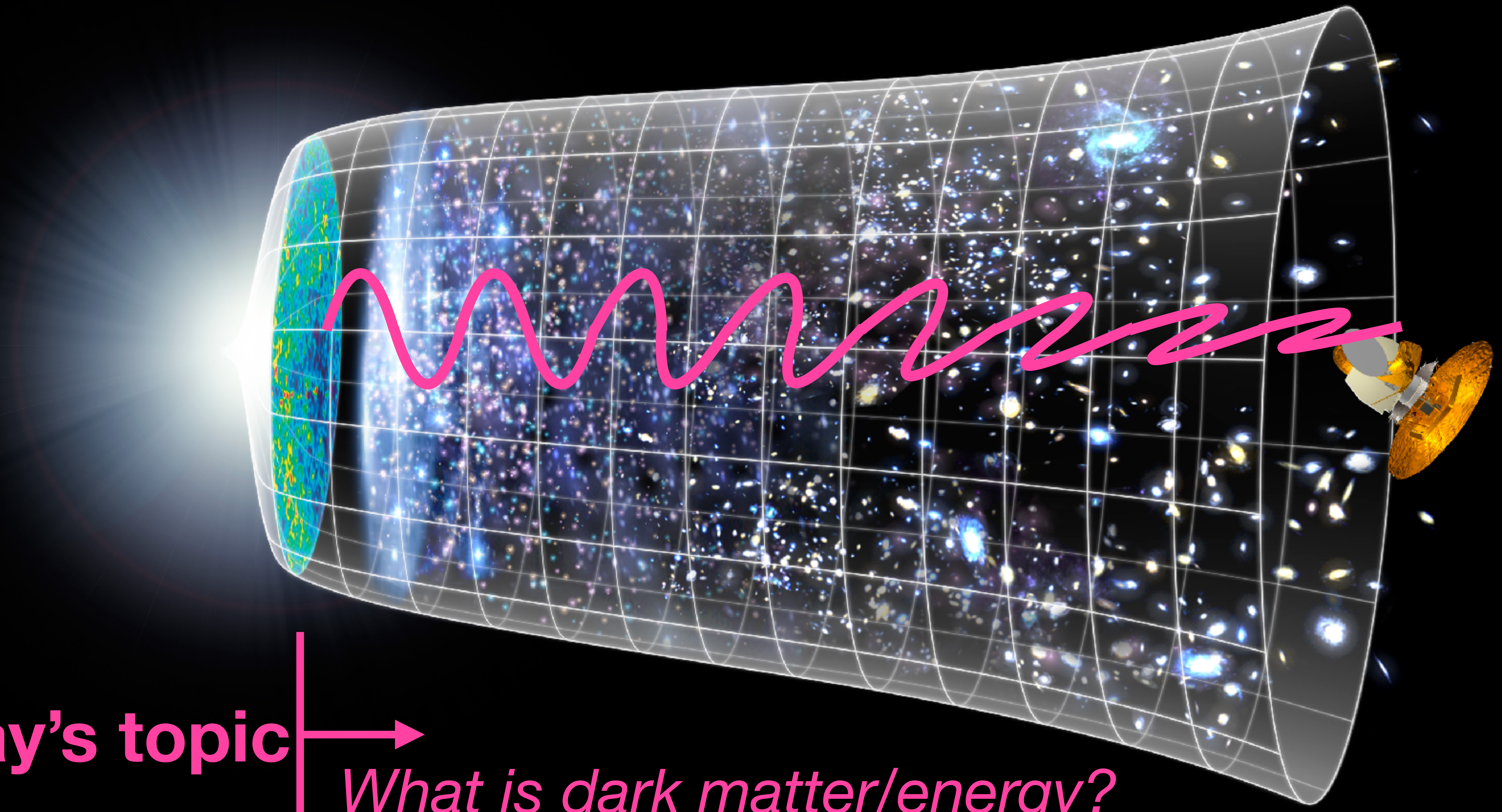

Credit: WMAP Science Team
The surface of "last scattering" by electrons
(Scattering generates polarisation!)
What powered the Big Bang?
What is dark matter/energy?
1131
S07C04_DM
00:19:55:00

How does the electromagnetic wave of the CMB propagate?



Today's topic → *What is dark matter/energy?*

How does the electromagnetic wave of the CMB propagate?



Today's topic

What is dark matter/energy?

The idea:

If dark energy/matter interacts with photons *even very weakly*, the interaction could influence photons over >13 billion years, leaving an observable signature in CMB polarisation.

Cosmic Birefringence

The Universe filled with a "birefringent material"

This "axion" field can be dark matter or dark energy!

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

Ni (1977); 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

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad \sum_{\mu\nu} F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E}) \qquad \sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$

Parity Even **Parity Odd**

Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)

Cosmic Birefringence

The Universe filled with a “birefringent material”

This “axion” field can be dark matter or dark energy!

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

Ni (1977); Turner & Widrow (1988)

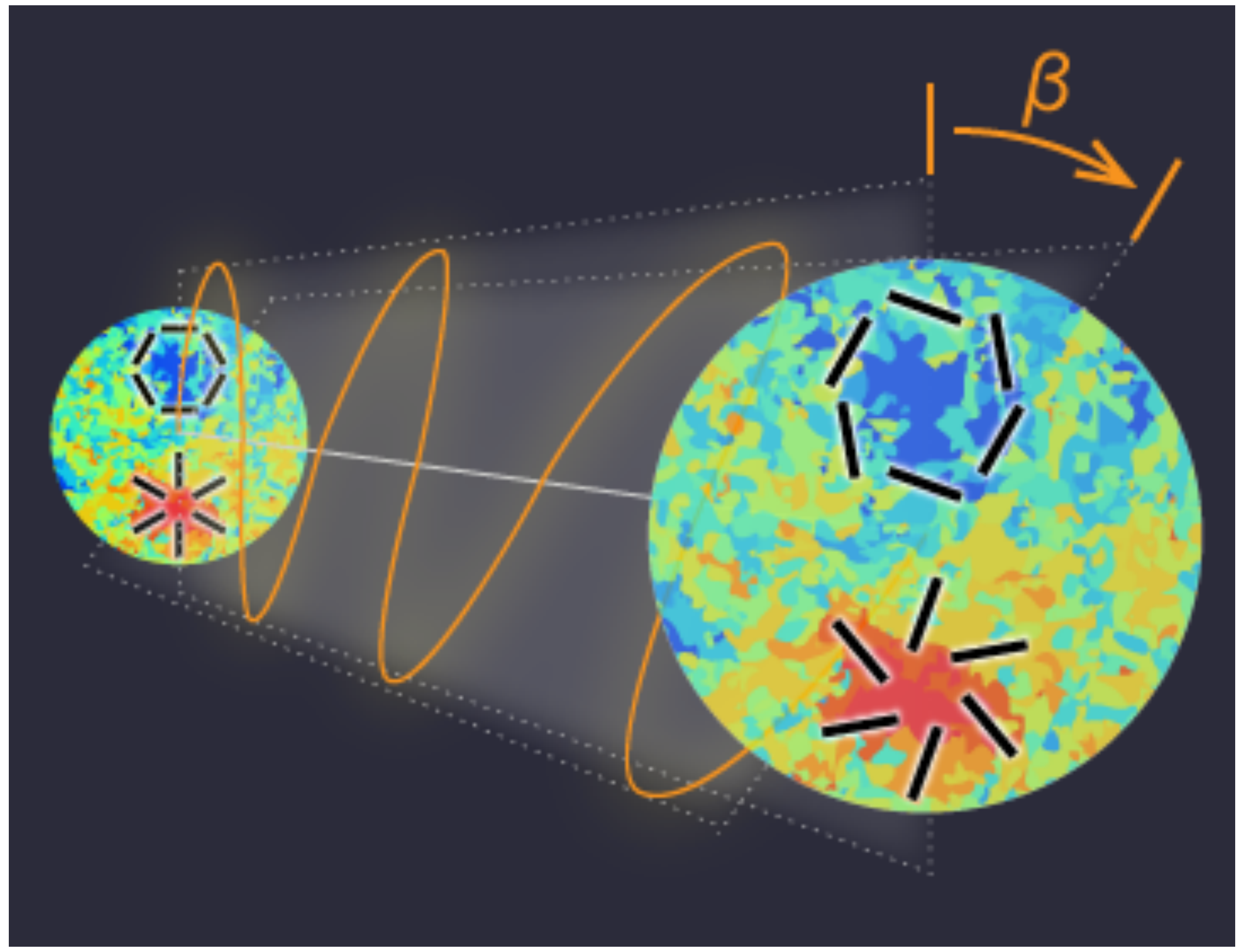
the effective Lagrangian for axion electrodynamics is

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



“Cosmic Birefringence”

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

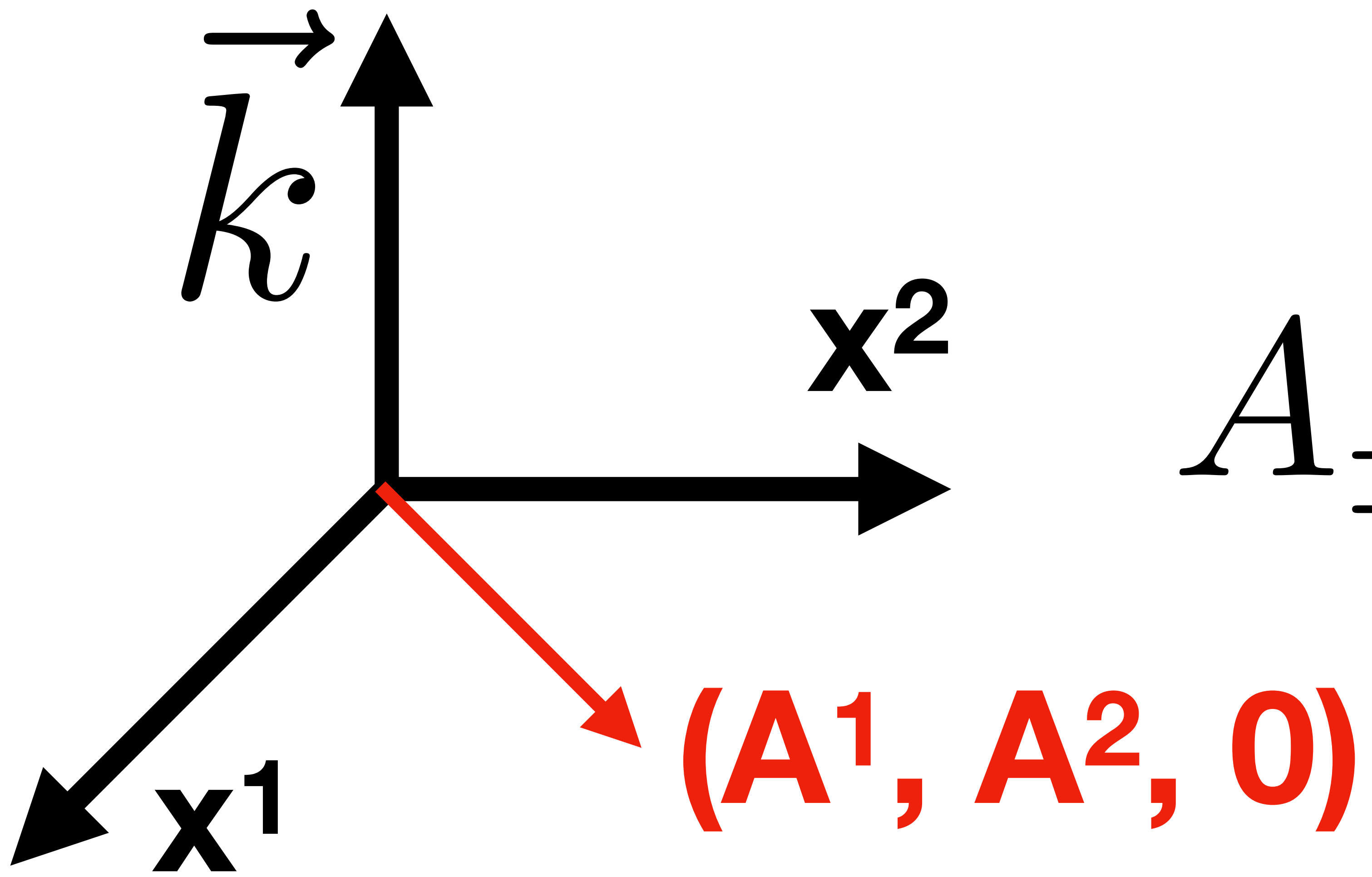
Standard Maxwell Theory

Warm up (1)

- To isolate a transverse wave, we require $A_0=0$ and $\mathrm{div}(A_i)=0$. Then, in vacuum,

$$\left(\frac{\partial^2}{\partial\eta^2} - \nabla^2\right) A_i(\eta, \mathbf{x}) = 0 \qquad\qquad ds^2 = a^2(-d\eta^2 + d\mathbf{x}^2)$$

- Go to Fourier space, choose the propagation direction of A_i to be in z-axis, and define right- and left-handed polarisation states as



$$A_\pm = \frac{A_1 \mp iA_2}{\sqrt{2}}$$

- A_+: Right-handed state
- A_-: Left-handed state

Standard Maxwell Theory

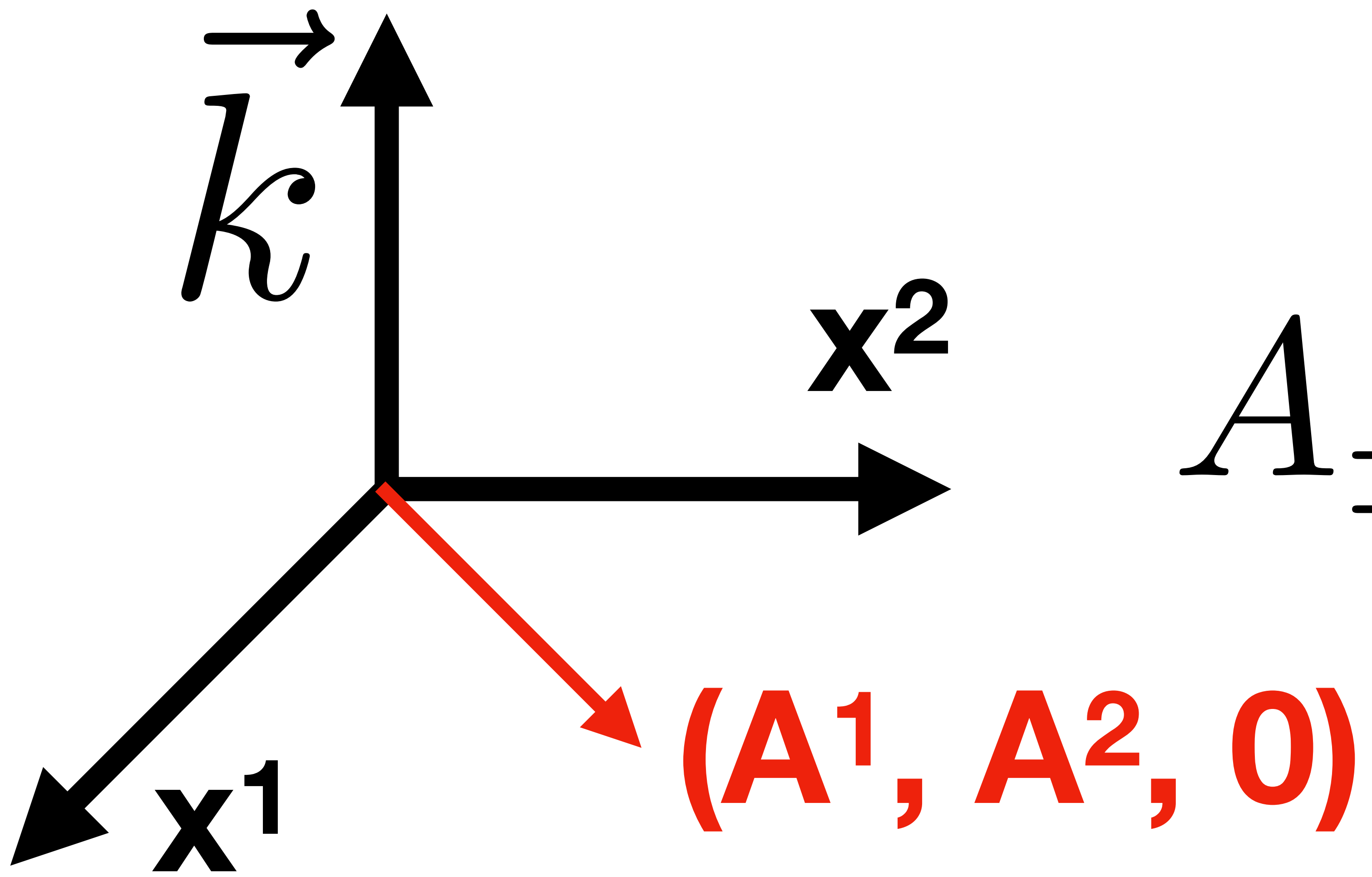
Warm up (2)

- To isolate a transverse wave, we require $A_0=0$ and $\mathrm{div}(A_i)=0$. Then, in vacuum,

$$\left(\frac{\partial^2}{\partial\eta^2} - \nabla^2\right) A_i(\eta, \mathbf{x}) = 0 \quad \Rightarrow \quad \left(-\omega_\pm^2 + k^2\right) A_\pm(\eta) = 0$$

Same dispersion relation for right- and left-handed states

- Go to Fourier space, choose the propagation direction of A_i to be in z-axis, and define right- and left-handed polarisation states as



$$A_\pm = \frac{A_1 \mp i A_2}{\sqrt{2}}$$

- A_+: Right-handed state
- A_-: Left-handed state

Cosmic Birefringence

Derivation (1)

- Now, include **the Chern-Simons term**!

> 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

- The equation of motion is modified to

$$\left(-\omega_\pm^2 + k^2\right)A_\pm(\eta) = 0 \;\Rightarrow\; \left(-\omega_\pm^2 + k^2 \pm 4g_a k\theta'\right)A_\pm(\eta) = 0$$

$$\frac{\omega_\pm^2}{k^2} = 1 \pm \frac{4g_a\theta'}{k} \quad (\theta' = \partial\theta/\partial\eta)$$

Cosmic Birefringence

Derivation (1)

- Now, include **the Chern-Simons term**!

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

- The equation of motion is modified to

$$\left(-\omega_\pm^2 + k^2\right) A_\pm(\eta) = 0 \Rightarrow \left(-\omega_\pm^2 + k^2 \pm 4g_a k\theta'\right) A_\pm(\eta) = 0$$

$$\frac{\omega_\pm^2}{k^2} = 1 \pm \frac{4g_a\theta'}{k} = \left(1 \pm \frac{2g_a\theta'}{k}\right)^2 - \frac{4g_a^2\theta'^2}{k^2}$$

Cosmic Birefringence

Derivation (1)

- Now, include **the Chern-Simons term**!

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

- The equation of motion is modified to

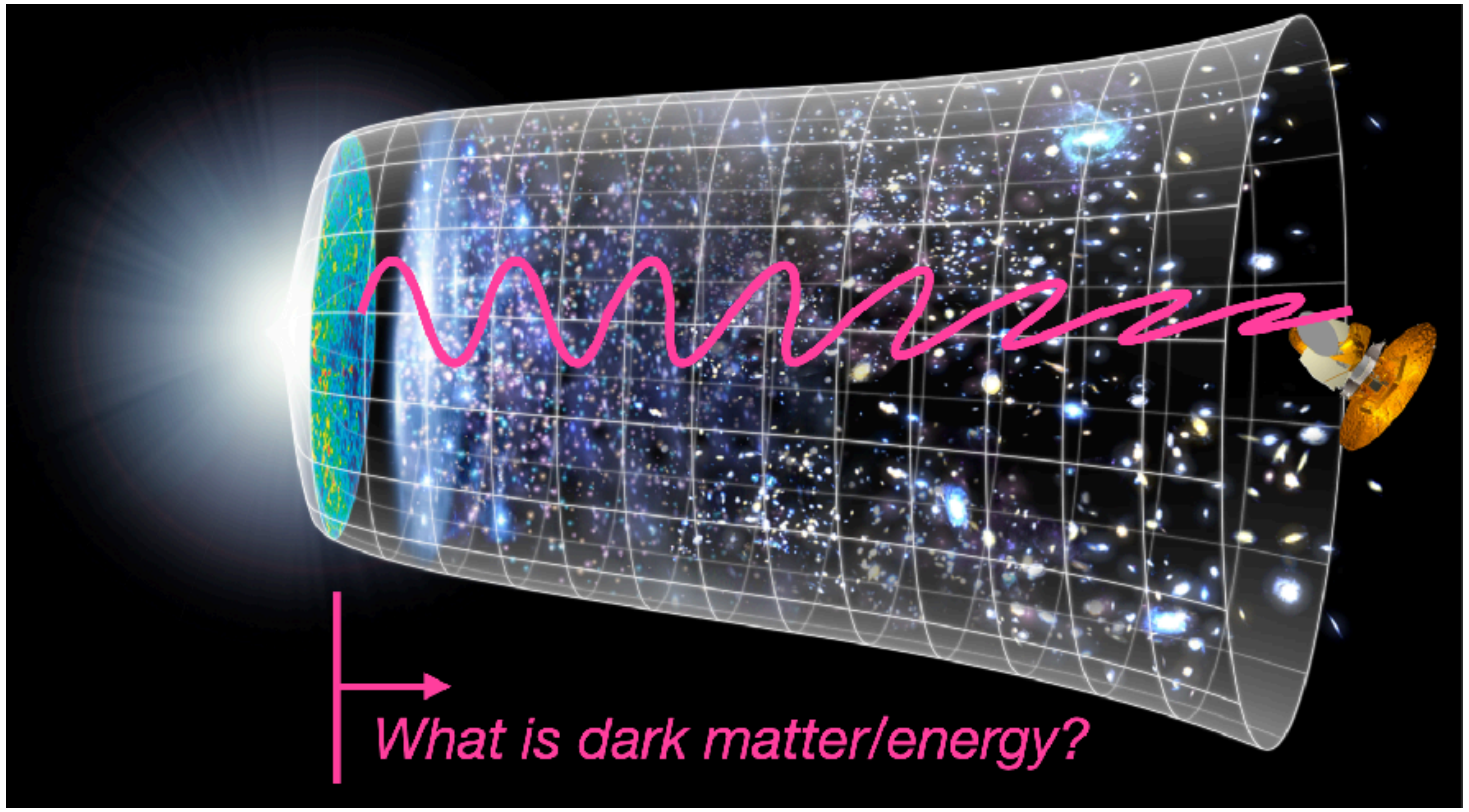
$$\left(-\omega_\pm^2 + k^2\right)A_\pm(\eta) = 0 \;\Rightarrow\; \left(-\omega_\pm^2 + k^2 \pm 4g_a k\theta'\right)A_\pm(\eta) = 0$$

$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2g_a\theta'}{k}$$

Phase velocities of right- and left-handed states are slightly different!

Cosmic Birefringence

Derivation (2)



- With

$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2g_a\theta'}{k}$$

Phase velocities of right- and left-handed states are slightly different!

- The plane of linear polarisation rotates clockwise on the sky by an angle β:

$$-\beta = \int d\eta \, \frac{\omega_+ - \omega_-}{2} = 2g_a \int d\eta \, \theta' = 2g_a \int dt \, \dot{\theta}$$

The effect accumulates over the distance!
=> CMB polarisation is sensitive to this effect

Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)

Cosmic Birefringence

Recap

This "axion" field can be dark matter or dark energy!

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

Ni (1977); Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

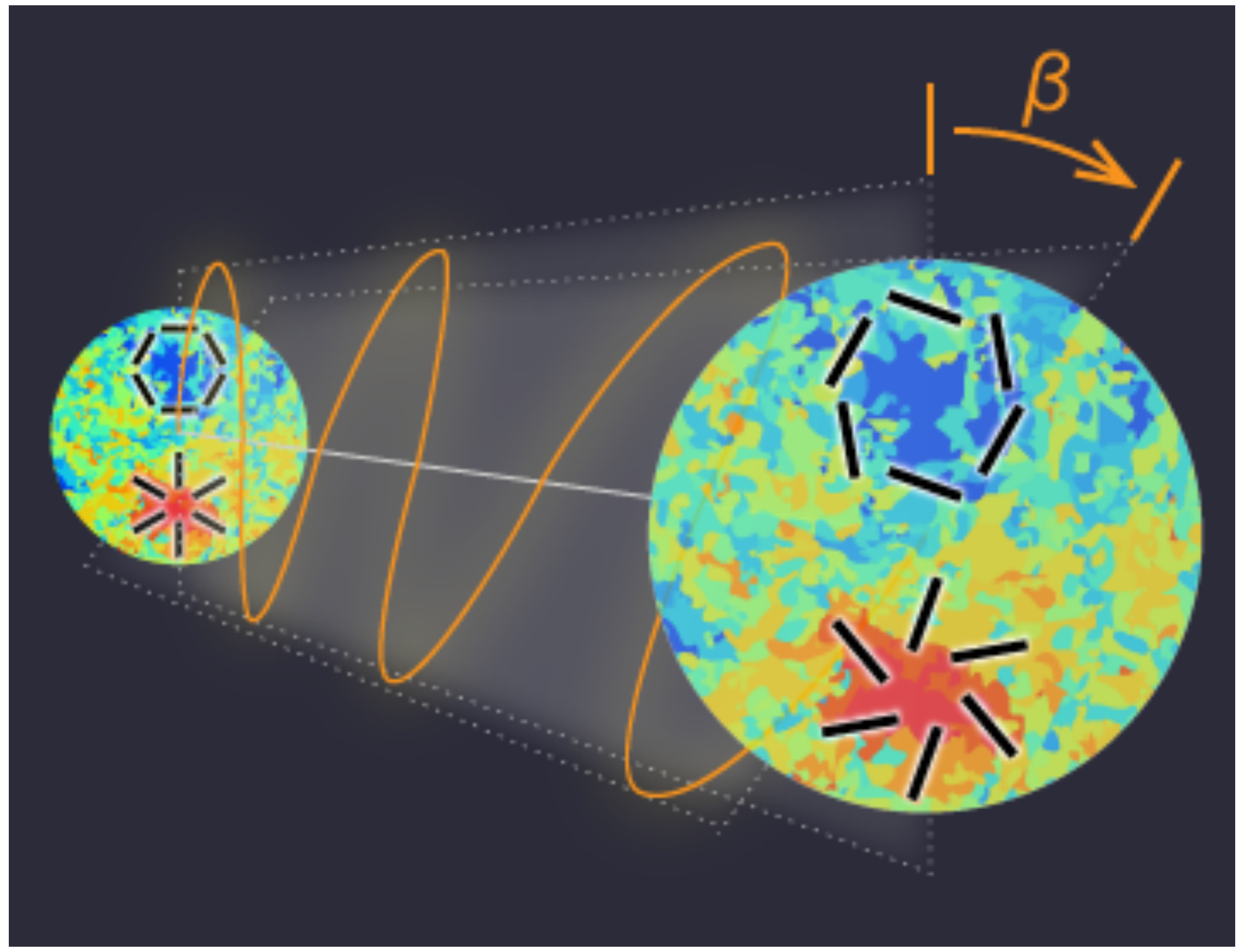
Chern-Simons term

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

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

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

$$\beta = -2g_a\int_{t_{\rm emitted}}^{t_{\rm observed}} dt\,\dot{\theta} = 2g_a\left[\theta(t_{\rm e}) - \theta(t_{\rm o})\right]$$



The difference between the fields values at the end points gives β.

Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)

Cosmic Birefringence

Recap

This "axion" field can be dark matter or dark energy!

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

Ni (1977); Turner & Widrow (1988)

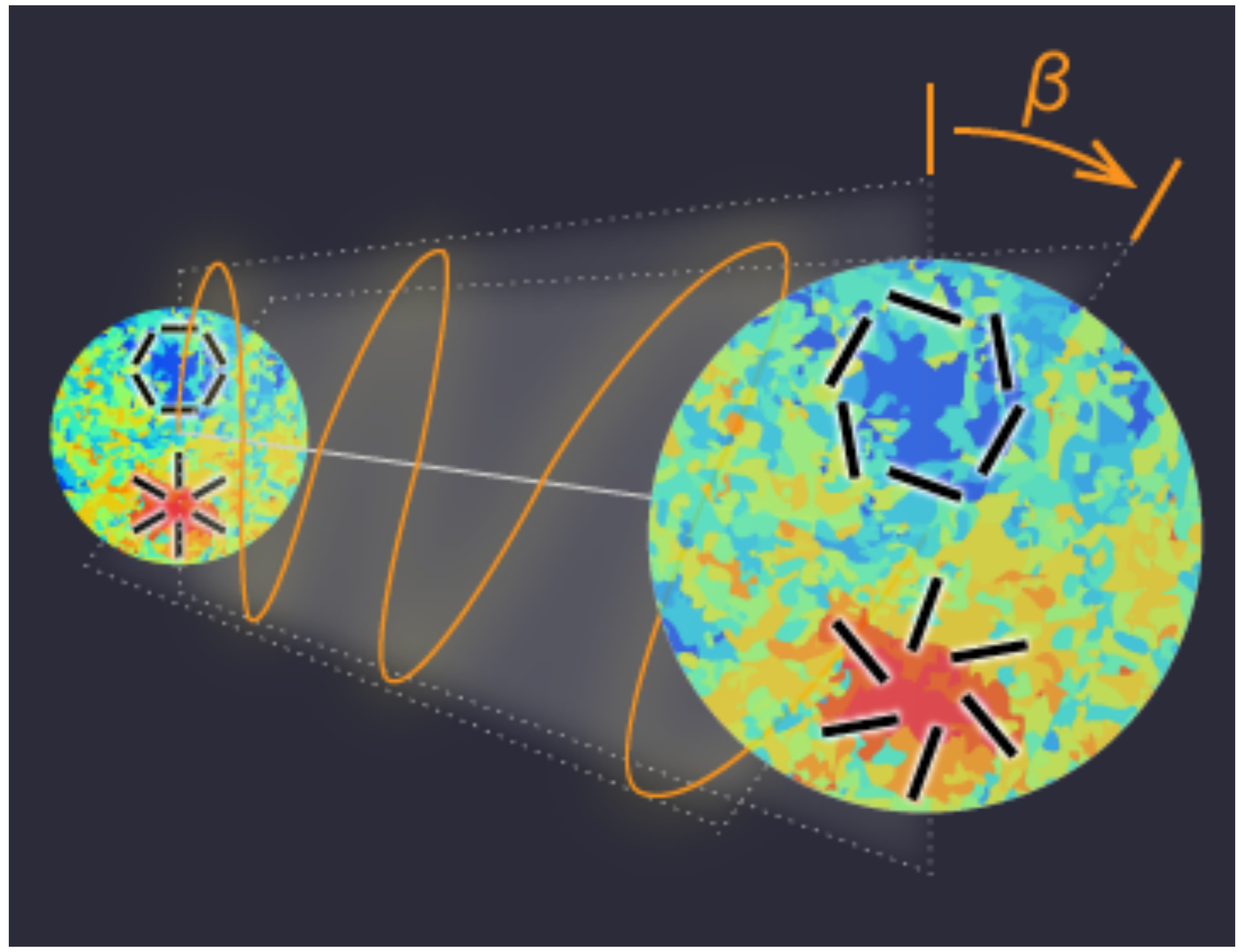
the effective Lagrangian for axion electrodynamics is

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



If θ varies over space:

$$\beta(\hat{n},\tau) = -2g_a\int_{t_{\rm emitted}}^{t_{\rm observed}} dt\,\frac{d\theta}{dt} = 2g_a\left[\theta(t_{\rm e},\hat{n}r_{\rm oe}) - \theta(t_{\rm o},\tau)\right]$$

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

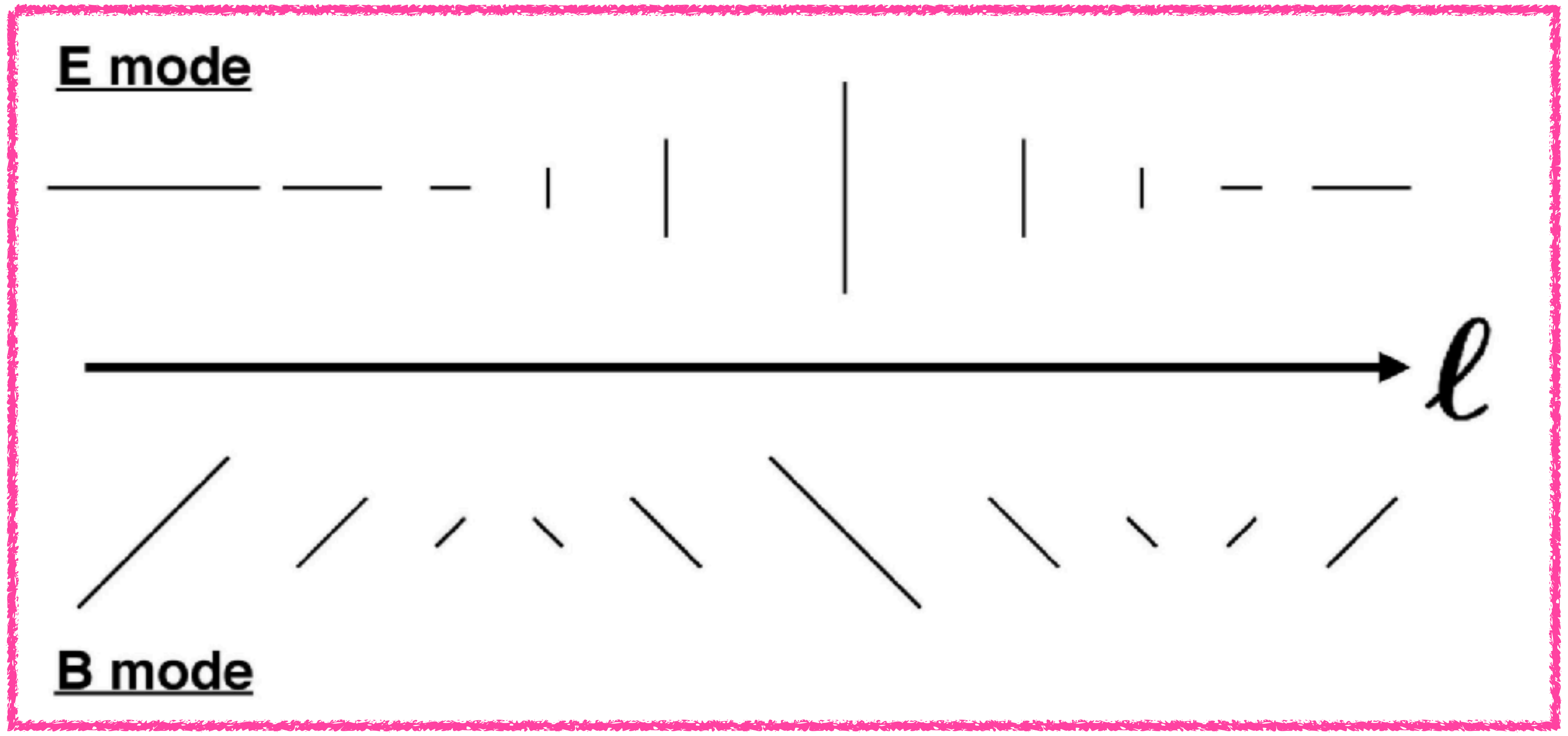
Why study the cosmic birefringence?

- 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!

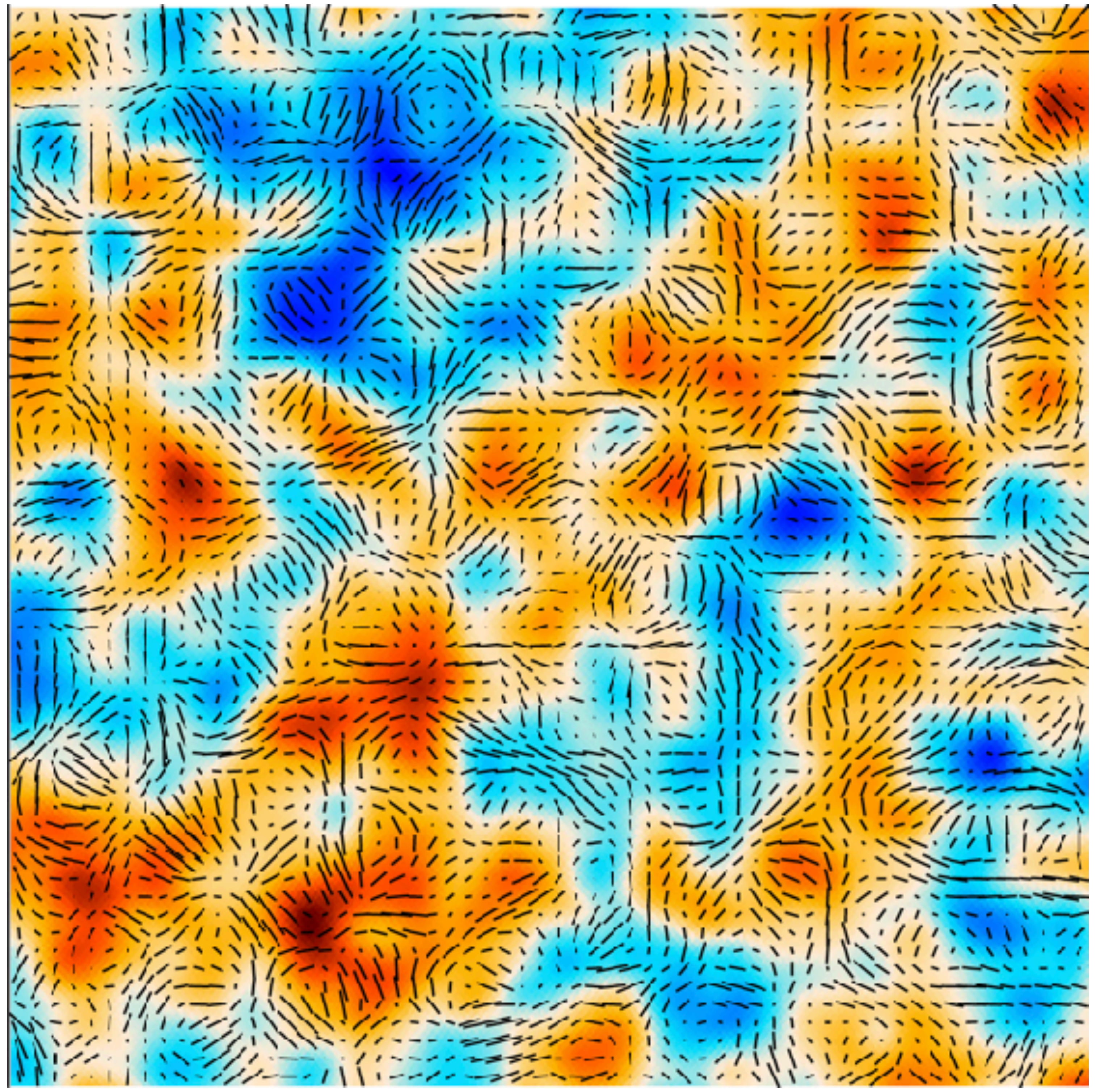
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarisation

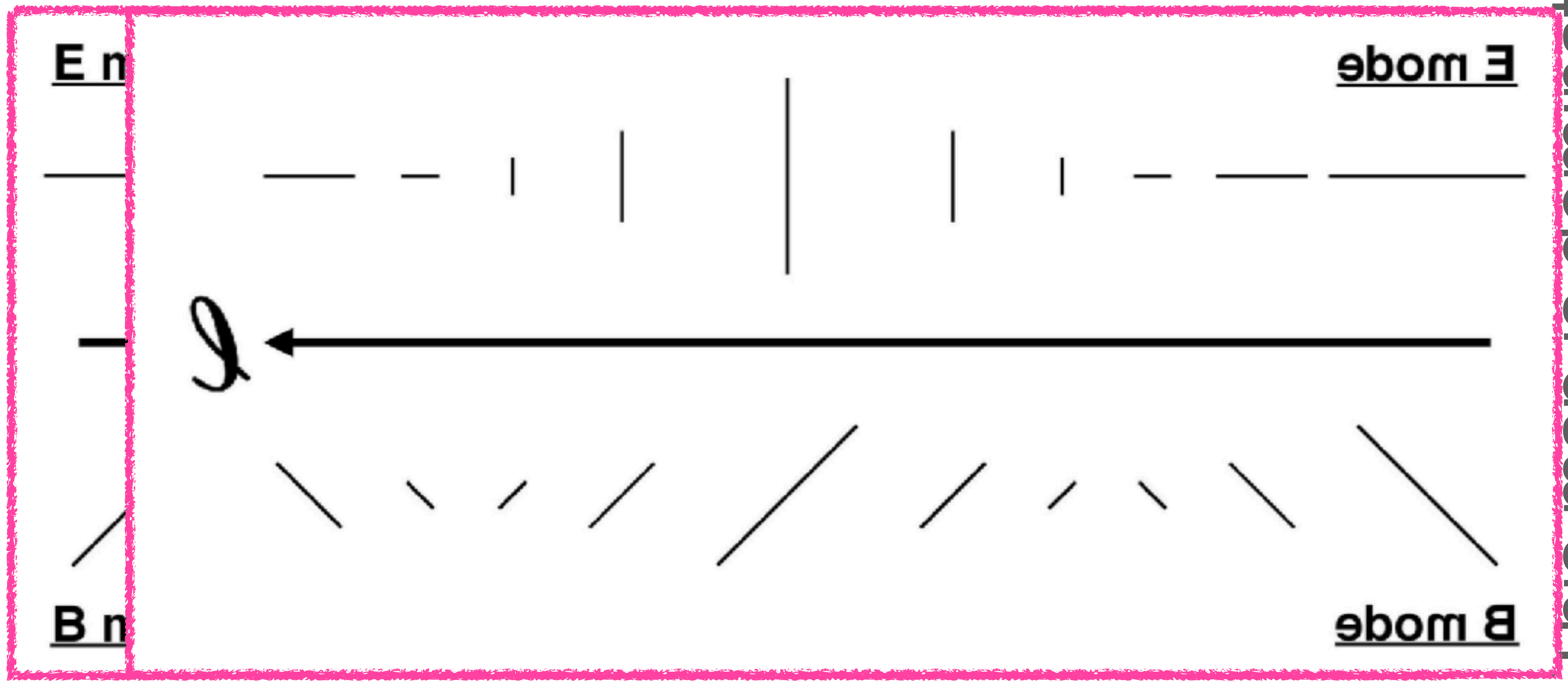


- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

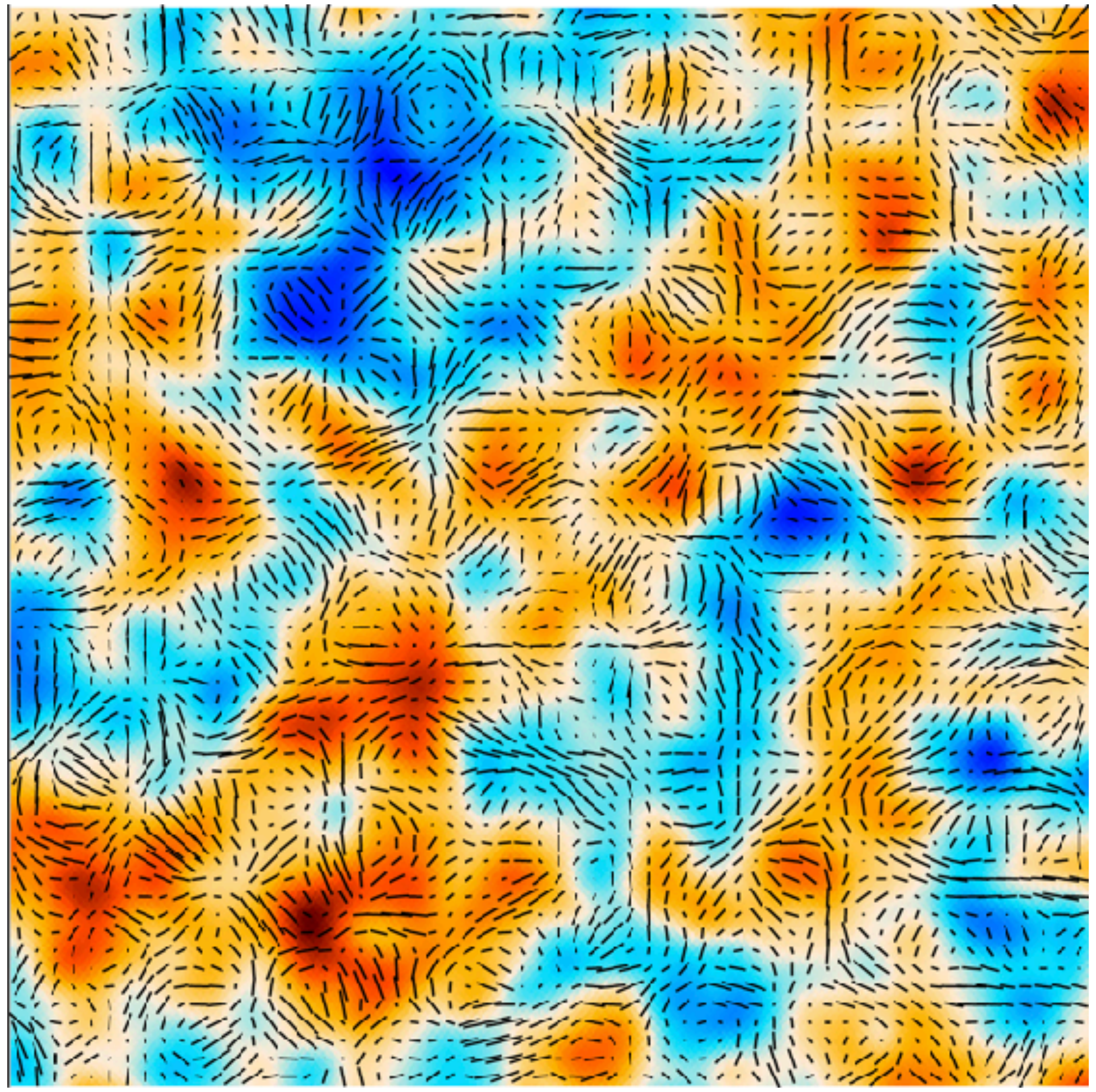
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarisation

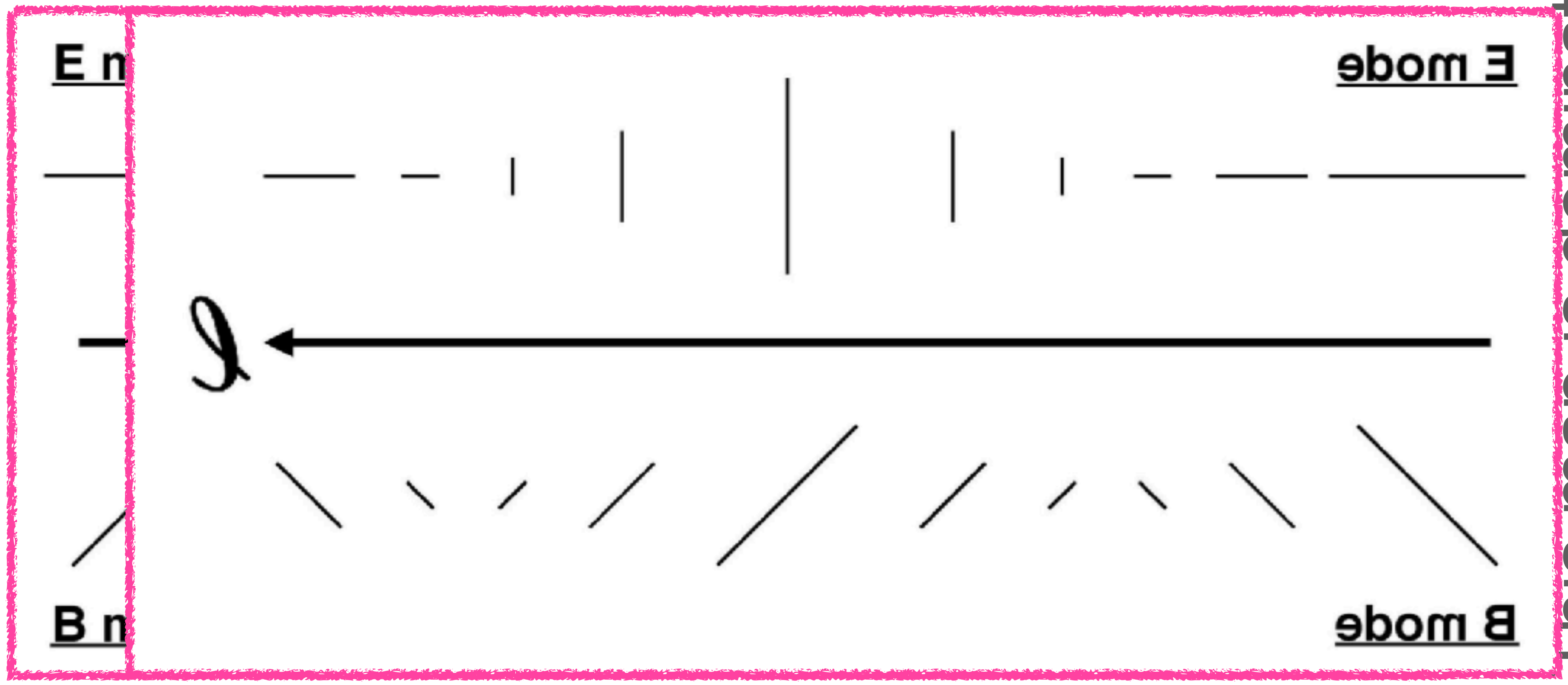


- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

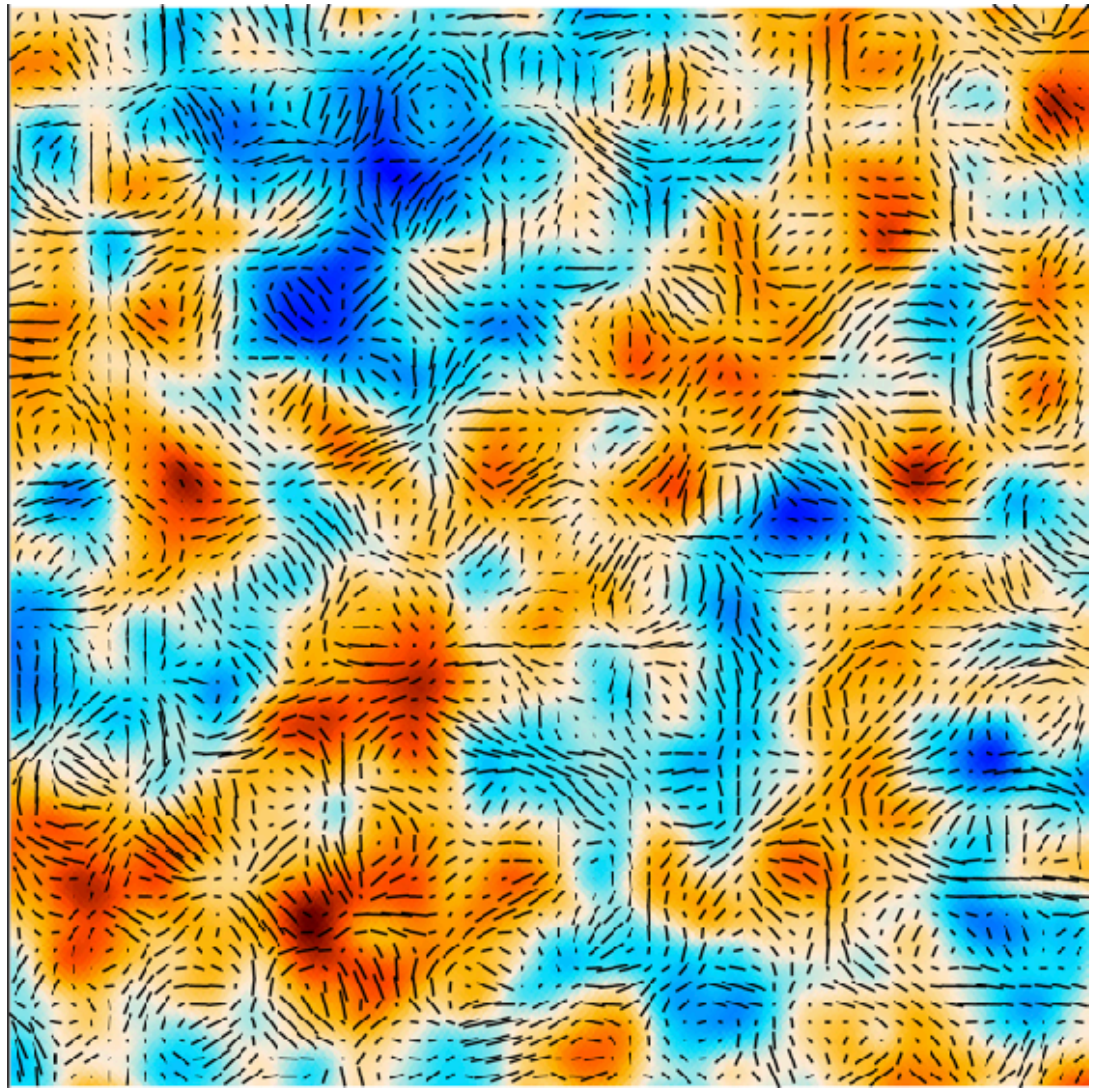
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarisation

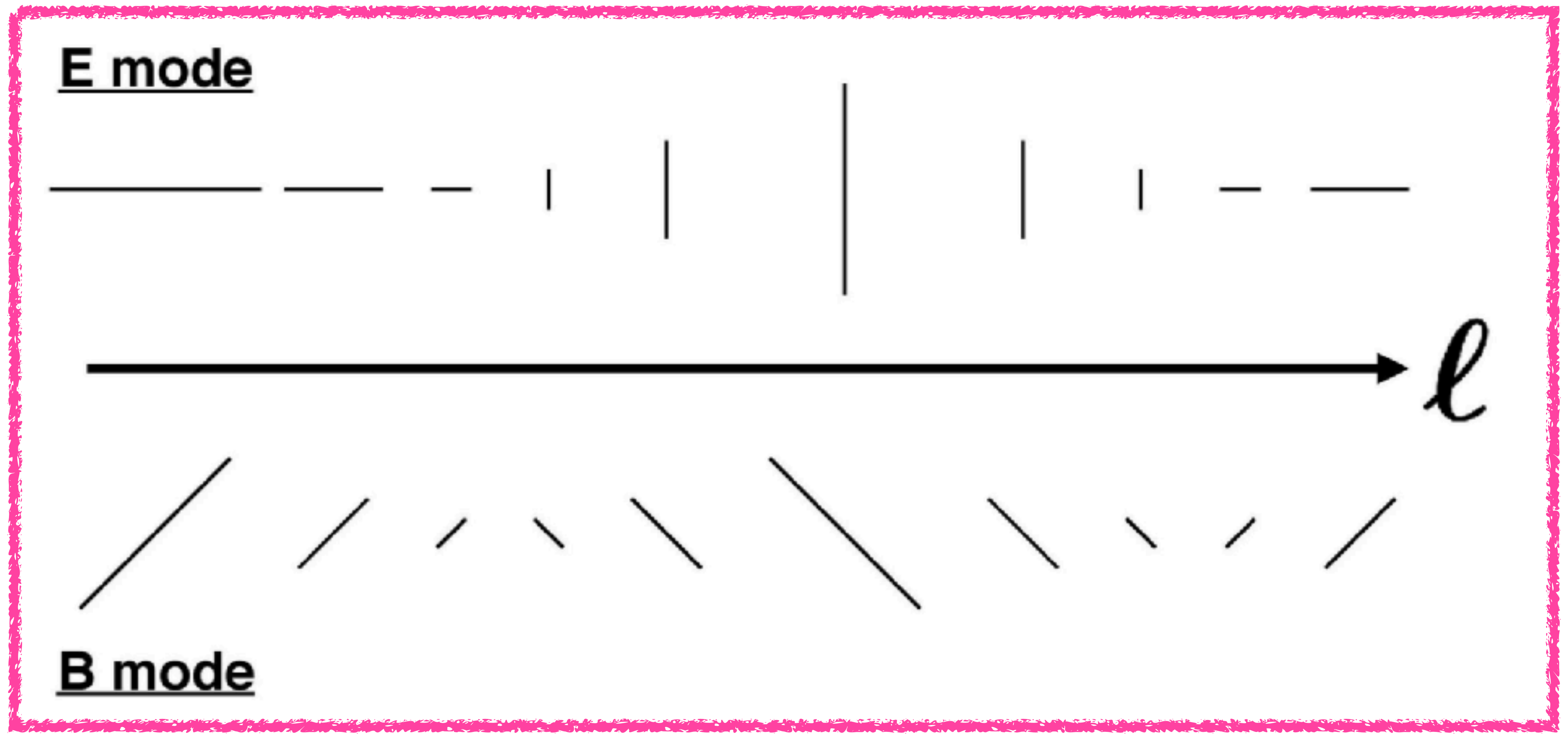


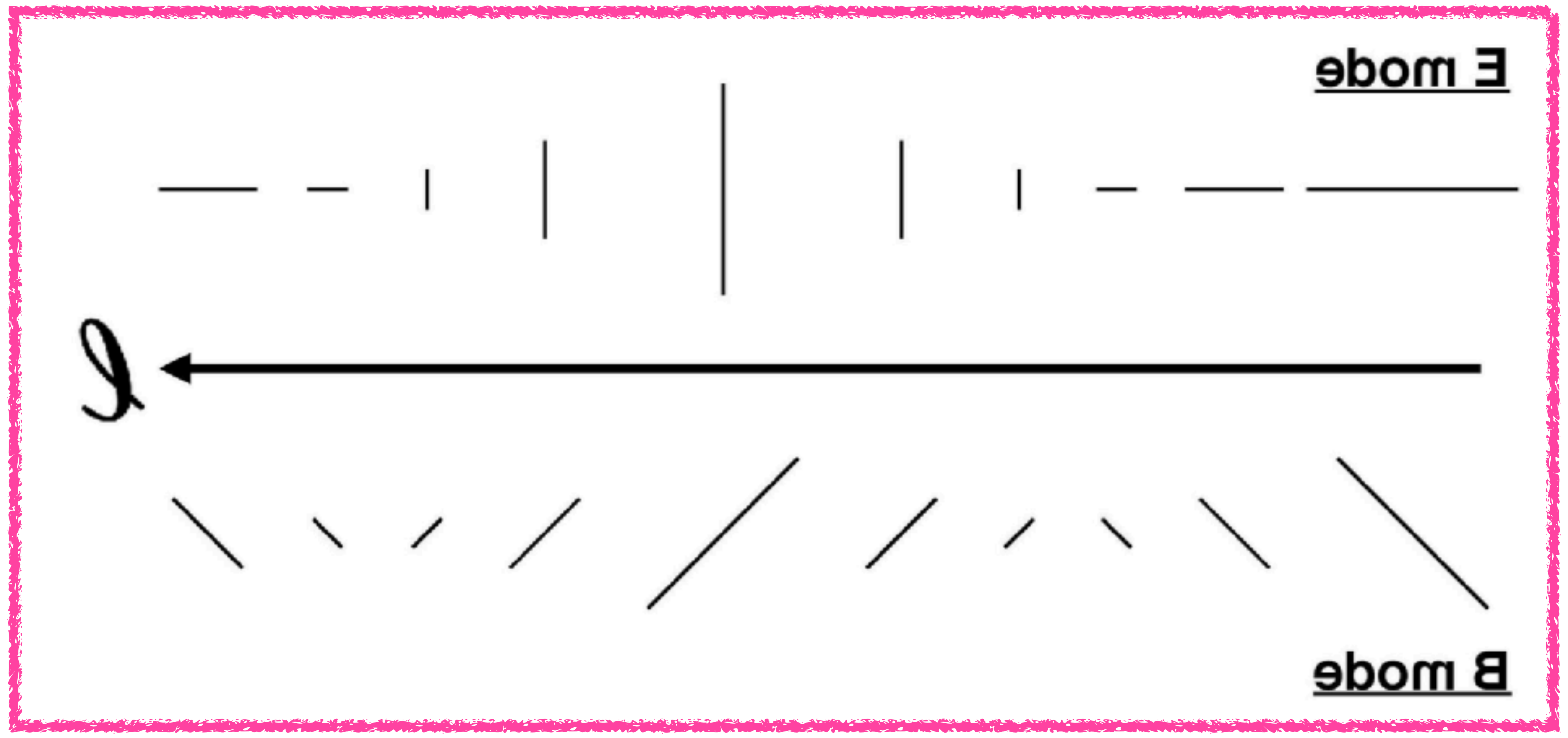
- **E-mode** : Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode** : Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

IMPORTANT”: These “E and B modes” are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

Parity Flip

E-mode remains the same, whereas B-mode changes the sign





- Two-point correlation functions invariant under the parity flip are

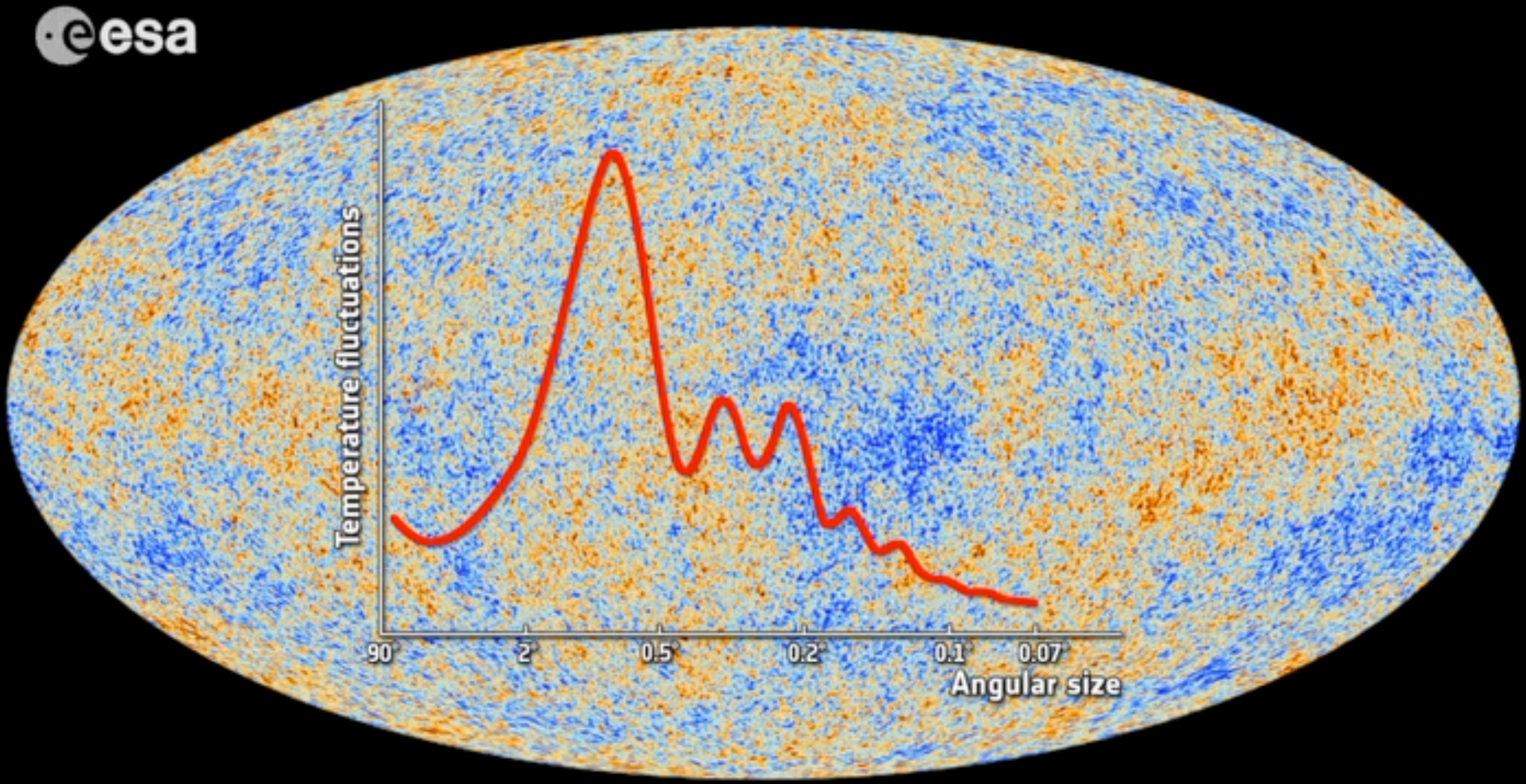
$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

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

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

- The other combinations <TB> and <EB> are not invariant under the parity flip.
  - **We can use these combinations to probe parity-violating physics (e.g., axions)**

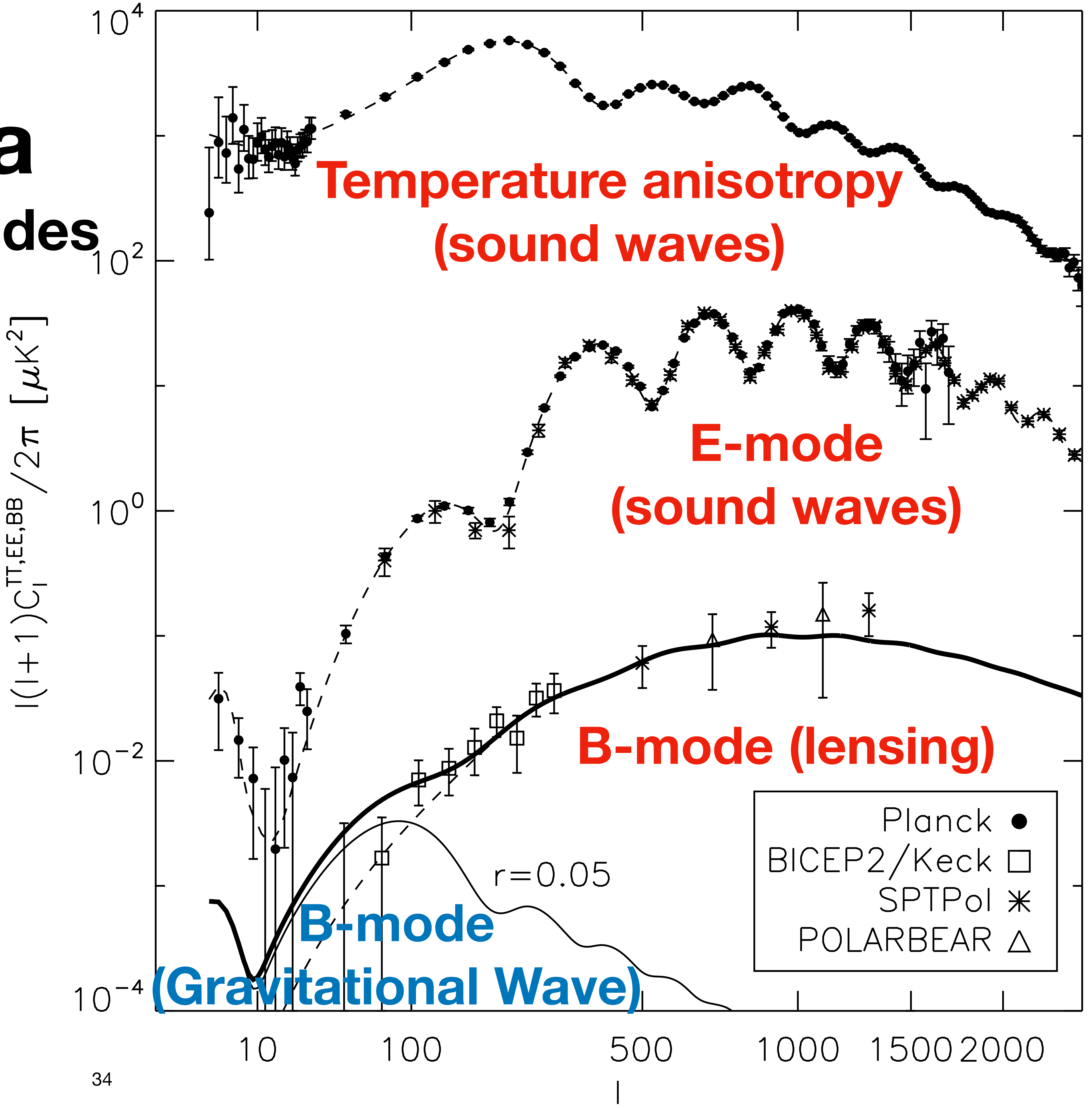
Power Spectrum, Explained



CMB Power Spectra

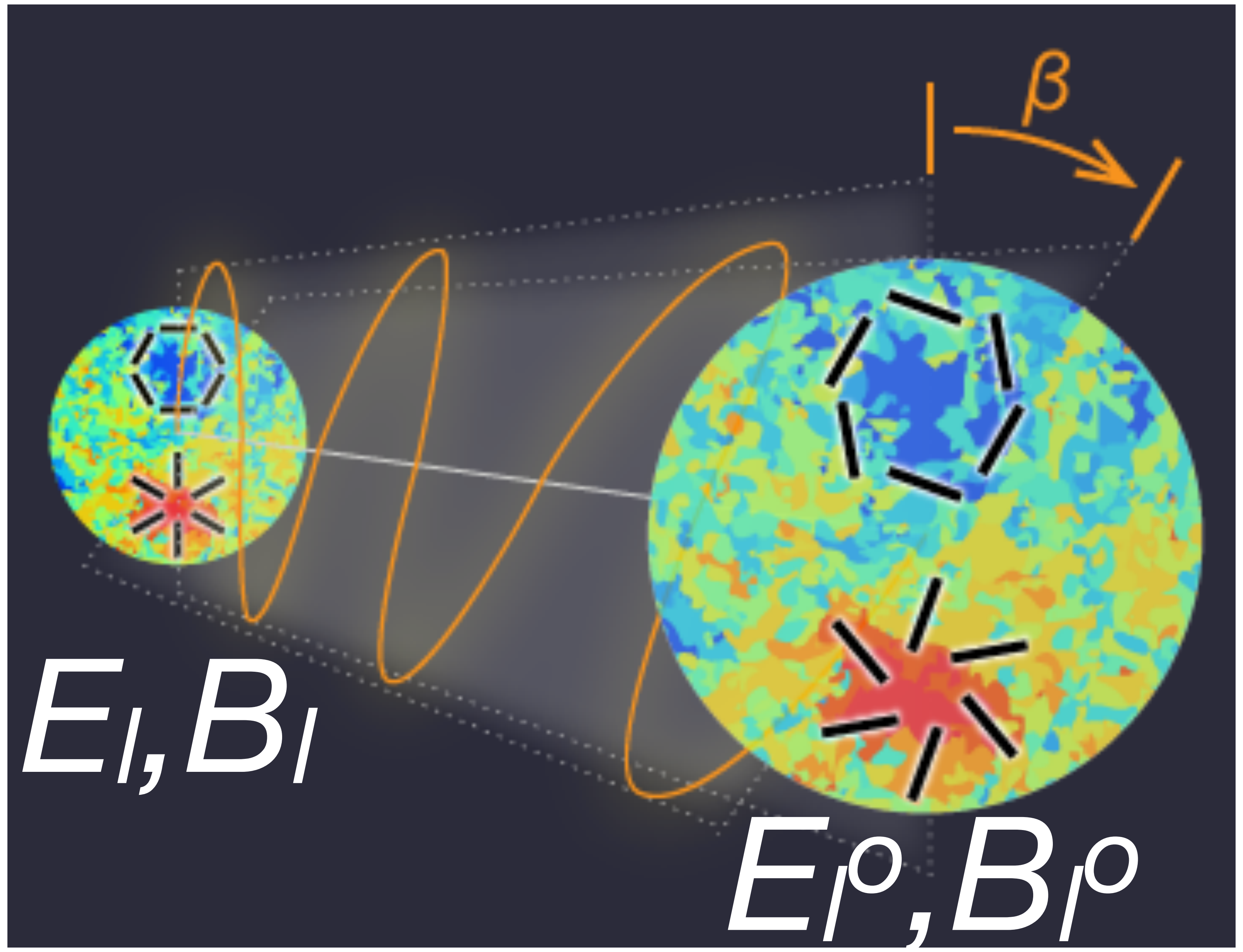
Progress over the last 3 decades

- This is the typical figure that you find in talks and lectures on CMB.
    - The temperature power spectrum and the E- and B-mode polarisation power spectra have been measured well.
- **Our focus is the EB spectrum, which is not shown here.**



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

E-B mixing by rotation of the plane of linear polarisation



- Observed E- and B-mode polarisation, E_l^o and B_l^o, are related to those before rotation as

$$E_\ell^{\rm o} \pm iB_\ell^{\rm o} = (E_\ell \pm iB_\ell)e^{\pm 2i\beta}$$

- which gives

$$E_\ell^{\rm o} = E_\ell \cos(2\beta) - B_\ell \sin(2\beta)$$

$$B_\ell^{\rm o} = E_\ell \sin(2\beta) + B_\ell \cos(2\beta)$$

Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)
Zhao et al. (2015)

Searching for the birefringence

- Computing observed difference between EE and BB spectra,

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

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

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

- We find

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

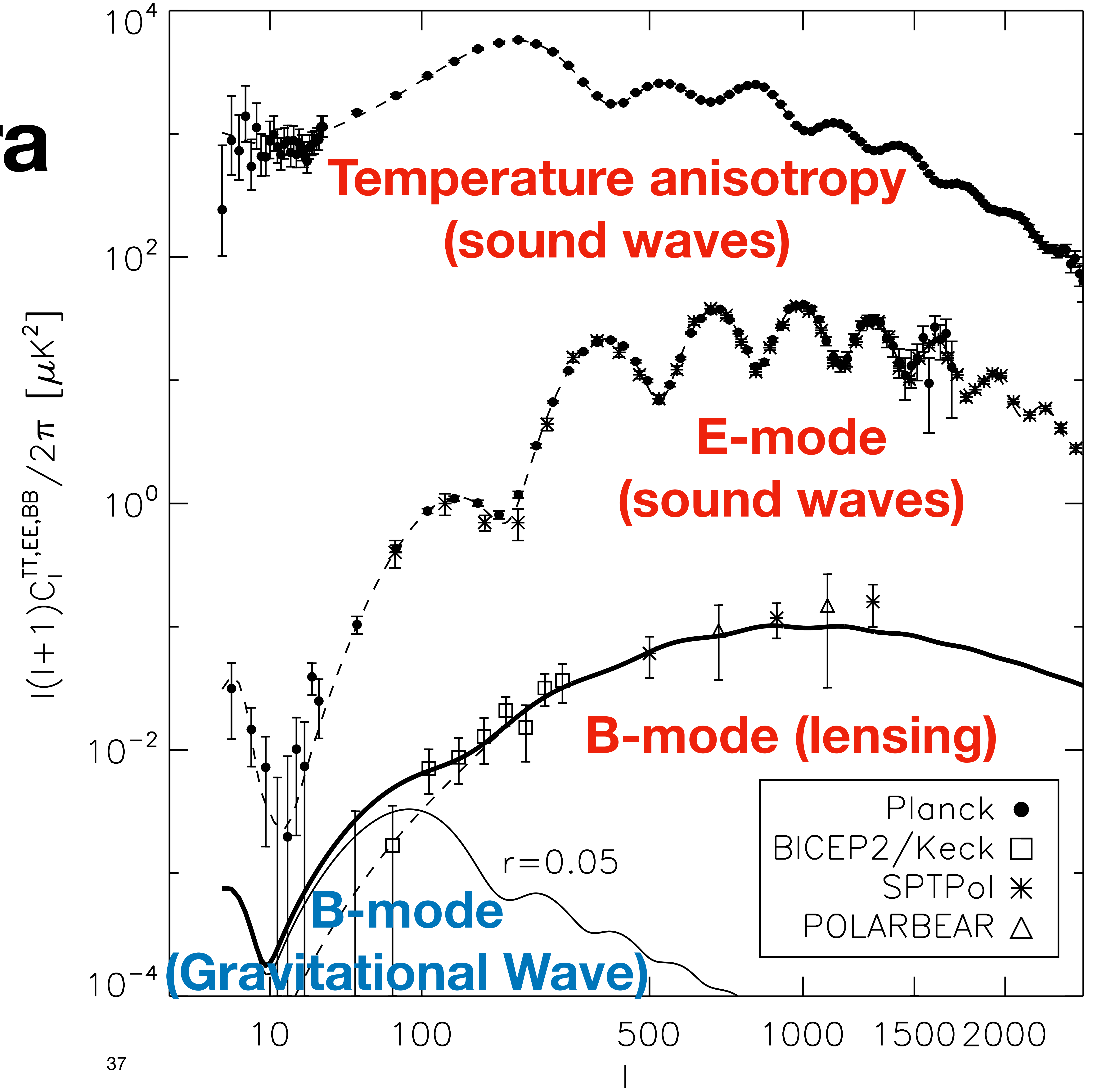
$$= \frac{1}{2}(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}})\tan(4\beta) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

EB is generated by the *difference* between EE and BB spectra.

CMB Power Spectra

EE >> BB!

- **In our Universe, CMB EE is much greater than BB. This makes CMB sensitive to birefringence.**
- This is the typical figure that you find in talks and lectures on CMB.
    - The temperature power spectrum and the E- and B-mode polarisation power spectra have been measured well.
- **Our focus is the EB spectrum, which is not shown here.**

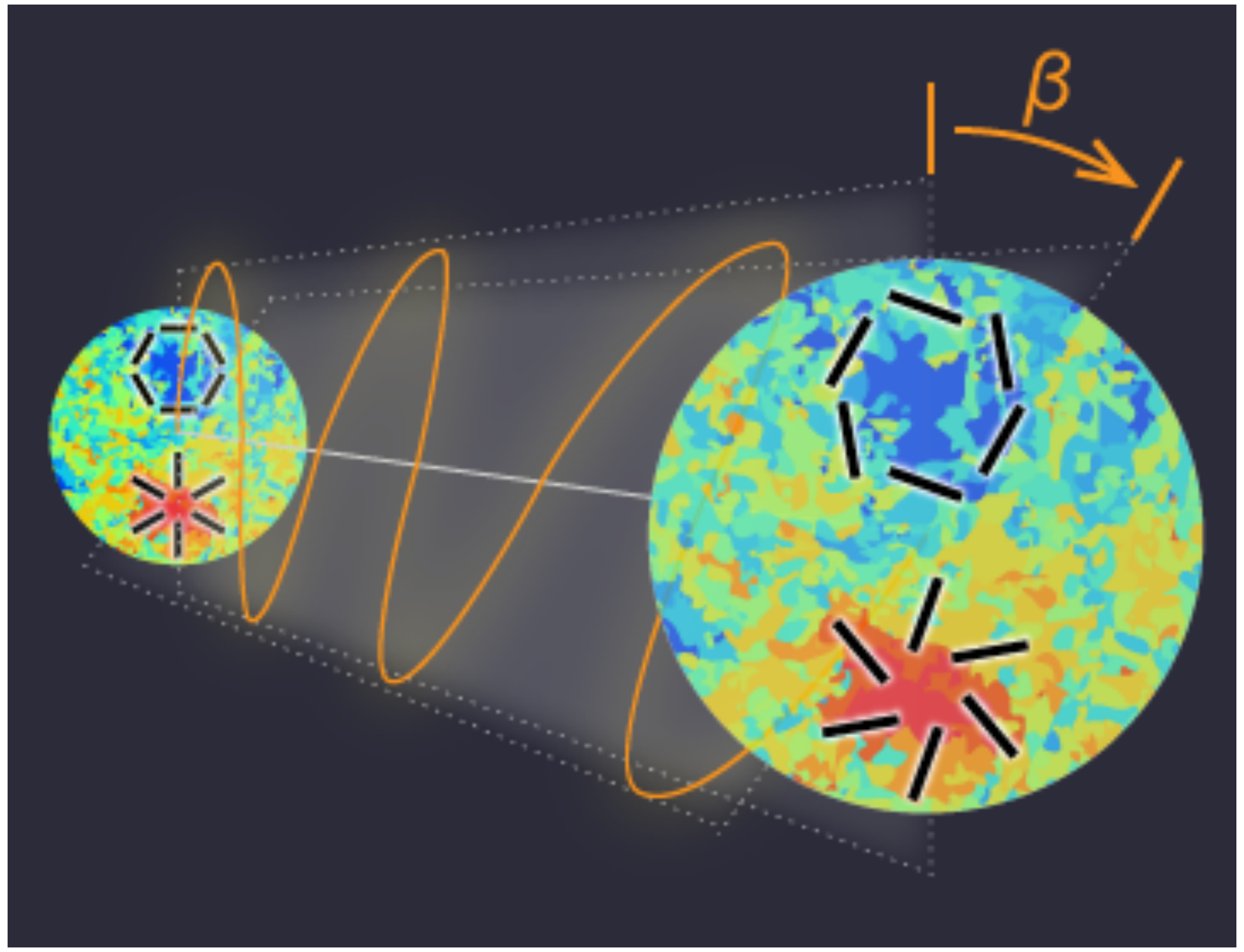


The Biggest Problem: Miscalibration of detectors

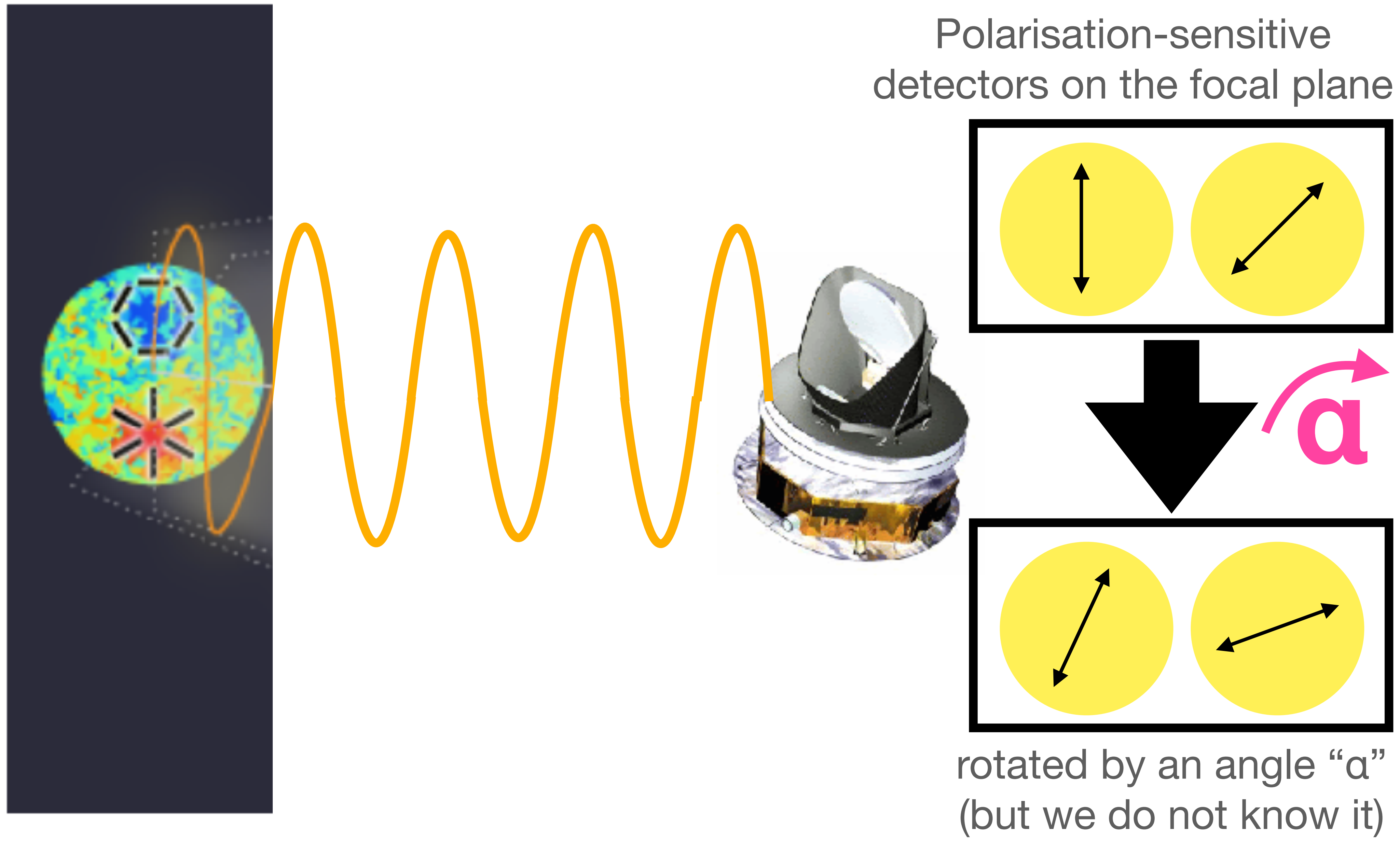
Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

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)
- $\alpha+\beta = 0.07 \pm 0.09$ 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 = 0.07 ± 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

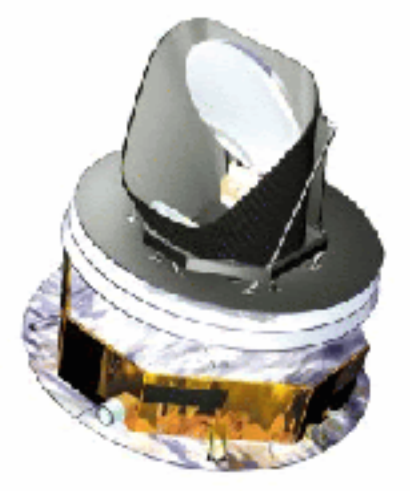
ESA’s Planck

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



ESA's Planck

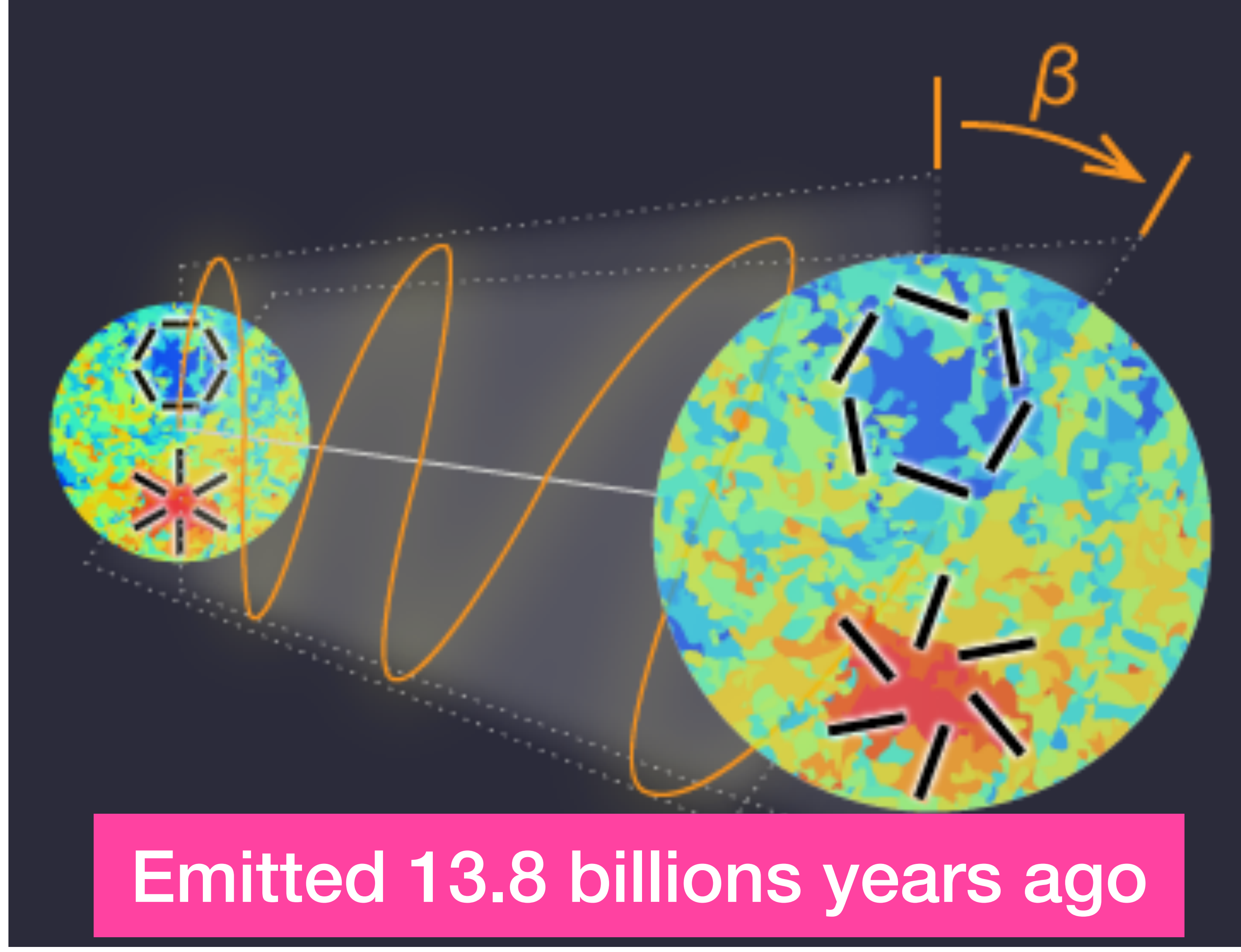
Credit: ESA

Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Searching for the birefringence

Improvement #2 (Minami et al. 2019)



But the source of foreground is much closer!

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

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

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

noise

- Thus,

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

measured

known accurately

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

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?

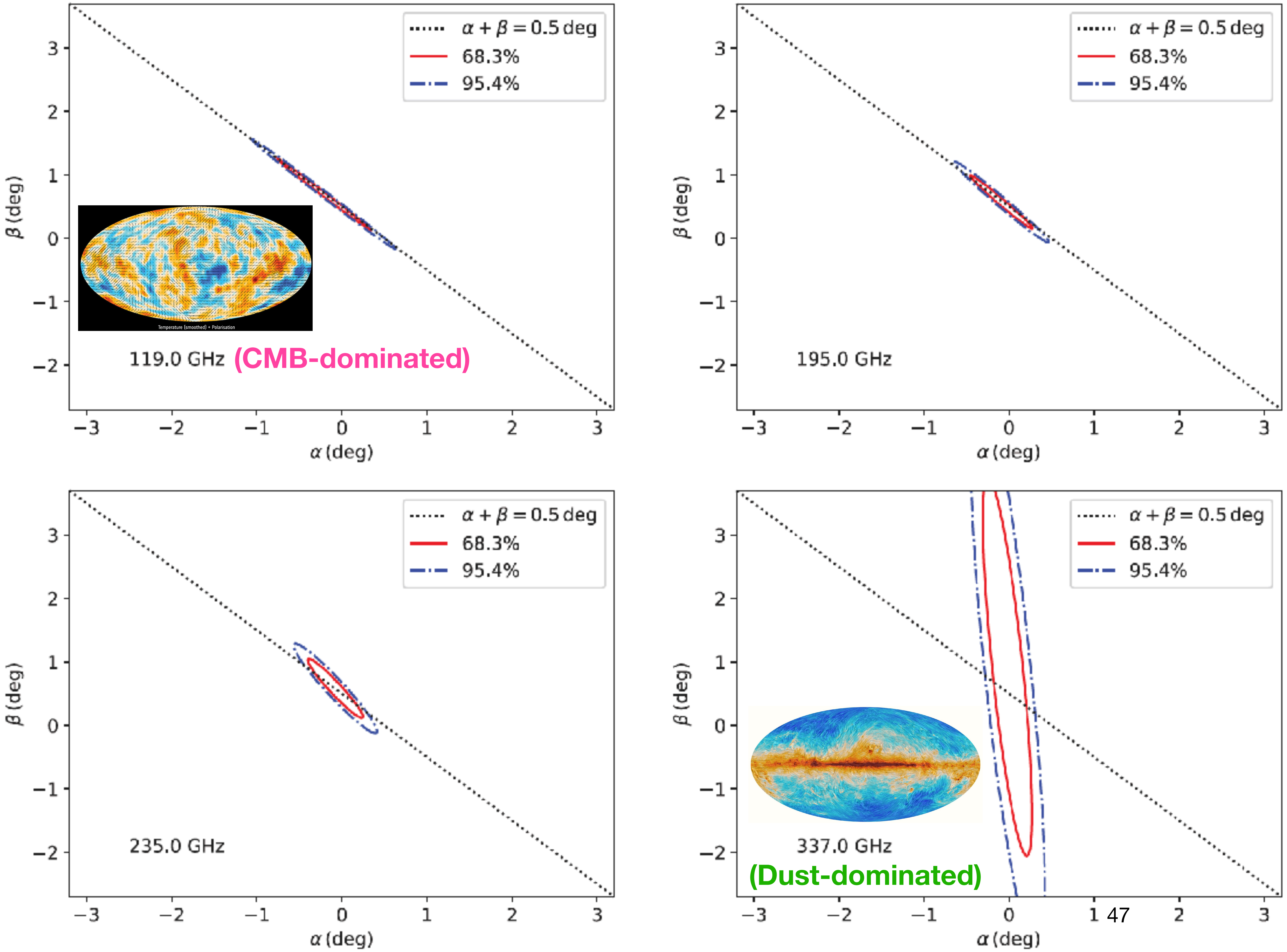
$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right) + \frac{1}{\cos(4\alpha)}\boxed{\langle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

- 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)

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.

PHYSICAL REVIEW LETTERS

Featured in Physics **Editors' Suggestion**

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

Yuto Minami and Eiichiro Komatsu
Phys. Rev. Lett. **125**, 221301 – Published 23 November 2020

Physics See synopsis: Hints of Cosmic Birefringence?

Yuto Minami
(Osaka U.)

Application to the Planck Public Data Release 3 (PR3)

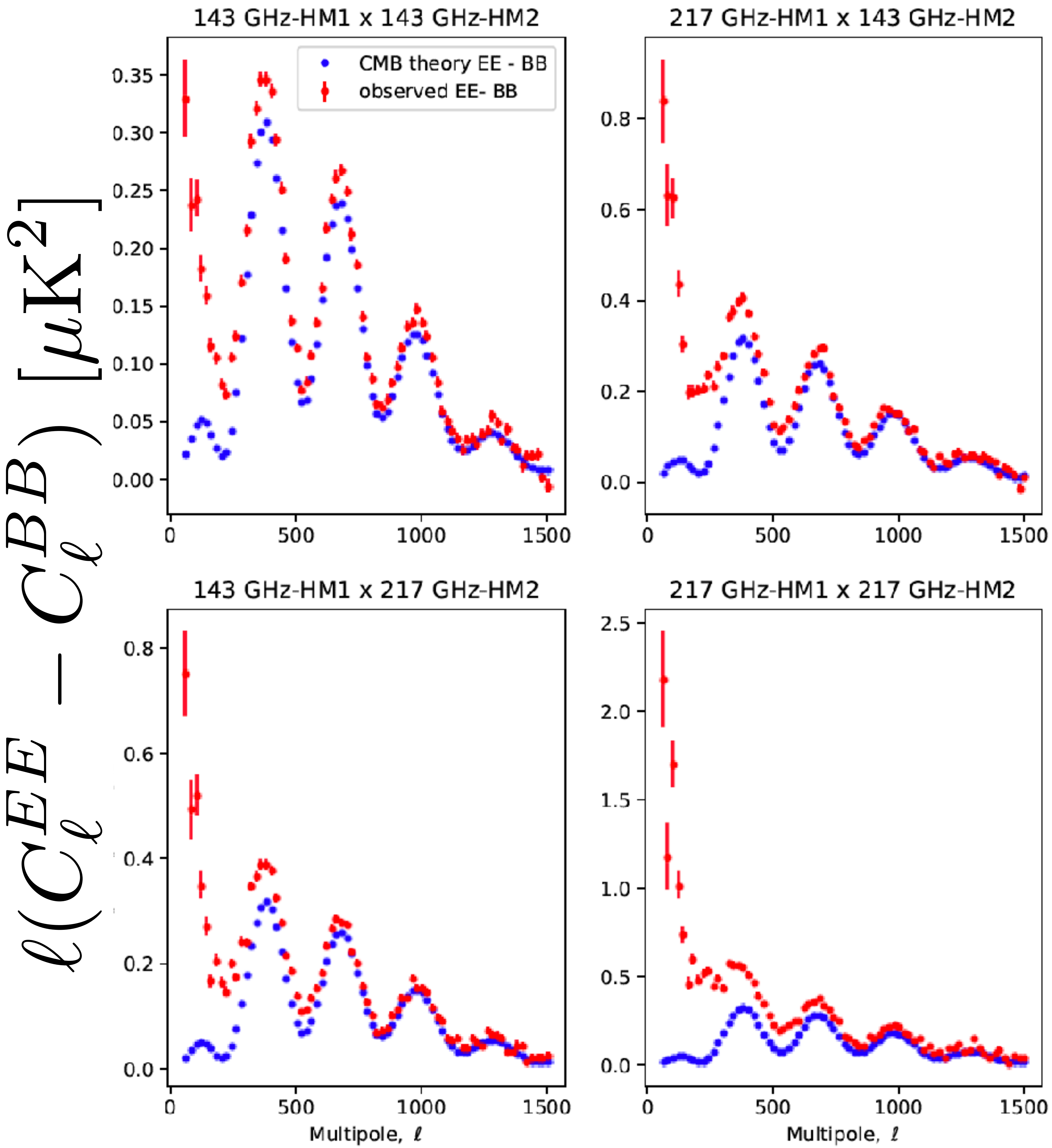
lmin = 51, lmax = 1490 (same as those used by the Planck team)

- Planck High Frequency Instrument (HFI) data (100, 143, 217, 353 GHz)

Main Result: β > 0 at 2.4σ for nearly full-sky data

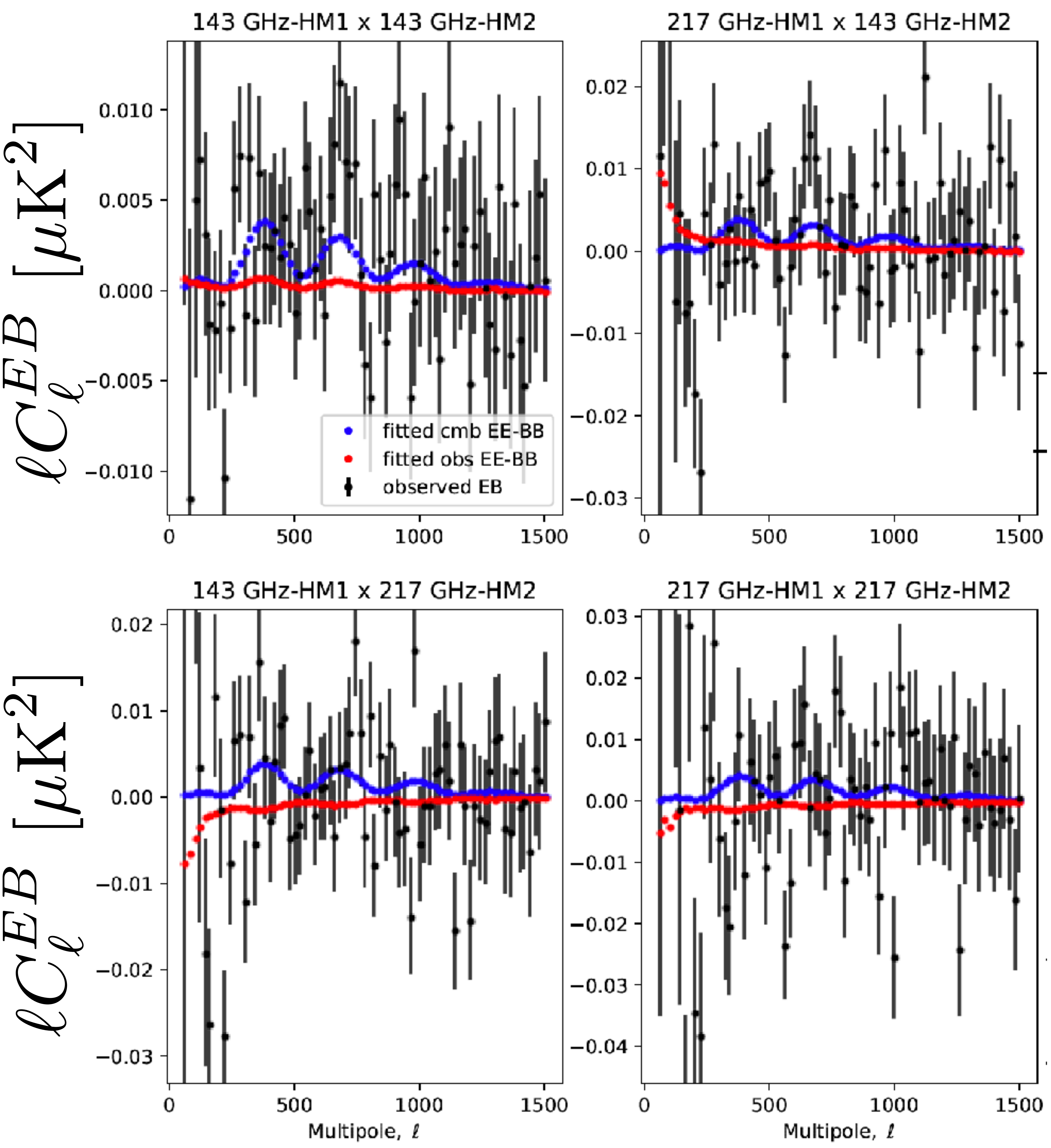
TABLE I. Cosmic birefringence and miscalibration angles from the Planck 2018 polarization data with 1σ (68%) uncertainties

Angles	α_ν=0	Results (deg)
β	0.289 ± 0.048 (This agrees with the result of the Planck team)	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



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

- 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 maybe unknown 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 $\beta = 0.35 \pm 0.14$ 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

Angles	Results (deg)
β	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

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…

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About

Open Access Access by MP

Cosmic Birefringence from the *Planck* Data Release 4

P. Diego-Palazuelos, J. R. Eskilt, Y. Minami, M. Tristram, R. M. Sullivan, A. J. Banday, R. B. Barreiro, H. K. Eriksen, K. M. Górski, R. Keskitalo, E. Komatsu, E. Martínez-González, D. Scott, P. Vielva, and I. K. Wehus

Phys. Rev. Lett. **128**, 091302 – Published 1 March 2022

Patricia Diego-Palazuelos
(Univ. Cantabria, Santander)

Johannes Røsok Eskilt
(Univ. Oslo)

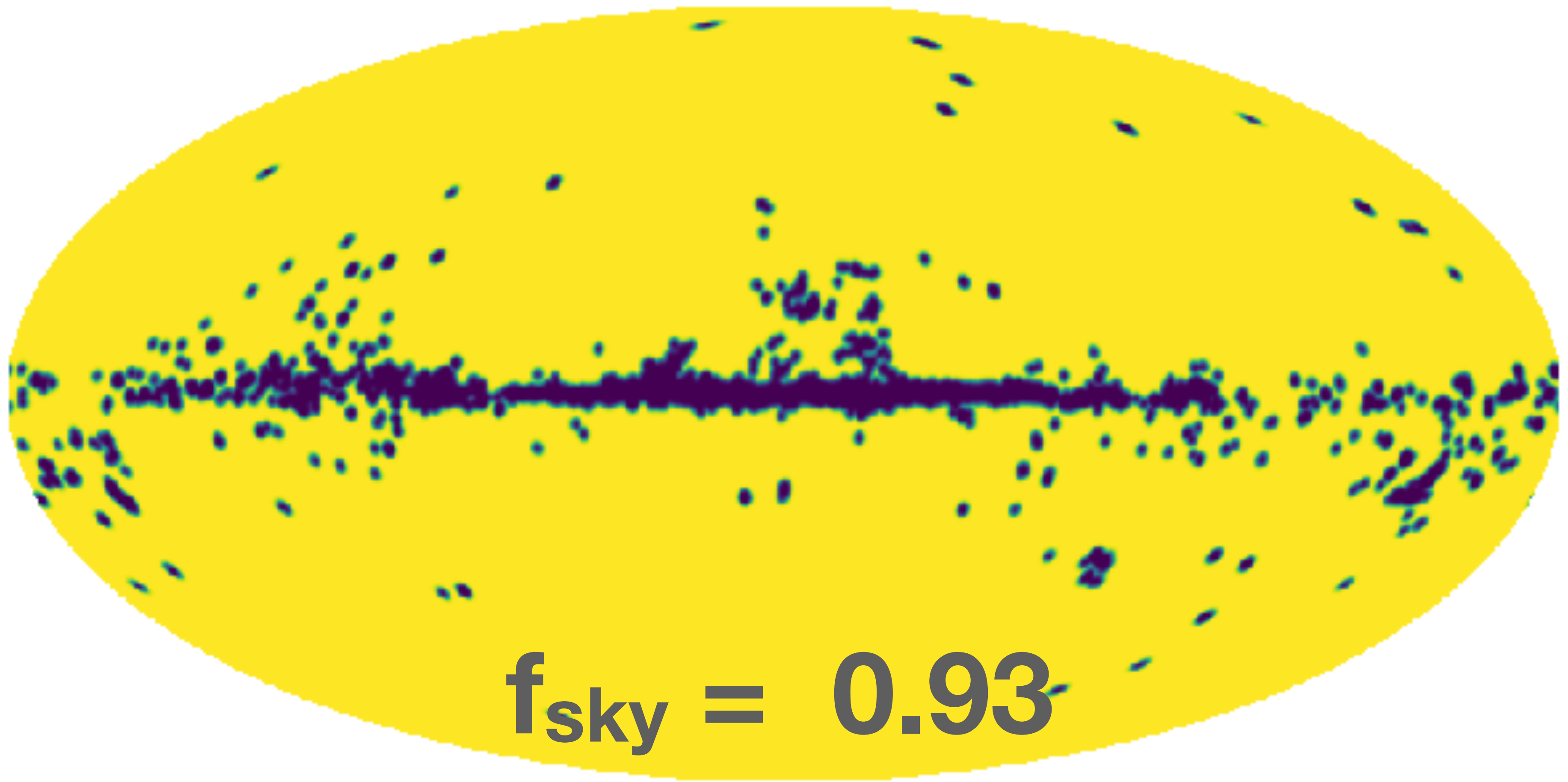
Double corresponding authors.
PhD students. *Young power!*

Diego-Palazuelos, Eskilt, et al. (2022)

Application to the Public Data Release 4 (PR4)

PR4 = "NPIPE" reprocessing of all the Planck data (Planck Collaboration 2020)

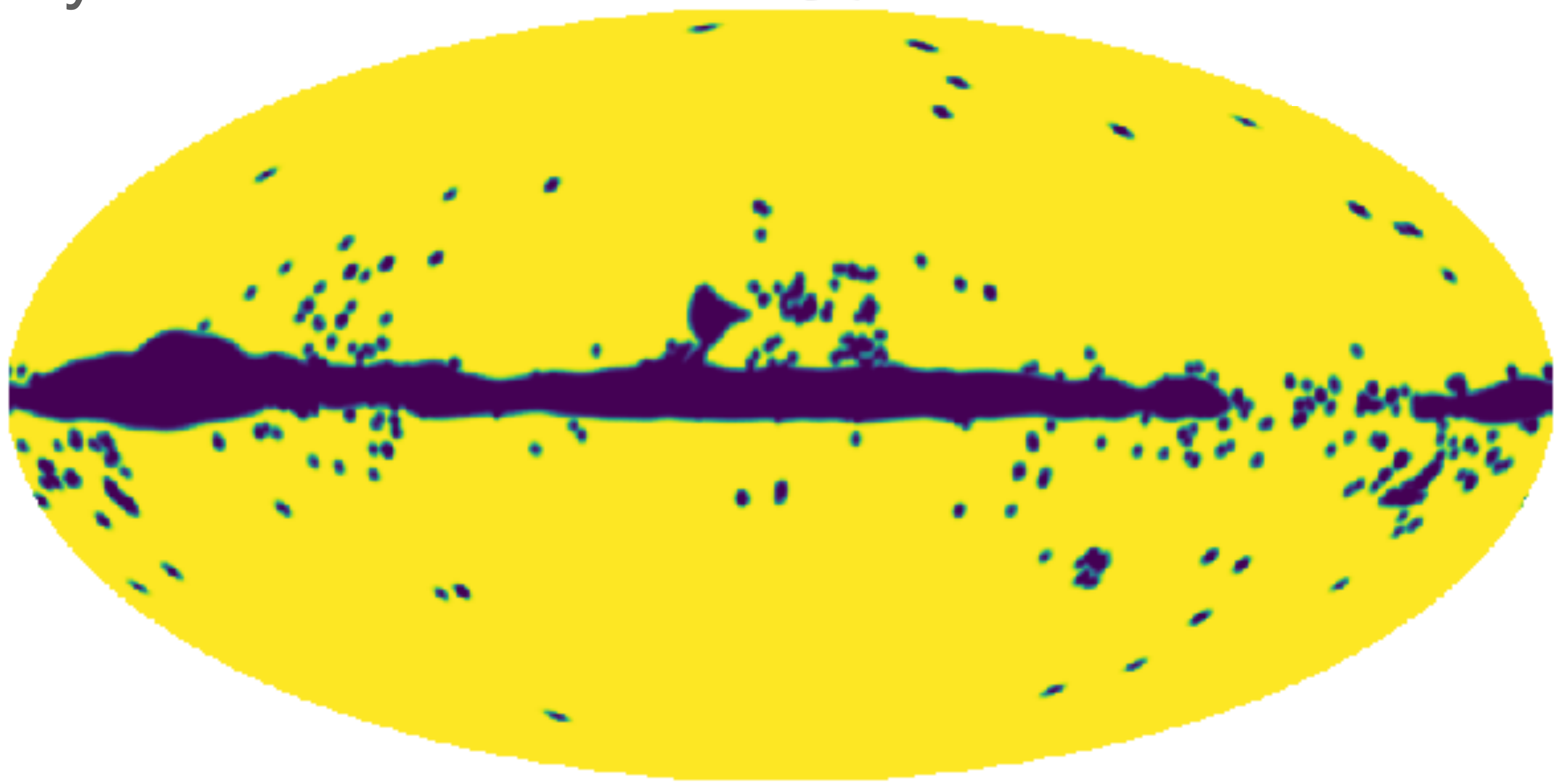
- Planck High Frequency Instrument (HFI) data (100, 143, 217, 353 GHz).
    - **These maps have <u>lower noise</u>** and better-characterised systematics than PR3.
    - We measure power spectra from A/B splits (each frequency band has 2 sets of detectors), to avoid possible correlated noise.
- Masks
    - Unlike for the PR3 analysis, we use the common mask for all frequencies.
    - Bright CO regions, Bright point sources, and four Galactic masks.
    - Fraction of sky used = 0.93, 0.90, 0.85, 0.75 and 0.63.



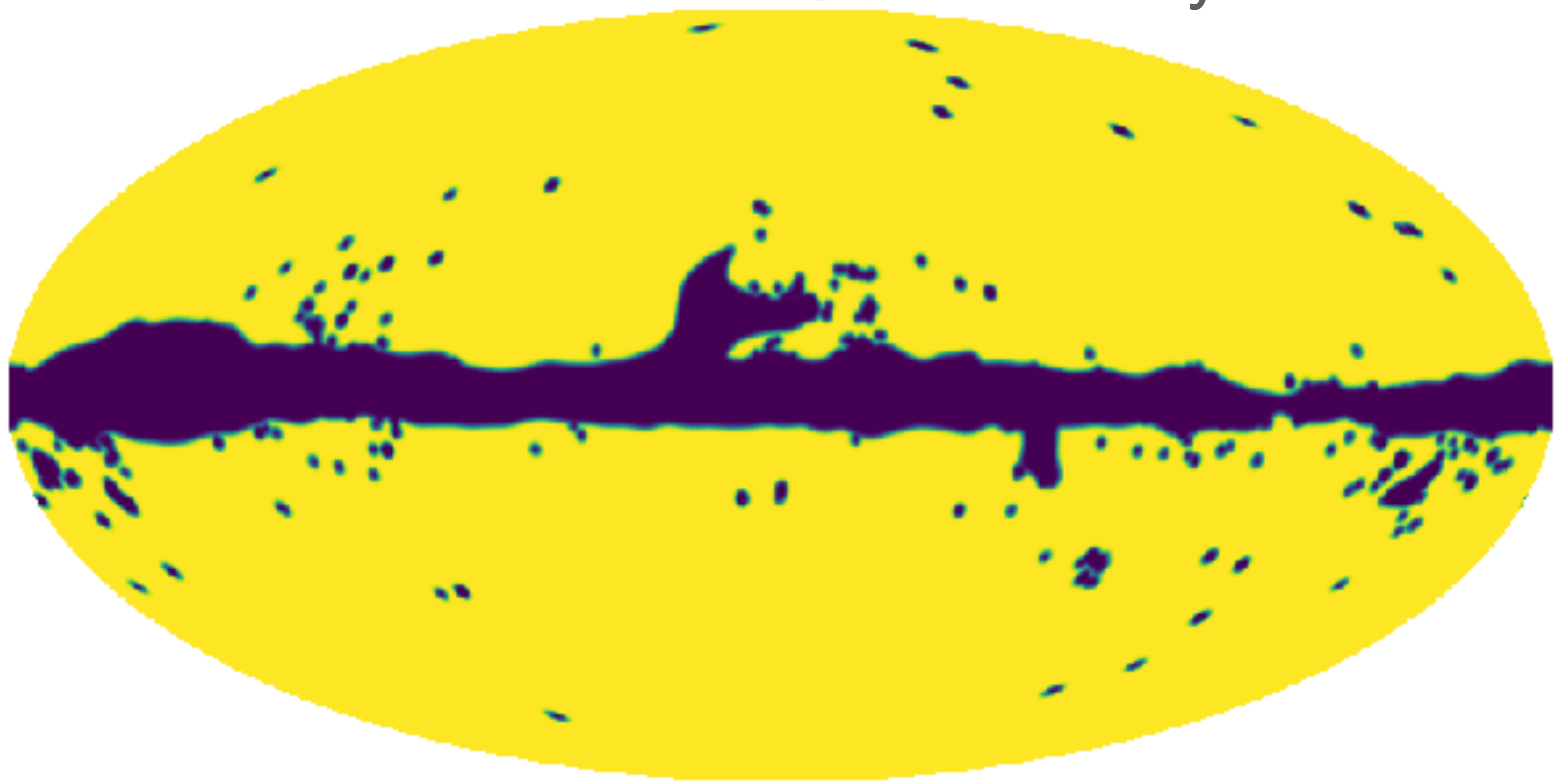
f_{sky} = **0.93**

= nearly full sky

f_{sky} = 0.90

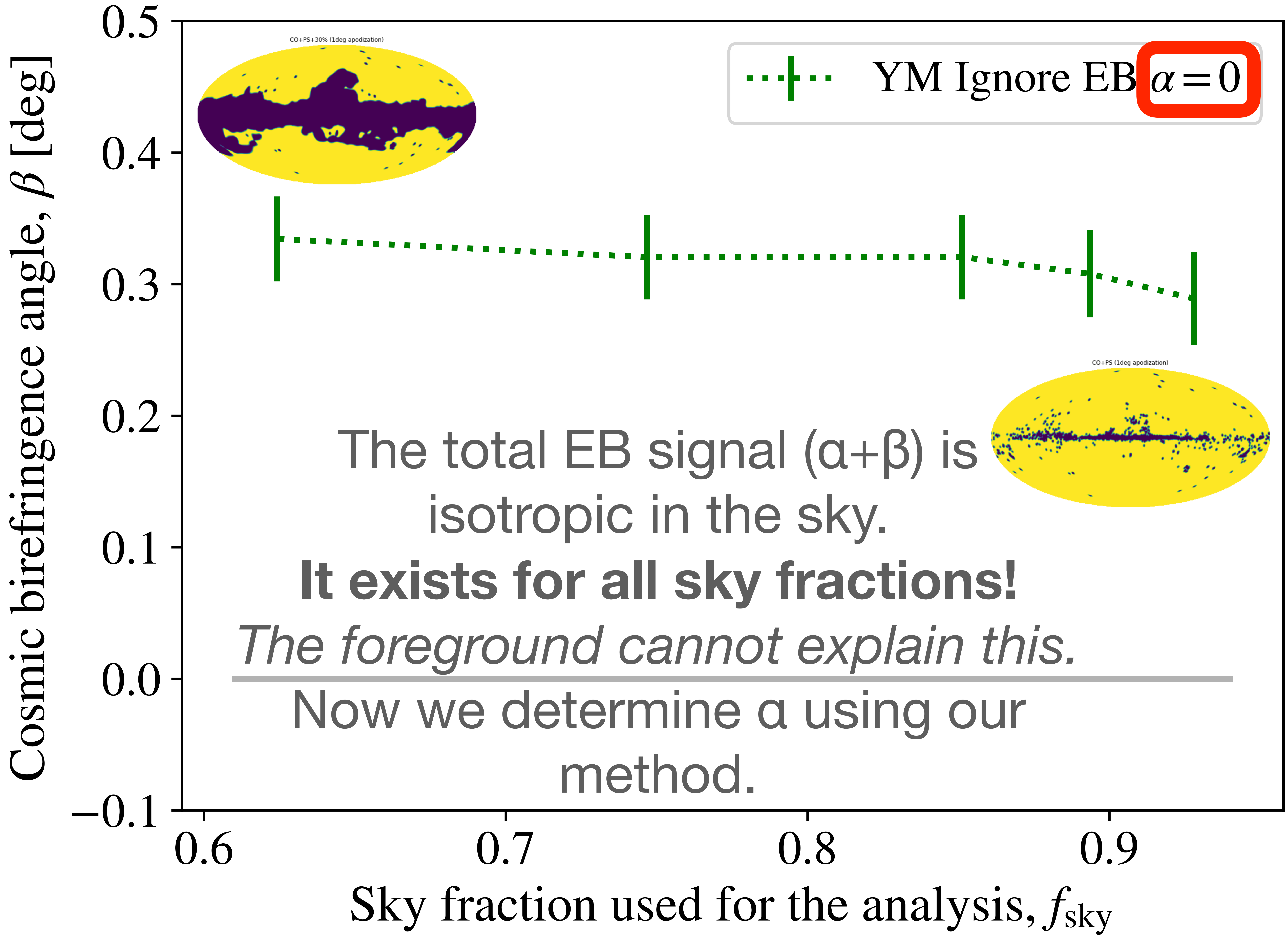


f_{sky} = 0.85



f_{sky} = 0.75

f_{sky} = 0.63



YM Ignore EB α = 0
CO+PS+30% (1deg apodization)
CO+PS (1deg apodization)
The total EB signal (α+β) is isotropic in the sky.
It exists for all sky fractions!
The foreground cannot explain this.
Now we determine α using our method.
Cosmic birefringence angle, β [deg]
Sky fraction used for the analysis, f_sky
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.6
0.7
0.8
0.9

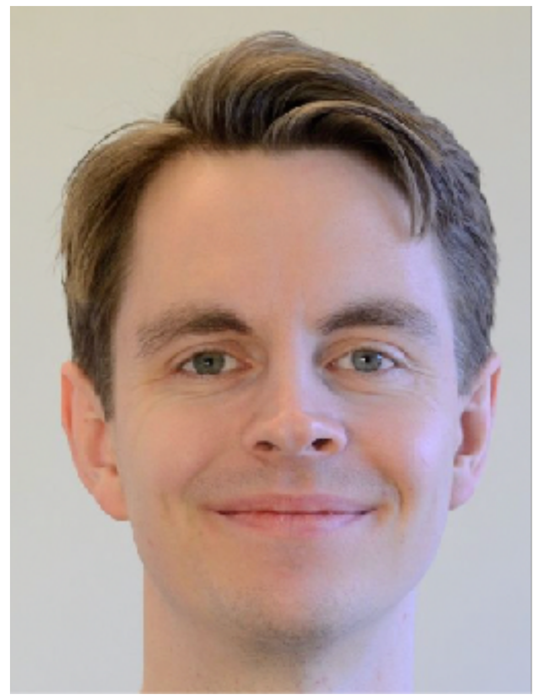
Diego-Palazuelos, Eskilt, et al. (2022)

Full-sky result, without accounting for foreground EB

The PR3 result confirmed, with a smaller statistical uncertainty

- We find **β = 0.30 ± 0.11 deg** (68% CL) for nearly full sky -> a 2.7σ result
  - Four independent pipelines were compared and the results agreed.

PDP JRE YM MT

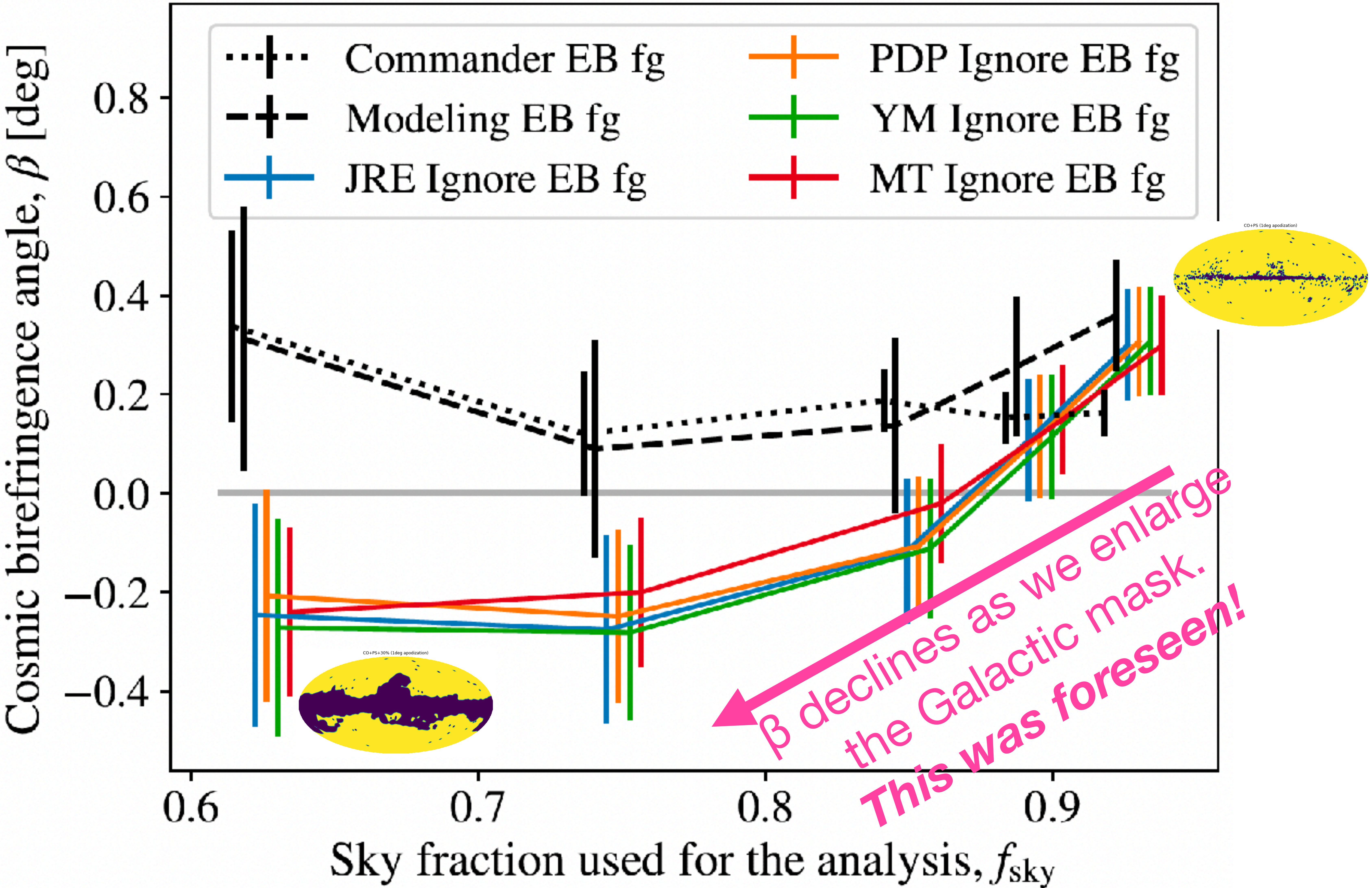



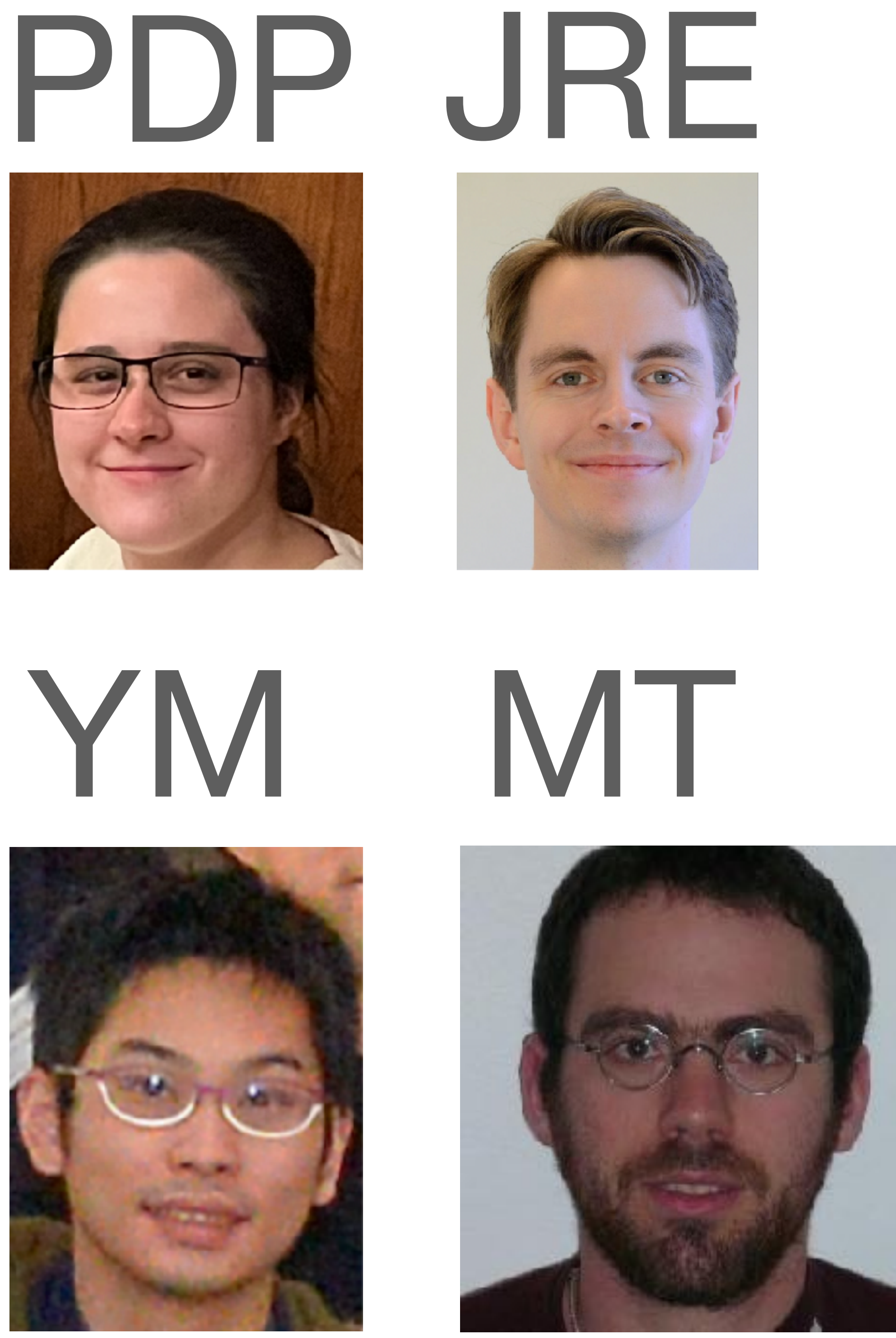
  - More statistical significance than the 2.4σ result of the PR3, 0.35 ± 0.14 deg.

Diego-Palazuelos, Eskilt, et al. (2022)

How do the results change with f_{sky}?

Hint for the foreground EB for smaller f_{sky}

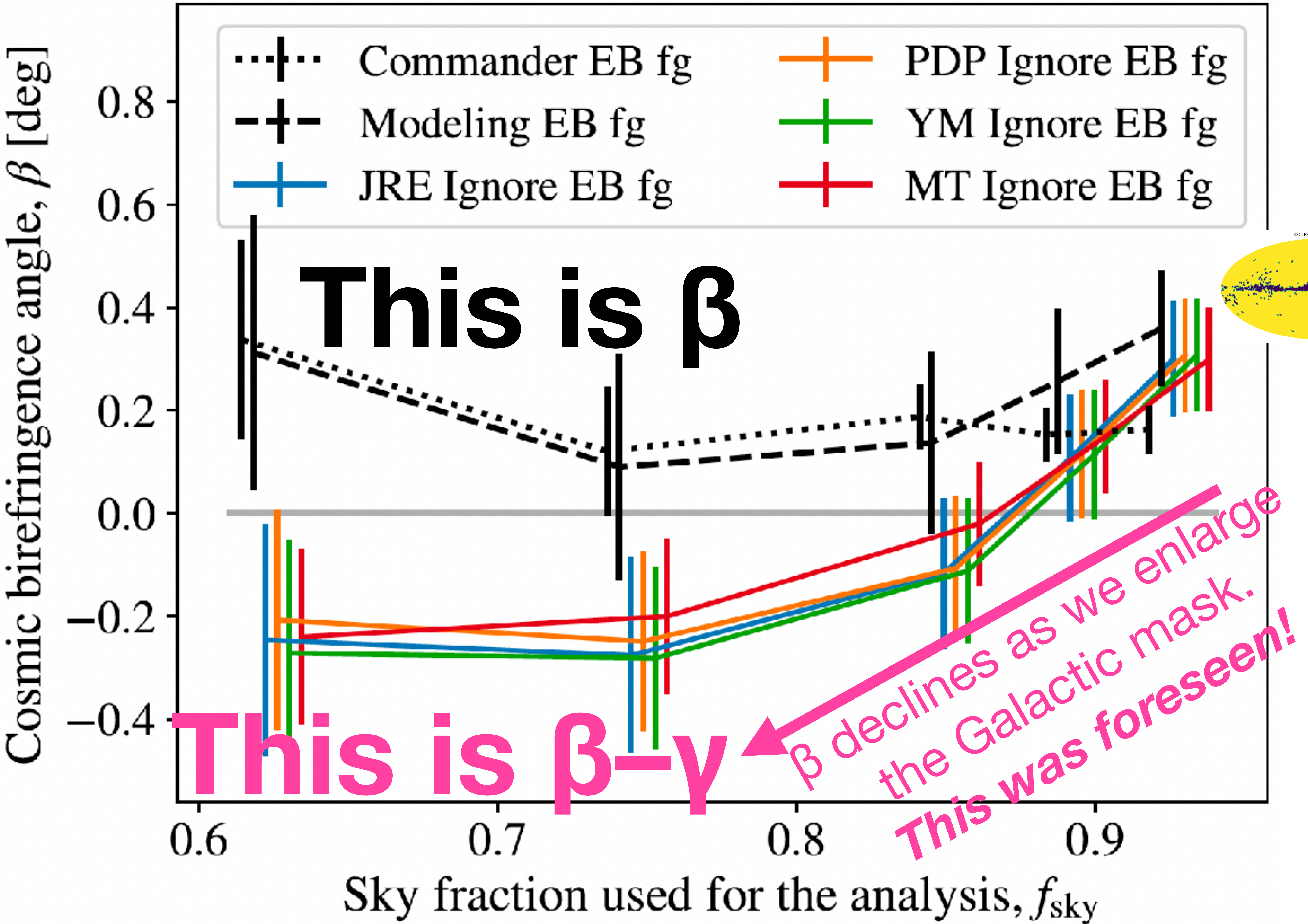


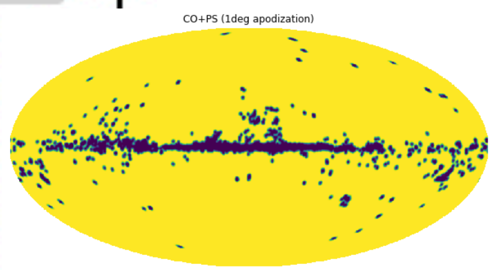


Diego-Palazuelos, Eskilt, et al. (2022)

How do the results change with f_{sky}?

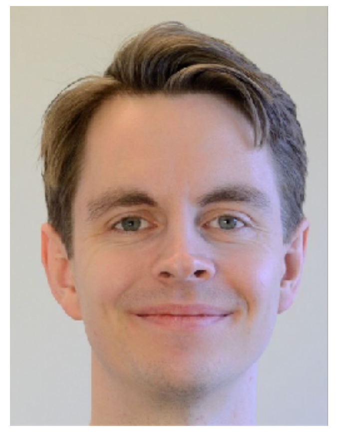
Hint for the foreground EB for smaller f_{sky}





PDP

JRE



YM

MT

Including the foreground EB

Introducing a new angle, “γ”

- When we do not ignore the intrinsic foreground EB, the *observed* foreground EB (including the miscalibration angle contribution, α) is given by

$$C_\ell^{EB,\mathrm{FG,o}} = \frac{1}{2}\sin(4\alpha)\left(C_\ell^{EE,\mathrm{FG}} - C_\ell^{BB,\mathrm{FG}}\right) + C_\ell^{EB,\mathrm{FG}}\cos(4\alpha)$$

new term

- Using a formula for trigonometric functions,

$$A\sin\varphi + B\cos\varphi = \sqrt{A^2+B^2}\sin(\varphi+\theta), \quad \tan\theta = B/A$$

- We obtain

α -> α+γ

$$C_\ell^{EB,\mathrm{FG,o}} = \sqrt{J_\ell^2 + (C_\ell^{EB,\mathrm{FG}})^2}\sin(4\alpha + 4\gamma_\ell)$$

$$\begin{cases} J_\ell \equiv \frac{1}{2}\left(C_\ell^{EE,\mathrm{FG}} - C_\ell^{BB,\mathrm{FG}}\right) \\ \tan(4\gamma_\ell) \equiv C_\ell^{EB,\mathrm{FG}}/J_\ell \end{cases}$$

Relating EB to TB

Here comes fascinating (unknown) physics of dust polarisation

- **How do we model the new angle γ?**
    - We don't really know for sure yet. *This is a fascinating opportunity for Galactic science!*
- Nonetheless, there may be a clue from the dust TB correlation.
    - **Discovery of a non-zero (positive) dust TB correlation** by the Planck collaboration was a surprise.
    - We still do not know its origin (see Huffenberger et al. 2020 and Clark et al. 2021 for the first attempts to explain it).
    - However, it seems reasonable to relate the possible dust EB correlation to the dust TB correlation.

Relating EB to TB

Here comes fascinating (unknown) physics of dust polarisation

- **So, a pretty generic approach:**

$$\frac{C_\ell^{EB,\mathrm{dust}}}{C_\ell^{EE,\mathrm{dust}}} \propto \frac{C_\ell^{TB,\mathrm{dust}}}{C_\ell^{TE,\mathrm{dust}}}$$

This is unknown

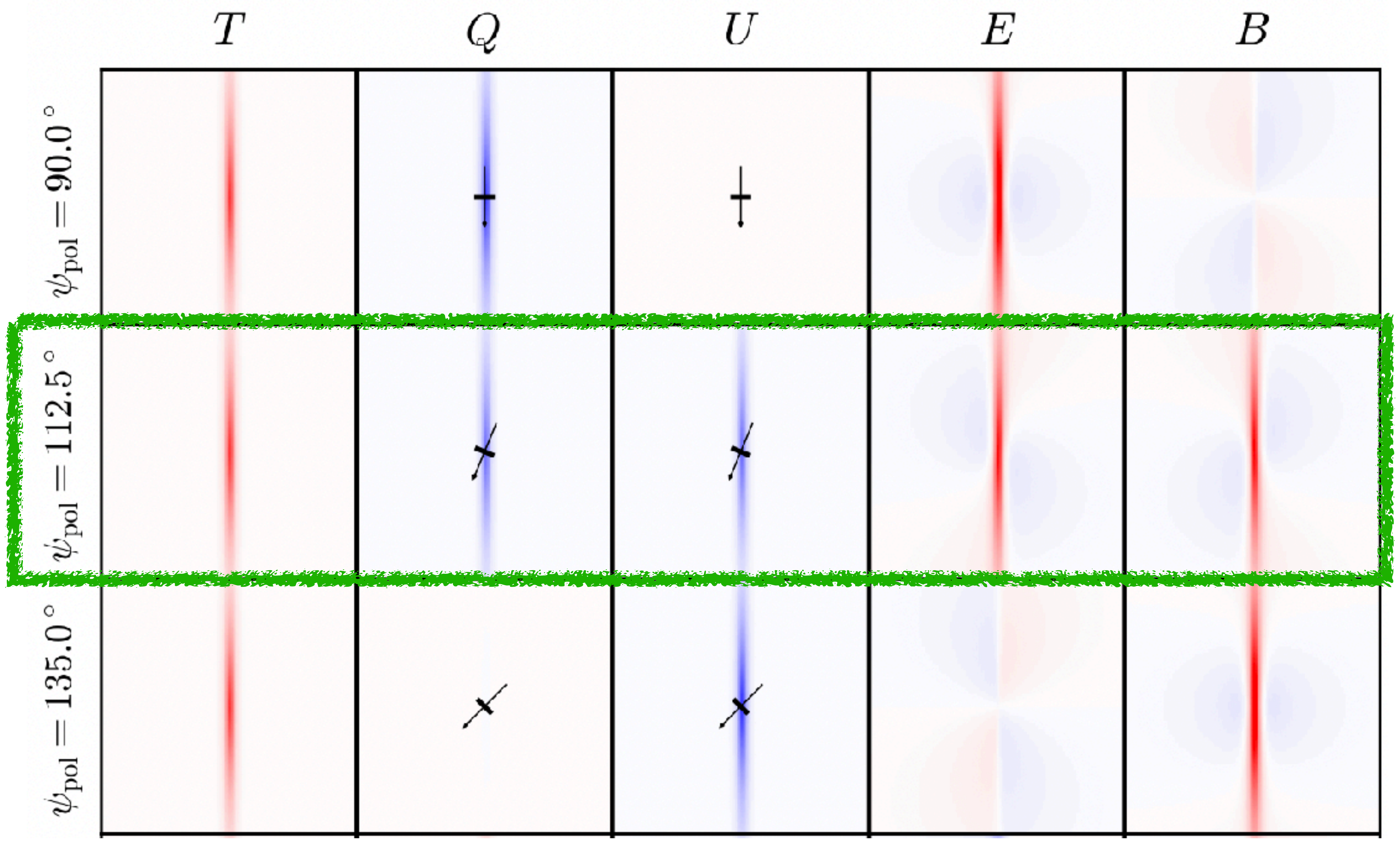
Measured well!

Measured well!

Measured well!

TE, TB, and EB correlation from a filament

Huffenberger, Rotti & Colins (2020)



- **Misalignment of filaments and magnetic fields creates TE>0, TB>0 and EB>0**

Relating EB to TB

Here comes fascinating (unknown) physics of dust polarisation

- **How do we model the new angle γ?**
  - Our *ansatz*, motivated by a physical consideration of Clark et al. (2021):

$$\begin{cases} C_\ell^{EB,\mathrm{dust}} = \boxed{A_\ell} C_\ell^{EE,\mathrm{dust}} \sin(4\psi_\ell^{\mathrm{dust}}) \\ \psi_\ell^{\mathrm{dust}} = \frac{1}{2}\arctan(C_\ell^{TB,\mathrm{dust}}/C_\ell^{TE,\mathrm{dust}}) \end{cases}$$

Free l-dependent amplitude parameters

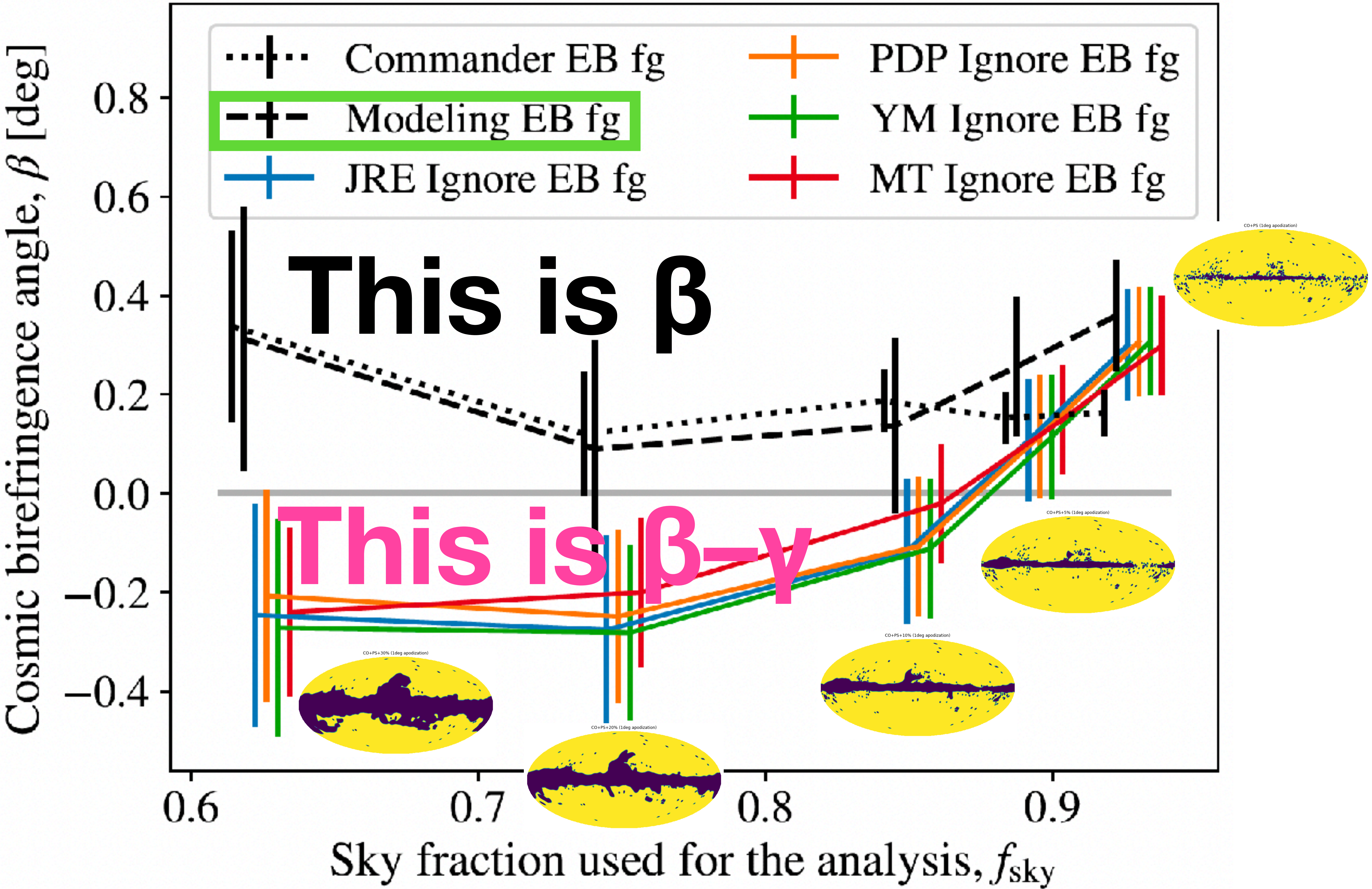
  - Then

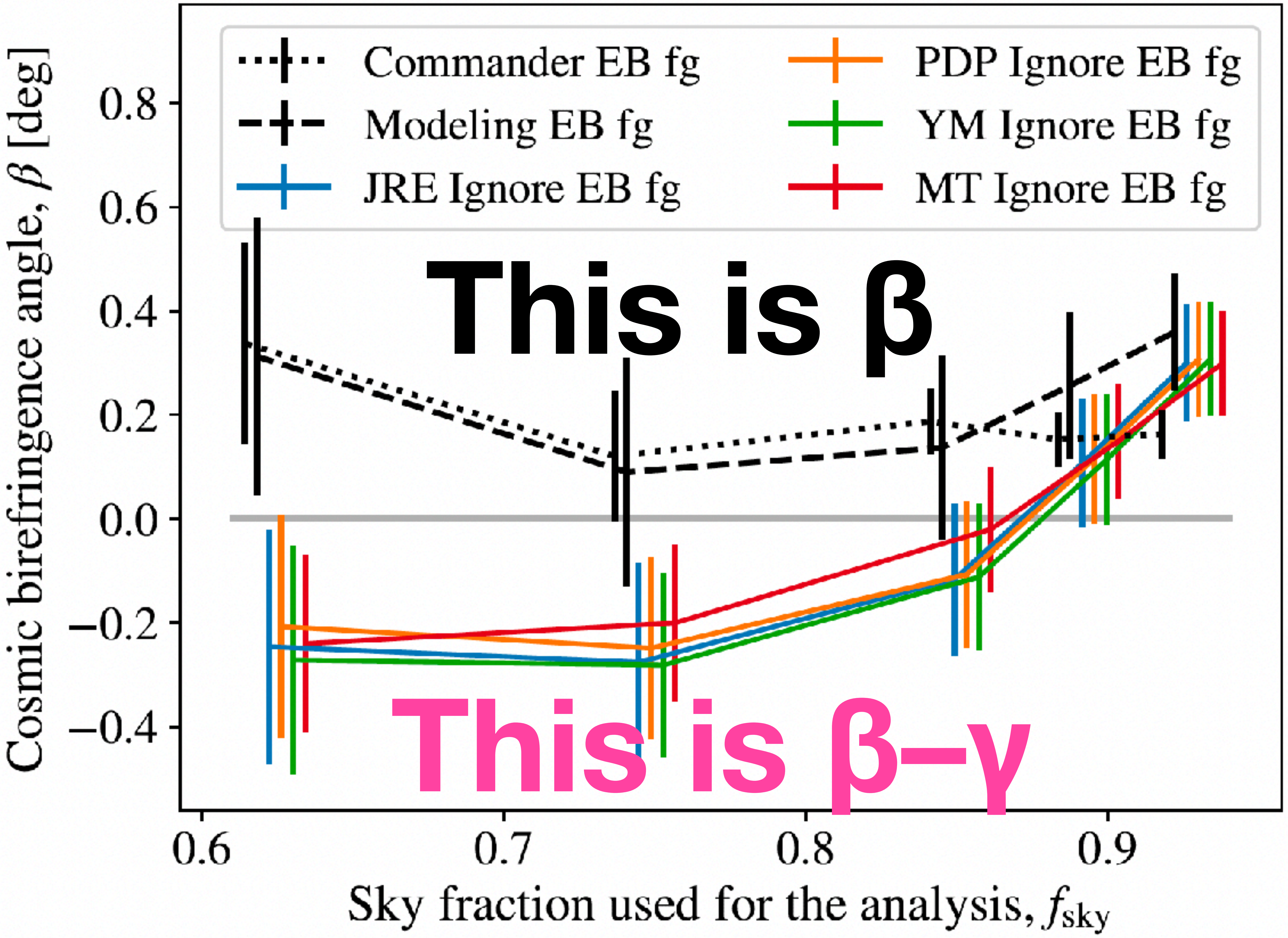
$$\boxed{\gamma_\ell \simeq \frac{A_\ell C_\ell^{EE,\mathrm{dust}}}{C_\ell^{EE,\mathrm{dust}} - C_\ell^{BB,\mathrm{dust}}} \frac{C_\ell^{TB,\mathrm{dust}}}{C_\ell^{TE,\mathrm{dust}}}}$$

for small angles.

Dashed line: Modeling the foreground EB

Trend for declining β is largely gone. But which f_{sky} we should choose?



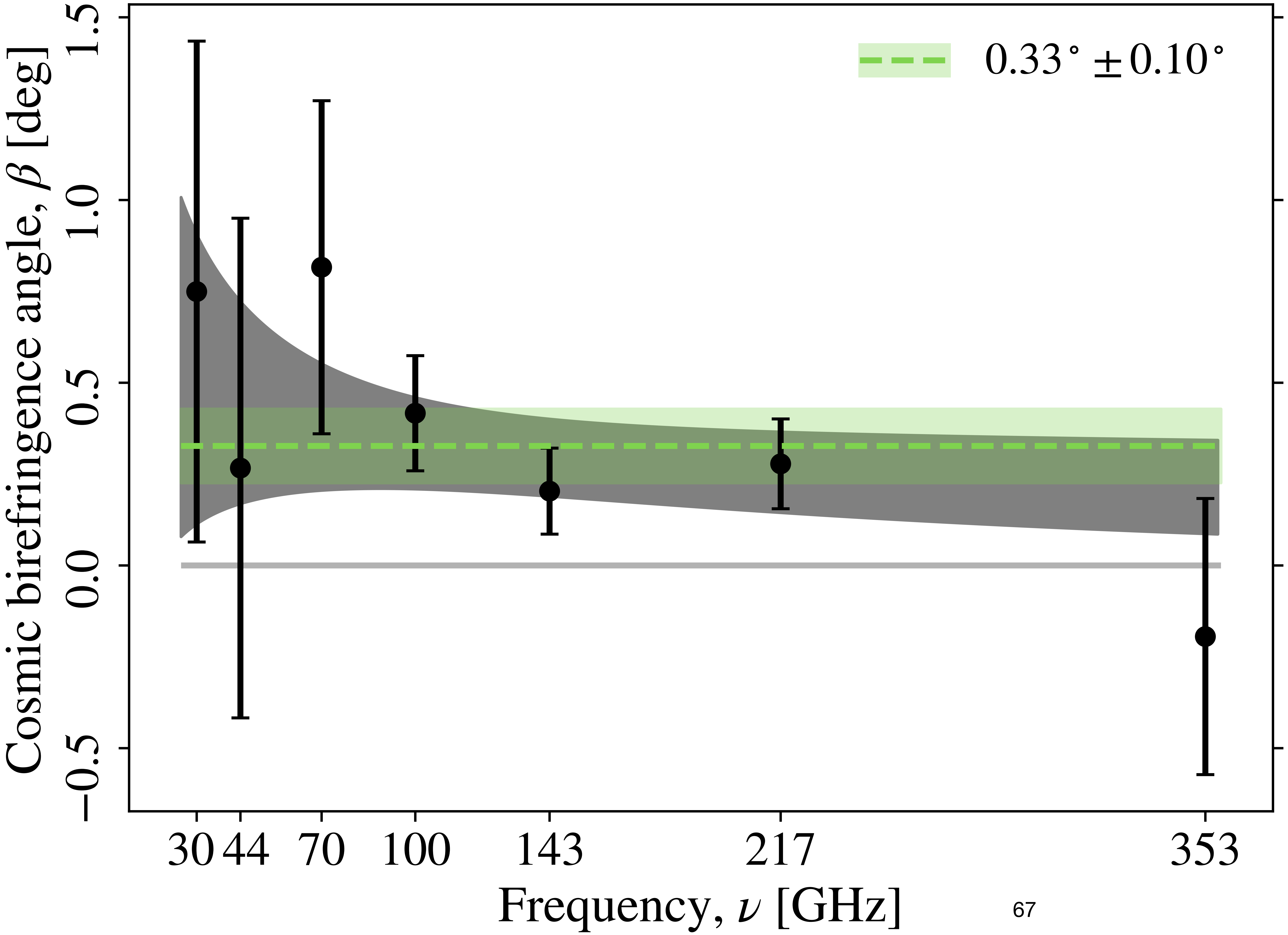


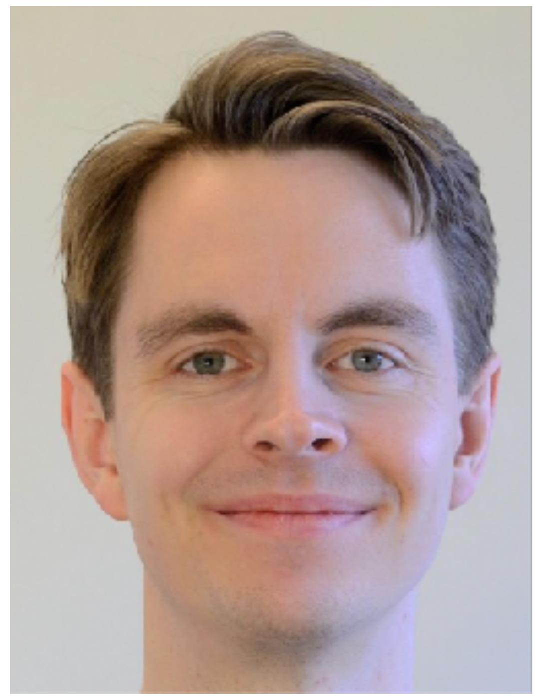
f_{sky}	0.93
β	0.36 ± 0.11
α_{100A}	-0.32 ± 0.13
α_{100B}	-0.43 ± 0.13
α_{143A}	0.03 ± 0.11
α_{143B}	0.15 ± 0.11
α_{217A}	-0.06 ± 0.11
α_{217B}	-0.07 ± 0.11
α_{353A}	-0.19 ± 0.10
α_{353B}	-0.23 ± 0.11
$10^2 A_{51-130}$	$2.5^{+1.6}_{-1.4}$
$10^2 A_{131-210}$	$0.8^{+1.2}_{-0.6}$
$10^2 A_{211-510}$	$1.5^{+2.4}_{-1.1}$
$10^2 A_{511-1490}$	$6.2^{+5.7}_{-4.1}$

- As foreseen, accounting for the foreground EB **increased** β from 0.30 to 0.36 for nearly full-sky data.
  - Which f_{sky} we should choose for the final result? **We do not know yet.** We need more investigation.
  - We need help from Galactic astrophysics! It is a fascinating subject.

No frequency dependence is found

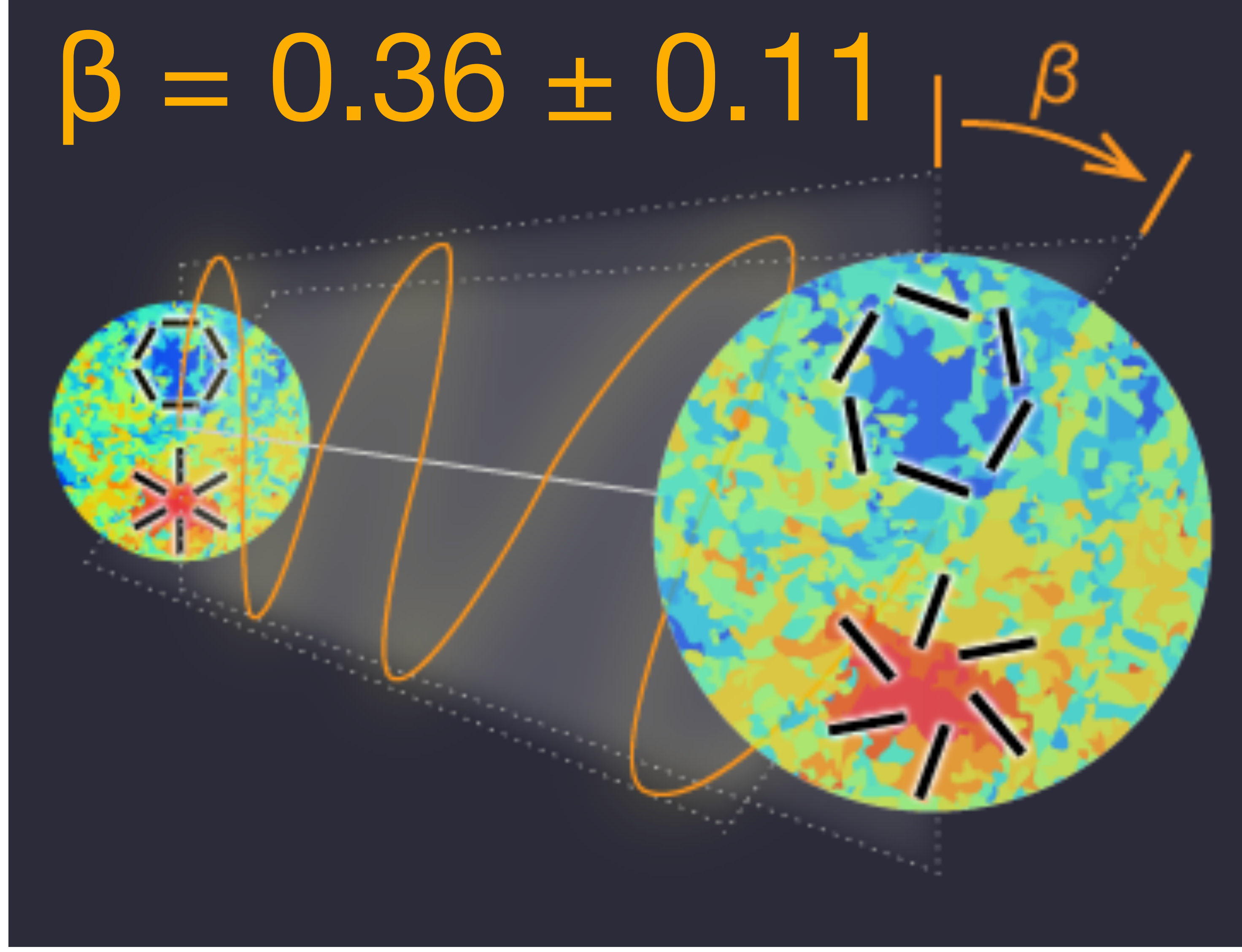
Consistent with the expectation from cosmic birefringence





- Johannes R. Eskilt measured β separately at all of 7 Planck polarised frequency bands.
- No evidence for frequency dependence:
  - For $\beta \sim (\nu/150\mathrm{GHz})^n$, $n = -0.35^{+0.48}_{-0.47}$ (68% CL)
  - Faraday rotation (n=–2) is disfavoured.

Conclusion



β = 0.36 ± 0.11 deg (68%CL; nearly full sky)

- No evidence for frequency dependence of β.
  - Consistent with a cosmological signal.
- Good news: **The impact of the known instrumental systematics is negligible.** We found this using the NPIPE simulations of the PR4 data.
- If the measured β is confirmed as cosmological, it would have profound implications for the fundamental physics behind dark matter and energy.
- Coming very soon: The joint analysis of WMAP and Planck!