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(Univ. Cantabria, Santander)

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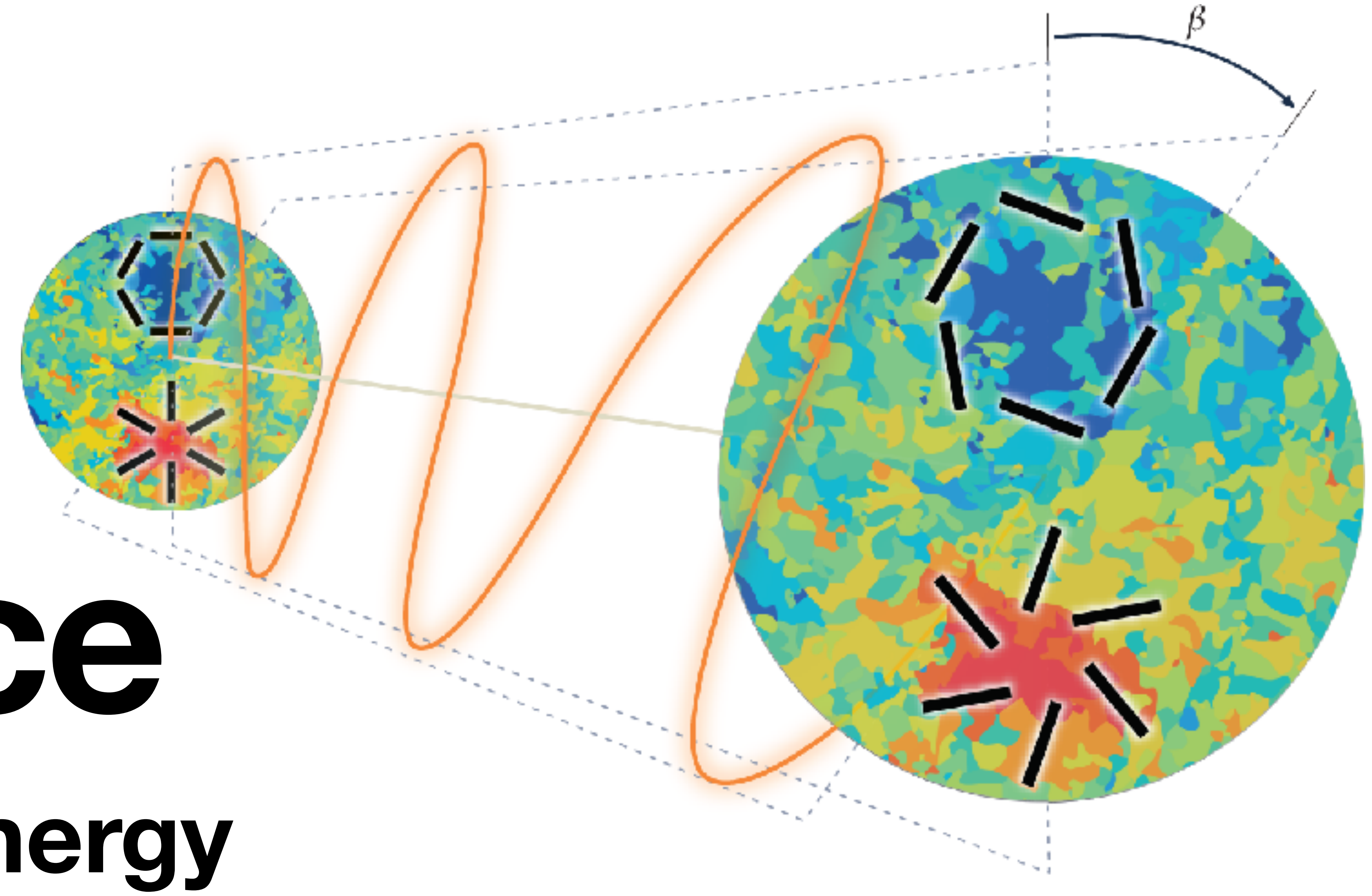

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Cosmic Birefringence

A New Probe of Dark Matter and Dark Energy

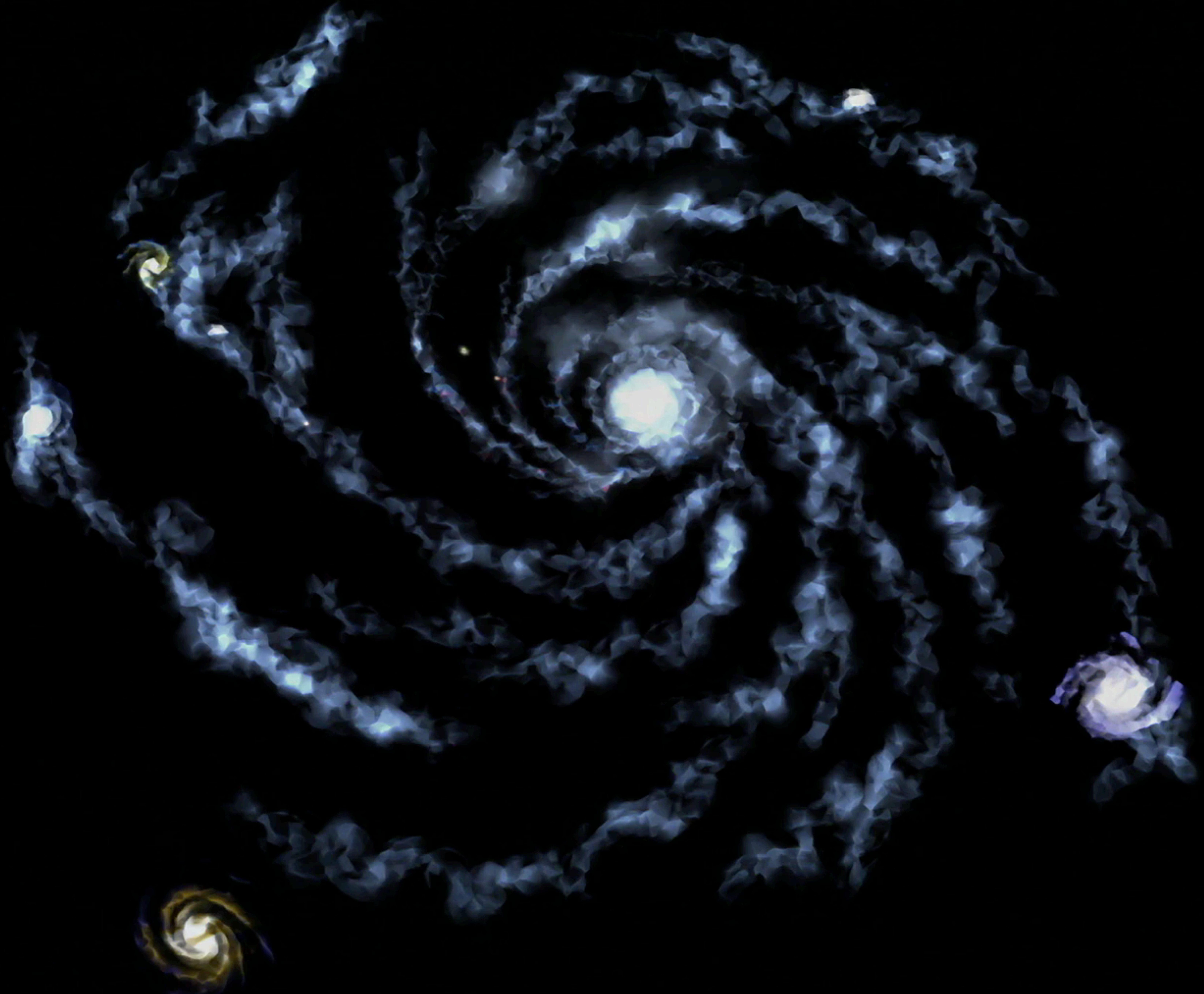
based on

- *Minami & EK, PRL, 125, 221301 (2020)*
- *Diego-Palazuelos, Eskilt, Minami, et al., PRL, 128, 091302 (2022)*
- *EK, Nature Reviews Physics, 4 (2022)*
- *Eskilt & EK, PRD, 106, 063503 (2022)*
- *Diego-Palazuelos, et al., arXiv:2210.07644*

Eiichiro Komatsu

Colloquium@WMU Münster, January 27, 2023

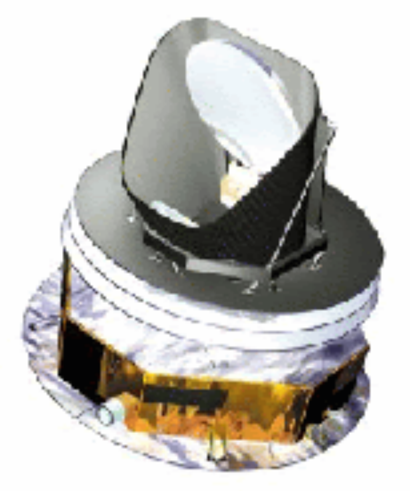
MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK



Standard Cosmological Model (ΛCDM) Requires New Physics

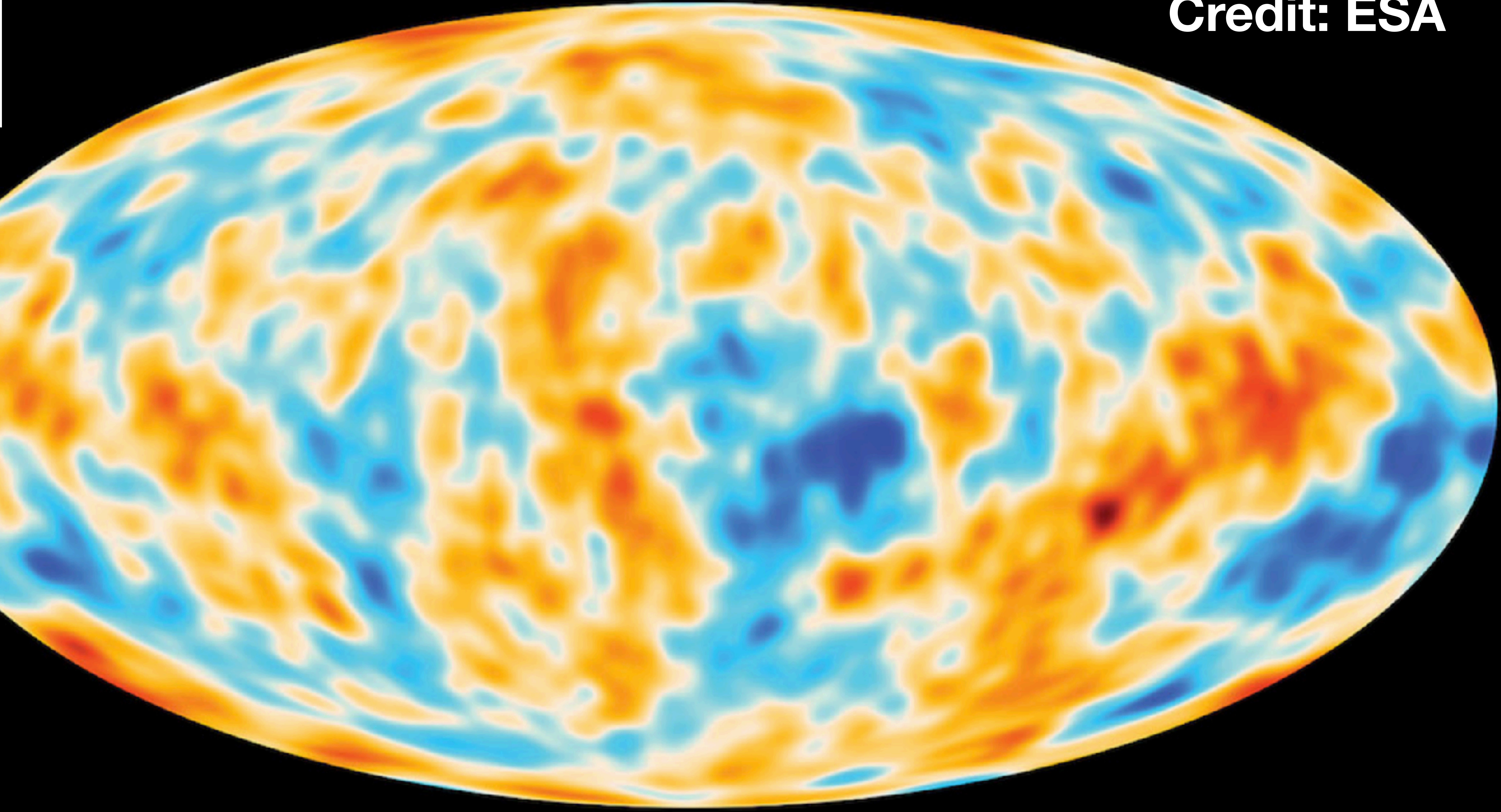
Physics beyond Standard Model of elementary particles and fields

- **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.



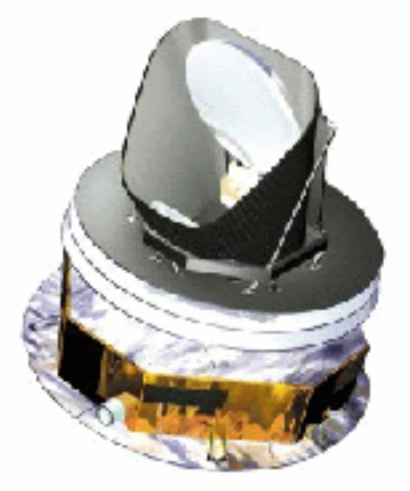
ESA’s Planck

Credit: ESA



Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago



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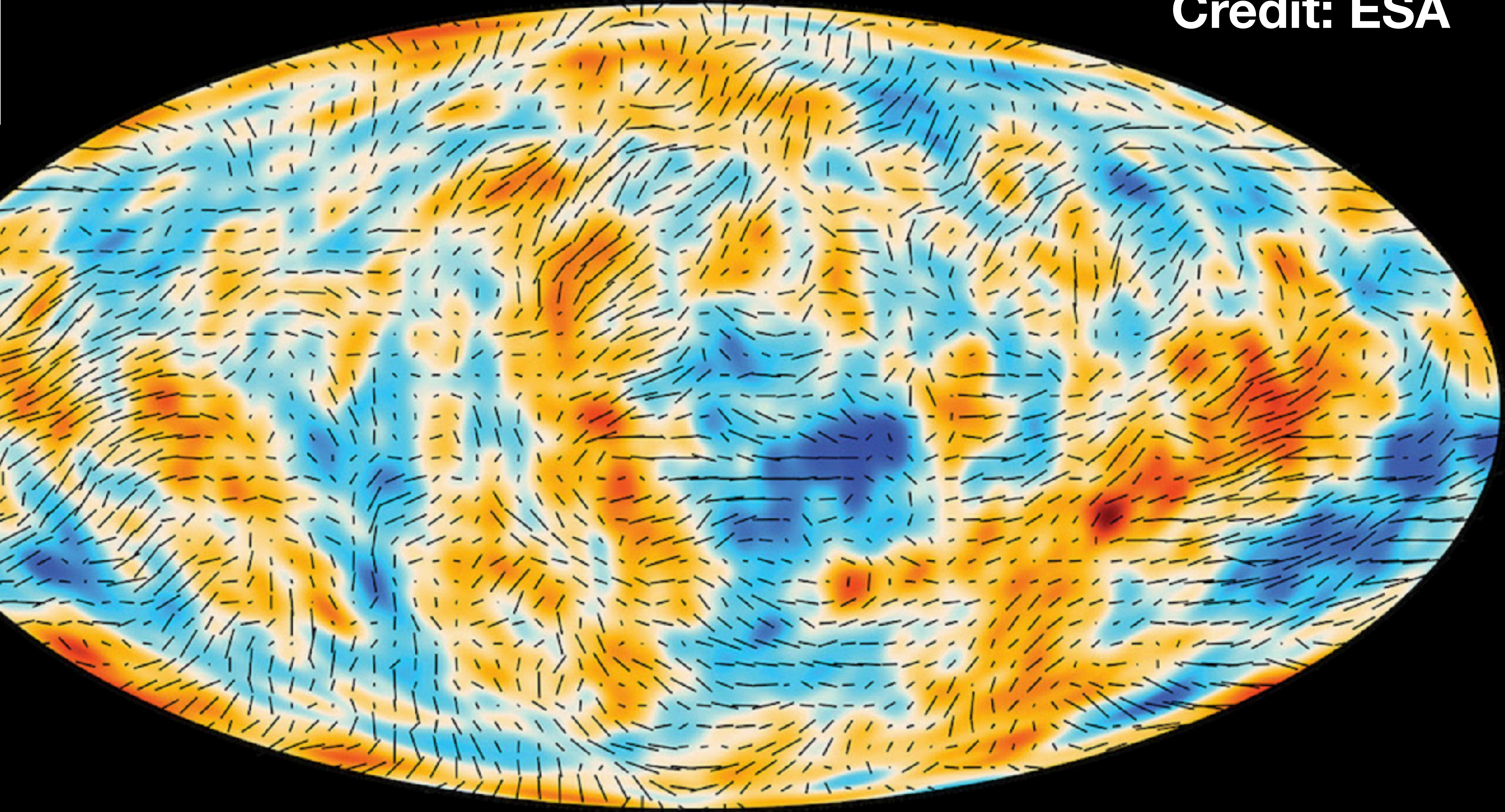


Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Credit: TALEX

Horizontally polarised

Credit: TALEX

Physics of CMB Polarisation

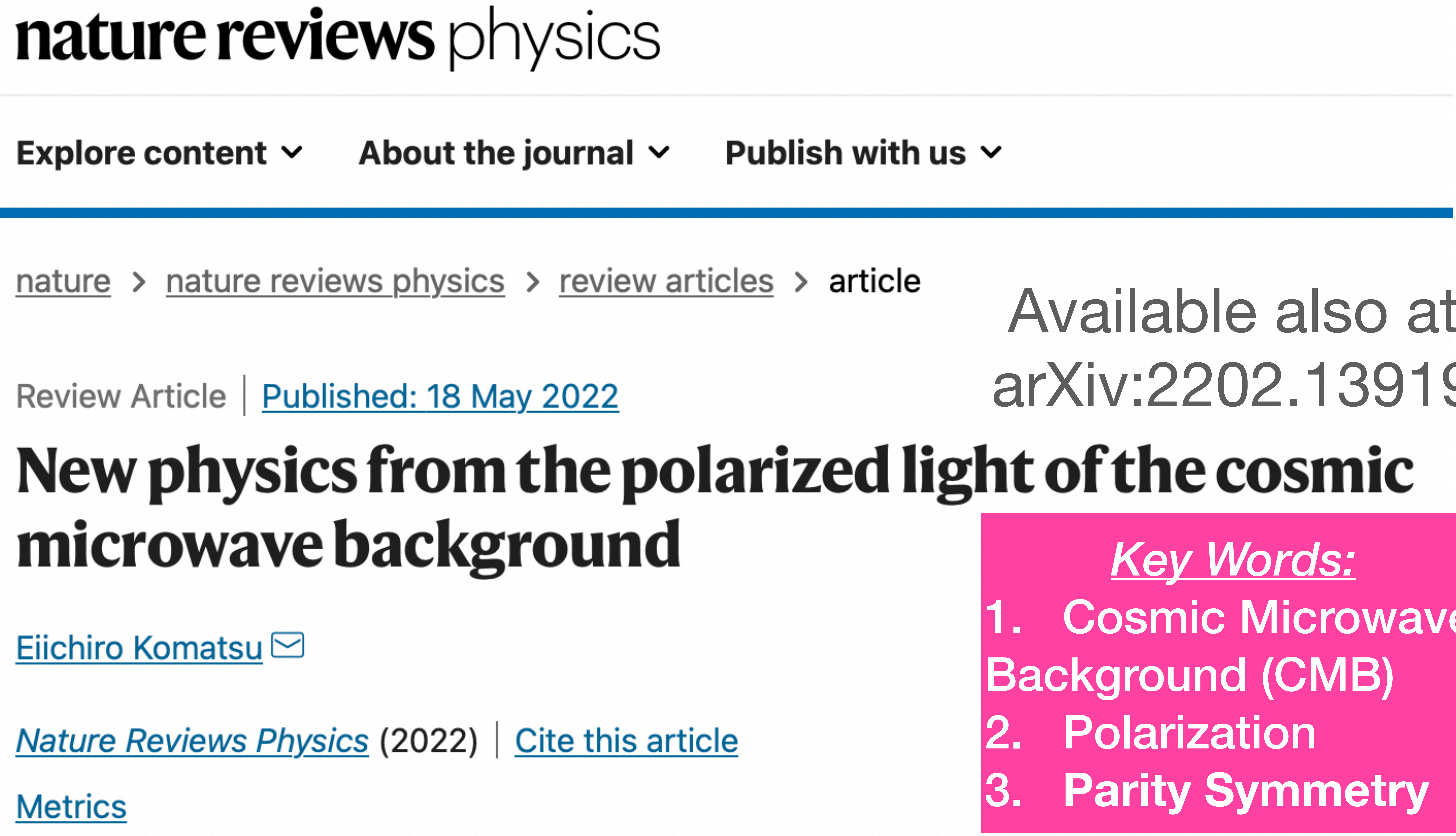
Necessary and sufficient condition: Scattering and Quadrupole Anisotropy

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)?
  - **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.



nature reviews physics

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

Available also at arXiv:2202.13919

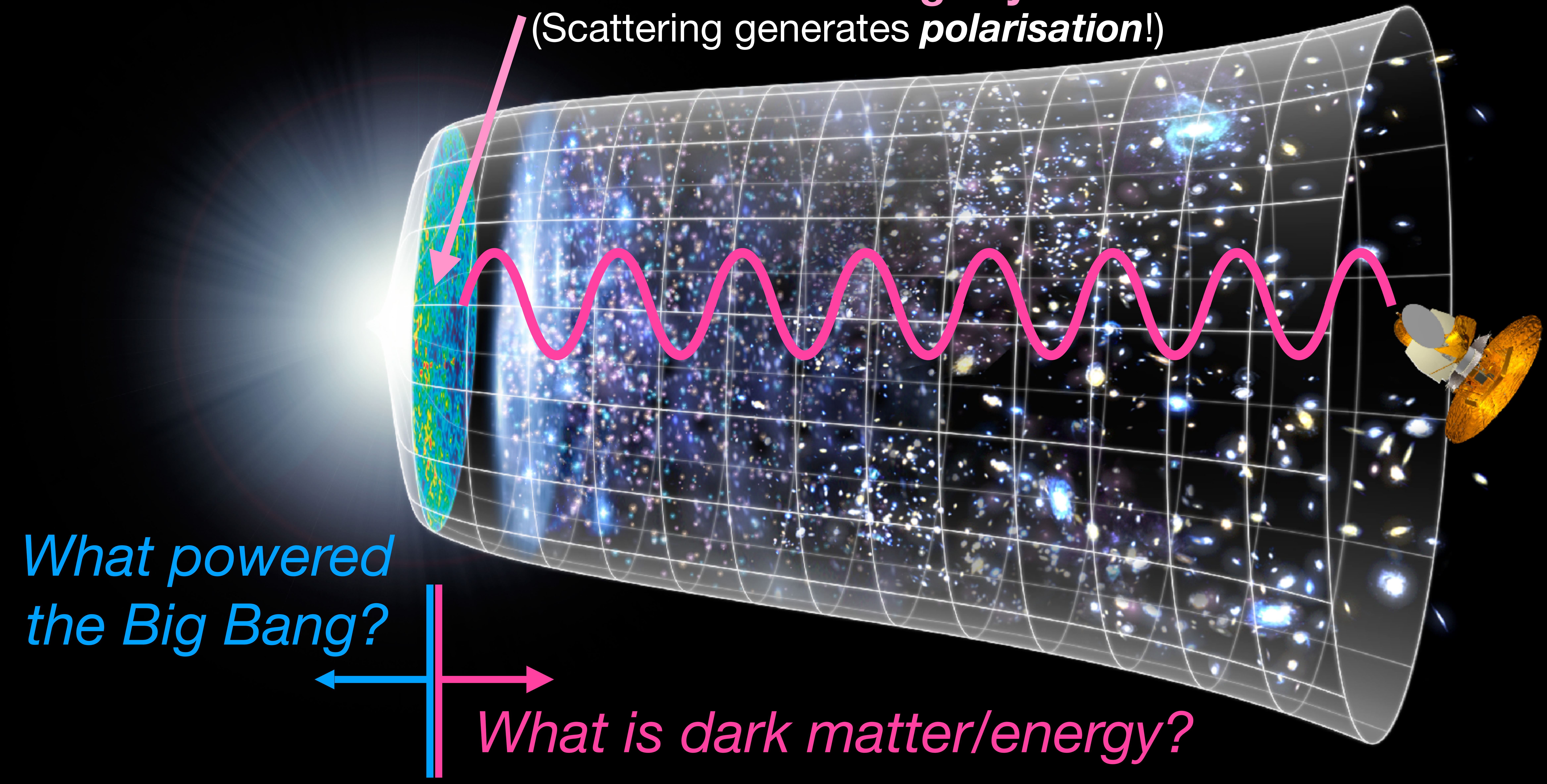
Key Words:

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

Credit: WMAP Science Team

The surface of “last scattering” by electrons

(Scattering generates ***polarisation***!)



What powered the Big Bang?

What is dark matter/energy?

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?

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

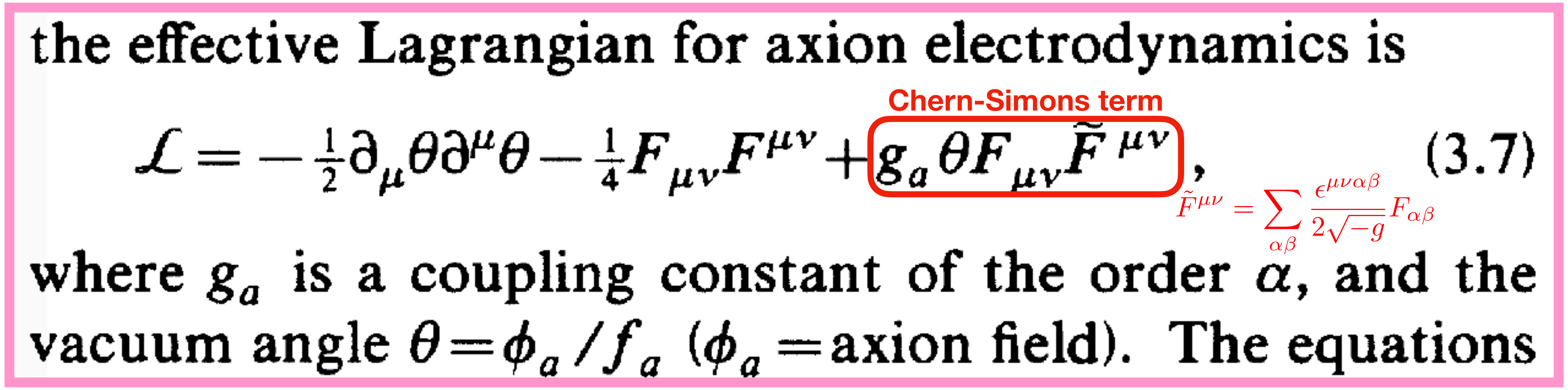
Cosmic Birefringence

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

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

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

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

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

Parity Even **Parity Odd**

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

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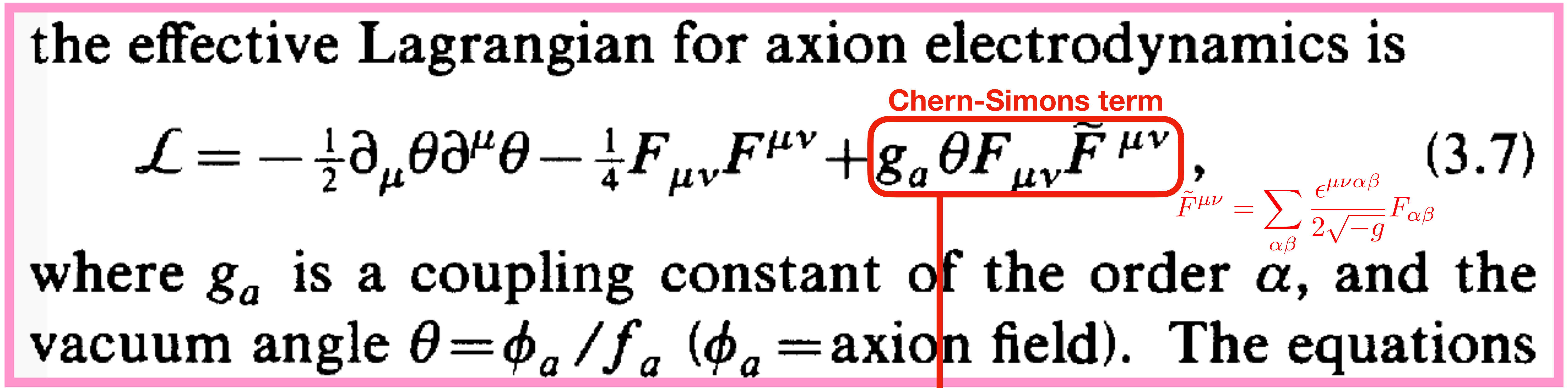

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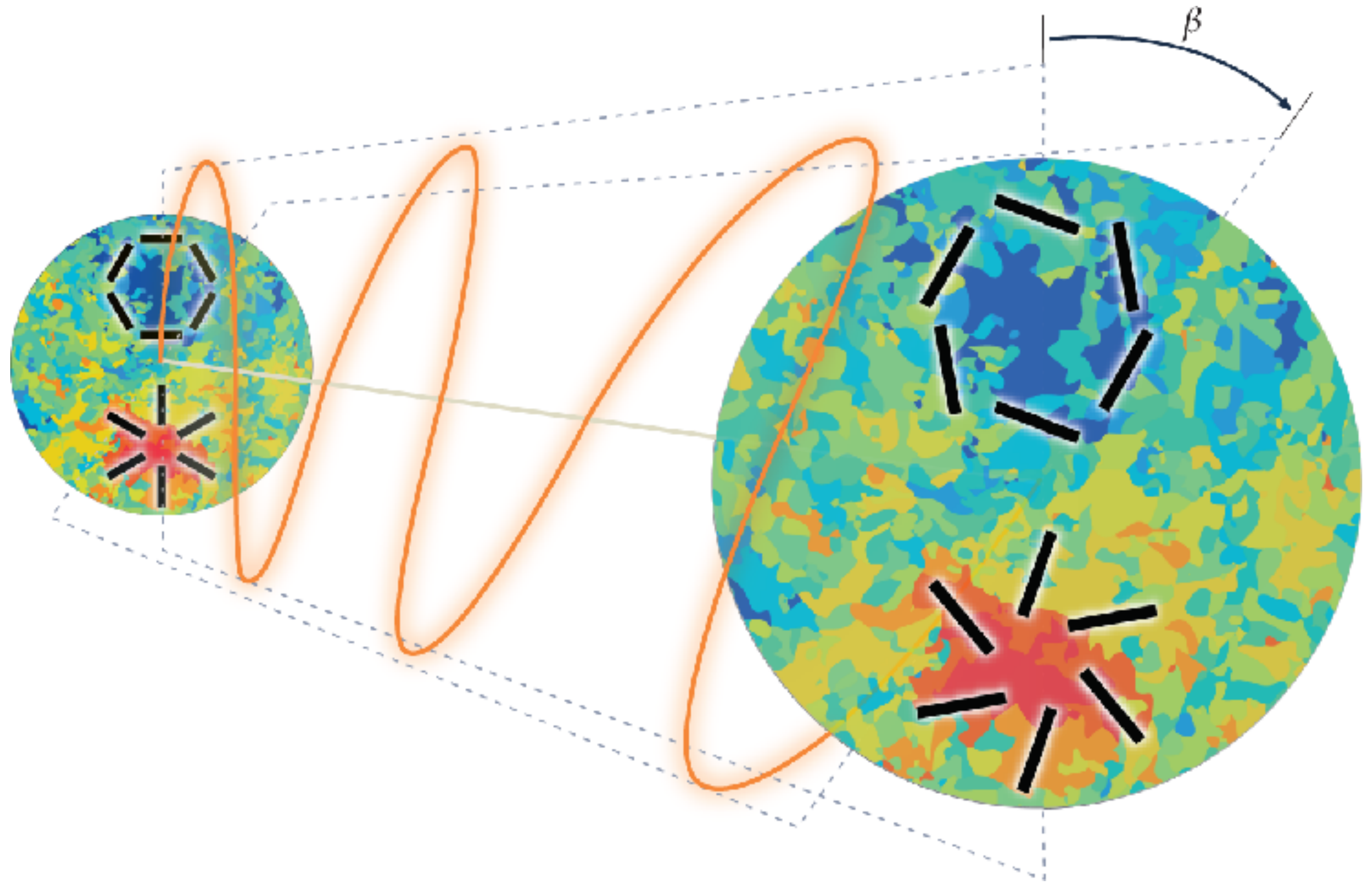


“Cosmic Birefringence”

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

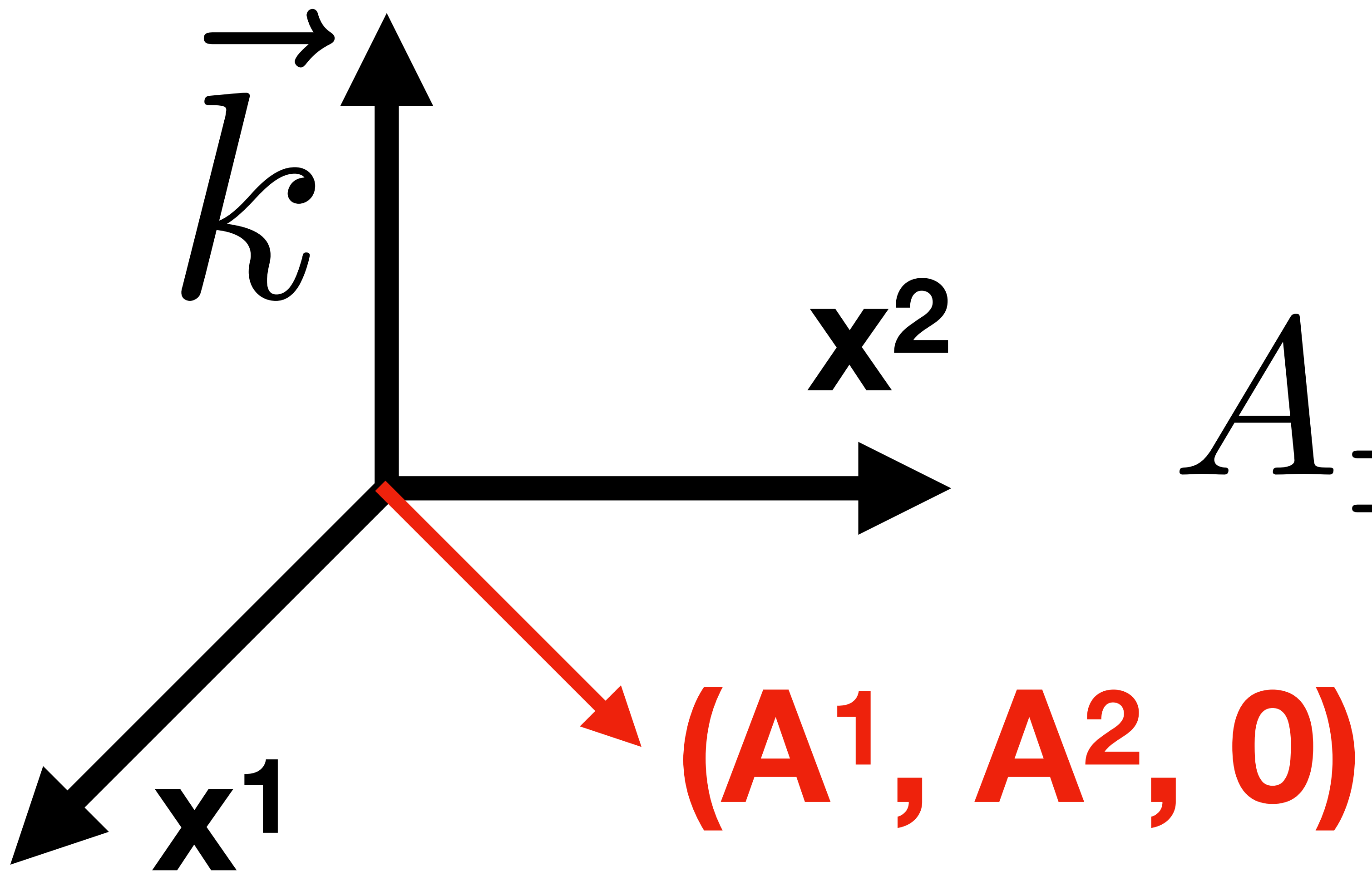
Standard Maxwell Theory

Warm up (1)

- To isolate a transverse wave, we require A_0=0 and 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

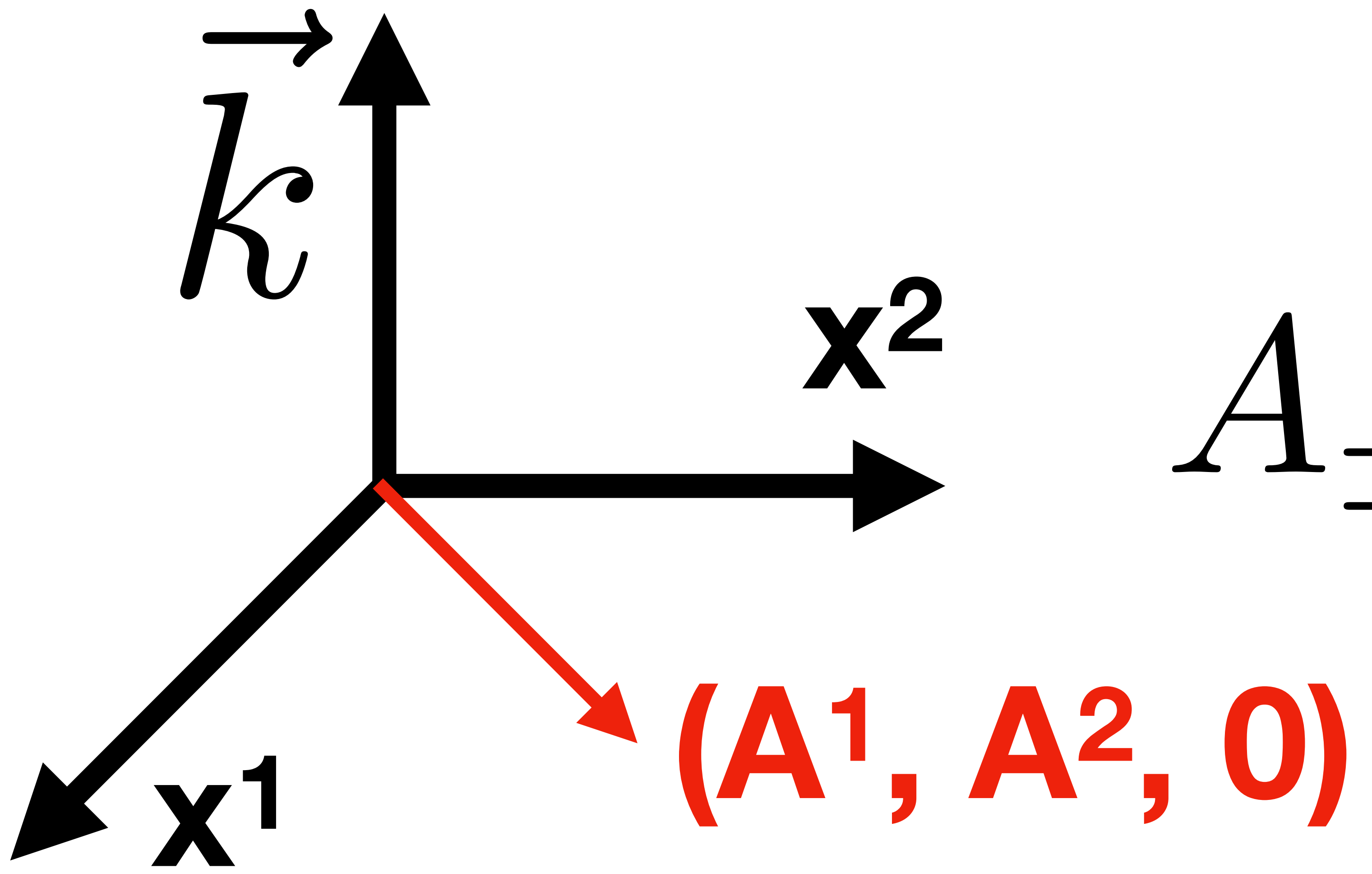
Warm up (2)

- 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



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- A_+: Right-handed state
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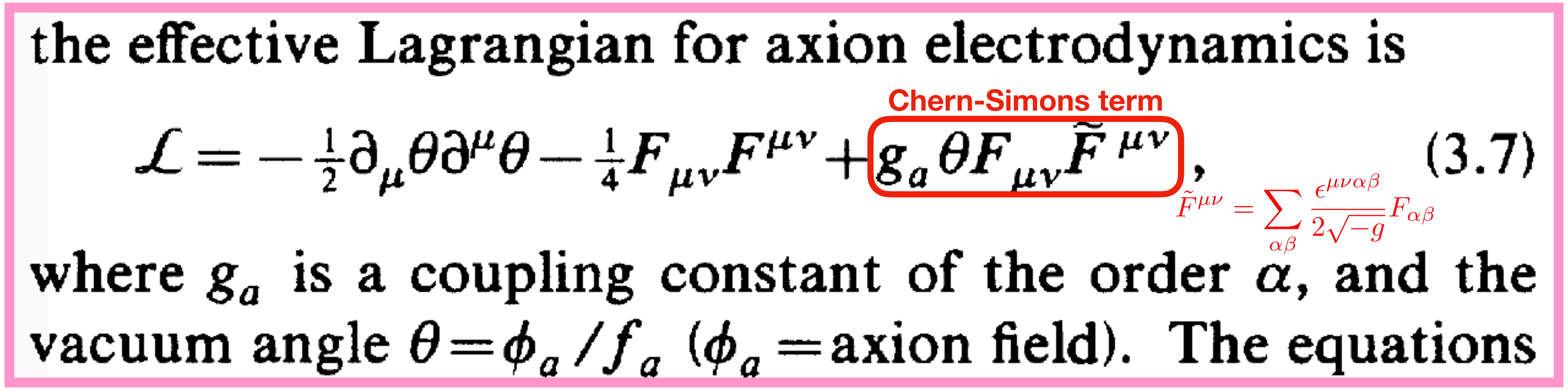
Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)

Cosmic Birefringence

Derivation (1)

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



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- The equation of motion is modified to

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

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

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

Cosmic Birefringence

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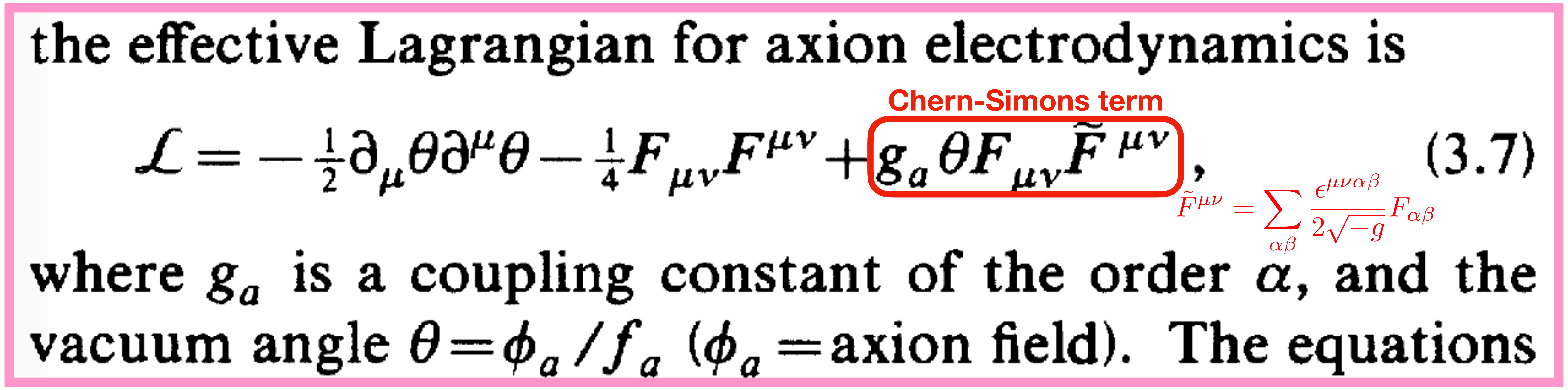

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$$\frac{\omega_\pm^2}{k^2}=1\pm\frac{4g_a\theta'}{k}=\left(1\pm\frac{2g_a\theta'}{k}\right)^2-\cancel{\frac{4g_a^2\theta'^2}{k^2}}$$

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

Cosmic Birefringence

Derivation (1)

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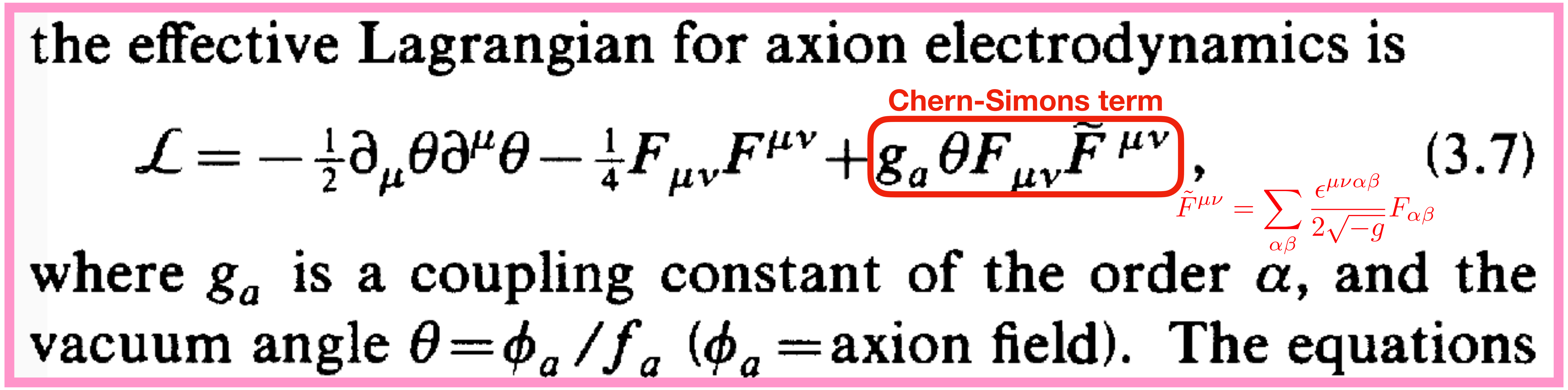

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$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2 g_a \theta'}{k}$$

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

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

Cosmic Birefringence

Derivation (2)

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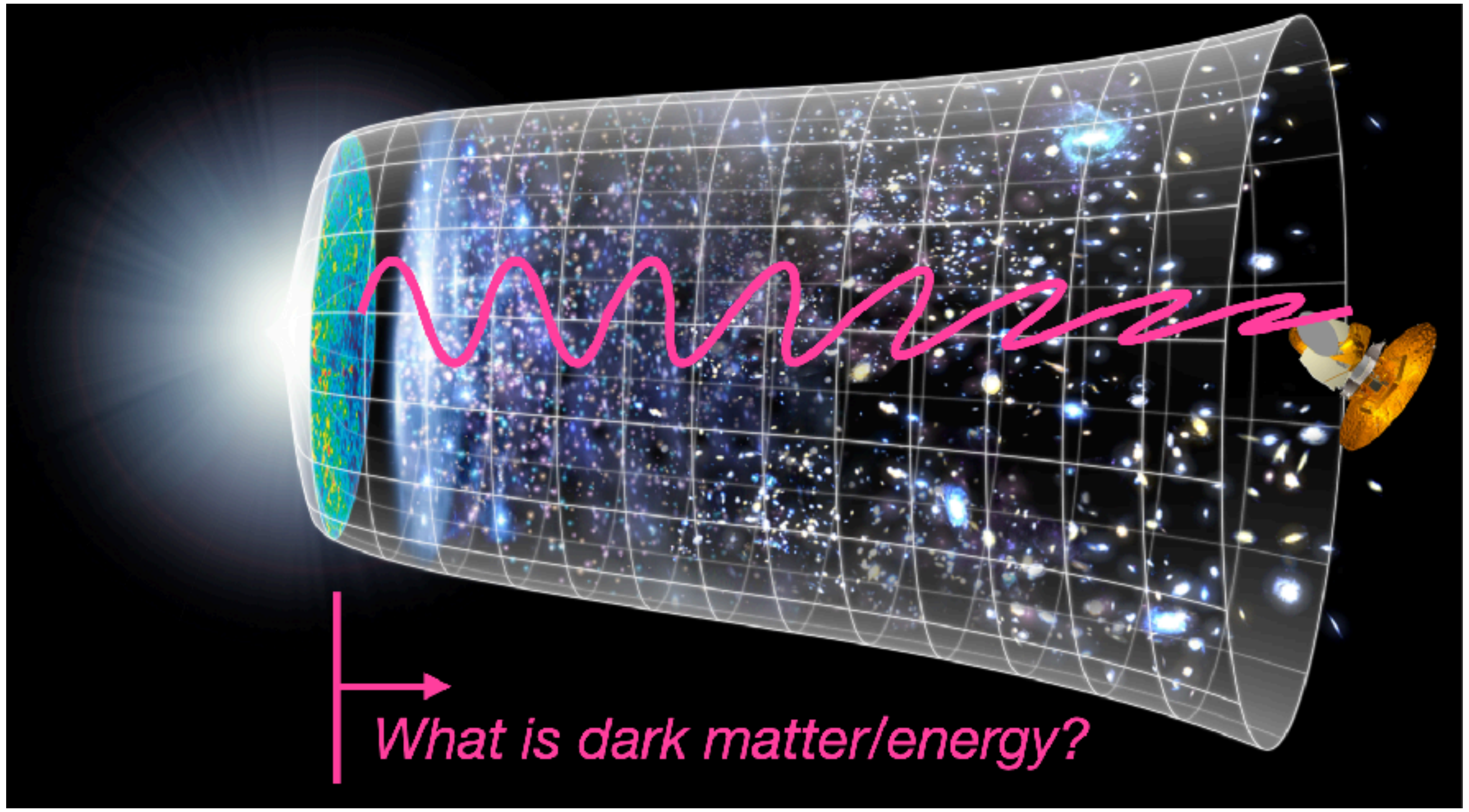

- The plane of linear polarisation rotates clockwise on the sky by an angle β:

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

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

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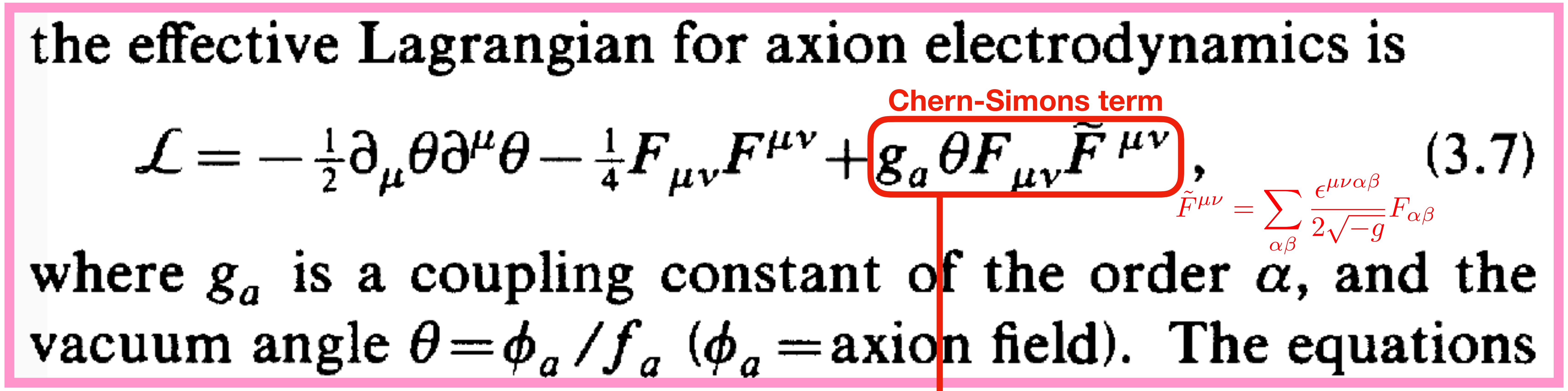

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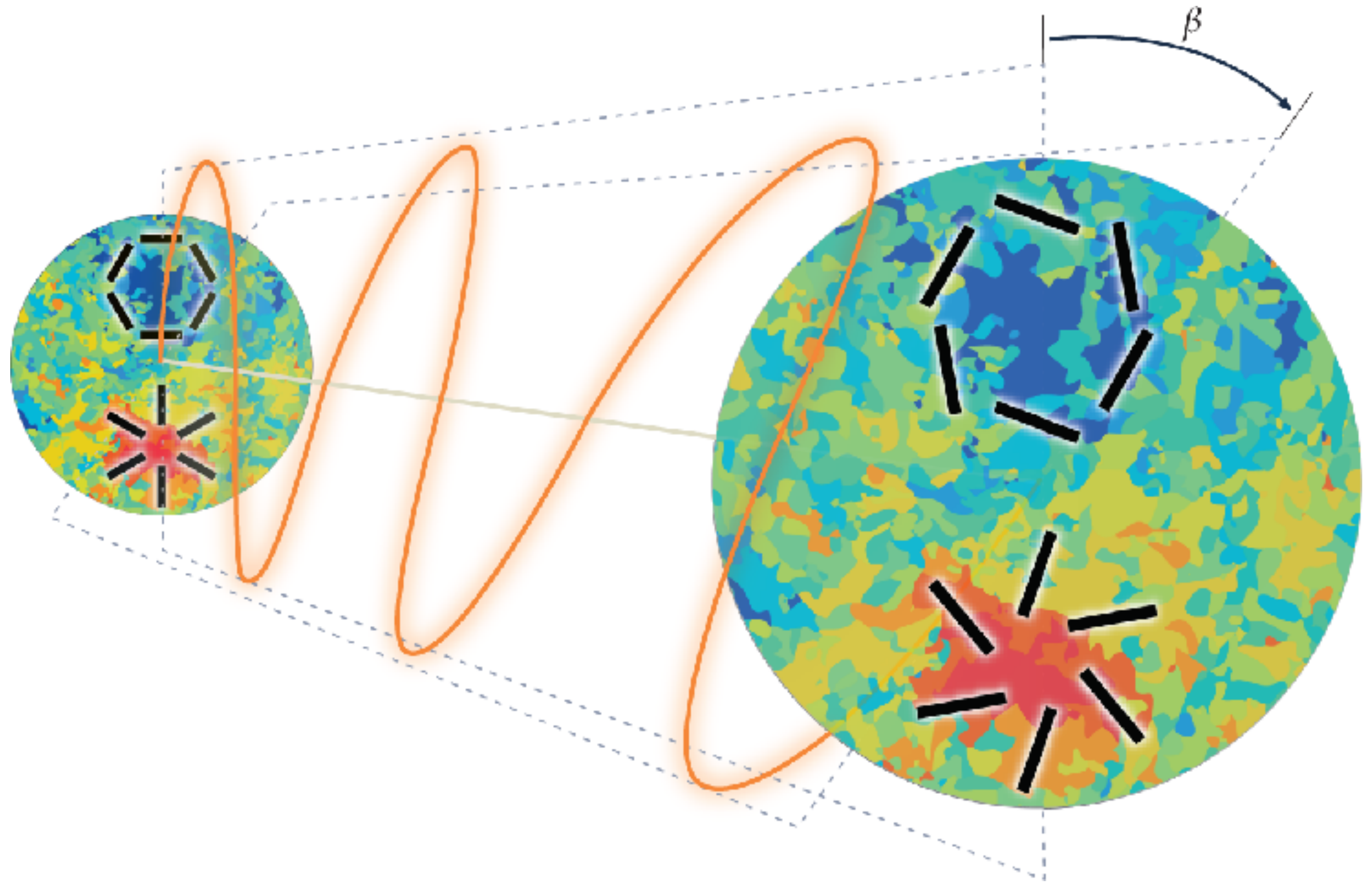
$$\beta = -2g_a\int_{t_\mathrm{emitted}}^{t_\mathrm{observed}} dt\,\dot{\theta} = 2g_a\left[\theta(t_\mathrm{e}) - \theta(t_\mathrm{o})\right]$$



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

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

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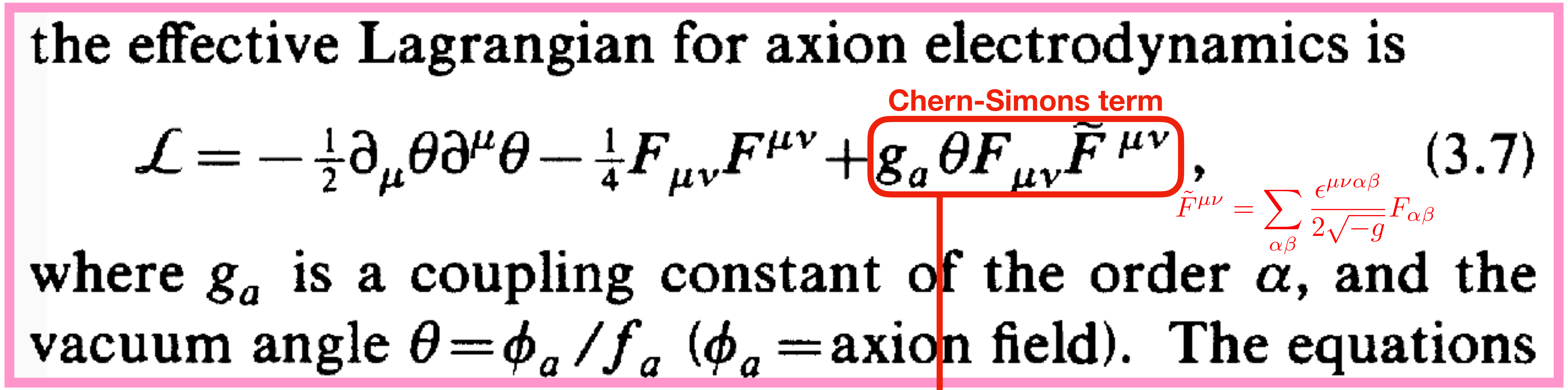

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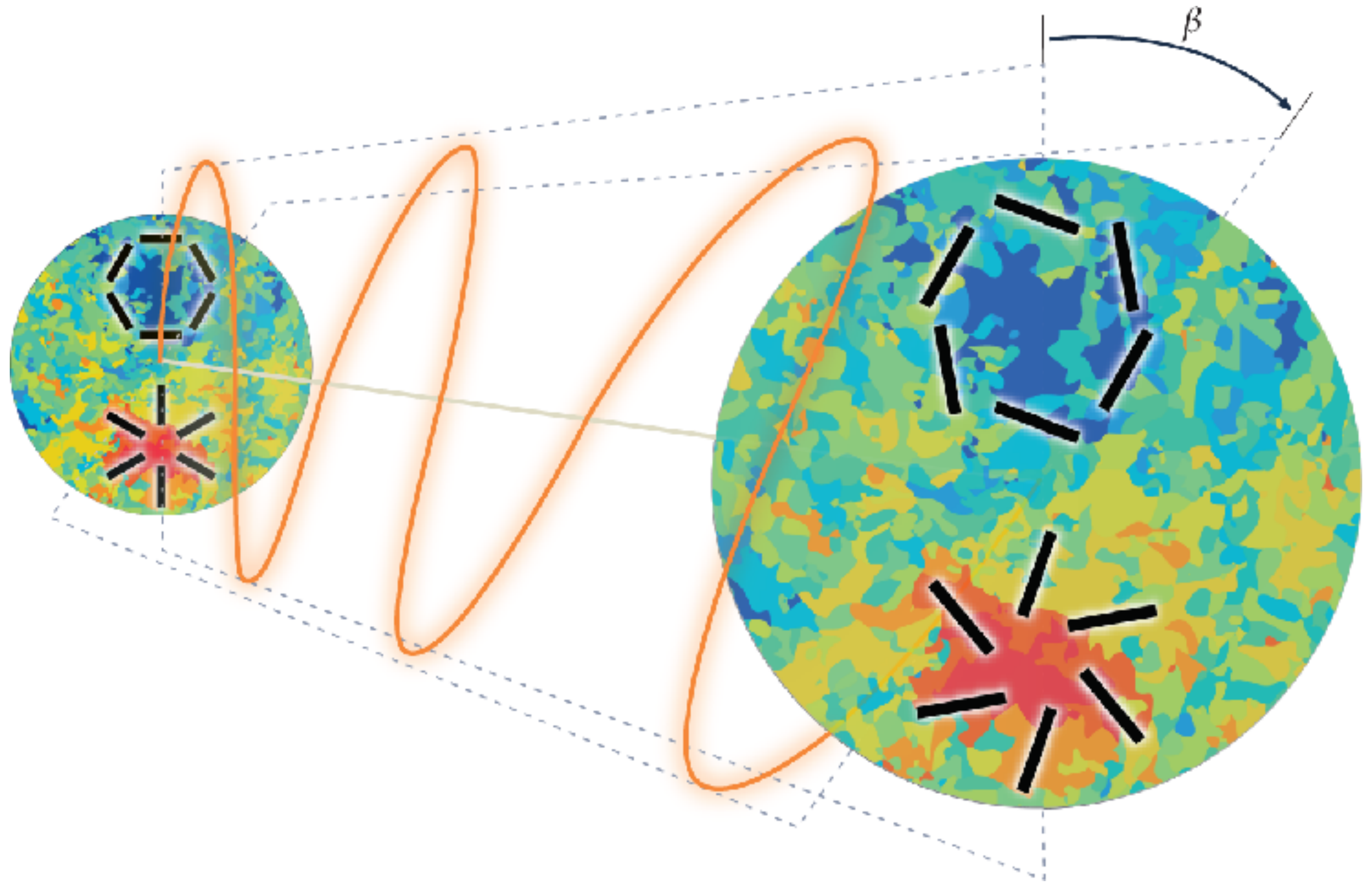


If θ varies over space:

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

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?

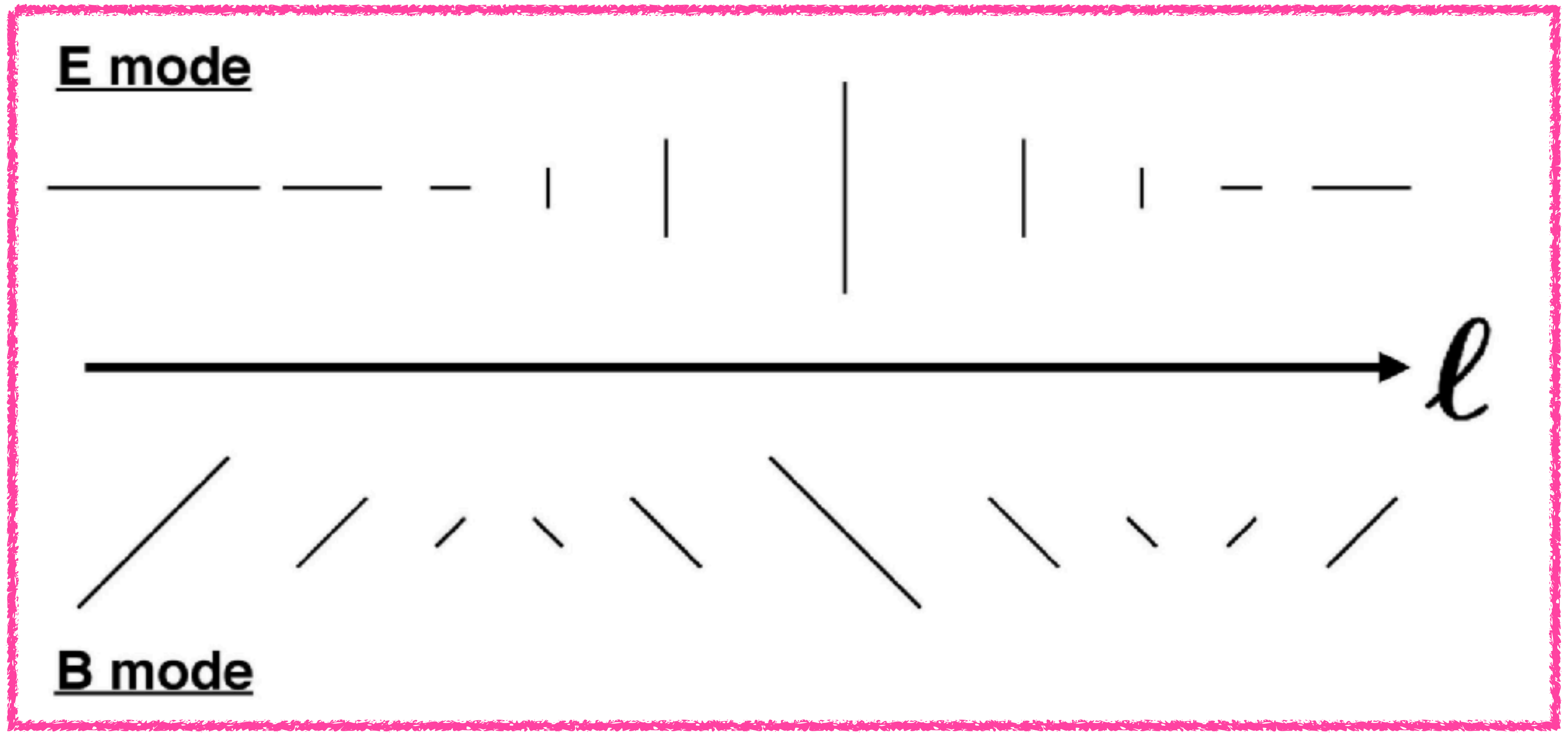
- We know that the weak interaction violates parity (Lee & Yang 1956; Wu et al. 1957).
  - Why should the laws of physics governing the Universe conserve parity?

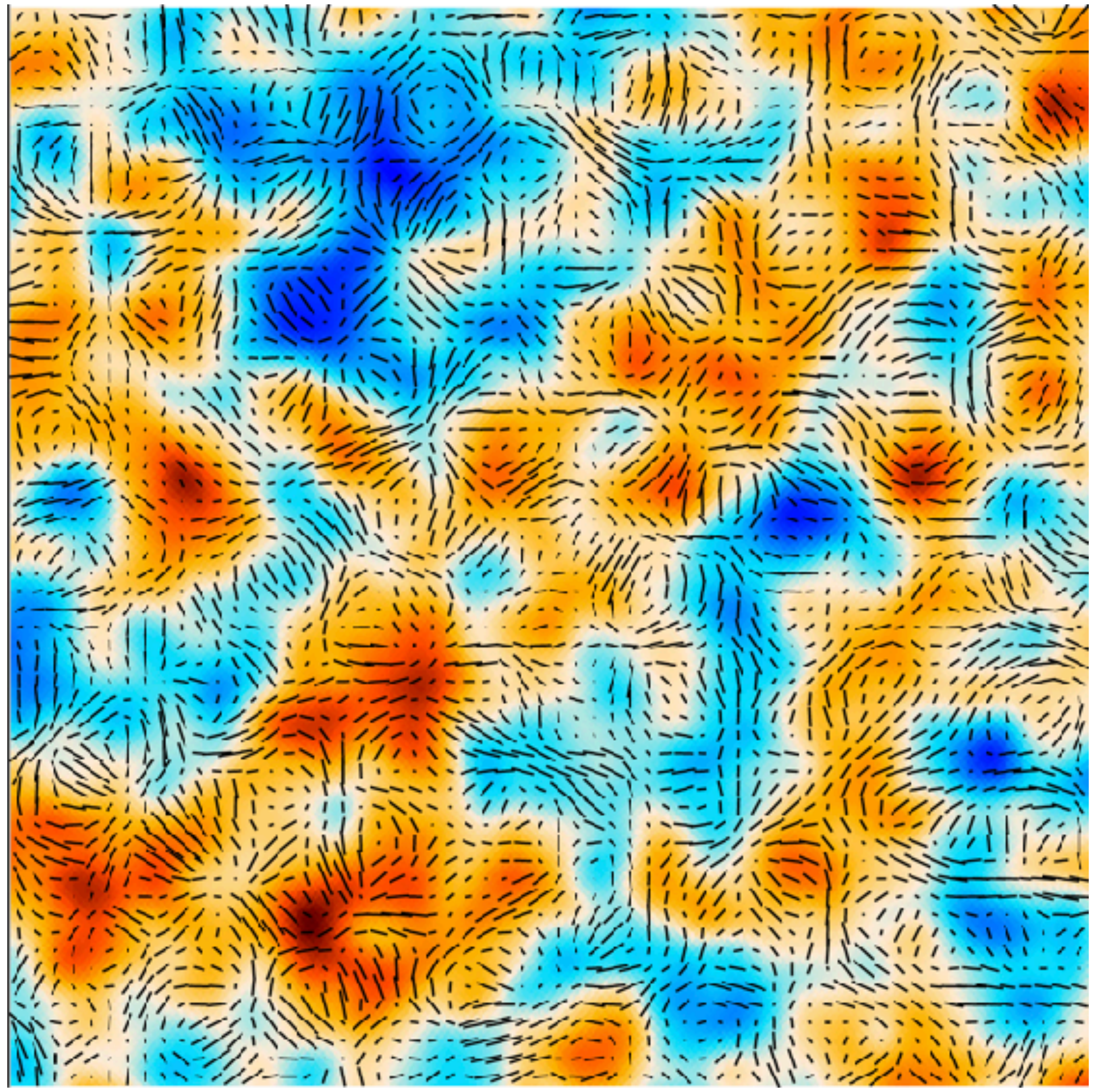
- Let's look!

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)

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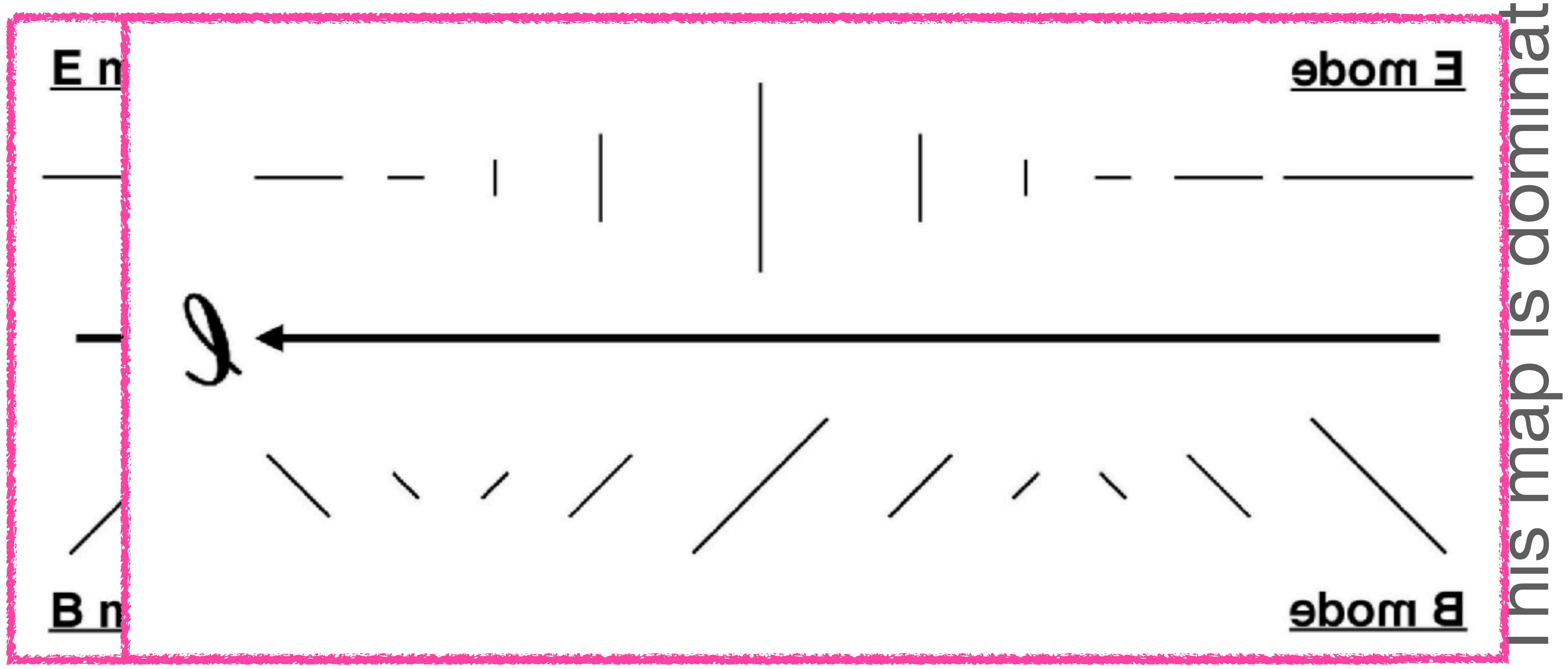

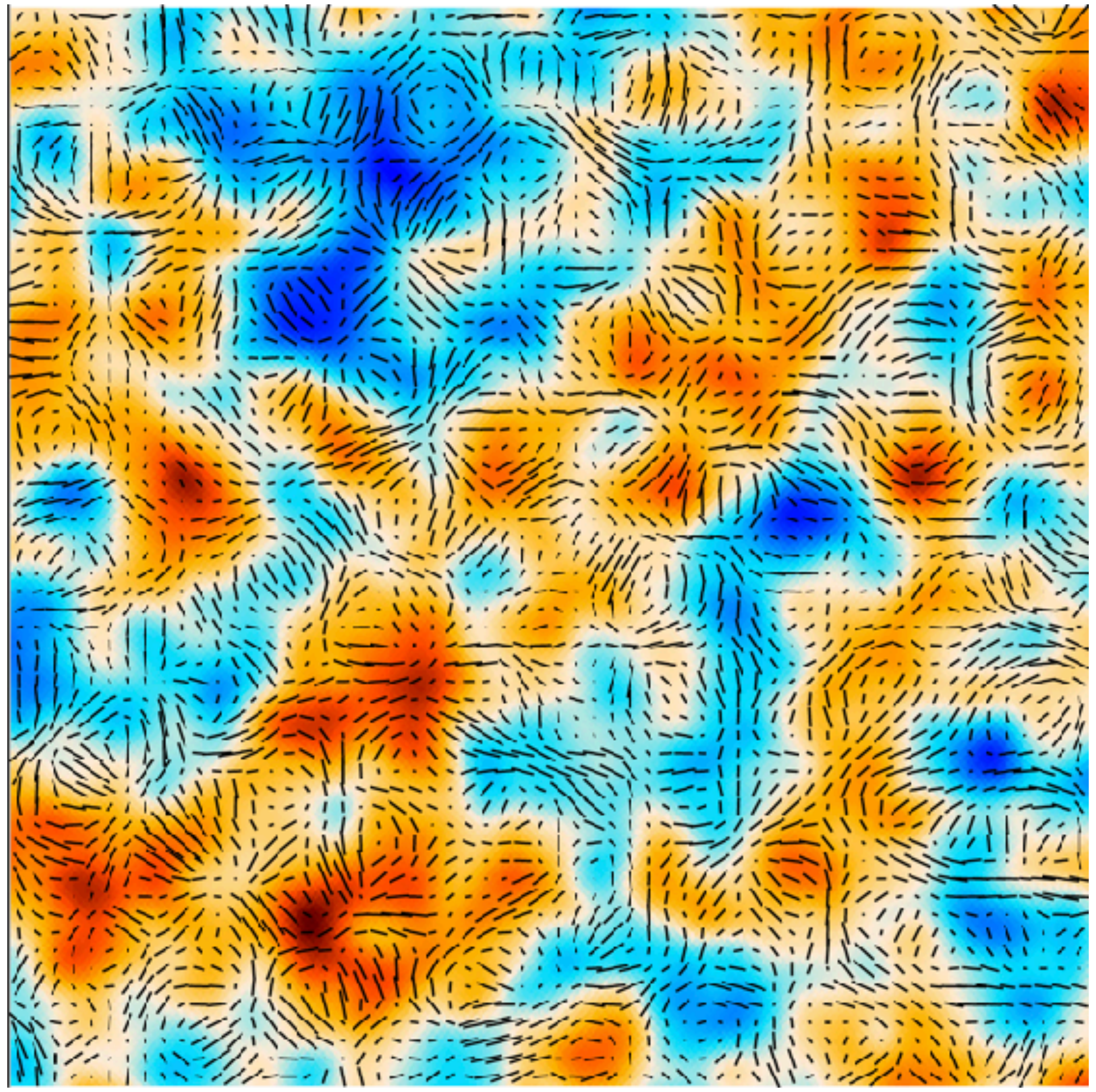

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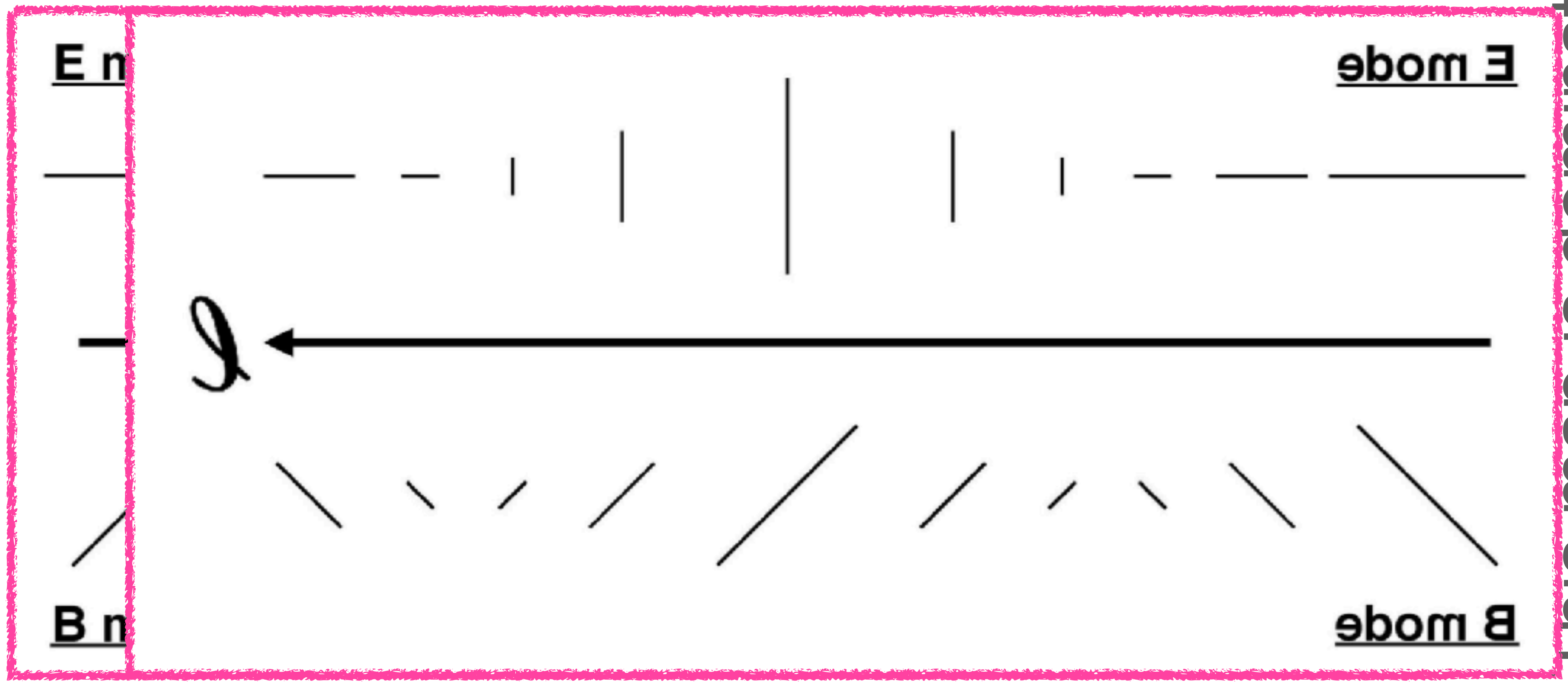

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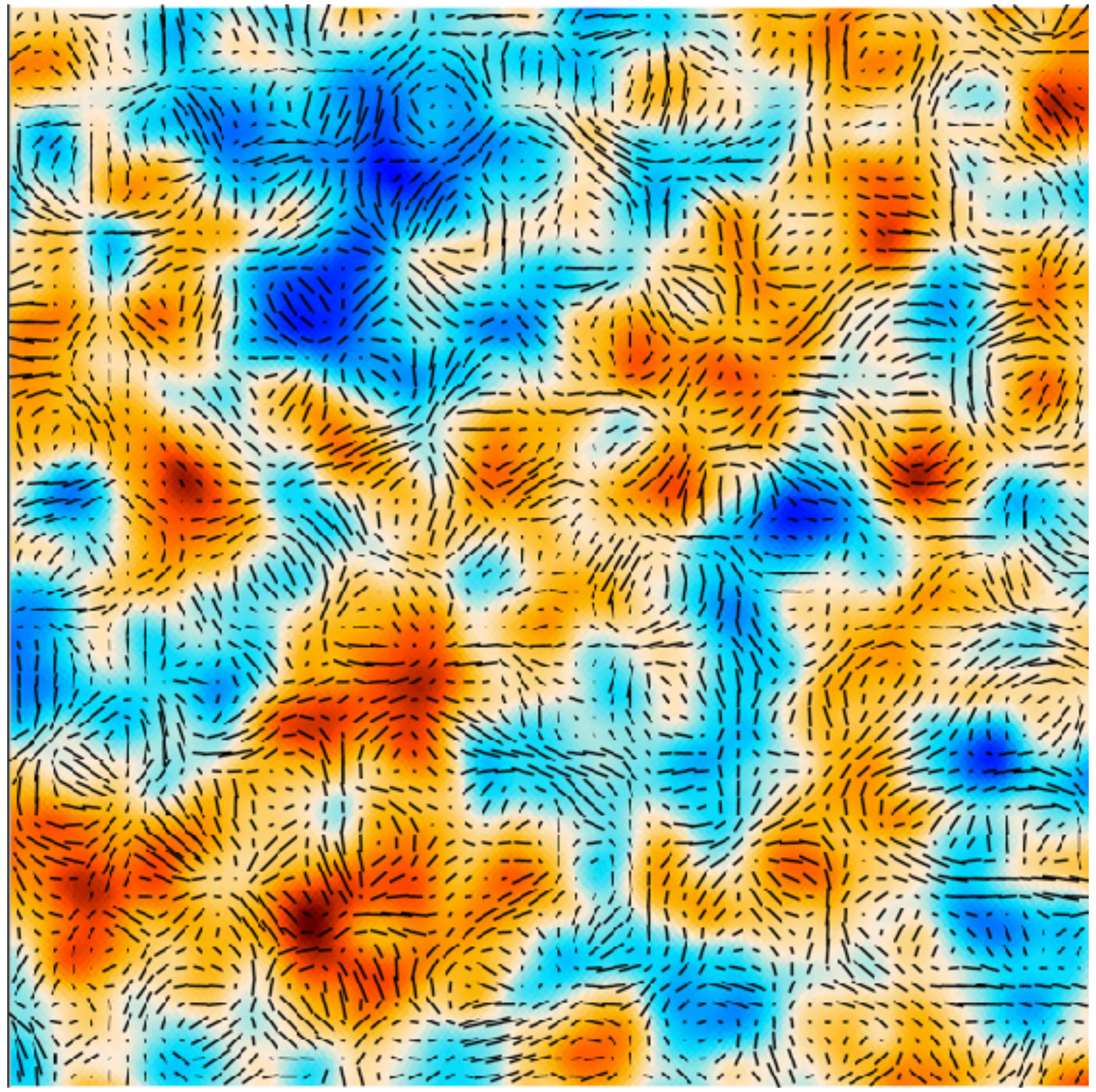

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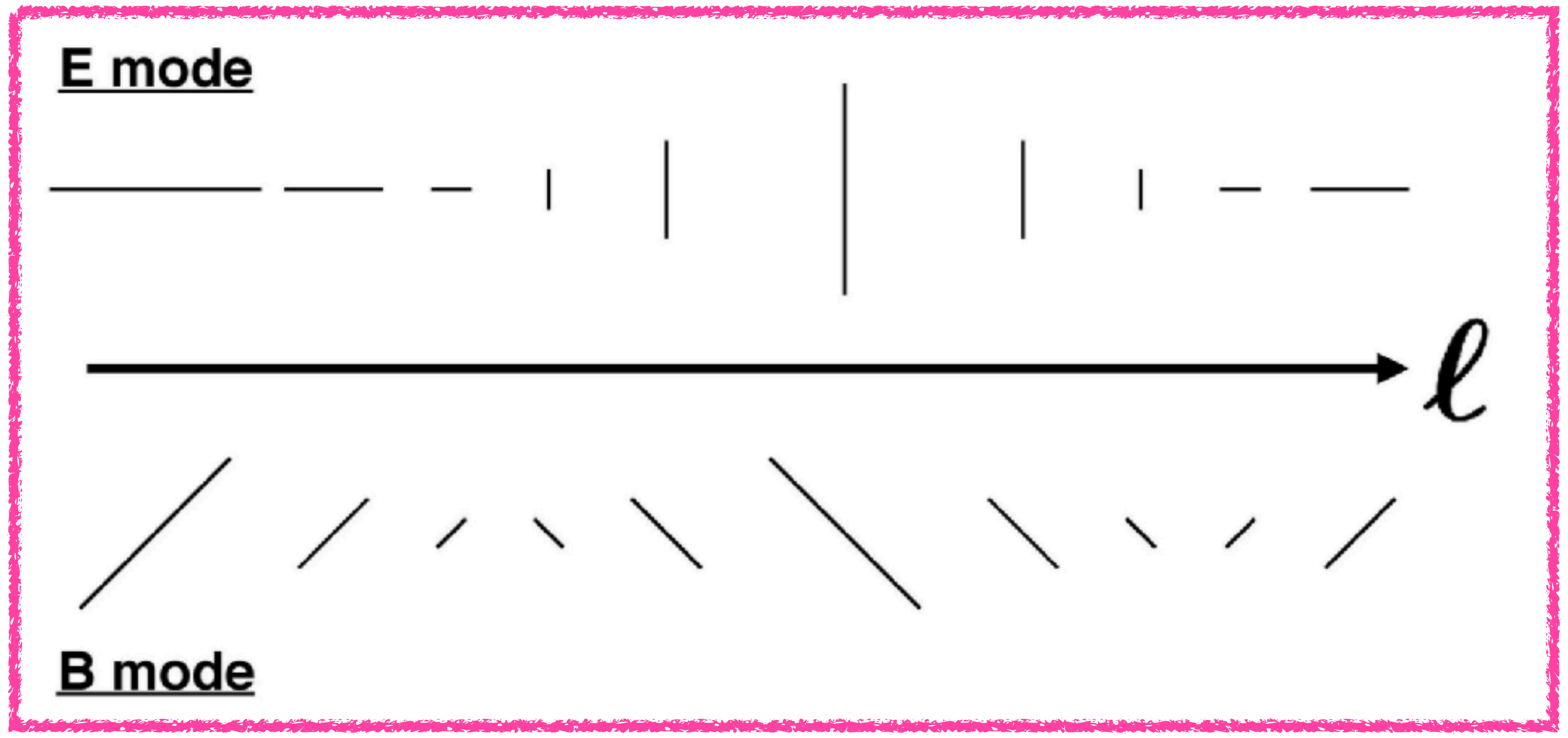
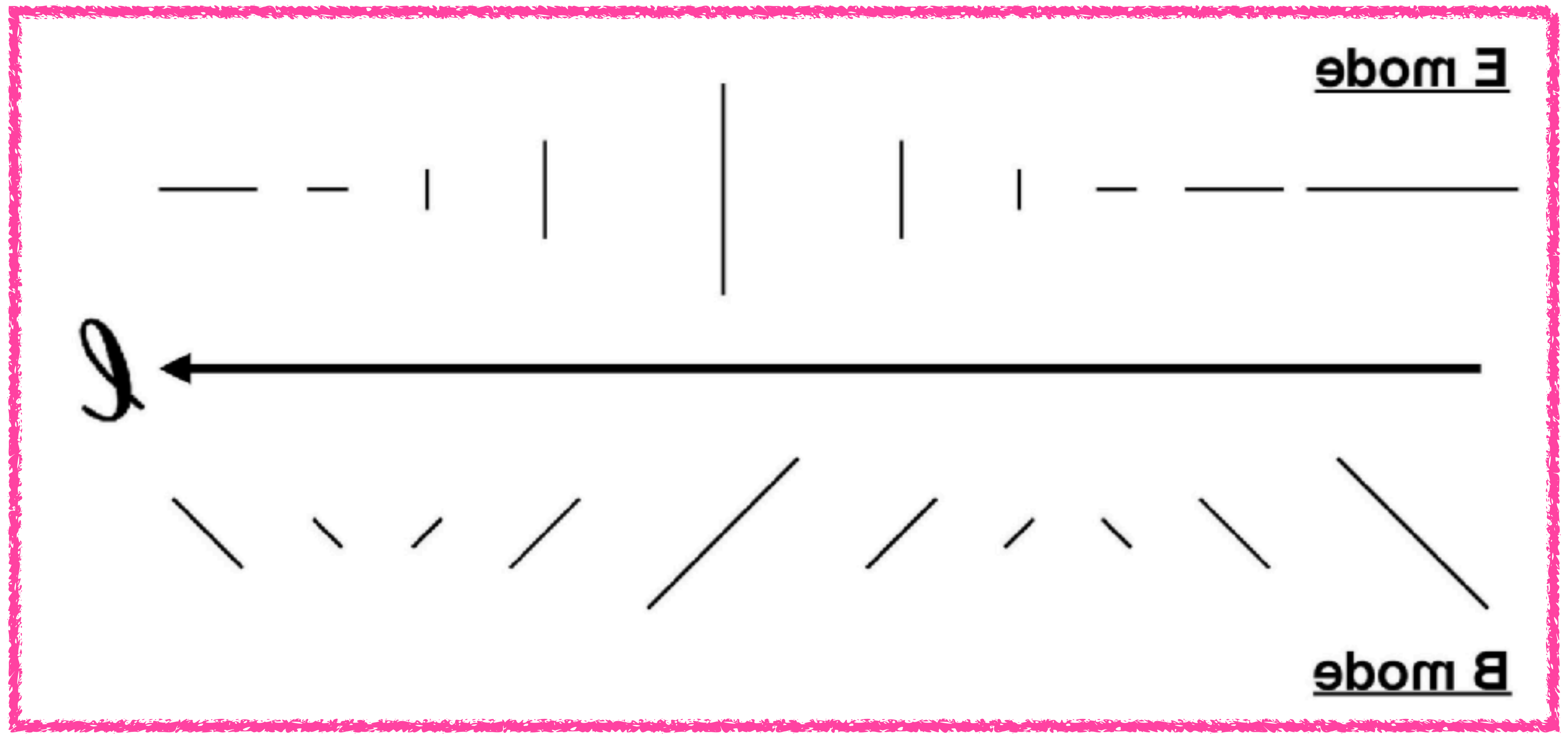
IMPORTANT”: These “E and B modes” are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

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

Parity Flip

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





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

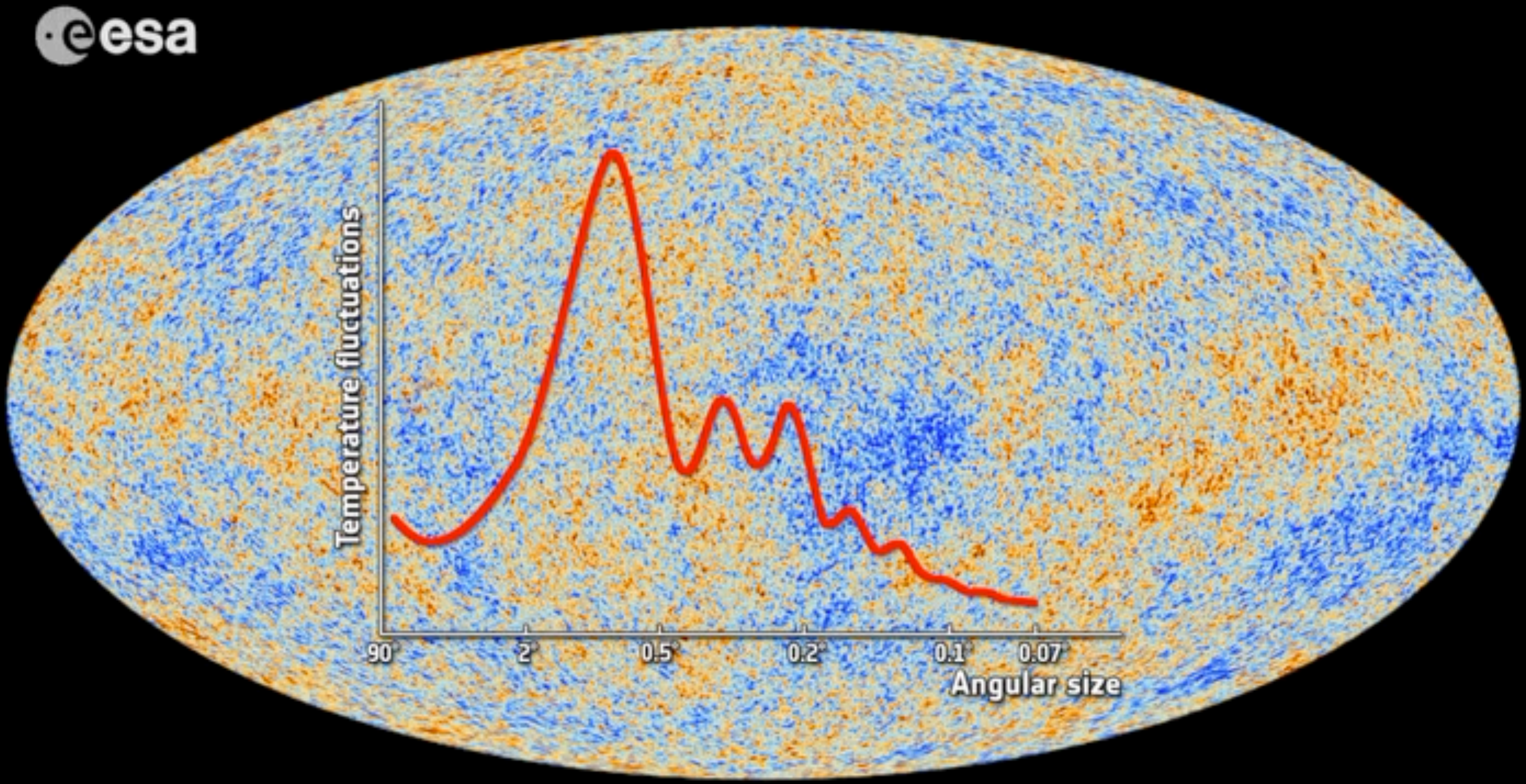
$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

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

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

- 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

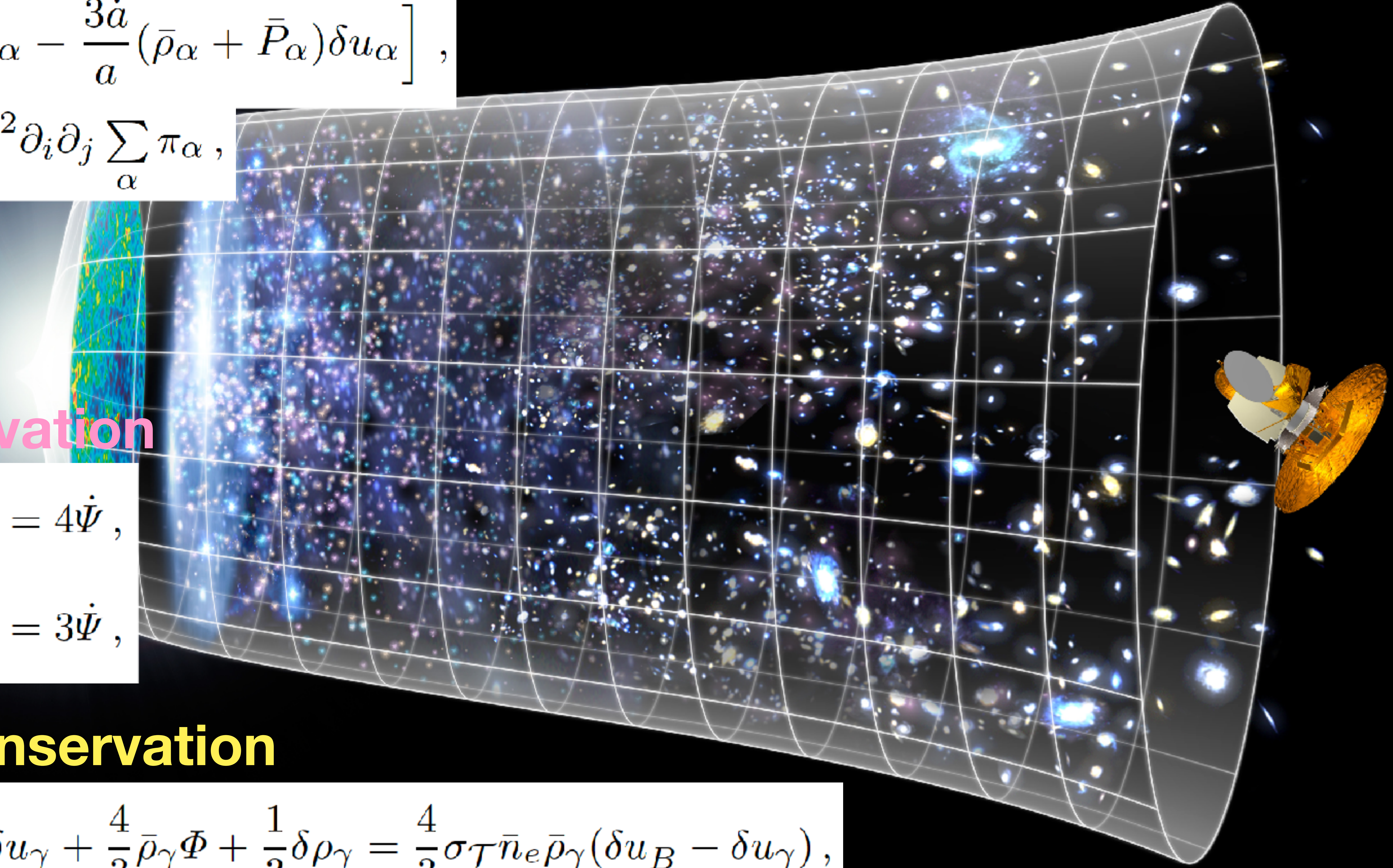


Gravitational Field Equations (Einstein's Eq.)

Credit: WMAP Science Team

$$\nabla^2 \Psi = 4\pi G a^2 \sum_\alpha \left[\delta\rho_\alpha - \frac{3\dot{a}}{a}(\bar{\rho}_\alpha + \bar{P}_\alpha)\delta u_\alpha \right] ,$$

$$\partial_i \partial_j (\Phi - \Psi) = -8\pi G a^2 \partial_i \partial_j \sum_\alpha \pi_\alpha ,$$



Energy Conservation

$$\frac{\partial}{\partial t}(\delta\rho_\gamma / \bar{\rho}_\gamma) - \frac{4q^2}{3a^2}\delta u_\gamma = 4\dot{\Psi} ,$$

$$\frac{\partial}{\partial t}(\delta\rho_B / \bar{\rho}_B) - \frac{q^2}{a^2}\delta u_B = 3\dot{\Psi} ,$$

Momentum Conservation

$$\frac{4}{3}\frac{\partial}{\partial t}(\bar{\rho}_\gamma \delta u_\gamma) + \frac{4\dot{a}}{a}\bar{\rho}_\gamma \delta u_\gamma + \frac{4}{3}\bar{\rho}_\gamma \Phi + \frac{1}{3}\delta\rho_\gamma = \frac{4}{3}\sigma_{\mathcal{T}} \bar{n}_e \bar{\rho}_\gamma (\delta u_B - \delta u_\gamma) ,$$

$$\frac{\partial}{\partial t}(\bar{\rho}_B \delta u_B) + \frac{3\dot{a}}{a}\bar{\rho}_B \delta u_B + \bar{\rho}_B \Phi = -\frac{4}{3}\sigma_{\mathcal{T}} \bar{n}_e \bar{\rho}_\gamma (\delta u_B - \delta u_\gamma) ,$$

Laws of physics!

From “HORIZON”

Gravitational Field Equations

+

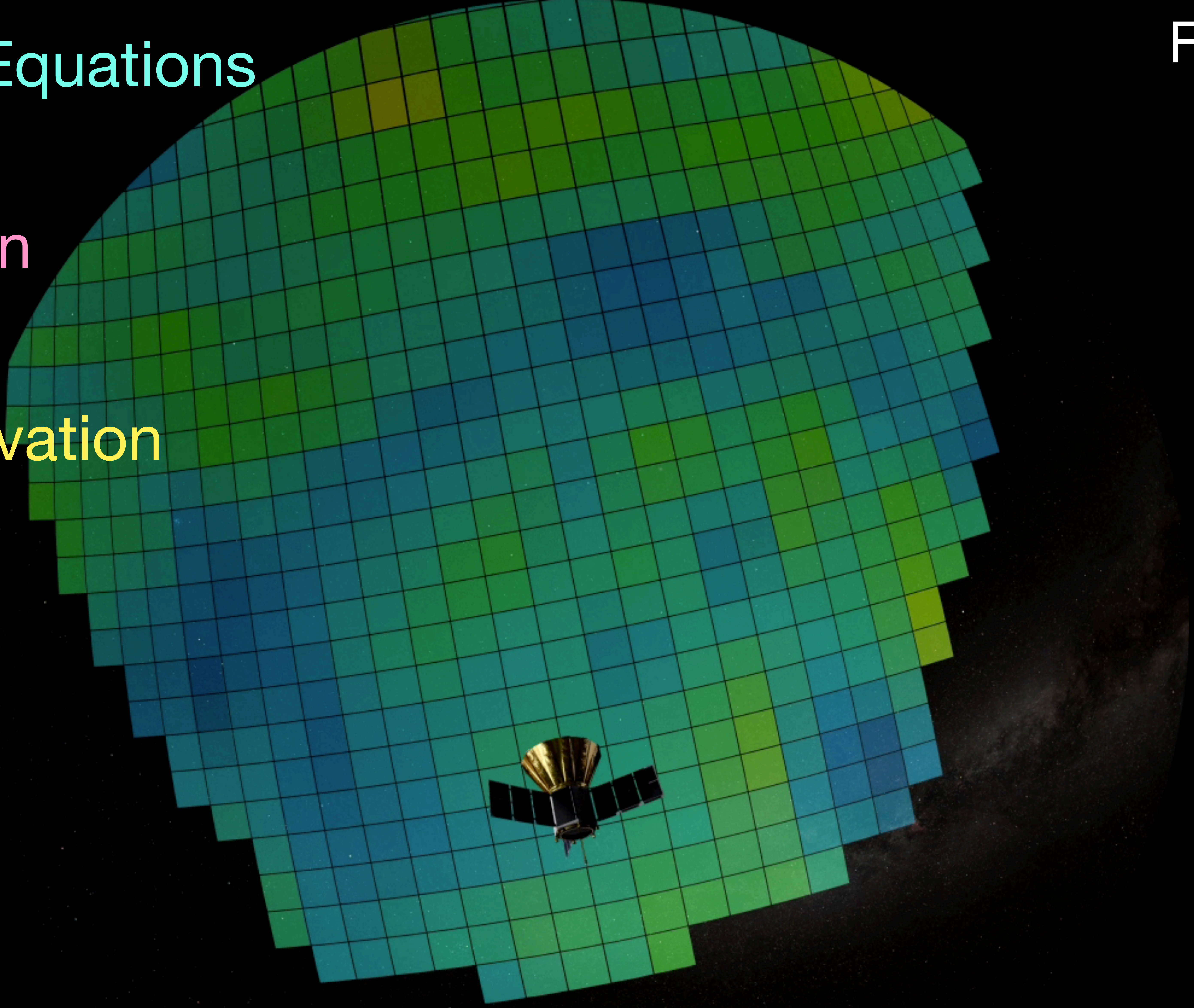
Energy Conservation

+

Momentum Conservation

=

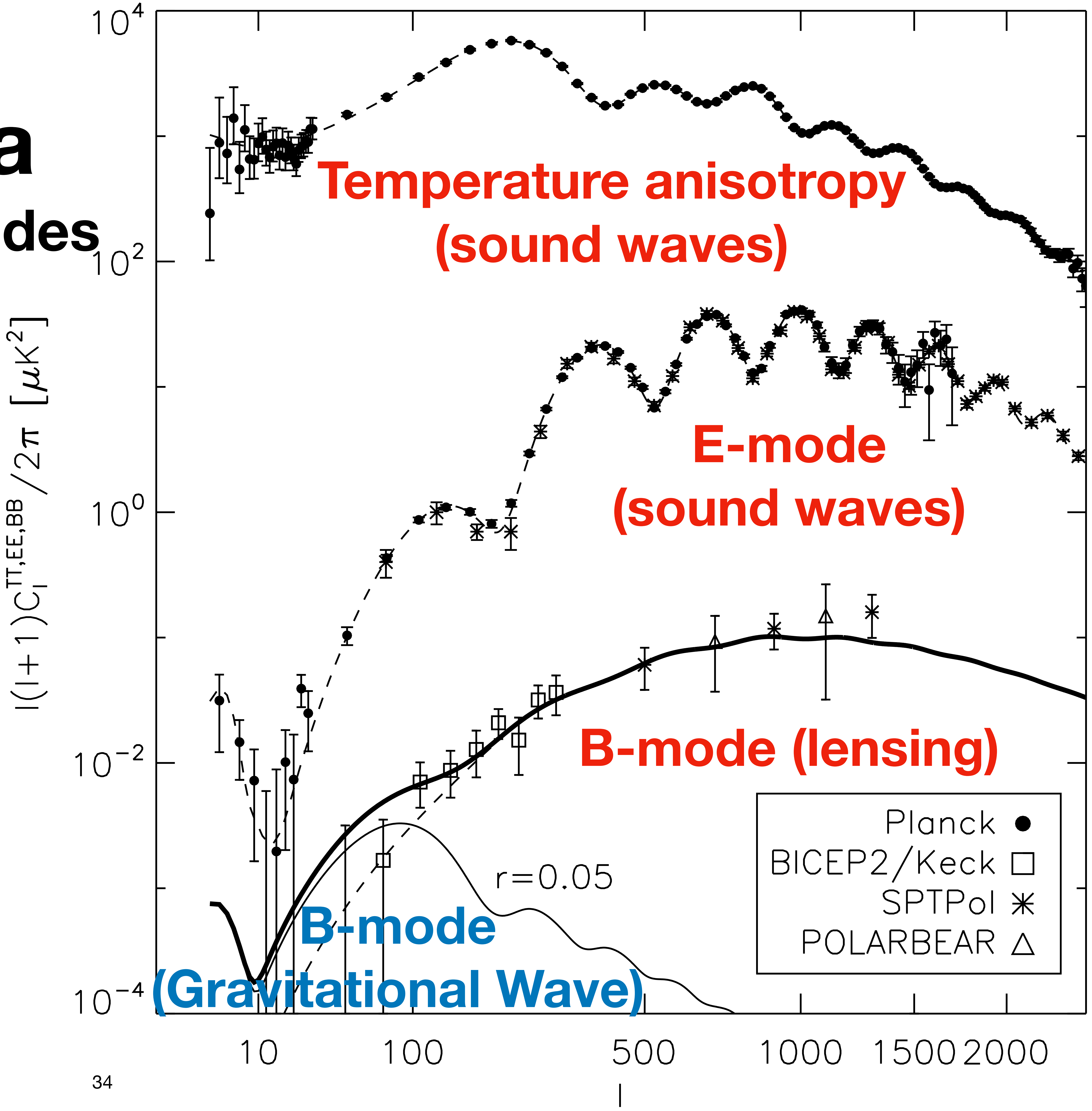
Sound Waves!



CMB Power Spectra

Progress over the last 3 decades

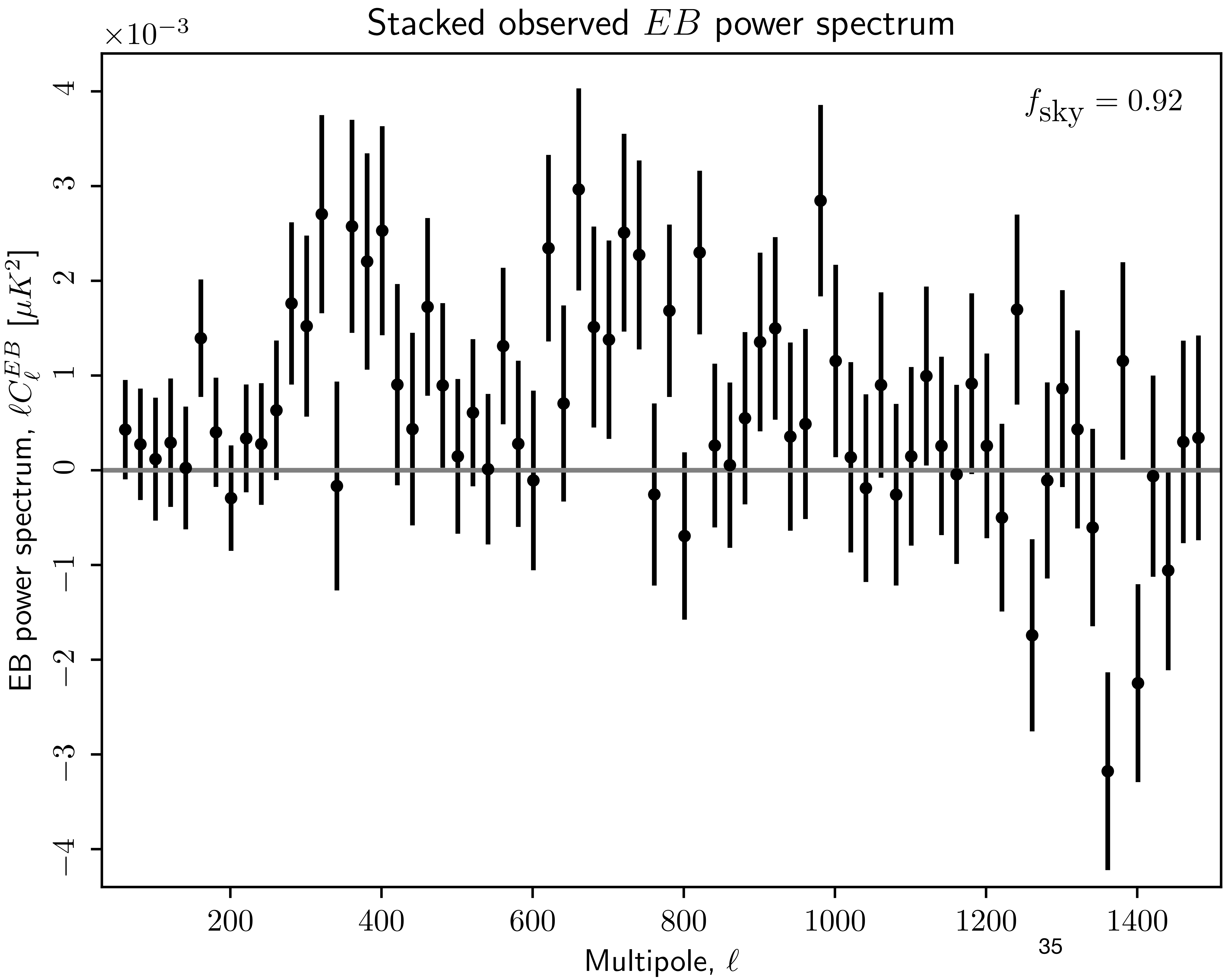
- This is the typical figure that you find in talks and lectures on CMB.
  - The temperature power spectrum and the E- and B-mode polarisation power spectra have been measured well.
- **Our focus is the EB spectrum, which is not shown here.**

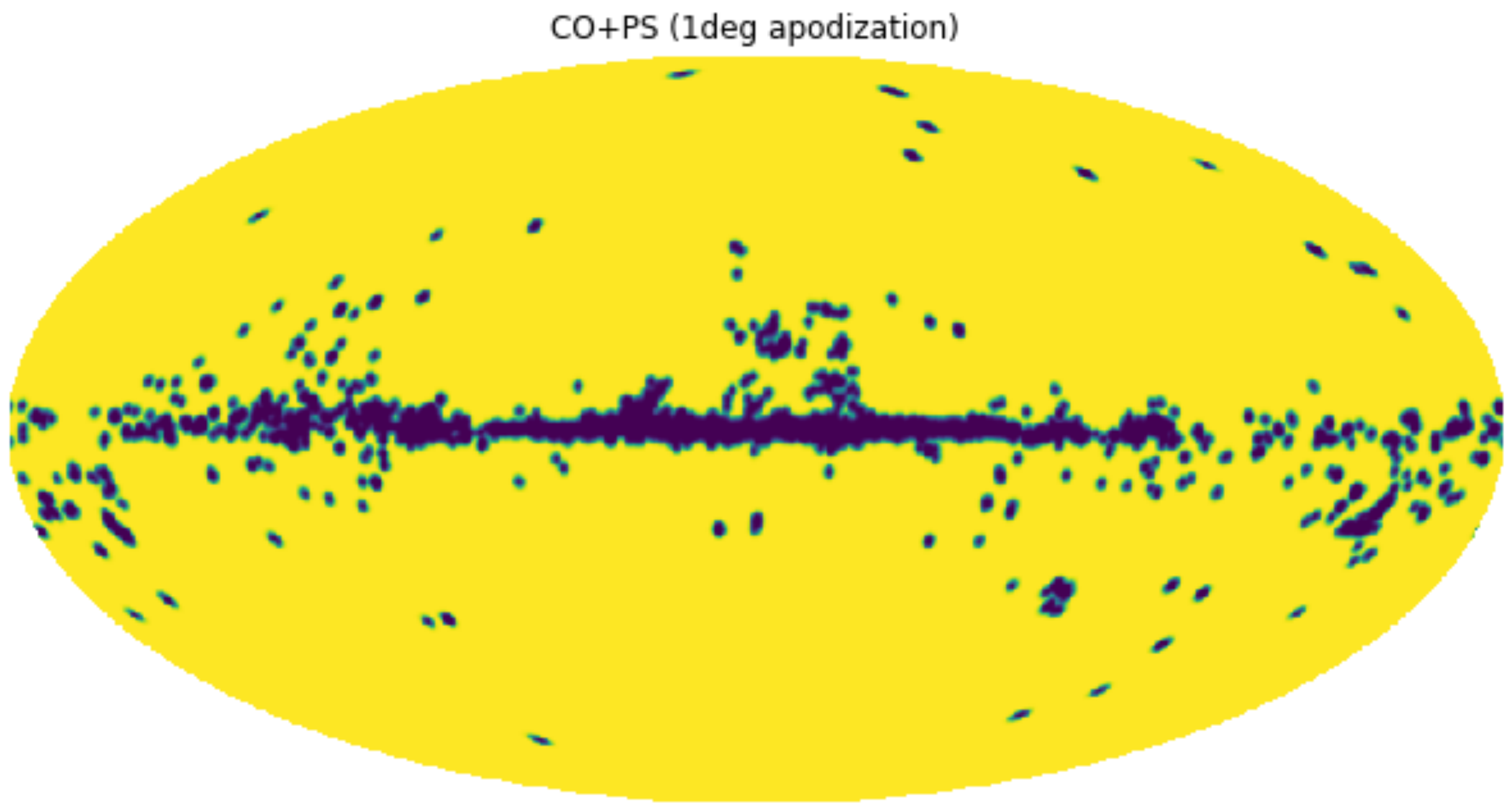


Eskilt & EK (2022)

This is the EB power spectrum (WMAP+Planck)

Nearly full-sky data (92% of the sky)



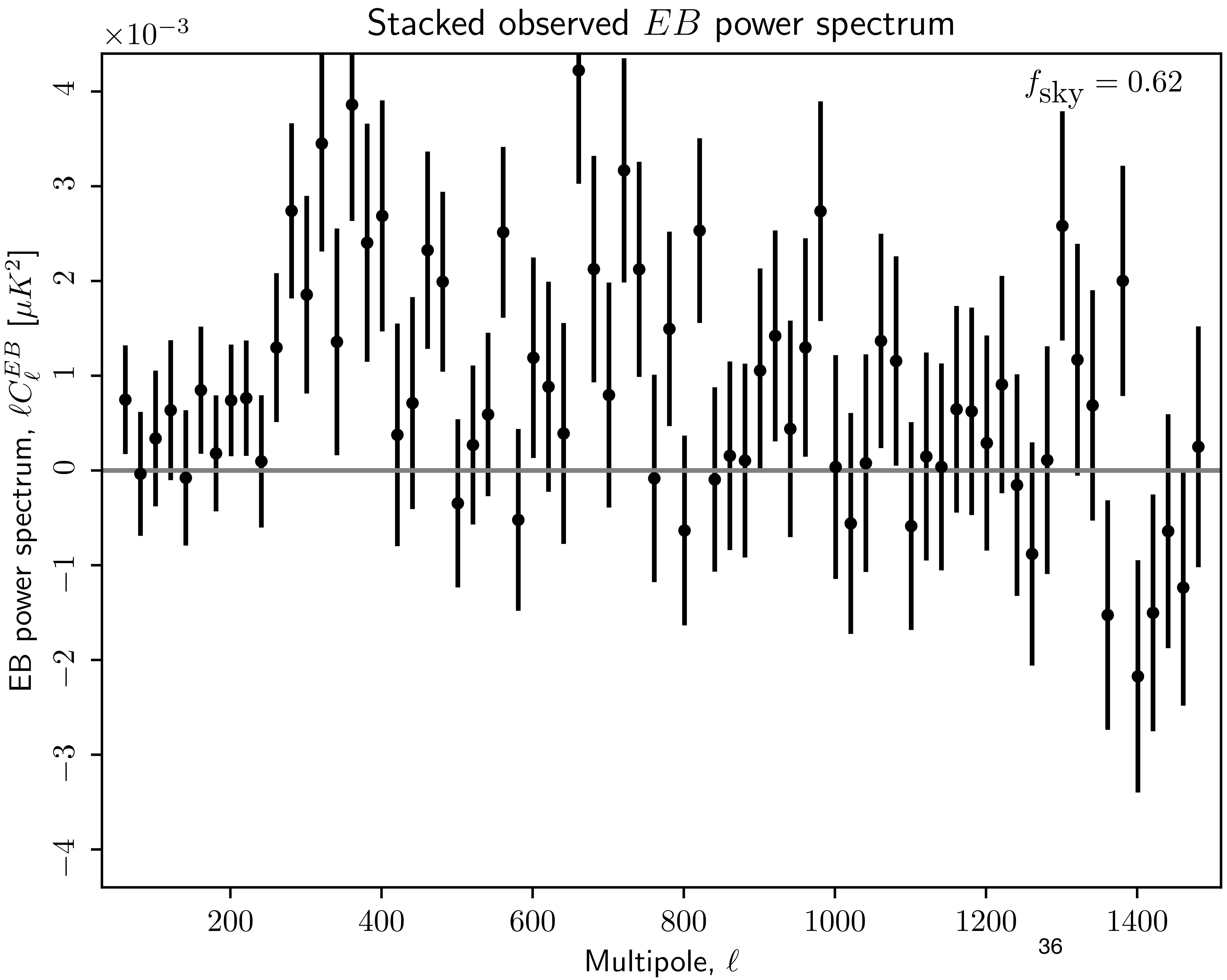


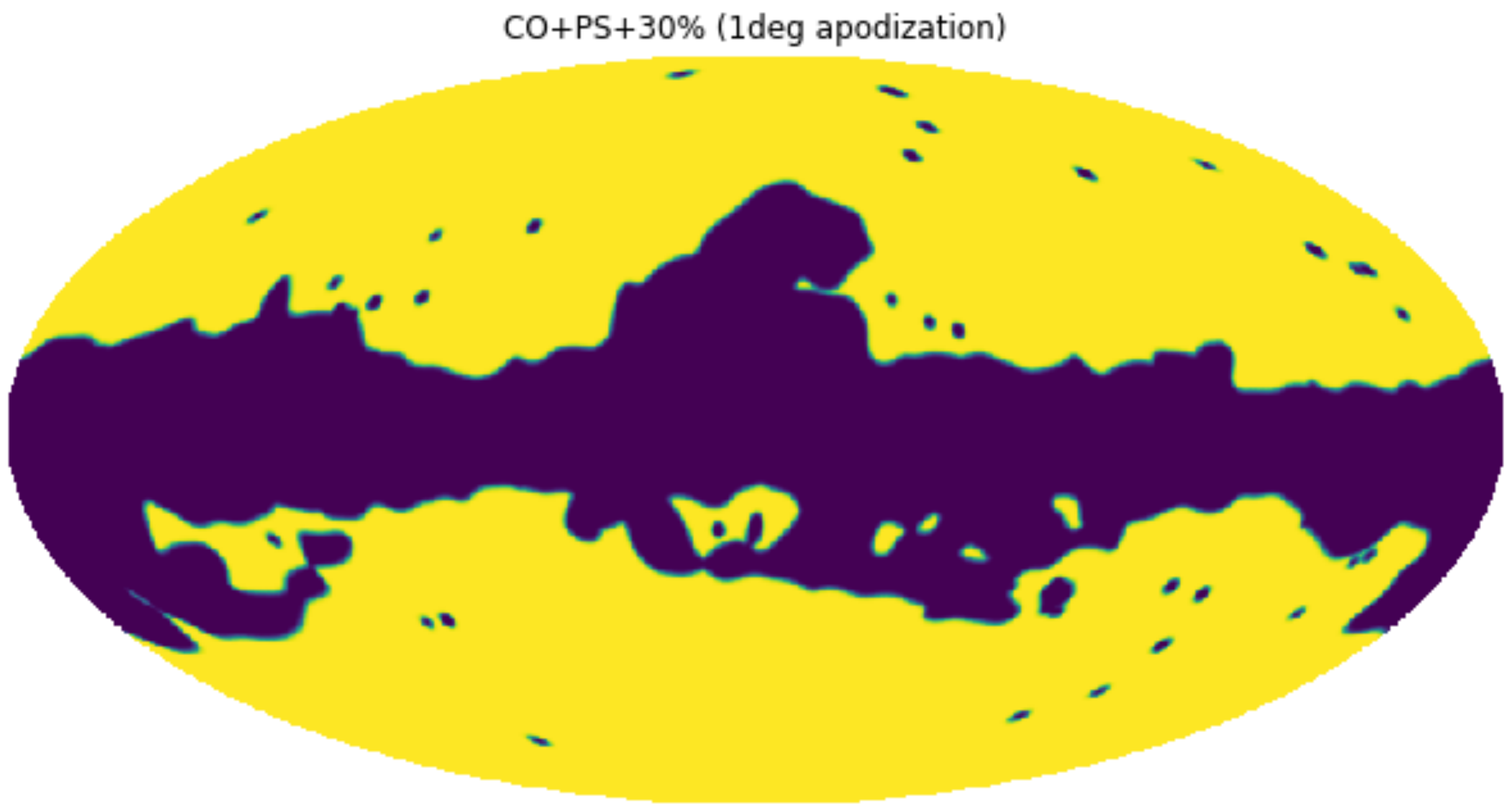
- $\chi^2 = 125.5$ for DOF=72
    - Unambiguous signal of something!

Eskilt & EK (2022)

This is the EB power spectrum (WMAP+Planck)

Galactic plane removed (62% of the sky)





- χ^2 = 138.4 for DOF=72
  - The signal exists regardless of the Galactic mask. This rules out the Galactic foreground.

The EB power spectrum from cosmic birefringence

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

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

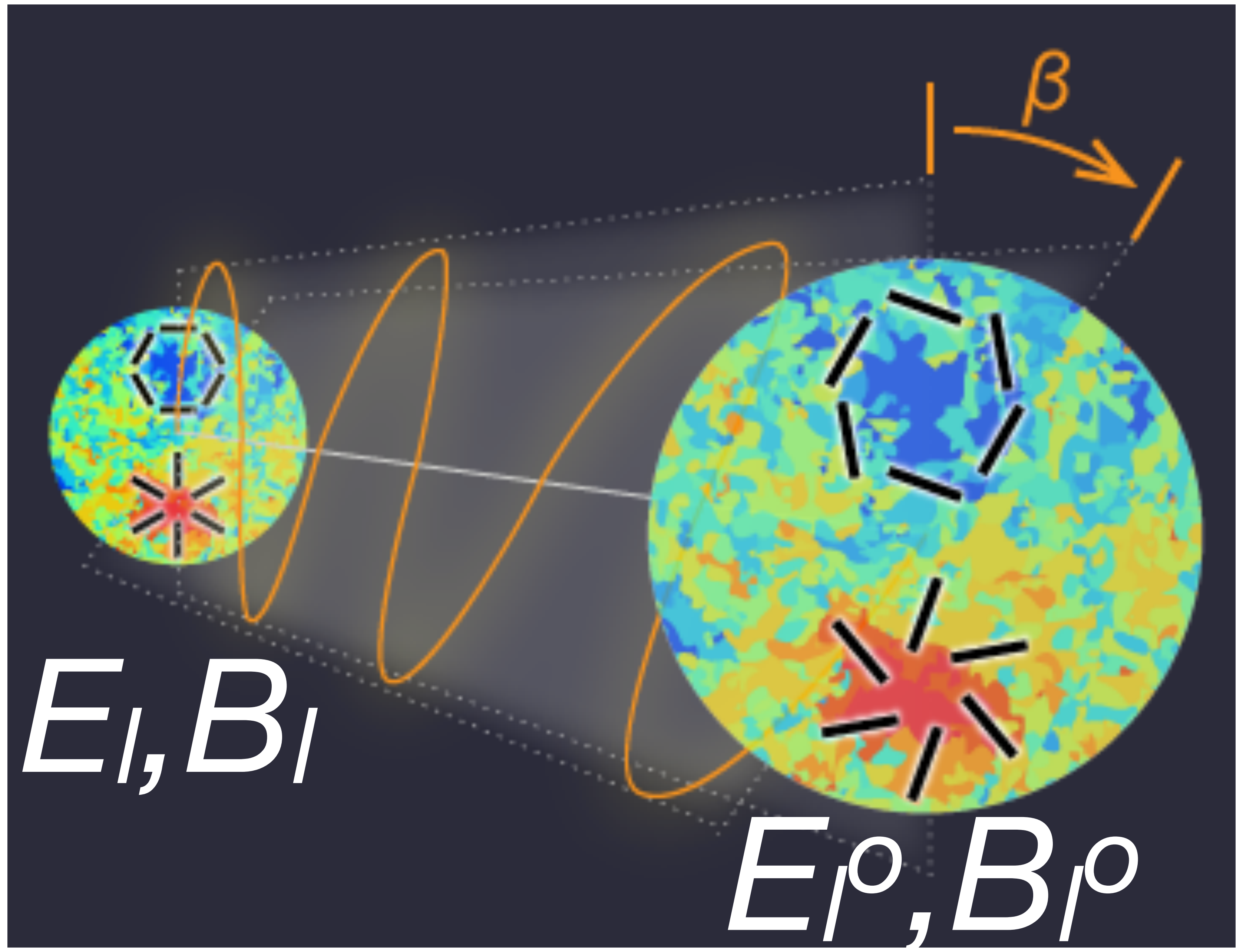
- Observed E- and B-mode polarisation, E_l^o and B_l^o, are related to those before rotation as

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

- which gives

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

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



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

Searching for cosmic 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

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

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

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

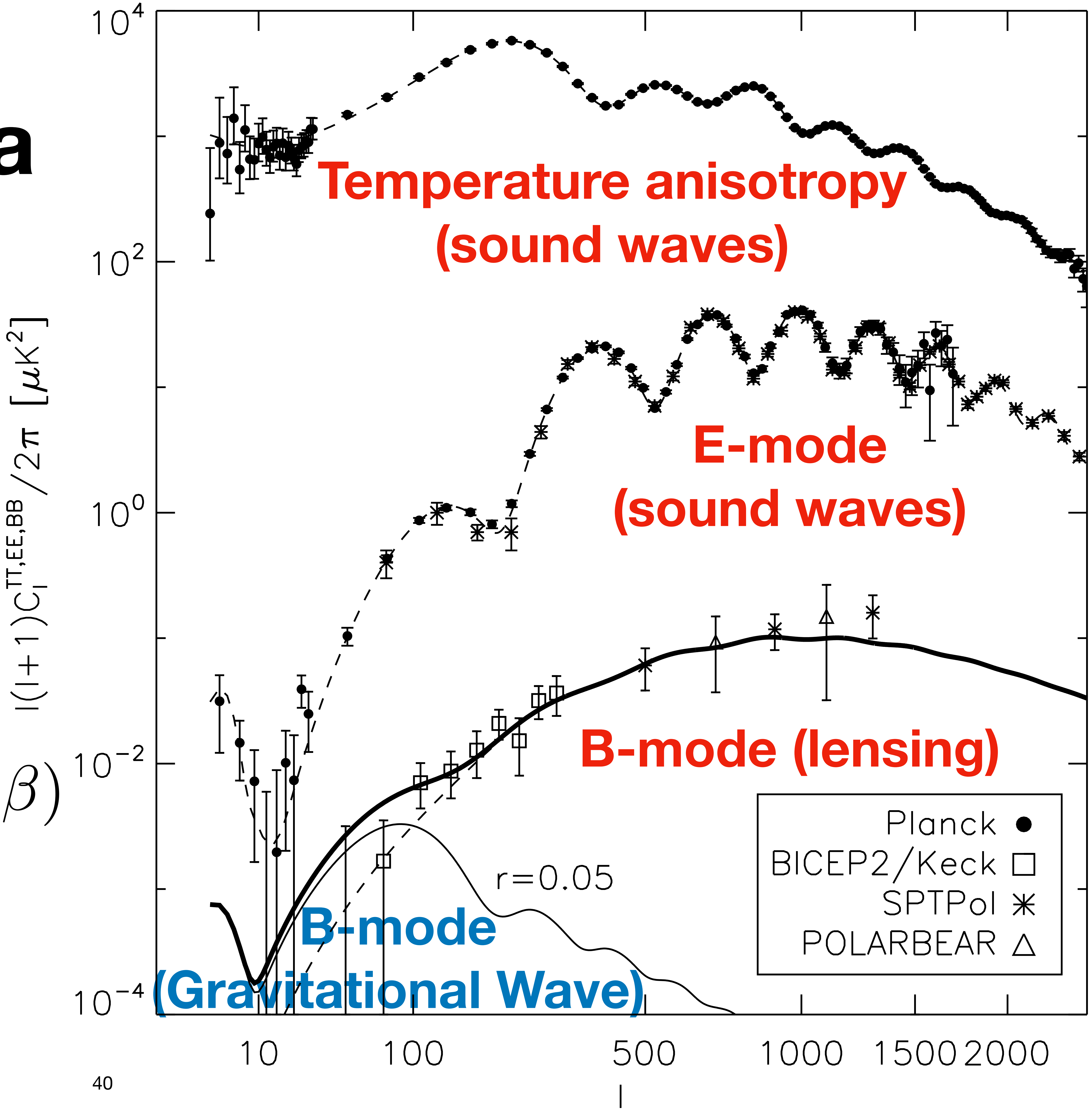
CMB Power Spectra

EE >> BB!

- In our Universe, CMB EE is much greater than BB. This makes CMB sensitive to birefringence.

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

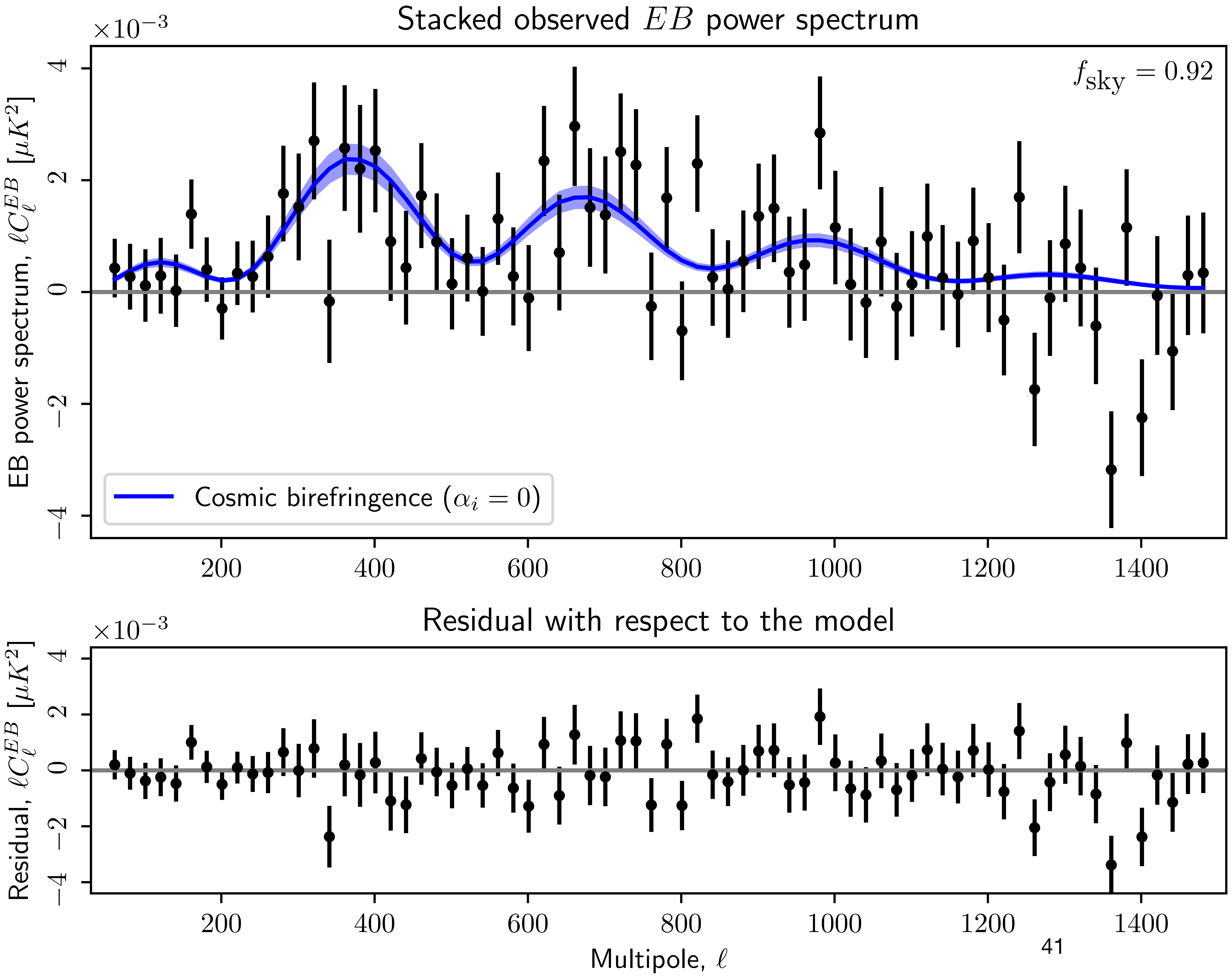
The expectation: *EB should look like EE*. Let's look at the data!

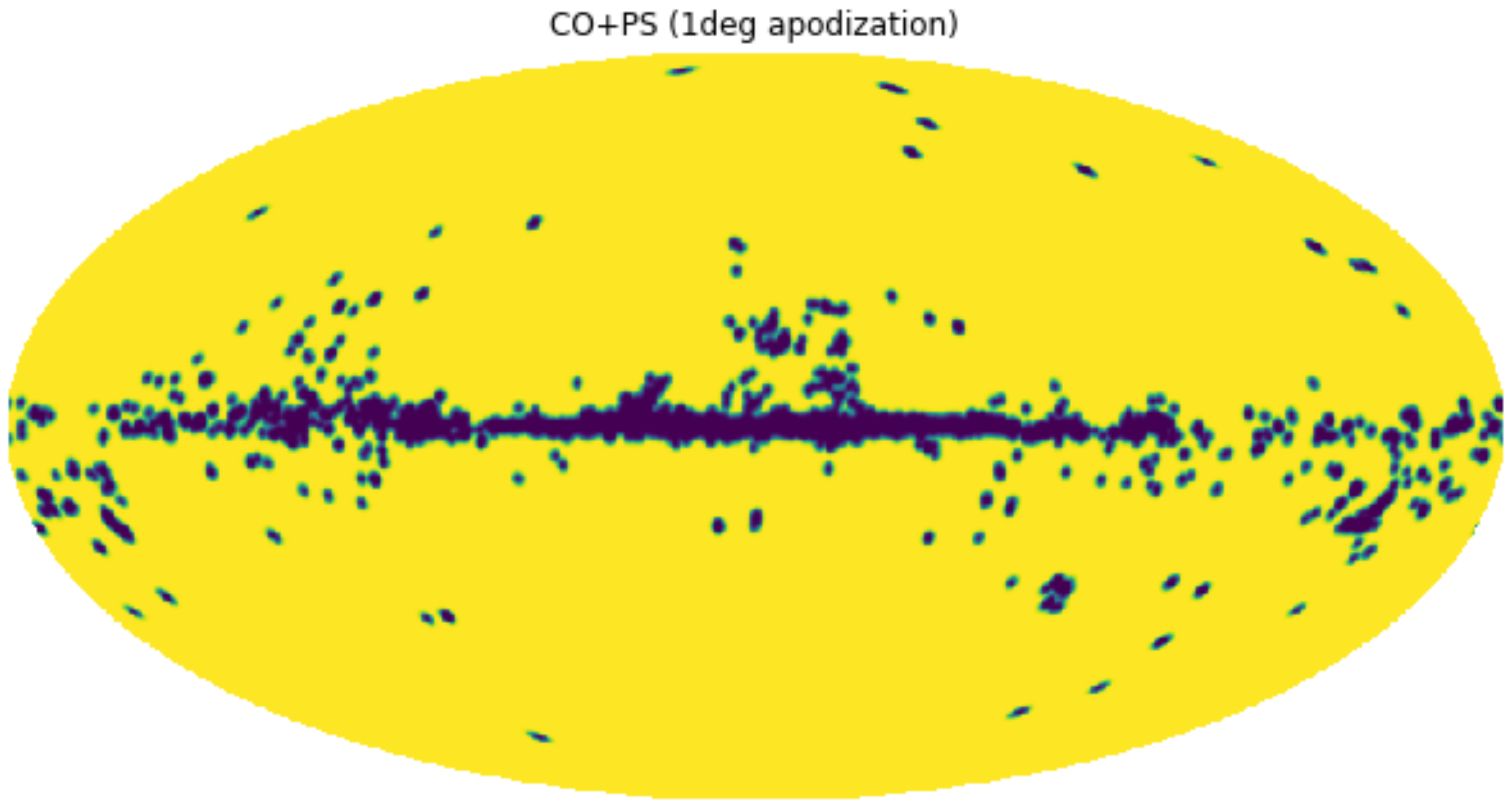


Eskilt & EK (2022)

Cosmic Birefringence fits well(?)

Nearly full-sky data (92% of the sky)



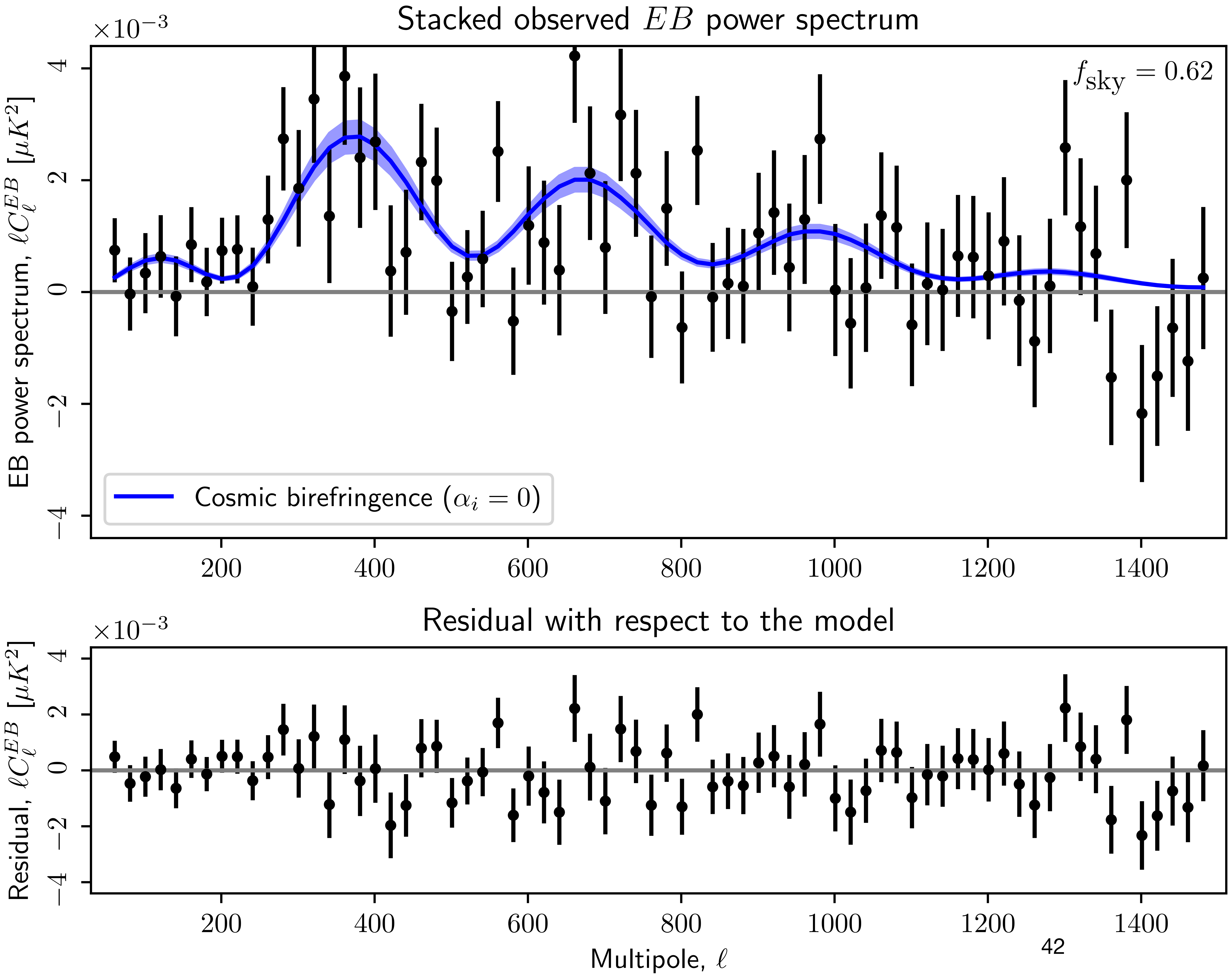


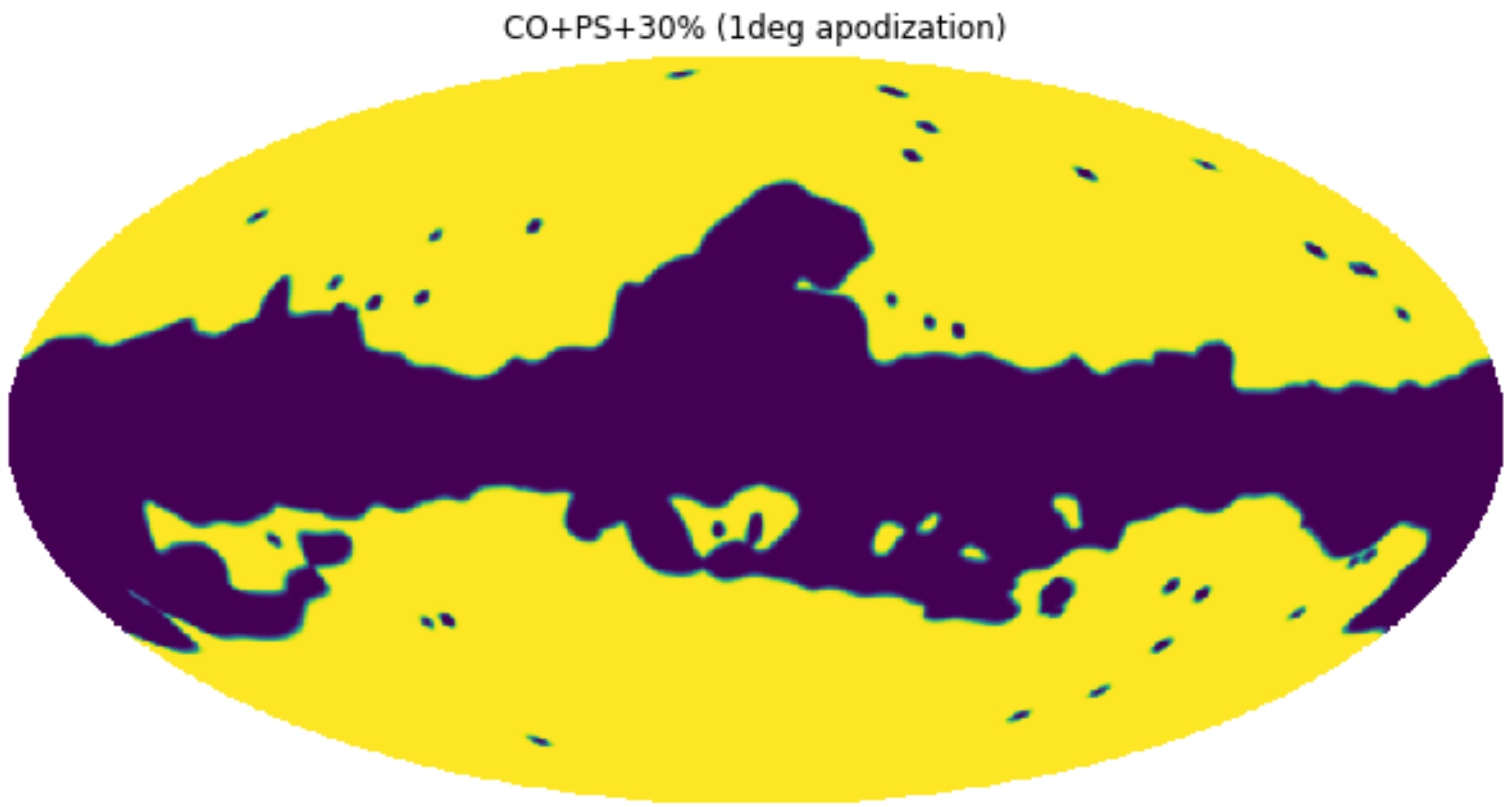
- β = 0.288 ± 0.032 deg
- $\chi^2 = 66.1$
    - Good fit! 9σ detection?

Eskilt & EK (2022)

Cosmic Birefringence fits well(?)

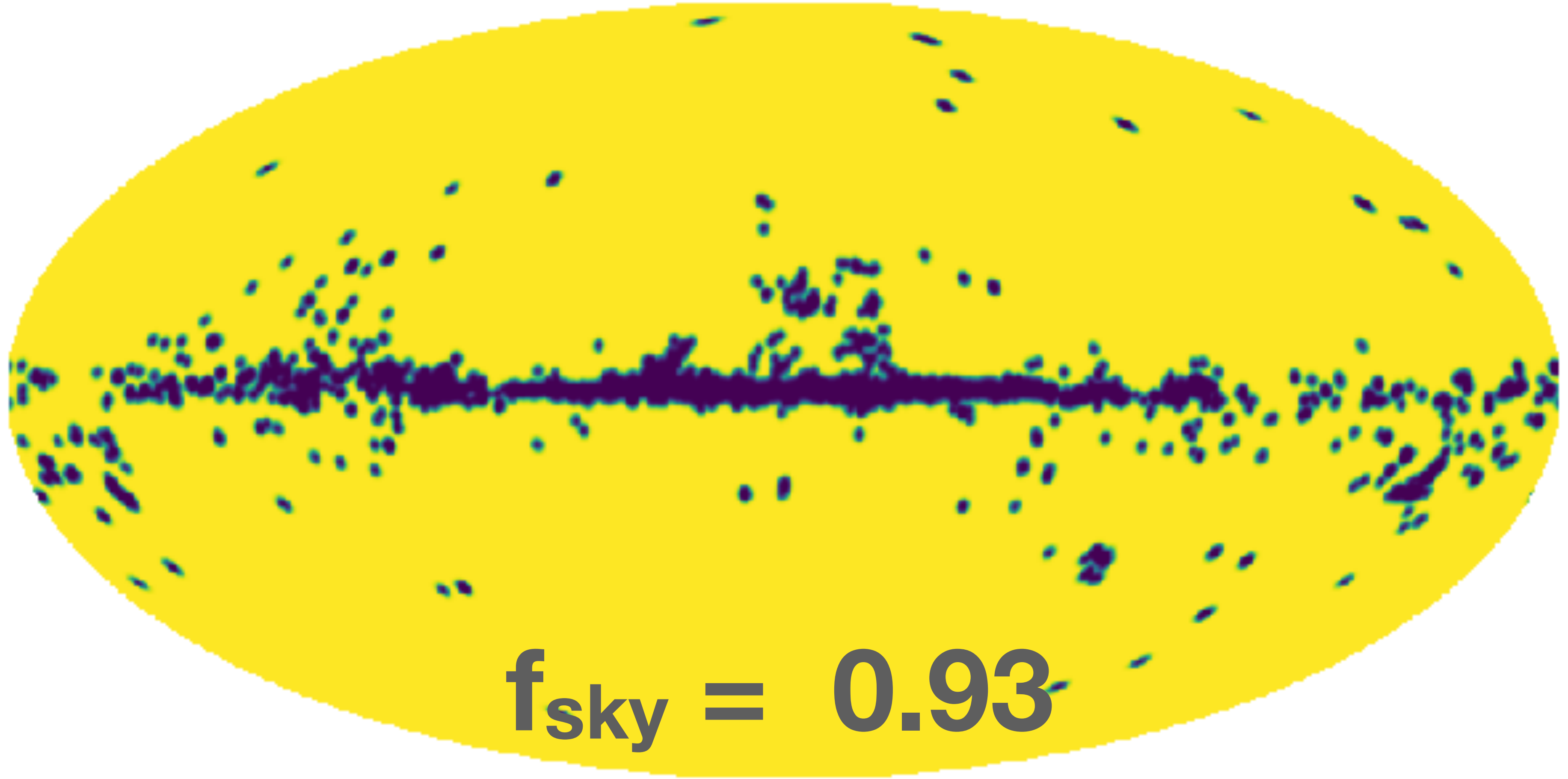
Galactic plane removed (62% of the sky)





- β = 0.330 ± 0.035 deg
- $\chi^2 = 64.5$
- Signal is robust with respect to the Galactic mask.

CO+PS (1deg apodization)

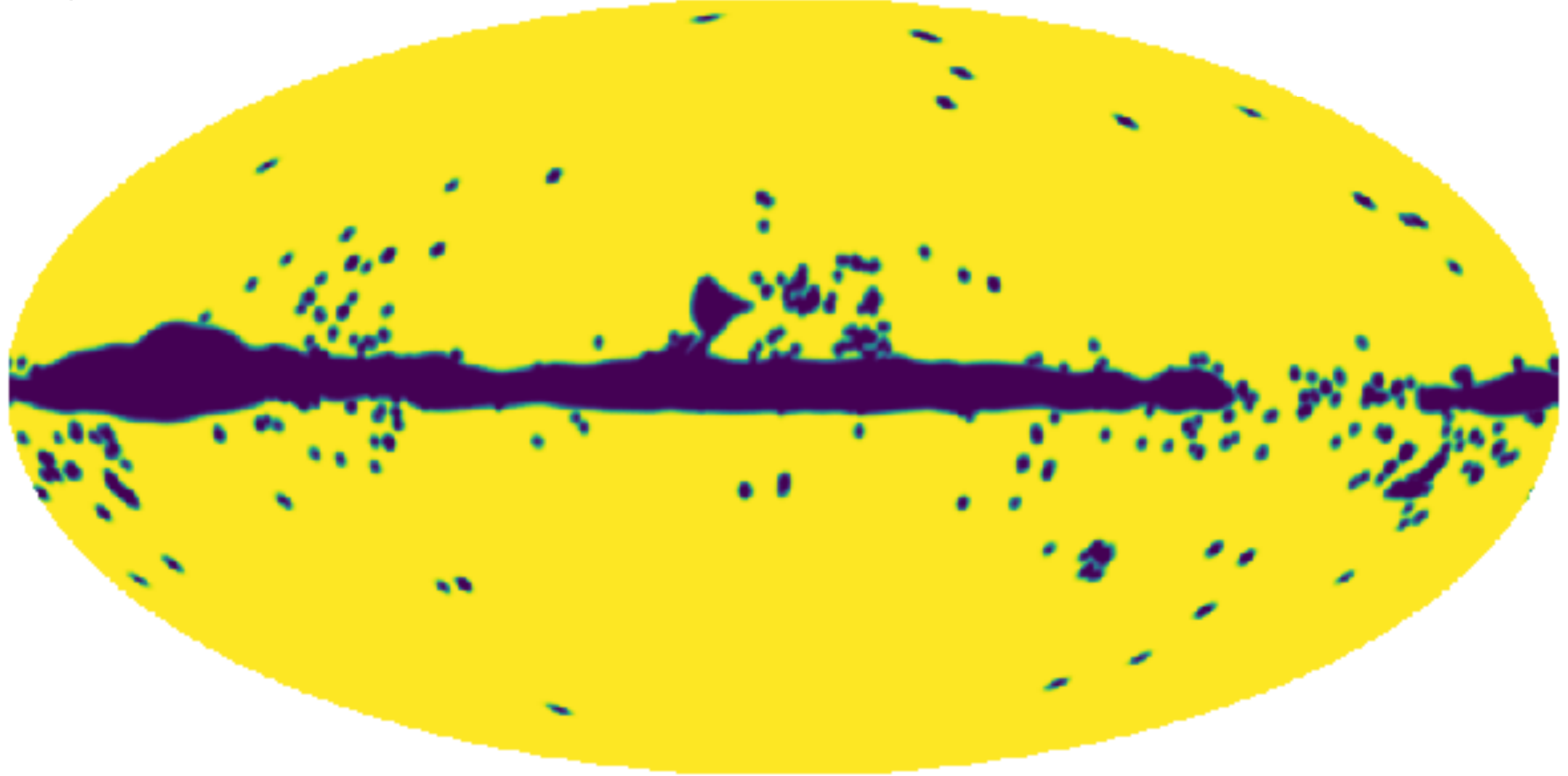


f_{sky} = 0.93

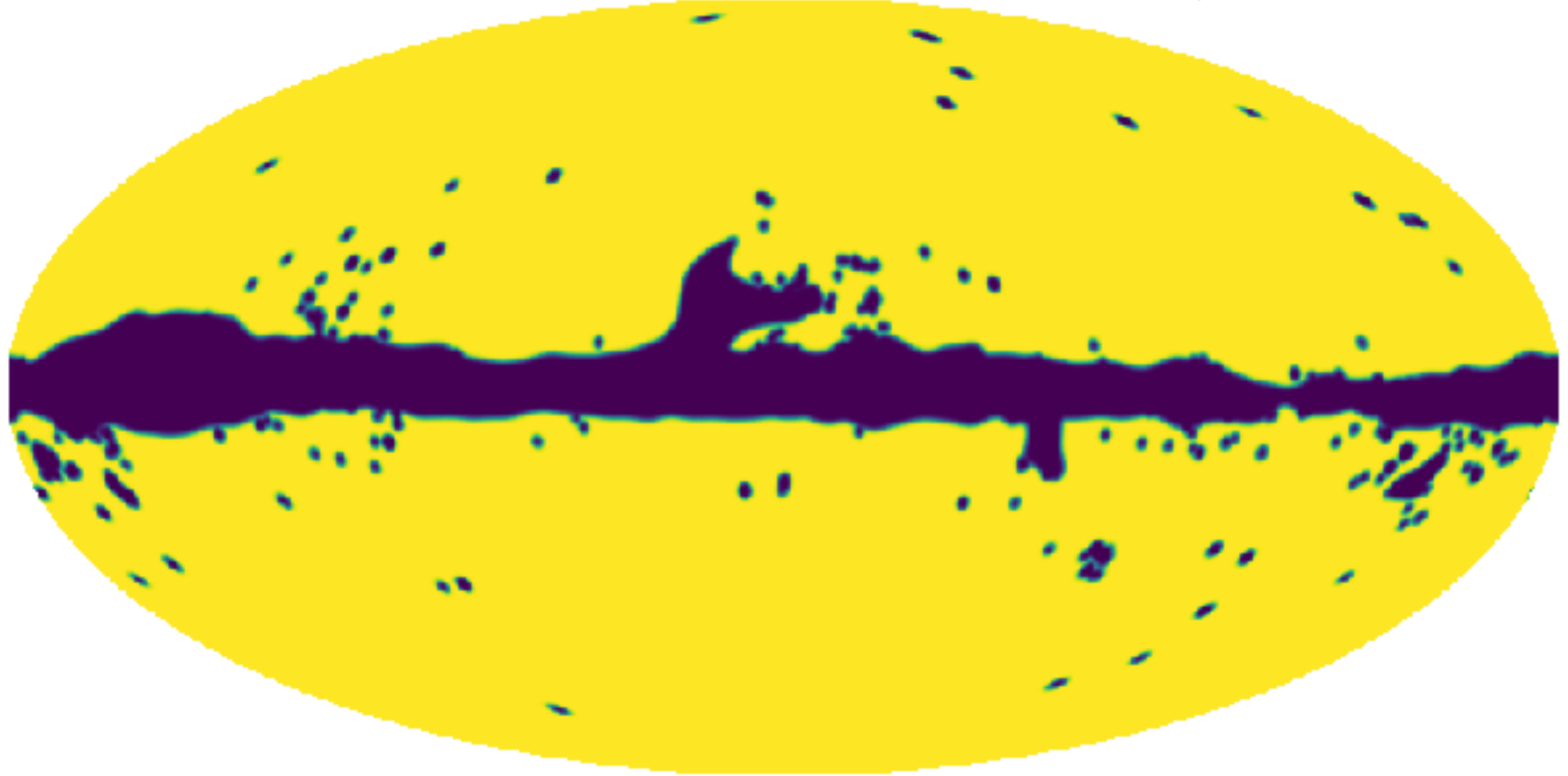
= nearly full sky

f_{sky} = 0.90

CO+PS+5% (1deg apodization)



CO+PS+10% (1deg apodization)



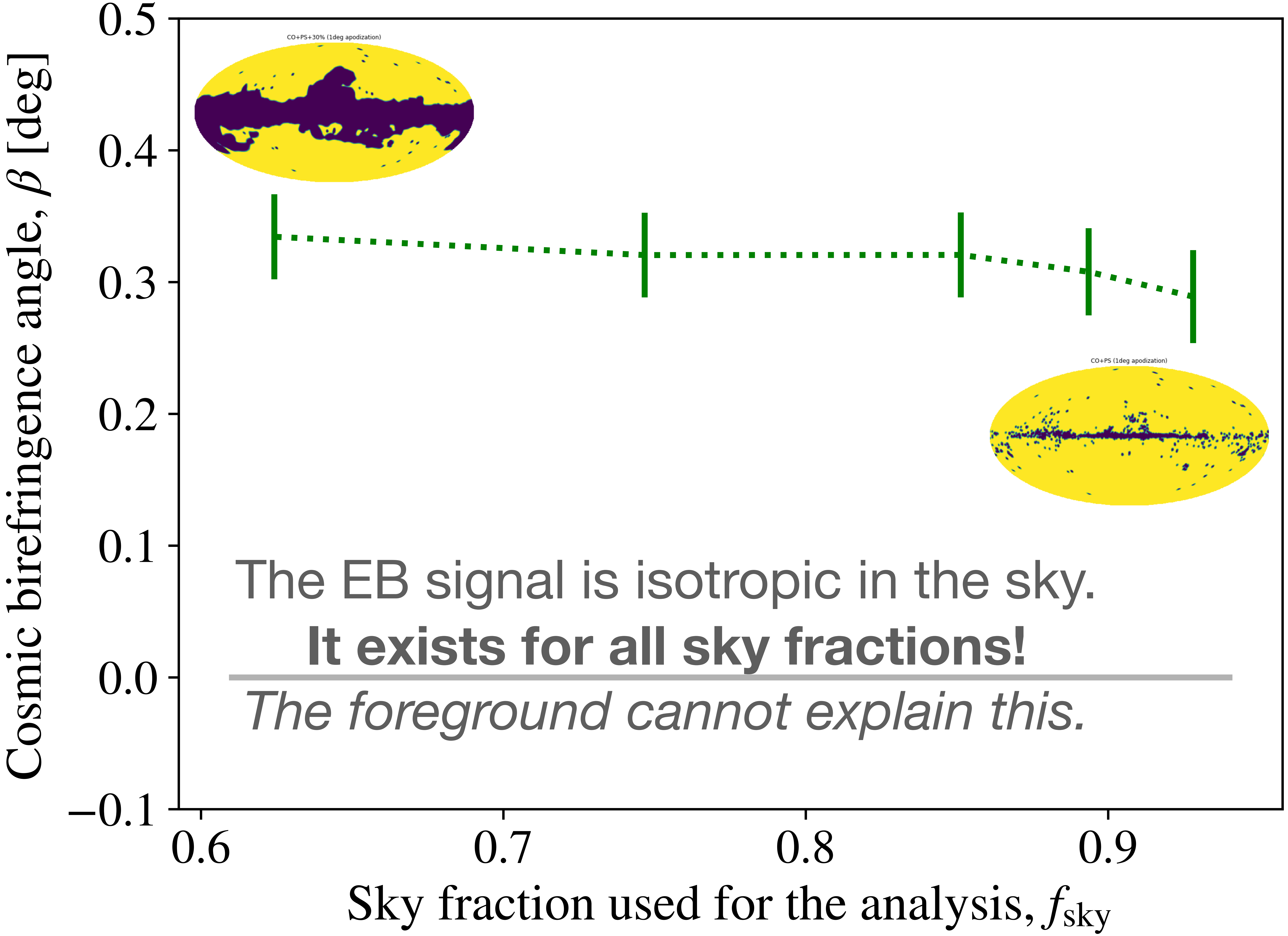
f_{sky} = 0.85

CO+PS+20% (1deg apodization)

f_{sky} = 0.75

CO+PS+30% (1deg apodization)

f_{sky} = 0.63



The EB signal is isotropic in the sky.

It exists for all sky fractions!

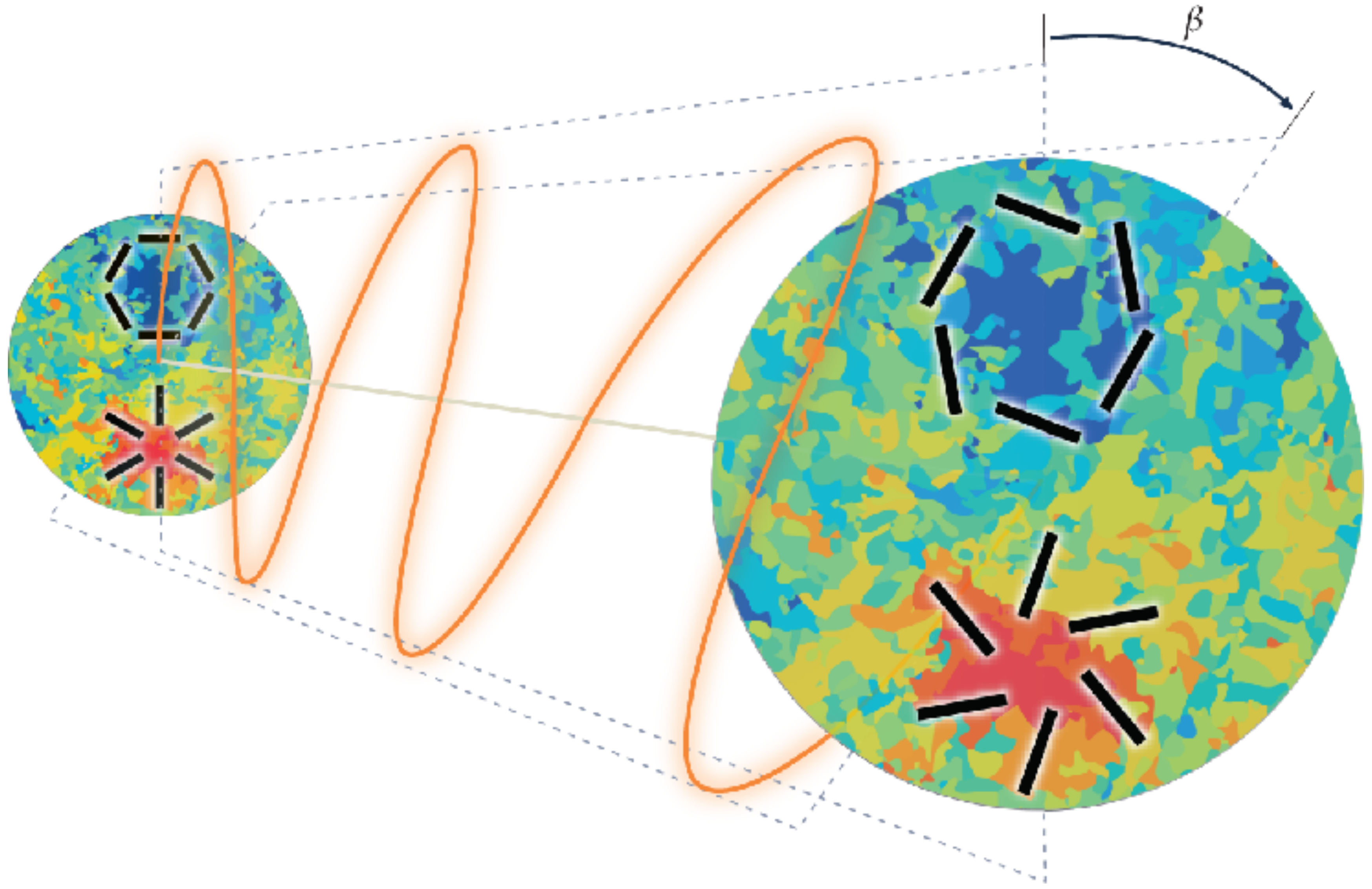
The foreground cannot explain this.

The Biggest Problem: Miscalibration of detectors

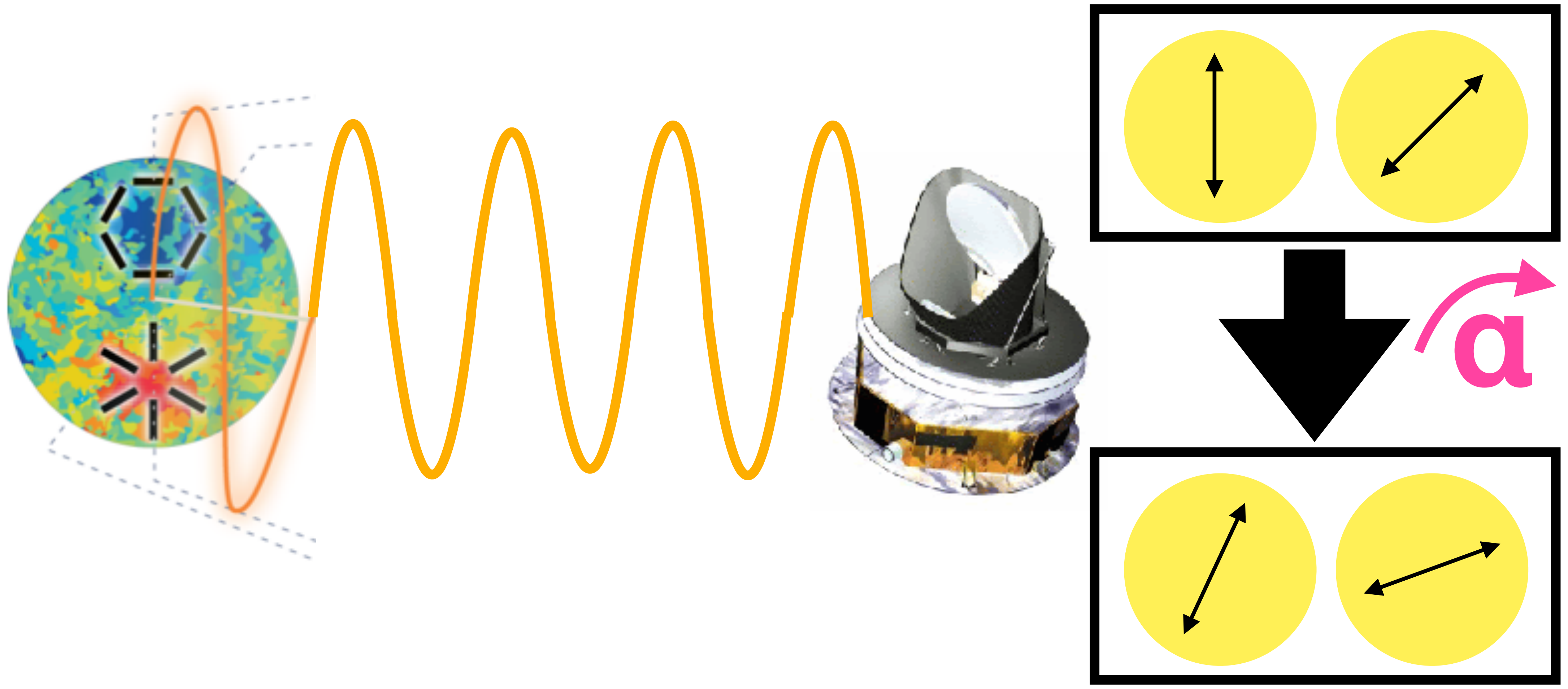
Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

Impact of miscalibration of polarisation angles

Cosmic or Instrumental?



OR



Polarisation-sensitive detectors on the focal plane

rotated by an angle “α” (but we do not know it)

- 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)

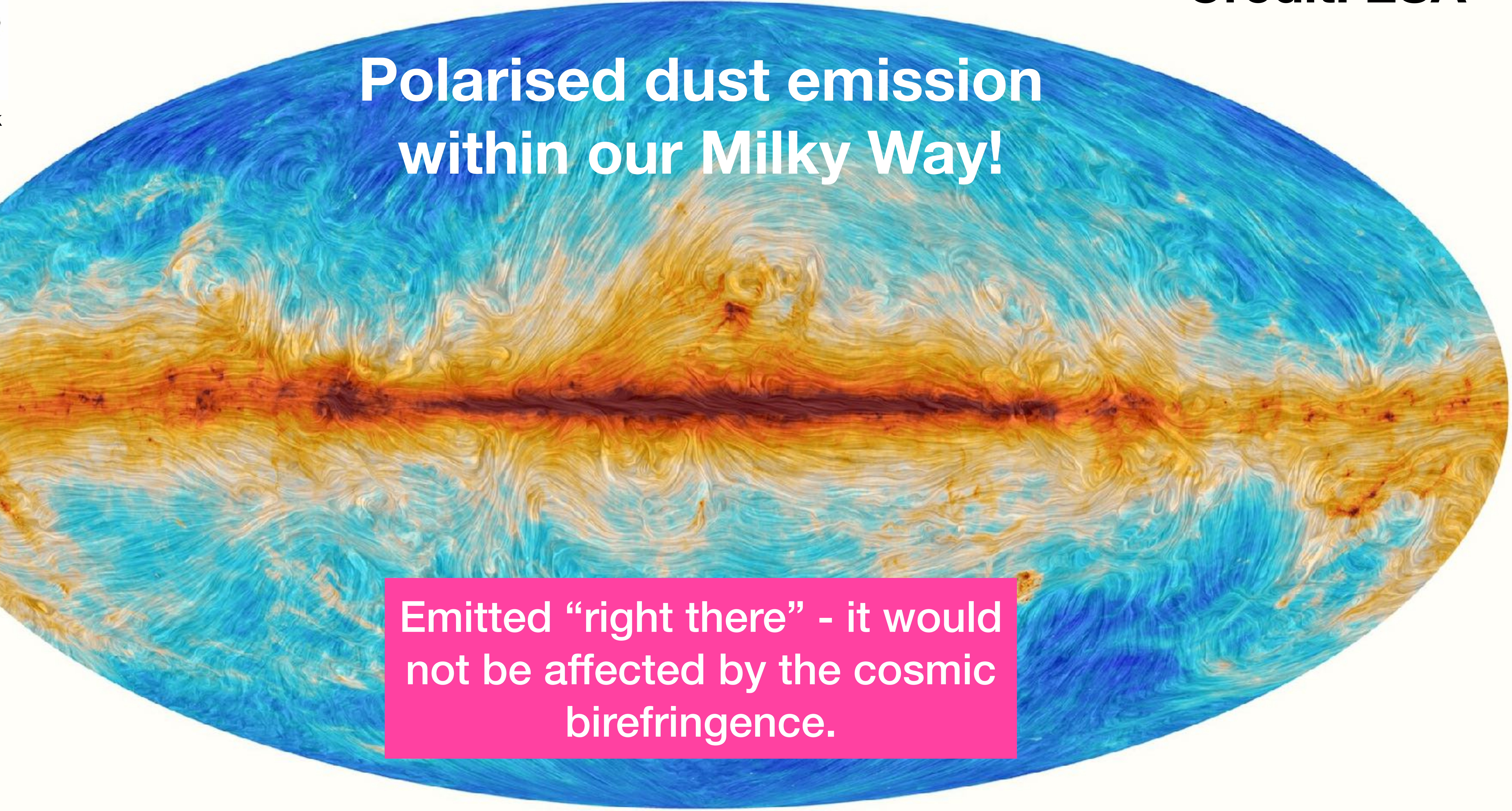
Uncertainty in the calibration of α has been the major limitation

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

Credit: ESA

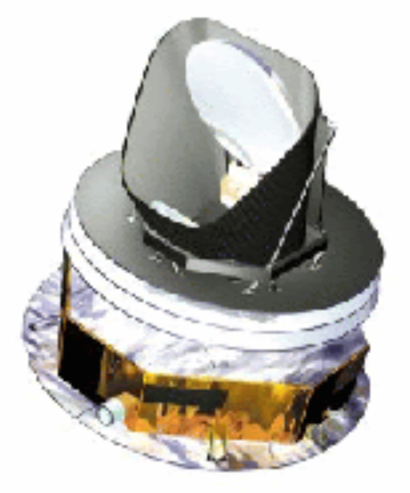
ESA’s Planck

Polarised dust emission within our Milky Way!



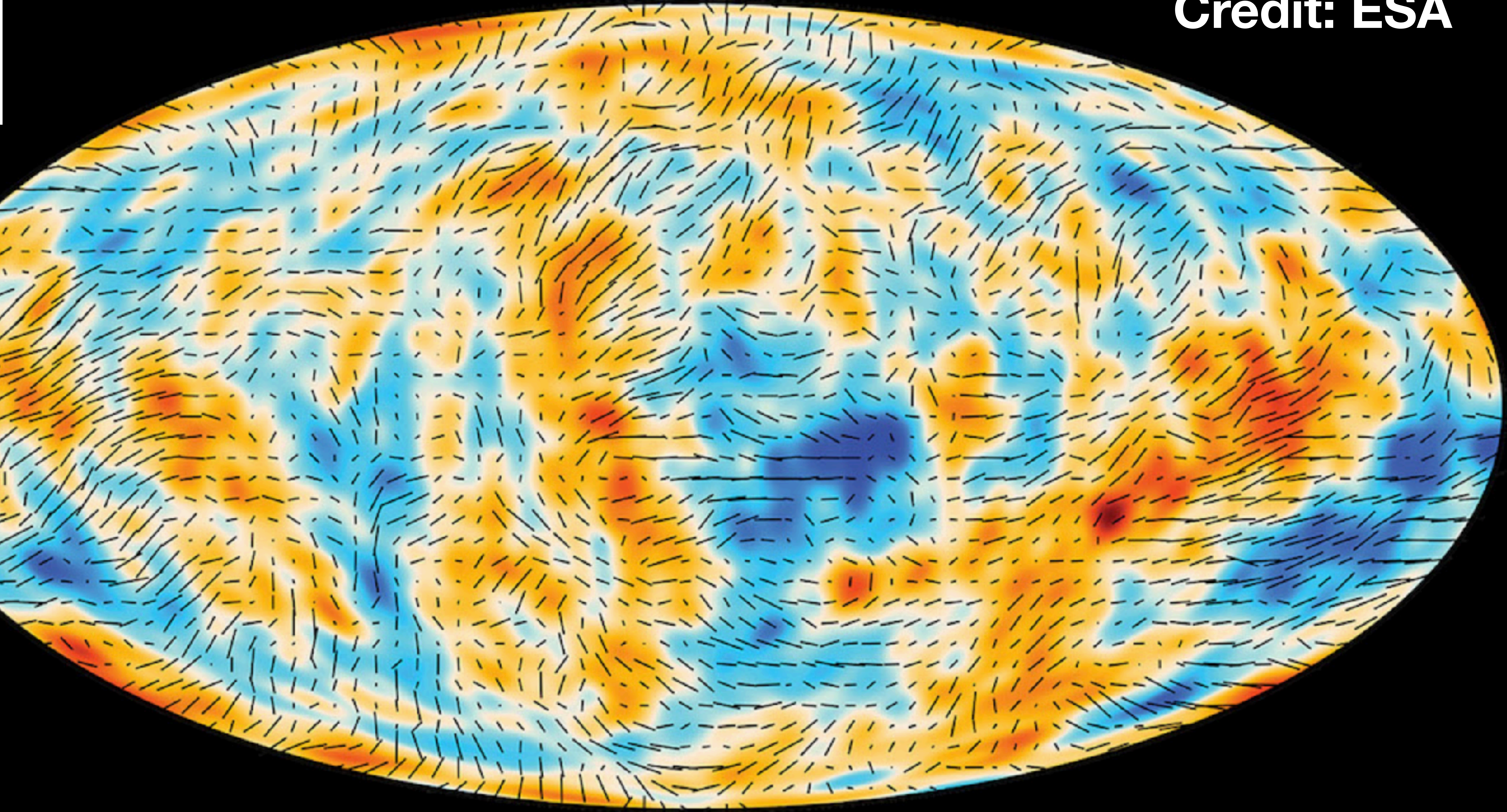
Emitted “right there” - it would not be affected by the cosmic birefringence.

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



ESA's Planck

Credit: ESA

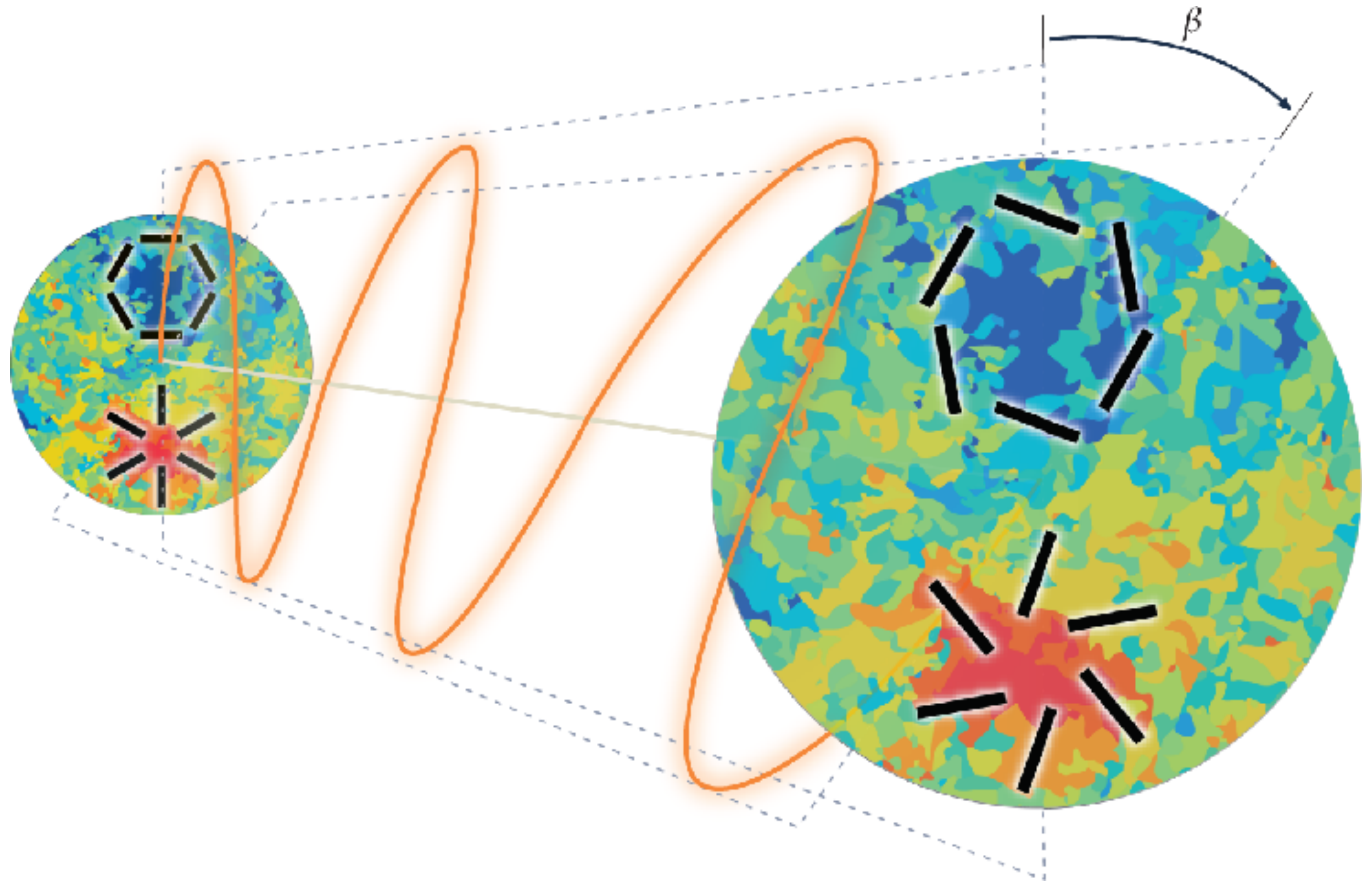


Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Searching for the birefringence

Including the miscalibration angle



Emitted 13.8 billions years ago

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.*

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

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

noise

- Thus,

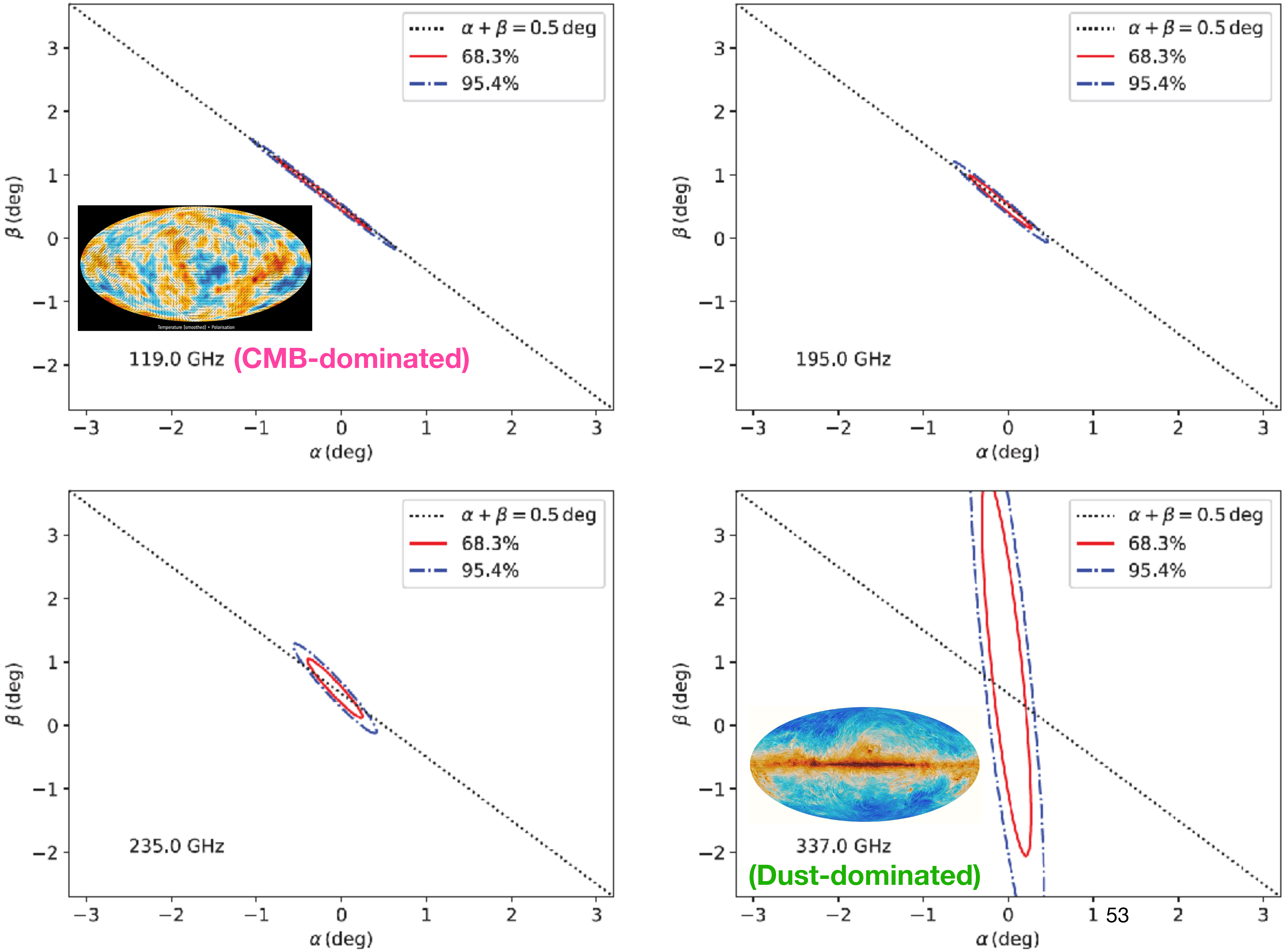
$$\langle C^{EB,\mathrm{o}}_{\ell}\rangle = \frac{\tan(4\alpha)}{2}\left(\underbrace{\langle C^{EE,\mathrm{o}}_{\ell}\rangle - \langle C^{BB,\mathrm{o}}_{\ell}\rangle}_{\text{measured}}\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\underbrace{\langle C^{EE,\mathrm{CMB}}_{\ell}\rangle - \langle C^{BB,\mathrm{CMB}}_{\ell}\rangle}_{\text{known accurately}}\right)$$
$$+\frac{1}{\cos(4\alpha)}\langle C^{EB,\mathrm{fg}}_{\ell}\rangle + \frac{\cos(4\beta)}{\cos(4\alpha)}\langle C^{EB,\mathrm{CMB}}_{\ell}\rangle\,.$$

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

Minami et al. (2019)

How does it work?

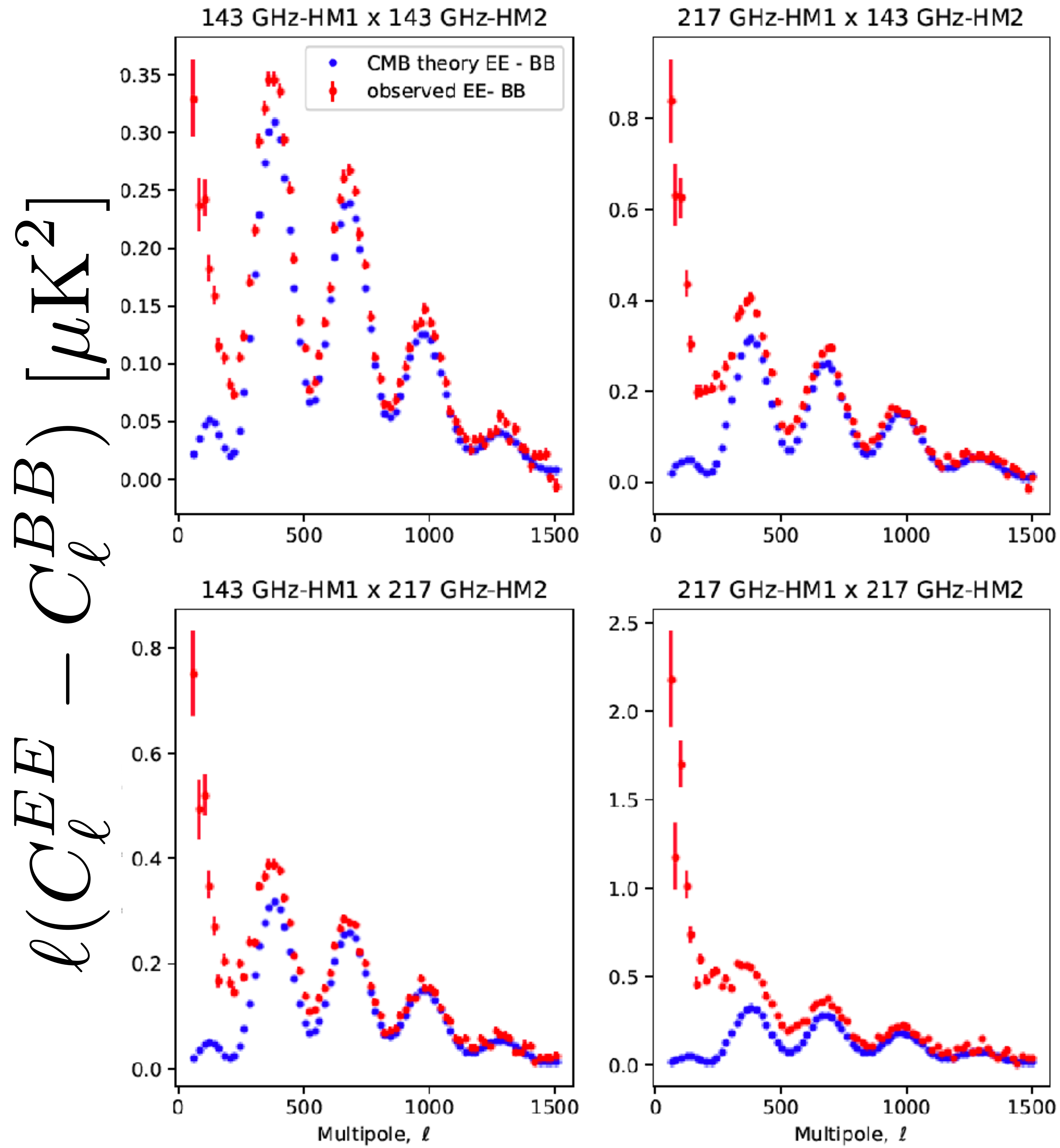
Simulation of future CMB data (LiteBIRD)



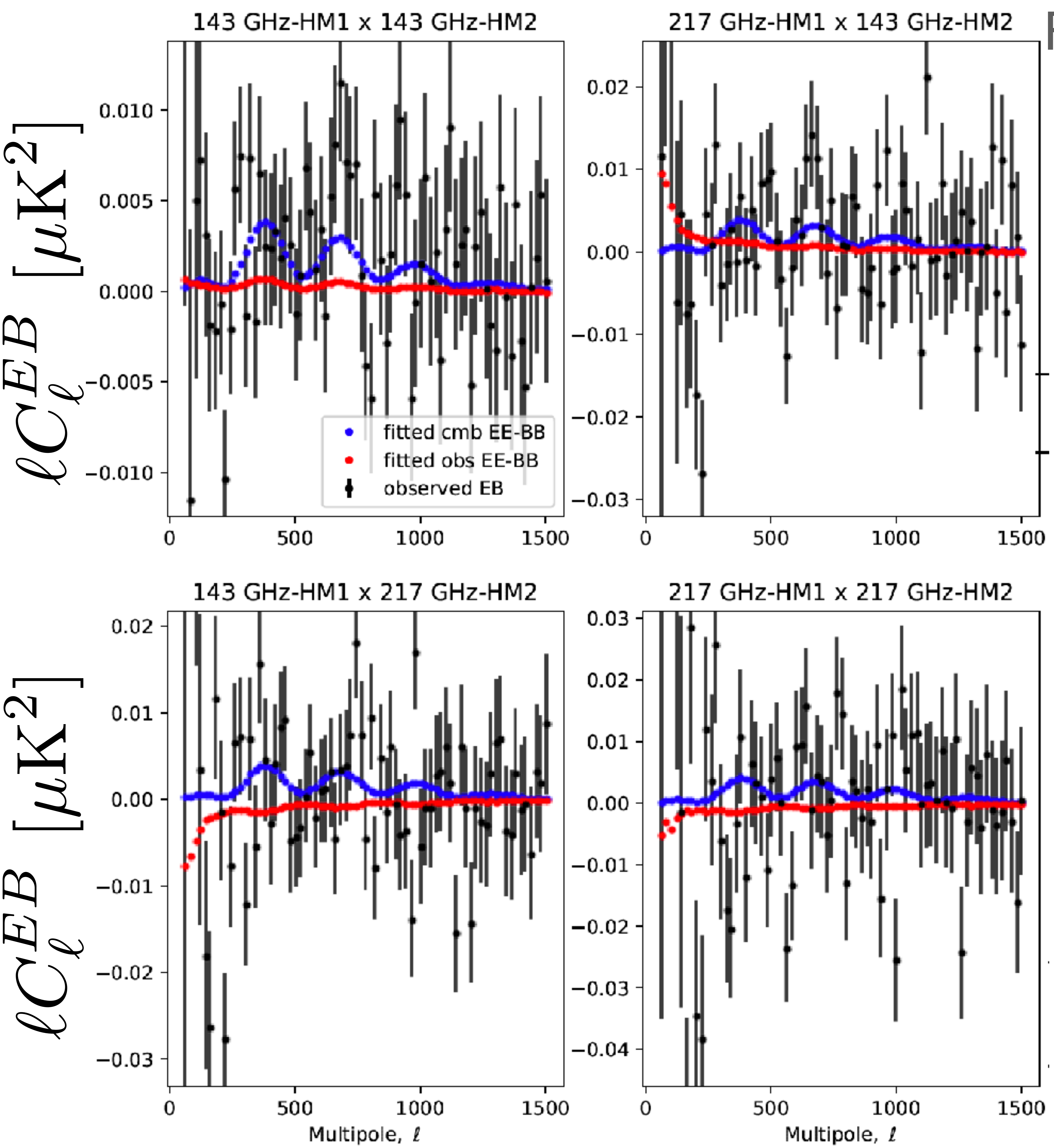
- When the data are dominated by CMB, the sum of two angles, α+β, is determined precisely.
    - This is the diagonal line.
- The foreground determines α with some uncertainty, breaking the degeneracy. Then σ(β) ~ σ(α) because σ(α+β) << σ(α).
- When the data are dominated by the foreground, it can determine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

From Planck HFI Data (Minami & EK 2020)

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



- Can we see β 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)*



From Planck HFI Data (Minami & EK 2020)

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

- Can we see β 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

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 correlation of the CMB, $\langle C_\ell^{EB,\mathrm{CMB}}\rangle$ but we take into account the foreground (dust) EB, $\langle C_\ell^{EB,\mathrm{fg}}\rangle$
  - We account for the dust EB by assuming that EB/EE is proportional to TB/TE **measured from the data**. Not really a modelling.

Minami et al. (2019); Minami & Komatsu (2020b); Diego-Palazuelos, Eskilt, et al. (2022)

Relating EB to TB

- **A 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!

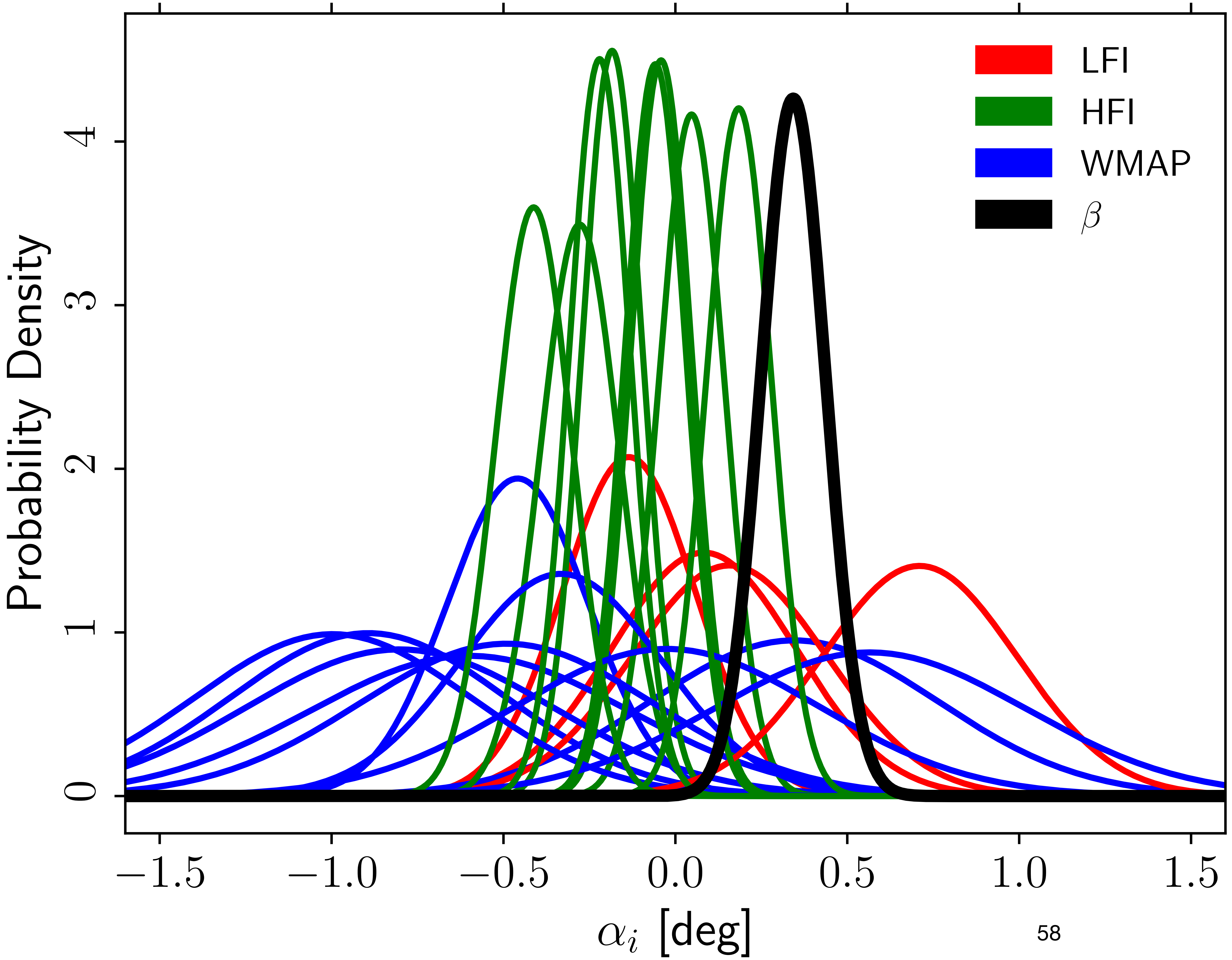
Measured well!

Measured well!

Eskilt & EK (2022)

Miscalibration angles (WMAP and Planck)

Nearly full-sky data (92% of the sky)

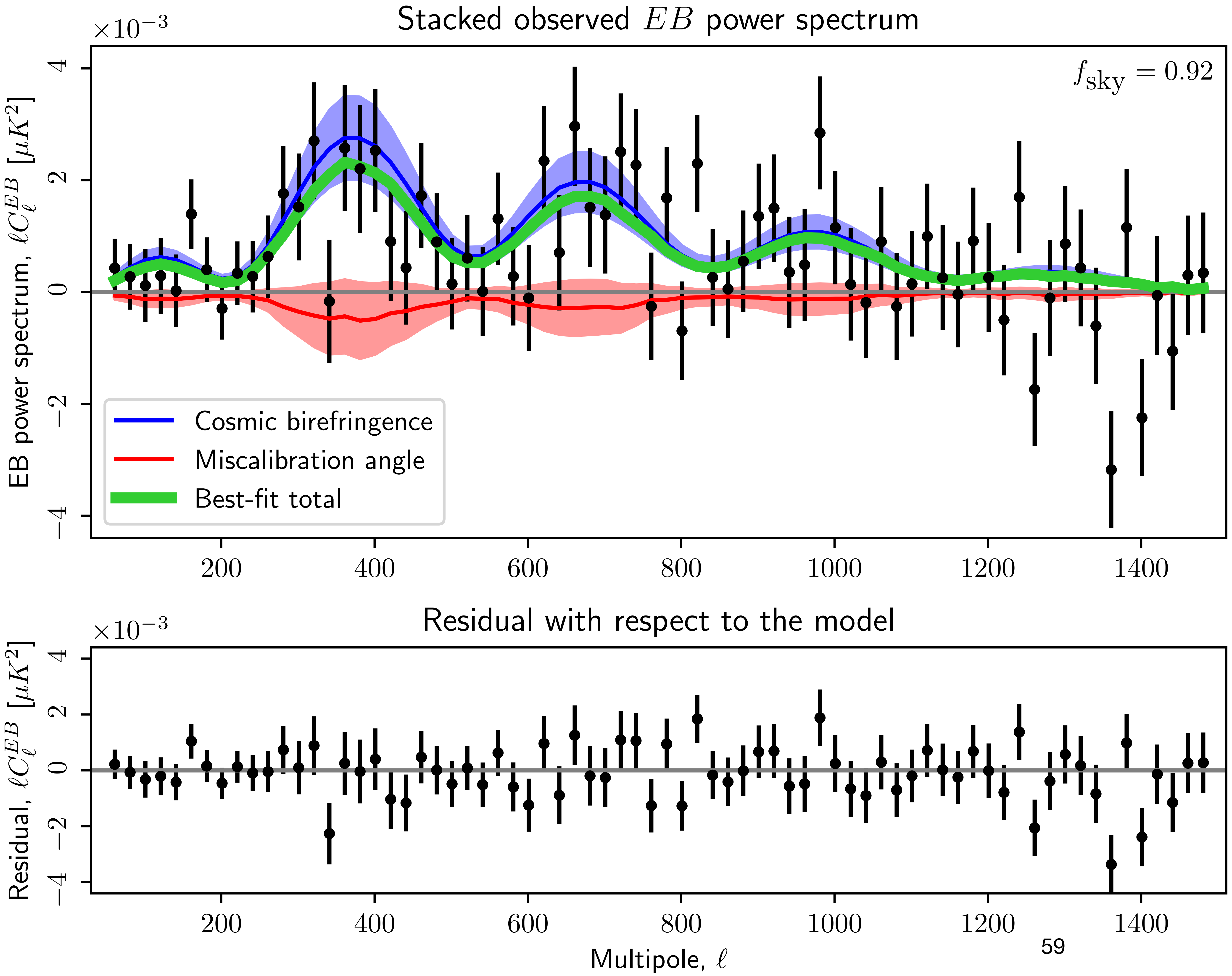


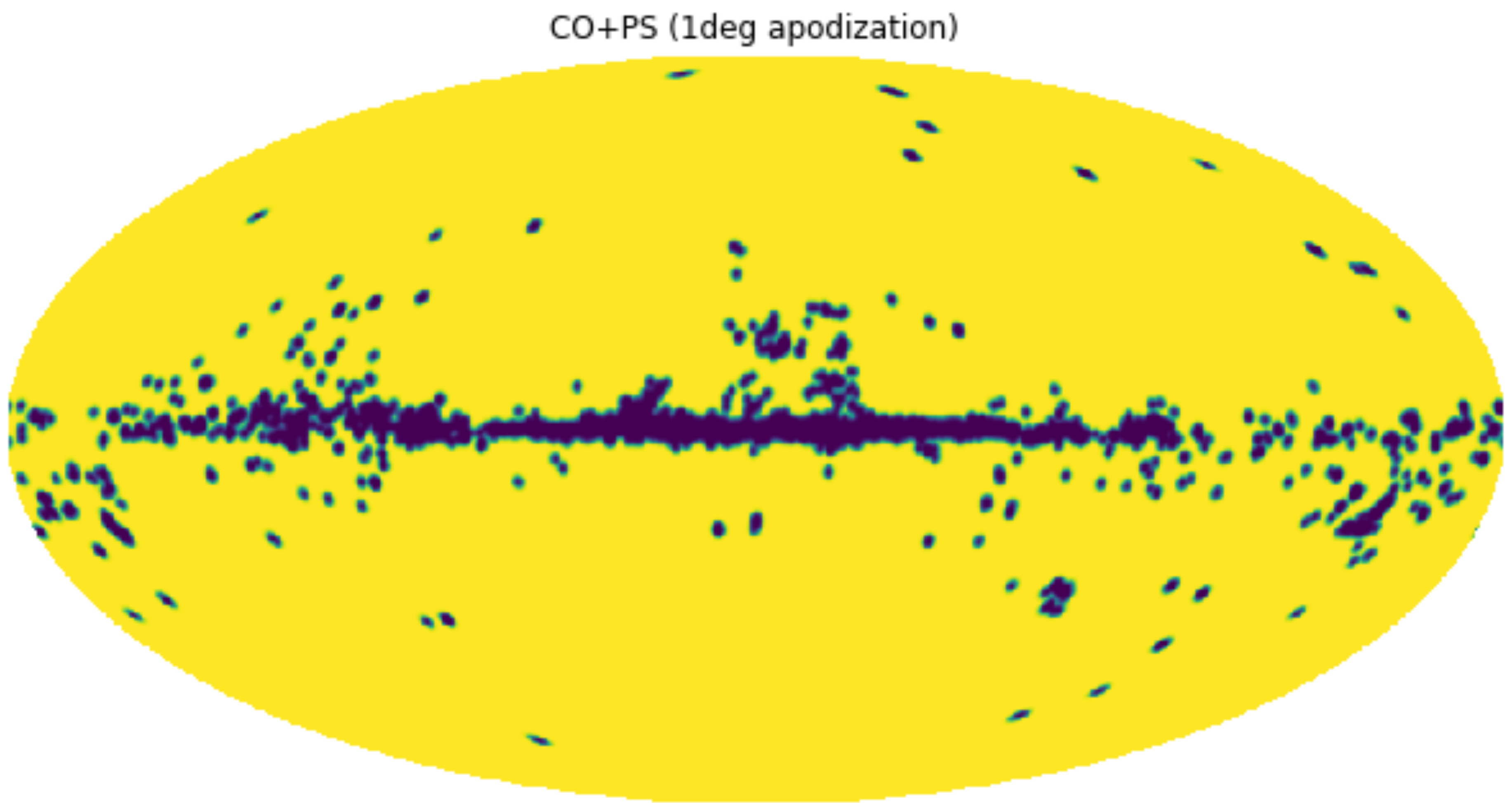
- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

Eskilt & EK (2022)

Cosmic Birefringence fits well (WMAP+Planck)

Nearly full-sky data (92% of the sky)



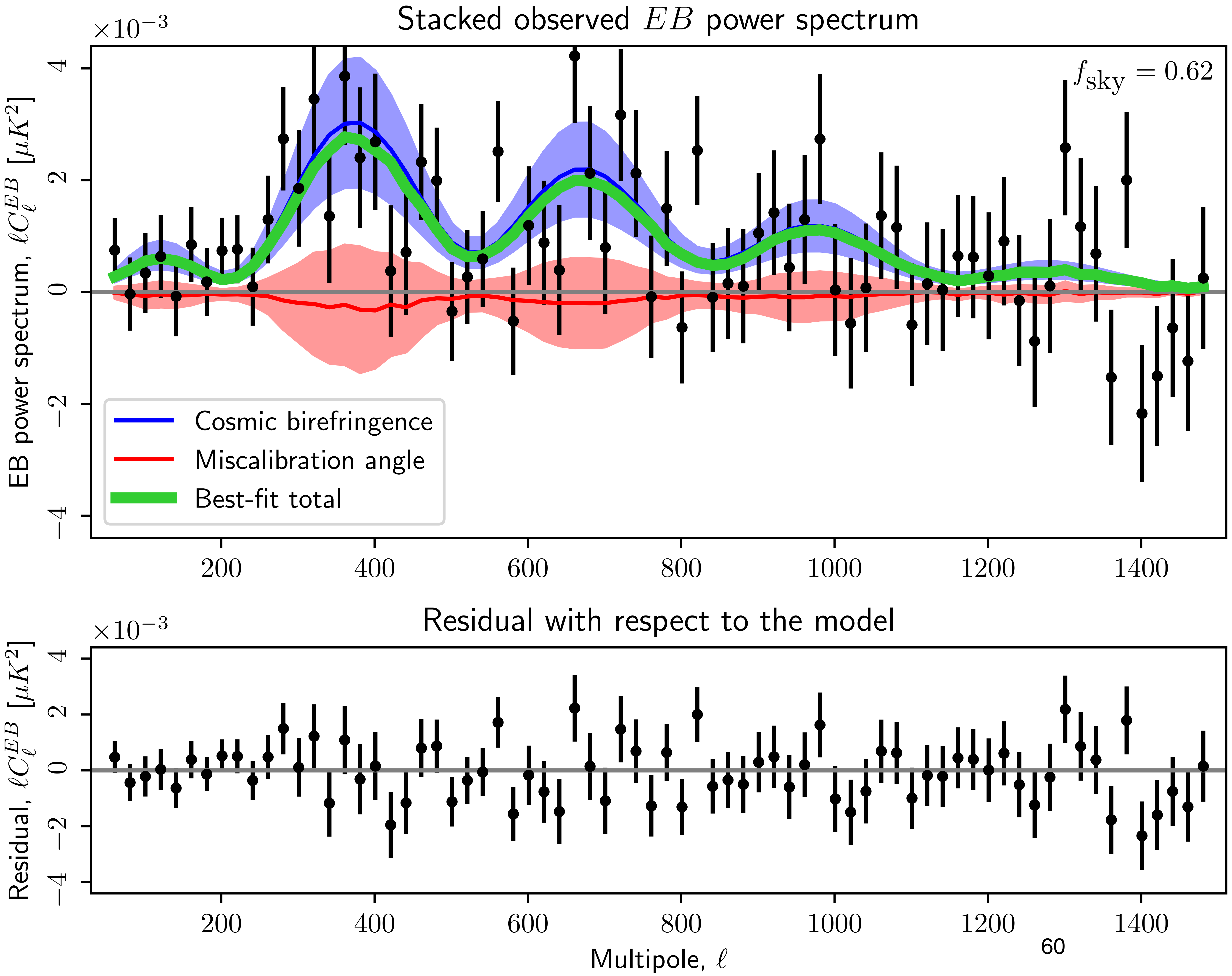


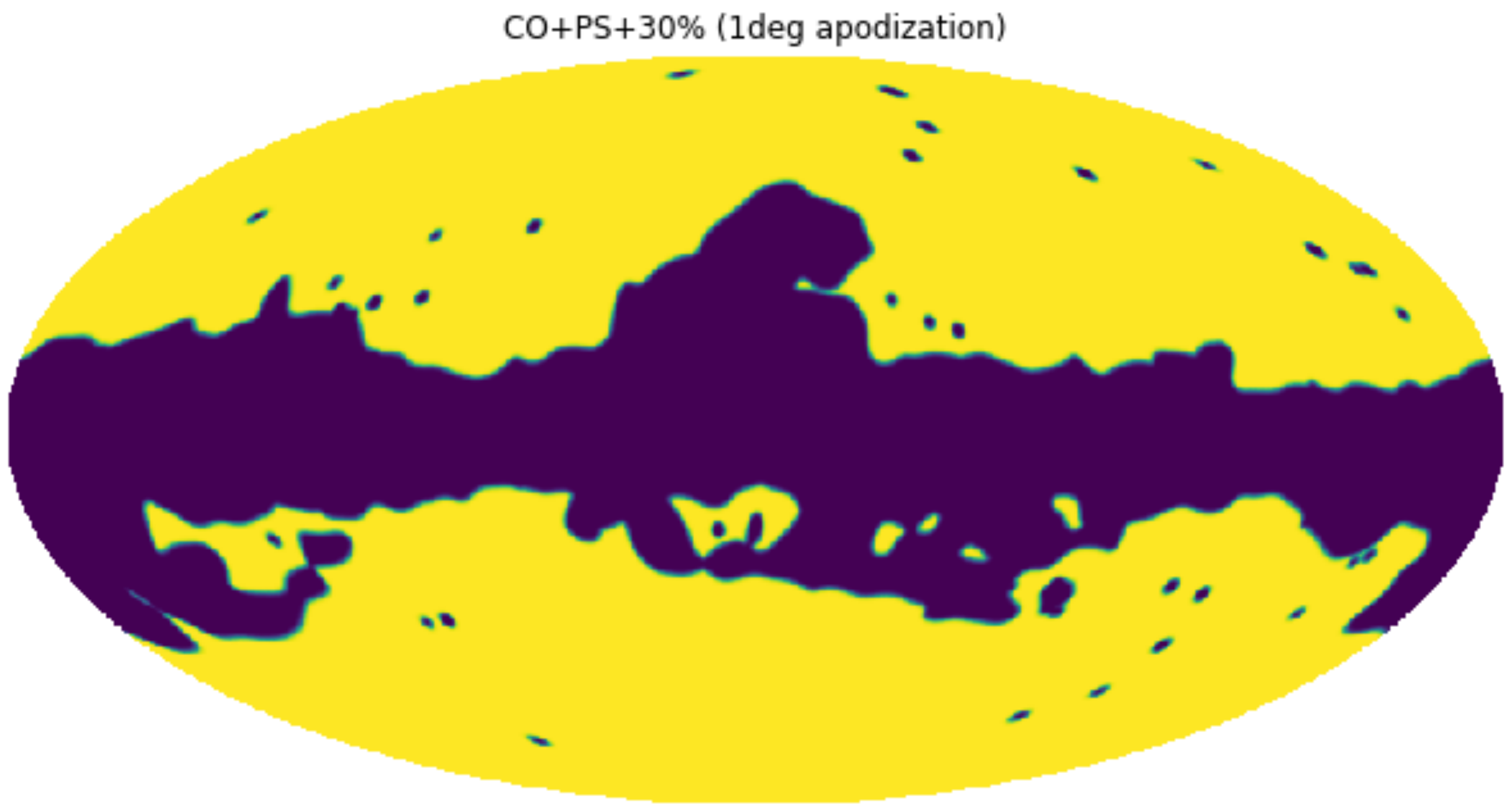
- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- χ^2 = 65.3 for DOF=72

Eskilt & EK (2022)

Cosmic Birefringence fits well (WMAP+Planck)

Robust against the Galactic mask (62% of the sky)



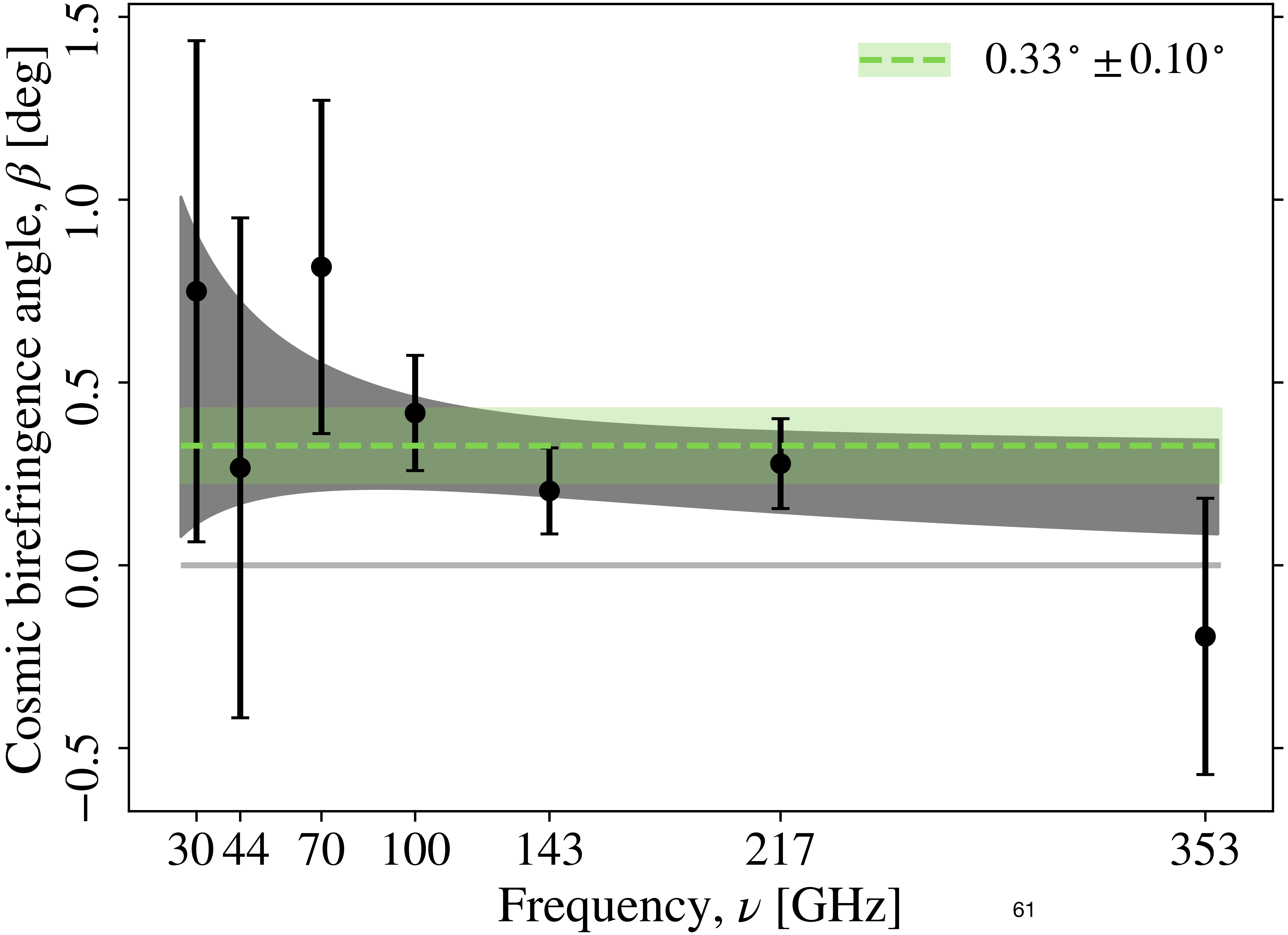


- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.37 ± 0.14 deg**
- $\chi^2 = 65.8$ for DOF=72

Eskilt (2022); Eskilt & EK (2022)

No frequency dependence is found

Consistent with the expectation from cosmic birefringence

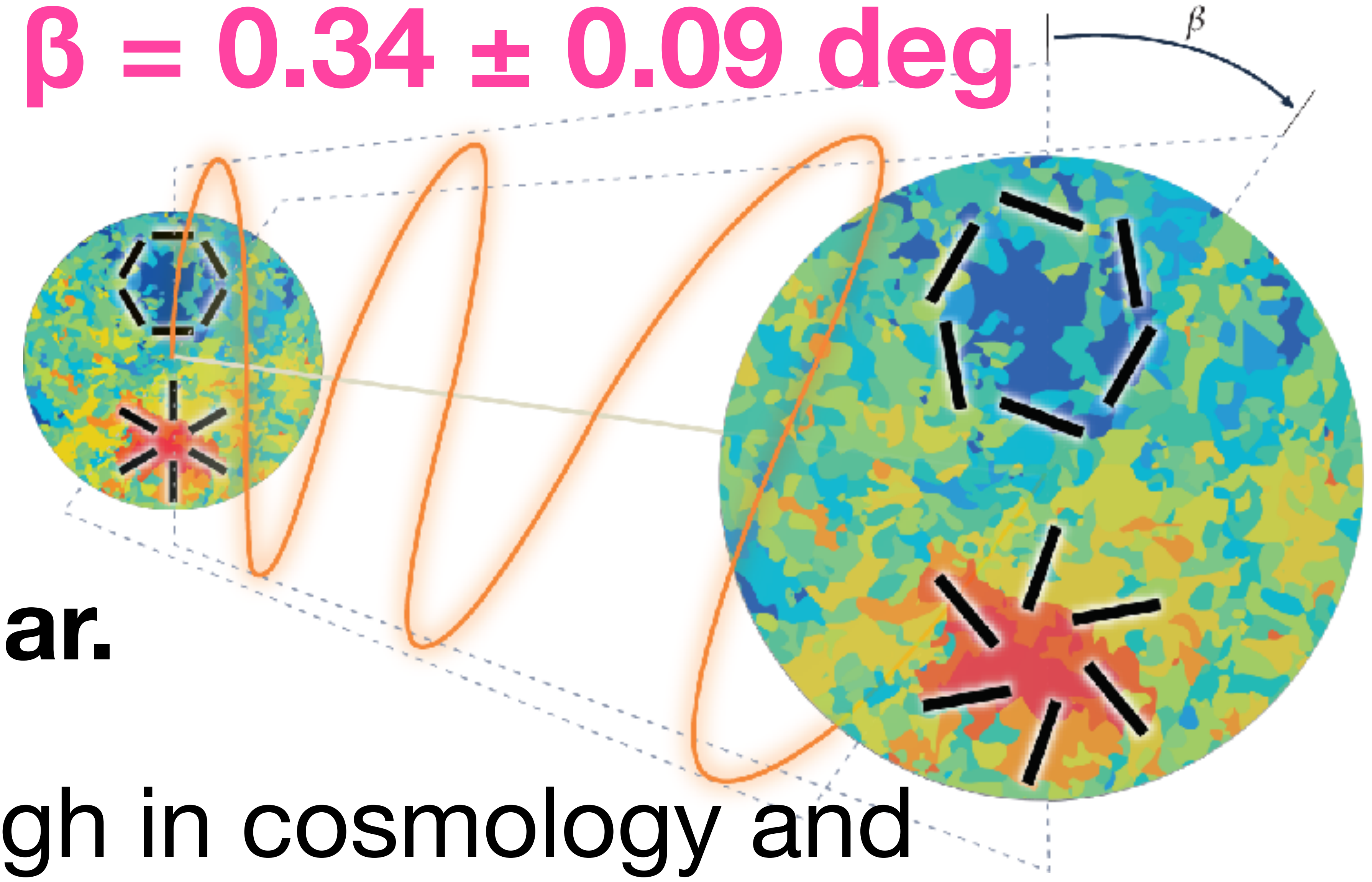


- No evidence for frequency dependence:
  - For $\beta \sim (\nu/150\text{GHz})^n$, **$n = -0.20^{+0.41}_{-0.39}$** (68% CL)
  - Faraday rotation (n=–2) is disfavoured.

Conclusion

β = 0.34 ± 0.09 deg (68%CL; nearly full sky)

β = 0.34 ± 0.09 deg



- I am old enough to know that **3.6σ can still disappear.**
    - If confirmed in the future, it would be a breakthrough in cosmology and fundamental physics.
- The signal is robust against the sky fraction used for the analysis and has no frequency dependence.
- Good news: **The impact of the known instrumental systematics of Planck is negligible** (*Diego-Palazuelos et al., arXiv:2210.07655*).
- It is fair to say that **there is something in the Planck data. No evidence for significant impacts of the Galactic foreground or the known systematics.**
    - But we keep investigating!