Cosmic Birefringence by Dark Photon

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Based on [arXiv:2307.14798] with
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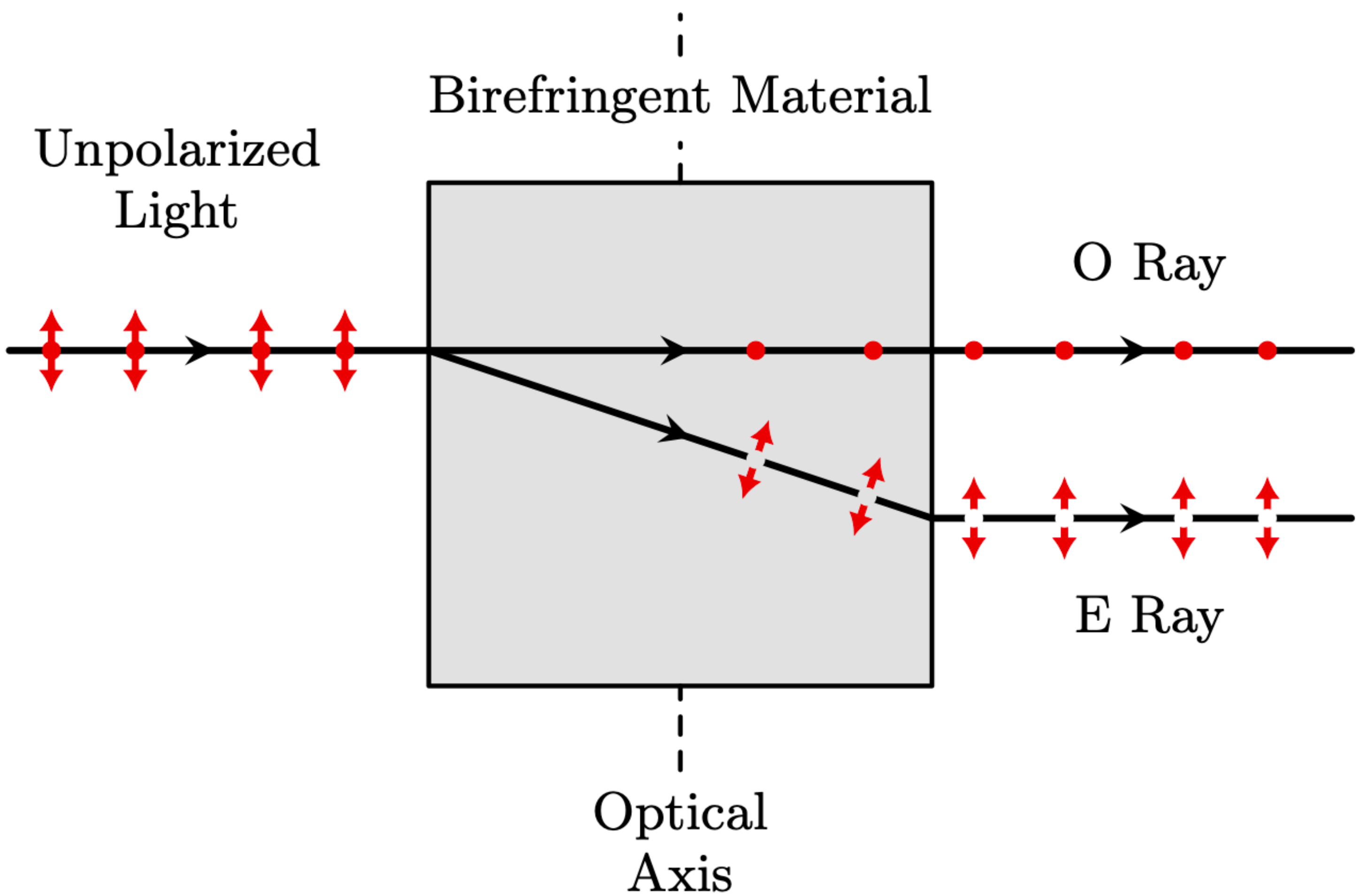
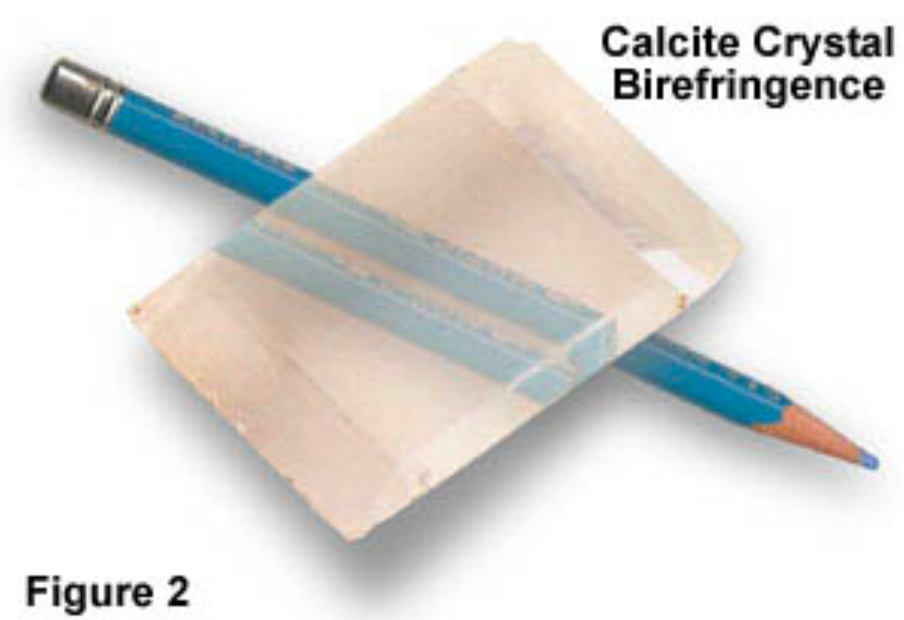
Birefringence

Some crystals have varying refractive index depending on polarization, splitting two linear polarization by refracting them into different directions:





Ni ('77); Turner & Widrow ('88); Carroll, Field & Jackiw ('90); Carroll & Field ('91); Harari & Sikivie ('92)

Cosmic Birefringence

If the Universe is filled with a pseudoscalar field, such as an axion, couple to photon by the Chern-Simons term:

$$\mathscr{L} = \frac{1}{2}\partial_\mu\theta\partial^\mu\theta - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{\frac{1}{2}g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

Integration by part, and the Bianchi identity ($\partial_\nu\tilde{F}^{\mu\nu} = 0$):

$$\mathscr{L}_{CS} = \frac{1}{2}g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu} = -\underline{g_a}A_\nu\underline{(\partial_\mu\theta)\tilde{F}^{\mu\nu}} \equiv A_\nu J^\nu$$

Ni ('77); Turner & Widrow ('88); Carroll, Field & Jackiw ('90); Carroll & Field ('91); Harari & Sikivie ('92)

Cosmic Birefringence

The Maxwell's equations

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{E} = -g_a(\nabla\theta)\cdot\mathbf{B}$$

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_a(\dot{\theta}\mathbf{B} - \mathbf{E}\times\nabla\theta)$$

Cosmic Birefringence

The Maxwell's equations become the wave equations:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

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$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_a(\dot{\theta}\mathbf{B} - \mathbf{E}\times\nabla\theta)$$

$$\rightarrow$$

$$-\frac{\partial^2 \mathbf{E}}{\partial t^2} + \nabla^2\mathbf{E} = g_a\left[\dot{\theta}\frac{\partial \mathbf{B}}{\partial t} - (\nabla\theta\cdot\nabla)\mathbf{B}\right]$$

$$-\frac{\partial^2 \mathbf{B}}{\partial t^2} + \nabla^2\mathbf{B} = -g_a\left[\dot{\theta}\frac{\partial \mathbf{E}}{\partial t} - (\nabla\theta\cdot\nabla)\mathbf{E}\right]$$

Assumptions: small g_a, θ caring much slower than $\mathbf{E}$ and $\mathbf{B}$.

Cosmic Birefringence

The Maxwell's equations become the wave equations:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \cdot \mathbf{E} = -g_a(\nabla \theta) \cdot \mathbf{B}$$
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_a(\dot{\theta}\mathbf{B} - \mathbf{E} \times \nabla \theta)$$

$$\Rightarrow$$

$$-\frac{\partial^2 \mathbf{E}}{\partial t^2} + \nabla^2 \mathbf{E} = g_a \left[\dot{\theta}\frac{\partial \mathbf{B}}{\partial t} - (\nabla \theta \cdot \nabla)\mathbf{B}\right]$$
$$-\frac{\partial^2 \mathbf{B}}{\partial t^2} + \nabla^2 \mathbf{B} = -g_a \left[\dot{\theta}\frac{\partial \mathbf{E}}{\partial t} - (\nabla \theta \cdot \nabla)\mathbf{E}\right]$$

Dispersion for right-handed(+) and left-handed (-) polarizations:

$\omega_\pm^2 = k^2 \pm g_a k\dot{\theta}$, or to linear order in g_a, $\boxed{\omega_\pm = k \pm \frac{1}{2} g_a k\dot{\theta}}$

Cosmic Birefringence

If the Universe is filled with a pseudoscalar field, such as an axion, couple to photon by the Chern-Simons term:

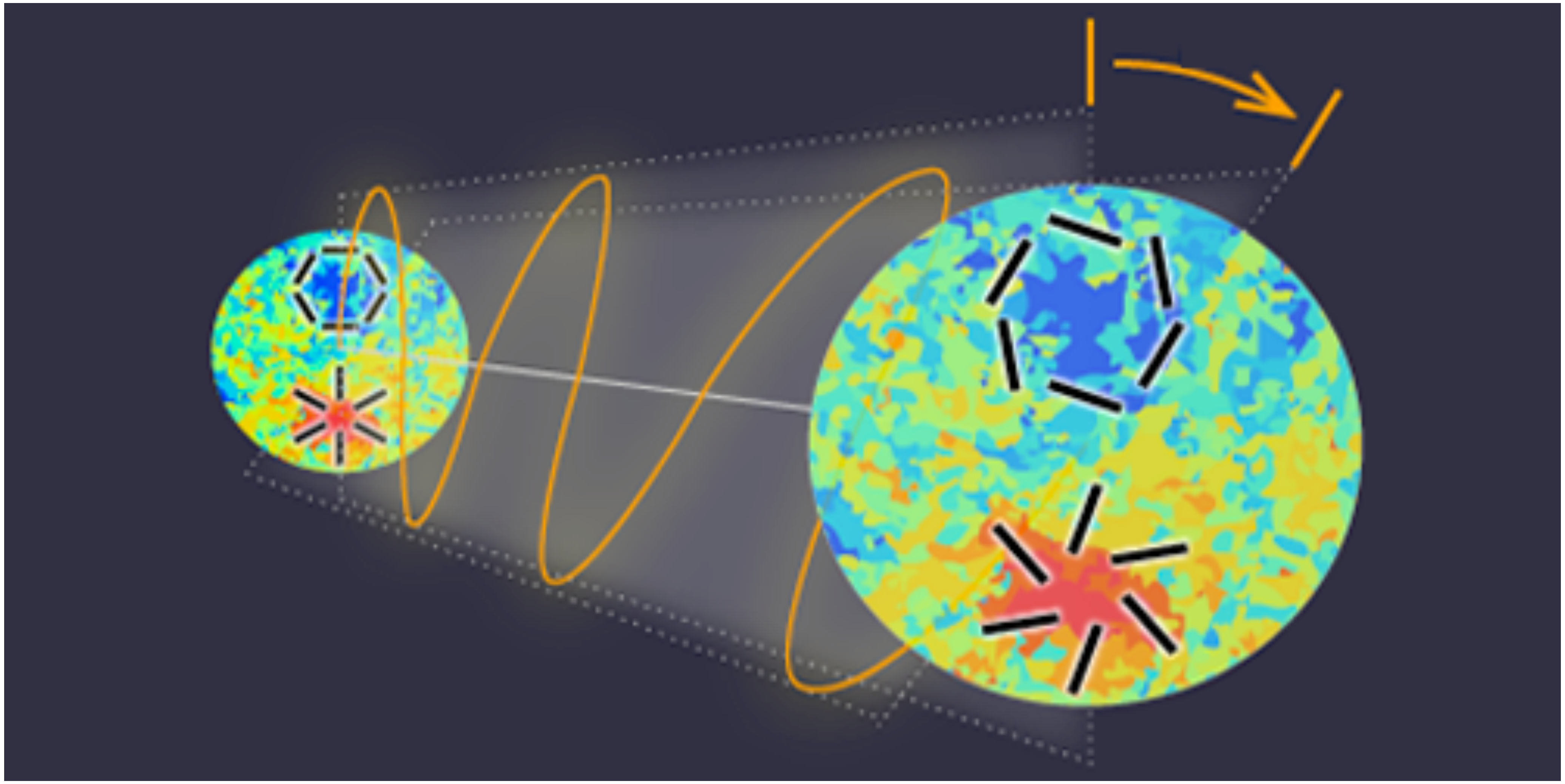
$$\mathscr{L} = \frac{1}{2}\partial_\mu\theta\partial^\mu\theta - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{\frac{1}{2}g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

The coupling makes the phase velocities of two circular polarization state diverge: $\omega_\pm = k \pm \frac{1}{2}g_a k\dot{\theta}$

→ Linear polarization rotates with $\beta = \frac{1}{2}g_a\int dt\dot{\theta}$

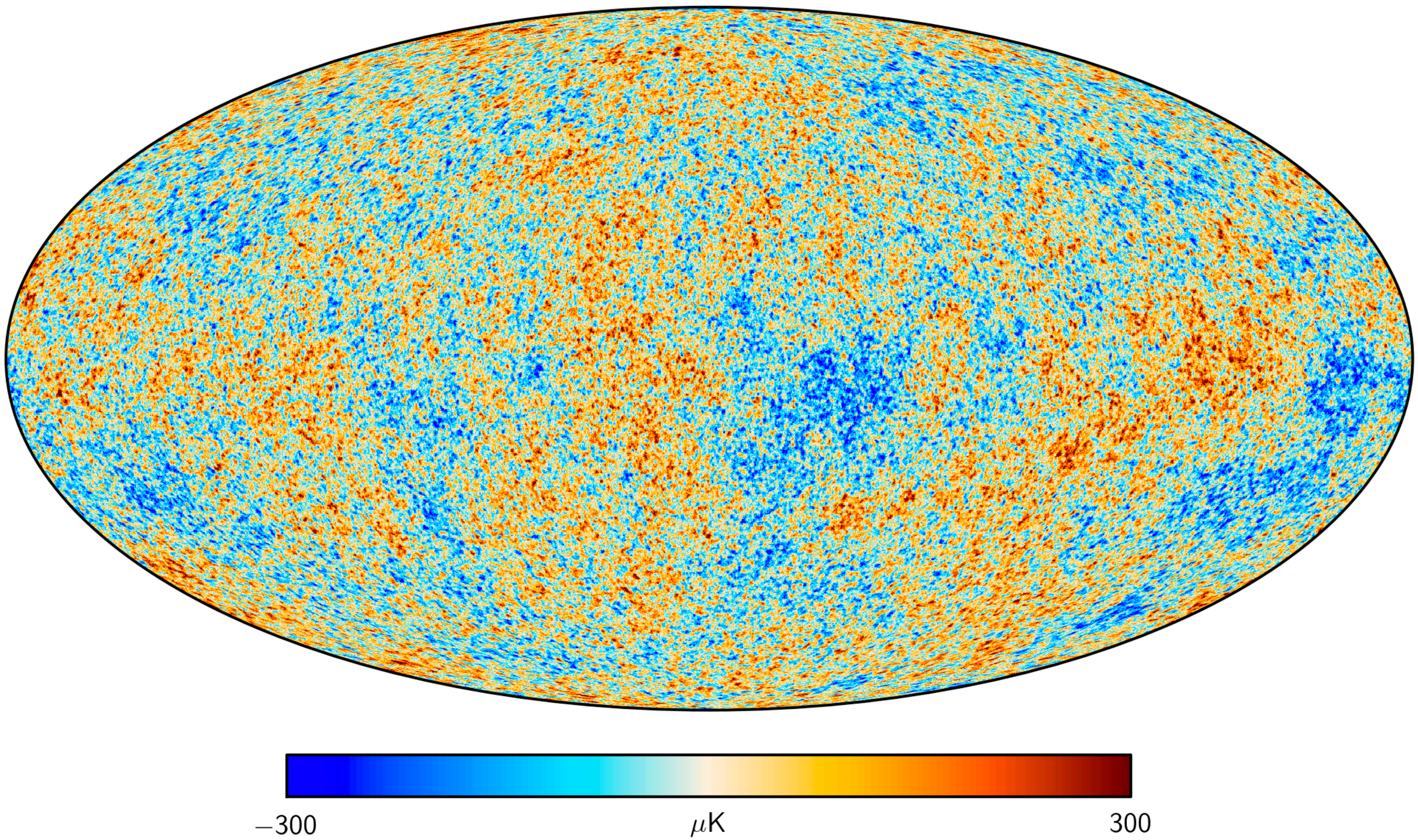
Cosmic Birefringence

Linear polarization rotates with $\beta = \frac{1}{2} g_a \int dt \dot{\theta}$



Credit: Y.Minami

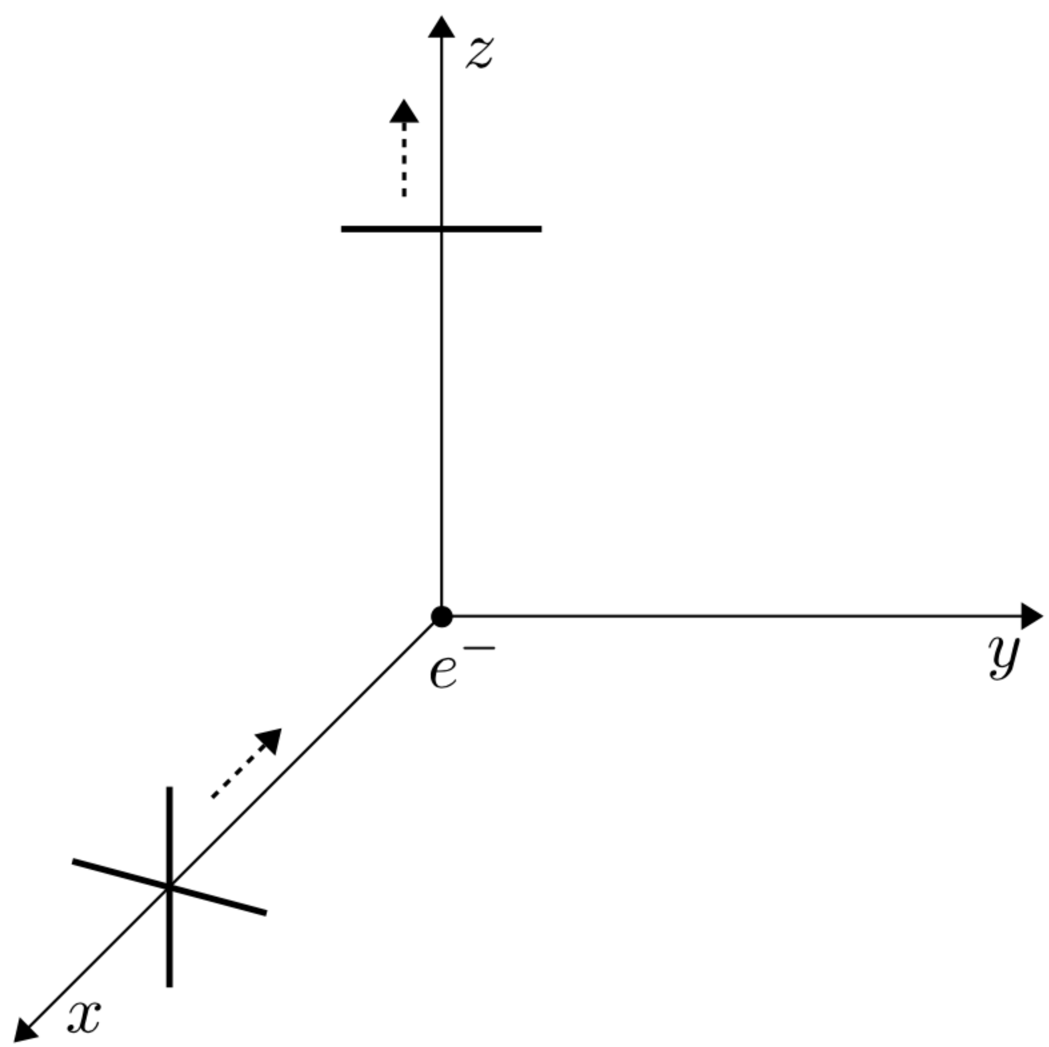
Temperature map of the CMB



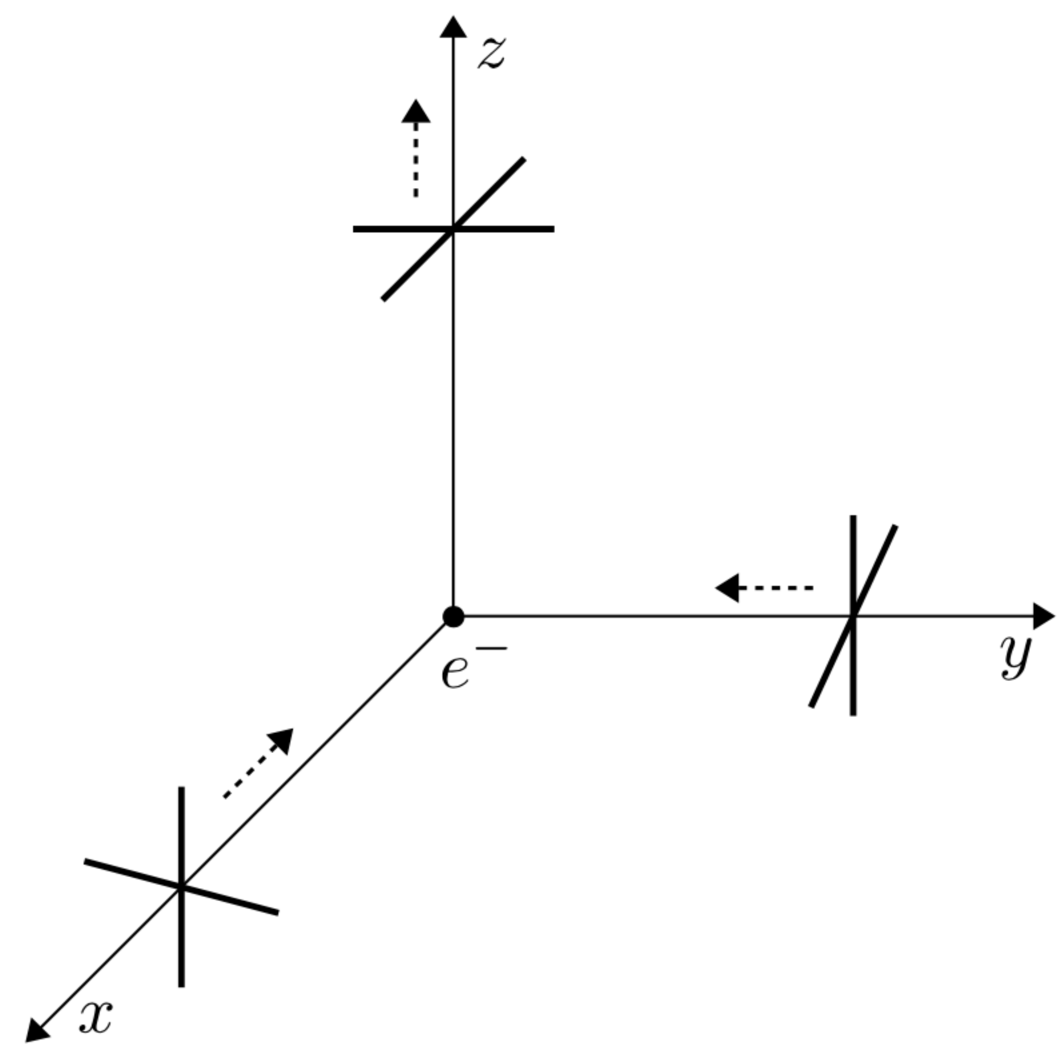
maximum likelihood posterior map
Plank Collaboration

Polarization of CMB

Scattering of plane wave

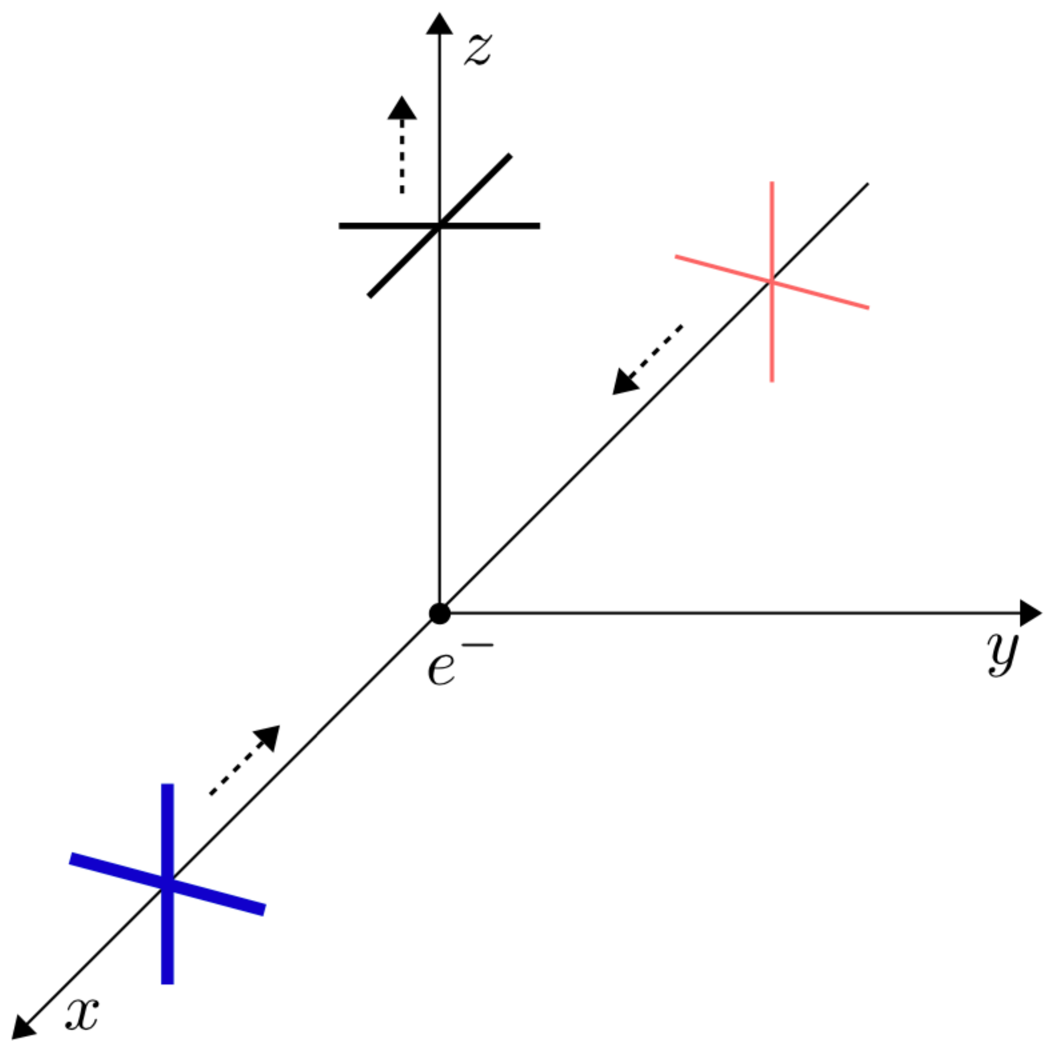


Scattering of monopole

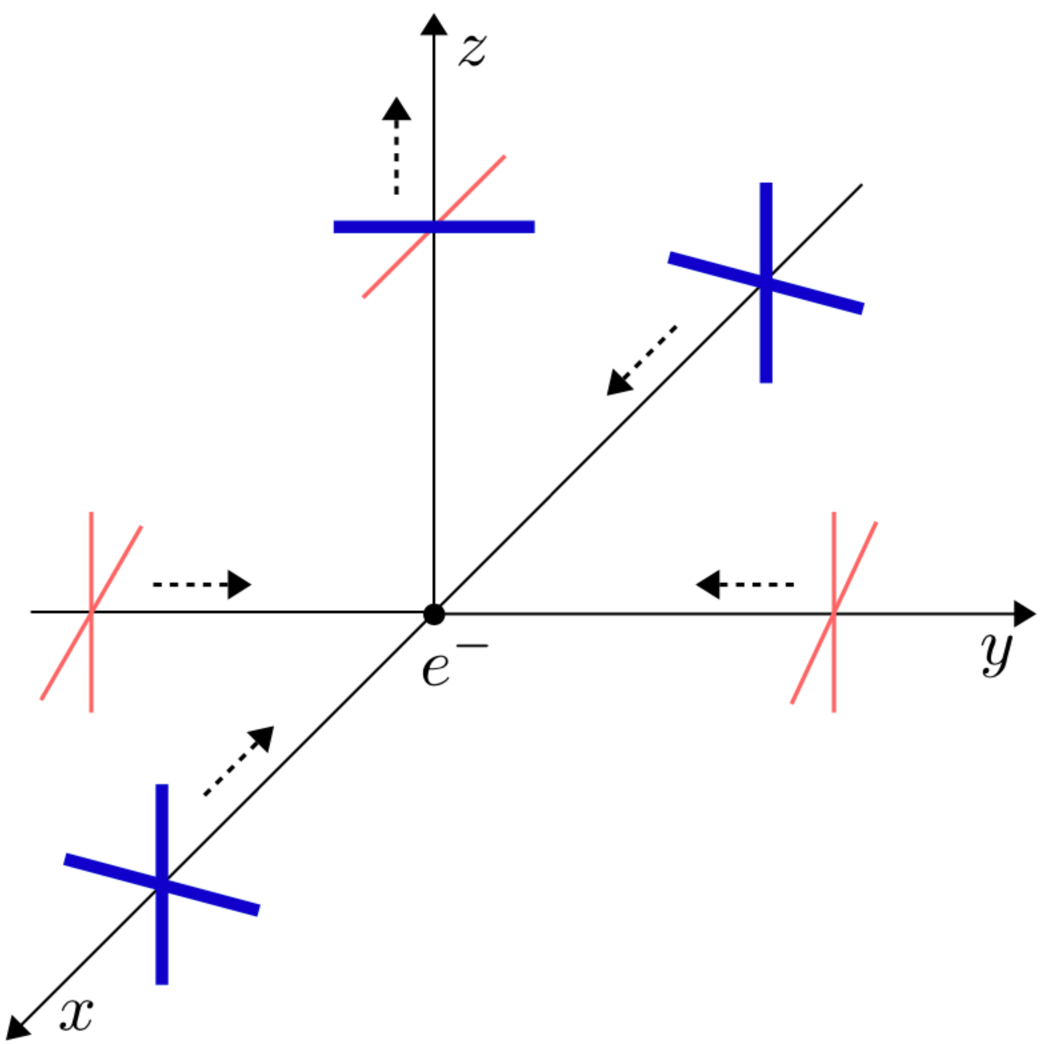


Polarization of CMB

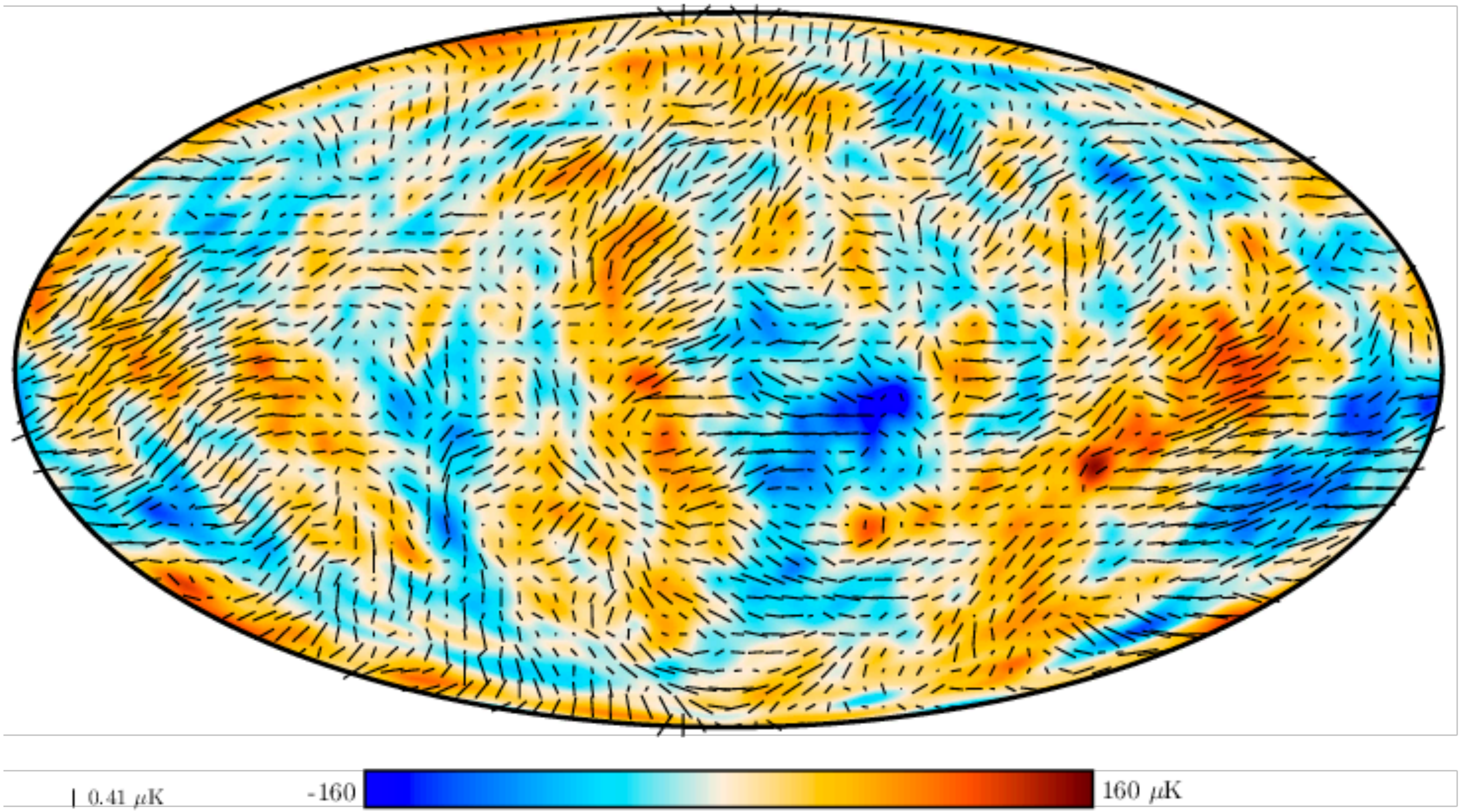
Scattering of dipole



Scattering of quadrupole



Polarization map of the CMB

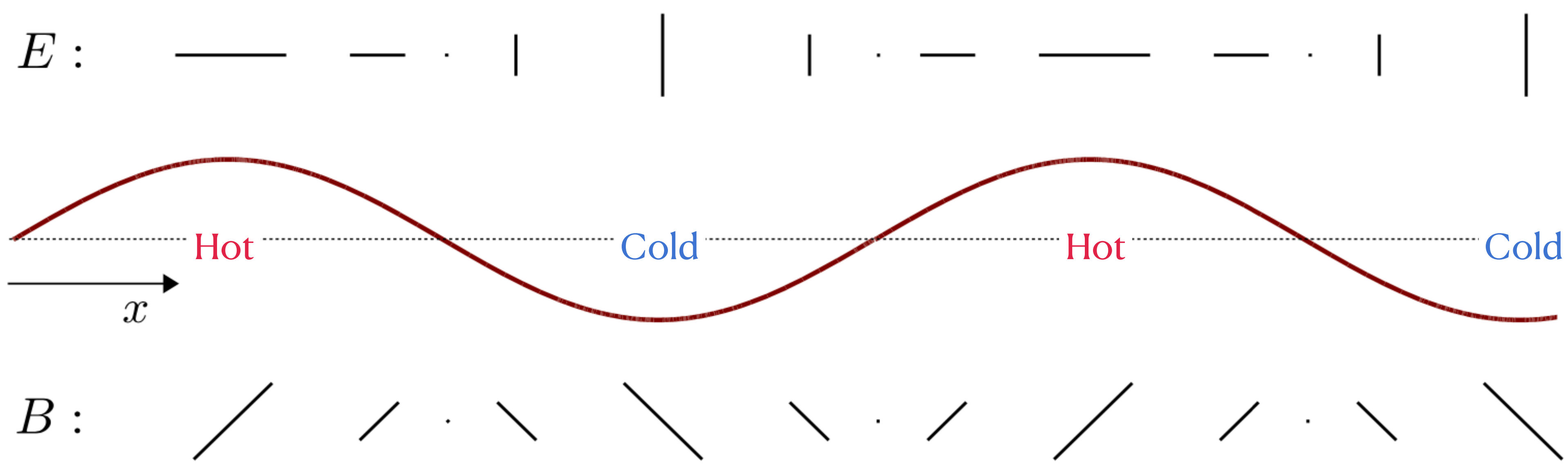


Plank map smoothed with 5° filter

Seljak & Zaldarriaga ('97); Kamionkowski, Kosowsky & Stebbins ('97)

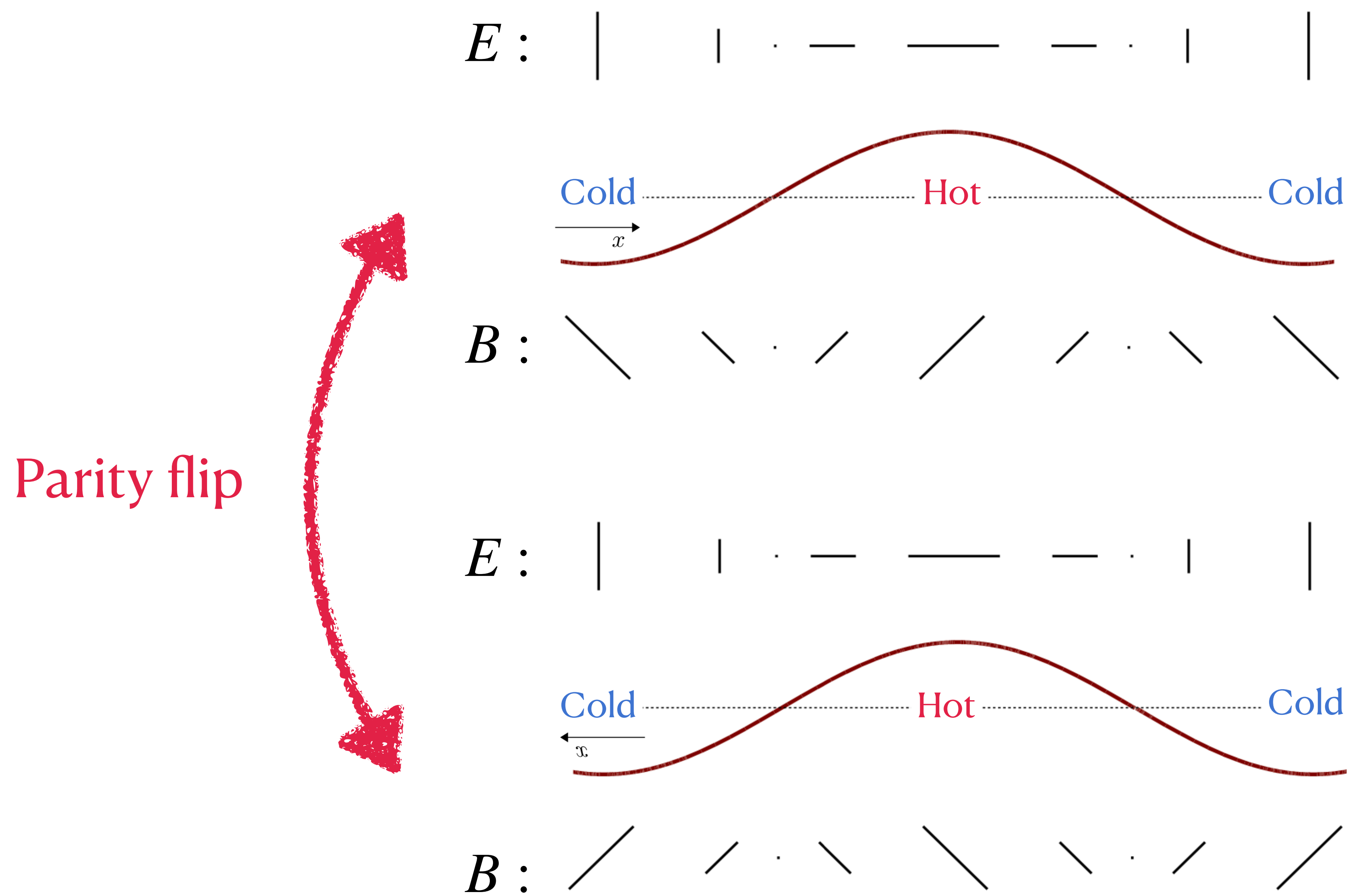
E- and B-mode of linear polarization

E-mode : Polarization directions are parallel or perpendicular to the wave number direction



B-mode : Polarization directions are 45° tilted with respect to the wave number direction

E- and B-mode of linear polarization



For the parity flip, E-mode remains the same,
whereas B-mode change the sign

E- and B-mode of linear polarization

Two-point correlation functions invariant under the parity flip:

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

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

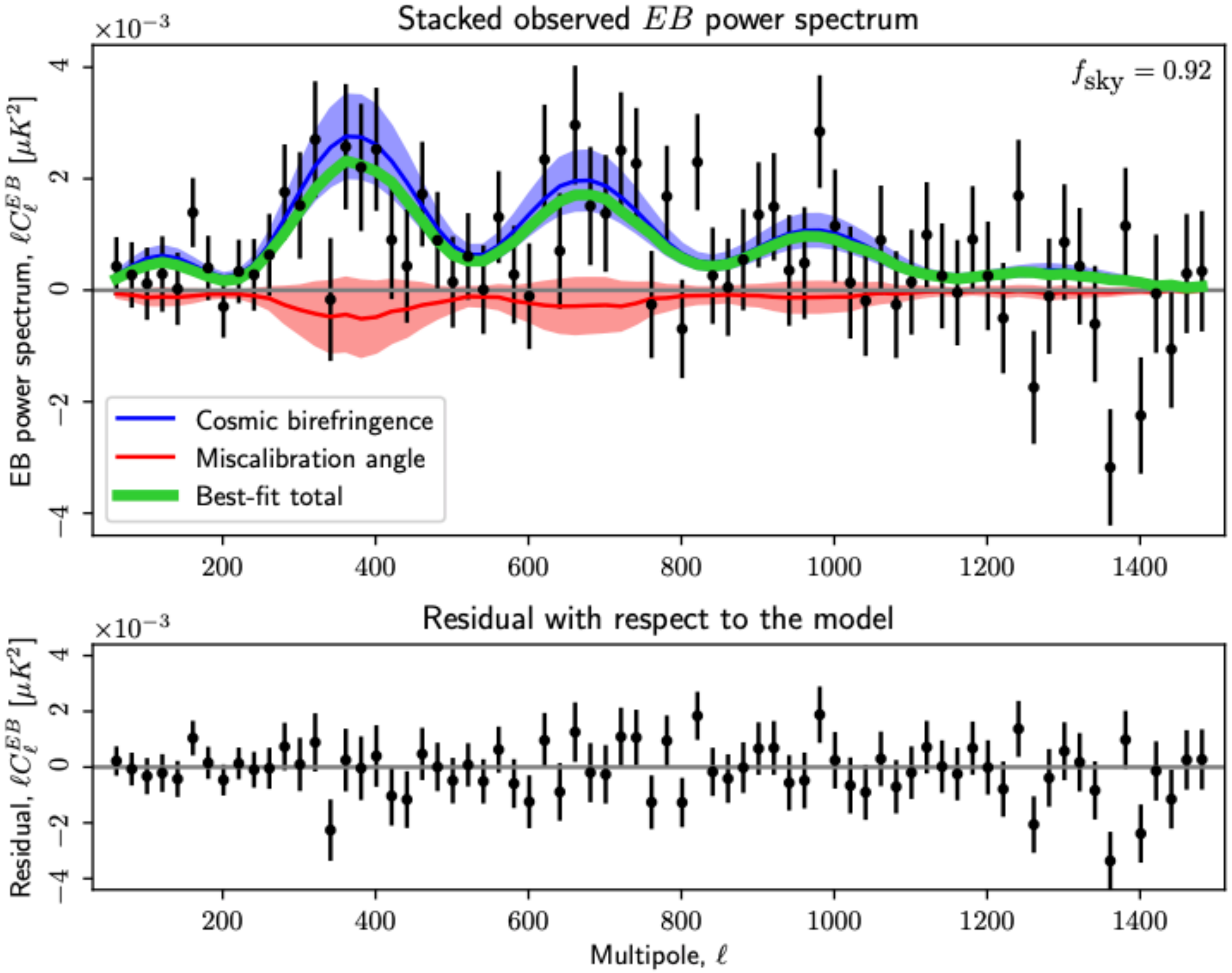
$$\langle T_\ell E^*_{\ell'} \rangle = \langle T^*_\ell E_{\ell'} \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_\ell^{TE}$$

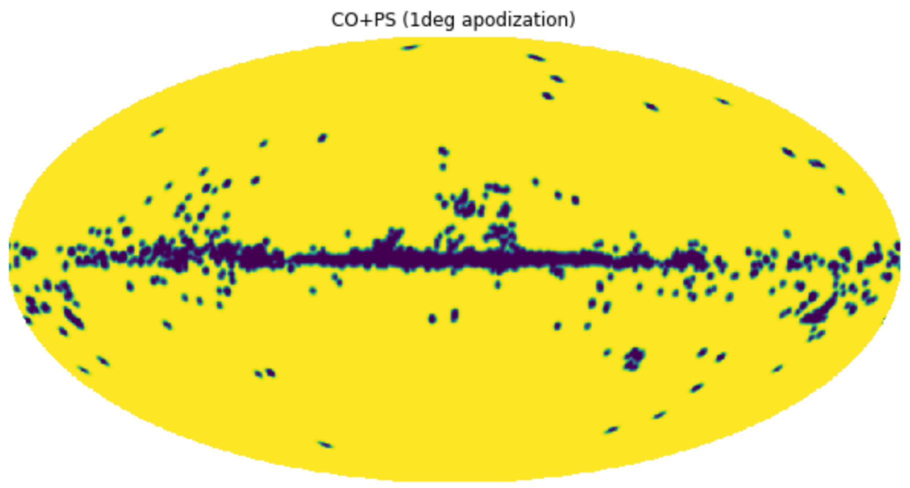
The other combinations $\langle T_\ell B^*_{\ell'} \rangle$ and $\langle E_\ell B^*_{\ell'} \rangle$ are not invariant under the parity flip:

We can use these combinations to probe parity-violating physics (e.g., Axions)

Eskilt & E. Komatsu, 2205.13962

Cosmic Birefringence (WMAP + Planck)





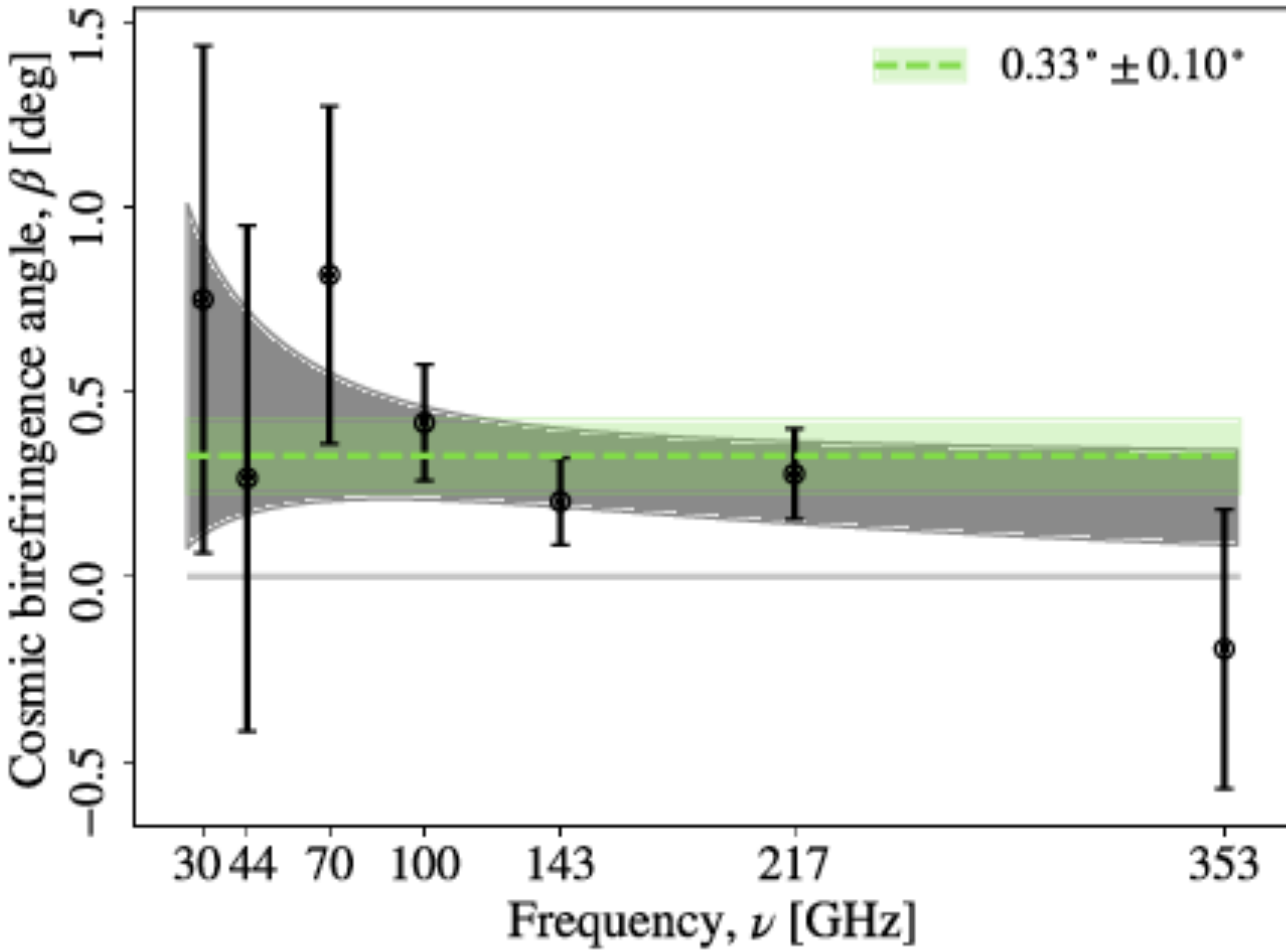
Miscalibration angles
Make only small contributions thanks to the cancellation.

$$\beta = 0.34^\circ \pm 0.09^\circ \quad 3.6\sigma$$

$\chi^2 = 65.3$ for $DOF = 72$

Eskilt (2022); Eskilt & E. Komatsu, 2205.13962

Frequency dependence?



$$\boxed{\text{For } \beta \sim (\nu/150\,\text{GHz})^n,\ n = -0.2^{+0.41}_{-0.39}(68\,\%\,\text{CL})}$$

Faraday rotation ($n = -2$) is disfavoured.

Motivation

- Axion or axion-like field is the simplest model that can explain cosmic birefringence.
- But, what else can generate cosmic birefringence?

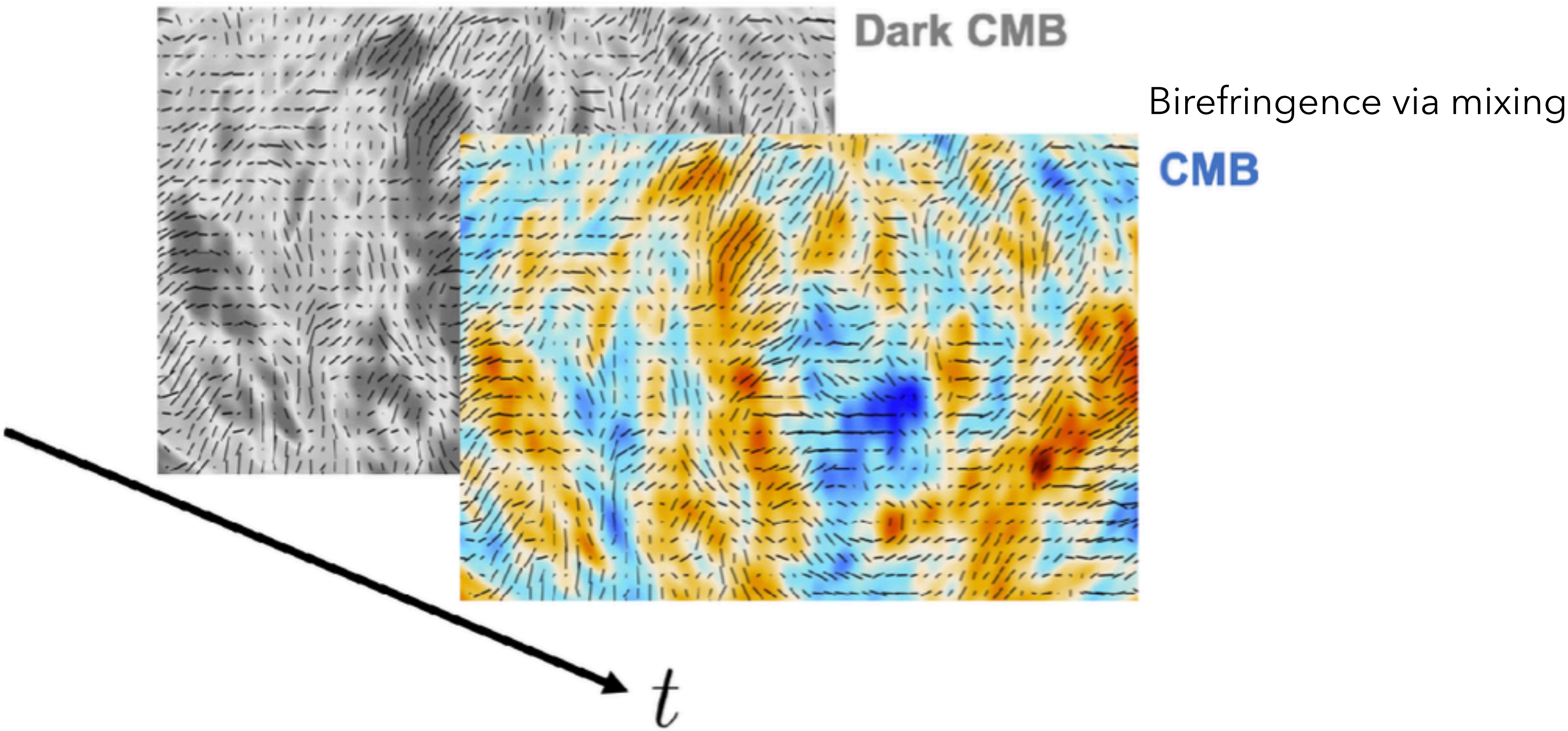
- The energy budget of our Universe is dominated by two dark components: Dark Matter and Dark Energy
- What if cosmic birefringence is coming from dark sector?
- Thus, detection of parity-violating physics in polarization of the CMB can shed light on our understanding of dark sector.

Lee, Kang, Gong, Jeong, Jung, and Park (2022)

Dark CMB

(Dark) Axion (like) field
Cosmic neutrino background ?
Dark neutrino ?
.....

Dark Birefringence



Lee, Kang, Gong, Jeong, Jung, and Park (2022)

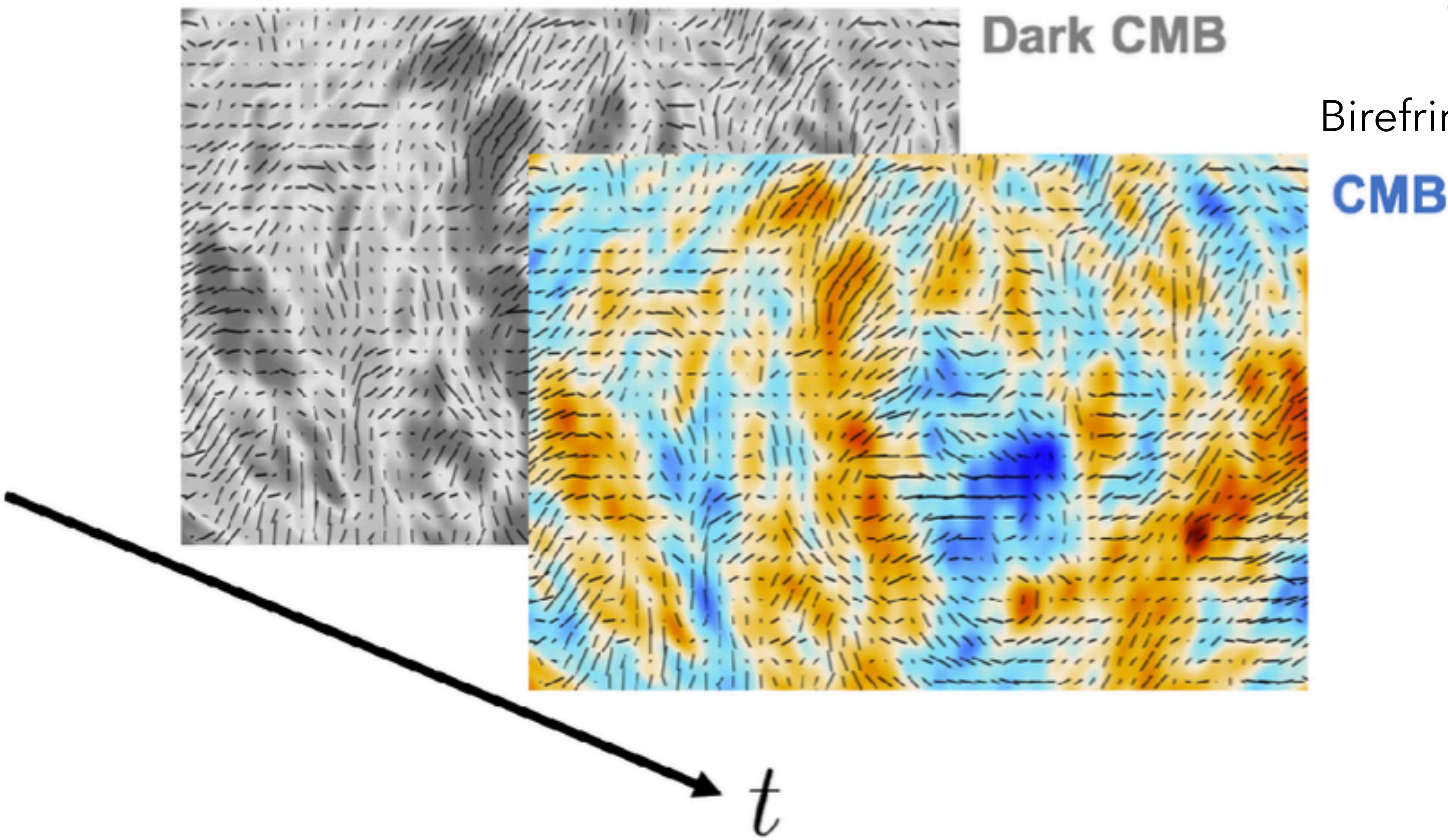
Dark CMB

(Dark) Axion (like) field
Cosmic neutrino background ?
Dark neutrino ?
.....

Dark Birefringence

$$\frac{\mathcal{O}_d}{\Lambda^d} X_{\mu\nu} \tilde{X}^{\mu\nu}$$

Birefringence via mixing



Mixing photon with dark photon

An alternative route to generate cosmic birefringence by kinetic mixing between the photon and massless dark photon:

$$\mathscr{L} = -\frac{1}{4}\hat{F}^{\mu\nu}\hat{F}_{\mu\nu} - \frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - \frac{\varepsilon}{2}\hat{F}_{\mu\nu}\hat{X}^{\mu\nu}$$

Diagonalizatoin: $\begin{pmatrix} \hat{A}^\mu \\ \hat{X}^\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\epsilon & 1 \end{pmatrix} \begin{pmatrix} A^\mu \\ X^\mu \end{pmatrix}$

The interaction terms:

$$eJ_\mu \hat{A}^\mu + e_X J_{X\mu}\hat{X}^\mu \approx e_X J_{X\mu} X^\mu + \left(eJ_\mu - \varepsilon e_X J_{X\mu}\right) A^\mu$$

SM photons couple to the dark-sector current, which is constrained by the milli-charged particle search in LEP and LHC.

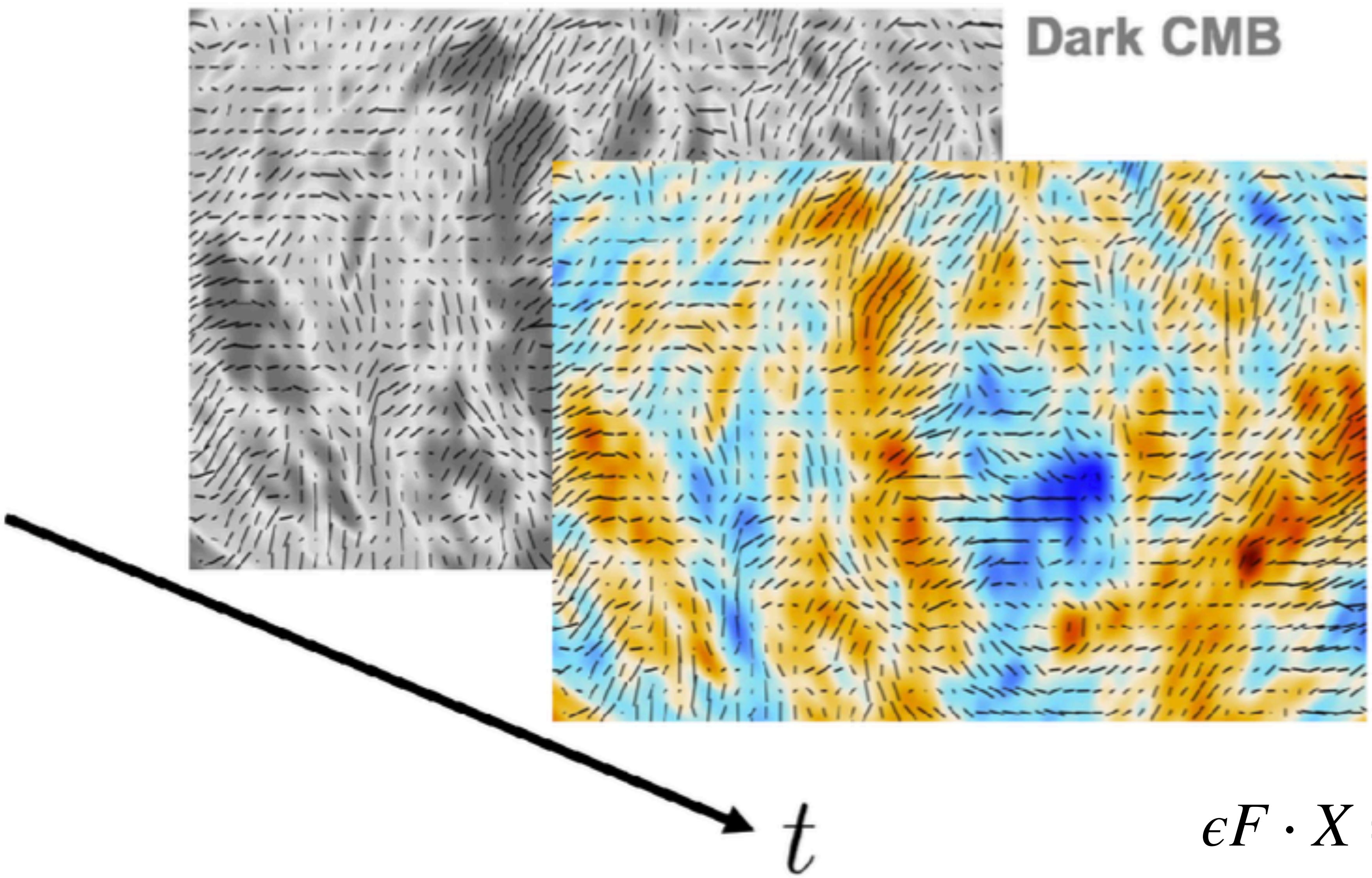
Dark CMB

Dark Birefringence $\dfrac{\mathcal{O}_d}{\Lambda^d} X_{\mu\nu}\tilde{X}^{\mu\nu}$

Dark CMB

Birefringence via mixing

CMB



$$\epsilon F \cdot X \Rightarrow \beta_\gamma \sim \epsilon \sqrt{\frac{I_X}{I_{CMB}}} \sin \beta_X$$

Coupled Maxwell's equations

Maxwell's equation for SM photon and dark photon

$$\partial_\mu F^{\mu\nu} = 4\pi \left(J^\nu + \epsilon J_X^\nu\right) \qquad \partial_\mu \tilde{F}^{\mu\nu} = 0$$

$$\partial_\mu X^{\mu\nu} = 4\pi J_X^\nu \qquad \partial_\mu \tilde{X}^{\mu\nu} = 0$$

Coupled Maxwell's equations

Maxwell's equation for SM photon and dark photon

$$\partial_\mu F^{\mu\nu} = 4\pi \left(J^\nu + \epsilon J_X^\nu\right) \qquad \partial_\mu \tilde{F}^{\mu\nu} = 0$$

$$\partial_\mu X^{\mu\nu} = 4\pi J_X^\nu \qquad \partial_\mu \tilde{X}^{\mu\nu} = 0$$

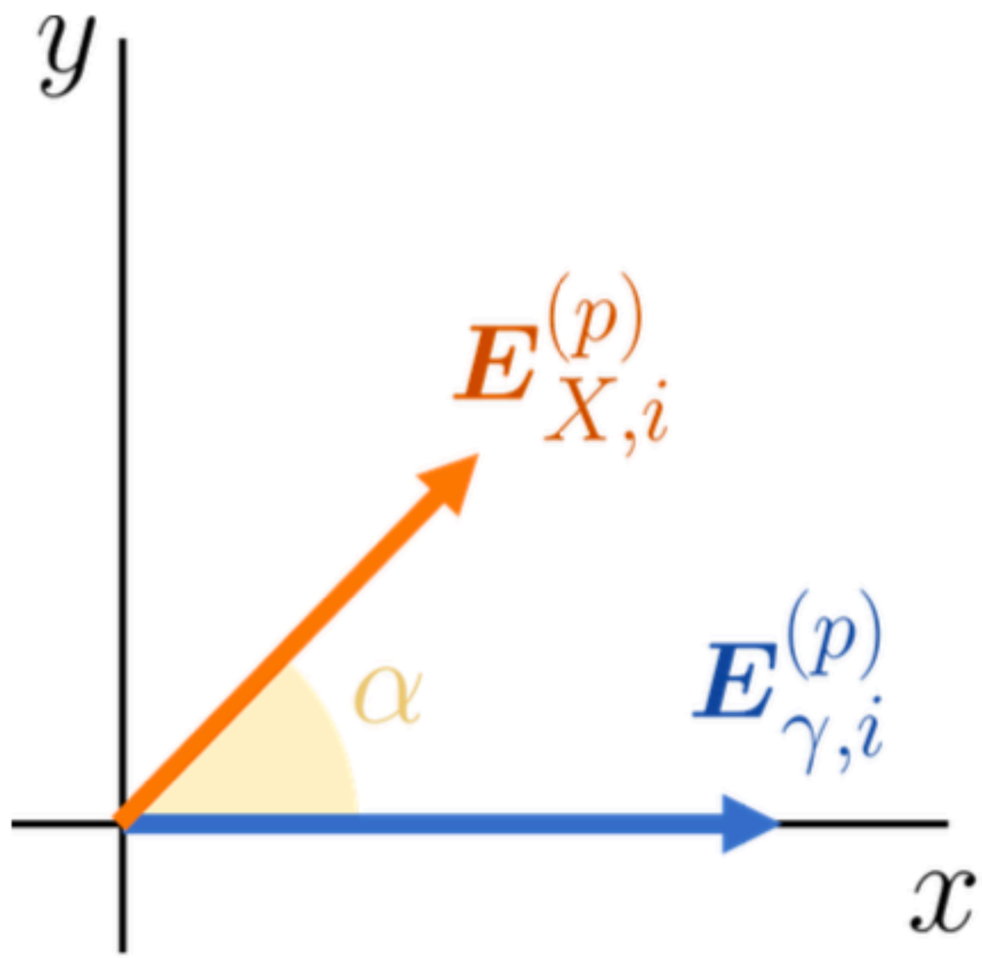
We solve these equations by defining $A^{'\mu} = A^\mu - \epsilon X^\mu$:

$$\partial_\mu F^{'\mu\nu} = 4\pi j^\nu \qquad \partial_\mu \tilde{F}^{'\mu\nu} = 0$$

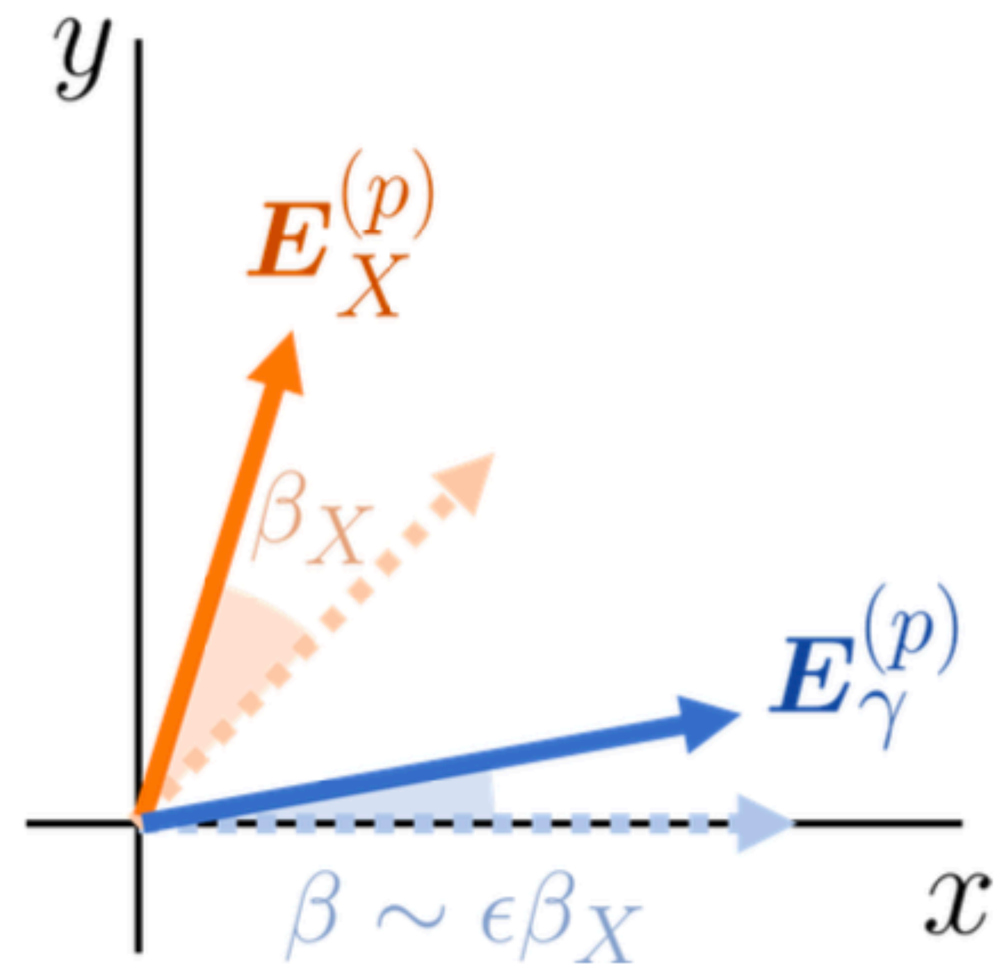
Dark photon has a relative phase α at the CMB-decoupling time.

Dark photon has birefringence β_X since the CMB-decoupling time.

Induced Birefringence



$\Rightarrow$



Initial misalignment (random)

Induced Birefringence

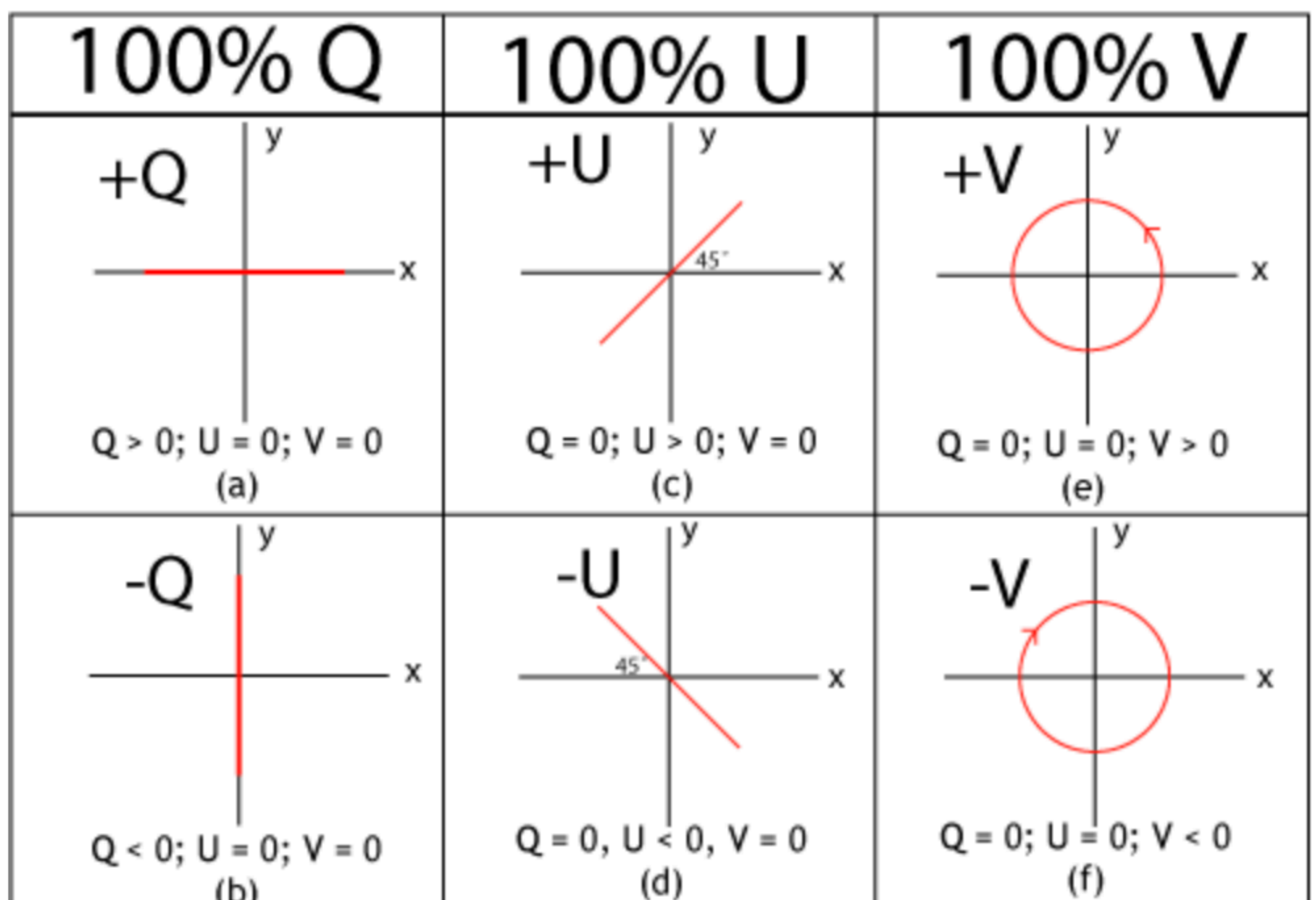
Lee, Kang, Gong, Jeong, Jung, and Park (2022)

Polarization of tensor

- Density matrix in terms of Stokes parameters

$$\rho = \frac{1}{2I}\begin{pmatrix} I+Q & U-iV \\ U+iV & I-Q \end{pmatrix}$$

$$\begin{aligned} I &= |E_x|^2 + |E_y|^2, \\ Q &= |E_x|^2 - |E_y|^2, \\ U &= 2\mathrm{Re}(E_x E_y^*), \\ V &= -2\mathrm{Im}(E_x E_y^*), \end{aligned}$$



$$\boxed{\beta(\hat{\boldsymbol{n}}) = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)}$$

Polarization of SM Photon

$$\rho = \frac{1}{2I}\begin{pmatrix} I+Q & U-iV \\ U+iV & I-Q \end{pmatrix} \qquad \epsilon F\cdot X \Rightarrow \beta_\gamma \sim \epsilon\sqrt{\frac{I_X}{I_{CMB}}}\sin\beta_X$$

- Density matrix after mixing

$$\rho = \rho_0 - 2\epsilon\sqrt{\frac{I_X}{I_0}}\sqrt{PP_X}\begin{pmatrix} (1-P)\cos\delta_X \sin\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & e^{-i\delta_X}\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) \\ e^{i\delta_X}\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & -(1-P)\cos\delta_X\sin\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

$$\boxed{\begin{aligned}
\frac{Q}{I} &= \rho_{11}-\rho_{22} = P - 4\epsilon(1-P)\sqrt{\frac{I_X}{I_0}}\sqrt{PP_X}\cos\delta_X\sin\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right)+\mathcal{O}(\epsilon^2)\,,\\
\frac{U}{I} &= \rho_{12}+\rho_{21} = 4\epsilon\sqrt{\frac{I_X}{I_0}}\sqrt{PP_X}\cos\delta_X\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right)+\mathcal{O}(\epsilon^2)\,,\\
\frac{V}{I} &= i(\rho_{12}-\rho_{21}) = 4\epsilon\sqrt{\frac{I_X}{I_0}}\sqrt{PP_X}\sin\delta_X\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right)+\mathcal{O}(\epsilon^2)\,.
\end{aligned}}$$

Observational Implications

- Density matrix after mixing

$$\rho = \rho_0 - 2\epsilon\sqrt{\frac{I_X}{I_0}}\sqrt{PP_X}\begin{pmatrix} (1-P)\cos\delta_X \sin\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & e^{-i\delta_X}\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) \\ e^{i\delta_X}\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & -(1-P)\cos\delta_X \sin\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

- Induced cosmic Birefringence

$$\beta(\hat{\boldsymbol{n}}) = \frac{1}{2}\arctan\left(\frac{U}{Q}\right) = 2\epsilon\sqrt{\frac{I_X P_X}{I_0 P}}\cos\delta_X \cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) + \mathcal{O}(\epsilon^2)$$

If α is random, isotropic birefringence $\beta_{iso} = \langle\beta(\hat{n})\rangle = 0$ at $\mathcal{O}(\epsilon)$,

However, $\beta_{iso} = \langle\beta(\hat{n})\rangle \simeq \epsilon^2\beta_X$

The recently reported cosmic birefringence at 3.6-σ level of $\beta_{iso} \sim 0.35^\circ \simeq 6.1\times 10^{-3}$

Observational Implications

- Density matrix after mixing

$$\rho = \rho_0 - 2\epsilon\sqrt{\frac{I_X}{I_0}}\sqrt{PP_X}\begin{pmatrix} (1-P)\cos\delta_X \sin\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & e^{-i\delta_X}\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) \\ e^{i\delta_X}\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & -(1-P)\cos\delta_X \sin\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

- Induced cosmic Birefringence

$$\beta(\hat{\boldsymbol{n}}) = \frac{1}{2}\arctan\left(\frac{U}{Q}\right) = 2\epsilon\sqrt{\frac{I_X P_X}{I_0 P}}\cos\delta_X\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) + \mathcal{O}(\epsilon^2)$$

Anisotropic birefringence at $\mathcal{O}(\epsilon^2)$,

$$\langle\beta^2_{\mathrm{aniso}}\rangle \simeq \epsilon^2\frac{I_X}{I_0}\left\langle\frac{P_X}{P}\right\rangle\sin^2\left(\frac{\beta_X}{2}\right) \lesssim 3\times 10^{-4}$$

Observational Implications

- Density matrix after mixing

$$\rho = \rho_0 - 2\epsilon\sqrt{\frac{I_X}{I_0}}\sqrt{PP_X}\begin{pmatrix} (1-P)\cos\delta_X \sin\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & e^{-i\delta_X}\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) \\ e^{i\delta_X}\cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & -(1-P)\cos\delta_X \sin\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

- Circular Polarization

$$\langle V^2 \rangle \simeq 4\epsilon^2 I_0 I_X \bar{P}\bar{P}_X \sin^2\left(\frac{\beta_X}{2}\right) \leq \mathcal{O}(10\mu K)$$

[Nagy et al. (SPIDER) (2017)]

The non-vanishing $V \sim U$ is a characteristic feature of our model with kinetic mixing.

Only a negligible amount of circular polarization is generated from the axion only scenario.

Observational Implications

- Spectral distortion

$$\frac{\delta I}{I_0} \simeq 2\epsilon \sqrt{\frac{I_X}{I_0}} \sqrt{\bar{P}\bar{P}_X} \left| \sin\left(\frac{\beta_X}{2}\right) \right| \lesssim 2\epsilon$$

For the blackbody photon,

$$\frac{I_X}{I_0} = \begin{cases} r & (k \ll T_X) \\ \exp\left(-\frac{1-r}{r}\frac{k}{2\pi T_\gamma}\right) & (k \gg T_X) \end{cases} \qquad T_X \equiv r T_\gamma$$

To satisfy the N_{eff} constraint from Planck, $r < 0.4$ [Gurian, Jeong, Ryan, and Shandera (2021)]

The frequency dependence is weak for the low k.

At high frequencies in the Wien tail, the intensity of dark photon is suppressed so the effect on the CMB polarization become tiny.

Current bounds on the spectral distortion is $\mathcal{O}(10^{-5})$ and expected to be improved up to $\mathcal{O}(10^{-8})$. [Kogut, Abitbol, Chluba, Delabrouille, Fixsen, Hill, Patil, and Rotti (2019)]

Conclusion

Evidence of Parity violation in Universe

- Cosmic birefringence has been measured with 3.6σ significance. and more (e.g.) galactic 4 point functions

We study the effect of birefringent dark photon that mixes with photon with mixing parameter ϵ

$$\epsilon F \cdot X \Rightarrow \beta_\gamma \sim \epsilon \sqrt{\frac{I_X}{I_{CMB}}} \sin \beta_X$$

	Dark Photon	**Axion**
Isotropic Birefringence	$\mathcal{O}(\epsilon^2 g_{\theta X} \Delta\theta)$	$\mathcal{O}(g_\theta \Delta\theta)^*$
Anisotropic Birefringence	$\mathcal{O}(\epsilon g_{\theta X} \Delta\theta)$	$\mathcal{O}(g_\theta \Delta\theta)$
Spectral Distortion	Yes	Yes**
Circular Polarization	$\mathcal{O}(\epsilon g_{\theta X} \Delta\theta)$	Negligible

The detection of parity-violating physics in polarization of the CMB will shed light on our understanding of dark sector.

Thank You for Attention!