# Cosmic Birefringence by Dark Photon

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**Based on [arXiv:2307.14798]**

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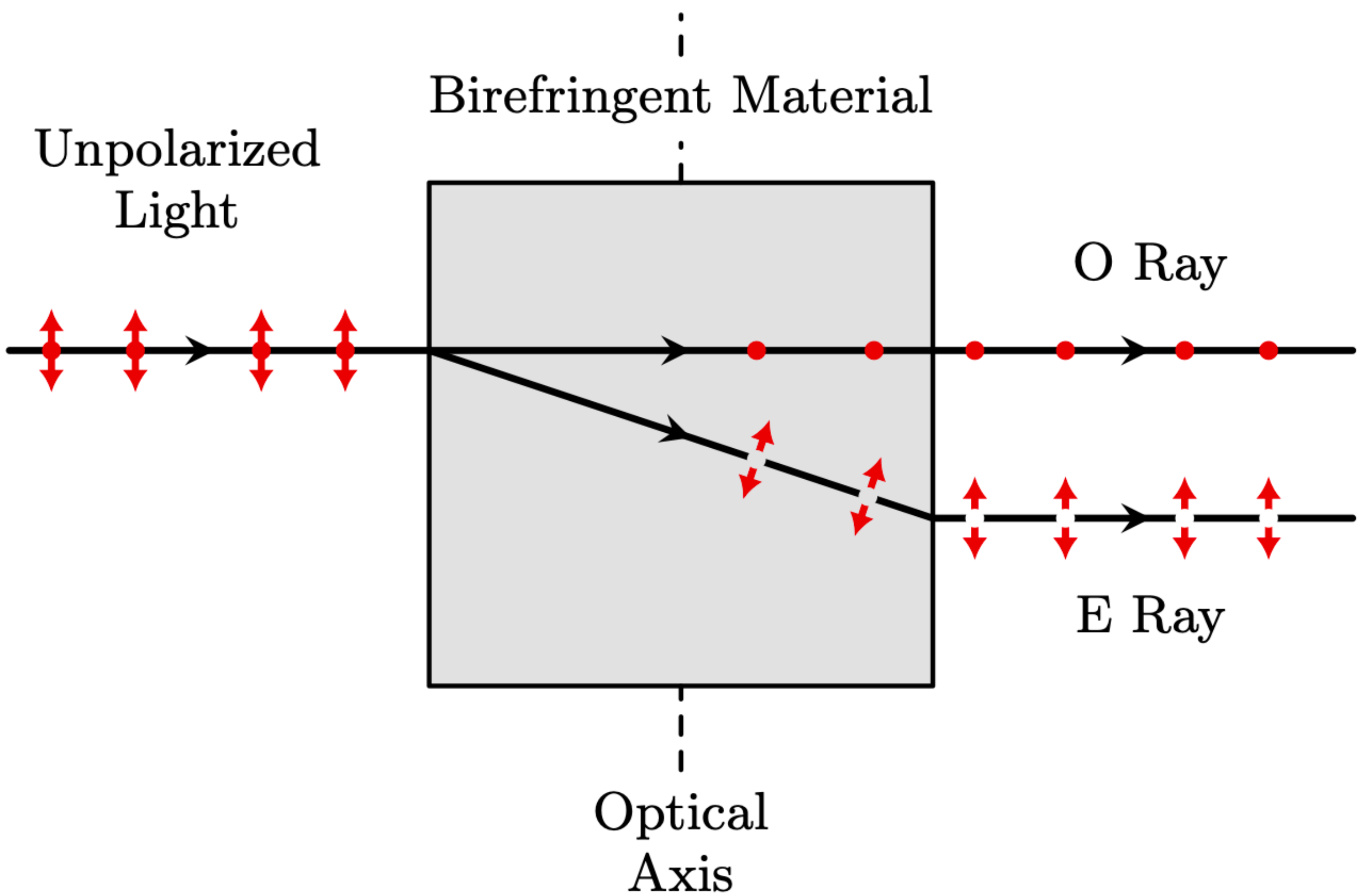
Korea University in Seoul, South Korea, 30 Nov. 2023

# Contents

# Birefringence

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



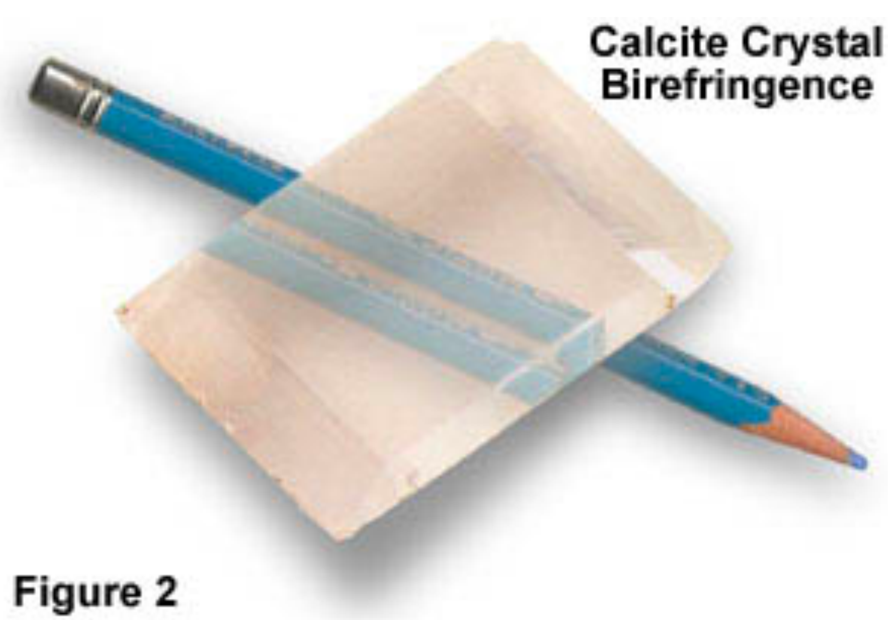




Figure 2

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:

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

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

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

# Cosmic Birefringence

The Maxwell's equations

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

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

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

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

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

# Cosmic Birefringence

The Maxwell's equations become the wave equations:

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

$$-\frac{\partial^2 \mathbf{E}}{\partial t2} + \nabla^2\mathbf{E} = g_a\left[\dot{\theta}\frac{\partial \mathbf{B}}{\partial t} - (\nabla\theta\cdot\nabla)\mathbf{B}\right]$$

$$-\frac{\partial^2 \mathbf{B}}{\partial t2} + \nabla^2\mathbf{B} = -g_a\left[\dot{\theta}\frac{\partial \mathbf{E}}{\partial t} - (\nabla\theta\cdot\nabla)\mathbf{E}\right]$$

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

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

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$\Rightarrow$

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

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

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

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

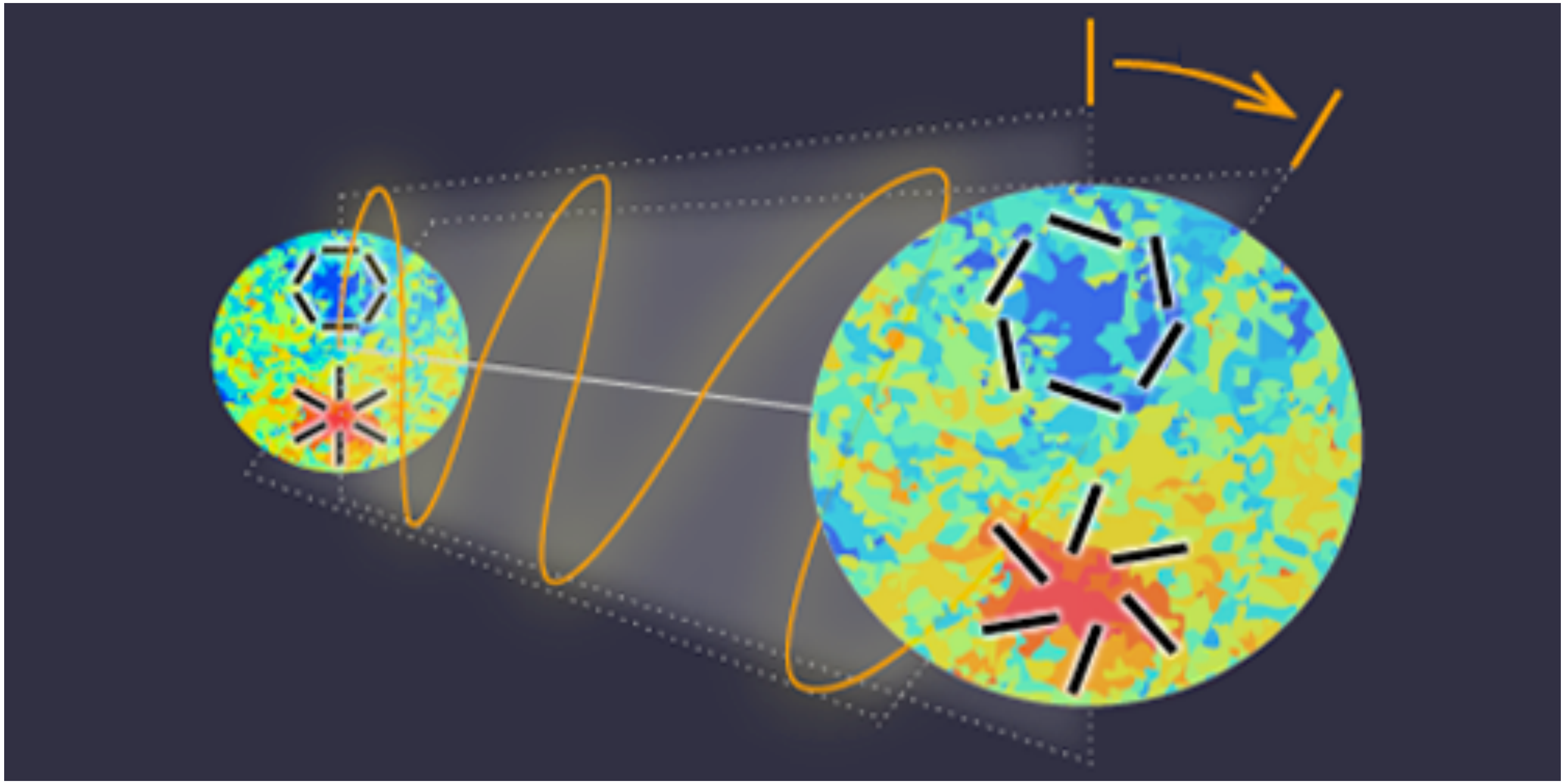
The coupling makes the phase velocities of two circular polarization state diverge: $\omega_\pm = k \pm \frac{1}{2}g_a k\dot{\theta}$

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

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

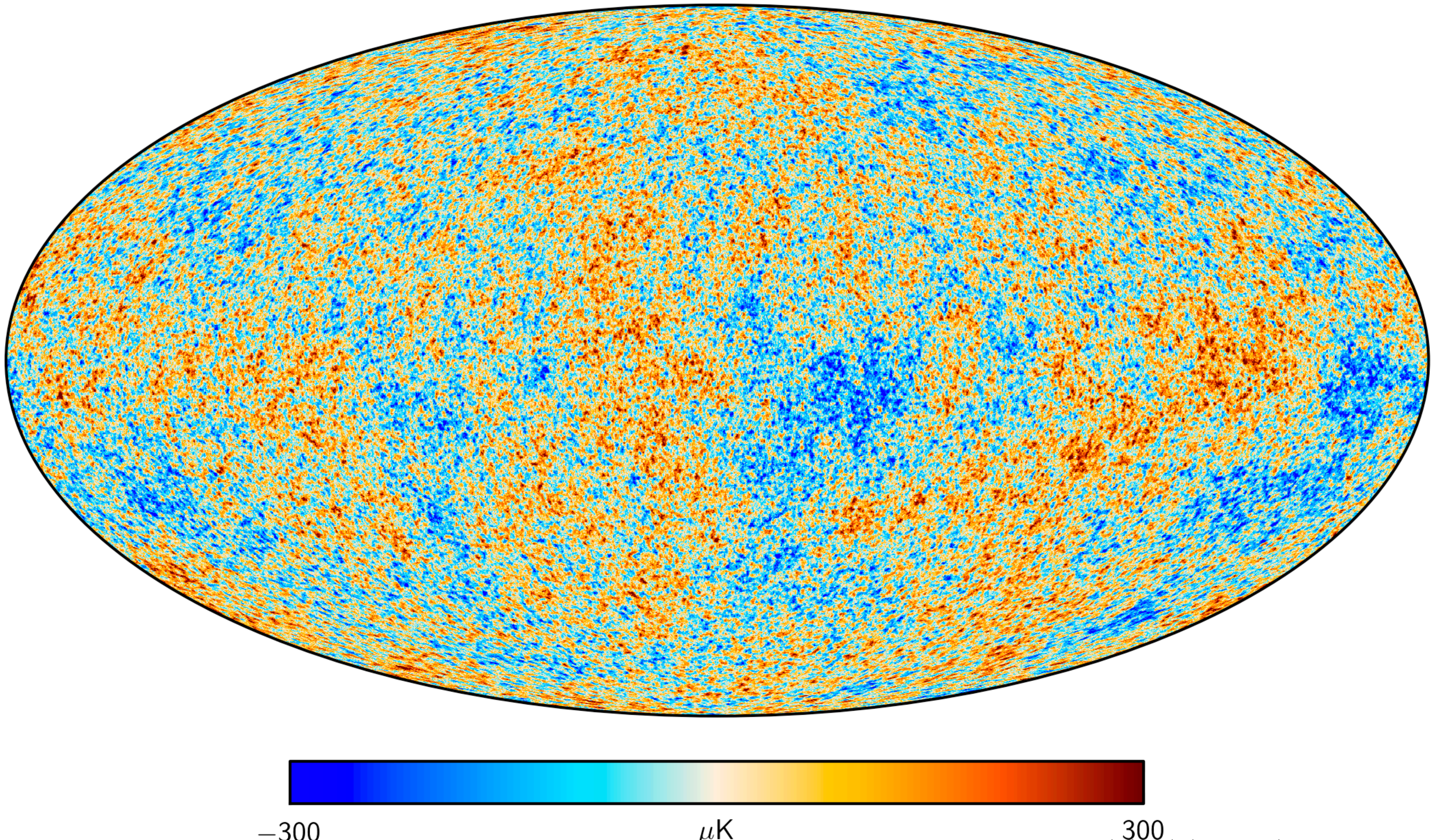
# Cosmic Birefringence

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



Credit: Y.Minami

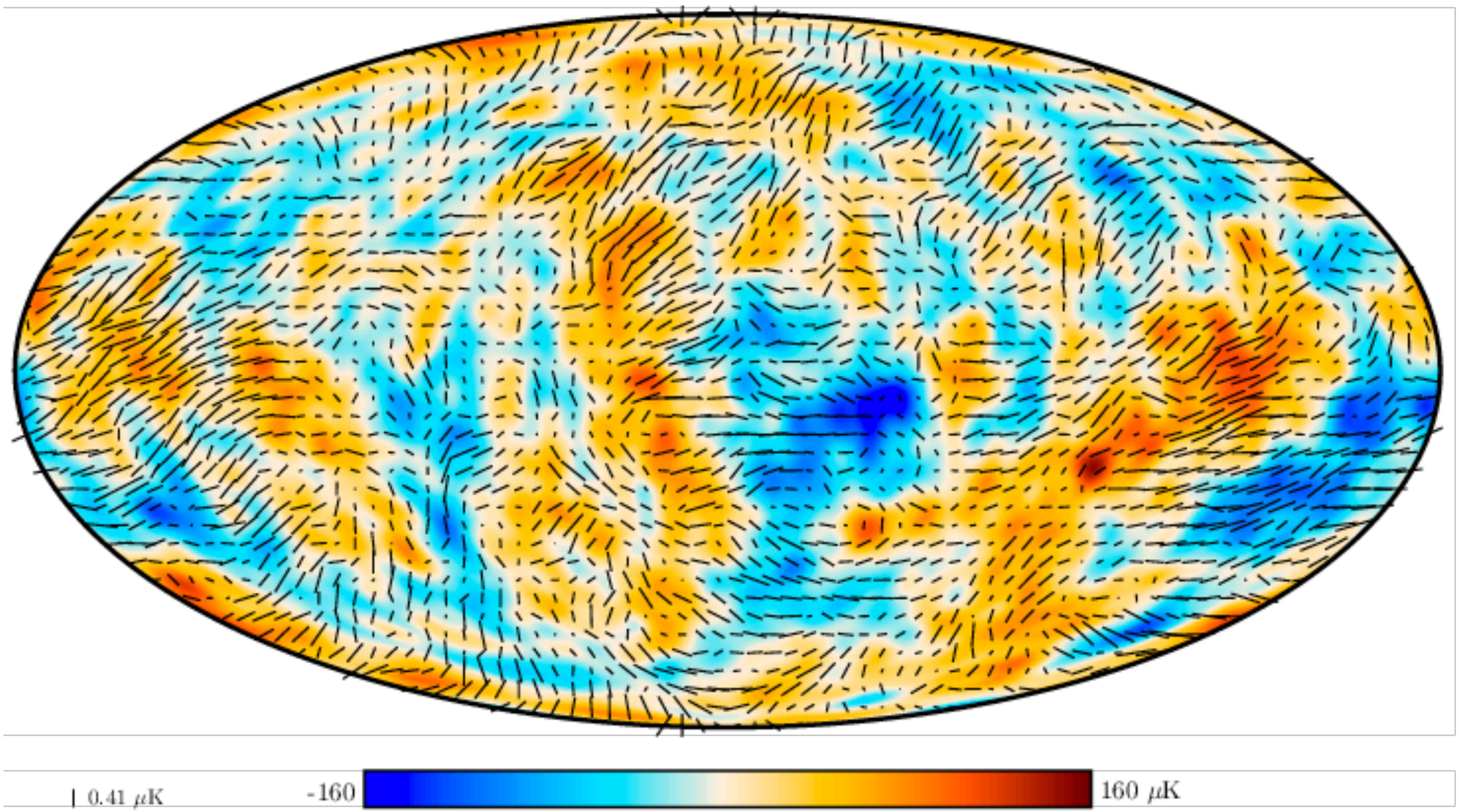
# Temperature map of the CMB




maximum likelihood posterior map

Plank Collaboration

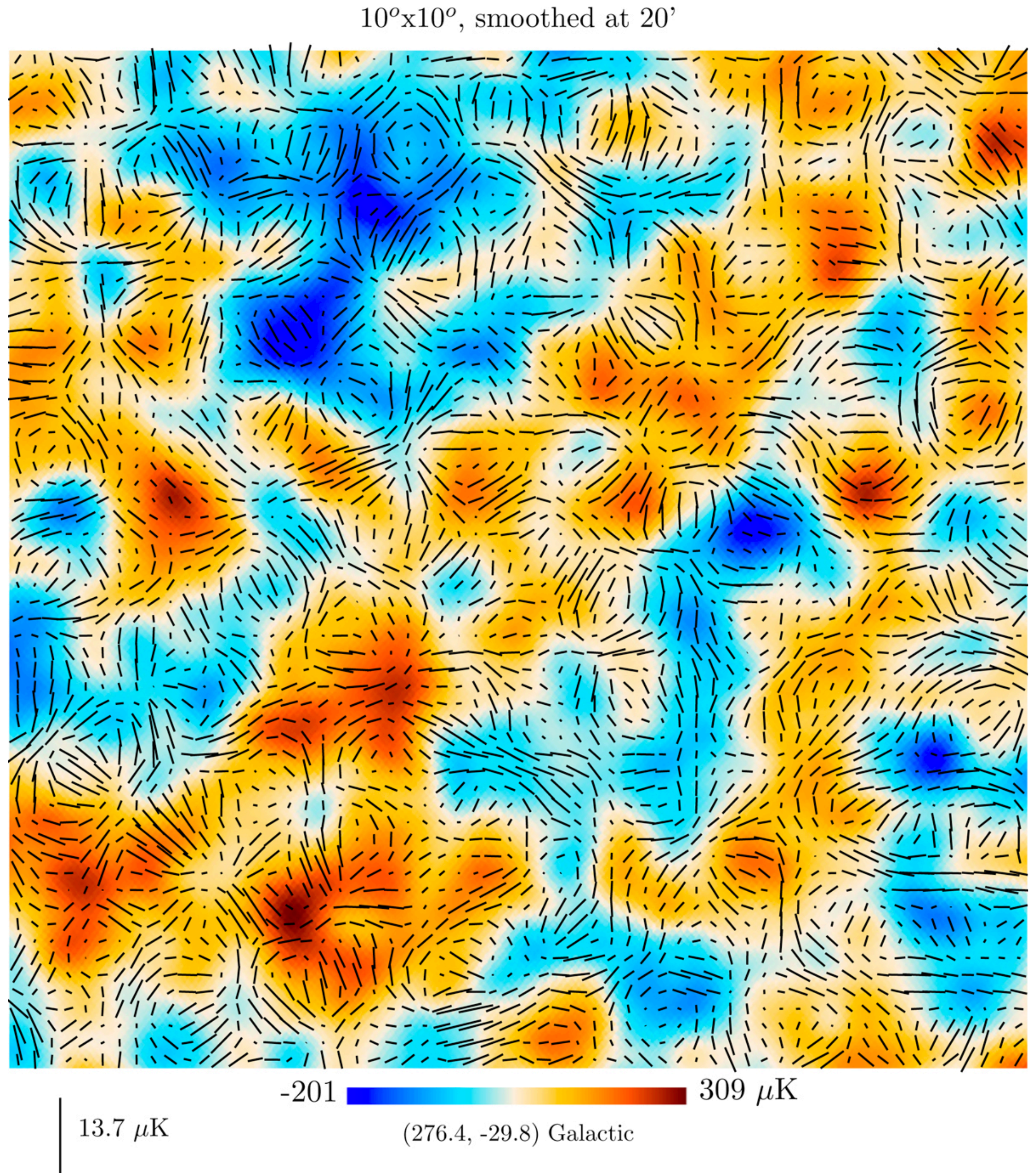
# Polarization map of the CMB

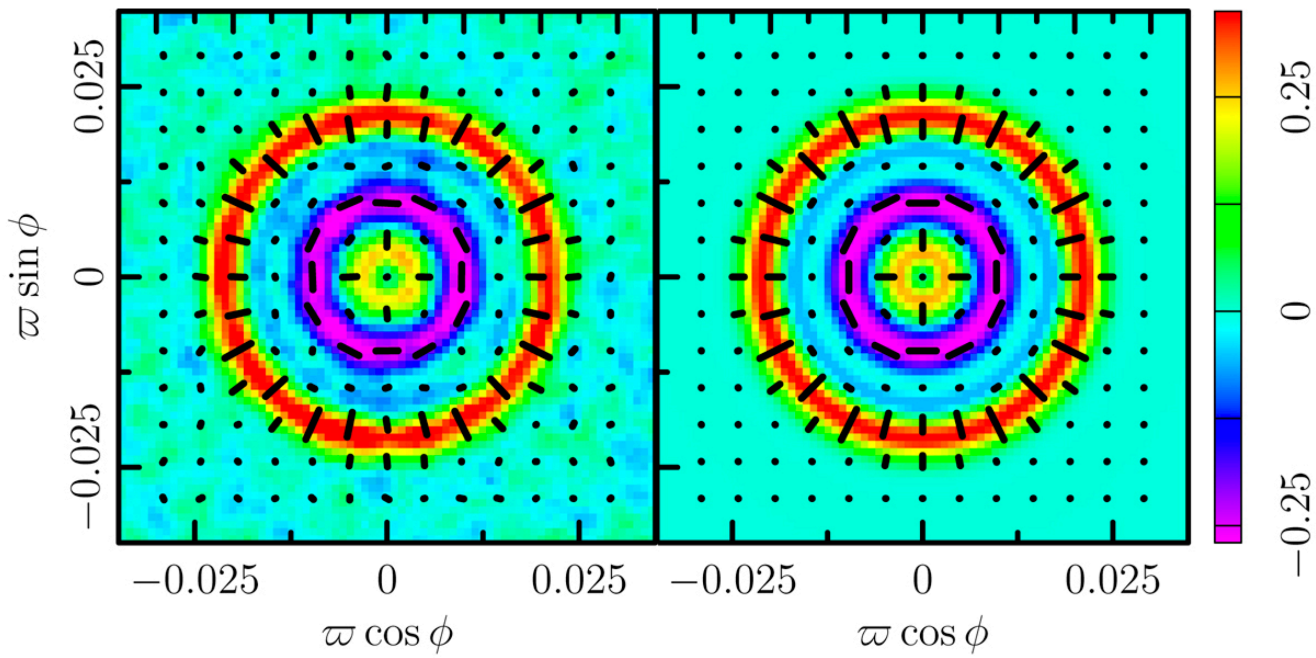



Plank map smoothed with 5° filter

Plank 2018 Results I

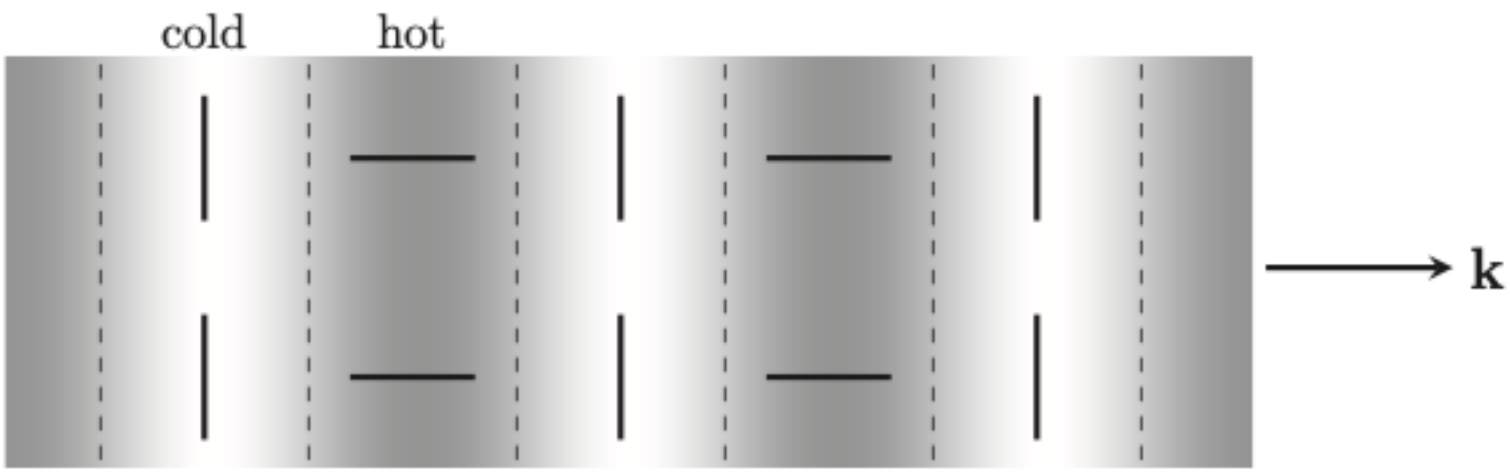
# CMB Polarization around the peak



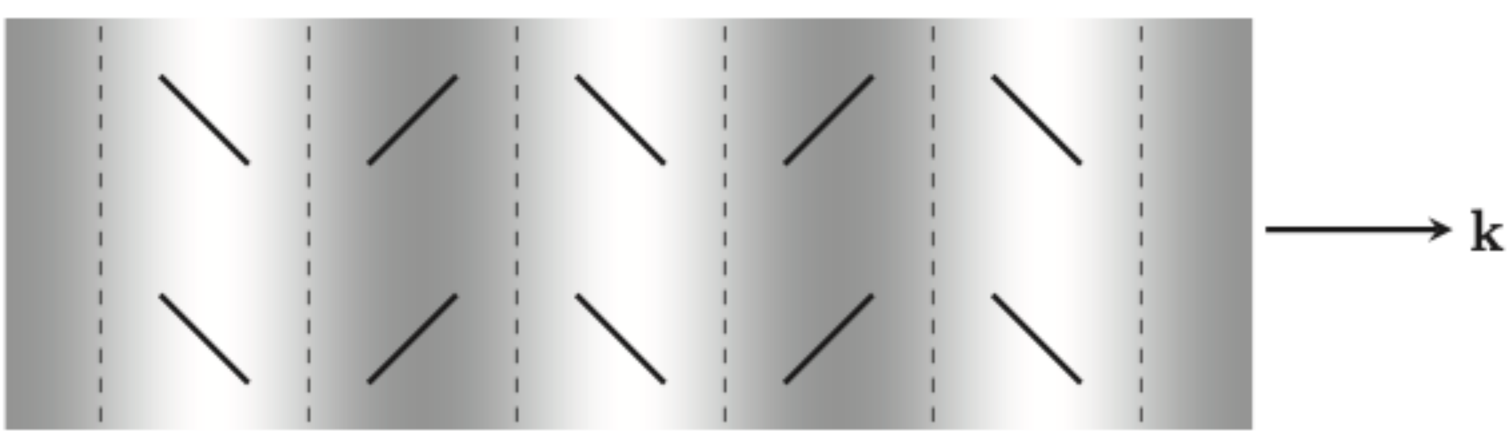



# E- and B-mode of linear polarization

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



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

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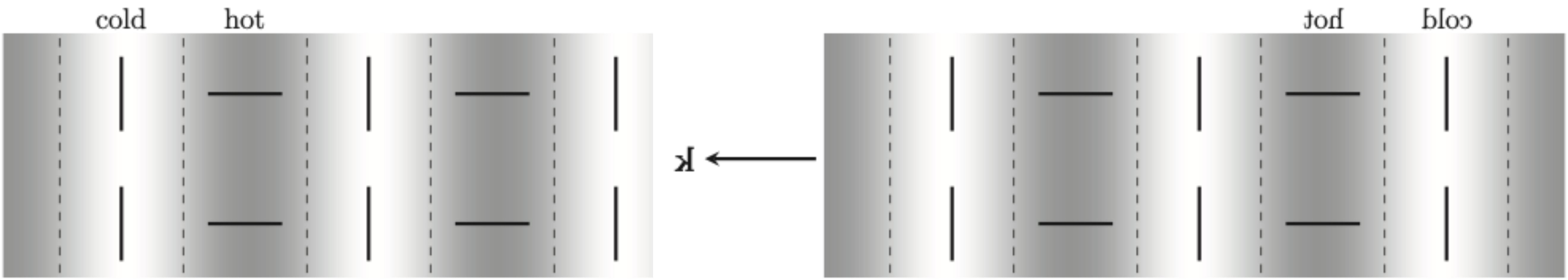


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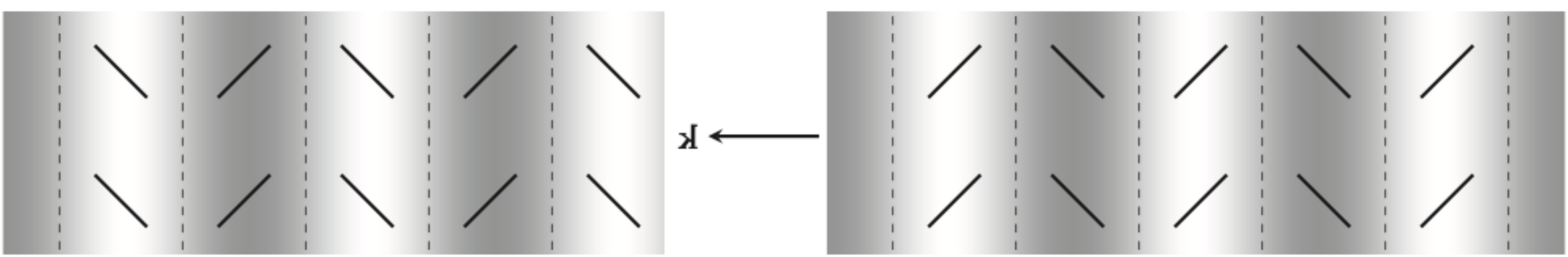

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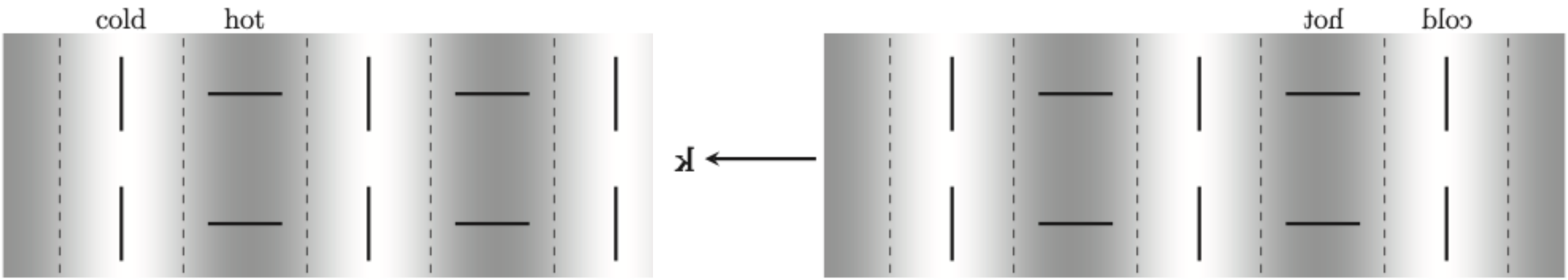
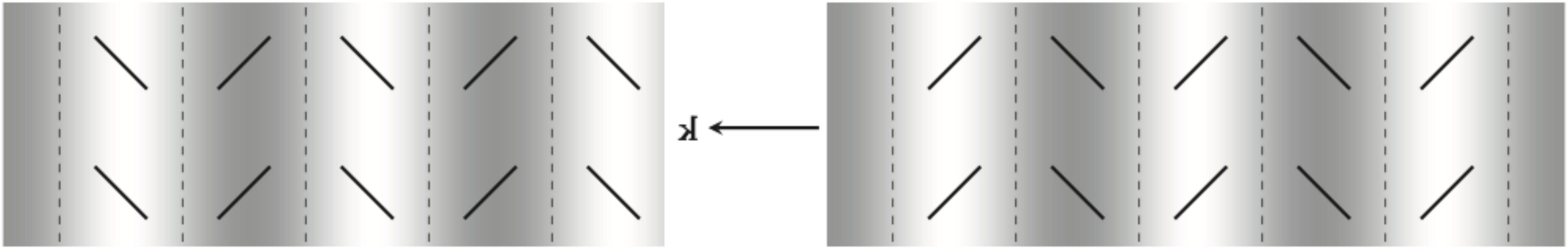



For the parity flip, E-mode remains the same,
whereas B-mode change the sign



# 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)

# EB correlation from the cosmic birefringence

**E** $\leftrightarrow$ **B** conversion by rotation of the linear polarization plane

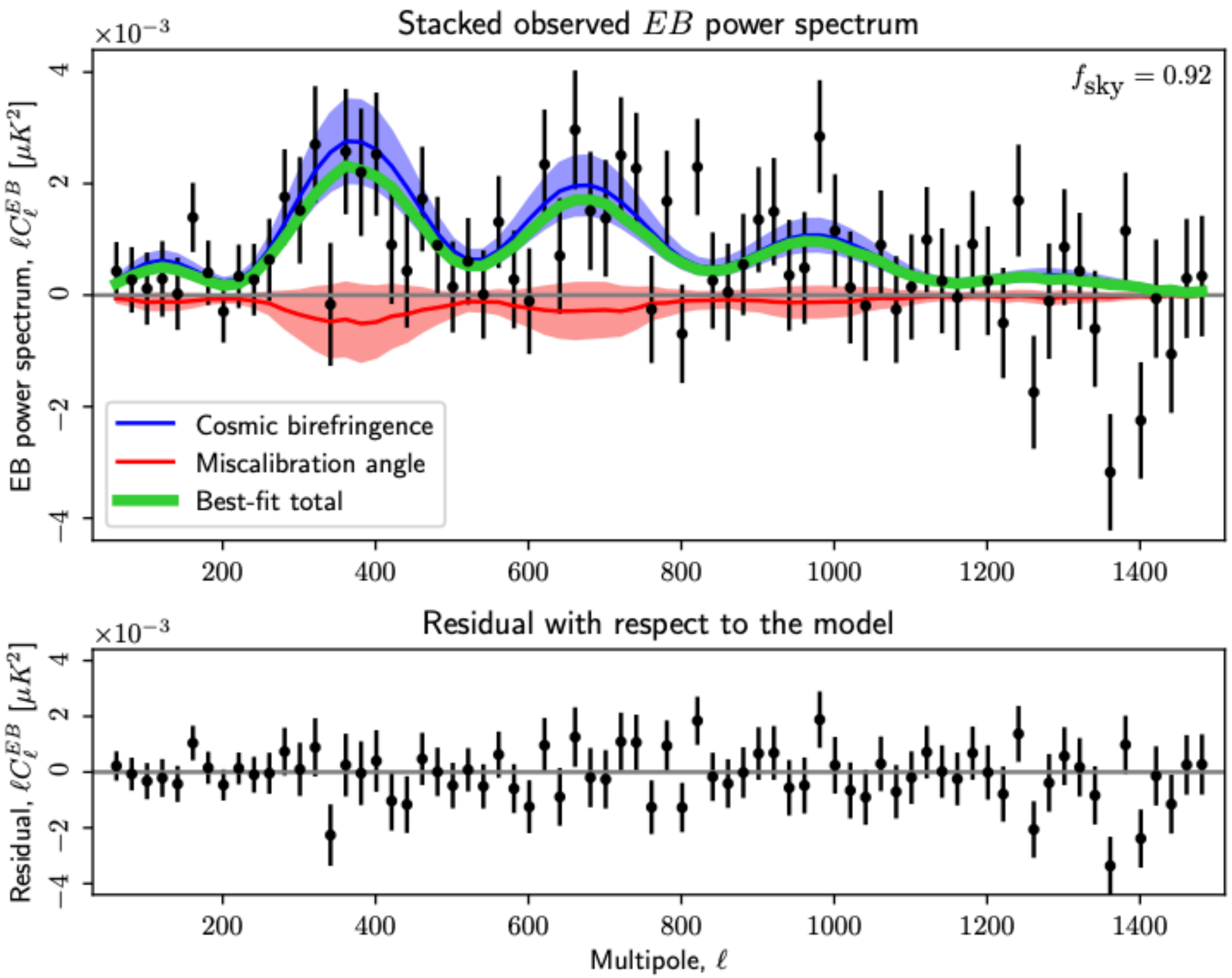
The intrinsic EE, BB, and EB power spectra 13.8 billion years ago would yield the observed EB as

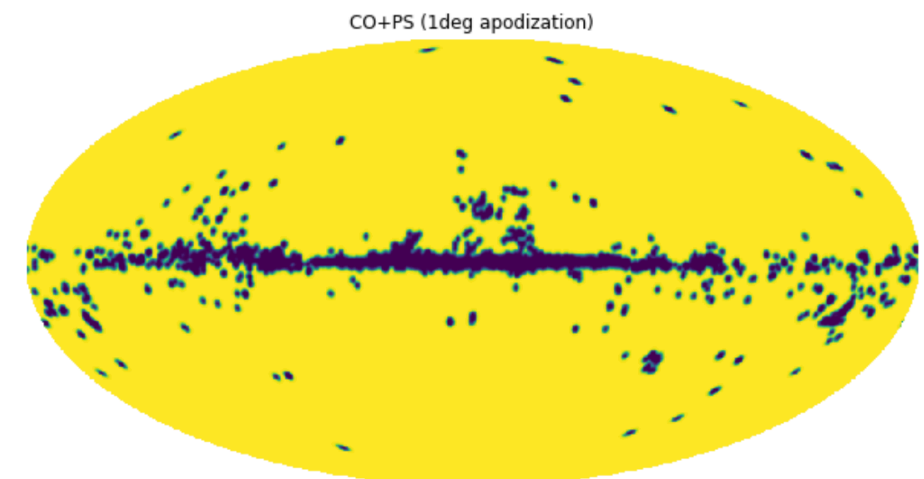
$$C_\ell^{EB,obs} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

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

Eskilt & E. Komatsu, 2205.13962

# Cosmic Birefringence (WMAP + Planck)



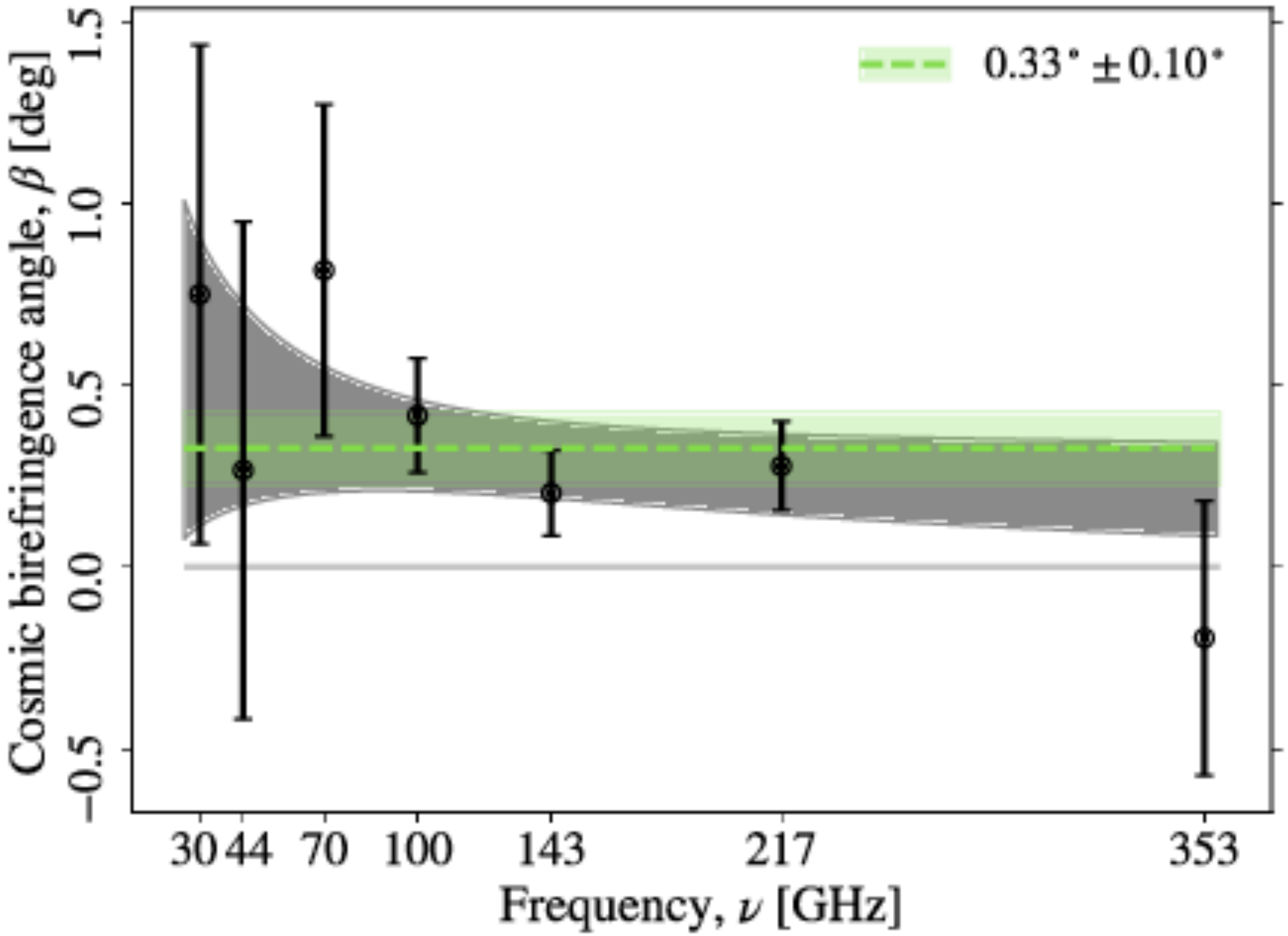

Miscalibration angles
Make only small contributions thanks to the cancellation.

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

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

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

# Frequency dependence?




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

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

# Mixing photon with dark photon

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

$$\mathscr{L} = -\frac{1}{4}\hat{F}^{\mu\nu}\hat{F}_{\mu\nu} - \frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - \frac{\varepsilon}{2}\hat{F}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}m_X^2\hat{X}^2 + eJ_\mu\hat{A}^\mu + e_X J_{X\mu}\hat{X}^\mu$$

Diagonalizatoin:

$$\begin{pmatrix}\hat{A}^\mu\\ \hat{X}^\mu\end{pmatrix} = \begin{pmatrix}1 & -\frac{\varepsilon}{\sqrt{1-\varepsilon^2}}\\ 0 & \frac{1}{\sqrt{1-\varepsilon^2}}\end{pmatrix}\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}A^\mu\\ X^\mu\end{pmatrix}$$

# Case 1: massive dark photon

The mixing angle $\theta = 0$ to make the SM photon massless.

The interaction terms:

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

SM photons do not directly couple to dark current
Strongly constrained by SM fermion coupling to the massive dark photon (Fabbricheshi et al., 2020).

We will NOT consider this case here.

# Case 2: massless dark photon

The mixing angle $\sin\theta = \epsilon, \cos\theta = \sqrt{1-\epsilon^2}$

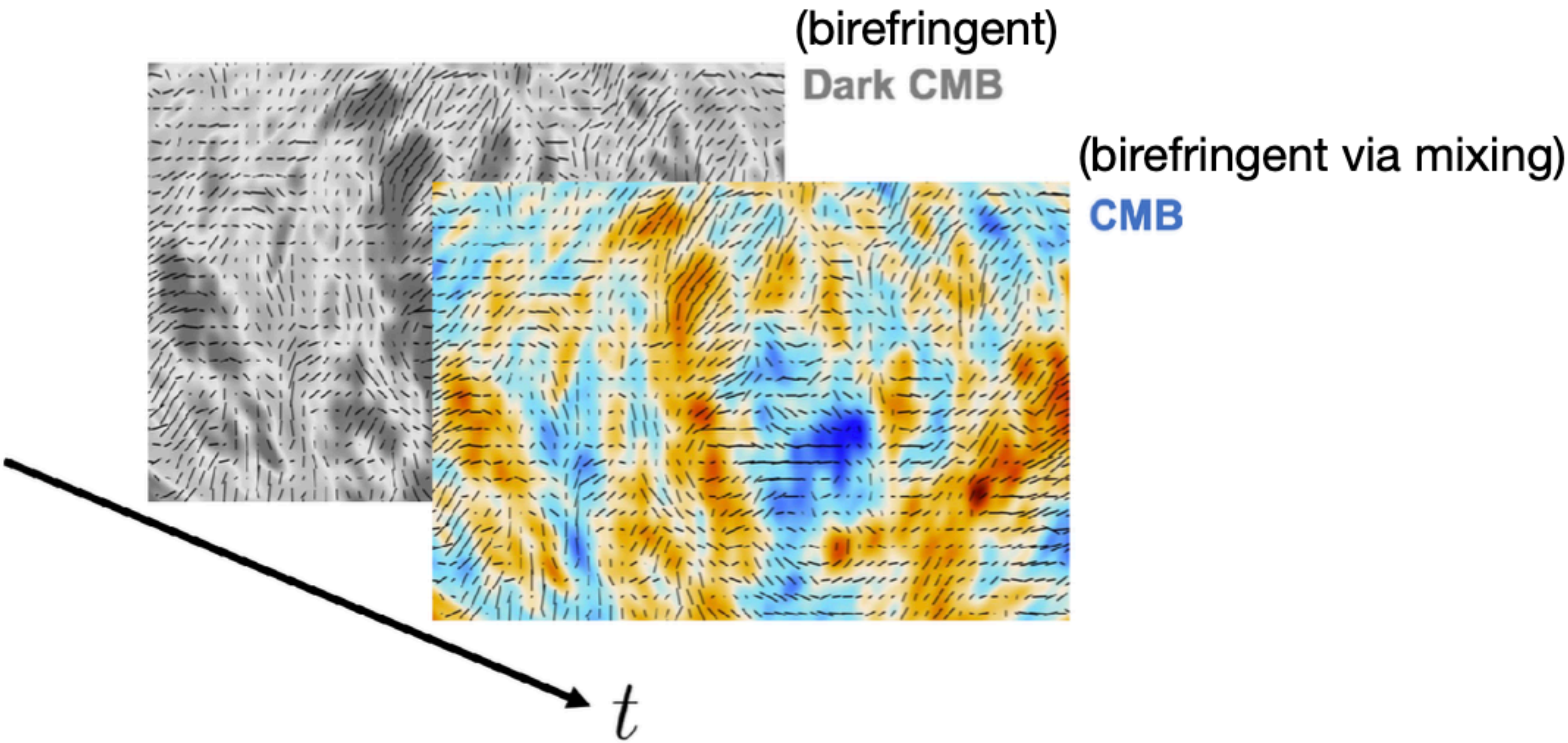
The interaction terms:

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

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

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

# Dark CMB



# Coupled Maxwell's equations

Maxwell's equation for SM photon and dark photon

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

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

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

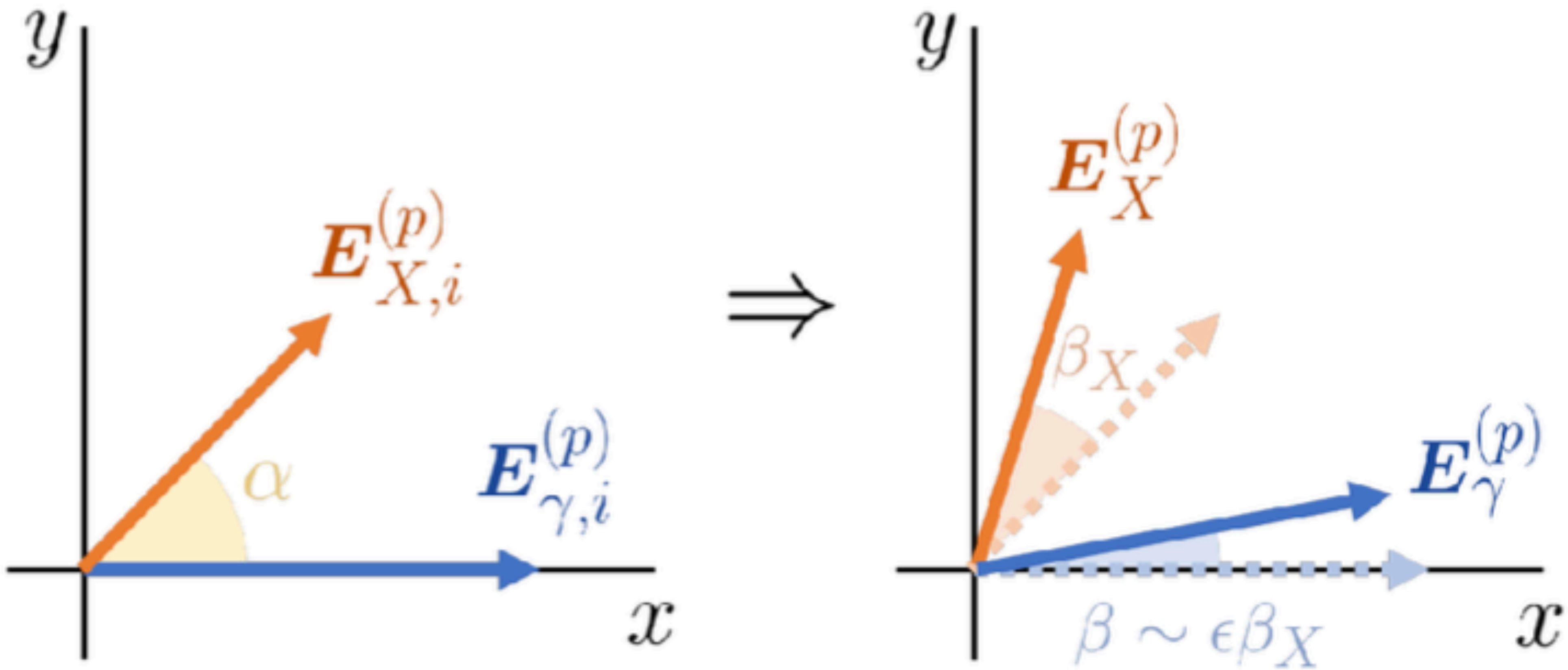
We solve these equations by defining $A'^\mu = A^\mu - \epsilon X^\mu$:

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

Dark photon has a relative phase $\alpha$ at the CMB-decoupling time.

Dark photon has birefringence $\beta_{DM}$ since the CMB-decoupling time.

# Induced Birefringence




initial misalignment (random) Induced Birefringence

# Polarization of SM Photon

Density matrix after photon-dark photon mixing

[Lee, Kang, Gong, Jeong, Jung and Park, 2307.14798]

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

- ***Birefringence ($U \neq 0$)*** $\beta(\hat{\boldsymbol{n}}) \simeq 2\epsilon\sqrt{\frac{I_X P_X}{I_0 P}}\cos\delta_X \cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right)$
  - **No isotropic birefringence at $O(\epsilon)$** $\langle\beta\rangle = 0$ if $\alpha$ is random
  - **Non-zero variance** $\langle\beta^2\rangle = \epsilon\frac{I_X}{I_0}\left\langle\frac{P_X}{P}\right\rangle\sin^2\left(\frac{\beta_X}{2}\right) \lesssim (1^\circ)^2$ [1603.08193]
- ***Circular polarization ($V \neq 0$)*** $\langle V^2\rangle \simeq 4\epsilon^2 I_0 I_X \bar{P}\bar{P}_X \sin^2\left(\frac{\beta_X}{2}\right) \lesssim (10\mu\mathrm{K})^2$

[1704.00215 ]

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

- The frequency dependence is weak as long as $T_{Dark-\gamma} \lesssim T_{CMB}$.
- Dark recombination preceded the baryonic recombination
- Unless we have a strong coupling to correlate the polarization of dark U(1) at dark recombination to the CMB's linear polarization, the relative linear polarization is random.
- The random angle removed the average birefringence signal. $\langle \beta \rangle = 0$
- Leading contribution = Spectral distortion, trispectrum, and Circular polarization.

# Conclusion

Parity is violated in Universe

- Cosmic birefringence
- and more (e.g.) galactic 4 point functions

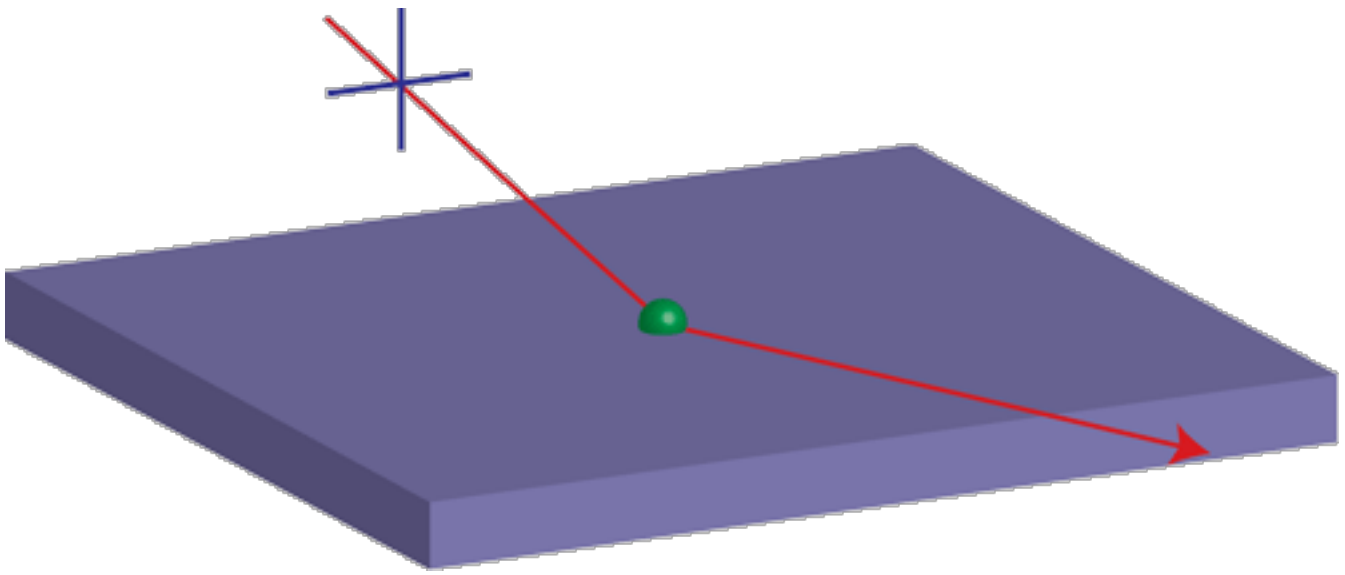
We study the effect of birefringent dark photon that mixes with photon with mixing parameter $\epsilon$

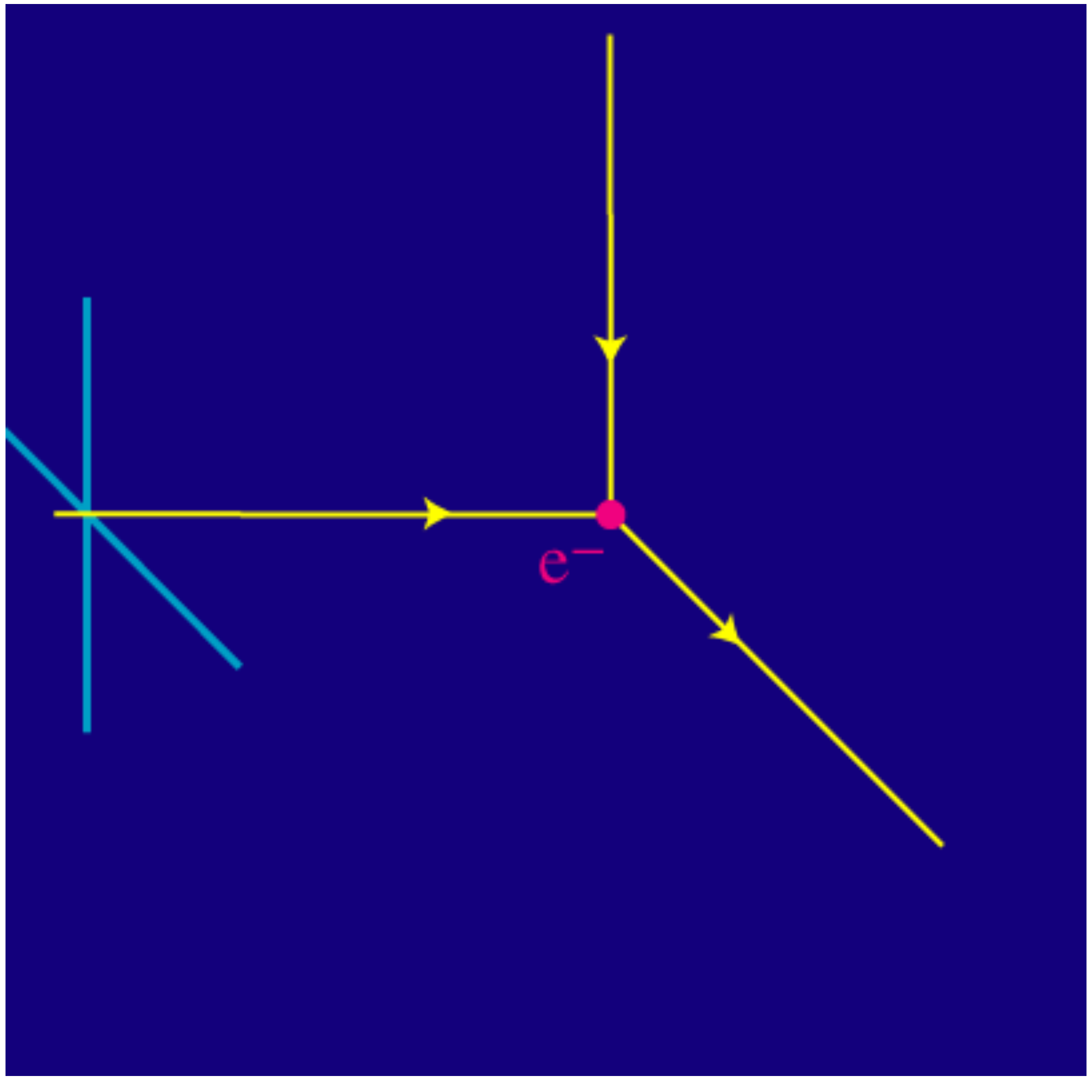
We found : isotropic birefringence $\langle \beta \rangle = 0$, $\langle \beta^2 \rangle \sim \epsilon$ and circular polarization $\sim \epsilon^2$ if the mixing is the source.

# Thank You for Attention!

http://background.uchicago.edu/~whu/intermediate/Polarization/

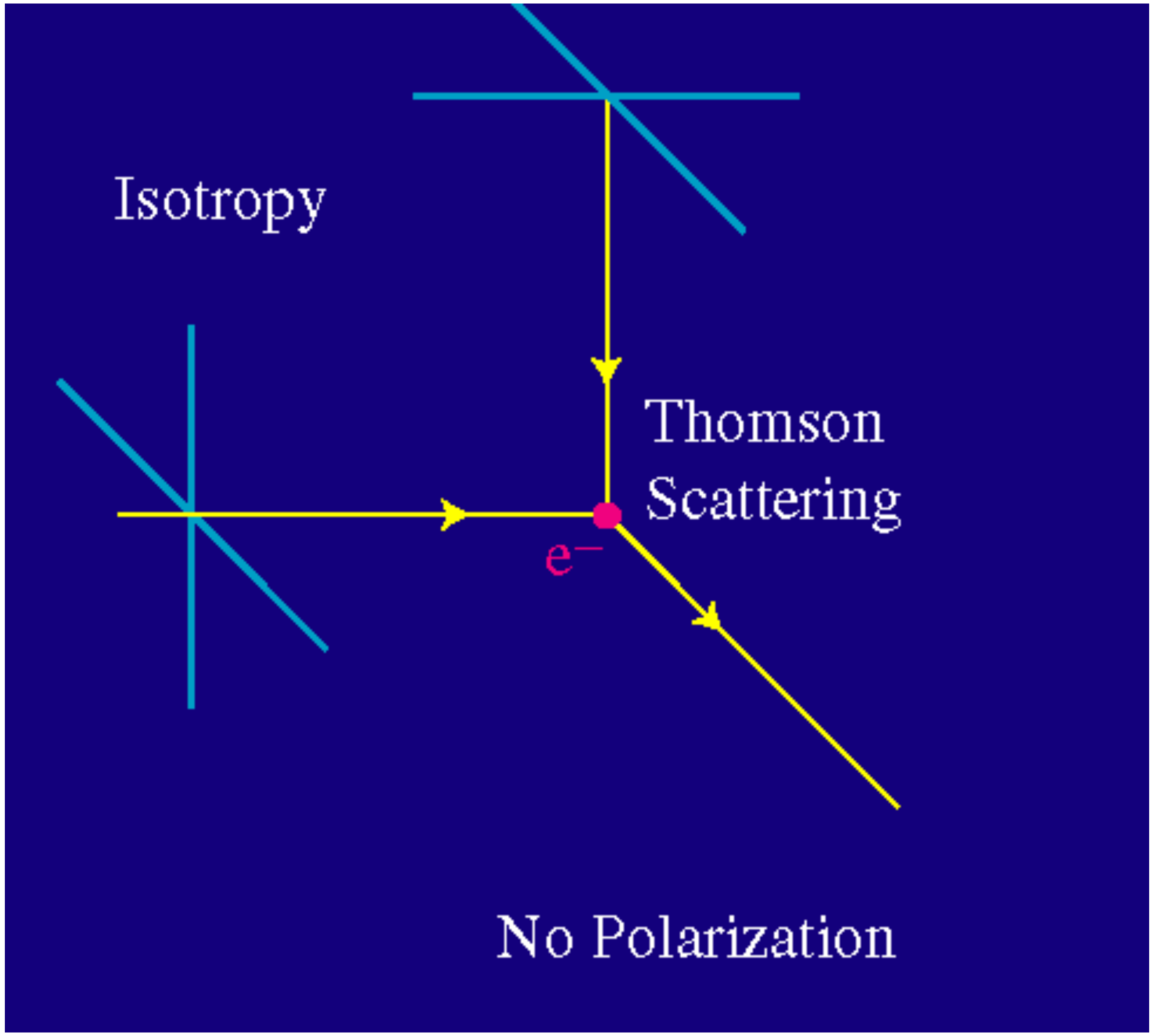
# Polarization and scattering

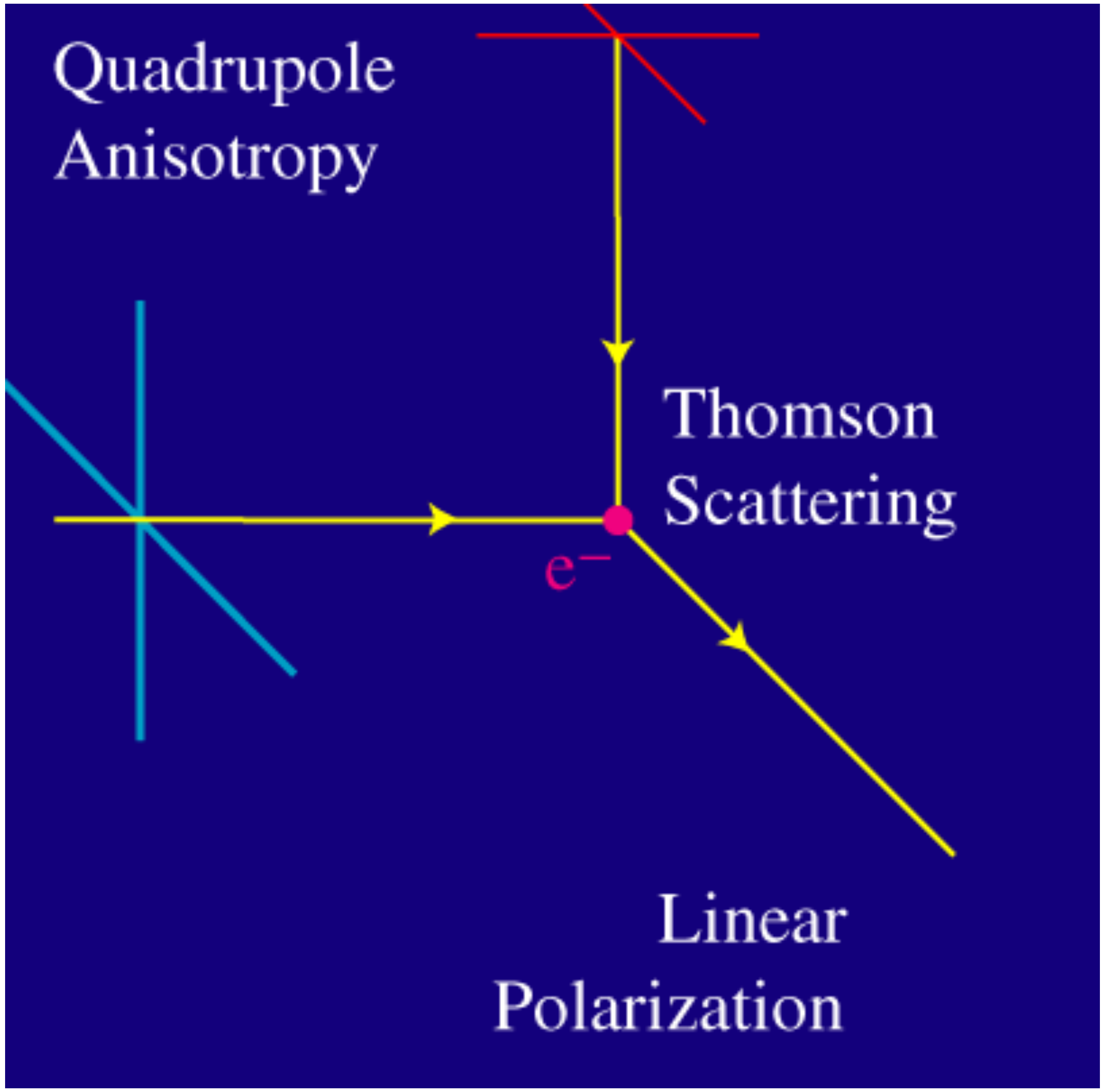




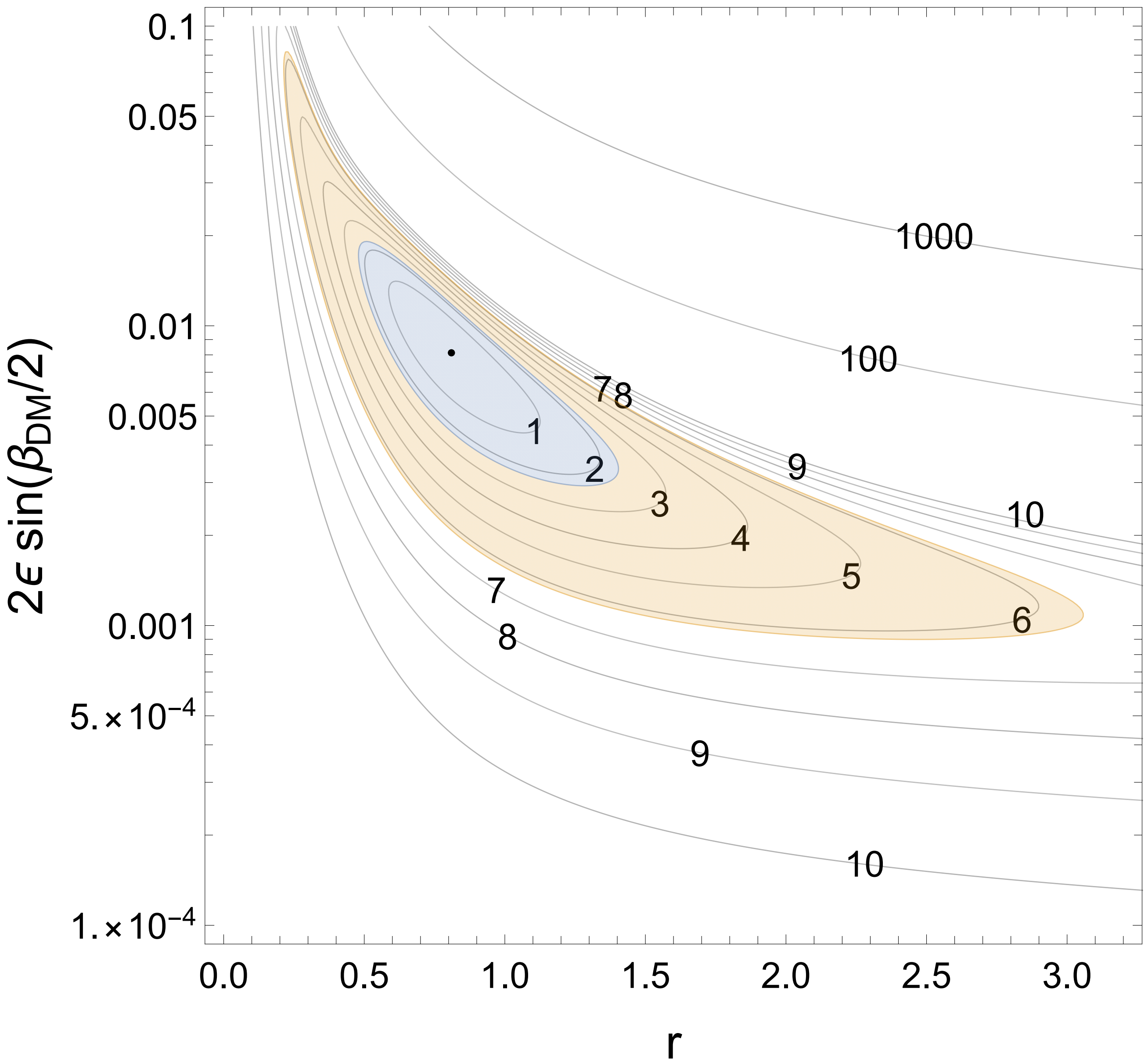
http://background.uchicago.edu/~whu/intermediate/Polarization/

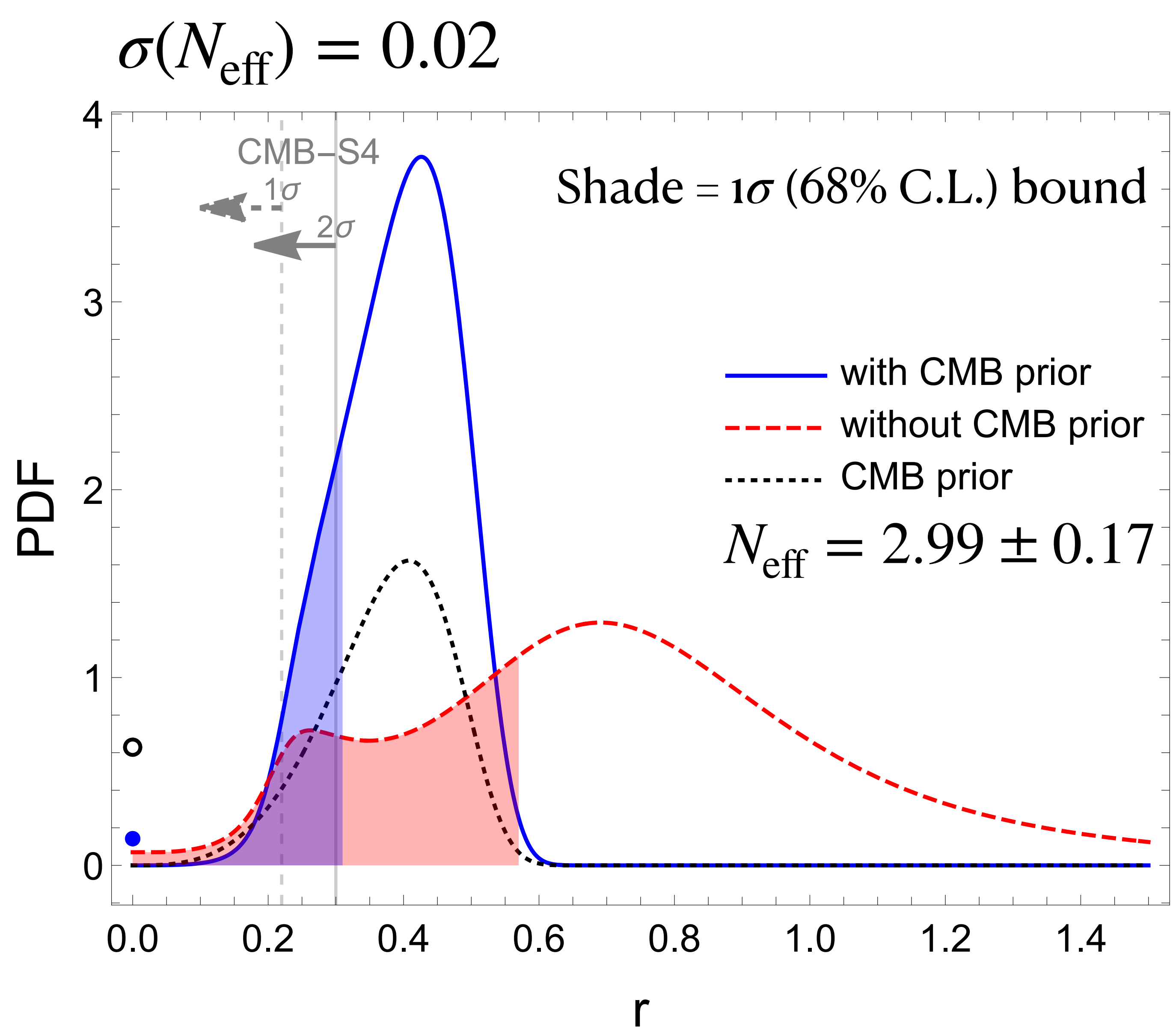
# Local anisotropy and Polarization



# Dark photon constraints



Fabbricheshi et al. (2020)

# Milli-charged particle bounds