Cosmic Birefringence from Dark Photon

Sung Mook Lee

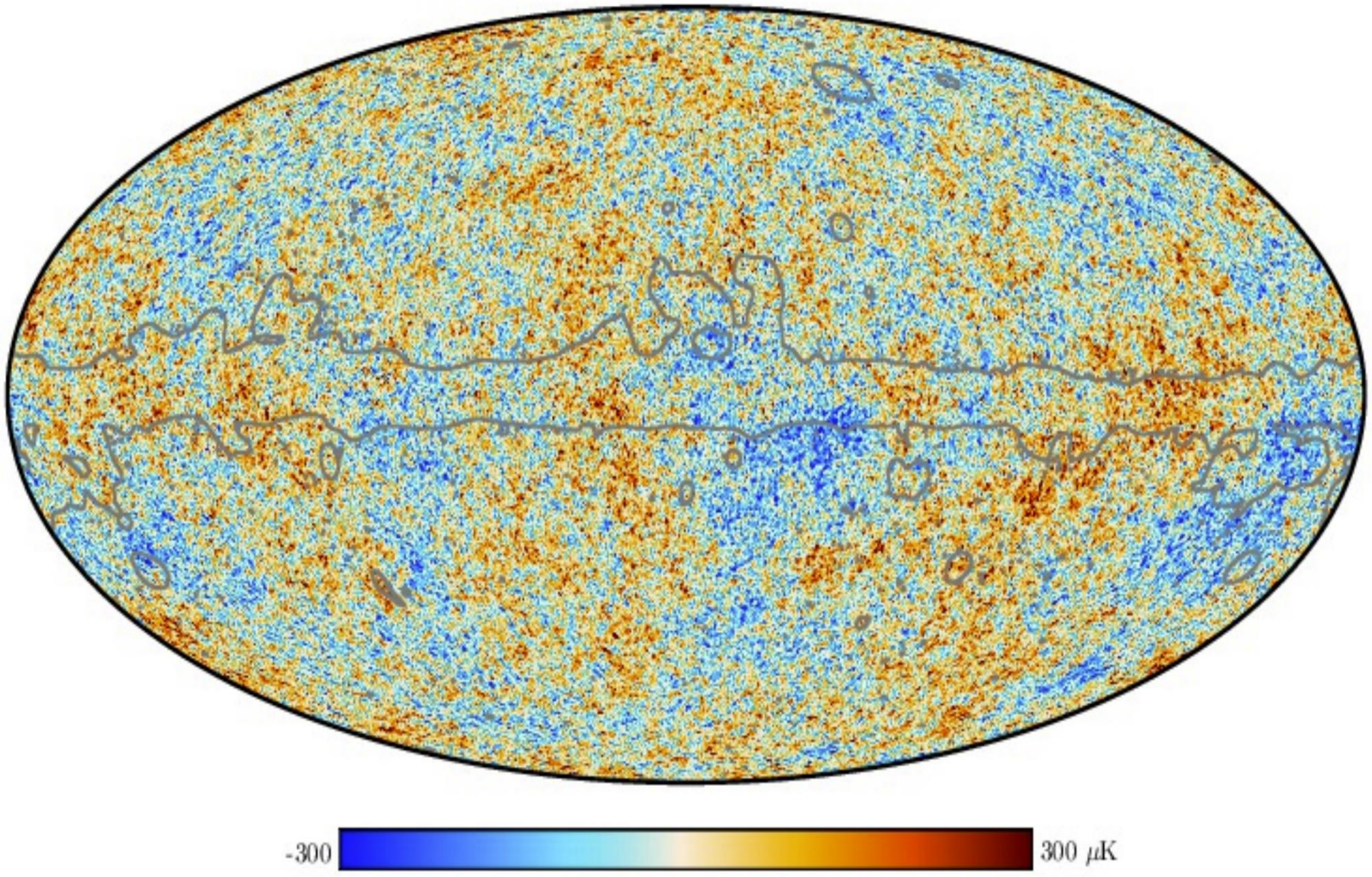
KAIST

Bases on **ArXiv: 2307.14798**

with Dong Woo Kang (JBNU), Jinn-Ouk Gong (Ewha Womans U.), Donghui Jeong (Penn State U./KIAS), Dong-Won Jung (Yonsei U.), Seong Chan Park (Yonsei U.)

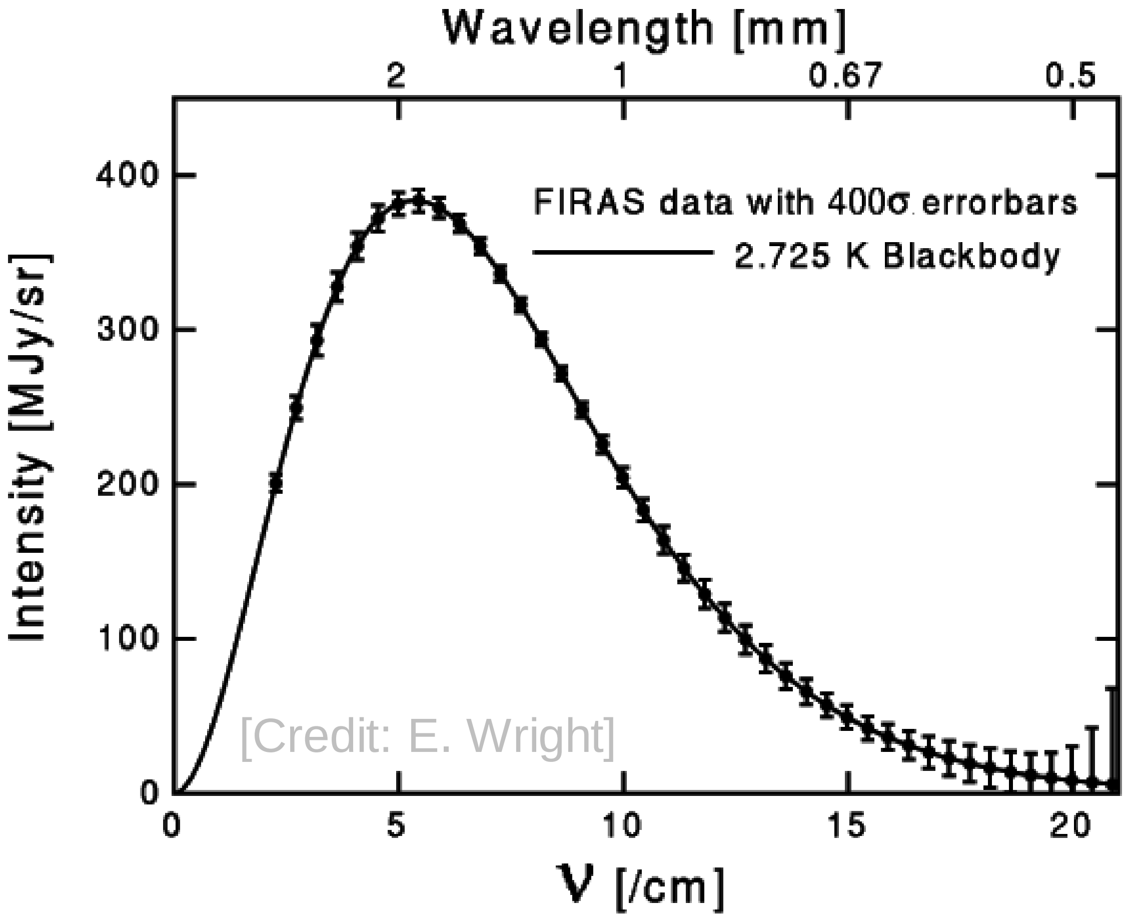
Cosmic Microwave Background (CMB)

[Planck 2018 Results 1807.06205]



Cosmic Microwave Background (CMB)

- **(Nearly) Perfect Blackbody**



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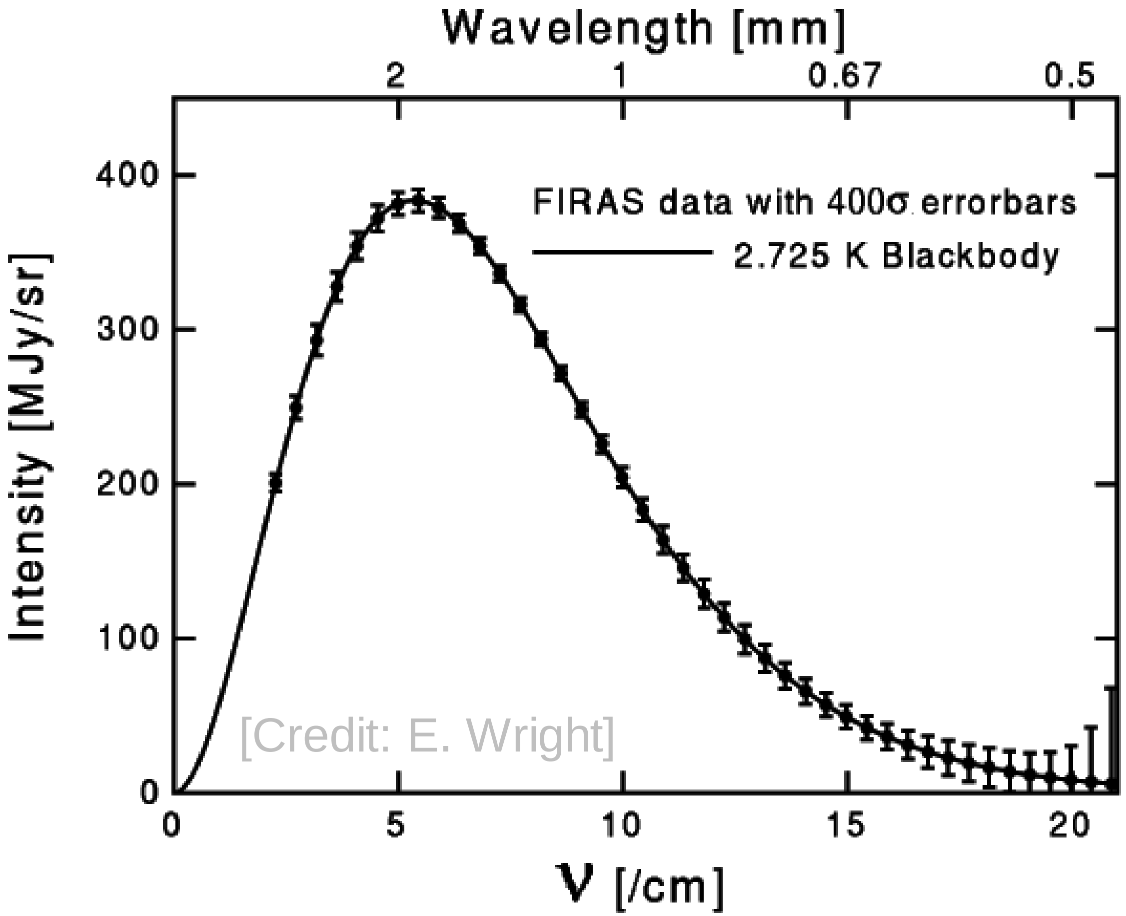
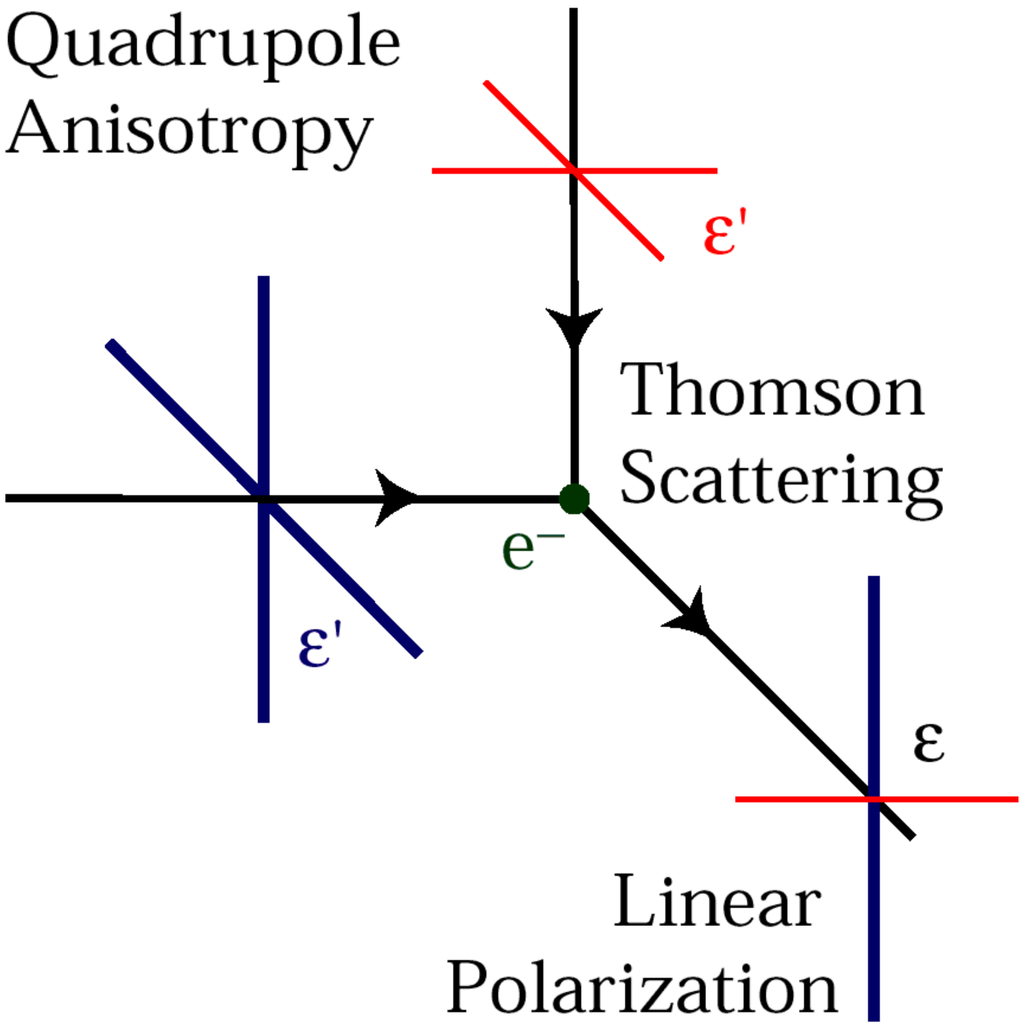


Any deviation?
(*spectral distortion*)

Polarization of CMB



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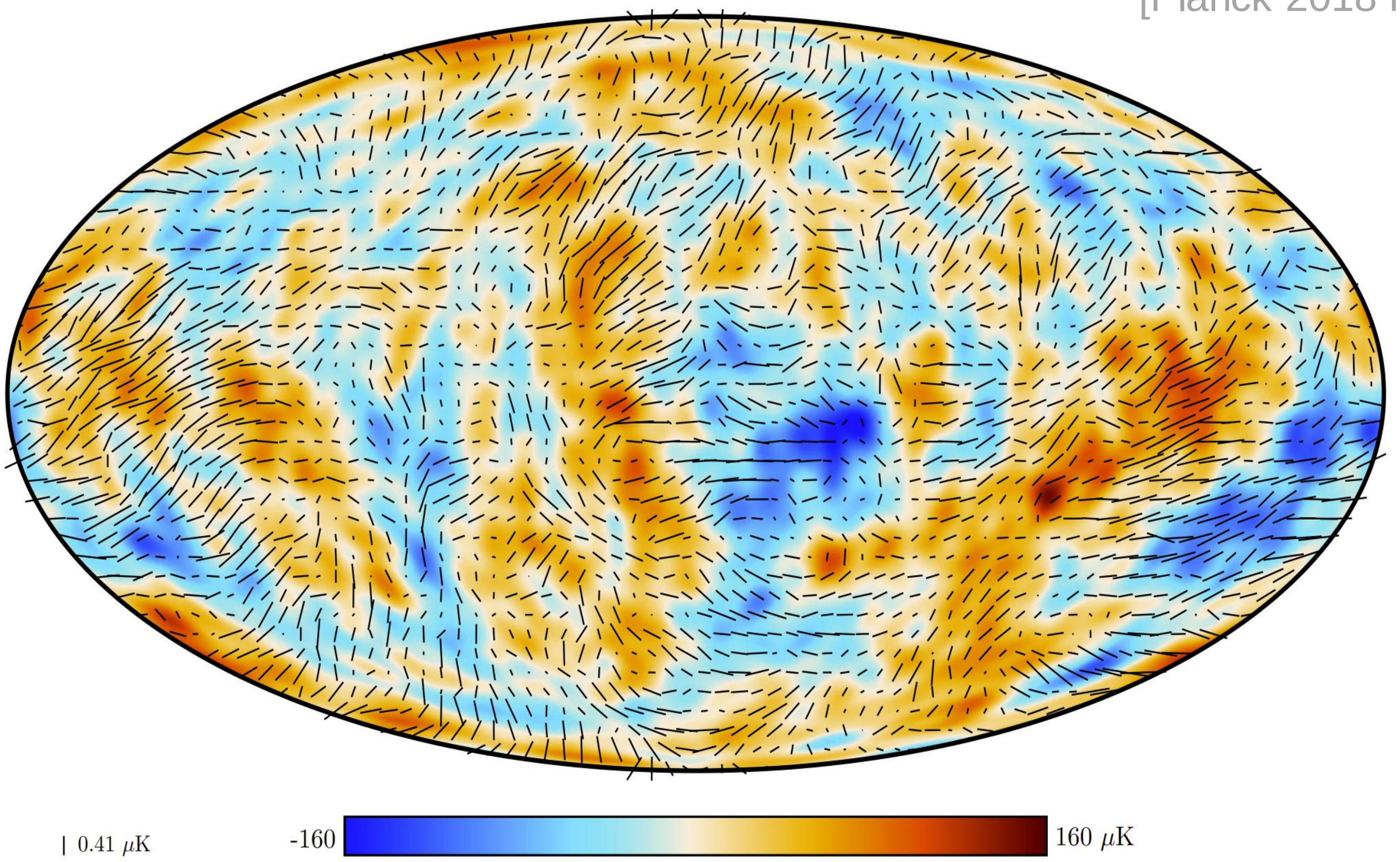
[Planck 2018 Results 1807.06205]



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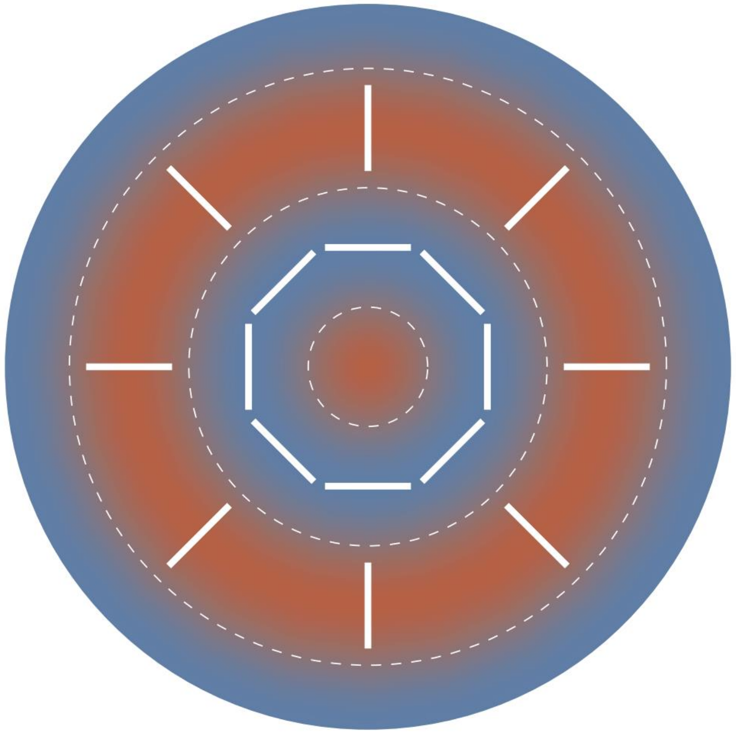
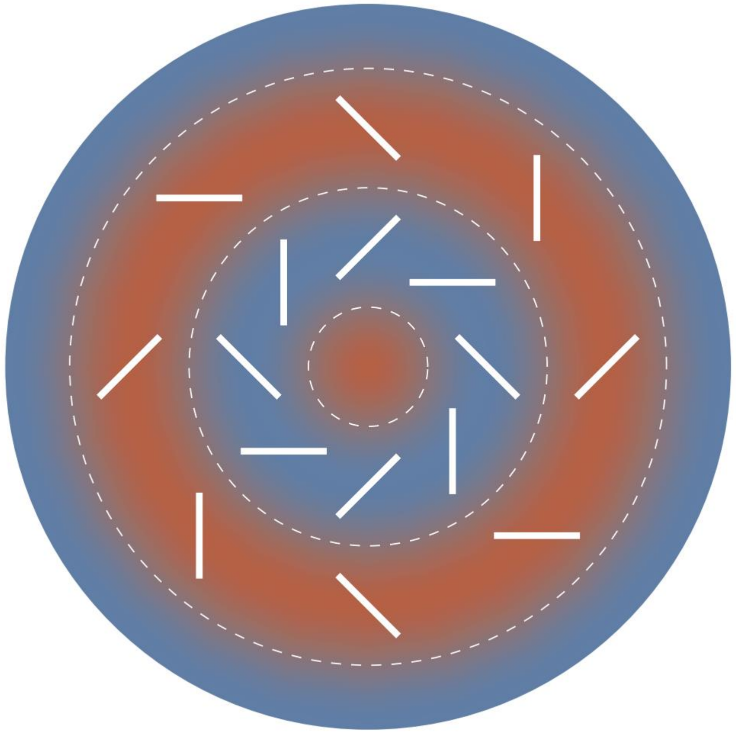


E-mode
Parity *Even*

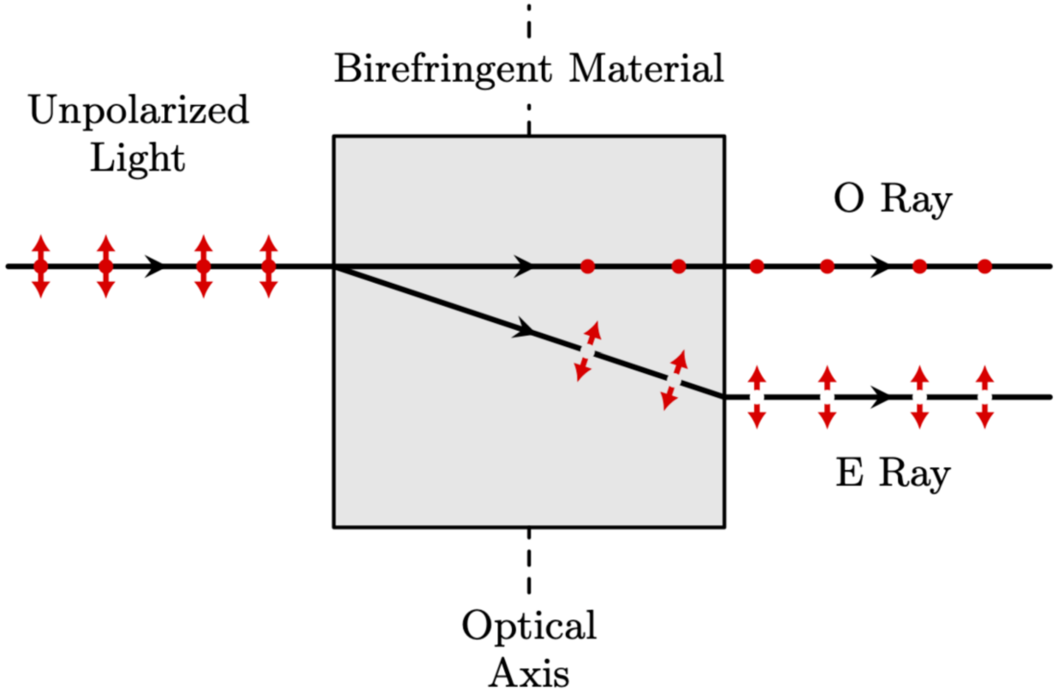


B-mode
Parity *Odd*

CMB Birefringence

Cosmic Birefringence

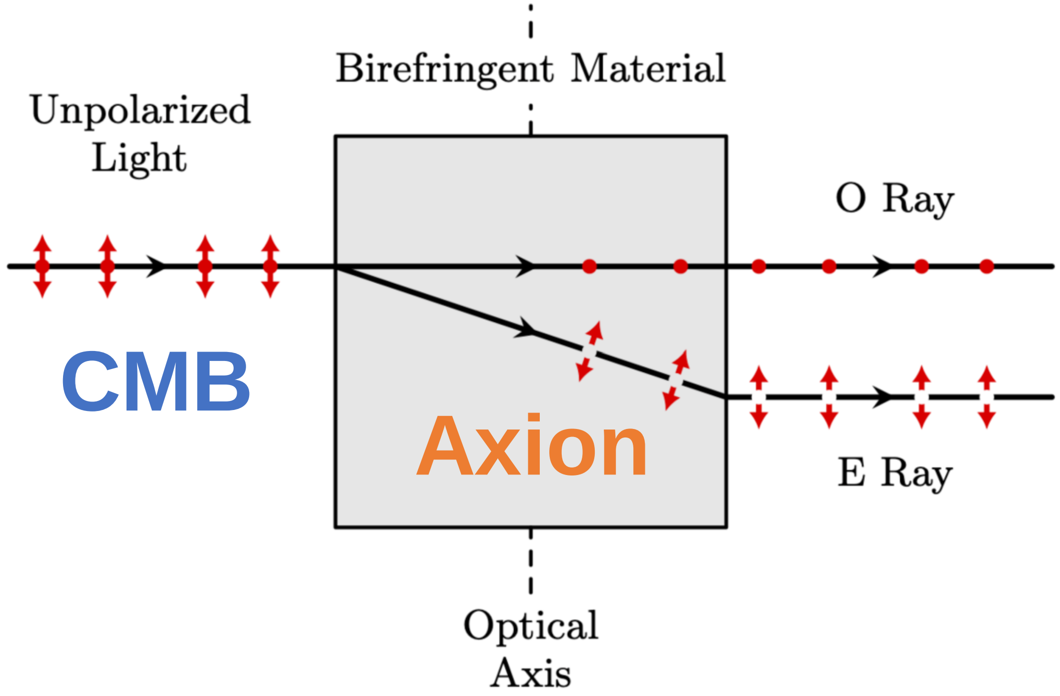
- **Birefringence**



[Image credit: A. Tsagkaropoulos]

Cosmic Birefringence

- **Birefringence**



[Image credit: A. Tsagkaropoulos]

Cosmic Birefringence

[For review, Komatsu 2202.13919]

- **Axion Background**

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}(\partial a)^2 - \frac{1}{4}g_a a F^{\mu\nu}\widetilde{F}_{\mu\nu}$$

Cosmic Birefringence

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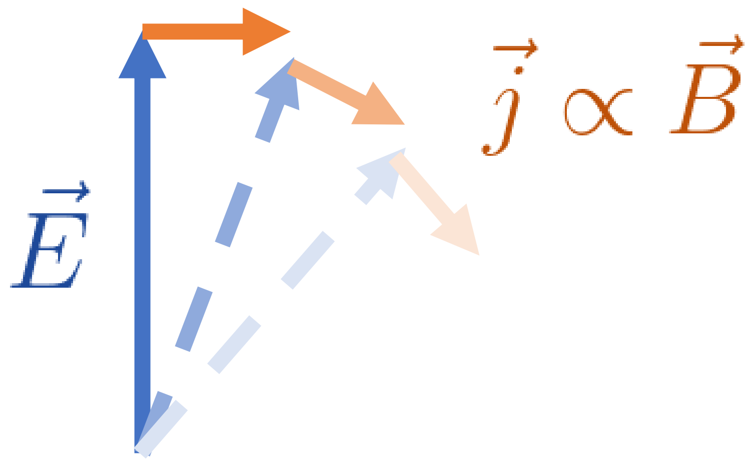

Cosmic Birefringence

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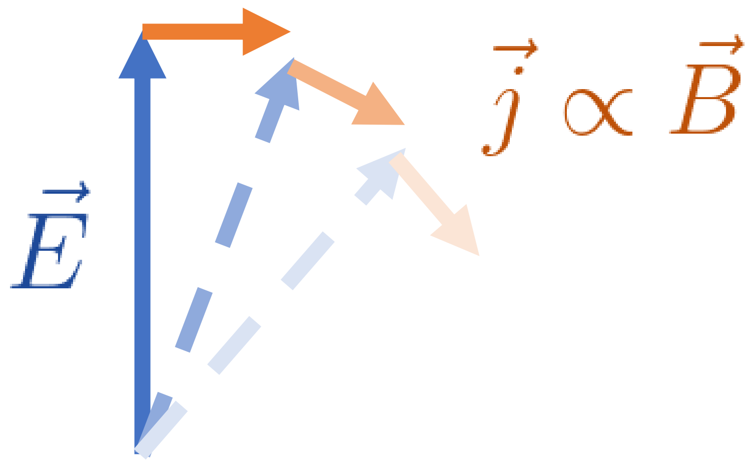
$$A''_\pm + \left(k^2 \mp k g_a a'\right) A_\pm = 0$$



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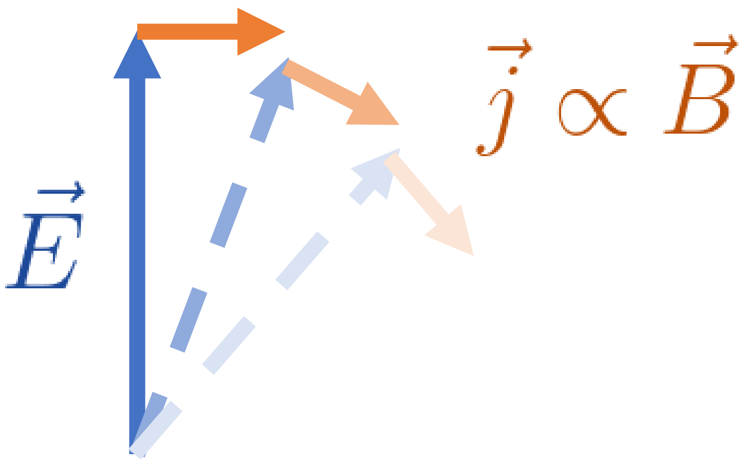
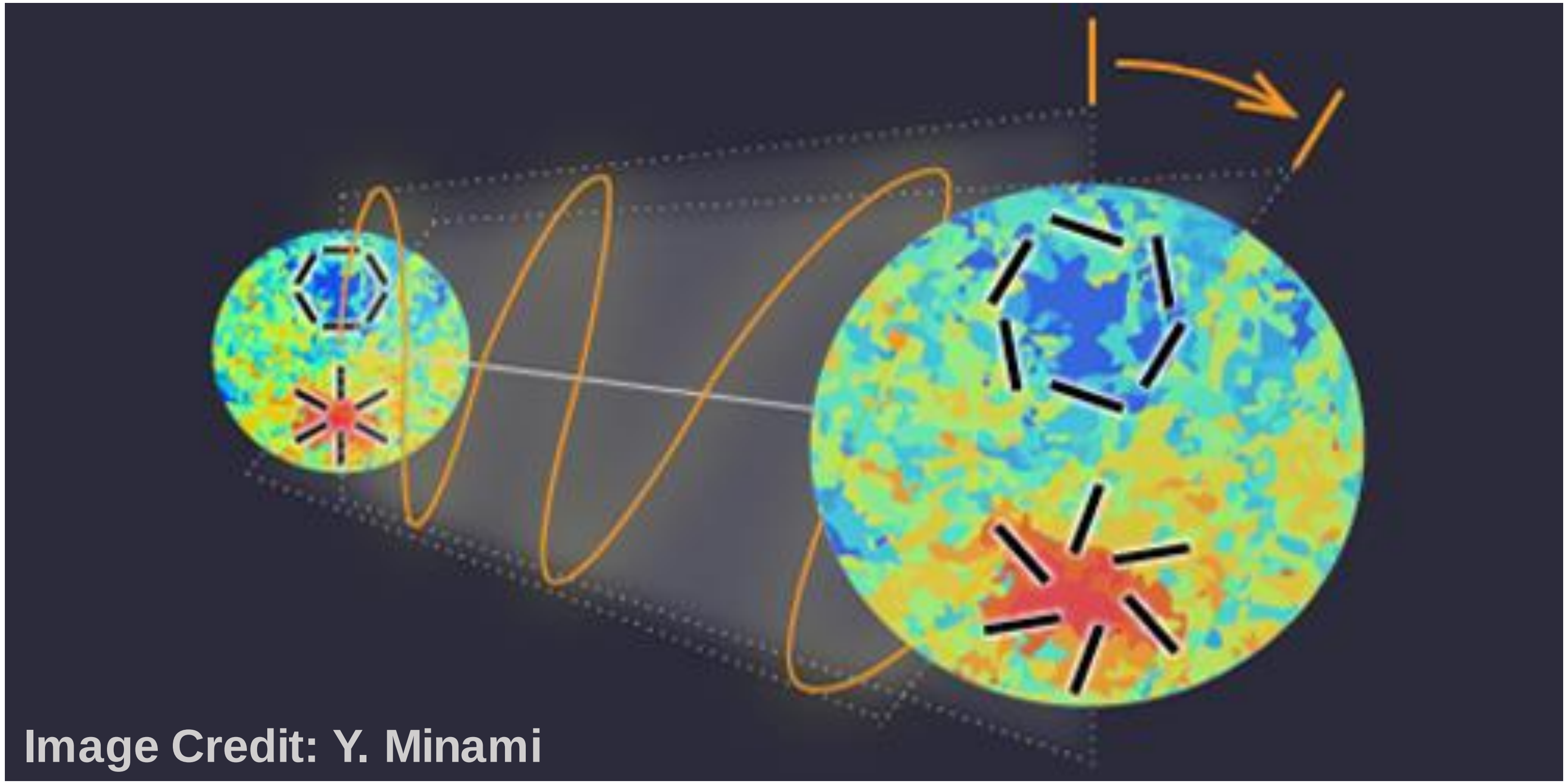
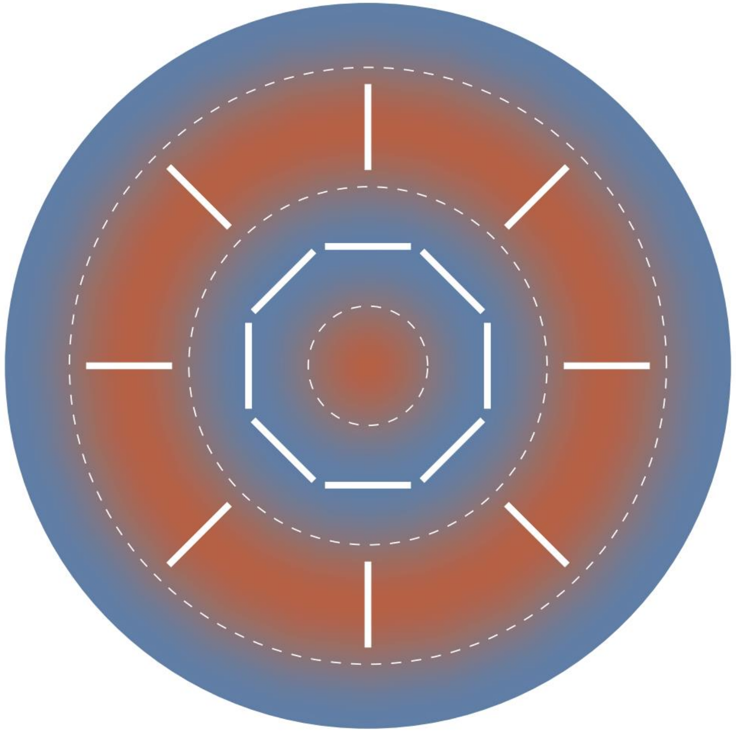


Cosmic Birefringence

$$\beta = \frac{1}{2} g_a \int_{\eta_{\rm dec}}^{\eta} d\bar{\eta}\; a'(\bar{\eta}) = \frac{1}{2} g_a \Delta a$$

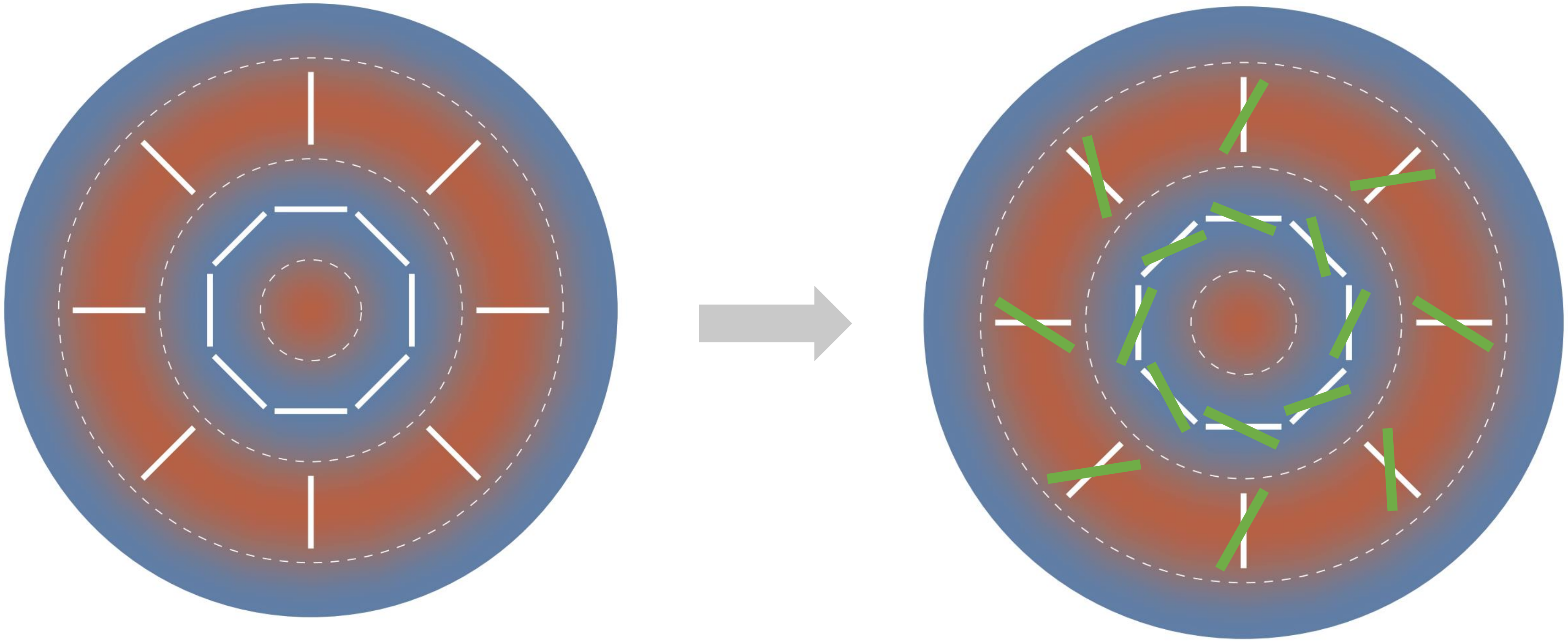


Polarization of CMB



E-mode
Parity *Even*

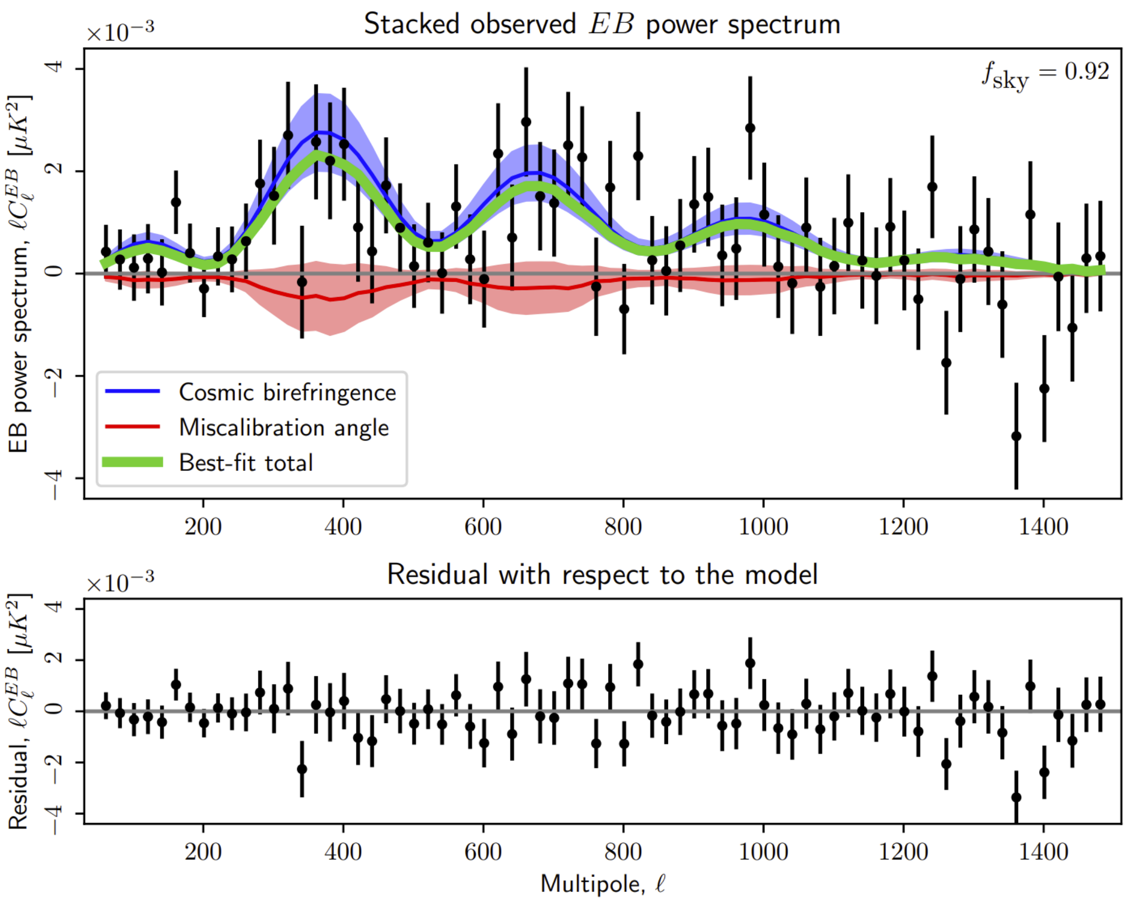
Polarization of CMB



E-mode
Parity *Even*

E-mode + B-mode

Cosmic Birefringence



[Eskilt, Komatsu 2205.13962]

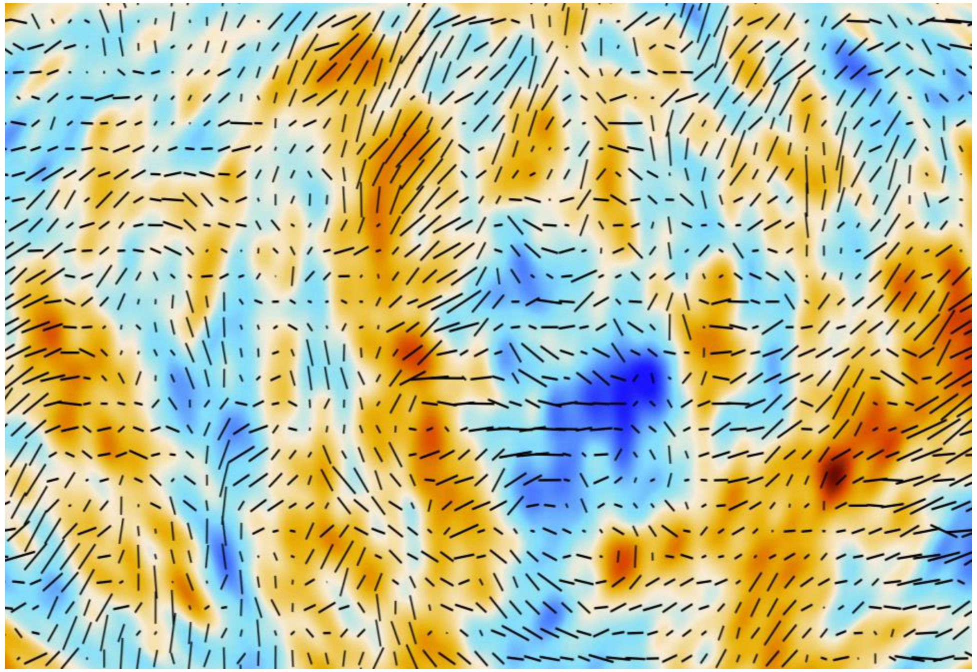
Isotropic Birefringence

$$\beta = 0.342^\circ\,{}^{+0.094^\circ}_{-0.091^\circ}$$

A hint for parity violation in our universe?

What if: Birefringent “Dark” Photon?

CMB and Dark CMB



CMB at Visible Universe

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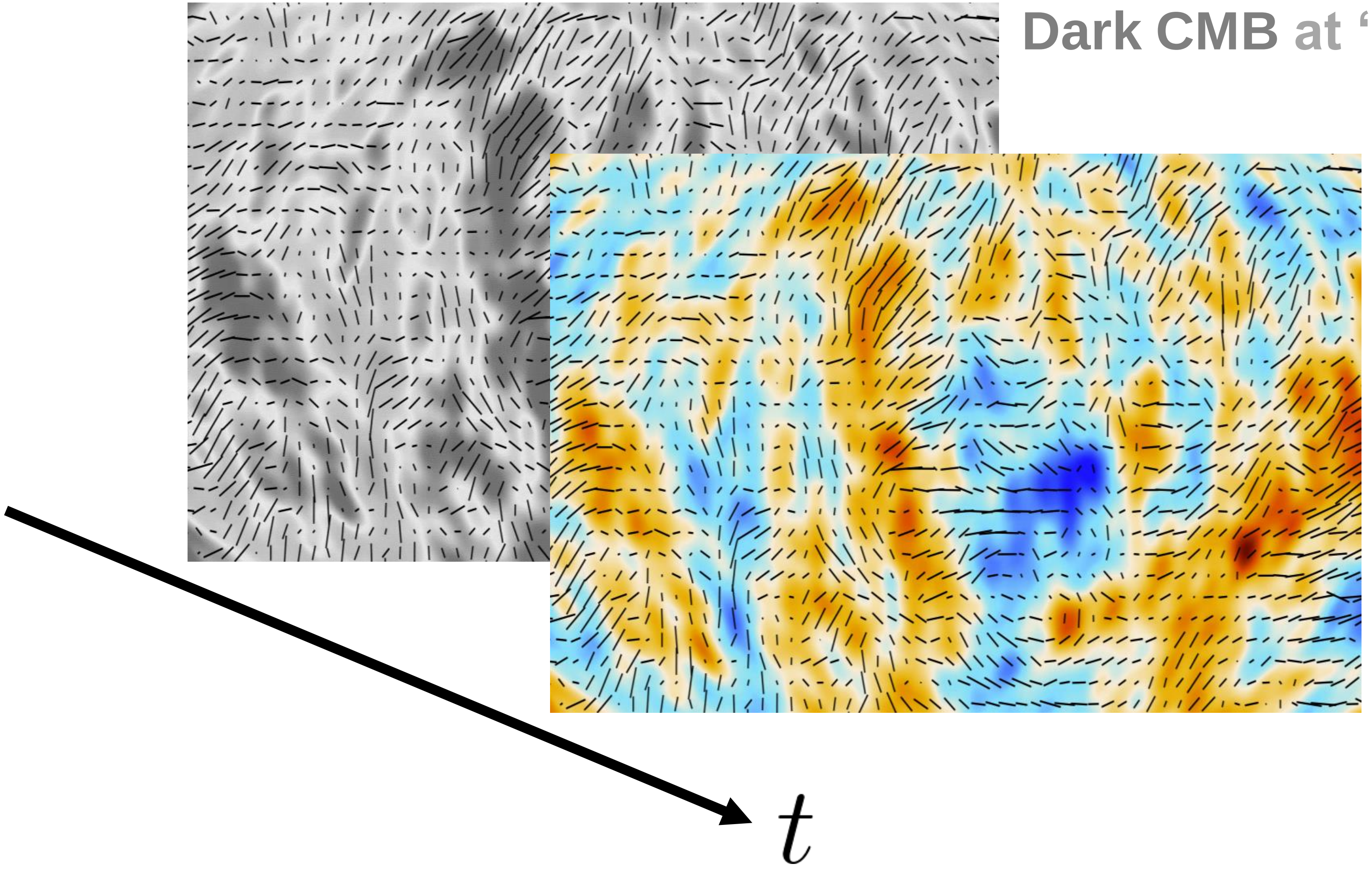
CMB and Dark CMB



Dark CMB at 'Dark Universe'

CMB at Visible Universe

Key Question

Axion

$aF\tilde{F}$ →

Photon (CMB)

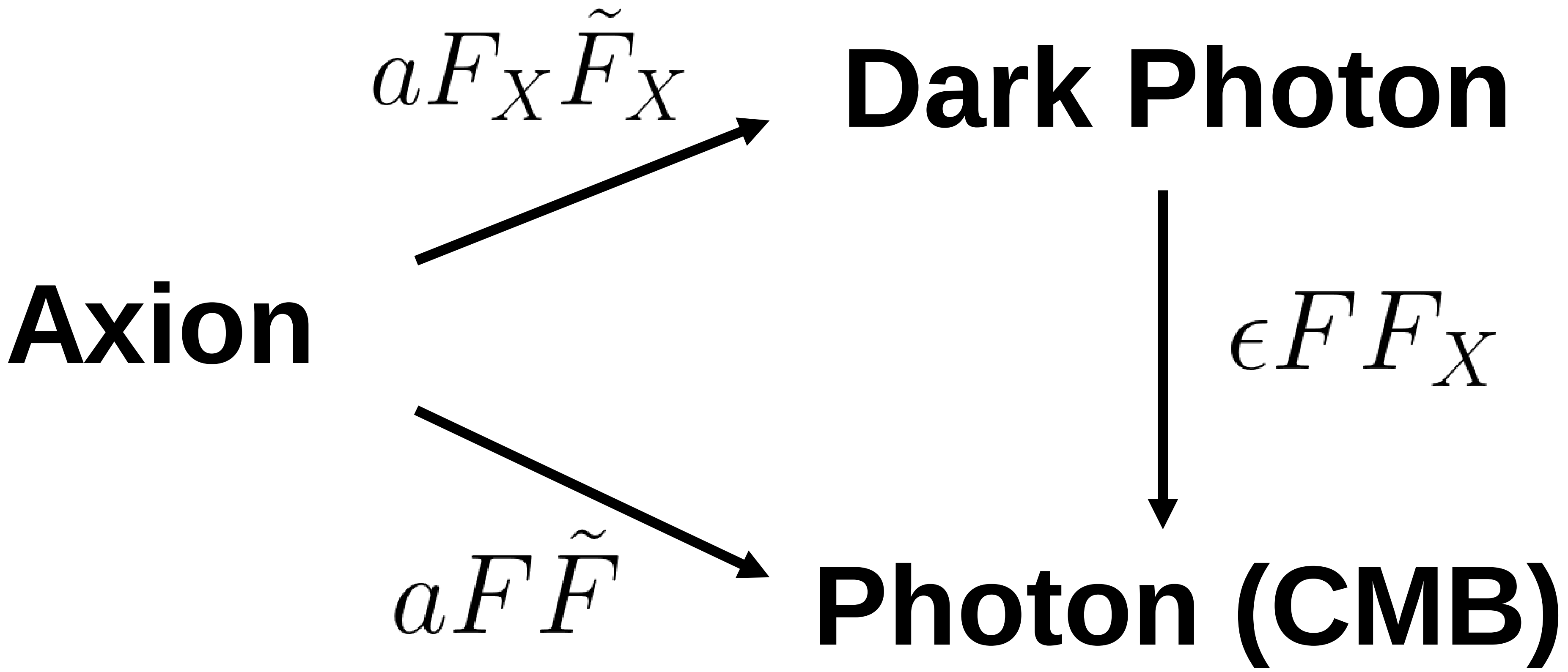
Key Question

$aF_X\tilde{F}_X$ → **Dark Photon**

Axion

$aF\tilde{F}$ → **Photon (CMB)**

Key Question



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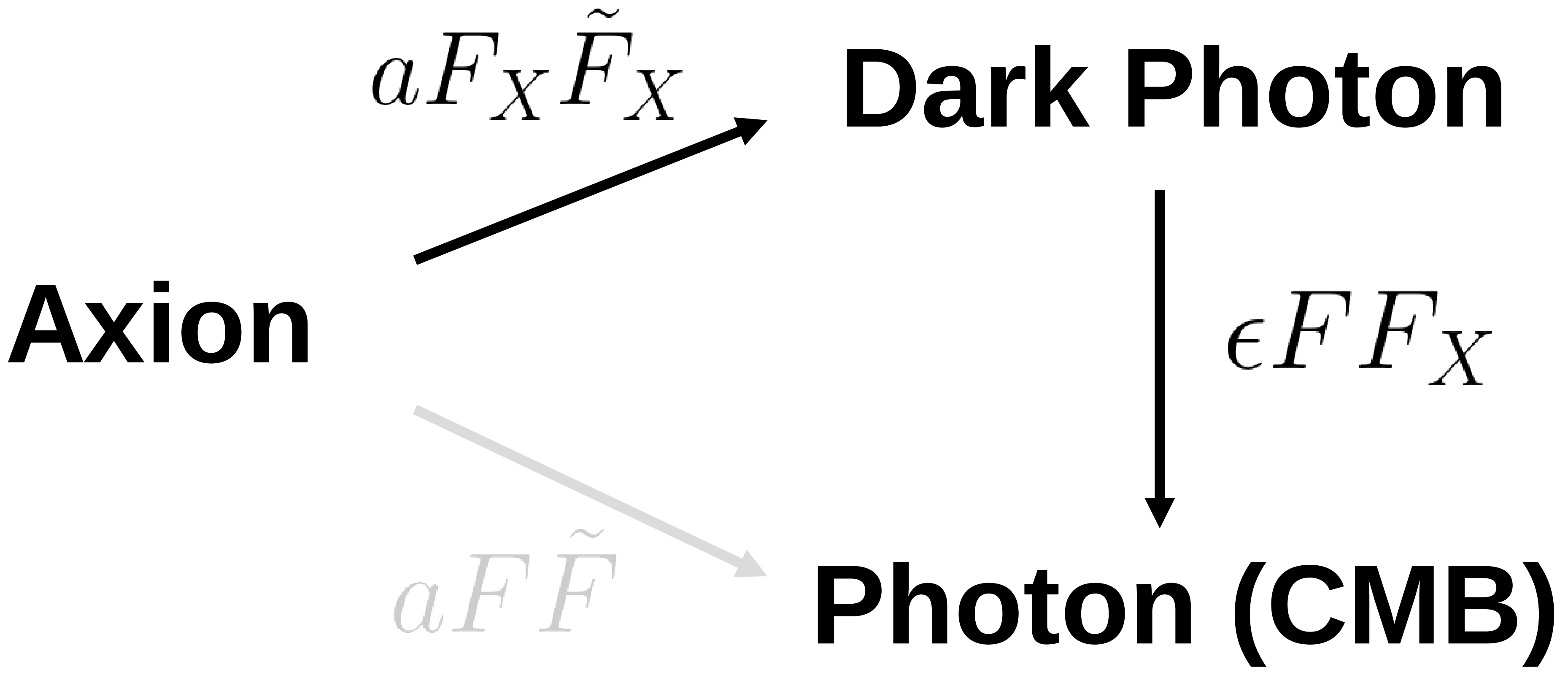

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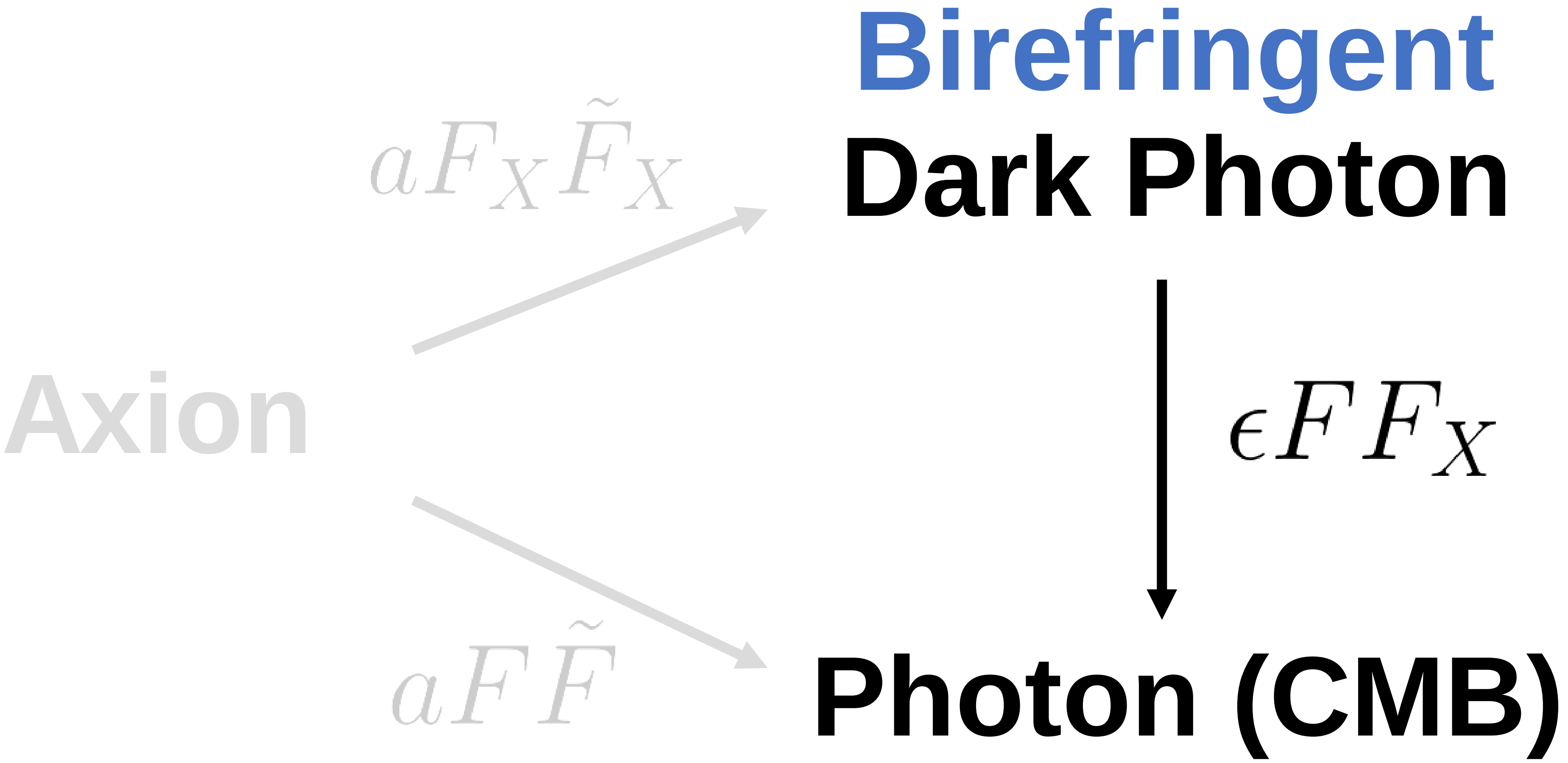

Massless Dark Photon & Kinetic Mixing

$$\frac{\mathcal{L}_{\rm kin}}{\sqrt{-g}} = -\frac{1}{4}\hat{F}^{\mu\nu}\hat{F}_{\mu\nu} - \frac{1}{4}\hat{F}_X^{\mu\nu}\hat{F}_{X\mu\nu} - \frac{\varepsilon}{2}\hat{F}_{\mu\nu}\hat{F}_X^{\mu\nu}$$

Massless Dark Photon & Kinetic Mixing

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Diagonalization

$$\begin{pmatrix} \hat{A} \\ \hat{A}_X \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\varepsilon & 1 \end{pmatrix} \begin{pmatrix} A \\ A_X \end{pmatrix}$$

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Interaction terms

$$\frac{\mathcal{L}_{\rm int}}{\sqrt{-g}} \supset e j_\mu \hat{A}^\mu + e_X j_{X\mu} \hat{A}_X^\mu$$

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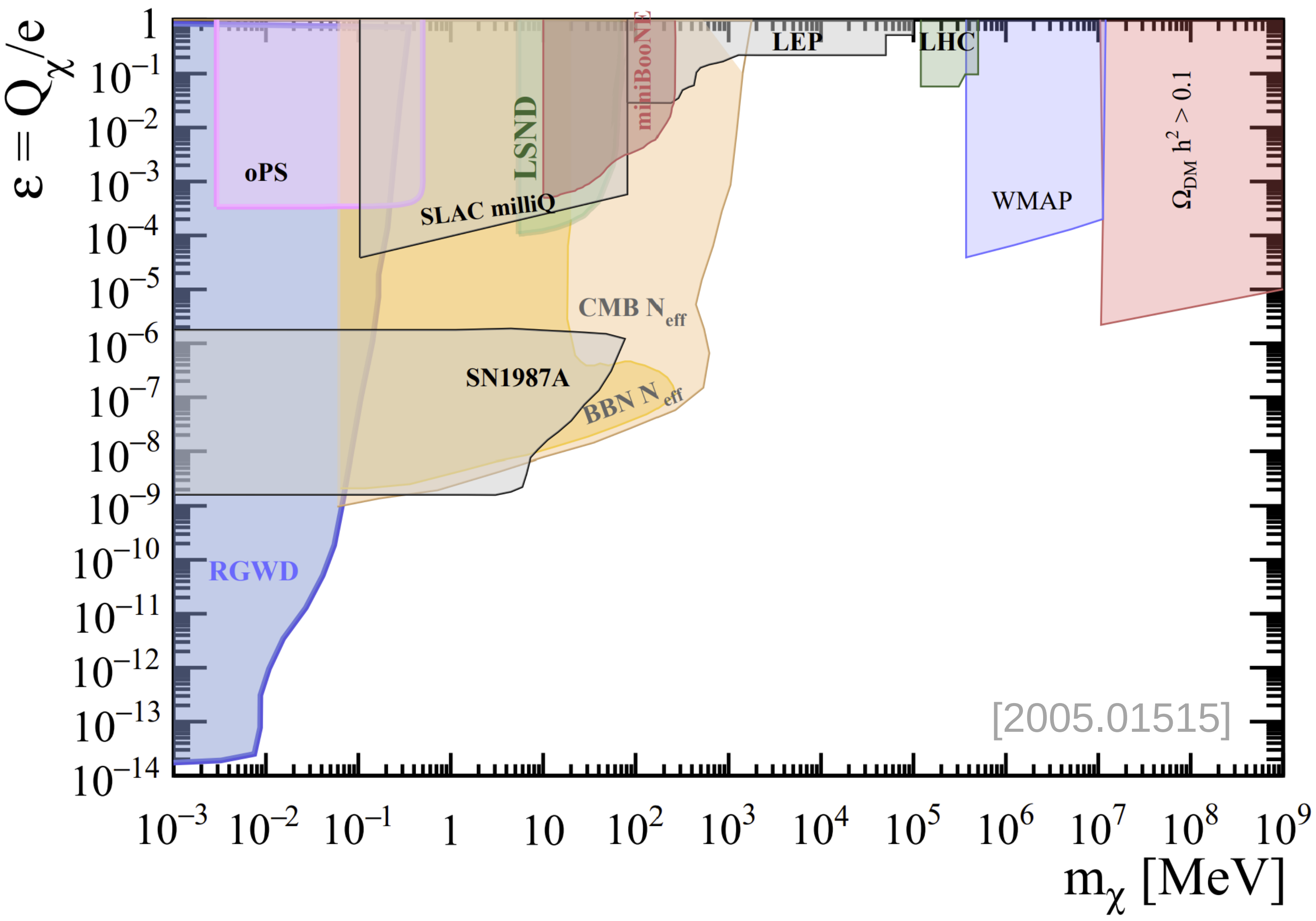
$$\frac{\mathcal{L}_{\rm int}}{\sqrt{-g}} \supset e j_\mu \hat{A}^\mu + e_X j_{X\mu}\hat{A}_X^\mu \qquad \epsilon \equiv -\varepsilon\frac{e_X}{e}$$

$$\approx (e j_\mu - \varepsilon e_X j_{X\mu})\, A^\mu + e_X j_{X\mu} A_X^\mu$$

milli-charged particle

Constraints on ϵ : milli-charged particle



Modified Maxwell Equations

$$\nabla_\mu F^{\mu\nu} = j^\nu + \epsilon j_X^\mu$$

$$\nabla_\mu F_X^{\mu\nu} = j_X^\nu$$

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$\tilde{A}^\mu \equiv A^\mu - \epsilon A_X^\mu$ ***freely propagates in SM vacuum*** $j^\nu = 0$

Theory of Polarization

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Decomposition $$\boldsymbol{E} = \boldsymbol{E}^{(p)} + \boldsymbol{E}^{(n)}$$

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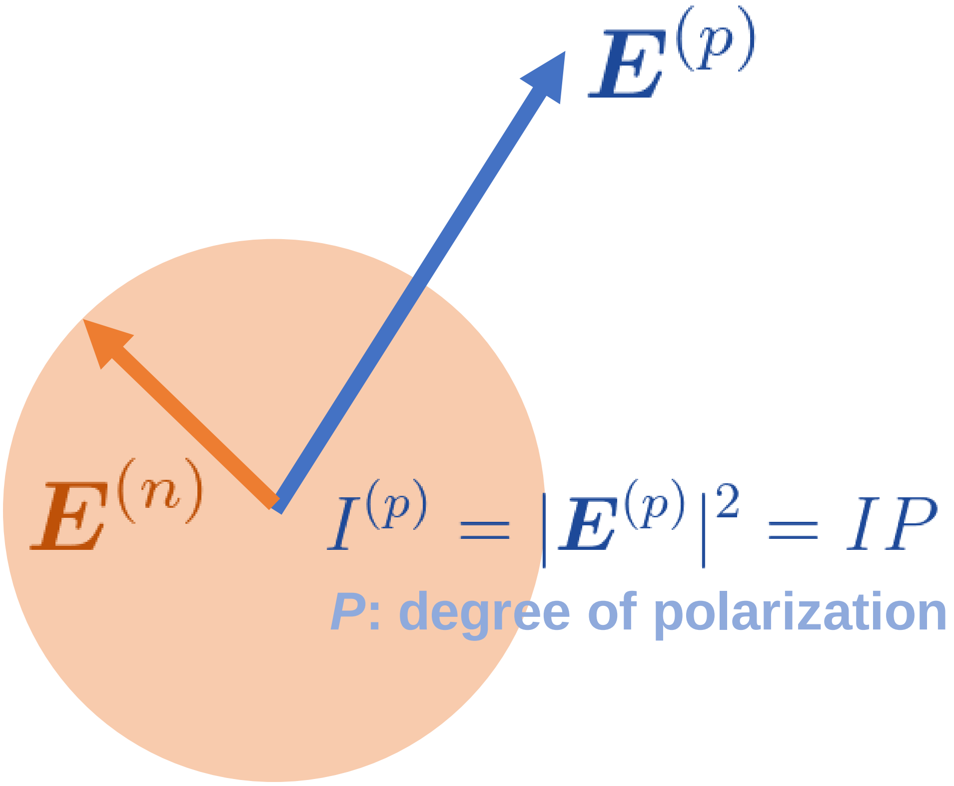


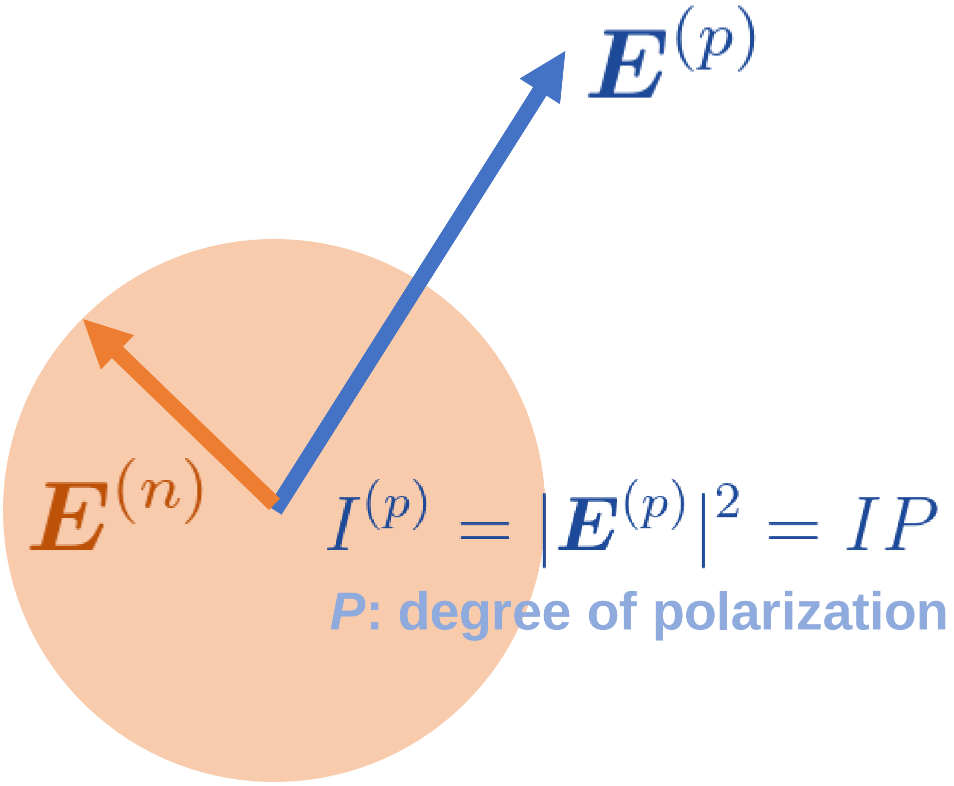
Theory of Polarization

Decomposition $\boldsymbol{E} = \boldsymbol{E}^{(p)} + \boldsymbol{E}^{(n)}$

Jones Matrix

$$J_{\alpha\beta} \equiv \langle E_\alpha E_\beta^* \rangle_T = E_\alpha^{(p)} E_\beta^{(p)*} + \frac{1}{2} I^{(n)} \delta_{\alpha\beta}$$

$$\left\langle E_\alpha^{(n)} E_\beta^{(n)*} \right\rangle_T$$



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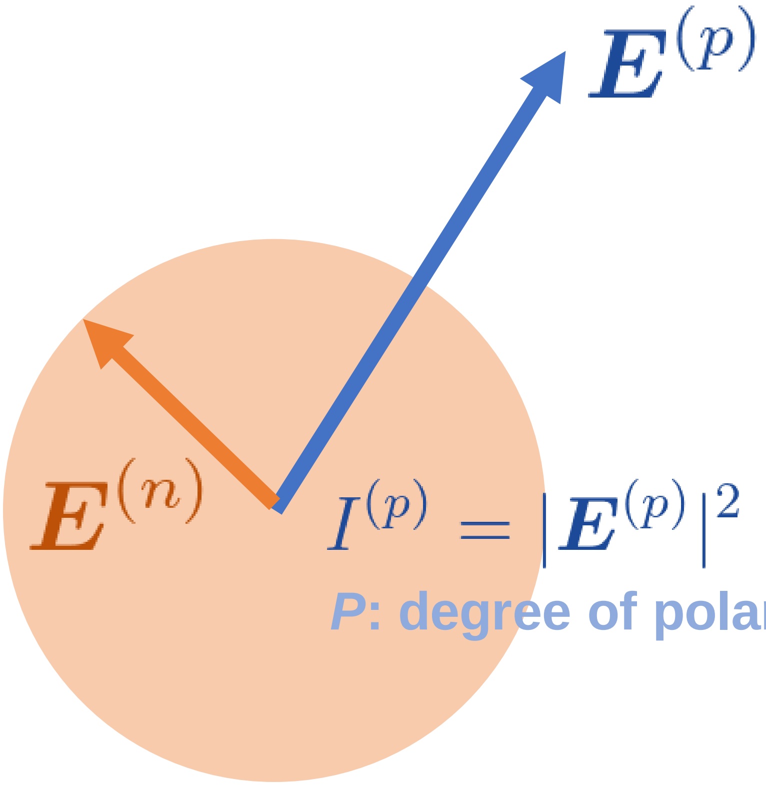
Intensity $I \equiv \mathrm{Tr}\, J$

Polarization Tensor $\rho_{\alpha\beta} = J_{\alpha\beta}/I$



$I^{(p)} = |\boldsymbol{E}^{(p)}|^2 = IP$

P: degree of polarization

Stokes Parameters

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

Stokes Parameters

Birefringence angle $\beta = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$

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

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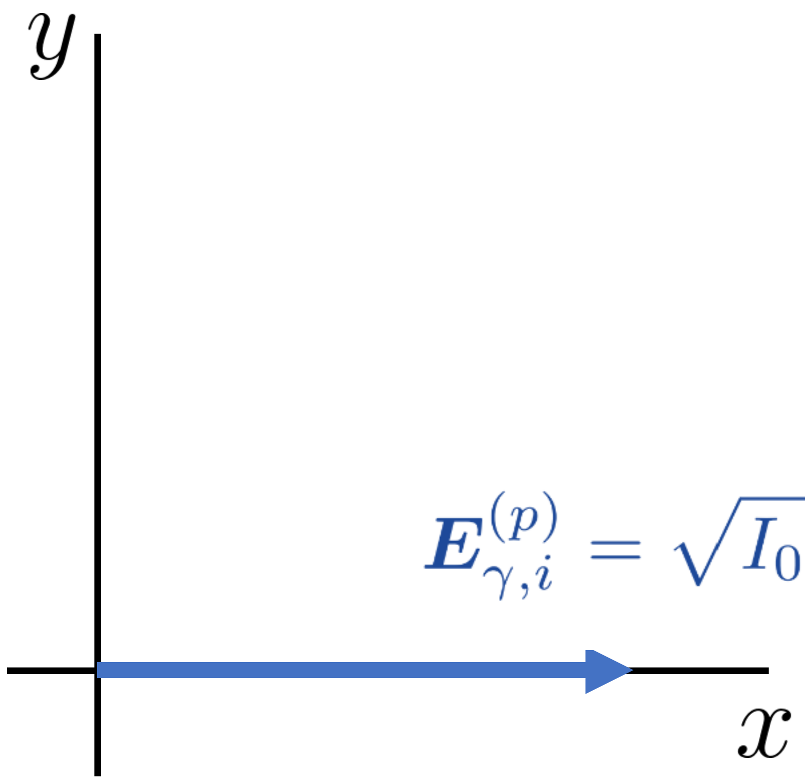
Circular polarization

‘Birefringent’ Dark Photon

Initial Setup and Birefringent DP

[**SML**, DW Kang, J-O Gong, D Jeong, D-W Jung, SC Park, 2307.14798]



$$\boldsymbol{E}_{\gamma,i}^{(p)} = \sqrt{I_0 P}\begin{pmatrix}1\\0\end{pmatrix}$$

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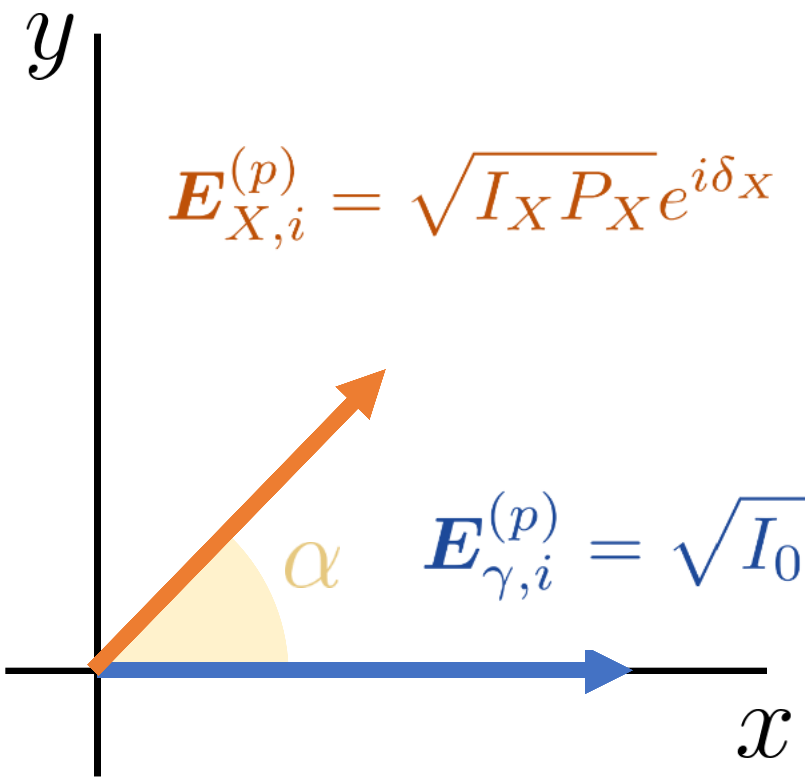
[**SML**, DW Kang, J-O Gong, D Jeong, D-W Jung, SC Park, 2307.14798]



$$\boldsymbol{E}^{(p)}_{X,i} = \sqrt{I_X P_X} e^{i\delta_X} \begin{pmatrix} \cos\alpha \\ \sin\alpha \end{pmatrix}$$

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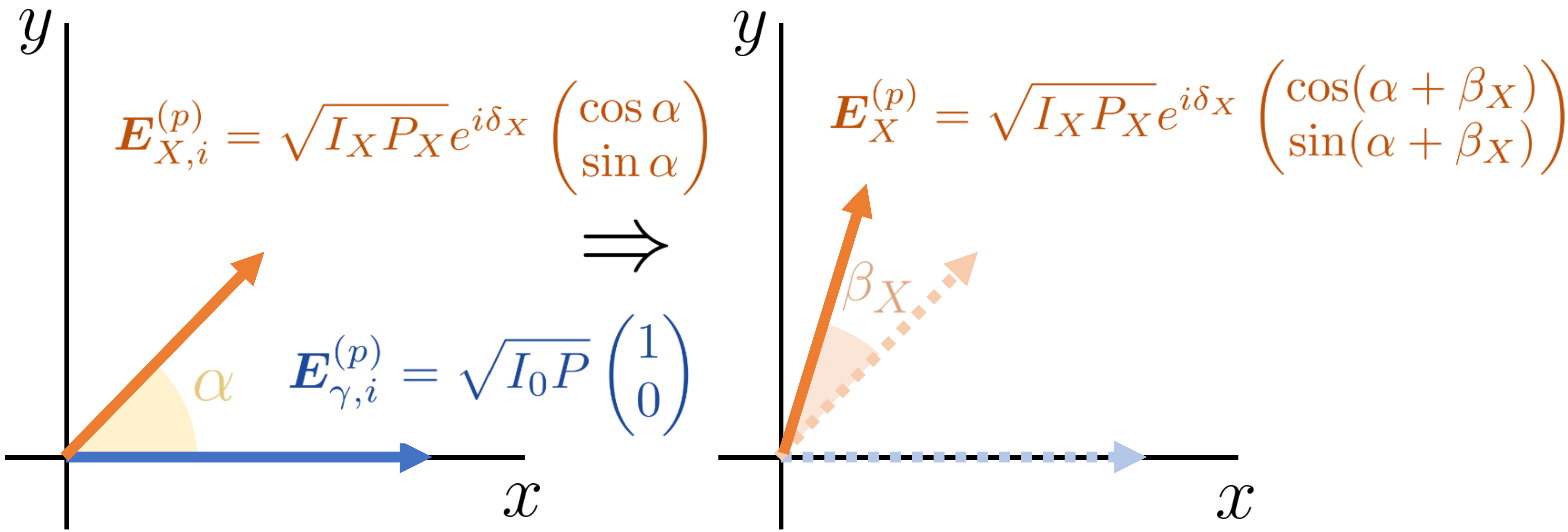
Initial Setup and Birefringent DP

[**SML**, DW Kang, J-O Gong, D Jeong, D-W Jung, SC Park, 2307.14798]



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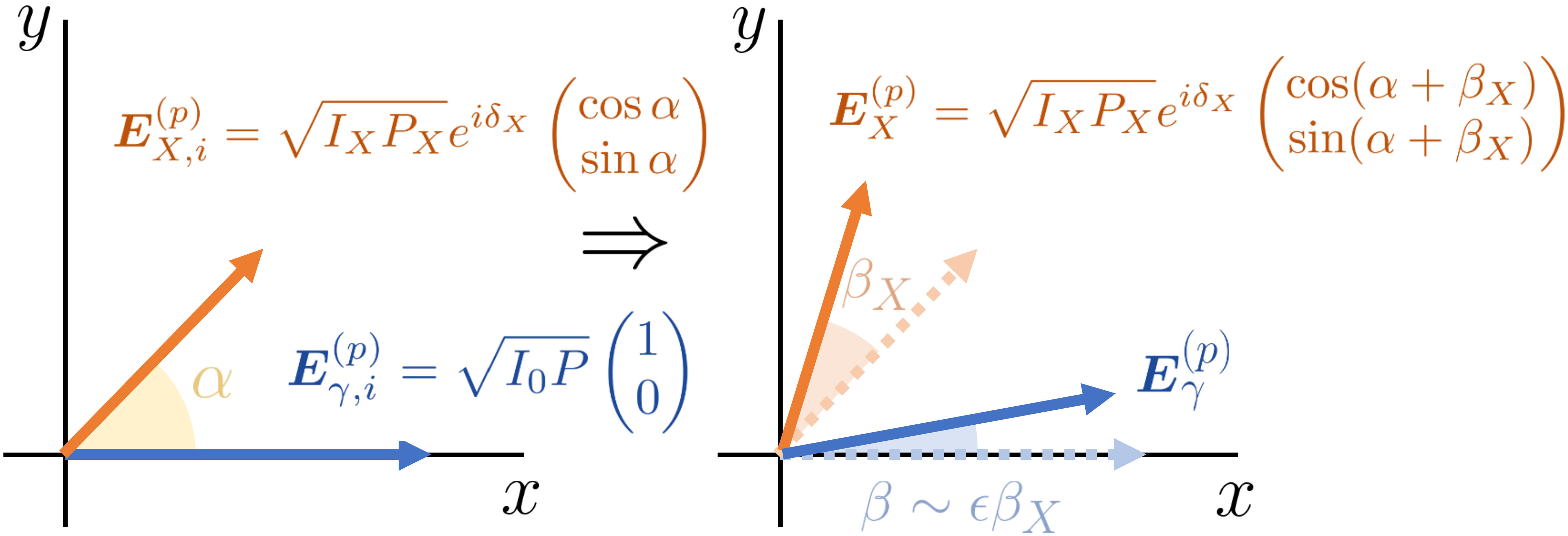

Birefringent Dark Photon

$$\boldsymbol{E}_X^{(p)} = \sqrt{I_X P_X} e^{i\delta_X} \begin{pmatrix} \cos(\alpha + \beta_X) \\ \sin(\alpha + \beta_X) \end{pmatrix}$$

$$\rho_X = \frac{1}{2} \begin{pmatrix} 1 + P_X \cos(2\alpha_X + 2\beta_X) & P_X \sin(2\alpha_X + 2\beta_X) \\ P_X \sin(2\alpha_X + 2\beta_X) & 1 - P_X \cos(2\alpha_X + 2\beta_X) \end{pmatrix}$$

- **Birefringence ($U \neq 0$)** $\beta_{X,\mathrm{tot}} = \frac{1}{2} \arctan\left(\frac{U_X}{Q_X}\right) = \alpha + \beta_X$
- ***No* circular polarization ($V = 0$)**
- ***No* Intensity change**

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- ***No* circular polarization *($V = 0$)***
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**** This is what happens with axion***

Effects on Photon & Implications

Jones Matrix of SM Photon

Observation: $\tilde{A}^\mu \equiv A^\mu - \epsilon A_X^\mu$ **freely propagates**

$\Rightarrow$ $\tilde{J}_{\alpha\beta} \equiv \left\langle \tilde{E}_\alpha \tilde{E}_\beta^* \right\rangle_T$ **is time-independent**

$$\tilde{J} \equiv \langle \tilde{E}\tilde{E}^* \rangle = \langle (E - \epsilon E_X)(E - \epsilon E_X)^* \rangle$$
$$= \langle EE^* \rangle + \epsilon \langle EE_X^* + E_X E^* \rangle + \mathcal{O}(\epsilon^2)$$

$$J(t) \equiv \langle EE^* \rangle_t = \langle EE^* \rangle_{t=0} + \epsilon \langle EE_X^* + E_X E^* \rangle |_{t=0}^{t}$$

Jones Matrix of SM Photon

$$J = J_0 + \epsilon\sqrt{I_0 I_X}\sqrt{PP_X}\begin{pmatrix} -4\cos\delta_X \sin\left(\alpha + \frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & 2e^{-i\delta_X}\cos\left(\alpha + \frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) \\ 2e^{i\delta_X}\cos\left(\alpha + \frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) & 0 \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

[**SML**, DW Kang, J-O Gong, D Jeong, D-W Jung, SC Park, 2307.14798]

- **This result is *independent* of the specific form of $\boldsymbol{\beta_X(t)}$**
- **Intensity changes (spectral distortion)**

$$\Delta I = I - I_0 = -4\epsilon\sqrt{I_0 I_X PP_X}\cos\delta_X \sin\left(\alpha + \frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right) + \mathcal{O}(\epsilon^2)$$

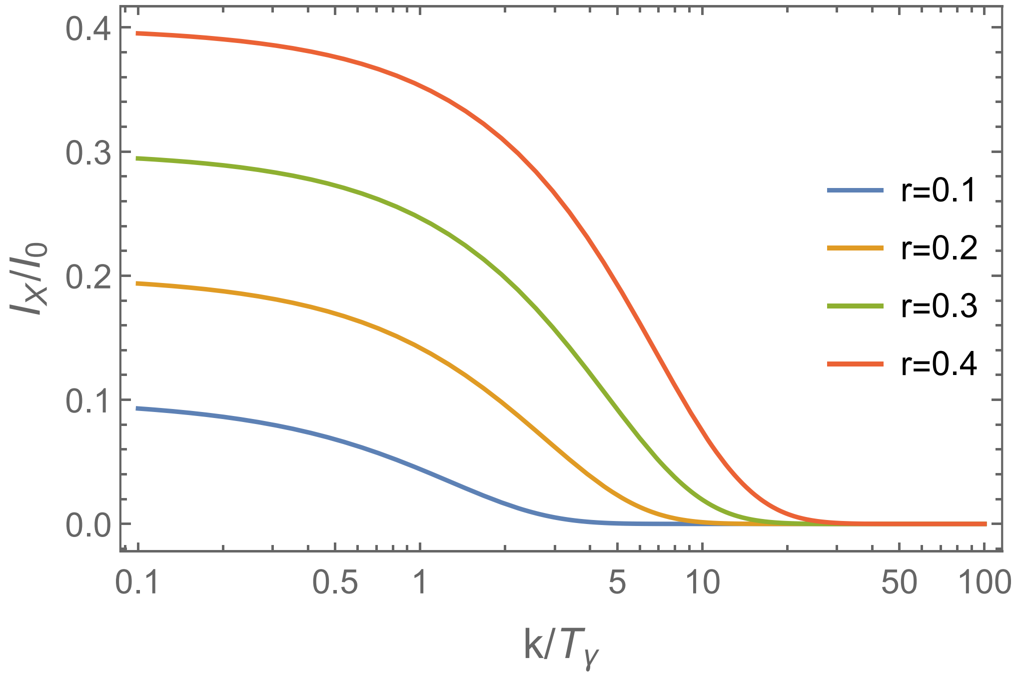
Spectral Distortion

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

For blackbody,

$$I \propto \frac{k^3}{\exp(k/2\pi T) - 1}$$

$$r \equiv \frac{T_X}{T_\gamma} \lesssim 0.4$$ from ΔN_{eff}



Characteristic frequency dependence (suppression at large k)

Polarization of SM Photon

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

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- ***Birefringence*** **($U \neq 0$)**

$$\beta(\hat{\boldsymbol{n}}) \simeq 2\epsilon\sqrt{\frac{I_X P_X}{I_0 P}}\cos\delta_X \cos\left(\alpha+\frac{\beta_X}{2}\right)\sin\left(\frac{\beta_X}{2}\right)$$

Polarization of SM Photon

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

[**SML**, DW Kang, J-O Gong, D Jeong, D-W Jung, SC Park, 2307.14798]

- ***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 $\boldsymbol{O(\epsilon)}$** $\langle\beta\rangle = 0$
  - **Non-zero variance** $\langle\beta^2\rangle = \epsilon^2\frac{I_X}{I_0}\left\langle\frac{P_X}{P}\right\rangle\sin^2\left(\frac{\beta_X}{2}\right)$

Polarization of SM Photon

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

[**SML**, DW Kang, J-O Gong, D Jeong, D-W Jung, SC Park, 2307.14798]

- ***Birefringence*** **$(U \neq 0)$**

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  - **No isotropic birefringence at $O(\epsilon)$** $\langle\beta\rangle = 0$
  - **Non-zero variance** $\langle\beta^2\rangle = \epsilon^2\frac{I_X}{I_0}\left\langle\frac{P_X}{P}\right\rangle\sin^2\left(\frac{\beta_X}{2}\right) \lesssim (1^\circ)^2$

[1603.08193]

Polarization of SM Photon

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

[**SML**, DW Kang, J-O Gong, D Jeong, D-W Jung, SC Park, 2307.14798]

- ***Circular Polarization*** $(V \neq 0)$

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

Polarization of SM Photon

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

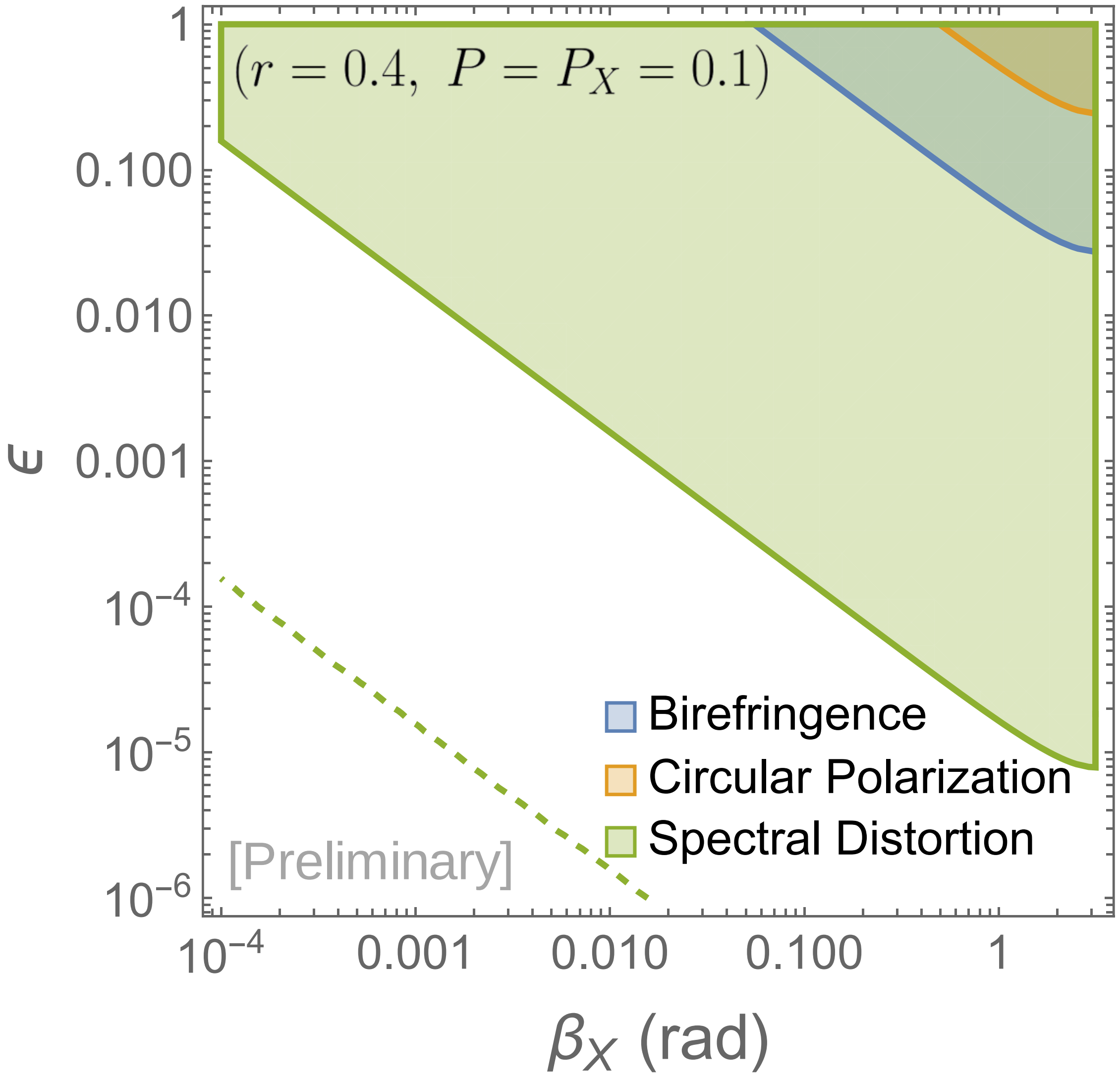
[**SML**, DW Kang, J-O Gong, D Jeong, D-W Jung, SC Park, 2307.14798]

- ***Circular Polarization*** $(V \neq 0)$

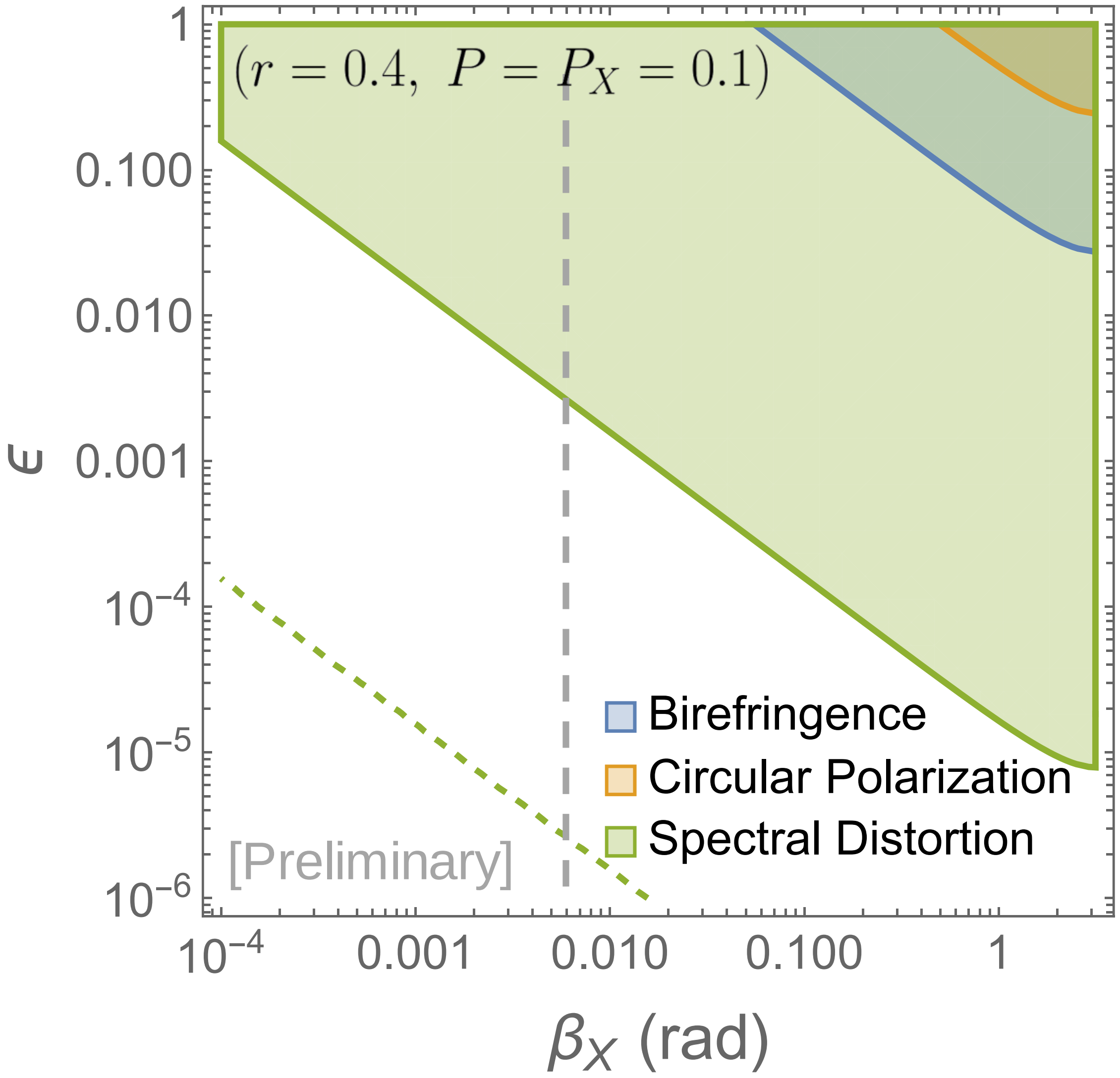
$$\langle V^2\rangle \simeq 4\epsilon^2 I_0 I_X \bar{P}\bar{P}_X \sin^2\left(\frac{\beta_X}{2}\right) \lesssim (10\mu\mathrm{K})^2$$

[1704.00215]

Possible Implication



Possible Implication



Conclusion

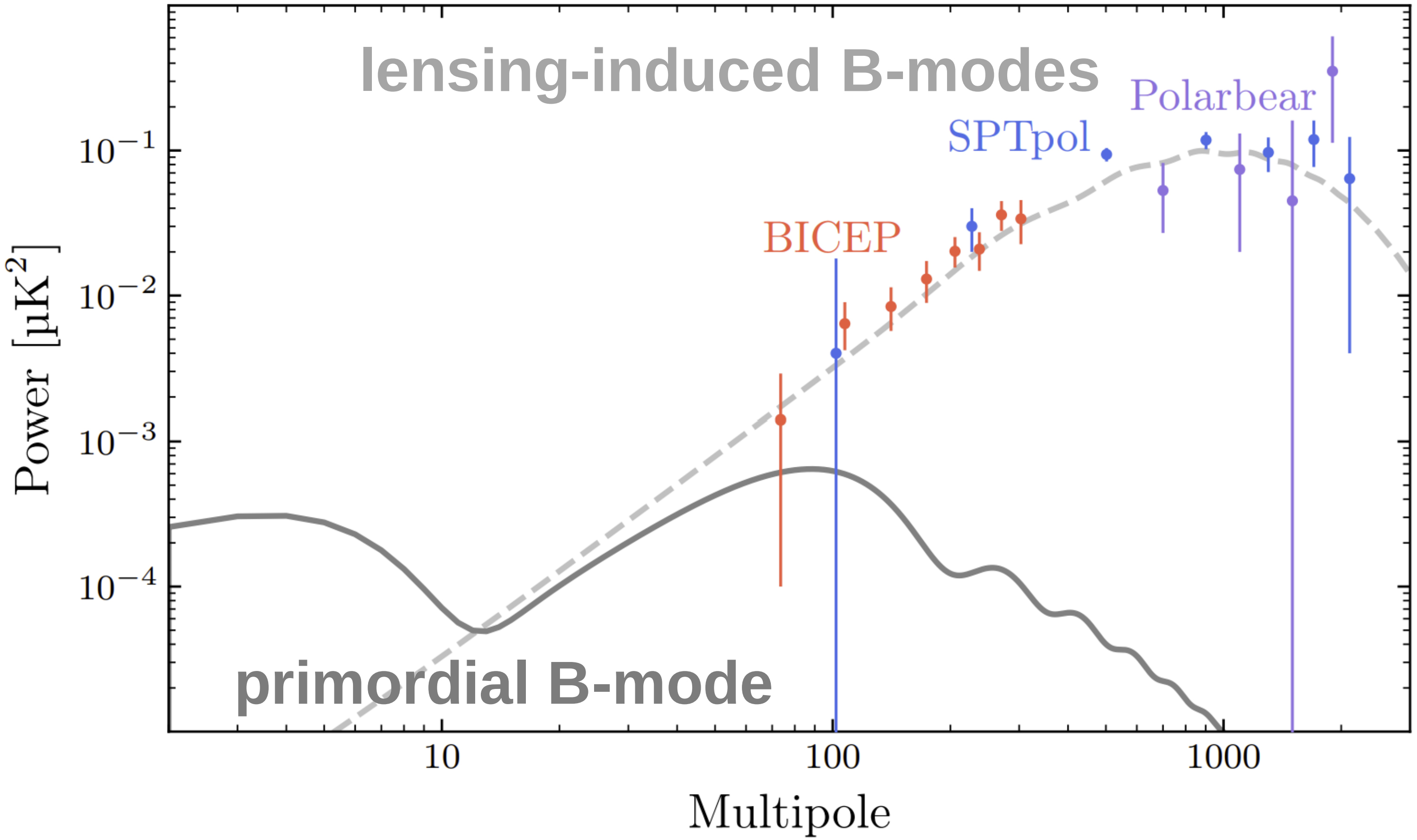
- **There have been some signals of *parity violation in cosmology*.**
  - **e.g. cosmic birefringence, galactic 4-point function, etc.**

- **This may signal the existence of parity violation in the *dark sector*.**

- **We constructed the *polarization tensor of two massless photons* and explored the *observational consequences* in CMB.**
  - **Spectral Distortion**
  - **Birefringence**
  - **Circular Polarization**

Back-ups

B-mode Polarization



EB Correlation

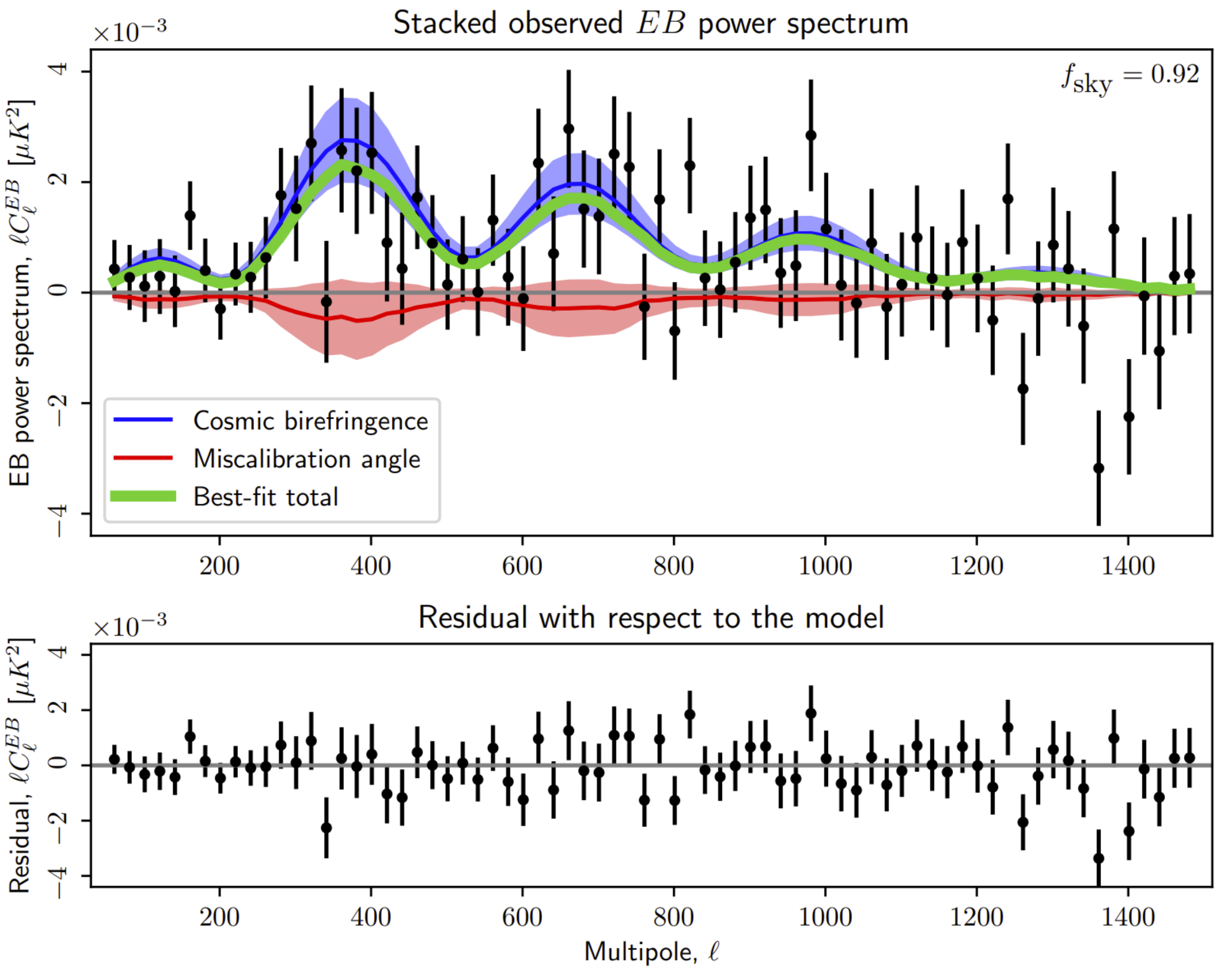
$$Q(\hat{n}) \pm iU(\hat{n}) = -\sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell}(E_{\ell m} \pm iB_{\ell m})\,{}_{\pm 2}Y_\ell^m(\hat{n})$$

$$Q^{\rm o} \pm iU^{\rm o} = (Q \pm iU)e^{\pm 2i\beta}$$

$$E^{\rm o}_{\ell m} = E_{\ell m}\cos(2\beta) - B_{\ell m}\sin(2\beta)$$
$$B^{\rm o}_{\ell m} = E_{\ell m}\sin(2\beta) + B_{\ell m}\cos(2\beta)$$

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

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



[Eskilt, Komatsu 2205.13962]

Pictorial Understanding