Probing time-dependent cosmic birefringence with LiteBIRD

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(working with people in IPMU CMB group (Baptiste, Marta, Ryosuke, Tomo, Yuji, …))

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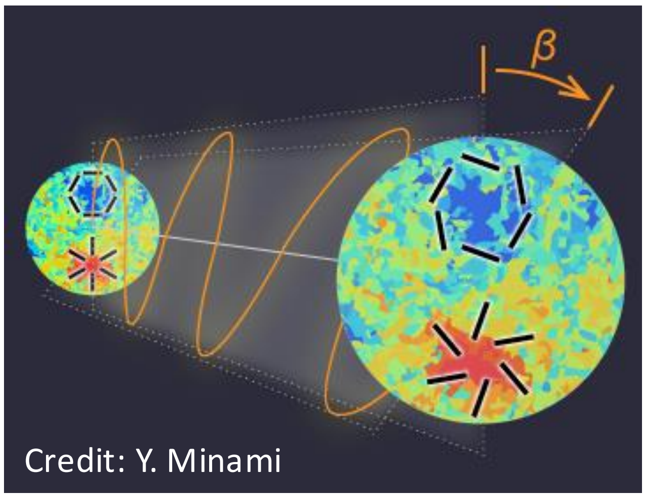
2026.7.3 @ Challenges at the CMB Frontier (Chino, Nagano)

Isotropic polarization rotation in CMB

Lue, Wang & Kamionkowski (1999); Feng+ (2005,2006); Liu, Lee & Ng (2006); …



Credit: Y. Minami

- Parity-violating interactions

$$\mathcal{L}_{\rm int} \supset \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

convert E- and B-mode polarization as

$$\begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix}^{\rm obs} = \begin{pmatrix} \cos(2\beta) & -\sin(2\beta) \\ \sin(2\beta) & \cos(2\beta) \end{pmatrix} \begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix}^{\rm CMB}$$

↑ observed ↑ intrinsic

- It produces a **parity-odd EB correlation**

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

↑assuming 0

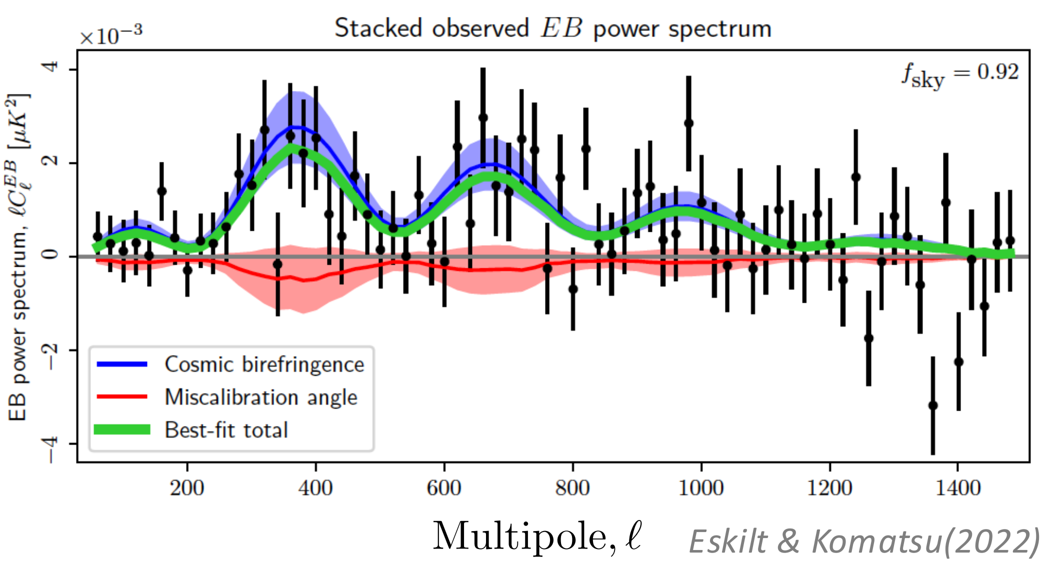
(note: β is assumed to be constant)

Measurements of cosmic birefringence

- Nonzero isotropic cosmic birefringence (ICB) angle was reported by *Planck* data:

PR3: $\beta = 0.35 \pm 0.14 \text{ deg}$ ***Minami, Komatsu (2020);***

PR4: $\beta = 0.30 \pm 0.11 \text{ deg}$ ***Diego-Palazuelos+ (2022);***



Eskilt & Komatsu(2022)

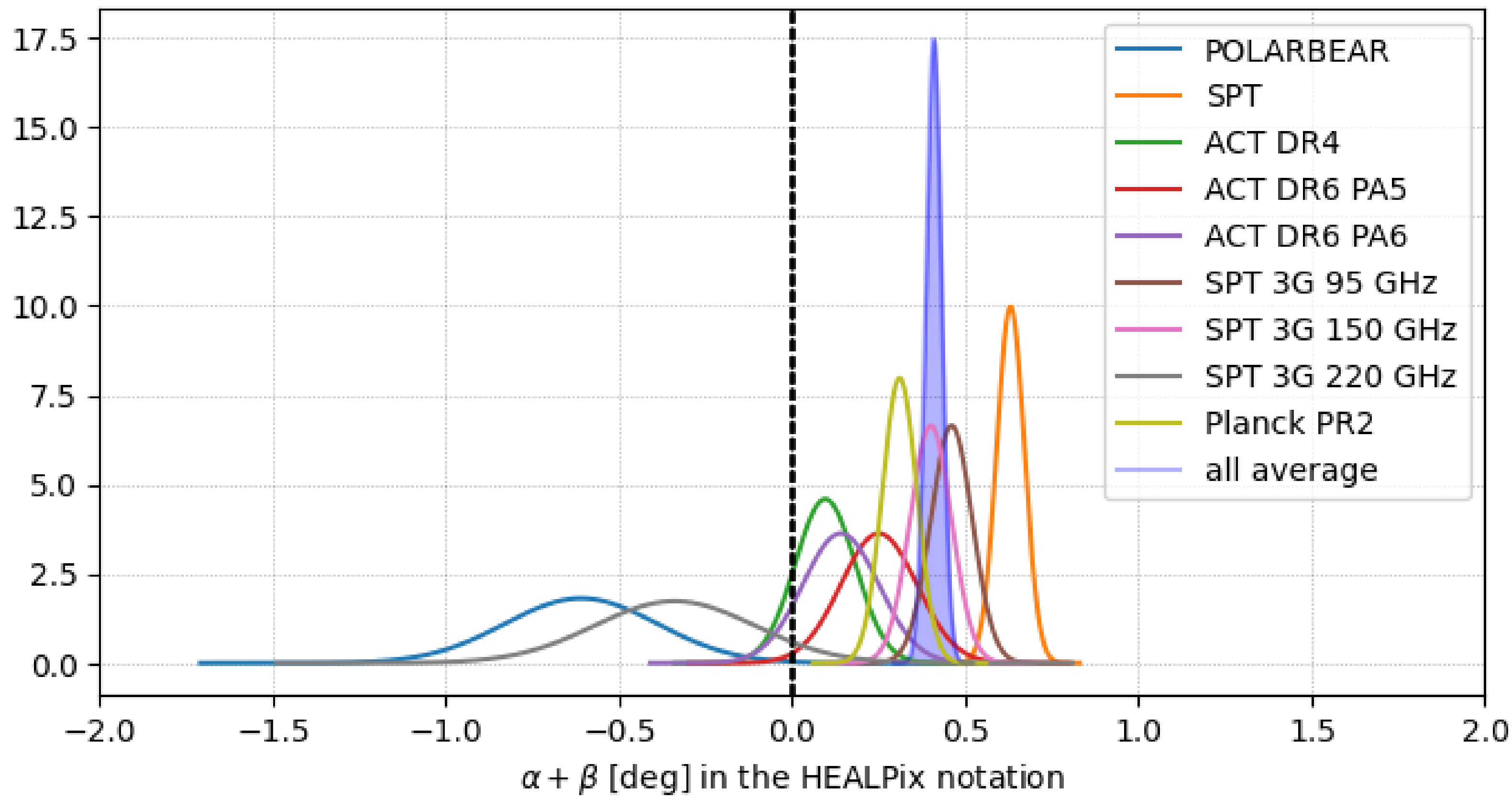
- *Planck/WMAP* joint analysis*:*

Eskilt & Komatsu (2022);

$$\boxed{\beta = 0.34 \pm 0.09 \text{ deg } (3.6\sigma)}$$

Other recent measurements overview

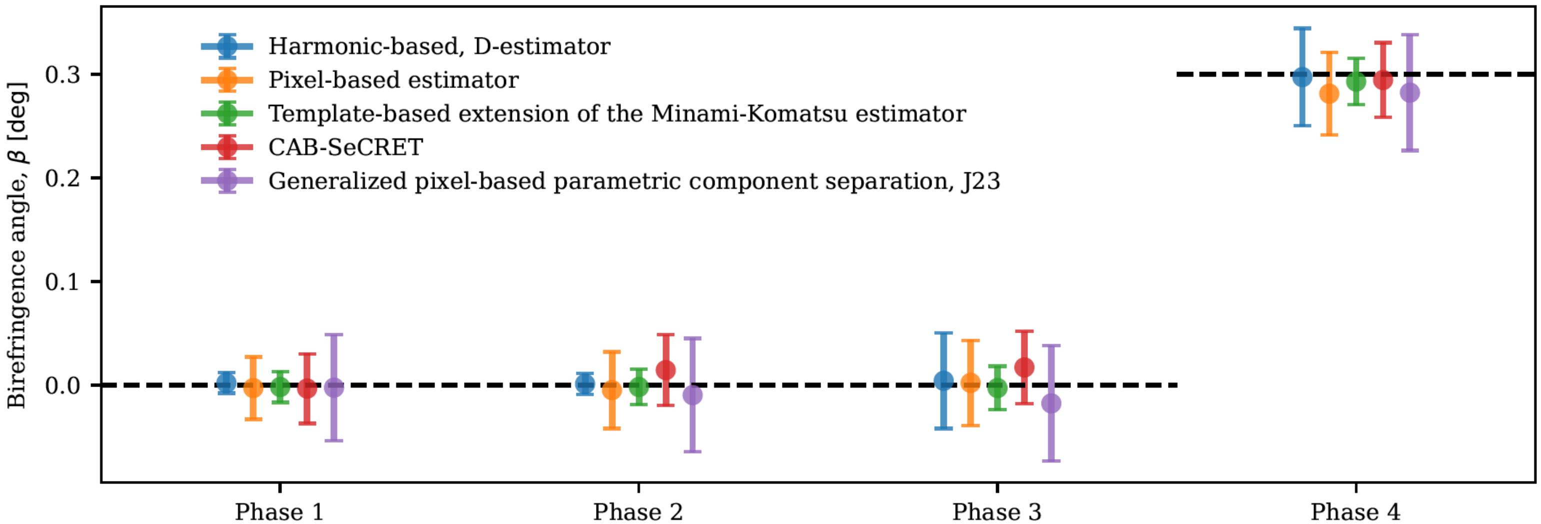
Credit: Fumihiro Naokawa



※ the calibration method as in Planck PR3, PR4 & WMAP is not used in these measurements

Future forecast with LiteBIRD

de la Hoz, Diego-Parazuelos, Errard, Gruppuso, Jost, Sullivan, Bortolami, Chinone, Hergt, Komatsu, Minami, IO, Paoletti, Scott, Vielva+ (2025)



Pipeline	Phase 1 β [$\times 10^{-2}$ deg]	Phase 2 β [$\times 10^{-2}$ deg]	Phase 3 β [$\times 10^{-2}$ deg]	Phase 4 β [$\times 10^{-2}$ deg]
D-estimator	0.2 ± 1.0	0.1 ± 1.0	0.4 ± 4.6	29.7 ± 4.7
Pixel-based estimator	-0.3 ± 3.0	-0.5 ± 3.7	0.2 ± 4.1	28.1 ± 4.0
Template-based MK	-0.2 ± 1.5	-0.2 ± 1.7	-0.3 ± 2.1	29.3 ± 2.2
CAB-SeCRET	-0.4 ± 3.4	1.4 ± 3.4	1.7 ± 3.5	29.4 ± 3.6
J23	-0.2 ± 5.1	-1.0 ± 5.5	-1.8 ± 5.6	28.2 ± 5.6

Implications for axion cosmology

(axion-like particle)

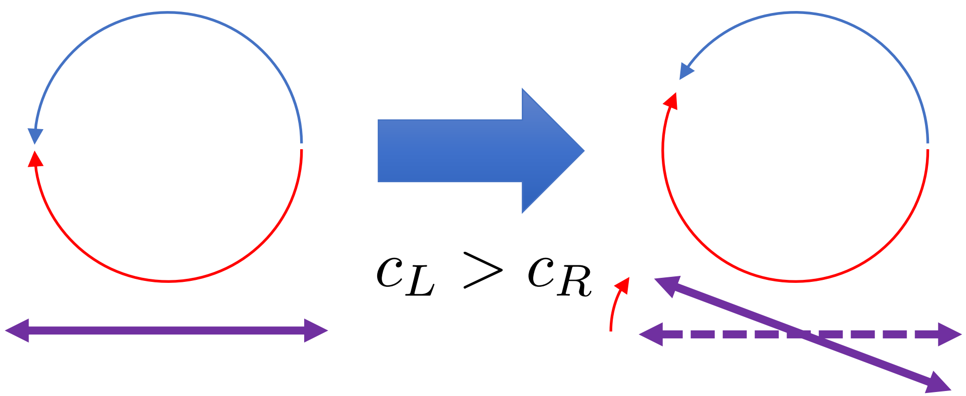
Cosmic birefringence by axion (ALP)

Harari & Sikivie (1992); Carroll (1998); …

$$\mathcal{L} \supset \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Dispersion relation of left- and right-handed polarization is modified:

$$\ddot{A}_k^{\mathrm{L/R}} + \omega_{\mathrm{L/R}}^2 A_k^{\mathrm{L/R}} = 0, \quad c_{\mathrm{L/R}} \equiv \frac{\omega_{\mathrm{L/R}}}{k} = \sqrt{1 \pm \underline{\frac{g_{\phi\gamma}\dot{\phi}}{k}}}$$



→ leading to the rotation of linear-polarization direction

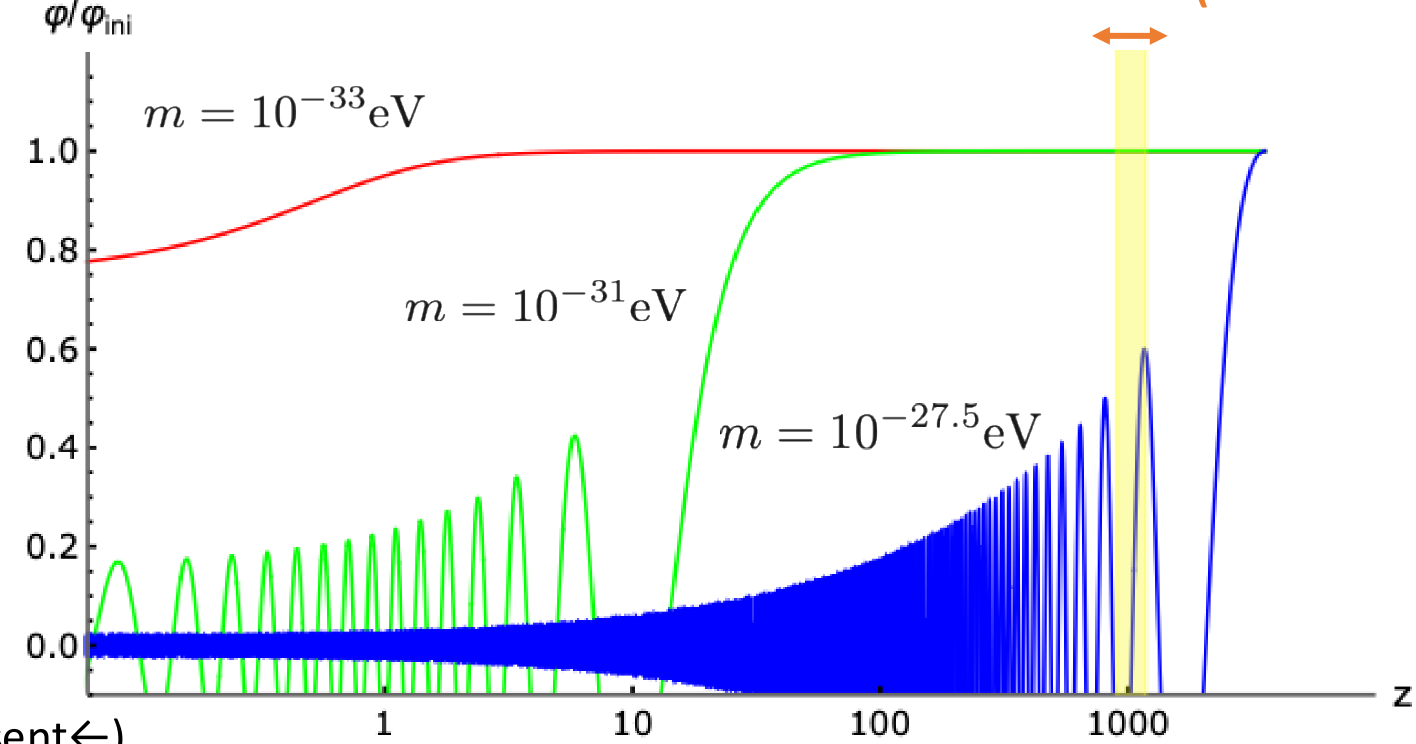
- Rotation angle is given by the integration of phase velocity difference

$$\beta = \frac{1}{2}\int_{t_{\mathrm{emit}}}^{t_{\mathrm{obs}}} dt(\omega_L - \omega_R) = \frac{g_{\phi\gamma}}{2}\int_{t_{\mathrm{emit}}}^{t_{\mathrm{obs}}} dt\dot{\phi} = \frac{g_{\phi\gamma}}{2}\underline{[\phi(t_{\mathrm{obs}}) - \phi(t_{\mathrm{emit}})]}$$

Birefringence from ALP field dynamics

- EOM: $\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$

CMB (last scattering surface)



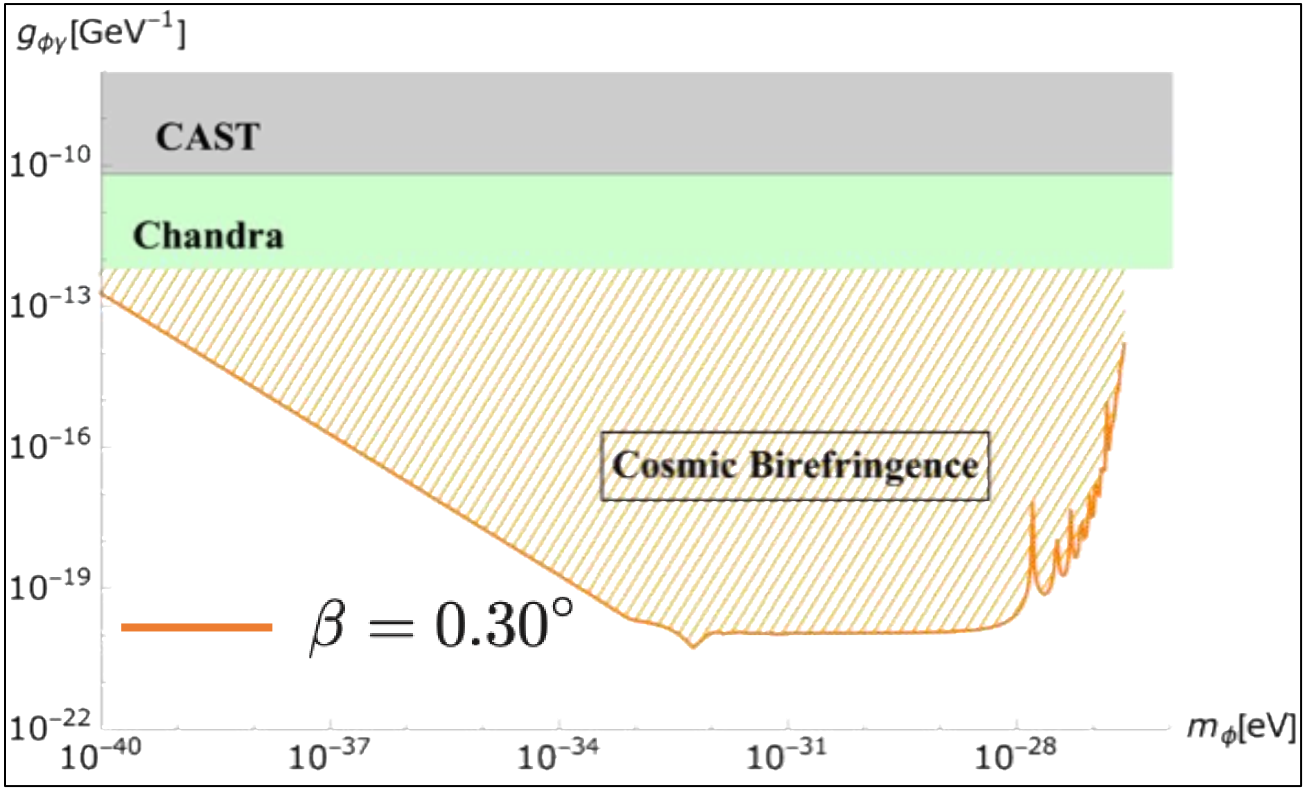
(present←)

$$\beta = \frac{g_{\phi\gamma}}{2}(\phi(t_0) - \langle\phi(t_{\mathrm{LSS}})\rangle)$$

- Field displacement depends on ALP mass

ALP discovery space

$$\beta = \frac{g_{\phi\gamma}}{2}(\phi(t_0) - \langle\phi(t_{\rm LSS})\rangle)$$



- Less ALP abundance

$$\frac{m_\phi^2 \phi^2/2}{\rho_c} = \Omega_\phi \ll 1$$

- nπ phase ambiguity

$$\beta = 0.30^\circ + n\pi$$

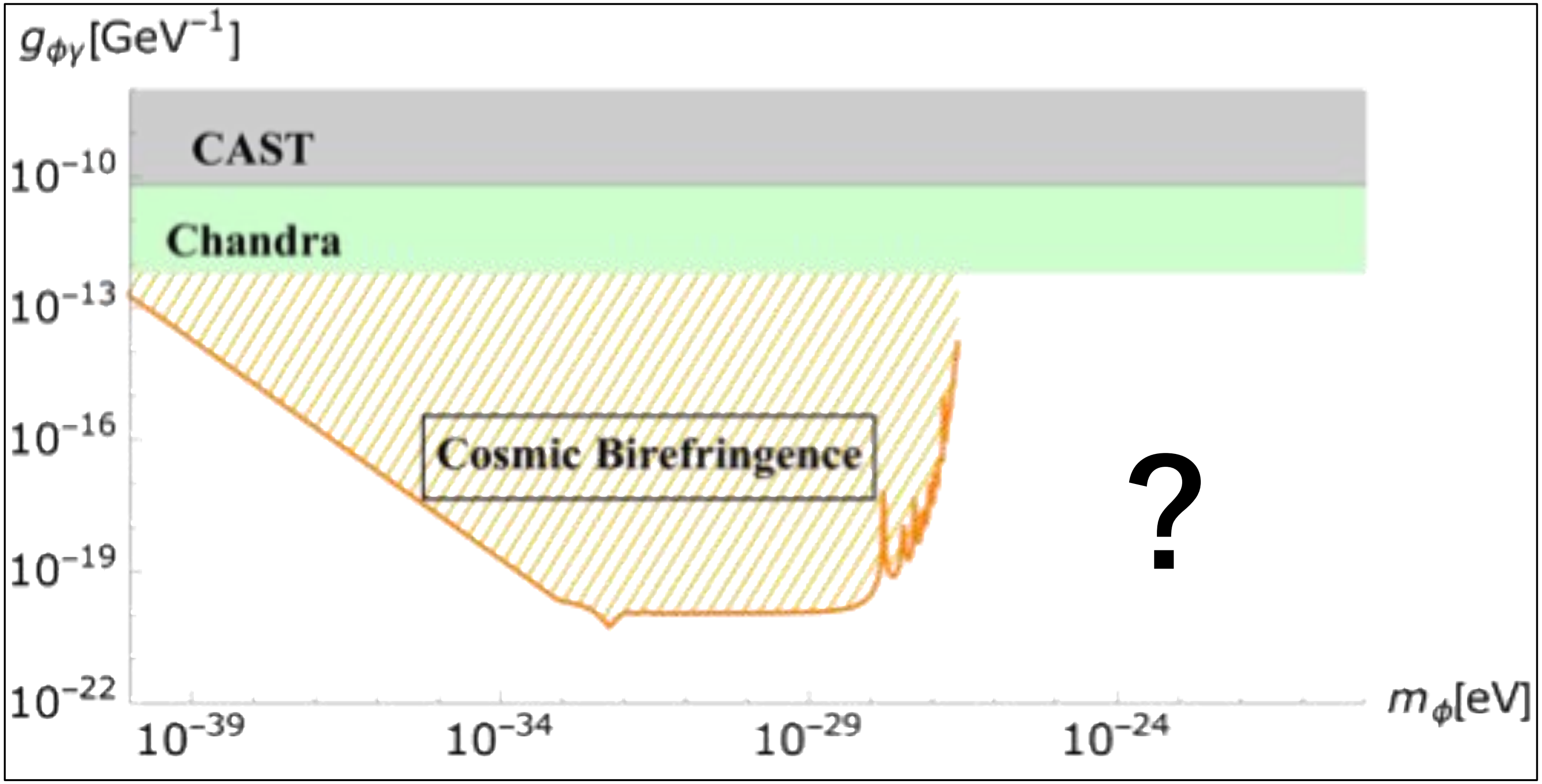
Naokawa, Namikawa, Murai, IO, Kamada, PRL (2024);

ALP abundance

$$\Omega_{\phi,\max} \simeq \begin{cases} 0.69 \quad (m \lesssim 10^{-33}\mathrm{eV}) \\ 6\times 10^{-3} h^{-2} \quad (10^{-32}\mathrm{eV} \lesssim m \lesssim 10^{-25}\mathrm{eV}) \end{cases}$$

ALP discovery space

$$\beta = \frac{g_{\phi\gamma}}{2}(\phi(t_0) - \langle\phi(t_{\rm LSS})\rangle)$$



How about fuzzy DM mass range?: $m_\phi \gtrsim 10^{-25}\mathrm{eV}$

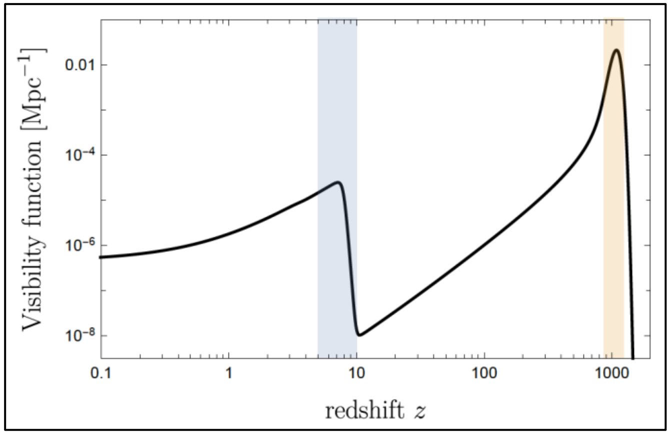
- Mixed CDM+FDM simulations

  → ALP undergoes **nonlinear clustering**

Schwabe, Gosenca, Behrens, Niemeyer, Easther (2020); Laguë, Schwabe, Hložek, Marsh, Rogers (2023);…

ALP oscillatory effects at CMB epoch

$\boxed{m_\phi \gg H_{\rm CMB} \sim 10^{-29}\ {\rm eV}}$



Credit: Nakatsuka, Namikawa, Komatsu (2022)

- Stokes parameters with ALP coupling

$$Q \pm iU \propto \int dt' g(t') \exp\left[\pm 2i\beta(t')\right]$$

$g(t')$: vigibility function

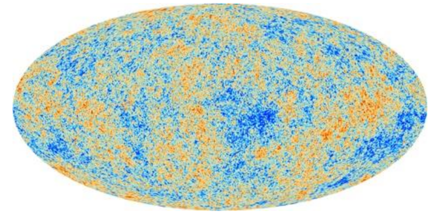
Rotation angle

$$\boxed{\begin{aligned}\beta &= \frac{g_{\phi\gamma}}{2}\left[\phi(t_0) - \phi(t_{\rm LSS})\right] \\ &= \frac{g_{\phi\gamma}}{2}\left[\phi_0 \cos(mt_0 + \delta_0) - \overset{\propto a(t')^{-3/2}}{\phi_{\rm LSS}(t')} \cos(mt' + \delta(t'))\right]\end{aligned}}$$

$$\propto e^{\pm i g_{\phi\gamma}\phi(t_0)} \underline{\int dt' g(t') \exp\left[\mp i g_{\phi\gamma}\phi_{\rm CMB}(t') \cos(mt' + \delta(t'))\right]}$$

$$\boxed{= \langle e^{\mp i g_{\phi\gamma}\phi(t_{\rm LSS})}\rangle}$$

CMB washout effect



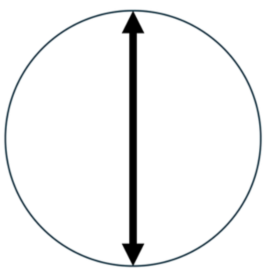
Finelli & Galaverni (2008);
Fedderke, Graham, Rajendran (2019);
Murai (2024); Zhang, Ferreira, IO, Namikawa (2024);

Last scattering surface

Time
(present)

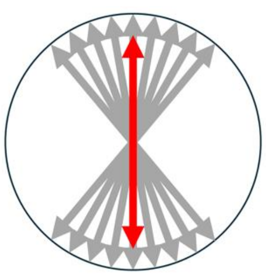
CMB polarization

$\Delta T \sim 10^5$ years



Standard polarization magnitude (w/o ALP coupling)

$$\langle e^{\mp i g_{\phi\gamma}\phi(t_{\rm LSS})}\rangle \sim 1 - g_{\phi\gamma}^2\langle\phi_{\rm LSS}^2\rangle/4 \quad m\Delta T \gg 1$$

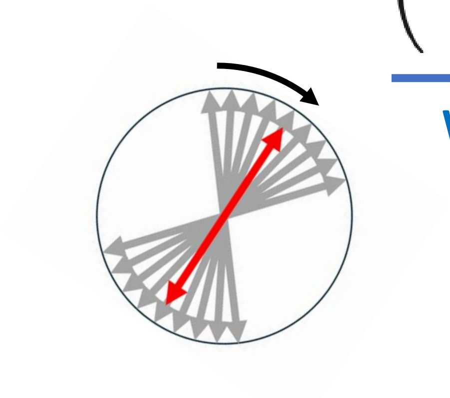


Reduced polarization magnitude (w ALP rapid oscillation)
by the superposition of randomly-oriented polarization

To be summarized...

- Stokes parameters with ALP-photon coupling for mass: $10^{-25}\mathrm{eV} \lesssim m_\phi \lesssim 10^{-23}\mathrm{eV}$

$$Q \pm iU \sim \underbrace{\left(1 - \frac{g_{\phi\gamma}^2 \langle \phi_{\mathrm{LSS}}^2 \rangle}{4}\right)}_{\text{Washout effect}} \exp \underbrace{\left[\pm i g_{\phi\gamma} \phi_0 \cos(m_\phi t_0 + \delta_0)\right]}_{\text{Polarization rotation effect}} (Q_0 \pm iU_0)$$



$$= \pm 2i\beta$$

(cosmic birefringence)

- For ALP mass as (fuzzy) dark matter

$$m_\phi \gtrsim 10^{-23}\ \mathrm{eV}$$
$$(t_{\mathrm{osc}} \lesssim \ \mathrm{years})$$

Polarization rotation becomes time-varying in real time measurements

$$(\mathrm{frequency} = \mathrm{DM\ mass}/(2\pi))$$

Constraining on axion parameter space

- Axion dark matter energy density: $\rho_\phi = \frac{1}{2} m_\phi^2 \phi^2 \longleftrightarrow \phi = \frac{\sqrt{2\rho_\phi}}{m_\phi}$

- Convert polarization magnitude into coupling constant:

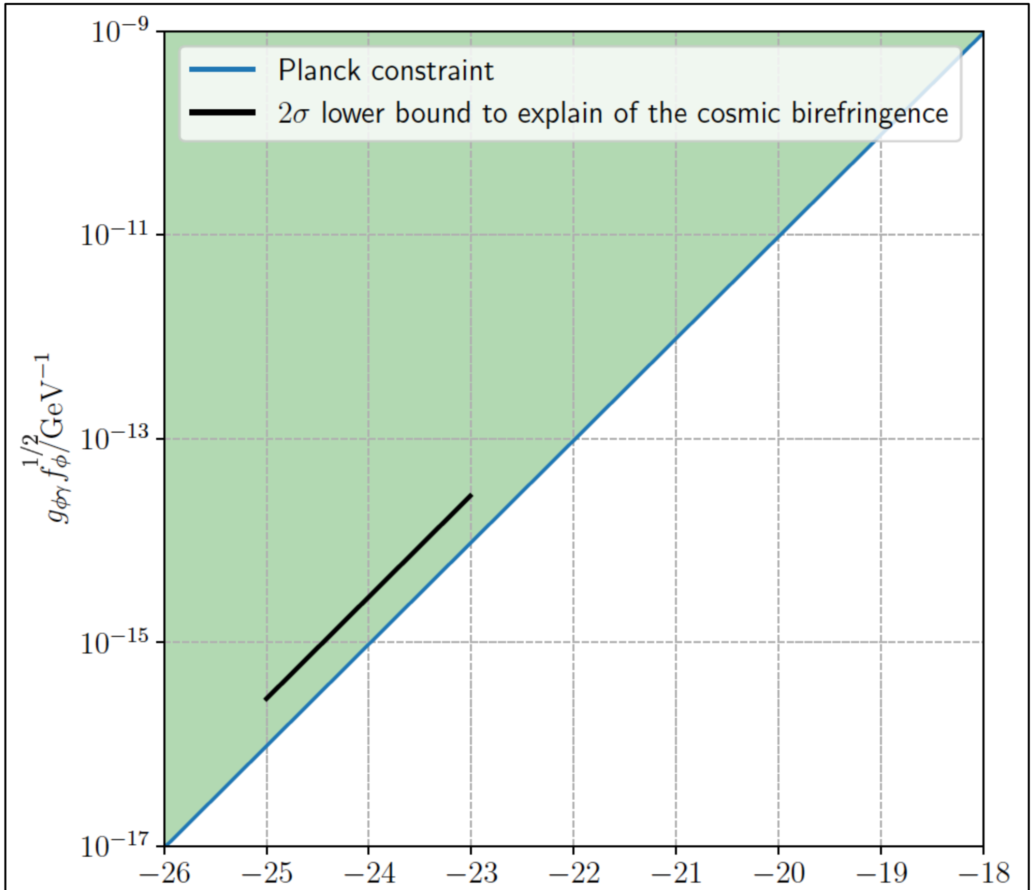
$$\beta = \frac{g_{\phi\gamma}}{2}\phi_0 \longleftrightarrow g_{\phi\gamma} = \sqrt{2}\beta m_\phi (\kappa \rho_{\mathrm{DM,local}})^{-1/2}$$

$\kappa \equiv \frac{\rho_{\phi,\mathrm{local}}}{\rho_{\mathrm{DM,local}}}$: axion dark matter fraction

$$\boxed{g_{\phi\gamma}\kappa^{1/2} \simeq 4.9 \times 10^{-14}\mathrm{GeV}^{-1} \left(\frac{\beta}{0.3\mathrm{deg}}\right)\left(\frac{m_\phi}{10^{-23}\mathrm{eV}}\right)\left(\frac{\rho_{\mathrm{DM,local}}}{0.3\mathrm{GeV/cm^3}}\right)^{-1/2}}$$

Washout effect v.s. Cosmic birefringence

Zhang, Ferreira, IO, Namikawa (2024) $(\beta \sim 0.3^\circ)$



Constant rotation ←

(comparing with observing time)

Comparable, but slightly excluded

Note

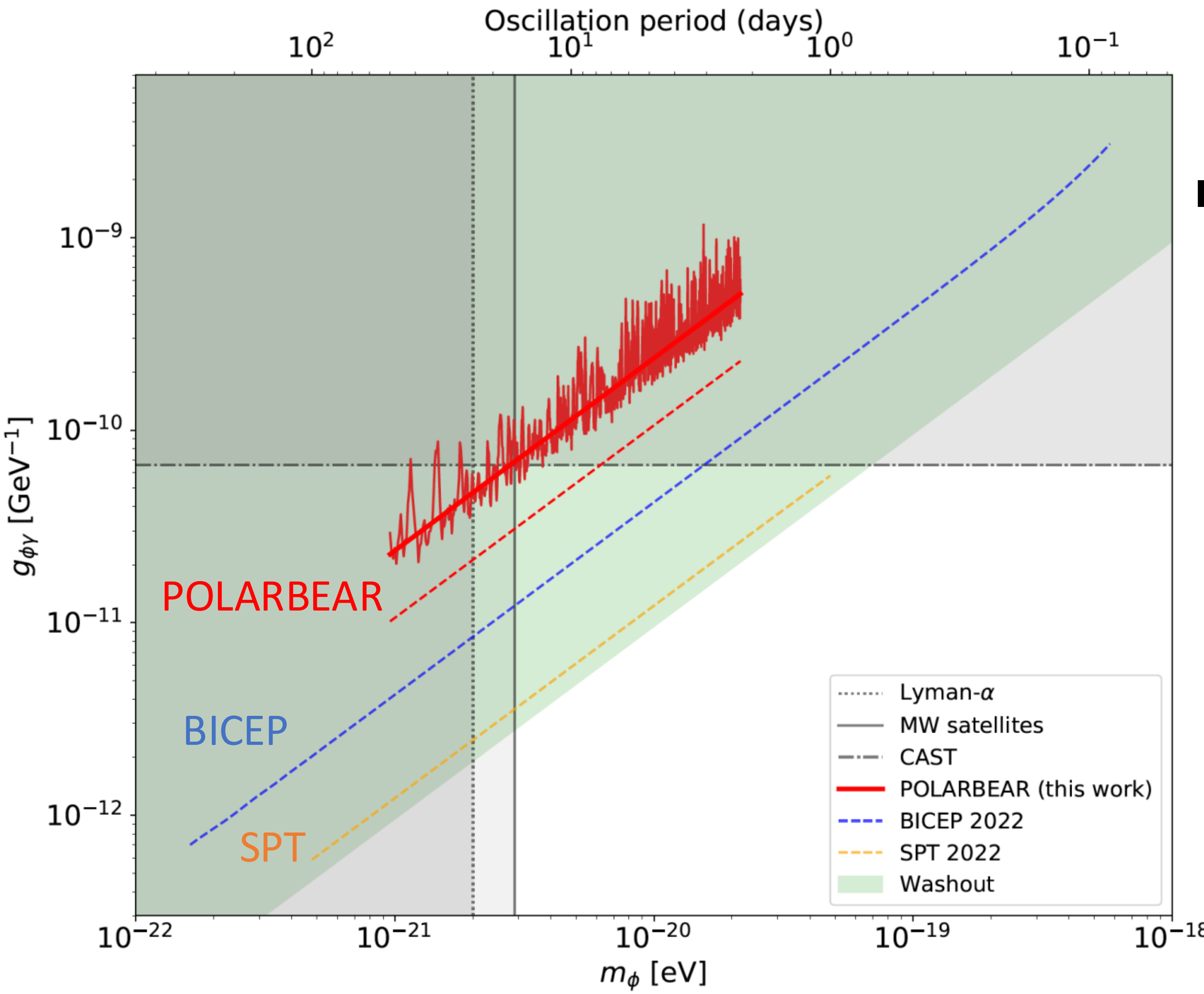
We assume that cosmological DM fraction

$$f_\phi \equiv \frac{\Omega_\phi}{\Omega_m}$$

equals to local DM fraction

$$\kappa \equiv \frac{\rho_{\phi,\mathrm{local}}}{\rho_{\mathrm{DM,local}}}$$

Time-dependent birefringence constraints



POLARBEAR 2023;

- Fit a sinusoidal model and extract limits on the coupling constant
  - 100% DM fraction is assumed

    $$(f_\phi = \kappa = 1)$$

  - Stochastic axion distribution is taken into account

    (POLARBEAR)

SPT-3G v.s. LiteBIRD for birefringence test

(not full survey)

	SPT-3G	LiteBIRD
Angular scales	$\text{high } \ell$	$\text{low } \ell$ $(2 \leq \ell \leq 200)$
Angular resolution	1.2’	30’
Map depth	$6.6\ \mu\text{K} \cdot \text{arcmin}$ (?)	$2.5 - 5.0\ \mu\text{K} \cdot \text{arcmin}$
Sky fraction	$f_{\text{sky}} \simeq 0.036$ (1500deg^2)	$f_{\text{sky}} = 0.6 - 0.7$ (full sky survey)
Observation time **for oscillation period**	***SPT-3G (2022)*** 12 hours – 100 days	**? ?** 1 day – 3 years

(very naive) Sensitivity estimation

- Birefringence signal: $C_\ell^{EB,o} = \frac{1}{2}\sin(4\beta)\left(C_\ell^{EE,CMB} - C_\ell^{BB,CMB}\right)$

$$\beta \ll 1,\ C_\ell^{BB} \ll C_\ell^{EE} \qquad \beta \simeq \frac{C_\ell^{EB,o}}{2C_\ell^{EE,CMB}}$$

Yadav+(2009); Gluscevic, Kamionkowski (2010);…

- Uncertainty of rotation angle: $\sigma_\beta^{-2} = \sum_\ell \sigma_{\beta,\ell}^{-2} = \sum_\ell \frac{(2C_\ell^{EE,CMB})^2}{\mathrm{Var}(C_\ell^{EB,o})}$

$$C_\ell^{EE,CMB} = \frac{2\pi}{\ell(\ell+1)} D_\ell^{EE} \qquad N_\ell^{EE} = N_\ell^{BB} = (\Delta_P)^2 \exp\left[\ell(\ell+1)\sigma_b^2\right]$$

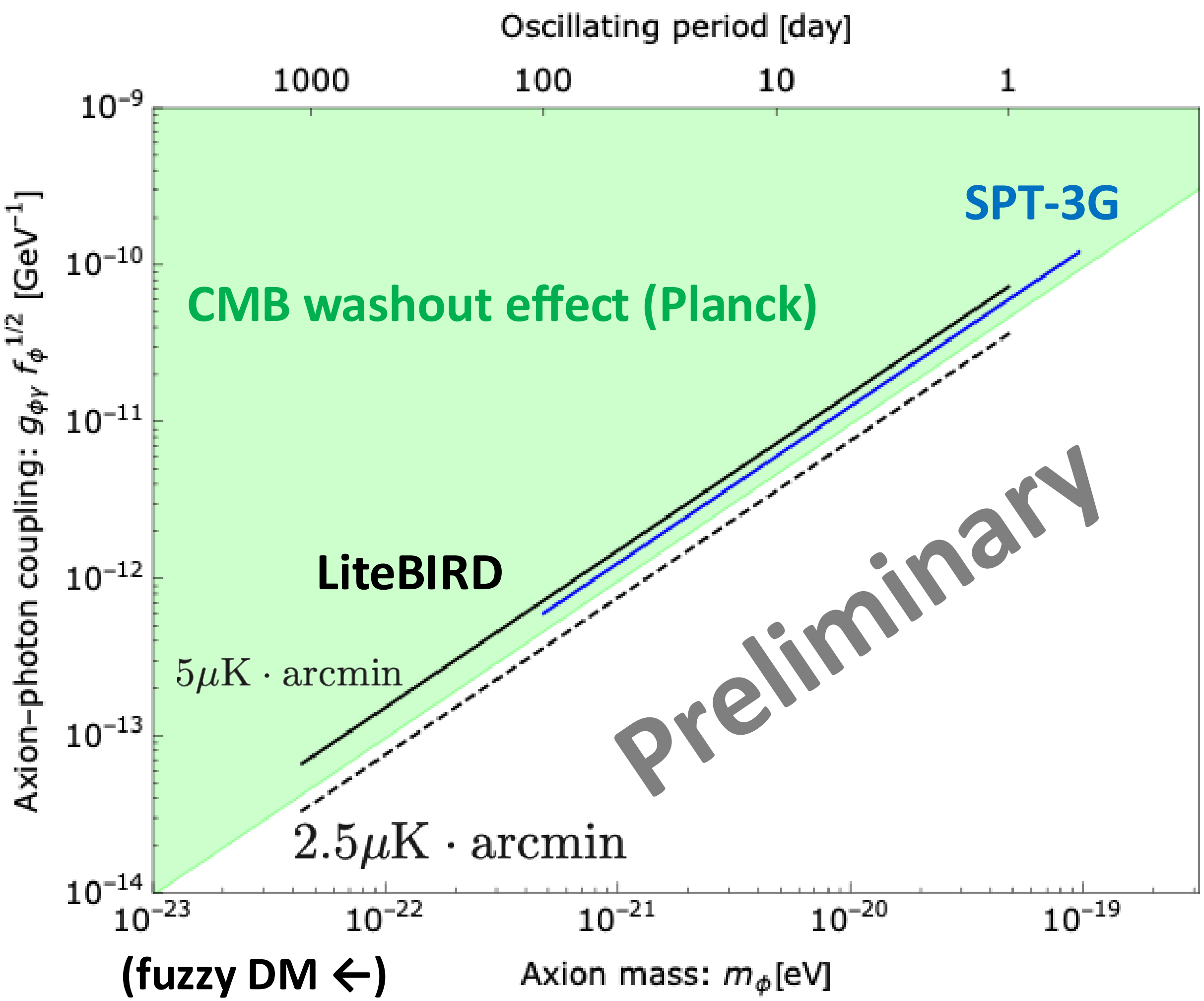
$$\rightarrow \quad \sigma_\beta^{-2} \simeq 16\pi^2 f_{\mathrm{sky}} \sum_\ell \frac{2\ell+1}{\ell^2(\ell+1)^2} \frac{(D_\ell^{EE})^2}{(\Delta_P)^4 \exp\left[2\ell(\ell+1)\sigma_b^2\right]}$$

- 2σ upper bound on angle magnitude for LiteBIRD: $\boxed{\sigma_b \equiv \theta_{\mathrm{FWHM}}/\sqrt{8\ln 2}}$

$$A_{95} = \sqrt{2\sigma_\beta} \sim 0.09 - 0.18\ \mathrm{deg}$$

Potential constraint with LiteBIRD

(IO+, in preparation)



(fuzzy DM ←)

- Assuming the same DM fraction: $f_\phi = \kappa$
- Stochastic effect on DM local density is not concerned in this plot

Summary & Outlook

- Cosmic birefringence is a phenomenon of polarization rotation effect in the presence of parity-violating physics, such as axion-photon interaction.
- For heavier mass range, oscillatory motion of axion field washes out the CMB polarization and puts an upper bound on the axion photon coupling constant.
- Probing time dependent cosmic birefringence is also important for the dark matter search. We made a very naïve sensitivity estimation expected by LiteBIRD.
- LiteBIRD potentially covers lower mass ranges than that with SPT-3G, POLARBEAR, BICEP, and improves the constraint on the parameter space.
- More realistic estimation is necessary.

Thank you very much!