Cosmic Birefringence and Its Implications for Physics beyond the Standard Model

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科研費
KAKENHI

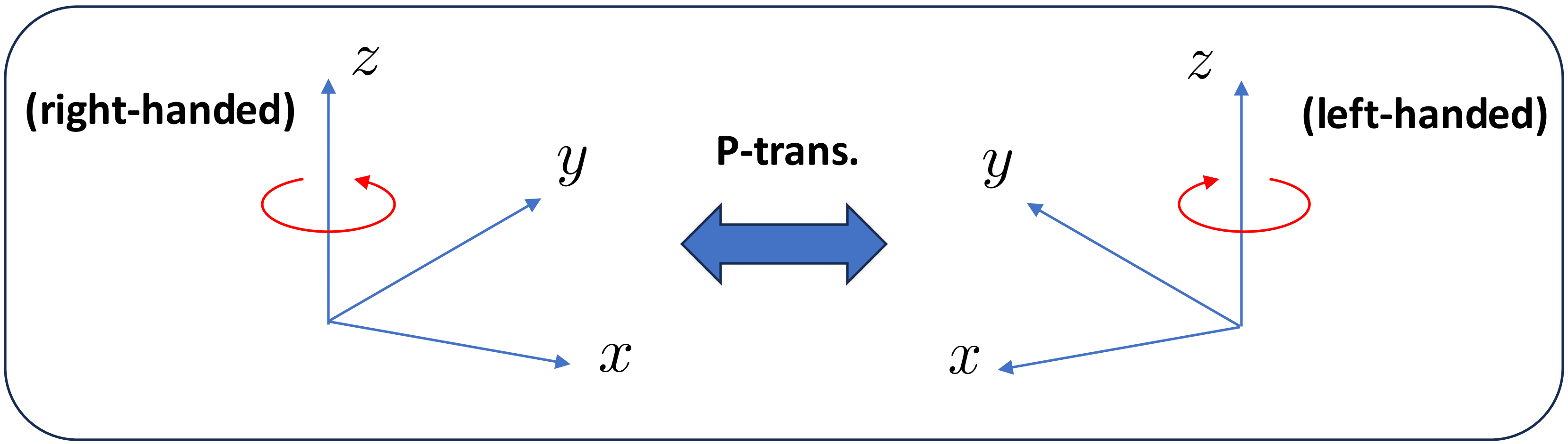
ダークマターの正体は何か？
広大なディスカバリースペースの網羅的研究
What is dark matter? - Comprehensive study of the huge discovery space in dark matter
文部科学省
科学研究費助成事業
学術変革領域研究
（2020–2024）

素粒子原子核研究所
Institute of Particle and Nuclear Studies

2025.8.12 @ Vietnam Cosmology 2025 (ICISE, Quy Nhon)

Parity transformation in physics

■ **Inversion of spatial coordinate:** $\mathrm{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$

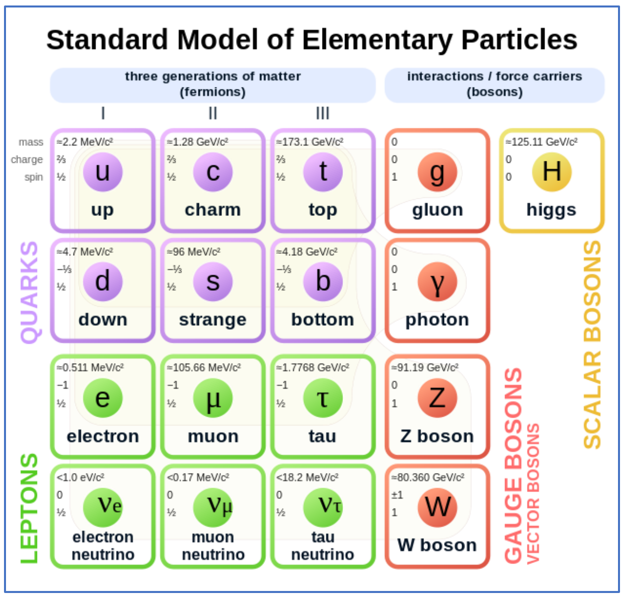


■ **Parity-symmetry：Physics does not change under the P-transformation.**

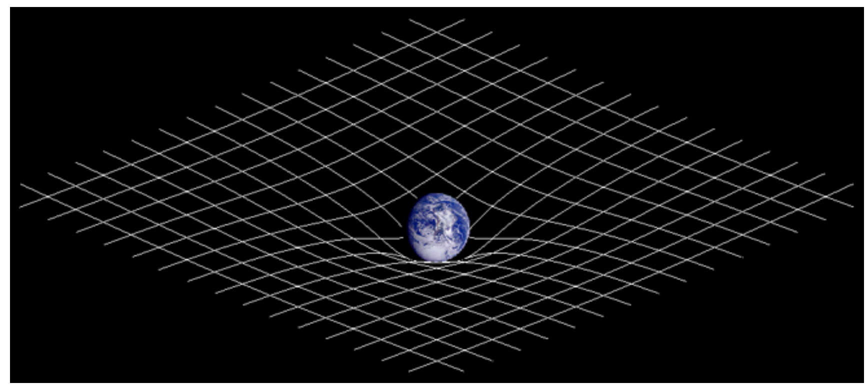
Standard cosmology is P-symmetric

(almost)

Micro scale：Standard Model



Macro scale：general relativity



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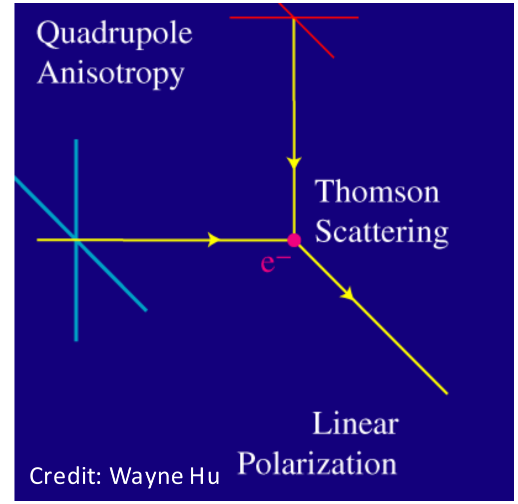
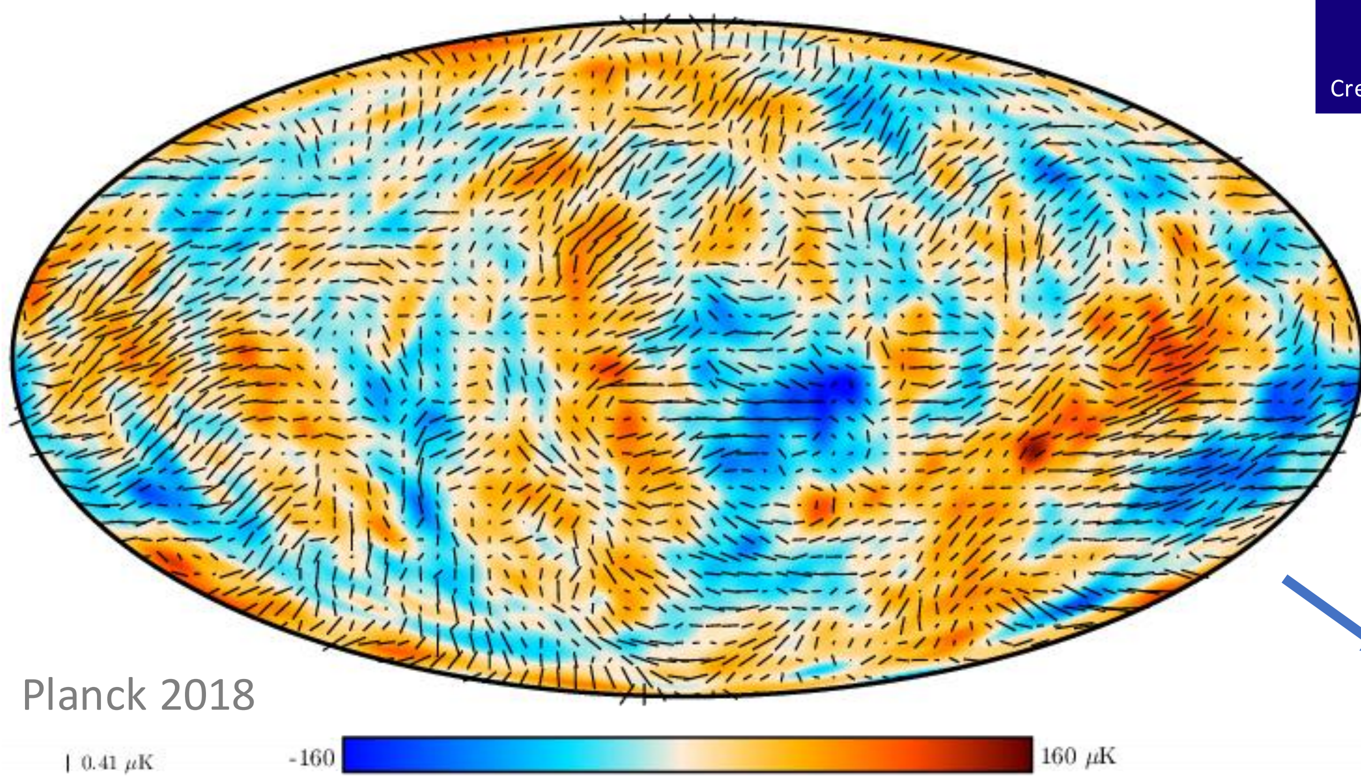
■ **(except weak force) Standard Model and GR is P-symmetric theories.**

Discovery of parity-violation → New Physics!

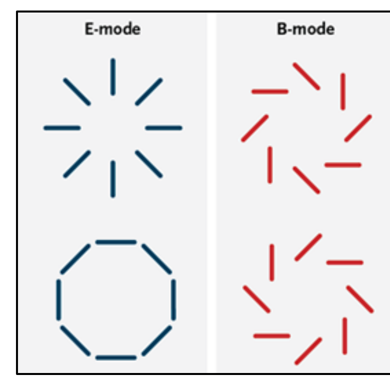
CMB polarization map



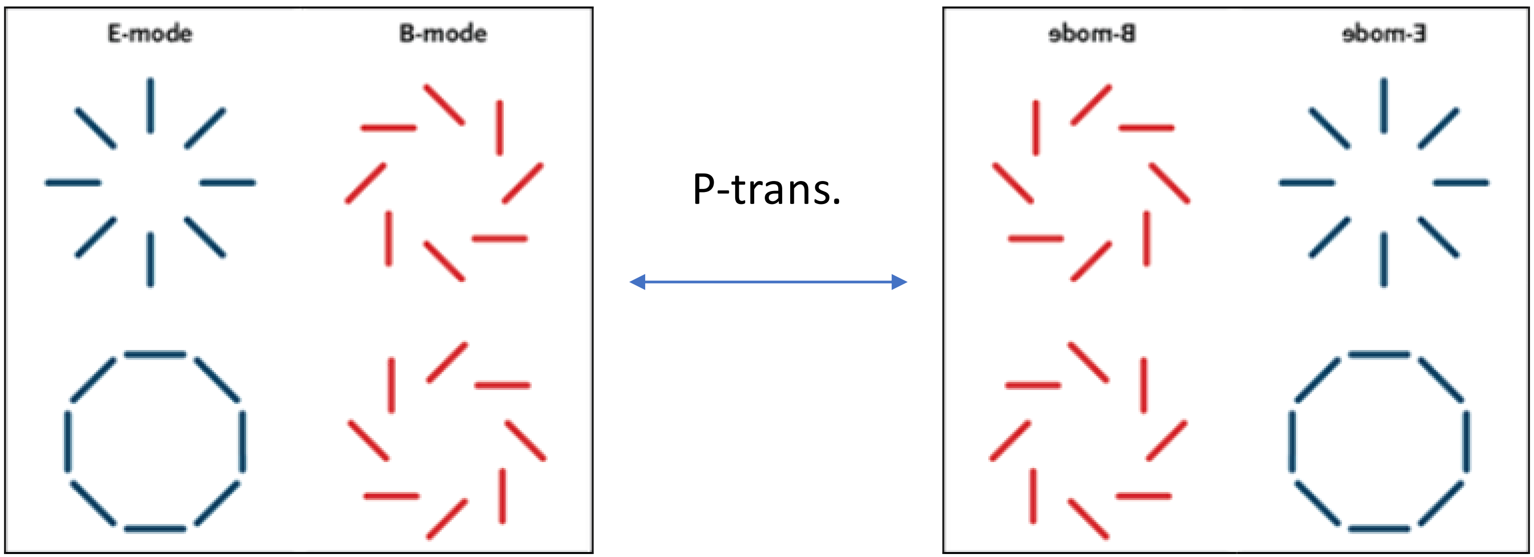


Planck 2018

E-mode v.s. B-mode



Parity flip in polarization pattern

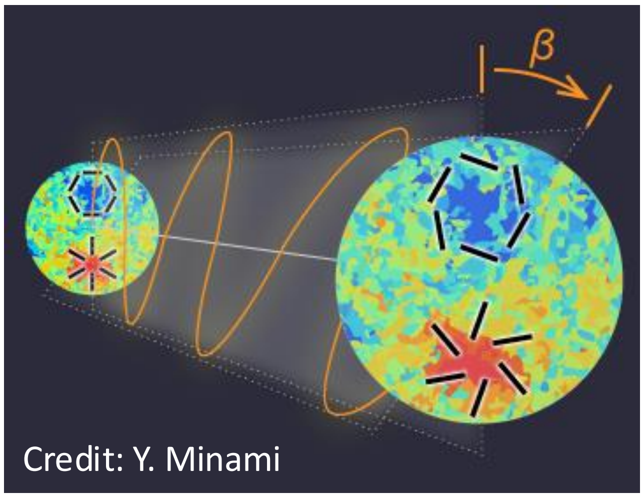


Parity-even: $C_\ell^{TT},\ C_\ell^{EE},\ C_\ell^{BB},\ C_\ell^{TE}$ (parity-invariant theory, well measured)

Parity-odd: $C_\ell^{TB},\ C_\ell^{EB}$ → **parity-violating physics, not well measured**

Isotropic polarization rotation in CMB

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



Credit: Y. Minami

- Parity-violating interactions

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

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**

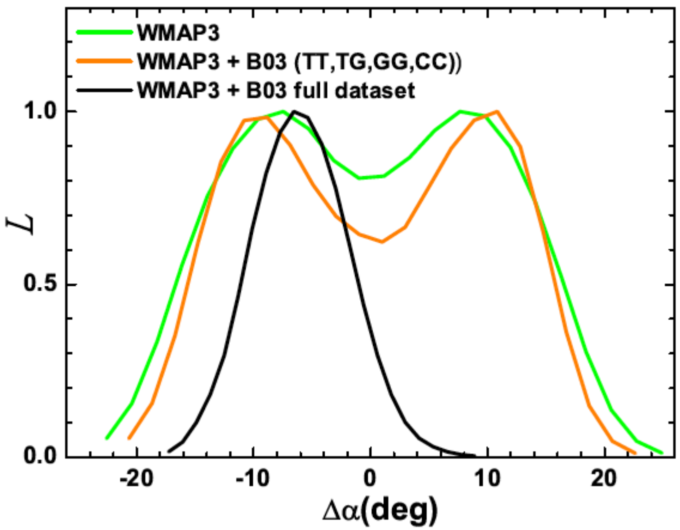
$$C_\ell^{EB,o} = \frac{1}{2}\sin(4\beta)\left(C_\ell^{EE,{\rm CMB}} - C_\ell^{BB,{\rm CMB}}\right) + \cos(4\beta) C_\ell^{EB,{\rm CMB}}$$

↑assuming 0

(note: β is assumed to be constant)

History of observations

First measurement: ***Feng, Li, Xia, Chen, Zhang (2006);***



- Joint analysis of WMAP and BOOMERANG data
- With B03 data of TC and GC,

$$\Delta\alpha = -6.0 \pm 4.0 \text{ deg}$$

- Only statistical error

Follow-up measurements

$$\text{WMAP Collaboration}: \ \Delta\alpha = -1.1 \pm 1.4 \pm 1.5 \text{ deg (Komatsu+ 2009)}$$

$$\text{QUaD Collaboration}: \ \Delta\alpha = 0.55 \pm 0.82 \pm 0.5 \text{ deg (Wu+ 2009)}$$

$$\text{Planck Collaboration}: \ \Delta\alpha = 0.31 \pm 0.05 \pm 0.28 \text{ deg (Planck XLIX 2016)}$$

$$\text{ACT Collaboration}: \Delta\alpha = 0.12 \pm 0.06 \text{ deg (Namikawa+ 2020)}$$

$$\text{SPT Collaboration}: \ \Delta\alpha = 0.63 \pm 0.04 \text{ deg (Bianchini+ 2020)}$$

Miscalibration of rotation angle

Wu (2008); Miller (2009); Komatsu (2010); …

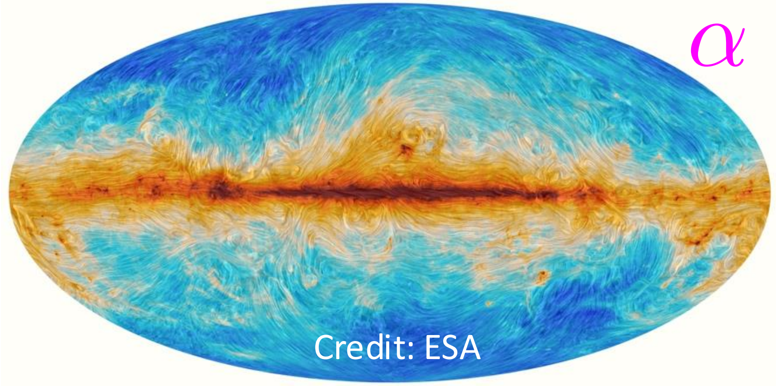
Credit: Minami & Komatsu

(intrinsic polarization rotation) (no intrinsic but a rotation of detector)

- Miscalibration of the polarization angle α also contributes to the birefringent signal
- Conventional measurements have detected the angle $\Delta\alpha = \alpha + \beta$

New calibration method

Minami, Ochi, Ichiki, Katayama, Komatsu, Matsumura (2019);



α only

- Assuming intrinsic rotation is proportional to path, galactic emission is not relevant for β

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

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

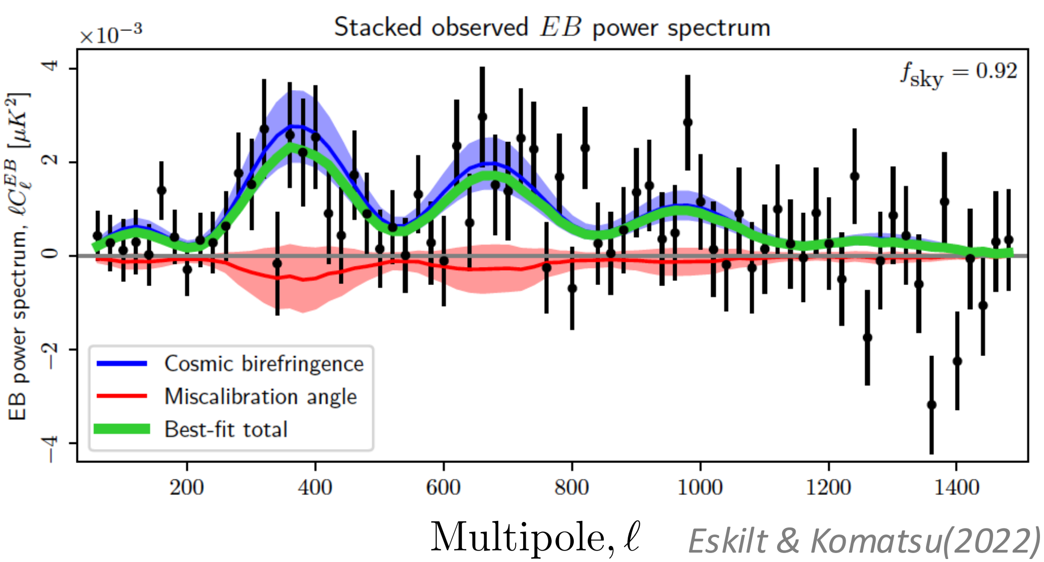
$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)$$
$$+ \frac{1}{\cos(4\alpha)}\langle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

Measurements of cosmic birefringence

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

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

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



Eskilt & Komatsu(2022)

- *Planck/WMAP* joint analysis*:*

Eskilt & Komatsu (2022);

$\beta = 0.34 \pm 0.09$ deg (3.6σ)

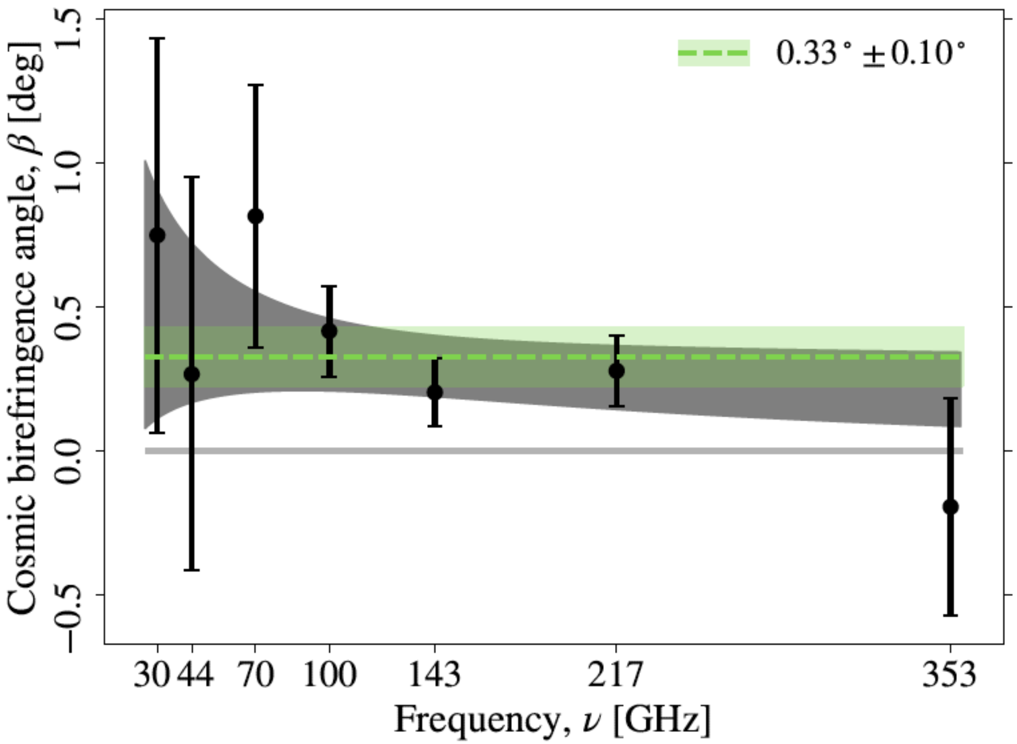
Another important observational fact

Eskilt (2022);

- Constraint on a frequency-dependence of the birefringence angle β:

$$\beta_\nu = \beta_0 \left(\frac{\nu}{\nu_0 = 150\mathrm{GHz}} \right)^n$$

(Planck DR4 polarization maps)



- For a nearly full-sky measurement,

$$\beta_0 = 0.29^{\circ}{}^{+0.10^\circ}_{-0.11^\circ}$$

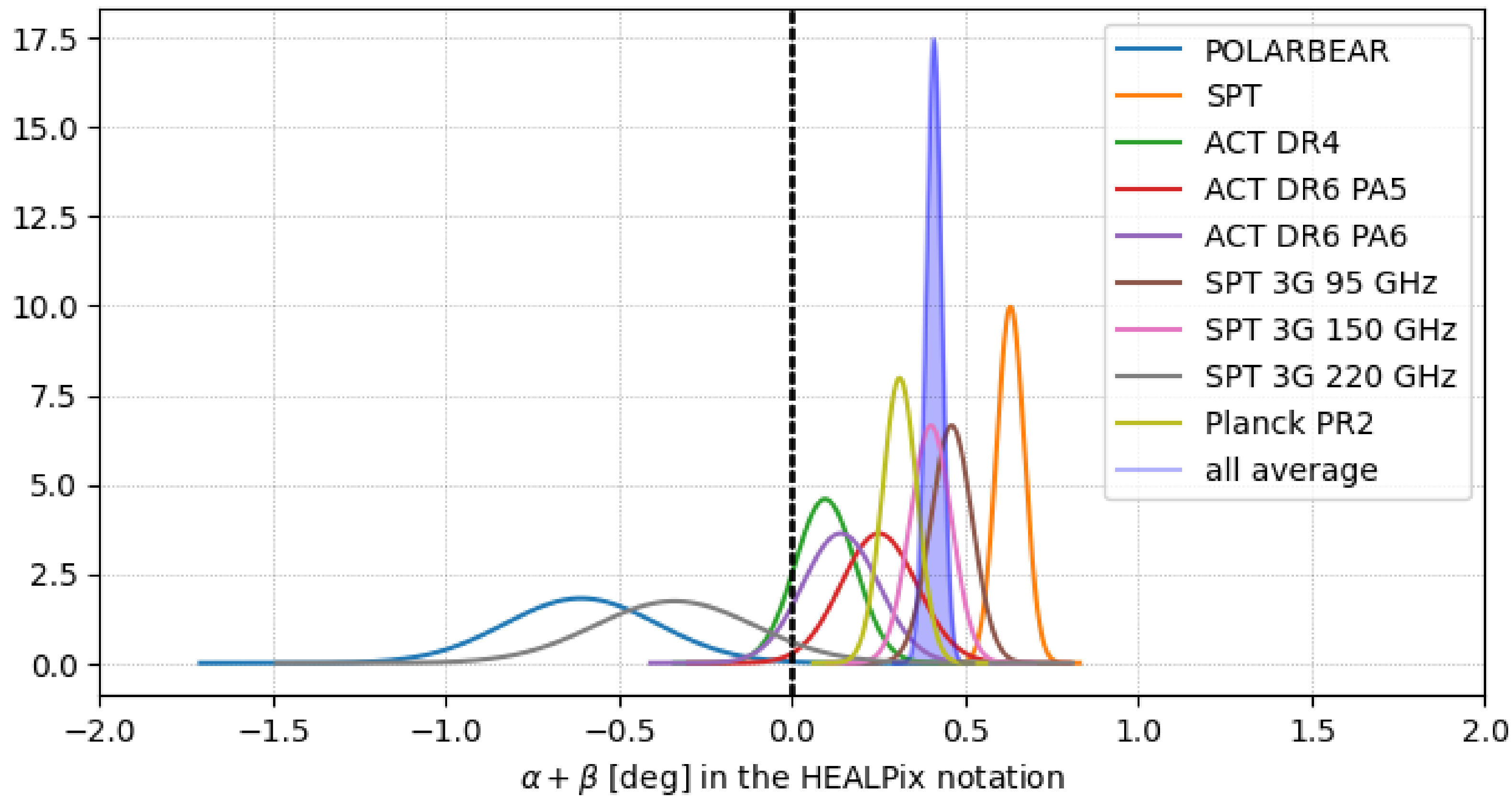
$$n = -0.35^{+0.48}_{-0.47}$$

- **Consistent with frequency-independent**

(excluding Faraday rotation effect)

ICB recent measurements overview

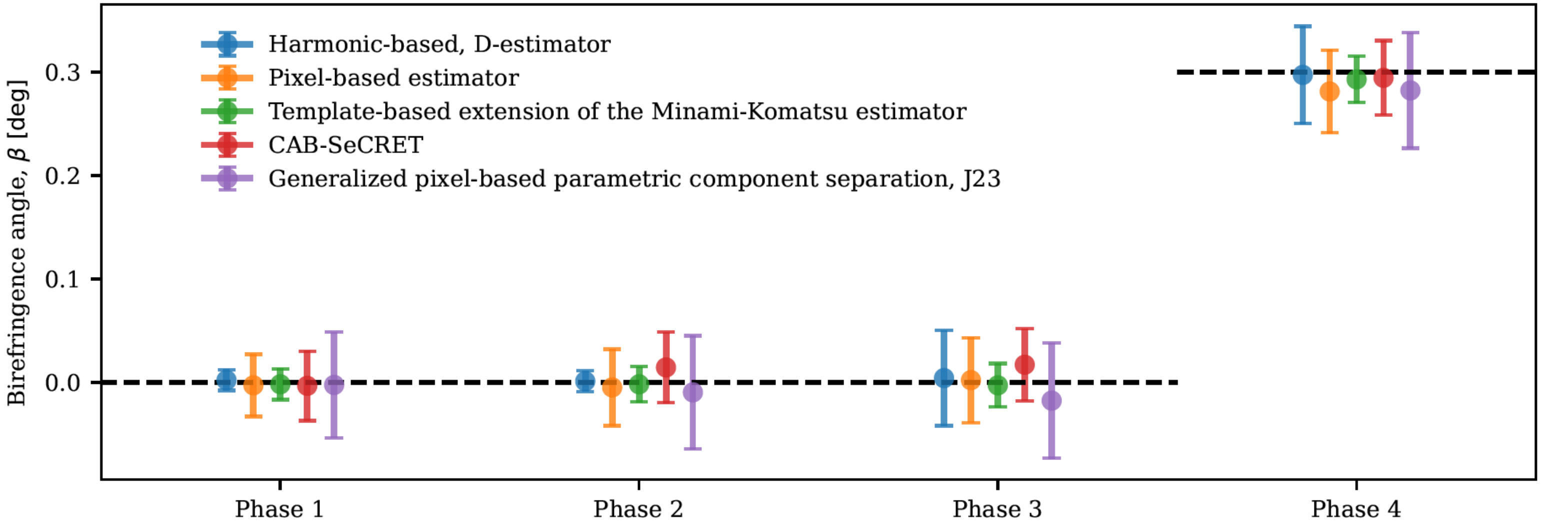
Credit: Fumihiro Naokawa



※ 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

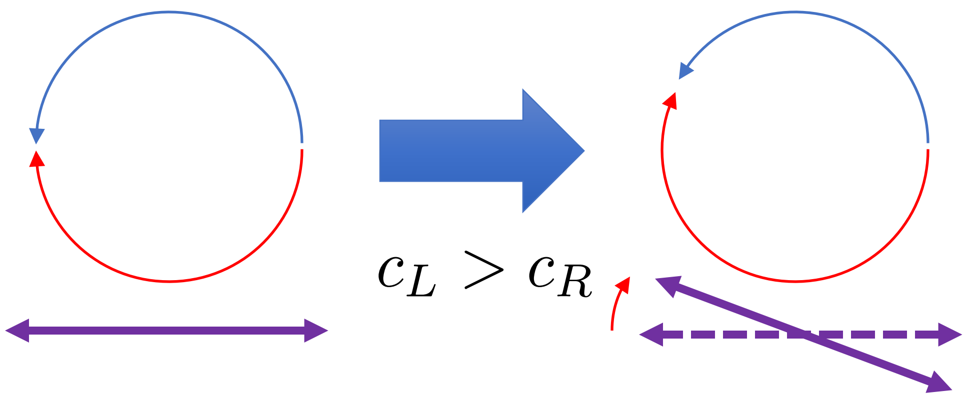
Cosmic birefringence by axion

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

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

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

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



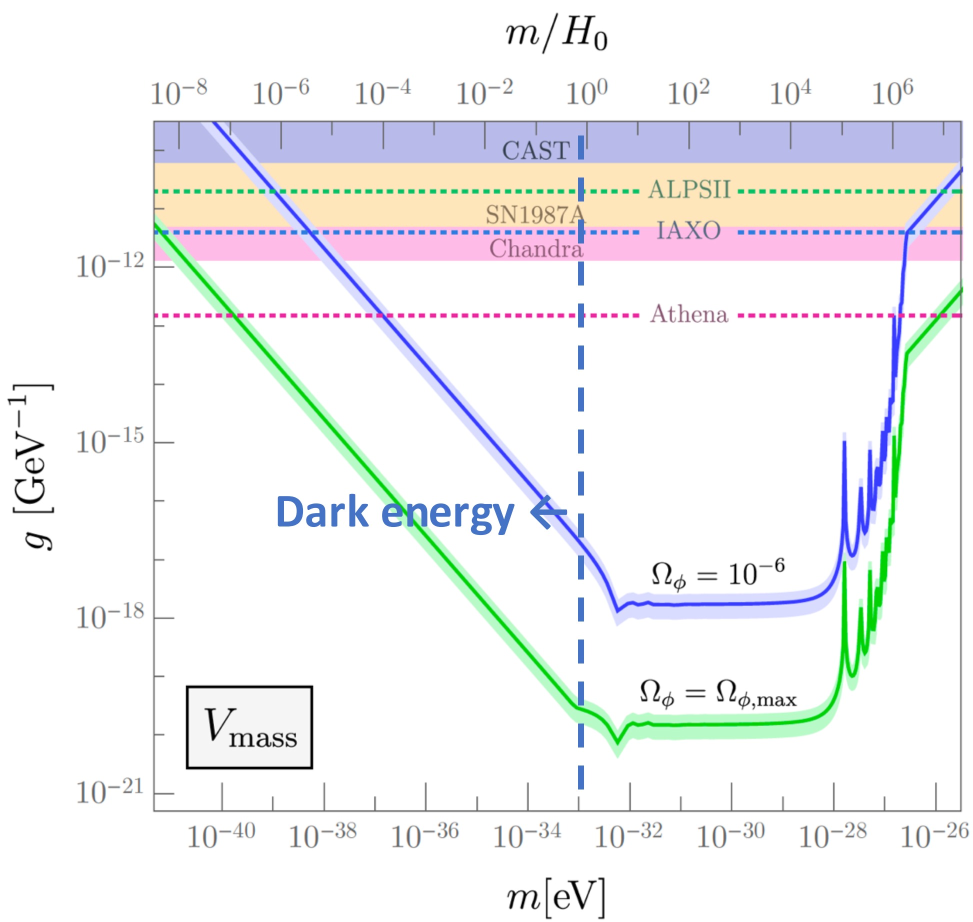
→ leading to the rotation of linear-polarization direction

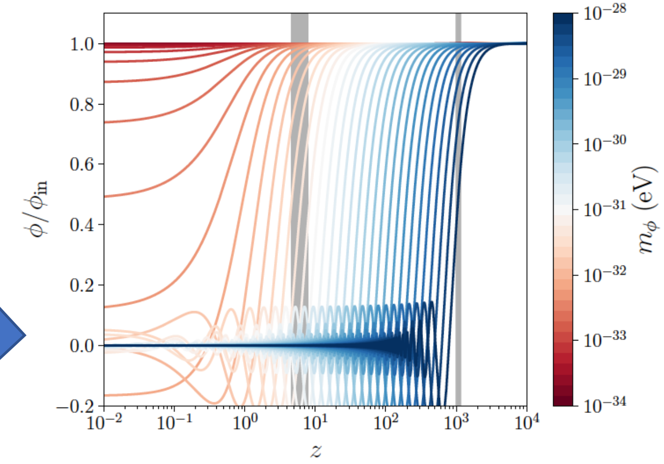
- Rotation angle is given by the integration of phase velocity difference

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

ICB from axion dark energy (DE)

Fujita, Murai, Nakatsuka & Tsujikawa (2020);…





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

- Due to a slow-roll motion of DE, field excursion is approximately

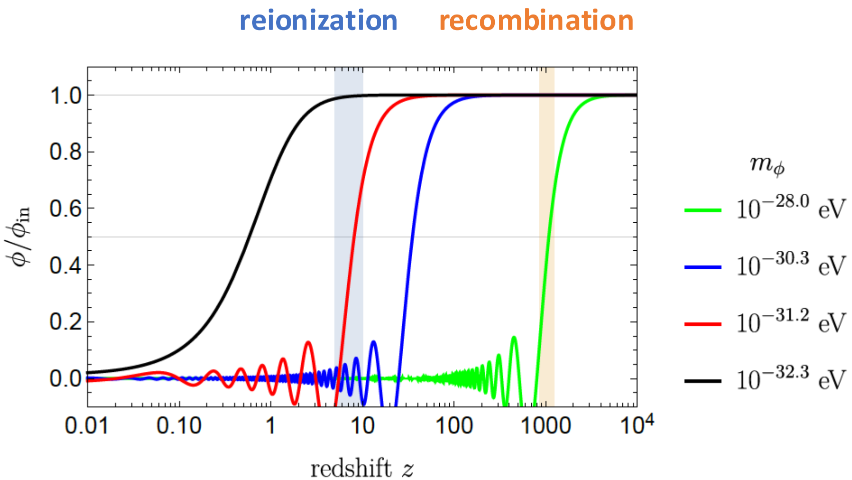
$$\Delta\phi \propto m^2\phi/H^2$$

$$\rightarrow \beta = \frac{g}{2}\Delta\phi \propto gm\sqrt{\Omega_\phi}$$

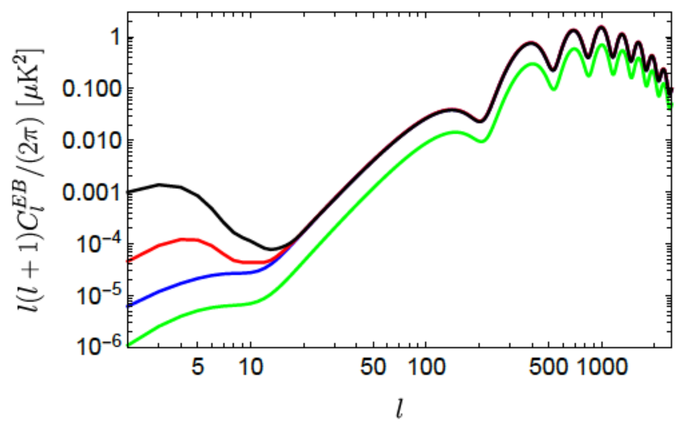
ICB constraints on heavier axions

Sherwin & Namikawa (2021); Nakatsuka, Namikawa & Komatsu (2022); …

- Axion dynamics at reionization/recombination provides unique EB spectral shapes



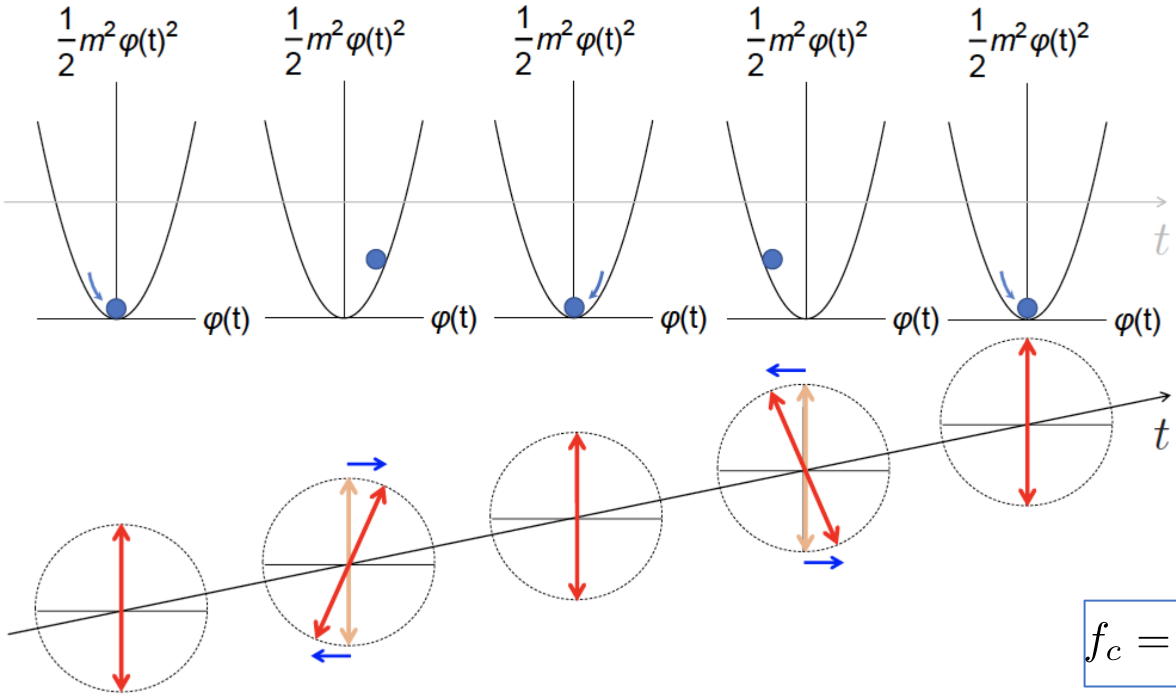
Nakatsuka, Namikawa, Komatsu (2022)



- Several constraints on…

Early dark energy	***Murai, Naokawa, Namikawa, Komatsu (2022); Eskilt+ (2023);***
Gravitational lensing	***Naokawa & Namikawa (2023);***
Polarized SZ effect	***Lee, Hotinli, Kamionkowski (2022); Namikawa & IO (2023);***
Topological defects	***Takahashi & Yin (2020); Ferreira, Gasparotto, Hiramatsu, IO, Pujolas (2023);***

Birefringence from axion dark matter



$$f_c = \frac{m_a}{2\pi} \simeq 2.4\text{Hz}\left(\frac{m_a}{10^{-14}\text{eV}}\right)$$

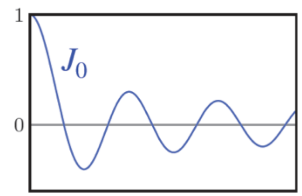
- Axion field with much heavier mass (behaving as dark matter) induces the polarization rotation oscillating in real time measurement scales

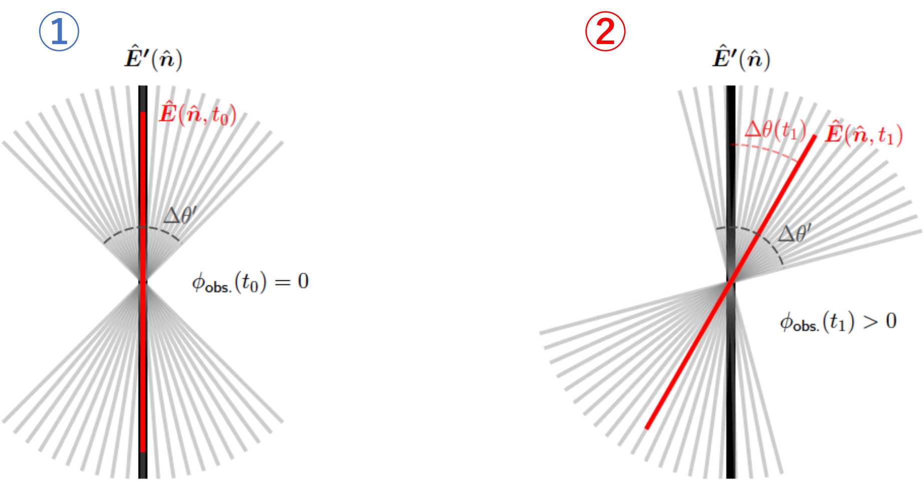
- Possible to observe by several observational approaches!

Oscillatory effects in Stokes parameters

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

$$Q(\hat{\mathbf{n}},t) \pm iU(\hat{\mathbf{n}},t) = \overset{①}{J_0(g_{\phi\gamma}\langle\phi_*\rangle)}\,\overset{②}{\exp\left[\pm i g_{\phi\gamma}\phi_0\cos(mt+\alpha)\right]}\left(Q_0(\hat{\mathbf{n}}) \pm iU_0(\hat{\mathbf{n}})\right)$$





Fedderke+ 2019

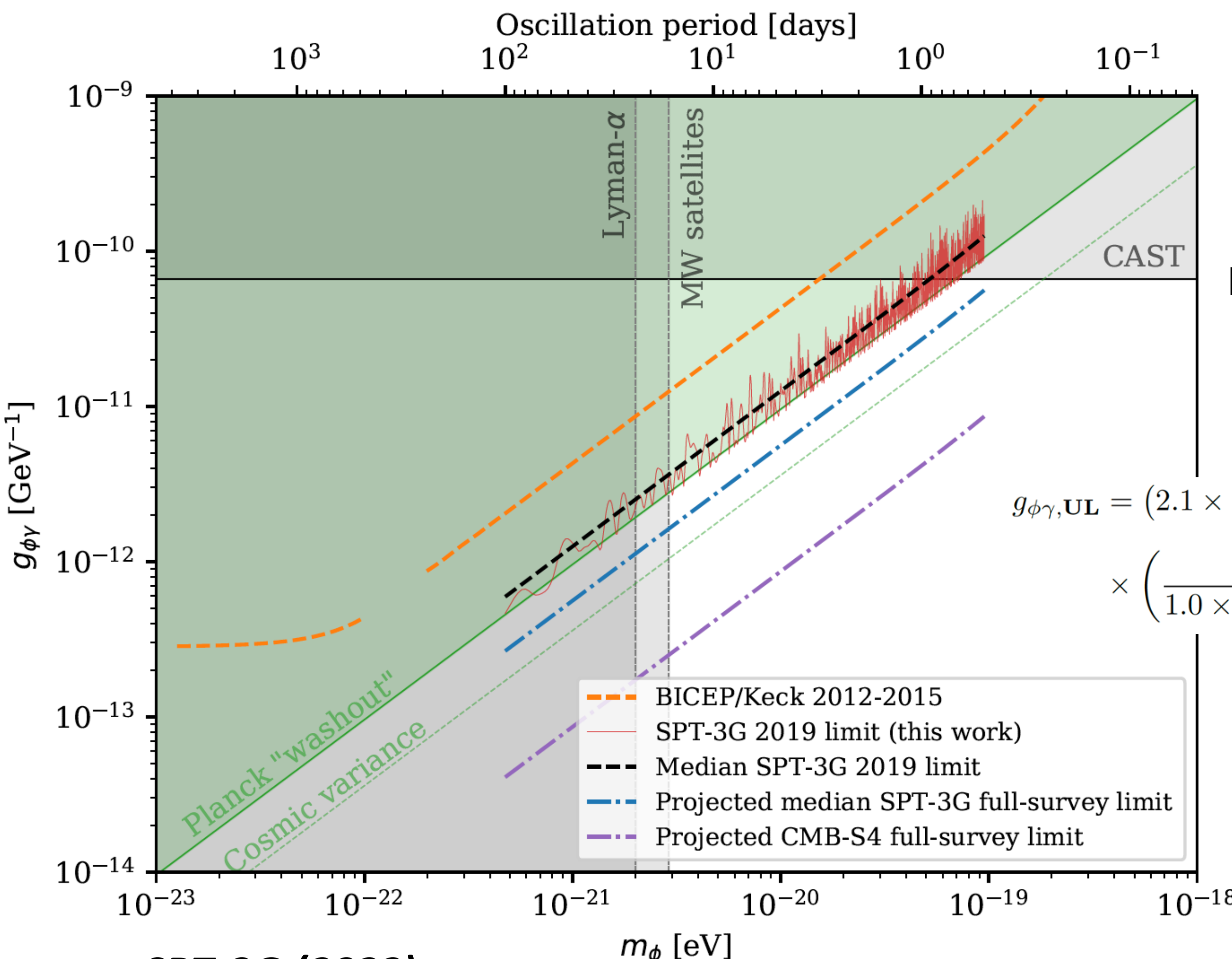
1. Washout effect of axion at decoupling

A rapidly-oscillating axion field in the decoupling epoch (~100,000 years) could suppress the polarization intensity

2. Local Axion DM Oscillation on Earth

We could measure the time-dependent polarization modulation oscillating on the order of hours to years (corresponding to $10^{-19}\mathrm{eV}$ to $10^{-22}\mathrm{eV}$)

Constraints on time-dependent cosmic birefringence (SPT, BICEP/Keck)



SPT-3G (2022)

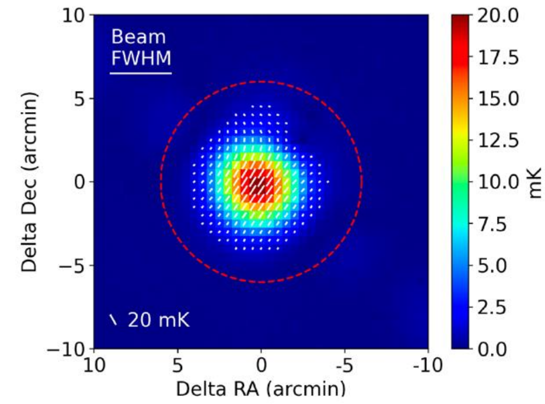
- Fit a sinusoidal model and extract limits on the coupling constant

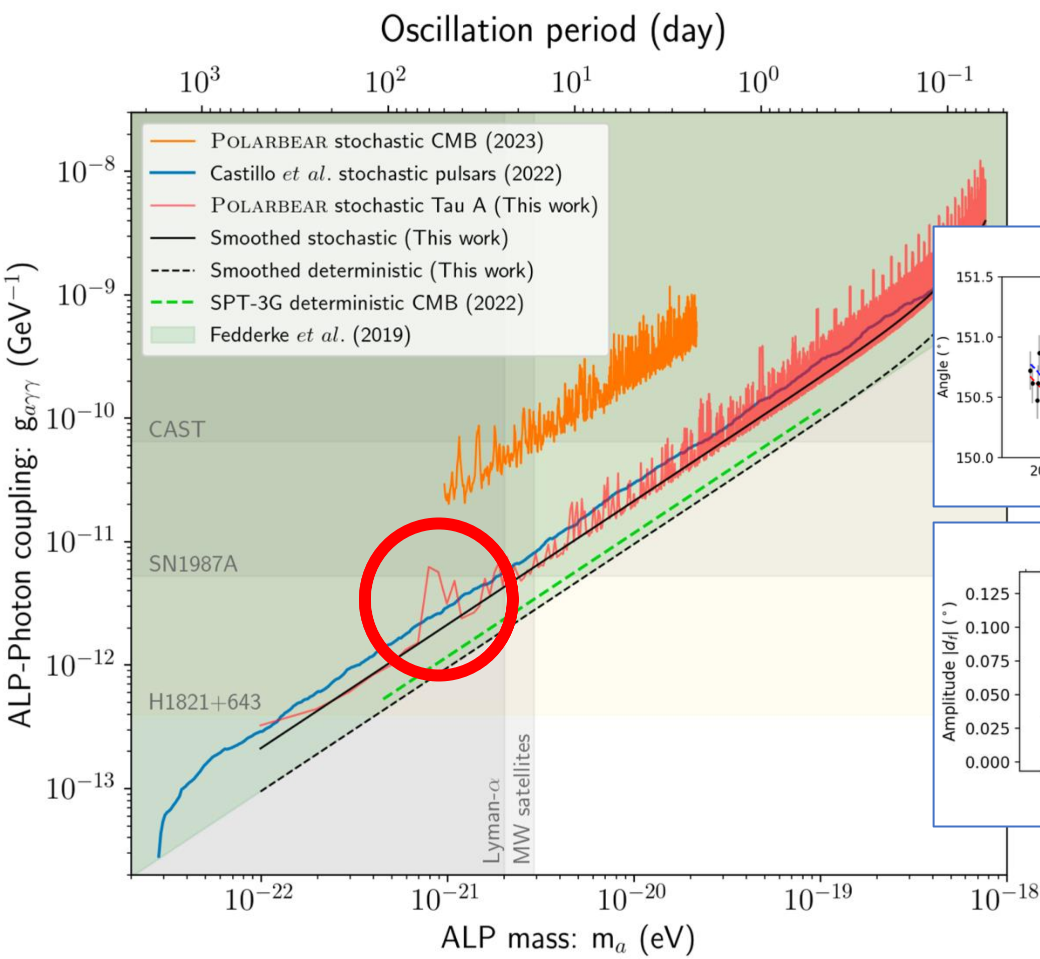
$$g_{\phi\gamma,\mathbf{UL}} = \left(2.1\times10^{9}\ \mathrm{GeV}\right)^{-1}\times\tilde{A} \times\left(\frac{m_\phi}{1.0\times10^{-21}\ \mathrm{eV}}\right)\times\left(\kappa\frac{\rho_0}{0.3\ \mathrm{GeV/cm^3}}\right)^{-1/2}$$

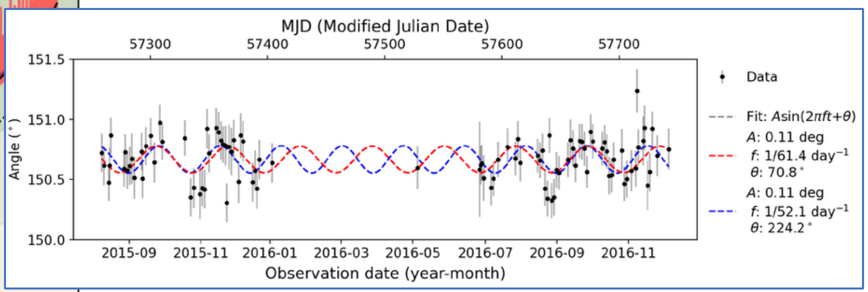
$$\tilde{A} < 0.142\ \mathrm{deg}$$

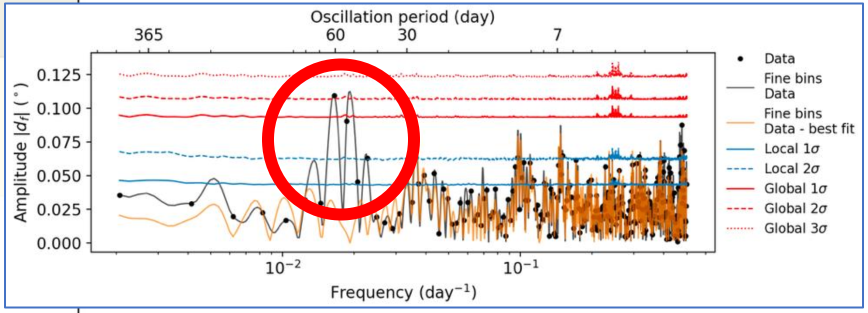
Evidence from Tau A?

POLARBEAR Collaboration (Adachi+ 2024);









■ Over 2σ significance of oscillations

Birefringence is testable not only with CMB

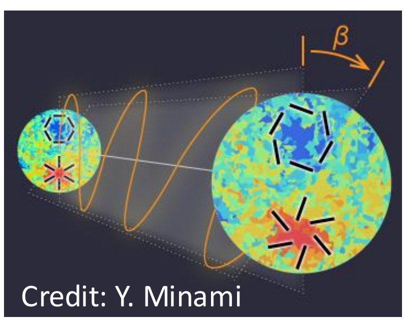
Dark energy	Fuzzy DM	QCD axion DM	(Axion mass)
10^{-33}	10^{-22}	10^{-6}	m_a[eV]

$(t_{\rm osc} \gg {\rm year})$ $(t_{\rm osc} \sim {\rm hour} - {\rm year})$ $(t_{\rm osc} \sim {\rm ms} - {\rm hour})$

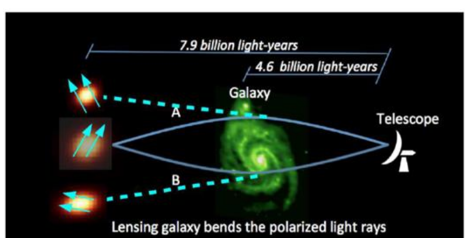
Laboratory (optical cavity) search

CMB search

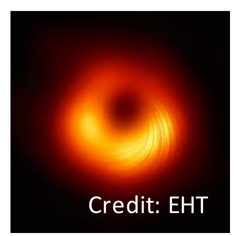
Astrophysical search



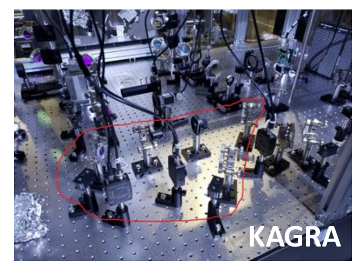
Credit: Y. Minami

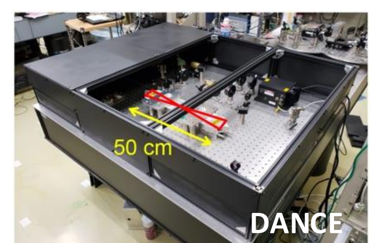


Credit: Y. Urakawa

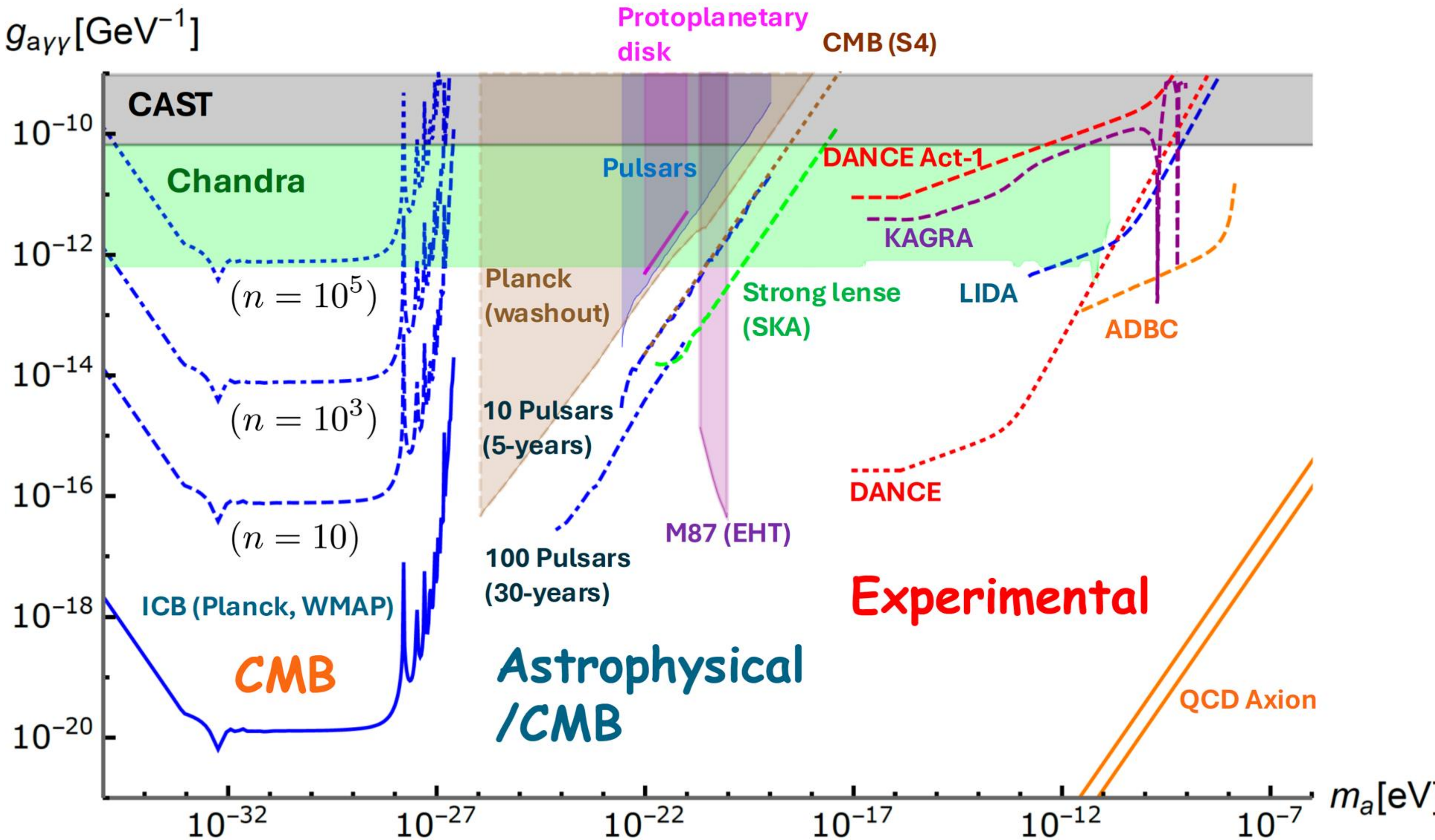

Credit: EHT


Credit: ESO





Axion-photon constraints overview



n: phase ambiguity of ICB (*Naokawa, Namikawa, Murai, IO, Kamada 2024*)

Birefringence from vector-type CS operator

Carroll, Field, Jackiw (1990); … Nakai, Namba, IO, Qiu, Saito (2024)

$$J_\mu K^\mu \ ; \ K^\mu \equiv 2A_\nu \tilde{F}^{\mu\nu} \qquad J_\mu : \text{matter field}$$

- This operator form is rewritten as the form of scalar-type CS operator:

$$c_{\rm EB}\boldsymbol{E}\cdot\boldsymbol{B}, \qquad \dot{c}_{\rm EB} = \boxed{J_0 \sim H c_{\rm EB}}$$

Problem?

- Gauge-dependent operator (but solvable by introducing Stueckelberg trick)
- It may allow a presence of photon mass: $m_\gamma \lesssim 10^{-18}\text{eV}$

ICB from cosmic neutrino background

Geng, Ho, Ng (2007);…

$$\mathcal{L} \supset \frac{c_\nu}{2M^2} \bar{\nu}\gamma_\mu \nu A_\nu \tilde{F}^{\mu\nu}$$

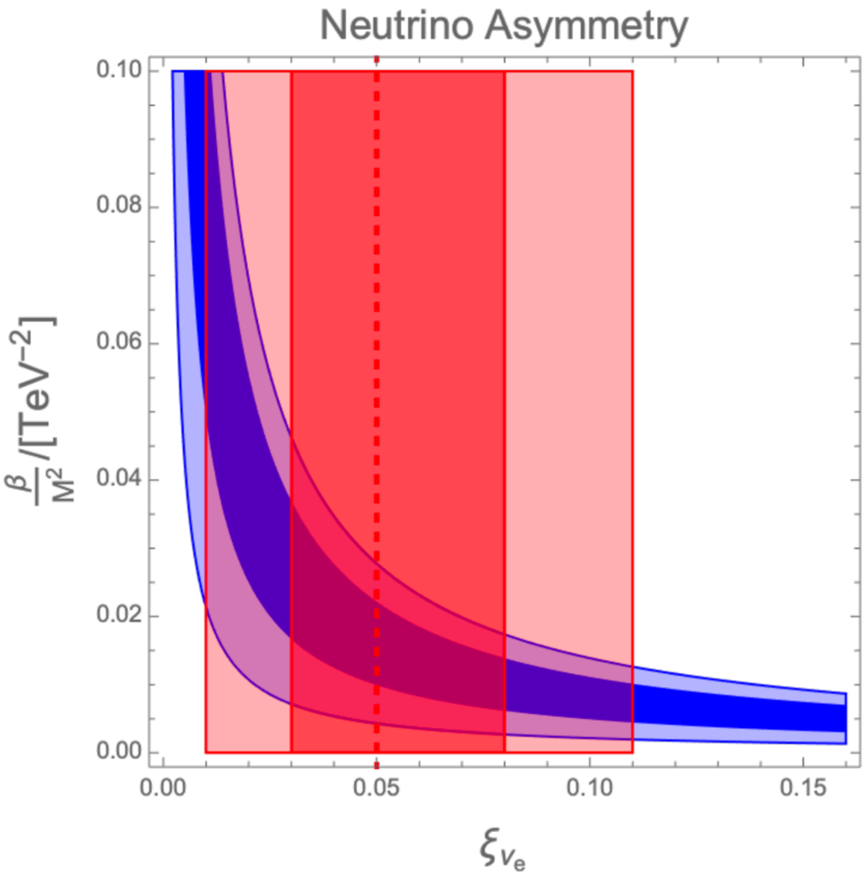
- The ICB angle is given by the asymmetry of neutrino and anti neutrino number density

$$\beta = \frac{c_\nu}{2M^2} \int_e^0 \Delta n_\nu dt$$

$$\Delta n_\nu = n_\nu - n_{\bar{\nu}}$$

$$= \frac{g T_\nu^3}{6\pi^2}(\pi^2 \xi_\nu + \xi_\nu^3) \qquad \xi_\nu \equiv \frac{\mu_\nu}{T_\nu}$$

$$\beta \simeq 0.3^\circ c_\nu \left(\frac{\xi_{\nu_e}}{0.05}\right)\left(\frac{7.9\mathrm{TeV}}{M}\right)^2$$



Zhou, Huang, Geng (2023)

Summary & Outlook

- Cosmic birefringence is a phenomenon of polarization rotation effect in the presence of parity-violating physics, such as axion-photon interaction.
- Recent measurements of isotropic cosmic birefringence angle in CMB is hard to explain by the Standard Model. It might give us a hint for several cosmological axion scenarios.
- Parity-violating photon coupling to the cosmic neutrino background is also potentially testable with the measurement of cosmic birefringence.
- More observational tests are to come!

Cảm ơn!