Cosmic birefringence and its implications

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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
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学術変革領域研究
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IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

2024.6.11 Copernicus Webinar

Cosmic birefringence

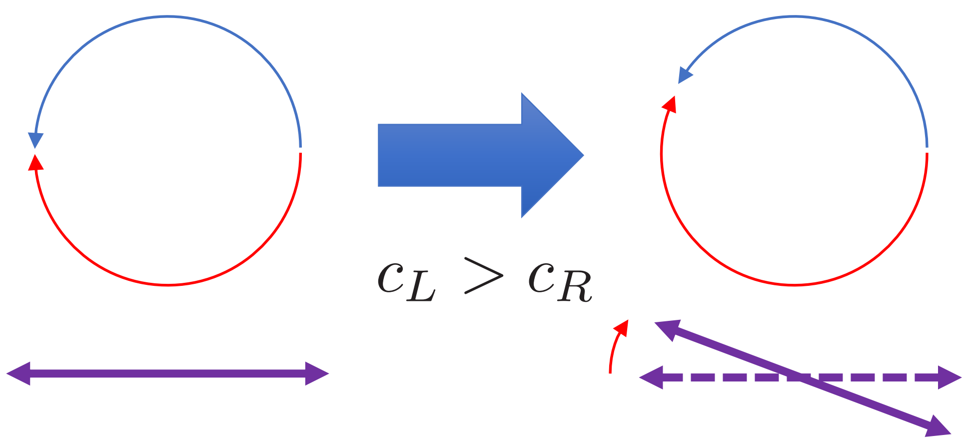
Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998); …

Parity-violating phenomenon by a cosmic birefringent material

Ex: pseudo scalar field - electromagnetic interaction

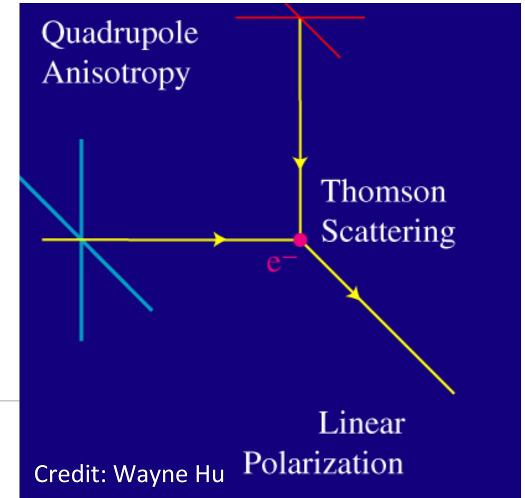
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma} \varphi F_{\mu\nu} \tilde{F}^{\mu\nu} \ , \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

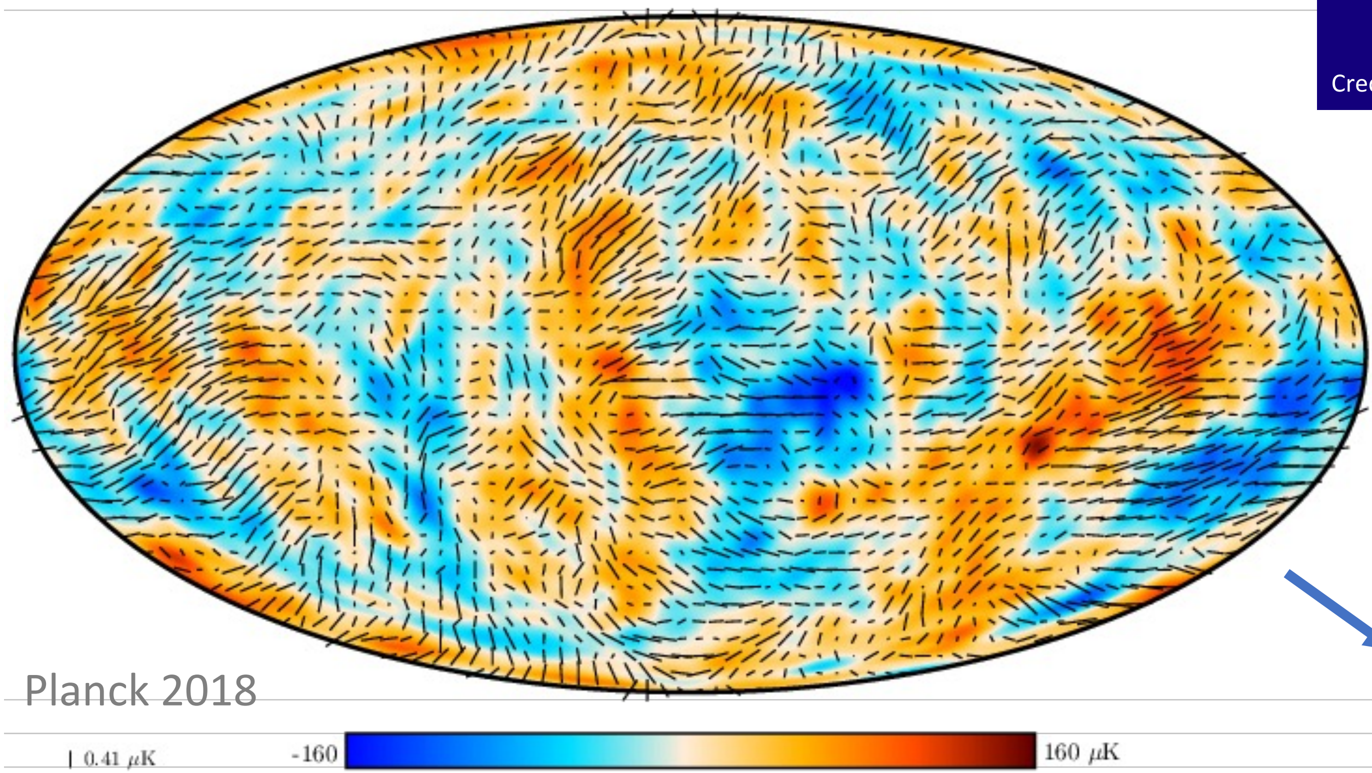
Dispersion relation: $\ddot{A}_k^{\mathrm{L/R}} + \omega^2_{\mathrm{L/R}} A_k^{\mathrm{L/R}} = 0, \quad c_{\mathrm{L/R}} \equiv \frac{\omega_{\mathrm{L/R}}}{k} = \sqrt{1 \pm \frac{g_{a\gamma}\dot{\varphi}}{k}}$



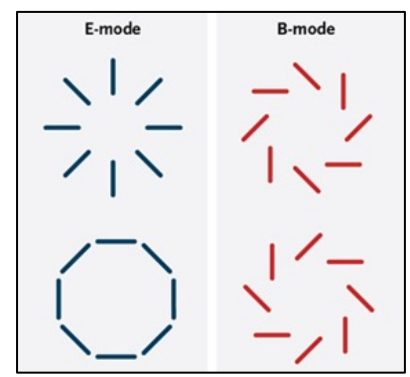
→ leading to the rotation of linear-polarization direction

CMB polarization map



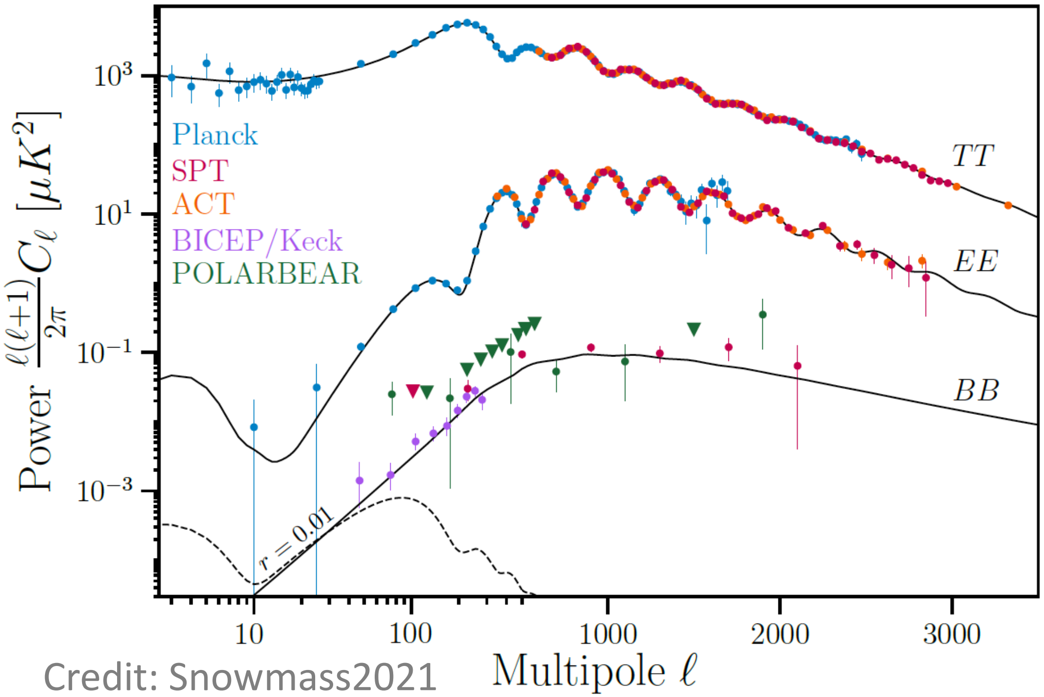


E-mode v.s. B-mode



CMB angular power spectra

$$\langle T(\boldsymbol{\ell})T^*(\boldsymbol{\ell}')\rangle = (2\pi)^2\delta^{(2)}(\boldsymbol{\ell}-\boldsymbol{\ell}')C_\ell^{TT}$$
$$\langle E(\boldsymbol{\ell})E^*(\boldsymbol{\ell}')\rangle = (2\pi)^2\delta^{(2)}(\boldsymbol{\ell}-\boldsymbol{\ell}')C_\ell^{EE}$$
$$\langle B(\boldsymbol{\ell})B^*(\boldsymbol{\ell}')\rangle = (2\pi)^2\delta^{(2)}(\boldsymbol{\ell}-\boldsymbol{\ell}')C_\ell^{BB}$$



Credit: Snowmass2021

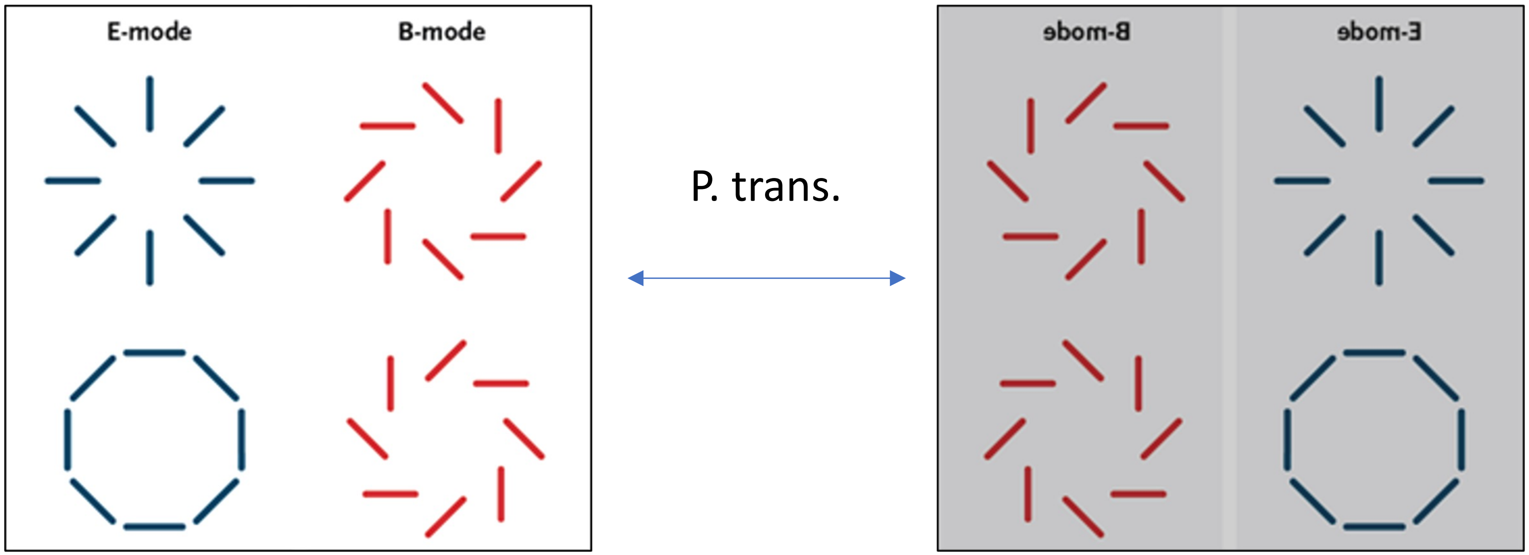
- Power spectra of T and E-mode have been precisely measured
- B-mode is still dominated by instrumental noises.

  (especially for the inflationary B-mode)

→ **More to come** in next decade!

Simons Observatory(2023~)
LiteBIRD(2032~)…

Parity flip in polarization pattern

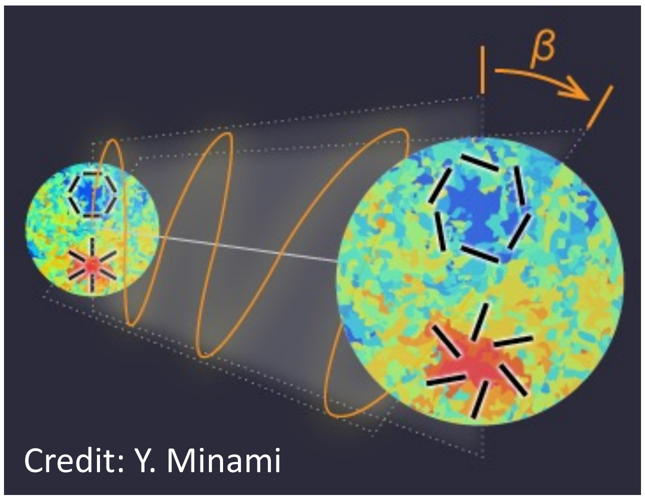


Parity-even: $C_\ell^{TT},\ C_\ell^{EE},\ C_\ell^{BB},\ C_\ell^{TE}$ (parity-invariant theory, well measured)

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

Generation EB correlation function

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



Credit: Y. Minami

■ Cosmic birefringence converts E and B 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 polarizations ↑ 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

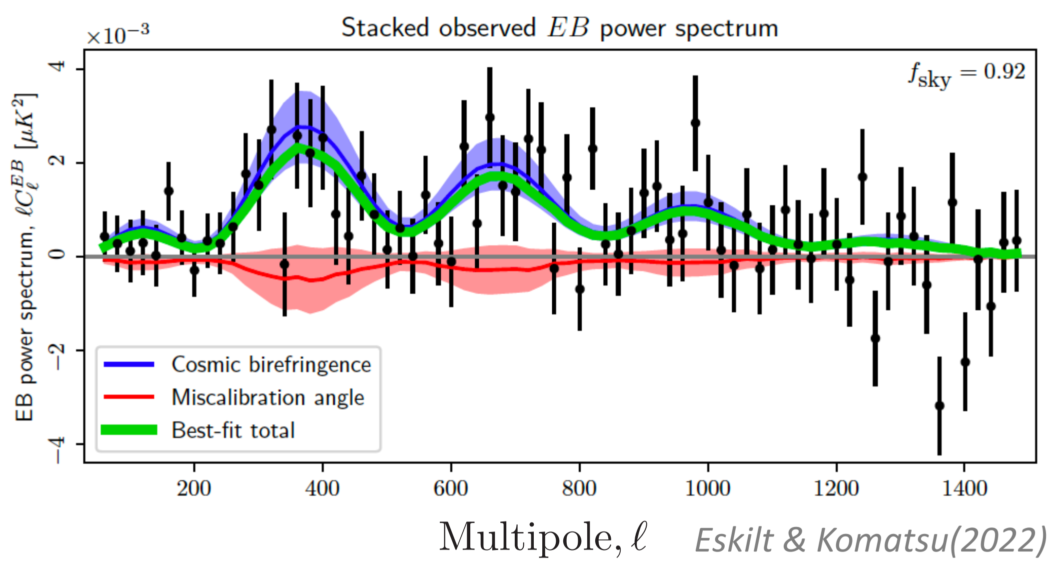
(note: β is assumed to be constant)

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);

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

To explain ICB…

- Linear polarization rotation is potentially caused by the axion-photon interaction

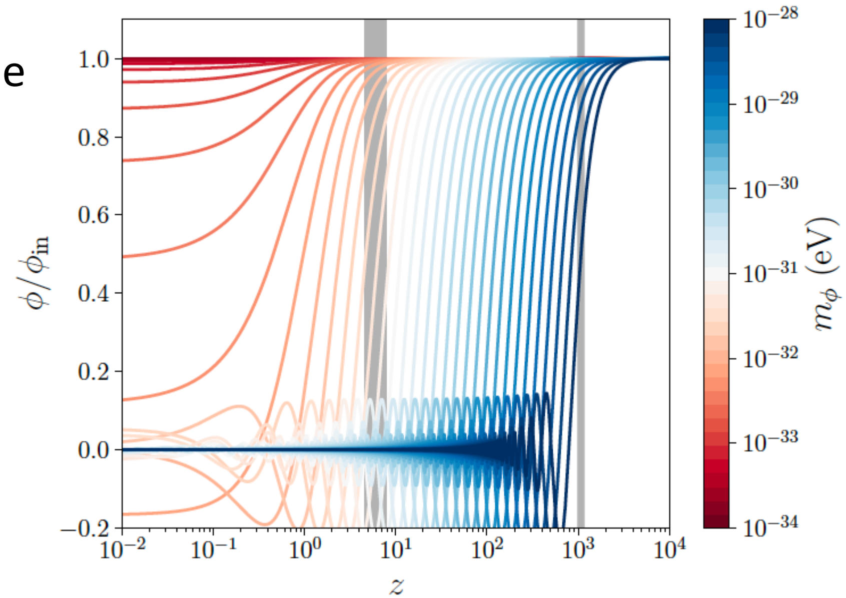
$$\mathcal{L}_{\rm int} = \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \rightarrow \quad \omega_{\rm L/R} = k\sqrt{1 \pm \frac{g_{\phi\gamma}\dot{\phi}}{k}} \simeq k \pm \frac{g_{\phi\gamma}}{2}\dot{\phi}$$

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

- Field displacement is given by a time evolution of axion background:

Ex) $V(\phi) = \frac{1}{2} m_\phi^2 \phi^2$

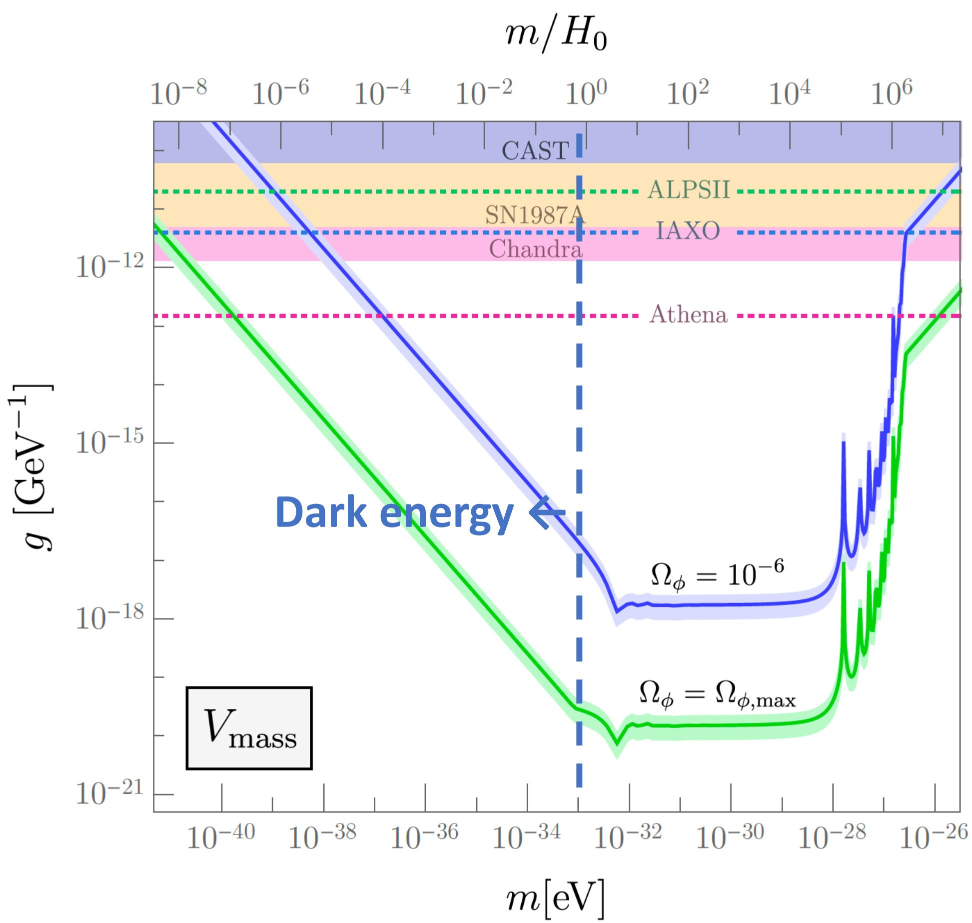
$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$



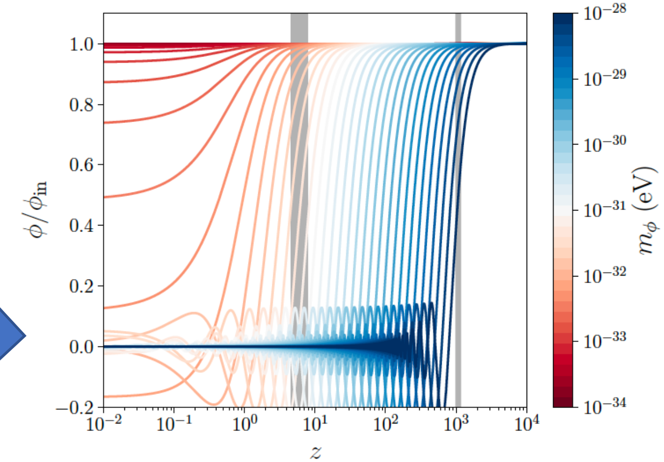
Lee, Hotinli, Kamionkowski (2022)

ICB from axion dark energy (DE)

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



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



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

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

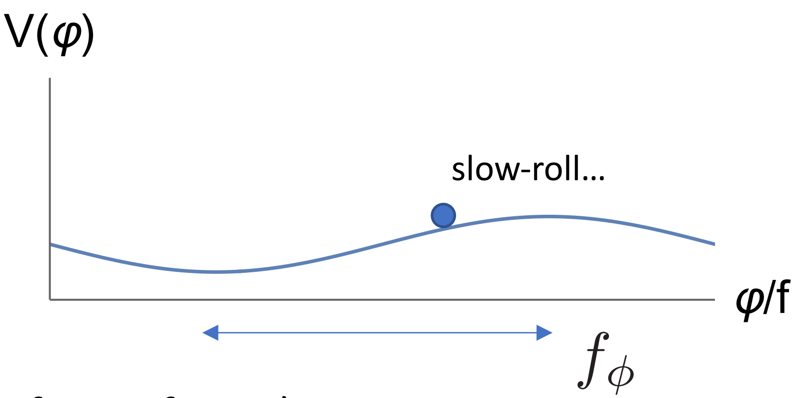
$$\rightarrow \beta = \frac{g}{2}\Delta\phi \propto gm\sqrt{\Omega_\phi}$$

Conventional issue of axion DE model

Friemann+ (1995); …

- Consider a **nearly flat** axion cosine potential

$$V(\phi) = m_\phi^2 f_\phi^2 \left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right]$$



- Slow-roll condition (constraint on the equation of state for DE) requires

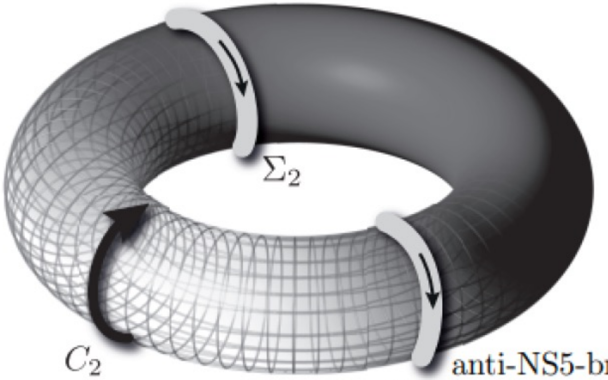
$$f_\phi \simeq 14 M_{\rm Pl} \left(\frac{\Omega_\phi}{0.69}\right)^{1/2} \left(\frac{m_\phi/H_0}{0.1}\right)^{-1} > M_{\rm Pl}$$

(In controlled setup, $f_\phi \ll M_{\rm Pl}$) ***Banks+ (2003);***

Or we could avoid it by relying on a fine-tuning of initial axion displacement…

Axion monodromy

Silverstein, Westphal (2008); McAllister, Silverstein, Westphal (2008);…



- Axion potential from wrapped branes:

$$V = \frac{2\epsilon}{(2\pi)^5 g_s^2 \alpha'^2}\sqrt{L^4 + g_s^2 a^2}$$

$$V \longrightarrow \mu^4 \frac{\phi}{f_a} \quad (a \gg L^2/g_s)$$

$$\mu^4 \equiv \frac{2\epsilon}{(2\pi)^5 g_s \alpha'^2}$$
$$\phi \equiv f_a a$$

- The potential energy is not bounded from above, but experiences a *monodromy*

→ extends axion field value to the periodic scale:

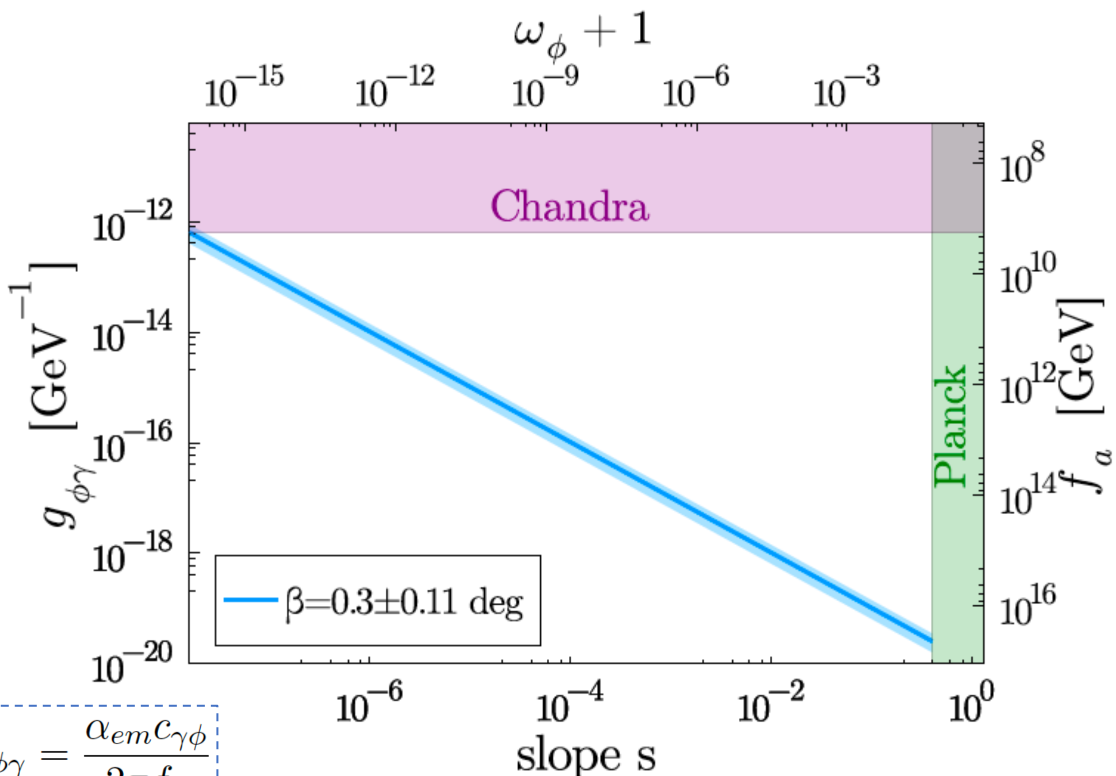
$$\phi \gg M_{\rm Pl} \text{ with } f_a \ll M_{\rm Pl}$$

(potentially explains the cosmic birefringence?)

Panda, Sumitomo, Trivedi (2010);…

ICB from monodromic axion DE

Gasparotto & IO (2022);



$$g_{\phi\gamma} = \frac{\alpha_{em} c_{\gamma\phi}}{2\pi f_a}$$

- Constraint on a potential slope

$$s \equiv \frac{dV/d\phi}{3M_{\rm Pl}^2 H_0^2} = \frac{\mu^4/f_a}{3M_{\rm Pl}^2 H_0^2}$$

of linear potential

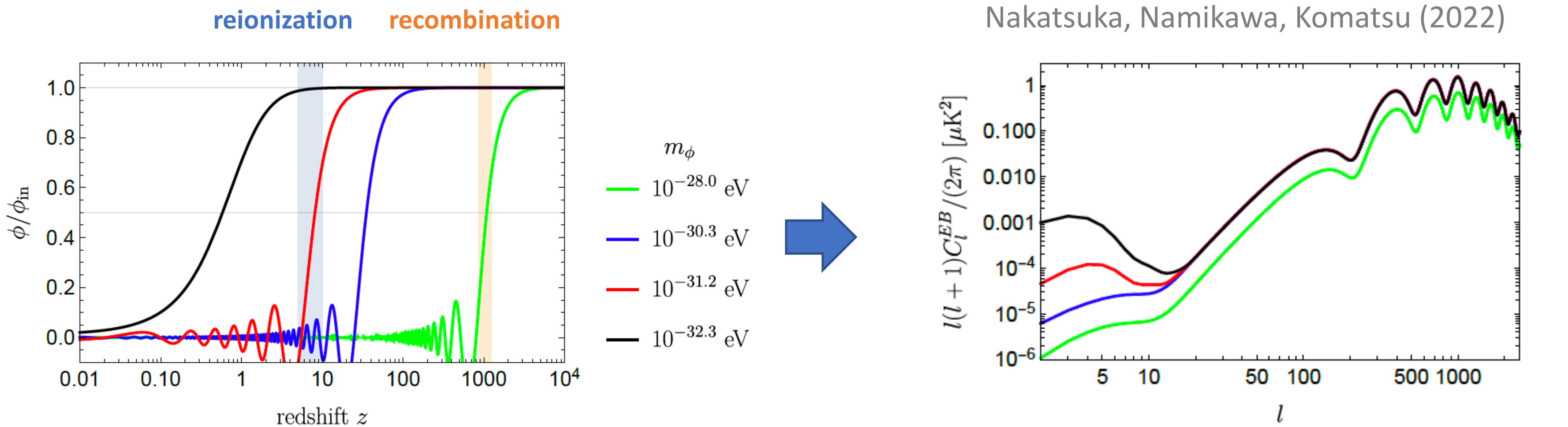
$$\frac{f_a}{c_{\gamma\phi}} = 4.52 \times 10^{16}\,\mathrm{GeV}\left(\frac{0.30\mathrm{deg}}{|\beta|}\right)\left(\frac{s}{0.4}\right)$$

← sub-Planckian (GUT) scale!

ICB constraints on heavier axions

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

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



- Several constraints on…

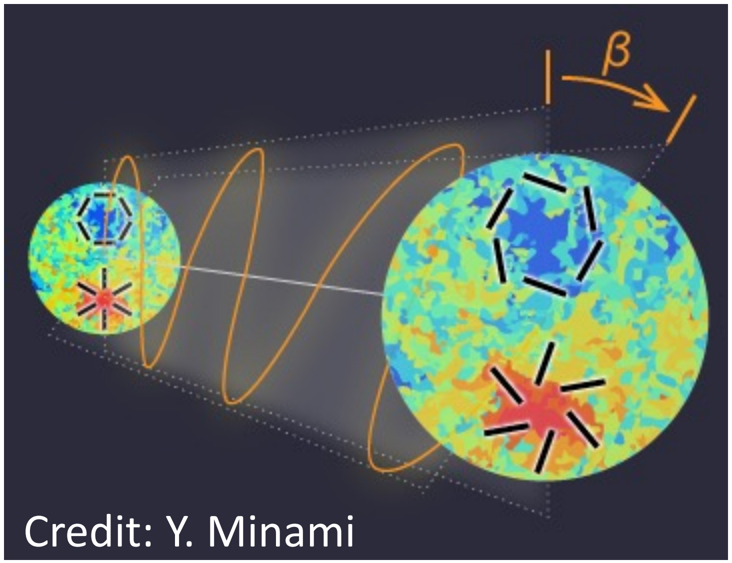
Early dark energy ***Murai, Naokawa, Namikawa, Komatsu (2022); Eskilt+ (2023);***

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);***

Question

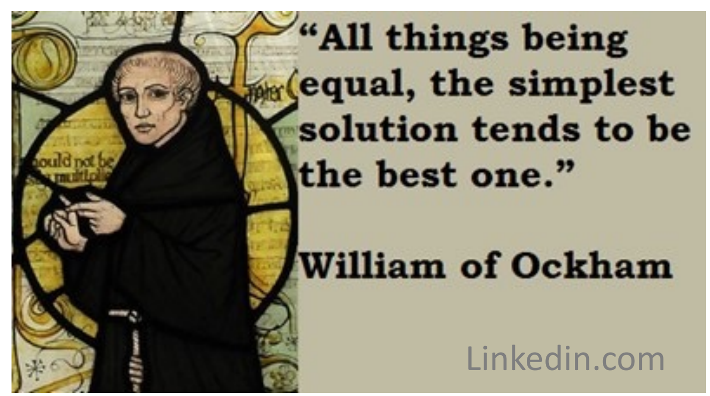


?

axions
new physics

Why new physics?

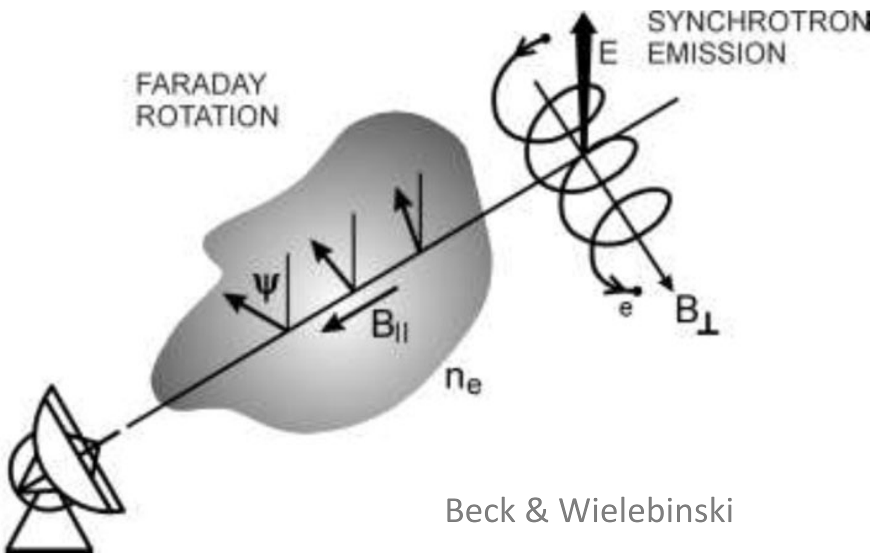
Why not our known physics in Standard Model?



Case 1: Faraday rotation in CMB

- Polarization rotation due to (cosmological) magnetic field and free electron:

$$\beta = \mathrm{RM}\ \lambda^2 \qquad \mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^d ds\ n_e(s) B_{\parallel}(s)$$



Beck & Wielebinski

- Large scale primordial magnetic field could provide EB correlation

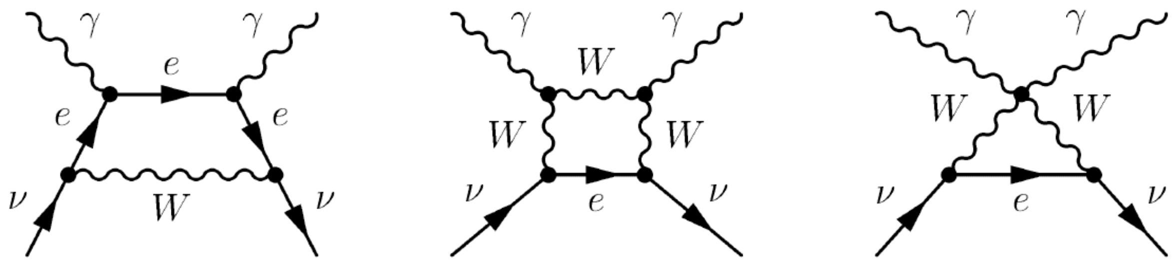
- Upper limit on primordial magnetic field from CMB observations:

$$B_{1\mathrm{Mpc}} \lesssim \mathcal{O}(1)\mathrm{nG}$$

Case 2: Cosmic neutrino background

Mohanty, Nieves, Pal (1997); Karl, Novikov (2000);…

Karl & Novikov (2004);



- Via loop-interactions, neutrino-antineutrino background asymmetry could provide a difference of photon's propagation between two helicities.

- Photon's rotation angle per length:

$$\frac{\phi}{l} = \frac{112\pi G_{\rm F}\alpha_{\rm em}}{45\sqrt{2}}\left[\ln\left(\frac{M_{\rm W}}{m_e}\right)^2 - \frac{8}{3}\right]\frac{\omega^2 T_\nu^2}{M_{\rm W}^4}(n_\nu - n_{\bar\nu}) \quad (\omega \ll M_W)$$

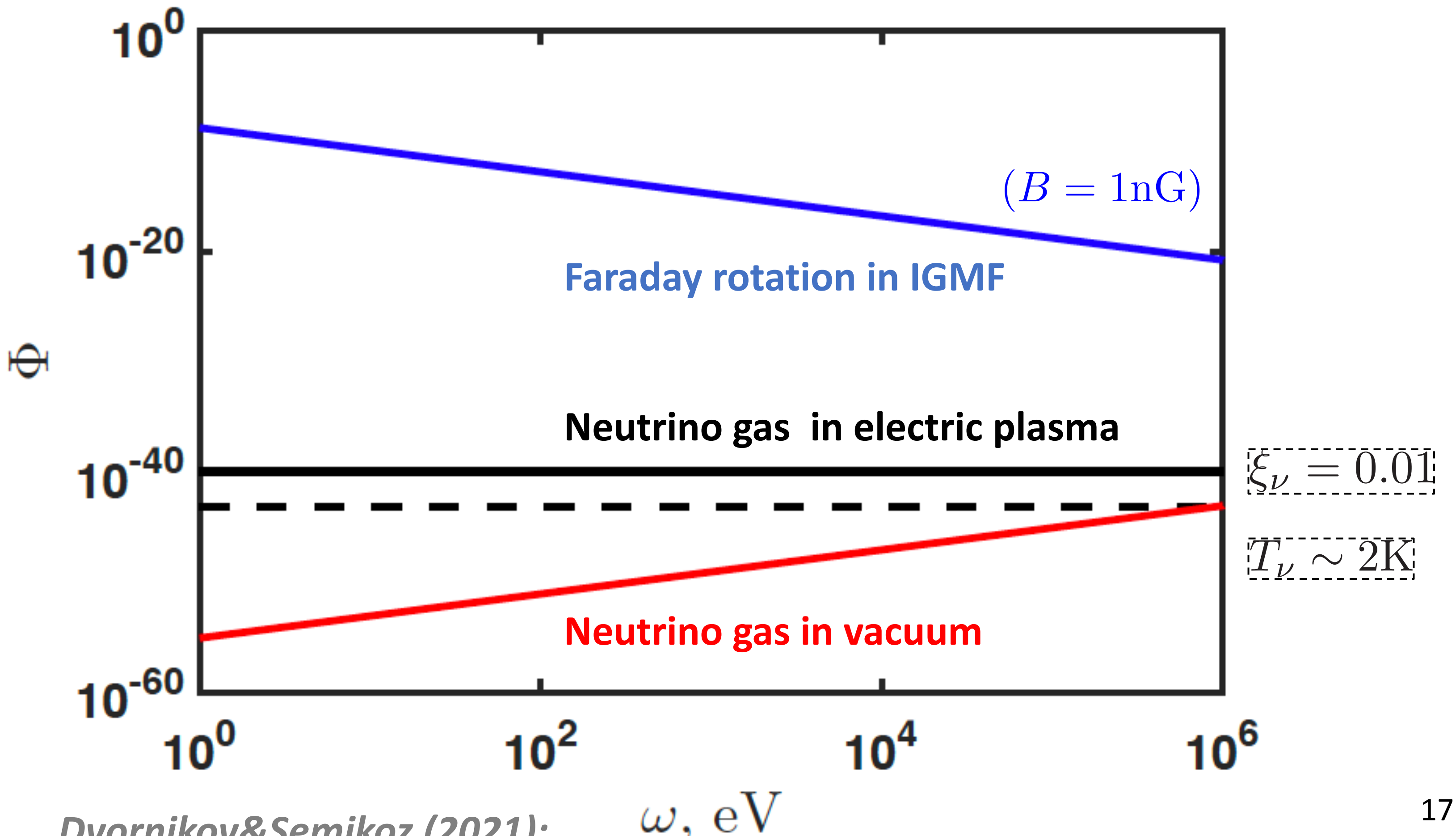
(In plasma): $$\frac{\phi}{l} = \frac{\sqrt{2}G_{\rm F}\alpha_{\rm em}}{3\pi}\left(\frac{\omega_p^2}{m_e^2}\right)(n_{\nu_e} - n_{\bar\nu_e}) \qquad \omega_p \equiv \sqrt{\frac{e^2 n_e}{m_e}}$$

neutrino-asymmetry: $n_\nu - n_{\bar\nu} \simeq \xi_\nu T_\nu^3/6 \qquad \xi_\nu \equiv \mu_\nu/T_\nu \ll 1$

Rotation angle at horizon size

$\Phi = \phi/(\ell/\ell_H) \quad \ell_H = H_0^{-1}$

Planck/WMAP: $\beta \simeq 0.005[\text{rad}]$



Dvornikov&Semikoz (2021);

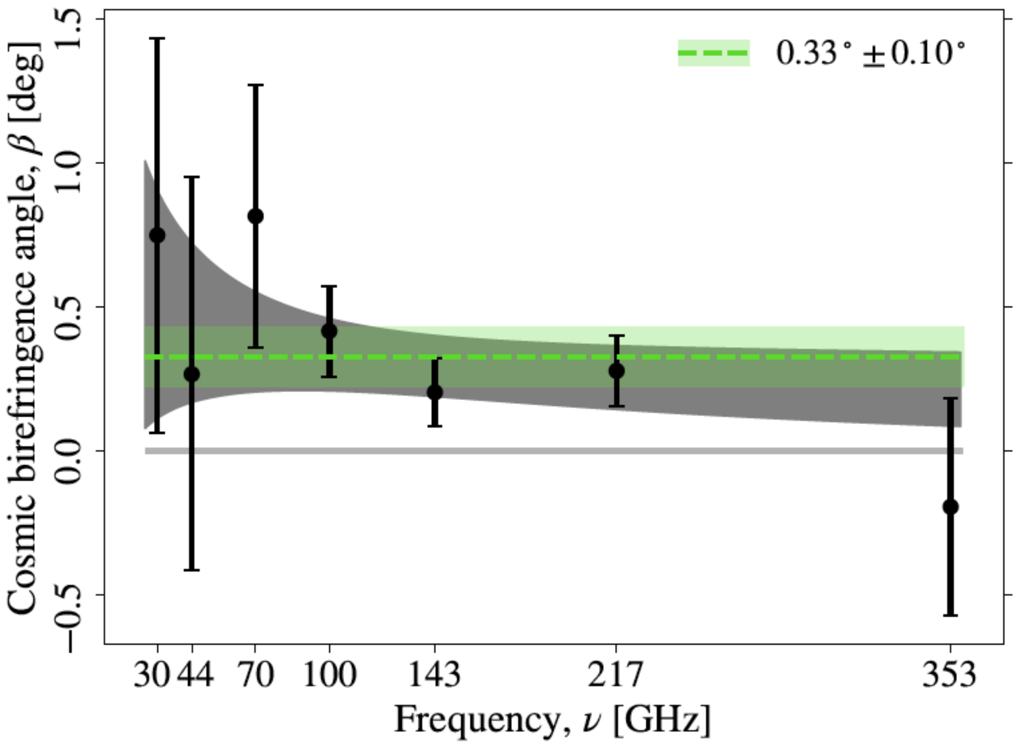
Another important observational fact

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**

To be summarized…

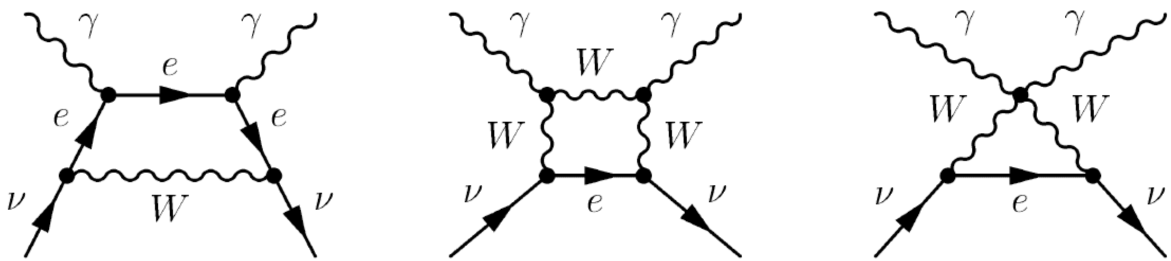
- Is it impossible to explain the measured cosmic birefringence angle in our known fields?

- We may need to consider beyond Standard Model.
  But we may not need a new field.

- **We can list up whole relevant cases by using an effective field theory (EFT) of Standard Model (SMEFT)!**

Effective Lagrangian approach

Ex) photon-neutrino loop interactions



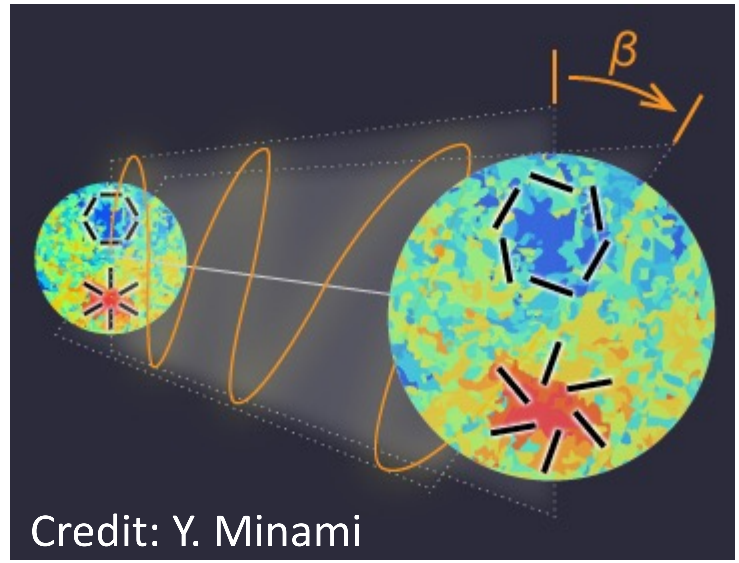
- For low energy $\ll m_e, M_W$

  above interactions can be described by the following operator: ***Karl & Novikov (2004);***

$$\frac{1}{m^6}[F_{\mu\alpha}(\partial_\gamma \tilde{F}_{\mu\beta})][\bar{\nu}\gamma_\alpha \partial_\beta \partial_\gamma (1+\gamma_5)\nu] + h.c.$$

- Leading to a list of the parity-violating operator: $-\frac{1}{4}F\hat{O}\tilde{F}$

Isotropic cosmic birefringence (ICB)



- To explain this, we need to consider:

$$\mathcal{L} = -\frac{1}{4}FF - \frac{1}{4}F\tilde{\mathcal{O}}\tilde{F}$$

- On a cosmological background

$$\phi_{\tilde{\mathcal{O}}} \equiv \langle \tilde{\mathcal{O}} \rangle,$$

the rotation angle is given by **its field displacement**

$$\beta = \frac{1}{2}\int_{t_{\rm LSS}}^{t_0} dt\, \frac{\partial \phi_{\tilde{\mathcal{O}}}}{\partial t} = \frac{1}{2}\left[\phi_{\tilde{\mathcal{O}}}(t_0) - \phi_{\tilde{\mathcal{O}}}(t_{\rm LSS})\right]$$

(present) (last scattering surface)

- If $\tilde{\mathcal{O}} = \tilde{\mathcal{O}}(\partial) \to \tilde{\mathcal{O}}(\omega)$, it leads to a frequency-dependent birefringence

→ inconsistent with observations

SMEFT and low-energy EFT (LEFT)

(caution: not Standard Model itself!)

- Include **all operators** of SM fields **respecting gauge symmetries**

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

  (LEFT: EFT below the electroweak breaking scale) $SU(3)_C \times U(1)_{EM}$

- Provided that no undiscovered light particles exist (such as axion)

Our results ***Nakai, Namba, IO, Qiu, Saito (2023);***

- Only a CS-type effective operator $\tilde{\mathcal{O}} F_{\mu\nu} \tilde{F}^{\mu\nu}$

  can produce a frequency-independent isotropic cosmic birefringence

But…

- **None of such effective operator leads to the desired birefringence angle**

CS-type scalar operator

$$\mathcal{L}_{\rm CS} = \frac{\alpha}{8\pi}\sum_a \frac{\tilde{\mathcal{O}}_a}{\Lambda_a^n} F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \begin{array}{l}(a: \ \text{operator species}) \\ (n: \ \text{dimension of the operator})\end{array}$$

$\tilde{\mathcal{O}}_a$: Lorentz scalars, singlets for SM symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$

■ List up all possible operators of each dimension in SMEFT/LEFT

Building blocks:

dimension 1	✓ Higgs field H	✓ Covariant derivative D
dimension 3/2	✓ SM fermion ψ	
dimension 2	✓ SM field strength tensor X	

Scalar operator (dimension-six)

$$\tilde{\mathcal{O}}_a = H^2 \text{ or } D^2$$

Grzadkowski+(2010);

- The operators relevant to CS are reduced to Higgs one:

$$\frac{\alpha}{8\pi}\frac{H^\dagger H}{\Lambda_H^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Higgs field gets a vev below electroweak scale and **becomes time-independent**.

Constraint on the time variation via electron mass: $\Delta m_e/m_e = (4 \pm 11) \times 10^{-3} (68\% \text{ C.L.})$

Planck (2015);

- From collider constraint, $\Lambda_H > \text{TeV}$

Higgs cannot explain the reported ICB

Scalar operator (dimension-seven)

$$\boxed{\tilde{\mathcal{O}}_a = \psi^2}$$

$$\sum_{\psi=e,\nu,d,u} \frac{\alpha}{8\pi} \frac{\tilde{\mathcal{O}}_\psi}{\Lambda_\psi^3} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

electron: $\tilde{\mathcal{O}}_e \equiv \tilde{C}_e^{ij} \bar{e}^i P_L e^j + \text{h.c.}\,,$ → **excluded (small density)**

---

neutrino: $\tilde{\mathcal{O}}_\nu \equiv \tilde{C}_\nu^{ij} \bar{\nu}^i P_L \nu^j + \text{h.c.}\,,$ → most relevant?

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quark:

$\tilde{\mathcal{O}}_d \equiv \tilde{C}_d^{ij} \bar{d}^i P_L d^j + \text{h.c.}\,,$

$\tilde{\mathcal{O}}_u \equiv \tilde{C}_u^{ij} \bar{u}^i P_L u^j + \text{h.c.}\,,$

→ **excluded (time-independent)**

$P_L \equiv (1-\gamma^5)/2$

Scalar operator (dimension-seven)

- Operator for neutrinos: $$\tilde{\mathcal{O}}_\nu = \frac{(\tilde{\mathcal{C}}_\nu^\dagger + \tilde{\mathcal{C}}_\nu)^{ij}}{2}\bar{\nu}^i\nu^j + \frac{(\tilde{\mathcal{C}}_\nu^\dagger - \tilde{\mathcal{C}}_\nu)^{ij}}{2}\bar{\nu}^i\gamma^5\nu^j$$ $(i : \text{flavor})$

  Evaluate cosmological background value:

$$\langle \bar{\nu}^i \nu^j \rangle = \delta^{ij}\mathcal{F}(t)\,,$$

$$\mathcal{F}(t) \equiv \int \frac{d^3p}{(2\pi)^3}\frac{m_i}{E_{\mathbf{p}}}\left[n^i(p,t) + \bar{n}^i(p,t)\right] \qquad \langle \bar{\nu}^i \gamma^5 \nu^j \rangle = 0$$

- At the last scattering surface,

$$\mathcal{F}(t_{\rm LSS}) \simeq 0.5\,\frac{m_i}{T_{\rm LSS}}\left(N^i + \bar{N}^i\right)\,, \;\; m_i \ll T_{\rm LSS} \qquad N_i^{1/3} = \mathcal{O}(10^{-10})\mathrm{GeV}$$

$$\beta \simeq -0.008^\circ \frac{\alpha}{137^{-1}}\sum_i \frac{m_i}{T_{\rm LSS}}(\tilde{\mathcal{C}}_\nu + \tilde{\mathcal{C}}_\nu^\dagger)^{ii}\frac{N^i + \bar{N}^i}{\Lambda_\nu^3}$$

Altmannshofer, Tammaro, Zupan (2021);

$$\Lambda_\nu > \mathcal{O}(10^{-2})\mathrm{GeV\ to\ }\mathcal{O}(10^2)\mathrm{GeV}$$

Neutrino cannot explain the reported ICB

Scalar operator (dimension-eight)

$$\boxed{\tilde{\mathcal{O}}_a = X^2} \quad \sum_{X=F,Z,W,G} \frac{\alpha}{8\pi} \left(\frac{X_{\alpha\beta} X^{\alpha\beta}}{\Lambda_X^4} + \frac{X_{\alpha\beta} \tilde{X}^{\alpha\beta}}{\Lambda_{\tilde{X}}^4} \right) F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- In the presence of background magnetic field, $F_{\mu\nu} = F_{\mu\nu}^{(\mathrm{bg})} + F_{\mu\nu}^{(\mathrm{p})}$

  the component $(F_{\alpha\beta}^{(\mathrm{bg})} F^{(\mathrm{p})\alpha\beta})(F_{\mu\nu}^{(\mathrm{bg})} \tilde{F}^{(\mathrm{p})\mu\nu})$ leads to $\boldsymbol{E}_{||} \cdot \boldsymbol{B}_{||}$ term

  (parallel to background vector)

→ **providing spatially-dependent cosmic birefringence**

- Weak bosons are unstable. Gluon condensate scale (QCD scale) would be much smaller than the cutoff mass scale (> TeV) → **excluded**

- For dimensions over 8: does not contain new building blocks, will give subdominant effect

  → **excluded**

Beyond SMEFT/LEFT?

- Consider new particles with CS-operators

$$\frac{\alpha}{8\pi}\frac{\Phi^\dagger\Phi}{\Lambda^2}F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \text{(for a scalar } \Phi\text{)}$$

$$\frac{\alpha}{8\pi}\frac{\bar{\chi}\chi}{\Lambda^3}F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \text{(for a fermion } \chi\text{)}$$

- The cosmological background is bounded from above by the energy density as

$$\langle\Phi^\dagger\Phi\rangle \lesssim \rho/m^2\ , \quad \langle\bar{\chi}\chi\rangle \lesssim \rho/m \qquad \rho < \rho_{c,\mathrm{LSS}} \simeq (3\times 10^{-13}\mathrm{TeV})^4$$

$$m \lesssim 10^{-14}\,\mathrm{eV}\left(\frac{|\beta|}{0.3^\circ}\right)^{-1/2}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-1} \quad \text{(scalar)}$$

$$m \lesssim 10^{-40}\,\mathrm{eV}\left(\frac{|\beta|}{0.3^\circ}\right)^{-1}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-3} \quad \text{(fermion)}$$

- Similar argument can be applied for a dark photon

Beyond SMEFT/LEFT?

- The vector-type CS-operator

$J_\mu K^\mu \; ; \; K^\mu \equiv 2A_\nu \tilde{F}^{\mu\nu}$ is allowed (if we have a Stückelberg field)

Then, it is rewritten as $c_{\mathrm{EB}} \boldsymbol{E} \cdot \boldsymbol{B}, \qquad \dot{c}_{\mathrm{EB}} = J_0 \sim H c_{\mathrm{EB}}$

- For a neutrino background, $J_0 \sim n_\nu$

$\beta = \mathcal{O}(0.1^\circ)$ is realized due to an enhancement of H^{-1}

- Generating a photon mass: $\mathcal{O}(10^{-18})\mathrm{eV}$ (upper bound)

Summary & Outlook

- Measured isotropic cosmic birefringence may give us a hint for new physics such as axions. But is it possible to explain it by Standard Model?
- SMEFT/LEFT is a powerful tool to systematically list up such operators in SM and its extension.
- Standard Model fields are impossible to explain the current measured angle of isotropic birefringence.
- Necessary to think of new light fields!

Thank you very much!