Can we explain cosmic birefringence without a new light field beyond Standard Model?

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JHEP 01 (2024) 08, 057 [arXiv:2310.09152[astro-ph.CO]]

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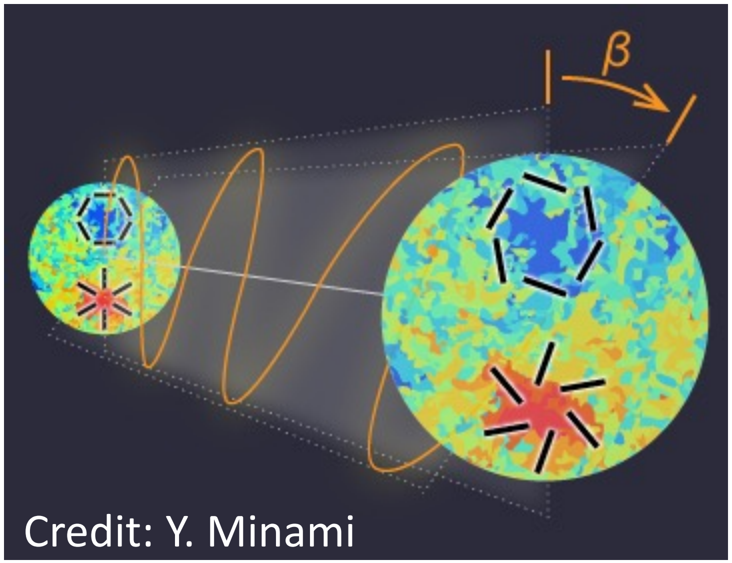
科研費
KAKENHI

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）

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

2024.3.7 @YITP (FY2023)

Motivation



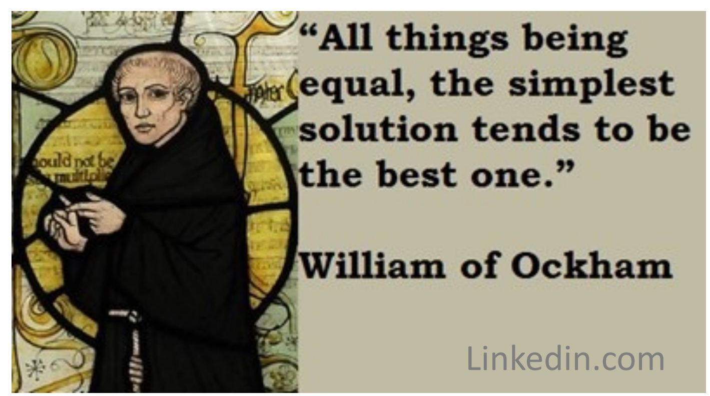
Credit: Y. Minami

?

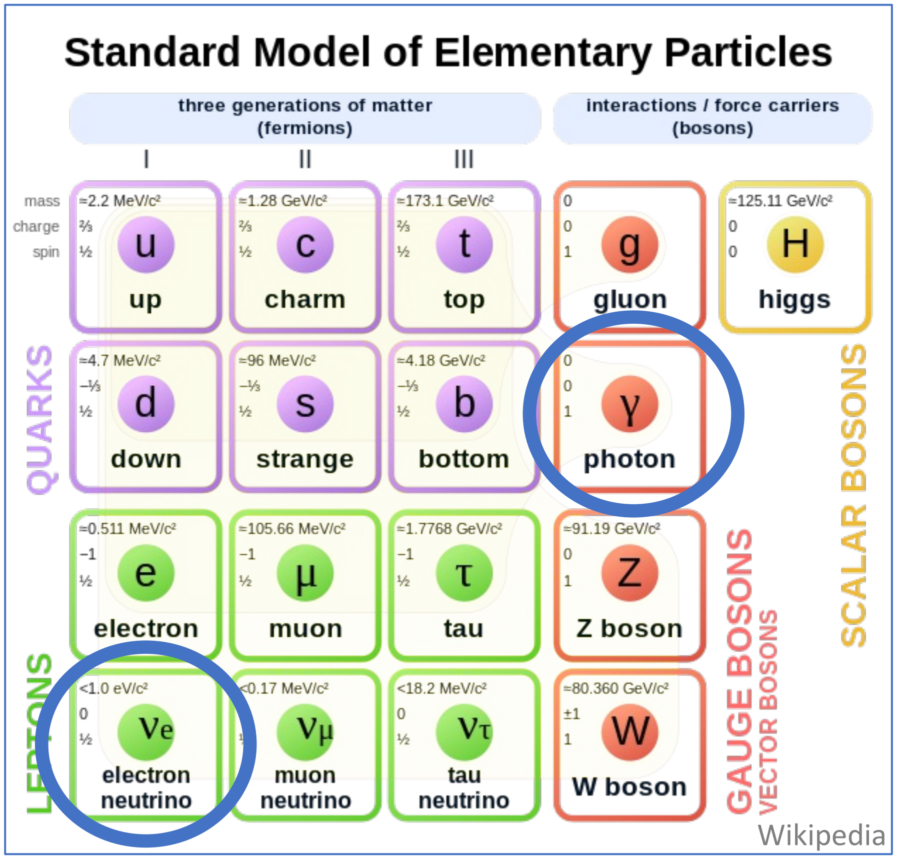
axion
new light field

Why new physics?

Why not our known physics in Standard Model?



Candidates in Standard Model



Requests:

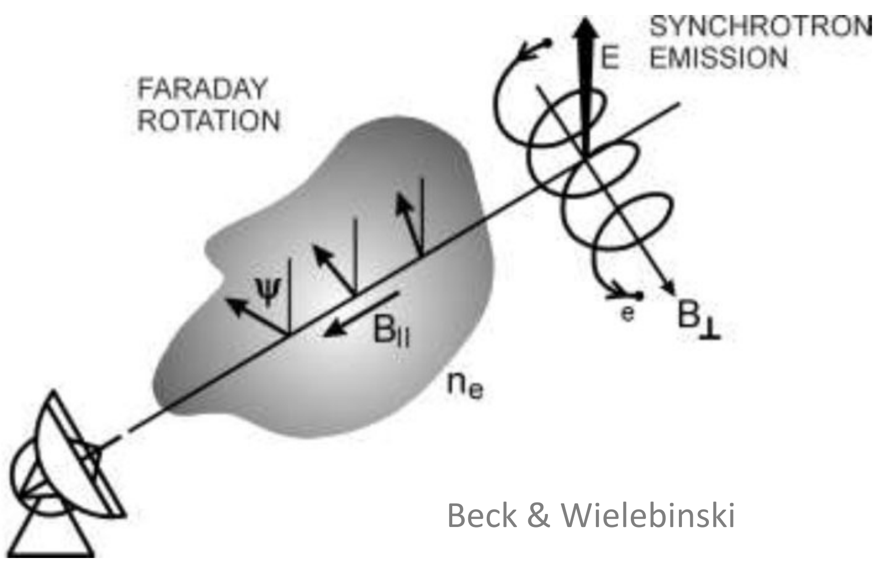
- Cosmic birefringence is a **parity-violating** effect
- Signal is isotropic: medium should be **homogeneous and stable**
- It would be a **neutral** component: charged cosmological background (electron, proton) would be suppressed due to small number density

→ Let’s focus on photon and (electron) neutrino!

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

- Helical magnetic field can provide EB correlation in CMB

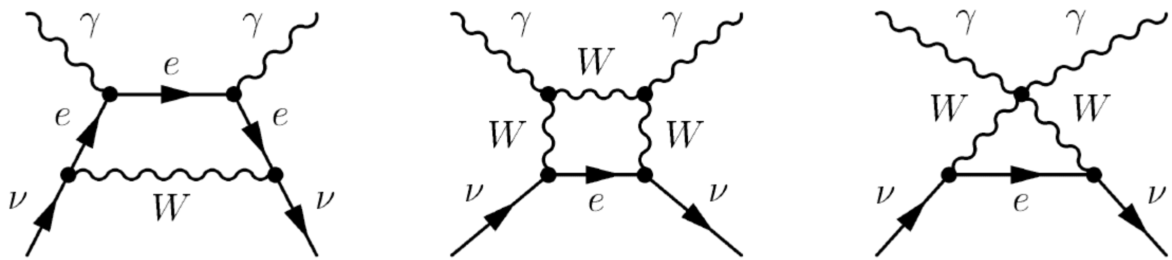
- Upper limit on primordial magnetic field from CMB observations:

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

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:

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

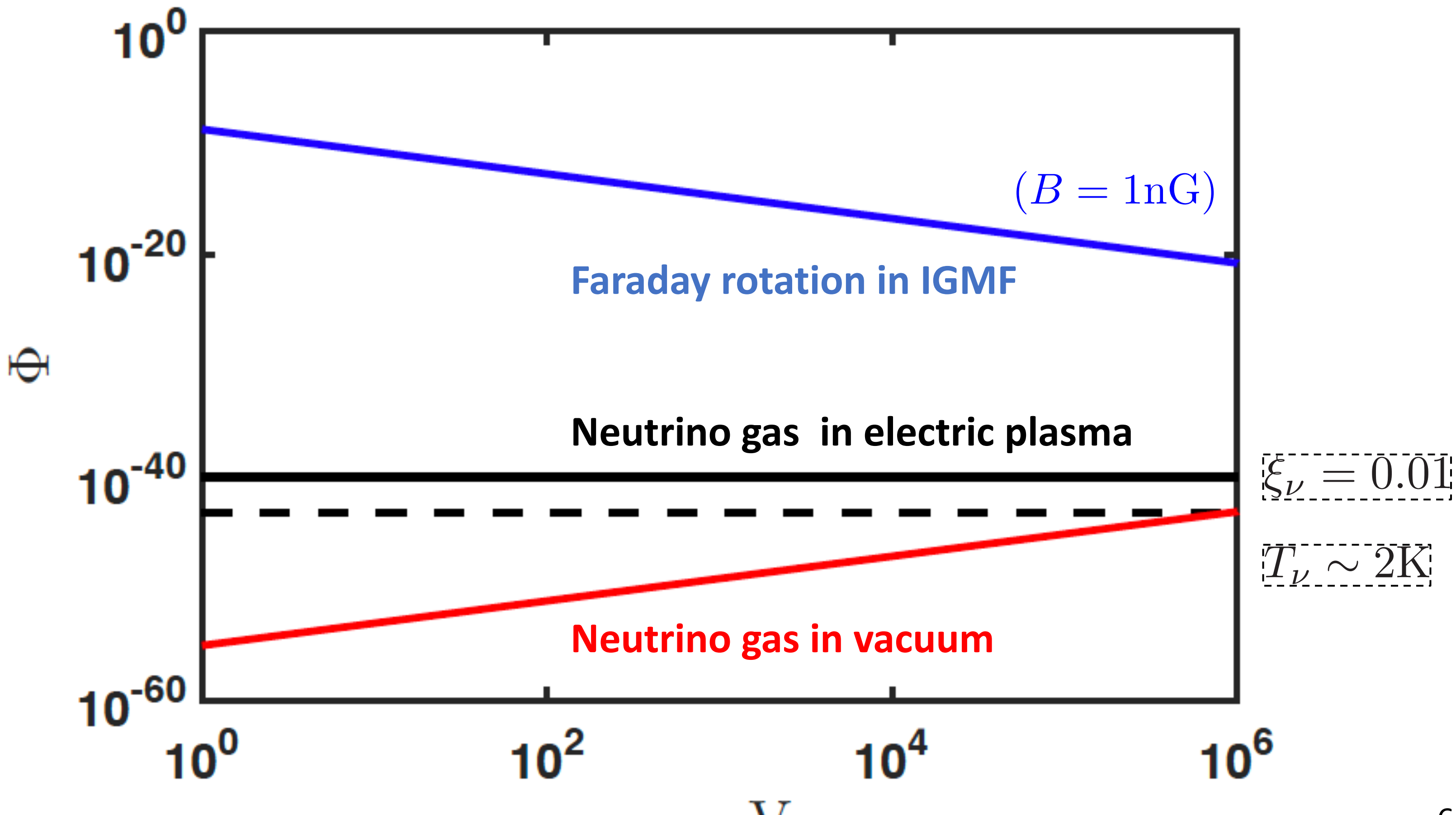
Off-shell: $$\frac{\phi}{l} = \frac{\sqrt{2}G_{\mathrm{F}}\alpha_{\mathrm{em}}}{3\pi}\left(\frac{\omega_p^2}{m_e^2}\right)(n_{\nu_e} - n_{\bar{\nu}_e}) \qquad \omega_p \equiv \sqrt{\frac{e^2 n_e}{m_e}}$$

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);

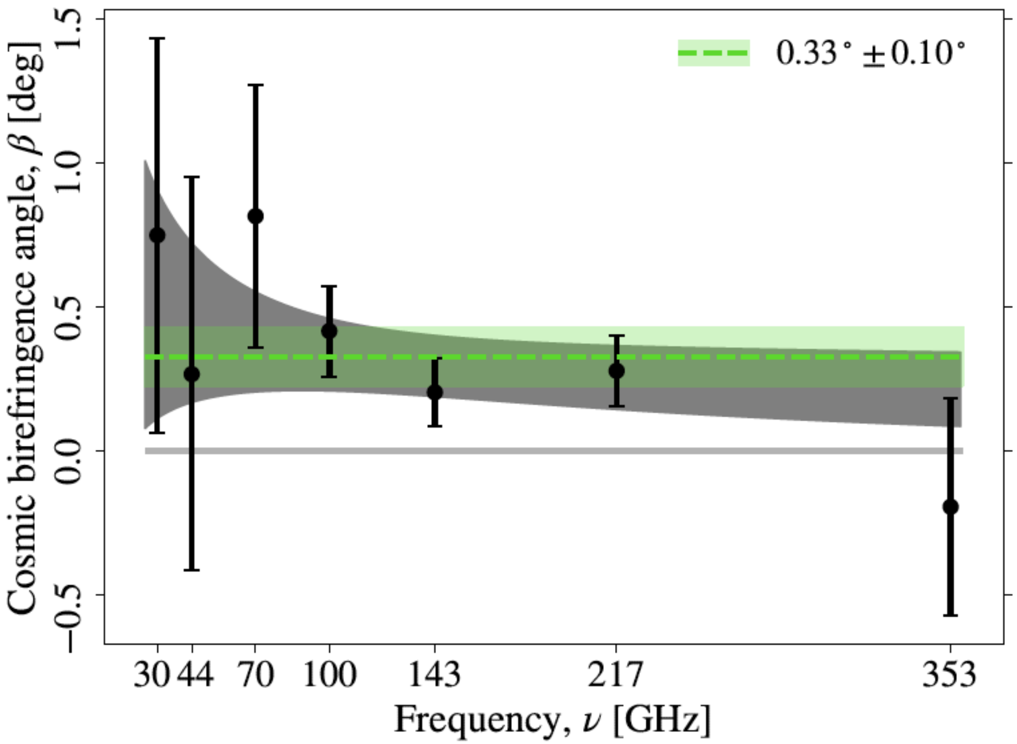
Another important observational fact

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**

Question

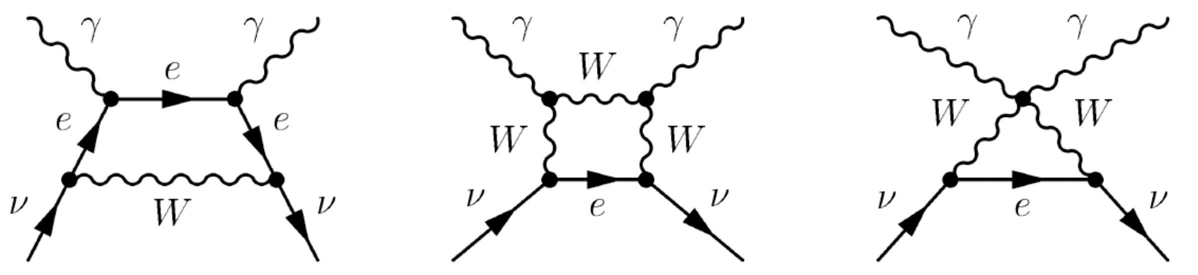
- Is it really impossible to explain the measured cosmic birefringence angle in our known fields?

- 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 Effective field theory (EFT) of Standard Model (SMEFT)!**

Effective Lagrangian approach

Ex) photon-neutrino loop interactions



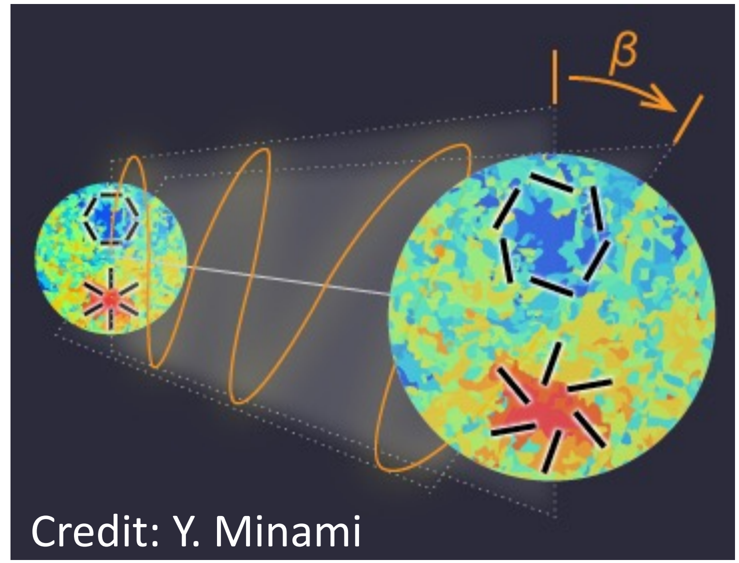
- For low energy $\ll m_e, M_W$

  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 list up 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

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, Qiu, IO, 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

$$\mathcal{L}_{\mathrm{CS}} = \frac{\alpha}{8\pi} \sum_a \frac{\tilde{\mathcal{O}}_a}{\Lambda_a^n} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

(a : operator species)
(n : dimension of the operator)

$\tilde{\mathcal{O}}_a$: 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)

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

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: $\Delta m_e/m_e = (4 \pm 11)\times 10^{-3}(68\%\ \mathrm{C.L.})$

Planck (2015);

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

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?

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)

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

- 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

Summary & Outlook

- Isotropic cosmic birefringence may give us a hint for new physics? Is it possible to explain by SM?
- SMEFT/LEFT is a powerful tool to systematically list up 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!