

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

Yu-Cheng QIU

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Summary

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

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with Yuichiro Nakai, Ryo Namba, Ippei Obata, Ryo Saito

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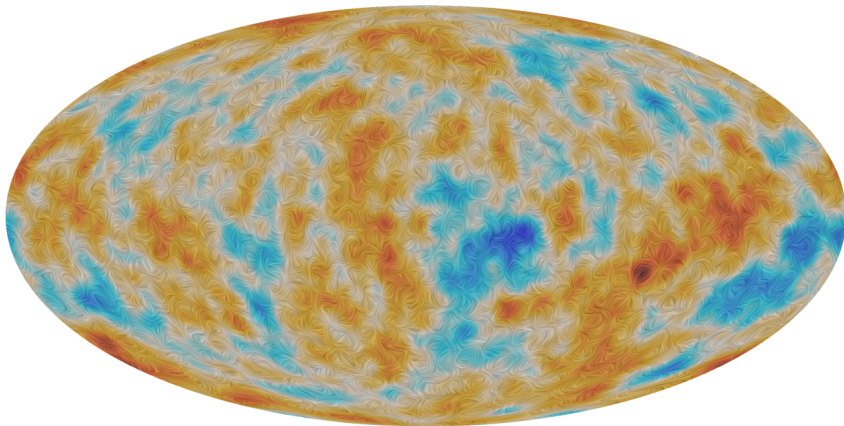


Figure: Copyright: ESA and the Planck Collaboration

Isotropic Cosmic Birefringence

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$$C_l^{EB,obs} \neq 0 \implies \beta \neq 0$$

- $\beta = 0.35^\circ \pm 0.14^\circ$ (2.4σ)
(Minami and Komatsu 2011.11254)
- $\beta = 0.34^\circ \pm 0.09^\circ$ (3.6σ)
(Eskilt and Komatsu 2205.13962)
- ... (5σ ?)

- 1 Isotropic
- 2 Frequency-blind

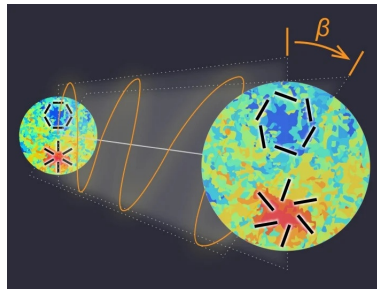


Figure: Credit: Yuto Minami

Axion (ALP) Explanation

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Consider Axion-photon coupling (Carroll and Field, 1991)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\theta(t)F_{\mu\nu}\tilde{F}^{\mu\nu}$$

This modifies equation of motion of photon (Choosing $A^0 = 0$ and $\nabla \cdot \vec{A} = 0$),

$$\left(\frac{\partial^2}{\partial \eta^2} - \nabla^2 + \dot{\theta} \nabla \times \right) \vec{A} = 0 \quad \Rightarrow \quad \omega_{\pm}^2 = k^2 \mp k\dot{\theta}$$

In the limit $\frac{|\dot{\omega}_{\pm}|}{\omega_{\pm}^2} \ll 1$, WKB approximation gives

$$A_{\pm} \propto e^{-i \int d\eta k} \exp \left(\pm i \int d\eta \frac{\dot{\theta}}{2} \right) \Rightarrow \beta = \frac{1}{2} \int_{\eta_{\text{LSS}}}^{\eta_0} d\eta \dot{\theta} = \frac{1}{2} [\theta(\eta_0) - \theta(\eta_{\text{LSS}})]$$

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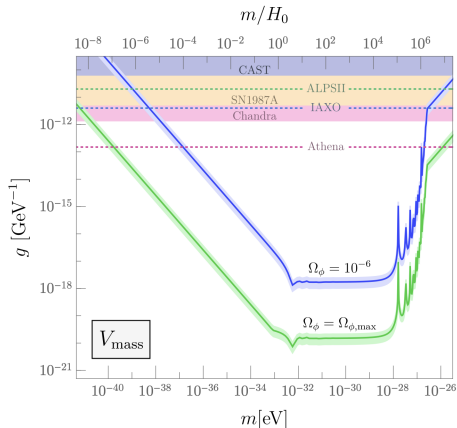
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Ultra-light
Axions!

Figure: Fujita et al. 2011.11894

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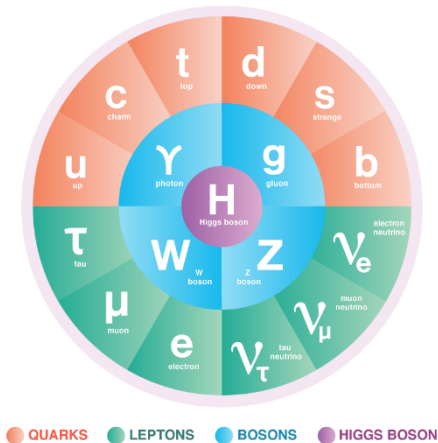
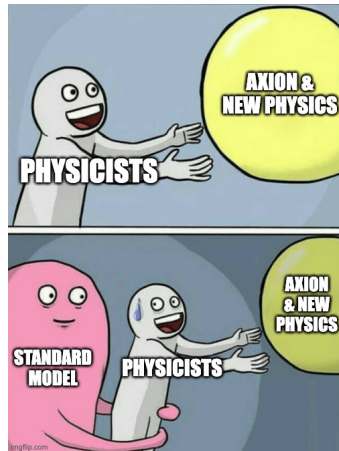


Figure: Artwork by Sandbox Studio, Chicago.



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- ICB is a propagating effect. Relevant operators are **quadratic** in \vec{E} and \vec{B} . In the vacuum, only $F_{\mu\nu}F^{\mu\nu}$ is relevant. Therefore, we need medium.
- Observed isotropy \implies medium is **homogeneous**.
- Derivative on \vec{E} and \vec{B} shall lead to frequency-dependent β , which do not fit the observation.

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- Derivative on \vec{E} and \vec{B} shall lead to frequency-dependent β , which do not fit the observation.

$$\mathcal{L} \sim c_{EE}(t)\vec{E} \cdot \vec{E} + c_{BB}(t)\vec{B} \cdot \vec{B} + c_{EB}(t)\vec{E} \cdot \vec{B}$$

- $\vec{E} \cdot \vec{B}$ -term violates parity, produces ICB.

Any operator that relevant to ICB should be reduced to $c_{EB}(t)\vec{E} \cdot \vec{B}$ in a cosmological background.



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- Of course, $\tilde{O}F_{\mu\nu}\tilde{F}^{\mu\nu} \rightarrow \tilde{O}\vec{E} \cdot \vec{B}$. Is it the only one?



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- Of course, $\tilde{O}F_{\mu\nu}\tilde{F}^{\mu\nu} \rightarrow \tilde{O}\vec{E} \cdot \vec{B}$. Is it the only one? 
- $\mathcal{J}_{\mu\nu\alpha\beta}F^{\mu\nu}\tilde{F}^{\alpha\beta}$ under the cosmological background,
 \mathcal{J} could be formed by $g_{\mu\nu}$ and $u_\mu \propto \nabla_\mu t$, t is cosmic time.

$$\mathcal{J}_{\mu\nu\alpha\beta} = \frac{1}{2} (g_{\mu\alpha}J_{\nu\beta} + g_{\mu\beta}J_{\nu\alpha} - g_{\nu\alpha}J_{\mu\beta} - g_{\nu\beta}J_{\mu\alpha}) , \quad J_{\mu\nu} = f(g_{\mu\nu}, u_\mu)$$

This reduce to

$$J_{\alpha\beta}F^{\alpha\mu}\tilde{F}^\beta{}_\mu \rightarrow \tilde{O}F_{\mu\nu}\tilde{F}^{\mu\nu} , \quad \tilde{O} = \frac{J_\mu{}^\mu}{4} = \frac{\mathcal{J}_{\alpha\beta}{}^{\alpha\beta}}{6}$$

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- $J_\mu K^\mu$, where $K^\mu = 2A_\nu\tilde{F}^{\mu\nu}$.
It is not $U(1)$ invariant unless $\nabla_{[\mu}J_{\nu]} = 0$, which means that $J_\mu \propto \nabla_\mu \tilde{O}$.
This makes $J_\mu K^\mu \rightarrow \tilde{O}F_{\mu\nu}\tilde{F}^{\mu\nu}$.

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- $J_{\mu\nu}F^{\mu\nu}$ may give rise to P-violating effect in the loop level.

Formally, $\delta J_{\mu\nu} = \hat{K}_{\mu\nu\alpha\beta}F^{\alpha\beta} \rightarrow F^{\mu\nu}\hat{K}_{\mu\nu\alpha\beta}F^{\alpha\beta}$.

If $\hat{K}_{\mu\nu\alpha\beta} \supset \tilde{O}_\epsilon \epsilon_{\mu\nu\alpha\beta}/2$, then $F^{\mu\nu}\hat{K}_{\mu\nu\alpha\beta}F^{\alpha\beta} \rightarrow \tilde{O}_\epsilon F_{\mu\nu}\tilde{F}^{\mu\nu}$.

However, \tilde{O}_ϵ is non-local, produces frequency-dependent ICB angle.

- **Cosmic Magnetic field** breaks parity.

However, it will produces Anisotropic Cosmic birefringence angle.

Dipole operator $J_{\mu\nu} F^{\mu\nu}$

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$$J_{\mu\nu} F^{\mu\nu}, \quad J_{\mu\nu} = \bar{\nu} \lambda \sigma_{\mu\nu} \nu, \quad \lambda = \underbrace{\mathfrak{M}}_{\text{magnetic}} + i \underbrace{e \gamma^5}_{\text{electric}}$$

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$$F^{\mu\nu} \hat{K}_{\mu\nu\alpha\beta} F^{\alpha\beta} \rightarrow \tilde{\mathcal{O}}_\epsilon F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad \tilde{\mathcal{O}}_\epsilon \propto \epsilon^{\mu\nu\alpha\beta} \hat{K}_{\mu\nu\alpha\beta}$$

$$\hat{K}_{\mu\nu\alpha\beta} \propto \bar{\nu}^{(bg)} \sigma_{\mu\nu} \lambda \frac{1}{i\not{\partial} - m} \sigma_{\alpha\beta} \lambda \nu^{(bg)}$$

Dipole operator $J_{\mu\nu} F^{\mu\nu}$

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$$F^{\mu\nu} \hat{K}_{\mu\nu\alpha\beta} F^{\alpha\beta} \rightarrow \tilde{\mathcal{O}}_\epsilon F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad \tilde{\mathcal{O}}_\epsilon \propto \epsilon^{\mu\nu\alpha\beta} \hat{K}_{\mu\nu\alpha\beta}$$

$$\hat{K}_{\mu\nu\alpha\beta} \propto \bar{\nu}^{(\text{bg})} \sigma_{\mu\nu} \lambda \frac{1}{i\not{\partial} - m} \sigma_{\alpha\beta} \lambda \nu^{(\text{bg})}$$

$$\begin{aligned} \tilde{\mathcal{O}}_\epsilon &\propto \bar{\nu}^{(\text{bg})} \epsilon^{\mu\nu\alpha\beta} \sigma_{\mu\nu} \lambda (i\not{\partial} - m)^{-1} \sigma_{\alpha\beta} \lambda \nu^{(\text{bg})} \\ &= -4im \bar{\nu}^{(\text{bg})} \lambda \gamma^5 (\partial^2 + m^2)^{-1} \lambda \nu^{(\text{bg})} \end{aligned}$$

Using $\epsilon^{\mu\nu\alpha\beta} \sigma_{\mu\nu} = -2i\gamma^5 \sigma^{\alpha\beta}$, $\sigma^{\mu\nu} \sigma_{\mu\nu} = 12$ and $\sigma^{\mu\nu} \gamma^\alpha \sigma_{\mu\nu} = 0$.

Dipole operator $J_{\mu\nu} F^{\mu\nu}$

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$$\langle \tilde{\mathcal{O}}_\epsilon \rangle \propto m \left\langle \bar{\nu}^{(\text{bg})} \lambda \gamma^5 (\partial^2 + m^2)^{-1} \lambda \nu^{(\text{bg})} \right\rangle$$

$\langle \bar{\nu} \gamma^5 \nu \rangle = 0 \neq \langle \bar{\nu} \nu \rangle$, this implies that

$$\langle \tilde{\mathcal{O}}_\epsilon \rangle \propto m(\mathfrak{M}\mathfrak{E} + \mathfrak{E}\mathfrak{M}) \int \frac{d^3 p_\nu}{(2\pi)^3} \frac{m}{E_\nu} \frac{n(p_\nu) + \bar{n}(p_\nu)}{(p_\nu + p_\gamma)^2 - m^2}$$

Let $p_\nu = (E_\nu, \mathbf{p}_\nu)$ and $p_\gamma = (\omega, \omega \mathbf{n})$, where $|\mathbf{n}| = 1$.

$$(p_\mu + p_\gamma)^2 - m^2 = 2\omega(E_\nu - \mathbf{n} \cdot \mathbf{p}_\nu)$$

$$\beta \propto \langle \tilde{\mathcal{O}}_\epsilon \rangle|_{\text{LSS}} \propto \frac{1}{\omega}, \quad \text{Frequency-dependent ICB}$$

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$$\frac{1}{2} \int d^4 k_1 d^4 k_2 A_\mu(k_1) \Pi^{\mu\nu}(k_1, k_2) A_\nu(k_2)$$

- Introduce helicity basis with respect to \mathbf{k} , $\{\epsilon_L^\mu, \epsilon_+^\mu, \epsilon_-^\mu\}$.
So $\epsilon_{L,\pm}^\mu u_\mu = 0$, $k_\mu \epsilon_\pm^\mu = 0 \neq k_\mu \epsilon_L^\mu$.

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So $\epsilon_{L,\pm}^\mu u_\mu = 0$, $k_\mu \epsilon_\pm^\mu = 0 \neq k_\mu \epsilon_L^\mu$.
- Including the background, one has $k_1^\mu + k_2^\mu \propto u^\mu \neq 0$.
Expand $k_1^\mu = \omega_1 u^\mu + |\mathbf{k}| \epsilon_L^\mu$ and $k_2^\mu = \omega_2 u^\mu - |\mathbf{k}| \epsilon_L^\mu$.
- With the background unit vector $u_\mu \propto \nabla_\mu t$, one has $\bar{B}^\mu = u_\nu \tilde{F}^{(0)\mu\nu}$.
- One could expand $\bar{B}^\mu = \bar{B}_L \epsilon_L^\mu + \bar{B}_+ \epsilon_+^\mu + \bar{B}_- \epsilon_-^\mu$.

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- One could expand $\bar{B}^\mu = \bar{B}_L \epsilon_L^\mu + \bar{B}_+ \epsilon_+^\mu + \bar{B}_- \epsilon_-^\mu$.
- $F_{\mu\nu} \tilde{F}^{\mu\nu} \implies \Pi^{\mu\nu} \supset \epsilon^{\mu\nu\alpha\beta} (k_1)_\alpha (k_2)_\beta \propto \epsilon^{\mu\nu\alpha\beta} u_\alpha (\epsilon_L)_\beta \propto \epsilon_+^{*\mu} \epsilon_+^\nu - \epsilon_-^{*\mu} \epsilon_-^\nu$
 $(F_{\alpha\beta}^{(0)} F^{(0)\alpha\beta})(F_{\mu\nu} \tilde{F}^{\mu\nu}) = |\bar{B}|^2 F \tilde{F}$ term gives ICB if $|\bar{B}|$ is uniform.

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$$(F_{\alpha\beta}^{(0)} F^{\alpha\beta})(F_{\mu\nu}^{(0)} \tilde{F}^{\mu\nu}) = (\bar{B}_\alpha u_\beta F^{\alpha\beta})(\bar{B}_\mu u_\nu \tilde{F}^{\mu\nu})$$

- $F^{\alpha\beta} \rightarrow k_1^\alpha A^\beta(k_1) - k_1^\beta A^\alpha(k_1)$ and $\tilde{F}^{\mu\nu} \rightarrow \epsilon^{\mu\nu\alpha\beta}(k_2)_\alpha A_\beta(k_2)$.
- $\bar{B}_\alpha u_\beta F^{\alpha\beta} \rightarrow \left[(\bar{B} \cdot k_1) u^\mu - (u \cdot k_1) \bar{B}^\mu \right] A_\mu(k_1)$
 $\propto (\bar{B}_+ \epsilon_+^\mu + \bar{B}_- \epsilon_-^\mu) A_\mu(k_1) + \dots$
- $\bar{B}_\mu u_\nu \tilde{F}^{\mu\nu} \propto (\bar{B}_+ \epsilon_+^\nu - \bar{B}_- \epsilon_-^\nu) A_\nu(k_2)$
- $(F_{\alpha\beta}^{(0)} F^{\alpha\beta})(F_{\mu\nu}^{(0)} \tilde{F}^{\mu\nu}) \supset C \bar{B}_+ \bar{B}_- (\epsilon_+^{*\mu} \epsilon_+^\nu - \epsilon_-^{*\mu} \epsilon_-^\nu) A_\mu A_\nu$.

This gives ACB due to the dependence on components of \bar{B} .



Relavant Operator $\tilde{O}F\tilde{F}$!

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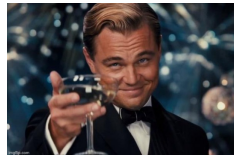
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To explain the observed frequency-independent ICB,
only CS-type operator $\tilde{O}_{F\mu\nu}\tilde{F}^{\mu\nu}$ should be considered.



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$$\mathcal{L}_{\text{CS}} = \frac{\alpha}{8\pi} \sum_a \frac{\tilde{\mathcal{O}}_a}{\Lambda_a^n} F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad n = \dim[\tilde{\mathcal{O}}_a]$$

Building Blocks:

$$H(\dim 1), \quad D_\mu(\dim 1), \quad \psi(\dim 3/2), \quad X_{\mu\nu}(\dim 2)$$

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Building Blocks:

$$H(\dim 1), \quad D_\mu(\dim 1), \quad \psi(\dim 3/2), \quad X_{\mu\nu}(\dim 2)$$

- $n = 2$: $H^\dagger H$
- $n = 3$: (LEFT) $\mathcal{C}^{ij} \bar{e}^i P_L e^j + \text{h.c.}, \quad (e \rightarrow \nu, d, u).$
One does not have hypercharge singlet in SM.
Therefore, one has to go down to $SU(3)_c \times U(1)_{\text{EM}}$. (Low-energy EFT)
- $n = 4$: $\sum_{X=F,Z,W,G} X_{\alpha\beta} X^{\alpha\beta} + X_{\alpha\beta} \tilde{X}^{\alpha\beta}$

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$$\frac{\alpha}{8\pi} \tilde{O} F_{\mu\nu} \tilde{F}^{\mu\nu} \xrightarrow{\text{Cosmos bg.}} \frac{1}{4} \phi_{\tilde{O}} F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad \phi_{\tilde{O}} = \frac{\alpha}{2\pi} \langle \tilde{O} \rangle$$

The ICB effect is given by (same as the axion)

$$\beta = \frac{1}{2} [\phi_{\tilde{O}}(t_{\text{LSS}}) - \phi_{\tilde{O}}(t_0)]$$

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$$\frac{\alpha}{8\pi} \frac{H^\dagger H}{\Lambda_H} F_{\mu\nu} \tilde{F}^{\mu\nu} \implies \phi_{\tilde{O}_2} = \frac{\alpha v^2}{2\pi \Lambda_H^2}, \quad v \equiv \langle H \rangle$$

$$\beta \simeq \frac{\alpha v_0^2}{2\pi \Lambda_H^2} \delta v, \quad \delta v \equiv \frac{v - v_0}{v_0}$$

- CMB gives $\frac{\Delta m_e}{m_e} < (4 \pm 11) \times 10^{-3}$, this indicates $\delta v \lesssim 10^{-3} - 10^{-2}$.
- Collider gives $\Lambda_H > 1 \text{ TeV}$.

$$\beta < (4 \times 10^{-5})^\circ \ll \beta_{\text{obs}}$$

$n = 3$ ICB

Charged particle are suppressed by baryon-to-photon ratio $\eta \sim 10^{-10}$.

Thus, the only possible candidate here is **Cosmic Neutrino Background(C ν B)**.

Assume Dirac neutrino.

$$\frac{\alpha}{8\pi} \frac{\tilde{O}_\nu}{\Lambda_\nu} F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad \tilde{O}_\nu = \frac{(\tilde{C}_\nu^\dagger + \tilde{C}_\nu)^{ij}}{2} \bar{\nu}^i \nu^j + \frac{(\tilde{C}_\nu^\dagger - \tilde{C}_\nu)^{ij}}{2} \bar{\nu}^i \gamma^5 \nu^j$$

- $\langle \bar{\nu}^i \gamma^5 \nu^j \rangle = 0$ and $\langle \bar{\nu}^i \nu^j \rangle = \delta^{ij} \mathcal{F}(t)$,

$$\mathcal{F}(t) = \int \frac{d^3 p}{(2\pi)^3} \frac{m_i}{E_p} [n^i(p, t) + \bar{n}^i(p, t)],$$

where m_i is the i -th neutrino mass and n^i is phase-space number density. (\bar{n} is that for anti-neutrino.)

- This indicates that

$$\phi_{\tilde{O}_\nu}(t) = \frac{\alpha}{4\pi} \frac{\text{tr}[(\tilde{C}_\nu^\dagger + \tilde{C}_\nu) \mathcal{F}(t)]}{\Lambda_\nu^3}$$

Majorana case with an extra 1/2.

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- Due to cosmic expansion, $\phi_{\tilde{\mathcal{O}}_\nu}(t_0) \ll \phi_{\tilde{\mathcal{O}}_\nu}(t_{\text{LSS}})$.
- At recombination $T_{\text{LSS}} \sim 0.3 \text{ eV}$,

$$\mathcal{F}(t_{\text{LSS}}) \simeq 0.5 \frac{m_i}{T_{\text{LSS}}} (N^i + \bar{N}^i) , \quad m_i \ll T_{\text{LSS}}$$

where N and \bar{N} are number density for neutrino and anti-neutrino.

- Possible ICB angle is

$$\beta \simeq \frac{1}{2} \phi_{\tilde{\mathcal{O}}_\nu}(t_{\text{LSS}}) \simeq 0.008^\circ \frac{\alpha}{137^{-1}} \sum_i \frac{m_i}{T_{\text{LSS}}} \left(\tilde{\mathcal{C}}_\nu + \tilde{\mathcal{C}}_\nu^\dagger \right) \frac{N^i + \bar{N}^i}{\Lambda_\nu^3} ,$$

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

- CνB neutrino number density today is $\sim 56 \text{ cm}^{-3}$.
Tracing back to LSS gives $N^{1/3} \sim \mathcal{O}(10^{-10}) \text{ GeV}$.
- Collider gives $\Lambda_\nu \simeq 10^{-2} - 10^2 \text{ GeV}$.
- Taking $\tilde{\mathcal{C}} \sim \mathcal{O}(1)$, $m_i \sim 0.1 \text{ eV}$ and $T_{\text{LSS}} \sim 0.3 \text{ eV}$, one has

$$\beta < (10^{-27})^\circ \ll \beta_{\text{obs}}$$

Can we explain
cosmic
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light field beyond
Standard Model?

Yu-Cheng QIU

Introduction

SM?

Relevant Operators

Possible ICB

A New Light Field?

Summary

$$\frac{\alpha}{8\pi} \frac{F_{\alpha\beta} F^{\alpha\beta} + F_{\alpha\beta} \tilde{F}^{\alpha\beta}}{\Lambda_F^4} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Cosmic Background magnetic field. Let $F \rightarrow F^{(0)} + F$.

Then, quadratic terms are

- $(F_{\alpha\beta}^{(0)} F^{\alpha\beta})(F_{\mu\nu}^{(0)} \tilde{F}^{\mu\nu}) \propto \vec{E}_{\parallel} \cdot \vec{B}_{\parallel} \implies$ Anisotropic CB
- $(F_{\mu\nu}^{(0)} \tilde{F}^{\mu\nu})^2 \propto \vec{E}_{\parallel} \cdot \vec{E}_{\parallel}$
- CS-type term $(F_{\alpha\beta}^{(0)} F^{(0)\alpha\beta})(F_{\mu\nu} \tilde{F}^{\mu\nu}) \propto \vec{E} \cdot \vec{B} \implies$ ICB

They are of the same order!

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$$\frac{\alpha}{8\pi} \frac{\Phi^\dagger \Phi}{\Lambda^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \text{for a scalar } \Phi$$
$$\frac{\alpha}{8\pi} \frac{\bar{\chi} \chi}{\Lambda^3} F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \text{for a fermion } \chi$$

$\langle \Phi^\dagger \Phi \rangle$ and $\langle \bar{\chi} \chi \rangle$ should be time-dependent backgrounds:

- Classical fields : similar to Axion
- Pair condensates : effectively the same to Axion & Require exotic cosmological scenario.
- Particles : like $C\nu B$.

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For a single particle, $E_p \geq m$. In the cosmological background

$$\langle \Phi^\dagger \Phi \rangle \lesssim \frac{\rho}{m^2}, \quad \langle \bar{\chi} \chi \rangle \lesssim \frac{\rho}{m}$$

At the LSS, one should have $\rho < \rho_{\text{c,LSS}} \simeq (3 \times 10^{-13} \text{ TeV})^4$. Therefore,

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

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

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- From EFT point of view, only **CS-type operator** could give frequency-blind ICB.
- SM particle could **not** give observed ICB under standard cosmology.
- If a new field is responsible to ICB under standard cosmology, it should be **light**.



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Thank You!

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$$\nu(x) = \int \frac{d^3 p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\mathbf{p}}}} \sum_s \left[a_{\mathbf{p}}^s u^s(p) e^{-ipx} + b_{\mathbf{p}}^{s\dagger} v^s(p) e^{ipx} \right]$$

$$\bar{\nu}(x) = \int \frac{d^3 p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\mathbf{p}}}} \sum_s \left[b_{\mathbf{p}}^s \bar{v}^s(p) e^{-ipx} + a_{\mathbf{p}}^{s\dagger} \bar{u}^s(p) e^{ipx} \right]$$

with $\{a_{\mathbf{p}}^r, a_{\mathbf{q}}^{s\dagger}\} = \{b_{\mathbf{p}}^r, b_{\mathbf{q}}^{s\dagger}\} = (2\pi)^3 \delta^{(3)}(\mathbf{p} - \mathbf{q}) \delta^{rs}$.

Dirac equation gives

$$u^s(p) = \begin{pmatrix} \sqrt{p \cdot \beta} \xi^s \\ \sqrt{p \cdot \bar{\beta}} \xi^s \end{pmatrix}, \quad v^s(p) = \begin{pmatrix} \sqrt{p \cdot \beta} \eta^s \\ -\sqrt{p \cdot \bar{\beta}} \eta^s \end{pmatrix}, \quad \xi^{\dagger} \xi = \eta^{\dagger} \eta = 1,$$

where $\beta^\mu = (1, \vec{\beta})$, $\bar{\beta}^\mu = (1, -\vec{\beta})$ and $\vec{\beta}$ are Pauli matrices.

Using $\bar{u}^s u^r = -\bar{v}^s v^r = 2m\delta^{sr}$ and $\bar{u}^s \gamma^5 u^r = \bar{v}^s \gamma^5 v^r = 0$, one has

$$\langle \bar{\nu} \gamma^5 \nu \rangle = 0, \quad \langle \bar{\nu} \nu \rangle = \int \frac{d^3 p}{(2\pi)^3} \frac{m}{E_{\mathbf{p}}} [n(p) + \bar{n}(p)]$$