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

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

Yu-Cheng QIU



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



CMB polarization

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

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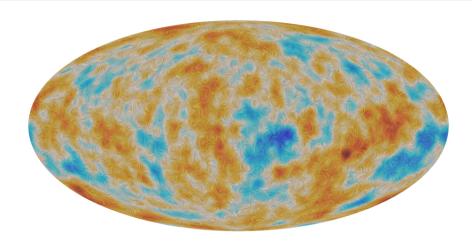


Figure: Copyright: ESA and the Planck Collaboration



Isotropic Cosmic Birefringence

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

Introduction

$$\langle C_I^{EB,obs} \rangle \neq 0 \implies \beta \neq 0$$

- $\beta = 0.35^{\circ} \pm 0.14^{\circ}$ (2.4 σ) (Minami and Komatsu 2011.11254)
- $\beta = 0.34^{\circ} \pm 0.09^{\circ}$ (3.6 σ) (Eskilt and Komatsu 2205.13962)
-
- Isotropic
- Frequency-blind

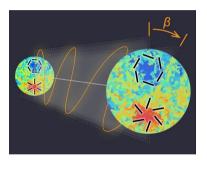


Figure: Credit: Yuto Minami



Axion (ALP) Explanation

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

Introduction

A New Light Field?

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

$$\mathcal{L} = -rac{1}{4} F_{\mu
u} F^{\mu
u} - rac{1}{4} heta(t) F_{\mu
u} ilde{F}^{\mu
u}$$

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

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

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

$$A_{\pm} \propto e^{-i\int d\eta k} \exp\left(\pm i\int d\eta rac{\dot{ heta}}{2}
ight) \implies eta = rac{1}{2} \int_{r_{
m LSS}}^{\eta_0} d\eta \dot{ heta} = rac{1}{2} \left[heta(\eta_0) - heta(\eta_{
m LSS})
ight]$$



Axion (ALP) Explanation

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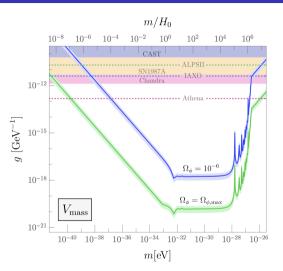
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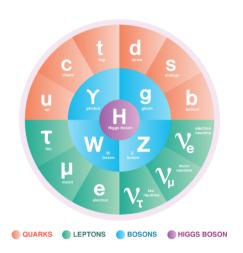
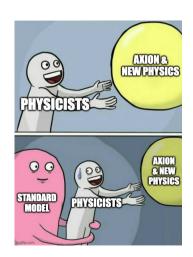


Figure: Artwork by Sandbox Studio, Chicago.





Isotropic Cosmic Birefringence

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

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Summar

- 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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- 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.

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

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

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





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ullet Of course, $\tilde{\mathcal{O}}F_{\mu\nu}\tilde{F}^{\mu\nu}\ o\ \tilde{\mathcal{O}}ec{E}\cdotec{\mathcal{B}}.$ Is it the only one?





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Summary



- Of course, $\tilde{\mathcal{O}}F_{\mu\nu}\tilde{F}^{\mu\nu} \to \tilde{\mathcal{O}}\vec{E}\cdot\vec{B}$. 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.

$$\mathcal{J}_{\mu
ulphaeta}=rac{1}{2}\left(g_{\mulpha}J_{
ueta}+g_{\mueta}J_{
ulpha}-g_{
ulpha}J_{\mueta}-g_{
ueta}J_{\mulpha}
ight)\;,\quad J_{\mu
u}=f(g_{\mu
u},u_{\mu})$$

This reduce to

$$J_{lphaeta}F^{lpha\mu} ilde{F}^{eta}_{\ \mu}\
ightarrow\ ilde{\mathcal{O}}F_{\mu
u} ilde{F}^{\mu
u}\ ,\quad ilde{\mathcal{O}}=rac{J_{\mu}{}^{\mu}}{4}=rac{\mathcal{J}_{lphaeta}{}^{lphaeta}}{6}$$

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Can we explain

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u}\ ,\quad ilde{\mathcal{O}}=rac{J_{\mu}{}^{\mu}}{4}=rac{\mathcal{J}_{lphaeta}{}^{lphaeta}}{6}$$

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



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

Relevant Operators

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

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

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

However, $\tilde{\mathcal{O}}_{\epsilon}$ is non-local, produces frequency-dependent ICB angle.



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Cosmic Magnetic field breaks parity.

However, it will produces Anisotropic Cosmic birefringence angle.

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However, $\tilde{\mathcal{O}}_{\epsilon}$ is non-local, produces frequency-dependent ICB angle.

Cosmic Magnetic field breaks parity.
 However, it will produces Anisotropic Cosmic birefringence angle.

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





SMEFT and LEFT

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Summary

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

Building Blocks:

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



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Summary

$$\mathcal{L}_{\text{CS}} = rac{lpha}{8\pi} \sum rac{ ilde{\mathcal{O}}_{ extsf{a}}}{\Lambda_{ extsf{a}}^{ extsf{a}}} F_{\mu
u} ilde{F}^{\mu
u} \;, \quad n = \dim[ilde{\mathcal{O}}_{ extsf{a}}]$$

Building Blocks:

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

- n = 2: $H^{\dagger}H$
- n=3: (LEFT) $\mathcal{C}^{ij}\bar{e}^{i}P_{L}e^{j}+\text{h.c.}$, $(e \to \nu, d, u)$. One does not have hypercharge singlet in SM. Therefore, one has to go down to $SU(3)_{c} \times U(1)_{EM}$. (Low-energy EFT)

•
$$n = 4$$
: $\sum_{X=F,Z,W,G} X_{\alpha\beta} X^{\alpha\beta} + X_{\alpha\beta} \tilde{X}^{\alpha\beta}$



ICB from $\tilde{\mathcal{O}}F\tilde{F}$?

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Summar

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

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

$$eta = rac{1}{2} \left[\phi_{ ilde{\mathcal{O}}}(t_{ extsf{LSS}}) - \phi_{ ilde{\mathcal{O}}}(t_0)
ight]$$

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Summary

$$\frac{\alpha}{8\pi} \frac{H^{\dagger} H}{\Lambda_H} F_{\mu\nu} \tilde{F}^{\mu\nu} \implies \phi_{\tilde{\mathcal{O}}_2} = \frac{\alpha v^2}{2\pi \Lambda_H^2} , \quad v \equiv \langle H \rangle$$
$$\beta \simeq \frac{\alpha v_0^2}{2\pi \Lambda_H^2} \delta v , \quad \delta v \equiv \frac{v - v_0}{v_0}$$

- 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

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Summary

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.

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

• $\langle \bar{\nu}^i \gamma^5 \nu^j \rangle = 0$ and $\langle \bar{\nu}^i \nu^j \rangle = \delta^{ij} \mathcal{F}(t)$, $\mathcal{F}(t) = \int \frac{d^3p}{d^3p} \frac{m_i}{m_i} \left[p^i(p,t) + \bar{p}^i(p,t) \right] dt$

$$\mathcal{F}(t) = \int rac{d^3p}{(2\pi)^3} rac{m_i}{E_{f p}} \left[n^i(p,t) + ar{n}^i(p,t)
ight] \; ,$$

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

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

Majorana case with an extra 1/2.

n = 3 ICB

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

$$\mathcal{F}(t_{\mathsf{LSS}}) \simeq 0.5 rac{m_i}{T_{\mathsf{LSS}}} \left(N^i + ar{N}^i
ight) \;, \quad m_i \ll T_{\mathsf{LSS}}$$

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

Possible ICB angle is

$$eta \simeq rac{1}{2}\phi_{ ilde{\mathcal{O}}_{
u}}(t_{\mathsf{LSS}}) \simeq 0.008^{\circ} rac{lpha}{137^{-1}} \sum_{i} rac{m_{i}}{T_{\mathsf{LSS}}} \left(ilde{\mathcal{C}}_{
u} + ilde{\mathcal{C}}_{
u}^{\dagger}
ight) rac{ extstyle N' + extstyle N'}{\Lambda_{
u}^{3}} \; ,$$

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Summary

$$\beta \simeq 0.008^{\circ} \frac{\alpha}{137^{-1}} \sum_{i} \frac{m_{i}}{T_{\rm LSS}} \left(\tilde{\mathcal{C}}_{\nu} + \tilde{\mathcal{C}}_{\nu}^{\dagger} \right) \frac{N^{i} + \bar{N}^{i}}{\Lambda_{\nu}^{3}} \; , \label{eq:beta_scale}$$

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

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

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Summar

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

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

Then, quadratic terms are

•
$$(F_{\alpha\beta}^{(0)}F^{\alpha\beta})(F_{\mu\nu}^{(0)}\tilde{F}^{\mu\nu})\propto \vec{E}_{\parallel}\cdot\vec{B}_{\parallel} \implies \text{Anistropic CB}$$

$$ullet$$
 $(F_{\mu
u}^{(0)} ilde{F}^{\mu
u})^2 \propto ec{E}_{\parallel}\cdotec{E}_{\parallel}$

• CS-type term
$$(F^{(0)}_{\alpha\beta}F^{(0)\alpha\beta})(F_{\mu\nu}\tilde{F}^{\mu\nu})\propto \vec{E}\cdot\vec{B}$$
 \Longrightarrow ICI

They are of the same order!



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Summar

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

 $\langle \Phi^{\dagger} \Phi \rangle$ 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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Summary

For a single particle, $E_{\mathbf{p}} \geq m$. 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 $\rho < \rho_{c,LSS} \simeq (3 \times 10^{-13} \, \text{TeV})^4$. Therefore,

$$m \lesssim 10^{-14} \, \mathrm{eV} \left(\frac{|\beta|}{0.3^{\circ}} \right)^{-1/2} \left(\frac{\Lambda}{\mathrm{TeV}} \right)^{-1} \quad \text{(Scalar)}$$
 $m \lesssim 10^{-40} \, \mathrm{eV} \left(\frac{|\beta|}{0.3^{\circ}} \right)^{-1} \left(\frac{\Lambda}{\mathrm{TeV}} \right)^{-3} \quad \text{(Fermion)}$



Takeaway

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

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Summary

- From EFT point of view, only CS-type operator could give frequency-blind ICB.
- SM particle could not give observed ICB under standard cosmology.



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Introduction

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A New Light Field?

Summary

Thank You!





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$$rac{1}{2}\int d^4k_1d^4k_2A_{\mu}(k_1)\Pi^{\mu
u}(k_1,k_2)A_{
u}(k_2)$$

- Introduce helicity basis with respect to **k**, $\{\epsilon_{\rm L}^{\mu}, \epsilon_{+}^{\mu}, \epsilon_{-}^{\mu}\}$. So $\epsilon_{\rm L,\pm}^{\mu} u_{\mu} = 0$, $k_{\mu} \epsilon_{\pm}^{\mu} = 0 \neq k_{\mu} \epsilon_{\rm L}^{\mu}$.
- Including the background, one has $k_1^\mu + k_2^\mu \propto u^\mu \neq 0$. Expand $k_1^\mu = \omega_1 u^\mu + |\mathbf{k}| \epsilon_1^\mu$ and $k_2^\mu = \omega_2 u^\mu |\mathbf{k}| \epsilon_1^\mu$.
- With the background unit vector $u_{\mu} \propto \nabla_{\mu} t$, one has $\overline{B}^{\mu} = u_{\nu} \tilde{F}^{(0)\mu\nu}$.
- One could expand $\overline{B}^{\mu} = \overline{B}_{L}\epsilon_{L}^{\mu} + \overline{B}_{+}\epsilon_{+}^{\mu} + \overline{B}\epsilon_{-}^{\mu}$.
- $F_{\mu\nu}\tilde{F}^{\mu\nu} \Longrightarrow \Pi^{\mu\nu} \supset \epsilon^{\mu\nu\alpha\beta}(k_1)_{\alpha}(k_2)_{\beta} \propto \epsilon^{\mu\nu\alpha\beta}u_{\alpha}(\epsilon_{\rm L})_{\beta} \propto \epsilon_+^{*\mu}\epsilon_+^{\nu} \epsilon_-^{*\nu}\epsilon_-^{\mu}(F_{\alpha\beta}^{(0)}F^{(0)\alpha\beta})(F_{\mu\nu}\tilde{F}^{\mu\nu}) = |\overline{B}|^2F\tilde{F}$ term gives ICB if $|\overline{B}|$ is uniform.



ACB from \overline{B}

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

• $F^{lphaeta} o k_1^lpha A^eta(k_1) - k_1^eta A^lpha(k_1)$ and $ilde F^{\mu
u} o \epsilon^{\mu
ulphaeta}(k_2)_lpha A_eta(k_2).$

$$\bullet \ \overline{B}_{\alpha}u_{\beta}F^{\alpha\beta} \to \left[(\overline{B} \cdot k_{1})u^{\mu} - (u \cdot k_{1})\overline{B}^{\mu} \right] A_{\mu}(k_{1}) \\ \propto (\overline{B}_{+}\epsilon^{\mu}_{+} + \overline{B}_{-}\epsilon^{\mu}_{-})A_{\mu}(k_{1}) + \cdots$$

•
$$\overline{B}_{\mu}u_{
u}\widetilde{F}^{\mu
u}\propto(\overline{B}_{+}\epsilon^{
u}_{+}-\overline{B}_{-}\epsilon^{
u}_{-})A_{
u}(k_{2})$$

$$\bullet \ (F_{\alpha\beta}^{(0)}F^{\alpha\beta})(F_{\mu\nu}^{(0)}\tilde{F}^{\mu\nu})\supset C\overline{B}_{+}\overline{B}_{-}(\epsilon_{+}^{*\mu}\epsilon_{+}^{\nu}-\epsilon_{-}^{*\mu}\epsilon_{-}^{\nu})A_{\mu}A_{\nu}.$$

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



Dipole operator

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$$J_{\mu\nu}F^{\mu\nu}$$
, $J_{\mu\nu} = \bar{\nu}^i \lambda^{ij} \sigma_{\mu\nu} \nu^j$, $\lambda = \underbrace{\mathfrak{M}}_{\mathsf{magnetic}} + \underbrace{i\mathfrak{E}\gamma^5}_{\mathsf{electric}}$

$$F^{\mu
u}\hat{K}_{\mu
ulphaeta}F^{lphaeta}
ightarrow ilde{\mathcal{O}}_{\epsilon}F_{\mu
u} ilde{F}^{\mu
u}\;,\quad ilde{\mathcal{O}}_{\epsilon}\propto\epsilon^{\mu
ulphaeta}\hat{K}_{\mu
ulphaeta} \ \hat{K}_{\mu
ulphaeta} \propto (ar{
u}^{i})^{(\mathrm{bg})}\sigma_{\mu
u}\lambda^{ij}rac{1}{i\partial\hspace{-0.1cm}/-m_{j}}\sigma_{lphaeta}\lambda^{jk}(
u^{k})^{(\mathrm{bg})}$$

$$\begin{split} \tilde{\mathcal{O}}_{\epsilon} &\propto (\bar{\nu}^{i})^{(\text{bg})} \epsilon^{\mu\nu\alpha\beta} \sigma_{\mu\nu} \lambda^{ij} (i\partial \!\!\!/ - m_{j})^{-1} \sigma_{\alpha\beta} \lambda^{jk} (\nu^{k})^{(\text{bg})} \\ &= -4 i m_{j} (\bar{\nu}^{i})^{(\text{bg})} \lambda^{ij} \gamma^{5} (\partial^{2} + m_{j}^{2})^{-1} \lambda^{jk} (\nu^{k})^{(\text{bg})} \end{split}$$

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

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$$\langle \tilde{\mathcal{O}}_{\epsilon}
angle \propto m_{j} \left\langle (ar{
u}^{i})^{(\mathrm{bg})} \lambda^{ij} \gamma^{5} (\partial^{2} + m_{j}^{2})^{-1} \lambda^{jk} (
u^{k})^{(\mathrm{bg})}
ight
angle$$

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

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

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

$$(p_{\mu}+p_{\gamma})^2-m_j^2=2\omega(\mathcal{E}_{
u}-\mathbf{n}\cdot\mathbf{p}_{
u})+m_i^2-m_j^2\overset{\mathsf{LSS}}{\simeq}2\omega(\mathcal{E}_{
u}-\mathbf{n}\cdot\mathbf{p}_{
u})$$

$$eta \propto \langle \tilde{\mathcal{O}}_{\epsilon}
angle ig|_{\mathsf{LSS}} \propto rac{1}{\omega} \,, \quad \mathsf{Frequency-dependent ICB}$$

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

with $\{a^r_{\mathbf{p}}, a^{s\dagger}_{\mathbf{q}}\} = \{b^r_{\mathbf{p}}, b^{s\dagger}_{\mathbf{q}}\} = (2\pi)^3 \delta^{(3)}(\mathbf{p} - \mathbf{q})\delta^{rs}$.

Dirac equation gives

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

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

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