Probing axion coupling to electrons by Chiral Magnetic Effects

Sang Hui Im (IBS-CTPU)

DK Hong, SHI, KS Jeong, D Yeom, *2207.06884*

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Dec 6th, 2023, Busan, Korea

Outline

- QCD axion and ALPs
- Experimental test of underlying UV physics for axions and importance of measuring the axion-electron coupling
- Chiral Magnetic Effect (CME)
- Probing the axion-electron coupling by CMEs

Strong CP problem and QCD axion

$$y_u H Q_L u_R^c + y_d H^* Q_L d_R^c + \frac{g_s^2}{32\pi^2}\theta G\tilde{G}$$

$$\bar{\theta} = \theta + \arg\det\left(y_u y_d\right) < 10^{-10}$$

Non-observation of neutron EDM

[Abel et al '20]

CP violation in the QCD

while $\delta_{\rm CKM} = \arg\det\left[y_u y_u^\dagger, y_d y_d^\dagger\right] \sim \mathcal{O}(1)$

The QCD vacuum energy is minimized at the CP-conserving point ($\bar{\theta} = 0$).

[Vafa, Witten '84]

$$V_{\rm QCD} \simeq -m_\pi^2 f_\pi^2 \cos\bar{\theta}$$

Promote $\bar{\theta}$ to a dynamical field (=QCD axion) : $\frac{g_s^2}{32\pi^2}\left(\theta + \frac{a}{f_a}\right)G\tilde{G}$

[Peccei, Quinn '77, Weinberg '78, Wilczek '78]

QCD axion lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{g_s^2}{32\pi^2} c_G \frac{a}{f_a} G^{\mu\nu}\tilde{G}_{\mu\nu}$$

$$+ \frac{a}{f_a} \sum_{A=W,B,\dots} \frac{g_A^2}{32\pi^2} c_A F^{A\mu\nu}\tilde{F}^A_{\mu\nu} + \frac{\partial_\mu a}{f_a}\left(\sum_{\psi=q,\ell,\dots} c_\psi \psi^\dagger \bar{\sigma}^\mu \psi + \sum_{\phi=H,\dots} c_\phi \phi^\dagger i\overleftrightarrow{D}^\mu \phi\right)$$

dictated by i) approximate $U(1)_{PQ}$: $a(x) \to a(x) + \alpha$

ii) periodicity : $\frac{a(x)}{f_a} \equiv \frac{a(x)}{f_a} + 2\pi$

$U(1)_{PQ}$ dominantly broken by c_G (QCD instantons) ⇨ $m_a^2 \simeq c_G^2 \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2}$

By the periodicity, the size of axion couplings are mostly determined by f_a up to model-dependent constants c_G, c_A, c_ψ, c_ϕ

Axion-Like Particles (ALPs)

- Share the same symmetric properties with QCD axion, but do not necessarily couple to gluons.
- Particularly motivated in string theory.

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, Marsh-Russell, '09]

$$\frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{a}{f_a}\sum_A \frac{g_A^2}{32\pi^2} c_A F^{A\mu\nu}\tilde{F}^A_{\mu\nu} + \frac{\partial_\mu a}{f_a}\left(\sum_\psi c_\psi \psi^\dagger \bar{\sigma}^\mu \psi + \sum_\phi c_\phi \phi^\dagger i \overleftrightarrow{D}^\mu \phi\right)$$

i) approximate $U(1)_{PQ}$ $\quad a(x) \to a(x) + c \;\; (c \in \mathbb{R})$

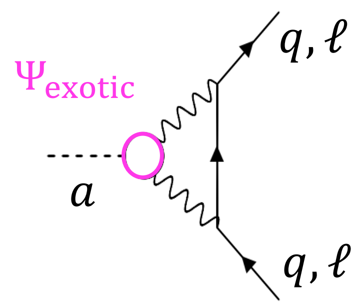
: ALP can be naturally light.

ii) periodicity $\quad \frac{a(x)}{f_a} \equiv \frac{a(x)}{f_a} + 2\pi$

: f_a characterizes typical size of ALP couplings up to model-dependent constants c_A, c_ψ, c_ϕ.

Characteristic patterns of axion couplings to the SM depending on classes of axion models

KSVZ-like models



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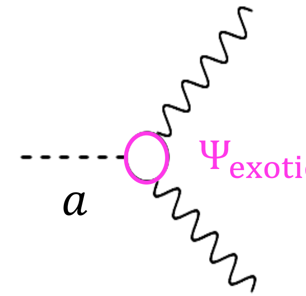
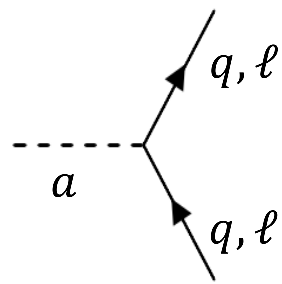


DFSZ-like models



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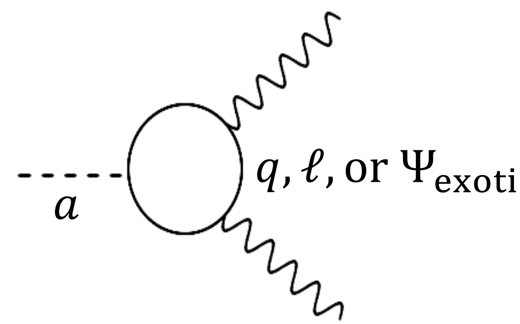
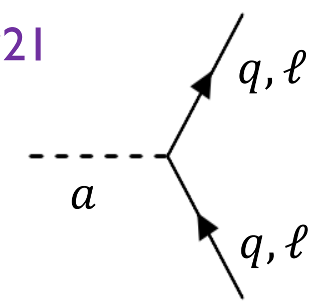


K Choi, SHI, HJ Kim, H Seong '21

String-theoretic models



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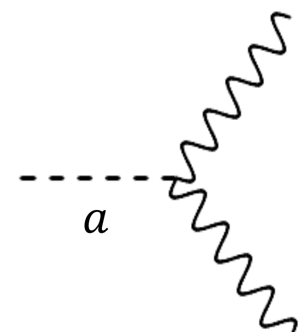
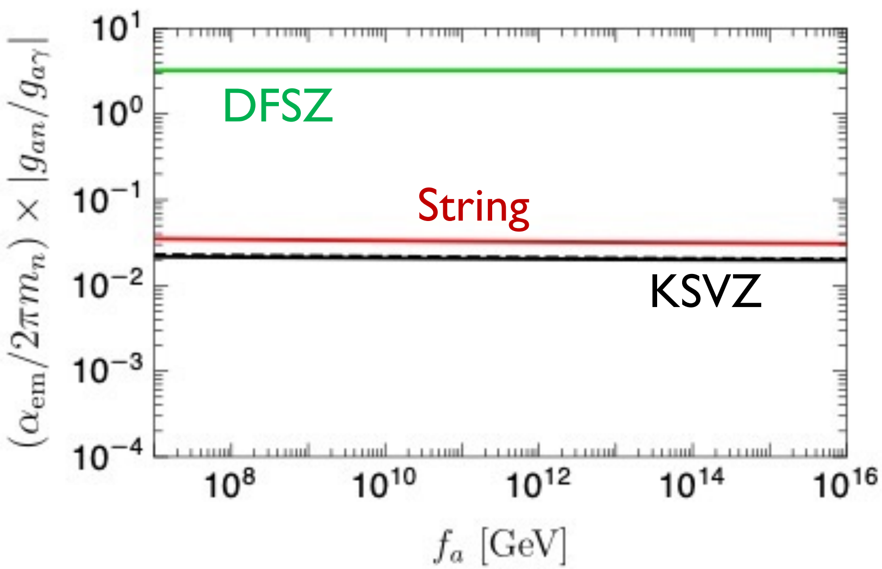
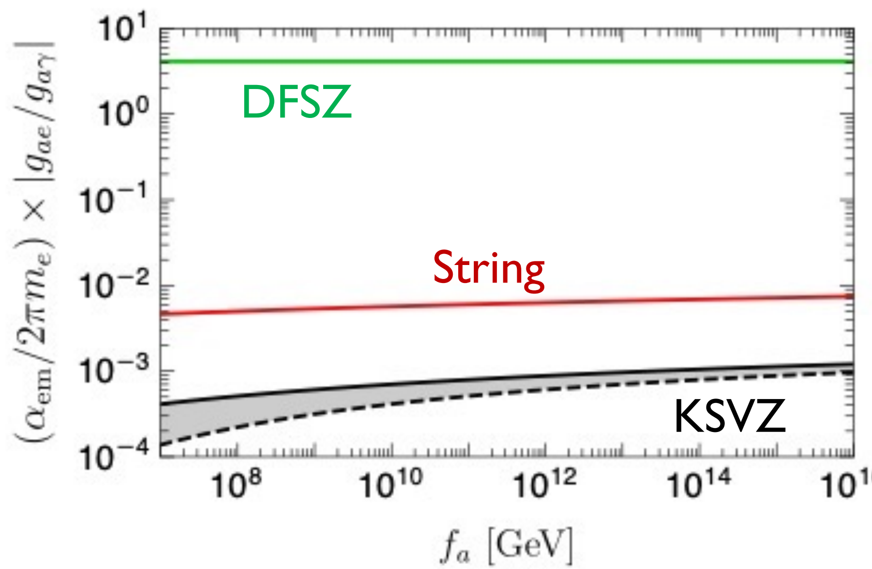


Experimental test of the classes of axion models

K Choi, SHI, HJ Kim, H Seong '21

For QCD axion ($c_G \neq 0$), $g_{ap} \sim \frac{m_p}{f_a}$ regardless of the classes of models

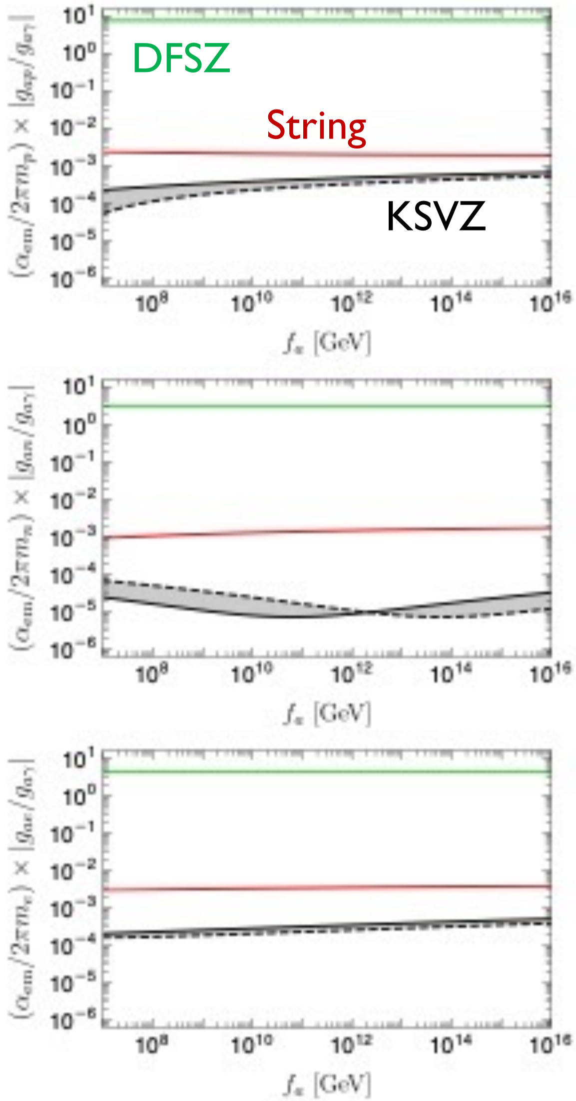




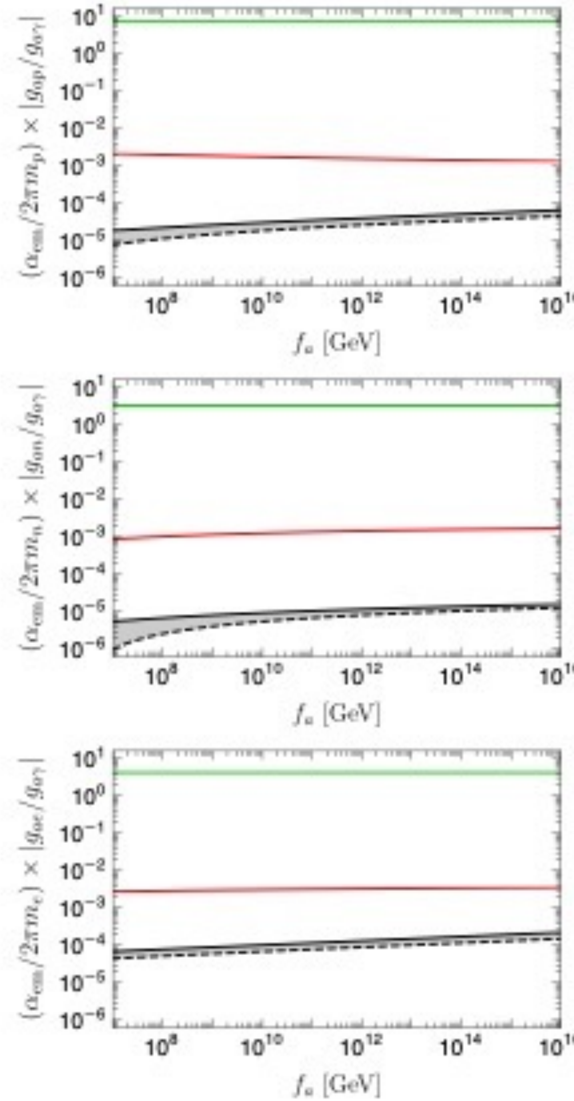
We need to measure the axion-electron coupling to determine the underlying UV physics for QCD axion.

For ALPs with $(c_G = 0)$, the axion-nucleon couplings can do the test as well.

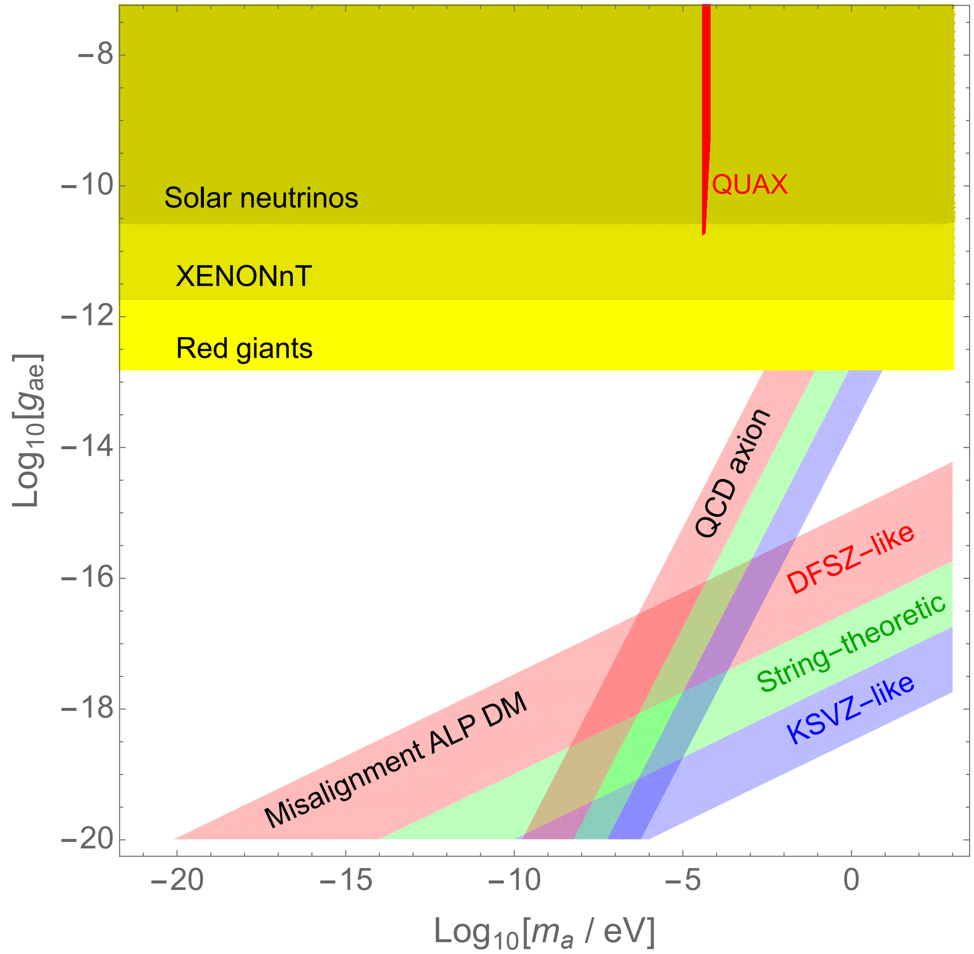
$c_W = 1\ (c_G = c_B = 0)$



$c_B = 1\ (c_G = c_W = 0)$



Experimental test of the axion-electron coupling?



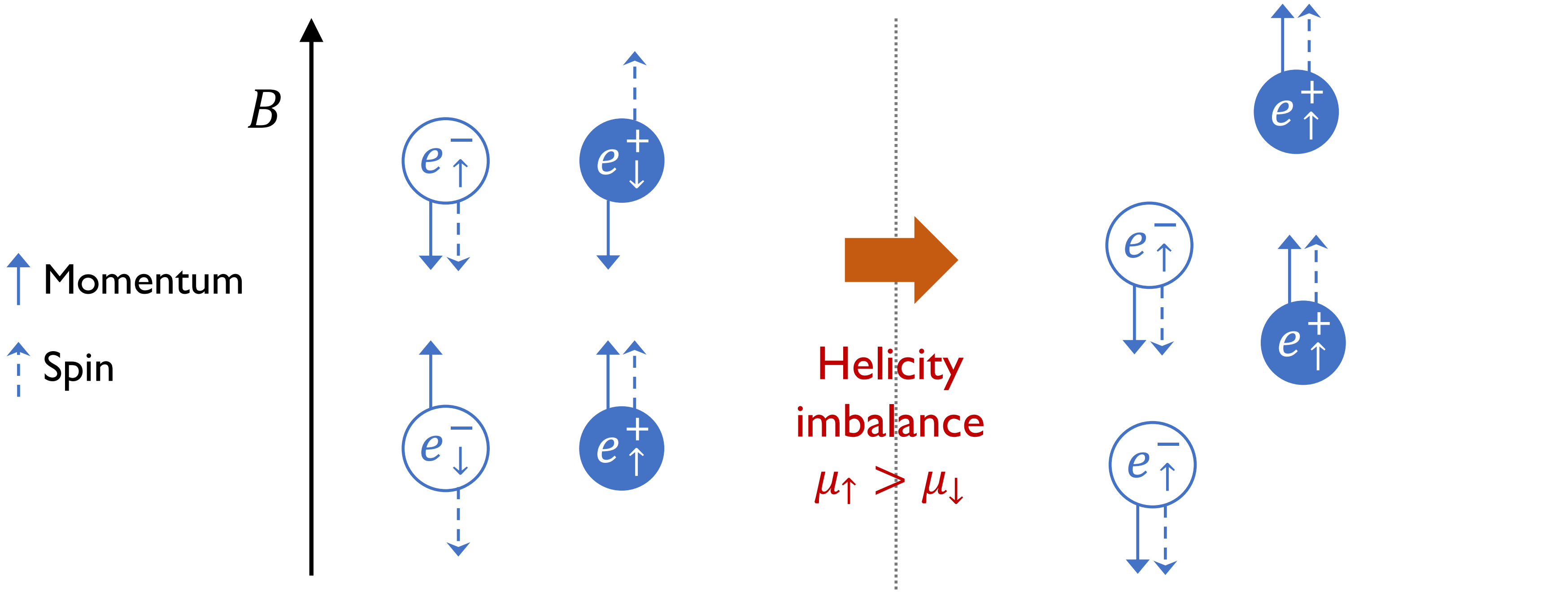
See also So Chigusa's talk

Currently only the QUAX experiment can cover a limited parameter space.

Chiral Magnetic Effect (CME) in a nutshell

Kharzeev, McLerran, Warringa '08
Fukushima, Kharzeev, Warringa '08

In thermal equilibrium



Net current $\vec{J} = 0$

Net current $\vec{J} \propto (\mu_\uparrow - \mu_\downarrow)\,\vec{B}$

- The *magnetic field* aligns the spin directions depending on EM charge.
- On top of that, if there is a *helicity imbalance,* a non-zero electric current is generated along the B-field direction.

- Chiral chemical potential

$$\mathcal{L} \supset \mu_5(n_R - n_L) = \mu_5 \left(\psi_R^\dagger \psi_R - \psi_L^\dagger \psi_L\right)$$
$$= \mu_5 \bar{\Psi}\gamma^0\gamma^5\Psi$$

$$\Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

It makes *chiral imbalance, leading to helicity imbalance*.

- (Vector) chemical potential

$$\mathcal{L} \supset \mu(n_R + n_L) = \mu \left(\psi_R^\dagger \psi_R + \psi_L^\dagger \psi_L\right)$$
$$= \mu \bar{\Psi}\gamma^0\Psi$$

It makes *charge imbalance* (i.e. particles vs antiparticles).

The *charge imbalance alone does not induce a current*. However, μ might be still relevant for the magnitude of the current for a given helicity imbalance.

Axion background as μ_5

Suppose that we have an axion-electron coupling with time-varying axion field background.

$$c_\Psi \frac{\partial_\mu a}{f_a} \bar{\Psi}\gamma^\mu\gamma^5\Psi \quad \Rightarrow \quad c_\Psi \frac{\dot{a}}{f_a} \bar{\Psi}\gamma^0\gamma^5\Psi$$

$$\mu_5(t) = c_\Psi \frac{\dot{a}}{f_a}$$

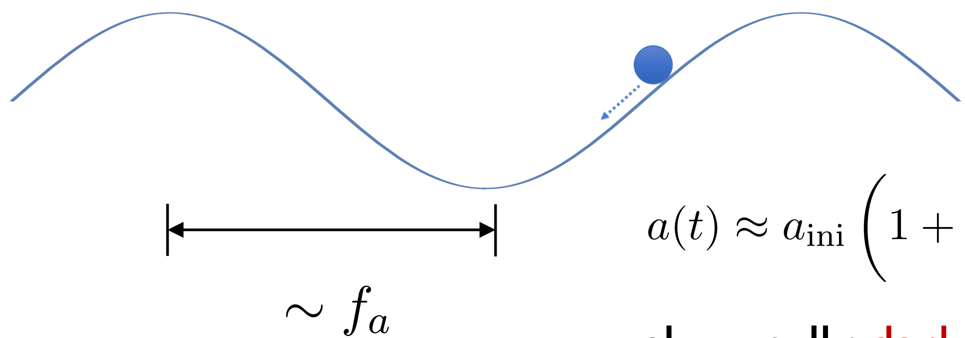
On the other hand, $$c_\Psi \frac{\nabla a}{f_a} \cdot \bar{\Psi}\vec{\gamma}\gamma^5\Psi \approx \underbrace{2c_\Psi \frac{\nabla a}{f_a}}\cdot \vec{S}_e$$

QUAX and (NV Center) are looking for $\vec{B}_{\text{eff}}$

Cosmological evolution of an axion field

$$\ddot{a}(t) + 3H\dot{a}(t) + m_a^2 a(t) = 0$$

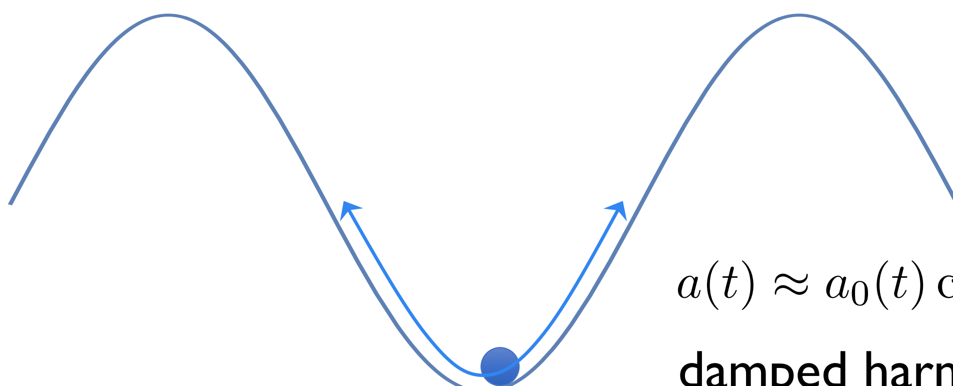
$$m_a \ll H \sim \frac{T^2}{M_{Pl}}$$



$$a(t) \approx a_{\rm ini}\left(1 + \frac{1}{20}\left[\frac{m_a^2}{H_{\rm ini}^2} - \frac{m_a^2}{H(t)^2}\right]\right)$$

slow-roll : dark energy

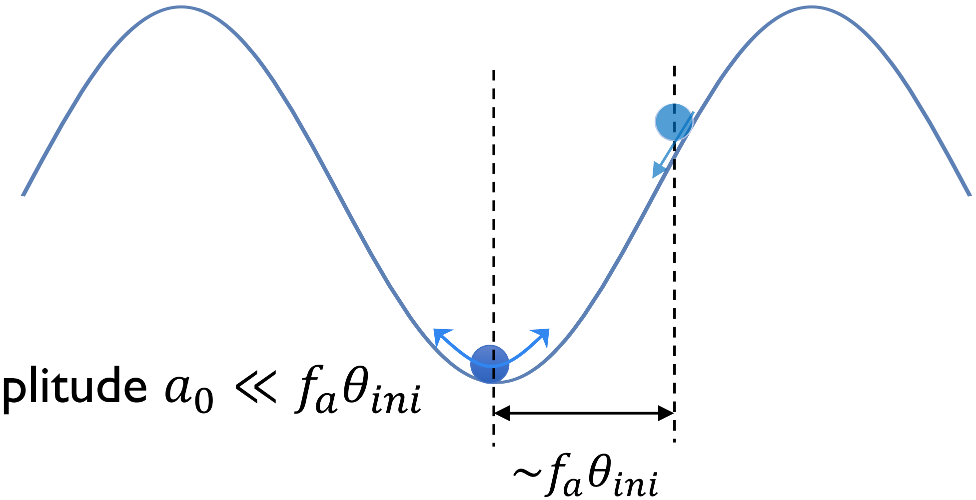
$$m_a \gg H \sim \frac{T^2}{M_{Pl}}$$



$$a(t) \approx a_0(t)\cos(m_a t)$$

damped harmonic
oscillator : cold dark matter

Misalignment production of axion dark matter and chiral chemical potential



Present oscillation amplitude $a_0 \ll f_a \theta_{ini}$

$$a(t, \vec{x}) \approx a_0 \cos m_a t$$

$$\rho_a = \frac{1}{2} m_a^2 a_0^2$$

$$\mu_5(t) = c_\Psi \frac{\dot{a}}{f_a}$$

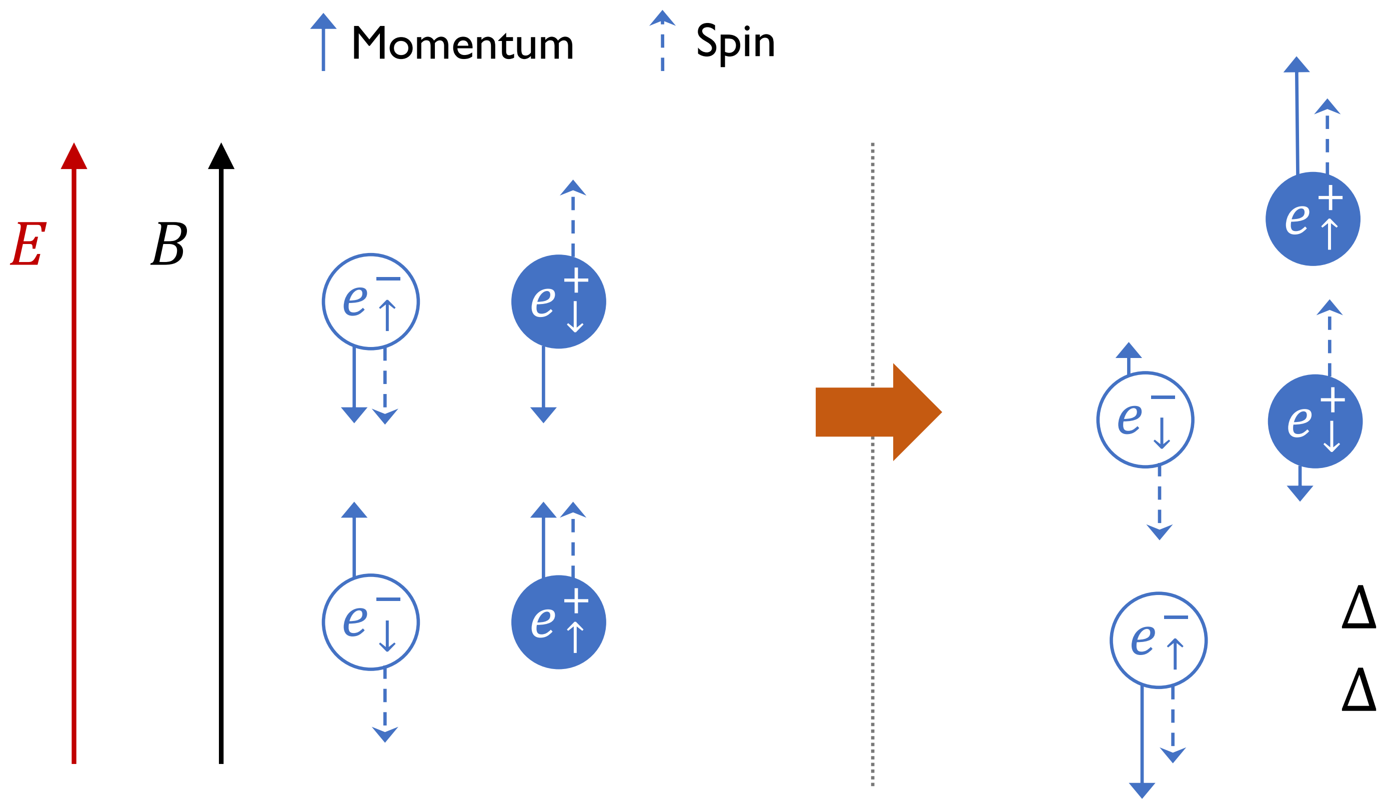
$$\boxed{\mu_5(t) \approx -c_\Psi \frac{\sqrt{2\rho_a}}{f_a} \sin m_a t}$$

The axion dark matter background gives rise to an oscillating chiral chemical potential for fermions coupled to the axion.

CME-induced current

Energy balance argument

Nielsen and Ninomiya '83
Fukushima, Kharzeev, Warringa '08



$$\Delta P_F^\uparrow = eEt$$
$$\Delta P_F^\downarrow = -eEt$$

Density change of helicity-up fermion states

$$\underbrace{\frac{\Delta P_F^{\uparrow}}{2\pi}}_{\text{Longitudinal number density}} \cdot \underbrace{\frac{eB}{2\pi}}_{\text{Transverse number density in the lowest Landau level}} = \frac{e^2}{4\pi^2}\vec{E}\cdot\vec{B}t$$

Longitudinal number density

Transverse number density in the *lowest* Landau level

Aharonov and Casher '79

Density change of helicity-down fermion states

$$\frac{\Delta P_F^{\downarrow}}{2\pi} \cdot \frac{eB}{2\pi} = -\frac{e^2}{4\pi^2}\vec{E}\cdot\vec{B}t$$

➡

$$\frac{d}{dt}(n_{\uparrow} - n_{\downarrow}) = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B}$$

which reproduces the chiral anomaly equation in massless limit

$$\partial_\mu(\bar{\Psi}\gamma^\mu\gamma^5\Psi) = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B} + 2m\bar{\Psi}i\gamma^5\Psi$$

$$\frac{d}{dt}(n_\uparrow - n_\downarrow) = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B}$$

$$\Rightarrow \underbrace{\frac{\mathcal{E}}{2}\frac{d}{dt}(N_\uparrow - N_\downarrow)}_{} = \frac{e^2}{4\pi^2}\mathcal{E}\int d^3x\vec{E}\cdot\vec{B}$$

Ɛ : Energy cost for flipping a helicity-down state to a helicity-up state

Energy cost per unit time needed for making helicity imbalance

||

$$\int d^3x\,\vec{j}\cdot\vec{E}$$

This energy cost has to be supplied by the electric power.

$$\Rightarrow \boxed{\vec{j} = \frac{e^2}{4\pi^2}\mathcal{E}\vec{B}}$$

Alternatively

$$
\begin{aligned}
j &= \int d\rho\, v \\
&= e \cdot \frac{eB}{2\pi} \cdot \left(\overbrace{\int_0^{p_F^{\uparrow}} \frac{dp_z}{2\pi}}^{dn^{\uparrow}} \overbrace{\frac{p_z}{\sqrt{p_z^2 + m^2}}}^{v} - \int_0^{p_F^{\downarrow}} \frac{dp_z}{2\pi} \frac{p_z}{\sqrt{p_z^2 + m^2}} \right) \\
&= \frac{e^2}{4\pi^2} \cdot \underbrace{\left(\sqrt{(p_F^{\uparrow})^2 + m^2} - \sqrt{(p_F^{\downarrow})^2 + m^2} \right)}_{\varepsilon} \cdot B
\end{aligned}
$$

Dirac eq.
$$\begin{pmatrix} -m & E - \vec{p}\cdot\vec{\sigma} - \mu_5 \\ E + \vec{p}\cdot\vec{\sigma} + \mu_5 & -m \end{pmatrix} \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} = 0$$

$h = \hat{p}\cdot\vec{\sigma}$ helicity

$\vec{p}\cdot\vec{\sigma} = |p|h$

$$\Rightarrow \quad E = \sqrt{(|p|h + \mu_5)^2 + m^2}$$

$$p_F^{\uparrow} = p_F + \mu_5$$
$$p_F^{\downarrow} = p_F - \mu_5$$

where p_F is the Fermi momentum when $\mu_5 = 0$.

$$\Rightarrow \quad \mathcal{E} = \sqrt{(p_F^{\uparrow})^2 + m^2} - \sqrt{(p_F^{\downarrow})^2 + m^2} \simeq 2\mu_5 v_F$$

$$\vec{j} \simeq \frac{e^2}{2\pi^2}\mu_5 v_F \vec{B}$$

In the original formula by (FKW '08) the v_F dependence is missing (Hong, SHI, Jeong, Yeom '22).

From DK Hong's slide

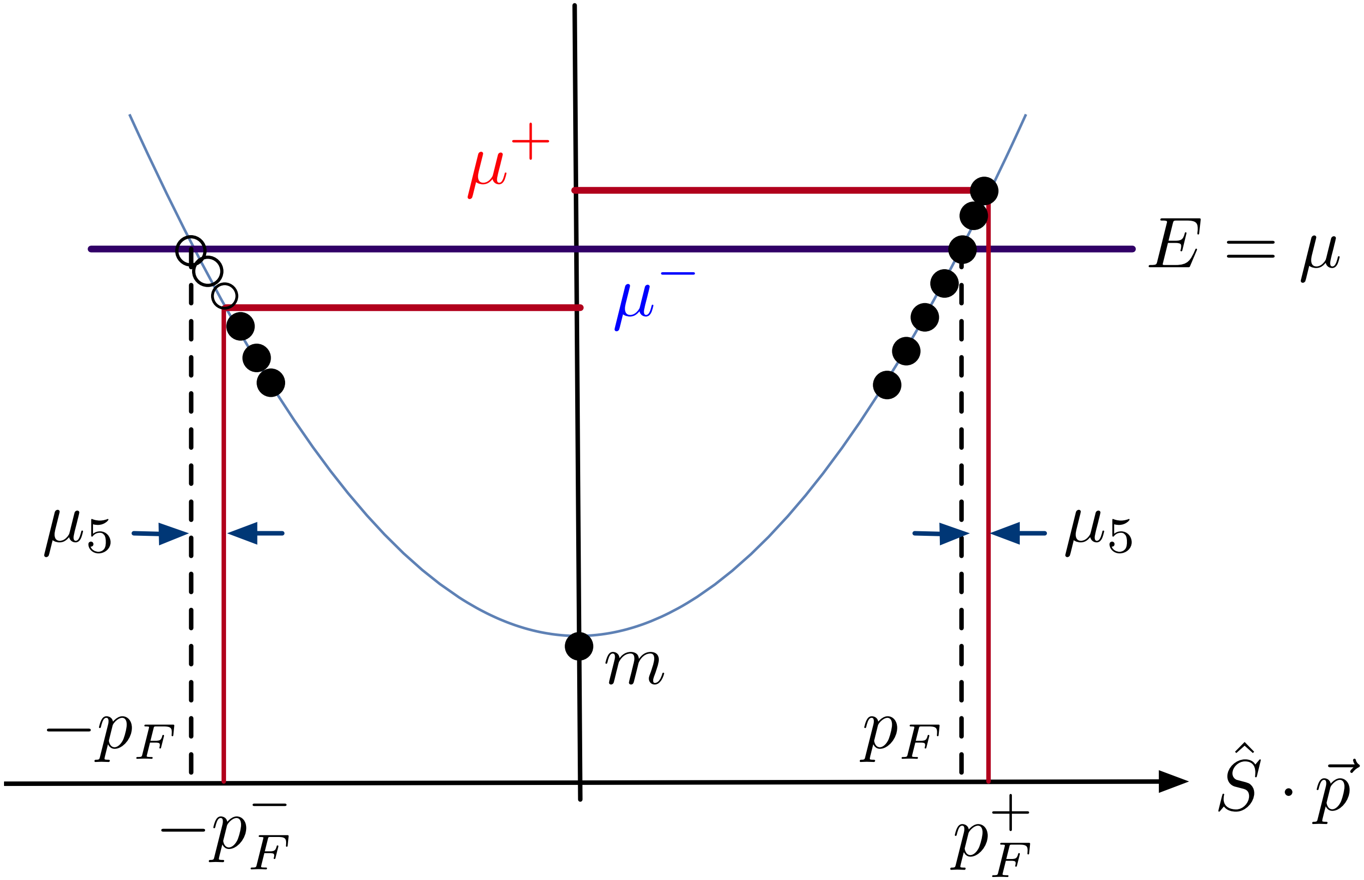
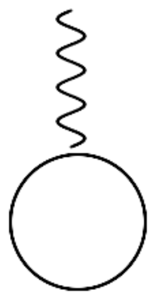


Figure: chiral medium

CME-induced current

Field-theoretic calculation



$$\langle j^\mu \rangle = e \left\langle \bar{\Psi} \gamma^\mu \Psi \right\rangle = -e \int \frac{\mathrm{d}^4 p}{(2\pi)^4} \,\mathrm{Tr}\left[\gamma^\mu S_F^{n=0}(p, \mu, \mu_5)\right]$$

$$S_F^{n=0}(p, \mu, \mu_5) = \left[\frac{2i\,(\tilde{\not{p}}_{\parallel} + m) P_- H_+ \, e^{-p_\perp^2/|eB|}}{\left[(1+i\epsilon)\,p_0 + \mu_+\right]^2 - p_z^2 - m^2} + \frac{2i\,(\tilde{\not{p}}_{\parallel} + m) P_- H_- \, e^{-p_\perp^2/|eB|}}{\left[(1+i\epsilon)\,p_0 + \mu_-\right]^2 - p_z^2 - m^2} \right]$$

: the electron propagator in the lowest Landau level in a dense medium

P_-: spin projection operator
$H_\pm$: helicity projection operator

$$\mu_\pm = \sqrt{p_F^{\pm\,2} + m^2}$$

: chemical potential for the helicity eigenstates

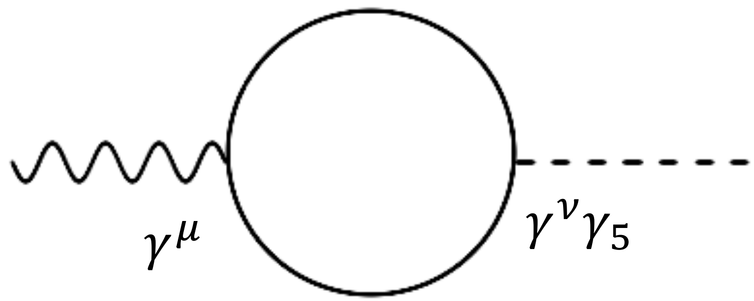
The field-theoretic calculation reproduces the CME formula obtained by the energy balance argument :

$$\langle j^3 \rangle = \frac{e^2 B}{4\pi^2}\left[\int_0^{\mu_+} \mathrm{d}p_0 \int_{p_z>0} |p_z|\,\delta\left(p_0^2 - p_z^2 - m^2\right) - \int_0^{\mu_-} \mathrm{d}p_0 \int_{p_z>0} |p_z|\,\delta\left(p_0^2 - p_z^2 - m^2\right)\right]$$

$$= \frac{e^2 B}{4\pi^2}\underbrace{\left[\sqrt{(p_F + \mu_5)^2 + m^2} - \sqrt{(p_F - \mu_5)^2 + m^2}\right]}_{\varepsilon} = \frac{e^2 B}{2\pi^2}\mu_5 v_F\left[1 + \mathcal{O}(v_F^2, r^2)\right],$$

CME and chiral anomaly in (1+1)D

Since only the electrons in the lowest Landau level (i.e. transverse zero modes) contribute to the CME current, the physics may be understood in terms of electrons moving in (1+1)D spacetime.



$$\Gamma^{\mu\nu}(q_1)\delta^{(2)}(q_1+q_2) \equiv \int \Pi_i \mathrm{d}^2 x_i e^{iq_i\cdot x_i} \langle 0|\, \mathrm{T} j^\mu(x_1) j_5^\nu(x_2)\, |0\rangle$$

In the vacuum,

$$\Gamma^{\mu\nu}_{\rm vac}(q) = \frac{eB}{4\pi^2}\left(\epsilon^{\nu\alpha} q_\alpha q^\mu + \epsilon^{\mu\nu} q^2\right) H(q^2, m^2)$$

$$H(q^2, m^2) = \frac{1}{q^2}\left(1 - \frac{1}{\sqrt{\tau(1-\tau)}}\tan^{-1}\sqrt{\frac{\tau}{1-\tau}}\right) \simeq -\frac{1}{4m^2}\ (q \to 0)$$

$$\tau \equiv \frac{q^2}{4m^2}$$

: No pole at $q^2 = 0$ for massive electrons

The chiral anomaly diagram vanishes as $q \to 0$ when there is no massless charged fermion. Coleman and Grossman '82

In a medium,

$$\Gamma^{\mu\nu}(q) = \frac{eB}{4\pi^2}(\epsilon^{\nu\alpha}q_\alpha q^\mu + \epsilon^{\mu\nu}q^2)F(q^2, m^2, \mu)$$

$$F(q^2, m^2, \mu) = \frac{1}{q^2}\left(\mathcal{O}\left(\frac{q^2}{m^2}\right) + \frac{p_F}{\mu} + \mathcal{O}\left(\frac{q}{\mu}\right)\right)$$

: a pole at $q^2 = 0$
even for massive electrons

$$\Rightarrow \quad \langle \partial_\nu j_5^\nu \rangle_A = ie\int \frac{\mathrm{d}^2 q}{4\pi^2} \lim_{q_0\to 0}\lim_{q_3\to 0} e^{iq\cdot x} q_\nu A_\mu(q)\Gamma^{\mu\nu}(q) = \frac{e^2 B}{4\pi^2} v_F \epsilon^{\mu\nu}F_{\mu\nu}$$

$$\langle j^3 \rangle = -e\mu_5 \lim_{q_0\to 0}\lim_{q_3\to 0}\Gamma^{30}(q) = \frac{e^2 B}{2\pi^2} v_F \mu_5$$

The CME can be understood as (1+1)D chiral anomaly in a medium induced by *gapless modes at the Fermi surface.*

Detecting axion dark matter via the CME

$$C_e \frac{\partial_\mu a}{f} \bar{\psi} \gamma^\mu \gamma_5 \psi \quad \Rightarrow \quad \mu_5 = C_e \frac{\dot{a}}{f}$$

$$a(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \sin(m_a t)$$

The axion dark matter field induces an oscillating chiral chemical potential if the axion couples to the electrons.

$$\mu_5 = C_e \frac{\sqrt{\rho_{\rm DM}}}{f} \cos(m_a t) \sim 0.25 \times 10^{-23} \text{ eV} \cdot \left(\frac{\rho_{\rm DM}}{0.4 \text{ GeV cm}^{-3}} \right)^{1/2} \cdot \left(\frac{10^{12} \text{ GeV}}{f/C_e} \right)$$

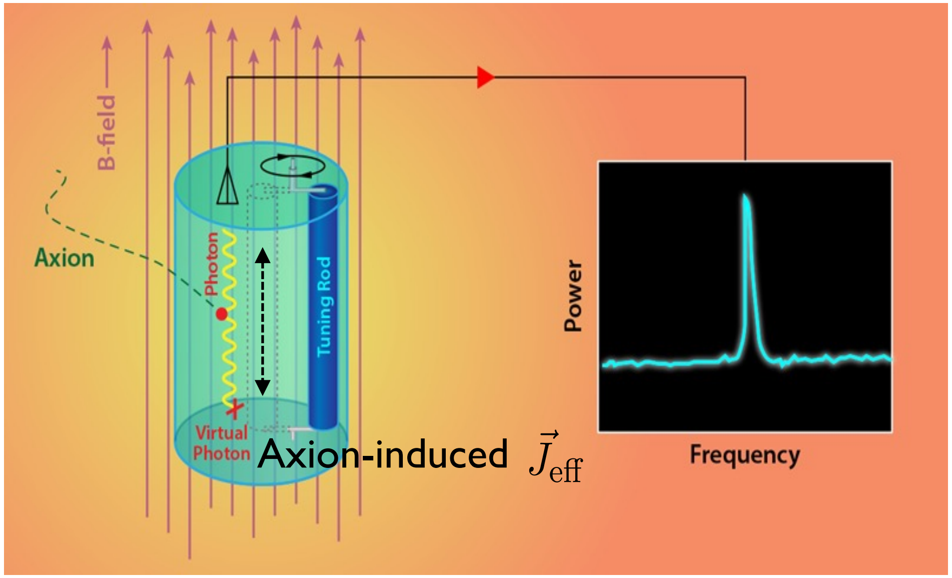
CME $\Rightarrow$

$$j^3 = \frac{e^2}{2\pi^2} \mu_5 v_F B = 6.8 \times 10^{-15} \text{A m}^{-2} \cos(m_a t) \times \left(\frac{v_F}{10^{-2}} \right) \cdot \left(\frac{\rho_{\rm DM}}{0.4 \text{ GeV cm}^{-3}} \right)^{1/2} \cdot \left(\frac{10^{12} \text{ GeV}}{f/C_e} \right) \cdot \left(\frac{B}{10 \text{ Tesla}} \right)$$

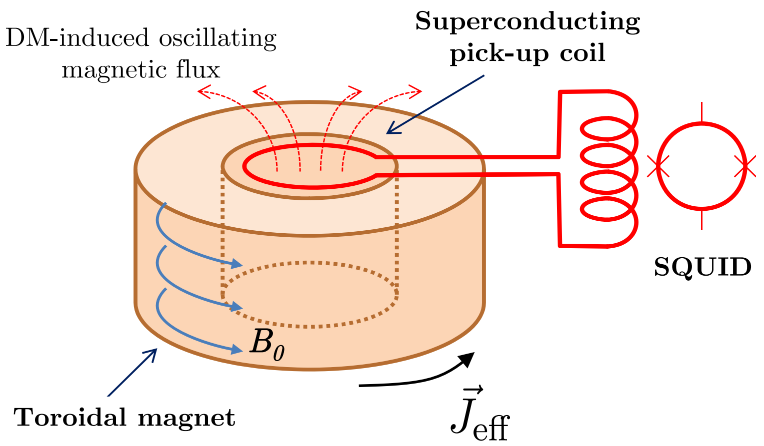
CME current measurement by modified axion haloscopes

Existing haloscopes for the axion-photon coupling may be used for detecting the CME current by replacing the "vacuum" with a "conductor".

$$J_{\mathrm{eff}} = g_{a\gamma}\, \dot{a}\, B \quad \Longleftrightarrow \quad J_{\mathrm{CME}} = \frac{e^2}{2\pi^2} \frac{C_e}{f_a} v_F\, \dot{a}\, B$$



Microwave resonant cavity



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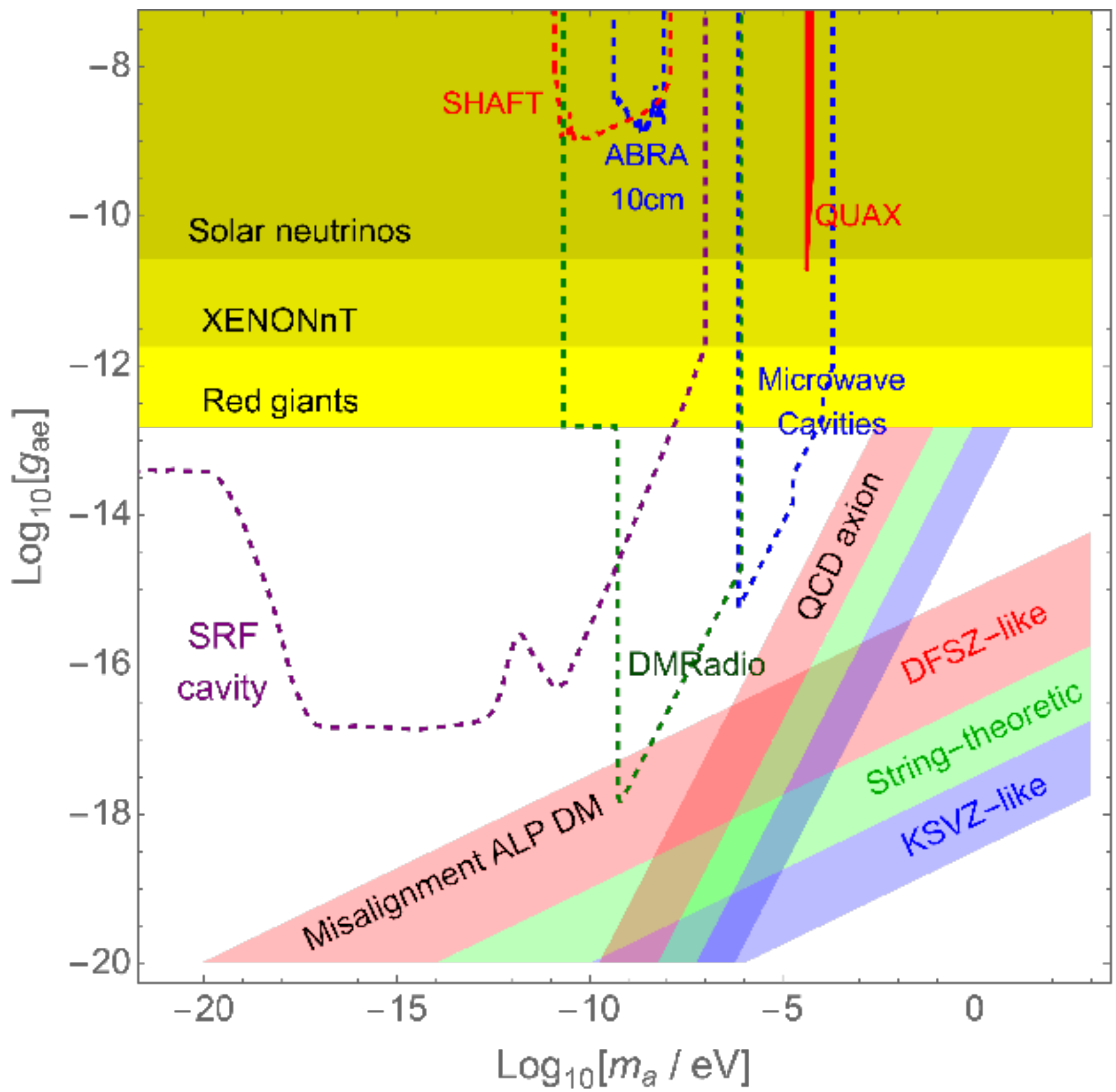
Kahn, Safdi, Thaler '16

Projected sensitivity from existing axion haloscopes



Conclusions

- Axions are theoretically well-motivated new particles which may be an important clue for underlying UV physics when they are discovered.
- The measurement of the axion-electron coupling is particularly important for determining the microscopic origin of axions.
- The chiral magnetic effect (CME) offers an intriguing possibility for the measurement of the axion-electron coupling, when the axion comprises a major fraction of dark matter.
- We have newly computed the CME-induced current and claim that it is proportional to the Fermi velocity of the electrons.

Back-up slides

Laboratory searches for axion DM -photonic probes

$$\frac{g_{a\gamma}}{4} aF\tilde{F} \quad \Rightarrow \quad \nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} \underbrace{- g_{a\gamma} \vec{B} \partial_t a}_{\vec{J}_{\rm eff}}$$

$\vec{J}_{\rm eff}$ effective current

Background axion DM field

$$a \approx a_0 \cos\left[m_a(t - \vec{v}\cdot\vec{x})\right]$$

$$\rho_a = \frac{1}{2} m_a^2 a_0^2 \qquad |\vec{v}| \sim 10^{-3} c$$

$$\Rightarrow \quad \vec{J}_{\rm eff} \approx g_{a\gamma} \sqrt{2\rho_a} \vec{B} \sin m_a t$$

The best experimental sensitivity on $g_{a\gamma}$ is obtained when $\rho_a = \rho_{DM}$.

Misalignment axion DM

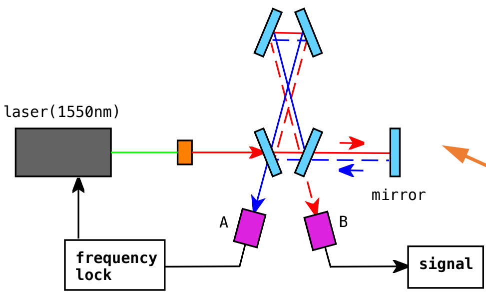
$$f_a \simeq 10^{17}\,\mathrm{GeV} \left(\frac{10^{-22}\,\mathrm{eV}}{m_a}\right)^{1/4} \sqrt{\frac{\rho_a}{\rho_{\rm DM}}} \quad \Rightarrow \quad g_{a\gamma} = \frac{e^2}{8\pi^2} \frac{1}{f_a} c_{a\gamma}$$

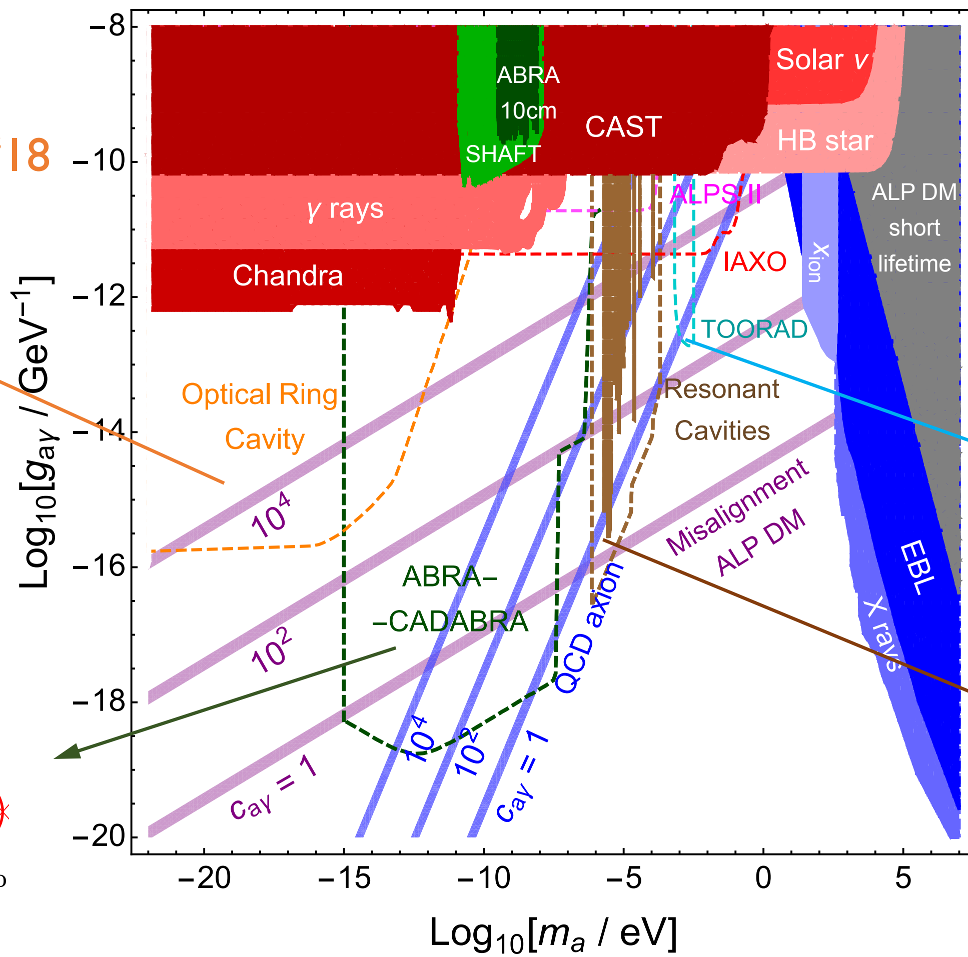
Given axion DM mass, $g_{a\gamma}$ is determined for $c_{a\gamma} \sim O(1)$.

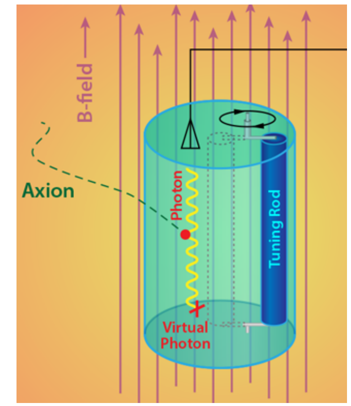
Current and future limits on $g_{a\gamma}$

Choi, SHI, Shin '20

Obata, Fujita, Michimura '18

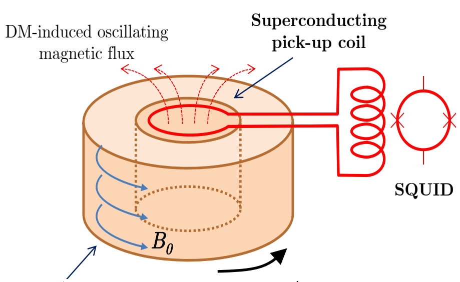






Marsh, Fong, Lentz, Smejkal, Ali '18

Kahn, Safdi, Thaler '16



$$\vec{J}_{\rm eff} = -g_{a\gamma}\vec{B}_0\partial_t a$$

ADMX, IBS-CAPP, MADMAX…

Laboratory searches for axion DM -nucleonic probes

$$g_{aN} \frac{\partial_\mu a}{2m_N} \bar{N}\gamma^\mu \gamma^5 N \quad \Rightarrow \quad \underbrace{g_{aN} \frac{\nabla a}{\gamma_N m_N}}_{\vec{B}_{\text{eff}}} \cdot \gamma_N \vec{S}_N$$

γ_N : nucleon gyromagnetic ratio

Background axion DM field

$$a \approx a_0 \cos\left[m_a(t - \vec{v}\cdot\vec{x})\right] \quad \Rightarrow \quad \vec{B}_{\text{eff}} \approx g_{aN} \frac{\sqrt{2\rho_a}}{\gamma_N m_N} \vec{v}_a \sin m_a t$$

$$\rho_a = \frac{1}{2} m_a^2 a_0^2 \qquad |\vec{v}| \sim 10^{-3} c$$

The best experimental sensitivity on g_{aN} is obtained when $\rho_a = \rho_{DM}$.

Misalignment axion DM

$$f_a \simeq 10^{17}\,\text{GeV} \left(\frac{10^{-22}\,\text{eV}}{m_a}\right)^{1/4} \sqrt{\frac{\rho_a}{\rho_{\text{DM}}}} \quad \Rightarrow \quad g_{aN} = \frac{m_N}{f_a} c_{aq} \times \mathcal{O}(1)$$

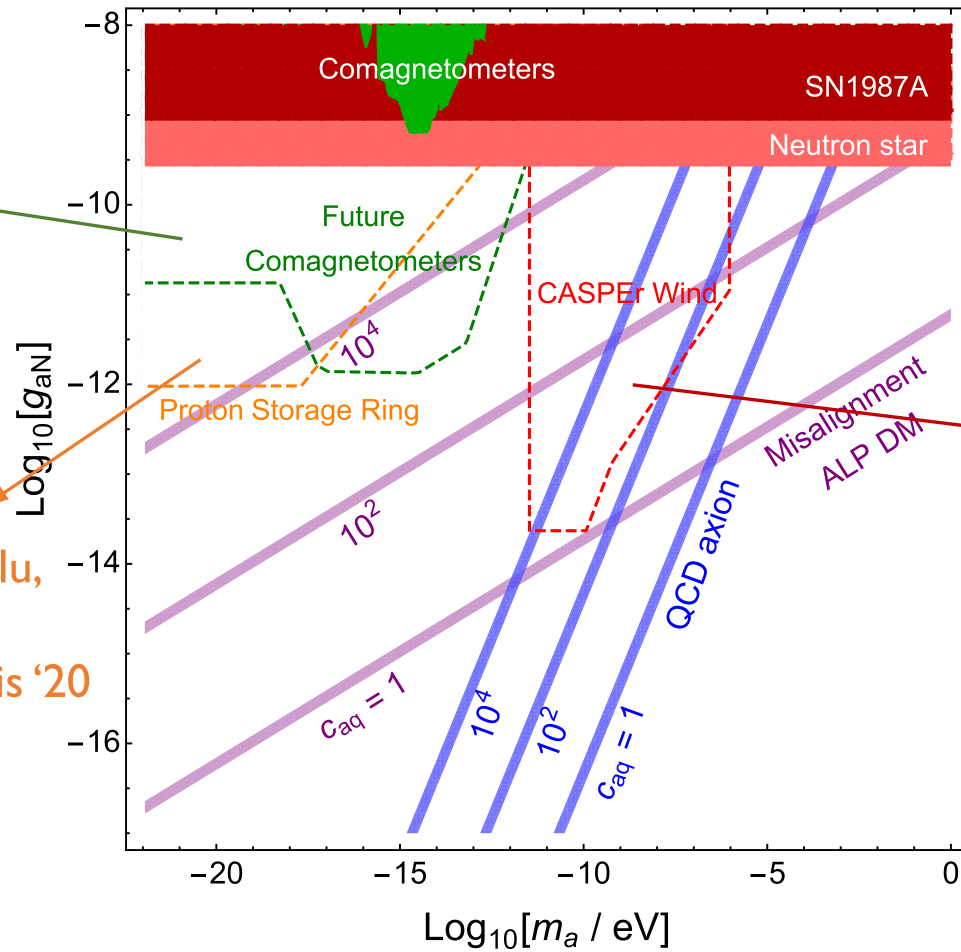
Given axion DM mass,
g_{aN} is determined for $c_{aq} \sim O(1)$.

Current and future limits on g_{aN}

Choi, SHI, Shin '20

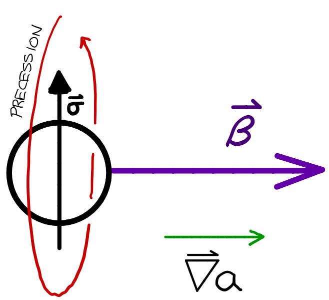
Bloch, Hochberg, Kuflik, Volansky '19

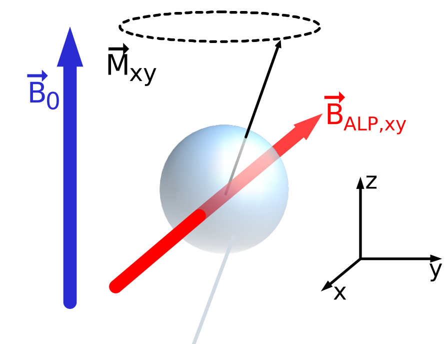
$$\frac{B^e_{\rm eff}}{B^N_{\rm eff}} \sim \frac{c_{ae} m_e}{c_{aN} m_N} \neq 1$$



Kimball et al '17

Graham, Haciomeroglu, Kaplan, Omarov, Rajendran, Semertzidis '20





NMR