Detecting axion dark matter with chiral magnetic effects

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Based on arXiv:2207.06884 done with

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Axion as a window to BSM

- Axion is one of the prime candidates for BSM.
- It could solve the strong CP problem.
- It is also an excellent candidate for Dark matter.

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The strong CP and axions

- QCD contains the θ term that breaks CP:

$$\mathcal{L}_{\rm QCD} \supset \frac{\theta}{16\pi^2}\epsilon^{\mu\nu\alpha\beta}\,{\rm Tr}\,F_{\mu\nu}F_{\alpha\beta}\,.$$

- The physical parameter for strong CP-violation

$$\bar\theta = \theta + {\rm Arg\,Det}M_q\ .$$

- The strong interaction preserves CP. Its bound comes from

$$d_n = \left(\frac{\rm const.}{m_N}\right)\left(\frac{m_q\,\bar\theta}{m_N}\right) < 2.9\times 10^{-26}\,e\cdot{\rm cm}$$

- hQCD calculation (DKH+Kim+Siwach+Yee, 2007):

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The strong CP and axions

- The strong CP problem is solved if θ is a dynamical field, $\theta = a(x)/f$, because $\mathcal{E}_{\rm vac}(\theta) \geq \mathcal{E}_{\rm vac}(0)$ by Vafa-Witten.
- Since the θ shifts under $U(1)_A$ rotation of colored fermions, the axions can be realized as the NG boson of PQ mechanism.
- When QCD confines, the axion potential develops:

$$V(a/f) \sim m_q \Lambda_{\rm QCD}^3 F(a/f)$$

- The axion mass is then

$$m_a \sim \sqrt{\frac{m_q \Lambda_{\rm QCD}^3}{f}}$$

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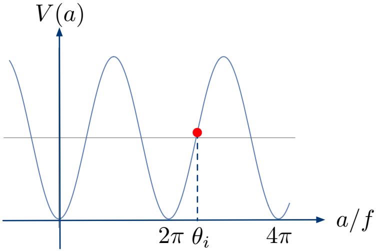
Axion as Dark matter

- The axion solves the strong CP problem dynamically.



Axion as Dark matter

- For $T \ll f$ and $H \ll m_a$, the axions are homogeneous and behave collectively as CDM, assuming inflation occurs after PQ symmetry breaking (Preskill+Wise+Wilczek, Abbott+Sikivie, Dine+Fischler 1983):

$$a(t) = \frac{\sqrt{2\rho_a}}{m_a} \sin(m_a t)$$

- For a large decay constant, axions are weakly coupled to SM particles and may constitue DM, $\rho_a \approx \rho_{\rm DM}$. (Turner 1986)

$$\Omega_a h^2 \approx 0.23 \times 10^{\pm 0.6} \left(\frac{f}{10^{12}\ {\rm GeV}}\right)^{1.175} \theta_i^2 F(\theta_i)\,,$$

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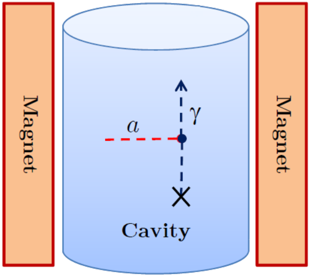
Existing experiments and proposals

- From its coupling to SM particles we can measure them.
- For example, axions couple to photons: Sikivie '83, RBF-UF, ADMX, HAYSTAC, CAPP, $\cdots$.

$$\mathcal{L}_{\rm int} \ni g_{a\gamma\gamma}\frac{a}{2f}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}\,.$$



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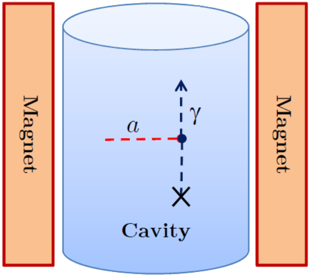
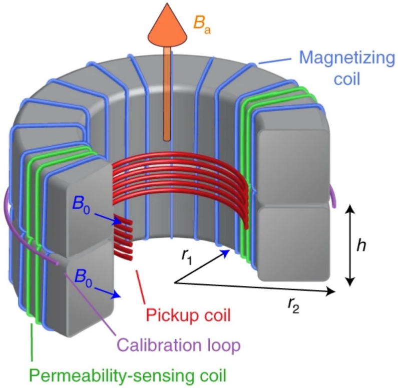


Existing experiments and proposals

- Axions couple to photons, modifying Maxwell equations: ABRACADABRA '16, DMRadio, $\cdots$

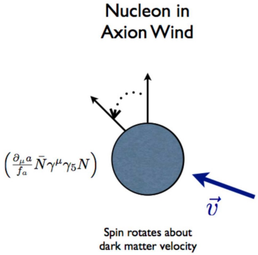
$$\nabla \times \vec{B} = g_{a\gamma\gamma} \dot{a} \vec{B} \,.$$

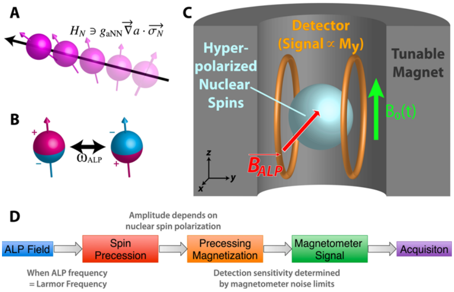


Existing experiments and proposals

- Axions couple to gluons and hadrons: CASPER, spin torsion, ...

$$\mathcal{L}_{\text{int}} \ni \frac{c_N}{f}\partial_\mu a \bar{N}\gamma^\mu\gamma_5 N + i\frac{g_d}{2}a(t)\bar{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu}$$

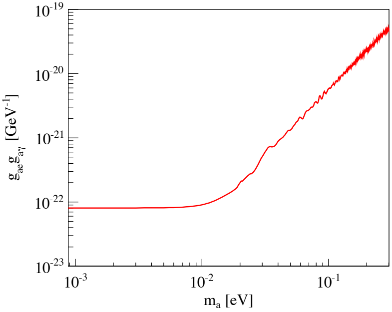




Existing experiments and proposals

- Axions couple to both electrons and photons: CAST

$$\mathcal{L}_{\rm int} \ni g_{a\gamma}\frac{a}{2f}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} + \frac{g_{ae}}{2m}\partial_\mu a\bar{\psi}\gamma^\mu\gamma_5\psi\,.$$



Existing experiments and proposals

- Axions couple to electrons: QUAX-ae (2019)

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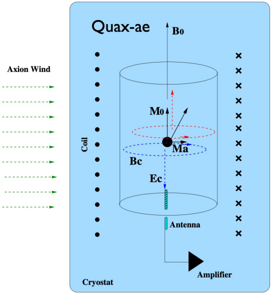

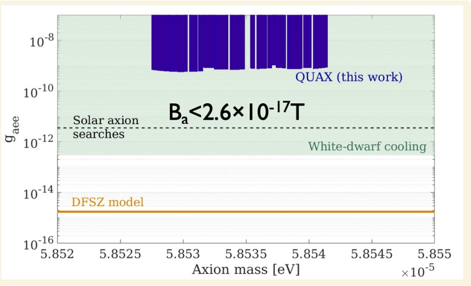

Low temperature Axion Chiral Magnetic Effect

- Electrons couple to axion DM: LACME (our proposal)

$$\mathcal{L}_{\rm int} = C_e \frac{\partial_\mu a}{f} \bar{\psi}\gamma^\mu \gamma_5 \psi \approx \frac{C_e}{f}\sqrt{2\rho_{\rm DM}} \cos(m_a t)\psi^\dagger \gamma_5 \psi \, .$$

- Axion DM acts as an axial chemical potential for electrons.

$$\mu_5 = C_e \frac{\sqrt{2\rho_{\rm DM}}}{f} \cos(m_a t)$$

- The axial chemical potential induces a helicity imbalance if $B \neq 0$. $\Rightarrow$ Chiral Magnetic Effects (Fukushima+Kharzeev+Warringa 2008).

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chiral magnetic effects in chiral medium

- CME is a current flow due to the helicity imbalance in (polarized) medium by the axial chemical potential μ_5 and B:

$$\left\langle \vec{j} \right\rangle = v_F \frac{e^2}{2\pi^2} \mu_5 \vec{B}$$

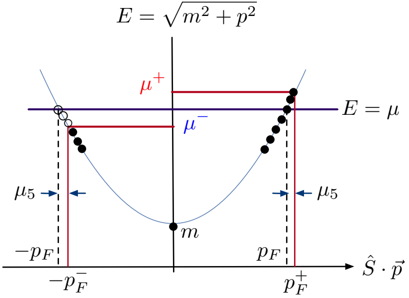

Figure: chiral medium

- In the original formula by (FKW 2008) the v_F dependence is missing (DKH+Im+Jeong+Yeom 2022).

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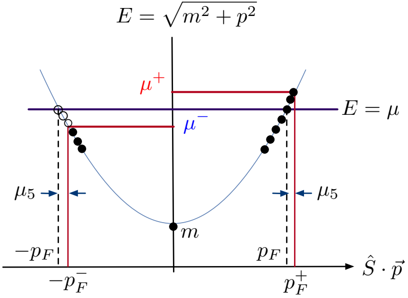

Figure: chiral medium

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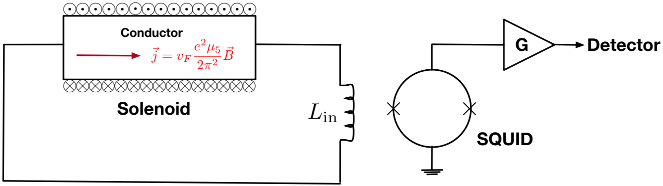
Axionic Chiral Magnetic Effects

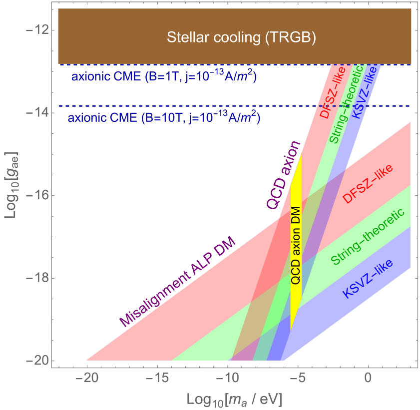
- We propose a new experiment (LACME) to detect this non-dissipative currents in a conductor:

$$j^3 = 6.8 \times 10^{-15}\mathrm{Am}^{-2}\left(\frac{v_F}{0.01c}\right)\left(\frac{\rho_{\mathrm{DM}}}{0.4\,\mathrm{GeVcm}^{-3}}\right)^{1/2}\left(\frac{10^{12}\,\mathrm{GeV}}{f/C_e}\right)\left(\frac{B}{10\,\mathrm{Tesla}}\right)$$



Axionic Chiral Magnetic Effects

- Projection of LACME, assuming $10^{-13}Am^{-2}$ sensitivity and $v_F = 0.01$ $(g_{ae} = 2C_e m_e/f)$:



Normal medium: What is the chemical potential?

- The chemical potential couples to a conserved number density to keep the average number constant.

$$\mathcal{L} = \mathcal{L}_{\rm vac} + \mu\bar{\psi}\gamma_0\psi \Rightarrow \frac{\delta}{\delta\mu}\mathcal{Z} = \left\langle \psi^\dagger\psi \right\rangle = \rho_0\,.$$

- This is a normal medium, which has a finite fermion number density,

$$\rho_0 = \frac{p_F^3}{3\pi^2}\,.$$

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Normal medium

- Consider a cold medium of (free) electrons :

$$\mathcal{L} = \bar{\psi}\left(i\partial\!\!\!/ - m + \mu\gamma^0\right)\psi$$

$$\Downarrow$$

$$E = -\mu \pm \sqrt{m^2 + \vec{p}^2}\,,$$

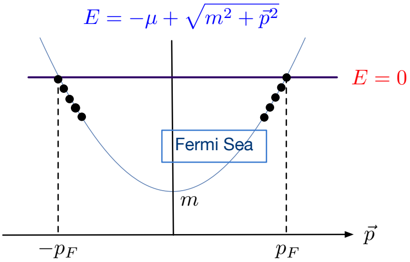

Figure: normal medium

Normal medium

- The current density in cold medium: $j^\mu = \bar{\psi}\gamma^\mu\psi$ with $\vec{\alpha} = \gamma^0\vec{\gamma}$

$$\begin{aligned}\langle j^\mu \rangle &= -ie\int \frac{\mathrm{d}^4 p}{(2\pi)^4}\mathrm{Tr}\left[\gamma^\mu\gamma^0\frac{1}{(1+i\epsilon)p_0 - \vec{p}\cdot\vec{\alpha} - m\gamma^0 + \mu}\right] \\ &= \int_0^\mu \mathrm{d}\mu' \frac{\partial}{\partial\mu'}\left\langle j^\mu(\mu')\right\rangle\end{aligned}$$

- Since the integration is finite, we shift $p_0 \to p_0' = p_0 + \mu'$ and use

$$\frac{1}{x+i\epsilon} = \mathrm{P}\frac{1}{x} - \pi i \mathrm{sgn}\left(\epsilon\right)\delta(x)$$

- The μ' dependence appears only in

$$-\pi i \mathrm{sgn}\left(p_0' - \mu'\right)\delta\left(\mu' - \vec{\alpha}\cdot\vec{p} - m\gamma^0\right)$$

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Normal medium

- Taking derivative with respect to μ' and integrating over p_0', we get

$$\begin{aligned}\langle j^\mu(\mu)\rangle &= e\int_0^\mu \mathrm{d}\mu' \int \frac{\mathrm{d}^3p}{(2\pi)^3}\mathrm{Tr}\left[\gamma^\mu\gamma^0\delta\left(\mu'-\vec{\alpha}\cdot\vec{p}-m\gamma^0\right)\right] \\ &= e\int_{0<|\vec{p}|<p_F}\frac{\mathrm{d}^3p}{(2\pi)^3}\mathrm{Tr}\left[\gamma^\mu\gamma^0\frac{1+\gamma^0}{2}\right] = e\frac{p_F^3}{3\pi^2}\delta^{\mu 0},\end{aligned}$$

where we have performed the Foldy-Wouthysen transformation for the δ function and the positive energy projection.

chiral chiral medium: What is the axial chemical potential?

- Now let us consider a chiral medium with $\mu_5 \neq 0$ and $\mu \neq 0$.
- Since the axial current is not conserved because of the anomaly and the mass term, what is the meaning of the axial chemical potential?

$$\partial_\mu j_5^\mu = 2m\bar{\psi}\psi + \frac{e^2}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} \neq 0 \,.$$

- Unlike μ, the axial chemical potential can not keep the axial number density constant. The mass term always flips the chirality.

$$\rho_A = \left\langle \psi^\dagger \gamma_5 \psi \right\rangle = \frac{\delta \mathcal{Z}}{\delta \mu_5} = \rho_L - \rho_R \neq \text{constant} \,.$$

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- To see the meaning of μ_5, let's consider the medium with μ_5.

$$\mathcal{L} = \bar{\Psi}\left(i\partial\!\!\!/ - m + \mu\gamma^0 + \mu_5\gamma^0\gamma_5\right)\Psi$$

- Now, we take a non-relativistic limit by subtracting out the rest mass and integrating out the negative states, χ:

$$\Psi \equiv \begin{pmatrix}\psi \\ \chi\end{pmatrix} e^{-imt} \qquad (\mu_{\rm NR} \equiv \mu - m)$$

$$\Rightarrow \mathcal{L}_{\rm NR} \; = \; \psi^\dagger\left[i\partial_0 - \frac{(i\vec{\sigma}\cdot\vec{\nabla} + \mu_5)^2}{2m}\right]\psi + \mu_{\rm NR}\psi^\dagger\psi + \cdots$$

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- Now since we are interested in modes near the Fermi surface, we expand the electron field as, following HDET (DKH '00),

$$\psi(x) = \sum_{\vec{v}_F} \psi(\vec{v}_F, x) e^{i\vec{p}_F\cdot\vec{x}}\,.$$

- The effective Lagrangian for modes near the Fermi sea becomes

$$\mathcal{L}_{\rm eff} \;=\; \sum_{\vec{v}_F}\left[\psi^\dagger\left(i\partial_0 - i\vec{\sigma}\cdot\vec{v}_F\vec{\sigma}\cdot\vec{\nabla}\right)\psi + \mu_5\vec{v}_F\cdot\psi^\dagger\vec{\sigma}\psi\right] + \cdots\,,$$

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$$\mathcal{L}_{\rm eff} \;=\; \sum_{\vec{v}_F}\left[\psi^\dagger\left(i\partial_0 - i\vec{\sigma}\cdot\vec{v}_F\vec{\sigma}\cdot\vec{\nabla}\right)\psi + \mu_5\vec{v}_F\cdot\psi^\dagger\vec{\sigma}\psi\right] + \cdots\,,$$

where we used $\mu_{\rm NR} \equiv p_F^2/2m\,.$

chiral chiral medium: What is the axial chemical potential?

- We now clearly see that the axial chemical potential μ_5 controls the spin density along the Fermi velocity.
- Since the spin symmetry is conserved in the NR limit, we see that $\mu_5 v_F$ is the spin chemical potential in NR medium that keeps constant the number of spins along the Fermi momentum direction.
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chiral magnetic effects

- In normal Fermi liquid the Fermi surface is isotropic and we do not see any net helicity imbalance even if $\mu_5 \neq 0$.
- However, if we apply magnetic fields, the spectrum of electrons in medium is quantized $(n = 1, 2, \cdots)$:

$$E_n(p_z) = \pm\sqrt{p_z^2 + m^2 + 2\,|eB|\,n}\,,$$

where $2n = 2n_r + 1 + |m_L| - \mathrm{sign}(eB)\,(m_L + 2s_z)$.

- For the lowest Landau level (LLL) electrons, the spins are always anti-parallel to the magnetic field. The axial chemical potential then generates net helicity imbalance:

$$\rho^{n=0}_{h=+1} - \rho^{n=0}_{h=-1} = \frac{|eB|}{4\pi^2}\left(p_F^+ - p_F^-\right) = \frac{|eB|}{2\pi^2}\mu_5\,.$$

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- Summing up all currents, we find with $r = \mu_5/\mu$

$$\begin{aligned}\langle j^3 \rangle &= \frac{e^2 B}{4\pi^2}\left[\int_0^{p_F^+} \frac{p_z \mathrm{d}p_z}{\sqrt{p_z^2+m^2}} - \int_0^{p_F^-} \frac{p_z \mathrm{d}p_z}{\sqrt{p_z^2+m^2}}\right] \\ &= \frac{e^2 B}{2\pi^2} \cdot \frac{2 v_F \mu_5}{\sqrt{1+r^2+2v_F r} + \sqrt{1+r^2 2 v_F r}} \\ &\approx v_F \frac{e^2 B}{2\pi^2}\mu_5 \,,\end{aligned}$$

Axion-electron coupling

- The axion-electron coupling depends on the UV model.
- The strength of the axion-electron coupling varies as

$$C_e \simeq \begin{cases} \mathcal{O}(1) & \text{DFSZ-like models} \\ \mathcal{O}(10^{-4} \sim 10^{-3}) & \text{KSVZ-like models} \\ \mathcal{O}(10^{-3} \sim 10^{-2}) & \text{String-theoretic axions}\,. \end{cases}$$

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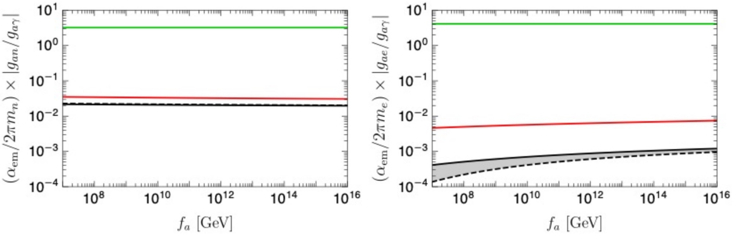
Axion-electron coupling (A slide from Sang Hui Im)

Distinguishing the models of an axion by coupling ratios

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



Green : DFSZ-like model

Red : String-theoretic model

Black : KSVZ-like model (dashed : $m_\Psi = 10^{-3} f_a$, solid : $m_\Psi = f_a$)

Axionic Chiral Magnetic Effects

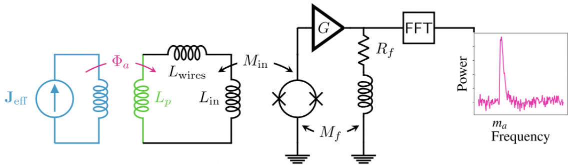


Figure: ABRACADABRA

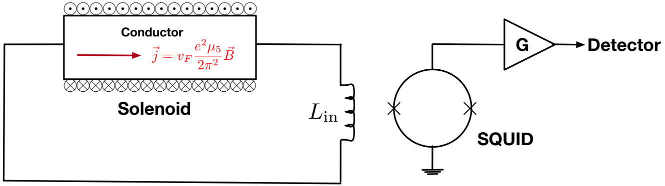


Figure: LACME

Axionic Chiral Magnetic Effects

- ABRACADABRA-10 cm has put a bound (2021)

$$g_{a\gamma\gamma} < 3.2 \times 10^{-11}\mathrm{GeV}^{-1}$$

- If we assume the same sensitivity for LACME,

$$\frac{f}{C_e} > 10^{6}\mathrm{GeV}$$

- It will be then comparable to or better than QUAX sensitivity:

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Chiral magnetic effects in medium

- Now consider chirally imbalanced medium:

$$\mathcal{L} = \bar{\psi}\left(i\partial\!\!\!/ - m + \mu\gamma^0 + \mu_5\gamma^0\gamma_5\right)\psi$$

- While the vector chemical potential shifts the ground state energy to populate the electrons up to the Fermi momentum p_F, the axial chemical potential shifts the momentum in the direction of spin to populate more the positive helicity states.
- If we transform the electron field, $\psi \to \psi' = e^{-i\mu_5 \vec{\Sigma}\cdot\vec{x}}\psi$, we absorb μ_5 into the momentum along the spin direction :

$$\mathcal{L} = \bar{\psi}'\left(i\gamma'\cdot\partial - m + \mu\gamma^0\right)\psi' .$$

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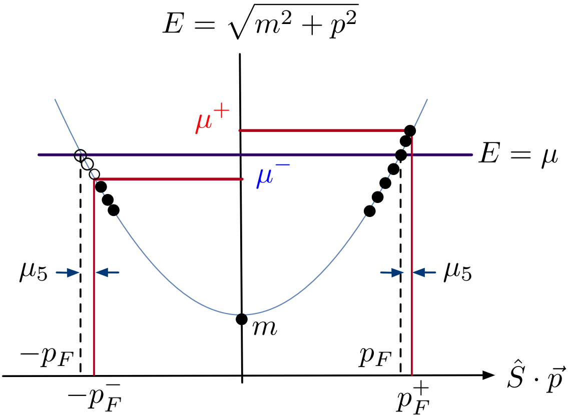

Figure: chiral medium

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- Because of the spin symmetry in the rest frame of medium, the axial chemical potential alone does not create net chiral imbalance unless mass vanishes, $m = 0$.
- However, under the magnetic field the spin degeneracy is lifted. The electrons in LLL states have their spin always anti-parallel to the magnetic field and indeed we have helicity imbalance under the magnetic field if $\mu_5 \neq 0$.
- The LLL propagator with $\tilde{p}_{\parallel} = (p_0 + \mu + \mu_5\gamma_5, 0, 0, p_z)$

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

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Chiral magnetic effects in medium

- At one-loop the current is given by

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

- The medium contribution is then

$$\begin{aligned} \langle j^3 \rangle &= \int_0^\mu \mathrm{d}\mu' \frac{\partial}{\partial \mu'} \langle j^\mu(\mu') \rangle \\ &= \frac{e^2 B}{4\pi^2} \left[\int_0^{\mu_+} \mathrm{d}p_0 \int_{p_z>0} |p_z| \delta\left(p_\parallel^2 - m^2\right) - \int_0^{\mu_-} \mathrm{d}p_0 \int_{p_z>0} |p_z| \, \delta\left(p_\parallel^2 - m^2\right) \right] \\ &= \frac{e^2 B}{4\pi^2} \left[\sqrt{(p_F + \mu_5)^2 + m^2} - \sqrt{(p_F - \mu_5)^2 + m^2} \right] \\ &= \frac{e^2 B}{2\pi^2} \mu_5 v_F \left[1 + \mathcal{O}(v_F^2, r^2) \right] . \end{aligned}$$

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\end{aligned}$$

Axial anomaly in medium

- CME is closely related to axial ABJ anomaly in 2D. To see this we consider the anomalous two-point function of LLL electrons in medium:

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

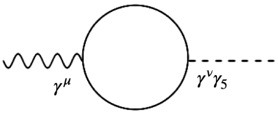

Figure: ABJ anomaly in 2D

Axial anomaly in medium

- In the HDL approximation or for $q/\mu \to 0$, we find

$$\Gamma^{\mu\nu}(q) = \frac{eB}{2\pi^2 v_F}\left[-\eta^{\mu 0}\epsilon^{\nu 0} + \frac{q^0}{2}\left(\frac{V^\mu \epsilon^{\nu\alpha} V_\alpha}{V\cdot q} + \frac{\bar{V}^\mu \epsilon^{\nu\alpha}\bar{V}_\alpha}{\bar{V}\cdot q}\right)\right],$$

where $V^\mu = (1,0,0,v_F)$ and $\bar{V}^\mu = (1,0,0,-v_F)$.

- The vector current is conserved:

$$q_\mu \Gamma^{\mu\nu}(q) = 0\,.$$

- The axial current is however anomalous:

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

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Axial anomaly in medium

- The ABJ anomaly becomes in the rest frame of the medium

$$\langle \partial_\nu j_5^\nu \rangle_A = \frac{e^2}{16\pi^2} v_F \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} \,.$$

- The anomaly is due to the gapless modes at the Fermi sea, which exists even for $m \neq 0$. (Cf. Coleman+Grossman '82)
- The anomaly should survive in the superfluid phase, where the electrons are gapped, and the axial supercurrent should have the anomalous coupling. (DKH+Im to appear.)

$$\left\langle \psi_L^T \gamma^0 C \psi_L \right\rangle = \Delta_L(p_F), \;\; \left\langle \psi_R^T \gamma^0 C \psi_R \right\rangle = -\Delta_R(p_F) \,.$$

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Axial anomaly and CME in medium

- From the anomalous two-point function one can calculate the CME, in the leading order in μ_5.

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

which agrees with our direct calculations!

Conclusion

- We show that dark matter axions or axion-like particles (ALP) induce non-dissipative alternating electric currents in conductors along the external magnetic fields due to the axial anomaly, realizing the chiral magnetic effects.

$$\vec{j} = v_F \frac{e^2}{2\pi^2}\frac{C_e}{f}\dot{a}\vec{B}\,. \quad (\mathrm{LACME})\,.$$

- We propose a new experiment to measure this current in medium to detect the dark matter axions or ALP. (LACME)
- This non-dissipative currents are the electron medium effects, directly proportional to the axion or ALP coupling to electrons, which depends on their microscopic physics.

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- Our experiment is complementary to existing experiments.
- We also find the fermi liquid suffers from the axial ABJ anomaly

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