Search for axion dark matter in the laboratory and in the cosmos

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20th Rencontre du Vietnam: BSM 50 years.

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Based on arXiv:2207.06884 and arXiv:2401.xxxxx (to appear) with Sang Hui Im (CTPU), K.S. Jeong, D.-h.Yeom (PNU): Stephen Lonsdale (PNU)

Axion as a window to BSM

- There are many candidates for dark matter.
- But, axion is still one of the prime candidates for dark matter.
- It is theoretically well motivated as a solution to the strong CP problem.
- Currently several experiments to detect axions are going on and new ones keep being proposed.
- In this talk I present two new proposals to detect axion DM in the lab. and in the cosmos.

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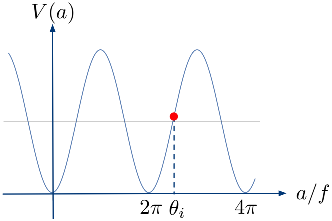
Axion as Dark matter

- The axion solves the strong CP problem dynamically.



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

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

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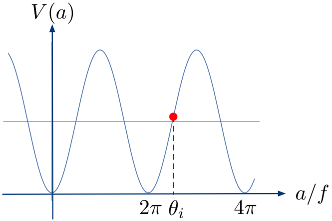

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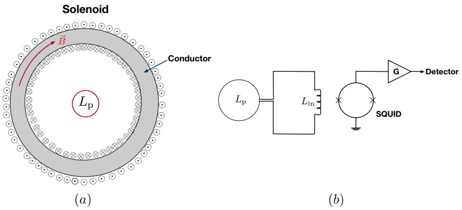
Axion as Dark matter

- Axions, coupled to SM particles, live long enough for a large decay constant and may constitue most of DM, $\rho_a \approx \rho_{\rm DM}$, (Turner 1986).

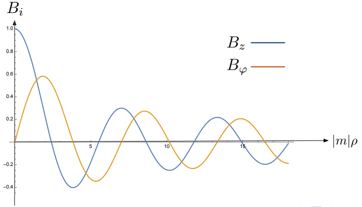
$$\Omega_a h^2 \approx 0.23 \times 10^{\pm 0.6} \left(\frac{f}{10^{12}\ \mathrm{GeV}} \right)^{1.175} \theta_i^2 F(\theta_i)\,,$$

Two stories on axion DM (LACME and Axion Vortex)

- A proposal to detect axions in the lab. (arXiv:2207.06884) :



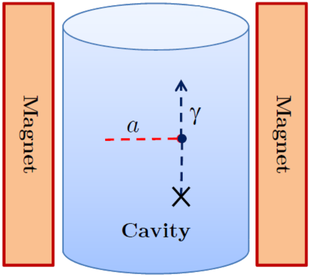
- Axion vortex in the cosmos ($m = g_{a\gamma}\dot{a} \sim 1/\mathrm{kpc}$) (to appear) :



Existing experiments and proposals

- From its coupling to photons: (Sikivie '83, ... CAPP)

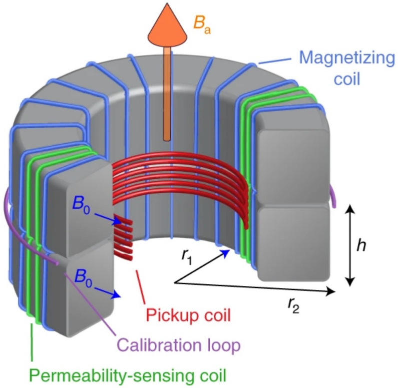
$$\mathcal{L}_{\rm int} \ni g_{a\gamma\gamma} \frac{a}{2f} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} \, .$$



Existing experiments and proposals

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

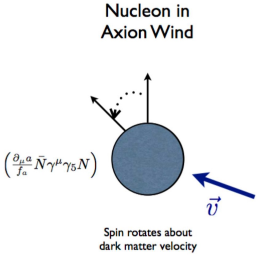
$$\nabla \times \vec{B} = g_{a\gamma\gamma}\dot{a}\vec{B}\,.$$

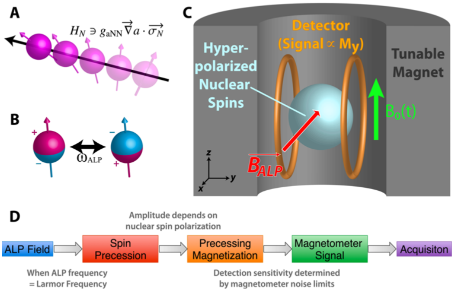


Existing experiments and proposals

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

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





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.

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

- μ_5 induces a net current in medium along B field. $\Rightarrow$ Chiral Magnetic Effects (Fukushima+Kharzeev+Warringa '08).

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- CME predicts a persistent current of oscillating electric currents.

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

- Our proposal (LACME) is to measure this current in a conductor to detect axion dark matter.

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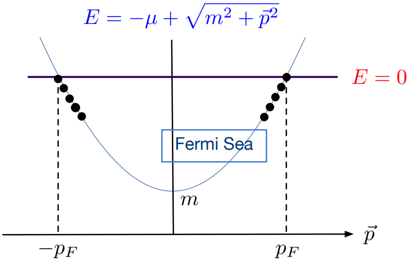
Normal medium

- Consider first a cold medium of (free) electrons.
- The (vector) chemical potential adds energy by μ to all states, filling up particles up to the Fermi surface.

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

$$\Downarrow$$

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



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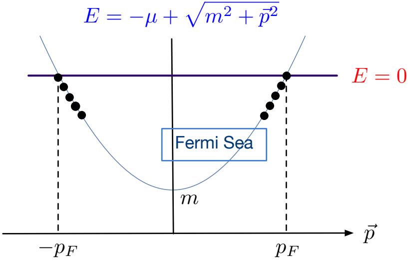

Figure: normal medium

Axionic Chiral Magnetic Effects

- Similarly, the axial chemical potential adds a kick to electrons along their spin direction to create a helicity imbalance :

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

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

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

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

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chiral magnetic effects in chiral medium

- μ_5 creates more particles moving along the spin direction.
- To create the helicity imbalance, we need a medium of polarized electrons.
- Under a magnetic field, electrons in the LLL are polarized opposite to the magnetic field:

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

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

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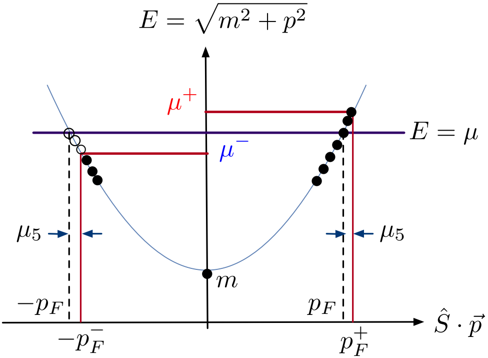


Figure: chiral medium

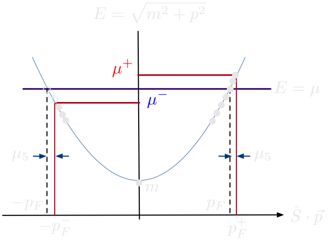
chiral magnetic effects in chiral medium

- Helicity imbalance

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

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

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



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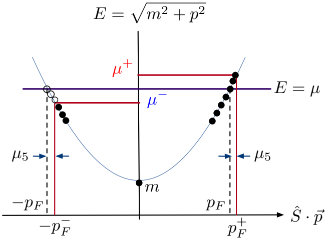

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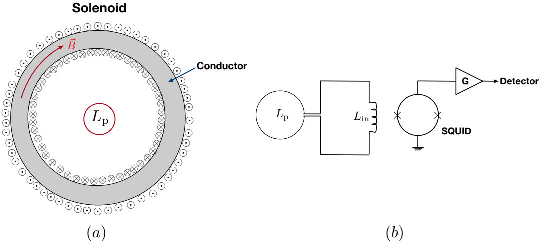
Axionic Chiral Magnetic Effects

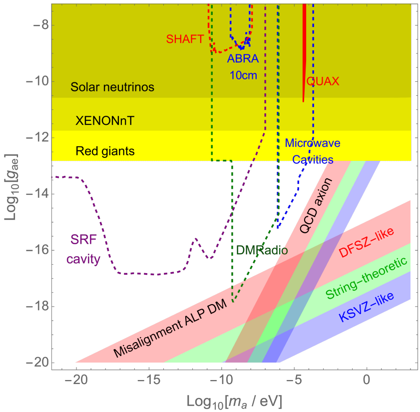
- We propose a new experiment (LACME) to detect this non-dissipative currents in a conductor:

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



Axionic Chiral Magnetic Effects

- Projection of LACME from existing axion haloscopes, assuming $v_F = 0.01$ $(g_{ae} = 2C_e m_e/f)$:



Axion-electron coupling

- The axion-electron coupling depends on the UV model.
- The strength of the axion-electron coupling varies as (See e.g. 2106.05816 by Choi+Im+Seong)

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

- The precise measurement of the axion-electron coupling can uncover its microscopic origin.

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Axion electrodynamics

- Axion electrodynamics for $\vec{\nabla} a = 0$:

$$\vec{\nabla} \cdot \vec{E} = 0\,, \quad \vec{\nabla} \times \vec{B} - \frac{\partial}{\partial t}\vec{E} = -g_{a\gamma}\dot{a}\vec{B}\,,$$

- In axion electrodynamics, the magnetic field sources itself, producing a current $\vec{J} = -m\vec{B}$ with $m = g_{a\gamma}\dot{a}$ even in the absence of charged particles.
- Magnetic fields are self-coupled. Superposition of magnetic fields is not possible.

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Axion electrodynamics

- When $\dot{a}$ is almost constant, there should exist a topological soliton carrying a finite magnetic flux.
- We therefore ask how the magnetic fields along the vortex should be distributed to minimize its energy for a given magnetic flux, which is topologically conserved.
- Our ansatz :

$$\vec{E} = 0\,, \quad \vec{B} = (0, B_\varphi(\rho), B_z(\rho))\ ,$$

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- The minimum energy saturates by configurations that satisfy the Maxwell equation or $\vec{B} = -m\vec{A}$ in the Coulomb gauge:

$$B''_\varphi + \frac{1}{\rho}B'_\varphi - \left(\frac{1}{\rho^2} - m^2\right)B_\varphi = 0\,; \quad B''_z + \frac{1}{\rho}B'_z + m^2 B_z = 0\,.$$

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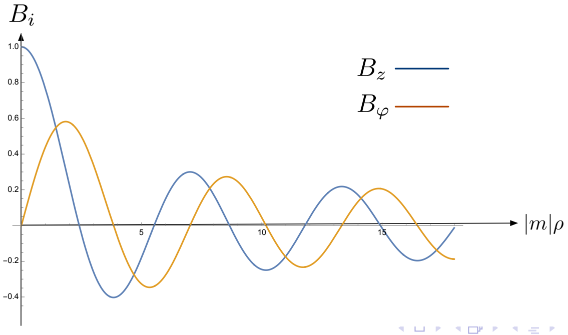
Axion magnetic vortex

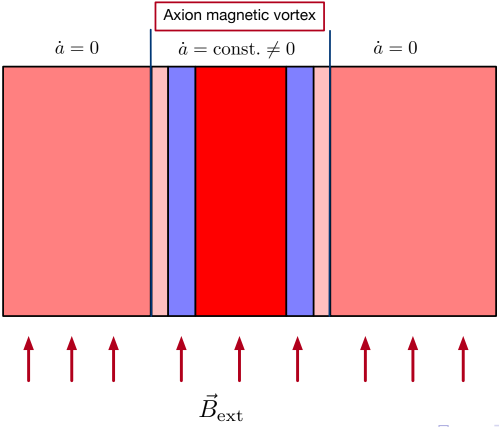
- The minimum energy configuration for a given flux Φ is with the normalization, $\mathcal{N} = 2\pi \int_0^{x_c} x J_0(x)\mathrm{d}x$,

$$B_\varphi(\rho) = -m|m| \frac{\Phi}{\mathcal{N}} J_1\left(|m|\,\rho\right), \;\; B_z(\rho) = m^2 \frac{\Phi}{\mathcal{N}} J_0(|m|\rho)\,.$$



Axion magnetic vortex

- If we apply an external magnetic field, $\vec{B}_{\text{ext}}$, an axion magnetic vortex will form spontaneously:



Axion magnetic vortex

- For the normal modes inside axion magnetic vortex

$$\delta a = \theta(t) f(|m|\rho)$$

- Fluctuations induce electric fields from the Faraday's law:

$$\begin{aligned} E_z(\rho) &= g_{a\gamma}\,\delta\ddot{a}\,\frac{\Phi}{\mathcal{N}}\left[J_0(|m|\rho) - |m|\rho\, J_1(|m|\rho)\right], \\ E_\varphi(\rho) &= -g_{a\gamma}\,\delta\ddot{a}\,\frac{\Phi}{\mathcal{N}}\, m\rho\, J_0(|m|\rho) \end{aligned}$$

- And it creates axion source that renormalizes the kinetic term,

$$\vec{E}\cdot\vec{B} = g_{a\gamma}\,\delta\ddot{a}\, m^2 \left(\frac{\Phi}{\mathcal{N}} J_0(|m|\rho)\right)^2$$

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Axion magnetic vortex

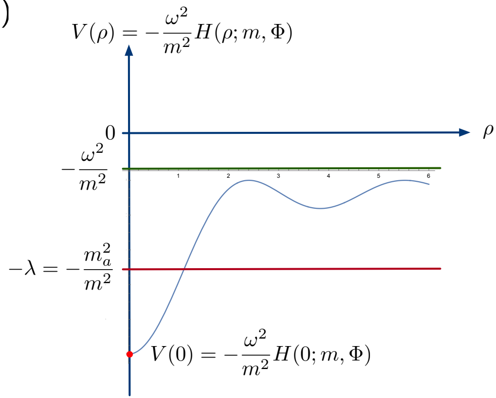
- The normal modes, $\delta a = \theta(t) f(|m|\rho)$, satisfy, after rescaling $|m|\rho$ to be ρ,

$$-\nabla^2 f(\rho) - \frac{\omega^2}{m^2} H(\rho) f(\rho) = -\lambda f(\rho)\,,$$

where $\omega^2 = -\ddot{\theta}/\theta$, $\lambda = m_a^2/m^2$, $H = 1 + g_{a\gamma}^2\, m^2 \left(\frac{\Phi}{\mathcal{N}} J_0(\rho)\right)^2$.

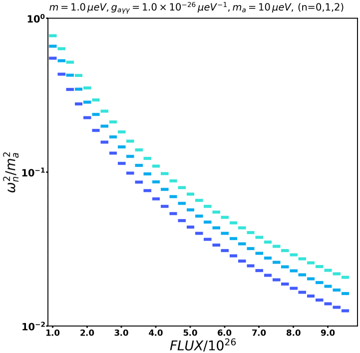
Axion magnetic vortex

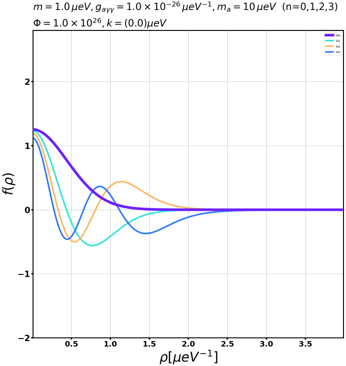
- Axion spectrum inside vortex is that of Schrödinger equation ($m = g_{a\gamma}\dot{a}$)



Axion magnetic vortex

- The size of vortex is $1/m \sim 1\,\mathrm{kpc}$ and the magnetic field in our galaxy is about $10\,\mu\mathrm{G} \Longrightarrow \Phi \sim 10^{26}$.
- A few low-lying energy eigenstates :





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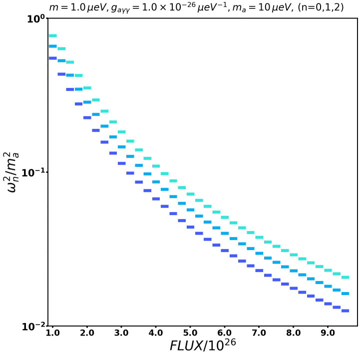

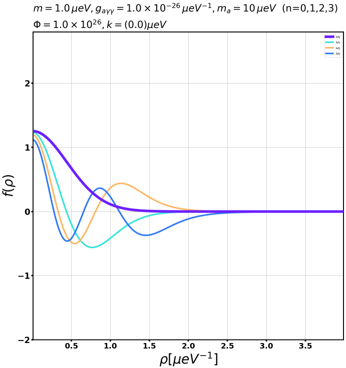

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- We show that dark matter axions or axion-like particles (ALP) induce non-dissipative alternating electric currents in conductors along the external magnetic fields due to the axial anomaly, realizing the chiral magnetic effects.

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

- 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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- If $\dot{a}$ is constant, there should exist a vortex solution of minimum energy for a give magnetic flux.
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