

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

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Workshop on Dark Universe

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

## Introduction

### Motivation

## Detecting axion dark matter

A new experimental proposal for axion DM

## Magnetic axion vortex

Axion electrodynamics

Axion magnetic vortex

## Conclusion

# 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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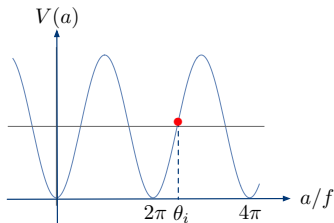
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# Axion as Dark matter

- ▶ The axion solves the strong CP problem dynamically.



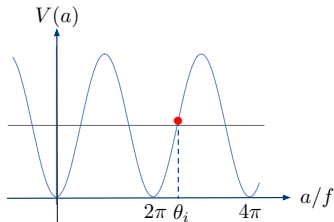
- ▶ For  $T \ll f$  and  $H \ll m_a$ , the axions are homogeneous and behave collectively as CDM (Preskill+Wiseman+Wilczek, Abbott+Sikivie, Dine+Fischler 1983):

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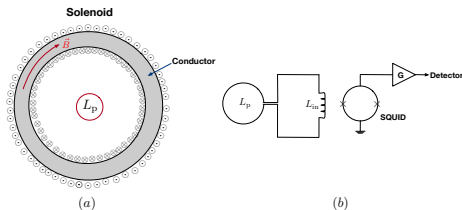
# Axion as Dark matter

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

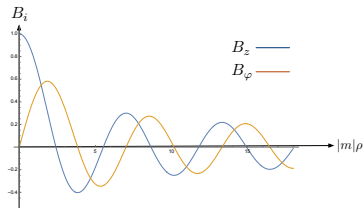
$$\Omega_a h^2 \approx 0.23 \times 10^{\pm 0.6} \left( \frac{f}{10^{12} \text{ GeV}} \right)^{1.175} \theta_i^2 F(\theta_i),$$

# Two stories on axion DM (LACME and Axion Vortex)

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



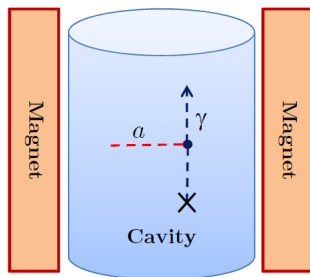
- ▶ Axion vortex in the cosmos ( $m = g_{a\gamma} \dot{a} \sim 1/\text{kpc}$ ) (to appear) :



## Existing experiments and proposals

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

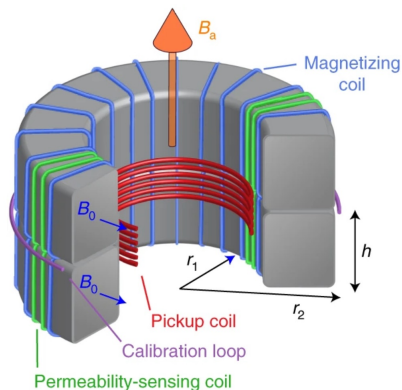
$$\mathcal{L}_{\text{int}} \ni g_{a\gamma\gamma} \frac{a}{2f} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} .$$



## Existing experiments and proposals

- ▶ Axions couple to photons, modifying Maxwell equations:  
ABRACADABRA '16, DMRadio, ...

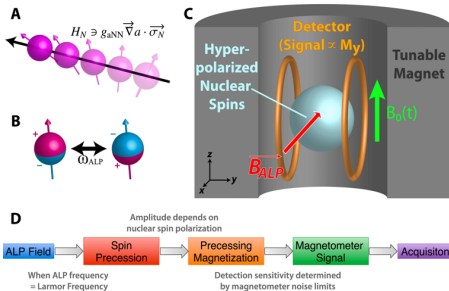
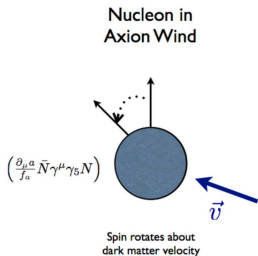
$$\nabla \times \vec{B} = g_{a\gamma\gamma} \dot{a} \vec{B}.$$



# 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)

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

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

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

- ▶  $\mu_5$  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  $\mu$  to all states, filling up particles up to the Fermi surface.

$$\mathcal{L} = \bar{\psi} (i\not{\partial} - m + \mu\gamma^0) \psi$$

$\Downarrow$

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

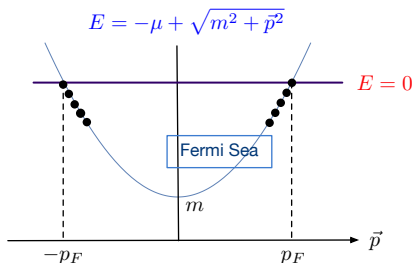


Figure: normal medium

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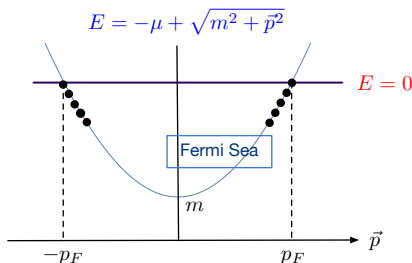


Figure: normal medium

## Axionic Chiral Magnetic Effects

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

$$\mathcal{L} = \bar{\Psi} (i\not{\partial} - m + \mu\gamma^0 + \mu_5\gamma^0\gamma_5) \Psi$$

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

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

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

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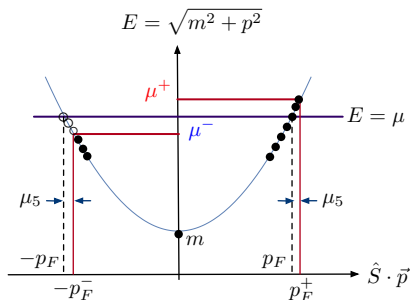
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# Axionic Chiral Magnetic Effects

- ▶  $\mu$  shifts the energy to create an imbalance in particle number:

$$E \rightarrow E + \mu$$

- ▶  $\mu_5$  shifts the momentum along the spin direction to create an helicity imbalance in medium:  $\hat{S} \cdot \vec{p} \rightarrow \hat{S} \cdot \vec{p} + \mu_5$

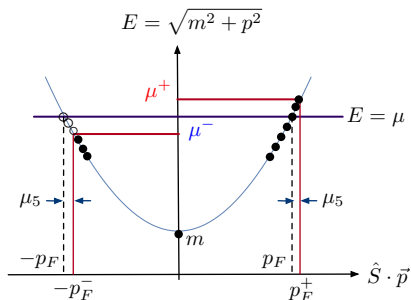




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## chiral magnetic effects in chiral medium

- ▶  $\mu_5$  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  $2n = 2n_r + 1 + |m_L| - \text{sign}(eB)(m_L + 2s_z)$ .

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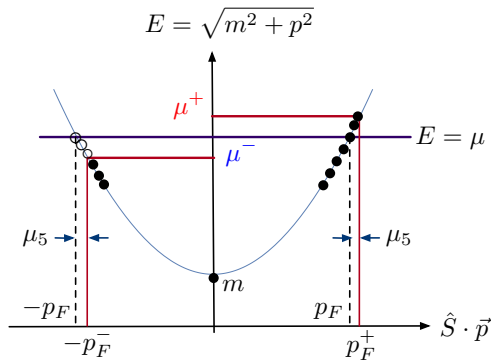


Figure: chiral medium

# chiral magnetic effects in chiral medium

- ▶ Helicity imbalance

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

- ▶ CME is a **current flow** due to the helicity imbalance in (**polarized**) medium by the axial chemical potential  $\mu_5$  and  $B$ .

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

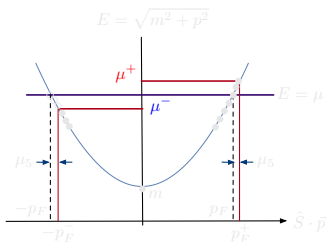


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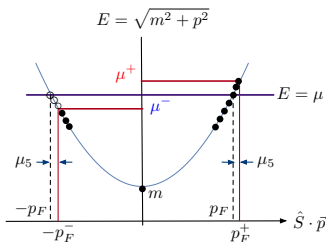
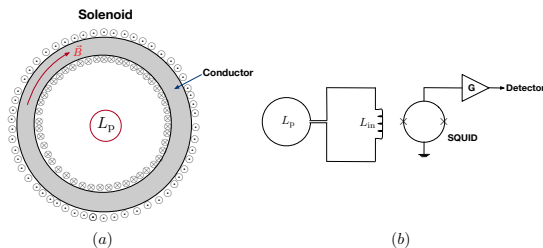


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# Axionic Chiral Magnetic Effects

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

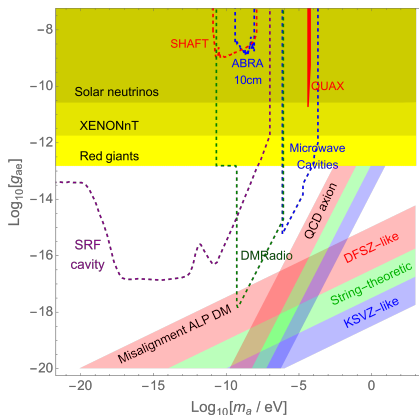
$$j^3 = 6.8 \times 10^{-15} \text{Am}^{-2} \left( \frac{v_F}{0.01c} \right) \left( \frac{\rho_{\text{DM}}}{0.4 \text{ GeVcm}^{-3}} \right)^{1/2} \left( \frac{10^{12} \text{ GeV}}{f/C_e} \right) \left( \frac{B}{10 \text{ Tesla}} \right)$$





# 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)

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

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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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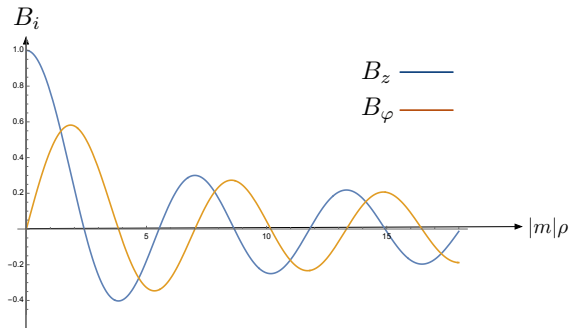
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# Axion magnetic vortex

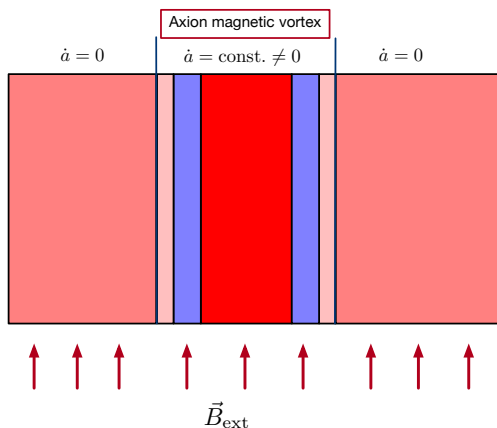
- ▶ The minimum energy configuration for a given flux  $\Phi$  is with the normalization,  $\mathcal{N} = 2\pi \int_0^{x_c} x J_0(x) dx$ ,

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



# 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:

$$E_z(\rho) = g_{a\gamma} \delta \ddot{a} \frac{\Phi}{\mathcal{N}} [J_0(|m|\rho) - |m|\rho J_1(|m|\rho)],$$

$$E_\varphi(\rho) = -g_{a\gamma} \delta \ddot{a} \frac{\Phi}{\mathcal{N}} m\rho J_0(|m|\rho)$$

- ▶ 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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- ▶ For the normal modes inside axion magnetic vortex

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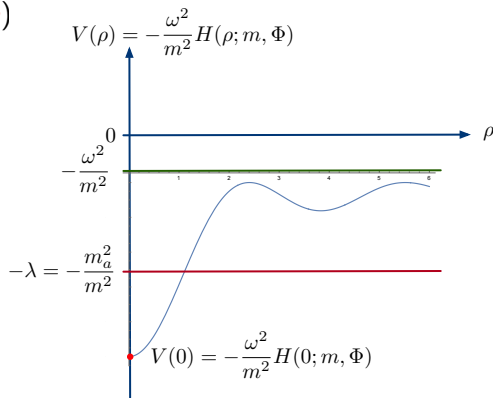
- ▶ The normal modes,  $\delta a = \theta(t)f(|m|\rho)$ , satisfy, after rescaling  $|m|\rho$  to be  $\rho$ ,

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

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

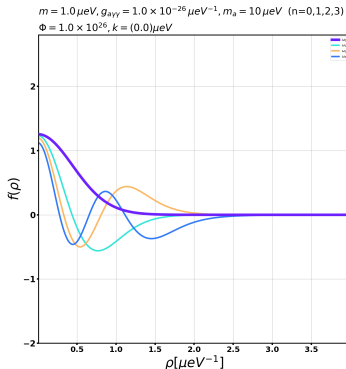
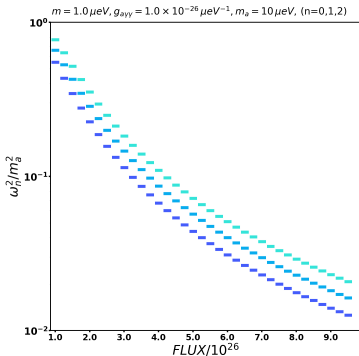
# Axion magnetic vortex

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



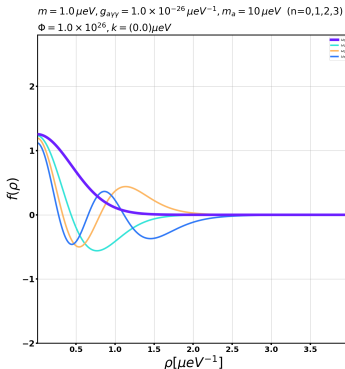
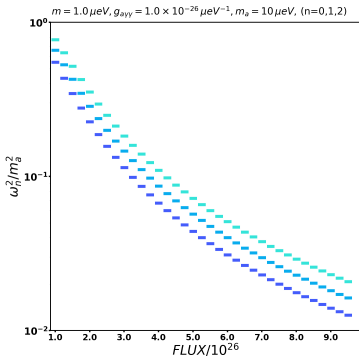
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- ▶ The size of vortex is  $1/m \sim 1 \text{ kpc}$  and the magnetic field in our galaxy is about  $10 \mu\text{G} \implies \Phi \sim 10^{26}$ .
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- ▶ We show that dark matter axions or axion-like 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)
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