Revisiting Chiral Magnetic Effects and Axions

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Bonne retraite, Pierre !

1. Introduction

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- But, axion is still one of the prime candidates for dark matter.
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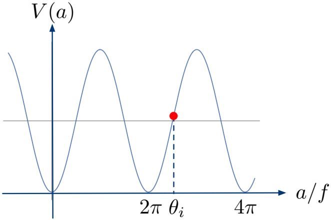

$$V(a) \simeq -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2} \sin^2\left(\frac{a}{2f}\right)}$$

- 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):

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

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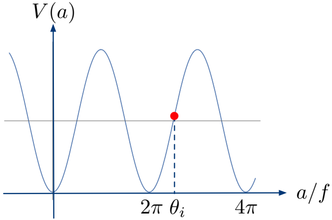

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Axion as Dark matter

- 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).

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

- In this talk I assume that the (QCD) axions, or possibly ALPs, constitute dark matter of our universe, and discuss its detection:

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Axion as Dark matter

- Axions are detectable, though not easy, because they couple to SM particles.
- Since Sikivie (1983), many experiments have been proposed and some probe theoretically interesting limits.
- We have proposed a new one, called LACME.
- It measures CME current in conductors that is directly proportional to electron-axion coupling, sensitive to the UV origin of axions. (DKH+Im+Jeong+Yeom, 2207.06884)

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2. Detecting Axions (LACME)

(2207.00997)

Axion DM couples to electrons

- Electrons dominantly couple to $\dot{a}$, since $v_a = |\vec{\nabla} a|/|\dot{a}| \sim 10^{-3}$:

$$\mathcal{L}_{\rm int} = C_e \frac{\partial_\mu a}{f} \bar{\psi} \gamma^\mu \gamma_5 \psi \approx C_e \frac{\dot{a}}{f} \psi^\dagger \gamma_5 \psi \, .$$

- Axion DM acts therefore as an axial chemical potential:

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

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Axial chemical potential

- What does the axial chemical potential (μ_5) do to electrons?
- It does a momentum kick to electrons along their spin direction!

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Axial chemical potential

- One can see this, as μ_5 can be absorbed by the redefining the electron fields, $\Psi \to \Psi' = e^{-i\mu_5 \vec{\Sigma}\cdot\vec{x}/3}\Psi$:

$$\begin{aligned} \mathcal{L} &= \bar{\Psi}\left(i\partial\!\!\!/ - m + \mu\gamma^0 + \mu_5\gamma^0\gamma_5\right)\Psi \\ &\Rightarrow \bar{\Psi}'\left(i\gamma'\cdot\partial - m + \mu\gamma^0\right)\Psi' \end{aligned}$$

where $\gamma^{\mu\prime} = e^{-i\mu_5\vec{\Sigma}\cdot\vec{x}}\gamma^\mu e^{i\mu_5\vec{\Sigma}\cdot\vec{x}}$.

Axial chemical potential

- Another way to see this is to take a non-relativistic limit for the electrons by subtracting out its rest mass and integrating out the negative energy states, χ:

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

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

Axial chemical potential

- μ_5 shifts the momentum along the spin direction:

$$\hat{S} \cdot \vec{p} \to \hat{S} \cdot \vec{p} + \mu_5$$

- The momentum shift will create an helicity imbalance in polarized medium.
- 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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chiral magnetic effects in chiral medium

- μ_5 creates an helicity imbalance in medium under magnetic field, $\vec{B}$:

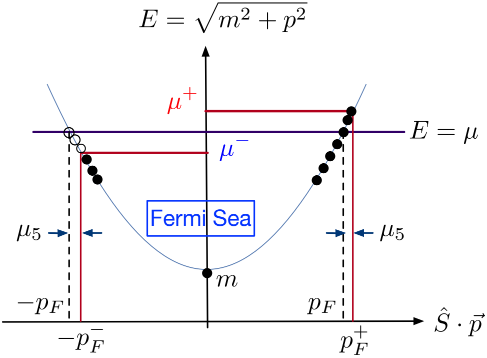


Figure: Polarized medium with μ_5 . $(\hat{S} \cdot \vec{p} = -\hat{B} \cdot \vec{p})$

chiral magnetic effects in chiral medium

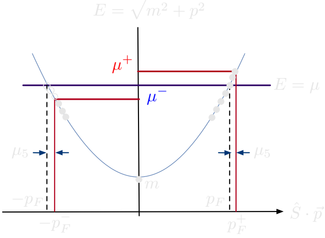
- Helicity imbalance in LLL electrons due to μ_5:

$$\Delta\rho = \rho^{n=0}_{h=+1/2} - \rho^{n=0}_{h=-1/2} \simeq \frac{|eB|}{2\pi^2}\,\mu_5 v_F \left[1 - e^{-(\mu-m)/T}\right] .$$

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

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

(For $T \ll E_F \approx 10$ eV)



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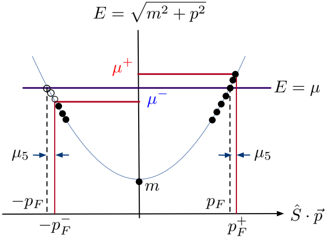

Figure: polarized medium

Axial chemical potential

- Because of the helicity imbalance, there will be a persistent current of electrons along the magnetic field.
- Chiral magnetic effect (Fukushima+Kharzeev+Warringa '08):

$$\vec{J} = a\mu_5 \vec{B}\,. \quad (a = \text{anomaly coeficient})$$

- The anomaly $a = v_F\, e^2/(2\pi^2)$. (DKH+Im+Jeong+Yeom '22)
- Since axion DM provides μ_5, one can detect axions by measuring CME currents (LACME)!

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Low temperature Axion Chiral Magnetic Effect (LACME)

- We propose a new experiment to detect this non-dissipative currents in conductors (DKH+Jeong+Im+Yeom '22):

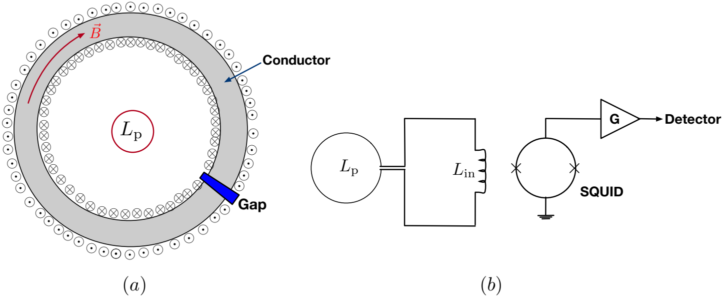

Figure: LACME

Low temperature Axion Chiral Magnetic Effect (LACME)

- Inside the solenoid the axion DM induce both the vacuum current and the CME current:

$$\vec{j} = \left[C_{a\gamma\gamma} + 4 v_F C_e \frac{\mu_m}{\mu_0} \right] \frac{\alpha}{2\pi f} \vec{B} \sqrt{2\rho_{\rm DM}} \cos(m_a t) \ ,$$

- For a material with large permeability like ferromagnetic conductors, $\mu_m/\mu_0 \gtrsim v_F^{-1} \approx 10^2$, the CME current can be dominant.
- For $B = 10\,\mathrm{T}$ and $\rho_a \approx \rho_{\rm DM}$, the CME current

$$j^3 = 6.8 \times 10^{-13} \mathrm{Am}^{-2} \left(\frac{v_F}{0.01c} \right) \cdot \left(\frac{10^{12}\,\mathrm{GeV}}{f/C_e} \right) \cdot \left(\frac{\mu_m}{100\mu_0} \right) .$$

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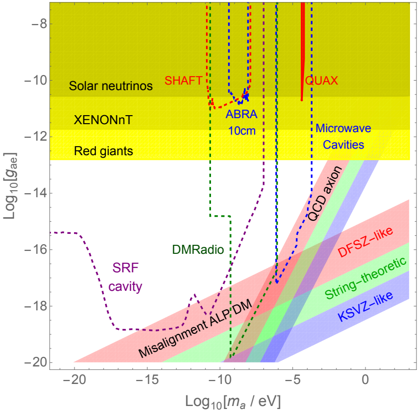
Axionic Chiral Magnetic Effects

- Projection of LACME from existing axion haloscopes, assuming $v_F = 0.01, \mu_m \approx 10^2 \mu_0$ $(g_{ae} = 2C_e m_e/f)$:



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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3. Revisiting Chiral Magnetic Effects

(2207.00997 and to appear)

Anomaly in Fermi liquid

- The salient feature of Fermi liquid is the existence of gapless modes, the fluctuations near the Fermi surface:
- Consider a cold medium of (free) electrons.

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

$$\Downarrow$$

$$\begin{aligned} E &= -\mu + \sqrt{m^2 + \vec{p}^2} \\ &\simeq \vec{v}_F \cdot (\vec{p} - \vec{p}_F)\,. \end{aligned}$$

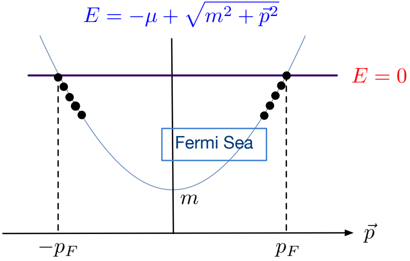

Figure: normal medium

Anomaly in Fermi liquid

- The Fermi liquid is naturally chiral in a sense that a gauge-invariant gap does not exist.
- We decompose the fermion fields as following (DKH 1998):

$$\psi = \psi_+ + \psi_- \quad \text{with} \quad \psi_\pm = \frac{1 \pm \vec{\alpha} \cdot \hat{v}_F}{2} \psi \,,$$

where ψ_+ describes the modes in the Fermi sea at low energy while ψ_- the modes in the Dirac Sea. ($E = -\mu \pm \sqrt{p^2 + m^2}$.)
- The Dirac mass term does not open a gap at the FS. It is a part of the chemical potential:

$$m\bar{\psi}\psi = m\left(\bar{\psi}_+\psi_- + \bar{\psi}_-\psi_+\right) = \frac{m^2}{2\mu}\bar{\psi}_+\gamma^0\psi_+ + \cdots \,.$$

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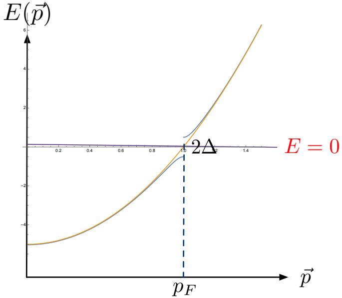
Anomaly in Fermi liquid

- The only gap that regulates the IR divergence is the Majorana mass term that breaks gauge symmetry as in superconductor :



Superconductor

$$\psi_+^\dagger \Delta \psi_{c+} + \text{h.c.}$$

$$(\psi_c = C\bar{\psi}^T)$$

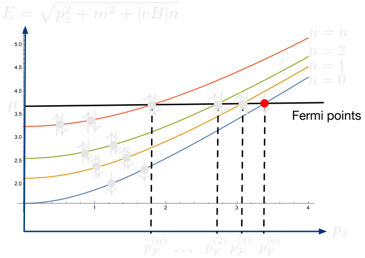
$$\langle \psi_\uparrow(\vec{p}_F)\psi_\downarrow(-\vec{p}_F)\rangle = \Delta(p_F)$$

$$= -\langle \psi_\downarrow(\vec{p}_F)\psi_\uparrow(-\vec{p}_F)\rangle \,.$$

- It also breaks the helicity symmetry just like the mass regulator breaks chirality in vacuum.

Anomaly in Fermi liquid

- Fermi liquid is gapless and consists of two chiral modes. It therefore may have axial anomaly (Coleman+Grossman 1982).
- Under a magnetic field, electrons fill Landau levels:



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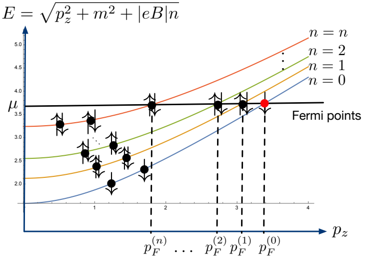

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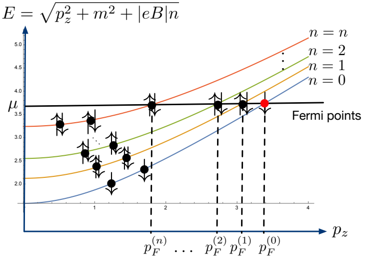

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Anomaly in Fermi liquid

- To calculate the ABJ anomaly in Fermi liquid we consider the anomalous two-point function of LLL electrons in medium, which are 2-dimensional:

$$\Gamma_5^{\mu\nu}(q_1)\delta^{(2)}(q_1+q_2) \equiv \int \Pi_i \mathrm{d}^2 x_i e^{iq_i\cdot x_i} \langle 0|\, \mathrm{T} j^\mu(x_1) j_5^\nu(x_2)\, |0\rangle \ .$$

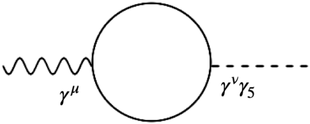

Figure: ABJ anomaly by LLL in Fermi Liquid

Axial anomaly in medium

- For $q/\mu \to 0$ (Manuel '96: DKH '98), using $j_5^\nu = \epsilon^{\nu\alpha} j_\alpha$, the anomalous two-point function of LLL becomes

$$\Gamma_5^{\mu\nu}(q) = \frac{eB}{2\pi^2 v_F}\left[-\eta^{\mu 0}\epsilon^{\nu 0} + \frac{q^0}{2}\left(\frac{V^\mu \epsilon^{\nu\alpha} V_\alpha}{V\cdot q} + \frac{\bar{V}^\mu \epsilon^{\nu\alpha} \bar{V}_\alpha}{\bar{V}\cdot q}\right)\right],$$

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

- The vector current is conserved:

$$q_\mu \Gamma_5^{\mu\nu}(q) = 0\,.$$

- The axial current is however anomalous:

$$\langle \partial_\nu j_5^\nu \rangle_A = ie \int \frac{\mathrm{d}^2 q}{4\pi^2} \lim_{q_0\to 0} \lim_{q_3\to 0} e^{iq\cdot x} q_\nu A_\mu(q) \Gamma_5^{\mu\nu}(q) = \frac{e^2 B}{4\pi^2} v_F \epsilon^{\mu\nu} F_{\mu\nu}\,.$$

Axial anomaly in medium

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

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

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

$$\langle j^3 \rangle = -e\mu_5 \lim_{q_0 \to 0} \lim_{q_3 \to 0} \Gamma_5^{30}(q) = \frac{e^2 B}{2\pi^2} v_F \mu_5 \, .$$

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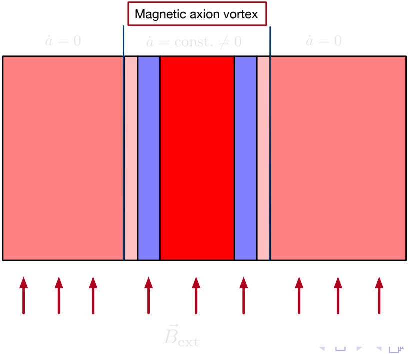
3. Magnetic Axion Vortex

with S. Lonsdale (2404.00997)

Axion electrodynamics

- Axion electrodynamics admits a stable vortex solution, carrying a constant magnetic flux, in the medium of homogeneous axions with a constant $\dot{a}$.
- Under an external magnetic field, an axion vortex forms:



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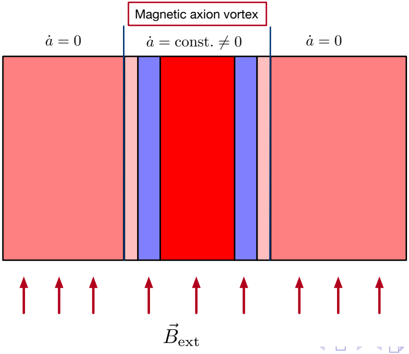

Axion electrodynamics

- Axion electrodynamics (Sikivie 1983) 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.
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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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Axion electrodynamics

- The energy for the static magnetic field with $\vec{J} = -m\vec{B}$:

$$\mathcal{E} = \int \mathrm{d}^3x \left\{ \frac{1}{2}\vec{B}^2 - \vec{A}\cdot\vec{J} \right\} = \int \mathrm{d}^3x \left\{ \frac{1}{2}\left(\vec{B} + m\vec{A}\right)^2 - \frac{1}{2}m^2\vec{A}^2 \right\}$$

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

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

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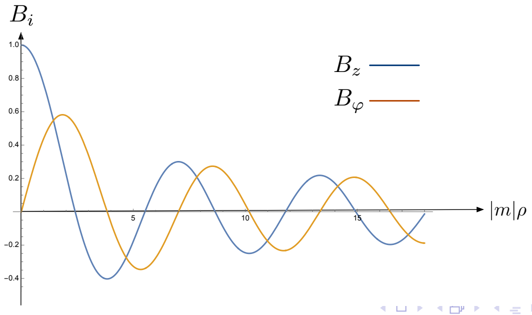
Axion magnetic vortex

- The minimum energy configuration for a given flux Φ is with the normalization, $\mathcal{N} = 2\pi \int_0^{x_c} xJ_0(x)\mathrm{d}x$,

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



Axion magnetic vortex

- Consider small fluctuations, $a_0 + \delta a$, to study its stability.
- For the normal modes inside the magnetic axion 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,

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Axion magnetic vortex

- The equation for normal modes is given as

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

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

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

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

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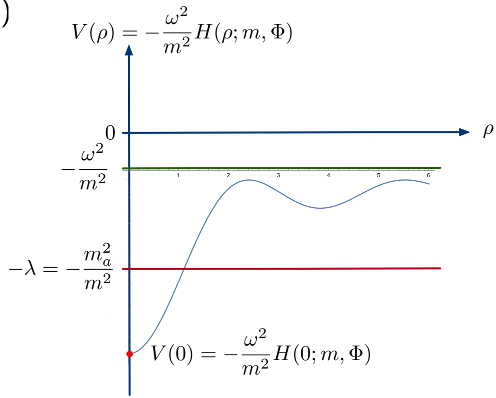
Axion magnetic vortex

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



Axion magnetic vortex

- As an illustration we plot a few low-lying states:

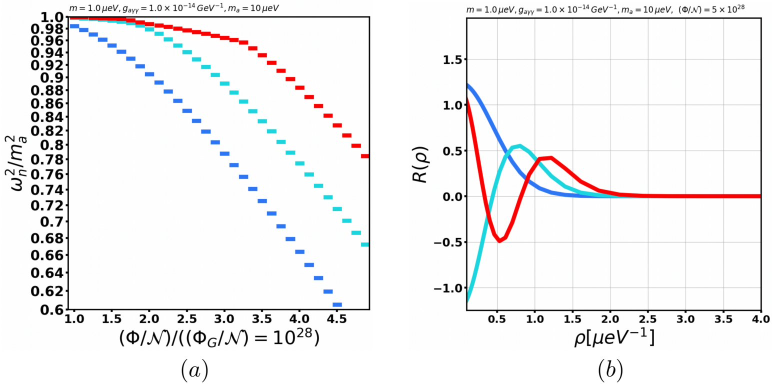


Figure: $m = 1\mu\mathrm{eV}$, $g_{a\gamma} = 10^{-14}\,\mathrm{GeV}^{-1}$ and $m_a = 10\mu\mathrm{eV}$

Axion magnetic vortex

- The soliton is stable because $\omega^2 < 0$ has no normalizable solution.
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- Since the axions decay into photons, however, the magnetic axion vortex will decay into photons eventually.

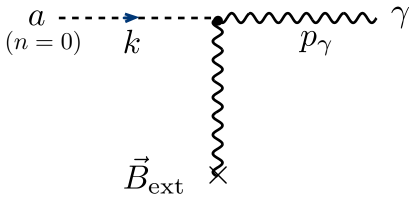

Figure: The ground state axion decays into a single photon.

Axion magnetic vortex

- For the ground state axions,

$$\delta a_{0k_z0} = \sin\left(\omega_0 t - k_z z\right) R_{0k_z0}(\rho) = \int \frac{d^2 k_\perp}{(2\pi)^2} C_{k_z}(\vec{k}_\perp)\, e^{i(\omega_0 t - k_z z - \vec{k}_\perp \cdot \vec{x}_\perp)} \,,$$

  the decay rate becomes at the leading order

$$\Gamma = g_{a\gamma}^2 \omega_0(k_z) \left(\frac{\Phi}{\mathcal{N}}\right)^2 |m|^3 \int_{|m|} \frac{d^2 k_\perp}{(2\pi)^2} \frac{|C_{k_z}(\vec{k}_\perp)|^2}{\sqrt{k_\perp^2 - |m|^2}} \,.$$

Magnetic vortices in galaxies

- The size of the vortex is of galactic scale:

$$m^{-1} = 250\,\mathrm{pc}\cdot\left(\frac{10^{-14}\,\mathrm{GeV}^{-1}}{g_{a\gamma}}\right)\cdot\left(\frac{\sqrt{0.8\ \mathrm{GeVcm}^{-3}}}{\dot{a}_0}\right).$$

- The magnetic fields are ubiquitous in our universe. At the center of the vortex, along the vortex,

$$B_z(0) = m^2\frac{\Phi}{\mathcal{N}} = 10\,\mu\,\mathrm{G}\left(\frac{\Phi/\mathcal{N}}{10^{44}}\right)\cdot\left(\frac{m}{10^{-35}\mathrm{GeV}}\right)^2.$$

- The decay rate of the ground state axions

$$\Gamma \approx \frac{\pi}{2}g_{a\gamma}B_z(0) = 1.7\,\mathrm{sec}^{-1}\left(\frac{g_{a\gamma}}{\mathrm{GeV}^{-1}}\right)\cdot\left(\frac{B_z(0)}{10\mu\mathrm{G}}\right),$$

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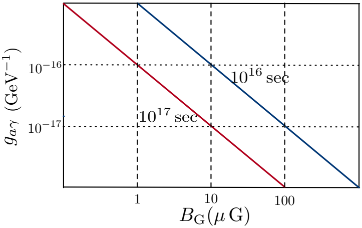

Figure: The lifetime of axions as a function of the magnetic field, $B_{\rm G}$, at the center of the vortex and the axion-photon coupling, $g_{a\gamma}$.

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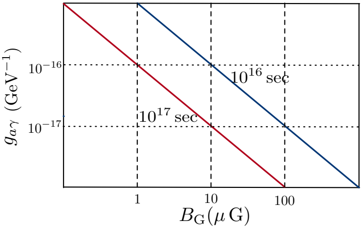

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Conclusion

- We have revisited CME to derive a correct formula (HIJY '22):

$$\vec{J} = \frac{e^2}{2\pi^2} v_F \mu_5 \vec{B}\,, .$$

- Using CME, we propose a new experiment to detect the dark matter axions or ALP. (LACME)

$$j^3 = 6.8 \times 10^{-13} \mathrm{Am}^{-2} \left(\frac{v_F \mu_m}{c\mu_0}\right) \left(\frac{\rho_{\mathrm{DM}}}{0.4\,\mathrm{GeVcm}^{-3}}\right)^{1/2} \left(\frac{10^{12}\,\mathrm{GeV}}{f/C_e}\right) \left(\frac{B}{10\,\mathrm{Tesla}}\right)$$

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  1. Energy level split in atoms: $\Delta \approx 2 \times 10^{-25}\,\mathrm{eV}\,\cos(m_a t)$.
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- The axion magnetic vortex is stable for small fluctuations.
- Axions are bound to the vortex, having energy $\omega < m_a$.
- The magnetic axion vortex in the Galaxy prefers very light axion DM. For QCD axions, $m_a \lesssim \mathcal{O}(1)\,\mathrm{neV}$.
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Thank you for listening !

Merci, Pierre !