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Intense Fields & Extreme Universe
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Hiroshima University

Anomaly-driven chiral magnetic effects

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広島大学 極限宇宙研究拠点
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Core of Research for the Energetic Universe
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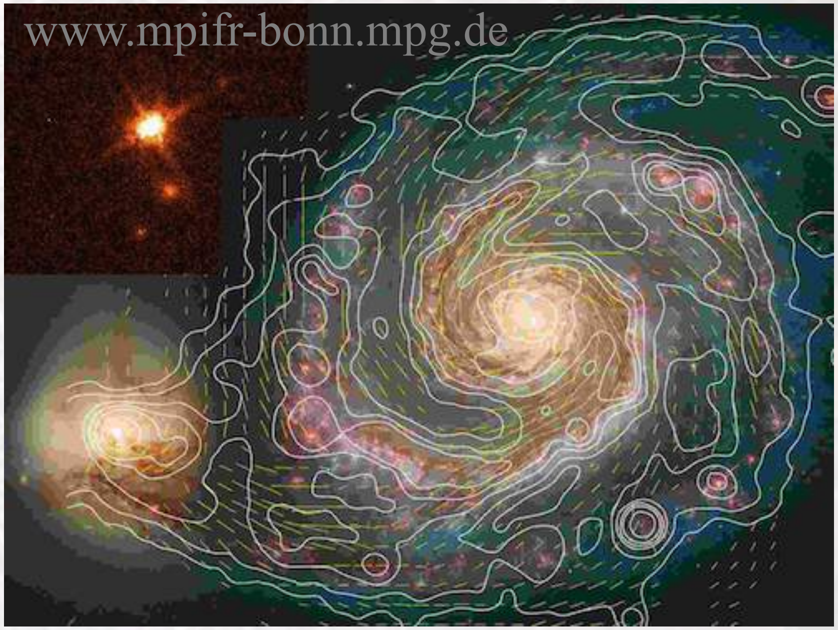
MAGNETIC FIELDS EVERYWHERE

[Miransky & Shovkovy, Physics Reports **576** (2015) pp. 1-209]

Universe

- Current galactic magnetic fields ~ 10^{-6} G
- Current magnetic fields in voids ~ 10^{-15} G



- Problem of magnetogenesis in Early Universe
- Perhaps during the electro-weak phase transition
  - **10^{20} to 10^{24} G** (~ 1 GeV to 100 GeV)

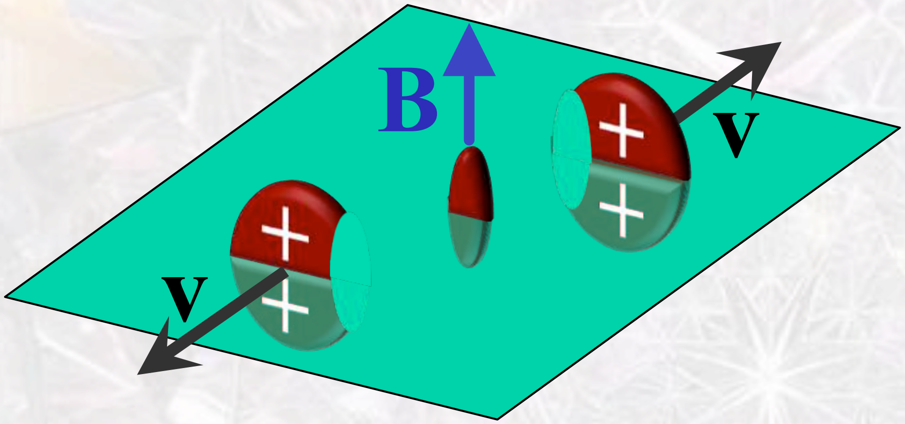
Dense baryonic matter

- Magnetized dense baryonic matter
  - **10^{10} to 10^{18} G** **(10 keV to 100 MeV)**
- Magnetic field may affect
  - Competition of ground state phases
  - EoS of dense baryonic matter
  - the M-R relation of compact stars
  - Transport and emission properties
  - Evolution of supernovas & protoneutron stars

[→ talks by Yasufumi Kojima & Teruaki Enoto]

Little Bangs

- Magnetized QGP at RHIC/LHC
  - **B ~ 10^{18} to 10^{19} G (~ 100 MeV)**



[Rafelski & Müller, PRL, 36, 517 (1976)],
[Kharzeev et al., arXiv:0711.0950],
[Skokov et al., arXiv:0907.1396],
[Voronyuk et al., arXiv:1103.4239],
[Bzdak &. Skokov, arXiv:1111.1949],
[Deng & Huang, arXiv:1201.5108]
…

- Using Lienard-Wiechert potentials,

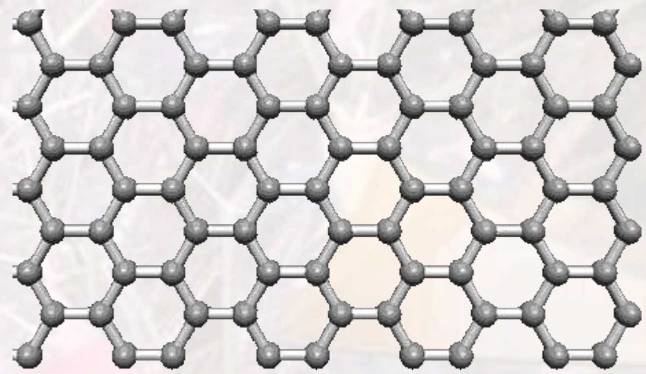
$$e\mathbf{E}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{R}_n - R_n\mathbf{v}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2)$$

$$e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{v}_n \times \mathbf{R}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2)$$

[→ talks by Kazunori Itakura & Ron Belmont]

Dirac/Weyl materials

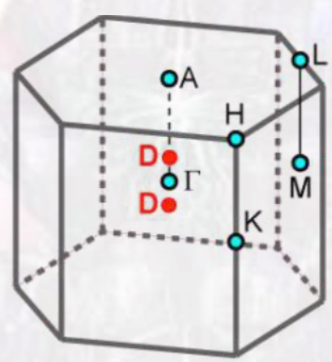
- High magnetic field lab
  - **10^5 G** (~ 100 meV @ vF=c/300)

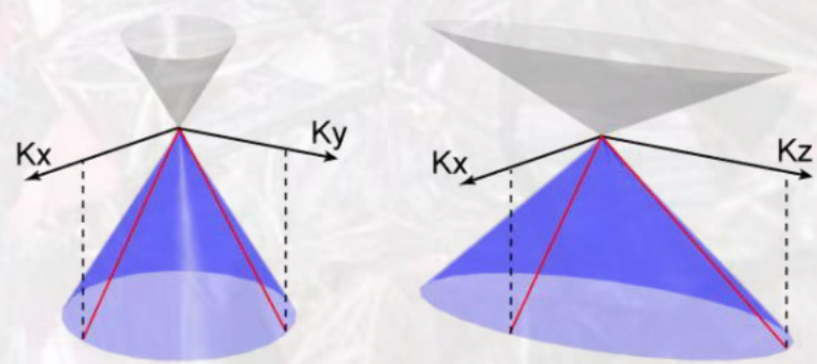


- Graphene
- 3D materials with Dirac/Weyl quasiparticles
  - $Bi_{1-x}Sb_x$ alloy (at $x \approx 4\%$)
  - Na_3Bi
  - Cd_3As_2
  - $ZrTe_5$
  - TaAs, NbAs, TaP, …

[Z. K. Liu et al., arXiv:1310.0391]
[M. Neupane et al., arXiv:1309.7892]
[S. Borisenko et al., arXiv:1309.7978]
[X. Li et al., arXiv:1412.6543]

[arXiv:1502.03807, arXiv:1502.04684, arXiv:1504.01350, arXiv:1507.00521]



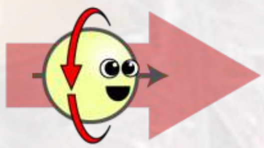


CHIRAL SEPARATION EFFECT

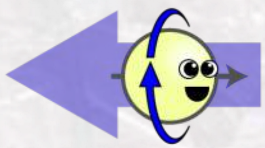
$$\langle \vec{j}_5 \rangle = -\frac{e\vec{B}}{2\pi^2}\mu$$

Chirality & Anomaly

- Chirality/helicity of a massless (or ultrarelativistic) particle is (approximately) conserved



Right-handed



Left-handed

$$\frac{\vec{\Sigma}\cdot\vec{\mathbf{p}}}{|\vec{\mathbf{p}}|}\Psi = \mathrm{sign}(p_0)\gamma^5\Psi$$

- Conservation of chiral charge is a property of massless Dirac theory (classically)

- The symmetry is anomalous at quantum level

$$\frac{\partial(n_R - n_L)}{\partial t} + \nabla\cdot\vec{j}_5 = -\frac{e^2}{16\pi^2}\varepsilon^{\mu\nu\kappa\lambda}F_{\mu\nu}F_{\kappa\lambda}$$

Chiral separation effect

- Slowly changing electric/chemical potential

$$\mu(z) = e\Phi(z) \quad \Rightarrow \quad eE_z = -\partial_z\left(e\Phi\right) = -\partial_z\mu$$

- From the anomaly relation,

$$\partial_z\, j_5^3 = -\frac{e^2}{2\pi^2} B_z\, E_z = \frac{e^2}{2\pi^2} B_z\, \partial_z\mu$$

- Suggesting that for massless fermions,

$$\left\langle \vec{j}_5 \right\rangle = -\frac{e\vec{B}}{2\pi^2}\mu$$

[Vilenkin, Phys. Rev. D 22 (1980) 3067]
[Metlitski & Zhitnitsky, Phys. Rev. D **72**, 045011 (2005)]
[Newman & Son, Phys. Rev. D **73** (2006) 045006]

- This can be easily derived in free theory

Landau spectrum at B≠0

- Dirac equation with massless fermions

$$\left[i\gamma^0\partial_0 - i\vec{\gamma}\cdot\left(\vec{\nabla}+ie\vec{A}\right)\right]\Psi = 0$$

- Energy spectrum

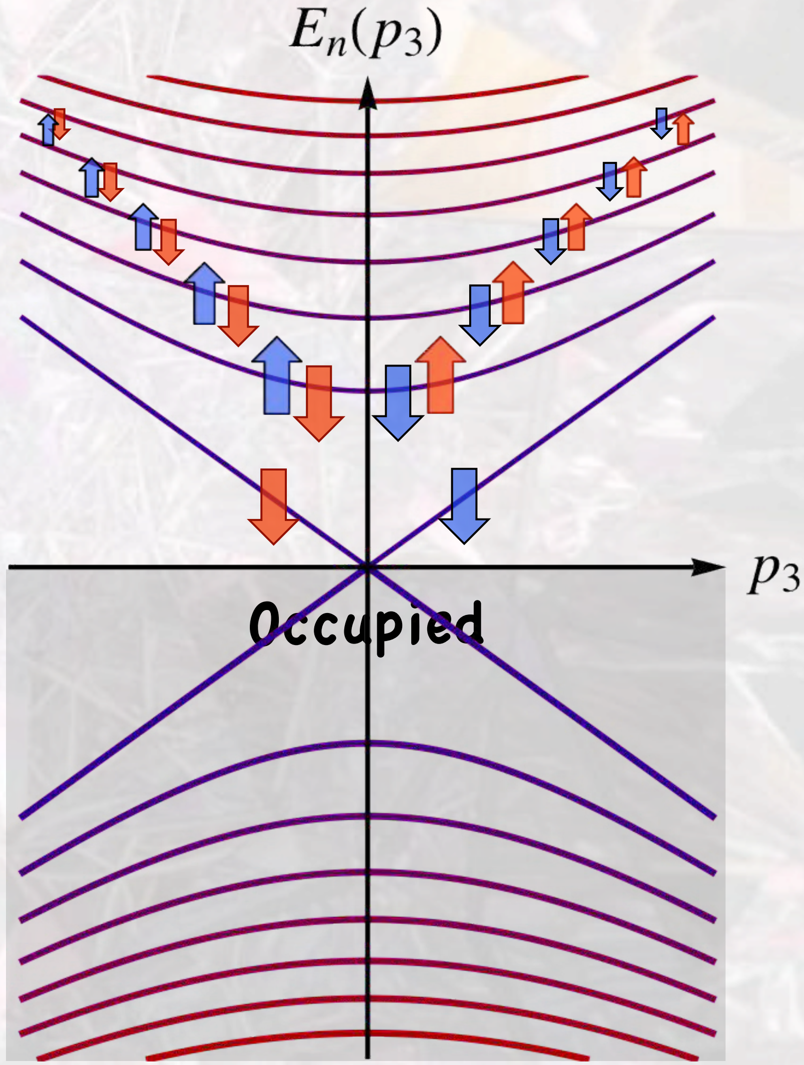
$$E_n^{(3+1)}(p_3) = \pm\sqrt{2n|eB| + p_3^2}$$

where

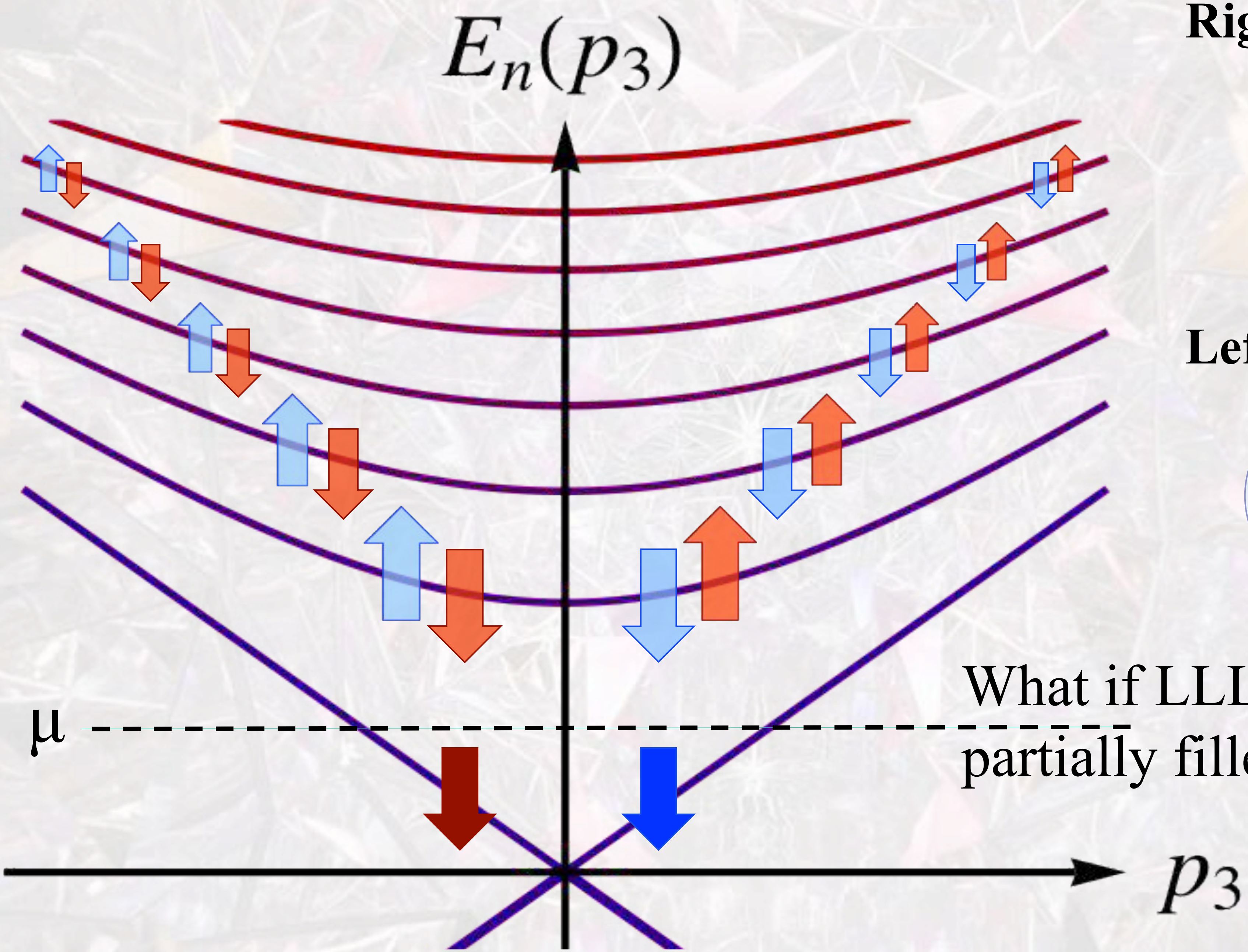
$$n = s + k + \frac{1}{2}$$

$s = \pm 1/2$ (spin)

$k = 0, 1, 2, \ldots$ (orbital)



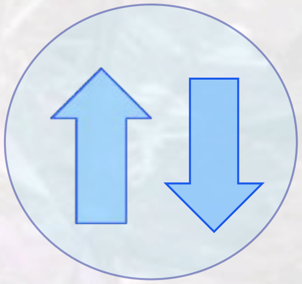
Landau spectrum & μ≠0



What if LLL is partially filled?

Right-handed:

Left-handed:

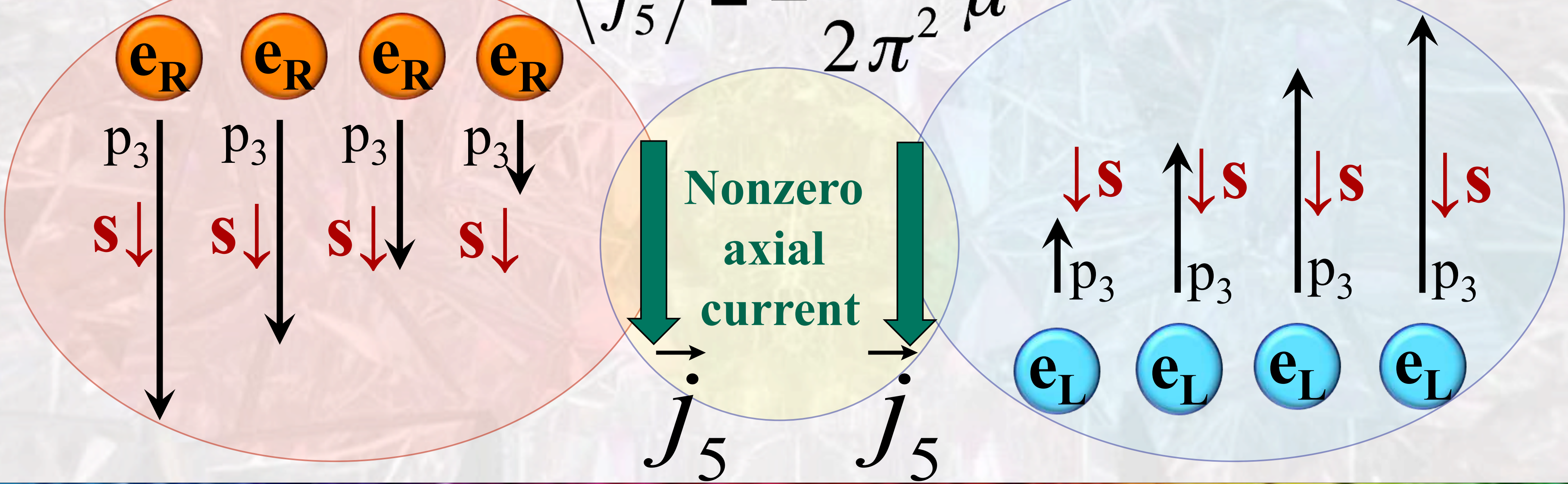


Partially filled LLL

- **Spin polarized** LLL is chirally asymmetric
  - states with $p_3<0$ (and $s=\downarrow$) are R-handed
  - states with $p_3>0$ (and $s=\downarrow$) are L-handed

i.e., a nonzero **axial** current is induced

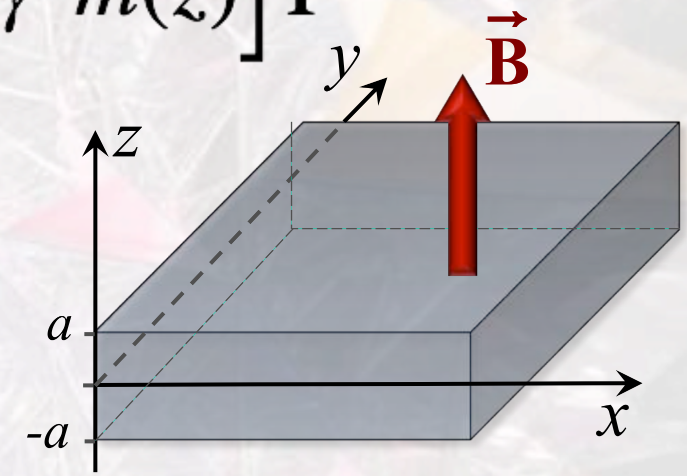
$$\langle \vec{j}_5 \rangle = -\frac{e\vec{B}}{2\pi^2}\mu$$



CSE in Dirac semimetals

- Model of Dirac semimetal with a slab geometry

$$H=\int d^3r\Psi^{+}\left[v_F\vec{\alpha}\cdot\left(-i\vec{\nabla}+e\vec{A}\right)+\gamma^0 m(z)\right]\Psi$$



where $\vec{A}=(0,Bx,0)$ and

$$m(z)=M\,\theta(z^2-a^2)+m\,\theta(a^2-z^2),$$

with vacuum band gap: $M\to\infty$ (broken chiral symmetry)

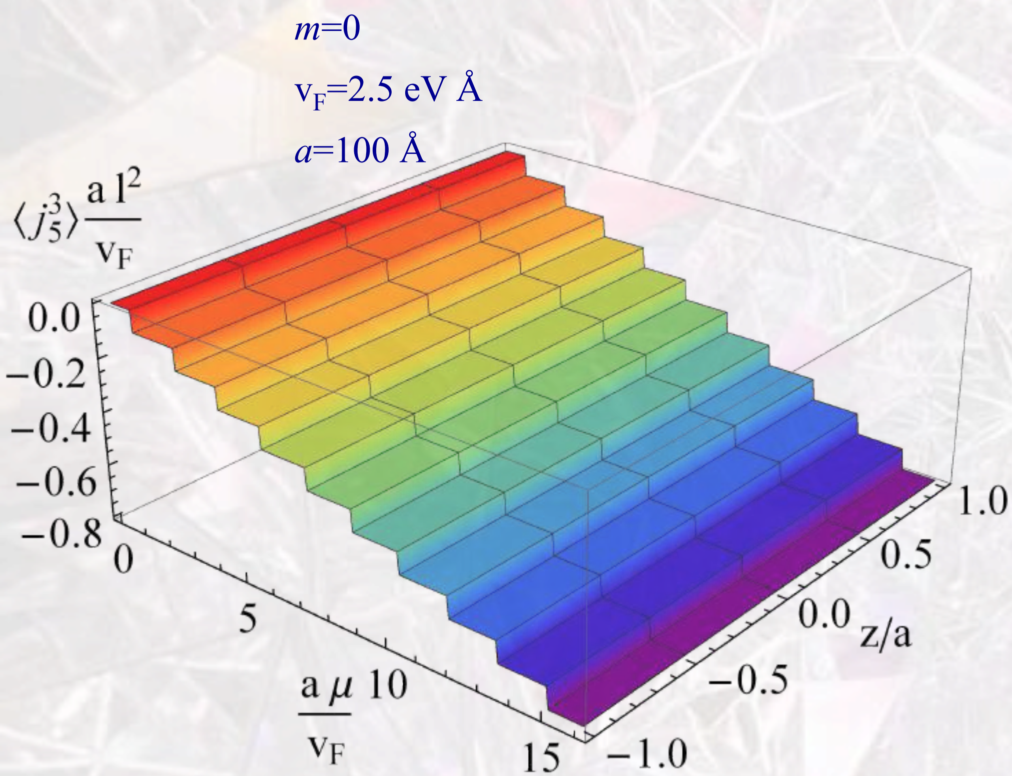
- Boundary conditions:

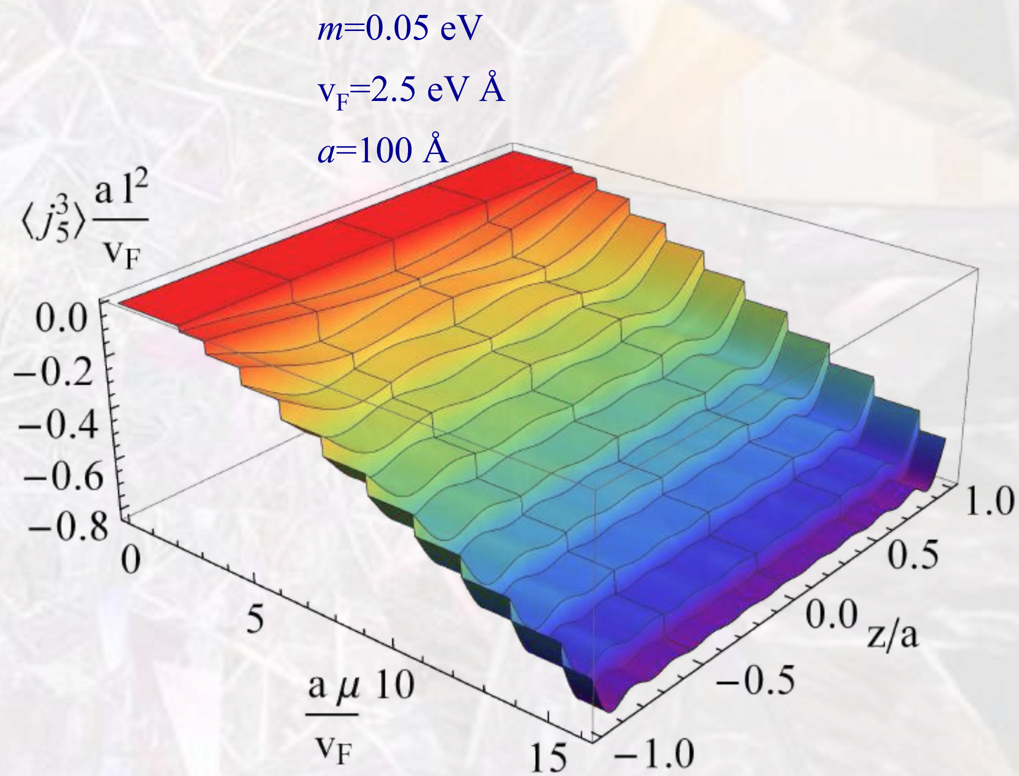
$$\Psi_{\text{bulk}}\left(\vec{r}_\perp,a\right)=\Psi_{\text{vacuum}}\left(\vec{r}_\perp,a\right)\quad\text{and}\quad\Psi_{\text{bulk}}\left(\vec{r}_\perp,-a\right)=\Psi_{\text{vacuum}}\left(\vec{r}_\perp,-a\right)$$

[Gorbar, Miransky, Shovkovy, Sukhachov, Phys. Rev. B **92**, 245440 (2015)]

Quantization of axial current

- Axial current density is non-uniform when *m≠0*



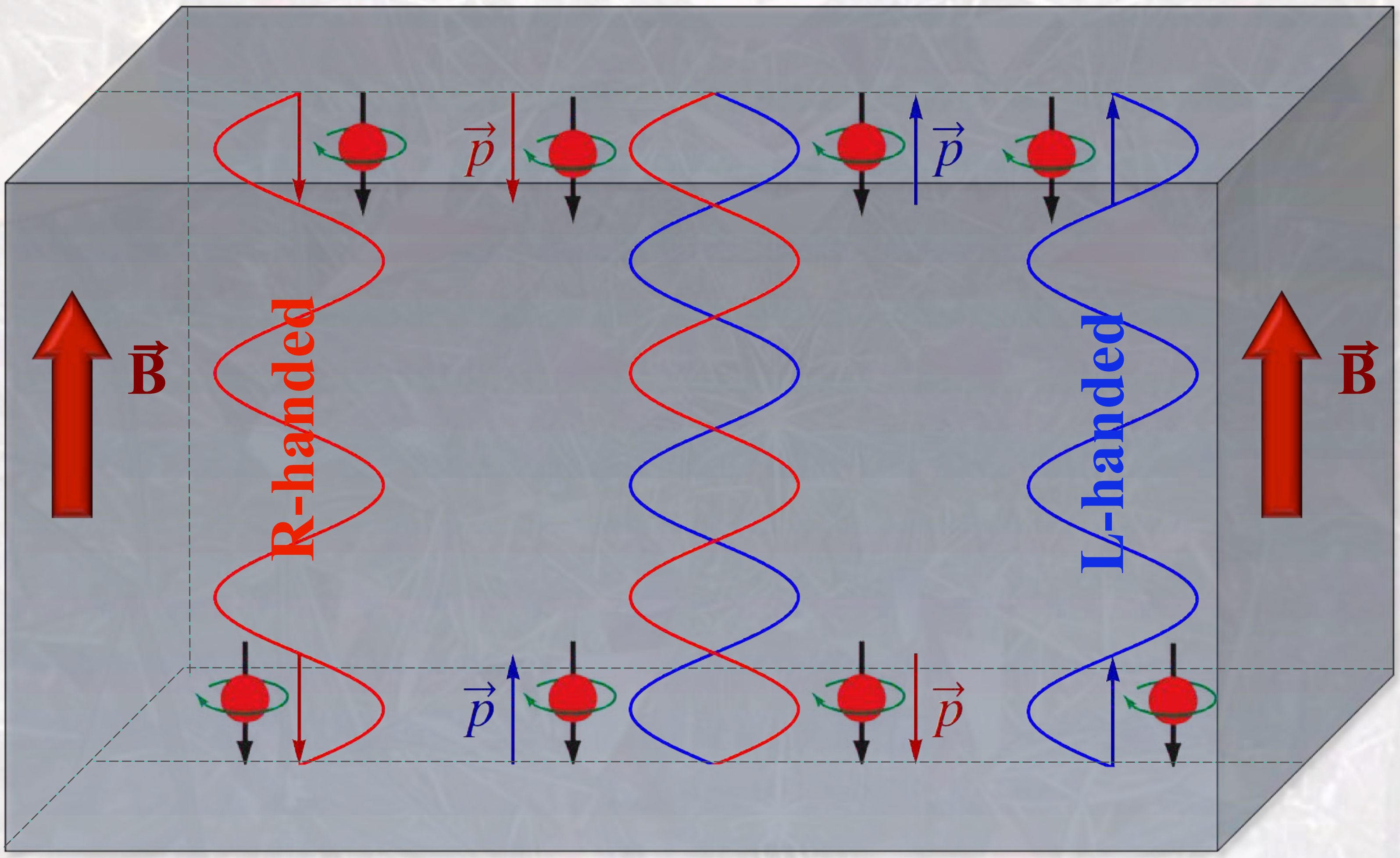


- Note that axial charge density vanishes: $\left\langle j_5^0 \right\rangle = 0$

[Gorbar, Miransky, Shovkovy, Sukhachov, Phys. Rev. B 92, 245440 (2015)]

Axial current as a standing wave?

- Recall that LLL is spin polarized



- A perfect chirality flip at the boundary

[Gorbar, Miransky, Shovkovy, Sukhachov, Phys. Rev. B 92, 245440 (2015)]

CHIRAL MAGNETIC EFFECT

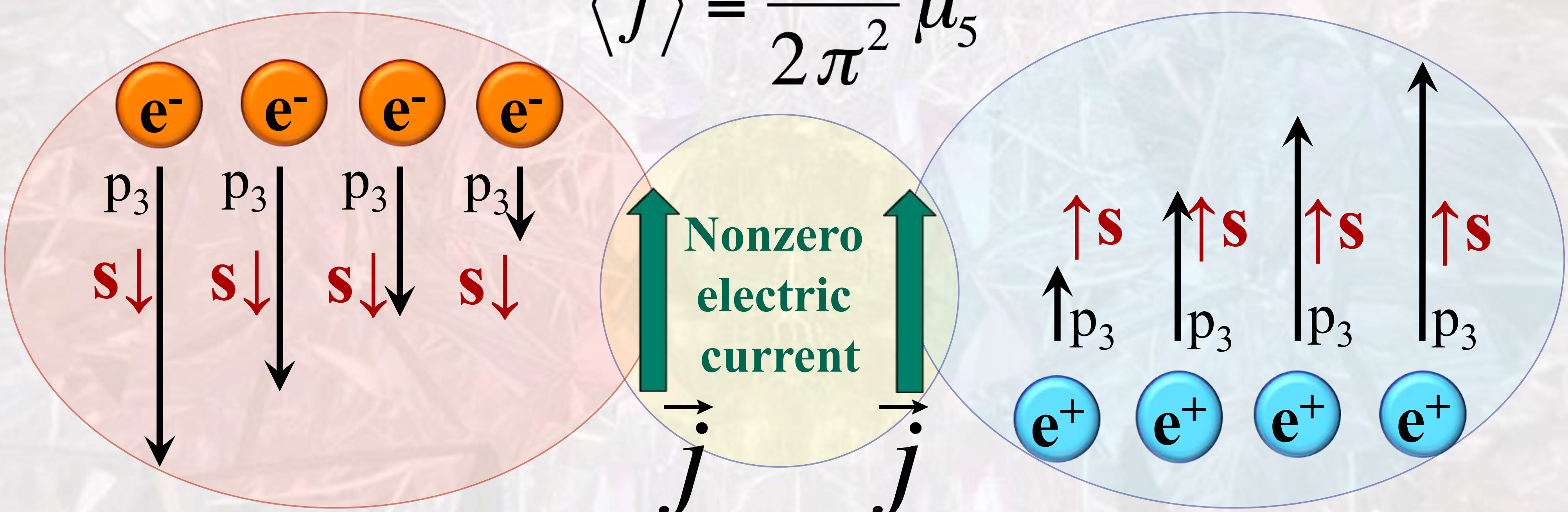
$$\left\langle \vec{j} \right\rangle = \frac{e^2 \vec{B}}{2\pi^2} \mu_5$$

Partially filled LLL @ $\mu_5 \neq 0$

- **Spin polarized** LLL is chirally asymmetric
  - states with $p_3<0$ (and $s=\downarrow$) are R-handed **electrons**
  - states with $p_3>0$ (and $s=\downarrow$) are L-handed **positrons**

i.e., a nonzero **electric** current is induced

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



CME in heavy ion collisions?

- Chiral charge can be produced by topological configurations in QCD

$$\frac{d(N_R - N_L)}{dt} = -\frac{g^2 N_f}{16\pi^2} \int d^3x\, F_a^{\mu\nu} \tilde{F}_{\mu\nu}^a$$

- A random fluctuation with nonzero chirality could result in

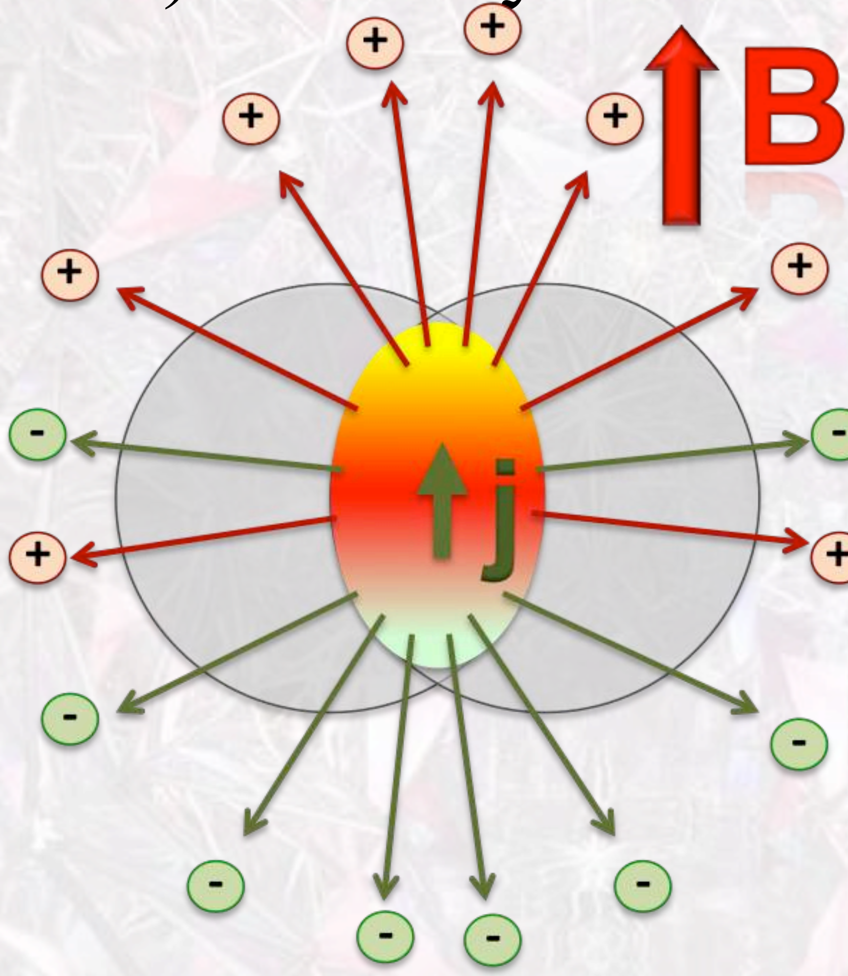
$$N_R - N_L \neq 0 \quad \Rightarrow \quad \mu_5 \neq 0$$

- This should lead to an electric current

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

Dipole CME

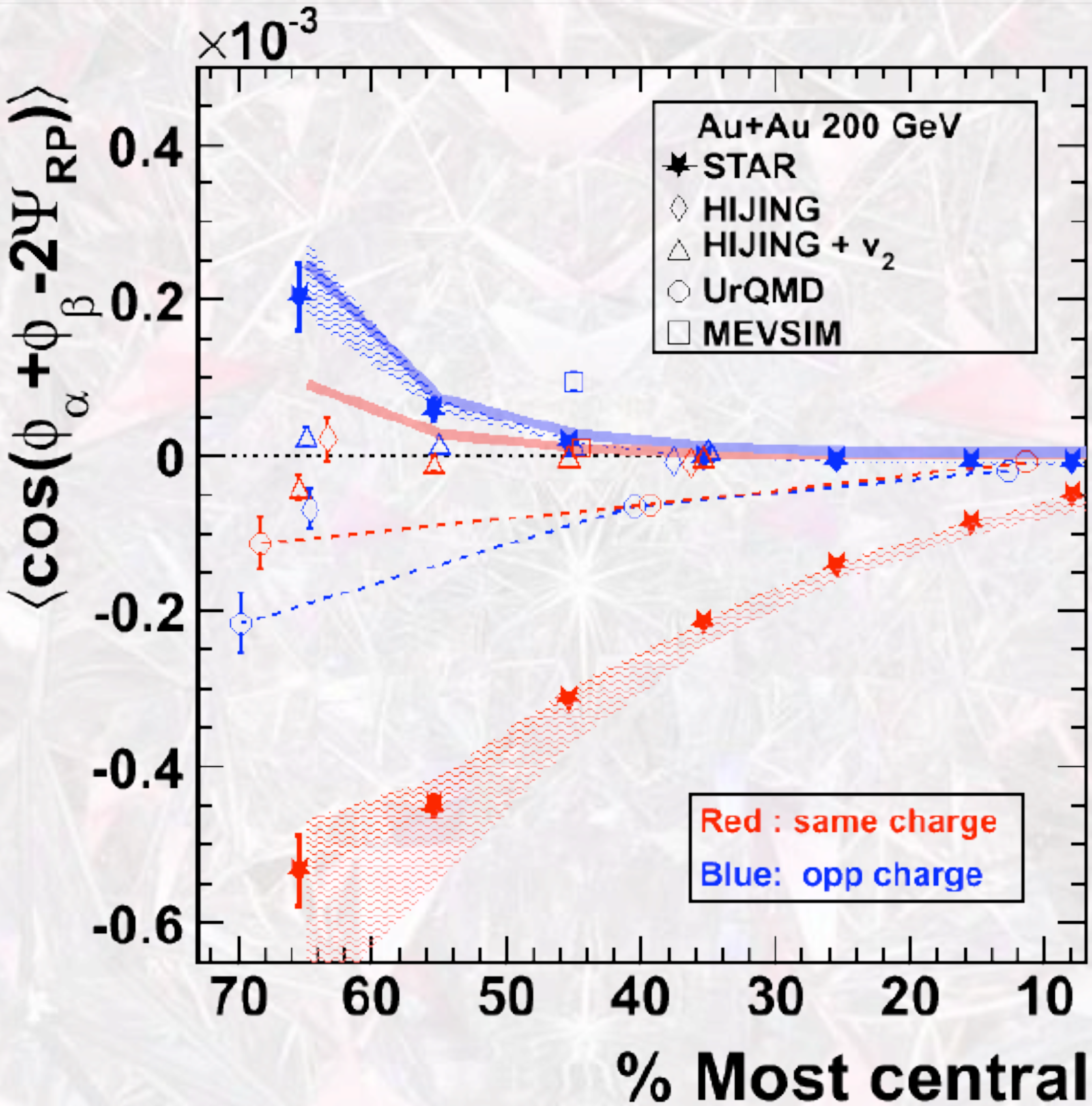
- Dipole pattern of electric currents (or charge correlations) in heavy ion collisions



[→ talk Ron Belmont]

[Kharzeev, McLerran, Warringa, Nucl. Phys. A **803**, 227 (2008)]
[Fukushima, Kharzeev, Warringa, Phys. Rev. D **78**, 074033 (2008)]

Experimental evidence



[B. I. Abelev et al. (STAR Collaboration), Phys. Rev. Lett. **103**, 251601 (2009)]
[B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C **81**, 054908 (2010)]
[Adamczyk et al. (STAR Collaboration), Phys. Rev. C **88**, 064911 (2013)]

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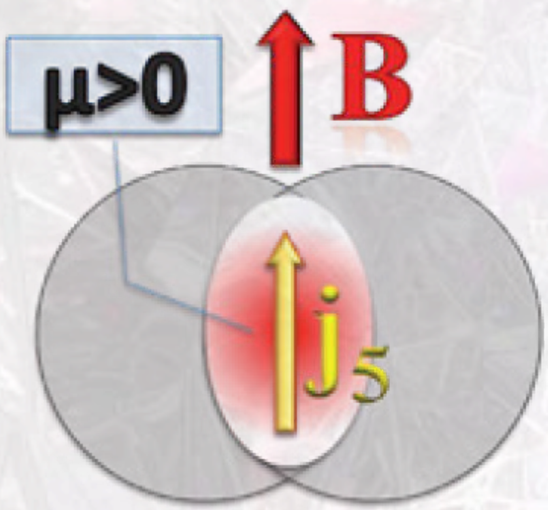
CHIRAL MAGNETIC WAVE

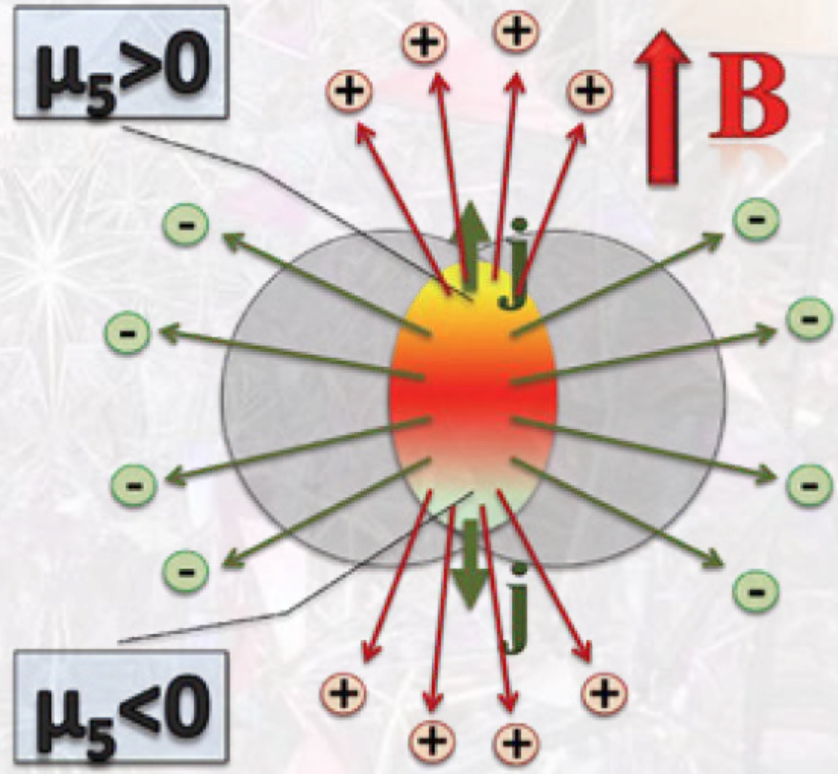
$$\left\langle \vec{j}_5 \right\rangle = \frac{e\vec{B}}{2\pi^2}\mu \qquad \left\langle \vec{j} \right\rangle = \frac{e\vec{B}}{2\pi^2}\mu_5$$

CMW/Quadrupole CME

- Start from a small baryon density and B≠0

$$\left\langle \vec{j}_5 \right\rangle = \frac{e\vec{B}}{2\pi^2}\mu \qquad \left\langle \vec{j} \right\rangle = \frac{e\vec{B}}{2\pi^2}\mu_5$$





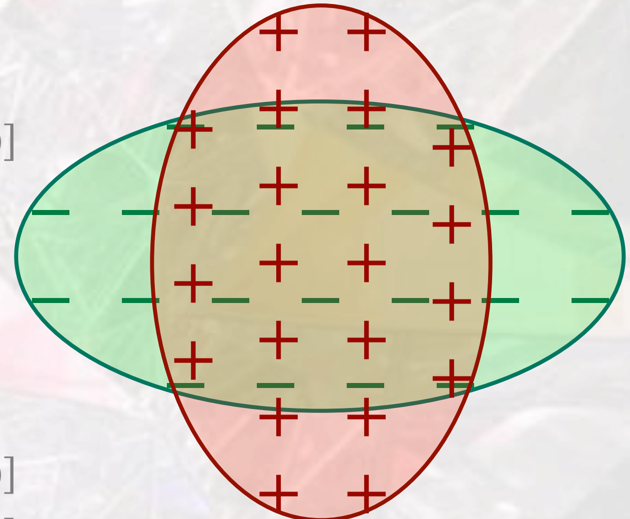
- Produce back-to-back electric currents

[Gorbar, Miransky, Shovkovy, Phys. Rev. D **83**, 085003 (2011)]
[Burnier, Kharzeev, Liao, Yee, Phys. Rev. Lett. **107** (2011) 052303]

Experimental evidence

- Elliptic flows of π^+ and π^- depend on charge asymmetry:

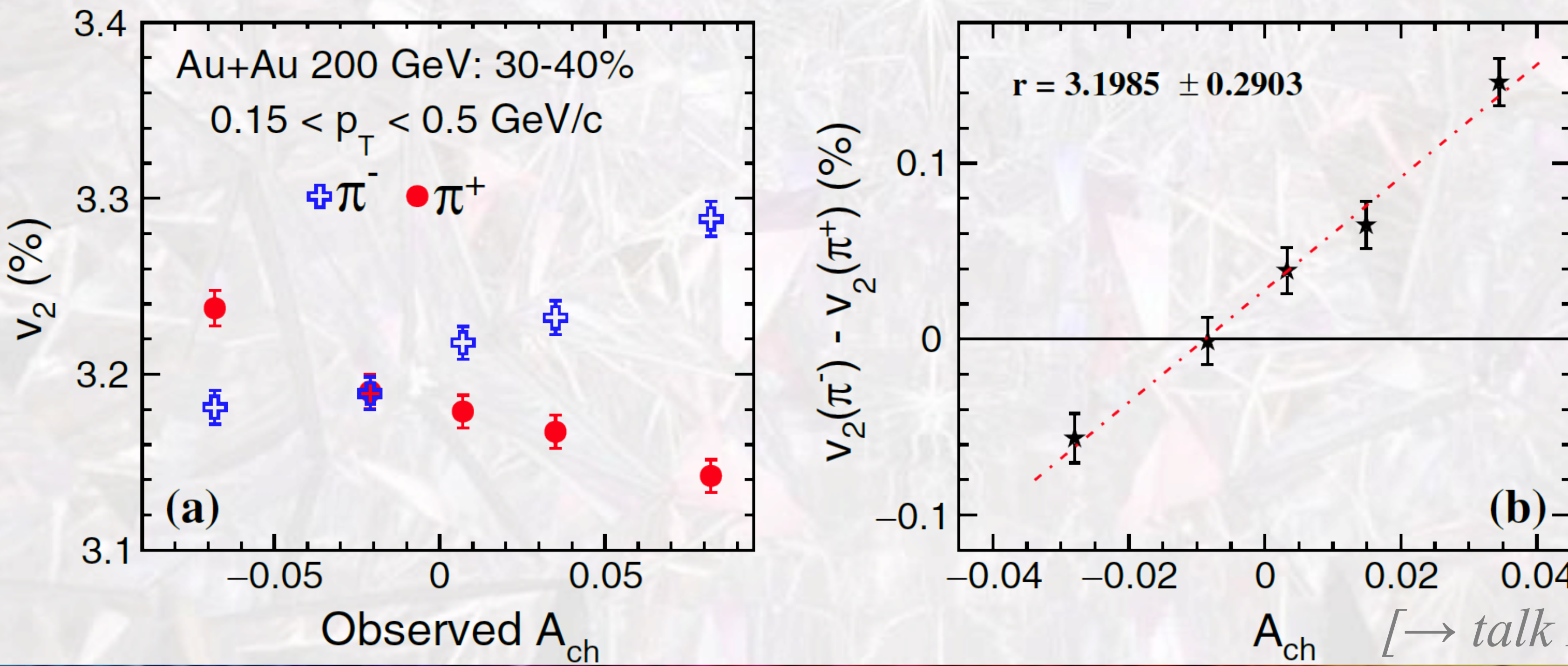
[Burnier, Kharzeev, Liao, Yee, PRL **107**, 052303 (2011)]



$$\frac{dN_\pm}{d\phi} \approx \bar{N}_\pm \left[1 + 2v_2 \cos(2\phi) \mp A_\pm r \cos(2\phi) \right]$$

[H. Ke (for STAR) J. Phys. Conf. Series **389**, 012035 (2012)]

[Adamczyk et al. (STAR), Phys. Rev. Lett. **114**, 252302 (2015)]



[→ *talk Ron Belmont*]

FURTHER DEVELOPMENTS

- Dynamical chiral shift

Chiral shift at B≠0

- The axial current (CSE) in free theory

$$\left\langle \bar{\psi}\gamma^3\gamma^5\psi \right\rangle = \frac{eB}{2\pi^2}\mu \quad \text{with} \quad \vec{B} = (0,0,B)$$

[Metlitski & Zhitnitsky, Phys. Rev. D **72**, 045011 (2005)]

+ **interactions** should induce a chiral shift parameter Δ associated with the condensate,

$$\delta L = \Delta\,\bar{\psi}\gamma^3\gamma^5\psi$$

This is a perturbative effect: there is no symmetry to protect Δ =0

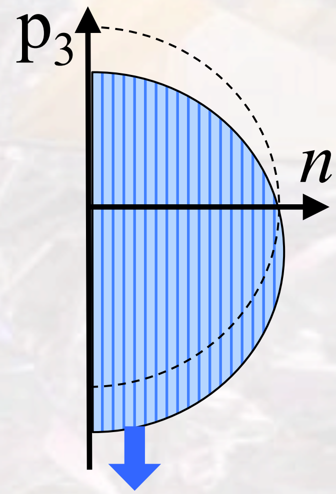
[Gorbar, Miransky, Shovkovy, Phys. Rev. C **80**, 032801(R) (2009)]

Chiral shift @ Fermi surface

- Chirality is $\approx$ well-defined at Fermi surface ($|p_3| \gg m$)
- L-handed Fermi surface:

$$n>0: \quad p_3 = +\sqrt{\left(\sqrt{\mu^2 - 2n|eB|} - s_\perp \Delta\right)^2 - m^2}$$

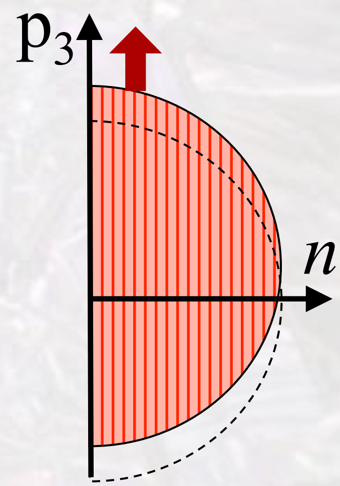
$$p_3 = -\sqrt{\left(\sqrt{\mu^2 - 2n|eB|} + s_\perp \Delta\right)^2 - m^2}$$



- R-handed Fermi surface:

$$n>0: \quad p_3 = -\sqrt{\left(\sqrt{\mu^2 - 2n|eB|} - s_\perp \Delta\right)^2 - m^2}$$

$$p_3 = +\sqrt{\left(\sqrt{\mu^2 - 2n|eB|} + s_\perp \Delta\right)^2 - m^2}$$



[Gorbar, Miransky, Shovkovy, Phys. Rev. D **83**, 085003 (2011)]

QED in weak field (B→0)

- The result has the form

$$\overline{\Sigma}^{(1)}(p) = \gamma^3\gamma^5\Delta(p) + \gamma^0\gamma^5\mu_5(p)$$

Near Fermi surface ($p_0 \to 0$, $|\mathbf{p}| \to p_F$)

$$\Delta(p) \approx \frac{\alpha eB\mu}{\pi m^2}\left(\ln\frac{m^2}{2\mu\left(|\mathbf{p}| - p_F\right)} - 1\right)$$

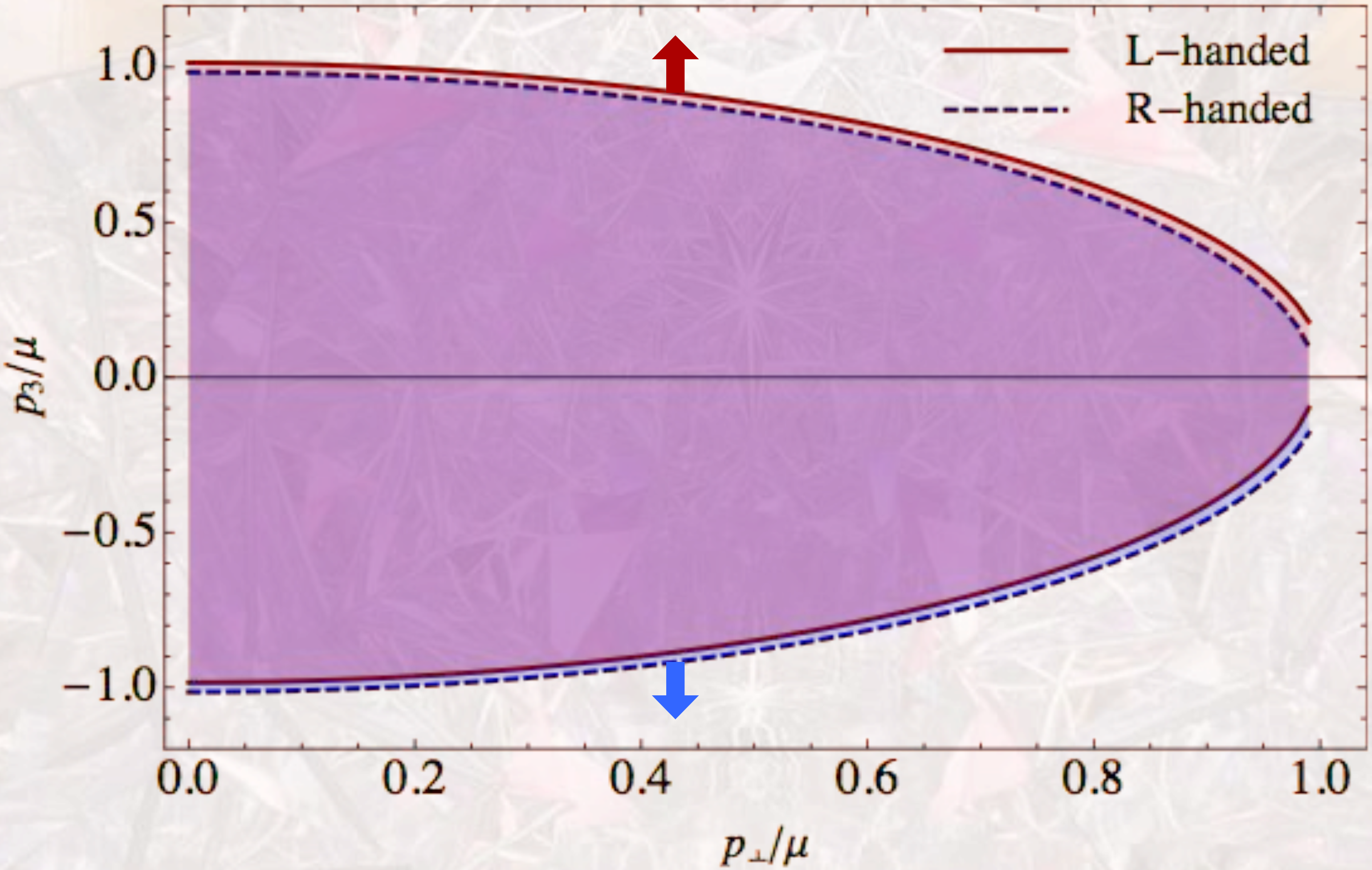
$$\mu_5(p) \approx -\frac{\alpha eB\mu}{\pi m^2}\frac{p_3}{p_F}\left(\ln\frac{m^2}{2\mu\left(|\mathbf{p}| - p_F\right)} - 1\right)$$

[Gorbar, Miransky, Shovkovy, Wang, Phys. Rev. D **88**, 025043 (2013)]

Dispersion relations in QED

- Let us use the condition (for a small B)

$$\mathrm{Det}\left[i\,\overline{S}^{-1}(p)+\overline{\Sigma}^{(1)}(p)\right]=0$$

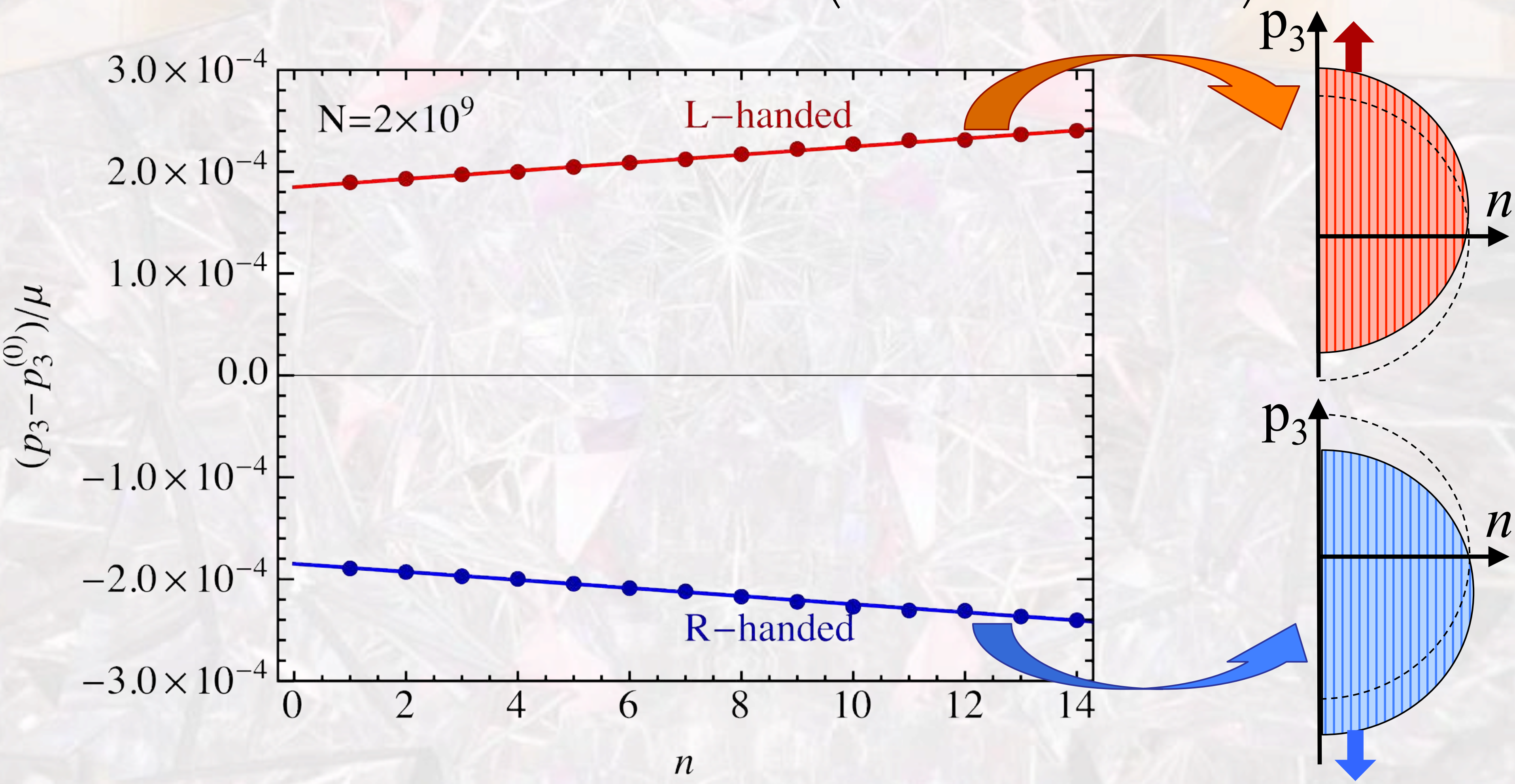


[Gorbar, Miransky, Shovkovy, Wang, Phys. Rev. D **88**, 025043 (2013)]

QED in strong field: δp_3

Model fit:

$$p_3 - p_3^{(0)} = \pm \frac{\alpha |eB|}{\mu} \left(0.76 + 0.49 \frac{|eB| n}{\mu^2} \right)$$



[Xia, Gorbar, Miransky, Shovkovy, Phys. Rev. D **90**, 085011 (2014)]

How large is the asymmetry?

In QED:

$$\frac{\alpha|eB|}{\mu} \approx 0.4\left(\frac{B}{10^{18}\,\mathrm{G}}\right)\left(\frac{100\,\mathrm{MeV}}{\mu}\right)\mathrm{MeV/c}$$

In QCD:

$$\frac{\alpha_s|eB|}{\mu} \approx 10\left(\frac{B}{10^{18}\,\mathrm{G}}\right)\left(\frac{400\,\mathrm{MeV}}{\mu}\right)\mathrm{MeV/c}$$

may have some observable consequences…

FURTHER DEVELOPMENTS

- Anomalous Maxwell equations for chiral plasmas

[Boyarsky, Gorbar, Ruchayskiy, Rudenok, Shovkovy, Vilchinskii, to appear]

Magnetic field/helicity

- Magnetic helicity evolution (inverse cascade) in the Early Universe

$$\nabla \times \vec{B} = \frac{4\pi}{c}\left(\sigma \vec{E} + C_5 \mu_5 \vec{B}\right) + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{E} = 4\pi \rho \,, \qquad \nabla \cdot \vec{B} = 0$$

[Vilenkin, Phys. Rev. D22, 3080 (1980)]
[Joyce & Shaposhnikov, astro-ph/9703005]
[Giovannini & Shaposhnikov, hep-ph/9710234]

- For specific helicity eigenmodes:

$$\frac{dB_k}{dt} \propto \frac{ck}{\sigma}\left(4\pi C_5 \mu_5 - ck\right) B_k$$

[Boyarsky et al., arXiv:1109.3350]
[Tashiro et al., arXiv:1206.5549]
[Manuel et al., arXiv:1501.07608]
[Buividovich et al., arXiv:1509.02076]
[Hirono et al., arXiv:1509.07790]

Feedback on μ_5(t)

- Constraint of the total helicity conservation

$$h_{\text{fermion}} = h_0 - h_{\text{gauge}}$$

- Common "homogeneous" approximation:

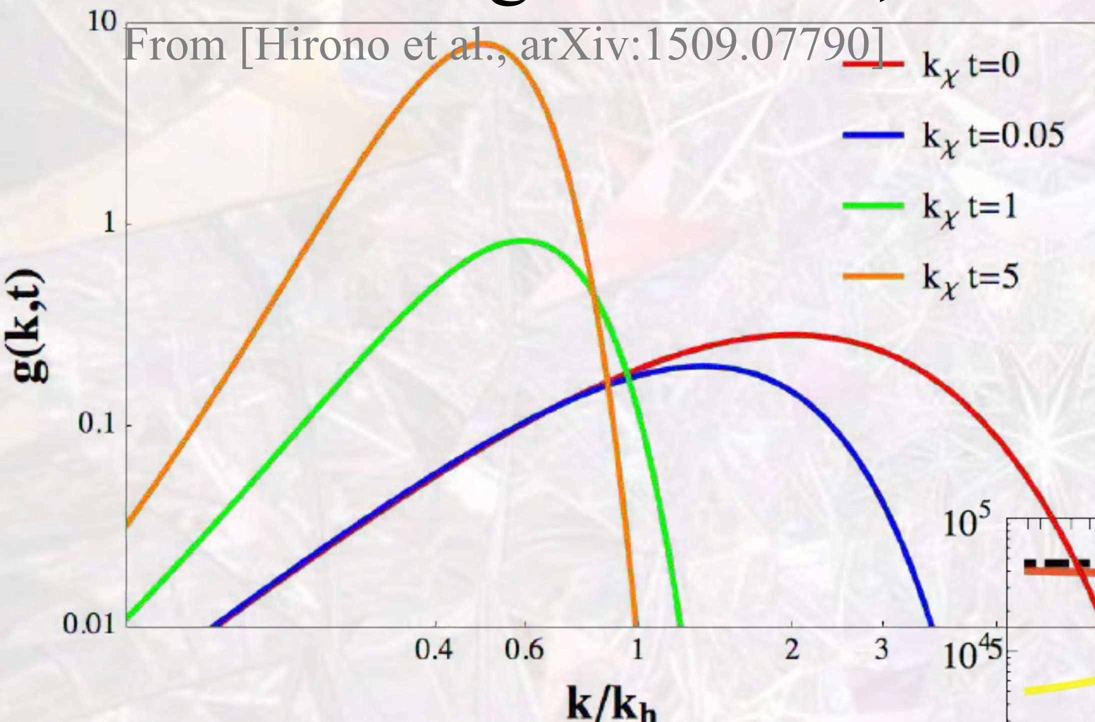
$$n_5(\vec{x},t) \approx \left\langle n_5(\vec{\mathbf{x}},t) \right\rangle_{\text{space}}, \quad \mu_5(t) \approx \frac{3c^3}{T^2} \left\langle n_5(\vec{\mathbf{x}},t) \right\rangle_{\text{space}}$$

- In other words, the value of μ_5 remains constant on distance scales

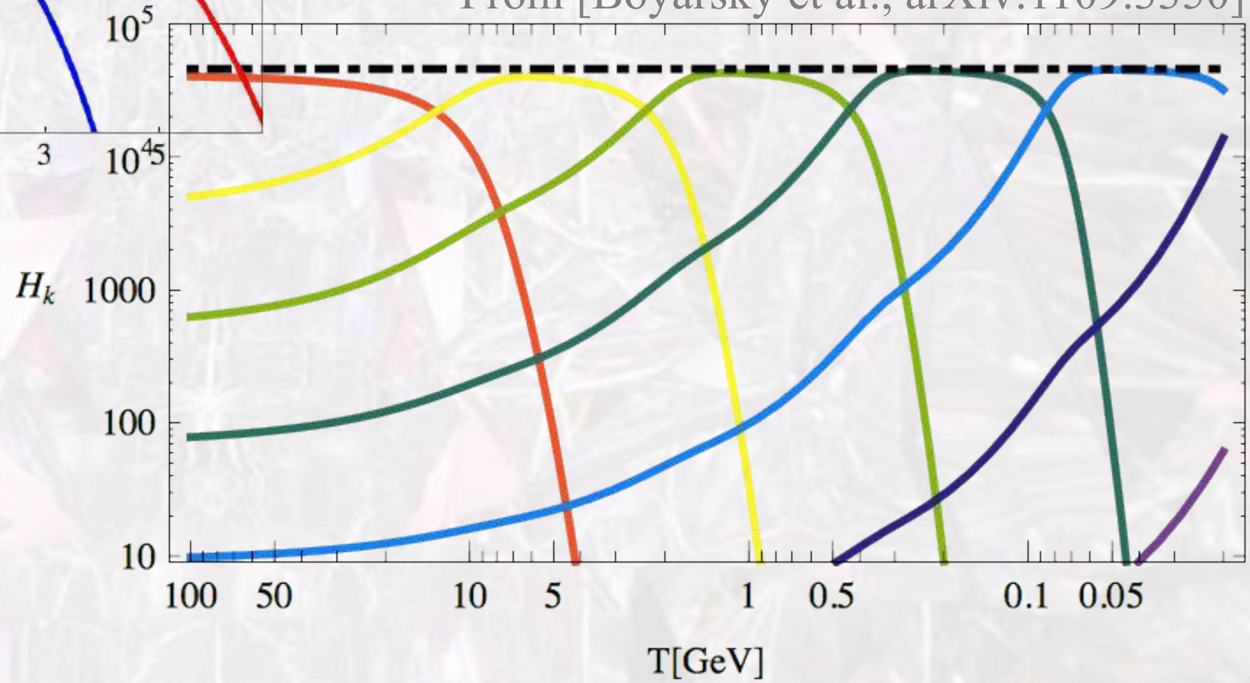
$$\Delta x \sim (k_{\text{crit}})^{-1} \sim (\mu_5)^{-1}$$

Magnetic field/helicity

- Magnetic helicity is transferred from short to long-wavelengths modes, while the value of μ_5 decreases



From [Hirono et al., arXiv:1509.07790]



From [Boyarsky et al., arXiv:1109.3350]

Open questions

- Will the cascade survive if there are variations of order $\delta\mu_5$ on distance scales $(k_{crit})^{-1}$?
- How large $\delta\mu_5$ can be tolerated?
- Will dynamical fluctuations of μ_5 stay under control?
- How to account for inhomogeneities in the anomalous Maxwell equations?

$$n_\lambda(\vec{x},t) = ? \qquad \vec{j}_\lambda(\vec{x},t) = ?$$

- How to obtain equations for $\mu(t,\mathbf{x})$ and $\mu_5(t,\mathbf{x})$?

Framework

- Chiral kinetic theory as a starting point:

$$\frac{\partial f_\lambda}{\partial t}+\frac{1}{1+\vec{\Omega}_\lambda\cdot\vec{B}}\left[\left(\vec{E}+\vec{v}\times\vec{B}+(\vec{E}\cdot\vec{B})\vec{\Omega}_\lambda\right)\cdot\frac{\partial f_\lambda}{\partial\vec{p}}+\left(\vec{v}+\vec{E}\times\vec{\Omega}_\lambda+(\vec{v}\cdot\vec{\Omega}_\lambda)\vec{B}\right)\cdot\frac{\partial f_\lambda}{\partial\vec{x}}\right]=I_{\text{coll}}$$

where

$$f_\lambda = f_\lambda^{(0)} + f_\lambda^{(1)} + f_\lambda^{(2)} + \ldots$$

$$f_\lambda^{(0)} = \frac{1}{\exp\left(\frac{cp-\mu_\lambda}{T}\right)+1}$$

is an expansion in powers of e-m field & $\vec{\nabla}\mu_\lambda, \partial_t\mu_\lambda$

[Boyarsky, Gorbar, Ruchayskiy, Rudenok, Shovkovy, Vilchinskii, to appear]

Equations for chemical potentials

- Resulting equation of motion for μ_λ:

$$\frac{\partial n_\lambda^{(0)}}{\partial \mu_\lambda}\left(\frac{\partial \mu_\lambda}{\partial t}+\frac{e\tau c^2}{3}\vec{\nabla}\cdot\vec{E}_\lambda\right)+\frac{e\tau\mu_\lambda}{3\pi^2 c}\left(\vec{E}_\lambda\cdot\frac{\partial \mu_\lambda}{\partial \vec{x}}\right)=\frac{\lambda e^2}{4\pi^2 c}\left(\vec{E}_\lambda\cdot\vec{B}\right)$$

where $n_\lambda^{(0)}=\dfrac{\mu_\lambda^3+\pi^2T^2\mu_\lambda}{3\pi^2c^3}$ and $\vec{E}_\lambda=\vec{E}-\dfrac{1}{e}\dfrac{\partial\mu_\lambda}{\partial\vec{x}}$

The corresponding equations for the currents:

CME, drift & diffusion, Hall type

$$\vec{j}=\frac{e\mu_5\vec{B}}{2\pi^2c}+\frac{e\tau T^2}{9c}\left(1+\frac{3\left(\mu^2+\mu_5^2\right)}{\pi^2T^2}\right)\left(e\vec{E}-\frac{\partial\mu}{\partial\vec{x}}\right)+\frac{e\tau^2\mu}{3\pi^2}\left(e\vec{E}-\frac{\partial\mu}{\partial\vec{x}}\right)\times\vec{B}+\vec{j}_{\text{new}}$$

$$\vec{j}_5=\frac{e\mu\vec{B}}{2\pi^2c}-\frac{e\tau T^2}{9c}\left(1+\frac{3\left(\mu^2+\mu_5^2\right)}{\pi^2T^2}\right)\frac{\partial\mu_5}{\partial\vec{x}}+\frac{2e\tau\mu_5\mu}{3\pi^2c}\left(e\vec{E}-\frac{\partial\mu}{\partial\vec{x}}\right)+\vec{j}_{5,\text{new}}$$

CSE, diffusion, CESE

New types of currents

- New contribution to the electric current:

$$\vec{j}_{\text{new}} = -\underbrace{\frac{2\tau\mu\mu_5}{3\pi^2 c}\frac{\partial\mu_5}{\partial\vec{x}}}_{\text{Chiral diffusion}} - \underbrace{\frac{e\tau^2\mu_5}{3\pi^2}\left(\frac{\partial\mu_5}{\partial\vec{x}}\times\vec{B}\right)}_{\text{Hall diffusion}} - \frac{e\tau^2\left(3\mu^2+3\mu_5^2+\pi^2T^2\right)}{9\pi^2 c}\frac{\partial\vec{E}}{\partial t}$$

- New contribution to the chiral current:

$$\vec{j}_{5,\text{new}} = -\overbrace{\frac{e\tau^2\mu}{3\pi^2}\left(\frac{\partial\mu_5}{\partial\vec{x}}\times\vec{B}\right)}^{\text{Chiral Hall diffusion}} + \overbrace{\frac{e\tau^2\mu_5}{3\pi^2}\left(e\vec{E}-\frac{\partial\mu}{\partial\vec{x}}\right)\times\vec{B}}^{\text{Chiral Hall effect}} - \frac{2e\tau^2\mu\mu_5}{3\pi^2 c}\frac{\partial\vec{E}}{\partial t}$$

- There is also a term $\propto \frac{e\tau}{6\pi^2}\left(\vec{E}\times\frac{\partial\mu}{\partial\vec{x}}\right)$

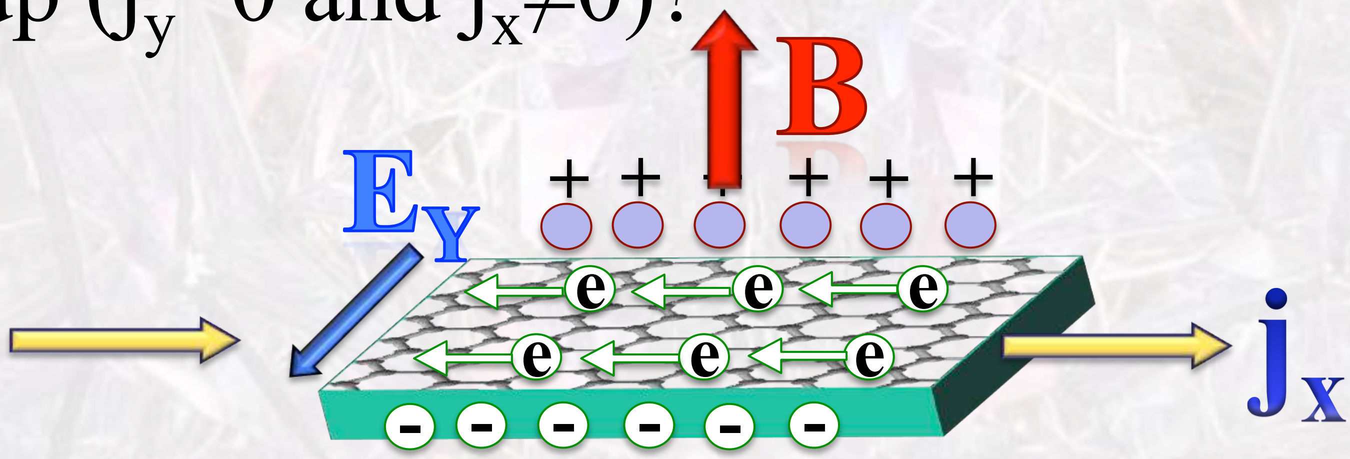
Question about Hall current

- Note that we had

$$\vec{j}^{\,(\text{Hall})} = \frac{e^2 \tau^2 \mu}{3\pi^2} \vec{E} \times \vec{B}$$

- Why is this proportional to τ^2 ?

- What do you observe in the usual experimental setup (j_y=0 and $j_x \neq 0$)?



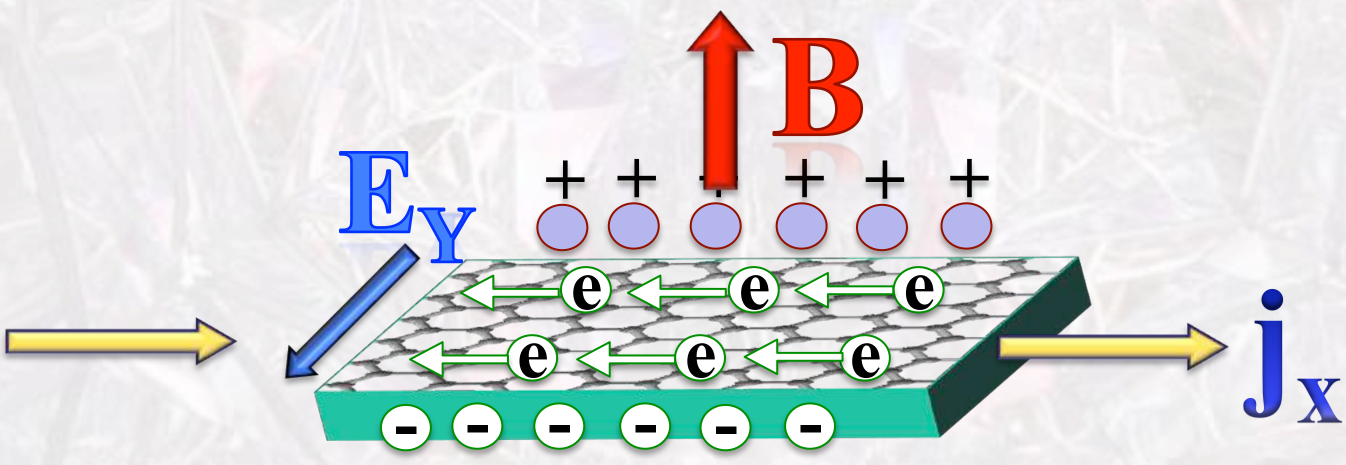
Question about Hall current

- Enforcing j_y=0 gives

$$a\tau E_y = b\tau^2 E_x B_z$$

Then, in the approximation used,

$$j_x = a\tau E_x + b\tau^2 E_y B_z = \frac{(a\tau)^2}{b\tau^2 B_z} E_y + b\tau^2 E_y B_z \approx \frac{a^2}{b B_z} E_y$$

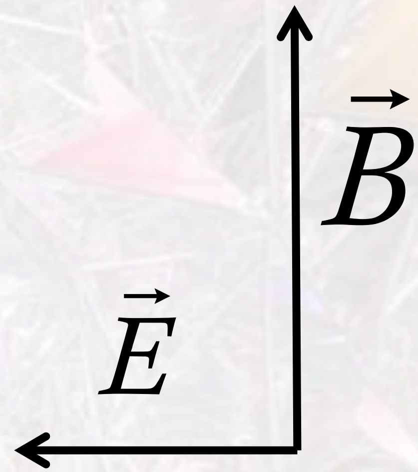


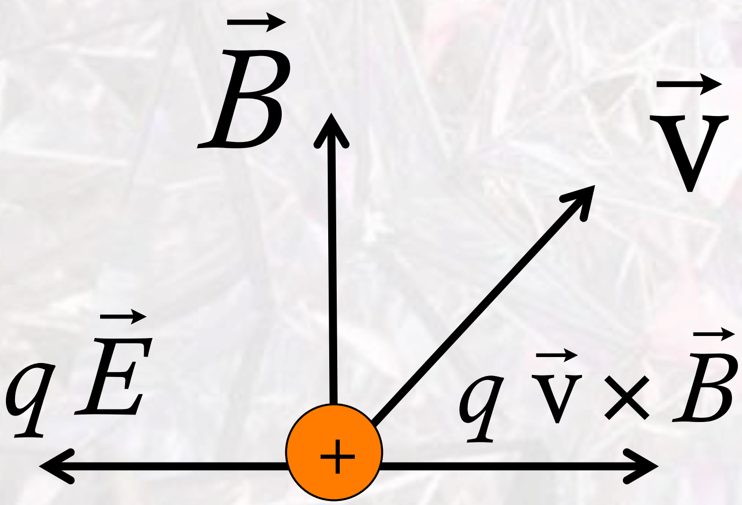
Plasma drift

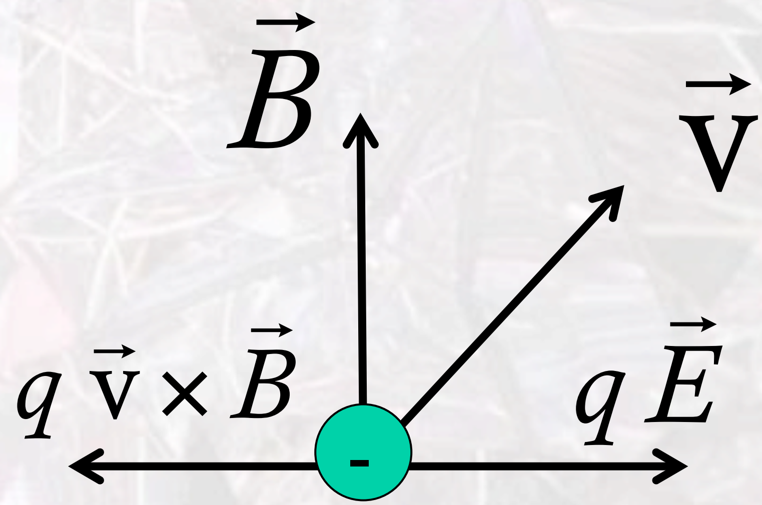
Plasma as a whole experiences a non-dissipative drift. Can this be included in $f_\lambda^{(0)}$?

Why should plasma drift?

Consider $\vec{E} \perp \vec{B}$ (with $E < B$):







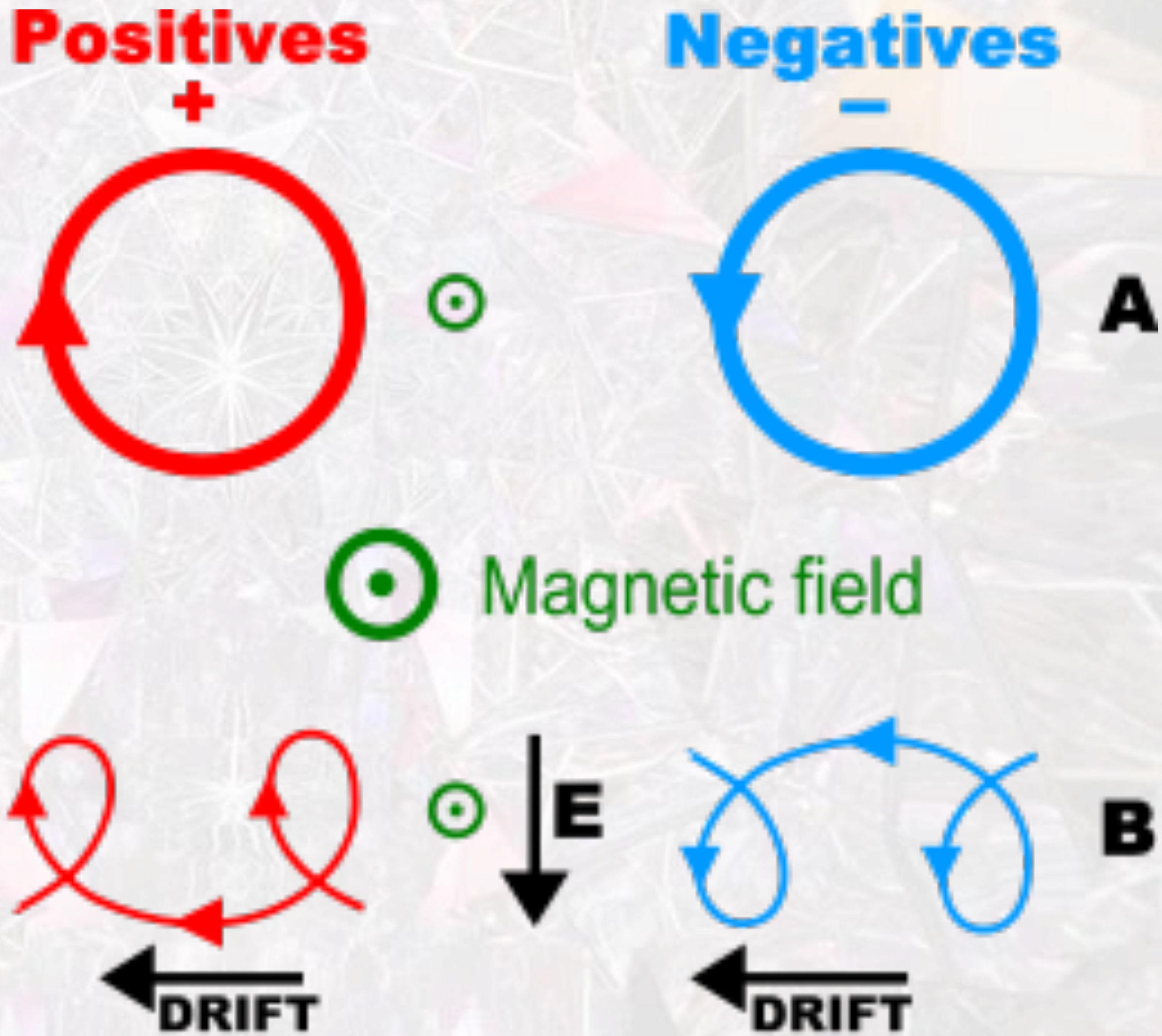
Frames of reference

Another viewpoint

$f_{\lambda}^{(0)}$

Drifting frame:

Lab frame:



$f_\lambda^{(0)}$ for magnetized plasma

- Consider a special case
  - Plasma consists of only e-m charged degrees of freedom
  - Fields so that $\vec{E} \perp \vec{B}$ (with $E < B$)
- No electric field in the drift frame
- Lab frame: use boosted Fermi-Dirac distribution

$$f_\lambda^{(\mathrm{lab})} = \frac{1}{\exp\left(\dfrac{c\,p - \vec{p}\cdot\vec{\mathrm{v}}_{\mathrm{drift}} - \mu_\lambda}{T}\right) + 1}$$

with

$$\vec{\mathrm{v}}_{\mathrm{drift}} = c\,\frac{\vec{E}\times\vec{B}}{B^2}$$

1^{st} Perturbation in drifting plasma

- Charge density

$$n_\lambda^{(\text{lab})} = n_\lambda^{(0)} - \tau \frac{\partial n_\lambda^{(0)}}{\partial \mu_\lambda}\left(\frac{\partial \mu_\lambda}{\partial t} + \vec{v}_{\text{drift}} \cdot \nabla \mu_\lambda\right) + \tau n_\lambda^{(0)}\left(\nabla \cdot \vec{v}_{\text{drift}}\right) + \dots$$

- Current density

$$\vec{j}_\lambda^{(\text{lab})} = c n_\lambda^{(0)} \frac{\vec{E}\times\vec{B}}{B^2} + \frac{\lambda e \mu_\lambda}{4\pi^2 c}\vec{B} + \frac{\lambda e \mu_\lambda}{4\pi^2 c}\vec{E}_\perp \frac{\left(\vec{E}\cdot\vec{B}\right)}{E_\perp^2}\left(\frac{B}{2E_\perp} ln \frac{B+E_\perp}{B-E_\perp} - 1\right)$$

$$-\tau \frac{\partial n_\lambda^{(0)}}{\partial \mu_\lambda}\left(g_1\left(\frac{e\left(\vec{E}\cdot\vec{B}\right)}{B^2}\vec{B} - \nabla\mu_\lambda\right) + g_2 \vec{v}_{\text{drift}}\left(\vec{v}_{\text{drift}}\cdot\nabla\mu_\lambda\right) + g_3 \frac{\partial \mu_\lambda}{\partial t}\vec{v}_{\text{drift}}\right) + \dots$$

Drift in QGP plasma?

- In QGP, gluons play a profound role
  - Gluons are neutral and, thus, are not drifting
  - The zeroth approximation is the usual Fermi-Dirac distribution

$$f_\lambda^{(0)} = \frac{1}{\exp\left(\frac{c\,p-\mu_\lambda}{T}\right)+1}$$

- Expansion in small e-m fields and gradients is well define

$$f_\lambda = f_\lambda^{(0)} + f_\lambda^{(1)} + f_\lambda^{(2)} + \ldots$$

- Expansion of the 1st type (no drift) may be better

Summary

- Chiral plasmas have widespread applications
  - Heavy-ion collisions
  - Cosmology
  - Dirac/Weyl semimetals
  - Neutron stars
- Anomaly plays a profound role in such plasmas
- Many interesting chiral/anomalous effects are triggered by a magnetic field
- Experimental search for signatures is underway