Non-static properties of the chiral magnetic conductivity

results will be published soon, stay tuned: 1909.xxxxx

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in collaboration with
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Outline

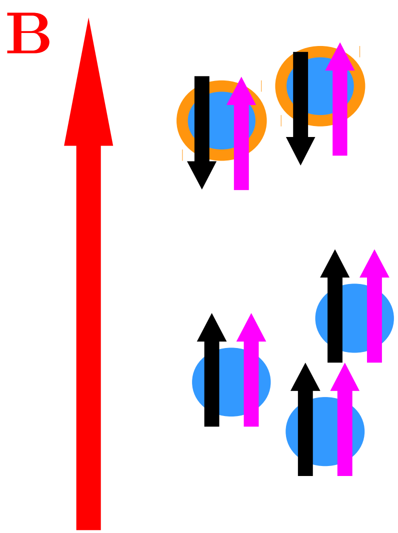
- **Motivation**
  about anomalous transport: features & relevance
  simple cartoon for CME & its phenomenology

- **CME in linear response**
  charge conservation and axial anomaly
  nontrivial properties of the static limit

- **Non-static response functions**
  anomaly ruled current vs. absent response
  some details of the nonstatic calculation
  examples of static μ_5 (***B***) and arbitrary ***B*** (μ_5)

Overview

$$\partial_\mu J_5^\mu = C_A \mathbf{E}\cdot\mathbf{B}$$



CME

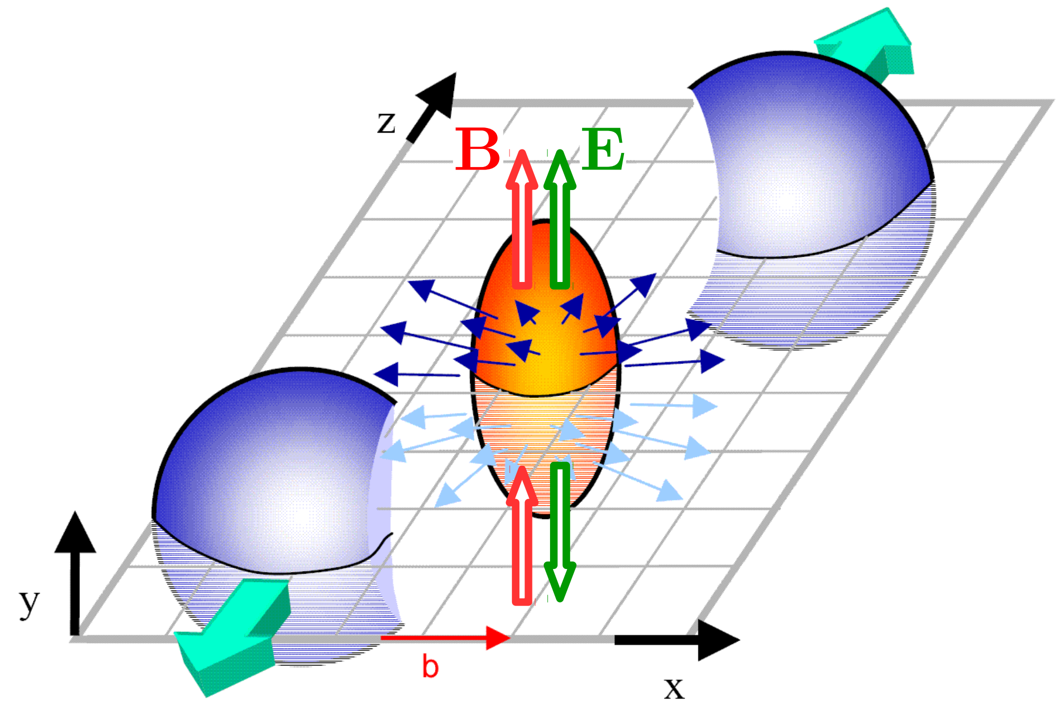
$\mu_5 \neq 0$

$n_R \neq n_L$

$\langle \mathbf{s} \rangle \sim \mathbf{B}$

$\langle \mathbf{p} \rangle \sim \mu_5 \langle \mathbf{s} \rangle$

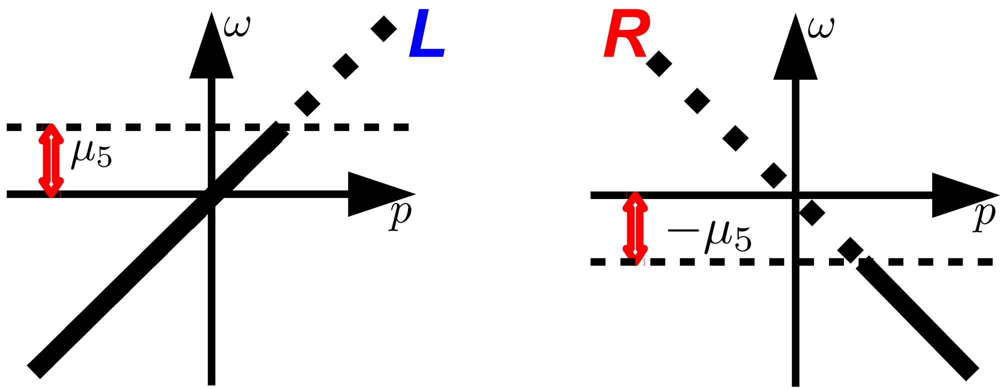
(+ opposite charge)



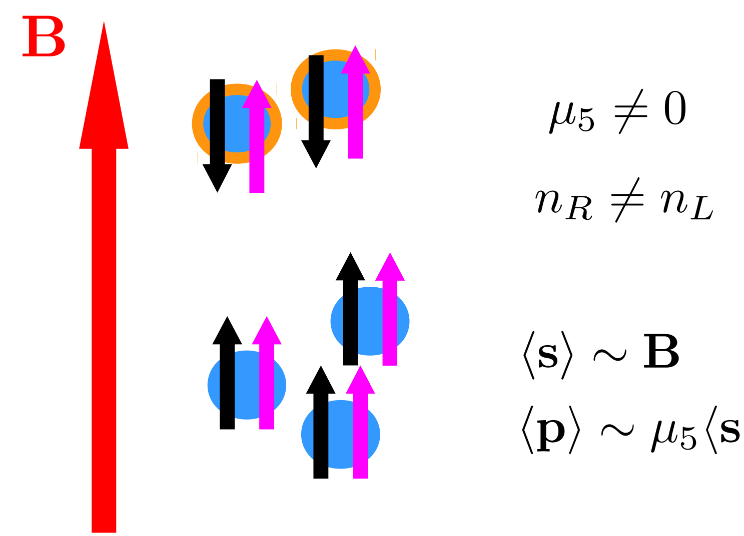
	$\mathbf{J}$	$=$ $\sigma\mathbf{E}$	$+$ $\sigma_A\mathbf{B}$
$\mathcal{P}$	*odd*	*even* × *odd*	*odd* × *even*
$\mathcal{T}$	*odd*	*odd* × *even*	*even* × *odd*

Simple picture of CME

chiral fermions in, affected by homog. E||B fields



CME = collective motion of vacuum particles with *arbitrarily large* momentum



(+ opposite charge)

$$\mathbf{J} = \sigma \mathbf{E} + C_A \mu_5 \mathbf{B}$$

$$\mathbf{J}_5 = \# \mu \mu_5 \mathbf{E} + C_A \mu \mathbf{B}$$

Consistent with Chern-Simons electrodynamics:

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - A^\mu J_\mu - \frac{C_A}{4} \theta \widetilde{F}^{\mu\nu} F_{\mu\nu}$$

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J} + C_A (M \mathbf{B} - \mathbf{P} \times \mathbf{E})$$

$$\nabla \cdot \mathbf{E} = \rho + C_A \mathbf{P} \cdot \mathbf{B} \qquad \mathbf{J} = \frac{e^2}{2\pi^2} (-\dot{\theta}) \mathbf{B}$$

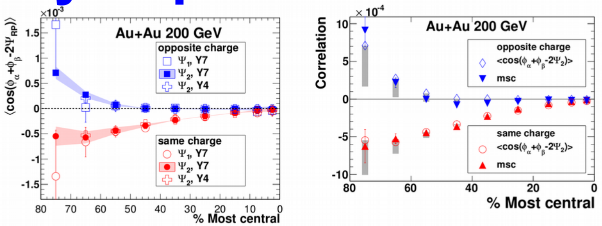
$$P^\mu = (M, \mathbf{P}) = \partial^\mu \theta$$

See: Kharzeev, Stephanov, Yee, PRD ***95,*** *051901 (2016)*

How to measure CME in HIC?

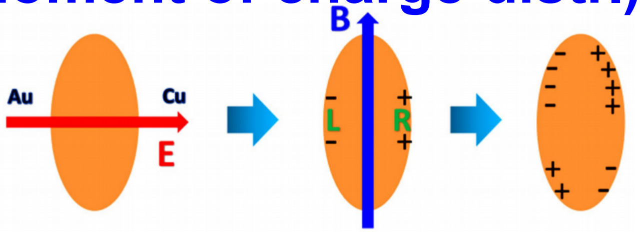
What signs to look for?

- **charge separation → dipole asymmetry in production**



- **CMW → Cu+Au coll. (quadrupole moment of charge distr.)**

  *see: Burnier, Liao, Kharzeev, Yee PRL **107**, 052303 (2011),*
  *Huang & Liao, PRL **110**, 232302 (2013)*



- **other things:**

  CSL ("chiral soliton lattice" nonzero quark masses → anoumalous Hall current & B—Omega coupling;
  K. Nishimura, aX:1711.02190
  transition radiation as a probe of chiral anomaly – circularly polarized photons at given angle to the jet direction
  Tuchin PRL 121, 182301 (2018)

main theor. uncertainties: related to initial state & LT of sources
from experimental POV: background...

Anomaly in QED

See for example: Landstenier, arXiv: *1610.04413 (2016)*

U(1) vector current: $J^\mu = \overline{\Psi}\gamma^\mu\Psi$

U(1) axialvector current: $J_5^\mu = \overline{\Psi}\gamma^\mu\gamma^5\Psi$

$$\partial_\mu J^\mu = 0$$

(consistent anomaly!)

$$\partial_\mu J_5^\mu = \frac{1}{2\pi^2}\mathbf{E}\cdot\mathbf{B} + \frac{1}{6\pi^2}\mathbf{E}_5\cdot\mathbf{B}_5$$

fermions coupled to gauge fields:

- maintaining gauge invariance
  - $\rightarrow$ *costs the anomalous divergence of the axial current*
- the anomaly comes from the UV behaviour of the fermionic propagator

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$$\partial_\mu J^\mu = \frac{1}{2\pi^2}\left(\mathbf{E}\cdot\mathbf{B}_5 + \mathbf{E}_5\cdot\mathbf{B}\right)$$

$$\partial_\mu J^\mu_5 = \frac{1}{2\pi^2}\left(\mathbf{E}\cdot\mathbf{B} + \mathbf{E}_5\cdot\mathbf{B}_5\right)$$

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$$\partial_\mu J^\mu = \frac{1}{2\pi^2}(\nabla\mu_5)\cdot\mathbf{B}$$

$$\partial_\mu J_5^\mu = \frac{1}{2\pi^2}\mathbf{E}\cdot\mathbf{B}$$

fermions coupled to gauge fields:

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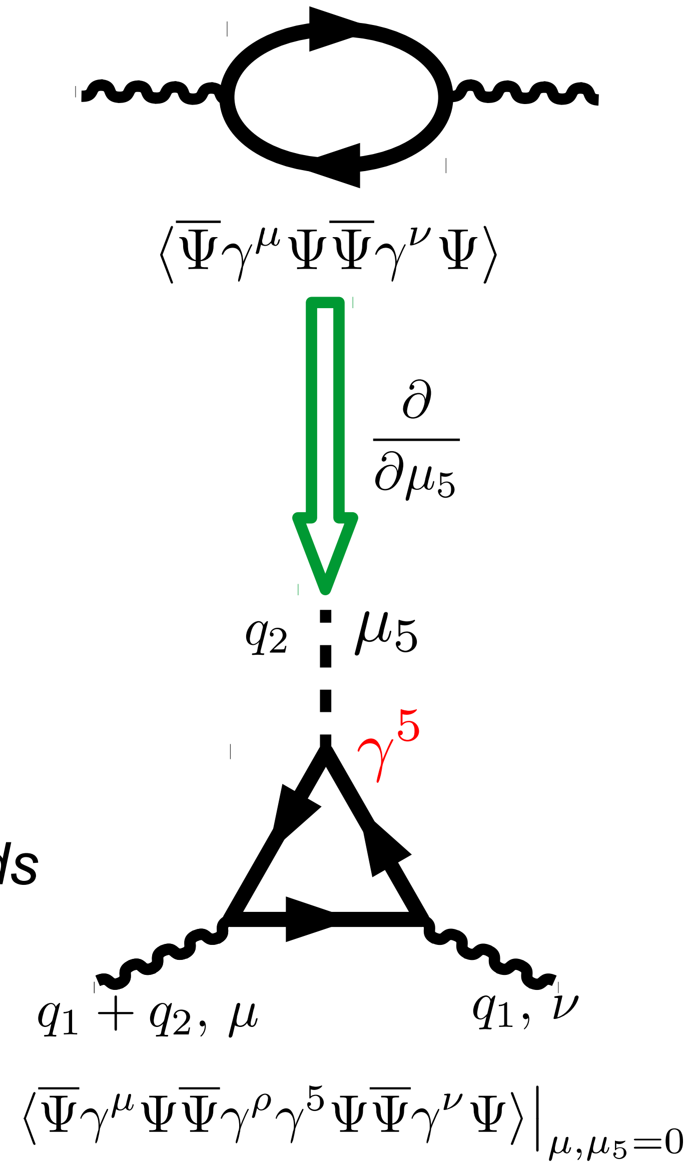
Anomalous conductivities

- **static (↔ steady state) current: *universal***
  → *given by the anomaly (1-loop)*
  → *no further quantum corrections!*

- **BUT relaxation dynamics:**
  → ***depends on the underlying theory***

- **approximation: linear response**
  → *microscopic dynamics is not effected by the extarnal fields*
  → *gradient corrections to hydrodynamic fields*



Linear response

$\mu = 0,\ \mathbf{E} = 0,\ \mathbf{B}_5 = 0$

$$\delta\langle J^\mu\rangle \sim \langle J^\mu J^0\rangle\mu + \langle J^\mu J^\nu\rangle A^{\text{ext}}_\nu +$$

$$+ \langle J^\mu J^0 J^0_5\rangle \mu\mu_5 +$$

$$+ \langle J^\mu J^\nu J^0_5\rangle A^{\text{ext}}_\nu \mu_5 + \langle J^\mu J^0 J^\nu_5\rangle \mu A^{\text{ext}}_{5,\nu} + \langle J^\mu J^\nu J^\rho_5\rangle A^{\text{ext}}_\nu A^{\text{ext}}_{5,\rho}$$

only gradient corr. $\sim \nabla\mu_5$

$$\delta\langle J^\mu_5\rangle \sim \langle J^\mu_5 J^0_5\rangle\mu_5 + \langle J^\mu_5 J^\nu_5\rangle A^{\text{ext}}_{5,\nu} +$$

$$+ \langle J^\mu_5 J^0 J^0\rangle \mu\mu + \langle J^\mu_5 J^0 J^\nu\rangle \mu A^{\text{ext}}_\nu + \langle J^\mu_5 J^\nu J^\rho\rangle A^{\text{ext}}_\nu A^{\text{ext}}_\rho +$$

$$+ \langle J^\mu_5 J^0_5 J^0_5\rangle \mu_5\mu_5 +$$

$$+ \langle J^\mu_5 J^0_5 J^\nu_5\rangle \mu_5 A^{\text{ext}}_{5,\nu} + \langle J^\mu_5 J^\nu_5 J^\rho_5\rangle A^{\text{ext}}_{5,\nu} A^{\text{ext}}_{5,\rho}$$

AVV triangle

$$i\delta G^{\rho\mu\nu}_{AVV}(q_1,q_2) = -\frac{ie^2}{2}\int_p \mathrm{tr}\Big\{\gamma^\mu iG^C(p+q_1+q_2)\gamma^\rho\gamma^5 iG^A(p+q_1)\gamma^\nu iG^A(p)+$$

$$+\gamma^\mu iG^R(p+q_1+q_2)\gamma^\rho\gamma^5 iG^C(p+q_1)\gamma^\nu iG^A(p)+$$

$$+\gamma^\mu iG^R(p+q_1+q_2)\gamma^\rho\gamma^5 iG^R(p+q_1)\gamma^\nu iG^A(p)+$$

$$+\gamma^\mu iG^C(p+q_1+q_2)\gamma^\nu iG^A(p+q_2)\gamma^\rho\gamma^5 iG^C(p)+$$

$$+\gamma^\mu iG^R(p+q_1+q_2)\gamma^\nu iG^C(p+q_2)\gamma^\rho\gamma^5 iG^A(p)+$$

$$+\gamma^\mu iG^R(p+q_1+q_2)\gamma^\nu iG^R(p+q_2)\gamma^\rho\gamma^5 iG^C(p)\Big\}$$

$$G^{R/A}(p) = \int_{-\infty}^{\infty}\frac{\mathrm{d}\omega}{2\pi}\frac{\rho(\omega,\mathbf{p})}{p_0-\omega\pm i0^+}$$

$$iG^{12/21}(p) = \rho(p)\cdot\begin{cases} -n_{FD}(p_0/T) \\ 1-n_{FD}(p_0/T)\end{cases}$$

$$G^{11/22} = \frac{G^{12}+G^{21}}{2}\pm\left(G^R+G^A\right)$$

$$G^C = (1-2n_{FD}(p_0/T))\,\rho(p)$$

– {same terms with *m=M>> all other scales*}

AVV triangle

$$q_{1\nu}\cdot\delta G^{\rho\mu\nu}_{AVV}(q_1,q_2)=0$$

$$(q_1+q_2)_\mu\cdot\delta G^{\rho\mu\nu}_{AVV}(q_1,q_2)=0$$

$$\partial\cdot J=0$$

$$q_{2\rho}\cdot\delta G^{\rho\mu\nu}_{AVV}(q_1,q_2)=-i\frac{e^2}{2\pi^2}\epsilon^{\mu\nu\rho\sigma}q_{1\sigma}q_{2\rho}$$

$$\Updownarrow$$

$$\partial\cdot J_5=C_A\mathbf{E}\cdot\mathbf{B}$$

(in the chiral limit!)

$$iG^{R/A}(p+q)q_\mu\Gamma^\mu_V iG^{R/A}(p)=G^{R/A}(p+q)-G^{R/A}(p)$$

$$iG^{C}(p+q)q_\mu\Gamma^\mu_V iG^{R/A}(p)=G^{C}(p+q)$$

$$iG^{R/A}(p+q)q_\mu\Gamma^\mu_V iG^{C}(p)=-G^{C}(p)$$

U(1) invariance (Ward-Takahasi)

Limiting cases

$$\delta\langle J^\mu_x\rangle = -\int_{q_1}\int_{q_2}\widetilde{A}^{\rm ext}_\nu(q_1)\widetilde{\mu}_5(q_2)i\delta G^{0\mu\nu}_{AVV}(q_1,q_2)e^{ix\cdot(q_1+q_2)}$$

$$\delta\langle J^\mu_x\rangle = -\int \mathrm{d}^4y\int \mathrm{d}^4z A^{\rm ext}_\nu(y)\mu_5(z)i\delta G^{0\mu\nu}_{AVV}(y-x,x-z)$$

q_{10} or $q_{20}\to 0$ setting external fields constant in time

$\mathbf{q}_1$ or $\mathbf{q}_2\to 0$ setting external fields homogeneous

Limiting cases – static point

$\mathbf{q}_2 \to 0$ percedes $q_{20} \to 0$ **ANOMALY** $\mathbf{J} = \frac{e^2}{2\pi^2}\mu_5 \mathbf{B}$

μ_5 first set to homogeneous

$q_{20} \to 0$ percedes $\mathbf{q}_2 \to 0$

μ_5 first set to time independent

- $q_{10} \to 0$ lastly: $\frac{2}{3} \times$ **ANOMALY**
- not $q_{10} \to 0$ lastly: **ZERO**

See: Hou, Hui, Ren, *JHEP* **5**, 46 (2011); Wu, Hou, Ren, *Phys. Rev. D* **96**, 096015 (2017)

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$q_{10} \to 0$ lastly: $\frac{2}{3} \times$ **ANOMALY**

$$\frac{q_{10}}{q_{10} + i0^+} \cdot \# \longrightarrow \frac{q_{10}}{q_{10} + i\gamma} \cdot \#$$

See: Hou, Hui, Ren, *JHEP* **5**, 46 (2011); Wu, Hou, Ren, *Phys. Rev. D* **96**, 096015 (2017)

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ZERO

See: Hou, Hui, Ren, *JHEP* **5**, 46 (2011); Wu, Hou, Ren, *Phys. Rev. D* **96**, 096015 (2017)

Limiting cases – absent current

$$\frac{\partial}{\partial q_{1k}} i\delta G^{0ij}_{AVV} =$$

$$= -\frac{e^2}{2}\int_p \mathrm{tr}\left\{\gamma^i\gamma^5\left(-\frac{\partial}{\partial p_0}G^A(p_0,\mathbf{p})\right)\gamma^j\frac{\partial}{\partial p_k}G^A(p_0,\mathbf{p})+\right.$$
$$-\gamma^i\gamma^5\left(-\frac{\partial}{\partial p_0}G^R(p_0,\mathbf{p})\right)\gamma^j\frac{\partial}{\partial p_k}G^R(p_0,\mathbf{p})+$$
$$-\gamma^i\gamma^5\frac{\partial}{\partial p_k}G^A(p_0,\mathbf{p})\gamma^j\left(-\frac{\partial}{\partial p_0}G^A(p_0,\mathbf{p})\right)+$$
$$\left.+\gamma^i\gamma^5\frac{\partial}{\partial p_k}G^R(p_0,\mathbf{p})\gamma^j\left(-\frac{\partial}{\partial p_0}G^R(p_0,\mathbf{p})\right)\right\}(1-2n(p_0))$$
$$-\{\text{same with } m = M \gg \text{ all other scales}\}+$$

→ ***seems to be robust against fermionic interactions***

See e.g.: Satow etal., PRD **90** *014027 (2014)*

$$e^2\int_p \mathrm{tr}\left\{\gamma^i\gamma^5 G^A(p)\gamma^j\frac{\partial G^A(p)}{\partial p_k}\right\}(-2n'(p_0))$$

$$+\frac{e^2}{2}\int_p \mathrm{tr}\left\{\gamma^i\gamma^5 g^A_M(p_0,\mathbf{p})\gamma^0 G^A_M(p_0,\mathbf{p})\gamma^j\frac{\partial}{\partial p_k}G^A_M(p_0,\mathbf{p})+\right.$$
$$-\gamma^i\gamma^5 g^R_M(p_0,\mathbf{p})\gamma^0 G^R_M(p_0,\mathbf{p})\gamma^j\frac{\partial}{\partial p_k}G^R_M(p_0,\mathbf{p})+$$
$$+\gamma^i\gamma^5 g^A_M(p_0,\mathbf{p})\frac{\partial}{\partial p_k}G^A_M(p_0,\mathbf{p})\gamma^j G^A_M(p_0,\mathbf{p})\gamma^0+$$
$$\left.-\gamma^i\gamma^5 g^R_M(p_0,\mathbf{p})\frac{\partial}{\partial p_k}G^R_M(p_0,\mathbf{p})\gamma^j G^R_M(p_0,\mathbf{p})\gamma^0\right\}(1-2n(p_0)) =$$

$$e^2\int_p \mathrm{tr}\left\{\gamma^i\gamma^5\gamma^0 G^A_M(p)\gamma^j\frac{\partial G^A_M(p)}{\partial p_k}\right\}g^A_M(p)(1-2n(p_0))$$

→ ***contribution from the regulator term only***

→ ***fermionic interactions could not change it!***

Limiting cases – constant μ_5

μ_5 is set first constant then homogeneous

B can be set to homogeneous with still non-trivial time-dependence

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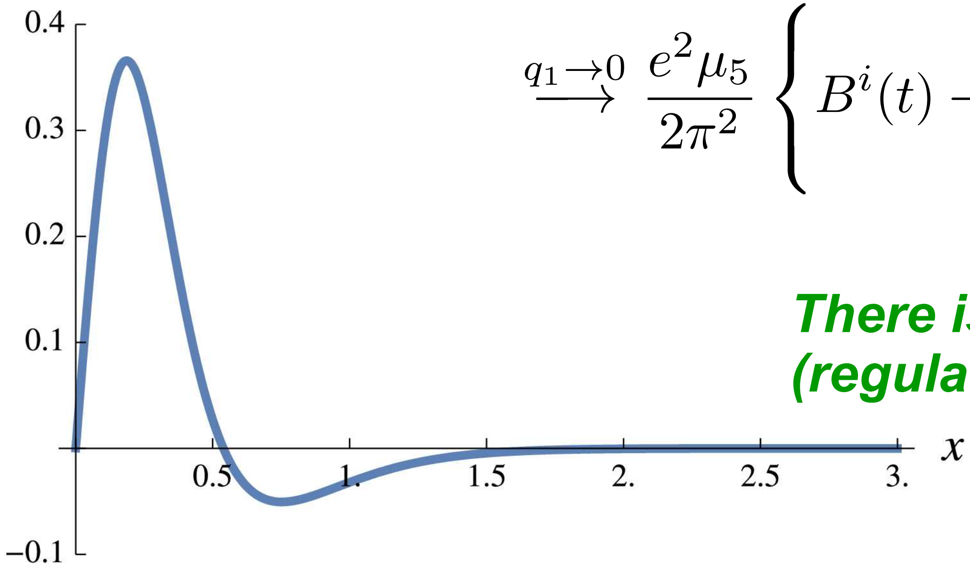
$$\widetilde{J}^i = \mu_5 \int_{-\infty}^{\infty} \mathrm{d}\tau \widetilde{B}^i(t+\tau, \mathbf{q}_1) \frac{e^2}{2\pi^2} \Big\{ \delta(\tau) + $$

$$ -4\theta(-\tau) \left[\frac{\partial}{\partial \tau} \left(\frac{\partial}{\partial \tau} \left(\frac{\sin(q_1 \tau)}{q_1 \tau} \right) \frac{T F_1(\tau T)}{q_1^2} \right) - \frac{\sin(q_1 \tau)}{q_1 \tau} T F_2(\tau T) \right] \Big\}$$



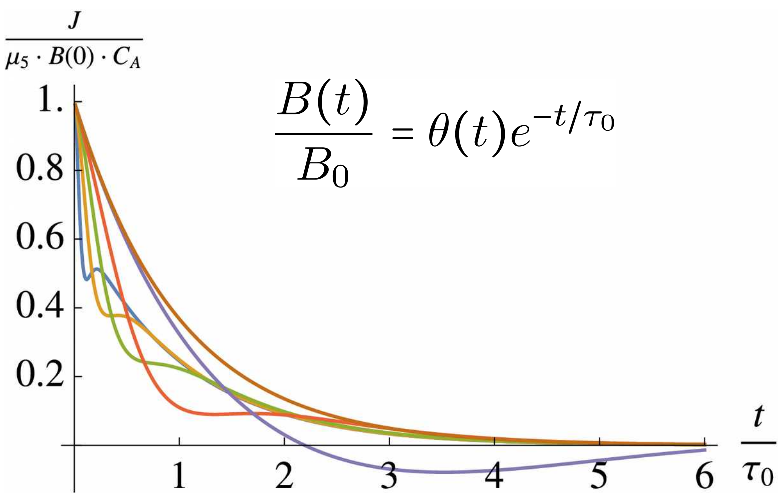
$$\xrightarrow{q_1 \to 0} \frac{e^2 \mu_5}{2\pi^2} \left\{ B^i(t) - 4 \int_0^{\infty} \mathrm{d}\tau B^i(t+\tau) T F_3(\tau T) \right\}$$

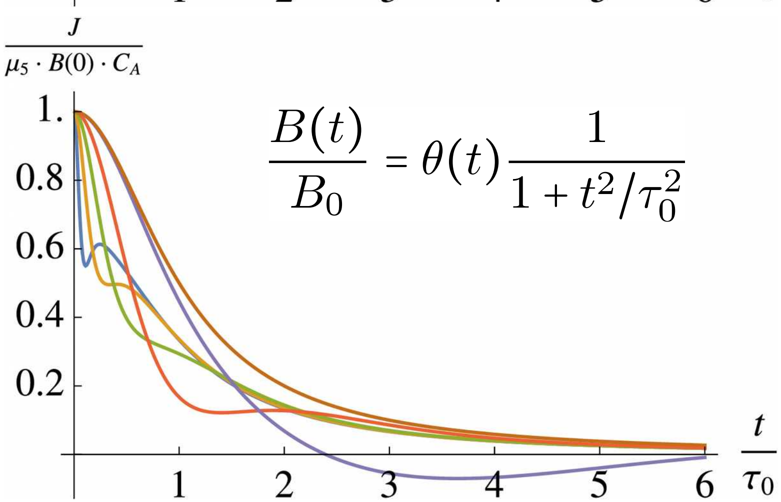
There is an instantaneous response (regulator terms!)

Limiting cases – constant μ_5

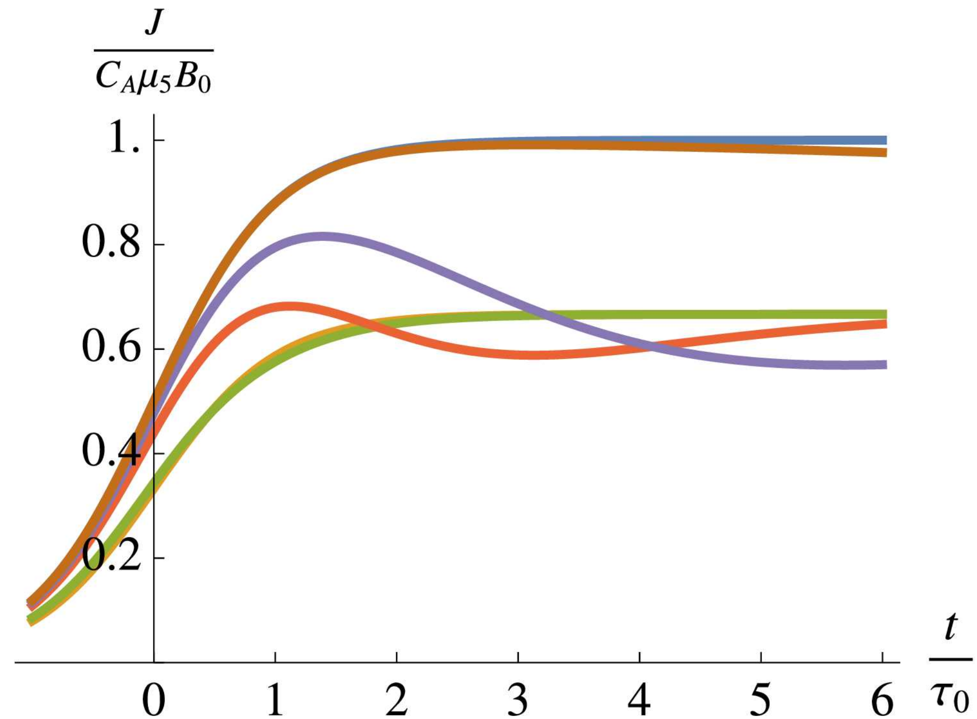
Magnetic field is homogeneous but time-dependent

Retardation is more pronounced for smaller temperatures





$\tau_0 T = 5.0,\ 2.0,\ 1.0,\ 0.5,\ 0.1$



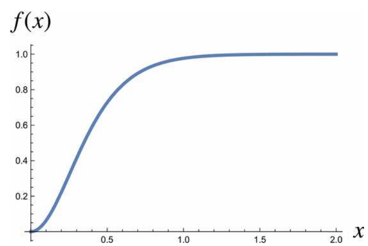
$$\frac{B(t)}{B_0} = \frac{1 + \tanh(t/\tau_0)}{2}$$

$\tau_0 T = 5.0,\ 1.0,\ 0.2,\ 0.1,\ 0.01$

Limiting cases – constant ***B***

Limiting cases – constant *B*

$$\widetilde{J}^i(t,\mathbf{q}_2) = \int\limits_{-\infty}^{\infty} \mathrm{d}\tau \widetilde{\mu_5}(t+\tau,\mathbf{q}_2)\frac{e^2}{2\pi^2}\left\{B^i\left(\delta(\tau)+\frac{\theta(-\tau)}{2}\left[q_2\sin(q_2\tau)-\frac{\partial}{\partial\tau}\left(\frac{\sin(q_2\tau)}{q_2\tau}\right)f(\tau T)\right]+\right.\right.$$



$$\left.+(\mathbf{B}\cdot\widehat{\mathbf{q}_2})\widehat{q_2}^{\,i}\frac{\theta(-\tau)}{2}\left[q_2\sin(q_2\tau)+\frac{\partial}{\partial\tau}\left(\frac{\sin(q_2\tau)}{q_2\tau}\right)f(\tau T)\right]\right\}$$

T=0

$$J^i(t,\mathbf{r}) = \frac{e^2}{2\pi^2}\left\{B^i\mu_5(t,\mathbf{r}) - \frac{2}{3}B^i\mu_5(t,\mathbf{r}) + \right.$$

$$+\frac{1}{8\pi}\int \mathrm{d}^2\widehat{\mathbf{r}'}\int\limits_0^{\infty}\mathrm{d}r'\left[\left(r'\partial_1^2\mu_5(t-r',\mathbf{r}+\mathbf{r}')\right)\left(B^i+B^i_{\parallel,\mathbf{r}'}\right)+\right.$$

$$-\left(\partial_1\mu_5(t-r',\mathbf{r}+\mathbf{r}')+\frac{\mu_5(t-r',\mathbf{r}+\mathbf{r}')-\mu_5(t,\mathbf{r}+\mathbf{r}')}{r'}\right)\left(B^i-3B^i_{\parallel,\mathbf{r}'}\right)+$$

$$\left.\left.+\left(\partial_1\mu_5(t-r',\mathbf{r}+\mathbf{r}')f(r'T)-\mu_5(t-r',\mathbf{r}+\mathbf{r}')Tf'(r'T)\right)\left(B^i-B^i_{\parallel,\mathbf{r}'}\right)\right]\right\}$$

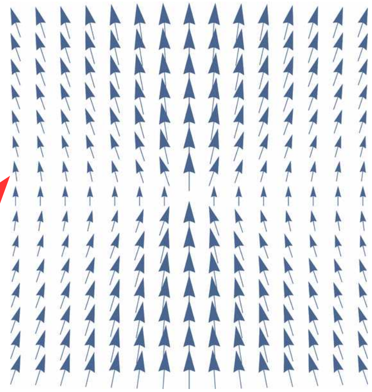
T>0

$$\mathbf{B}_{\parallel,\mathbf{r}} = (\mathbf{B}\cdot\widehat{\mathbf{r}})\widehat{\mathbf{r}}$$

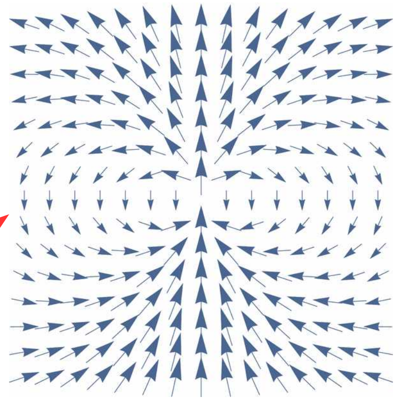
Point-like μ_5 – constant ***B***

$$\mathbf{J}(t,\mathbf{r}) = \frac{e^2}{2\pi^2}\left\{\frac{1}{3}\mathbf{B}\mu_5(t)\delta^{(3)}(\mathbf{r}) + \right.$$

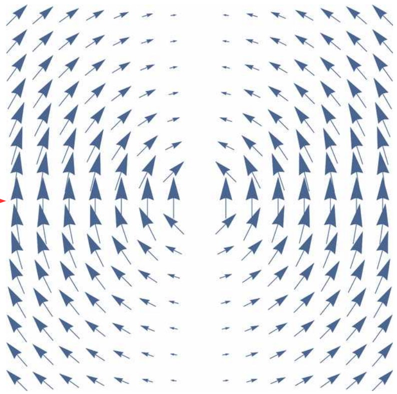
$$+\frac{1}{2}\left[\frac{\mu_5''(t-r)}{r}\boxed{(\mathbf{B}+(\mathbf{B}\cdot\widehat{\mathbf{r}})\widehat{\mathbf{r}})}+\right.$$



$$-\left(\frac{\mu_5'(t-r)}{r^2}+\frac{\mu_5(t-r)-\mu_5(t)}{r^3}\right)\boxed{(\mathbf{B}-3(\mathbf{B}\cdot\widehat{\mathbf{r}})\widehat{\mathbf{r}})}+$$



$$\left.\left.+\frac{\mu_5'(t-r)f(rT)+\mu_5(t-r)Tf'(rT)}{r^2}\boxed{(\mathbf{B}-(\mathbf{B}\cdot\widehat{\mathbf{r}})\widehat{\mathbf{r}})}\right]\right\}$$



For a centered source:

$$\mu_5(\mathbf{r},t) = \mu_5(t)\delta^{(3)}(\mathbf{r})$$

B

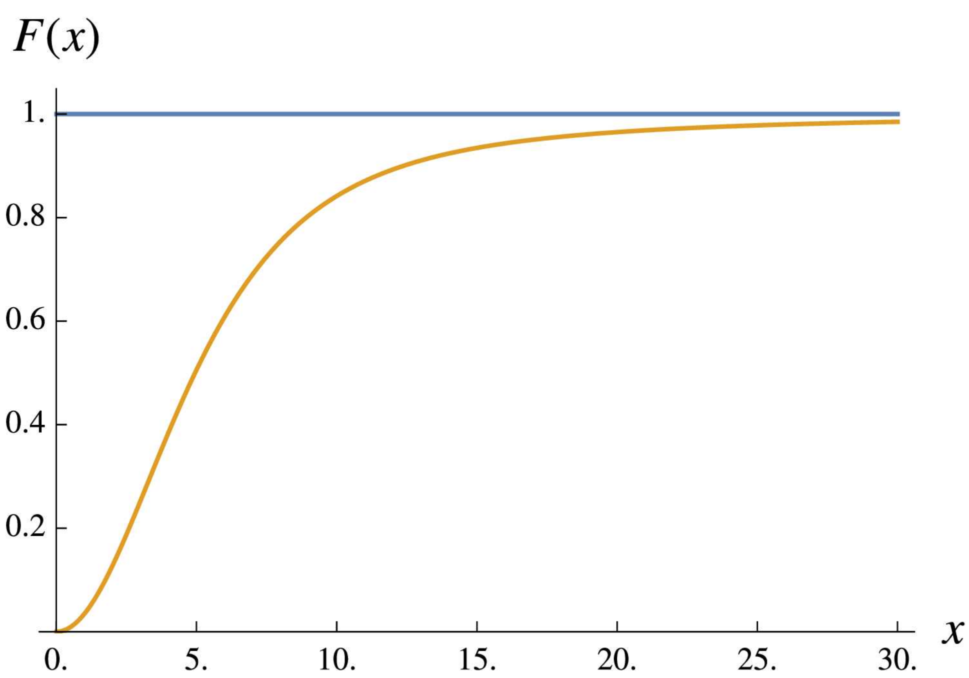
Quenched μ_5 – constant ***B***

Sudden change in μ_5 – asymptotic current?

$$\mu_5(t,\mathbf{r}) = \theta(t)\mu_5(\mathbf{r})$$

$$\widetilde{J}^i(t\to\infty,\mathbf{q}) = \frac{\mu_5(\mathbf{q})}{2}\left[B^i - \widehat{q}^i(\mathbf{B}\cdot\widehat{\mathbf{q}}) + (B^i - \widehat{q}^i(\mathbf{B}\cdot\widehat{\mathbf{q}}))\int_0^\infty \mathrm{d}\tau \frac{\partial}{\partial\tau}\left(\frac{\sin q\tau}{q\tau}\right) f(\tau T)\right] =$$

$$=: \frac{\mu_5(\mathbf{q})}{2}\left(B^i - \frac{q^i(\mathbf{B}\cdot\mathbf{q})}{q^2}\right) F(q/T)$$



T→0 : current-dipole,

$$\mathbf{J} = \frac{1}{4\pi}\frac{1}{2}\nabla_{\mathbf{r}} \times \int \mathrm{d}^3\mathbf{r}' \frac{\mu_5(\mathbf{r}'-\mathbf{r})\mathbf{B}\times\mathbf{r}'}{(r')^3}$$

T→ larger than any scale (even that of spatial inhomogeneities: zero current

q~5T: cut-off, spatially localized current

Quenched μ_5 – constant *B*

Sudden change in μ_5 – asymptotic current?

$$\mu_5(t,\mathbf{r}) = \theta(t)\mu_5(\mathbf{r})$$

$$\widetilde{J}^i(t\to\infty,\mathbf{q}) = \frac{\mu_5(\mathbf{q})}{2}\left[B^i - \widehat{q}^i(\mathbf{B}\cdot\widehat{\mathbf{q}}) + (B^i - \widehat{q}^i(\mathbf{B}\cdot\widehat{\mathbf{q}}))\int_0^\infty \mathrm{d}\tau \frac{\partial}{\partial\tau}\left(\frac{\sin q\tau}{q\tau}\right) f(\tau T)\right] =$$

$$=: \frac{\mu_5(\mathbf{q})}{2}\left(B^i - \frac{q^i(\mathbf{B}\cdot\mathbf{q})}{q^2}\right) F(q/T)$$

for a centered source: $\mu_5(\mathbf{q}) = V_D \cdot \mu_5$

$$\overline{\mathbf{J}} = \frac{1}{V_D}\int_D \mathrm{d}^3\mathbf{r}\,\mathbf{J}(t\to\infty,\mathbf{r}) = \frac{e^2}{2\pi^2}\mu_5\mathbf{B}\,\frac{1-f(RT)}{3}$$

Perspectives

- **Other plans**

  practical expression, suitable for hydro implementation
  (maybe high T expansion? Coarse grained transport coeffs.?)

  realistic sources of n_5 from QCD?

  n_5 production from color fields: also AVV!

- **Outlook**

  - effects of axion dynamics on transport in compact stars
  - possibility of CMW modes because of n_5 fluctuations?

Take home message

- **Non-static contributions matter!**

SIZABLE!
→ **corrections to the static anomaly current**
→ **delay in response on low-T**

- **Order of limits matters!**

→ **different order of limits correspond to physical regimes dominated by different scales**

→ **constant μ_5 corresponds to the absence of the current means: CME is a nonequilibrium phenomenon**

Thank you for listening!

Questions? Comments?

谢谢大家！

results will be published soon, stay tuned! 1909.xxxxx

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Backup

AVV triangle

$$q_{1\nu}\delta G^{\rho\mu\nu}_{AVV}(q_1,q_2) =$$

$$iG(p+q)q\cdot\Gamma_V iG(p) = G(p+q) - G(p)$$

$$= -\frac{ie^2}{2}\int_p \mathrm{tr}\Big\{\gamma^\mu iG^C(p+q_1+q_2)\gamma^\rho\gamma^5 G^A(p+q_1) - \gamma^\mu iG^C(p+q_1+q_2)\gamma^\rho\gamma^5 G^A(p)$$

$$+\gamma^\mu iG^R(p+q_1+q_2)\gamma^\rho\gamma^5 G^C(p+q_1)+$$

$$-\gamma^\mu iG^R(p+q_1+q_2)\gamma^\rho\gamma^5 G^C(p)+$$

$$+\gamma^\mu G^C(p+q_1+q_2)\gamma^\rho\gamma^5 iG^A(p)+$$

$$-\gamma^\mu iG^C(p+q_2)\gamma^\rho\gamma^5 iG^A(p)+$$

$$+\gamma^\mu iG^R(p+q_1+q_2)\gamma^\rho\gamma^5 iG^C(p) - \gamma^\mu iG^R(p+q_2)\gamma^\rho\gamma^5 iG^C(p)\Big\}$$

– {same terms with *m=M>>all other scales*}

AVV triangle

$$q_{1\nu}\delta G^{\rho\mu\nu}_{AVV}(q_1,q_2) =$$

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$$-\gamma^\mu iG^R(p+q_1+q_2)\gamma^\rho\gamma^5 G^C(p)+$$

$$+\gamma^\mu G^C(p+q_1+q_2)\gamma^\rho\gamma^5 iG^A(p)+$$

$$-\gamma^\mu iG^C(p+q_2)\gamma^\rho\gamma^5 iG^A(p)+$$

$$+\gamma^\mu iG^R(p+q_1+q_2)\gamma^\rho\gamma^5 iG^C(p) - \gamma^\mu iG^R(p+q_2)\gamma^\rho\gamma^5 iG^C(p)\Big\}$$

– {same terms with *m=M>>all other scales*}

AVV triangle

$$G(p)\gamma^5 + \gamma^5 G(p) = \gamma^5 g(p)$$

$$\begin{aligned}
q_{2\rho}\cdot i\delta G^{\rho\mu\nu}_{AVV}(q_1,q_2) = -\frac{ie^2}{2}\int_p \mathrm{tr}\Big\{ & \gamma^\mu\gamma^5 \overbrace{iG^C(p+q_1+q_2)\not{q}_2 iG^A(p+q_1)}^{G^C(p+q_1+q_2)}\gamma^\nu iG^A(p)+ \\
& +\gamma^\mu\gamma^5 \overbrace{iG^R(p+q_1+q_2)\not{q}_2 iG^C(p+q_1)}^{-G^C(p+q_1)}\gamma^\nu iG^A(p)+ \\
& +\gamma^\mu\gamma^5 \overbrace{iG^R(p+q_1+q_2)\not{q}_2 iG^R(p+q_1)}^{G^R(p+q_1+q_2)-G^R(p+q_1)}\gamma^\nu iG^A(p)+ \\
& +\gamma^\mu\gamma^5 iG^C(p+q_1+q_2)\gamma^\nu \overbrace{iG^A(p+q_2)\not{q}_2 iG^C(p)}^{G^A(p+q_2)-G^A(p)}+ \\
& +\gamma^\mu\gamma^5 iG^R(p+q_1+q_2)\gamma^\nu \overbrace{iG^C(p+q_2)\not{q}_2 iG^A(p)}^{G^C(p+q_2)}+ \\
& +\gamma^\mu\gamma^5 iG^R(p+q_1+q_2)\gamma^\nu \overbrace{iG^R(p+q_2)\not{q}_2 iG^C(p)}^{-G^C(p)}\Big\}
\end{aligned}$$

$$\underbrace{-\{m = M \gg q_1,\ q_2;\ g(p)\neq 0\}}_{@ = -i\frac{e^2}{2\pi^2}\epsilon^{\mu\nu\rho\sigma}q_{1\sigma}q_{2\rho}}$$

AVV triangle

$$G(p)\gamma^5 + \gamma^5 G(p) = \gamma^5 g(p)$$

When only the Pauli-Villars term contributes:

$$\frac{\partial}{\partial q_{1k}} i\delta G^{0ij}_{AVV} =$$

$$= \frac{ie^2}{2} \int_p \mathrm{tr}\Big\{\gamma^\mu \gamma^5 (1-2n_{FD}(p_0/T))\Big[$$

$$ig^R_M(p+q_1+q_2)\not{q}_2 iG^R_M(p+q_1)\gamma^\nu iG^R_M(p) + iG^R_M(p+q_1+q_2)\gamma^\nu iG^R_M(p+q_2)\not{q}_2 ig^R_M(p) +$$

$$ig^A_M(p+q_1+q_2)\not{q}_2 iG^A_M(p+q_1)\gamma^\nu iG^A_M(p) + iG^A_M(p+q_1+q_2)\gamma^\nu iG^A_M(p+q_2)\not{q}_2 ig^A_M(p)\Big]\Big\} =$$

$$\approx ie^2(-8iM^2)\epsilon^{\mu\nu\rho\sigma} q_{1\sigma} q_{2\rho} \int_p (1-2n_{FD}(p_0/T)) \left[\frac{1}{\left[(p_0+i0^+)^2 - p^2 - M^2\right]^3} - \frac{1}{\left[(p_0-i0^+)^2 - p^2 - M^2\right]^3}\right] =$$

$$= -\frac{4e^2}{\pi^3}\epsilon^{\mu\nu\rho\sigma} q_{1\sigma} q_{2\rho} 2\pi i \left(\frac{3}{8}\int_0^\infty \mathrm{d}y \frac{y^2}{(y^2+1)^{5/2}} - \lim_{N\to\infty}\sum_{n=0}^{N}\int_0^\infty \mathrm{d}y \frac{y^2}{\left(\frac{(2n+1)^2\pi^2}{M^2} + 1 + y^2\right)^3}\frac{2}{M}\right) =$$

$$\xrightarrow{M\to\infty} -i\frac{8e^2}{\pi^2}\epsilon^{\mu\nu\rho\sigma} q_{1\sigma} q_{2\rho}\left(\frac{3}{8}\cdot\frac{1}{3} - \frac{1}{16}\right) = -i\frac{e^2}{2\pi^2}\epsilon^{\mu\nu\rho\sigma} q_{1\sigma} q_{2\rho}$$

Limiting cases – absent current

$$\frac{\partial}{\partial q_{1k}} i\delta G^{0ij}_{AVV} =$$

$$= \underbrace{ie^2 \int_p \mathrm{tr}\left\{\gamma^i\gamma^5 G^A(p)\gamma^j \frac{\partial G^A(p)}{\partial p_k}\right\}(-2n'(p_0))}_{=:A} + \underbrace{2ie^2 \int_p \mathrm{tr}\left\{\gamma^i\gamma^5\gamma^0 G^A_M(p)\gamma^j \frac{\partial G^A_M(p)}{\partial p_k}\right\} g^A_M(p)(1-2n(p_0))}_{=:B} = 0$$

$$A = \frac{ie^2\cdot 4\pi}{16\pi^4}\int_{-\infty}^{\infty}\mathrm{d}p_0 \int_0^{\infty}\mathrm{d}p p^2 \mathrm{tr}\left\{\gamma^5\gamma^i \not{p}\gamma^j\left(\gamma^k - \frac{2p^k\not{p}}{(p_0-i0^+)^2-p^2}\right)\right\}\frac{-2n'(p_0)}{[(p_0-i0^+)^2-p^2]^2} = \frac{2e^2}{\pi^3}\epsilon^{ijk}\int_0^{\infty}\mathrm{d}p p^2\int_{-\infty}^{\infty}\mathrm{d}p_0 \frac{p_0 n'(p_0)}{[(p_0-i0^+)^2-p^2]^2} =$$

$$= -\frac{e^2}{\pi^3}\epsilon^{ijk}\int_0^{\infty}\mathrm{d}p p^2\int_{-\infty}^{\infty}\mathrm{d}p_0 n'(p_0)\frac{\partial}{\partial p_0}\frac{1}{(p_0-i0^+)^2-p^2} = \frac{ie^2}{\pi^2}\epsilon^{ijk}\int_0^{\infty}\mathrm{d}p p^2\int_{-\infty}^{\infty}\mathrm{d}p_0 n''(p_0)\frac{\delta(p_0-p)-\delta(p_0+p)}{2p} =$$

$$= \frac{ie^2}{\pi^2}\epsilon^{ijk}\int_0^{\infty}\mathrm{d}p p n''(p) = -\frac{ie^2}{\pi^2}\epsilon^{ijk}\int_0^{\infty}\mathrm{d}p n'(p) = \frac{ie^2}{2\pi^2}\epsilon^{ijk},$$

$$B = \frac{2ie^2}{16\pi^4}4\pi\int_{-\infty}^{\infty}\mathrm{d}p_0(1-2n(p_0))\int_0^{\infty}\mathrm{d}p \mathrm{tr}\left\{\gamma^5\gamma^i\gamma^0(\not{p}+M)\gamma^j\left(\gamma^k - \frac{2p^k(\not{p}+M)}{(p_0-i0^+)^2-p^2-M^2}\right)\right\}\frac{2M}{[(p_0-i0^+)^2-p^2-M^2]^3} =$$

$$= \frac{ie^2}{\pi^3}\int_{-\infty}^{\infty}\mathrm{d}p_0\int_0^{\infty}\mathrm{d}p \frac{M^2p^2(1-2n(p_0))}{[(p_0-i0^+)^2-p^2-M^2]^3}\mathrm{tr}\left\{\gamma^5\gamma^i\gamma^0\gamma^j\gamma^k\right\} = -\frac{4e^2}{\pi^3}\epsilon^{ijk}\int_{-\infty}^{\infty}\mathrm{d}p_0\int_0^{\infty}\mathrm{d}p\frac{M^2p^2(1-2n(p_0))}{[(p_0-i0^+)^2-p^2-M^2]^3} =$$

$$= -i\epsilon^{ijk}\frac{e^2}{2\pi^2}\int_0^{\infty}\mathrm{d}p\frac{M^2}{(p^2+M^2)^{3/2}} = -i\epsilon^{ijk}\frac{e^2}{2\pi^2} = -A$$

Limiting cases – constant ***B***

$$\frac{\partial \mathfrak{g}^{ij}}{\partial q_{1k}}\epsilon^{ljk}B_l = -\frac{e^2}{\pi^2}\int\limits_{-\infty}^{\infty}\mathrm{d}p_0 \mathrm{sgn}(p_0)(1-2n(p_0))\int\limits_{0}^{\infty}\mathrm{d}p\delta\left(p_0^2-p^2-m^2\right)\int\limits_{-1}^{1}\mathrm{d}x$$

$$\left\{\frac{\partial}{\partial x}\frac{B_{\parallel}^{i}x(p_0q_{20}+q_2px+(x^2+1)p^2)+B_{\perp}^{i}x\left(p_0q_{20}+\left(\frac{1-x^2}{2}+1\right)p^2\right)}{(p_0+q_{20}+i0^+)^2-p^2-q_2^2-2q_2px-m^2}+\right.$$

$$\left.+B_{\perp}^{i}\frac{p^2}{(p_0+q_{20}+i0^+)^2-p^2-q_2^2-2q_2px-m^2}\right\}$$

$$J^i = \int_{q_2} e^{iq_2\cdot x}\widetilde{\mu_5}(q_{20},\mathbf{q}_2)\frac{1}{2}\left(\left.\frac{\partial \mathfrak{g}^{ij}}{\partial q_{1k}}\right|_{q_1=0,m\to 0}-\left.\frac{\partial \mathfrak{g}^{ij}}{\partial q_{1k}}\right|_{q_1=0,m=\infty}\right)\epsilon^{ljk}B_l$$

Stochastic axial charge – constant *B*

Naive model to the axial charge dynamics: diffusion!
All QCD properties put into D and τ

$$\left(\frac{\partial}{\partial t} - D\nabla^2 + \frac{1}{\tau}\right) n_5(t,\mathbf{r}) = g(t,\mathbf{r}),$$

topological fluctuations with zero net charge:

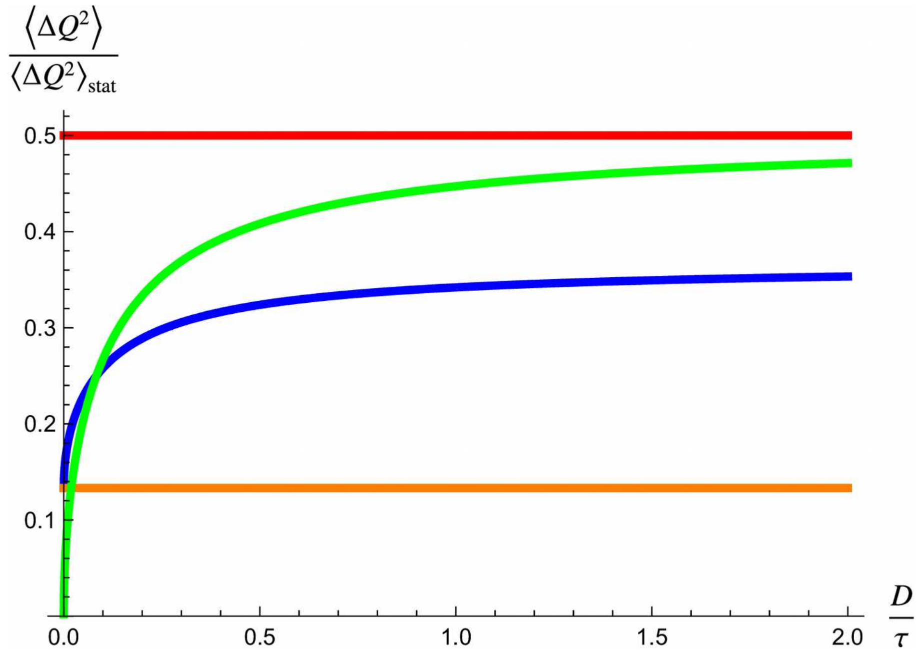
$$\langle\!\langle g(x) \rangle\!\rangle = 0$$

$$\langle\!\langle g(x)g(y) \rangle\!\rangle = \kappa^2 \delta^{(4)}(x-y)$$

Charge transported through a surface perpendicular to the B direction:

$$\Delta Q_\parallel = \int_0^t \mathrm{d}t' \int_S \mathrm{d}^2\mathbf{r}_\perp\, \widehat{\mathbf{B}} \cdot \mathbf{J}(t', \mathbf{r}_\perp),$$

Fluctuation of charge – long time behavior



$$\langle\!\langle (\Delta Q_\parallel)^2 \rangle\!\rangle_0 = \frac{C_A^2 B^2 \gamma A}{4} t \sqrt{\frac{\tau}{D^3}},$$

$$\frac{\langle\!\langle (\Delta Q_\parallel)^2 \rangle\!\rangle}{\langle\!\langle (\Delta Q_\parallel)^2 \rangle\!\rangle_0} = \frac{\sqrt{2}\sqrt{D/\tau}}{\sqrt{2D/\tau - \sqrt{4D/\tau + 1} + 1} + \sqrt{2D/\tau + \sqrt{4D/\tau + 1} + 1}} \longrightarrow \begin{cases} 0, & \frac{D}{\tau} \to 0, \\ \frac{1}{2}, & \frac{D}{\tau} \to \infty \end{cases}$$