"Chirality and Criticality", INT, Seattle, May 11-22, 2020

Chirality

a theoretical overview

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Outline

1. QCD and chirality

2. Chiral Magnetic Effect (CME) and topology of gauge fields

3. CME as a probe of topological fluctuations in QCD

4. CME in heavy ion collisions and the isobar run

5. Broader implications:

    a) Dirac and Weyl materials
    b) quantum computing with CME
    c) chiral anomaly at the EIC

*Disclaimer: **not** a systematic review of ongoing theory developments many of which will be described at this Workshop*

Strong interactions and chirality

Chiral symmetry $SU_R(3)xSU_L(3)$ precedes QCD.

Current algebra (with Schwinger terms – anomalies),

PCAC, σ Model, Goldberger-Treiman relation, Gell Mann-Okubo formula, …

encode the predictions of chiral symmetry for the low-energy collective excitations (pions, …) and their interactions with matter (nucleons).



M. Gell Mann



S. Okubo



M. Goldberger



S. Treiman

QCD and chirality

QCD lagrangian in the chiral limit of massless u,d,s quarks

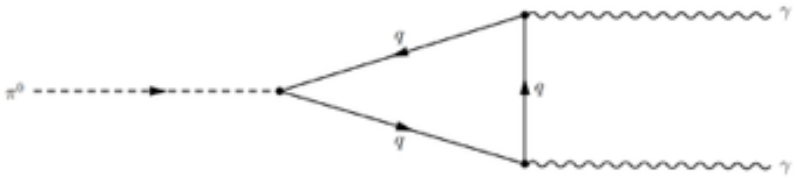
possesses chiral symmetry $U_R(3)xU_L(3) = SU_V(3)x\ SU_A(3)xU_V(1)xU_A(1)$

$SU_V(3)xU_V(1)$ remains unbroken; $SU_A(3)$ is broken spontaneously

(pions, kaons, …) and $U_A(1)$ is broken explicitly by quantum interactions

with gluons, and photons in QCDxQED –

the keyhole for looking into the QCD dynamics!





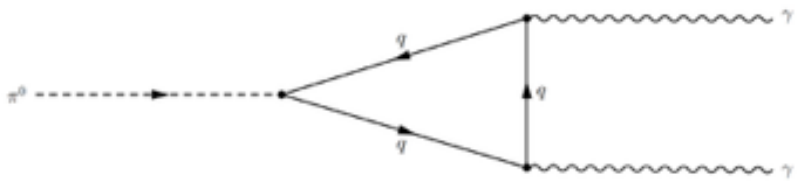
Three paths towards understanding QCD:

1. Spontaneous chiral symmetry breaking (**large distances**):
   chiral perturbation theory, effective lagrangians,
   quark condensate, Goldstone bosons
   experiment: static properties, pion scattering, …

2. Asymptotic freedom (probing **short distances**):
   electromagnetic current commutators, operator product
   expansion, perturbative QCD
   experiment: DIS, hard processes

3. Need a **link between short and large distances**: anomalies!
   dual description in terms of UV and IR degrees of freedom.
   Real-time response of QCD matter to e.m. field
   experiment: coherent e.m. fields and vorticity
   (heavy ions, neutron stars, electron scattering, …)

The chiral anomaly



S. Adler ‘69
J. Bell, R. Jackiw ’ 69

Abelian case (coupling to photons): $\partial_\mu j_5^\mu = \frac{e^2}{16\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$

can be re-written as $\partial_\mu(j_5^\mu + h^\mu) = 0$ $\qquad j_5^\mu = j_R^\mu - j_L^\mu$

with Chern-Simons current:

$$h^\mu = -\frac{e^2}{8\pi^2}\epsilon^{\mu\nu\rho\sigma}A_\nu F_{\rho\sigma}$$

Gauge-dependent –

what is the physical meaning?

$$h^0 = \frac{e^2}{4\pi^2\hbar^2}\boldsymbol{A}\cdot\boldsymbol{B}$$

$$\boldsymbol{h} = \frac{e^2}{4\pi^2\hbar^2}(A^0\boldsymbol{B} - \boldsymbol{A}\times\boldsymbol{E})$$

Chern-Simons current

Consider electromagnetic wave with frequency ω;

the electric field fluctuates: $\mathbf{E}(t,\mathbf{r}) = \Re(e^{-i\omega t}\mathcal{E}(\mathbf{r}))$

in Coulomb gauge $\nabla\mathbf{A} = 0$ away from source: $A^0 = 0$ ("radiation gauge")

the time-averaged Chern-Simons current becomes:

$$\boldsymbol{h} = \frac{e^2}{4\pi^2\hbar^2}(A^0\,\boldsymbol{B} - \boldsymbol{A}\times\boldsymbol{E}) \Rightarrow \langle\boldsymbol{h}\rangle = \frac{e^2}{8\pi^2\hbar^2\omega}\Re(\mathrm{i}\,\boldsymbol{\mathcal{E}}\times\boldsymbol{\mathcal{E}}^*)$$

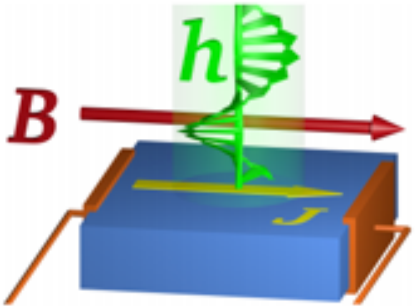
For circularly polarized light moving along z axis: $\boldsymbol{\mathcal{E}} = E_0\,(\hat{\boldsymbol{x}} \pm \mathrm{i}\,\hat{\boldsymbol{y}})$

$$\langle h^z\rangle = \pm\,\frac{e^2}{4\pi^2\hbar}\,\frac{E_0^2}{\hbar\omega}$$

photon helicity

number of photons

Chiral anomaly – transfer of chirality from light to fermions

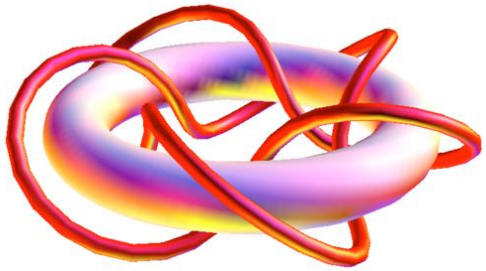


S.Kaushik, DK, E.Philip, PRB 99(2019)075150

Chern-Simons number

Consider now the CS density:

$$h^0 = \frac{e^2}{4\pi^2\hbar^2} \boldsymbol{A}\cdot\boldsymbol{B}$$



the integral of this quantity is known as magnetic helicity: $K = \int \boldsymbol{A}\cdot\boldsymbol{B}\,\mathrm{d}^3x$

[Abelian part of CS 3-form]

What is the physical meaning? $\boldsymbol{B}\cdot\hat{n}|_S = 0$

again, let us use the Coulomb gauge: $\boldsymbol{A}(\boldsymbol{x}) = -\frac{1}{4\pi}\int \frac{\boldsymbol{r}}{r^3}\times\boldsymbol{B}(\boldsymbol{y})\,\mathrm{d}^3y$

magnetic helicity then takes the form: $K = -\frac{1}{4\pi}\iint \boldsymbol{B}(\boldsymbol{x})\cdot\frac{\boldsymbol{r}}{r^3}\times\boldsymbol{B}(\boldsymbol{y})\,\mathrm{d}^3x\,\mathrm{d}^3y$

that can be considered as a sum over the Gauss linking numbers of magnetic flux:

$$K = \sum_{i=1}^{N}\sum_{j=1}^{N} L_{ij}\Phi_i\Phi_j \qquad N\to\infty,\quad \Phi_i\to 0$$

$$L_{12} = -\frac{1}{4\pi}\oint_1\oint_2 \frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}\sigma}\cdot\frac{\boldsymbol{r}}{r^3}\times\frac{\mathrm{d}\boldsymbol{y}}{\mathrm{d}\tau}\,\mathrm{d}\tau\,\mathrm{d}\sigma$$

Moffatt 1969,
Arnold, Khesin 1998
Berger 1999

Chern-Simons number: magnetic helicity

Anomaly implies non-conservation of CS number

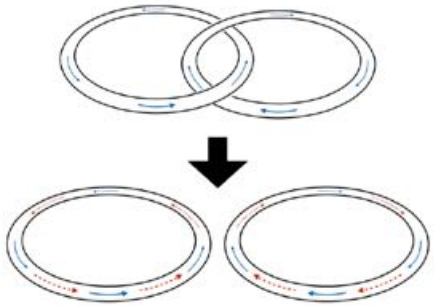
$$K = \int \boldsymbol{A} \cdot \boldsymbol{B}\, \mathrm{d}^3 x$$

in Coulomb gauge, $\nabla \cdot \boldsymbol{A}_P = 0$ $\qquad$ $\boldsymbol{A}_P \cdot \hat{n}|_S = 0$

$$\frac{\mathrm{d}K}{\mathrm{d}t} = -2 \int \boldsymbol{E} \cdot \boldsymbol{B}\, \mathrm{d}^3 x + 2 \oint_S \boldsymbol{A}_P \times \boldsymbol{E} \cdot \hat{n}\, \mathrm{d}^2 x$$

flux of circularly polarized photons through the surface

Reconnection of magnetic flux (change of magnetic helicity) induces an electric field – can there be an electric current?



Chern-Simons number: magnetic helicity

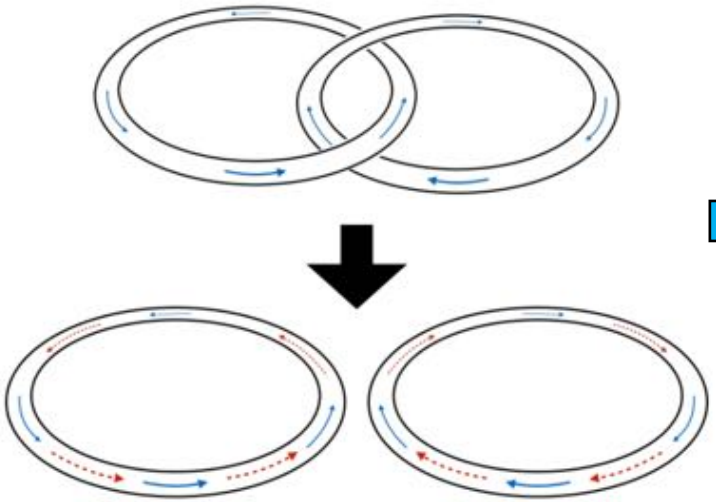
Magnetic helicity: $\mathcal{H}(\mathcal{K}) = \sum_i \mathcal{S}_i \varphi_i^2 + 2 \sum_{i,j} \mathcal{L}_{ij} \varphi_i \varphi_j$

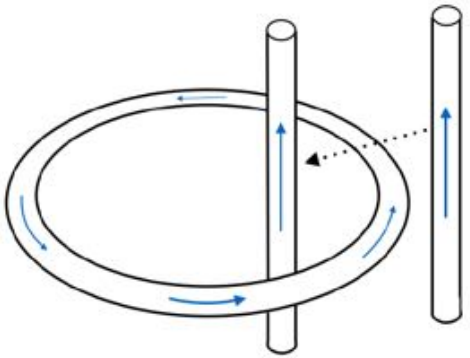
Non-Abelian CS:
Jones polynomials, …
Witten ‘89



self-linking Gauss linking

Change of magnetic helicity is due to ”magnetic reconnections”:





$$\frac{d}{dt}\Phi = -\oint_{C_1} \boldsymbol{E} \cdot d\boldsymbol{x}$$

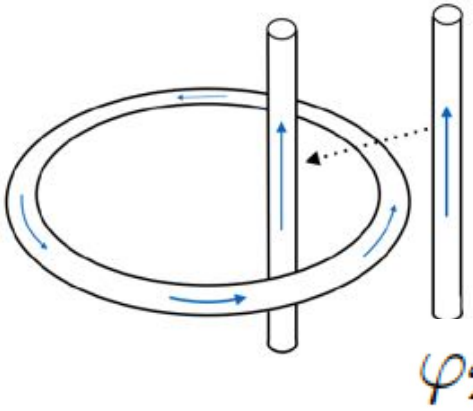
Y.Hirono, DK, Y.Yin
PRL117(2016)172301

Magnetic helicity and CME

Magnetic helicity: $$\mathcal{H}(\mathcal{K}) = \sum_i \mathcal{S}_i \varphi_i^2 + 2 \sum_{i,j} \mathcal{L}_{ij} \varphi_i \varphi_j$$

self-linking Gauss linking

Change of magnetic flux through a closed loop:



$$\frac{d}{dt}\Phi = -\oint_{C_1} \boldsymbol{E} \cdot d\boldsymbol{x}$$

Y.Hirono, DK, Y.Yin
PRL117(2016)172301

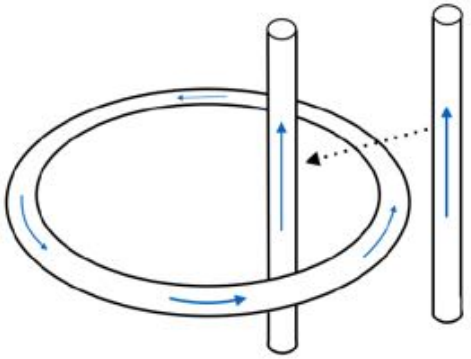
$$\Delta\Phi = \varphi_2 = -\oint_{C_1} \left[\int_0^{\Delta t} \boldsymbol{E}(t) dt \right] \cdot d\boldsymbol{x}$$

“large gauge transformation”

Gauge dependence of CS number enables its change through magnetic reconnections, and thus the transfer of chirality to fermions which is the chiral anomaly! (QCD: reconnection=instanton)

Magnetic helicity and CME

Y.Hirono, DK, Y.Yin
PRL117(2016)172301



$$\Delta\Phi = \varphi_2 = -\oint_{C_1}\left[\int_0^{\Delta t}\boldsymbol{E}(t)dt\right]\cdot d\boldsymbol{x}$$

$$\Delta\boldsymbol{p}_F = \pm\int_0^{\Delta t} e\boldsymbol{E}(t)dt$$

If chiral fermions are present,
the induced electric field will change the
fermi-momentum differently for R and chiralities:

$$\oint \Delta\boldsymbol{p}_F(s)\cdot d\boldsymbol{x} \equiv \int \Delta\boldsymbol{p}_F(s)\cdot\frac{d\boldsymbol{x}}{ds}ds = \pm e\oint_{C_1}\left[\int_0^{\Delta t}\boldsymbol{E}(t)dt\right]\cdot d\boldsymbol{x} = \mp e\varphi_2$$

Density of states of R antiparticles:

$$\Delta\bar{N}_R = \frac{-\oint_{C_1}\Delta\boldsymbol{p}_F\cdot d\boldsymbol{x}}{2\pi}\times\frac{e\varphi_1}{2\pi} = \frac{e^2\varphi_1\varphi_2}{4\pi^2}$$

and L particles:

$$\Delta N_L = \frac{e^2\varphi_1\varphi_2}{4\pi^2}$$

CME from the change of topology

Y.Hirono, DK, Y.Yin
PRL117(2016)172301

In (1+1) dimensions, chirality = direction of motion, so
R and L fermions move in opposite directions, and carry currents:

$$\oint_{C_1} \Delta \boldsymbol{J}_R \cdot d\boldsymbol{x} = (-e) \times \Delta \bar{N}_R = -\frac{e^3 \varphi_1 \varphi_2}{4\pi^2}$$

antiparticle; moves to the right (+ direction)

$$\oint_{C_1} \Delta \boldsymbol{J}_L \cdot d\boldsymbol{x} = (-) \times e \times \Delta N_L = -\frac{e^3 \varphi_1 \varphi_2}{4\pi^2}$$

moves to the left (+ direction); particle

$$\oint_{C_1} \Delta \boldsymbol{J} \cdot d\boldsymbol{x} = \oint_{C_1} \Delta \left[\boldsymbol{J}_R + \boldsymbol{J}_L\right] \cdot d\boldsymbol{x} = -\frac{e^3 \varphi_1 \varphi_2}{2\pi^2}$$

CME from the change of topology

Y.Hirono, DK, Y.Yin
PRL117(2016)172301

General result for an arbitrary change of magnetic flux topology (= CS 3-form):

$$\sum_i \oint_{C_i} \Delta \boldsymbol{J} \cdot d\boldsymbol{x} = -\frac{e^3}{2\pi^2} \Delta \mathcal{H}$$

if we include the electric charge e in the definition of magnetic flux, the pre-factor is the chiral anomaly coefficient that enters the CME current

K.Fukushima, DK, H.Warringa '08

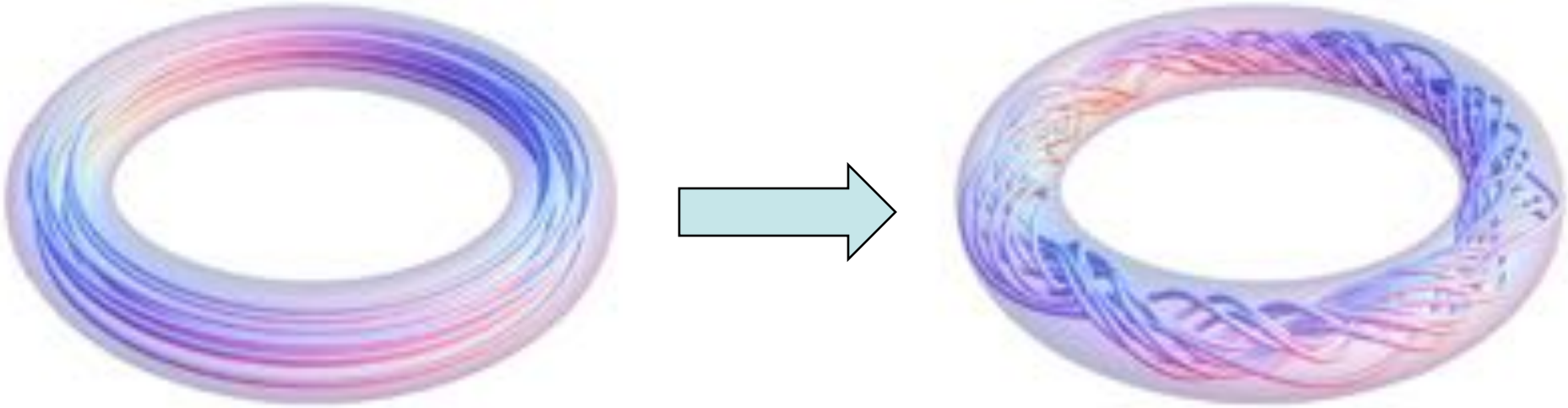
$$\mathcal{H}(\mathcal{K}) = \sum_i \mathcal{S}_i \varphi_i^2 + 2 \sum_{i,j} \mathcal{L}_{ij} \varphi_i \varphi_j$$

1. The current would not appear without a change in topology (absence of gauge invariance w.r.t. large gauge transformation).

2. Its magnitude is completely fixed by the change in topological invariant.

3. CME would be absent for fixed μ_5 ,such as in the early work by A.Vilenkin '80

Chirality transfer from fermions to gauge fields



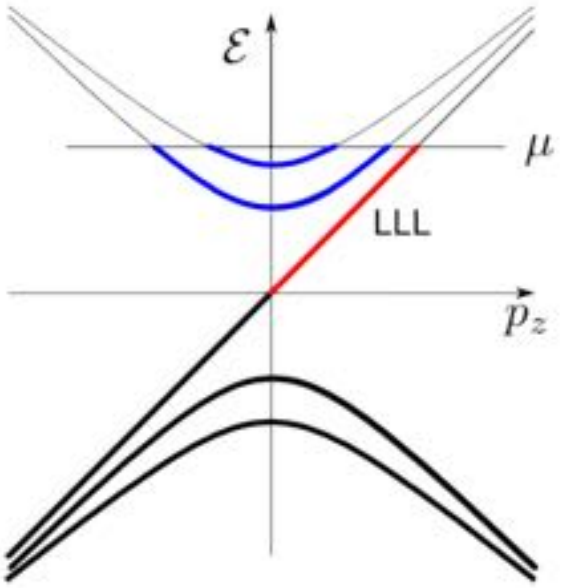
$$\nabla \times \boldsymbol{B} = \boldsymbol{j}$$

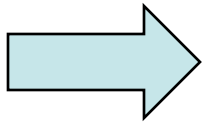
$$\boldsymbol{j}_{\mathrm{CME}} = C_{\mathrm{A}}\ \mu_A\ \boldsymbol{B} = \sigma_A \boldsymbol{B}$$

$$\nabla \times \boldsymbol{B} = \sigma_A\ \boldsymbol{B}$$

solutions:
Chandrasekhar-Kendall states

Chirality transfer from fermions to magnetic helicity







$$h_m \equiv \int d^3x \; \boldsymbol{A} \cdot \boldsymbol{B}$$

$$h_0 \equiv h_m + h_F = \text{const}$$

$$\partial_\mu j^\mu_A = C_\mathrm{A} \boldsymbol{E} \cdot \boldsymbol{B}$$

$$\int d^3x \; \boldsymbol{E} \cdot \boldsymbol{B} = -\frac{1}{2} \frac{\partial h_m}{\partial t}$$

Chandrasekhar-Kendall states

$$h_m \equiv \int d^3x \; \vec{A} \cdot \vec{B}. \qquad h_m(\mathcal{K}) = \sum_{i=1}^{N} \phi_i^2 \; \mathcal{S}_i + 2 \sum_{i,j} \phi_i \phi_j \; \mathcal{L}_{ij}$$

CK states are the solutions of: $\nabla \times \boldsymbol{B} = \sigma_A \; \boldsymbol{B}$

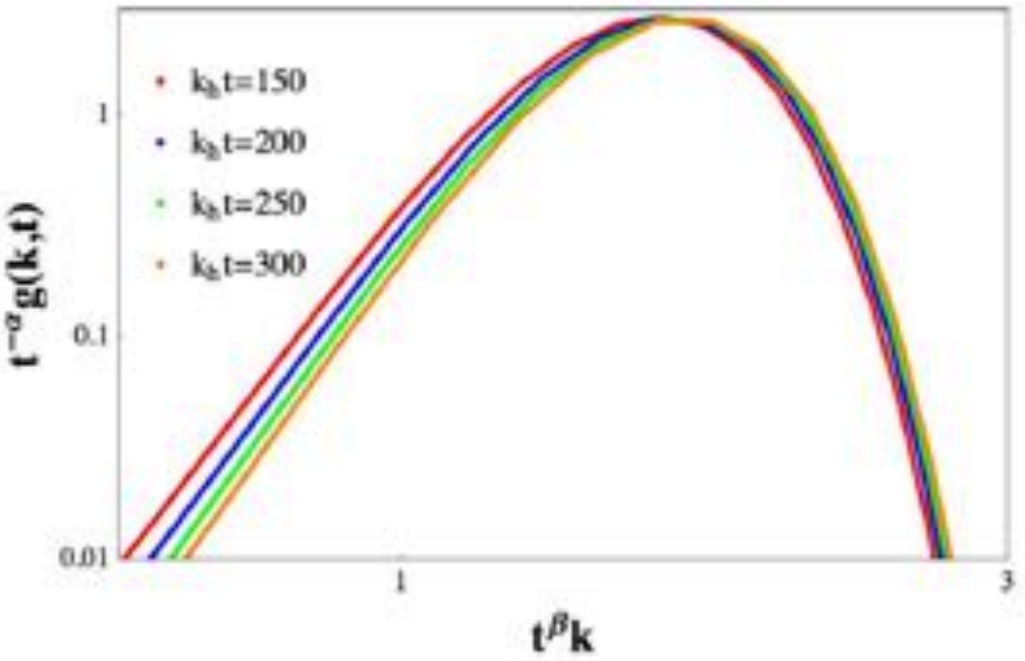
$$\nabla \times \boldsymbol{W}_{lm}^{\pm}(\boldsymbol{x}; k) = \pm k \boldsymbol{W}_{lm}^{\pm}(\boldsymbol{x}; k) \,, \qquad \nabla \cdot \boldsymbol{W}_{lm}^{\pm}(\boldsymbol{x}; k) = 0 \,,$$

$$\boldsymbol{B}(\boldsymbol{x}, t) = \sum_{l,m} \int_0^{\infty} \frac{dk}{\pi} k^2 \left[\alpha_{lm}^{+}(k, t) \boldsymbol{W}_{lm}^{+}(\boldsymbol{x}; k) + \alpha_{lm}^{-}(k, t) \boldsymbol{W}_{lm}^{-}(\boldsymbol{x}; k) \right]$$

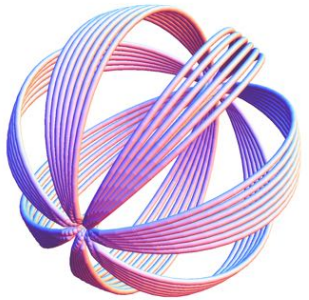
$$h_m(t) = \int_0^{\infty} \frac{dk}{\pi} \; k g(k, t) \,, \qquad g(k, t) \equiv g_{+}(k, t) - g_{-}(k, t)$$

$$g_{\pm}(k, t) \equiv \sum_{l,m} |\alpha_{lm}^{\pm}(k, t)|^2$$

Self-similar inverse cascade of magnetic helicity driven by CME



helical magnetogenesis in the Universe?



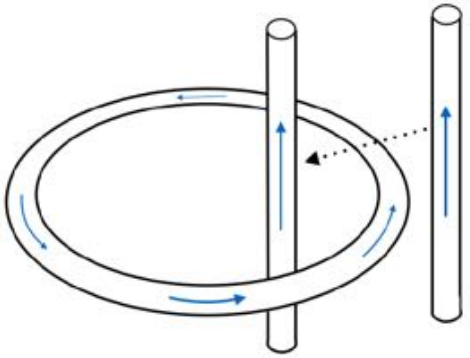
$$g(k,t) \sim t^{\alpha} \tilde{g}(t^{\beta} k) \qquad \alpha = 1\,, \qquad \beta = 1/2$$

Y. Hirono, DK, Y.Yin, PRD'15

N. Yamamoto, PRD'16

The link between "helical magnetogenesis" and baryogenesis in Early Universe:
DK, E.Shuryak, I.Zahed, arXiv:1906.0480

CME as a probe of topological fluctuations in QCD

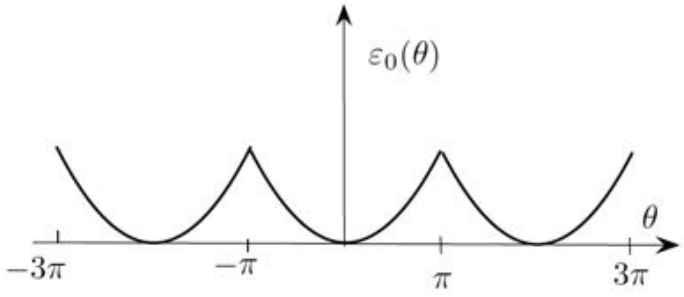


External flux = electric field = “θ – angle”

examples:

(1+1) QED (Schwinger model)

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi - m\bar{\psi}\psi - \bar{\psi}\gamma^{\mu}\psi A_{\mu} - \frac{1}{4e^2}F_{\mu\nu}^2 - \frac{\theta}{4\pi}\epsilon_{\mu\nu}F^{\mu\nu}$$



confinement, chiral symmetry breaking, chiral anomaly

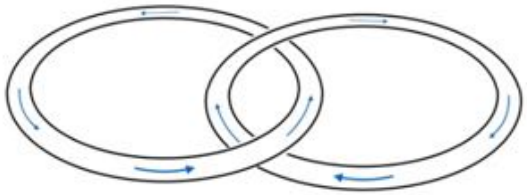
$$\partial^{\mu} j_{\mu}^{5} = \frac{1}{\sqrt{\pi}}\partial^2\phi = \frac{e}{2\pi}\epsilon_{\mu\nu}F^{\mu\nu}$$

= Schwinger terms in the current algebra:

$$[j_0(x_1), j_1(x_1')] = -\frac{i}{\pi}\partial_1\delta(x_1 - x_1')$$

[Kac-Moody U(1) algebra]

CME as a probe of topological fluctuations in QCD



External flux = electric field = “θ – angle”

examples:

toroidal compactification of string theory on a two-torus

$$S = \int d^2x \frac{1}{4\pi g^2}[(\partial_\mu \phi_1)^2 + (\partial_\mu \phi_2)^2] + i\frac{B}{4\pi}\int d^2x \epsilon_{IJ}\epsilon_{\mu\nu}\partial_\mu \phi_I \partial_\nu \phi_J$$

θ-term

Cardy, Rabinovici ‘82
Shapere, Wilczek ’89

4D extension: condensation of dyons

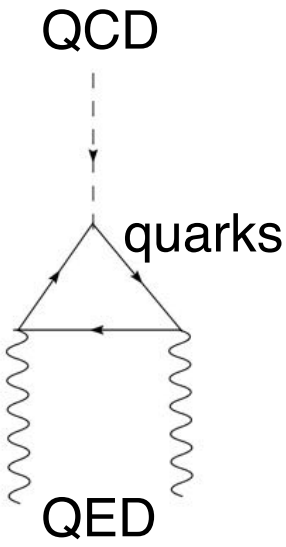
active ongoing work in QCD!

CME as a probe of topological fluctuations in QCD

$$\mathcal{L}_{\rm MCS} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - A_\mu J^\mu - \frac{c}{4}\,\theta \tilde{F^{\mu\nu}}F_{\mu\nu}$$

$$\theta \tilde{F^{\mu\nu}}F_{\mu\nu} = \theta\partial_\mu J^\mu_{CS} = \partial_\mu\left[\theta J^\mu_{CS}\right] - \partial_\mu\theta J^\mu_{CS}$$

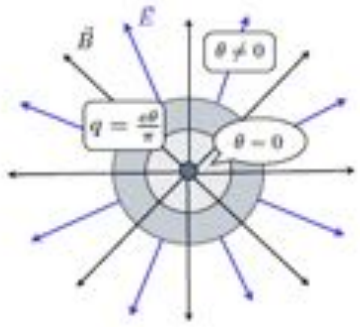
$$\mathcal{L}_{\rm MCS} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - A_\mu J^\mu + \frac{c}{4}\,P_\mu J^\mu_{CS} \qquad P_\mu = \partial_\mu\theta = (M, \vec{P})$$



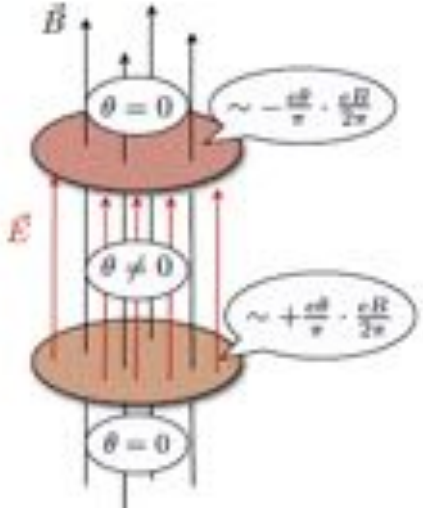
DK, Ann. Phys.'10

$$\vec{\nabla}\times\vec{B} - \frac{\partial\vec{E}}{\partial t} = \vec{J} + c\left(M\vec{B} - \vec{P}\times\vec{E}\right)$$
$$\vec{\nabla}\cdot\vec{E} = \rho + c\vec{P}\cdot\vec{B},$$
$$\vec{\nabla}\times\vec{E} + \frac{\partial\vec{B}}{\partial t} = 0,$$
$$\vec{\nabla}\cdot\vec{B} = 0,$$

Similar to "axion electrodynamics", but without axion kinetic terms F. Wilczek, '87



Witten effect



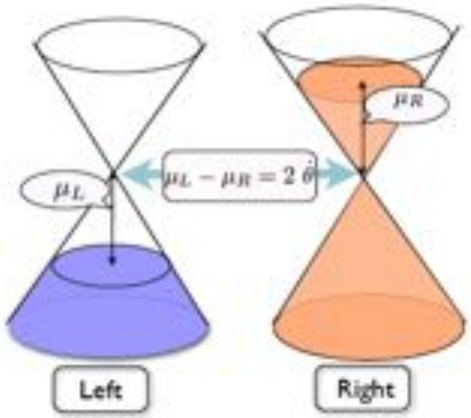
fermion number violation on domain walls ➪ current!

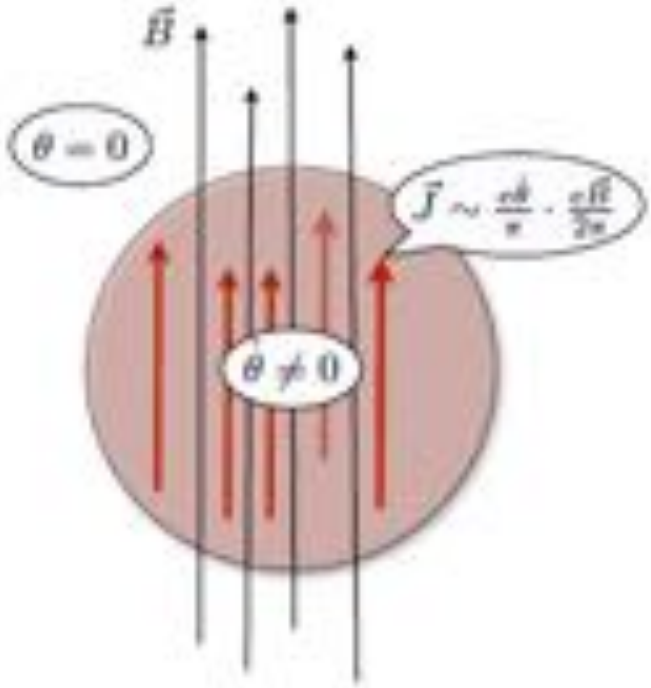
CME as a probe of topological fluctuations in QCD

DK, Ann. Phys.'10

$$\vec{\nabla}\times\vec{B}-\frac{\partial\vec{E}}{\partial t}=\vec{J}+c\left(M\vec{B}-\vec{P}\times\vec{E}\right)$$
$$\vec{\nabla}\cdot\vec{E}=\rho+c\vec{P}\cdot\vec{B},$$
$$\vec{\nabla}\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=0,$$
$$\vec{\nabla}\cdot\vec{B}=0,$$

$$P_\mu=\partial_\mu\theta=(M,\vec{P})$$





$$2\,\dot{\theta}=\mu_L-\mu_R$$

Time-dependent θ angle



chiral chemical potential

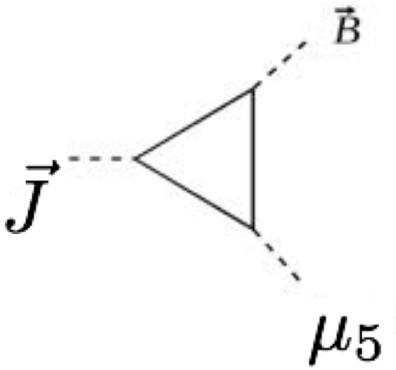
Chiral Magnetic Effect

DK'04; DK, L.McLerran, H.Warringa '07
K.Fukushima, DK, H.Warringa,
"Chiral magnetic effect" PRD'08;
Review and list of refs: DK, arXiv:1312.3348

Chiral chemical potential is formally equivalent to a background chiral gauge field: $\mu_5 = A_5^0$

In this background, and in the presence of B, vector e.m. current is generated:

$$\partial_\mu J^\mu = \frac{e^2}{16\pi^2}\left(F_L^{\mu\nu}\tilde{F}_{L,\mu\nu} - F_R^{\mu\nu}\tilde{F}_{R,\mu\nu}\right)$$



Compute the current through $J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$

Absent in Maxwell theory!

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

Coefficient is fixed by the chiral anomaly, no corrections

Chirally imbalanced system is a non-equilibrium, steady state

Real-time dynamics of CME

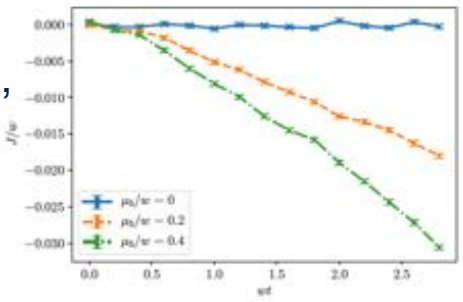
Study of real-time CME dynamics in (1+1) QED using a digital quantum computer – IBM-Q

DK, Y. Kikuchi, arXiv:2001.00698

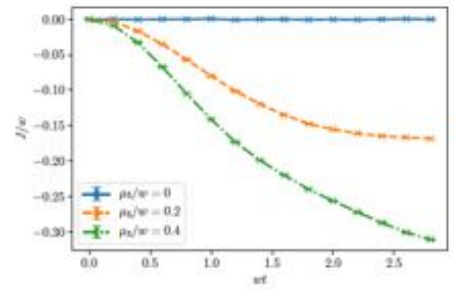
$$S = \int \mathrm{d}^2x \left[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{g\theta}{4\pi} \epsilon^{\mu\nu} F_{\mu\nu} + \bar{\psi}(\mathrm{i}\gamma^\mu D_\mu - m)\psi \right]$$

Jordan-Wigner transformation – spin chain

CME current, μ_5 quench:

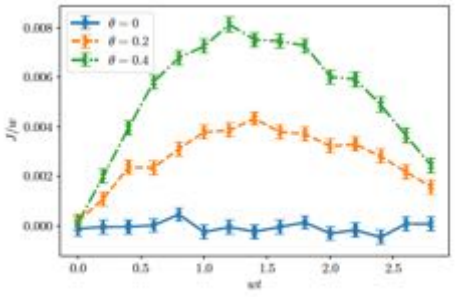


(a) $M/w = 0.1$

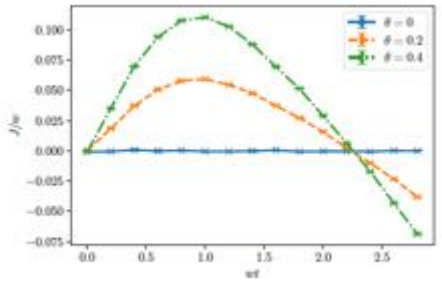


(b) $M/w = 0.5$

CME current, θ quench:



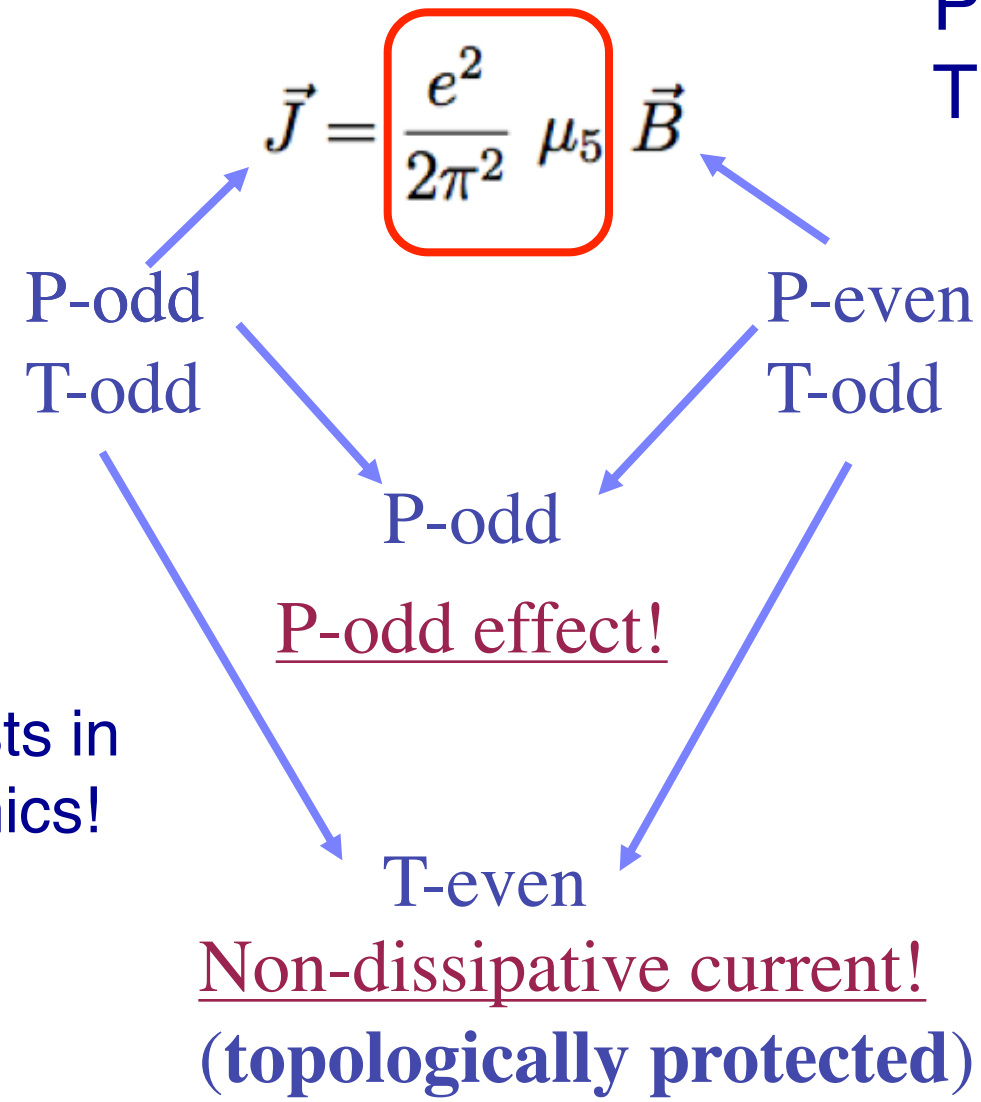
(a) $M/w = 0.1$



(b) $M/w = 0.5$

Chiral magnetic conductivity: discrete symmetries

P – parity
T – time reversal



Effect persists in hydrodynamics!

cf Ohmic conductivity:

$$\vec{J} = \sigma \vec{E}$$

T-odd, dissipative

Systematics of anomalous conductivities

	Magnetic field	Vorticity
Vector current	$\frac{\mu_A}{2\pi^2}$	$\frac{\mu\mu_A}{2\pi^2}$
Axial current	$\frac{\mu}{2\pi^2}$	$\frac{\mu^2+\mu_A^2}{4\pi^2}+\frac{T^2}{12}$

The CME in relativistic hydrodynamics: The Chiral Magnetic Wave

DK, H.-U. Yee, arXiv:1012.6026 [hep-th]; PRD

$$\vec{j}_V = \frac{N_c\, e}{2\pi^2}\mu_A \vec{B}; \quad \vec{j}_A = \frac{N_c\, e}{2\pi^2}\mu_V \vec{B},$$

CME Chiral separation

$$\begin{pmatrix} \vec{j}_V \\ \vec{j}_A \end{pmatrix} = \frac{N_c\, e\vec{B}}{2\pi^2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \mu_V \\ \mu_A \end{pmatrix}$$



Propagating chiral wave: (if chiral symmetry is restored)

$$\left(\partial_0 \mp \frac{N_c e B \alpha}{2\pi^2}\partial_1 - D_L\partial_1^2\right) j^0_{L,R} = 0$$

Gapless collective mode is the carrier of CME current in MHD:

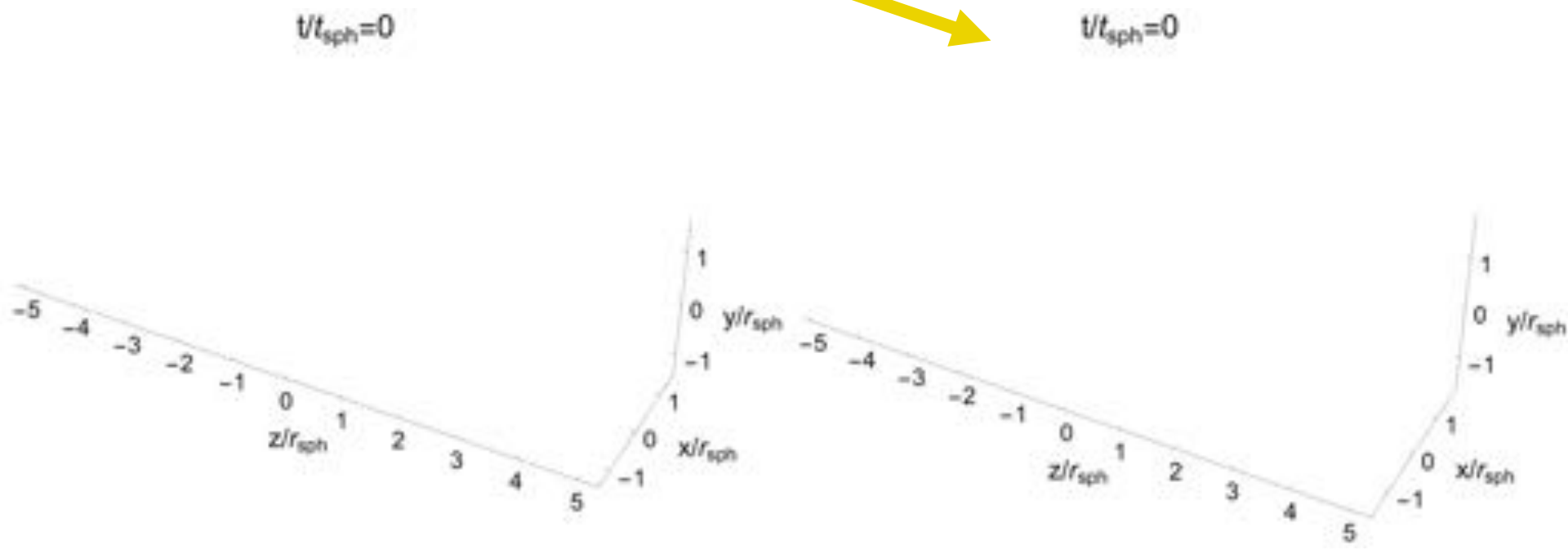
$$\omega = \mp v_\chi k - iD_L k^2 + \cdots$$

M. Mace, N. Mueller, S. Schlichting, S. Sharma, arxiv:1704.05887; PRD'17

Chiral Magnetic Wave in real time!

Anomalous transport in real time

j_a^0:axial charge $\rightarrow$ j_v^0:vector charge

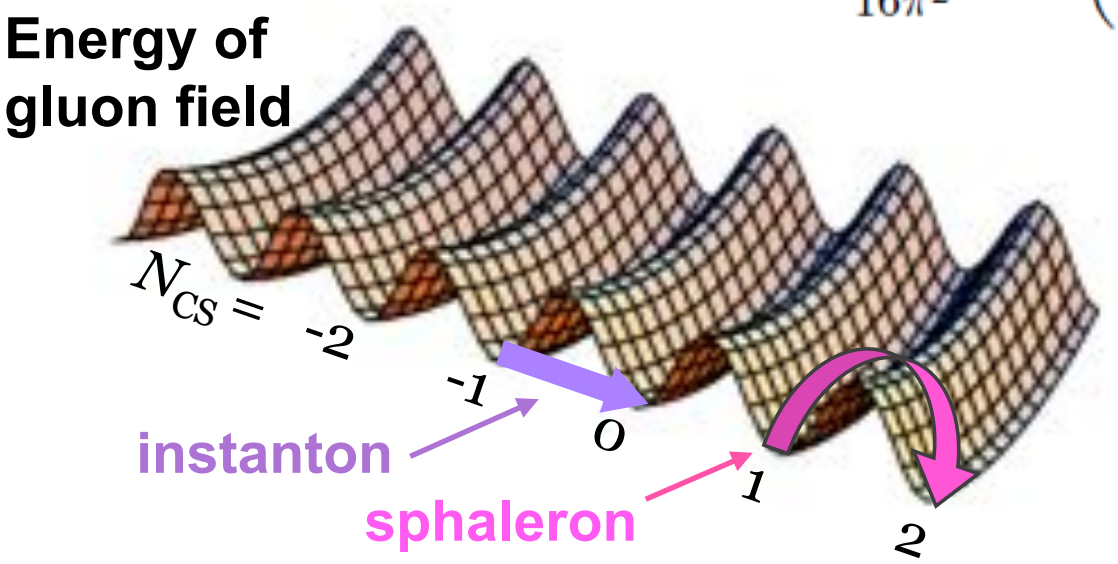


Static U(1) magnetic field in z-dir

Chirality in QCD vacuum

The instanton solutions in Minkowski space-time describe the tunneling events between the topological sectors of the vacuum marked by different integer values of $N_{CS} \equiv \int d^3x K_o$

$$K_\mu = \frac{1}{16\pi^2}\epsilon_{\mu\alpha\beta\gamma}\left(A^a_\alpha \partial_\beta A^a_\gamma + \frac{1}{3} f^{abc} A^a_\alpha A^b_\beta A^c_\gamma\right)$$

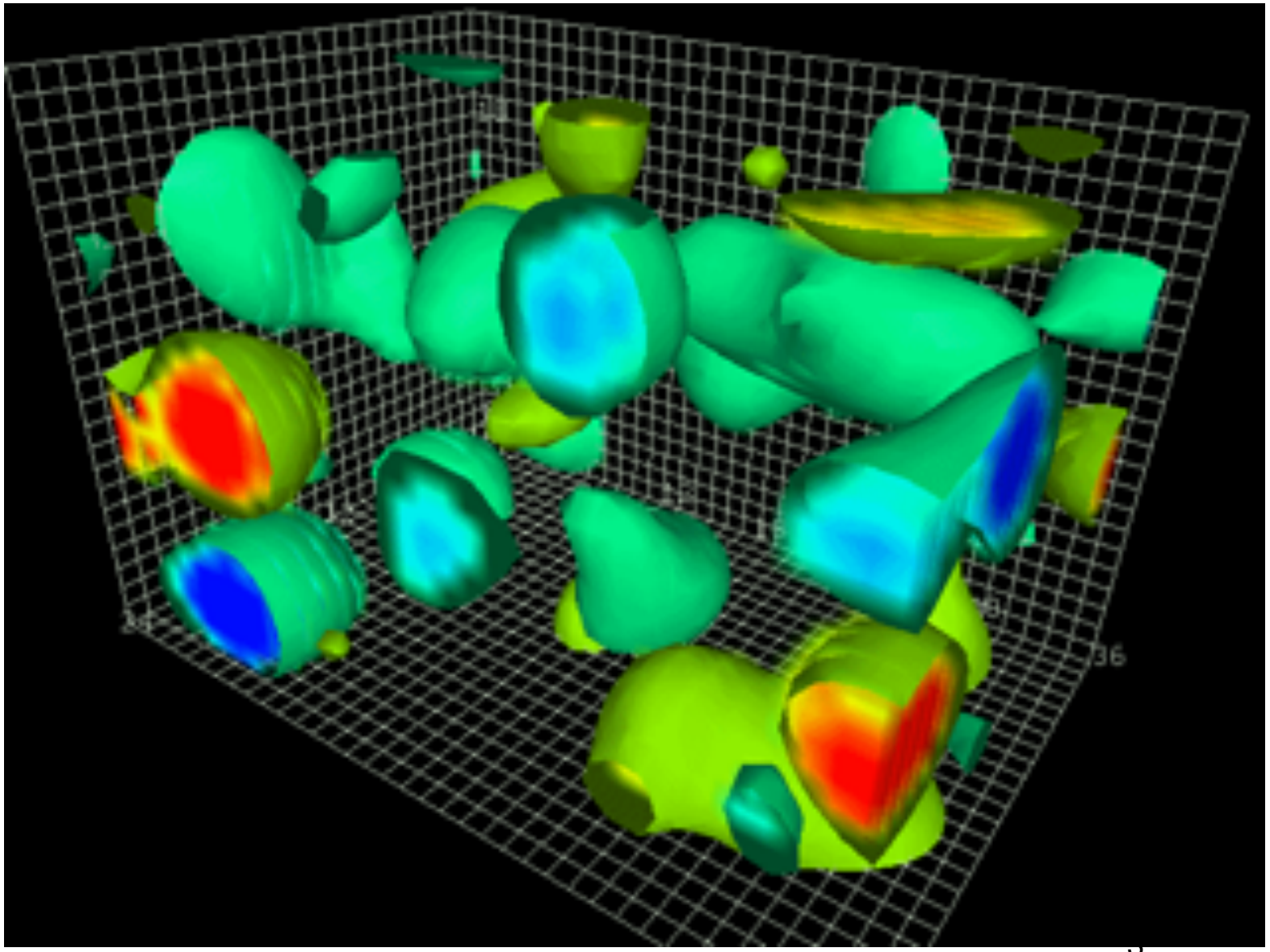




Is it possible to directly observe these chirality-changing transitions in experiment?

Topological number fluctuations in QCD vacuum (3+1)d

("cooled" configurations)



Can one detect QCD topological transitions in heavy ion collisions?



Relativistic Heavy Ion Collider (RHIC) at BNL



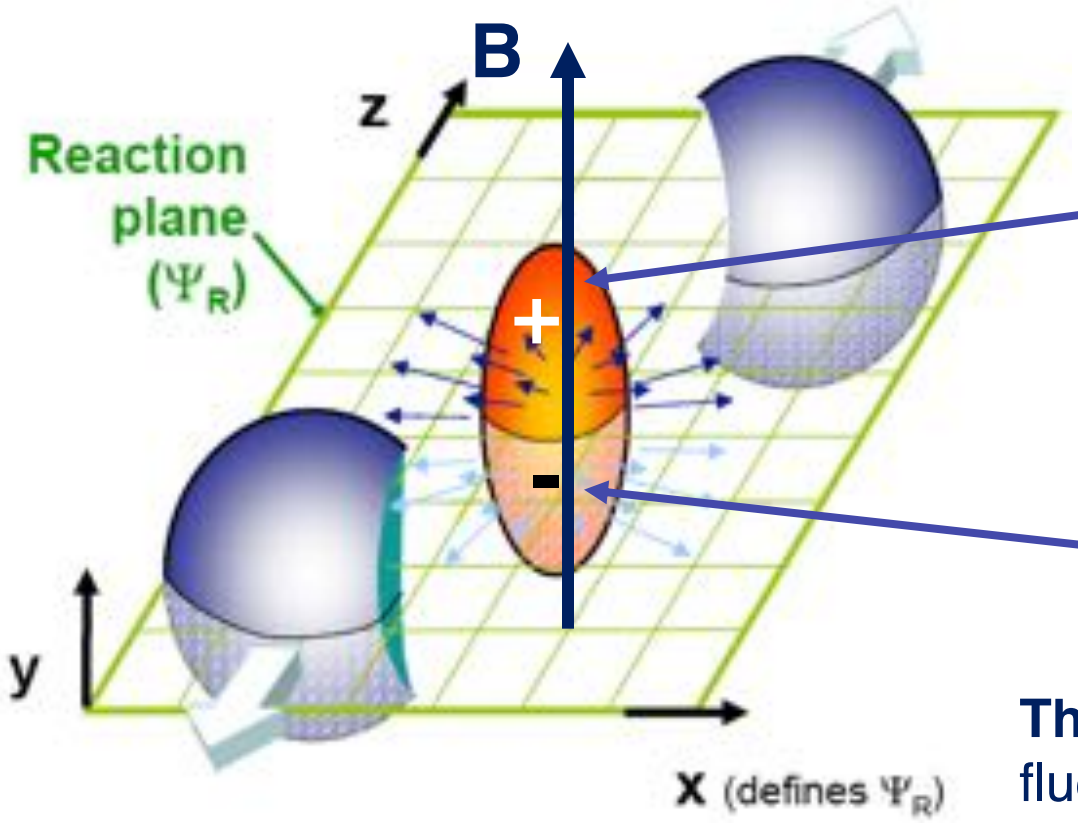
The STAR Collaboration at RHIC



Charged hadron tracks in a Au-Au collision at RHIC

CME as a probe of topological transitions and chiral symmetry restoration in QCD plasma

Electric dipole moment due to chiral imbalance



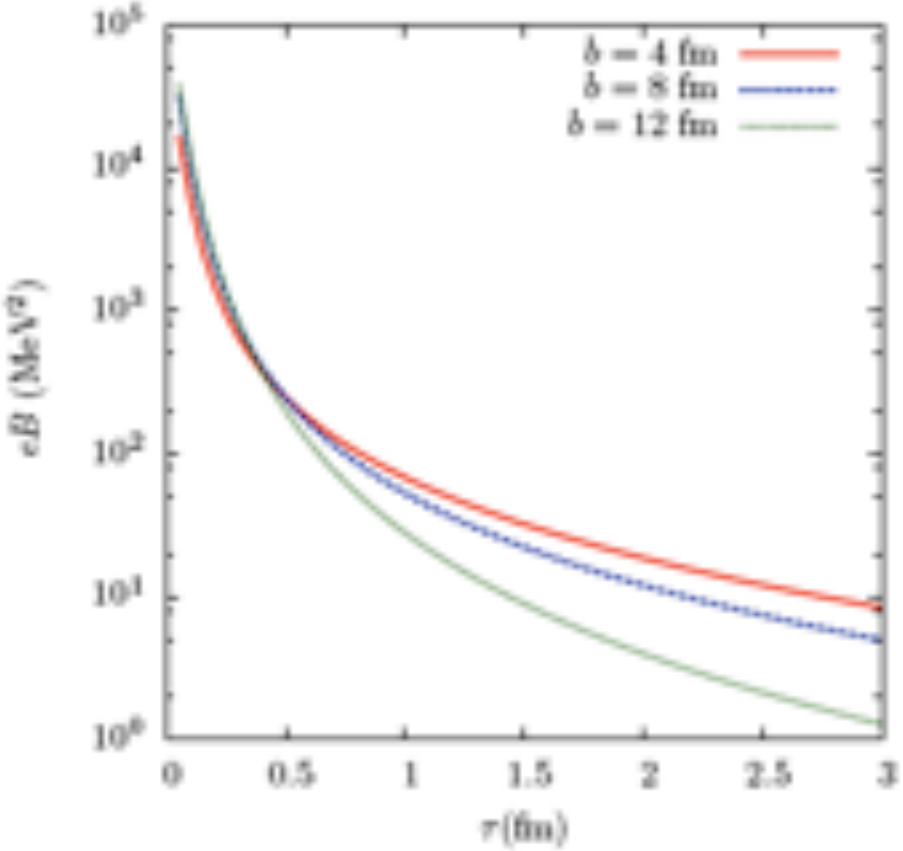
excess of positive charge

excess of negative charge

The problem:
fluctuating sign, reflecting topological fluctuations in QCD - backgrounds!

DK, hep-ph/0406125; Phys.Lett.B633(2006)260

Heavy ion collisions as a source of the strongest magnetic fields available in the Laboratory



DK, McLerran, Warringa,
Nucl Phys A803(2008)227

Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).

Physics Letters B 633 (2006) 260–264

Parity violation in hot QCD: Why it can happen, and how to look for it

Dmitri Kharzeev

Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

Received 23 December 2004; received in revised form 27 October 2005; accepted 23 November 2005

hep-ph/0406125

PHYSICAL REVIEW C **70**, 057901 (2004)

Parity violation in hot QCD: How to detect it

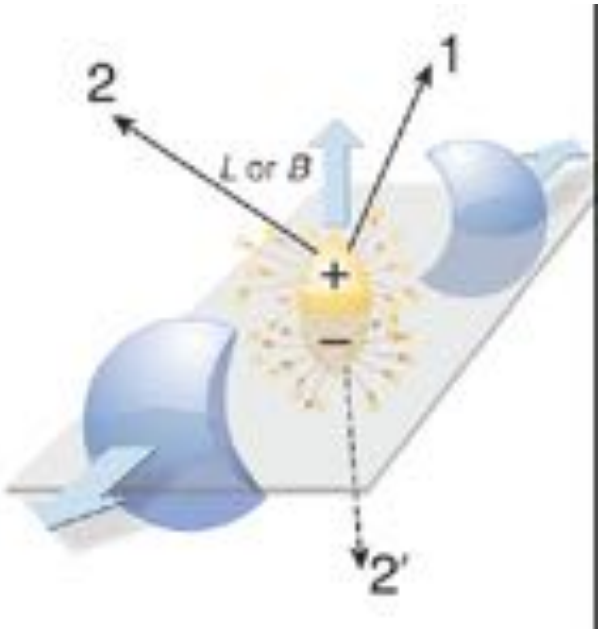
Sergei A. Voloshin
Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201, USA
(Received 5 August 2004; published 11 November 2004)

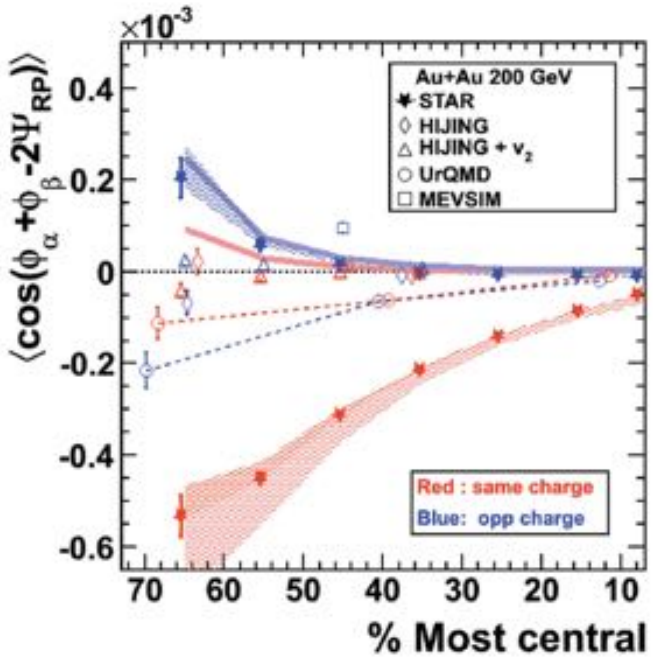
In a recent paper (hep-ph/0406125) Kharzeev argues for the possibility of *P*- and/or *CP*-violation effects in heavy-ion collisions, the effects that can manifest themselves via asymmetry in π^* production with respect to the direction of the system angular momentum. Here we present an experimental observable that can be used to detect and measure the effects.

PRL 103, 251601 (2009) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)





$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP}) \rangle = \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle$$

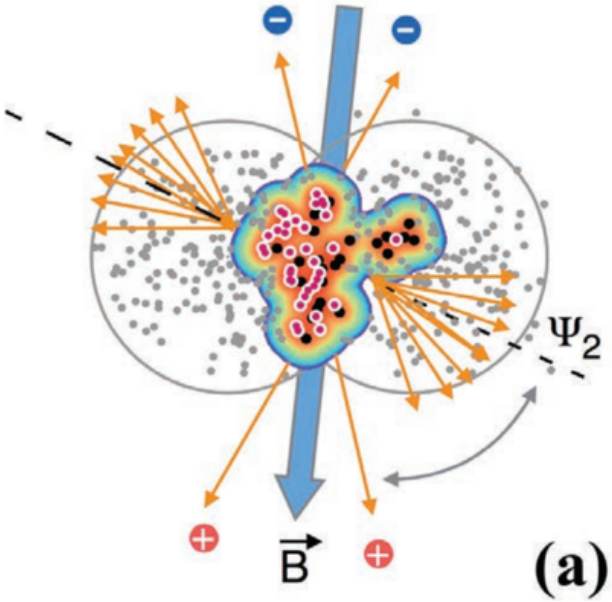
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\rm IN}] - [\langle a_\alpha a_\beta \rangle + B_{\rm OUT}] \approx -\langle a_\alpha a_\beta \rangle + [B_{\rm IN} - B_{\rm OUT}],$$

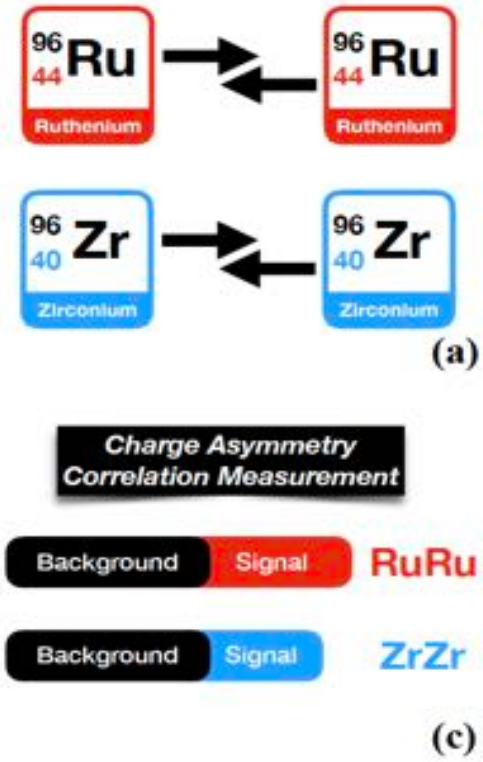
NB: P-even quantity (strength of P-odd fluctuations) – subject to large background contributions

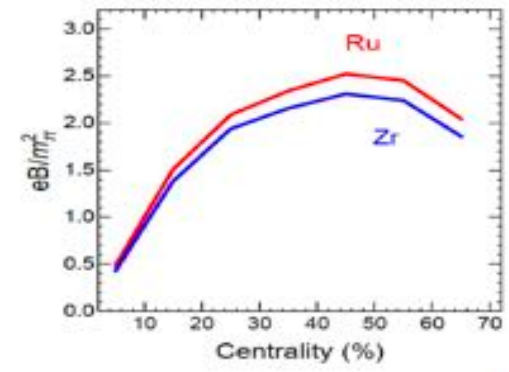
Separating the signal from background is the main subject of the ongoing work –
Talks at this Workshop: S. Voloshin, A. Tang, R. Lacey, G. Ma, S. Shi

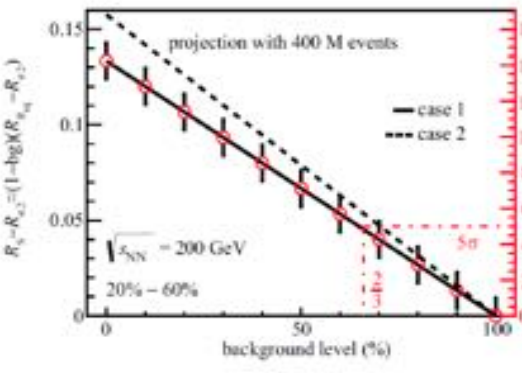
Review of CME with heavy ions: DK, J. Liao, S. Voloshin, G. Wang, Rep. Prog. Phys.'16

Major new development: the isobar run ('19), results expected soon









STAR Collaboration

Quantitative description of CME in heavy ion collisions: ongoing effort

BEST COLLABORATION plays a major role

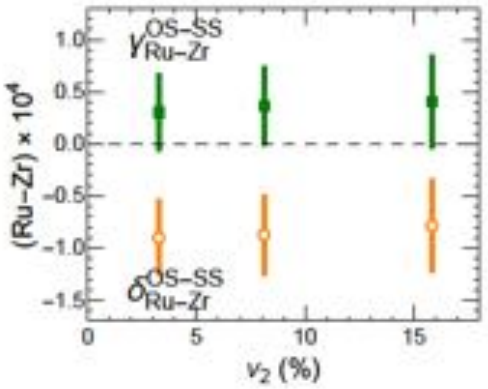


FIG. 5. (color online) Predictions from EBE-AVFD simulations for observables γ^{OS-SS}_{Ru-Zr} and δ^{OS-SS}_{Ru-Zr} as a function of bin-wise elliptic flow v_2 from event-shape analysis with three identical bins for RuRu and ZrZr systems. The simulation results are obtained with $n_s/s = 20\%$.

Signatures of Chiral Magnetic Effect in the Collisions of Isobars

Shuzhe Shi,[2] Hui Zhang,[3,1] Defu Hou,[1,*] and Jinfeng Liao[4,†]

arxiv:1910.1401

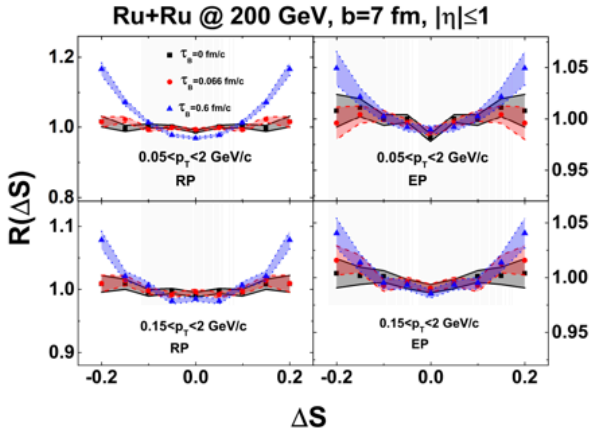


FIG. 6: (Color online) ΔS dependence of the $R(\Delta S)$ correlator of mid-pseudorapidity ($|\eta| \leq 1$) light quarks in Ru+Ru collisions at $\sqrt{s_{NN}} = 200$ GeV and impact parameter b=7 fm for different lifetimes of the magnetic field, transverse momentum ranges, and reaction planes. Widths of colored bands correspond to the statistical errors due to the finite number of events used in the study.

N. Magdy, S. Shi, J. Liao, N. Ajitanand, and R. A. Lacey (2017), 1710.01717.

Two main uncertainties in quantitative modeling of CME:

1. Initial conditions for the chiral charge asymmetry
   (but this is exactly what we want to learn about!)

2. Evolution of magnetic field in the plasma

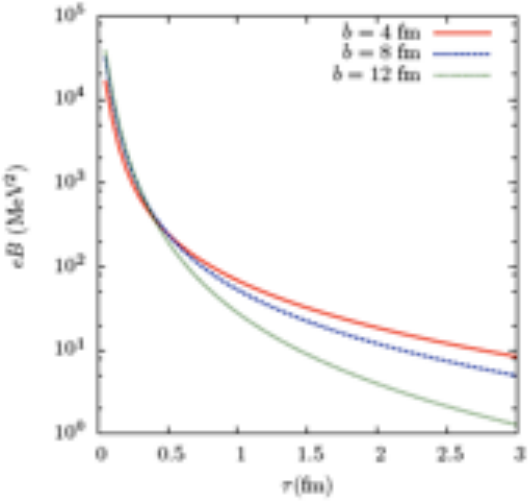


Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).



?

conductivity,
induction,
magnetic diffusion,
reconnections, …

EM fields in heavy ion collisions: a perturbative approach

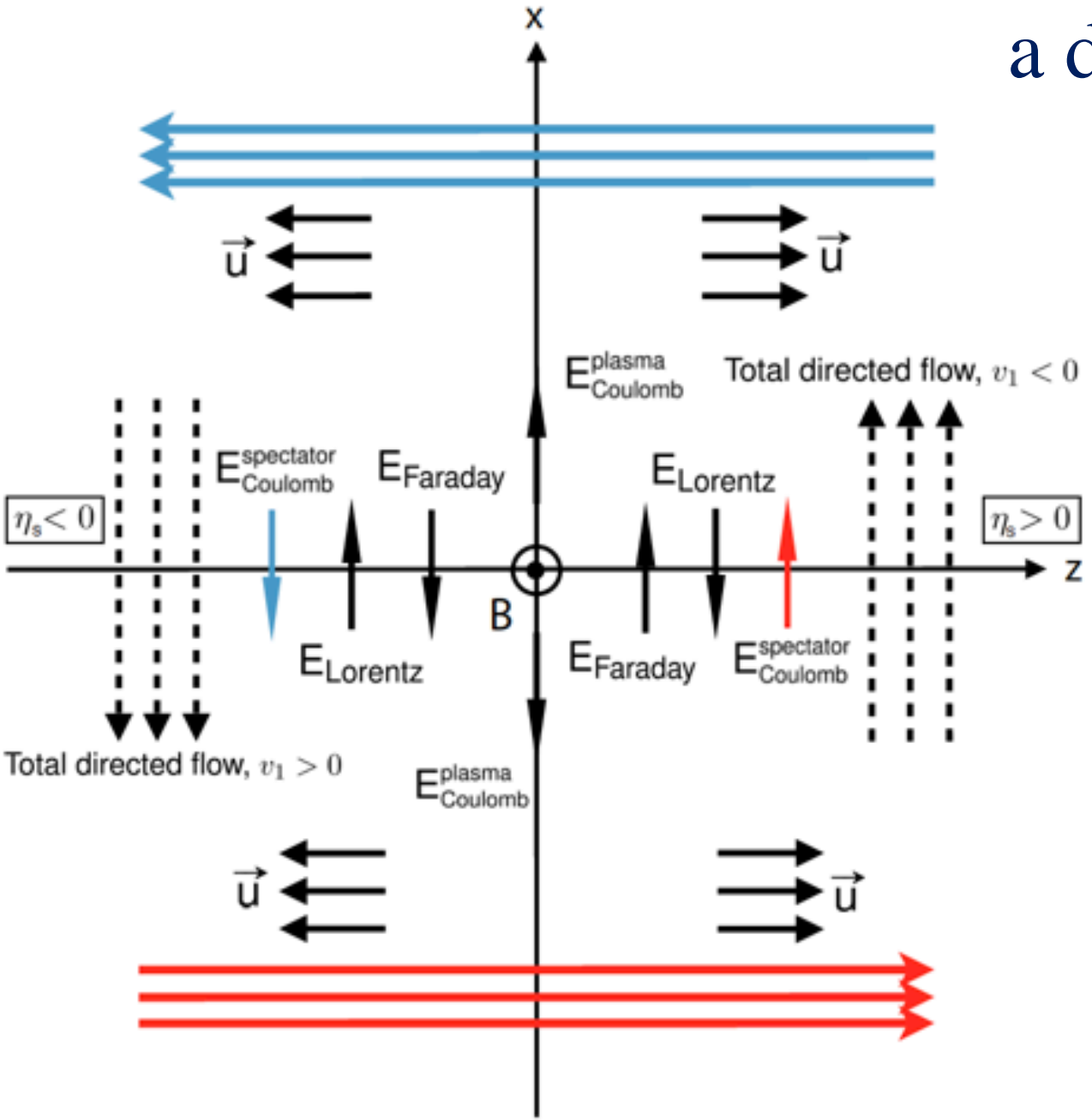
The starting point: solve Maxwell equations on top of the expanding hydrodynamical background, neglect back-reaction on the bulk of hydro evolution – but extract the charge dependence of the flow

Complementary approaches include:

Perturbative treatments:
Indiana-Wuhan group (J. Liao, D. Hou, S. Shi, H. Zhang,…)
Iowa State group (K. Tuchin, E. Stewart)
Frankfurt group (D. Rischke, V. Roy, S. Pu)
….

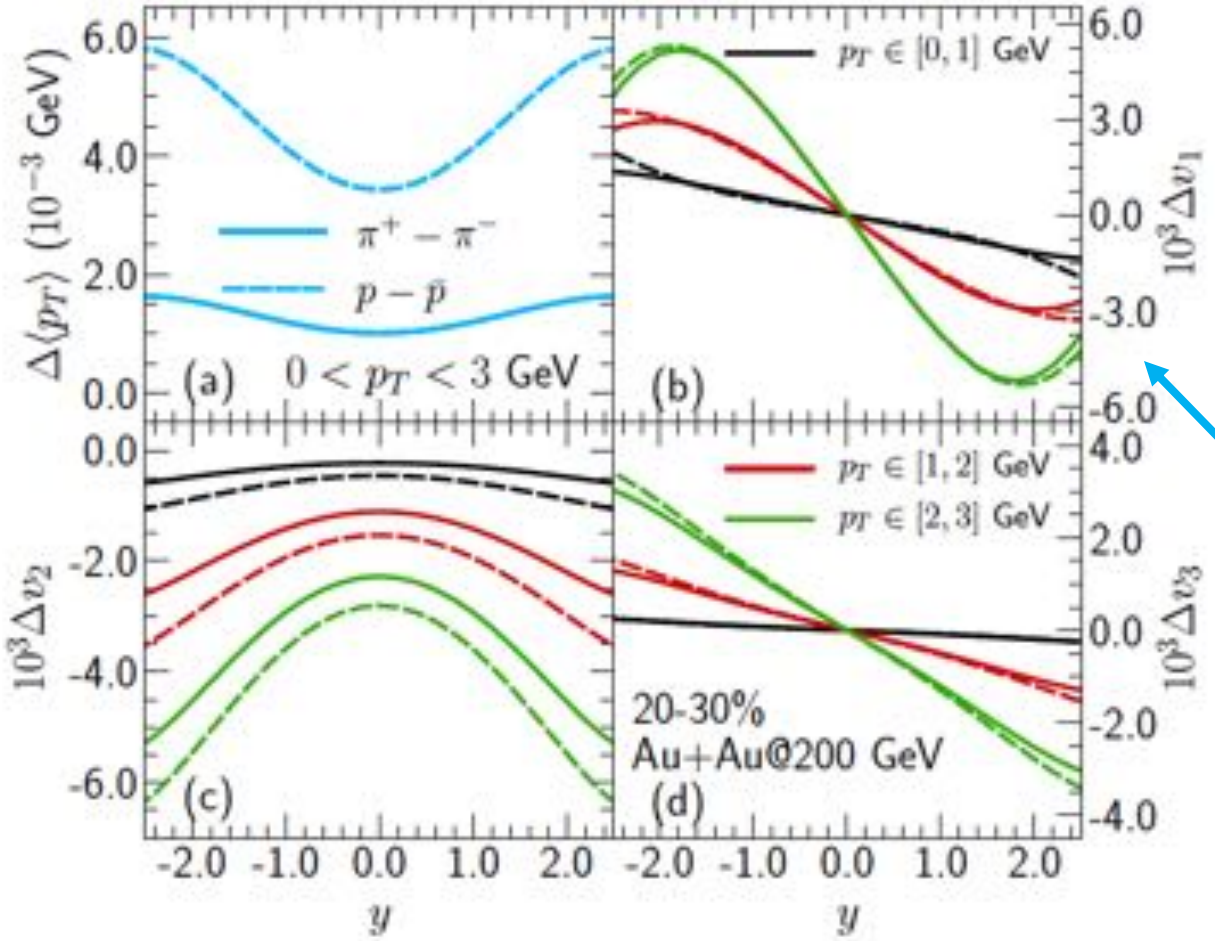
Full MHD:
CMHD (G. Inghirami et al): full back-reaction, but no viscosity

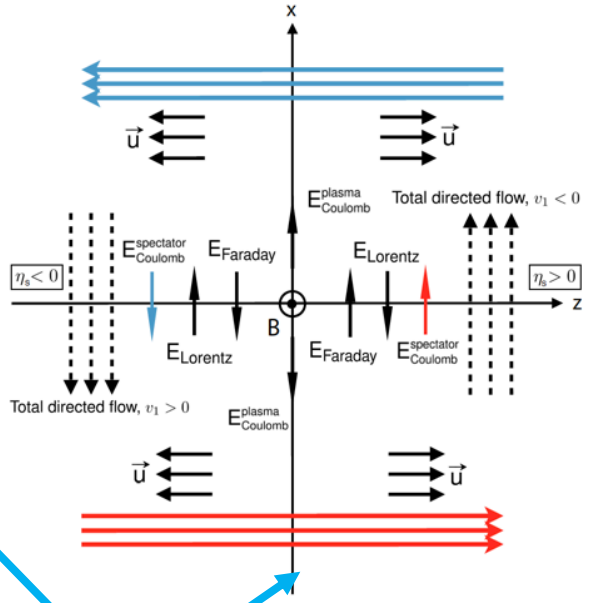
EM fields in heavy ion collisions: a delicate balance



U. Gursoy, DK, E. Marcus, K. Rajagopal, C. Shen, PRC98(2018)055201

Charge-dependent flow: the results





Faraday + Coulomb > Lorentz
(partial cancellation)

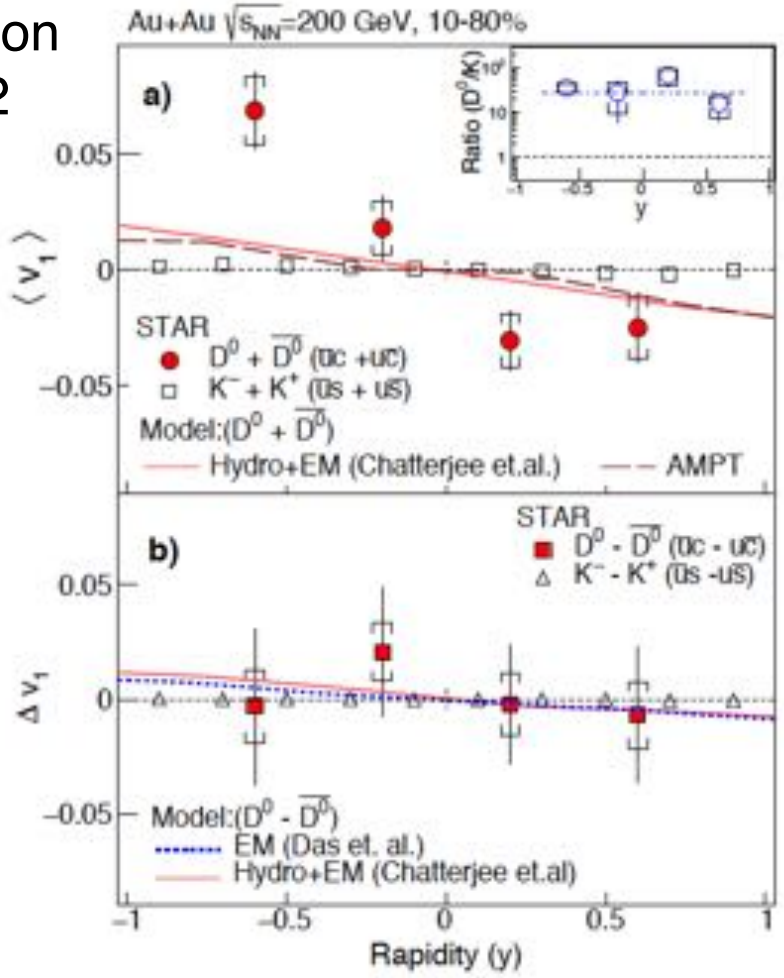
detectable charge dependence, stronger for protons
("blueshift")

Comparison to the data

STAR Review: version A1 May 7, 2019

First observation of the directed flow of D^0 and $\overline{D^0}$ in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV

STAR Collaboration
arXiv:1905.02052



Plenary talk by
Z. Xu (STAR) at QM'19

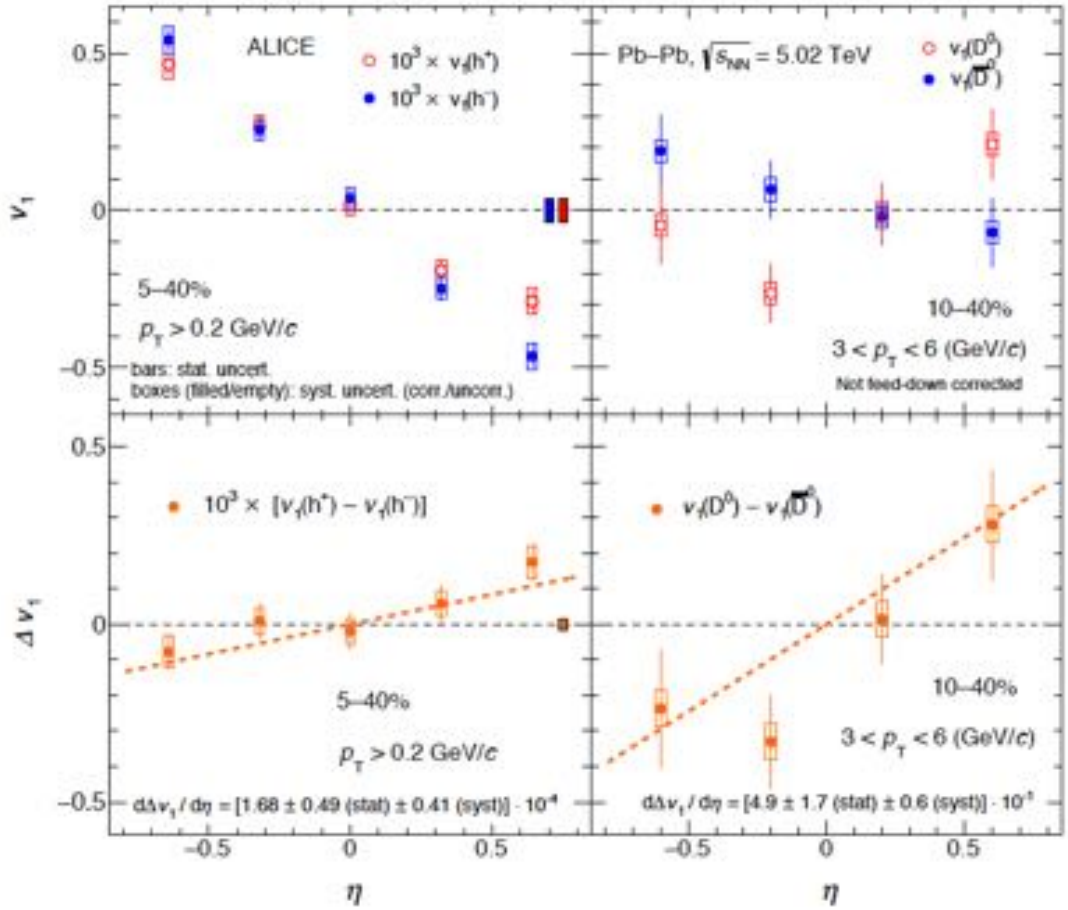
Charge dependence is not visible (for K's), smaller than predicted

Comparison to the data

Plenary talk at QM'19 by
M. Weber (ALICE) arXiv:1910:14406

CERN-EP-2019-241
28 October 2019

Probing the effects of strong electromagnetic fields with charge-dependent directed flow in Pb–Pb collisions at the LHC



Same order of magnitude, but wrong sign!

Most likely, the effect of back-reaction - **Need MHD!?**

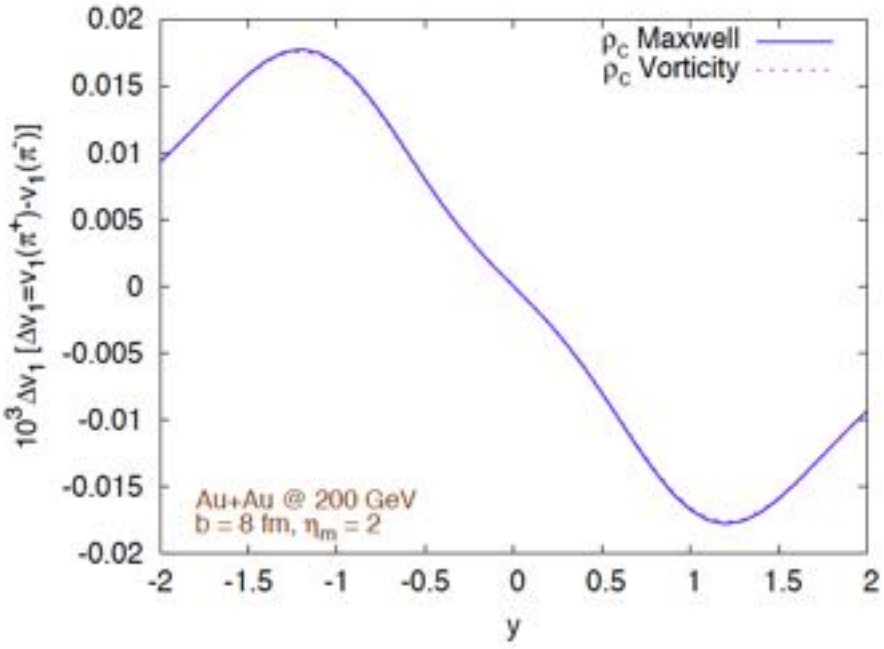
Charm: important probe of early magnetic field
S.Das et al, PLB768(2017)260
S.Chatterjee and P.Bozek (2018)

Towards the CMHD in heavy ion collisions (CMHD – Chiral MagnetoHydroDynamics)

Magnetic fields in heavy ion collisions: flow and charge transport

Gabriele Inghirami,[1,2] Mark Mace,[1,2] Yuji Hirono,[3,4] Luca Del Zanna,[5,6,7] Dmitri E. Kharzeev,[8,9,10] and Marcus Bleicher[11,12,13,14]

arXiv:1908.07605, EPJC '20



CMHD (with full back-reaction!), based on ECHO-QGP; ideal (3+1) hydro evolution

Charge dependence of pion directed flow

Magnitude consistent with limits from STAR data; **same sign as perturbative result!**

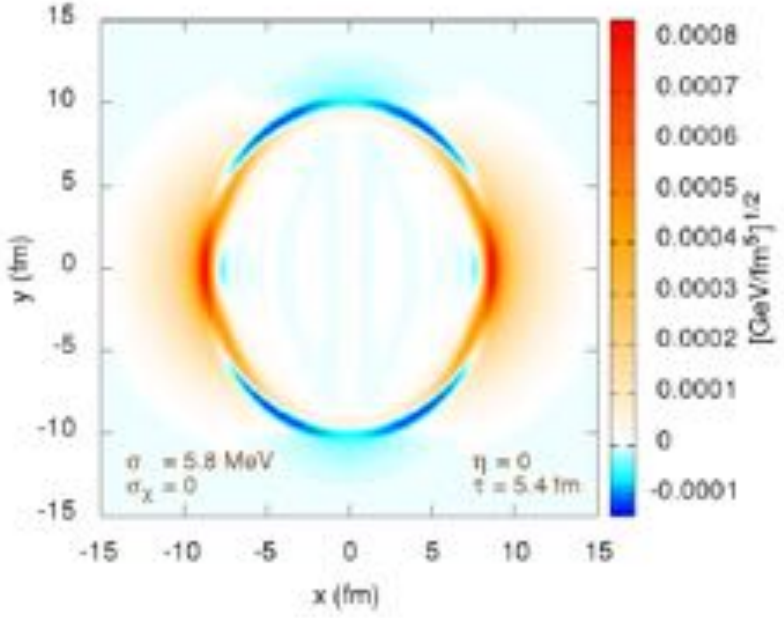
Magnetic fields in heavy ion collisions: flow and charge transport

Gabriele Inghirami,[1,2] Mark Mace,[1,2] Yuji Hirono,[3,4] Luca Del Zanna,[5,6,7] Dmitri E. Kharzeev,[8,9,10] and Marcus Bleicher[11,12,13,14]

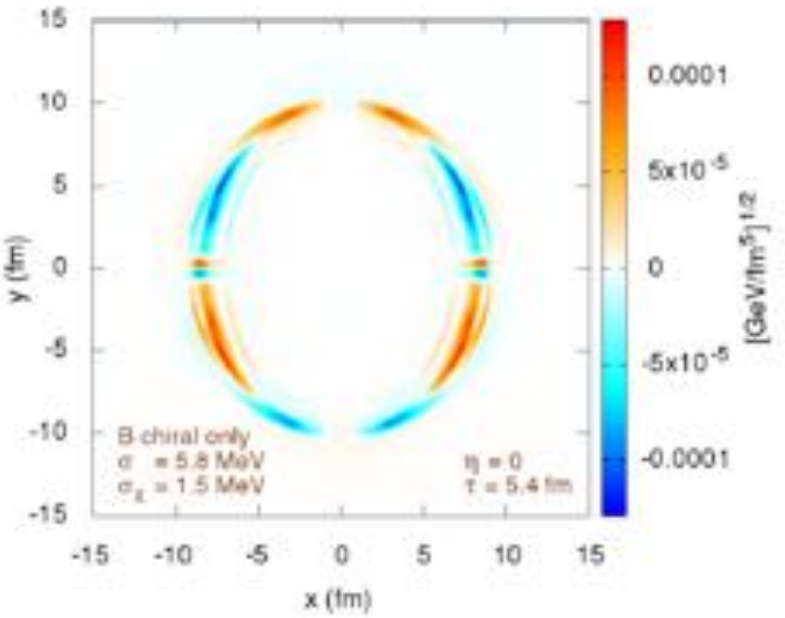
arXiv:1908.07605

Electric charge density at mid-rapidity:

No CME



CME



Charge separation along B!

Broader connections: Chiral fermions in Dirac & Weyl semimetals



SOVIET PHYSICS JETP VOLUME 32, NUMBER 4 APRIL, 1971

POSSIBLE EXISTENCE OF SUBSTANCES INTERMEDIATE BETWEEN METALS AND DIELECTRICS

A. A. ABRIKOSOV and S. D. BENESLAVSKIĬ

L. D. Landau Institute of Theoretical Physics

Submitted April 13, 1970

Zh. Eksp. Teor. Fiz. 59, 1280–1298 (October, 1970)

The question of the possible existence of substances having an electron spectrum without any energy gap and, at the same time, not possessing a Fermi surface is investigated. First of all the question of the possibility of contact of the conduction band and the valence band at a single point is investigated within the framework of the one-electron problem. It is shown that the symmetry conditions for the crystal admit of such a possibility. A complete investigation is carried out for points in reciprocal lattice space with a little group which is equivalent to a point group, and an example of a more complicated little group is considered. It is shown that in the neighborhood of the point of contact the spectrum may be linear as well as quadratic.





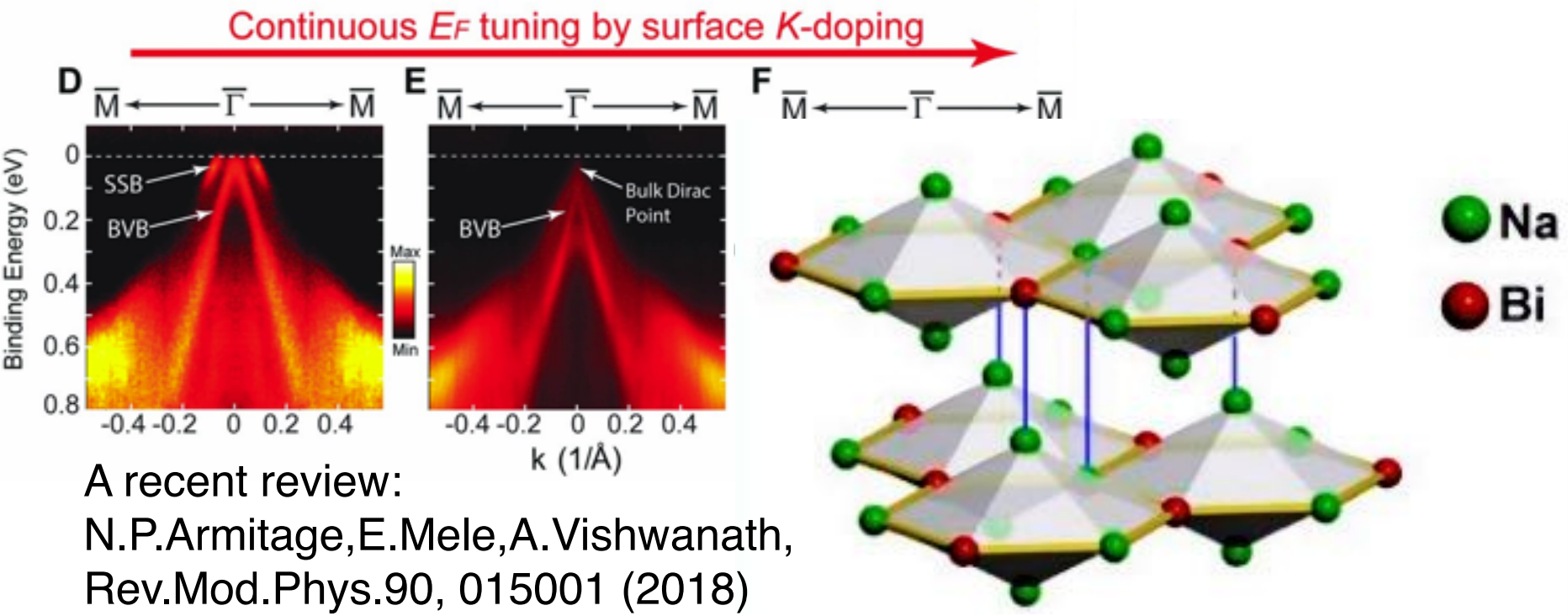




Scientific Background on the Nobel Prize in Physics 2016

TOPOLOGICAL PHASE TRANSITIONS AND TOPOLOGICAL PHASES OF MATTER

The discovery of Dirac/Weyl semimetals – 3D chiral materials



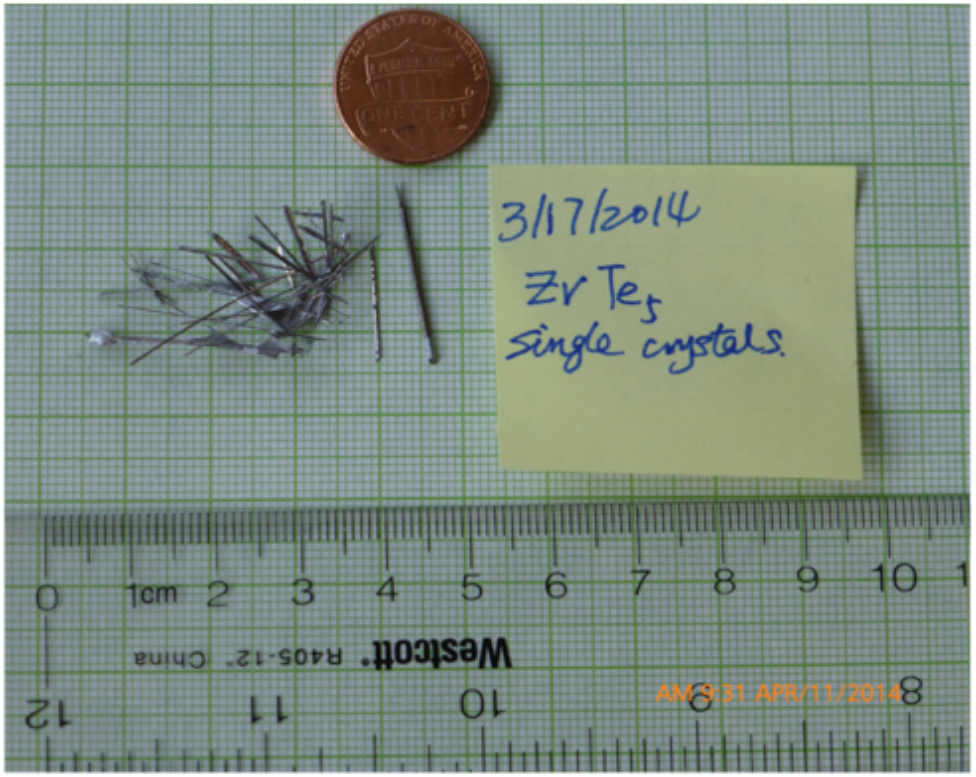
A recent review:
N.P.Armitage,E.Mele,A.Vishwanath,
Rev.Mod.Phys.90, 015001 (2018)

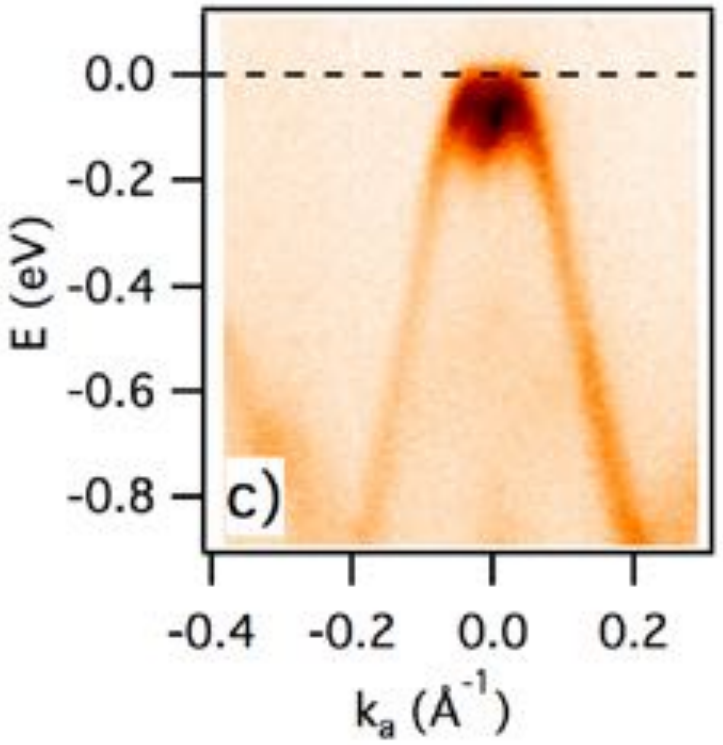
Z.K.Liu et al., Science 343 p.864 (**Feb 21, 2014**)

Even number of space-time dimensions –
so chiral anomaly operates, can study CME!

Observation of the chiral magnetic effect in $ZrTe_5$

Qiang Li,[1] Dmitri E. Kharzeev,[2,3] Cheng Zhang,[1] Yuan Huang,[4] I. Pletikosić,[1,5]
A. V. Fedorov,[6] R. D. Zhong,[1] J. A. Schneeloch,[1] G. D. Gu,[1] and T. Valla[1]





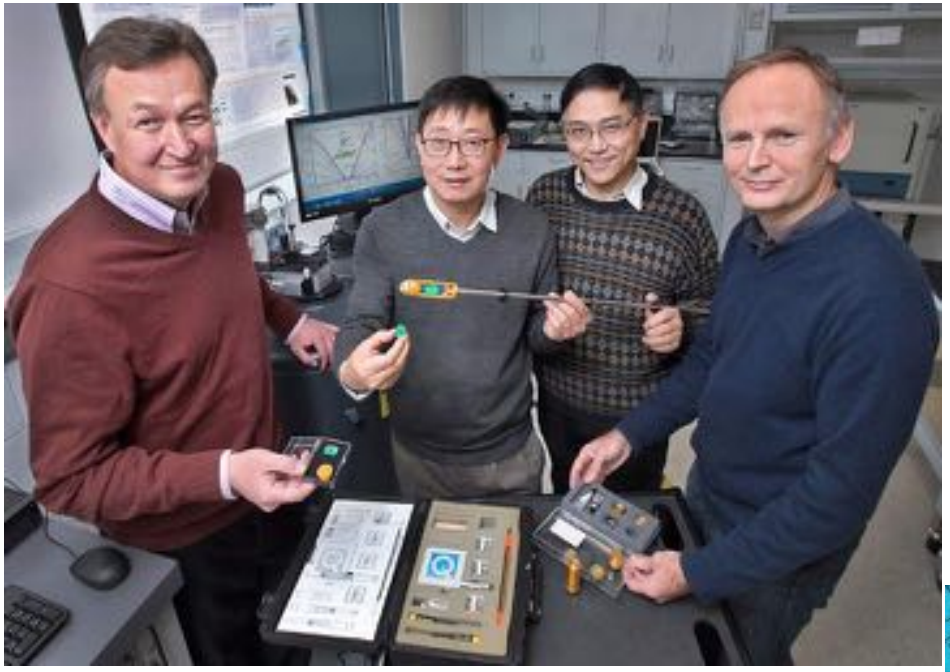
arXiv:1412.6543 (December 2014); Nature Physics **12**, 550 (2016)

CME in chiral materials

Observation of the chiral magnetic effect in $ZrTe_5$

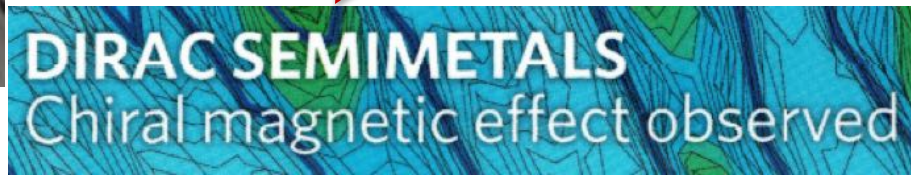
Qiang Li,[1] Dmitri E. Kharzeev,[2,3] Cheng Zhang,[1] Yuan Huang,[4] I. Pletikosić,[1,5]
A. V. Fedorov,[6] R. D. Zhong,[1] J. A. Schneeloch,[1] G. D. Gu,[1] and T. Valla[1]

BNL - Stony Brook - Princeton - Berkeley



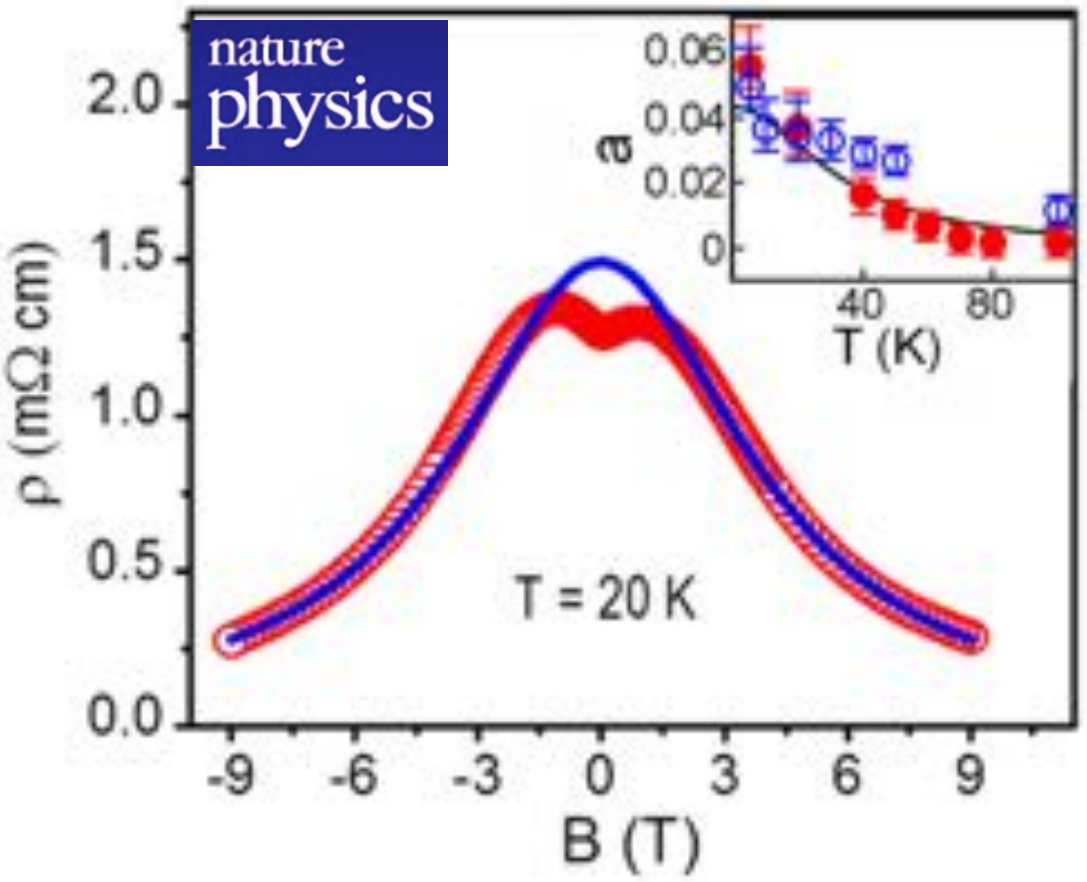
Nature Phys.
12 (2016) 550

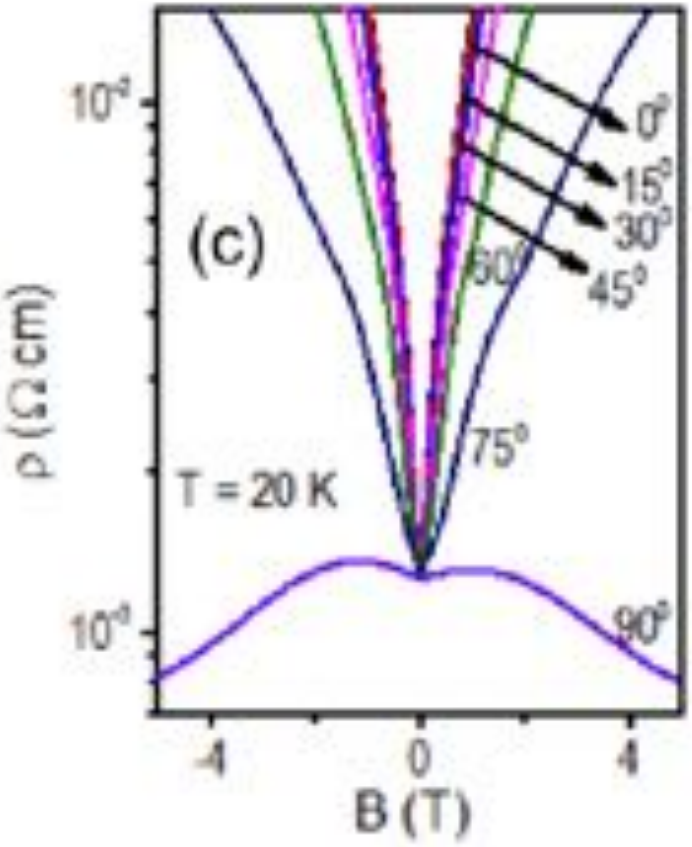




arXiv:1412.6543 [cond-mat.str-el]

Q. Li et al,
Nature Physics **12**, 550 (2016)
arXiv:1412.6543





Can one control CME by circularly polarized light?

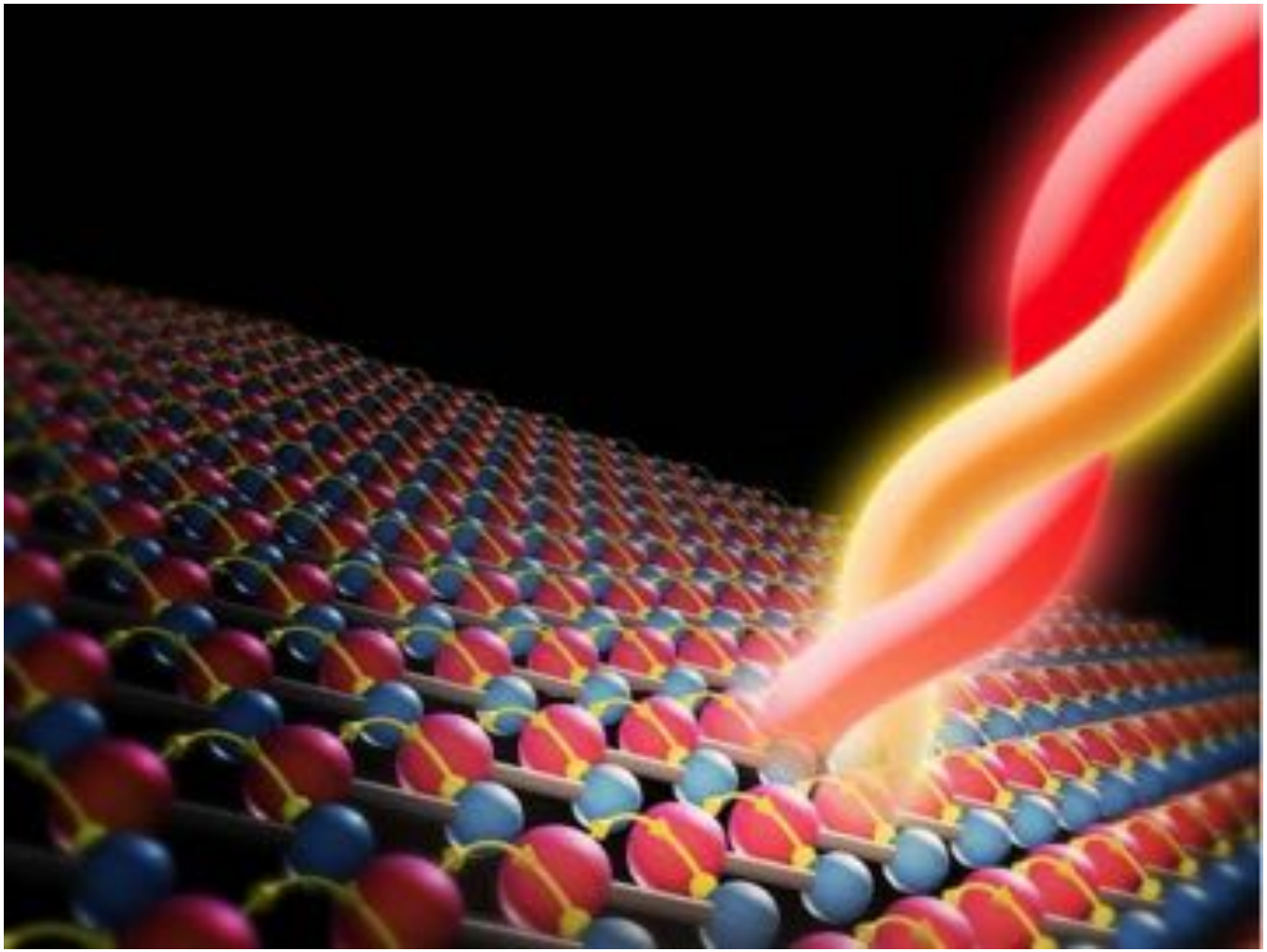


Image credit: Science Daily

Chiral magnetic photocurrent

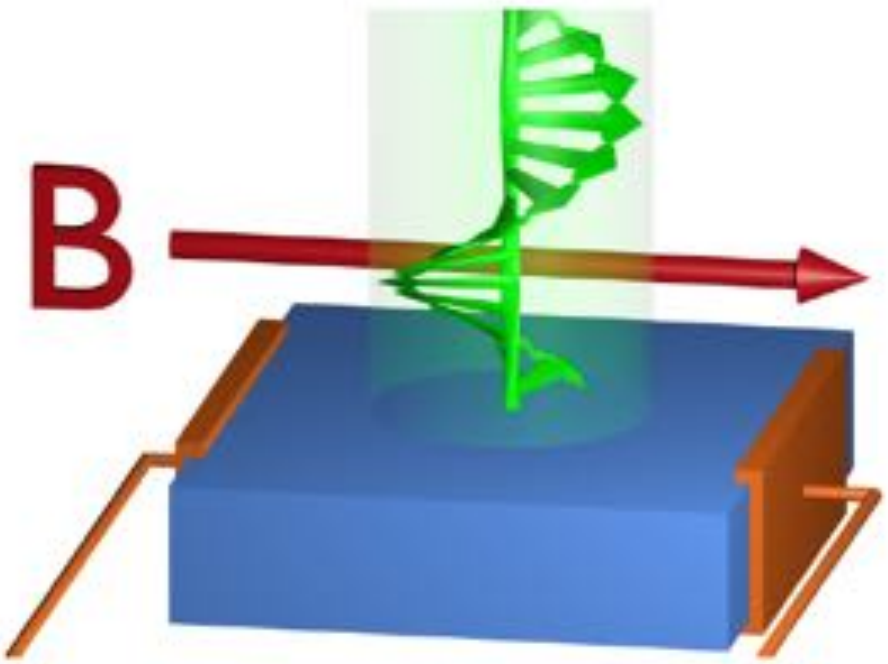


FIG. 1. The CPL incident on a Dirac or Weyl semimetal induces an asymmetry between the number of left- and right-handed chiral quasiparticles. In an external magnetic field, as a consequence of the chiral anomaly, this chiral asymmetry induces a chiral magnetic photocurrent along the direction of the magnetic field.



S. Kaushik, E. Philip, DK
arXiv:1810.02399; PRB'19

Chiral anomaly can provide an even stronger photocurrent (with CPL), I ~ 100 nA for $ZrTe_5$

$$\kappa_{\mathrm{CMP}} = \int_0^\infty \frac{e^2}{2\pi^2\hbar^2} B_{\mathrm{ext}}\, \mu_5 \, \mathrm{d}z$$

$$= \pm \frac{e^2}{2\pi^2\hbar^2} B_{\mathrm{ext}} \frac{\tau_V}{\chi} \frac{\alpha}{\pi} \frac{I_{\mathrm{in}}}{\hbar\omega} \Re(a_x a_y^*).$$

Ultrafast control of chiral currents in Weyl semimetals

arXiv:1901.00986.
Nature Comm. 2020

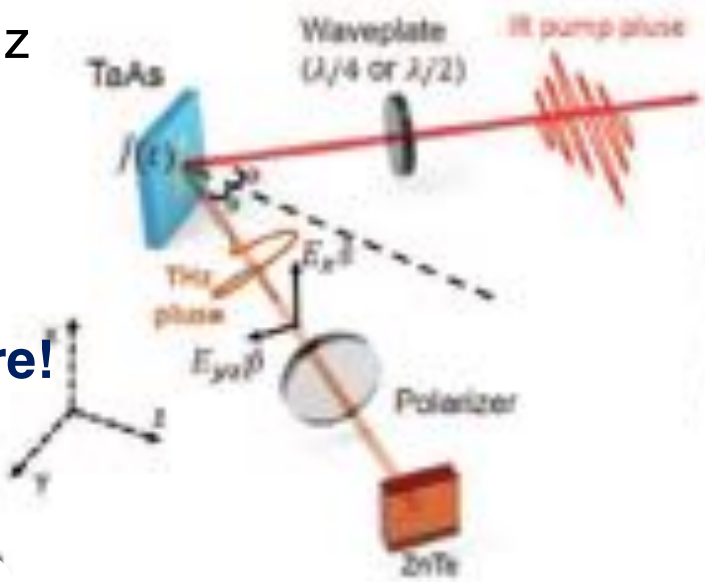
Chiral terahertz wave emission from the Weyl semimetal TaAs

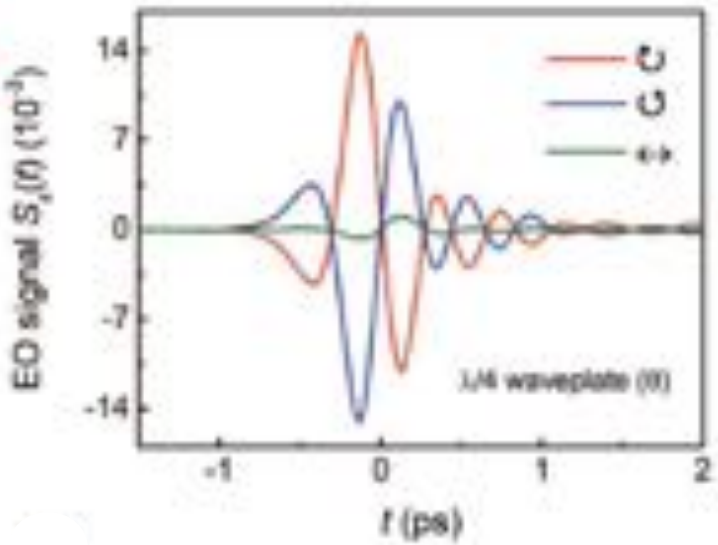
Y. Gao[1], S. Kaushik[2], E.J. Philip[2], Z. Li[3,4], Y. Qin[1,5], Y.P. Liu[6], W.L. Zhang[1], Y.L. Su[1], X. Chen[2], H. Weng[4,7], D.E. Kharzeev[2,8,9*], M.K. Liu[2*] & J. Qi[1*]

nature COMMUNICATIONS

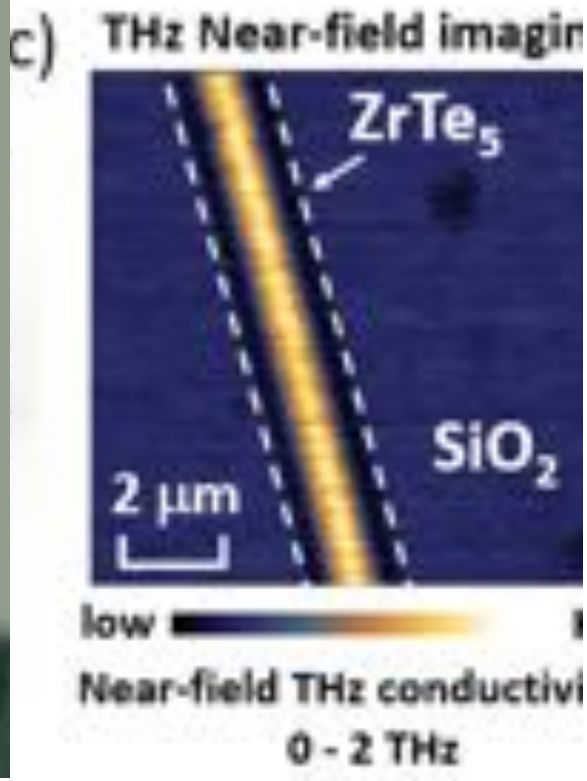
ω = 380 THz
λ = 800 nm
80 fs pulse

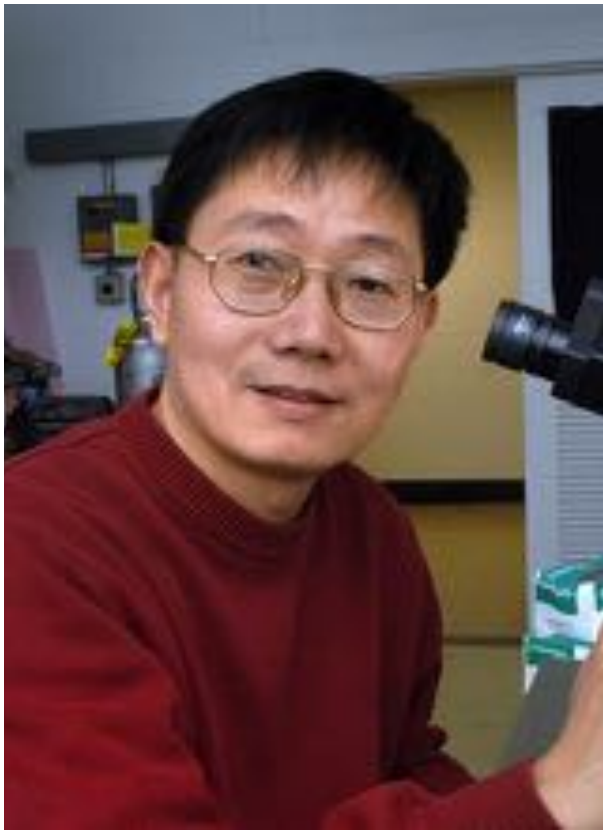
Room temperature!









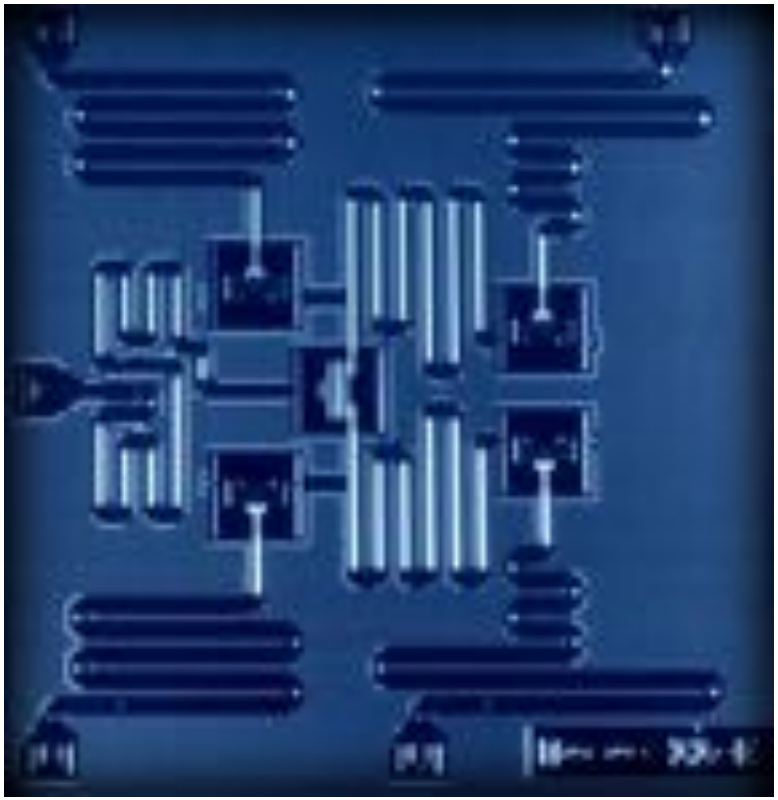


Work in progress,
M.Liu, Q.Li's labs

Rich non-equilibrium dynamics influenced by external fields, light, strain, twist, …. – a variety of theoretical approaches being developed, including the Chiral kinetic theory:

Talk by I. Shovkovy

Superconducting qubits



IBM five qubit processor credit: IBM-Q

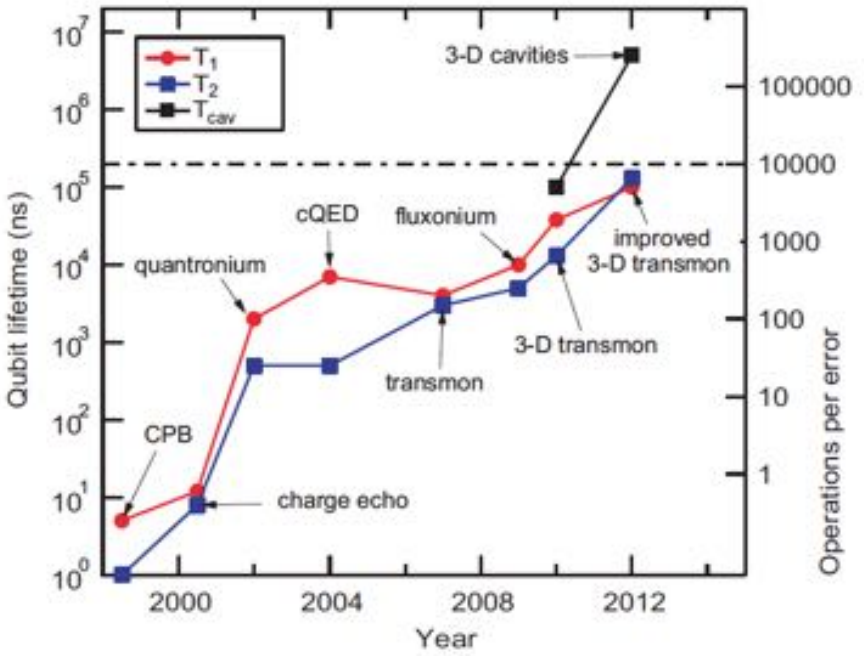
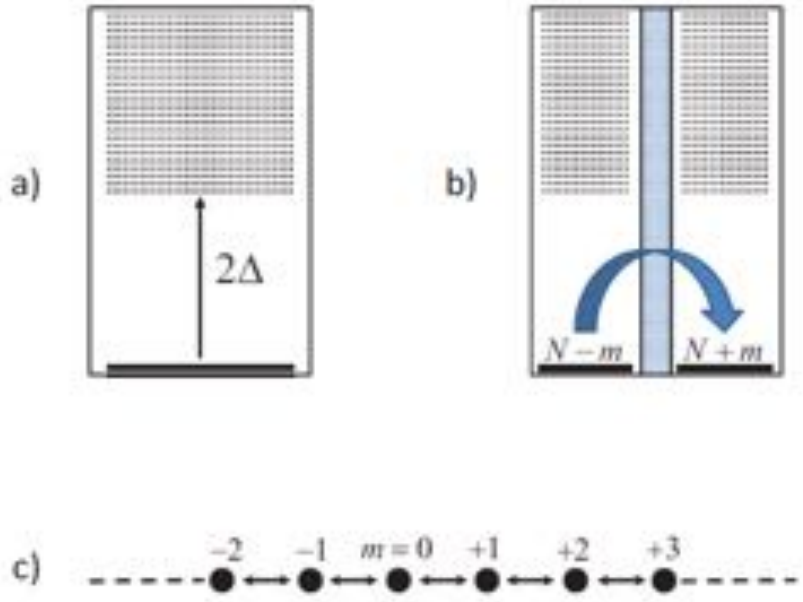


Fig. 2.1 "Schoelkopf's Law" plot illustrating the exponential growth for superconducting (charge-) qubit coherence times. Recent experiments (Geerlings *et al.*, 2013) with the 'fluxonium' qubit design have achieved T_1 times exceeding one millisecond.

S. Girvin, 2013

Superconducting qubits: tunneling through the Josephson junction

Review:
S. Girvin, 2013



$$|m\rangle = |N_{\rm L} - m, N_{\rm R} + m\rangle$$

$$|\varphi\rangle = \sum_{m=-\infty}^{+\infty} e^{+im\varphi}|m\rangle$$

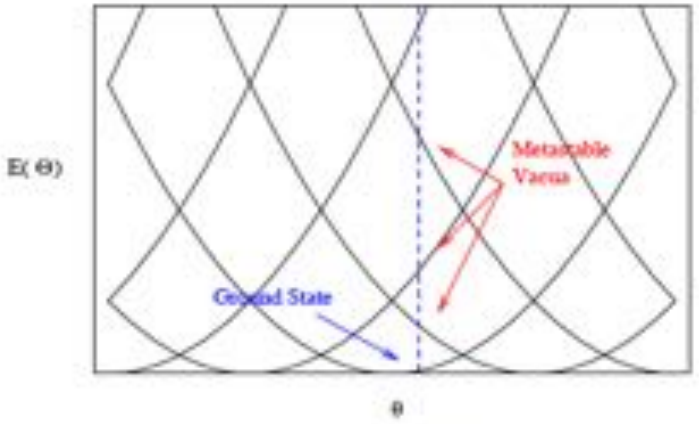
$$\varphi = ka$$

Fig. 3.2 a) Spectrum of a superconducting Cooper pair box (CPB). For the case of an even number of electrons, there is a unique non-degenerate state separated from the excited states by a gap 2Δ. b) A pair of CPB's connected by a tunnel barrier to form a Josephson junction. Ignoring the Coulomb energy, there is a large family of degenerate ground states labeled by an integer m representing the number of Cooper pairs transferred from one condensate to the other. c) 'Tight-binding' lattice along which the junction 'moves' via Josephson tunneling between 'sites' labeled by adjacent values of m.

The wavevector

Direct analogy to the "θ angle" and "θ vacuum" of QCD

θ Vacuum in QCD and the Cooper pair box



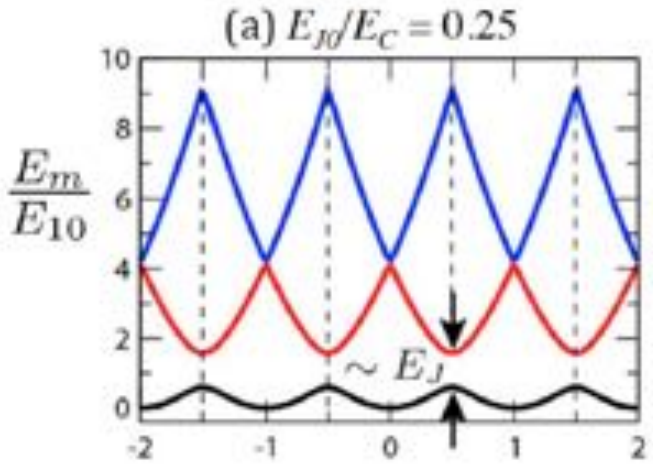


Fig. 1. Vacuum energy in gluodynamics as a function of θ. At fixed θ, there is a ground state and a tower of extra vacua.

DK, R.Pisarski, M.Tytgat,
arXiv:0012012 (2000)

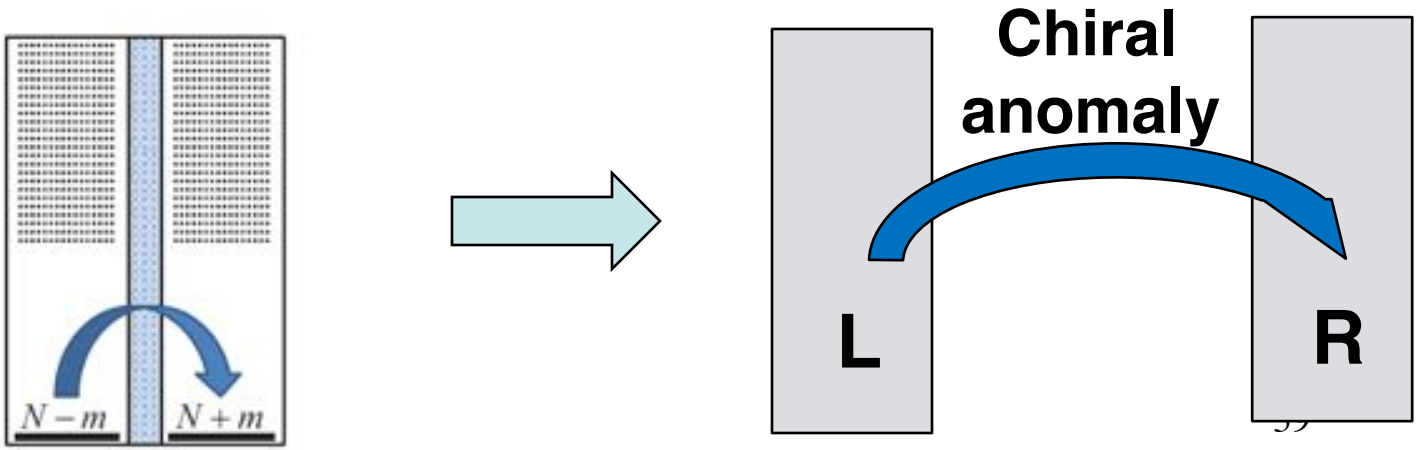
G.Wendin,
arXiv:1610.02208 (2016)

Figure 3. Level spectrum (band structure) of the Cooper pair box (CPB) as a function of the offset charge n_g for different ratios E_{J0}/E_C [25]: (a) charge qubit [23]; (b) Quantronium [15]; (d) Transmon [25]. 'Historically', the CPB evolved from the original charge qubit (1999)

+ CME-like effects in parity-breaking superconductors ➡ "chiral magnetic JJ":
M. Chernodub, J. Garaud, DK, arXiv: 1908.00392; 2003.10917

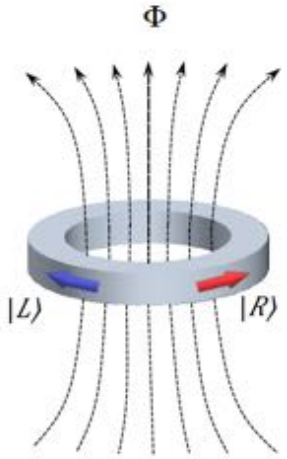
Can the basic physics of the superconducting qubit be realized in a different system, potentially capable of operating at much higher temperatures, higher frequencies, and larger ratio of coherence and gate times?

Probably yes – use the chiral fermions!



Chiral ring: a simple model

Dirac fermion
(1+1), compactified



Magnetic flux;
(3+1) gauge field

$$\mathcal{L} = \bar{\psi}\{i\gamma^0 D_0 + iv_F\gamma^i D_i\}\psi - \frac{1}{4}F_{\mu\nu}^2$$

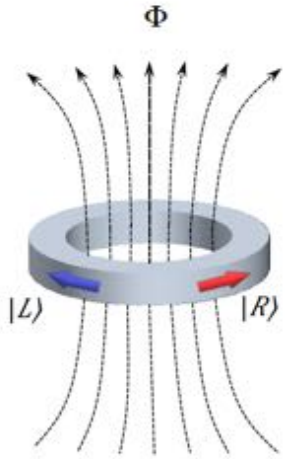
control
Hamiltonian,
$\Phi = \Phi(t)$

$$\hat{H} = \hbar\omega\left[-i\frac{\partial}{\partial\varphi} - \frac{\Phi}{\Phi_0}\right]\hat{\sigma}_z$$

CME in the Chiral Qubit

$$\hat{H} = \hbar\omega \left[-i\frac{\partial}{\partial\varphi} - \frac{\Phi}{\Phi_0} \right] \hat{\sigma}_z$$

$$E_n^{R,L} = \pm\hbar\omega \left(n + \frac{\Phi}{\Phi_0} \right); \; n \in \mathbb{Z}$$



An infinite tower of states (Dirac sea), all of which respond to magnetic field (chiral anomaly): need to sum over all occupied states!

$$J_n^{R,L} = -\frac{\partial E_n^{R,L}}{\partial\Phi} = \mp e\frac{\hbar\omega}{2\pi}, \qquad J = J_R + J_L = e\frac{\hbar\omega}{2\pi}\left(\sum_{n=-\infty}^{N_L} 1 - \sum_{m=-\infty}^{N_R} 1 \right)$$

$$J = -e\,\frac{\mu_5}{\pi}.$$

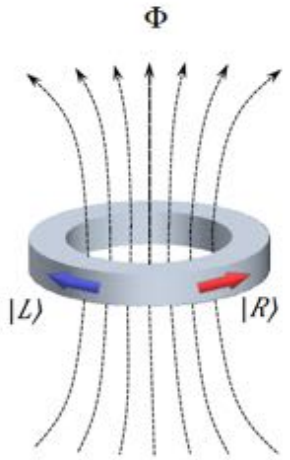
CME in (1+1) dimensions!

DK, Q.Li,
arXiv:1903.07133

Chiral Qubit: the Hamiltonian

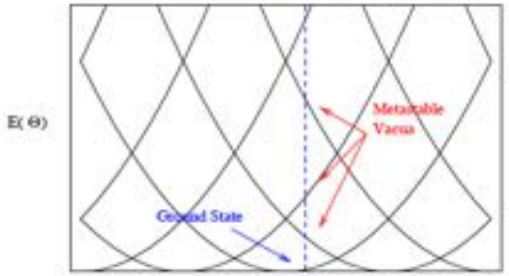
$$\hat{H} = \hbar\omega \left[-i\frac{\partial}{\partial\varphi} - \frac{\Phi}{\Phi_0} \right] \hat{\sigma}_z$$

$$E_n^{R,L} = \pm\hbar\omega \left(n + \frac{\Phi}{\Phi_0} \right);\ n \in \mathbb{Z}$$



An infinite tower of states (Dirac sea), all of which respond to magnetic field (chiral anomaly): need to sum over all occupied states!

$$U_{tot}(\Phi) = U_0 \left[\left(\frac{\Phi}{\Phi_0} - \frac{1}{2} \right)^2 - \beta \cos\left(\frac{\Phi}{\Phi_0} \right) \right]$$

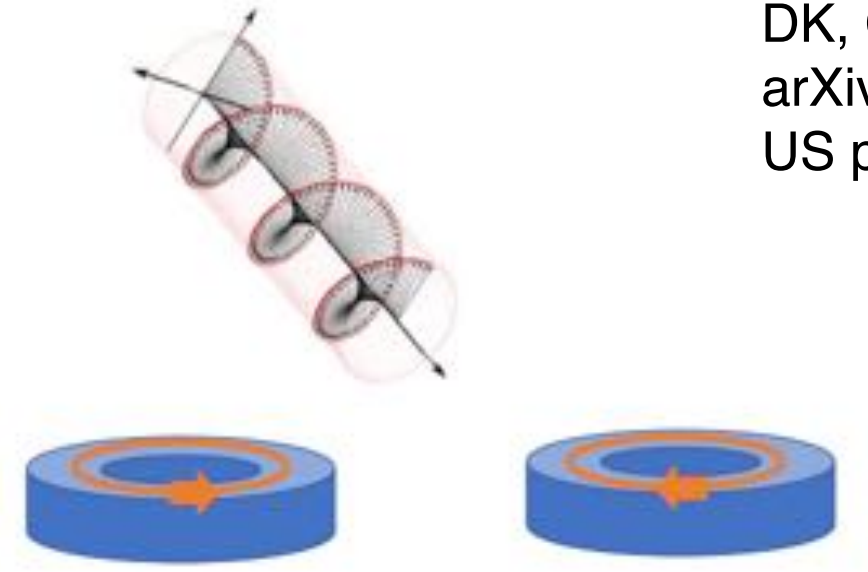


This Hamiltonian is identical to the Hamiltonian of the superconducting qubit!

DK, Q.Li,
arXiv:1903.07133

The chiral qubit

DK, Q.Li,
arXiv:1903.07133[quant-ph];
US pat. 62/758,029

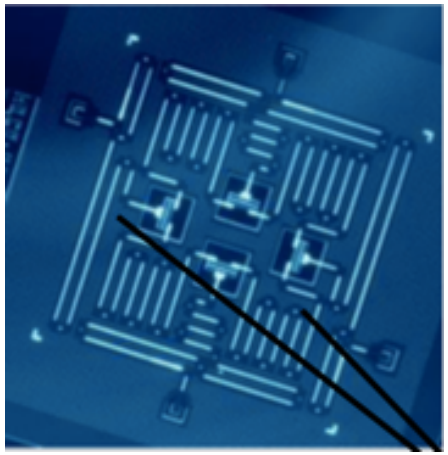


$$|0\rangle = \frac{1}{\sqrt{2}}\left(|R\rangle + |L\rangle\right)$$

$$|1\rangle = \frac{1}{\sqrt{2}}\left(|R\rangle - |L\rangle\right)$$

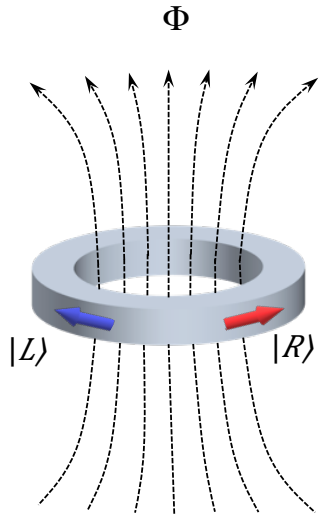
The qubit can be controlled by the circularly polarized IR light or external magnetic flux (for thin rings)

The chiral qubit

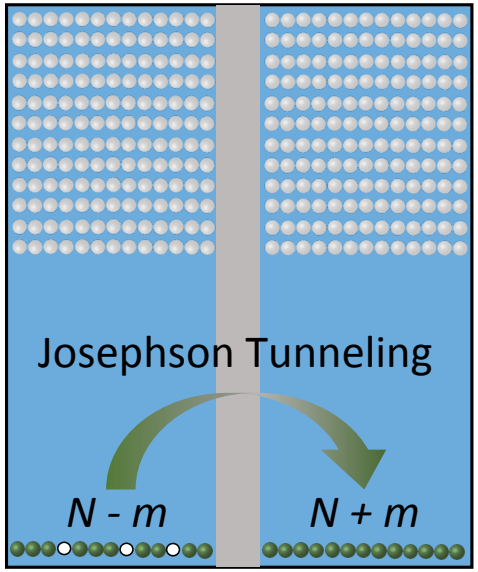


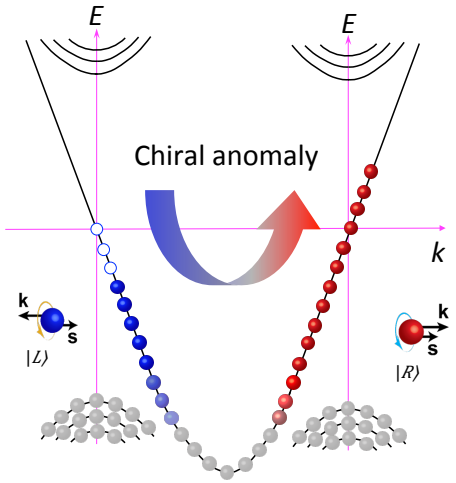
IBM-Q











DK, Q. Li, US patent **62/758,029** (2018); arXiv:1903.07133[quant-ph];

Summary

1. Chiral Magnetic Effect and related quantum transport phenomena are direct probes of topology of gauge fields

2. CME in heavy ion collisions is a unique opportunity to observe in the lab topological fluctuations in QCD
   (this may be the last chance in the foreseeable future of Mankind!)

3. The matrix element of topological CS current over the proton defines the gluon contribution to proton's spin – explore QCD topology at EIC

4. CME has been observed in many chiral materials, with important present and future applications that range from THz sensors to quantum computers