Topological aspects of strong correlations and gauge theories,

TIFR, India, September 6-10, 2021

Chiral Matter

from quarks to quantum computers

Lecture 3

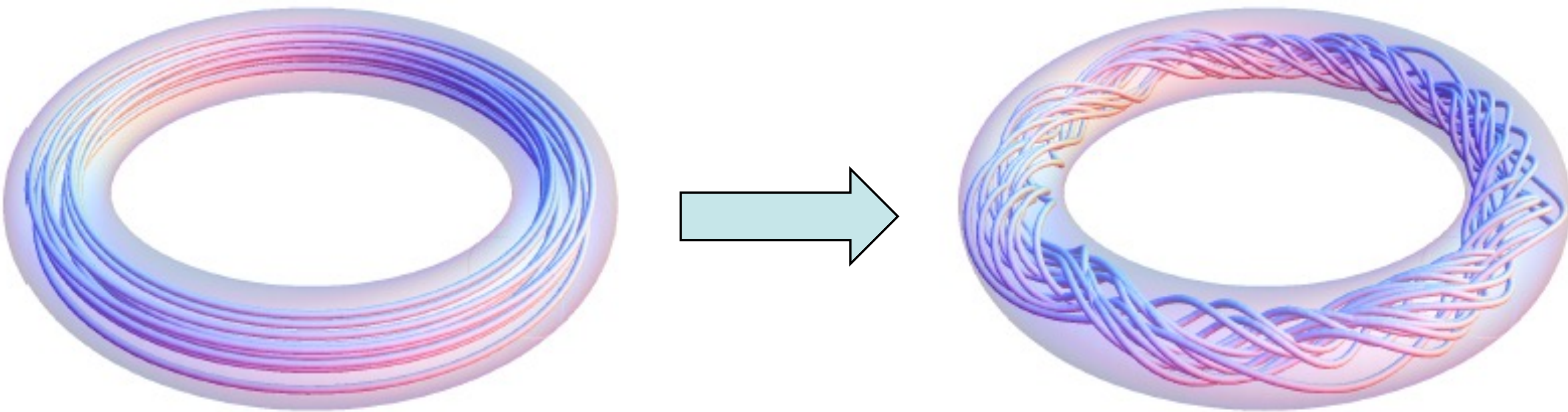
Dmitri Kharzeev

Center for Nuclear Theory
Stony Brook University

C²QA Co-design Center for Quantum Advantage

Brookhaven National Laboratory

Chirality transfer from fermions to gauge fields



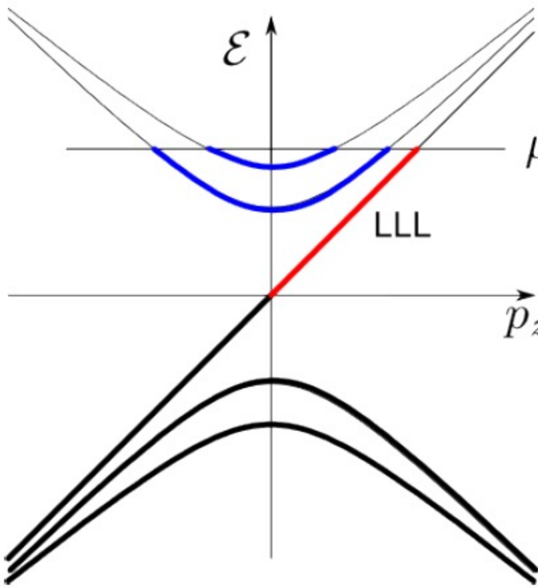
$$\nabla \times \boldsymbol{B} = j$$

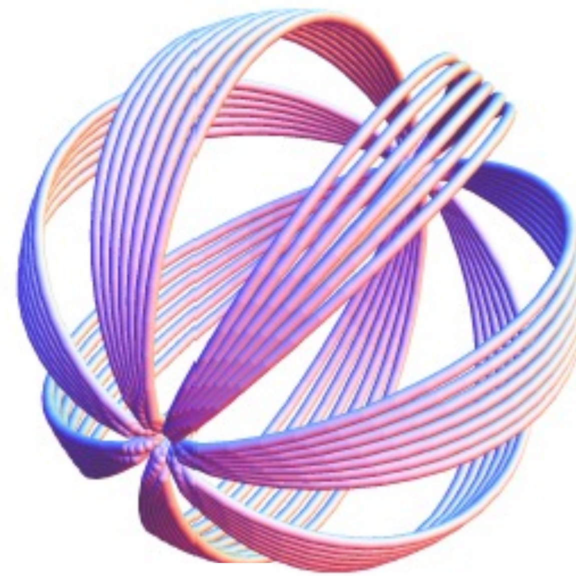
$$j_{\mathrm{CME}} = C_{\mathrm{A}} \, \mu_A \, \boldsymbol{B} = \sigma_A \boldsymbol{B}$$

$$\Rightarrow \quad \nabla \times \boldsymbol{B} = \sigma_A \, \boldsymbol{B}$$

solutions:
Chandrasekhar-Kendall states

Chirality transfer from fermions to magnetic helicity





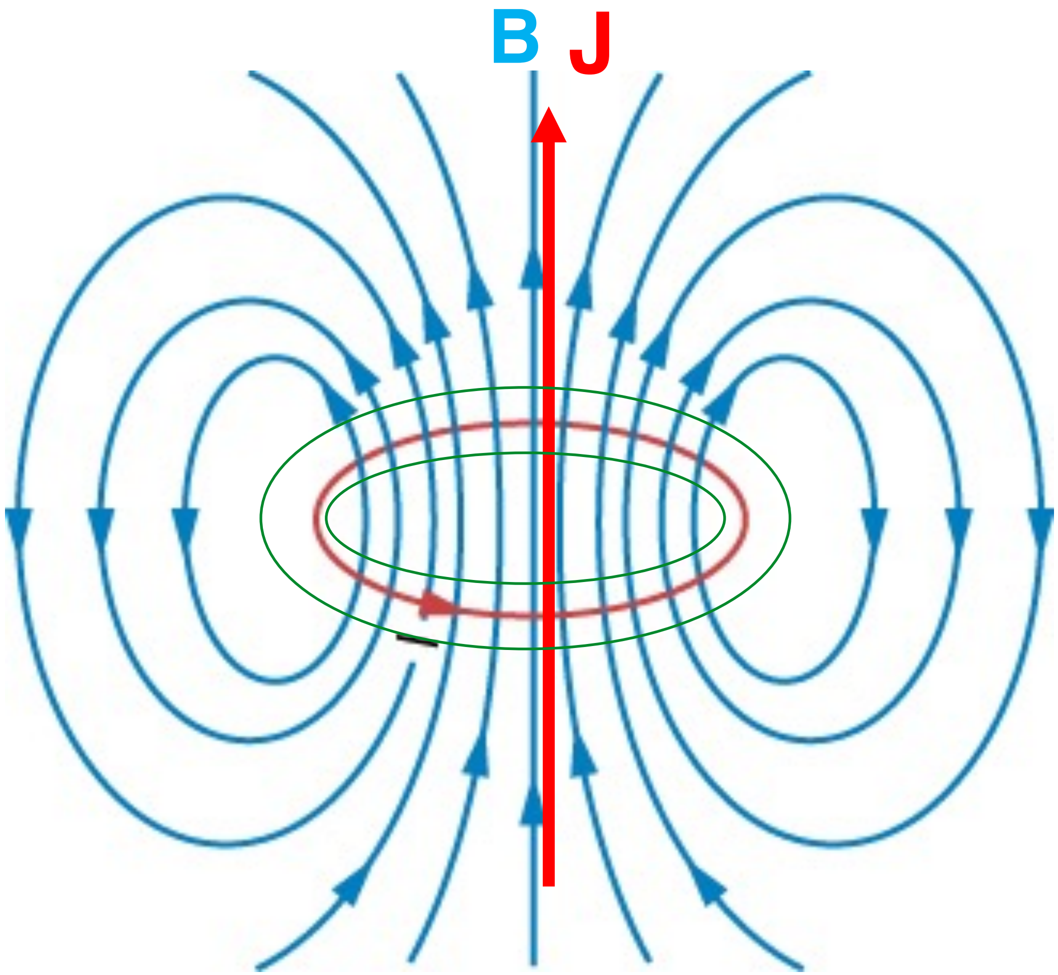
$$\partial_\mu j^\mu_A = C_\mathrm{A} \boldsymbol{E} \cdot \boldsymbol{B}$$

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

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

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

Chiral magnetic instability

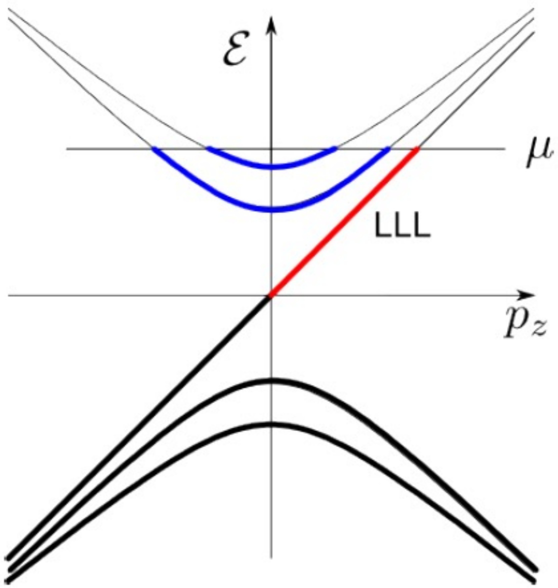


Transfer of chiral charge of the fermions to the magnetic helicity

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

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

Inverse cascade of magnetic helicity



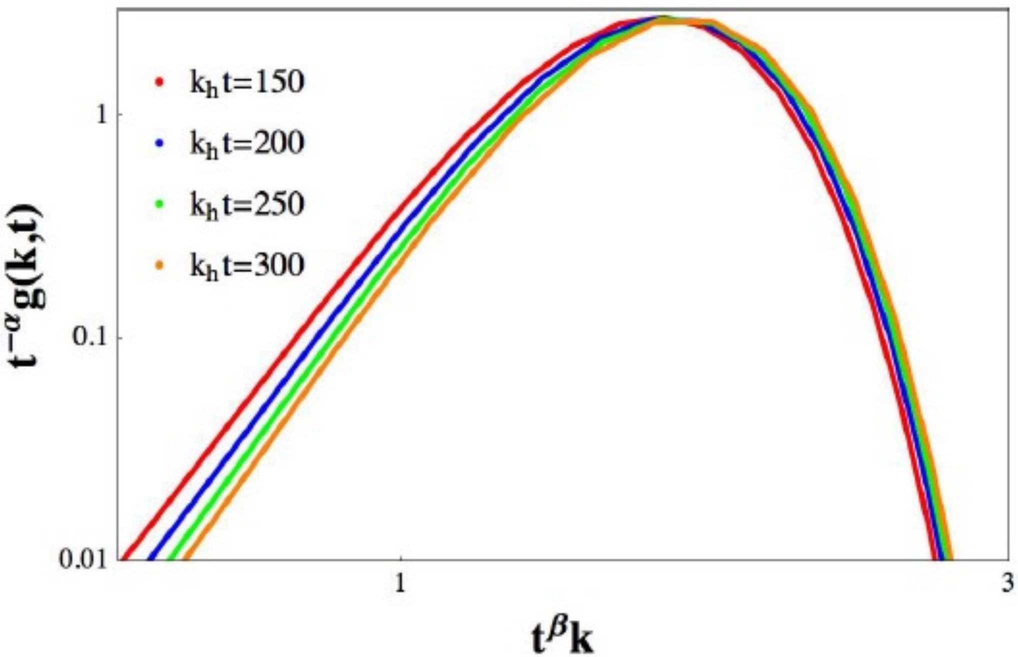
Instability at k< $c_A \mu_A$ leads to the growth of magnetic helicity

Increase of of magnetic helicity reduces μ_A

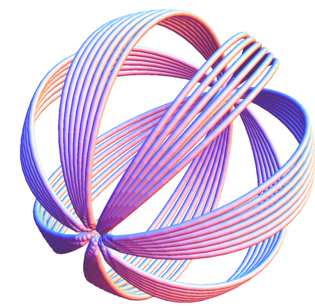
Inverse cascade:

M.Joyce and M.Shaposhnikov, PRL 79 (1997) 1193;
R.Jackiw and S.Pi, PRD 61 (2000) 105015;
A.Boyarsky, J.Frohlich, O.Ruchayskiy, PRL 108 (2012) 031301; PRD 92 (2015) 043004;
H.Tashiro, T.Vachaspati, A.Vilenkin, PRD 86 (2012) 105033

Self-similar inverse cascade of magnetic helicity driven by CME



helical magnetogenesis
in the Universe?



Work by A. Brandenburg, T. Vachaspati,
A. Boyarsky, O. Ruchaysky, T. Kaniashvili,…

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

Y. Hirono, DK, Y.Yin, PRD’15

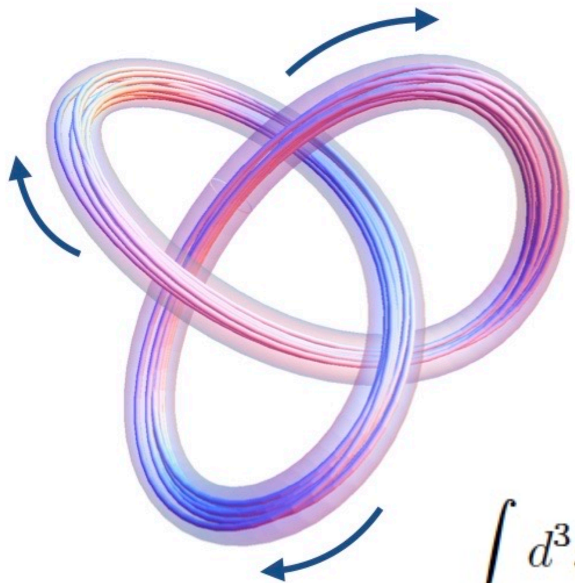
N. Yamamoto, PRD’16

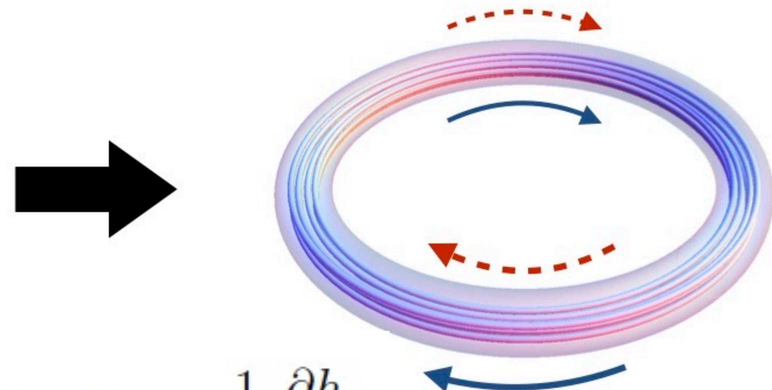
Possible link between “helical magnetogenesis” and baryogenesis in Early Universe:

DK, E.Shuryak, I.Zahed, arXiv:1906.0480, PRD

CME current and magnetic reconnections

Y. Hirono, DK, Y. Yin,
PRL 117(2016) 172301





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

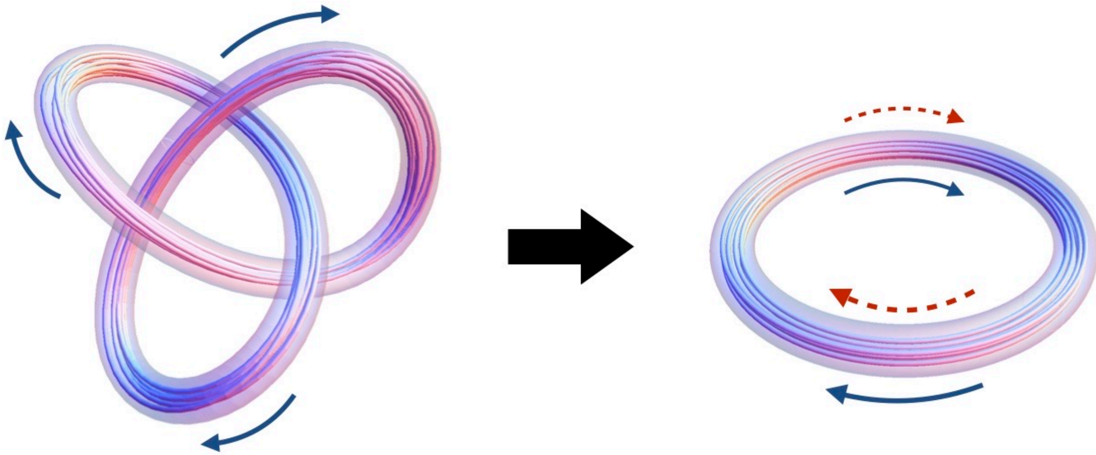
Changing magnetic flux through the area spanned by the tube will generate the electric field (Faraday's induction):

$$\frac{d}{dt}\Phi_B = -\oint_C \boldsymbol{E}\cdot d\boldsymbol{x}$$

The electric field will generate electric current of fermions (chiral anomaly in 1+1 D):

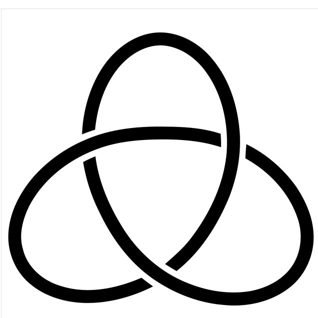
$$\Delta J = \Delta J_R + \Delta J_L = \frac{q^3\Phi^2}{2\pi^2 L}$$

Y. Hirono, DK, Y. Yin,
PRL 117(2016) 172301



Helicity change per magnetic reconnection is $\Delta\mathcal{H} = 2\Phi^2$.

Multiple magnetic reconnections not changing chirality
do not induce net current (need to break left-right symmetry).



For N_+ positive and N_- negative crossings on
a planar knot diagram, the total magnetic helicity is:

$$\mathcal{H} = 2(N_+ - N_-)\Phi^2$$

The total current induced by reconnections
to a chiral knot:

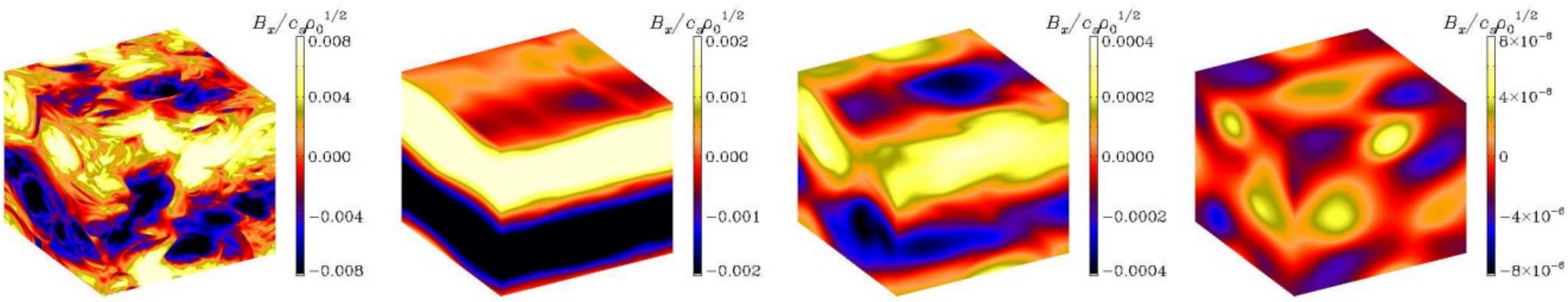
$$J = \frac{q^3\mathcal{H}}{4\pi^2 L}$$

CME in the Early Universe

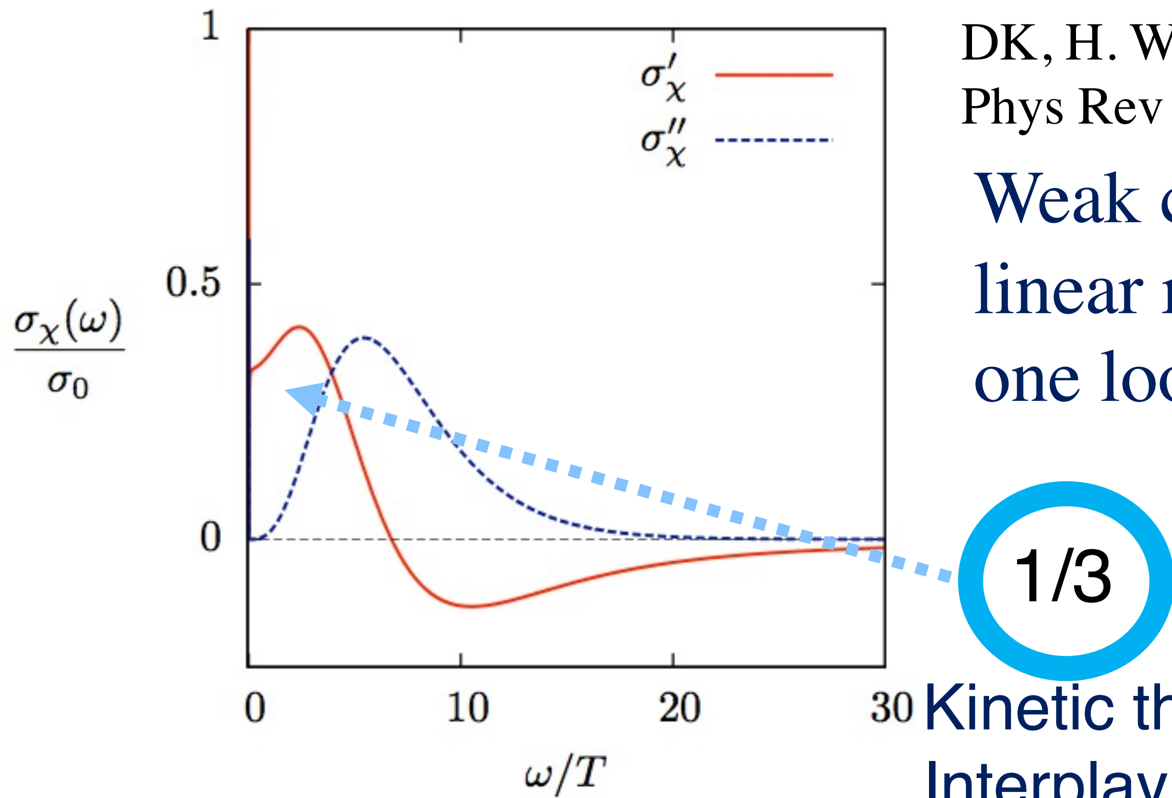
Astrophys. J. 845, L21 (2017)
Preprint typeset using LaTeX style emulateapj v. 08/22/09

THE TURBULENT CHIRAL MAGNETIC CASCADE IN THE EARLY UNIVERSE

Axel Brandenburg[1,2,3,4], Jennifer Schober[3], Igor Rogachevskii[5,1,3], Tina Kahniashvili[6,7], Alexey Boyarsky[8], Jürg Fröhlich[9], Oleg Ruchayskiy[10], and Nathan Kleeorin[5,3]



Dynamical chiral magnetic effect: time-dependent fields



DK, H. Warringa
Phys Rev D80 (2009) 034028

Weak coupling:
linear response,
one loop computation

Kinetic theory interpretation:
Interplay of the Berry phase (+2/3)
and magnetization current (-1/3)

S.Zhong, J.Moore, I.Souza PRL 2016

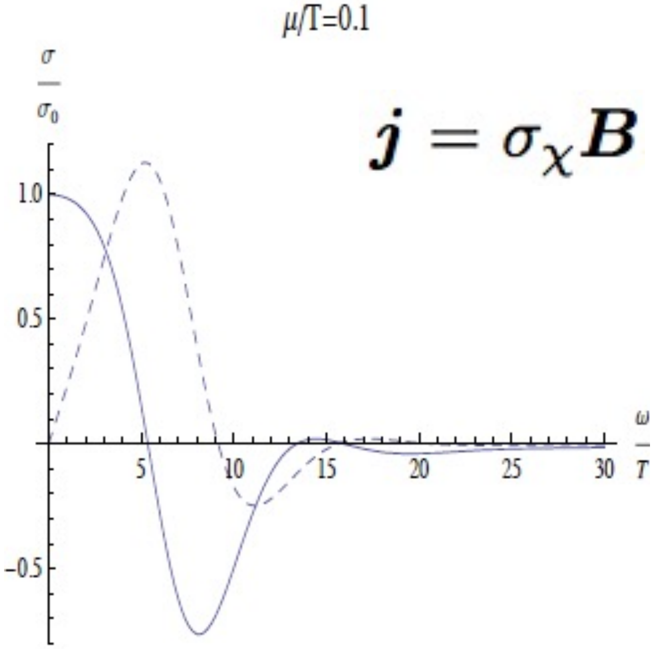
J.Ma, D. Pesin, 1510.01304 Phys Rev B

DK, M.Stephanov, H.-U.Yee. 1612.01674 Phys Rev D

+ CME induced by **strain**:
D.Pikulin, A.Chen, M.Franz, PRX 2016
A.Cortijo, DK, K.Landsteiner, M.Vozmediano, PRB 2016

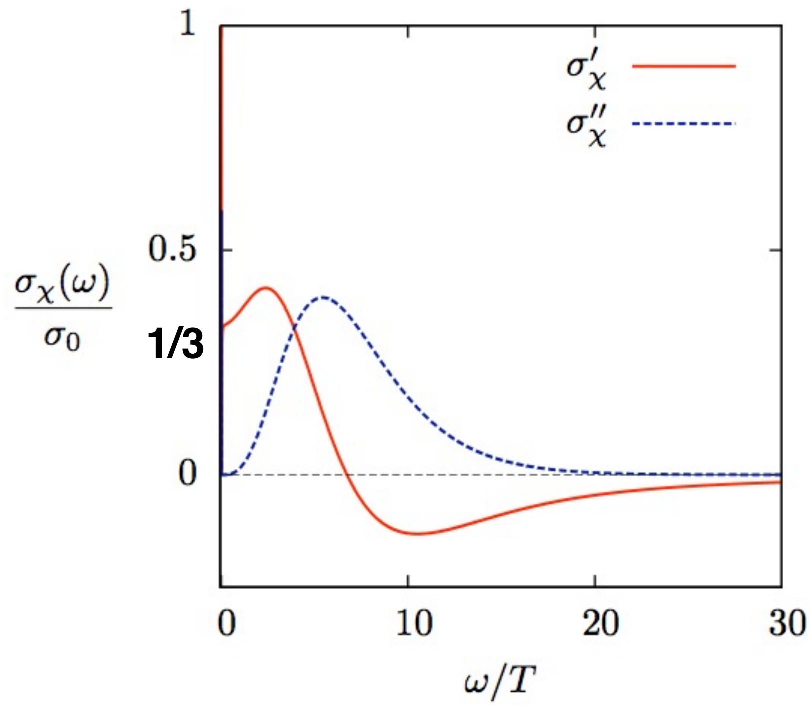
Dynamical chiral magnetic effect

Strong coupling



H.-U. Yee, arXiv:0908.4189, JHEP 0911:085, 2009;

Weak coupling



D.K., H. Warringa
Phys Rev D80 (2009) 034028

A.Rebhan, A.Schmitt, S.Stricker JHEP 0905, 084 (2009), G.Lifshytz, M.Lippert, arXiv:0904.4772;.A. Gorsky, P. Kopnin, A. Zayakin, arXiv:1003.2293, A.Gynther, K. Landsteiner, F. Pena Benitez, JHEP 1102 (2011) 110; V. Rubakov, arXiv:1005.1888, C. Hoyos, T. Nishioka, A. O'Bannon, JHEP1110 (2011) 084; …

CME persists at strong coupling - **hydrodynamical formulation?**

Hydrodynamics and symmetries

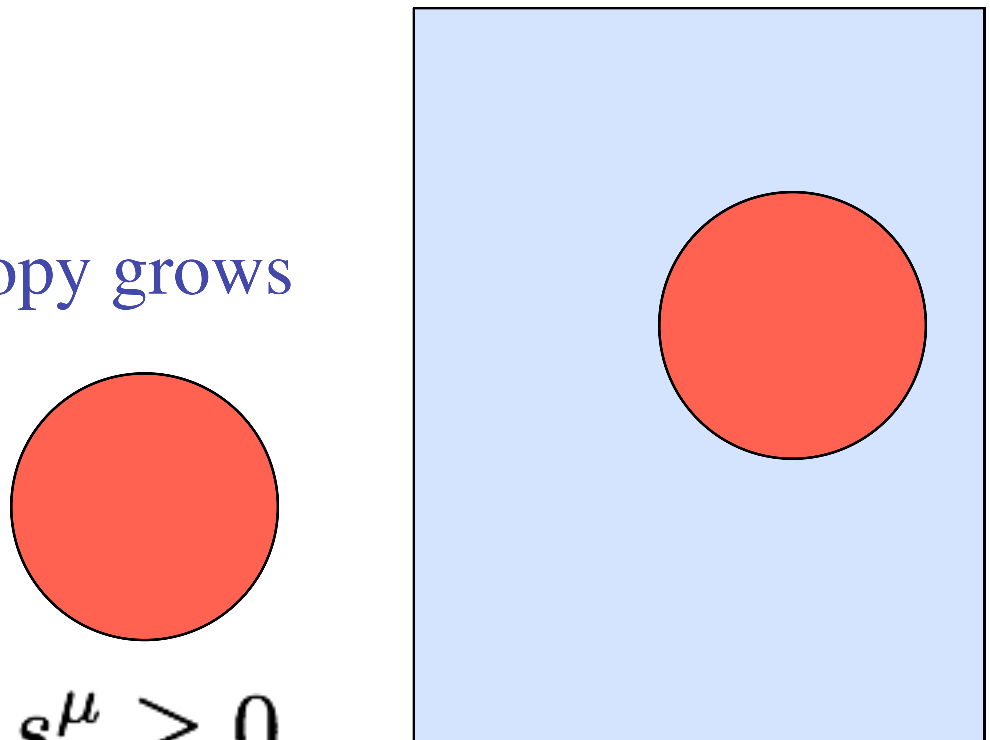
- Hydrodynamics: an effective low-energy TOE. States that the response of the fluid to slowly varying perturbations is completely determined by conservation laws (energy, momentum, charge, ...)
- Conservation laws are a consequence of symmetries of the underlying theory
- What happens to hydrodynamics when these symmetries are broken by quantum effects (anomalies of QCD and QED)?

Son, Surowka; Landsteiner, Megias, Pena-Benitez; Sadofyev, Isachenkov; Kalaydzhyan, Kirsch; DK, Yee; Zakharov; Jensen, Loganayagam, Yarom; Neiman, Oz; ….

No entropy production from P-odd anomalous terms

DK and H.-U. Yee, 1105.6360; PRD

Entropy grows



Mirror reflection: entropy decreases ?

$$\partial_\mu s^\mu \le 0$$

Decrease is ruled out by 2nd law of thermodynamics

$$\partial_\mu s^\mu \ge 0$$

↓

$$\partial_\mu s^\mu = 0$$

Allows to compute analytically 13 out of 18 anomalous transport coefficients in 2nd order relativistic hydrodynamics

DK and H.-U. Yee, 1105.6360; PRD

Conformally invariant Chiral magnetohydrodynamics

$$T^{\mu\nu\cdots}_{\alpha\beta\cdots}(x) \to e^{w\phi(x)} T^{\mu\nu\cdots}_{\alpha\beta\cdots}(x)$$

$$w = [\text{mass dimension}] + [\#\text{ of upper indices}] - [\#\text{ of lower indices}]$$

$$\mathcal{D}_\mu f = \nabla_\mu f + w\mathcal{W}_\mu$$

$$\mathcal{W}_\mu = u^\nu \nabla_\nu u_\mu - \frac{(\nabla_\nu u^\nu)}{3} u_\mu$$

$$\begin{gathered}\sigma^{\mu\nu}\mathcal{D}_\nu\bar{\mu}\ ,\ \omega^{\mu\nu}\mathcal{D}_\nu\bar{\mu}\ ,\ \Delta^{\mu\nu}\mathcal{D}^\alpha\sigma_{\nu\alpha}\ ,\ \Delta^{\mu\nu}\mathcal{D}^\alpha\omega_{\nu\alpha}\ ,\ \sigma^{\mu\nu}\omega_\nu\ ,\\ \sigma^{\mu\nu}E_\nu\ ,\ \sigma^{\mu\nu}B_\nu\ ,\ \omega^{\mu\nu}E_\nu\ ,\ \omega^{\mu\nu}B_\nu\ , u^\nu\mathcal{D}_\nu E^\mu\ ,\\ \epsilon^{\mu\nu\alpha\beta}u_\nu E_\alpha\mathcal{D}_\beta\bar{\mu}\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu B_\alpha\mathcal{D}_\beta\bar{\mu}\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu E_\alpha B_\beta\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu\mathcal{D}_\alpha E_\beta\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu\mathcal{D}_\alpha B_\beta\ .\end{gathered} \tag{2.60}$$

$$\omega^\mu \equiv \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}u_\nu\omega_{\alpha\beta} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}u_\nu\nabla_\alpha u_\beta \qquad E^\mu = F^{\mu\nu}u_\nu \quad , \quad B^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}u_\nu F_{\alpha\beta}$$

$$\sigma_{\mu\nu} = \frac{1}{2}(\mathcal{D}_\mu u_\nu + \mathcal{D}_\nu u_\mu) \quad , \quad \omega_{\mu\nu} = \frac{1}{2}(\mathcal{D}_\mu u_\nu - \mathcal{D}_\nu u_\mu) \quad , \quad \mathcal{D}_\mu u_\nu = \sigma_{\mu\nu} + \omega_{\mu\nu}$$

The CME in relativistic hydrodynamics: The Chiral Magnetic Wave

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

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

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)

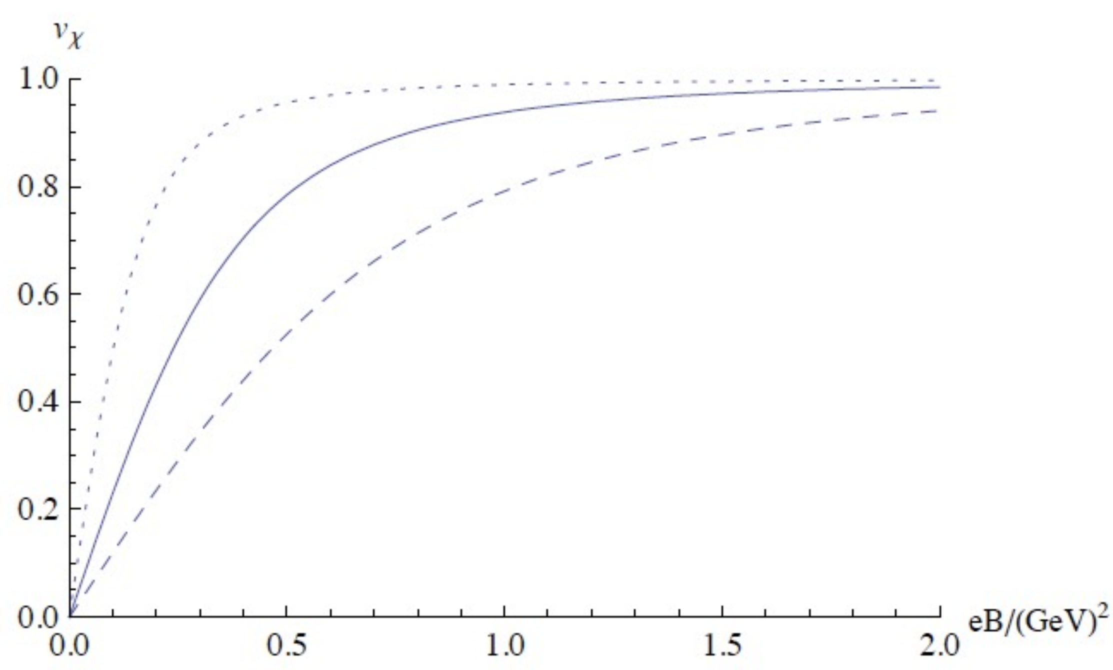
$$\left(\partial_0 \mp \frac{N_c e B \alpha}{2\pi^2}\partial_1 - D_L \partial_1^2\right) j^0_{L,R} = 0$$

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

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

The Chiral Magnetic Wave:
oscillations of electric and chiral charges coupled by the chiral anomaly

In strong magnetic field, CMW propagates with the speed of light!



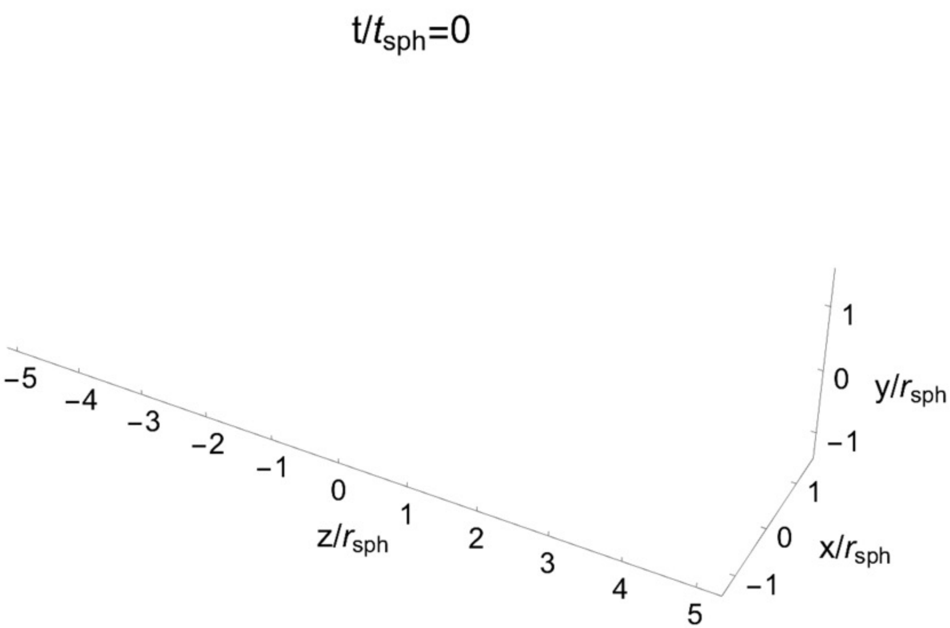
DK, H.-U. Yee, Phys Rev D'11

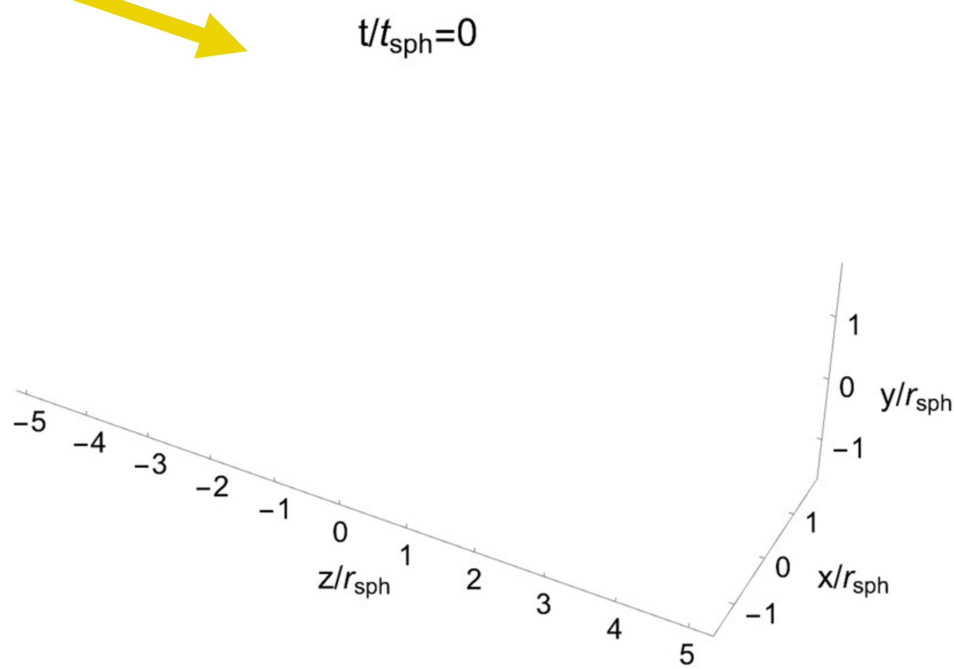
M. Mace, N. Mueller, S. Schlichting, S. Sharma, arxiv:1704.05887; PRD'17

Chiral Magnetic Wave in real time!

Anomalous transport in real time

j_a^0:axial charge $\vec{B}$ j_v^0:vector charge

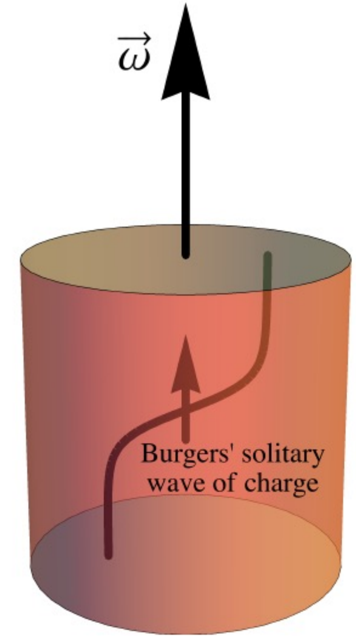




Static U(1) magnetic field in z-dir

G.Basar, DK, H.-U.Yee,
PhysRevB89(2014)035142

Anomalous transport induced by vorticity



Consider a "hot" system (QGP, DSM) with $\frac{\mu}{T} \ll 1$

The chemical potential is then proportional to charge density:

$$\mu \approx \chi^{-1}\rho + \mathcal{O}\left(\rho^3\right)$$

the CME current is

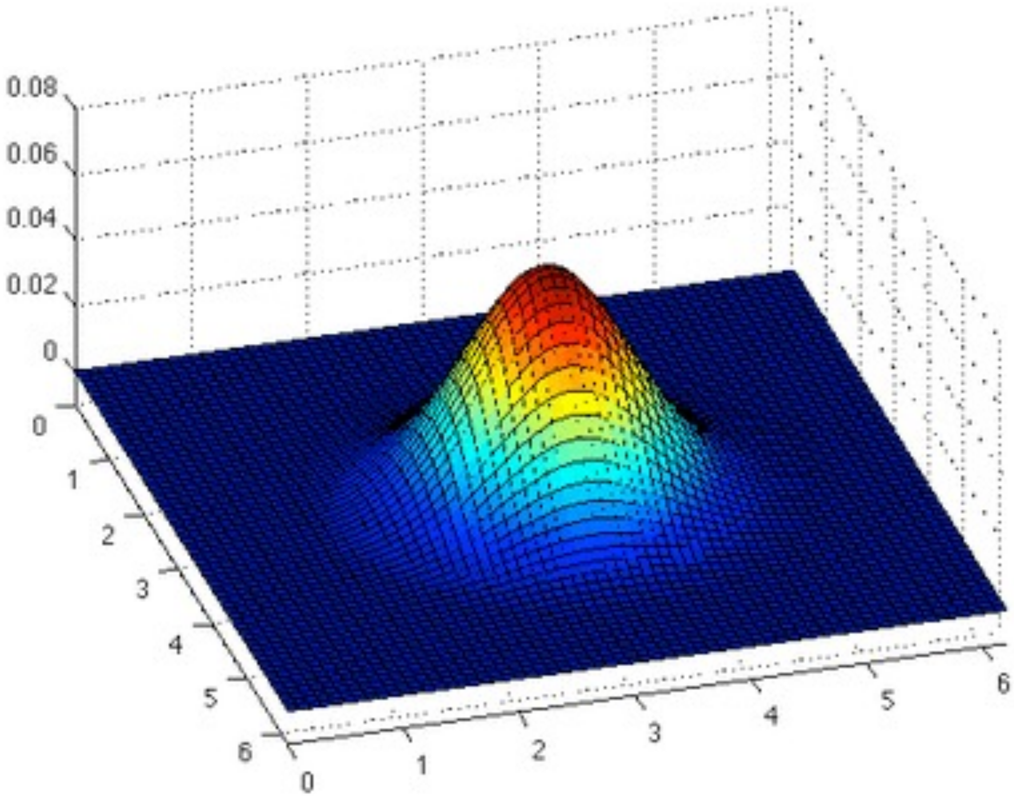
$$J^3 = \frac{ke}{4\pi^2}\left(\chi^{-2}\rho^2 + \frac{\pi^2}{3}T^2\right)\omega - D\partial_3\rho + \mathcal{O}\left(\partial^2, \rho^3\right)$$

and the charge conservation $\partial_t\rho + \partial_3 J^3 = 0$ leads to

$$\partial_t\rho + C\rho\partial_x\rho - D\partial_x^2\rho = 0 \qquad C = \frac{ke\omega}{2\pi^2\chi^2} \qquad x \equiv x^3$$

The Burgers' equation

$$\partial_t \rho + C\rho\partial_x \rho - D\partial_x^2 \rho = 0$$



Exactly soluble by Cole-Hopf transformation -

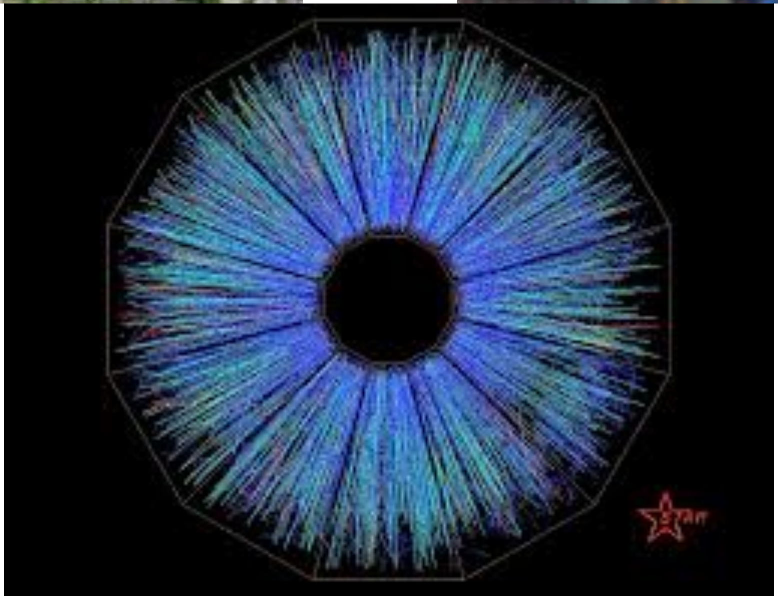
initial value problem, integrable dynamics

describes shock waves, solitons, ...

Searching for QCD topological transitions in heavy ion collisions

Relativistic Heavy Ion Collider (RHIC) at BNL

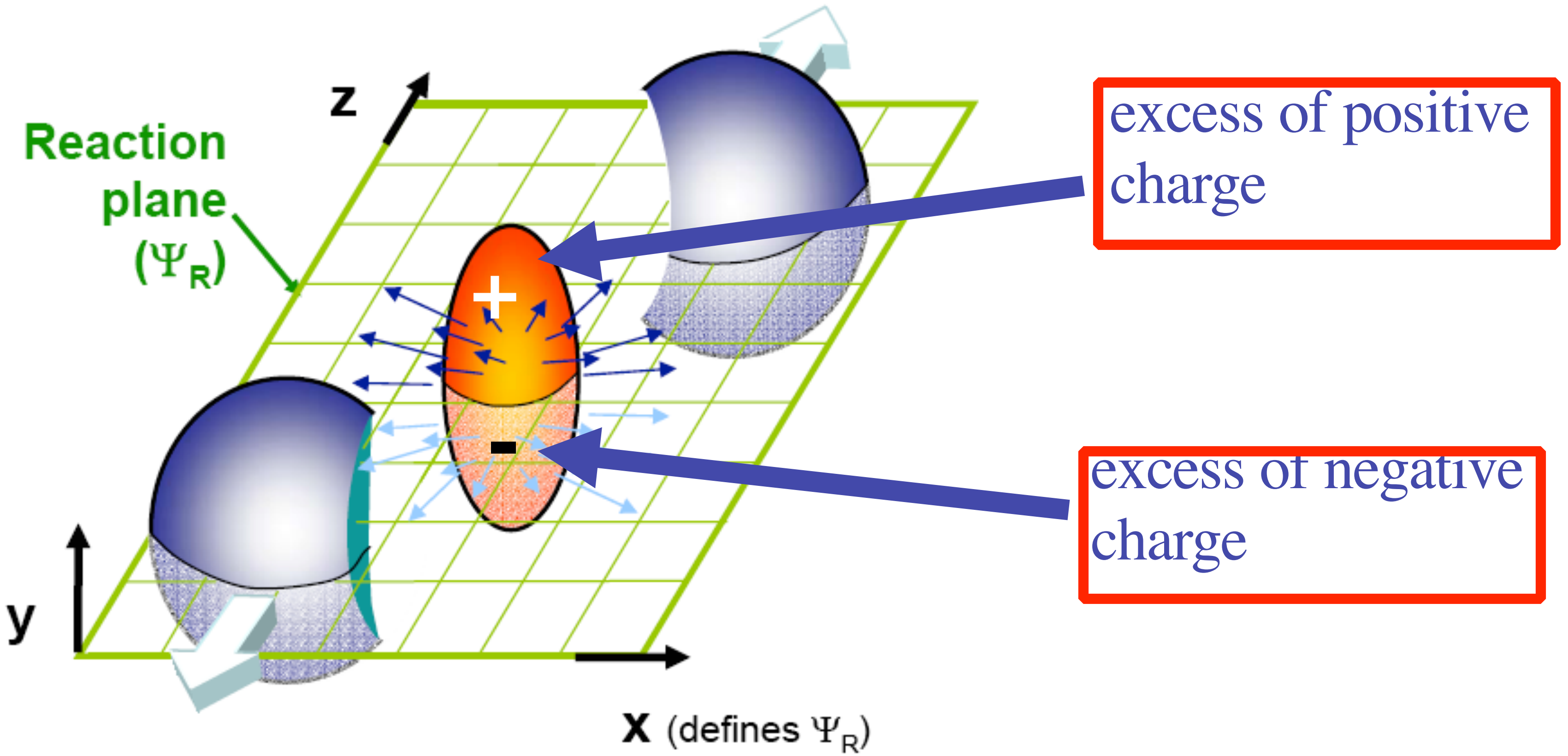
The STAR Collaboration at RHIC



Charged hadron tracks in a Au-Au collision at RHIC

Charge asymmetry w.r.t. reaction plane as a signature of chirality imbalance

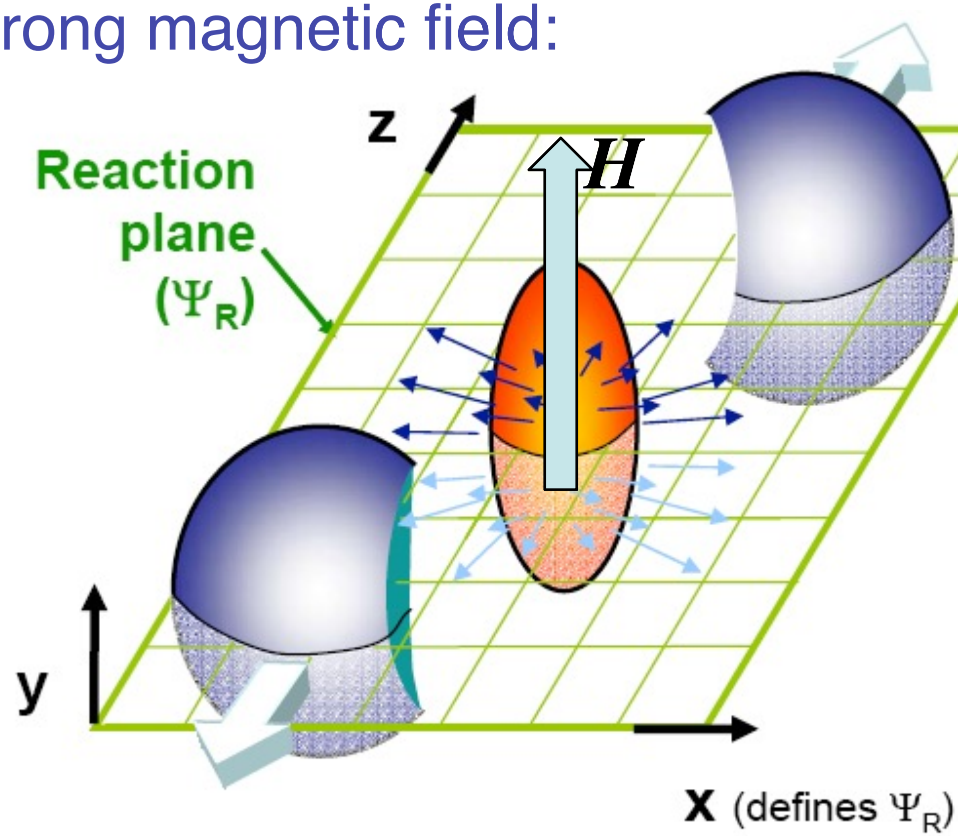
Electric dipole moment due to chiral imbalance



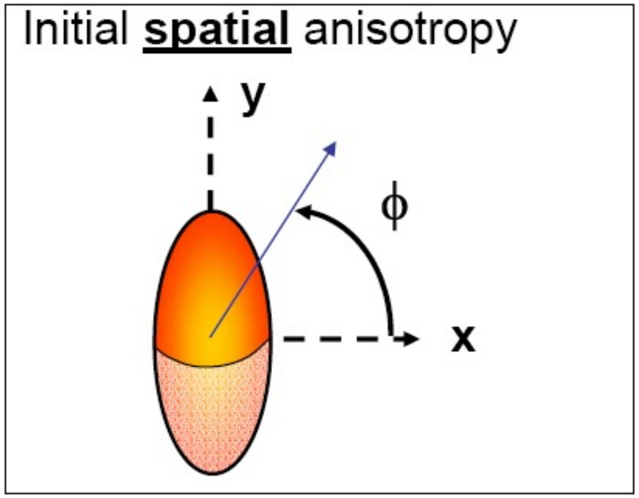
DK, hep-ph/0406125; Phys.Lett.B633(2006)260

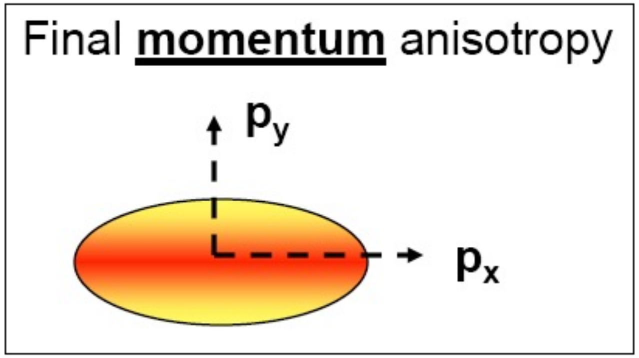
Is there a way to observe CME in nuclear collisions at RHIC and LHC?

Relativistic ions create a strong magnetic field:

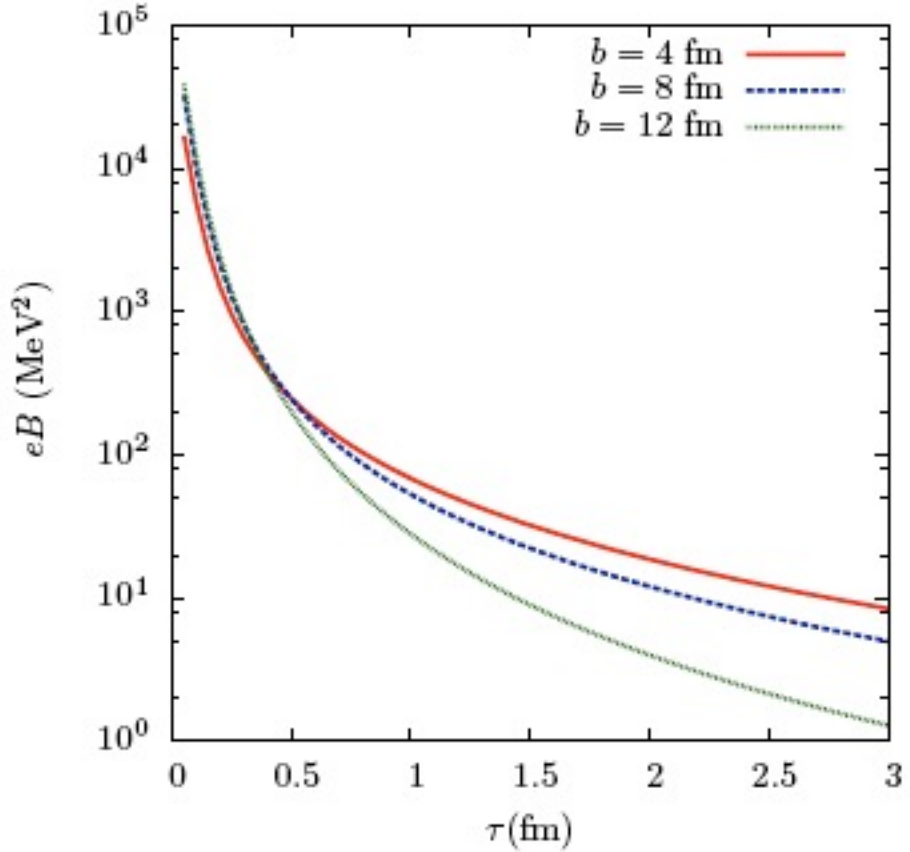


DK, McLerran, Warringa '07





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 ($Y_0 = 5.4$).

Comparison of magnetic fields

The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html

Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

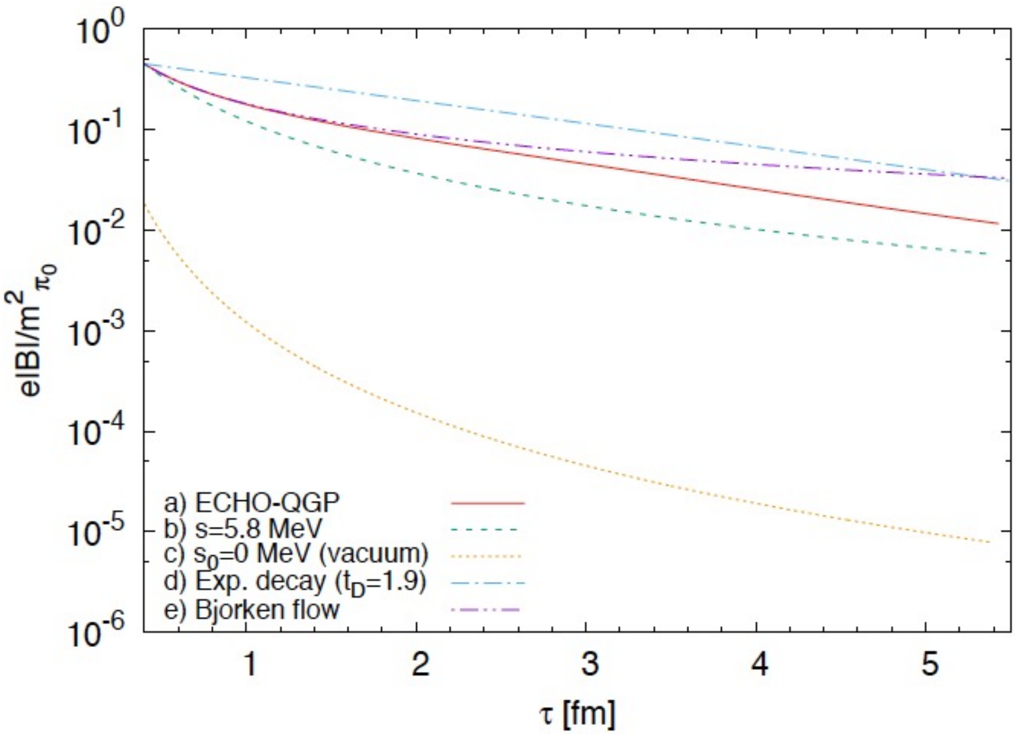
$$e\,B(\tau = 0.2\,\mathrm{fm}) \;=\; 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

Evolution of magnetic field in full ideal MHD

Numerical magneto-hydrodynamics for relativistic nuclear collisions

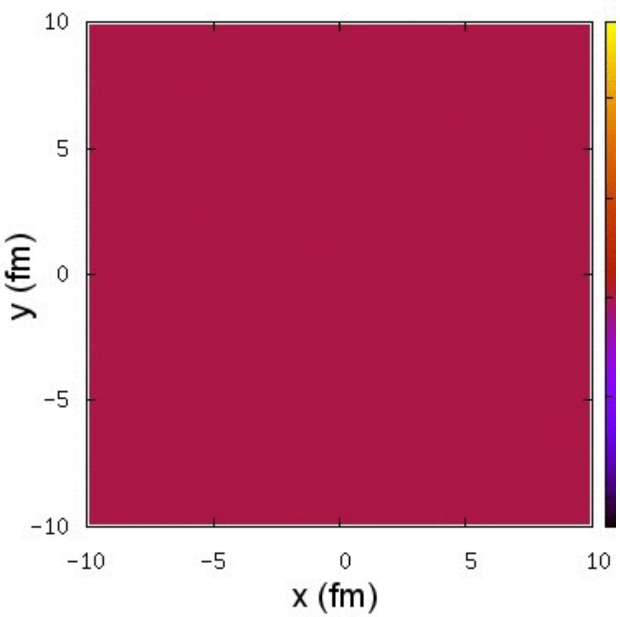
Gabriele Inghirami,[1,2,3,4,*] Luca Del Zanna,[5,6,7] Andrea Beraudo,[8]
Mohsen Haddadi Moghaddam,[9,8] Francesco Becattini,[5,6] and Marcus Bleicher[1,2,3,4]

arxiv:1609.03042

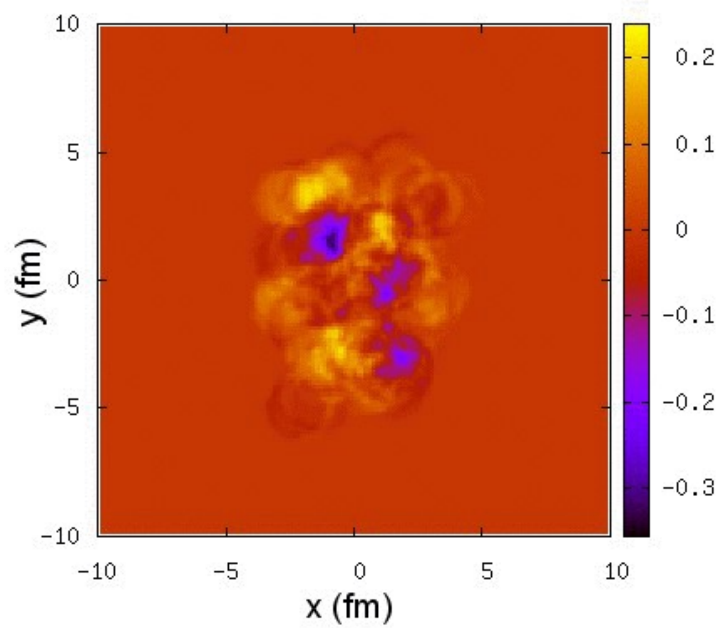


CMHD

Electric charge



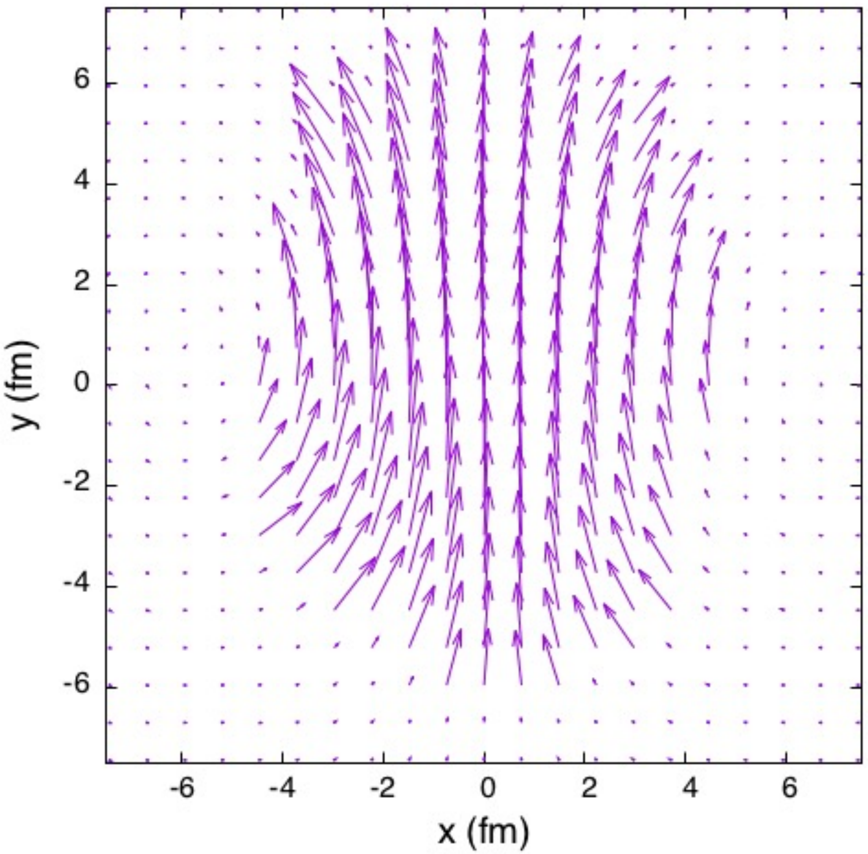
Chiral charge



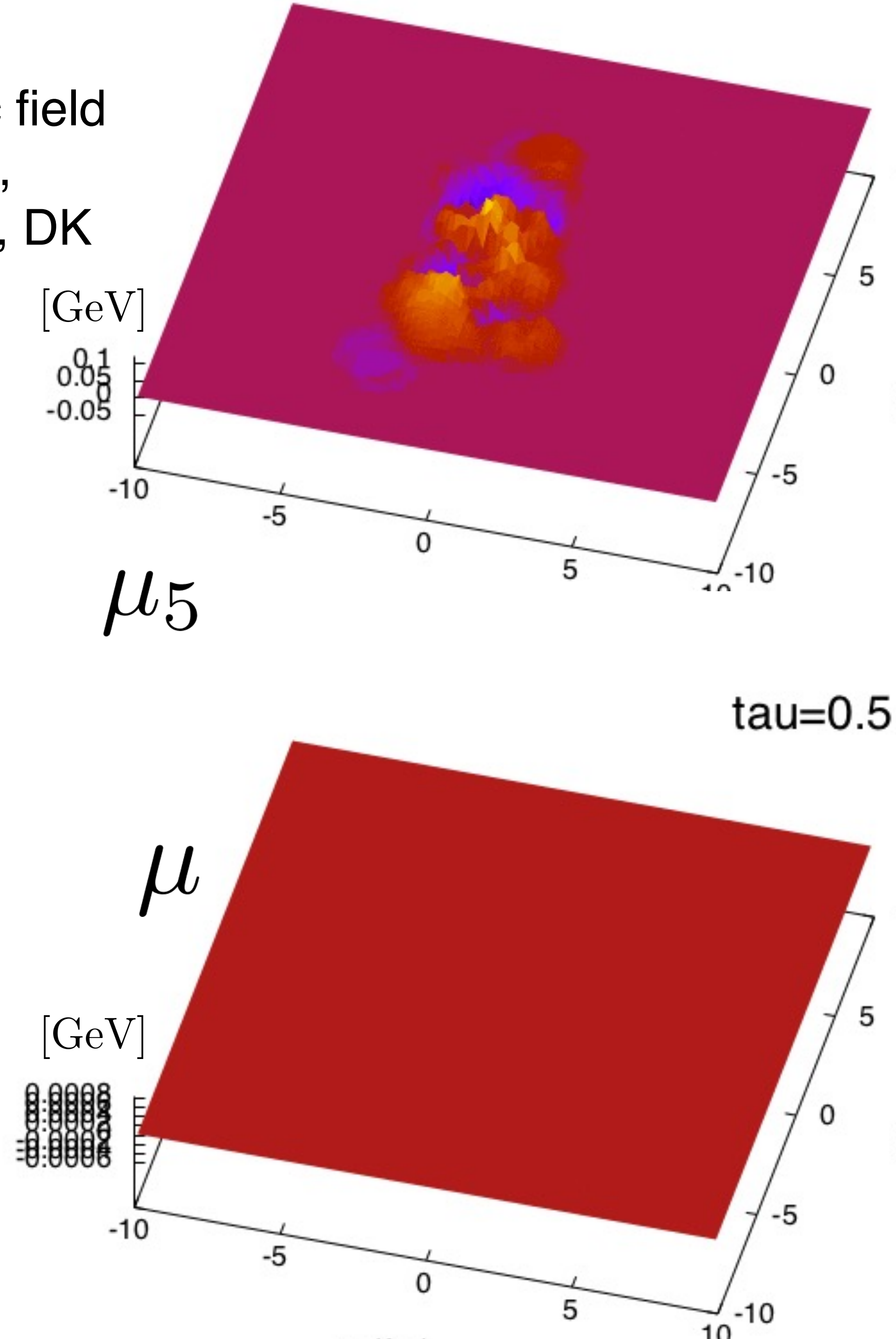
Y.Hirono, T.Hirano, DK, (Stony Brook – Tokyo), arxiv:1412.0311
(3+1) ideal CMHD (Chiral MagnetoHydroDynamics)

BEST Theory Collaboration

CMHD with dynamical MHD magnetic field from ECHO-QGP: Y. Hirono, M. Mace, G. Inghirami, F. Becattini, L.Del Zanna, DK

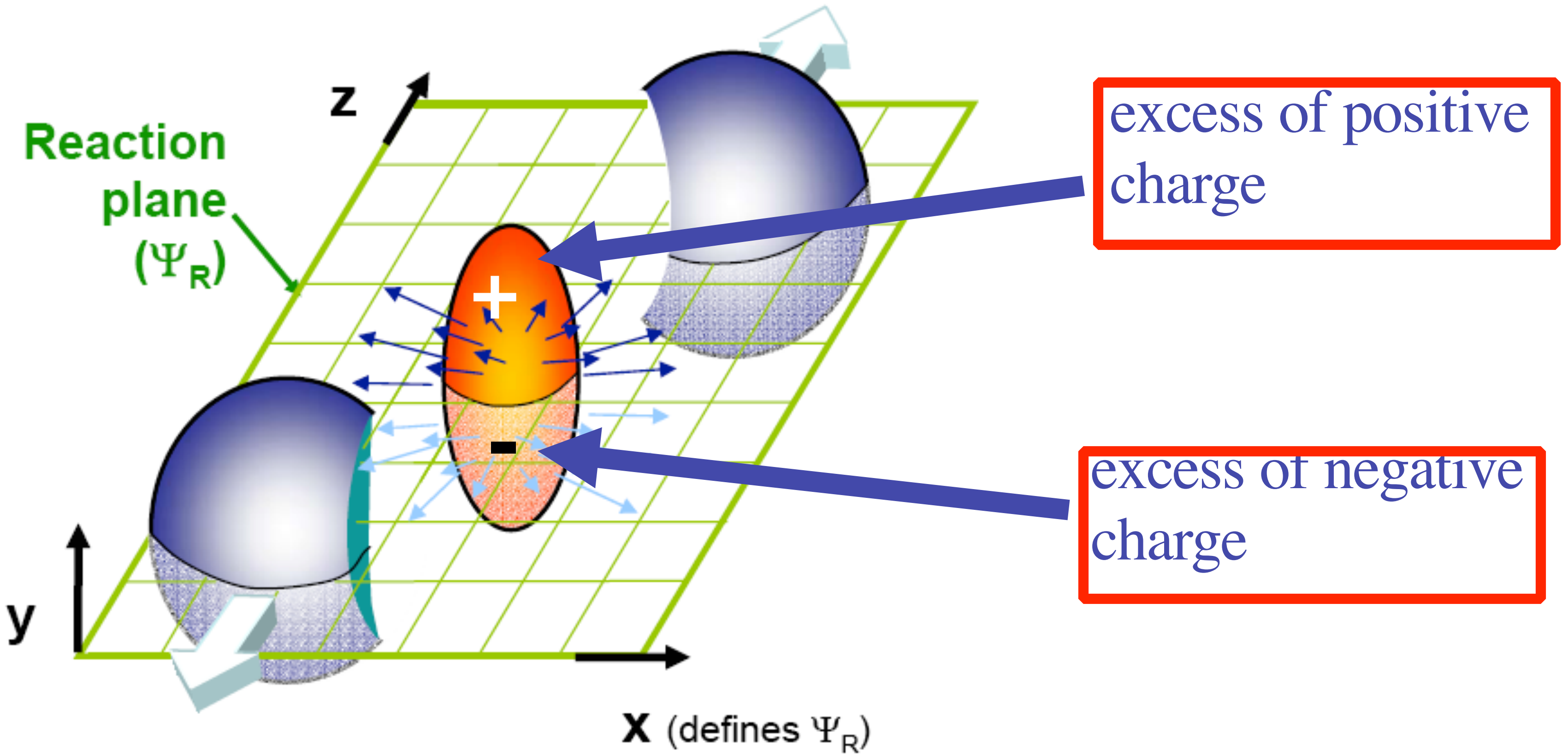


B field evolution
in transverse plane



Charge asymmetry w.r.t. reaction plane as a signature of chirality imbalance

Electric dipole moment due to chiral imbalance

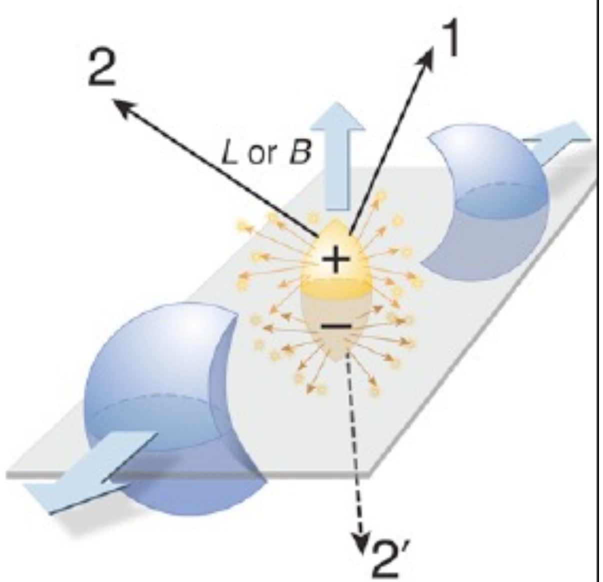


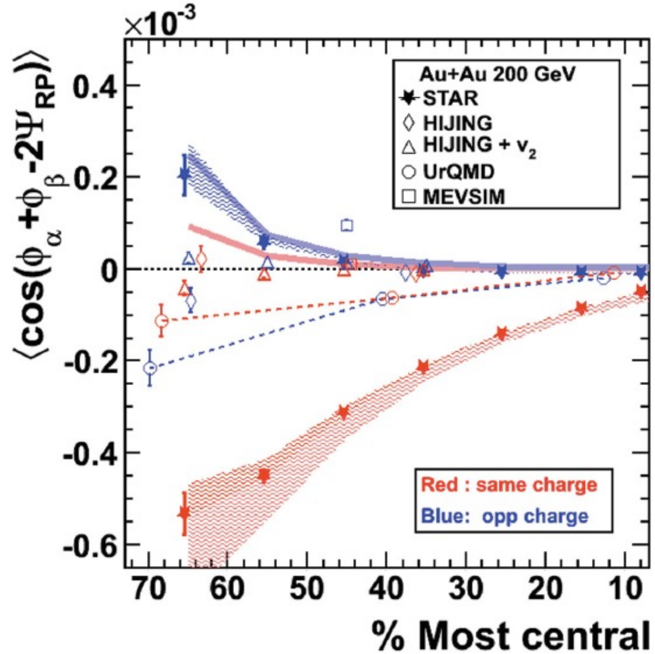
DK, hep-ph/0406125; Phys.Lett.B633(2006)260

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

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)





S.Voloshin '04

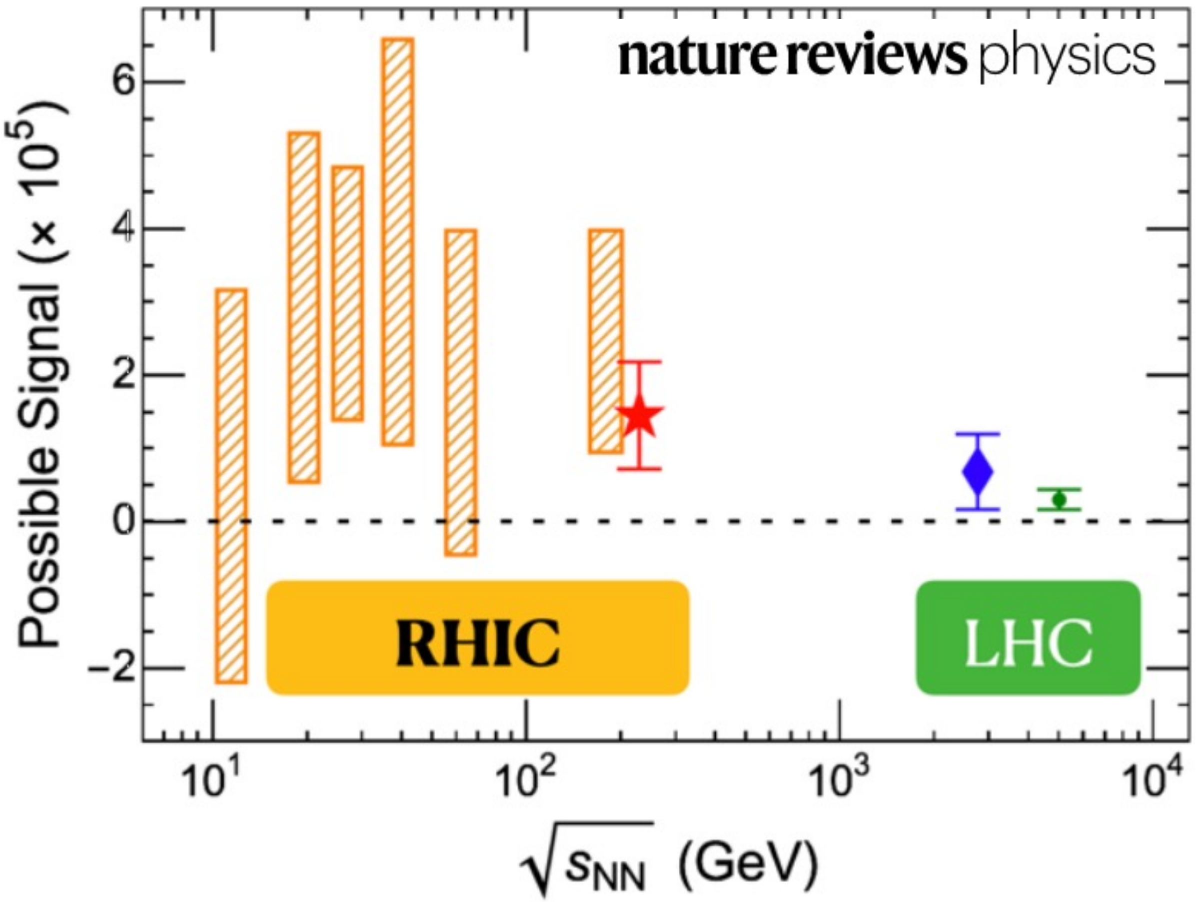
$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP})\rangle = \langle \cos\Delta\phi_\alpha \, \cos\Delta\phi_\beta\rangle - \langle \sin\Delta\phi_\alpha \, \sin\Delta\phi_\beta\rangle$$

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

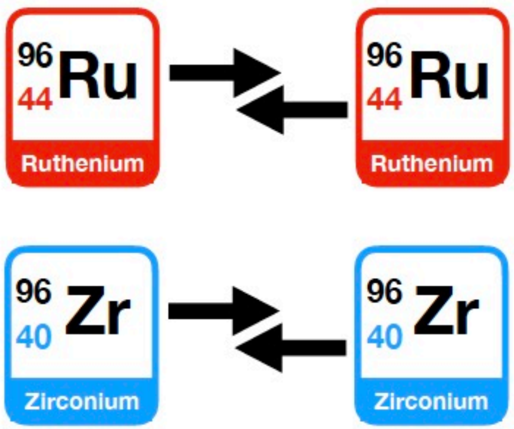
NB: P-even quantity (strength of P-odd fluctuations) –
– subject to large background contributions

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

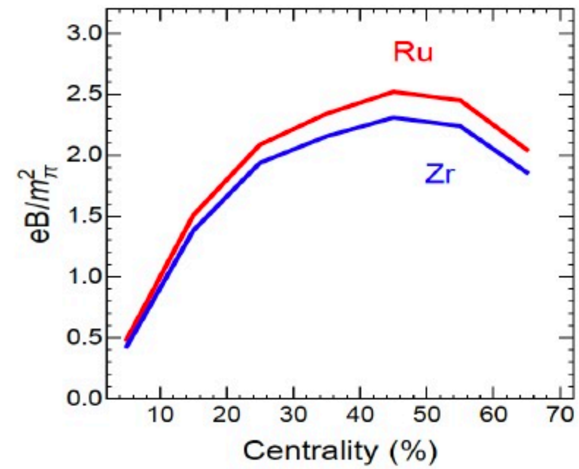
Review + Compilation of the current data: DK, J. Liao, Nature Reviews (Phys.) 3 (2021) 55



Detection of QCD topological transitions using the isobar collisions at RHIC

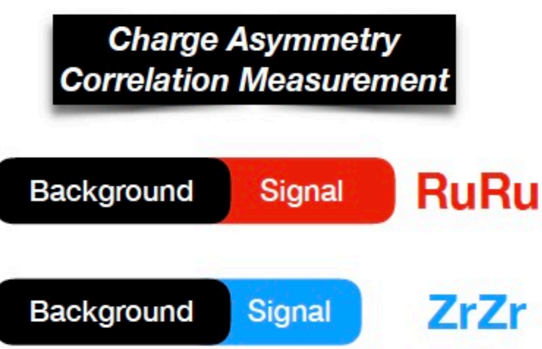


(a)



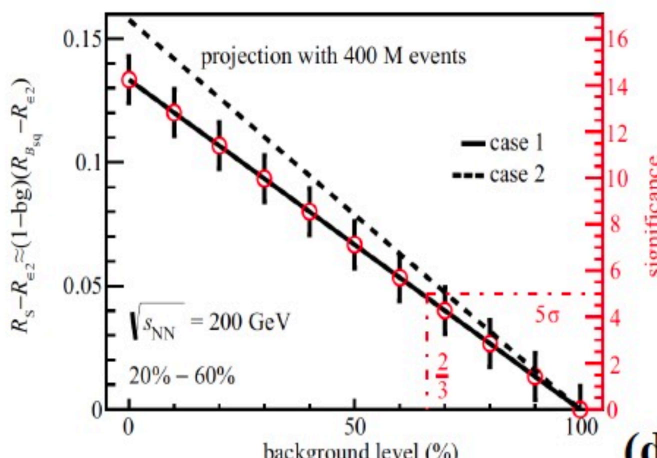
(b)

Isobar run just completed in May '18; 2 billion events recorded per each pair



(c)

DK, J.Liao, Nuclear Physics News, v.28,no.2 (2018)



(d)

STAR Collaboration

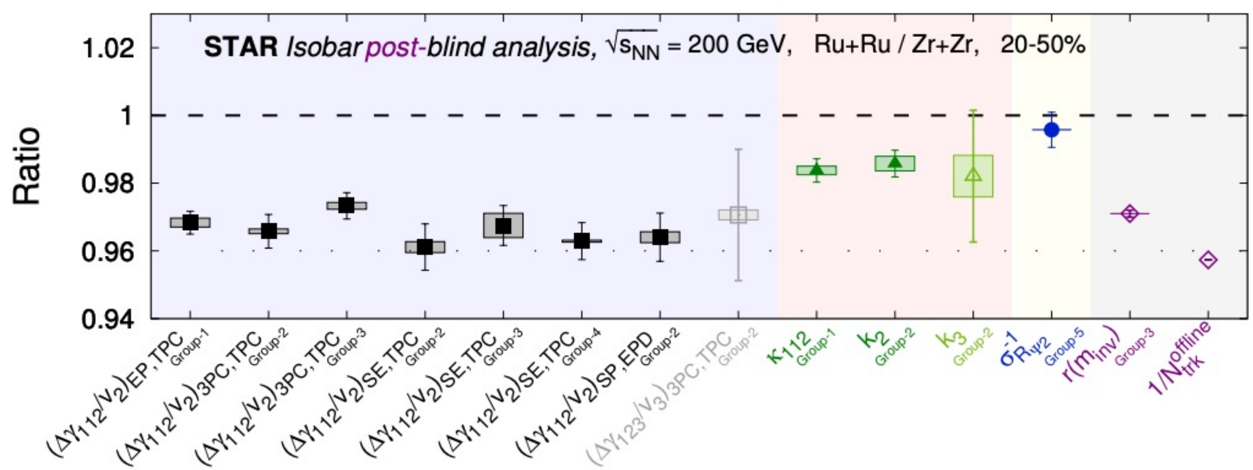
Expect Ru/Zr > 1 for CME signal, and Ru/Zr =1 for background

Detection of QCD topological transitions using the isobar collisions at RHIC

The results have just been released! (Aug 31, 2021)

Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at RHIC

between the two isobar systems. Observed differences in the multiplicity and flow harmonics at the matching centrality indicate that the magnitude of the CME background is different between the two species. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.



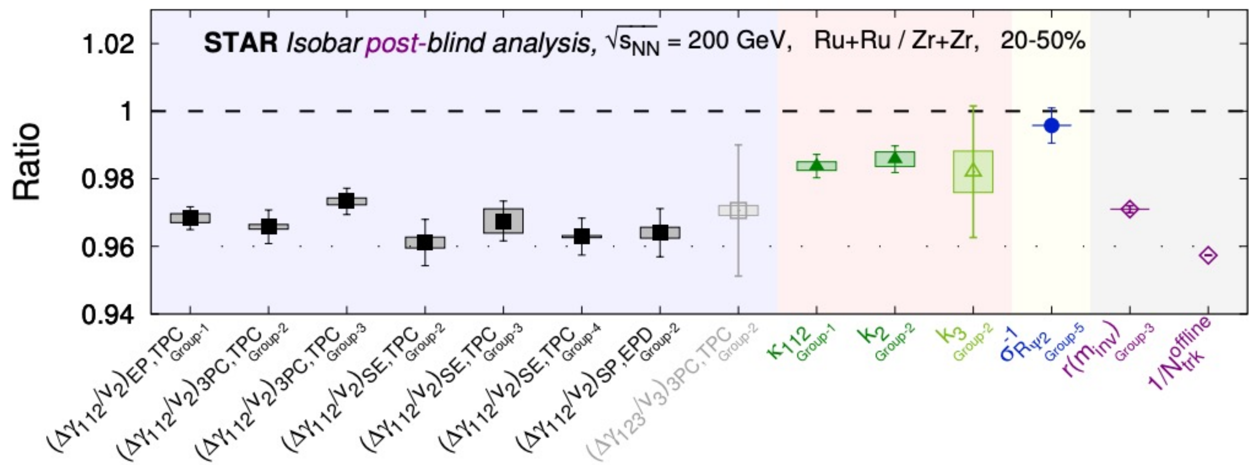
< 1 !

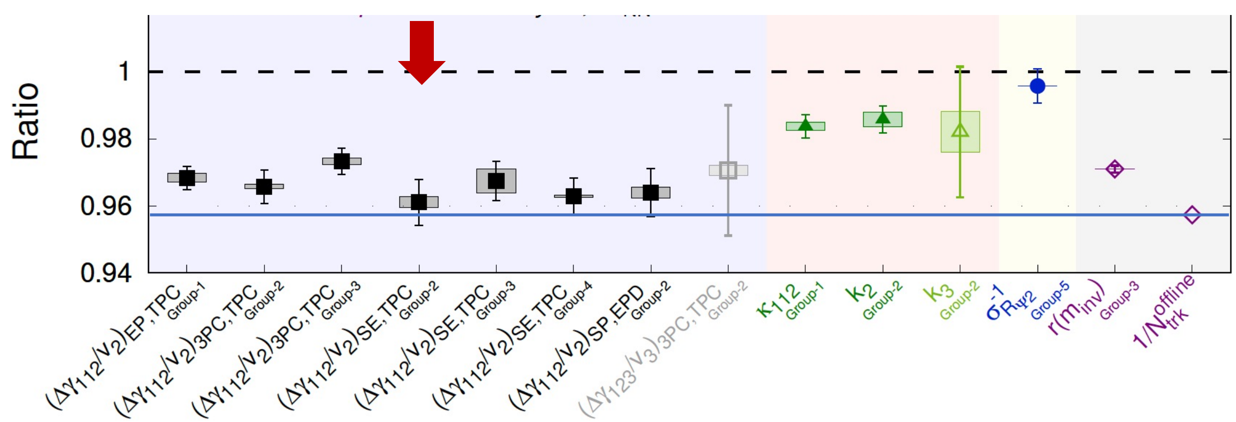
CME excluded?

not predicted by any theory, CME or not

Direct detection of QCD topological transitions using the isobar collisions at RHIC

of clusters scaling with multiplicity, the value of $\Delta\gamma$ scales with the inverse of multiplicity [20], i.e. $N\Delta\gamma \propto v_2$ with the proportionality presumably equal between the two isobars. Because of this, it may be considered that the proper baseline for the ratio of $\Delta\gamma/v_2$ between the two isobars is the ratio of the inverse multiplicities of the two systems. Analysis with respect to this baseline is not documented in the pre-blinding procedures of this blind analysis, so is not reported as part of the blind analysis. We include this inverse multiplicity ratio as the right-most point in Fig. 27.





Depending on the observable, CME is present at 1-4 σ level

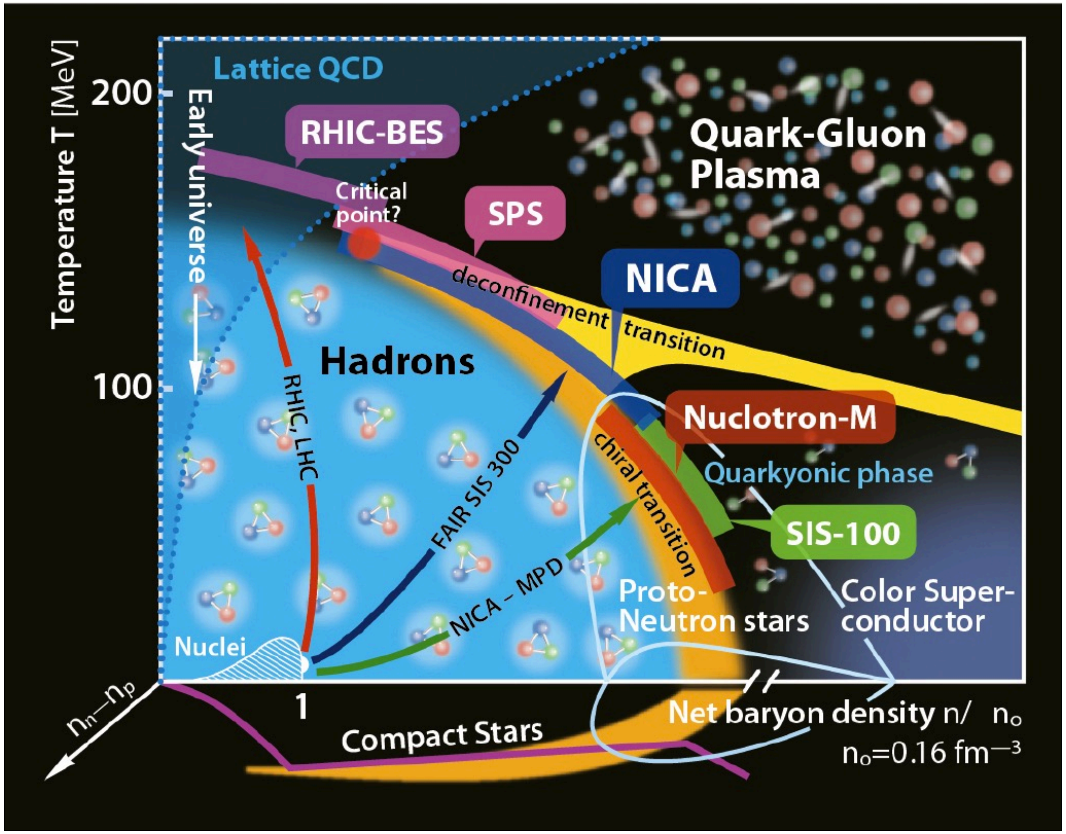
Detailed analysis is needed, and is ongoing

Stay tuned!

Chern-Simons fluctuations near a critical point

K. Ikeda, DK, Y. Kikuchi, arXiv: 2012.02926

Motivation: what happens to topological fluctuations near the critical point? Could there be an enhancement due to criticality?



Chern-Simons fluctuations near a critical point

Simple system that exhibits a critical point: massive Schwinger model near θ = π

S. Coleman, Annals Phys. 101(1976) 239

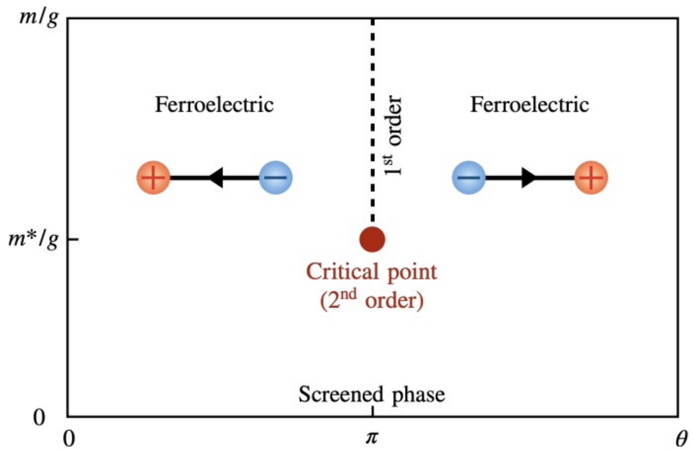


FIG. 1: Phase diagram of the massive Schwinger model in the $(\theta, m/g)$ plane. At $\theta = \pi$ and large masses $m > m^*$, the ferroelectric phases with opposite orientations of electric field are separated by the line of the first order phase transition. This line terminates at $m^* \approx 0.33g$ at the critical point, where the phase transition is second order. For small masses $m \ll m^*$, the electric field is screened by the production of light fermion-antifermion pairs.

K. Ikeda, DK, Y. Kikuchi, arXiv: 2012.02926

$$S = \int \mathrm{d}^2 x \left[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \bar{\psi}(\mathrm{i}\gamma^\mu D_\mu - m e^{\mathrm{i}\gamma_5 \theta})\psi \right]$$

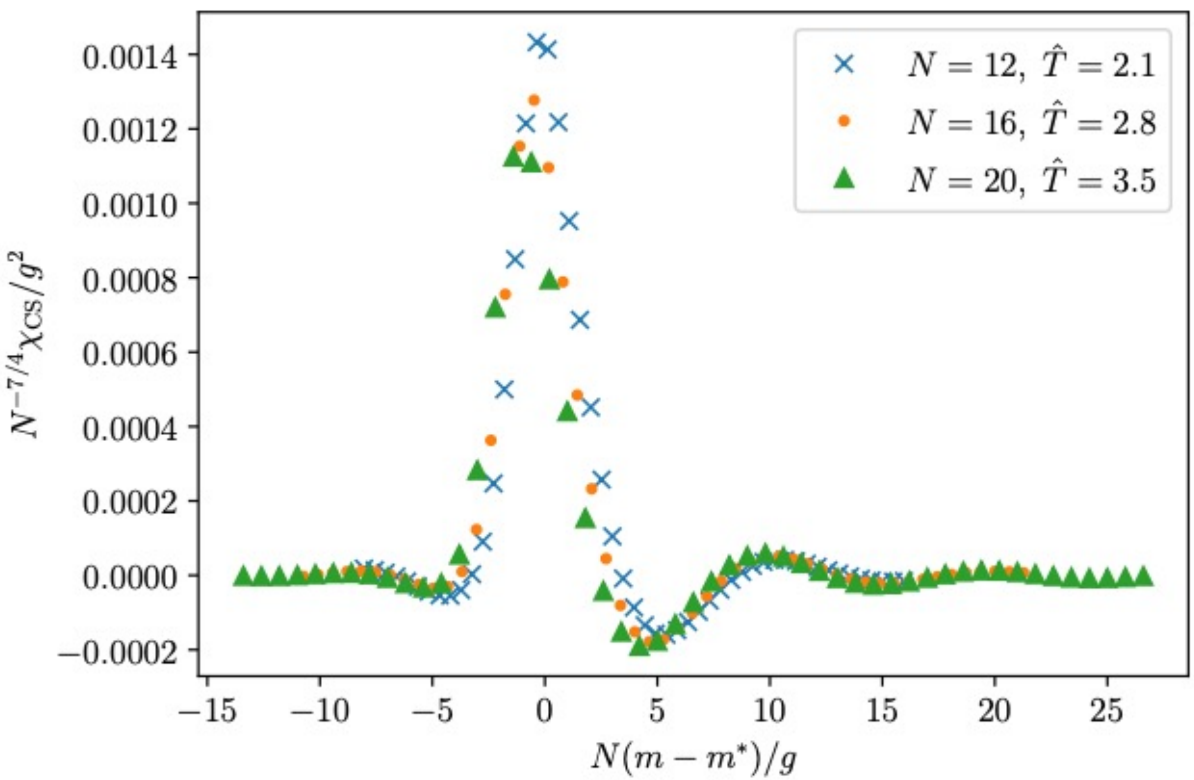
bosonization

$$H = \int \mathrm{d}x \Big[\frac{1}{2}\dot{\varphi}^2 + \frac{1}{2}(\partial_1 \varphi)^2 + \frac{\mu^2}{2}\left(\varphi + \frac{\theta}{2\sqrt{\pi}}\right)^2 - c m \mu \cos(2\sqrt{\pi}\varphi) \Big].$$

$$\mu = \frac{g}{\sqrt{\pi}}$$

$$U(\varphi) = \frac{\mu^2}{2}\left(\varphi + \frac{\theta}{2\sqrt{\pi}}\right)^2 - c m \mu \cos\left(2\sqrt{\pi}\varphi\right)$$

Chern-Simons fluctuations near a critical point: a digital quantum simulation



K. Ikeda, DK, Y. Kikuchi, arXiv: 2012.02926

Sharp peak in topological fluctuations near the critical point!

Search for CME in low-energy heavy ion collisions?

Real-time dynamics of CME

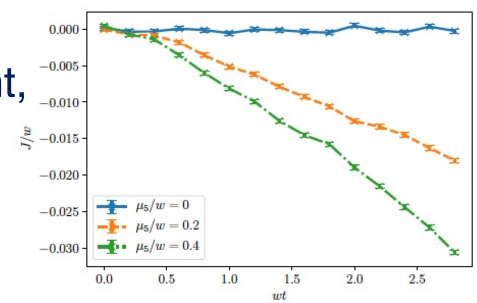
Study of real-time CME dynamics in (1+1) QED using a digital quantum simulation (IBM-Q)

DK, Y. Kikuchi, arXiv:2001.00698, Phys.Rev.Res. 2 (2020)

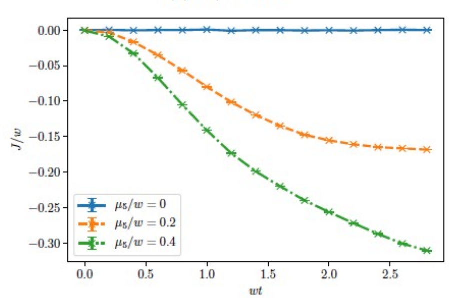
$$S = \int \mathrm{d}^2x \left[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{g\theta}{4\pi} \epsilon^{\mu\nu} F_{\mu\nu} + \bar{\psi}(\mathrm{i}\gamma^\mu D_\mu - m)\psi \right]$$

Jordan-Wigner transformation – spin chain

CME current, μ_5 quench:

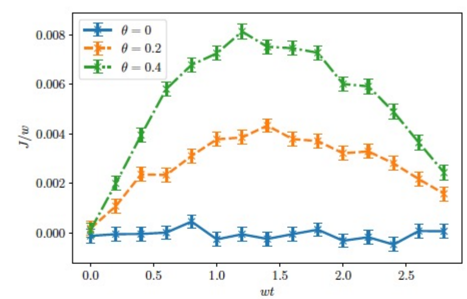


(a) $M/w = 0.1$

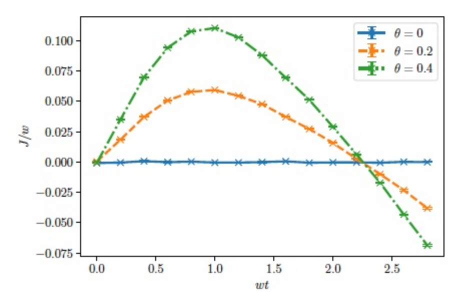


(b) $M/w = 0.5$

CME current, θ quench:



(a) $M/w = 0.1$

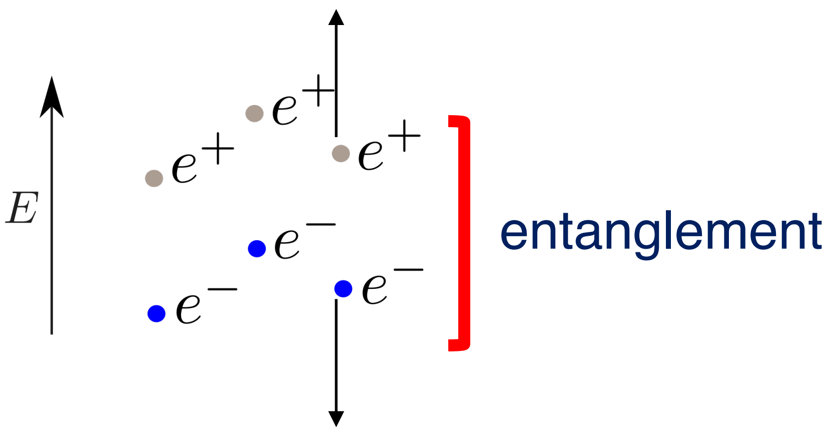


(b) $M/w = 0.5$

Real-time dynamics of CME and "chiral entanglement"

A. Florio, DK, PRD '21

Study of real-time evolution of entanglement between the left- and right-movers in Schwinger pair production by electric pulses



$$S_G = \int \mathrm{d}k_1 \left[\left(1 - |\beta_{k_1,t^*}|^2\right) \log\left(1 - |\beta_{k_1,t^*}|^2\right) + |\beta_{k_1,t^*}|^2 \log\left(|\beta_{k_1,t^*}|^2\right) \right] ,$$

Gibbs entropy

↕

Entanglement entropy

$$|\alpha_{k_1,t^*}|^2 = 1 - |\beta_{k_1,t^*}|^2$$

$$S_E = -\int \mathrm{d}k_1 \left[|\alpha_{k_1,t^*}|^2 \log\left(|\alpha_{k_1,t^*}|^2\right) + |\beta_{k_1,t^*}|^2 \log\left(|\beta_{k_1,t^*}|^2\right) \right]$$

Real-time dynamics of CME and "chiral entanglement"

A. Florio, DK,
to appear on June 3

Entanglement entropy can be reconstructed from the moments of multiplicity distribution:

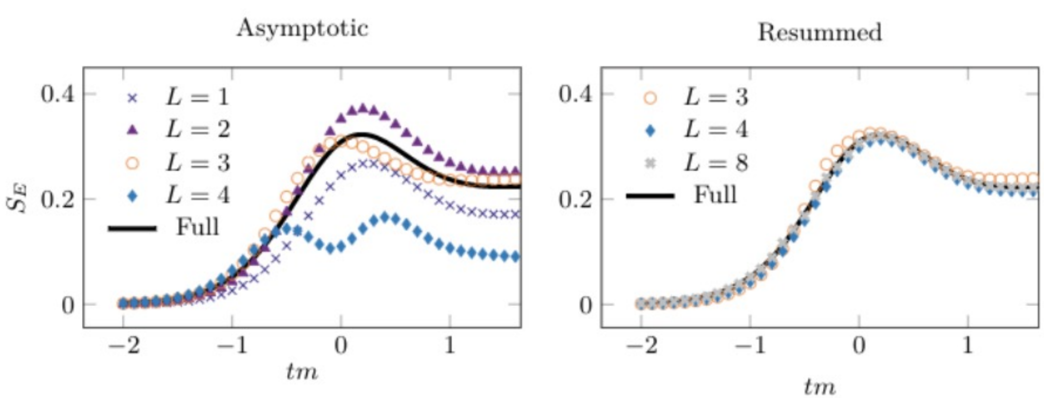
$$S_E = \sum_{l=1}^{\infty} \frac{C_{2l}}{(2l)!}(2\pi)^{2l}|B_{2l}|$$

Bernoulli numbers

Derived first for shot noise in Quantum Point Contacts:

I. Klich, L. Levitov, PRL (2009)

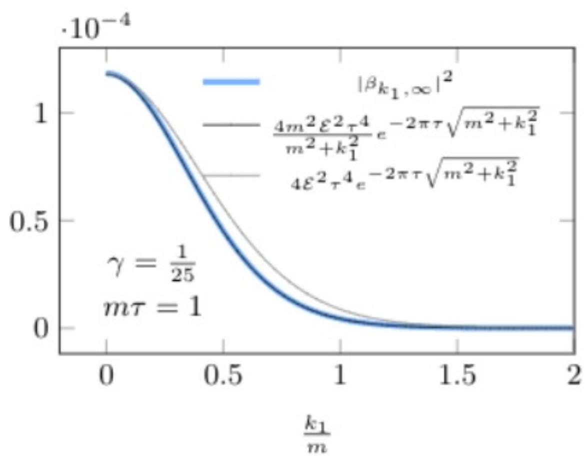
An efficient way to resum this series is found, using Pade-Borel methods:

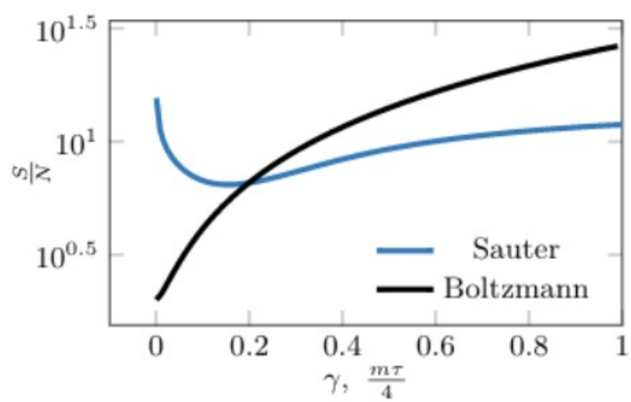


Real-time dynamics of CME and "chiral entanglement"

A. Florio, DK, PRD '21

Short pulses lead to an approximately thermal entropy and momentum spectrum:





Semiclassical derivation:

DK, K. Tuchin, NPA (2005)

Could entanglement be at the origin of "fast equilibration" in high-energy hadron and heavy ion collisions?

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

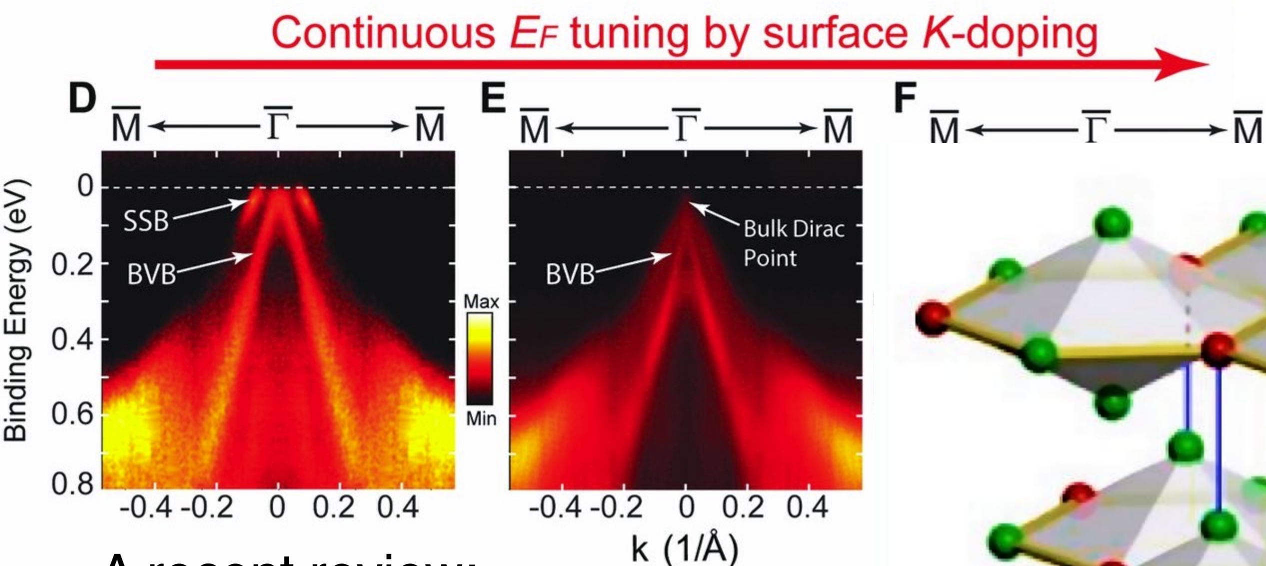
Zh. Eksp. Teor. Fiz. 59, 1280–1298 (October, 1970)

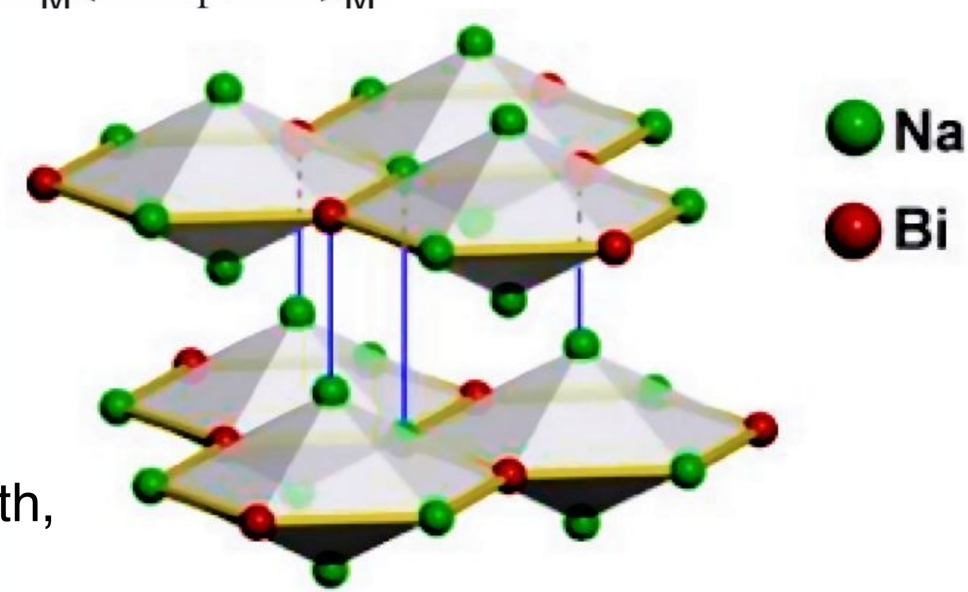
The question of the possible existence of substances having an electron spectrum without any energy gap and, at the same time, not possessing a Fermi surface is investigated. First of all the question of the possibility of contact of the conduction band and the valence band at a single point is investigated 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





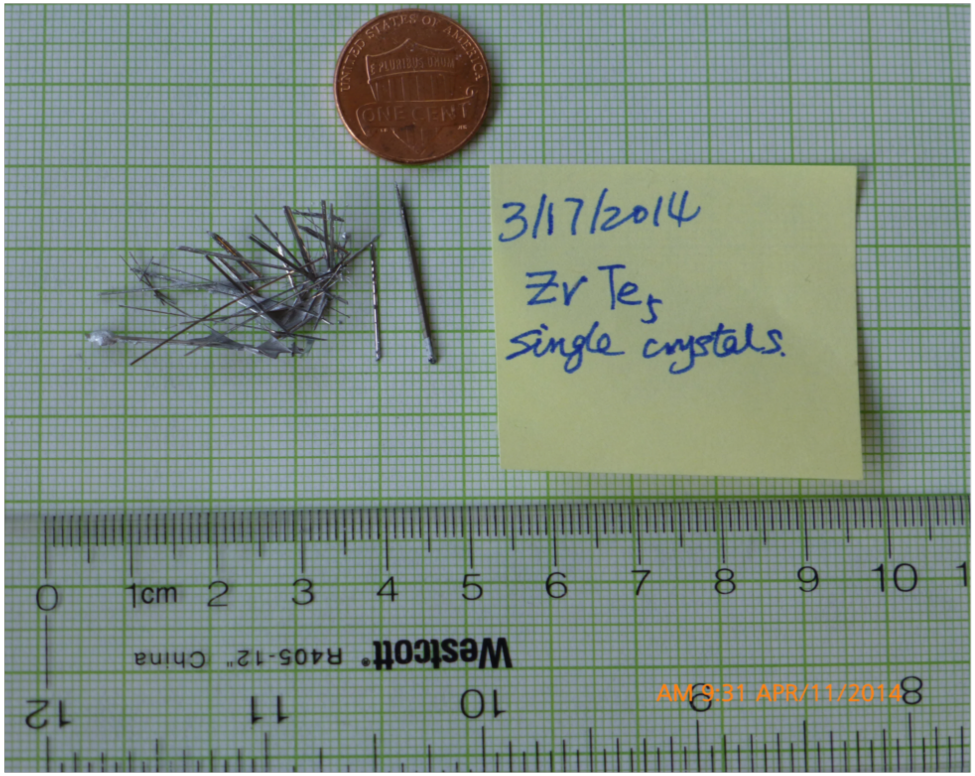
A recent review:
N.P.Armitage,E.Mele,A.Vishwanath,
Rev.Mod.Phys.90, 015001 (2018)

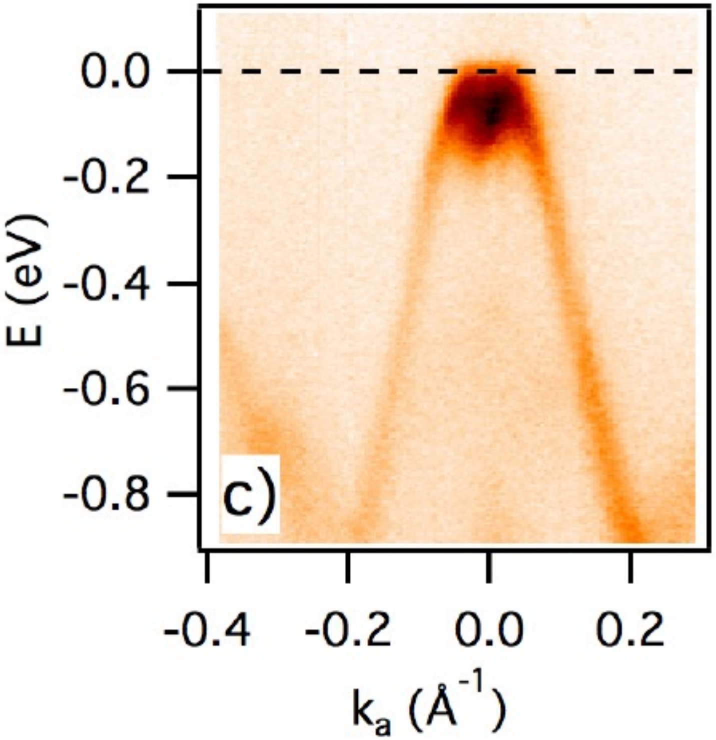
Z.K.Liu et al., Science 343 p.864 (**Feb 21, 2014**)

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]





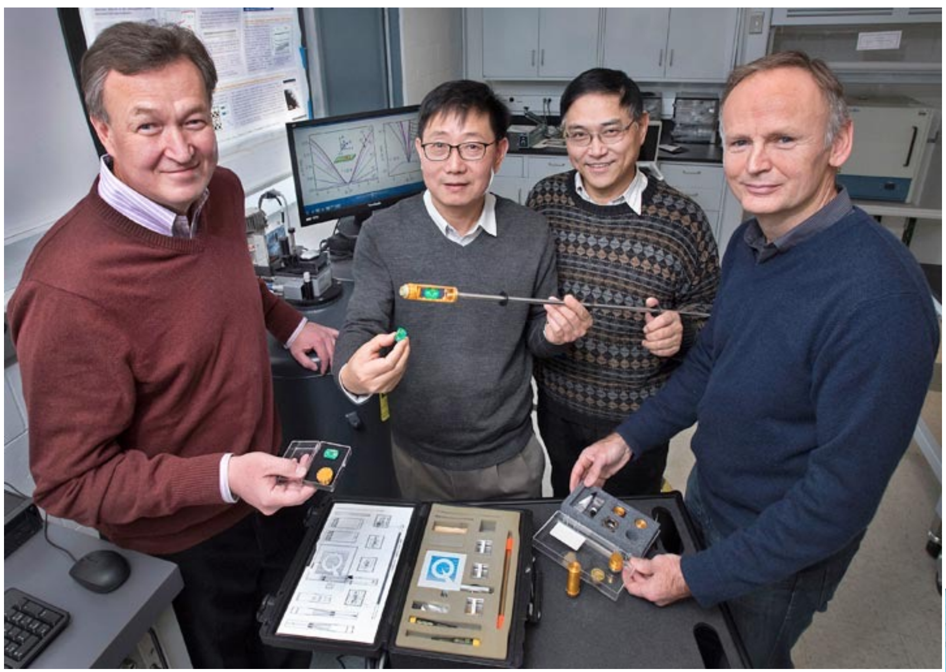
arXiv:1412.6543 (December 2014); Nature Physics **12**, 550 (2016)

CME in condensed matter:

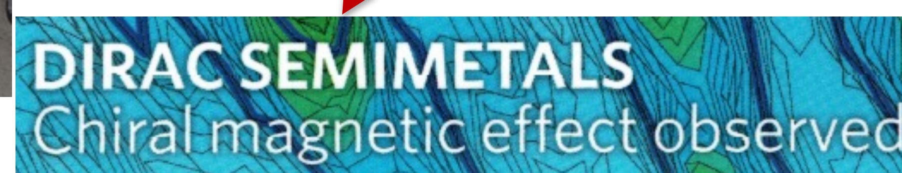
Observation of the chiral magnetic effect in $ZrTe_5$

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]

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]

Put the crystal in parallel E, B fields – the anomaly generates chiral charge:

$$\frac{d\rho_5}{dt} = \frac{e^2}{4\pi^2\hbar^2 c}\vec{E}\cdot\vec{B} - \frac{\rho_5}{\tau_V}.$$

and thus the chiral chemical potential:

$$\mu_5 = \frac{3}{4}\frac{v^3}{\pi^2}\frac{e^2}{\hbar^2 c}\frac{\vec{E}\cdot\vec{B}}{T^2+\frac{\mu^2}{\pi^2}}\tau_V.$$

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]

so that there is a chiral magnetic current:

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

resulting in the quadratic dependence of CME conductivity on B:

$$J^i_{\rm CME} = \frac{e^2}{\pi\hbar}\,\frac{3}{8}\frac{e^2}{\hbar c}\,\frac{v^3}{\pi^3}\,\frac{\tau_V}{T^2+\frac{\mu^2}{\pi^2}}\, B^i B^k E^k \equiv \sigma^{ik}_{\rm CME}\, E^k.$$

adding the Ohmic one – negative magnetoresistance

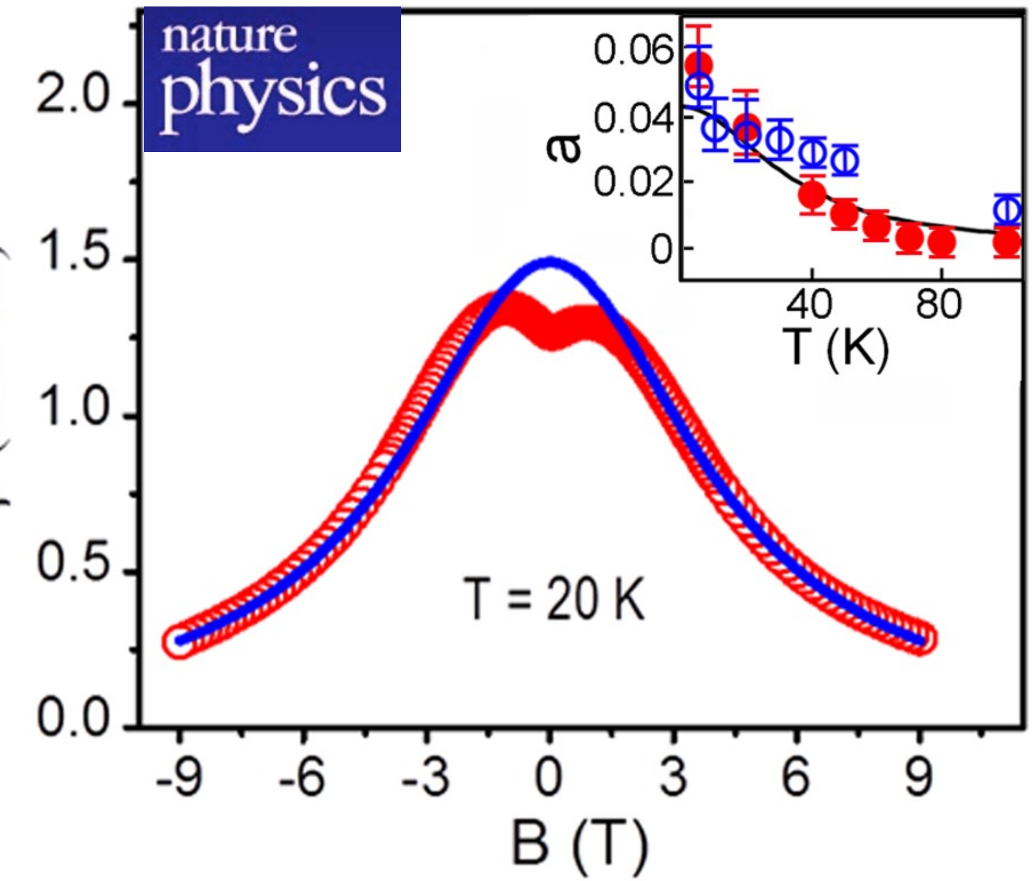
Son, Spivak, 2013

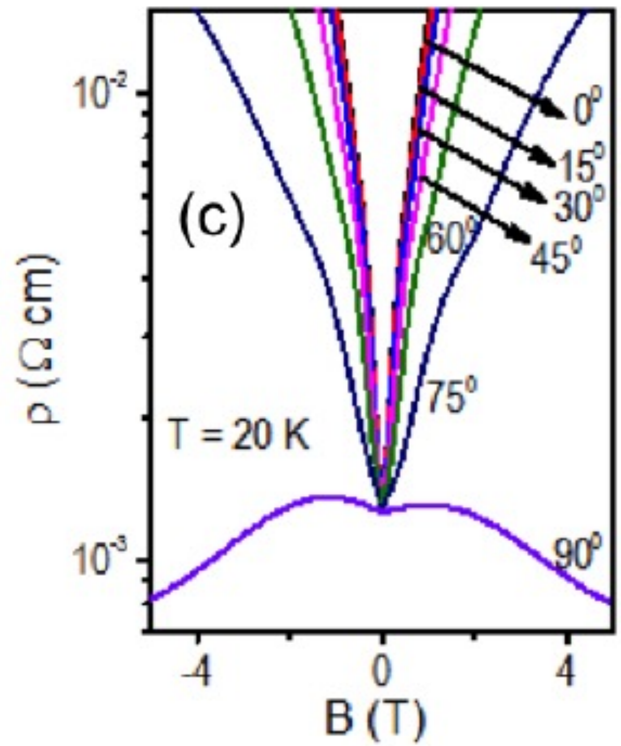
Chiral Magnetic Effect Generates Quantum Current

Separating left- and right-handed particles in a semi-metallic material produces anomalously high conductivity

February 8, 2016

Nature Physics **12**, 550 (2016)

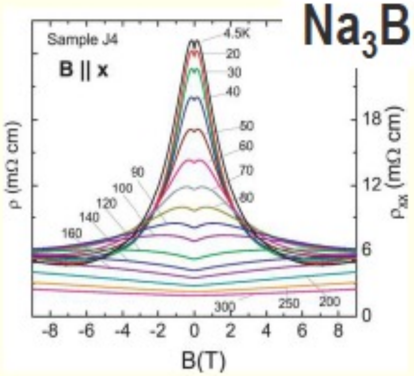




Chiral magnetic effect in Dirac/Weyl semimetals

Dirac semimetals:

Na$_3$Bi



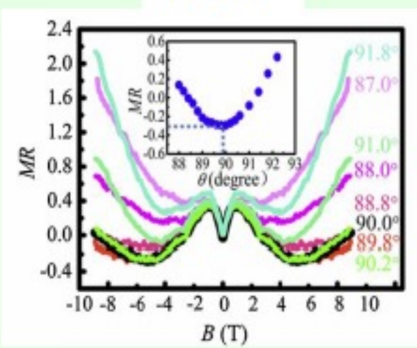
$ZrTe_5$ - Q. Li, D. Kharzeev, et al (BNL and Stony Brook Univ.) arXiv:**1412.6543**; doi:10.1038/NPHYS3648

Na_3Bi - J. Xiong, N. P. Ong et al (Princeton Univ.) arxiv:**1503.08179**; Science 350:413,2015

Cd_3As_2- C. Li et al (Peking Univ. China) arxiv:**1504.07398**; Nature Commun. 6, 10137 (2015).

Weyl semimetals

TaAs



TaAs - X. Huang et al (IOP, China) arxiv:**1503.01304**; Phys. Rev. X 5, 031023

NbAs - X. Yang et al (Zhejiang Univ. China) arxiv:**1506.02283**

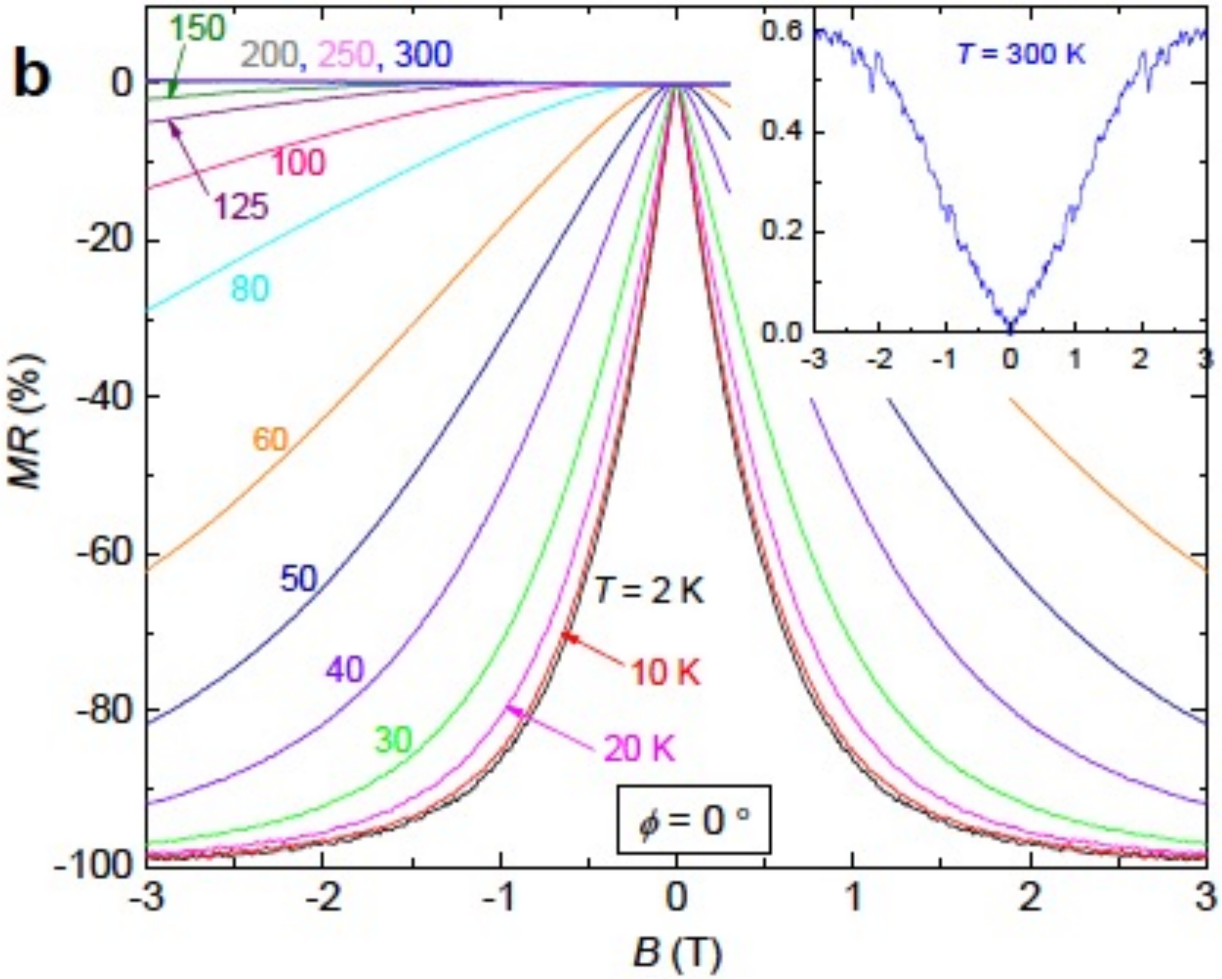
NbP - Z. Wang et al (Zhejiang Univ. China) arxiv:**1504.07398**

TaP - Shekhar, C. Felser, B. Yang et al (MPI-Dresden) arxiv:**1506.06577**

$Bi_{1-x}Sb_x$ at $x \approx 0.03$ - Kim, et al. "Dirac versus Weyl Fermions in Topological Insulators: Adler-Bell-Jackiw Anomaly in Transport Phenomena. Phys. Rev. Lett., 111, 246603 (2013).

Negative MR in $TaAs_2$

Y.Luo et al, 1601.05524



Towards the room temperature CME?

Can one control CME by circularly polarized light?

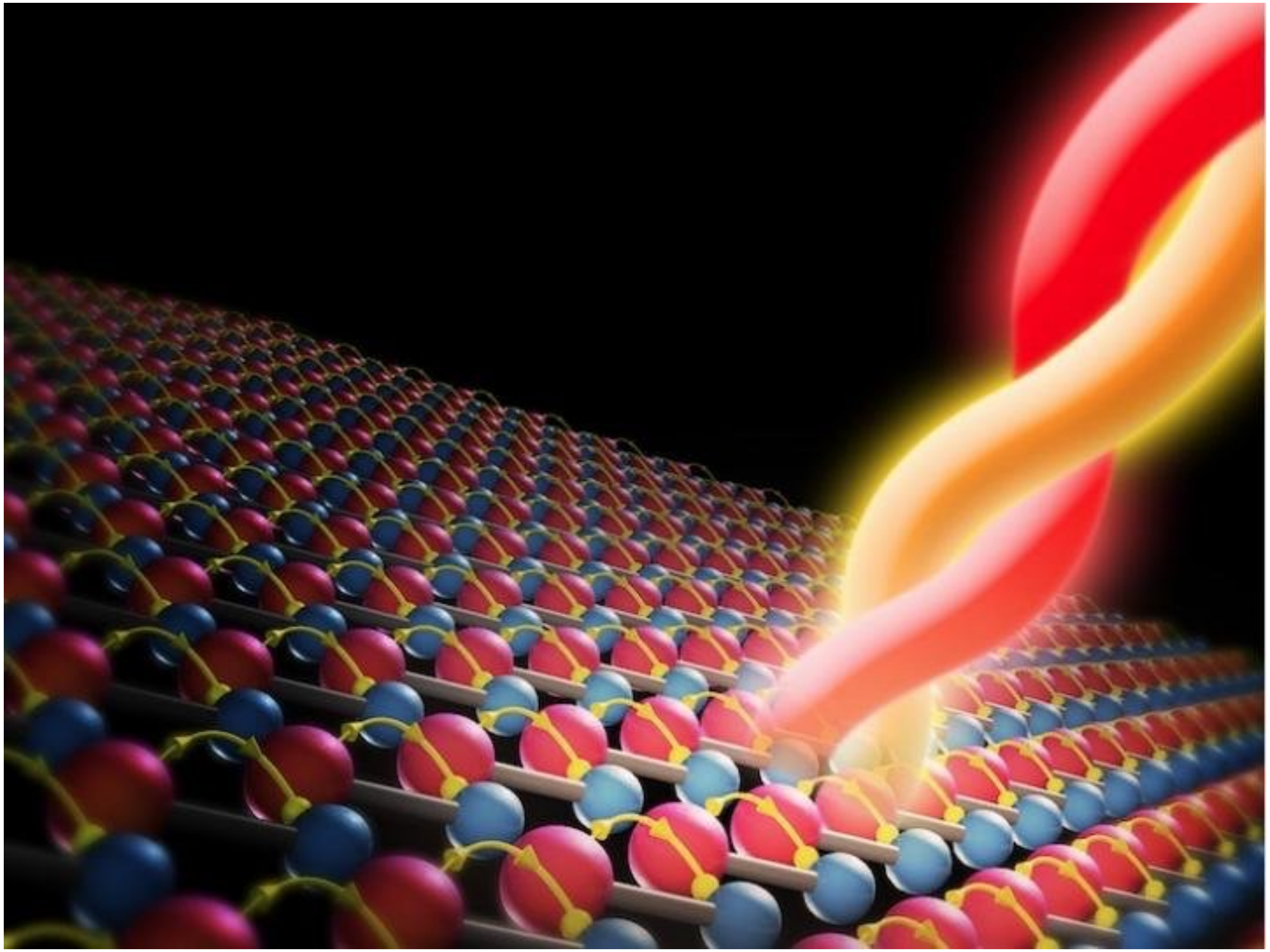


Image credit: Science Daily

Chiral magnetic photocurrent

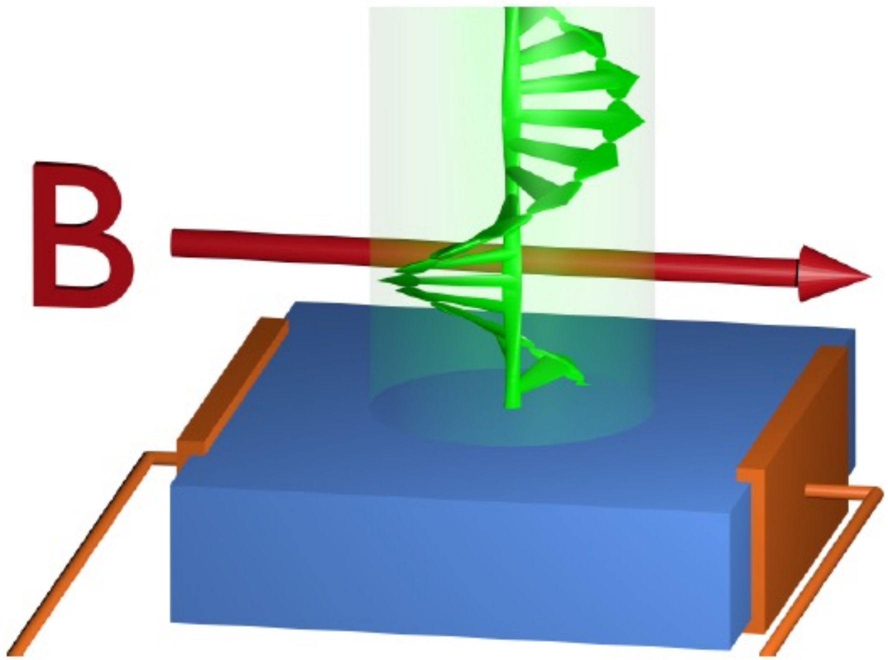


FIG. 1. The CPL incident on a Dirac or Weyl semimetal induces an asymmetry between the number of left- and right-handed chiral quasiparticles. In an external magnetic field, as a consequence of the chiral anomaly, this chiral asymmetry induces a chiral magnetic photocurrent along the direction of the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

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

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

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

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

Ultrafast control of chiral currents in Weyl semimetals

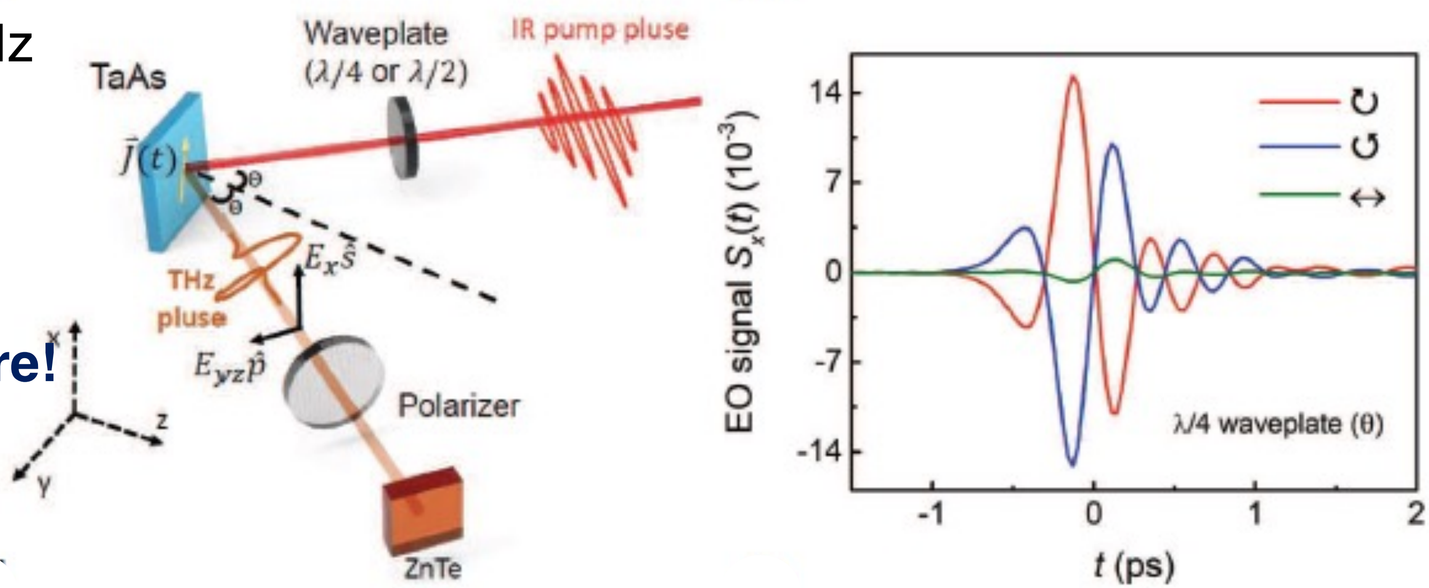
arXiv:1901.00986.
Nature Comm. 2020

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*]

ω = 380 THz
λ = 800 nm
80 fs pulse

Room temperature!



Chiral straintronics

L. Gao, S. Kaushik, DK, E. Philip
arXiv:2010.07123, PRB'21

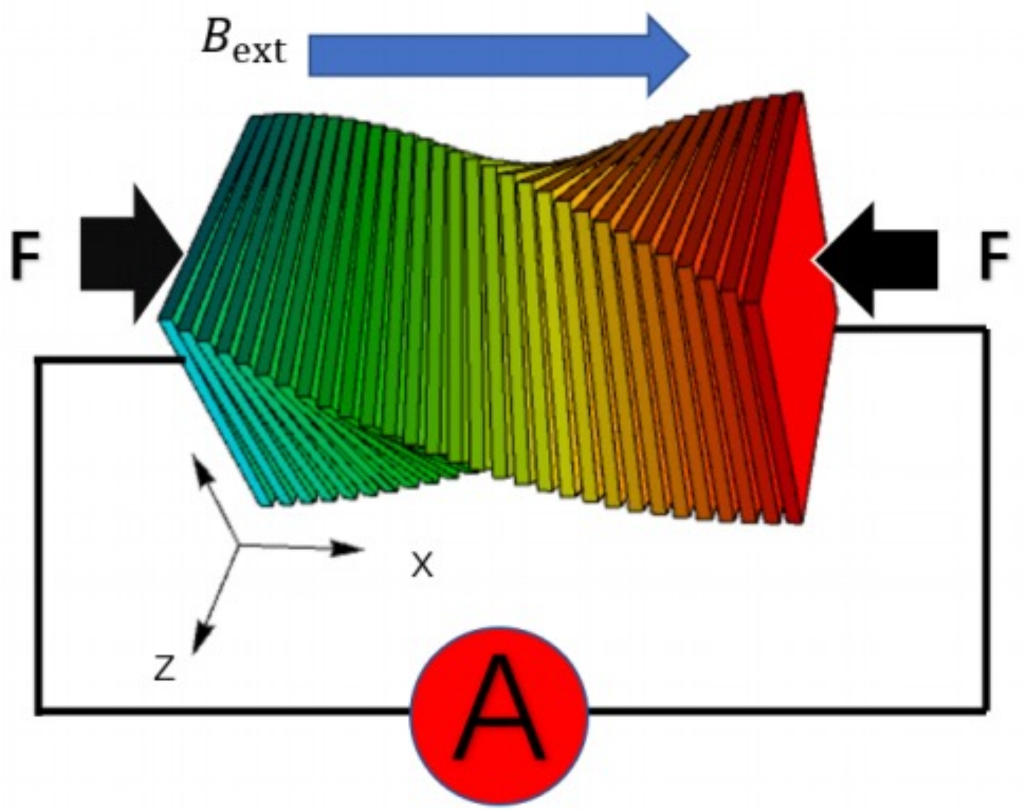
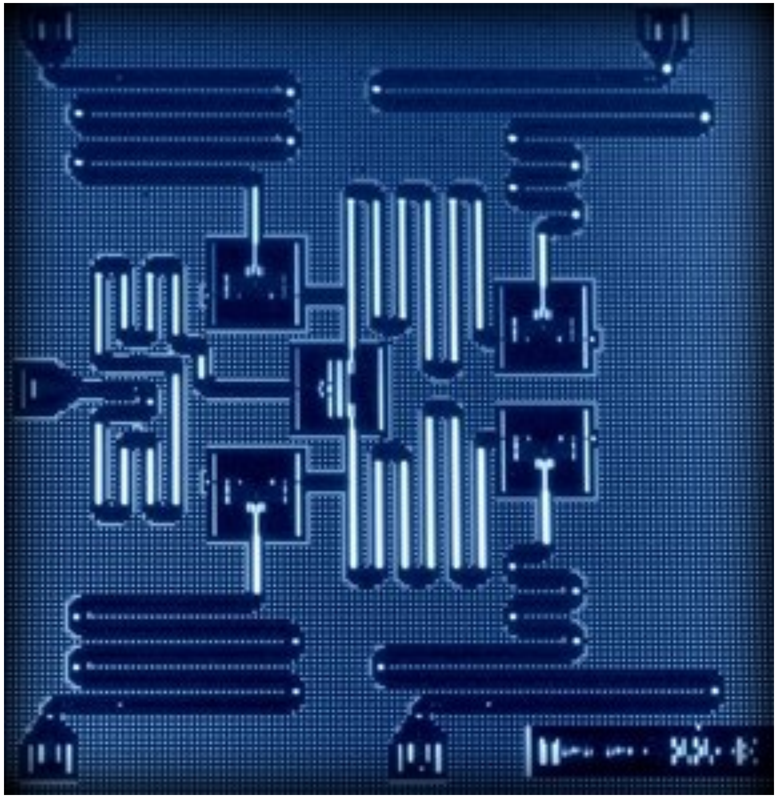


FIG. 1. The chiral magnetic current induced by torsion and compression in the presence of an external magnetic field.

Superconducting qubits



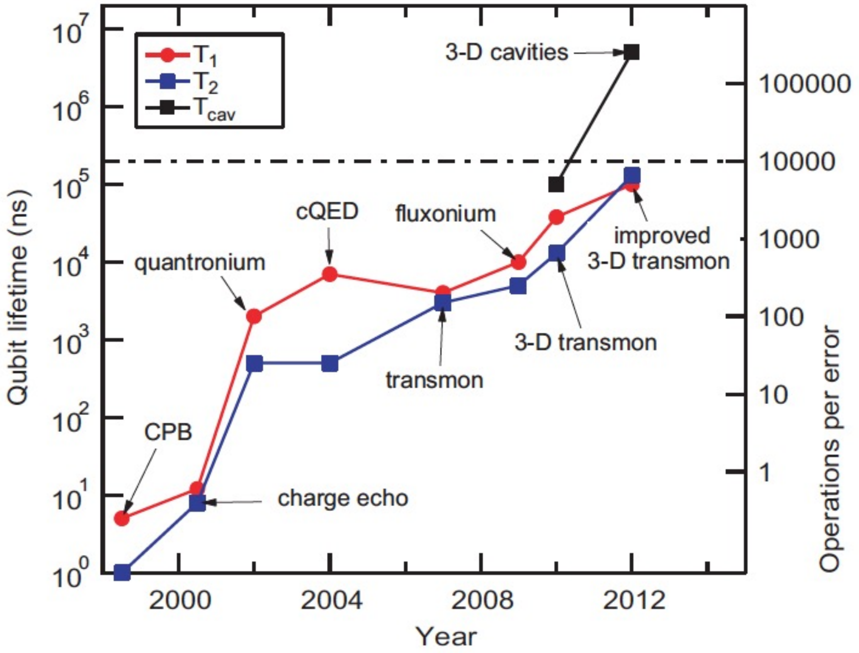


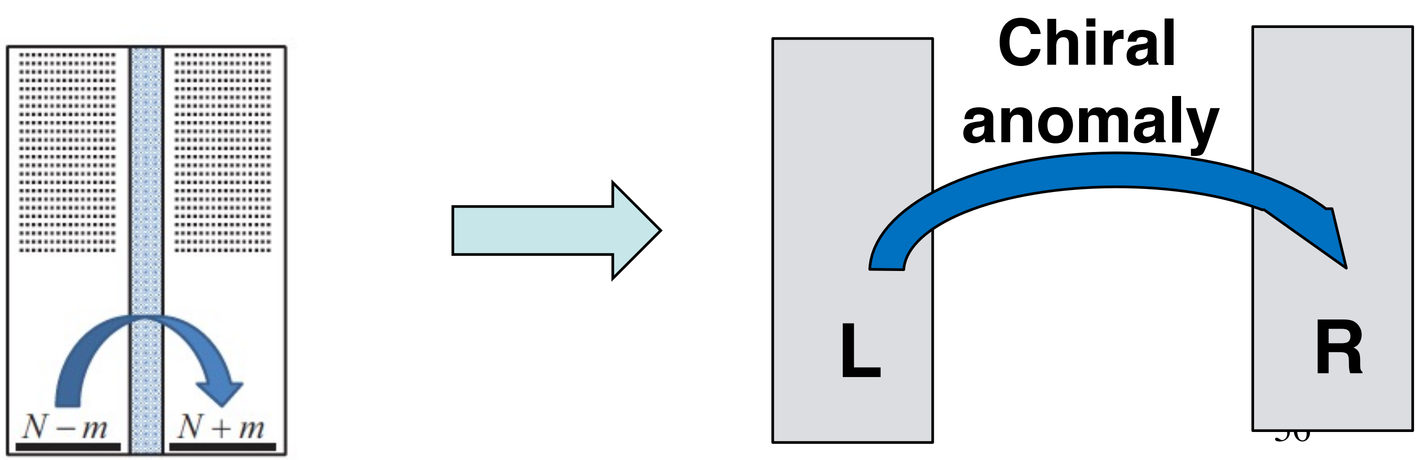
Fig. 2.1 "Schoelkopf's Law" plot illustrating the exponential growth for superconducting (charge-) qubit coherence times. Recent experiments (Geerlings *et al.*, 2013) with the 'fluxonium' qubit design have achieved T_1 times exceeding one millisecond.

IBM five qubit processor credit: IBM-Q

S. Girvin, 2013

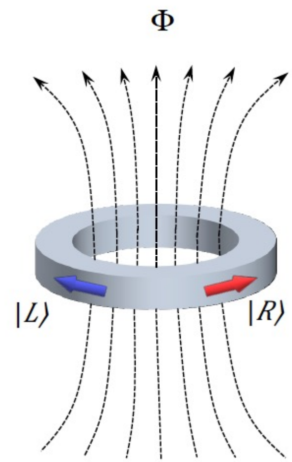
Can the basic physics of the superconducting qubit be realized in a different system, potentially capable of operating at much higher temperatures, higher frequencies, and larger ratio of coherence and gate times?

Probably yes – use the chiral fermions!



Chiral ring: a simple model

Dirac fermion
(1+1), compactified



Magnetic flux;
(3+1) gauge field

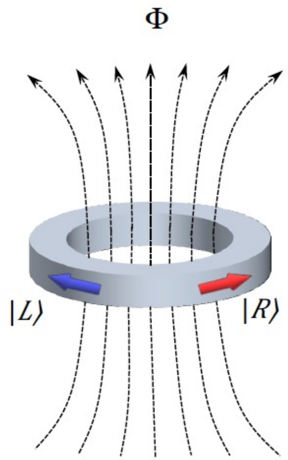
$$\mathcal{L} = \bar{\psi}\{i\gamma^0 D_0 + i v_F \gamma^i D_i\}\psi - \frac{1}{4}F_{\mu\nu}^2$$

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

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

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!

$$J_n^{R,L} = -\frac{\partial E_n^{R,L}}{\partial \Phi} = \mp e\frac{\hbar\omega}{2\pi},$$

$$J = J_R + J_L = e\frac{\hbar\omega}{2\pi} \left(\sum_{n=-\infty}^{N_L} 1 - \sum_{m=-\infty}^{N_R} 1 \right)$$

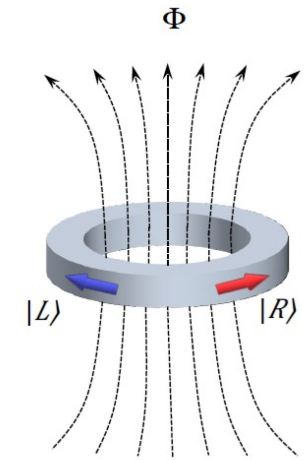
$$J = -e\,\frac{\mu_5}{\pi}.$$

CME in (1+1) dimensions!

DK, Q.Li,
arXiv:1903.07133

Chiral Qubit: the Hamiltonian

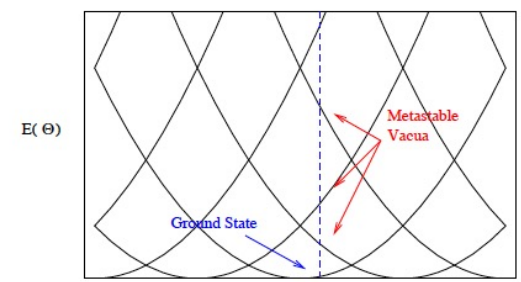
$$\hat{H} = \hbar\omega \left[-i \frac{\partial}{\partial \varphi} - \frac{\Phi}{\Phi_0} \right] \hat{\sigma}_z$$



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

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

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

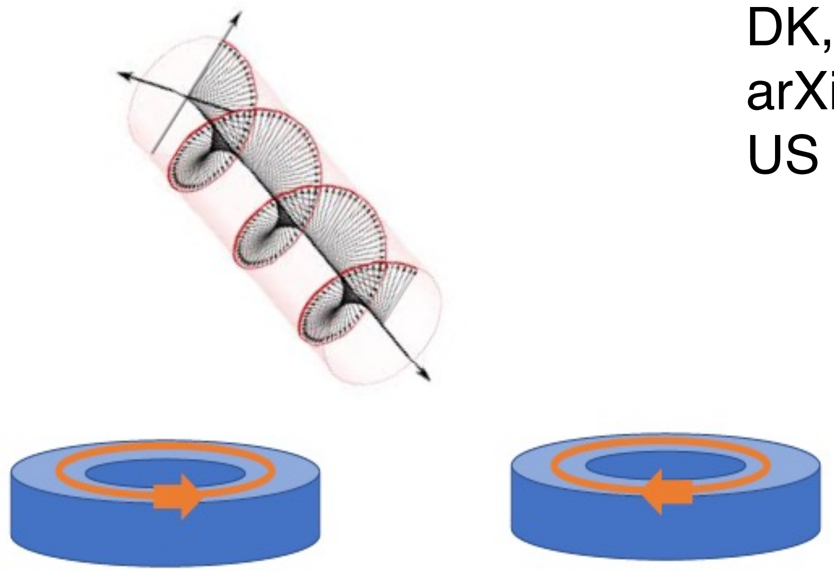


This Hamiltonian is identical to the Hamiltonian of the superconducting qubit!

DK, Q.Li, arXiv:1903.07133

The chiral qubit

DK, Q.Li,
arXiv:1903.07133[quant-ph];
US pat. 10657456

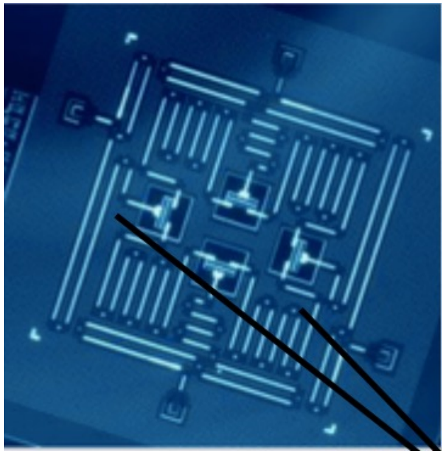


$$|0\rangle = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$$

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

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

The chiral qubit



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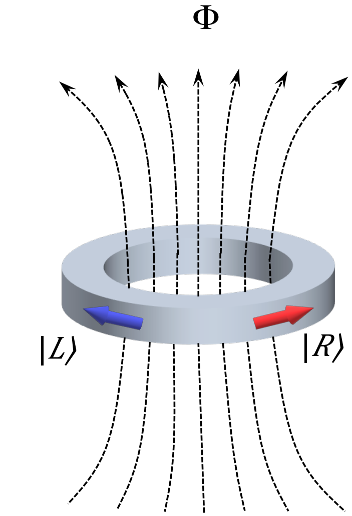

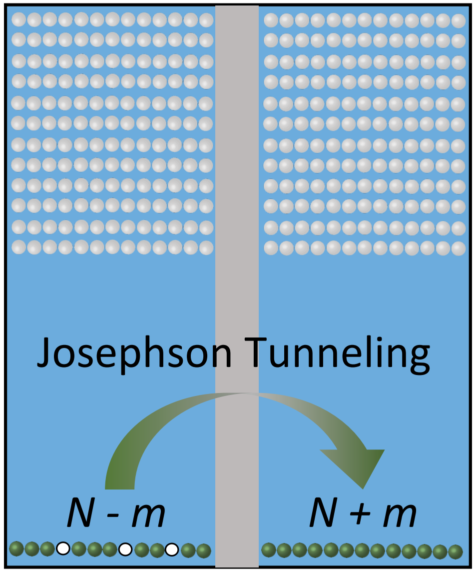

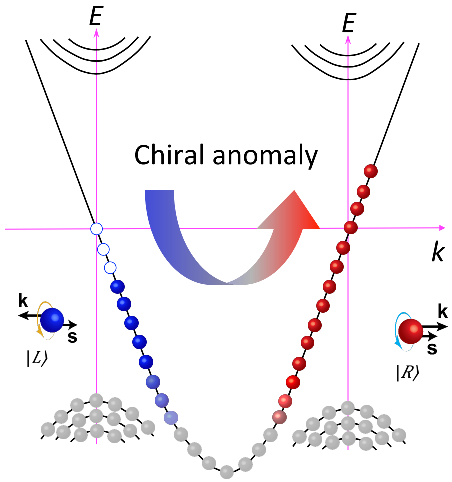

DK, Q. Li, US patent **62/758,029** (2018); arXiv:1903.07133[quant-ph]; ongoing work

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

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

Reviews:

DK, K. Landsteiner, A. Schmitt, H.U.Yee (Eds),
“Strongly interacting matter in magnetic fields”,
Springer, 2013; arxiv:1211.6245

DK, “The chiral magnetic effect and anomaly-induced transport”,
Prog.Part.Nucl.Phys. 75 (2014) 133; arxiv: 1312.3348

DK, “Topology, magnetic field and strongly interacting matter”,
arxiv: 1501.01336; Ann. Rev. Nucl. Part. Science (2015)

DK, J.Liao, S.Voloshin, G.Wang, “Chiral magnetic and vortical effects in high-energy nuclear collisions: A status report” Prog. Part. Nucl. Phys. 88 (2016) 1