ASU Theoretical Physics colloquium, June 2, 2021

Chiral Magnetic Effect:

from quarks to quantum computers

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C2QA Co-design Center for Quantum Advantage

U.S. DEPARTMENT OF ENERGY Office of Science

Stony Brook University | Center for Nuclear Theory

BROOKHAVEN NATIONAL LABORATORY

Outline

1. What is Chirality?

2. Chirality and transport

3. Chiral Magnetic Effect (CME):
   chiral transport induced by quantum anomaly

4. CME as a probe of gauge field topology

5. Real-time CME and entanglement

6. CME in heavy ion collisions and the RHIC isobar run

7. Broader implications:

   a) Dirac and Weyl materials
   b) quantum computing with CME

*Disclaimer: **not** a systematic review of ongoing developments*

3 min introduction to CME on YouTube :


#breakthroughjuniorchallenge

Chiral Magnetic Effect(CME)

https://www.youtube.com/watch?v=n4L7VPpEwqo&ab_channel=MeisenWang

Chirality: the definition

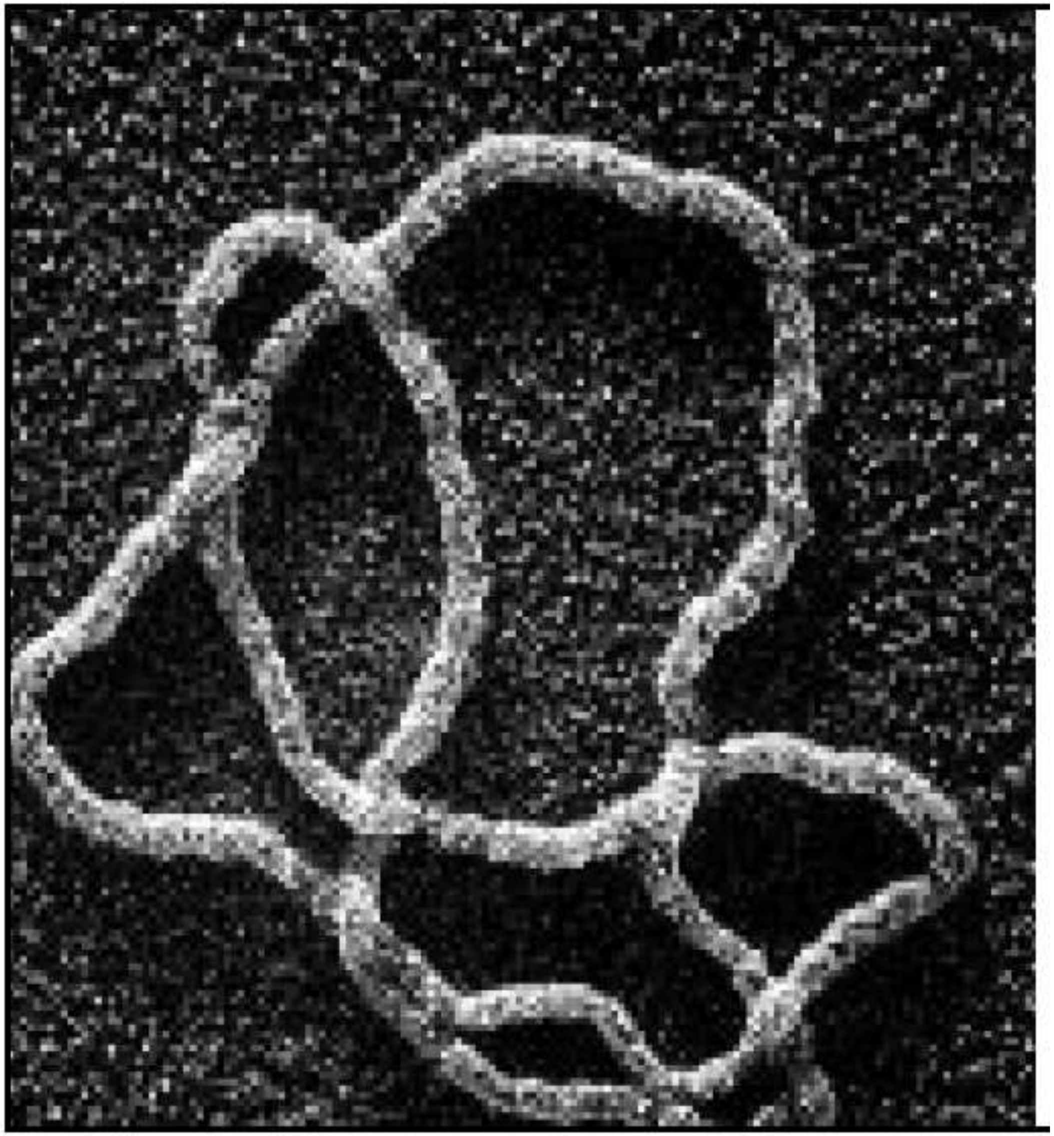
Greek word: χειρ (cheir) - hand

Lord Kelvin (1893):

"I call any geometrical figure, or groups of points, chiral, and say it has chirality, if its image in a plane mirror, ideally realized, cannot be brought to coincide with itself."

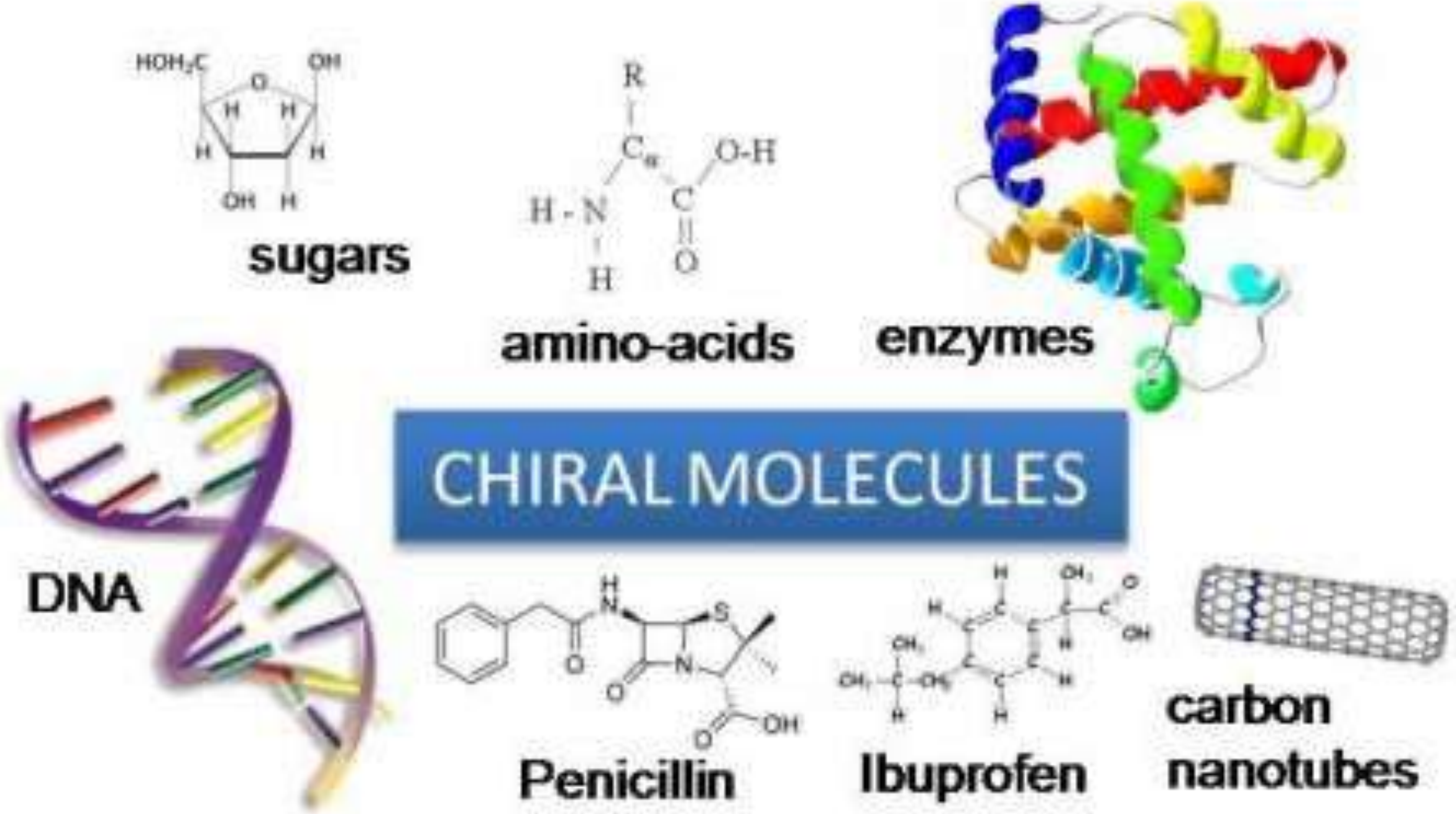
Chirality: DNA

Chirality: DNA



De Witt Sumners, Notices of the AMS, 1995

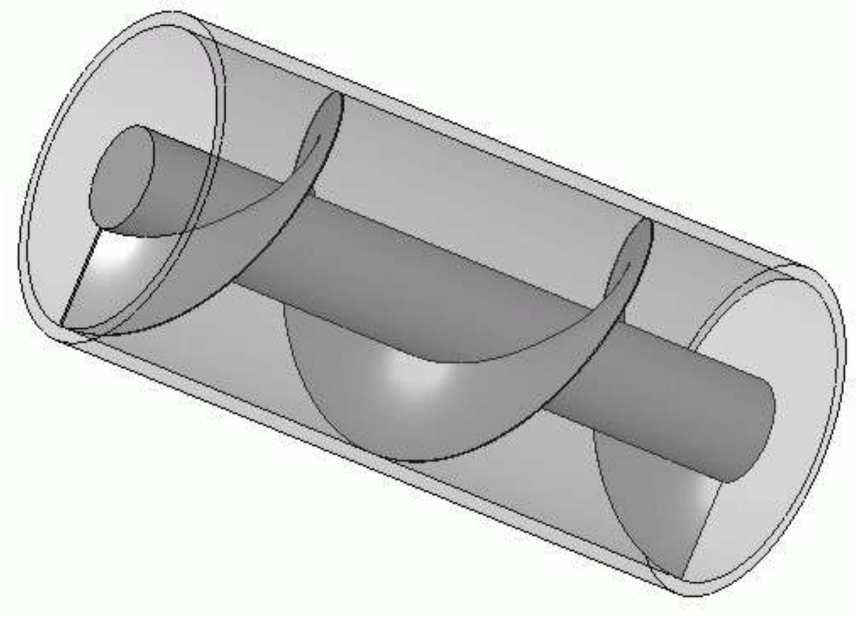
Living organisms contain almost only left-handed (LH) amino-acids and right-handed (RH) sugars – you would starve on LH sugar! (artificial sweeteners)



2500 chiral drugs! (most of the new)

www.rowland.harvard.edu/rjf/fischer

Chiral transport, 240 B.C.



The Archimedes screw

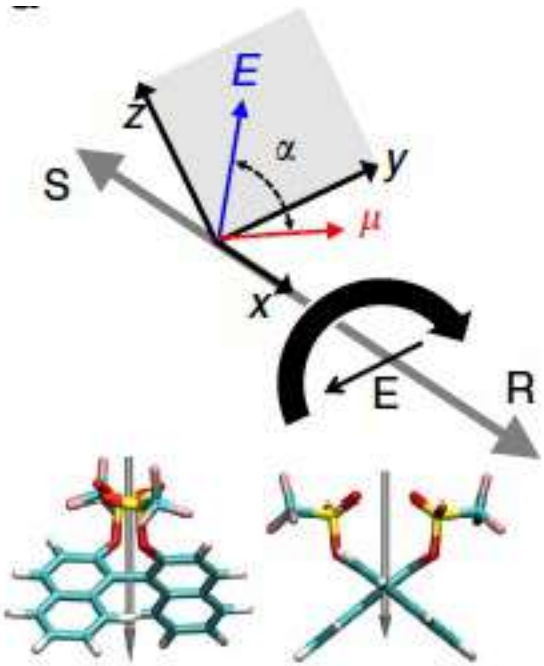
Chiral propulsion

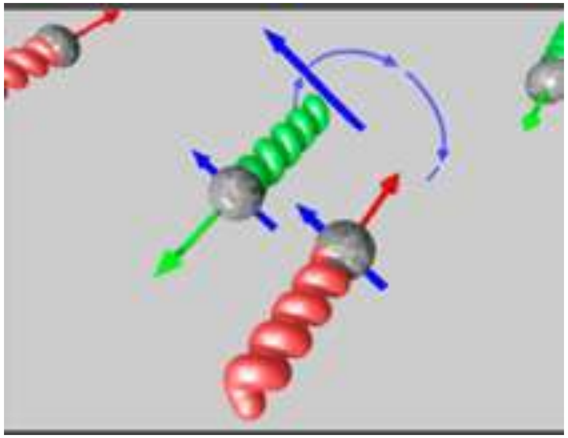
$$\vec{V} \sim \vec{\Omega} \quad ?$$

vector　　pseudo-vector

Velocity parallel to angular velocity requires the breaking of parity: chiral propeller

Propeller effect in a fluid





How to rotate the chiral molecule in a fluid?

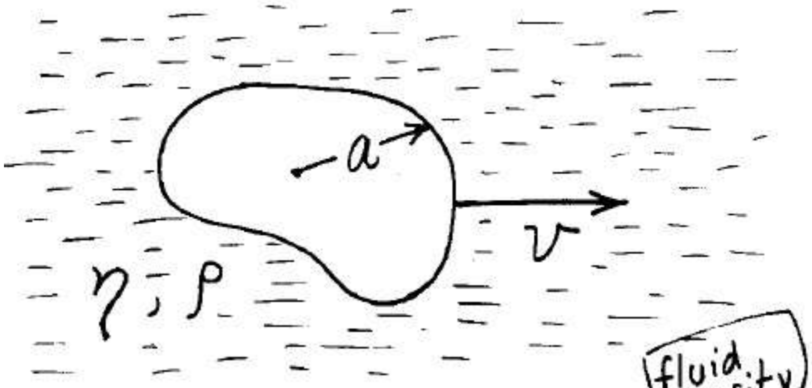
Use the coupling of an external electric field to the molecule’s electric dipole moment!

Rotating electric field – rotating molecule

Baranova, Zel’dovich ‘78

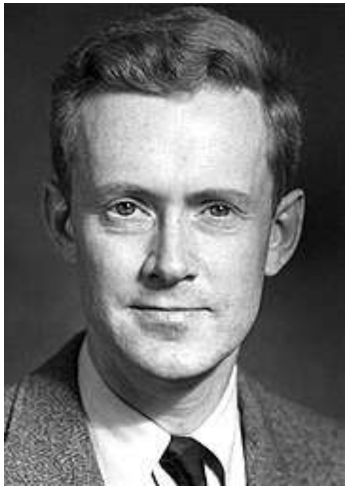
Life at low Reynolds number

E. M. Purcell
Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138
(Received 12 June 1976)



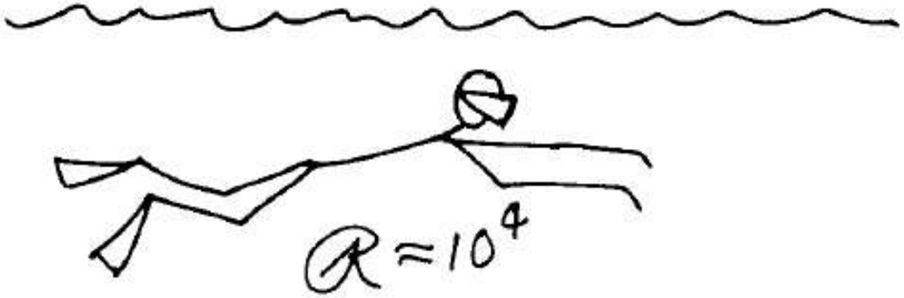
$$\frac{\text{inertial forces}}{\text{viscous forces}} \approx \frac{a v \overset{\boxed{\text{fluid density}}}{\rho}}{\underset{\boxed{\text{fluid viscosity}}}{\eta}}$$

$$\mathcal{R} \equiv \frac{av\rho}{\eta} = \frac{av}{\underset{=10^{-2}\,\frac{\text{cm}^2}{\text{sec}}\ \text{for water}}{\nu}}$$



E.M.Purcell
(1912-1997)

Nobel prize, 1952
(Nuclear Magnetic
Resonance)


$\mathcal{R} \approx 10^4$


$\mathcal{R} \approx 10^2$


$\mathcal{R} \approx 10^{-4}$

Navier-Stokes:

$$-\nabla p + \eta \nabla^2 \vec{v} = \cancel{\rho \frac{\partial \vec{v}}{\partial t}} + \cancel{\rho (\vec{v} \cdot \nabla) \vec{v}}$$

Stokes equation
("creeping flow")

T-invariance!

If $\mathcal{R} \ll 1$:

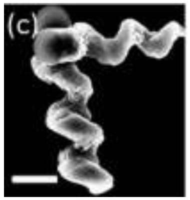
Time doesn't matter. The pattern of motion is the same, whether slow or fast, whether forward or backward in time.

Sir G. Stokes
(1819-1903)

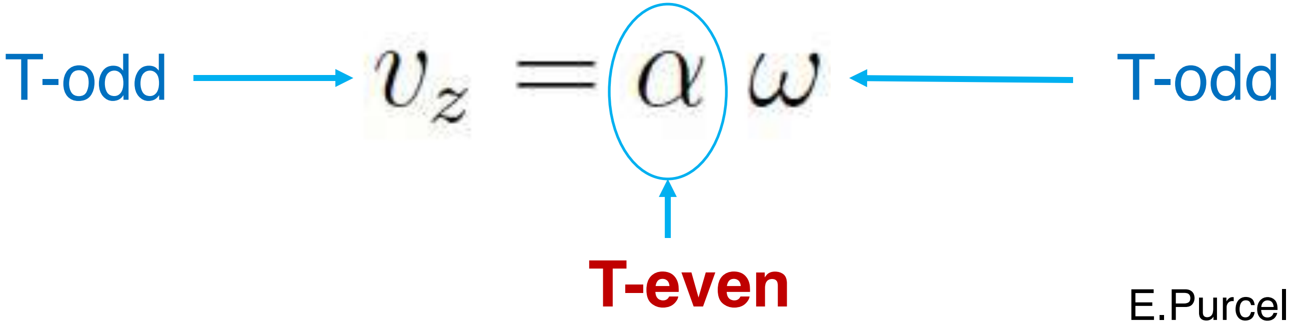
The Scallop Theorem

Geometry of the gauge field on the space of shapes

A.Shapere, F.Wilczek '88



Chiral propulsion



T-odd → $v_z = \boxed{\alpha}\,\omega$ ← T-odd

T-even

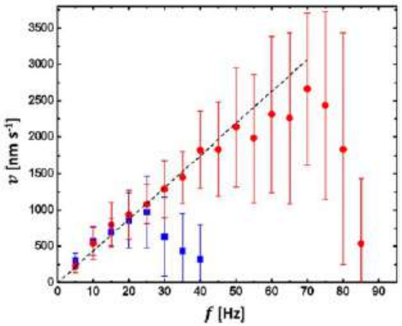
E.Purcell ’76

Chiral propulsion in the Stokes regime is **non-dissipative** (T-even) and determined entirely by geometry;

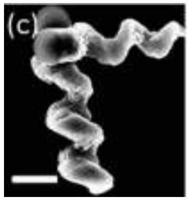
A.Shapere, F.Wilczek ‘88

it does not depend on viscosity!

S.Ayf, I.Kuk, DK,
arXiv:1804.08664

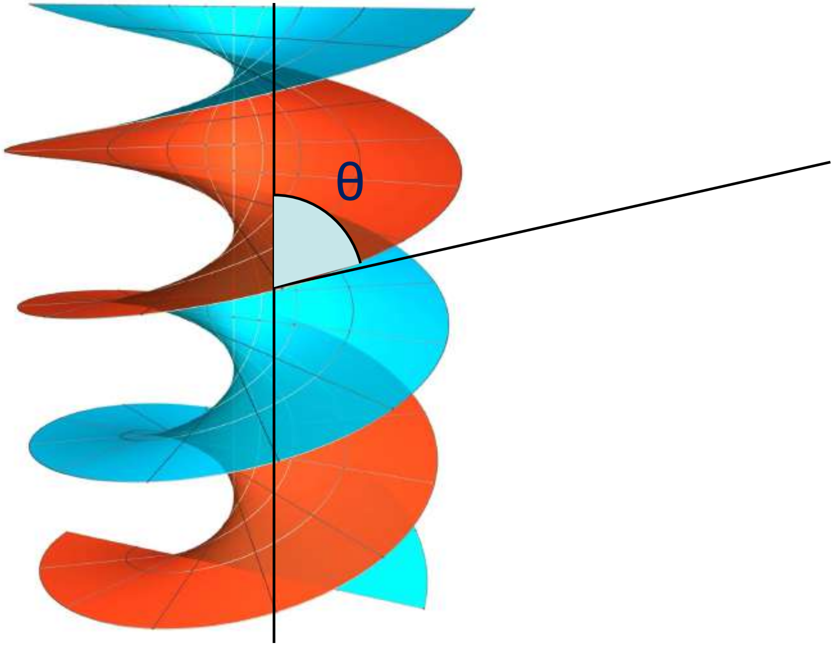


Classical analog of anomaly-induced transport that we are going to consider in this talk



Chiral propulsion

Chiral propulsion in the Stokes regime
is determined entirely by geometry.
What is the value of the pitch angle θ that is optimal for chiral propulsion?



A very simple answer:

$$\alpha \sim \cos\theta \;\; \sin 2\theta$$

$$\Downarrow$$

$$\theta = \tan^{-1}(1/\sqrt{2}) \simeq 35.26^\circ$$

L.Korneev, DK, A.Abanov
arXiv:2105.12181 [physics.flu-dyn]

Motility modes of Spiroplasma melliferum BC3: A helical, wall-less bacterium driven by a linear motor

March 2003 · Molecular Microbiology 47(3):657-69

DOI:10.1046/j.1365-2958.2003.03200.x

Source · PubMed

Authors:

Rami Gilad

Asher Porat

Shlomo Trachtenberg

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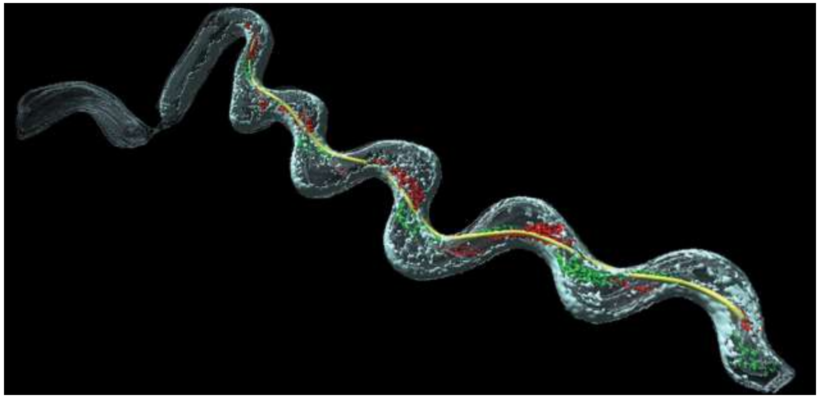

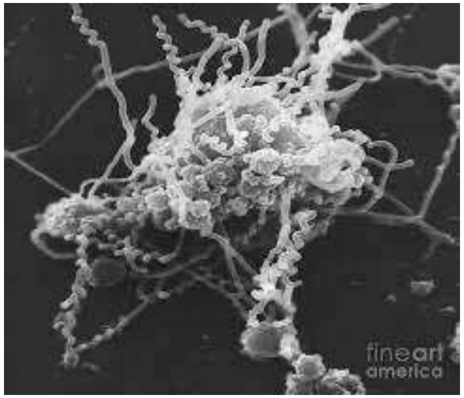

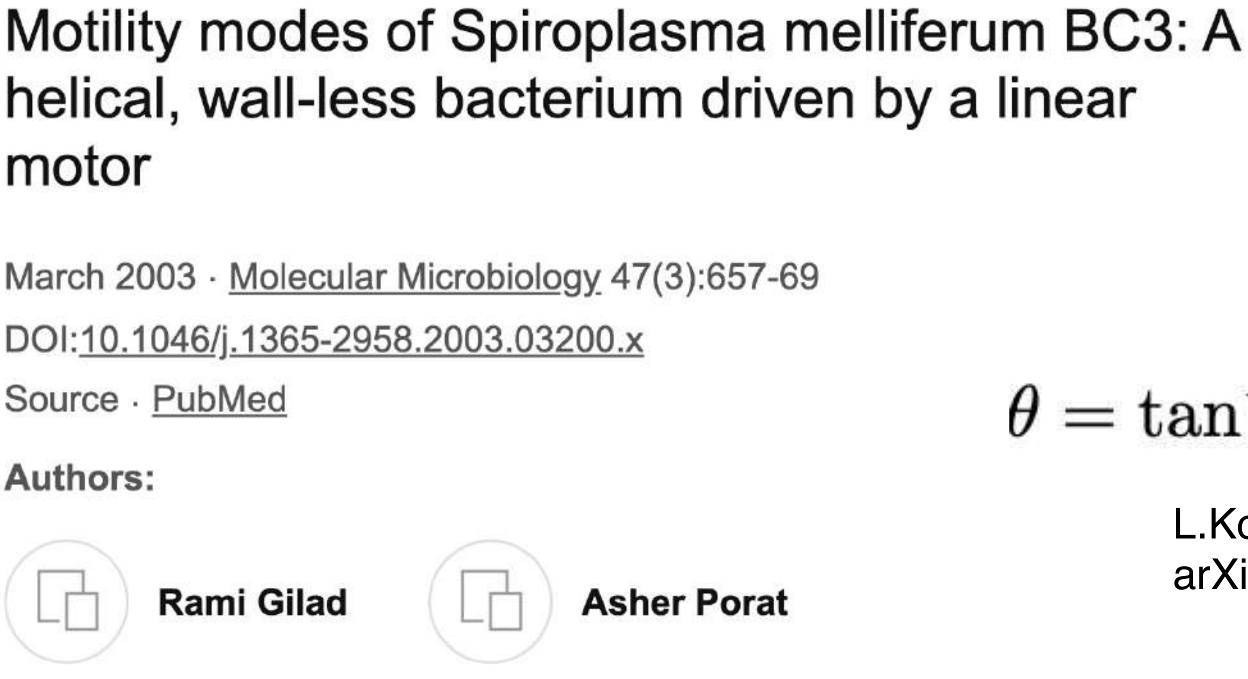

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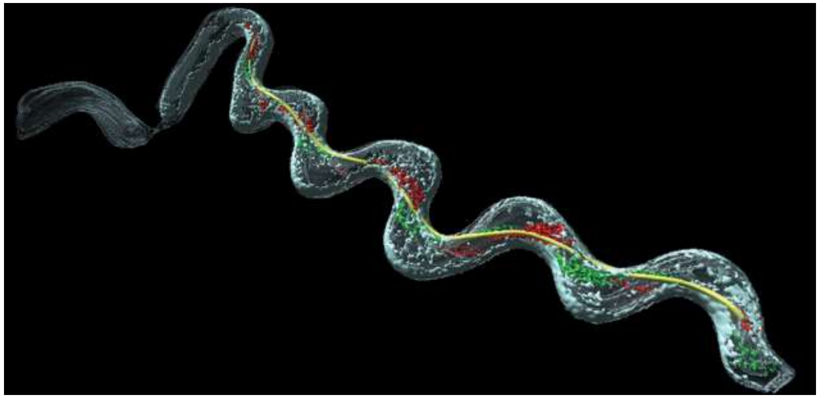
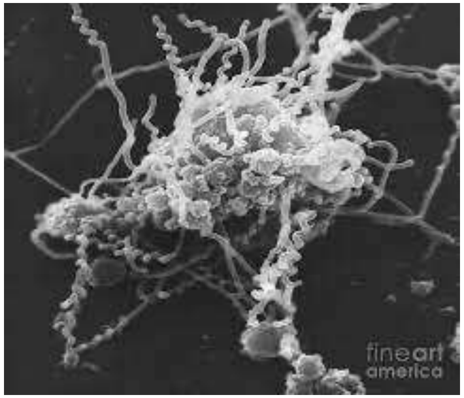




“…helical pitch angle observed for the helical Spiroplasma melliferum is 35 degrees…”

Chirality and quantum transport

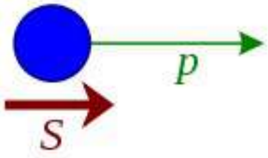
Chiral fermions

Fermions:
E. Fermi,1925

Dirac equation:
P. Dirac, 1928

$$(i\partial\!\!\!/ - m)\psi = 0$$

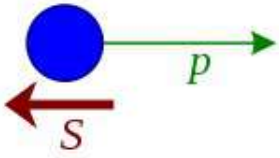
Right-handed:



Weyl fermions:
H. Weyl, 1929

$$\sigma^{\mu}\partial_{\mu}\psi = 0$$

Left-handed:



Majorana fermions:
1937
E.Majorana, 1906-38**?**

$$-i\partial\!\!\!/\psi + m\psi_c = 0$$

$$\psi_c := i\psi^*$$

Currents in a magnetic field

$$\vec{J} \sim \vec{B}$$

?

vector

pseudo-vector

An electric current parallel to B requires a parity breaking

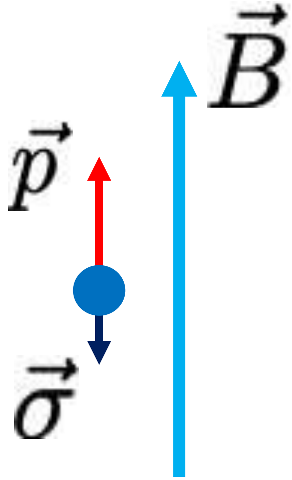
Currents in a magnetic field

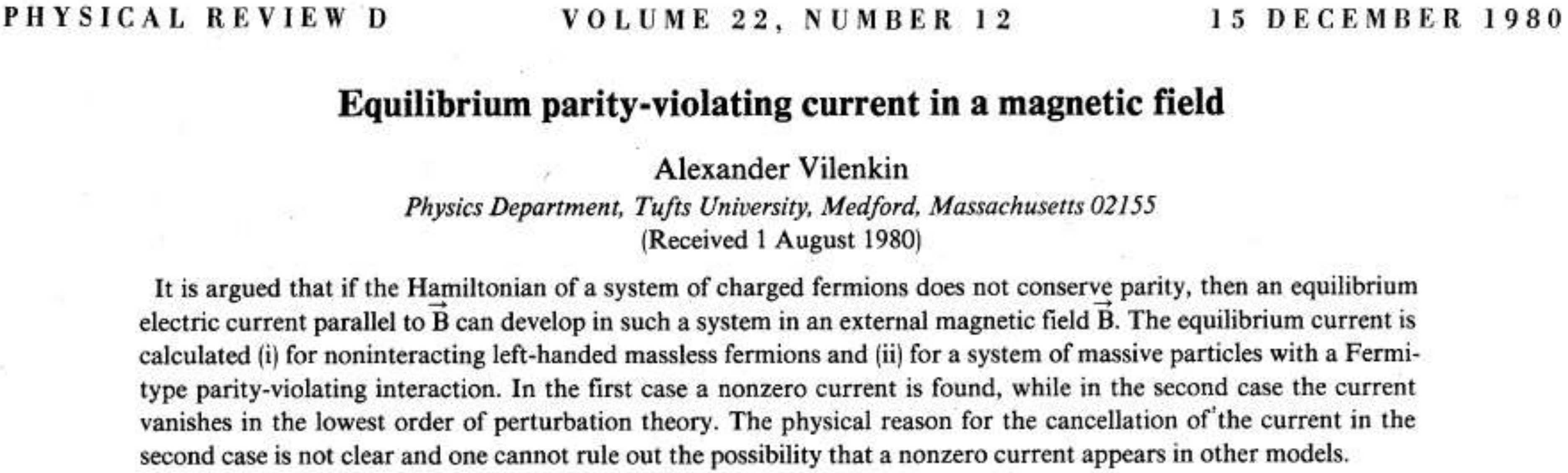
Consider a gas of massless charged Weyl fermions of a certain chirality, say left-handed (cf weak interactions)

Put this gas in an external magnetic field B; the interaction of spin with B, and the locking of momentum to spin

$$\langle \vec{\sigma} \cdot \vec{p} \rangle = -1$$

induce the current $\vec{J} \sim \vec{B}$



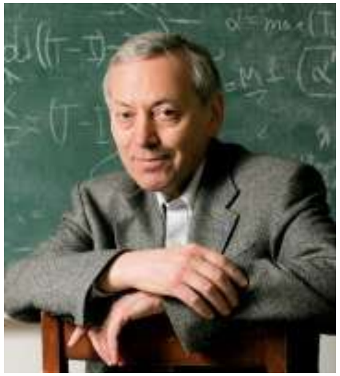


PHYSICAL REVIEW D VOLUME 22, NUMBER 12 15 DECEMBER 1980

Equilibrium parity-violating current in a magnetic field

Alexander Vilenkin
Physics Department, Tufts University, Medford, Massachusetts 02155
(Received 1 August 1980)

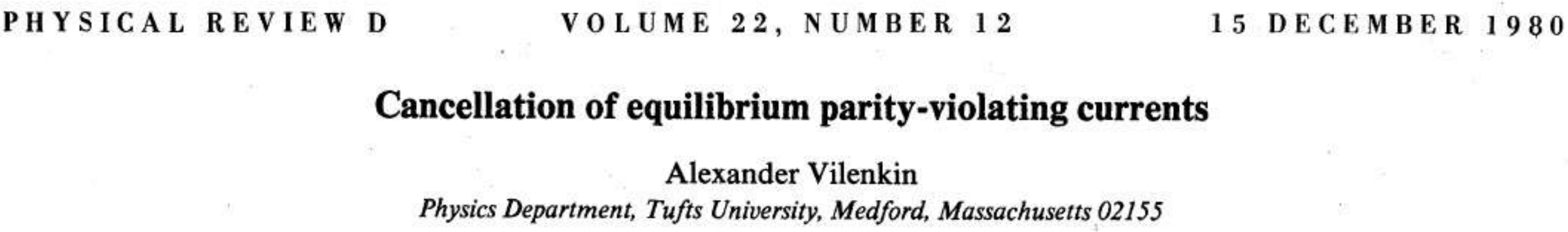
It is argued that if the Hamiltonian of a system of charged fermions does not conserve parity, then an equilibrium electric current parallel to $\vec{B}$ can develop in such a system in an external magnetic field $\vec{B}$. The equilibrium current is calculated (i) for noninteracting left-handed massless fermions and (ii) for a system of massive particles with a Fermi-type parity-violating interaction. In the first case a nonzero current is found, while in the second case the current vanishes in the lowest order of perturbation theory. The physical reason for the cancellation of the current in the second case is not clear and one cannot rule out the possibility that a nonzero current appears in other models.



But: no current in equilibrium

Bloch theorem, …

C.N. Yang



PHYSICAL REVIEW D VOLUME 22, NUMBER 12 15 DECEMBER 1980

Cancellation of equilibrium parity-violating currents

Alexander Vilenkin
Physics Department, Tufts University, Medford, Massachusetts 02155

Early work on currents in magnetic field due to P violation

(see DK, Prog.Part.Nucl.Phys. 75 (2014) 133
for a complete (?) list of references)

A.Vilenkin (1980) “Equilibrium parity-violating current in a magnetic field”;
(1980) “Cancellation of equilibrium parity-violating currents”

G. Eliashberg (1983) JETP 38, 188
L. Levitov, Yu.Nazarov, G. Eliashberg (1985) JETP 88, 229

M. Joyce and M. Shaposhnikov (1997) PRL 79, 1193;
M. Giovannini and M. Shaposhnikov (1998) PRL 80, 22

A. Alekseev, V. Cheianov, J. Frohlich (1998) PRL 81, 3503

The way out: chiral anomaly

For massless fermions, the axial current

$$J_\mu^A = \bar{\Psi}\gamma_\mu\gamma_5\Psi = J_\mu^R - J_\mu^L$$

is conserved classically due to the global $U_A(1)$ symmetry:

$$\partial^\mu J_\mu^A = 0$$

This is because left- and right-handed fields decouple in the massless limit:

$$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) \to 0$$

However, this conservation law is destroyed by quantum effects

Chiral anomaly

The axial current is not conserved:

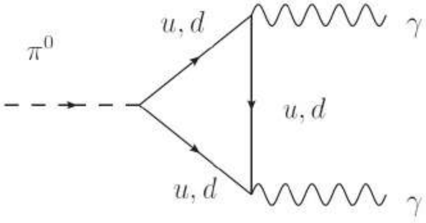
$$\partial_\mu J^\mu_A = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B}$$

S. Adler ‘69
J. Bell, R. Jackiw ’69

This is a consequence of UV regularization of QFT.

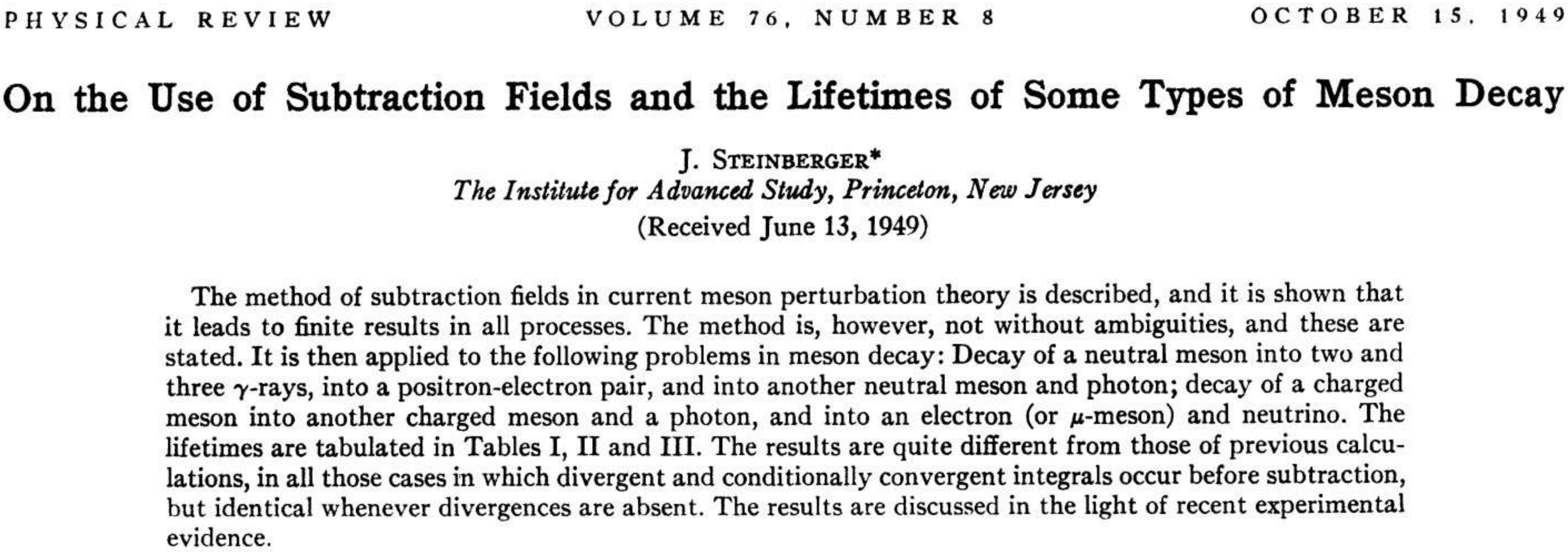
A textbook example: neutral pion decay

$$\pi^0 \to \gamma\gamma$$



J. Steinberger
(1921- Dec 2020;
Nobel prize 1988)

computed the decay
rate in 1949!



PHYSICAL REVIEW VOLUME 76, NUMBER 8 OCTOBER 15, 1949

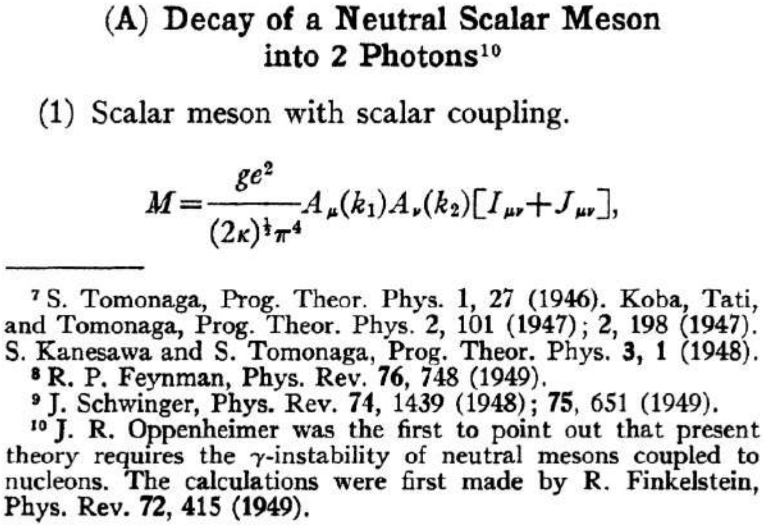
On the Use of Subtraction Fields and the Lifetimes of Some Types of Meson Decay

J. STEINBERGER*
The Institute for Advanced Study, Princeton, New Jersey

(Received June 13, 1949)

The method of subtraction fields in current meson perturbation theory is described, and it is shown that it leads to finite results in all processes. The method is, however, not without ambiguities, and these are stated. It is then applied to the following problems in meson decay: Decay of a neutral meson into two and three γ-rays, into a positron-electron pair, and into another neutral meson and photon; decay of a charged meson into another charged meson and a photon, and into an electron (or μ-meson) and neutrino. The lifetimes are tabulated in Tables I, II and III. The results are quite different from those of previous calculations, in all those cases in which divergent and conditionally convergent integrals occur before subtraction, but identical whenever divergences are absent. The results are discussed in the light of recent experimental evidence.

J. Steinberger
(1921- Dec 2020;
Nobel prize 1988)



(A) Decay of a Neutral Scalar Meson into 2 Photons[10]

(1) Scalar meson with scalar coupling.

$$M=\frac{ge^2}{(2\kappa)^{\frac{1}{2}}\pi^4}A_\mu(k_1)A_\nu(k_2)[I_{\mu\nu}+J_{\mu\nu}],$$

---

[7] S. Tomonaga, Prog. Theor. Phys. 1, 27 (1946). Koba, Tati, and Tomonaga, Prog. Theor. Phys. 2, 101 (1947); 2, 198 (1947). S. Kanesawa and S. Tomonaga, Prog. Theor. Phys. 3, 1 (1948).

[8] R. P. Feynman, Phys. Rev. 76, 748 (1949).

[9] J. Schwinger, Phys. Rev. 74, 1439 (1948); 75, 651 (1949).

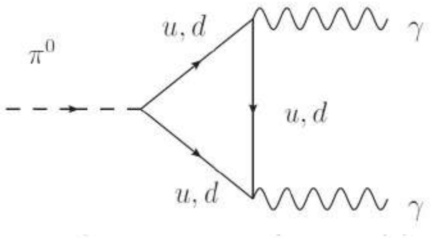
[10] J. R. Oppenheimer was the first to point out that present theory requires the γ-instability of neutral mesons coupled to nucleons. The calculations were first made by R. Finkelstein, Phys. Rev. 72, 415 (1949).

J. R. Oppenheimer
(1904 - 1967)

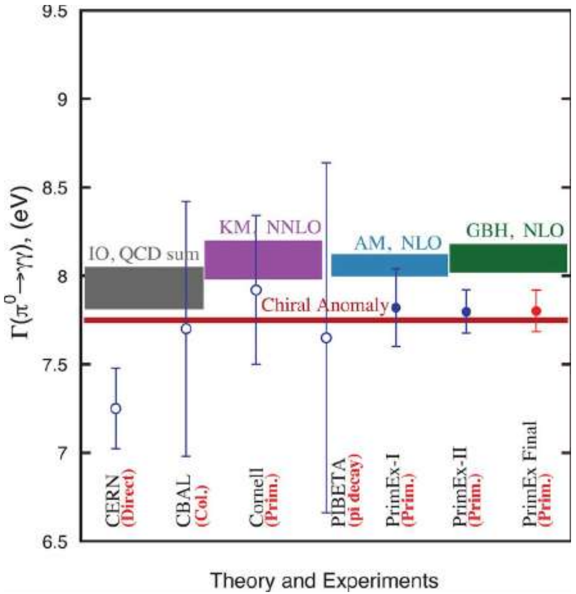
Science

Science 01 May 2020:
Vol. 368, Issue 6490, pp. 506-509
DOI: 10.1126/science.aay6641

$$\partial_\mu J^\mu_A = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B}$$



$$\Gamma\left(\pi^0 \to \gamma\gamma\right) = \frac{m^3_{\pi^0}\alpha^2 N_c^2}{576\pi^3 F^2_{\pi^0}} = 7.750 \pm 0.016 \text{ eV}$$



REPORT

Precision measurement of the neutral pion lifetime

I. Larin[1,2], Y. Zhang[3,4], A. Gasparian[5,*], L. Gan[6], R. Miskimen[2], M. Khandaker[7], D. Dale[8], S. Danagoulian[5], E
Pasyuk[9], H. Gao[3,4], A. Ahmidouch[5], P. Ambrozewicz[5], V. Baturin[9], V. Burkert[9], E. Clinton[2], A. Deur[9], A. Dolgolenko[1], D. Dutta[10], G. Fedotov[11,12], J. Feng[6], S. Gevorkyan[13], A. Glamazdin[14], L. Guo[15], E. Isupov[11], M. M. Ito[9], F. Klein[16], S. Kowalski[17], A. Kubarovsky[9], V. Kubarovsky[9], D. Lawrence[9], H. Lu[18], L. Ma[19], V. Matveev[1], B. Morrison[20], A. Micherdzinska[21], I. Nakagawa[22], K. Park[9], R. Pedroni[5], W. Phelps[23], D. Protopopescu[24], D. Rimal[15], D
Romanov[25], C. Salgado[7], A. Shahinyan[26], D. Sober[16], S. Stepanyan[9], V. V. Tarasov[1], S. Taylor[9], A. Vasiliev[27], M. Wood[2
L. Ye[10], B. Zihlmann[9], PrimEx-II Collaboration[†]

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[25]*Department of Physics, Moscow Engineering Physics Institute, Moscow, Russia.*

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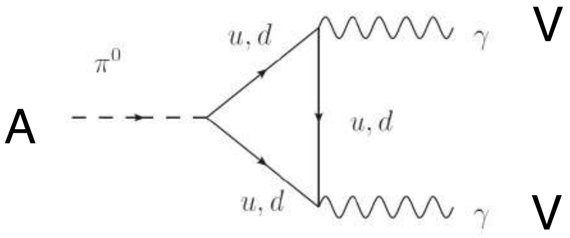
[27]*Institute for High Energy Physics, NRC "Kurchatov Institute," Protvino, 142281, Russia.*

Chiral anomaly

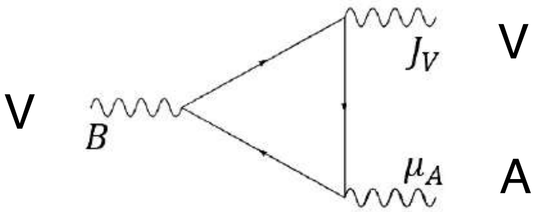
The axial current is not conserved:

S. Adler ‘69
J. Bell, R. Jackiw ’69

$$\partial_\mu J^\mu_A = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B}$$



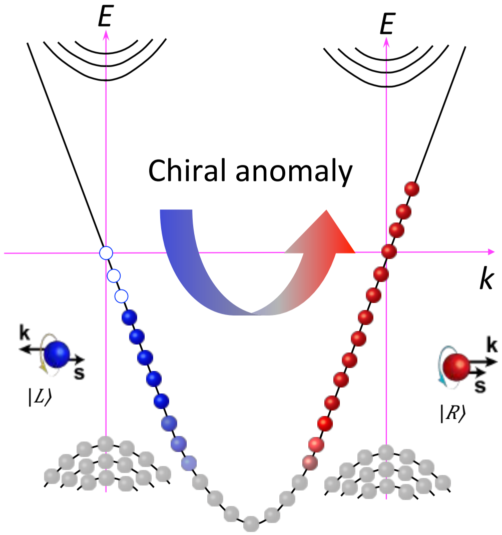
The chiral charge is not conserved;
a chirally imbalanced state of chiral fermions is not
a true ground state of the system!



Chiral anomaly

$$J_A \equiv -J_L + J_R$$

LEFT **RIGHT**



In classical background fields (E and B), chiral anomaly induces an imbalance between left- and right-handed fermions;

$$\partial_\mu J^\mu_A = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B}$$

chiral chemical potential:

$$\mu_5 = \frac{1}{2}(\mu_R - \mu_L)$$

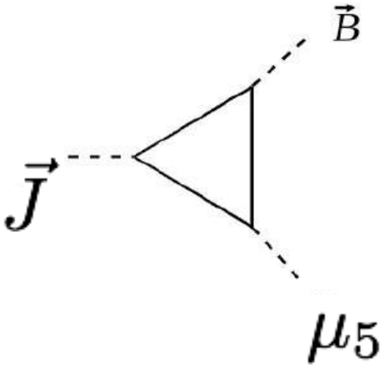
Adler; Bell, Jackiw (1969); Nielsen, Ninomiya (1983)

Chiral Magnetic Effect

DK'04; DK, A. Zhitnitsky '07; 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 [Prog.Part.Nucl.Phys]

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 $J^\mu = \dfrac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$

Absent in Maxwell theory!

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

Coefficient is fixed by the chiral anomaly, no corrections

Chirally imbalanced system is a non-equilibrium, steady state

Chiral Magnetic Effect

Alternative derivation:

K.Fukushima, DK, H.Warringa,
“Chiral magnetic effect” PRD’08;

Consider the thermodynamical potential at finite : $\mu_5 = A_5^0$

$$\Omega = \frac{|eB|}{2\pi} \sum_{s=\pm} \sum_{n=0}^{\infty} \alpha_{n,s} \int_{-\infty}^{\infty} \frac{dp_3}{2\pi} \left[\omega_{p,s} + T \sum_{\pm} \log\left(1 + e^{-\beta(\omega_{p,s} \pm \mu)}\right) \right]$$

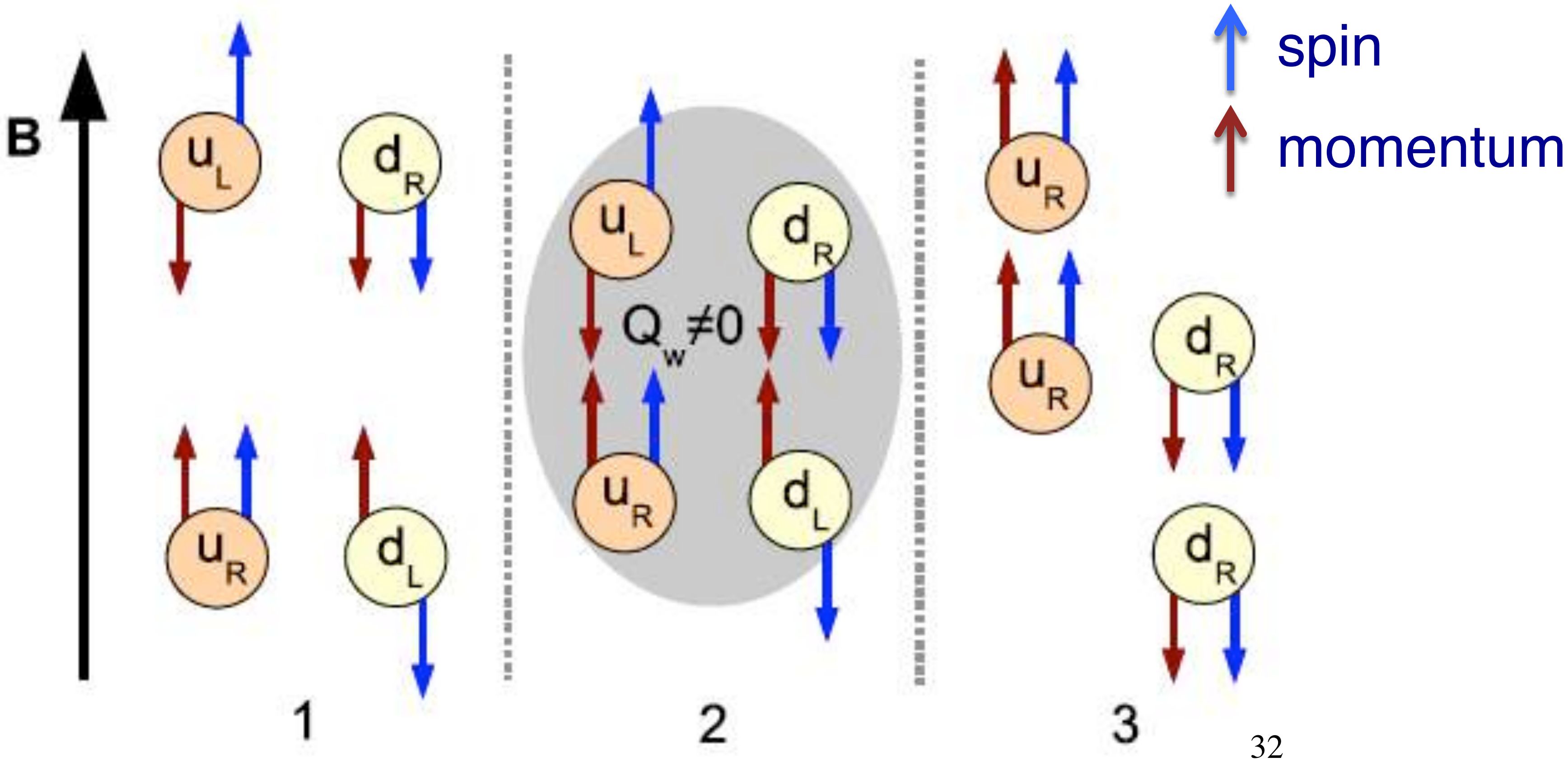
$$\omega_{p,s}^2 = \left[\mathrm{sgn}(p_3)(p_3^2 + 2|eB|n)^{1/2} + s\mu_5 \right]^2 + m^2$$

Compute the current through $j_3 = \left.\frac{\partial \Omega}{\partial A_3}\right|_{A_3=0}$ using $\partial/\partial A_3 = e d/dp_3$

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

Chirality in 3D:
the Chiral Magnetic Effect

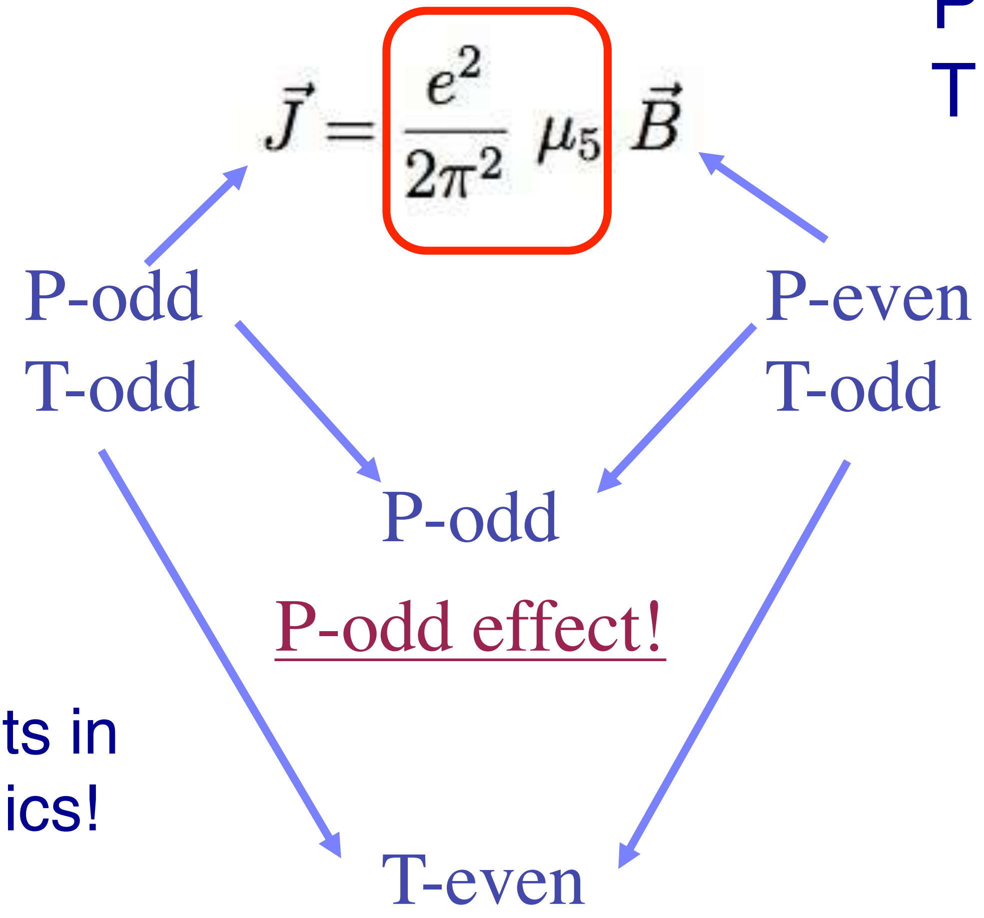
chirality + magnetic field = current



DK'04; DK, A.Zhitnitsky '07; DK, L.McLerran, H. Warringa '07; K. Fukushima, DK, H. Warringa

Chiral magnetic conductivity: discrete symmetries

P – parity
T – time reversal



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

P-odd
T-odd

P-even
T-odd

P-odd

P-odd effect!

T-even

Non-dissipative current!

(topologically protected)

Effect persists in hydrodynamics!

cf Ohmic conductivity:

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

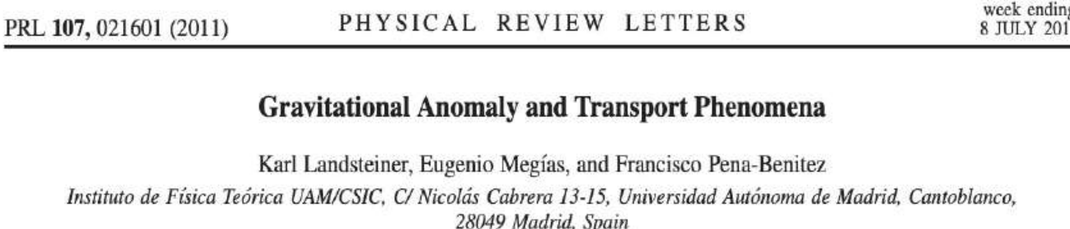
T-odd, dissipative

Systematics of anomalous conductivities

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

AVE and anomalous gravito-magnetic moment:

M. Buzzegoli, DK, PRD (2021)



PRL **107,** 021601 (2011) PHYSICAL REVIEW LETTERS week endin 8 JULY 201

Gravitational Anomaly and Transport Phenomena

Karl Landsteiner, Eugenio Megías, and Francisco Pena-Benitez

Instituto de Física Teórica UAM/CSIC, C/ Nicolás Cabrera 13-15, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain

CME vs superconductivity


Fritz and Heinz London

London theory of superconductors, ‘35:

$$\vec{\mathbf{J}} = -\lambda^{-2}\vec{\mathbf{A}} \qquad \nabla \cdot \vec{\mathbf{A}} = 0$$

$$\vec{\mathbf{E}} = -\dot{\vec{\mathbf{A}}} \qquad \boxed{\vec{\mathbf{E}} = \lambda^2 \dot{\vec{\mathbf{J}}}}$$

CME:

$$\vec{J} \sim \mu_5 \vec{B}$$

for $\vec{E} || \vec{B}$

$$\boxed{\vec{\mathbf{E}} \sim \mathrm{B}^{-2}\, \dot{\vec{\mathbf{J}}}}$$

Chiral anomaly:

$$\partial_\mu J^\mu_A = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B}$$

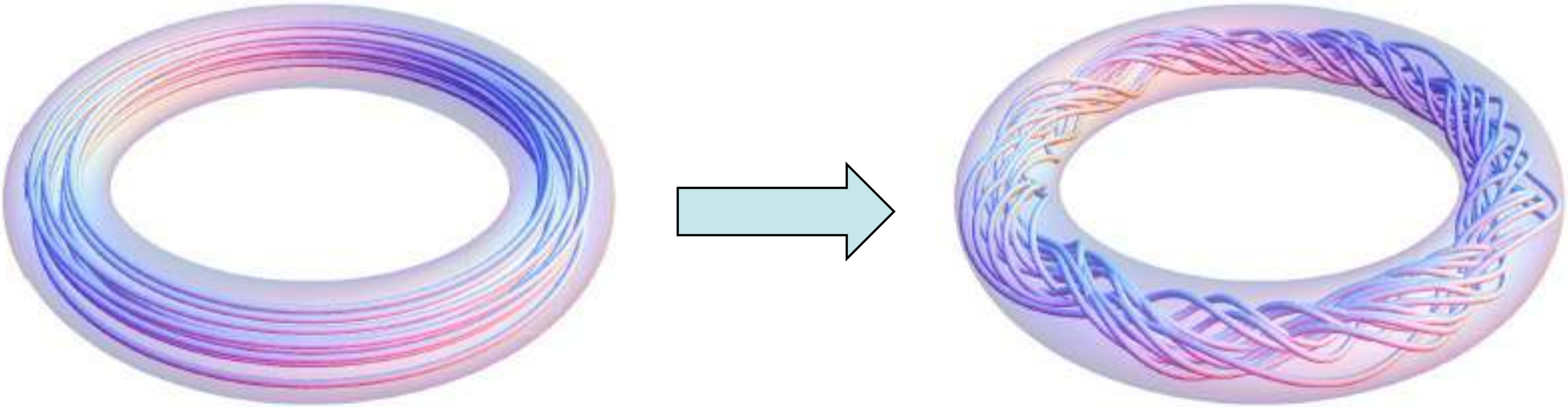
$$\Downarrow$$

$$\mu_5 \sim \vec{E}\vec{B}\, t$$

superconducting current, tunable by magnetic field!

DK, arXiv:1612.05677

Chirality transfer from fermions to gauge fields



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

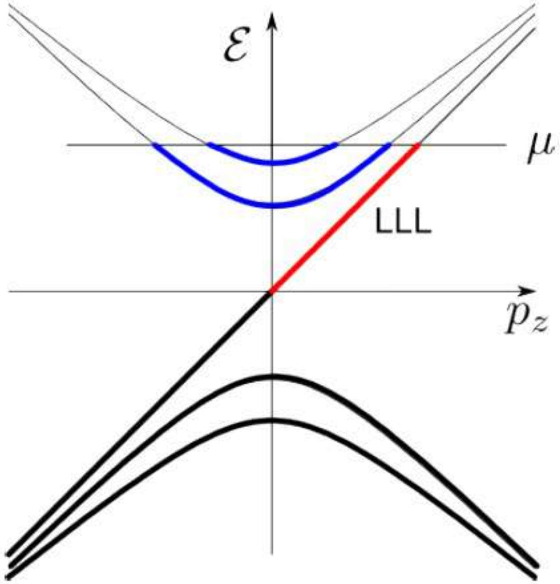
$$\boldsymbol{j}_{\mathrm{CME}} = C_{\mathrm{A}}\ \mu_A\ \boldsymbol{B} = \sigma_A \boldsymbol{B}$$

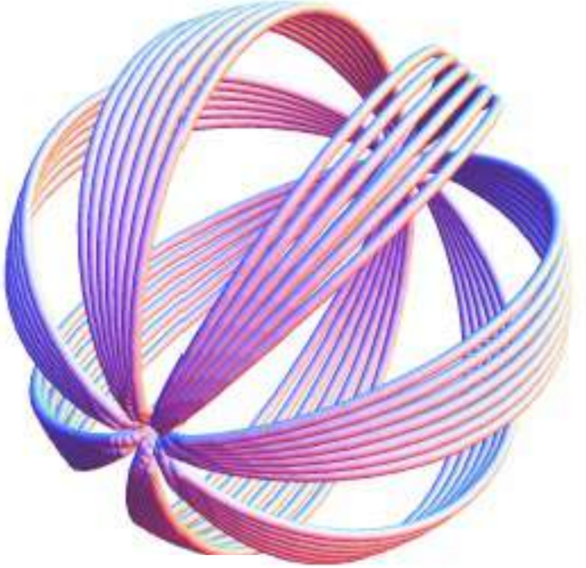
$$\Rightarrow$$

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

solutions:
Chandrasekhar-Kendall states

Chirality transfer from fermions to magnetic helicity





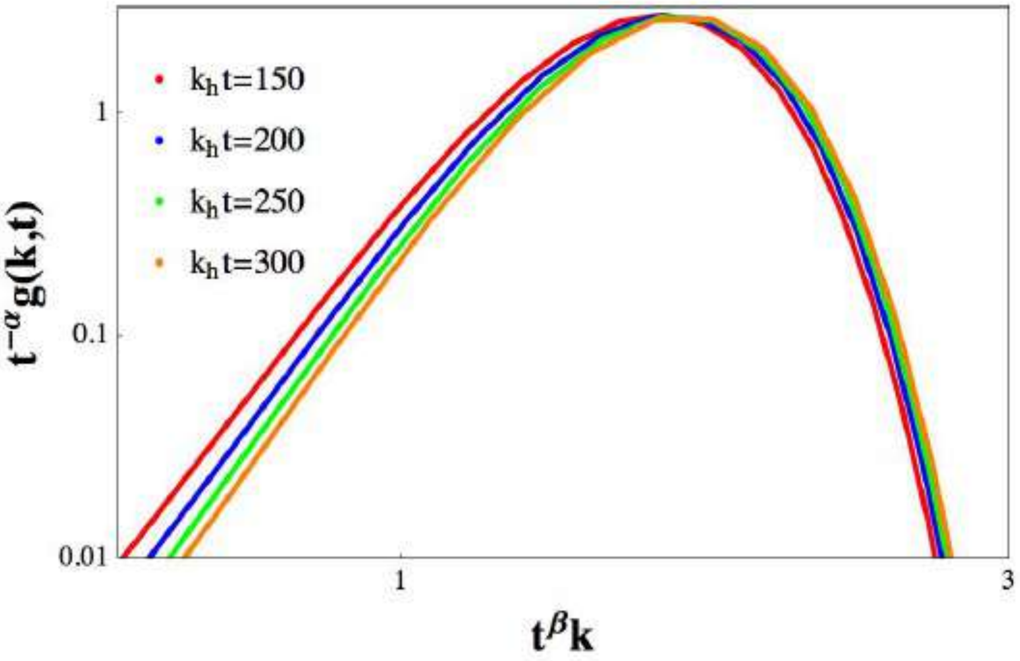
$$h_m \equiv \int d^3x\ \boldsymbol{A}\cdot\boldsymbol{B}$$

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

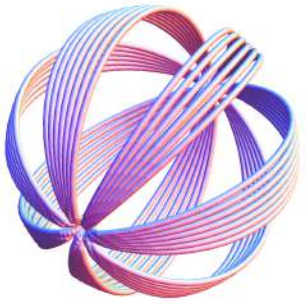
$$\partial_\mu j^\mu_A = C_\mathrm{A} \boldsymbol{E}\cdot\boldsymbol{B}$$

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

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,…

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

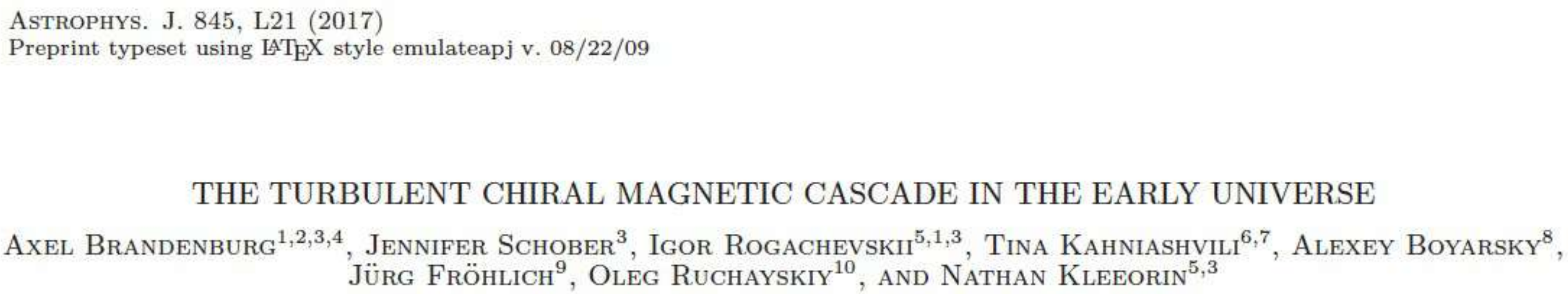
Y. Hirono, DK, Y.Yin, PRD'15

N. Yamamoto, PRD'16

Possible link between "helical magnetogenesis"
and baryogenesis in Early Universe:

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

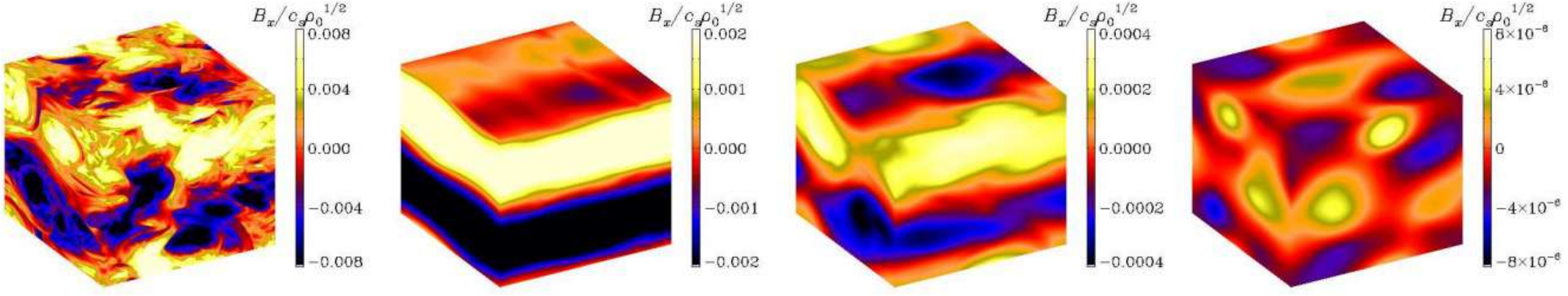
CME in the Early Universe



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]



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:

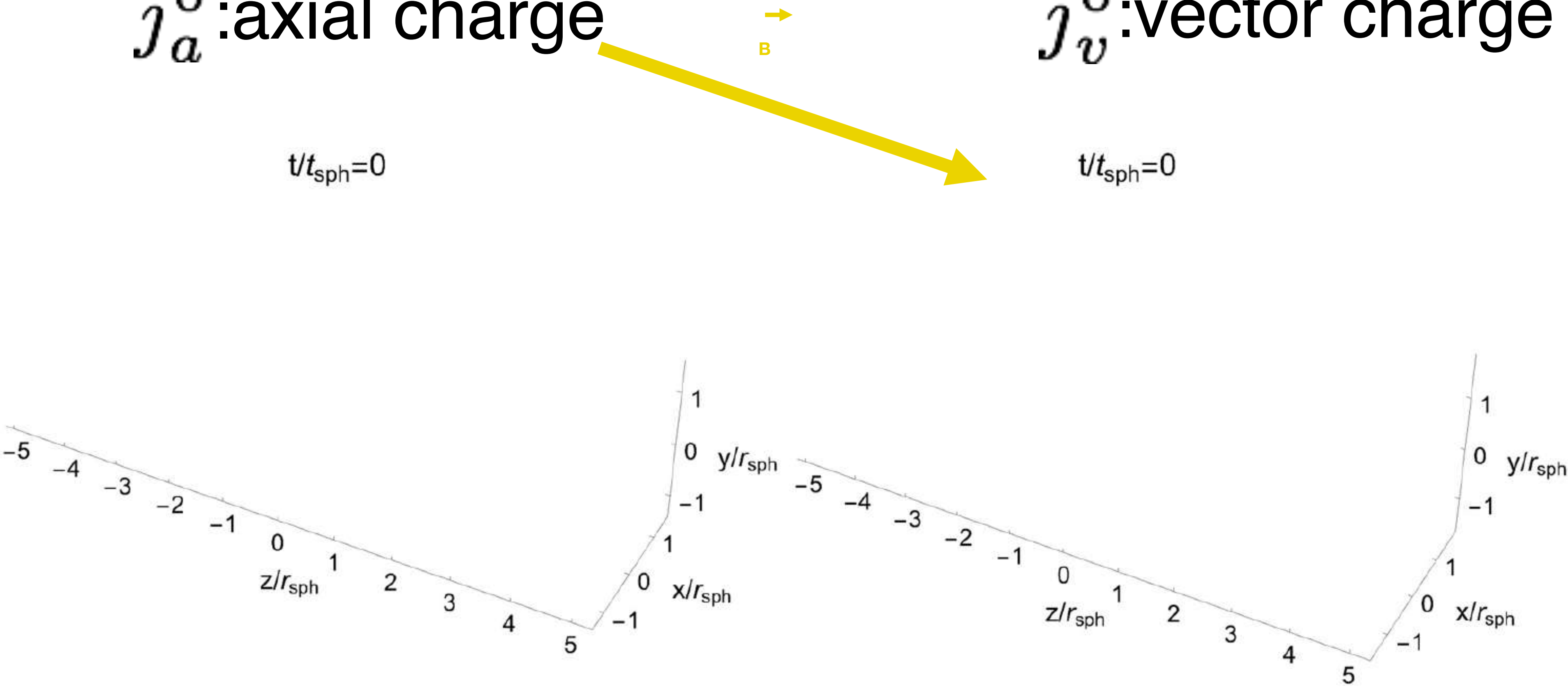
$$\omega = \mp v_\chi k - i D_L k^2 + \cdots$$

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 j_v^0 :vector charge

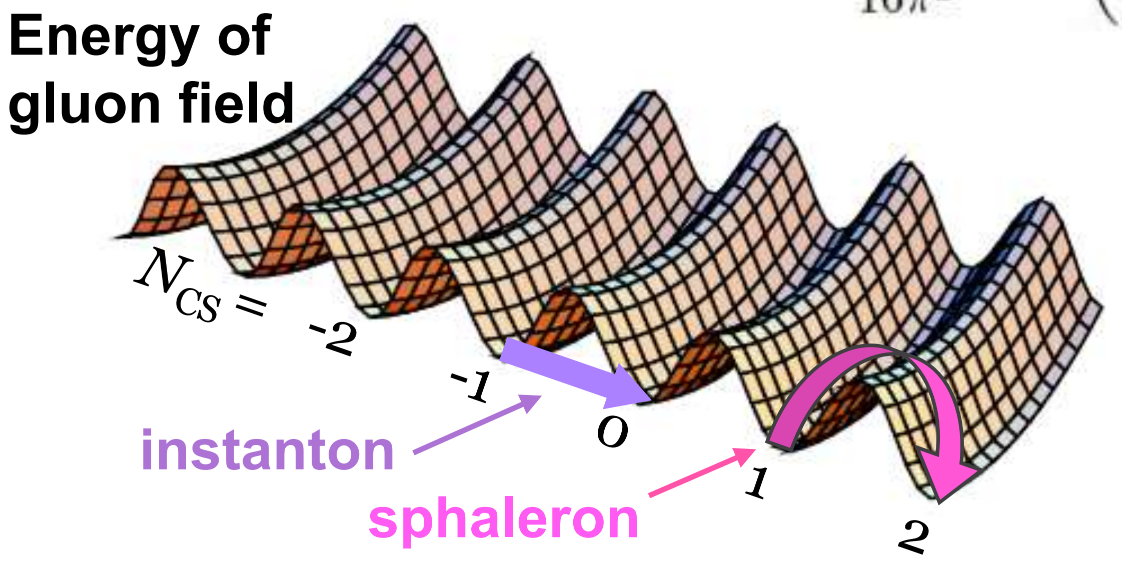


Static U(1) magnetic field in z-dir

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 $N_{CS} = \int d^3x K_o$

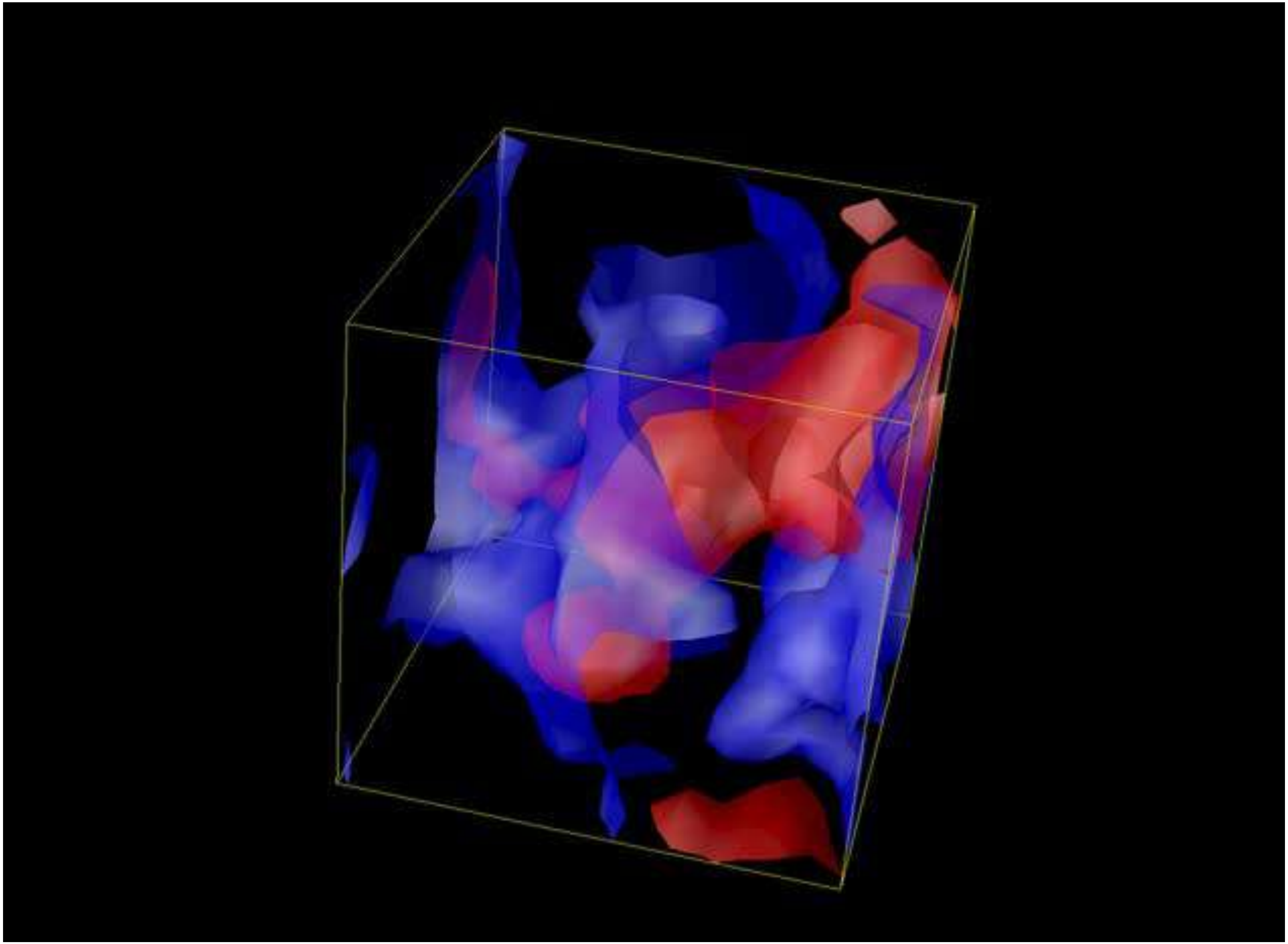
$$K_\mu = \frac{1}{16\pi^2}\epsilon_{\mu\alpha\beta\gamma}\left(A^a_\alpha \partial_\beta A^a_\gamma + \frac{1}{3}f^{abc}A^a_\alpha A^b_\beta A^c_\gamma\right)$$



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

“Topological foam” in QCD vacuum, (3+1) Dimensions

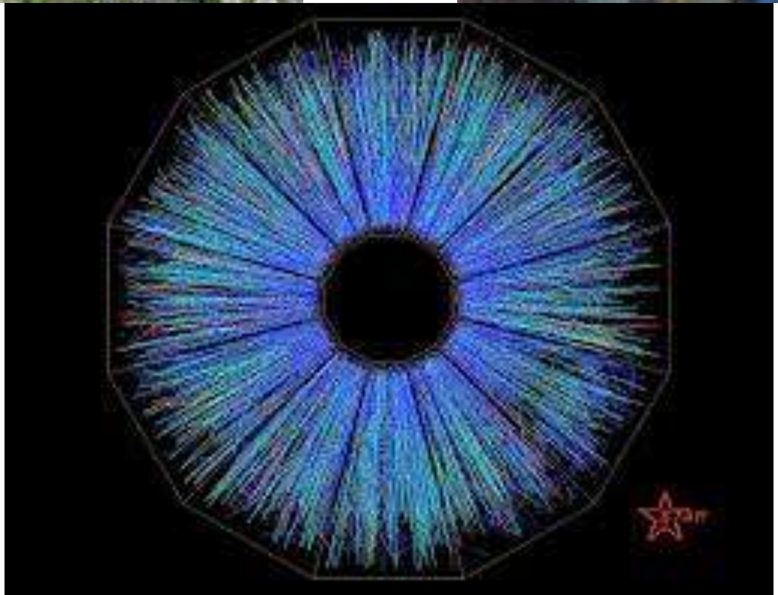
ITEP Lattice Group



Can one detect QCD topological transitions in heavy ion collisions?

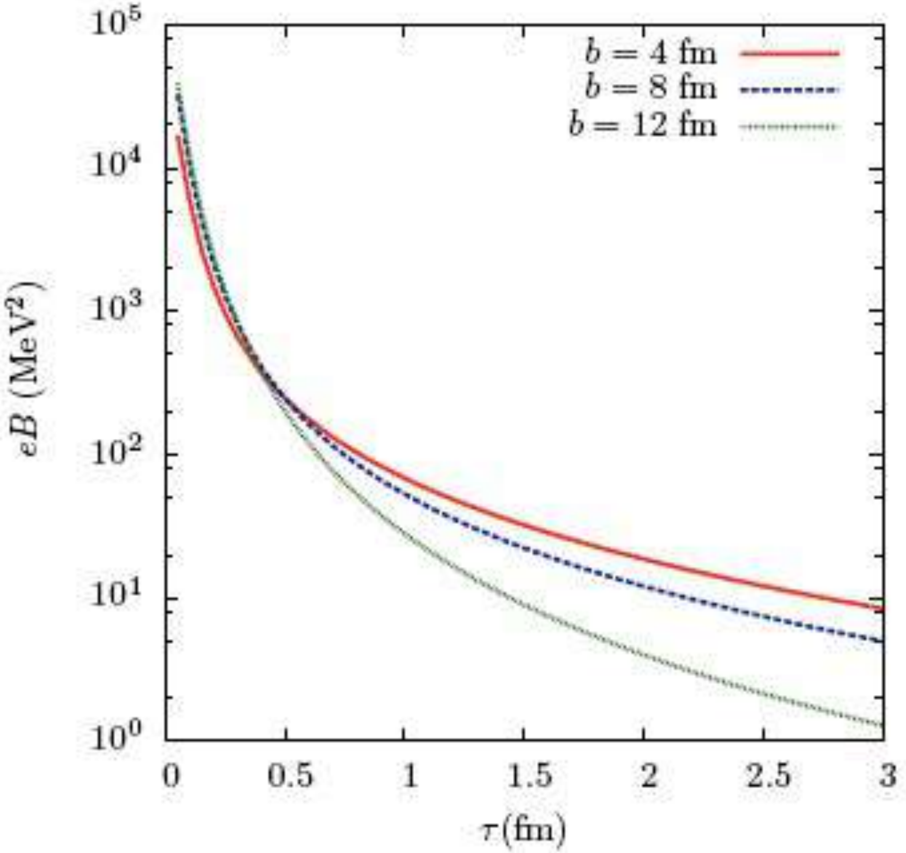
Relativistic Heavy Ion Collider (RHIC) at BNL

The STAR Collaboration at RHIC



Charged hadron tracks in a Au-Au collision at RHIC

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

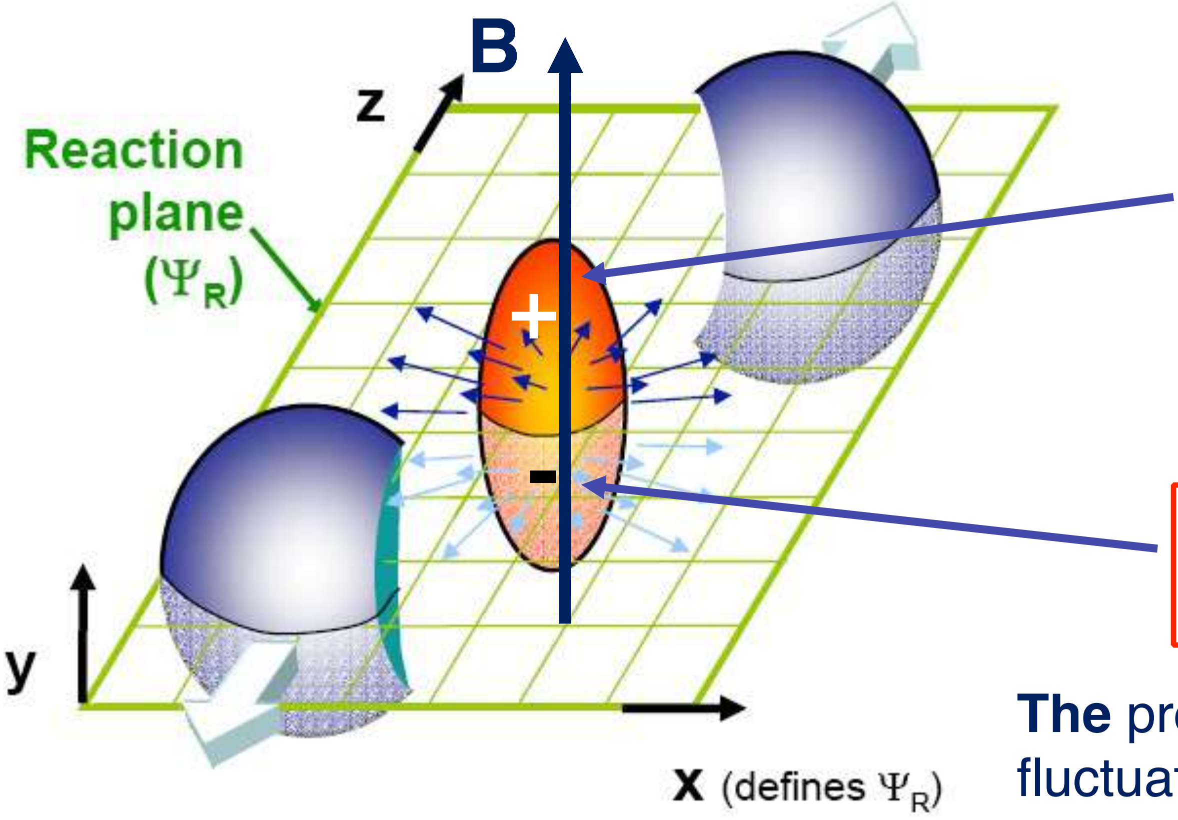


DK, McLerran, Warringa,
Nucl Phys A803(2008)227

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 ($Y_0 = 5.4$).

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

Electric dipole moment due to chiral imbalance

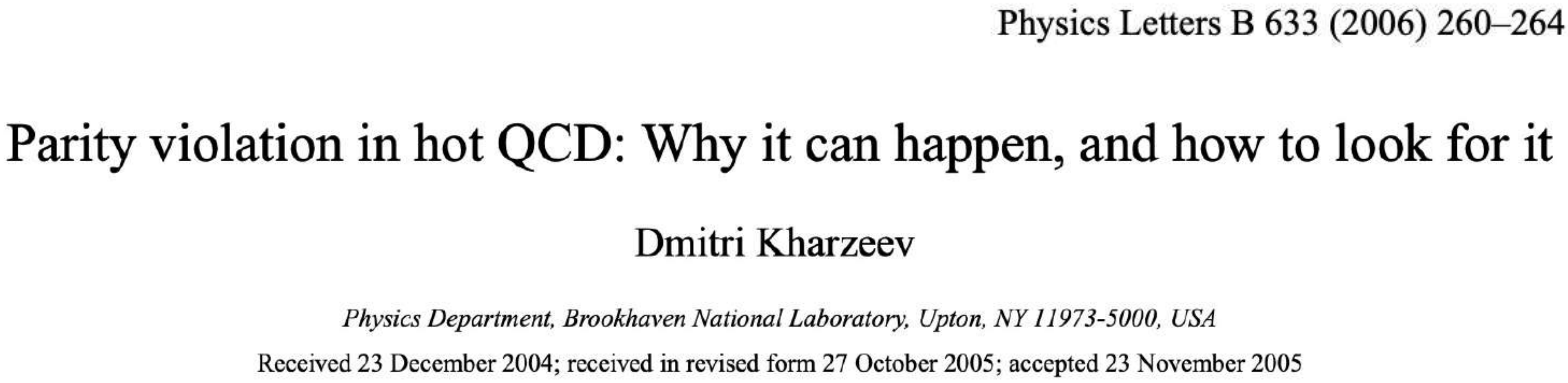


excess of positive charge

excess of negative charge

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

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



Physics Letters B 633 (2006) 260–264

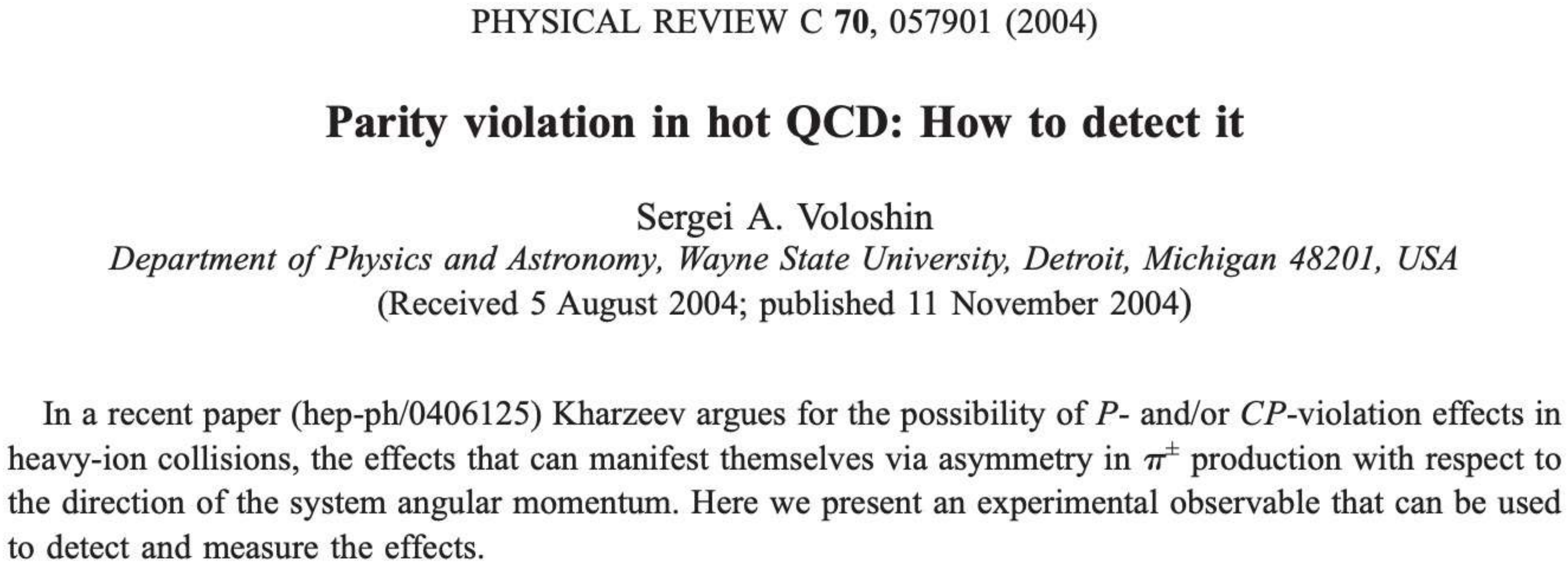
Parity violation in hot QCD: Why it can happen, and how to look for it

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 $\pi^{\pm}$ 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.

nature reviews physics

DK, J. Liao, Nature Rev. (Phys) 3 (2021) 55

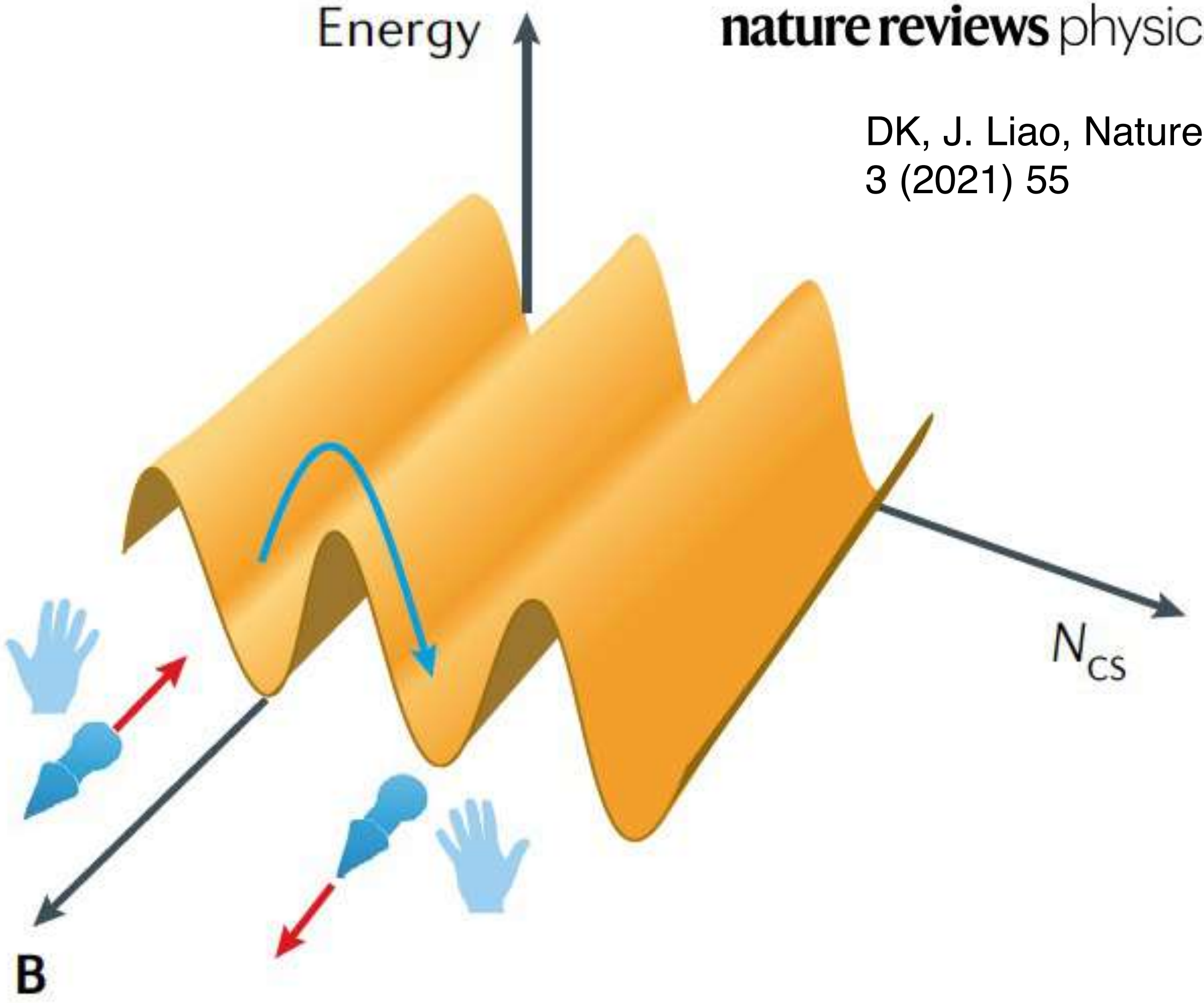


Fig. 1 | **An illustration of the mechanism that underlies the chiral magnetic effect in quantum chromodynamics matter.** The QCD vac-

PRL **103,** 251601 (2009)

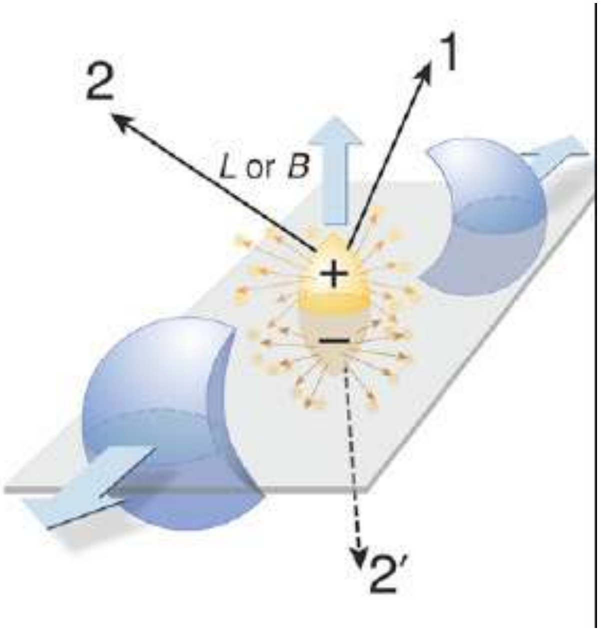
Selected for a Viewpoint in *Physics*

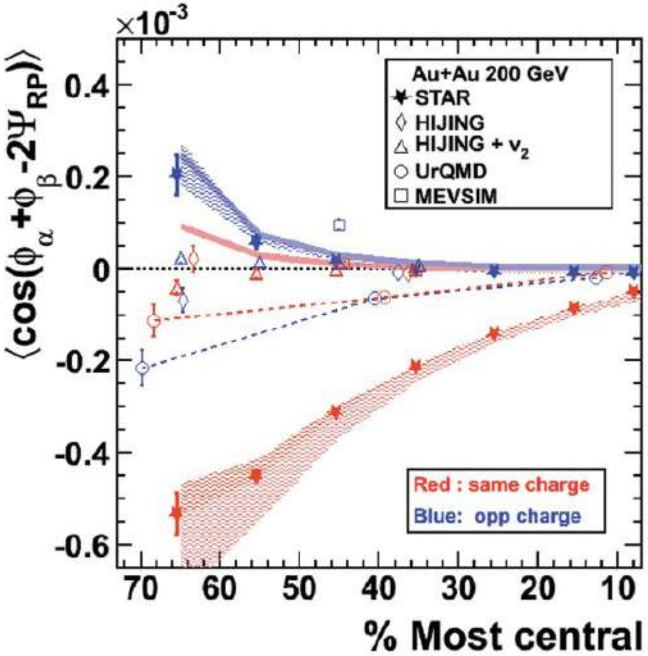
PHYSICAL REVIEW LETTERS

week ending
18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)





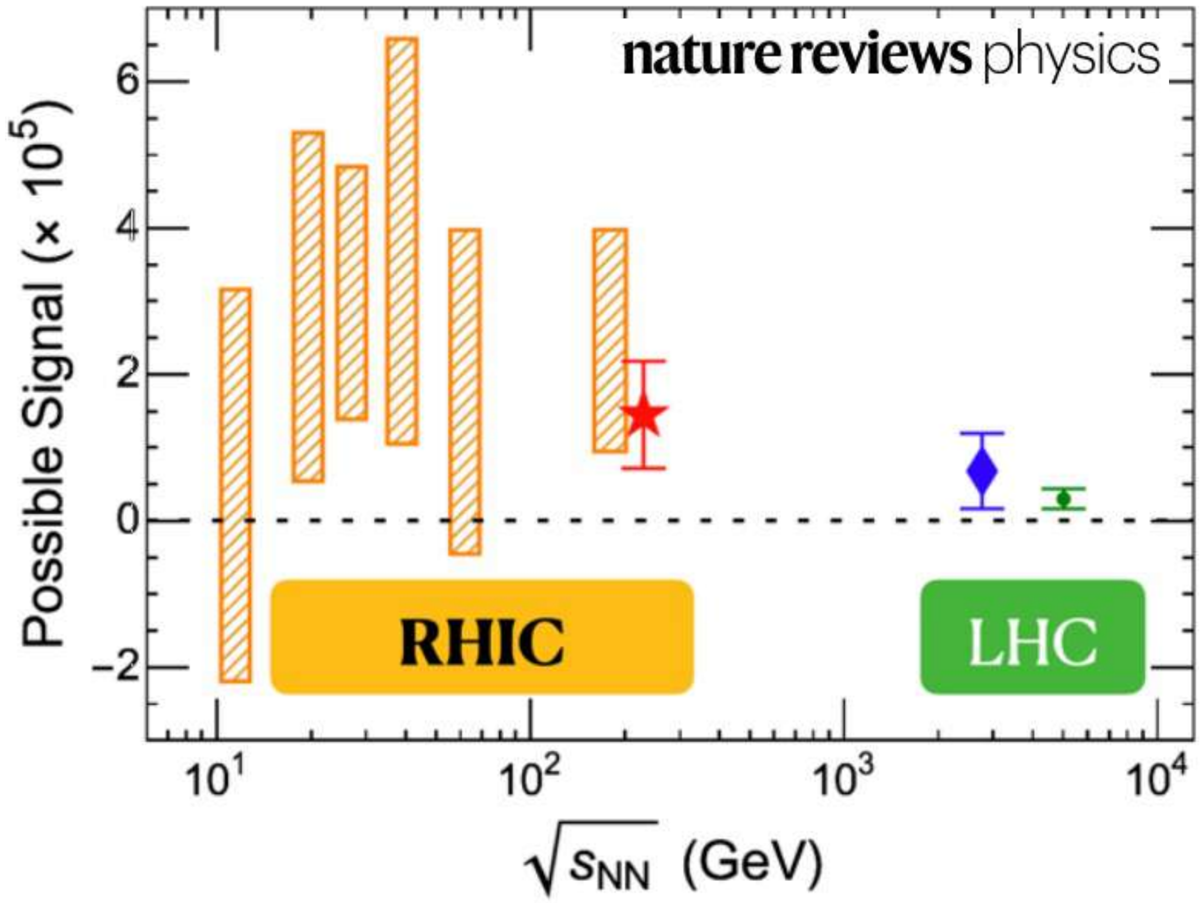
$$\gamma \equiv \langle\cos(\phi_\alpha+\phi_\beta-2\Psi_{\mathrm{RP}})\rangle = \langle\cos\Delta\phi_\alpha\,\cos\Delta\phi_\beta\rangle - \langle\sin\Delta\phi_\alpha\,\sin\Delta\phi_\beta\rangle$$

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

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

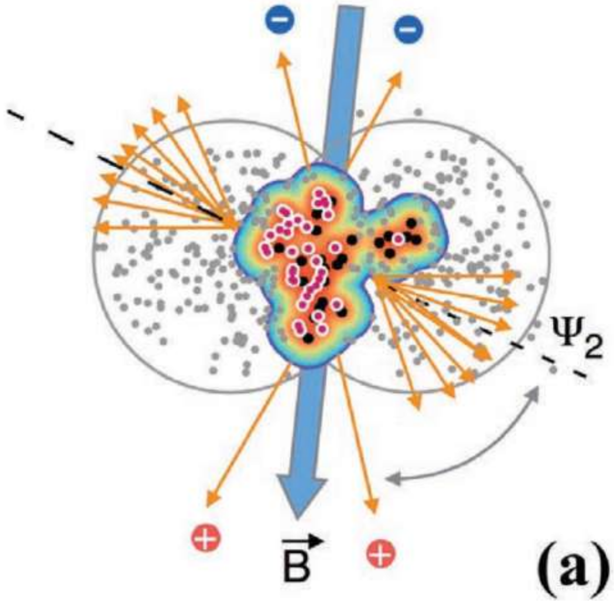
Review of CME with heavy ions: DK, J. Liao, S. Voloshin, G. Wang, Rep. Prog. Phys.’16

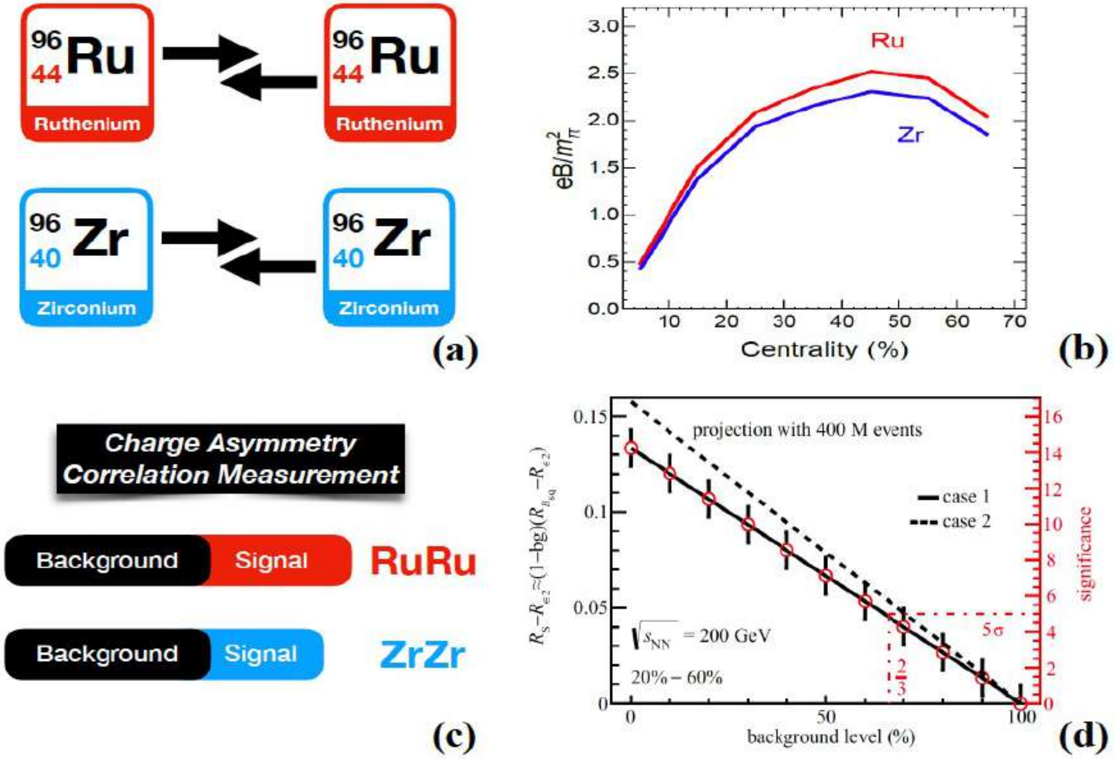
Review + Compilation of the current data: DK, J. Liao, Nature Reviews (Phys.) 3 (2021) 55



Separating the signal from background is the main subject of the ongoing work –

Major new development: the isobar run, results will appear in 2021!



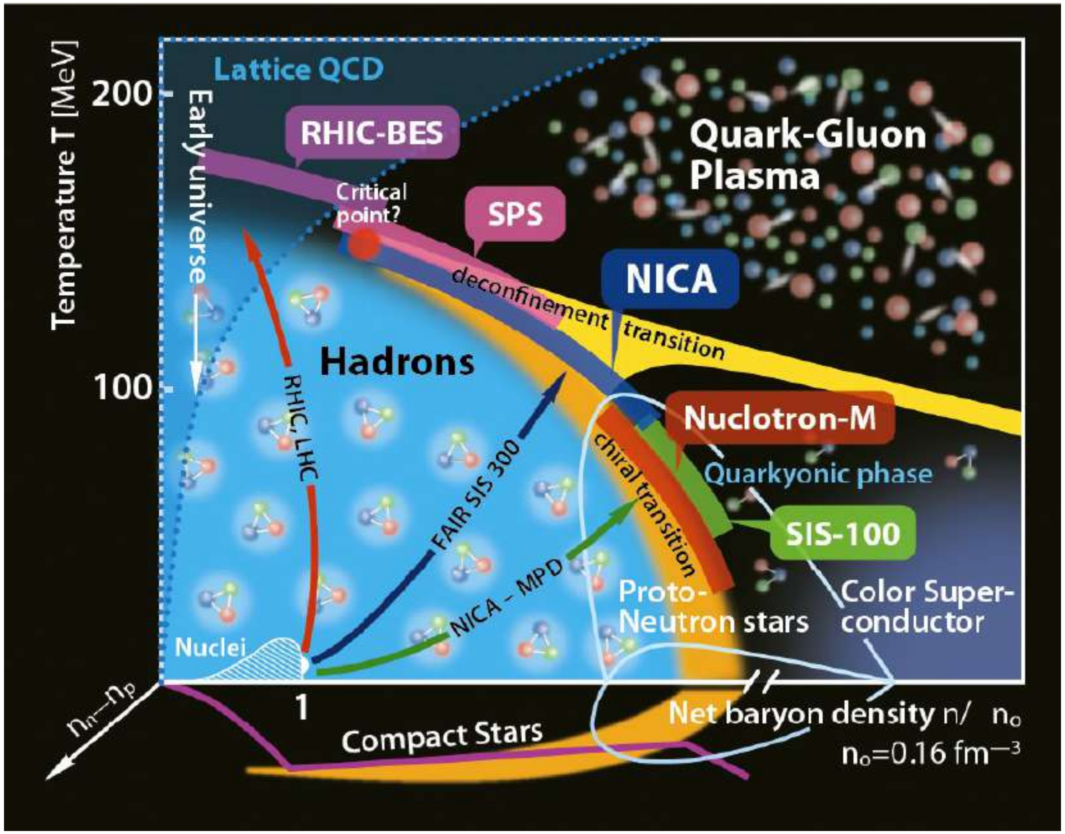


STAR Collaboration

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

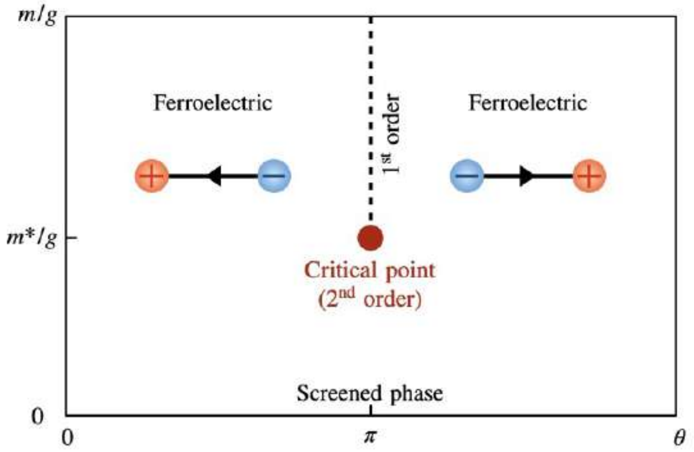


FIG. 1: Phase diagram of the massive Schwinger model in the $(\theta, m/g)$ plane. At $\theta = \pi$ and large masses $m > m^*$, the ferroelectric phases with opposite orientations of electric field are separated by the line of the first order phase transition. This line terminates at $m^* \approx 0.33g$ 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

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

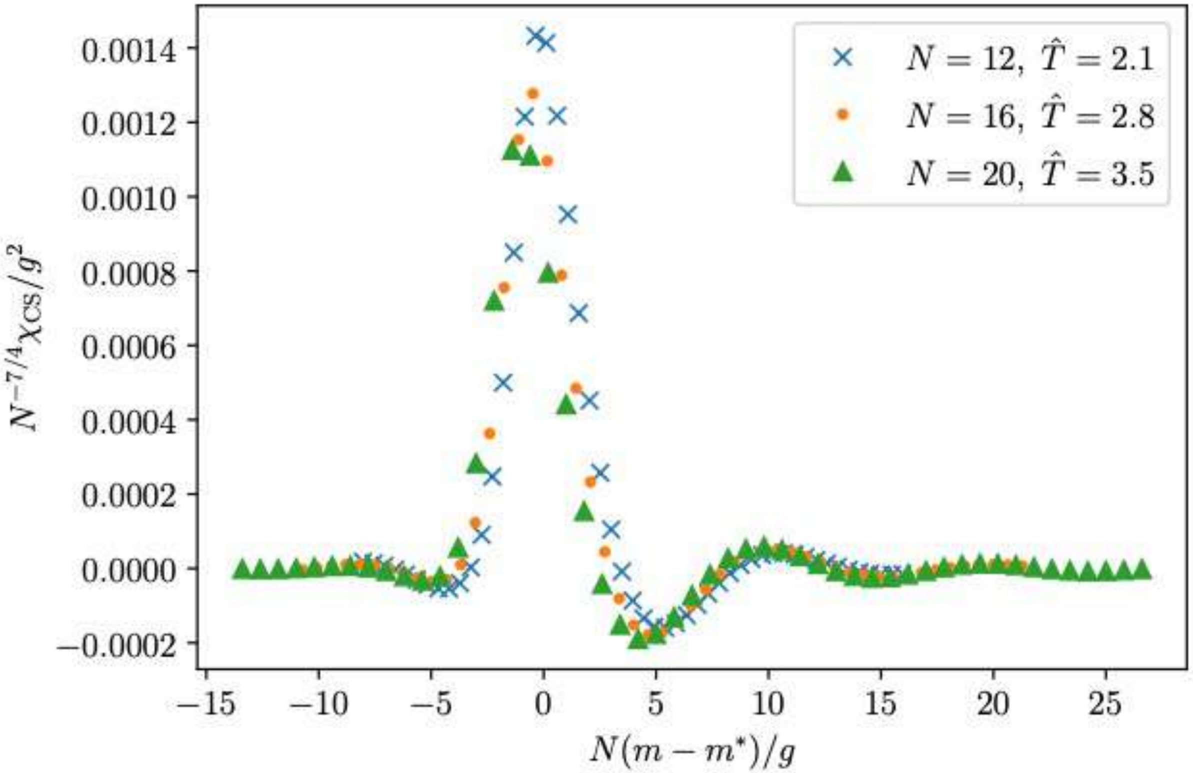
↓ bosonization

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

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

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

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)

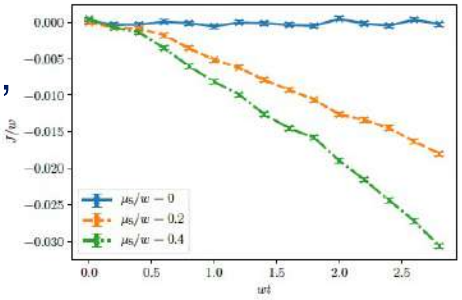
$$S = \int \mathrm{d}^2 x \left[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{g\theta}{4\pi} \epsilon^{\mu\nu} F_{\mu\nu} + \bar{\psi}(\mathrm{i}\gamma^\mu D_\mu - m)\psi \right]$$

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

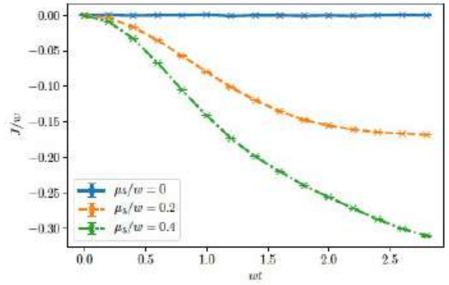
Jordan-Wigner transformation – spin chain

CME current,

μ_5 quench:



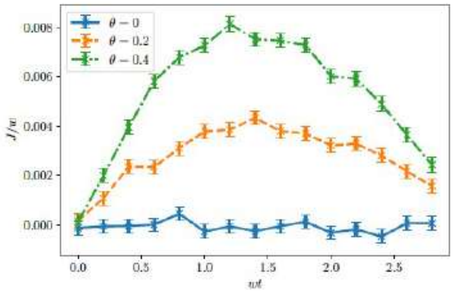
(a) $M/w = 0.1$



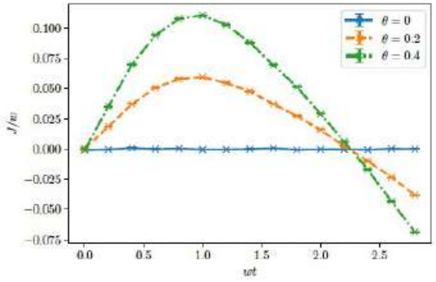
(b) $M/w = 0.5$

CME current,

θ quench:



(a) $M/w = 0.1$



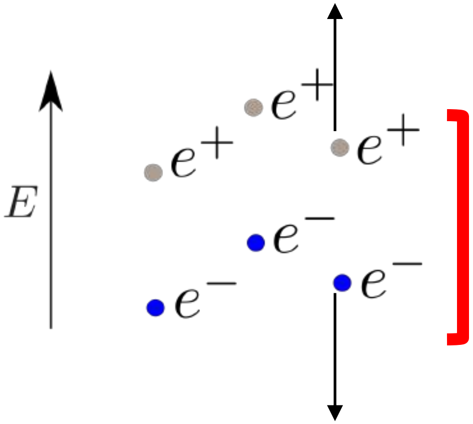
(b) $M/w = 0.5$

Real-time dynamics of CME and “chiral entanglement”

A. Florio, DK,
to appear on June 3

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

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



entanglement

Gibbs entropy

⇕

Entanglement entropy

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

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

Real-time dynamics of CME and “chiral entanglement”

A. Florio, DK,
to appear on June 3

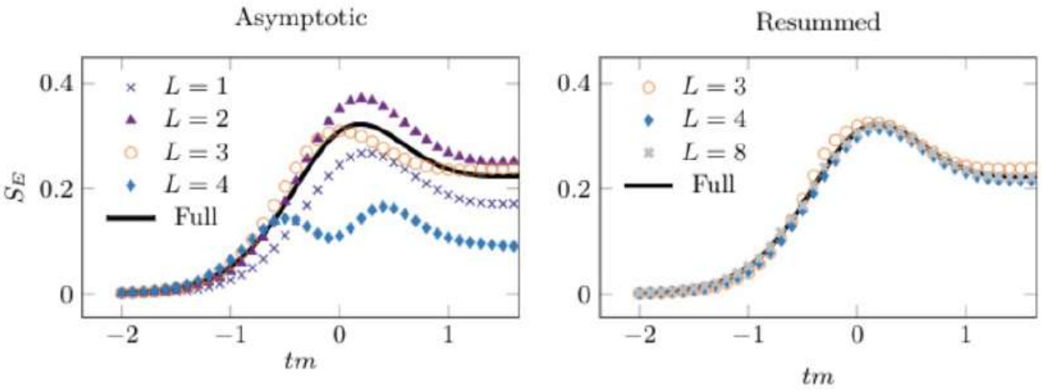
Entanglement entropy can be reconstructed from the moments of multiplicity distribution:

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

Derived first for shot noise in Quantum Point Contacts:

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

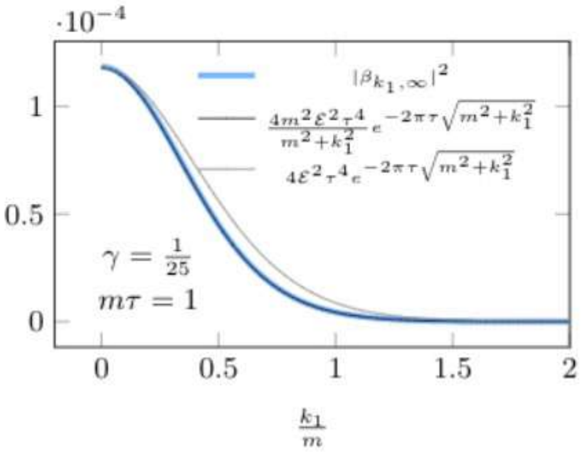
An efficient way to resum this series is found, using Pade-Borel methods:

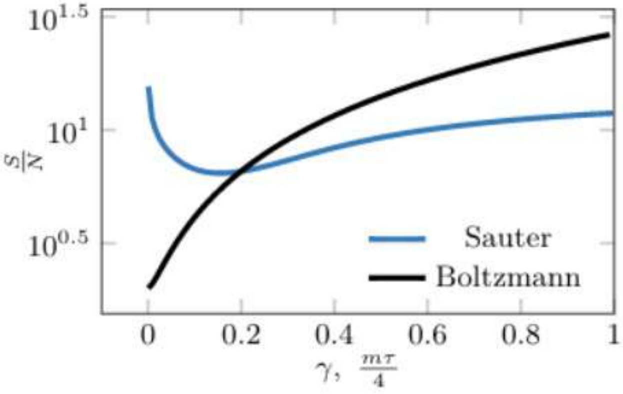


Real-time dynamics of CME and “chiral entanglement”

A. Florio, DK,
to appear on June 3

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



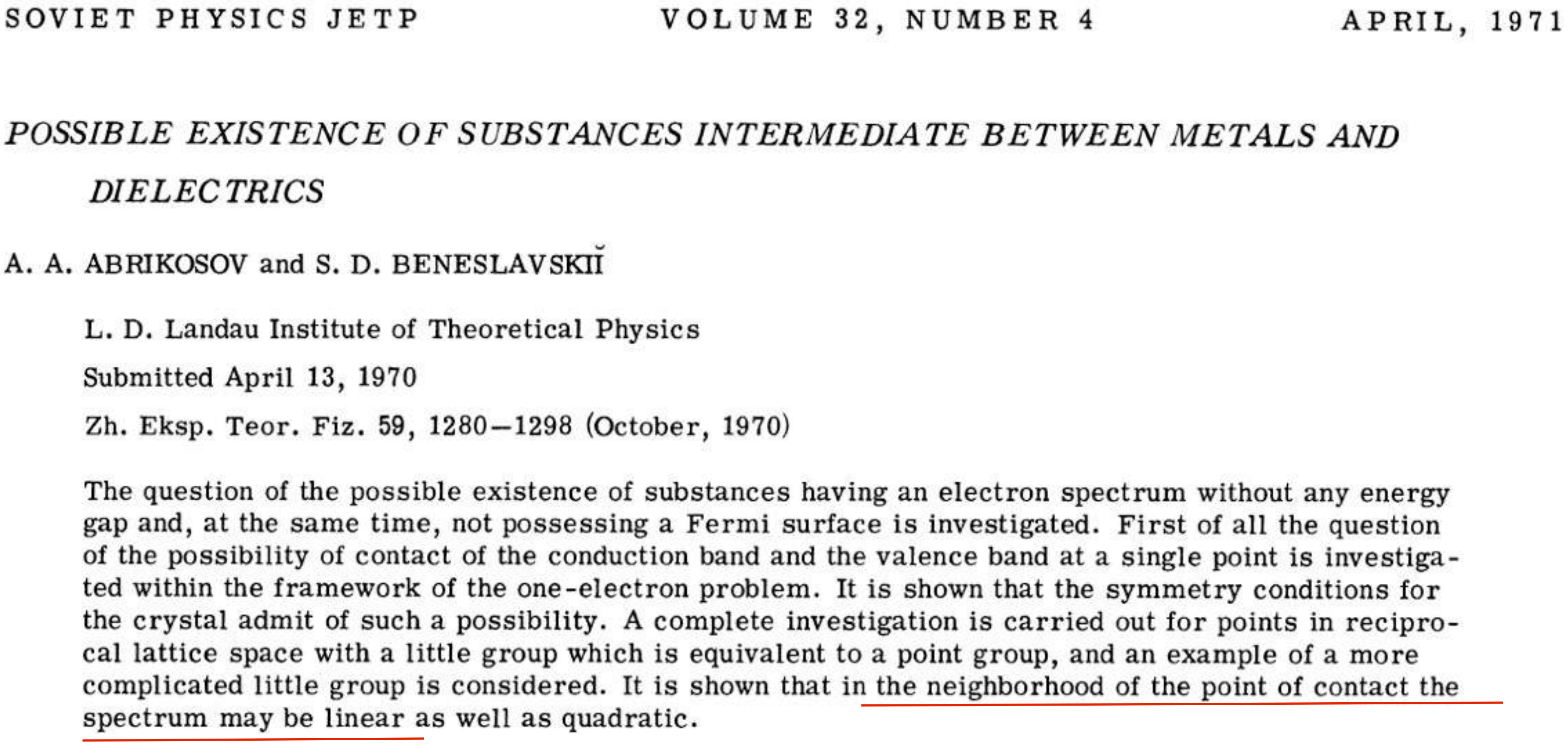


Semiclassical derivation:

DK, K. Tuchin, NPA (2005)

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

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

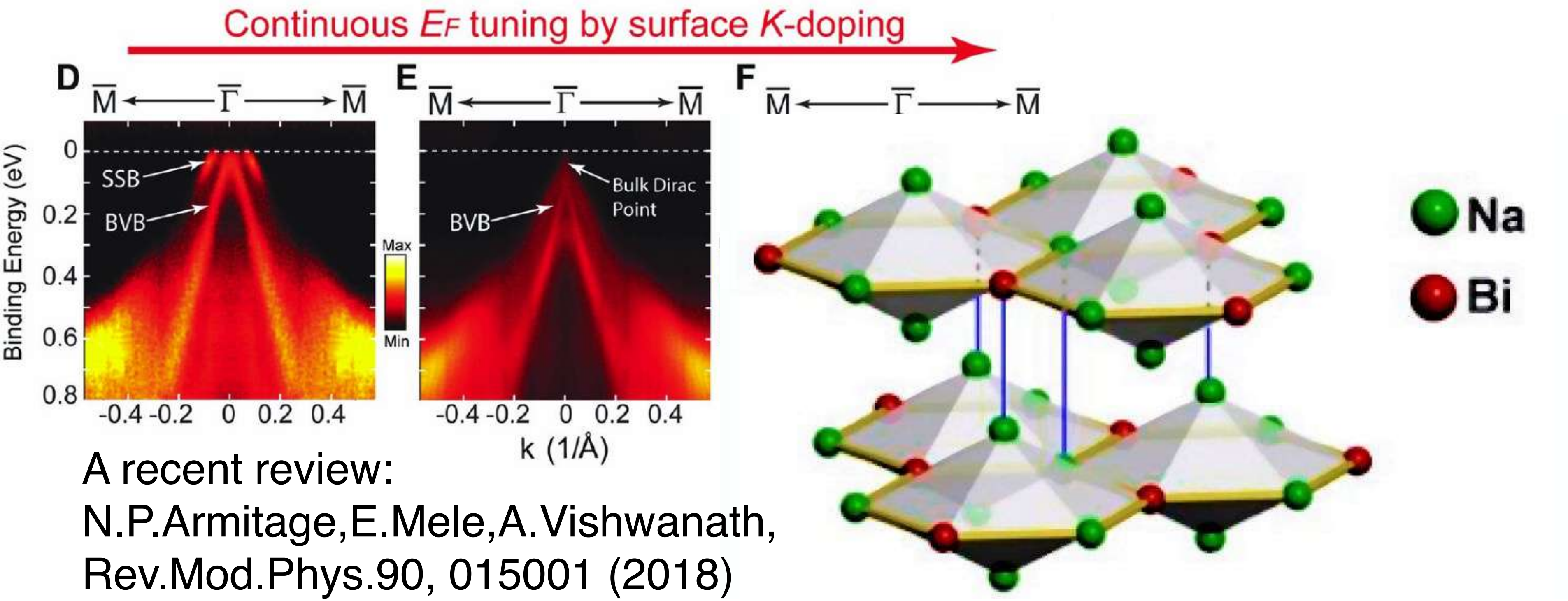
Zh. Eksp. Teor. Fiz. 59, 1280–1298 (October, 1970)

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



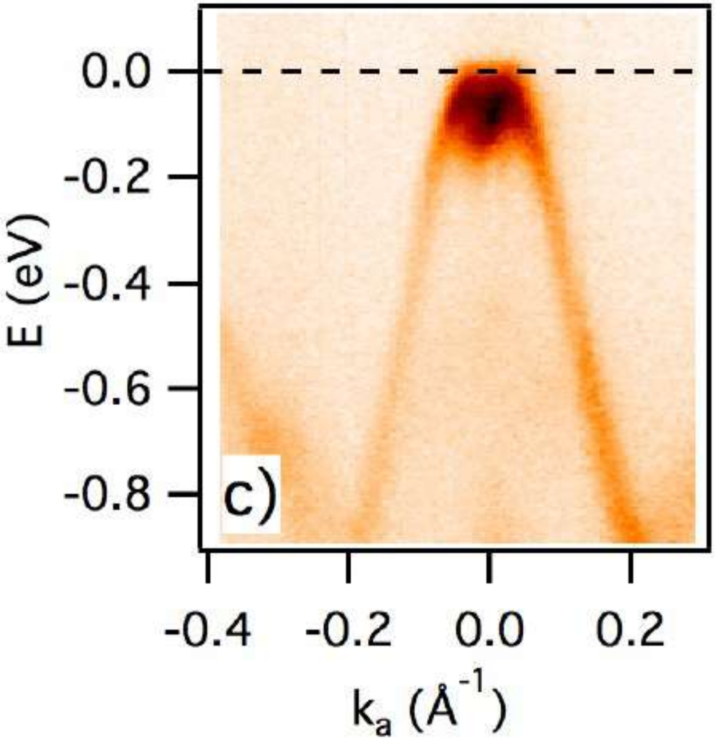
A recent review:
N.P.Armitage,E.Mele,A.Vishwanath,
Rev.Mod.Phys.90, 015001 (2018)

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]



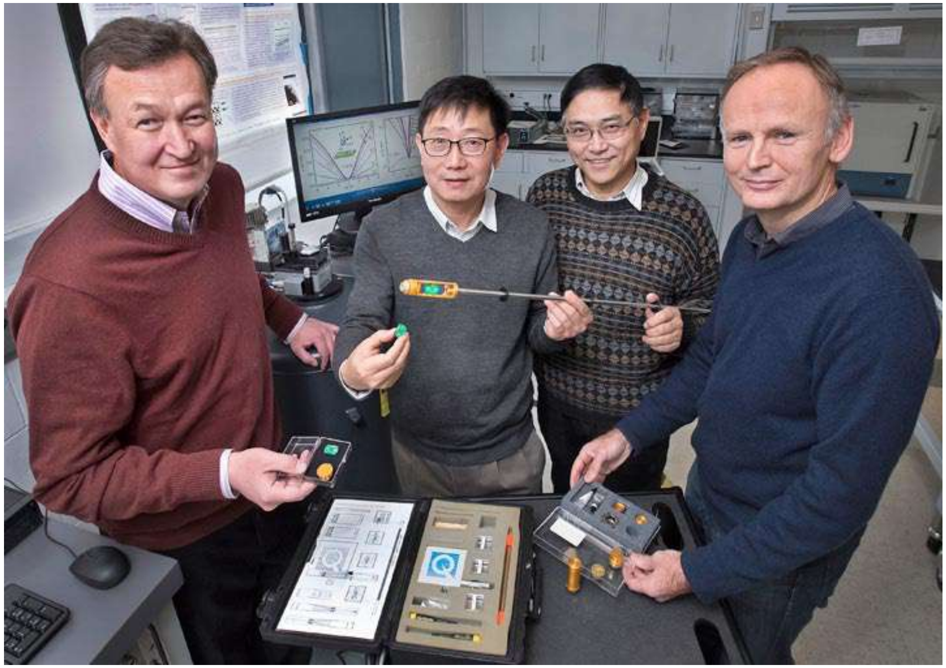
arXiv:1412.6543 (December 2014); Nature Physics **12**, 550 (2016)

CME in chiral materials

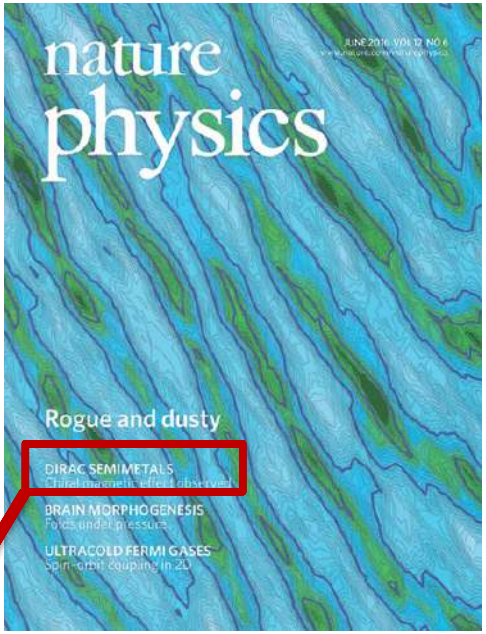
Observation of the chiral magnetic effect in $ZrTe_5$

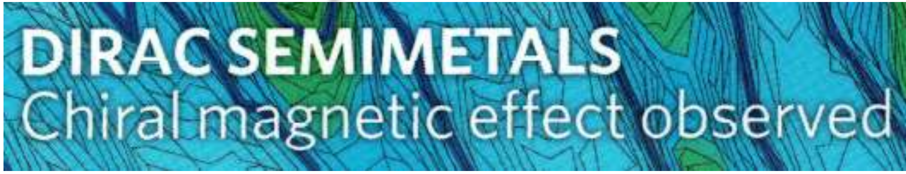
Qiang Li,[1] Dmitri E. Kharzeev,[2,3] Cheng Zhang,[1] Yuan Huang,[4] I. Pletikosić,[1,5] A. V. Fedorov,[6] R. D. Zhong,[1] J. A. Schneeloch,[1] G. D. Gu,[1] and T. Valla[1]

BNL - Stony Brook - Princeton - Berkeley



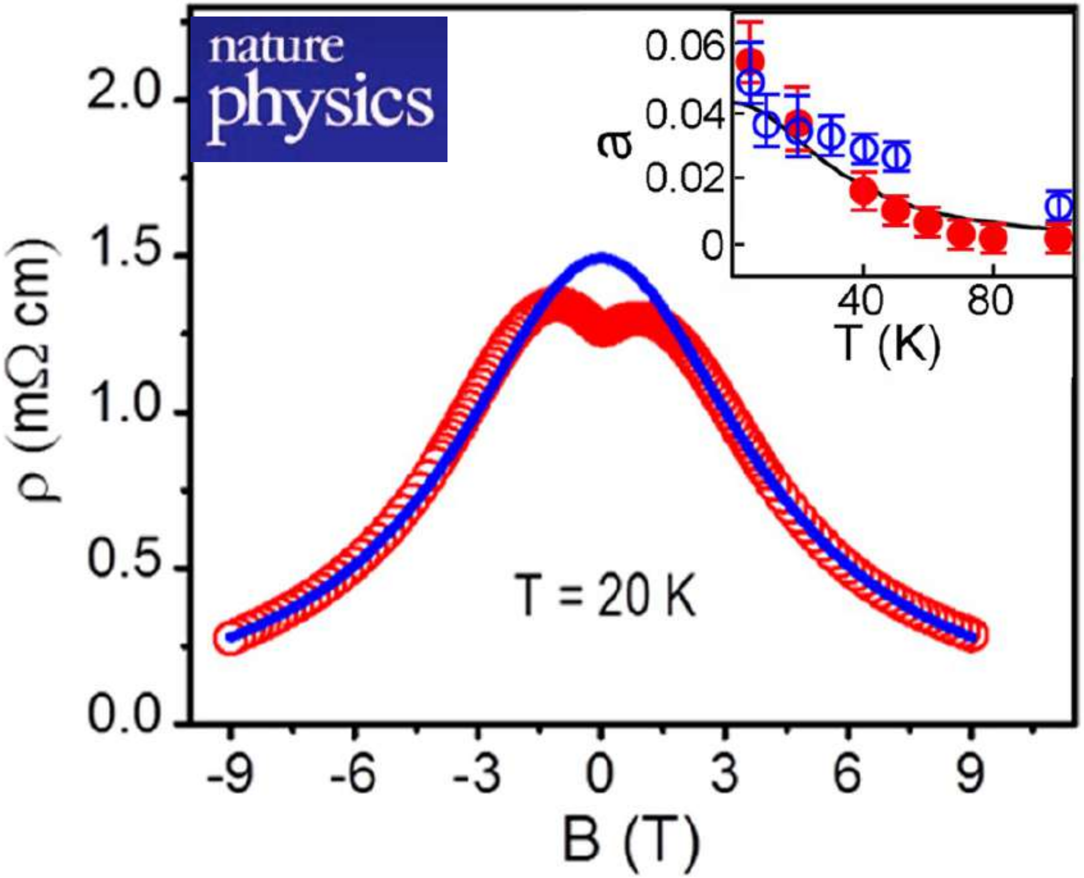
Nature Phys.
12 (2016) 550

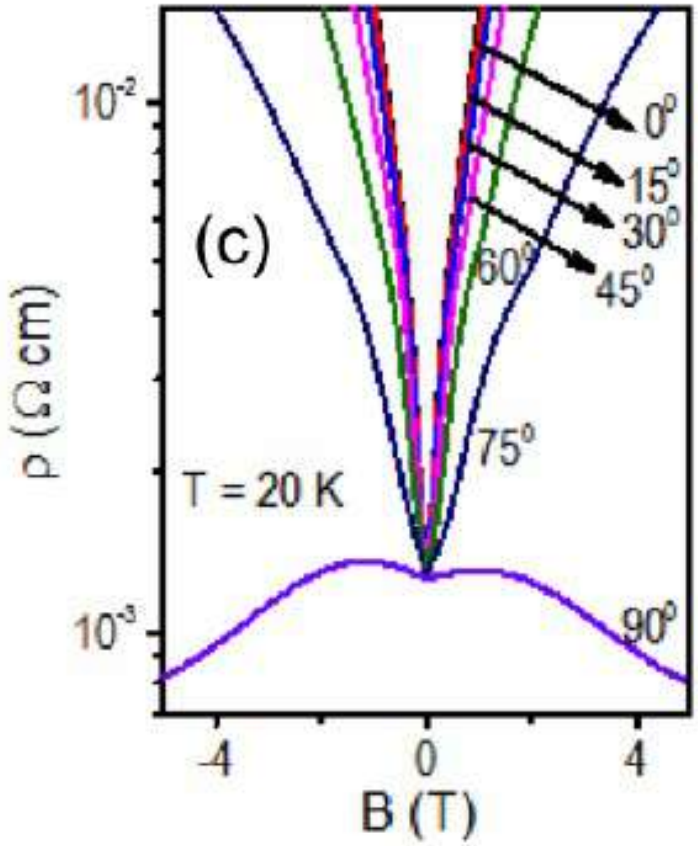




arXiv:1412.6543 [cond-mat.str-el]

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





Can one control CME by circularly polarized light?

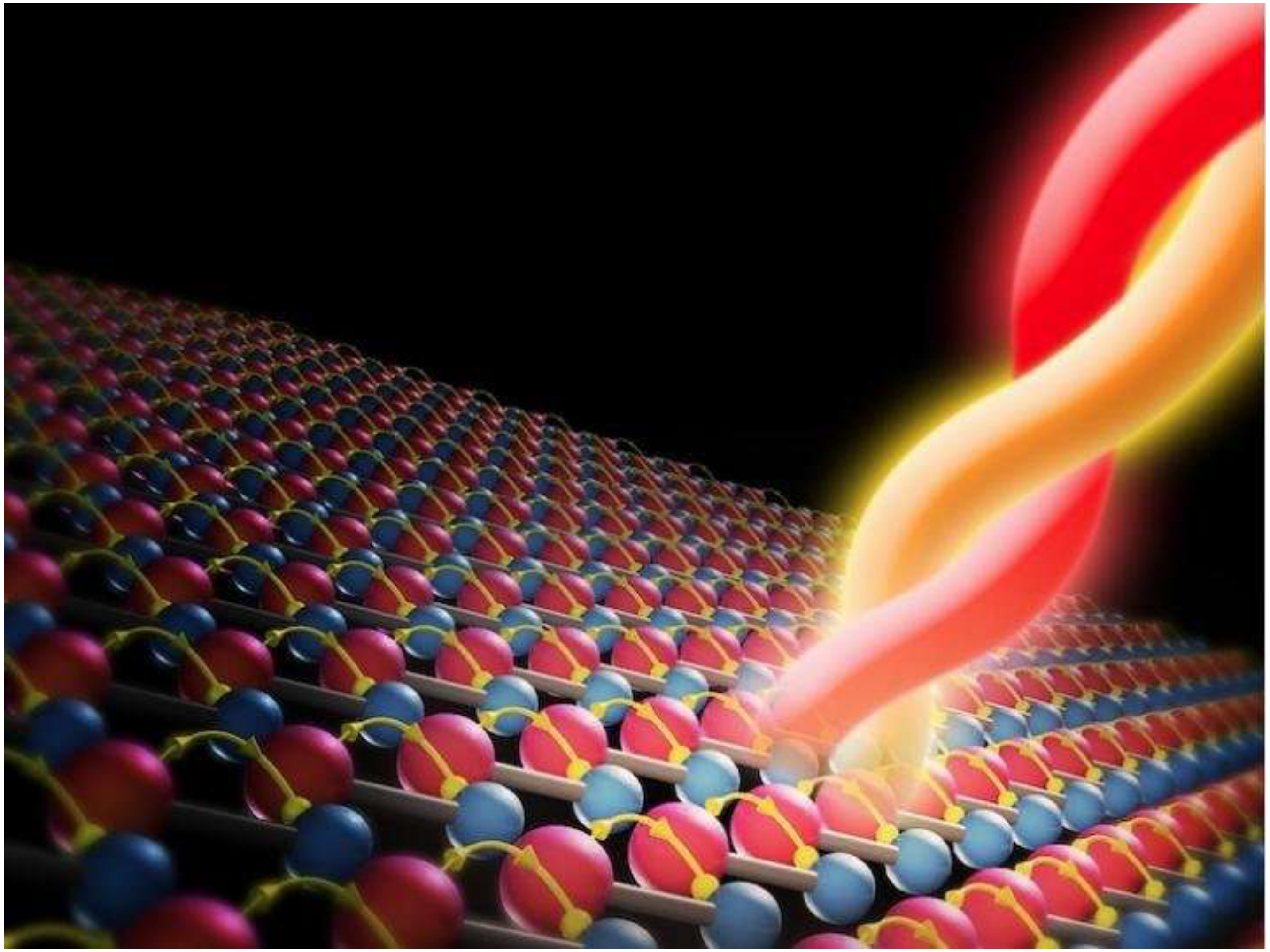


Image credit: Science Daily

Chiral magnetic photocurrent

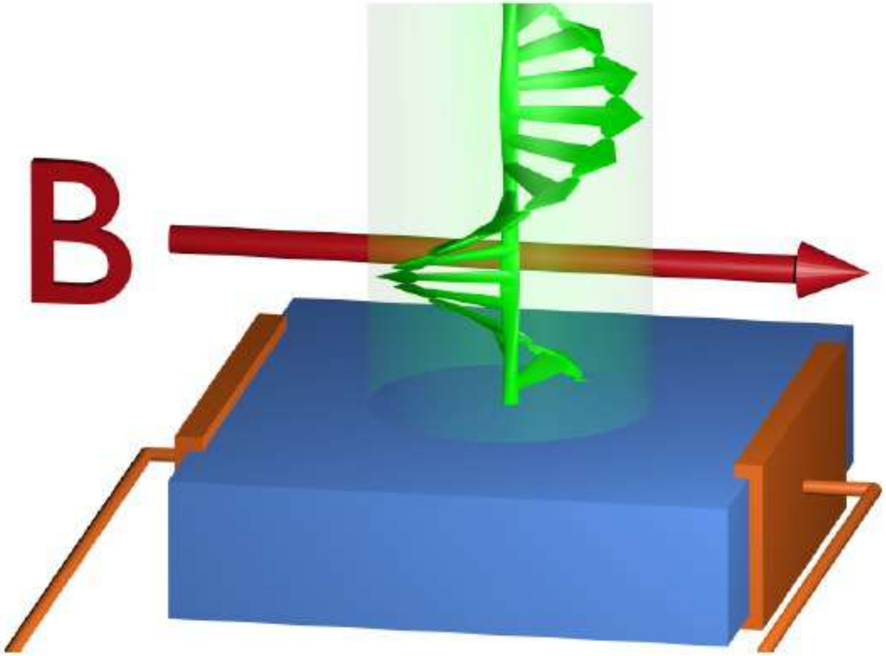


FIG. 1. The CPL incident on a Dirac or Weyl semimetal induces an asymmetry between the number of left- and right-handed chiral quasiparticles. In an external magnetic field, as a consequence of the chiral anomaly, this chiral asymmetry induces a chiral magnetic photocurrent along the direction of the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

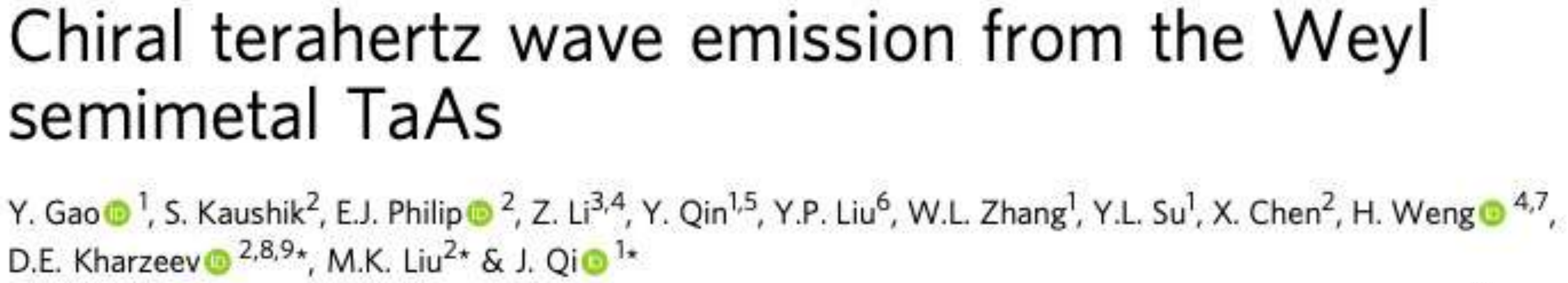
S. Kaushik, E. Philip, DK
arXiv:1810.02399; PRB'19

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

$$\kappa_{\rm CMP} = \int_0^\infty \frac{e^2}{2\pi^2\hbar^2} B_{\rm ext}\, \mu_5 \, {\rm d}z = \pm \frac{e^2}{2\pi^2\hbar^2} B_{\rm ext} \frac{\tau_V}{\chi} \frac{\alpha}{\pi} \frac{I_{\rm in}}{\hbar\omega} \Re(a_x a_y^*).$$

Ultrafast control of chiral currents in Weyl semimetals

arXiv:1901.00986.
Nature Comm. 2020



Chiral terahertz wave emission from the Weyl semimetal TaAs

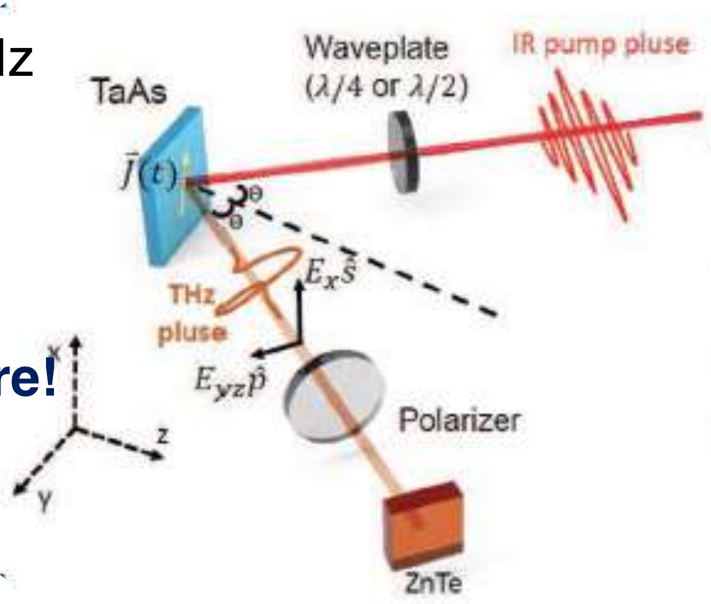
Y. Gao[1], S. Kaushik[2], E.J. Philip[2], Z. Li[3,4], Y. Qin[1,5], Y.P. Liu[6], W.L. Zhang[1], Y.L. Su[1], X. Chen[2], H. Weng[4,7], D.E. Kharzeev[2,8,9*], M.K. Liu[2*] & J. Qi[1*]

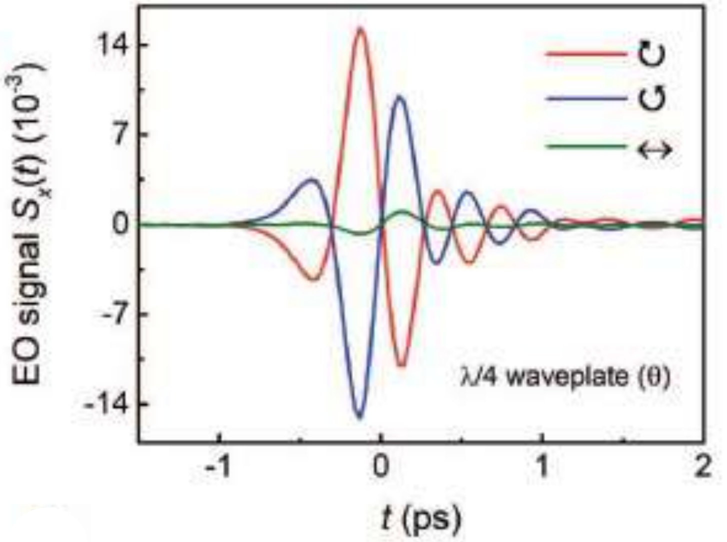
nature COMMUNICATIONS

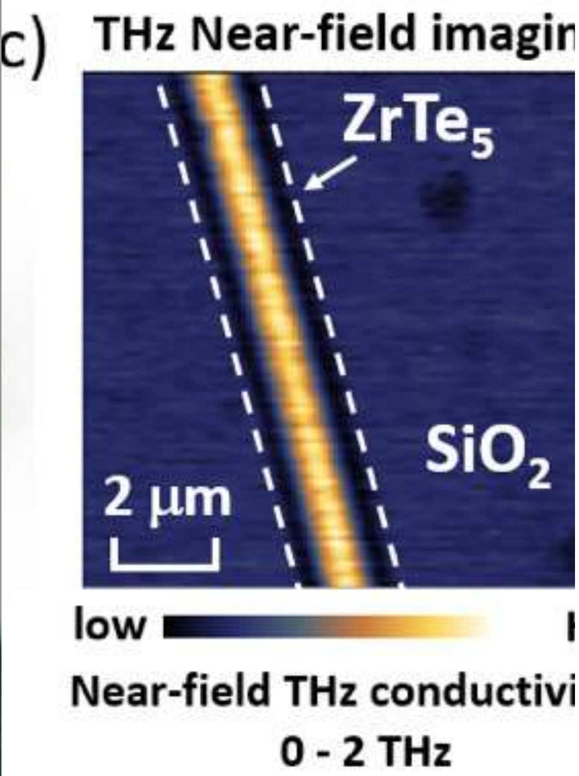
PHYSICS TOP 50 READ ARTICLES OF 2020 OFFICIAL AUTHOR

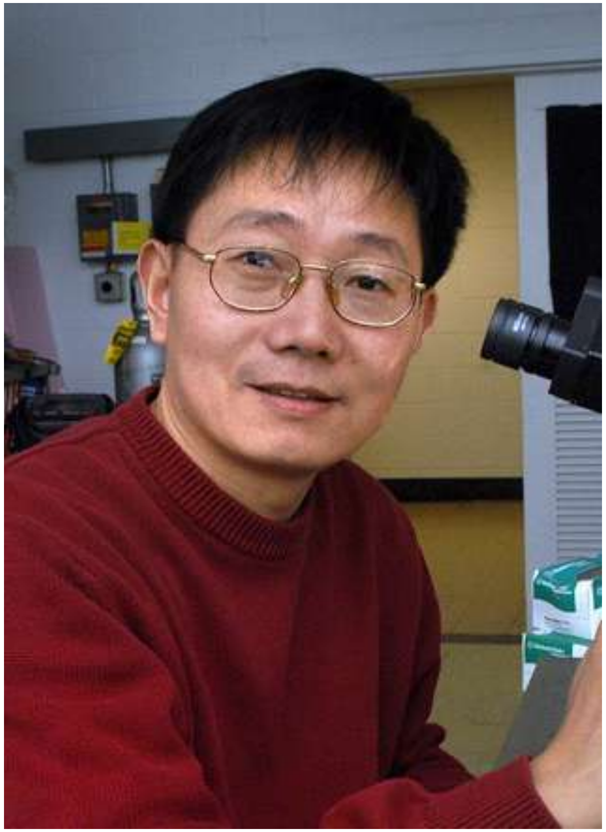
ω = 380 THz
λ = 800 nm
80 fs pulse

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

Chiral straintronics

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

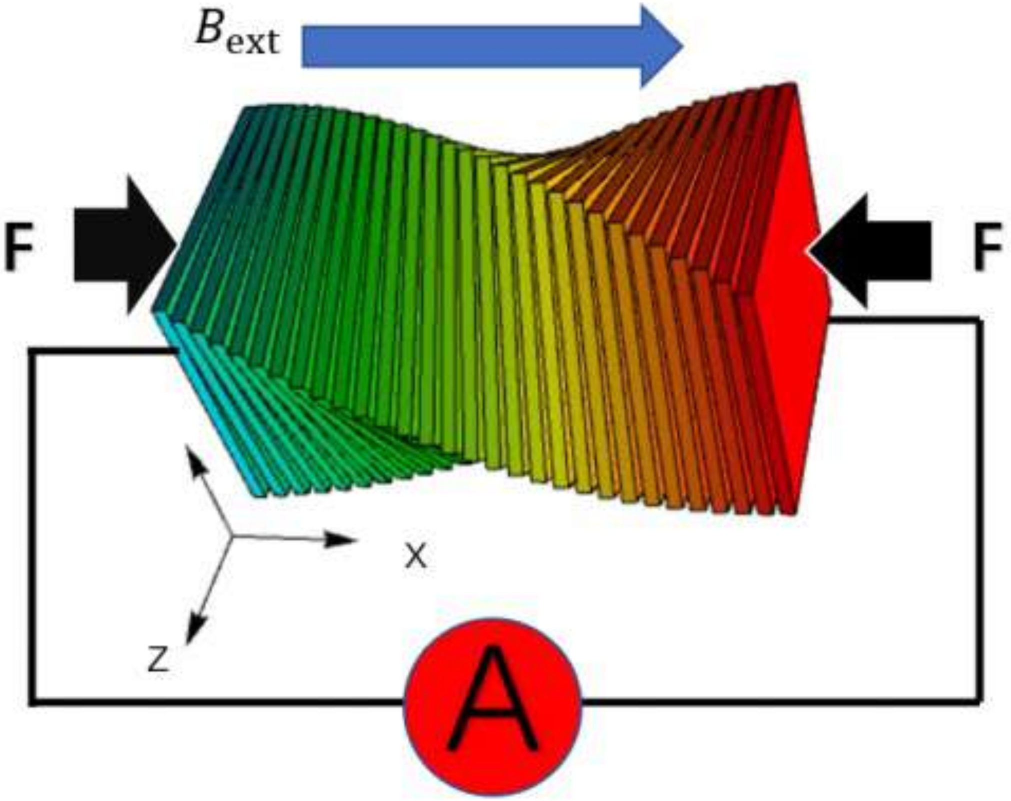
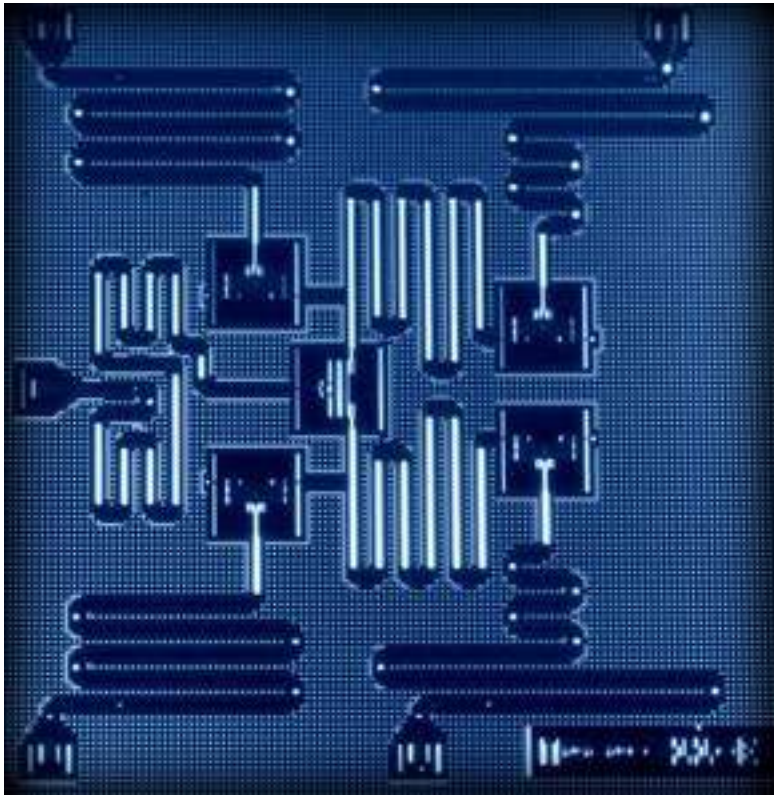


FIG. 1. The chiral magnetic current induced by torsion and compression in the presence of an external magnetic field.

Superconducting qubits



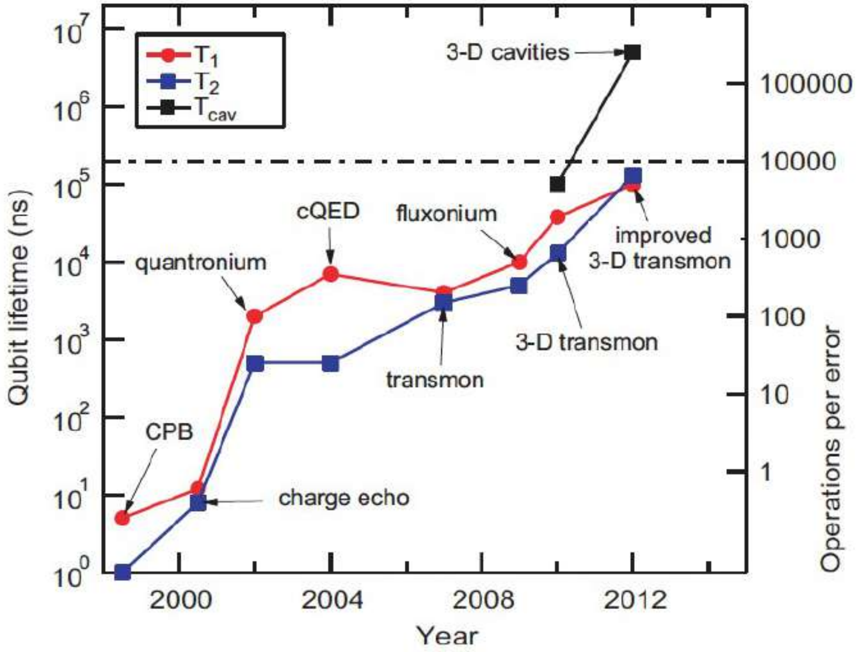


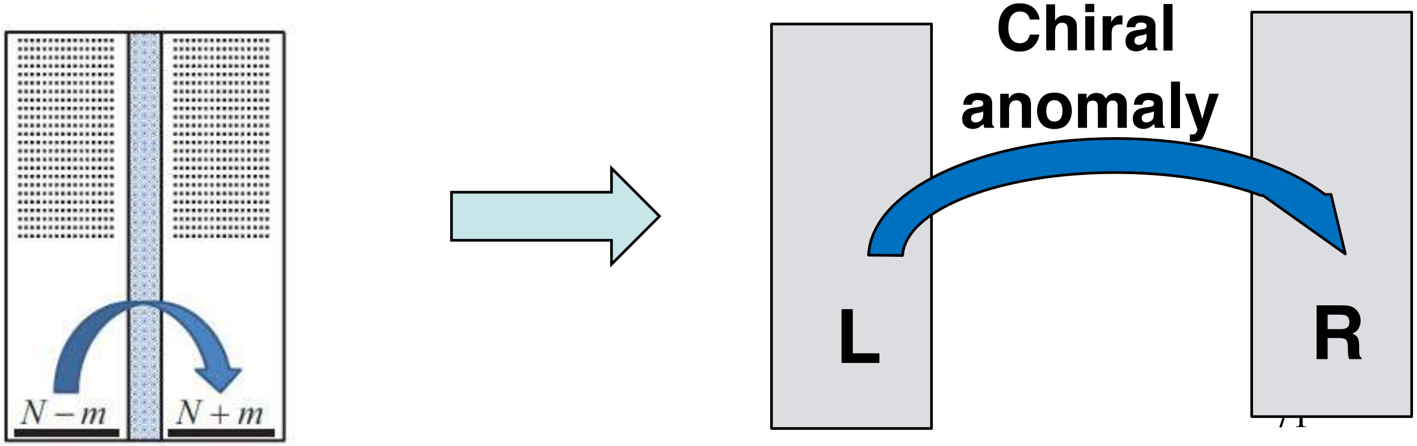
Fig. 2.1 "Schoelkopf's Law" plot illustrating the exponential growth for superconducting (charge-) qubit coherence times. Recent experiments (Geerlings *et al.*, 2013) with the 'fluxonium' qubit design have achieved T_1 times exceeding one millisecond.

IBM five qubit processor credit: IBM-Q

S. Girvin, 2013

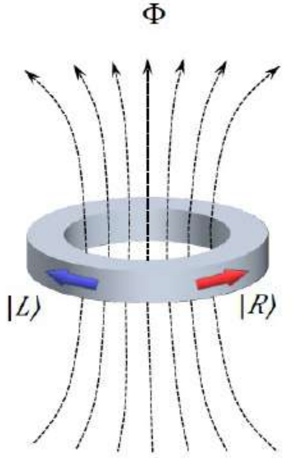
Can the basic physics of the superconducting qubit be realized in a different system, potentially capable of operating at much higher temperatures, higher frequencies, and larger ratio of coherence and gate times?

Probably yes – use the chiral fermions!



Chiral ring: a simple model

Dirac fermion
(1+1), compactified



Magnetic flux;
(3+1) gauge field

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

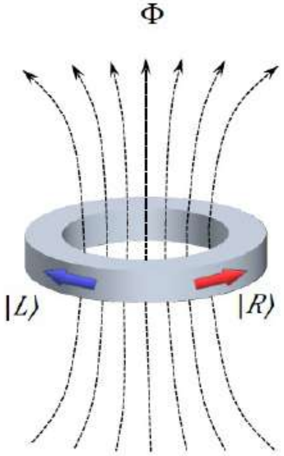
$$\hat{H} = \hbar\omega\left[-i\frac{\partial}{\partial\varphi} - \frac{\Phi}{\Phi_0}\right]\hat{\sigma}_z$$

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!

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

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

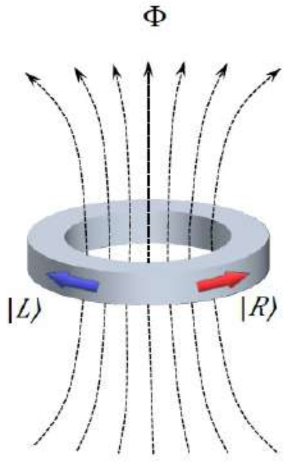
$$J = -e\,\frac{\mu_5}{\pi}.$$

CME in (1+1) dimensions!

DK, Q.Li,
arXiv:1903.07133

Chiral Qubit: the Hamiltonian

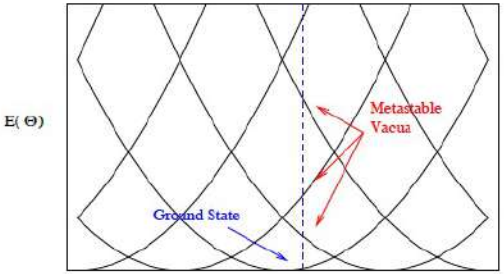
$$\hat{H} = \hbar\omega \left[-i \frac{\partial}{\partial\varphi} - \frac{\Phi}{\Phi_0} \right] \hat{\sigma}_z$$



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

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

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

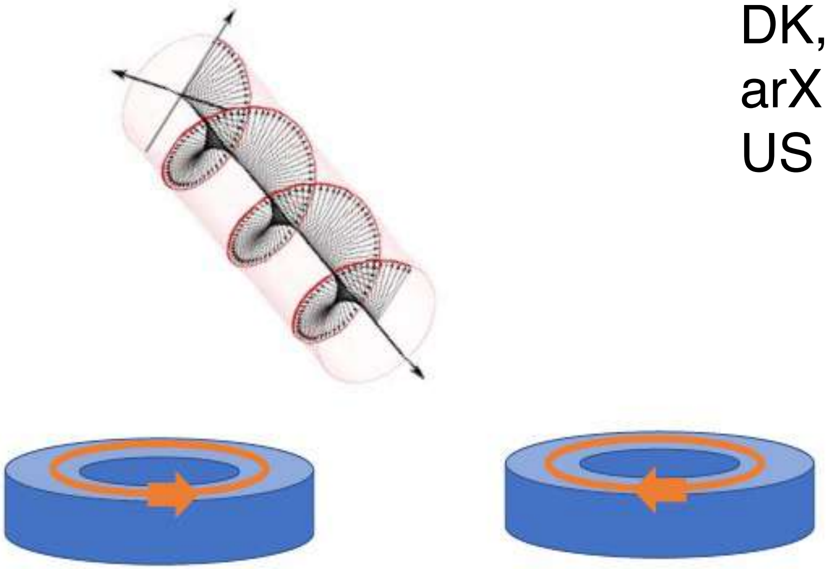


This Hamiltonian is identical to the Hamiltonian of the superconducting qubit!

DK, Q.Li,
arXiv:1903.07133

The chiral qubit

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

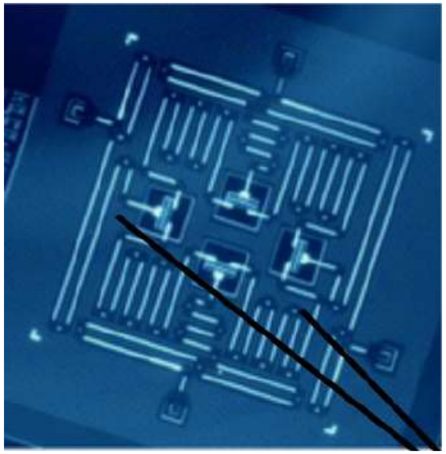


$$|0\rangle = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$$

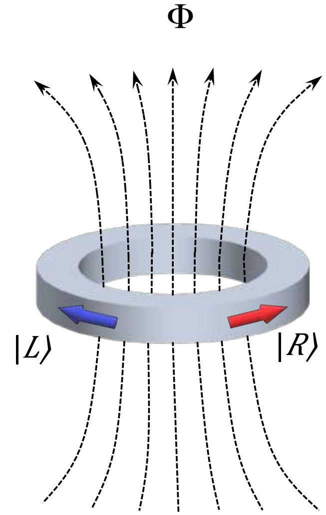
$$|1\rangle = \frac{1}{\sqrt{2}}(|R\rangle - |L\rangle)$$

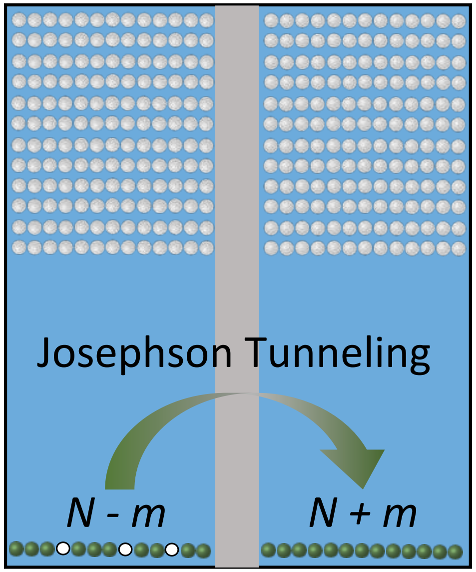
The qubit can be controlled by the circularly polarized IR light or external magnetic flux (for thin rings)

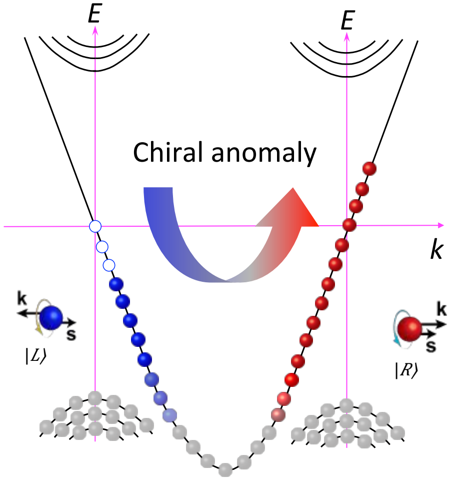
The chiral qubit



IBM-Q







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