7^{th} International Conference on Chirality, Vorticity, and Magnetic Field

In Heavy Ion Collisions

University of Chinese Academy of Sciences, Beijing, July 15-19, 2023

Chiral Magnetic Effect in heavy ion collisions and beyond

Dmitri Kharzeev

U.S. DEPARTMENT OF ENERGY Office of Science

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C2QA Co-design Center for Quantum Advantage

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Outline

1. Chirality in subatomic physics

2. Chirality of gauge fields, and why it matters

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

4. CME as a probe of topological structure of the QCD vacuum

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

6. Broader implications:

   a) CME in condensed matter
   b) CME and quantum computers
   b) CME in the Universe

3 min introduction to CME on YouTube :

#breakthroughjuniorchallenge

Chiral Magnetic Effect(CME)

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

Chirality in subatomic world: chiral fermions

Fermions:
E. Fermi, 1925

Dirac equation:
P. Dirac, 1928

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

Weyl fermions:
H. Weyl, 1929

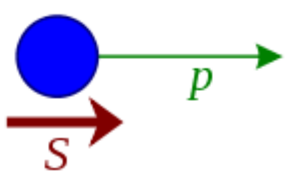
$$\sigma^\mu \partial_\mu \psi = 0$$

Majorana fermions:
1937

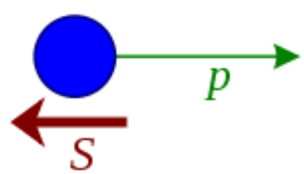
$$-i\partial\!\!\!/\psi + m\psi_c = 0$$

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

Right-handed:



Left-handed:



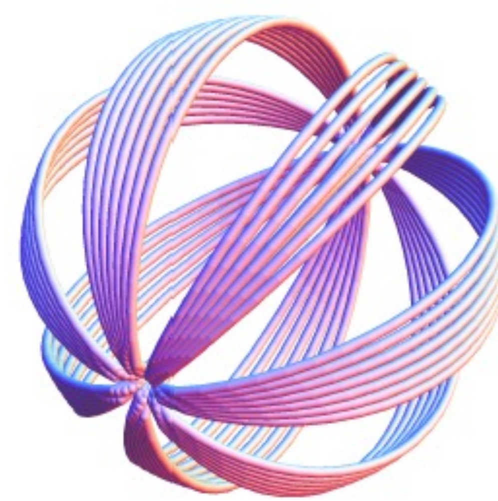
Chirality of gluon field

Chiral fermions

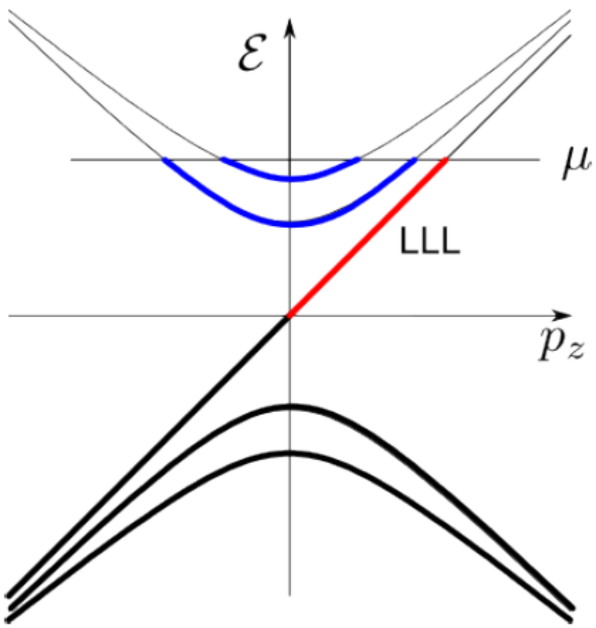
Chirality of EM field

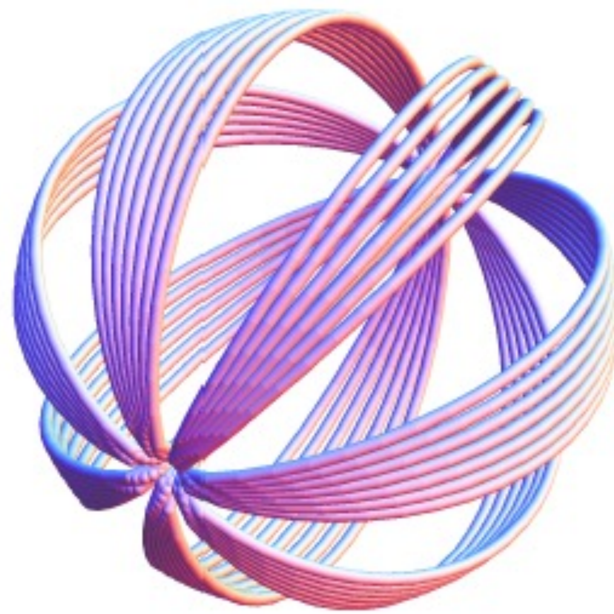
Chirality of gauge fields

Gauge fields can form **chiral knots** – for example, knots of magnetic flux in magnetohydrodynamics (magnetic helicity), characterized by Chern-Simons number



Chiral anomaly: chirality transfer from fermions to gauge fields (or vice versa)





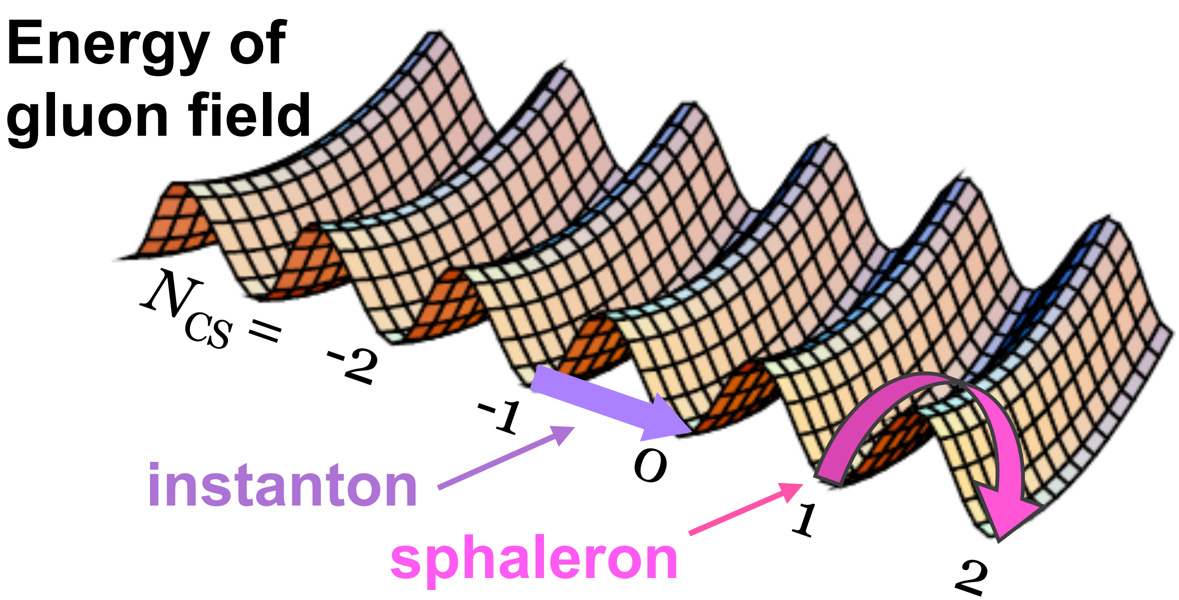
From: Y. Hirono, DK, Y. Yin, PRD 92 (2015) 12

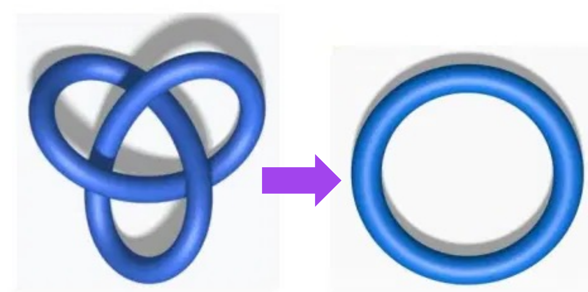
Chirality in the vacuum of the Standard Model

The instanton and sphaleron solutions in non-Abelian gauge theories describe transitions between topological sectors of the vacuum marked by different integer values of the Chern-Simons number:

$$N_{CS} \equiv \int d^3x K_o \qquad K_\mu = \frac{1}{16\pi^2}\epsilon_{\mu\alpha\beta\gamma}\left(A^a_\alpha \partial_\beta A^a_\gamma + \frac{1}{3} f^{abc} A^a_\alpha A^b_\beta A^c_\gamma\right)$$

QCD (Quantum ChromoDynamics) vacuum:





Chirality and the origin of Matter-Antimatter asymmetry in the Universe

A.D. Sakharov, 1967

Sakharov conditions for baryogenesis:

1. Baryon number violation
2. C and CP symmetries violation
3. Interactions out of thermal equilibrium

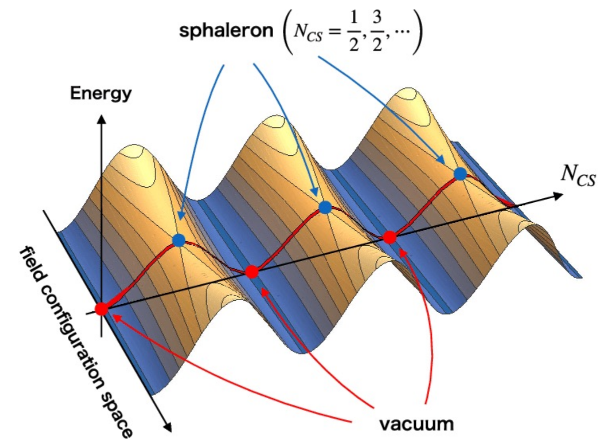
VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles

Chirality and the origin of Matter-Antimatter asymmetry in the Universe

Within the Standard Model, baryon number violating sphaleron transitions in hot electroweak plasma operate in the expanding Early Universe.



Graphics: Hamada, Kikuchi,'20

Can we study these processes in the lab?

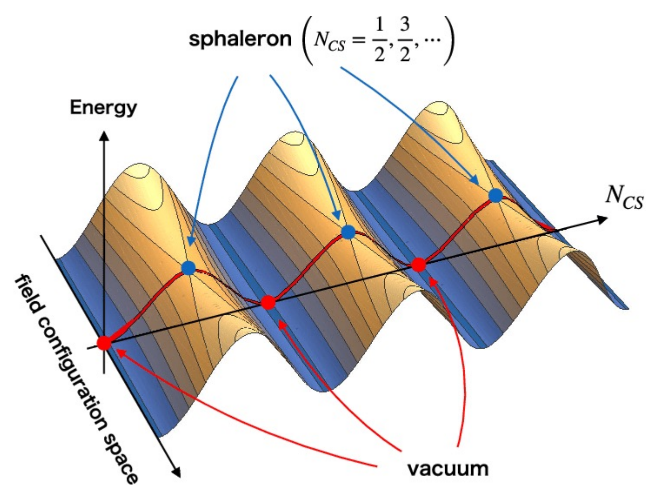
No – the temperature of electroweak phase transition is too high, $T_{EW} \approx 160\ GeV \sim\ 10^{15}$ K

But: we can study analogous processes in another non-Abelian gauge theory of the Standard Model – QCD!

Generation of chirality in the QCD plasma

The temperature of QCD phase transition is 1,000 times lower: $T_{QCD} \approx 160\ MeV \sim\ 10^{12}$ K

QCD plasma can be produced and studied in the ongoing heavy ion experiments at RHIC (BNL) and LHC (CERN).

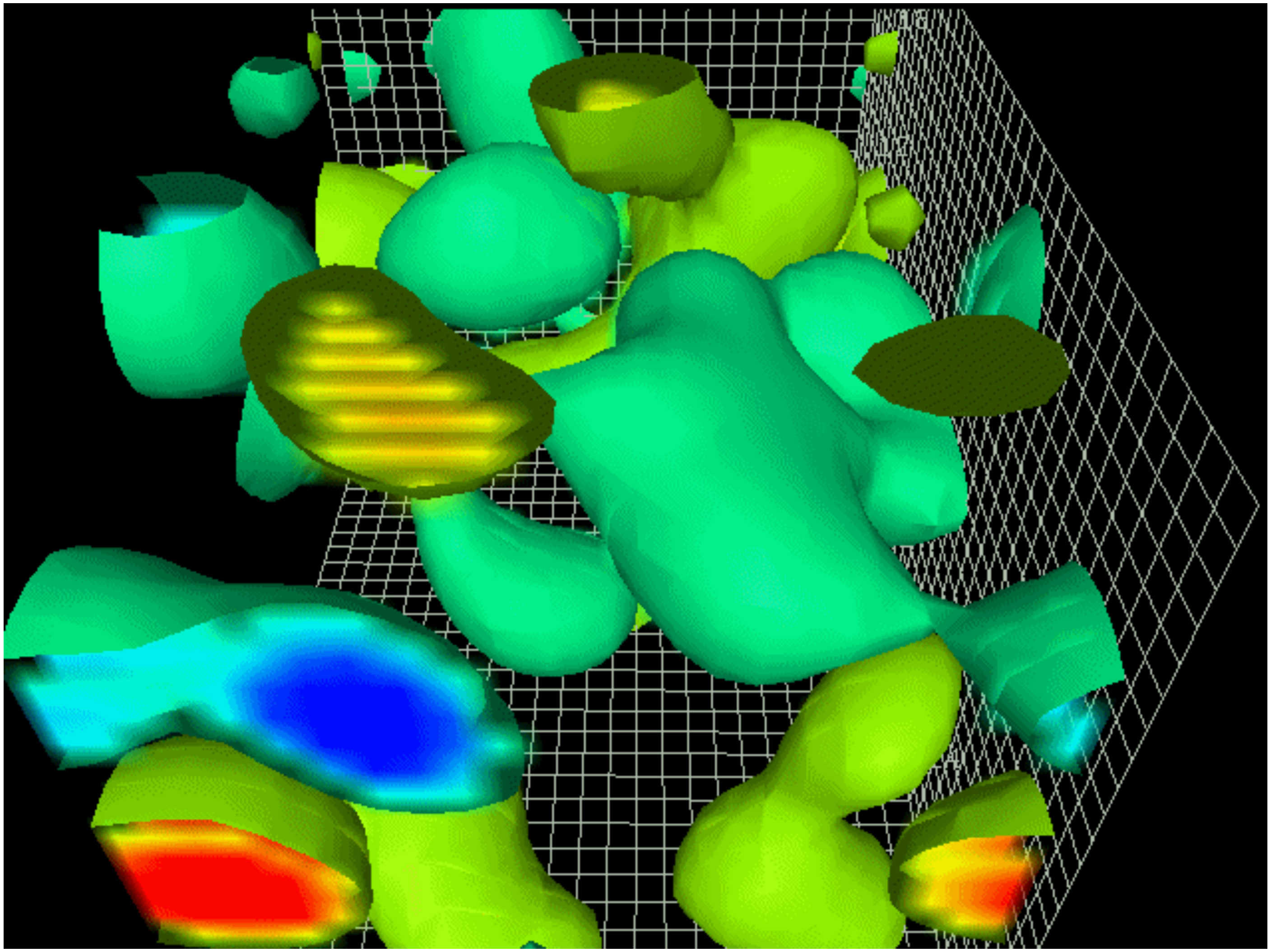


Graphics: Hamada, Kikuchi,'20

QCD sphalerons induce chirality violation (instead of baryon number violation), and rapid expansion of the produced plasma drives it out of thermal equilibrium – thus we expect to see a substantial **generation of net chirality**, <u>of fluctuating sign</u>, **in heavy ion collisions**!

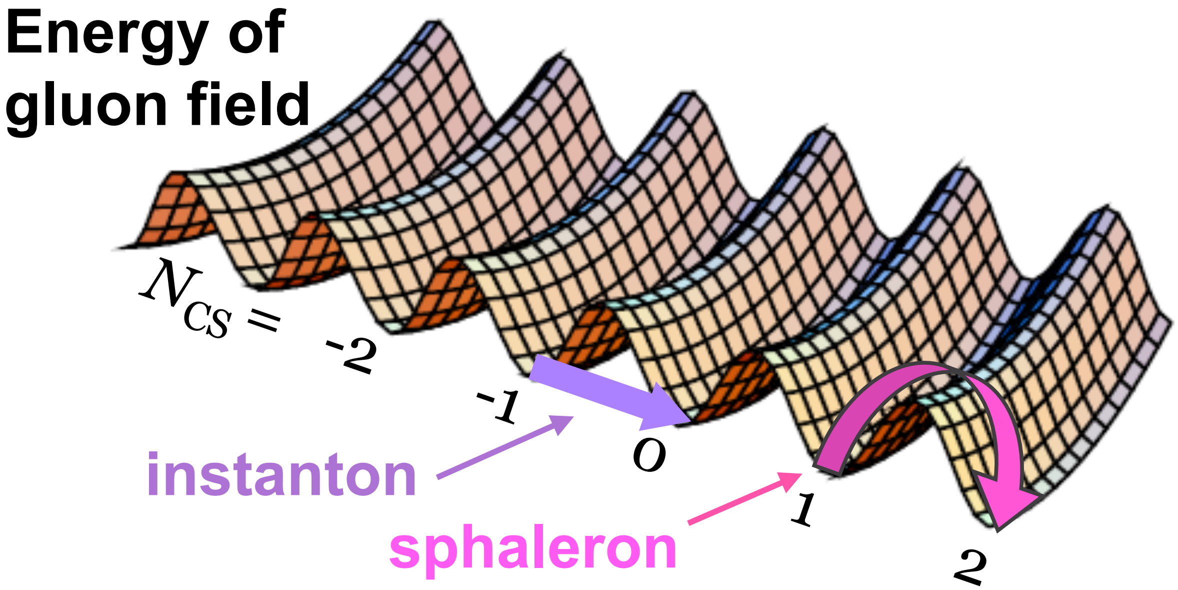
Topological transitions in QCD vacuum

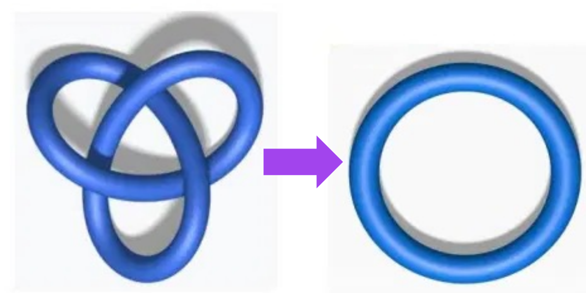
D. Leinweber



Chirality in the vacuum of the Standard Model

Topological chirality-changing transitions between the vacuum sectors of QCD are responsible for the spontaneous chiral symmetry breaking and thus most of the mass of visible Universe.

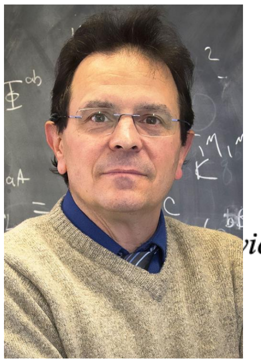




Is it possible to directly observe these chirality-changing transitions in experiment?

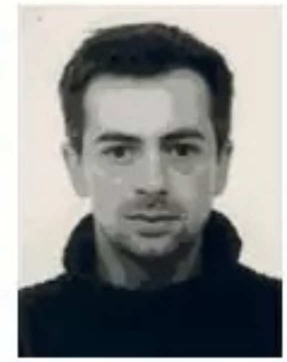
We addressed this problem in the 1998 paper with Rob Pisarski and Michel Tytgat:

VOLUME 81, NUMBER 3 PHYSICAL REVIEW LETTERS 20 JULY 1998



Possibility of Spontaneous Parity Violation in Hot QCD

Dmitri Kharzeev,[1] Robert D. Pisarski,[2] and Michel H. G. Tytgat[2,3]
[1]*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000*
[2]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000*
ice de Physique Théorique, CP 225, Université Libre de Bruxelles, Boulevard du Triomphe, 1050 Bruxelles, Belgi
(Received 3 April 1998)



We argue that for QCD in the limit of a large number of colors, the axial U(1) symmetry of massless quarks is effectively restored at the deconfining phase transition. If this transition is of second order, metastable states in which parity is spontaneously broken can appear in the hadronic phase. These metastable states have dramatic signatures, including enhanced production of η and η' mesons, which can decay through parity violating decay processes such as $\eta \to \pi^0\pi^0$, and global parity odd asymmetries for charged pions. [S0031-9007(98)06613-7]

A working group with STAR experimentalists was formed to find a way to detect this local parity violation (chirality imbalance):

J. Sandweiss, S. Voloshin, J. Thomas, E. Finch, A. Chikanian, R. Longacre, …

But after a few years of hard work it has become clear that the proposed pion correlations are very difficult to detect.

Detecting the topological structure of QCD vacuum

Topological transitions in the QCD plasma change chirality of quarks. However, quarks are confined into hadrons, and their chirality cannot be detected in heavy ion experiments.

Therefore , to observe these chirality-changing transitions we have to find a way to convert chirality of quarks into something observable – perhaps, a (fluctuating) **electric dipole moment of the QCD plasma**? This would require an external magnetic field or an angular momentum.

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

Physics Letters B 633 (2006) 260–264

This idea was developed further with my colleagues and friends:

Charge separation induced by $\mathcal{P}$-odd bubbles in QCD matter

Dmitri Kharzeev [a,*], Ariel Zhitnitsky [b]

[a] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*
[b] *Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, V6T 1Z1, Canada*

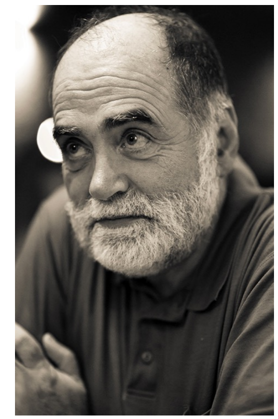
Received 19 June 2007; received in revised form 17 September 2007; accepted 1 October 2007

The effects of topological charge change in heavy ion collisions: "Event by event $\mathcal{P}$ and $\mathcal{CP}$ violation"

Dmitri E. Kharzeev [a], Larry D. McLerran [a,b], Harmen J. Warringa [a,*]

[a] *Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*
[b] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*

Received 15 November 2007; received in revised form 28 January 2008; accepted 3 February 2008



PHYSICAL REVIEW D **78,** 074033 (2008)

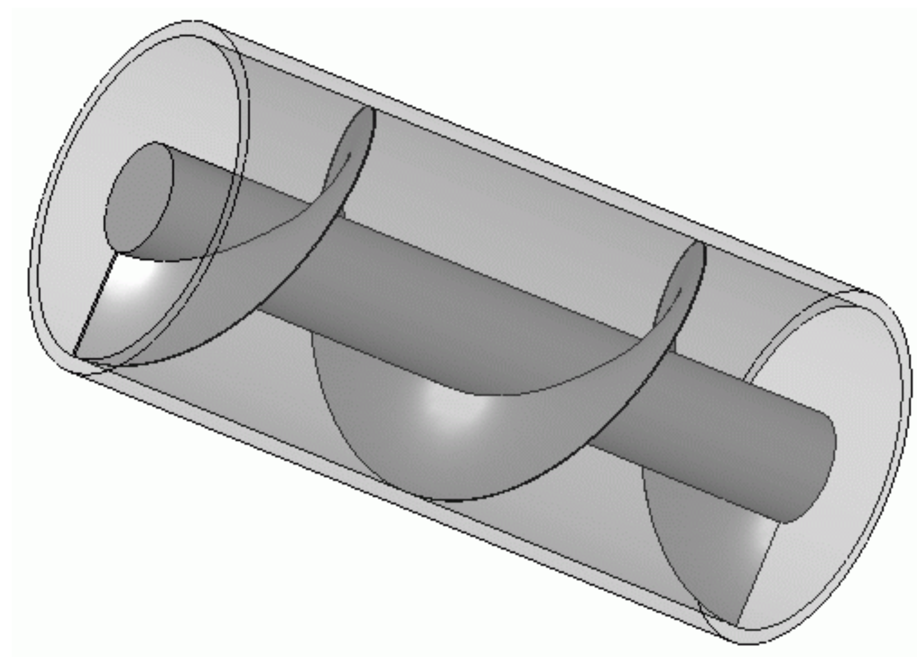
Chiral magnetic effect

Kenji Fukushima,[1,*] Dmitri E. Kharzeev,[2,+] and Harmen J. Warringa[2,‡]

[1]*Yukawa Institute, Kyoto University, Kyoto, Japan*
[2]*Department of Physics, Brookhaven National Laboratory, Upton New York 11973, USA*
(Received 2 September 2008; published 31 October 2008)

We called it the Chiral Magnetic Effect (CME)

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

Currents in a magnetic field

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

vector pseudo-vector

An electric current parallel to B requires a parity breaking

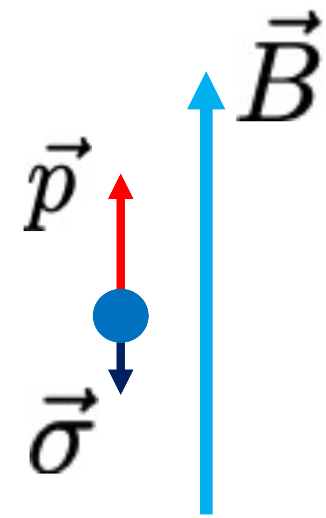
Currents in a magnetic field

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

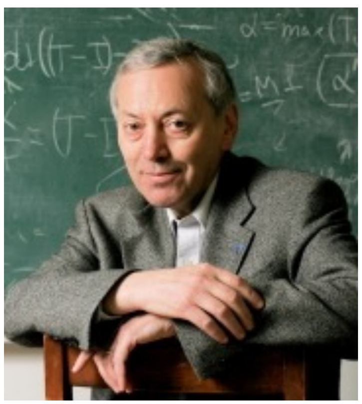


PHYSICAL REVIEW D VOLUME 22, NUMBER 12 15 DECEMBER 1980

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:

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

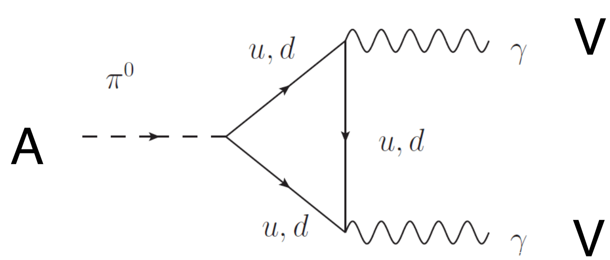
However, this conservation law is destroyed by quantum effects

Chiral anomaly

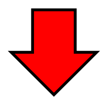
The axial current is not conserved:

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

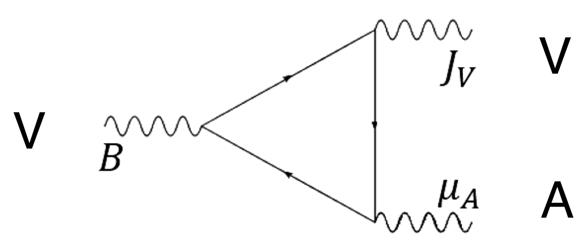
S. Adler '69
J. Bell, R. Jackiw ' 69



b. 1939 1928-1990 1939-2023



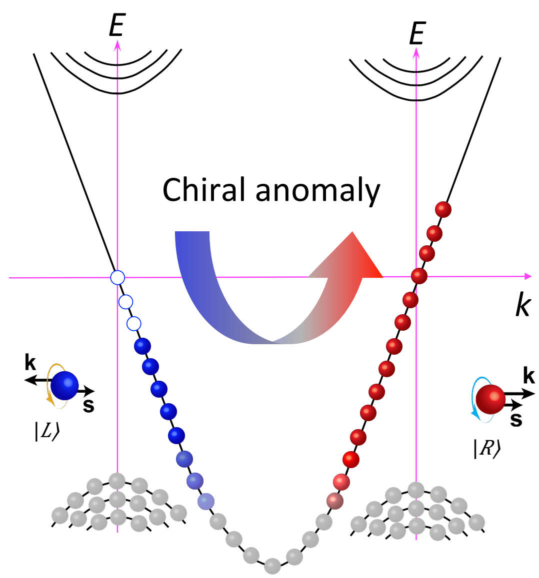
The chiral charge is not conserved;
a chirally imbalanced state of chiral fermions is not
a true ground state of the system!



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:

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

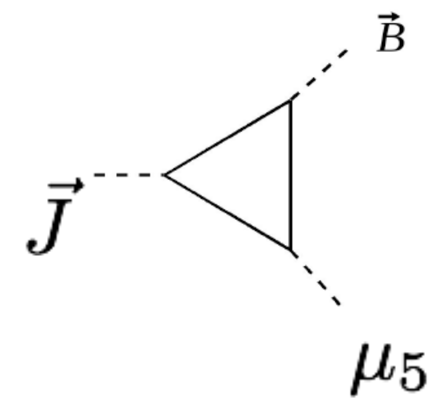
$$\mu_5 = \frac{1}{2}(\mu_R - \mu_L)$$

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

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

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 $\mu_5 = A_5^0$

$$\Omega = \frac{|eB|}{2\pi} \sum_{s=\pm} \sum_{n=0}^{\infty} \alpha_{n,s} \int_{-\infty}^{\infty} \frac{\mathrm{d}p_3}{2\pi} \left[\omega_{p,s} + T \sum_{\pm} \log(1 + e^{-\beta(\omega_{p,s} \pm \mu)}) \right]$$

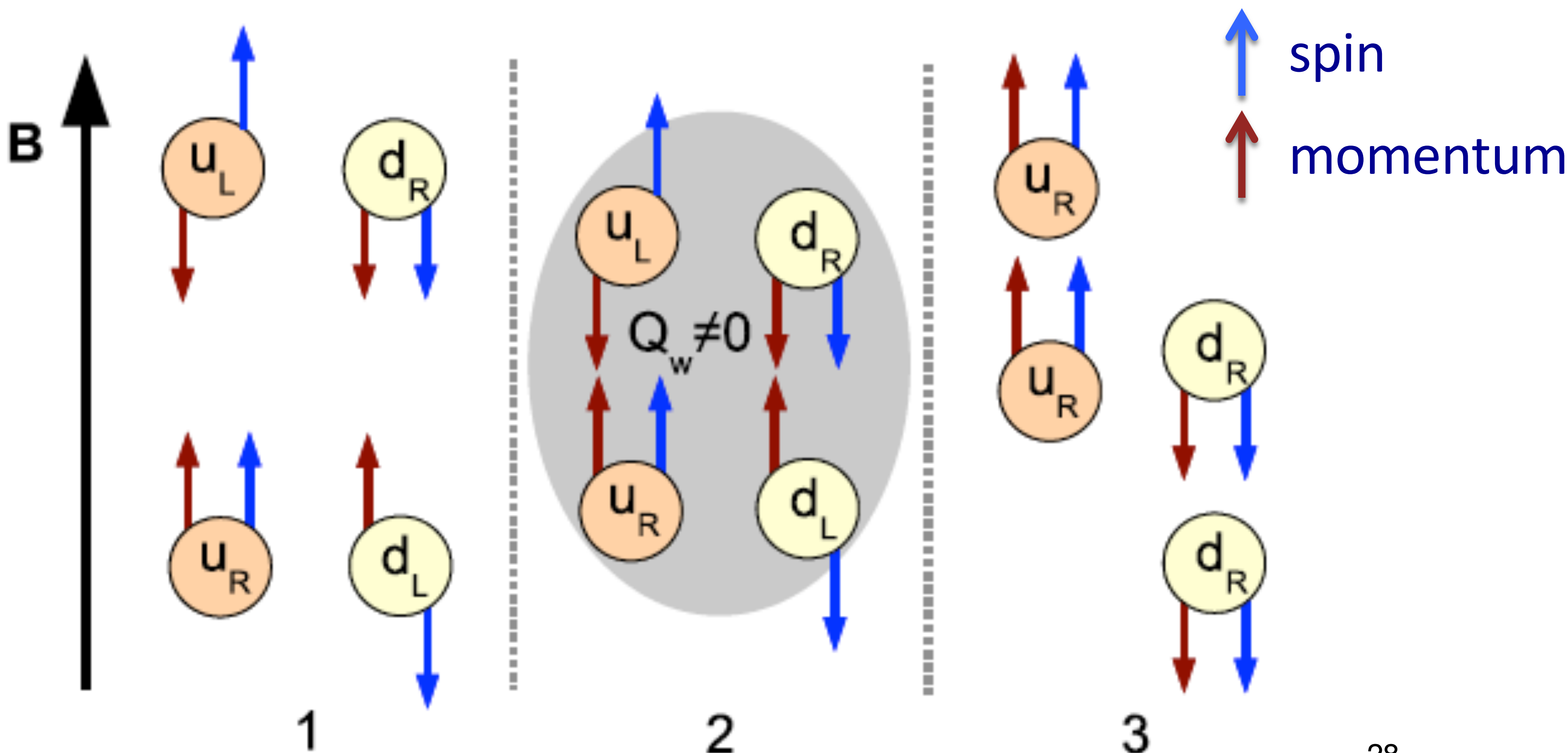
$$\omega_{p,s}^2 = \left[\mathrm{sgn}(p_3)(p_3^2 + 2|eB|n)^{1/2} + s\mu_5 \right]^2 + m^2$$

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

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

Chirality in 3D: the Chiral Magnetic Effect

chirality + magnetic field = current



DK'04; DK, L.McLerran, H. Warringa '07; K. Fukushima, DK, H. Warringa '08

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!

D.Son, P.Surowka '09

DK, H.U.Yee '11

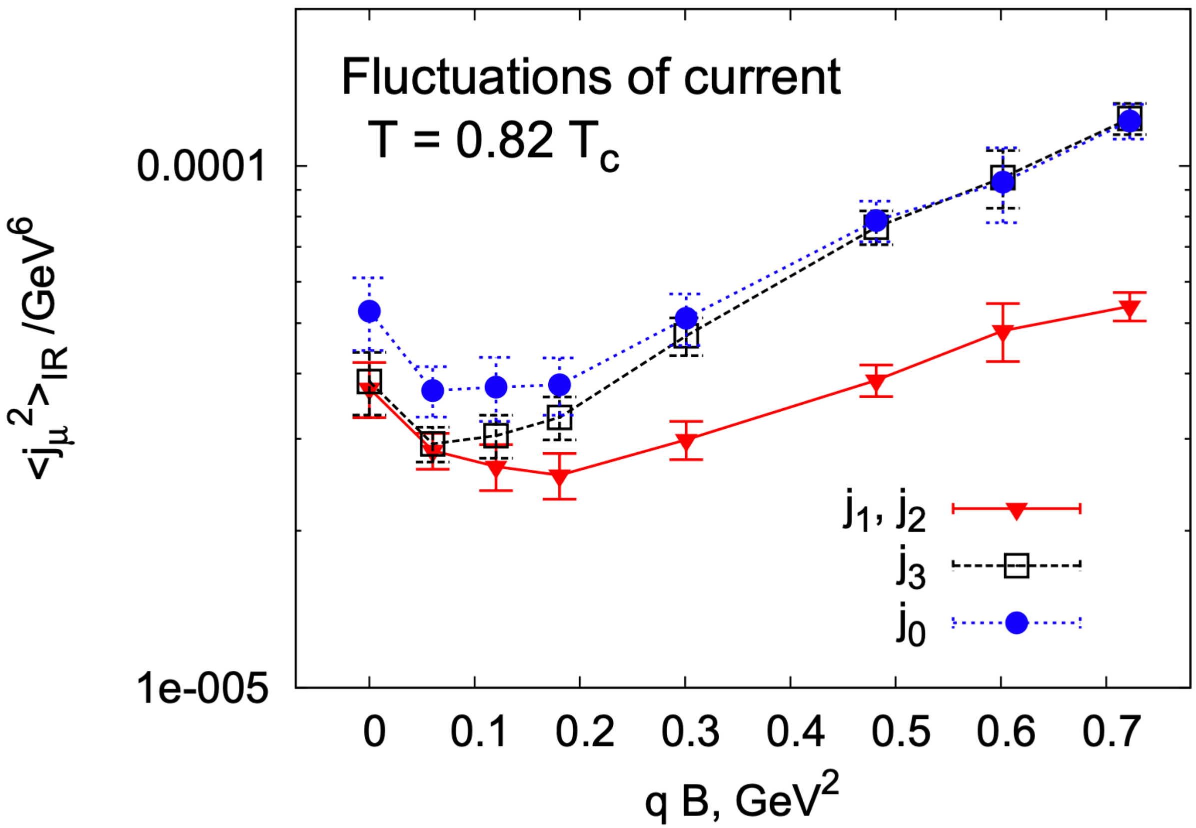
cf Ohmic conductivity:

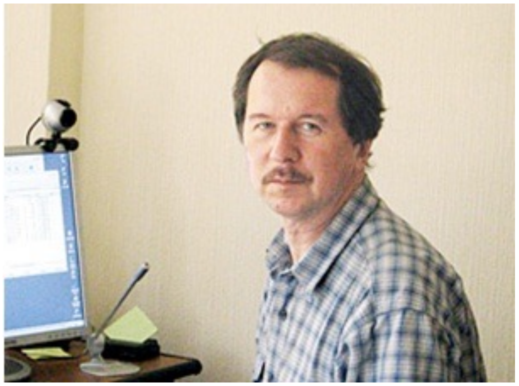
$$\vec{J} = \sigma \vec{E}$$

T-odd, dissipative

“Numerical evidence for chiral magnetic effect in lattice gauge theory”,

P. Buividovich, M. Chernodub, E. Luschevskaya, M. Polikarpov, arXiv 0907.0494; PRD’09





M. Polikarpov
1952-2013

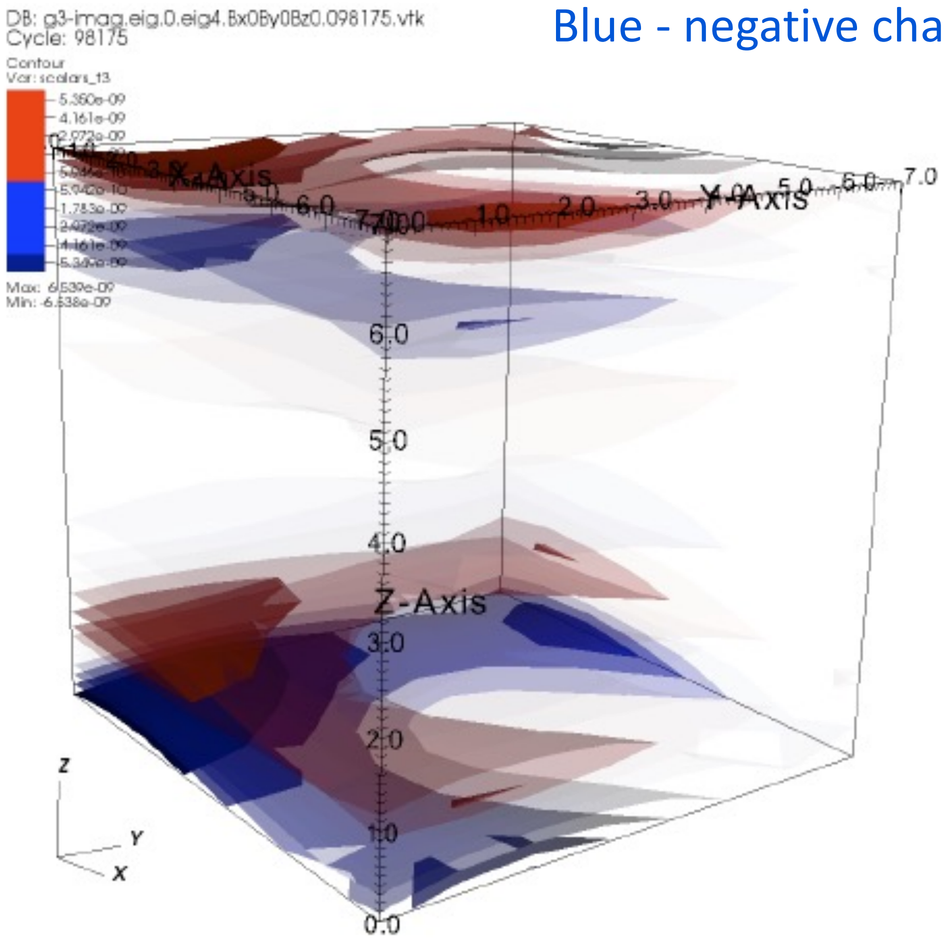
Fluctuations of electric current along the direction of magnetic field are enhanced

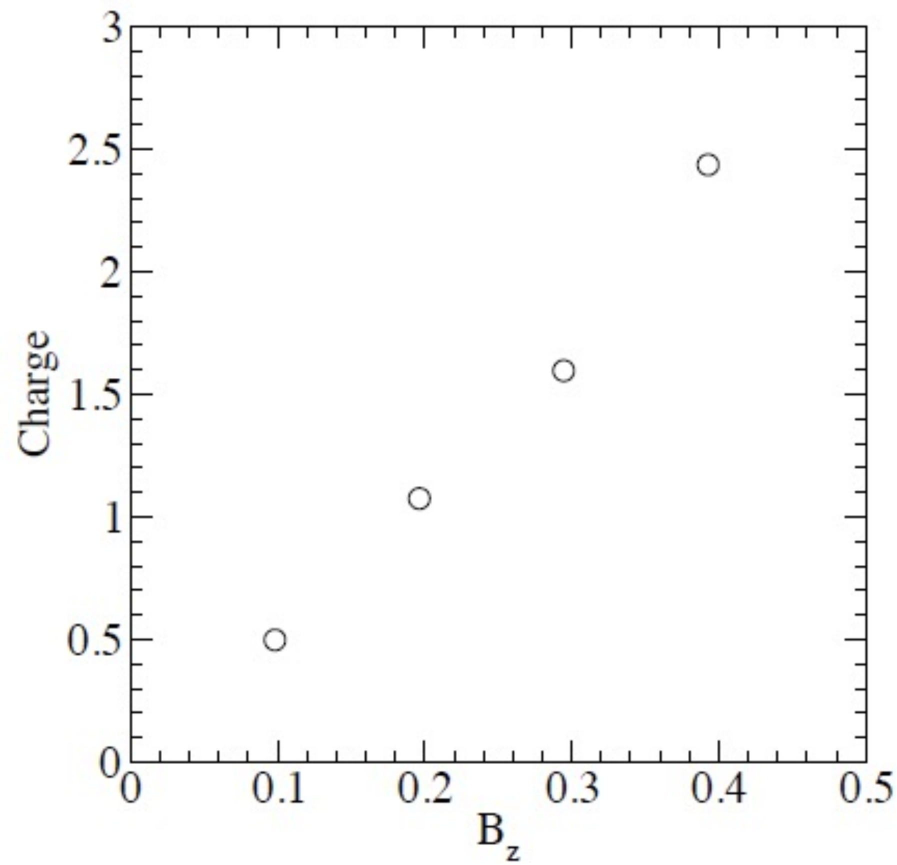
“Chiral magnetic effect in 2+1 flavor QCD+QED”,

M. Abramczyk, T. Blum, G. Petropoulos, R. Zhou, ArXiv 0911.1348, PRD

Red - positive charge

Blue - negative charge





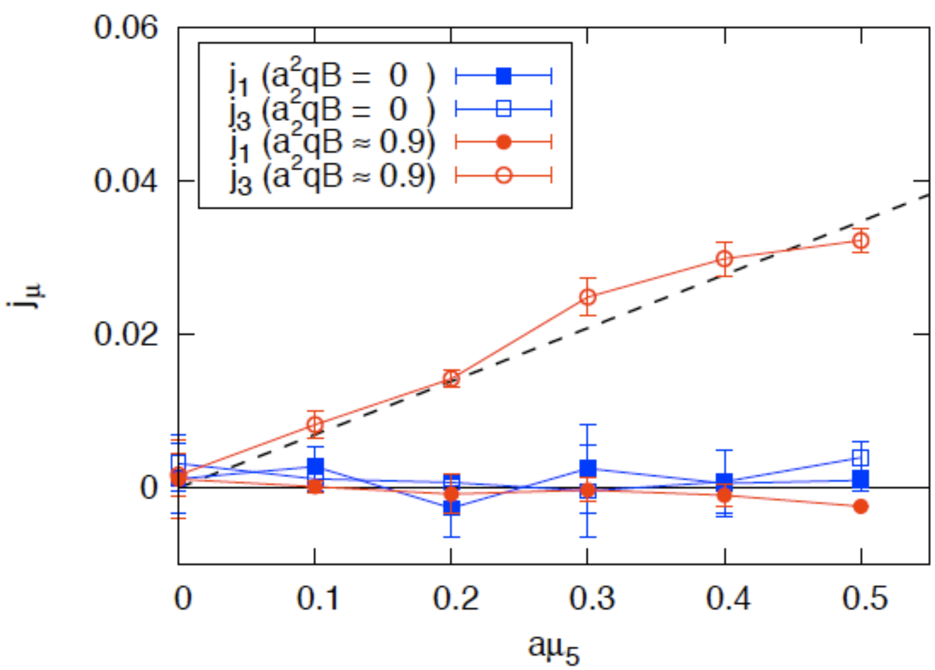
2+1 flavor Domain Wall Fermions, fixed topological sectors, 16^3 x 8 lattice arXiv:1105.0385, PRL

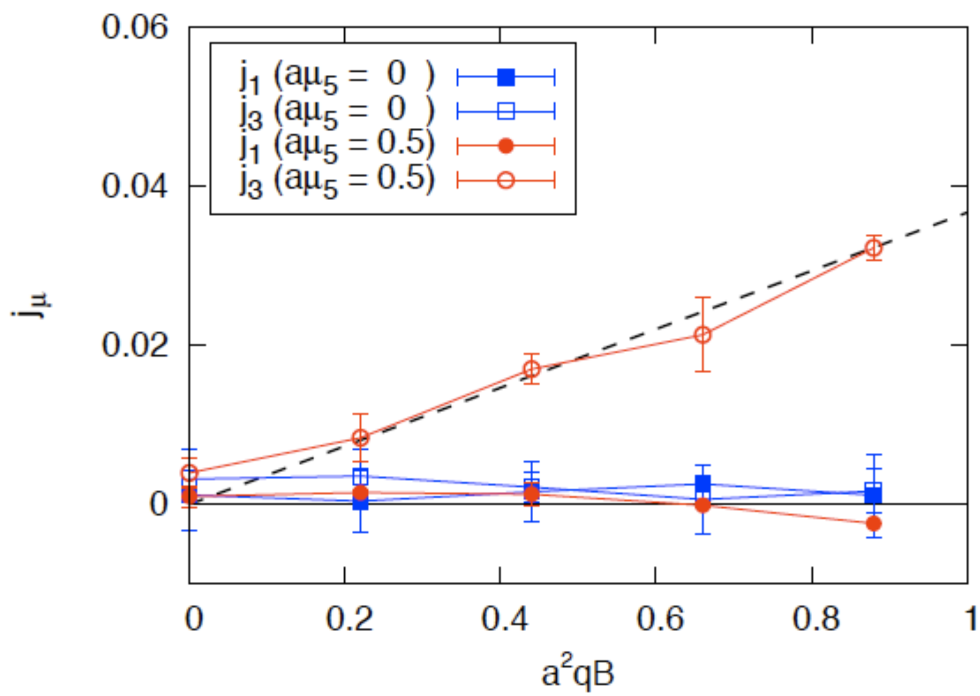
Chiral magnetic effect in lattice QCD with chiral chemical potential

Arata Yamamoto
Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan

(Dated: May 3, 2011)

We perform a first lattice QCD simulation including two-flavor dynamical fermion with chiral chemical potential. Because the chiral chemical potential gives rise to no sign problem, we can exactly analyze a chirally asymmetric QCD matter by the Monte Carlo simulation. By applying an external magnetic field to this system, we obtain a finite induced current along the magnetic field, which corresponds to the chiral magnetic effect. The obtained induced current is proportional to the magnetic field and to the chiral chemical potential, which is consistent with an analytical prediction.

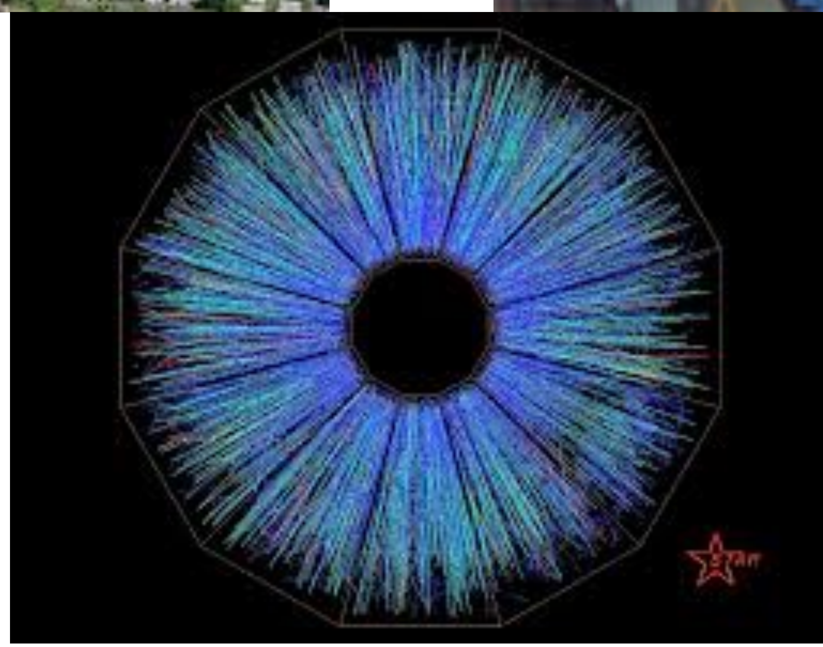




Can one detect QCD topological transitions in heavy ion collisions?

Relativistic Heavy Ion Collider (RHIC) at BNL

The STAR Collaboration at RHIC



Charged hadron tracks in a Au-Au collision at RHIC [STAR experiment] nature reviews physics

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

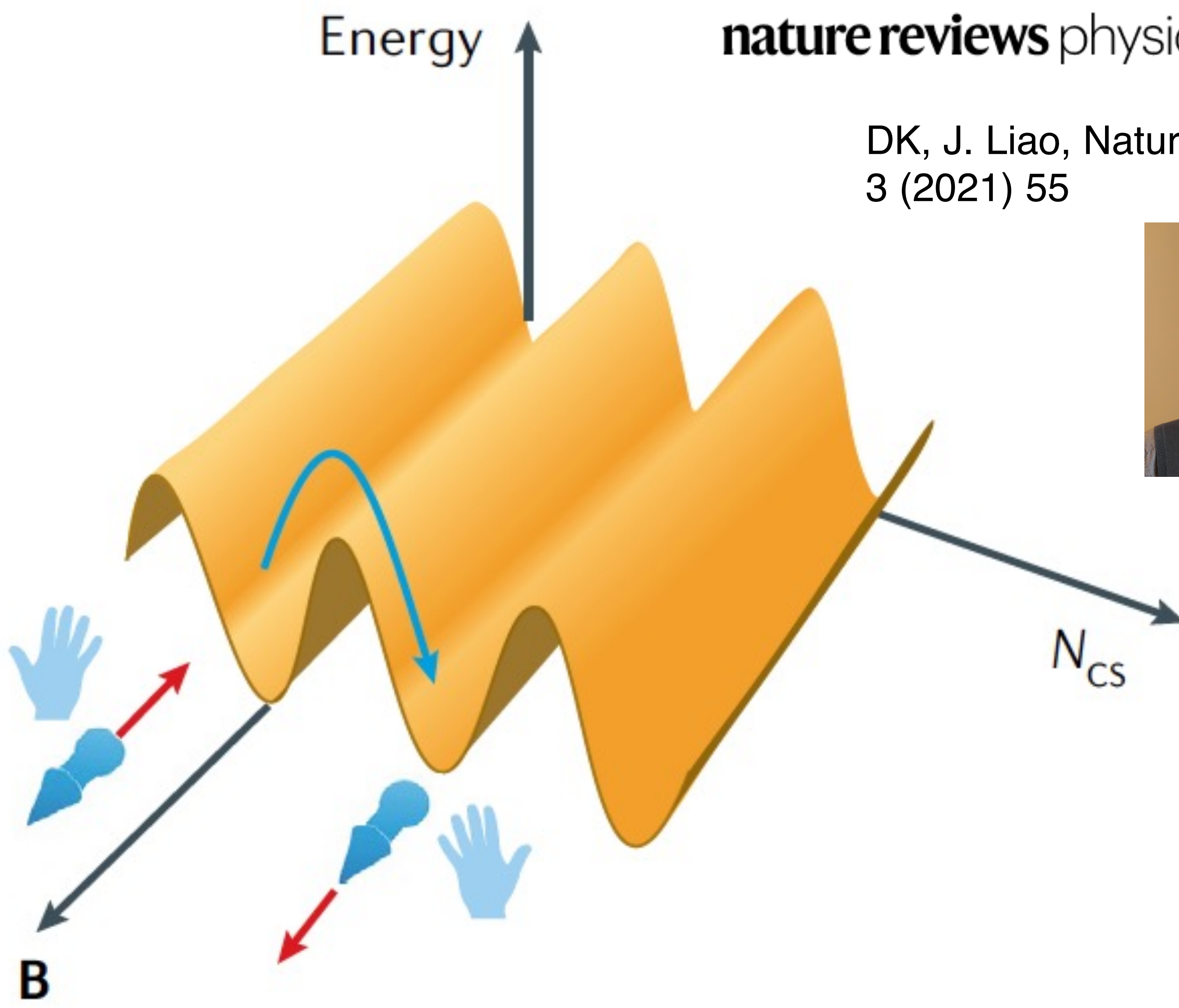


Fig. 1 | **An illustration of the mechanism that underlies the chiral magnetic effect in quantum chromodynamics matter.** The QCD vac-

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

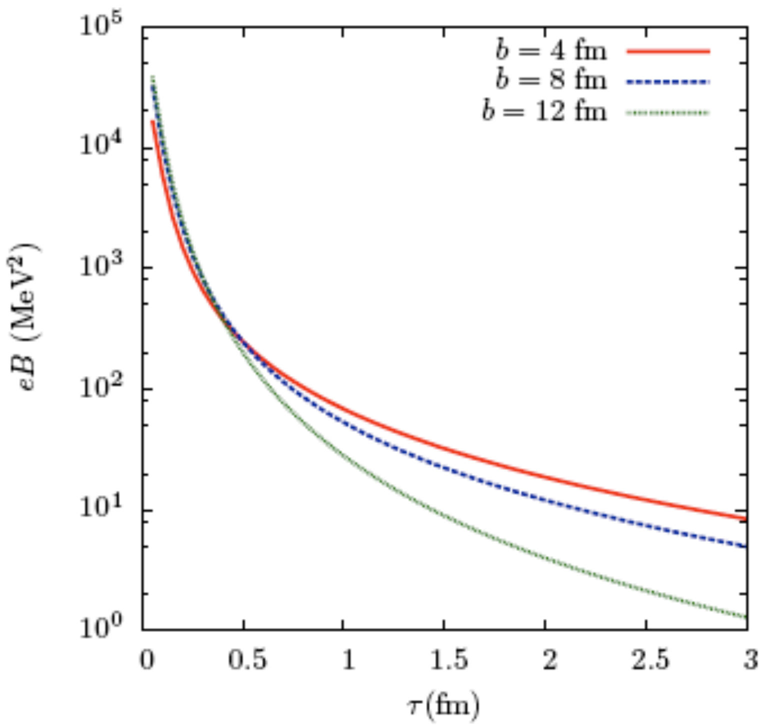
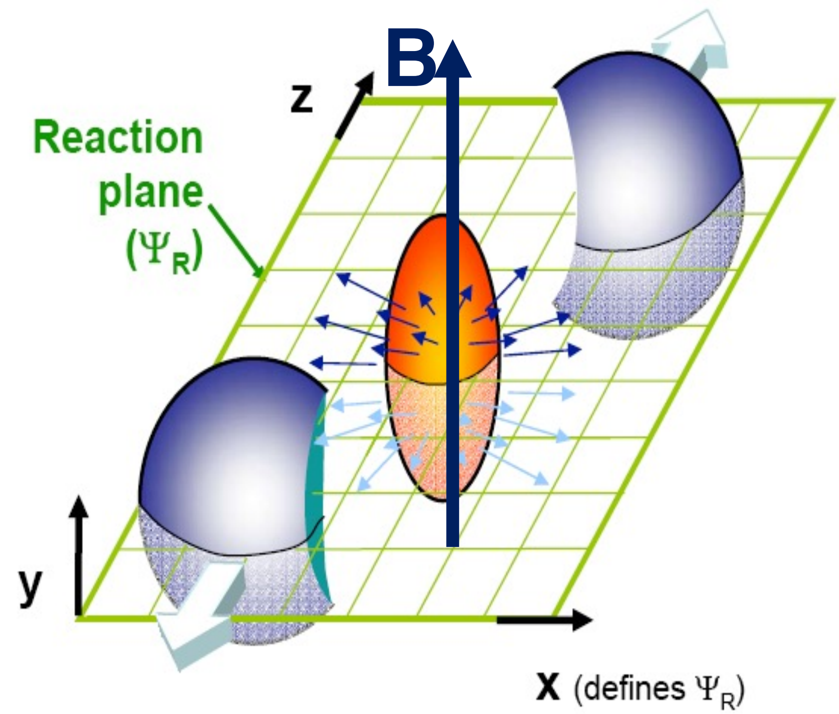


Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).

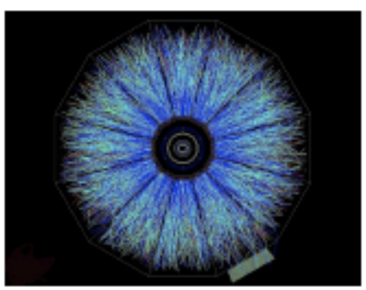


DK, McLerran, Warringa, Nucl Phys A803(2008)227

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



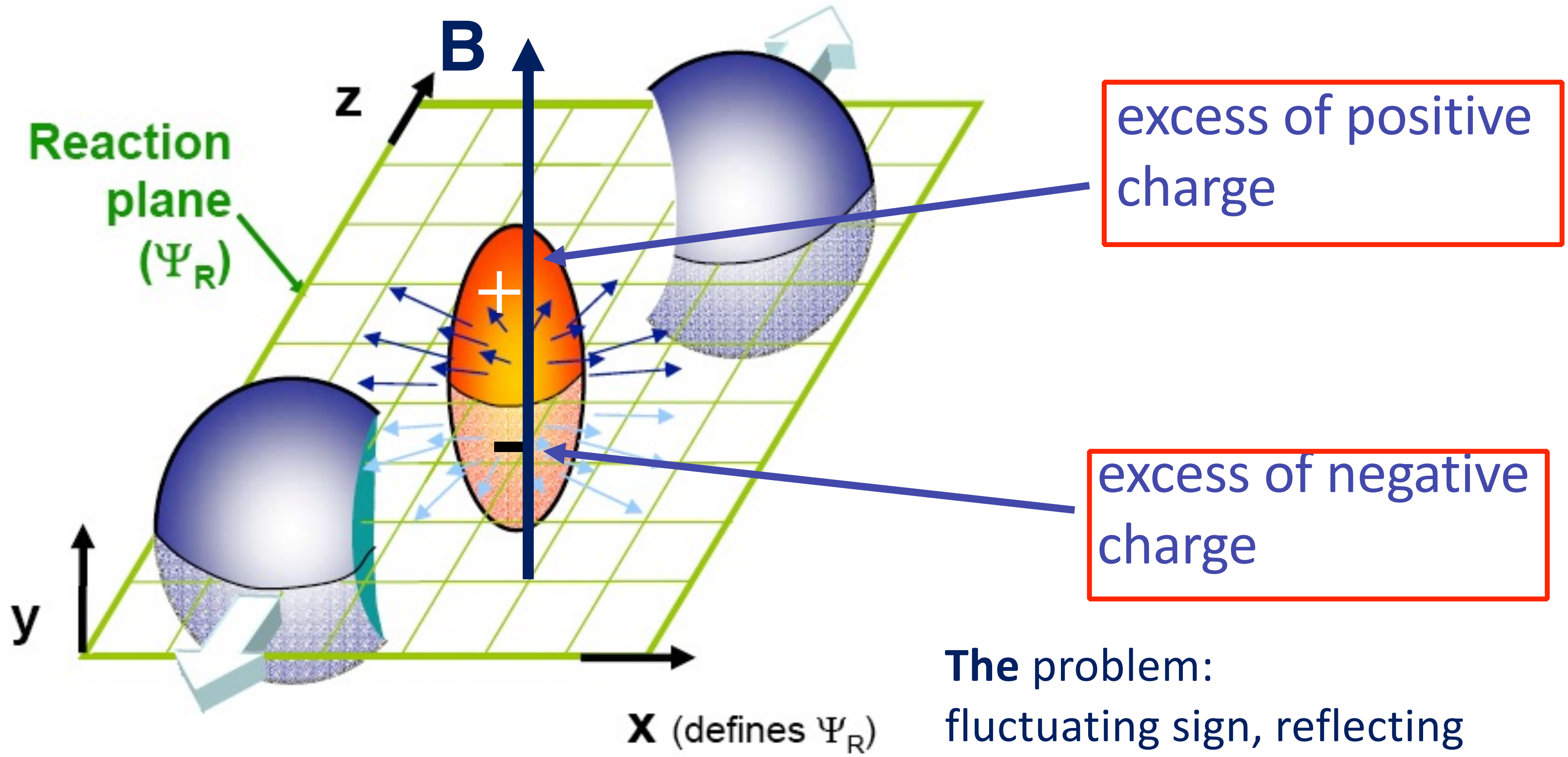
Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

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

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

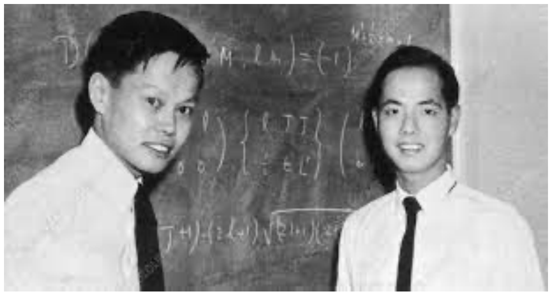
Electric dipole moment due to chiral imbalance

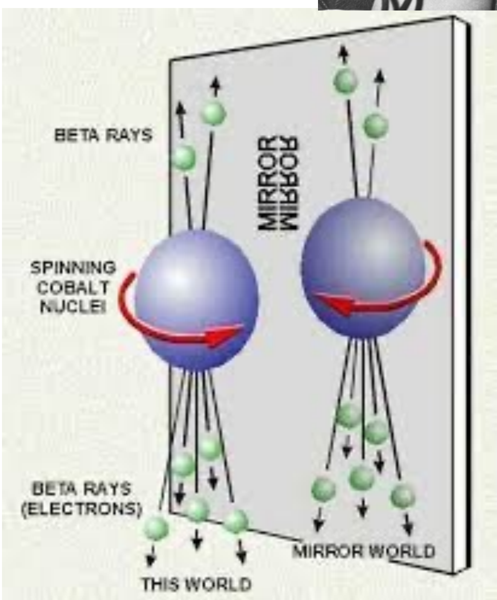


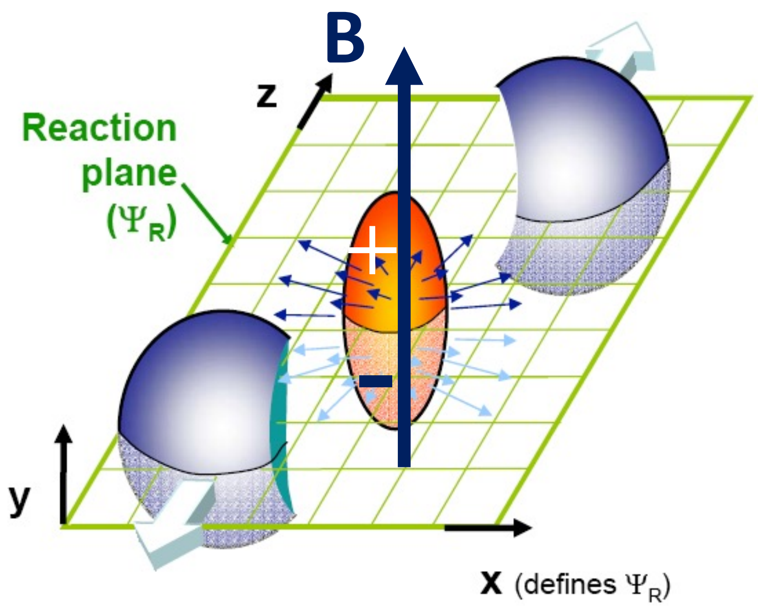
The problem:
fluctuating sign, reflecting topological fluctuations in QCD
- backgrounds!

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

CME as a probe of topological transitions and Event-by-event parity violation in QCD plasma



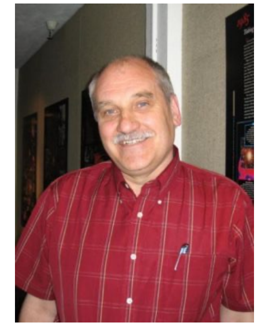




Global Parity violation in Weak interactions

Local, Event-by-event Parity violation in Strong Interactions **?**

Separating the signal from background: the beginning

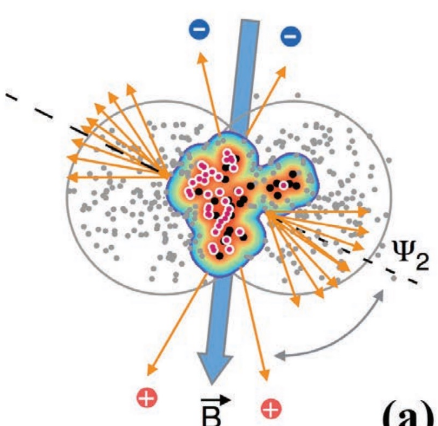


PHYSICAL REVIEW C **70**, 057901 (2004)

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.



(a)

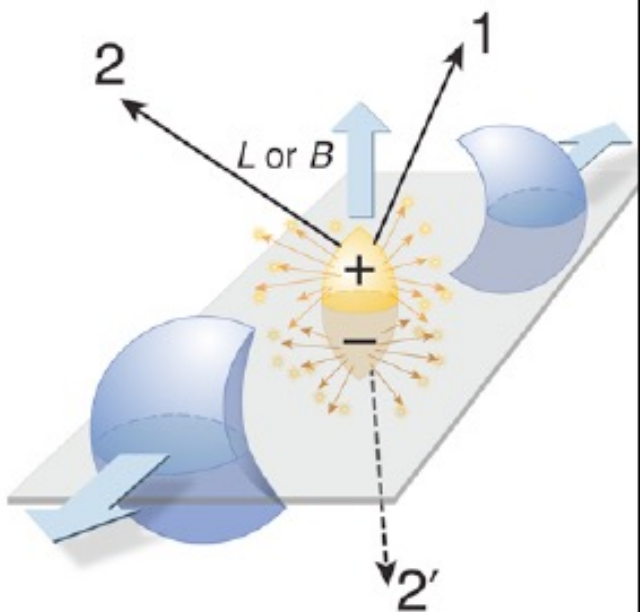
$$\begin{aligned}\langle\cos(\phi_a-\Psi_2)\cos(\phi_b-\Psi_2)& \\ -\sin(\phi_a-\Psi_2)\sin(\phi_b-\Psi_2)\rangle& \qquad (1)\\ =\langle\cos(\phi_a+\phi_b-2\Psi_2)\rangle=(v_{1,a}v_{1,b}-a_a a_b)\,\langle\cos(2\Psi_2)\rangle&\end{aligned}$$

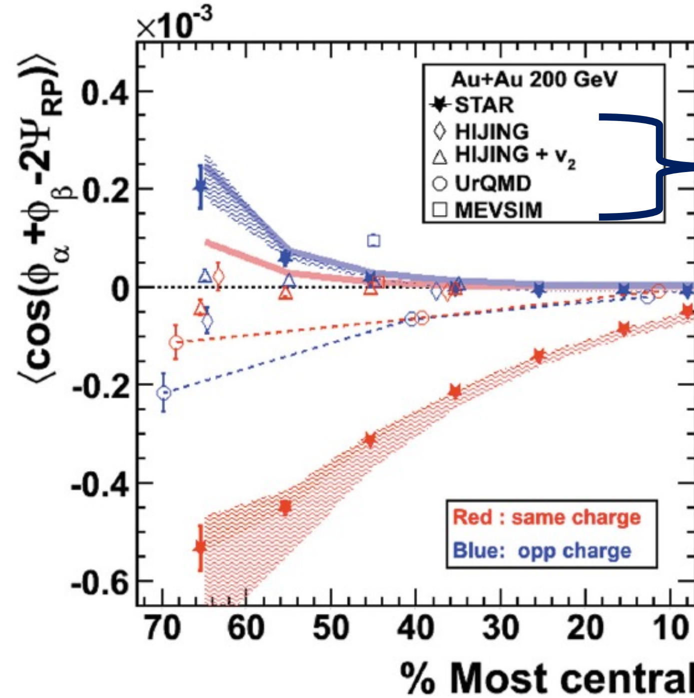
Measure the difference of charged hadron fluctuations along and perpendicular to magnetic field
(direction of $\vec{B}$ is defined by the reaction plane)

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)





Monte Carlo generators do not describe the data

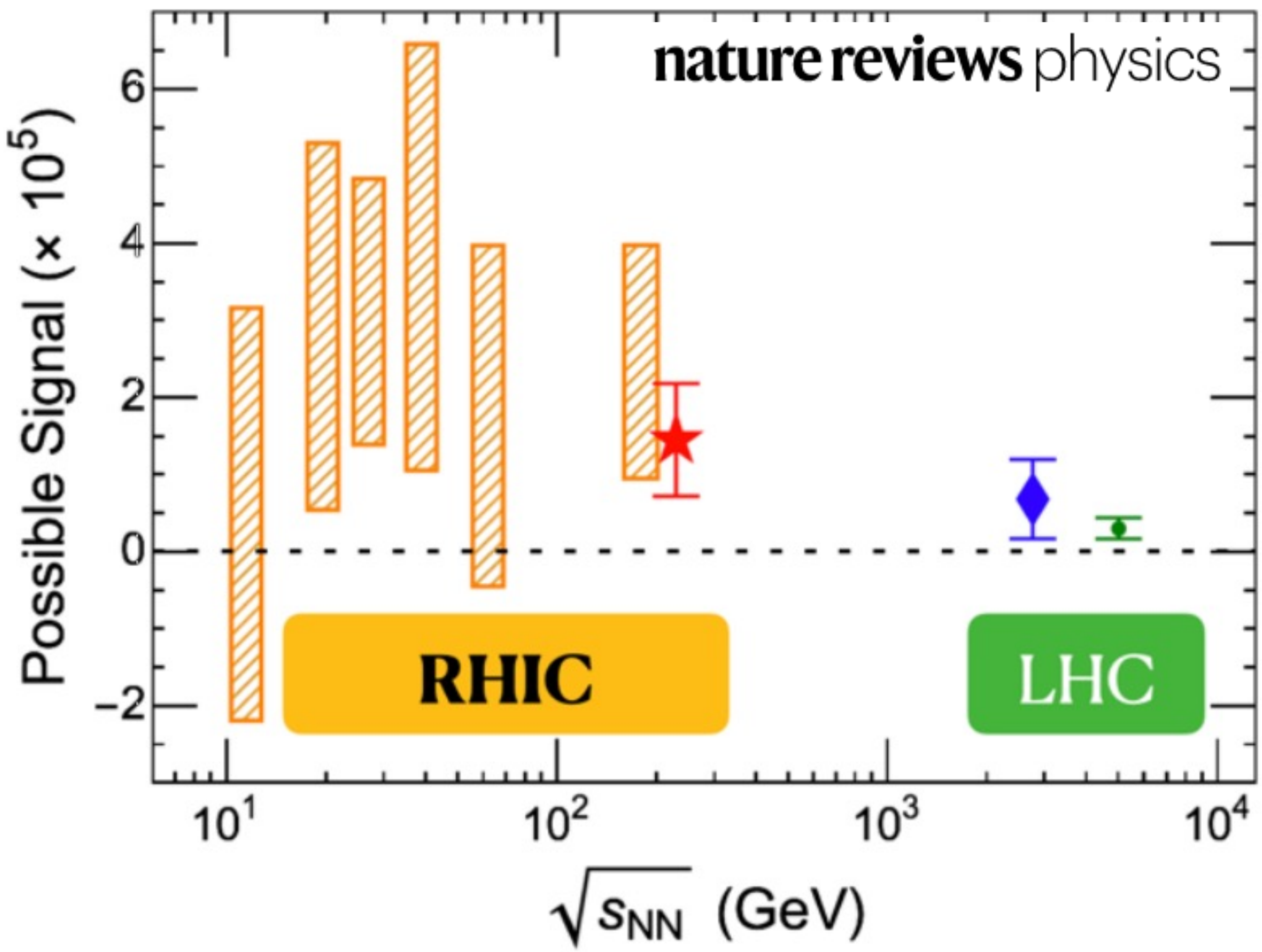
$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \rangle = \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle$$

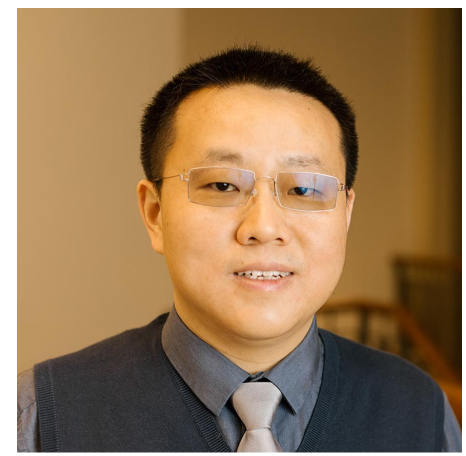
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\mathrm{IN}}] - [\langle a_\alpha a_\beta \rangle + B_{\mathrm{OUT}}] \approx -\langle a_\alpha a_\beta \rangle + [B_{\mathrm{IN}} - B_{\mathrm{OUT}}],$$

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





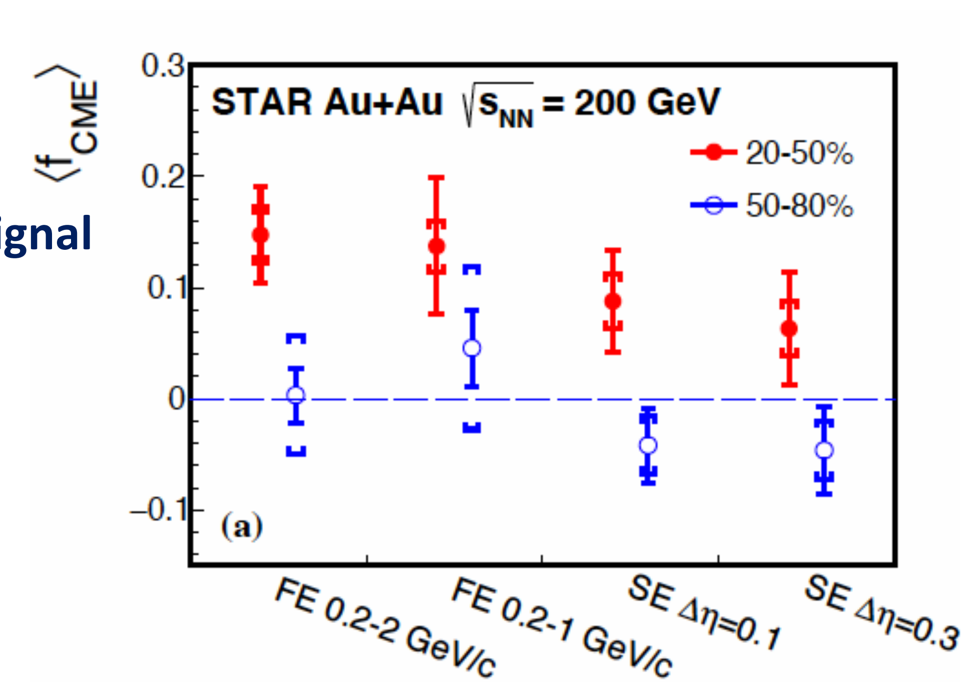
Separating the signal from background is the main subject of the ongoing work. Sophisticated new methods of isolating the signal have been developed by the STAR Collaboration.

The most recent analysis of AuAu collisions at $\sqrt{s} =$ 200 GeV/(nucleon pair) indicates the **presence of CME in mid-central collisions** (most favorable for the effect: both QCD plasma and magnetic field are present) **at 3 σ level** (FE)

Search for the chiral magnetic effect via charge-dependent azimuthal correlations relative to spectator and participant planes in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

STAR Collaboration, arXiv:2106.09243

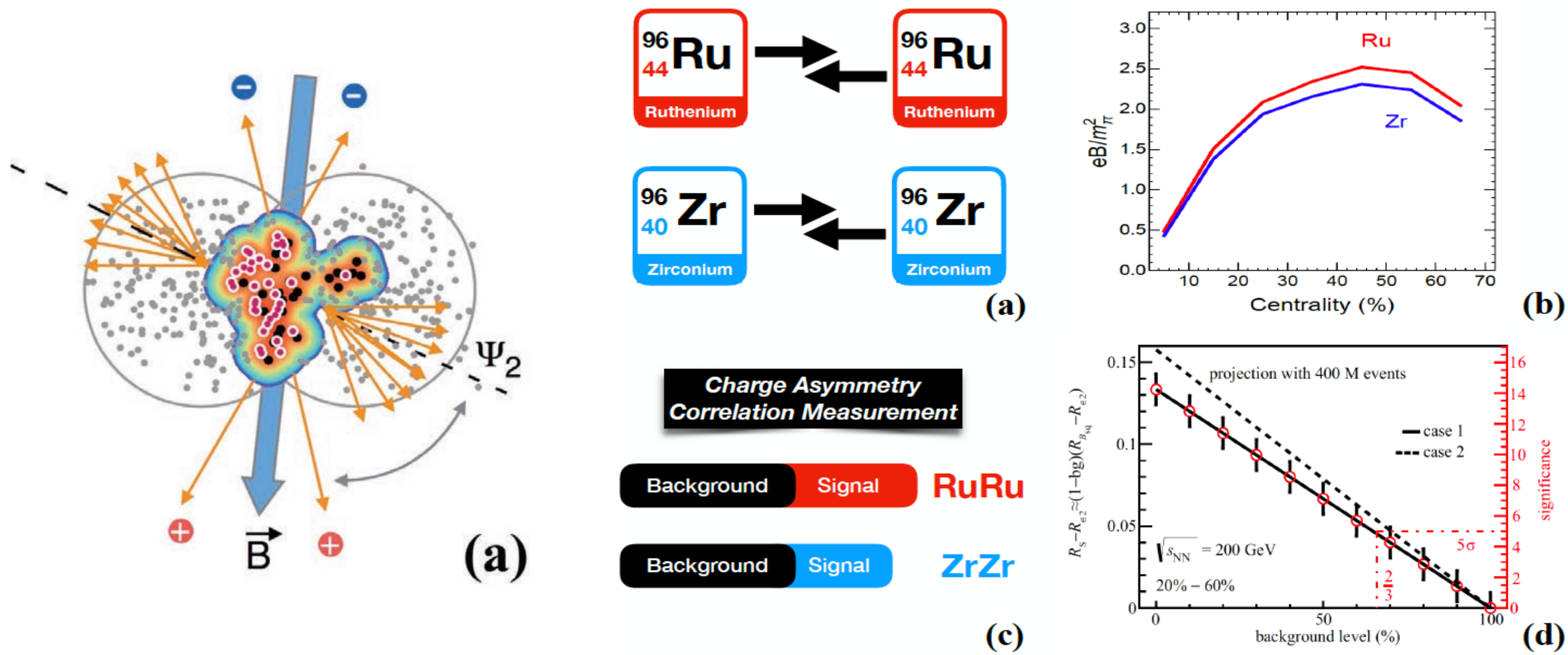
CME signal



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

Big new development: the isobar run, results will appear in the fall of 2021!

Isobars: same shape = same background, different Z = different magnetic field – change in signal!



STAR Collaboration

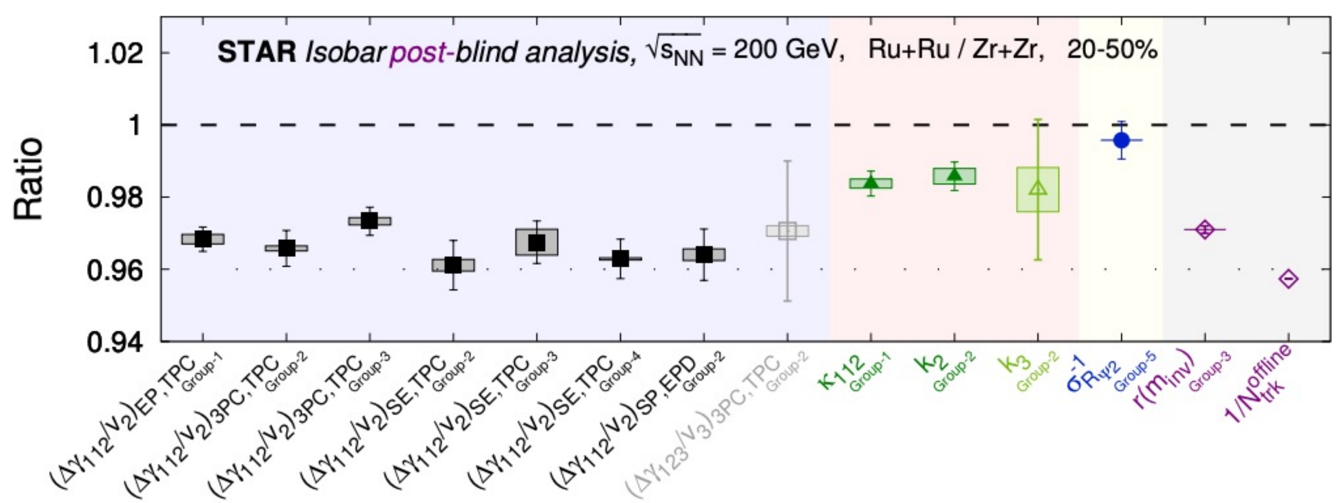
Search for CME using the isobar collisions at RHIC

The results have been released on Aug 31, 2021

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

STAR, nucl-ex 2109.00131, PRC (2022)

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

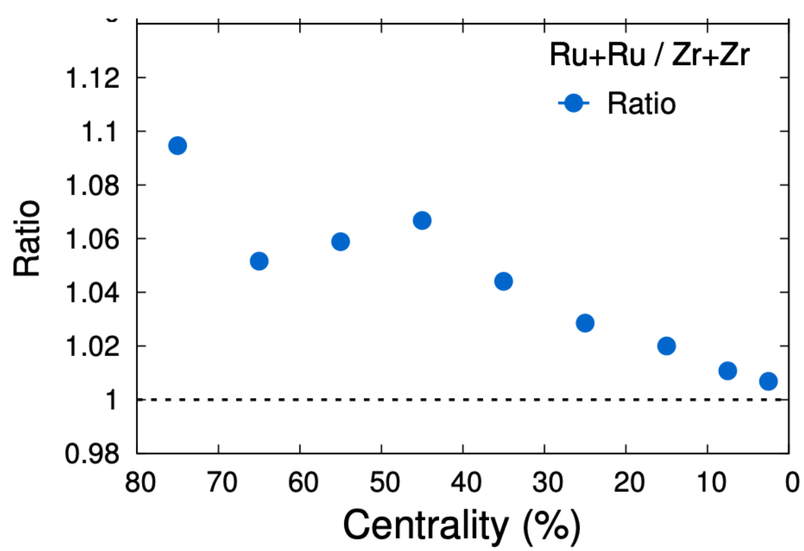
Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at RHIC

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.

STAR, nucl-ex 2109.00131, PRC (2022)

The predefined criteria assume that the multiplicities in RuRu and ZrZr collisions (in the same cross section cuts) are the same.
Is this criterion supported by the data?

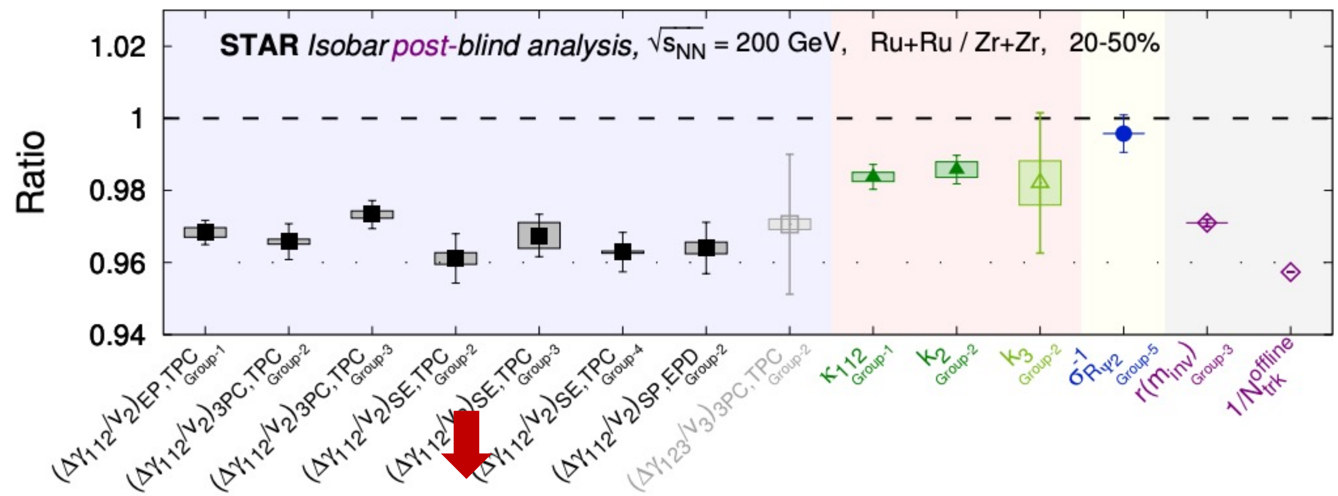
No. The **measured** multiplicities are **significantly** different:



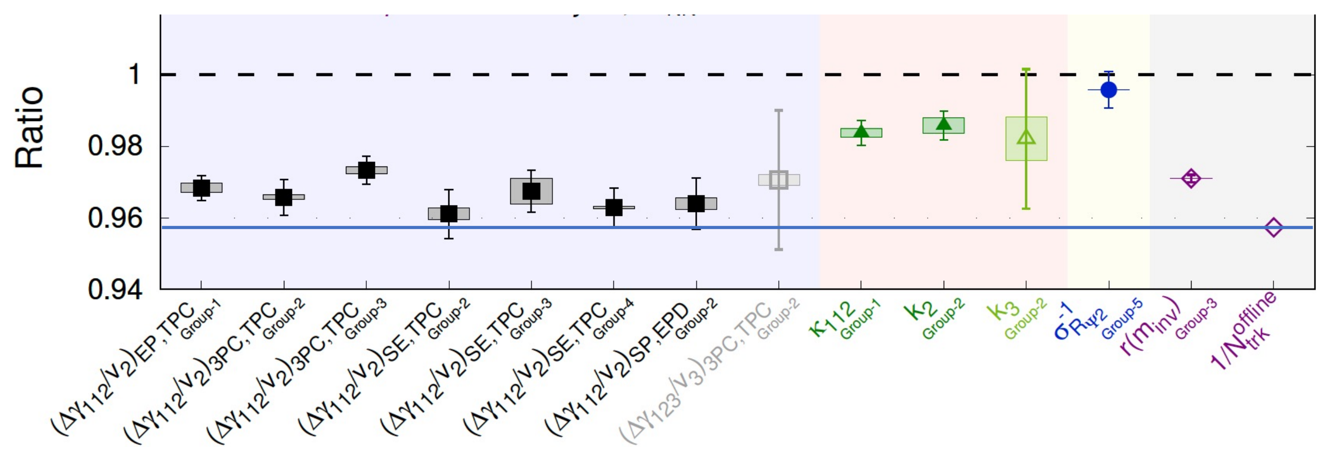
Since both signal and background scale as 1/N, the baseline has to be changed.
This is not part of the "predefined criteria".
Also: different v_2, p_T spectra?

CME search with 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



Recent theoretical analysis:

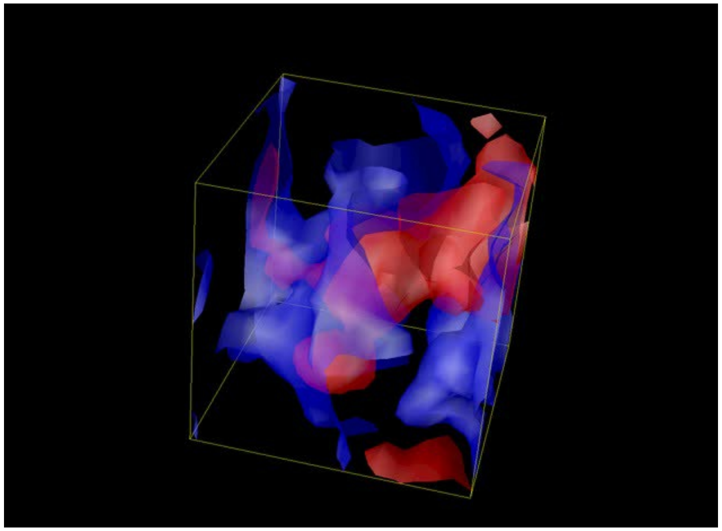
CME fraction is 6.8+-2.6 %

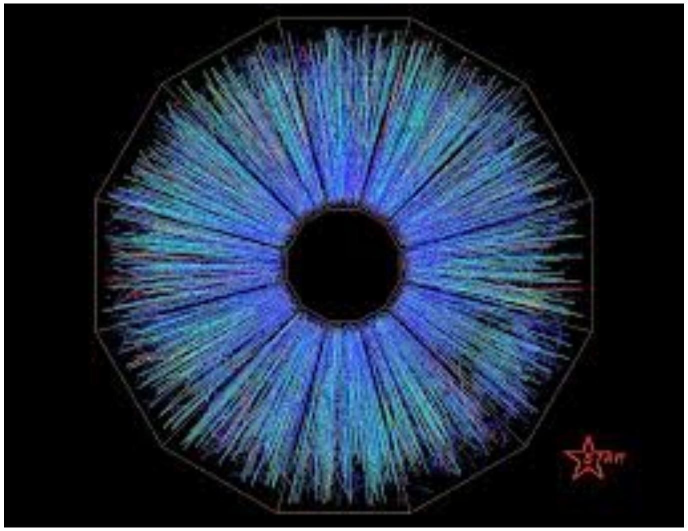
DK, J. Liao, S. Shi, arXiv:2205.00120, Phys. Rev. C106(2022)

The future of CME at RHIC

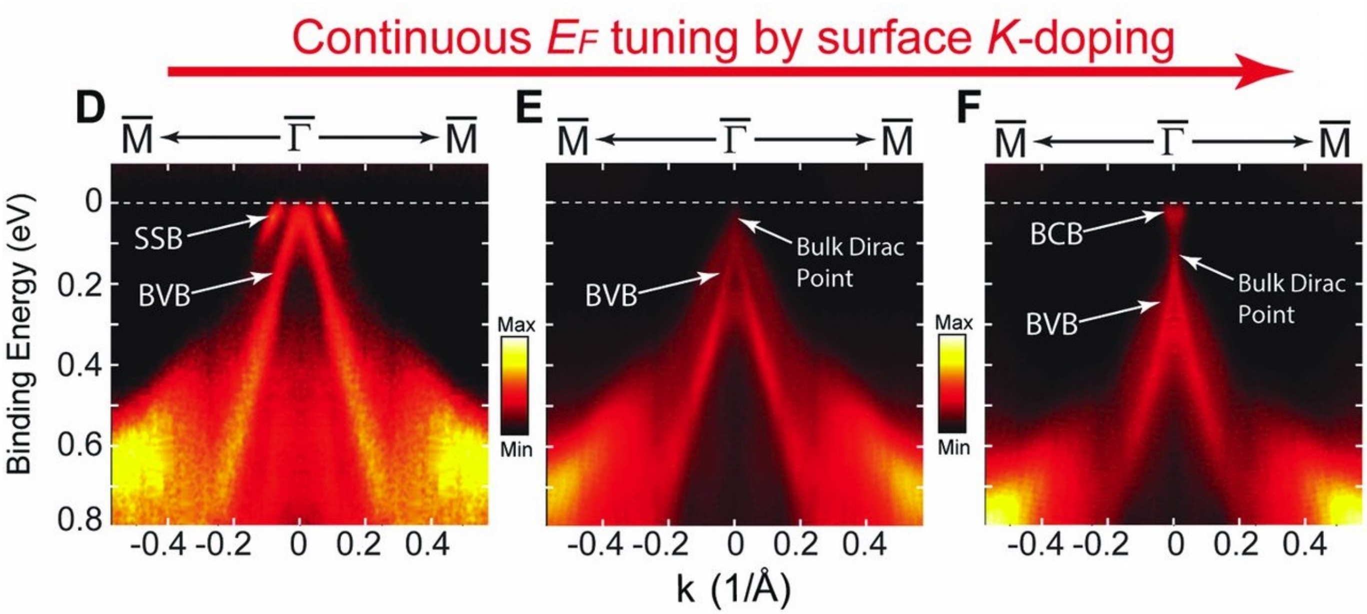
With ~ 10 billion more AuAu events, **if** the central value of the CME fraction stays the same, the statistical significance of STAR data is expected to reach 5σ

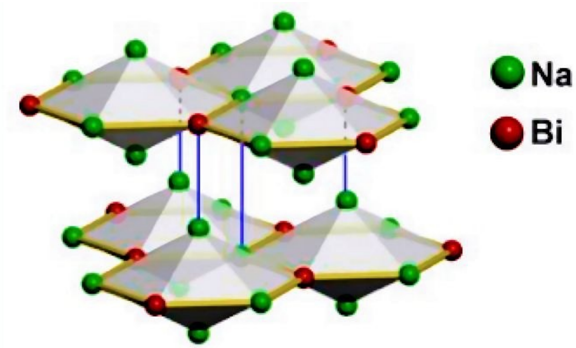
A lot of ongoing work by experimentalists and theorists





Broader connections: Chiral fermions in Dirac & Weyl semimetals





Recent reviews:

N.P. Ong and S. Liang, Nature Rev. Phys. (2021); P. Narang, C. Garcia, C. Felser, Nature Mat. (2021)

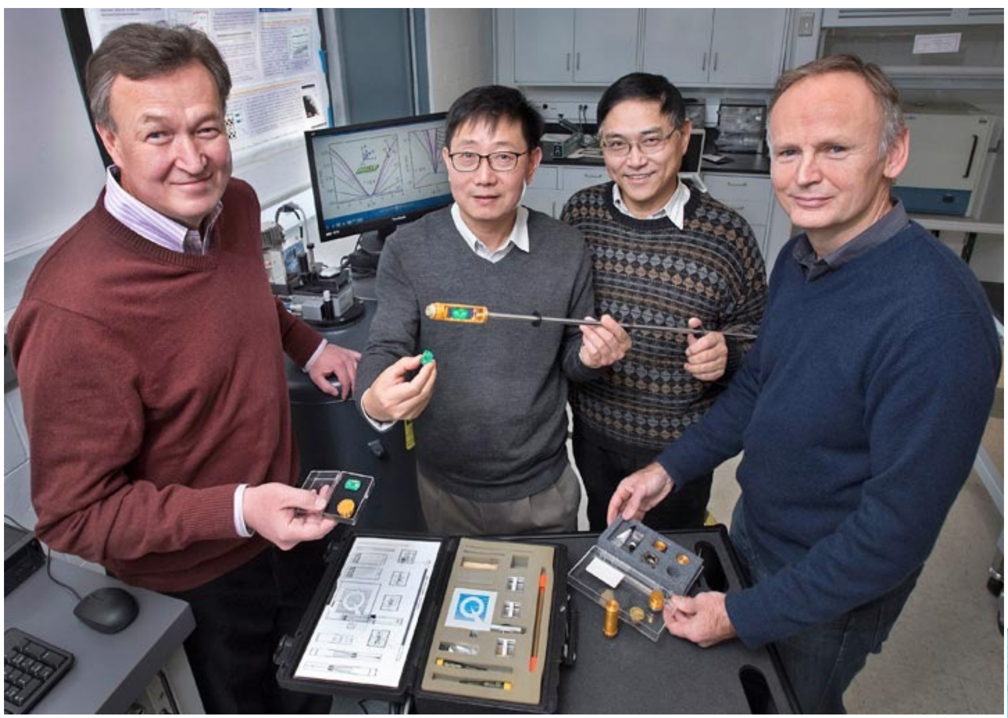
Even number of space-time dimensions –
so chiral anomaly operates, can study CME!

CME in chiral materials

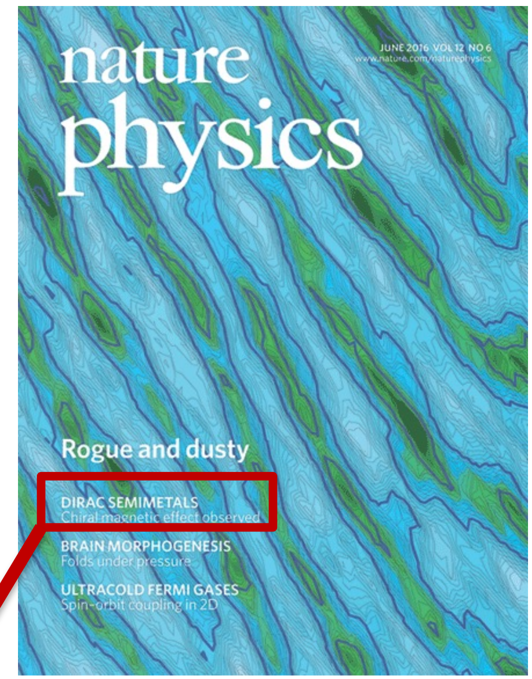
Observation of the chiral magnetic effect in $ZrTe_5$

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]

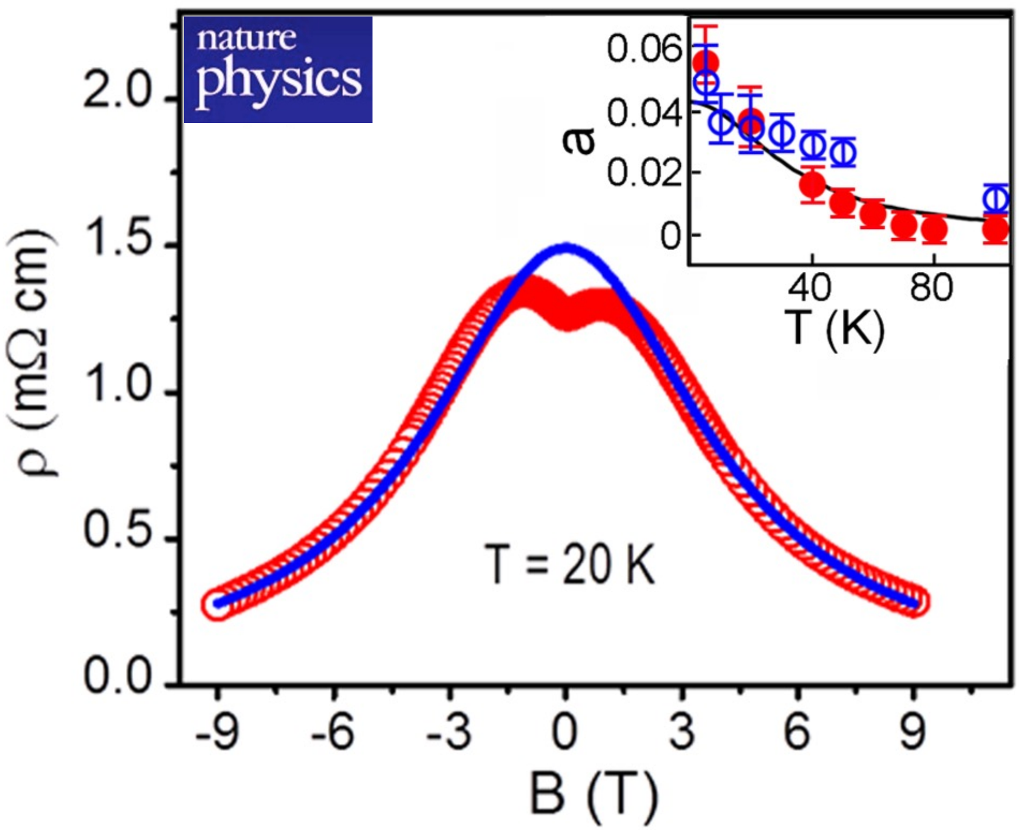
Parallel electric and magnetic fields source the chiral anomaly: $\partial_\mu J^\mu_A = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B}$

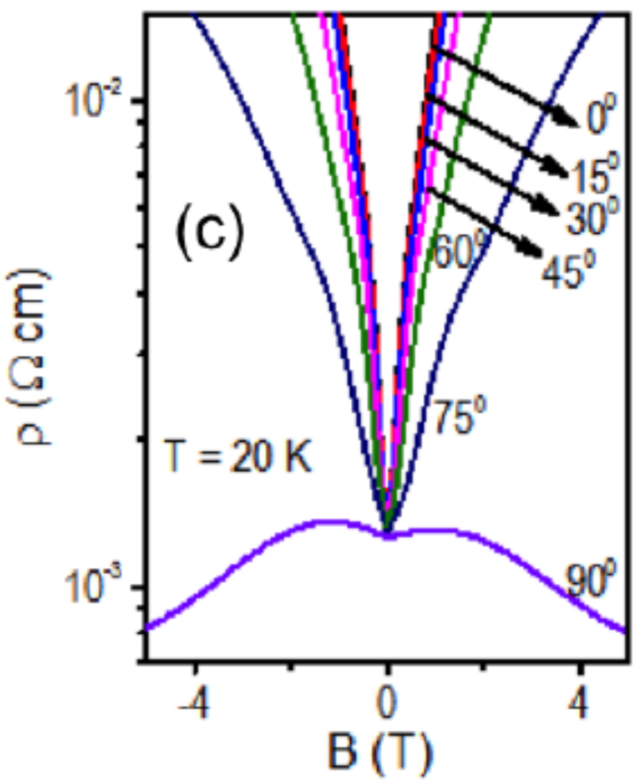
and thus the chiral chemical potential $\mu_5 \sim EB\,\tau$

The CME current is $J \sim \mu_5 B^2 \tau$ – longitudinal magnetoconductivity ~ B^2 (at weak B)

D. Son, B. Spivak '13

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





CME in chiral materials

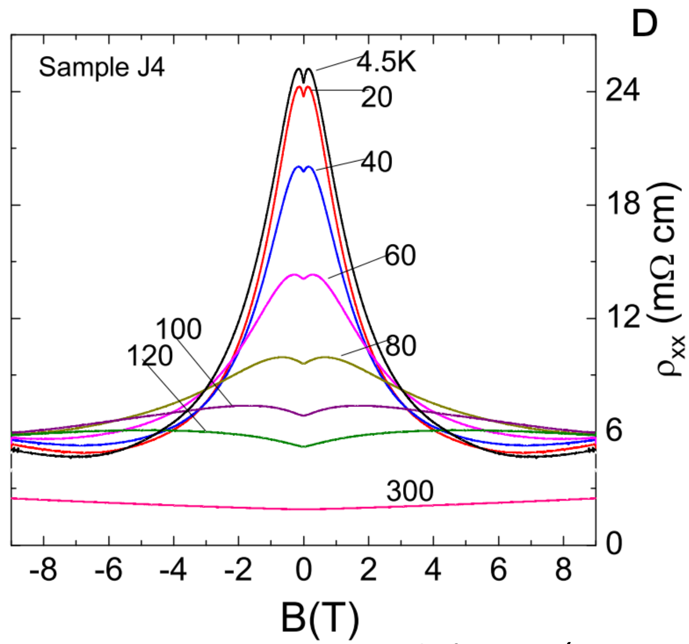
Impressive results from other groups:

arXiv:1503.08179

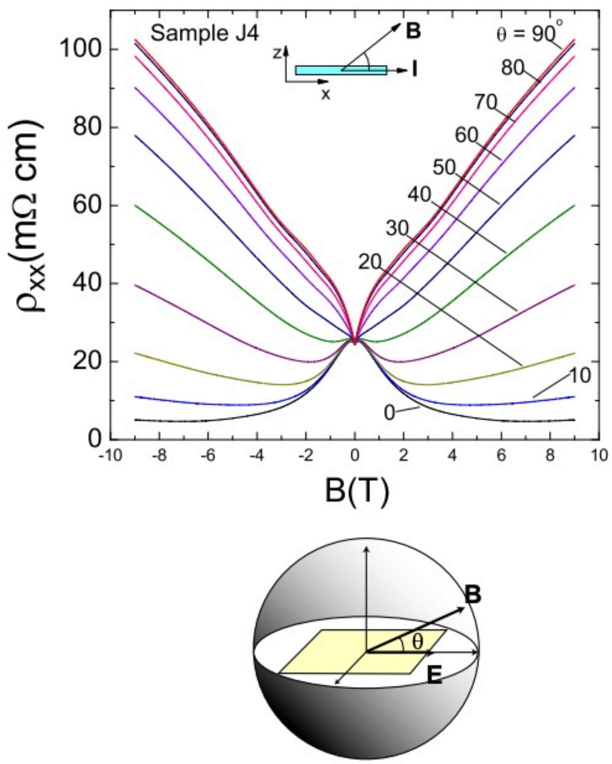
Signature of the chiral anomaly in a Dirac semimetal – a current plume steered by a magnetic field*

Jun Xiong[1], Satya K. Kushwaha[2], Tian Liang[1], Jason W. Krizan[2], Wudi Wang[1], R. J. Cava[2], and N. P. Ong[1]
Departments of Physics[1] and Chemistry[2], Princeton University, Princeton, NJ 08544

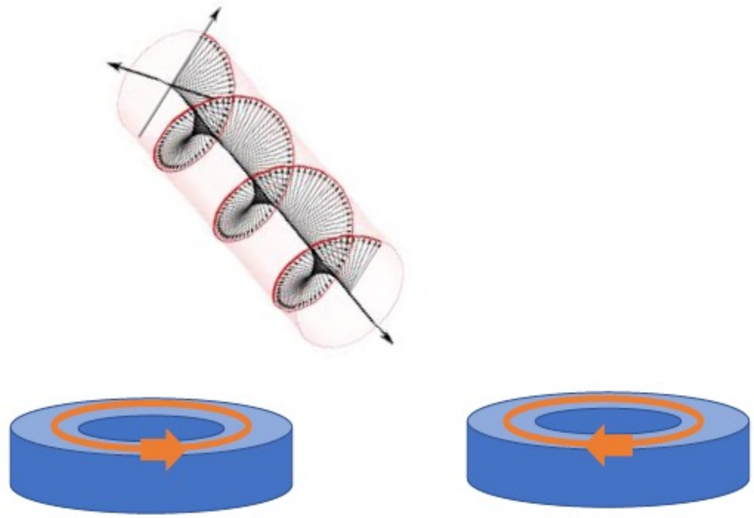
(Dated: March 30, 2015)



Science '15



Quantum computing with chirality: the chiral qubit



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

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

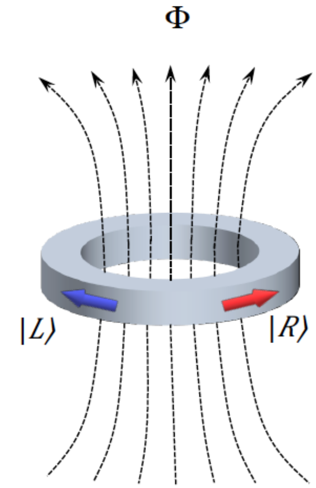
$$|1\rangle = \frac{1}{\sqrt{2}}(|R\rangle - |L\rangle)$$

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

Chiral Qubit: the Hamiltonian

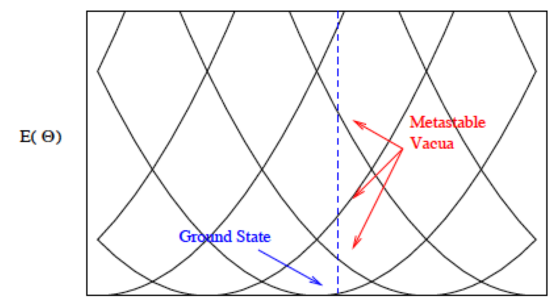
$$\hat{H} = \hbar\omega \left[-i \frac{\partial}{\partial \varphi} - \frac{\Phi}{\Phi_0} \right] \hat{\sigma}_z$$

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



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

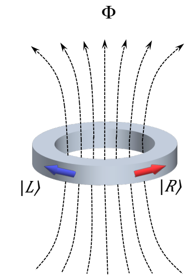
$$U_{tot}(\Phi) = U_0 \left[\left(\frac{\Phi}{\Phi_0} - \frac{1}{2} \right)^2 - \beta \cos \left(\frac{\Phi}{\Phi_0} \right) \right]$$



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

DK, Q.Li, arXiv:1903.07133

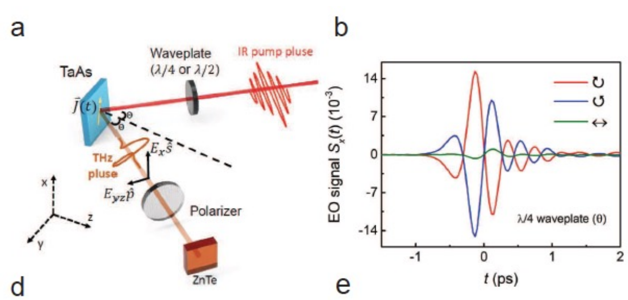
CME in chiral materials: practical applications

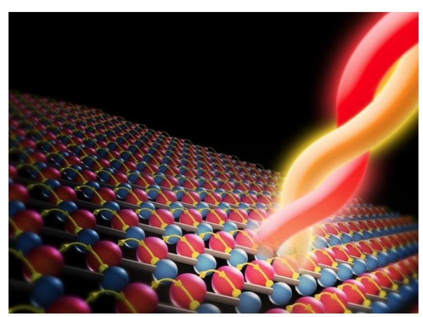


Currently, CME has been established in dozens of different chiral materials. Active ongoing work on applications beyond the academic domain, including quantum sensors, quantum memories, quantum transducers, and quantum qubits

Chiral terahertz wave emission from the Weyl semimetal TaAs

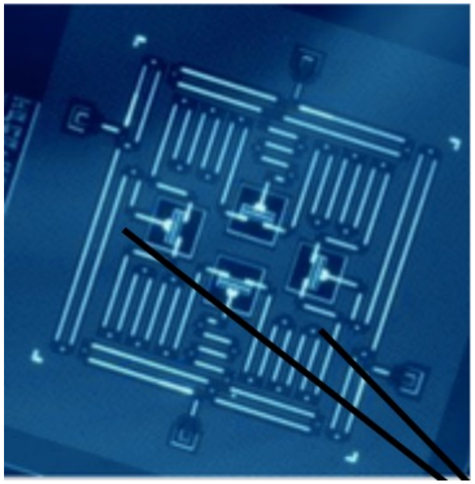
Y. Gao[1], S. Kaushik[2], E.J. Philip[2], Z. Li[3,4], Y. Qin[1,5], Y.P. Liu[6], W.L. Zhang[1], Y.L. Su[1], X. Chen[2], H. Weng[4,7], D.E. Kharzeev[2,8,9*], M.K. Liu[2*] & J. Qi[1*]





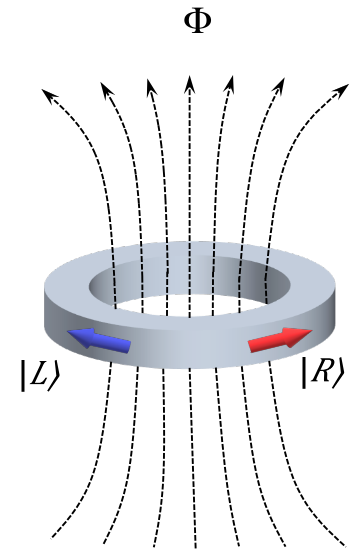
nature COMMUNICATIONS

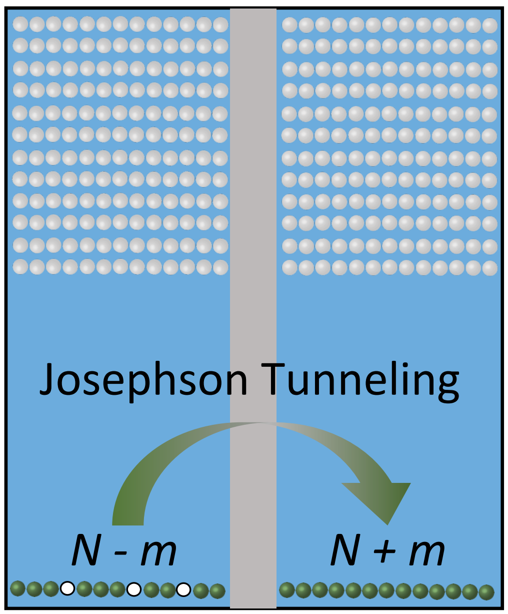
The chiral qubit

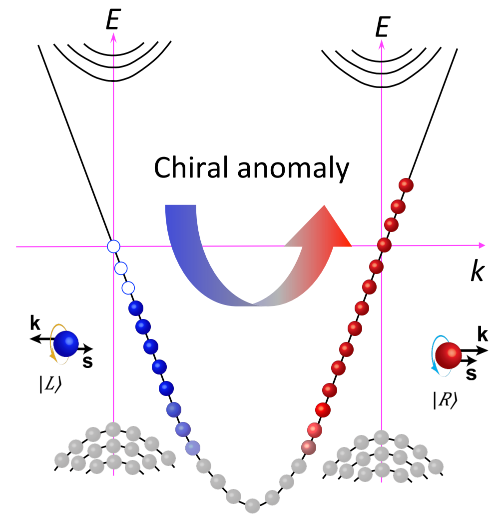


IBM-Q

?



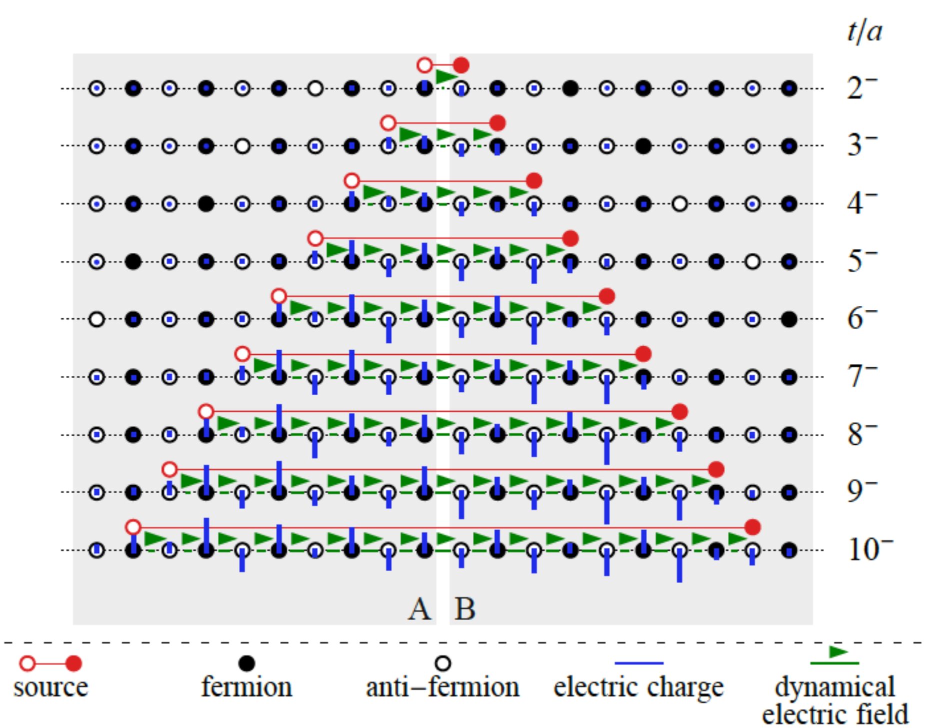


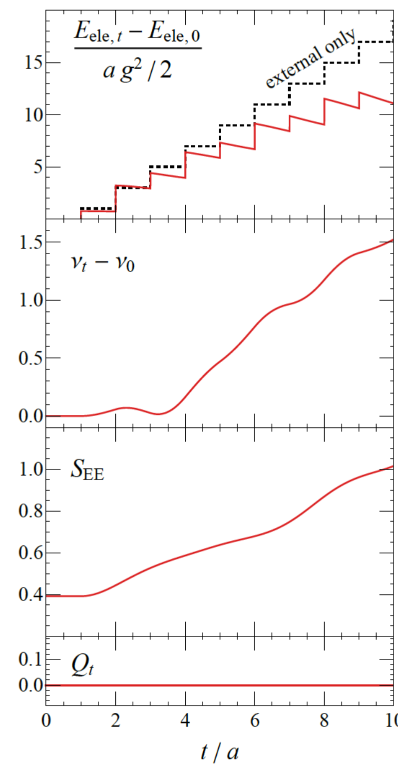


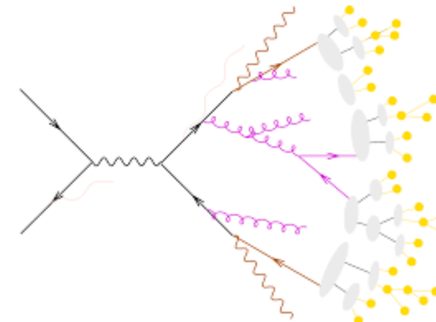
DK, Q. Li, US patent **62/758,029** (2018); arXiv:1903.07133[quant-ph]; ongoing work

Fascinating new intersections between chirality and quantum information

Quantum entanglement between the jets!





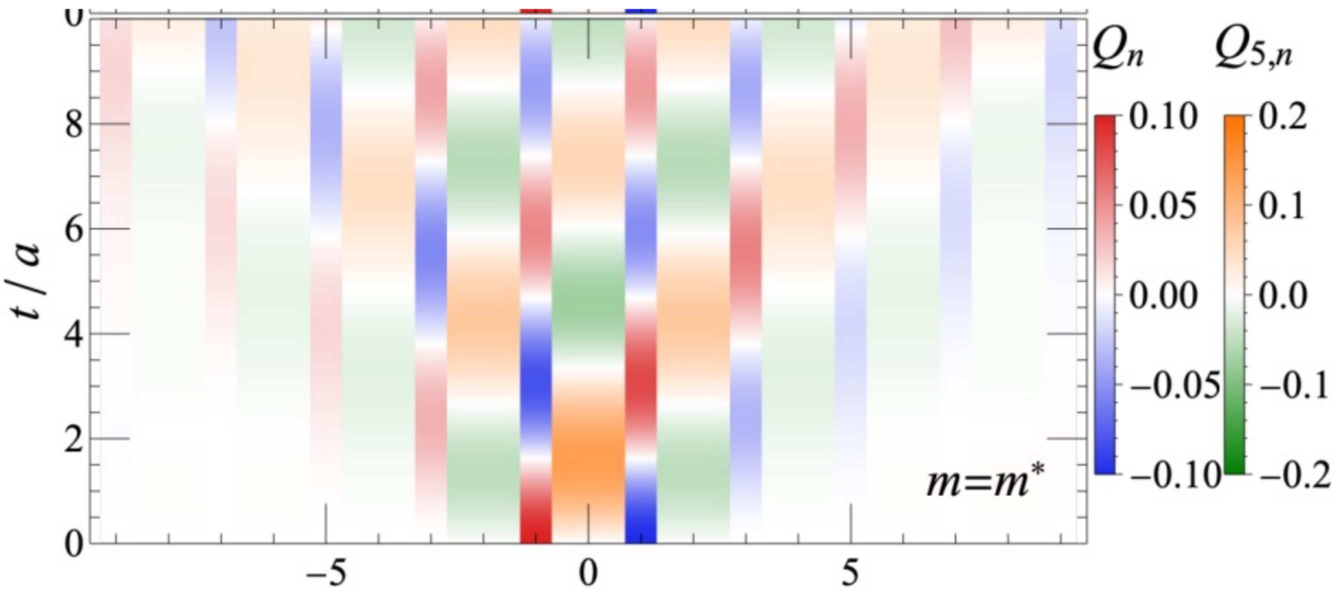


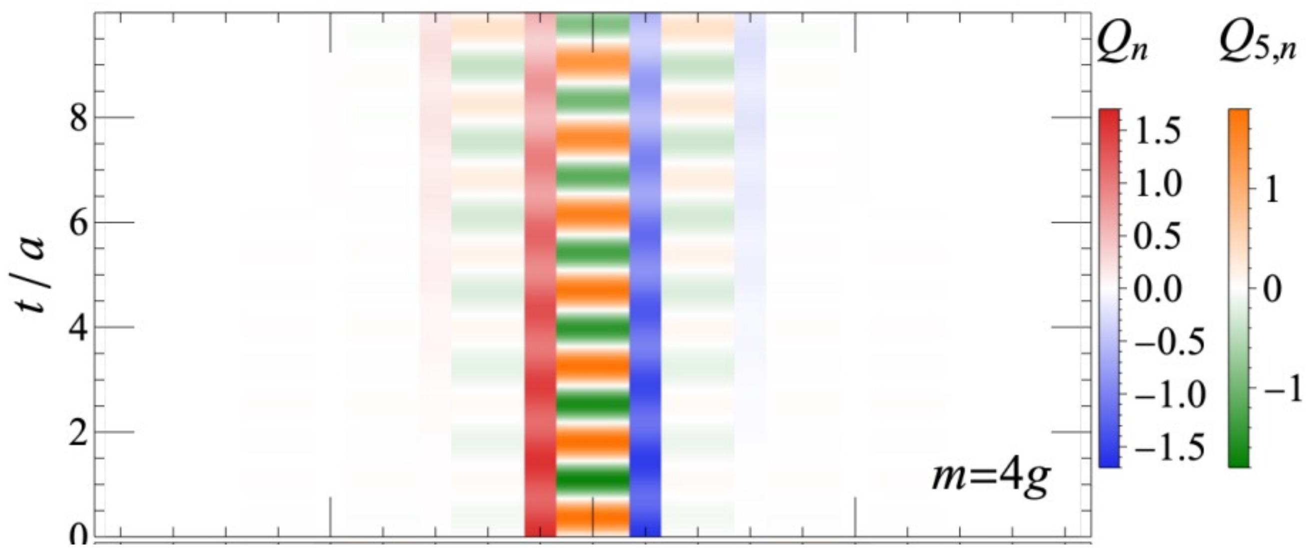
A.Florio, D. Frenklakh, K. Ikeda, DK, V. Korepin, S. Shi, K. Yu, arXiv:2301.11991; PRL, in press

C²QA Co-design Center for Quantum Advantage

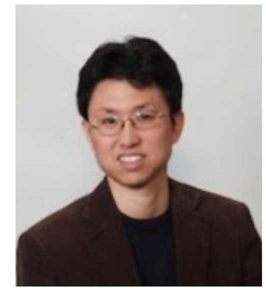
Study this at RHIC and EIC!

Nonlinear chiral magnetic waves





Chiral magnetic wave: coupled oscillations of electric and chiral charges
DK, H.U. Yee, '10



Quantum simulation reveals the existence of a novel nonlinear chiral magnetic wave at large m/g

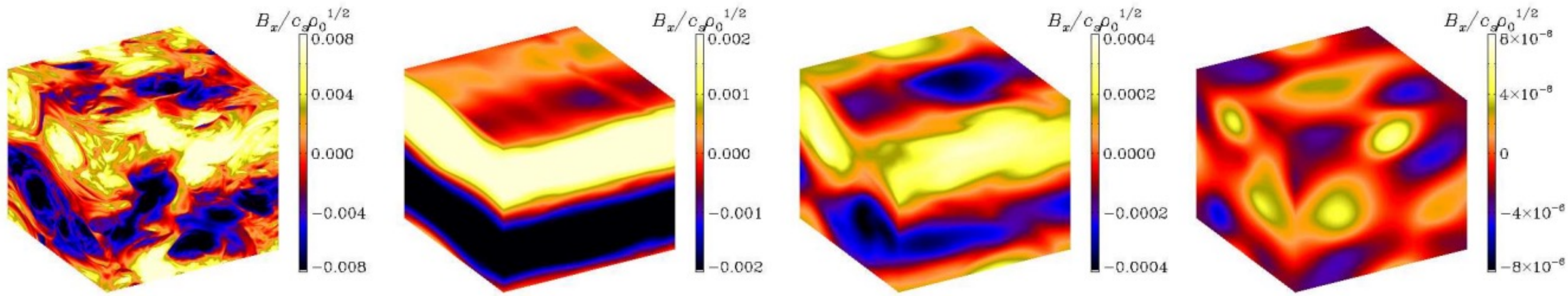
K. Ikeda, DK, S. Shi, arXiv:2305.05685; subm. PRL

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 Astrophysical Journal, 911:110 (14pp), 2021 April 20
https://doi.org/10.3847/1538-4357/abe4d7

Relic Gravitational Waves from the Chiral Magnetic Effect

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Topological structure of QCD vacuum and gravitational waves

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Gravitational waves and primordial black holes from chirality imbalanced QCD first-order phase transition with $\mathcal{P}$ and $\mathcal{CP}$ violation

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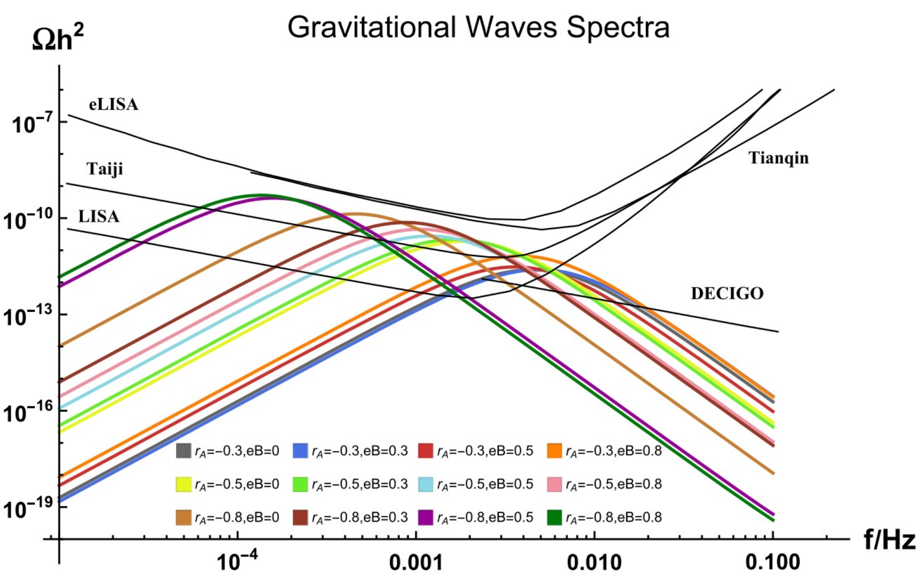

(b) Gravitational waves spectra for different r_A and eB.

Collapse of P-odd bubbles in QCD plasma may lead to detectable gravitational waves

The possibility of local parity violation at high temperatures in high-energy heavy-ion collisions as well as in the early universe was proposed as early as last century [58,59].

The Importance of Pure Theory

Juan Maldacena

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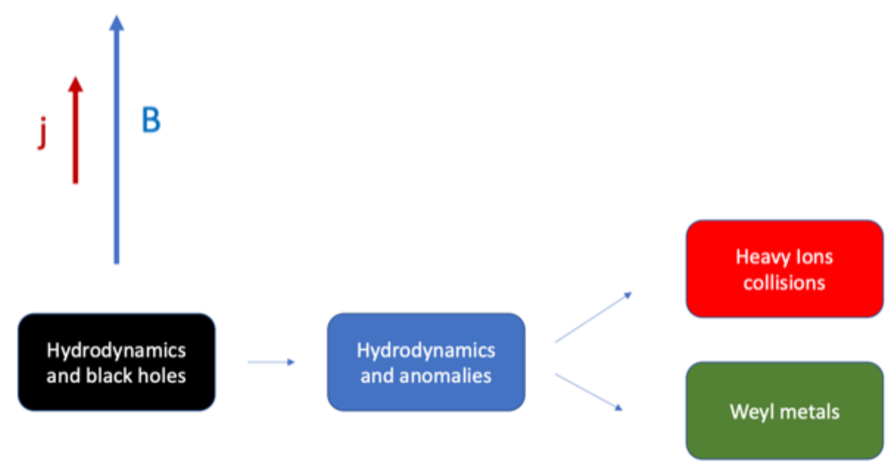
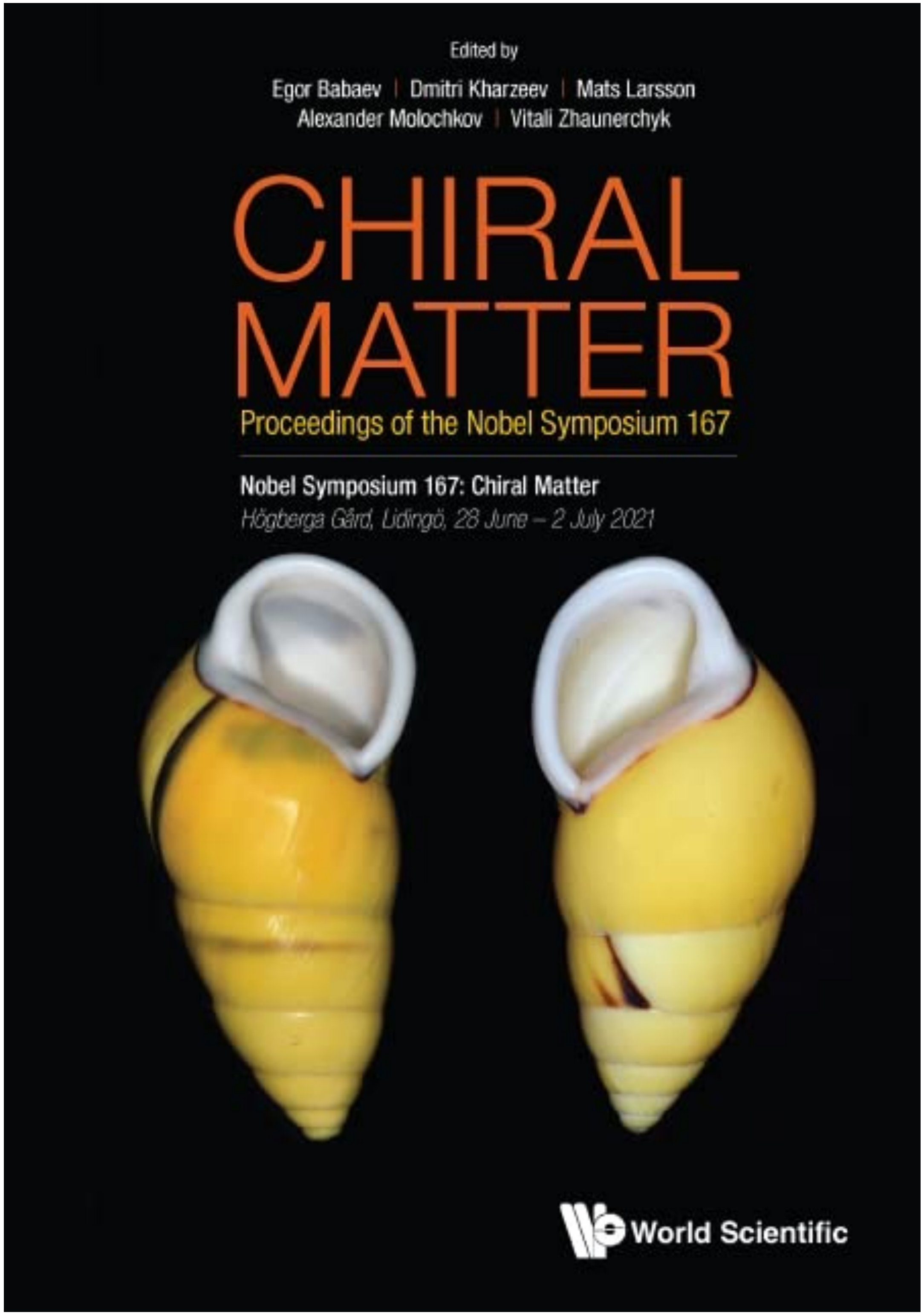
Case study

Anomalies and the chiral magnetic effect

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Summary

1. Chiral Magnetic Effect is a direct probe of topology of gauge fields

2. CME in heavy ion collisions is a unique opportunity
   to detect in the lab the topological structure of
   non-Abelian gauge theories.

   This observation is possible with heavy ion collisions at RHIC;
   conclusive results are expected very soon

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