The chiral magnetic effect

in quark-gluon plasma and condensed matter

D. Kharzeev

Stony Brook University

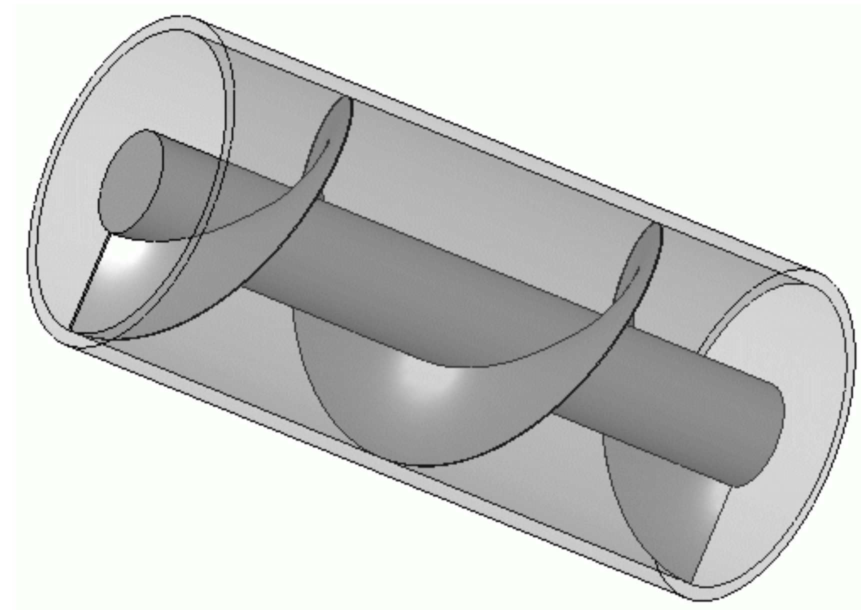
RIKEN BNL Research Center

BROOKHAVEN NATIONAL LABORATORY

Chirality and transport:

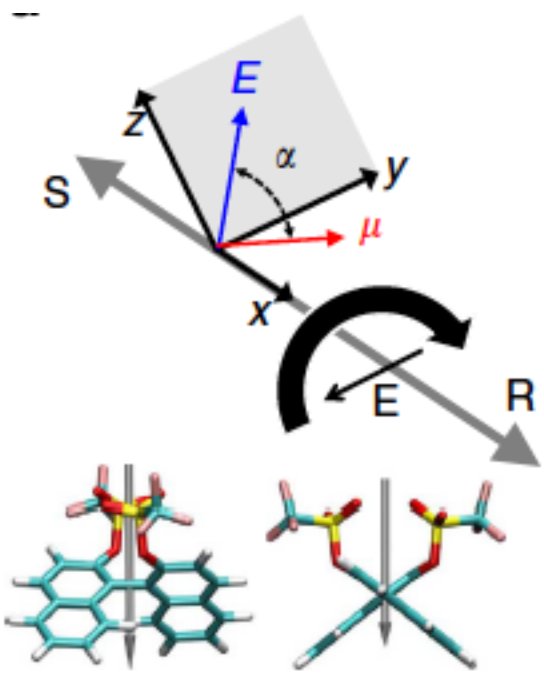
classical physics

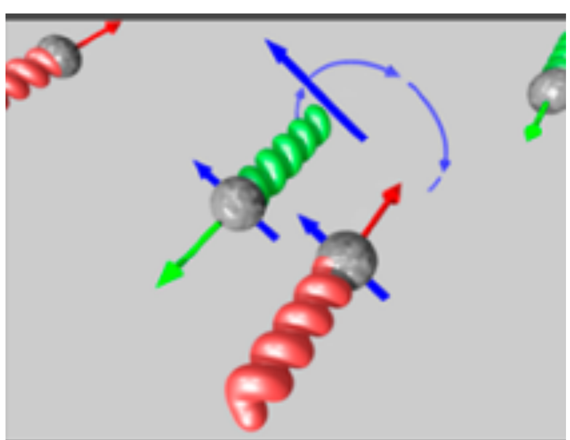
Chirality and hydrodynamics 240 B.C.



The Archimedes screw

Propeller effect in a fluid



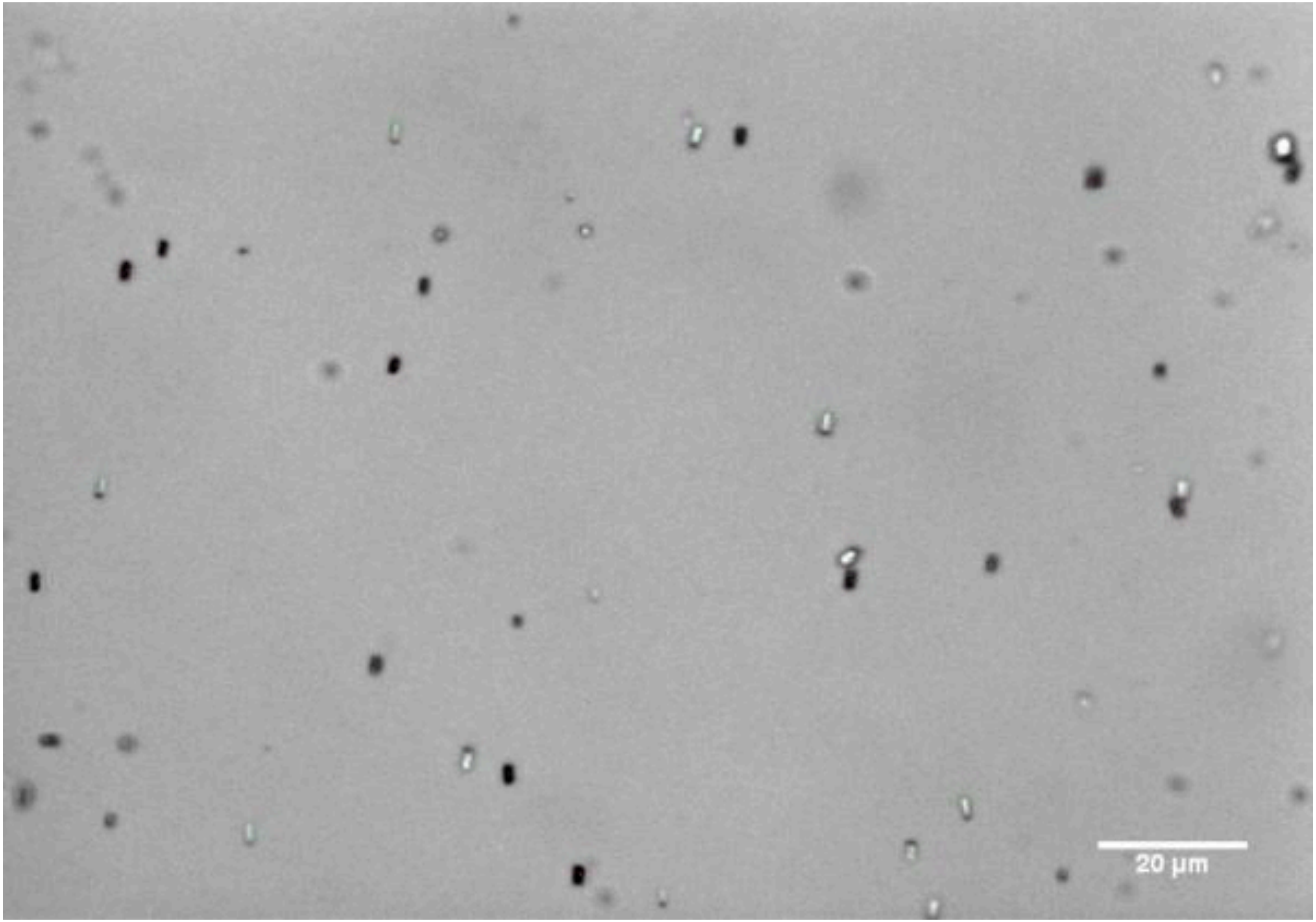


How to rotate the chiral molecule in a fluid?

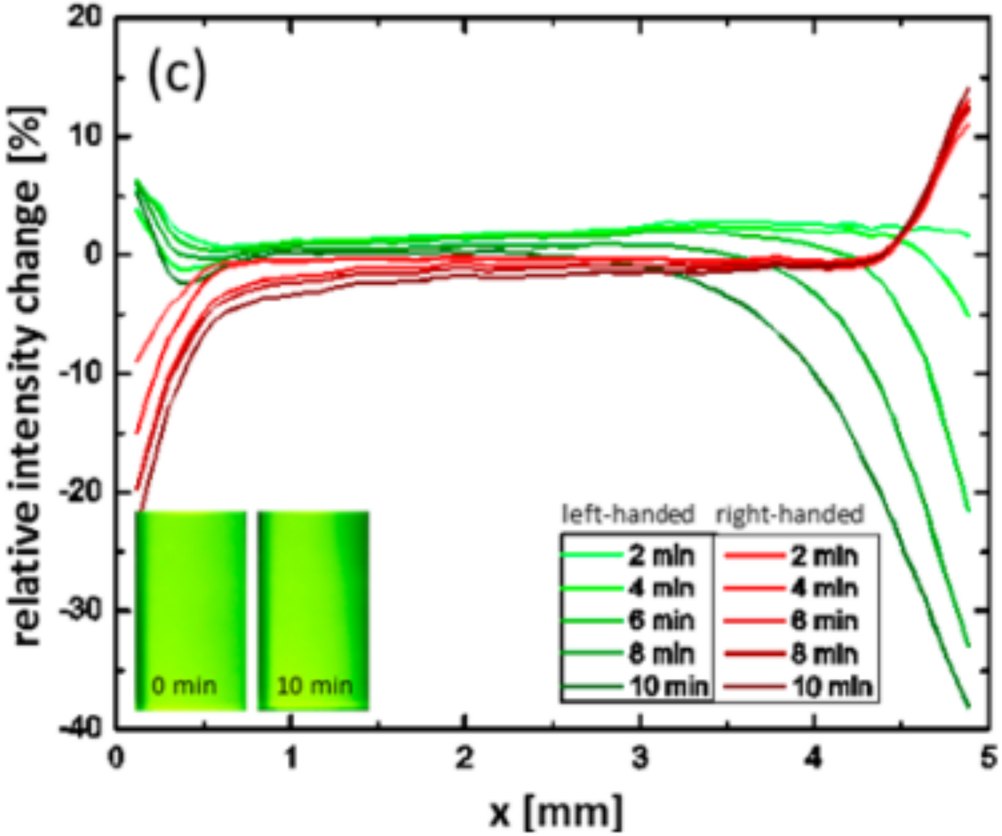
Use the coupling of an external electric field to the molecule's electric dipole moment!

Rotating electric field – rotating molecule

Baranova, Zel'dovich '78



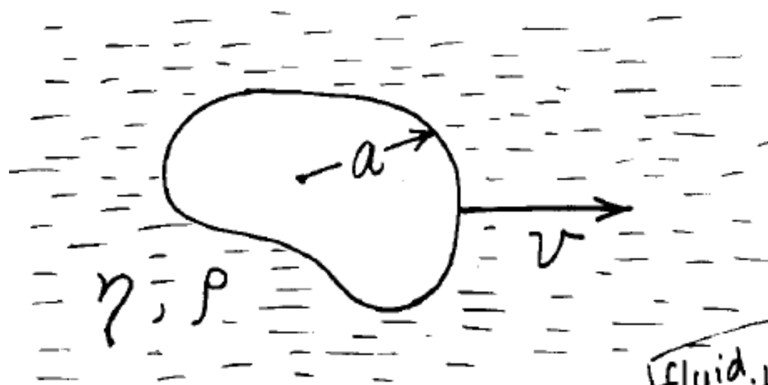
D.Schamel et al, JACS 135, 12353 (2013)



D.Schamel et al, JACS 135, 12353 (2013)

Life at low Reynolds number

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



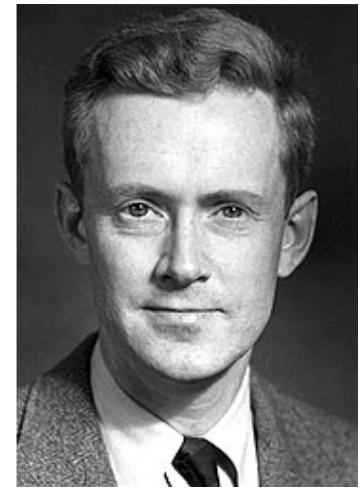
fluid density

$$\frac{\text{inertial forces}}{\text{viscous forces}} \approx \frac{a v \rho}{\eta}$$

fluid viscosity

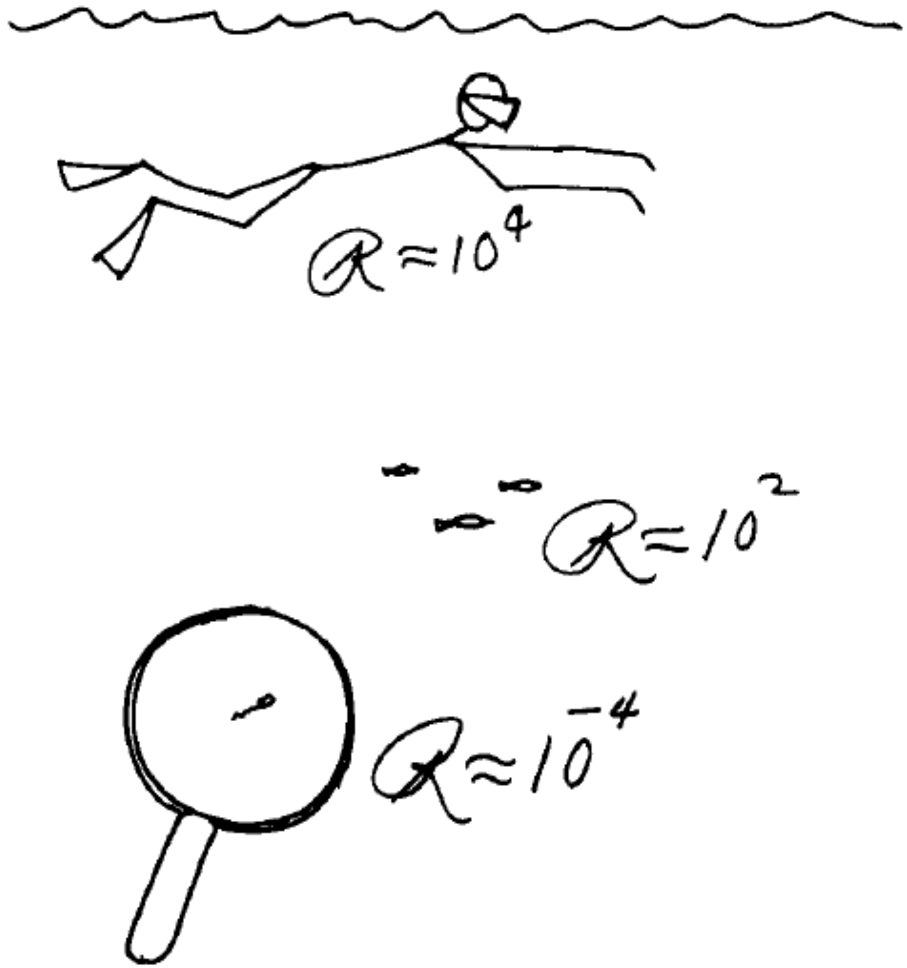
$$\mathcal{R} \equiv \frac{a v \rho}{\eta} = \frac{a v}{\nu}$$

$= 10^{-2}\ \frac{cm^2}{sec}$ for water



E.M.Purcell
(1912-1997)

Nobel prize, 1952
(Nuclear Magnetic
Resonance)


$R \approx 10^{4}$
$R \approx 10^{2}$
$R \approx 10^{-4}$

Navier - Stokes:

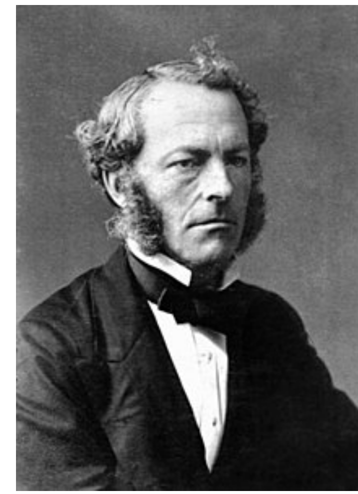
$$-\nabla p + \eta \nabla^2 \vec{v} = \cancel{\rho \frac{\partial \vec{v}}{\partial t}} + \cancel{\rho (\vec{v} \cdot \nabla) \vec{v}}$$

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)

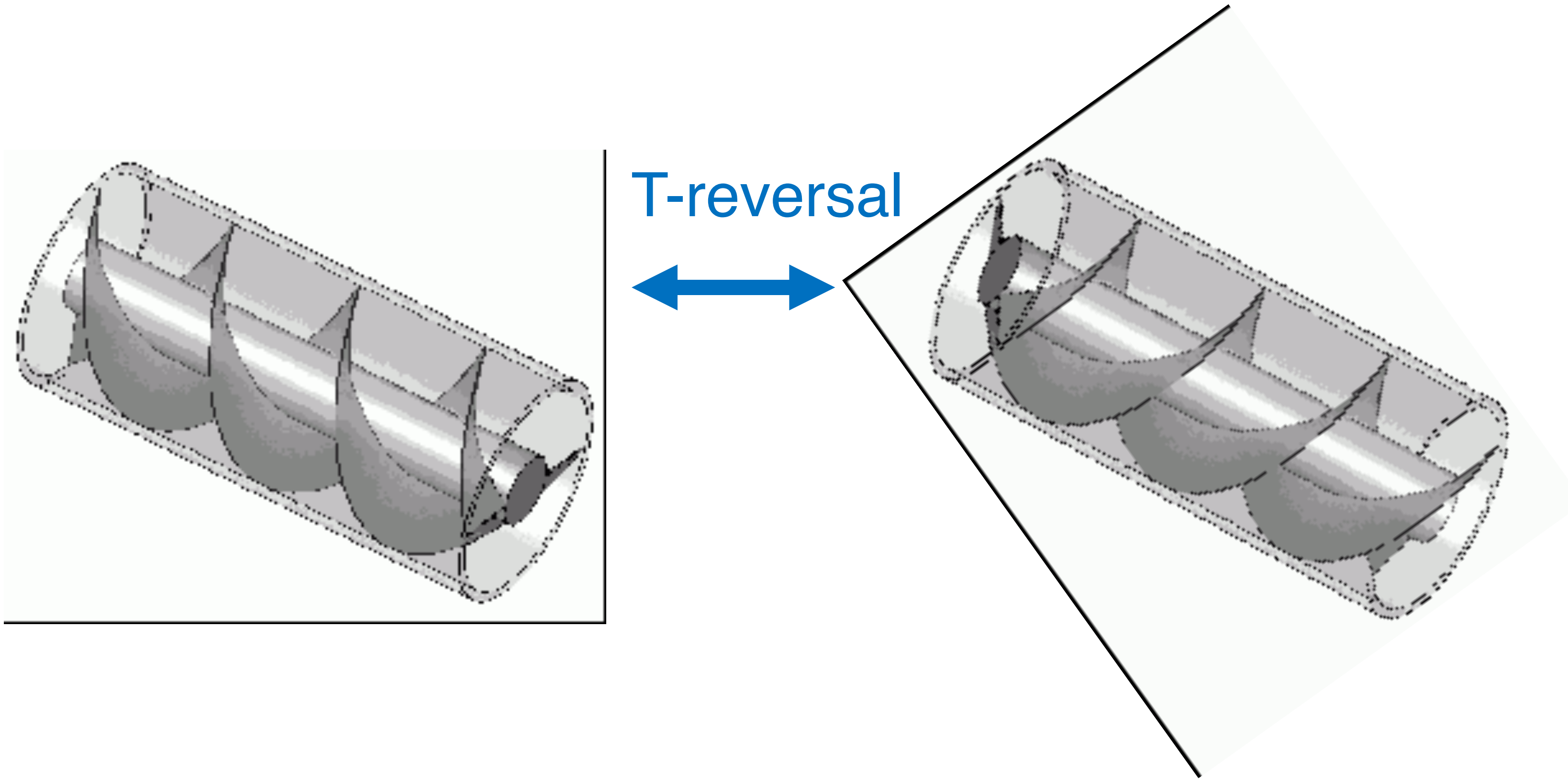
The Scallop Theorem

Geometry of the gauge field on the space of shapes

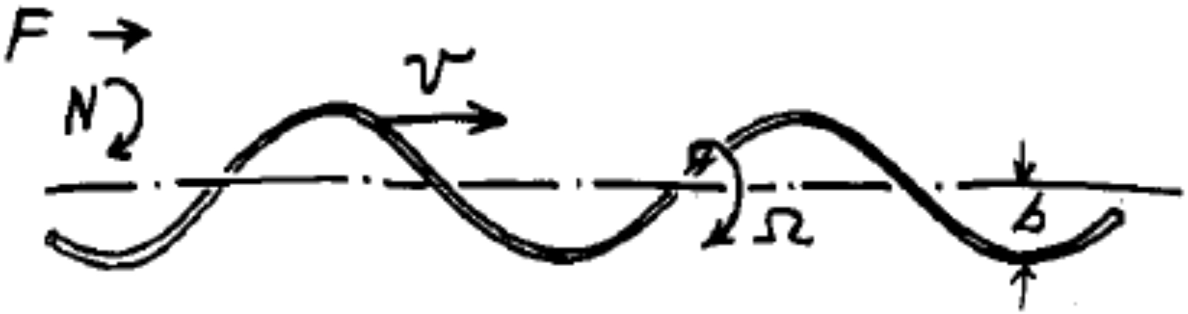
A.Shapere, F.Wilczek '88

Need to break T-invariance to move – chirality!

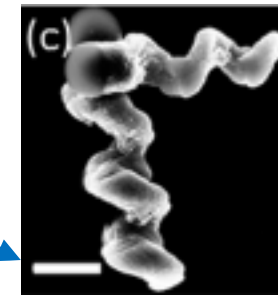
Left-handed screw



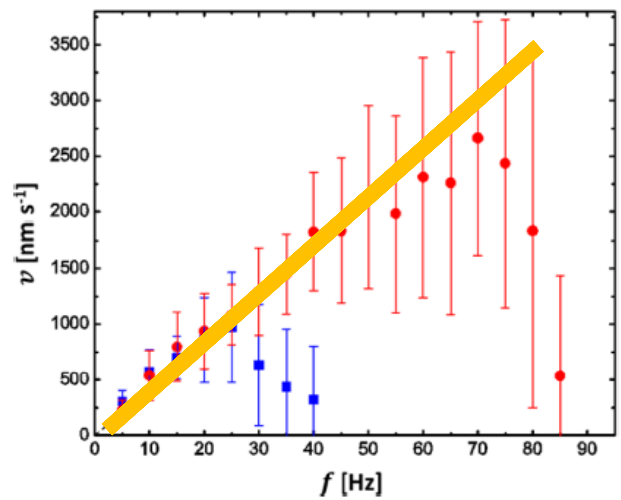
The propulsion matrix



0.5 µm



B=20 G
B=50 G



(force) $F = Av + B\Omega$

(torque) $N = Cv + D\Omega$

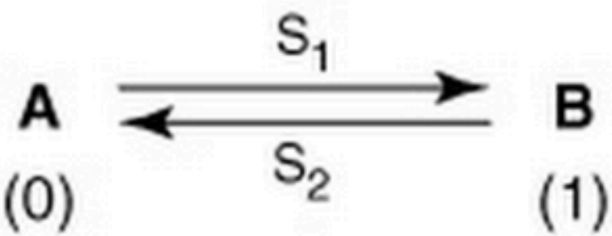
$$|P| \equiv \begin{vmatrix} A & B \\ C & D \end{vmatrix}$$

Chiral propellers at
low Reynolds number

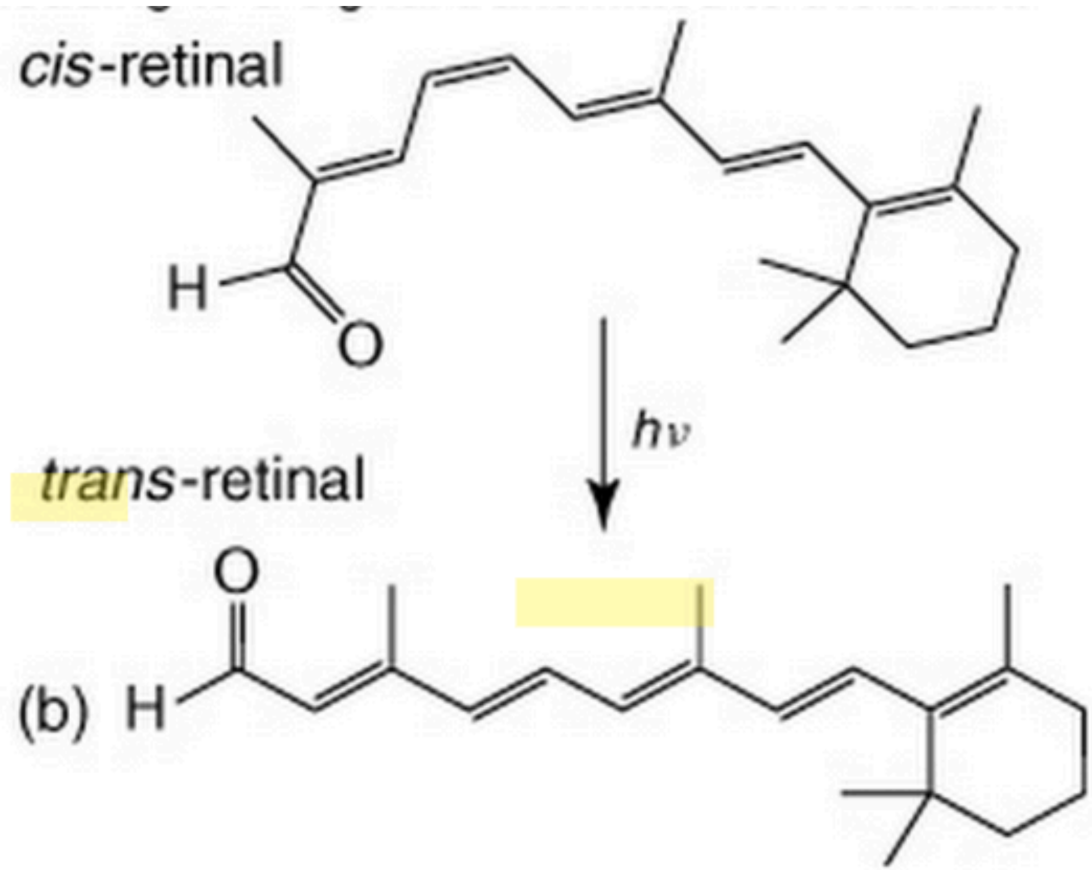
S.Ayf, I.Cook, DK, to appear

Chirality imbalance = transport

Chirality and vision



(a)

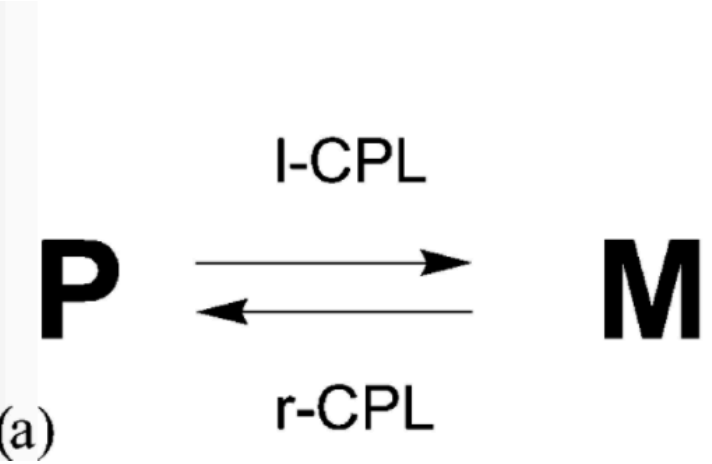


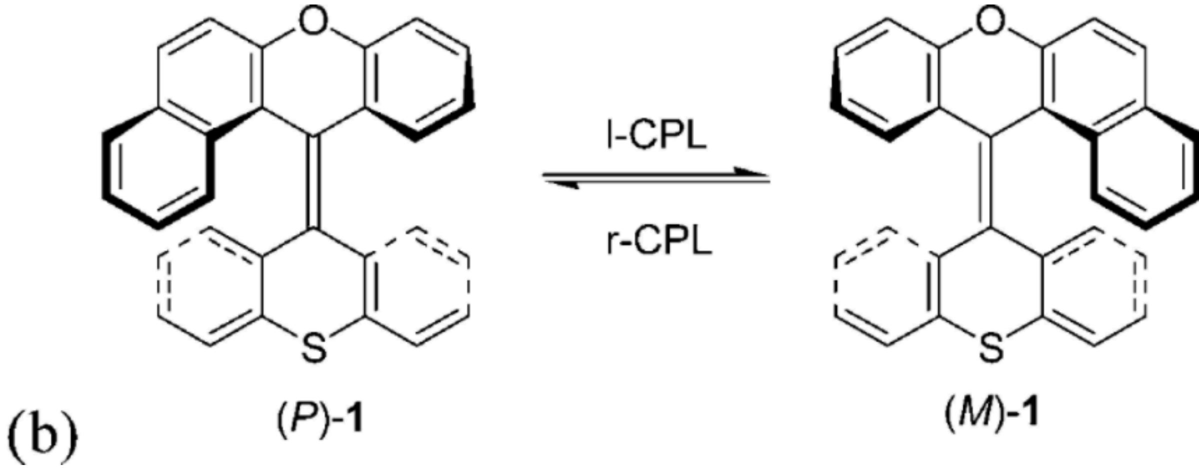
B. Feringa, W. Browne,
"Molecular switches", 2011

Protein-bound retinal molecule as a chiroptical switch:
the mechanism of vision chiral photo-pharmacology

Chiroptical switching of chiral molecules

Need circularly polarized light (CPL), with frequency optimized for inducing the tunnel transition between the enantiomers.





Review: B.Feringa, *J. Org. Chem.*, **2007**, *72* (18), pp 6635–6652

Applications: pharmaceutics, “chiral photomedicine”, optical data storage and processing, …

Scientific Background on the Nobel Prize in Chemistry 2016

MOLECULAR MACHINES

J.-P.Sauvage

Sir J.F.Stoddart

B.L. Feringa

Chirality and quantum transport

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:

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

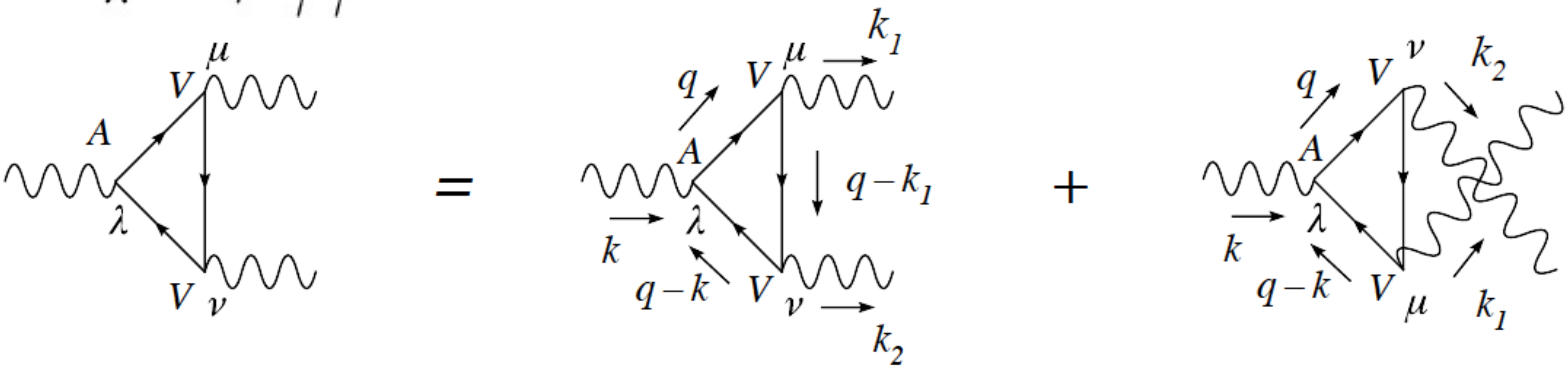
However this conservation law is destroyed by quantum effects

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

Chiral anomaly

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

$\pi^0 \rightarrow \gamma\gamma$



$$k_\lambda \Delta^{\lambda\mu\nu}(k_1, k_2) = a_n \epsilon^{\mu\nu\alpha\beta} k_{1\alpha} k_{2\beta} \qquad a_n = -i/2\pi^2$$

$$\Delta^{\lambda\mu\nu} = a_n \frac{k^\lambda}{k^2} \epsilon^{\mu\nu\alpha\beta} k_{1\alpha} k_{2\beta}$$

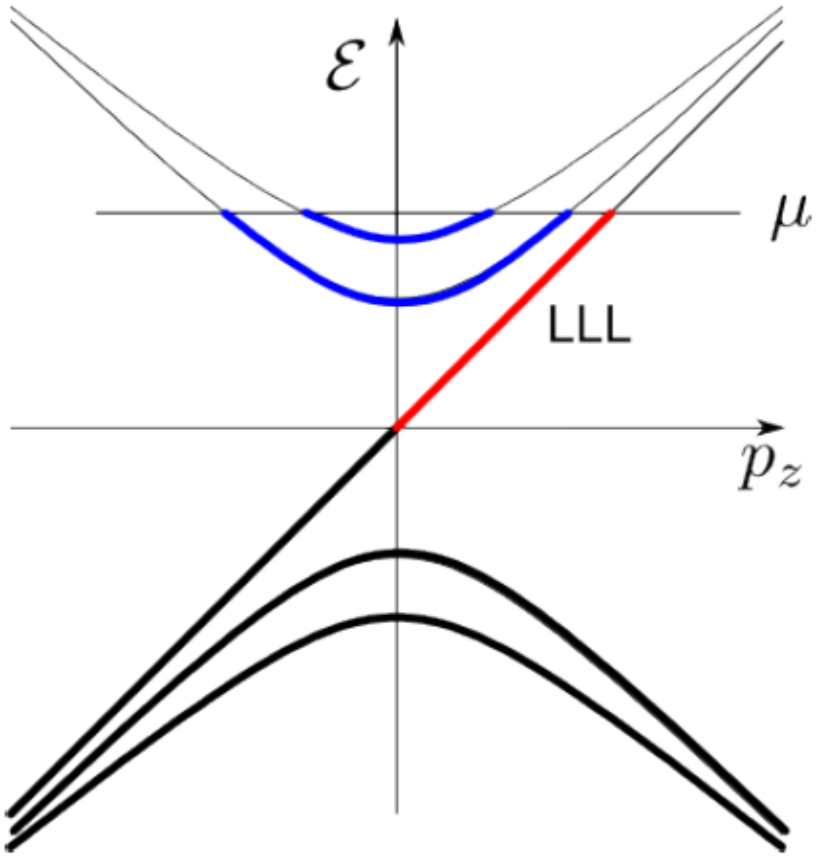
The chiral anomaly does not vanish at finite mass, and mass corrections have been evaluated, see e.g.

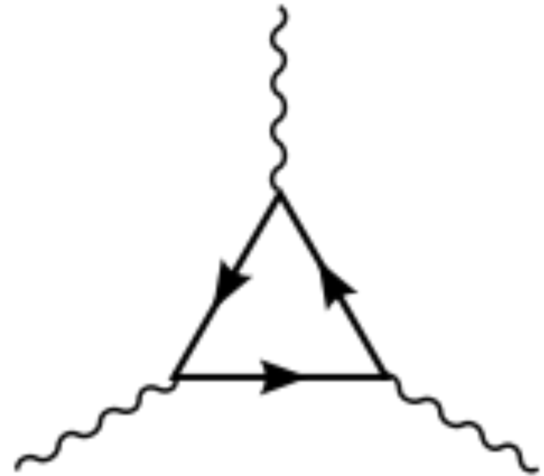
A.D. Dolgov, V.I. Zakharov, Nucl. Phys. B27 (1971) 525
R. Armillis et al, JHEP 0912 (2009) 029

Possibility of anomalous transport in systems with a finite gap (strange quarks, semiconductors)?

$$w_L = -\frac{4\,i}{s} - \frac{4\,i\,m^2}{s^2}\log\left(-\frac{s}{m^2}\right) + O(m^3) \qquad s \equiv k^2$$

Chiral anomaly





In classical background fields (E and B), chiral anomaly induces a collective motion in the Dirac sea

Adler; Bell, Jackiw; Nielsen, Ninomiya; …

Chiral Magnetic Effect

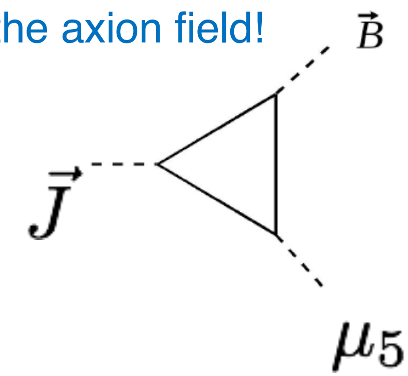
K.Fukushima, DK, H.Warringa, PRD'08;
Review and list of refs: DK, arXiv:1312.3348

Chiral chemical potential is formally equivalent to a background chiral gauge field:

$$\mu_5 = A_5^0$$

Time derivative of the axion field!

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

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

The result:

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

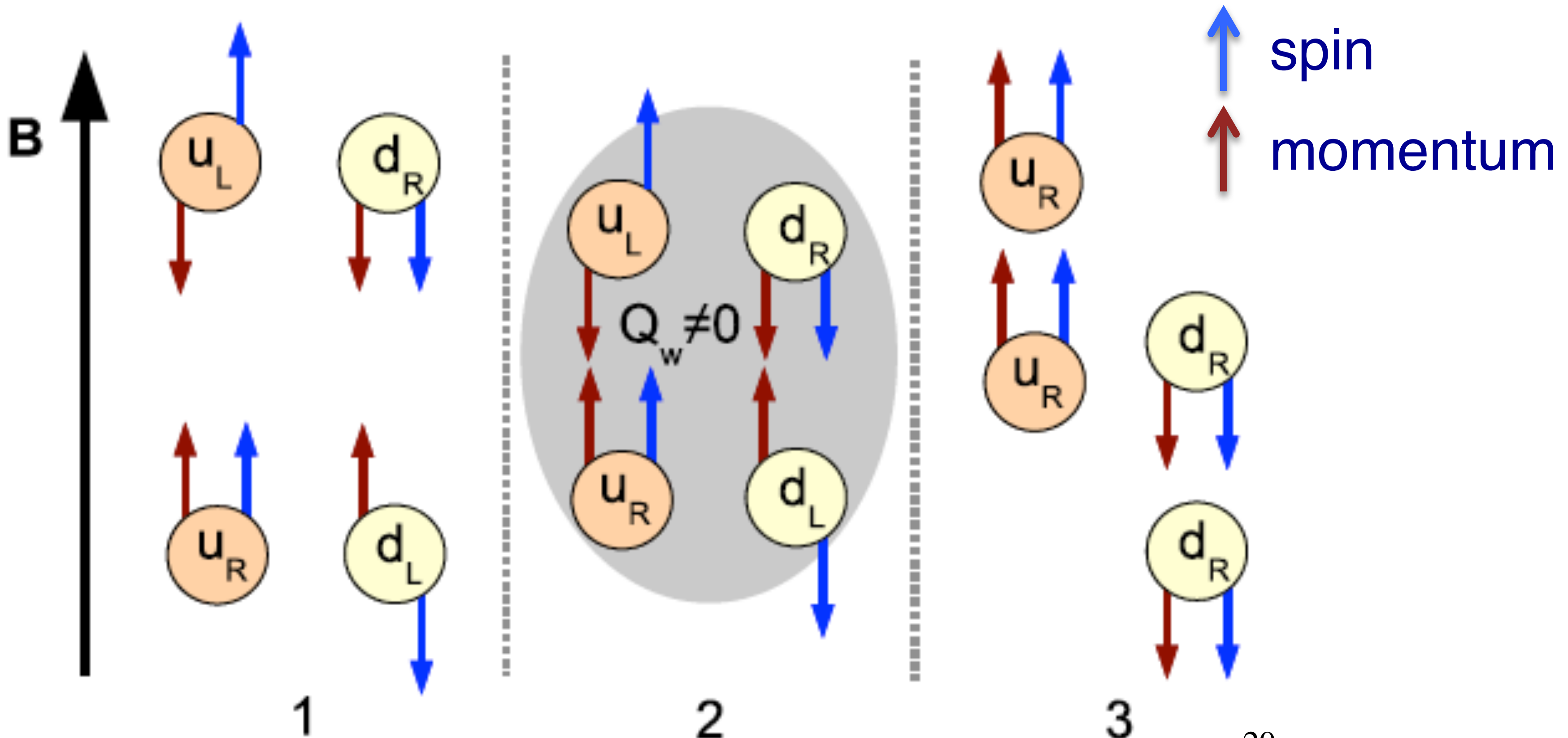
Coefficient is fixed by the axial anomaly, no corrections

Absent in Maxwell theory!

The same form as found by Vilenkin'80, but no cancelation since the chiral charge is not conserved

Chirality in 3D: the Chiral Magnetic Effect

chirality + magnetic field = current



arXiv:1105.0385, PRL

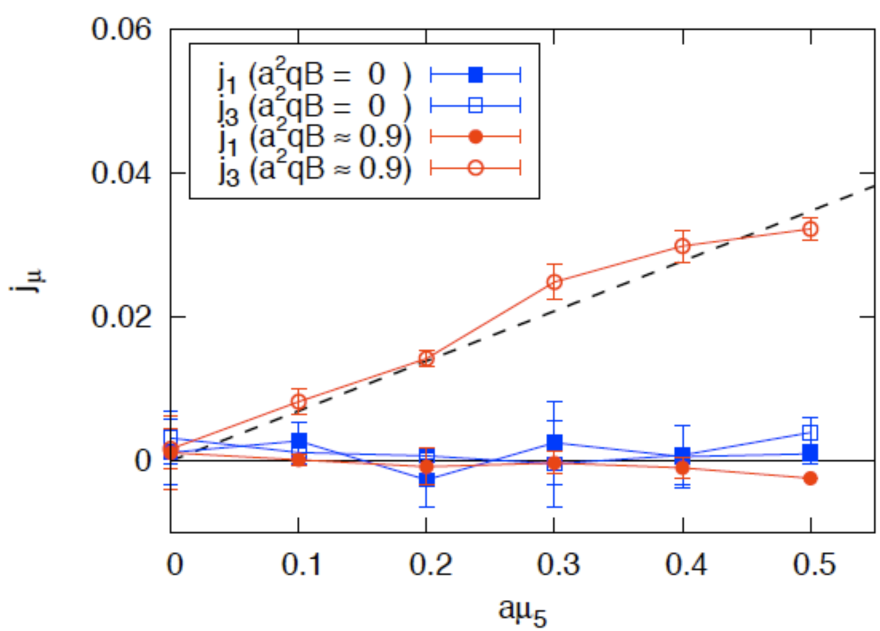
Chiral magnetic effect in lattice QCD with chiral chemical potential

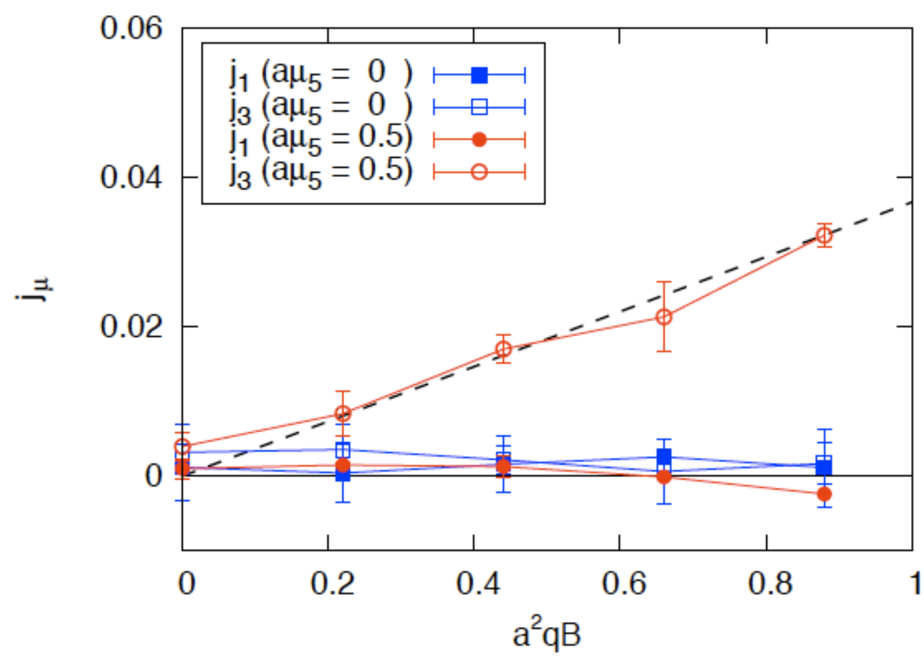
Arata Yamamoto

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

(Dated: May 3, 2011)

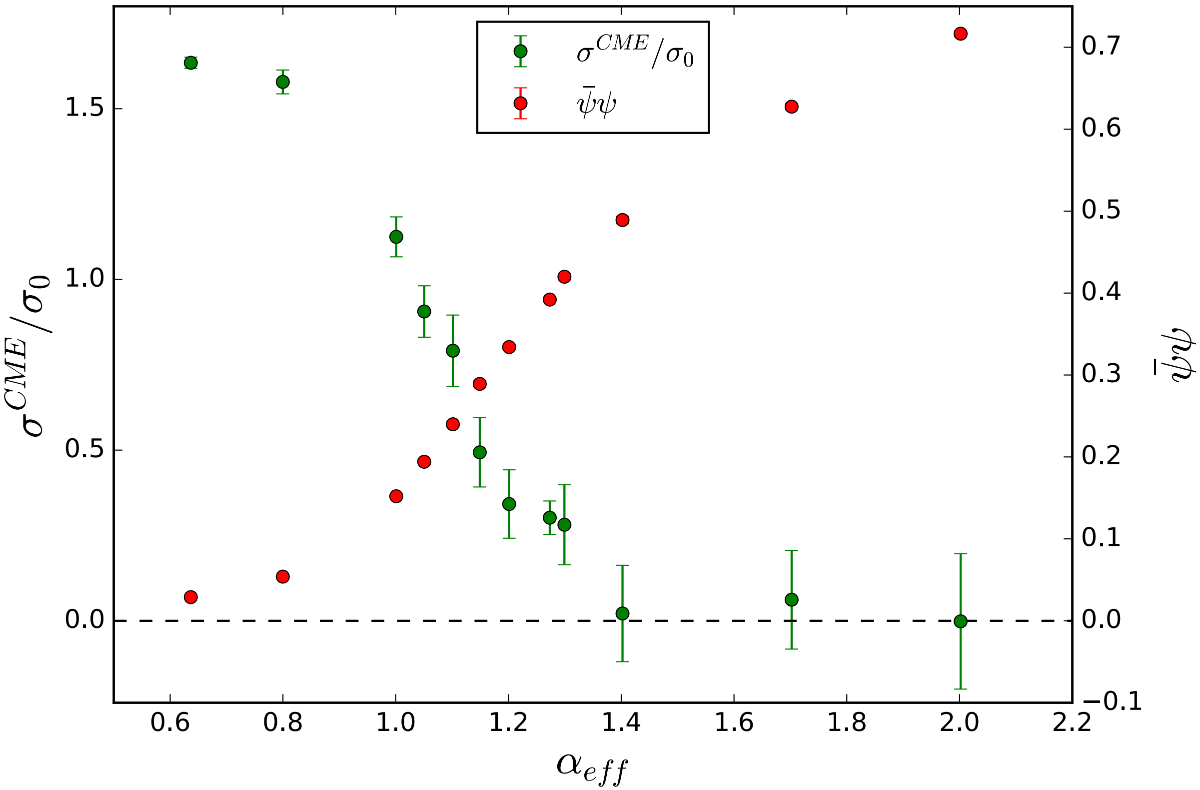
We perform a first lattice QCD simulation including two-flavor dynamical fermion with chiral chemical potential. Because the chiral chemical potential gives rise to no sign problem, we can exactly analyze a chirally asymmetric QCD matter by the Monte Carlo simulation. By applying an external magnetic 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.





Chiral magnetic effect as a signature of chiral symmetry restoration

DK'04
DK, McLerran, Warringa'07
Fukushima, DK, Warringa '08



V.Braguta et al, arxiv:1704.07132, and to appear

The spontaneous breaking of chiral symmetry does not allow the chiral magnetic current to propagate

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

<u>P-odd effect!</u>

Effect persists in hydrodynamics!

T-even

<u>Non-dissipative current!</u>

(topologically protected)

cf Ohmic conductivity:

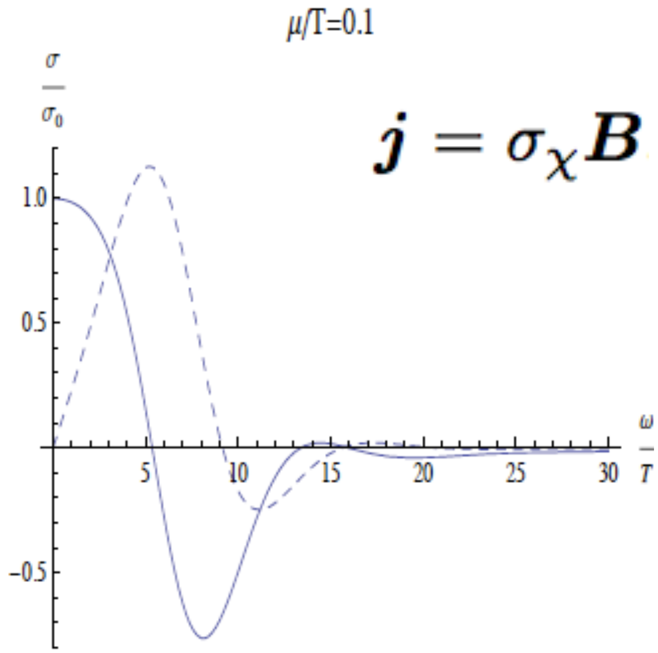
$$\vec{J} = \sigma \vec{E}$$

T-odd, dissipative

Dynamical chiral magnetic effect

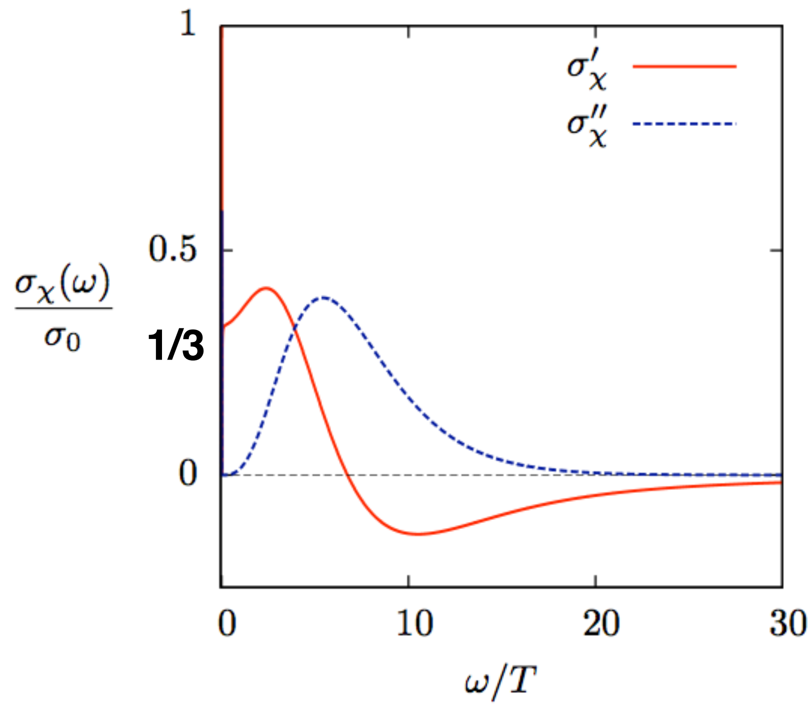
Strong coupling

$$\boldsymbol{j} = \sigma_\chi \boldsymbol{B}$$



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

Weak coupling



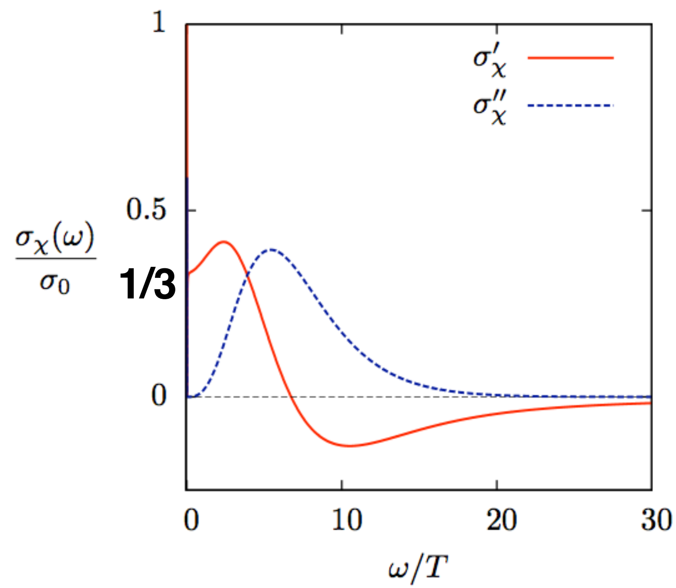
D.K., H. Warringa Phys Rev D80 (2009) 034028

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

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

CME out of equilibrium: chiral kinetic theory

CKT:
M. Stephanov, Y. Yin, PRL109(2012)162001;
J.W. Chen, S. Pu, Q. Wang, X.-N.Wang, PRL110(2013)262301;
J.W. Chen, T. Ishii, S. Pu, N. Yamamoto, PRD93(2016)125023; …



AC CME conductivity: why 1/3?

2/3 from Berry phase, 1/3 from energy shift – so at finite frequency expect 2/3 – what is the missing -1/3?

Magnetization current!

DK, M.Stephanov, H.-U.Yee.
arXiv:1612.01674; PRD’17

Hydrodynamics and symmetries

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

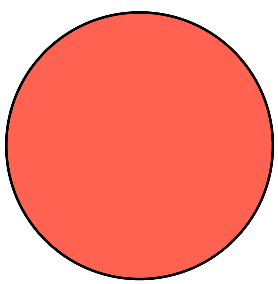
Son, Surowka; Landsteiner, Megias, Pena-Benitez; Sadofyev, Isachenkov; Kalaydzhyan, Kirsch; DK, Yee; Zakharov; Jensen, Loganayagam, Yarom; Neiman, Oz; ….

No entropy production from P-odd anomalous terms

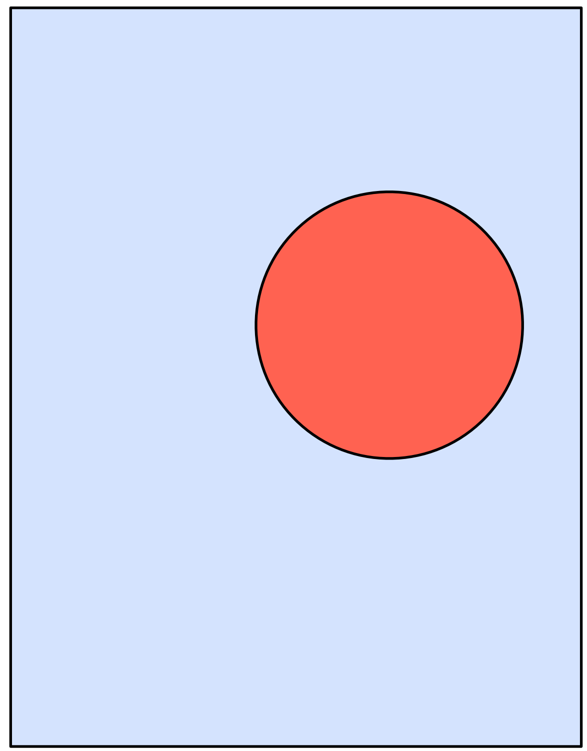
DK and H.-U. Yee, 1105.6360; PRD

Mirror reflection: entropy decreases ?

Entropy grows



$$\partial_\mu s^\mu \geq 0$$



$$\partial_\mu s^\mu \leq 0$$

Decrease is ruled out by 2nd law of thermodynamics

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

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

Systematics of anomalous conductivities

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

The CME in relativistic hydrodynamics: The Chiral Magnetic Wave

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

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

CME Chiral separation

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

Propagating chiral wave: (if chiral symmetry is restored)

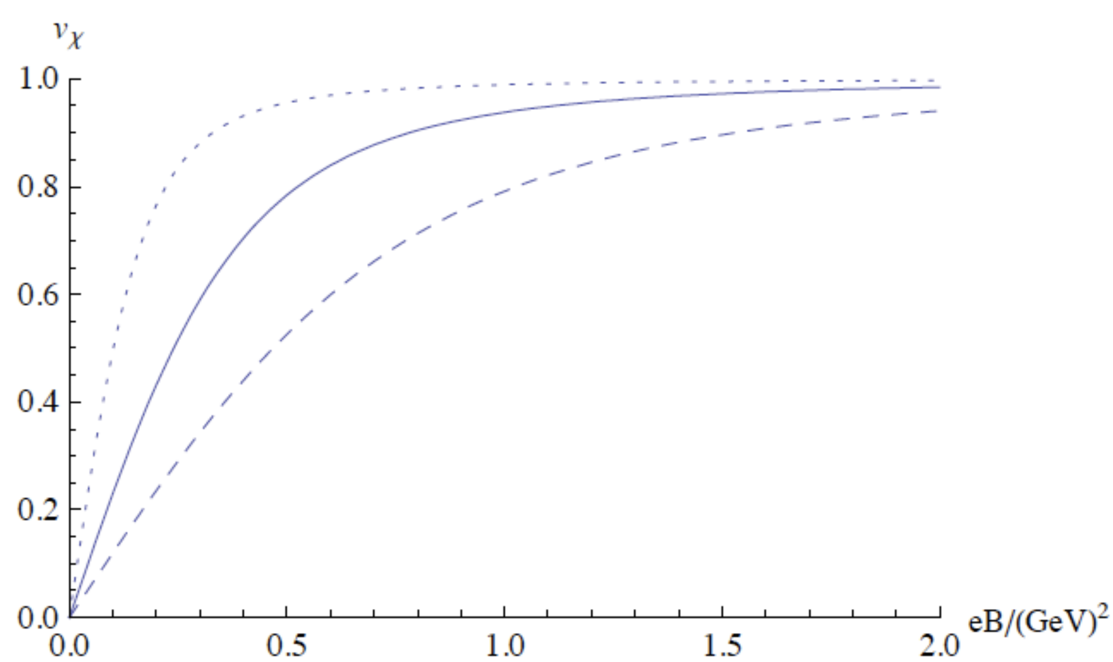
$$\left(\partial_0 \mp \frac{N_c e B \alpha}{2\pi^2}\partial_1 - D_L \partial_1^2\right) j^0_{L,R} = 0$$

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

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

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

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



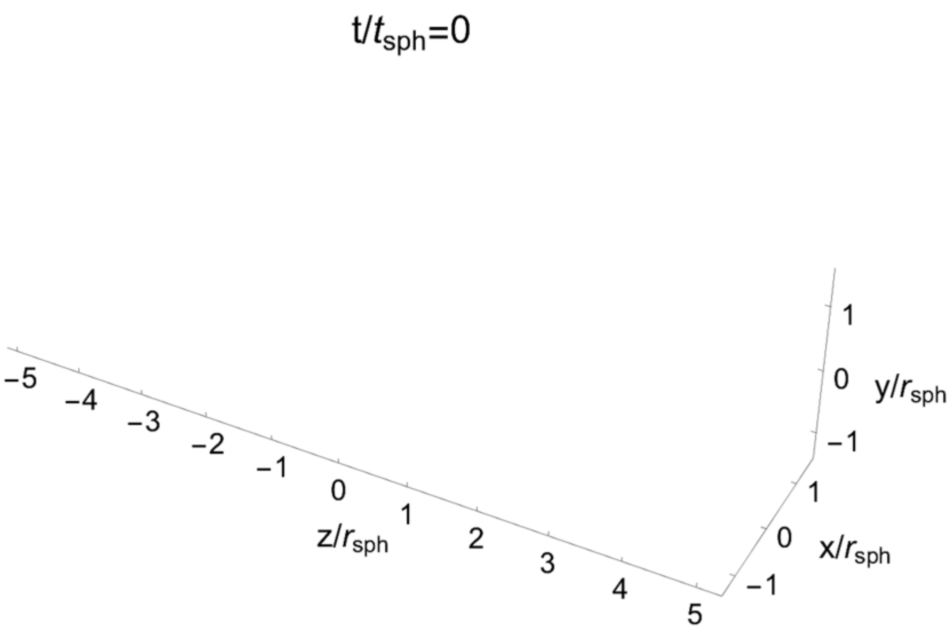
DK, H.-U. Yee, Phys Rev D'11

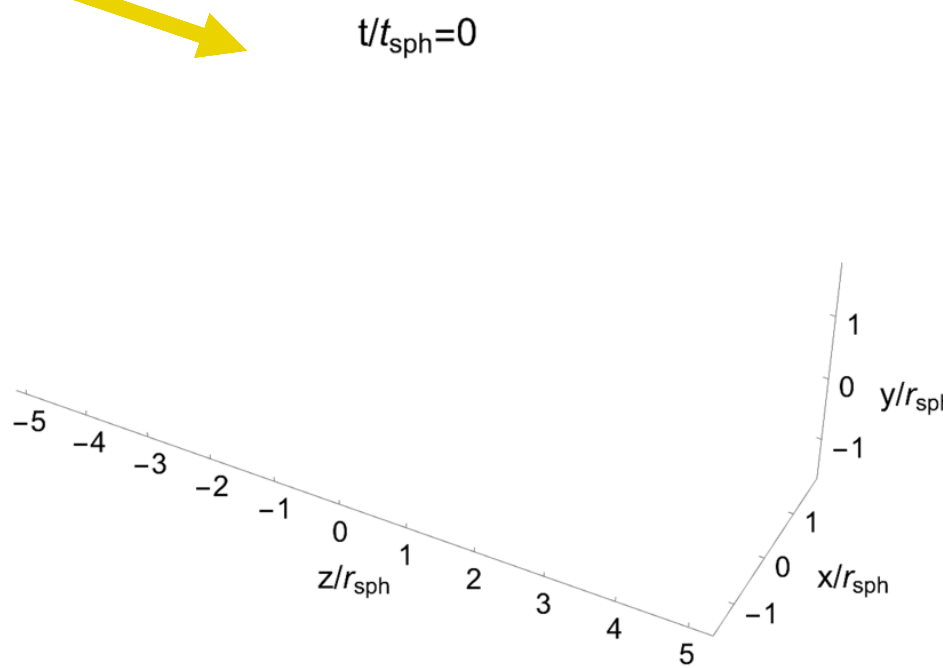
M. Mace, N. Mueller, S. Schlichting, S. Sharma, arxiv:1704.05887; PRD’17

Chiral Magnetic Wave in real time!

Anomalous transport in real time

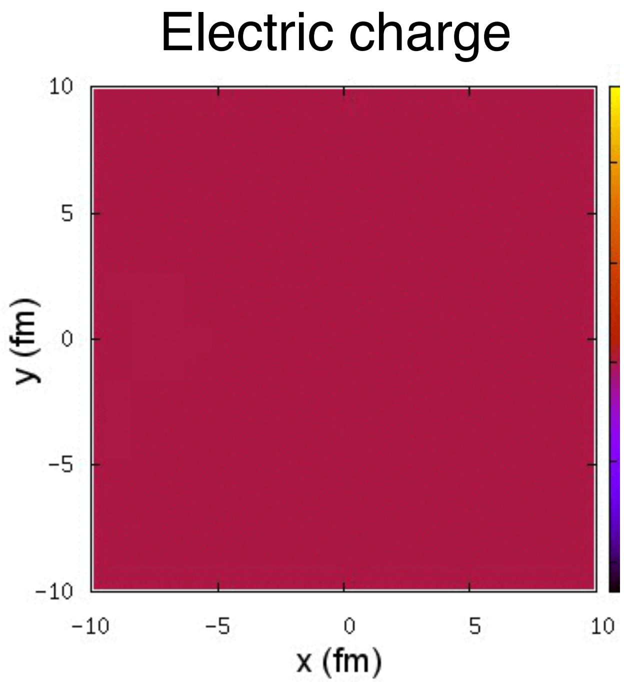
j_a^0:axial charge $\qquad\vec{B}\qquad$ j_v^0:vector charge

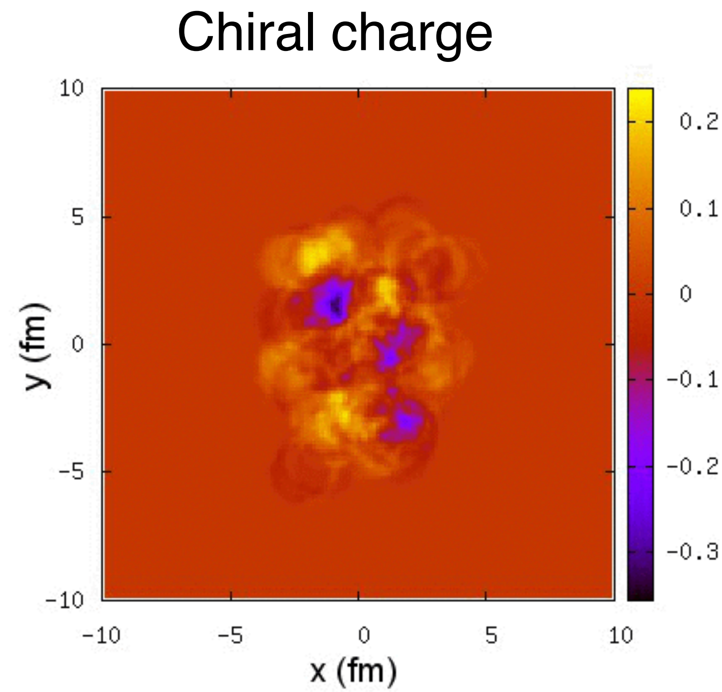




Static U(1) magnetic field in z-dir

Chiral Magnetohydrodynamics (CMHD)

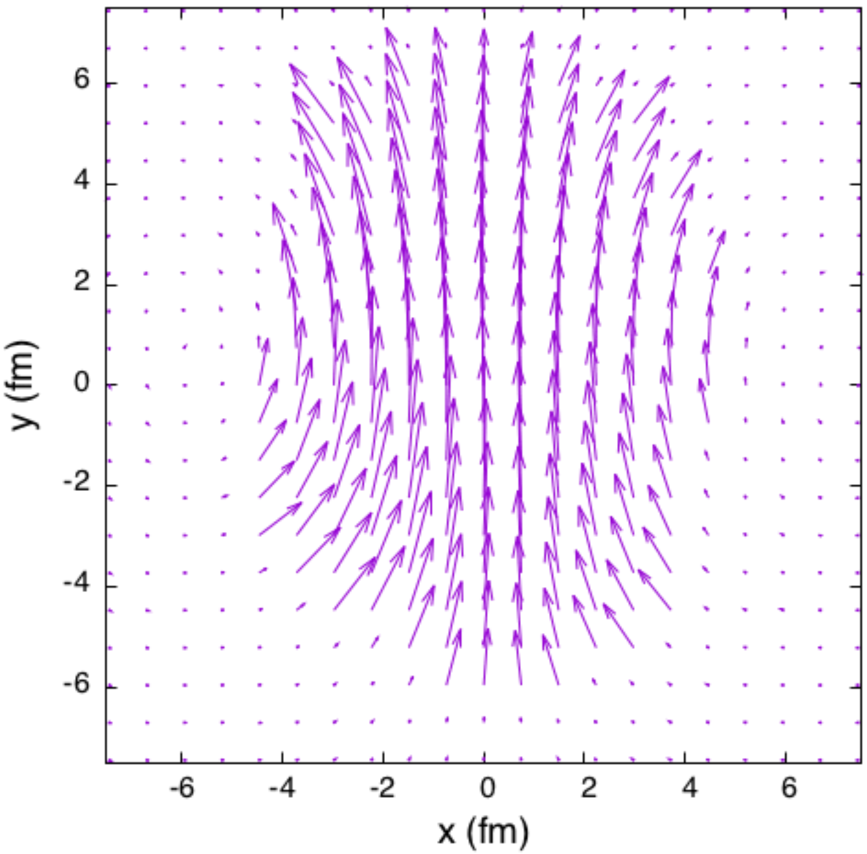




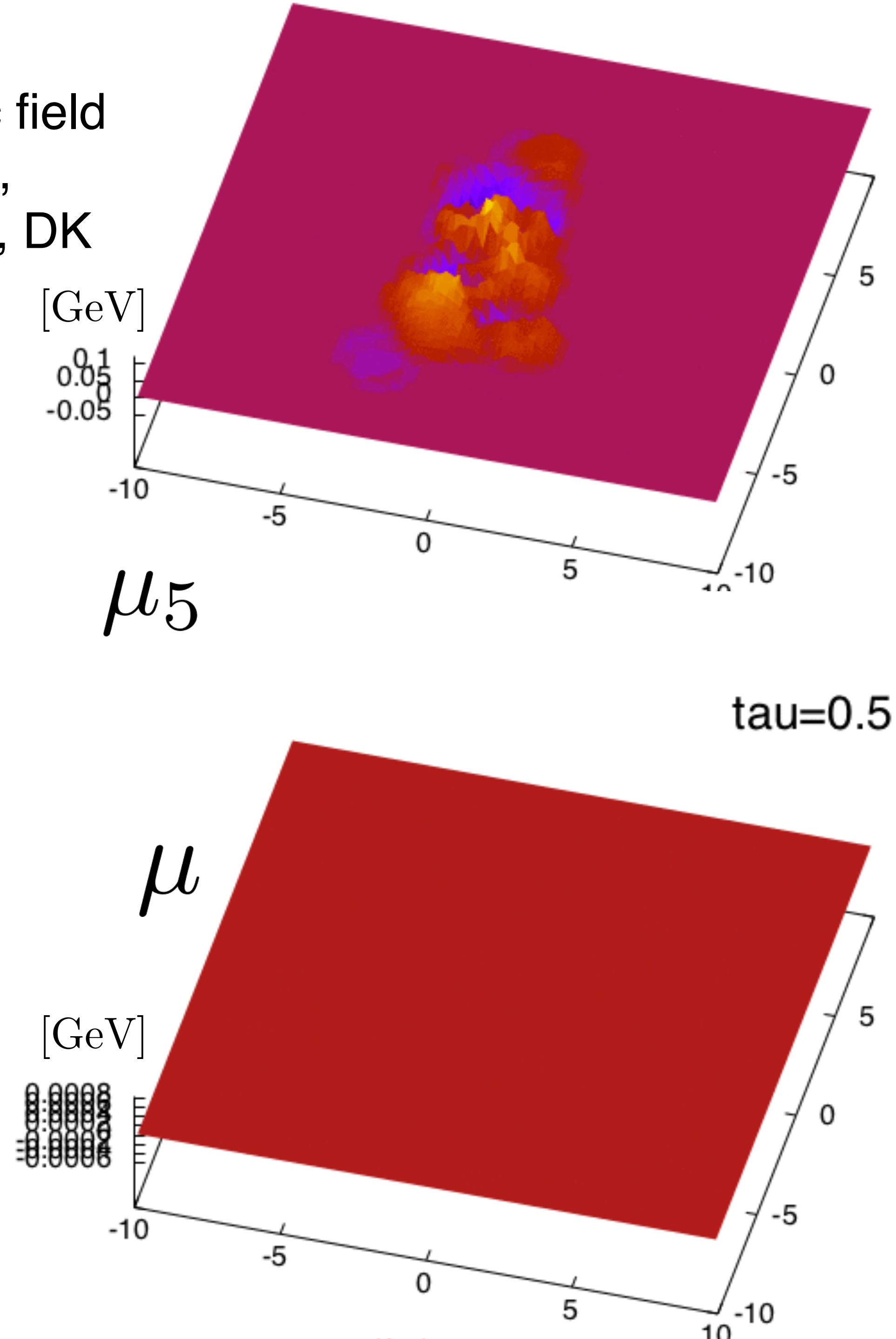
Y.Hirono, T.Hirano, DK, (Stony Brook – Tokyo), arxiv:1412.0311
(3+1) ideal CMHD (Chiral MagnetoHydroDynamics)

BEST Theory Collaboration (DOE)

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

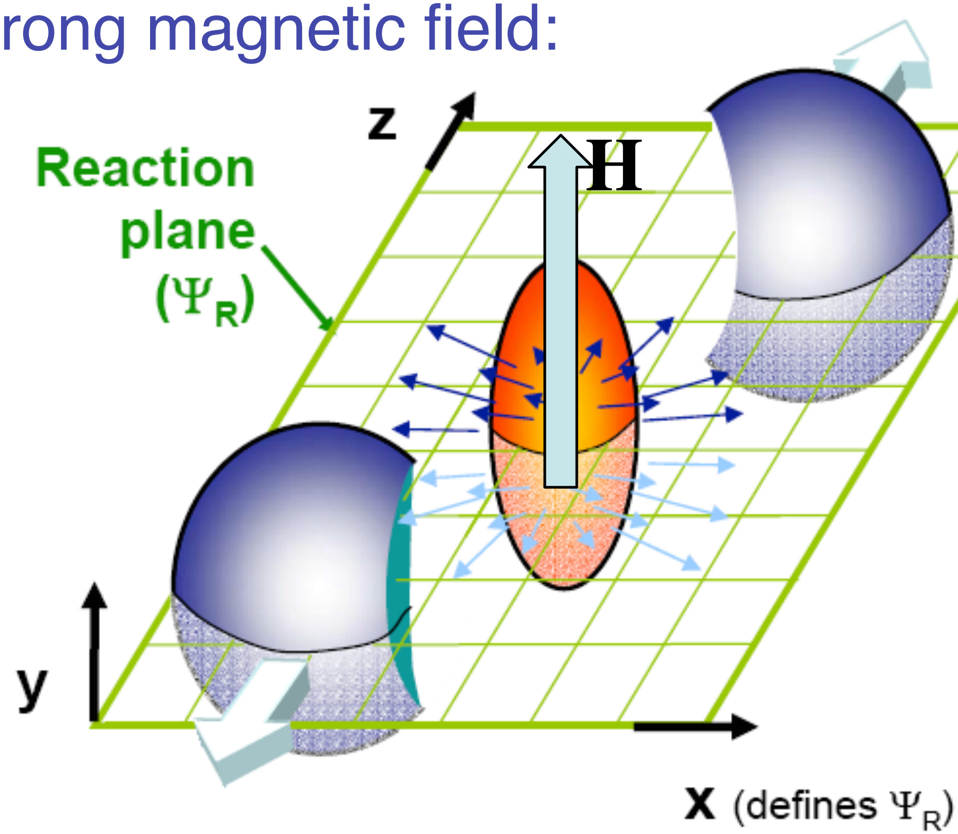


B field evolution
in transverse plane

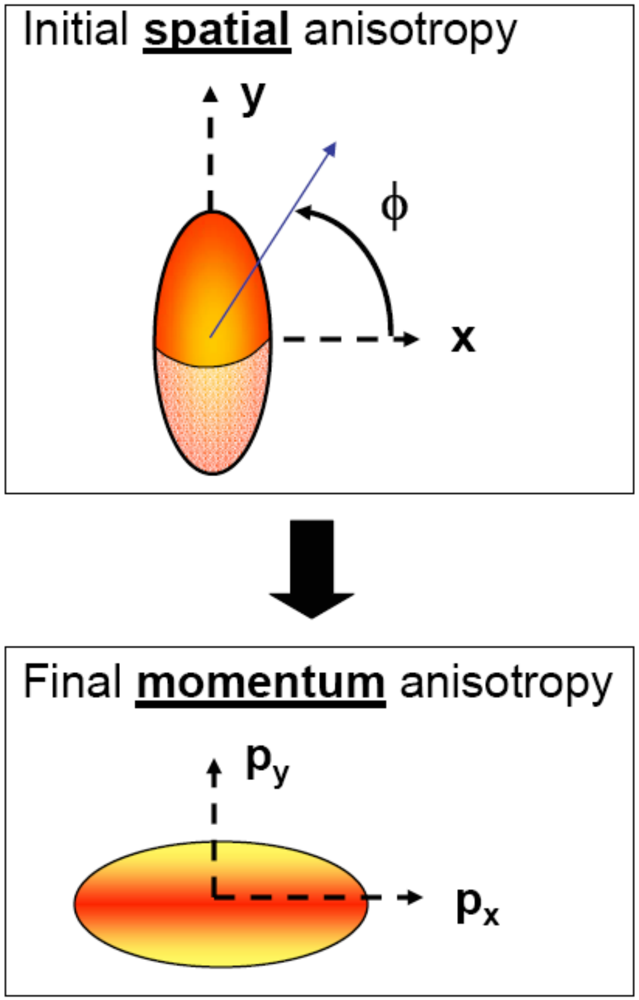


Is there a way to observe CME in nuclear collisions at RHIC and LHC?

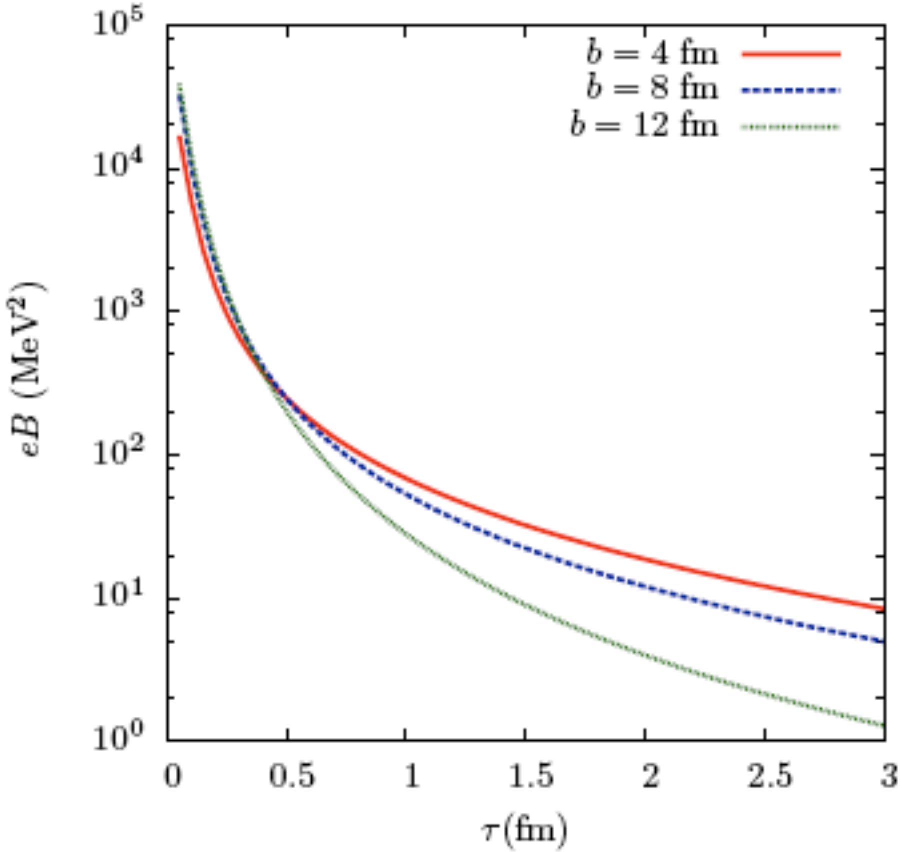
Relativistic ions create a strong magnetic field:



DK, McLerran, Warringa '07



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



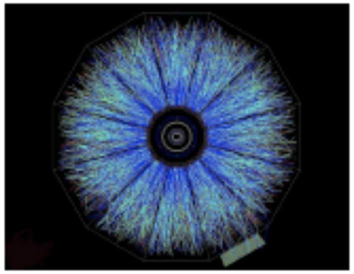
DK, McLerran, Warringa, Nucl Phys A803(2008)227

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

Comparison of magnetic fields

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

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



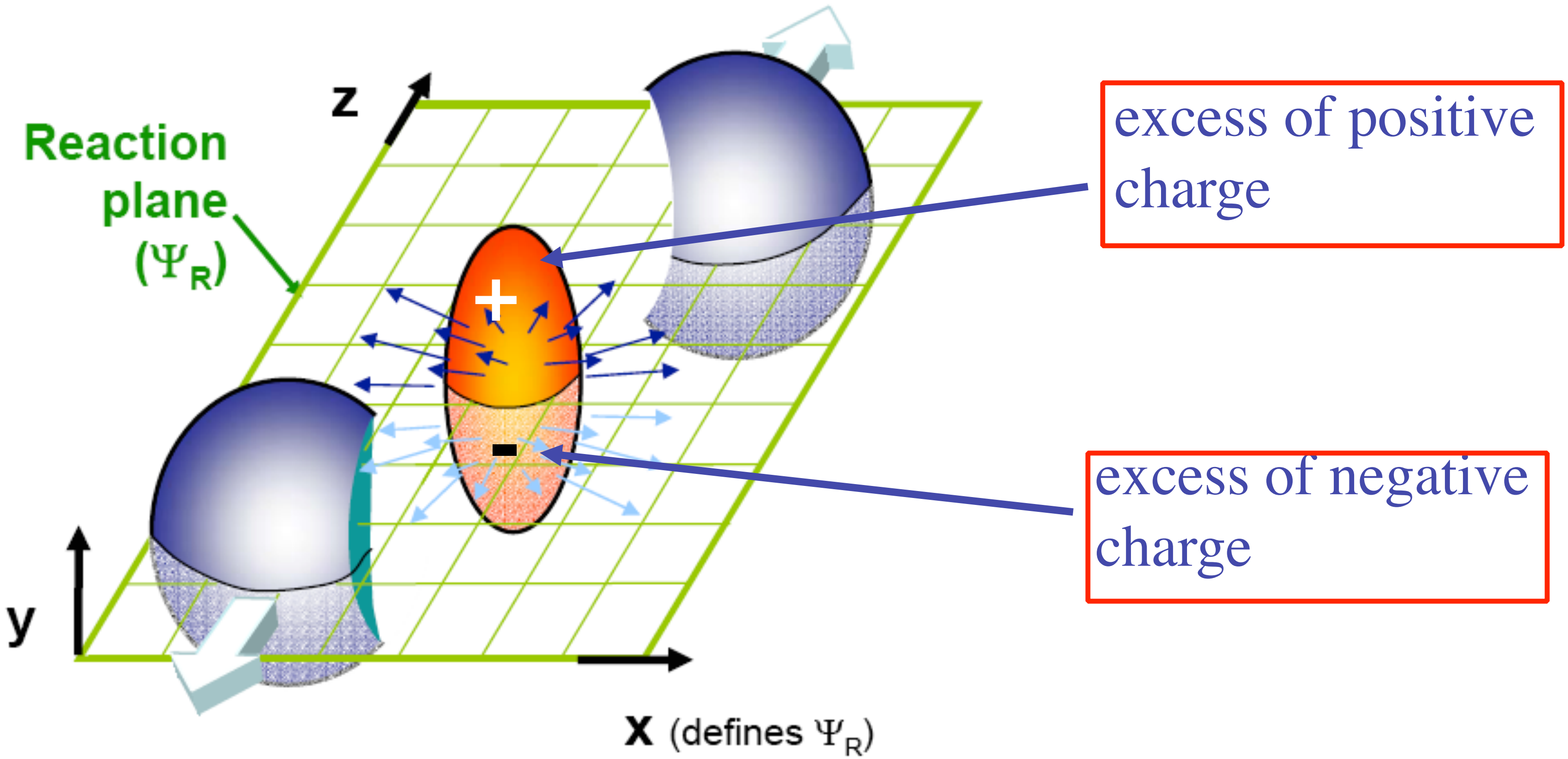
Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

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

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

Electric dipole moment due to chiral imbalance

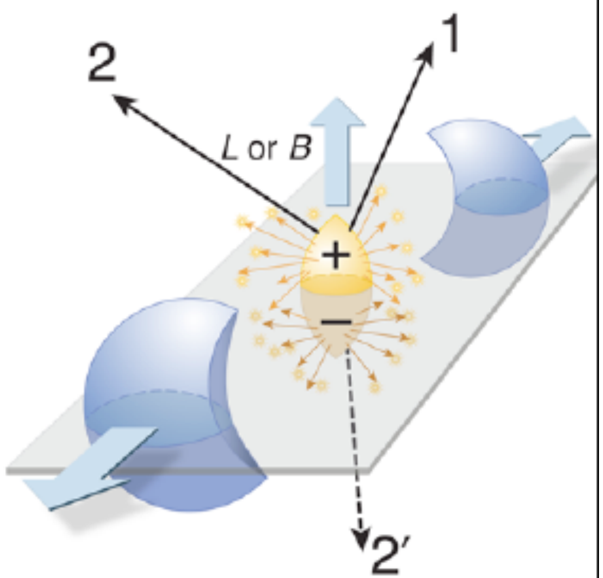


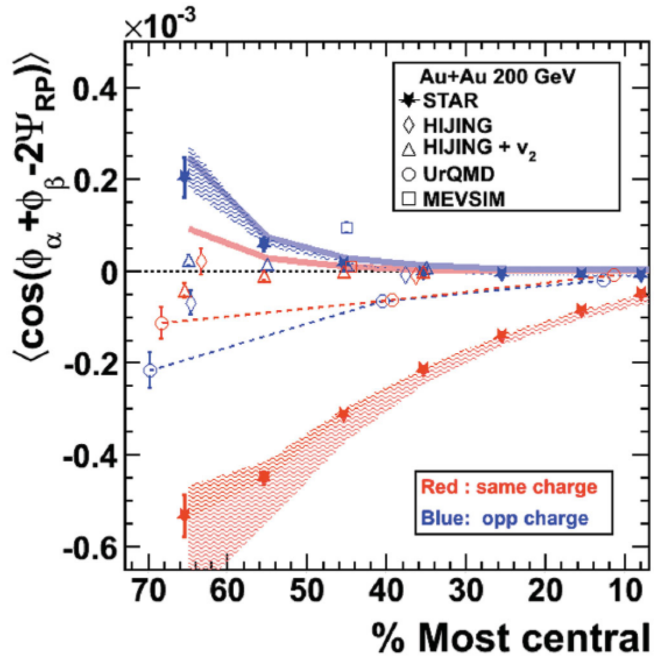
DK, hep-ph/0406125; Phys.Lett.B633(2006)260

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

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)





S.Voloshin ‘04

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

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

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

Observation of charge-dependent azimuthal correlations in pPb collisions and its implication for the search for the chiral magnetic effect

The CMS Collaboration*

arxiv:1610.00263
October 2, 2016

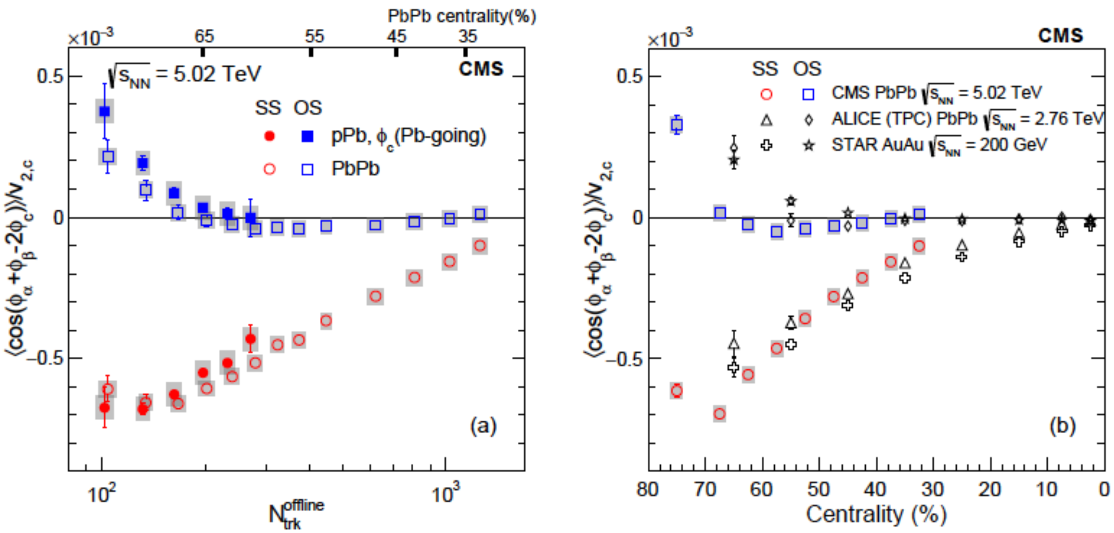


Figure 2: In (a), the same sign (SS) and opposite sign (OS) three-particle correlator averaged over $|\eta_\alpha - \eta_\beta| < 1.6$ as a function of $N_{trk}^{offline}$ in pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown. In (b), the same correlation as a function of centrality is presented in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from CMS, at $\sqrt{s_{NN}} = 2.76$ TeV from ALICE, and in AuAu collisions at $\sqrt{s_{NN}} = 0.2$ TeV from STAR. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

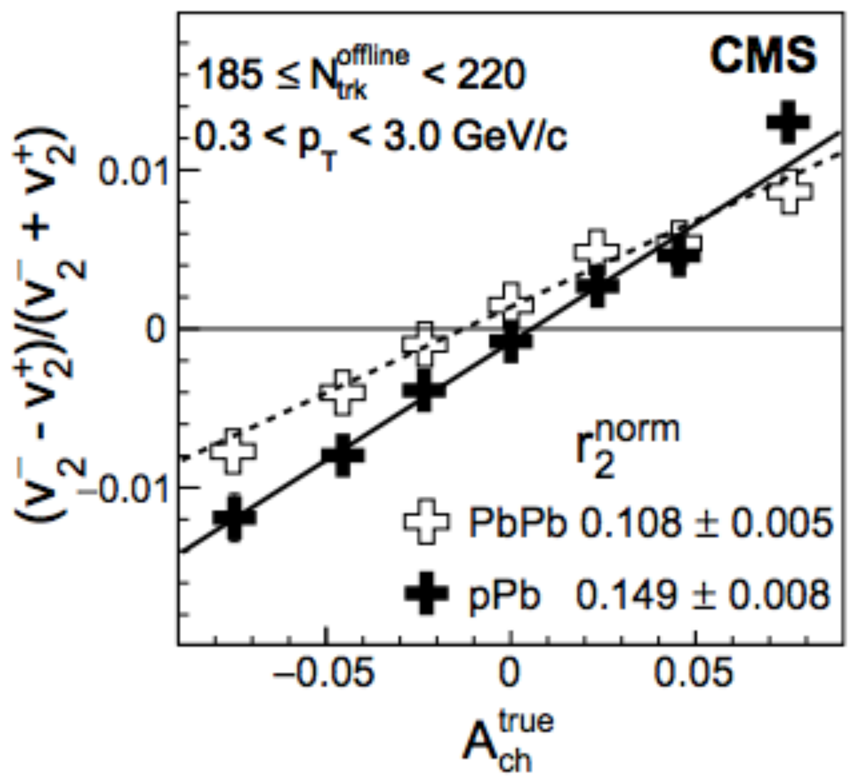
Background everywhere?
(dAu at RHIC!)

Magnetic field in pA?

Challenges to the chiral magnetic wave using charge-dependent azimuthal anisotropies in pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration*

arXiv:1708.08901



Important data that challenges all existing theoretical models!

Is there a way to get a conclusive answer?

Chiral Magnetic Effect Task Force Report

Vladimir Skokov (co-chair),[1,*] Paul Sorensen (co-chair),[2,†] Volker Koch,[3]
Soeren Schlichting,[2] Jim Thomas,[3] Sergei Voloshin,[4] Gang Wang,[5] and Ho-Ung Yee[6,1]

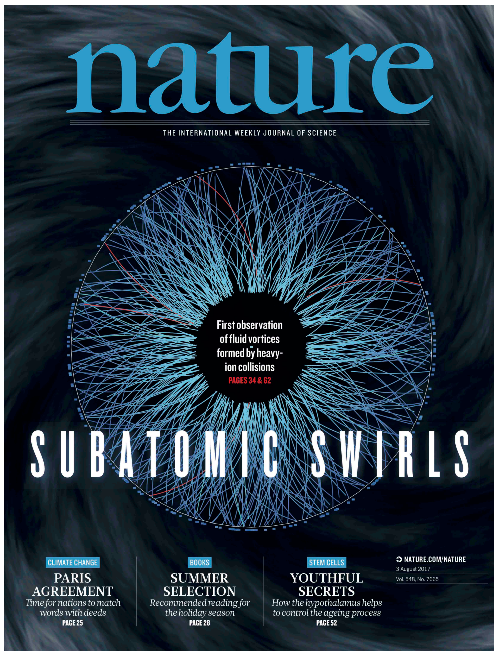
arxiv:1608.00982

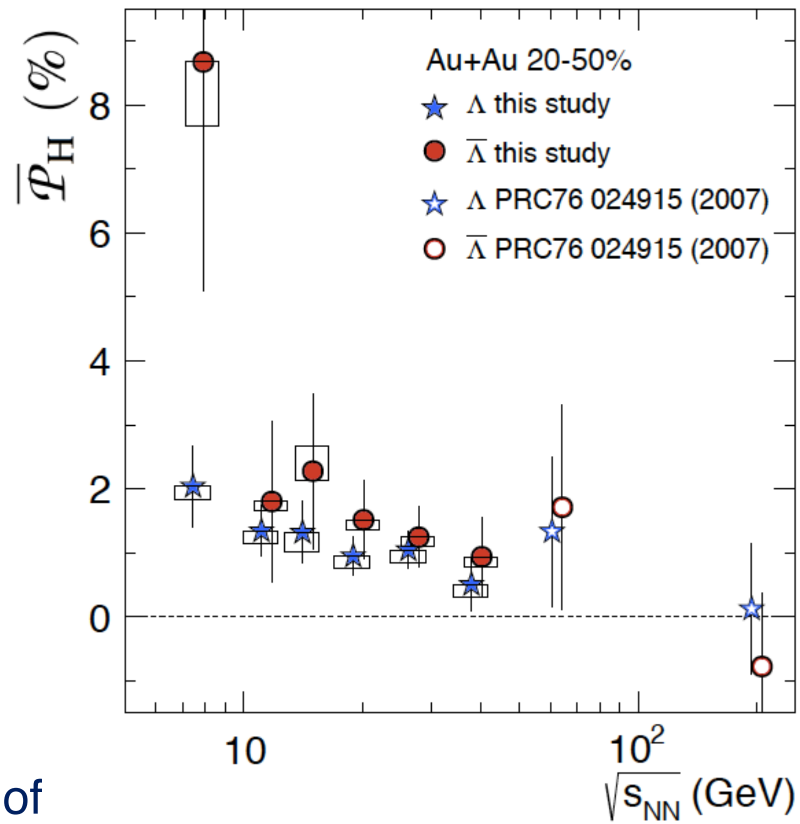
The unique identification of the chiral magnetic effect in heavy-ion collisions would represent one of the highlights of the RHIC physics program and would provide a lasting legacy for the field. The current plan for completing the RHIC mission envisions a second phase of RHIC. **We have specifically investigated the case for colliding nuclear isobars (nuclei with the same mass but different charge) and find the case compelling. We recommend that a program of nuclear isobar collisions to isolate the chiral magnetic effect from background sources be placed as a high priority item in the strategy for completing the RHIC mission.**

Approved dedicated Spring 2018 CME run at RHIC with Zr (Z=40), Ru (Z=44) isobars – a clear, "yes or no" answer

The effect of vorticity: Λ polarization

STAR Coll., Nature 2017





The vorticity has to survive till hadronization.

The difference in the polarization of Λ and anti-Λ ?

Hint at magnetic field $B \sim 0.01\ (M_\pi)^2$ at hadronization

e.g. F.Beccatini et al, arXiv:1610.02506, PRC'17

Vortical susceptibility of QCD matter:

$$\langle \sigma_z \rangle = \frac{\langle \bar{\Psi} \sigma_{xy} \gamma_5 \Psi \rangle}{\langle \bar{\Psi} \Psi \rangle} = \frac{N_c}{\pi^2 f_\pi^2}\, \mu\ \Omega_z$$

A.Aristova, D.Frenklakh, A.Gorsky, DK, 1606.05882; JHEP

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)

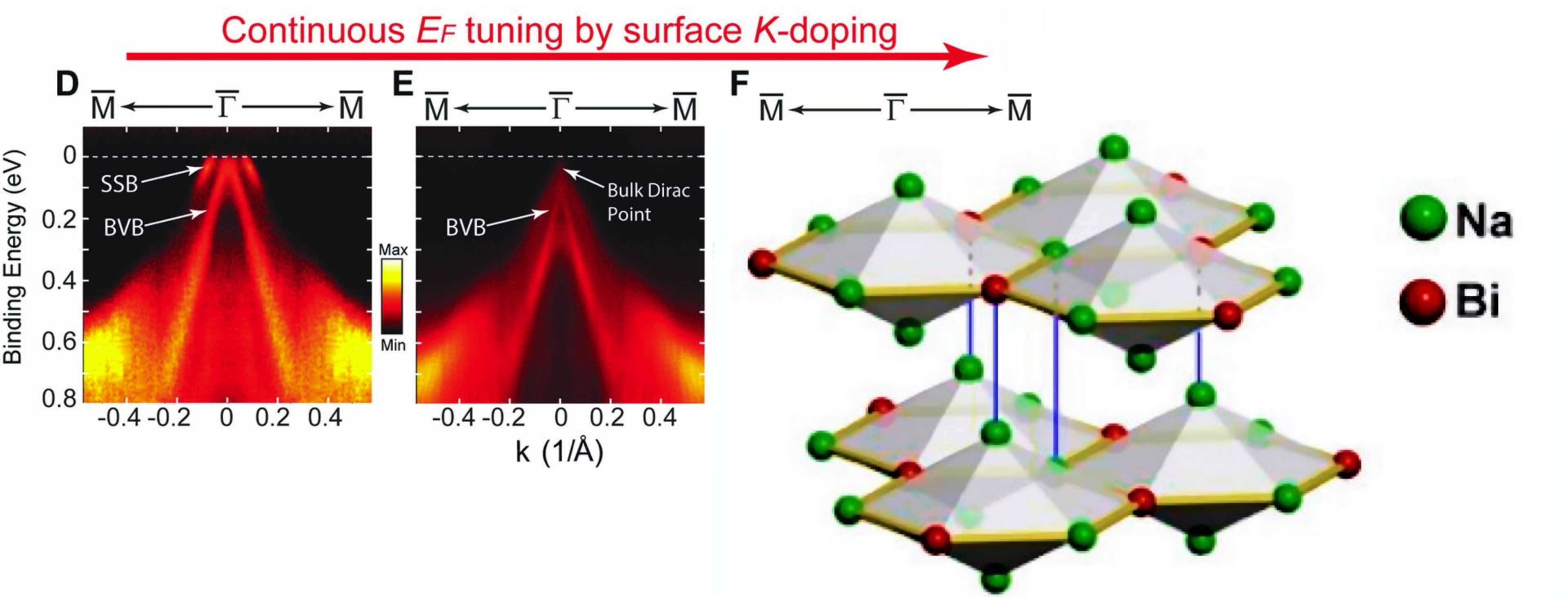
The question of the possible existence of substances having an electron spectrum without any energy gap and, at the same time, not possessing a Fermi surface is investigated. First of all the question of the possibility of contact of the conduction band and the valence band at a single point is investigated 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 and Weyl semimetals – 3D chiral materials



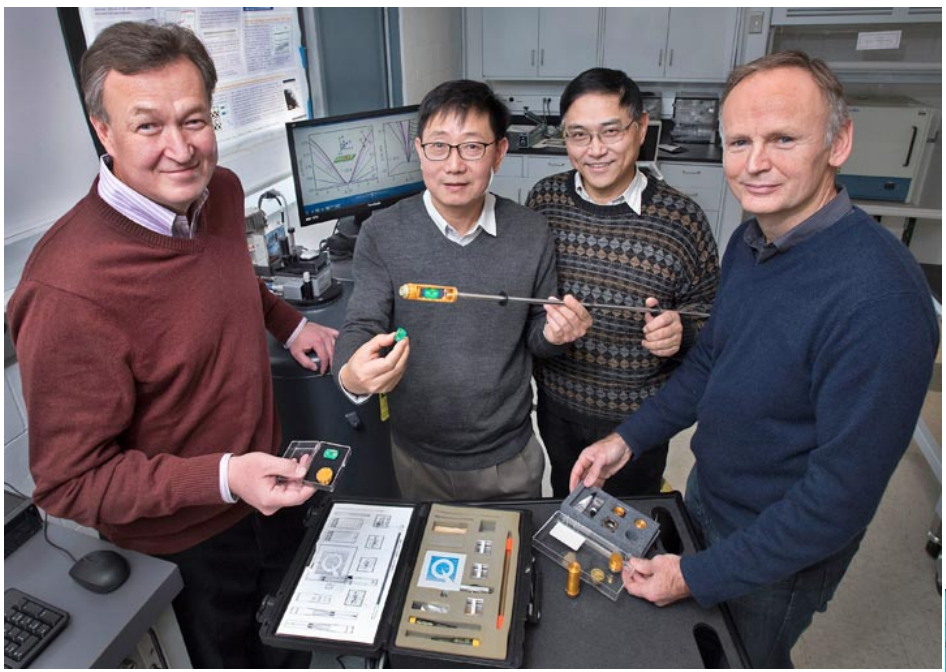
Z.K.Liu et al., Science 343 p.864 (**Feb 21, 2014**)

CME in condensed matter:

Observation of the chiral magnetic effect in $ZrTe_5$

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

BNL - Stony Brook - Princeton - Berkeley



Nature Phys. 12 (2016) 550

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

Observation of the chiral magnetic effect in $ZrTe_5$

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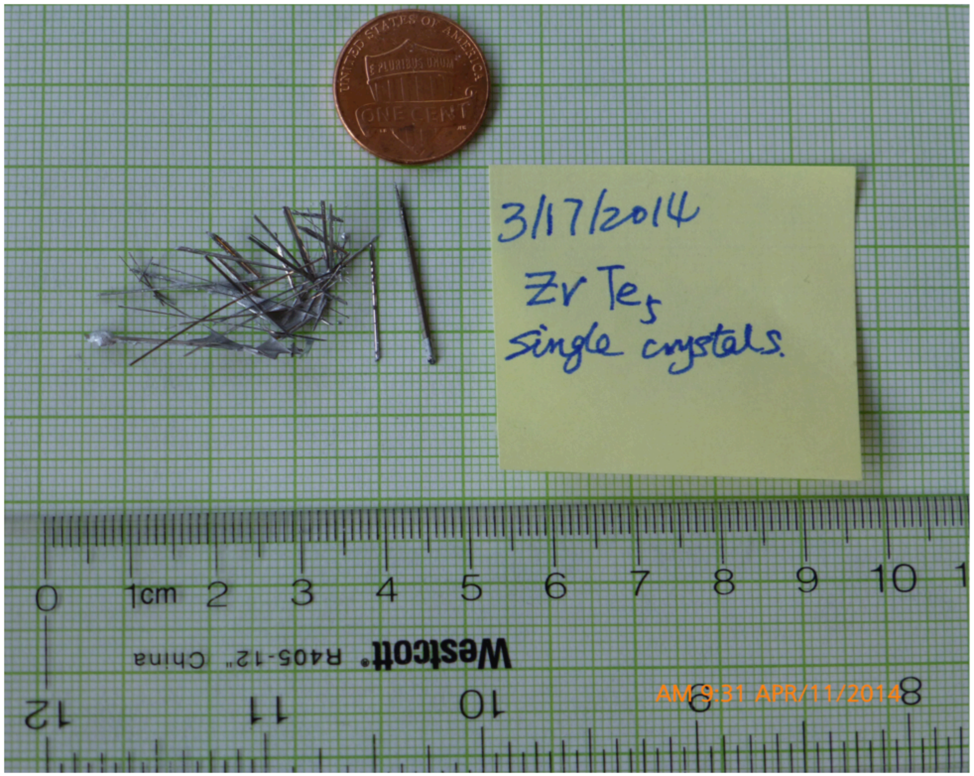

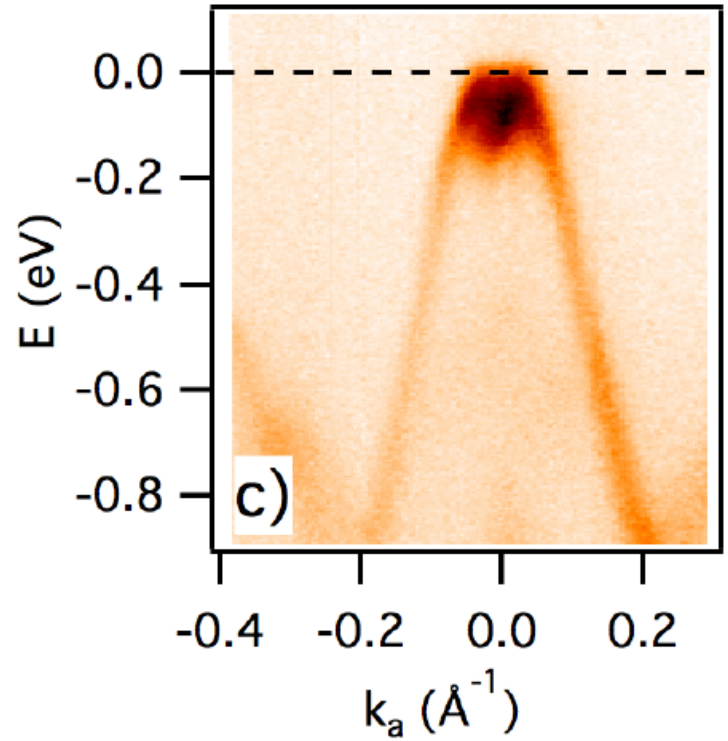

arXiv:1412.6543 (December 2014); Nature Physics **12**, 550 (2016)

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

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

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

and thus the chiral chemical potential:

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

Observation of the chiral magnetic effect in $ZrTe_5$

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

so that there is a chiral magnetic current:

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

resulting in the quadratic dependence of CME conductivity on B:

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

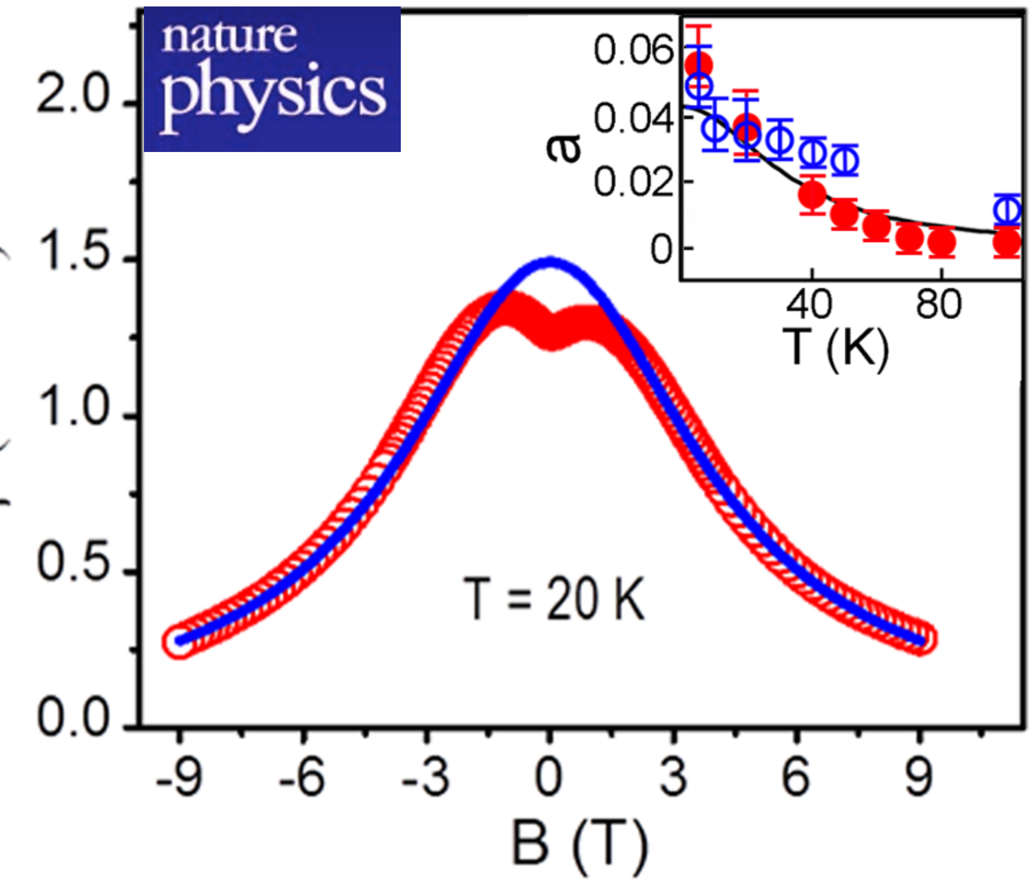
adding the Ohmic one – negative magnetoresistance

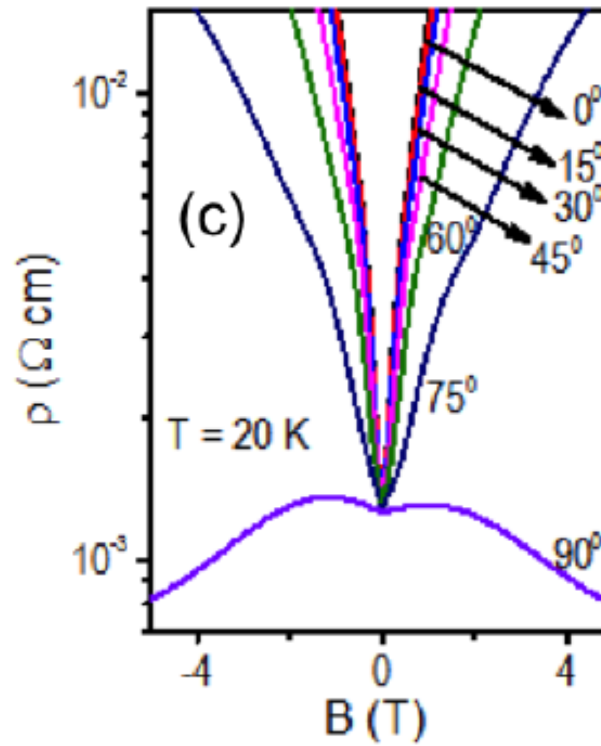
Chiral Magnetic Effect Generates Quantum Current

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

February 8, 2016

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



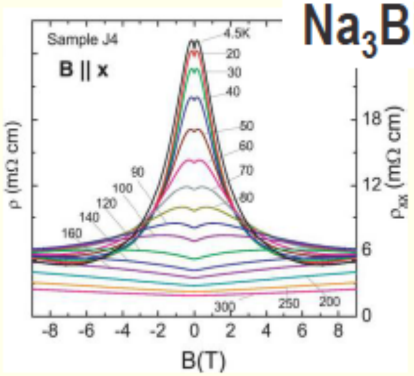


Qiang Li's Distinguished CQM lecture at Simons Center, Feb 19, 2016
on video:
http://scgp.stonybrook.edu/video_portal/video.php?id=2458

Chiral magnetic effect in Dirac/Weyl semimetals

Dirac semimetals:

Na_3Bi



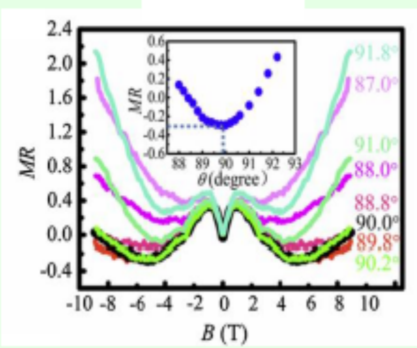
$ZrTe_5$ - Q. Li, D. Kharzeev, et al (BNL and Stony Brook Univ.) arXiv:**1412.6543**; doi:10.1038/NPHYS3648

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

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

Weyl semimetals

TaAs



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

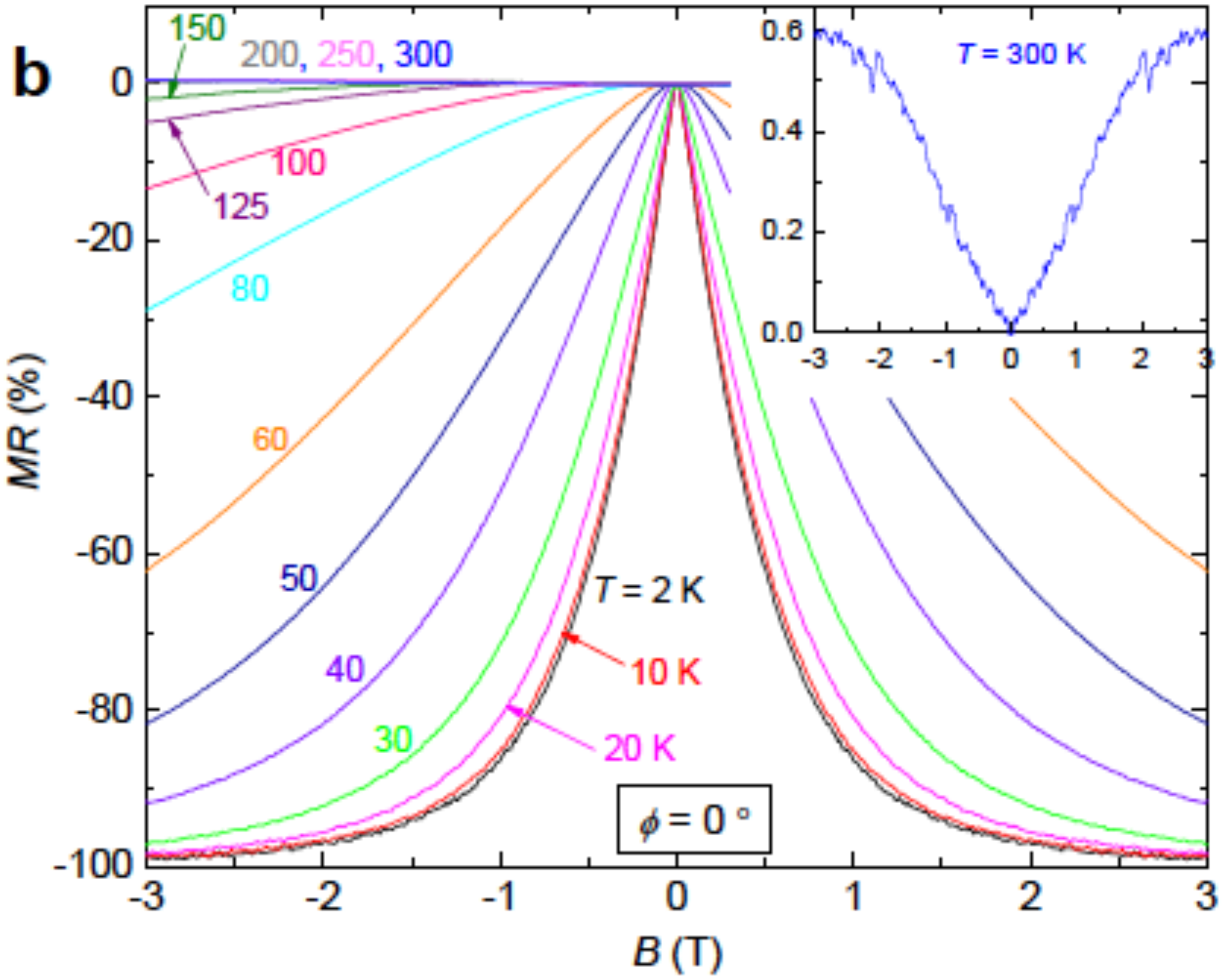
NbAs - X. Yang et al (Zhejiang Univ. China) arxiv:**1506.02283**

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

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

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

Negative MR in $TaAs_2$



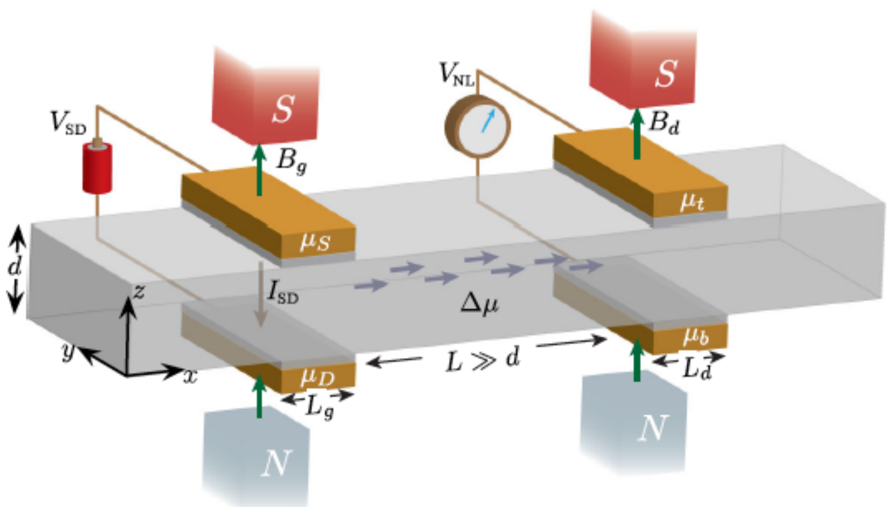
Y.Luo et al, 1601.05524

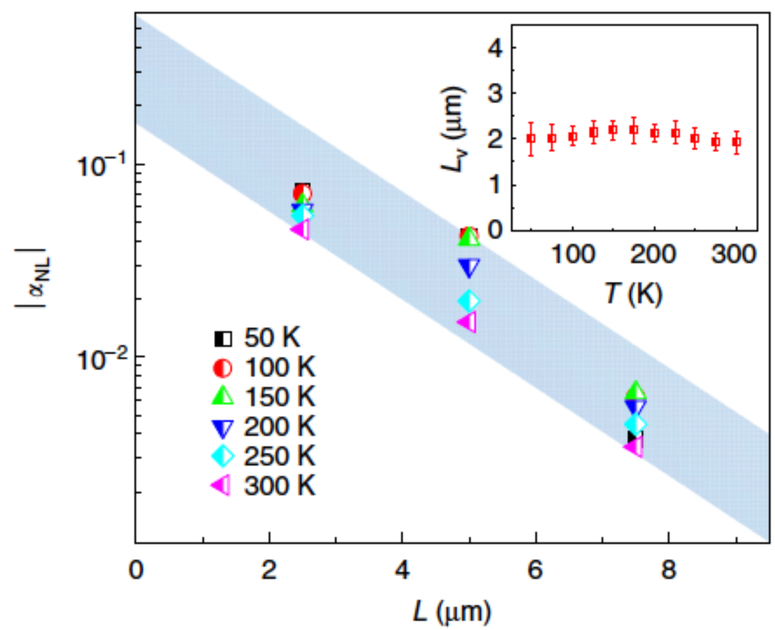
Towards the room temperature CME

Nonlocal chiral transport

C.Zhang et al, Nature Comm.'17
DOI: 10.1038/ncomms13741

S.Parameswaran, T.Grover,
D.Abanin, D.Pesin, A.Vishwanath
PRX4, 031035 (2014)





$$|V_{\rm NL}(x)| \propto V_{\rm SD}\, e^{-\frac{L}{L_V}}$$

CME as a new type of superconductivity

Fritz and Heinz London

London theory of superconductors, '35:

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

$$\vec{\mathbf{E}} = -\dot{\vec{\mathbf{A}}}$$

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

CME:

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

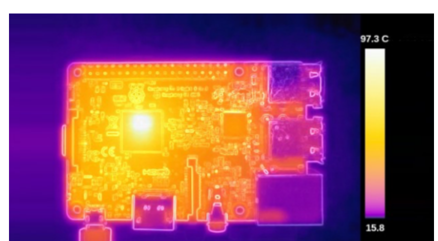
consider a micro-device of O(μm) size, so that Chirality is conserved; then

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

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

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

superconducting current, tunable by magnetic field!



DK, arXiv:1612.05677

Chiral photonics

Faraday rotation due to surface states in $(Bi_{1-x}Sb_x)_2Te_3$ topological insulator

Y. M. Shao[1,*], K. W. Post,[1], J. S. Wu[1], S. Dai[1], A. J. Frenzel[1], A. R. Richardella[2], J. S. Lee[2], N. Samarth[2], M. M. Fogler[1], A. V. Balatsky[3,4], D. E. Kharzeev[5,6] and D. N. Basov[1]

[1]*Physics Department, University of California-San Diego, La Jolla, California 92093, USA*

[2]*Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA*

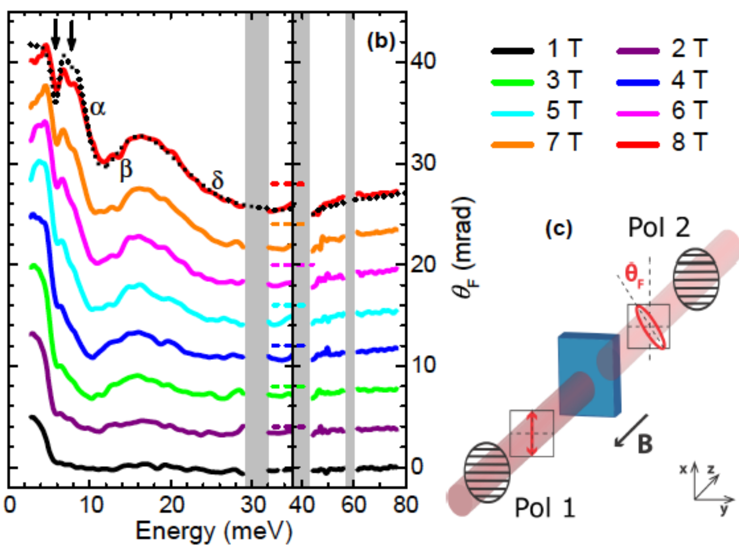
[3]*Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, SE-106 91 Stockholm, Sweden*

[4]*Institute for Materials Science, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

[5]*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA*

[6]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA*

Nano Letters, 2017



Response of surface states grows linearly in B (chiral anomaly)

$$\vec{\nabla} \cdot \vec{E} = \rho + c\vec{P} \cdot \vec{B}$$

Rotation of light polarization on axion domain walls in the Universe?

currents from time-dependent axion fields?

PUPT-2535

Detection of sub-MeV Dark Matter with Three-Dimensional Dirac Materials

Yonit Hochberg[1,2], Yonatan Kahn[3], Mariangela Lisanti[3], Kathryn M. Zurek[4,5], Adolfo G. Grushin[6,7], Roni Ilan[8], Sinéad M. Griffin[6,9], Zhen-Fei Liu[6,9], Sophie F. Weber[6,9], and Jeffrey B. Neaton[6,9,10,11]

arXiv:1708.08929

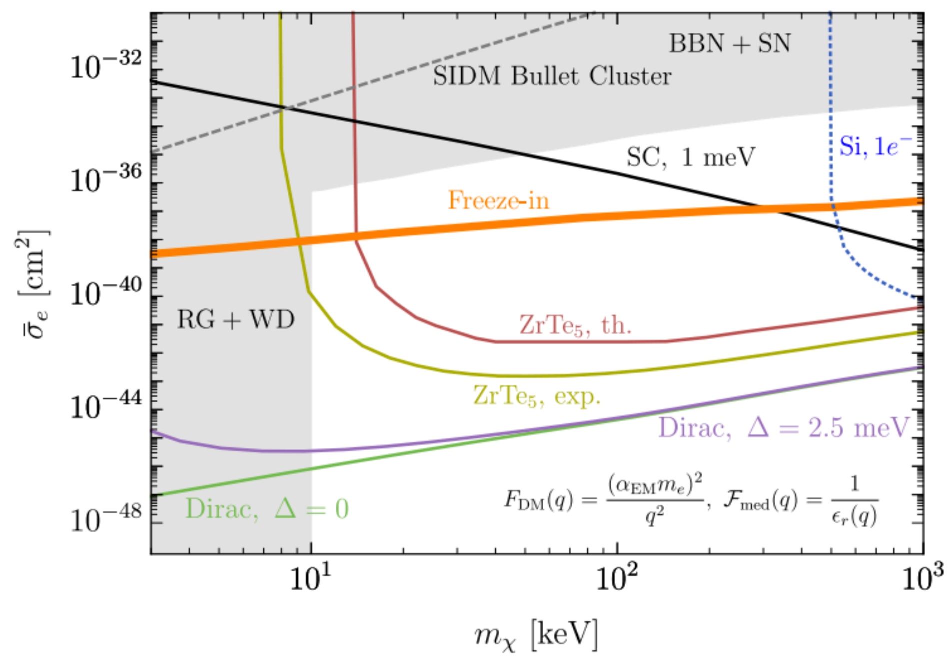


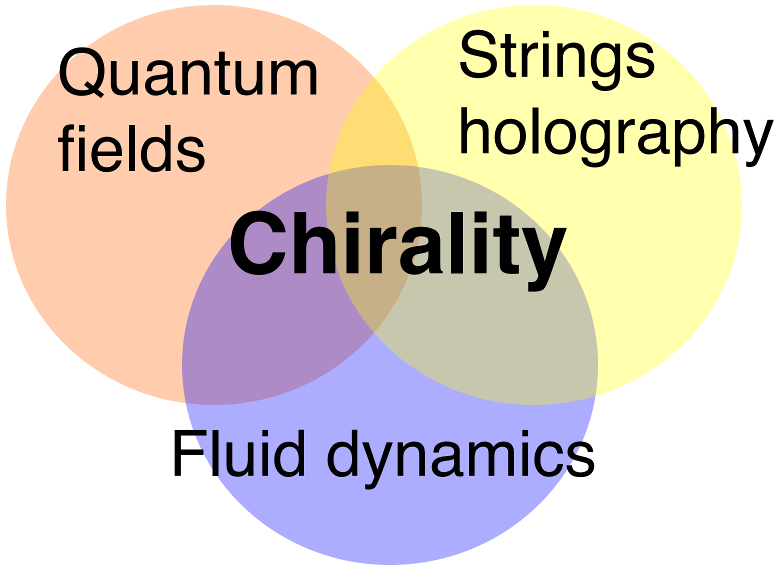
Figure 4: Projected reach of dark matter scattering in Dirac materials through a light kinetically mixed dark photon mediator with in-medium effects included. We show the expected background-free 95% C.L. sensitivity (3.0 events) that can be obtained with 1 kg-yr exposure. For the two

Summary

Nuclear physics

Particle physics

Cosmology



Biophysics

Condensed matter physics

Real-world applications

Reviews:

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

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

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

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