Symposium on Contemporary QCD Physics and Relativistic Nuclear Collisions

in honor of Jean-Paul Blaizot, Miklos Gyulassy, and Larry McLerran

CCNU, Wuhan, November 10-11, 2019

The Chiral Magnetic Effect:

from heavy ions to quantum computers

Dmitri Kharzeev

BEST COLLABORATION

Center for Frontiers in Nuclear Science

CQM Center for Quantum Materials

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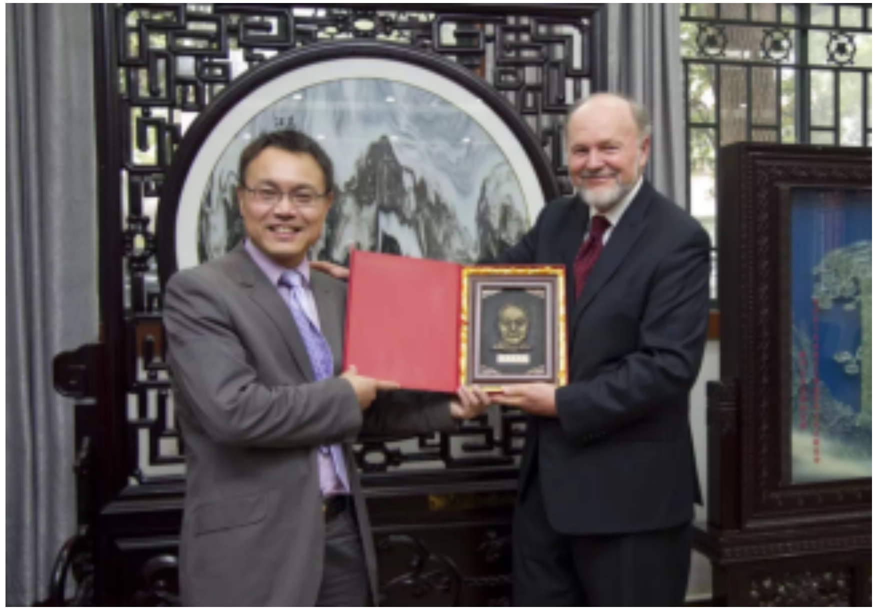
Jean-Paul

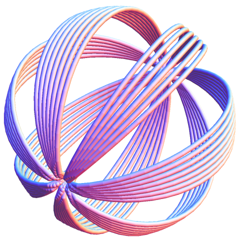
Miklos



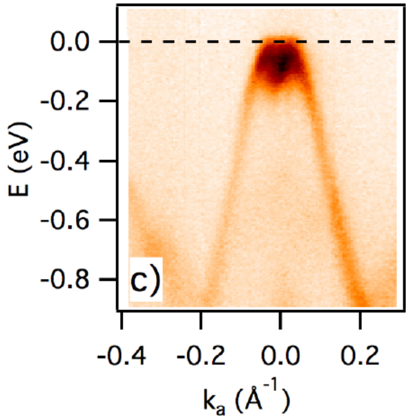
Larry

Alice

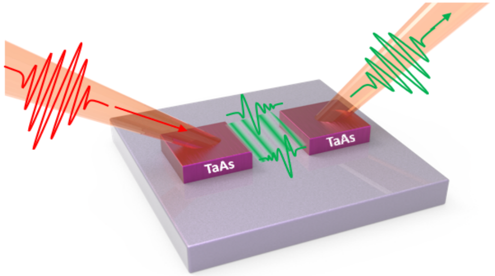
The Chiral Magnetic Effect
en trois services:



1. Fundamental chiral fermions
   - Heavy ion collisions
   - Early Universe: baryogenesis, helical magnetogenesis



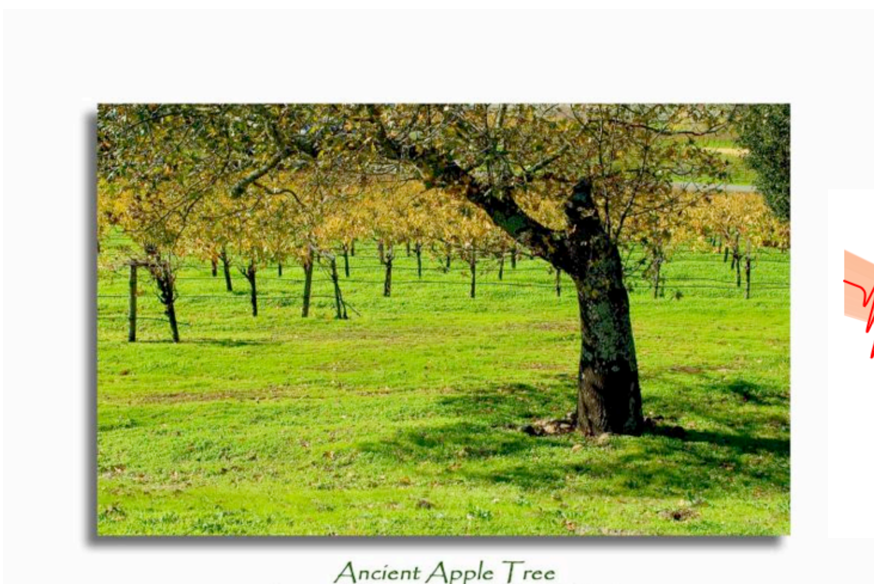
2. Emergent chiral fermions
   - 3D chiral materials: Dirac, Weyl, … semimetals
3. Applications to quantum computing
   - The "chiral qubit"

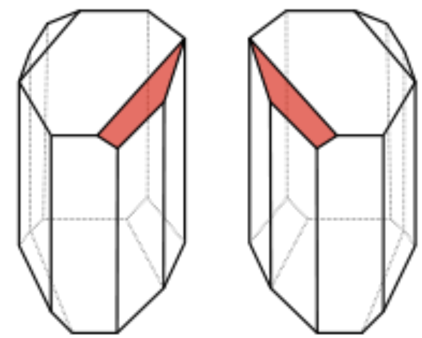


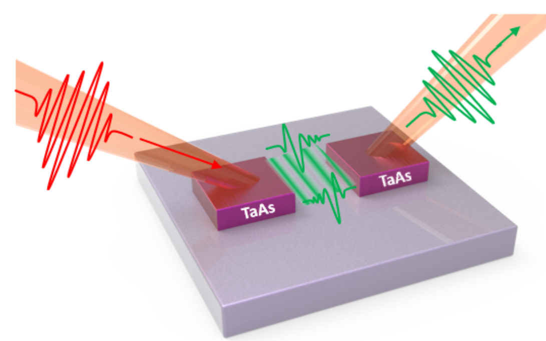
CME: “fundamental” and “applied”

There is no such thing as a special category of science called applied science; there is science and its applications, which are related to one another as the fruit is related to the tree that has borne it.

Louis Pasteur







Topological number fluctuations in non-Abelian expanding plasmas:

baryogenesis in the Early Universe

chiro-genesis in heavy ion collisions

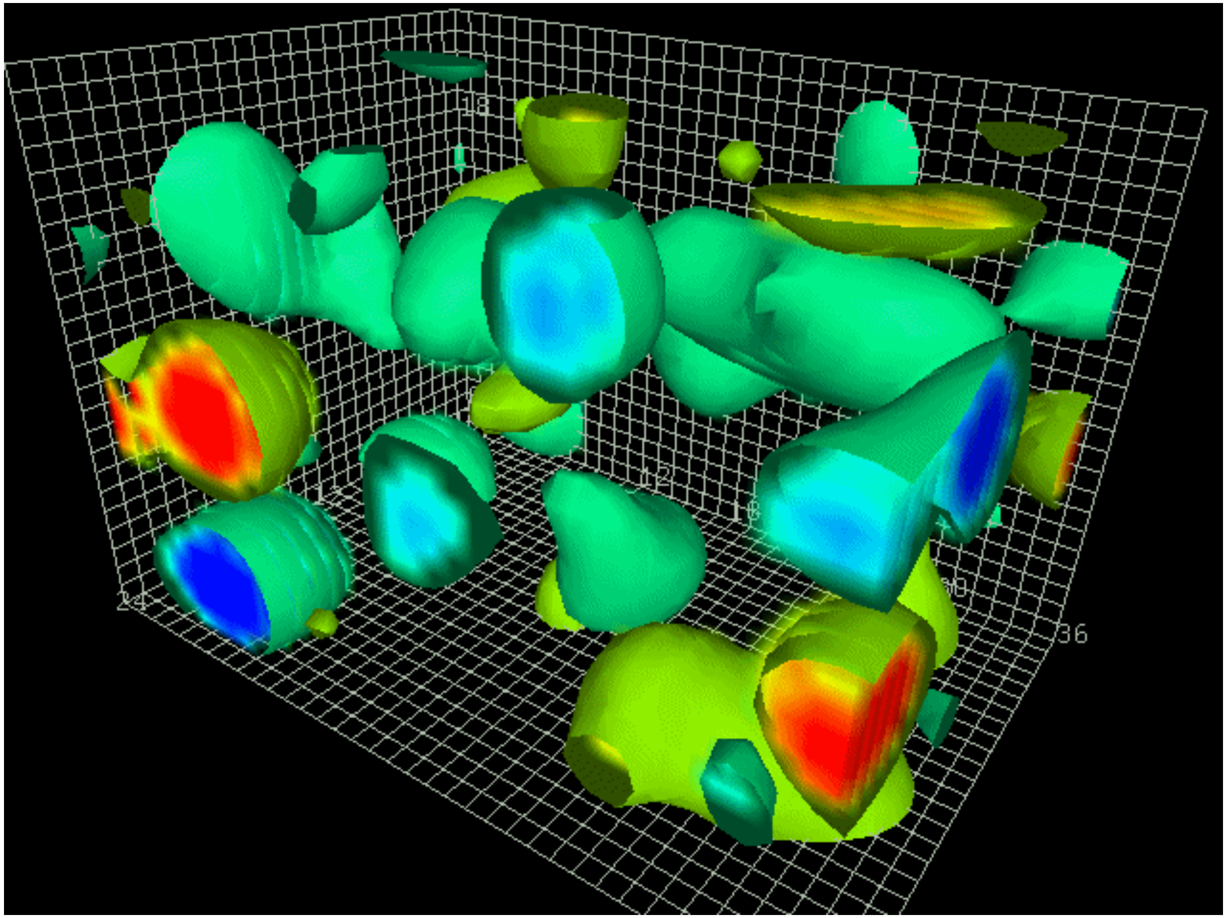
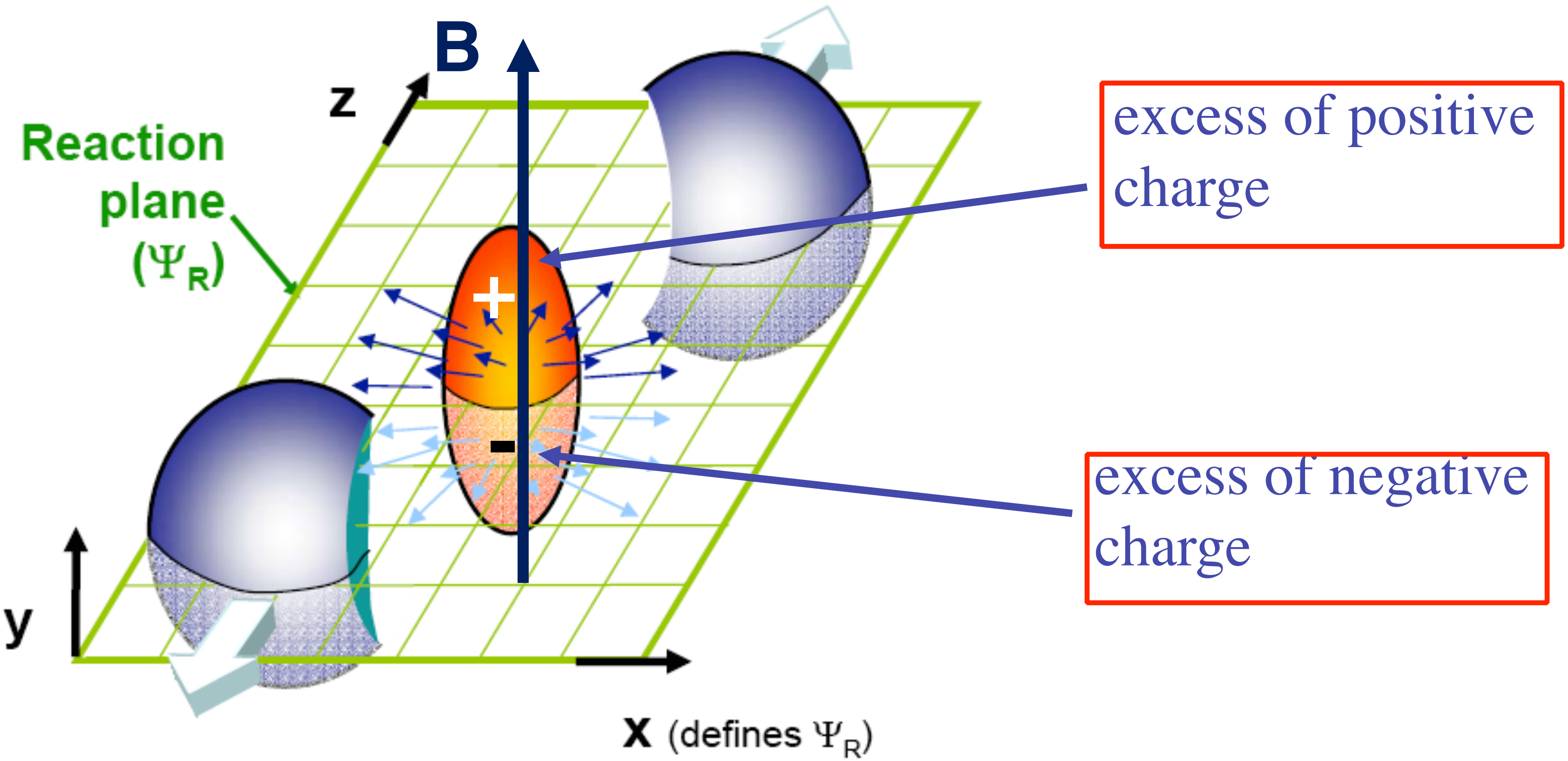


Image: D. Leinweber

Charge separation in a magnetic field as a signature of topological transitions in QCD matter

Electric dipole moment due to chiral imbalance



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

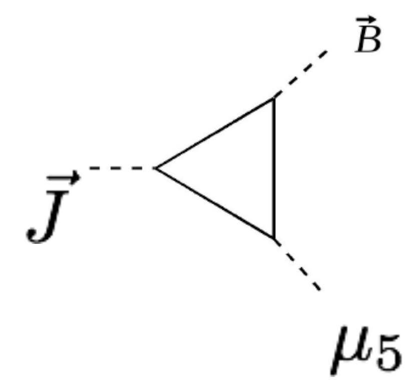
Chiral Magnetic Effect

DK, L.McLerran, H.Warringa NPA'07
K.Fukushima, DK, H.Warringa, "Chiral magnetic effect" PRD'08

Chiral chemical potential is generated (locally) due to topological transitions:

$$\mu_5 = A_5^0$$

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!

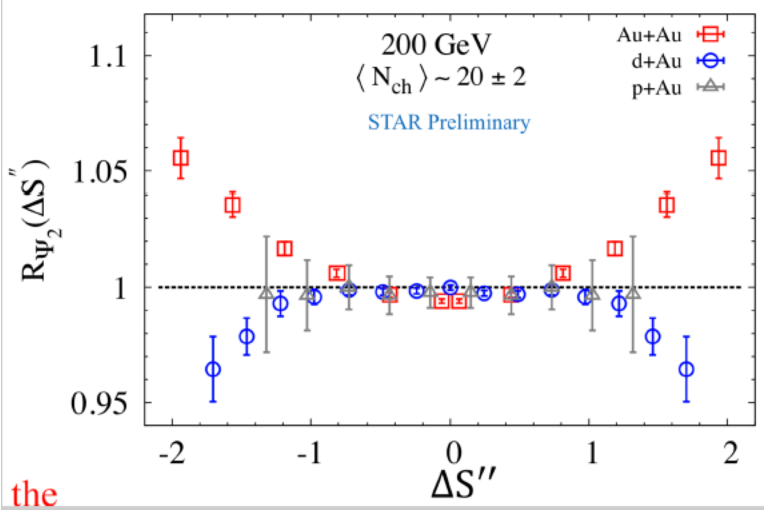
$$\boxed{\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}}$$

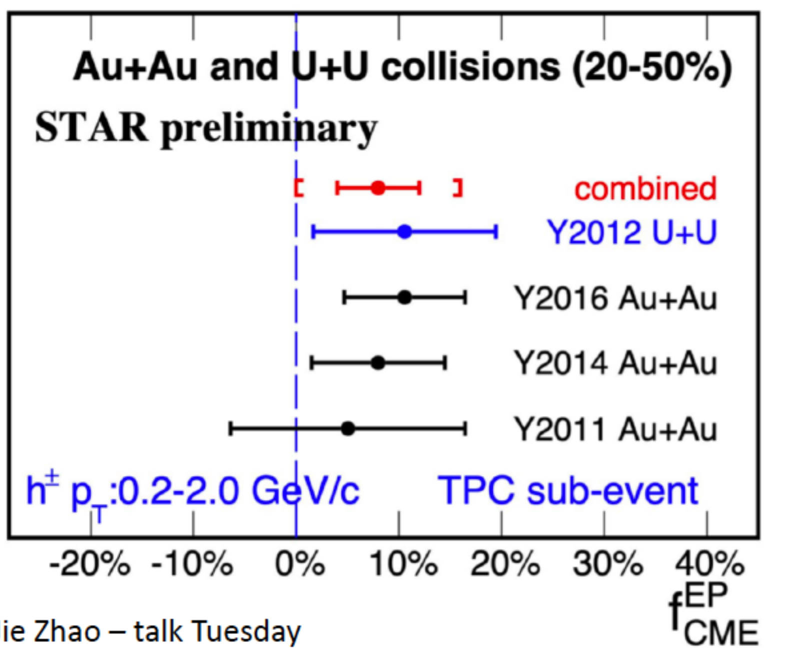
Coefficient is fixed by the chiral anomaly, no corrections

Quark Matter 2019: ongoing search for CME

Experimental search for CME:

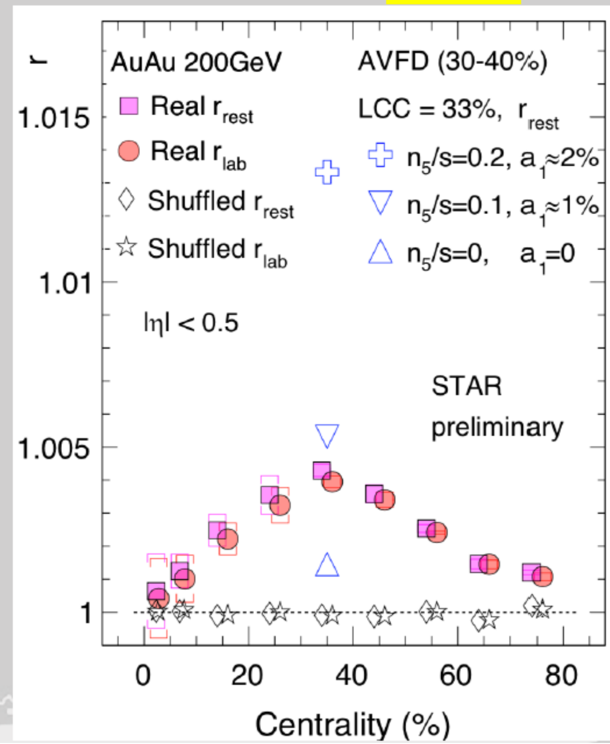
large backgrounds,
new methods of analysis emerge





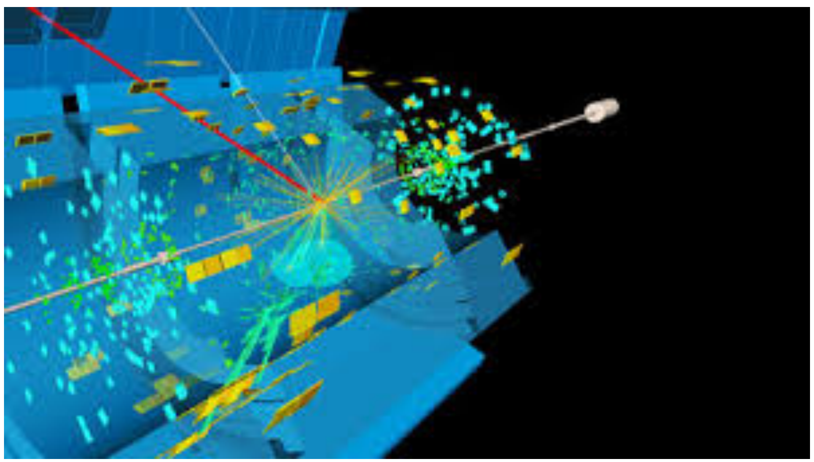
Jie Zhao – talk Tuesday

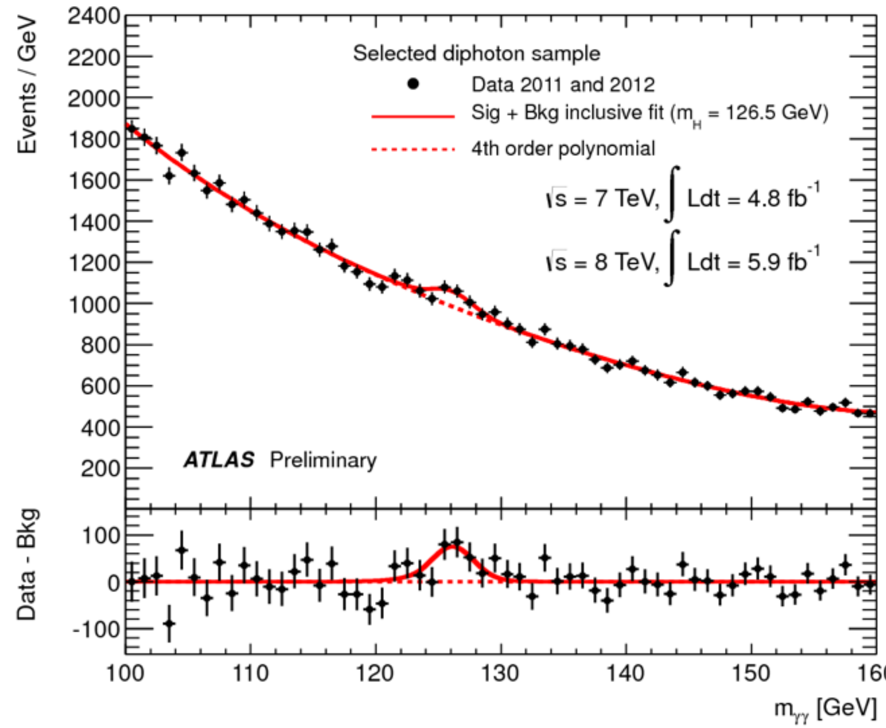
talk #669 by Y. Lin
poster #57 by A. Tang



Most (all?) recent discoveries in Physics required a thorough and painstaking background subtraction.

Example: the discovery of the Higgs boson





The search for CME is no different –
large backgrounds, urgent need to understand them

Dedicated 2018 isobar run at RHIC: STAR Collaboration

QM talks by J.Liao, M.Lisa, Z.Xu (STAR)

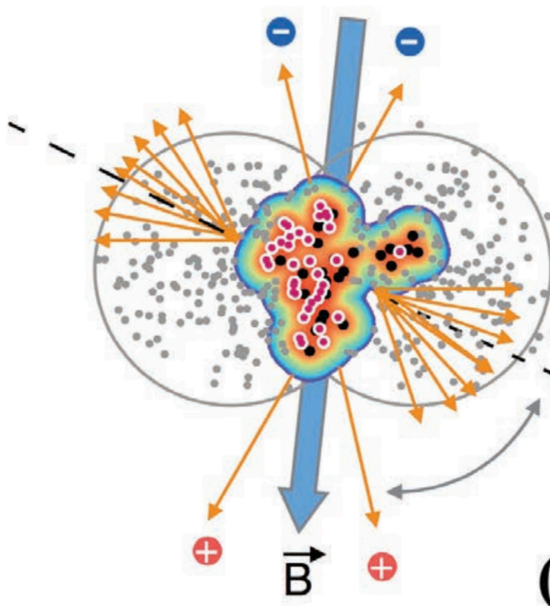
Featured Articles

Isobar Collisions at RHIC to Test Local Parity Violation in Strong Interactions

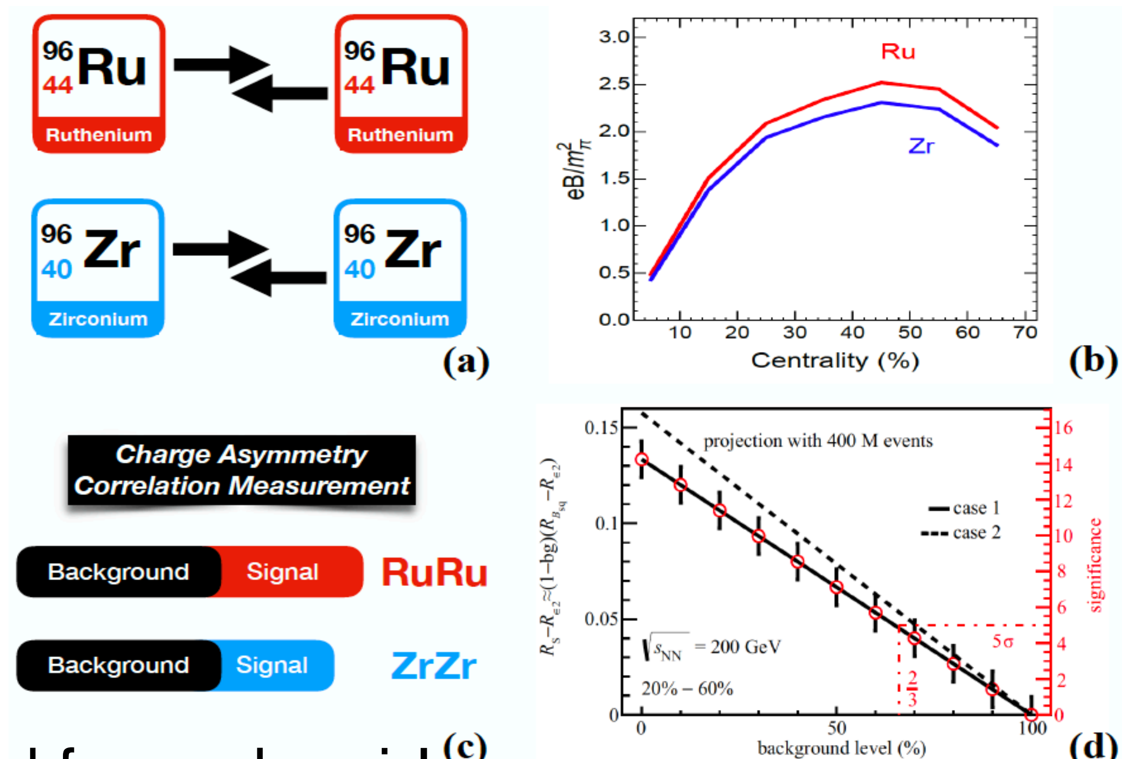
D. E. Kharzeev & J. Liao

Pages 26-31 | Published online: 29 Mar 2019

Nuclear Physics News International

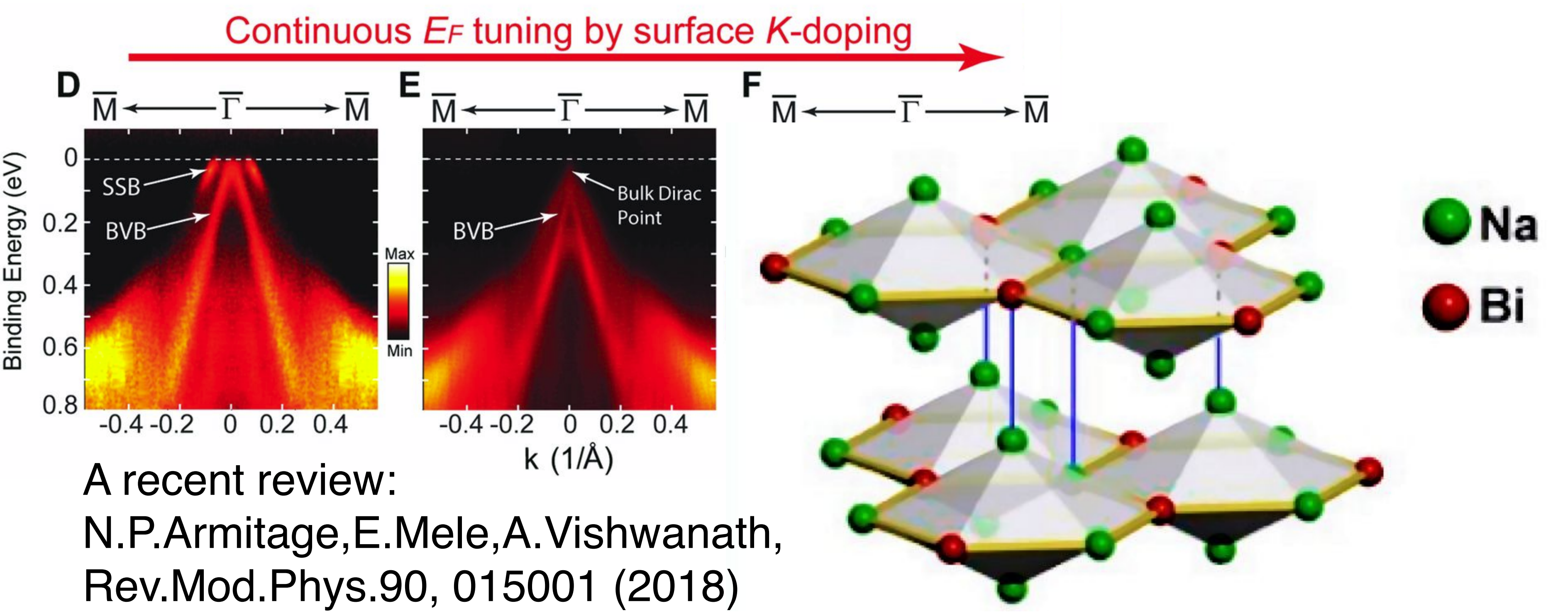


(a)



~ 3 Billion events recorded for each pair!

CME with emergent chiral fermions – 3D chiral materials



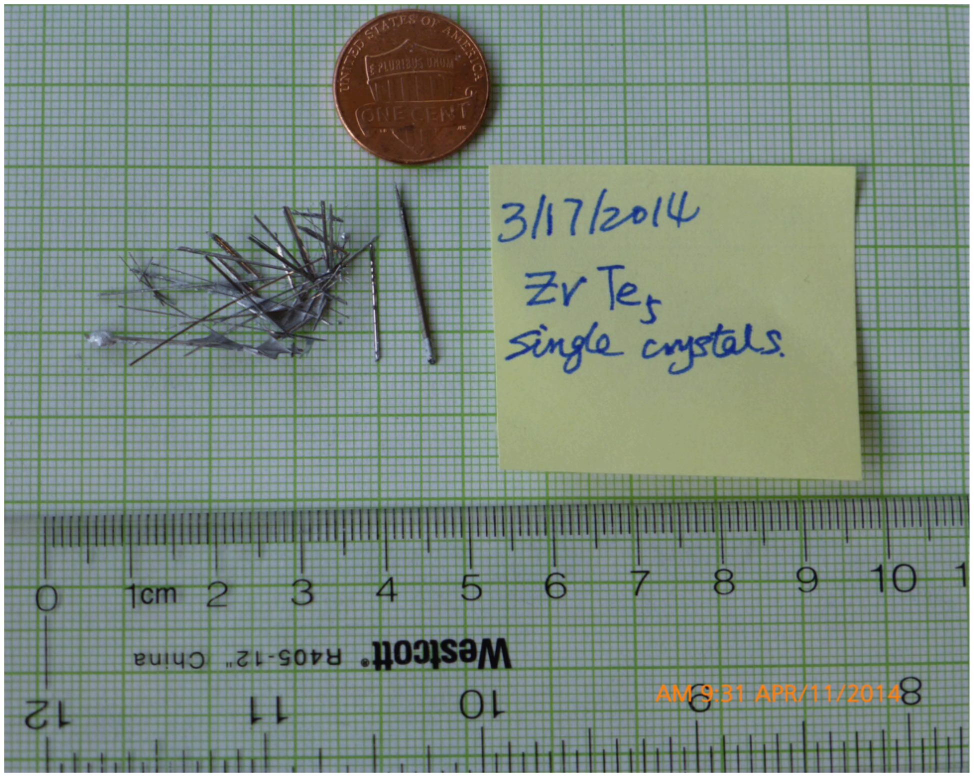
A recent review:
N.P.Armitage,E.Mele,A.Vishwanath,
Rev.Mod.Phys.90, 015001 (2018)

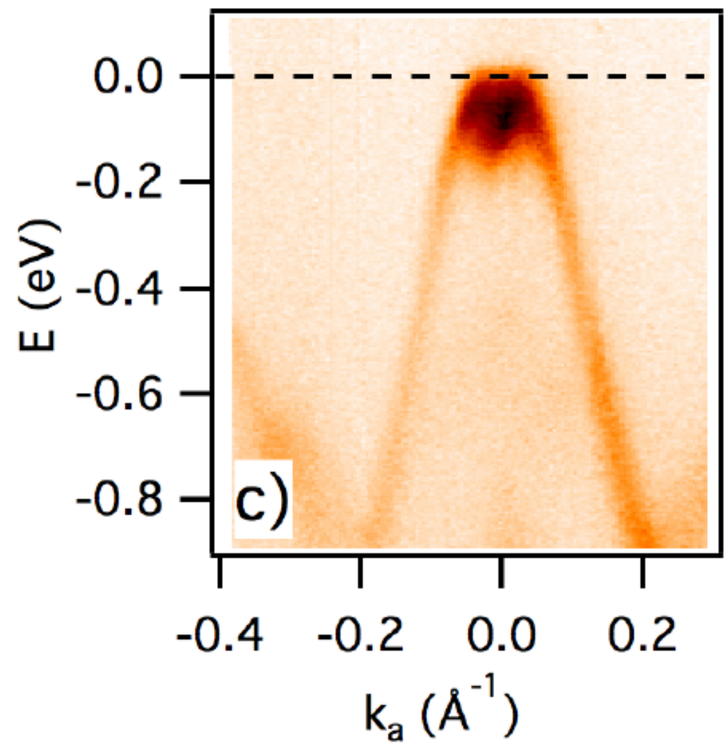
Z.K.Liu et al., Science 343 p.864 (**Feb 21, 2014**)

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 $ZrTe_5$

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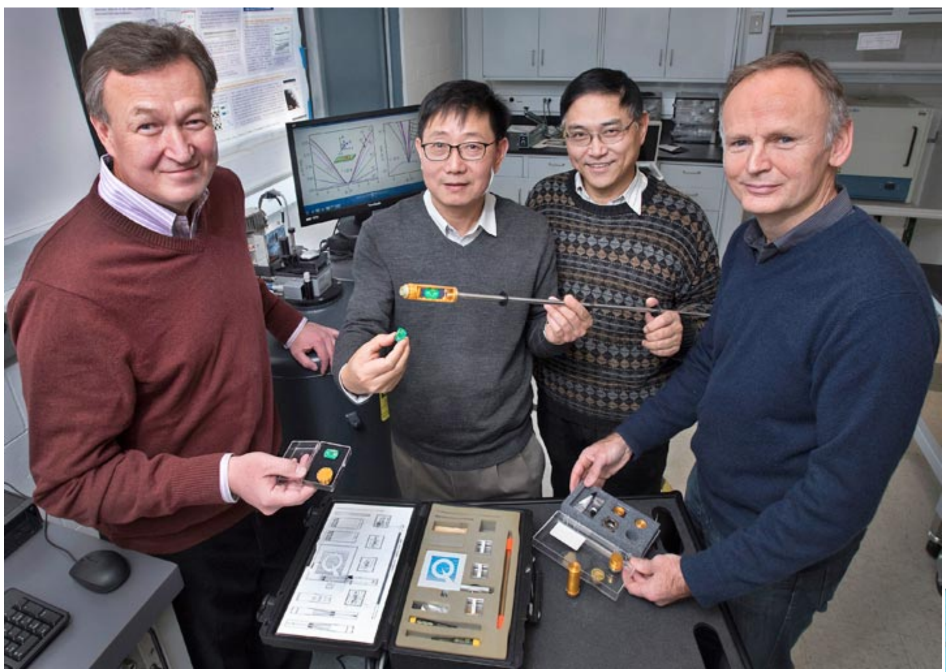
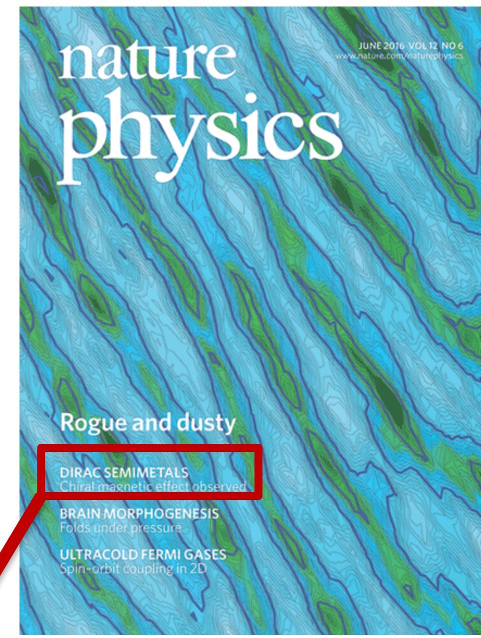
BNL - Stony Brook - Princeton - Berkeley

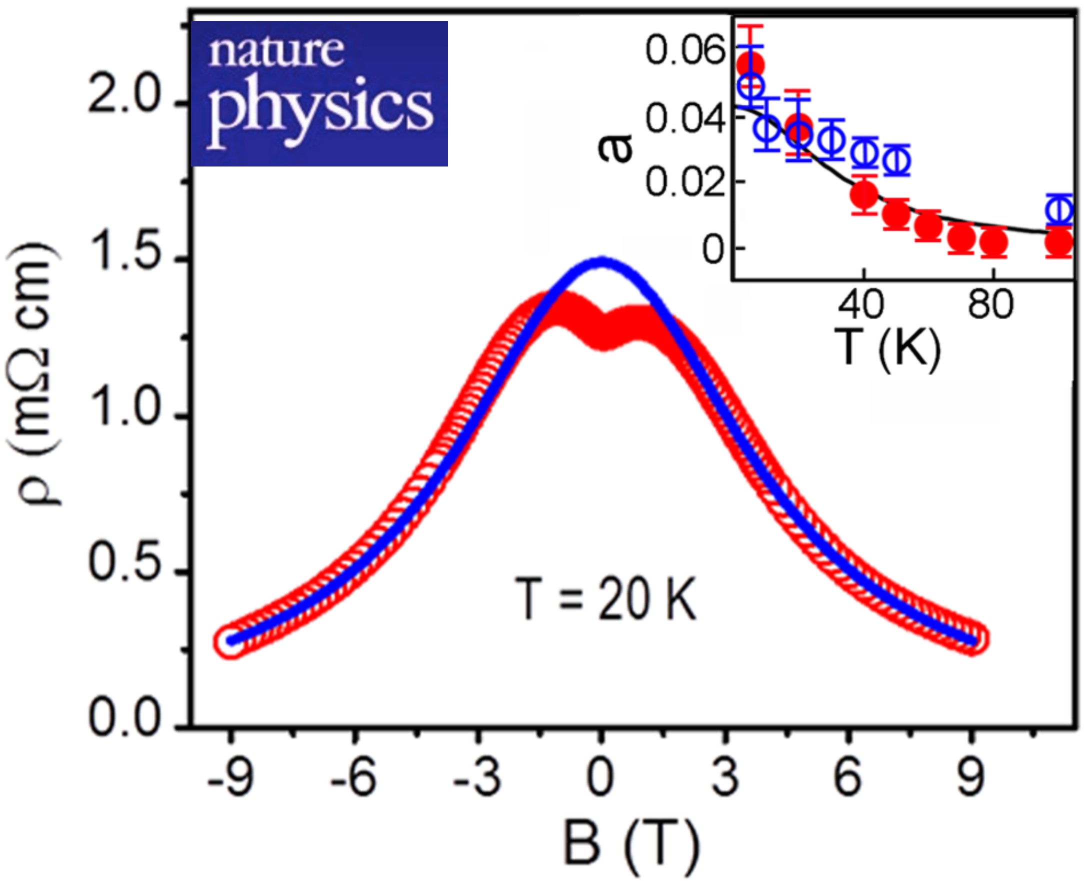


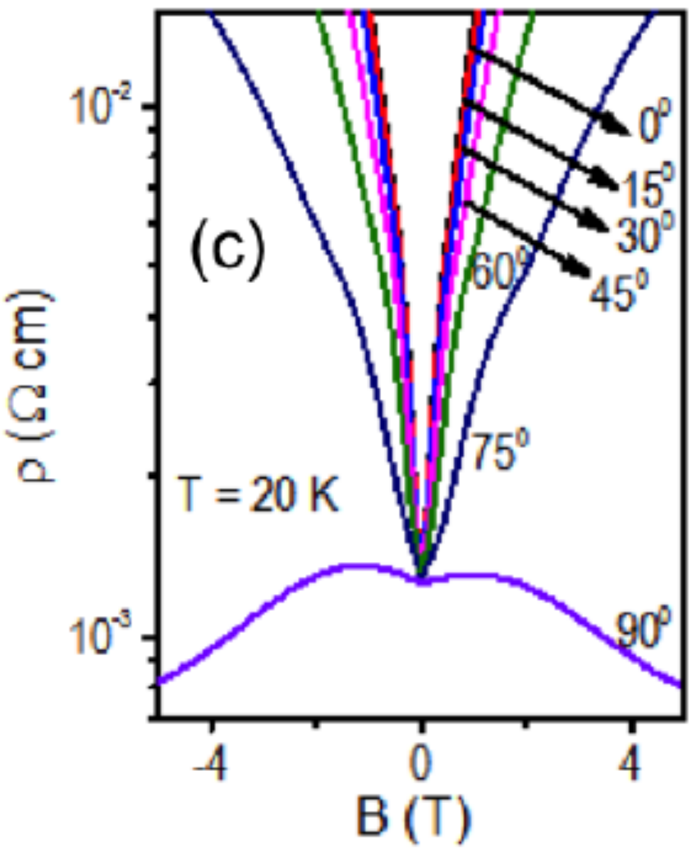
Nature Phys. 12 (2016) 550



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

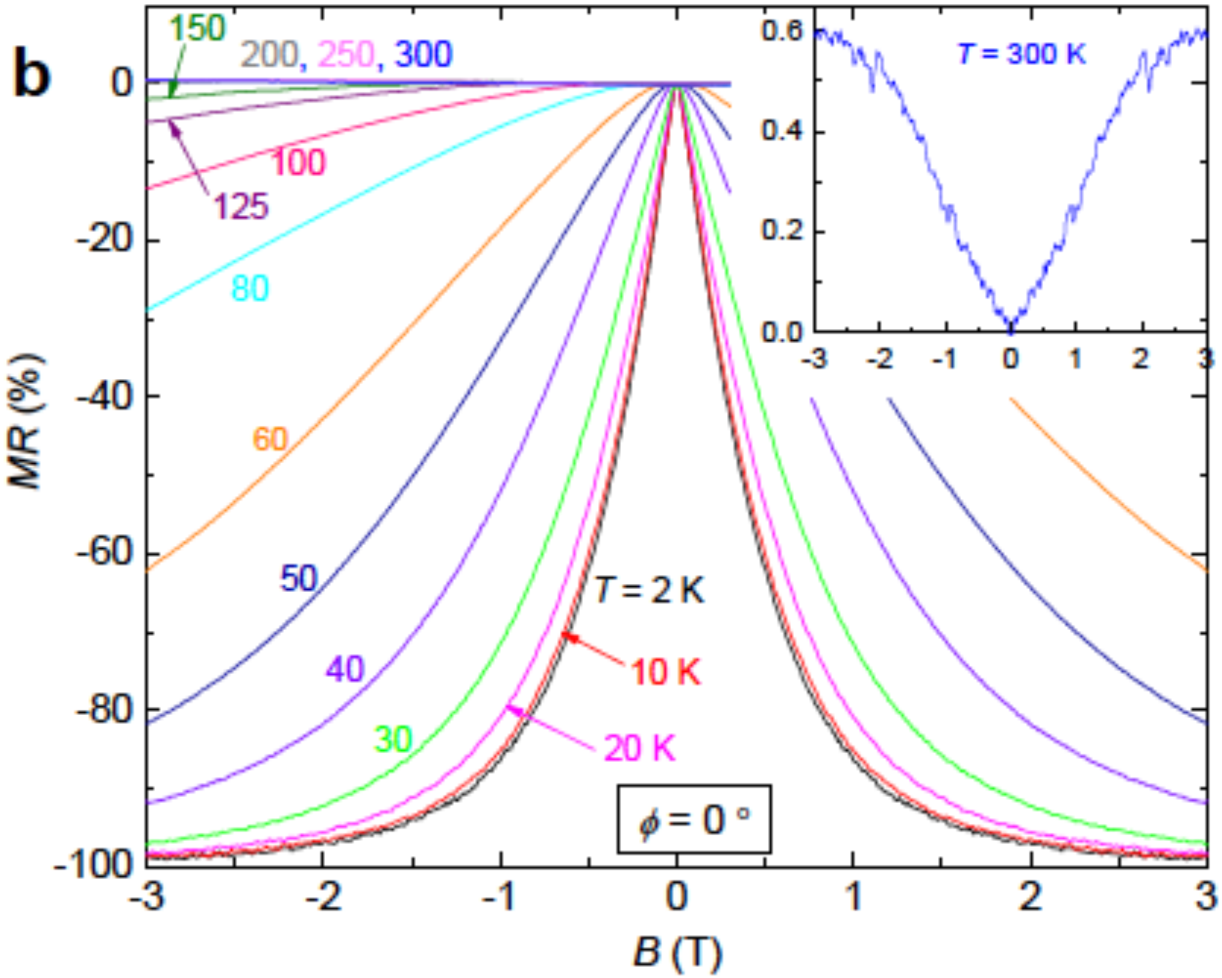
Q. Li et al,
Nature Physics **12**, 550 (2016)
arXiv:1412.6543





Negative MR in $TaAs_2$

Y.Luo et al, 1601.05524



Towards the room temperature CME?

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:

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

assume that chirality is conserved:

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

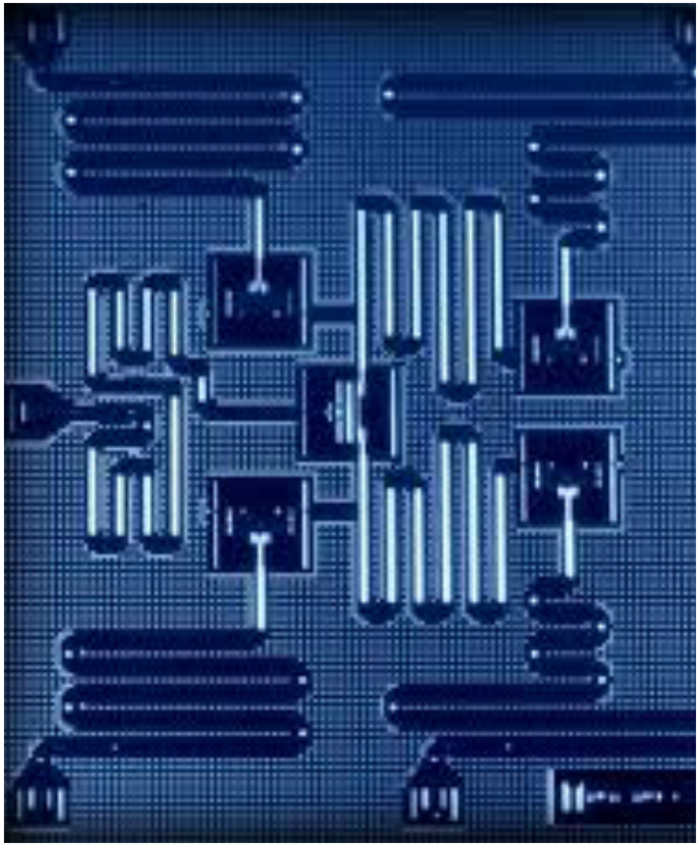
for $\vec{E} || \vec{B}$

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

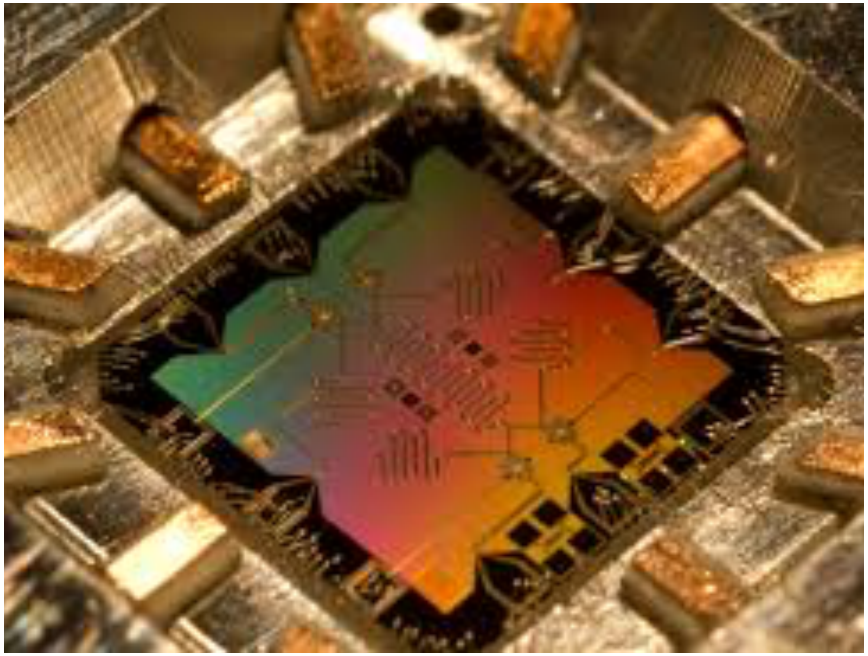
superconducting current, tunable by magnetic field!

DK, arXiv:1612.05677

Superconducting quantum computers

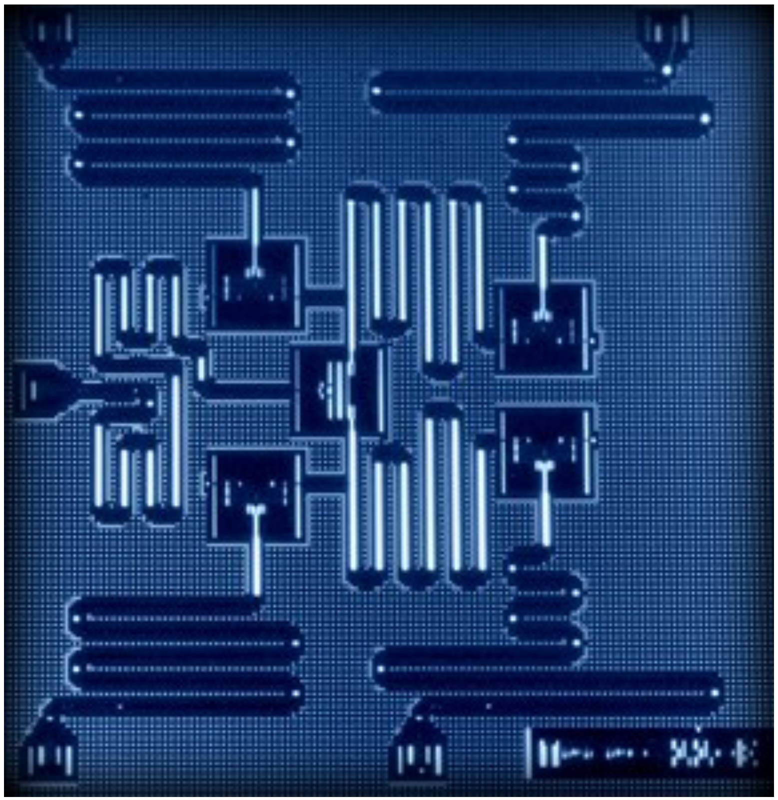


IBM-Q



Google

Superconducting qubits



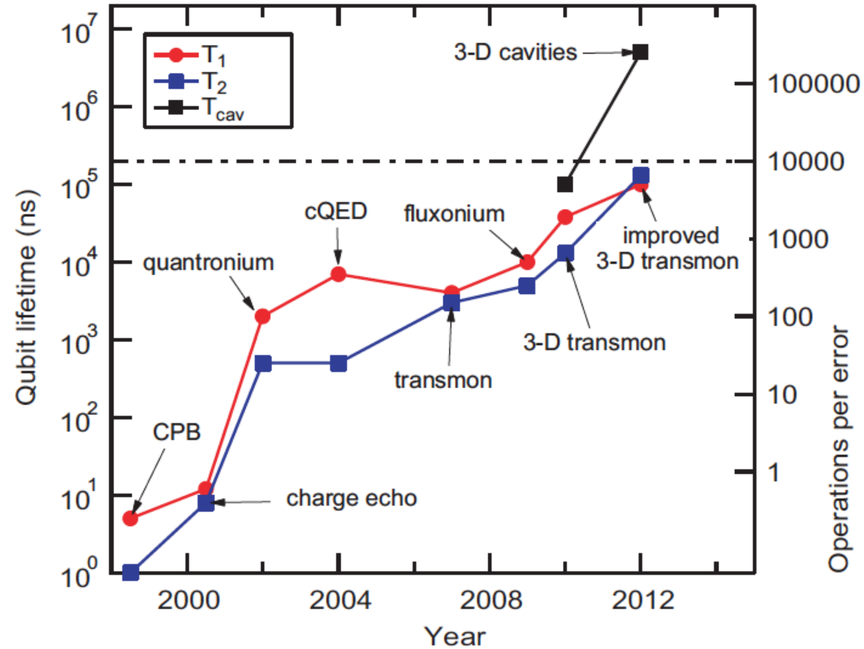


Fig. 2.1 "Schoelkopf's Law" plot illustrating the exponential growth for superconducting (charge-) qubit coherence times. Recent experiments (Geerlings *et al.*, 2013) with the 'fluxonium' qubit design have achieved T_1 times exceeding one millisecond.

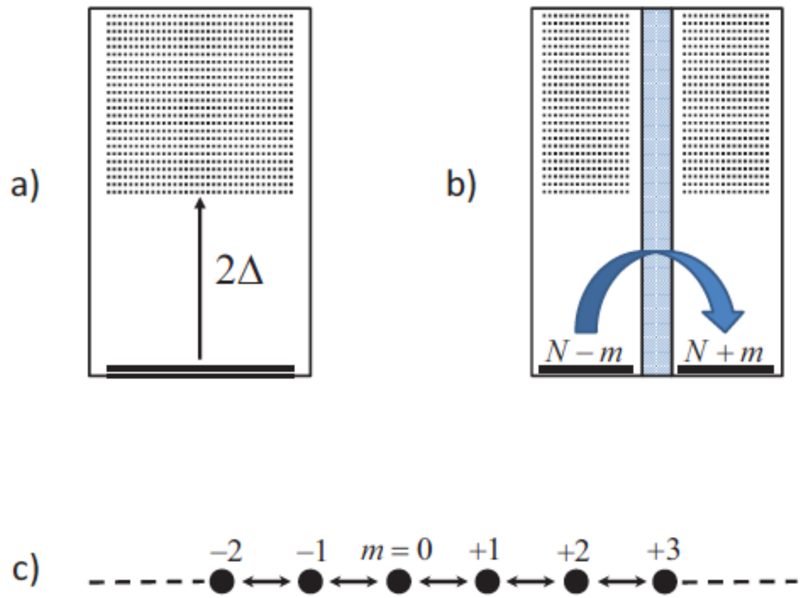
IBM five qubit processor credit: IBM-Q

S. Girvin, 2013


IBM

Superconducting qubits: tunneling through the Josephson junction

Review:
S. Girvin, 2013



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

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

$$\varphi = ka$$

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

The wavevector

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

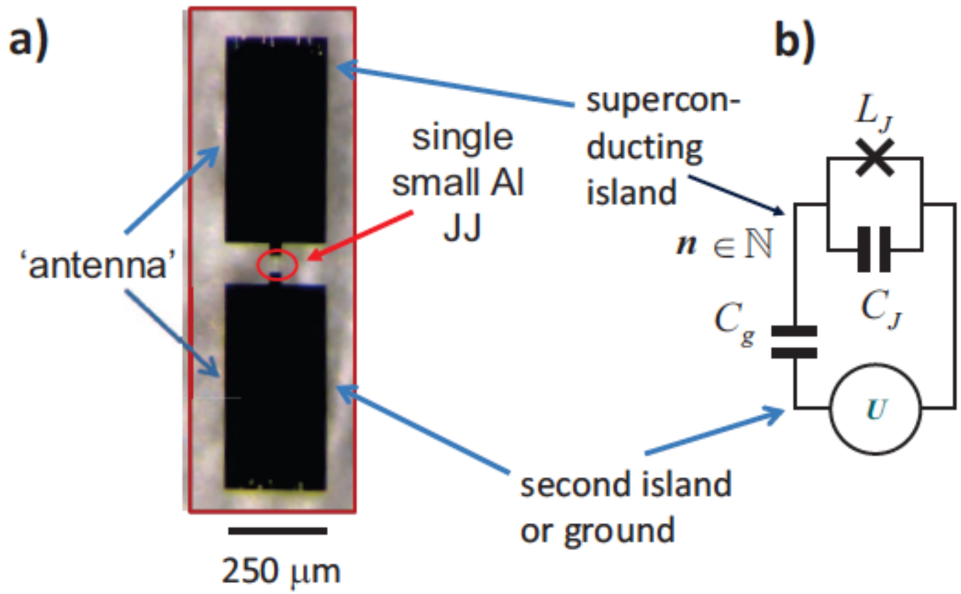
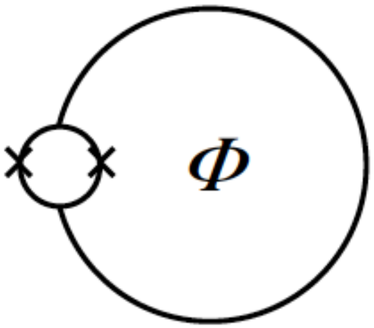
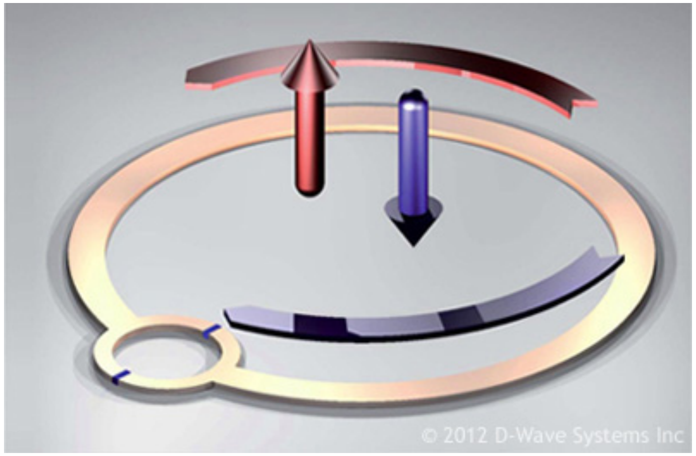


Fig. 4.1 a) Cooper pair box qubit (R. Schoelkopf lab) and b) its equivalent circuit showing a voltage source biasing the box through a coupling ('gate') capacitor c_g. The cross denotes the Josephson junction. The voltage source may represent an intentionally applied bias or be the result of random charges in the insulating substrate supporting the device. The particular device illustrated in (a) is a transmon qubit in a 3D cavity for which there is no dc bias applied (although there may be a random offset voltage due to charges trapped in the substrate).

From: S. Girvin, 2013

Superconducting qubits





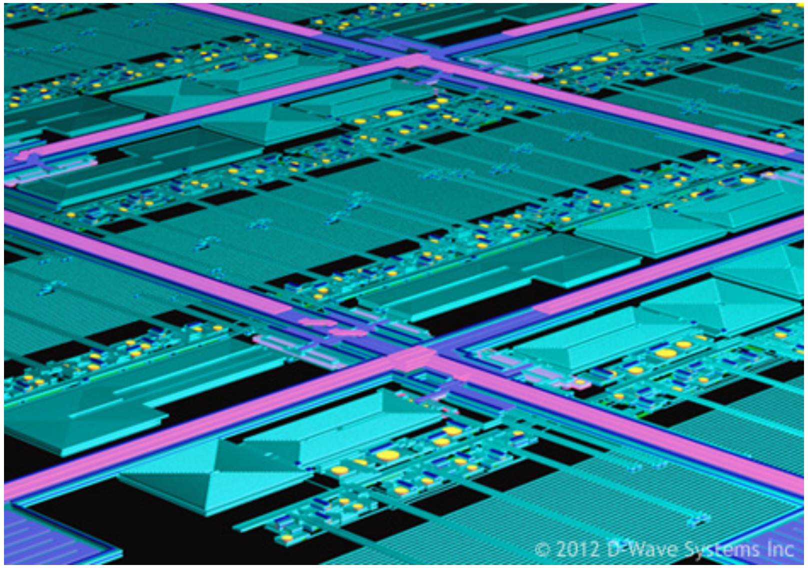
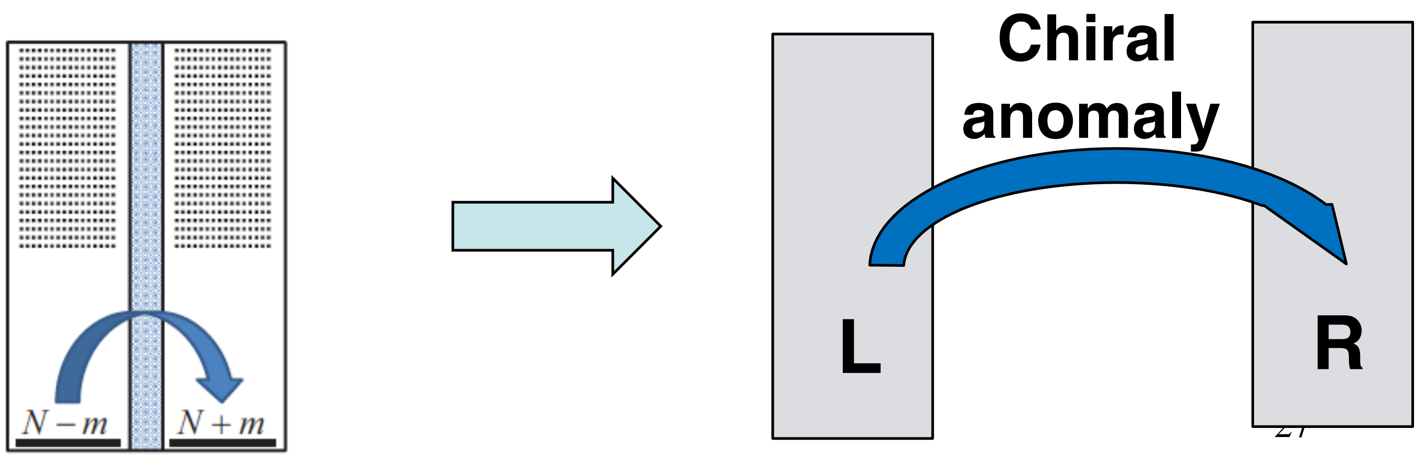


Image credits:
D Wave

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?

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?

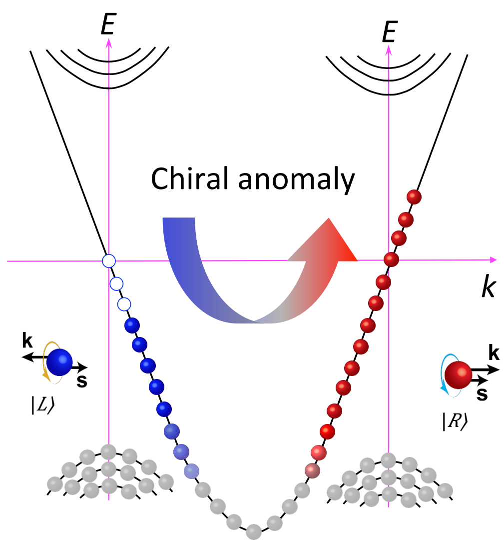
Probably yes – use the chiral fermions!



Chiral 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;

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

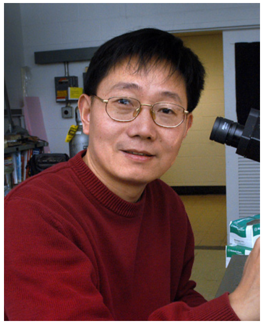
chiral chemical potential:

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

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

Chiral Qubit?

DK, Q.Li,
arXiv:1903.07133
[quant-ph]



Chirality flipping time inferred from CME current measurements (negative magnetoresistance) is

$$\tau_V \sim O(\text{ns}).$$

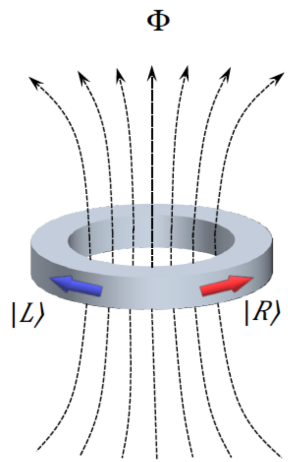
The corresponding chirality-preserving length is

$$l_v \sim v_F\, \tau_V \sim O(\mu\text{m}).$$

Therefore, in a micron-sized ring the current dissipation should be small

Chiral ring: a simple model

Dirac fermion
(1+1), compactified



Magnetic flux;
(3+1) gauge field

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

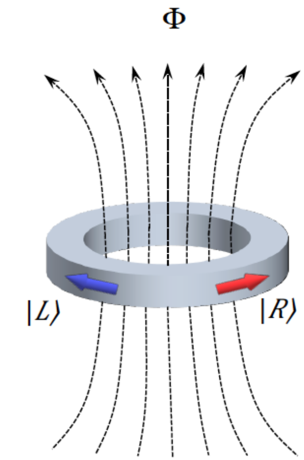
control
Hamiltonian,
$\Phi = \Phi(t)$

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

CME in the Chiral Qubit

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

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



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

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

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

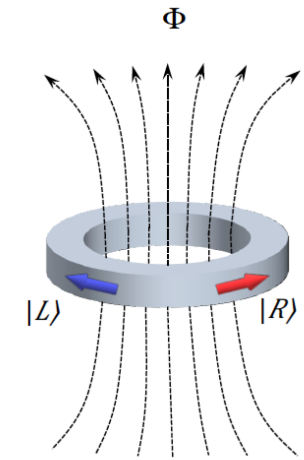
CME in (1+1) dimensions!

DK, Q.Li,
arXiv:1903.07133

Chiral Qubit: the Hamiltonian

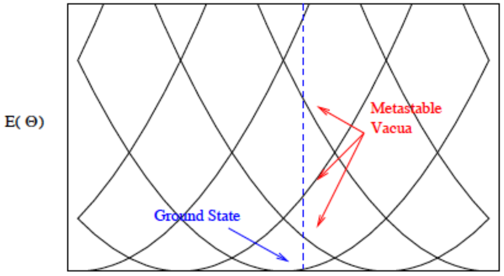
$$\hat{H} = \hbar\omega \left[-i\frac{\partial}{\partial\varphi} - \frac{\Phi}{\Phi_0} \right] \hat{\sigma}_z$$

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



An infinite tower of states (Dirac sea), all of which respond to magnetic field (chiral anomaly): need to sum over all occupied states. The finite part of the energy:

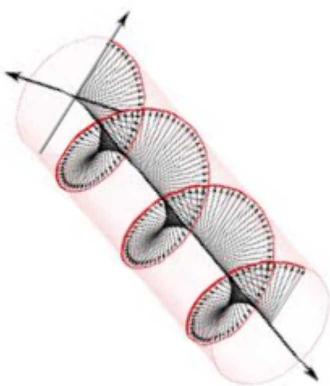
$$U_{tot}(\Phi) = U_0 \left[\left(\frac{\Phi}{\Phi_0} - \frac{1}{2} \right)^2 - \beta \cos\left(\frac{\Phi}{\Phi_0} \right) \right]$$



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

DK, Q.Li, arXiv:1903.07133

The chiral qubit



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

Dirac semimetal;
TI; graphene in
magnetic field?

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

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

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

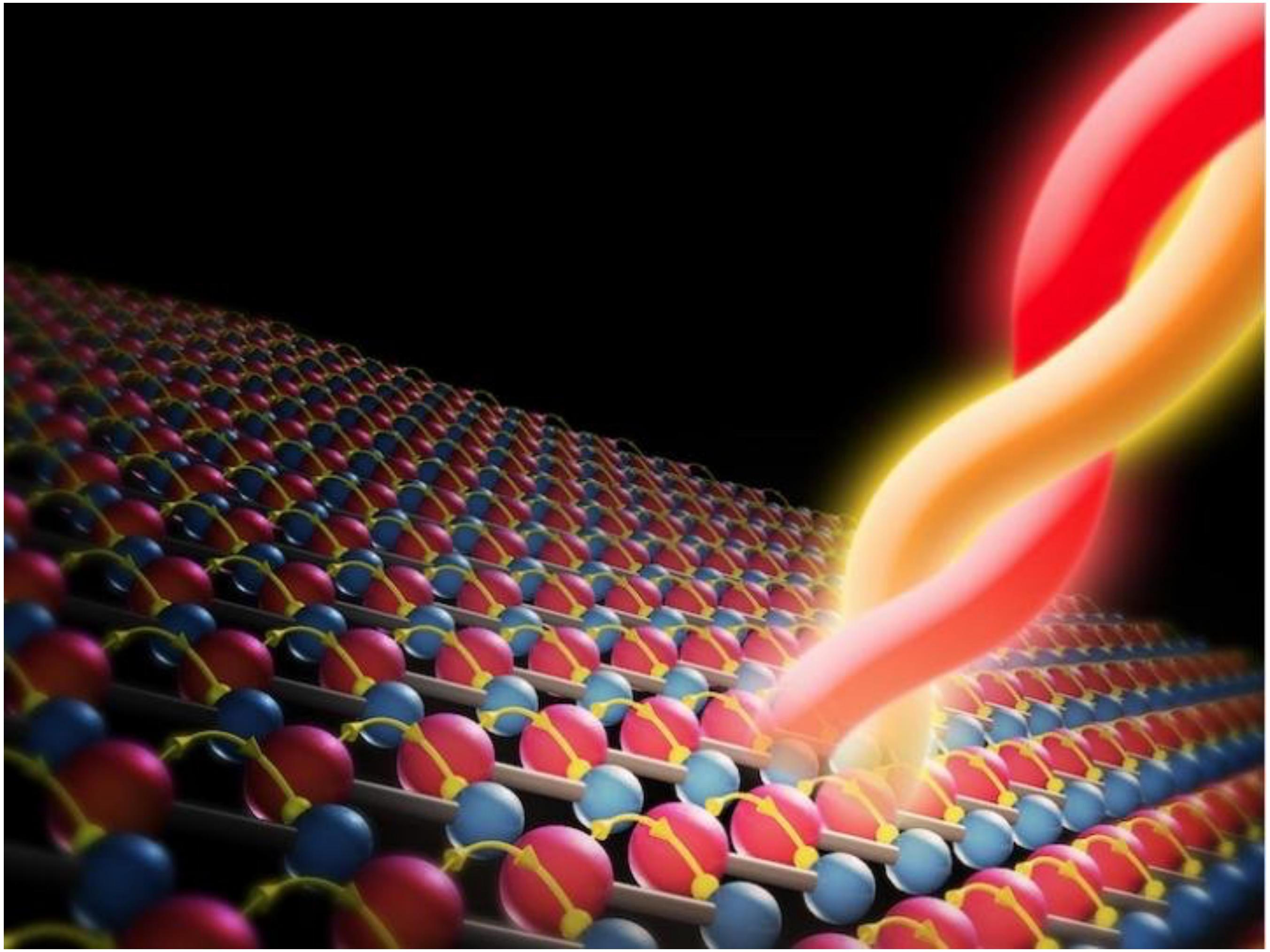


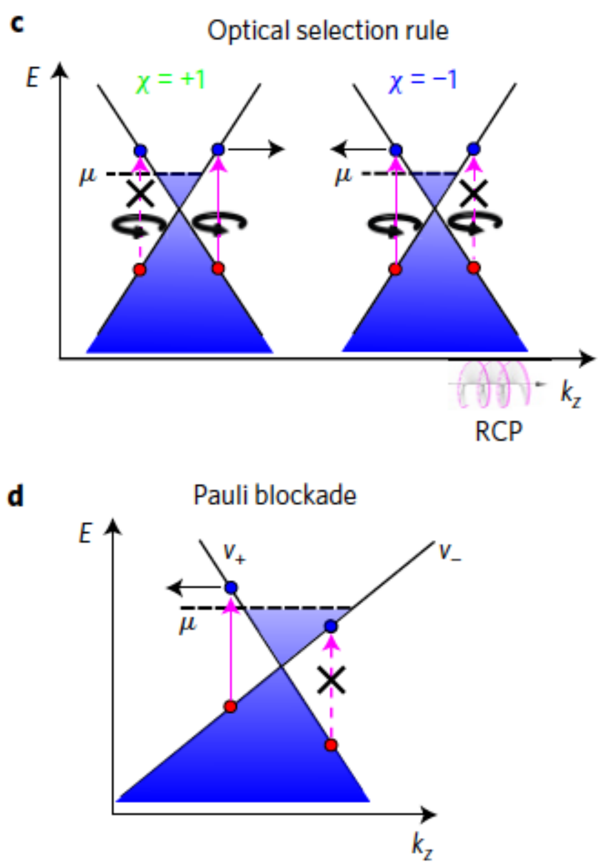
Image credit: Science Daily

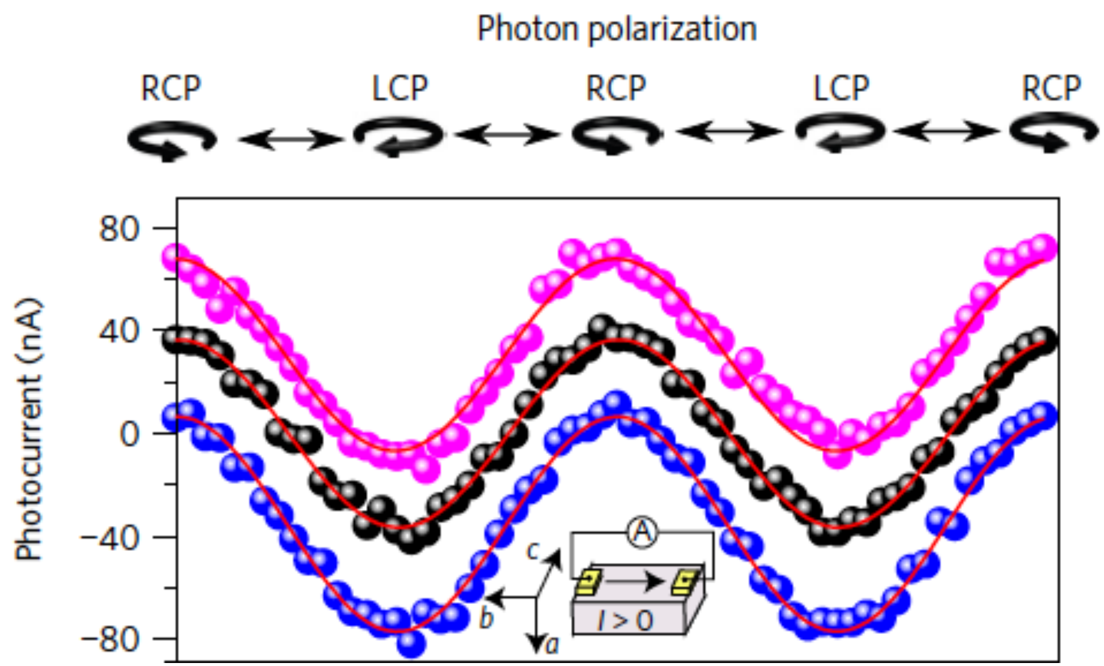
Optical response in Weyl semimetals

Photocurrent in tilted Weyl semimetal TaAs:

C.-K. Chan, N.H. Lindner, G. Refael, P.A. Lee, Phys.Rev.B95, 041104 (2017)

Q.Ma et al, Nature Physics 13, 842 (2017)





Chiral magnetic photocurrent

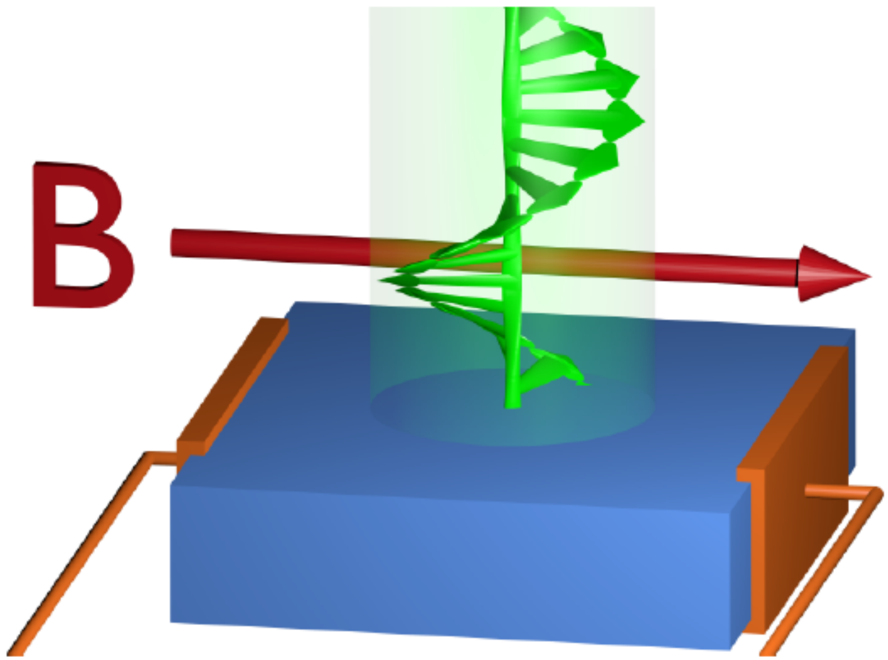


FIG. 1. The CPL incident on a Dirac or Weyl semimetal induces an asymmetry between the number of left- and right-handed chiral quasiparticles. In an external magnetic field, as a consequence of the chiral anomaly, this chiral asymmetry induces a chiral magnetic photocurrent along the direction of the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

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

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

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

CME photocurrent: long coherence time

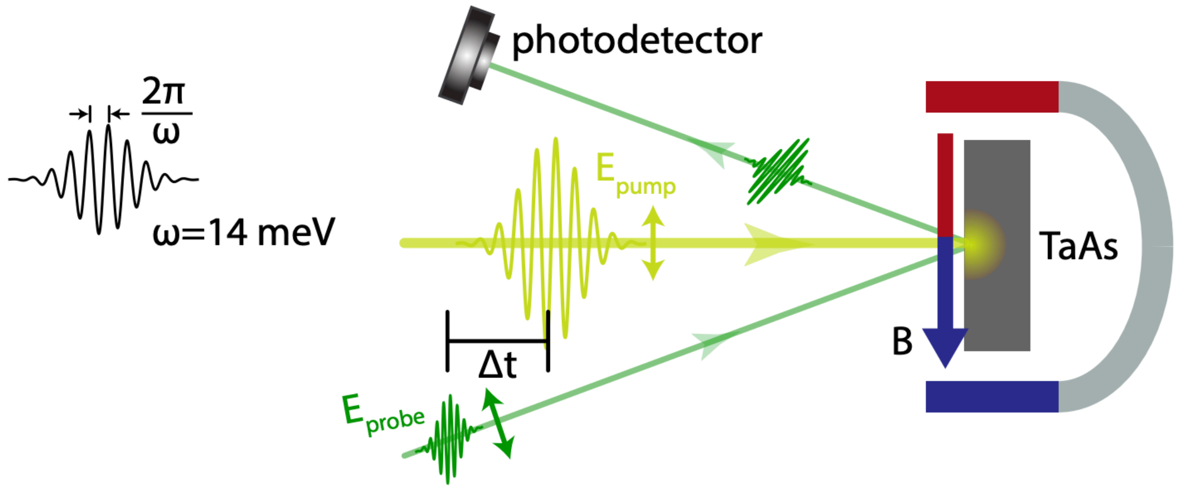


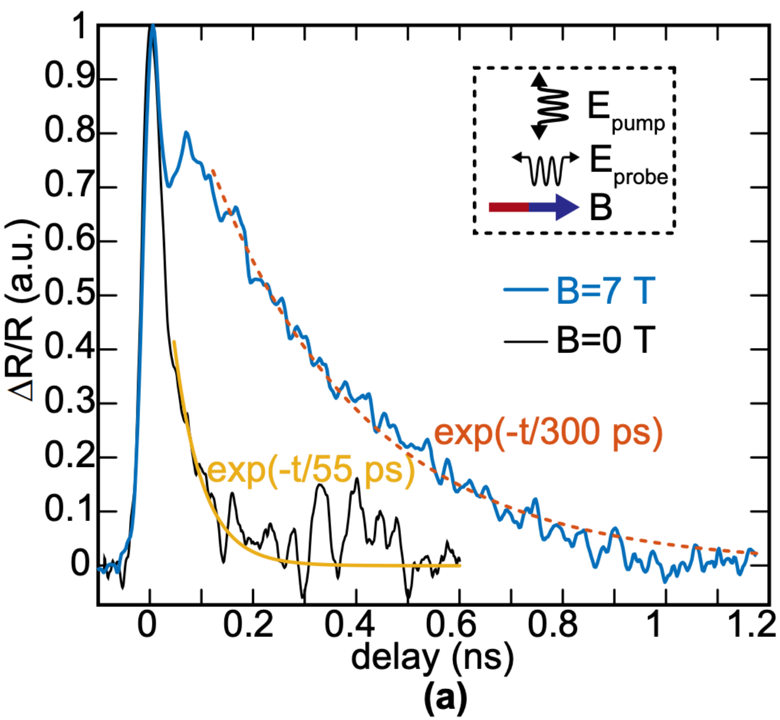
FIG. 2. **Experimental Setup**The pump-probe setup at the photon energy of $\hbar\omega$=14 meV in reflection geometry. The pump and probe pulses are co-polarized to the (100) face of TaAs crystal that is placed inside a magnet with B field parallel to pump/probe polarization.

Optical Control of Chiral Charge Pumping in a Topological Weyl Semimetal

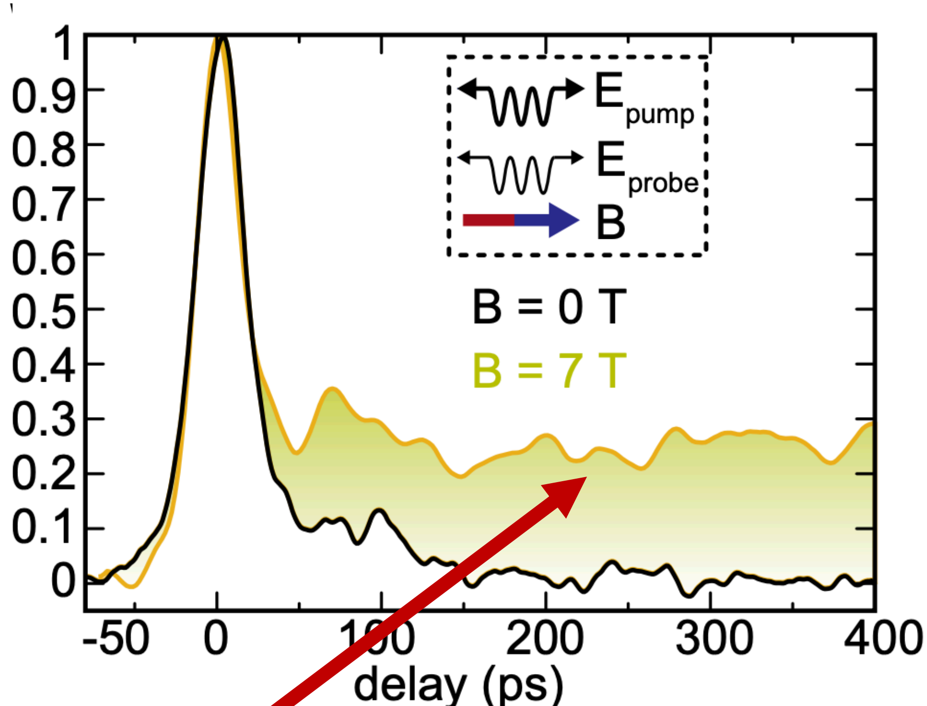
arXiv:1905.02236

M. Mehdi Jadidi,[1,a] Mehdi Kargarian,[2] Martin Mittendorff,[3,4] Yigit Aytac,[3,5] Bing Shen,[6] Jacob C. König-Otto,[7] Stephan Winnerl,[7] Ni Ni,[6] Alexander L. Gaeta,[1] Thomas E. Murphy,[3] and H. Dennis Drew[8,b]

CME photocurrent: long coherence time



6. $\boldsymbol{E}_{\mathrm{pump}} \perp \boldsymbol{E}_{\mathrm{probe}} \parallel \boldsymbol{B}$ (=7 T). (a) Relative pump-indu



$\boldsymbol{E}_{\mathrm{pump}} \parallel \boldsymbol{E}_{\mathrm{probe}} \parallel \boldsymbol{B}$

Anomaly creates long-lived (~100 ns!)
charged excitations
(chiral magnetic waves?)

M. Jadidi et al.,
arXiv:1905.02236

Coupling of CME current to IR field in Weyl semimetals

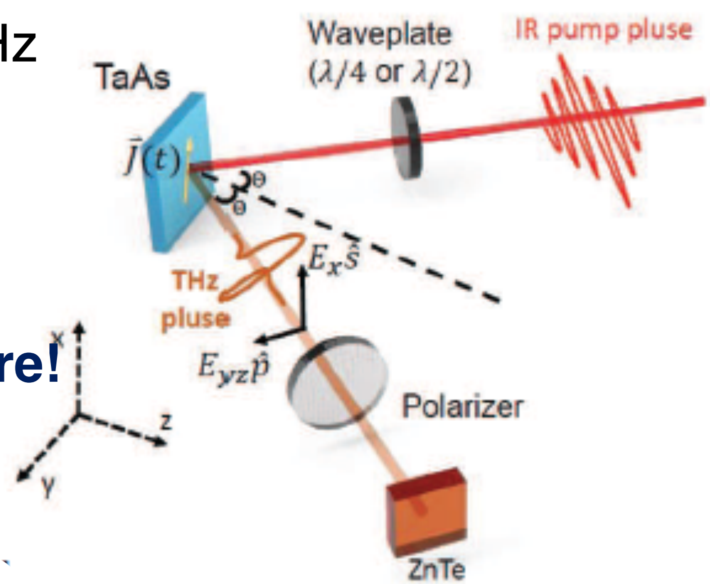
arXiv:1901.00986
PRX

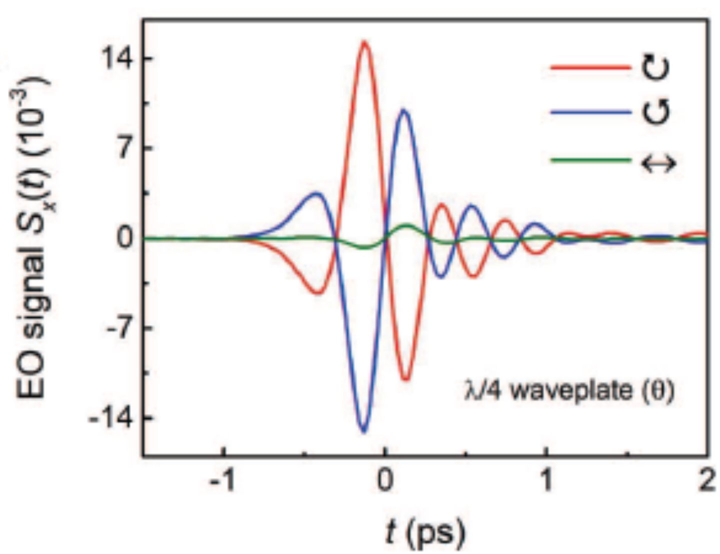
Coherent terahertz emission with tunable ellipticity and optical chirality from the Weyl semimetal TaAs

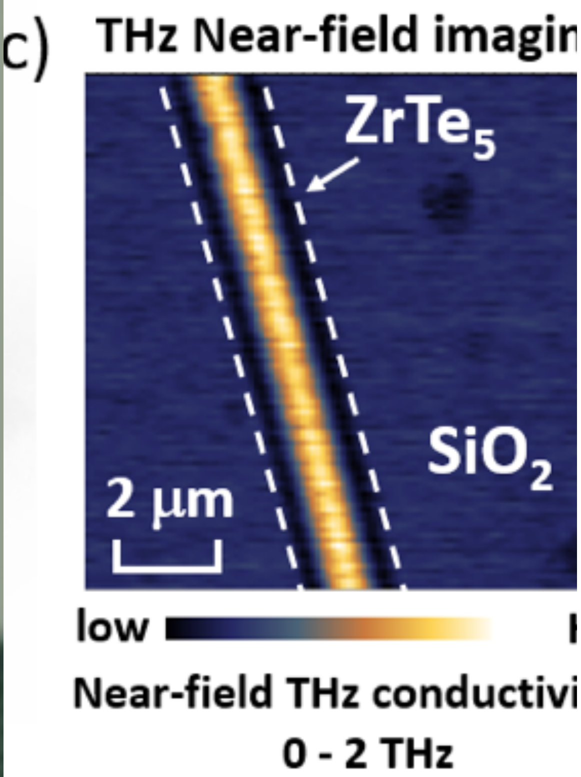
Y. Gao,[1] Y. Qin,[1] Y. P. Liu,[1] Y. L. Su,[1] S. Kaushik,[2] E. J. Philip,[2] X. Chen,[2] Z. Li,[3,4] H. Weng,[4,5] D. E. Kharzeev,[2,6,7] M. K. Liu,[2,*] and J. Qi[1,†]

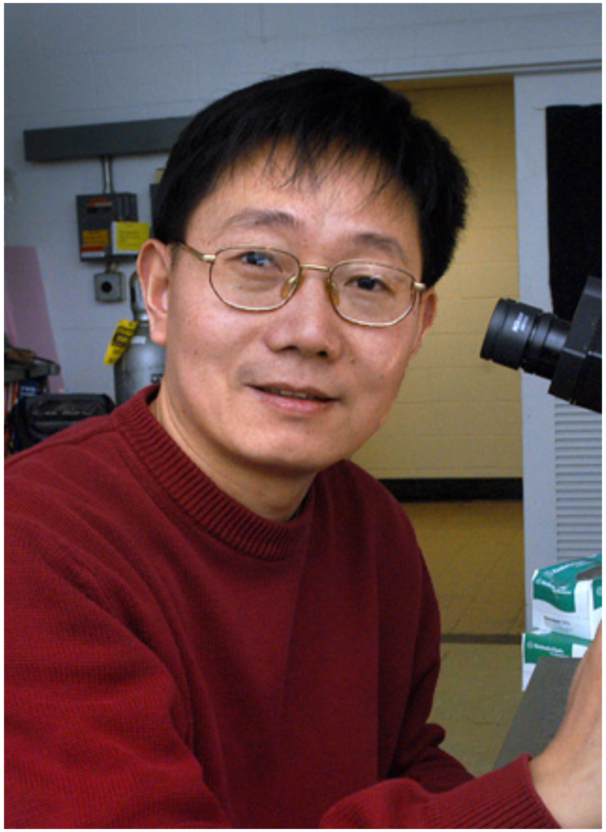
ω = 380 THz
λ = 800 nm
80 fs pulse

Room temperature!







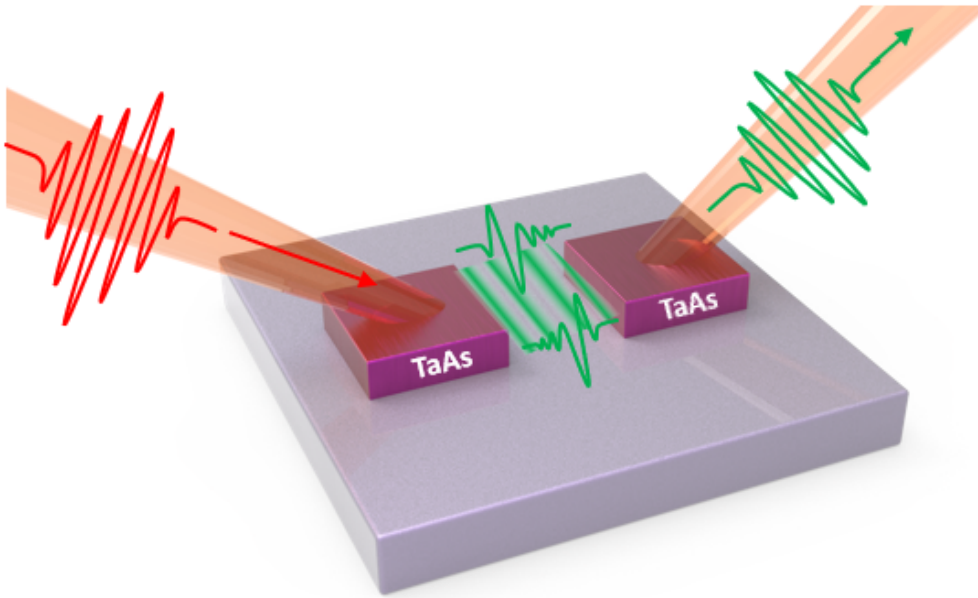


Work in progress,
M.Liu, Q.Li's labs

Entanglement of chiral qubits

Work in progress,

M.Liu, Q.Li's labs



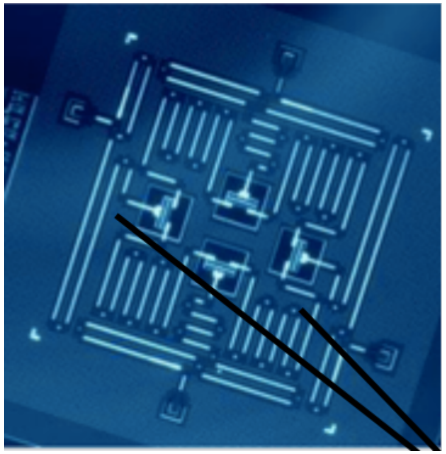
Does this have a chance to work?

Perhaps:

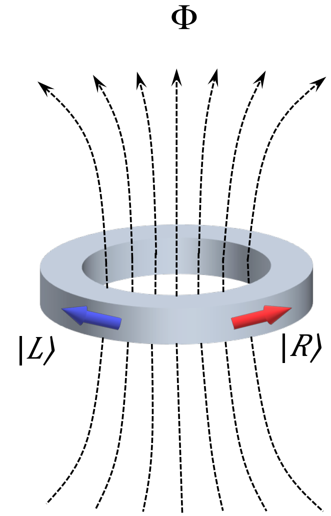
- Chiral qubits can operate at high (room?) temperature
- High frequency, ~ 10 THz (4 orders of magnitude faster than SC qubits)
- Coherence time is short, ~ 10 ns, **but** what matters is the ratio of coherence and gate times, which is high, ~ $\mathbf{10^5}$
- No need for transduction – IR frequency of the fiber optics
- Scalability: “frequency collision” may be avoided by using different ring radii

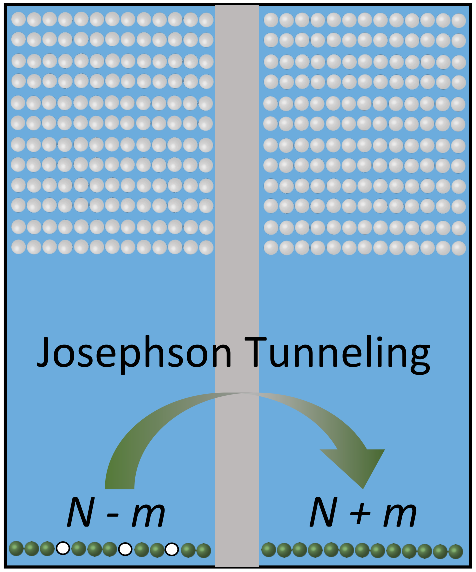
but a lot has to be understood and done

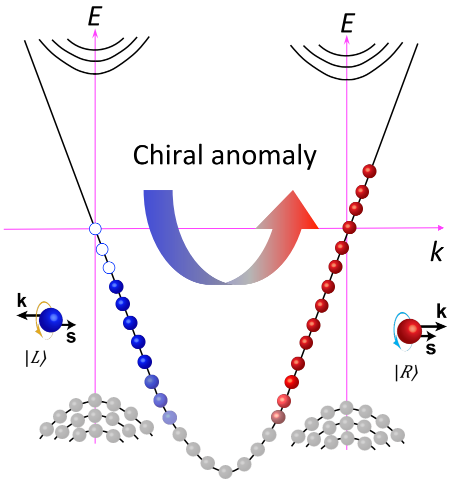
The chiral qubit



IBM-Q







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

Jean-Paul, Larry, and Miklos:

Many happy returns, and

thank you for your friendship!