Quark-Gluon Plasma: An Old & New Phase of Quantum Matter

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Human use of fire was instrumental for civilization.

Early conception of varied phases of matter & transitions: e.g. boiling water into steam, burning wood into ashes.

Early philosophers (e.g. Empedocles): all matter made of four elements — fire, air, water, earth
From Fire to Extreme Temperature

Our heating capability has since advanced VERY dramatically…

Curiosity questions that even K-12 kids may wonder about:

* What is the highest temperature ever?
* What is the highest man-made temperature?
* What does the matter look like at such extreme temperature?

——> a scientific frontier of high energy physics
Heating It Up: Energy Scale Matters

Heating increases temperature and enhances the thermal motion of whatever micro. degrees of freedom: a combat of random thermal motion v.s. ordered structure (with the latter typically due to dynamical interaction)

From NASA

\[
\begin{align*}
10^2 \sim 10^3 K & \quad 10^4 \sim 10^5 K \\
0.01 \sim 0.1 \text{ eV} & \quad 1 \sim 10 \text{ eV} \\
\text{Inner electrons "peeled off"} & \sim \text{keV} \sim 10^7 \text{K}
\end{align*}
\]
Heating It Up: Energy Scale Matters

Getting to ~ MeV ~ 10 Million Kelvin

—> Need to know quantum field theory (relativity+QM)

—> Need to know nuclear physics

What’s coming up next upon further heating?

Emissions!!
massless photons — all the time!

What’s next?

\[ e^{-M_e/T} \]

\[ M_e \sim 0.5 \text{MeV} \]

Ions (nuclei) —
when do they break up?

Nuclear binding energy:

\[ \sim \text{MeV} \]
Heating It Up: Energy Scale Matters

Again, what’s coming up next?
— what is the next massive particle?
— what is behind nuclear force?
Hadrons! Specifically, Pions!

\[ \pi^\pm, \pi^0 \]

\[ M_\pi \sim 140\text{MeV} \sim 10^{12} K \]

\[ R_{nuc} \sim 1 \text{fm} \sim 200\text{MeV} \]

What do we expect next?
* Heating toward \( T \sim M_{\pi} \), many pions are thermally produced.
* Repeating the same story of atoms at nuclear level?
* Many more hadron types, to be produced sequentially?
* Maybe hadrons to be broken up?

Yukawa
Heating It Up: The “Weird” Hadrons

As it turns out, there are thousands different types of hadrons…

“Atomic physics” for hadrons based on quarks? If yes, then some binding scale of hadrons?
Heating It Up: The “Weird” Hadrons

Surprisingly, hadrons seem to be unbreakable!

Upon injection of energy, a highly excited hadron becomes STRING like, and eventually breaks into more hadrons (not quarks)!
Heating It Up: The “Weird” Hadrons

So… are we going to stay with hadrons despite how hot we heat up matter?

The answer is NO! Surprisingly, there is a predicted limiting temperature for hadrons.

# of hadron types grows exponentially with mass!

\[ \frac{dN}{dM} \sim M^\alpha \exp \left( \frac{M}{T_H} \right) \]

This statistical sum diverges for \( T > T_H \sim 160\text{MeV} \! \)

WHAT IS THE MATTER BEYOND THAT?
Quantum Chromodynamics (QCD)

To answer the question, we will need to understand better the fundamental theory of strong nuclear force: QCD, a non-Abelian gauge theory of quarks and gluons.

Asymptotic Freedom: coupling becomes large at low energy or long distance scale.

\[ \Lambda_{QCD} \sim 200 \text{MeV} \quad R \sim 1 \text{fm} \]
The QCD Vacuum: Confinement

The missing particles: quarks & gluons (in the QCD lagrangian) are not seen in physically observed states.

QED dipole field

QCD dipole field

Free Quark Searches

All searches since 1977 have had negative results.

Q-bar-Q Potential

QCD vacuum as “dual superconductor” with dual Meissner effect
The QCD Vacuum: Chiral Symmetry Breaking

*The missing symmetries: while the Lagrangian has (approximate) chiral symmetry, the vacuum and hadron spectrum do not have that.*

**Massless Dirac Lagrangian**

\[
\mathcal{L} = i \bar{\Psi} \gamma^\mu \partial_\mu \Psi
\]

\[
\mathcal{L} \rightarrow i \bar{\Psi}_L \gamma^\mu \partial_\mu \Psi_L + i \bar{\Psi}_R \gamma^\mu \partial_\mu \Psi_R
\]

\[
\Lambda_A : \Psi \rightarrow e^{i \gamma_5 \theta} \Psi
\]

**Puzzle #1: why non-degenerate?**

\[
m_\pi \approx 140 \text{MeV} , \ m_{f0} \approx 600 \text{MeV}
\]

\[
m_\rho \approx 770 \text{MeV} , \ m_{a1} \approx 1260 \text{MeV}
\]

**Puzzle #2: why \( M_n \gg 3 \times M_{\{u,d\}} \)?**

\[
m_\pi \approx 140 \text{MeV} , \ m_n \approx 940 \text{MeV}
\]

\[
\text{why } M_n /3 \gg M_{\pi} /2?
\]
Spontaneous Chiral Symmetry Breaking

Quark level picture:

Dirac Sea

Lagrangian (SM) mass:

\[ M_{u,d} = 5 \sim 10 \text{MeV} \]

\[ \Delta \sim \langle \bar{\Psi} \Psi \rangle \]

Constituent mass:

\[ M_{\text{con.}} \sim 300 \text{MeV} \]

QCD vacuum is not empty, but a complex, nonperturbative form of condensed matter.

[It accounts for 99% of the mass of our visible matter in universe.]
It appears most certain that when the system is hot/dense enough:

1. Individual hadrons will lose their identities —> quarks/gluons

2. The vacuum ordered structure would be destroyed.

—> Must be a distinctive new phase of nuclear matter!

[Early ideas: T.D. Lee, Wick, Collins, Perry, McLerran, Shuryak, Kapusta, ...]
Condensed Matter Physics of QCD

“Disturb” the vacuum by tuning external conditions: New states of matter under extreme conditions!

from Stephanov, arXiv:0701002
Answer from Lattice QCD

from Lattice QCD (HotQCD)

a relativistic pion gas

More precisely, Hadron Resonance Gas

* Two benchmarks at low/high $T$
* A transition regime in the middle
* Crossover (instead of a phase transition)
The high T phase of QCD matter (a few hundred MeV & up) is a distinctive quark-gluon plasma (QGP).

Where can we find it?!
Early Universe After Big Bang

The highest ever temperature was in the beginning of universe. The QGP temperature was available back then.

The quark-gluon plasm is an old phase of matter! Can we replicate such epoch state of matter in laboratory?
Little Bang in Heavy Ion Collisions (HIC)

T. D. Lee: “Vacuum Engineering”

An artistic presentation: “nuclei as heavy as bulls, colliding into new phase of matter”

our most powerful heating machine ever
Little Bang in Heavy Ion Collisions (HIC)

Is QGP created?
Just how hot?
How do we know?

from STAR & PHENIX @ RHIC
from ATLAS @ LHC
Some Basics of Heavy Ion Collisions

To give some ideas (taking Gold-Gold 200GeV at RHIC as example):
- 197 (79p+118n) nucleons colliding with 197 nucleons
  (Nuclei A as a handle)
- 100GeV/nucleon, 200GeV N-N C.M. energy, 42mb x-section
  (Collision Energy as a handle)
- 39TeV in, about 28TeV left in the middle → creating ~7500 particles
- We observe the final state hadrons’ identity and 3-momentum
- Estimated initial temperature ~300MeV (Trillion Kelvin) > Tc ~170MeV
- Estimated initial energy density 5-10GeV/fm^3 > H.G. threshold 1GeV/fm^3
Centrality: 

- (most) central $\rightarrow$ (most) peripheral

Impact parameter $b$: 

- (very) small $\rightarrow$ (very) large

Initial geo. anisotropy: 

- (very) small $\rightarrow$ (very) large

Final hadron multiplicity: 

- high $\rightarrow$ low (exp. classification)

Fireball geometry from initial overlap: crucial!
QGP Shining Bright!

QGP is hot stuff: about trillion degrees!

Official Guinness World Record:
the highest man-made temperature!

RHIC / LHC
QGP Thermally Produces Hadrons

From STAR

QGP is hot stuff!
Fifty beryllium-copper diaphragm microphones were also used to record the pressure of the blast wave. These were supplemented by mechanical pressure gauges,[104] These indicated a blast energy of 9.9 kilotons of TNT (41 TJ) ± 0.1 kilotons of TNT (0.42 TJ). With only one of the mechanical pressure gauges working correctly that indicated 10 kilotons of TNT (42 TJ). [105]

Fermi prepared his own experiment to measure the energy that was released as blast. He later recalled that:

About 40 seconds after the explosion the air blast reached me. I tried to estimate its strength by dropping from about six feet small pieces of paper before, during, and after the passage of the blast wave. Since, at the time, there was no wind I could observe very distinctly and actually measure the displacement of the pieces of paper that were in the process of falling while the blast was passing. The shift was about 2 1/2 meters, which, at the time, I estimated to correspond to the blast that would be produced by ten thousand tons of T.N.T. [106]
QGP Blasting Out!

Strong blast wave seen in final hadrons distributions

—> highly explosive

—> high initial energy density & pressure gradient!

\[ \epsilon_{in} \sim 20\text{GeV/fm}^3 \gg 1 \sim 2\text{GeV/fm}^3 \]
Anisotropic Blast: Elliptic Flow

\[
\frac{dN}{dP_t \, d\phi} = \frac{dN}{dP_t} \left[ 1 + 2 v_2 (P_t) \cos (2 \phi) + \ldots \right]
\]

This response is very sensitive to fluid dissipation from STAR.

\[ Au + Au, \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ \frac{v_2}{n_q} \]

\[ 0.15 \]
\[ 0.1 \]
\[ 0.05 \]
\[ 0 \]

\[ \begin{array}{c}
  \circ K_S^0 \\
  \Delta^- + \Delta^+ \\
  \Lambda + \bar{\Lambda} \\
  \bar{\Omega} + \Omega \\
  \phi \\
  \pi^+ + \pi^- \\
  p + \bar{p}
\end{array} \]

Event plane method (TPC)

0-80% most central

\[ (m_T - m)/n_q (\text{GeV/c}^2) \]

\[ 0 \]
\[ 0.5 \]
\[ 1 \]
\[ 1.5 \]
\[ 2 \]

\[ 1 \leq 4\pi (\eta/s)_{QGP} \leq 2.5 \]
QGP: Nearly Perfect Quantum Liquid

\[ \eta \sim \rho v_T \lambda \sim n_\text{pT} \lambda \]
\[ s \sim \eta \]
\[ \eta/s \sim p_\text{T} \lambda \sim \lambda / \lambda_{dB} \]

QGP is a quantum liquid:

\[ \lambda_{\text{M.F.P.}} \sim \lambda_{\text{de Broglie}} \]

[A recent ravel: cold atomic gas with infinite scattering length]

It has nearly perfect fluidity:

less dissipative than known substance;
very close to conjectured lower bound.
QGP Properties: What It Does

* Nearly perfect fluidity: mapping fine details of initial conditions

* Highly opaque for a colored penetrating jet probe ~ 100GeV

* Screening the QCD binding force in quarkonia states

* Many many other interesting findings…

With RHIC and LHC, not only we create QGP, we’ve also learned a whole lot about the properties of QGP!

[Perhaps one good place to get to know it all: Quark Matter Conference Proceedings]
The (Creative) Use of QGP & HIC

The QGP (new material) & HIC (new laboratory) provide exciting opportunities for many interesting new physics

* Learning about initial nuclear wave functions
* Relativistic viscous hydrodynamics (on its edge)
* Predicting new hadrons (strangeness fluctuations)
* Far from equilibrium physics (BEC in the very hot)
* Understanding confinement from deconfined QGP
* Producing rare particles (anti-hyper-triton, anti-alpha,…)
* Constraining nuclear structure (C12 ~ 3 alpha cluster?)
* Universal critical phenomenon for QCD
* Applied string theory (aka gauge/gravity duality)
* Cosmology & early universe,
  * ……

I will have time to tell you only one recent interesting story.
Anomalous Transport in Chiral & Quantum QGP

All available in one UNIQUE LABORATORY: Heavy Ion Collisions
Electricity

We owe a lot to foundation builders of ELECTRICITY, which people and society today heavily rely upon.

In just a few hundred years

Ohm’s Law

$$jv = \sigma E,$$
Hundreds of Years from Now: Quarkicity?

How about hot QCD matter, the quark-gluon plasma, when probed with $E$ & $B$ fields?

Unleashed imagination: QGP put into a thin wire

Maybe we shall consider file for a patent of *quarkical devices*

Of course we still have the good old Ohm’s Law $jv = \sigma E$,

*But what else?*
QGP with Restored Chiral Symmetry

* The quark-gluon plasma at high temperature has restored chiral symmetry for light flavors of quarks.

Restored chiral symmetry in QGP allows us to “see” more: we can separately look at right- and left-handed quarks!

\[ L = i \bar{\Psi} \gamma^\mu \partial_\mu \Psi \rightarrow i \bar{\Psi}_L \gamma^\mu \partial_\mu \Psi_L + i \bar{\Psi}_R \gamma^\mu \partial_\mu \Psi_R \]

\[ J^\mu = J^\mu_R + J^\mu_L , \quad J^5_L = J^\mu_R - J^\mu_L \]

The R/L sectors respond to E/B fields independently, and differently!

QGP: L/R \( \rightarrow \) V/A

\[ \vec{E} \quad \text{or} \quad \vec{B} \]
Generalized “Ohm Table” for QGP

\[
\begin{pmatrix}
\vec{J} \\
\vec{J}_5
\end{pmatrix}
= \begin{pmatrix}
\sigma & \sigma_5 \mu_5 \\
\sigma_\chi \mu \mu_5 & \sigma_5 \mu
\end{pmatrix}
\begin{pmatrix}
\vec{E} \\
\vec{B}
\end{pmatrix}
\]

* Chiral Magnetic Effect (CME)
[Vilenkin, 1980; Kharzeev 2004; Kharzeev, McLerran, Warringa, 2008; …]

\[
\vec{J} = \sigma_5 \mu_5 \vec{B}
\]

* Chiral Separation Effect (CSE)
[Son, Zhitnitsky, 2004; Metlitski, Zhitnitsky, 2004; …]

\[
\vec{J}_5 = \sigma_5 \mu \vec{B}
\]

* Chiral Electric Separation Effect (CESE)
[Huang, JL, 2013; Jiang, Huang, JL, 2014; …]
A Chiral QGP?! 

* The Chiral Magnetic (CME) is an anomalous transport

\[ \vec{J} = \sigma_5 \mu_5 \vec{B} \]

- $P$ odd
- $CP$ even
- $P$ even
- $CP$ odd
A Chiral QGP?!

* The Chiral Magnetic (CME) is an anomalous transport

\[ \mathbf{J} = \sigma_5 \mu_5 \mathbf{B} \]

- \( P \) odd
- \( CP \) even
- \( P \) even
- \( CP \) odd

In NORMAL environment, this will NOT happen.
A Chiral QGP?! 

* The Chiral Magnetic (CME) is an anomalous transport

\[ \bar{J} = \sigma_5 \mu_5 \vec{B} \]

In NORMAL environment, this will NOT happen. For this to occur: need a P- and CP-Odd environment!

A (convenient) way to quantify IMBALANCE in the numbers of LH vs RH chiral fermions

\[ \mu_5 \]

But how to get that in the 1st place?
Between RH & LH World...

Drive on left
Links fahren
Tenez la gauche
Tenere la Sinistra

DRIVE-FRANCE.com

Drive Right Lane Help
Free UK Delivery
£ 9.95
Between RH & LH World...

Leaping between RH & LH Worlds, you only need a TUNNEL!
All You Need is E-dot-B!

* The “TUNNEL” we need, is provided by E-dot-B, thanks to CHIRAL ANOMALY, another fundamental property!

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$dQ_5/dt = \int_X C_A \vec{E} \cdot \vec{B}$$

* $C_A$ is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect
All You Need is E-dot-B!

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* C_A is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect
Topological objects in QCD are known to exist and play vital roles. [e.g. ’t Hooft, hep-th/0010225]

\[ Q_w = \frac{g^2}{32\pi^2} \int d^4x \ F_{\mu\nu}^a \tilde{F}_a^{\mu\nu} \sim \vec{E}^a \cdot \vec{B}^a \]
Topological Objects Provide E-dot-B

The Mobius Strip is a neat example to illustrate the gauge field topology.

# of twisting before gluing: topological charge $|Q \sim E \cdot B|$.

Two ways of twisting: LH vs RH (+ or - $|Q|$).

Mobius strip, the simplest nontrivial example of a fiber bundle.
Topological Objects Provide E-dot-B

The Mobius Strip is a neat example to illustrate the gauge field topology.

# of twisting before gluing:

topological charge $|Q \sim E\cdot B|$

Two ways of twisting:
LH vs RH (+ or - $|Q|$)

Nonzero topological charge generates chirality change

Chirality imbalance $\longleftrightarrow$ QCD topological fluctuations!
So How Does CME Work?

\( \mu_R = \mu_L \)  
\( \mu_5 = 0 \)
So How Does CME Work?

One may recognize strong similarity between CME & anomaly.
So How Does CME Work?

One may recognize strong similarity between CME & anomaly.

The CME conductivity is
* fixed entirely by quantum anomaly
* universal from weak to strong coupling
* $T$-even, non-dissipative

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$
Macro Transport from Micro Quantum Anomaly

Theoretical challenge: how to understand and formulate the macroscopic manifestations of chiral anomaly in many-body system?
* How to modify kinetic theory?
* How to modify hydrodynamics?

Experimental challenge: can we observe anomaly driven transport in real many-body systems?
* Quark-gluon plasma in heavy ion collisions
  * Dirac & Weyl semi-metals
Chiral Kinetic Theory

Chiral fermions out-of-equilibrium: how anomaly shows up?

[Son, Yamamoto; Stephanov, Yin; Chen, Son, Stephanov, Yee, Yin; Gao, Liang, Pu, Wang, Wang;...: 2012~2015]

\[
\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial x} \dot{x} + \frac{\partial f}{\partial p} \dot{p} = C[f], \\
\dot{x} - v - \frac{\dot{p} \times b}{2|p|^2} = 0; \\
\dot{p} - E - \dot{x} \times B = 0;
\]

* Definite chirality: Spin “rotates” with momentum \(\rightarrow\) Berry Phase
* CKT: Introducing O(h-bar) quantum effect
* Correctly accounting for anomaly effects

The Chiral Kinetic Theory framework is under rapid development, and will provide the framework for quantitative modeling of anomaly effects for early stage of heavy ion collisions!
Hydrodynamics with Chiral Anomaly

Conservation law:
\[ \partial_\mu J^\mu = 0 \quad \rightarrow \quad \partial_\mu J^\mu = C E^\mu B_\mu \]

Constituent relation:
\[ J^\mu = n u^\mu + \nu^\mu \]

\[ \nu^\mu = -\sigma T P^{\mu\nu} \partial_\nu \left( \frac{\mu}{T} \right) + \sigma E^\mu + \xi \omega^\mu + \xi B^\mu \]

[Son, Surowka, 2009;…] CVE CME

Chiral Fluid: Microscopic Quantum Anomaly manifests itself as macroscopic hydrodynamic currents!

*It provides a hydro framework for simulating anomaly effects.*

*Initial attempts of applying Chiral-Hydro to heavy ion were made.*

[Hirano, Hirono; Yin, Yee; Hirono, Hirano, Kharzeev; Yin, Liao;… ]

[In passing: fluid rotation induces similar effects as magnetic field]
Strong EM Fields in Heavy Ion Collisions

- Strongest B field (and strong E field as well) naturally arises! [Kharzeev, McLerran, Warringa; Skokov, et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao; Skokov-McLerran; Tuchin; ...]
- "Out-of-plane" orientation (approximately)

\[ E, B \sim \gamma \frac{Z \alpha_{EM}}{R_A^2} \sim 3m_{\pi}^2 \]
From CME Current to Charge Separation

The dipole flips e-by-e

\[ \gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle \]
\[ = \langle v_1,\alpha v_1,\beta \rangle + B_{in} - \langle a_\alpha a_\beta \rangle + B_{out} \]

[Kharzeev 2004; Kharzeev, McLerran, Warringa, 2008; ...]

[Voloshin, 2004]

[STAR 2009] Data triggered wide initial enthusiasm
Separation of CME & Flow-Driven Background

\[ \gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle \\
= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}] \]

\[ [B_{in} - B_{out}] \sim v_2 \sim \gamma \]

Could one make some sense of data by two-component picture?

[Bzdak, Koch, JL, 2012; Blocynski, Huang, Zhang, JL, 2013]

H: “CME Signal”
F: “Flow Driven Background”
Toward Quantitative CME

Hydrodynamics with chiral anomaly and charge separation in relativistic heavy ion collisions

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Charge separation!

\[
\partial_\mu J^\mu = \partial_\mu (n u^\mu + Q_f C_A \mu_A B^\mu) = 0
\]

\[
\partial_\mu J_A^\mu = \partial_\mu (n_A u^\mu + Q_f C_A \mu_V B^\mu) = -Q_f^2 e C_A E_{\mu} B^\mu
\]

\[
\left[ \frac{dN_H}{d\phi} \right]_{\text{CME}} \propto [1 + 2 Q^H a_1^H \sin(\phi) + \ldots]
\]
Toward Quantitative CME

\[ \gamma_{\alpha,\beta}^{\text{data}} \simeq \gamma_{\alpha,\beta}^{\text{CME}} + \gamma_{\alpha,\beta}^{\text{TMC}}, \quad \delta_{\alpha,\beta}^{\text{data}} \simeq \delta_{\alpha,\beta}^{\text{CME}} + \delta_{\alpha,\beta}^{\text{TMC}} \]

[Yi Yin, JL, PLB arXiv:1504.06906]

The messages:
* B field lifetime \( \sim 1\text{fm} \) is OK!
* Needed axial charge realistic!
* Data consistent with CME!

Predictions!

\(~ \text{percent of initial entropy density, or } \sim (0.2\text{GeV})^3 !\)
Toward Quantitative CME

The first event-by-event anomalous hydro simulations with glasma initial conditions for axial charges

[Hirono, Hirano, Kharzeev, arXiv:1412.0311]

* The correlations are sensitive to the CME contributions
* Comparison with data suggests “room” for backgrounds.
Chiral Magnetic Wave (CMW)

Wave: propagating “oscillations” of two coupled quantities e.g. sound wave (pressure & density); EM wave (E & B fields)

EM wave

CME + CSE —> gapless collective excitations, the CMW

\[
\mathbf{J} = \sigma_5 \mu_5 \mathbf{B} \\
\mathbf{J}_5 = \sigma_5 \mu \mathbf{B}
\]

\[
\left( \partial_0 \pm \frac{Qe}{4\pi^2} \chi \mathbf{B} \cdot \nabla \right) \delta J^0_{R/L} = (\partial_0 \pm v_B \partial_B) \delta J^0_{R/L} = 0.
\]

[Kharzeev, Yee, 2010; Burnier, Kharzeev, JL, Yee, 2011]
CMW Induced Flow Splitting

CMW $\rightarrow$ charge quadrupole of QGP $\rightarrow$ flow splitting

[Kharzeev, Yee, 2010; Burnier, Kharzeev, JL, Yee, PRL2011]

\[ \nu_2^+ - \nu_2^- = r_e A \]

\[ r = 3.1985 \pm 0.2903 \]

[STAR, PRL2015]
New Territory of CME Search: Table-Top Exp.

The anomalous transport phenomena are universal phenomena across boundaries of disciplines, encompassing a wide range of chiral systems!

**Weyl semimetal**
(non-degenerated bands)

- TaAs
- NbAs
- NbP
- TaP

**Dirac semimetal**
(doubly degenerated bands)

- ZrTe$_5$
- Na$_3$Bi,
- Cd$_3$As$_2$

Massless fermion dispersion:

\[
\hat{H} = \hbar v_F \begin{pmatrix}
0 & k_x - ik_y \\
k_x + ik_y & 0
\end{pmatrix} = \hbar v_F \sigma \cdot \mathbf{k},
\]

These quasiparticles also exhibit chiral anomaly!
New Territory of CME Search: Table-Top Exp.

\[ N_{L,R} \approx \frac{e^2}{4\pi^2 \hbar^2 c} \vec{E} \cdot \vec{B} \tau_v \]

\[ \mu \equiv \mu_L - \mu_R \sim \vec{E} \cdot \vec{B} \tau_v \]

\[ \vec{J}_{CME} = \frac{e^2}{2\pi^2} \mu \vec{B} \]

\[ J^i_{CME} = \sigma_{CME}^{ik} E^k; \quad \sigma_{CME}^{zz} \sim B^2 \]

\[ \sigma = \sigma_0 + \sigma_{CME} = + \sigma_0 + a(T)B^2 \]
Summary

An old and new phase of quantum matter: quark-gluon plasma.

Heavy ion collisions create such QGP with unprecedented high temperature ~ trillion K.

Microscopic chiral anomaly manifests as anomalous transport effects in a chiral QGP: Chiral Magnetic Effect, Chiral Magnetic Wave, …
Toward Physics of Beam Energy Scan

* Establishing a chiral QGP at higher energy
* Searching for chiral critical point or 1st-order transition at lower energy

Beam Energy Scan Theory (BEST) Collaboration:
BNL, IU, LBNL, McGill U, Michigan State U, MIT, NCSU, OSU, Stony Brook U, U Chicago, U Conn, U Huston, UIC