From Gluon Topology to Chiral Anomaly: Emergent Phenomena in QGP

Jinfeng Liao
Indiana University, Physics Dept. & CEEM
RIKEN BNL Research Center
Research Supported by NSF & DOE
Emergent Phenomena

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and “applications”.

It embodies many deep aspects of relativistic quantum field theory (confinement, asymptotic freedom, anomalies/instantons, spontaneous symmetry breaking ...)

For this talk: two emergent phenomena in the QGP
More Is Different

Emergence can be highly nontrivial at various levels. Understanding these are NO LESS fundamental than the basic laws: aka Anderson, “More is different”!

The simple/natural phase of “lego matter”

The emergent phase of “lego matter”: it has its own life!
sQGP as New Emergent Phase
The simple/natural phase of QCD matter is the quark-gluon plasma at VERY HIGH temperature.

\[ T \gg \Lambda_{QCD} \sim 200\text{MeV} \]
The Vacuum Phase of QCD

Confinement  Chiral symmetry breaking

Dirac Sea

Hadron spectroscopy: vacuum excitations

\[ T \ll \Lambda_{QCD} \sim 200\text{MeV} \]

QCD vacuum is emergent:

it is not empty, but a complex, nonperturbative form of matter.

Original motivation of heavy ion collisions:
create the natural phase of QCD
So Where Are We at RHIC and the LHC?

The old dream

strongly coupled
confined phase

Tc

asymptotically free QGP

The new paradigm thanks to discoveries at RHIC and LHC (1~3Tc):

strongly coupled QGP (sQGP)

~3Tc

Tc

strongly coupled
confined phase

T ≪ \Lambda_{QCD} \sim 200\text{MeV}

T \sim \Lambda_{QCD} \sim 200\text{MeV}

T ≫ \Lambda_{QCD} \sim 200\text{MeV}

nearly perfect fluidity
extremely color opaque
sQGP: A New Emergent Phase

Liberation of Thermal DoF

Degree of color liberation

Shuryak, Liao,…: this is a chromo-magnetic monopole plasma!

Pisarski, …: this is a semi-QGP!

The two pictures are in complement, from Electric or Magnetic language respectively, and reconciled into one coherent message:

The sQGP is a new emergent phase of QCD matter, with suppressed quarks/gluons and a significant monopole component;

It naturally bridges the confined phase and wQGP!
The Mobius Strip is a neat example to illustrate the gauge field topology.

't Hooft-Polvalov monopole in George-Glashow model with SU(2)

\[ L = -\frac{1}{2} \text{Tr} F_{\mu \nu} F^{\mu \nu} + \text{Tr} D_\mu \phi D^\mu \phi - V(\phi) \]

with higgs-type condensate

\[ |\hat{x}| \to \infty \]
\[ |U \in SU^{-1}| = v \neq 0 \]

Mapping: \[ S^2 \to SU(2) \]

Topological charge & Magnetic charge

\[ g = \frac{4\pi n}{e}, \quad n \in \mathbb{Z} \]

BPS limit:

\[ V \to 0 \]
Important Features of Emergent Monopoles

In the Higgs phase with VEV to be $v$:

- Gluons $\rightarrow M_w = e \ast v$
- Higgs $\rightarrow M_H \sim v \ast \lambda$
- Monopoles $\rightarrow M_m = g \ast v$
- M-core $\rightarrow$ size: $R \sim \frac{1}{e \ast v}$

At strong coupling $T \sim T_c$, they become the light, and well localized objects ("particles" if you like), being the emergent and dominant D.o.F.

The monopoles undergo condensate at $T_c$, leading to confinement.

[Liao, Shuryak, Chernodub, Zakharov, D’Elia, Ratti, Zahed, Larsen, ......]
The model implementations of electric and magnetic components are well constrained by available lattice data.

* Electric density: L-loop suppression

\[ \chi_T = c_q L + c_g L^2 \]

* Magnetic density: constrained by total pressure

\[ (1 - \chi_T) \]

* Running coupling: L-loop suppression

\[ \alpha_s(Q^2) = \alpha_c / \left[ 1 + \frac{9\alpha_c}{4\pi} \log \left( \frac{Q^2}{T_c^2} \right) \right] \]

* Screening:

\[ f_E(T) = \sqrt{\chi_T}, \quad f_M(T) = c_m g \]

[Xu, JL, Gyulassy, arXiv:1411.3673(CPL); 1508.00552(JHEP)]
The SEVEN set of single hadron observables

\[
[ (\text{RHIC}+\text{LHC}) \times (\text{RAA}+\text{V2}) \times (\text{pion}) ] \\
+ [ (\text{LHC}) \times (\text{RAA}+\text{V2}) \times (D) ] \\
+ [ (\text{LHC}) \times (\text{RAA}) \times (B) ],
\]

are nicely explained by CUJET3.0 framework (with essentially only ONE model parameter) that implements the nonperturbative near-Tc physics!

[Xu, JL, Gyulassy, arXiv:1411.3673(CPL); 1508.00552(JHEP)]
**sQGP Properties from CUJET3.0**

* sQGP in the near $T_c$ region is special, with emergent monopoles.

* CUJET3.0, based on sQGMP, explains 7 sets of jet energy loss observables from RHIC to LHC, and predicts specific $T$-dependence of sQGP transport properties!

[Xu, JL, Gyulassy, arXiv:1411.3673(CPL); 1508.00552(JHEP)]
Let Us Now Move to Quarks:

Basic Dynamics – Chiral Anomaly

Emergent Phenomenon – Chiral Magnetic Effect
Exciting Progress: See Recent Reviews


Chiral Anomaly

* Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

**Classical symmetry:**

\[ \mathcal{L} = i \bar{\Psi} \gamma^\mu \partial_\mu \Psi \]
\[ \mathcal{L} \rightarrow i \bar{\Psi}_L \gamma^\mu \partial_\mu \Psi_L + i \bar{\Psi}_R \gamma^\mu \partial_\mu \Psi_R \]
\[ \Lambda_A : \Psi \rightarrow e^{i \gamma_5 \theta} \Psi \]

**Broken at QM level:**

\[ \partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B} \]
\[ \frac{d Q_5}{dt} = \int_x C_A \vec{E} \cdot \vec{B} \]

* C_A is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect
Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

\[ \partial_{\mu} J_{5}^{\mu} = C_{A} \vec{E} \cdot \vec{B} \]

\[ dQ_{5}/dt = \int_{x} C_{A} \vec{E} \cdot \vec{B} \]

Illustrated with Lowest-Landau-Level (LLL) picture: the LLL is chiral!
Would chiral anomaly, usually considered at microscopic level, manifest itself macroscopically as emergent phenomenon in a system of many chiral fermions?

This is a relevant question, for e.g. the quark-gluon plasma, where light quarks have approximate chiral symmetry at high T.

The restored chiral symmetry in quark-gluon plasma (QGP) phase
Anomalous Transport: Chiral Magnetic Effect

* The Chiral Magnetic (CME) is an anomalous transport

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

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

\[\mu_5\]

\[\Rightarrow\]

**A CHIRAL QGP!**

Such imbalance can be generated through chiral anomaly coupled with topological fluctuations (F-F-dual) of the gluonic sector.
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
From CME Current to Charge Separation

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

**strong radial blast:** position $\rightarrow$ momentum

\[ \frac{dN_\pm}{d\phi} \propto \ldots + a_\pm \sin(\phi - \Psi_{RP}) \]

\[ < a_\pm > \sim \pm < \mu_5 > B \]

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

Charge Separation, or Electric Dipole in Pt Space (along out-of-plane)
Charge Separation Observable

\[ \frac{dN_{\pm}}{d\phi} \propto \ldots + a_{\pm} \sin(\phi - \Psi_{RP}) \]

\[ \langle a_{\pm} \rangle \sim \pm \langle \mu_5 \rangle \quad B \to 0 \]

The dipole flips e-by-e and averages to zero (no global P-violation)

[Voloshin, 2004]

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

known to be very small

what we are looking for

known to be very small

The hope was: these two cancel out to be negligible...

As it was pointed out later, the backgrounds turn out to be NOT negligible…

[STAR 2009]

[Bzdak, Koch, JL, 2009, 2010; Wang; Pratt, …]
The CME-induced charge separation can be measured via suitable particle correlations.

\[ H_{CME} \rightarrow 2a_1^2 \]

Compelling experimental evidence for CME in QGP! — can we quantitatively explain such signal?

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

[Voloshin, 2004] [STAR PRL 2014]
Hydrodynamics That Knows Left & Right

conservation law:

\[ \partial_\mu J^\mu = 0 \quad \rightarrow \quad \partial_\mu J^\mu = CE^\mu B_\mu \]

constituent relation:

\[ J^\mu = n u^\mu + \nu^\mu \]

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

[Son, Surowka, 2009;…]

Chiral Fluid: Microscopic chiral anomaly emerges as macroscopic hydrodynamic currents!

It is the “21st century hydrodynamics”: new development since Navier-Stocks!

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]
Chiral Viscous Fluid Dynamics Simulations

[Jiang, Shi, Yin, JL, 2016.]

\[ D_\mu J_R^\mu = + \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \]
\[ D_\mu J_L^\mu = - \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \]
\[ J_R^\mu = n_R u_\mu + \nu_R^\mu + \frac{\sigma}{2} E_\mu + \frac{N_c q}{4\pi^2} \mu_R B^\mu \]
\[ J_L^\mu = n_L u_\mu + \nu_L^\mu + \frac{\sigma}{2} E_\mu - \frac{N_c q}{4\pi^2} \mu_L B^\mu \]
\[ \nu_{R,L}\mu = (\nu_{NS}\mu - \nu_{R,L}\mu) / \tau_{rlx} \]

on top of 2+1D VISHNew---OSU Group

\[ D_\mu T^{\mu\nu} = 0 \quad n = 0 \]

B field + \mu_A \Rightarrow charge separation

\[ dN_\pm/d\phi \propto 1 + 2a_{1\pm} \sin(\phi - \psi_{RP}) + ... \]
Chiral Viscous Fluid Dynamics Simulations

Initial Condition

No B Field

With B Field

[Jiang, Shi, Yin, JL, 2016.]
Chiral Viscous Fluid Dynamics Simulations

Initial Condition

Left Hand Density

Right Hand Density

[Jiang, Shi, Yin, JL, 2016.]
Chiral Viscous Fluid Dynamics Simulations

With realistic initial axial charge density and short magnetic lifetime, the data can be describe well.

\[ B = \frac{B_0}{1 + \left( \frac{\tau}{\tau_B} \right)} \]

\[ \tau_B = 0.6 \text{fm/c} \]

\[ \frac{n_A}{s} \propto \left( \frac{dN}{d\eta} \right)^{-1/3} \]

[Chiral Viscous Fluid Dynamics Simulations]

[STAR, MS & HHK (n_A/s=14%), KKV (n_A/s=10%)]

[10, 20, 30, 40, 50, 60] Centrality (%)
Is Strangeness Chiral?

Measuring charge separation for Kaons: an exciting opportunity to tell to which extent the strange quarks are chiral!

Blue symbols are for charged kaons.

[Jiang, Shi, Yin, JL, 2016.]
Summary: Emergent Phenomena in sQGP

* The sQGP near $T_c$ consists an emergent component of chromo-magnetic monopoles.

* The CUJET3.0, implementing such physics, explains jet energy loss data, and predicts nontrivial $T$-dependence of sQGP transport properties.

* The chiral anomaly emerges in sQGP as Chiral Magnetic Effect.

* New Chiral Viscous Fluid Dynamics simulations can quantitatively describe the CME-induced charge separation as measured by STAR.
Backup Slides
Event-By-Event Magnetic Fields

Azimuthal orientation fluctuates!
Proton is a finite size object!

Bloczynski, Huang, Zhang, JL, PLB 718 (2013) 1529
[arXiv:1209.6594]
Quantifying Rotation of QGP

Convenient parameterization:

\[ \langle \omega_y \rangle (t, b, \sqrt{s_{NN}}) = A(b, \sqrt{s_{NN}}) + B(b, \sqrt{s_{NN}}) (0.58t)^{0.35} e^{-0.58t} \]

\[ A = \left[ e^{-0.016b\sqrt{s_{NN}}} + 1 \right] \times \tanh(0.28b) \times [0.001775 \tanh(3 - 0.015\sqrt{s_{NN}}) + 0.0128] \]

\[ B = \left[ e^{-0.016b\sqrt{s_{NN}}} + 1 \right] \times [0.02388b + 0.01203] \times [1.751 - \tanh(0.01\sqrt{s_{NN}})] . \]

Chiral Viscous Fluid Dynamics Simulations

[Jiang, Shi, Yin, JL, 2016.]

**Dependence on viscous parameters**
*(conductivity, relaxation time)*
Chiral Viscous Fluid Dynamics Simulations

[Chiral Viscous Fluid Dynamics Simulations, Jiang, Shi, Yin, JL, 2016.]

\[ B = \frac{B_0}{1 + \left( \frac{\tau}{\tau_B} \right)} \]

Charge separation is linearly proportional to the initial axial charge density.

It is not sensitive to the initial vector charge density.
Charge separation is very sensitive to $B$ field lifetime.

$B = \frac{B_0}{1 + \left(\frac{\tau}{\tau_B}\right)}$

Chiral Viscous Fluid Dynamics Simulations

[Jiang, Shi, Yin, JL, 2016.]
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]

\[
\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial x} \dot{x} + \frac{\partial f}{\partial p} \dot{p} = C[f],
\]

\[
\dot{x} - v - \frac{\dot{p} \times b}{2|p|^2} = 0; \quad \dot{p} - E - \dot{x} \times B = 0;
\]

* Definite chirality: Spin “rotates” with momentum -> 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!
A first quantification of charge separation from initial anomalous current by non-eq. CME!
Upcoming Isobaric Collisions

New Proposal of Isobaric Collisions @ RHIC:
up to 10% variation in B field, thus ~20% shift of CME signal!

---

**96_{40}Zirconium vs 96_{44}Ruthenium**

<table>
<thead>
<tr>
<th></th>
<th>96_{44}Ru+96_{44}Ru</th>
<th>vs</th>
<th>96_{40}Zr+96_{40}Zr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>≤</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMW</td>
<td>&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CME</td>
<td>&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVE</td>
<td>=</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The isobaric collisions will be a crucial test!
Toward Physics of Beam Energy Scan

* Establishing a chiral QGP at higher energy via anomalous chiral effects
* Searching for chiral critical point & 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