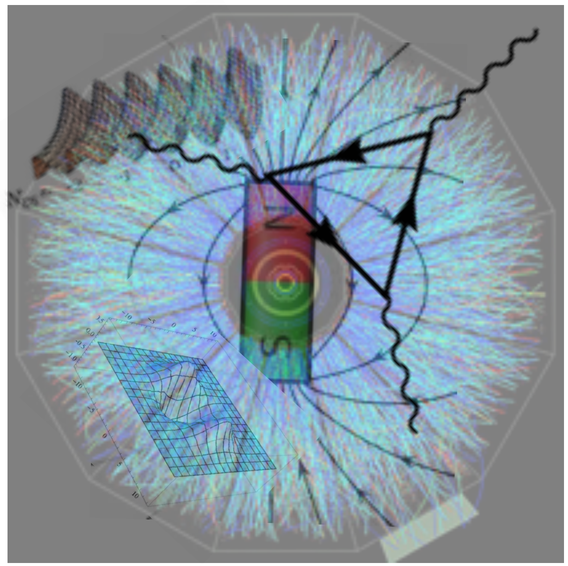
SQM2016 @ Berkeley JUN. 29, 2016

From Gluon Topology to Chiral Anomaly: Emergent Phenomena in QGP



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Research Supported by NSF & DOE

Emergent Phenomena

F. Wilczek @ QM2014

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

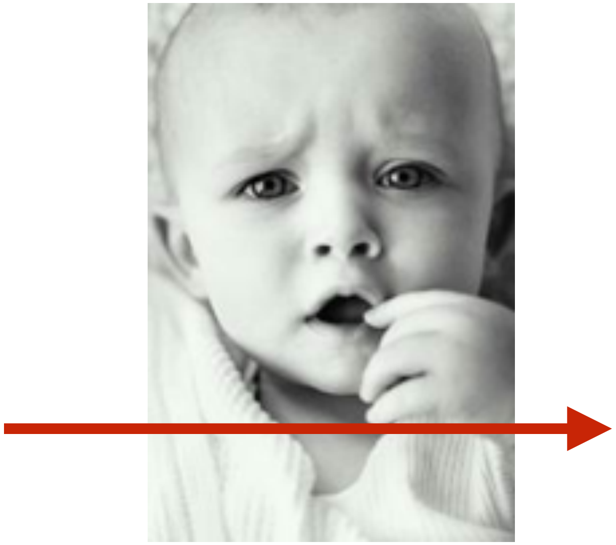
In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

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"

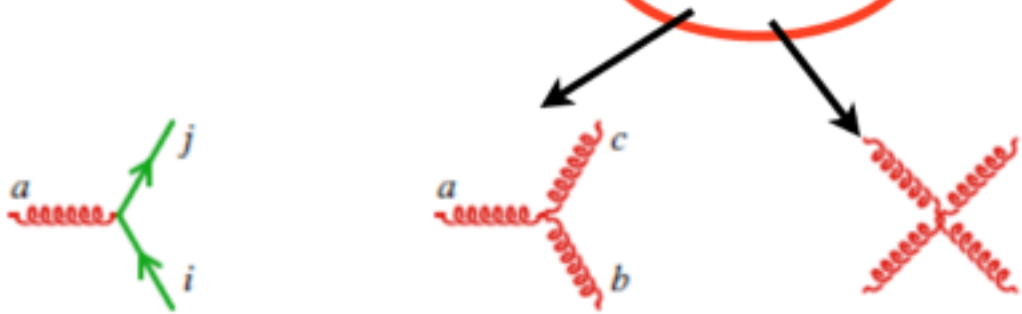
The emergent phase of "lego matter": it has its own life!

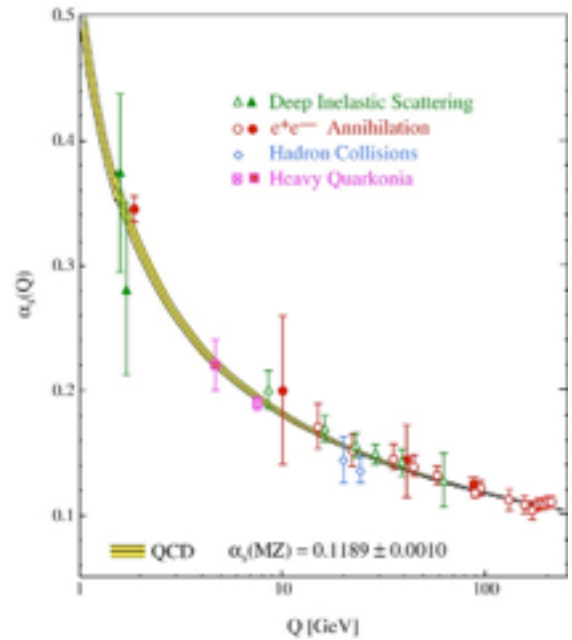
sQGP as New Emergent Phase

The Simple/Natural Phase of QCD

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - M - g A\!\!\!/_a G^a)\psi - \frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu}$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$

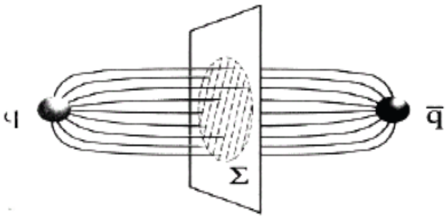


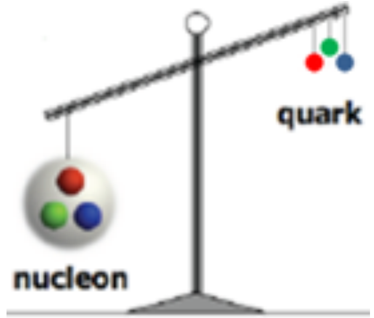


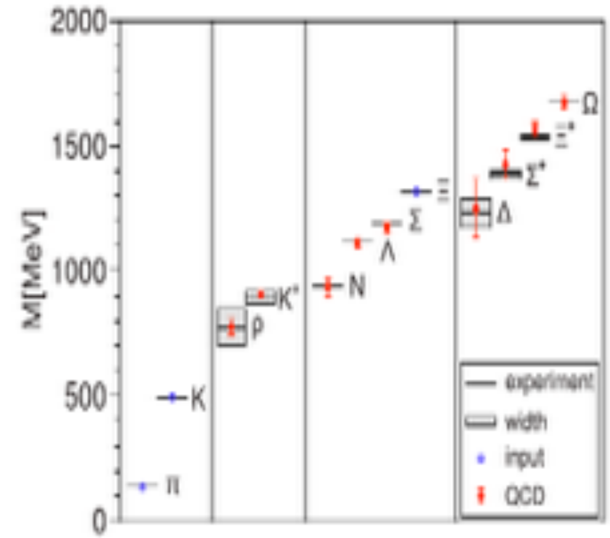
The simple/natural phase of QCD matter is the quark-gluon plasma at VERY HIGH temperature.

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

The Vacuum Phase of QCD

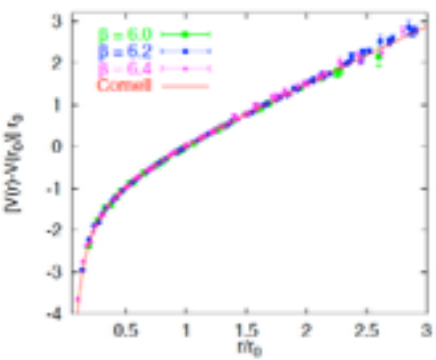


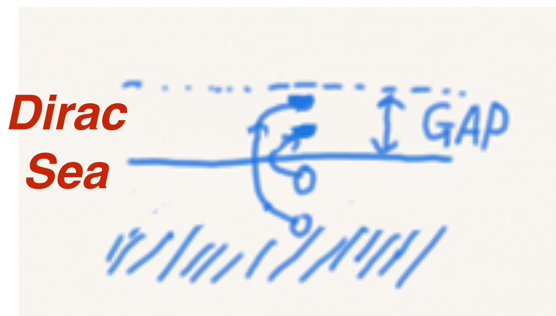




Confinement

Chiral symmetry breaking





Hadron spectroscopy: vacuum excitaitons

$$T \ll \Lambda_{QCD} \sim 200\mathrm{MeV}$$

QCD vacuum is emergent:

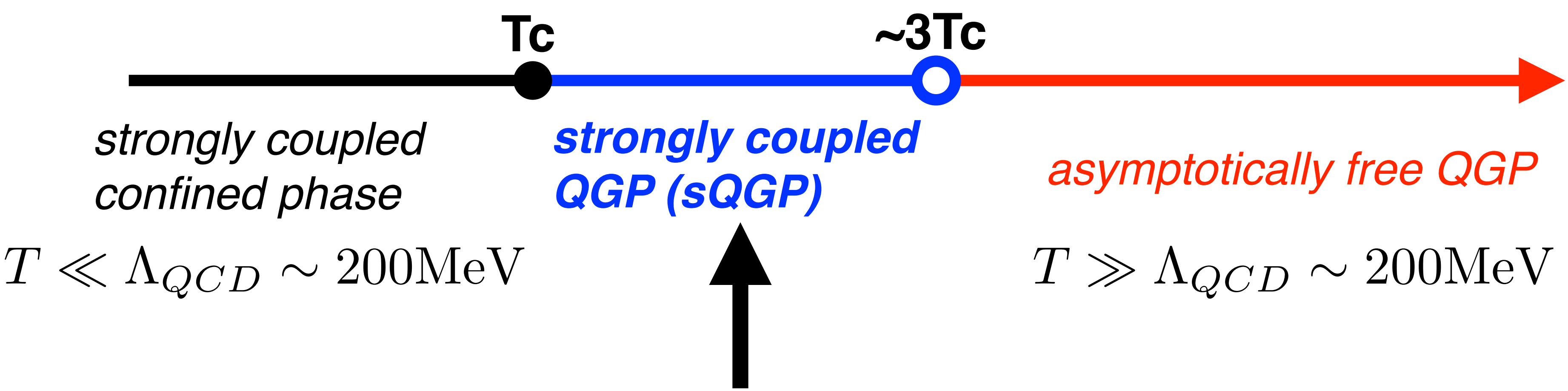
it is not empty, but a complex, nonperturbative form of matter.

Original motivation of heavy ion collisions: create the natural phase of QCD

So Where Are We at RHIC and the LHC?

The old dream

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

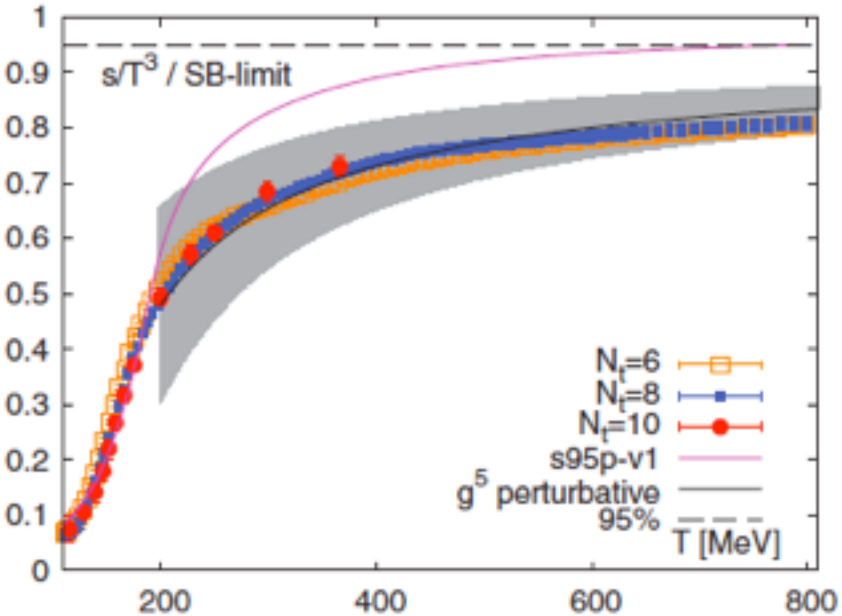


nearly perfect fluidity
extremely color opaque
……

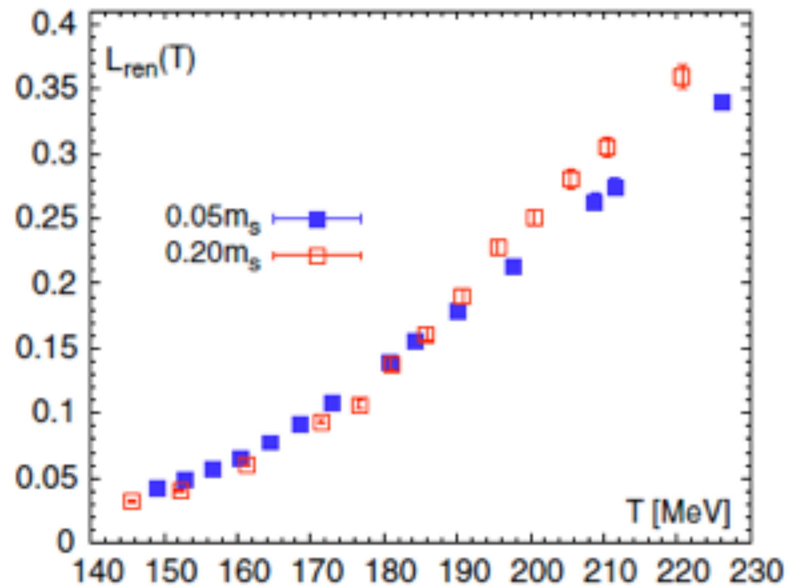
$$T \sim \Lambda_{QCD} \sim 200\mathrm{MeV}$$

sQGP: A New Emergent Phase

Liberation of Thermal DoF



Degree of color liberation

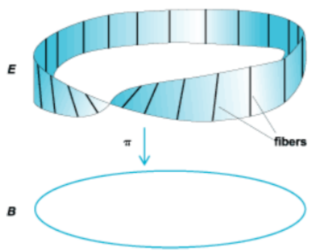


Shuryak, Liao,…: this is a chromo-magnetic monopole plasma!

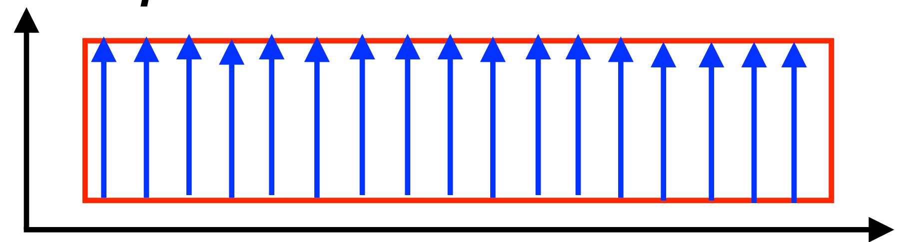
Pisarski, …: this is a semi-QGP!

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!

Topological Objects: How Are Monopoles Made?



Möbius strip, the simplest nontrivial example of a fiber bundle



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

\# of twisting before gluing: topological charge

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

$$L = -\frac{1}{2}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} + \mathrm{Tr}\, D_\mu\phi D^\mu\phi - V(\phi)$$ with higgs-type condensate

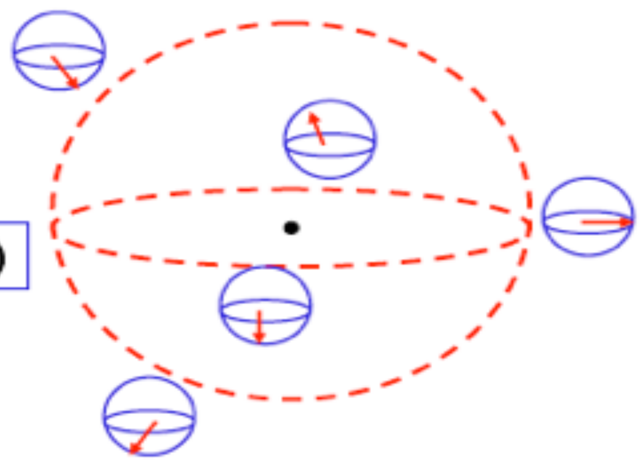
$$|\vec{x}| \longrightarrow \infty$$

$$|U\Phi U^{-1}| = v \neq 0$$

$$\text{Mapping}: \quad S^2 \longrightarrow SU(2)$$

Topological charge &
Magnetic charge

$$g = \frac{4\pi n}{e}, \qquad n \in \mathbb{Z}$$



BPS limit:
$V \to 0$

Important Features of Emergent Monopoles

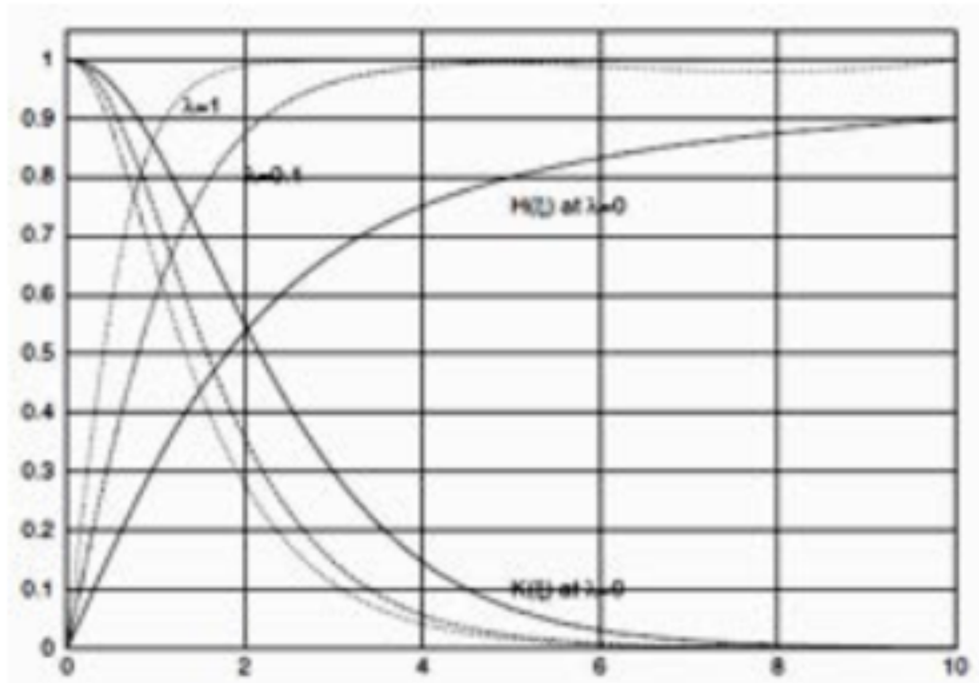
In the Higgs phase with VEV to be v:

Gluons → $M_W = e * v$

Higgs → $M_H \sim v * \lambda$

Monopoles → $M_m = g * v$

M-core → size: $R \sim \dfrac{1}{e * v}$

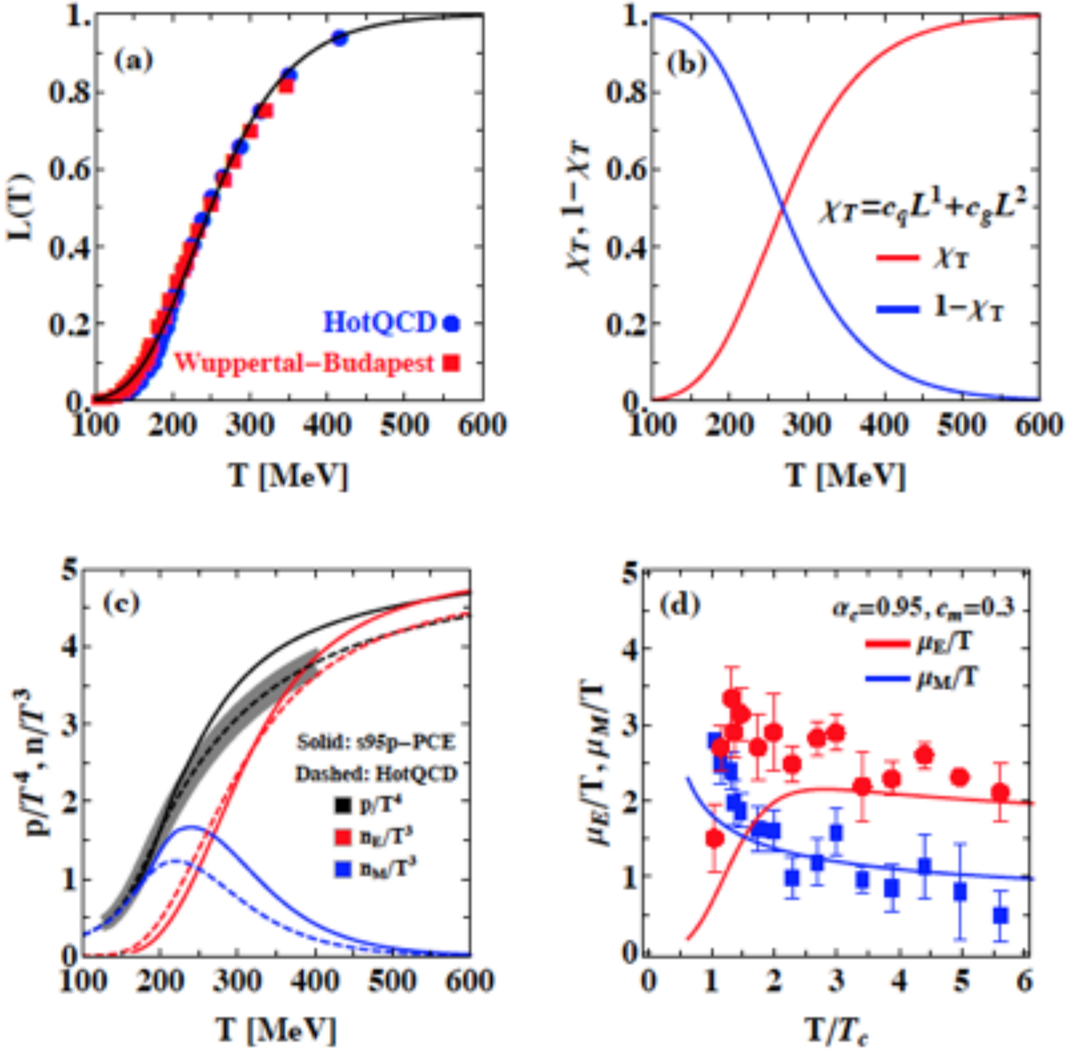


At strong coupling T~Tc, they become the light, and well localized objects ("particles" if you like), being the emergent and dominant D.o.F.

The monopoles undergo condensate at Tc, leading to confinement.

[Liao, Shuryak, Chernodub, Zakharov, D'Elia, Ratti, Zahed, Larsen, ……]

The Making of sQGP in CUJET3.0



* *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

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

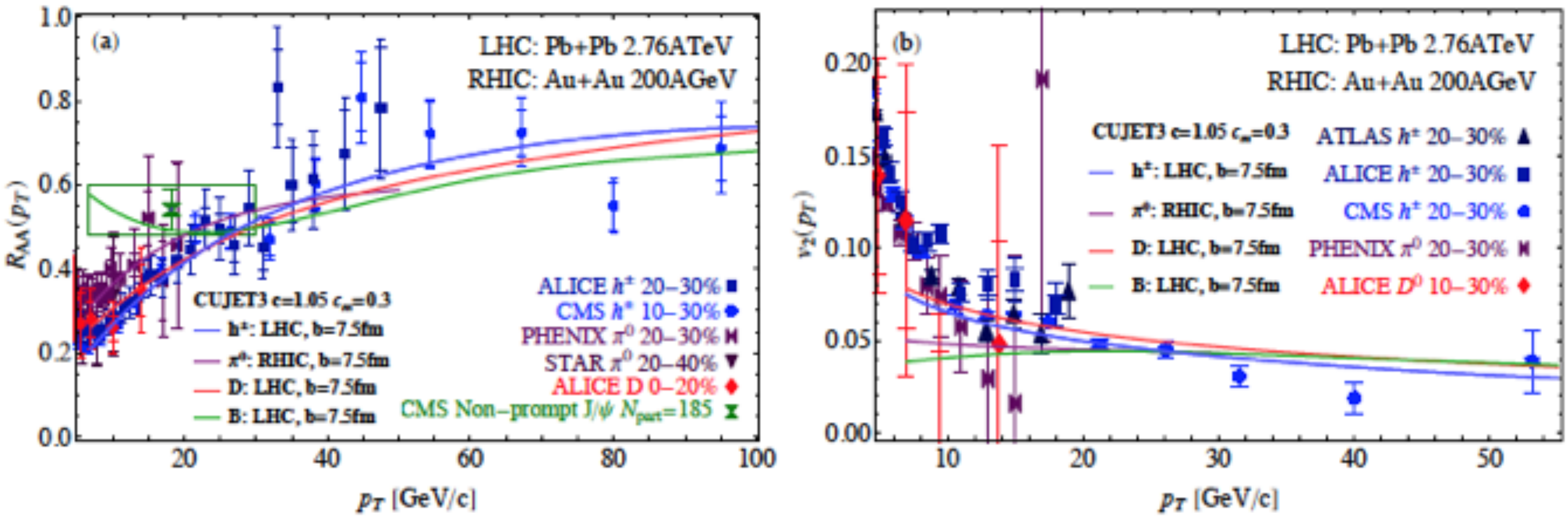
* *Screening:*

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

The model implementations of electric and magnetic components are **well constrained by available lattice data.**

[Xu, JL, Gyulassy, arXiv:1411.3673(CPL); 1508.00552(JHEP)]

CUJET3.0 Explains (RHIC+LHC)*(Raa+V2)!



The **SEVEN** set of single hadron observables

*[(RHIC+LHC) * (RAA+V2) * (pion)]*

*+ [(LHC) * (RAA+V2) * (D)]*

*+ [(LHC) * (RAA) * (B)],*

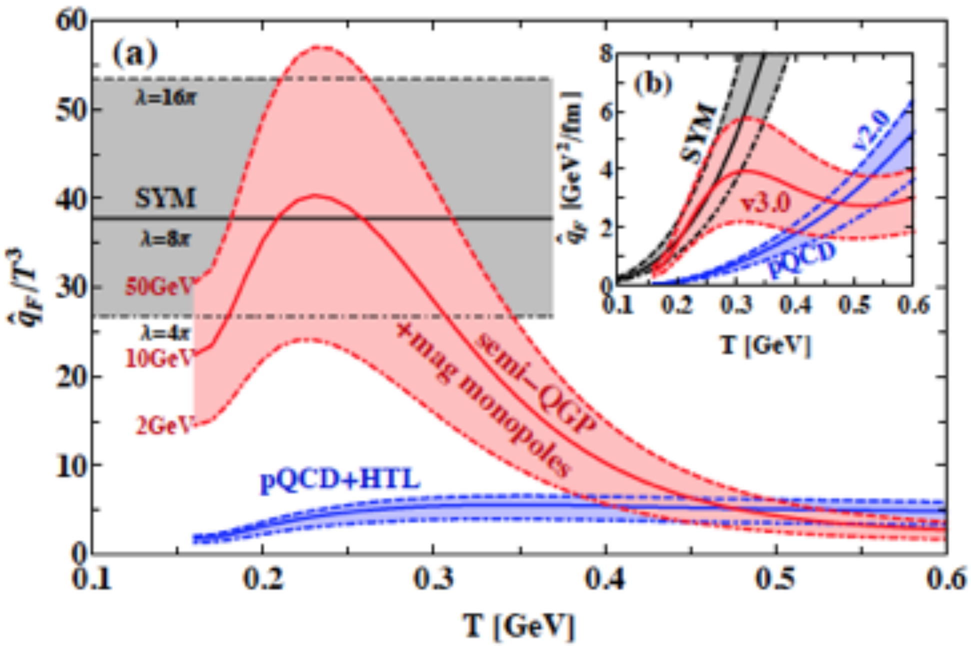
are nicely explained by CUJET3.0 framework
(with essentially only ONE model parameter)
that implements the nonperturbative near-Tc physics!

[Xu, JL, Gyulassy, arXiv:1411.3673(CPL); 1508.00552(JHEP)]

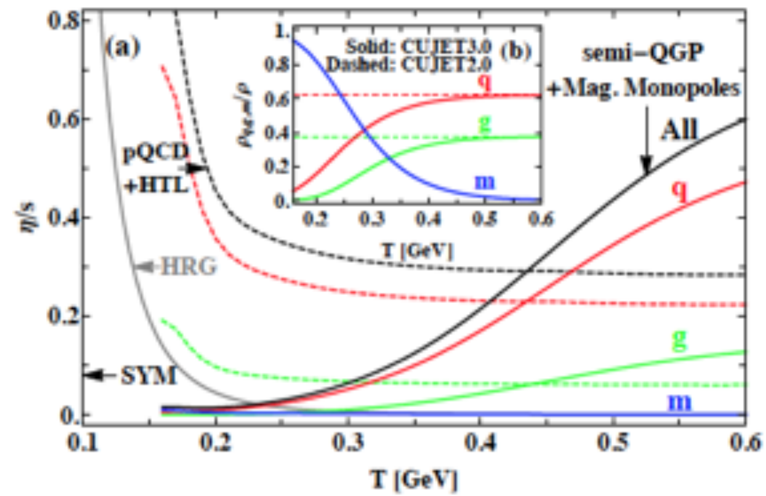
sQGP Properties from CUJET3.0

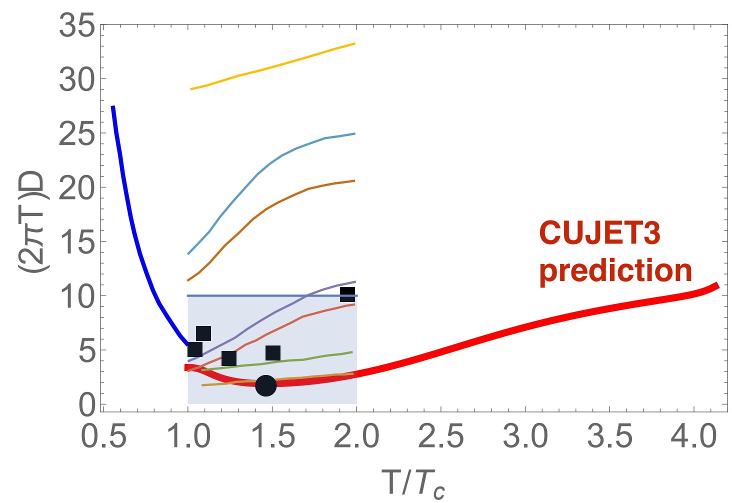
*** sQGP in the near Tc region is special, with emergent monopoles.**

*** 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

Progress in Particle and Nuclear Physics 88 (2016) 1–28

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Review

Chiral magnetic and vortical effects in high-energy nuclear collisions—A status report

CrossMark

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Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050 [hep-ph]].

J. Liao, Pramana 84, no. 5, 901 (2015) [arXiv:1401.2500 [hep-ph]].

Chiral Anomaly

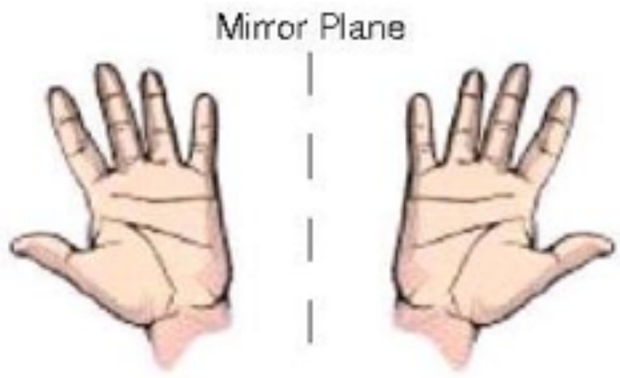
Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

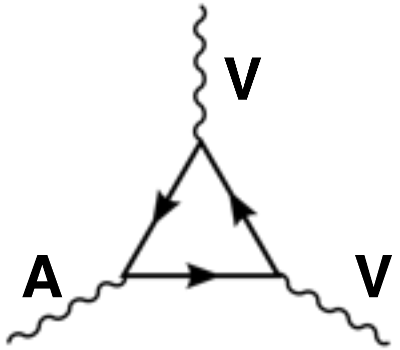
Classical symmetry:

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

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

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





Broken at QM level:

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

$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$$

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

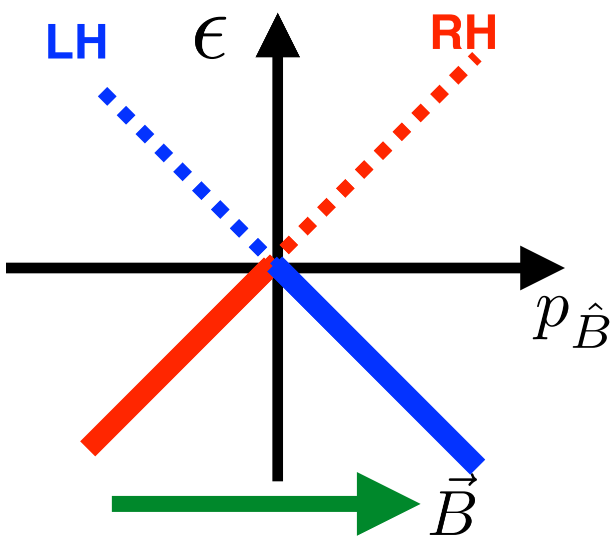
Chiral Anomaly

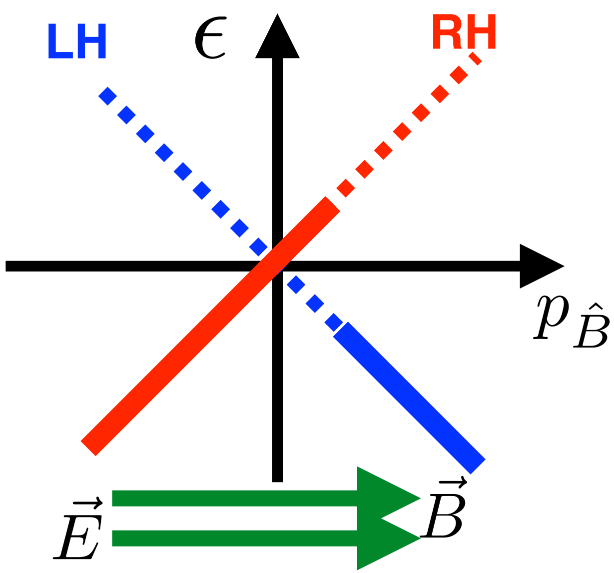
Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

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

$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$$

$$J_5^\mu = J_R^\mu - J_L^\mu$$



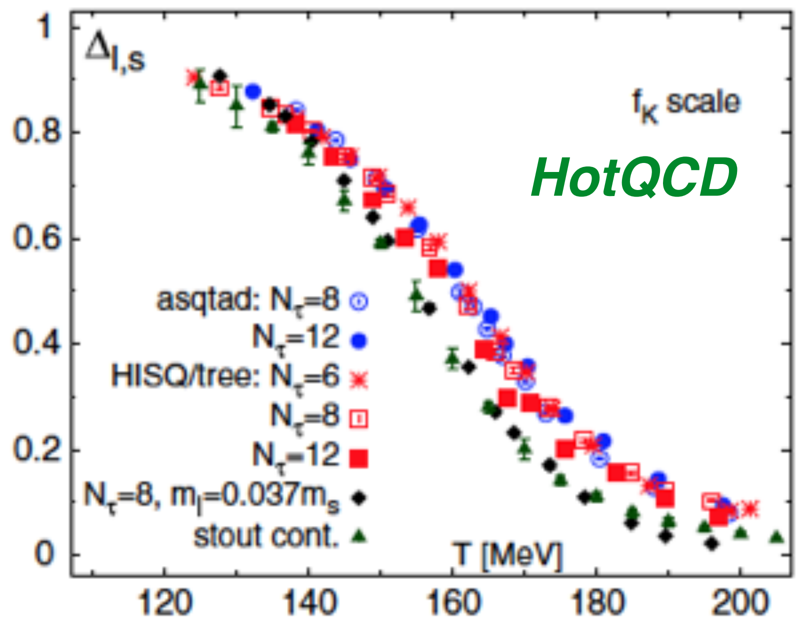


Illustrated with Lowest-Landau-Level (LLL) picture: the LLL is chiral!

Chiral Anomaly in Many-Body System

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**

$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$

P odd
CP even

P even
CP odd

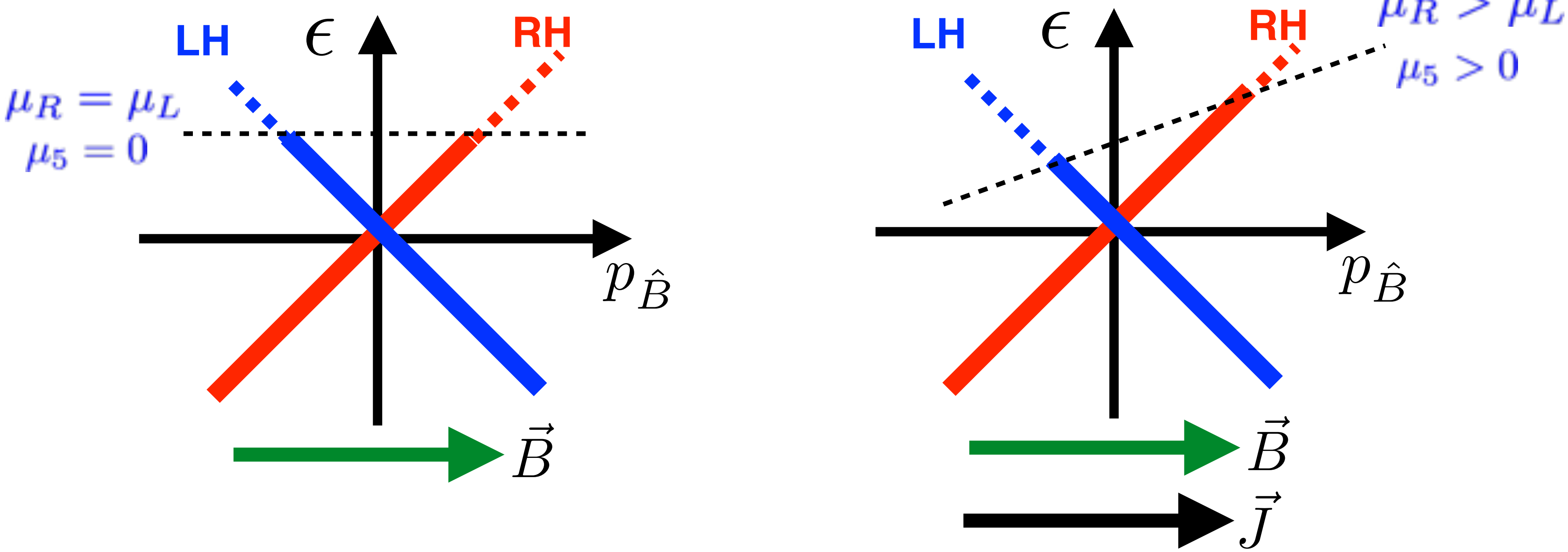
In NORMAL environment, this will NOT happen.
For this to occur: need a P- and CP-Odd environment!

$$\mu_5$$

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

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

$$\updownarrow$$

$$\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}$$

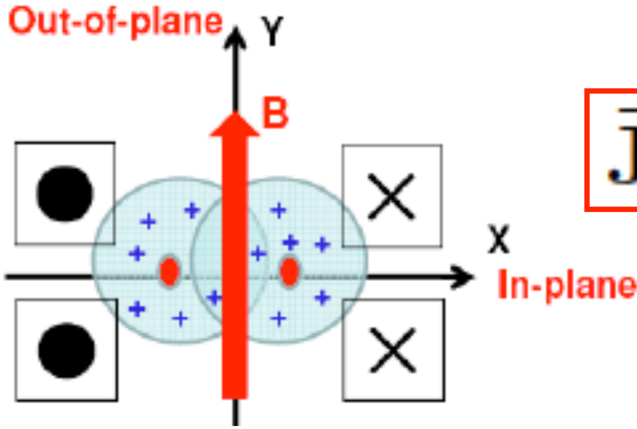
The CME conductivity is

**** fixed entirely by quantum anomaly***

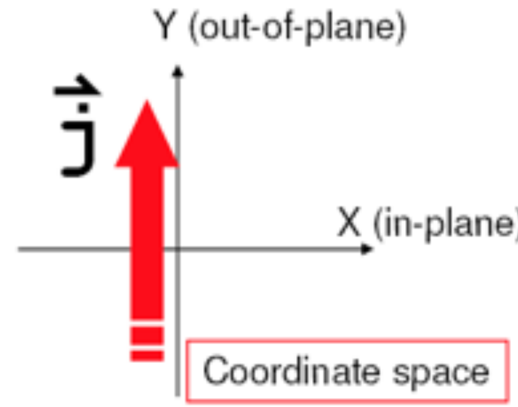
**** universal from weak to strong coupling***

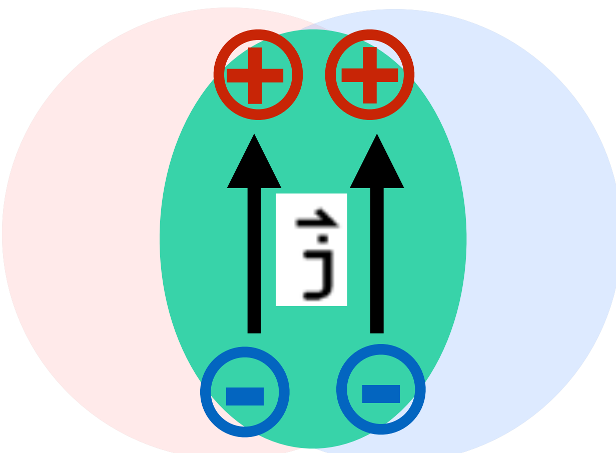
**** T-even, non-dissipative***

From CME Current to Charge Separation

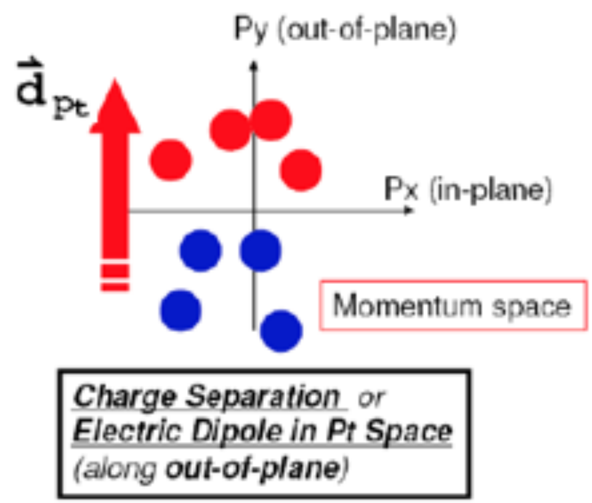


$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$





strong radial blast:
position —> 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 Observable

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

$$< a_\pm > \sim \pm < \mu_5 > B \to 0$$

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

[Voloshin, 2004]

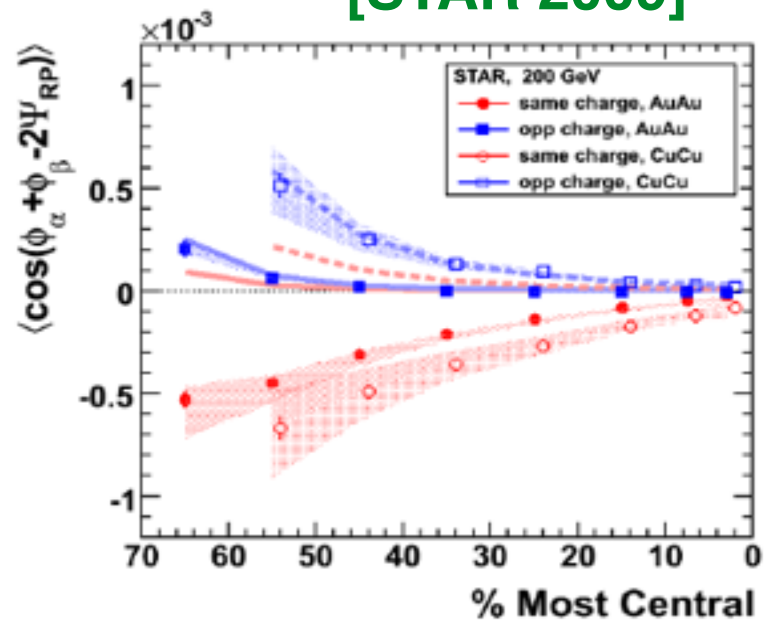
$$\gamma = \langle cos(\phi_\alpha + \phi_\beta - 2\psi_{RP})\rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}]$$

known to be very small

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

what we are looking for

[STAR 2009]



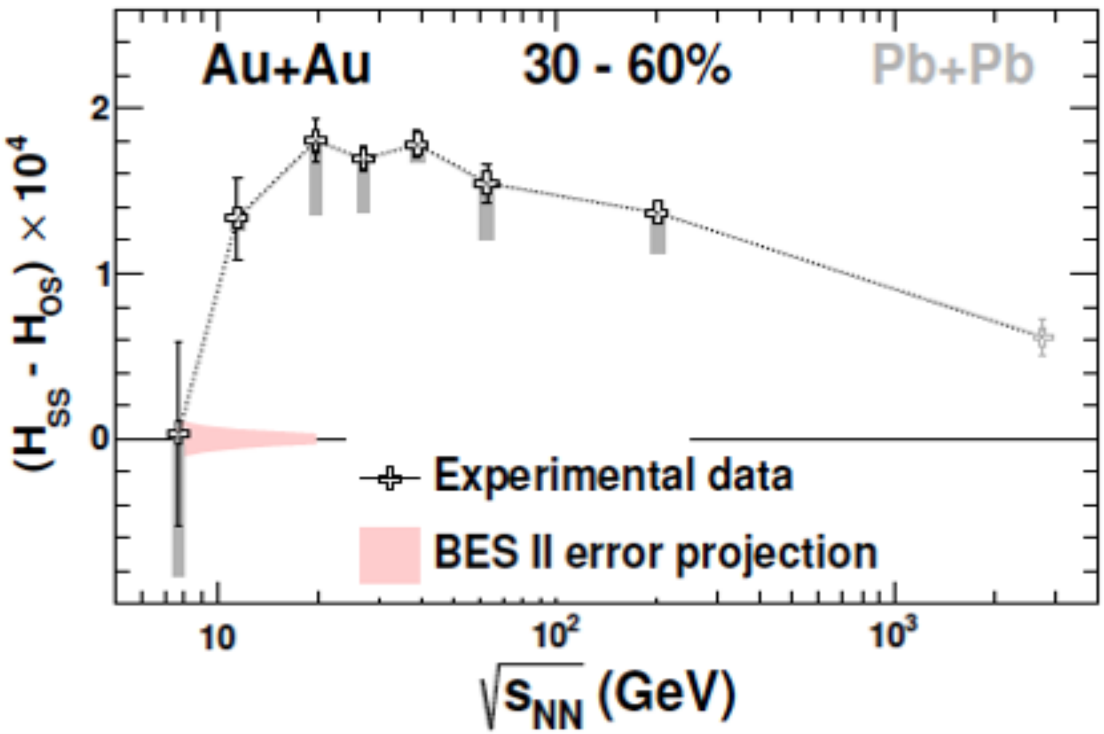
As it was pointed out later, the backgrounds turn out to be NOT negligible…

[Bzdak, Koch, JL, 2009, 2010; Wang; Pratt, …]

Experimental Signal of CME

The CME-induced charge separation can be measured via suitable particle correlations.

[Voloshin, 2004] [Bzdak, Koch, JL, 2012; Blocynski, Huang, Zhang, JL, 2013]



$$H_{CME} \to 2a_1^2$$

[STAR PRL 2014]

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

Hydrodynamics That Knows Left & Right

conservation law: $\partial_\mu J^\mu = 0 \rightarrow \partial_\mu J^\mu = C E^\mu B_\mu$

constituent relation: $J^\mu = n u^\mu + \nu^\mu$

$\partial_\mu s^\mu \geq 0$ $\nu^\mu = -\sigma T P^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right) + \sigma E^\mu + \xi \omega^\mu + \xi_B B^\mu$

[Son, Surowka, 2009;…]

CVE **CME**

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.]

$$D_\mu J_R^\mu = + \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad D_\mu J_L^\mu = - \frac{N_c q^2}{4\pi^2} E_\mu B^\mu$$

$$J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{\sigma}{2} E^\mu + \frac{N_c q}{4\pi^2} \mu_R B^\mu$$

$$J_L^\mu = n_L u^\mu + \nu_L^\mu + \frac{\sigma}{2} E^\mu - \frac{N_c q}{4\pi^2} \mu_L B^\mu$$

CME

$$d\, \nu_{R,L}^\mu = (\nu_{NS}^\mu - \nu_{R,L}^\mu) / \tau_{rlx}$$

on top of 2+1D VISHNew—— OSU Group

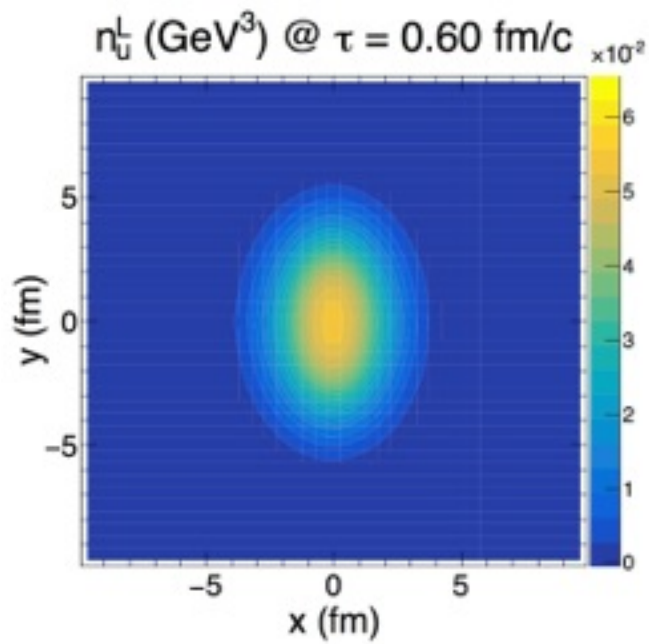
$$D_\mu T^{\mu\nu} = 0 \qquad\qquad n = 0$$

B field + μ_A ⇒ charge separation

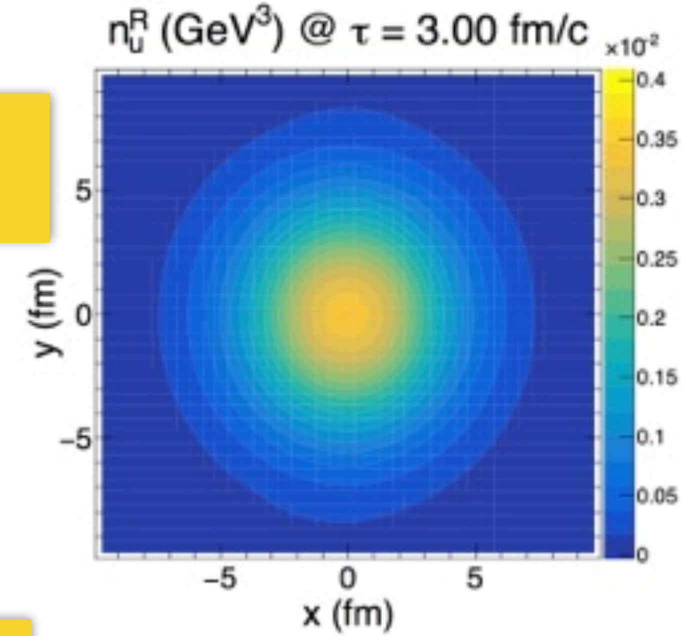
$$dN_\pm/d\phi \propto 1 + 2\, a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots$$

Chiral Viscous Fluid Dynamics Simulations

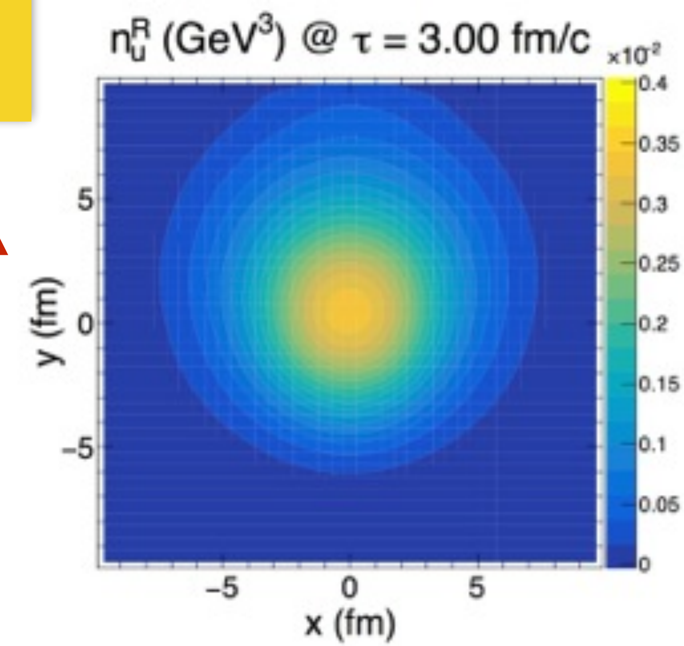
Initial Condition



No B Field



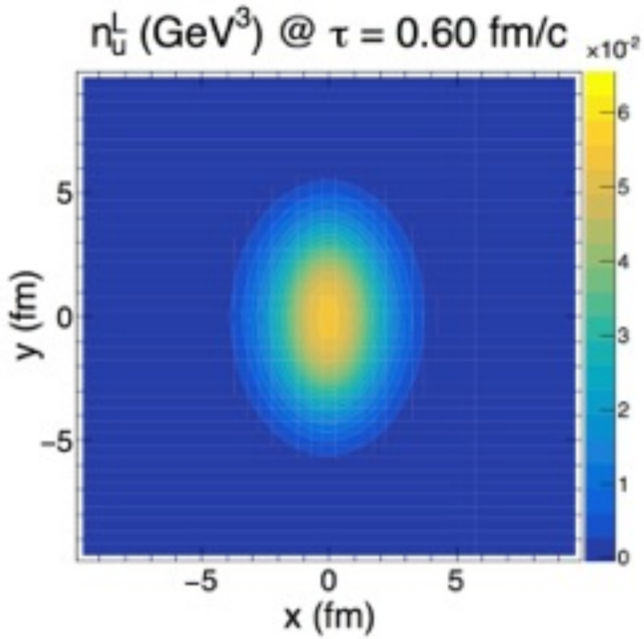
With B Field



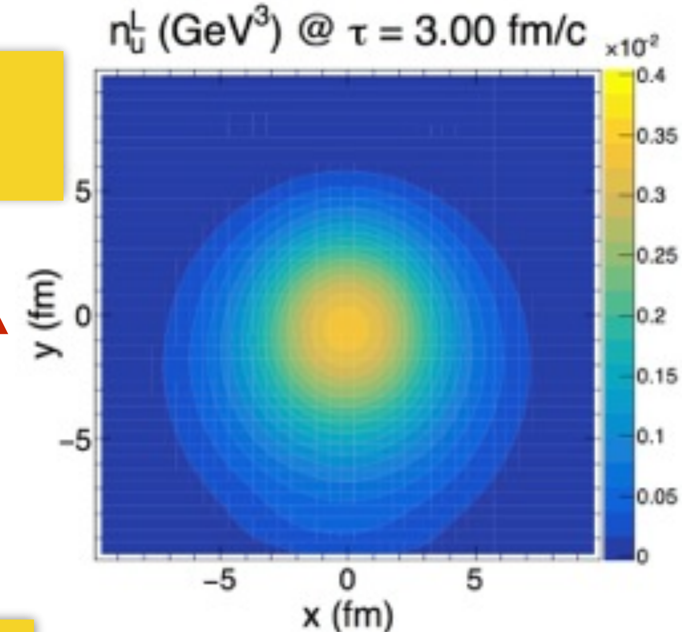
[Jiang, Shi, Yin, JL, 2016.]

Chiral Viscous Fluid Dynamics Simulations

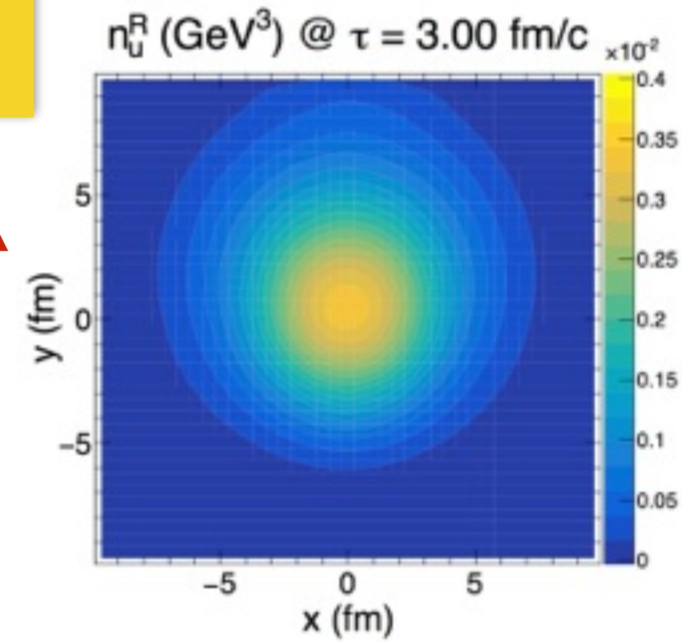
Initial Condition



Left Hand Density

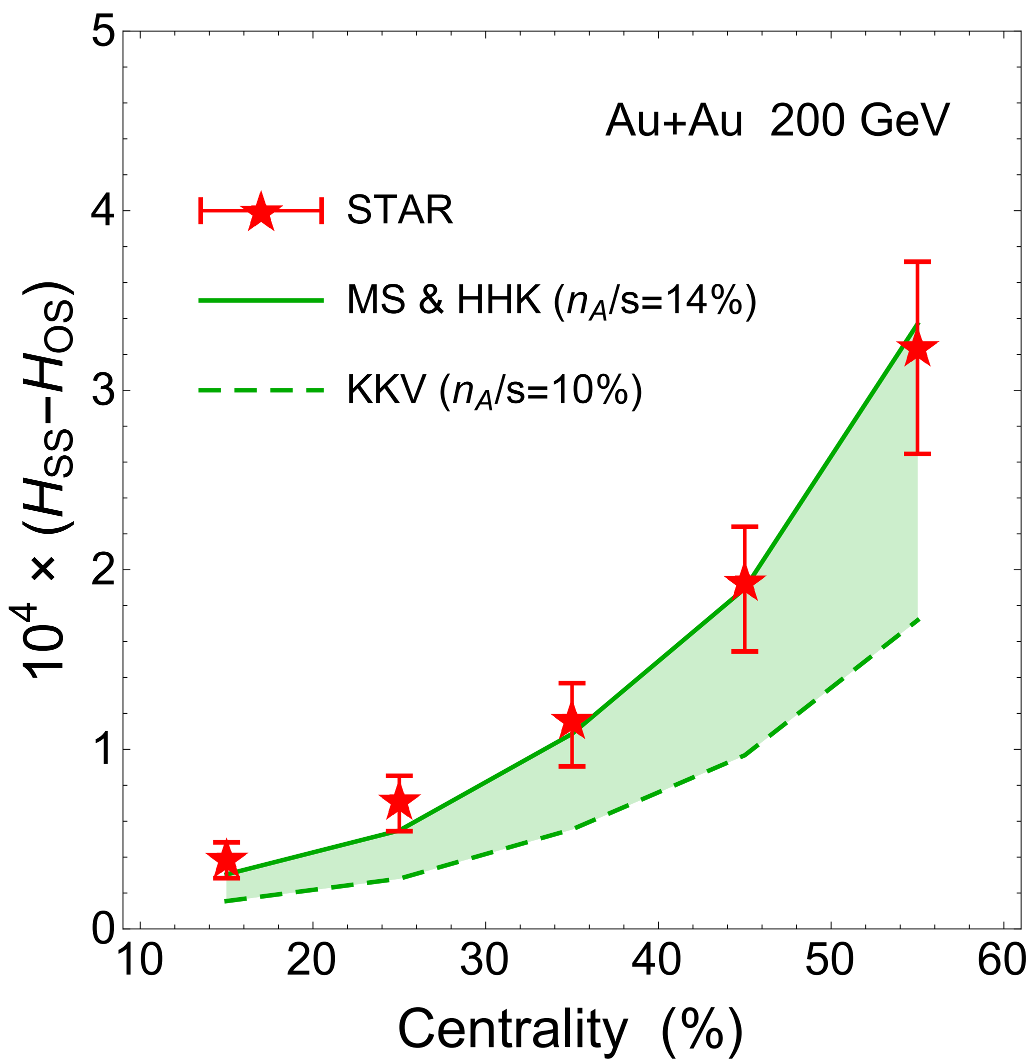


Right Hand Density



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

Chiral Viscous Fluid Dynamics Simulations



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

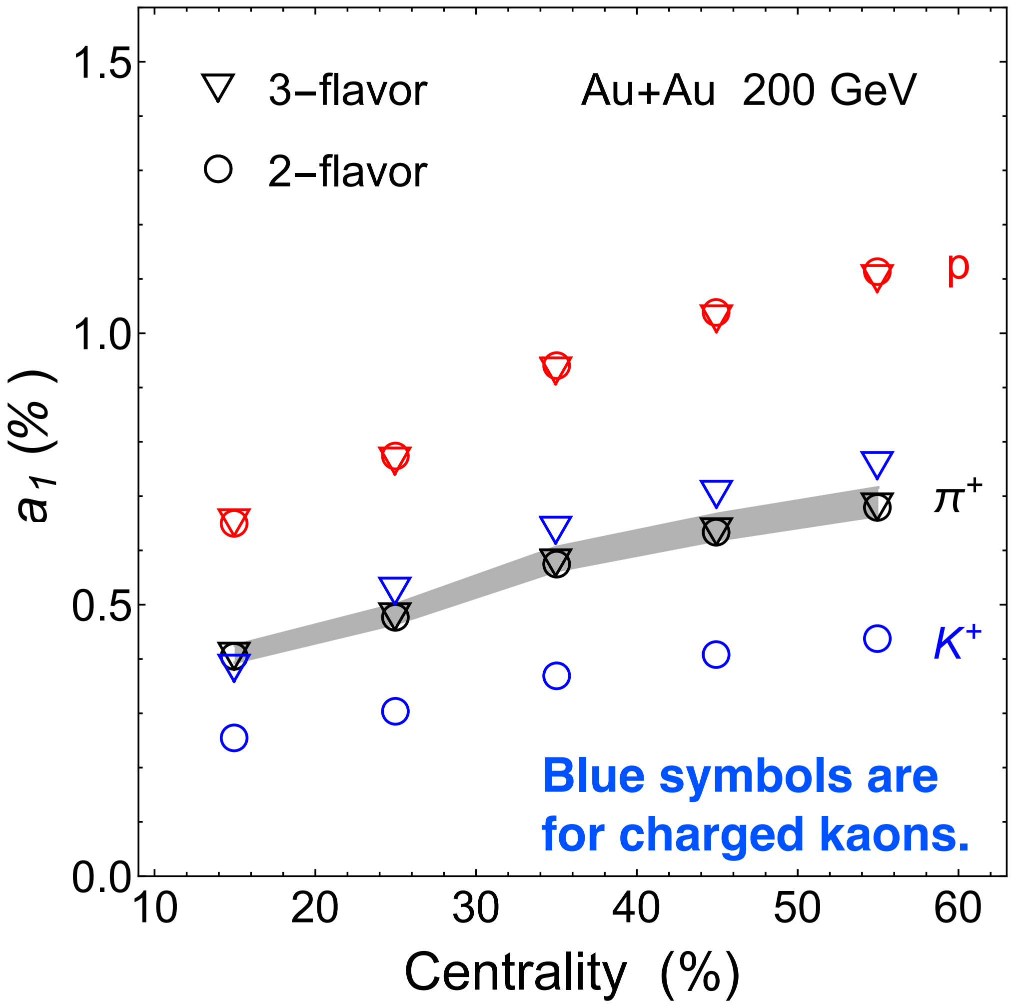
$$\tau_B = 0.6\mathrm{fm/c}$$

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

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

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

Is Strangeness Chiral?



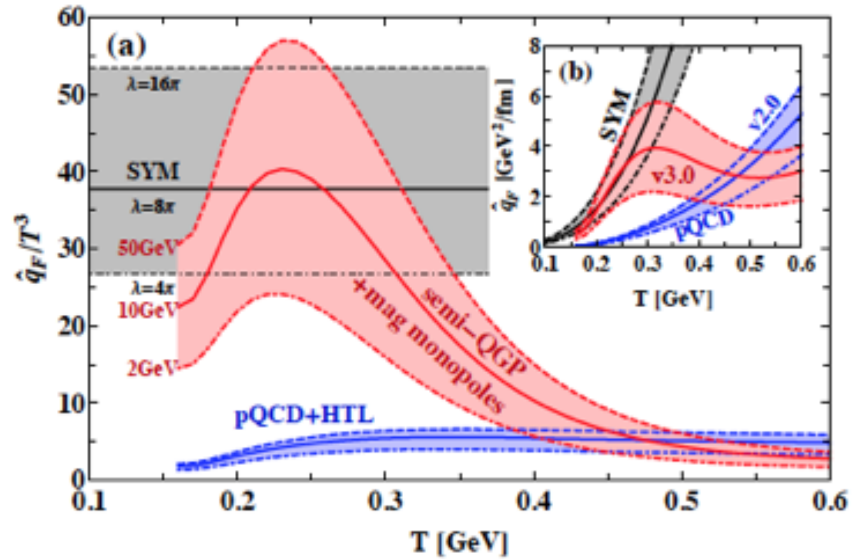
[Jiang, Shi, Yin, JL, 2016.]

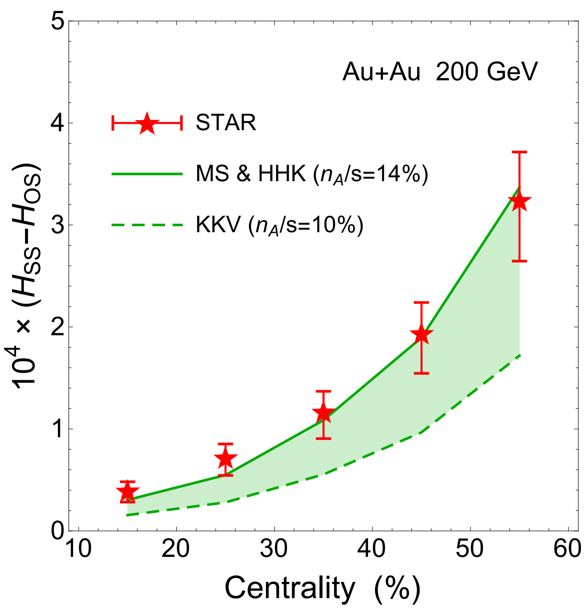
Measuring charge separation for Kaons: an exciting opportunity to tell to which extent the strange quarks are chiral!

Summary: Emergent Phenomena in sQGP

*** The sQGP near Tc 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.**





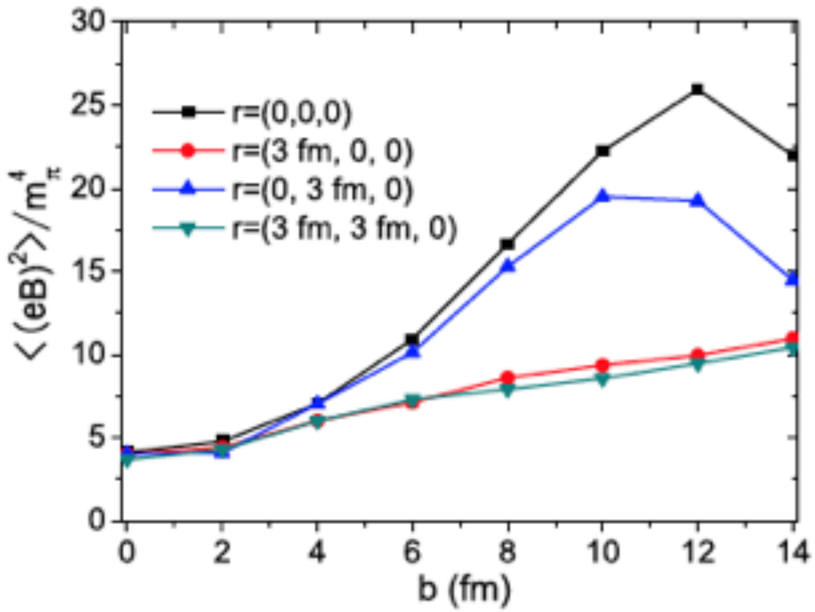
*** The chiral anomaly emerges in sQGP as Chiral Magnetic Effect.**

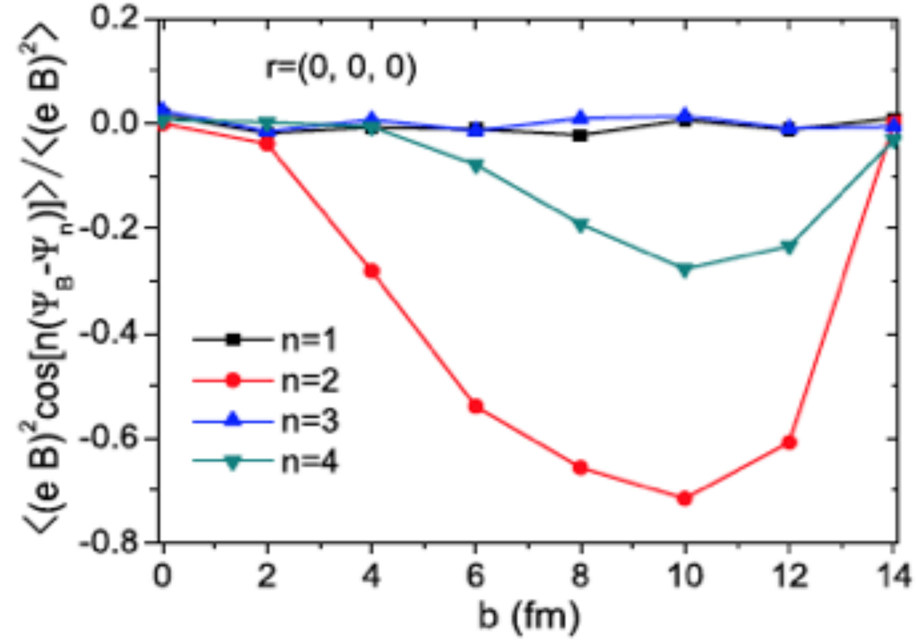
*** New Chiral Viscous Fluid Dynamics simulations can quantitatively describe the CME-induced charge separation as measured by STAR.**

Backup Slides

Event-By-Event Magnetic Fields

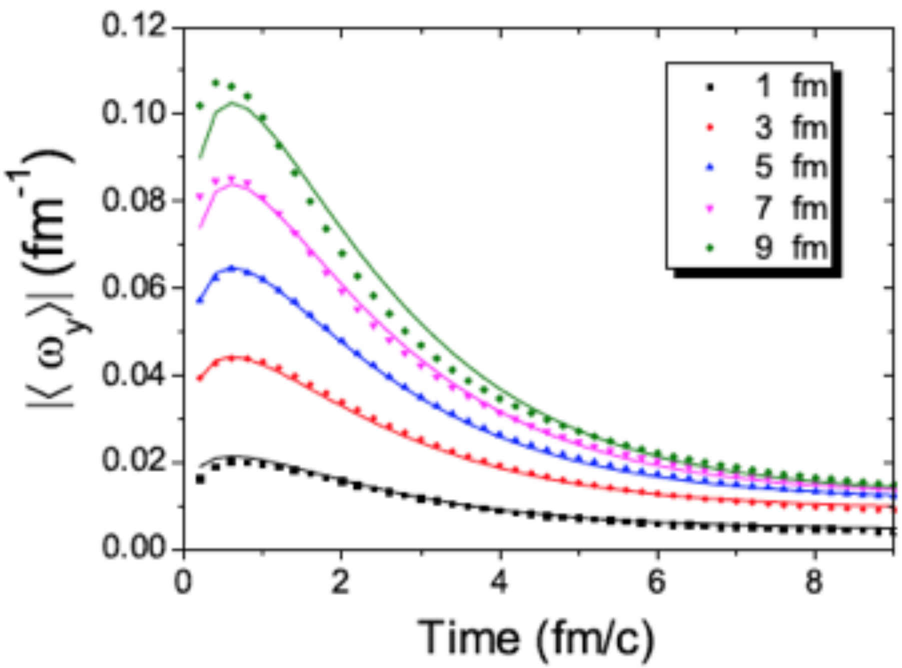
Azimuthal orientation fluctuates!
Proton is a finite size object!

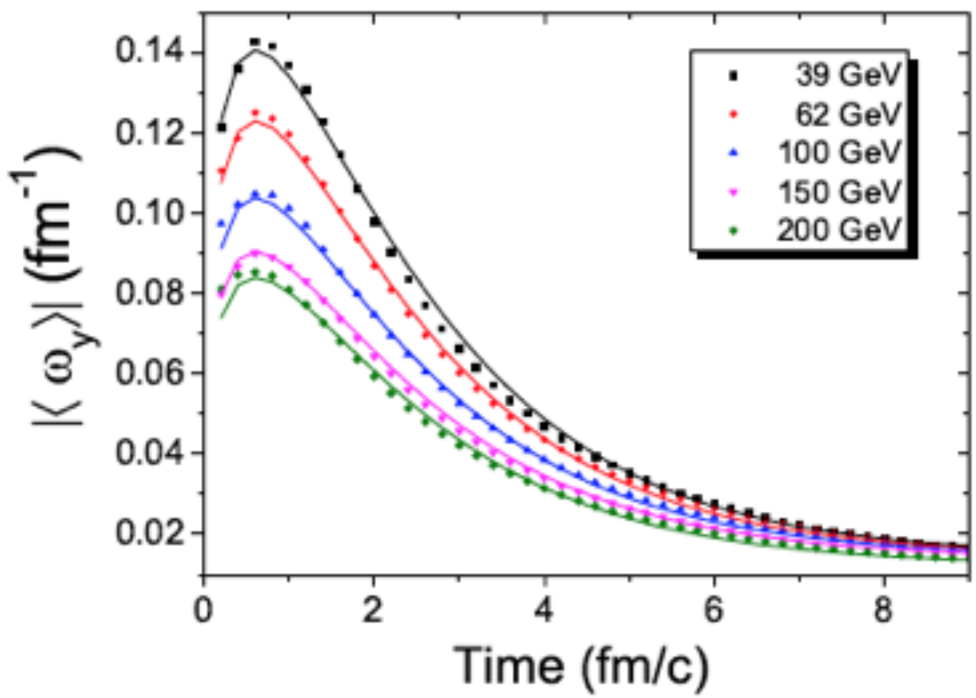




Bloczynski, Huang, Zhang, JL, PLB 718 (2013) 1529
[arXiv:1209.6594]

Quantifying Rotation of QGP





Convenient parameterization:

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

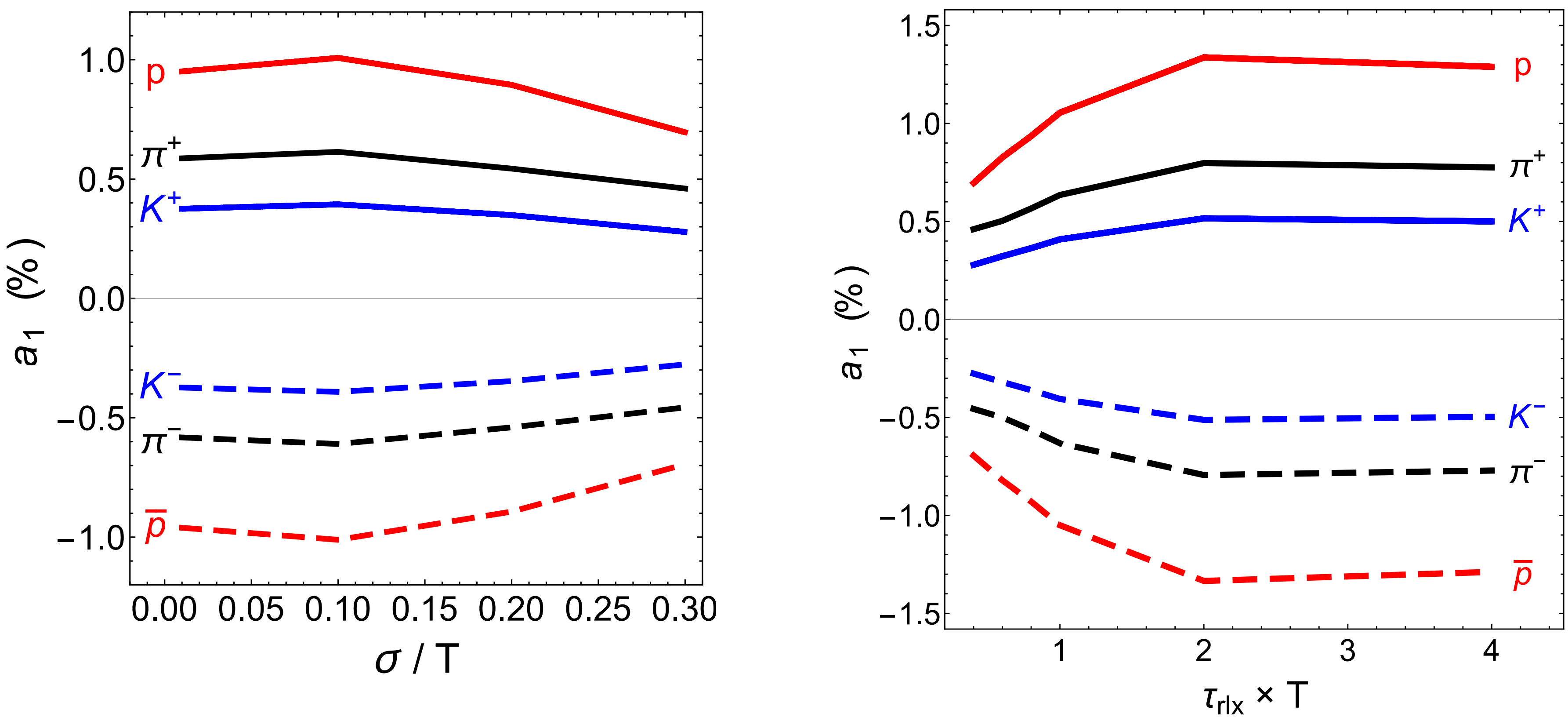
$$A = \left[e^{-0.016\,b\,\sqrt{s_{NN}}} + 1\right] \times \tanh(0.28\,b) \times [0.001775\tanh(3 - 0.015\sqrt{s_{NN}}) + 0.0128]$$

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

Yin Jiang, Zi-Wei Lin, JL,
arXiv:1602.06580[hep-ph]

Chiral Viscous Fluid Dynamics Simulations

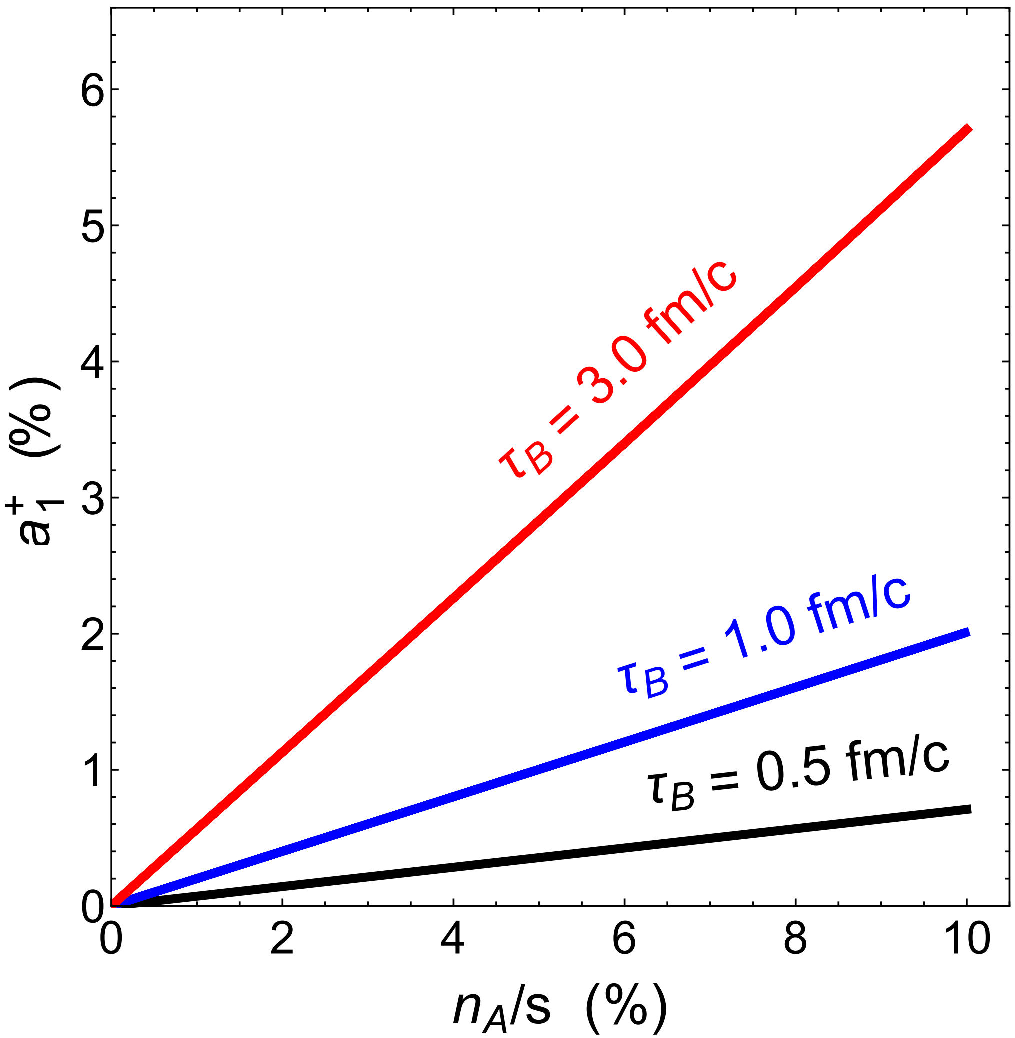
[Jiang, Shi, Yin, JL, 2016.]



Dependence on viscous parameters (conductivity, relaxation time)

Chiral Viscous Fluid Dynamics Simulations

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



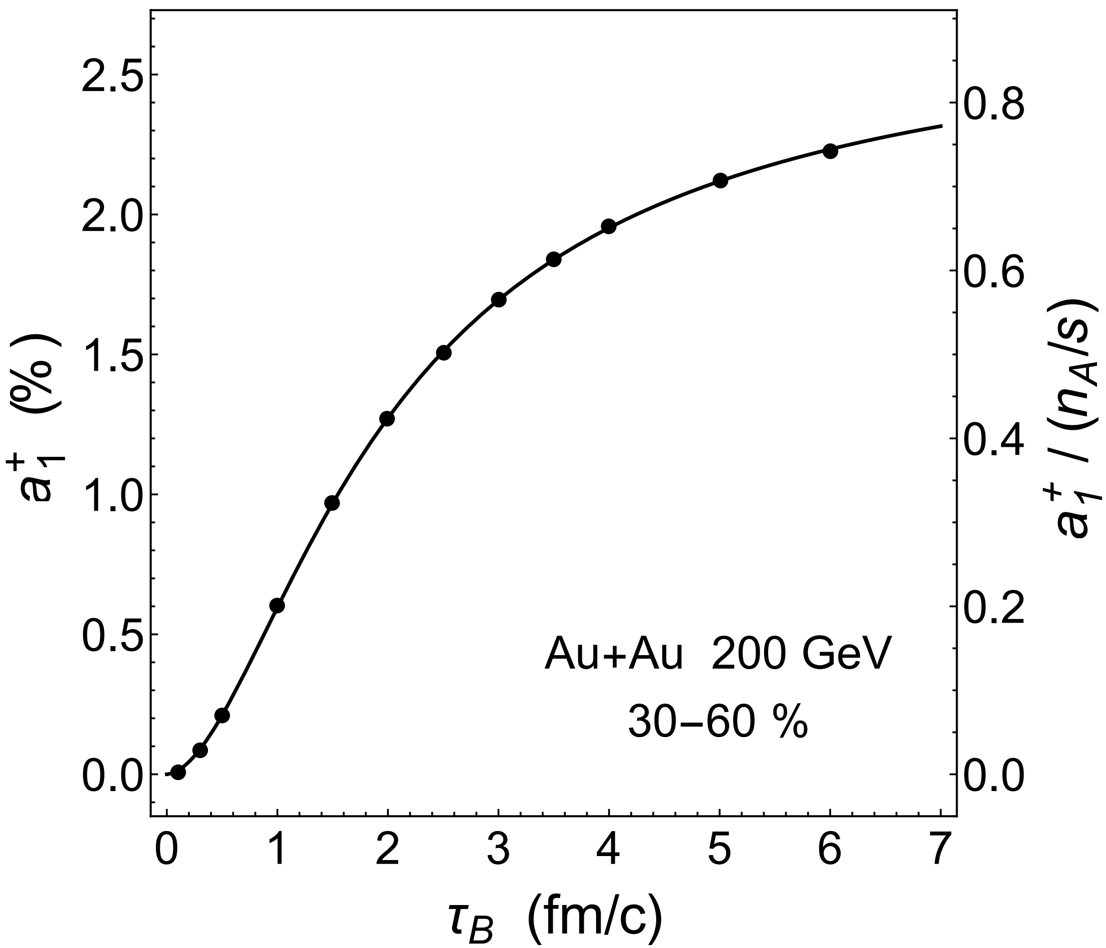
$$B = \frac{B_0}{1 + \left(\frac{\tau}{\tau_B}\right)}$$

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

It is not sensitive to the initial vector charge density.

Chiral Viscous Fluid Dynamics Simulations

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



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

Charge separation is very sensitive to B field lifetime.

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]

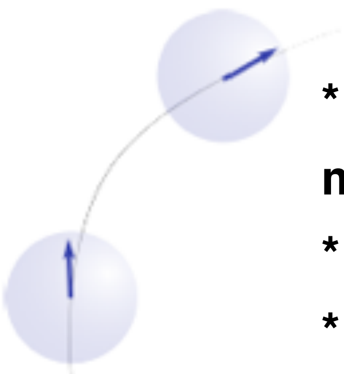
$$\frac{df}{dt} \equiv \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \boldsymbol{x}}\dot{\boldsymbol{x}} + \frac{\partial f}{\partial \boldsymbol{p}}\dot{\boldsymbol{p}} = C[f]$$

$$\dot{\boldsymbol{x}} - \boldsymbol{v} - \overbrace{\dot{\boldsymbol{p}} \times \boldsymbol{b}}^{\text{anom. velocity}} = 0;$$

$$\dot{\boldsymbol{p}} - \boldsymbol{E} - \dot{\boldsymbol{x}} \times \boldsymbol{B} = 0;$$

$$\boldsymbol{b} = \frac{\hat{\boldsymbol{p}}}{2|\boldsymbol{p}|^2}$$

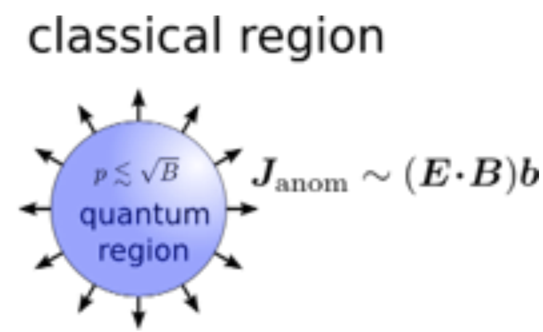
Berry curvature



*** Definite chirality: Spin "rotates" with momentum —> Berry Phase**

*** CKT: Introducing O(h-bar) quantum effect**

*** Correctly accounting for anomaly effects**

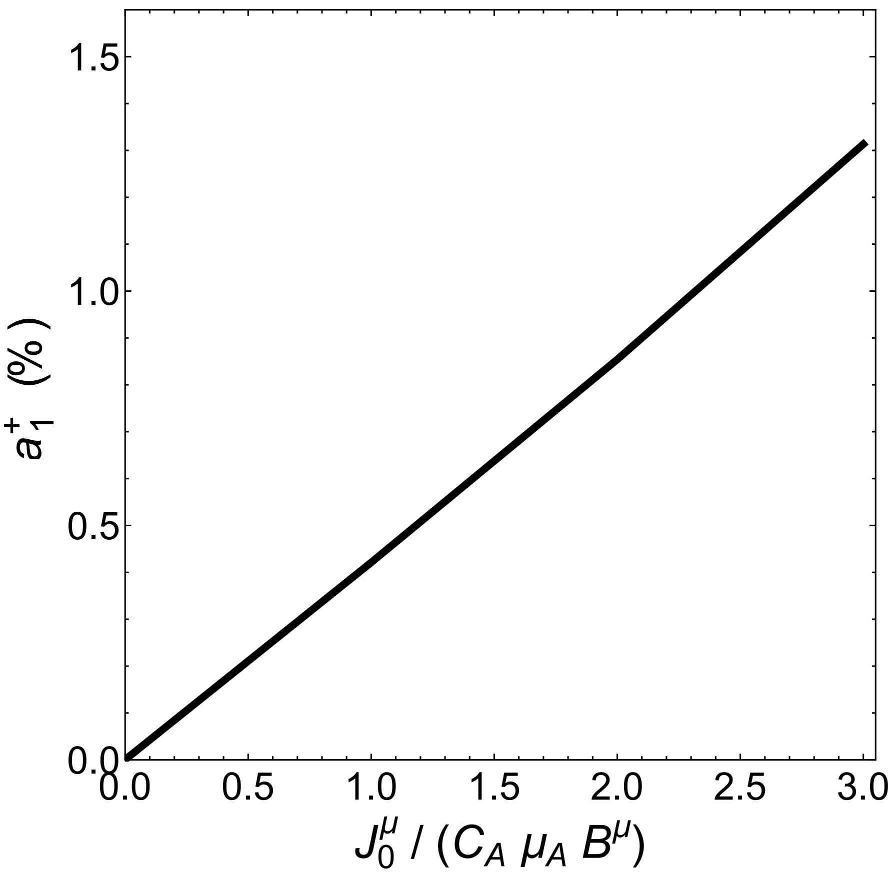


The Chiral Kinetic Theory framework is under rapid development, and will provide the framework for quantitative modeling of anomaly effects for early stage of heavy ion collisions!

Chiral Viscous Fluid Dynamics Simulations

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

$$J^\mu(\tau = \tau_0) = a\,(C_A \mu_A B^\mu)$$



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!

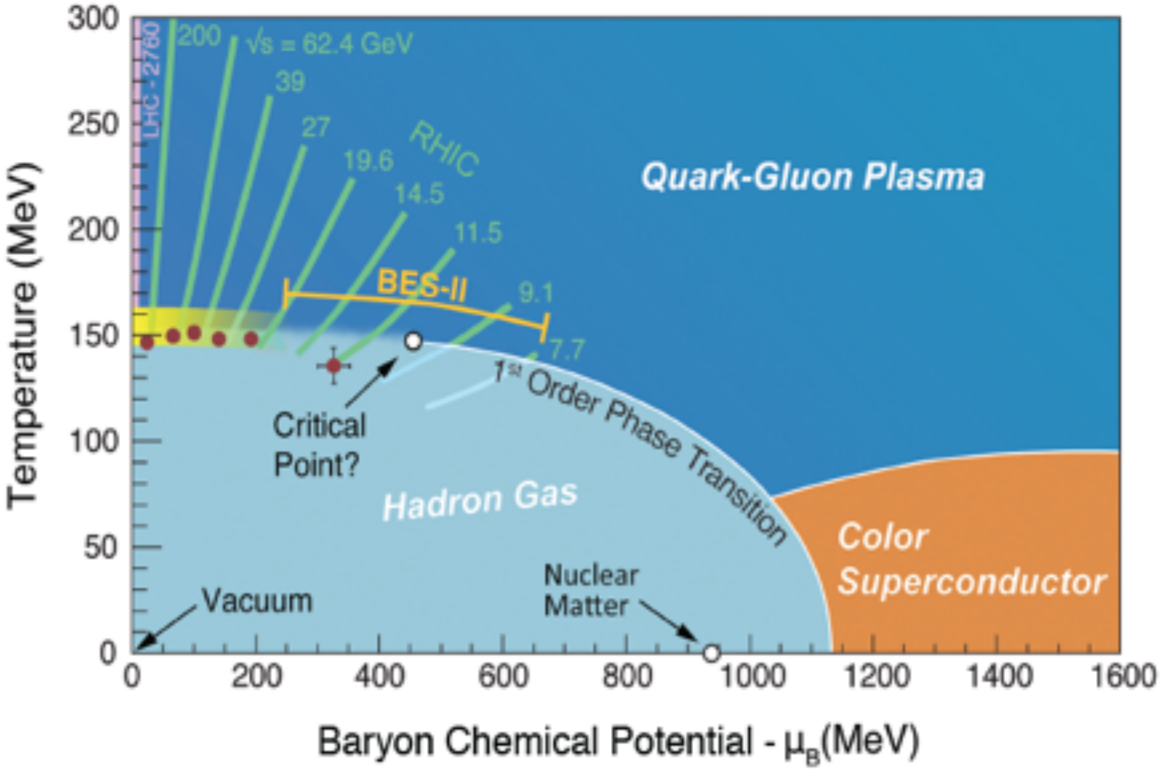
— ${}^{96}_{40}$Zirconium vs ${}^{96}_{44}$Ruthenium

	${}^{96}_{44}Ru+{}^{96}_{44}Ru$ vs ${}^{96}_{40}Zr+{}^{96}_{40}Zr$
Flow	≤
CMW	>
CME	>
CVE	=

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***



BEST COLLABORATION

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