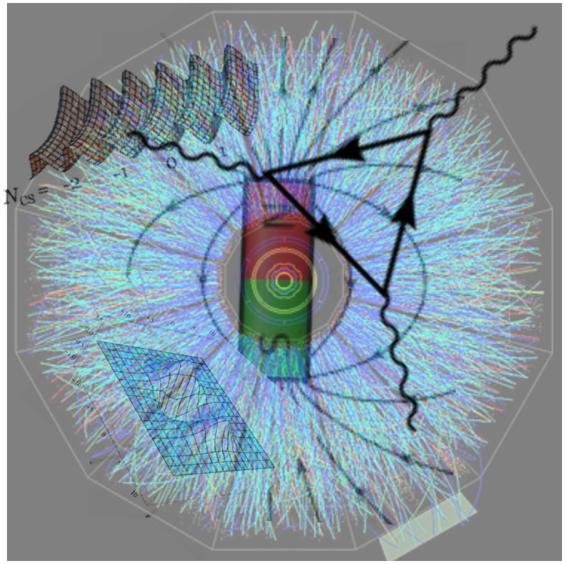
GHP2017 @ Washington DC   Feb. 1st, 2017

Anomalous Chiral Transport In High Energy Nuclear Collisions



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Research Supported by NSF & DOE

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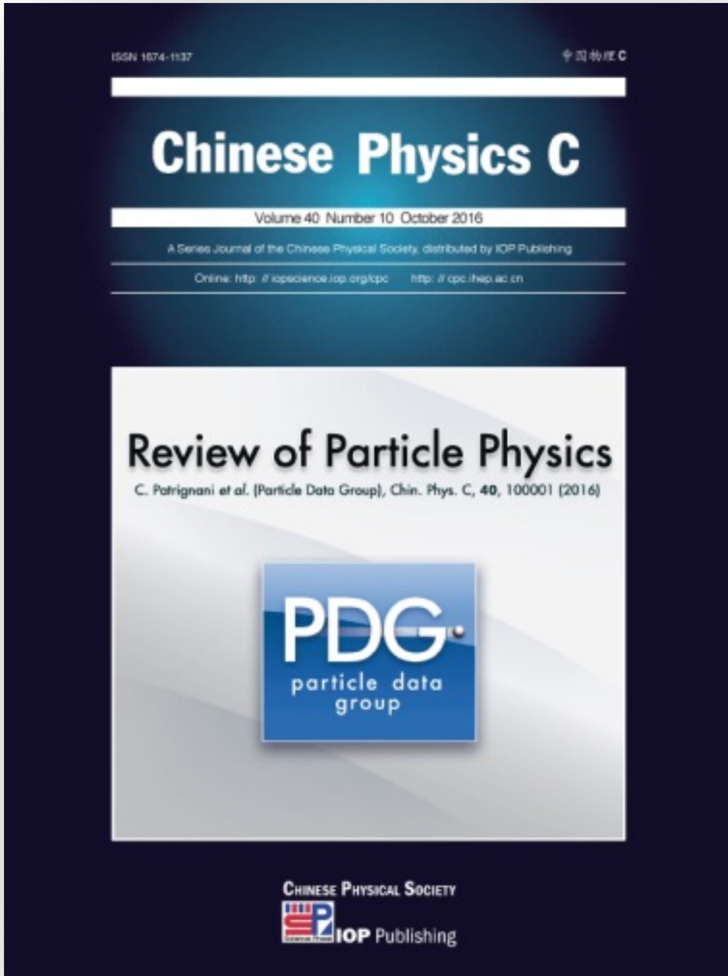
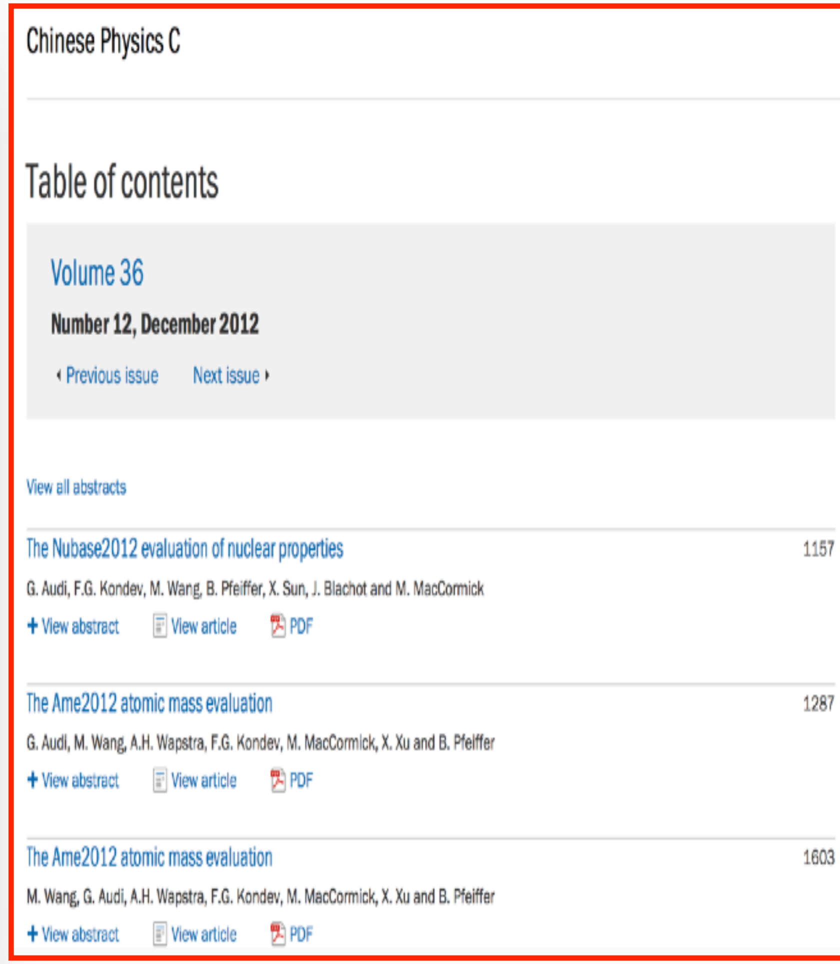
BEST COLLABORATION

Publication of Important Nuclear/Particle Data



PDG Review of Particle Physics 2016 (& 2014) @ CPC



Chinese Physics C

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M. Wang, G. Audi, A.H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu and B. Pfeiffer

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Atomic Mass Evaluation 2017 & 2012 @ CPC

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- Publishers of the 2012 and 2017 Atomic Mass Evaluation

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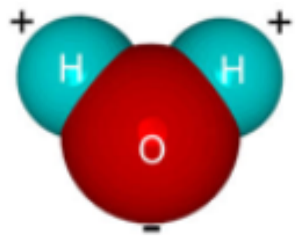
Nuclear Matter: At the Heart of All Matter

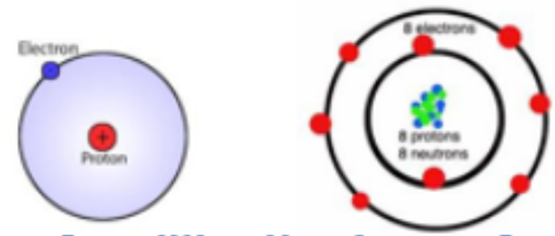
The physical world has a hierarchy of structures.

matter

molecule

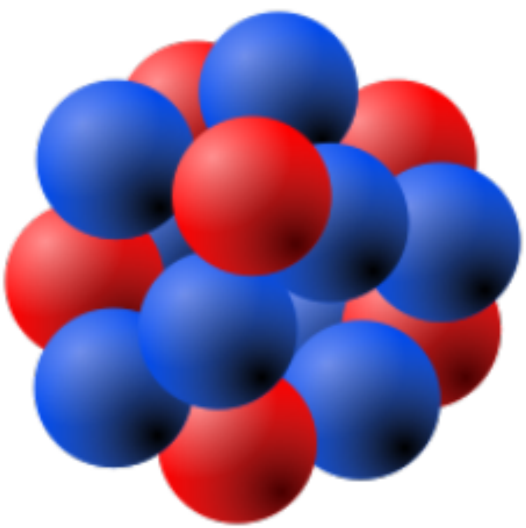


atoms



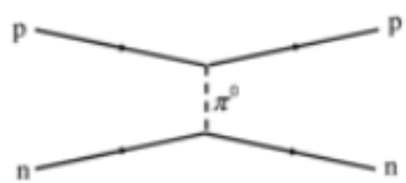
[a millionth of a mm]

atomic nucleus

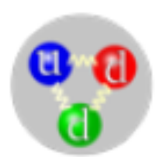


[a trillionth of a mm]

proton



nuclear force

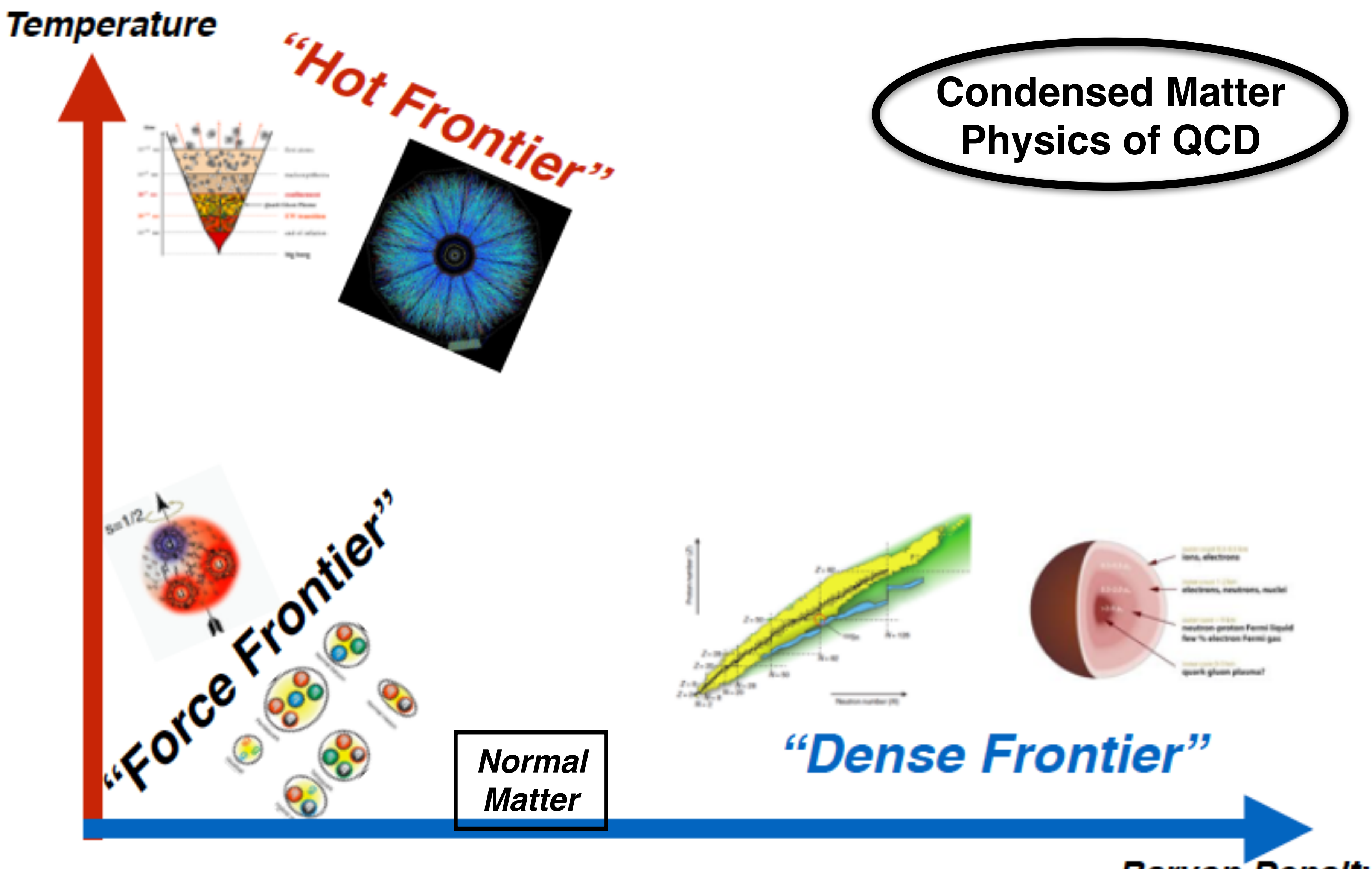


neutron

Most basic entities: quarks and gluons.

Quantum Chromodynamics (QCD)

A Map of the Extreme Matter

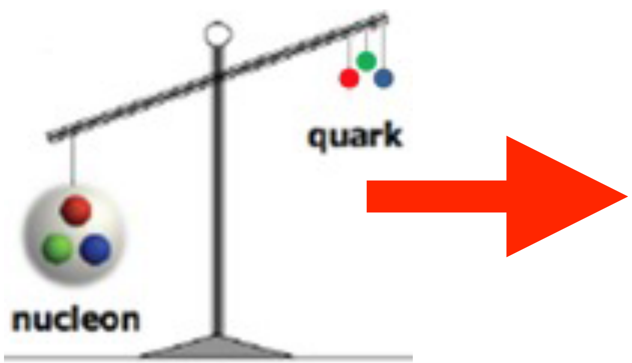


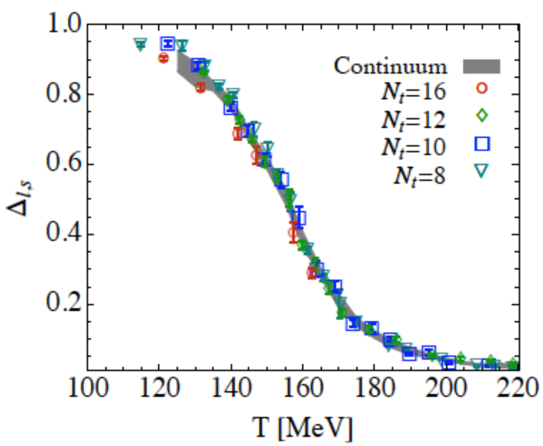
This talk will focus on the "hot frontier".

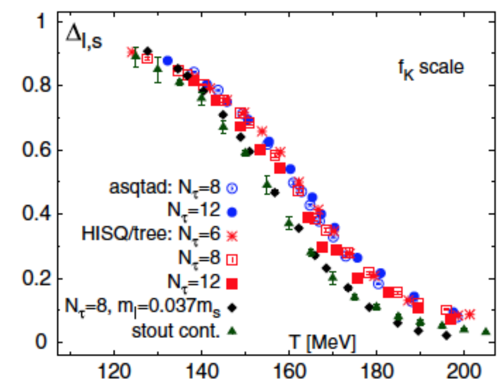
QCD & Chiral Symmetry

Different frontiers are intrinsically connected:
they are described by the SAME QCD,
with the SAME set of fundamental symmetries.

**** Spontaneously broken chiral symmetry in the vacuum***
is a fundamental property of QCD.

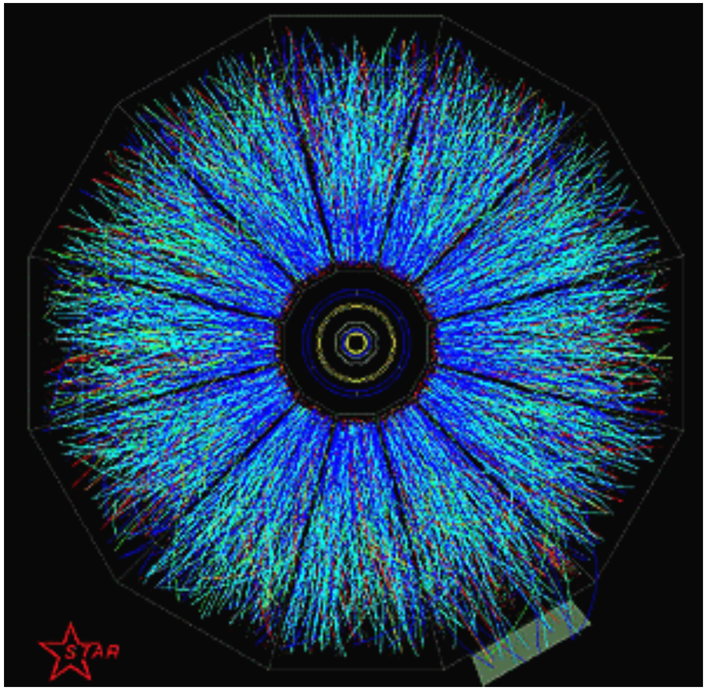


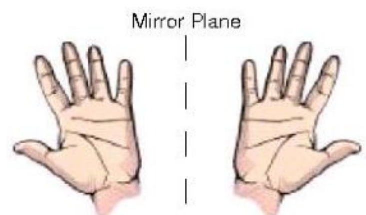




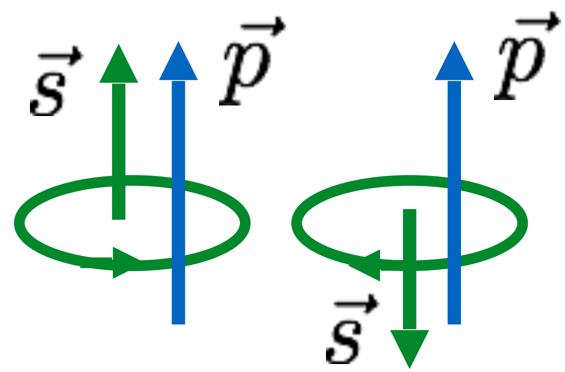
**** A chirally symmetric quark-gluon plasma at high temperature***
is also a fundamental property of QCD!

“Little Bang” in High Energy Nuclear Collision





CHIRAL FERMIONS



**** Quark-gluon plasma (QGP) is created in such collisions.***

**** It is PRIMORDIALLY HOT ~ trillion degrees ~ early universe.***

**** Is chiral symmetry restored?***

From Chiral Anomaly to Chiral Magnetic Effect

Chiral Anomaly

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

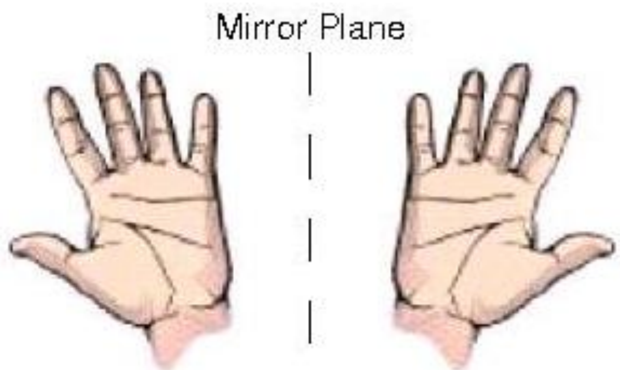
Classical symmetry:

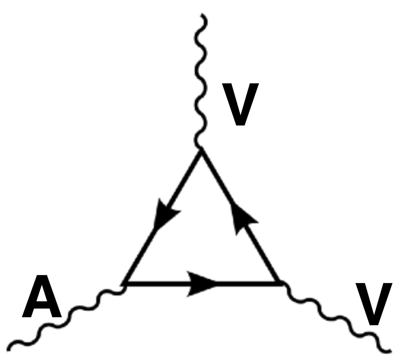
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

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

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

$$\partial_\mu J_5^\mu = 0$$





[e.g. pi0—> 2 gamma]

Broken at QM level:

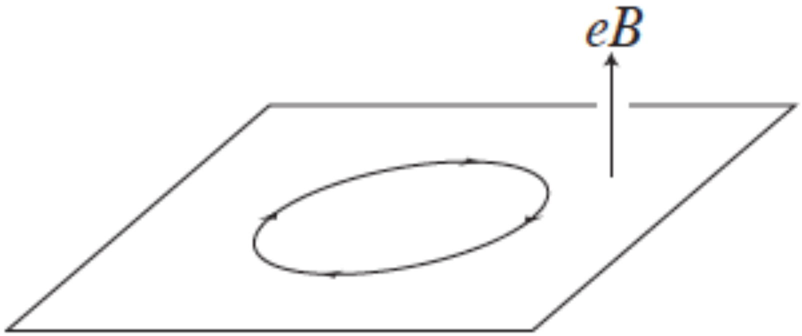
$$\partial_\mu J_5^\mu = C_A \vec{E}\cdot\vec{B}$$

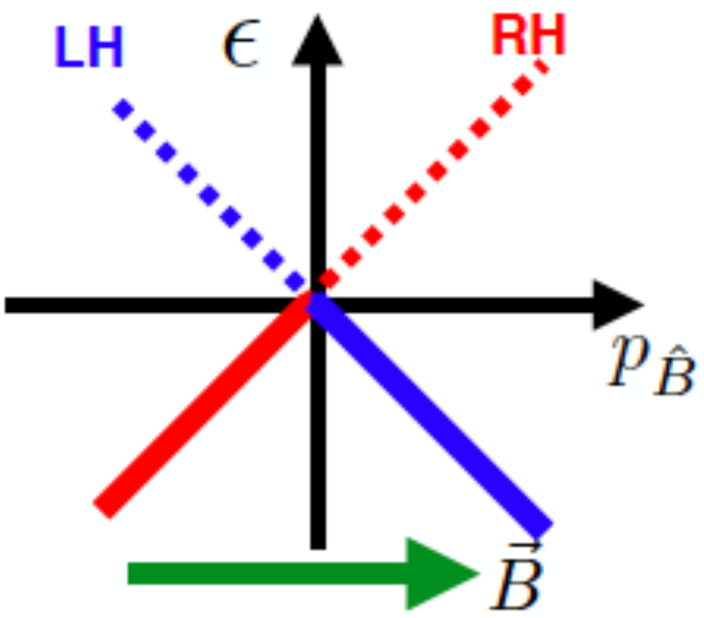
$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$$

* C_A is universal anomaly coefficient

* Anomaly is intrinsically QUANTUM effect

Landau Levels in Magnetic Field





$$E_n^2 = p_z^2 + 2nB$$

Lowest-Landau-Level (LLL):
LLL is chiral!

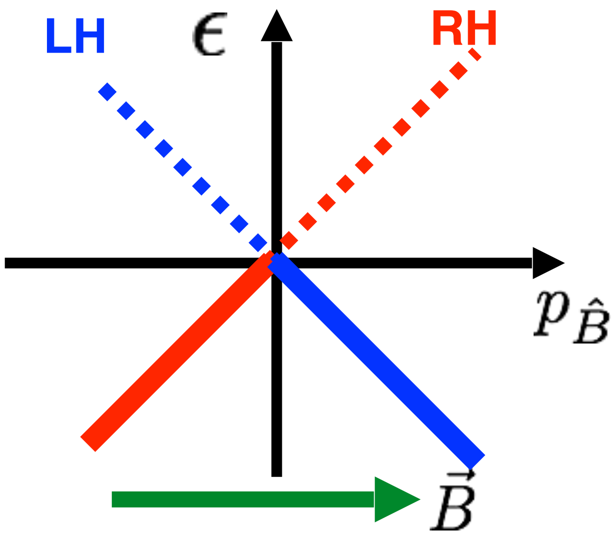
Chiral Anomaly

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!

From Micro. Laws To Macro. Phenomena

Micro. Laws:

Symmetry;
Lagrangian;
Conservation laws;
……

Macro. Phenomena:

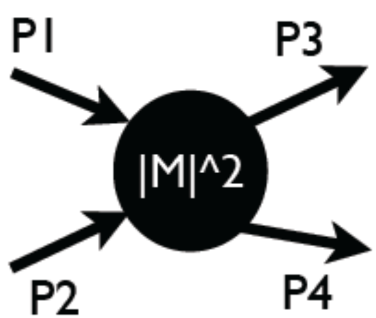
Thermodynamics;
Phase transitions;
Transport;
Hydrodynamics;
……

Would chiral anomaly, usually considered
at microscopic level,
manifest itself MACROSCOPICALLY
in a many-body system of chiral fermions?
If so, how?

Emergence in Hydrodynamic Context

Symmetry	Micro. Conservation Law	Emergent Macro. Hydro
translational invariance	energy and momentum conserved	$\partial_\mu T^{\mu\nu} = 0$
phase invariance	charge conserved	$\partial_\mu J^\mu = 0$

$$\mathcal{L} \to \mathcal{L}$$



Emergence in Hydrodynamic Context

Symmetry	Micro. Conservation Law	Emergent Macro. Hydro
translational invariance	energy and momentum conserved	$\partial_\mu T^{\mu\nu} = 0$
phase invariance	charge conserved	$\partial_\mu J^\mu = 0$

WHAT ABOU "HALF"-SYMMETRY???
i..e ANOMALY?!
— classical symmetry that is broken in quantum theory

Anomalous Transport: Chiral Magnetic Effect

*** The Chiral Magnetic (CME) is an anomalous transport current**

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

P odd
CP even

P even
CP odd

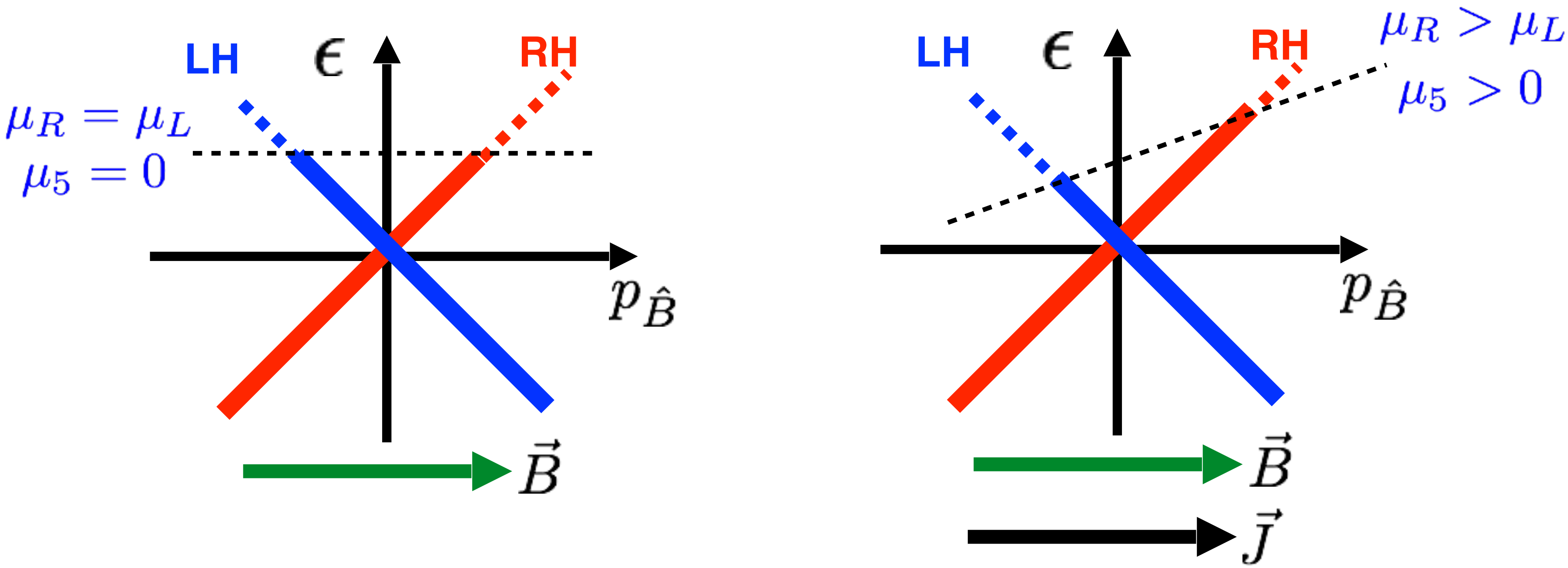
In NORMAL environment, this will NOT happen.
For this to occur: need a P- and CP-Odd environment!

$$\mu_5$$

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

Such imbalance can be generated through chiral anomaly coupled with E-dot-B (e.g. topological fluctuations of QCD).

So How Does CME Work?



One may recognize deep connection between CME & anomaly.

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

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

The CME conductivity is

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

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

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

We need to modify hydrodynamics!

Hydrodynamics That Knows Left & Right

conservation law:

$$\partial_\mu J^\mu = 0 \longrightarrow \partial_\mu J^\mu = C E^\mu B_\mu$$

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

Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

[Fluid rotation induces similar effects as magnetic field]

CME in Heavy Ion Collisions

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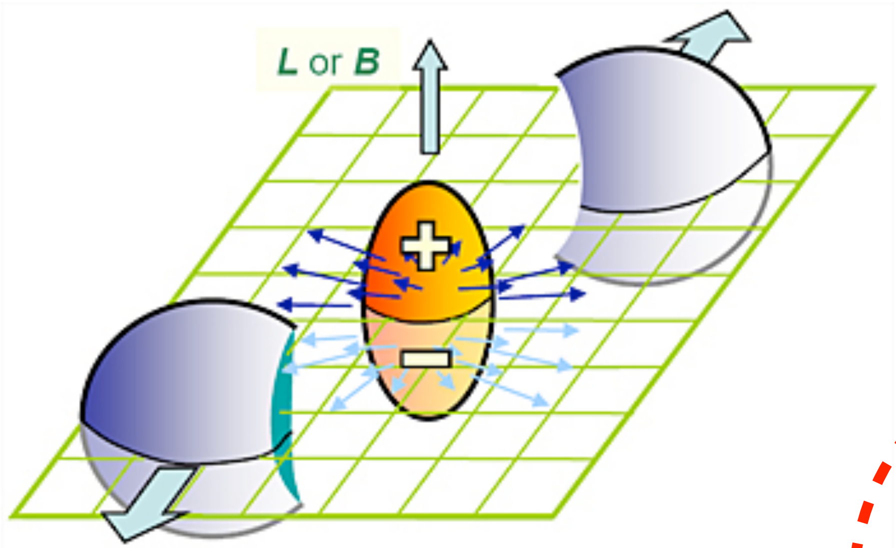
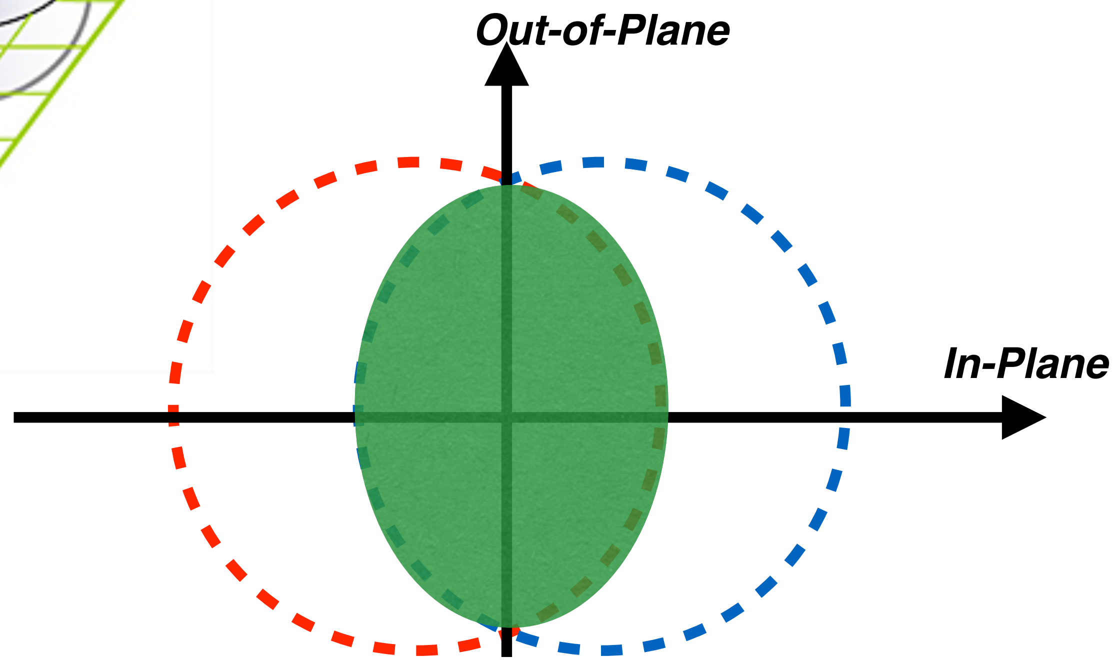
Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050 [hep-ph]].

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

The Setup of Heavy Ion Collision



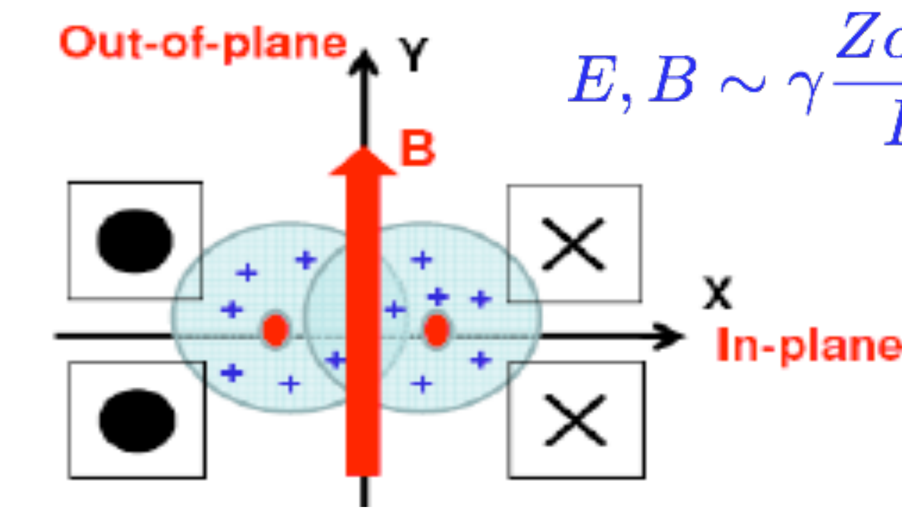


The quark-gluon plasma is a type of CHIRAL MATTER, with (approximately) chiral quarks.

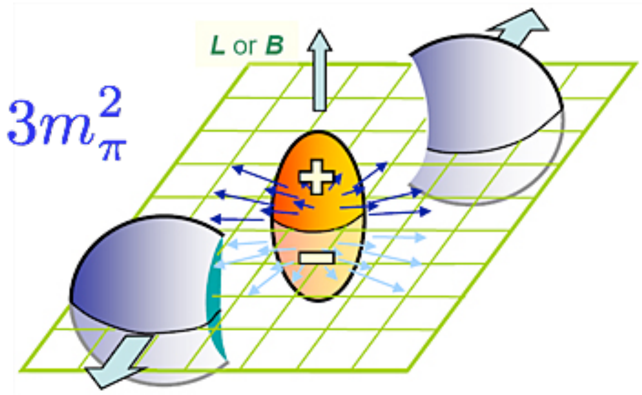
Can we observe CME??

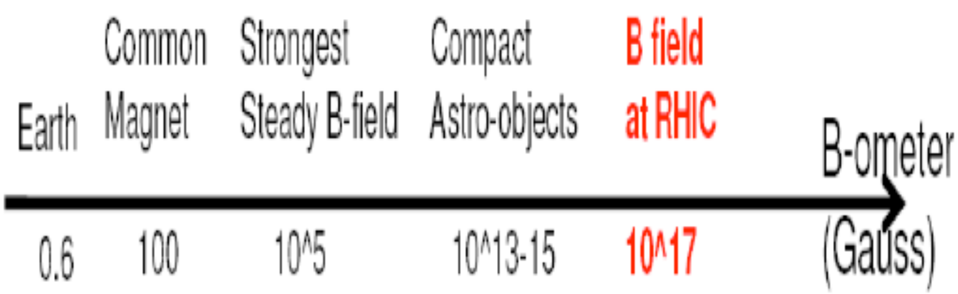
$$\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}$$

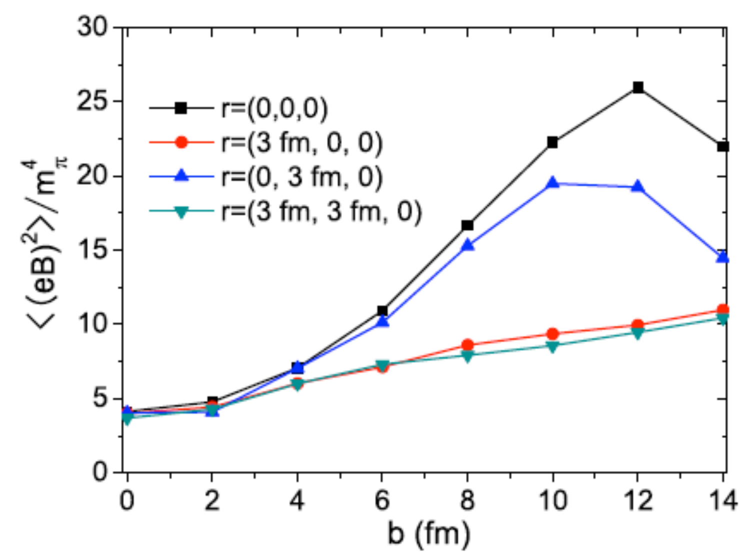
Strong EM Fields in Heavy Ion Collisions



$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$





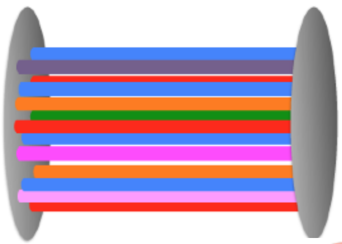


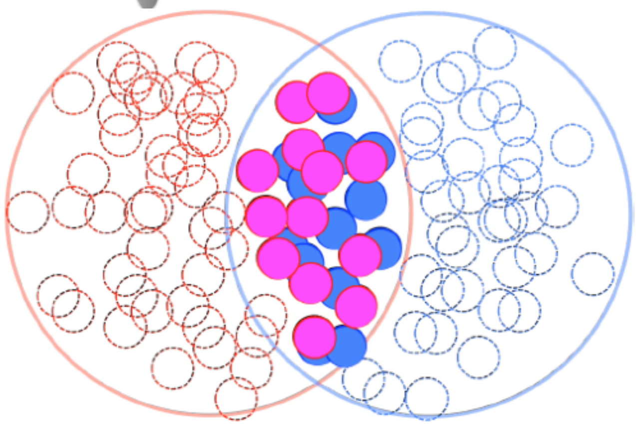
- Strongest B field (and strong E field as well) naturally arises! [Kharzeev,McLerran,Warringa;Skokov,et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao; Skokov-McLerran;Tuchin; ...]
- “Out-of-plane” orientation (approximately)

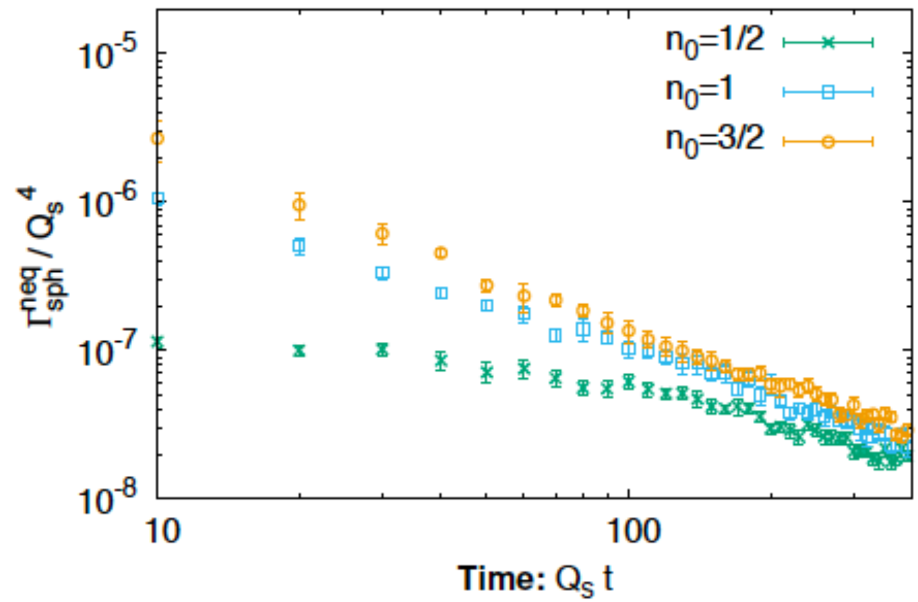
Generation of Initial Chirality Imbalance

Initial strong color E-B fields generate nonzero topological charges that translate into chirality imbalance.

[Mace, Schlichting, Venugopalan, 1601.07342]





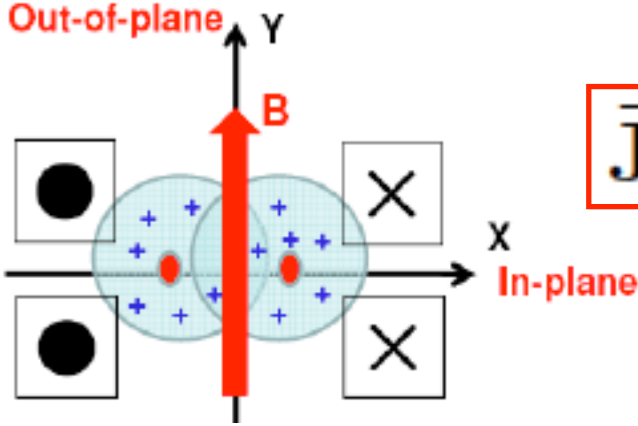


A simple estimate of initial axial charge density:

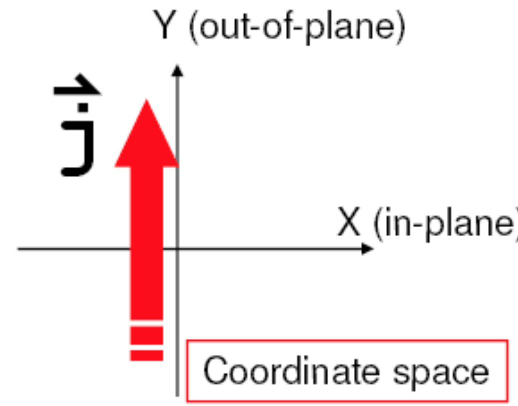
[c.f. Hirono,Hirano,Kharzeev,2014; Mueller, Schaefer, 2010; Kharzeev, Krasnitz,Venugopalan]

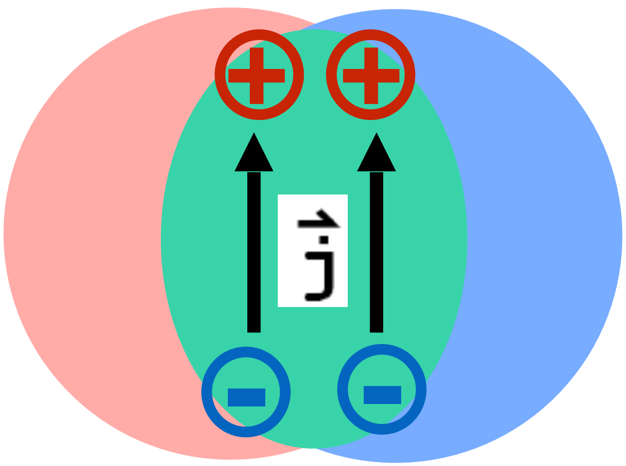
$$\sqrt{\langle n_5^2 \rangle} \simeq \frac{Q_s^4\,(\pi \rho_{tube}^2 \tau_0)\,\sqrt{N_{coll.}}}{16\pi^2\, A_{overlap}}$$

From CME Current to Charge Separation

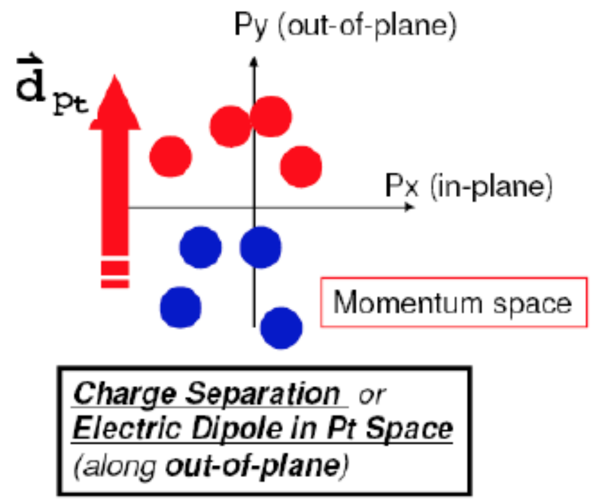


$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$





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;…]

Summarizing Exp. Search Status

Main challenge: flow-driven background v.s. CME signal

Vary v2 for fixed B:

AuAu v.s. UU;

Varying event-shape;

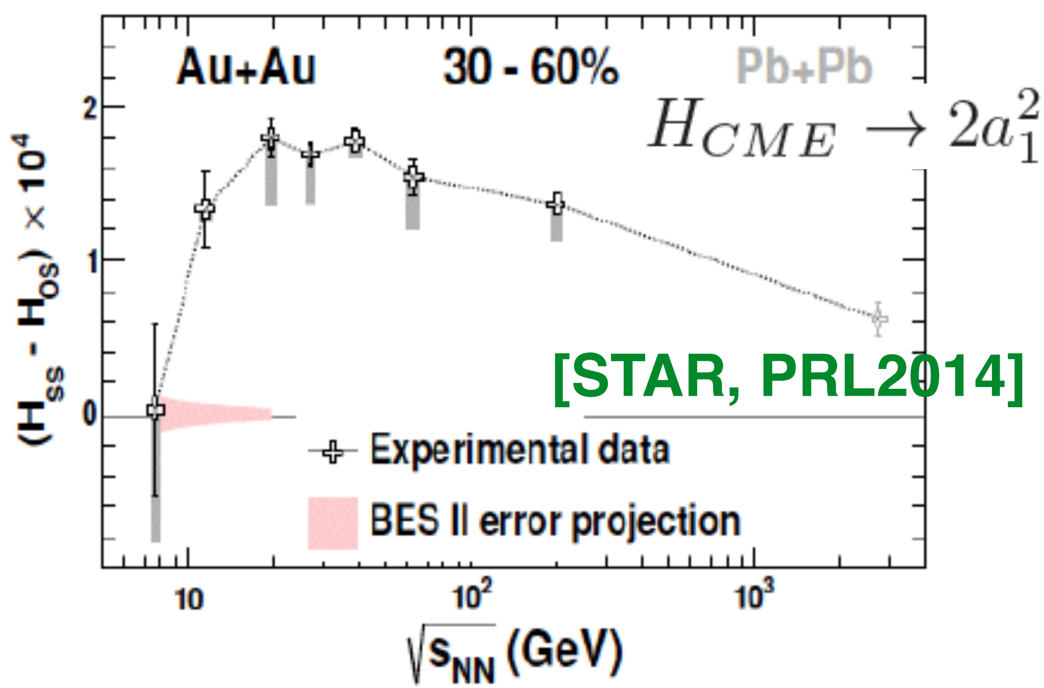
2-component subtraction.

Vary B for fixed v2:

Isobaric collisions with

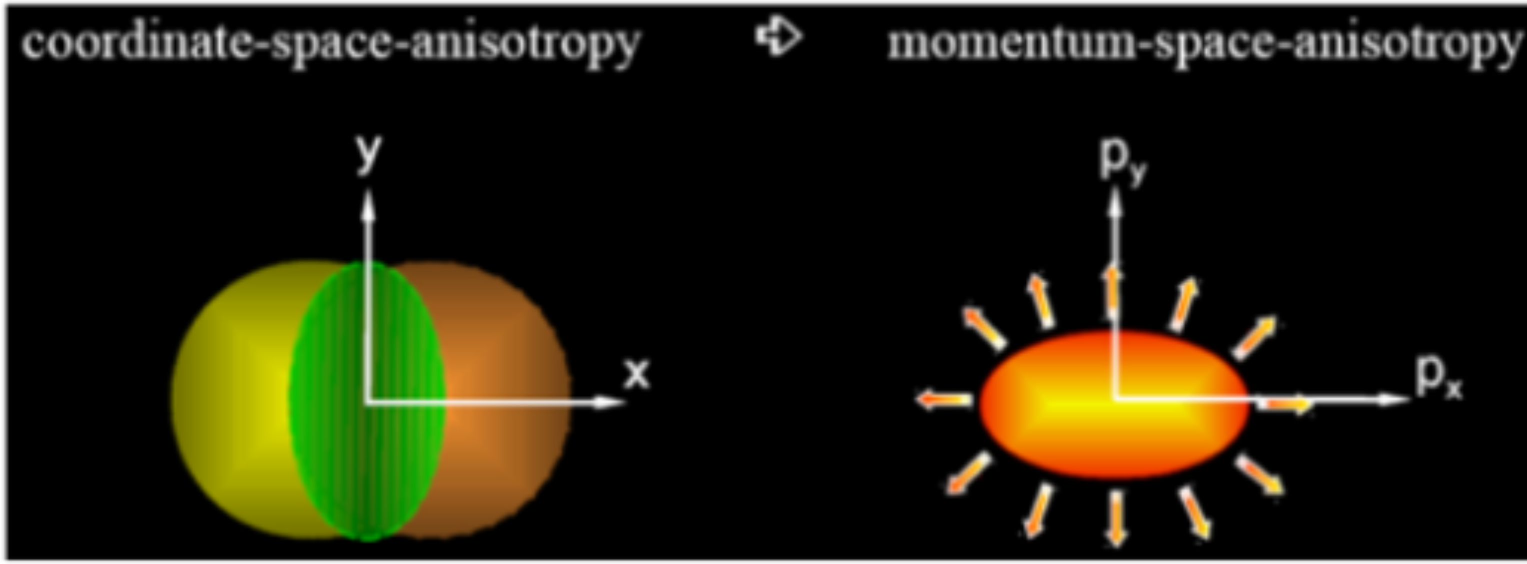
RuRu v.s. ZrZr

Our best guess for now:



Encouraging experimental evidence for CME in QGP — can we quantitatively compute CME signal?

The Flowing Quark-Gluon Plasma



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

** Nearly perfect fluidity: mapping fine details of initial conditions*

$1 \le 4\pi(\eta/s)_{QGP} \le 2.5$ **the smallest among known substances**

** The QGP's rapid expansion is well described by relativistic viscous fluid dynamics.*
** Chiral fermion currents are "carried" by the bulk flow.*

Anomalous Viscous Fluid Dynamics (AVFD)

[Jiang, Shi, Yin, JL, arXiv:1611.04586.]

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

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

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

CME

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

on top of 2+1D VISHNew—– OSU Group

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

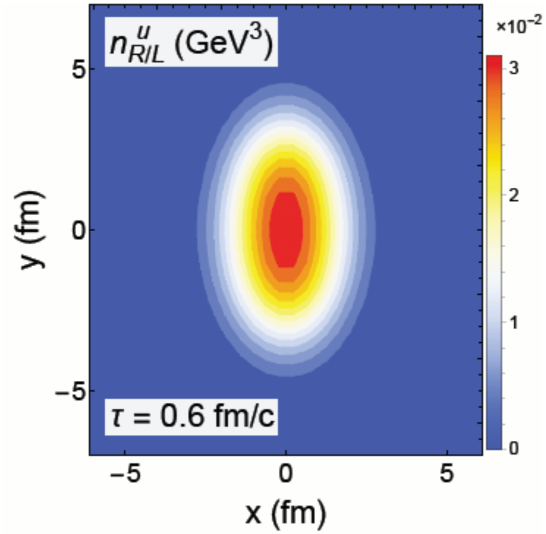
B field + μ_A $\Rightarrow$ charge separation

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

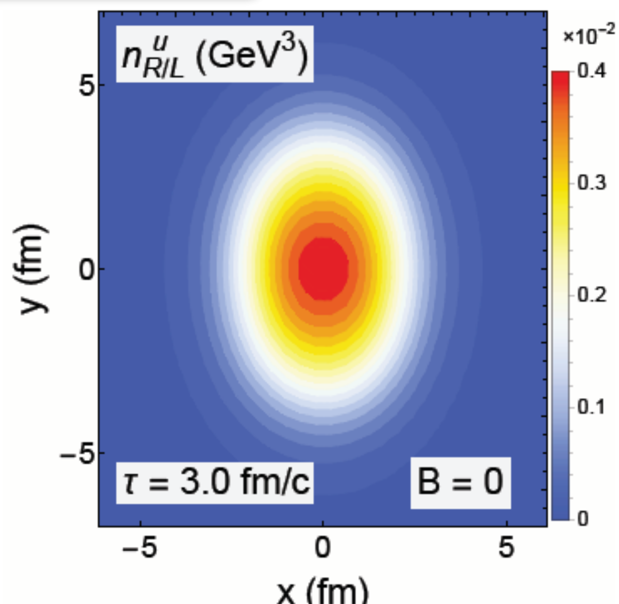
Anomalous Viscous Fluid Dynamics (AVFD)

[Jiang, Shi, Yin, JL, arXiv:1611.04586.]

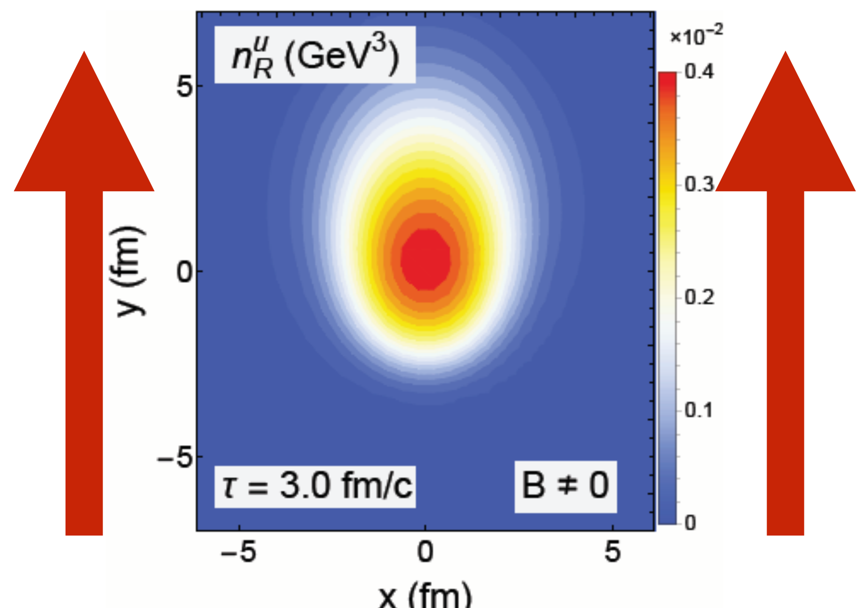
Initial density profile



Zero B Field @ 3fm/c time



Nonzero B Field @ 3fm/c time



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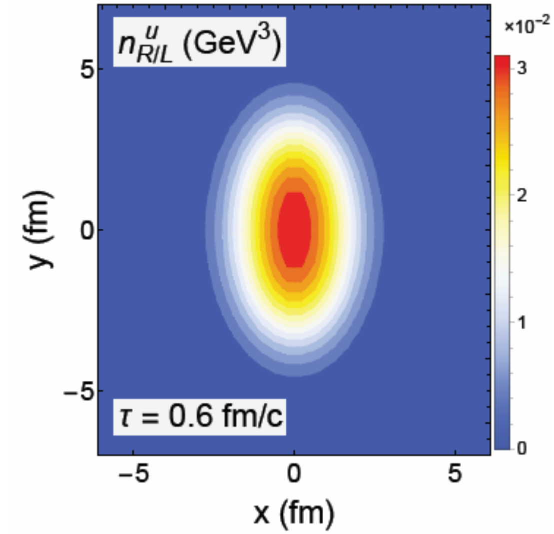
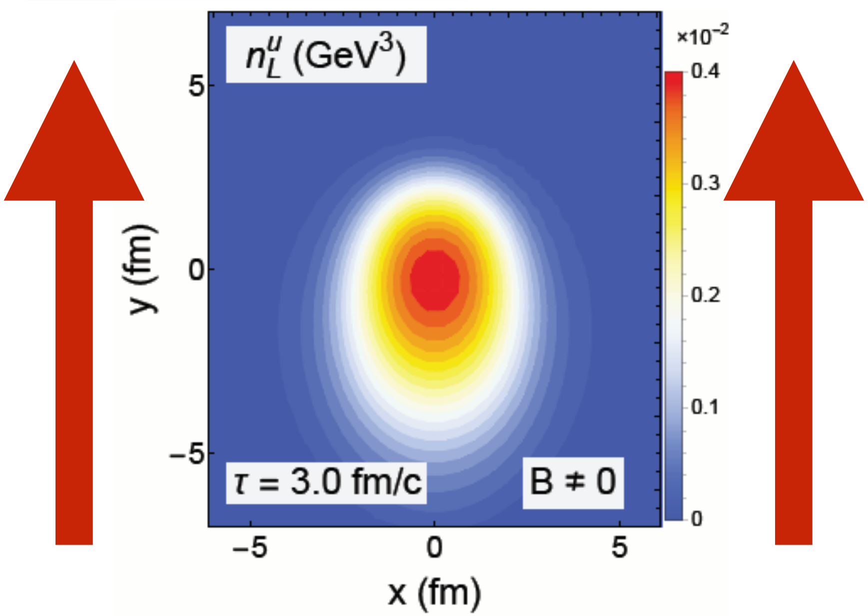
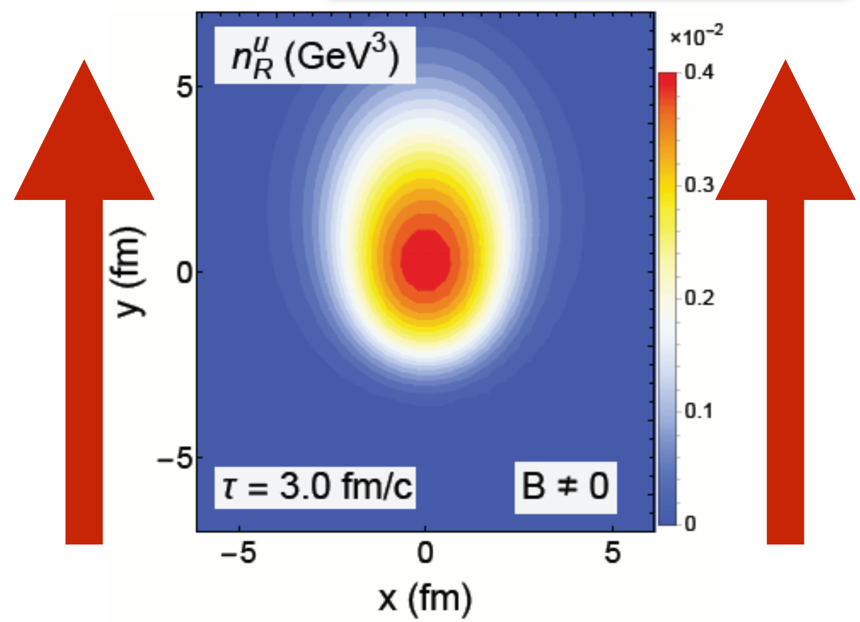
Initial density profile



Nonzero B Field LH @ 3fm/c time

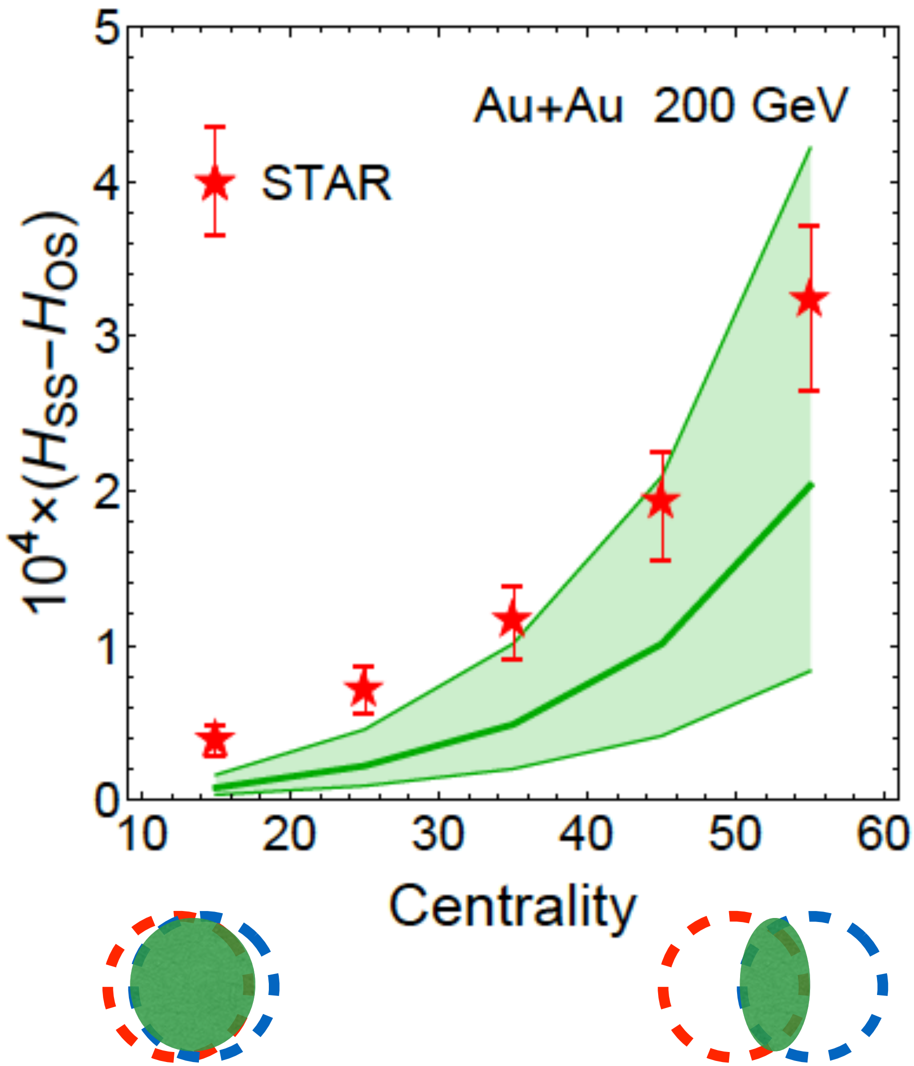
Nonzero B Field RH @ 3fm/c time





Anomalous Viscous Fluid Dynamics (AVFD)

[Jiang, Shi, Yin, JL, arXiv:1611.04586.]



$$B(\tau) = \frac{B_0}{1+(\tau/\tau_B)^2}$$

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

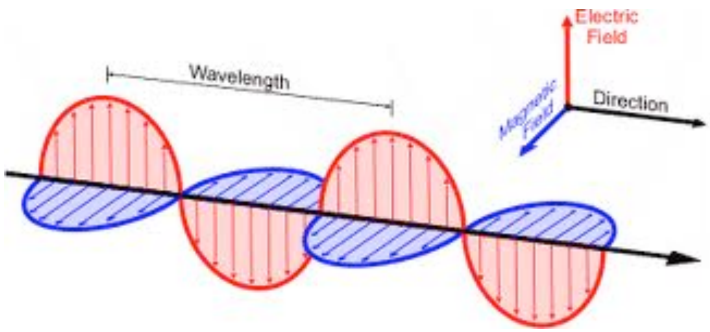
$$\sqrt{\langle n_5^2 \rangle} \simeq \frac{Q_s^4\,(\pi\rho_{tube}^2\tau_0)\,\sqrt{N_{coll.}}}{16\pi^2\,A_{overlap}}$$

With realistic initial axial charge density and short magnetic lifetime, data could be described.

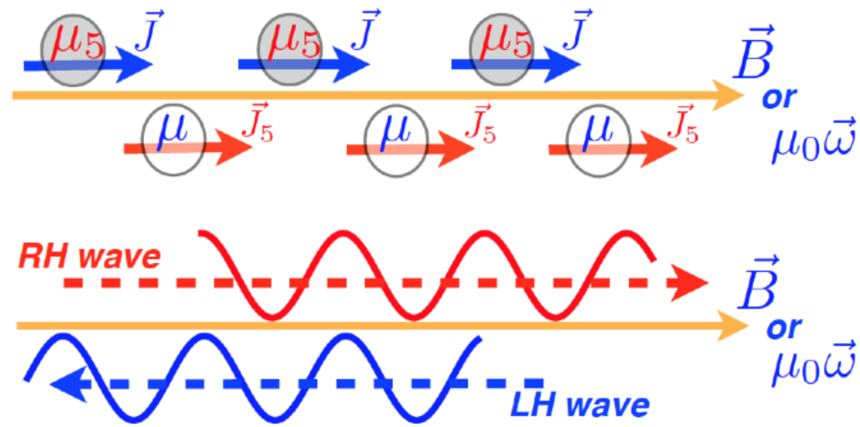
A Wealth of
Anomalous Chiral Transport Phenomena

Chiral Magnetic Wave (CMW)

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



EM wave



Chiral Magnetic Wave

CME + CSE —> gapless collective excitations, the CMW

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

$$\vec{\mathrm{J}}_5 = \sigma_5 \mu \vec{\mathrm{B}}$$

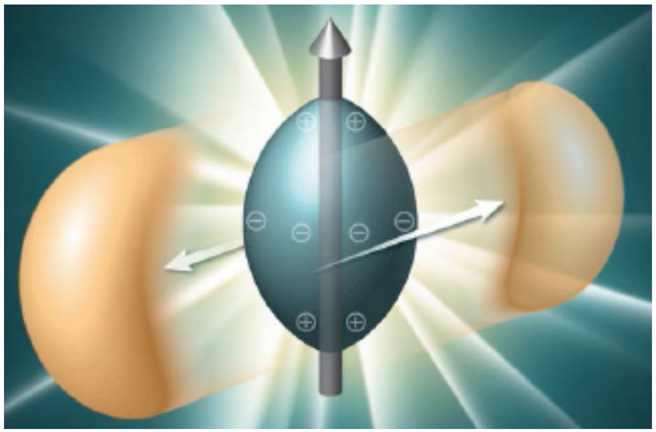
$$\left(\partial_0 \pm \frac{(Qe)}{(4\pi^2)\chi}\vec{\mathrm{B}}\cdot\nabla\right)\delta J^0_{R/L} = \left(\partial_0 \pm v_B \partial_{\hat{\mathrm{B}}}\right)\delta J^0_{R/L} = 0.$$

[Kharzeev, Yee, 2010; Burnier, Kharzeev, JL, Yee, 2011]

CMW Induced Flow Splitting

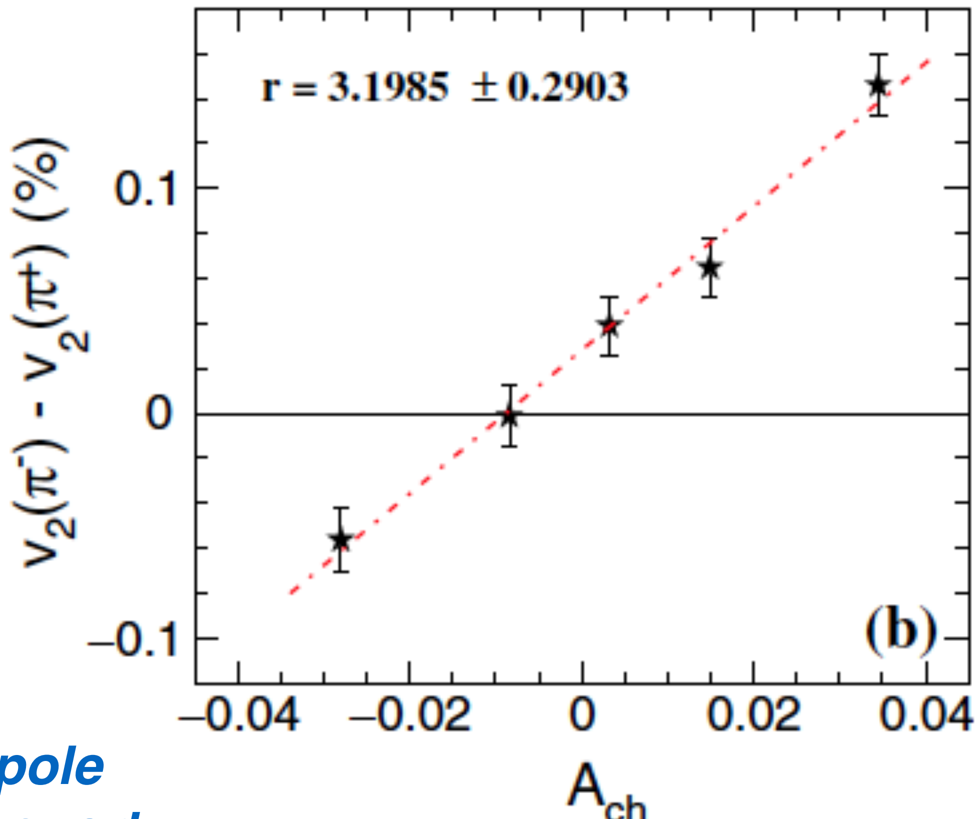
CMW —> charge quadrupole of QGP —> elliptic flow splitting

[Burnier, Kharzeev, JL, Yee, PRL2011; and arXiv: 1208.2537]



$$v_2^- - v_2^+ = r_e \, A$$

charge quadrupole due to CMW transport



[STAR, PRL2015]

[Also seen by ALICE@LHC]

Chiral Vortical Effect

Interesting analogy between magnetic field and fluid rotation!

EM vector field $\vec{A}$ | $\vec{V}$ Fluid velocity field

Magnetic field $\vec{B} = \vec{\nabla} \times \vec{A}$ | $\vec{\omega} = \vec{\nabla} \times \vec{V}$ Fluid vorticity

Lorentz force

$$\vec{F}_{Lorentz} = e\,\vec{v} \times \vec{B}$$

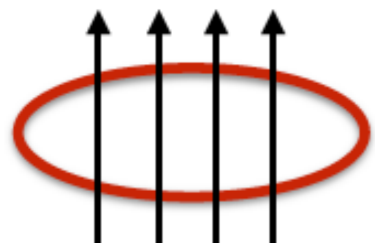
Coriolis force

$$\vec{F}_{cor} = 2m\,\vec{v} \times \vec{\omega}$$

$\vec{\omega}\ or\ \vec{B}$

Chiral Magnetic Effect

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



Chiral Vortical Effect

$$J_V = \frac{1}{\pi^2}\mu\mu_5\omega$$

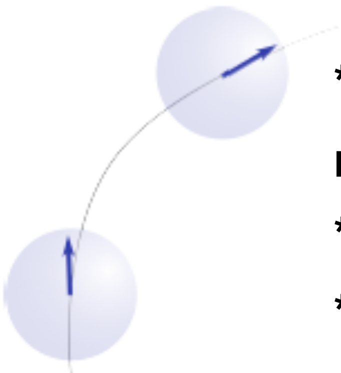
**** Collective excitations: Chiral Vortical Wave***

**** Sizable angular momentum and fluid vorticity in QGP.***

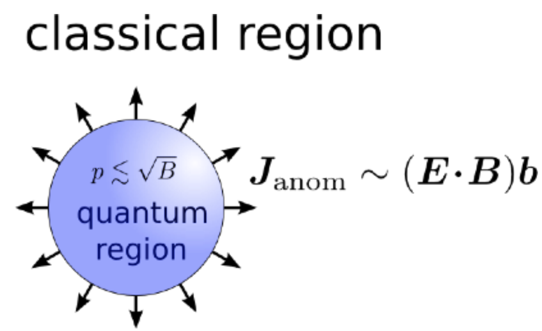
Non-Equilibrium CME: Chiral Kinetic Theory

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]



* Definite chirality: Spin "rotates" with momentum —> Berry Phase
* CKT: Introducing O(h-bar) quantum effect
* Correctly accounting for anomaly



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

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

Berry curvature

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

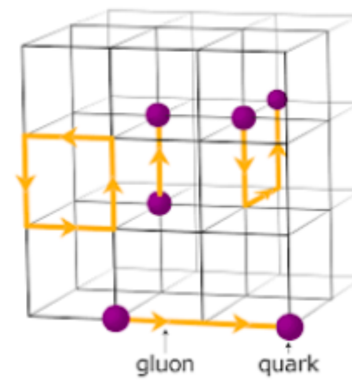
$$\dot{\boldsymbol{p}} - \boldsymbol{E} - \dot{\boldsymbol{x}} \times \boldsymbol{B} = 0;$$

Non-Equilibrium CME: Classical Statistical Field

Dirac equation knows anomaly!

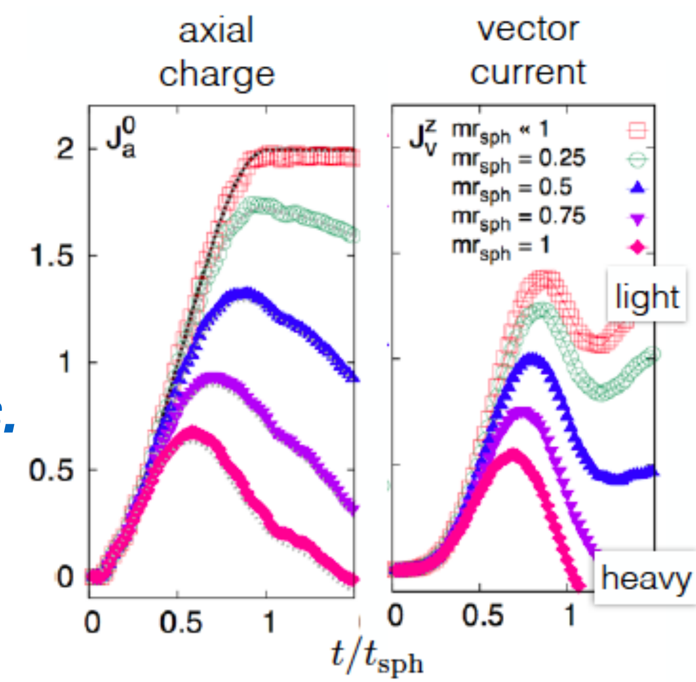
Chiral Magnetic Effect: $\vec{j}_v \propto j_a^0 \vec{B}$

axial charge density — *magnetic field*



- Solve operator Dirac equation in the presence of SU(N) and U(1) gauge fields

$$i\gamma^0\partial_t\hat{\psi} = (-i\not{D}_W^s + m)\hat{\psi}$$



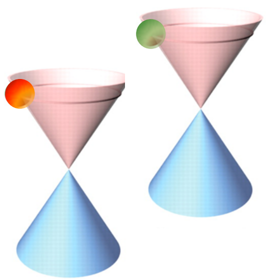
CME can be automatically generated during the fermion production process.

[Mueller, Schlichting, Mace, Sharma, 1612.02477; Fukushima, 2015]

New Territory of CME Physics: 3D Semimetals

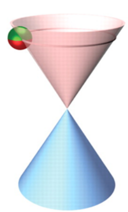
The anomalous transport phenomena are universal phenomena across boundaries of disciplines, encompassing a wide range of chiral systems!

Weyl semimetal
(non-degenerated bands)

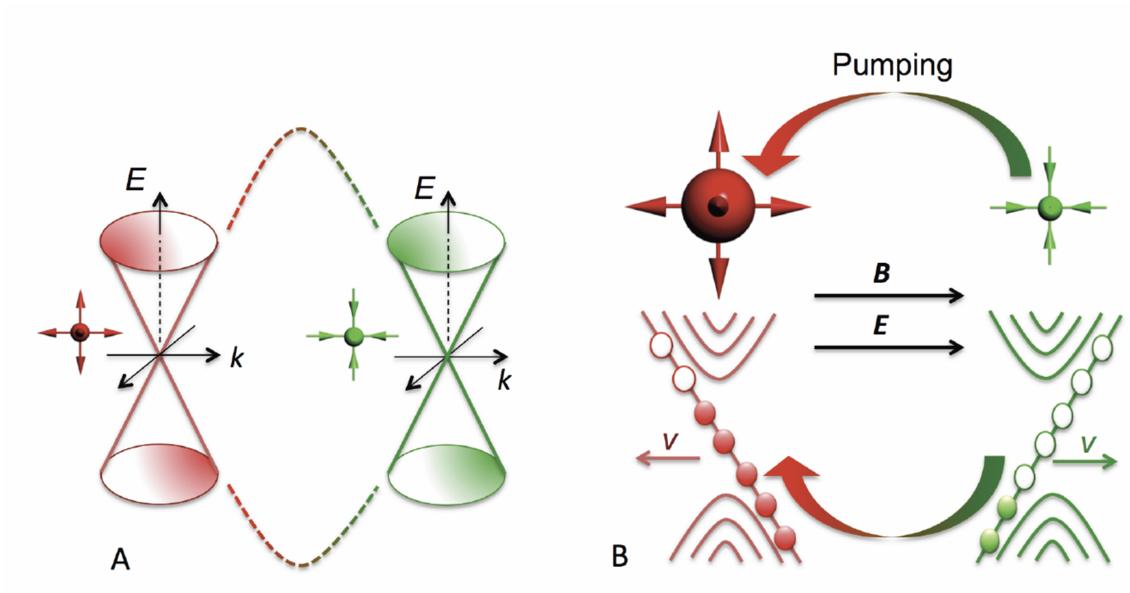


TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2



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

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

One should expect to see CME in semimetals —
CME in fact becomes a signal of chiral fermions!

New Territory of CME Physics: Table-Top Exp.

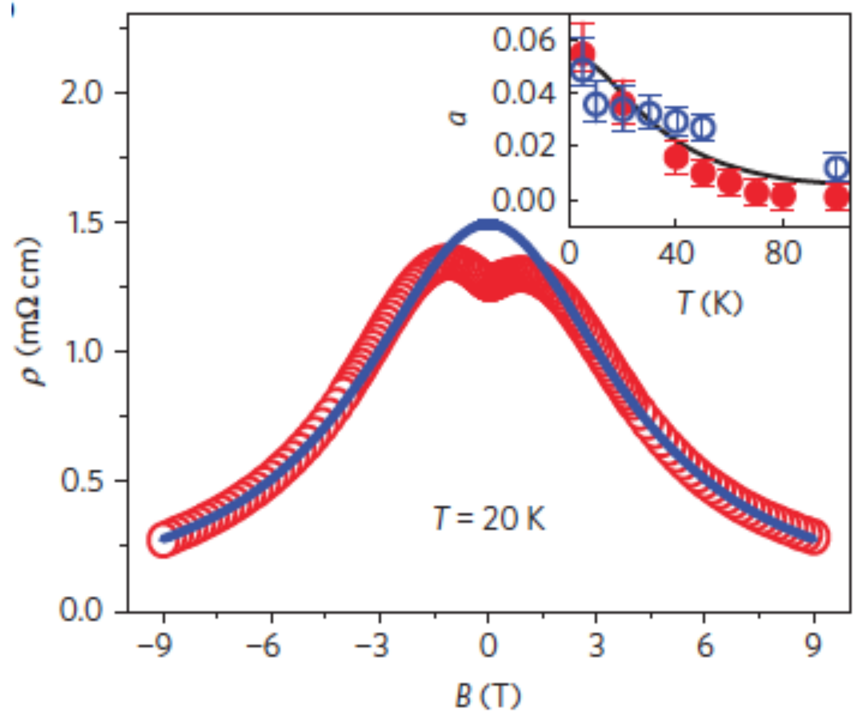
$$N_{L,R} \approx \frac{e^2}{4\pi^2\hbar^2 c}\vec{E}\cdot\vec{B}\tau_v$$

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

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

$$J^i_{CME} = \sigma^{ik}_{CME}E^k\,; \quad \sigma^{zz}_{CME} \sim B^2$$

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



nature physics

LETTERS

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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 [cond-mat.str-el]

Summary & Outlook

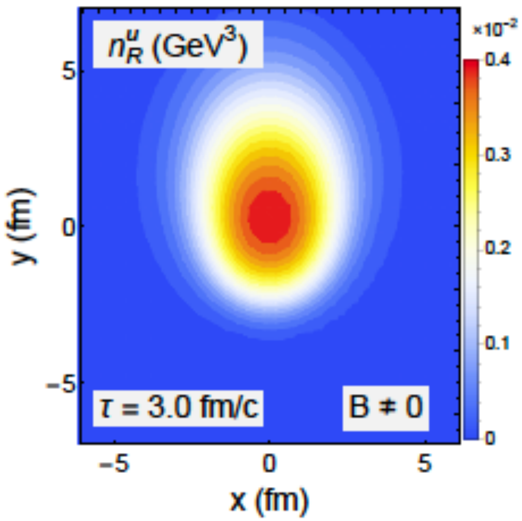
Summary

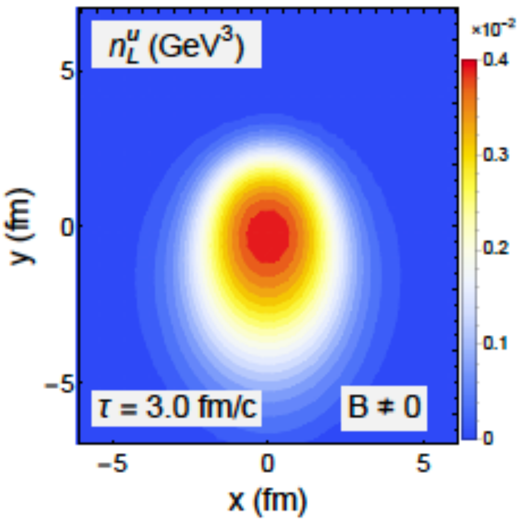
Microscopic chiral anomaly emerges as anomalous chiral transport in chiral matter (e.g. QGP): Chiral Magnetic Effect, Chiral Magnetic Wave, Vortical Effects, …

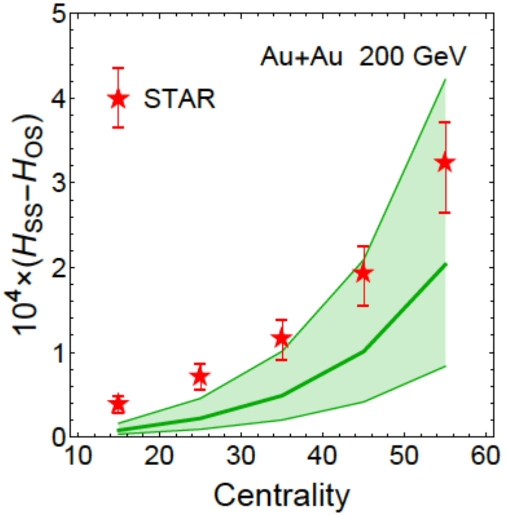
Theoretical frameworks have been developed for anomalous chiral transport: anomalous hydro; chiral kinetic theory; classical statistical field theory

Anomalous-Viscous Fluid Dynamics, with reasonable parameters and initial conditions, predicts CME signals that could quantitatively explain data.

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







Toward Completion of RHIC Science Mission

RHIC is a unique test ground for rich, novel QCD phenomena.

RHIC Run Plan

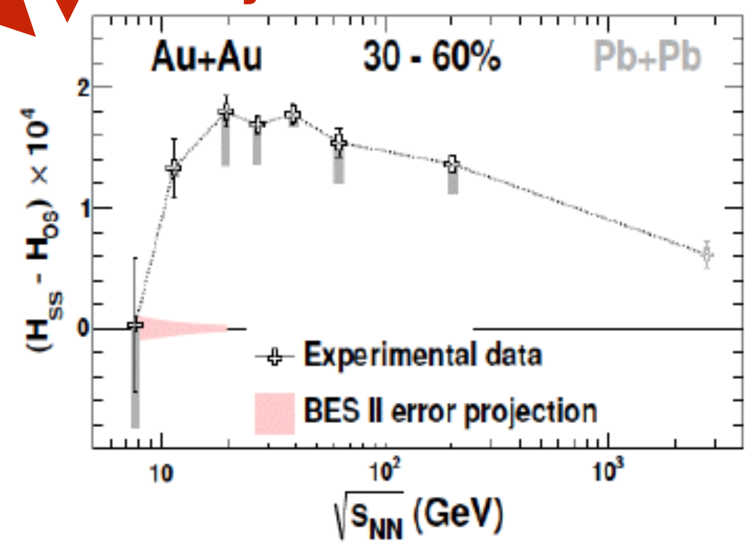
2016	2017	2018	2019	2020	2021	2022+
-200 GeV Au+Au -d+Au Energy Scan	-500 GeV p+p -62.4 or 27 GeV?	Isobar Zr+Zr and Ru+Ru	BES-II	BES-II		Full Energy Au+Au

Dedicated run for CME search!

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

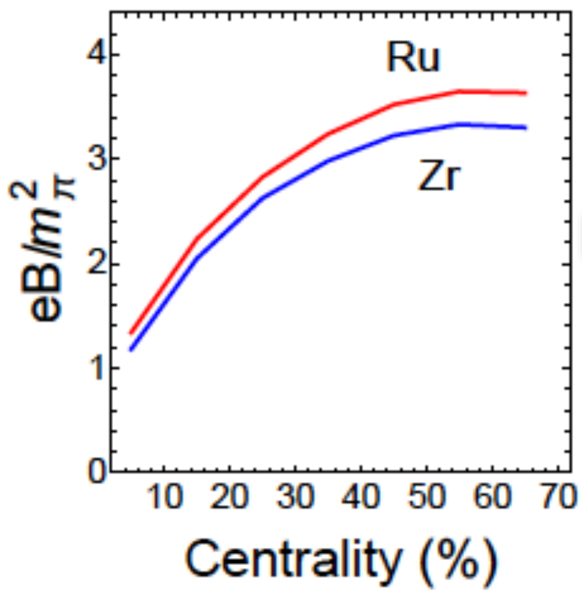
Up to 10% variation in B field, thus ~20% shift of CME signal!

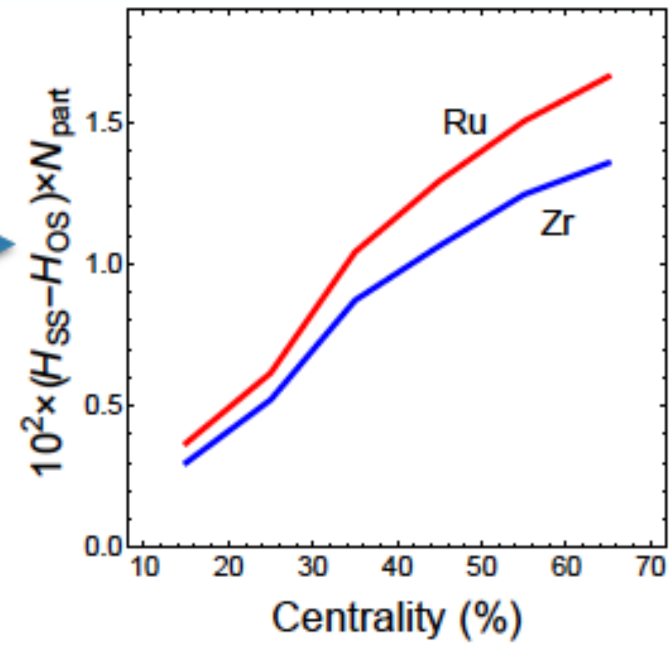
Partly for CME search



Predictions for Isobaric Collisions

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



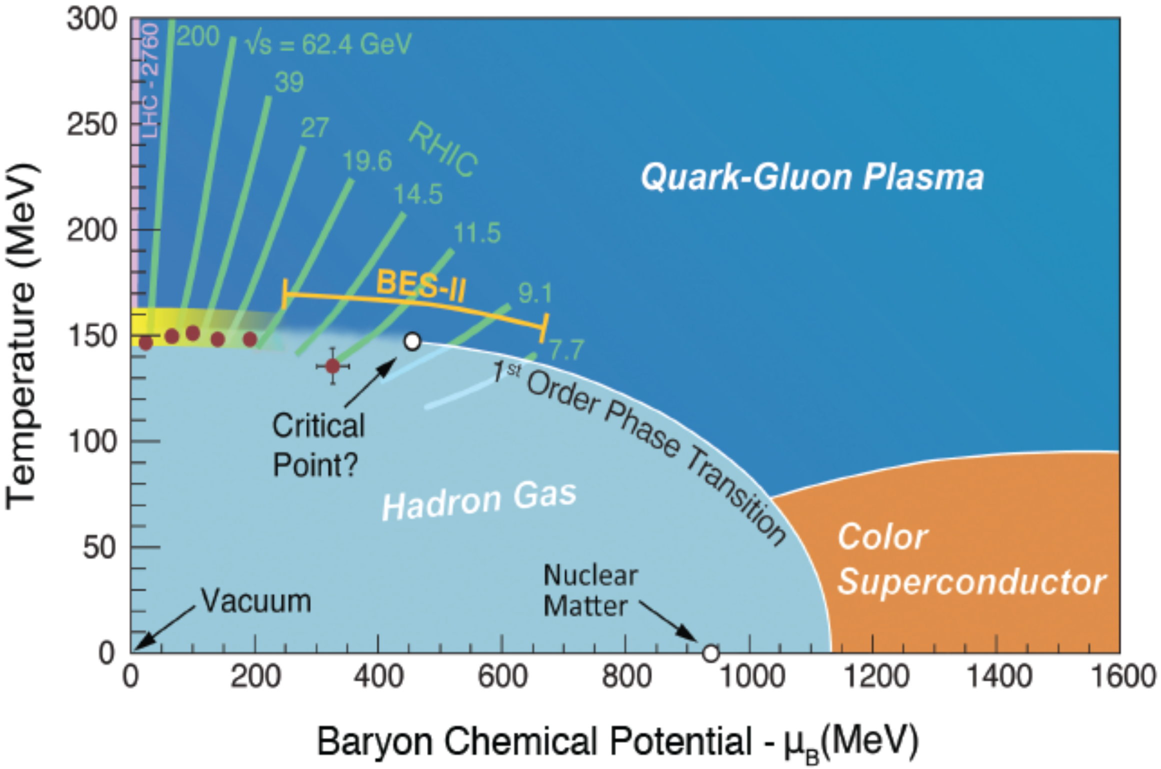


15~20% difference

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

Stay tuned for exciting news in the near future!

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