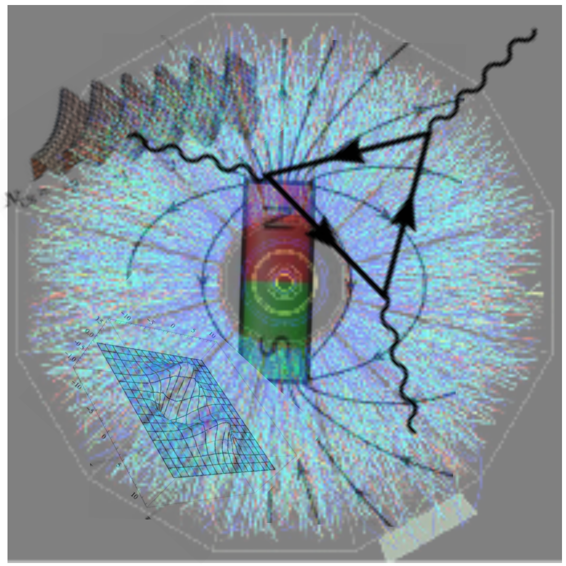
Anomalous Chiral Transport and Fluid Dynamics



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Research Supported by NSF & DOE

BEST COLLABORATION

Introductory Discussions

Properties of Matter under New Conditions

Very strong magnetic field —> Magnetic Polarization!

Very strong global rotation —> Rotational Polarization!

Non trivial interplay between external conditions & internal degrees of freedom (spin/momentum/angular momentum)

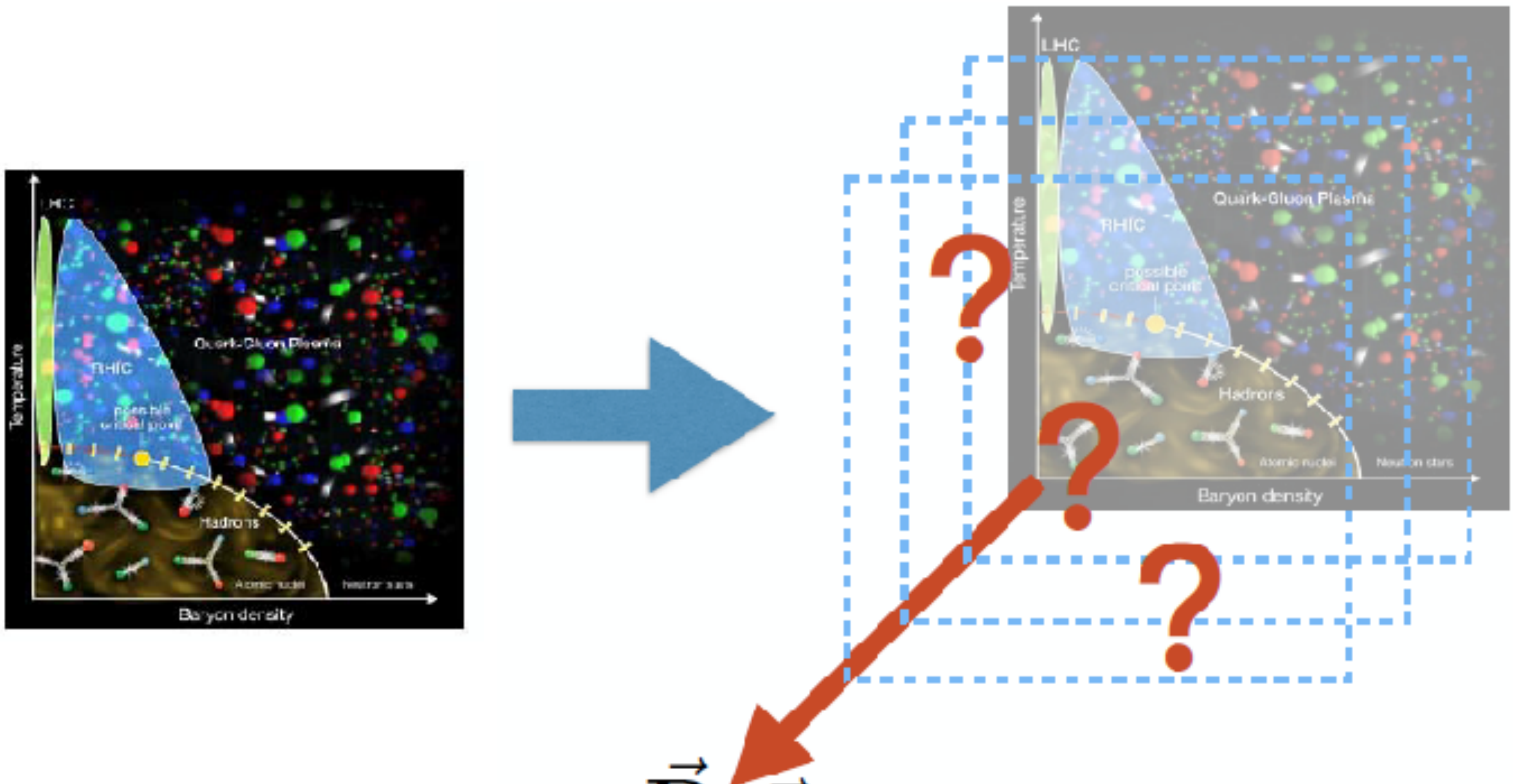
Thermodynamic properties of matter:

- ***Equation of State***
- ***Phase Structure***
- ***Macroscopic Polarization***
- ***......***

Transport properties of matter:

- ***Transport coefficients***
- ***Anomalous transport effects***
- ***......***

Opening New Dimensions for Phase Diagram

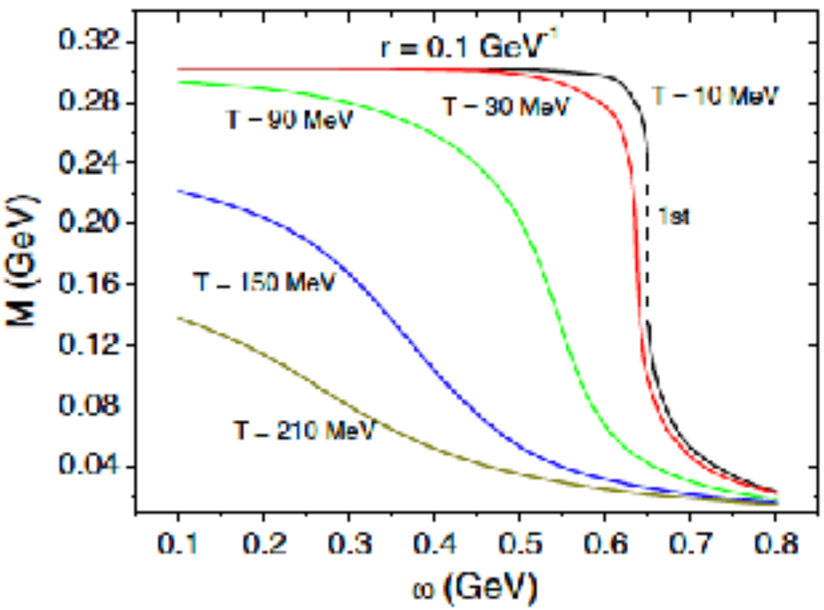


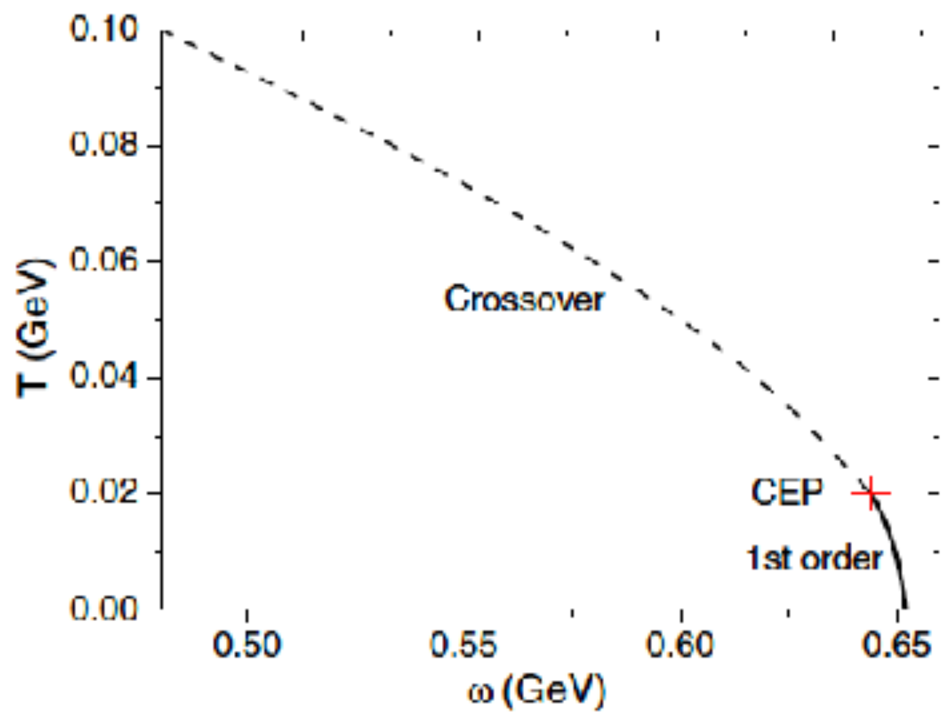
$$\vec{\mathbf{B}}, \vec{\omega}, \mathbf{n_5}, \ldots$$

For example: very interesting and intriguing phenomena of Magnetic Catalysis & Inverse Magnetic Catalysis

Opening New Dimensions for Phase Diagram

Another very recent example:
Rotational suppression effect of fermion pairing phenomena
(chiral condensate; color superconductivity; cold fermi gas;…)





[“Pairing phase transitions of matter under rotation”,
Y.Jiang & JL: Phys.Rev.Lett.117(2016)no.19,192302]

Anomalous Chiral Transport

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

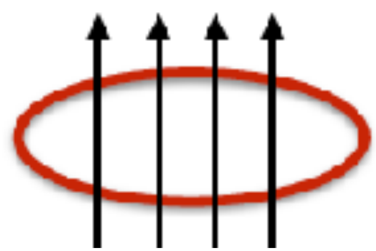
$$\vec{F}_{Lorentz} = e\,\vec{v} \times \vec{B}$$

Coriolis force

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

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

QM: A-B phase



QM: Sagnac phase

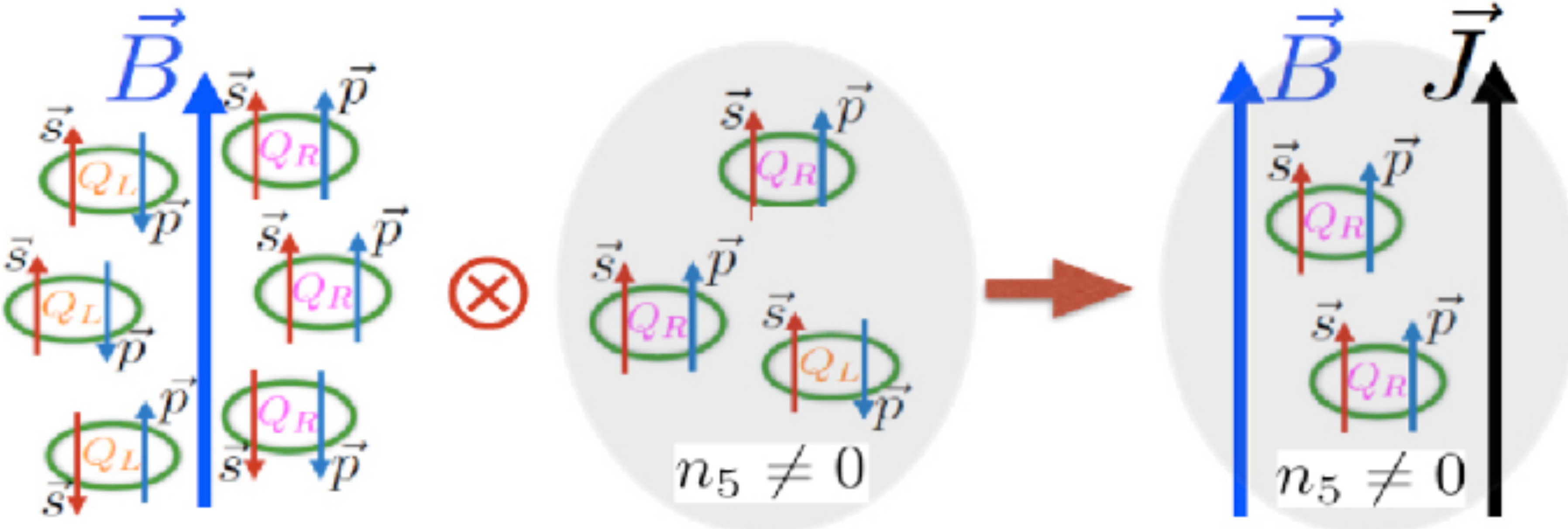
Chiral fermions:
Chiral Magnetic Effect (CME)

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

Chiral fermions:
Chiral Vortical Effect (CVE)

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

Intuitive Picture of CME



Intuitive understanding of CME:

magnetic polarization —>
correlation between micro.
SPIN & EXTERNAL FORCE

⊗

Chiral imbalance —>
correlation between directions of
SPIN & MOMENTUM

→ ***Current along external B field!***

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

It Is Anomalous!

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

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

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

—>CHIRAL MATTER, with nonzero macroscopic chirality

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

$$\updownarrow$$

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

The CME conductivity is

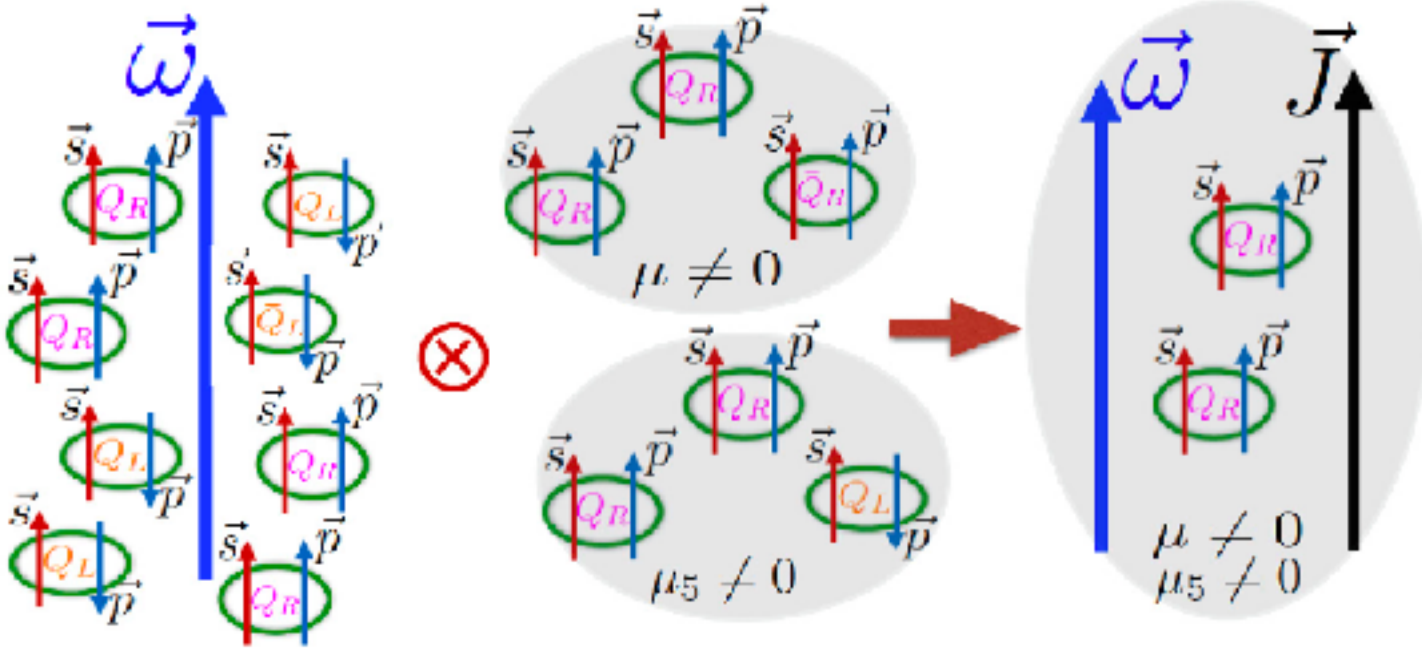
**** fixed entirely by quantum anomaly***

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

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

We need to modify hydrodynamics!

Intuitive Picture of CVE



Intuitive understanding of CVE:

rotational polarization —>
correlation between micro.
SPIN & EXTERNAL FORCE

$\otimes$

Chiral imbalance —>
correlation between directions of
SPIN & MOMENTUM

→ ***Current along fluid rotation axis!***

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

Anomalous Chiral Transport: Deep & Rich

Including the macroscopic CME current leads to many interesting and exciting new possibilities!

*** Plasma physics: CME currents —> new chiral magnetohydro dynamics, chiral plasma instabilities, …***

*** Astrophysical environment: supernovae matter, neutron star matter***

*** Cosmology: cosmic magnetic fields, CP violation, …***

*** Dirac/Weyl Semimetals***

Fluid Dynamics with Chiral Anomaly

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	$\partial_\mu J^\mu = 0$

WHAT ABOU "HALF"-SYMMETRY???

i..e ANOMALY?!

— classical symmetry that is broken in quantum theory

Hydrodynamics That Knows Left & Right

Normal Hydrodynamics

$$\partial_\mu J^\mu = 0$$

$$J^\mu = n u^\mu + \nu^\mu$$

Viscous Current

$$\nu^\mu = -\frac{\sigma T}{2} \Delta^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right)$$

Diffusion

$$+ \frac{\sigma}{2} E^\mu$$

Conduction

Anomalous Hydrodynamics

$$\partial_\mu J^\mu = C_A E^\mu B_\mu$$

Anomaly

$$J^\nu = n u^\mu + \nu^\mu + \nu_a^\mu$$

Viscous Current | Anomalous Current

$$\nu^\mu = -\frac{\sigma T}{2} \Delta^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right)$$

Diffusion

$$+ \frac{\sigma}{2} E^\mu$$

Conduction

$$\nu_a^\mu = \xi_B B^\mu$$

CME

$$+ \xi\, \omega^\mu$$

CVE

Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

[Fluid rotation induces similar effects as magnetic field]

Fluid Dynamics with Chiral Anomaly

Blackboard

Simulation Results from Anomalous Viscous Fluid Dynamics (AVFD)

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 ⇒ charge separation

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

Anomalous Viscous Fluid Dynamics (AVFD)

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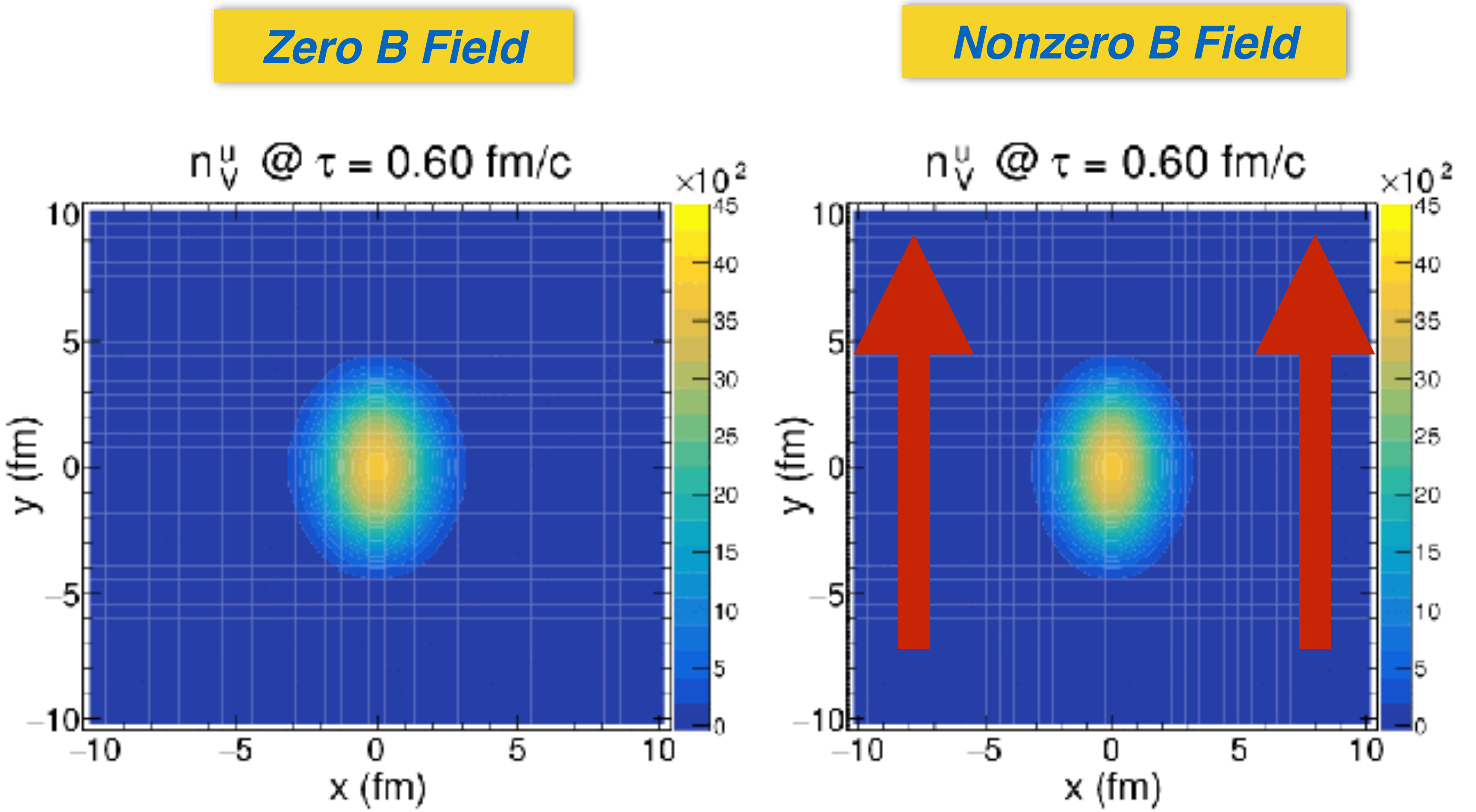

Anomalous Viscous Fluid Dynamics (AVFD)

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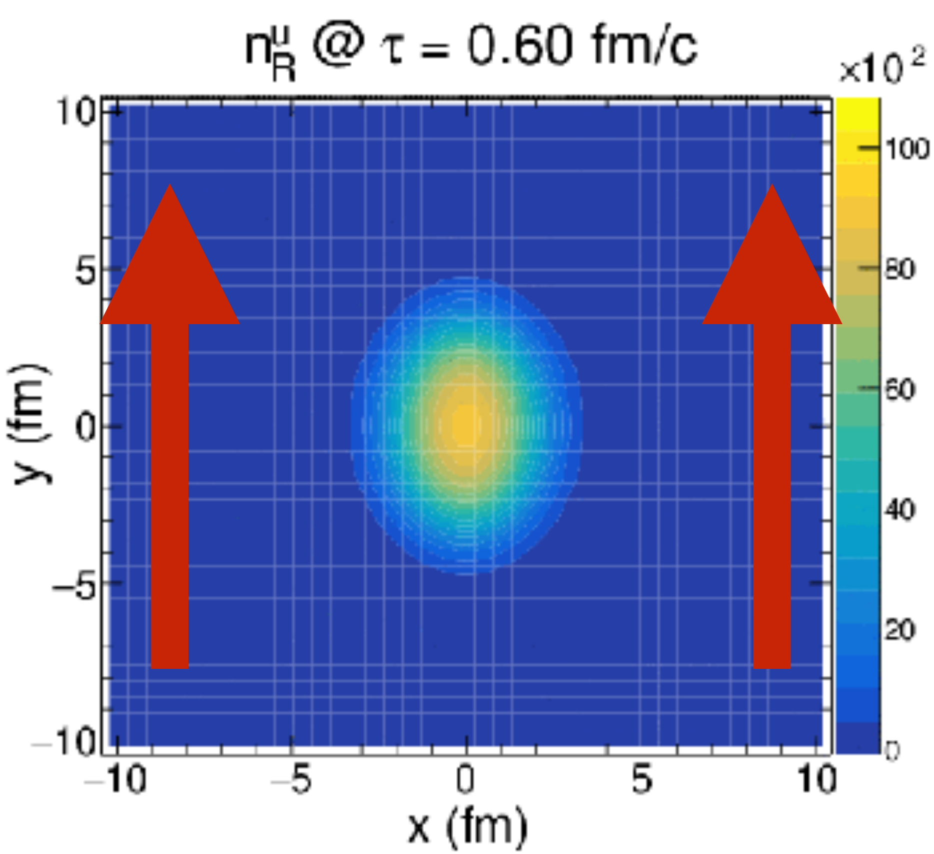
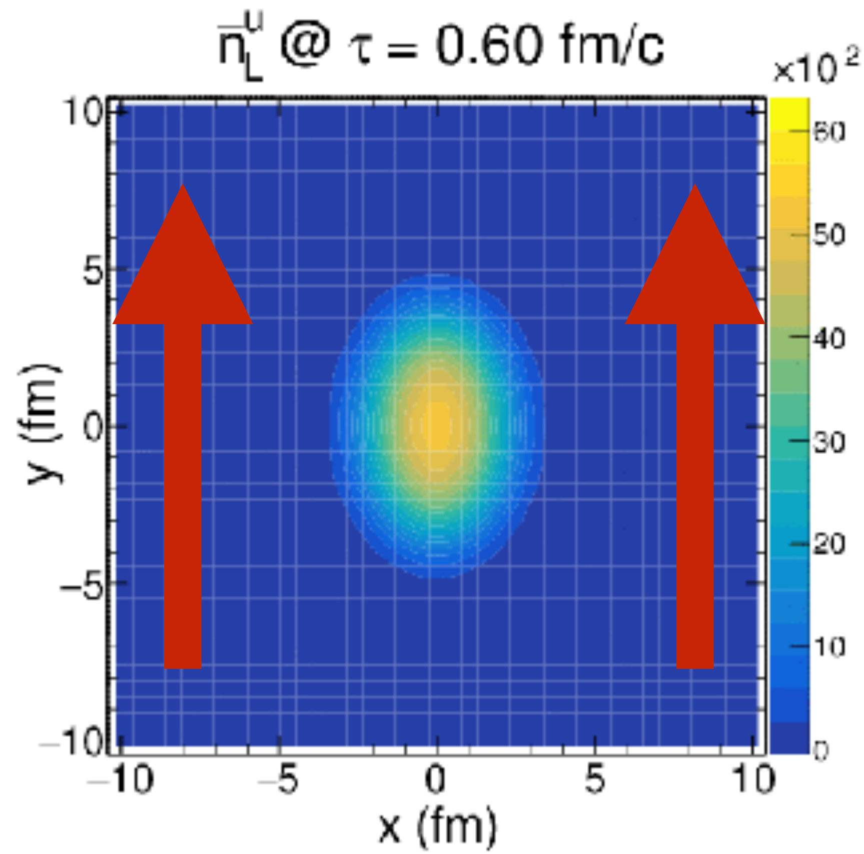
Right-Handed Density



Left-Handed Density



Anomalous Viscous Fluid Dynamics (AVFD)

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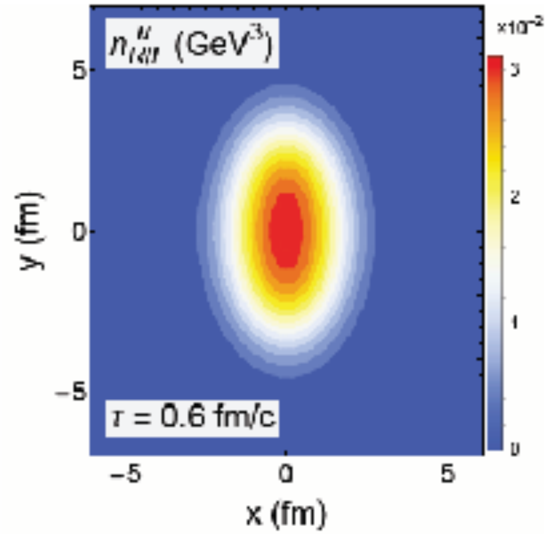
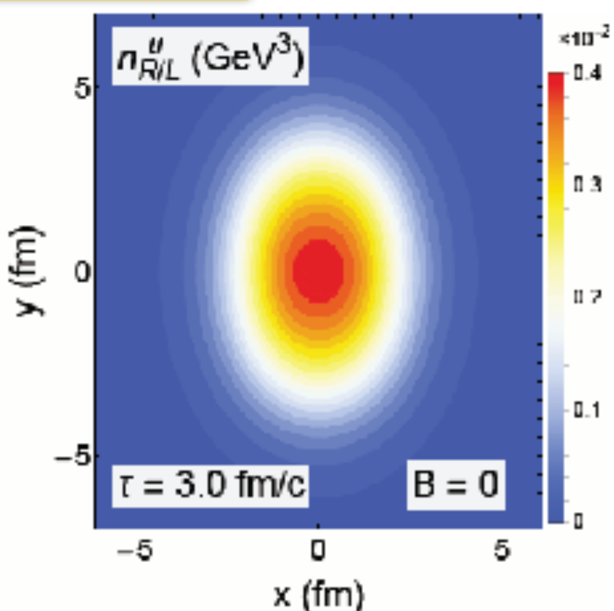
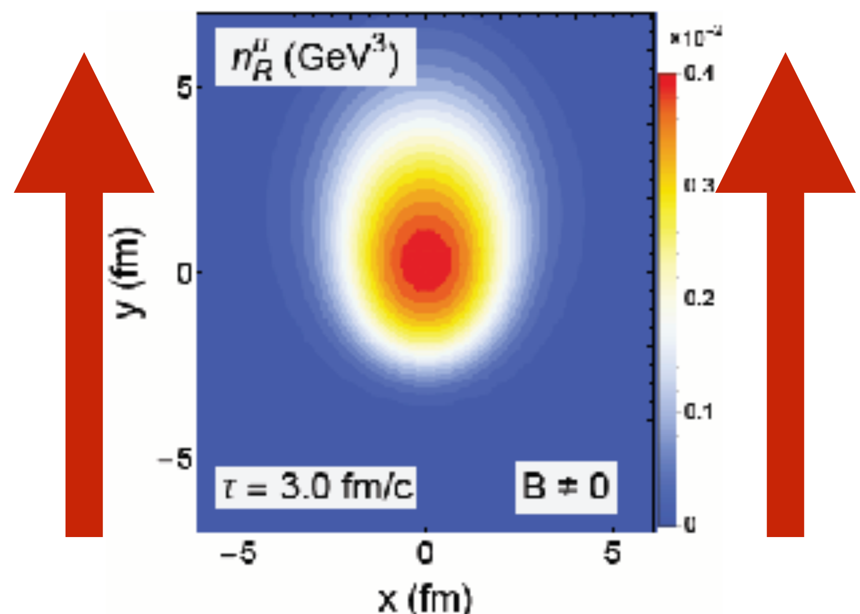
Initial density profile



Zero B Field @ 3fm/c time



Nonzero B Field @ 3fm/c time



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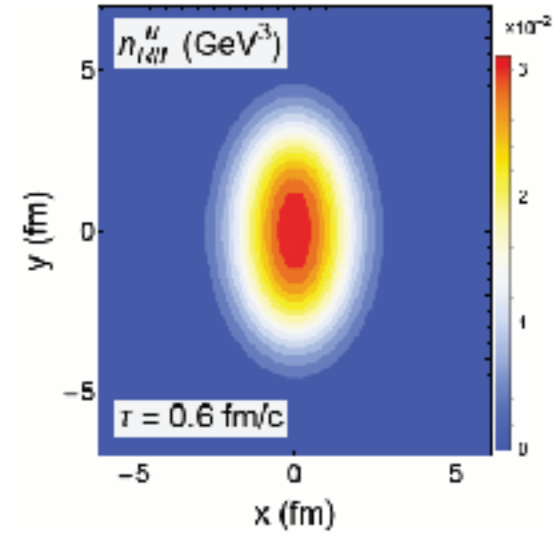
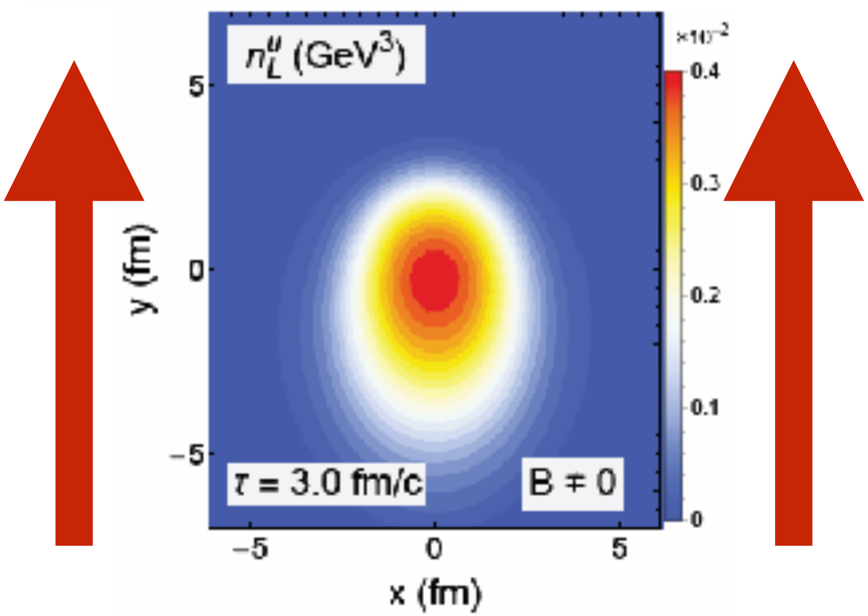
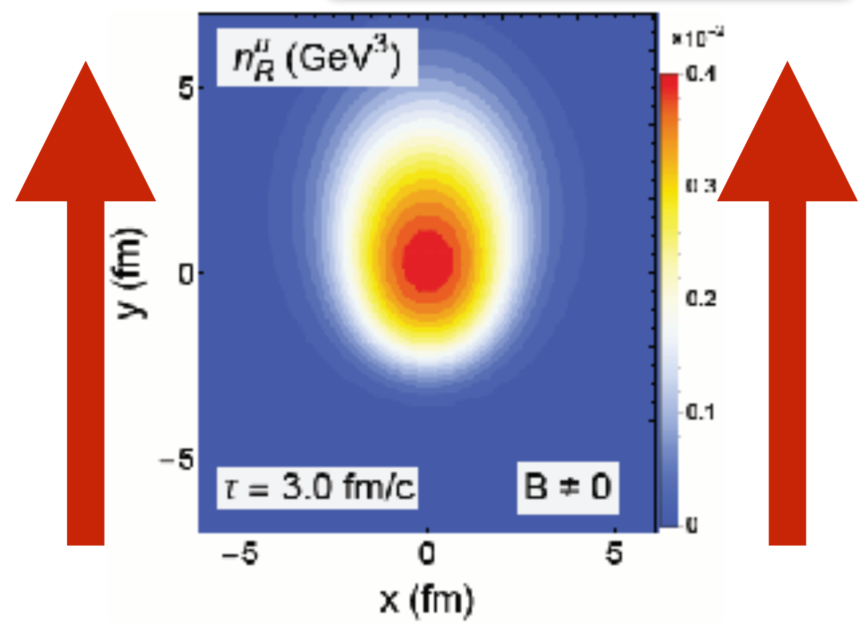
Initial density profile



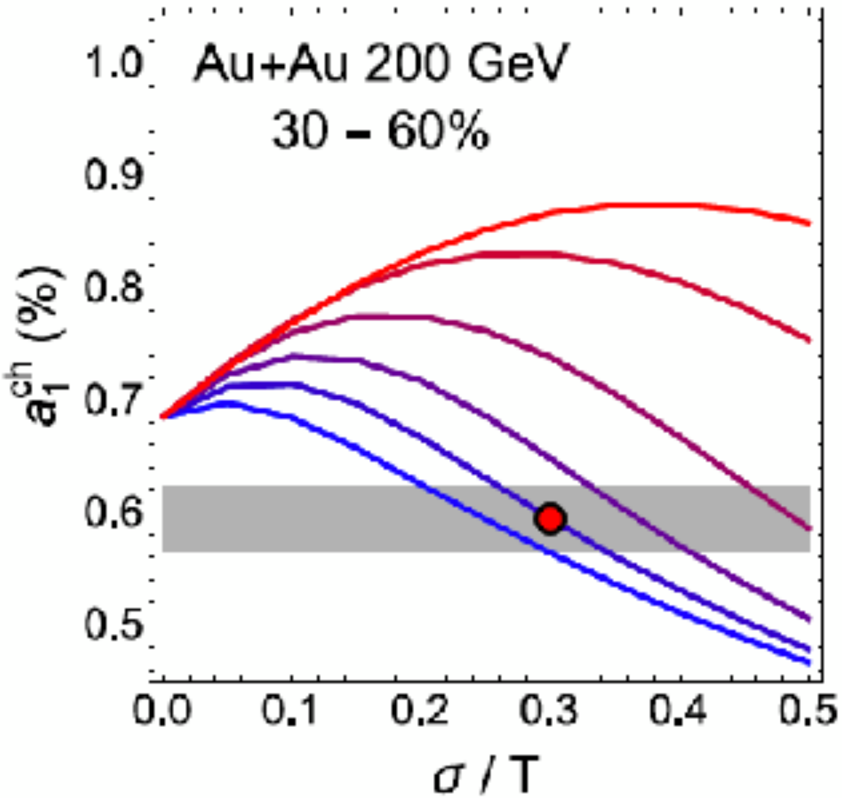
Nonzero B Field LH @ 3fm/c time



Nonzero B Field RH @ 3fm/c time



Viscous Effect on CME Transport



$\tau_r T = 0.3, 0.5, 0.7, 1.0, 1.5, 2.0$
(from bottom/blue to top/red)

$$\Delta^{\mu}{}_{\nu}\, d\, \nu_{R,L}{}^{\nu} = -\frac{1}{\tau_{rlx}}(\nu_{R,L}{}^{\mu} - \nu_{NS}{}^{\mu})$$

$$\nu_{NS}{}^{\mu} = \frac{\sigma}{2} T \Delta^{\mu\nu} \partial_{\nu} \frac{\mu}{T} + \frac{\sigma}{2} q\, E^{\mu}$$

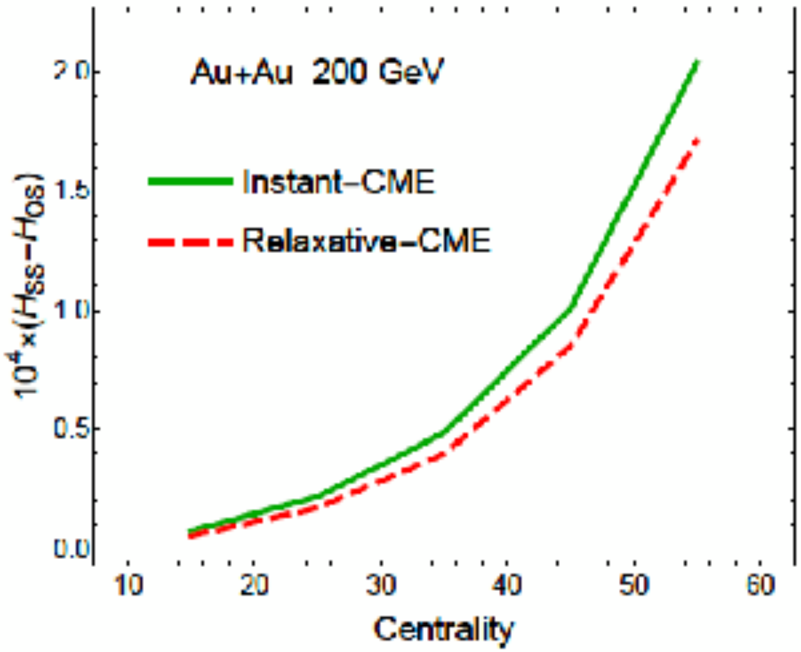
- Viscous transportation has sizable (~30%) effect on charge separation.
- "Canonic" parameters are employed.

Important uncertainty to get under control!

Relaxation Effect on CME Current

$$J_{R/L}^{\mu} = n_{R/L}\, u^{\mu} + \nu_{R/L}^{\mu} \pm \frac{N_c q}{4\pi^2} \mu_{R/L}\, B^{\mu}$$

$$\Delta^{\mu}{}_{\nu}\, d\, \nu_{R,L}^{\nu} = -\frac{1}{\tau_{rlx}} (\nu_{R,L}^{\mu} - \nu_{NS}^{\mu})$$



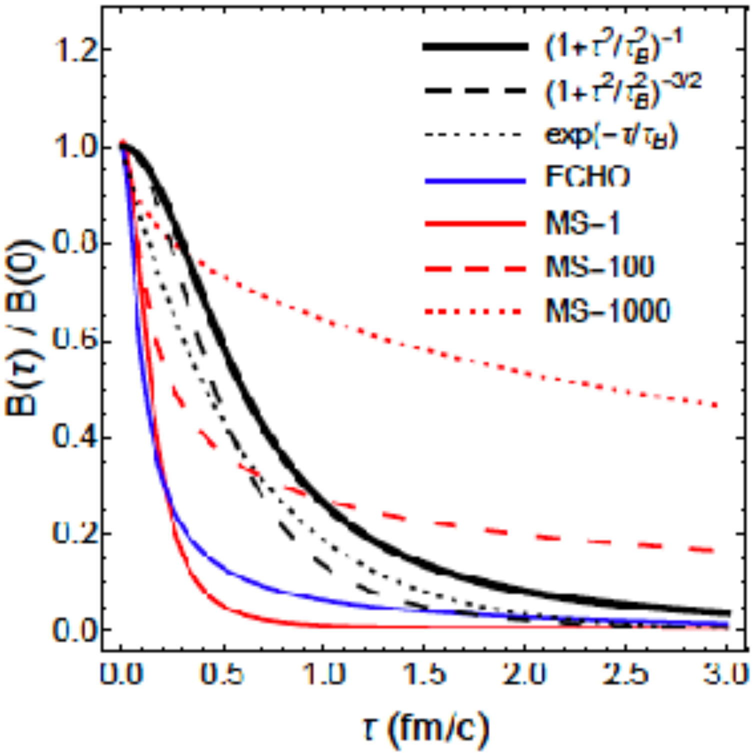
V.S.

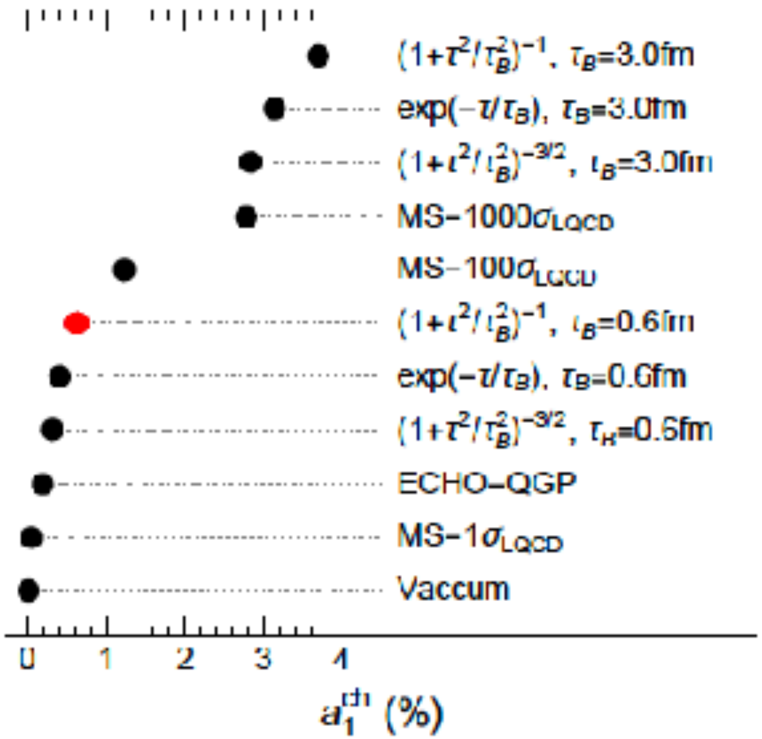
$$J_{R/L}^{\mu} = n_{R/L}\, u^{\mu} + \nu_{R/L}^{\mu}$$

$$\Delta^{\mu}{}_{\nu}\, d\, \nu_{R,L}^{\nu} = -\frac{1}{\tau_{rlx}} (\nu_{R,L}^{\mu} - \nu_{NS}^{\mu} \pm \frac{N_c q}{4\pi^2} \mu_{R/L}\, B)$$

Need further theoretical input!

Time Evolution of Magnetic Field





Important uncertainty to get under control!

Anomalous Viscous Fluid Dynamics (AVFD)

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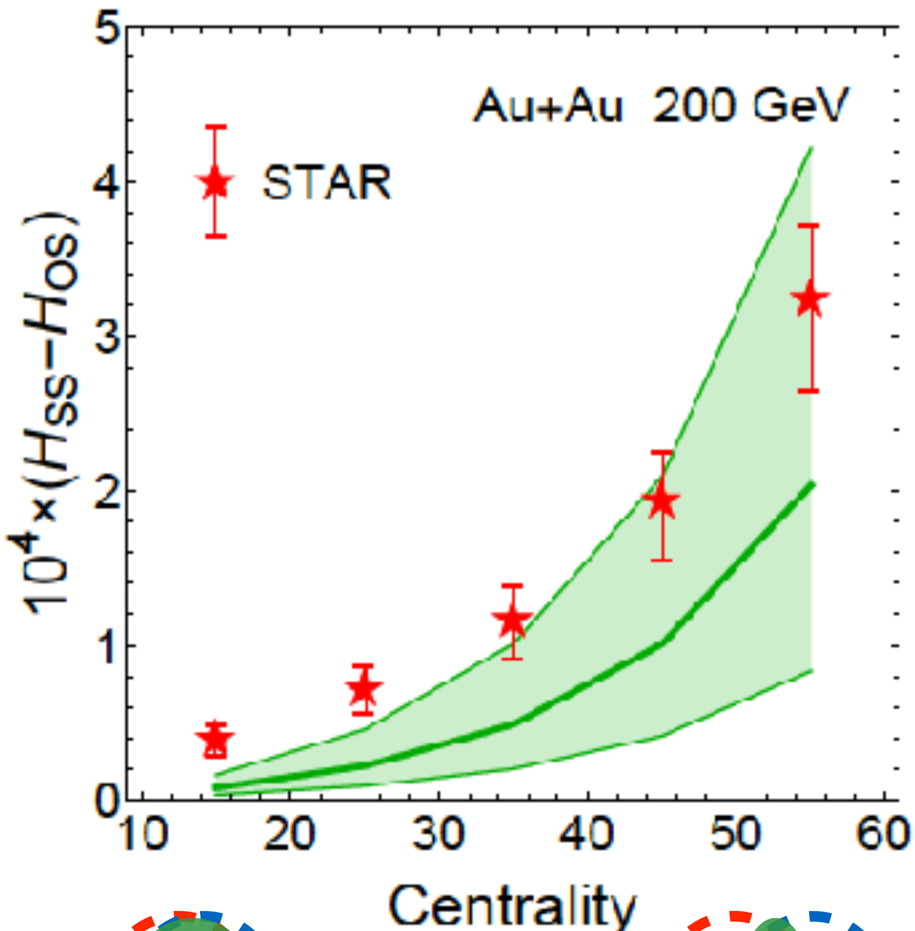
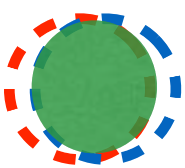
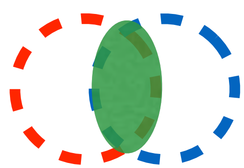






$$B(\tau) = \frac{B_0}{1+(\tau/\tau_B)^2}$$

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

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

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

Toward Completion of RHIC Science Mission

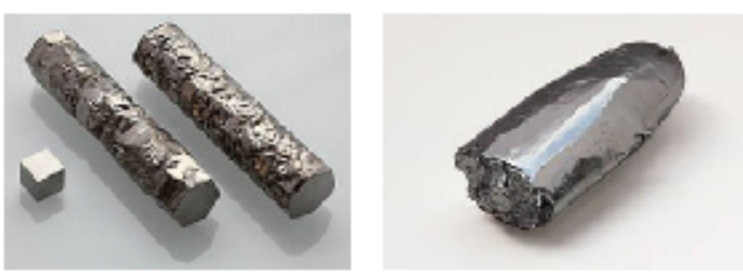
RHIC is a unique test ground for rich, novel QCD phenomena.

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

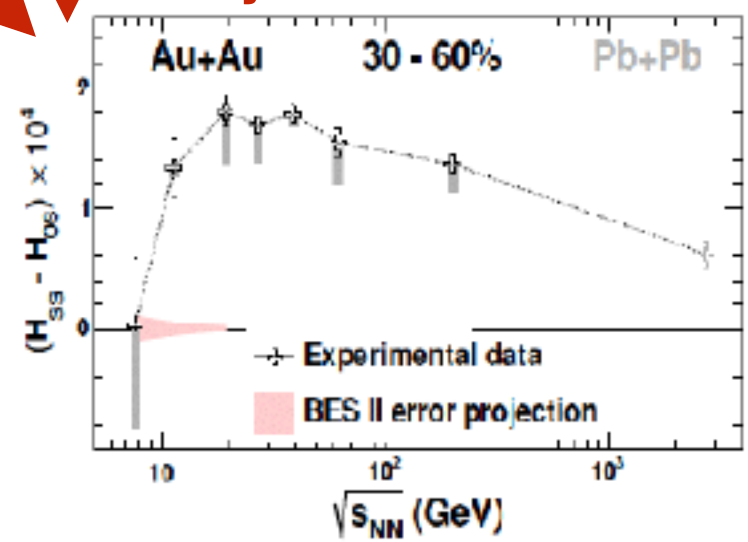
Dedicated run for CME search!

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



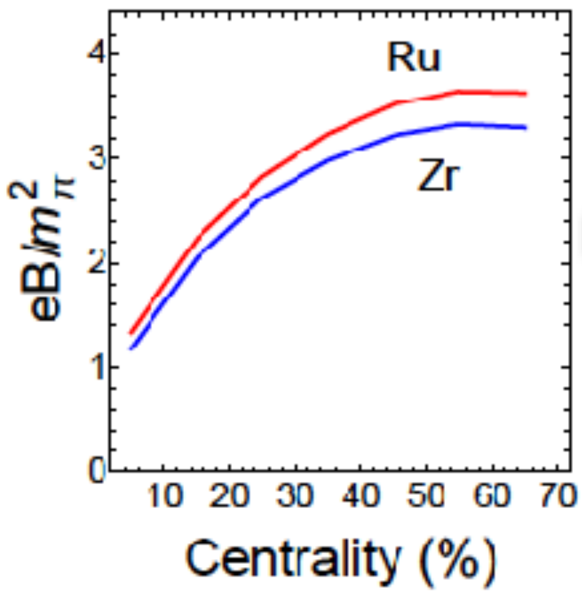
Up to 10% variation in B field, thus ~20% shift of CME signal!

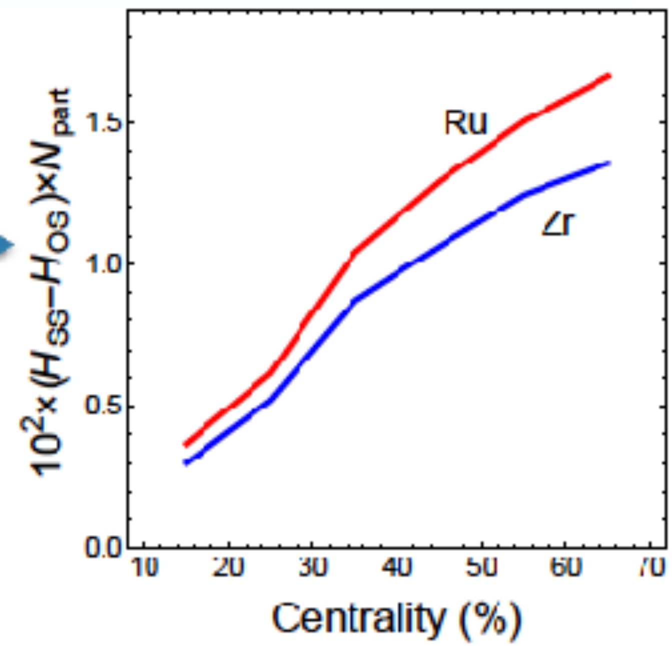
Partly for CME search



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!

Some Concluding Remarks

Q & A