QCD Phase Structure III, CCNU, Wuhan

Anomalous transport effects in heavy-ion collisions

Xu-Guang Huang

Fudan University, Shanghai

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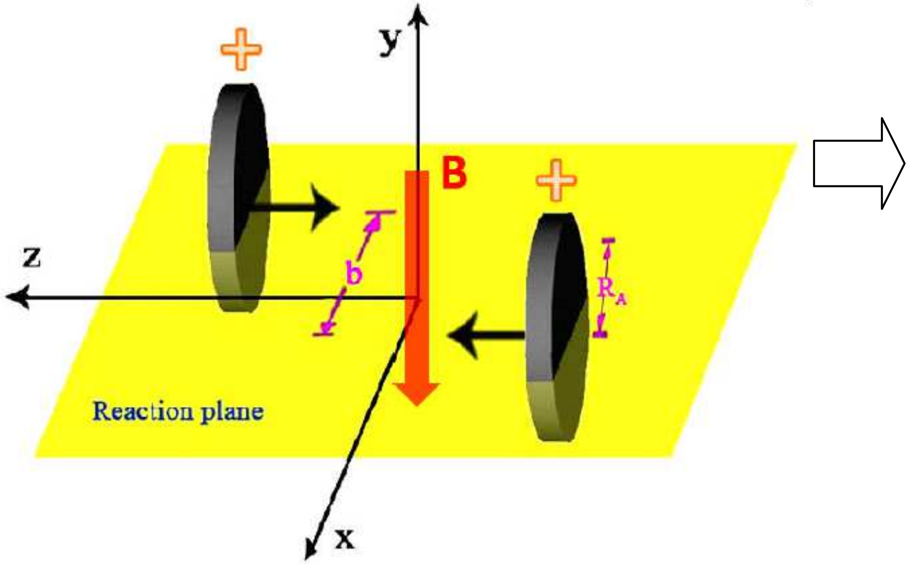
Outline

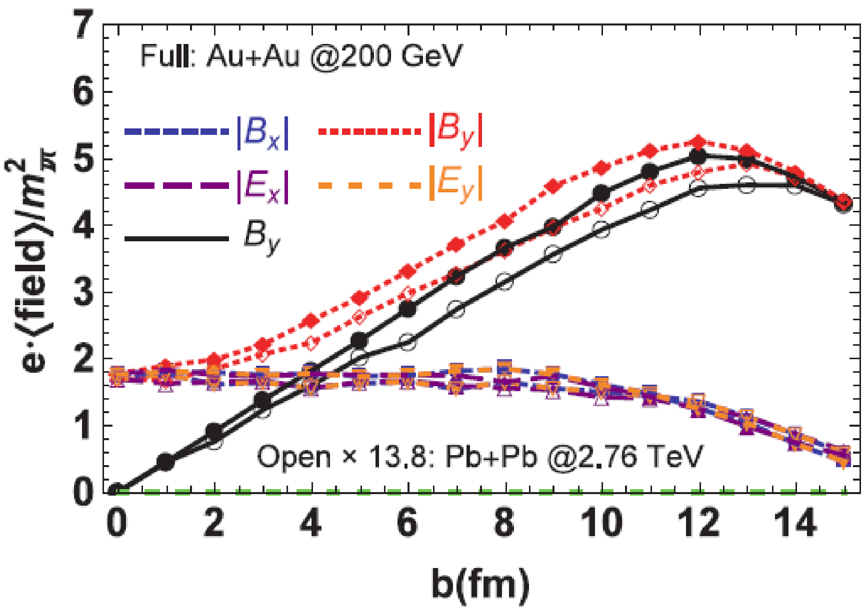
- Electromagnetic (EM) fields and vorticity in heavy-ion collisions
- EM-field induced anomalous transports (chiral magnetic effect, etc.)
- Vorticity induced anomalous transports (chiral vortical effect, etc.)
- summary

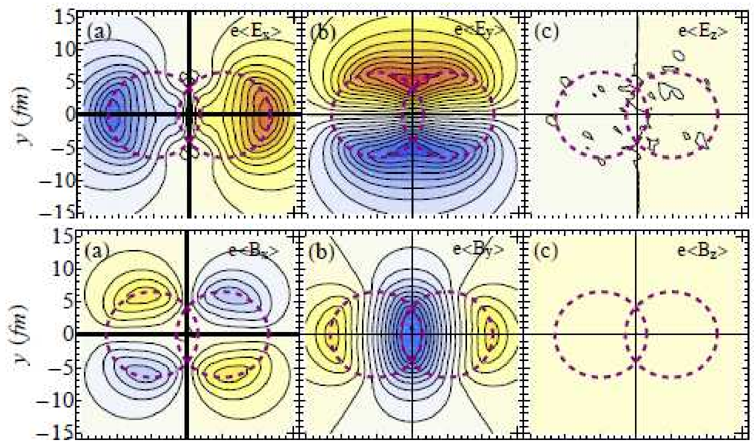
EM fields and vorticity

EM fields in heavy-ion collisions

Heavy-ion collisions generate EM fields







- **Very strong fields, eB~10^18-20 G**
- **Event-by-event fluct.**
- **Event averaged eB:**

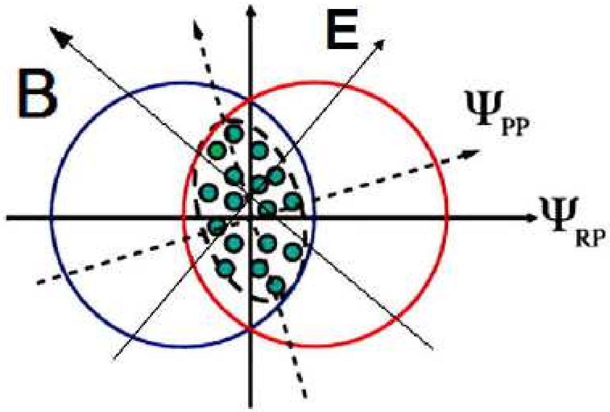
$$e\langle B_y\rangle \propto \frac{\sqrt{s}}{2m_N}\frac{Z}{A^{2/3}}\frac{b}{2R_A}m_\pi^2, \quad \text{for } b < 2R_A$$

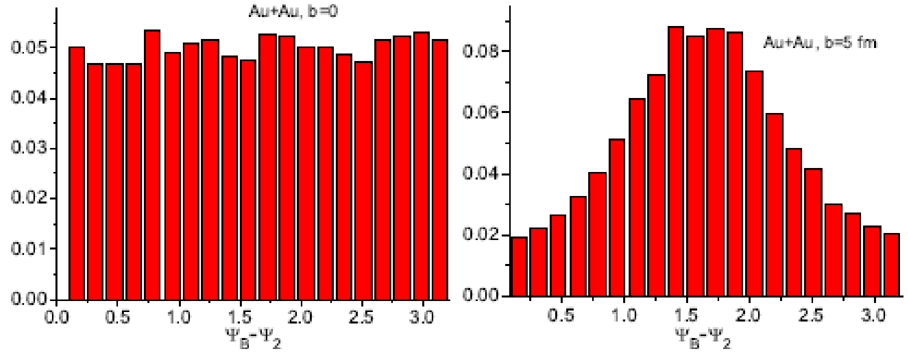
Skokov et al 2009, 2012, Deng and XGH 2012, 2015 … …

EM fields in heavy-ion collisions

Heavy-ion collisions generate EM fields

Fluctuating azimuthal direction

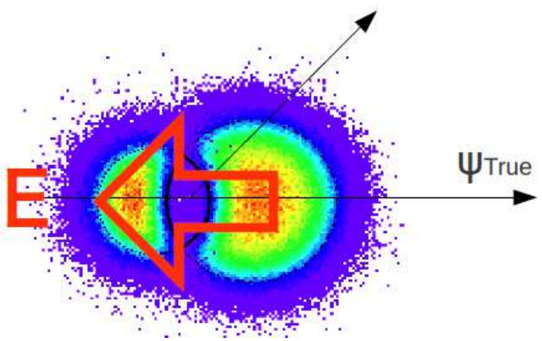




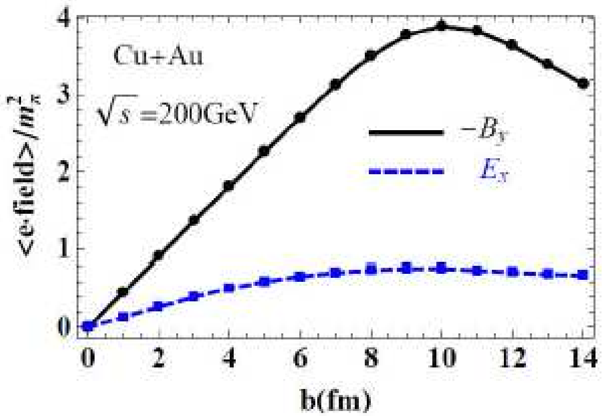
Bloczynski, XGH, Liao, Zhang, 2012

Strong in-plane E field in Cu + Au collisions

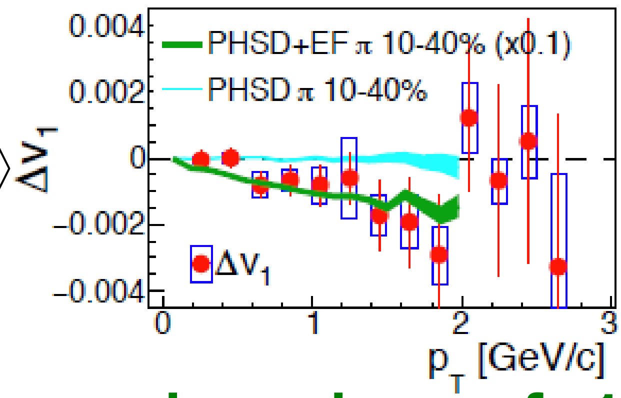
Hirono and Hirano, 2012



Deng and XGH, 2015



STAR 2015

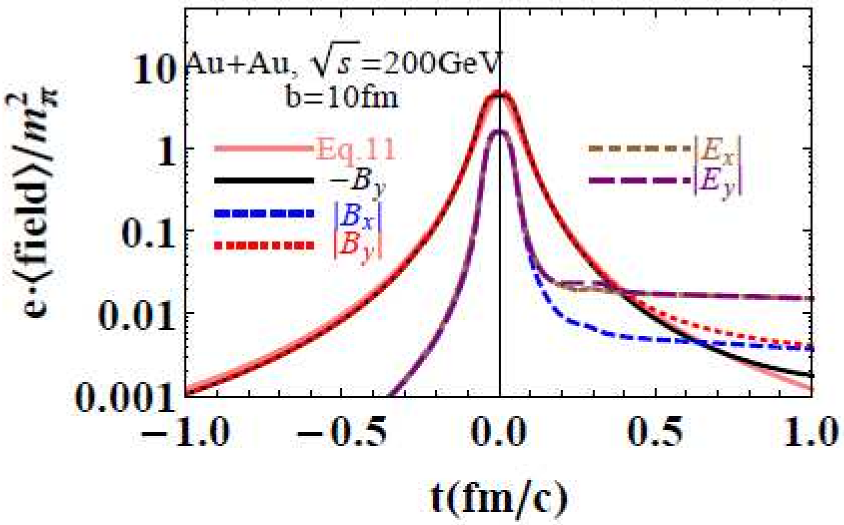


Charge dependence of v1

EM fields in heavy-ion collisions

Heavy-ion collisions generate EM fields

Time evolution of the B field (insulating medium)



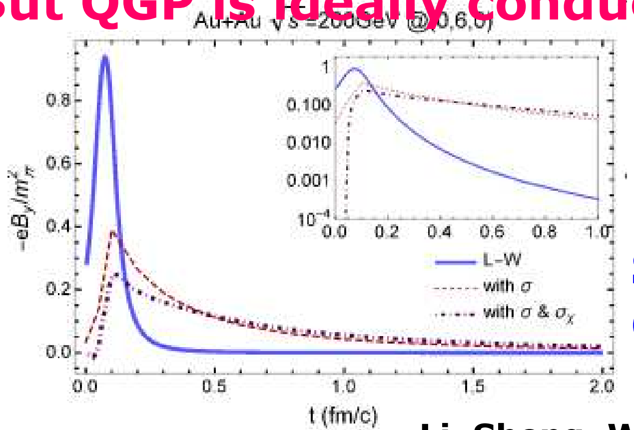
Well fitted by

$$\langle eB_y(t)\rangle \approx \frac{\langle eB_y(0)\rangle}{(1+t^2/t_B^2)^{3/2}}$$

Life time of B field

$$t_B \approx R_A/(\gamma v_z) \approx \frac{2m_N}{\sqrt{s}} R_A$$

But QGP is ideally conducting: lattice of Ding etal $\sigma \approx (1/3) C_{EM} T$



Li, Sheng, Wang 2016

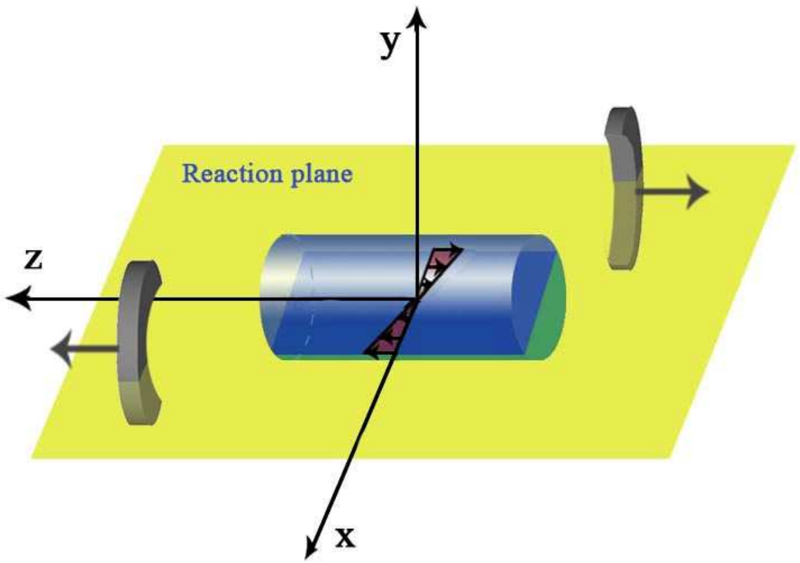
See talk by Qun Wang

Open question: what is the time dependence of B field?

Pengfei's suggestion: high pt charmonium v2 sensitive to lifetime of B

Vorticity in heavy-ion collisions

Heavy-ion collisions generate vorticity



Finite angular moment (AM)

⇓

Manifested as flow shear*

⇓

Finite vorticity(local rotation)

$$\vec{\omega} = \vec{\nabla} \times \vec{v}$$

$$J_0 \sim Ab\sqrt{s}/2 \quad \Rightarrow \quad J \sim \int d^3x I(x)\omega(x)$$

$I(x) \sim [x^2 - (x\cdot\hat{\omega})^2]\varepsilon(x)$ is the moment of inertia density

J_0 is about 10^6 for RHIC Au+Au @ 200 GeV, system volume is ~ fm^3, very large AM density

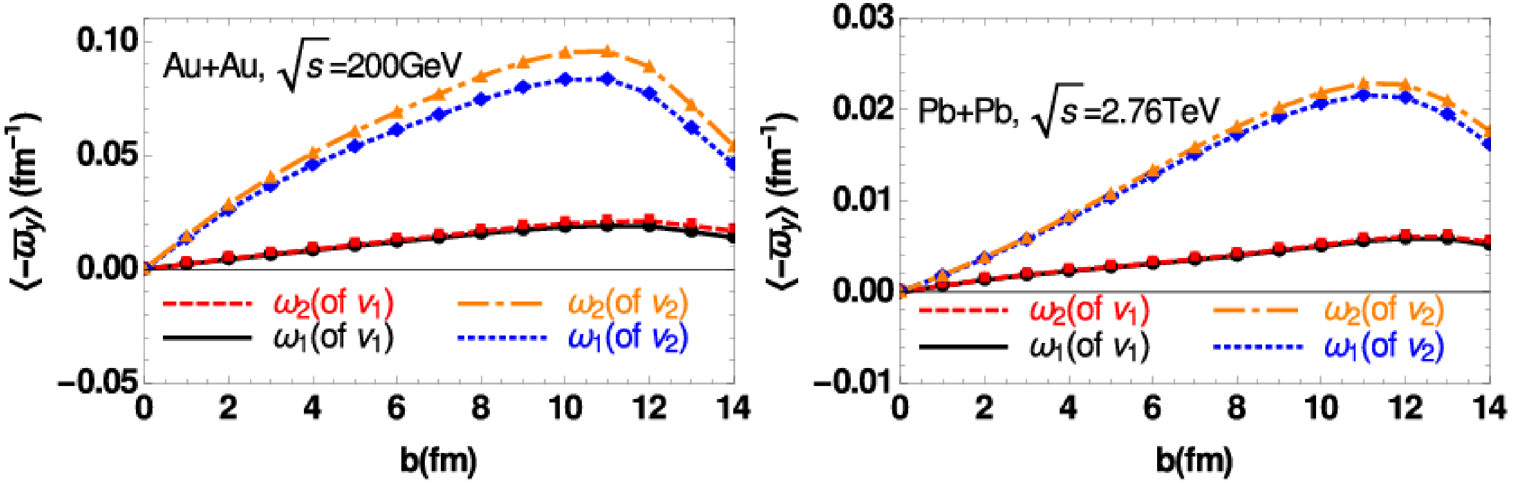
*For low energy collision, the system after collision may be globally rotating

Vorticity in heavy-ion collisions

Heavy-ion collisions generate vorticity

The detailed simulations of vorticity come out very recently

(Jiang, Lin, Liao 2016; Deng and XGH 2016) **Talk by Jinfeng Liao**

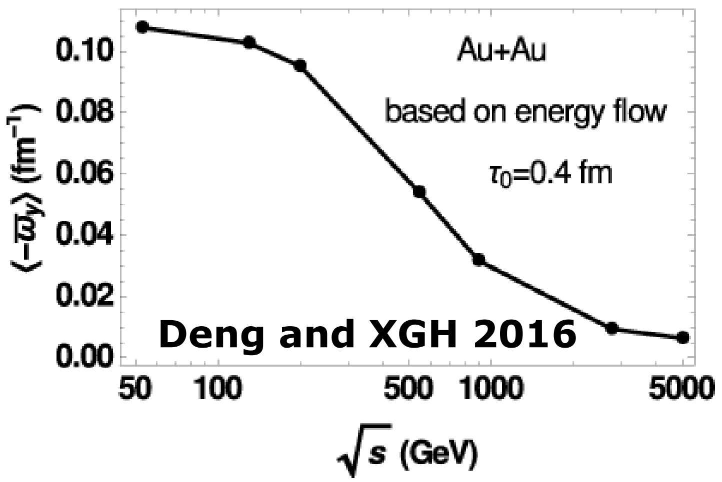


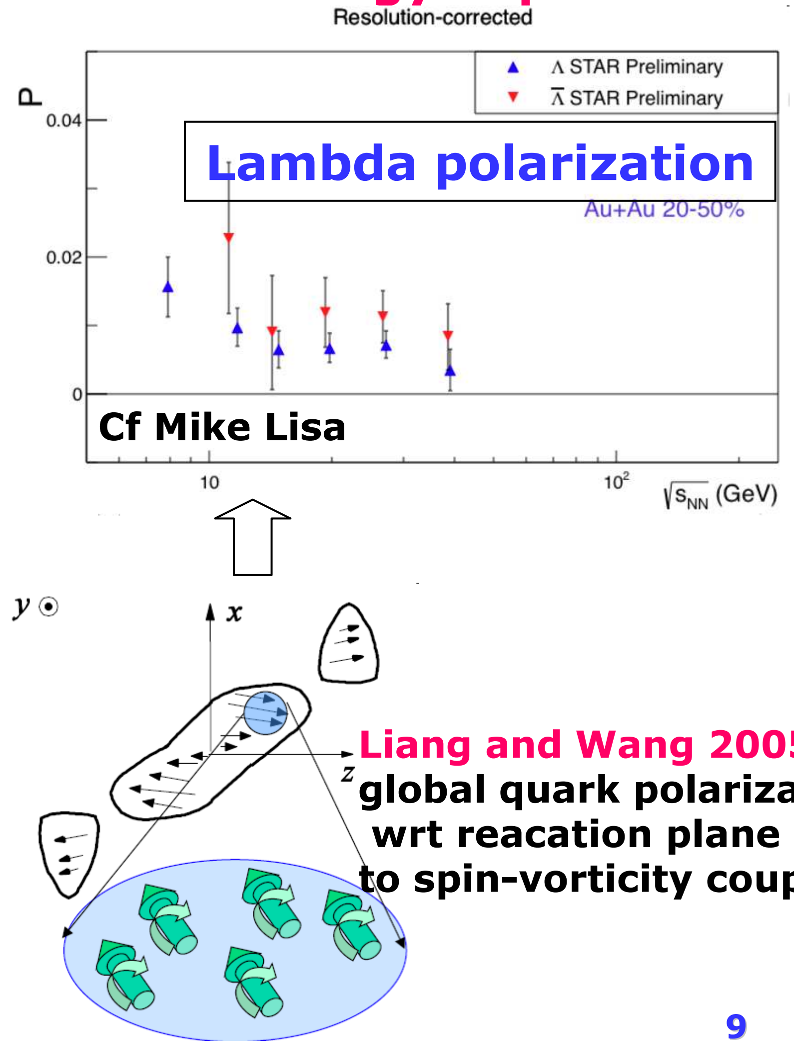
- **Vorticity of energy flow at RHIC at b=10 fm is 10^22 Hz. (Fastest man-made rotation via laser light ~ 10^7 Hz (Arita etal Nat.Comm. 2013))**
- **RHIC: Take T~300 MeV, T*vorticity~10^4 MeV^2 comparable to magnetic field eB~10^4 MeV^2. But at LHC, T*vorticity is much smaller than eB.**
- **At b<2R_A, increase with b; then drops. Anglular momentum of the overlapping region has a similar behavior.**

Vorticity in heavy-ion collisions

Heavy-ion collisions generate vorticity

Vorticity at mid-rapidity has very nontrivial energy dependence





Liang and Wang 2005: global quark polarization wrt reacation plane due to spin-vorticity coupling

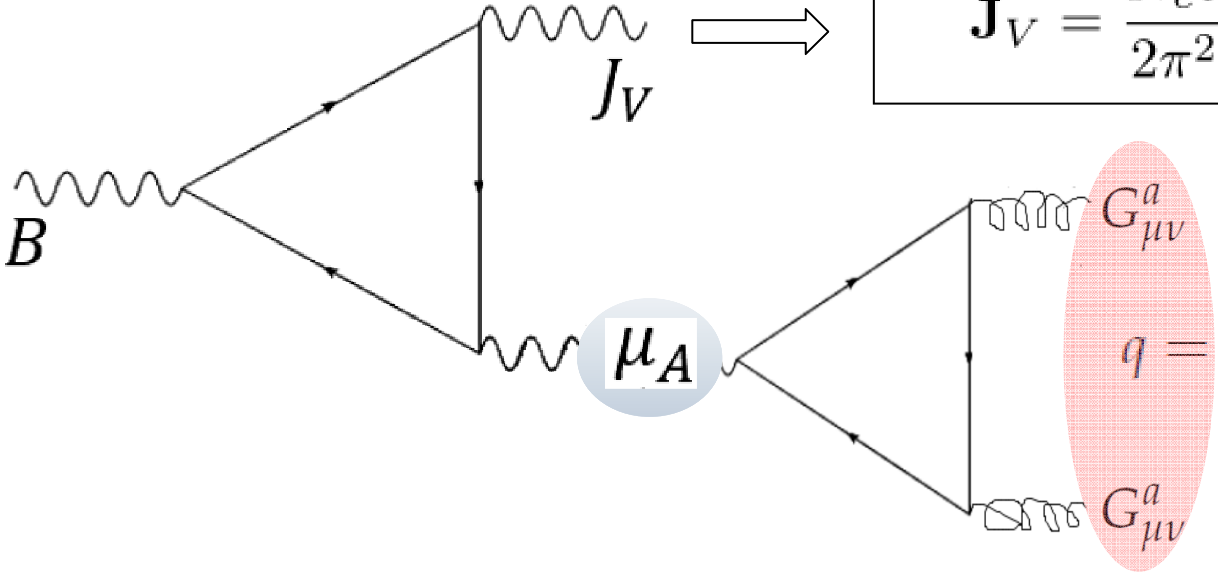
- Reason: higher energy: more AM carried by finite rapidity particles; mid-rapidity closer to Bjorken boost invariant; larger moment of inertia
- Indicates stronger vortical effect at lower energy (BES is ideal for vortical effect)

EM-field induced anomalous transports

Chiral magnetic effect

B fields can monitor nontrivial topology of QCD

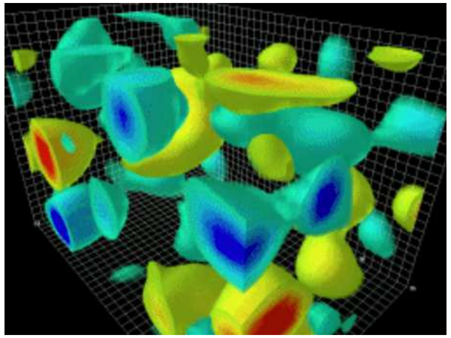
QED VVA triangle anomaly



Chiral magnetic effect (CME)

$$\mathbf{J}_V = \frac{N_c e}{2\pi^2}\mu_A \mathbf{B}$$

$$q = \frac{g^2}{32\pi^2}\int d^4x G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$



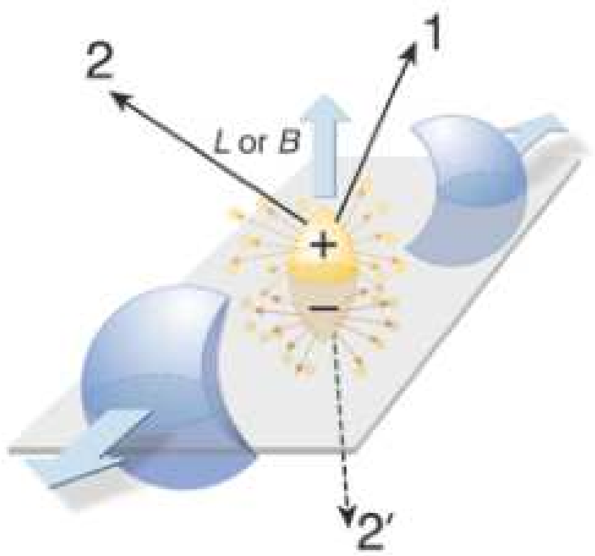
QCD VVA triangle anomaly

- **Parity-odd transport**
- **Time-reversal even, no dissipation**
- **Fixed by anomaly coefficient, universal**

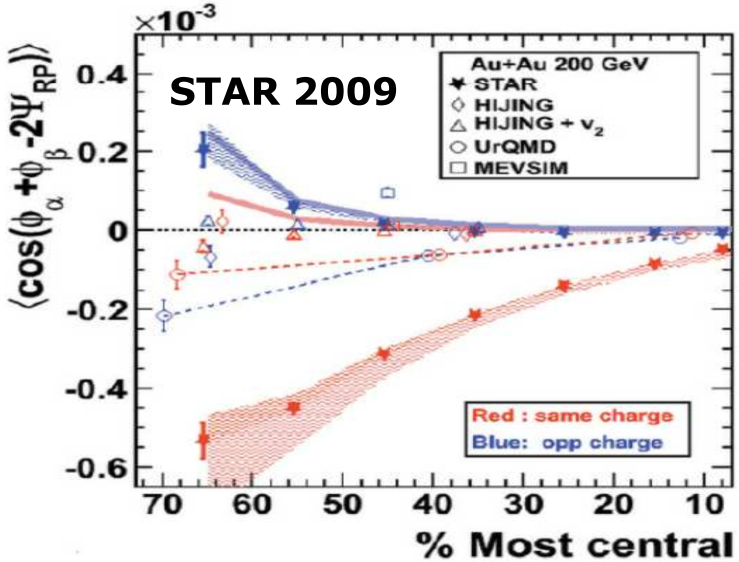
Kharzeev 2004, Kharzeev, Warringa, McLarren, Fukushima2008 … …

Chiral magnetic effect

Phenomenology of CME in heavy-ion collisions:
Event-by-event charge separation wrt. reaction plane



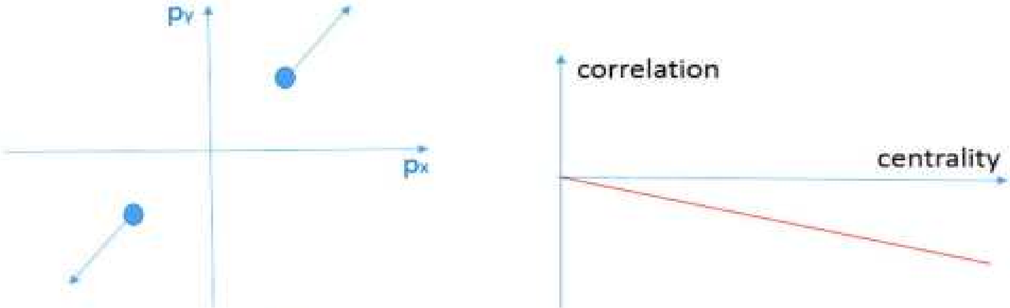
The gamma correlator **(Voloshin 2004)**



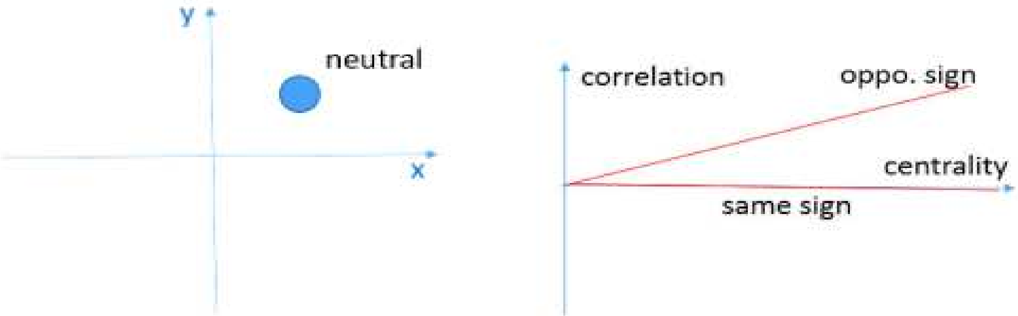
- **Positive opposite-sign correlation, negative same-sign correlation**
- **Increase with centrality = B increases with centrality**
- **Nearly independent of collision energy = B * t_B ~ constant**
- **Delta gamma disspears for low energy = no chiral symmetry res.**

Chiral magnetic effect

- Other sources of $\langle\cos(\phi_\alpha + \phi_\beta)\rangle$:
  - Transverse momentum conservation**(Pratt etal 2011, Liao etal 2011)**: $\langle\cos(\phi_\alpha + \phi_\beta)\rangle \approx -v_2/N$, charge independent.



  - Local charge conservation**(Pratt and Schlichting, 2011)**: $\langle\cos(\phi_\alpha + \phi_\beta)\rangle \propto v_2/N$ for opposite sign $\langle\cos(\phi_\alpha + \phi_\beta)\rangle \approx 0$ for same sign.

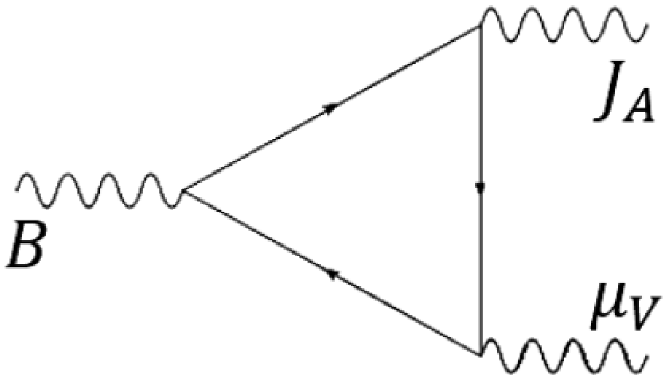


  - Dipole fluctuation**(Teaney and Yan 2010)**, clustering correlation **(Wang, 2010),… …**

Main challenge: how to subtract the background effects

Chiral magnetic wave

Same QED VVA triangle anomaly, but with V and A interchanged



Chiral separation effect (CSE)

$$\mathbf{J}_A = \frac{N_c e}{2\pi^2}\mu_V \mathbf{B}$$

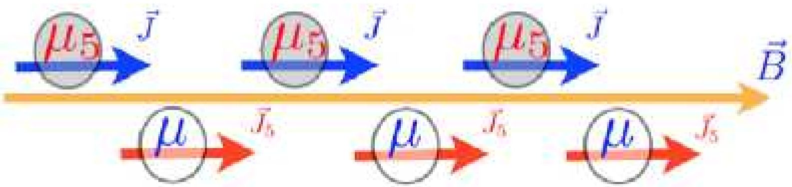
Son and Zhitnitsky 2004,

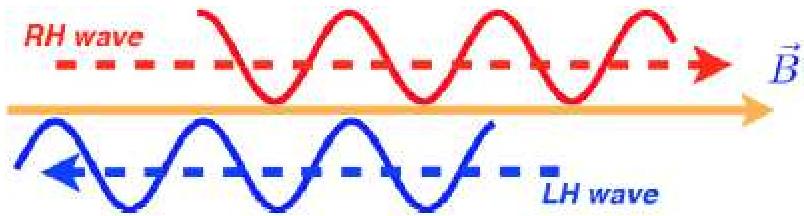
Metlitski and Zhitnitsky 2004

CME + CSE give gapless wave modes: chiral magnetic wave

(Kharzeev and Yee 2010)

$$v_R = \frac{N_c e}{4\pi^2}\frac{\partial \mu_R}{\partial n_R}$$





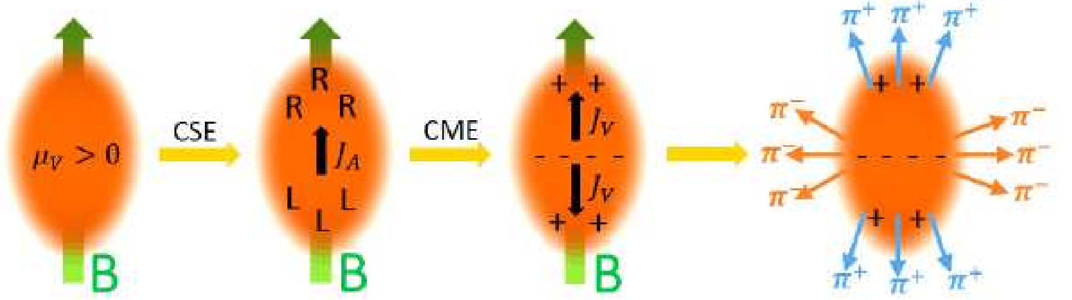
(Courtesy: Jinfeng Liao)

$$v_L = -\frac{N_c e}{4\pi^2}\frac{\partial \mu_L}{\partial n_L}$$

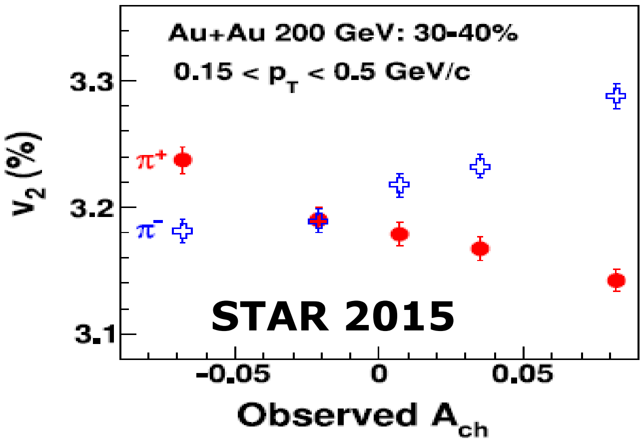
Chiral magnetic wave

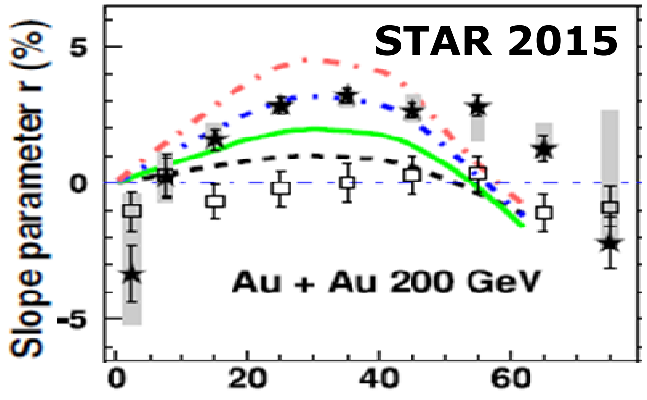
Phenomenology of CMW in heavy-ion collisions:
Elliptic flow splitting of charged pions (Burnier, Kharzeev, Liao, Yee 2011)

Intuitive picture



- CMW $\Rightarrow$ $v_2(\pi^-) \neq v_2(\pi^+)$: $v_2(\pi^-) - v_2(\pi^+) \approx r A_\pm$: linear approx. in net charge asymmetry $A_\pm = (N_+ - N_-)/(N_+ + N_-)$





Chiral magnetic wave

- Other sources of $v_2(\pi^\pm)$ difference.
  - Quark transport and coalescence **(Dunlop,Lisa, and Sorensen 2011;Campbell and Lisa 2013)**:

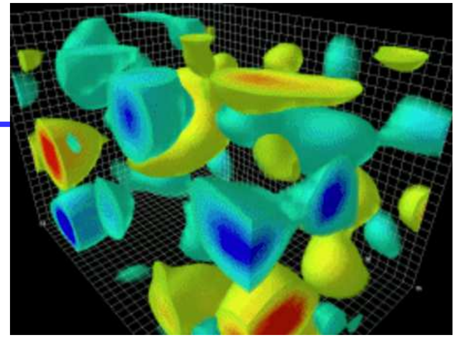
    Neutron rich $\Rightarrow v_2(d) > v_2(u)$ (assume transported quarks v_2 is larger than produced quarks) $\Rightarrow v_2(\pi^- = d\bar{u}) > v_2(\pi^+ = \bar{d}u)$
  - Hadronic mean-field potential **(Xu,Chen, Ko, and Lin 2012)**:

    Works at low-energy collision. Neutron rich $\Rightarrow$ repulsive (attractive) potential for $\pi^-(\pi^+)\Rightarrow \pi^-(\pi^+)$ is push-forward (pull-back) in in-plane $\Rightarrow v_2(\pi^-) \gtrsim v_2(\pi^+)$
  - Electric field effect **(Deng and XGH, 2012; Stephanov and Yee, 2013)**:

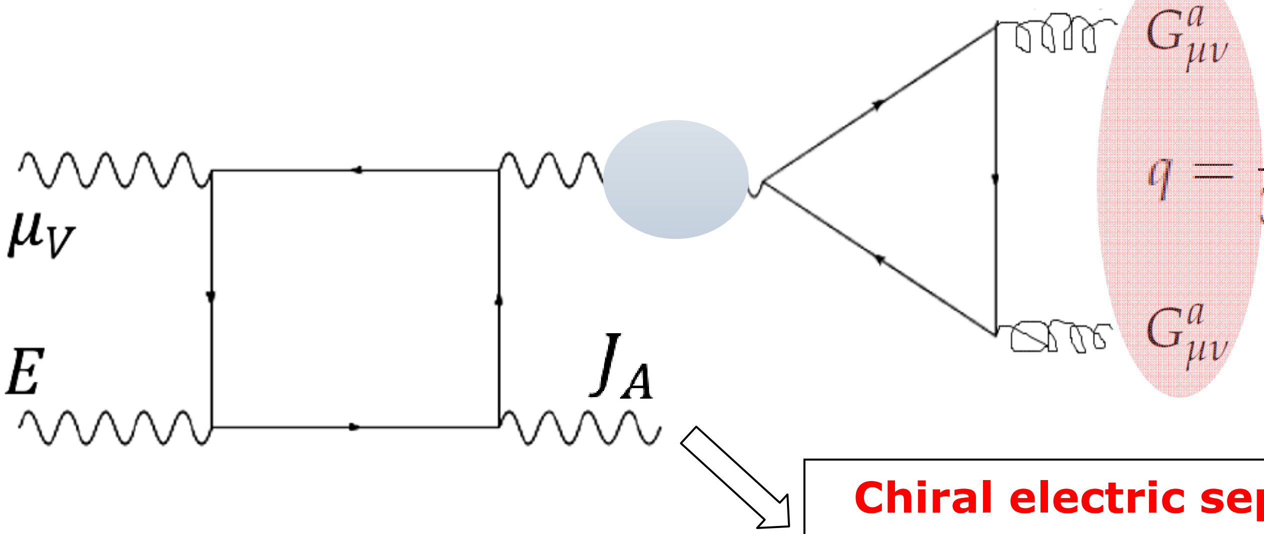
    Electric field points outwards in y direction $\Rightarrow$ positive (negative) charges move outwards(inwards) in y direction $\Rightarrow$ charge quadrupole $\Rightarrow v_2(\pi^-) > v_2(\pi^+)$
  - Local charge conservation and rapidity cut**(Bzdak and Bozek 2013)**:

    $v_2(|\eta| \sim 1) < v_2(|\eta| \sim 0) \Rightarrow$ consider a positive-negative charge pair, if at $\eta = 1$ and the positive charge inside and negative charge outside the rapidity window then $A > 0$ and the corresponding v_2 is smaller than that when the pair is inside the rapidity window $\Rightarrow v_2(\pi^+)_A < v_2(\pi^+)_{A=0} \Rightarrow$ at small A $v_2(\pi^+)_A = v_2(\pi^+)_{A=0} - \#A$. Similarly, $v_2(\pi^-)_A = v_2(\pi^-)_{A=0} + \#A$
  - Viscous hydrodynamics combined with finite isospin effectmay also explain the data **(Hatta, Monnai, Xiao 2015)**
  - … …

Chiral electric separation effect



Electric field induced anomalous transport



$$q = \frac{g^2}{32\pi^2}\int d^4x G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

Chiral electric separation effect (CESE)

$$\mathbf{J}_A \approx 14.5163\,\mathrm{Tr}_f(Q_e Q_A)\frac{\mu_V\mu_A}{T^2}\frac{e^2 T}{g^4\ln(1/g)}\mathbf{E}$$

- **P-odd, C-odd, T-odd transport (may be dissipative)**
- **Non-universal (receive perturbative correction)**

XGH and Liao 2013, Jiang, XGH, Liao 2015 … …

Chiral electric separation effect

- Collective modes by CESE, CME, and CSE.
- The complete electromagnetic response of a chiral matter:

$$
\begin{aligned}
j_V^\mu &= \sigma E^\mu + \frac{e}{2\pi^2}\mu_A B^\mu, \\
j_A^\mu &= \sigma_5 E^\mu + \frac{e}{2\pi^2}\mu_V B^\mu.
\end{aligned}
$$

- Coupled evolution of vector and axial currents leads to several collective modes **(XGH and Liao, PRL110(2013)232302)**:
  - If $\mathbf{B} = B\hat{z}$ and $\mathbf{E} = 0$: two Chiral magnetic waves along $\mathbf{B}$

    $$\omega = \pm\sqrt{(v_\chi k_z)^2 - (e\sigma_0/2)^2} - i(e\sigma_0/2)$$

  - If $\mathbf{B} = 0$ and $\mathbf{E} = E\hat{z}$ + A-background: two Chiral electric waves

    $$\omega = \pm\sqrt{(v_e k_z)^2 - (e\sigma_0/2)^2} - i(e\sigma_0/2)$$

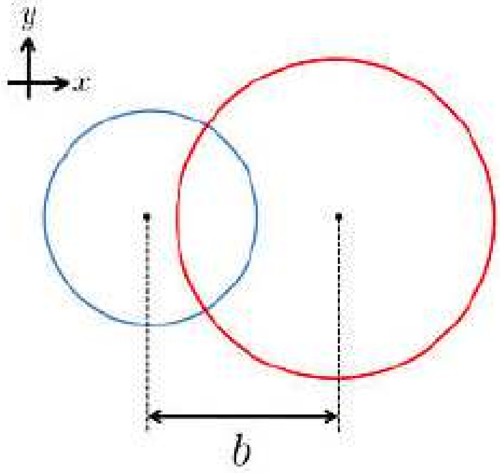
  - If $\mathbf{B} = 0$ and $\mathbf{E} = E\hat{z}$ + V-background: one Vector density wave and one Axial density wave along E-field

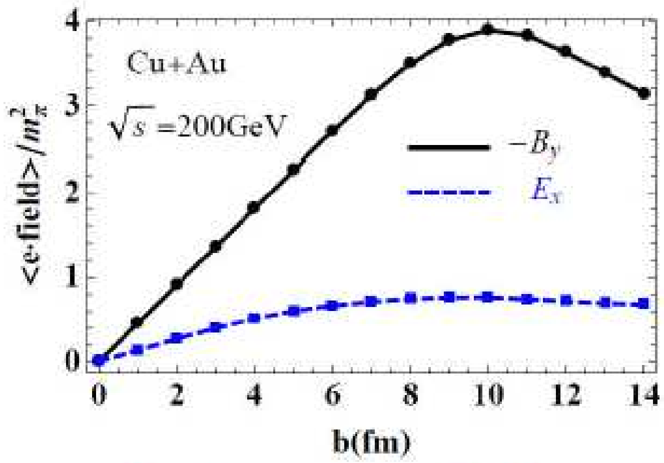
    $$
    \begin{aligned}
    \omega_V &= v_v k_z - ie\sigma_0, \\
    \omega_A &= v_a k_z
    \end{aligned}
    $$

- These collective excitations transport chirality and charge, and leads to novel charge azimuthal distribution $\Rightarrow$

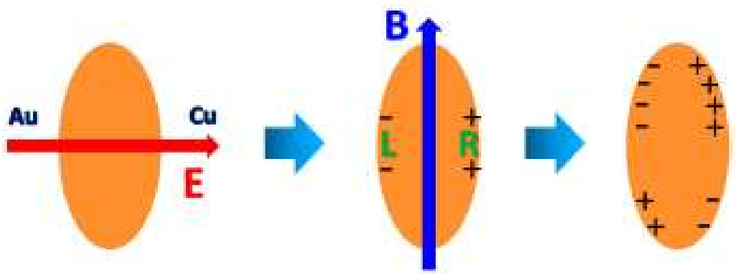
Chiral electric separation effect

- Possible implication: Recall that in-plane E-field in AuCu collisions.





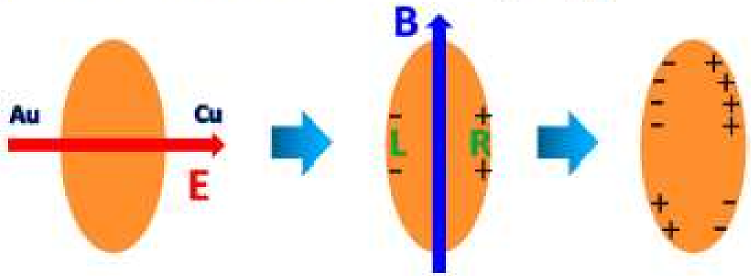
- In-plane dipole due to usual Ohm conduction + out-of-plane dipole due to CME + quadrupole due to CESE and CME in Cu + Au collisions.



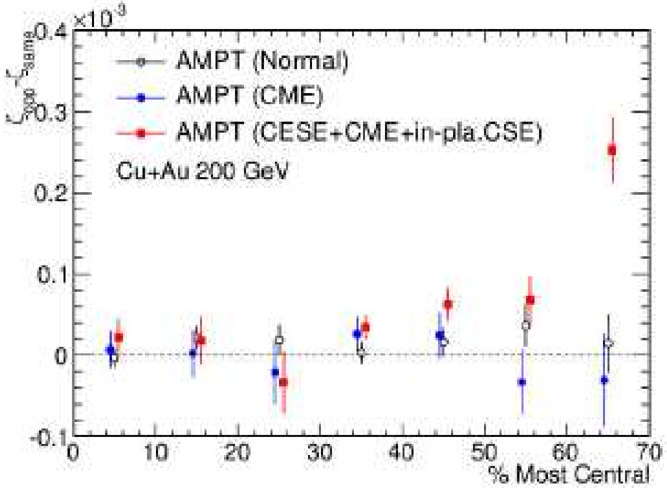
$$
\begin{aligned}
f_1(q,\phi) \quad \propto \quad & 1 + 2v_1^0\cos(\phi-\psi_1) + 2qd_E\cos(\phi-\psi_E) + 2\chi q d_B\cos(\phi-\psi_B) \\
& + 2v_2^0\cos[2(\phi-\psi_2)] + 2\chi q h_B\cos[2(\phi-\psi_c)] + \text{higher harmonics}
\end{aligned}
$$

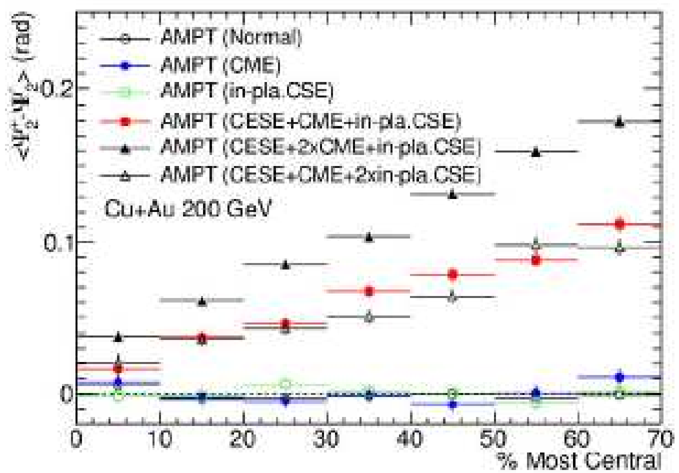
Chiral electric separation effect

- Signals for CESE in Cu + Au: $\zeta_{\alpha\beta} = \langle \cos[2(\phi_\alpha + \phi_\beta - 2\psi_{\mathrm{RP}})] \rangle$ and Ψ_2^q (the event-plane for hadrons of charge q).



- $\Delta\zeta = \zeta_{opp} - \zeta_{same}$ and $\Delta\Psi = \langle|\Psi_2^+ - \Psi_2^-|\rangle$ sensitive to CESE, survive final interaction(**Ma and XGH, PRC 91(2015)054901**)





- Possible backgrounds for $\Delta\zeta = \zeta_{opp} - \zeta_{same}$: local charge conservation, chiral magnetic wave. Need more studies.

Vorticity induced anomalous transport

Chiral vortical effect

A modified "relativistic Larmor theorem"

$$eB \sim 2\mu_V\omega$$

$$\mathbf{J}_V = \frac{N_c e}{2\pi^2}\mu_A\mathbf{B} \quad \Longrightarrow \quad \mathbf{J}_V = \frac{N_c\mu_V\mu_A}{\pi^2}\boldsymbol{\omega}$$

Chiral magnetic effect — **Vector chiral vortical effect**

This naïve mapping does not work for axial current. The calculation gives the vorticity induced axial current:

$$\mathbf{J}_A = N_c\left(\frac{T^2}{6} + \frac{\mu_V^2+\mu_A^2}{2\pi^2}\right)\boldsymbol{\omega}$$

Axial chiral vortical effect

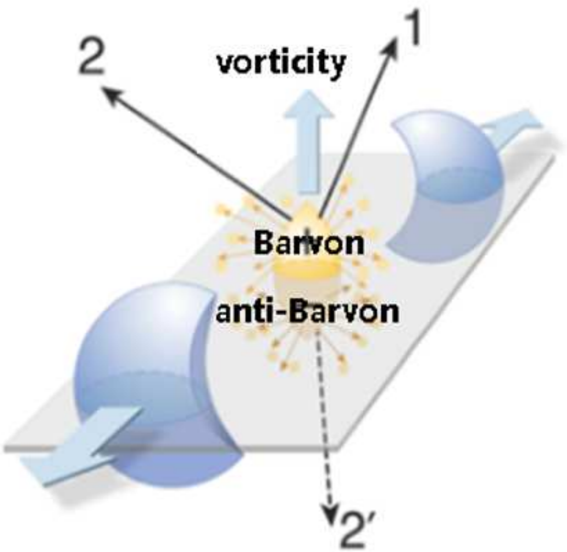
- **Related to chiral anomaly and gravitational anomaly**
- **Universal (receive no perturbative correction*)**

*** T^2 term may have perturbative correction**

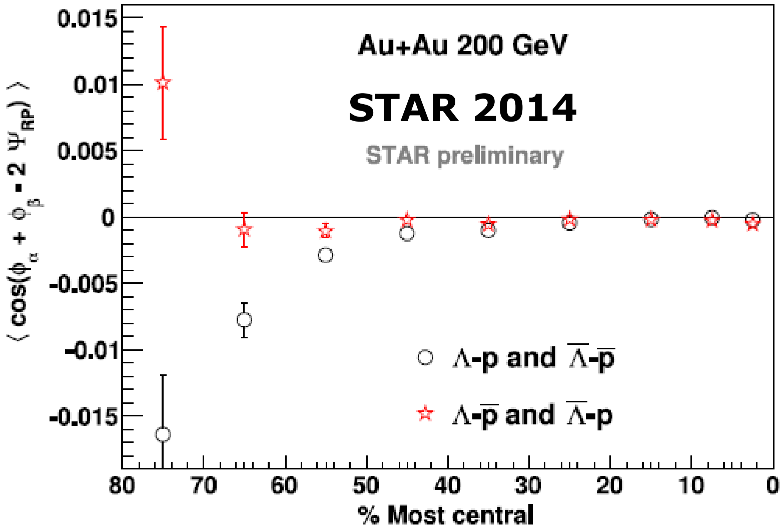
Banerjee etal 2008, Son and Surowka 2009, Landersteiner etal 2011

Chiral vortical effect

Phenomenology of vector CVE in heavy-ion collisions:
Event-by-event baryon separation wrt. reaction plane



The vortical gamma correlator



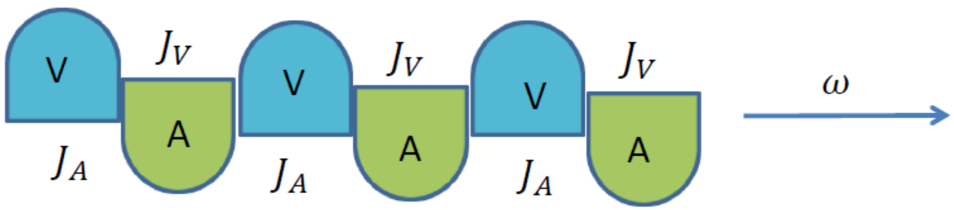
- **Positive opposite-sign correlation, negative same-sign correlation**
- **Increase with centrality = vorticity increases with centrality**

Back ground effects: e.g., transverse momentum conservation, local baryon conser.

Chiral vortical wave

The vortical analogue of chiral magnetic wave

$$\vec{J}_A = \left(\frac{T^2}{6} + \frac{\mu^2 + \mu_5^2}{2\pi^2}\right)\vec{\omega}, \qquad \vec{J}_V = \frac{\mu\mu_5}{\pi^2}\vec{\omega}$$



Courtesy: Yin Jiang

- **A new collective mode. To reveal its dispersion we use continuity eq.**

$$\partial_t n_{L,R} + \nabla \cdot \vec{J}_{L,R} = 0$$

- **Substitute CVE currents. Obtain Burgers wave equation which is linearized to normal wave equation**

$$\partial_t n_{L,R} = \pm \frac{\omega\alpha^2}{\pi^2}\partial_x(n_{L,R}^2) \Longrightarrow \pm \boxed{\frac{2\omega\alpha^2}{\pi^2}} n_0 \partial_x(n_{L,R})$$

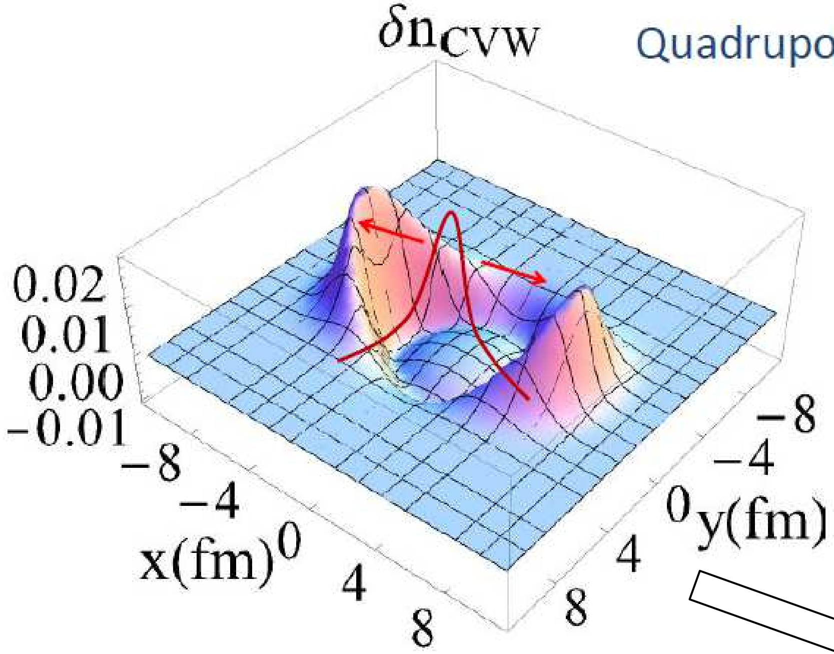
$$\alpha = \frac{\partial\mu}{\partial n}$$ **~ inverse baryon susceptiblity**

CVW velocity

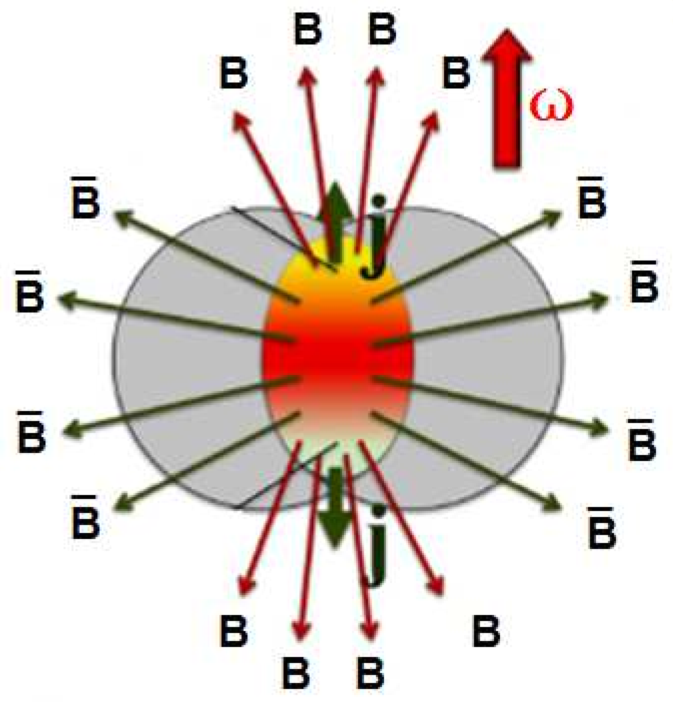
Jiang, XGH, Liao 2015

Chiral vortical wave

Experimental implication: baryon charge quadrupole



- More baryon charges at the tips of the fireball, more antibaryon charges at the center



- Stronger in-plane radial expansion lets antibaryons get larger elliptic flow than baryons

Chiral vortical wave

Lambda-anti-Lambda v_2 splitting

•Chemical potential shift of quark of flavor f (leading order in q):

$$\delta\mu_f \propto 2q^f_\Omega \cos(2\phi_s)$$

$$q^f_\Omega = [\int dxdy(\delta n_f)\cos(2\phi_s)]/[\int dxdy(\delta n_f)]$$ ~ quadrupole moment

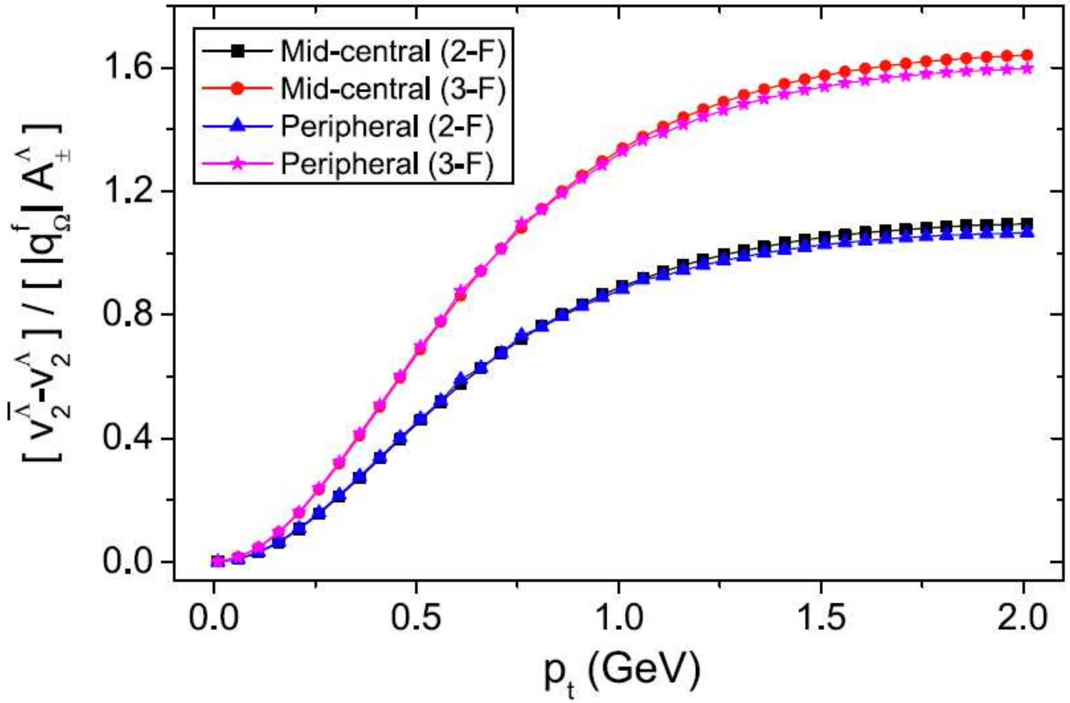
•Lambda (carries baryon charge but no electric charge: responses to CVW but not CMW)

$$\delta\mu_\Lambda \propto 2(q^u_\Omega + q^d_\Omega + q^s_\Omega)\cos(2\phi_s)$$

$$\Downarrow$$

$$\Delta v_2 = v_2^{\bar{\Lambda}} - v_2^{\Lambda} \propto |q^f_\Omega| A^\Lambda_\pm$$

$$A^\Lambda_\pm = (N^\Lambda - N^{\bar{\Lambda}})/(N^\Lambda + N^{\bar{\Lambda}})$$



Summary

	E	B	ω
J_V	σ Ohm's law	$\frac{N_C e}{2\pi^2}\mu_A$ Chiral magnetic effect	$\frac{N_C}{\pi^2}\mu_V\mu_A$ Vector chiral vortical effect
J_A	$\propto \frac{\mu_V\mu_A}{T^2}\sigma$ Chiral electric separation effect	$\frac{N_C e}{2\pi^2}\mu_V$ Chiral separation effect	$N_C\left(\frac{T^2}{6}+\frac{\mu_V^2+\mu_A^2}{2\pi^2}\right)$ Axial chiral vortical effect

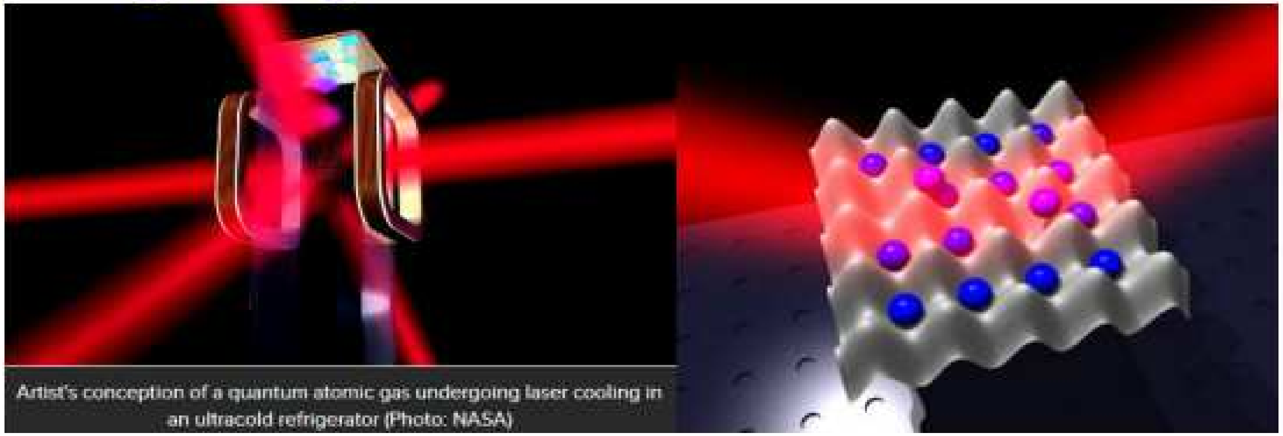
⇨ Collective waves: chiral magnetic wave, chiral electric waves, chiral vortical wave, vector and axial density wave, … …

Thank you!

Anomalous transport in cold atomic gases

Motivation

- The CME/CSE/CVE etc are masked by various backgrounds in HICs, it is hard to pin down and to explore their properties in HICs.
- Question: Is there any system that exhibits anomalous transport in a controllable way?
- Answer: Yes! One example is the Dirac or Weyl semimetal **(Li, et al, 1412.6543 and many other recent experimental progresses).**
- Here we propose another possibility: The cold atomic gases.
- Atomic gases experiments. $10^5 - 10^6$ atoms put in magnetic trap or optical trap, and cooled down to nano Kelvin by using laser cooling or evaporating cooling



Artist's conception of a quantum atomic gas undergoing laser cooling in an ultracold refrigerator (Photo: NASA)

- A lot of exciting low-temperature phenomena have been observed: superfluidity, Bose-Einstein condensation, BCS-BEC crossover, novel superfluid, polaron gases, ferromagnetisim,......

Spin-orbit coupled atomic gases

- In 2011, a new type of cold Bose gases generated in which the spin is coupled to the orbital motion of the atoms **(Spielman et al 2011)**. The single-particle Hamiltonian(Rashba-Dresselhaus SOC):

$$\mathcal{H} = \frac{\mathbf{p}^2}{2m} - \lambda \sigma_x p_y$$

- In 2012, same type spin-orbit coupling (SOC) for Fermi gases produced in MIT **(Zwierlein group 2012)** and in Shanxi**(Zhang group 2012)**.
- Other types of SOC also possible, e.g., the Weyl SOC: **(Spielman et al 2012)**

$$\mathcal{H} = \frac{\mathbf{p}^2}{2m} - \lambda \sigma \cdot \mathbf{p}$$

- Now we show: there are CME and CSE in Weyl spin-orbit coupled Fermi gases.

Semiclassical equations of motion

- Consider the Weyl SOC, $\lambda\sigma\cdot\mathbf{p}$, in single atom Hamiltonian

$$\mathcal{H} = \frac{\mathbf{p}^2}{2m} - \lambda\mathbf{p}\cdot\sigma$$

- Along $\mathbf{p}$, the spin has two projection which defines two helicities (we will call them chiralities as well) , right-hand (project along $\mathbf{p}$) and left-hand (project along $-\mathbf{p}$).
- Consider atoms in a harmonic trap and let them rotate.

$$\begin{aligned} \mathcal{H} &= \frac{[\mathbf{p}-\mathbf{A}(\mathbf{x})]^2}{2m} - \lambda[\mathbf{p}-\mathbf{A}(\mathbf{x})]\cdot\sigma + A_0(\mathbf{x}) \\ A_0(\mathbf{x}) &= V(\mathbf{x}) - (m/2)(\omega\times\mathbf{x})^2 - \mu \\ \mathbf{A}(\mathbf{x}) &= m\omega\times\mathbf{x} \end{aligned}$$

- Integrate out the spin degree of freedom and at $O(\hbar)$ level: the semiclassical EOM **(Niu 1998-)**

$$\begin{aligned} \sqrt{G_c}\dot{\mathbf{x}} &= \nabla_{\mathbf{k}}\varepsilon_c + c\hbar\mathbf{E}\times\Omega + c\hbar(\Omega\cdot\nabla_{\mathbf{k}}\varepsilon_c)\mathbf{B}, \\ \sqrt{G_c}\dot{\mathbf{k}} &= \mathbf{E} + \nabla_{\mathbf{k}}\varepsilon_c\times\mathbf{B} + c\hbar(\mathbf{E}\cdot\mathbf{B})\Omega \end{aligned}$$

where $\mathbf{k}=\mathbf{p}-\mathbf{A}$ is the kinetic momentum, $\sqrt{G_c}=1+c\hbar\mathbf{B}\cdot\Omega$, $\mathbf{E}=-\nabla V(\mathbf{x})$— effective E-field, $\mathbf{B}=2m\omega$—effective B-field, Ω—Berry curvature. $c=\pm$ for right- or left-hand.

Chiral anomaly

- The kinetic equation reads (Son and Yamamoto 2012, Stephanov and Yin 2012, Gao,Wang,Pu,Chen,Wang 2012)

$$\partial_t f_c + \dot{\mathbf{x}} \cdot \nabla_{\mathbf{x}} f_c + \dot{\mathbf{k}} \cdot \nabla_{\mathbf{k}} f_c = I[f_c]$$

- Direct calculation gives the $U(1)$ chiral anomaly in current of chirality c:

$$\partial_t n_c + \nabla_{\mathbf{x}} \cdot \mathbf{j}_c = c(\mathbf{E}\cdot\mathbf{B}) \int \frac{d^3\mathbf{k}}{(2\pi)^3} f_c \nabla_{\mathbf{k}} \cdot \Omega = c f_c(\mathbf{k}_0) \frac{W}{4\pi^2} \mathbf{E}\cdot\mathbf{B}$$

where W is the winding number of the Berry curvature.

- Write down the current $\mathbf{j}_c$ explicitly:

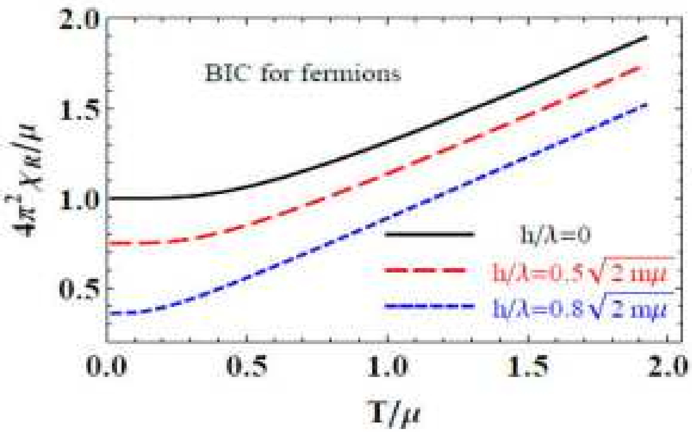
$$\begin{aligned} \mathbf{j}_c &= \int \frac{d^3\mathbf{k}}{(2\pi)^3} f_c \nabla_{\mathbf{k}} \varepsilon_c + c\mathbf{E} \times \int \frac{d^3\mathbf{k}}{(2\pi)^3} \Omega f_c \\ &\quad + c\mathbf{B} \int \frac{d^3\mathbf{k}}{(2\pi)^3} (\Omega \cdot \nabla_{\mathbf{k}} \varepsilon_c) f_c. \end{aligned}$$

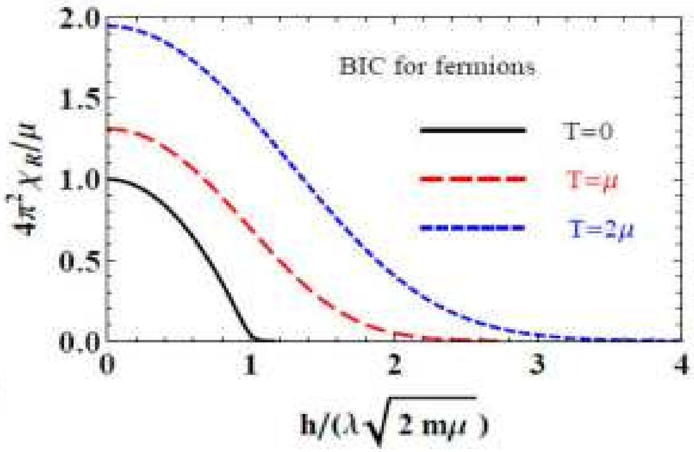
- The third term is $\mathbf{B}$-induced currents:

$$\mathbf{j}_c^{\mathbf{B}-\mathrm{ind}} = \chi_c \mathbf{B}, \quad \chi_c = c \int \frac{d^3\mathbf{k}}{(2\pi)^3} (\Omega \cdot \nabla_{\mathbf{k}} \varepsilon_c) f_c$$

Chiral magnetic/separation effects

- The $\mathbf{B}$-induced conductivity χ_c for Fermi gas **(XGH, Sci.Rep. 6, 20601 (2016))**





- *If there is parity-odd domains* in the Fermi gases $\Rightarrow$ $\mu_R = \mu + \mu_A, \mu_L = \mu - \mu_A \Rightarrow$

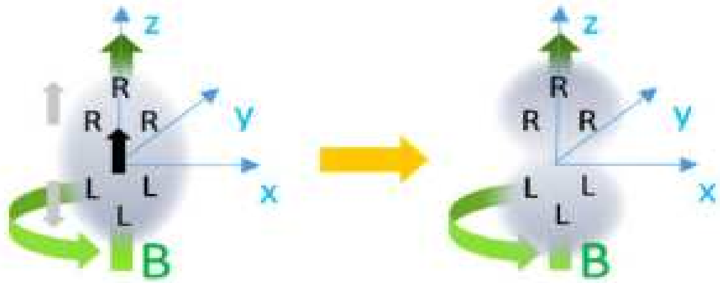
$$\mathbf{j}_V^{\mathbf{B}-\mathrm{ind}} \equiv \mathbf{j}_R^{\mathbf{B}-\mathrm{ind}} + \mathbf{j}_L^{\mathbf{B}-\mathrm{ind}} = \frac{\mu_A}{2\pi^2}\mathbf{B},$$

$$\mathbf{j}_A^{\mathbf{B}-\mathrm{ind}} \equiv \mathbf{j}_R^{\mathbf{B}-\mathrm{ind}} - \mathbf{j}_L^{\mathbf{B}-\mathrm{ind}} = \frac{\mu}{2\pi^2}\mathbf{B}$$

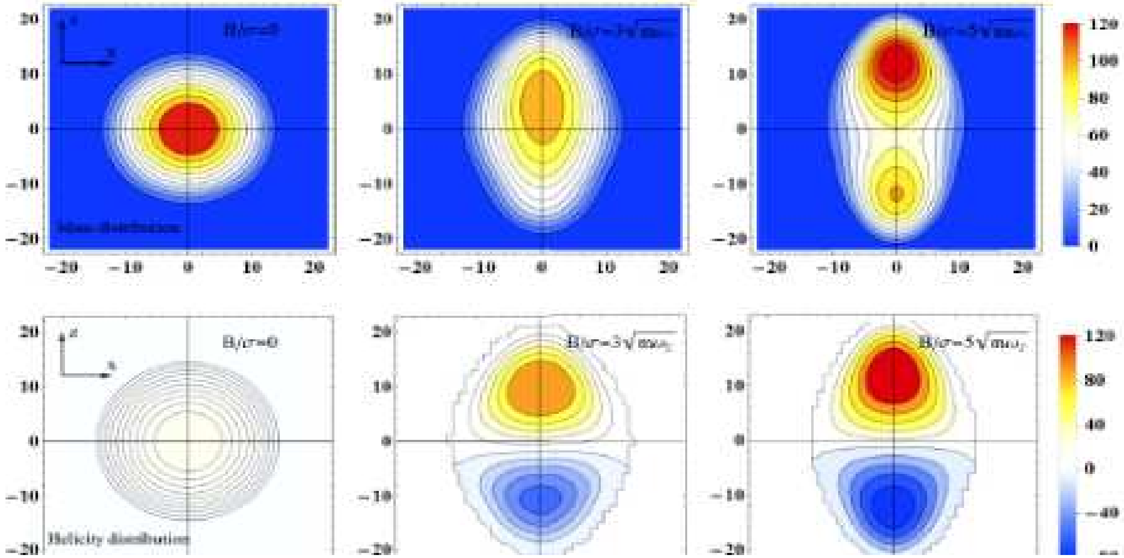
- These are exactly the chiral magnetic/speration effects!
- Question: how can produce parity-odd domins in Fermi gases?

Chiral dipole and mass quadrupole

- Very like what happen in QGP, the CMW exists in SOC atomic gases, which transport chirality and mass **(XGH, Sci.Rep. 6, 20601 (2016))**

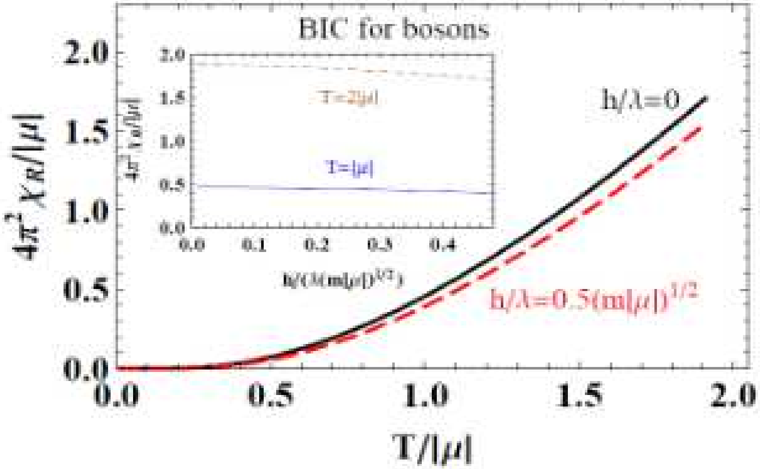


- Unlike in QGP, the presence of trap will finally stop these transport currents and system reaches a equilibrium configuration where appear a mass quadrupole and chiral dipole. The mass quadrupole may be tested by light absorption images technique.

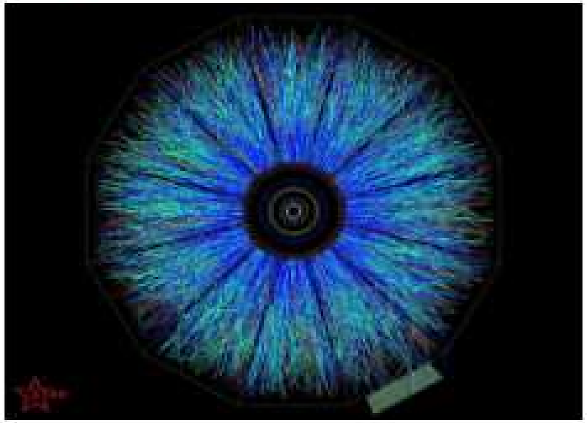


Link the hottest to the coldest

- The similar thing happens also in Bose gases, e.g., the BIC



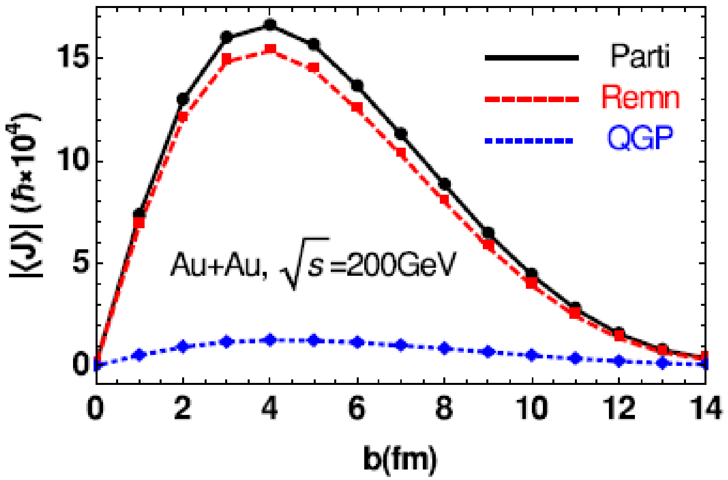
- The CME/CSE initiated in the study of the hottest matter, the QGP, can possibly be realized in the coldest matter, the cold atoms.

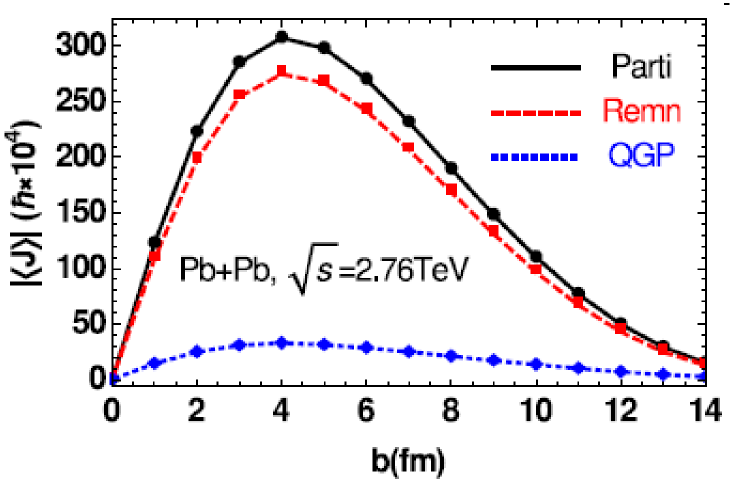


Artist's conception of a quantum atomic gas undergoing laser cooling in an ultracold refrigerator (Photo: NASA)

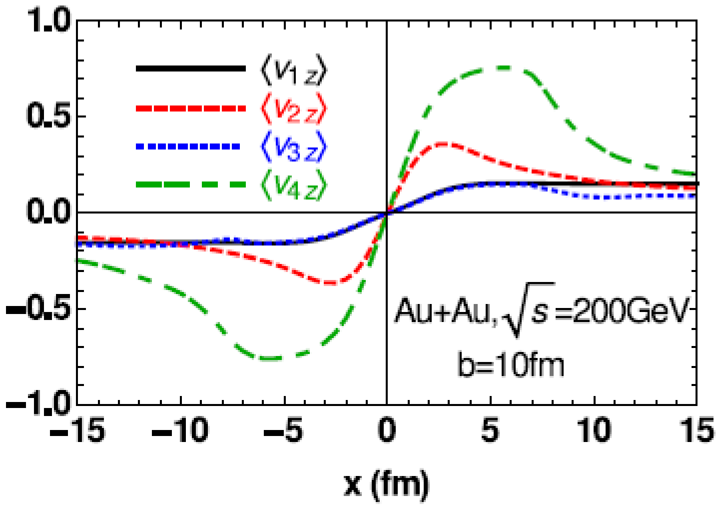
Backup

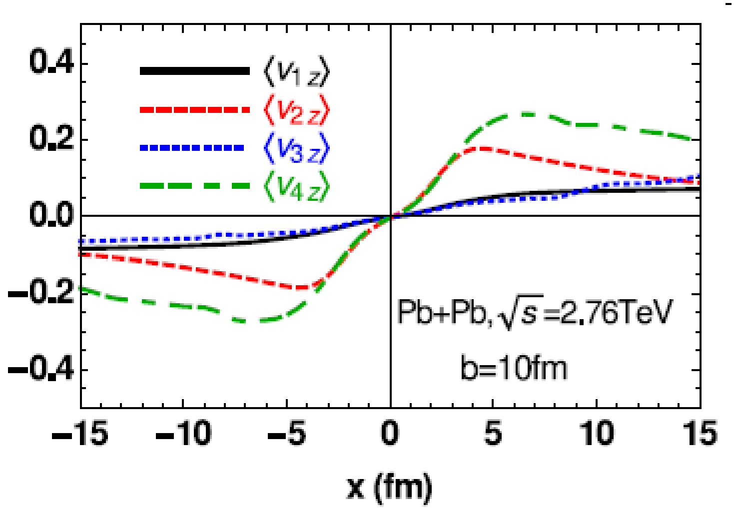
Angular momentum in overlapping region





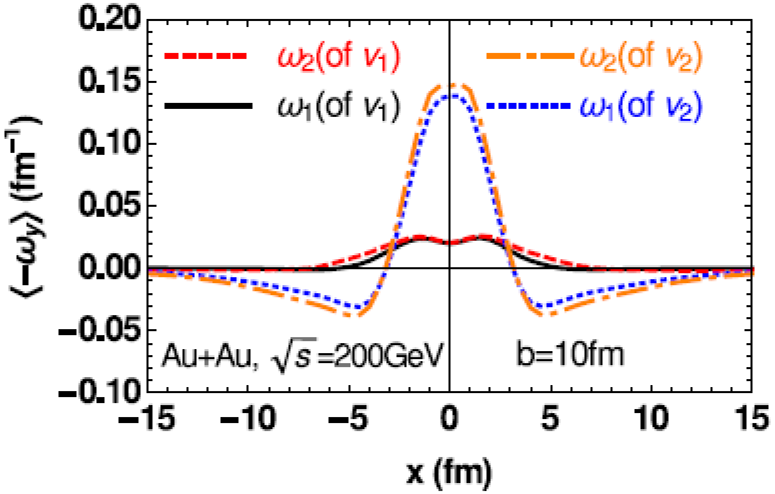
Velocity profile

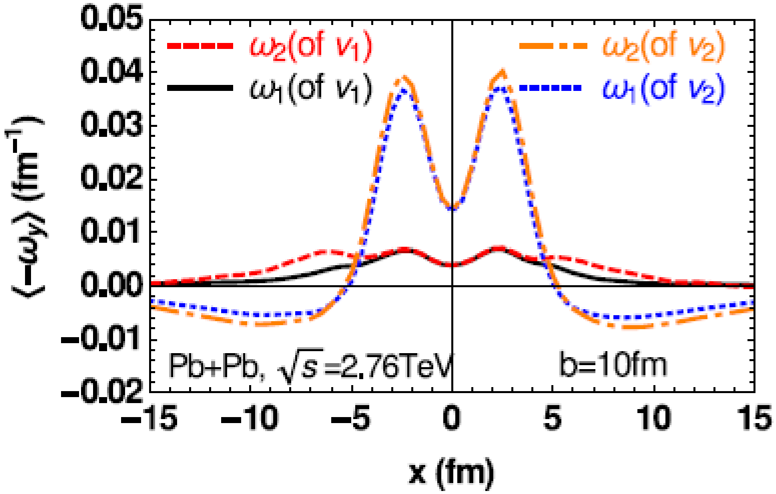




Backup

Spacial distribution





Rapidity dependence