Topical Workshop on Beam Energy Scan 2016

Vorticity-Driven Effects in Rotating Quark-Gluon Plasma

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Outline

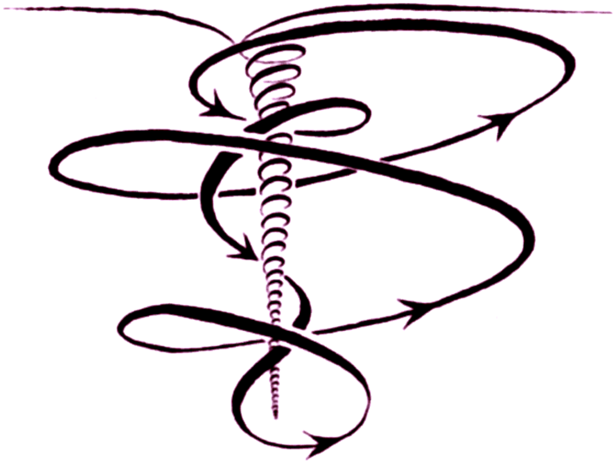
- Introduction
- Vorticity in the QGP (arXiv:1602.06580)
- Vorticity effects on phase transition(in preparation)
- Chiral vortical wave (Phys. Rev. D 92, 071501).
- Conclusions

Introduction

- In HIC large momentum and finite impact parameter will generate large angular momentum, *vorticity* and magnetic field.
- Energy shift for charge-blind polarization will change the phase diagram.
- Anomalous transport will generate the *Chiral Vortical Wave*.

How large is the vorticity in HIC?

- ✓ Sizeable amplitude
- ✓ Relatively long life time



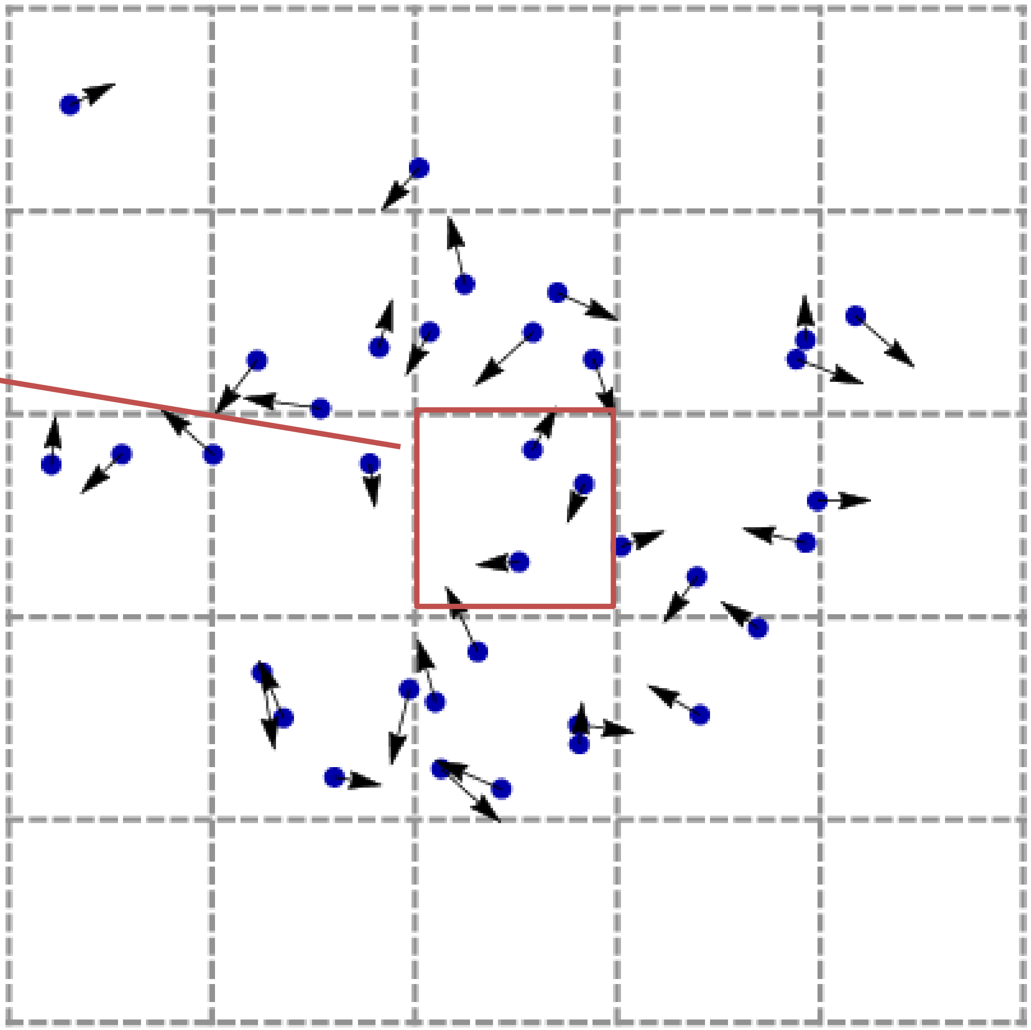
AMPT simulation

- Velocity field

$$\vec{v} = \frac{\sum \vec{p}}{\sum E}$$

- Vorticity

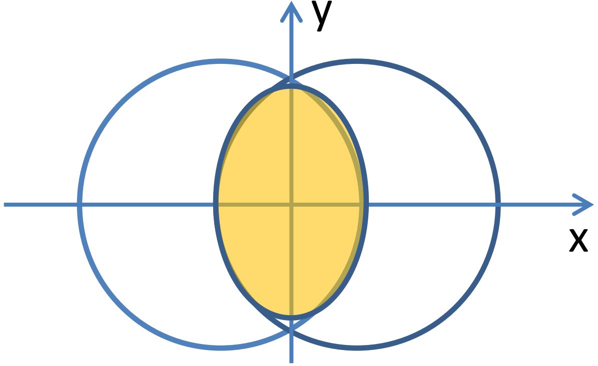
$$\vec{\omega} = \frac{1}{2} \nabla \times \vec{v}$$

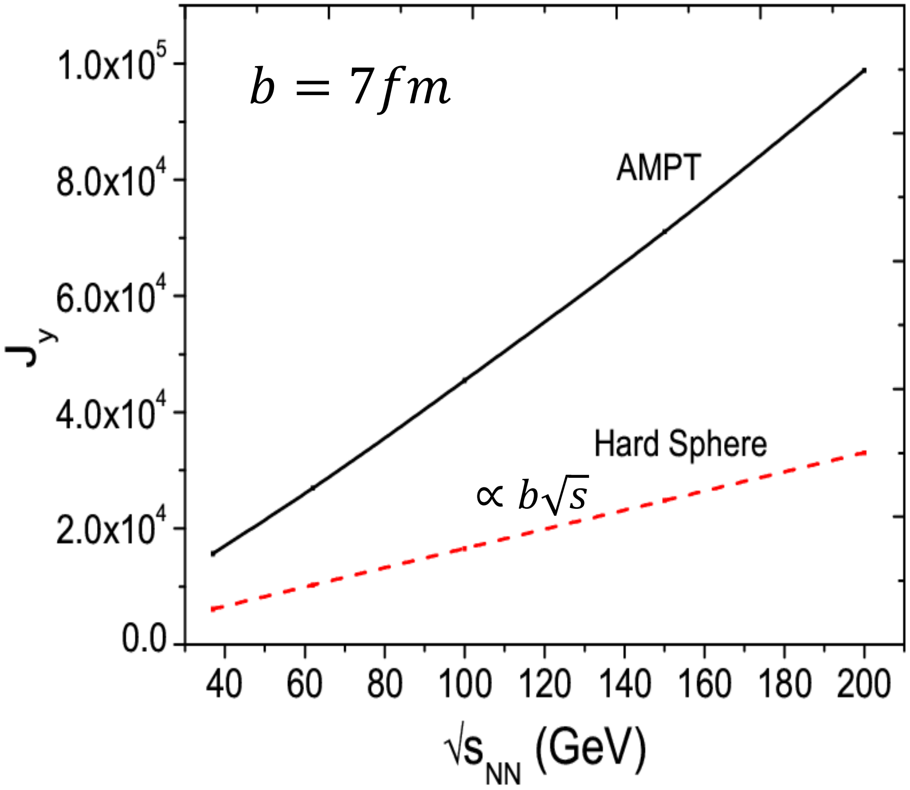


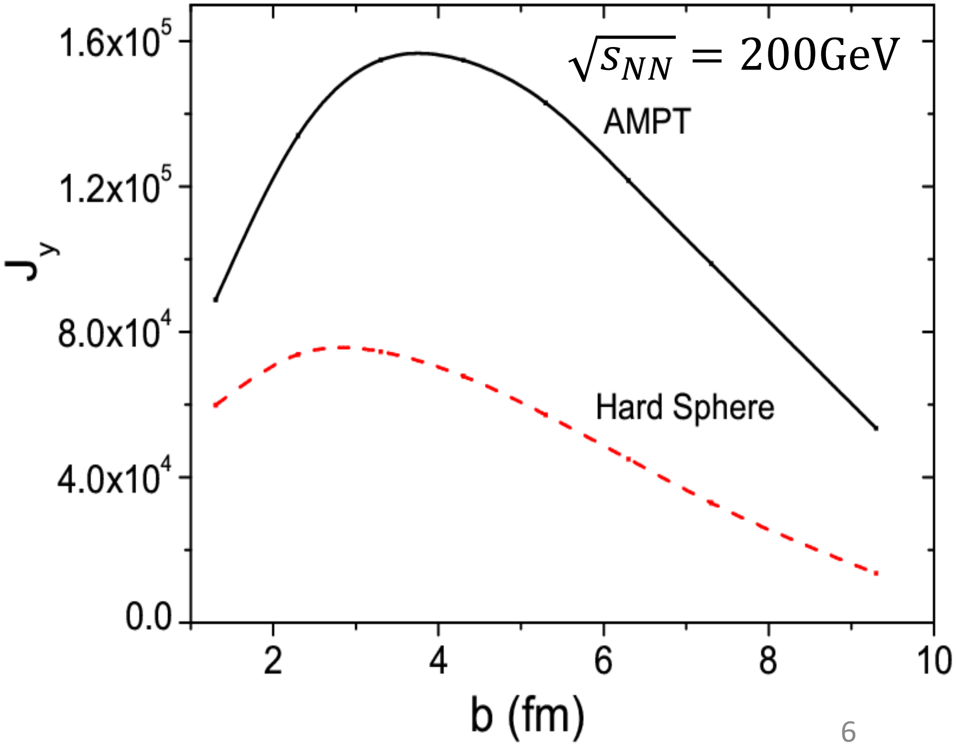
Angular momentum in QGP

- $\sqrt{s}$ and b dependence
- AMPT simulation

$10\%\sim20\%\ J_{tot}$



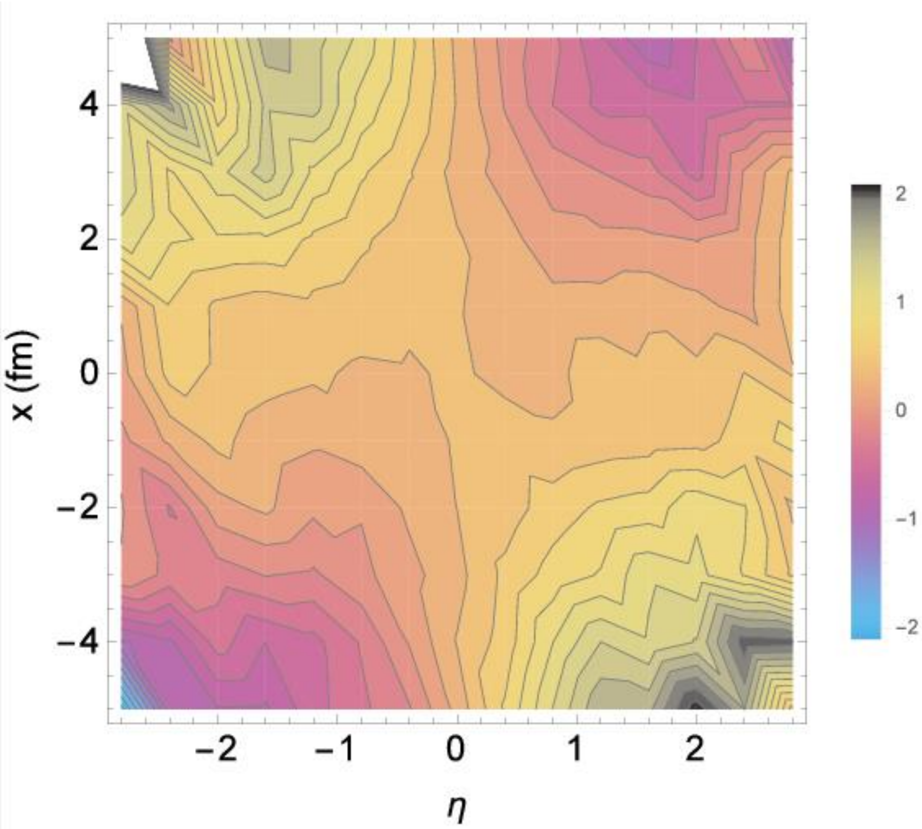




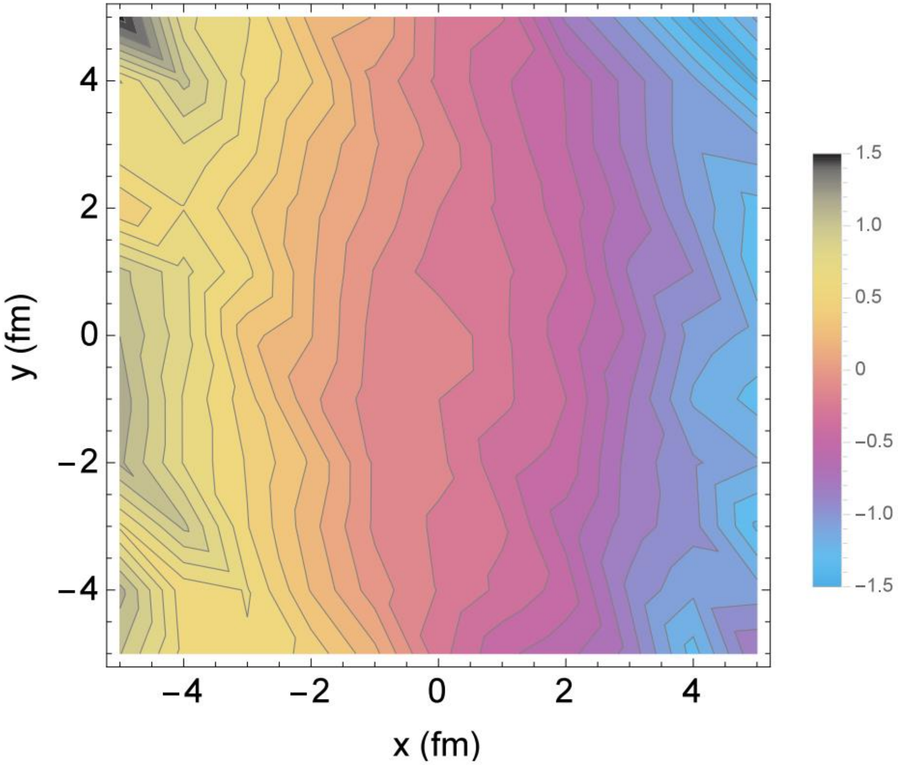
Vorticity in QGP

- ω_y dominates

Au-Au@$\sqrt{s_{NN}} = 200\ GeV, b = 7.3 fm$



$y = 0$



$\eta = 1$

Understanding with radial flow

- For a background radial velocity $\hat{e}_\rho$

Even of η

$$v(\rho,\phi,\eta) = v_0(\rho)[1 + 2c_2(\rho,\eta)\cos(2\phi)]$$

- Vorticity $\vec{\omega} = \frac{1}{2}\nabla \times \vec{v}$

$$\omega_y = \frac{2v_0}{t} ch^2\eta\left[\partial_\eta c_2 \cos(2\phi)\right]\cos(\phi)$$

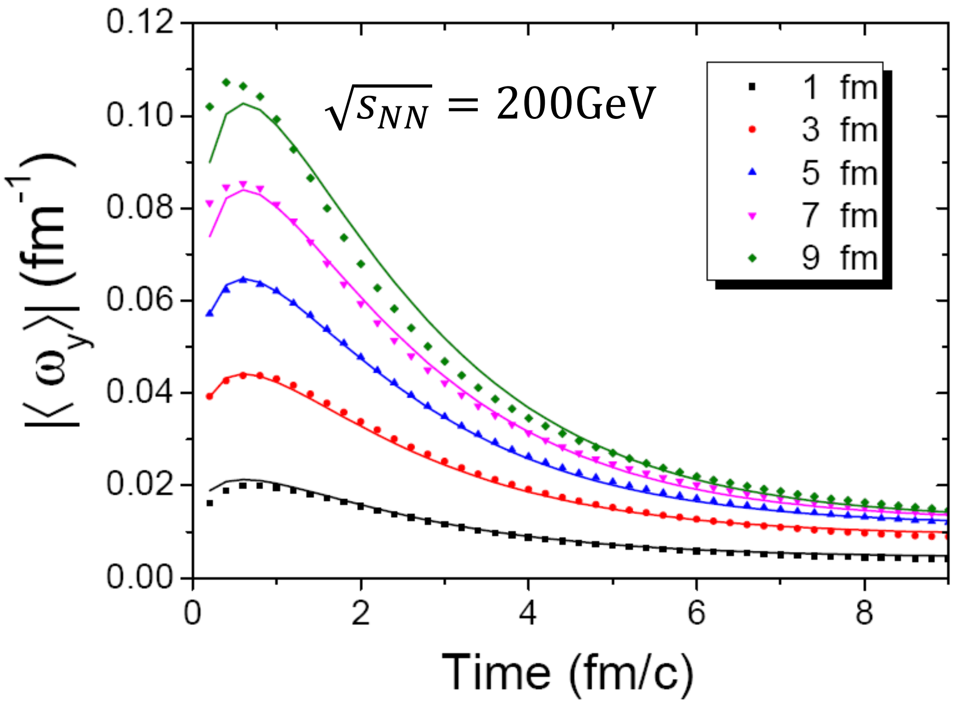
$$y = 0, x > 0, \omega_y = \frac{2v_0}{t} ch^2\eta\left[\partial_\eta c_2\right]$$

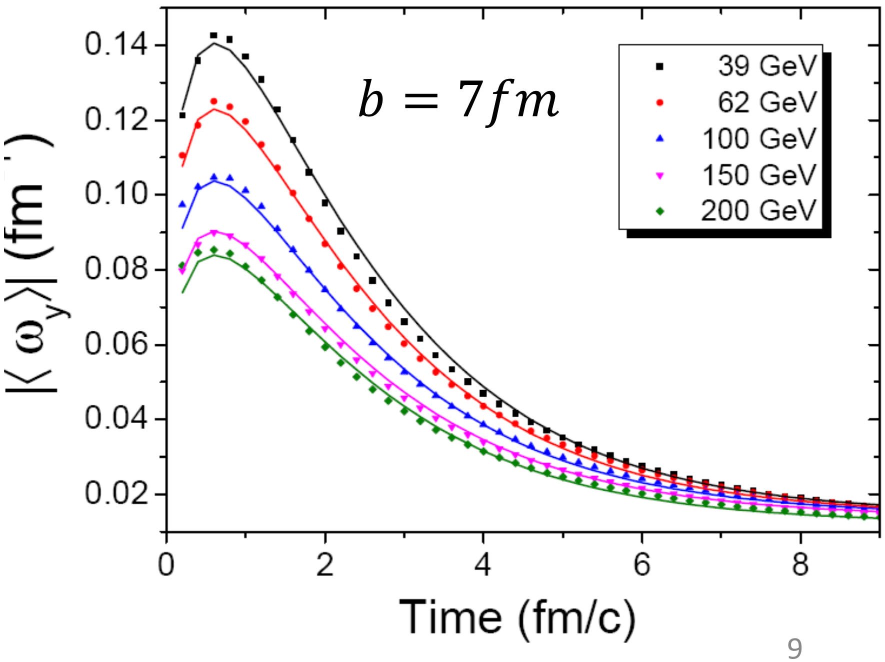
$$y = 0, x < 0, \omega_y = \frac{2v_0}{t} ch^2\eta\left[-\partial_\eta c_2\right]$$

Averaged Vorticity in QGP

- Averaged with moment of inertia $\rho^2\epsilon(r)$
- Fitting formula for potential application arXiv:1602.06580

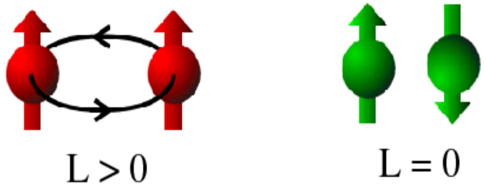
$$\langle \omega_y \rangle = A(b,\sqrt{s_{NN}}) + B(b,\sqrt{s_{NN}})(0.58\,t)^{0.35}e^{-0.58\,t}$$





Vortical effects on phase transition

- ✓ Inhomogeneous condensates
- ✓ Spin 0 condensates are weaken
- ✓ Phase transition order changes



NJL model with rotation

- Mean field approximation gives

$$H = \left(i\gamma^0\,\vec{\gamma}\ \ \cdot\overrightarrow{\partial} + M\,\gamma^0\right) - \vec{J}\cdot\vec{\omega}$$

where $M(\vec{r}) = m_0 - 2\,G\,\langle\bar{\psi}\psi\rangle$.

- Free energy

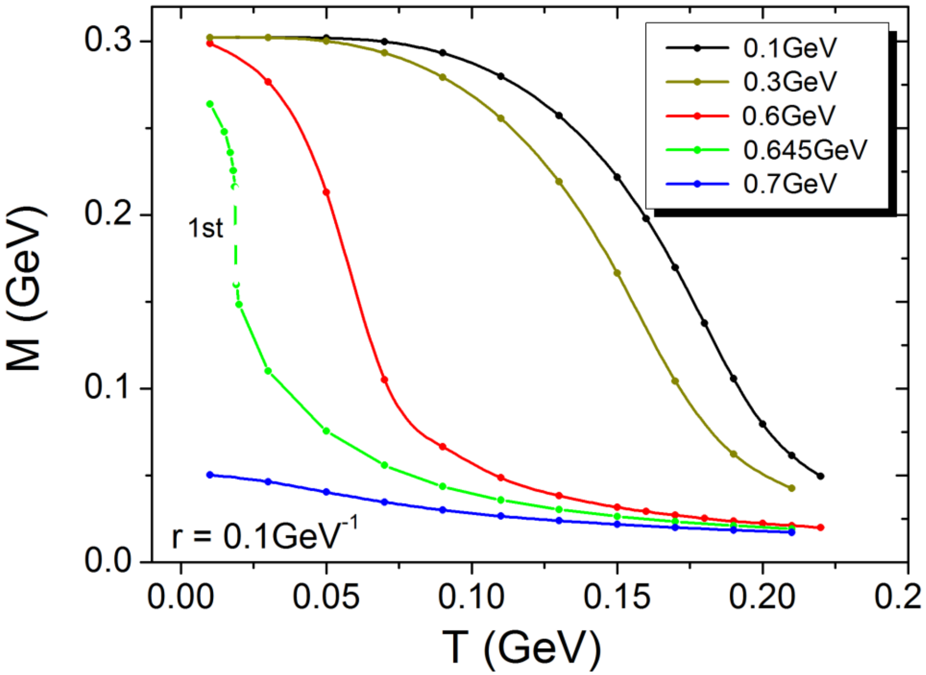
$$\Omega = \int d^3r\,\{\frac{(M-m_0)^2}{4G}$$

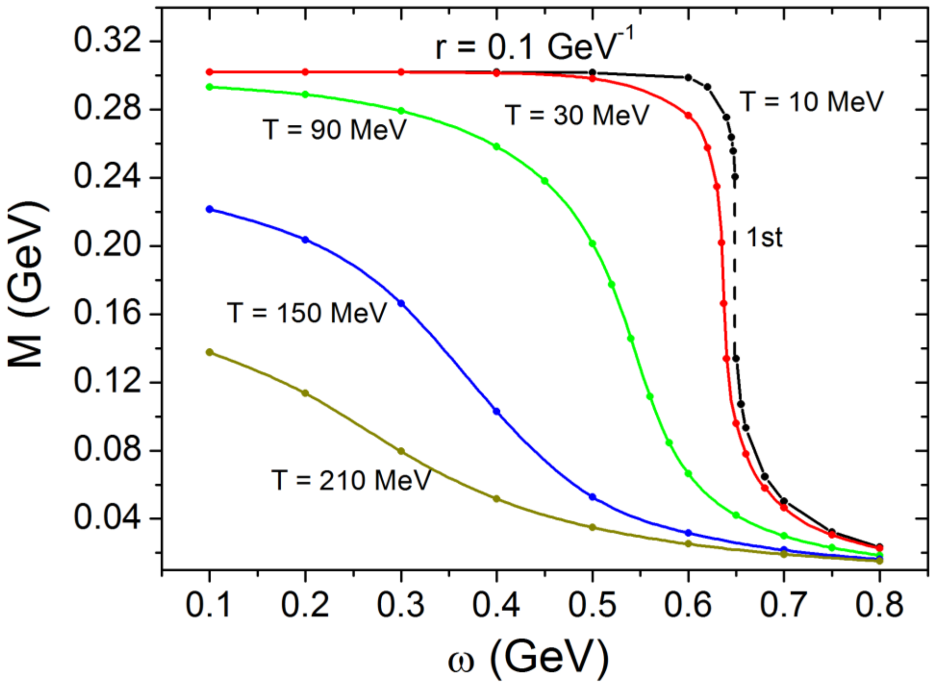
$$-\Sigma_{nk_t^2k_z}2T(J_n^2 + J_{n+1}^2)[\ln\left(1+e^{\frac{\epsilon_n}{T}}\right) + \ln\left(1+e^{\frac{-\epsilon_n}{T}}\right)]\}$$

Chiral phase transition

- Large ω: 1^{st} order; small ω: cross-over

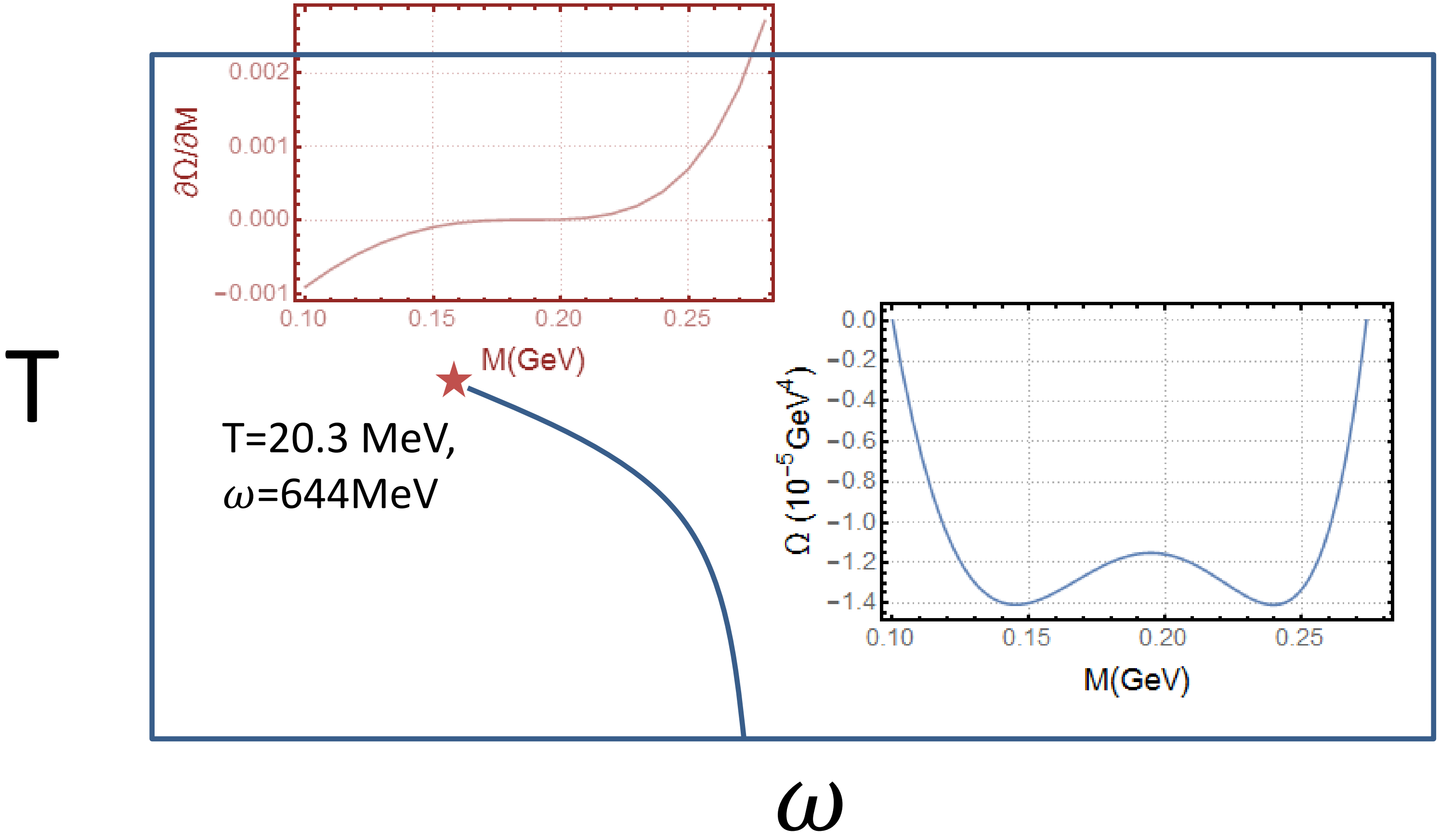
$$\delta\Omega/\delta M = 0;\ \delta^2\Omega/\delta M^2 \geq 0$$





New Critical end point

- There should be a critical end point(2^{nd} order) in T-ω phase diagram.



T=20.3 MeV,
ω=644MeV

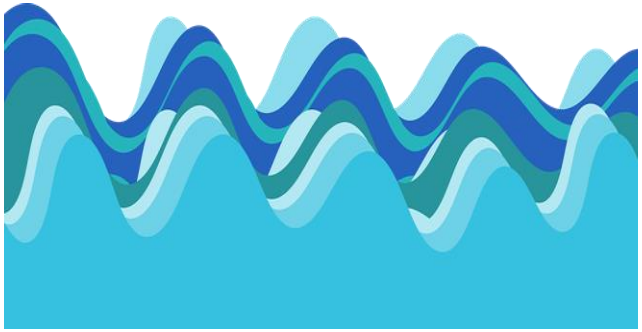
More details

- Rotation will weaken spin 0 condensate. And it may enhance those nonzero ones.
- T-ω phase diagram is similar to T-μ diagram, i.e. 1st order PT and CEP.
- New phase diagram will produce new EOS. 1st order PT will contribute largely to the moment of inertia.

✓ System size: $\omega R < 1$.

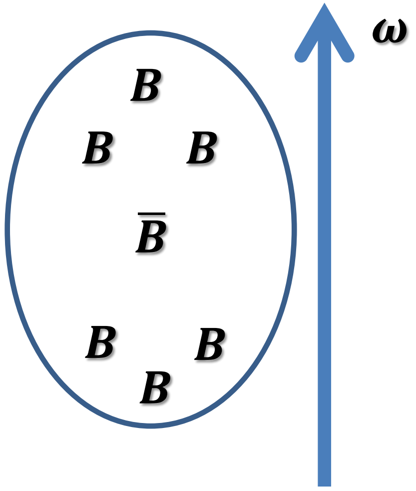
✓ Relativistic case: rotation generates space dependence.

Transport effects induced by vorticity



- ✓ Chiral vortical wave
- ✓ Quadrupole of hadron distribution

Spin-Vorticity Coupling



- Charge blind polarization effect

$$\Delta H = -\vec{S} \cdot \vec{\omega}$$

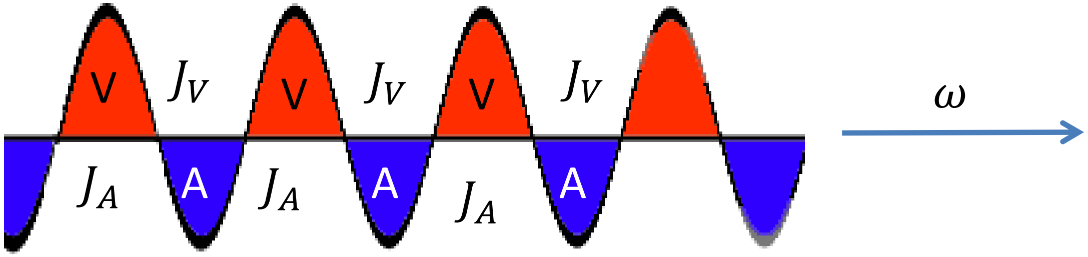
Charge blind

- For chiral fermions:
- Right ones tend to move along vorticity;
- Left ones in the opposite direction.

CVE and axial CVE

- Leading terms of CVE and axial CVE

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



- Rotating to chirality basis

$$\vec{J}_{L,R} = \left(\mp\frac{T^2}{12} \mp \frac{\mu_{L,R}^2}{\pi^2}\right)\vec{\omega}$$

Chiral Vortical Wave

- These effects generate a new collective mode.
- Combining with current conservation

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

and assuming $\mu_{L,R} = \alpha\, n_{L,R}$ where $\alpha = \frac{\partial \mu}{\partial n}$.

- Wave equation

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

Linearization

- With a background quark density n_0

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

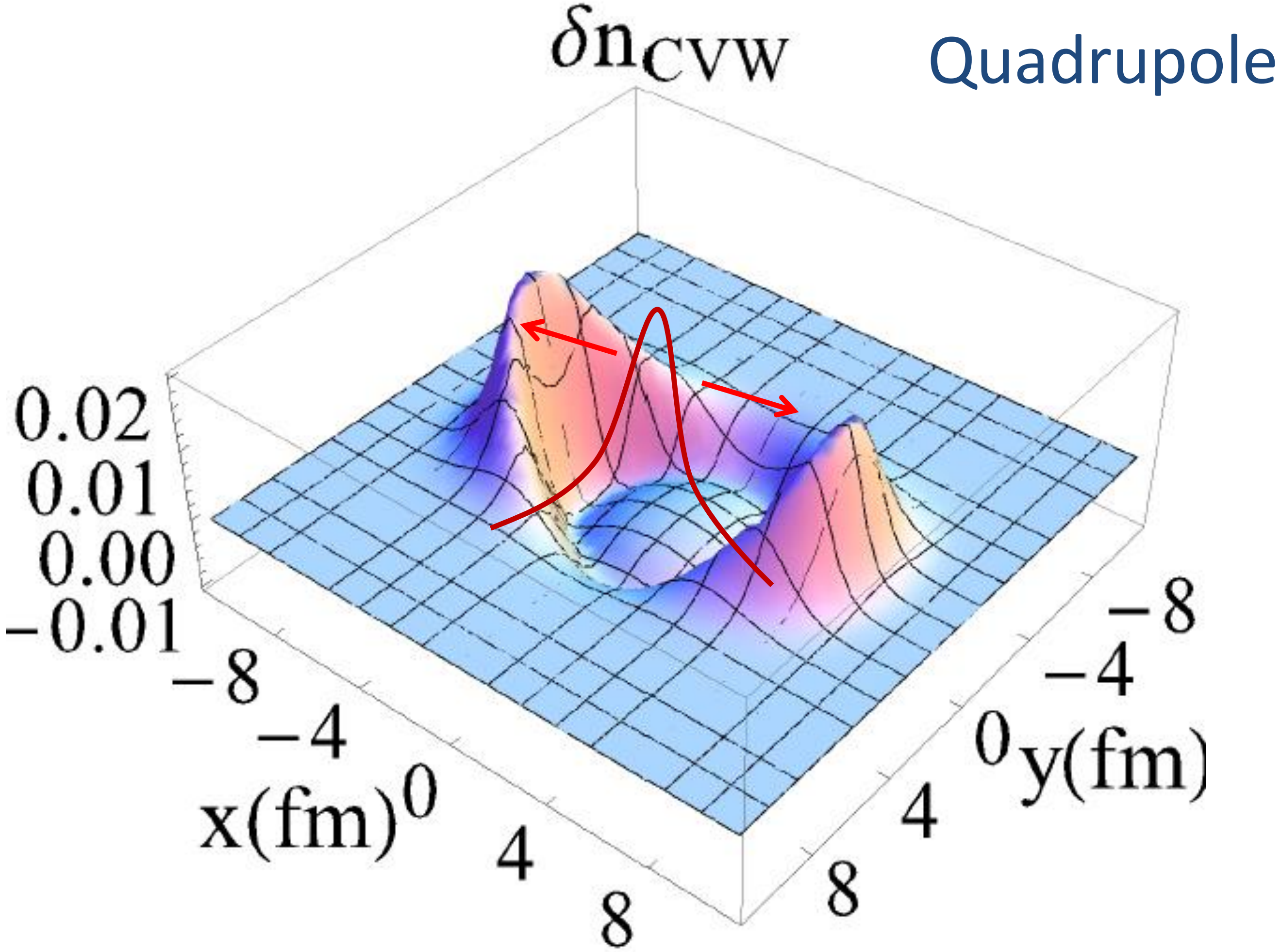
- Wave solution

$$n_{L,R} = f(x, y \boxed{\pm \frac{2\omega\alpha^2}{\pi^2} n_0} t)$$

velocity

Wave solution

- Initial condition $n_{L,R}(t = t_0) = f(\vec{r})$



Quadrupole

- CVW would generate a quadrupole moment for hadron density eventually.

$$\mu_f = \frac{\mu_0}{3} - 2q_{\Omega}^{f}\cos(2\phi_s)$$

- Evolution stops at the end of QGP.
- It could be detected by the v_2 splitting of hadrons and anti hadrons.

Observables

- Quark chemical potential

$$\mu_{u,d,s} = \frac{\mu_0}{3} - 2q_{\Omega}^{u,d,s}\cos(2\phi_s)$$

- Hadrons chemical potential

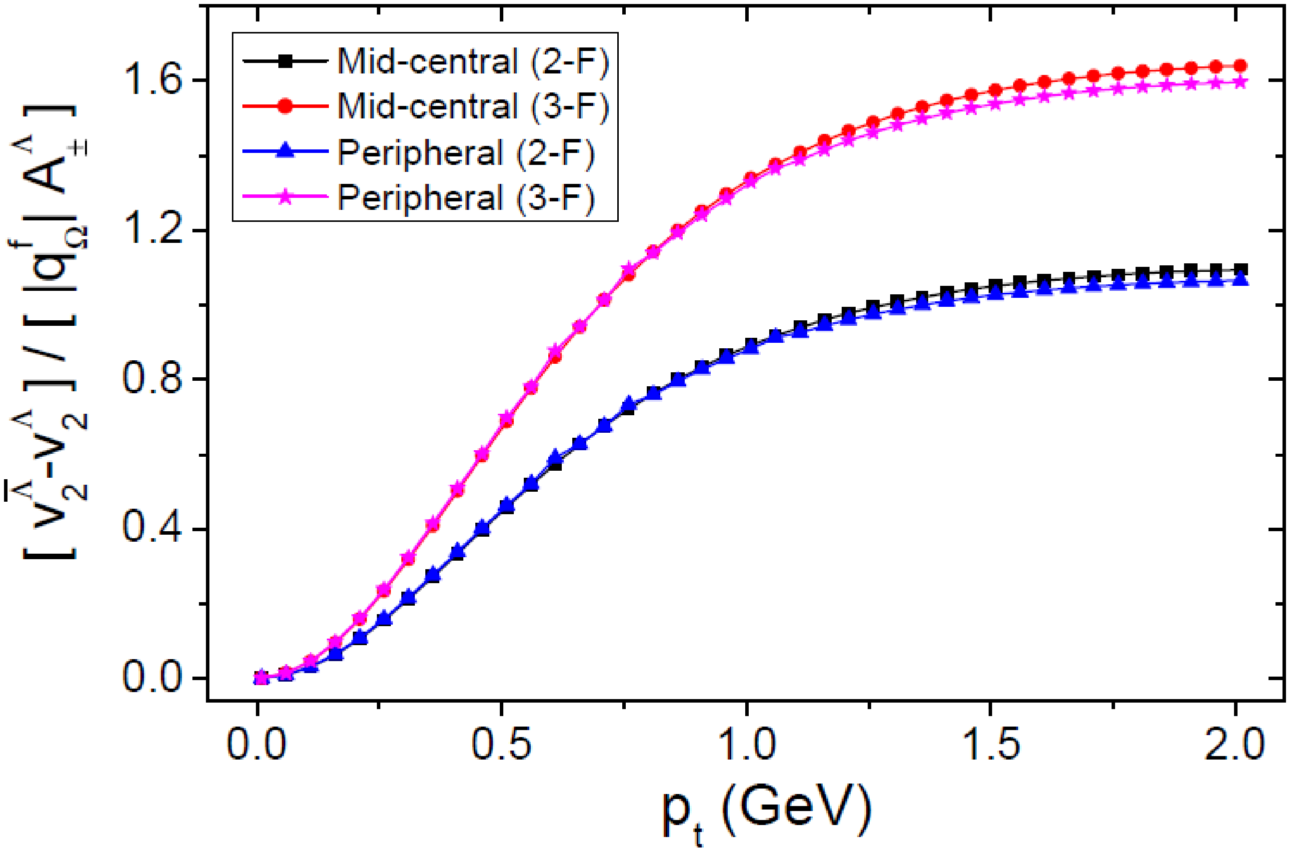
$$\mu_{\Lambda} = \mu_0 - 2(q_{\Omega}^{f} + q_{\Omega}^{f} + f q_{\Omega}^{f})\cos(2\phi_s)$$

- Background chemical potential

$$A_{\pm}^{H} = \frac{N^{H} - N^{\bar{\bar{H}}}}{N^{H} + N^{\bar{\bar{H}}}} \propto \mu_0$$

v_2 difference

- For small q_Ω^f, $v_2(\overline{H}) - v_2(H) \propto q_\Omega^f A_\pm^H \propto q_\Omega^f \mu_0$



Conclusions

- In heavy ion collision the fireball carries a large angular momentum and vorticity (AMPT model) .
- Vorticity will weaken spin 0 condensate. And it may enhance those nonzero ones.
- The *Chiral Vortical Wave* will change the hadron distribution. This effect could be detected by the v_2 difference between anti-baryon and baryon.

Thank you for your attention!