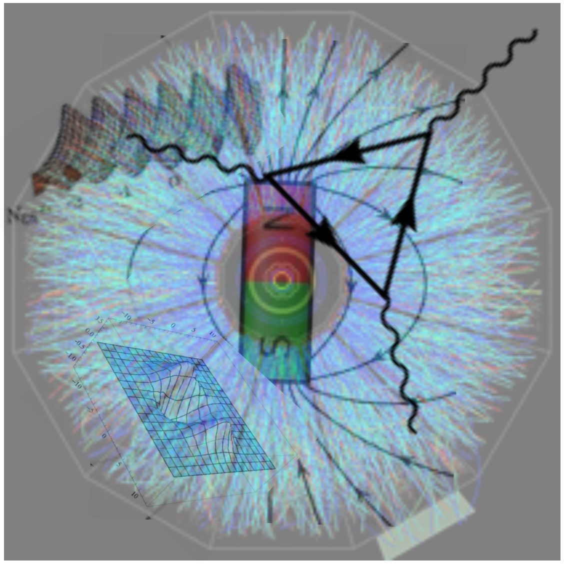
QCD Phase Structure III @ CCNU   JUN 6-9, 2016

Strongly Interacting Matter Under Rotation



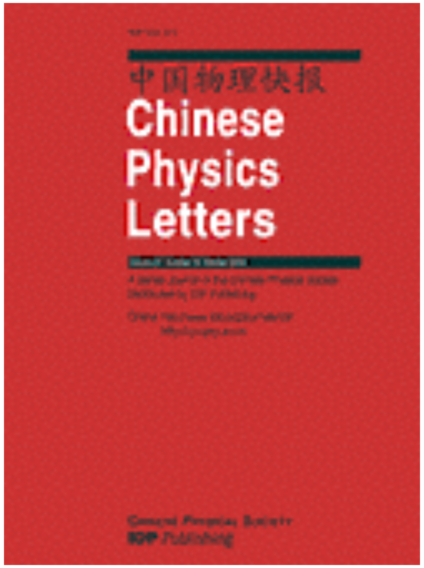
Jinfeng Liao

Indiana University, Physics Dept. & CEEM

RIKEN BNL Research Center

Research Supported by NSF

My 1st Adventure into QCD Phase Structure



"合抱之木，生于毫末；
九层之台，起于累土；
千里之行，始于足下。"

CHIN.PHYS.LETT. Vol. 19, No. 2 (2002) 177

Formation Region and Amplitude of Colour Superconductivity in an Instanton-Induced Model *

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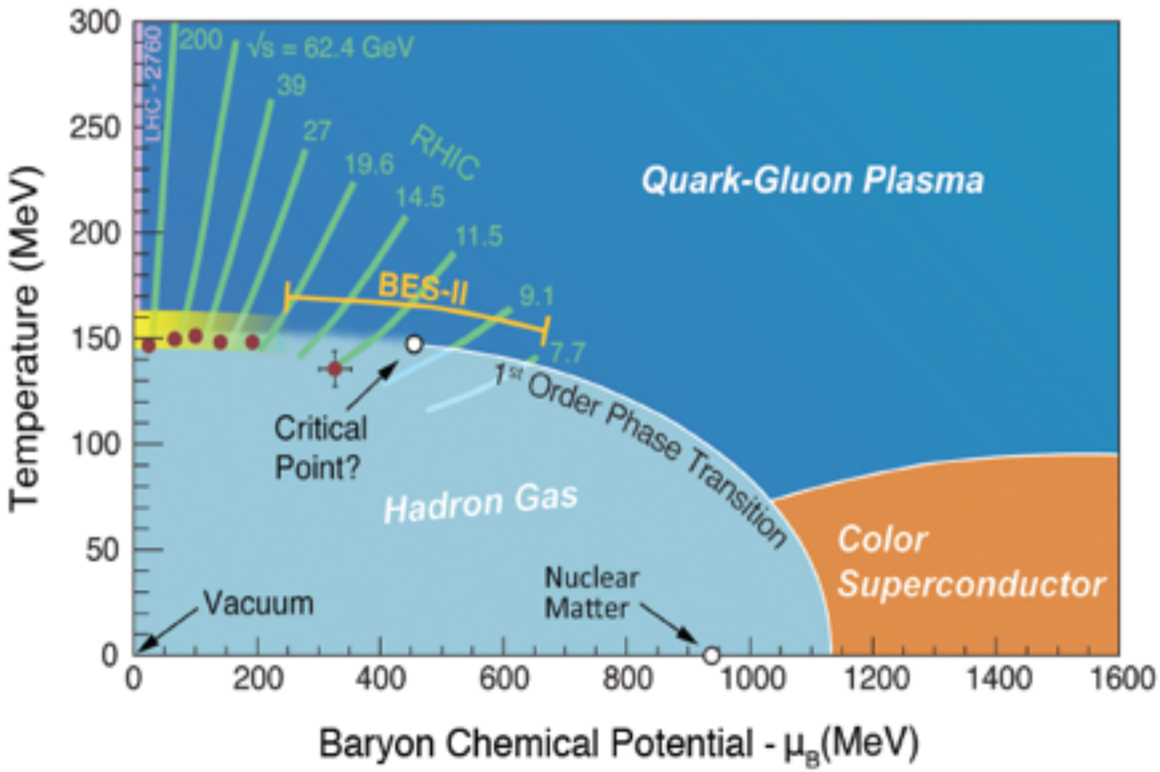
(Received 4 October 2001)

Colour superconductivity is investigated in the frame of a two flavour instanton-induced model. The ratio of diquark to quark–antiquark coupling constants is restricted to be $c/(N_c - 1)$ with $1 \le c \le 2.87$ and controls the formation region and amplitude of colour superconductivity. While the finite current quark mass changes the chiral transition significantly, it does not considerably change the colour superconductivity.

Toward Physics of Beam Energy Scan

*** Quantitatively establish a chiral QGP at higher energy collisions**
*** Search for QCD critical point at lower energy collisions**



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

Exciting Progress: See Recent Reviews

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

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Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

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

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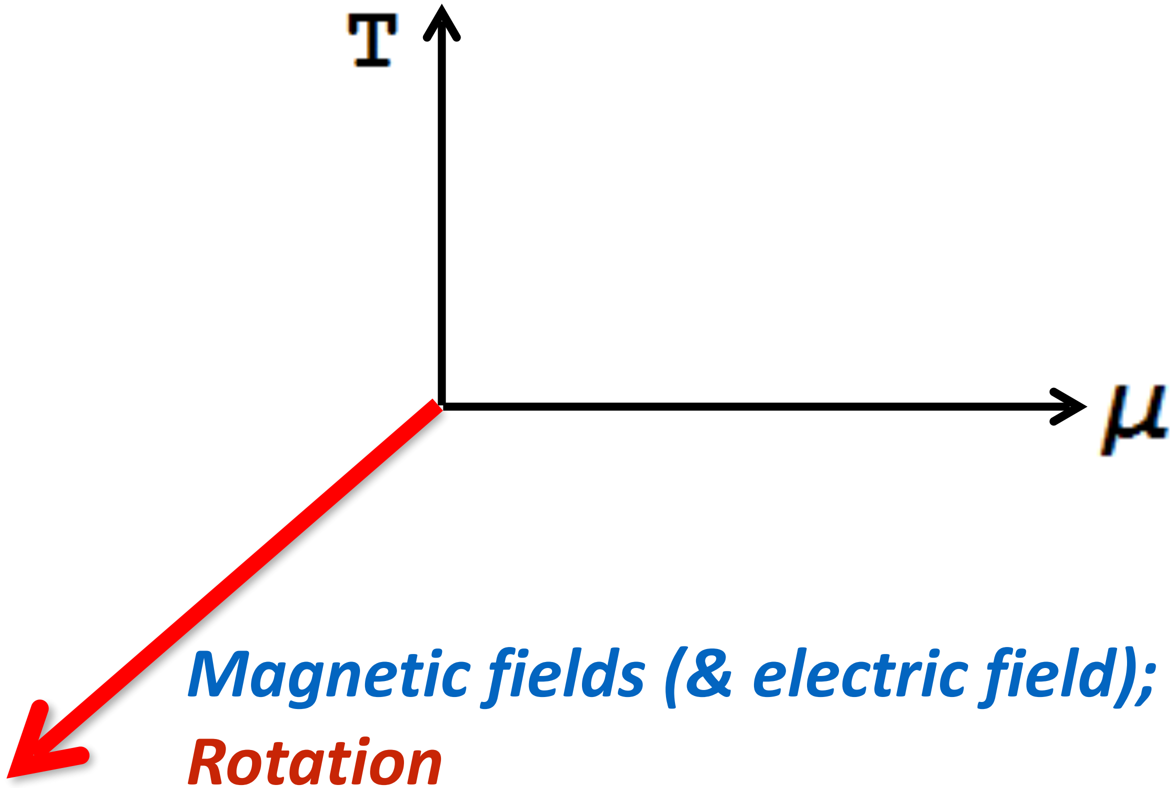
Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050 [hep-ph]].

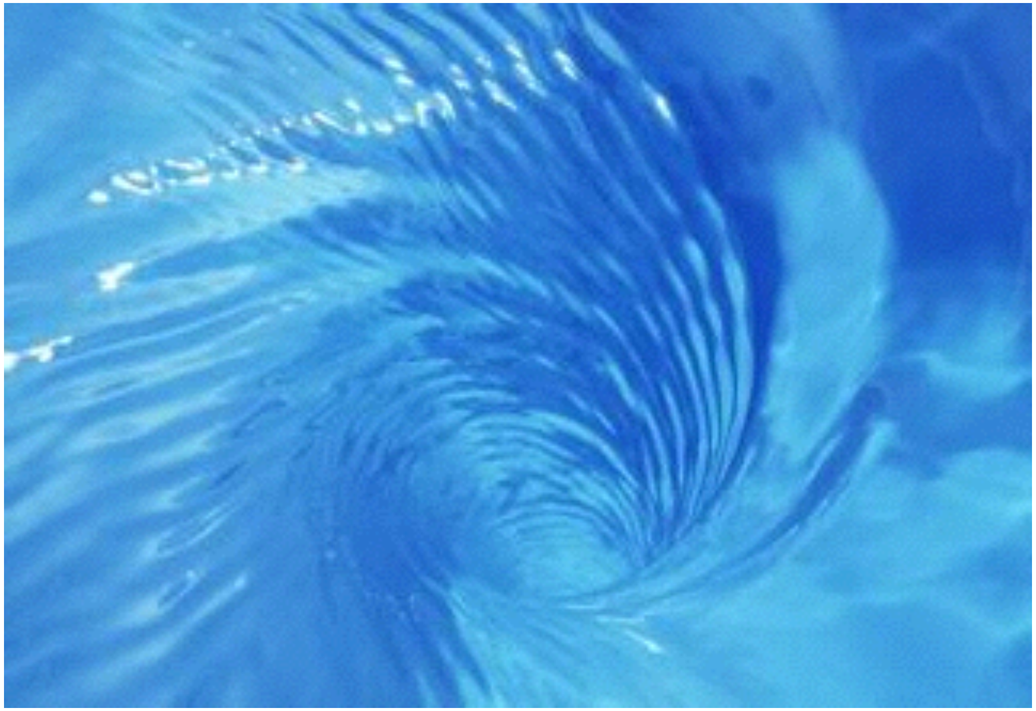
J. Liao, Pramana 84, no. 5, 901 (2015) [arXiv:1401.2500 [hep-ph]].

Phase Diagram: Many More "Dimensions"



Magnetic fields (& electric field);
Rotation
(or macroscopic angular momentum);
Isospin density;
Fermion Contents (Nf, rep., …);
……

Why Rotation?

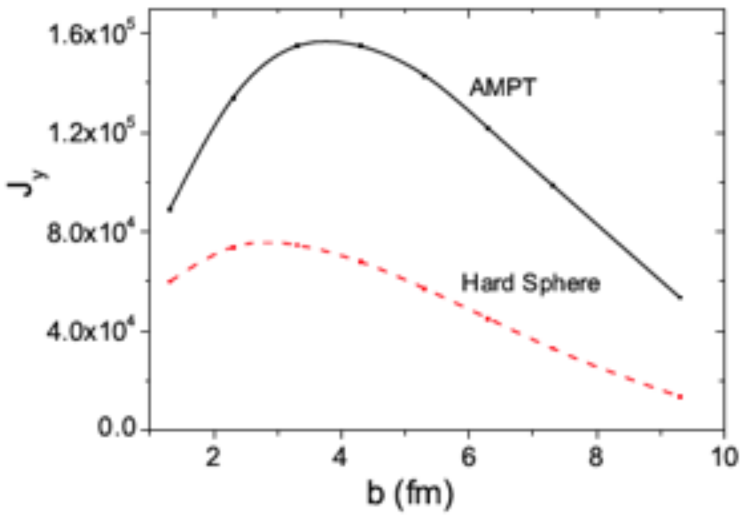


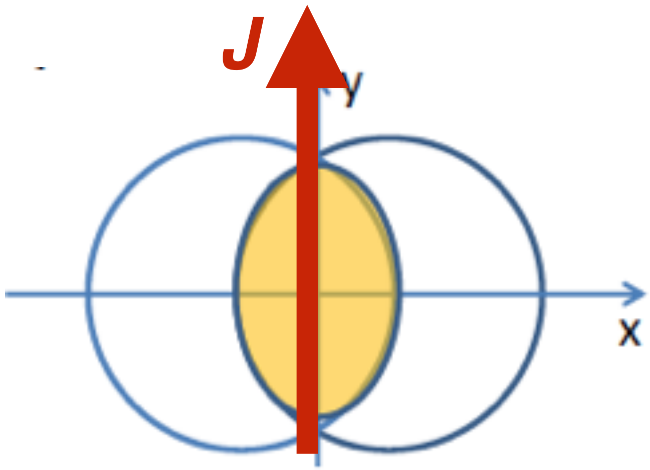
* There are many systems of interest that are rotating:
  QGP in heavy ion collisions; neutron star; cold atoms; …

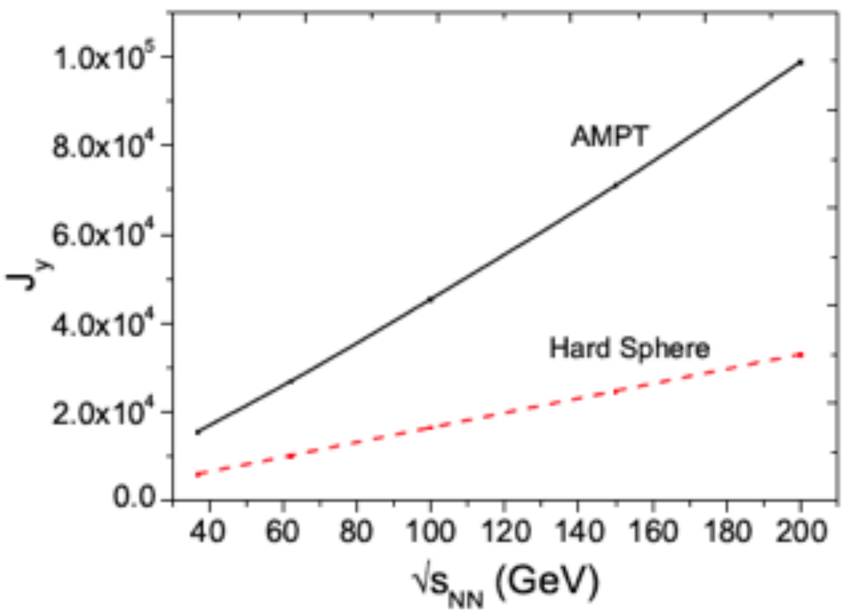
* Interesting analogy between B field and rotation, as noticed in recent studies of anomalous chiral transport.

* Thermodynamics & phase transitions are affected by B field, so likely also by rotation.

Rotating Quark-Gluon Plasma



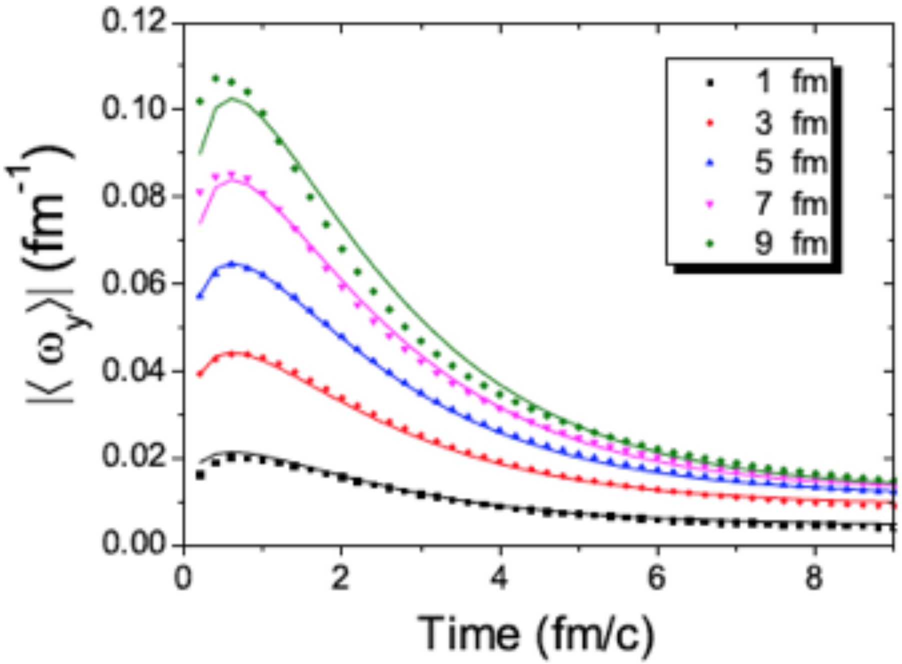


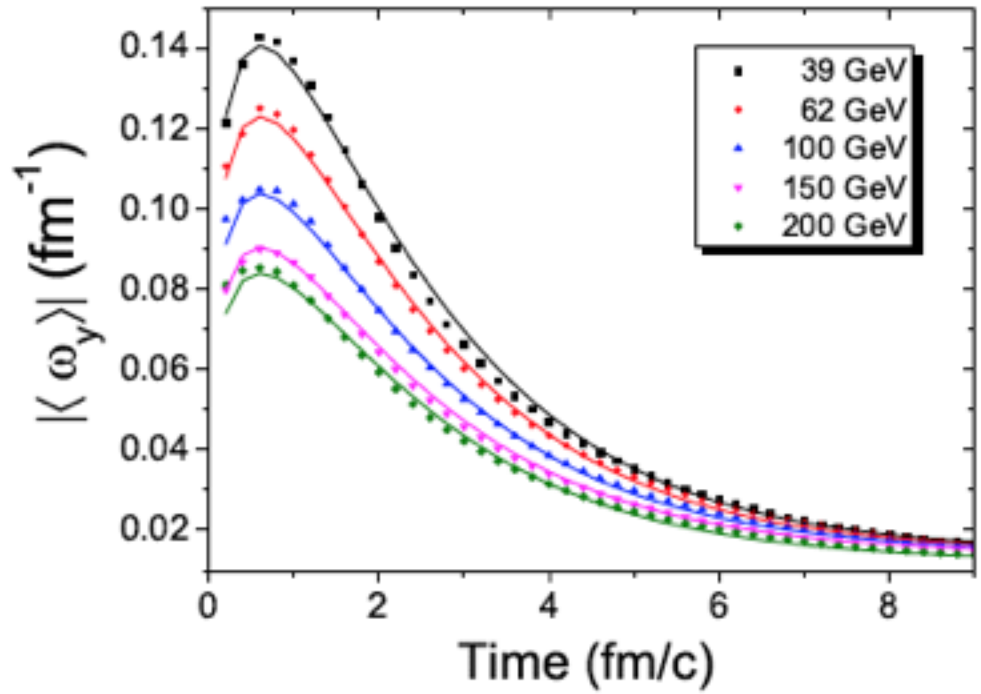


Angular momentum is conserved in time.

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

Rotating Quark-Gluon Plasma





Convenient parameterization:

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

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

[see also Deng & Huang,1603.06117]

There are interesting effects, e.g. Lambda polarization [c.f. Liang & Wang, PRL 2005; …]

Analogy between B Field and Rotation

Fluid velocity field

$$\vec{V}$$

Fluid vorticity

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

EM vector field

$$\vec{A}$$

Magnetic field

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

At classical level:

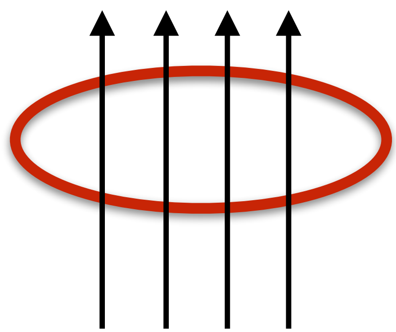
$$\vec{F}_{Lorentz} = e\,\vec{v} \times \vec{B}$$

(Lorentz force)

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

(Coriolis force)

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



At quantum level:

$$\phi_B = e \int \vec{B} \cdot d\vec{S}$$

(Aharonov-Bohm effect)

$$\phi_\omega = 2m \int \vec{\omega} \cdot d\vec{S}$$

(Sagnac effect)

An angular momentum from rotation and a magnetic flux generate a similar quantum phase of topological character.

B/Omega Analogy I: Anomalous Currents

In a Parity-Odd medium, vectors & axial vectors can be mixed up, and one can be generated from the other.

For rotating fluid:

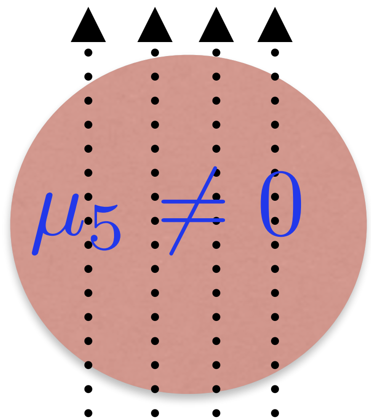
$$\vec{V} \cdot \vec{\omega} \neq 0$$

$$\omega \rightarrow V \parallel \omega$$

Chiral Vortical Effect

$$\vec{J} \propto \mu_5 (\mu \vec{\omega})$$

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



For EM field:

$$\vec{E} \cdot \vec{B} \neq 0$$

$$\vec{B} \rightarrow \vec{E} \parallel \vec{B}$$

Chiral Magnetic Effect

$$\vec{J} \propto \mu_5 (e\vec{B})$$

Intuitive understanding of CME & CVE:

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

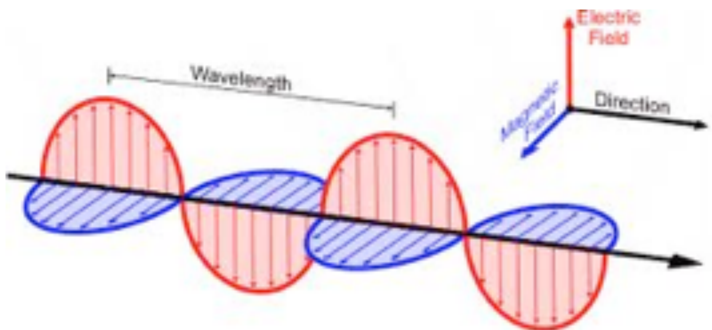
$\otimes$

Chiral imbalance —> correlation between directions of SPIN & MOMENTUM

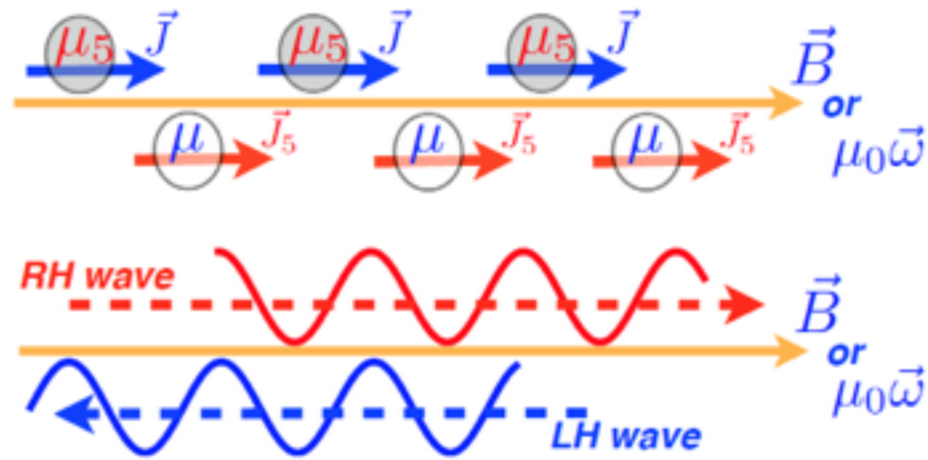
→ ***Current along external force!***

B/Omega Analogy II: Anomalous Waves

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



EM wave



Chiral Density Wave

Chiral Magnetic Wave

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

[Kharzeev, Yee, PRD2010; Burnier, Kharzeev, JL, Yee, PRL2011]

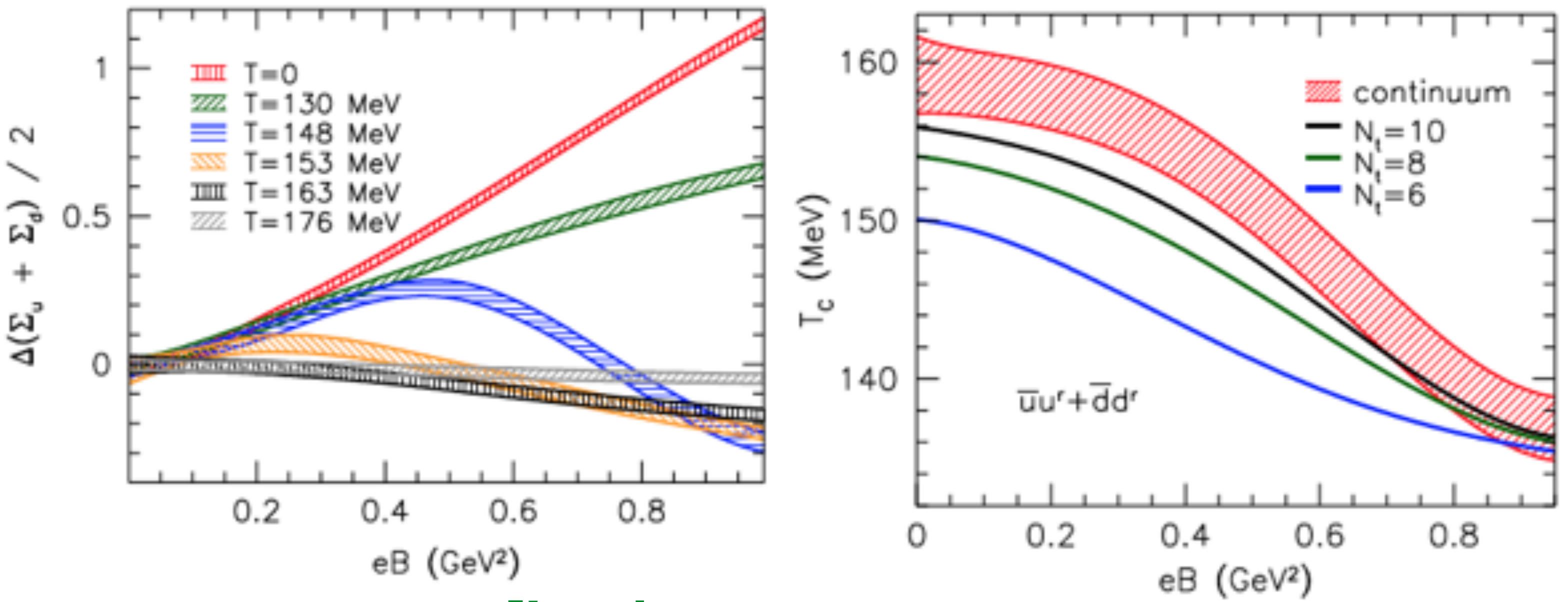
Chiral Vortical Wave

$$\left(\partial_0 \pm \frac{\mu_0}{(2\pi^2)\chi_{\mu_0}}\vec{\omega}\cdot\nabla\right)\delta J^0_{R/L} = 0$$

[Jiang, Huang, JL, arXiv: 1504.03201, PRD2015]

Influence of Rotation on Phase Structure?

We know that magnetic fields can change the thermodynamic properties and phase structure of QCD matter.



[Lattice results by Bali, et al]

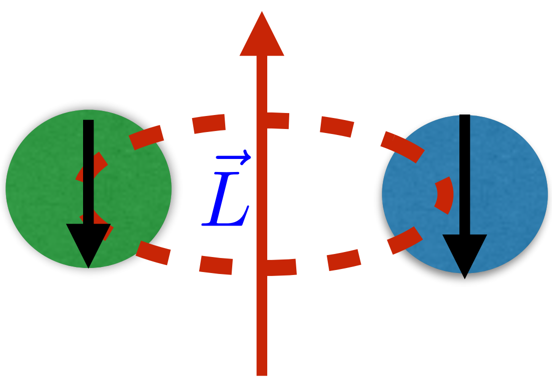
And we know the similarity between B field and rotation.
It is thus tempting to ask:
influence of rotation on phase structure?
[BTW: it could be studied on lattice,
c.f. Yamamoto & Hirono, 2013]

Rotational Suppression of Scalar Pairing

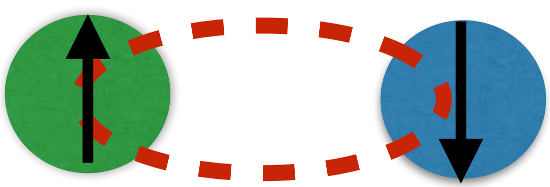
Let us consider pairing phenomenon in fermion systems.
There are many examples:
superconductivity, superfluidity, chiral condensate, diquark, …

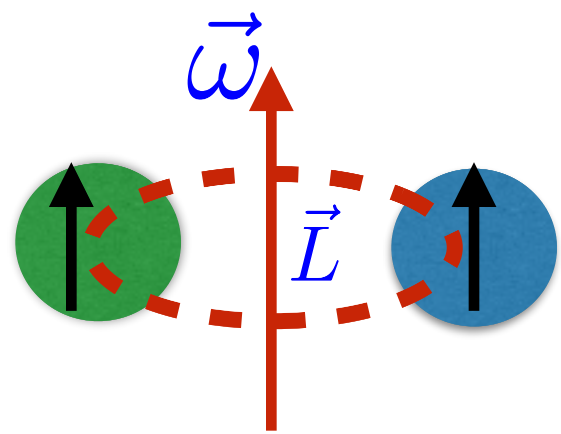
We consider scalar pairing state, with J=0.

$$\vec{S} = \vec{s}_1 + \vec{s}_2 \qquad \vec{J} = \vec{L} + \vec{S}$$



Rotation tends to polarize ALL angular momentum, both L and S, thus suppressing scalar pairing.





[Yin Jiang, JL, to appear;
See also: Chen, Fukushima, Huang, Mameda, arXiv:1512.08974]

Description of Slowly Rotating Fermion System

Dirac Lagrangian in rotating frame:

$$g_{\mu\nu} = \begin{pmatrix} 1-\vec{v}^2 & -v_1 & -v_2 & -v_3 \\ -v_1 & -1 & 0 & 0 \\ -v_2 & 0 & -1 & 0 \\ -v_3 & 0 & 0 & -1 \end{pmatrix}$$

$$\vec{v} = \vec{\omega} \times \vec{x}.$$

$$\bar{\gamma}^\mu = e_a{}^\mu \gamma^a$$

$$\Gamma_\mu = \frac{1}{4} \times \frac{1}{2}[\gamma^a, \gamma^b]\Gamma_{ab\mu}$$

$$\mathcal{L} = \bar{\psi}\left[i\bar{\gamma}^\mu(\partial_\mu + \Gamma_\mu) - m\right]\psi$$

Under slow rotation:

$$\mathcal{L} = \psi^\dagger \left[i\partial_0 + i\gamma^0\vec{\gamma}\cdot\vec{\partial} + (\vec{\omega}\times\vec{x})\cdot(-i\vec{\partial}) + \vec{\omega}\cdot\vec{S}_{4\times 4}\right]\psi$$

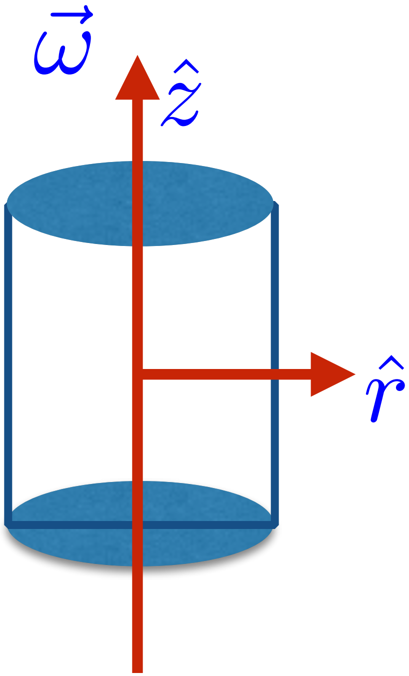
$$\hat{H} = \gamma^0(\vec{\gamma}\cdot\vec{p} + m) - \vec{\omega}\cdot(\vec{x}\times\vec{p} + \vec{S}_{4\times 4}) = \hat{H}_0 - \vec{\omega}\cdot\hat{\vec{J}}$$

Rotational polarization effect!

[Yin Jiang, JL, to appear.]

Description of Slowly Rotating Fermion System

Eigenstates of free Hamiltonian: $\hat{H}, \hat{p}_z, \hat{\vec{p}}_t^2, \hat{J}_z, \hat{h}_t \equiv \gamma^5\gamma^3\vec{p}_t \cdot \vec{S}$



$$u_{k_z,k_t,n,s} = \sqrt{\frac{E_k+m}{4E_k}} e^{ik_z z} e^{in\theta} \begin{pmatrix} J_n(k_t r) \\ s\, e^{i\theta} J_{n+1}(k_t r) \\ \frac{k_z - is\,k_t}{E_k+m} J_n(k_t r) \\ \frac{-s\,k_z + ik_t}{E_k+m} e^{i\theta} J_{n+1}(k_t r) \end{pmatrix}$$

$$v_{k_z,k_t,n,s} = \sqrt{\frac{E_k+m}{4E_k}} e^{-ik_z z} e^{in\theta} \begin{pmatrix} \frac{k_z - is\,k_t}{E_k+m} J_n(k_t r) \\ \frac{s\,k_z - ik_t}{E_k+m} e^{i\theta} J_{n+1}(k_t r) \\ J_n(k_t r) \\ -s\, e^{i\theta} J_{n+1}(k_t r) \end{pmatrix}$$

Interaction: NJL type 4-fermion

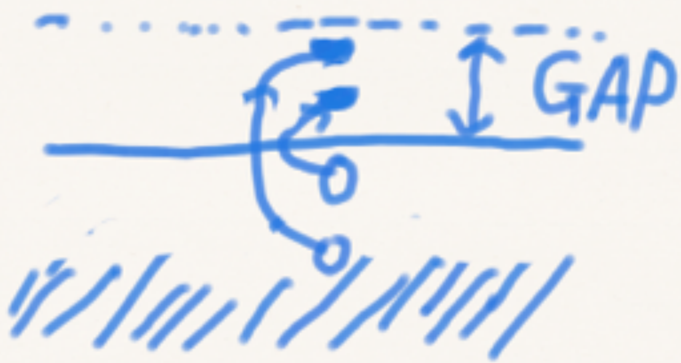
$$\mathcal{L}_{I_{eff}} = G(\bar{\psi}\psi)^2 + G_d(i\psi^T C\gamma^5\psi)(i\psi^\dagger C\gamma^5\psi^*)$$

widely used for studying fermion pairings

[Yin Jiang, JL, to appear.]

The Chiral Condensate: Q-bar-Q Pairing

Dirac Sea



Constituent mass **Lagrangian (SM) mass**

$$M = m - 2G \langle \bar{\psi}\psi \rangle$$

Pairing states: L=1, S=1, and J=0

$$\Omega = \int d^3\vec{r} \Big\{ \frac{(M-m)^2}{4G} - \frac{1}{4\pi^2} \sum_n \int dk_t^2 \int dk_z$$
$$\times \quad [J_n(k_t r)^2 + J_n(k_t r)^2]$$
$$\times T \Big[\ln\left(1 + e^{(\epsilon_n - \mu)/T}\right) + \ln\left(1 + e^{-(\epsilon_n - \mu)/T}\right)$$
$$+ \ln\left(1 + e^{(\epsilon_n + \mu)/T}\right) + \ln\left(1 + e^{-(\epsilon_n + \mu)/T}\right) \Big] \Big\}$$

$$\epsilon_n = \sqrt{k_z^2 + k_t^2 + M^2} - (n + \tfrac{1}{2})\omega$$

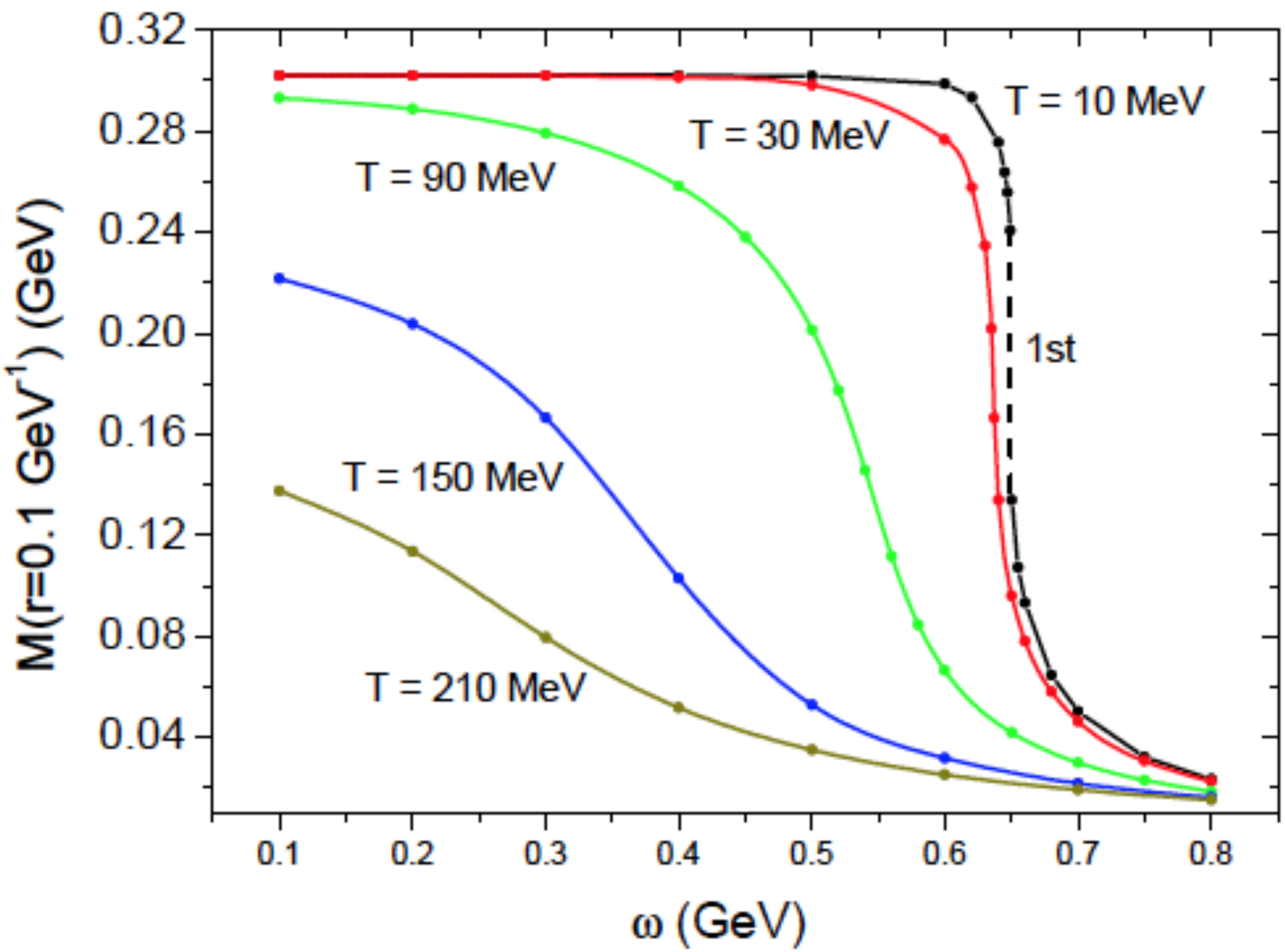
Gap equation:

$$\frac{\delta \Omega}{\delta M(r)} = 0$$

$$\frac{\delta^2 \Omega}{\delta M(r)^2} > 0$$

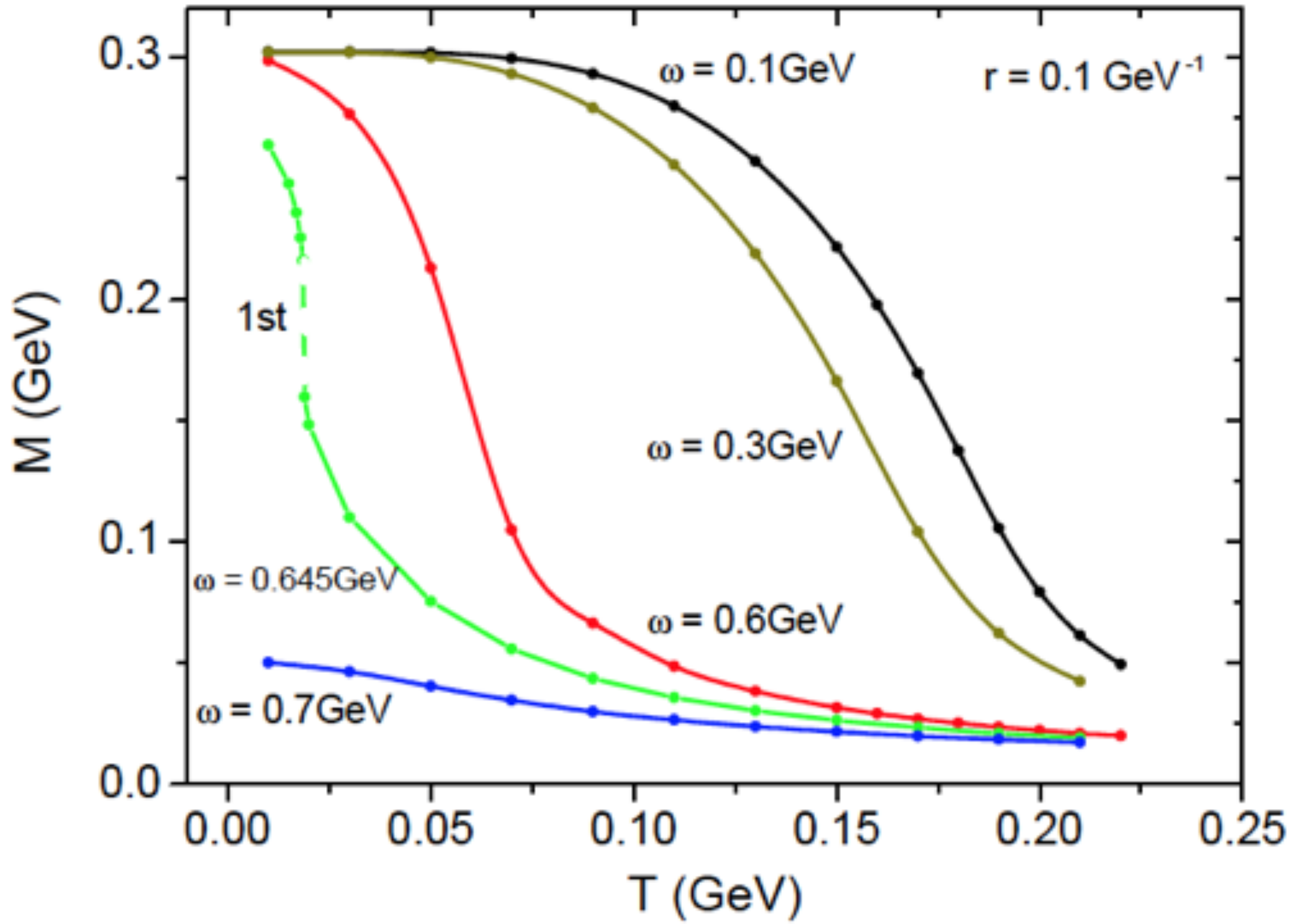
[Yin Jiang, JL, to appear.]

Rotational Suppression of Scalar Pairing



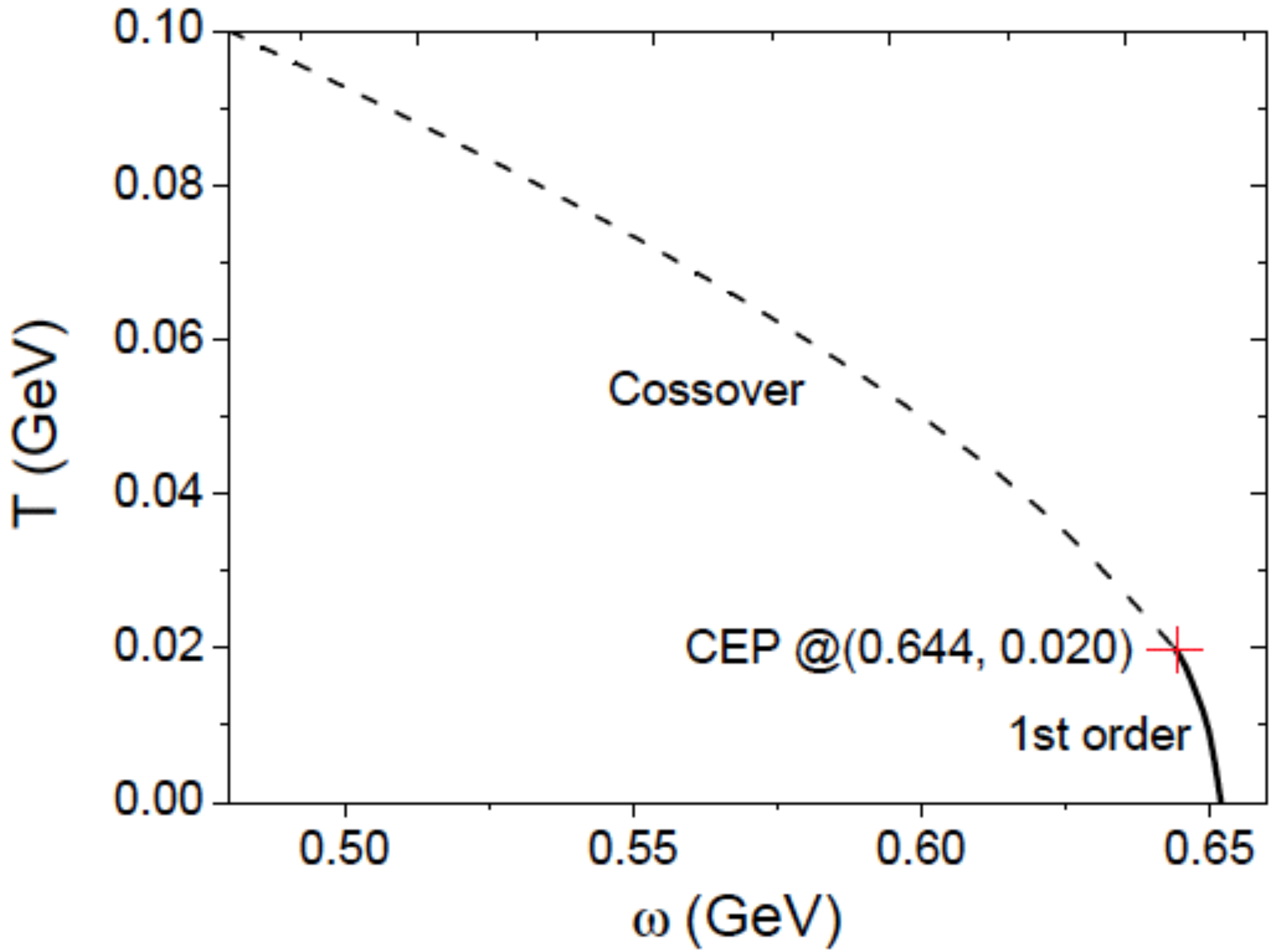
[Yin Jiang, JL, to appear.]

Rotational Suppression of Scalar Pairing



[Yin Jiang, JL, to appear.]

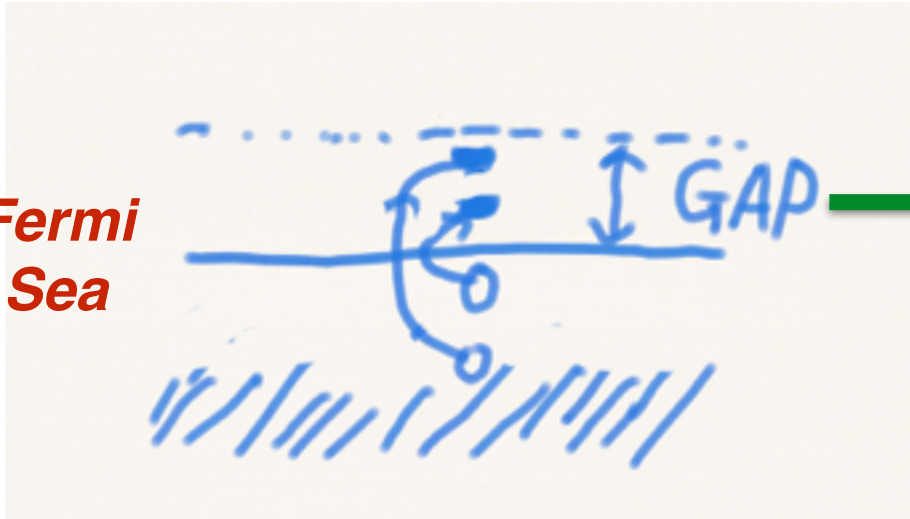
A Possible New Critical Point



[Yin Jiang, JL, to appear.]

The Diquark Condensate: Q-Q Pairing

Fermi Sea



Color superconductivity:

$$\Delta = -2G_d \langle i\psi^T C \gamma^5 \psi \rangle$$

Pairing states:
L=0, S=0, and J=0

$$\epsilon_n^{\Delta\pm} = [(\sqrt{k_z^2 + k_t^2 + m^2} \pm \mu)^2 + \Delta^2]^{\frac{1}{2}} - (n + \tfrac{1}{2})\omega$$

$$\begin{aligned} \Omega \; = \; & \int d^3\vec{r} \Big\{ \frac{\Delta^2}{4G_d} - \frac{1}{4\pi^2} \sum_n \int dk_t^2 \int dk_z \\ \times \; & [J_n(k_t r)^2 + J_n(k_t r)^2] \\ \times & T \Big[\ln\left(1 + e^{\epsilon_n^{\Delta+}/T}\right) + \ln\left(1 + e^{-\epsilon_n^{\Delta+}/T}\right) \\ + & \ln\left(1 + e^{\epsilon_n^{\Delta-}/T}\right) + \ln\left(1 + e^{-\epsilon_n^{\Delta-}/T}\right) \Big] \Big\} \end{aligned}$$

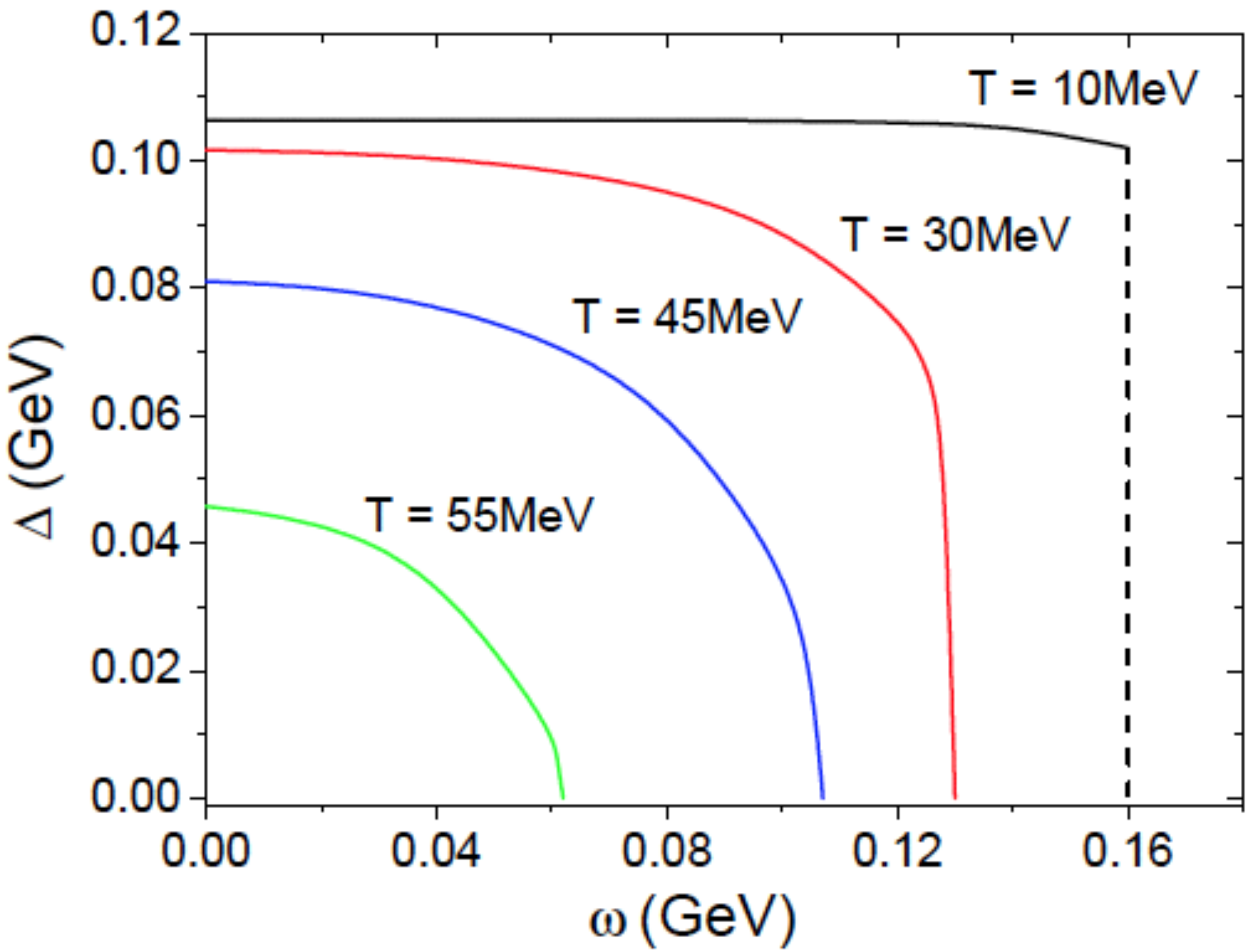
Gap equation:

$$\frac{\delta\Omega}{\delta\Delta(r)} = 0$$

$$\frac{\delta^2\Omega}{\delta\Delta(r)^2} > 0$$

[Yin Jiang, JL, to appear.]

Rotational Suppression of Scalar Pairing



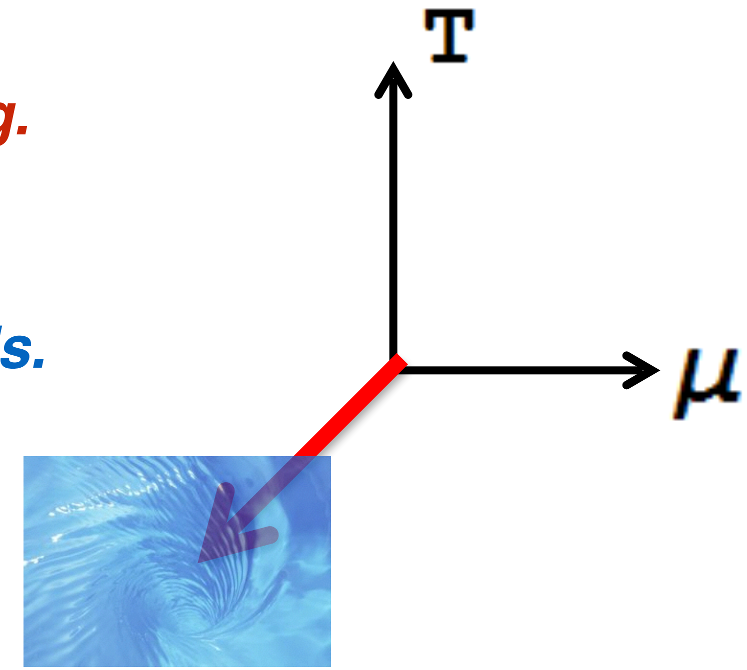
[Yin Jiang, JL, to appear.]

Summary & Outlook

Properties of strongly interacting matter under rotation are interesting.

Rotation induces anomalous chiral transport effects, like magnetic fields.

There is a generic, rotational suppression effect on scalar condensate from fermion pairing.



Many possible interesting development in the future:

** emergence of new pairing phases*

(J>0 condensate, vortices, instabilities, …)

** phenomenology: heavy ion collisions; neutron star*

** lattice simulations*

** cold atomic gas experiments*