# Strongly interacting QCD matter under extreme conditions

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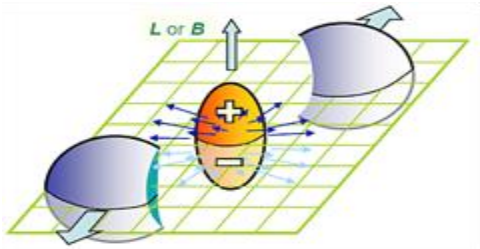
**Central China Normal University**

ExHIC-d workshop on QCD and hadronic dense matter (ExHIC-d 2025)

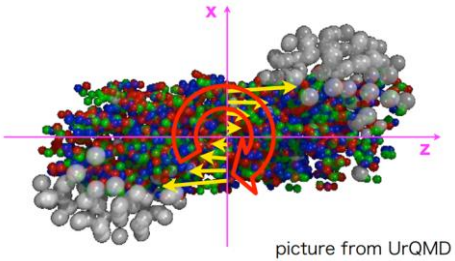
# Outlines

- **Introduction and motivation**
- **Phase structure under rotation and Magnetic field**
- **Transport properties rotating magnetized matter**
- **Summary**

# QCD under new extreme conditions



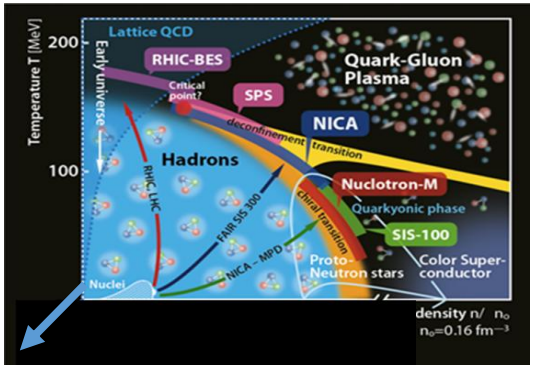

$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$




picture from UrQMD

$$L \approx \frac{A\sqrt{s_{NN}}}{2} b\hbar \sim 10^6 \hbar$$

**Explore the new dimensions of the QCD phase diagram**



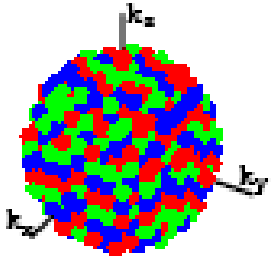

B, ω

Khazeev, Liao Nature 2021, Becattini- Karpenko etal 2015, 2016; Jiang-Lin-Liao 2016; Deng-XGH-Ma-Zhang 2020; Deng-XGH 2016, Xie-Csernai etal 2014; Pang-Petersen-Wang-Wang 2016; Xia-Li-Wang 2017,2018; Sun-Ko 2017;… … )

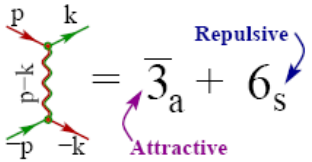
# Color Super-Conductivity (CSC)

Ground state of dense quark matter is CSC

(i) Deconfined quarks( $\mu >> \Lambda_{QCD}$ )
(ii) Pauli principle(s=1/2)




(i) Effective models( $\mu \geq \Lambda_{QCD}$ )
(ii) One-gluon exchange( $\mu >> \Lambda_{QCD}$ )




Cooper instability

Color superconductivity

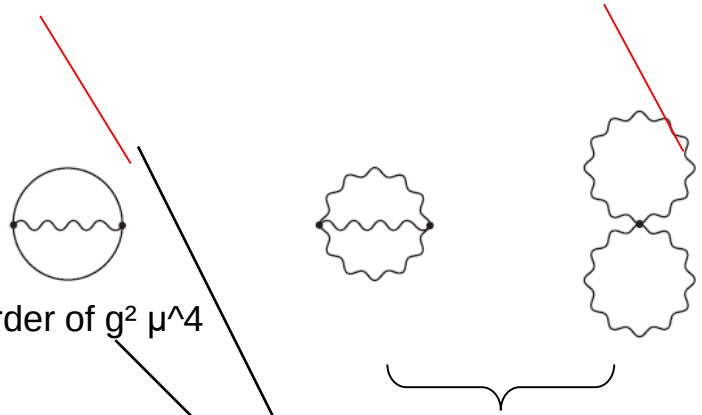
$$< (\bar{\psi}^C)_i^\alpha \gamma_5 \psi_j^\beta >\neq 0$$


B. Barrois, NPB 129, 390 (1977)
D. Bailin and A. Love, Phys. Rep. 107,325 (1984)
M. Alford et al., PLB 422, 247 (1998)
R. Rapp et al., PRL 81, 53 (1998)

# CJT effective action of QCD

$$\Gamma[\bar{D},\bar{S}] = \frac{1}{2}\{Tr\ln\bar{D}^{-1} + Tr(D^{-1}\bar{D} - 1) - Tr\ln\bar{S}^{-1} - Tr(S^{-1}\bar{S}) - 2\Gamma_2[\bar{D},\bar{S}]$$

2-loop approximation



Order of g² μ^4

Powers of T

Stationary points

$$\left.\frac{\delta\Gamma}{\delta\bar{\mathcal{D}}}\right|_{\mathcal{D}=\mathcal{D},\mathcal{S}=\mathcal{S}} = 0\,, \qquad \left.\frac{\delta\Gamma}{\delta\bar{\mathcal{S}}}\right|_{\mathcal{D}=\mathcal{D},\mathcal{S}=\mathcal{S}} = 0$$

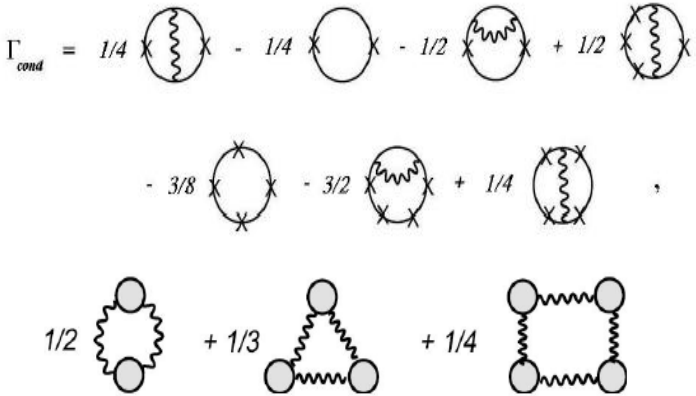
$$\mathcal{D}^{-1} = D^{-1} + \Pi[\mathcal{S}] \qquad \mathcal{S}^{-1} = \mathcal{S}_0^{-1} + \Sigma$$

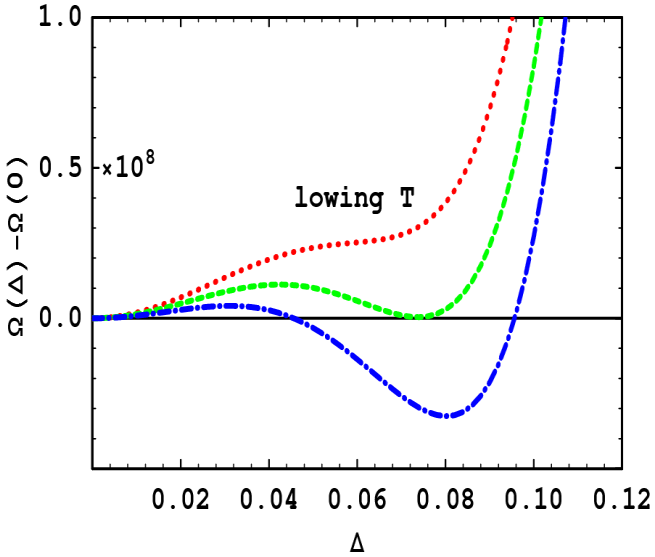
$$\Gamma_2[\bar{\mathcal{D}},\bar{\mathcal{S}}] = -\frac{1}{2}\mathrm{Tr}\{\bar{\mathcal{D}}\Pi[\bar{\mathcal{S}}]\}$$

D. Rischke Prog. Part. Nucl. Phys. 52 197 (2004)

# Gauge field fluc. induce 1st order PT of CSC in dense QCD

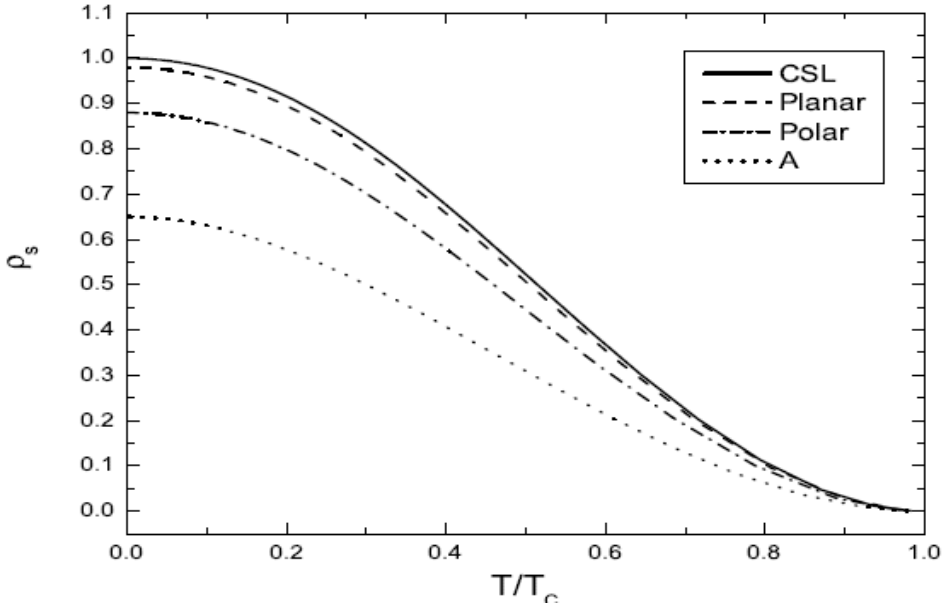
**Ginnakis, Hou, Ren, Rischke, PRL 93 (04) ; PRD73 (06)**




**Introduction of $\Delta^3$ term in free energy by flucts. Inducing 1st order PT in stead of 2nd order PT in MFA**

# Spin 1 CSC in compact star




**Feng, Hou, Ren,Wu, PRL 105(2010)**

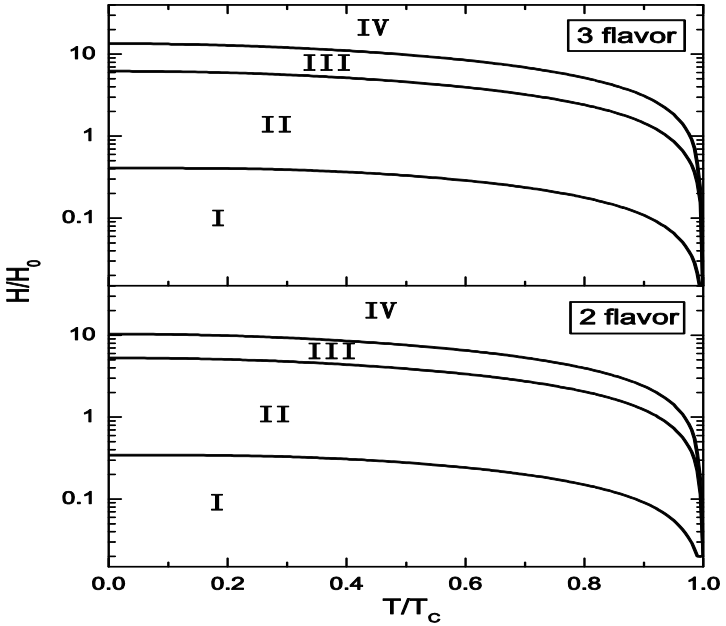
$$f(\theta) = \begin{cases} 1, & \text{for CSL phase} \\ \sqrt{\frac{3}{4}(1+\cos^2\theta)}, & \text{for planar phase} \\ \sqrt{\frac{3}{2}}\sin\theta, & \text{for polar phase} \\ \sqrt{3}\cos^2\frac{\theta}{2}. & \text{for A phase} \end{cases}$$

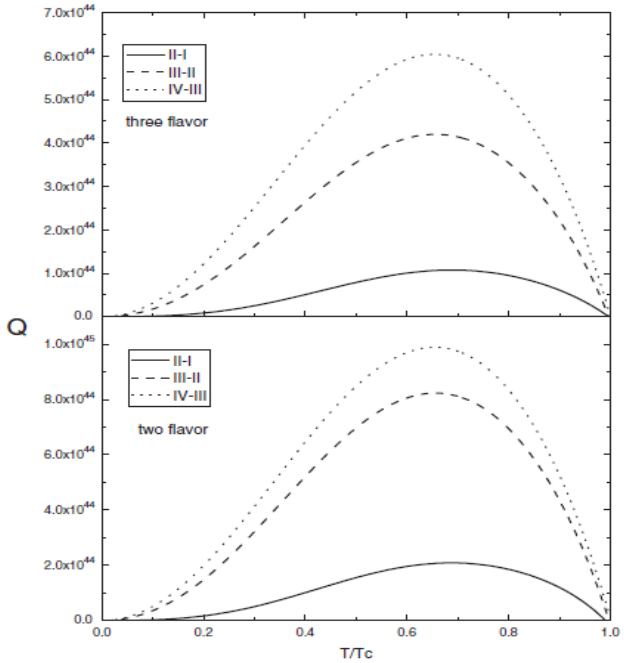
$$E_{\mathbf{k}} = \sqrt{(k-\mu)^2 + \Delta^2 f^2(\theta)}$$

# Nonspherical states in dense QCD with B

H0=5.44×10^14 G, 1.97×10^14 G

| | I | II | III | IV | $T_C(10^{-1}$ MeV) |
|---|---|---|---|---|---|
| Two-flavor | $CSL_u$, $CSL_d$ | $(polar)_u$, $(planar)_d$ | $(normal)_u$, $(polar)_d$ | $(normal)_u$, $(normal)_d$ | 1.35 |
| Three-flavor | $CSL_u$, $CSL_{d,s}$ | $(polar)_u$, $(planar)_{d,s}$ | $(normal)_u$, $(polar)_{d,s}$ | $(normal)_u$, $(normal)_{d,s}$ | 0.49 |



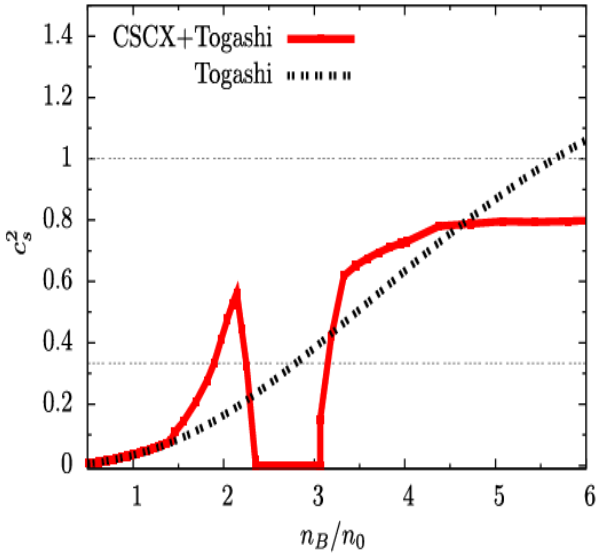



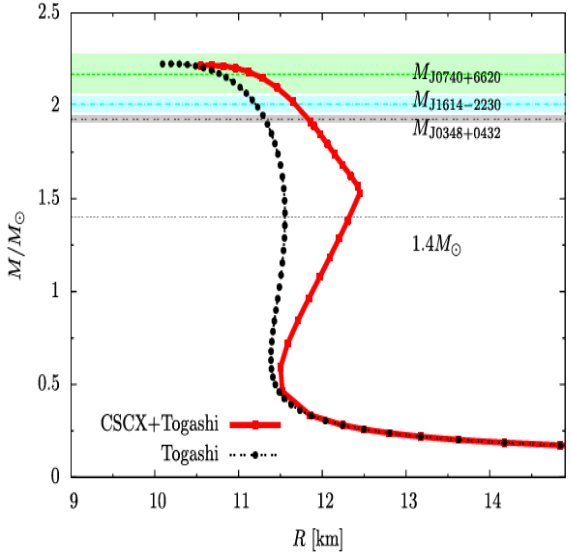

Feng, Hou, Ren,Wu, PRL 105(2010)

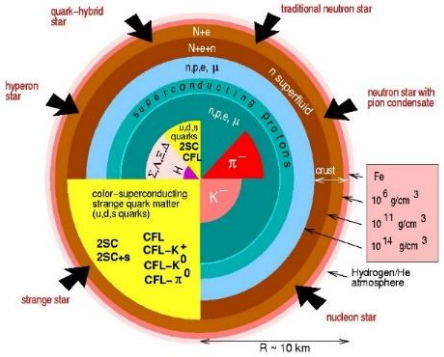
Wu, He, Hou, Ren, PRD84 (2011)

# EoS of dense QCD matter and NSs

**T. Kojo, DF Hou, Okafor, Togashi.**
**PRD 104 (2021) 063036**



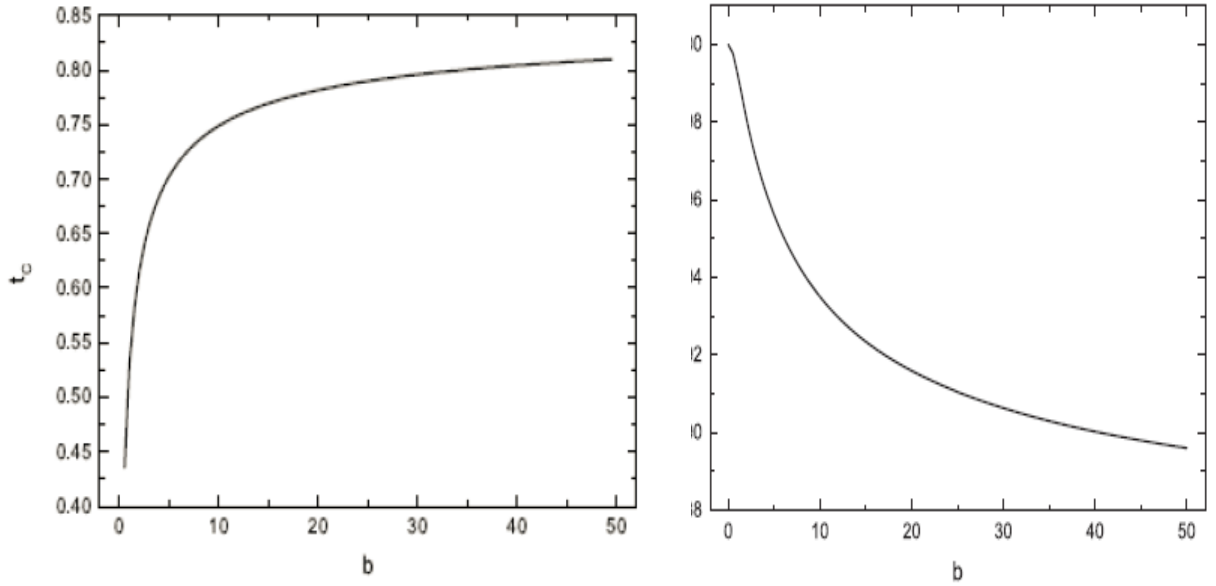



# Magnetic ( Inverse ) BEC catalysis at W/S coupling

**Feng, Hou, Ren PRD 92(2015)**

**Dimensional reduction & enhancement of fluctuation**




**The ratio of critical tc versus magnetic field b at weak and strong coupling**

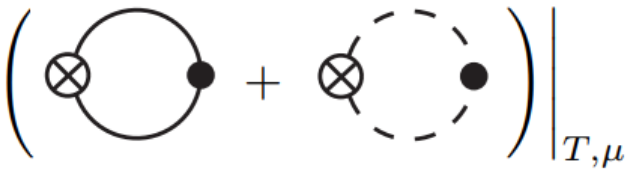
# FRGE and phase structute

## FRG flow equation

- For continuum field theory
- Non-perturbative
- (known) microscopic laws → complex macroscopic phenomena
- Flow from classical action S[φ] to effective action Γ[φ]
- Scale dependent effective action $\Gamma_k[\varphi]$

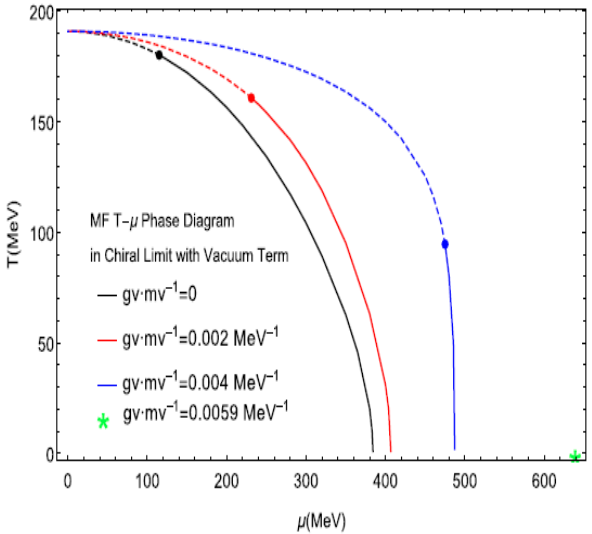
Wetterich, PLB301, 90 (1993).

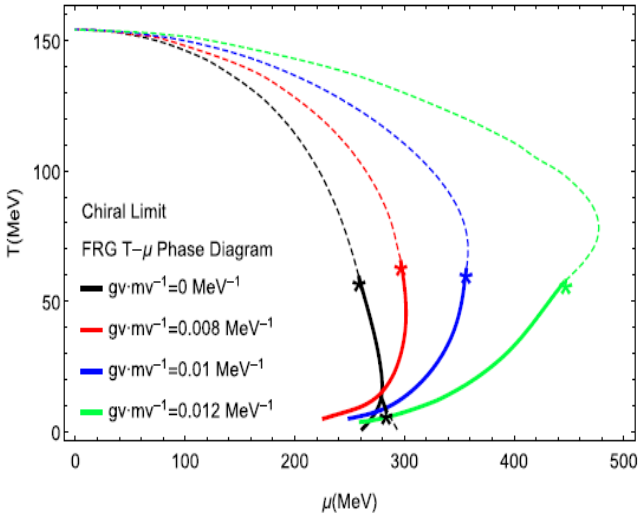
$$\partial_k \Gamma_k = \frac{1}{2} \mathrm{Tr} \left[ \frac{\partial_k R_k}{\Gamma_k^{(2)} + R_k} \right]$$



# FRGE study of phase diagram: Flucts on CEP

Zhang, Hou , Kojo, Qin, PRD96 (2017)




Nematic Isotropic (NI) Puzzle with FRGE

Qin, Hou, Huang, Li, Zhang, PRB98, (2018)

# FRGE study of the quark-meson model with ω and ρ vector mesons

- **A puzzling feature:** FRG studies often show a **back-bending** of the phase boundary at low temperature —an unphysical minus entropy.
- This behavior may result from pairing instabilities and insufficient regulation in IR.

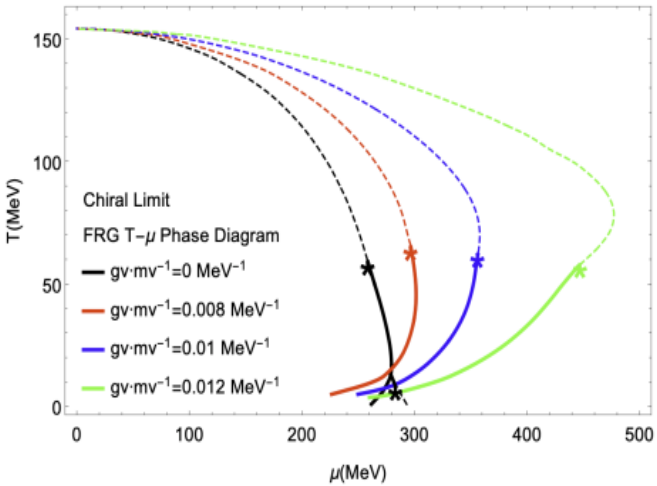



FIG. 2: The phase diagram of the FRG with different vector couplings. Dashed (solid) lines show the second (first) order phase transition. Stars show the tri-critical end point (TCP).

*Zhang et al., Phys. Rev. D* **96** *no.* 11 (2017)

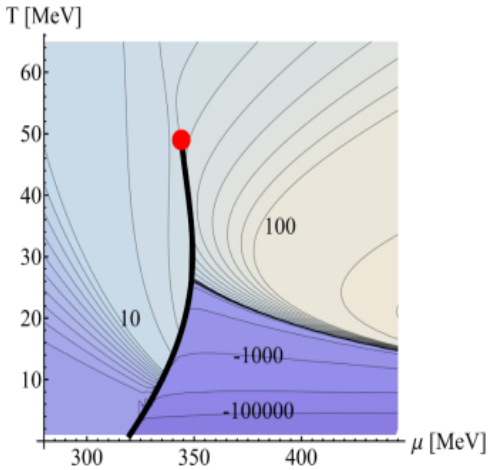
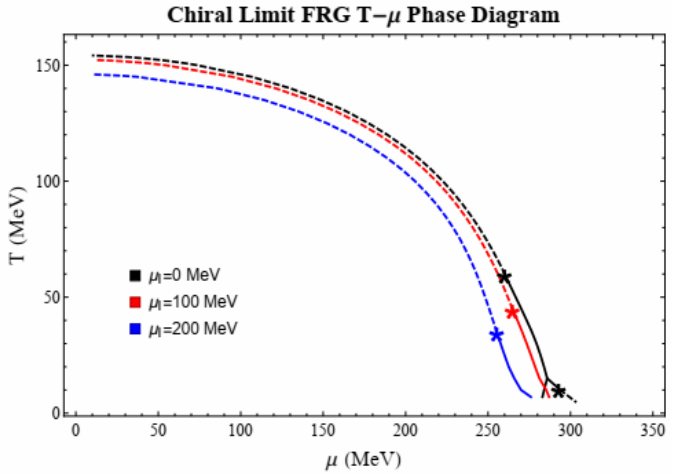
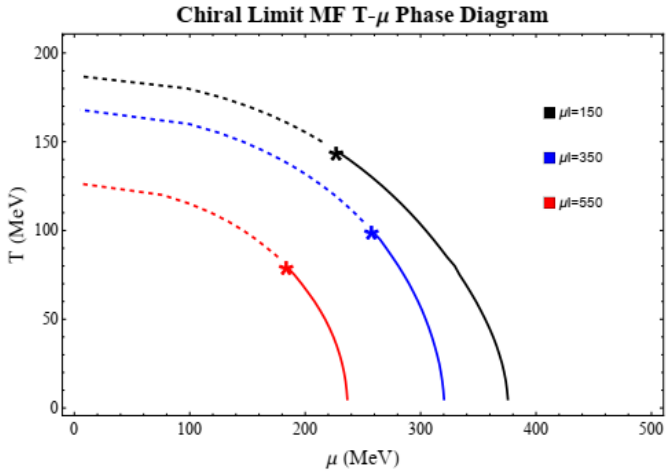



FIG. 4: (color online) The dimensionless entropy density, $s/T^3$, is shown as a contour plot together with the CEP and the first-order phase transition line, cf. Fig. 3. The inset numbers denote the corresponding values of $s/T^3$. Beyond the first-order line, a regime with negative entropy density is found.

*Tripolt et al., Phys. Rev. D* **97** *no.* 3 (2018)

Osman， Hou, Wang， Zhang， EPJC（2025）




- FRG:
  - **Sensitive to isospin chemical potential** $\mu_I$ and vector meson interactions.
  - Inclusion of $\mu_I$ and $\rho$ meson **suppresses back-bending**.
  - Tricritical point (TCP) shifts to lower temperature and chemical potential.
  - Shows **weaker first-order transitions** and smoother crossovers at larger $\mu_I$.
- MF: As $\mu_I$ increases, the TCP moves to **lower temperature** and **lower quark chemical**

# Strong Coupling Expansion of Gluodynamices on a Lattice under Rotation

Sheng Wang,Jun-Xia Chen, De-Fu Hou, Hai-Cang Ren.
arXiv:2505.15487

Gibbs free energy reads

$$\mathcal{F} = -T\ln\mathcal{Q} \qquad \mathcal{Q} = \mathrm{Tr}\,\exp[-\frac{1}{\mathrm{T}}(\mathrm{H}-\omega \mathrm{J_z})]$$

For a slow rotation, we have

$$\mathcal{F}[\mathcal{W},T] = \mathcal{F}^{(0)} - \frac{1}{2}I\omega^2 + O(\omega^4) = \mathcal{F}^{(0)} - \frac{v^2}{2R^2}I + O(\omega^4)$$

The transition temperature to the leading order correction by a small linear speed $v = \omega R$ at the boundary is given by

$$T_d = T_d^{(0)}(1 + Bv^2)$$

The symmetry breaking solution

$$\mathcal{W} = \mathcal{W}_0 + v^2\mathcal{W}_1$$

our analysis revealed that determine the coefficient $B$ independent of the strong coupling approximation, i.e.

$$\boldsymbol{B = -\frac{\Delta I}{2R^2 L}}$$

where $L$ is the latent heat and $\Delta I$ is the discontinuity in the moment of inertia at the transition.

# Strong Coupling Expansion of Gluodynamices on a Lattice under Rotation

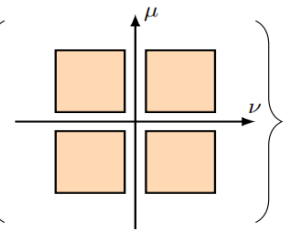
The action in the rotating background is[1]

$$\boldsymbol{S_G} = \frac{2N_c}{g^2}\sum_X [(1-\rho^2\omega^2)\left(1-\frac{1}{N_c}\mathrm{ReTr}\bar{U}_{xy}\right)+(1-y^2\omega^2)\left(1-\frac{1}{N_c}\mathrm{ReTr}\bar{U}_{xz}\right)$$

$$+(1-x^2\omega^2)\left(1-\frac{1}{N_c}\mathrm{ReTr}\bar{U}_{yz}\right)+3-\frac{1}{N_c}\mathrm{ReTr}(\bar{U}_{xt}+\bar{U}_{yt}+\bar{U}_{zt})$$

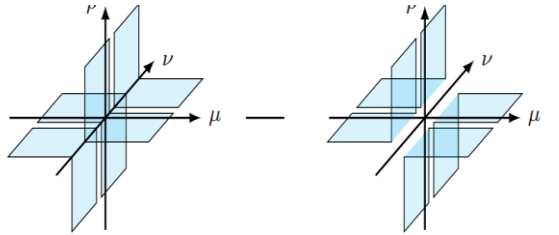
$$+\frac{1}{N_c}\mathrm{ReTr}\left(iy\omega\left(\bar{V}_{xyt}+\bar{V}_{xzt}\right)-ix\omega\left(\bar{V}_{yxt}+\bar{V}_{yzt}\right)+xy\omega^2\bar{V}_{xzy}\right)]$$

$$\overline{U}_{\mu\nu} = \frac{1}{4}\left\{\right.$$




$$\left.\right\}$$

$$\overline{V}_{\mu\nu\rho} = \frac{1}{8}\left\{\right.$$

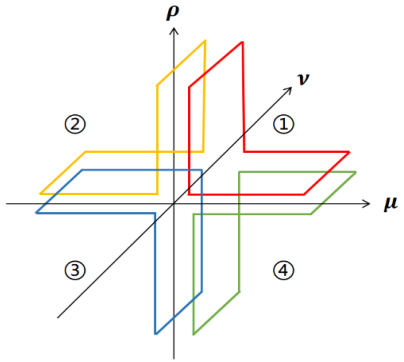



$$\left.\right\}$$

Spatial coordinate average $\sum_X \rightarrow \sum_P$ Plaquatte average[2]

$$\boldsymbol{S_G} = \mathcal{S}_0 - \frac{1}{g^2}(E_0+\omega E_1+\omega^2 E_2)$$

$$\mathcal{Q} = \int \prod_{x,\mu} dU_\mu(x) e^{-\mathcal{S}_G[U]}$$





[1] A. Yamamoto , Y. Hirono. PRL . arXiv:1303.6292.

[2] M. Gross, J. Bartholomew, and D. Hochberg. Report No. EFI- 83-35-CHICAGO, 1983.

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For a slow rotation, we have

$$\mathcal{F}[\mathcal{W},T] = \mathcal{F}^{(0)} - \frac{1}{2}I\omega^2 + O(\omega^4) = \mathcal{F}^{(0)} - \frac{v^2}{2R^2}I + O(\omega^4)$$

The transition temperature to the leading order correction by a small linear speed $v = \omega R$ at the boundary is given by

$$T_d = T_d^{(0)}(1 + Bv^2) \qquad \boldsymbol{B = -\frac{1}{24\sigma a^2} \approx -0.01119}$$

We found that the deconfinement T decreases with the angular velocity, opposite to the tendency revealed in lattice simulation but in line with most of holographic results.
We also found the string tension enhances by rotation.


S Chen, DF Hou, HC Ren, arXiv:2505.15487
K. Fukushima, Y. Shimada, arXiv: 2506. 03560
JC Yang, XG Huang arXiv: 2307.5755
Braguta et. al. arXiv:2102.05084

# De Hass-van Alphen Effect with Rotation

Shu-Yun Yang, Ren-Da Dong, DF Hou, Hai-Cang Ren, PRD 107, 076020 (2023)

finite T

$$P_{\mathrm{dHvA}} = -\frac{(eB)^{\frac{1}{2}}}{2\pi^2 R^2}\sum_{l=1}^{\infty}\frac{1}{l^{3/2}}\sum_{M>0}\frac{\cos\left[\frac{l\pi}{eB}(\mu+M\omega)^2-\frac{\pi}{4}\right]}{\sinh\frac{2l\pi^2 T(\mu+M\omega)}{eB}}.$$

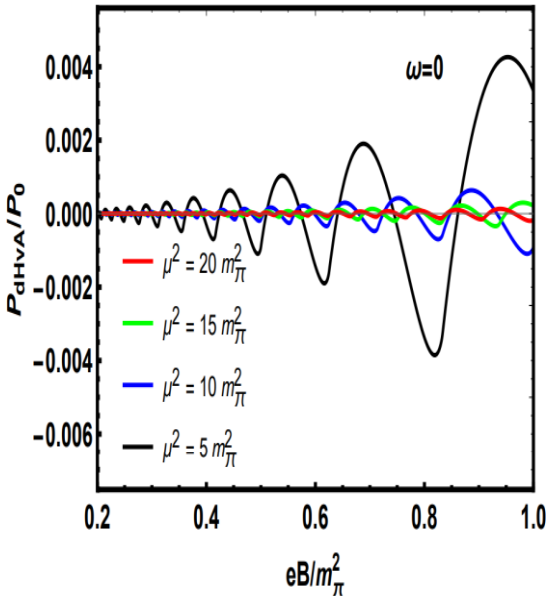
Zero T:

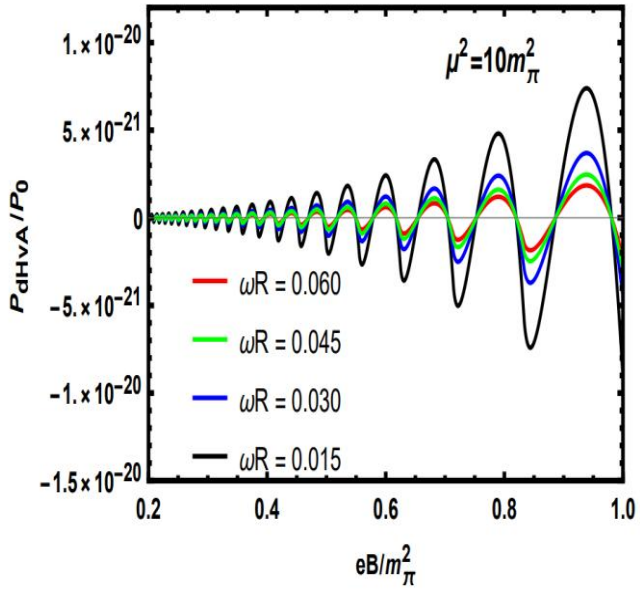
$$P_{\mathrm{dHvA}} = -\frac{(eB)^{\frac{3}{2}}}{4\pi^4 R^2}\sum_{M>0}\frac{1}{\mu+M\omega}\sum_{l=1}^{\infty}\frac{1}{l^{5/2}}\cos\left[\frac{l\pi}{eB}(\mu+M\omega)^2-\frac{\pi}{4}\right]$$

In rotation, the thermodyn Equl. is established under a AM. The equal distrib. of different AM states within a LL is offset by the nonzero AV with higher AM more favored than lower ones, which amounts to lifting the degeneracy of LL. The dHvA oscillation is thereby expected to be reduced by rotation

# De Hass-van Alphen Effect with Rotation

dHvA in NS with rotation (R=1km)

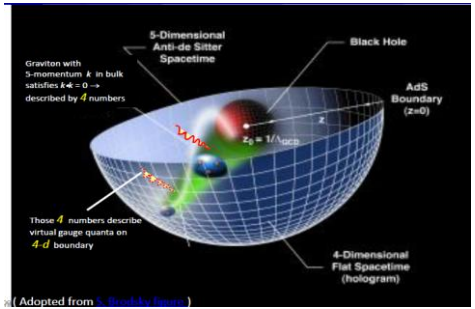



Huge suppression of dHvA oscill.(17 order) due to large size

Shu-Yun Yang, Ren-Da Dong, DF Hou, Hai-Cang Ren, PRD 107, 076020 (2023)

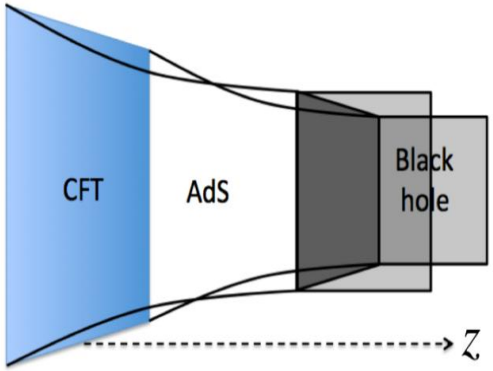
# sQGP matter via AdS/CFT




**4dim. Large-Nc strongly coupled SU(Nc) N=4 SYM ( finite T).**

Maldacena ‘97 ↕ **conjecture**

Witten ‘98




**Type II B Super String theory on AdS5-BH×S5**

Some complicated Field theory calculations become simple “geometric’ problems in higher dimensions

# Phase diagram @2+1 flavor

## ➢ Holographic model:

*[1] R.G. Cai, etc , Phys.Rev.D 106 (2022) 12, L121902 • e-Print: 2201.02004*

### ➢ The action:

$$S_M = \frac{1}{2\kappa_N^2}\int d^5x\sqrt{-g}[\mathcal{R} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{Z(\phi)}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi)],$$

where the potential and kinetic functions read

$$V(\phi) = -12\cosh[c_1\phi] + \left(6c_1^2 - \frac{3}{2}\right)\phi^2 + c_2\phi^6,$$

Capturing the behavior of EOS at zero chemical potential.

$$Z(\phi) = \frac{1}{1+c_3}sech[c_4\phi^3] + \frac{c_3}{1+c_3}e^{-c_5\phi}.$$

Capturing the flavor dynamic.

### ➢ The metric:

$$ds^2 = -e^{-\eta(r)}f(r)dt^2 + \frac{dr^2}{f(r)} + r^2(dx_1^2 + dx_2^2 + dx_3^2),$$

$$\phi = \phi(r), \qquad A_t = A_t(r),$$

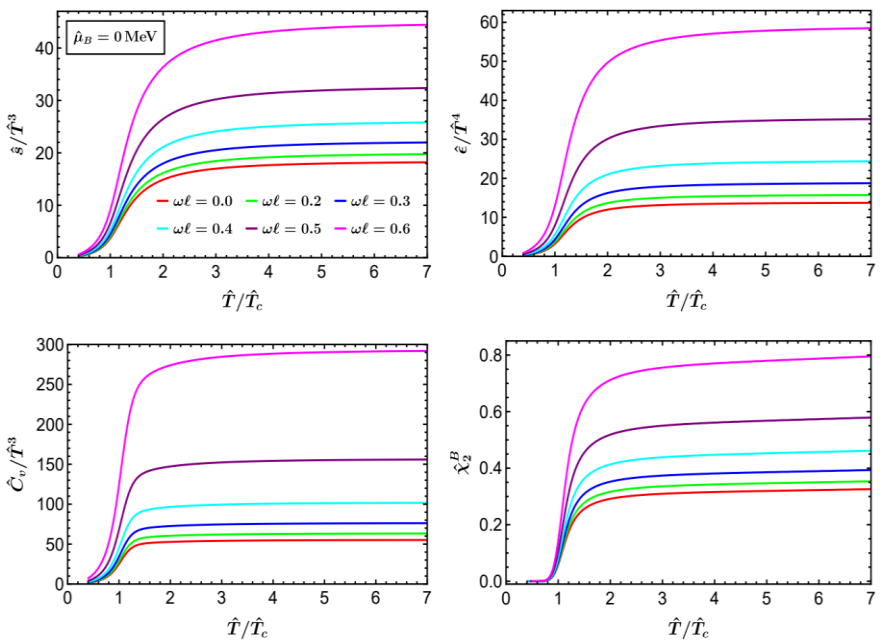
### ➢ The Hawking temperature and entropy density:

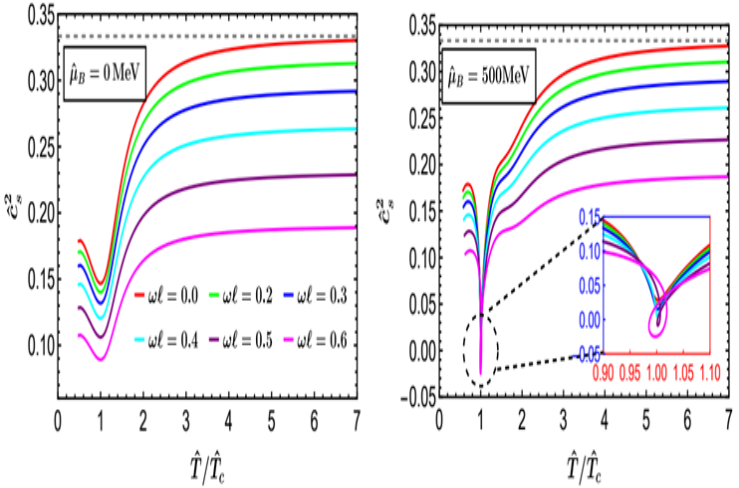
$$T = \frac{1}{4\pi}f'(r_h)e^{-\eta(r_h)/2} \qquad s = \frac{2\pi}{\kappa_N^2}r_h^3.$$

effective Newton constant

# Phase diagram @2+1 flavor

- Thermodynamics *with rotation*:

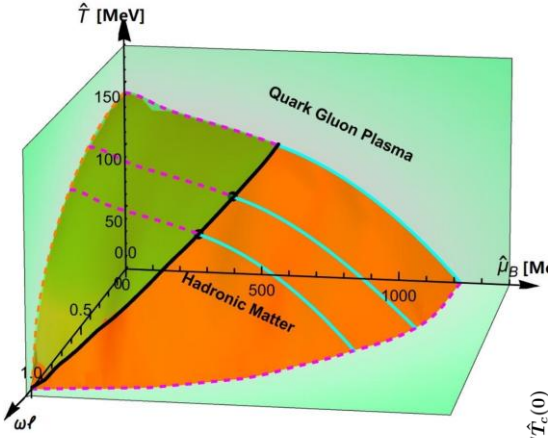



*Yan-Qing Zhao, Song He, Defu Hou, Li Li, Zhibin Li, JHEP 04 (2023) 115 • e-Print: 2212.14662*

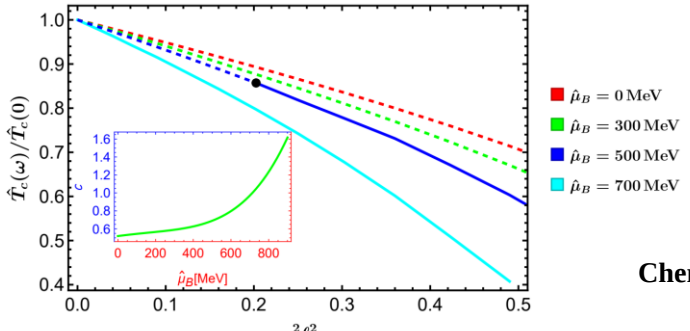
## ➢ 2+1 flavor:

- ✓ **black solid line:** denoting the location of CEP.
- ✓ At high $\hat{T}$ and small $\hat{\mu}_B$: **Being the smooth crossover.**
- ✓ At low $\hat{T}$ and large $\hat{\mu}_B$: **Being 1st-order transition.**
- ✓ $\omega \uparrow \Rightarrow \hat{T}_c \downarrow,\ \hat{\mu}_c \downarrow, \hat{T}_{cep} \downarrow,\ \hat{\mu}_{cep} \downarrow.$



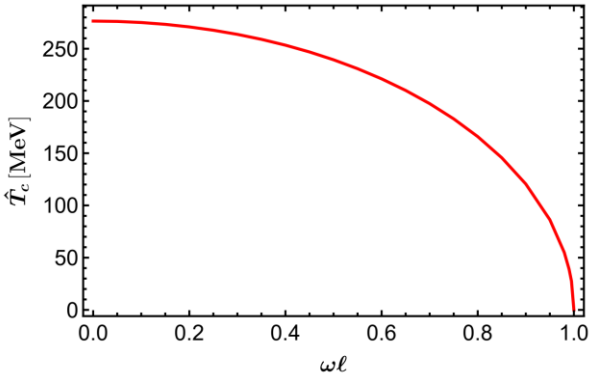

$$\hat{T}_c(\omega)/\hat{T}_c(0) \approx 1 - c\,\omega^2$$

- ✓ At finite $\hat{\mu}_B$ and smaller $\omega$.
  The value of c depends on $\hat{\mu}_B$.



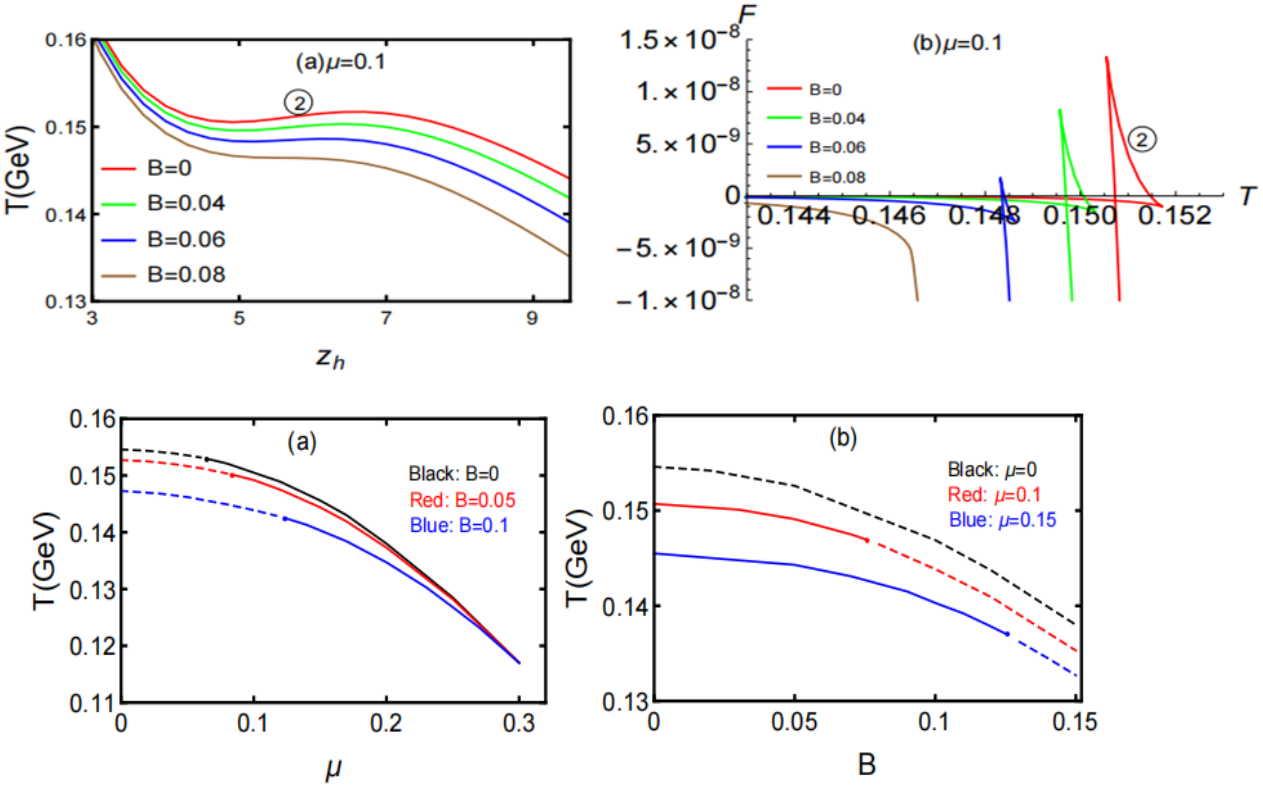

## ➢ Pure gluon($\hat{\mu}_B = 0$):

**Analytically:** $\hat{T}_c(\omega) = T_c\sqrt{1-\omega^2\ell^2}$



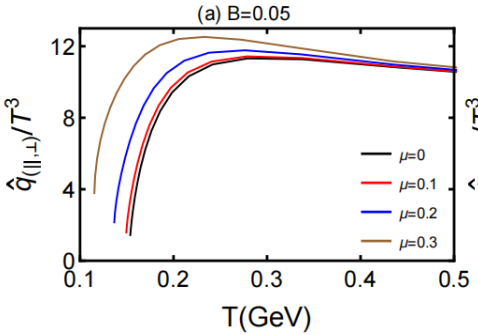

Chen, Zhang, Li, Hou , M.Huang ,JHEP 07 (2021) 132

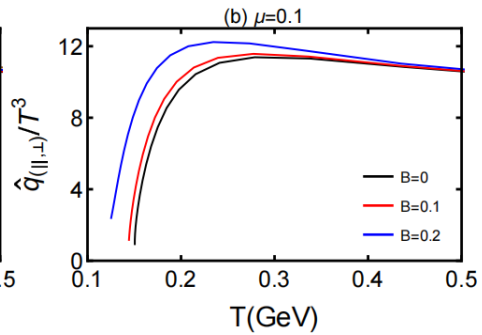
# Phase Structure with magnetic field

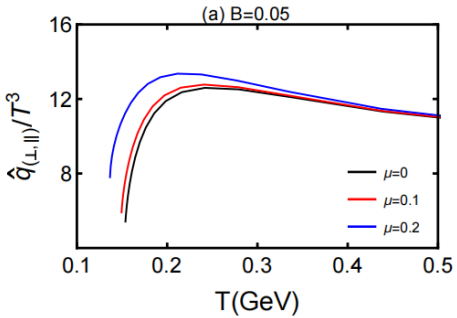


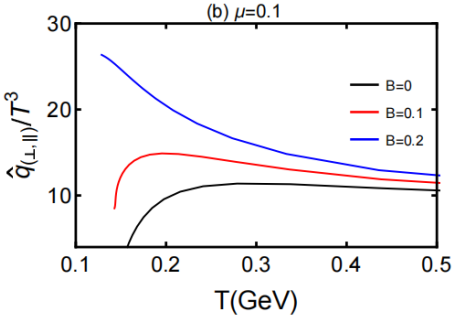

Zhou-Run Zhu, De-fu Hou, Phys.Rev.D 110 (2024) 6, 066010

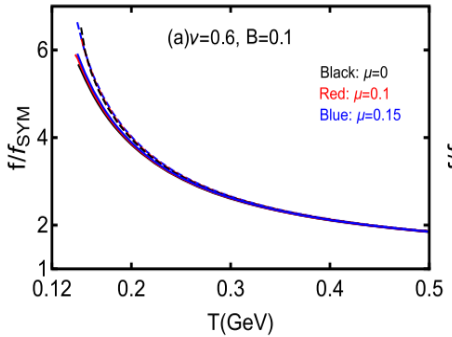
# Jet quenching around Tc with B

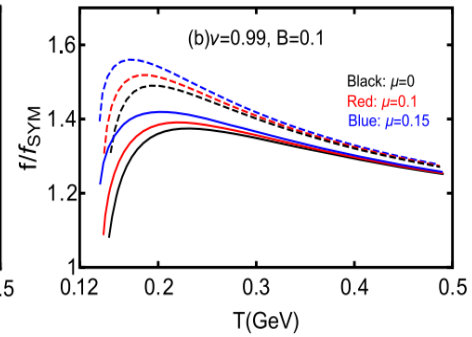



$\hat{q}_\perp > \hat{q}_\parallel$ ; μ、B enhance $\hat{q}$

$\hat{q}$ enhenced around $T_c$ agrees with Laticce results(150-250MeV);

**Zhou-Run Zhu, De-fu Hou, Phys.Rev.D 110 (2024) 6, 066010 .**

# Dragging force

J.X. Chen, DH, H.C Ren , JHEP03 (2024) 171 , arXiv: 2308.08126

Components of drag force

$$\frac{dp_\mu}{dt} = -\frac{1}{2\pi\alpha'}\frac{\partial \mathcal{L}}{\partial(\frac{\partial X^\mu}{\partial r})}$$

Drag force of $\mu$ component

Azimuthal $$\frac{dp_\phi}{dt} = -\frac{\pi\sqrt{\lambda}T^2}{2}\omega l_0^2\frac{1}{\sqrt{1-v^2}}$$

Radial $$\frac{dp_l}{dt} = -\omega^2 l_0\frac{1}{\sqrt{1-v^2}}[\frac{T\sqrt{\lambda}}{2(1-v^2)^{\frac{1}{4}}} - m_{rest}]$$ → cut off $r_m = 2\pi\alpha' m_{rest}$

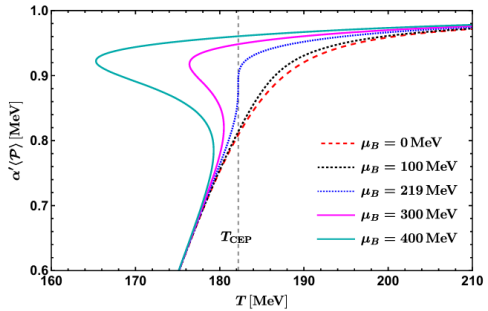
Longitudinal $$\frac{dp_z}{dt} = -\frac{\pi\sqrt{\lambda}T^2}{2}\frac{v}{\sqrt{1-v^2}}(1+\frac{\omega^2 l_0^2}{2}\frac{1}{1-v^2})$$ $\propto \omega^2$

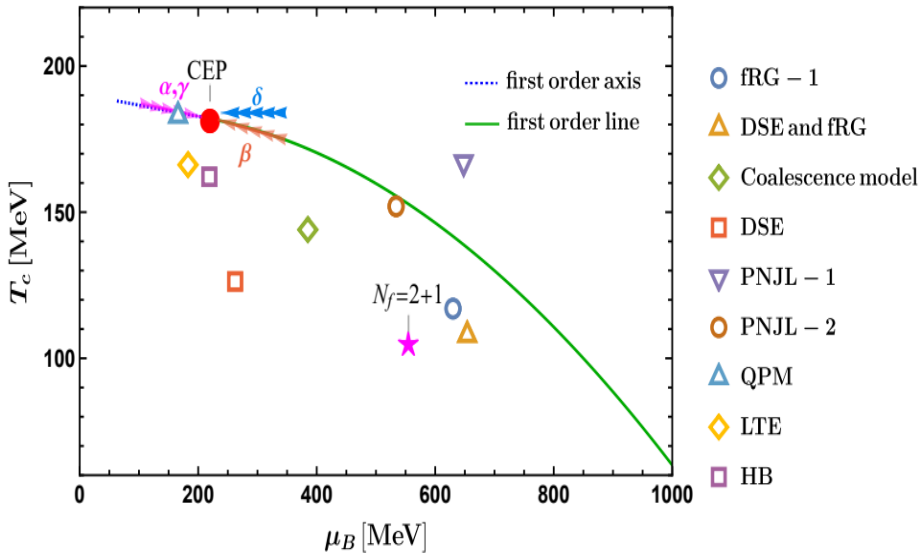
$\omega = 0$ ⟹ $\frac{dp_\phi}{dt} = 0,$ $\frac{dp_l}{dt} = 0,$ $\frac{dp_z}{dt} = -\frac{\pi\sqrt{\lambda}T^2}{2}\frac{v}{\sqrt{1-v^2}}$

*S. S. Gubser, PRD74, 126005 (2006); C. P. Herzog, etc. JHEP 07, 013 (2006).*

# Phase structure and critical phenomena in 2-flavor QCD

Yan-Qing Zhao, Song He, Defu Hou, Li Li, Zhibin Li （ Phys.Rev.D 109 (2024) 8, 086015 ）



Yan-Qing Zhao, Song He, Defu Hou, Li Li, Zhibin Li （ Phys.Rev.D 109 (2024) 8, 086015 ）

**Critical behavior**

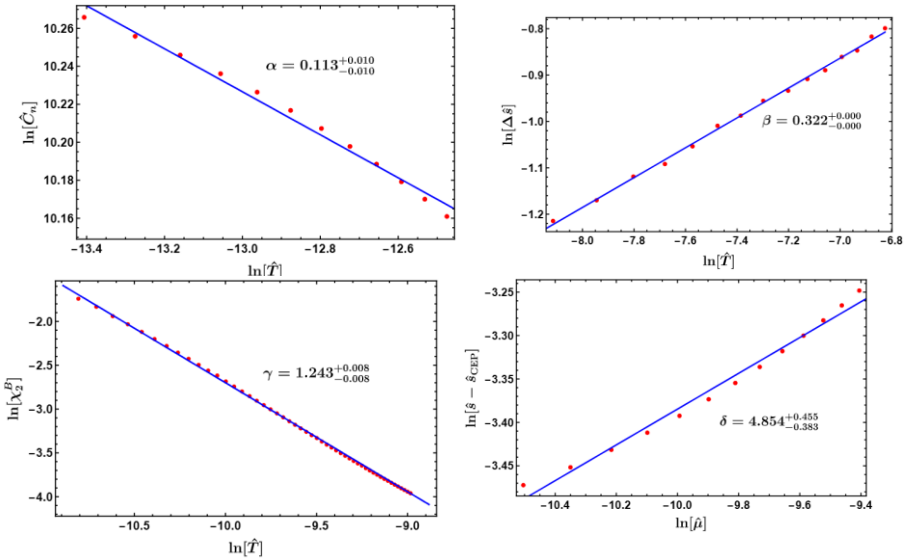
| | Experiment | 3D Ising | Mean field | DGR model | Ours |
|---|---|---|---|---|---|
| $\alpha$ | 0.110-0.116 | 0.110(5) | 0 | 0 | $0.113^{+0.010}_{-0.010}$ |
| $\beta$ | 0.316-0.327 | 0.325±0.0015 | 1/2 | 0.482 | $0.322^{+0.000}_{-0.000}$ |
| $\gamma$ | 1.23-1.25 | 1.2405±0.0015 | 1 | 0.942 | $1.243^{+0.008}_{-0.008}$ |
| $\delta$ | 4.6-4.9 | 4.82(4) | 3 | 3.035 | $4.854^{+0.455}_{-0.383}$ |

$$C_n \equiv T\left(\frac{\partial s}{\partial T}\right)_{n_B} \sim |T - T_{\rm CEP}|^{-\alpha}$$

$$\Delta s = s_> - s_< \sim (T_{\rm CEP} - T)^{\beta}.$$

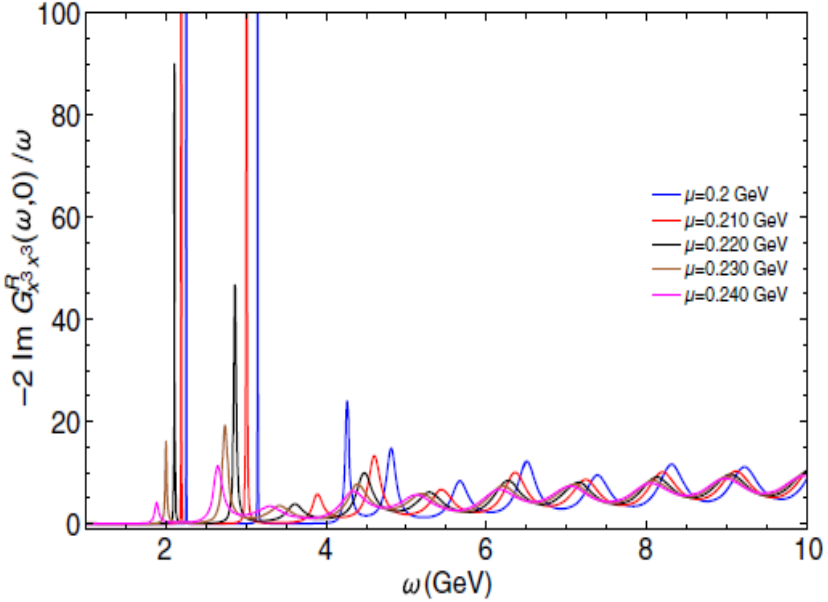
$$\chi_2^B = \frac{1}{T^2}\left(\frac{\partial n_B}{\partial \mu_B}\right)_T \sim |T - T_{\rm CEP}|^{-\gamma}.$$

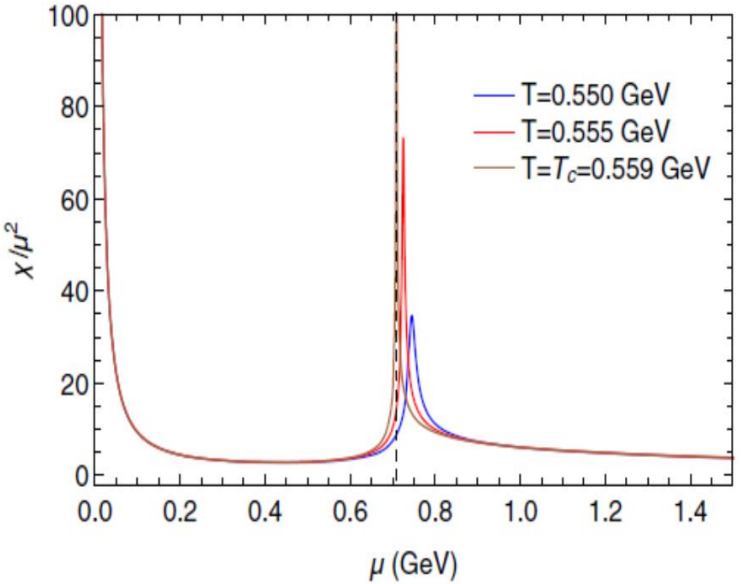
$$s - s_{\rm CEP} \sim |\mu_B - \mu_{\rm CEP}|^{1/\delta}$$



# The spectral function of heavy vector mesons

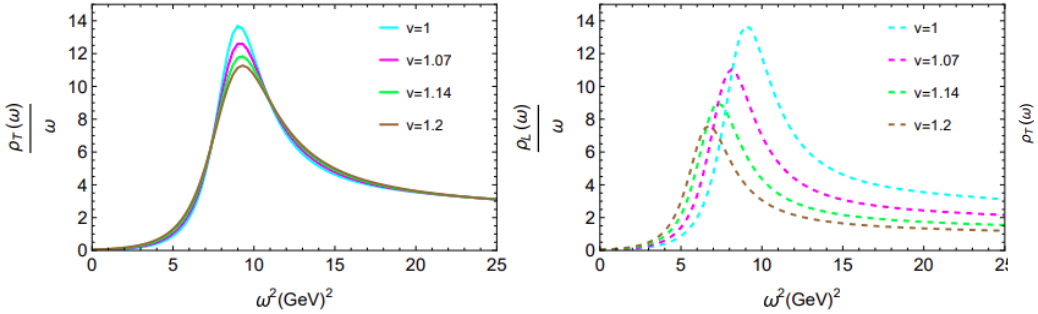
Mamani , Hou, Braga, PRD 105, 126020 (2022)



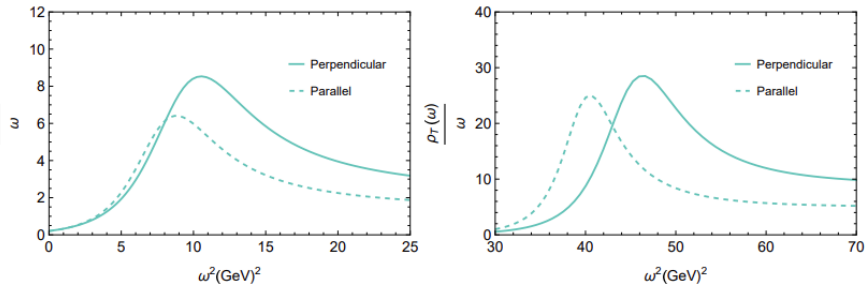



# Spectra functions of J/Ψ and ϒ(1S)

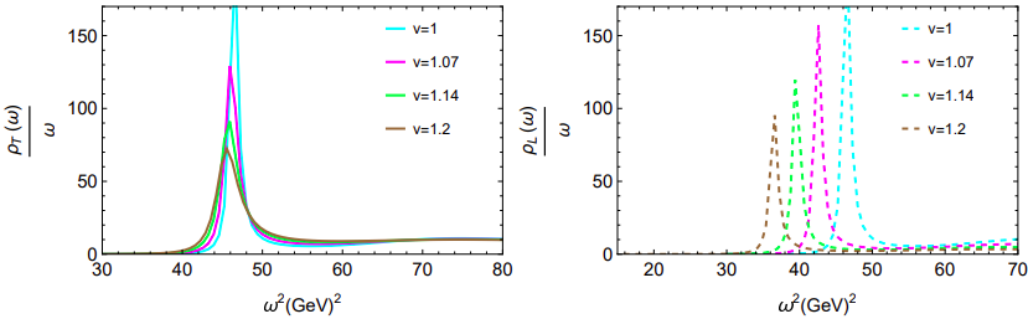
W.B. Chang and De-Fu Hou, Phys. Rev. D 109, 086010 (2024).




The spectral function of J/Ψ with different anisotropic parameters,




The solid line represents the case where the anisotropy is perpendicular to the polarization direction; the dashed line represents the parallel case



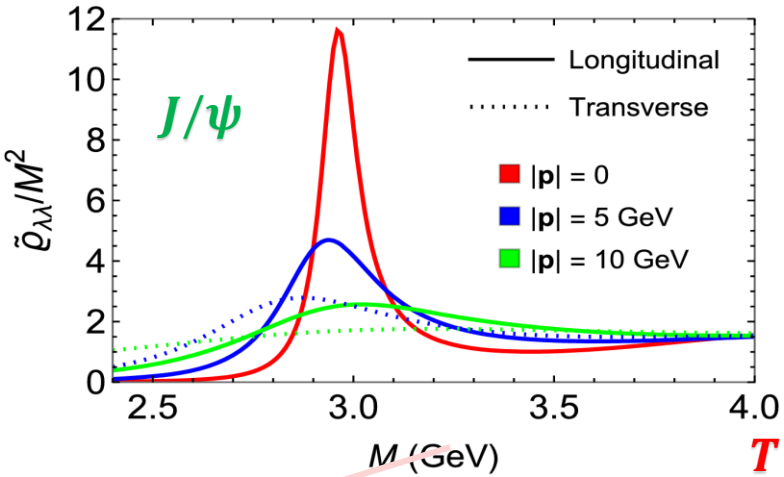

ϒ(1S)

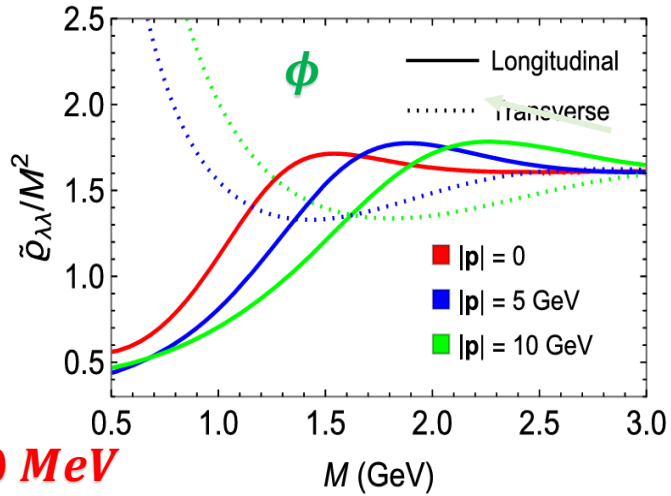
1) Anisotropy accelerates the dissociation of bound states.
2) When the anisotropy is parallel to the polari. direction, this effect becomes even more pronounced.

# Spin alignments of $J/\psi$ and $\phi$ mesons in hot plasma

Motion of $J/\psi$ relative to a thermal background breaks symmetry between longitudinally polarized state and transversely polarized state

**Spectral function**



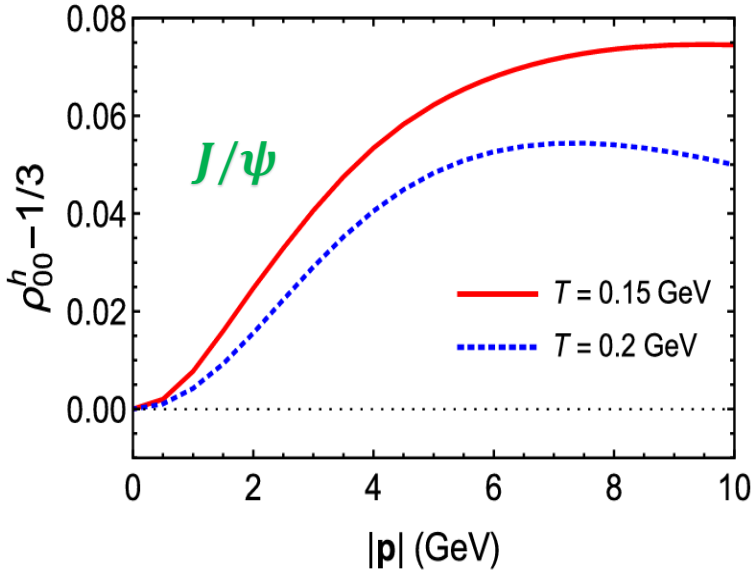

$T = 150\ MeV$

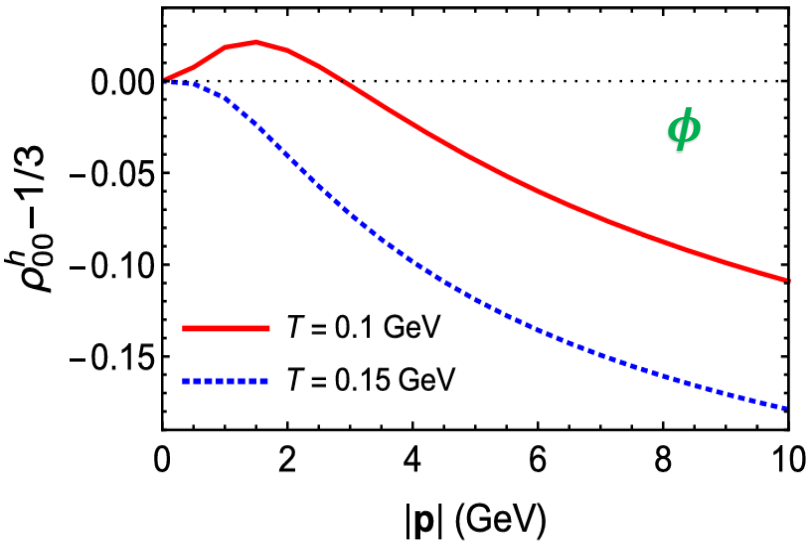
**At zero momentum, spectral functions for all spin states are degenerate because of the rotation symmetry.**

XL Sheng,YQ Zhao SW Li , F Becattini, DF Hou PRD 110 (2024) 056047

# Spin alignment in the helicity frame

XL Sheng,YQ Zhao SW Li , F Becattini, DF Hou PRD 110 (2024) 056047




**A positive deviation from $1/3$, corresponding to a negative $\lambda_\theta$ parameter.**

**A negative deviation from $1/3$, absolute value becomes larger at larger $|p|$.**

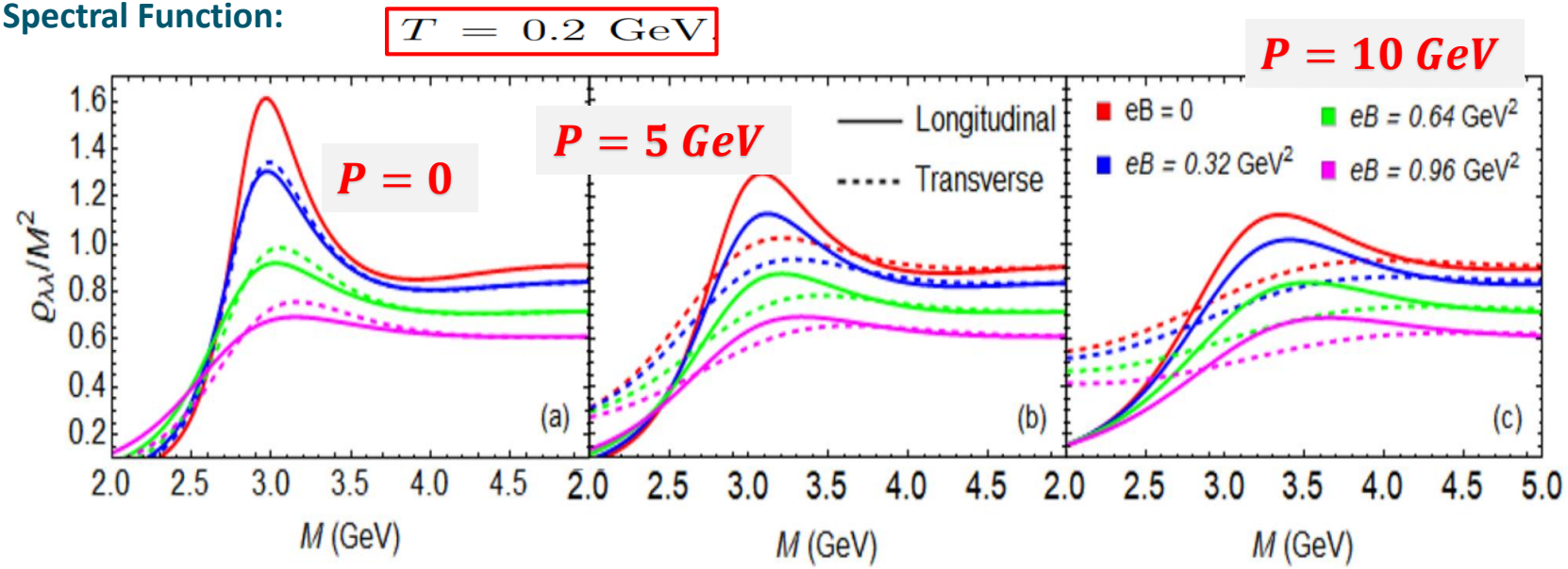
**$\rho_{00}^h$ at $T = 0.1$ GeV has a nonmonotonic dependence to $|p|$.**

# $J/\psi$ meson in magnetized plasma

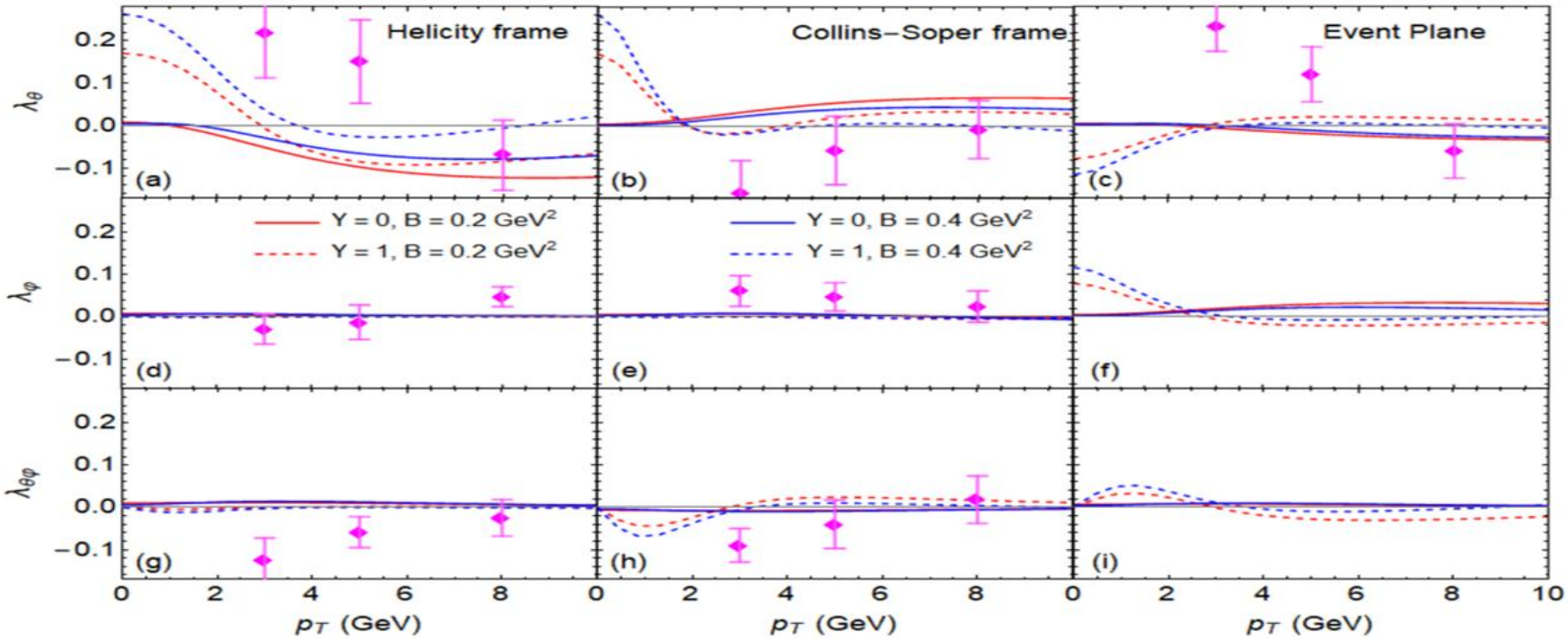
- Magnetic field parallel to momentum

Yan-Qing Zhao ,Xin-Li Sheng ,Si-Wen Li DF Hou , JHEP08 (2024)070

- Spectral Function:




A nonzero magnetic field or a nonzero momentum will induce a separation between longitud. transversely polarized modes.




For the helicity frame and the Collins-Soper frame, we find that the $\lambda_\theta$ parameter is dominant when measuring along the event plane direction, all three parameters $\lambda_\theta^{\mathrm{EP}}$, $\lambda_\varphi^{\mathrm{EP}}$, and $\lambda_{\theta\varphi}^{\mathrm{EP}}$ are of the same order.

ALICE Collaboration, S. Acharya et al., Phys. Rev. Lett. 131 no. 4,(2023) 042303

# Summary

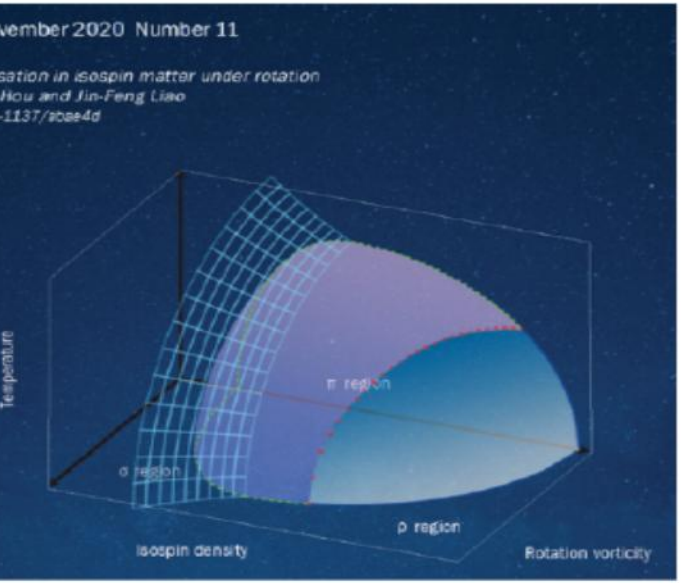
**Properties of strongly interacting matter under extreme conditions are very interesting!**

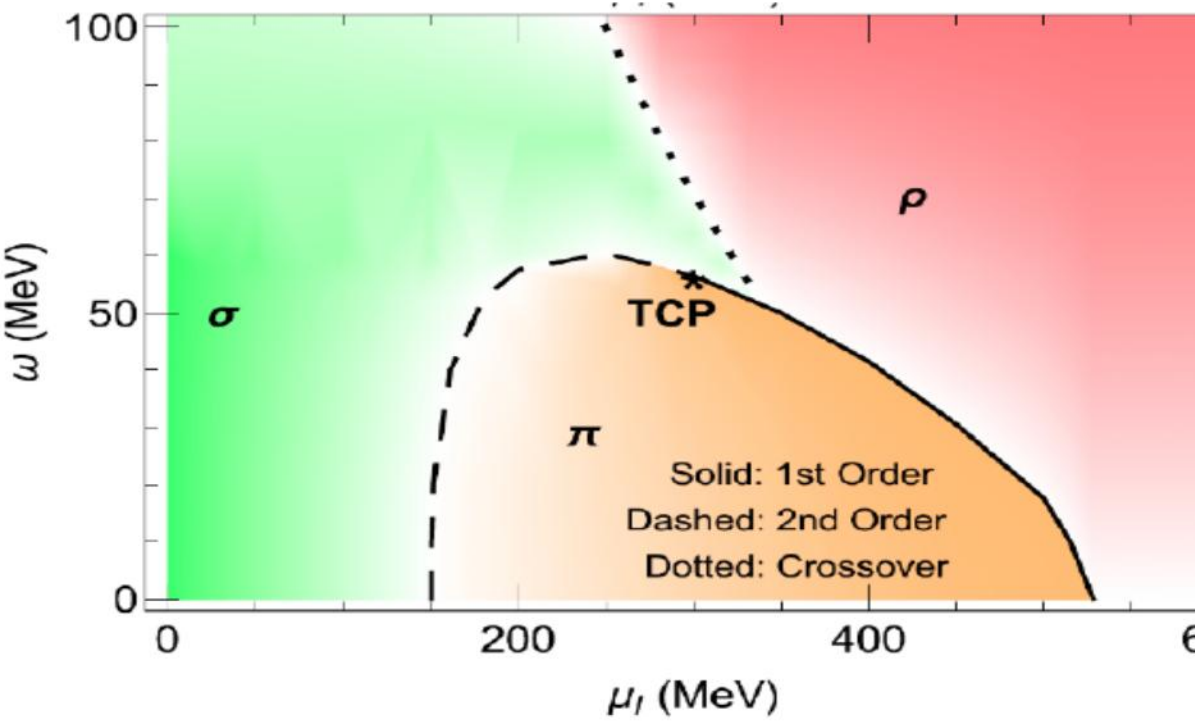
- **QCD Phase diagram under rotation and Magnetic field**
- **Transport properties of rotating magnetized matter**
- **Spectral function and the spin alignment of vector meson**
- **How to understand the different results of rotation from lattice？（Polarization induced by Magnetic field and rotation?)**

**Thank you very much for your attention!**

**Static isospin matter: pion superfluidity;**

**sospin matter under rotation: emergence of rho condensat**



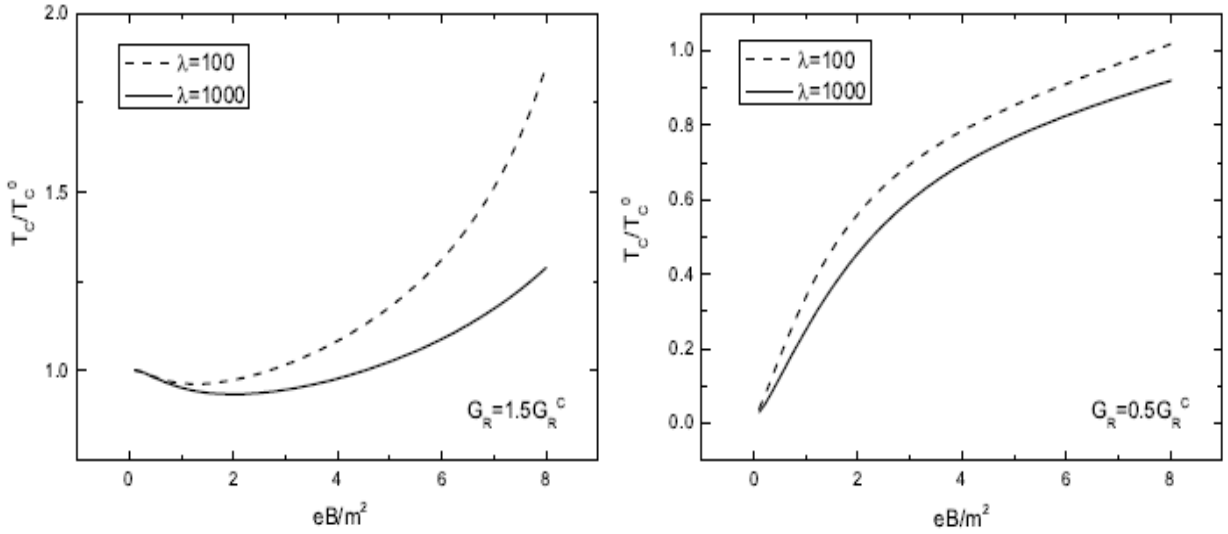




**Rich phase structures found;**

**Could be relevant to low energy**

**or neutron star matter**

# Magnetic ( Inverse ) BEC catalysis at W/S coupling




Condensation temperature versus the dimensionless magnetic field

Feng, Hou, Ren , Wu, _**PRD 93 (2016)085019**