Phase structure of dense QCD matter with magnetic field and Rotation

Defu Hou

Central China Normal University, Wuhan

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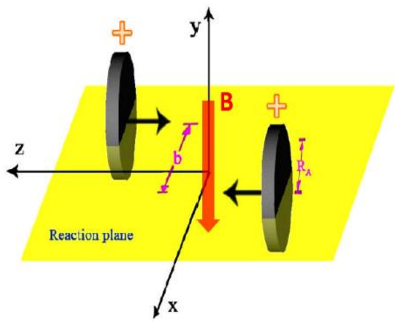
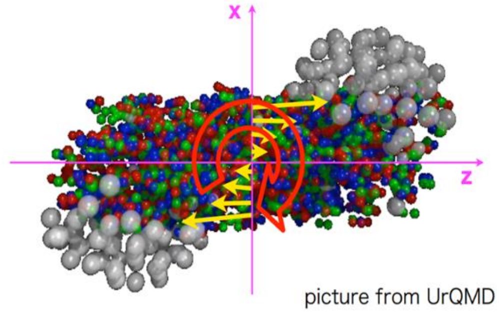
Quarks and compact stars , Busan , Sep 26-28, 2019

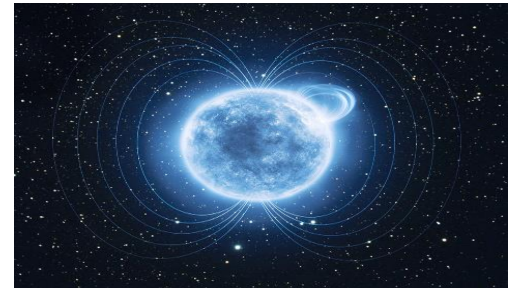
Outlines

- Motivations
- Phase structures with magnetic field
- Rotation effects on phase structures
- Summary

Phase structure under new extrem condition





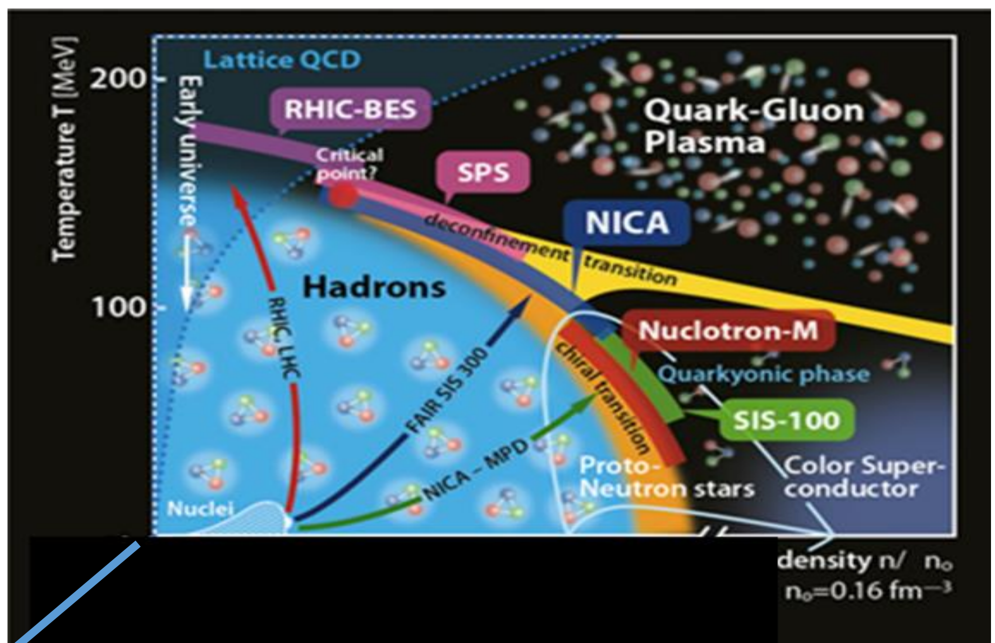


Strongest EM fields

Largest local rotation

What are their effects on the QCD phase structure

Explore the new dimensions of the QCD phase diagram

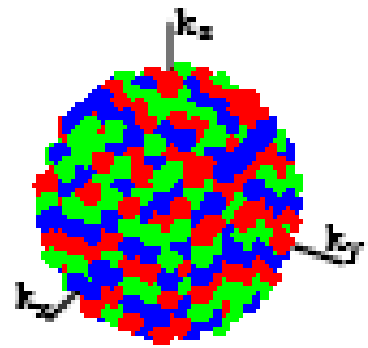


B, ω, E, ni…

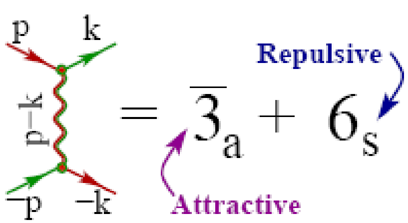
Color Super-Conductivity (CSC)

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)

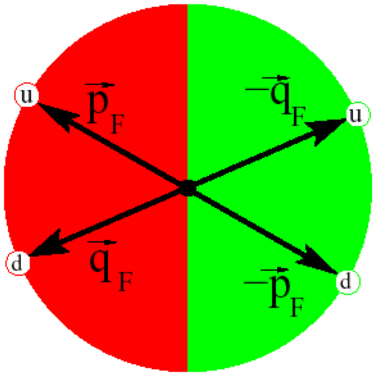
Phase structures in CSC

- BSC-like pairing

J=0: 2SC: u_r, d_r, u_g, d_g

CFL: all flavor and color

M. Alford, K. Rajagopal and F. Wilczek, NPB 537, 443 (1999)



J=1: CSL

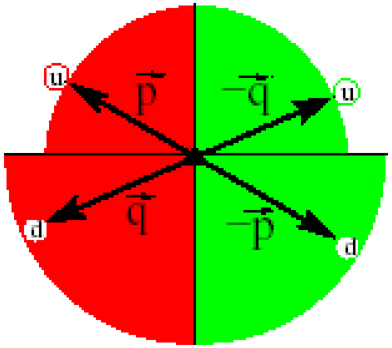
T. Schaefer, PRD 62, 094007 (2000)
A. Schmitt, PRD 71, 054016 (2005)

- Non-BCS pairing

gapless CSC

LOFF

……

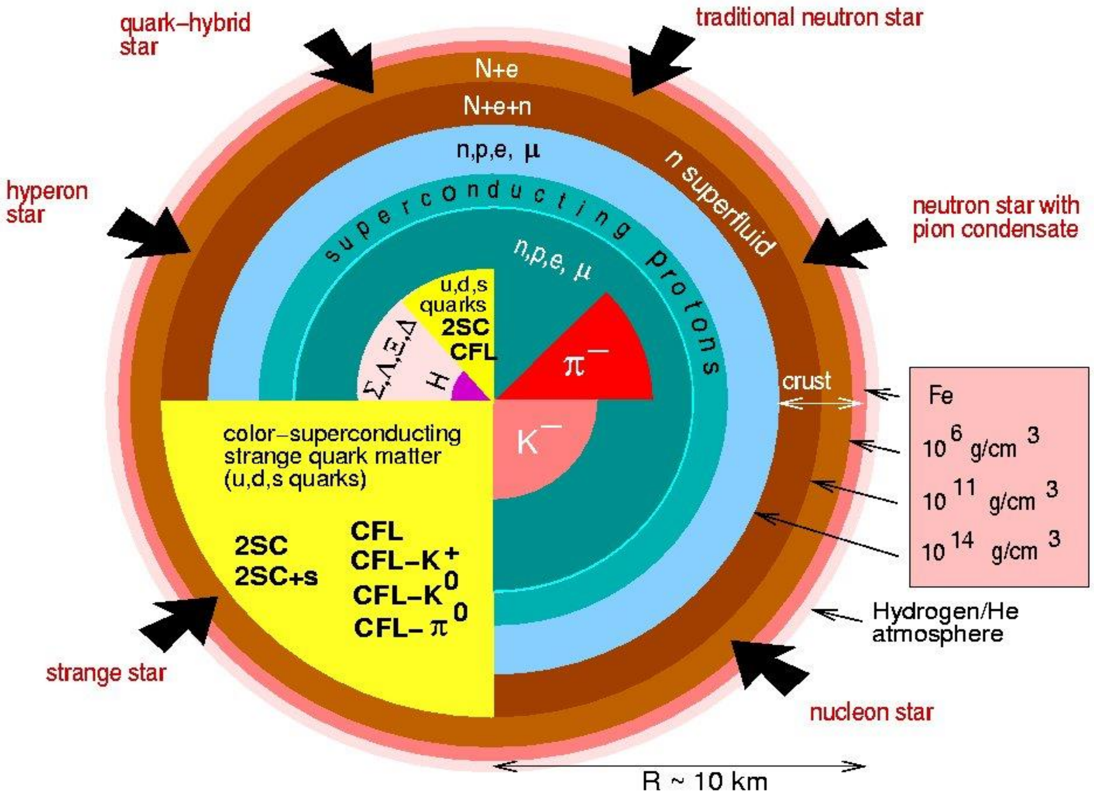


Shovkovy and M. Huang, PLB 546, 205 (2003)
M. Alford et al., PRL 92, 222001 (2004)
M. Alford et al., PRD 63, 074016 (2001)
…….

CSC in a compact star

Profile of neutron star

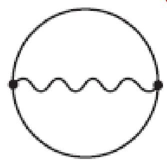
Webber, astro-ph/0407155



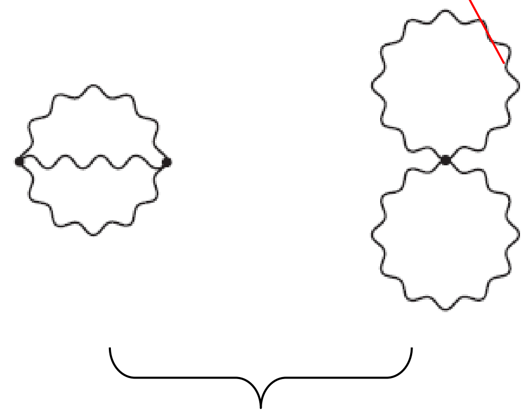
CJT effective action of QCD

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

2-loop approximation



Order of $g^2\ \mu$^4



Powers of T

Stationary points

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

$$\Downarrow \qquad \Downarrow$$

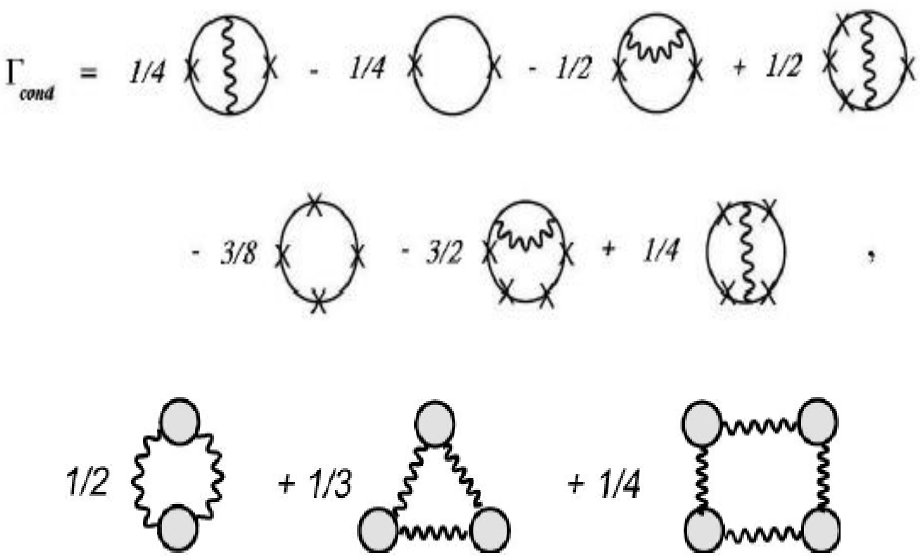
$$\mathcal{D}^{-1} = D^{-1} + \Pi[\mathcal{S}] \qquad \mathcal{S}^{-1} = \mathcal{S}_0^{-1} + \Sigma$$

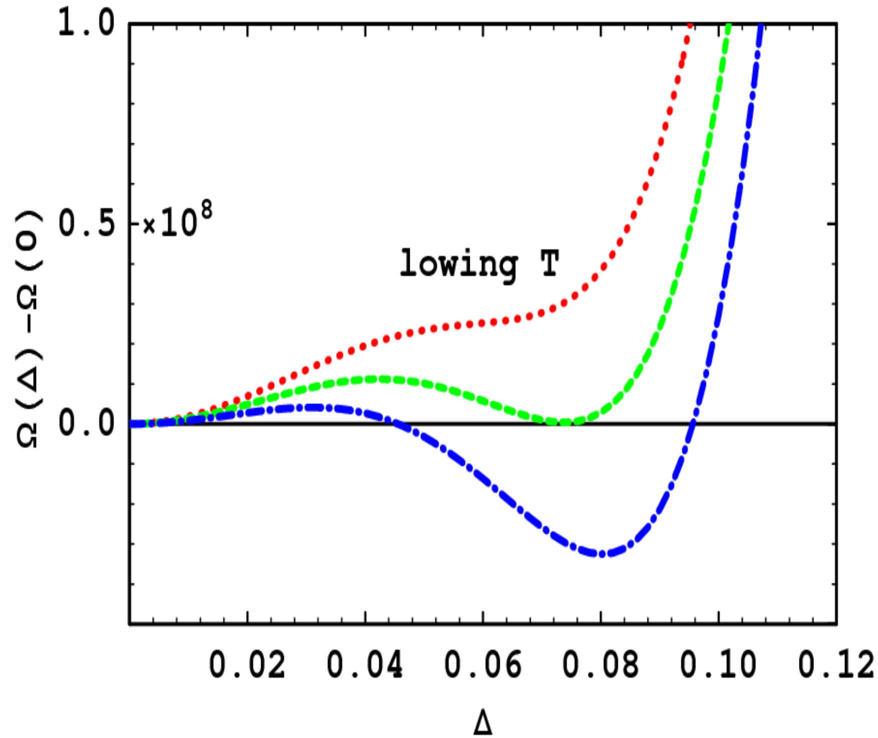
$$\Gamma_2[\bar{\mathcal{D}},\bar{\mathcal{S}}] = -\frac{1}{2}\mathrm{Tr}\{\bar{\mathcal{D}}\,\Pi[\bar{\mathcal{S}}]\}$$

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

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

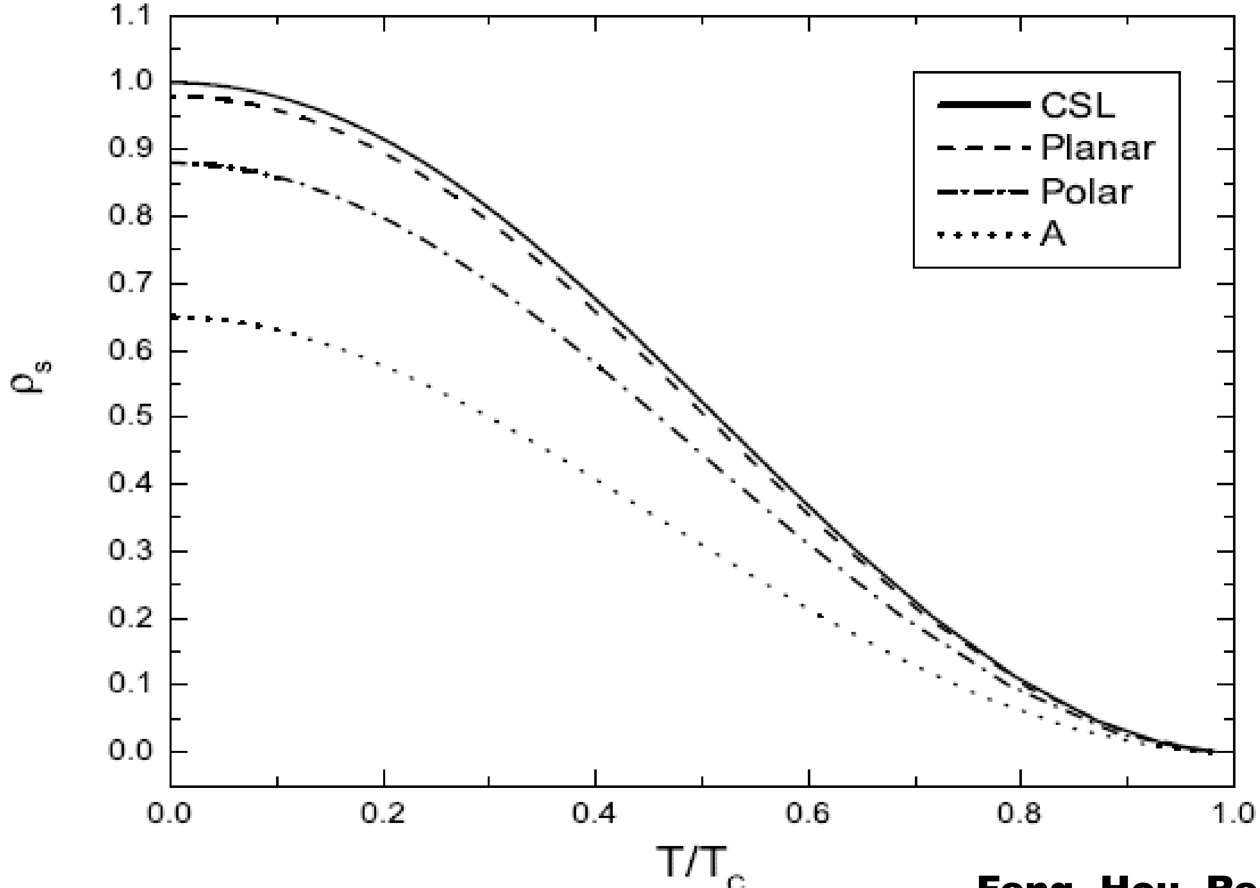
Ginnakis, Hou, Ren, Rischke, PRL 93 (04) ; PRD73 (06)





Introduction of Δ^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



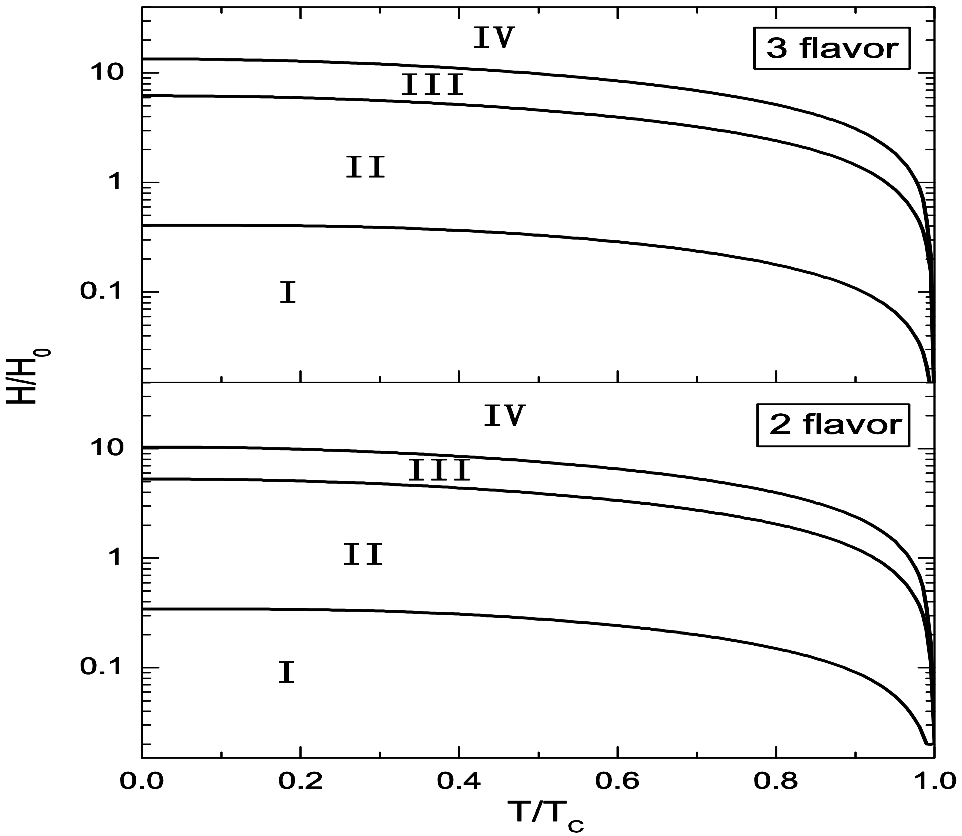
Feng, Hou, Ren,Wu, PRL 105(2010)

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

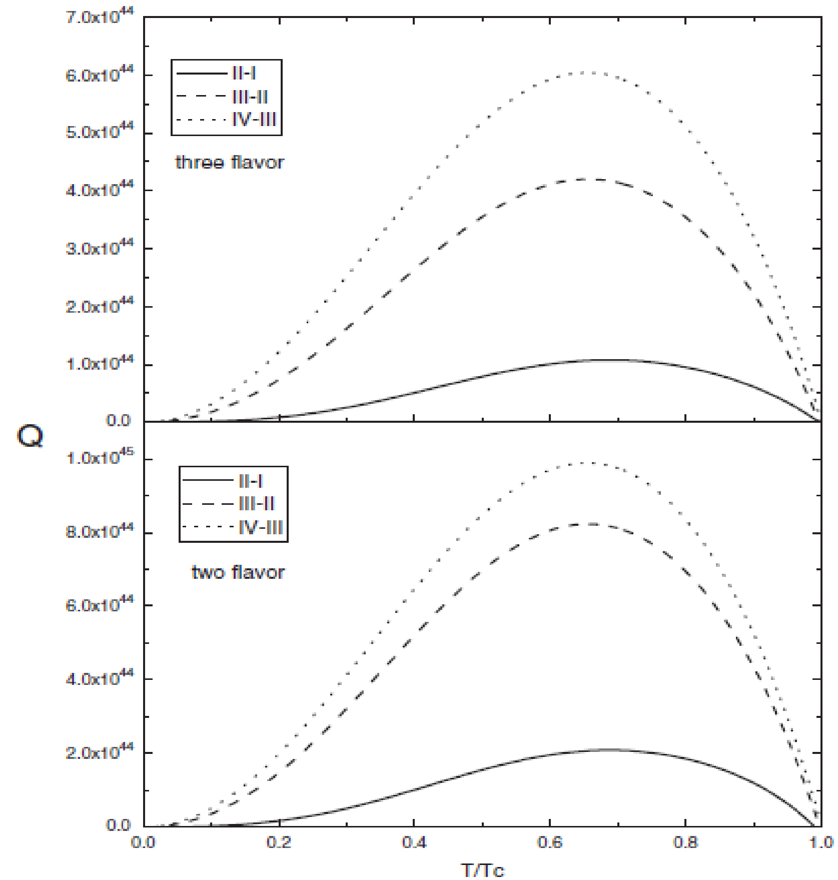
$$\overline{(k-\mu)^2 + \Delta^2 f^2(\theta)}$$

Nonspherical states in dense QCD with B

	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



H0=5.44×10^14 G, 1.97×10^14 G



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

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

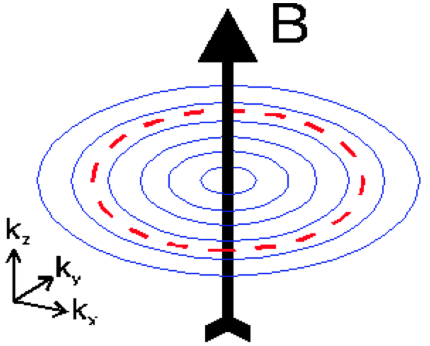
Chiral Magnetic Catalysis

- Chiral magnetic catalysis: Gusyin, Miransky & Shovkovy (1994)

$$< 0 | \bar{\psi}\psi | 0 > \overset{\lim\ m=0}{=} -\frac{|eB|}{2\pi}$$

Dynamical breakdown of chiral symmetry takes place at $m=0$ and $B \neq 0$ even without any additional interactions between fermions.

The essence of this effect is the dimensional reduction 3+1->1+1 in the dynamics of fermion pairing in a magnetic field.



$$E_n(p_3) = \pm\sqrt{m_{dyn}^2 + 2|eB|n + p_3^2}, \quad n = 0,1,2......$$

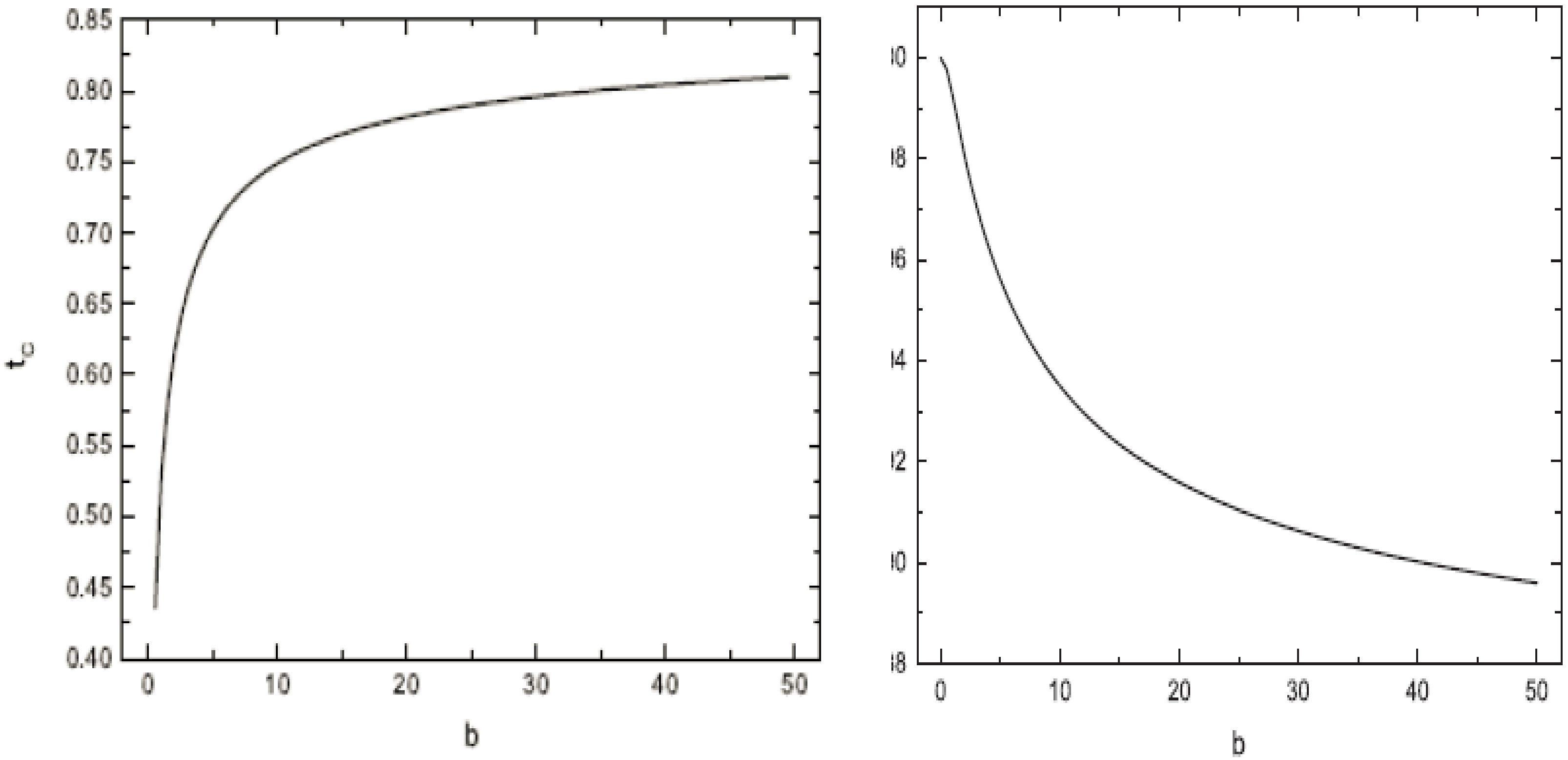
In a strong magnetic field, all charged fermions will be restricted in lowest Landau level only, thus effectively reduce the dimension of the system.

$$m_{dyn} \approx C\sqrt{eB}\exp\left[-\left(\frac{\pi}{\alpha}\right)^{1/2}\right]$$

Magnetic (Inverse) BEC catalysis at W/S coupling

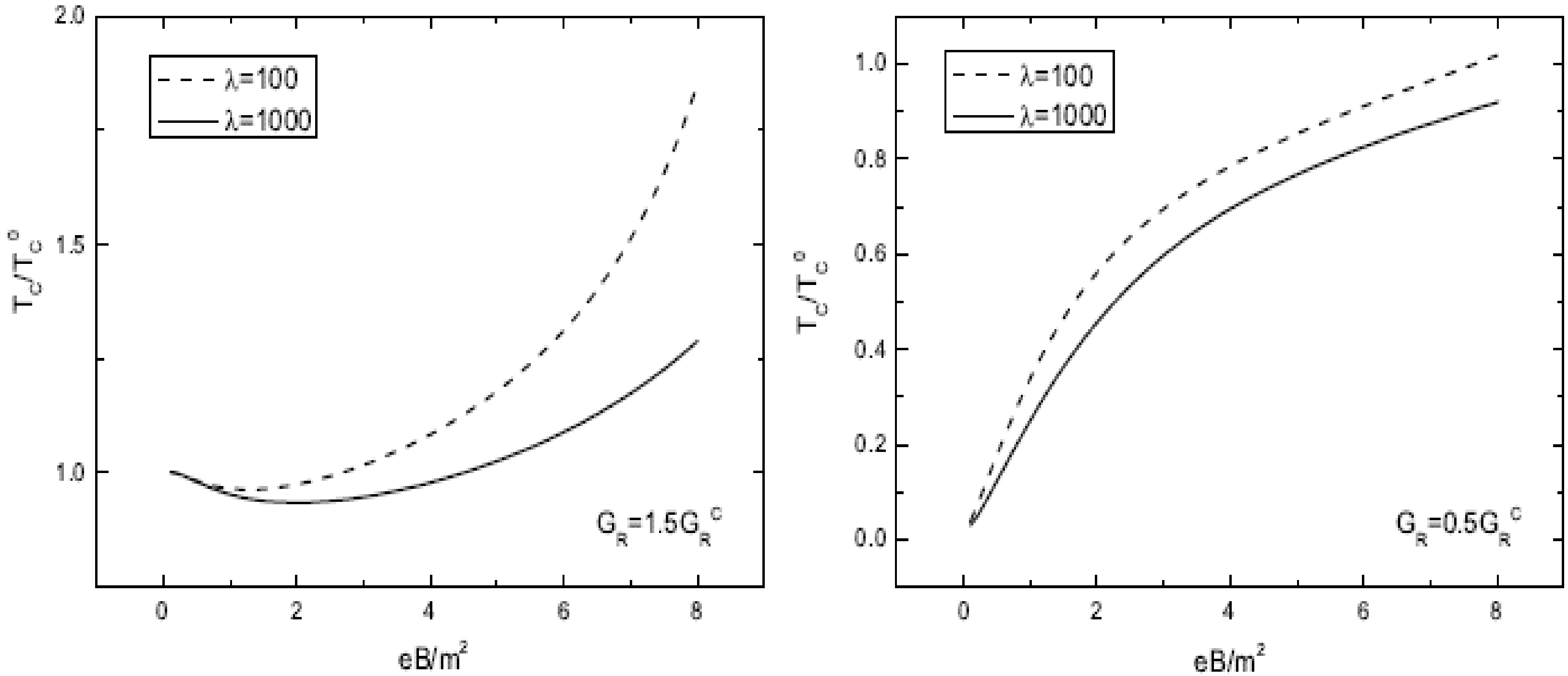
Feng, Hou, Ren PRD 92(2015)

Dimensional reduction & enhancement of fluctuation



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

Magnetic (Inverse) BEC catalysis at W/S coupling



Condensation temperature versus the dimensionless magnetic field

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

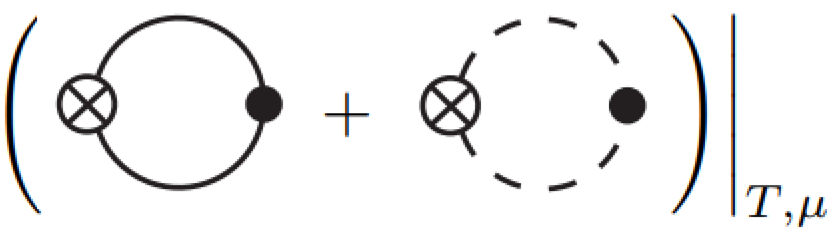
FRGE and phase structute

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).

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



FRG study of phase structure at finite density

Zhang, Hou, Kojo, Qin Phys.Rev. D96,114029 (2017)

$$\mathcal{L} = \bar{\psi}\Big[i\gamma_\mu\partial^\mu - g_s(\sigma + i\gamma_5\,\boldsymbol{\tau}\cdot\boldsymbol{\pi}) - g_v\gamma_\mu\omega^\mu - \gamma_0\mu\Big]\psi$$
$$+ \tfrac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \tfrac{1}{2}\partial_\mu\boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi} - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$- U(\sigma,\boldsymbol{\pi},\omega)$$
$$F_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \qquad \psi = (u,d)^T$$

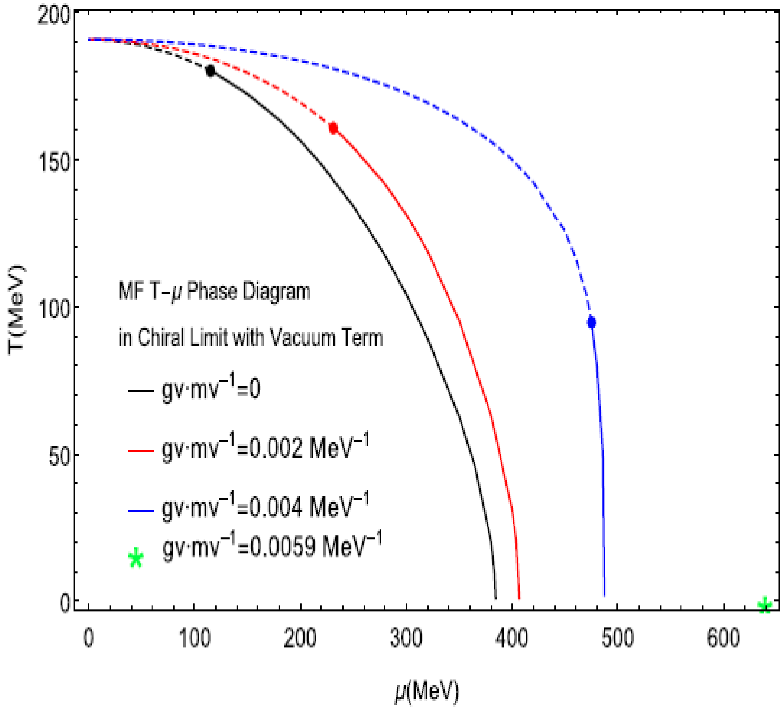
The potential for σ, π, and ω is

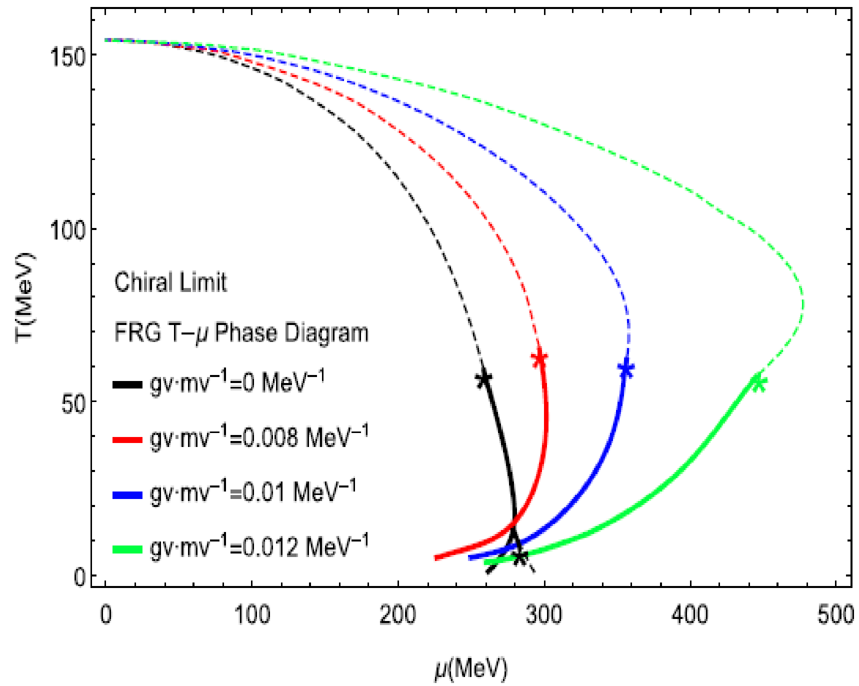
$$U(\sigma,\boldsymbol{\pi},\omega) = \frac{\lambda}{4}(\sigma^2 + \boldsymbol{\pi}^2 - f_\pi^2)^2 - \frac{m_v^2}{2}\omega_\mu\omega^\mu,$$ For chiral limit

$$U(\sigma,\boldsymbol{\pi},\omega) = \frac{\lambda}{4}(\sigma^2 + \boldsymbol{\pi}^2 - \nu^2)^2 + H\sigma - \frac{m_v^2}{2}\omega_\mu\omega^\mu,$$ For explicit SB

FRGE study of phase diagram: Flucts on CEP

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

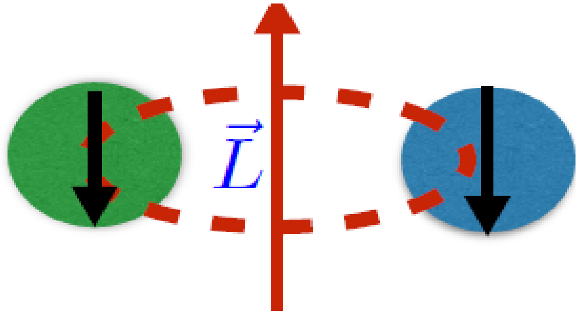


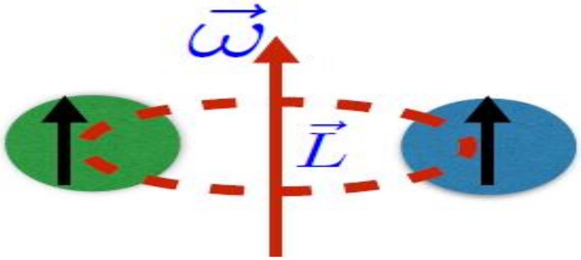


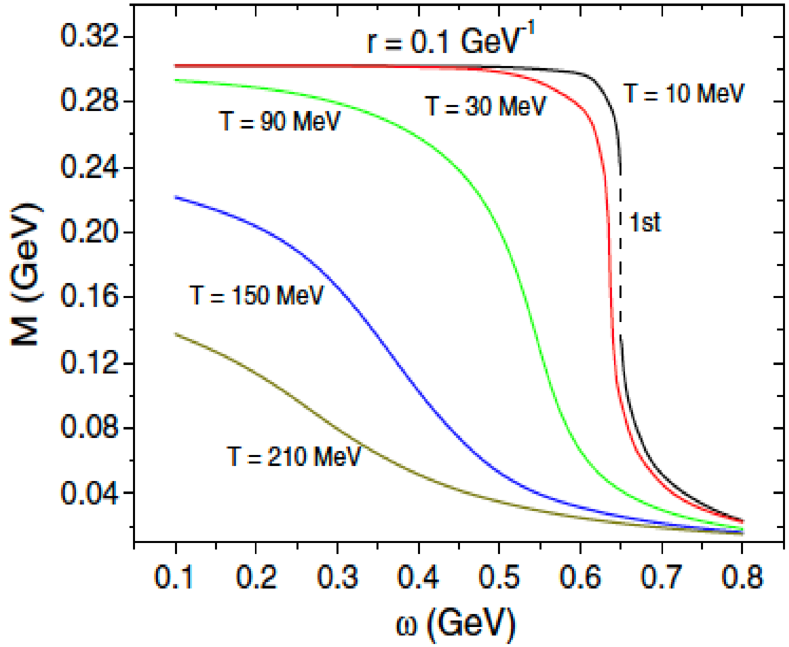
Nematic Isotropic (NI) Puzzle with FRGE

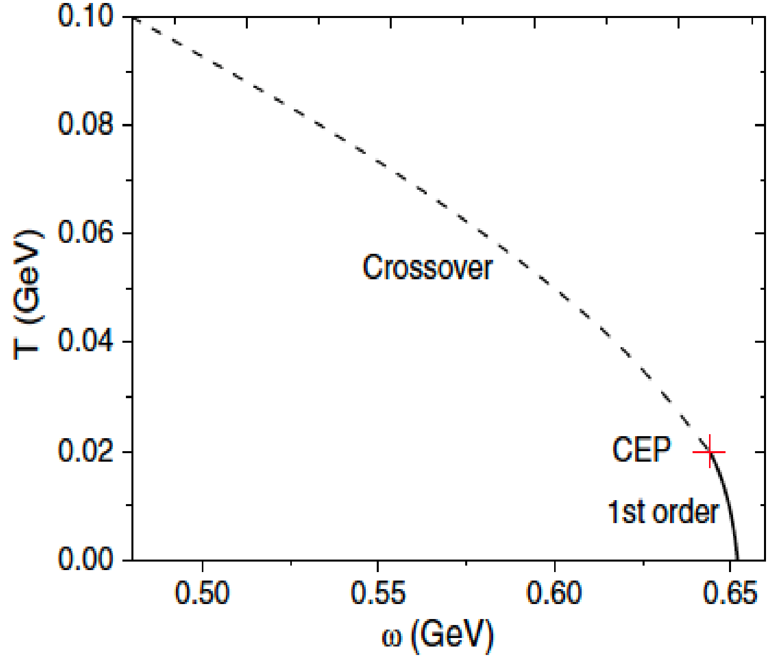
Qin, Hou, Huang, Zhang, PRB98, (2018)

Phase structure under rotation









Jiang,Liao: PRL117(2016)192303

Description of rotating system

Dirac Lagrangian in rotating frame:

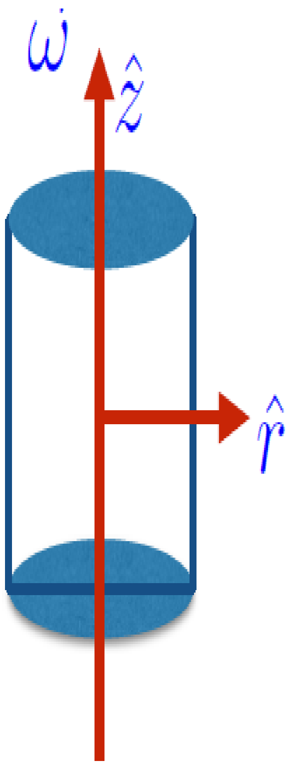
$$g_{\mu\nu} = \begin{pmatrix} 1-\vec{v}^2 & -v_1 & -v_2 & -v_3 \\ -v_1 & -1 & 0 & 0 \\ -v_2 & 0 & -1 & 0 \\ -v_3 & 0 & 0 & -1 \end{pmatrix}$$

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

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

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

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



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!

Mesonic superfluidity under rotation

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu\partial^\mu - m_0 + \frac{\mu_I}{2}\gamma_0\tau_3)\psi \quad +G_s\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\boldsymbol{\tau}\psi)^2\right]$$
$$-G_v\left[(\bar{\psi}\gamma_\mu\boldsymbol{\tau}\psi)^2 + (\bar{\psi}\gamma_\mu\gamma_5\boldsymbol{\tau}\psi)^2\right]$$

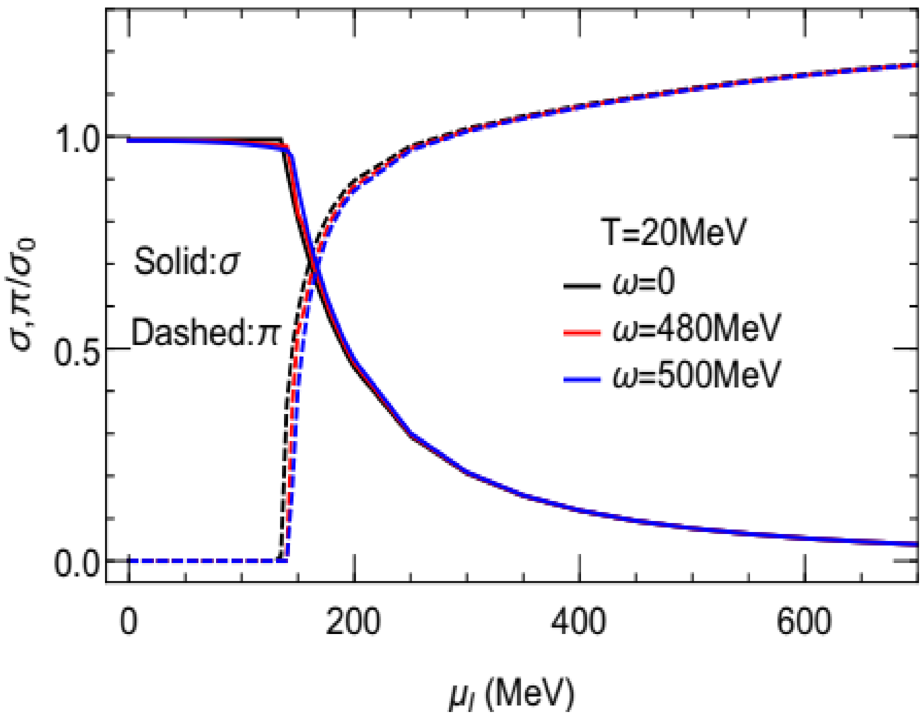
MF approximation: $\sigma = \langle\bar{\psi}\psi\rangle,\ \pi = \langle\bar{\psi}i\gamma_5\boldsymbol{\tau}\psi\rangle,\ \rho = \langle\bar{\psi}i\gamma_0\gamma_5\tau_3\psi\rangle$

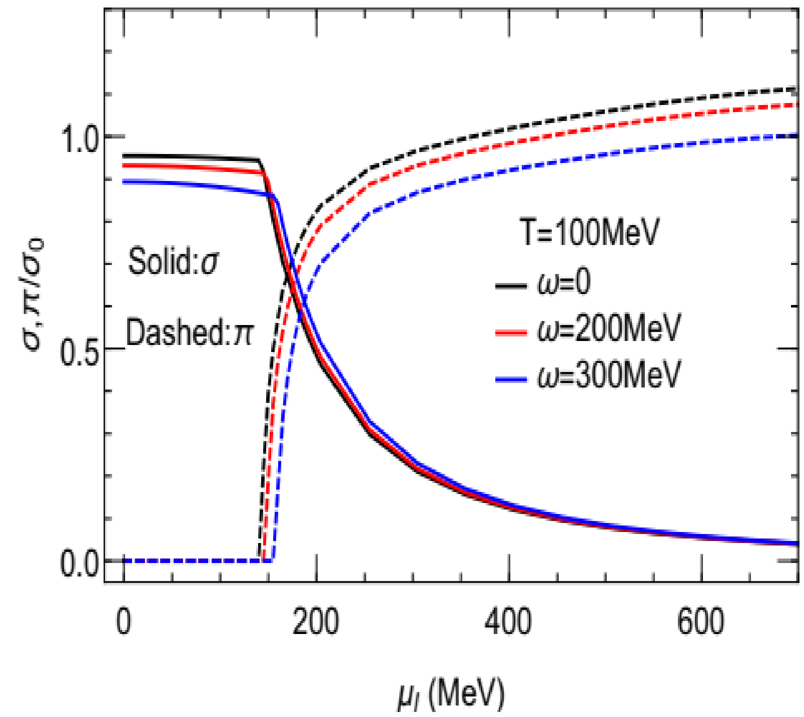
$$\begin{aligned}\Omega \ =\ & G(\sigma^2+\pi^2) - G\rho^2 - \frac{\mathrm{N_c N_f}}{16\pi^2}\sum_n\int \mathrm{d}k_t^2 \int \mathrm{d}k_z[J_{n+1}(k_t r)^2 + J_n(k_t r)^2] \\ \times\ & T\Big[\ln\Big(1+\exp(-\frac{\omega^+ - (n+\frac{1}{2})\omega}{T})\Big) + \ln\Big(1+\exp(\frac{\omega^+ - (n+\frac{1}{2})\omega}{T})\Big) \\ & +\ln\Big(1+\exp(-\frac{\omega^- - (n+\frac{1}{2})\omega}{T})\Big) + \ln\Big(1+\exp(\frac{\omega^- - (n+\frac{1}{2})\omega}{T})\Big)\Big]\end{aligned}$$

Rotational suppression of Pion superfluid

Rotation weaken spin 0 condensate, inverse catalysis effect

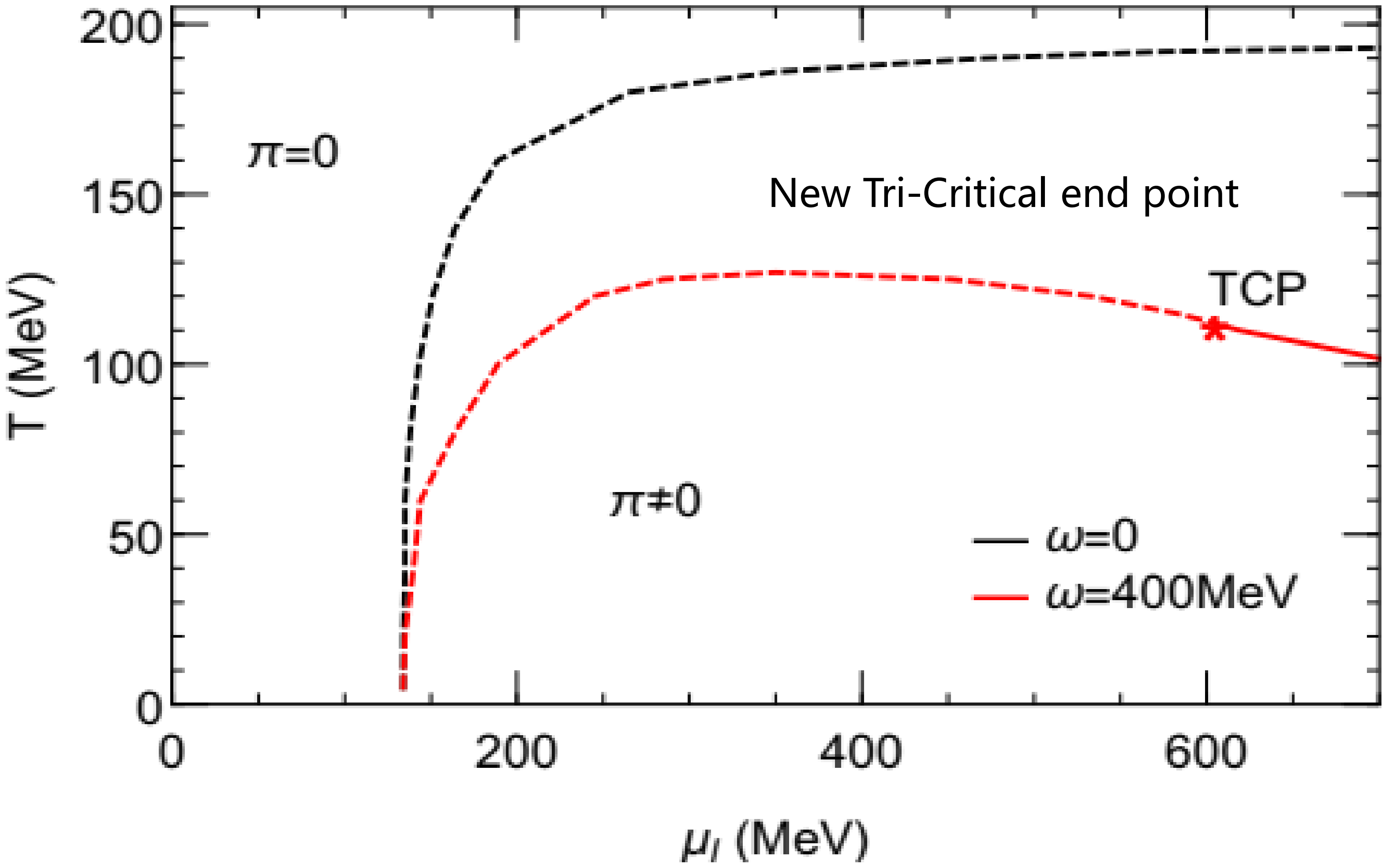
H. Zhang, DF Hou, JF Liao, arxiv 1812.11787





He, M. Jin and P. Zhuang, Phys. Rev. D 71,116001 (2005);
L. He and P. Zhuang, Phys. Lett. B 615, 93 (2005)

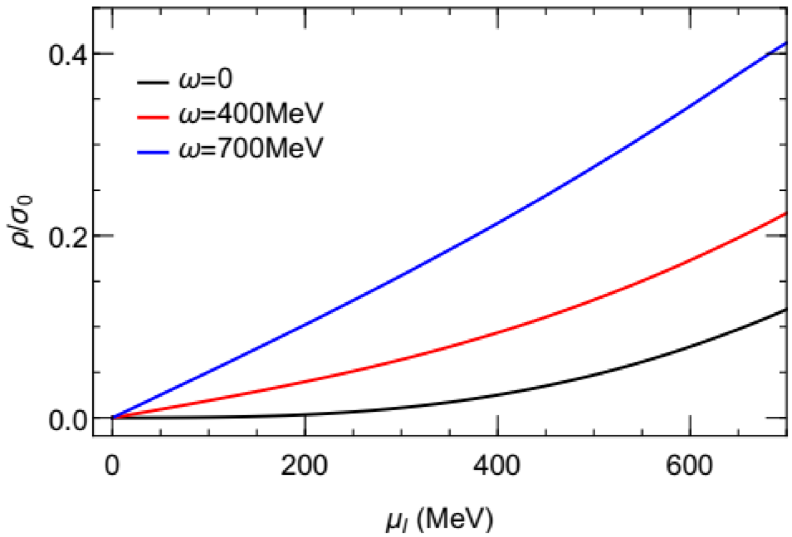
Pion superfluidity phase diagram in T-μI

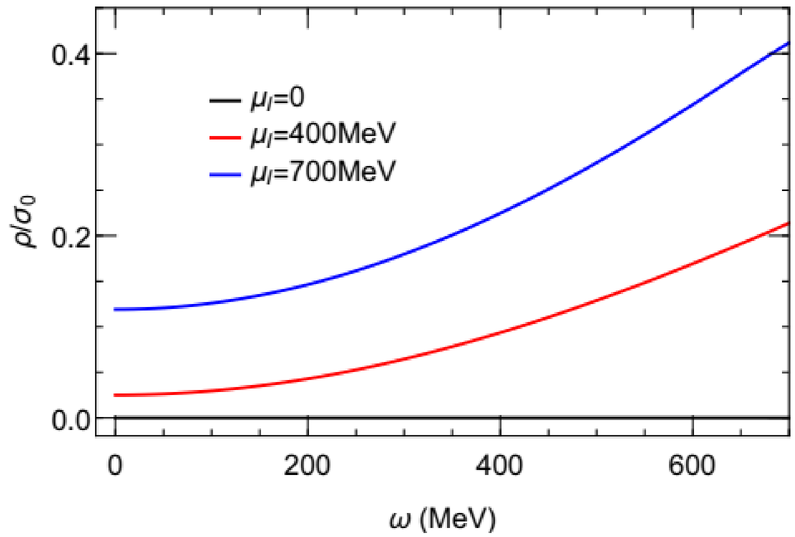


Enhenced Rho Superfluid under rotation

Rotation enhances spin 1 condensate ρ channel

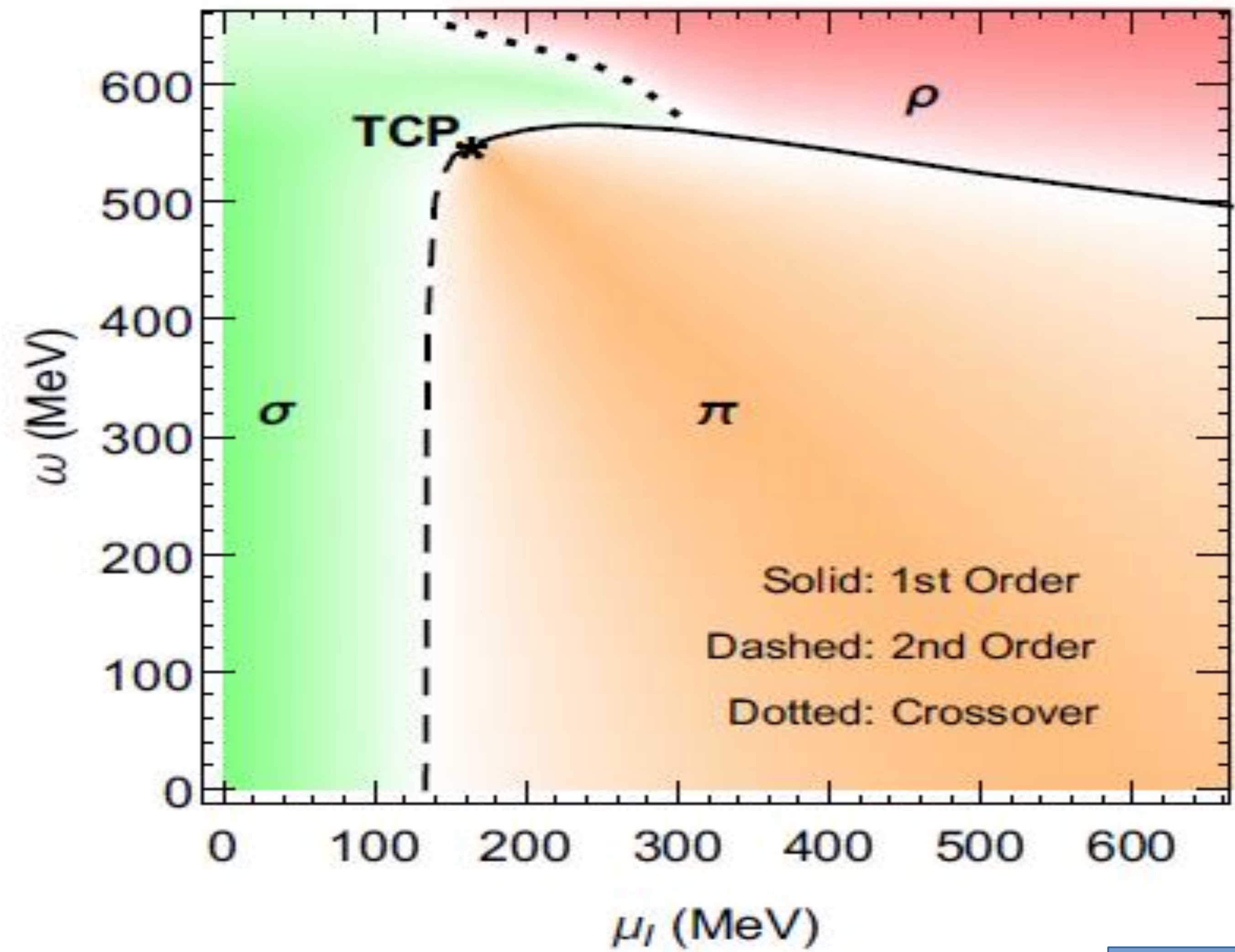
Rho condensate with none zero isospin chemical potential under rotation





New mesonic superfluid phase diagram

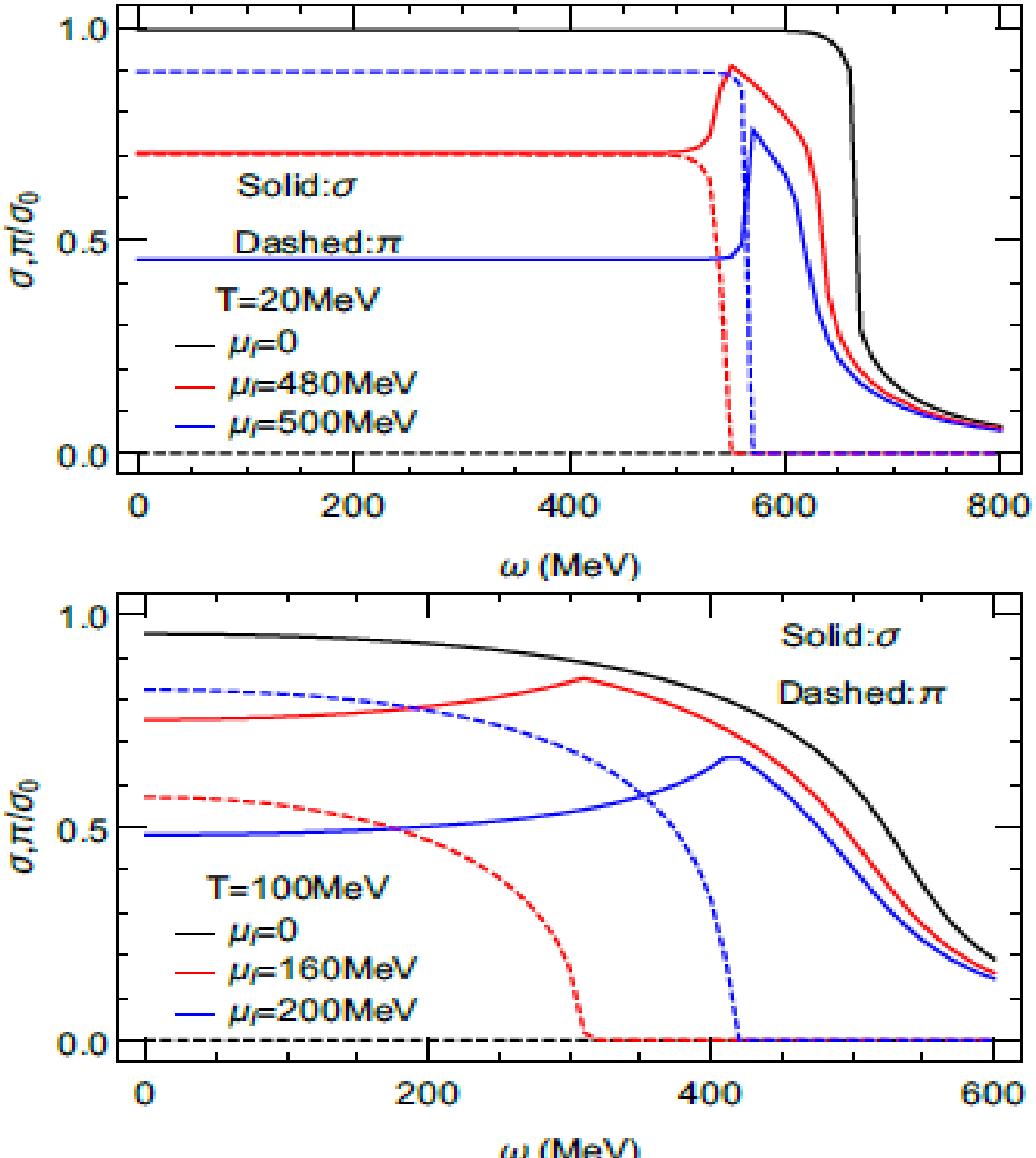
H. Zhang, DF Hou, JF Liao, arxiv 1812.11787



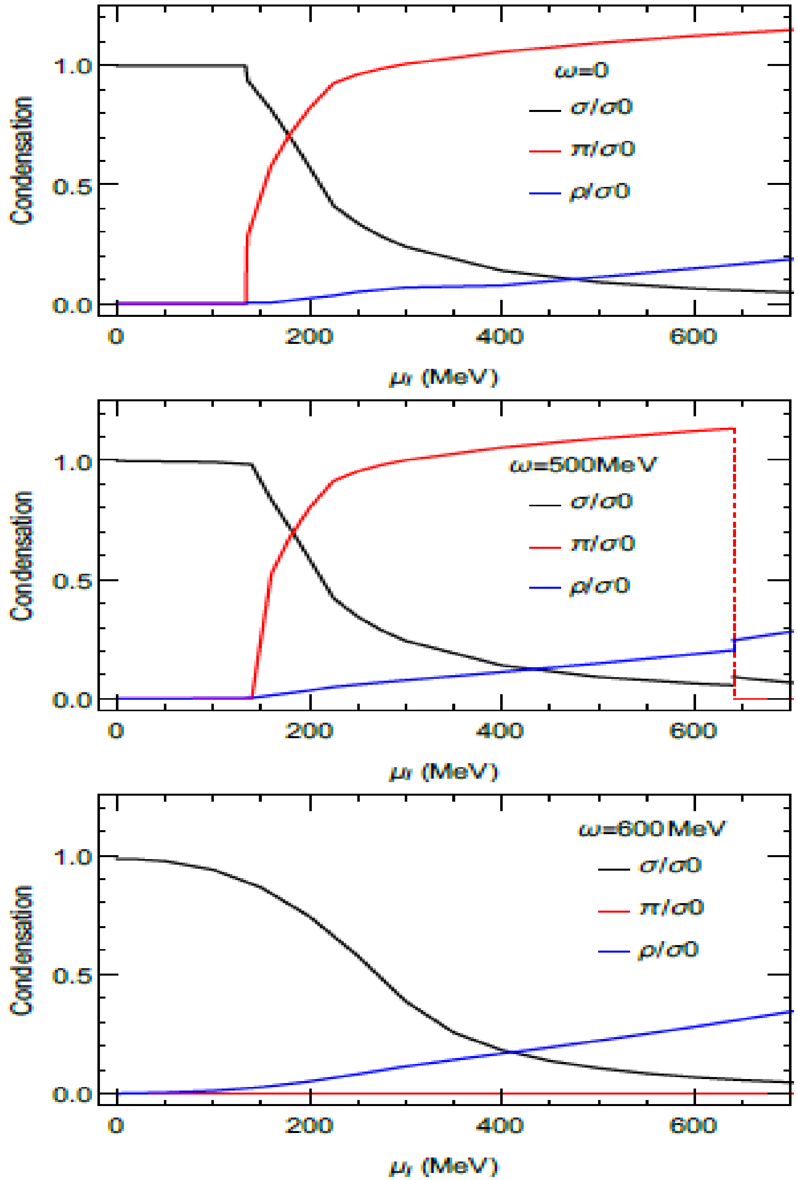
Summary and outlook

- **Dense QCD matter has very rich phase structures.**
- **Fluctuations are important for TCP of QCD, FRG provides an useful tool**
- **Magnetic field has nontrivial effects on phase structure**
- **(Magnetic Catalyse & inverse Magetic catalyse)**
- **Rotation suppresses spin 0 condensate , enhances nonzero spin ones**
- **A new phase diagram for isospin matter under rotation with a new TCP**

Thank you very much for your attention!



1.0
0.5
0.0
σ,π/σ0
Solid:σ
Dashed:π
T=20MeV
μI=0
μI=480MeV
μI=500MeV
0
200
400
600
800
ω (MeV)
1.0
0.5
0.0
σ,π/σ0
Solid:σ
Dashed:π
T=100MeV
μI=0
μI=160MeV
μI=200MeV
0
200
400
600
ω (MeV)


ω=0
σ/σ0
π/σ0
ρ/σ0
Condensation
μI (MeV)
ω=500MeV
σ/σ0
π/σ0
ρ/σ0
Condensation
μI (MeV)
ω=600MeV
σ/σ0
π/σ0
ρ/σ0
Condensation
μI (MeV)