QCD Phase structure under Rotation

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

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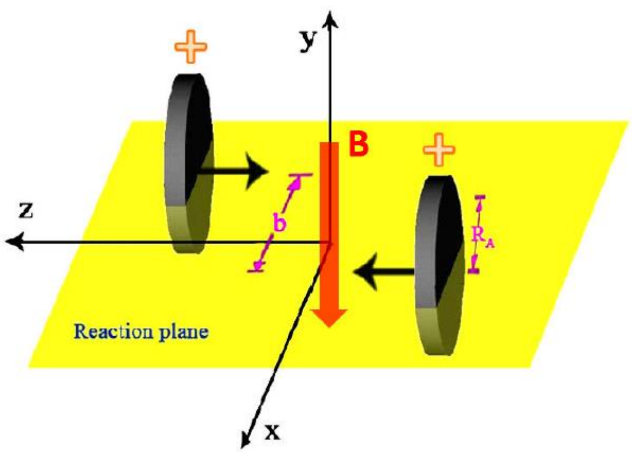
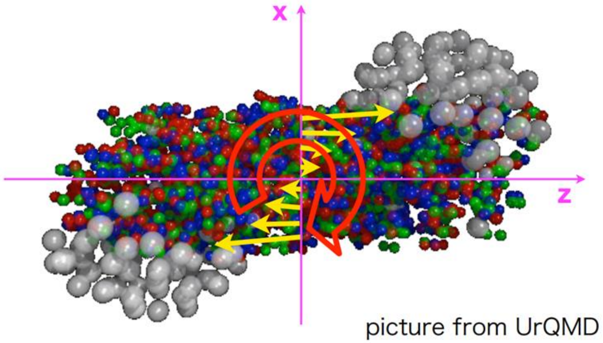
Outlines

- **Motivations**
- **Rotation suppression of Pion Superfluidity**
- **Enhenced Rho superfluidity under rotation**
- **Summary and outlook**

Phase structure under new extrem condition





Strongest EM fields

Largest local rotation

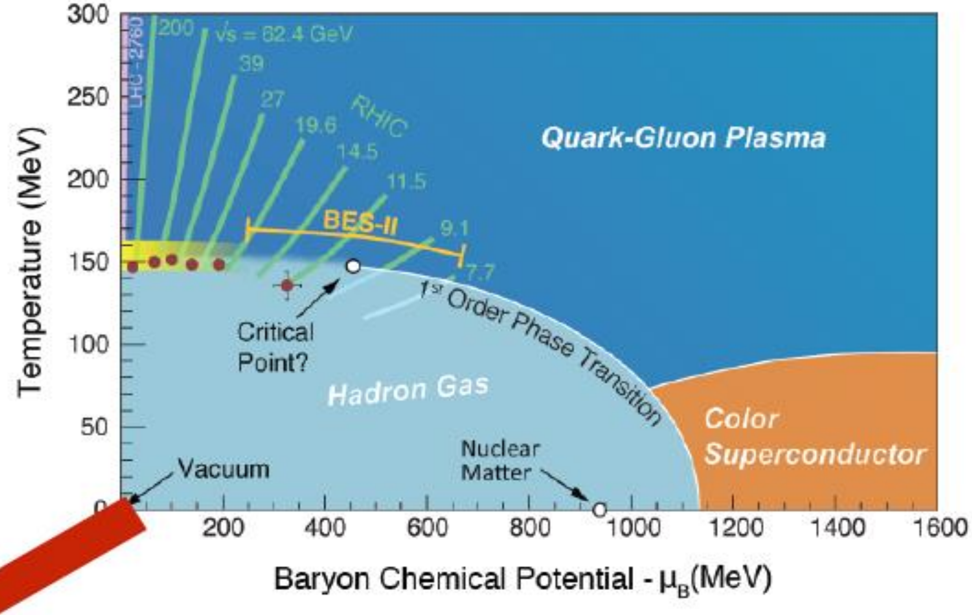
What are their effects to the QCD phase structures?

What are their effects on the QCD dynamics transports ?

(CME, CMW, CVE, etc.)

New Dimensions of the Phase Diagram

Putting the strongly interaction matter under strong magnetic field or fluid rotation!



$\vec{B}$

$\vec{\omega}$

Opening up new dimensions: Toward Hyper-Phase-Diagram!

Phase structure under rotation

Jiang and Liao, PRL2016,

Chen, Fukushima, Huang , Mameda,PRD 2016

Mameda , Yamamoto, (2016).

Chernodub and S. Gongyo, PRD 2017

Ebihara, K. Fukushima and K. Mameda, PLB2017,

Y. Liu and I. Zahed, PRL2018

Huang, Nishimura and Yamamoto, JHEP 2018

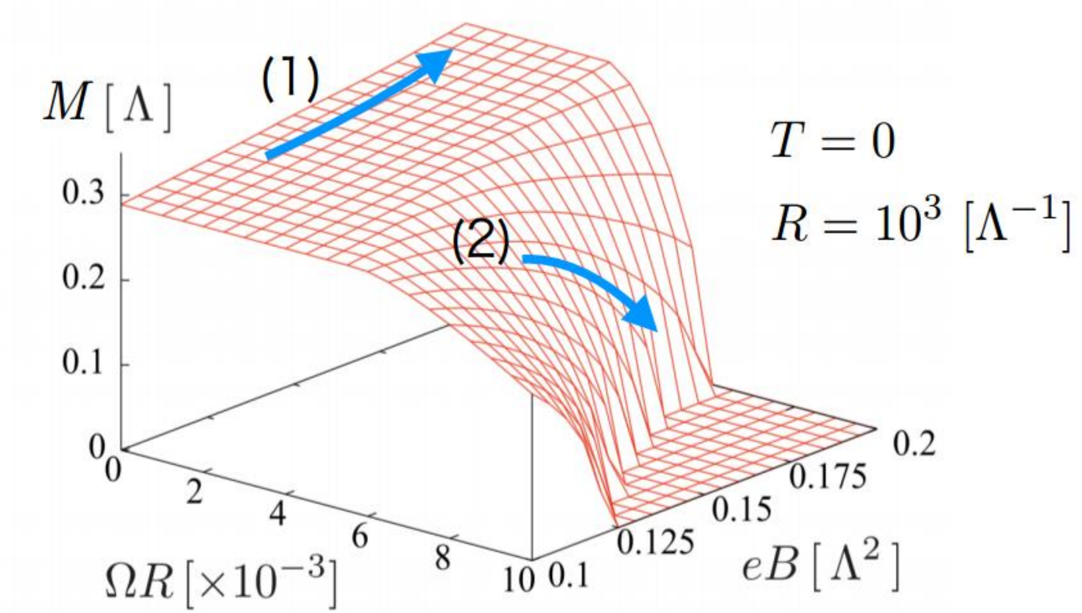
X. Wang, Wei, Li and M. Huang PRD2019

Wang, Jiang , He, Zhuang arXiv:1901.04697

Talks: HL Chen , LY He, Y. Jiang,

K. Fukushima, JF Liao

Dirac fermion in rotation and B field



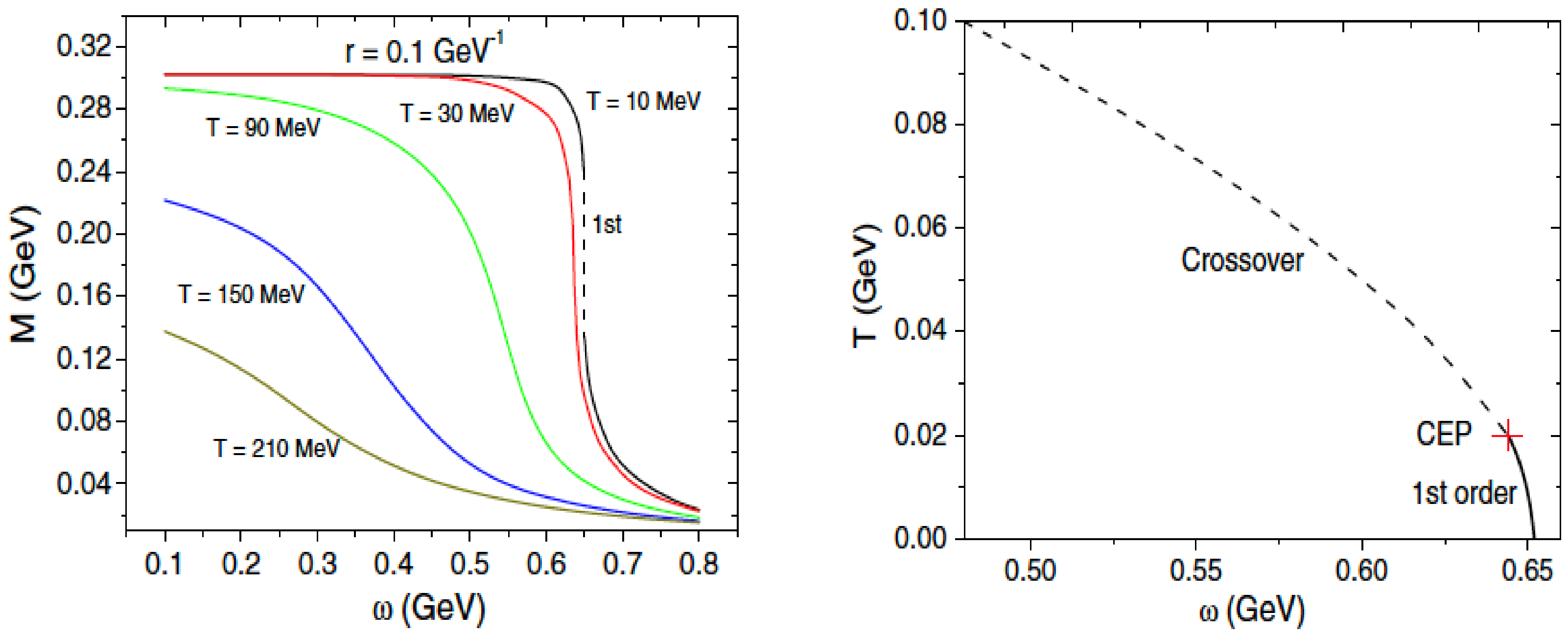
(1) eB increases → M increases   Magnetic Catalysis

(2) eB increases → M decreases   Inverse of MC

'Rotational magnetic inhibition'

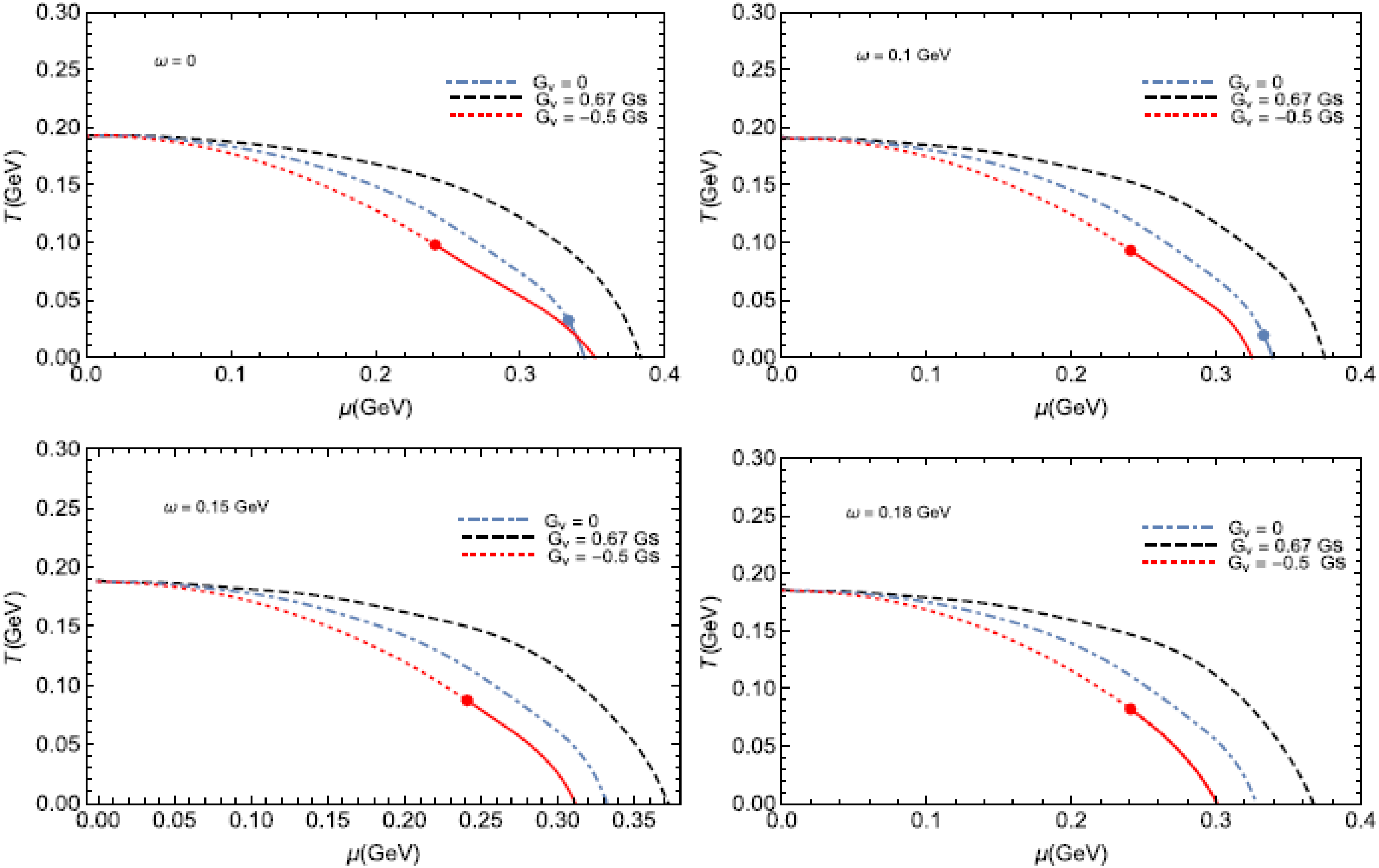
Chen-Fukushima-XGH-Mameda PRD2016 , Hao Lei Chen's talk

Rotation suppression of scalar pairing



Jiang,Liao: PRL2016

Quark matter under rotation with verctor interaction



Description of rotating system

Dirac Lagrangian in rotating frame:

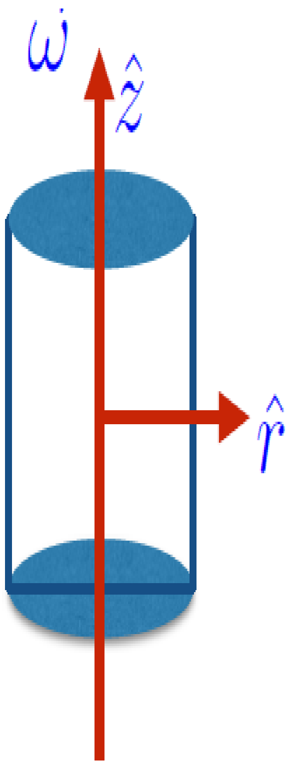
$$g_{\mu\nu} = \begin{pmatrix} 1-\vec{v}^2 & -v_1 & -v_2 & -v_3 \\ -v_1 & -1 & 0 & 0 \\ -v_2 & 0 & -1 & 0 \\ -v_3 & 0 & 0 & -1 \end{pmatrix}$$

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

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

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

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



Under slow rotation:

$$\mathcal{L} = \psi^\dagger\left[i\partial_0 + i\gamma^0\vec{\gamma}\cdot\vec{\partial} + (\vec{\omega}\times\vec{x})\cdot(-i\vec{\partial}) + \vec{\omega}\cdot\vec{S}_{4\times4}\right]\psi$$

$$\hat{H} = \gamma^0(\vec{\gamma}\cdot\vec{p} + m) - \vec{\omega}\cdot(\vec{x}\times\vec{p} + \vec{S}_{4\times4}) = \hat{H}_0 - \vec{\omega}\cdot\hat{\vec{J}}$$

Rotational polarization effect!

Mesonic superfluidity under rotation

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

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

$$\mathcal{L}_R = \psi^\dagger\left[(\vec{\omega}\times\vec{x})\cdot(-i\vec{\partial}) + \vec{\omega}\cdot\vec{S}_{4\times4}\right]\psi$$

MF approximation:

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

Thermodynamic potential of isospin matter with rotation

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

$$\omega^{\pm} = \sqrt{4G^2\pi^2 + (\sqrt{(m_0 - 2G\sigma)^2 + k_t^2 + k_z^2} \pm \widetilde{\mu_I})^2}$$

$$\widetilde{\mu}_I = \frac{\mu_I}{2} + G_V \rho$$

$$\frac{\partial\Omega}{\partial\sigma} = \frac{\partial\Omega}{\partial\pi} = \frac{\partial\Omega}{\partial\rho} = 0$$

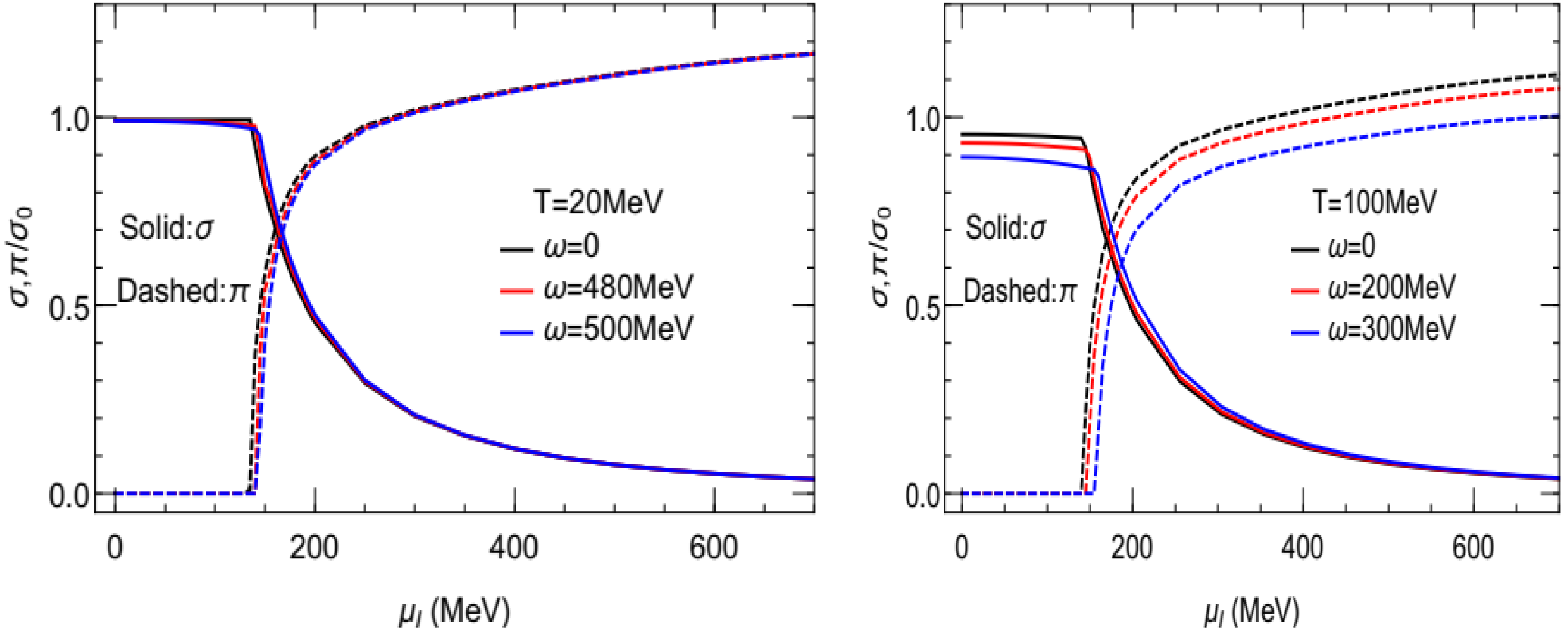
Parameters:

$$m_0 = 5 \text{ MeV}, \; G_s = G_v = G = 5.03 \text{ GeV}^{-2}, \; \Lambda = 650 \text{ MeV}, \; r = 0.1 \text{ GeV}^{-1}$$

Rotational suppression of Pion superfluid

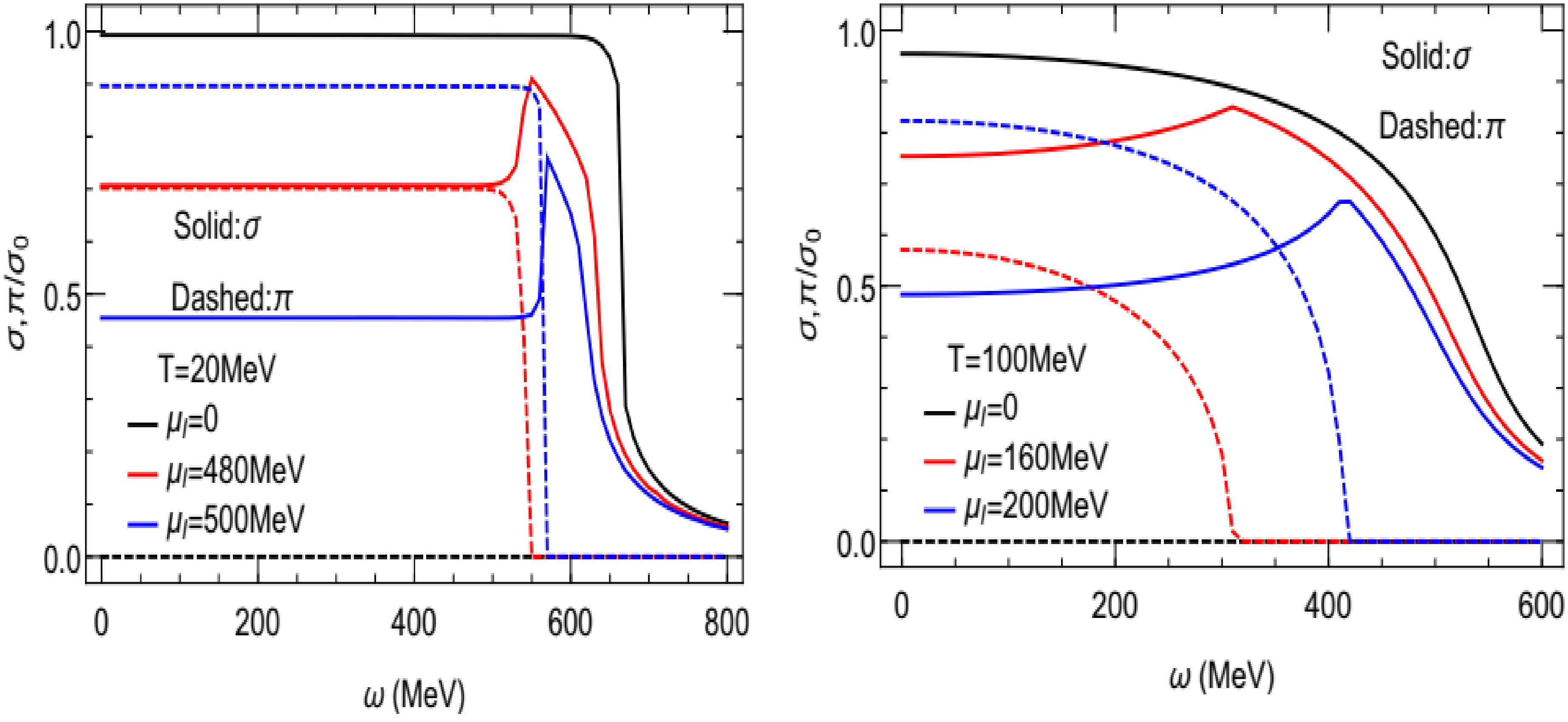
Rotation weaken spin 0 condensate, inverse catalysis effect

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

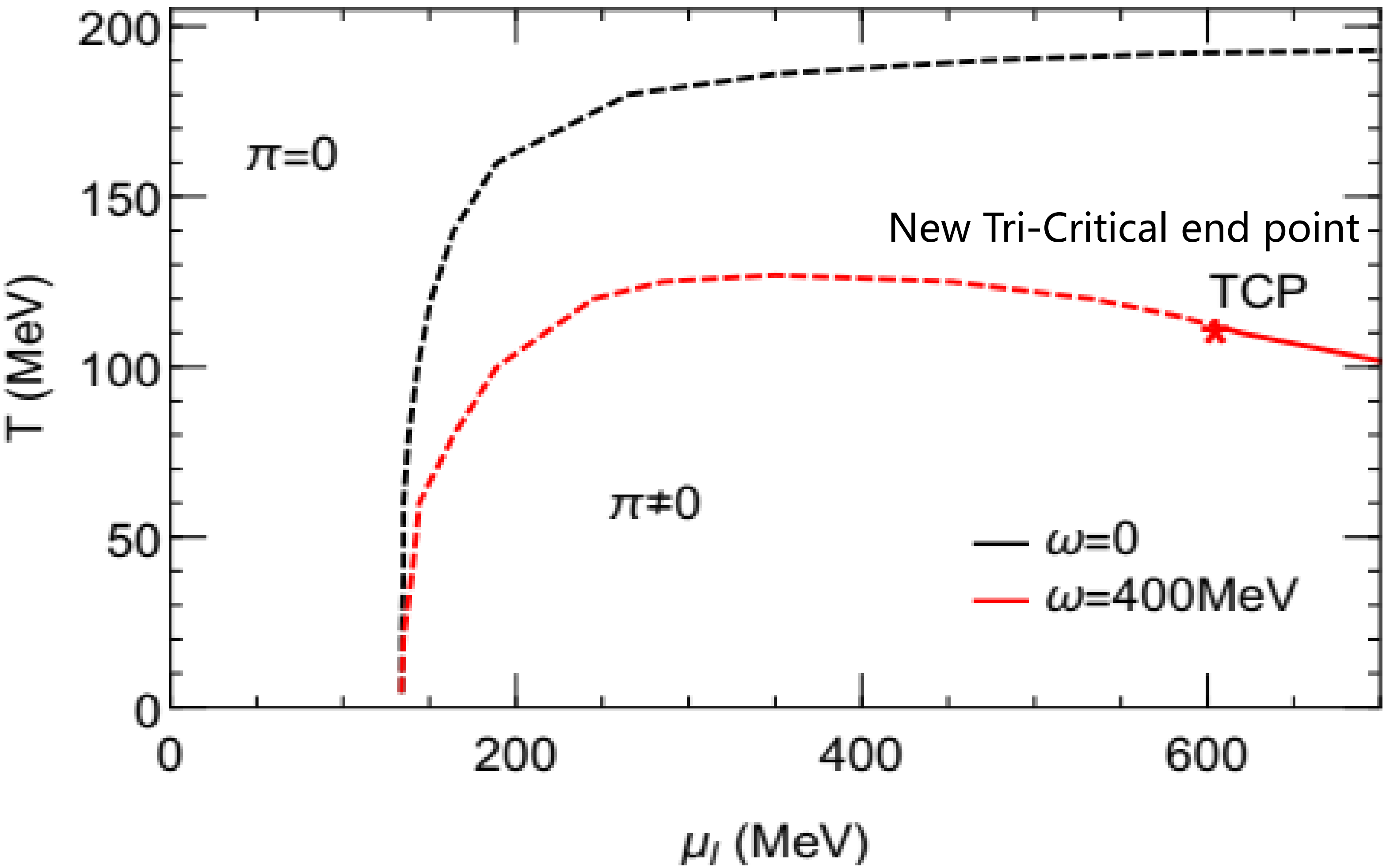


He, M. Jin and P. Zhuang, Phys. Rev. D 71,116001 (2005);
L. He and P. Zhuang, Phys. Lett. B 615, 93 (2005)

Rotational suppression of Pion superfluid



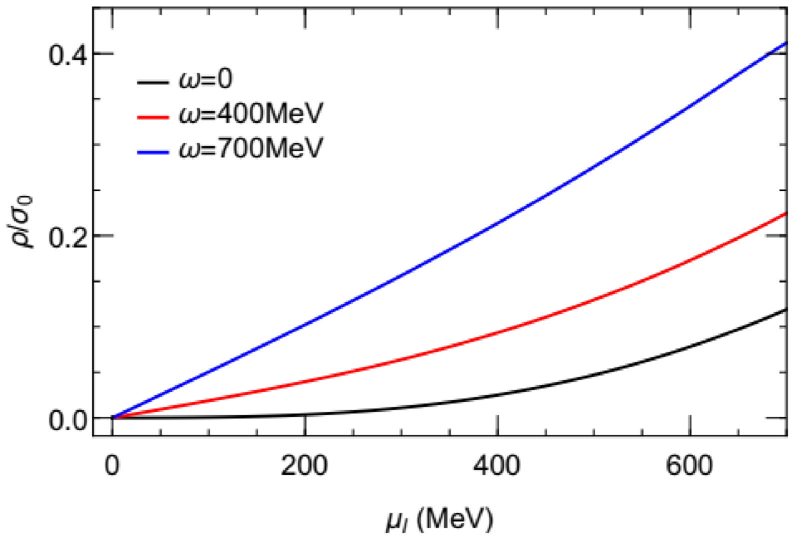
Pion superfluidity phase diagram in T-μI

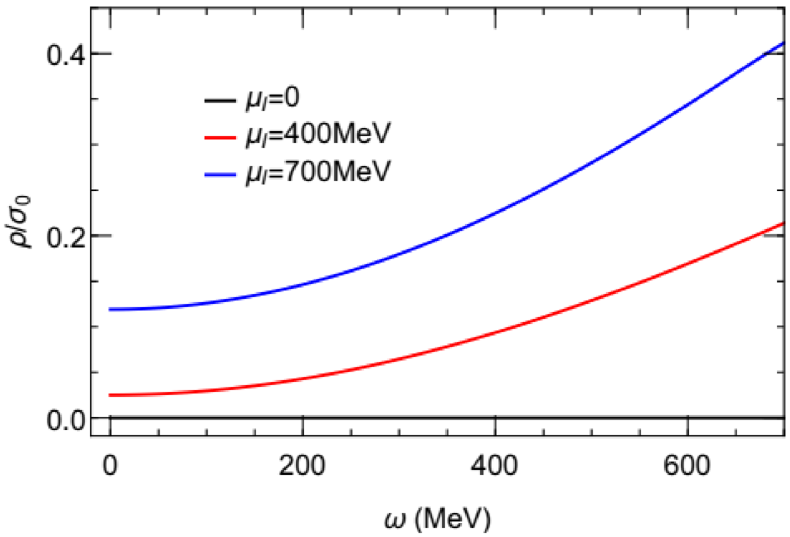


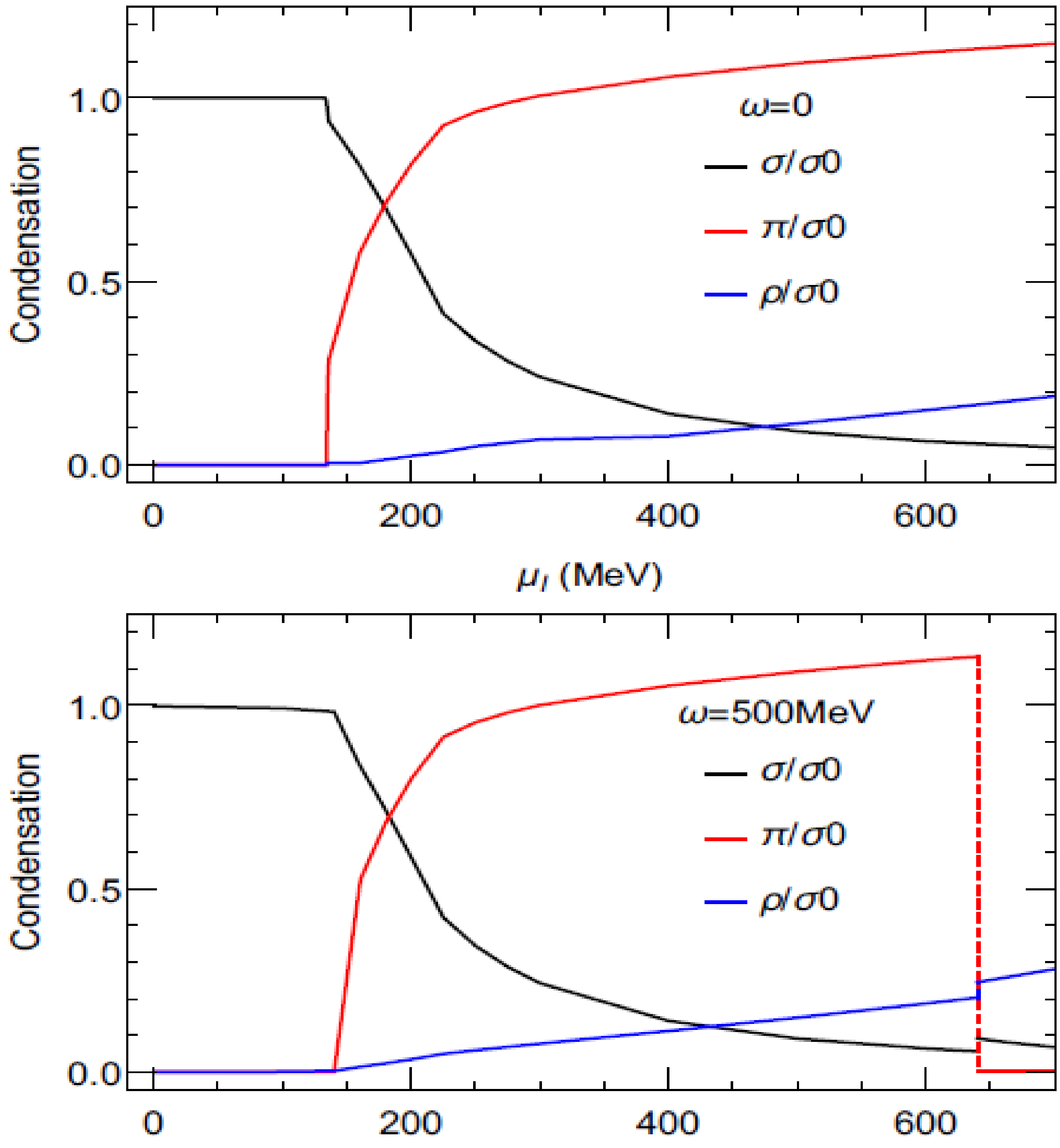
Enhenced Rho Superfluid under rotation

Rotation enhances spin 1 condensate ρ channel

Rho condensate at T=mu=0 with none zero isospin chemical potential under rotation

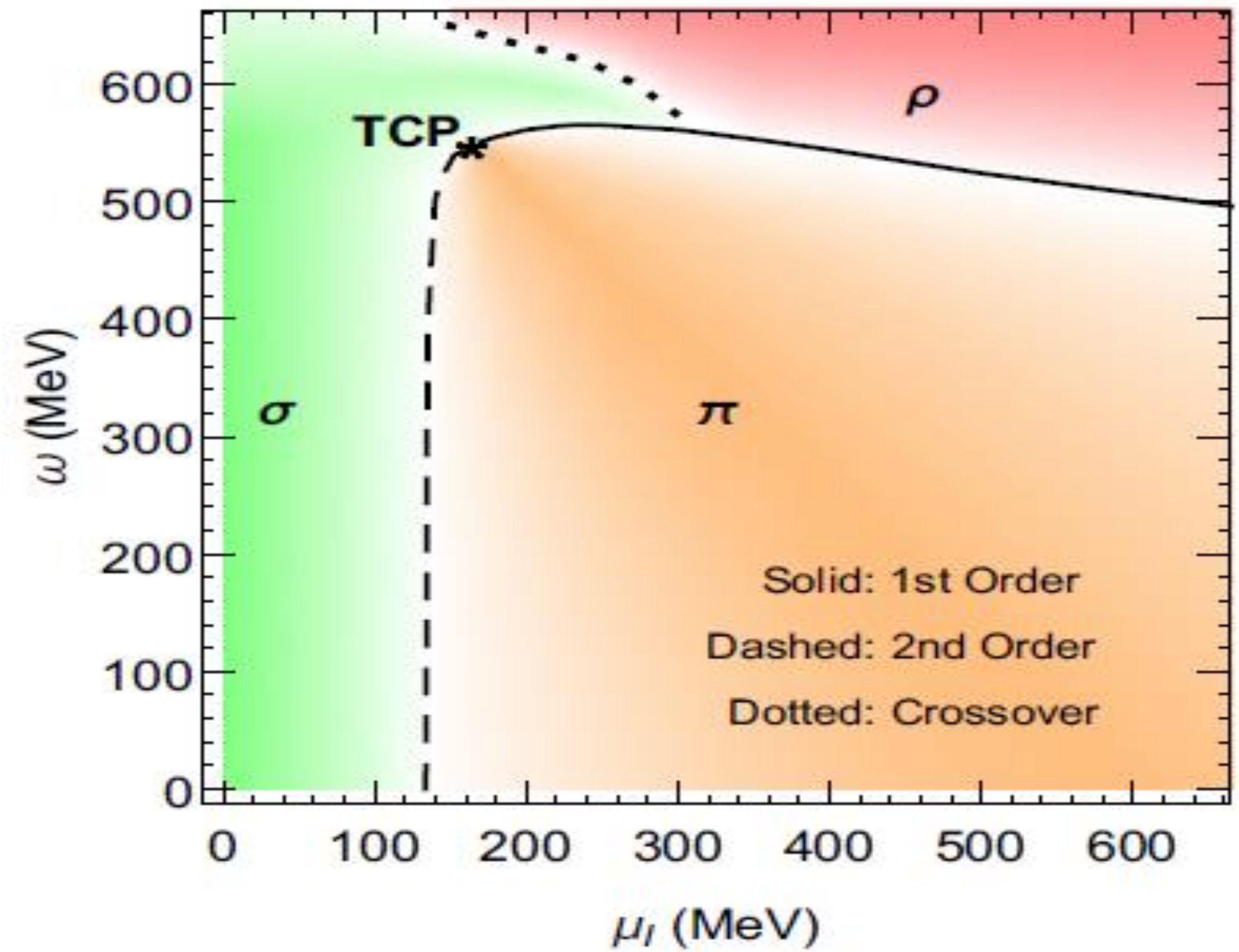






Condensation
1.0
0.5
0.0
0
200
400
600
ω=0
σ/σ0
π/σ0
ρ/σ0
μ_I (MeV)
Condensation
1.0
0.5
0.0
0
200
400
600
ω=500MeV
σ/σ0
π/σ0
ρ/σ0

New mesonic superfluid phase diagram



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Summary and outlook

- **Inverse catalysis effect on the pion superfluidity**
- **Rotation suppresses spin 0 condensate , enhances nonzero spin condensate**
- **Rho condensate at T=mu=0 with none zero μ I under rotation.**
- **A new phase diagram for isospin matter under rotation with a new TCP**

- **Finite size effect on the phase structure**
- **Beyond MFA**
- **Possible splitting deconfinement and chiral transitions**
- **Possible application to compact stars by including finite baryon chemical potential**

Thank you very much for your attention!

Prefer σ than π: Hund's rules

σ: L=1, s=1, J=0 (more state)
π: L=0, s=0, J=0