Bag model perspective on favoring the hadronic phase under rotation

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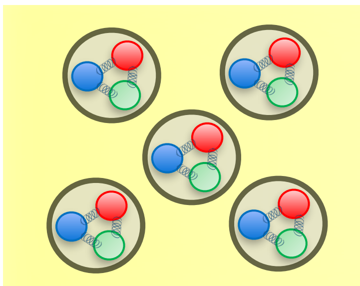
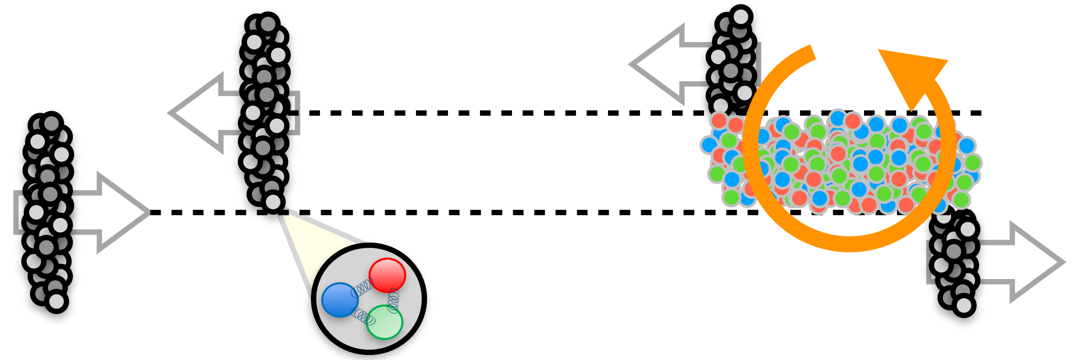
QCD matter under rotation

present

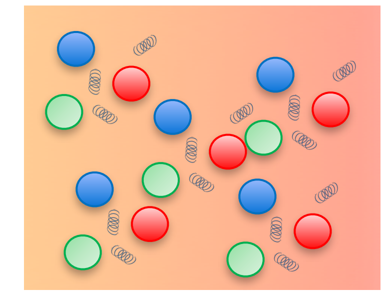


hadron

heavy-ion collision

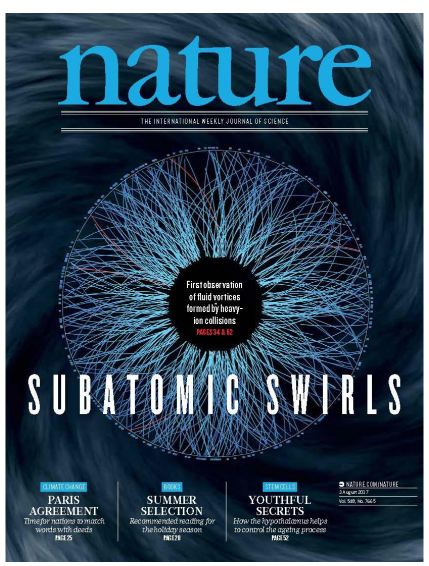


just after big-bang



quark-gluon plasma

STAR collab. (2017)

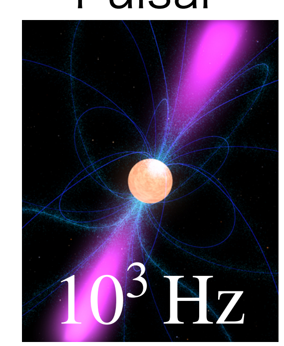


10^{22} Hz

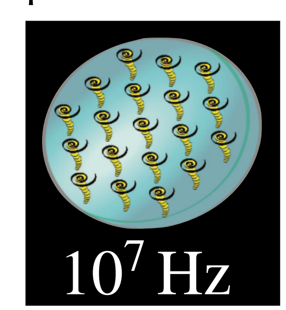
Earth

tornado

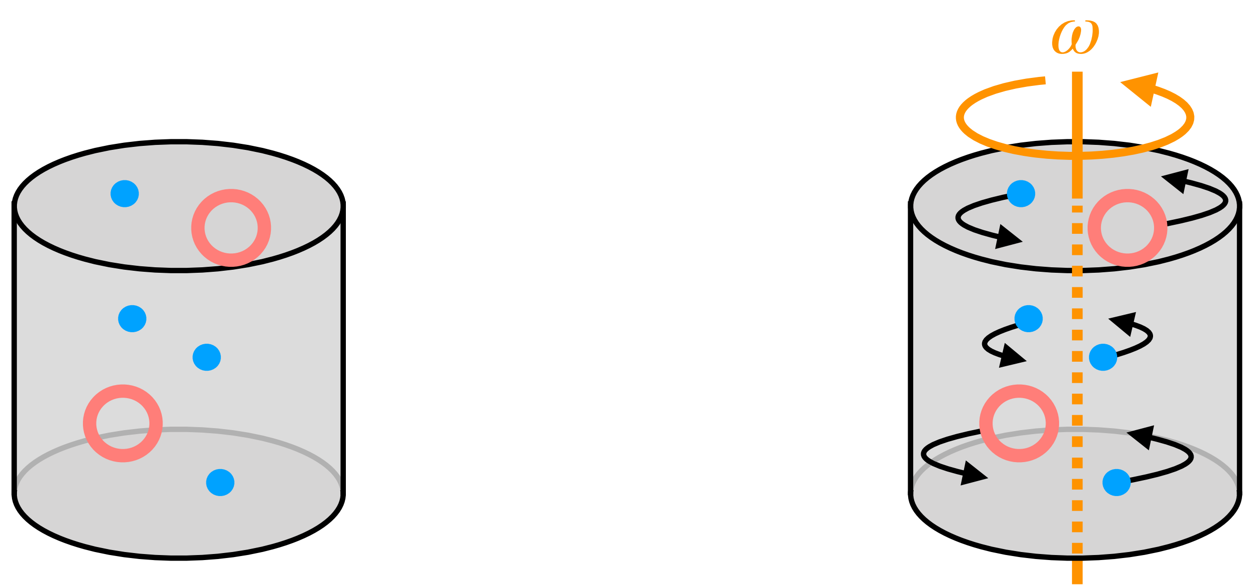
Pulsar



superfluid ^{4}He



How to introduce rotation in thermodynamics

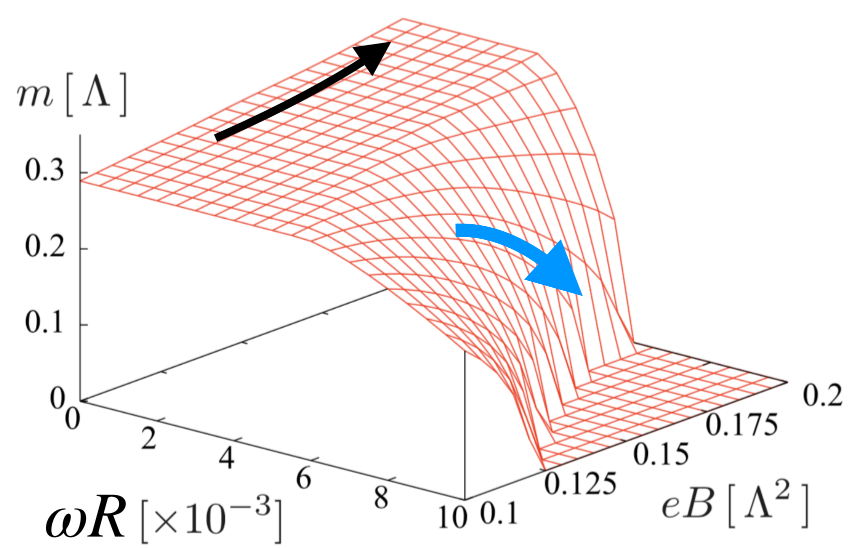


$\exp[-\beta H]$ $\exp[-\beta(H - \omega J_z)]$

Landau-Lifshitz (1958) Vilenkin (1979)

ex.) chiral symmetry under B Chen-Fukushima-Huang-KM (2016)

catalysis by B



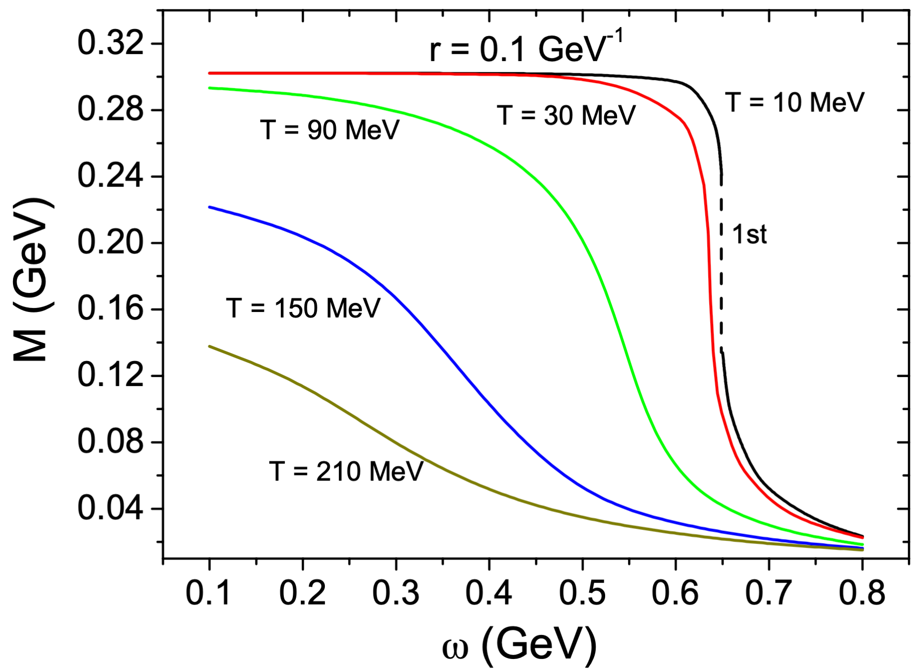
Inverse catalysis by

$\omega J_z \sim \mu N$

Ebert, Klimenko (1999)
Preis, Rebhan, Schmitt (2012)

Chiral symmetry

Jiang, Liao (2016)

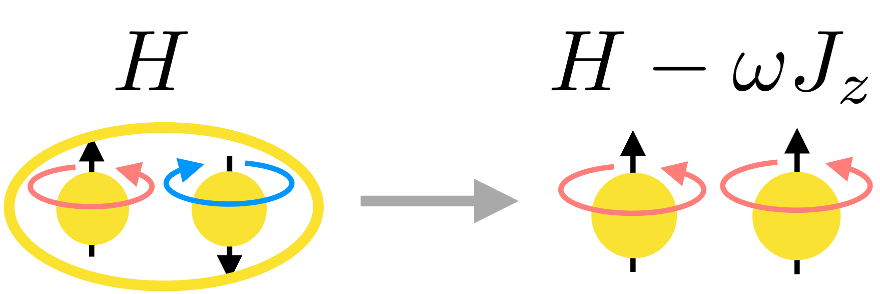


chiral restoration favored

underlying physics

1. low-energy modes suppression by $\omega J_z \sim \mu N$

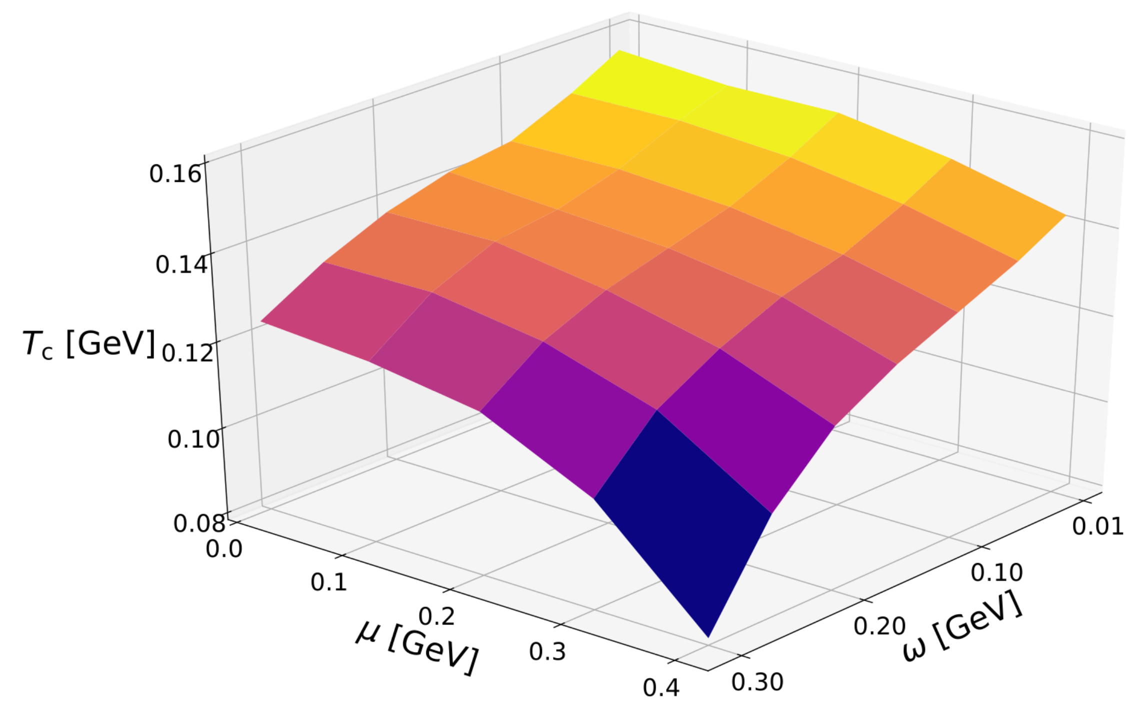
2. spin-alignment



Confinement

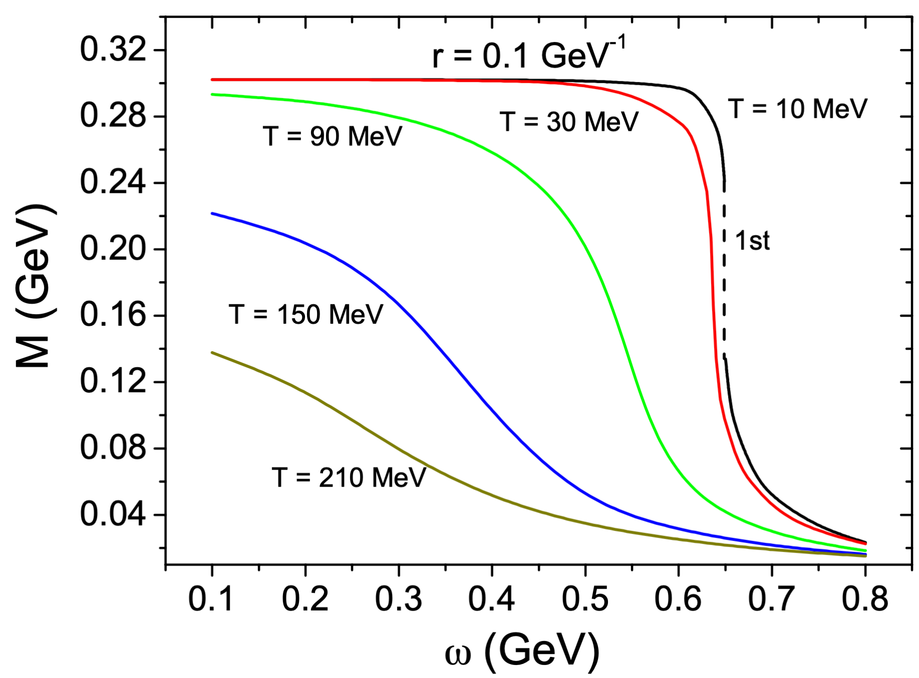
deconfinement favored

Fujimoto-Fukushima-Hidaka (2021)

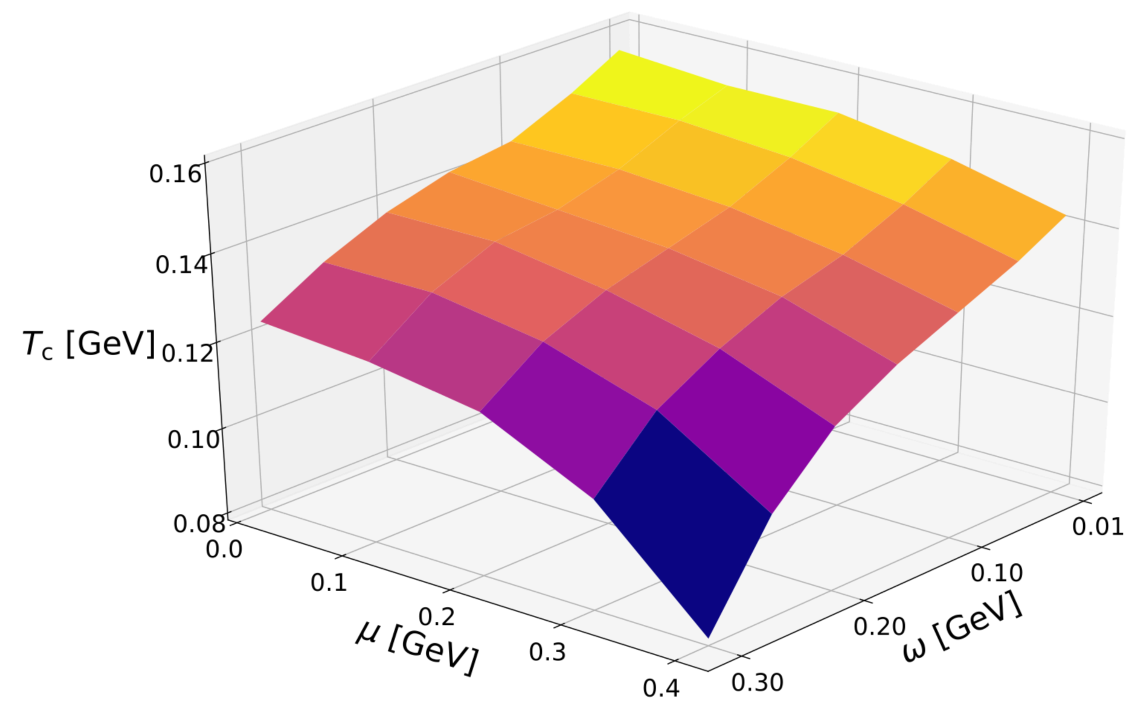


Rotational effect on QCD thermodynamics

Jiang, Liao (2016)



Fujimoto-Fukushima-Hidaka (2021)



"QGP favored?"

NJL
Chernodub-Gongyo (2017)

FRG
(QM model)
Chen-Zhu-Huang (2023)

HRG

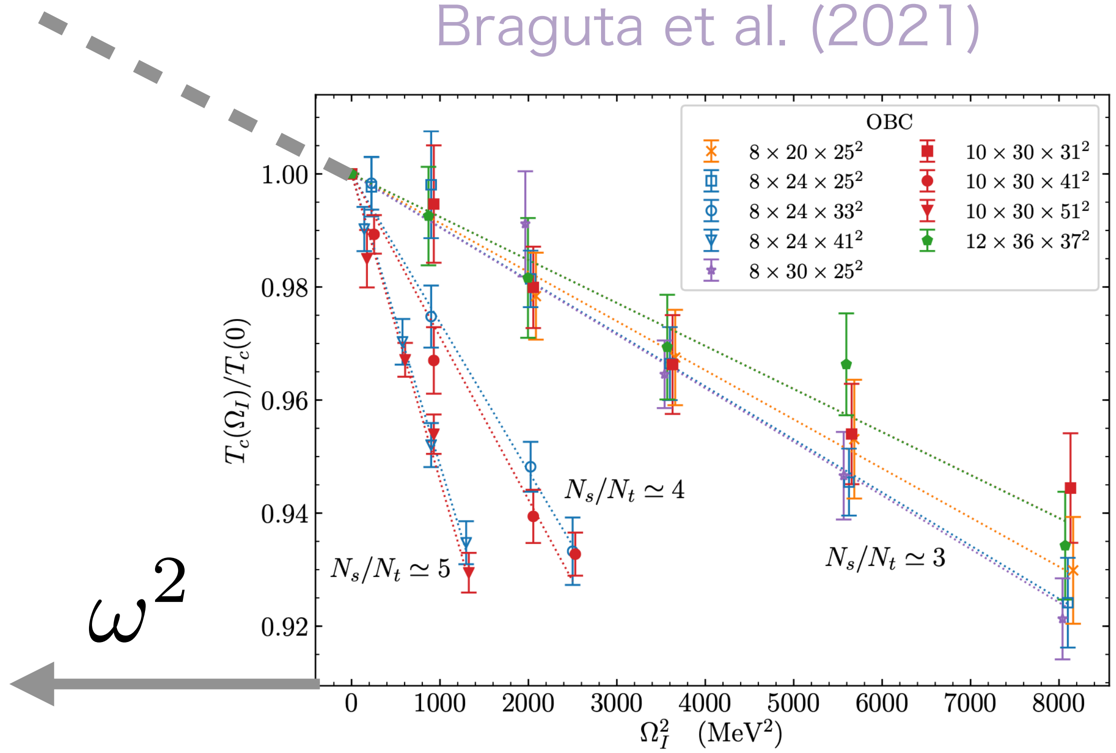
1-loop
perturbation
Chen-Fukushima-Shimada (2022)

holography
Chen-Li-Huang (2022)
Chen-Zhang-Li et al. (2021)
Braga-Faulhaber-Junqueira (2022)

How about lattice QCD?

Euclidean rotation

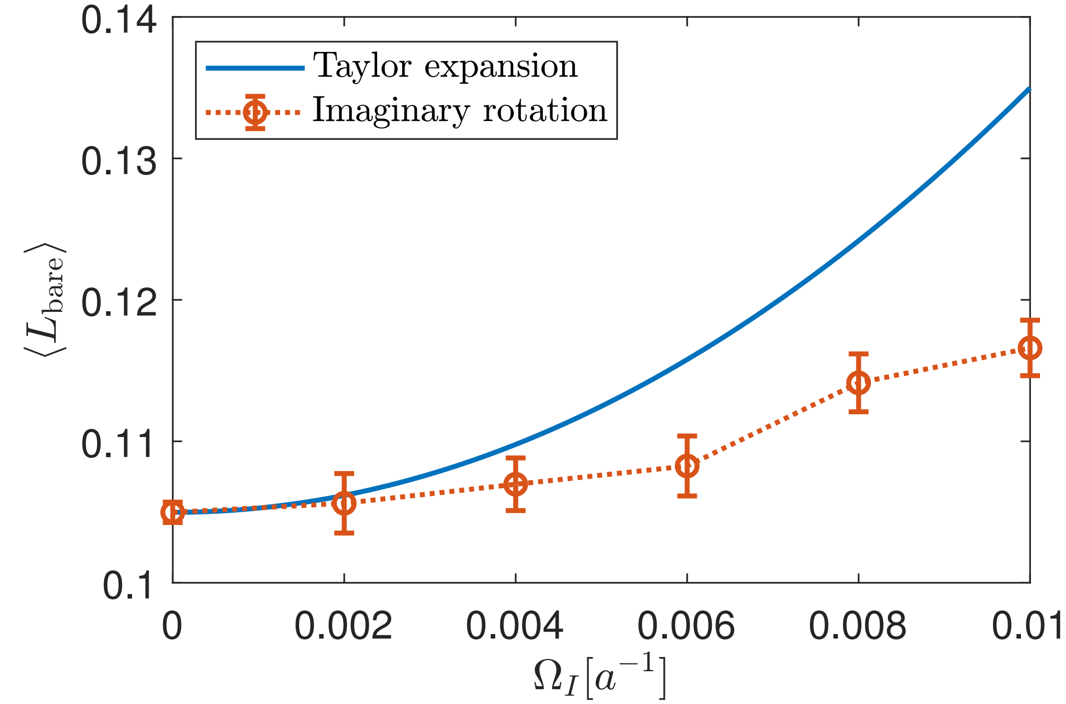
Braguta et al. (2021)



due to analytical structure?

Minkowskian rotation

Yang-Huang (2023)



seems not

~~“QGP favored?”~~

“Hadronic phase favored!”

Where the difference comes from

- lattice QCD

$$H_{\rm QCD} \longrightarrow H_{\rm QCD} - \omega J_{\rm QCD}$$

- model approaches

$$H_i \longrightarrow H_i - \omega J_i$$

for **free** particles $i = q, g, \pi, \cdots$

with unchanged model parameter (≃ nonperturbative interactions)

Justified?

See Yin Jiang's talk

$q, \bar{q}$: directly affected by ω

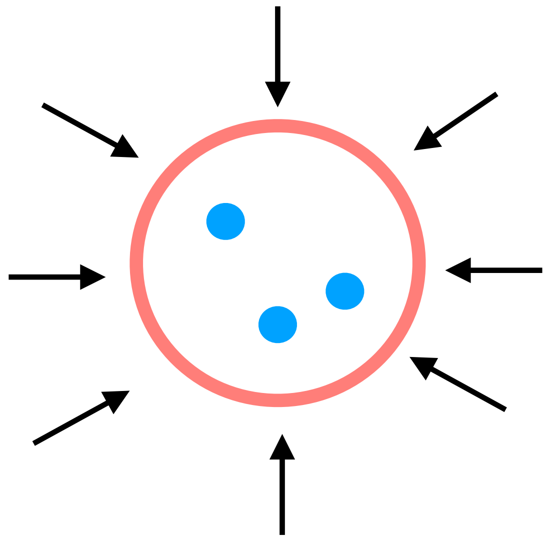
$g, c, \bar{c}$

cf.) inverse magnetic catalysis Bali, Bruckmann, Endrodi et al. (2012)

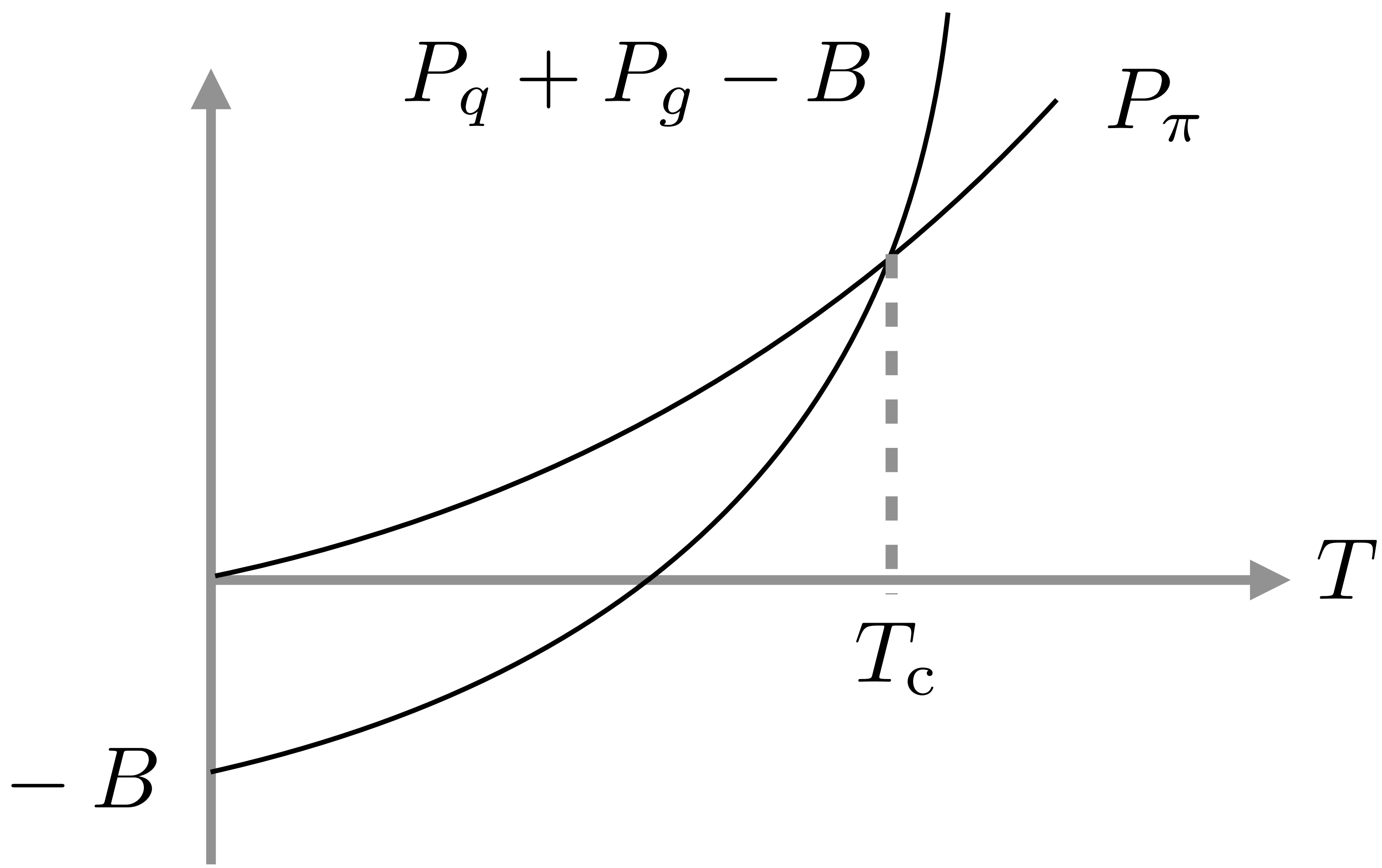
Bag model

confinement + asymptotic freedom

Chodos-Jaffe-Johnson et al. (1974)



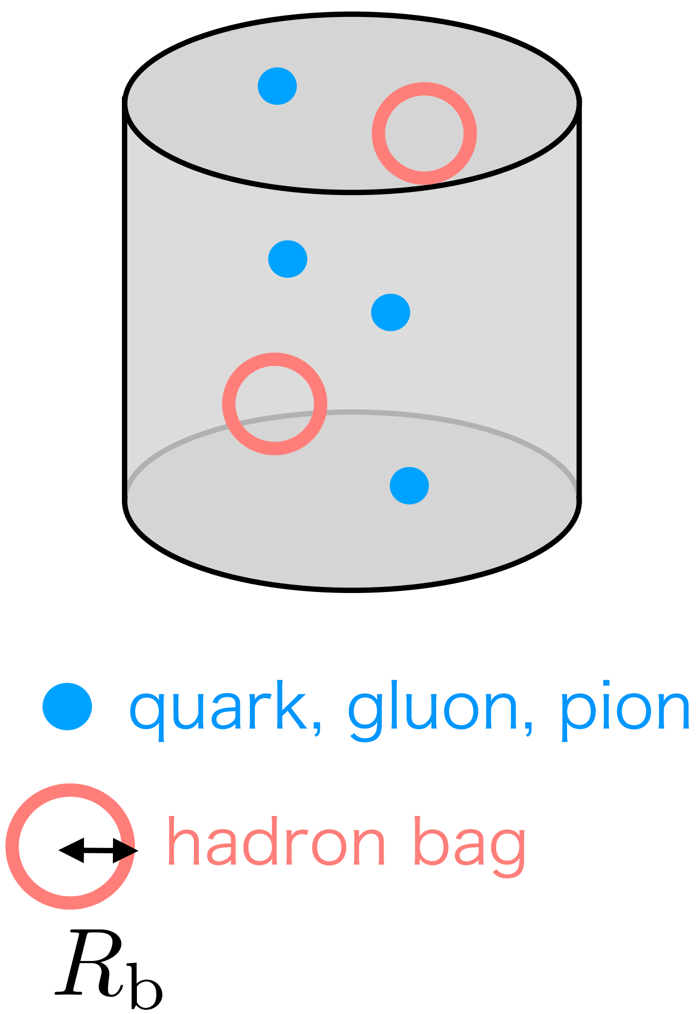
$$B := \epsilon_{\mathrm{pert}} - \epsilon_{\mathrm{QCD}}$$



Static bag model

criterion

$$P_\pi(T) = P_q(T) + P_g(T) - B$$



✓ $$P = \pm T \sum_p \ln\left[1 \pm \mathrm{e}^{-\epsilon/T}\right]$$

✓ B : Dirac eq. in static cavity

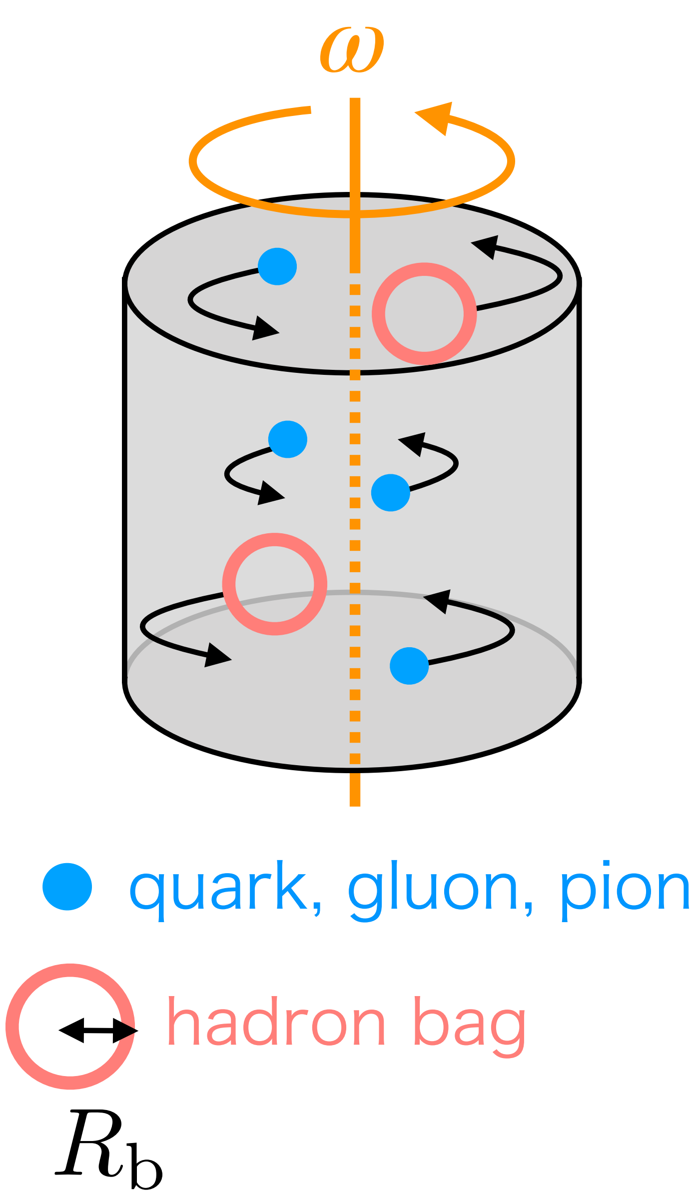
$$E_p = 3 \cdot \frac{\alpha}{R_\mathrm{b}} + \frac{4\pi}{3} R_\mathrm{b}^3 B$$

$$\frac{\mathrm{d}E_p}{\mathrm{d}R_\mathrm{b}} = 0, \quad E_p = M_p$$

Revolving bag model

criterion

$$P_\pi(T,\omega) = P_q(T,\omega) + P_g(T,\omega) - B(\omega)$$



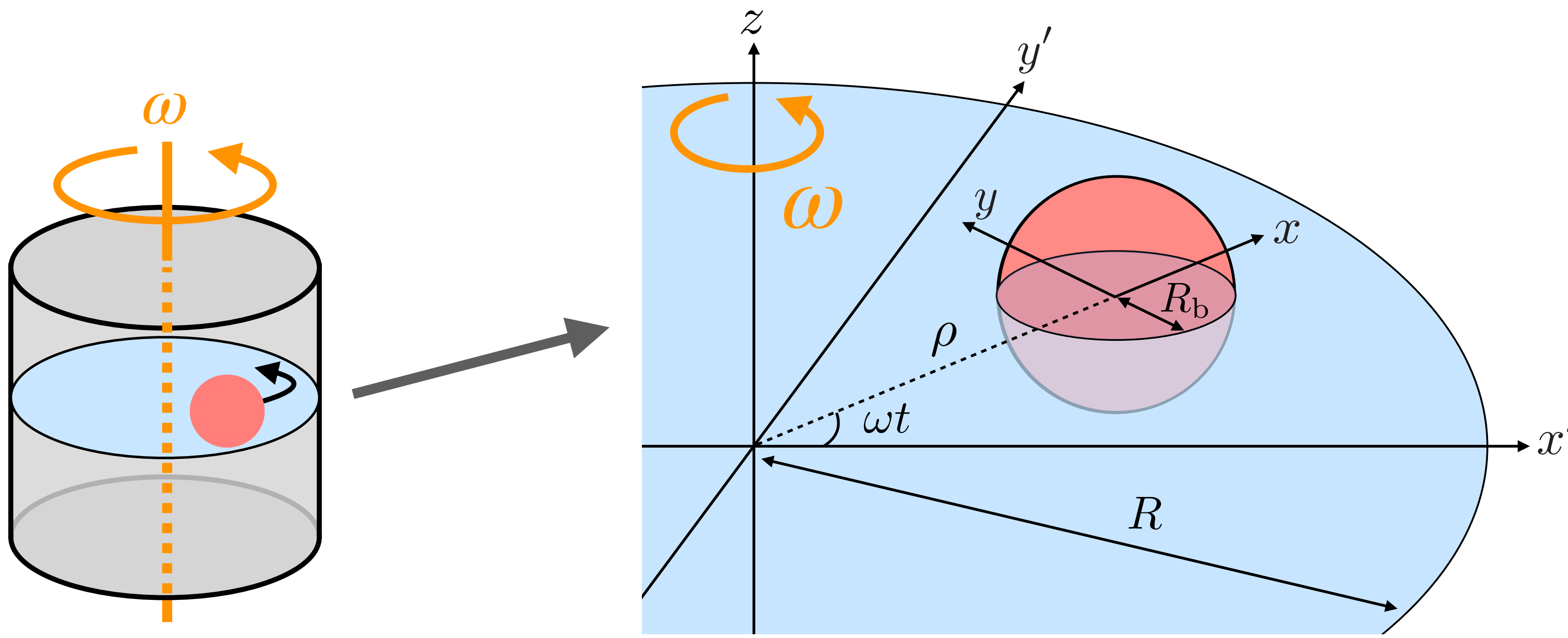
✓ $$P = \pm T \sum_p \ln\left[1 \pm \mathrm{e}^{-(\epsilon - \omega j_z)/T}\right]$$

✓ B : Dirac eq. in revolving cavity

$$E_p = 3\left[\frac{\alpha}{R_\mathrm{b}} + \Delta E(\omega)\right] + \frac{4\pi}{3}R_\mathrm{b}^3 B(\omega)$$

$$\frac{\mathrm{d}E_p}{\mathrm{d}R_\mathrm{b}} = 0, \quad E_p = M_p$$

Dirac eq. in bag coordinate



radial infinite potential well

$$(H_0 + H')\psi = E\psi \qquad H_0 = \gamma^0(-\mathrm{i}\boldsymbol{\gamma}\cdot\boldsymbol{\nabla} + U)$$

$$H' = -\omega J_z + \mathrm{i}\omega\rho\partial_y$$

effect on nonperturbative interaction

perturbative correction

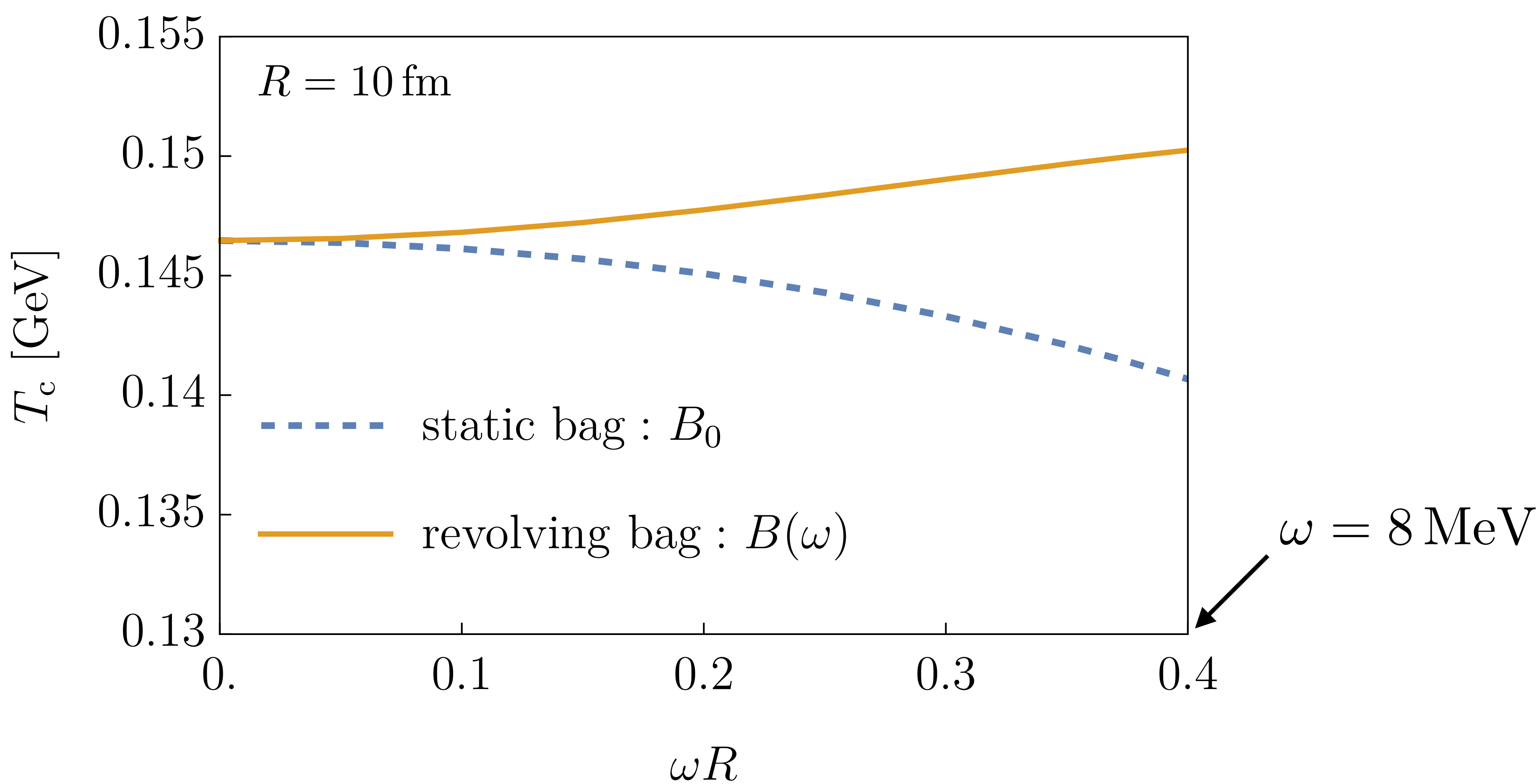
$$\Delta E(\omega)$$

bag constant

$$B(\omega) = B_0\left[1 + c(\omega R)^2\right]$$

Numerical result

KM-Takizawa (2023)



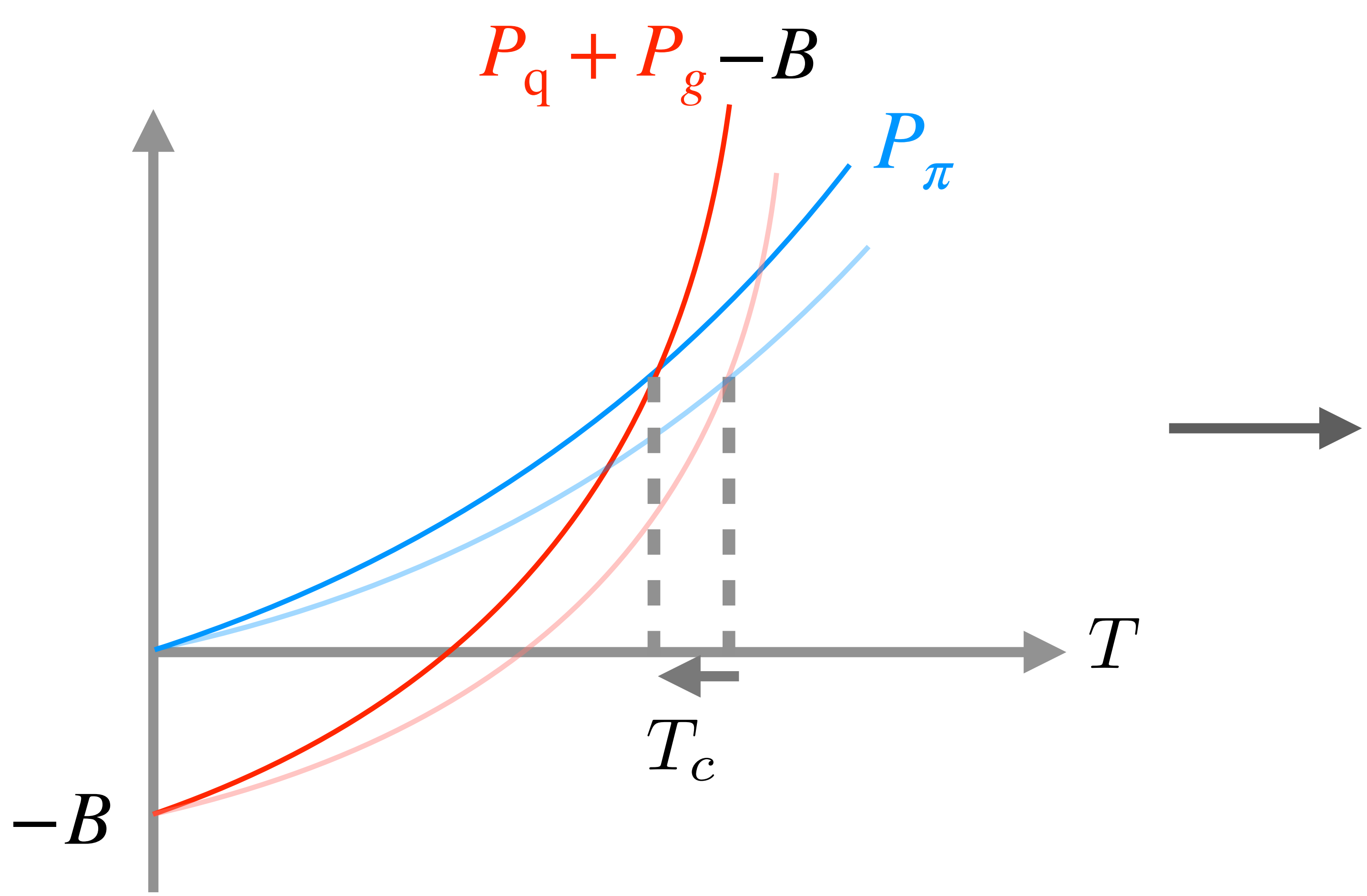
"QGP favored" static bag ⟷ other model approaches

"Hadronic phase favored" revolving bag ⟷ lattice QCD

Moment of inertias

static bag $$\Delta P_i \simeq \frac{1}{2V}\omega^2 I_i, \quad I_i \sim \langle J_i^2 \rangle$$

$$\Delta B = 0$$



$$I_q + I_g > I_\pi$$

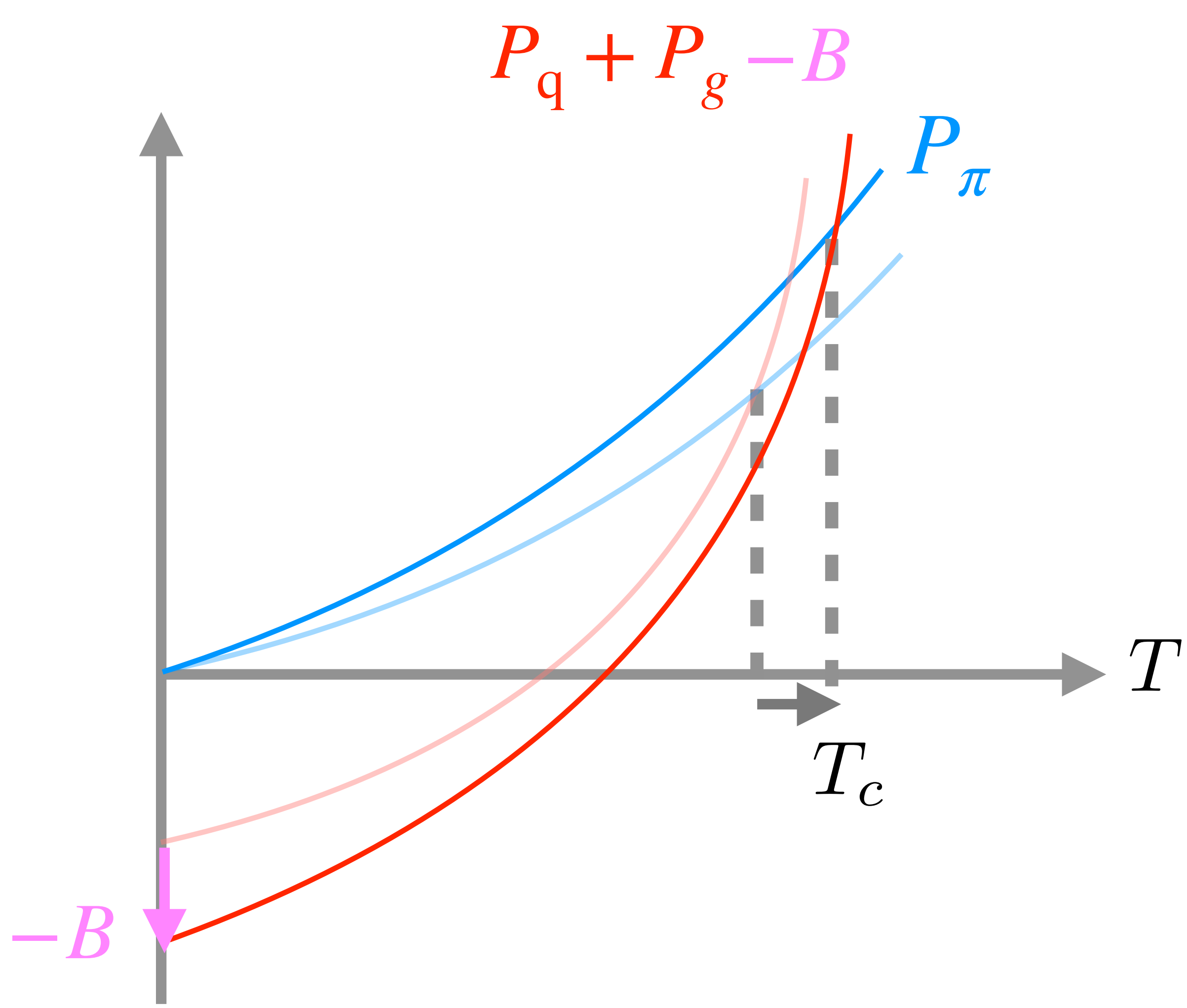
dof = 40 dof = 3

Moment of inertias

revolving bag

$$\Delta P_i \simeq \frac{1}{2V}\omega^2 I_i, \quad I_i \sim \langle J_i^2 \rangle$$

$$\Delta B \simeq \frac{1}{2V}\omega^2 I_\mathrm{b}, \quad I_\mathrm{b} \sim \int \mathrm{d}V \rho^2 B_0$$



$\longrightarrow$ $I_q + I_g - I_\mathrm{b} < I_\pi$

Moment of inertias

revolving bag

$$\Delta P_i \simeq \frac{1}{2V}\omega^2 I_i, \quad I_i \sim \langle J_i^2 \rangle$$

$$\Delta B \simeq \frac{1}{2V}\omega^2 I_\mathrm{b}, \quad I_\mathrm{b} \sim \int \mathrm{d}V \rho^2 B_0$$

I_b = moment of inertia of $B_0 \sim \epsilon_\mathrm{QCD} \sim \langle (F^a_{\mu\nu})^2 \rangle_\mathrm{vac}$

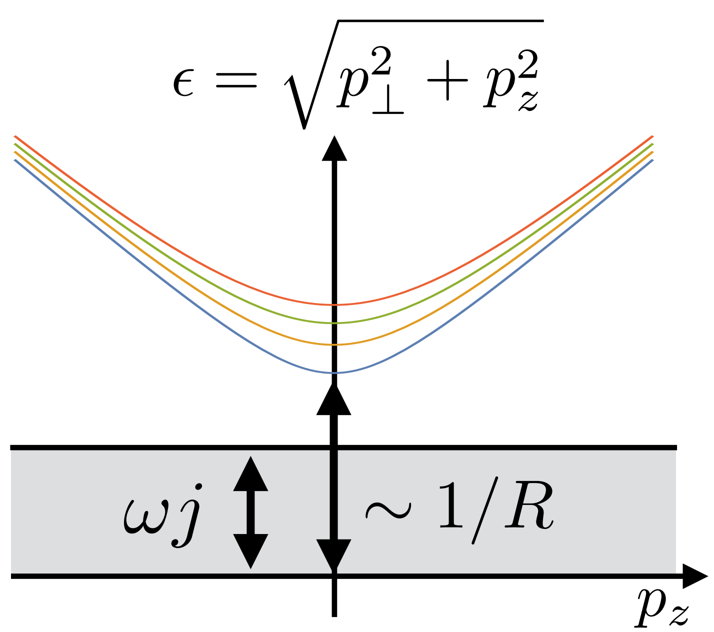
neglected
static bag ⟷ other model approaches

taken into account
revolving bag ⟷ lattice QCD

Vacuum affected by rotation?

causality $\omega R < 1$ → discrete momentum $p_\perp \sim 1/R$ → $\epsilon = \sqrt{p_\perp^2 + p_z^2} > \omega j$

Ambrus-Winstanley (2016)



$$n_{\rm F} = \frac{1}{e^{\beta(\epsilon - \omega j)} + 1} \xrightarrow[T \to 0]{} \theta(\omega j - \epsilon) = 0$$

NO visible rotational effect

Ebihara-Fukushima-KM (2017)

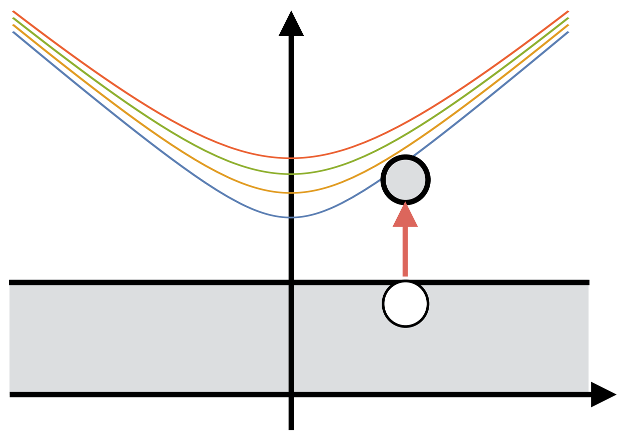
robust property

MIT b.c. Chernodub-Gongyo (2017)

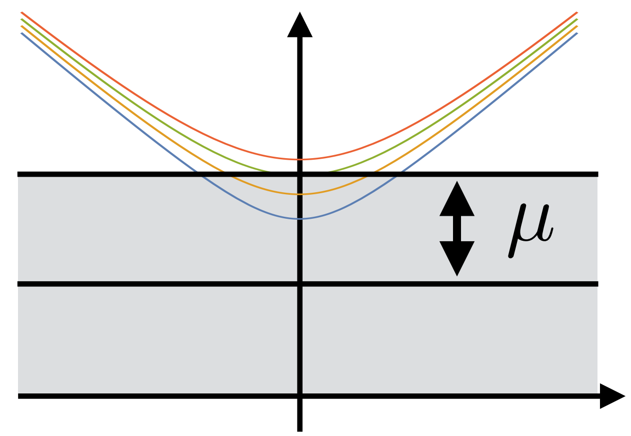
spherical MIT b.c. Zhang-Shi-Luo-Zong (2020)

When visible?

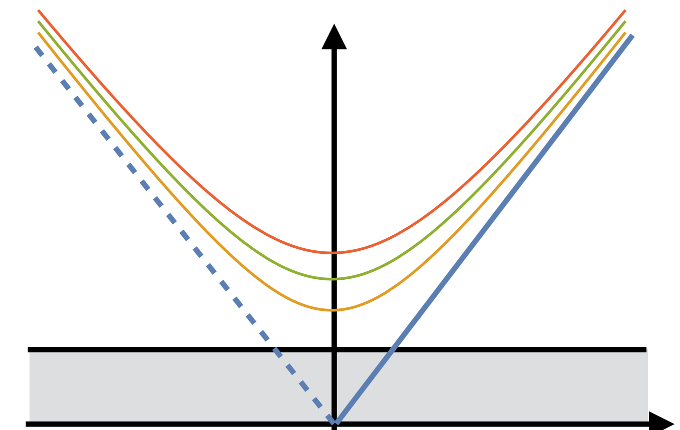
temperature



density



magnetic field



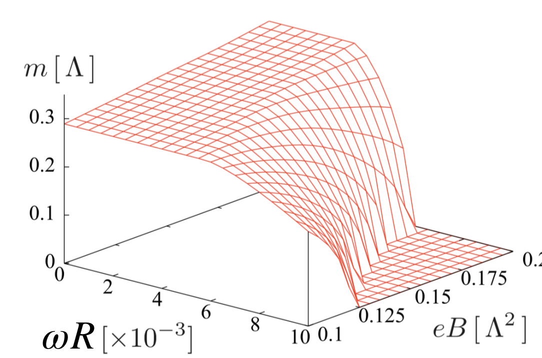
Landau quantization

CVE Vilenkin (1979)

$$J = \left(\frac{\mu^2}{4\pi^2} + \frac{T^2}{12} \right) \omega$$

NJL under B

Chen-Fukushima-Huang-KM (2016)



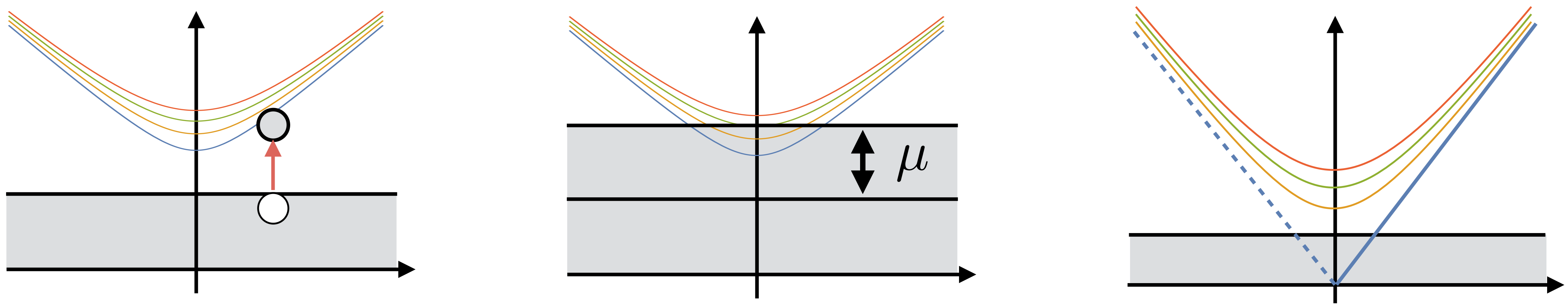
magneto-vortical transport

Hattori-Yin (2016)

$$J^0 = \frac{eB\omega}{4\pi^2}$$

When visible?

temperature | density | color magnetic field



Landau quantization

QCD vacuum = color magnetic media

$$E = \sqrt{p_z^2 + 2|g\mathcal{B}|(n + 1/2 - 2s_z)} \longrightarrow$$ vacuum energy, β-function

Savvidy (1977) Nielsen-Olesen (1978)
Nielsen-Ninomiya (1979)

invisible in perturbative vacuum

$$\theta(\omega j - \epsilon) = 0$$

visible in QCD vacuum

$$B(\omega) = B_0\left[1 + c(\omega R)^2\right]$$

reason of negative MoI? Braguta-Chernodub-Roenko (2023)

Summary

- We developed the revolving bag model

- This model fills a gap between other models and lattice

revolution of confinement potential $\simeq$ moment of inertia of condensate

- The rotational effect on **QCD vacuum** is much important (unlike that on the perturbative vacuum)

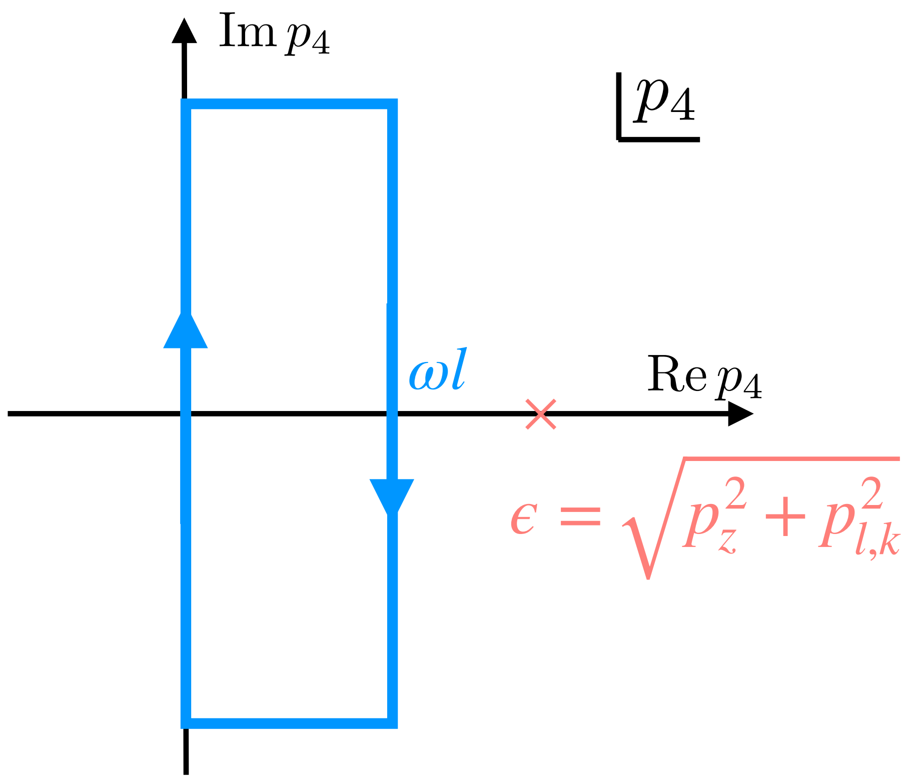
- We need a perturbative/nonperturbative analysis rotating matter

Perturbation theory of rotating scalar

KM-Kuboniwa (in prep.)

$$\Pi_1(l,k) = 12\lambda \frac{1}{\pi R^2} \sum_{l',k'} \int \frac{\mathrm{d}p_z}{2\pi} I\left(l,l',k,k'\right) \frac{1}{2\epsilon} \left(\frac{1}{\mathrm{e}^{\beta(\epsilon-\omega l')}-1} + \frac{1}{\mathrm{e}^{\beta(\epsilon+\omega l')}-1} \right)$$

$$+12\lambda \frac{1}{\pi R^2} \sum_{l',k'} \int \frac{\mathrm{d}p_4}{2\pi} \int \frac{\mathrm{d}p_z}{2\pi} I\left(l,l',k,k'\right) \frac{1}{p_4^2+\epsilon^2}$$



No rotational effect at zero temperature