Chiral symmetry breaking in accelerating and rotating frames

Based on PRD 113, 034005 (2026)

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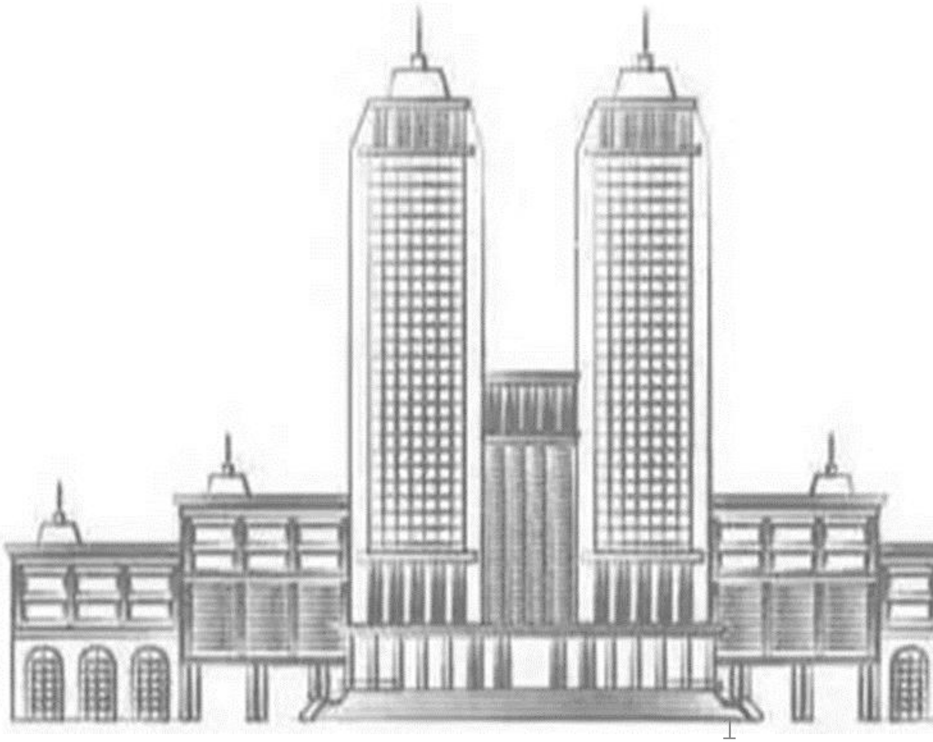


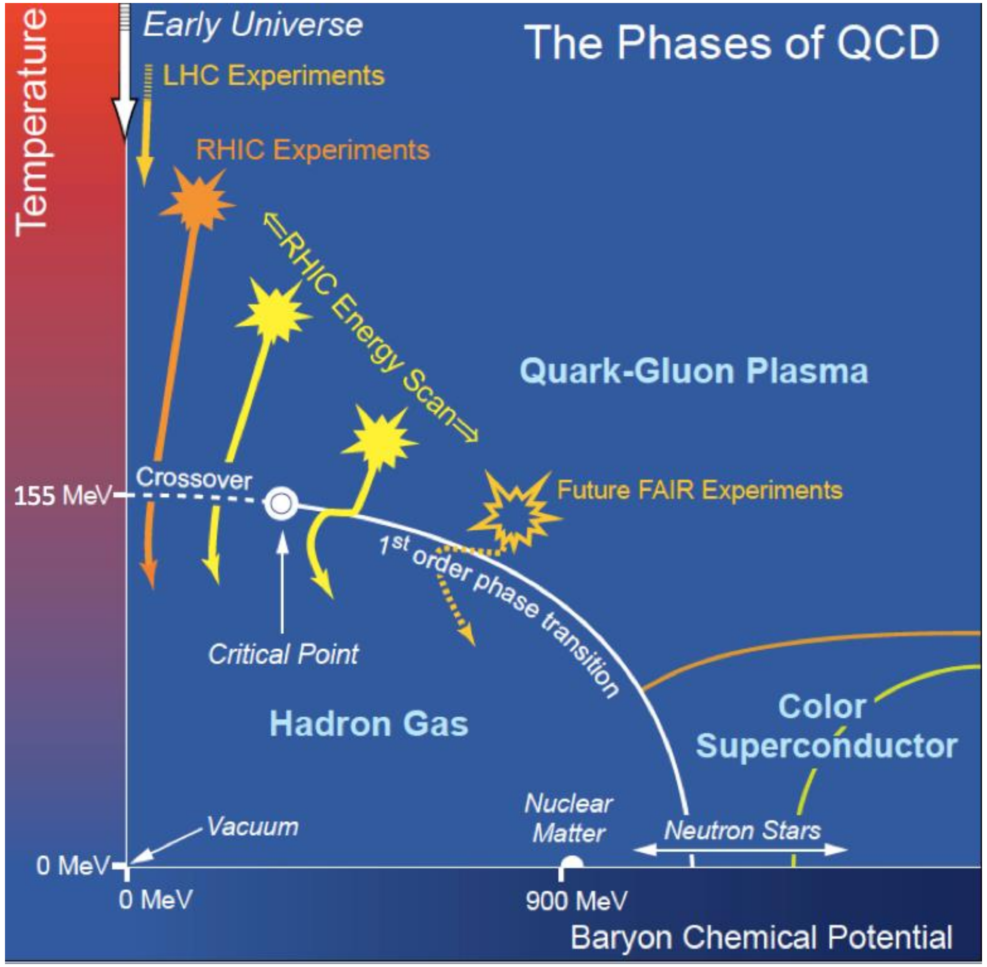
Outline

- QCD phase transition: $T-\mu,\omega,a$
- Puzzle of rotation and acceleration
- Chiral symmetry under acceleration

  NLσ model analysis and NJL model analysis

  The dependence of the renormalization scheme
- Under rotation and acceleration
- Summary

QCD phase transition



Order parameter for chiral phase transition:

Chiral condensate $<\bar{\psi}\psi>$

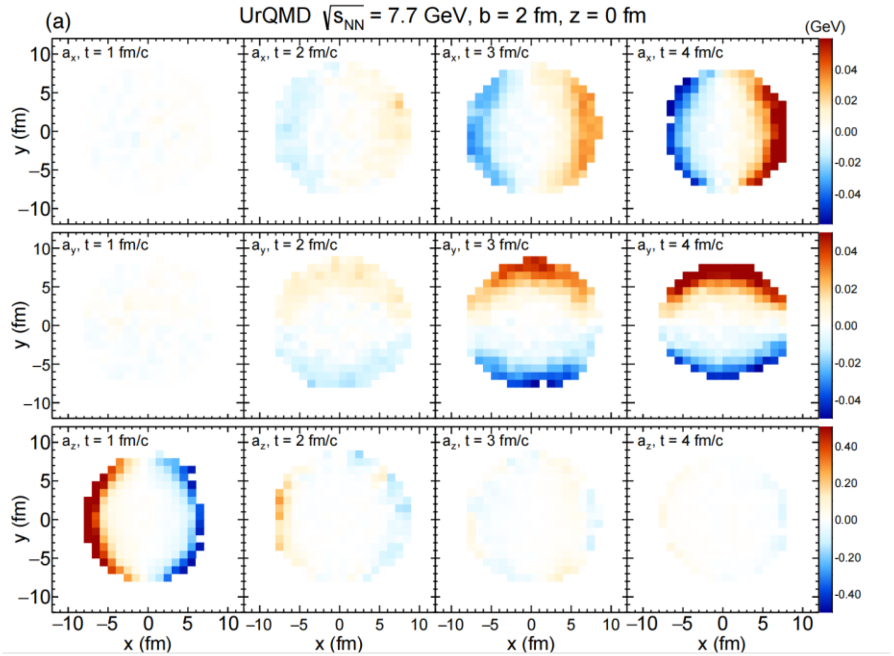
Hardronic phase $<\bar{\psi}\psi>\neq 0$ Chiral symmetry breaking

QGP phase $<\bar{\psi}\psi>=0$ Chiral symmetry restored

In this work, we study the phase structure under rotation and acceleration

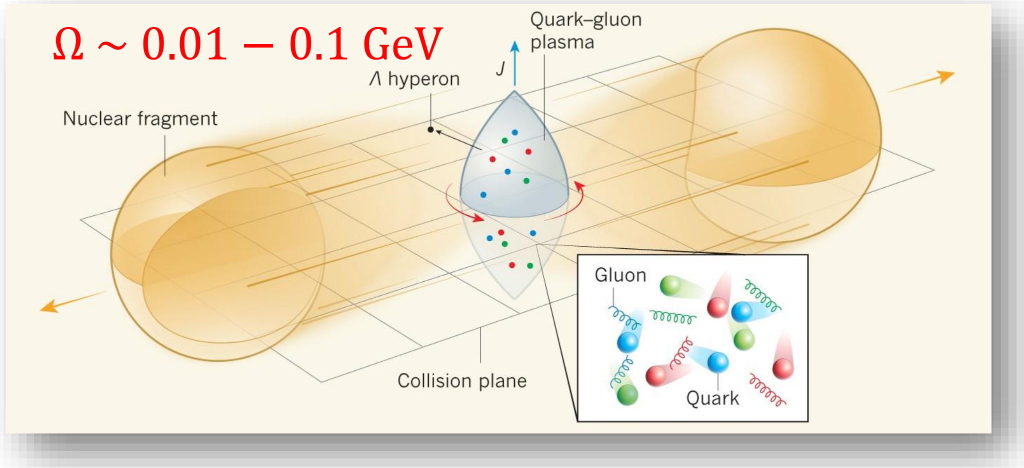
Why do we need to consider rotation and acceleration?

Rotation and Acceleration in Heavy-Ion Collisions



The UrQMD simulation result for the acceleration distribution.

Taken from arXiv:2604.00302

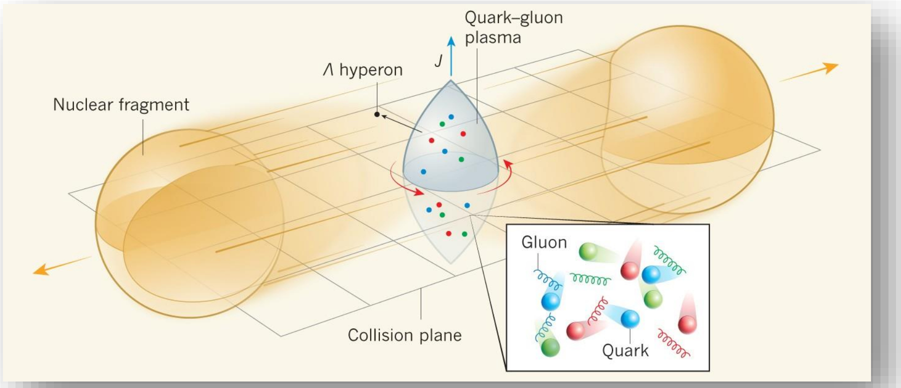


In heavy ion collisions, the acceleration can reach a scale of about 0.1 GeV.

In a non-central collision, there exists a rapid rotation.

What effect will come from rotation and acceleration?

Acceleration and Rotation Effects



$$\mathrm{H} \rightarrow \mathrm{H} - \mathrm{J} \cdot \Omega$$

•In a rotating system, the Hamiltonian acquires an additional term, which allows rotation to be interpreted as an effective chemical potential. Therefore, it is natural to expect that rotation will have a nontrivial impact on the QCD phase transition.

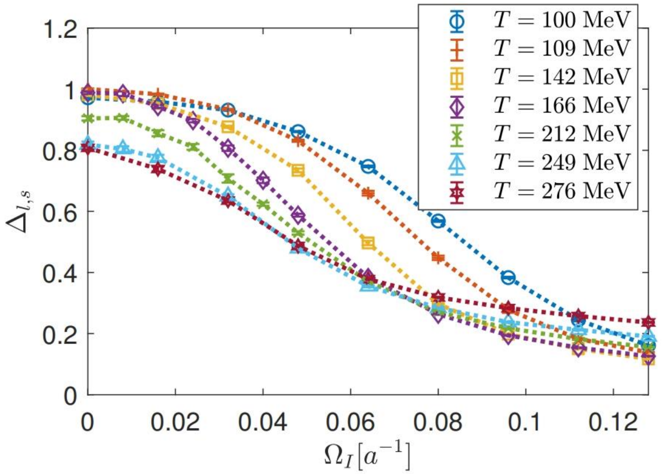
$$T = a/2\pi$$

•According to the Unruh effect, a uniformly accelerated observer with proper acceleration a perceives the Minkowski vacuum as a thermal bath at temperature $T = a/2\pi$. This suggests that acceleration may also influence the phase transition.

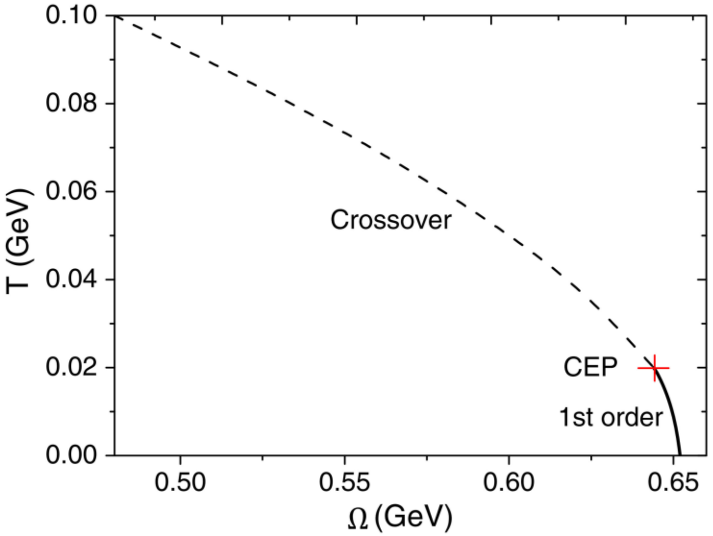
Puzzle of rotation

Lattice VS model

$\Omega\uparrow\rightarrow\ \mathrm{T_c}\downarrow$ VS $\Omega\uparrow\rightarrow\ \mathrm{T_c}\uparrow$



Ji-Chong Yang and Xu-Guang Huang arxiv:2307.05755



Y. Jiang and J. Liao, Phys. Rev. Lett. 117, 192302 (2016) arXiv:1606.03808

•**Effective models:**: Rotation **suppresses** chiral condensate→ T_c decreases with Ω

Lattice QCD（imaginary rotation）:

As Ω_I increases:

•Chiral condensate ↓ ,Polyakov loop ↑→ Analytic continuation would imply real rotation **enhances** chiral symmetry breaking.

Possible sources of discrepancy:

•Limitations of mean-field approximation?

•Limitations of effective models?

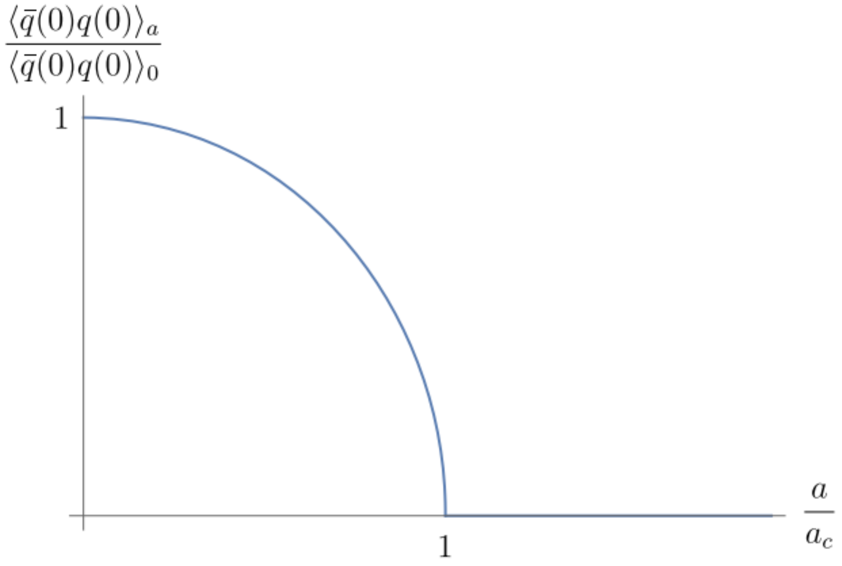
•Can lattice results be extrapolated to real rotation?

•Role of gluons? …

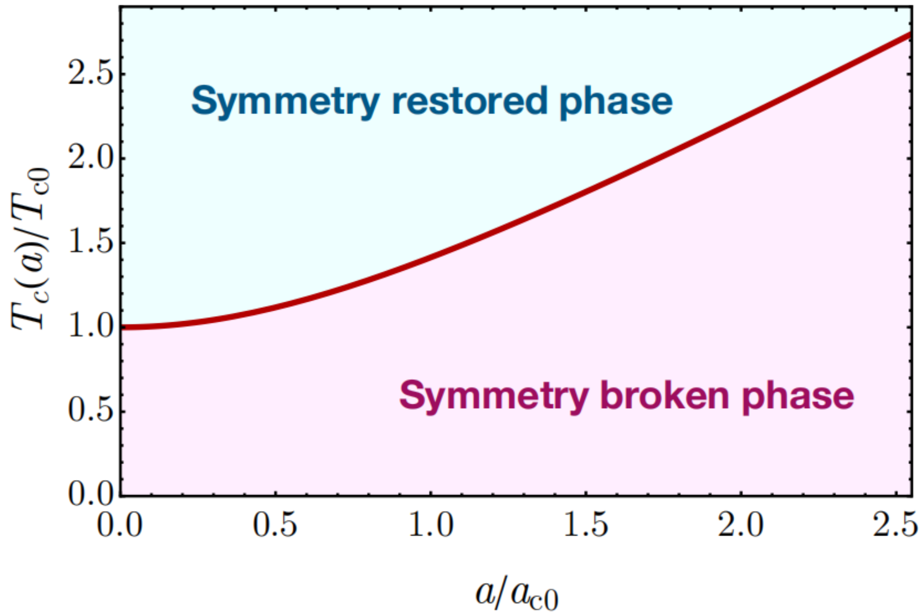
Puzzle of acceleration

Restoration vs. Breaking

$a \uparrow \rightarrow \mathrm{T_c} \downarrow$ VS $a \uparrow \rightarrow \mathrm{T_c} \uparrow$



Casado-Turrión, Adrián, and Antonio Dobado. *Physical Review D* 99.12 (2019): 125018.



Chernodub, Maxim N. *arXiv:2501.16129* (2025)

- Some works: $a \uparrow$ → **restoration** of chiral symmetry
- Other works: $a \uparrow$ → **breaking** of chiral symmetry

The renormalization scheme is the key issue.

Framework

We use the quantum field theory in curved spacetime and adopt two low-energy effective models.

	NLσM (Bosonic)	NJL (Fermionic)
DOF	σ, π^a	$\psi, \bar{\psi}$
Order parameter	$\sigma = \langle \sigma \rangle$	$\sigma = -G_\pi \langle \bar{\psi}\psi \rangle$
Method	Klein-Gordon eq. in curved spacetime	Dirac eq. in curved spacetime
Why used	Cross-check, scalar case	Quark DOF, more realistic

NLσ model Lagrangian: $$\mathcal{L}_{NL\sigma M} = -\frac{1}{2}\Phi^T \Box \Phi - M_\pi^2 f_\pi \sigma$$

NJL model Lagrangian: $$\mathscr{L}_{NJL} = \bar{\psi}\left[i\gamma^\mu \nabla_\mu - m_0\right]\psi + \frac{G_\pi}{2}\left[(\bar{\psi}\psi)^2 + \left(\bar{\psi} i\gamma^5 \boldsymbol{\tau}\psi\right)^2\right]$$

We work in Rindler spacetime(accelerating coordinate).

$$ds^2 = \xi^2 dt^2 - d\xi^2 - dx_\perp^2$$

Route:
Solve KG/Dirac eq. → Propagator G(x,x) → Gap eq. → σ(a, T)

The propagator G(x,x) is divergent, which means we need to introduce the choice of a renormalization scheme：

Subtraction of Rindler vacuum vs Minkowski vacuum

→ two different phase diagrams

Rindler coordinates

Rest frame of a uniformly accelerated observer
→ Rindler coordinates Metric

Metric: $ds^2 = \xi^2 dt^2 - d\xi^2 - dx_\perp^2$

A uniformly accelerated observer is stationary at point $\xi = \frac{1}{a}$ in Rindler coordinates.

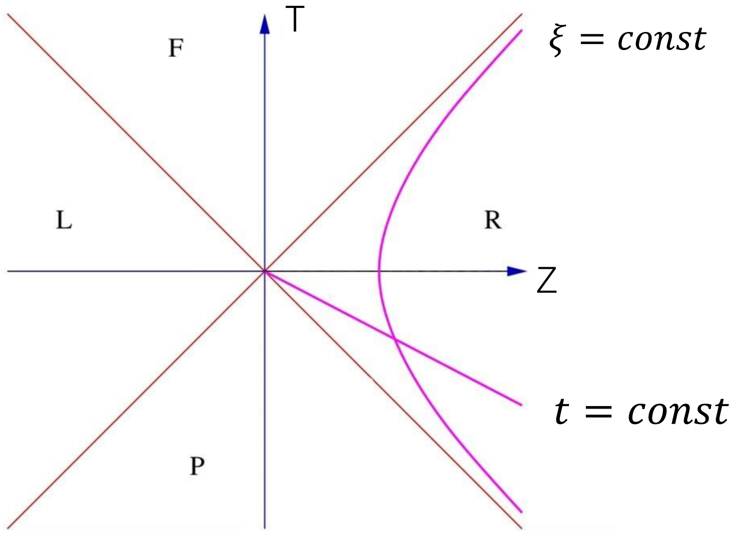
Unruh Effect: A uniformly accelerated observer (a **Rindler observer**) perceives the Minkowski vacuum as a thermal bath with temperature

$$T_U = a/(2\pi)$$

Vacuum Ambiguity

The **Rindler vacuum** $|0\rangle_R$ is not equivalent to the **Minkowski vacuum** $|0\rangle_M$.

This inequivalence leads to two distinct renormalization schemes.



Define the **creation** and **annihilation** operators for Rindler spacetime: ： $a_R(\omega)$ 和 $a_R^\dagger(\omega)$,

According to the definition, it satisfies: $a_R|0\rangle_R=0$

The particle number operator satisfies：

$${}_M\langle 0|a_R^\dagger a_R\,|0\rangle_M \sim \left(exp\left(\frac{2\pi\omega}{a}\right) - 1\right)^{-1}$$

(For boson)

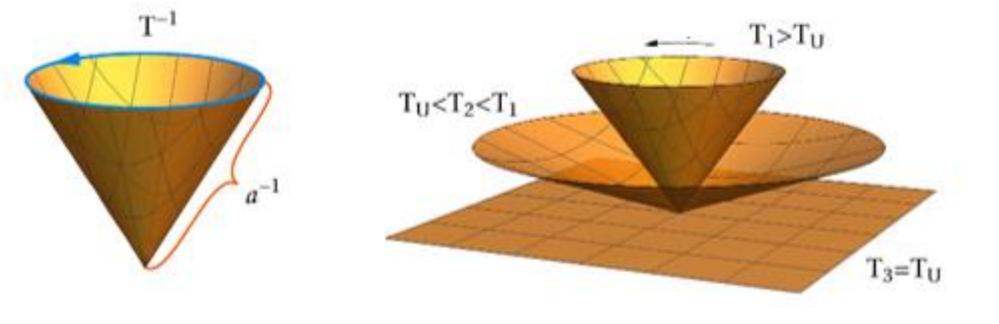
Euclidean Rindler spacetime

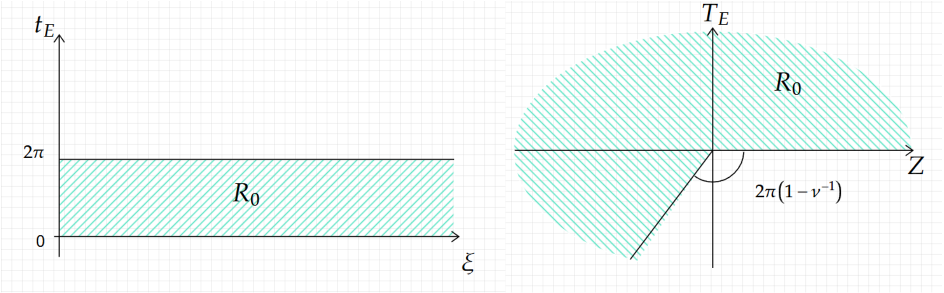
The Euclidean Rindler coordinate:

$$\boldsymbol{ds^2 = -\frac{\xi^2}{\nu^2} dt_E - d\xi^2 - dx_1^2 - dx_2^2}$$

where the Euclidean time is periodic,

$$0 < t_E < 2\pi,\ \ \nu = 2\pi \mathrm{T}/a$$





Regularity condition

•$\nu = 1(T = T_U)$
- the Euclidean geometry is smooth;
- the conical singularity disappears.

•$\nu > 1(T > T_U)$
- a positive angular deficit (conical geometry) appears.

•$\nu < 1(T < T_U)$
- the angular deficit becomes negative;
- The geometry meaning becomes unclear
- Indicating an unstable stage

To avoid a negative angular deficit, we impose $\nu \geq 1$ in this work, which leads to the condition $T \geq T_U$.

Renormalization in the NLσ Model

The diagonal part of Green function: $G_\nu(x_E, x_E; m=0) = \int_0^\infty \frac{\mathrm{d}\omega}{\pi^2} \frac{1}{(2\pi)} \coth(\omega\beta_R/2) \frac{\pi\omega}{2\xi^2}$

I: Subtract the Rindler vacuum expectation value

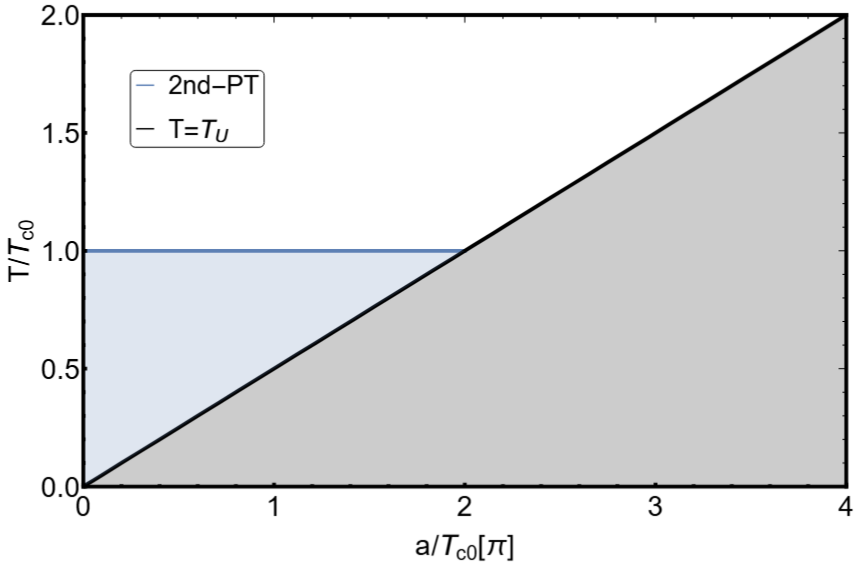
$$\langle \hat{O} \rangle_{ren} = \langle \hat{O} \rangle_\beta - \langle \hat{O} \rangle_R$$

$$\sigma^2 = f_\pi^2 - \frac{T^2}{a^2\xi^2} \frac{N}{12}$$

$$T_c = a\xi \sqrt{\frac{12 f_\pi^2}{N}}$$

The position of the accelerating observer:

$$\xi = 1/a$$



II: Subtract the Minkowski vacuum expectation value

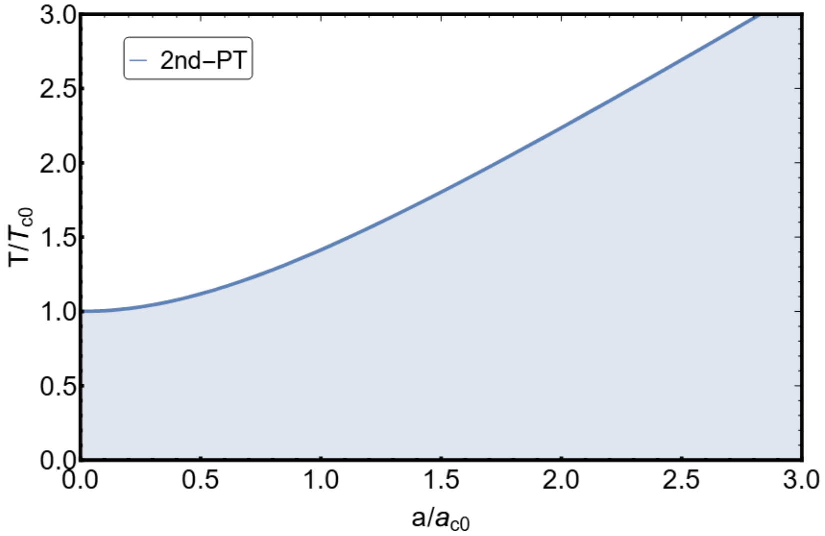
$$\langle \hat{O} \rangle_{ren} = \langle \hat{O} \rangle_\beta - \langle \hat{O} \rangle_M$$

$$\sigma^2 = f_\pi^2 - \frac{1}{(a\xi)^2} \frac{N}{12} \left(T^2 - \frac{a^2}{(2\pi)^2} \right)$$

$$T_c(a) = \sqrt{\frac{12 f_\pi^2}{N} + (\frac{a}{2\pi})^2}$$
$$= \sqrt{T_{c0}^2 + (\frac{a}{2\pi})^2}$$

The position of the accelerating observer:

$$\xi = 1/a$$



Different vacuum choices lead to different result.

NJL model analysis

The Green's function $\boldsymbol{G}$ is

$$G_\nu = \int_0^\infty \mathrm{d}\omega \int \frac{\mathrm{d}^2\mathbf{k}}{(2\pi)^2} \frac{\sinh(\beta_R\omega/2 - \omega|t_E - t'_E|)}{\cosh(\beta_R\omega/2)} \frac{\sinh\pi(\omega + i\gamma^{\hat{0}}\gamma^{\hat{3}}/2)}{\pi^2} K_{i\omega-\gamma^{\hat{0}}\gamma^{\hat{3}}/2}(m_\perp\xi) K_{i\omega-\gamma^{\hat{0}}\gamma^{\hat{3}}/2}(m_\perp\xi') e^{i\mathbf{k}\cdot(\mathbf{x}_1-\mathbf{x}_2)}$$

I: Subtract the Rindler vacuum expectation value

$$\begin{aligned} G_\nu(x_E, x_E; m=0) &= \int_0^\infty \mathrm{d}\omega \frac{\omega}{\pi^2\xi^2} \tanh(\beta_R\omega/2) \\ &= \int_0^\Lambda \mathrm{d}\omega \frac{\omega}{\pi^2 a^2\xi^2} + \int_0^\infty \mathrm{d}\omega \frac{\omega}{\pi^2 a^2\xi^2} \frac{2}{e^{\beta\omega}+1} \\ &= \frac{1}{6a^2\xi^2}\left(\frac{3\Lambda^2}{\pi^2} - T^2\right) \end{aligned}$$

The gap equation: $\frac{1}{G_\pi} = \frac{1}{6a^2\xi^2}\left(\frac{3\Lambda^2}{\pi^2} - T^2\right)$

The critical temperature is $T_c = a\xi\sqrt{\frac{3\Lambda^2}{\pi^2} - \frac{6}{G}}.$

II: Subtract the Minkowski vacuum expectation value

$$G_\nu^{ren}(x_E, x_E; m=0) = \frac{1}{6a^2\xi^2}\left(\frac{3\Lambda^2}{\pi^2} - T^2 + \frac{a^2}{(2\pi)^2}\right)$$

The critical temperature is

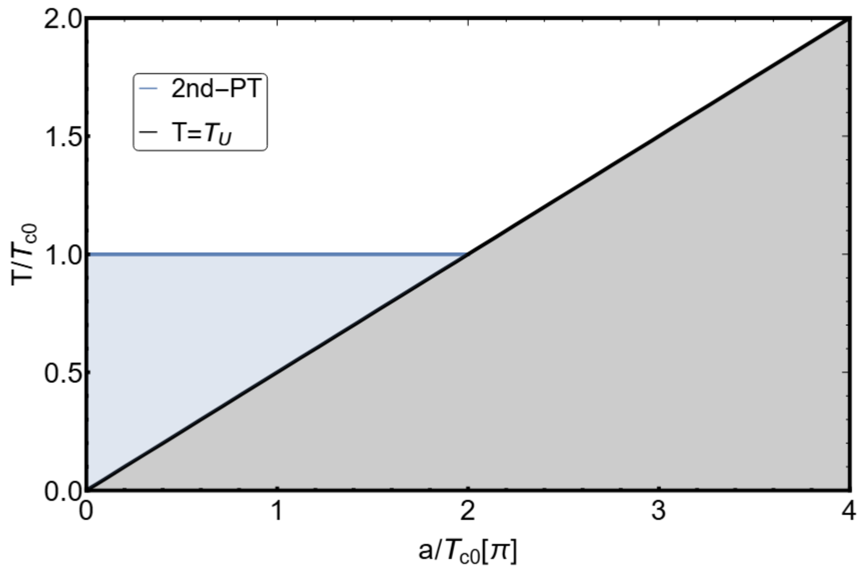
$$\begin{aligned} T_c(a) &= \sqrt{\frac{3\Lambda^2}{\pi^2} - \frac{6}{G} + \frac{a^2}{(2\pi)^2}} \\ &= \sqrt{T_{c0}^2 + (\frac{a}{2\pi})^2}, \end{aligned}$$

Regularization scheme

I: Subtract the Rindler vacuum expectation value

$$\langle \hat{O} \rangle_{ren} = \langle \hat{O} \rangle_{\beta} - \langle \hat{O} \rangle_{R} \qquad T_c = a\xi\sqrt{\frac{3\Lambda^2}{\pi^2} - \frac{6}{G_\pi}}$$

T_c is independent of acceleration

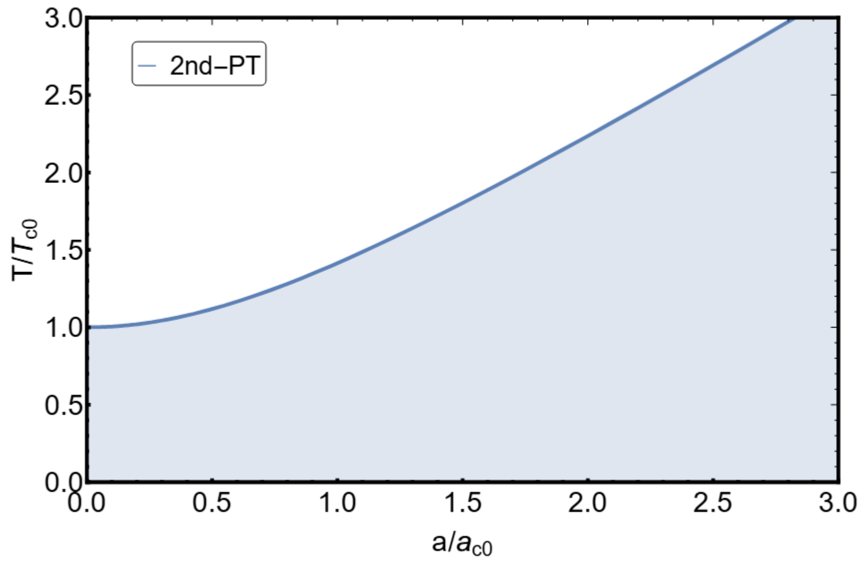


II: Subtract the Minkowski vacuum expectation value

$$\langle \hat{O} \rangle_{ren} = \langle \hat{O} \rangle_{\beta} - \langle \hat{O} \rangle_{M} \qquad T_c(a) = \sqrt{\frac{3\Lambda^2}{\pi^2} - \frac{6}{G} + \frac{a^2}{(2\pi)^2}}$$

$$= \sqrt{T_{c0}^2 + (\frac{a}{2\pi})^2}$$

T_c is enhanced by acceleration



The conclusion is independent of the effective model.

NJL Model under Acceleration and Rotation

Framework

Metric:

$$g_{\mu\nu} = \begin{pmatrix} \xi^2 - r^2\bar{\Omega}^2 & \bar{\Omega}y & -\bar{\Omega}x & 0 \\ \bar{\Omega}y & -1 & 0 & 0 \\ -\bar{\Omega}x & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$\Downarrow$

Solving the Dirac equation

$\Downarrow$

Gap equation

$\Downarrow$

Numerical solution

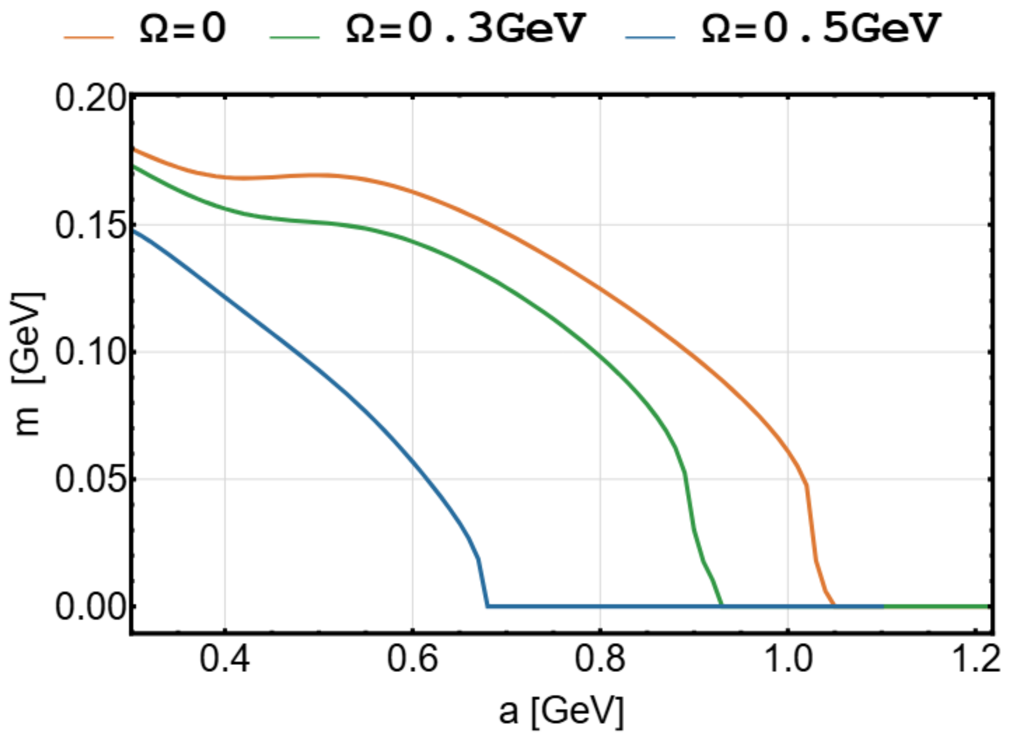
Assumptions

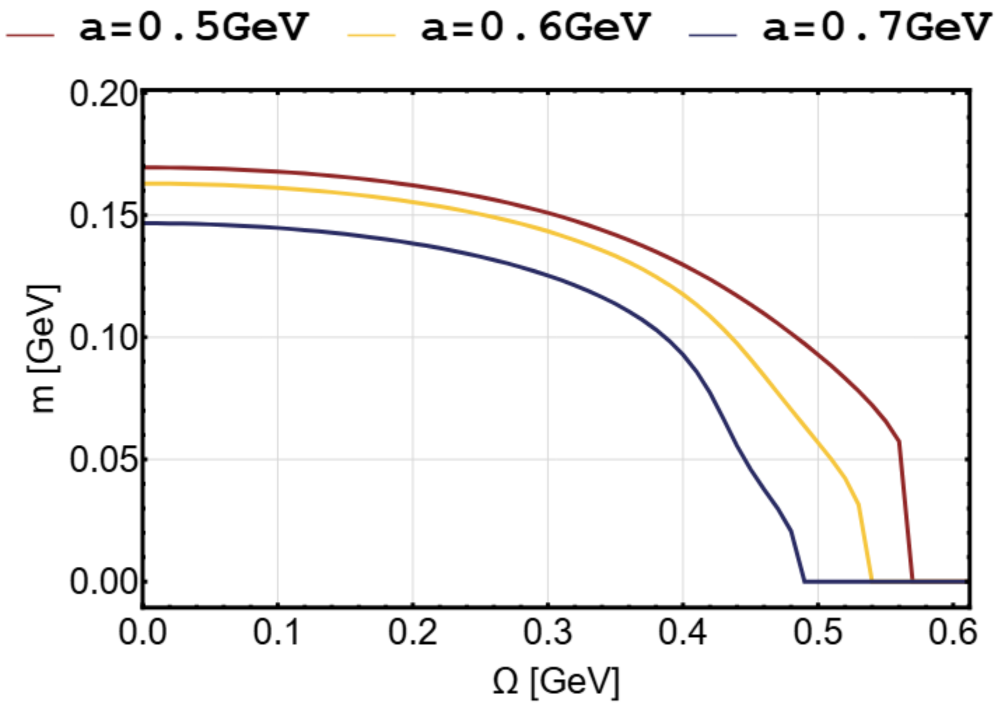
Acceleration and rotation are parallel.

We subtract the Rindler vacuum expectation

$$\boldsymbol{T = T_U}.$$

Result





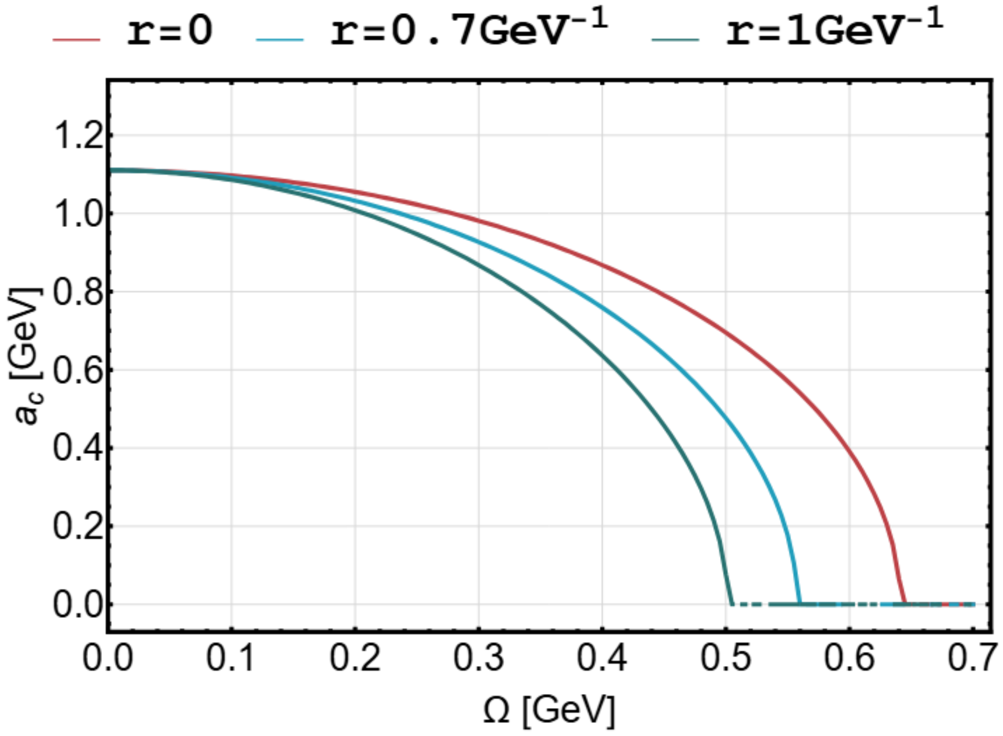
- **Acceleration induces thermalization**
- **Rotation induces an effective chemical potential**
- **Both acceleration and rotation restore chiral symmetry**

Analytical Result in the Massless Limit

The gap equation can be solved analytically.

$$G_\pi\left(\frac{\Lambda^2}{2\pi^2}-\frac{a^2\left(r^4\Omega^4+1\right)-r^2\Omega^4+3\Omega^2}{24\pi^2\left(r^2\Omega^2-1\right)^2}\right)=1.$$

The critical acceleration is obtained directly from this equation.



Rotation lowers the critical acceleration.

The effects of rotation become increasingly significant with increasing radius.

Summary

✓ We developed a unified framework to study chiral symmetry under acceleration and rotation.

✓ Different renormalization schemes lead to different phase diagrams.

✓ Under the Rindler vacuum subtraction, both acceleration and rotation favor chiral symmetry restoration.

Thanks!