QCD phase structure under acceleration

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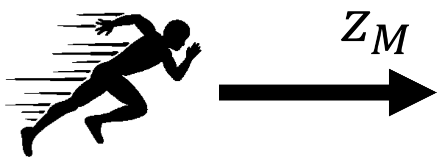
  What is acceleration?
- Acceleration in heavy-ion collisions
- Acceleration effects on QCD phase structure
- Summary and outlooks

Introduction

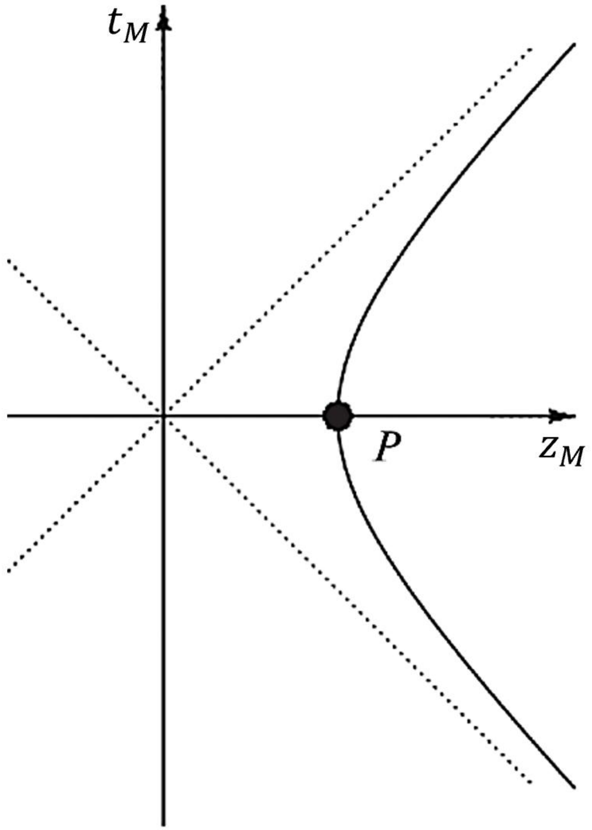
Acceleration

- Acceleration along z-direction in Minkowski spacetime



Three acceleration: $$a_M = \frac{d^2 z_M}{dt_M^2}$$

Proper acceleration: $$a = \gamma_M^3 a_M$$



- Constant a = observer feels constant force
- There is always a dark region behind the accelerated observer

Accelerating frame and Rindler coordinates

- An observer with constant proper acceleration in Minkowski spacetime

$$t_M^2 - \left(z_M - z_M(0) + \frac{1}{a}\right)^2 = -\frac{1}{a^2}, \quad z_M > z_M(0)$$

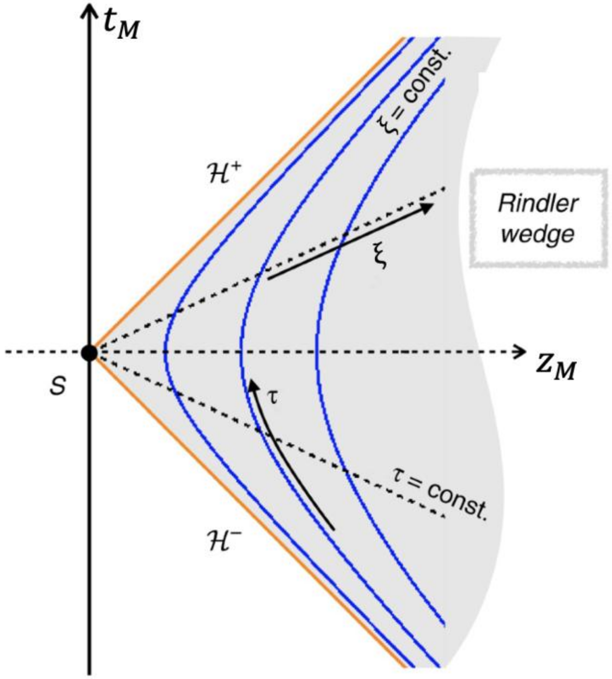
- The coordinates (τ, z) in which the observer is static is the Rindler coordinates

$$t_M = \left(z + \frac{1}{a}\right)\sinh(a\tau),$$
$$z_M = \left(z + \frac{1}{a}\right)\cosh(a\tau) + z_M(0) - \frac{1}{a}.$$

$$ds^2 = dt_M^2 - dz_M^2 = (1 + az)^2 d\tau^2 - dz^2$$

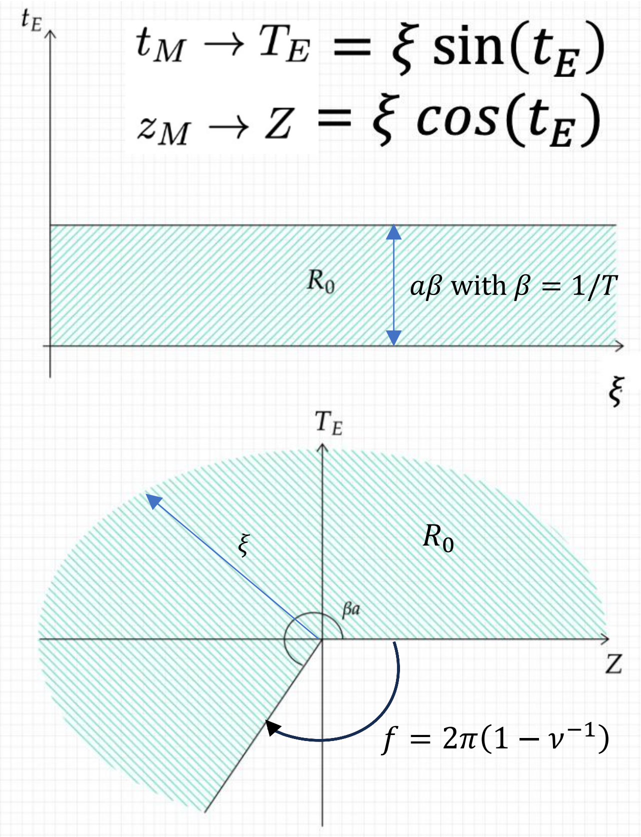
$$t = a\tau$$
$$\xi = z + 1/a$$

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



Observer at $\xi = 1/a$ has proper acceleration a

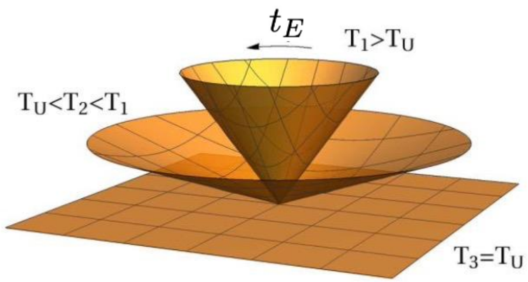
Euclidean Rindler coordinates and Unruh temperature



Euclidean Rinder coordinates at finite temperature T is a cone with deficit angle $f = 2\pi(1 - \nu^{-1})$ with $\nu = \frac{2\pi T}{a} = T/T_U$. To avoid a negative f, we need $T > T_U$

$$T_U = \frac{a}{2\pi}$$: Unruh temperature

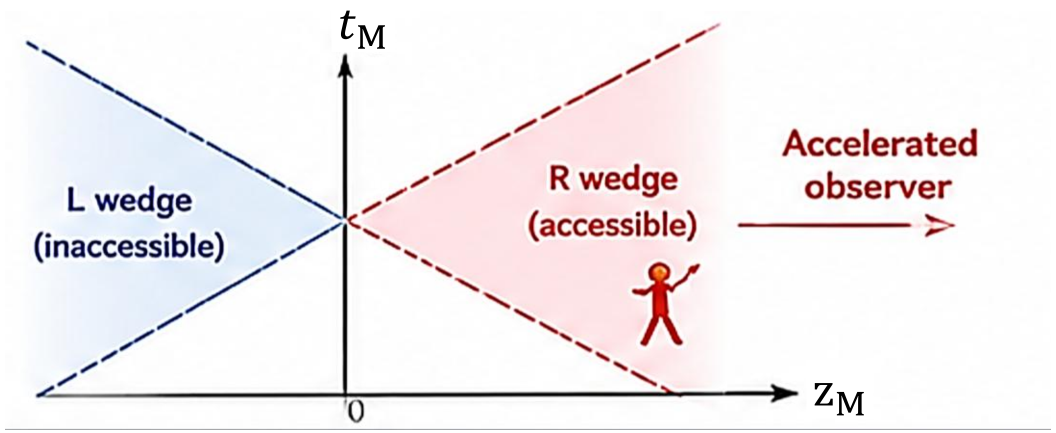
Identify $t_E = 0$ and $t_E = a\beta$



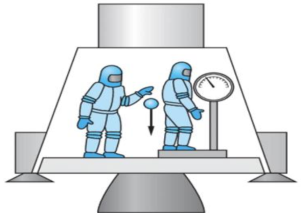
- Unruh temperature is not only geometric, it is the temperature of Minkowski vacuum seen by accelerating observer (Unruh effect)

Unruh effect and Entanglement

- An quantum information interpretation of Unruh effect

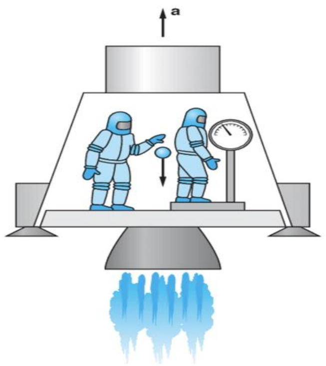


- The inertial observer and accelerated observer do not agree with the vacua



Minkowski vacuum

$$a_k^M|0_M\rangle = 0$$

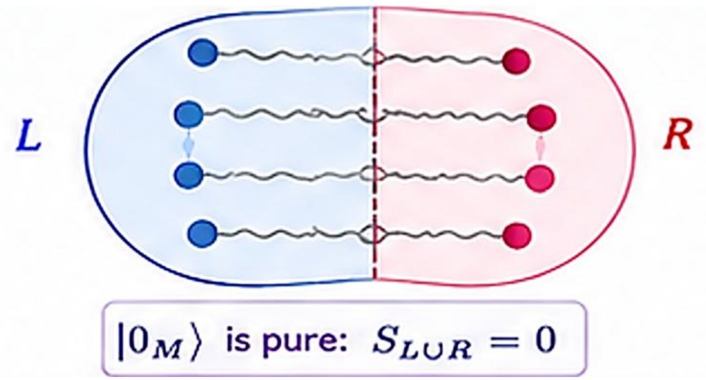


Rindler vacuum

$$a_k^R|0_R\rangle = 0$$

Unruh effect and Entanglement

- If the observer carry fermion detector



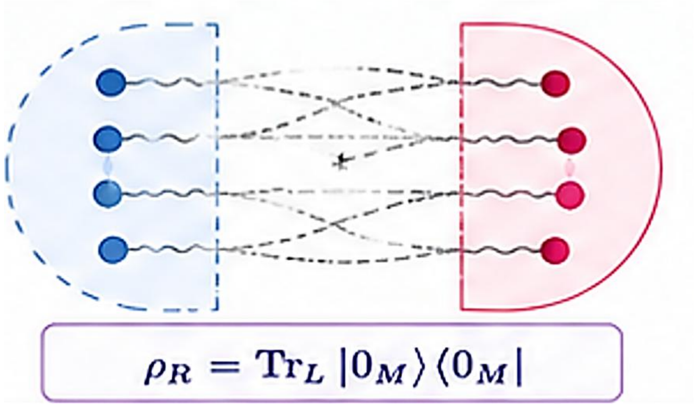
Minkowski vacuum: left-right entangled state*:

$$|0\rangle_M = \cos\theta_\omega |0\rangle_R |0\rangle_L + \sin\theta_\omega |1\rangle_R |1\rangle_L$$

Density operator $\rho_M = |0\rangle_M \langle 0|$

Von Neuman entropy $S_M = -\mathrm{Tr}\rho_M \ln \rho_M = 0$

- The right-wedge accelerated observer do not communicate with left-wedge:



The right-wedge state is a mixed state:

$$\rho_R = \frac{1}{1+e^{-2\pi\omega/a}} \left(|0\rangle_R \langle 0| + e^{-2\pi\omega/a} |1\rangle_R \langle 1| \right)$$

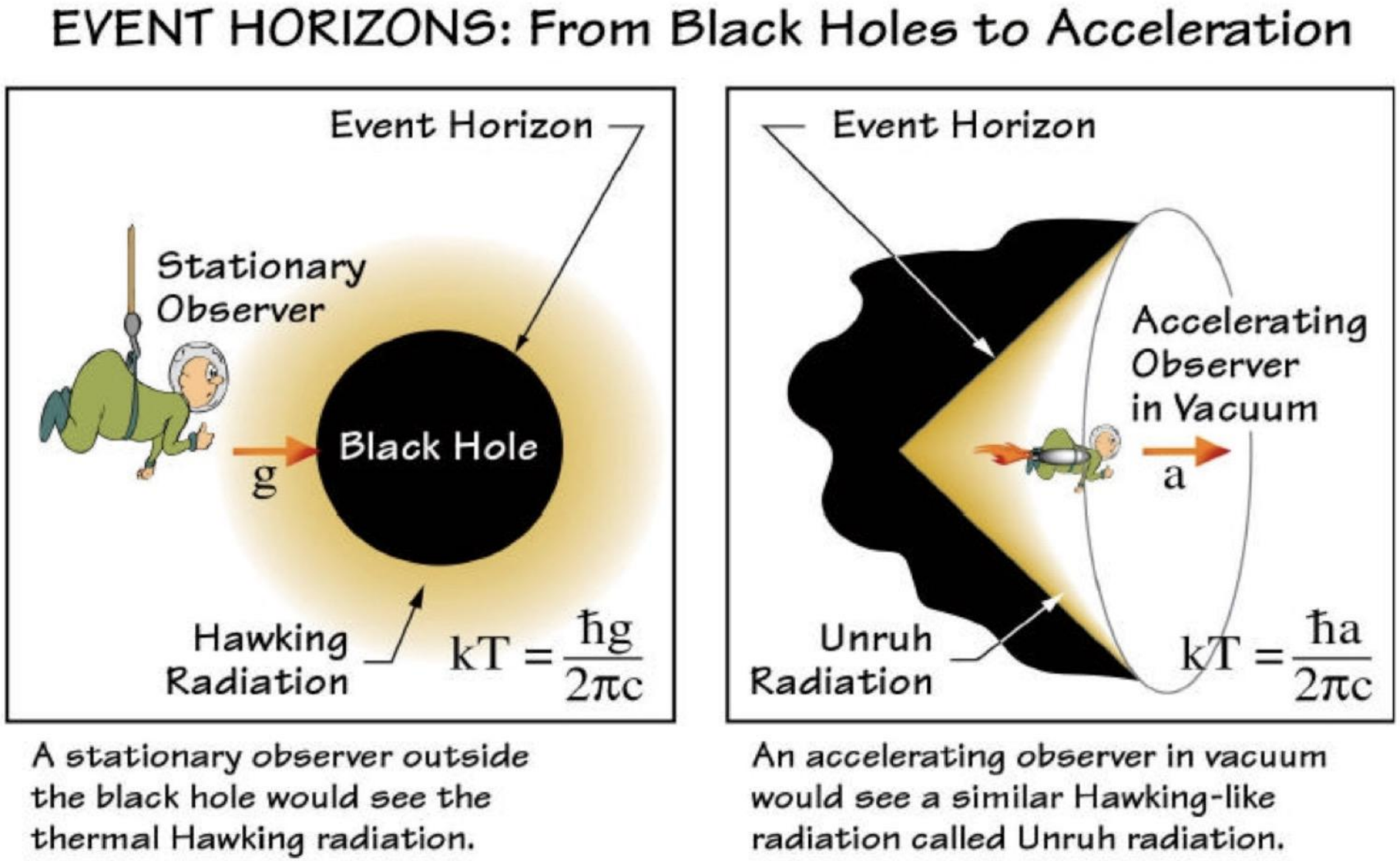
It is just a thermal state of fermions:

$$\rho_R = \frac{1}{Z} e^{-H_R/T} \qquad T = \frac{a}{2\pi} \quad \text{(Unruh temperature)}$$

Entanglement entropy = R-wedge thermal entropy

*Here, the Bogoliubov coefficients are determined by $\tan\theta_\omega = e^{-\pi\omega/a}$

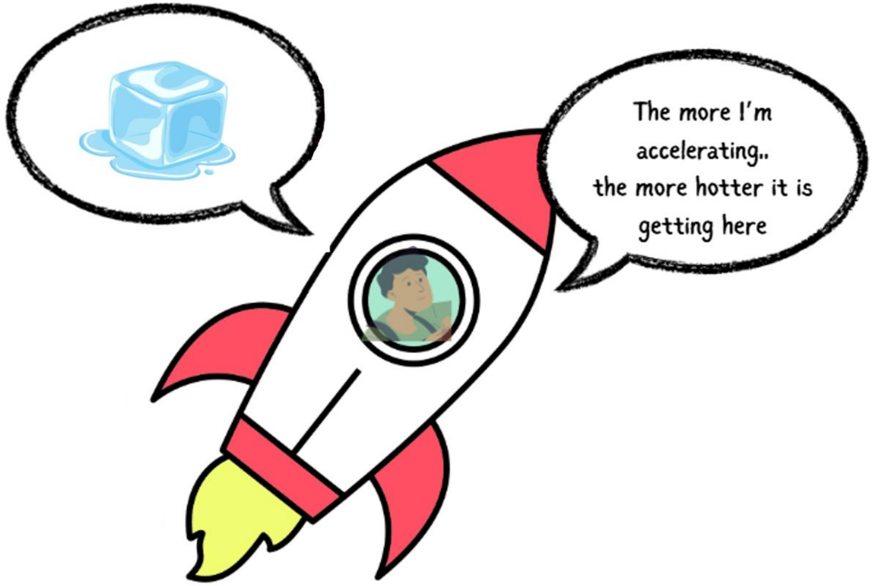
Unruh radiation and Hawking radiation



(Figure from Pisin Chen 2014)

Would acceleration melt accelerated matter?

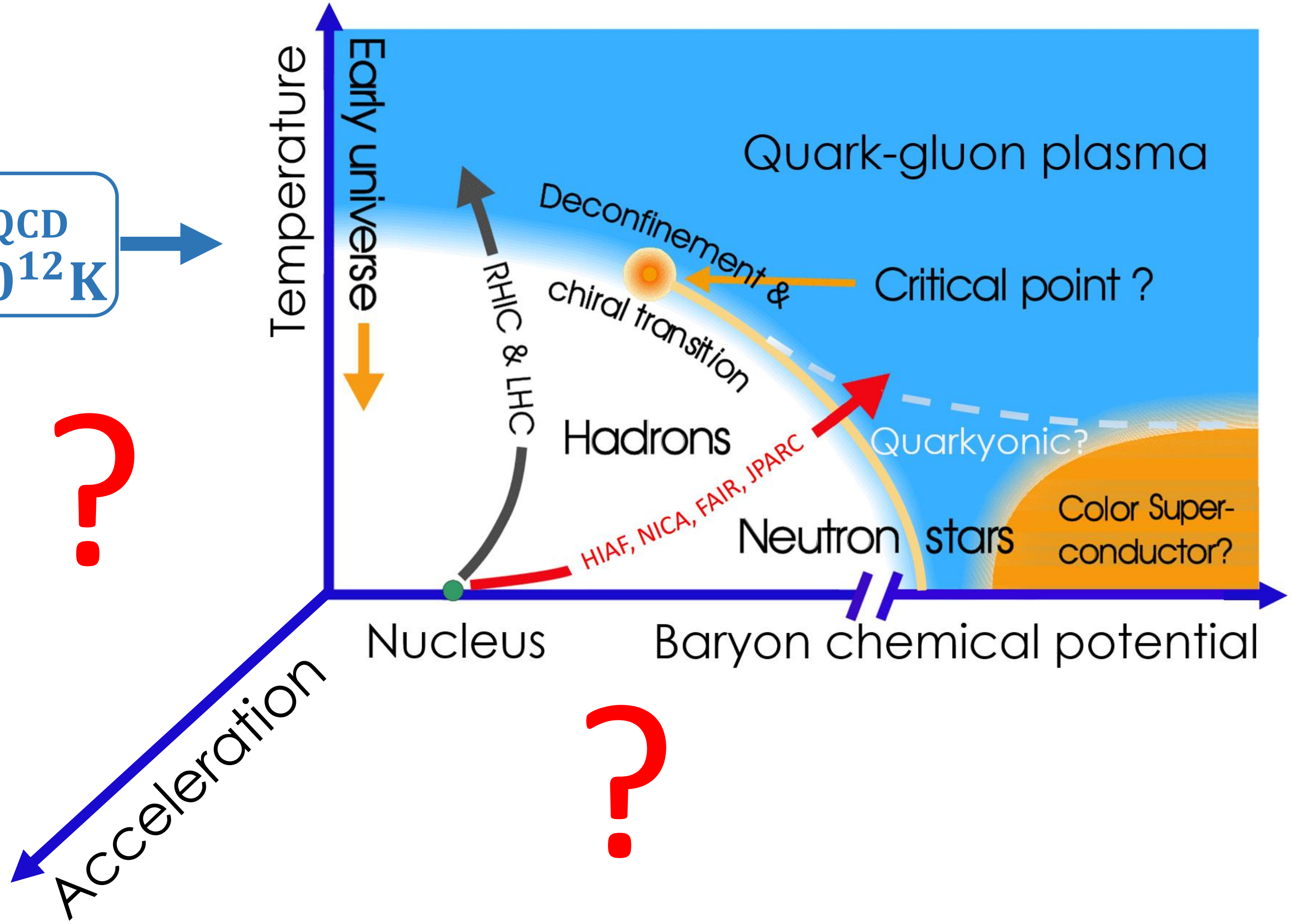
- Question: would acceleration melt the co-accelerated ice?



- Question: would acceleration affect, e.g., chiral condensate?

QCD phase diagram extended by acceleration

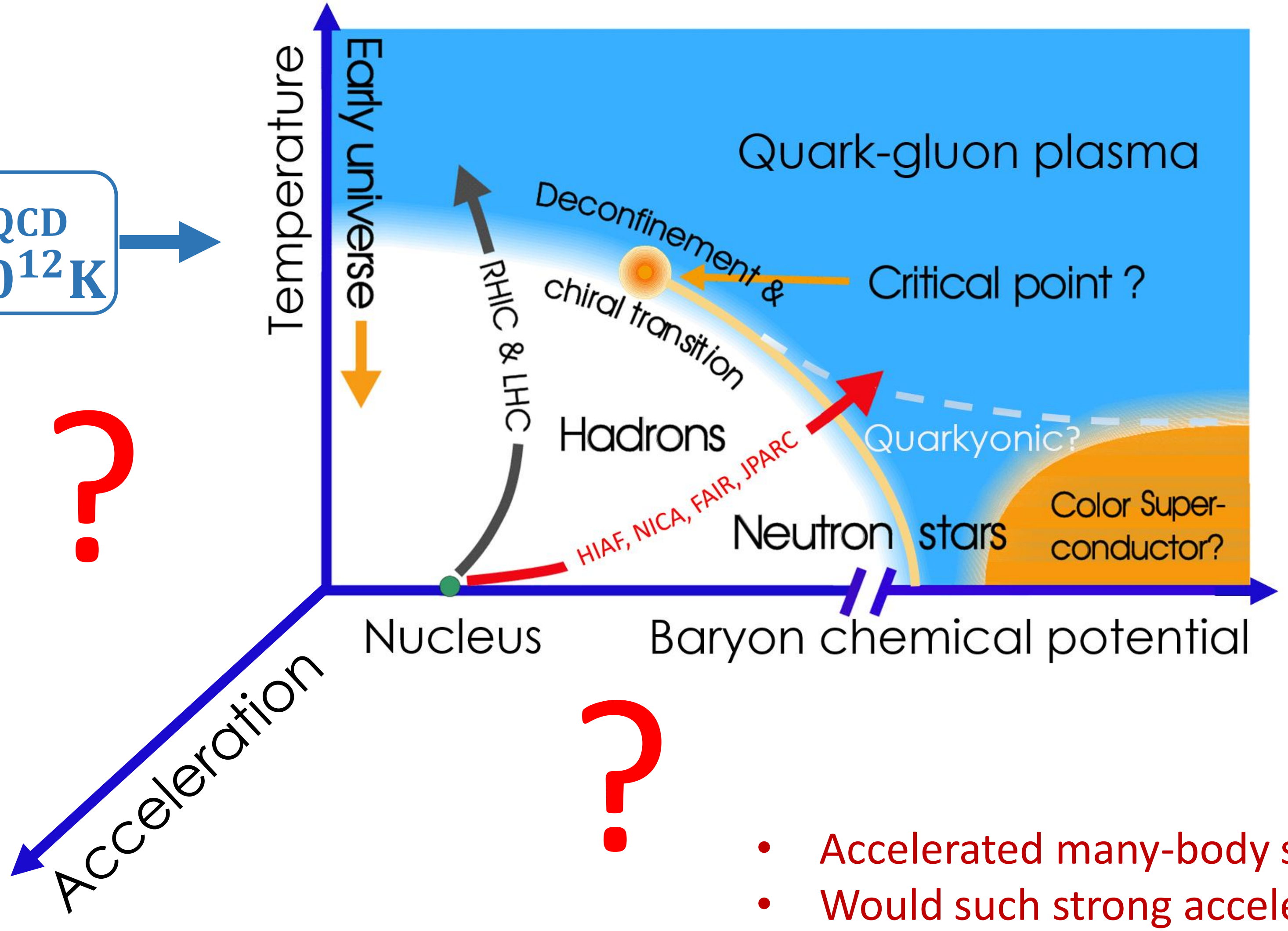
$T_c \sim \Lambda_{QCD}$
$\sim 10^{12}$K



- Chiral condensate and confinement?
- Effects combined with finite density, temperature, … ?
- Possible signatures in HICs?

QCD phase diagram extended by acceleration

$T_c \sim \Lambda_{QCD}$
$\sim 10^{12}$K



- Chiral condensate and confinement?
- Effects combined with finite density, temperature, … ?
- Possible signatures in HICs?

- Accelerated many-body system equilibrium (not only Unruh)?
- Would such strong acceleration accessible in experiment?

Accelerating and rotating thermal equilibrium

- Many-body system can remain equilibrium with acceleration and rotation
- Local equilibrium density operator (determined by max-entropy principle)

$$\rho_{\mathrm{LE}} = \frac{1}{Z_{\mathrm{LE}}} \exp\left[-\int d\Xi_\mu \left(T^{\mu\nu}\beta_\nu - \frac{1}{2} J^{\mu\rho\sigma}\varpi_{\rho\sigma}\right)\right]$$

- True global equilibrium ρ_{eq} is a time-independent LE

$$\Rightarrow \quad \beta^\mu \text{ and } \varpi^{\mu\nu} \text{ are constants}$$

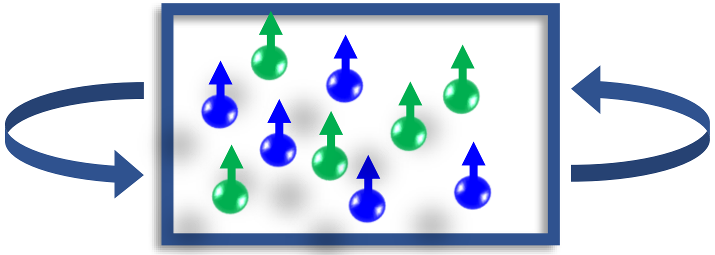
$$\begin{cases} \beta^\mu = (\beta, \mathbf{0}) \\ \varpi_{0i} = \beta a^i \\ \varpi_{ij} = \beta \epsilon^{ijk}\Omega^k \end{cases} \Rightarrow \quad \rho_{\mathrm{eq}} = \frac{1}{Z_{\mathrm{eq}}} \exp\left[-\beta\left(H - \boldsymbol{a}\cdot\boldsymbol{K} - \boldsymbol{\Omega}\cdot\boldsymbol{J}\right)\right]$$

Boost operator

Angular momentum

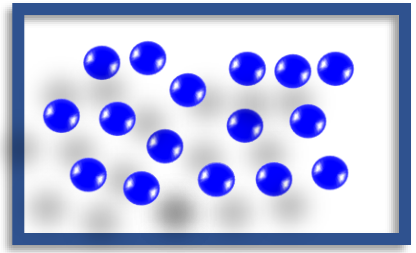
Effect of rotation: Comparison with chemical potential

- Hints for possible rotation effect: comparison with chemical potential



Rotation

$$H = H_0 - \Omega J_z$$



Chemical potential

$$H = H_0 - \mu N$$

For massless Dirac fermions

$$P = \frac{7\pi^2}{180\beta^4} + \frac{(\Omega/2)^2}{6\beta^2} + \frac{(\Omega/2)^4}{12\pi^2}$$

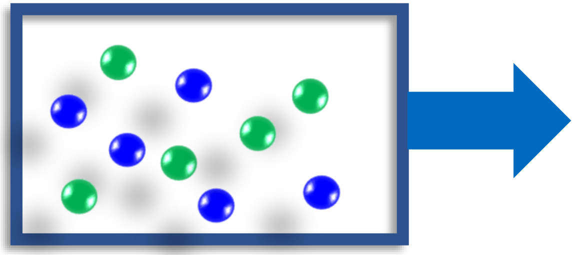
(At rotating axis, for unbounded system)

$$P = \frac{7\pi^2}{180\beta^4} + \frac{\mu^2}{6\beta^2} + \frac{\mu^4}{12\pi^2}$$

(Ambrus and Winstanley 2019; Palermo etal 2021)

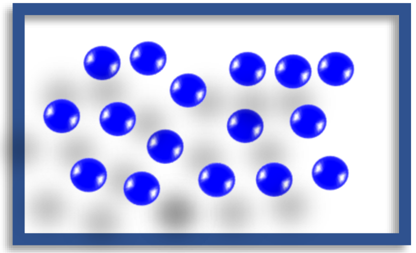
Effect of acceleration: Comparison with chemical potential

- Hints for possible acceleration effect: comparison with chemical potential



Acceleration

$$H = H_0 - aK_z$$



Chemical potential

$$H = H_0 - \mu N$$

For massless Dirac fermions

$$P = \frac{7\pi^2}{180\beta^4} + \frac{(a/2)^2}{6\beta^2} - \frac{17}{15}\frac{(a/2)^4}{12\pi^2}$$

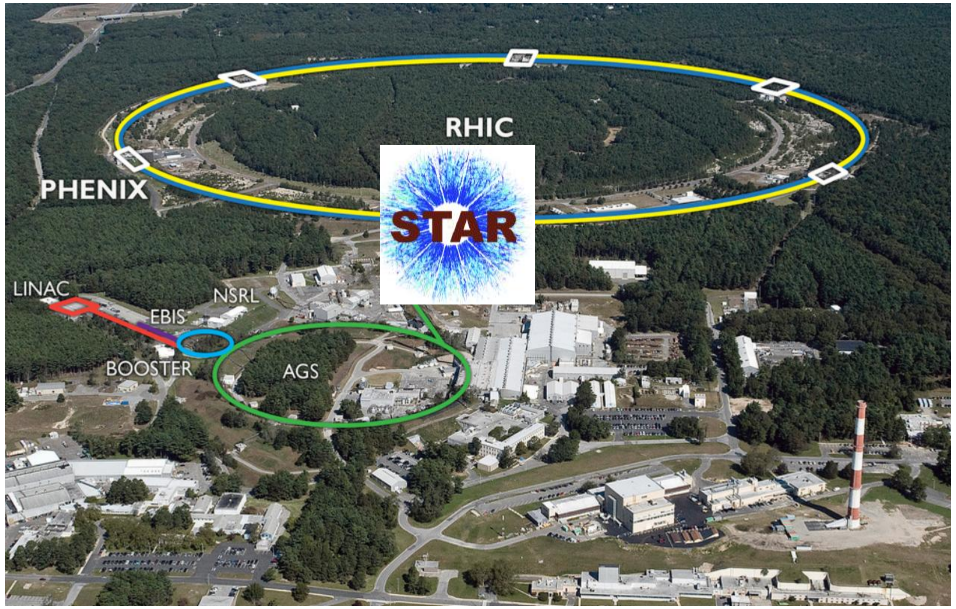
$$P = \frac{7\pi^2}{180\beta^4} + \frac{\mu^2}{6\beta^2} + \frac{\mu^4}{12\pi^2}$$

(Ambrus-Gecic 2025)

Acceleration in heavy ion collisions

Heavy-ion collisions

- Currently operating heavy-ion colliders



RHIC@BNL,2000 -

Top energy: Au + Au @ $\sqrt{s} = 200$ GeV

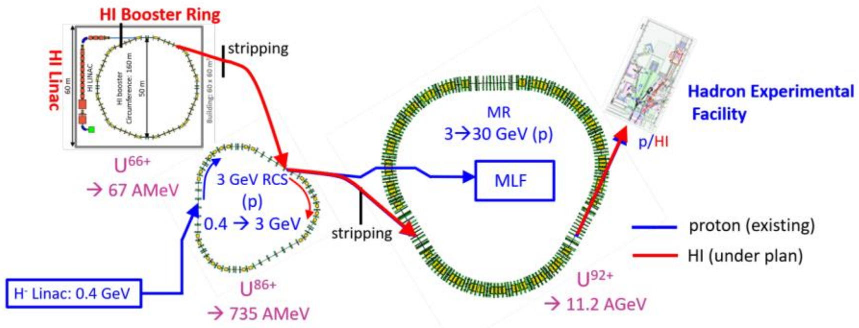
LHC@CERN, 2010 -

Top energy: Pb + Pb @ $\sqrt{s} = 5.02$ TeV

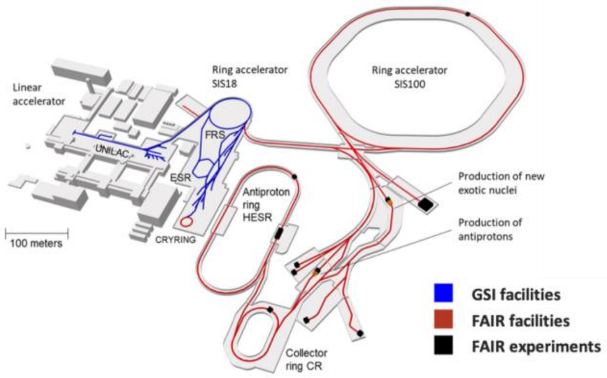
Heavy-ion collisions

- Future heavy-ion colliders (cover low collision energies)

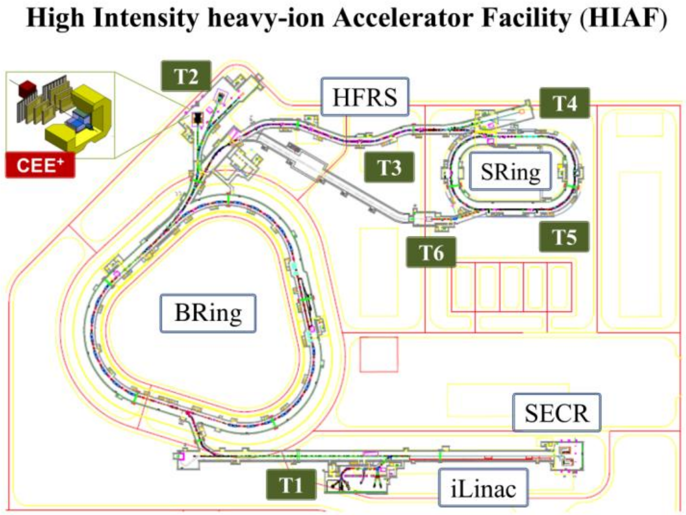
NICA@Russia



J-PARC@Japan



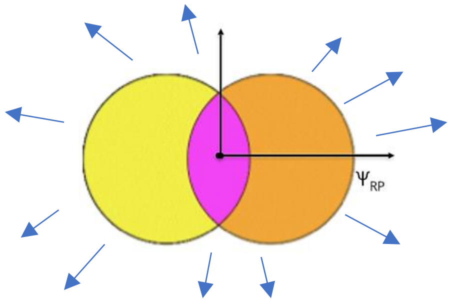
FAIR@Germany



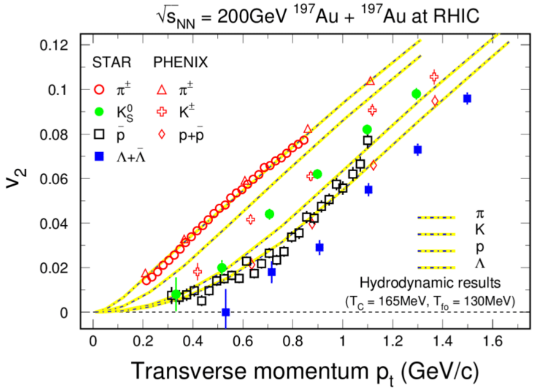
HIAF@China

Strong acceleration in heavy-ion collisions

- Strong elliptic flow indicates strong fluid acceleration



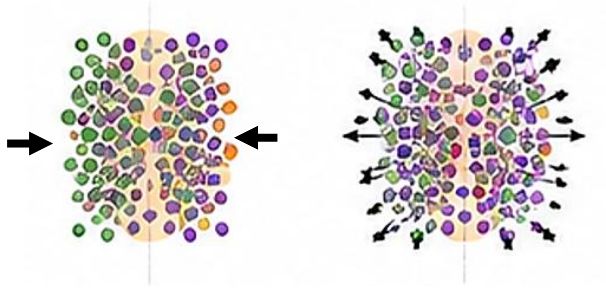
$$\boldsymbol{a} = \frac{d\boldsymbol{v}}{dt} = -\frac{1}{\varepsilon + P}\boldsymbol{\nabla} P$$



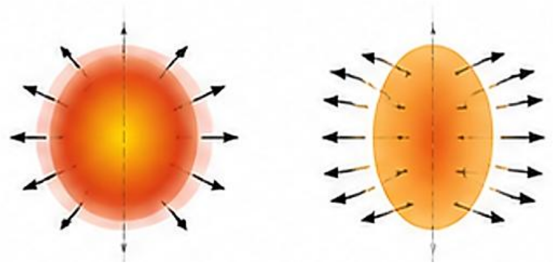
Elliptic flow due to fluid acceleration

- But high-energy and low-energy collisions may differ

1. Low-energy collisions: Deceleration (stopping)
Baryons lose longitudinal momentum while passing through each other.

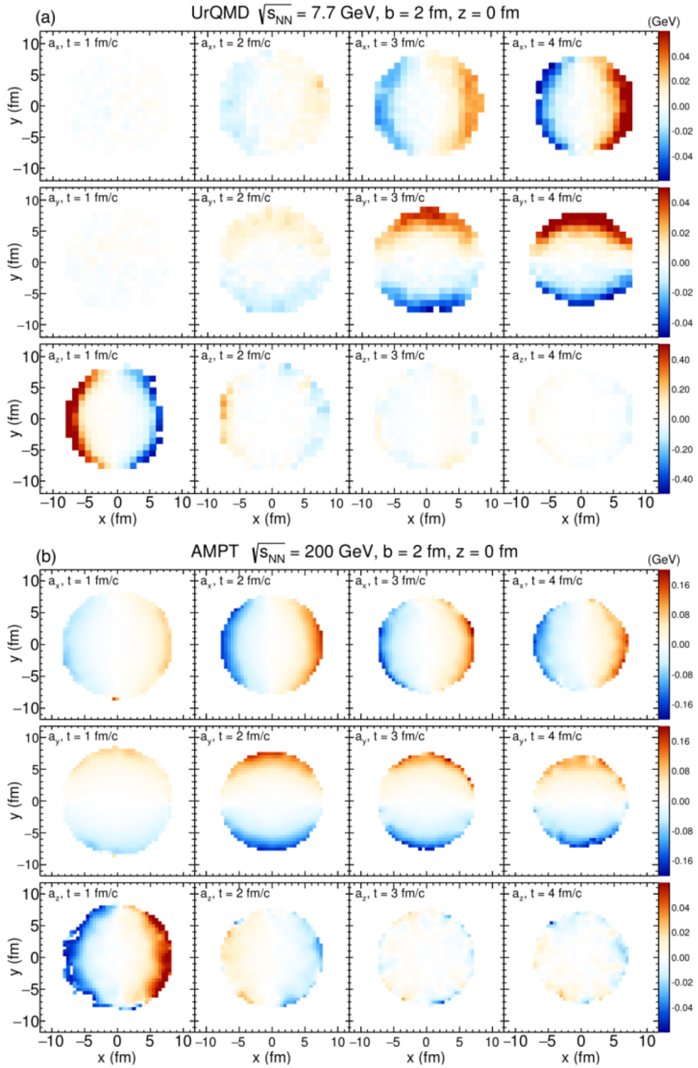


2. High-energy collisions: Acceleration from pressure gradients
Large pressure gradients in the produced matter push fluid elements

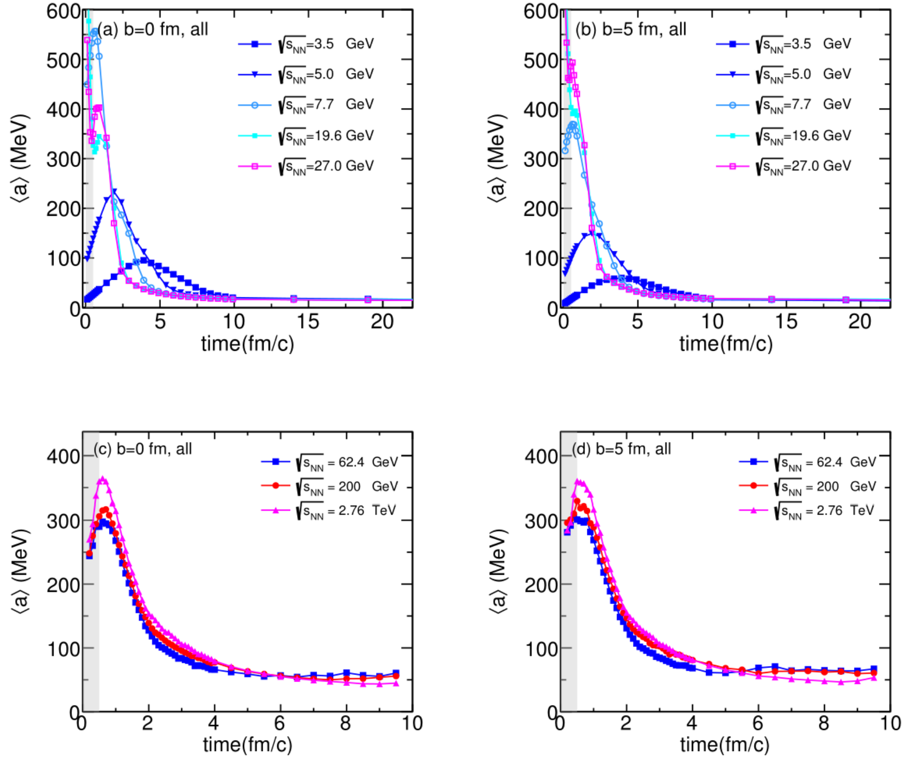


Strong acceleration in heavy-ion collisions

- Spatial distribution



- Proper acceleration $a = \sqrt{-a^{\mu}a_{\mu}}$



- ➢ Very strong acceleration (~ few 100 MeV)
- ➢ Last longer at lower energies

(Zhong-Deng-XGH-Ma 2026; Prokhorov etal 2025)

Thermalization or refrigeration?

- Thermalization by acceleration in heavy-ion collisions

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NUCLEAR PHYSICS A

From color glass condensate to quark–gluon plasma through the event horizon

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Abstract

We propose a new thermalization scenario for heavy ion collisions which at sufficiently high energies implies the phase transition to the quark–gluon plasma. The key ingredient of our approach is the Hawking–Unruh effect: an observer moving with an acceleration a experiences the influence of a thermal bath with an effective temperature $T = a/2\pi$, similar to the one present in the vicinity of a black hole horizon. For electric charges moving in external electromagnetic fields of realistic strength, the resulting temperature appears too small to be detected. However for partons in strong color fields the effect should be observable: in the color glass condensate picture, the strength of the color-electric field is $E \sim Q_s^2/g$ (Q_s is the saturation scale, and g is the strong coupling), the typical acceleration is $a \sim Q_s$, and the heat bath temperature is $T = Q_s/2\pi \sim 200$ MeV. In nuclear collisions at sufficiently high energies the effect can induce a rapid thermalization over the time period of $\tau \simeq 2\pi/Q_s \simeq 1$ fm accompanied by phase transitions. We consider a specific example of chiral symmetry restoration induced by a rapid deceleration of the colliding nuclei. We argue that parton saturation in the initial nuclear wave functions is a necessary precondition for the formation of quark–gluon plasma. We discuss the implications of our "black hole thermalization" scenario for various observables in relativistic heavy ion collisions.

- Acceleration as refrigeration: enhancement of chiral condensate

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Acceleration as refrigeration: acceleration-driven spontaneous symmetry breaking in thermal medium

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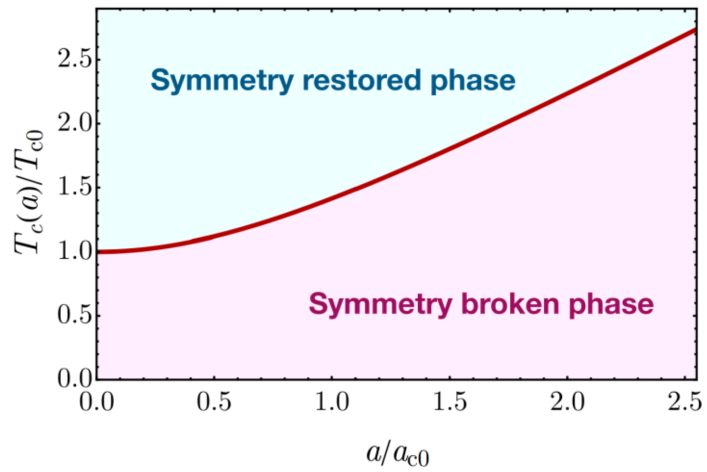


Phase transitions under acceleration

Nonlinear sigma model analysis

- The model

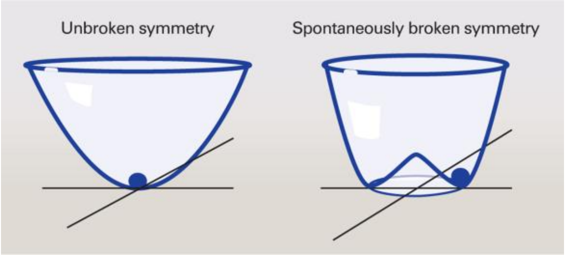
$$\mathcal{L}_{NL\sigma M} = -\frac{1}{2}\Phi^T \Box \Phi - M_\pi^2 f_\pi \sigma, \quad \Phi^T = (\pi^a, \sigma) \qquad \Phi^T\Phi = f_\pi^2.$$

- Mean-field effective action (large-N)

$$\Gamma[\sigma,\lambda] = \int \mathrm{d}^4x \left(-\frac{1}{2}\sigma\Box\sigma + \frac{\lambda}{2}(\sigma^2 - f_\pi^2) + \frac{N}{2}\ln\frac{-\Box+\lambda}{-\Box} - M_\pi^2 f_\pi \sigma\right)$$

- Gap equations

$$\frac{\delta\Gamma}{\delta\sigma} = -\Box\sigma + \lambda\sigma - M_\pi^2 f_\pi = 0,$$
$$\frac{\delta\Gamma}{\delta\lambda} = \frac{\sigma^2 - f_\pi^2}{2} + \frac{N}{2}G(x,x;\lambda) = 0,$$



- Field operator and Green function (propagator)

$$\hat{\phi} = \int_0^\infty \mathrm{d}\omega \int \frac{\mathrm{d}^2\mathbf{k}}{2\pi}\sqrt{\frac{\sinh \pi\omega}{\pi^2}} K_{i\omega}(m_\perp \xi)(\hat{a}_{\omega,k}\mathrm{e}^{-i\omega t + i\mathbf{k}\cdot\mathbf{x}} + \hat{a}^\dagger_{\omega,k}\mathrm{e}^{i\omega t - i\mathbf{k}\cdot\mathbf{x}}) \Rightarrow G(x,x') = i\langle 0_R|T\phi(x)\phi(x')|0_R\rangle$$

Nonlinear sigma model analysis

- Extend it to Euclidean time

$$G_E(x_E, x'_E) = \int_0^\infty \mathrm{d}\omega \int \frac{\mathrm{d}^2\mathbf{k}}{(2\pi)^2} \frac{\sinh \pi\omega}{\pi^2} K_{i\omega}(m_\perp \xi) K_{i\omega}(m_\perp \xi') e^{-\omega|t_E - t'_E| + i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')},$$

- Extend it to finite temperature

$$G_\nu(t_E, t'_E) = G_\nu(t_E + \beta_R, t'_E) \text{ where } \beta_R = 1/T_R = a/T \text{ and } \nu = 2\pi T/a$$

$$G_\nu(x_E, x'_E) = \sum_n G_E(t_E - t'_E + \beta_R n)$$
$$= \int_0^\infty \mathrm{d}\omega \int \frac{\mathrm{d}^2\mathbf{k}}{(2\pi)^2} \frac{\cosh \omega(|t_E - t'_E| - \beta_R/2)}{\sinh(\beta_R \omega/2)} \frac{\sinh \pi\omega}{\pi^2} K_{i\omega}(m_\perp \xi) K_{i\omega}(m_\perp \xi') \mathrm{e}^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')}$$

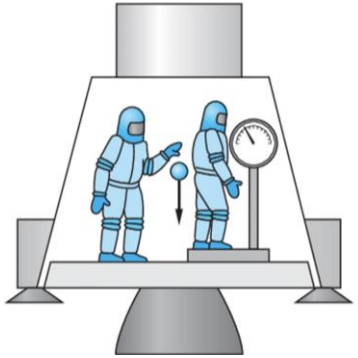
- Gap equation at chiral limit

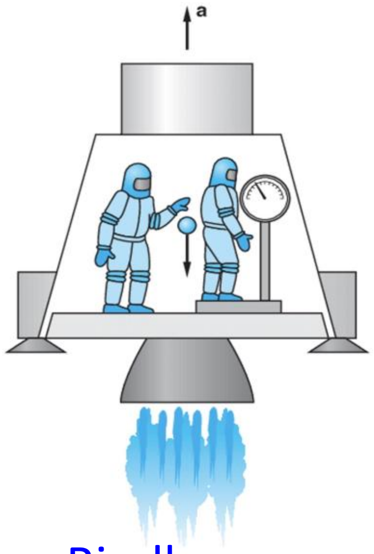
$$\sigma^2 = f_\pi^2 - N G_\nu(x_E, x_E; 0)$$

- There is divergence in the above one-loop result: vacuum contribution

Nonlinear sigma model analysis

- What vacuum contribution to subtract?





Minkowski vacuum

$$a_k^M|0_M\rangle = 0,$$

Rindler vacuum

$$a_k^R|0_R\rangle = 0$$

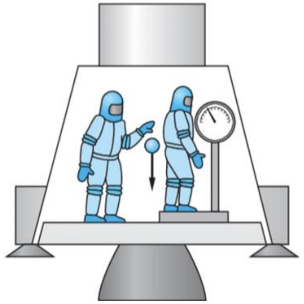
Related by a Bogoliubov transformation

$$a_k^R = \left[2\sinh\left(\frac{\pi\omega}{a}\right)\right]^{-1/2}\left(e^{\pi\omega/2a}a_k^{(1)M} + e^{-\pi\omega/2a}a_{-k}^{(2)M\dagger}\right)$$

Nonlinear sigma model analysis

- Subtraction with respect to the Minkowski vacuum

$$a_k^M|0_M\rangle = 0,$$



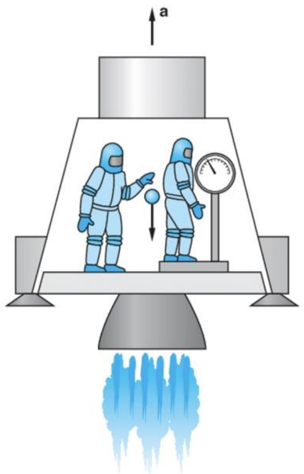
$$\sigma^2 = f_\pi^2 - \frac{1}{(a\xi)^2}\frac{N}{12}\left(T^2 - \frac{a^2}{(2\pi)^2}\right)$$

Local observer with constant acceleration a: $\xi = 1/a$ ⇒

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

- Subtraction with respect to the Rindler vacuum

$$a_k^R|0_R\rangle = 0$$



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

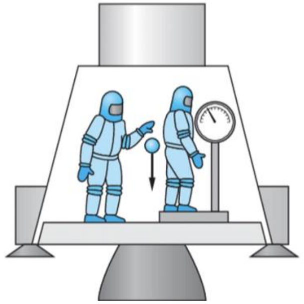
Local observer with constant acceleration a: $\xi = 1/a$ ⇒

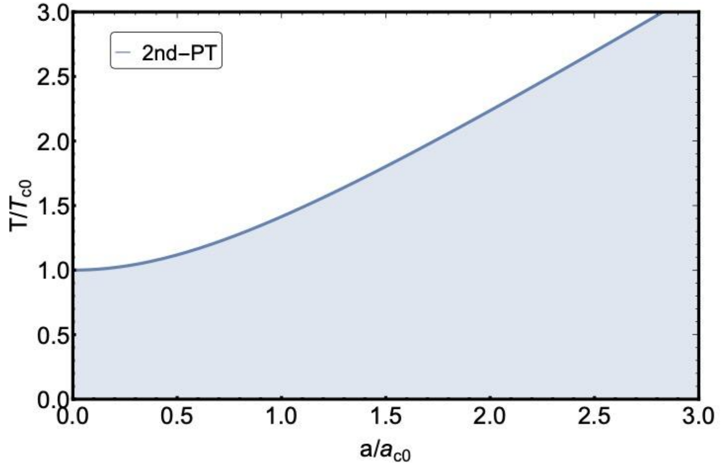
$$T_c(a) = \sqrt{\frac{12f_\pi^2}{N}} = T_{c0}$$

Nonlinear sigma model analysis: phase diagram

- Subtraction with respect to the Minkowski vacuum

$$a_k^M|0_M\rangle = 0$$

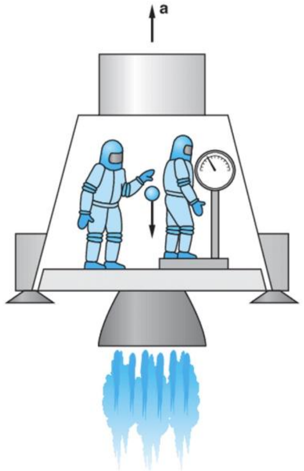


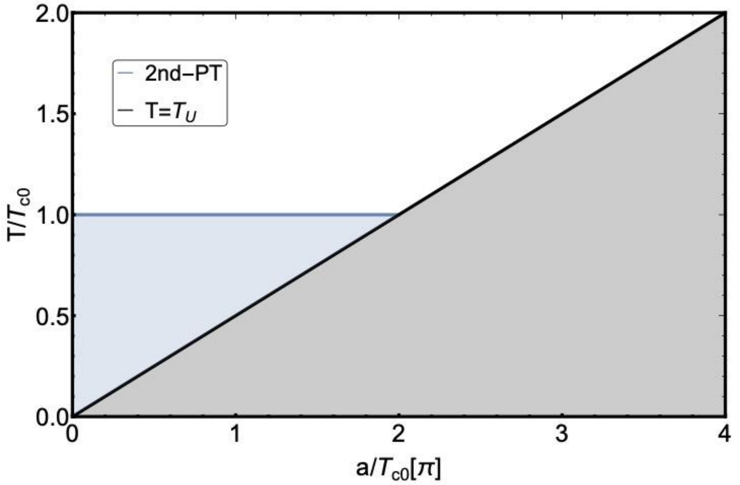


(Zhu-Chen-XGH 2025; see also Chernodub 2025)

- Subtraction with respect to the Rindler vacuum

$$a_k^R|0_R\rangle = 0$$





(Zhu-Chen-XGH 2025)

NJL model analysis

- Let us go into more micro degree of freedom by considering NJL for quarks

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

- Gap equation

$$\frac{m - m_0}{G_{\pi}} = i\,\mathrm{Tr}(S), \qquad S(x,x') = (\hat{D} + m)G(x,x'),$$

- Euclidean Green function (propagator)

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

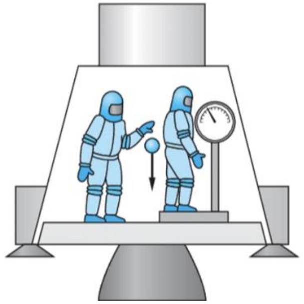
- Extend it to finite temperature

$$\begin{aligned} G_{\nu} &= \sum_n (-1)^n G_E(t_E - t'_E + \beta_R n) \\ &= \int_0^{\infty} \mathrm{d}\omega \int \frac{\mathrm{d}^2\mathbf{k}}{(2\pi)^2} \frac{\sinh(\beta_R\omega/2 - \omega|t_E - t'_E|)}{\cosh(\beta_R\omega/2)} \frac{\sinh \pi(\omega + i\gamma^{\hat{0}}\gamma^{\hat{3}}/2)}{\pi^2} K_{i\omega-\gamma^{\hat{0}}\gamma^{\hat{3}}/2}(m_{\perp}\xi) K_{i\omega-\gamma^{\hat{0}}\gamma^{\hat{3}}/2}(m_{\perp}\xi') e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')}. \end{aligned}$$

NJL model analysis

- Subtraction with respect to the Minkowski vacuum

$$a_k^M |0_M\rangle = 0,$$

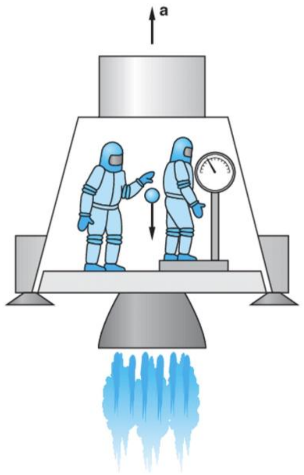


Local observer with constant acceleration a: $\xi = 1/a$

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

- Subtraction with respect to the Rindler vacuum

$$a_k^R |0_R\rangle = 0$$



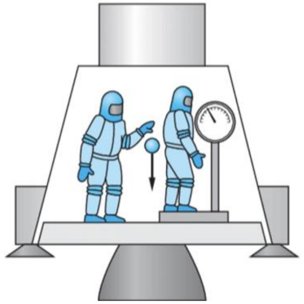
Local observer with constant acceleration a: $\xi = 1/a$

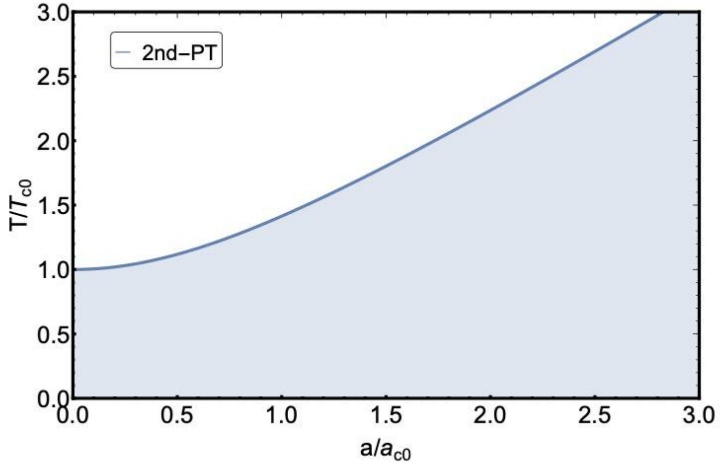
$$T_c(a) = \sqrt{\frac{3\Lambda^2}{\pi^2} - \frac{6}{G_\pi}} = T_{c0}$$

NJL model analysis

- The phase diagram is completely consistent with NLsM analysis

$a_k^M|0_M\rangle = 0,$

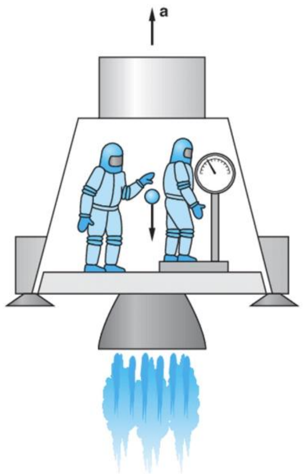


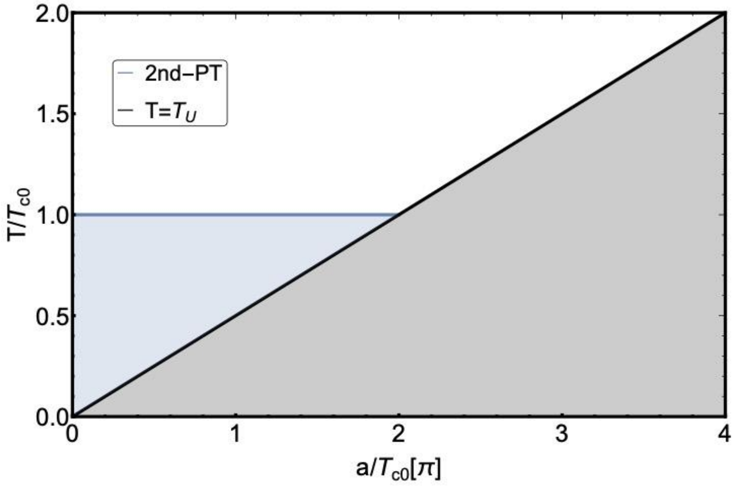


(Zhu-Chen-XGH 2025; see also Chernodub 2025)

- The phase diagram is completely consistent with NLsM analysis

$a_k^R|0_R\rangle = 0$





(Zhu-Chen-XGH,2025)

PQCD analysis

- Consider high-temperature regime of SU(N) gluons.
- Look at whether acceleration makes Polyakov potential deeper or shallower:

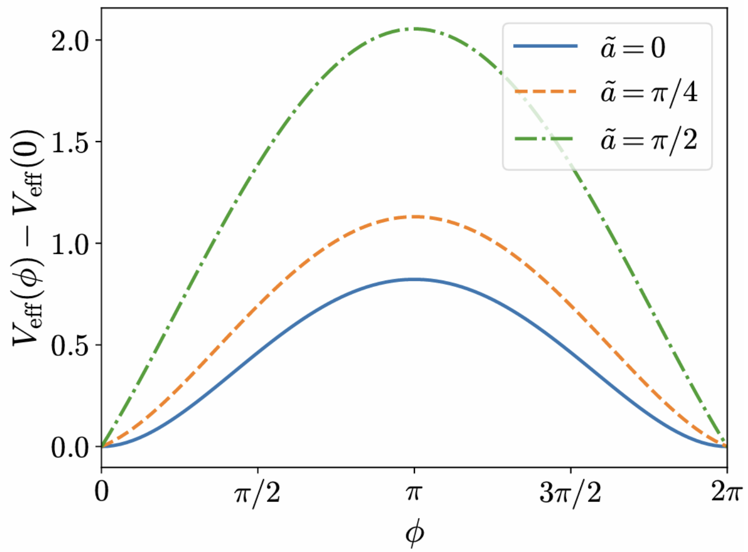
$$V_{\mathrm{eff}}(x) = T_{\mathrm{loc}}^4 \sum_{\boldsymbol{\alpha}} \left[\frac{2\pi^2}{3} \mathrm{B}_4\left(\frac{\boldsymbol{\phi}\cdot\boldsymbol{\alpha}}{2\pi} \right) - \tilde{a}^2 \mathrm{B}_2\left(\frac{\boldsymbol{\phi}\cdot\boldsymbol{\alpha}}{2\pi} \right) - \frac{11\tilde{a}^4}{240\pi^2} \right]$$

with $T_{\mathrm{loc}} = \dfrac{T_0}{a\xi}$, $\tilde{a} = \dfrac{a}{T_0}$, and

Bernoulli polynomials:

$$\mathrm{B}_2(x) = x^2 - x + \frac{1}{6} \,,$$

$$\mathrm{B}_4(x) = x^4 - 2x^3 + x^2 - \frac{1}{30}$$



- Acceleration deepens the potential
- No tendence to weaken deconfinement

(Chen-Fukushinma-Gao-XGH-Shimada-Zhu 2026)

Lattice formulation

- Formulate lattice action in the following accelerating metric

$$g_{\mu\nu} = \begin{pmatrix} (1+gz)^2 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$S_G^{lat} = \frac{\beta}{N_c} \sum_n \left\{ (1+gz) \sum_{i<j<4} \mathrm{Retr}\left[1 - \bar{U}_{ij}^2\right] + \sum_{i=1,2,3} \frac{\mathrm{Retr}\left[1 - \bar{U}_{4i}^2\right]}{1+gz} \right\}$$

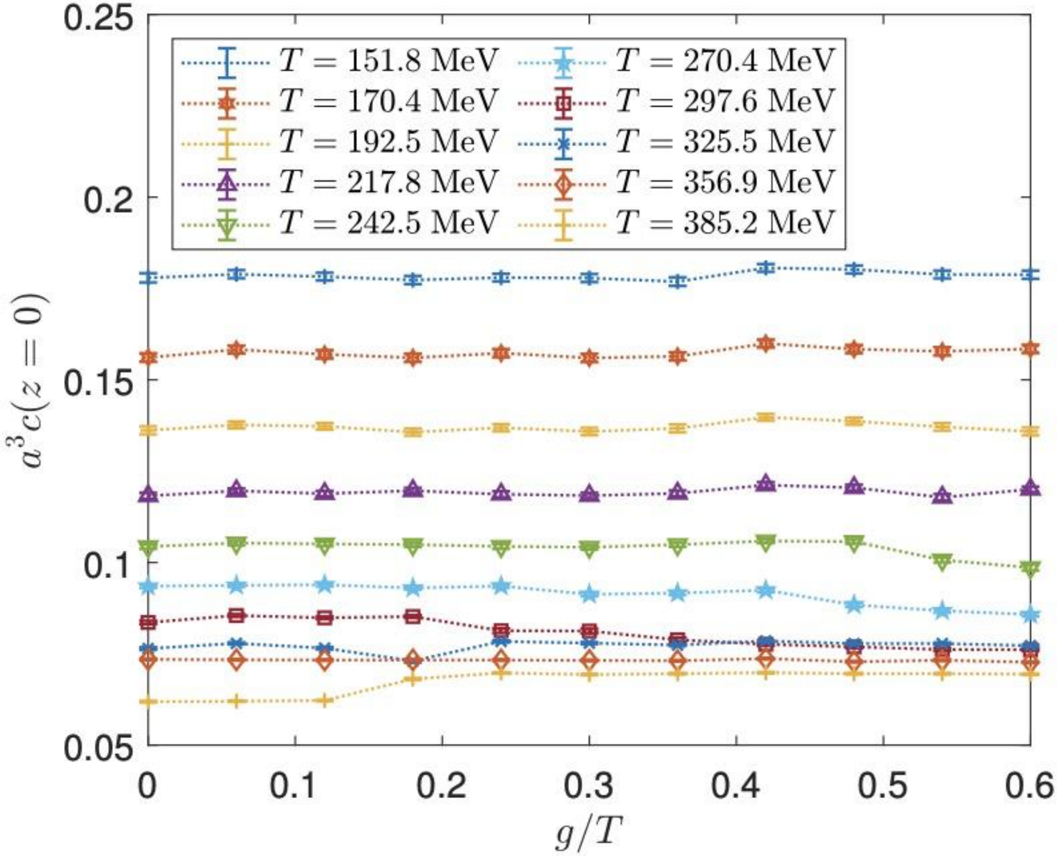
$$S_F^{lat} = \sum_{n,n'} \bar{\chi}(n) D \chi(n'),$$

$$D_F = \left\{ \sum_{i=x,y,z} \sum_{\Delta_i = \pm i} (1+g\bar{z}) \eta_{\Delta_i}(n) U_{\Delta_i}(n) \delta_{n,n'-\delta_i} + \eta_\tau(n) \left(U_\tau(n) \delta_{n,n'-\tau} - U_{-\tau}(n) \delta_{n,n'+\tau} \right) \right.$$
$$\left. + \frac{g}{2} \eta_z(n) \left(U_z(n) \delta_{n,n'-z} + U_{-z}(n) \delta_{n,n'+z} \right) + 2(1+gz) am \delta_{n,n'} \right\}$$

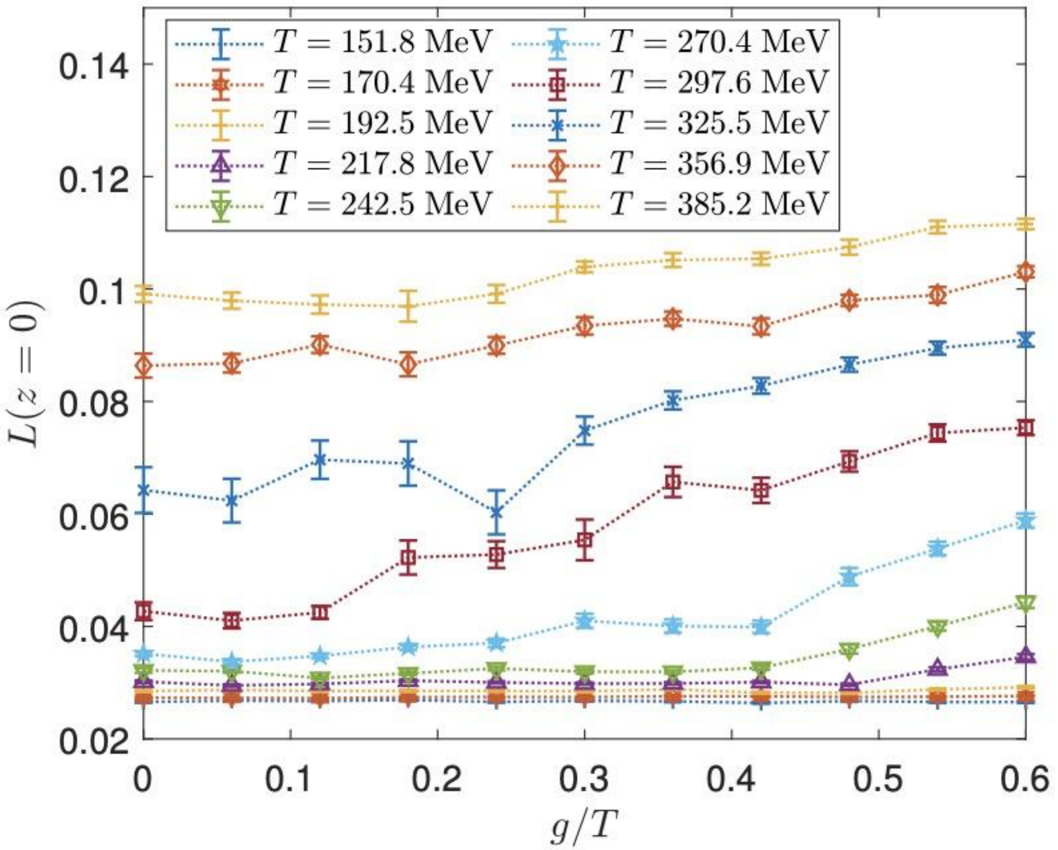
$$= + \frac{1}{2} g \gamma_3^E \cdot$$

Lattice results

- Measurements are done at quenched limit



Chiral condensate vs acceleration g



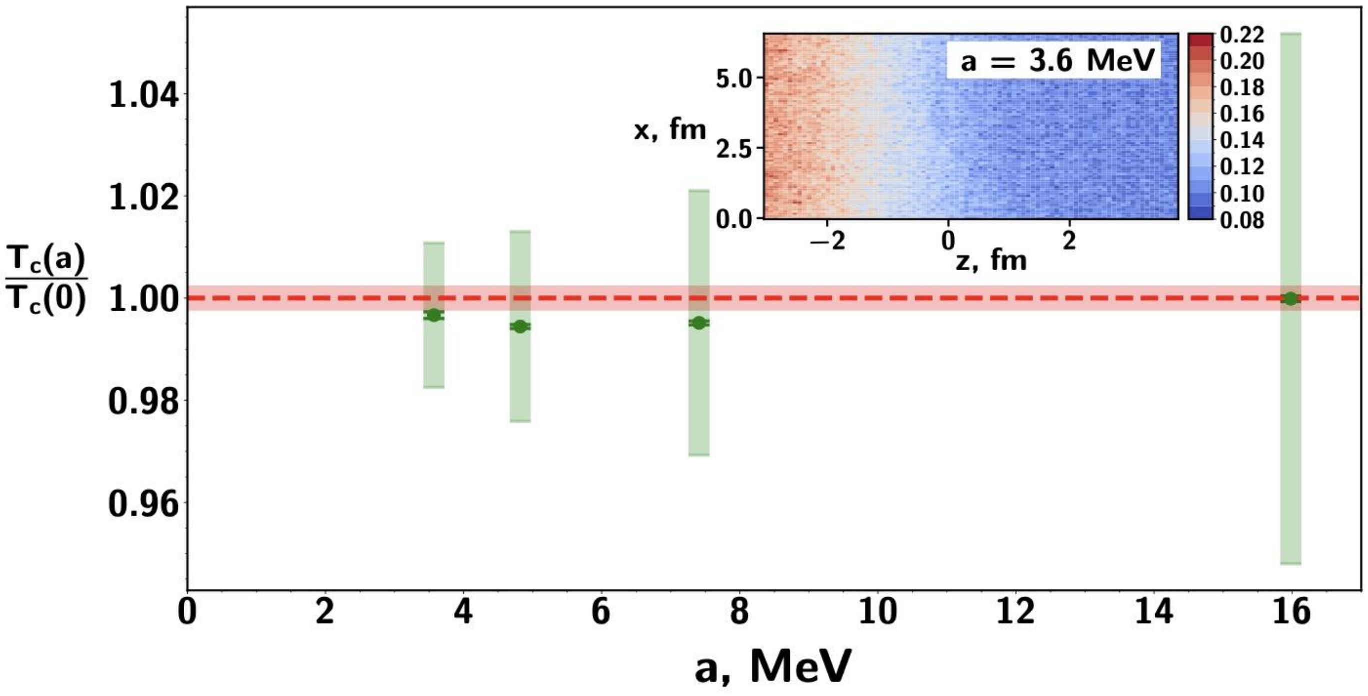
Polyakov loop vs acceleration g

No acceleration dependence measured

(Yang-XGH, to appear)

Lattice results

- A recent simulation for pure Yang-Mills



Deconfinment temperature as determined by Polyakov loop

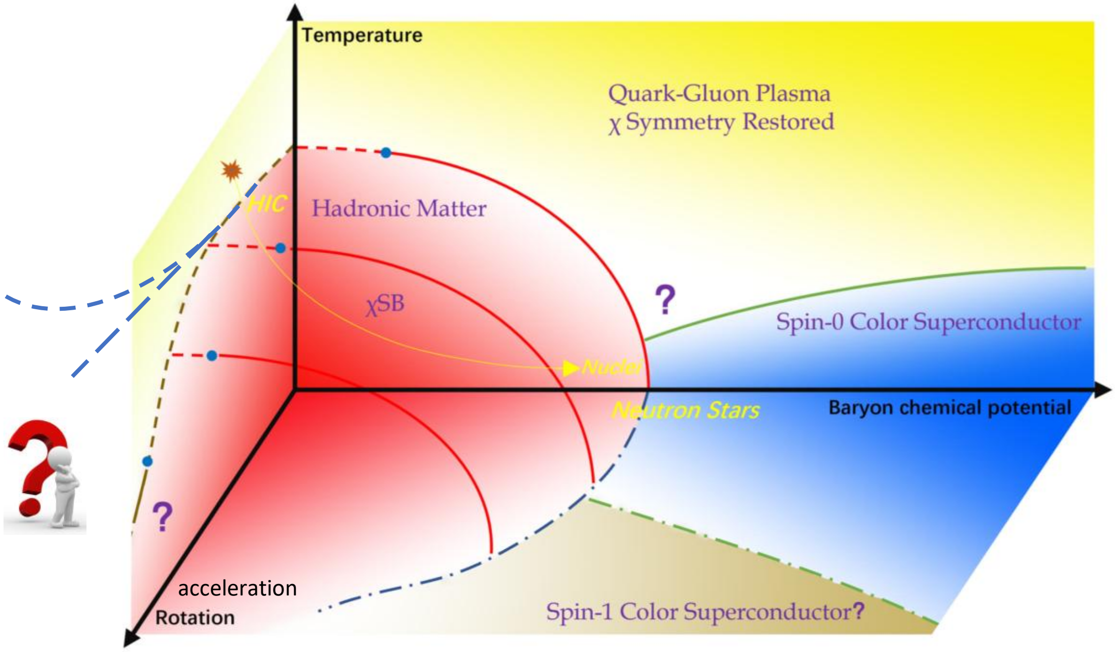
(Braguta etal 2024)

No acceleration dependence measured

Summary and outlooks

Summary and outlooks

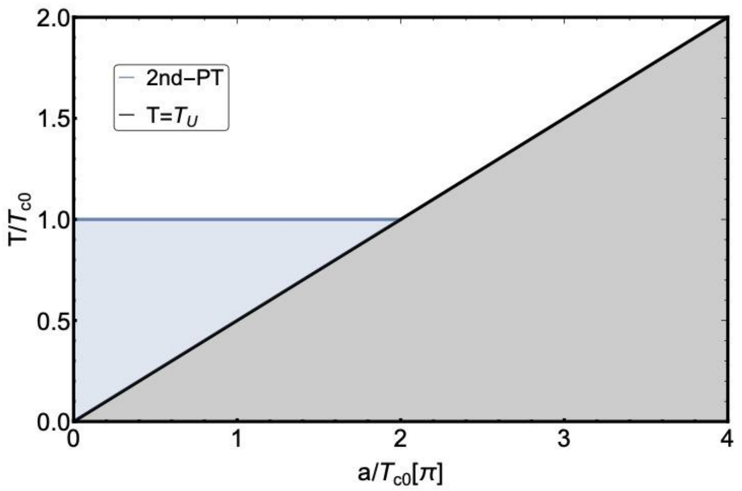
- Quark-gluon matter under acceleration is an interesting topic.
- Acceleration effects may depend crucially on subtraction scheme
- It is important for heavy ion collisions.
- Outlooks
  - Combing with rotation, B-field, etc.
  - What would be a good observable for Unruh effect in heavy-ion collisions?
  - Quantum simulation of accelerated QCD?
  - … …



Thank you!

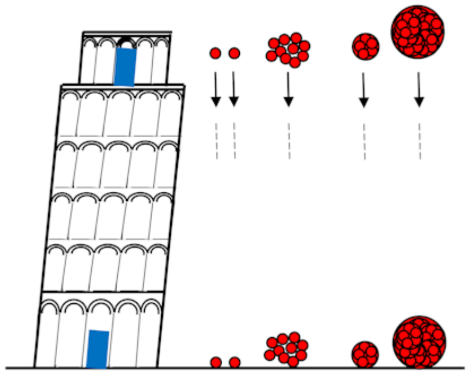
Nonlinear sigma model analysis: phase diagram

- Calculation is just calculation, but which one accelerating observer really sees?
- Perhaps the one with respect to the Rindler vacuum is more reasonable



$$G(x,x') = i\langle 0_R|T\phi(x)\phi(x')|0_R\rangle,$$

$$G_M(x,x') = i\langle 0_M|T\phi(x)\phi(x')|0_M\rangle$$



Equivalence principle: Local experiments in a free-falling frame give the same results as in inertial frame