Spatial confinemement/deconfinement transition in rotating and accelerating QGP

Victor Braguta

in collaboration with
Maxim Chernodub, Vladimir Goy, Jayanta Dey, Artem Roenko

Joint Institute for Nuclear Research

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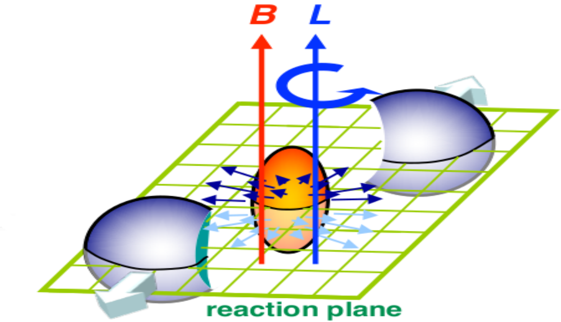
QCD under extreme conditions



- Relativistic rotation
  $\Omega \sim 10$ MeV $(v \sim c$ at $r \sim 10 - 20$ fm, $\sim 10^{22}\, s^{-1})$ [STAR'17]
- Large acceleration
  - $\alpha \sim 1$ GeV [D. Kharzeev'2005]
  - $\alpha \sim 0.1 - 1$ GeV [G.Prokhorov'2025]

Acceleration in HIC

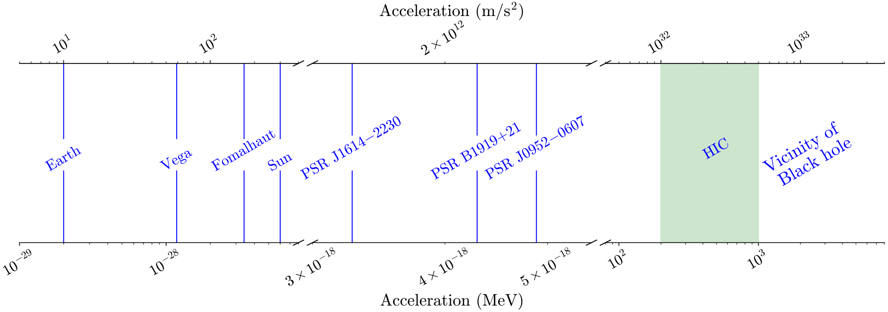


figure from [V. Braguta'2026]

- HIC accelerations can be met in the vicinity of the black hole horizon
- HIC might allow to study quantum effects in gravity?

Rotating Gluodynamics/QCD

- The study is conducted in rotating reference frame (non-inertia frame)
- Influence of non-inertia reference frame can be reduced to external gravitational field
- The metric is well known $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

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

- Aim: investigation of confinement/deconfinement phase transition in rotating gluodynamics/QCD

[V. Braguta'2024, V. Braguta'2025]

Accelerating Gluodynamics/QCD

- HIC is complicated process
- Toy model:
  uniformly accelerated observer ($\vec{a} \parallel \hat{z}$)
  homogeneous magnetic field

  $\frac{d^2 z}{dt^2} = \alpha = const$
- The trajectory:

  $t(\tau) = \frac{1}{\alpha}\sinh \alpha\tau,\ z(\tau) = \frac{1}{\alpha}\cosh \alpha\tau$
- Aim: investigation of confinement/deconfinement phase transition in accelerating gluodynamics/QCD [V. Braguta'2026]
- The first lattice study of gluodynamics with acceleration was carried out without gravity using TE law [M. Chernodub'2024]

Comoving frame

- How to paramerise non-inertial frame?
- Rindler space $x^\mu = (\tilde{t}, x, y, \tilde{z})$
  $t = (1+\alpha\tilde{z})\sinh\alpha\tilde{t},\ z = (1+\alpha\tilde{z})\cosh\alpha\tilde{t},\quad$ observer at $\tilde{z} = 0$
- Metric: $ds^2 = (1+\alpha\tilde{z})^2(d\tilde{t})^2 - dx^2 - dy^2 - d\tilde{z}^2$

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

- Similar to the Schwarzschild black hole close to the horizon
  Bonus: QCD close to the black hole horizon can be studied
- The horizon: $g_{00}(\tilde{z}_h) = 0 \;\Rightarrow\; \tilde{z}_h = -\frac{1}{\alpha}$

Tolman-Ehrenfest law

- Thermal equilibrium in homogeneous system

$$T(\vec{r}) = const$$

- Thermal equilibrium in external gravity (TE law)

$$\sqrt{g_{00}(\vec{r})}\, T(\vec{r}) = T_0 = const$$

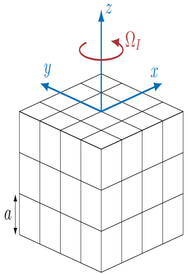
  - Rotation: $T(r) = \frac{T_0}{1-\Omega^2 r^2}$
  - Acceleration: $T(z) = \frac{T_0}{1+\alpha z}$

- We use the designations

  - Rotation: $T = T(r = 0)$
  - Acceleration: $T = T(z = 0)$

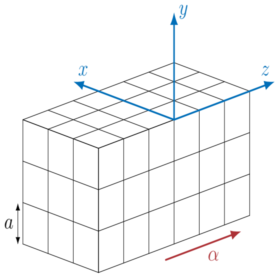
Lattice set up

- Partition function
  $Z = \int DAe^{-S}$,
  $S = \frac{1}{4g^2} \int d^4x \sqrt{g}\; g^{\mu\nu} g^{\alpha\beta} F_{\mu\alpha} F_{\nu\beta}$
- Focus on confinement/deconfinement transition
  Measure local Polyakov loop $L(\vec{r})$
- Open/Dirichle/Periodic BCs
  Don't see significant dependence on tbe BCs



Rotation

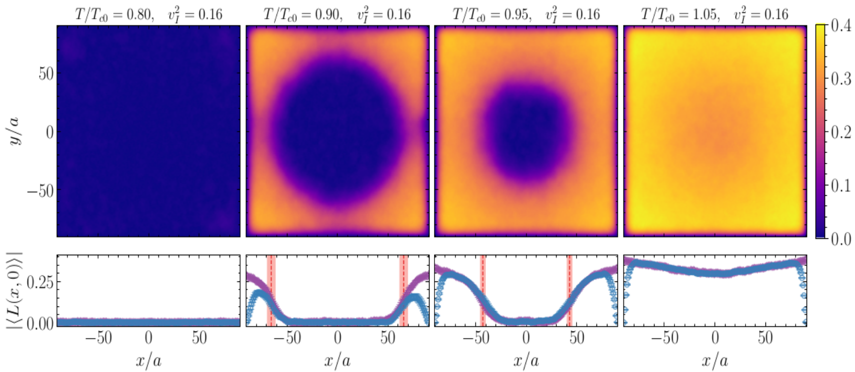
- The sign problem for $\Omega \neq 0$
  simulations are conducted as $\Omega_I = i\Omega$
- Small angular velocities:
  $\Omega \ll \Lambda_{QCD}$ and $\Omega R < 1$
- The infinite volume limit $L_z \to \infty$



Acceleration

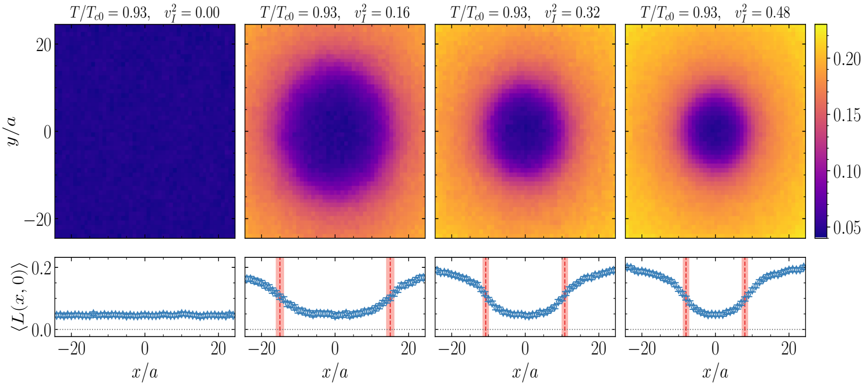
- Free from the sign problem
- Weak accelerations
  $\alpha \ll \Lambda_{QCD}$ and $\alpha L_z \ll 1$
- The infinite volume limit $L_x, L_y \to \infty$

Spatial phase transition in rotating GP



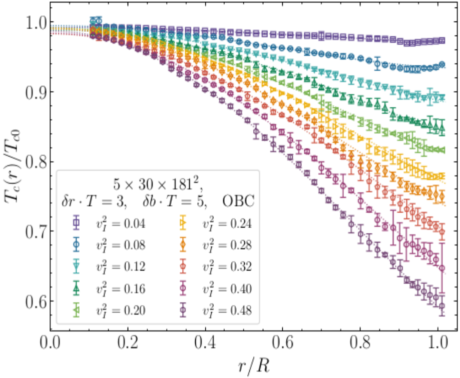
- Finite temperature confinement/deconfinement becomes spatial transition:
  For a certain parameters spatially separated confinement and deconfinement phases coexist simultaneously
- For $\Omega^2 < 0$ confinement in the center and deconfinement in the periphery
- Confinement/inhomogeneous state/deconfinement
  Inhomogeneous state takes place below T_{c0}
- Theoretical studies: [M. Chernodub'2022, S. Chen'2024]

Spatial transition in QCD



- It remains to be true for quarks (Preliminary results!)

Local critical temperature $T_c(r, \Omega_I)$



- TE prediction:

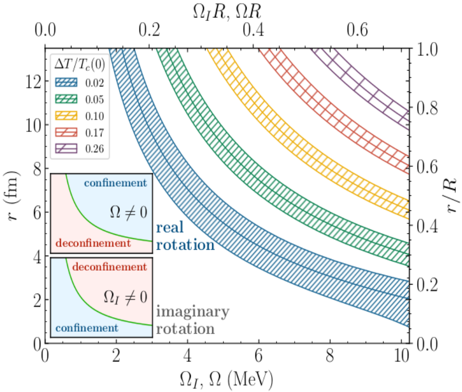
$$T(r) = \frac{T}{1+\Omega_I^2 r^2} = T_{c0} \Rightarrow T_c(r, \Omega_I) = T_{c0}(1 + \Omega_I^2 r^2)$$

- Our results can be well described by the formula

$$\frac{T_c(r,\Omega_I)}{T_{c0}} = 1 - \kappa_2 (\Omega_I r)^2, \quad \kappa_2 > 0$$

- In disagreement with TE law
- Within the uncertainty $\frac{T_c(r=0,\Omega_I)}{T_{c0}} = 1$

Analytical continuation to real rotation

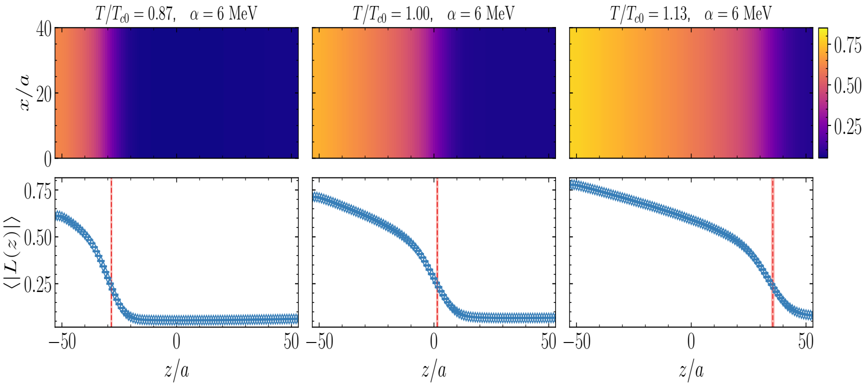


- Analytical continuation $\Omega_I^2 \to -\Omega^2$:

$$\frac{T_c(r,\Omega)}{T_{c0}} = 1 + \kappa_2 (\Omega r)^2$$

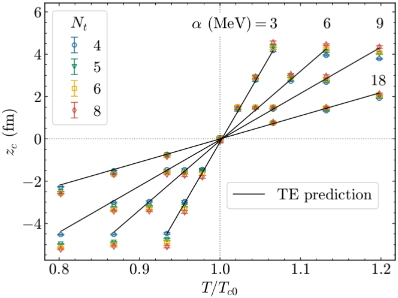
- Inhomogeneous state can be realised for $T > T_{c0}$
- Deconfinement in the center and confinement in the periphery

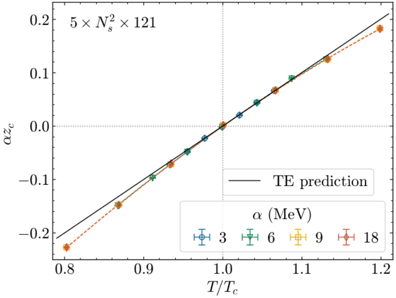
Spatial transition in accelerating GP



- Finite temperature confinement/deconfinement becomes spatial transition for $\alpha \neq 0$
- Deconfinement is close and confinement is far from the horizon
- Confinement/inhomogeneous state/deconfinement
  Inhomogeneous state takes place below and above T_{c0}

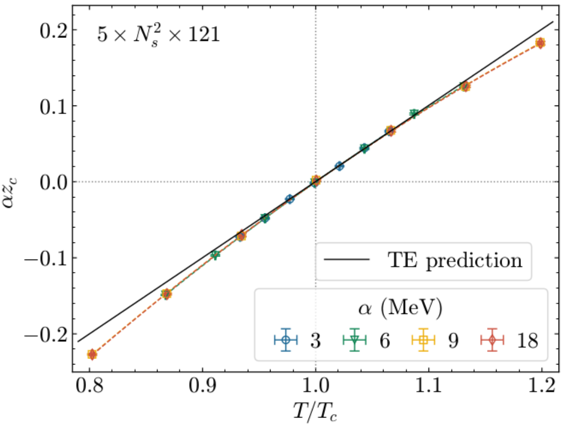
Boundary between the phases





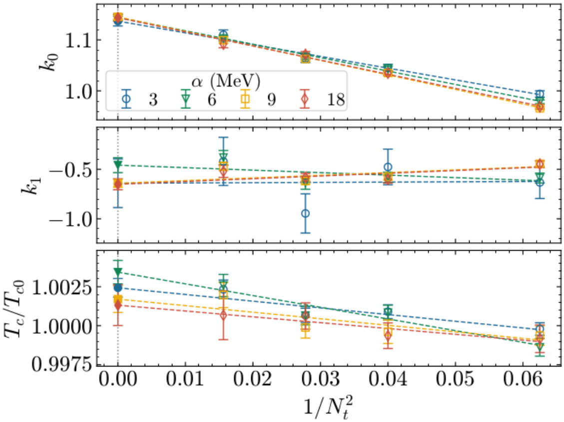
- TE prediction:
  $T_c = T(z_c) = \frac{T}{1+\alpha z_c} \Rightarrow z_c = \frac{1}{\alpha}\left(\frac{T}{T_c} - 1\right)$
- Rather good description of our data by TE law!
- Visible deviation from the TE law for larger accelerations

Beyond TE law



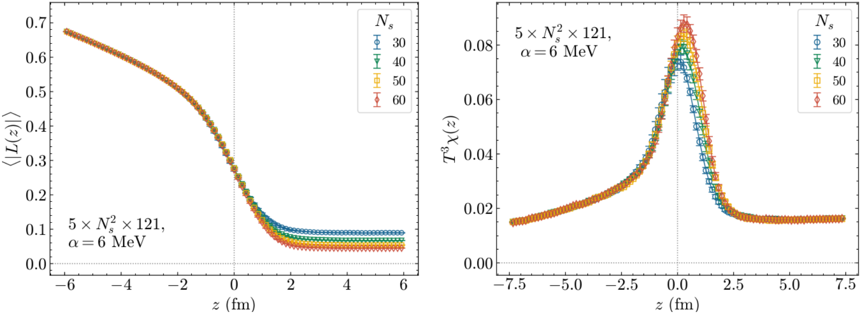
- Fitting of data
  $\alpha z_c = k_0 \left(\frac{T}{T_c} - 1 \right) + k_1 \left(\frac{T}{T_c} - 1 \right)^2$
- k_0, k_1 account deviation from TE law, $T_c(\alpha)$ possible shift of T_{c0}

Beyond TE law



- We tried a lot of options: in the continuum limit $k_0 \sim 1.10 - 1.15$
- Possible explanations: lattice renormalization of the α, crossover transition, higher order α-corrections to TE law...
- Within the uncertainty $T_c(\alpha) = T_{c0}$

Properties of spatial transitions



- Type of phase transition can be studied from scaling of χ^{max} and σ
- First order phase transition: $\chi^{max} \sim V \sim N_s^2$ and $\sigma \sim 1/V \sim 1/N_s^2$
- Height: $\chi^{max}\big|_{V\to\infty} \to const$ and width $\sigma|_{V\to\infty} \to const$
- Both spatial transitions for $\Omega \neq 0$ and $\alpha \neq 0$ are crossovers
- There is the smallest width of the transition $\sigma_0 \sim 1$ fm because of finite correlatin length

Local action

$$S_G = \int d^4x \, \Big[\frac{1}{2g^2} \left((E_x^a)^2 + (E_y^a)^2 + (E_z^a)^2 + (H_y^a)^2 \right) + \\ + \frac{1}{2\tilde{g}^2} \left((H_x^a)^2 + (H_z^a)^2 \right) \Big]$$

- Linear in Ω terms can be neglected
- External gravitational field leads to the asymmetric action with $\frac{g^2}{\tilde{g}^2} = 1 - (\Omega r_0)^2$
- The asymmetry $g^2/\tilde{g}^2$ is larger in the periphery region leading to the shift of the local critical temperature
- Local thermalization approximation was checked on the lattice

What about accelerating GP?

Local action for $\Omega \neq 0$

$$S_G = \int d^4x \, \Big[\frac{1}{2g^2} \left((E_x^a)^2 + (E_y^a)^2 + (E_z^a)^2 + (H_y^a)^2 \right) + \\ + \frac{1}{2\tilde{g}^2} \left((H_x^a)^2 + (H_z^a)^2 \right) \Big], \quad \frac{g^2}{\tilde{g}^2} = 1 - (\Omega r_0)^2$$

Local action for $\alpha \neq 0$

$$S_G = \int d^4x \, \Big[\frac{1}{2g^2} \left((E_x^a)^2 + (E_y^a)^2 + (E_z^a)^2 \right) + \\ + \frac{1}{2\tilde{g}^2} \left((H_x^a)^2 + (H_y^a)^2 + (H_z^a)^2 \right) \Big], \quad \frac{g^2}{\tilde{g}^2} = (1 + \alpha z_0)^2$$

Property of Rindler space

- The observer is located at $z = 0$

$$ds^2 = -(1 + \alpha z)^2 \, d\tau^2 - dx^2 - dy^2 - dz^2$$

- Is the coordinate of the observer exceptional?
- No! One can change the coordinate of the observer
- For the observer at $z = z_1$

$$ds^2 = -(1 + \alpha_1(z - z_1))^2 \, d\tau^2 - dx^2 - dy^2 - dz^2$$

$$\alpha_1 = \tfrac{\alpha}{1+\alpha(z_1 - z_0)}, \quad T_1 = \tfrac{T_0}{1+\alpha_0(z_1 - z_0)}$$

- To change the observer $z_0 \to z_1$, one has to change parameters $\alpha_0 \to \alpha_1, \quad T_0 \to T_1$

Gluodynamics in the Rindler space

- The observer at $z = z_0$:
  $S_G = \frac{1}{2g^2} \int d\tau_0 d^3x \left(\frac{(\vec{E}^a)^2}{1+\alpha_0(z-z_0)} + (1 + \alpha_0(z - z_0))(\vec{H}^a)^2 \right) =$
  $\frac{1}{2g^2} \int d\tau_0 d^3x \left((\vec{E}^a)^2 + (\vec{H}^a)^2 \right) + O(\alpha)$

- The observer at $z = z_1$:
  $S_G = \frac{1}{2g^2} \int d\tau_1 d^3x \left(\frac{(\vec{E}^a)^2}{1+\alpha_1(z-z_1)} + (1 + \alpha_1(z - z_1))(\vec{H}^a)^2 \right) =$
  $\frac{1}{2g^2} \int d\tau_0 d^3x \left((\vec{E}^a)^2 + (\vec{H}^a)^2 \right) + O(\alpha)$

- The only difference is $T_0 \neq T_1$

- For this reason TE law describes the data well

- This approximation works for $\alpha\zeta \ll 1$
  It is violated for $\alpha \sim 1/\zeta \sim \Lambda \sim 200$ MeV

- What do we have close to the black hole horizon?

Conclusion

- We conducted lattice study of rotating and accelerating gluodynamics
- New state of gluon plasma: spatially separated confinement and deconfinement phases coexist simultaneously
- It was found that finite temperature confinement/deconfinement becomes spatial crossover
- The transition looks as follows: confinement/inhomogeneous state/deconfinement
- This behaviour results from the fact that gravity modifies gluon action leading to different local critical temperatures
- We believe that our results remain to be true for QCD
- QGP phase in the vicinity of black hole?
- Future study: gluodynamics close to the horizon

THANK YOU!