String tension and Polyakov loop in a rotating background

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[1] J.-X. Chen, S. Wang, D.-F. Hou, and H.-C. Ren, Phys. Rev.D 110,026020 (2025), arXiv: 2410.04763 [hep-ph].

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- Background

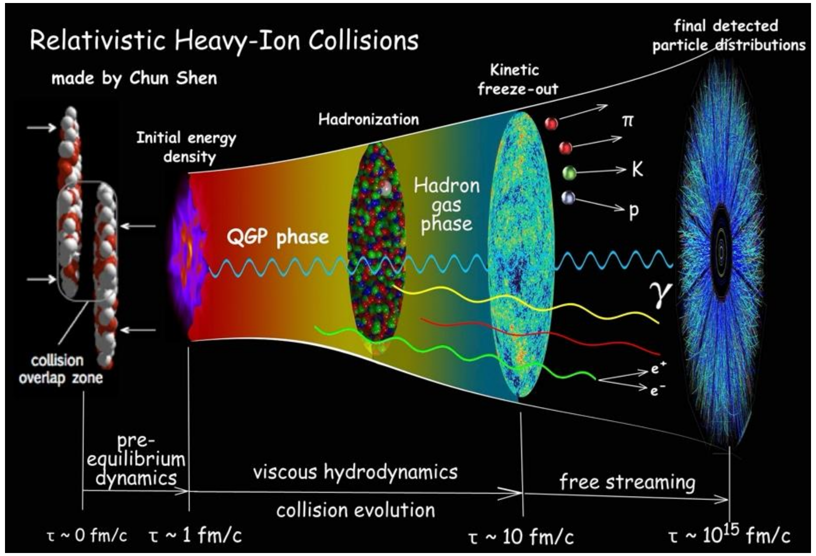
  Motivation, holographic model

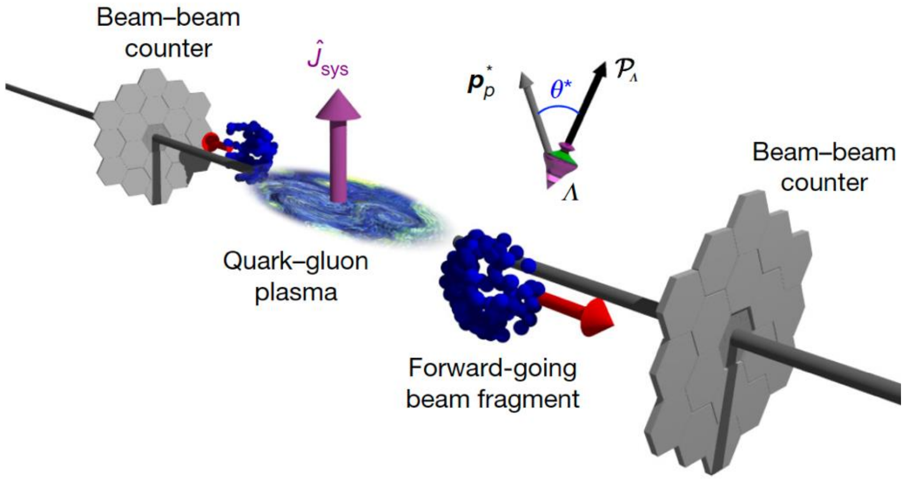
- Innovation and result

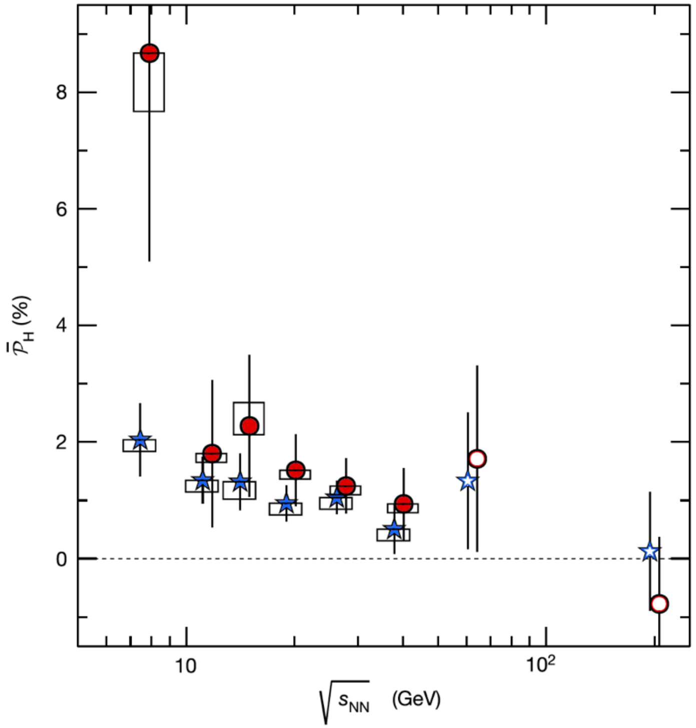
  Effect of rotation on the Polyakov loop and string tension

- Summary and outlook

Motivation







Strong vorticity fields exist in relativistic heavy-ion collisions $\Omega = (9 \mp 1) \times 10^{21} s^{-1}$

[1] Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94 (2005) 102301
[2] L. Adamczyk et al. (STAR), Nature 548, 62 (2017)

Polyakov loop and string tension

Lattice:

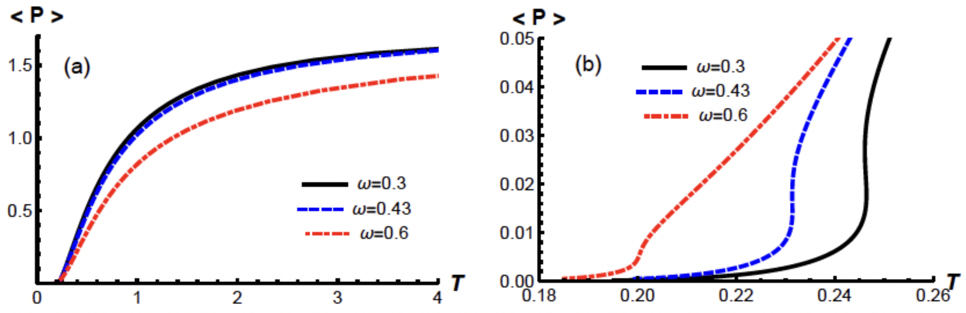
V. V. Braguta, A. Y. Kotov, D. D. Kuznedelev, et al, arXiv:2102.05084 [hep-lat].

$$T_c(\Omega)/T_c(0) = 1 + C_2\Omega^2 \quad \text{with} \quad C_2 > 0$$

Angular velocity Ω ↑ Temperature T ↑

Holography:

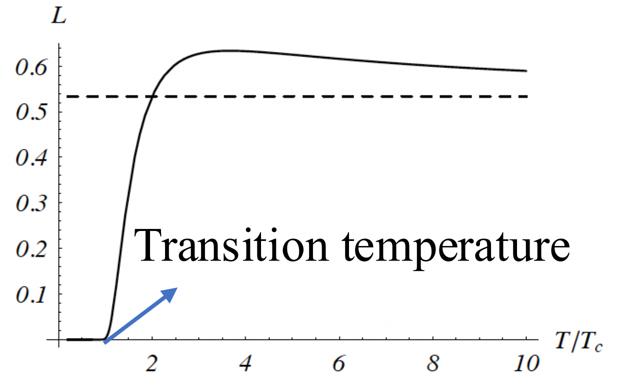
X. Chen, L. Zhang, D. Li, D. Hou, and M. Huang, (2020), arXiv:2010.14478 [hep-ph].



Angular velocity Ω ↑ Temperature T ↓

O. Andreev, Phys. Rev. Lett. 102 (2009) 212001, arXiv:0903.4375 [hep-ph].

$T < T_c, L \simeq 0$	Confined phase
$T > T_c, L > 0$	Deconfined phase



Expectation value of the Polyakov loop versus temperature

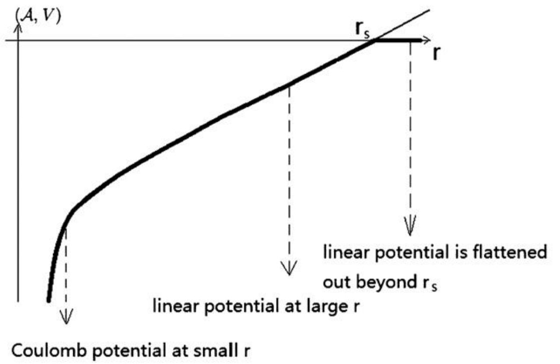
O. Andreev and V. I. Zakharov, Phys. Rev. D 74 (2006) 025023, arXiv:hep-ph/0604204.

In large distance limit, the string tension is

$$\kappa = \frac{V}{r}$$

V → Heavy quark potential

r → Distance between the quark and anti-quark



Research method

Research method： Lattice QCD、NJL model、 AdS/CFT duality

- AdS/CFT duality： The strongly coupled gauge theory in four-dimensional space-time is dual to the weakly coupled string theory on $AdS_5 \times S^5$.

String theory ⟺ Gauge theory

The Large N limit of superconformal field theories and supergravity

Juan Martin Maldacena (Harvard U.) (Nov, 1997)

Published in: *Int.J.Theor.Phys.* 38 (1999) 1113-1133 (reprint), *Adv.Theor.Math.Phys.* 2 (1998) 231-252 • e-Print: hep-th/9711200 [hep-th]

pdf DOI cite claim reference search 20,112 citations

Background geometry

Minkowski background metric in cylindrical coordinates

$$ds^2 = \frac{R^2}{w^2} h \left(-f dt^2 + dl^2 + l^2 d\phi^2 + dz^2 + \frac{1}{f} dw^2 \right)$$

Azimuth angle

$$h = e^{\frac{1}{2}cw^2}, f = 1 - \frac{w^4}{w_t^4}$$

Warp factor generates confinement

Global transformation

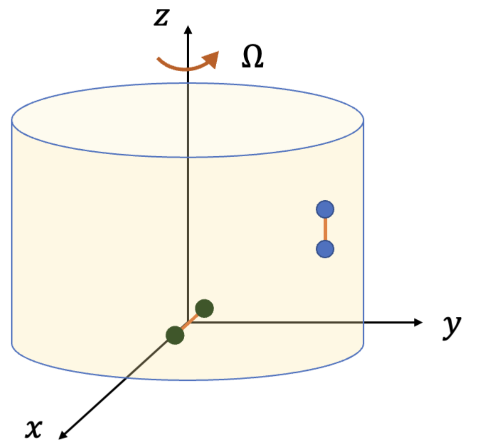
$\phi \rightarrow \phi + \Omega t$

Lattice QCD, effective field theories, and so on.

$$ds^2 = \frac{R^2}{w^2} h[-(f - \Omega^2 l^2)dt^2 + l^2 d\phi^2 + 2\Omega l^2 dt d\phi + dl^2 + dz^2 + \frac{1}{f} dw^2]$$

Hawking temperature

$$T = \frac{1}{\pi w_t}$$



Background geometry

Minkowski background metric in cylindrical coordinates

$$ds^2 = \frac{R^2}{w^2} h \left(-f dt^2 + dl^2 + l^2 d\phi^2 + dz^2 + \frac{1}{f} dw^2 \right)$$

Local Lorentz transformation

$$t \to \frac{1}{\sqrt{1-(\Omega l_0)^2}} (t + \Omega l_0^2 \phi)$$

$$\phi \to \frac{1}{\sqrt{1-(\Omega l_0)^2}} (\phi + \Omega t)$$

$$ds^2 = \frac{R^2}{w^2} h \{ \frac{1}{1-(\Omega l_0)^2} [(-f + \Omega^2 l^2) dt^2 + (l^2 - \Omega^2 l_0^4 f) d\phi^2 + 2\Omega (l^2 - l_0^2 f) dt d\phi] + dl^2 + dz^2 + \frac{1}{f} dw^2 \}$$

Hawking temperature $T = \frac{\sqrt{1-(\Omega l_0)^2}}{\pi w_t}$

Euler-Lagrange equations

Taking $\sigma^{\alpha} = (t, w)$ as the string world-sheet coordinates, and assume

$$l = l(t,w), \phi = \phi(t,w), z = z(t,w)$$

Nambu-Goto action $S = -\frac{1}{2\pi\alpha'}\int dtdw\sqrt{-g}$

Determinant of the induced metric

$$g_{\alpha\beta} = G_{\mu\nu}\frac{\partial X^{\mu}}{\partial \sigma^{\alpha}}\frac{\partial X^{\nu}}{\partial \sigma^{\beta}}$$

Metric of target space

Euler-Lagrange equations

$$\frac{d}{dt}\left(\frac{\partial\sqrt{-g}}{\partial \dot{l}}\right) + \frac{d}{dw}\left(\frac{\partial\sqrt{-g}}{\partial l'}\right) - \frac{\partial\sqrt{-g}}{\partial l} = 0$$

$$\frac{d}{dt}\left(\frac{\partial\sqrt{-g}}{\partial \dot{\phi}}\right) + \frac{d}{dw}\left(\frac{\partial\sqrt{-g}}{\partial \phi'}\right) - \frac{\partial\sqrt{-g}}{\partial \phi} = 0$$

$$\frac{d}{dt}\left(\frac{\partial\sqrt{-g}}{\partial \dot{z}}\right) + \frac{d}{dw}\left(\frac{\partial\sqrt{-g}}{\partial z'}\right) - \frac{\partial\sqrt{-g}}{\partial z} = 0$$

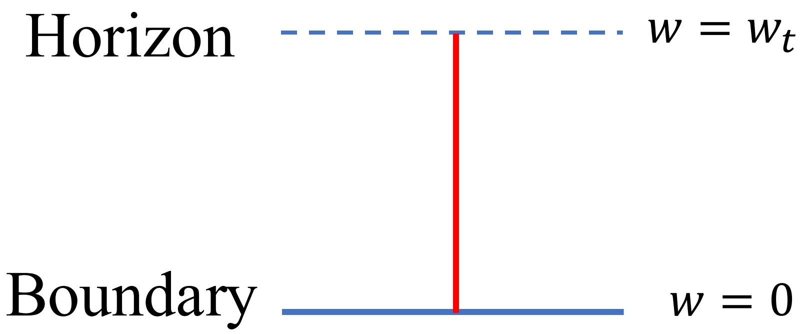
Polyakov loop

Expectation value of Polyakov loop $L = e^{-S_q}$ → Nambu-Goto action of a single quark with an imaginary time

without rotation

Solution ansatz

$$l = const., \phi = const., z = const.$$



with rotation

Solution ansatz for small Ω

$$l = l_0 + \Omega^2 l_1(w)$$

$$\phi = \phi_0 + \Omega \phi_1(w)$$

$$z = z_0 + \Omega^2 z_1(w)$$

Solve EoM ⟹

Solution

$$l = l_0$$

$$\phi_1' = -\frac{w^2 h(w_t)}{w_t^2 h f}$$

$$z = z_0$$

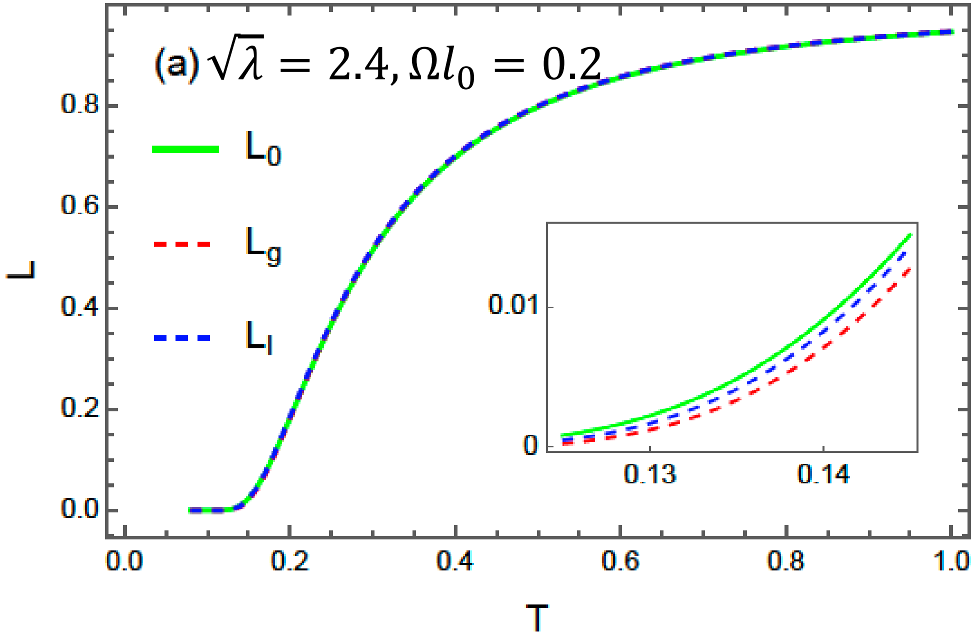
[1] Y. Aref'eva, A.A. Golubtsova and E. Gourgoulhon, JHEP 04 (2021) 169

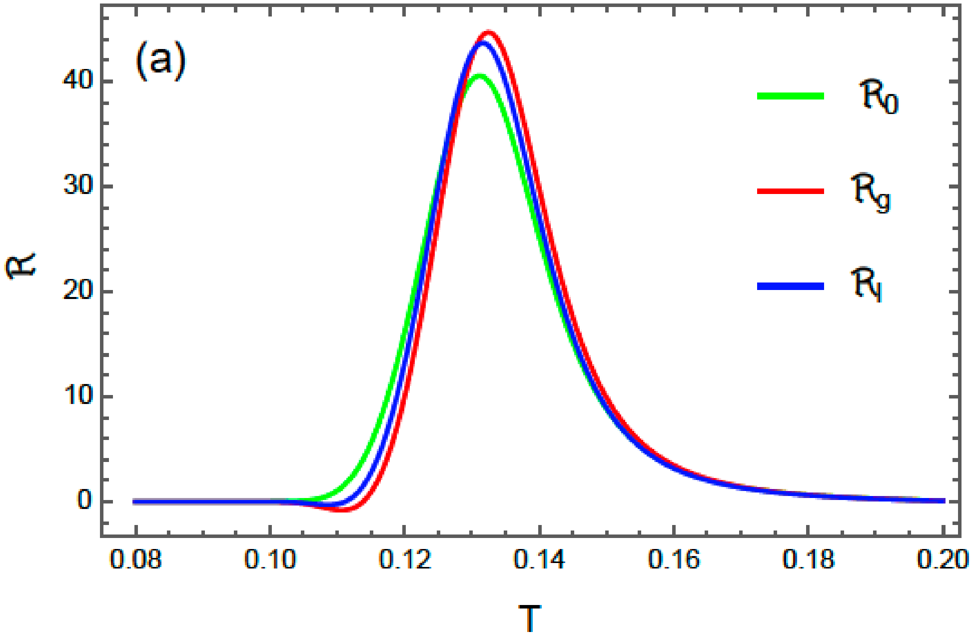
Result 1: Polyakov loop

$$L = \color{red}{L_0} + \Omega^2 l_0^2 L_1$$

O. Andreev, Phys. Rev. Lett. 102 (2009) 212001, arXiv:0903.4375 [hep-ph].

Curvature $$\mathcal{R} = \frac{\left|\frac{d^2L}{dT^2}\right|}{\left[1+\left(\frac{dL}{dT}\right)^2\right]^{\frac{3}{2}}} \simeq \mathcal{R}_0 + \Omega^2 l_0^2 \mathcal{R}_1$$





Transition temperature ↑

[1] V. V. Braguta, A. Y. Kotov, D. D. Kuznedelev, et al, Phys.Rev. D 103 no. 9, (2021) 094515, arXiv:2102.05084 [hep-lat].
[2] Y. Chen, X. Chen, D. Li, and M. Huang, Phys. Rev. D 111 no. 4, (2025) 046006, arXiv:2405.06386 [hep-ph].
[3] F. Sun, J. Shao, R. Wen, K. Xu, and M. Huang, Phys. Rev. D 109 no. 11, (2024) 116017, arXiv:2402.16595 [hep-ph].

Result 1: Polyakov loop

Transition temperature without rotation

$\sqrt{\lambda}$	$T_d^{(0)}$	δT_g	δT_l	C_g	C_l
0.94	104.21	5.28	3.92	0.63	0.47
1.44	114.18	3.29	2.00	0.36	0.22
2.4	131.18	1.71	0.57	0.16	0.05

Unit is MeV

$\sqrt{\lambda}$ ↑ $T_d^{(0)}$ ↑ δT ↓

$$C = \frac{\delta T}{T v^2}$$

Linear velocity on the boundary

$$C = -\frac{1}{2T_d^{(0)}} \frac{\frac{d\mathcal{R}_1}{dT}}{\frac{d^2\mathcal{R}_0}{dT^2}}\Bigg|_{T=T_d^{(0)}}$$

V. V. Braguta, A. Y. Kotov, D. D. Kuznedelev, et al, Phys.Rev. D 103 no. 9, (2021) 094515, arXiv:2102.05084 [hep-lat].

Coefficient of lattice 0.7

[1] O. Andreev, Phys. Rev. Lett. 102 (2009) 212001, arXiv:0903.4375 [hep-ph].
[2] O. Andreev and V. I. Zakharov, JHEP 04 (2007) 100, arXiv:hep-ph/0611304.

Result 2: String tension

String tension for a quarkonium parallel to the rotation axis

$$\kappa_{g\parallel} = \underline{\frac{\sqrt{\lambda}\pi T^2}{2b}\sqrt{1-b^2}e^{\frac{3\sqrt{3}bT_1^2}{2T^2}}}\left[1 - \underline{\frac{1}{2(1-b^2)}\Omega^2 l_0^2}\right] \quad < 0 \qquad b = \frac{2}{\sqrt{3}}\sin\left(\frac{1}{3}\sin^{-1}\frac{T^2}{T_1^2}\right) \qquad T_1 = \frac{1}{\pi}\sqrt{\frac{c}{\sqrt{27}}}$$

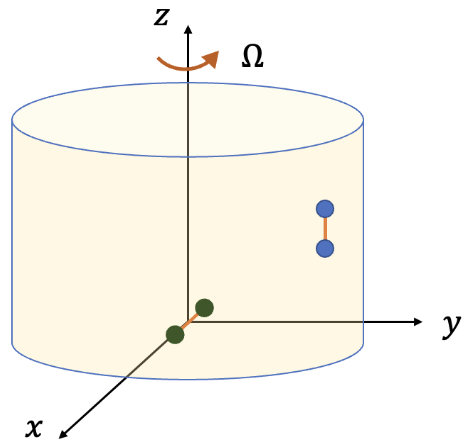
String tension for a quarkonium symmetric with respect to the rotation axis

$$\kappa_{g\perp} = \underline{\frac{\sqrt{\lambda}\pi T^2}{2b}\sqrt{1-b^2}e^{\frac{3\sqrt{3}bT_1^2}{2T^2}}}\left[1 - \underline{\frac{1}{24(1-b^2)}\Omega^2 r^2}\right] \quad < 0$$

O. Andreev and V. I. Zakharov, JHEP 04 (2007) 100, arXiv:hep-ph/0611304.

String tension in local rotating background

$$\kappa_l = \underline{\frac{\sqrt{\lambda}\pi T^2}{2b}\sqrt{1-b^2}e^{\frac{3\sqrt{3}bT_1^2}{2T^2}}}\left\{1 - \underline{\left[\frac{b^2}{2(1-b^2)} + \frac{3\sqrt{3}bT_1^2}{2T^2} - 1\right]\Omega^2 l_0^2}\right\} \quad < 0$$



Summary and outlook

- The deconfinement phase transition temperature increases with increasing angular velocity.

[1] V. V. Braguta, A. Y. Kotov, D. D. Kuznedelev, et al, Phys.Rev. D 103 no. 9, (2021) 094515, arXiv:2102.05084 [hep-lat].
[2] Y. Chen, X. Chen, D. Li, and M. Huang, Phys. Rev. D 111 no. 4, (2025) 046006, arXiv:2405.06386 [hep-ph].
[3] F. Sun, J. Shao, R. Wen, K. Xu, and M. Huang, Phys. Rev. D 109 no. 11, (2024) 116017, arXiv:2402.16595 [hep-ph].
[4] S. Wang , J.-X. Chen, D.-F. Hou, and H.-C. Ren, arXiv:2505.15487 [hep-ph].
[5] F. Kenji and S. Yusuke, Phys. Lett. B, arXiv: 2506.03560 [hep-ph].

- The string tension decreases with the increasing angular velocity in all cases examined.

Thanks for your attention

Several methods

- Global transformation $\phi \to \phi + \Omega t$

The angular velocity of QGP $\Omega \simeq 1 \times 10^{22} s^{-1} \simeq 7MeV$

radius $8fm \simeq 40.5GeV^{-1}$ the linear velocity $v \simeq 0.3$

Lattice QCD, effective field theories, and so on.

- Local Lorentz transformation

$$t \to \frac{t + vx}{\sqrt{1 - v^2}}$$

$$x \to \frac{x + vt}{\sqrt{1 - v^2}}$$

$$v = \Omega l_0$$
$$x = l_0 \phi$$

$$t \to \frac{1}{\sqrt{1 - (\Omega l_0)^2}} (t + \Omega l_0^2 \phi)$$

$$\phi \to \frac{1}{\sqrt{1 - (\Omega l_0)^2}} (\phi + \Omega t)$$

Period $T = 2\pi\sqrt{1 - (\Omega l_0)^2} \leq 2\pi$

This method can only describe a small neighbourhood around l_0.

- Kerr-AdS5, rotating string