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Gluon matter under weak acceleration: lattice results

Maxim Chernodub
Institut Denis Poisson, CNRS, Tours, France
Department of Physics, West University of Timișoara, Romania
in collaboration with
Vladimir Goy, Alexander Molochkov, Daniil Stepanov, and Arina Pochinok
Pacific Quantum Center, Far Eastern Federal University, 690922 Vladivostok, Russia

INSTITUT DENIS POISSON — FORQ group — West University of Timișoara — FIZICĂ — Timișoreana

Motivation

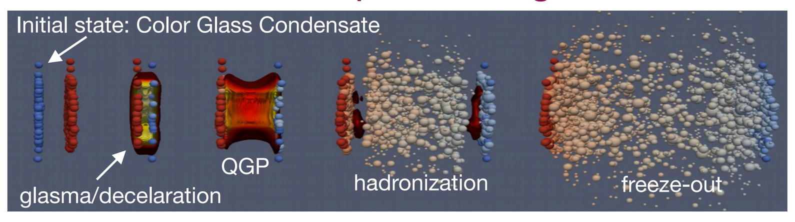
Effects of high temperatures, high densities, strong (electro)magnetic fields, vorticity on quark-gluon plasma have been intensively studied. Here we ask the question: what is the effect of acceleration on the phase diagram of QCD?

Relevant to early stages of heavy ion collisions, and presumably, extreme astrophysical environments (the Early Universe?)

Uniformly accelerating fluid possesses an event horizon, similar to black holes.
→ Intriguing questions related to the Unruh temperature and the Hawking radiation.

→ Rapid thermalization of gluon matter due to high deceleration, $a \sim 1$ GeV, and tunneling through the Rindler horizon.

[D. Kharzeev, K. Tuchin, From Color Glass Condensate to Quark Gluon Plasma through the event horizon, Nucl. Phys. A753, 316 (2005)]



[adapted after MADAI collaboration, Hannah Petersen, Jonah Bernhard]

Good news first: No sign problem!

acceleration in imaginary time formalism in Euclidean $a_E = -a$ acceleration in Minkowski

hint: [acceleration] = meters per second^2 — for $t \to -i\tau$, one gets: $\frac{l}{t^2} \to -\frac{l}{\tau^2}$

Can be calculated in first-principle Monte Carlo simulations on the lattice! (just a sign flip)

Theory

A uniform acceleration of a fluid

Under a uniform acceleration a, a generic particle system resides in **global thermal equilibrium** characterized by temperature $T(x)$, which is an inhomogeneous function of spacetime coordinate x.

The fluid is described by the inverse temperature four-vector $\beta^\mu(x) = u^\mu(x)/T(x)$ associated with the local fluid velocity $u^\mu(x)$.

→ satisfies the Killing equation: $\partial^\mu \beta^\nu + \partial^\nu \beta^\mu = 0$.

→ an acceleration solution: $\beta^\mu(x)\partial_\mu = \frac{1}{T_0}[(1+az)\partial_t + at\partial_z]$.

A shorthand notation, equivalent to $\beta^t = \frac{1}{T_0}(1+az)$ and $\beta^z = \frac{at}{T_0}$ (acceleration a along the z axis)

→ physical quantities:

$$T(x) = \frac{T_0}{\sqrt{(1+az)^2 - (at)^2}} \quad \text{temperature}$$

$$u^\mu(x)\partial_\mu = \frac{T(x)}{T_0}[(1+az)\partial_t + at\partial_z] \quad \text{local fluid velocity}$$

$$a^\mu(x)\partial_\mu = a\frac{T^2(x)}{T_0^2}[at\partial_t + (1+az)\partial_z] \quad \text{local acceleration}, \; a^\mu = u^\nu \partial_\nu u^\mu$$

We associate this particular temperature gradient with acceleration "a" of hot matter with central temperature T_0.

At $t = 0$:

$$T(x) = \frac{T_0}{1+az} \quad \text{[inhomogeneous temperature]} \qquad z > z^R = -\frac{1}{a} \quad \text{[Rindler horizon =event horizon]}$$

$$u^\mu(x) = \delta^{\mu,t} \quad \text{[locally static fluid]}$$

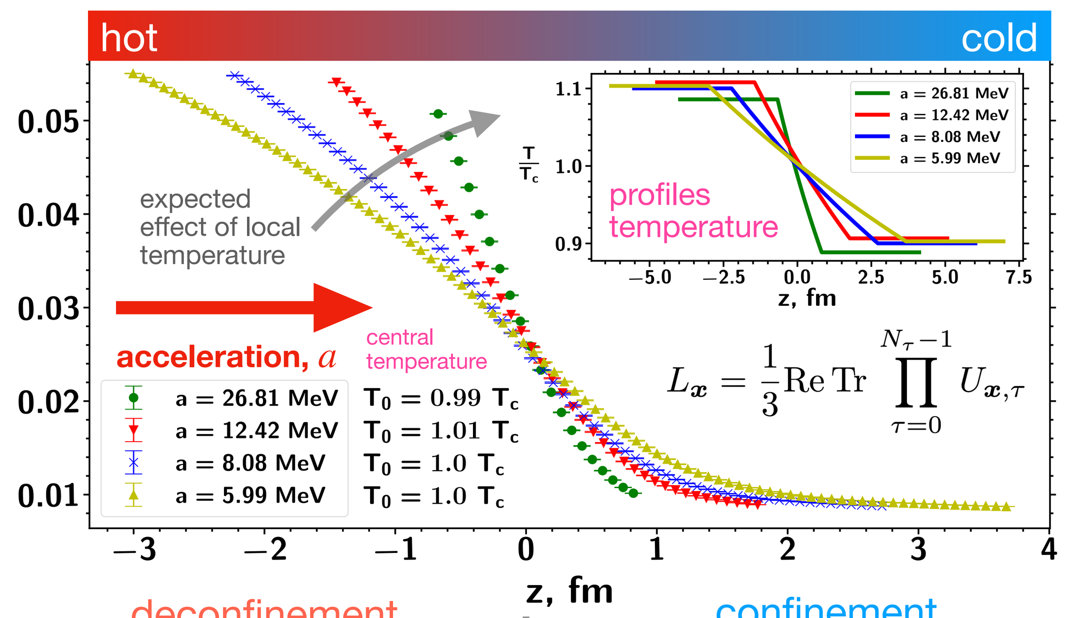
$$a^\mu(x) = \frac{a\delta^{\mu,z}}{1+az} \quad \text{Tolman-Ehrenfest (Luttinger) relation} \quad a = -\frac{1}{T}\frac{\partial T}{\partial z}$$

[for example: C. Cercignani and G. M. Kremer, The Relativistic Boltzmann Equation: Theory and Applications (Springer, 2002)]

First-principle lattice results

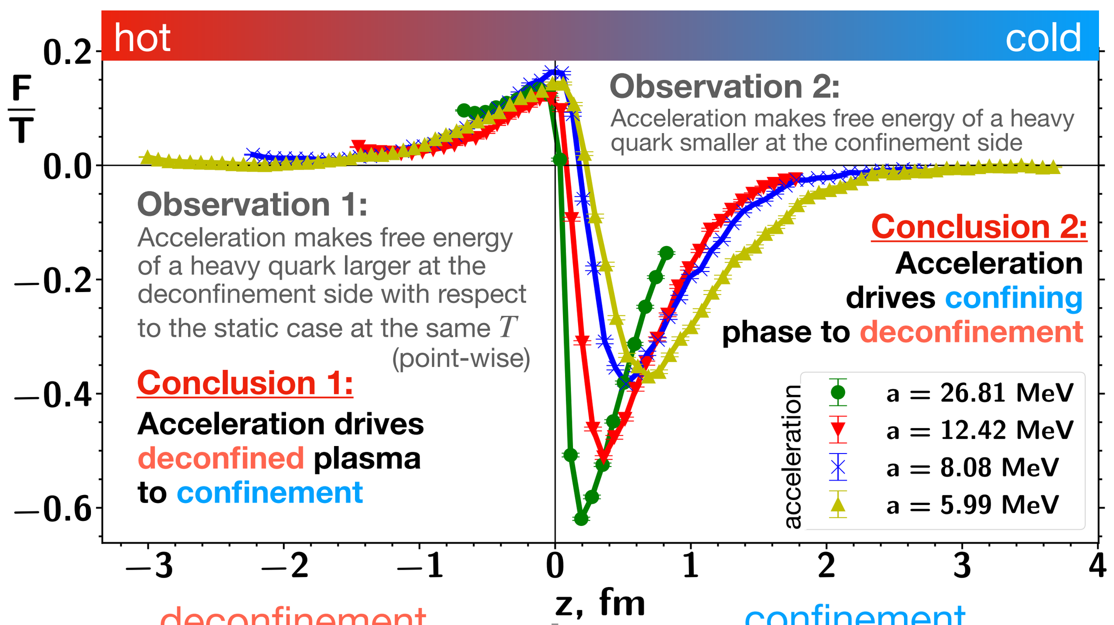
Polyakov loop (unrenormalized)

order parameter of confinement of color

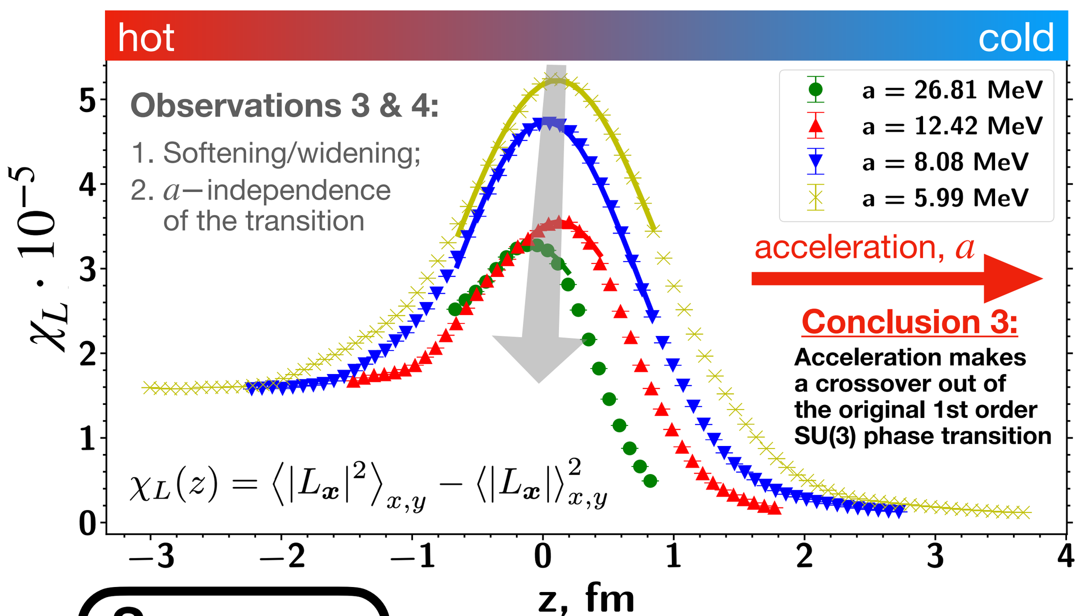


$$L_x = \frac{1}{3}\mathrm{Re\,Tr}\prod_{\tau=0}^{N_\tau - 1} U_{x,\tau}$$

Change in free energy of a heavy quark under acceleration (renormalized free energy)

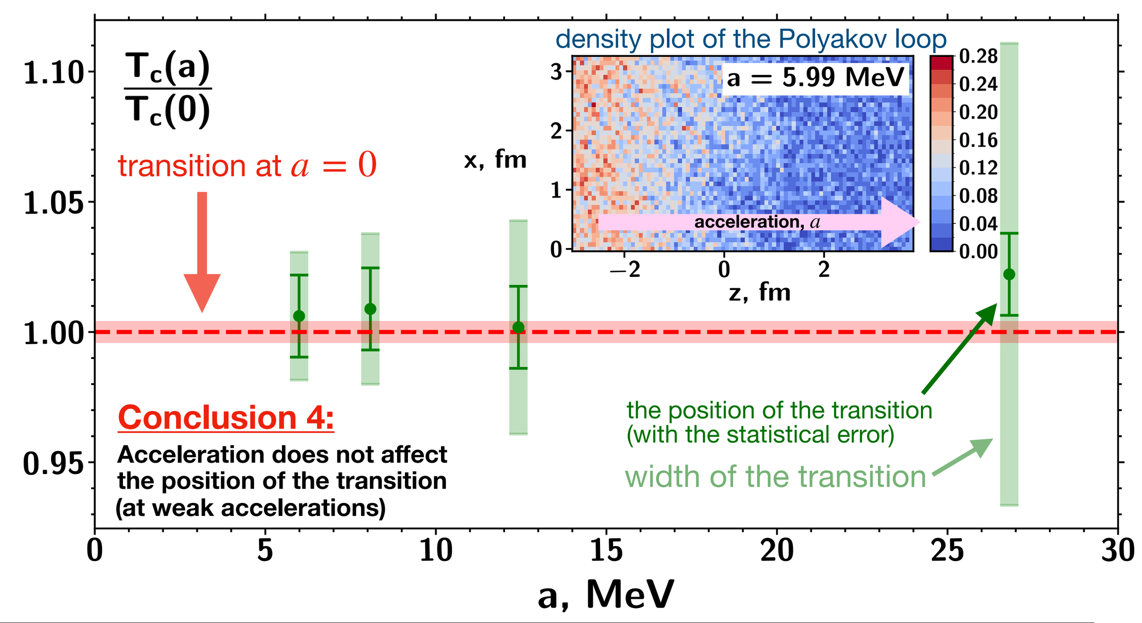


Polyakov loop susceptibility



$$\chi_L(z) = \langle |L_x|^2 \rangle_{x,y} - \langle |L_x| \rangle_{x,y}^2$$

Phase diagram of gluon plasma under acceleration



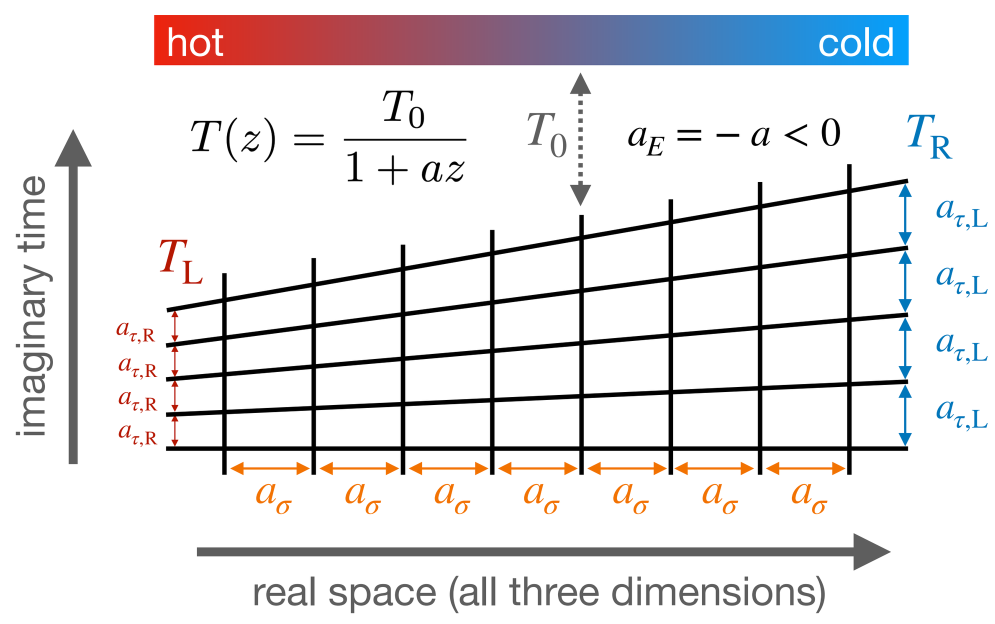
Summary

1. Acceleration does not affect the critical temperature of the deconfinement transition (at least, for the weak accelerations studied, $a \simeq (6\ldots27)$ MeV)
   → at least, for quarks, we expect the chiral symmetry restoration due to acceleration! [Chiral symmetry restoration in the NJL model due to acceleration: T. Ohsaku, Phys. Lett. B599 (2004) 102]
2. Even the weakest studied acceleration, $a \simeq 6$ MeV, makes a crossover of the original 1st order thermal phase transition in SU(3) Yang-Mills theory
   → acceleration hinders the search for a real thermodynamic phase transition!

Details of lattice calculations

to keep finite volume effects under full control — to simulate acceleration at global thermodynamic equilibrium

In order to simulate the lattice gauge theory at **fixed** spatial volume geometry, $L_x = L_y = L_z = \text{const}$, and **varying** temperature, $T = T(z)$, we need to work with an anisotropic lattice that has two different lattice spacings in the spatial (a_σ) and imaginary-time (a_τ) directions.



$$T(z) = \frac{T_0}{1+az}$$

The Wilson action with anisotropic couplings:

[F. Karsch, SU(N) gauge theory couplings on asymmetric lattices, Nucl. Phys. B 205, 285 (1982).]

$$S = \sum_x \sum_{i>j=1}^{3} \beta_\sigma(x_3)\left(1 - \mathcal{P}_{x,ij}\right) + \sum_x \sum_{i=1}^{3} \beta_\tau(x_3)\left(1 - \mathcal{P}_{x,4i}\right)$$

spatial plaquettes — temporal plaquettes — $z \equiv x_3$

plaquettes: $\mathcal{P}_P = \frac{1}{3}\mathrm{Re\,Tr}\,U_P$

$$P_{n,\mu\nu} = \{n, \mu\nu\} \qquad z \equiv x_3$$

$$U_{x,\mu\nu} = U_{x\mu}U_{x+\hat\mu,\nu}U^\dagger_{x+\hat\nu,\nu}U^\dagger_{x,\nu}$$

Lattice size: $N_\tau \times N_x \times N_y \times N_z$ (natural numbers)

Simulation at: $N_\tau = 6, 8$; $N_x = N_y = 42$
$N_z = 170, 148, 126, 104$

Physical size: $L_\tau \times L_x \times L_y \times L_z$ (physical length)

Imaginary-time length: $L_\tau(z) = N_\tau a_\tau(z)$ (space-dependent)

Real-space length: $L_\sigma = N_\sigma a_\sigma$ (constant)

The anisotropy of the lattice spacings:

$$\xi = \frac{a_\sigma}{a_\tau}$$

The physical lattice spacings are functions of the lattice couplings.

$$a_\sigma = a_\sigma(\beta_\sigma, \beta_\tau)$$
$$a_\tau = a_\tau(\beta_\sigma, \beta_\tau)$$

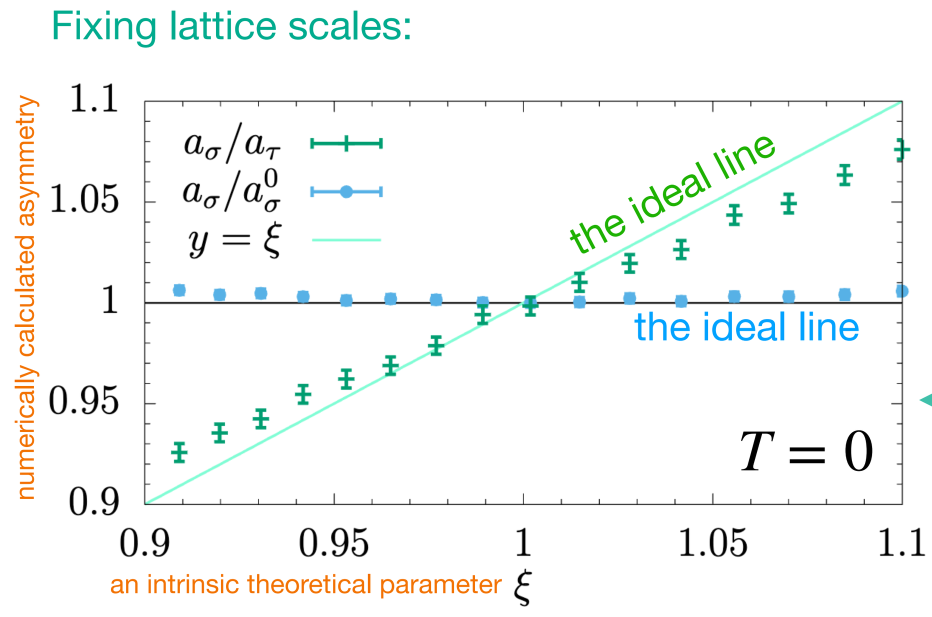
Physical temperature: $T(z) = \frac{1}{L_\tau(z)}$
The length of the imaginary time: $L_\tau(z) = N_\tau a_\tau(z)$

For acceleration: $T(z) = \frac{T_0}{1 - a_E z}$
The spacing of the imaginary time: $a_\tau(z) = a_0(1 - a_E z)$

Temperature T_0 at the central $z = 0$ plane: $T_0 = T(z=0) \equiv \frac{1}{N_\tau a_0}$, $a_0 = a_\tau(z=0)$

Inhomogeneous lattice spacing
Fixed lattice spacing at the center $z = 0$
Euclidean acceleration, $a_E = -a < 0$

Fixing lattice scales:



Choosing a curve in the plane of the lattice couplings $(\beta_\sigma, \beta_\tau)$ such that ξ changes while the spatial lattice spacing a_σ stays constant.
(given by a complicated nonlinear behavior even in perturbation theory: not shown)
The mismatch of the scale fixing is less than 1% (= very accurate)

A de-confusion corner:

a_σ, a_τ, a_0 : lattice spacings (very standard notation)

a : acceleration in Minkowski spacetime (also, confusingly, very standard notation)

$a_E \equiv -a$: acceleration in the Euclidean spacetime (after Wick rotation to imaginary time)