Study of the QGP physics in center vortices

Electric and magnetic gluon propagators after/before center vortex removal

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Quark gluon plasma

- Heavy-ion experiment (RHIC,2004) produces a quark gluon plasma in the deconfinement phase.
- Not free gas, but strongly interacting matter.
  - Perfect fluid (Hydro calc. and elliptic flow)
  - Small shear viscosity (also by lattice simulations)
  - Strongly interacting QGP; however, *understanding of dynamics of QGP is an unsoved problem*, so that we need new idea.
- Here, we study what *magnetic degrees of freedom* causes in the QGP phase.

Magnetic degrees of freedom in hot Yang-Mills theory (1)

◆Magnetic gluons in hot medium produces magnetic mass (~g^2(T)T) as an infrared cutoff of thermal QCD.
Linde PLB96,289(1981); for lat. cal. , Nakamura, et. al, PRD69 (2004) 014506 (SU(3)) and Heller, et. al; PRD57,1438,(1998) (SU(2)).

◆Spatial-Wilson loop above the critical temperature shows a linearly rising potential and its thermal string tension scales as magnetic couplings. *Bali, et. al, PRL71,3059(1993)*

◆Gribov-Zwanziger (GZ) confinement scenario also shows the remnant of confining in QGP and its non-vanishing string tension depends on magnetic scaling. *Nakagawa, PRD73 (2006) 094504*

◆Gribov-type dispersion relation may work well in the deconfinement phase. Zwanziger,PRL94(2005)182301;PRD76(2007)125014

Magnetic degrees of freedom in hot Yang-Mills theory (2)

◆<u>Center vortices </u>(as a topological defect of SU(N) gauge theory) are responsible for non-perturbative phenomena such as color confinement and chiral symmetry breaking. This idea has originally been discussed by t'Hooft, Mack, Cornwall, etc.

◆<u>Role of magnetic monopole in hot medium </u>has been studied by Chernodub and Zakharov and they explain the dynamics of sQGP. *PRL98(2007)082002* ; also, Shuryak gives a similar idea based on monopole. *PRC75(2007)054907; PPNP62(2009)48*.

◆<u>Center vortices in the hot medium</u>;
Chernodub, Nakamura, Zakharov, PRD78,074021(2008)

◆However, there is *no clear connection between thermal gluons as a basic element of QCD (or QGP) and topological objects.*

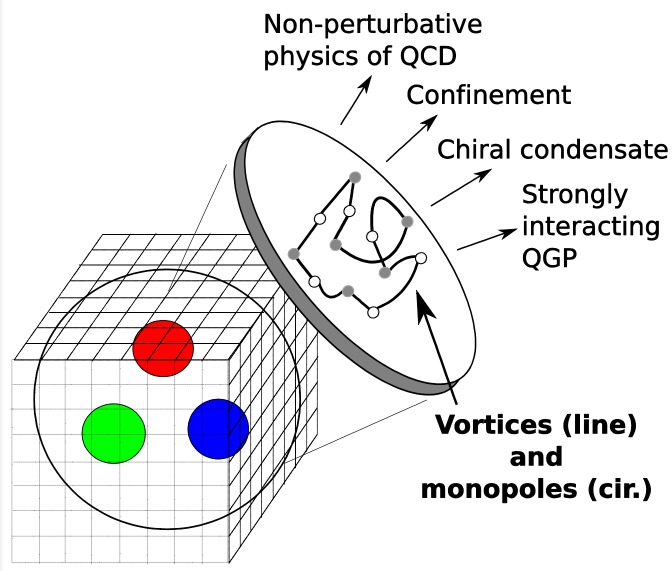
Center vortices on the lattice

◆ *Center vortices are responsible for the color confinement and chiral symmetry breaking*.

◆ Center vortices as topological defect are defined via *center group Z(N) of the gauge group SU(N).*

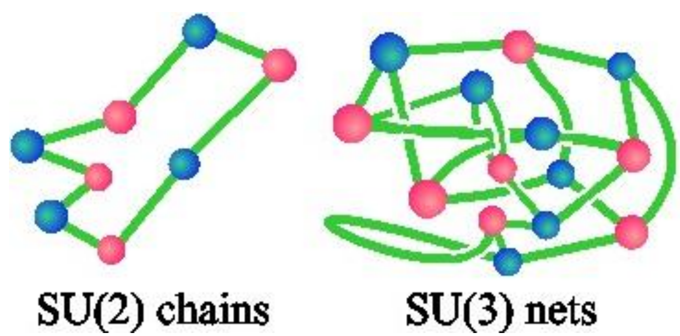
◆ Lattice numerical simulations support

- ☐Identify center vortices on the lattice
- ☐Vortex density shows asymptotic scaling
- ☐Phase transition and spatial string tension



Lens of center vortex mechanism (projection)

Illustration of vortex-monopole chain; *Chernodub, et. Al, PRD78:074021,2008*

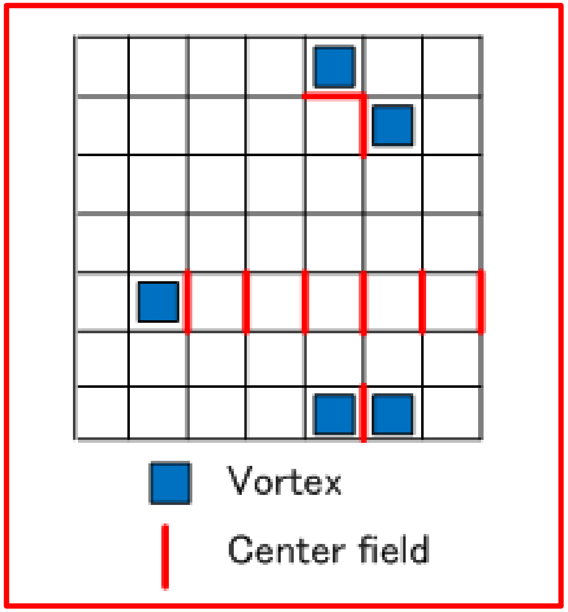


Maximal center projection

- Numerical technique
  - Direct Maximal Center Projection (MCP) by Debbio, et. al, PRDv58,094501
- We apply the MCP to all configurations of the SU(2) gauge field

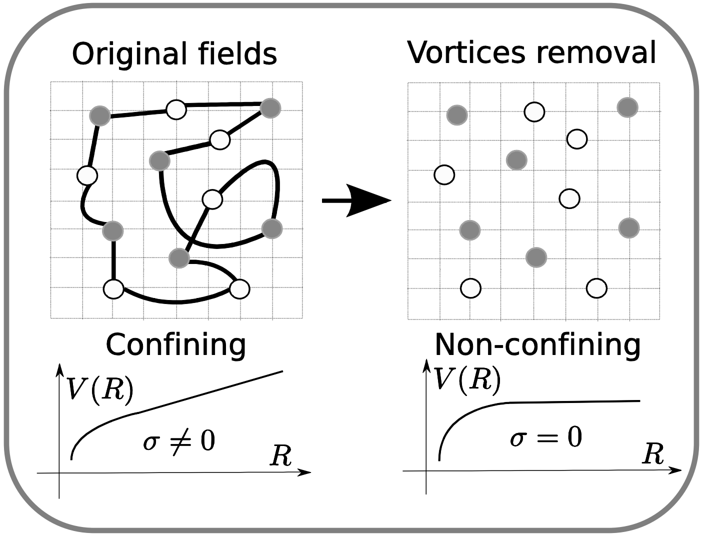
$$\text{All the Us} \Rightarrow \pm \mathrm{I} \quad \text{Maximize } R = \frac{1}{VT} \sum_{x,t} \mathrm{Tr}\left[U_\mu(x,t)\right]^2$$

$$Z_\mu(x) = \mathrm{sgn}\,\mathrm{Tr}\left[U_\mu(x)\right]$$



- Removing center vortex (via de Forcrand – D'Elia procedure,PRL82,4582(1999))

$$U_\mu(x) \to U'_\mu(x) = Z_\mu(x) U_\mu(x)$$



- *Vortices carry the non-perturbative IR physics of QCD*
- *Handling vortices numerically enables us to switch on/off non-perturbative mode !! In particular, this technique shall be applied to the QGP physics.*

Gluon propagators at finite temperature

◆Self-energy and propagators

$$\Pi^{\mu\nu} = GP_T^{\mu\nu} + FP_L^{\mu\nu} \quad D^{\mu\nu} = \frac{1}{G+k^2}P_T^{\mu\nu} + \frac{1}{F+k^2}P_L^{\mu\nu} + \frac{\rho}{k^2}\frac{k^\mu k^\nu}{k^2} \quad \rho = 0 : \text{Landau gauge}$$

◆Projection operators

$$P_T^{00} = P_T^{0i} = P_T^{i0}, \qquad P_T^{ij} = \delta^{ij} - \frac{k^i k^j}{\vec{k}^2}, \qquad P_L^{\mu\nu} = \delta^{\mu\nu} - \frac{k^\mu k^\nu}{k^2} - P_T^{\mu\nu},$$

◆Electric and magnetic gluon propagators in the momentum space

$$(P_T)^2 = P_T,\ (P_L)^2 = P_L,\ P_T P_L = 0$$

$$D_E(\vec{k}, k_0 = 0) = D^{00} = \frac{1}{F+\vec{k}^2}, \quad D_M(\vec{k}, k_0 = 0) = D^{ii} = \frac{1}{G+\vec{k}^2}$$

$$F(\vec{0},0) = m_E \sim g(T)T \qquad G(\vec{0},0) = m_M \sim g^2(T)T$$

Gluon propagators on the lattices

◆Gauge potentials and correlators

$$A_\mu^a(x,t) = \mathrm{Tr}\sigma^a U_\mu(x,t) \quad D_{\mu\nu}(x,t) = \left\langle A_\mu(x,t) A_\nu^*(x,t) \right\rangle$$

◆Unequal-time propagators ($t = t^{'} - t^{''}$)

$$D_{\mu\nu}(\vec{q},t) = \frac{1}{V(N_c^2-1)} \sum_x A_\mu^a(x,t^{'}) A_\nu^a(y,t^{''}) e^{iq(x-y)}$$

◆Sum of t with q_0=0,

$$D_{\mu\nu}(\vec{q},q_0=0) = \frac{1}{N_t} \sum_t D_{\mu\nu}(\vec{q},t)$$

◆But note that for the Coulomb gauge equal-time gluon propagator ($t^{'} = t^{''}$) will be calculated because of unfixing the temporal direction of gauge field.

Numerical setting

◆ SU(2) lattice calculation with quenched Wilson-gauge action

◆ Landau (Coulomb) gauge on the lattice in the path-integral formula satisfies the following condition:

$$\partial_\mu A_\mu(x,t) = 0 \;\Rightarrow\; \text{Maximize } R = \frac{1}{VT}\sum_{x,t} \mathrm{Re\,Tr}\,U_\mu(x,t) \left| \sum_\mu \mathrm{Tr}\,\sigma^{a}\left(U_\mu(x) - U_\mu(x-\hat{\mu})\right) \right|^2 \le 10^{-eps}$$

Wilson-Mandula Method (PLB185,127(1987))

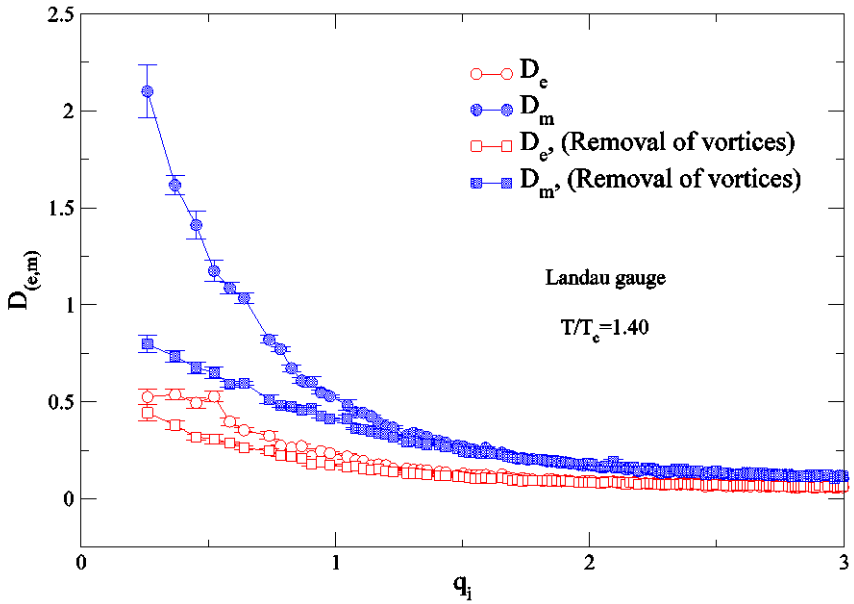
◆Parameters:

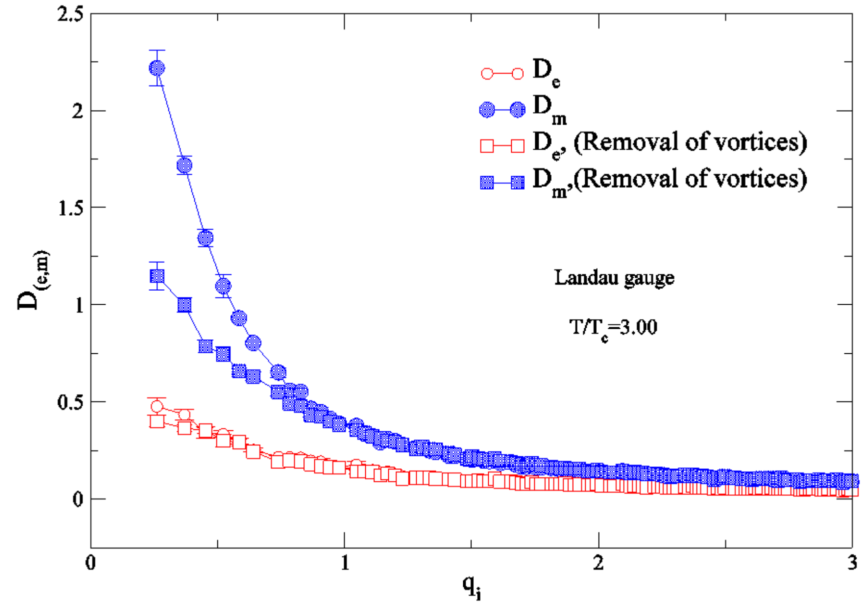
- ◆ Lattice size : 24x24x24x4
- ◆ beta : 2.2-2.6, corresponding to the temperatures T/Tc are approx. 1.40, 3.00 and 6.00.
- ◆ Configurations: 10k dicarded and 20-30 confs. circa are used to measure.
- ◆ Convergence criteria: eps = 10^(-08) for gauge fixing and eps = 10^(-16) for maximal center projection.

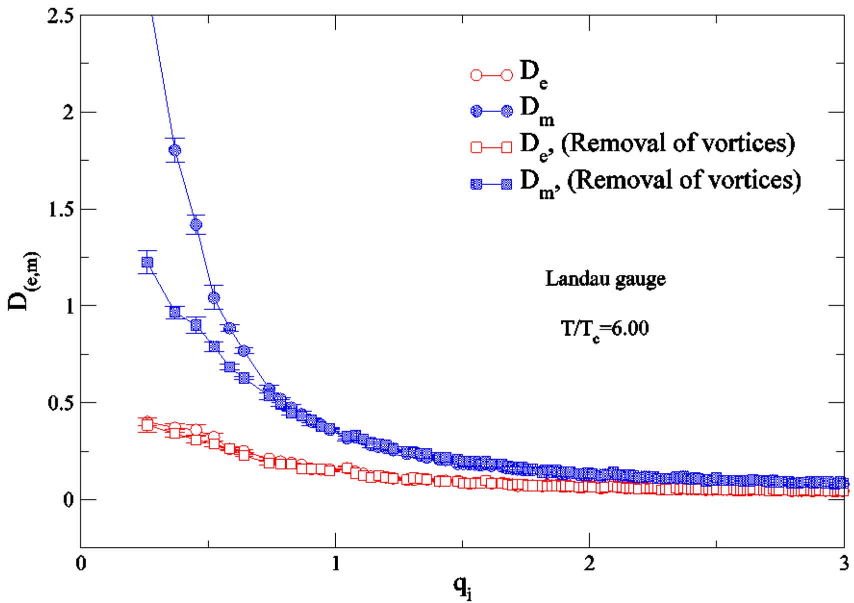
◆Procedure:

Gauge updated --> Maximal center projection --> Gauge fixing

Gluon propagators in the Landau gauge(1)



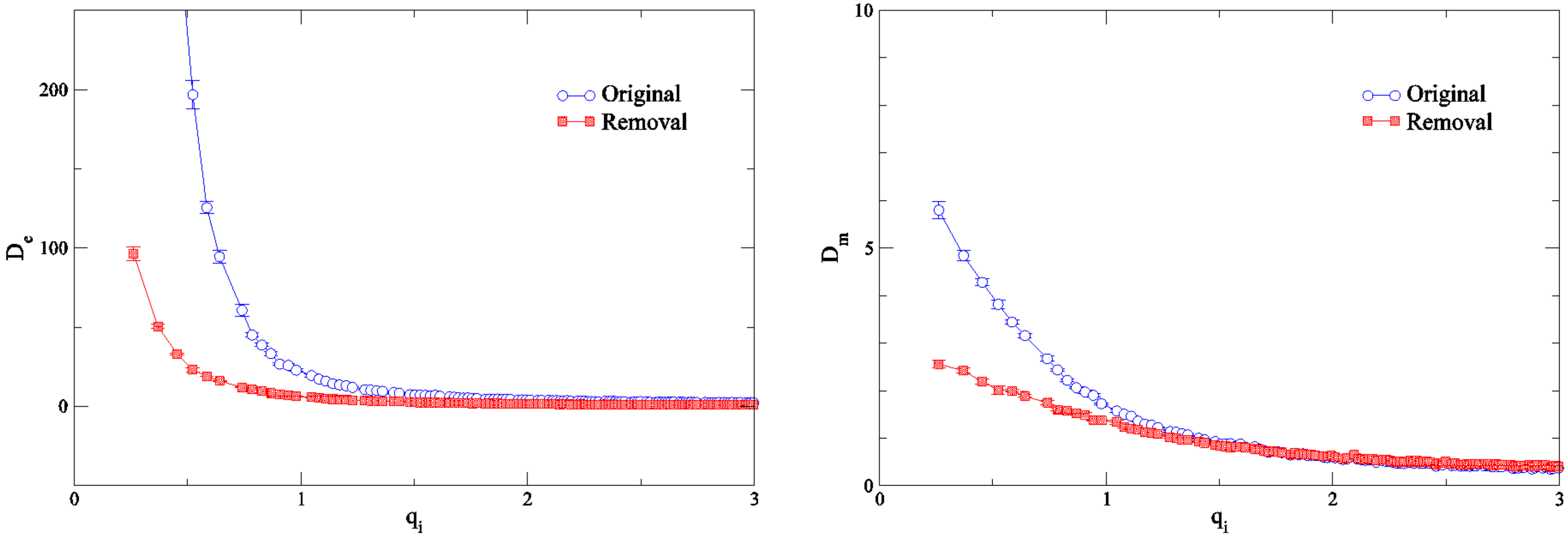




- *Magnetic gluons drastically change in infrared regions*
- *At higher T (LHC temp.), the center vortices affect the gluon propagators.*

Gluon propagators in the Coulomb gauge(1)

$$T/T_c \approx 1.40$$



Gribov-Zwanziger confinement scenario for the Coulomb gauge QCD survives.

◆Time-time (electric) correlator diverges in the infrared limit.
→ Instantaneous linearly rising potential and non-zero thermal string tension that depends on magnetic scaling.

◆Spatial-Spatial (magnetic) correlator is suppressed in the infrared limit.

◆The same behavior occurs in the deconfinement phase; *there exists confinement caused by magnetic degrees of freedom in the QGP phase*.

Summary of this talk

◆ We have studied the sQGP physics from the hot gluon propagators *via the lens of center vortex mechanism*.

◆ We found that magnetic degrees of freedom are so important via the study of the gluon propagators after/before center vortices; conversely center vortices are still important objects above Tc.

◆ In Landau and Coulomb gauges, we get similar results; that is, the magnetic sector is very singular even in the QGP phase.

◆ *Magnetic degrees of freedom cause (magnetic) confinement in the deconfinement phase*. We have to consider this point properly to understand sQGP.

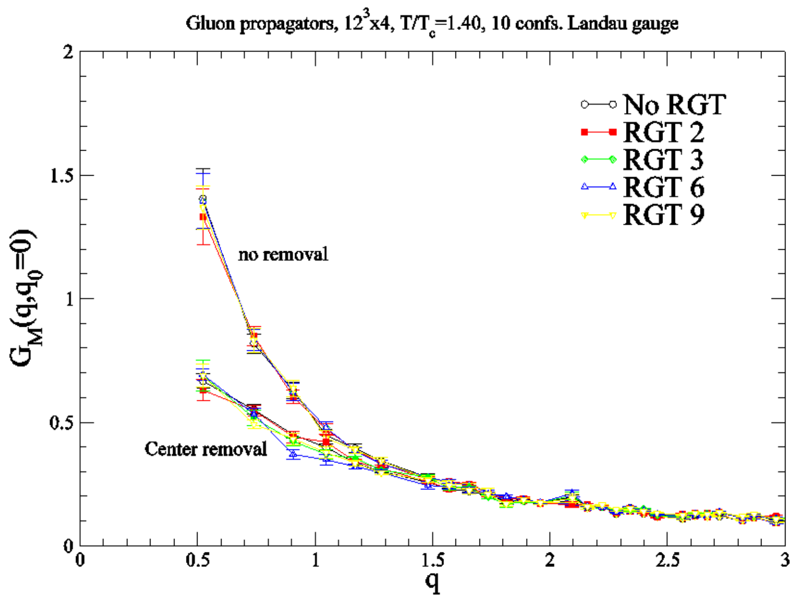
Future plans

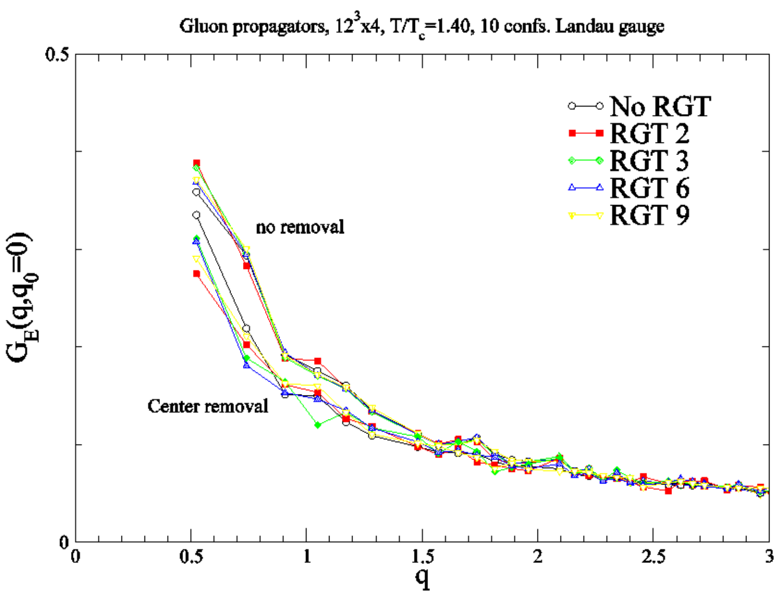
◆ More temperature dependence and volume dependence.
◆ Calculation of trasport coefficient after/before center removal; it reveals the reason of small shear viscosity. (in progress)
◆ Equation of state after/before center removal; how strongly the non-perturbative mode influences on the EOS.

Backup slides

Effect for a numerical ambiguity of the maximal center (gauge) procedure

after some random gauge transformations





◆ The procedure “direct maximal center gauge (projection)” (Debbio, et. al, PRDv58,094501) produces a lot of gauge ambiguities (copies); but the influence to the gluon propagators is very small.

Spatial Wilson loop in the QGP

◆ Spatial Wilson loop gives a linearly rising potential in the QGP.

G.S. Bali, et. al, PRL71,3059(1993)

$W(R,S) \sim \exp(-\sigma_s RS)$

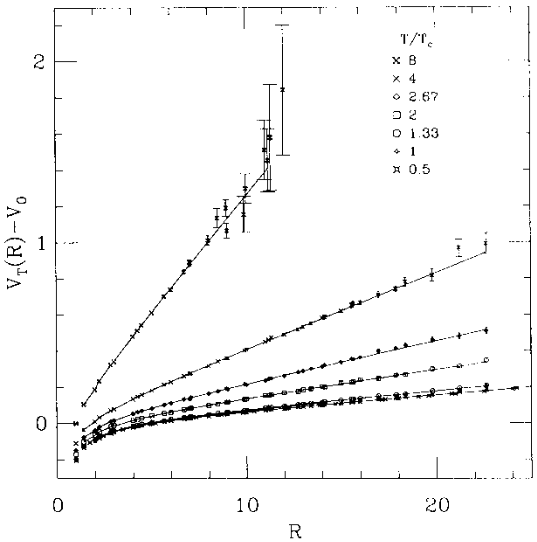


FIG. 1. The pseudopotentials $V_T(R)$ minus the (constant) self-energy contributions V_0 [Eq. (4)] on lattices of size $N_\tau \times 32^3$ for $\beta = 2.74$ as a function of the spatial separation R measured in lattice units.

$T > T_c$

$\sqrt{\sigma_s(T)} = cg^2(T)T$

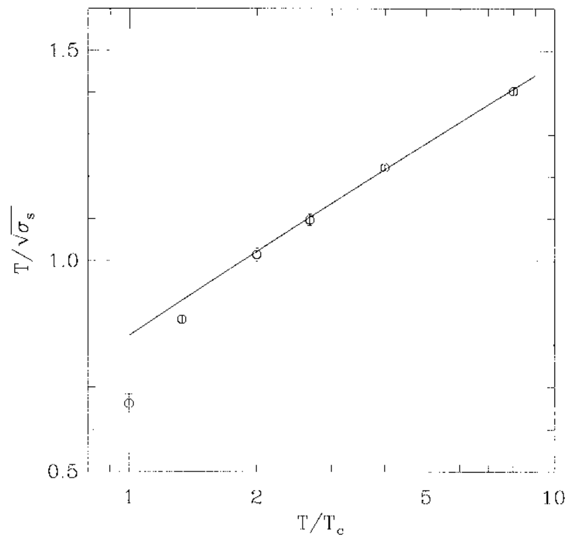
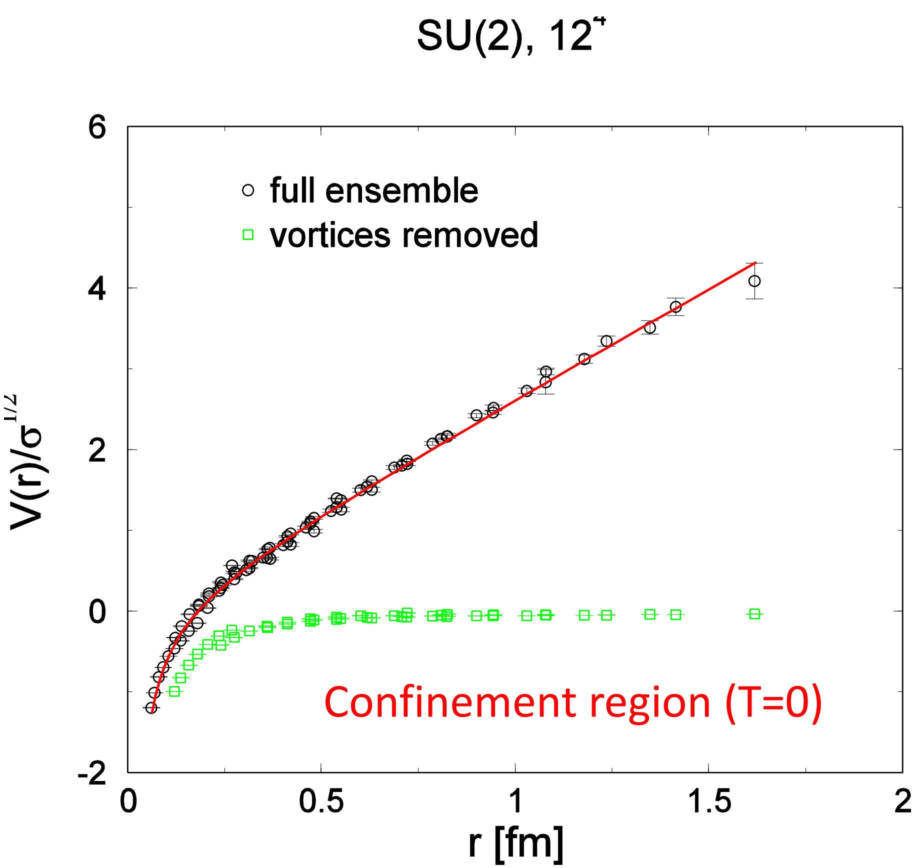


FIG. 3. The ratio of the critical temperature and square root of the spatial string tension versus temperature for $\beta = 2.74$. The line shows a fit to the data in the region $2 \le T/T_c \le 8$ using the two-loop relation for $g(T)$ given in Eq. (7).

Linearly rising potentials

◆Removing vortices eliminates confinement.



- This figure is from "SU(2) gluon propagators from the lattice – a preview", hep-lat/0104003, Kurt Langfeld

The result changes drastically after vortices removal

- Modified configurations have only perturbative propertis

- All the non-perturbative infrared physics must be carried by {Z}.

Example for center vortex removal

◆ Numerical study of Coulomb gauge QCD via center vortex (Greensite, Olejnik, Zwanziger, PRD69, 074506 (2004))

- Gribov-Zwanziger scenario in the Coulomb gauge QCD: Instantaneous interaction (link-link correlator on the lattice) produces a confining potential even in the QGP phase.

$T/T_c \sim 1.40$