厳密な中心対称性を保つ $N_f = 3$ QCD の有限温度相転移の解析

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Confinement and Chiral Symmetry Breaking

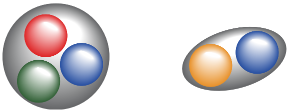
QCD shows “TWO” important non-perturbative phenomena

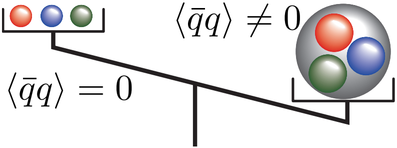
Confinement

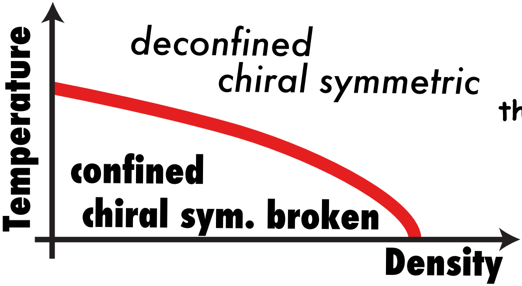
there are no isolated quarks

Chiral Sym. Breaking

$\mathrm{SU}(N_f)_L \times \mathrm{SU}(N_f)_R \to \mathrm{SU}(N_f)_V$







these properties are lost
at high temp. and/or density
or some conditions

Phase Transition at Finite Temperature from Lattice QCD

- simultaneous phase transition ??
- confinement and chiral symmetry breaking are related ??

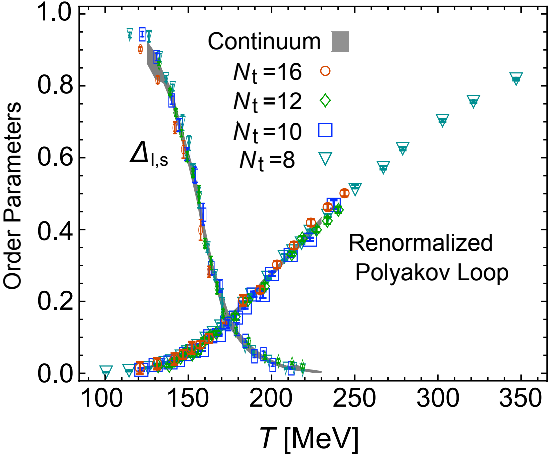


Figure : Wuppertal-Budapest Coll. '10 (Fig. from Fukushima-Sasaki '13)

Real World is Ambiguous

perhaps, there are no clear phase transitions and no critical points in QCD

confinement

no definite order parameter

chiral symmetry

$m_q \neq 0 \Longrightarrow$ not exact symmetry

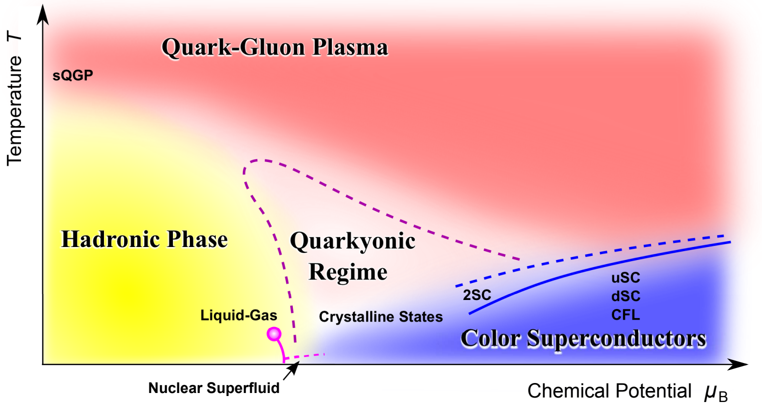


Figure : QCD phase diagram (Fukushima-Sasaki '13)

Confinement = Center Symmetry ??

Polyakov Loop $L = (1/N_c)\mathrm{Tr} e^{ig\int_0^{1/T} A_4 d\tau}$

$$\langle L \rangle \sim e^{-f_q/T}$$

T:temperature, f_q:single-quark free energy

used as "an order parameter"

- confined phase
  $f_q \to \infty \Rightarrow \langle L \rangle = 0$
- deconfined phase
  $f_q < \infty \Rightarrow \langle L \rangle \neq 0$

Polyakov Loop: an order parameter of CENTER SYMMETRY

by center transformation

$$L \to zL \neq L$$

with $z \in \mathbf{Z}_N$

- center symmetric $\Rightarrow \langle L \rangle = 0$
- center broken $\Rightarrow \langle L \rangle \neq 0$

But, center symmetry is "explicitly" broken by quarks

QCD and Others

QCD: fundamental theory of strong interaction

$\Longrightarrow$ SU(3) gauge theory with 6 massive quarks in color $\mathbf{3}$ rep.

but, there are a large class of gauge theories

- different gauge group, SU(2), Z_N, SO(3), G_2, ...
- different number of flavor, different group rep., Higgs fields, ...

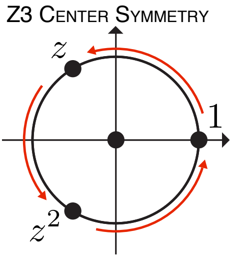
$\Longrightarrow$ *deeper understanding* of “our” QCD

For example.

- QCD with adjoint fermions : “exact center symmetry”
  - mismatch of phase transitions
    $T_\chi \simeq 8T_d$ — Karsch-Lütgemeier ’99
- G_2-gauge theory : “trivial center”
  - simultaneous 1st order phase transitions
    $T_\chi \simeq T_d$ — Danzer-Gattringer-Maas ’09

Outline of This Work

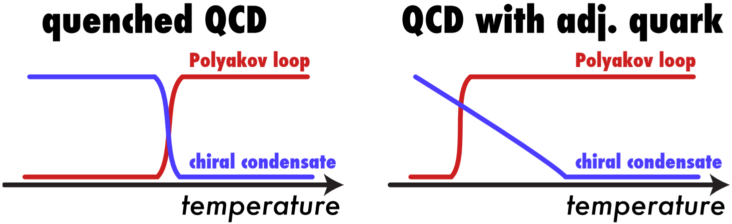
in order to understand non-perturbative nature of QCD, we focus on "Z_3-center symmetry"



by introducing some boundary conditions, we formulate

$N_f = 3$ QCD with "exact center symmetry"

- from lattice QCD simulation, we study
  - center symmetry phase transition
  - interplay with chiral properties
- "center symmetry" would give insights into confinement and chiral symmetry breaking, and other gauge theories, such as



Non-Abelian Gauge Theory with Exact Center Symmetry

quark breaks center symmetry of Yang-Mills theory

- Z_N transformation ($z \in \mathbf{Z}_N$)

$$\psi_f(x, \tau + 1/T) = -z\psi_f(x, \tau)$$

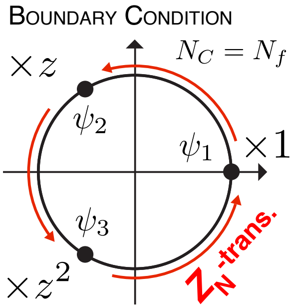
- "flavor" dependent Z_N boundary condition as

$$\psi_f(x, \tau + 1/T) = -z^{f-1}\psi_f(x, \tau)$$

- this theory possesses center symmetry

$$S = \int d^4x \left[\sum_f \bar{\psi}_f \left(\not{D} + m \right) \psi_f + \frac{1}{2} \mathrm{Tr}\; G_{\mu\nu} G_{\mu\nu} \right]$$

by relabeling of flavor index



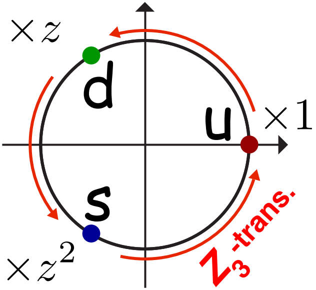
References: PNJL model analysis

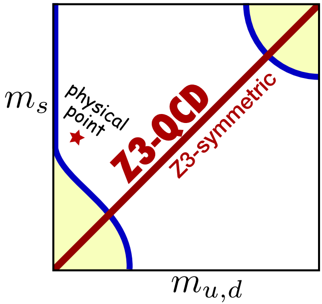
- Kouno-Sakai-Makiyama-Tokunaga-Sakai-Yahiro, arXiv:1202.5584.
- Kouno-Misumi-Kashiwa-Makiyama-Sasaki-Yahiro, Phys. Rev. D88, 016002 (2013).

Z3-QCD — exact center symmetry with dynamical quarks

$N_f = 1+1+1$ flavor QCD with flavor dependent $\mathbf{Z}_3$ boundary conditions

Z3-QCD Boundary Condition





■ twisted boundary $z \in \mathbf{Z}_3$ corresponds to imaginary chemical potential

$$\mu/T = 2\pi i/3$$

at Roberge-Weiss symmetric point, i.e., $Z_{\mathrm{GC}}(\mu/T = 2\pi i/3) = Z_{\mathrm{GC}}(0)$

- but *flavor symmetry* is partially broken as

$$\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R \to [U(1)_L]^2 \times [U(1)_R]^2$$

About Lattice QCD Simulation Setup

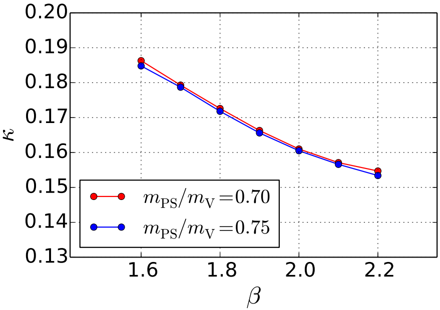
- $(1+1+1)$-flavor dynamical quark simulation
  - Iwasaki gauge action and Wilson fermion

$$D_{\mathrm{W}}(x,y) = \delta_{x,y} - \kappa \sum_{\mu=1}^{4} \left\{ (1-\gamma_\mu) U_\mu(x) \delta_{x+\mu,y} + (1+\gamma_\mu) U_\mu^\dagger(x-\mu) \delta_{x-\mu,y} \right\}$$

- with flavor dependent Z_3 twisted boundary

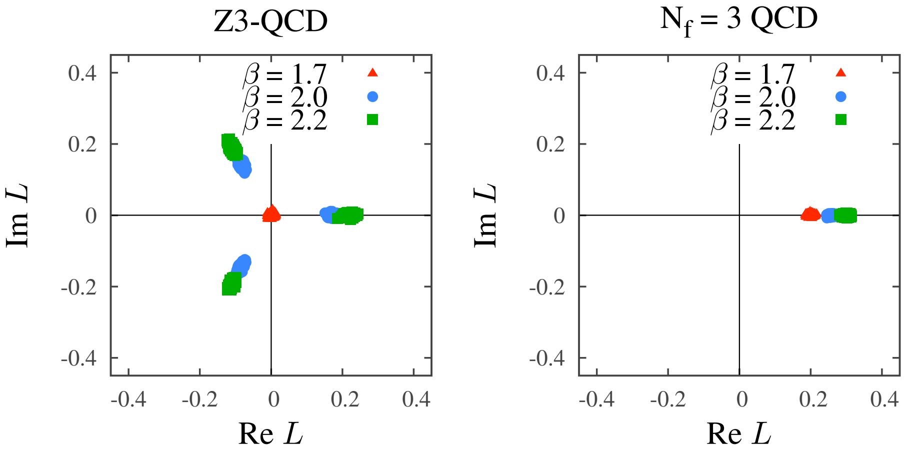
$$(\psi_1, \psi_2, \psi_3)_{(x,\tau+1/T)} = -(\psi_1, z\psi_2, z^2\psi_3)_{(x,\tau)}$$

  where $z = \exp(2\pi i/3)$
- simulate at $m_{\mathrm{PS}}/m_{\mathrm{V}} = 0.70$
  - tuning coupling β and mass κ
- lattice size $16^3 \times 4$
  - $T = 1/N_t a$: a lattice spacing
  - high $\beta \Longrightarrow$ high T
- compare $N_f = 3$ QCD
  with the same parameters



Z3 Symmetric Structure

Polyakov loop shows Z_3-symmetric distributions



Hysteresis

- $T > T_c$

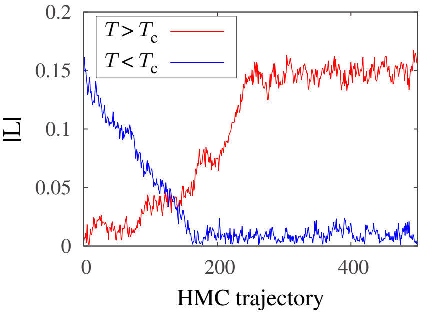
$\langle L \rangle = 0$ is unstable

$\Rightarrow \langle L \rangle \neq 0$

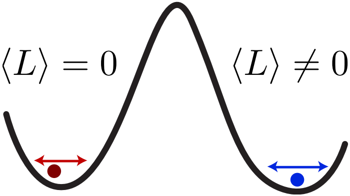
- $T < T_c$

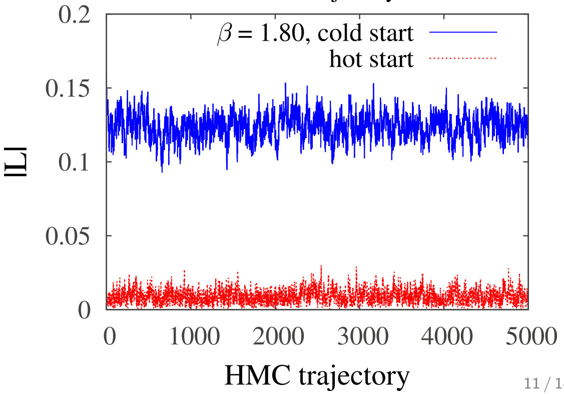
$\langle L \rangle \neq 0$ is unstable

$\Rightarrow \langle L \rangle = 0$

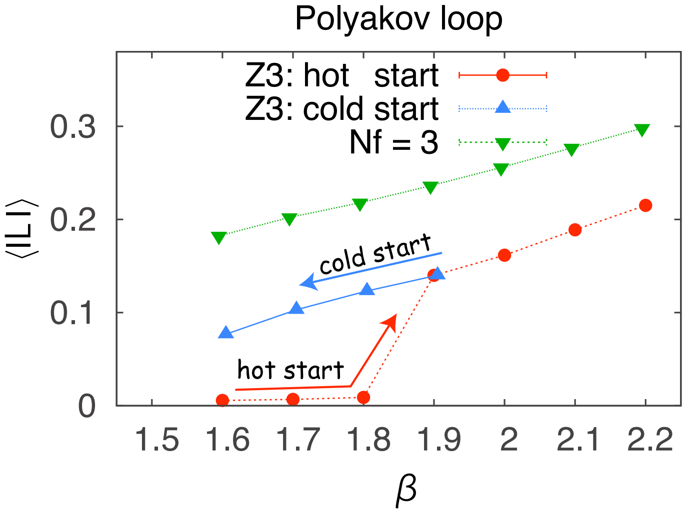


■ Around T_c,
P-loop shows hysteresis
$\Rightarrow$ 1st order transition





Center Symmetry Phase Transition



- hot start shows steep transition around $\beta \sim 1.8$

- cold start $\langle L \rangle \neq 0$ even around $\beta \sim 1.6$

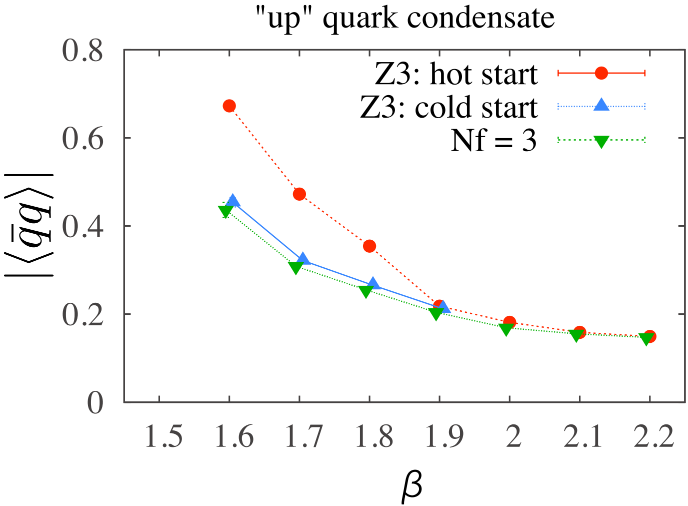
$\Rightarrow$ CHECK lower β

- hot start: initial state $\langle L \rangle = 0$
- cold start: initial state $\langle L \rangle \neq 0$

Chiral Condensate

chiral condensate is dragged by center structure

- "exact" center symmetric phase $\Longrightarrow$ change becomes steeper
- center broken phase $\Longrightarrow$ Z_3-QCD $\simeq N_f = 3$



• phase transition is smeared by finite quark mass

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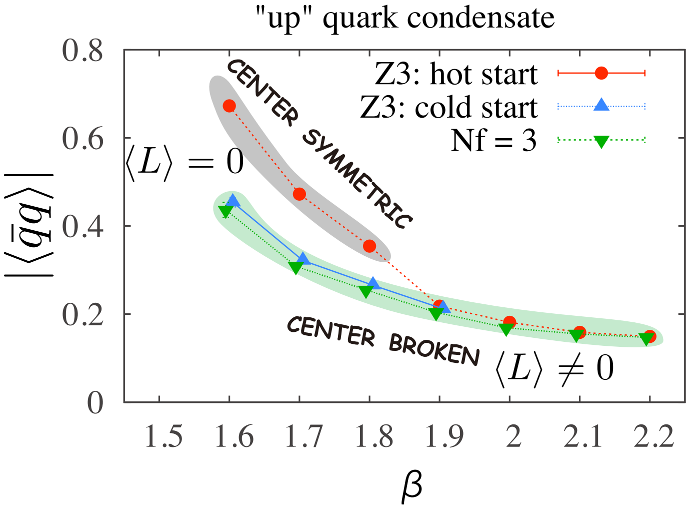

- phase transition is smeared by finite quark mass

Summary

in order to understand the role of "center symmetry" in QCD,
by introducing flavor dependent twisted boundary,
we study $N_f = 3$ QCD with "exact center symmetry"

- "exact" center symmetry shows 1st order phase transition
  - similar to SU(3) Yang-Mills and QCD with adjoint quark
- unlike adj. QCD,
  chiral condensate is affected by "center structure" of configuration
- $m_q \to 0$, it is likely that both chiral & center show 1st order transition