Finite-T phase transition of Nf=3 QCD with exact center symmetry

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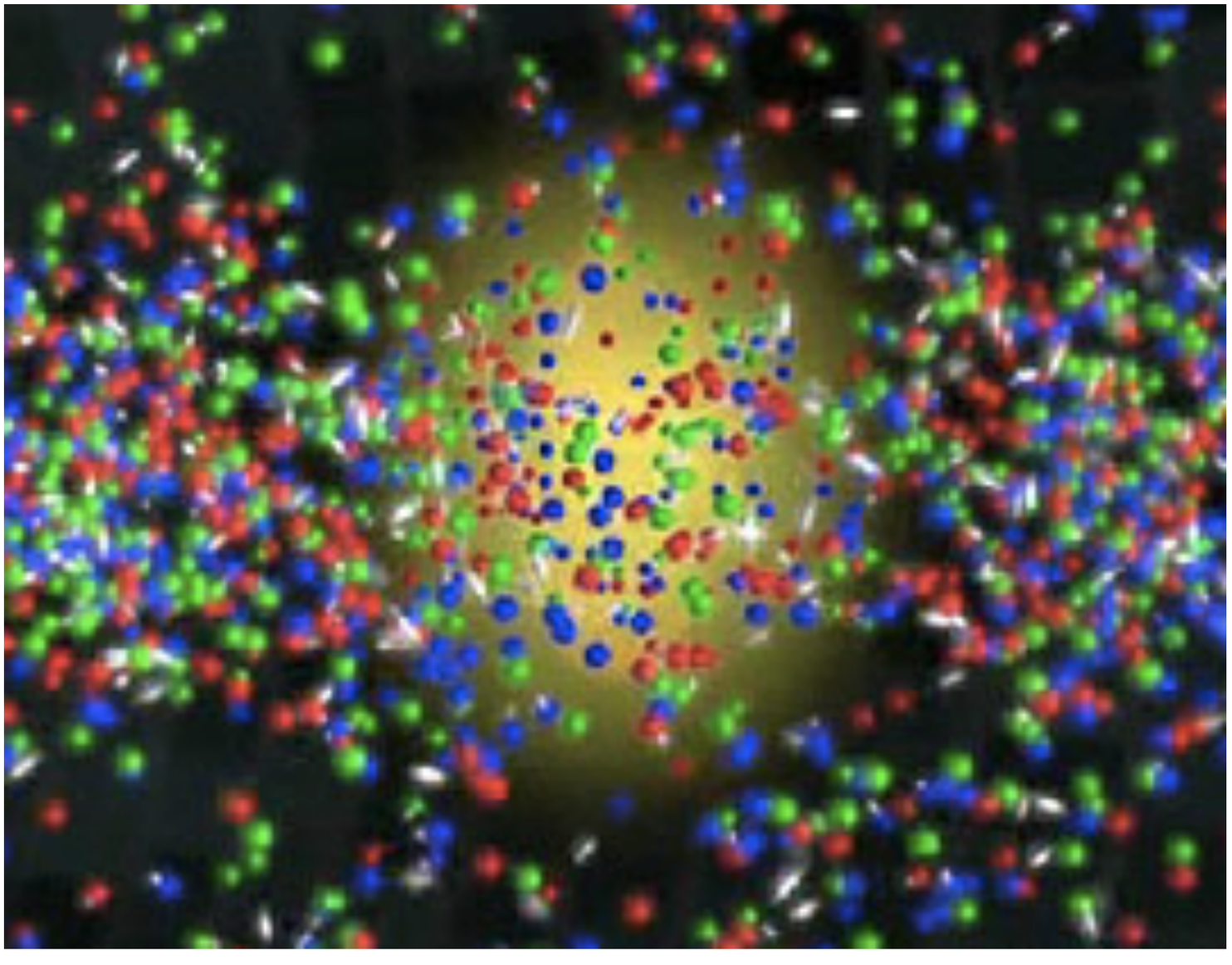
Background

Correlation of deconfining and chiral transitions exists ?

Long-standing question related to the essence of QCD



Background

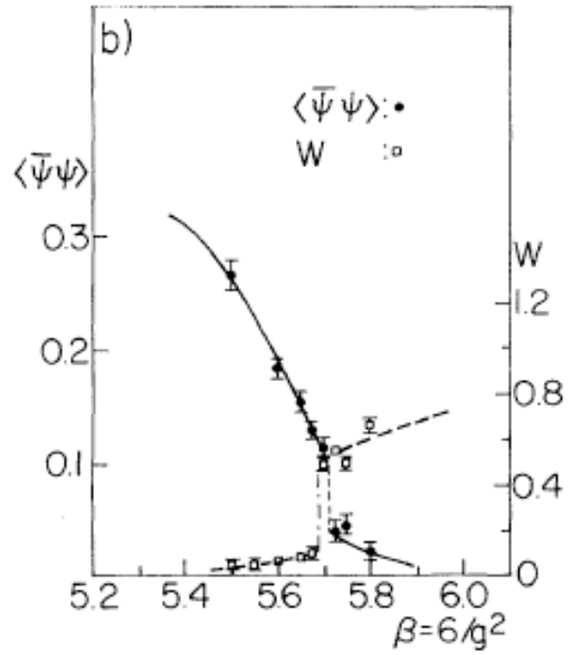
◆Confining order parameter = VEV of Polyakov loop？

Quenched limit

- Exact Z3 center symmetry
- VEV of P-loop is the order parameter of Z3
- enables us to study deconfining transition

$$\langle |L| \rangle = 0 \quad \rightarrow \quad F_q = \infty \qquad \text{confining}$$

$$\langle |L| \rangle \neq 0 \quad \rightarrow \quad F_q \neq \infty \qquad \text{deconfining}$$

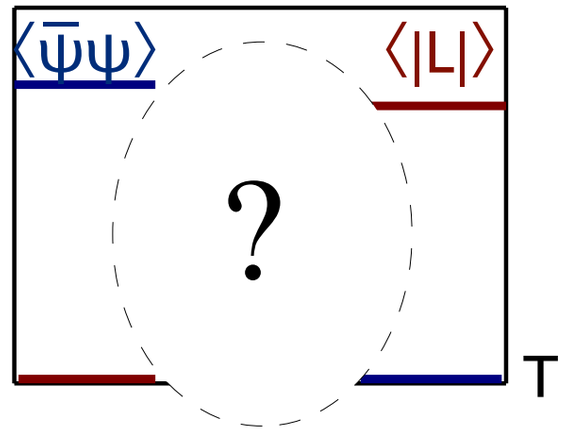


Kogut et. al. , Phys.Rev.Lett. 50 (1983) 393

center transition Td ~ chiral transition Tc

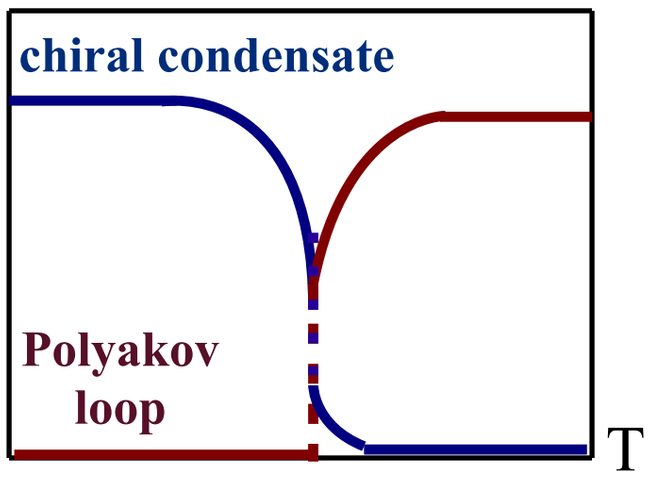
Realistic QCD：Dynamical quarks break Z3 sym.

〈L〉 is an approx order parameter



Lattice QCD simulation

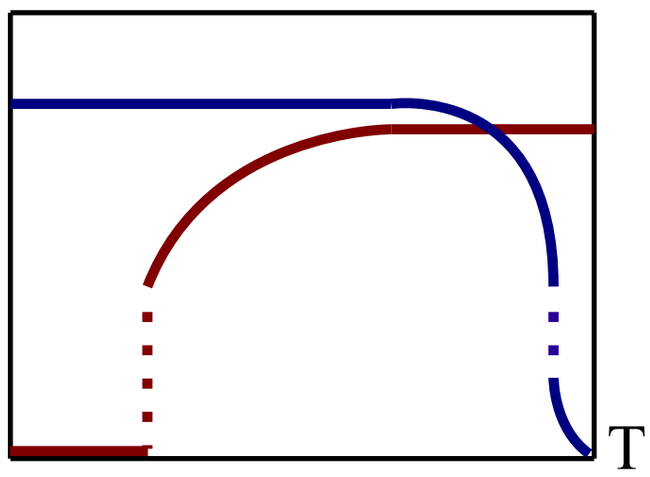
- Quenched QCD (exact Z3)



$T_d \sim T_c$

Kogut, et.al. (1983)

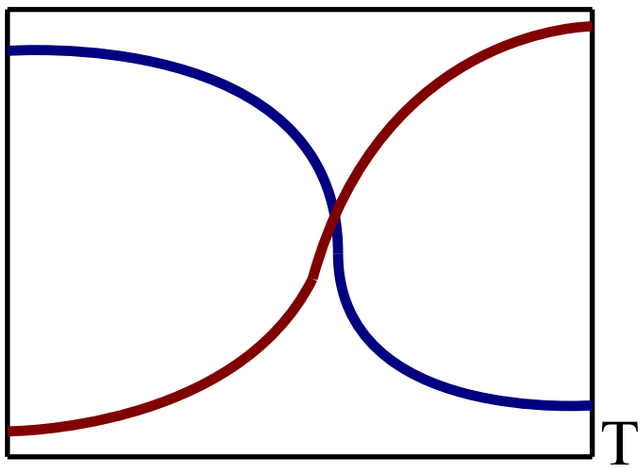
- Adjoint QCD (exact Z3)



$T_d < T_c$

Karsch, et.al. (1999)

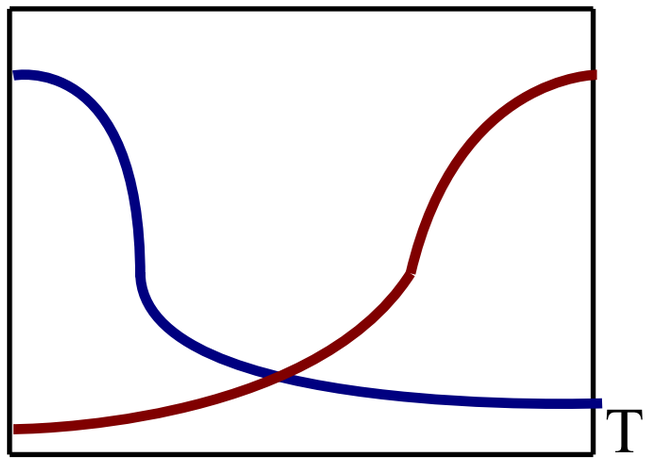
- Nf=2+1 QCD (no Z3)



Nf=2+1 QCD (Z3×)

$T_d \sim T_c$

HotQCD collab.(2008)



Nf=2+1 QCD (Z3×)

$T_d > T_c$

BMW collab.(2008)

No consensus for now.
What if we have Z3-symmetric QCD model with dynamical fundamental quarks?

Z3-QCD

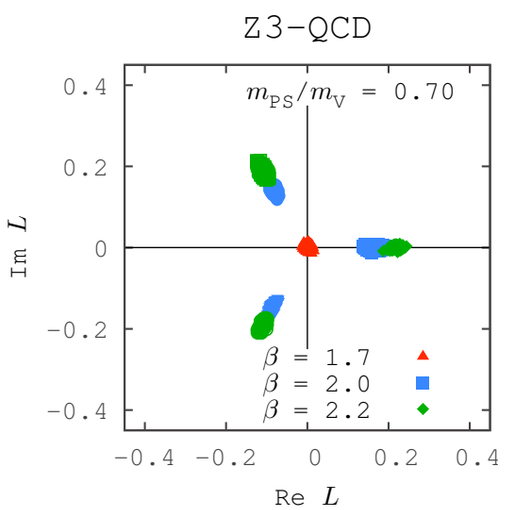
◆Z3-exact QCD model

Kouno, Sakai, Makiyama, Tokunaga, Sasaki, Yahiro (2012)

- Consider SU(3) gauge theory with 3 degenerate fundamental quarks
- Z3 transformation = $2\pi/3$ rotation of b.c. in imaginary time direction
- Appropriate flavor-dependent twisted BC realizes Z3 symmetry

Z3-twisted b.c.

$$(\psi_1,\ \psi_2,\ \psi_3)_{x,\tau+\beta} = (\psi_1,\ e^{2\pi i/3}\psi_2,\ e^{4\pi i/3}\psi_3)_{x,\tau}$$



Distribution of P-loop

Z3-transformation ↕ ↕ Flavor redefinition

$$(e^{2\pi i/3}\psi_1,\ e^{4\pi i/3}\psi_2,\ \psi_3)_{x,\tau}$$

Z3-symmetric 3-flavor QCD

◆Finite-T lattice simulation of Z3-QCD

- center-symmetric dynamical lattice simulation
- can exactly discuss center symmetry transition
- may obtain new knowledge on confinement

1st calculation on Z3 + fund. QCD model

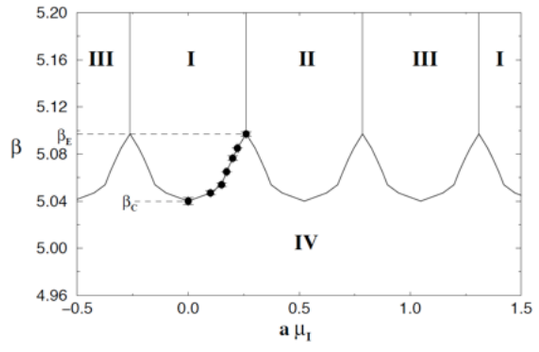
- **Two conjectures**

§ Flavor symmetry Kouno, et.al. (2013) with PNJL model

- Z3 bc breaks $SU(3)_L \times SU(3)_R \rightarrow [U(1)^2_L] \times [U(1)^2_R]$ (will disappear in $T \rightarrow 0$)
- For $\langle L \rangle = 0$ ($T<T_d$), thermodynamical potential for meson is flavor symmetric
- Influence of b.c. will be dynamically activated in $T>T_d$

§ 2pi/3 periodicity of chiral transition

- Chiral transition has 2pi/3 periodicity in b.c.
- Tc will be identical to that of Nf=3

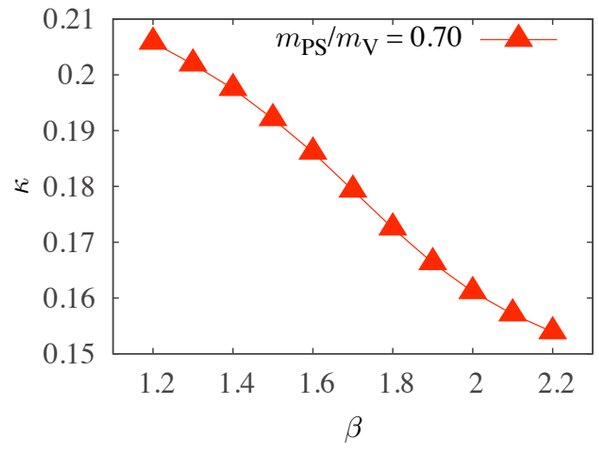


D'Elia and Lombardo (2002)

Setup of lattice simulation in finite T

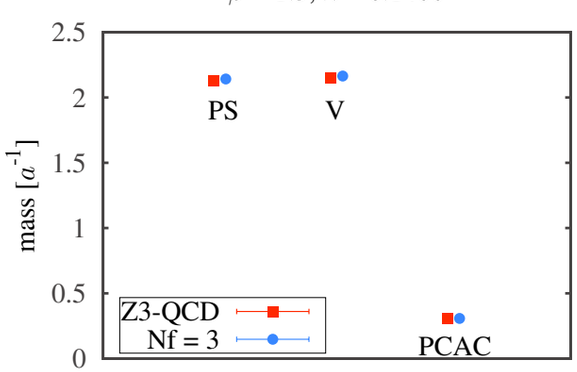
Iwasaki gauge action, Wilson fermion, RHMC

- **κ for constant m_π/m_ρ** (16^4)
  - κ (m_π/m_ρ=0.70) are fixed for β=1.2~2.2
  - found identical meson spectrum of Z3 & Nf=3



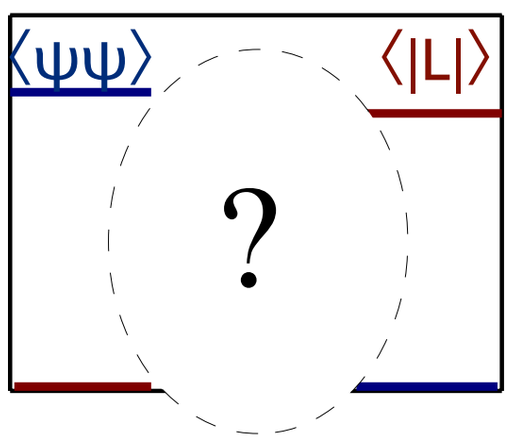
$\beta = 1.5, \kappa = 0.1400$

For 〈L〉 =0, flavor symmetry seems to remain



- **Finite-T QCD** (16^3 × 4)
  - T dependence of P-loop and its susceptibility
  - T dependence of χ-condensate and its suscep.

Comparison of Z3-QCD vs Nf=3 QCD

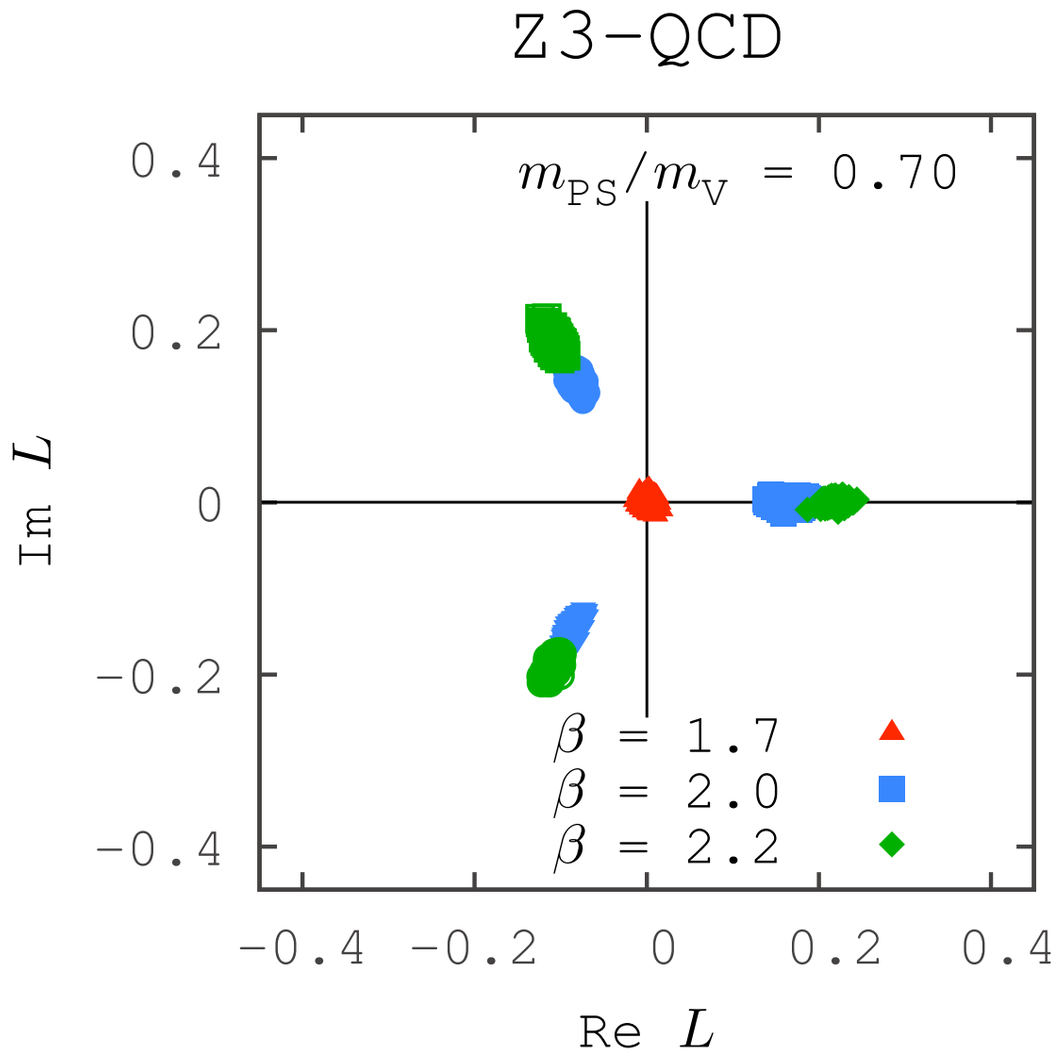


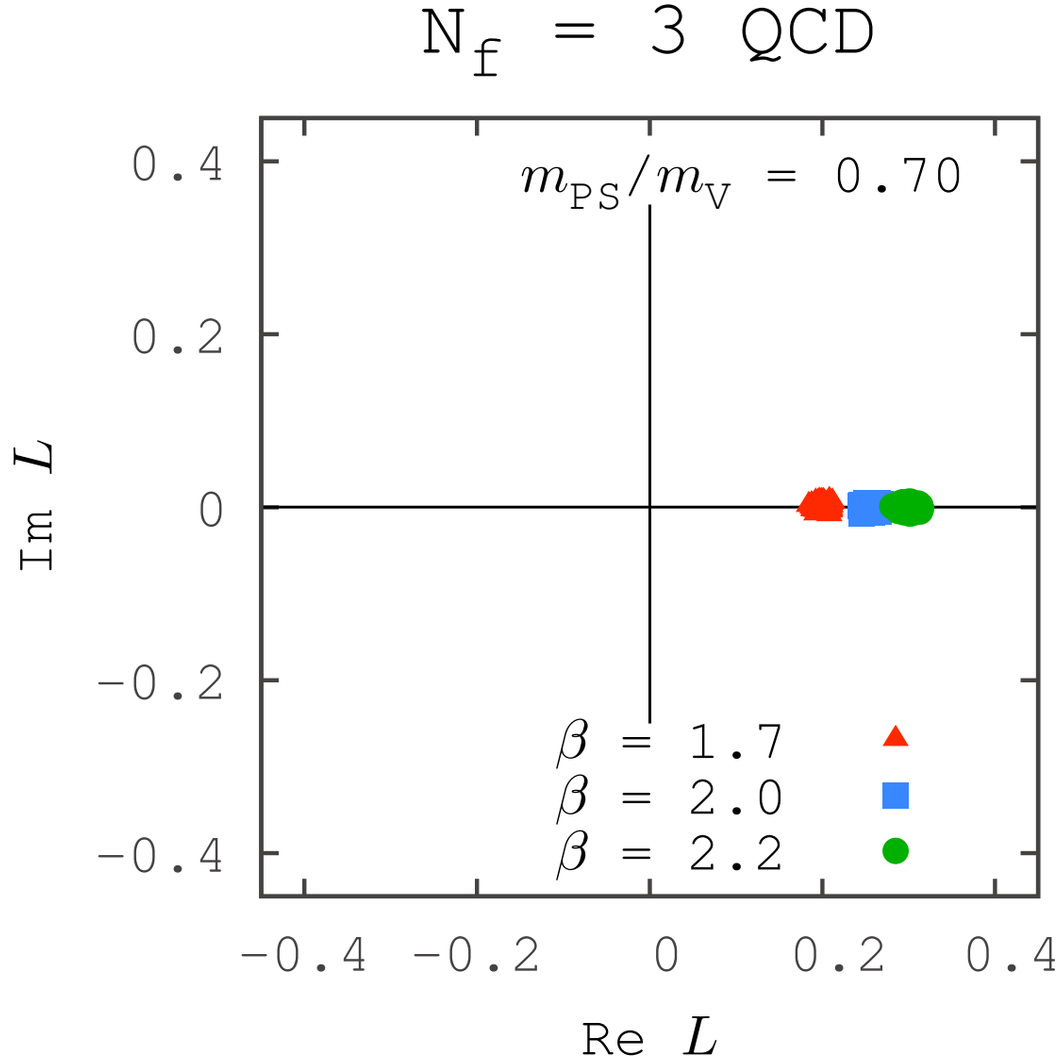
Z3-QCD

Finite-T simulation

Z3-QCD vs Nf=3 QCD

Distribution plot of P-loop





Low-T：around the origin ~ Z3-sym

High-T：equiv. 3 vacua ~ SSB of Z3

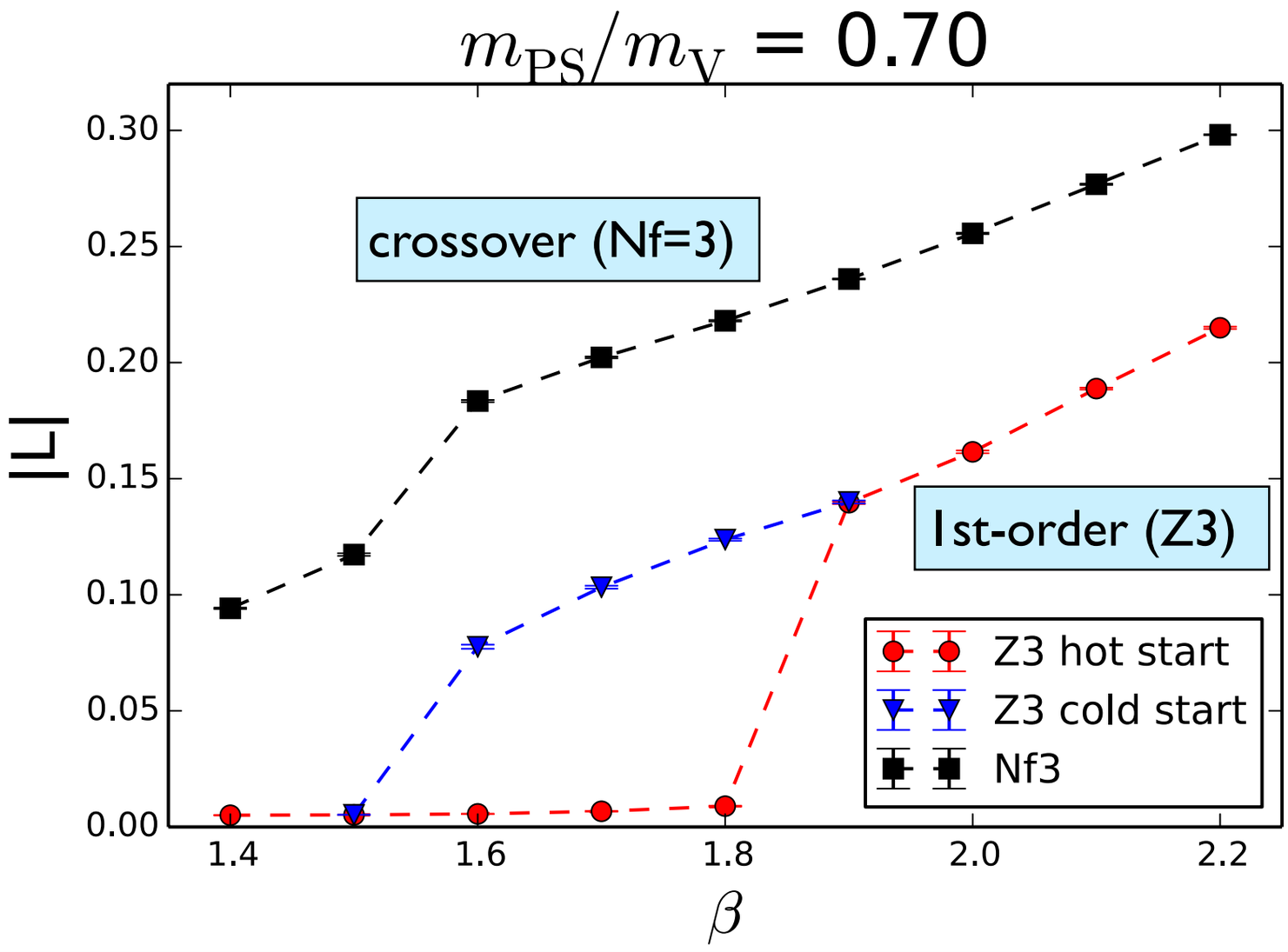
→ Z3 at the action level

Low-T：on the real axis

High-T：on the real axis

→ Explicit Z3 breaking

VEV of Polyakov loop ⟨|L|⟩

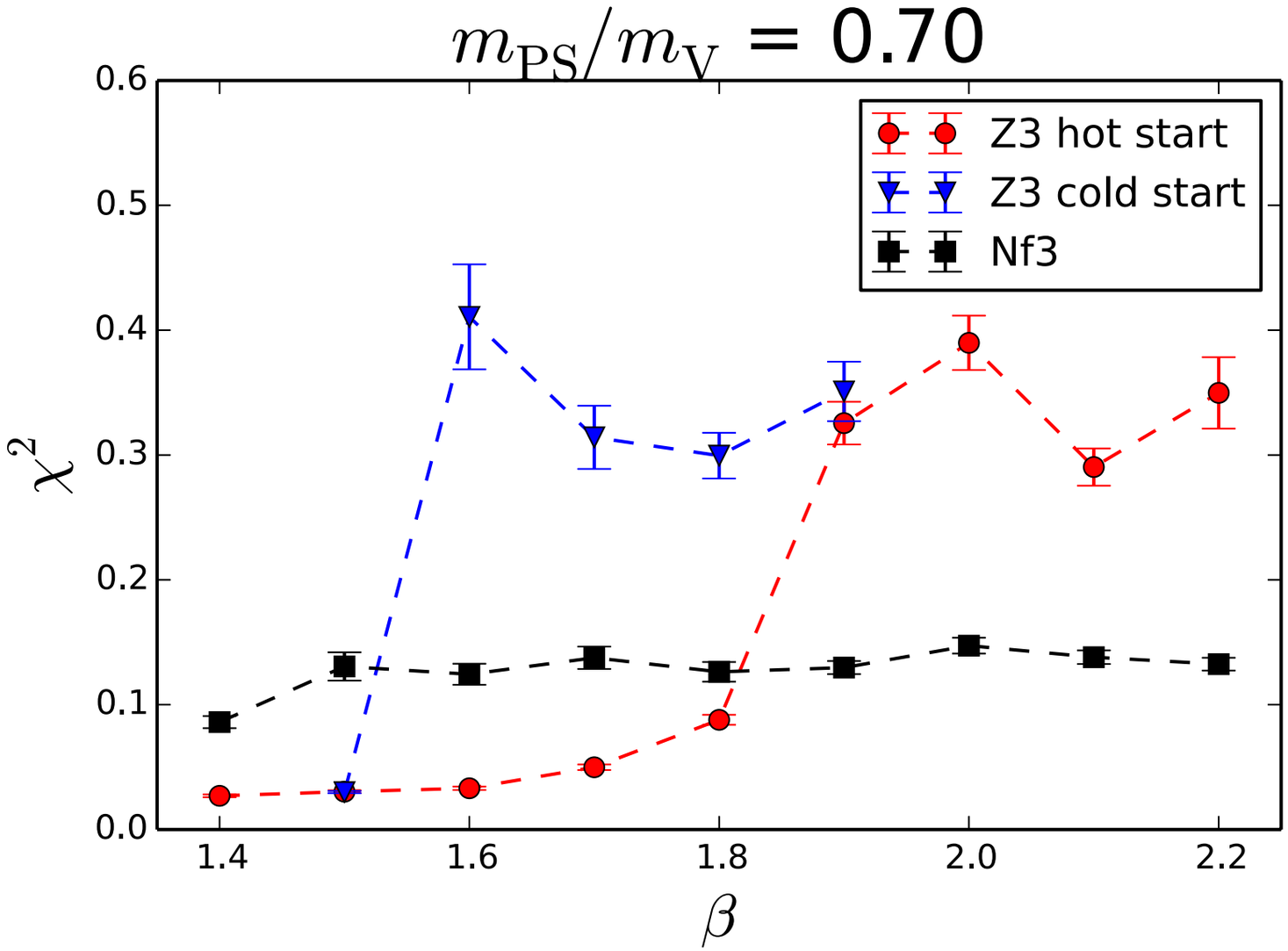


At β~1.6, ⟨|L|⟩ = 0 → ⟨|L|⟩ ≠ 0 with hysteresis

→ 1st-order Z3 phase transition

Z3 (1st-order) vs Nf=3(crossover)

Susceptibility of Polyakov loop ⟨|L|⟩

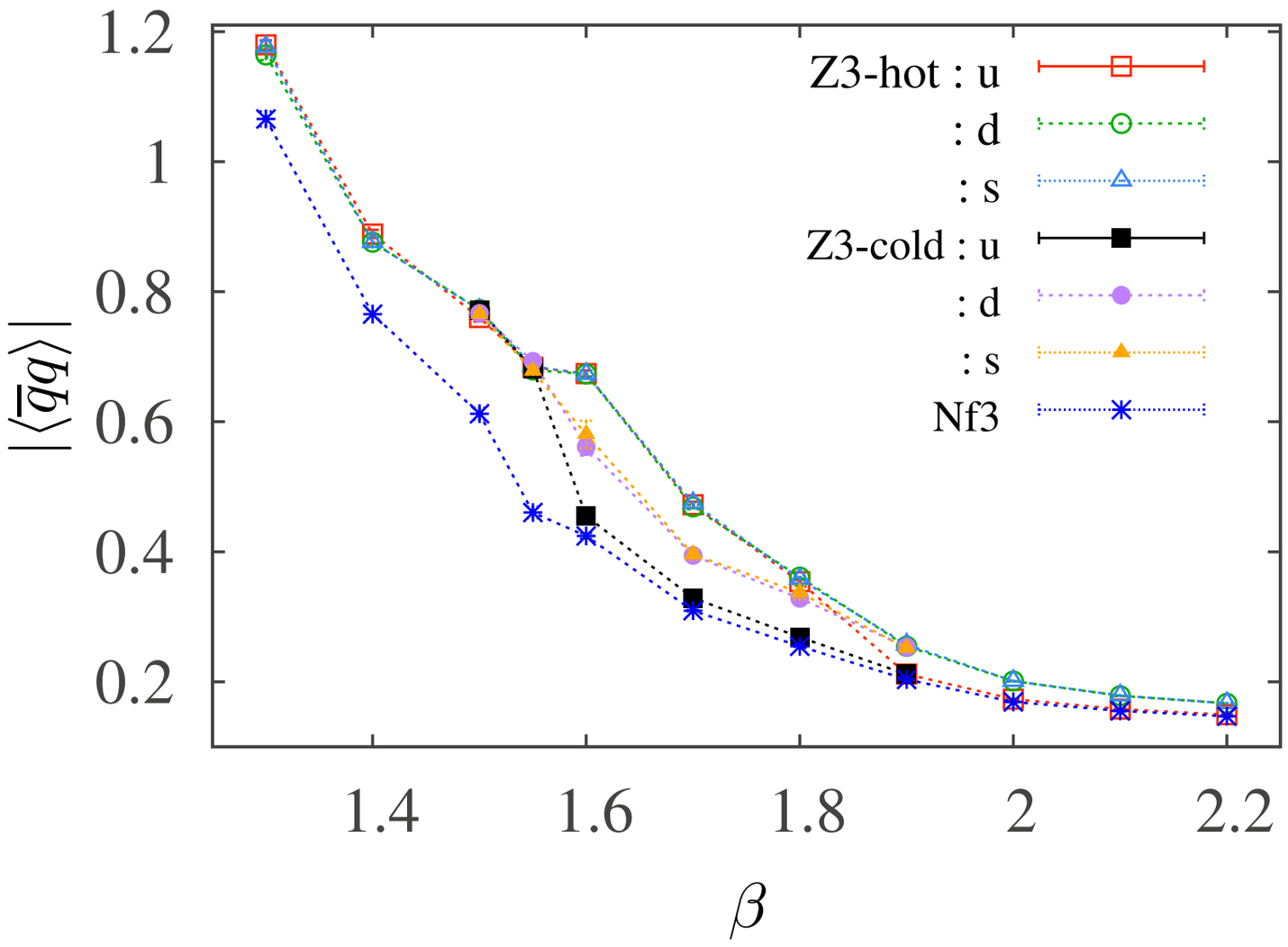


At β~1.6, ⟨|L|⟩ ≠ 0 with clear hysteresis

→ 1st-order Z3 phase transition

Z3 (1st-order) vs Nf=3(crossover)

Chiral condensate $\langle\bar{\psi}\psi\rangle$

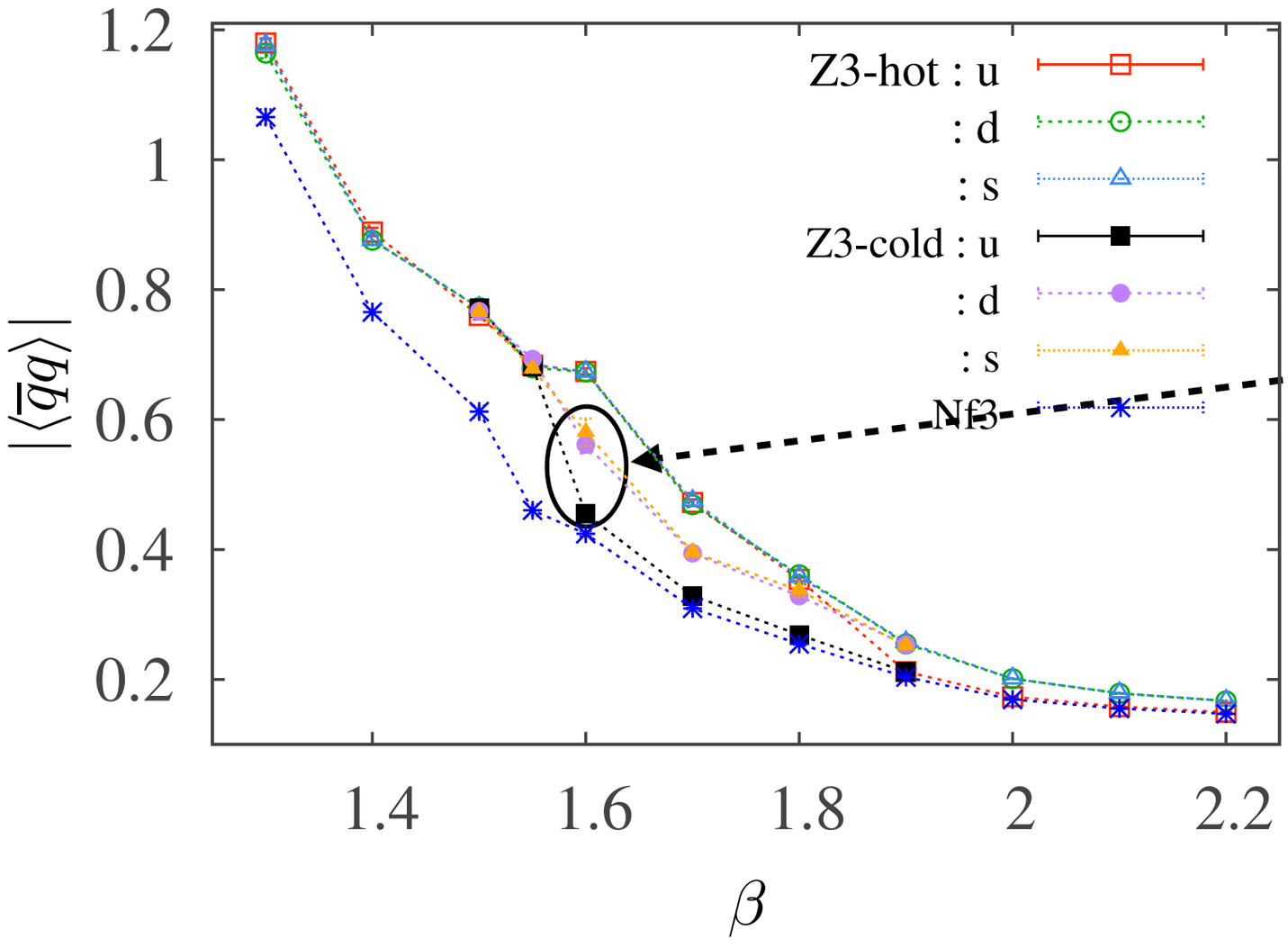


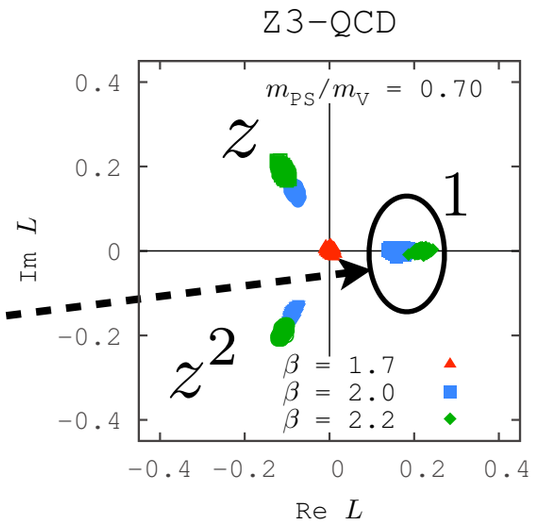
At β~1.6, chiral condensate decreases rapidly with hysteresis (affected by P-loop)

qualitatively the same behavior as usual QCD → the same Tc

consistent with D'Elia and Lombardo (2002)

Chiral condensate ⟨ψ̄ψ⟩





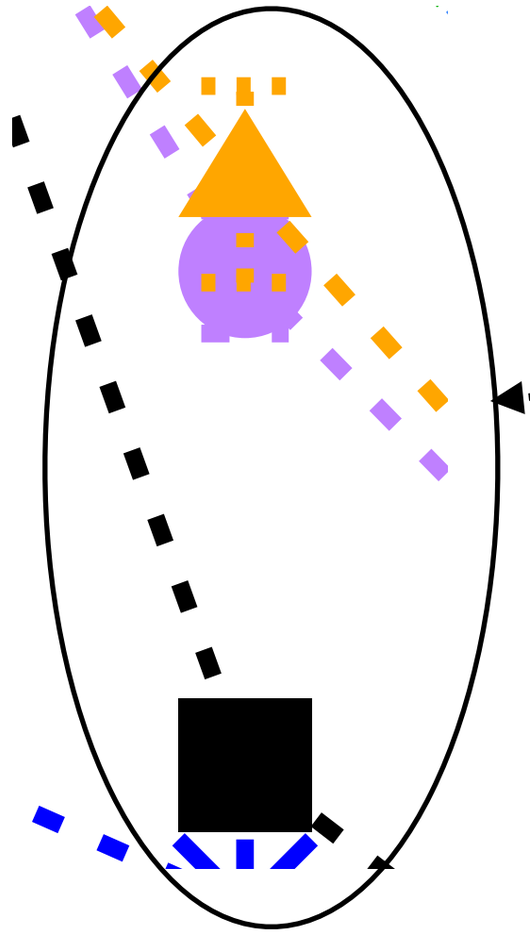
・ relation of flavor & Z3

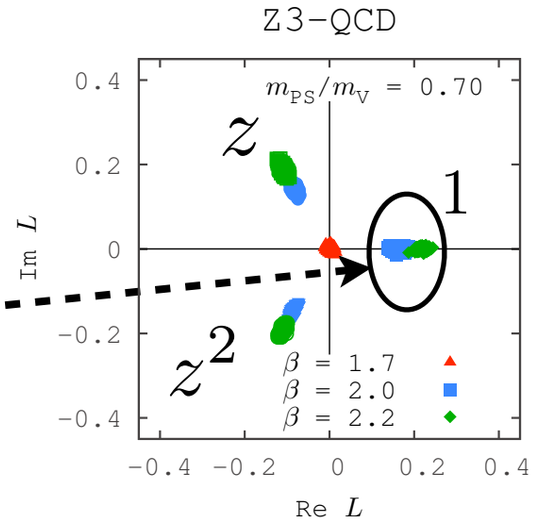
split-flavor b.c.
× P-loop phase =1

At β>1.6, flavor symmetry is broken
associated with direction of Z3 breaking

For ⟨L⟩ ≠ 0, b.c. dynamically affects mesonic spectrum

Chiral condensate $\langle\bar{\psi}\psi\rangle$





・ relation of flavor & Z3

split-flavor b.c.
× P-loop phase =1

At β>1.6, flavor symmetry breaking
gets manifest due to the center breaking

For $\langle L\rangle \neq 0$, BC dynamically affects mesonic spectrum

Summary

- **Lattice QCD simulation of Z3-QCD**
- **First-order center phase transition**
- **Chiral transition T consistent with QCD**
- **Chiral condensate also has hysteresis**
- **Flavor symmetry breaking in meson sect.**

Discussion & future work

- **Our result shows deep relation & correlation between center & chiral transition**
- **In a chiral limit, it seems chiral 1st-order phase transition occurs at about Td.**
- **Need simulations with smaller quark mass**
- **More study is required to understand flavor symmetry breaking in low-T phase**