Exploring the IR sector of QCD out of equilibrium

Based on ongoing work with J. Berges, K. Boguslavski, J. M. Pawlowski
Related work ongoing by JB, KB, JMP and T. Butler, P. Radpay (resp.)

Lillian de Bruin
ITP, Universität Heidelberg

Cold Quantum Coffee seminar: 26 April 2022

Outline

Motivation and objectives

Wilson Loops and Polyakov loop correlators

The scalar algebra field

Conclusions and ongoing/future work

Initial overoccupation and thermalization

Thermalization dynamics from initial overoccupation

- heavy on collisions
- early universe re-heating
- ultracold quantum gases

↓

Bose condensation

- gauge invariant order param. field in QCD
- relativistic scalar inflation
- nonrelativistic Bose field

Initial overoccupation and thermalization

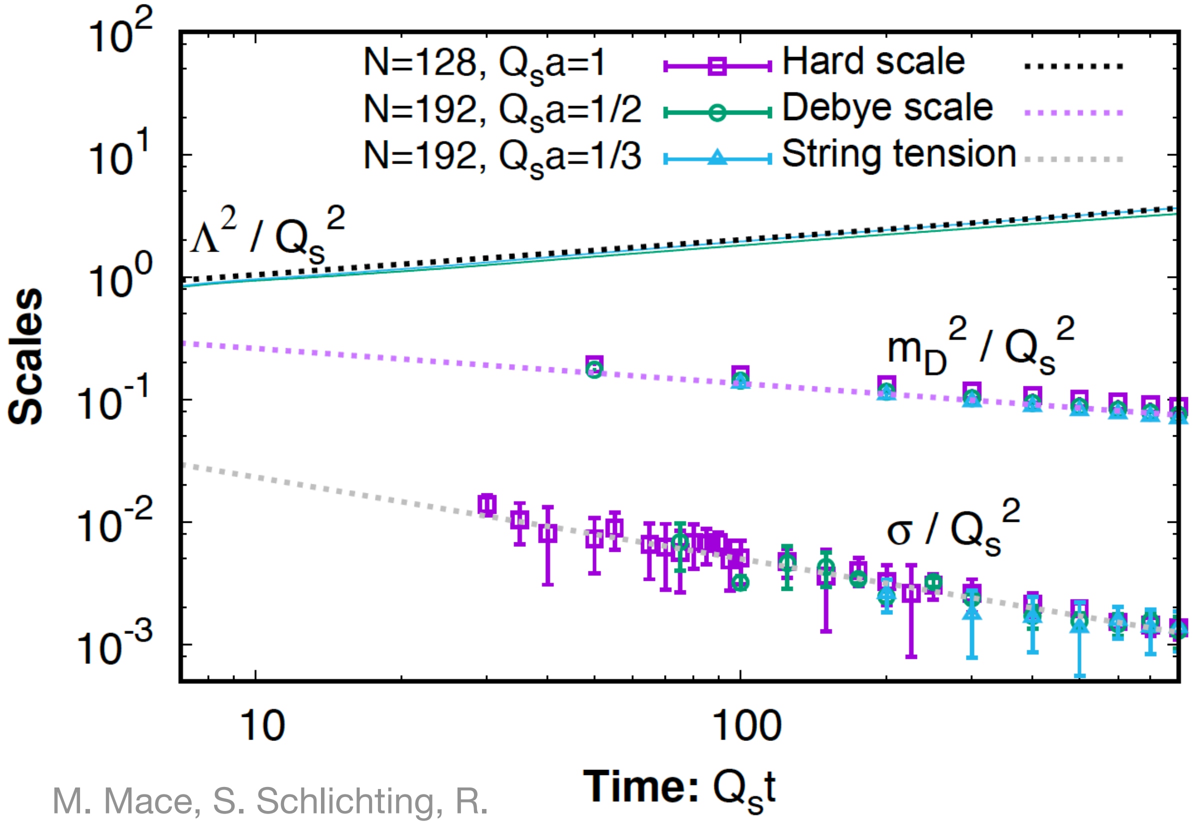
Thermalization dynamics from initial overoccupation

- heavy on collisions
- early universe re-heating
- ultracold quantum gases

Bose condensation

- gauge invariant order param. field in QCD
- relativistic scalar inflation
- nonrelativistic Bose field

Thermalization: separation of scales



M. Mace, S. Schlichting, R. Venugopalan, PRD (2016)

Ultrasoft scale evolves faster than **soft** scale!

Objectives

One of the basic questions we need to answer is: to what extent do IR modes influence thermalization of the QGP out of equilibrium?

In order to study dynamics at this scale, we need to identify an appropriate order parameter

Wilson loops and Polyakov loop correlators

Characteristics of over-occupied QGP

Gluons produced in heavy ion collisions are expected to have typical momenta on order of saturation scale Q —> Over-occupation of gluons at time t~1/Q

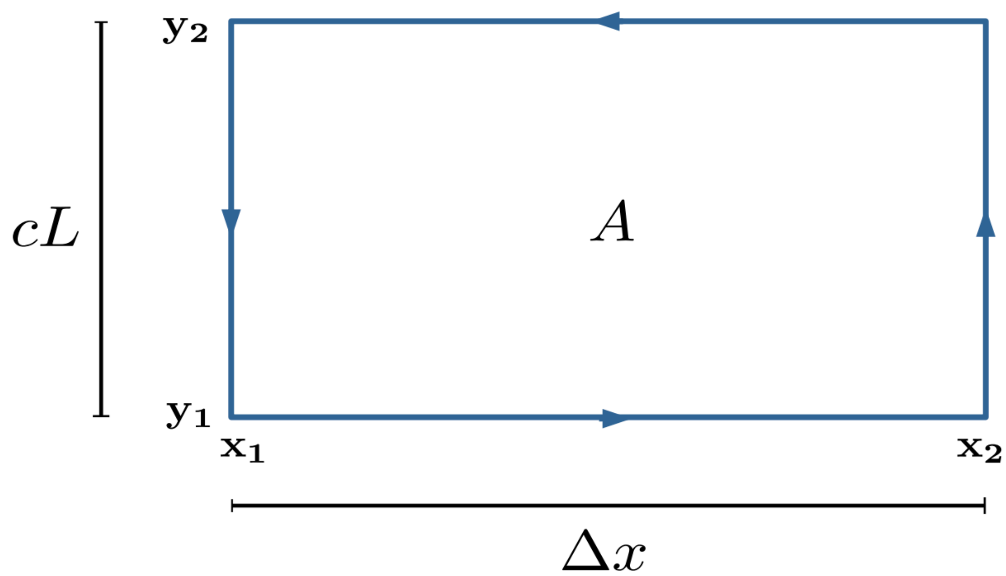
Running gauge coupling is small: $\alpha_s(Q_s) \ll 1$

System is considered strongly correlated due to high gluon occupancy

Non-perturbative quantum problem can be mapped to classical-statistical lattice gauge theory

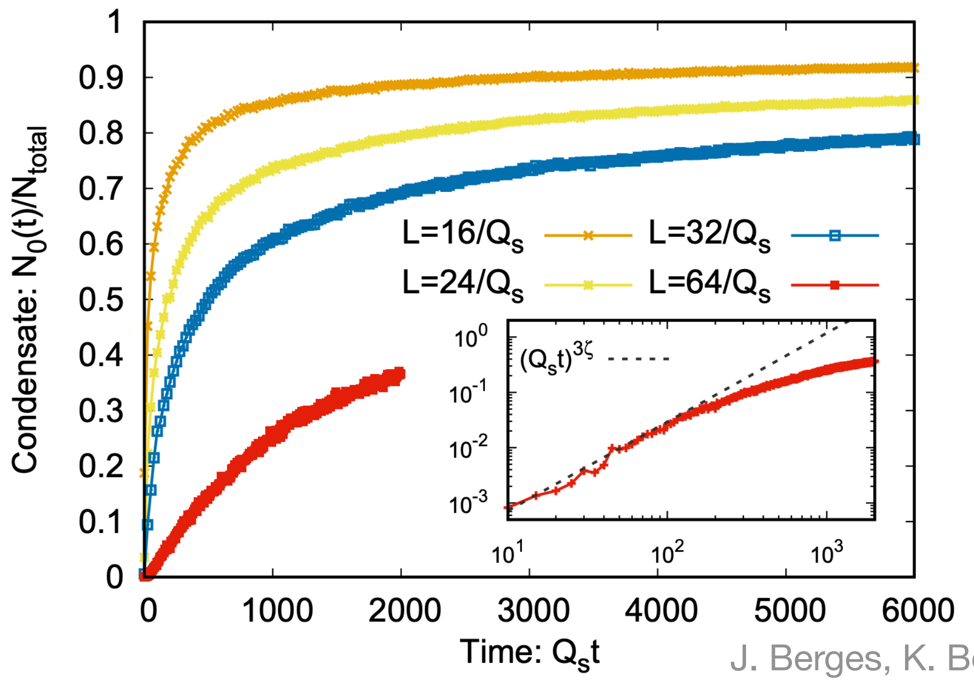
Spatial Wilson loops

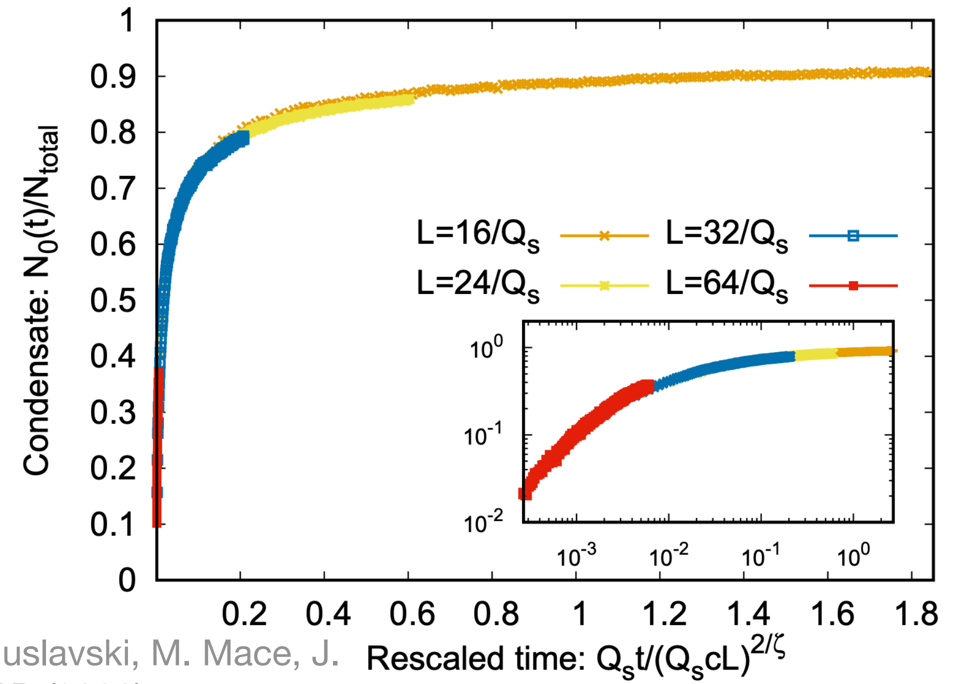
Gauge invariant quantity that captures long-distance behavior of gauge fields



$$\langle W(\Delta x, \Delta y; t)\rangle = \left\langle \frac{1}{N_c} \mathrm{Tr}\mathcal{P} e^{-ig\int_{C[\Delta x, \Delta y]} \mathcal{A}_i(\mathbf{z};t)dz_i} \right\rangle$$

Condensate fraction: Wilson loop





J. Berges, K. Boguslavski, M. Mace, J. M. Pawlowski, PRD (2020)

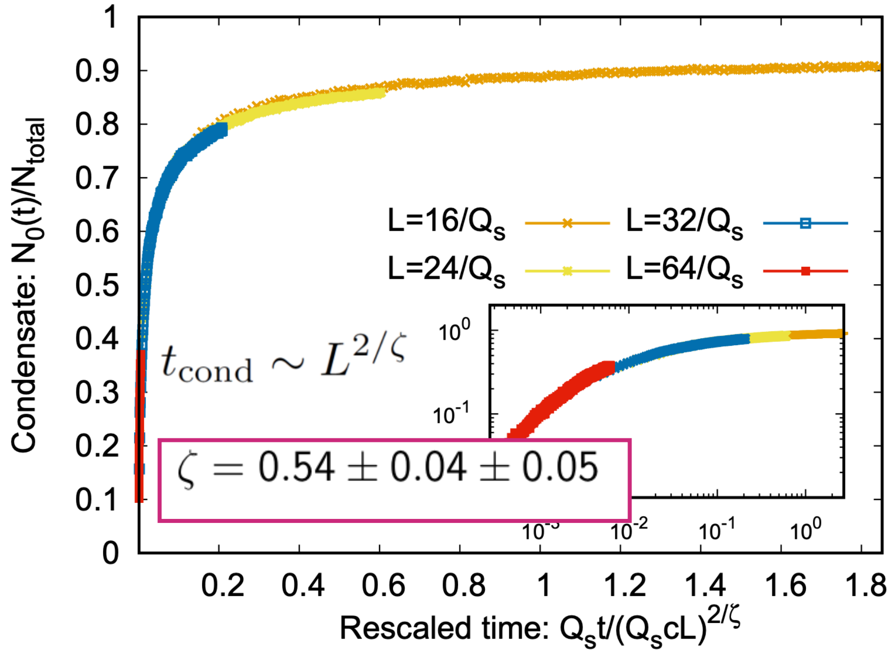
$$\frac{N_0(t,L)}{N_{\mathrm{total}}} = \frac{1}{V}\int_0^L d^d x\, \langle W(\Delta x, L, t)\rangle$$
$$= \frac{1}{V}\int_0^L d^d \Delta x\, \omega_S(\Delta x\, L/t^{\zeta})$$

$$t_{\mathrm{cond}} \sim L^{2/\zeta}$$

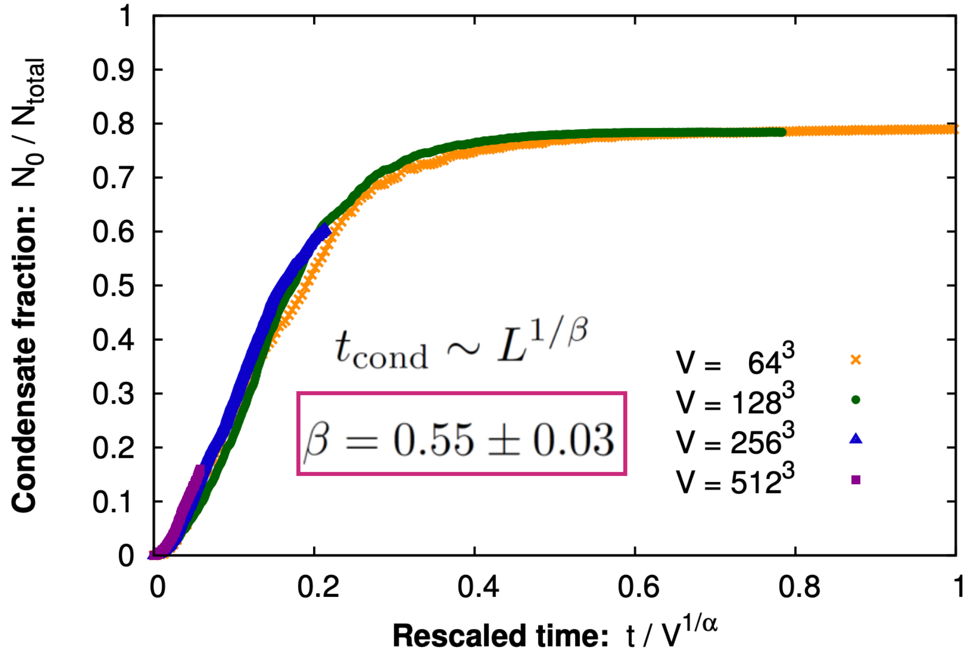
$$\zeta = 0.54 \pm 0.04 \pm 0.05$$

Condensation from initial overoccupation

Gauge fields



Scalar fields



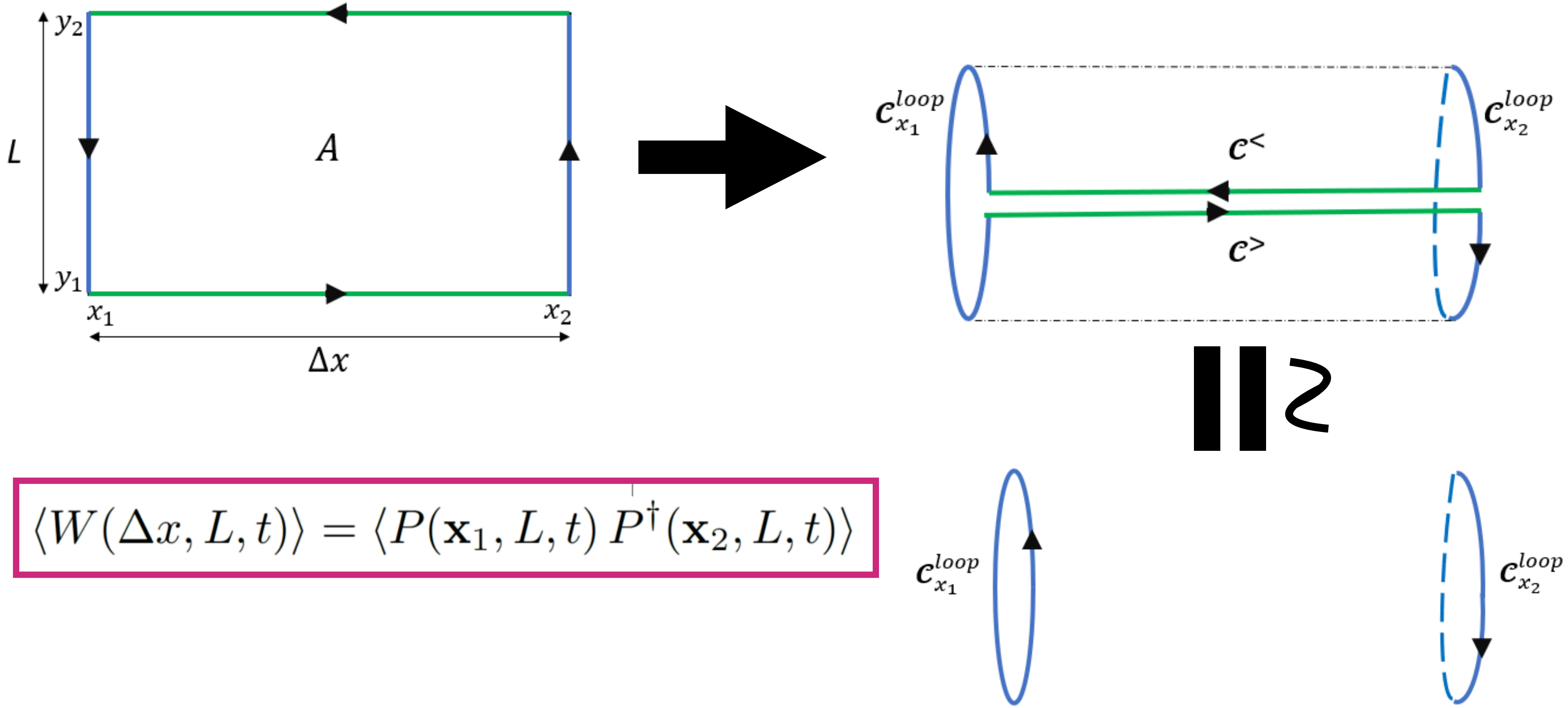
A. Piñeiro Orioli, J. Berges, K. Boguslavski PRD (2015)

$$\frac{N_0(t,L)}{N_{\text{total}}} = \frac{1}{V}\int_0^L d^dx\,\langle W(\Delta x, L, t)\rangle = \frac{1}{V}\int_0^L d^d\Delta x\,\omega_S\left(\Delta x\, L/t^{\zeta}\right)$$

$$N^{\phi}_{\text{total}} = \langle \phi(\mathbf{x},t)\,\phi^{\dagger}(\mathbf{x},t)\rangle$$

$$\frac{N_0^{\phi}(t)}{N^{\phi}_{\text{total}}} = \frac{1}{N^{\phi}_{\text{total}}V}\int_0^L d^dx\,\langle \phi(x)\phi^{\dagger}(0)\rangle = \frac{1}{N^{\phi}_{\text{total}}V}\int_0^L d^d\Delta x\, f_S\left(\Delta x/t^{\beta}\right)$$

Spatial "Polyakov" loop

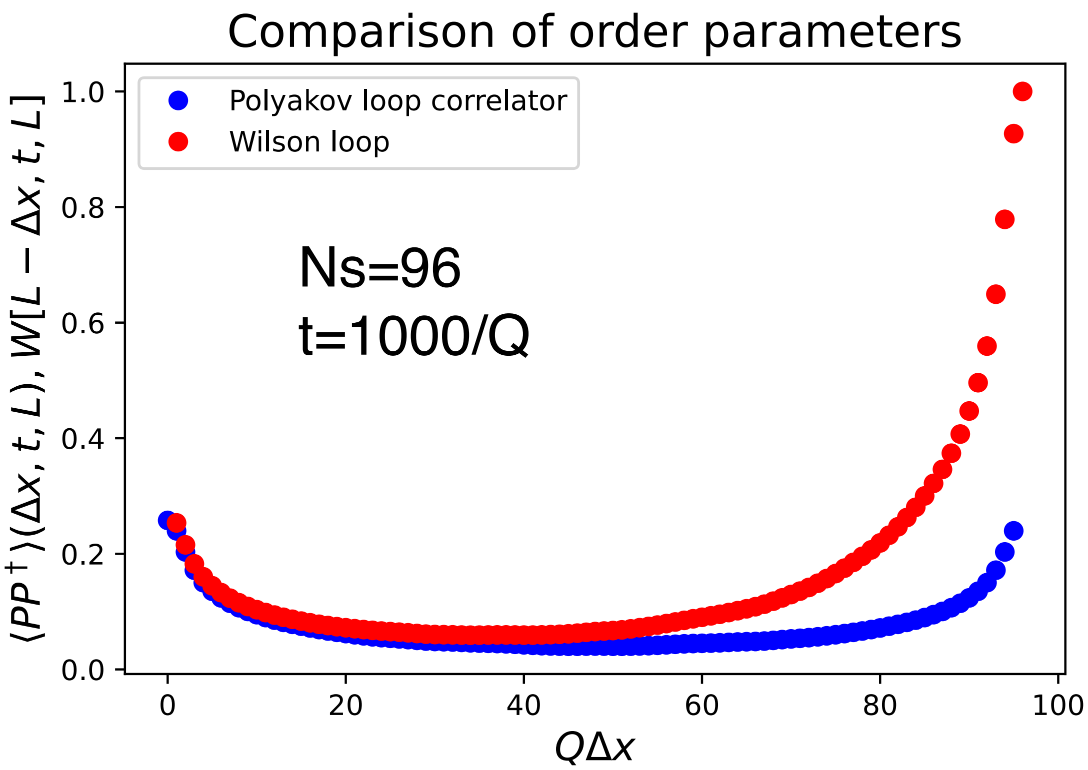


$$\langle W(\Delta x, L, t)\rangle = \langle P(\mathbf{x}_1, L, t)\, P^\dagger(\mathbf{x}_2, L, t)\rangle$$

T. Butler

Spatial Polyakov loop cont'd.

$$P(\mathbf{x}) = \frac{1}{N_c} \mathrm{Tr}\, \mathcal{P} e^{-ig \int_0^L dy\, A_y(x,y)}$$

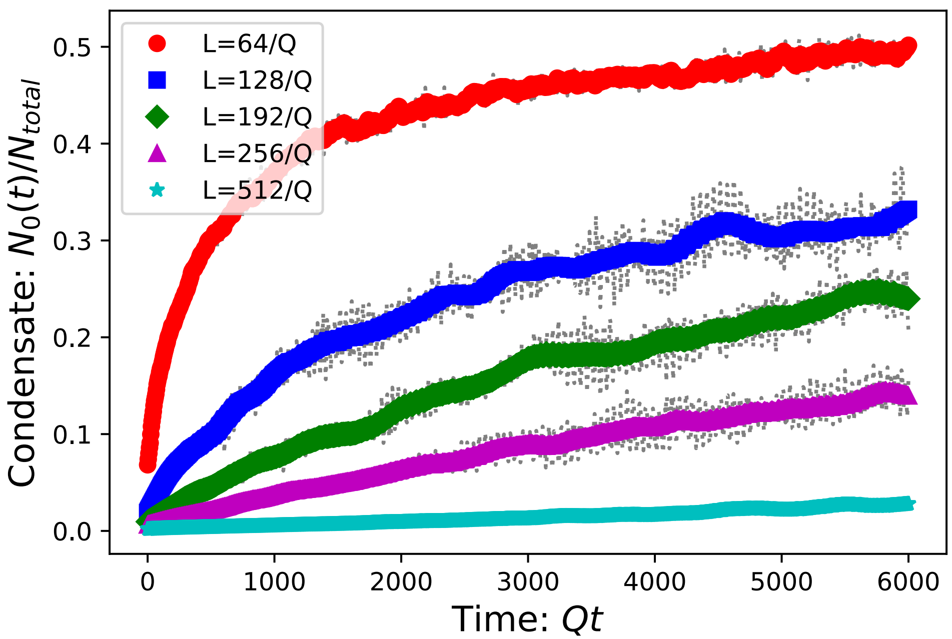


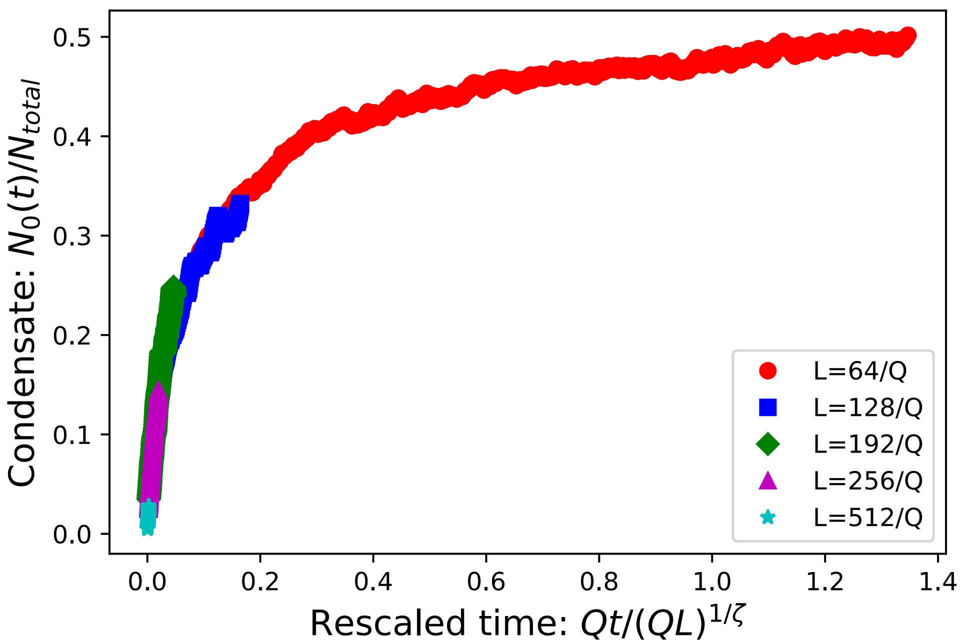
Same dynamics as the Wilson loop

T. Butler

Correlator is local, symmetric in x — cleaner order parameter!

Spatial Polyakov loop cont'd.





$$\frac{N_0(t,L)}{N_{\text{total}}} \equiv \frac{1}{L}\int_0^L d\Delta x\, \frac{\langle PP^\dagger(t,\Delta x,L)\rangle}{\langle PP^\dagger(t,0,L)\rangle}$$

J. Berges, K. Boguslavski, T. Butler, J. M. Pawlowski, (in preparation)

$$t_{\text{cond}} \sim (L)^{1/\zeta}$$

$$\zeta = 0.33 \pm 0.05\ (\text{stat.})$$

The scalar algebra field

The scalar algebra field

We can rewrite the Polyakov loop

$$P(\mathbf{x}) = \frac{1}{N_c} \mathrm{tr} \mathcal{P} \exp \left\{ -ig \int_0^L dy \; A_y(x,y) \right\} ,$$

as

$$P(\mathbf{x}) = exp \left\{ i\phi \right\} ,$$

where ϕ is the algebra-valued scalar field.

Diagonalization of *P(x)*

$P(x)$ can be diagonalized by gauge transformations $U \in SU(N)$,

$$P(\mathbf{x}) \to U^{-1}(y=0)P(\mathbf{x})U(y=cL)$$

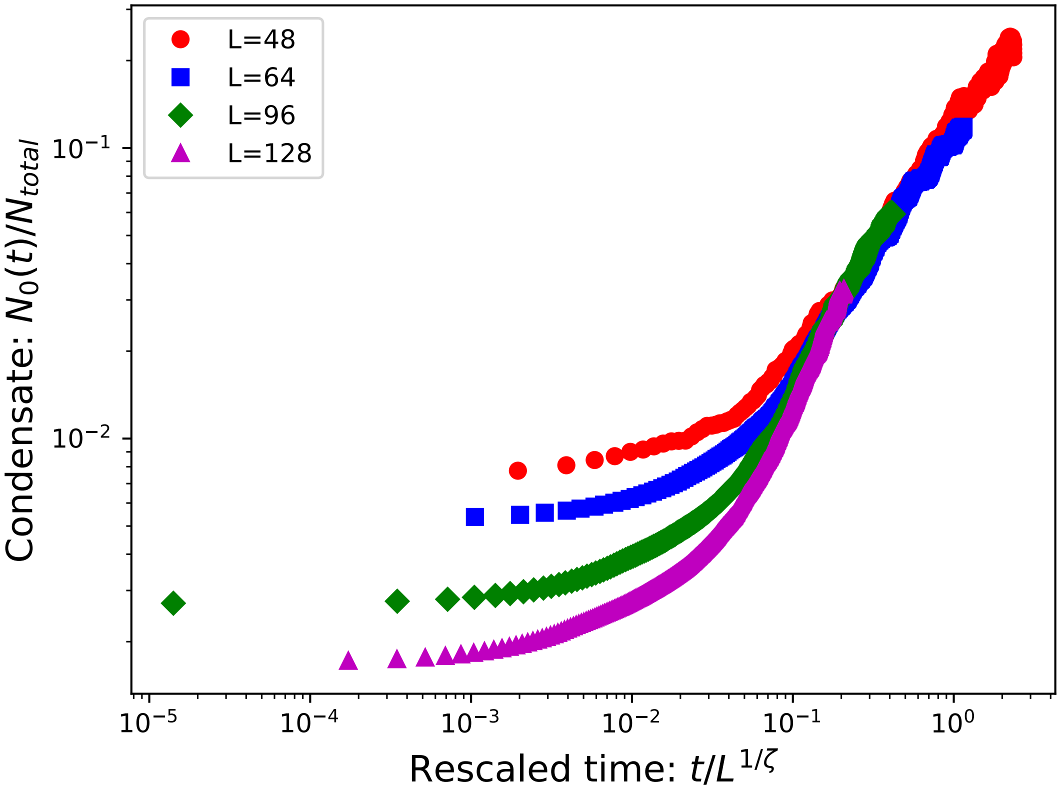
The eigenvalues φ_n of ϕ are directly related to the eigenvalues of the Polyakov loop, $\exp\{i\varphi_n\}$, and are gauge invariant in the fundamental representation.

We want to explore this scalar field as an order parameter.

Condensate fraction: algebra fields

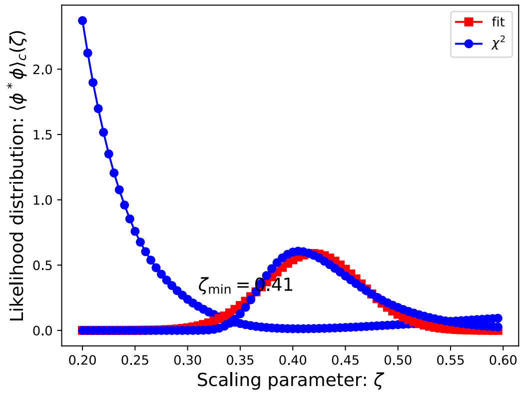
Connected correlator of algebra fields:

$$\langle \phi^* \phi \rangle_c (\Delta x, t) = \langle \phi^* \phi \rangle (\Delta x, t) - \langle \phi^*(x_1, t) \rangle \langle \phi(x_2, t) \rangle$$



$$t_{\text{cond}} \sim (L)^{1/\zeta}$$

$$\zeta = 0.41$$



Related questions

Rigorously establishing the non-triviality of the Polyakov loop correlator, connected algebra field correlator —> Study higher order correlation functions of these order parameters

P. Radpay

Conclusion

- The algebra-valued scalar field is a promising order parameter for gauge invariant condensation
- There's much to be done in this direction
  - e.g. study longtime limits