Quantum Simulation of String Breaking in Schwinger Model as Open Quantum System

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Motivations

- Goal: understand thermalization, production of QGP and deconfinement—confinement transition in heavy ion collisions **nonperturbatively**

- Euclidean lattice QCD suffers from **sign problem** for real-time dynamics; real-time Hamiltonian simulation requires **exponentially large Hilbert space**

- Quantum technology is developing quickly, one hopes to use quantum computer to simulate quantum field theory, especially QCD

- Consider simple QFT: U(1) gauge theory in 1+1D (Schwinger model) which exhibits features such as confinement; embed the Schwinger model inside a thermal scalar field environment

- Quantum simulation of the nonequilibrium dynamics of the Schwinger model, study string breaking and thermalization

Schwinger Model Coupled w/ Thermal Scalar Field

- **U(1) gauge theory in 1+1D** $\mathcal{L} = \overline{\psi}(iD^\mu\gamma_\mu - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$ $\quad \gamma^0 = \sigma_z \quad \gamma^1 = -i\sigma_y$

- **Hamiltonian formulation in axial gauge $A_0 = 0$ and discretization**

$$H_S = \frac{1}{2a}\sum_n \Big(\sigma^+(n)L_n^-\sigma^-(n+1) + \sigma^+(n)L_{n-1}^+\sigma^-(n-1)\Big) + \frac{m}{2}\sum_n(-1)^n\big(\sigma_z(n)+1\big) + \frac{ae^2}{2}\sum_n \ell_n^2$$

- **Total Hamiltonian** $H = H_S + H_E + H_I$

J. B. Kogut and L. Susskind
Phys. Rev. D11(1975) 395–408

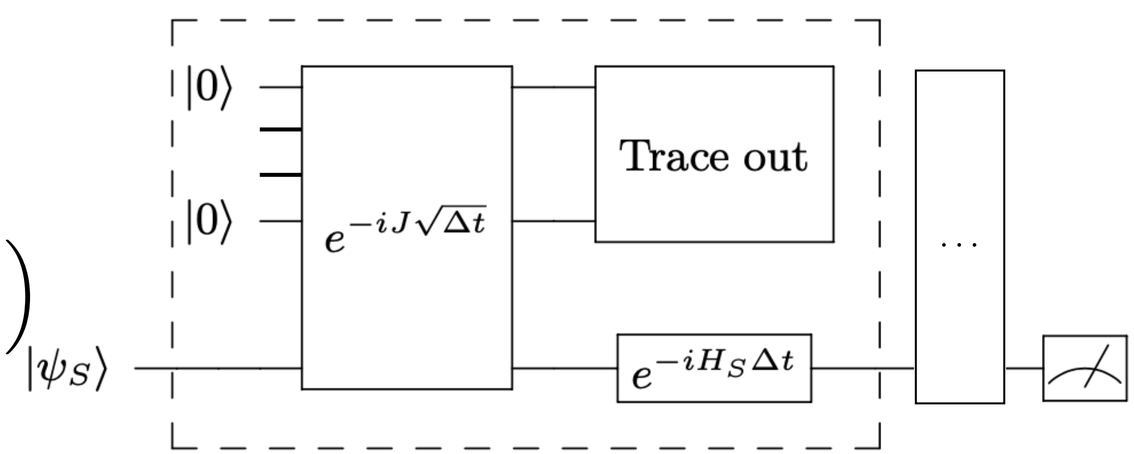
$$H_E = \int dx\left[\frac{1}{2}\Pi^2 + \frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{4!}g\phi^4\right] \qquad H_I = \lambda\int dx\,\phi(x)\overline{\psi}(x)\psi(x) = \int dx\,O_E(x)O_S(x)$$

- **Lindblad equation in quantum Brownian motion limit** see, e.g. XY 2102.01736

$$\frac{\mathrm{d}\rho_S(t)}{\mathrm{d}t} = -i\big[H_S, \rho_S(t)\big] + a^2\sum_{n,m} D(k_0 = 0, a(n-m))$$
$$\times\Big(\widetilde{O}_S(m)\rho_S(t)\widetilde{O}_S^\dagger(n) - \frac{1}{2}\big\{\widetilde{O}_S^\dagger(n)\widetilde{O}_S(m), \rho_S(t)\big\}\Big)$$

$$\widetilde{O}_S(n) \equiv O_S(n) - \frac{1}{4T}\big[H_S, O_S(n)\big]$$

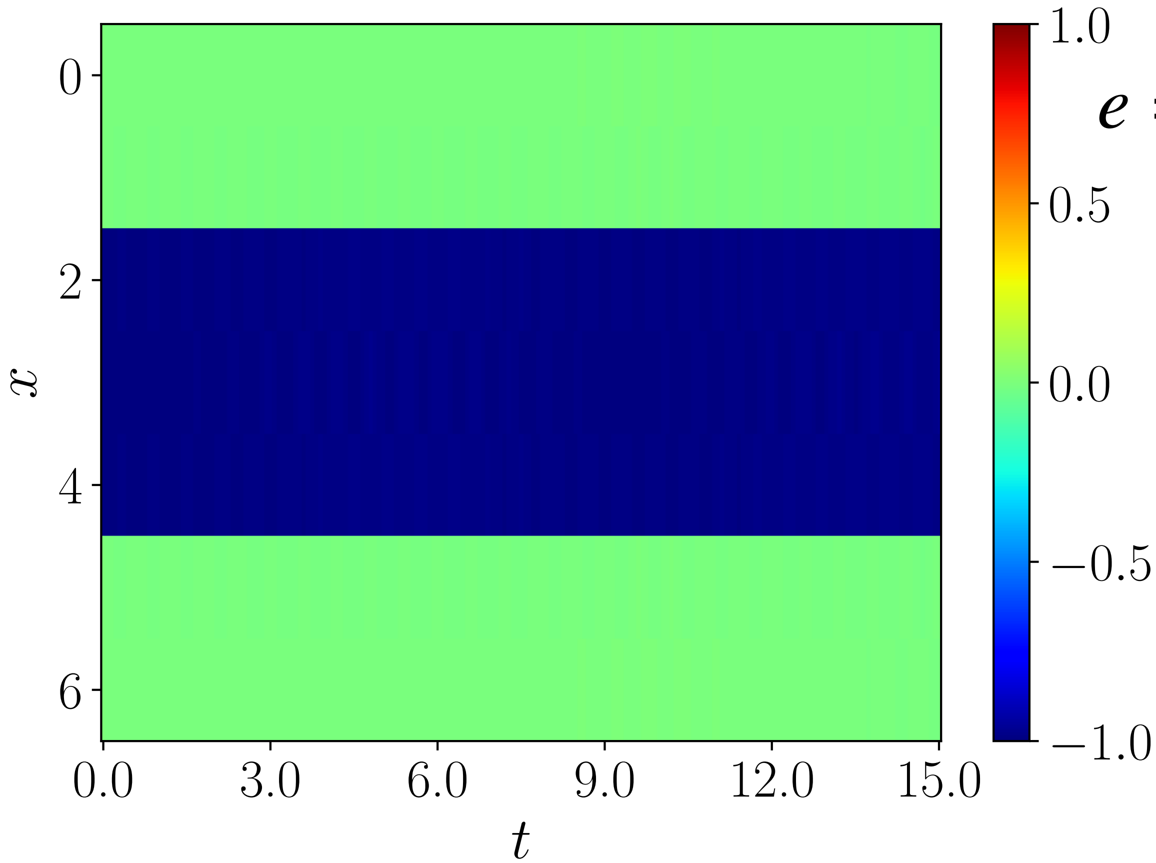
$$O_S(n) = (-1)^n\frac{\sigma_z(n)+1}{2}$$



$$J = \begin{pmatrix} 0 & L_1^\dagger & \dots & L_m^\dagger \\ L_1 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ L_m & 0 & \dots & 0 \end{pmatrix}$$

Quantum circuits

Quantum Simulation: Electric Flux v.s Time

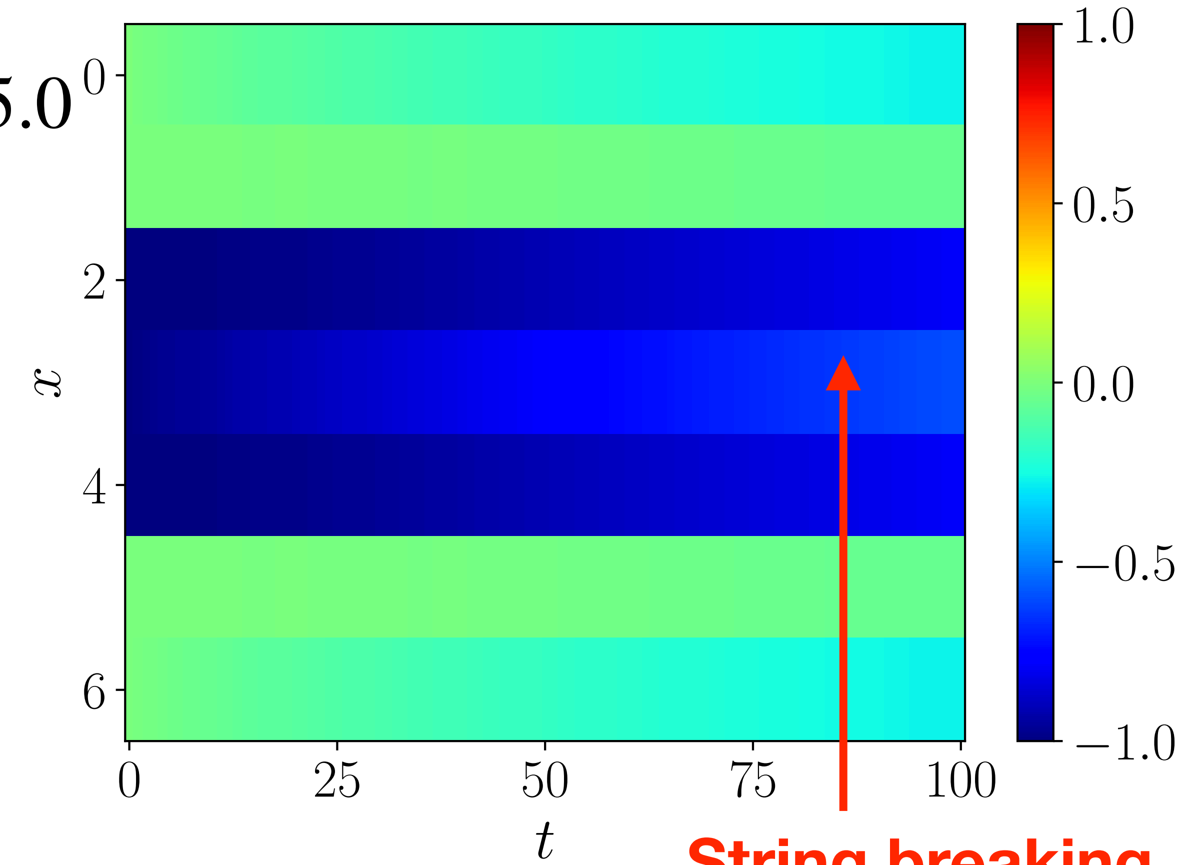


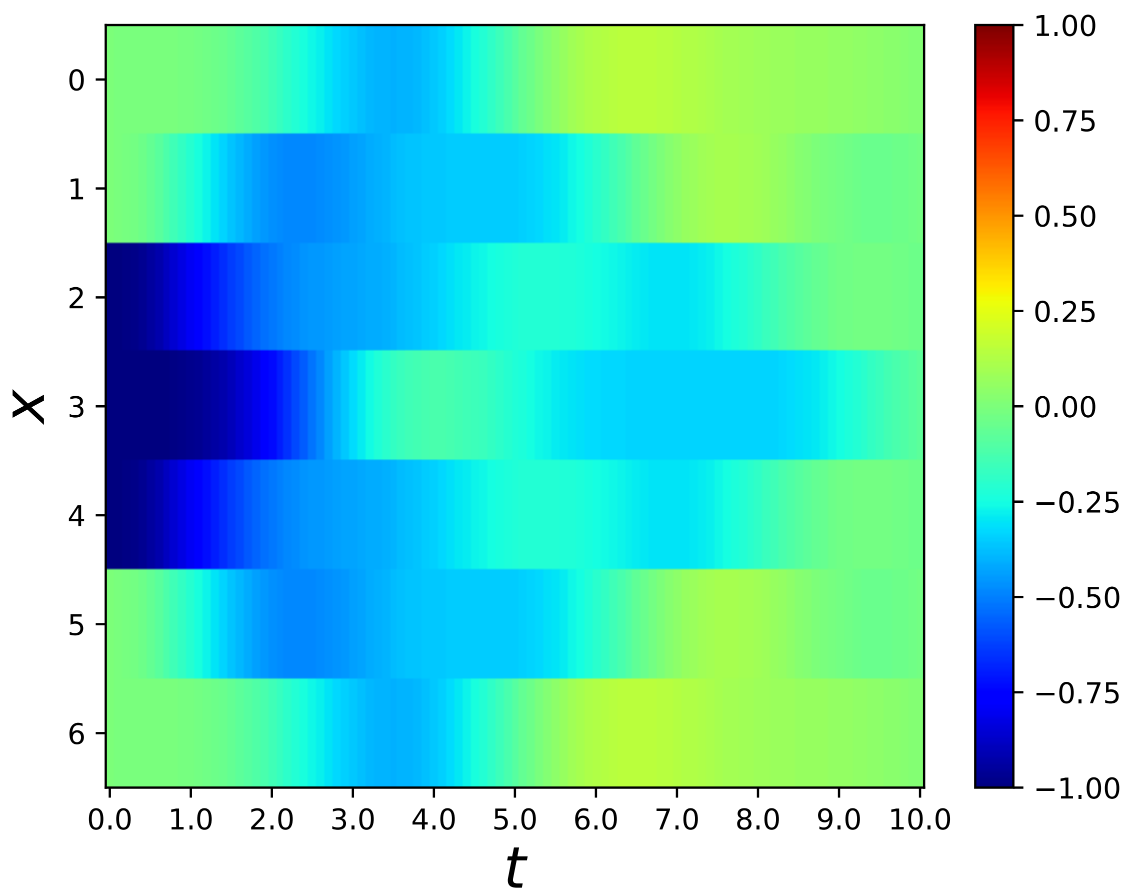
$e = 0.8,\ m = 5.0$

$\beta = 0.1$

<—Vacuum

OQS —>





$e = 0.36$

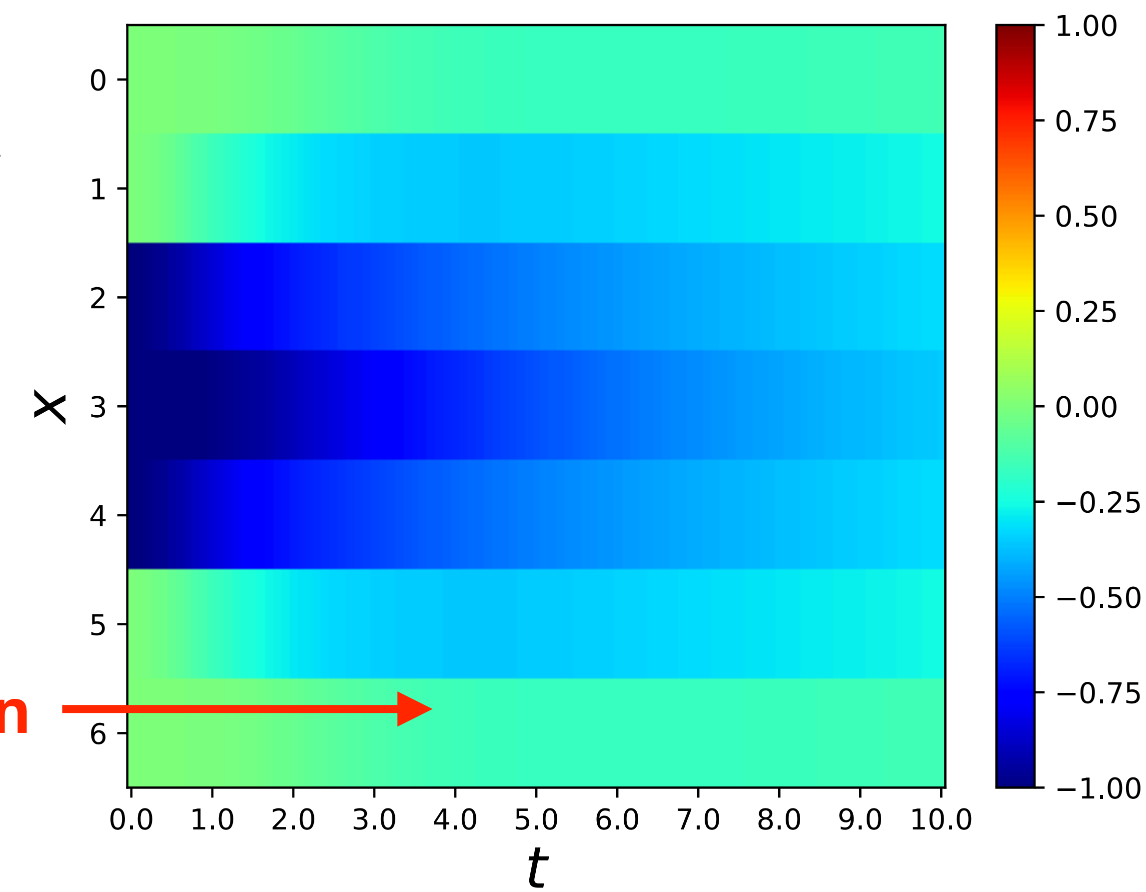
$m = -0.17$

$\beta = 0.5$

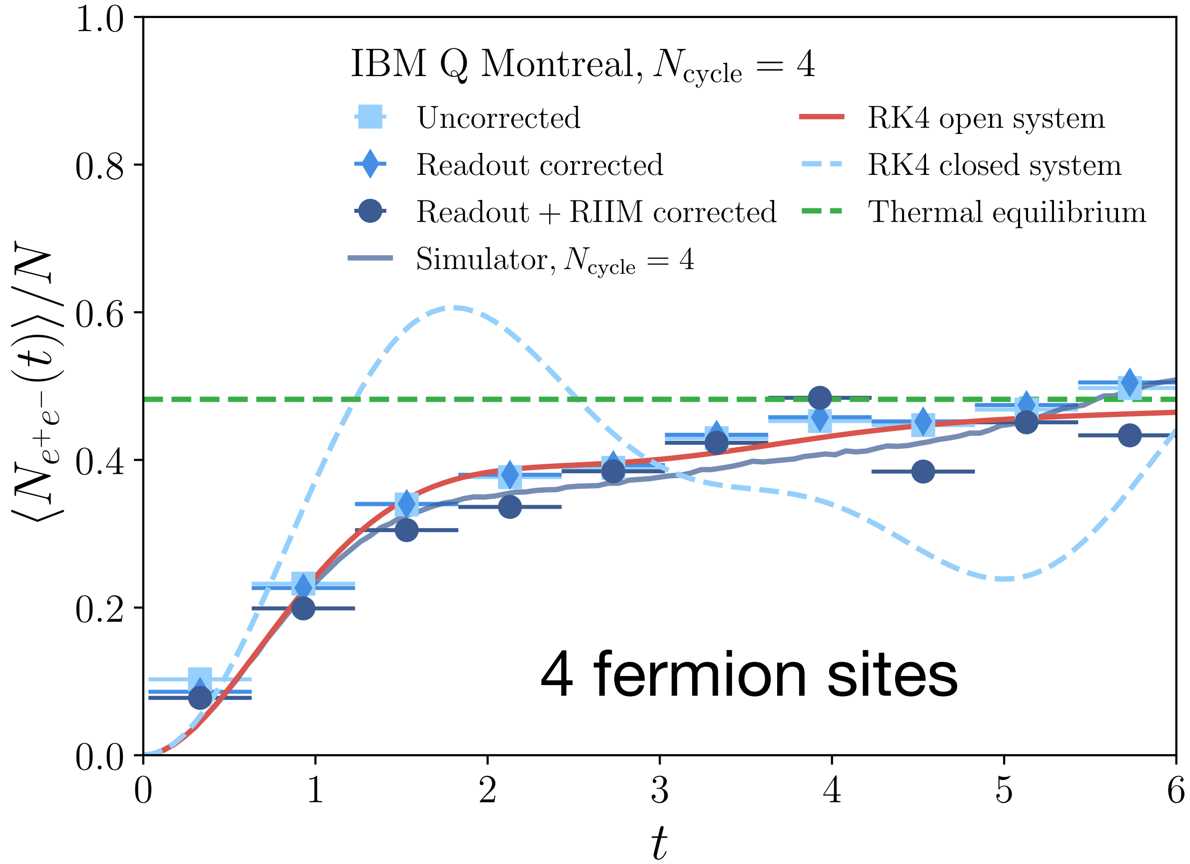
<—Vacuum

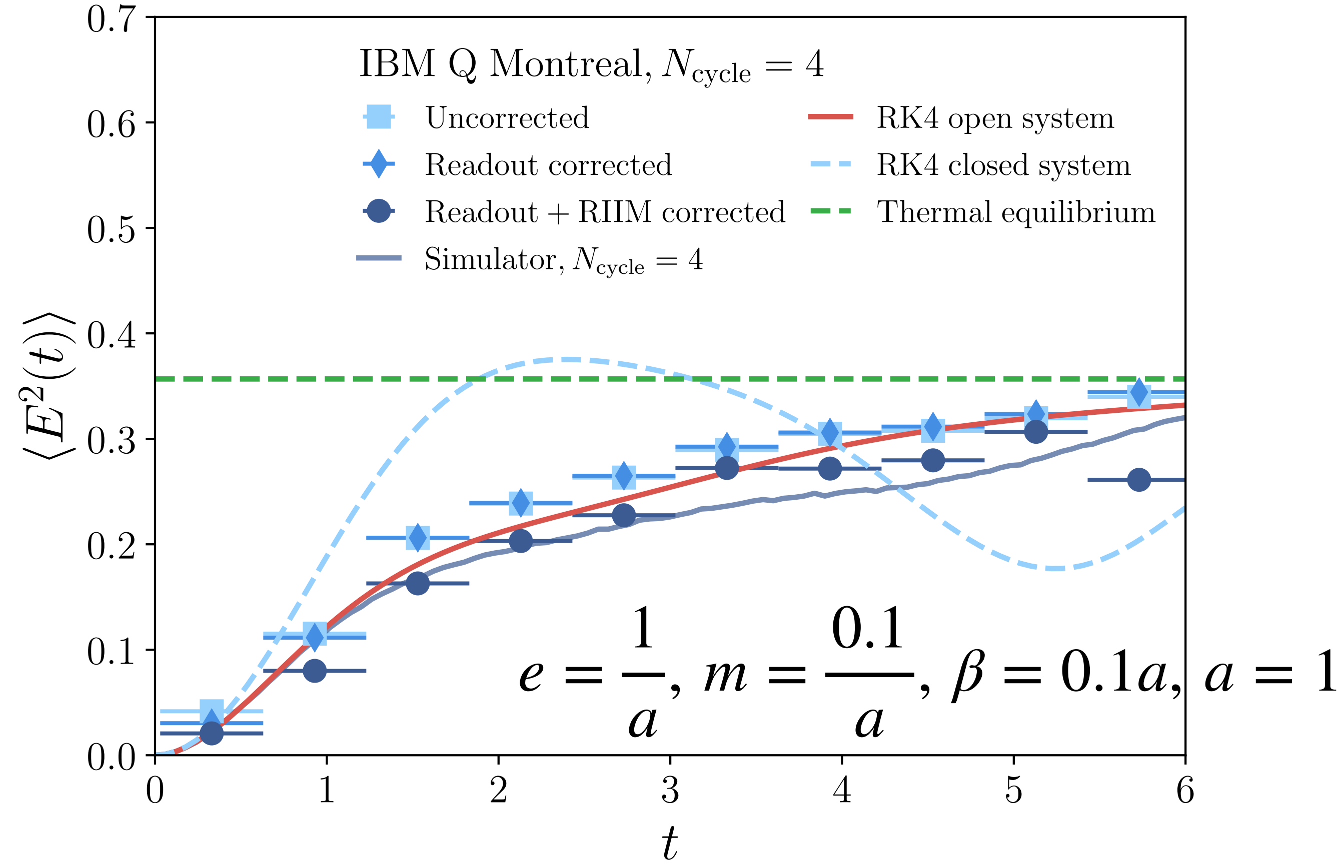
OQS —>

Reconnection



Quantum Simulation of Thermalization and Summary





- Quantum simulation of Schwinger model coupled w/ thermal scalar field: string breaking and reconnection, thermalization of Schwinger model
- Current devices can simulate thermalization on a small scale lattice
- Future considerations: non-Abelian gauge theory in higher dimensions