# Toward dense QCD in quantum computers

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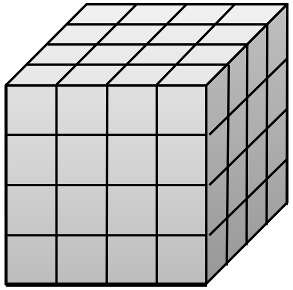
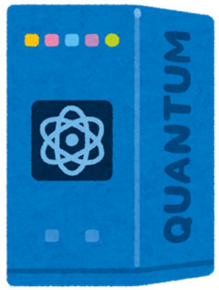
# Lattice gauge theory in quantum computers

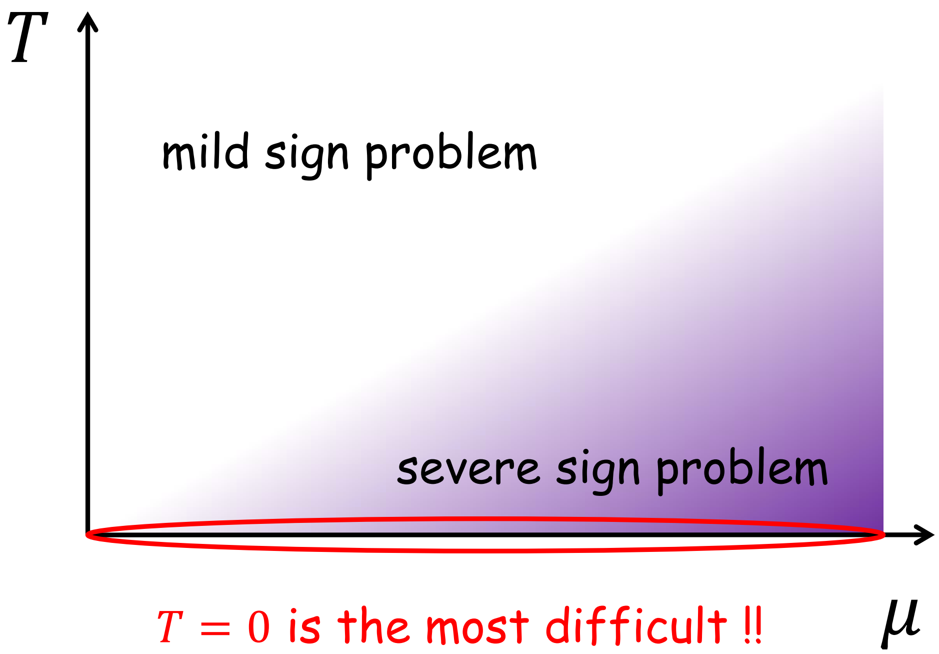


nonzero density



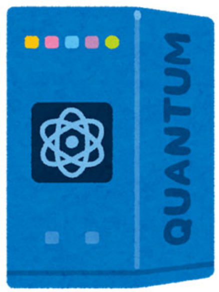

quantum computer

# Lattice gauge theory in quantum computers




$T = 0$ is the most difficult !!

⇨




quantum computer

# Algorithms

Lagrangian formalism

$$Z = \int DA\, e^{-\int d\tau\, L}$$

chemical potential

thermal average

Hamiltonian formalism

$$E = \langle \Psi | H | \Psi \rangle$$

particle number

ground state

# Algorithms

Hamiltonian $H$ & fermion number operator $Q$

$$[H, Q] = 0 \quad \longrightarrow \quad Q|\Psi(q)\rangle = q|\Psi(q)\rangle$$

"nonzero density" = ground state $|\Psi(q)\rangle$ w/ fermion number $q \neq 0$

# Algorithms

ground state of **full Hamiltonian**

ground state of **solvable Hamiltonian**

$$|\Psi(q)\rangle = \prod_{s=1,\cdots,S} U(s)\,|\Psi_0(q)\rangle$$

quantum-gate operation s.t. $[U(s), Q] = 0$

# Algorithms

**quantum adiabatic algorithm**

Farhi *et al.* (2000)

- ✓ adiabatic theorem
- ✓ $U(s)$ contains no free parameters
- ✓ exact in $S \to \infty$

**quantum variational algorithm**

Peruzzo *et al.* (2014)

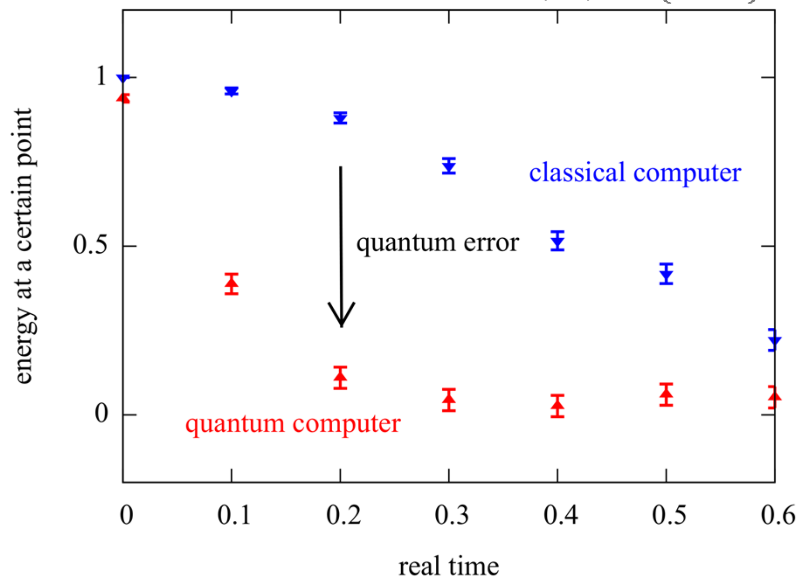
- ✓ hybrid variational method
- ✓ $U(s)$ contains variational parameters
- ✓ $S$ can be small

# Algorithms

noisy intermediate-scale quantum (NISQ)

# of gate operations must be small

Yamamoto (2021)




✓ exact in $S \to \infty$

✓ $S$ can be small

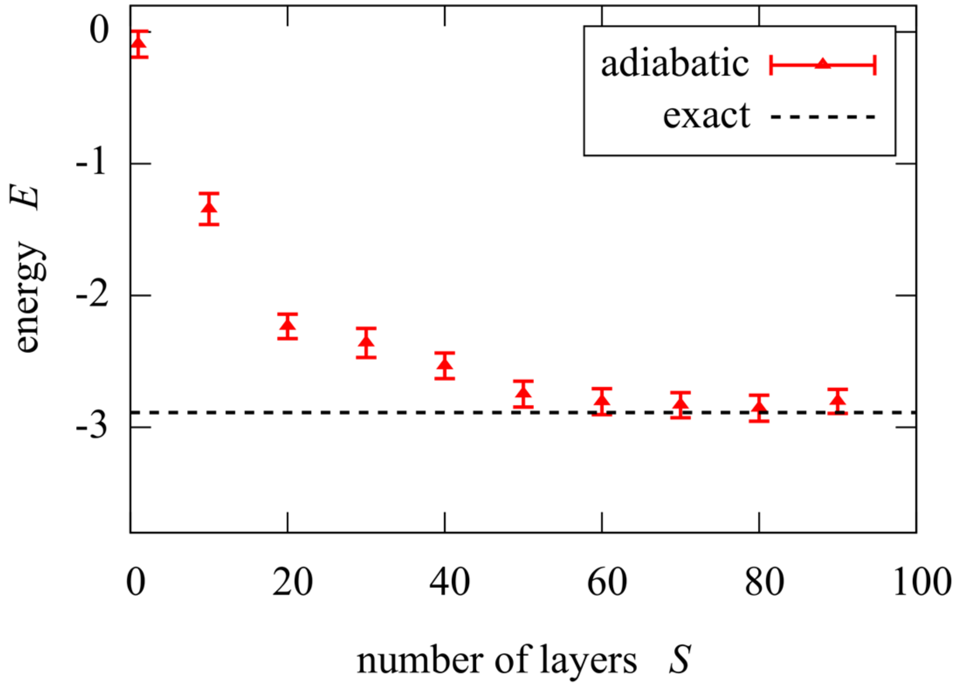
# Benchmark test

benchmark test of adiabatic & variational algorithms

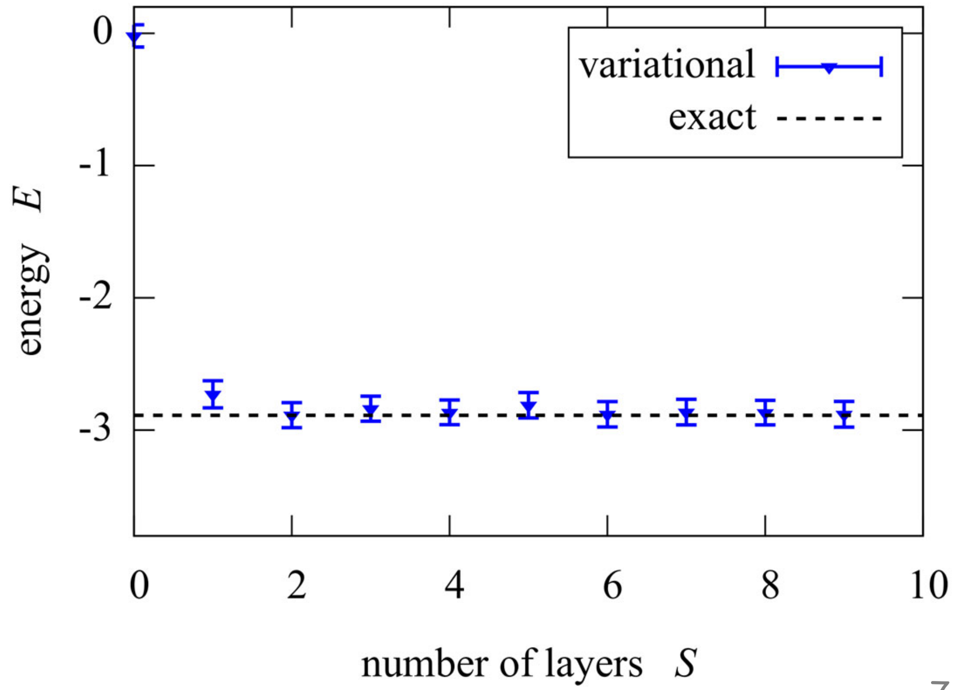
- ✓ "simulator" (classical computer to mimic quantum computer)
- ✓ Schwinger model
- ✓ 8-site lattice

# Benchmark test

adiabatic algorithm

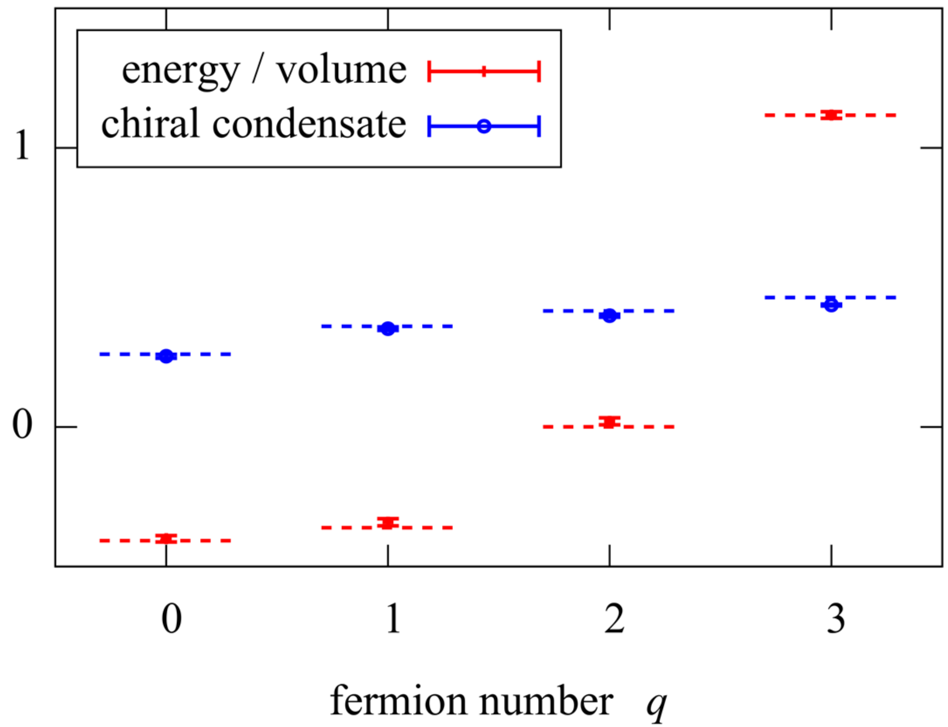



variational algorithm



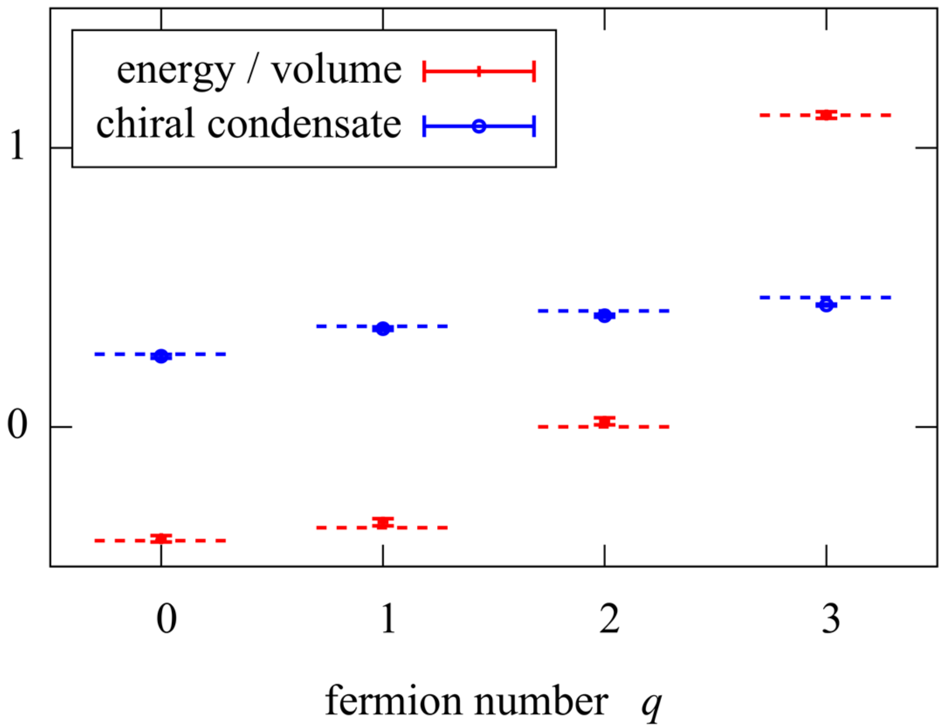
# Benchmark test

ground state energy & chiral condensate



# Benchmark test

ground state energy & chiral condensate

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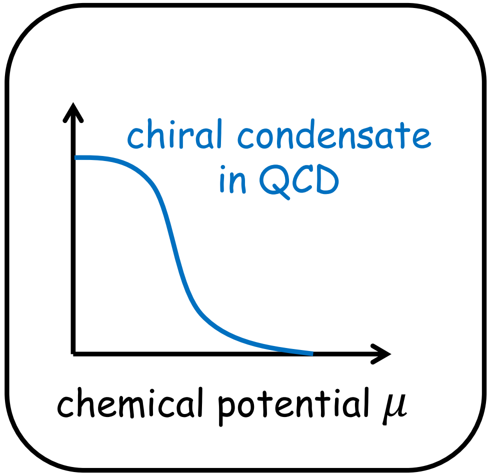

# Summary

- ✓ quantum simulation of lattice gauge theory at nonzero density
- ✓ benchmark tests of adiabatic & variational algorithms
- ✓ applicable to QCD, someday in the future