Variational quantum simulator of interacting bosons

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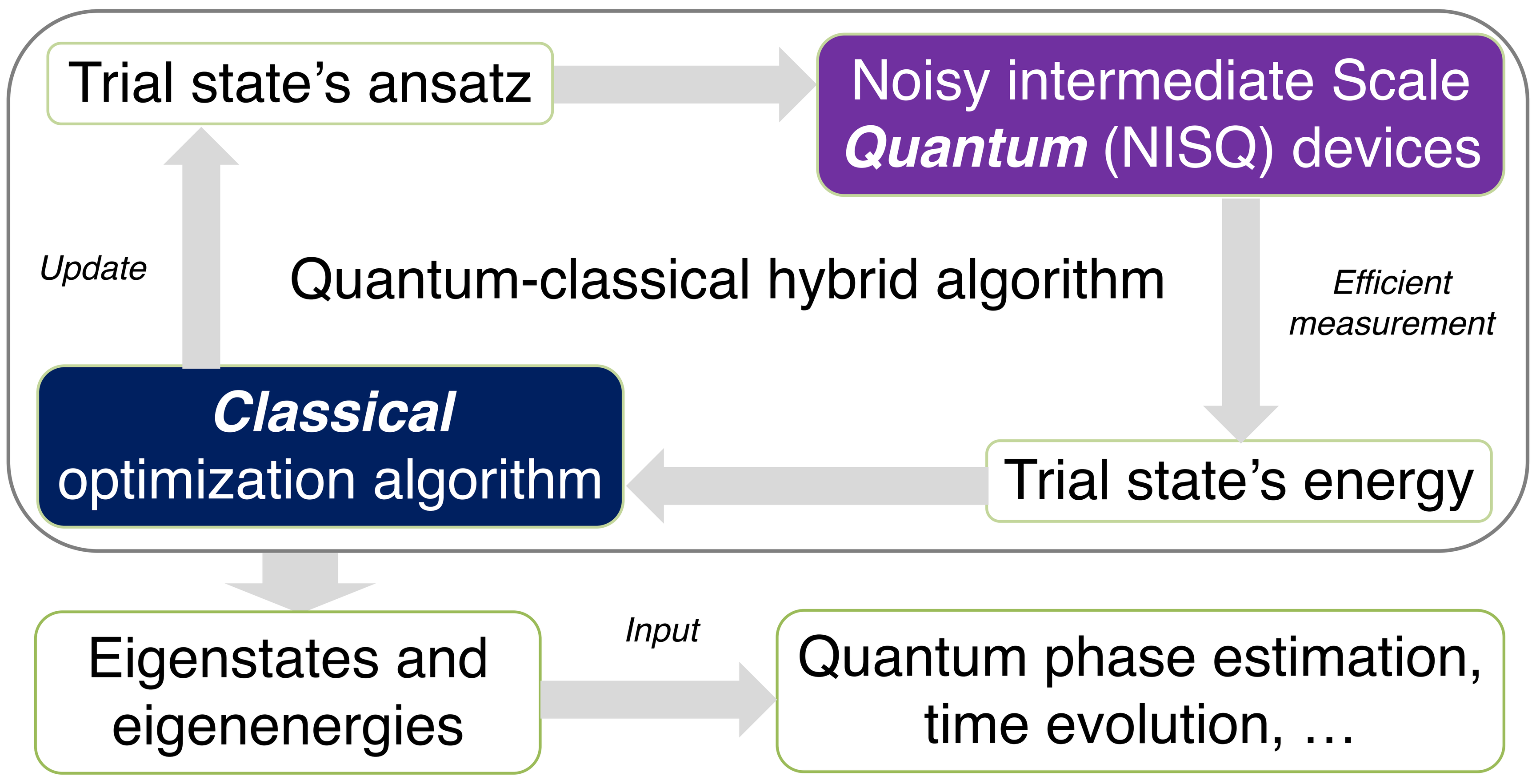
Overview

- VQE for interacting bosons
- Determine excited states by penalizing the overlap
- Proof-of-principle experiment on Rigetti's 8Q device

Variational quantum eigensolver (VQE)



Applications on boson systems:

- Light-matter interaction
- Electron-phonon coupling
- Quantum field theory

Boson encoding by qubits

Goal: encode the states in a truncated boson Hilbert space by a finite number of qubits

Number basis encoding

$|n = N\rangle = |1 \dots 11\rangle_q$

$\vdots$

$|n = 3\rangle = |0 \dots 11\rangle_q$

$|n = 2\rangle = |0 \dots 10\rangle_q$

$|n = 1\rangle = |0 \dots 01\rangle_q$

$|n = 0\rangle = |0 \dots 00\rangle_q$

Position basis encoding

Ref: Phys. Rev. Lett. 121, 110504

x, Δ

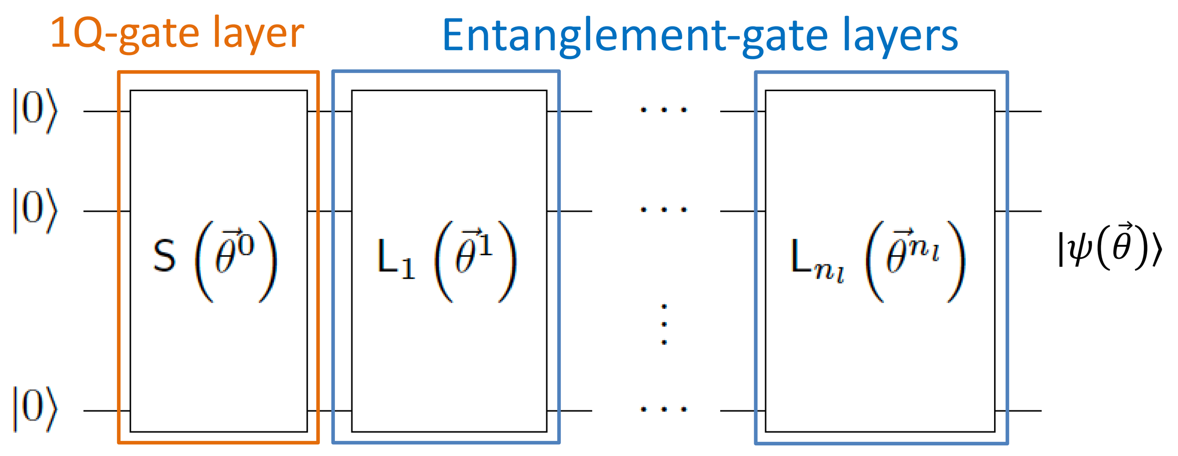
$|x = \Delta\frac{N-1}{2}\rangle = |1 \dots 11\rangle_q$

$|x = \Delta(\frac{N-1}{2}-1)\rangle = |1 \dots 10\rangle_q$

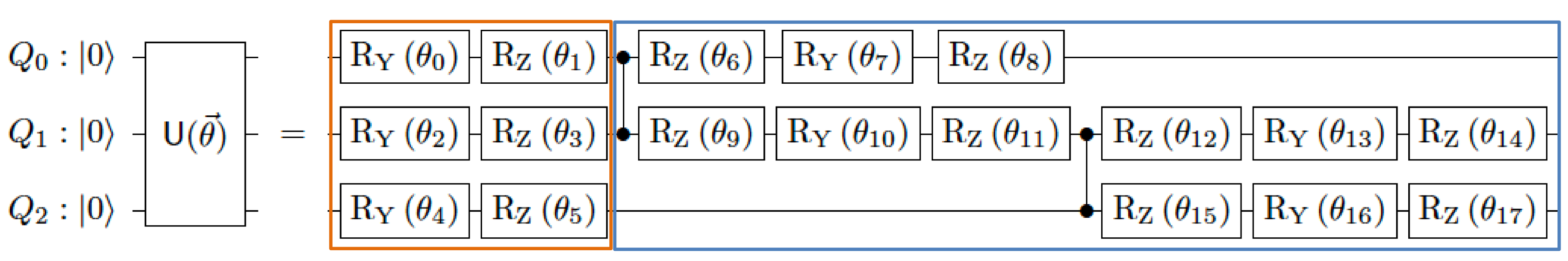
$\vdots$

$|x = \Delta(-\frac{N-1}{2})\rangle = |0 \dots 00\rangle_q$

Hardware efficient trial state's ansatz



Optimize toward shallowest circuit: ansatz only consists of gates that are natively supported by the hardware

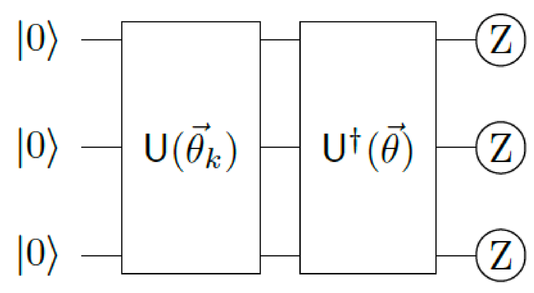


Cost function and optimization

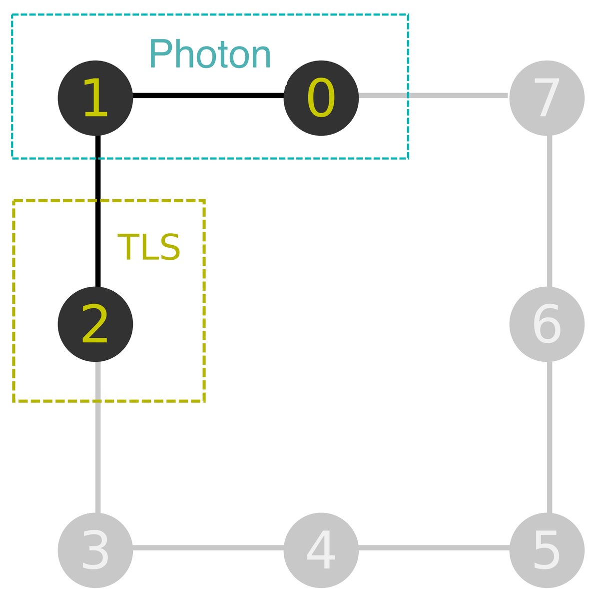
Eigenstates: $|\psi_j\rangle = \underset{|\psi(\vec{\theta})\rangle}{\operatorname{argmin}}\, C_j$

Cost function: $C_j = \underbrace{\langle\psi(\vec{\theta})|H|\psi(\vec{\theta})\rangle}_{\text{energy}} + \underbrace{\sum_{k=0}^{j-1} |\langle\psi_k|\psi(\vec{\theta})\rangle|^2}_{\text{overlap penalty}}$

SPSA optimization algorithm
→ Stochastic optimization
→ More robust with noisy environment



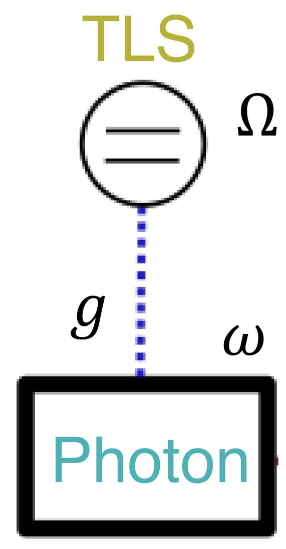
VQE for Rabi model on Rigetti's 8Q device



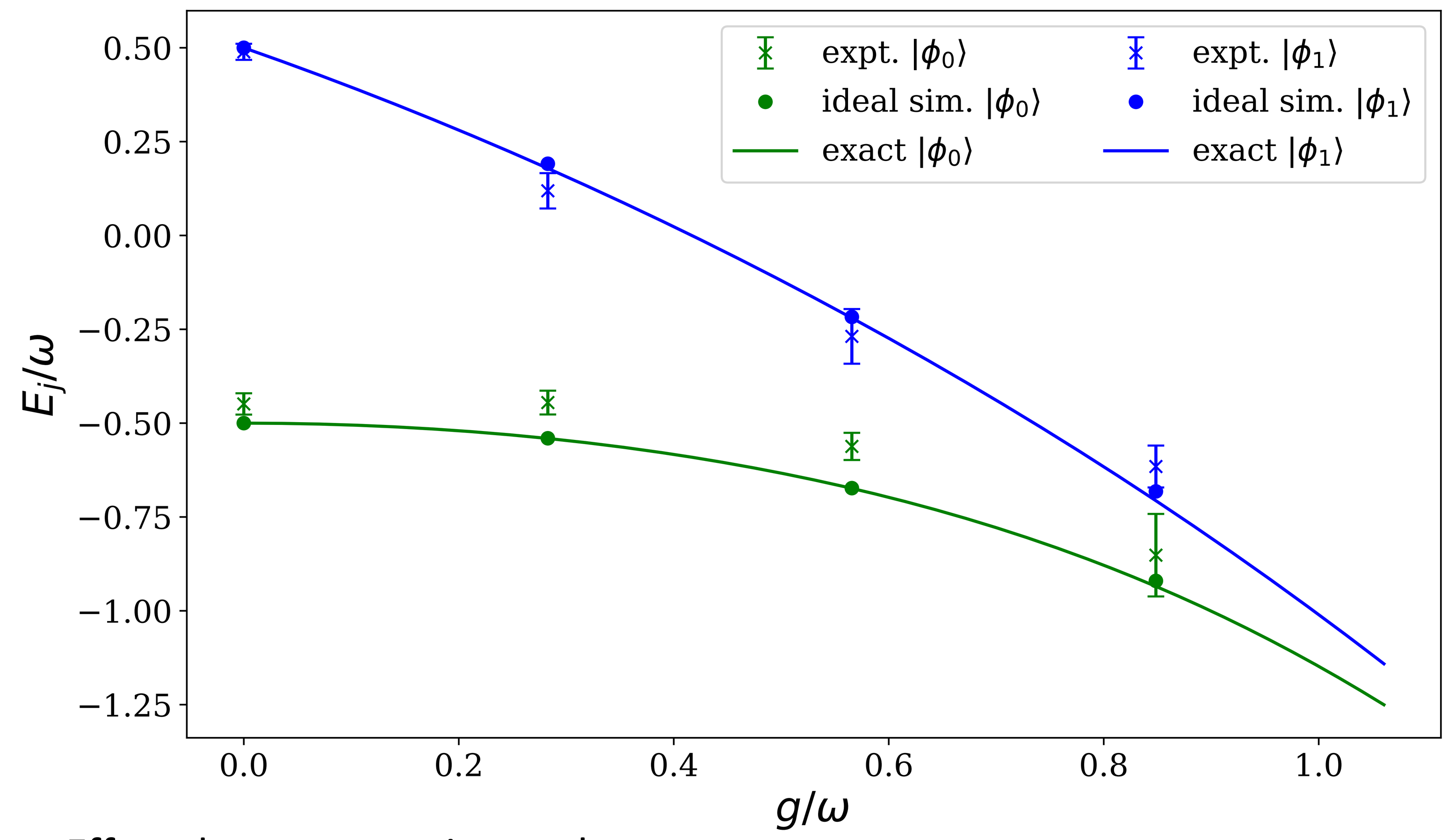
Rabi model – one of the simplest model of light-matter interaction

$$H = \omega a^\dagger a + \frac{\Omega}{2}\sigma_z + \frac{g}{2}(a^\dagger + a)\sigma_x$$

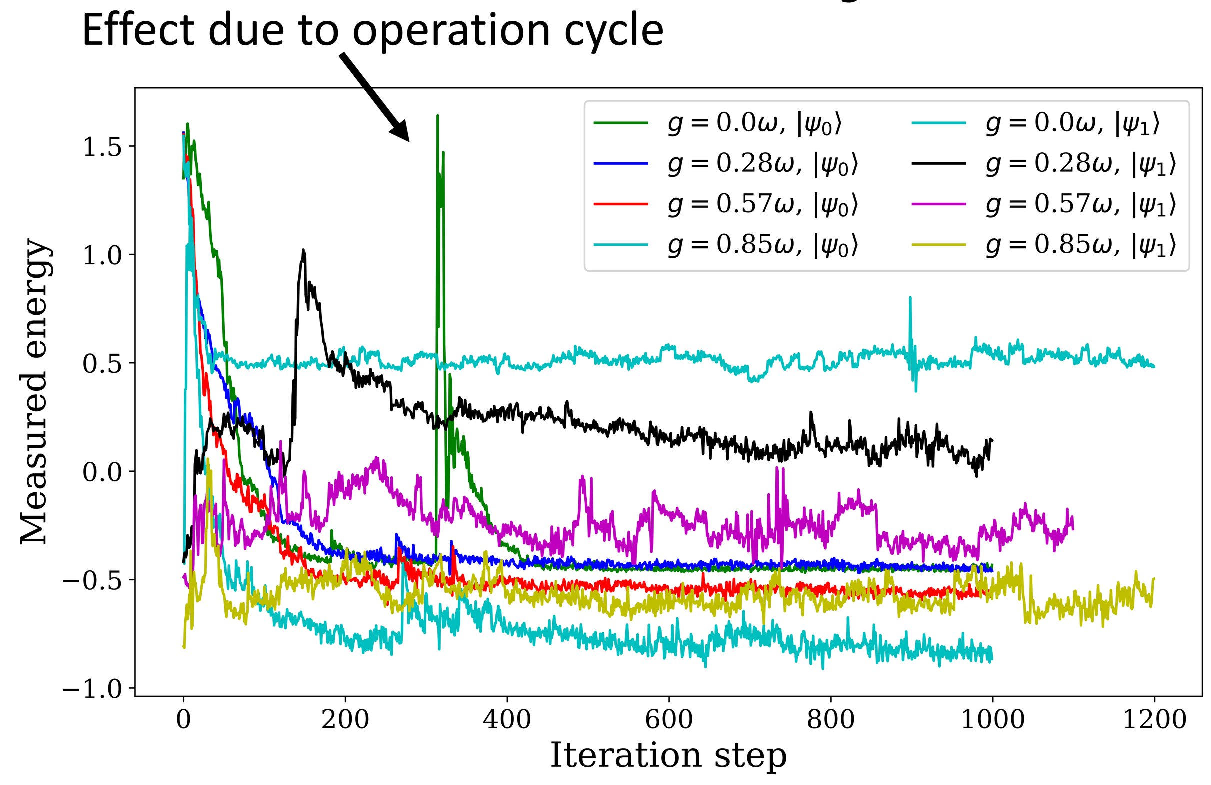
The photon mode (truncated to up to three photons) is encoded using two qubits



- Ground state and first-excited state eigenenergies
- Narrowing of energy gap with increasing coupling g
- Discrepancy between experimental result and exact solution: hardware noises and sampling errors



Effect due to operation cycle



Noisier first-excited state optimization due to overlap measurement

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