A universal quantum processor based on an optical tweezer array

Caltech

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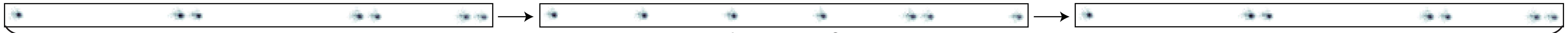


Dynamical array reconfiguration

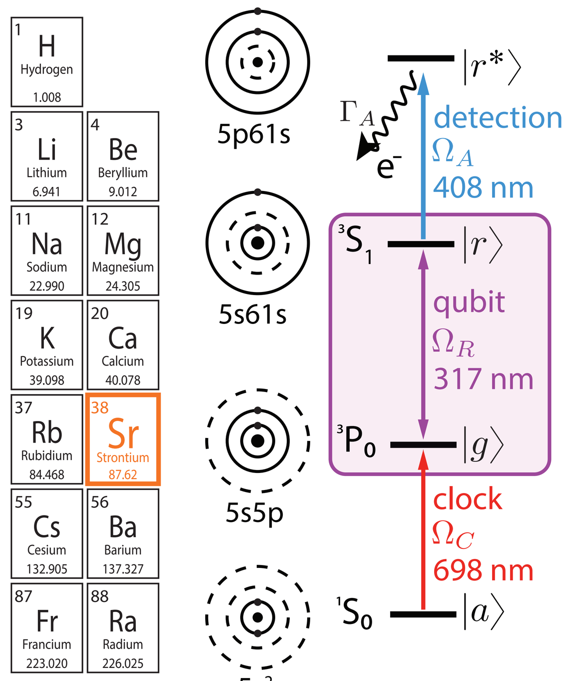
Strontium Rydberg physics

Alkaline-earth element with two valence electrons.

Low-lying optical transitions for imaging and cooling, as well as a metastable "clock" state for information storage.

High-lying Rydberg state which allows for controllable entanglement generation and many-body simulation.

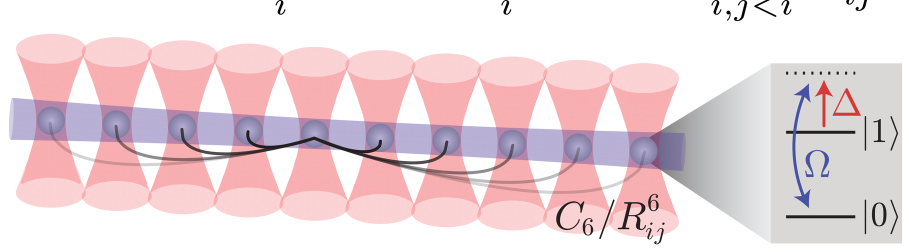
Rydberg qubit



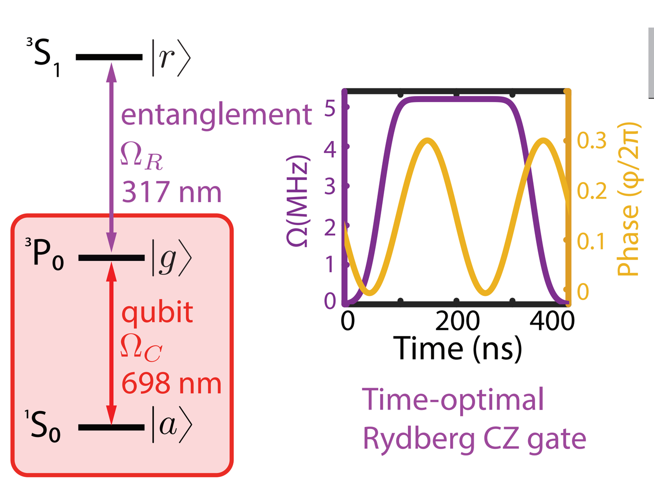
Operation	Fidelity
Rydberg π-pulse	>0.9995
Rydberg coherence	60 cycles
Rydberg detection	0.9996
Bell state generation	0.9985
Clock transfer	0.9995
Imaging survival	0.9997
Imaging detection	0.9996

Dynamics are governed by the Rydberg Hamiltonian

$$\hat{\mathcal{H}}(\Omega,\Delta,C_6)=\frac{1}{2}\Omega\sum_i \hat{\sigma}_x^i-\Delta\sum_i \hat{n}^i+C_6\sum_{i,j<i}\frac{1}{R_{ij}^6}\hat{n}^i\hat{n}^j$$



Clock qubit



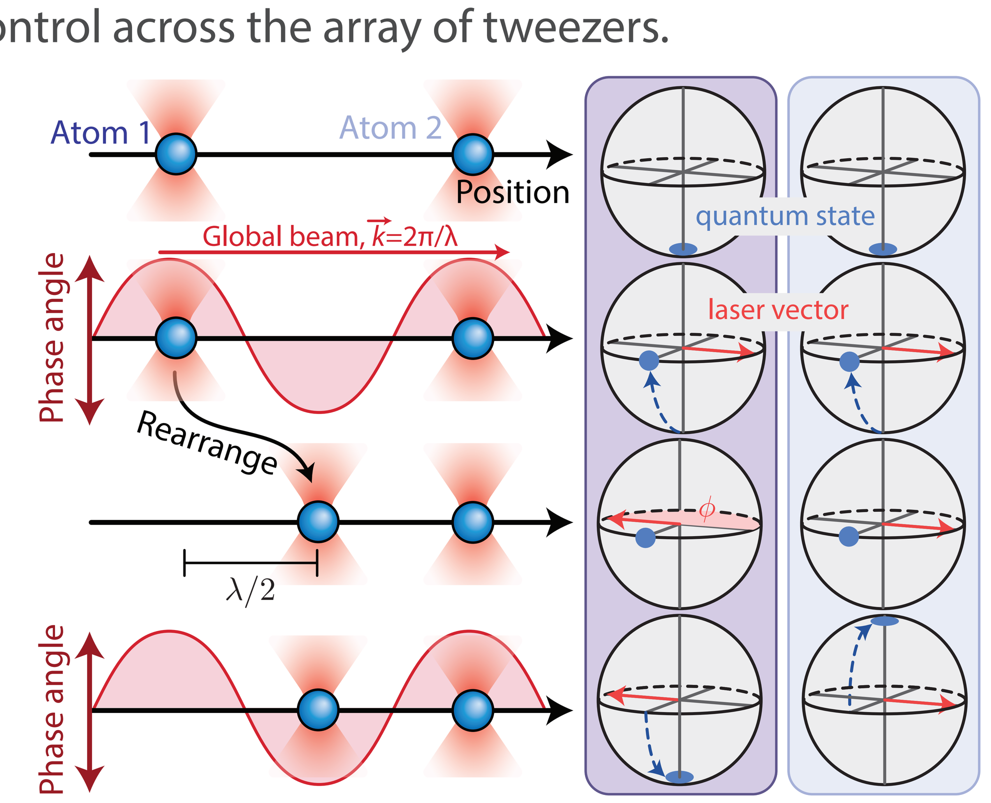
Time-optimal Rydberg CZ gate

Operation	Fidelity
Clock π/2-pulse	0.998
Single site addressing	0.998
Rabi coherence	50 cycles
Imaging fidelity	>0.9995
Bell state fidelity	0.976(raw) 0.989(SPAM)
CZ gate fidelity	0.997

Single-site addressing

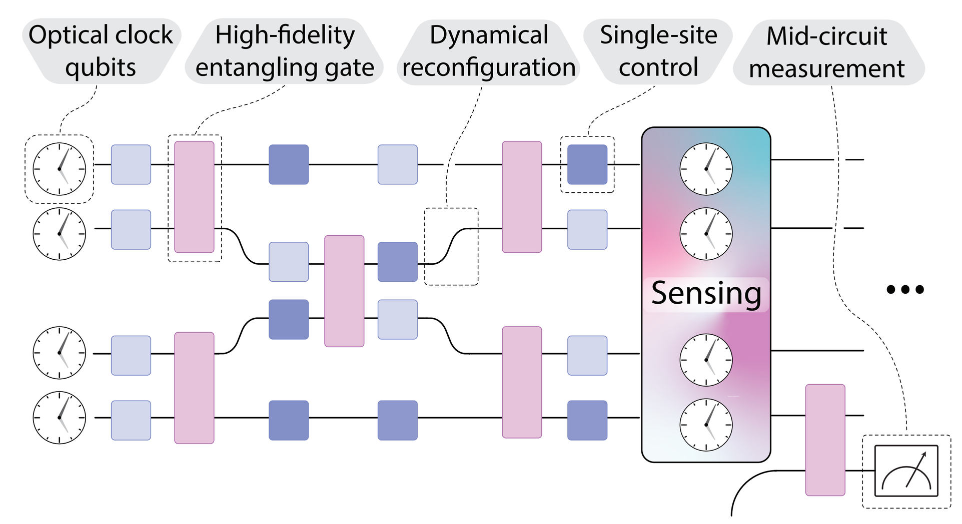
arXiv:2303.16885 (2023)

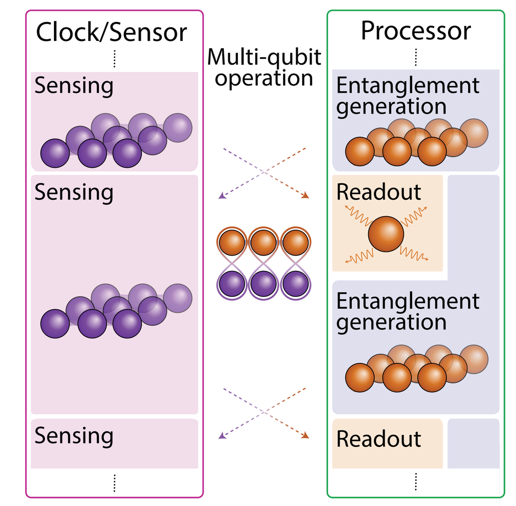
We achieve single-site addressing with individual motional control across the array of tweezers.



Universal quantum operations for tweezer clocks

arXiv: 2402.16220 (2024) and N06.00003 (Thursday) for more information

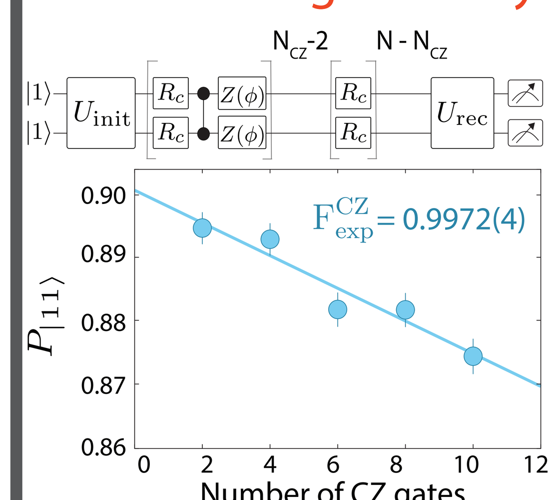




We demonstrate a scalable universal quantum processor based on optical clock qubits which is designed to perform any computational task and at the same time is a highly sensitive clock.

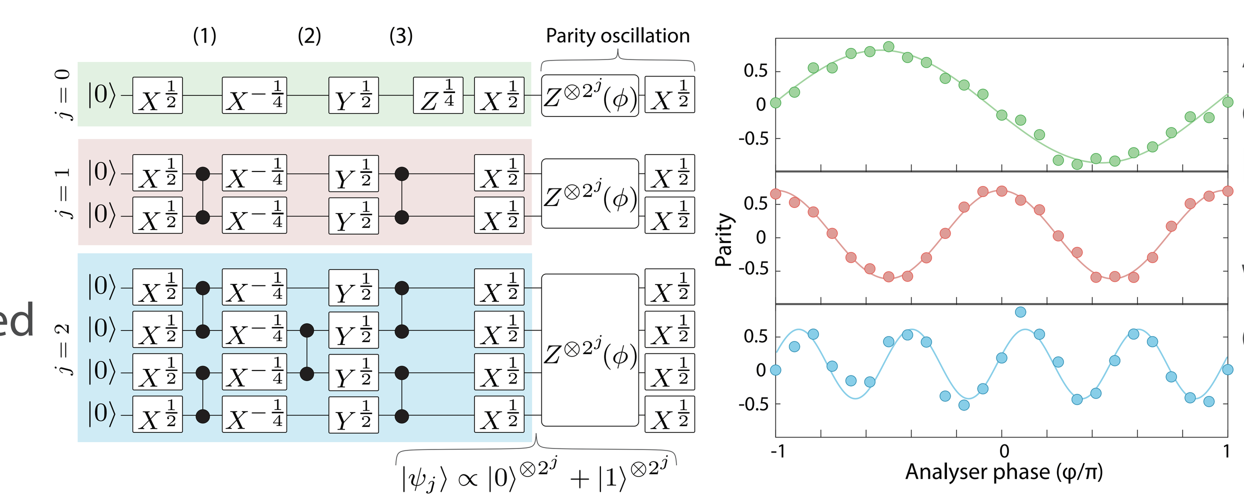
Our results further point to a modular device with distinct quantum processing and sensing modules, realizing a vision of a quantum computer connected to a high-precision sensor.

Record-high-fidelity CZ gate



We have a full error model showing that >0.999 fidelity can be achieved by near-term upgrade.

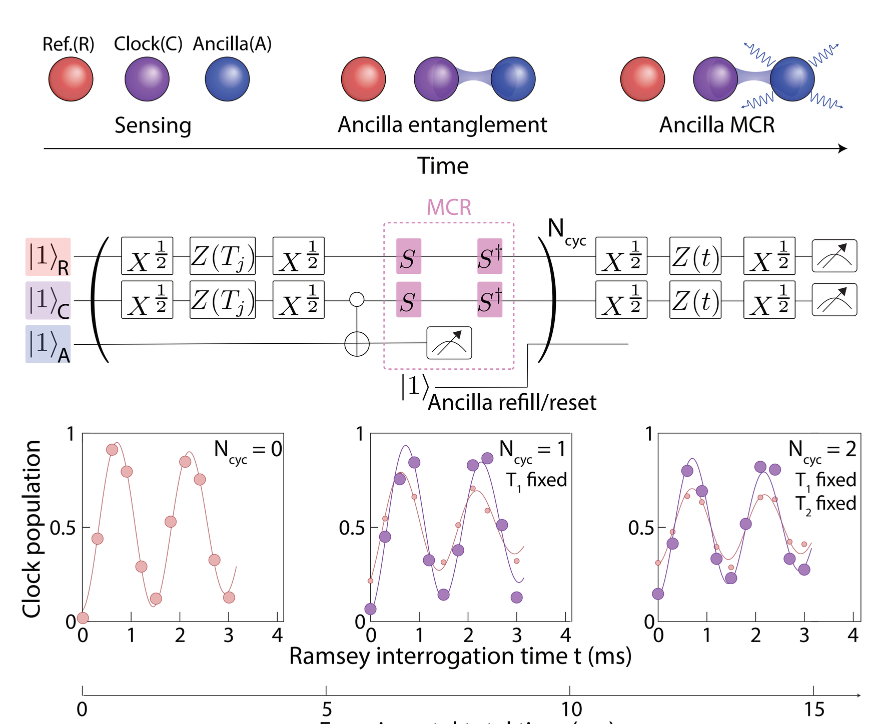
Simultaneous cascaded GHZ states generation



A cascade of GHZ states enables the Heisenberg limit accuracy.

We achieve a 4-qubit GHZ fidelity of 0.71(2).

Repeated ancilla-based quantum logic spectroscopy

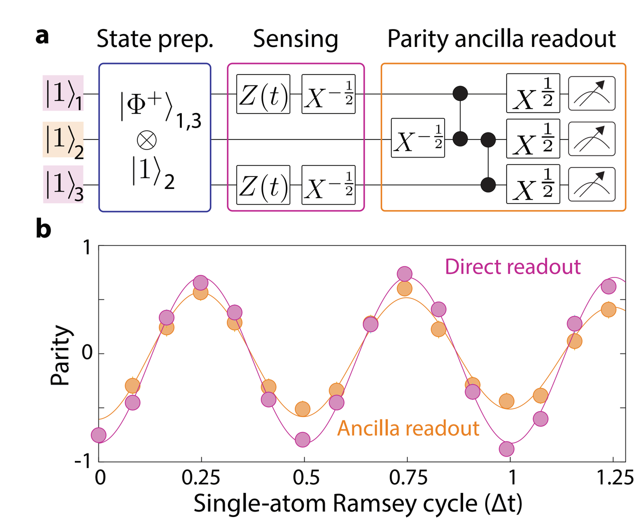


A non-destructive, indirect readout of an atom is realized by mapping its state onto an ancillary atom, followed by a readout of the ancilla.

Repeated rounds of QLS with minimal (2.9 ms) dead time, enabled by ancilla replacement.

We find improved contrast in the final measurement round as compared to reference clock atoms.

Weight-2 parity readout



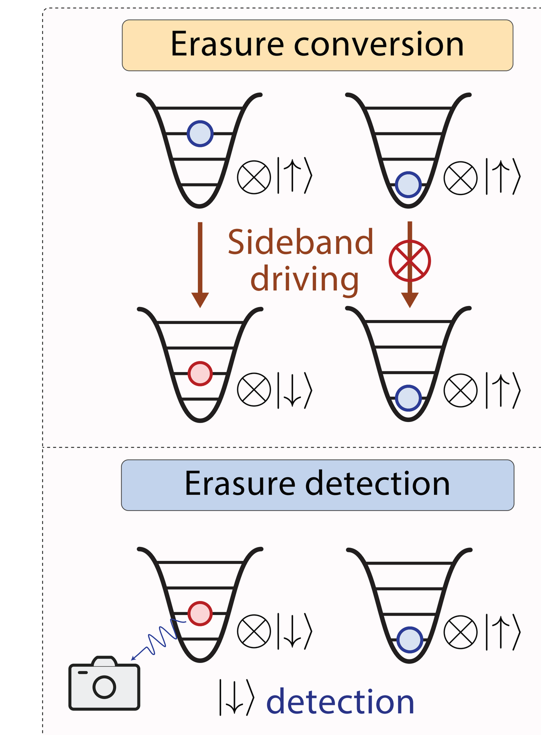
A parity signal from an entangled quantum register can be read out via a single ancilla qubit. Also central to QEC!

Toolbox for clock qubits

arXiv: 2311.15580 (2023) and N07.00008 (Thursday)

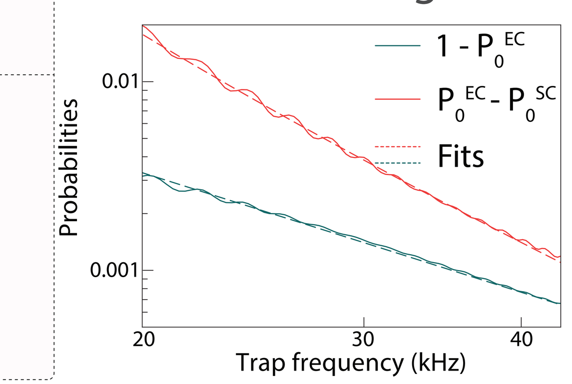
We demonstrate how motional degrees of freedom in optical tweezers can be used as quantum information carrier.

Erasure conversion, detection, and cooling

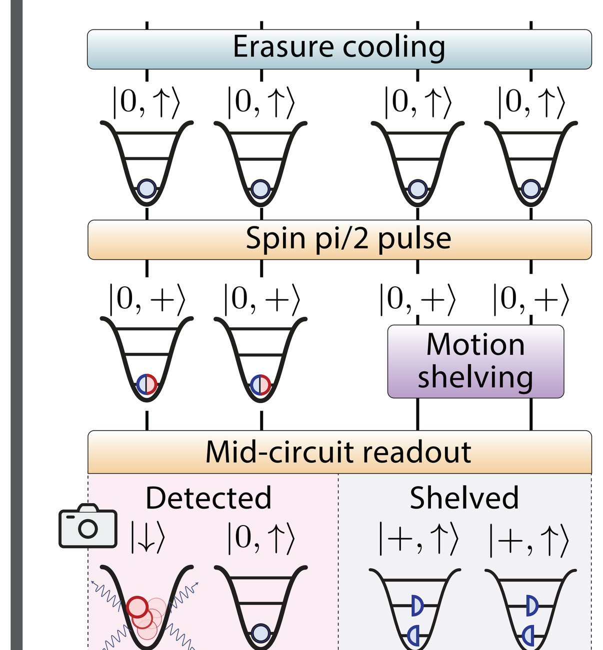


Temperature in tweezer array affects operation fidelities. We work in the sideband resolved regime.

Our protocol outperforms traditional cooling.



Mid-circuit readout



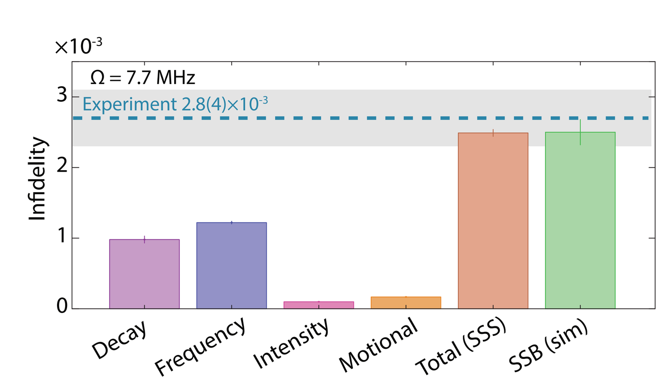
We perform spin-motion transduction to store quantum information in motional states and protect certain atoms from imaging.

This enables mid-circuit read-out, which is central to quantum error correction as well as certain metrology schemes.

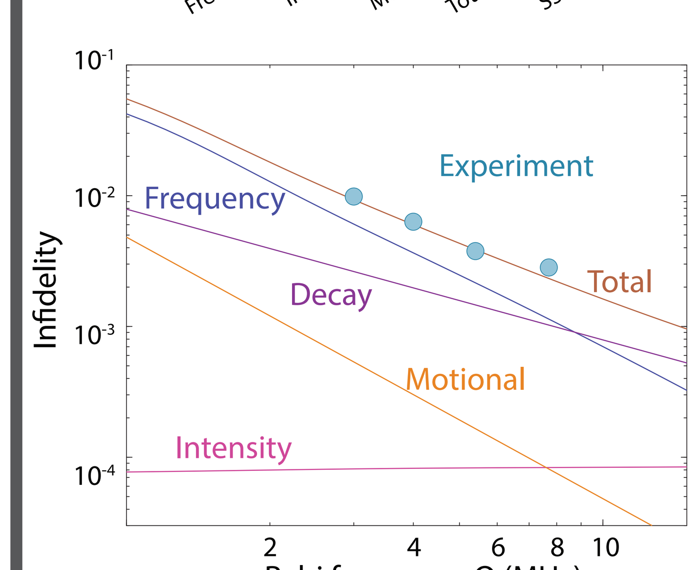
We also demonstrate the motional entanglement and simultaneous hyper-entanglement of both motion and electronic states. (Read our paper if interested!)

Scaling law of quantum gate fidelity

Manuscript in preparation; N07.00008 (Thursday) for more information

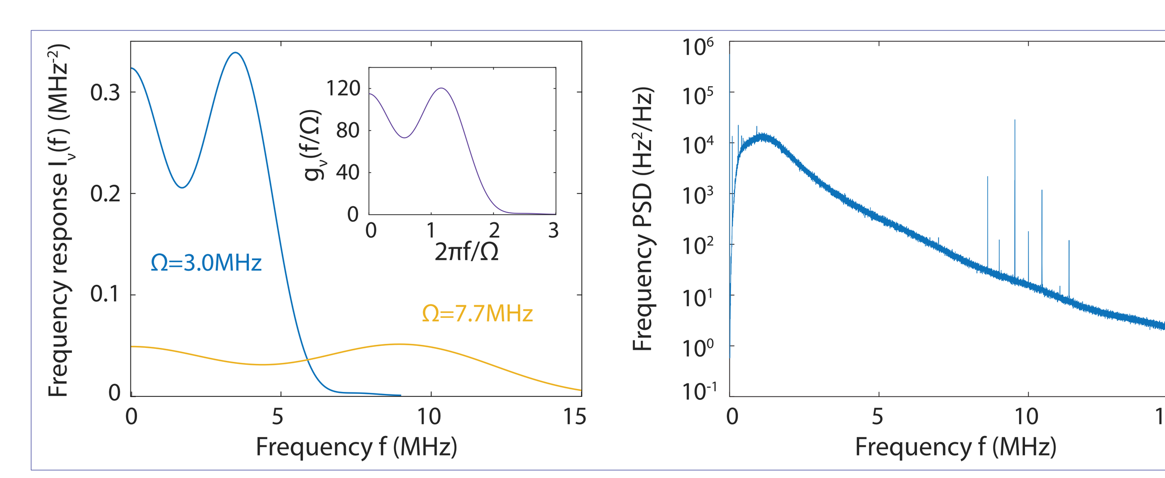


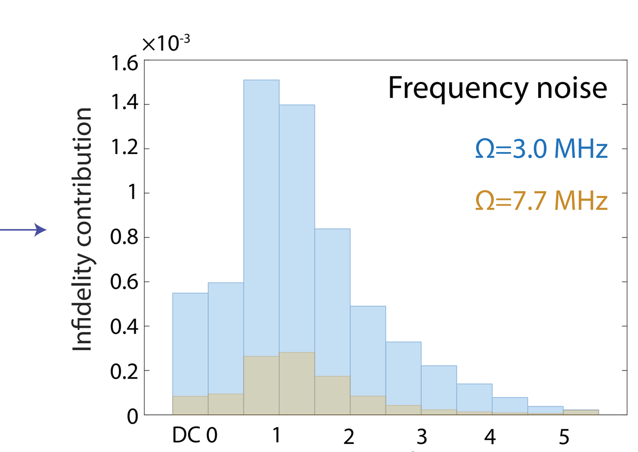
We have a full error model that identifies dominant error sources and accurately predicts the CZ gate fidelity.



For each error source, the gate infidelity has a power-law-like dependence on the Rabi frequency.

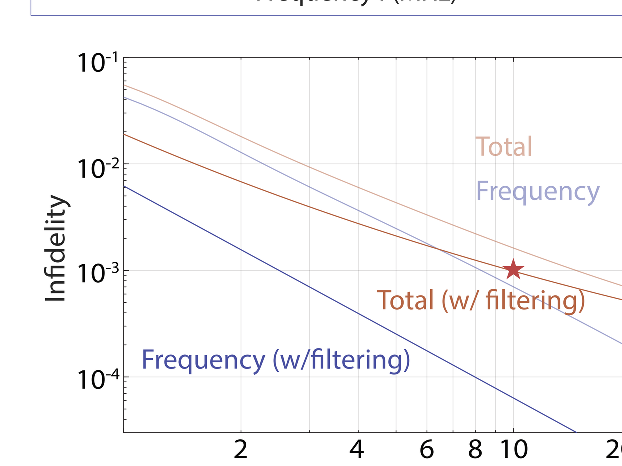
It is favorable to perform the gate faster to achieve higher fidelity.





An efficient prediction of the gate fidelity from the laser noise is enabled by the linear response theory.

The sensitivity to laser noise PSD is characterized by a gate-dependent response function.



With a modest increase in Rabi frequency and cavity filtering the frequency noise with the current cavity, we can readily achieve fidelity >0.999.

Acknowledgement

DARPA