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Two-qubit Quantum Logic Gates for Neutral Atoms Based on the Spin-Flip Blockade

Sandia National Laboratories

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APS DIVISION of ATOMIC, MOLECULAR and OPTICAL PHYSICS
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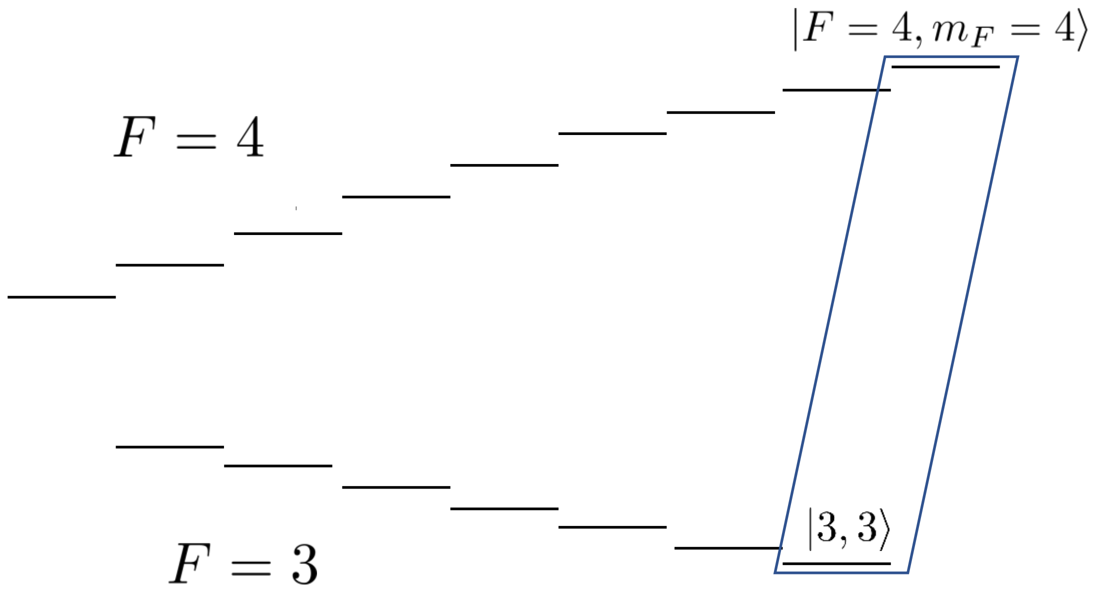
Cesium system

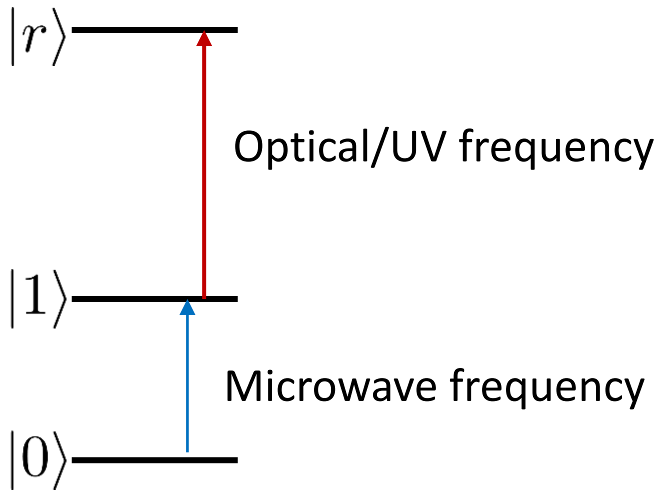
Motivation: Designing a high fidelity Entangling gate for Neutral atom qubits

Entanglement achieved via Rydberg states

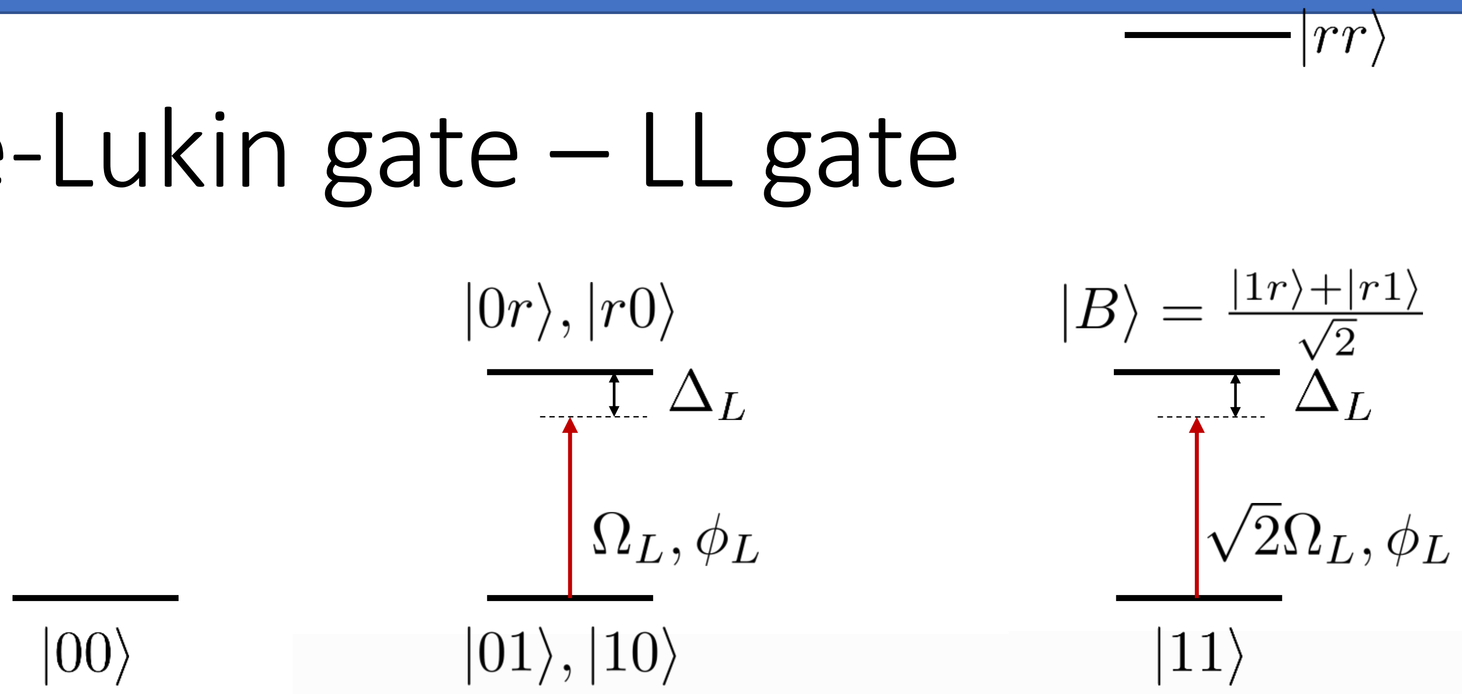
$$H_{int} = V_{rr}|rr\rangle\langle rr|$$



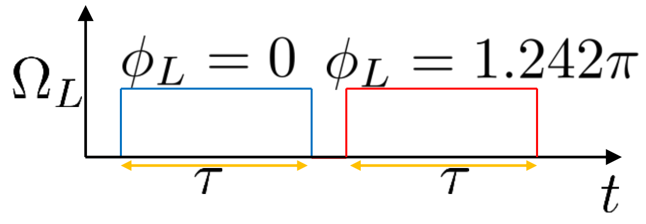
Cs $6s$



Levine-Lukin gate – LL gate

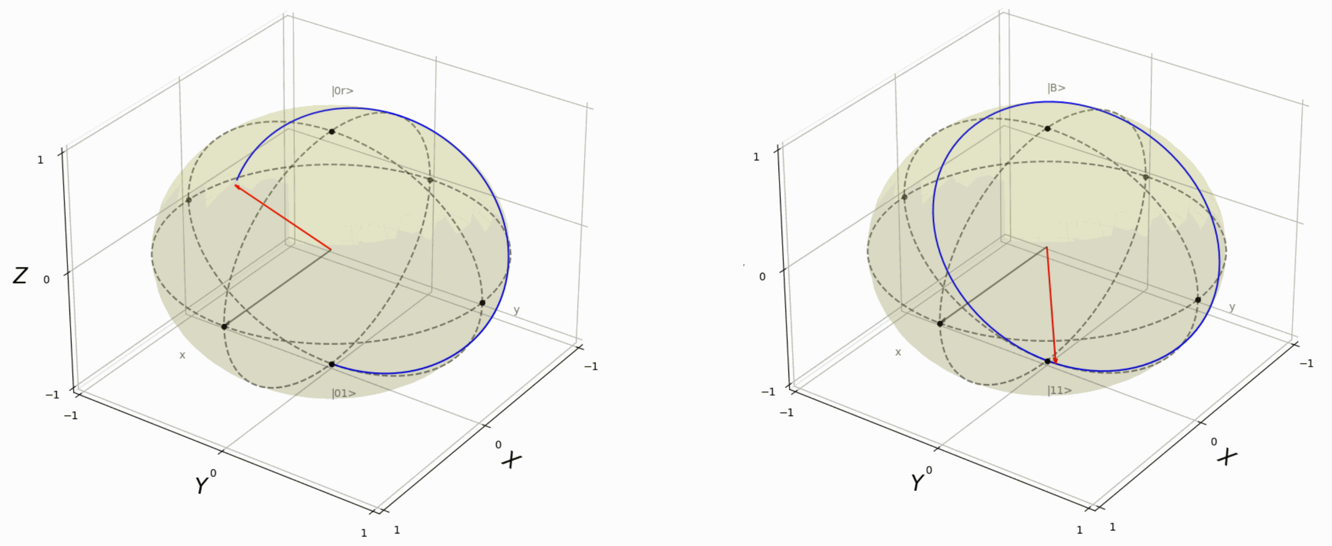


$$|00\rangle \to |00\rangle$$
$$|01\rangle \to e^{i\alpha}|01\rangle$$
$$|10\rangle \to e^{i\alpha}|10\rangle$$
$$|11\rangle \to e^{i\beta}|11\rangle$$



$$\sqrt{2}\Omega_L \tau = 2\pi$$

$$\Delta_L = 0.377\Omega_L \implies \beta - 2\alpha = \pi$$



Levine, Lukin et al; Phys. Rev. Lett. 123, 170503

nature physics

ARTICLES

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Entangling atomic spins with a Rydberg-dressed spin-flip blockade

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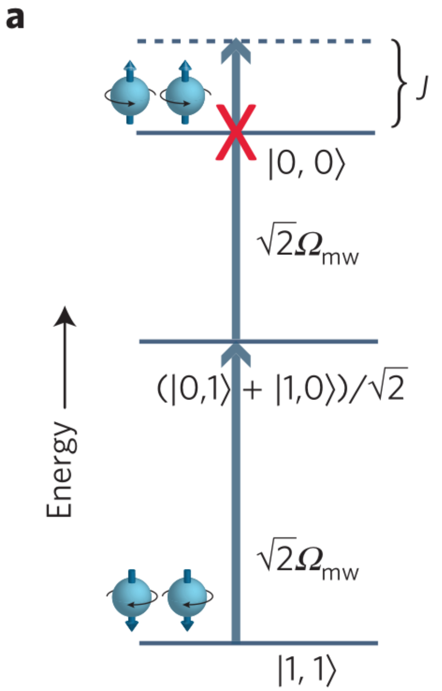
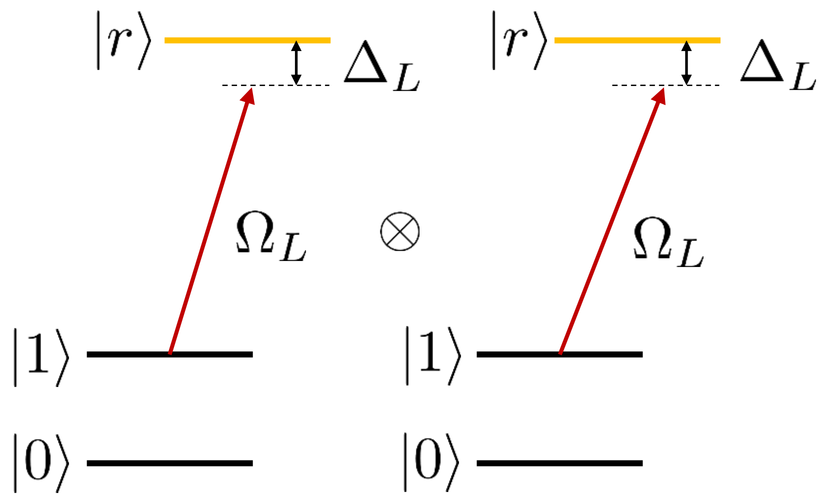
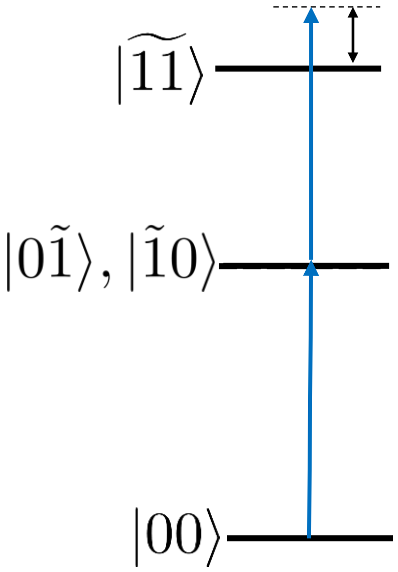




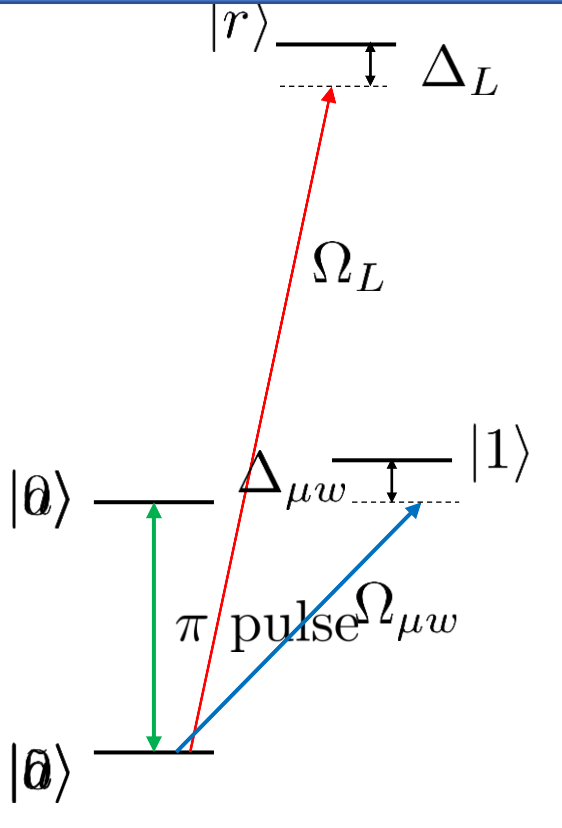
$$\Longrightarrow \quad \boxed{J = E^2_{LS} - 2E^1_{LS}}$$



LL gate in the hyperfine regime

$$H^1_{hf} = E_0|0\rangle\langle 0| + E_1|1\rangle\langle 1| + E_a|a\rangle\langle a|$$

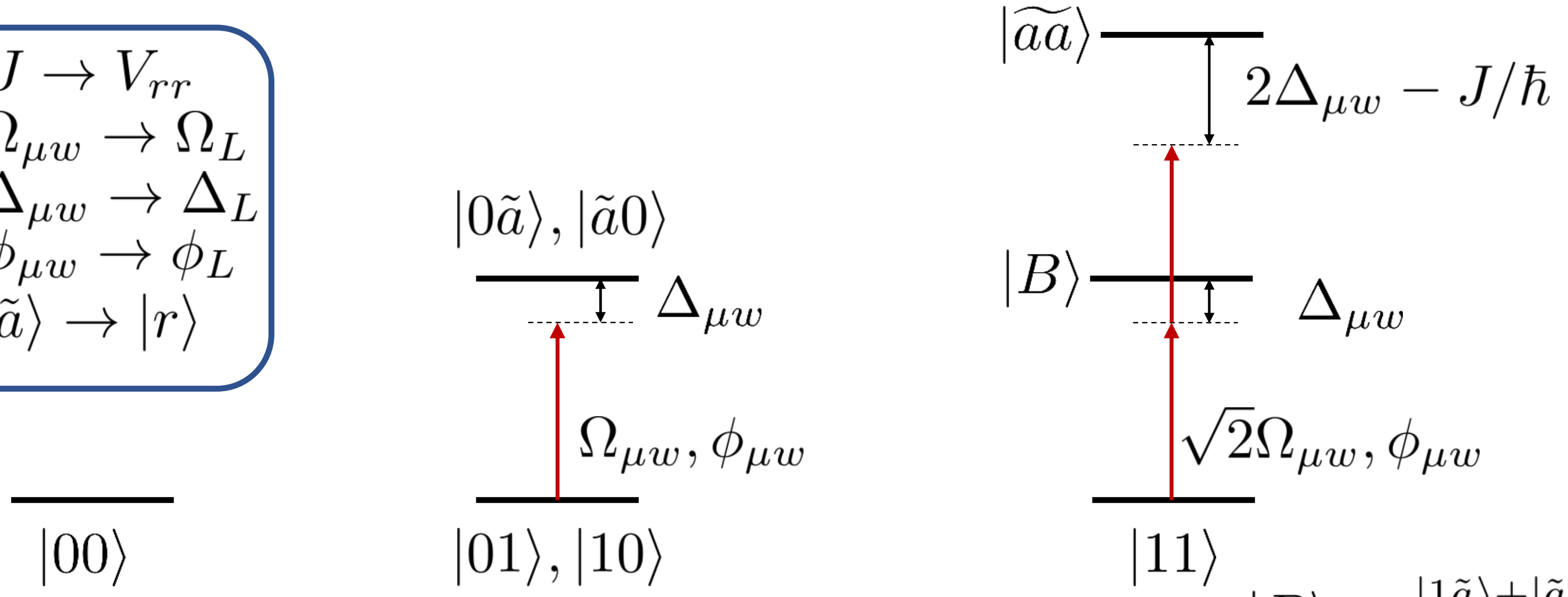
$$H_{hf} = H^1_{hf} \otimes \mathbf{1} + \mathbf{1} \otimes H^1_{hf} + J|\widetilde{aa}\rangle\langle\widetilde{aa}|$$



$$= \cos(\theta/2)|a\rangle + \sin(\theta/2)|r\rangle$$

$$\left(\tan\theta = \frac{\Omega}{-\Delta}\right)$$

$J \to V_{rr}$
$\Omega_{\mu w} \to \Omega_L$
$\Delta_{\mu w} \to \Delta_L$
$\phi_{\mu w} \to \phi_L$
$|\tilde{a}\rangle \to |r\rangle$



$$|B\rangle = \frac{|1\tilde{a}\rangle + |\tilde{a}1\rangle}{\sqrt{2}}$$

Jandura, Pupillo; arXiv:2202.00903 (2022)

$$J \to V_{rr}$$
$$\Omega_{\mu w} \to \Omega_L$$
$$\Delta_{\mu w} \to \Delta_L$$
$$\phi_{\mu w} \to \phi_L$$
$$|\tilde{a}\rangle \to |r\rangle$$

J is much smaller than V

If we aim for perfect blockade, our gates become much slower

Is there a way around this?

Yes! Quantum optimal control is the answer!

Optimal Quantum control for the LL gate

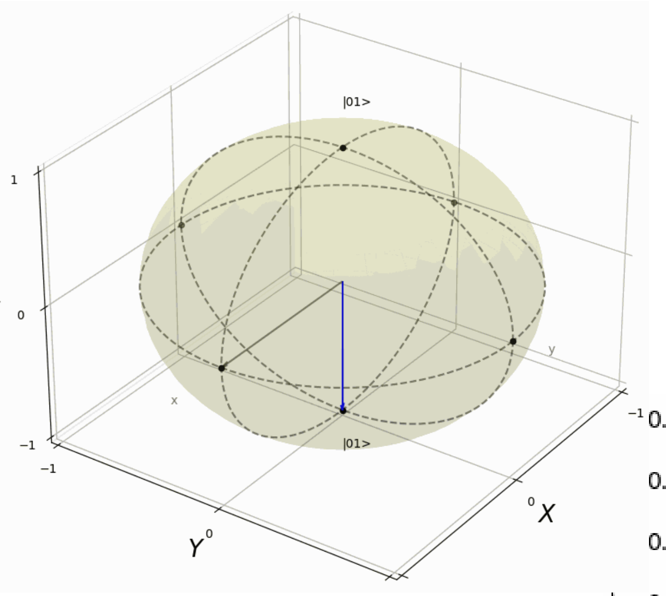
We use Gradient Ascent Pulse Engineering (GRAPE)

We maximize $\mathcal{F}$ by using $\vec{\nabla}_{\vec{\phi}}\mathcal{F}$.

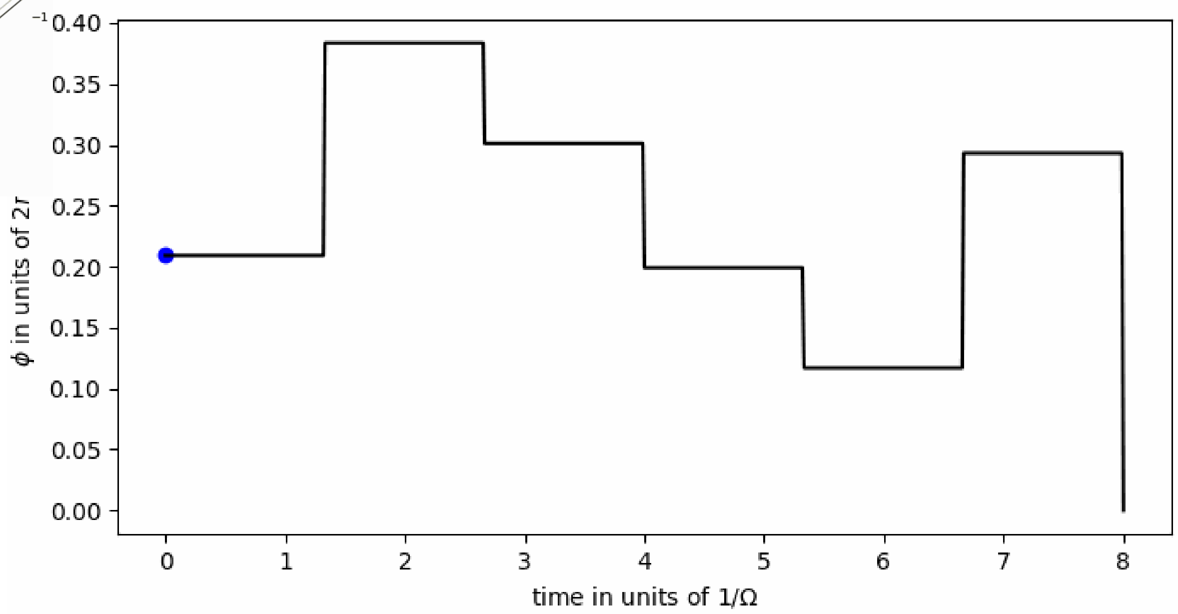
$$\mathcal{F} = \mathrm{Tr}((\mathrm{CZ})^{\dagger}U[\phi(t)])$$

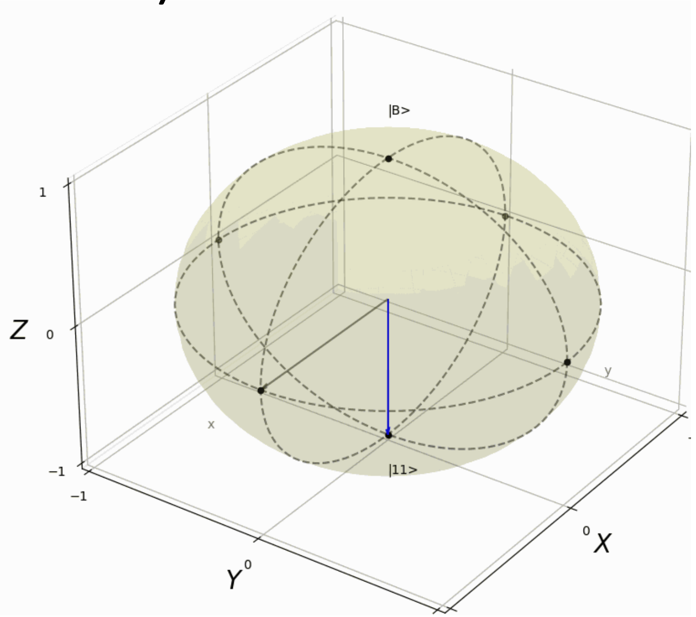
$$\Delta_L = 0, \Omega_L = 1$$

$$\vec{\phi} = (\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6)$$



$$|01\rangle \rightarrow e^{i\phi_1}|01\rangle$$

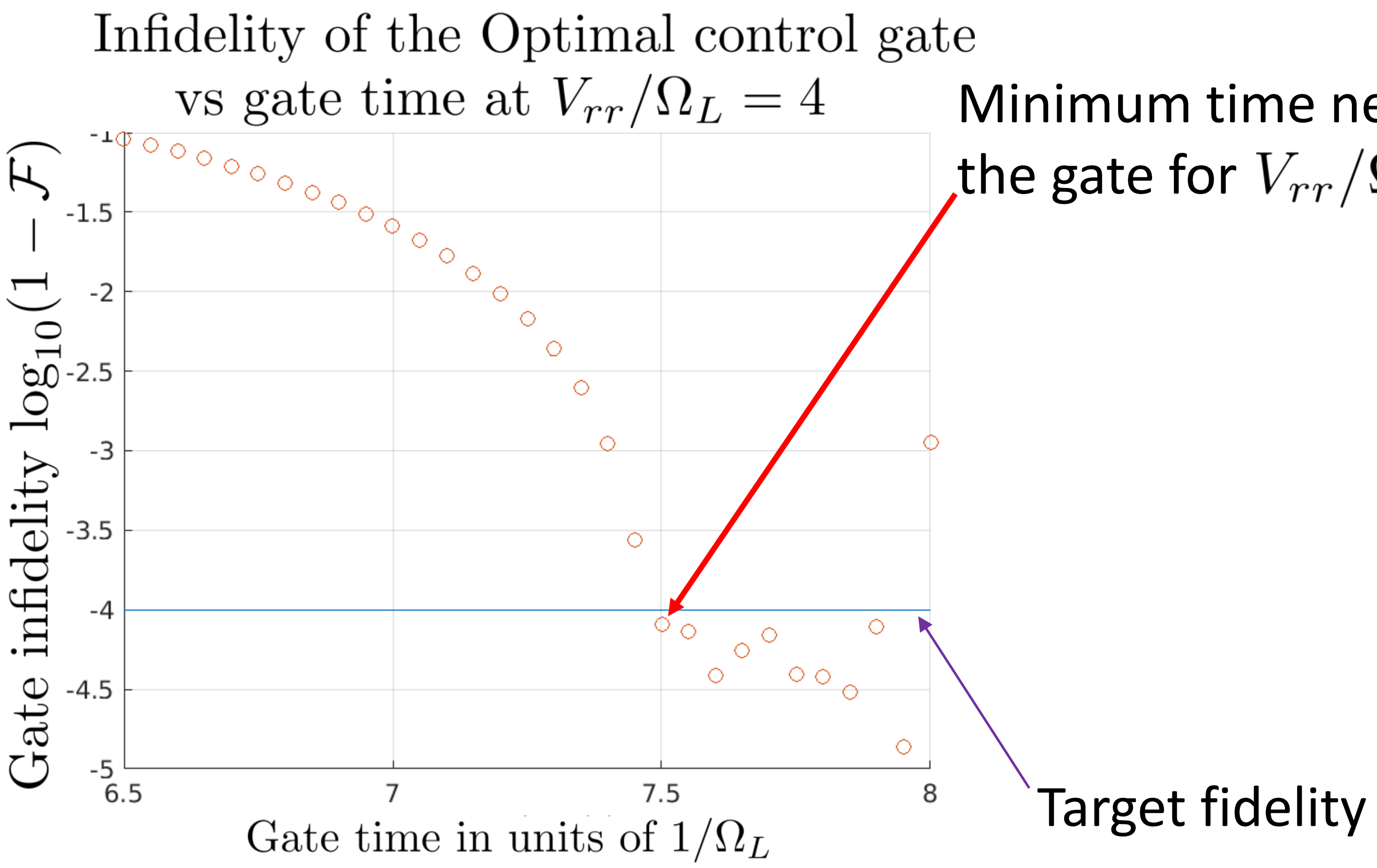




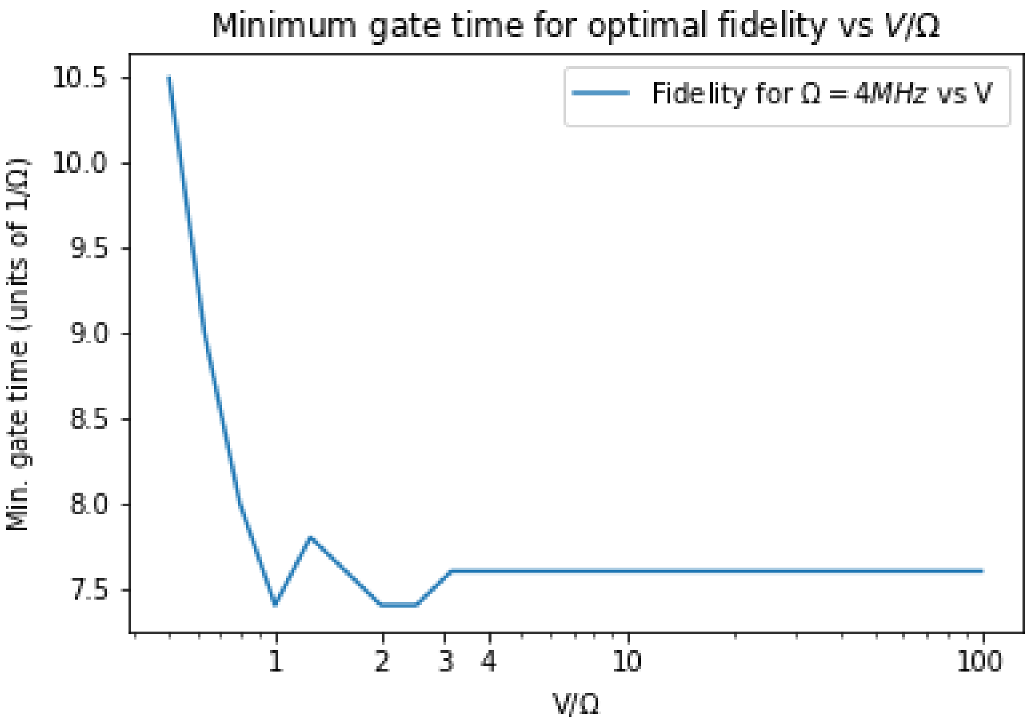
$$|11\rangle \rightarrow e^{i\phi_2}|11\rangle$$

$$\phi_2 - 2\phi_1 = \pi$$

Quantum speed-limit



Some counterintuitive results!



Imperfect blockade doesn't slow down your gate too much! In fact, it can make it faster!

$$H = \frac{\Omega}{2}(\sigma_\phi^1 + \sigma_\phi^2) + \frac{V_{rr}}{2}(\sigma_z^1 \otimes \sigma_z^2 + \sigma_z^1 + \sigma_z^2)$$

Known result from Spin Quantum control!

$$J = \omega(J_x \cos\phi + J_y \sin\phi) + \kappa J_z^2$$

The fastest state preperation times arise when $\kappa \sim \Omega$.

-The cost: More population is pumped into $|rr\rangle$

Tunability of interaction strength

By changing our dressing parameters, Δ_L, Ω_L
We can change J and the Rydberg character of the dressed states

$$P_{\tilde{a}} = |\langle r|\tilde{a}\rangle|^2$$

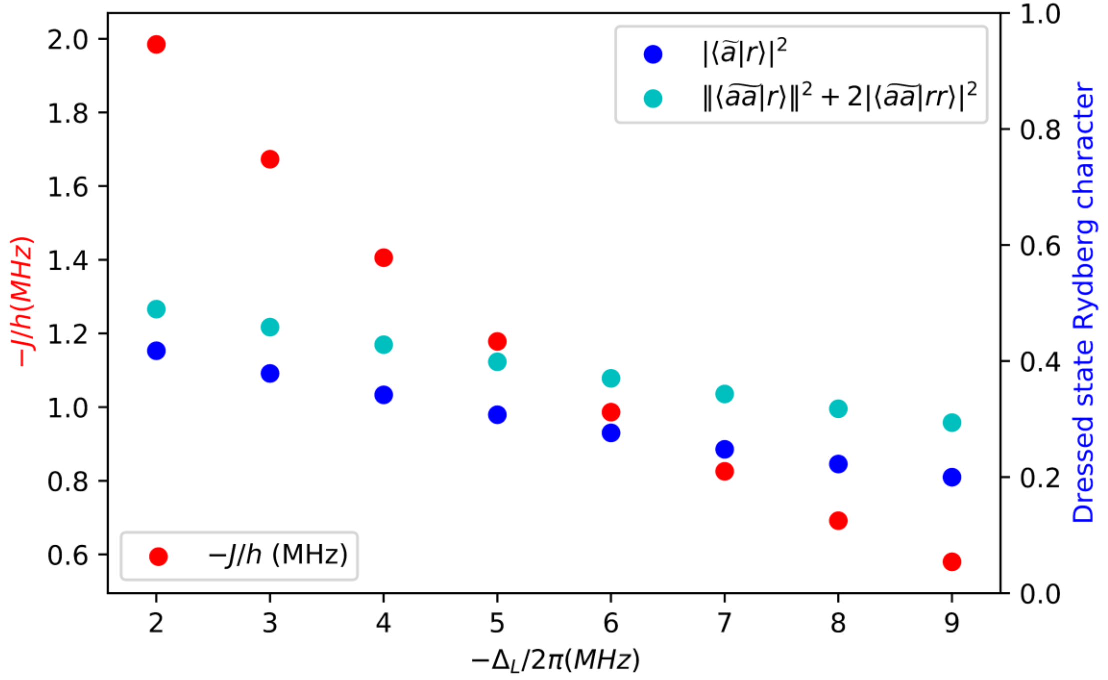
$$P_{\widetilde{aa}} = \|\langle r|\widetilde{aa}\rangle\|^2 + 2|\langle rr|\widetilde{aa}\rangle|^2$$

$$\Gamma_{\tilde{a}} = P_{\tilde{a}}\Gamma_r$$

$$\Gamma_{\widetilde{aa}} = P_{\widetilde{aa}}\Gamma_r$$

We can choose between a stronger interaction strength vs a weaker decay!

$$\Omega_L/2\pi = 12MHz, V_{rr}/2\pi = -40MHz$$



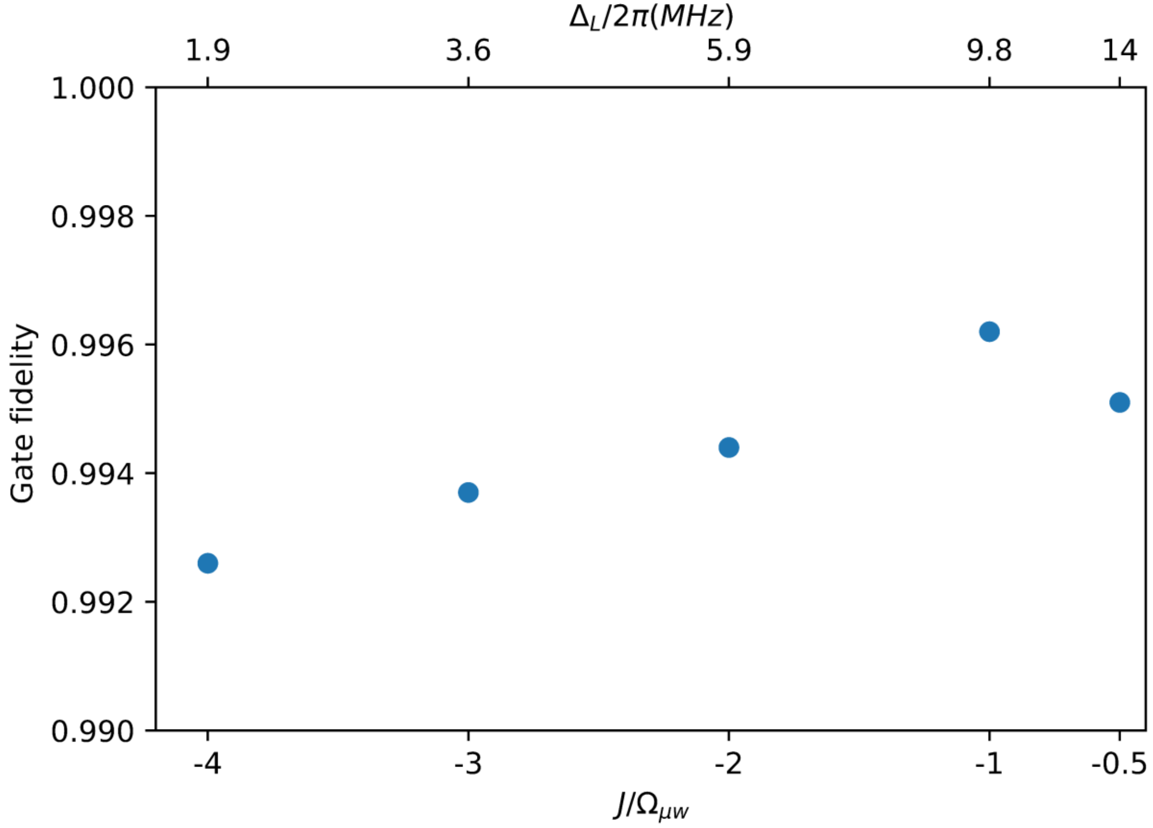
Limitations and usefulness

- One big limitation here: $J/2\pi \sim 1MHz$

$$V_{rr}/2\pi \sim 20 - 100MHz$$

$$\Omega_L/2\pi = 12MHz, V_{rr}/2\pi = -40MHz$$
$$\Omega_{\mu w}/2\pi = 0.5MHz$$

But hey, it's fine if $J/\Omega_{\mu w}$ is small!



Also microwaves are slower than Lasers!

$$\Omega_{\mu w} < \Omega_L$$

Summary and outlook

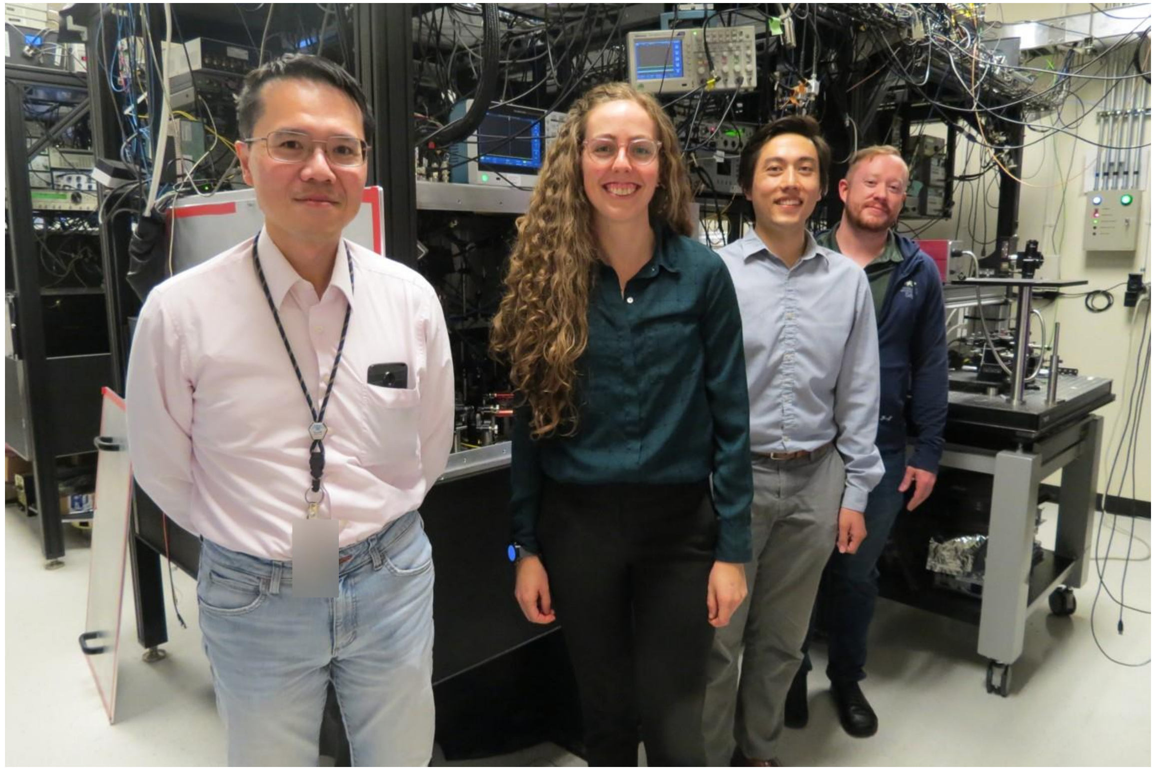
- Imperfect blockade is not a limitation, in fact it might be an advantage.
- Entangling protocols can be implemented in the microwave regime, and dressing can help fully exploit finite and weak blockades.

Other things I am not talking about here

- Adiabatic gates in the dressed regime
- Anti-blockade dressing for better fidelities

Collaborators

- UNM: Sivaprasad Omanakuttan and Ivan Deutsch.



- Sandia Collaborators: Yuan-Yu Jau, Matt Chow, Bethany Little.

Thank you for your attention!