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Quantum Information Processing with Trapped Rydberg Ions

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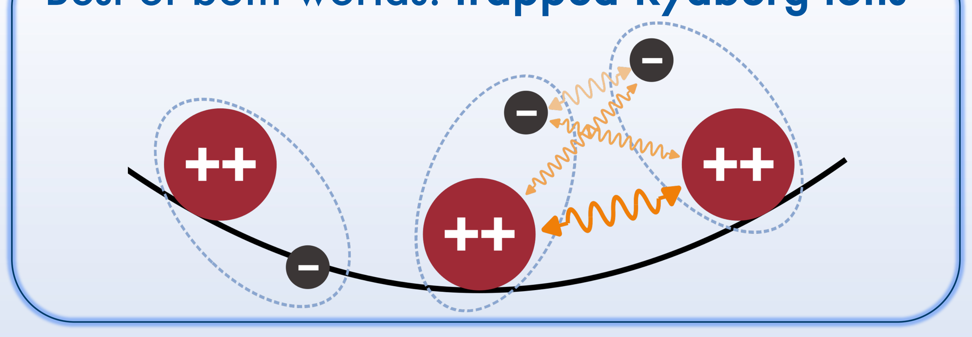
ABSTRACT

Combining the strong, long-range interactions of cold Rydberg atoms with the controllability of trapped ions, trapped Rydberg ions provide a promising platform for scalable quantum information processing. As demonstrated in a breakthrough experiment [1], microwave dressing of Rydberg states induces permanent rotating dipole moments leading to strong interactions between highly excited ions. Due to the separation of timescales, the fast electronic dynamics of Rydberg ions decouple from the slower motional modes of the linear Coulomb crystal, which typically mediate entangling gates in ground-state ion systems. Therefore, Rydberg ions enable significantly faster gate operations. We demonstrate how the unique properties of trapped Rydberg ions can be exploited to realize fast and high-fidelity entangling gates, along with the associated challenges and strategies to overcome them. Different types of gate protocols for two- and three-qubit entangling gates with trapped Rydberg ions are presented and sources of infidelity are analyzed.

Rydberg atoms
Strong dipole–dipole interactions allow realization of fast gates

Best of both worlds: trapped Rydberg ions

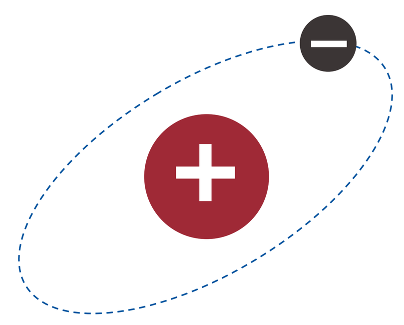


Trapped ions
One of the best controlled and isolated quantum systems

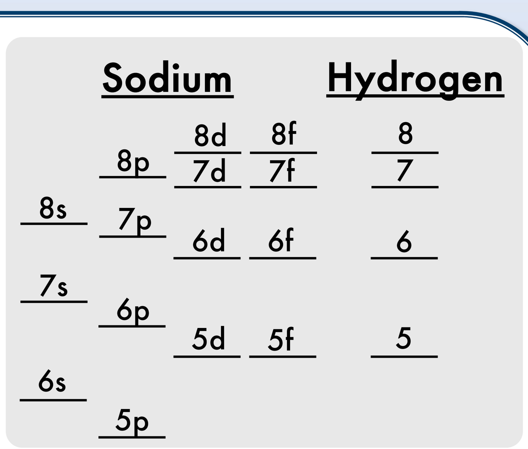
RYDBERG PHYSICS

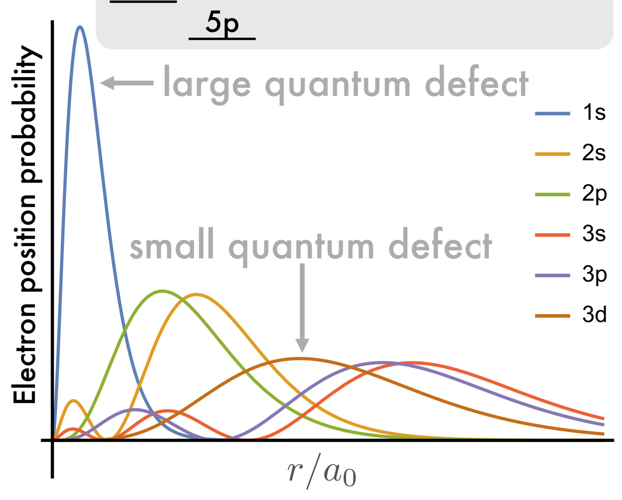
Binding energy $E = -\dfrac{Z^2 E_{\mathrm{Ryd}}}{(n-\delta_l)^2}$

quantum defect



Property	n-scaling	Z-scaling
Energy levels E_n	n^{-2}	Z^2
Level spacing ΔE_n	n^{-3}	Z^2
Radius $\langle r\rangle$	n^2	Z^{-1}
Dipole moment adjacent states d	n^2	Z^{-1}
Polarizability α	n^7	Z^{-4}
Radiative lifetime τ	n^3	Z^{-4}
Dipole–dipole interaction C_3, $V_{dd} \sim R^{-3}$	n^4	Z^{-2}
Van der Waals interaction C_6, $V_{vdW} \sim R^{-6}$	n^{11}	Z^{-6}





MICROWAVE DRESSING

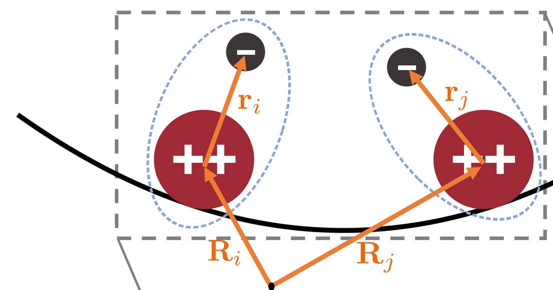
Dipole–dipole interaction $V_{ij} = \dfrac{1}{4\pi\epsilon_0}\dfrac{\mathbf{d}_i\cdot\mathbf{d}_j - 3(\mathbf{n}_{ij}\cdot\mathbf{d}_i)(\mathbf{n}_{ij}\cdot\mathbf{d}_j)}{|\mathbf{R}_{ij}|^3}$ $\quad \mathbf{n}_{ij} = \dfrac{\mathbf{R}_{ij}}{|\mathbf{R}_{ij}|}$

→ Without MW, no permanent dipole moments: $d_i = d_j = 0$

→ V_{ij} has no first order effect

→ Second order: vdW $\sim n^{11}R^{-6}Z^{-6} \sim$ kHz

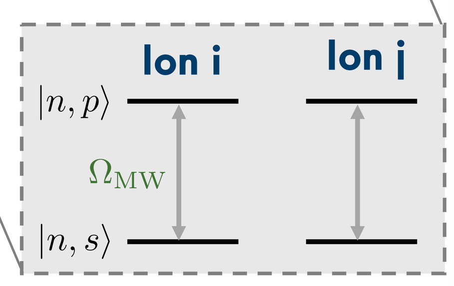
- Principal quantum number n is limited due to trap ionisation

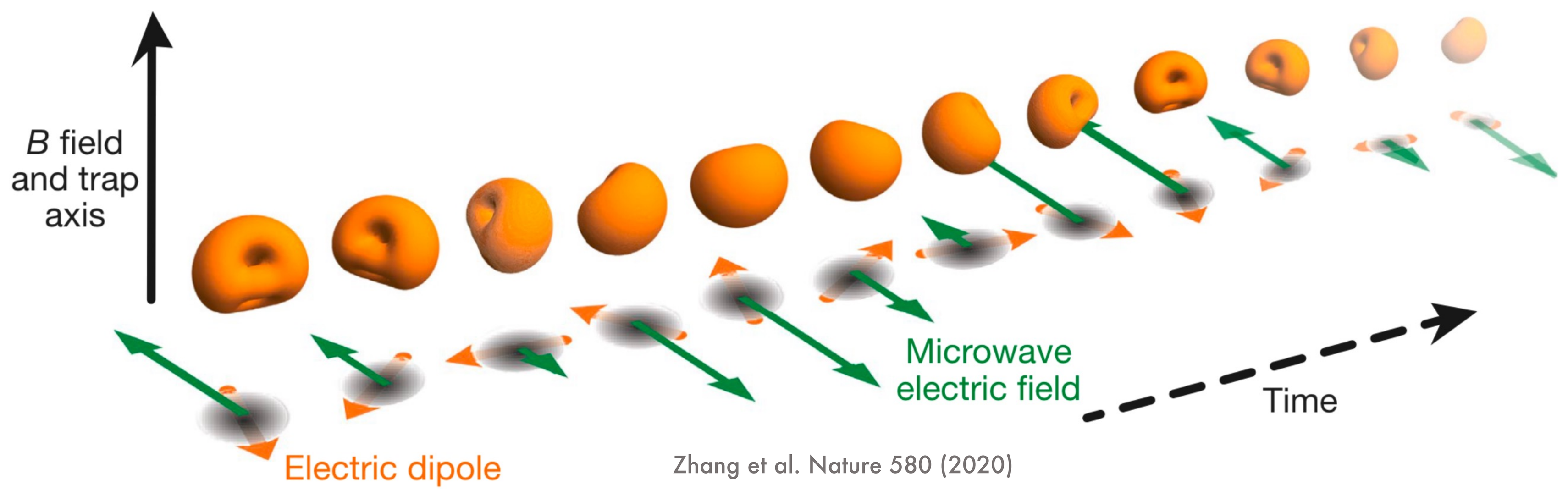


Dressed states: $|\mathcal{D}_\pm\rangle_{\mathrm{lab}} \sim |n,s\rangle \mp e^{-i\omega_{\mathrm{MW}}t}|n,p\rangle \sim$ ⊕ $\mp e^{-i\omega_{\mathrm{MW}}t}$ ⊕⊖

Interacting rotating dipole moments

$^{88}\mathrm{Sr}^+$: $R_{ij} = 2.3\,\mu\mathrm{m}$, $n = 46$
→ $V_{ij} \approx 2\pi \times 25.8$ MHz





Zhang et al. Nature 580 (2020)

PULSE OPTIMIZATION

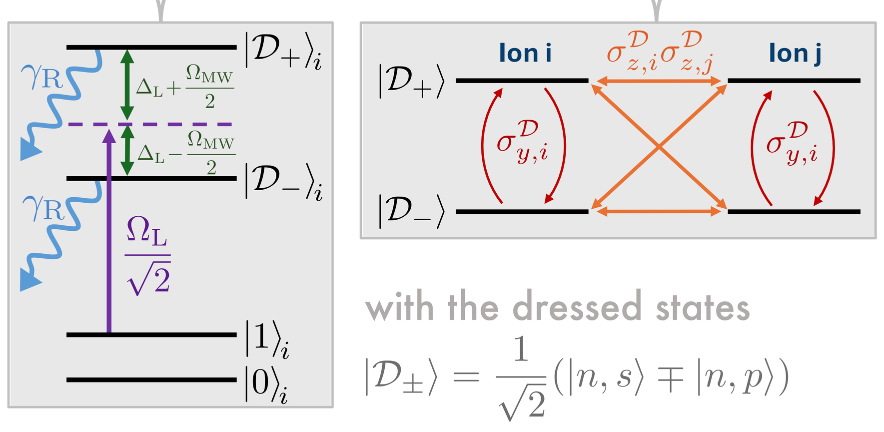
Hamiltonian

$$H = \sum_{i,\pm}\Big[\Big(\Delta_{\mathrm{L}} \pm \frac{\Omega_{\mathrm{MW}}}{2} - \frac{\mathrm{i}}{2}\gamma_{\mathrm{R}}\Big)|\mathcal{D}_\pm\rangle\langle\mathcal{D}_\pm|_i + \frac{\Omega_{\mathrm{L}}}{2\sqrt{2}}\big(|1\rangle\langle\mathcal{D}_\pm|_i + \mathrm{H.c.}\big)\Big] + \sum_{i\neq j}\frac{V_{ij}}{4}\big[\sigma^{\mathcal{D}}_{z,i}\sigma^{\mathcal{D}}_{z,j} + \sigma^{\mathcal{D}}_{y,i}\sigma^{\mathcal{D}}_{y,j}\big]$$

Pulses $\Omega_{\mathrm{L}}(t) = \boxed{\Omega_0}\sin^2\left(\dfrac{\pi t}{\tau}\right)$

$\Delta_{\mathrm{L}}(t) = \boxed{\delta_0} - \boxed{\Delta_0}\sin^2\left(\dfrac{\pi t}{\tau}\right)$

optimization parameters



Optimization

We optimize the pulse parameters to yield the highest fidelity $\mathcal{F} = |\langle\Psi_{\mathrm{I}}|U_{\mathrm{T}}U(\tau)|\Psi_{\mathrm{I}}\rangle|^2$ with $|\Psi_{\mathrm{I}}\rangle = |+\rangle^{\otimes N}$

with the dressed states $|\mathcal{D}_\pm\rangle = \dfrac{1}{\sqrt{2}}(|n,s\rangle \mp |n,p\rangle)$

Infidelity caused by decay $\bar{p}_{\mathrm{int}} \approx 1 - \left|1 - \dfrac{\gamma_{\mathrm{R}}}{2}\displaystyle\int_0^\tau \mathrm{d}t \sum_{i,\pm} p_\pm^{(i)}\right|^2$,

where $p_\pm^{(i)}$ is the population of $|\mathcal{D}_\pm\rangle_i$

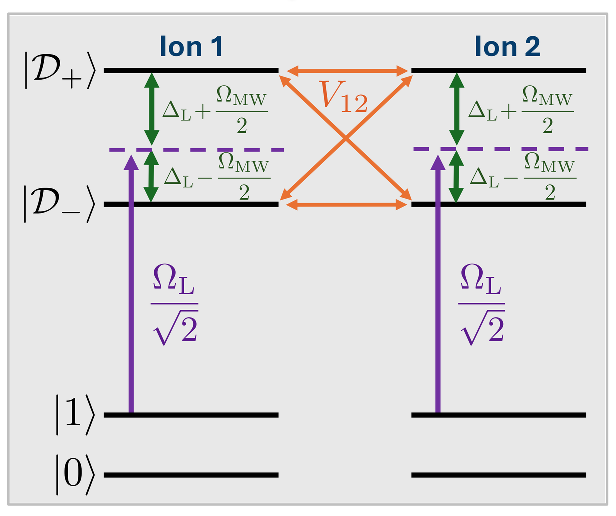
$U_{\mathrm{T}} = \mathrm{CZ}$, $N = 2$

$U_{\mathrm{T}} = \mathrm{CCZ}$, $N = 3$

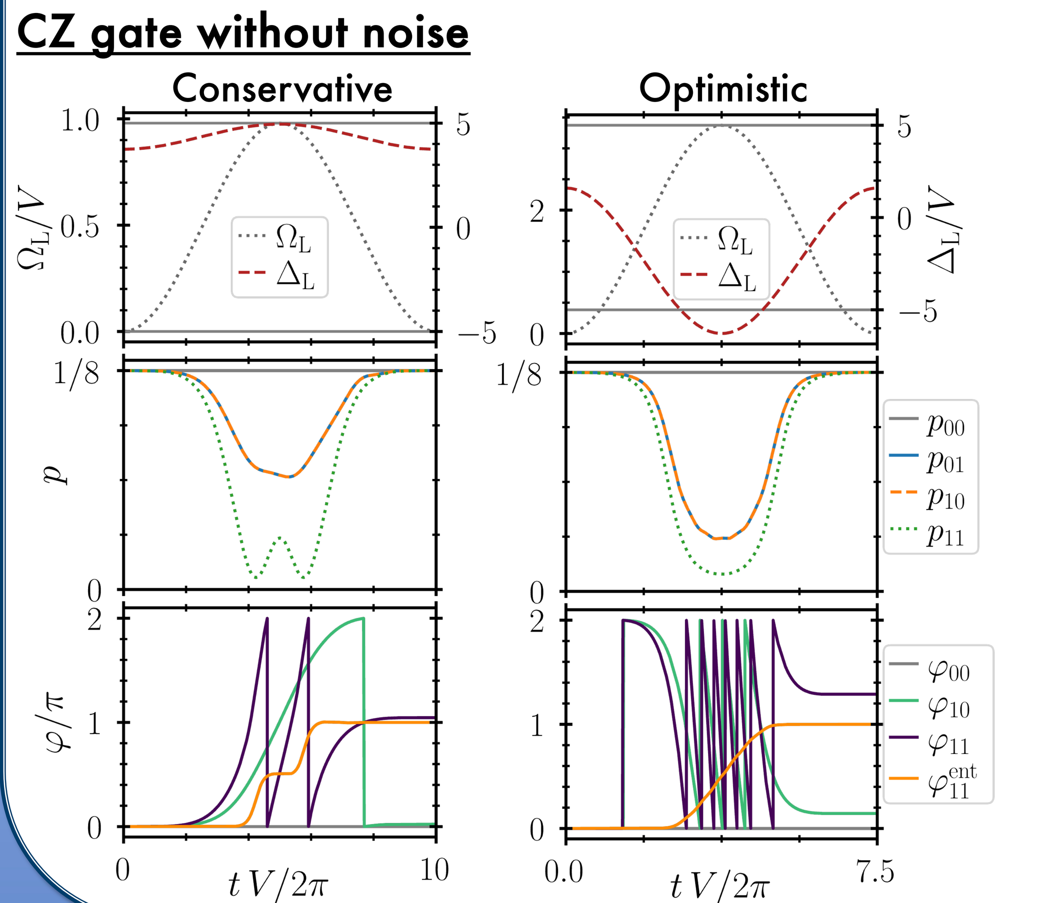
RESULTS: IMPLEMENTING CZ GATES

$\mathrm{CZ}: |ab\rangle \to (-1)^{ab}|ab\rangle$, $(a,b) \in \{0,1\}^2$

	Conservative	Optimistic
$V_{12} = V$	$2\pi \times 10$ MHz	$2\pi \times 25$ MHz
Ω_{MW}	$2\pi \times 100$ MHz	$2\pi \times 250$ MHz
Ω_0	$2\pi \times [0, 10]$ MHz	$2\pi \times [0, 100]$ MHz
δ_0	$2\pi \times [0, 100]$ MHz	$2\pi \times [0, 250]$ MHz
Δ_0	$2\pi \times [-100, 100]$ MHz	$2\pi \times [-250, 250]$ MHz

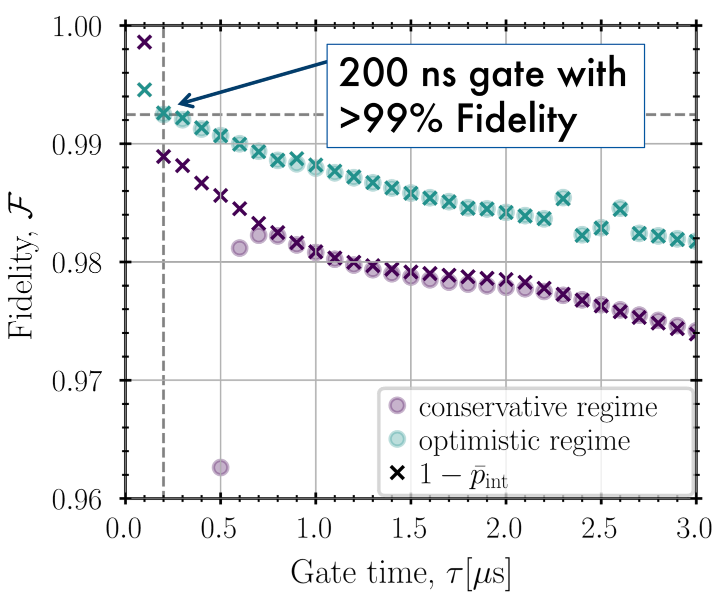


CZ gate without noise



CZ gate with Rydberg decay

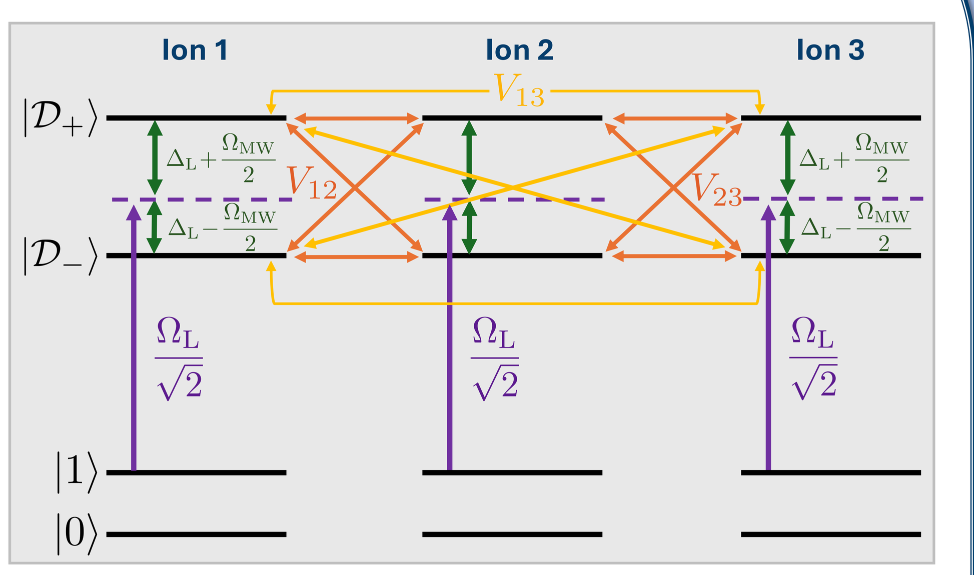
$\tau_{\mathrm{R}} = 7.8\,\mu s$, $\gamma_{\mathrm{R}} = 0.128$ MHz



RESULTS: IMPLEMENTING CCZ GATES

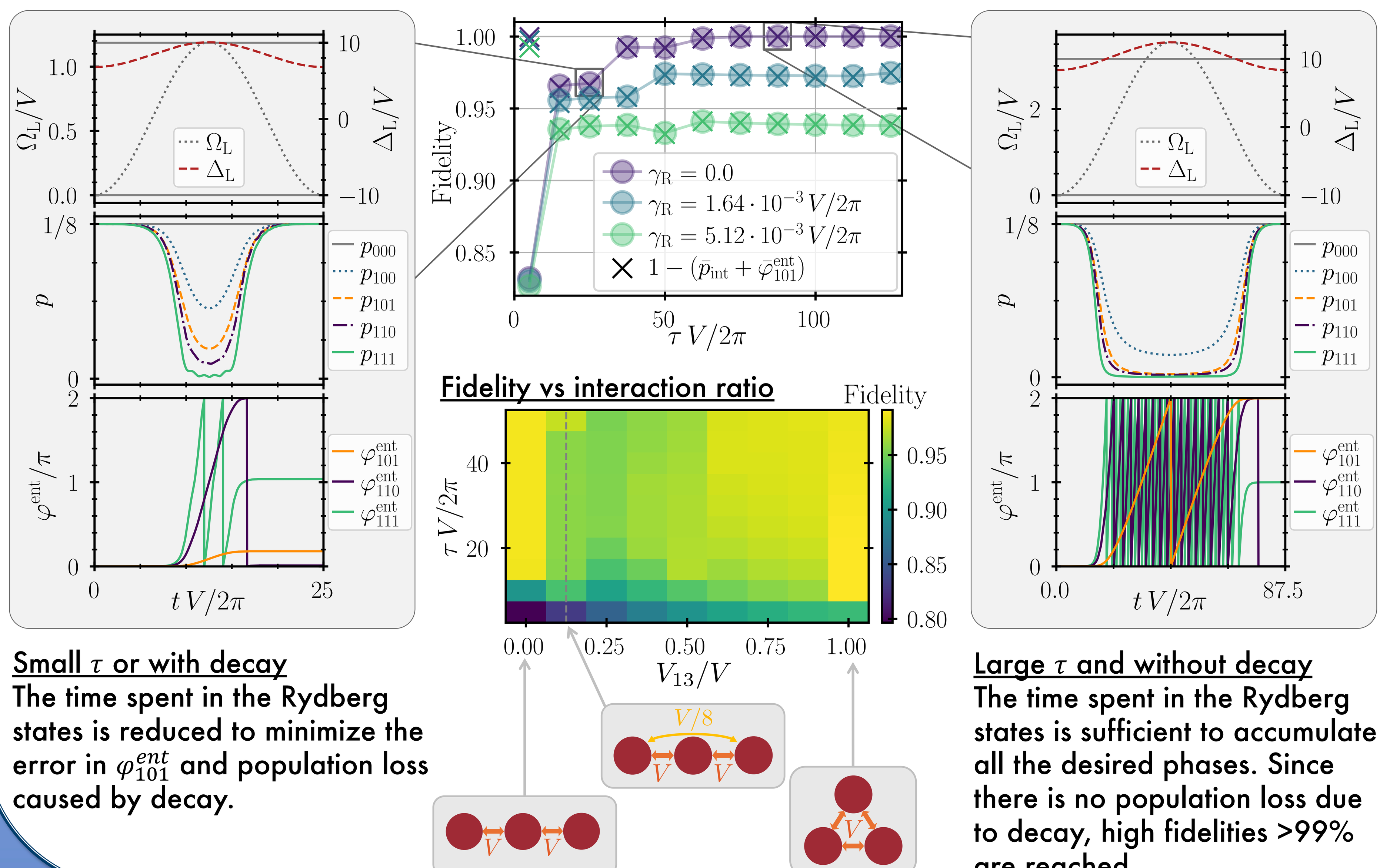
$\mathrm{CCZ}: |abc\rangle \to (-1)^{abc}|abc\rangle$, $(a,b,c) \in \{0,1\}^3$

Parameters	
$V_{12} = V_{23} = V$	$2\pi \times 25$ MHz
Ω_{MW}	$2\pi \times 500$ MHz
Ω_0	$2\pi \times [0, 100]$ MHz
δ_0	$2\pi \times [0, 250]$ MHz
Δ_0	$2\pi \times [-250, 250]$ MHz



CCZ gate with and without Rydberg decay

Main source of infidelity: population loss $\bar{p}_{\mathrm{int}}$ due to decay and the phase error in $\varphi^{\mathrm{ent}}_{101}$



Small τ or with decay
The time spent in the Rydberg states is reduced to minimize the error in $\varphi^{\mathrm{ent}}_{101}$ and population loss caused by decay.

Large τ and without decay
The time spent in the Rydberg states is sufficient to accumulate all the desired phases. Since there is no population loss due to decay, high fidelities >99% are reached.

OUTLOOK

Alternative implementations of multi-ion gates, e.g., with phase jumps → Development of quantum error correction protocols → Design of scalable and fault-tolerant architectures for quantum information processing

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REFS

[1] Zhang, C. *et al.* 2020 *Nature* **580**, 345–349.
[2] Müller, M. *et al.* 2008 *New J. Phys.* 10, 093009.
[3] Mokhberi, A. *et al.* 2020 *Academic Press* **69**, 233–306.
[4] Wilkinson, J.W.P. *et al* 2025 *New J. Phys.* **27** 064502.