SAND2023-04555C

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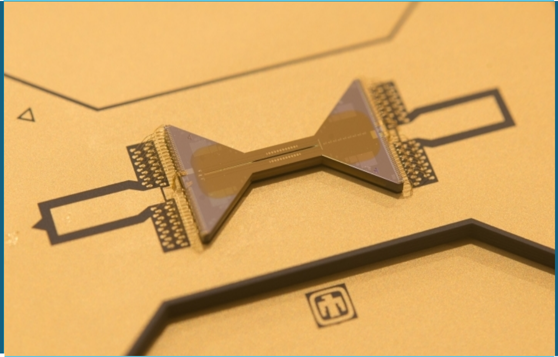
# Demonstration of Mølmer–Sørensen Gates Robust to ±10 kHz Motional Frequency Error



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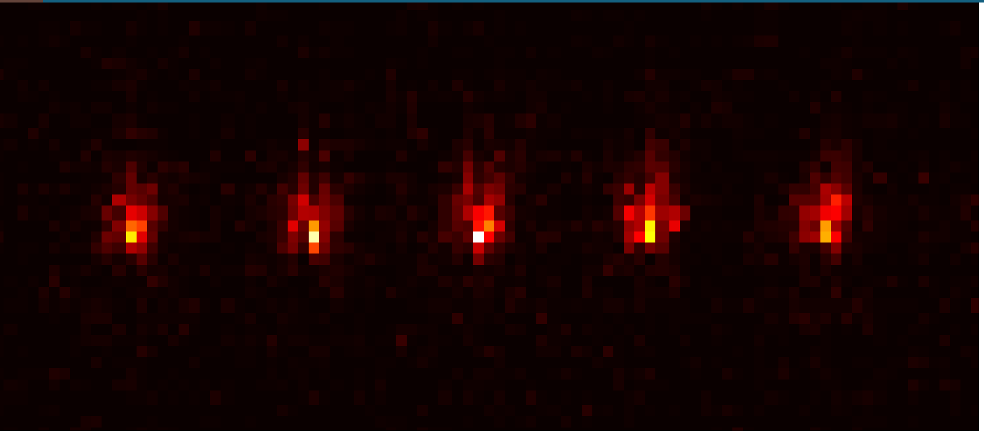

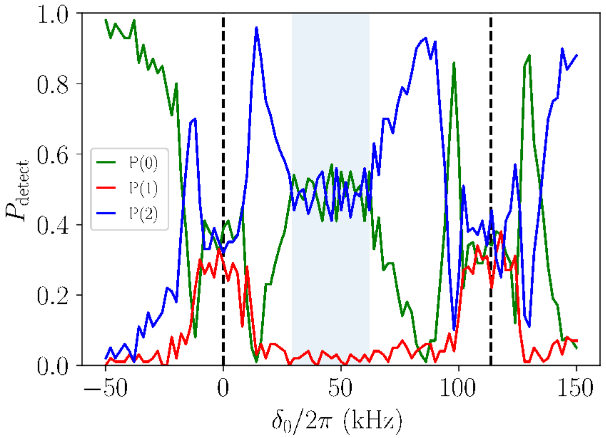


QSCOUT

JAQAL

Presenting: Matthew Chow[1,2,3]

Team: Brandon P. Ruzic[1], Ashlyn D. Burch[1], Megan K. Ivory, Dan S. Lobser[1], Melissa C. Revelle[1], Christopher G. Yale[1], Susan M. Clark[1]

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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arXiv : 2210.02372

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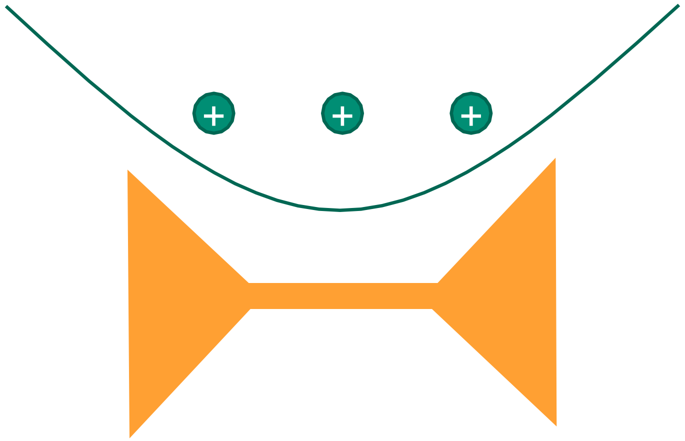
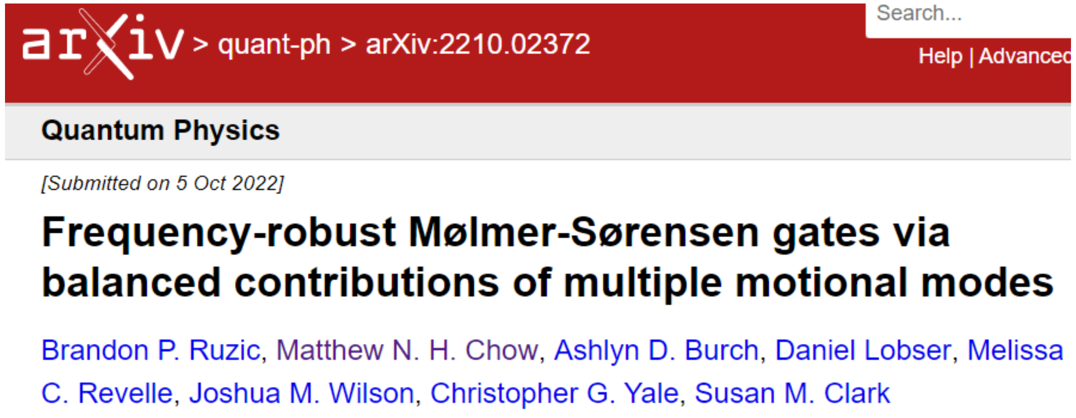
3. *Center for Quantum Information and Control, University of New Mexico, Albuquerque, NM*

# Overview: We develop and demonstrate an entangling gate on trapped ions that is robust to a dominant noise source.

## Ion RF Paul Trap




arXiv > quant-ph > arXiv:2210.02372

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Quantum Physics

*[Submitted on 5 Oct 2022]*

**Frequency-robust Mølmer-Sørensen gates via balanced contributions of multiple motional modes**

Brandon P. Ruzic, Matthew N. H. Chow, Ashlyn D. Burch, Daniel Lobser, Melissa C. Revelle, Joshua M. Wilson, Christopher G. Yale, Susan M. Clark

**Critical challenge: Error mitigation for entangling gates**

- Design pulses for robust operation

arXiv : 2210.02372

# Trapped ions show great promise for quantum computing…

# …but the entangling gates suffer from technical noise.

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## Trapped ions show great promise

- SPAM > 0.99999

  [Zukas 2021]

- Single qubit rotations > 0.9999

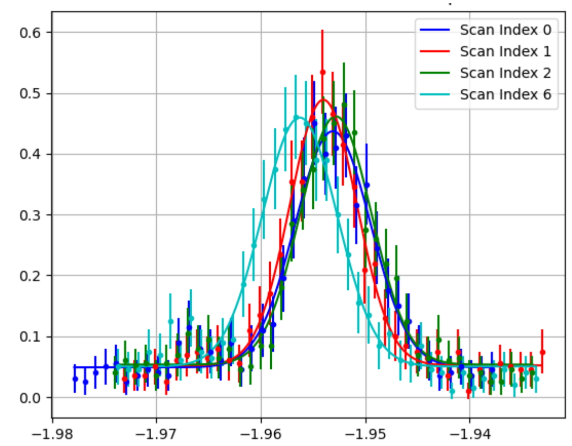
  [Ballance 2016, Gaebler 2016]

- Peak entangling gate ≥ 0.999

  [Ballance 2016, Gaebler 2016]

## … however

- Motional frequency drifts impact the entangling gate.




Sideband Frequency (MHz)

- It's hard to scale to many ions.

★ Solution? Develop gates that are robust to trap frequency drift that can be implemented on long chains.

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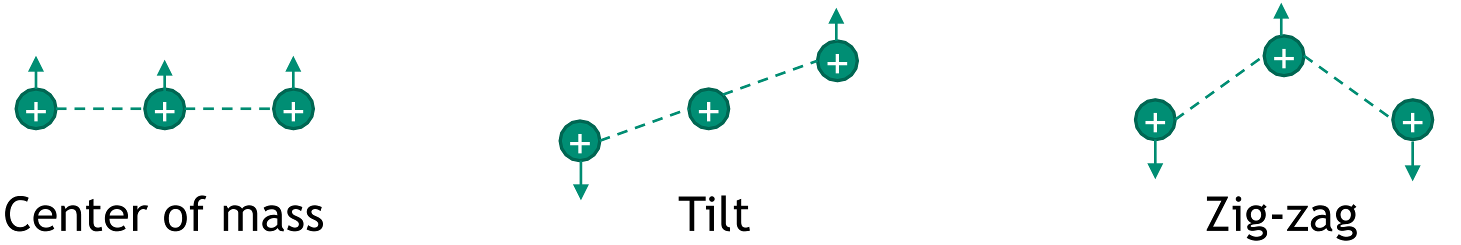
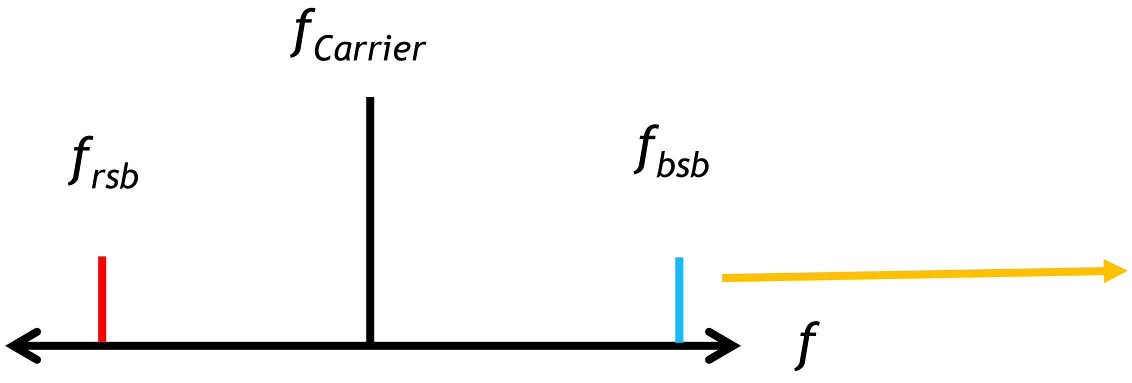
# Shared motional modes mediate entangling interactions

E.g: 3-ion normal modes of motion

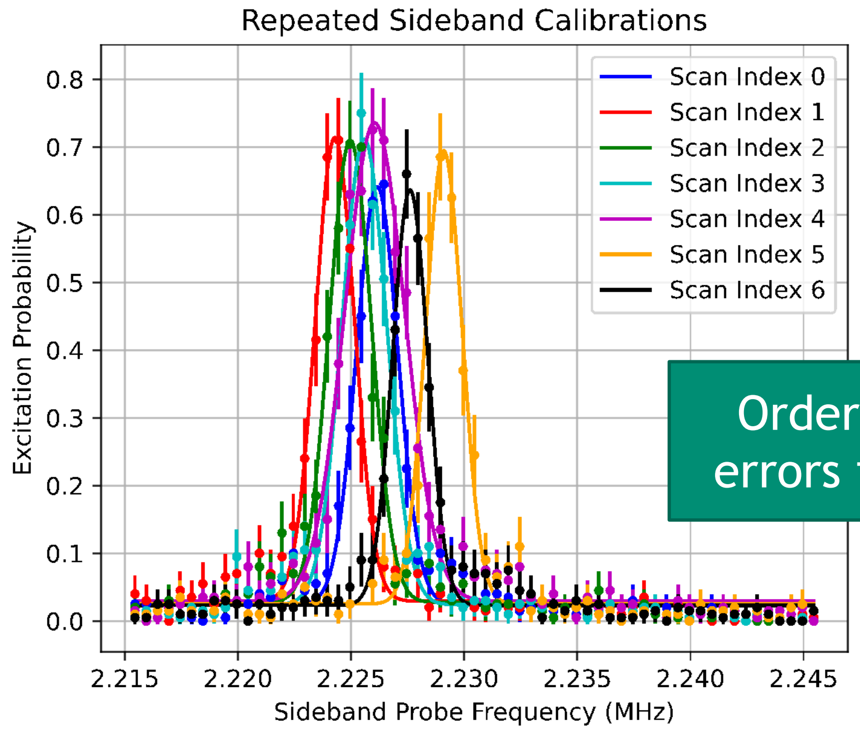



Red sideband: n-1
Remove a phonon

Blue sideband: n+1
Add a phonon

- Motional sidebands at the normal mode trap frequencies
- Coulomb interaction couples ions together
  - Vibrational levels act as “bus” connecting qubits




Order 1kHz errors typical

… however

Motional frequency drifts impact the entangling gate.

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# The Mølmer-Sørensen (MS) interaction drives spin entanglement and coherent displacement.

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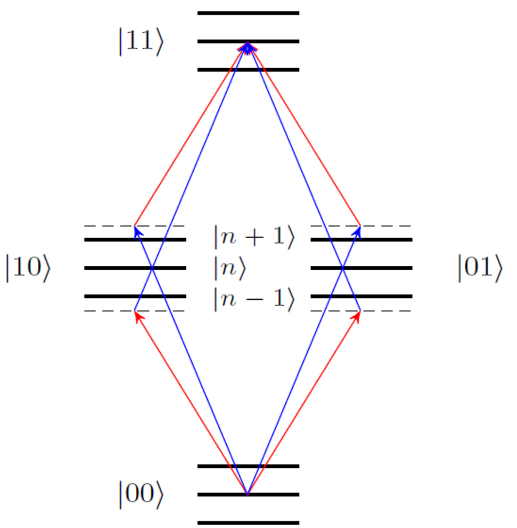


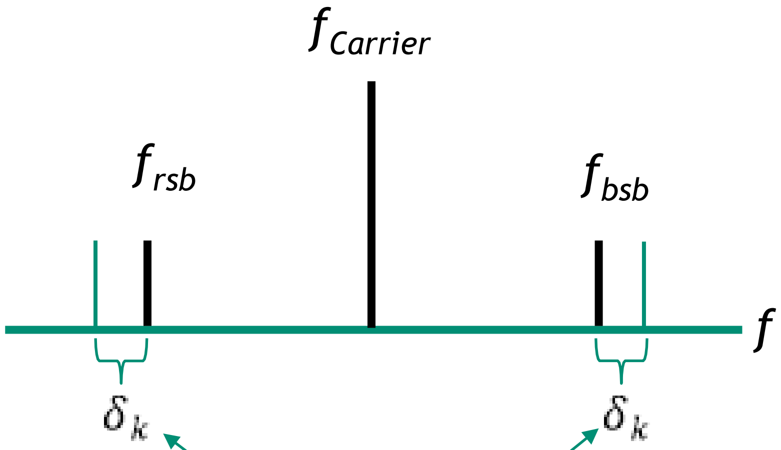


Apply 2 Symmetrically Detuned Tones

Interaction Hamiltonian:

$$\hat{H}_I = -\Omega(t)\sum_k \hat{S}_{\phi,k}\hat{a}_k e^{i\delta_k t} + h.c.$$

Bosonic annihilation operator for mode $k$

Spin operator, $\hat{S}_{\phi,k} = (\eta_{1,k}\sigma_{\phi,1} + \eta_{2,k}\sigma_{\phi,2})/2$

Propagator:

$$\hat{U}(t) = \prod_k e^{-i\beta_k(t)\hat{S}^2_{\phi,k}}\hat{D}(\hat{S}_{\phi,k}\alpha_k(t))$$

Phase space trajectory: $\alpha_k(t) = i\int_0^t \Omega(t')e^{-i\delta_k t'}dt'$

Governs spin entanglement: $\beta_k(t) = \frac{i}{2}\int_0^t \frac{d\alpha_k(t')}{dt'}\alpha_k^*(t') - \alpha(t')\frac{d\alpha_k^*}{dt'}\,dt'$

Gate angle: $\theta(t) = \sum_k \eta_{1,k}\eta_{2,k}\beta_k(t)$

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# Experimental indicators of two error mechanisms guide analysis of robust gate implementations

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If $\alpha_k(\tau) \neq \alpha(0)$,

then the motional state at the end of the gate is not where it started.
We call this **displacement error, $\epsilon_d$.**

Experimental Indicator : $|01\rangle$ and $|10\rangle$

If $\theta(\tau) \neq \pi/2$,

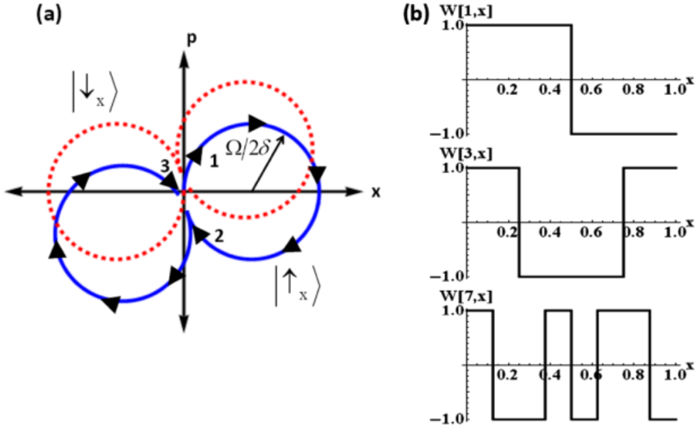
then the entangling angle accumulated is not equal to the target value.
We call this **rotation error, $\epsilon_r$.**

Experimental indicator: ratio of $|00\rangle$ to $|11\rangle$

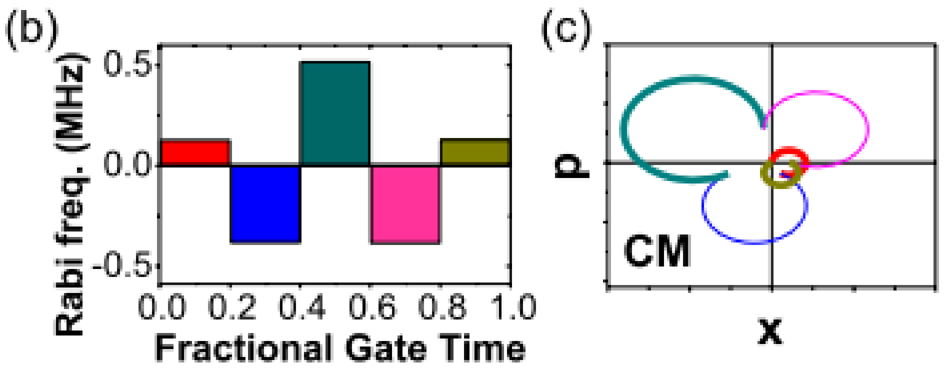
For robust gate, both $\epsilon_d$ and $\epsilon_r$ need to be small over a broad acceptable range of input parameters.

Pioneering work by Brown and Monroe groups have found ways to minimize $\epsilon_d$:

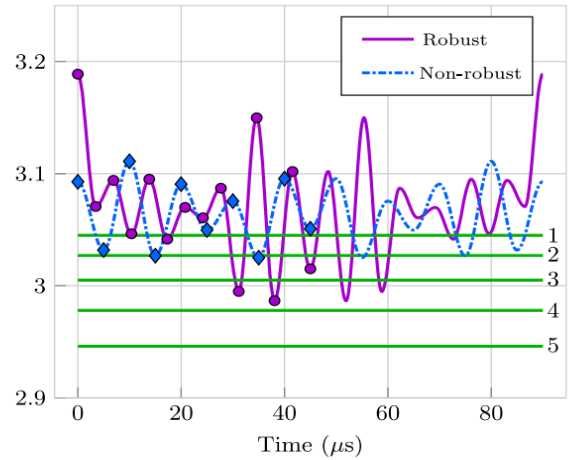
[Hayes et al 2012]




[Choi et al 2014]




[Leung et al 2018]




Order 1kHz robustness

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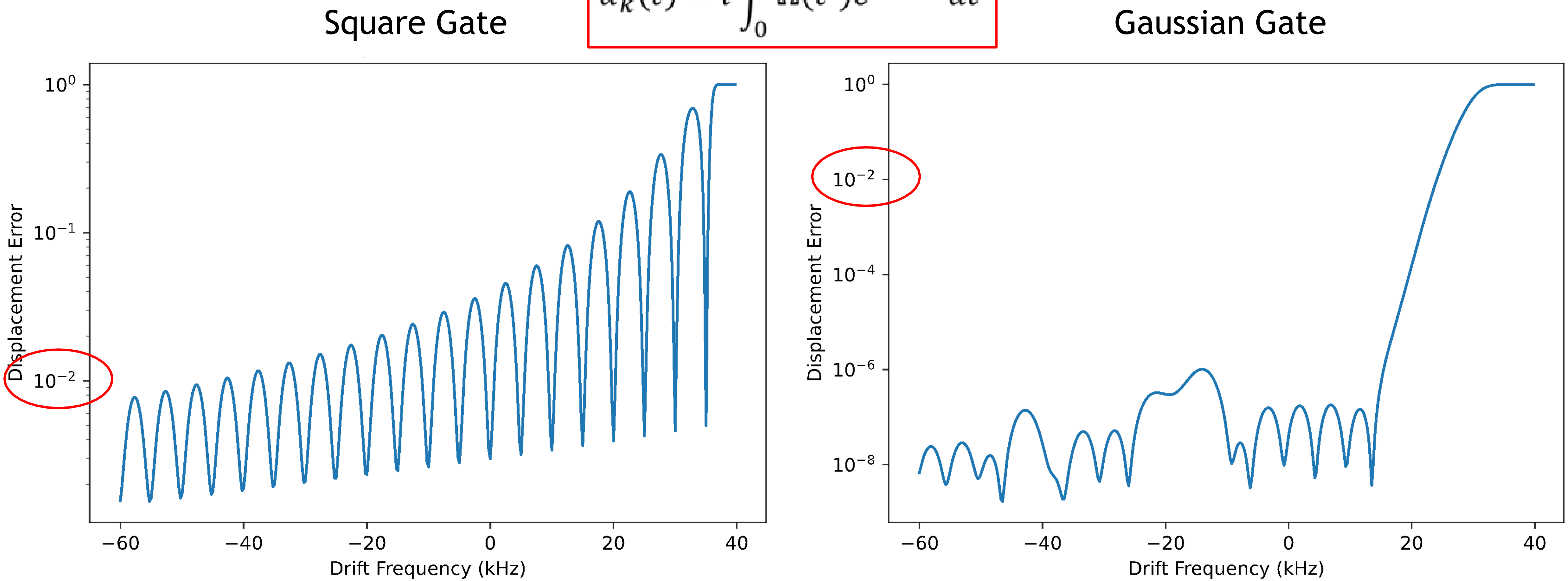
# Gaussian pulse shape is 'naturally' robust to displacement error.

$$\alpha_k(t) = i\int_0^t \Omega(t')e^{-i\delta_k t'}dt'$$




In the Gaussian gate, we still need the right detuning and amplitude to get the right area enclosed, but this shows broadly robust spin-motion disentanglement at the end of a Gaussian gate.

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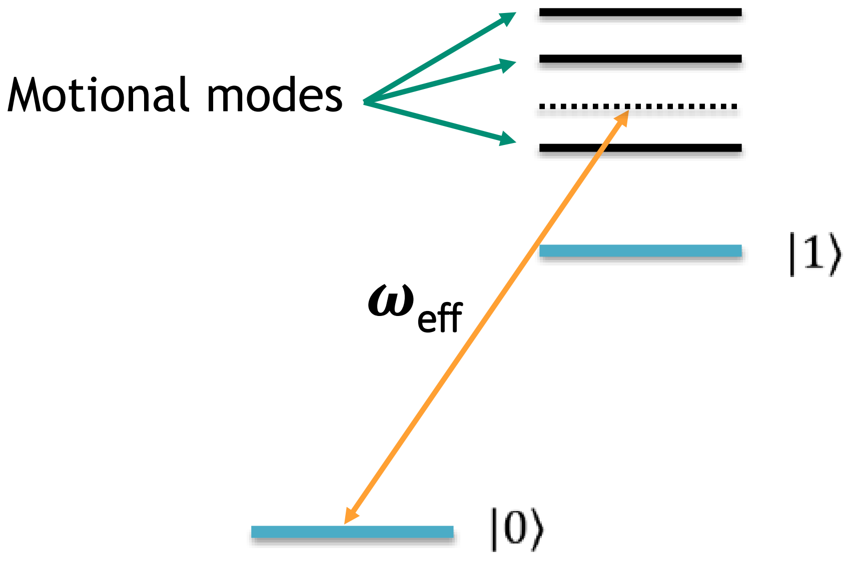
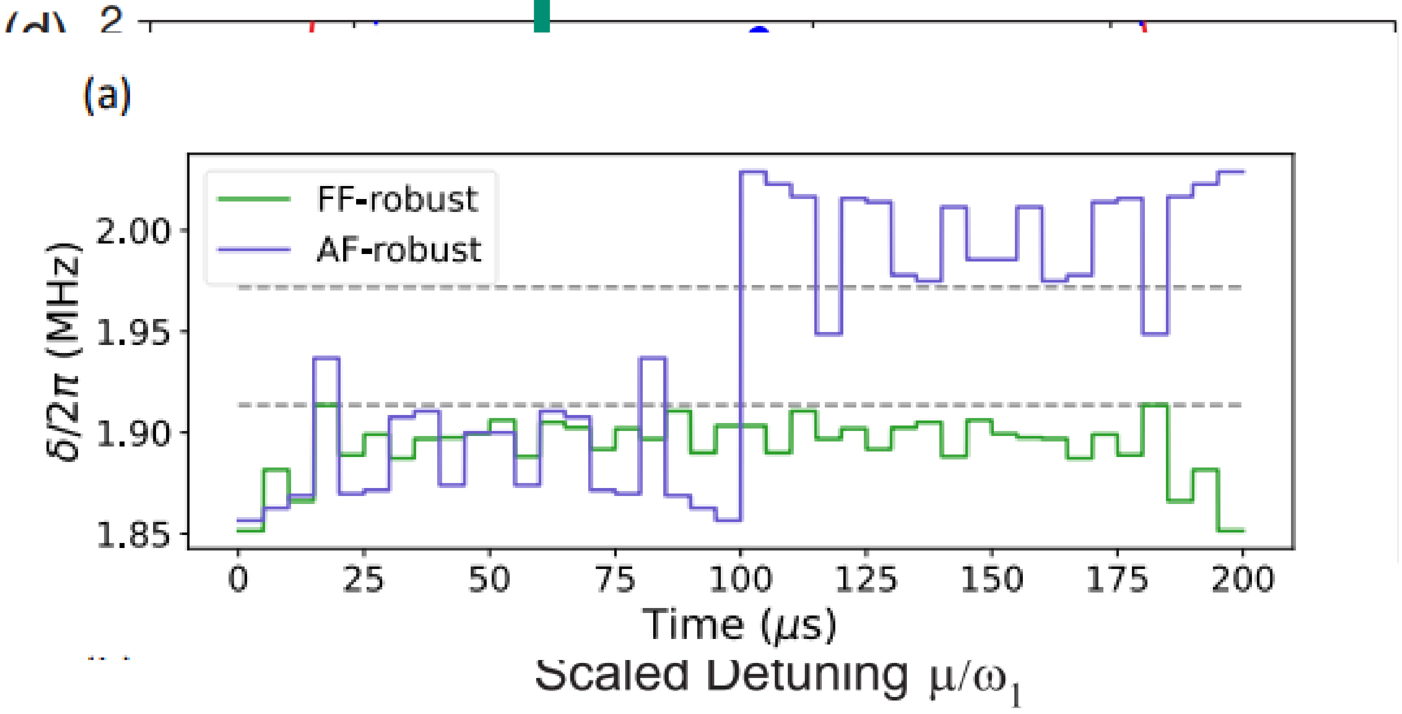
# Rotation error is suppressed by balancing the contributions of multiple motional modes.

Gaussian gives freedom to choose any sufficiently large detuning without displacement error

→ So choose $\omega$ such that $\frac{d\theta}{d\omega} = 0$

Jia et. Al, 2022 (Ken Brown group) recently showed this can be done dynamically as well.




Kim et. Al, PRL 103, 120502 (2009) – Monroe group

arXiv:2210.02372

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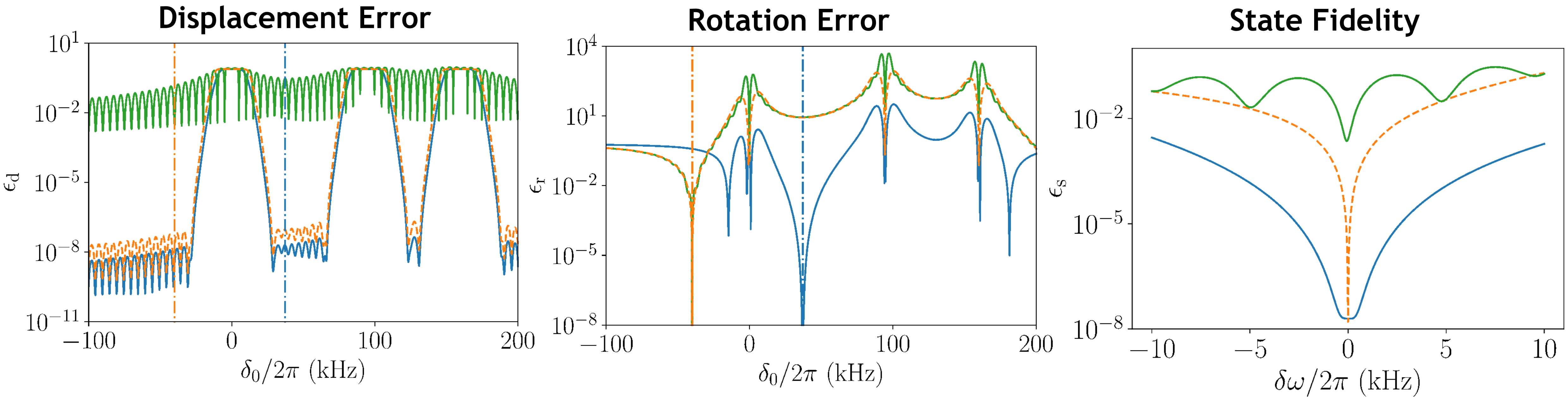
# ‘Balanced’ gaussian gates take care of both rotation and displacement error

Gaussian amplitude modulation and a specific frequency give broad robustness to frequency error




**Pulse shape: Balanced Gaussian, Gaussian, Square**

Gates are simple to implement: no need to optimize tons of pulse-shape parameters

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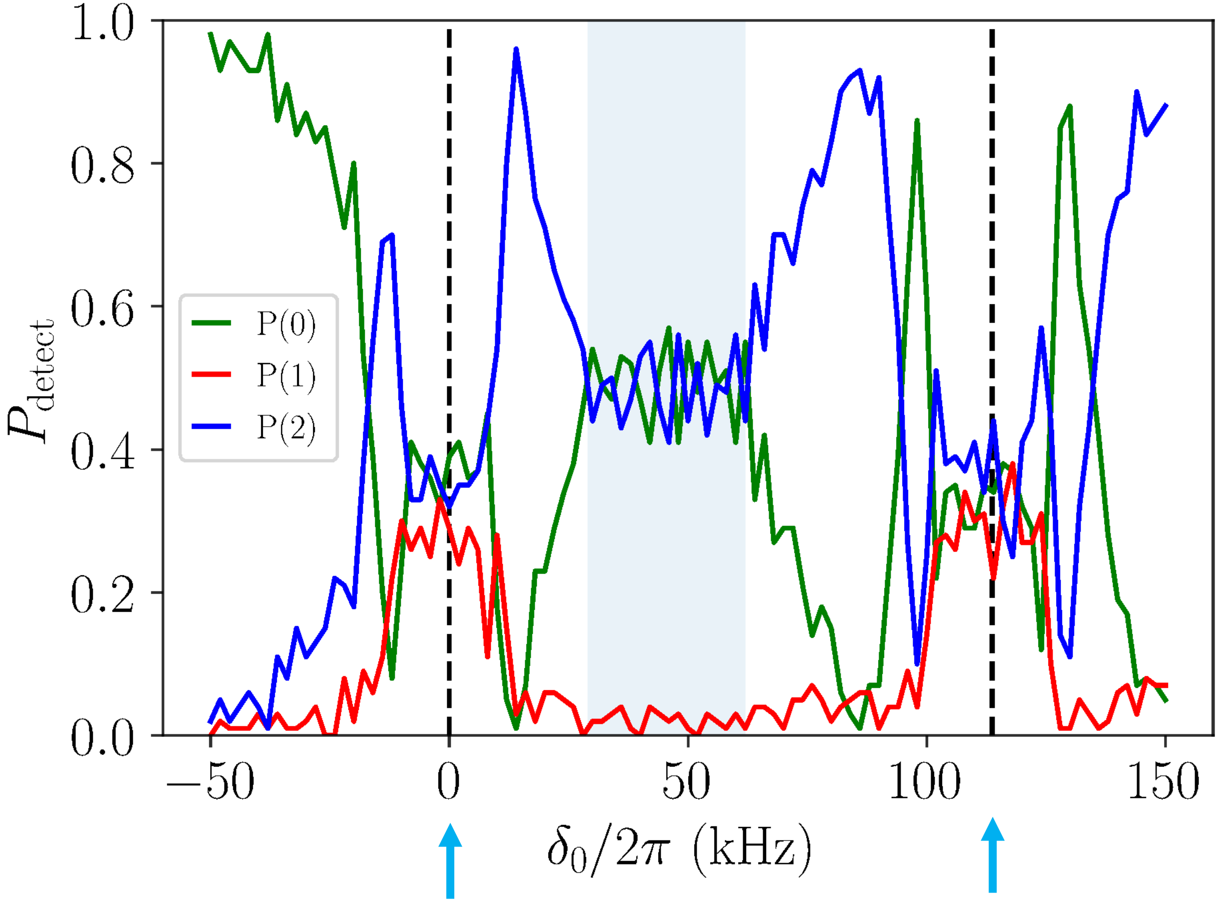
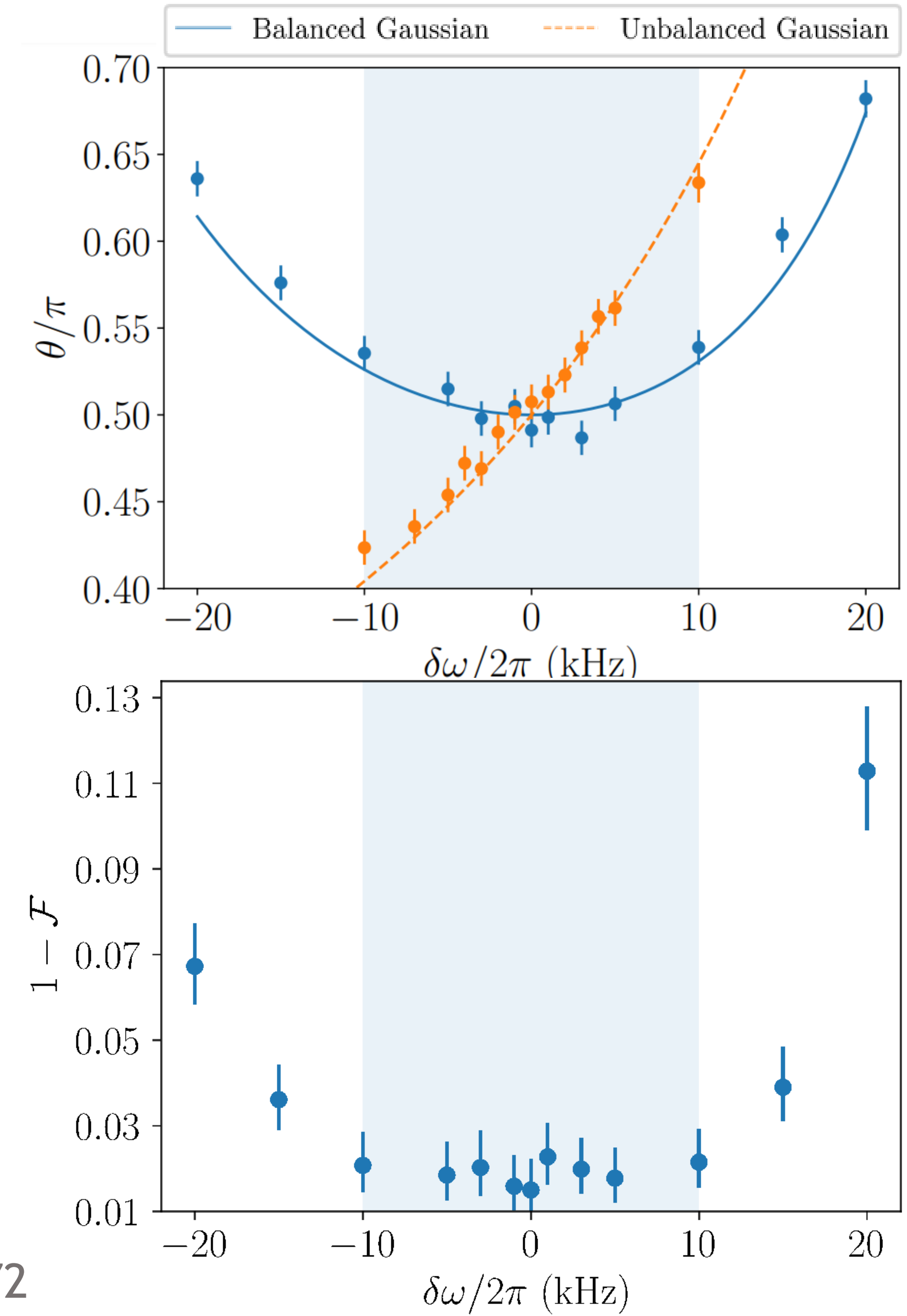
# Experiment shows balanced Gaussian is robust to ±10 kHz trap frequency drift

Peak fidelity = 98.5(6)%
Drop in fidelity over ±10 kHz < 1%




3 ion modes: Zig-zag Tilt




4 ions

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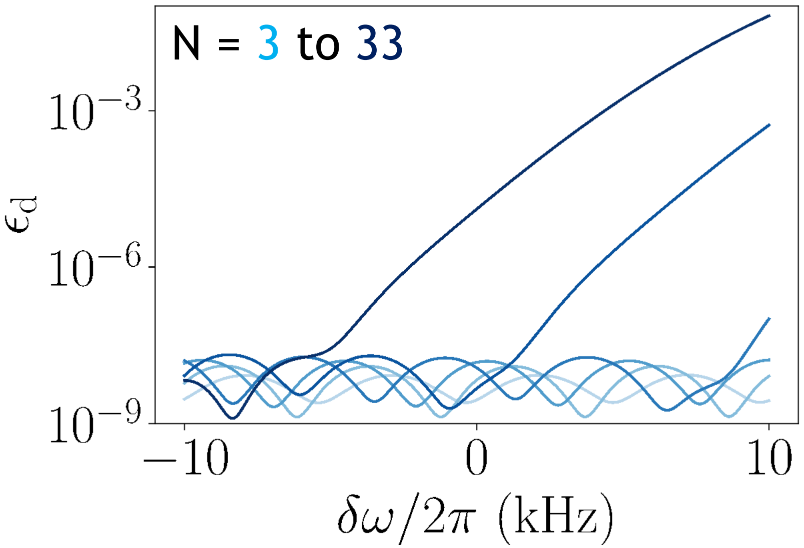
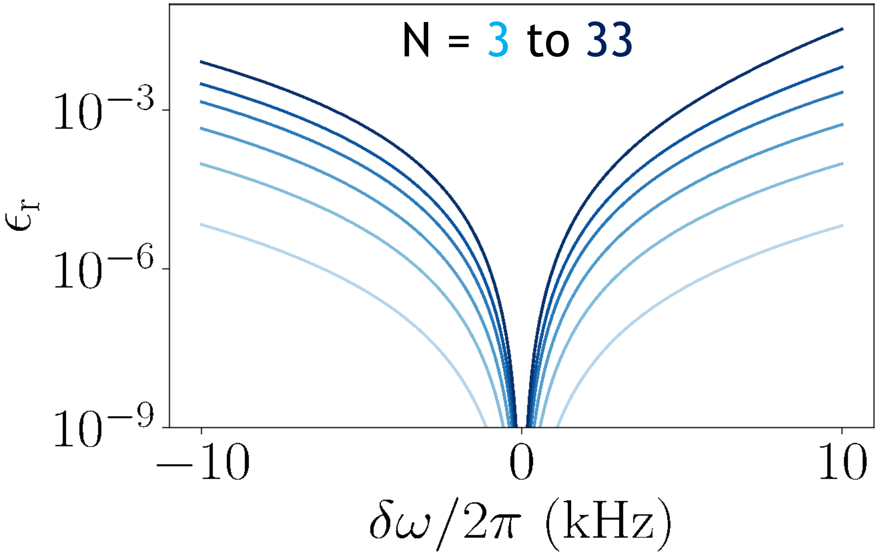
# We find good prospects for scaling to more ions.

- Numerical simulations for chains of up to 33 ions
- Fixed center ion separation: results shown are for 3 $\mu$m

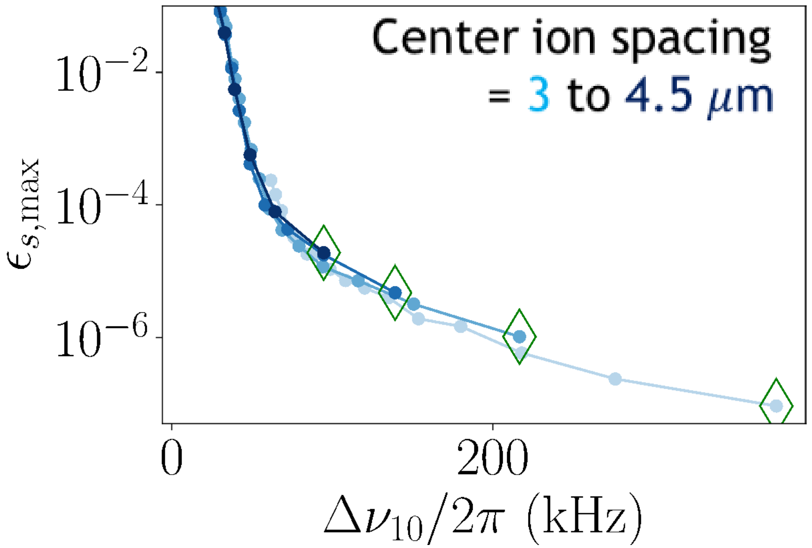
**Displacement Error**




**Rotation Error**




**Max infidelity over ±3 kHz**




- Sensitivity (right plot) depends almost entirely on the splitting of nearest two modes

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# QSCOUT Team

QSCOUT

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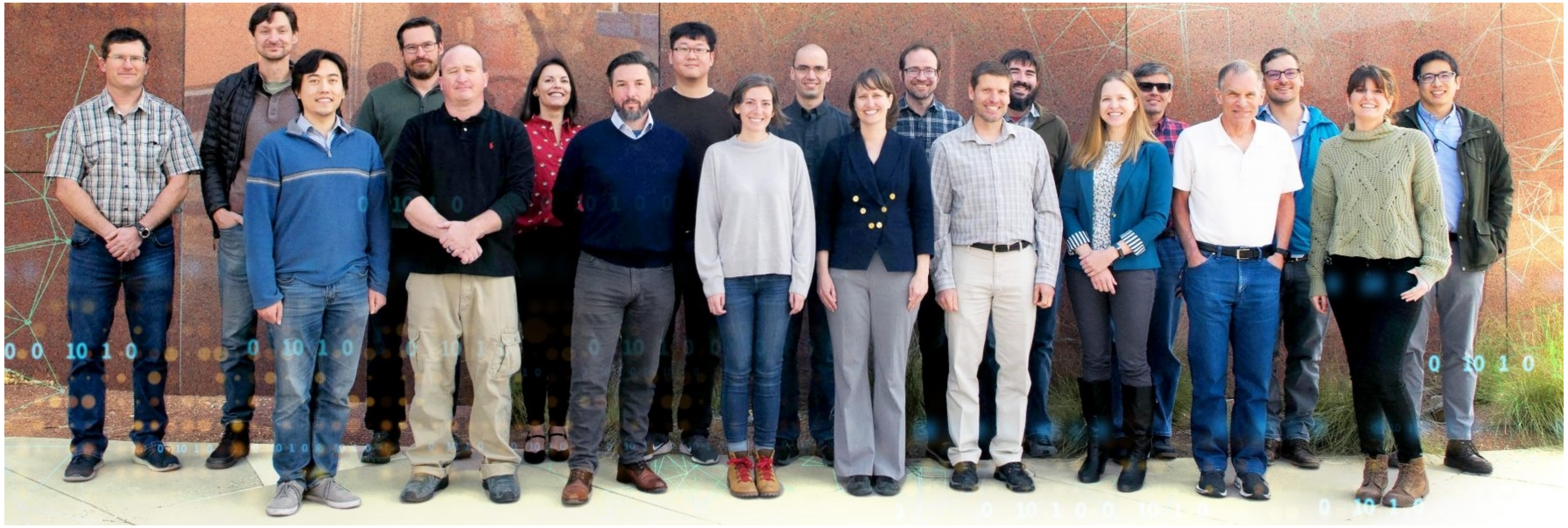
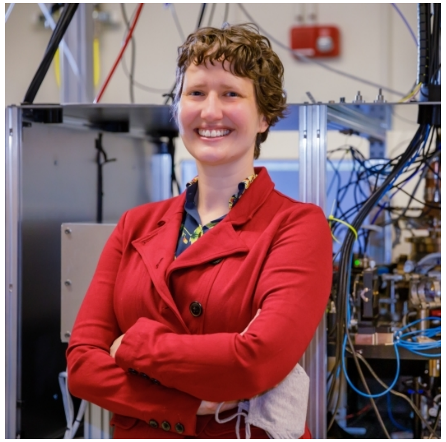
Brandon Ruzic



Susan Clark



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Eric Ou
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# Extra Slides Beyond

# The "Standard" (square, constant frequency) MS gates have issues.

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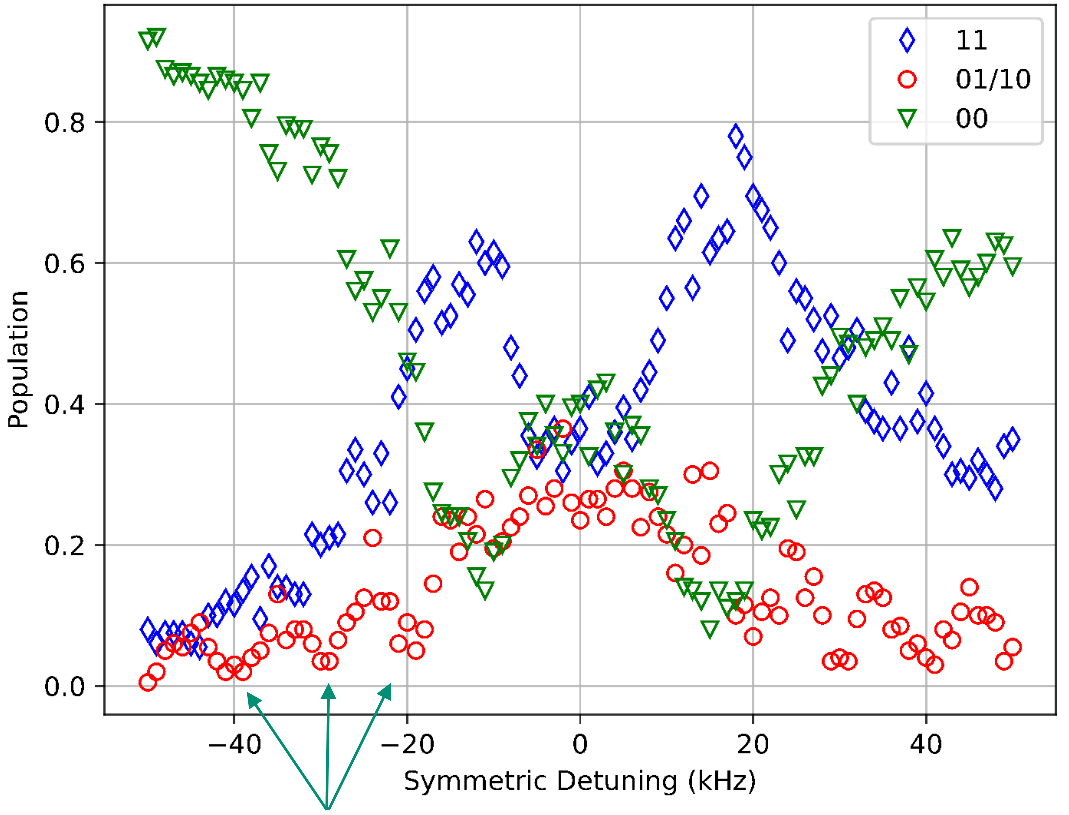
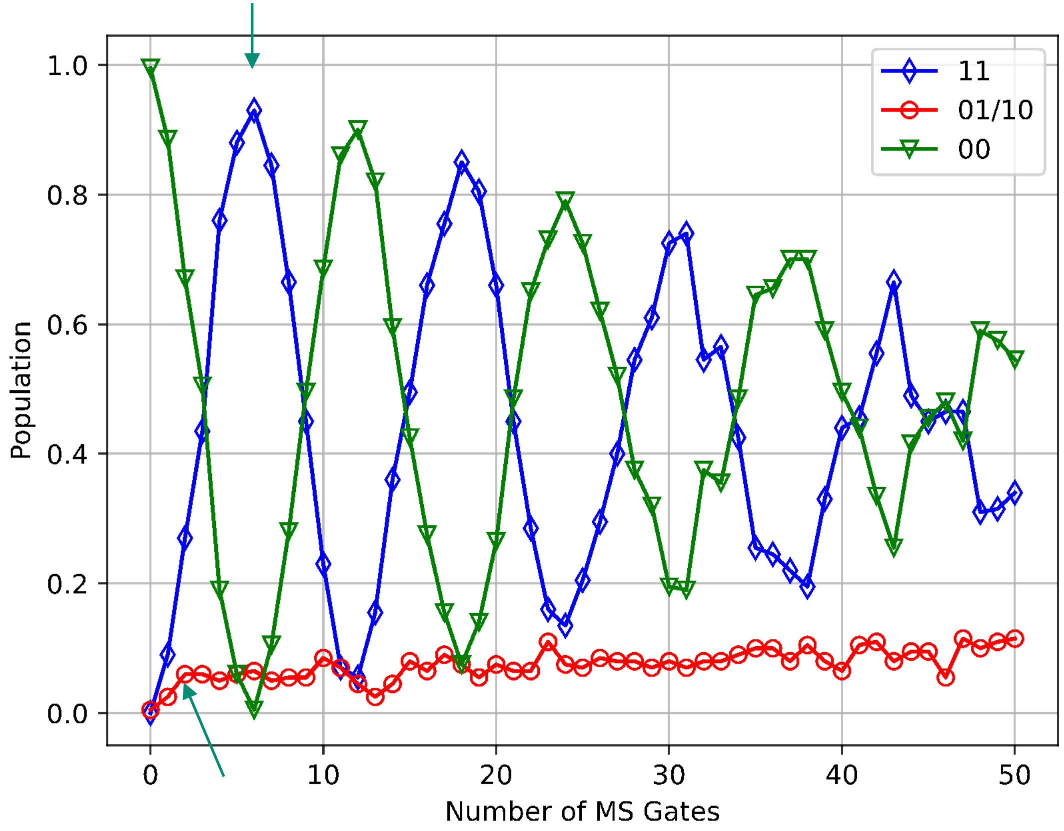
Ideally, the gate generates flopping between $|00\rangle$ and $|11\rangle$ - never populating odd parity states.




- Odd parity population does not go to zero.
- Narrow acceptable detuning range

- *Best* Fidelity ≈ 96.4%, estimated from the max 11 population
- Odd parity population persistent

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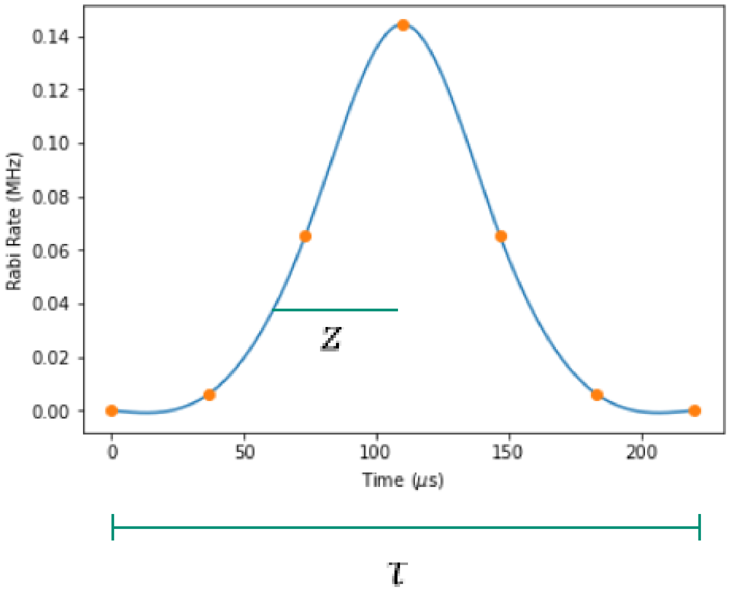
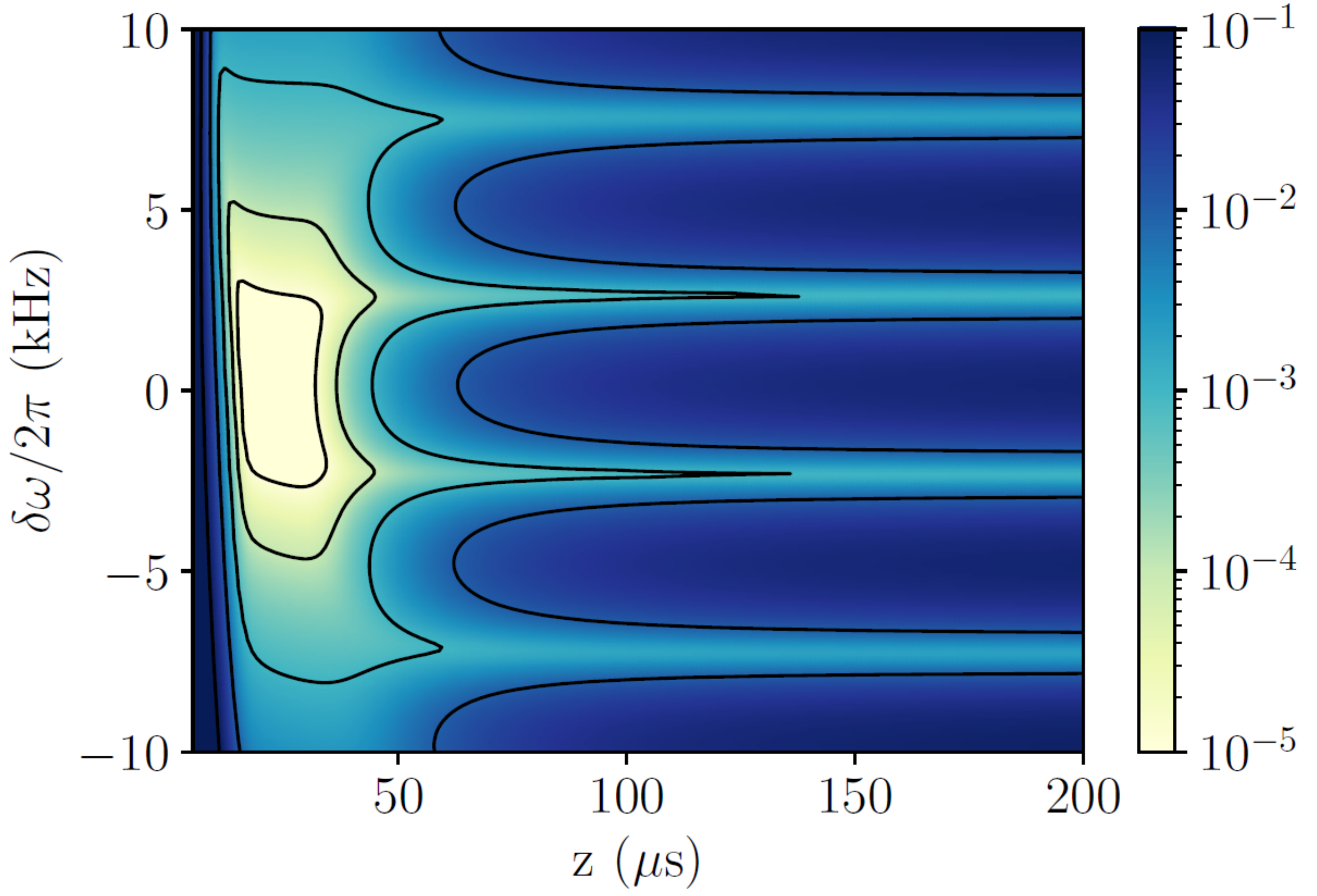
# Gaussian pulse parameters




$z$ : time-domain standard deviation

$\tau$ : gate time, truncation window



# RF Traps for Ions

Trapping requirement: A restoring force when displaced from trap center
(in any direction)

Cannot use
t
Field lines
start/en

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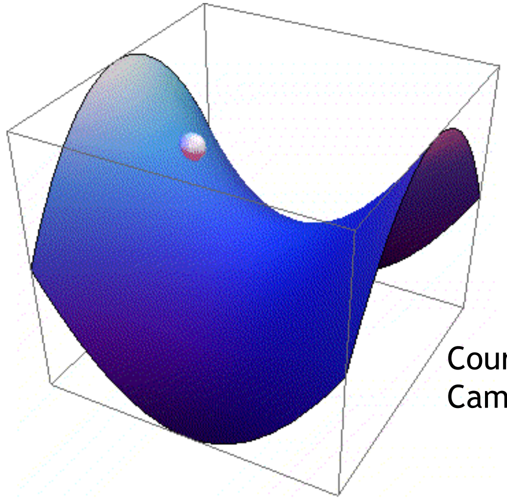
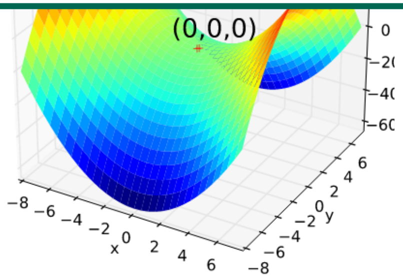
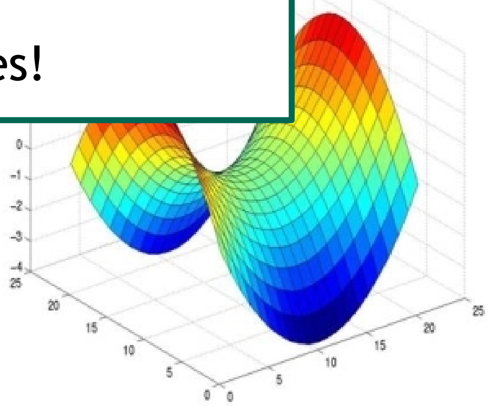


Courtesy of Wes Campbell

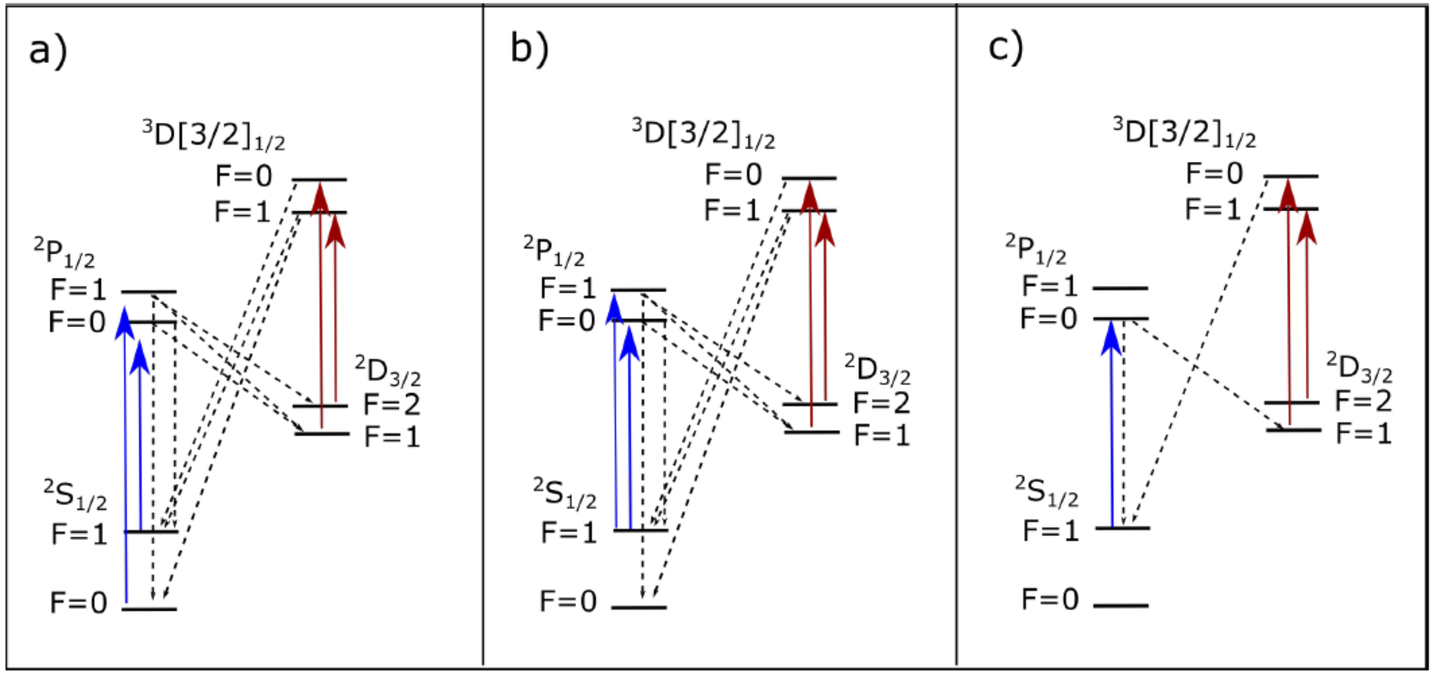
Before ion escapes, field reverses!



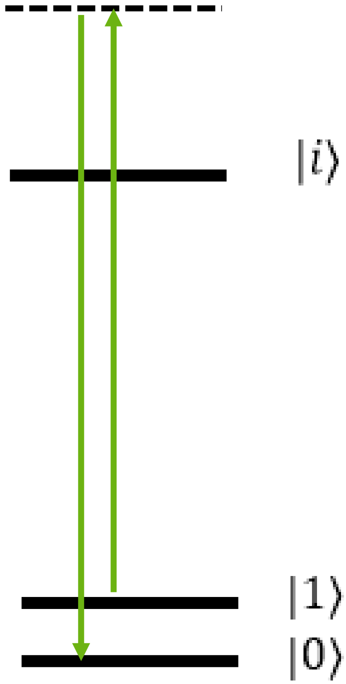



# Crash Course in Trapped Ion Quantum Computing

$^{171}Yb^{+}$




Cool
Pump
Detect




Qubit Rotations

- Sidebands on cooling laser (370nm) allow incoherent control processes
- Pulsed laser (355nm) Raman transitions for qubit rotations

# Shared motional modes mediate entangling interactions

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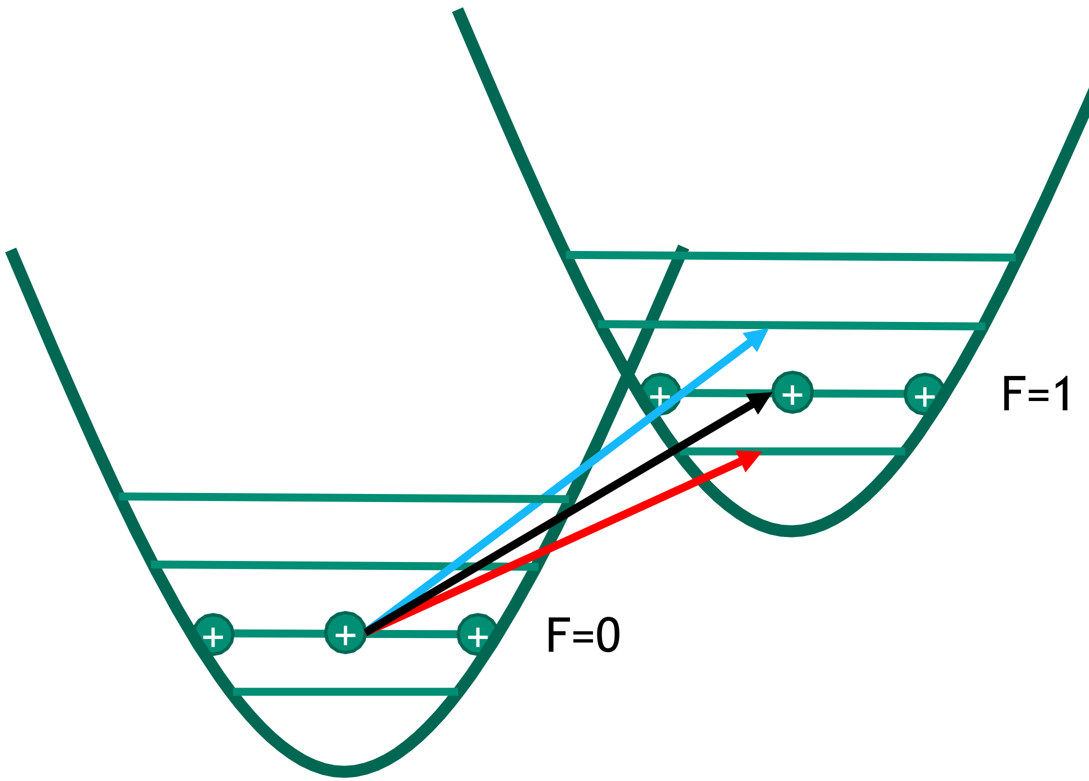


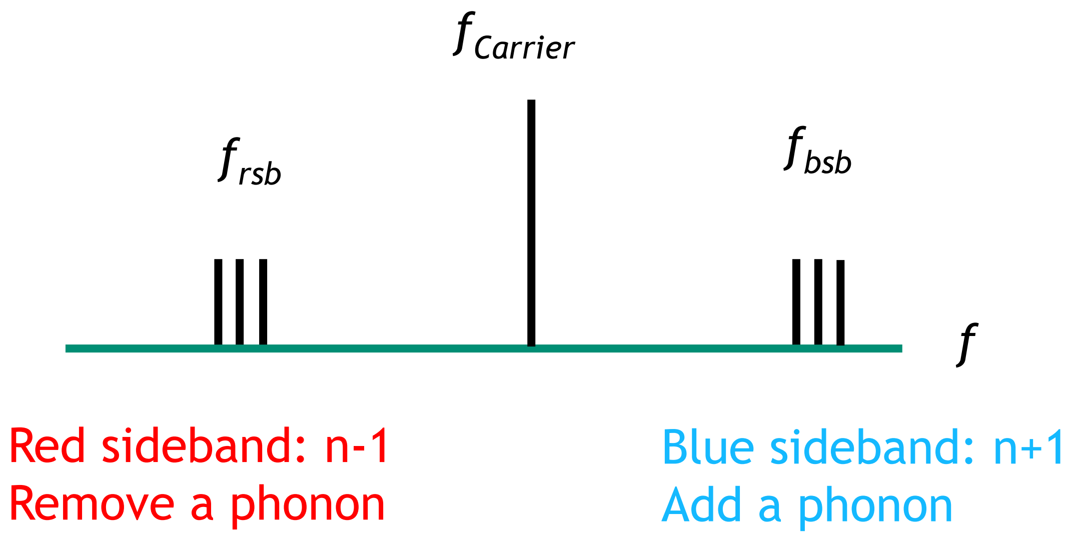


- Motional sidebands at the trap frequency
- Number of modes ∝ Number of ions
- Coulomb interaction couples ions together
  - Vibrational levels act as “bus” connecting qubits

arXiv : 2210.02372

# Intuition for Phase Space Trajectories (PSTs)

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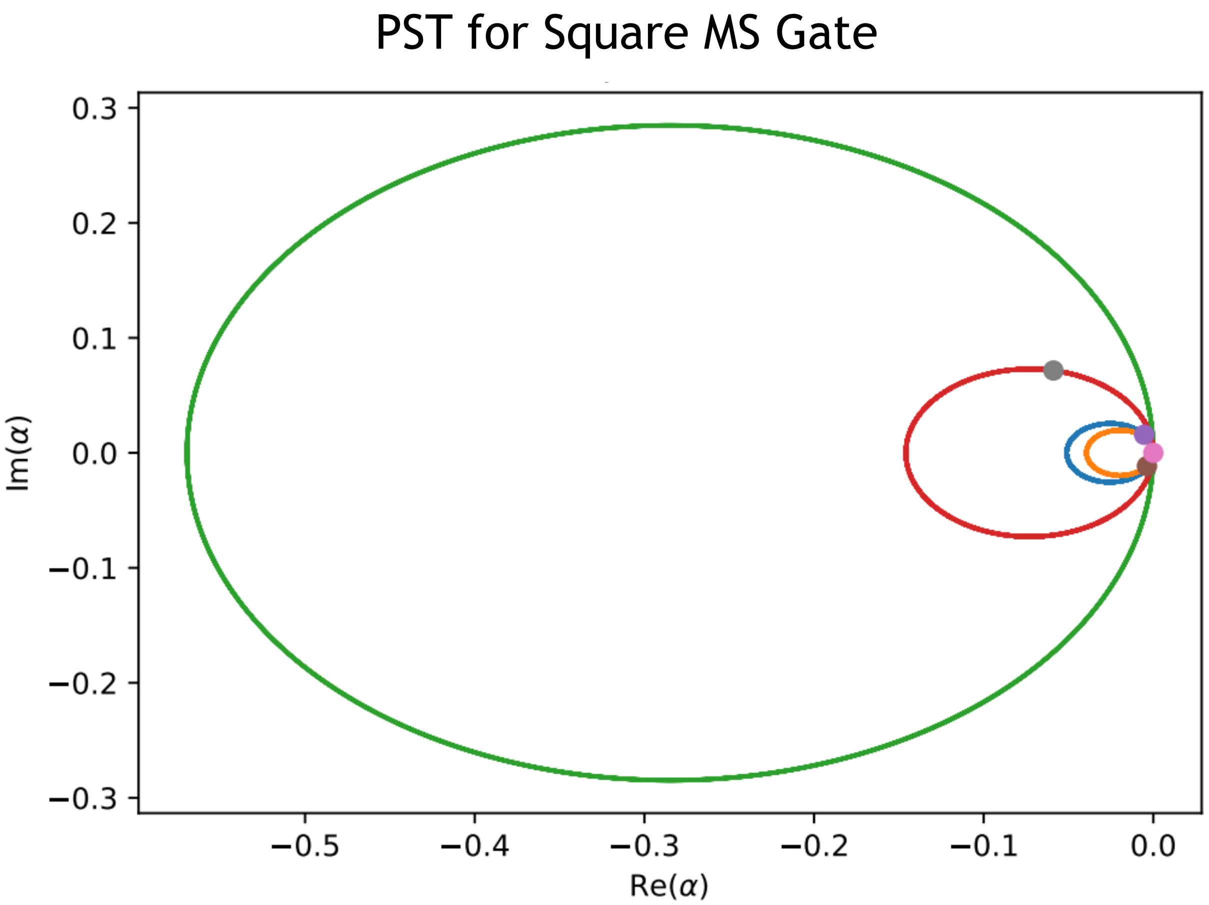


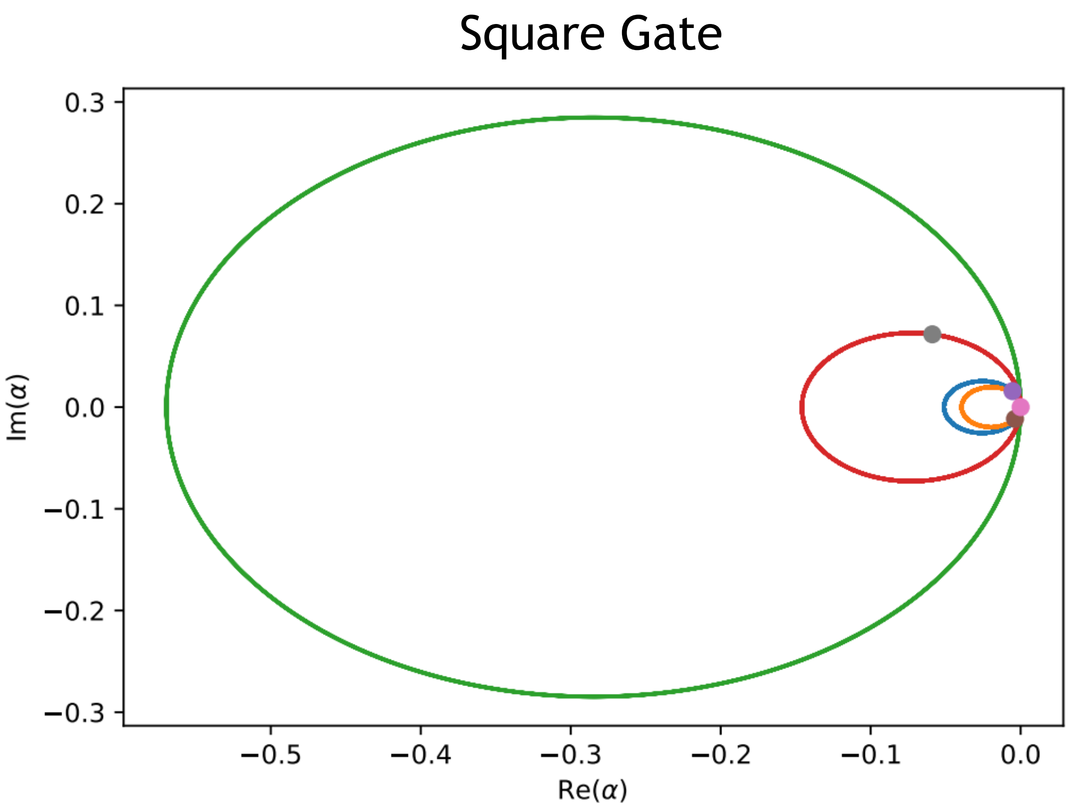

**How pulse parameters come into play:**

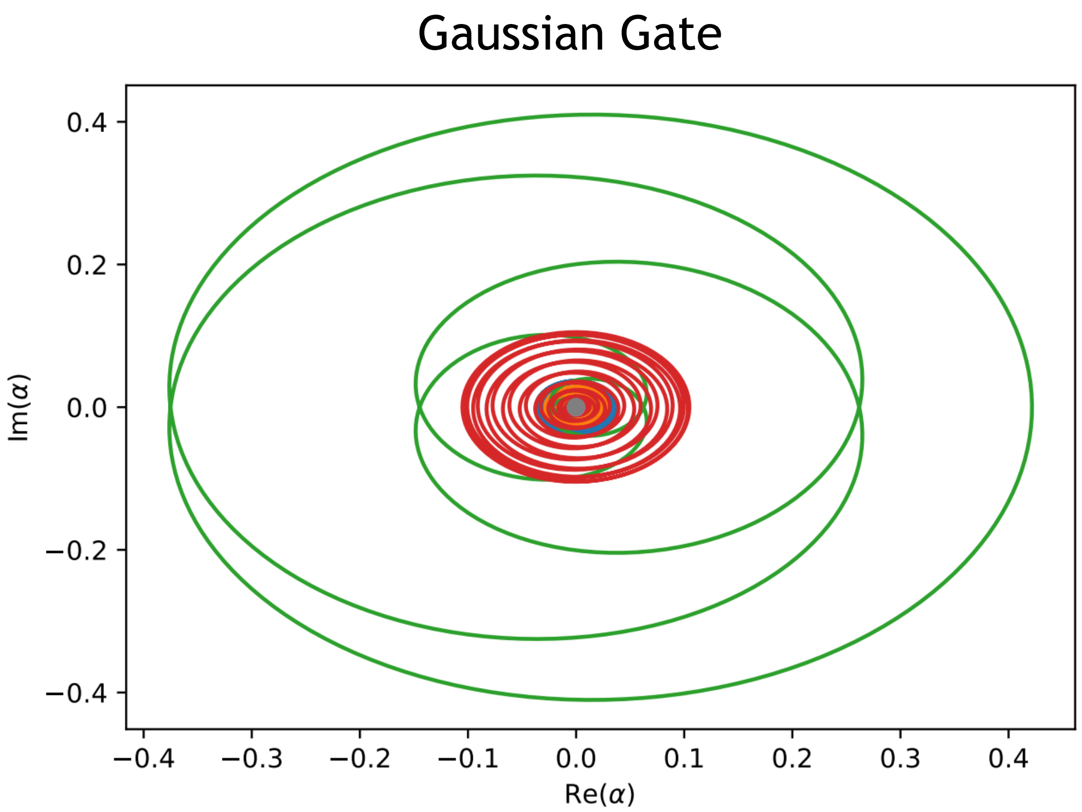
- Detuning controls the angular velocity and radius in phase space.
  - Smaller detuning → Bigger, slower circles
- Rabi rate controls only radius.
- Phase can change the direction of rotation.

**Figures of merit:**

- Loop closure of each mode: $\alpha_k(0) = \alpha_k(t_{gate})$?
- Area enclosed: Is the gate angle right?

# Gaussian MS Gates Show Better Loop Closure than Square MS




**Gate parameters (for both):**

- Detuning is -40 kHz below the lowest frequency mode in a 2 ion chain.
- 200 $\mu s$ duration

**Notable differences:**

- All modes end close to the starting point for Gaussian gate.
- Time averaged displacement close to zero for the Gaussian gate.

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# Displacements During the MS Gate



Interaction Hamiltonian:

$$\hat{H}_I = \frac{\hbar\eta\Omega}{2}\left(\hat{a}e^{-i(\delta t + \phi^M)} + \hat{a}^\dagger e^{+i(\delta t + \phi^M)}\right)\hat{\sigma} \cdot \phi^s$$

State dependent drive force gives coherent displacement by $\alpha_k$ on mode *k* [1]:

$$\hat{D}(\hat{\alpha}_k) = exp(\hat{\alpha}_k a_k^\dagger - \hat{\alpha}_k^\dagger a_k)$$

In the simplest case (+1 eigenstate of $\hat{\sigma}_\phi$, no laser phase difference) [1]:

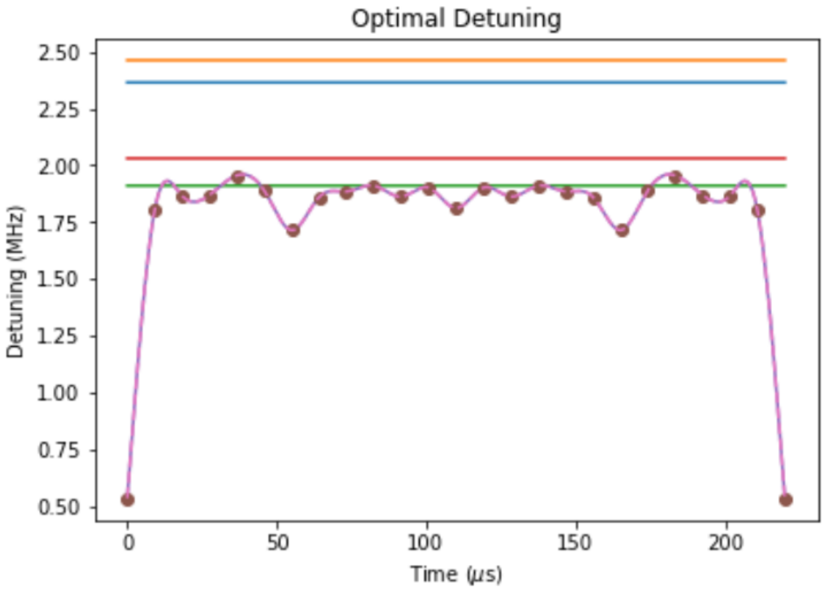
$$\alpha_k = \frac{\Omega}{2}(\eta_{i,k} + \eta_{j,k}) \int_0^t e^{i\theta_k(t')}\, dt' \text{ where } \theta_k(t') = \int_0^{t'} \delta_k(t'')dt'' \text{ is the accumulated phase}$$

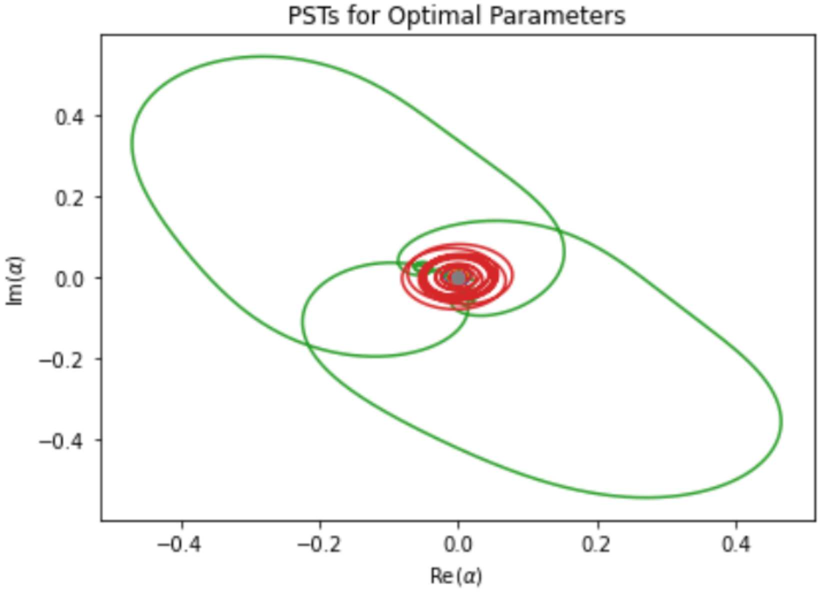
So, for a constant detuning and Rabi rate, we get circular trajectories in phase space, with closure condition: $t_{gate} = 2\pi m/\delta_k$.

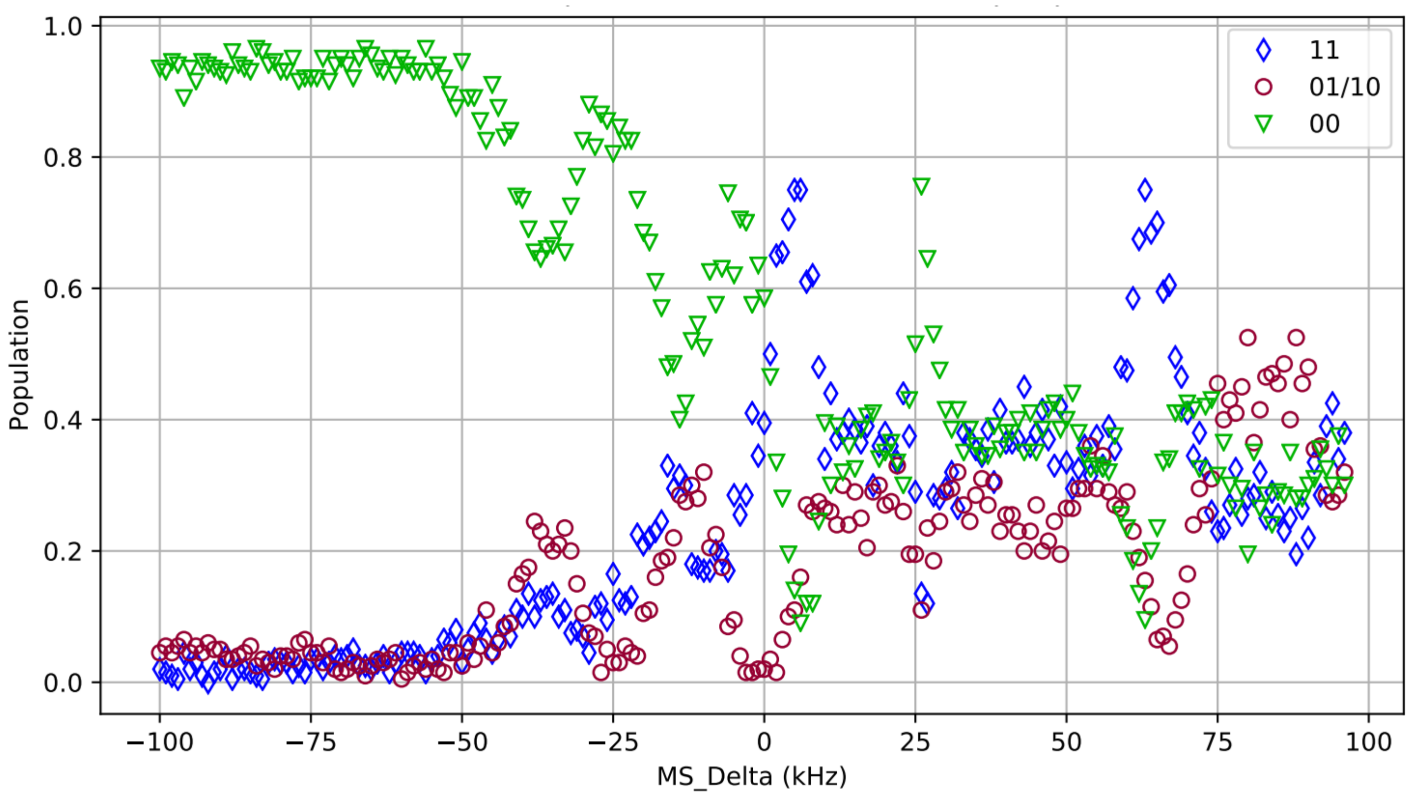
Closed loops are required for spin-motion disentanglement at the end of the gate.

[1] Leung et al., PRL 120, 020501 (2018)

# FM and Constant Frequency Gaussians Are Comparable

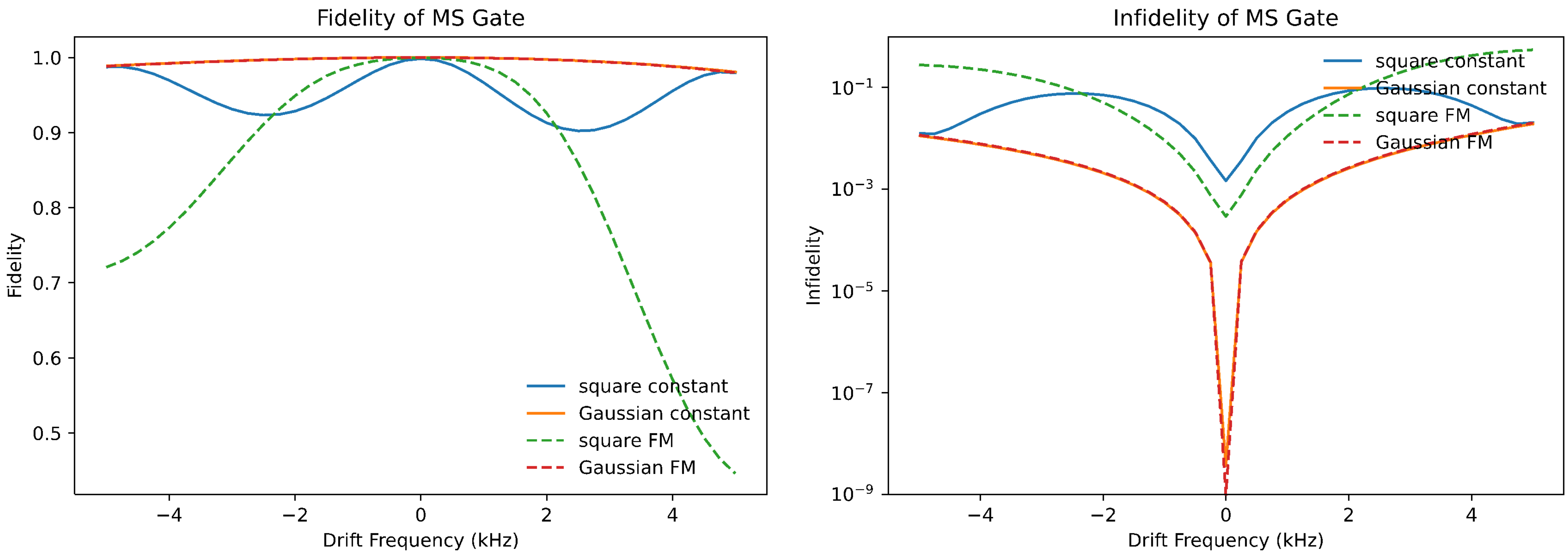



- See essentially the same odd parity population near optimized detuning.
- Area enclosed still has roughly the same sensitivity (slope of 11/00 crossing) as constant frequency case.

# Gaussian Pulse Shape Dominates Gate Performance (with Current Cost Functions)




**Next steps:**

- Further development of gate angle cost function
- Batch optimization
- Transfer function optimization
- Larger chains

# Optimizer/Data Comparison For FM Gaussian