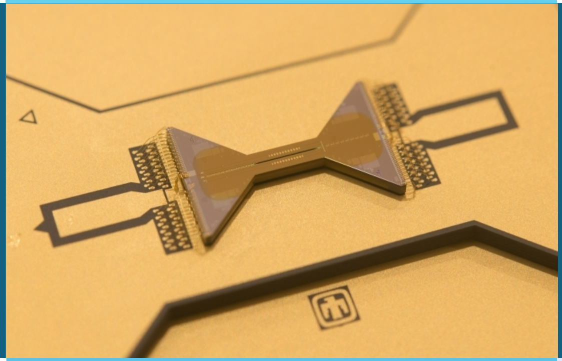
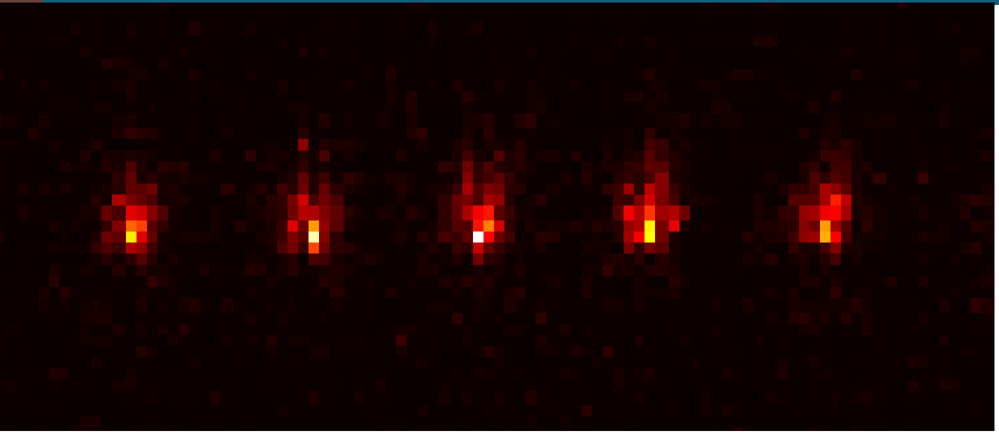
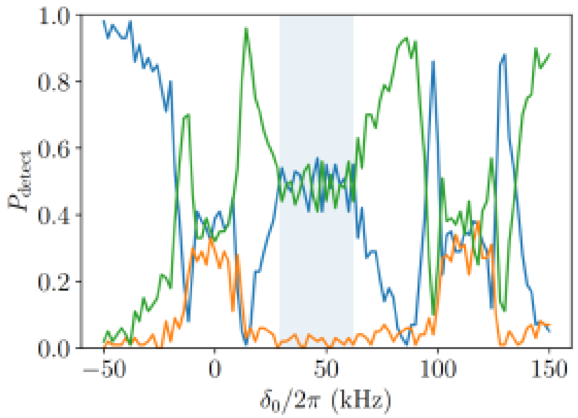
SAND2022-13778C

Center for Quantum Information and Control

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







QSCOUT

JAQAL

Presenting: Matthew Chow[1,2,3]

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

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arXiv:2210.02372

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

U.S. DEPARTMENT OF ENERGY

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SAND #

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

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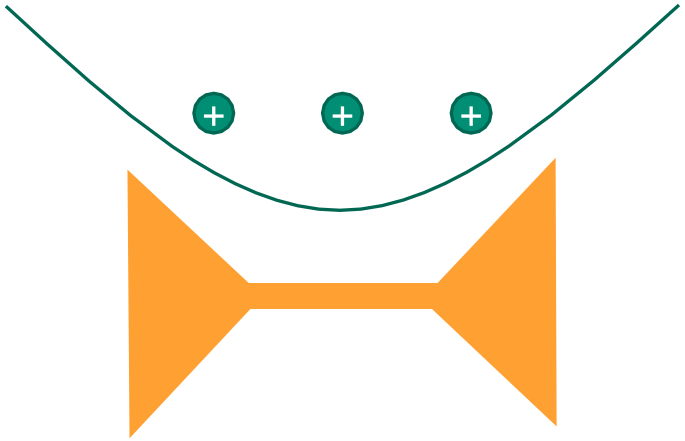
Ion RF Paul Trap

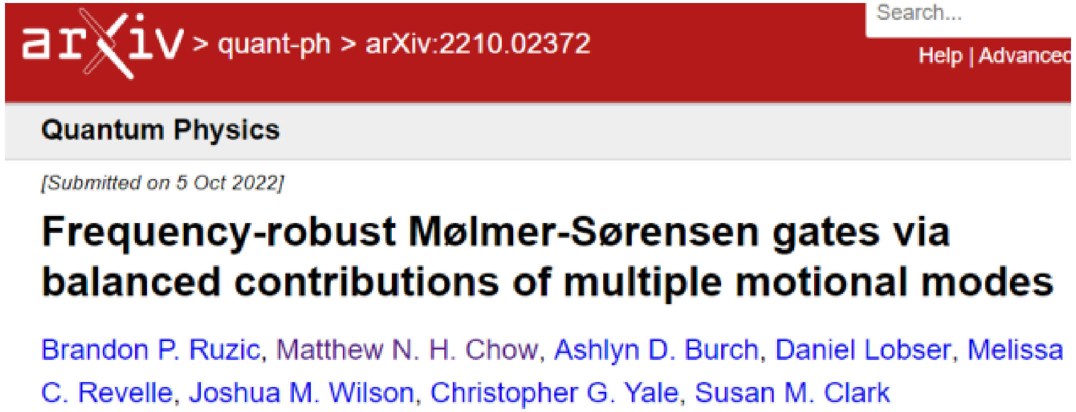


Critical challenge: Error mitigation for entangling gates

Design pulses for robust operation

Schedule:

- Intro to trapped ion QC
- Mølmer–Sørensen Gates
- How our gate design achieves robustness to trap frequency drift.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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

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

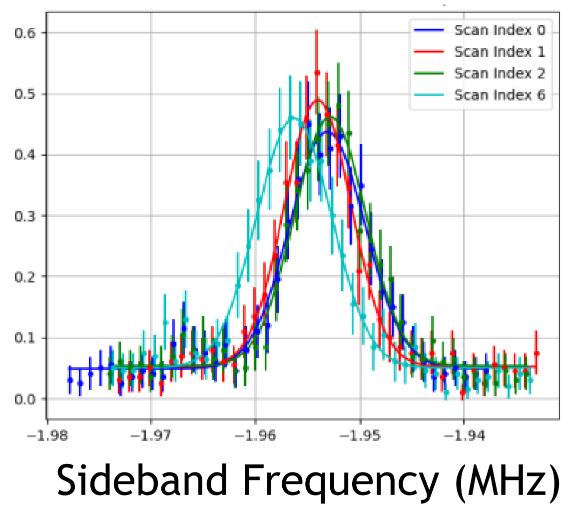
  [Ballance 2016, Gaebler 2016]

- Peak entangling gate ≥ 0.999

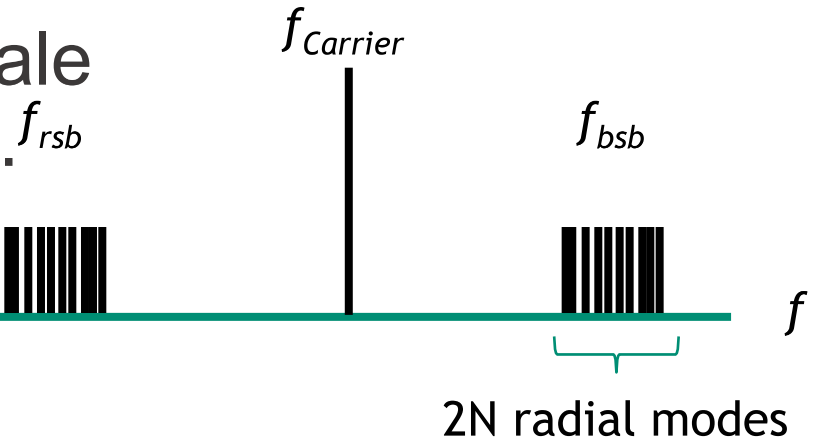
  [Ballance 2016, Gaebler 2016]

… however

- Motional frequency drifts impact the entangling gate.



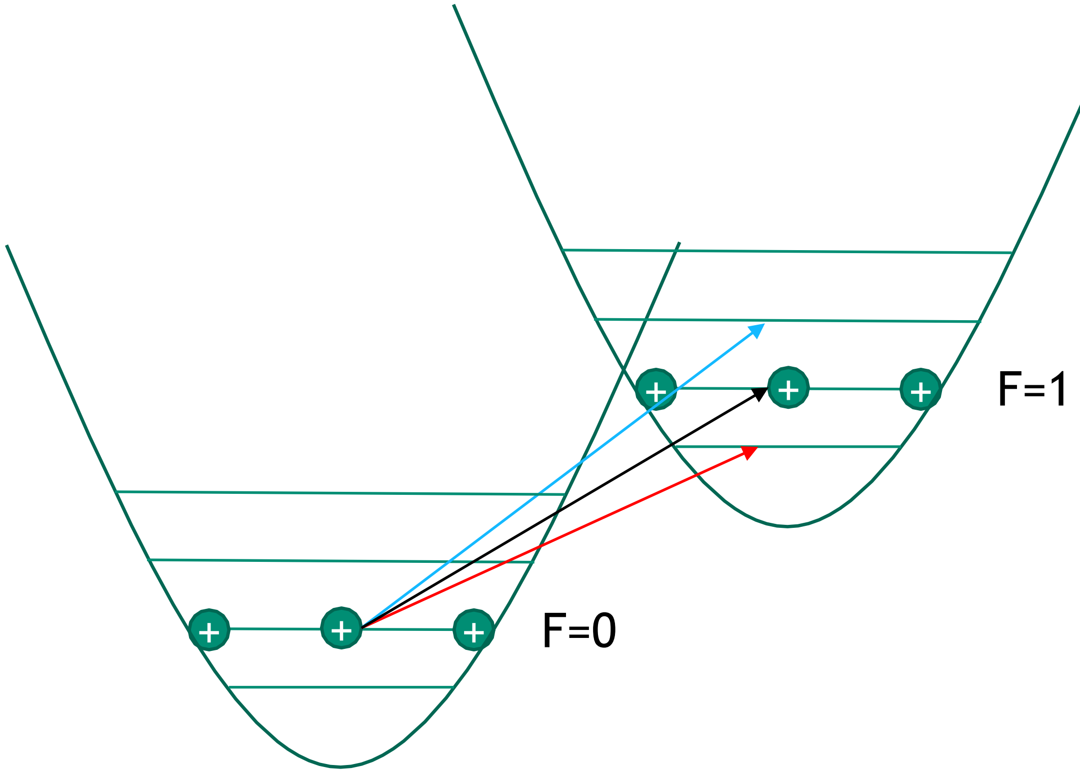
- It's hard to scale to large chains.

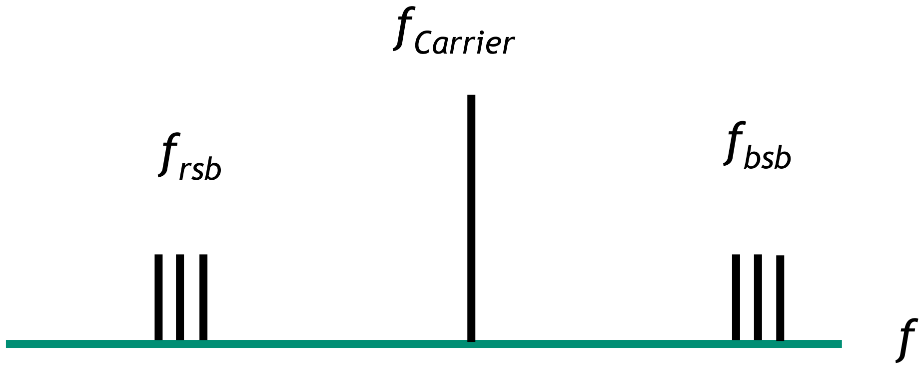


Solution? Develop gates that are robust to trap frequency drift that can be implemented on long chains.

arXiv : 2210.02372

Shared motional modes mediate entangling interactions





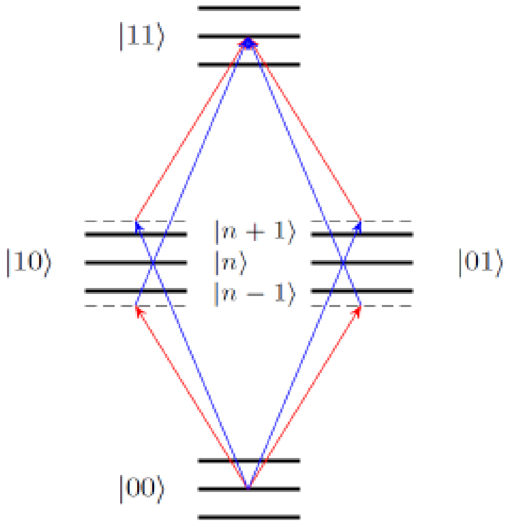
Red sideband: n-1
Remove a phonon

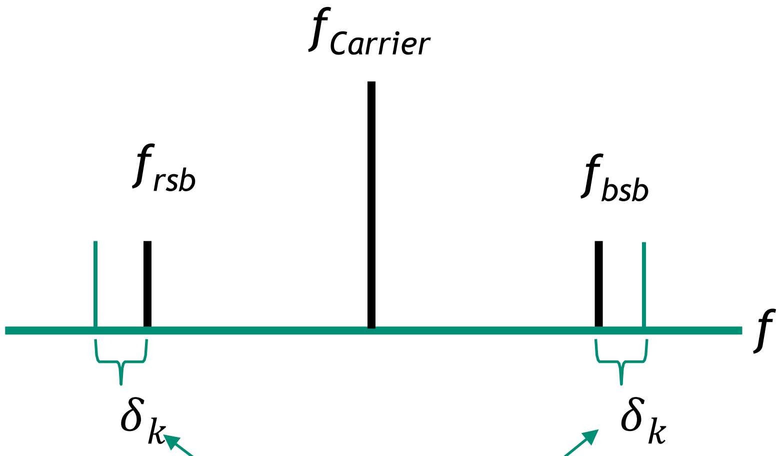
Blue sideband: n+1
Add a phonon

- 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

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





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

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

arXiv : 2210.02372

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

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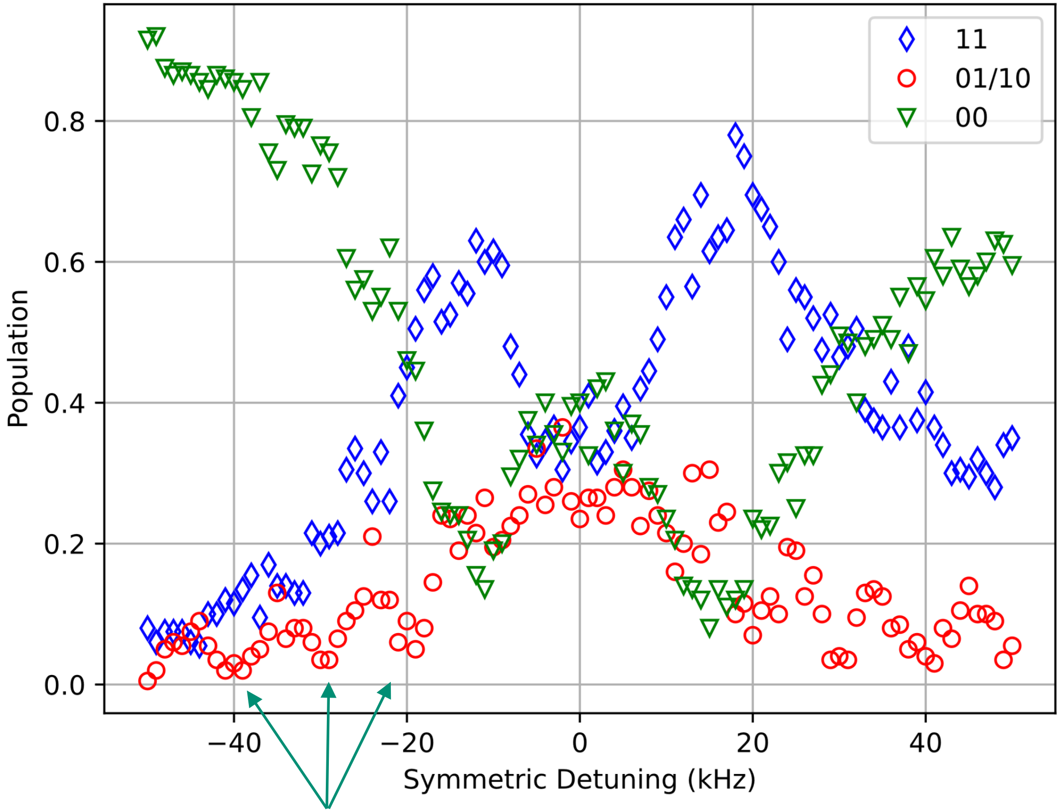
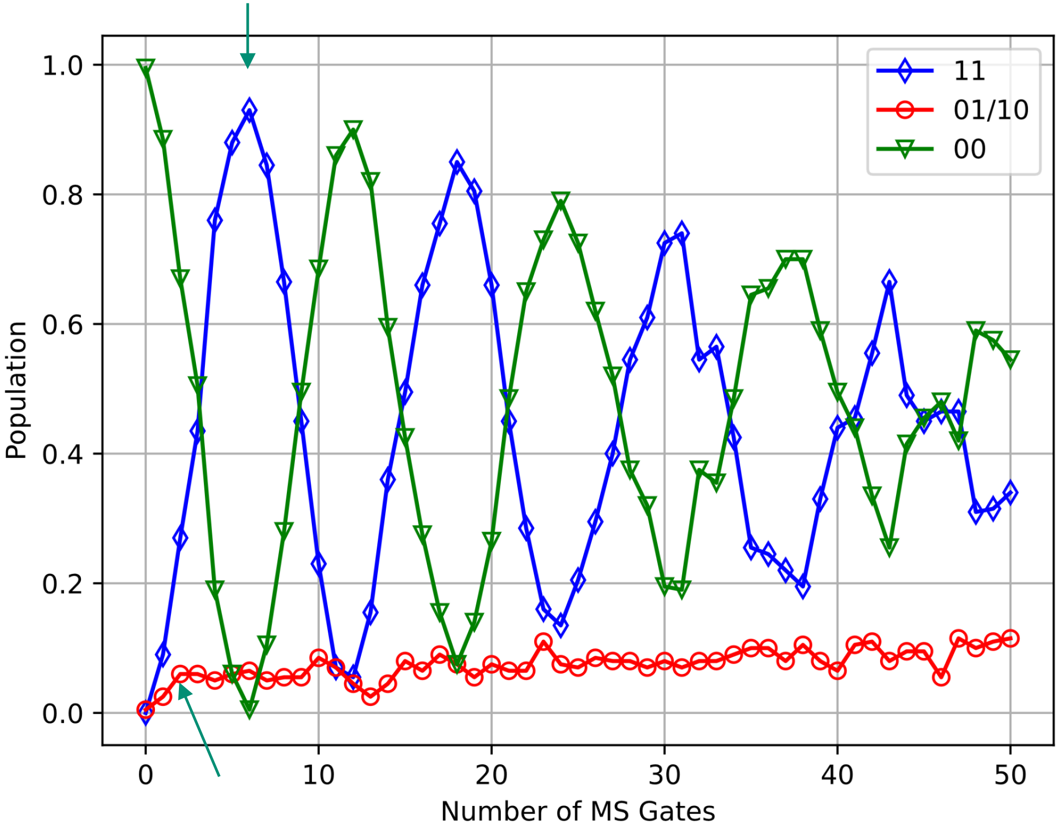
Ideally, the gate generates flopping between $|00\rangle$ and $|11\rangle$ - never populating odd parity states.



- 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

arXiv : 2210.02372

Separating displacement and rotation error clarifies gate failure analysis.

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,** ϵ_d.

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

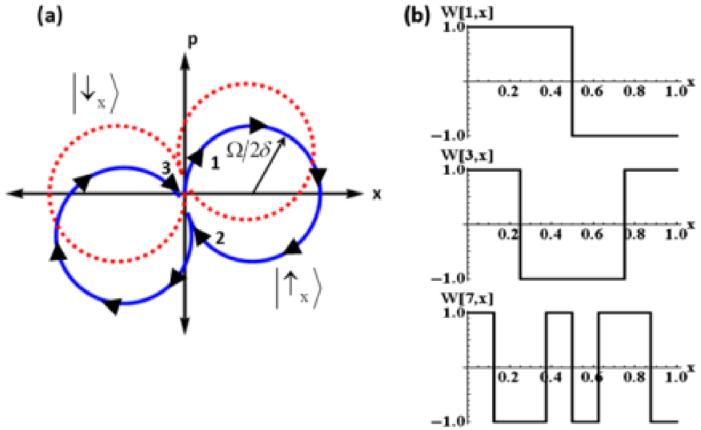
If $\theta(\tau) \neq \pi/2$,

then the entangling phase accumulated is not equal to the target value.
We call this **rotation error,** ϵ_r.

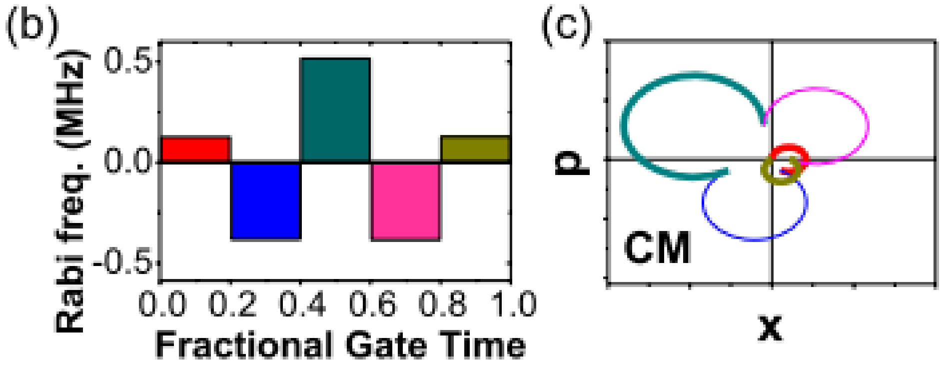
Experimental indicator: ratio of $|00\rangle$ to $|11\rangle$

For robust gate, both ϵ_d and ϵ_r to be small over a broad acceptable range of input parameters.
Pioneering work by Brown and Monroe groups have found ways to minimize ϵ_d:

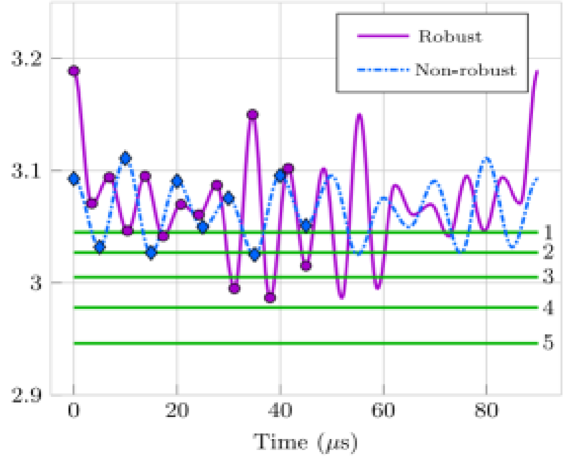
[Hayes et al 2012]



[Choi et al 2014]

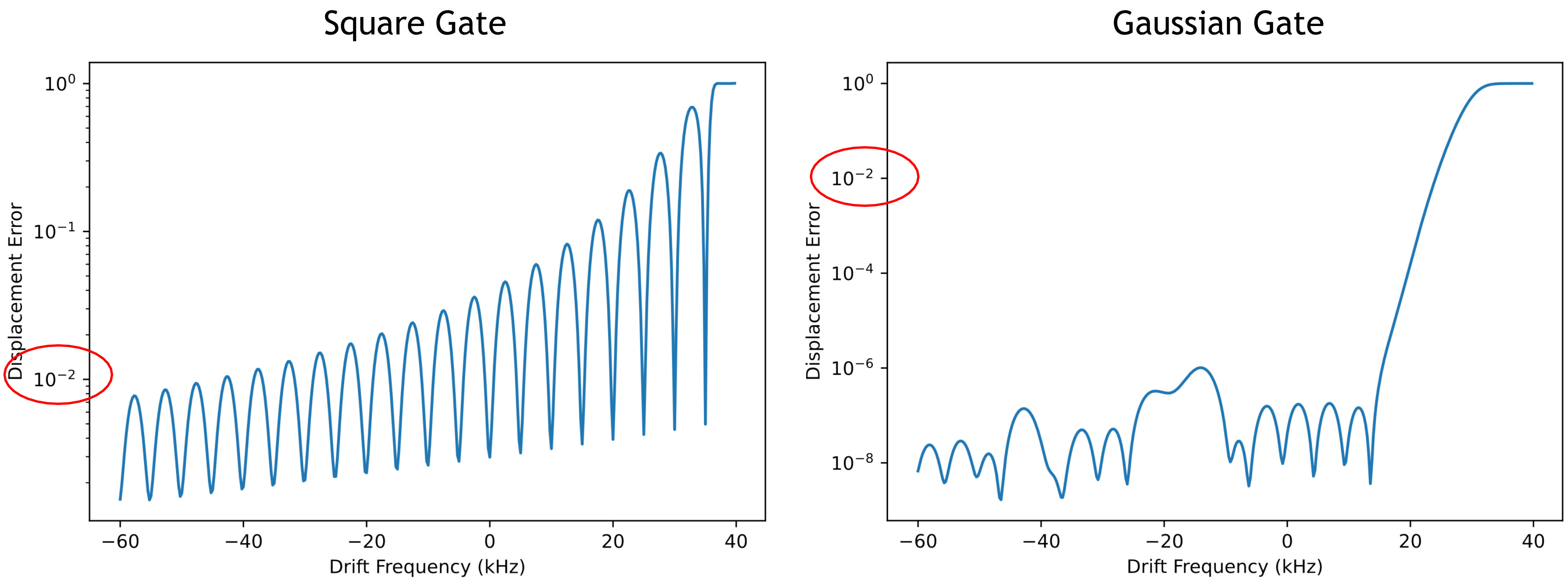


[Leung et al 2018]



arXiv : 2210.02372

Gaussian pulse shape is ‘naturally’ robust to displacement error.

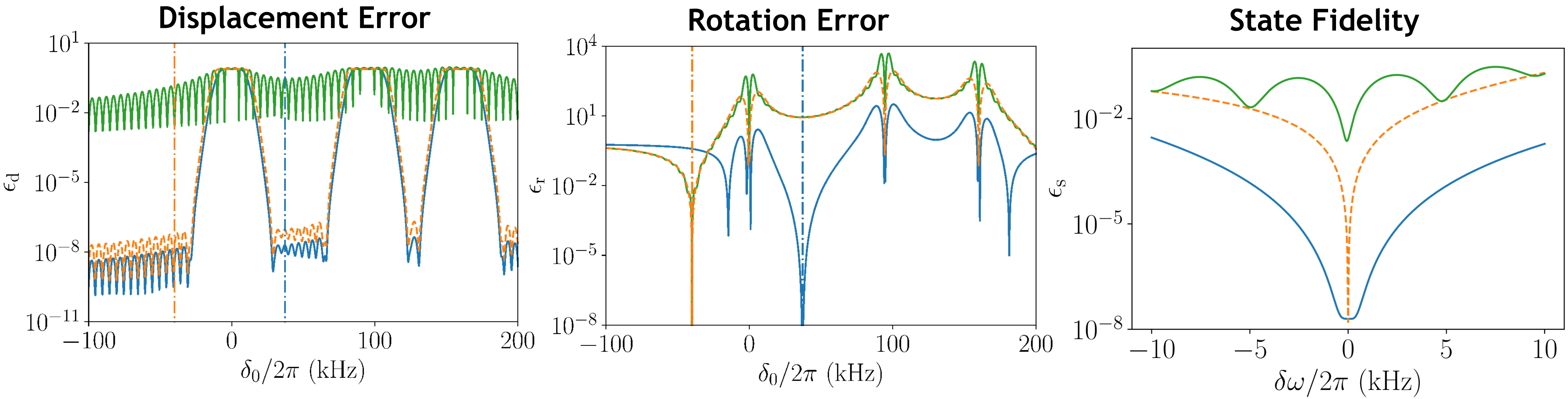


In the Gaussian gate, we still need the right detuning and amplitude to get the right area enclosed, but this shows broadly robust spin-motion disentanglement at the end of a Gaussian gate.

arXiv : 2210.02372

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

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



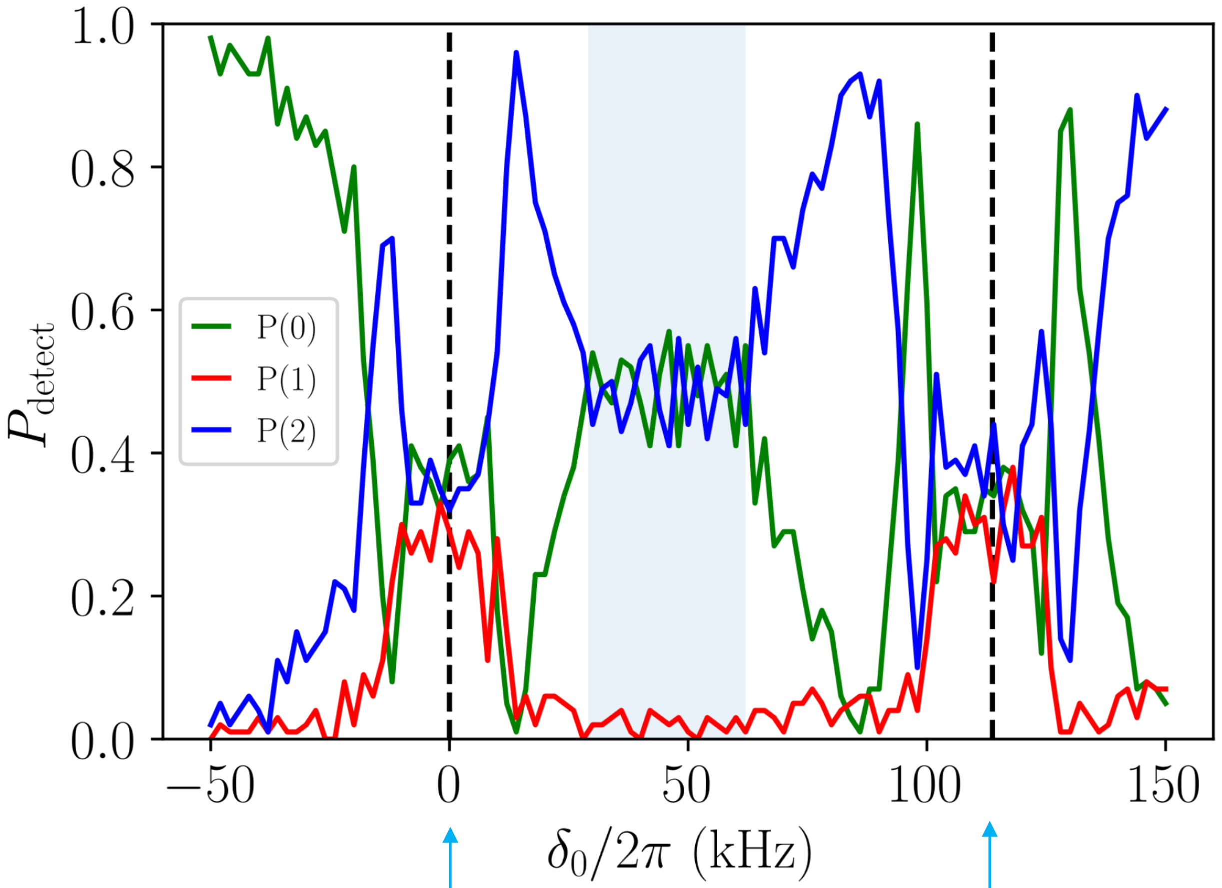
Pulse shape: Balanced Gaussian, Gaussian, Square

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

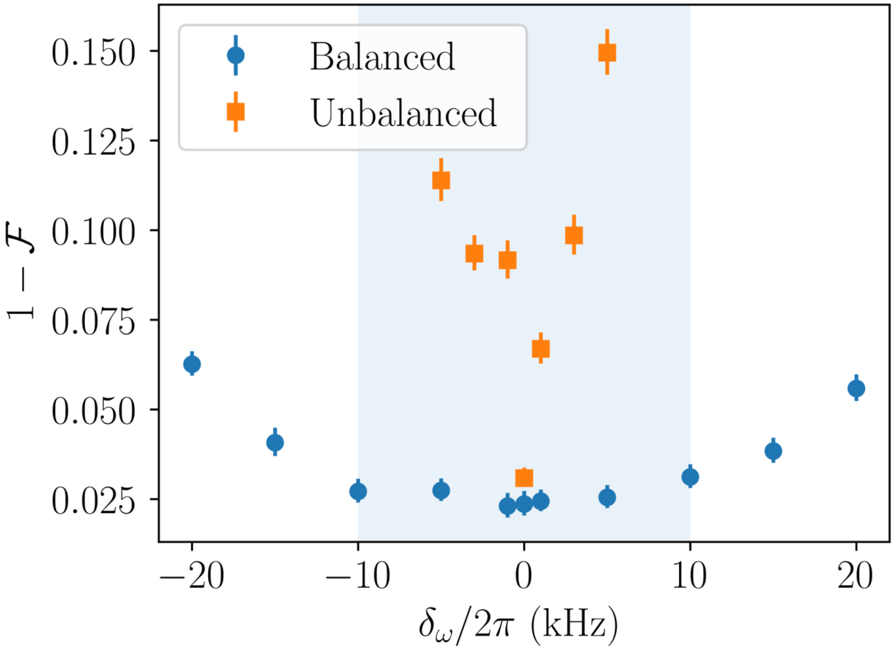
arXiv : 2210.02372

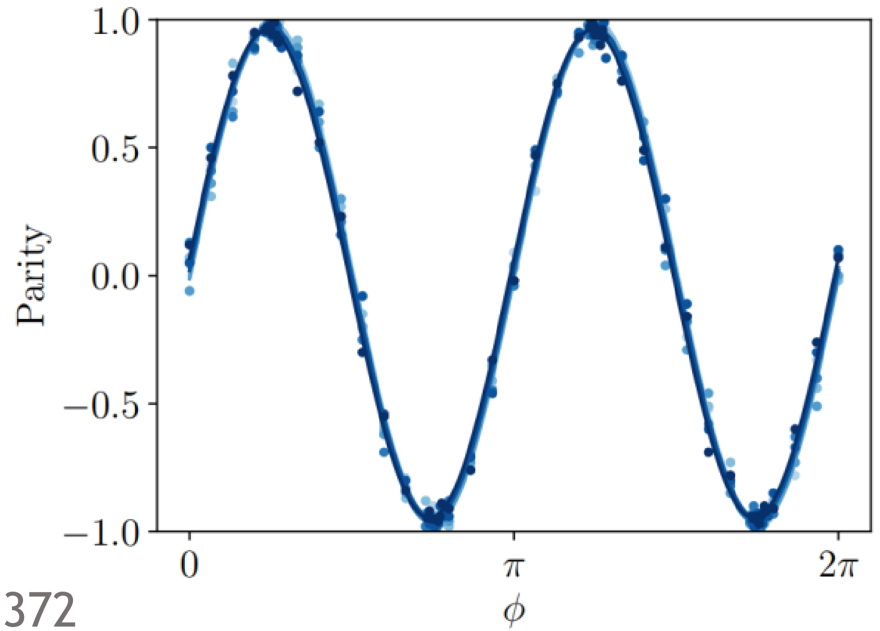
Experiment shows balanced Gaussian is robust to +/-10 kHz trap frequency drift

Peak fidelity = 97.7(4)%
Drop in fidelity over +/-10 kHz < 1%



3 ion modes: Zig-zag Tilt





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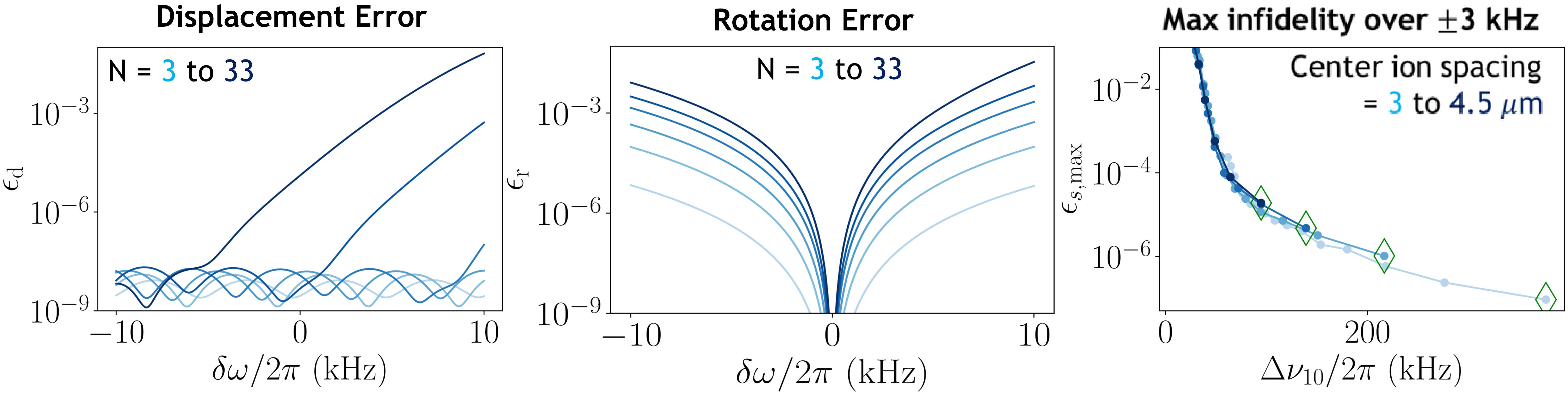
We find good prospects for scaling to more ions.

- Numerical simulations for chains of up to 33 ions
- Fixed center ion separation: results shown are for 3 μm

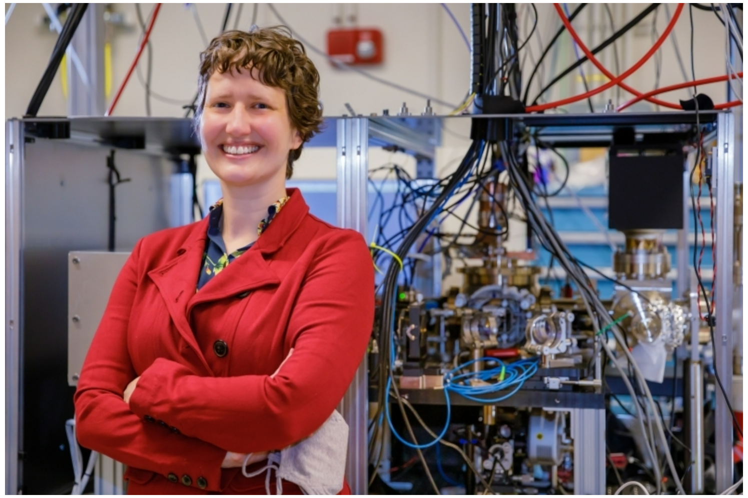


- Sensitivity (right plot) depends almost entirely on the splitting of nearest two modes

arXiv : 2210.02372

QSCOUT Team

Email: qscout@sandia.gov to be added to mailing list
Website: qscout.sandia.gov
Jaqal: github/jaqal



QSCOUT

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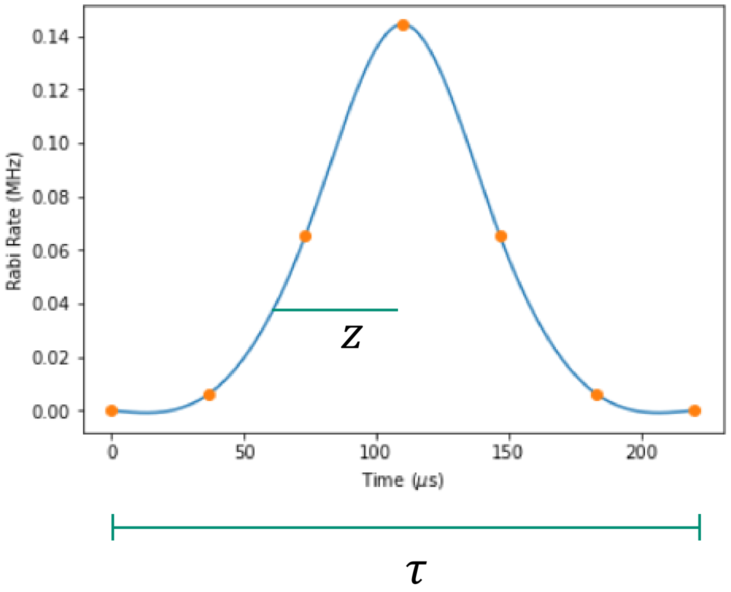
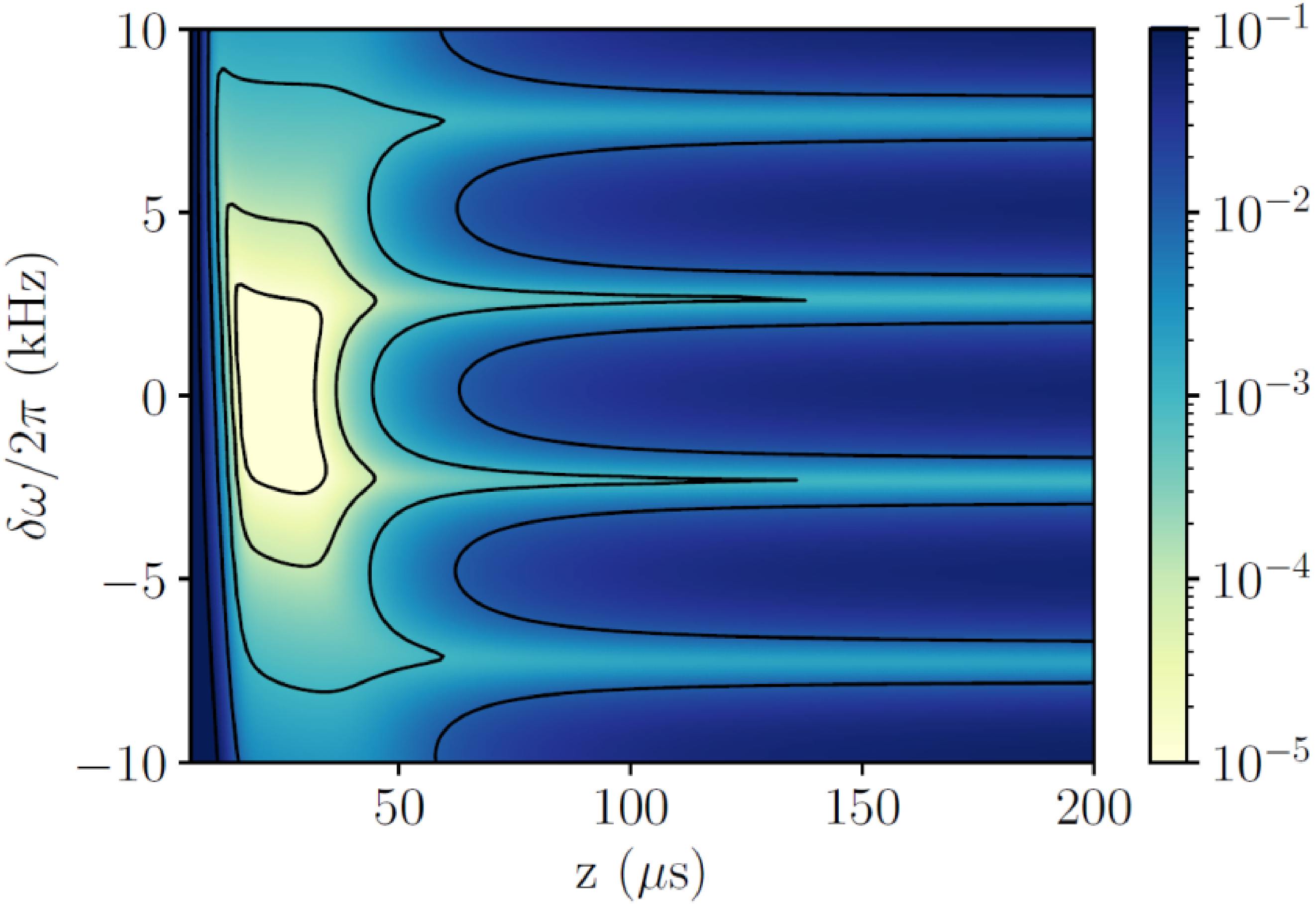
Extra Slides Beyond

Gaussian pulse parameters



z : time-domain standard deviation

τ : gate time, truncation window



RF Traps for Ions

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

Cannot use
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Field lines
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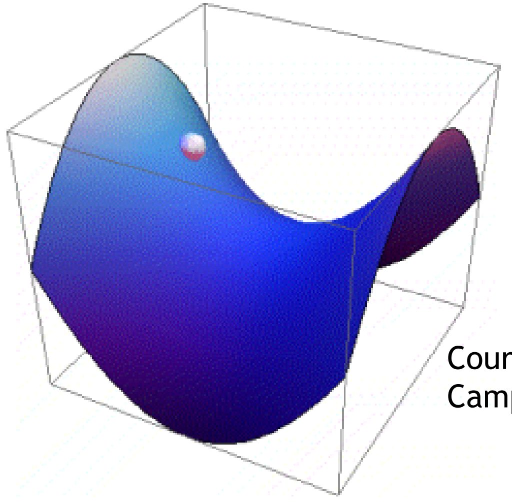
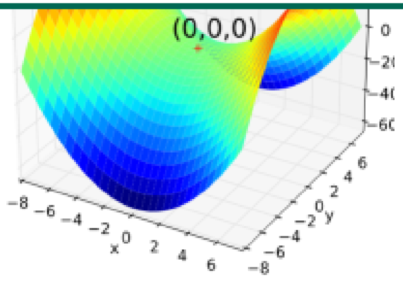
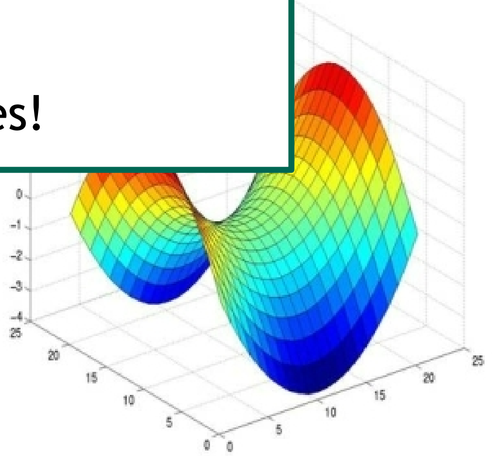



Courtesy of Wes Campbell

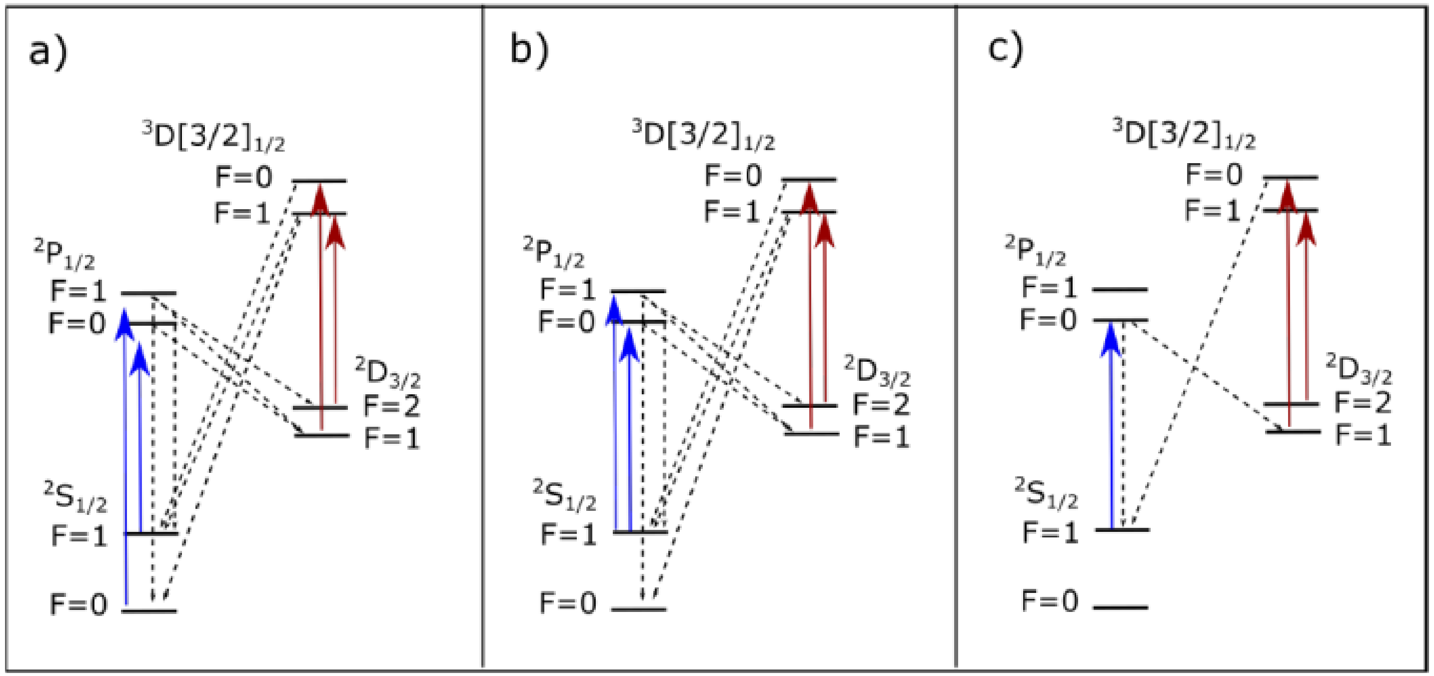
Before ion escapes, field reverses!



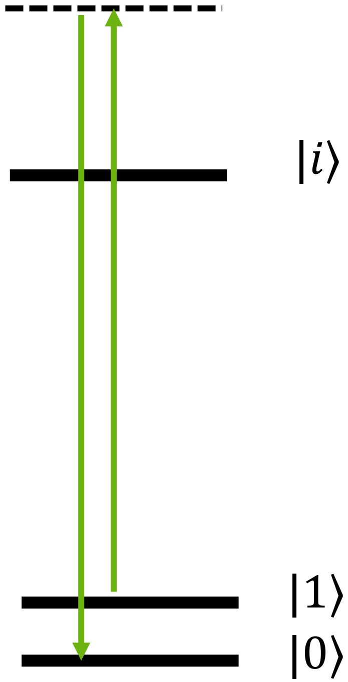


Crash Course in Trapped Ion Quantum Computing

$^{171}Yb^{+}$



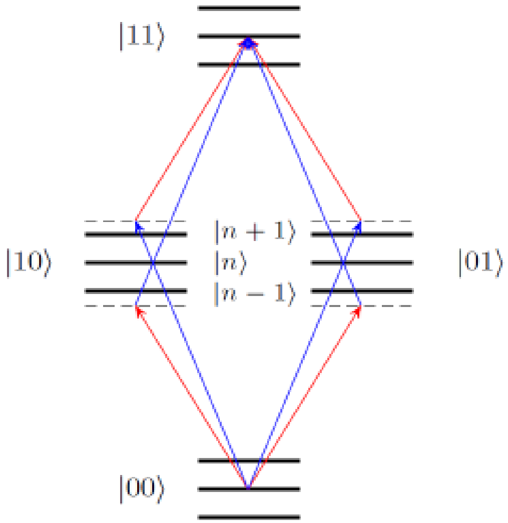
Cool Pump Detect

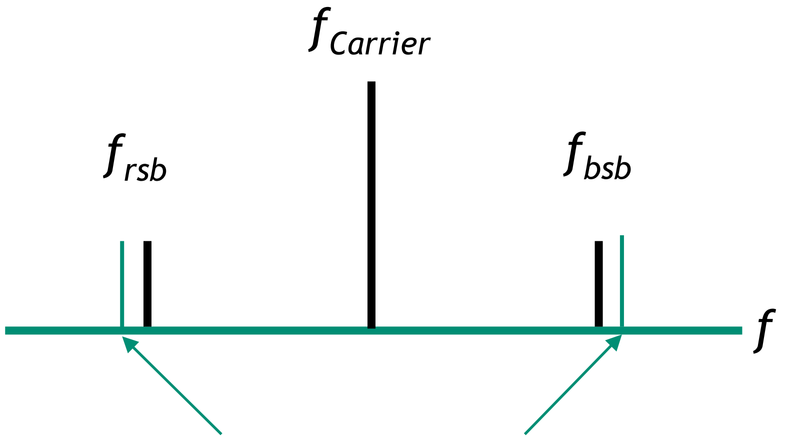


Qubit Rotations

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

The Mølmer-Sørensen (MS) gate is derived from a spin-dependent force.





Apply 2 Symmetrically Detuned Tones

Spin dependent force[1]:

$$\hat{H}_I = \frac{\hbar\eta\Omega}{2}\left(\hat{\sigma}_+\hat{a}e^{-i(\delta t-\phi_r)} + \hat{\sigma}\_\hat{a}^\dagger e^{+i(\delta t-\phi_r)}\right) + \frac{\hbar\eta\Omega}{2}\left(\hat{\sigma}_+\hat{a}^\dagger e^{+i(\delta t+\phi_b)} + \hat{\sigma}\_\hat{a}e^{-i(\delta t+\phi_b)}\right)$$

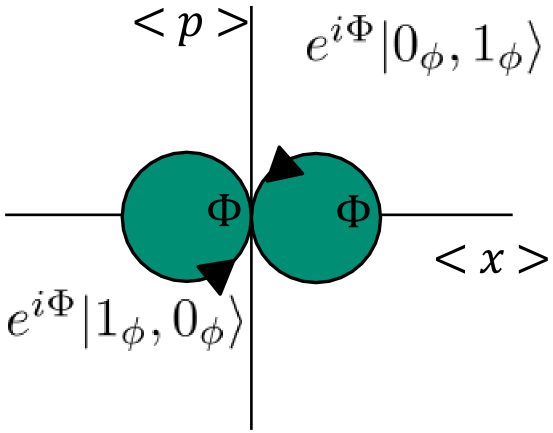
Jaynes-Cummings + Anti Jaynes-Cummings

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

Rearrange into Spin and Motion Phases

Drive loops in phase space, pick up geometric phase.

- Spin and motional parts of the wavefunction are disentangled when phase loops close.
- Fully Entangling Gate encloses a phase space area of $\frac{\pi}{2}$



[1] Lee, Patricia J., "Quantum Information Processing with Two Trapped Cadmium Ions", Univ of Michigan, 2006

Gaussian MS Gates Show Better Loop Closure than Square MS

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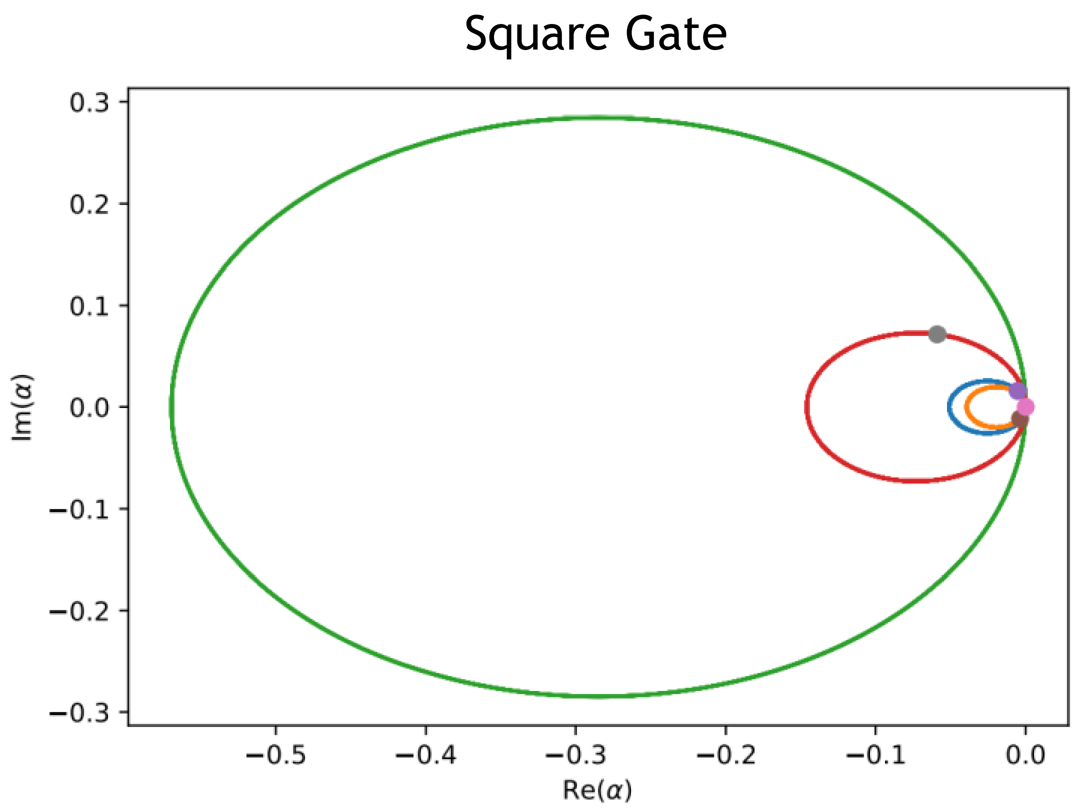
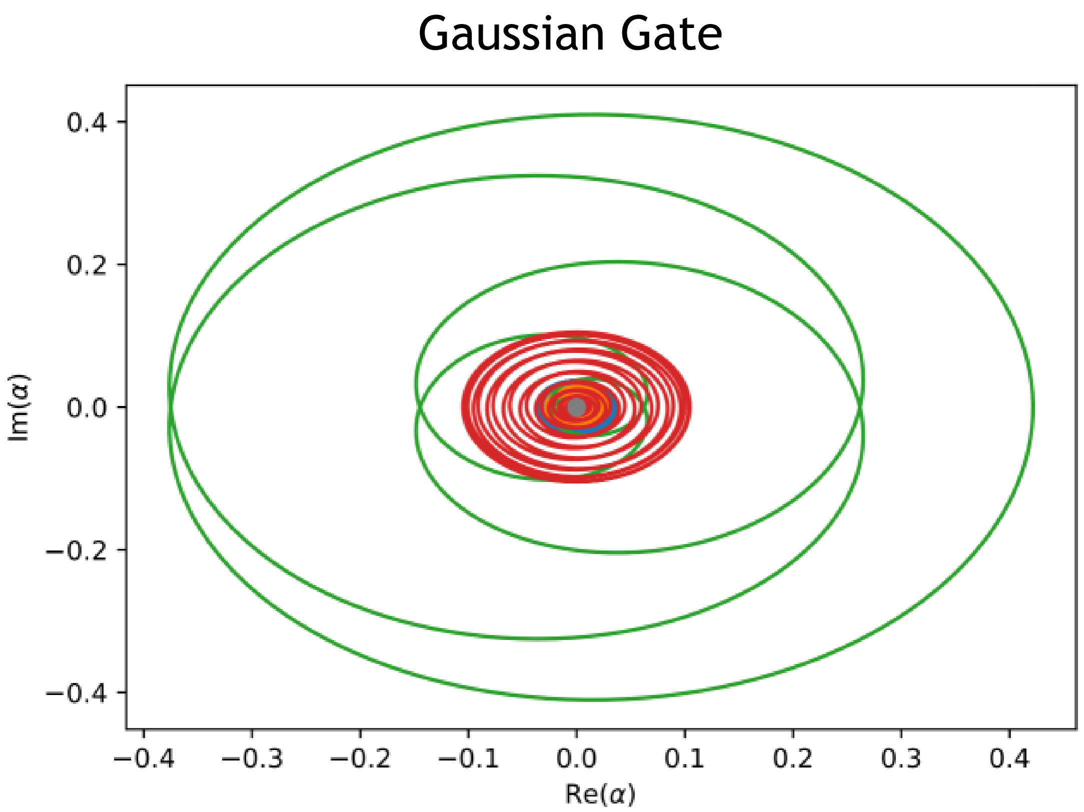




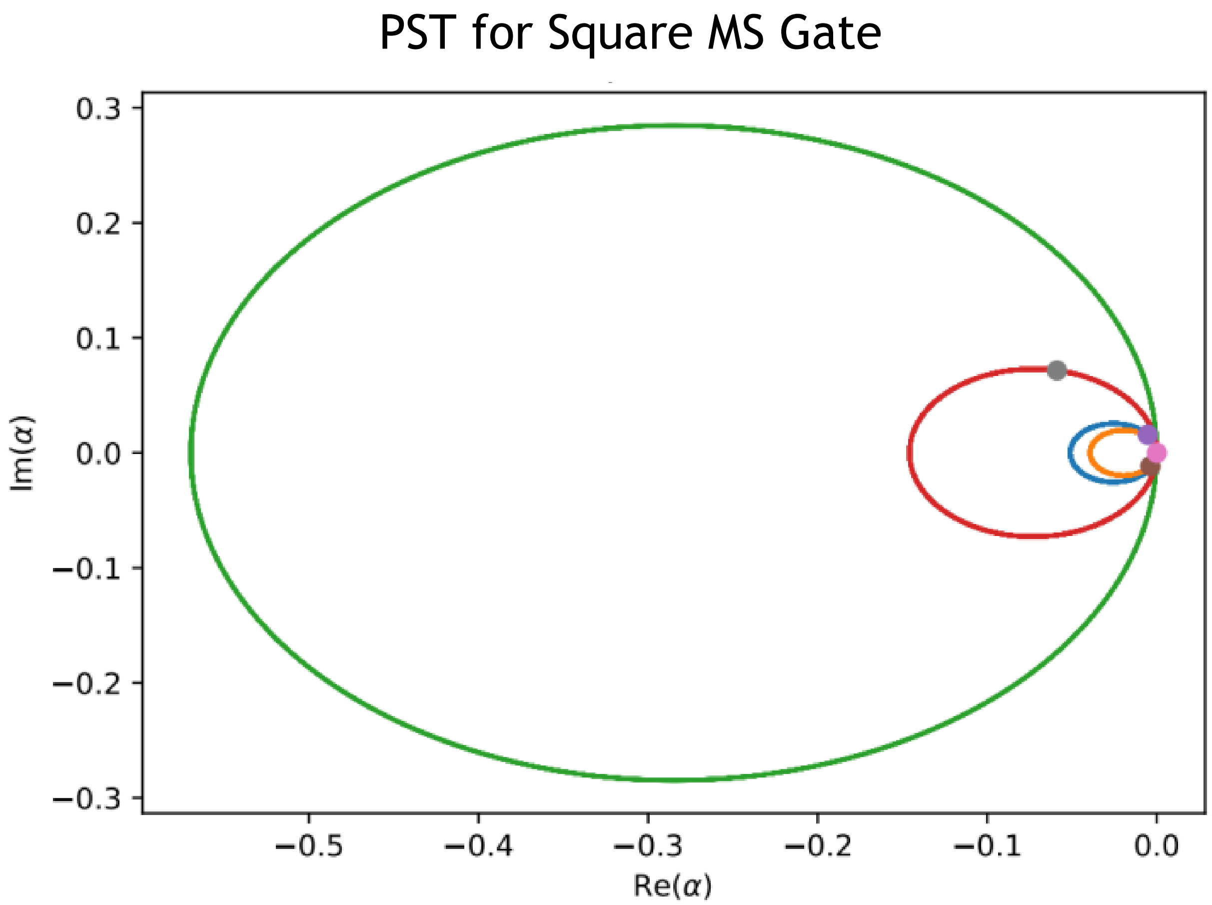
Gate parameters (for both):

- Detuning is -40 kHz below the lowest frequency mode in a 2 ion chain.
- 200 μs duration

Notable differences:

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

Intuition for Phase Space Trajectories (PSTs)



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?

Displacements During the MS Gate

QSCOUT

Interaction Hamiltonian:

$$\hat{H}_I = \frac{\hbar\eta\Omega}{2}\left(\hat{a}e^{-i(\delta t+\phi_M)} + \hat{a}^{\dagger}e^{+i(\delta t+\phi_M)}\right)\hat{\sigma}\bullet\phi_s$$

State dependent drive force gives coherent displacement by α_k on mode k [1]:

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

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

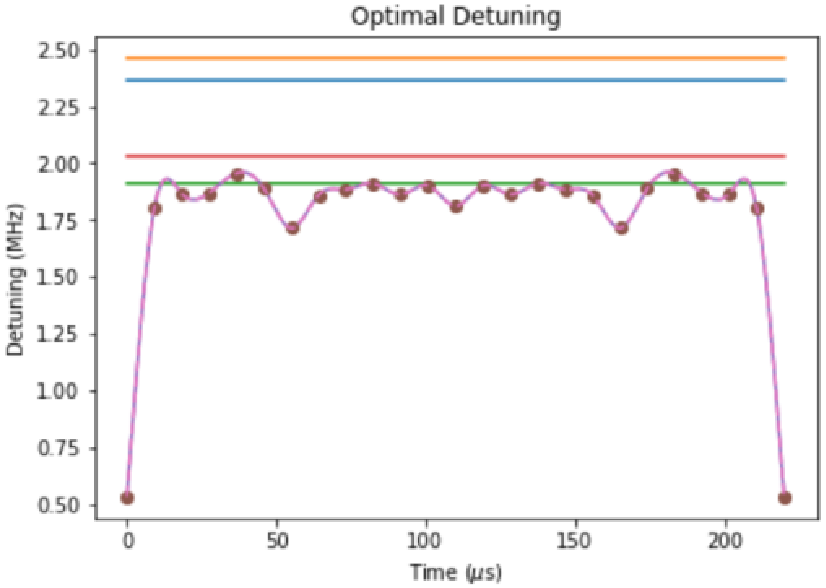
$$\alpha_k = \frac{\Omega}{2}\left(\eta_{i,k} + \eta_{j,k}\right)\int_0^t e^{i\theta_k(t')}\,dt' \text{ where } \theta_k(t') = \int_0^{t'} \delta_k(t'')dt'' \text{ is the accumulated phase}$$

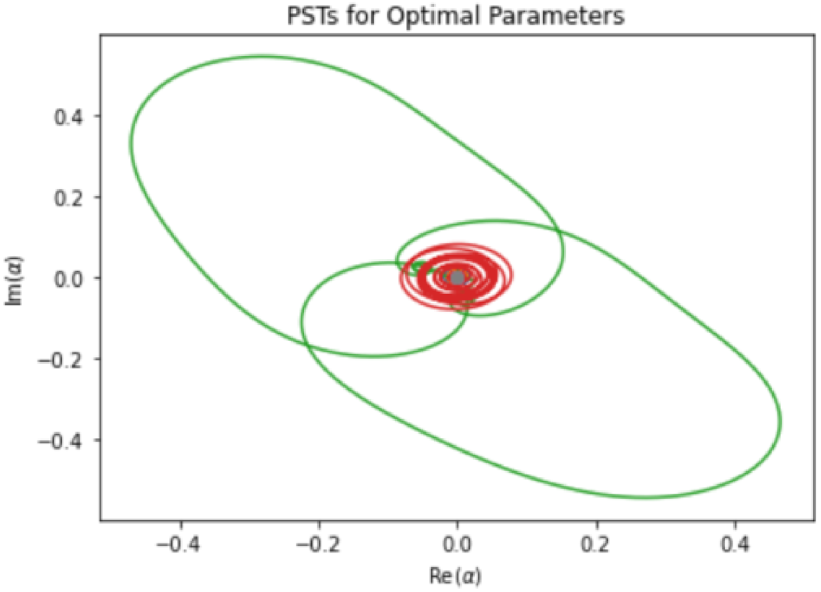
So, for a constant detuning and Rabi rate, we get circular trajectories in phase space, with closure condition: $t_{gate} = 2\pi m/\delta_k$.

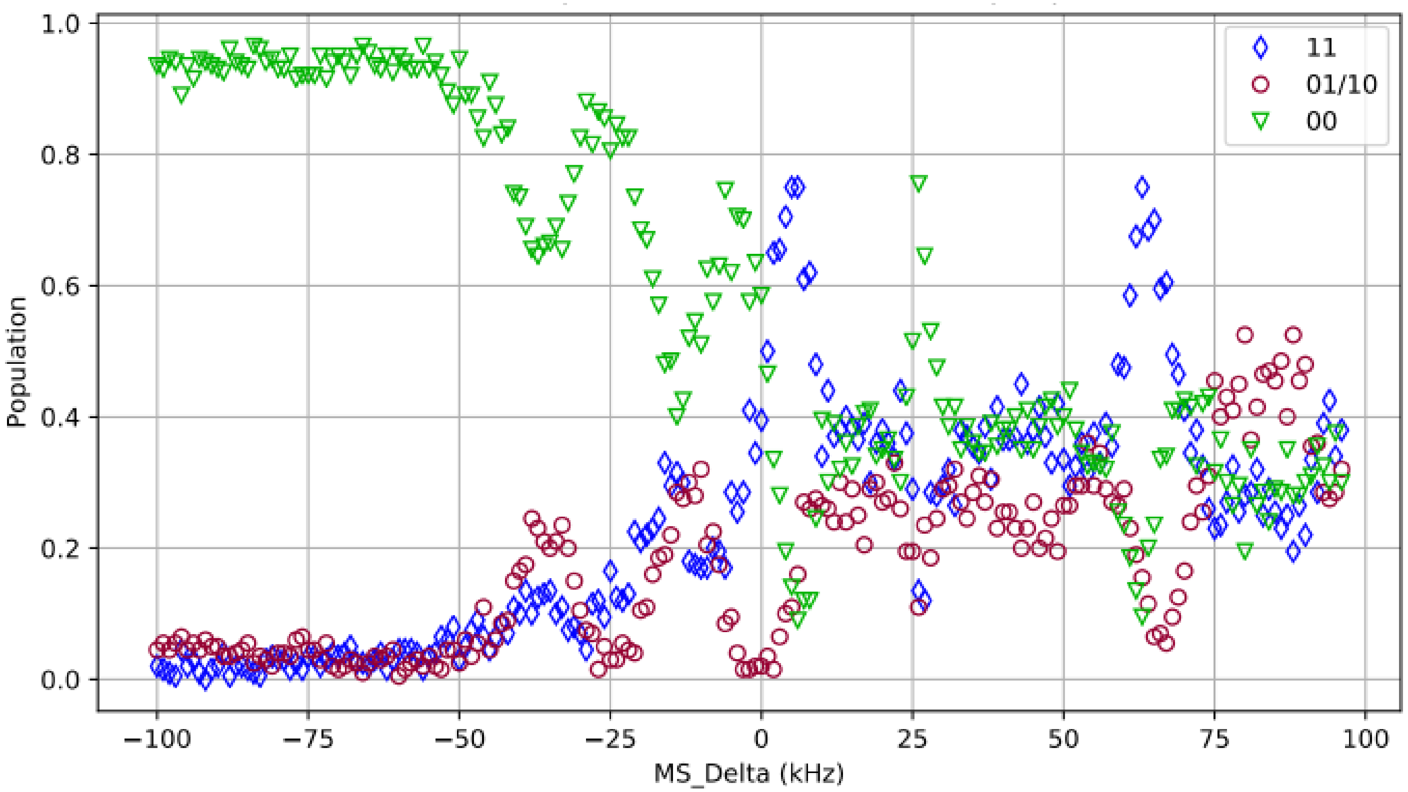
Closed loops are required for spin-motion disentanglement at the end of the gate.

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

FM and Constant Frequency Gaussians Are Comparable

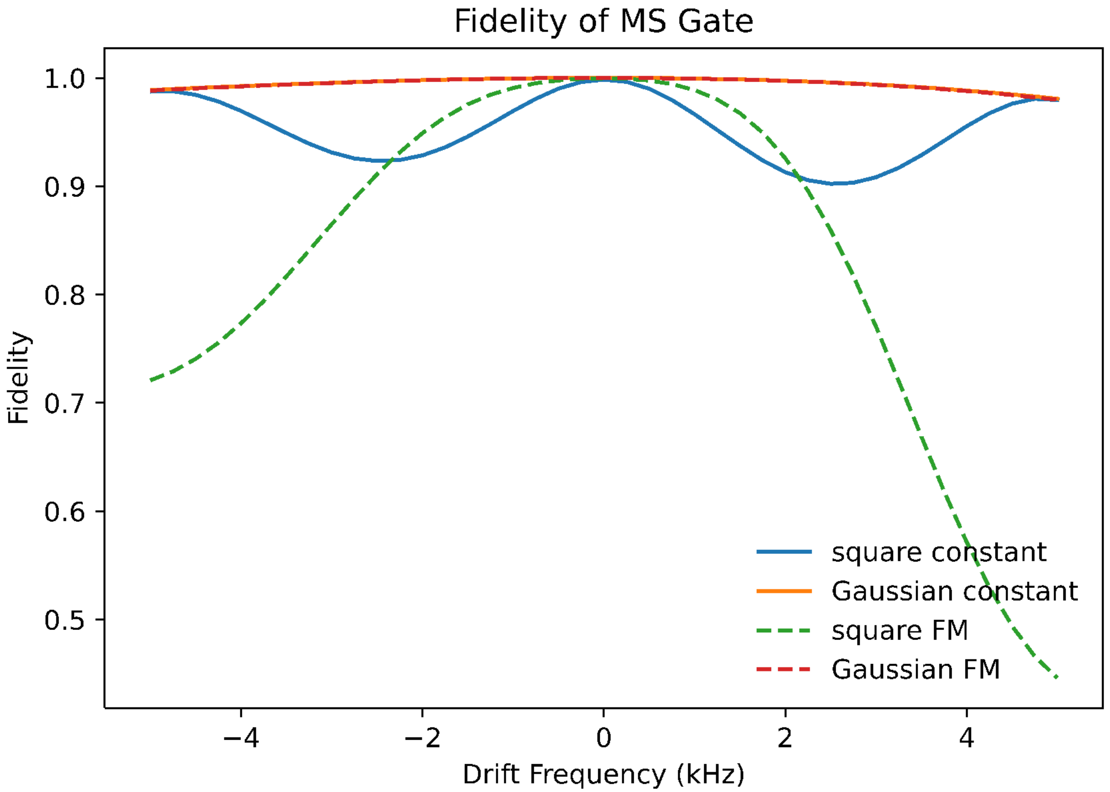


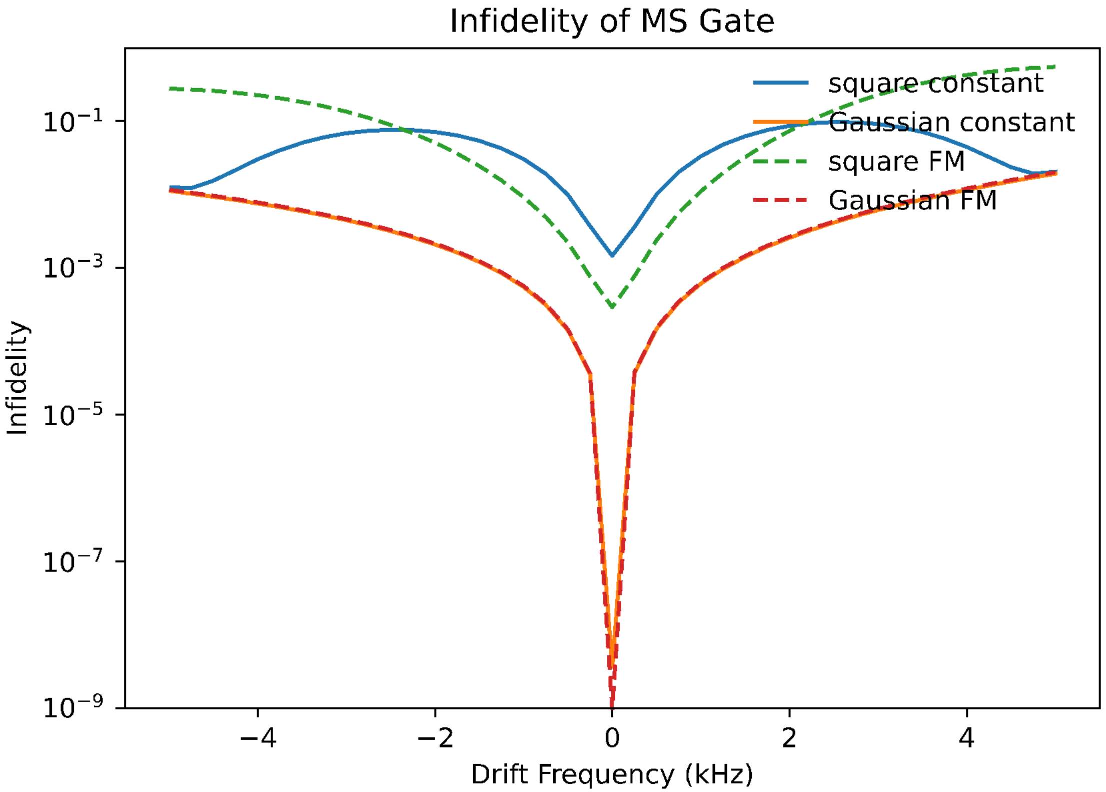




- See essentially the same odd parity population near optimized detuning.
- Area enclosed still has roughly the same sensitivity (slope of 11/00 crossing) as constant frequency case.

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

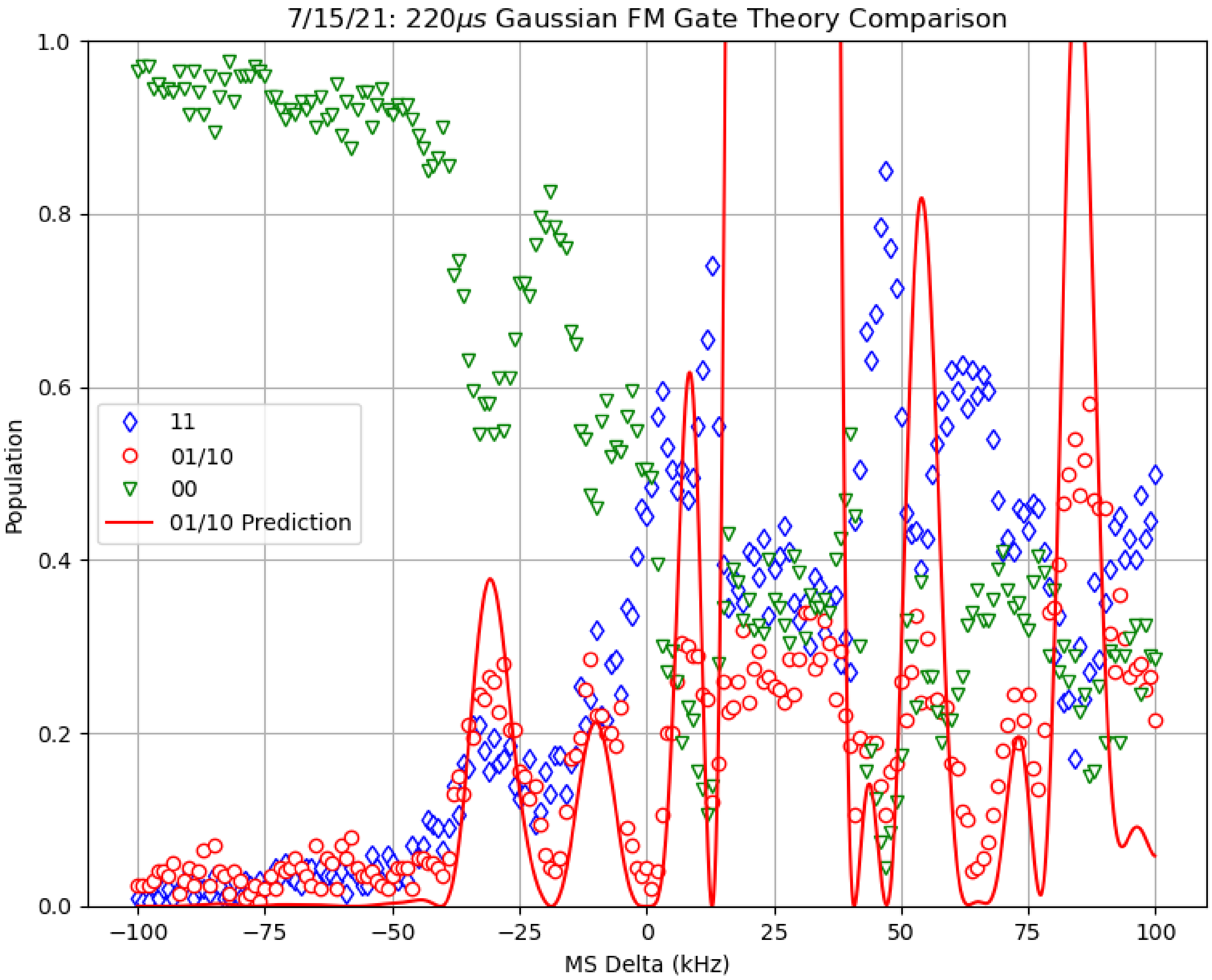




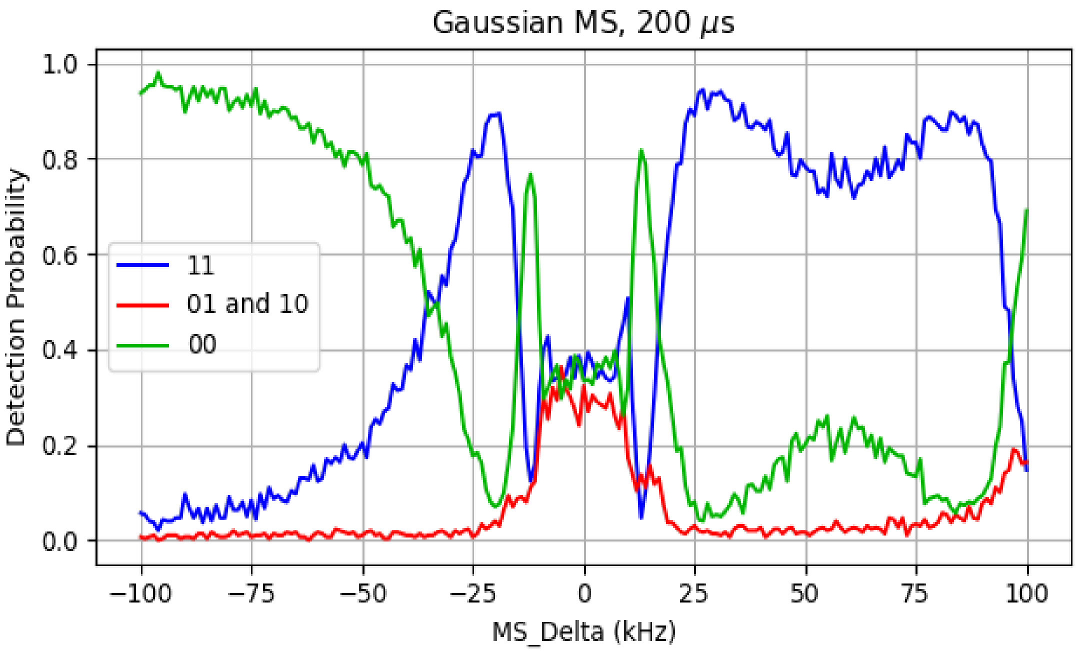
Next steps:

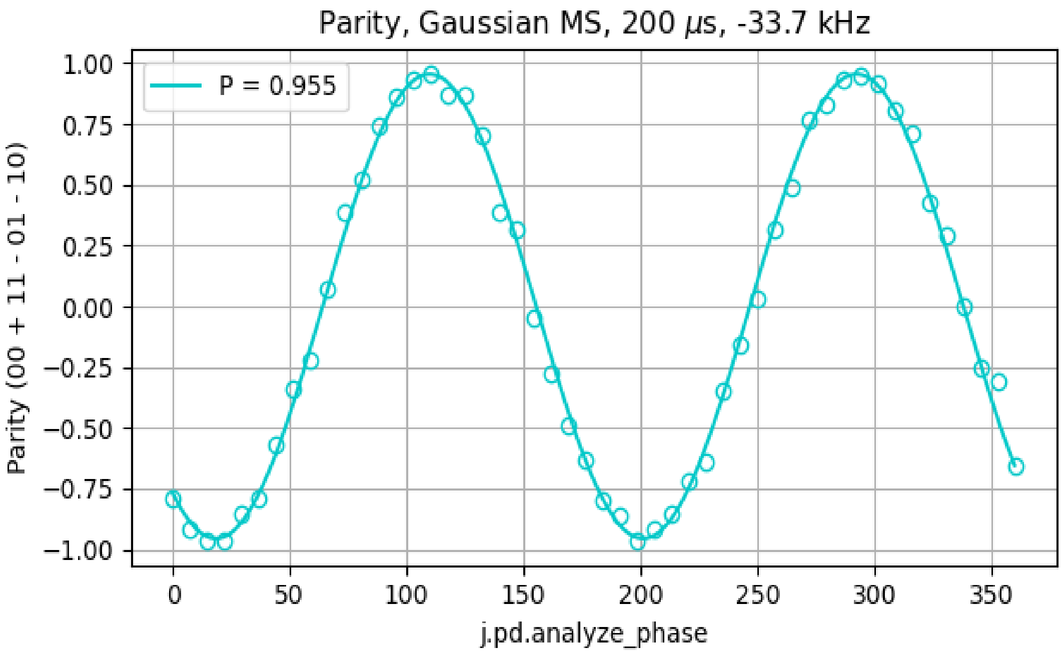
- Further development of gate angle cost function
- Batch optimization
- Transfer function optimization
- Larger chains

Optimizer/Data Comparison For FM Gaussian



Constant Frequency Gaussian MS Gates Work Well





Mølmer-Sørensen Entangling Gate

- $|00\rangle \rightarrow \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

Implementing with Octet

- Gaussian pulse shaping drastically improved our two-qubit gate performance

Entanglement Fidelity ~ 0.98

- Narrow acceptable detuning and amplitude range
- Area enclosed sensitive to small changes in trap RF