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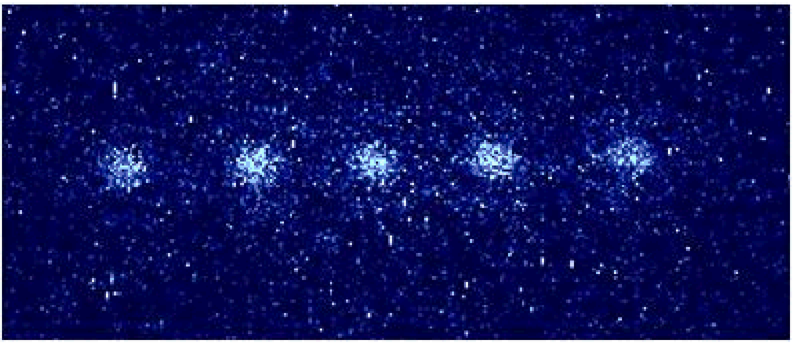

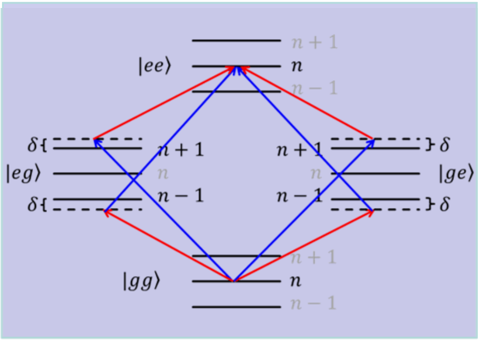

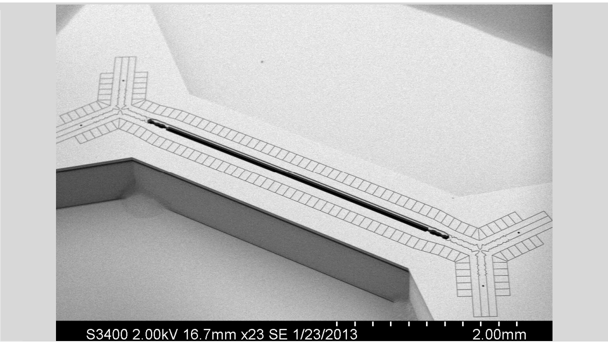

Quantum Information Processing in surface ion traps

Peter Maunz, Jonathan Mizrahi, Kenneth Rudinger,
Eric Nielsen, and Robin Blume-Kohout

February, 2015

IARPA

National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY

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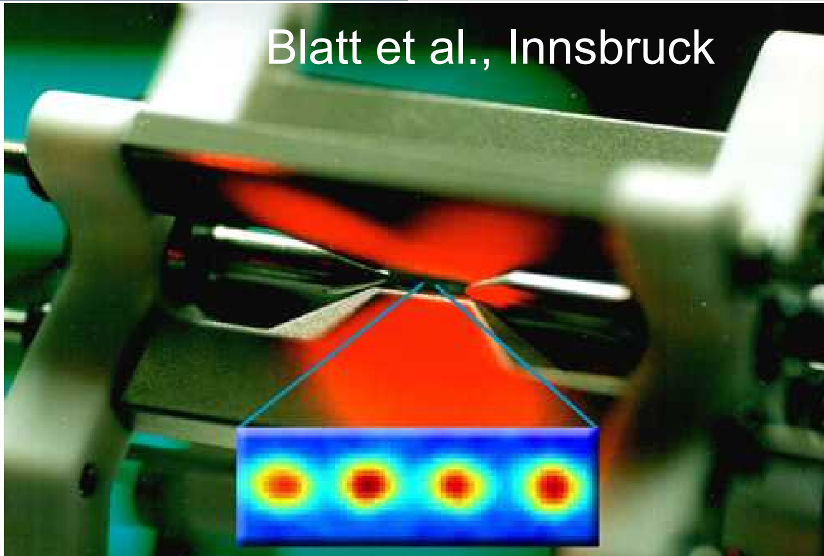
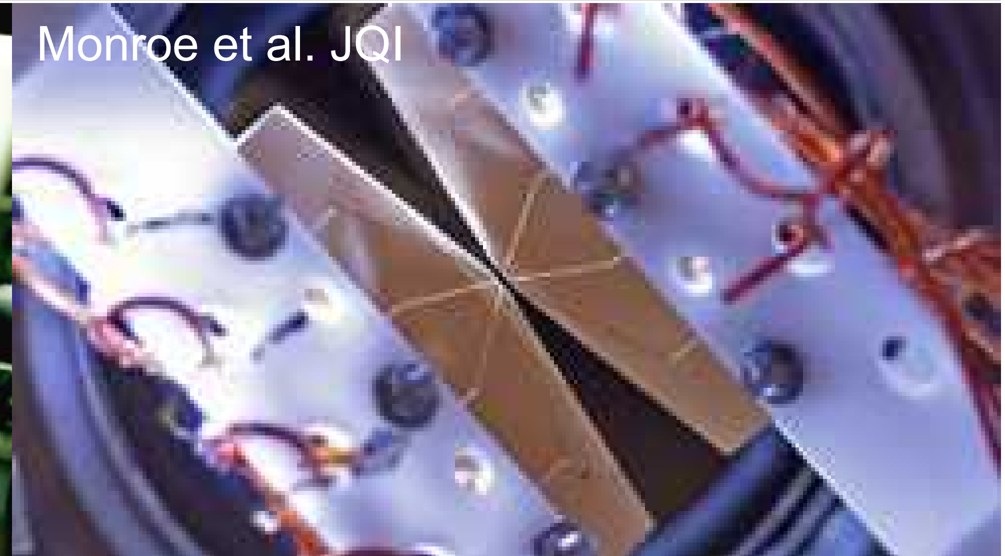
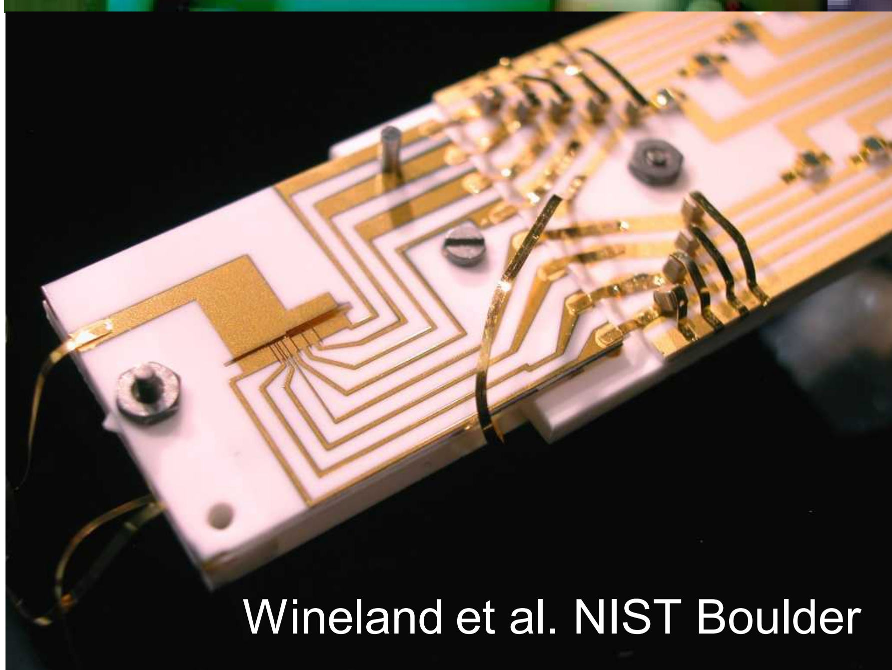
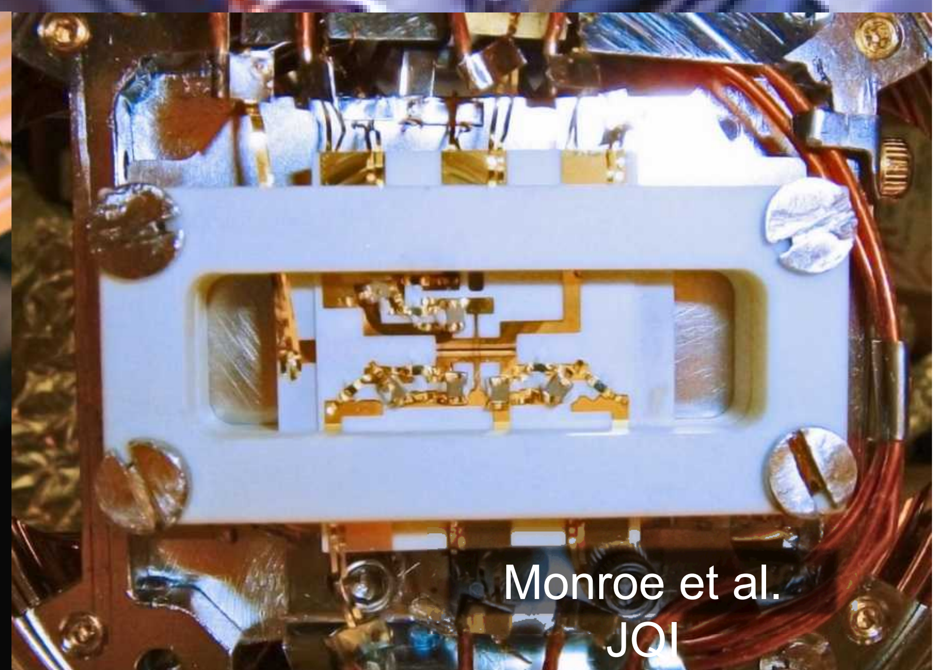
Towards scalable ion traps









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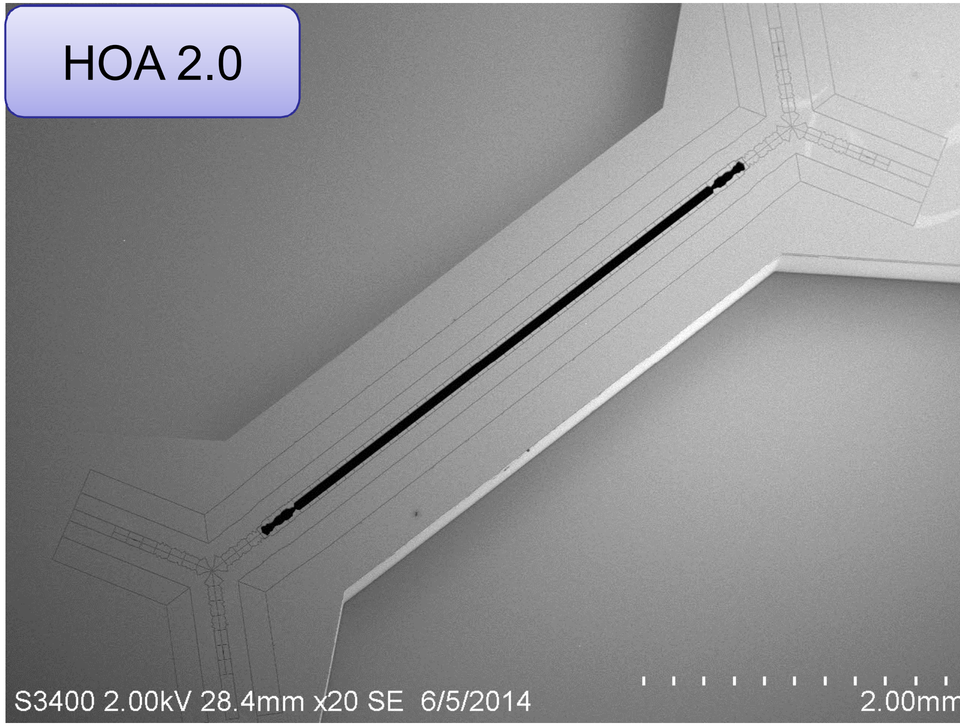
Micro-fabrication

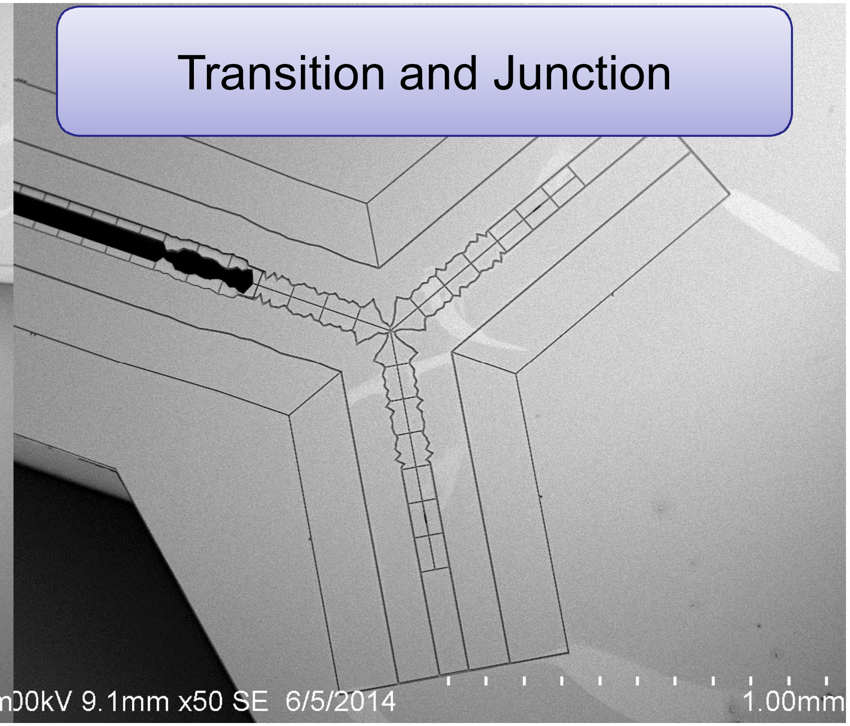
- Microfabrication enables scalable traps
- Optimize traps for Quantum information processing
- In realizing QIP we can learn and solve
  the challenges in small micro-fabricated traps

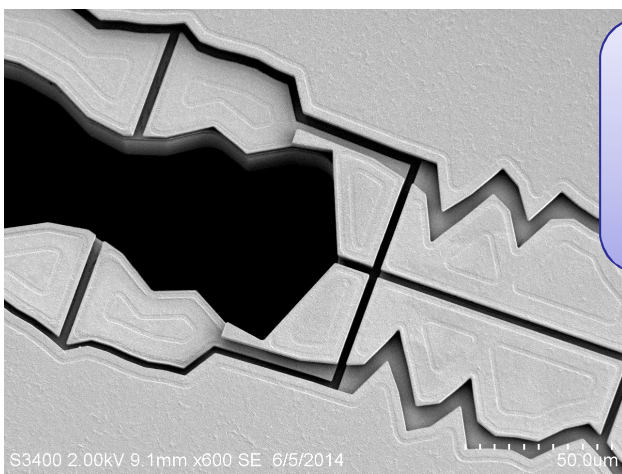
Trap details

HOA 2.0

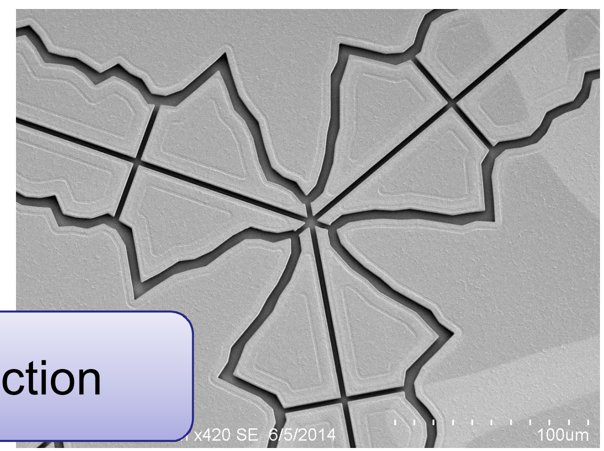


Transition and Junction



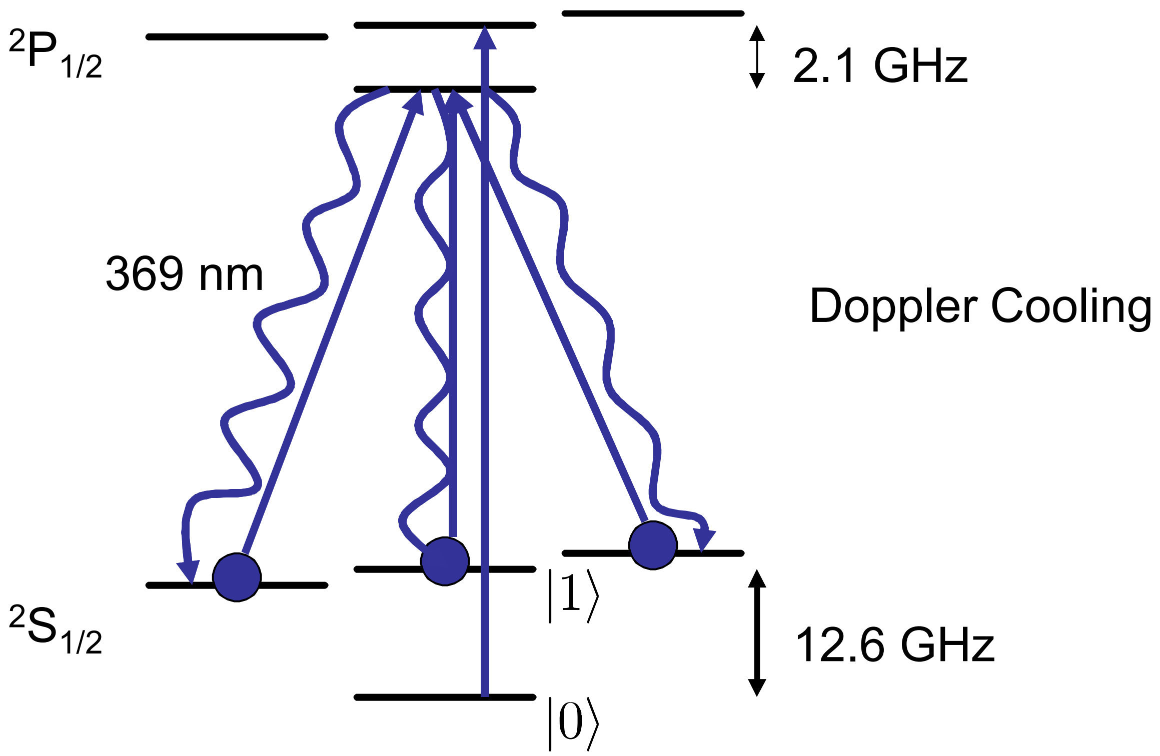


Vertical distance
12 μm



Junction

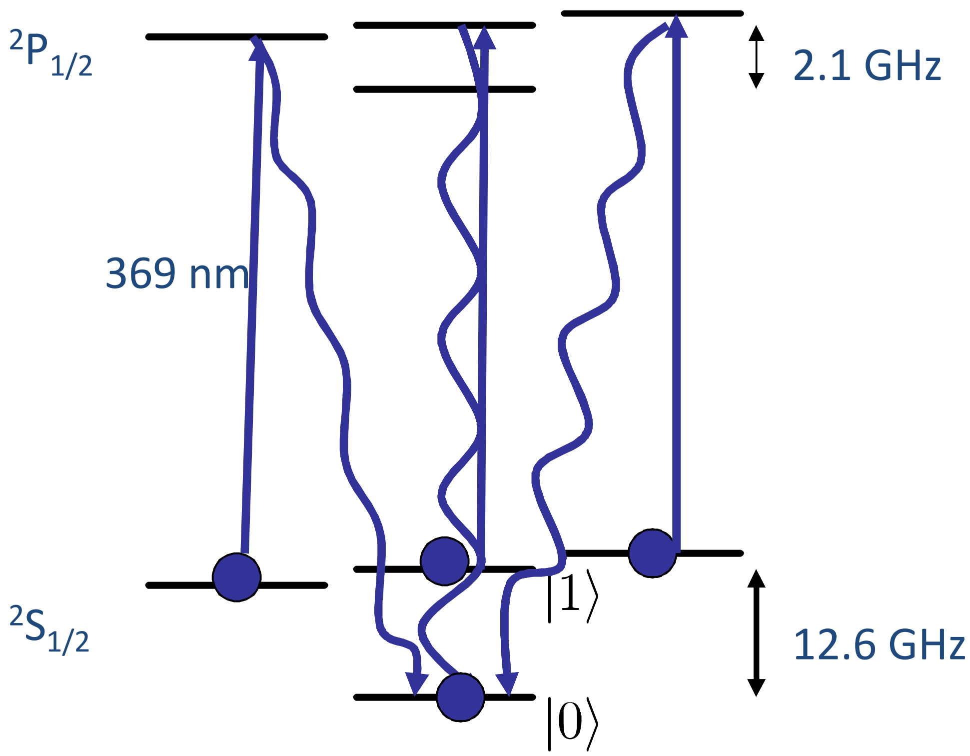
The Ytterbium Qubit



clock state qubit, magnetic field insensitive.

S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

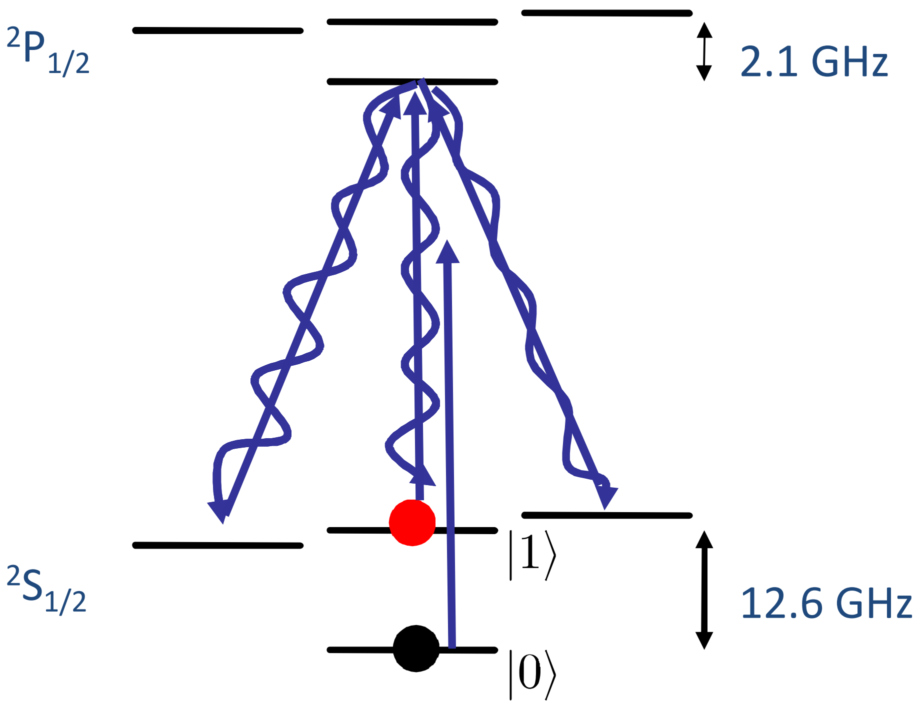
state initialization

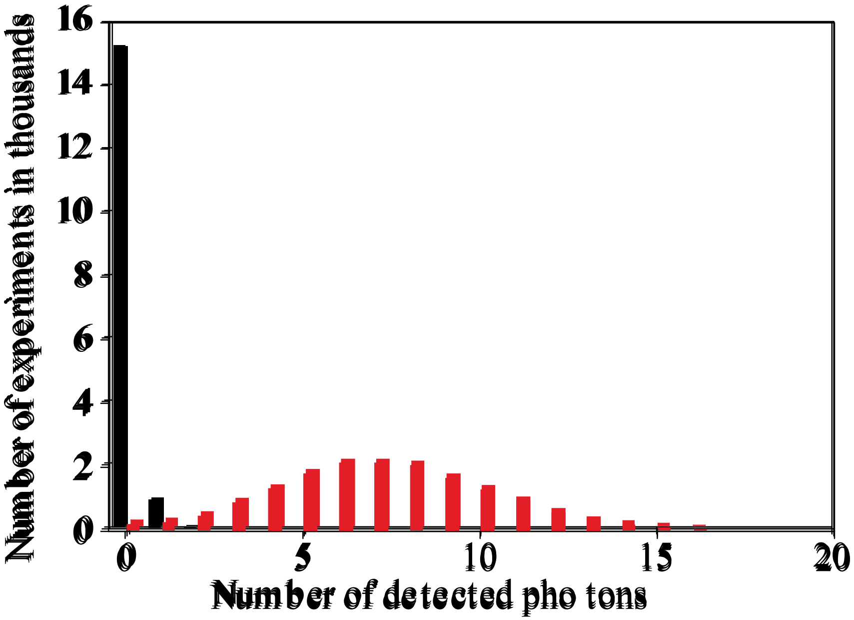


clock state qubit, magnetic field insensitive.

S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

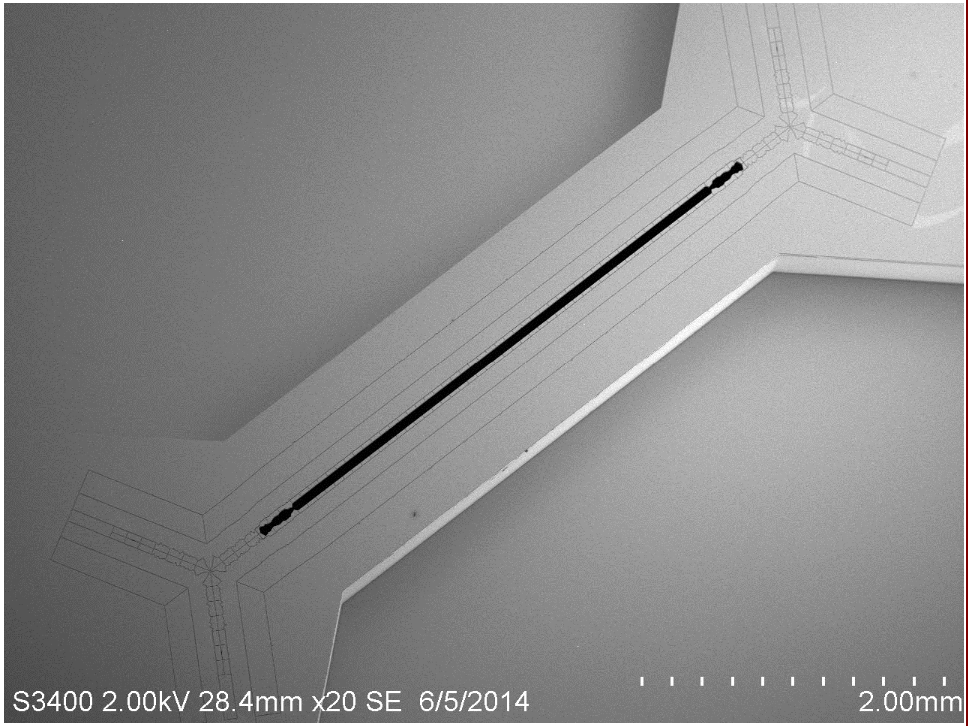
$^{171}Yb^{+}$ state detection





S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

Trap characteristics



Trap frequencies:

- radial 2.7 MHz
- rf frequency used : 49 MHz
- stable for two ions

Trapping times:

- Single ion: Up to 74h observed
- Two ions: Up to 4h observed
- Without cooling: >5 minutes

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Quantum process verification

- Quantum tomography
  - Recipe
    $$\langle\langle E_j | G_{\text{characterize}} | \rho_i \rangle\rangle$$
  - In trapped ion system:
    $$\langle\langle E_k | \quad G_{\text{analyze}} \; G_{\text{characterize}} \, G_{\text{prepare}} \quad | \rho \rangle\rangle$$
  - Needs perfect gates to prepare and analyze
  - Result is process matrix

- Randomized benchmarking
  - Folds the characterization of the process in a single number
  - Not very helpful for debugging
  - Only sensitive to some errors in second order

- Gate Set Tomography
  - Developed by Robin Blume-Kohout et al at Sandia

Gate Set Tomography

Gate Set Tomography

$$\langle\langle E_k | \quad G_{\text{analyze}} \; G_{\text{characterize}} \, G_{\text{prepare}} \quad | \rho \rangle\rangle$$

Does not rely on perfect gates, operation of gates is extracted from their operation

$$\langle\langle E_k | F_i G_l^{2^n} F_j | \rho \rangle\rangle$$

F_i Fiducials to rotated in all bases

$G_l^{2^n}$ Germ set designed to linearly amplify all possible errors

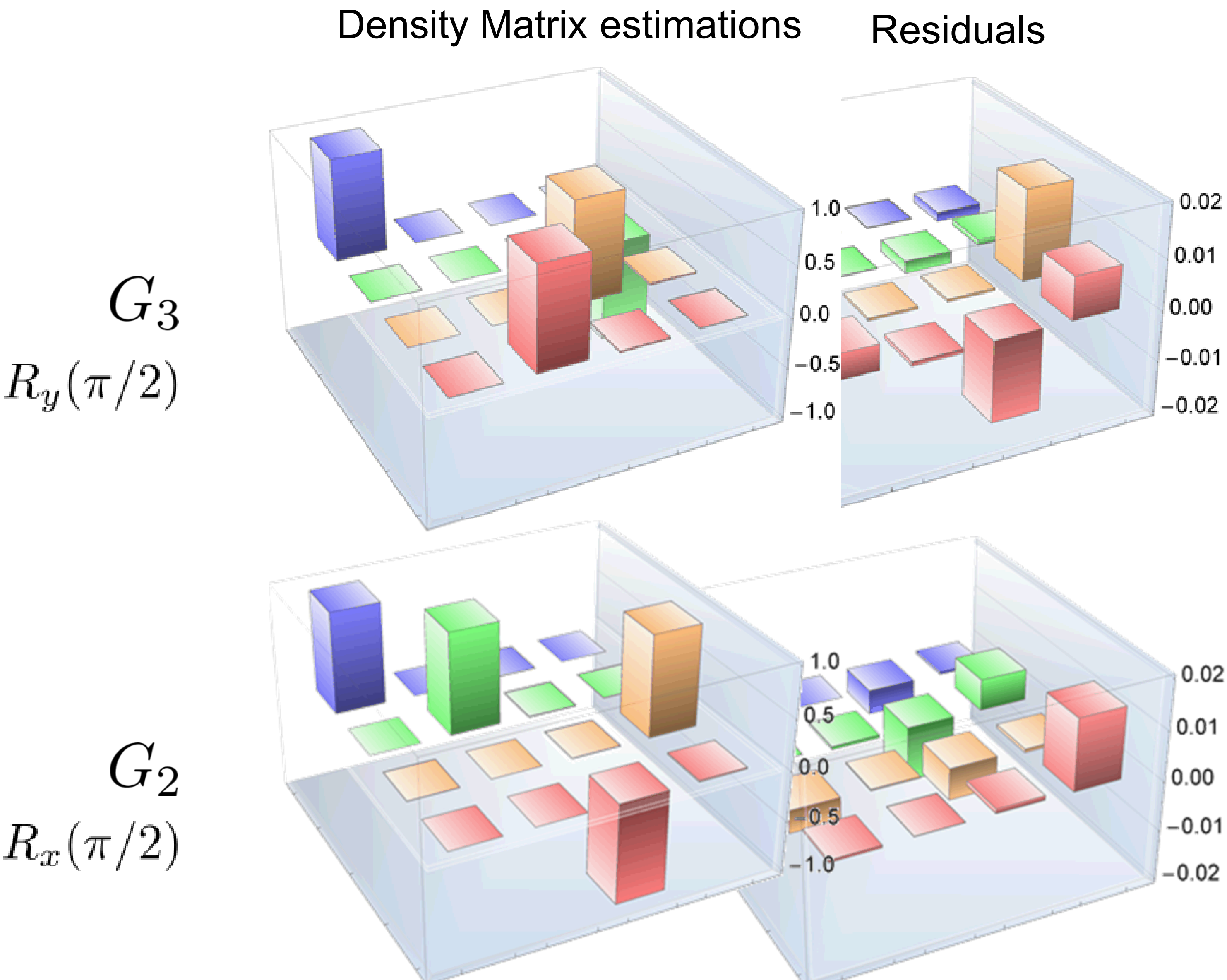
- Delivers detailed debugging information
- Consistency checks of the approximation

Robin Blume-Kohout et al. *Robust, Self-consistent, Closed-form Tomography of Quantum Logic Gates on a Trapped Ion Qubit*. ArXiv 1310.4492 e-print, October 16, 2013.

GST: results

	ML estimate (long dataset)	Target gates
ρ	$\begin{pmatrix} 0.0092 & -0.0017+0.0088i \\ h.c. & 0.9908 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$
E	$\begin{pmatrix} 0.988 & 0.0019+0.0089i \\ h.c. & 0.012 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$
G_1	$\begin{pmatrix} 1.0001 & -0 & 0.0003 & 0.0001 \\ 0.0001 & 0.9994 & -0.0003 & -0 \\ -0.0001 & 0.0006 & 0.999 & -0.0003 \\ -0 & -0.0001 & 0.0002 & 0.9998 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$
G_2	$\begin{pmatrix} 1 & -0.0001 & -0.0045 & -0.0005 \\ 0 & 0.9994 & -0.006 & -0.0018 \\ -0.005 & -0.0112 & -0.0064 & -0.9991 \\ 0.0006 & 0.0063 & 0.9993 & 0.0143 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$
G_3	$\begin{pmatrix} 1.0001 & 0.0033 & 0.0001 & 0.0049 \\ 0.0033 & -0.0001 & -0.0005 & 0.9992 \\ -0.0002 & -0.0024 & 0.9995 & -0.0161 \\ -0.0019 & -0.9989 & 0.0179 & 0.0085 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$
G_4	$\begin{pmatrix} 1.0001 & -0 & 0.0062 & 0.0028 \\ -0 & 0.9997 & 0.0127 & 0.0022 \\ 0.0066 & 0.0164 & -0.9976 & 0.0065 \\ -0.004 & -0.0004 & -0.0066 & -0.9981 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$

Gate Errors


Density Matrix estimations
Residuals
G_3
$R_y(\pi/2)$
G_2
$R_x(\pi/2)$
1.0
0.5
0.0
−0.5
−1.0
0.02
0.01
0.00
−0.01
−0.02

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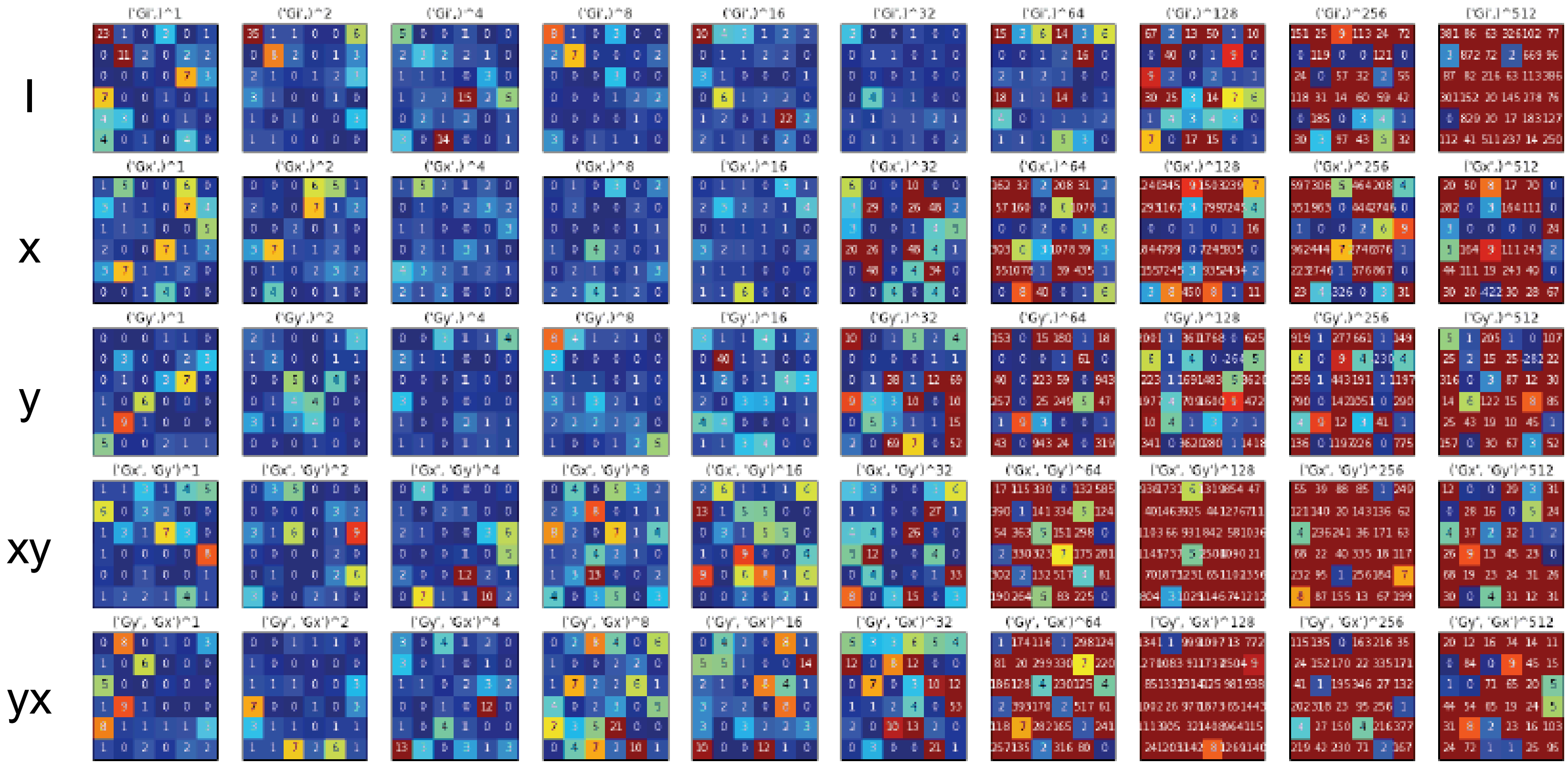
GST: non-Markovian noise

Hierarchical χ^2

for best fit to L=1,2,4,8,16,32

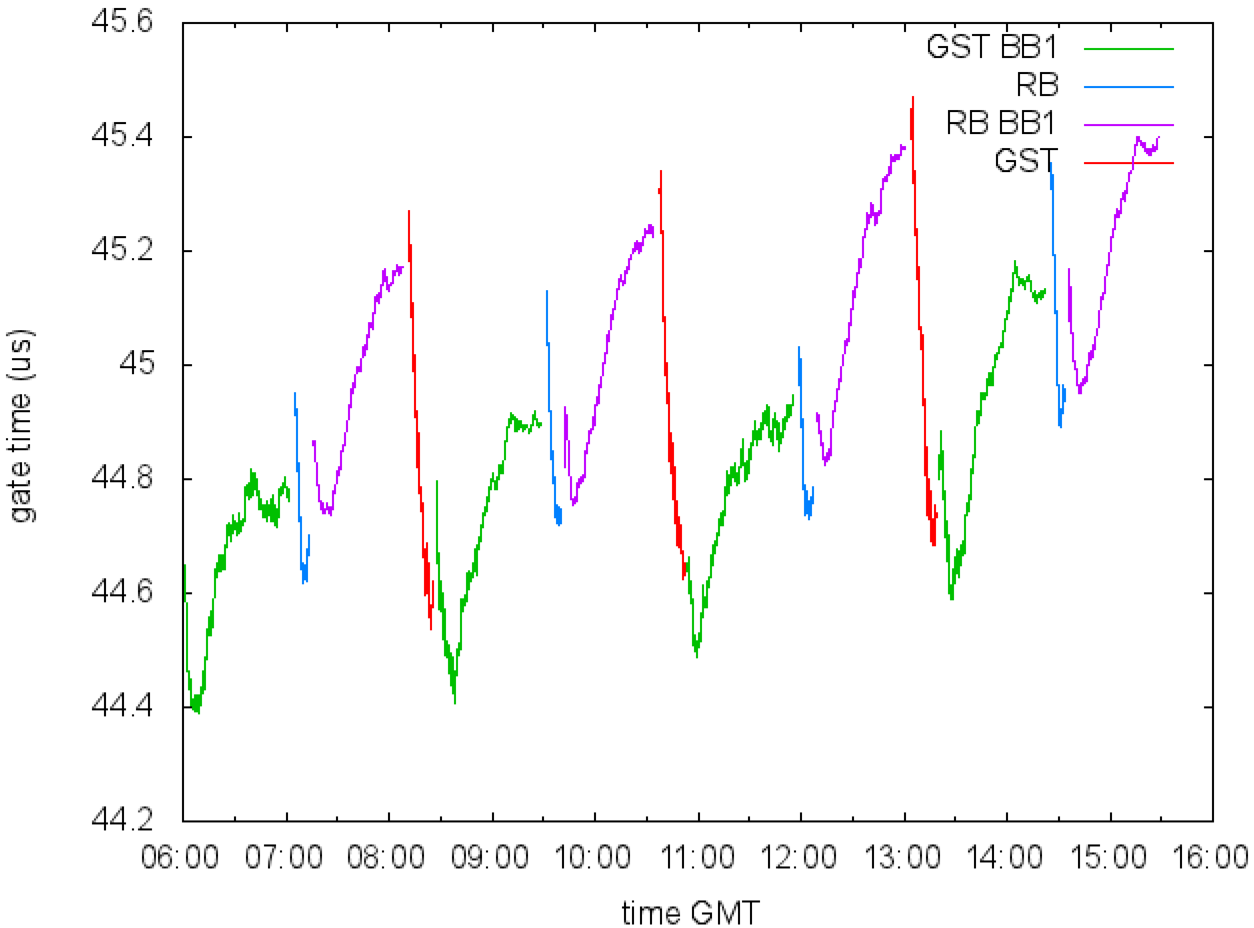


Hierarchical χ^2 for $L = 1, 2, 4, 8, 16, 32, 64, 128, 256, 512$

Drift control

- Improved the system: temperature stabilization, elimination of components from microwave system
- Microwave π-times are measured independently and concurrently
- Feedback (locking) scheme adjusts π-times dynamically

Measured π/2-times



Drift control algorithm

GateTimeIntegrator = GateTime << 5

GST sequence

Prepare dark state
Apply 21 GateTime microwave pulse
State detection result = 1 if bright else 0

GateTimeIntegrator -= result
GateTime = GateTimeIntegrator >> 5

GST: results

Comparison to target gates

Gate	Process Infidelity	Trace Dist.	Frobenius Dist.	Error Generator
Gi	0.000226	0.007575	0.002768	$\begin{pmatrix} -4\times10^{-5} & 0.0001 & -0.0001 & -2\times10^{-5} \\ 1\times10^{-6} & -0.0003 & -0.0002 & -0.0052 \\ -2\times10^{-5} & 0.0001 & -0.0001 & -5\times10^{-5} \\ 1\times10^{-5} & 0.0055 & 4\times10^{-5} & -0.0005 \end{pmatrix}$
Gx	0.00005	0.00692	0.00247	$\begin{pmatrix} -4\times10^{-5} & -1\times10^{-5} & 0.002 & -0.0013 \\ -2\times10^{-5} & -0.0001 & -0.0009 & 0.0007 \\ 0.002 & 0.0008 & -4\times10^{-5} & -0.0041 \\ -0.0013 & -0.0009 & 0.0041 & -0.0001 \end{pmatrix}$
Gy	0.000113	0.007158	0.002555	$\begin{pmatrix} -0.0001 & -0.0009 & 1\times10^{-5} & -0.0025 \\ -0.0009 & -0.0001 & -0.0003 & 0.0043 \\ -7\times10^{-6} & 0.0004 & -0.0001 & 0.0003 \\ -0.0025 & -0.0043 & -0.0004 & -0.0001 \end{pmatrix}$

Worst case process infidelity: 2×10^{-4}

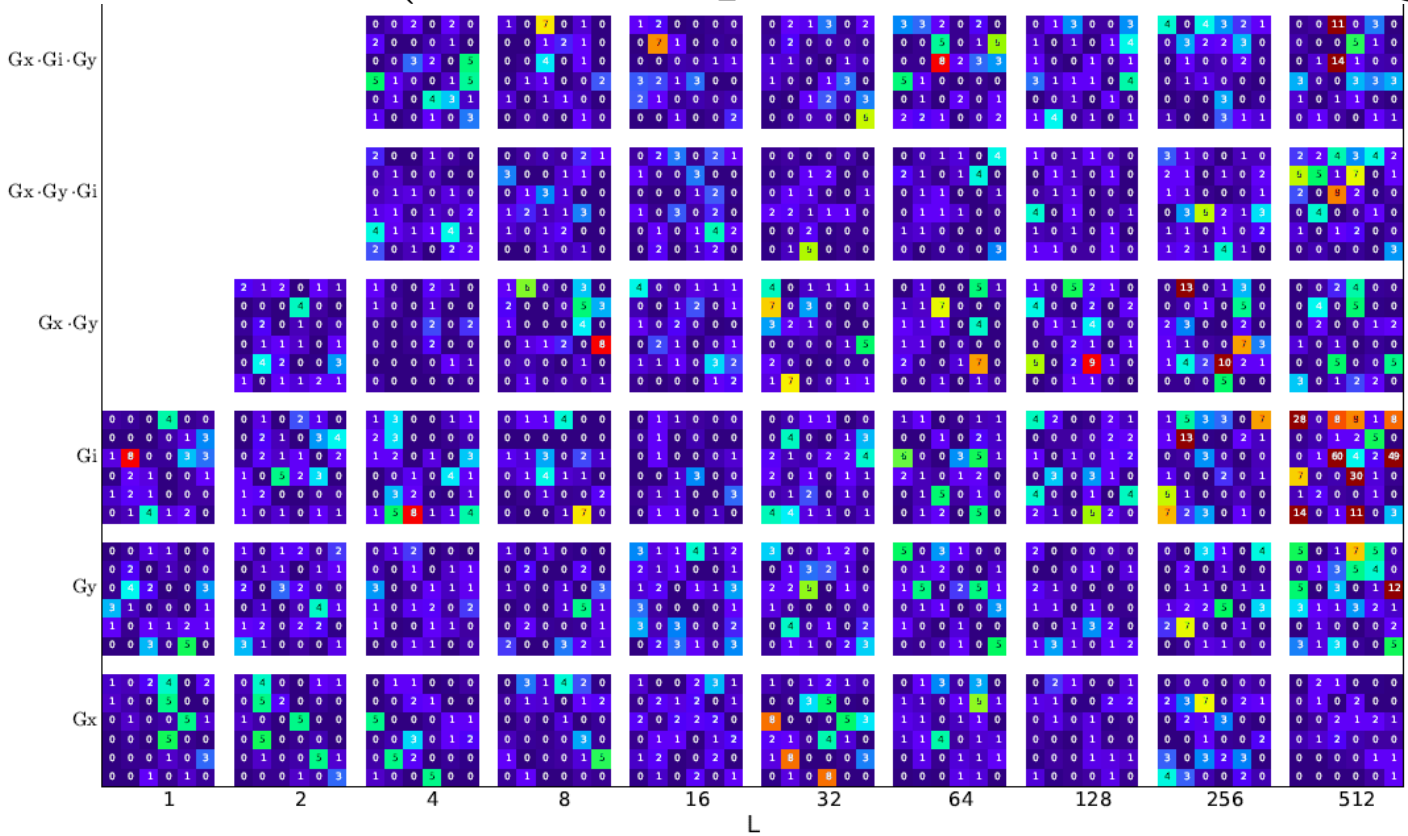
GST results

Gate analysis

Gate	Eigenvalues	Fixed pt	Rotn. axis	Angle	Diag. decay	Off-diag. decay
Gi	1 0.9999 $0.9996e^{i0.0}$ $0.9996e^{-i0.0}$	0.9775 0.0004 -0.2107 0.0063	0.5252 -0.009 0.8506 -0.0244	0.001699π	0.000121	0.000365
Gx	$1e^{i1.6}$ $1e^{-i1.6}$ 1 0.9999	1 0 -0.0003 0.0017	-3×10^{-6} -1 -3×10^{-5} -0.0009	0.501308π	0	0.000046
Gy	$0.9999e^{i1.6}$ $0.9999e^{-i1.6}$ 0.9999 0.9999	-0.9896 0.0008 0.1437 -0.0016	-0.2474 0.0001 0.9689 -0.0001	0.501366π	0.000109	0.000136

non-Markovian noise after optimization

χ^2 of GST fit (BB1 compensated microwave gates)



- Same color scale as before
- Very good results for the BB1 compensated gates Gx and Gy

There is a qubit in the box!

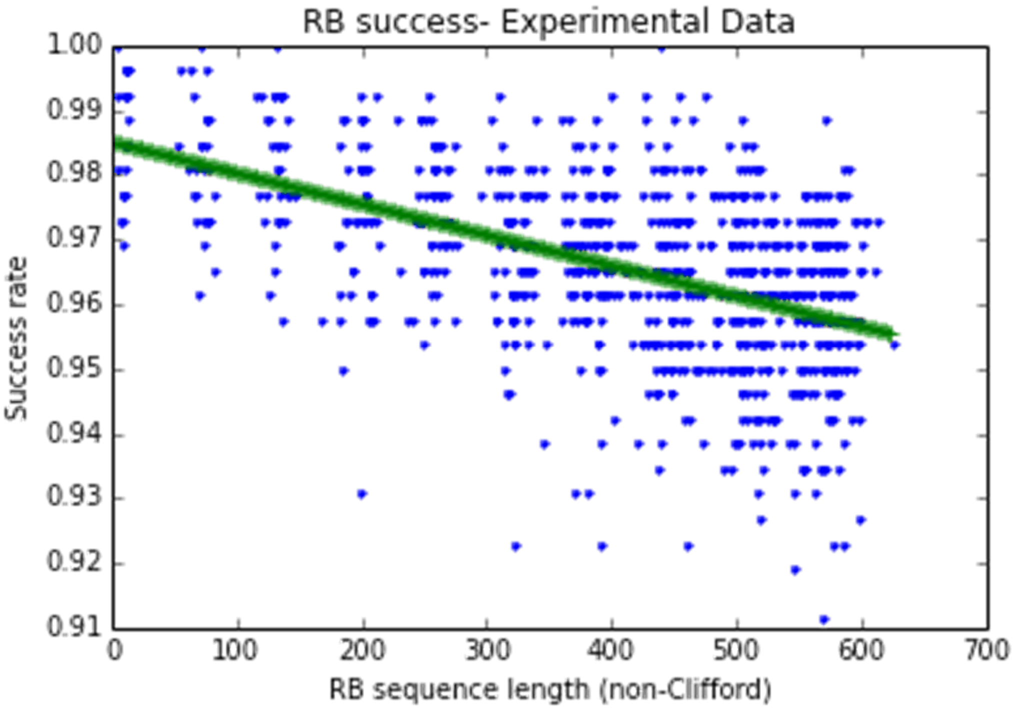
Randomized benchmarking and GST

Randomized Benchmarking:

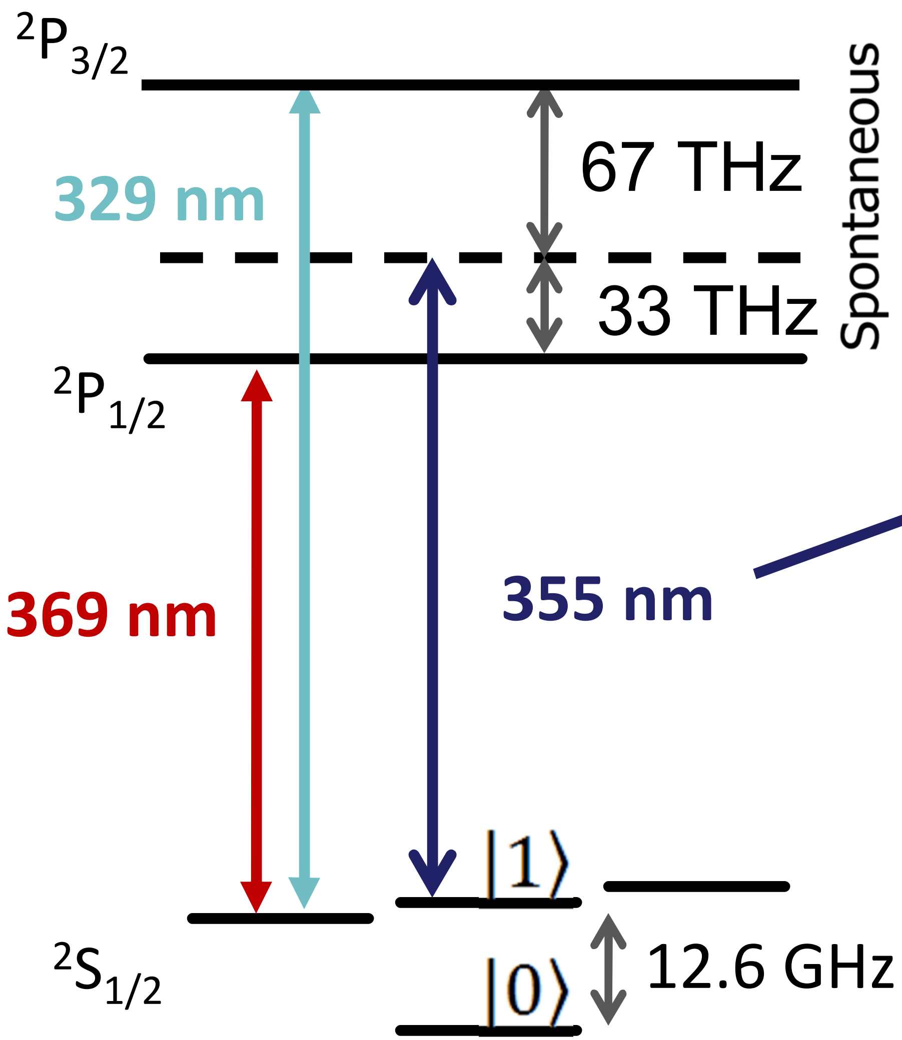
- Average infidelity per gate 4.9×10^{-5}
- GST worst case gate infidelity 2×10^{-4}

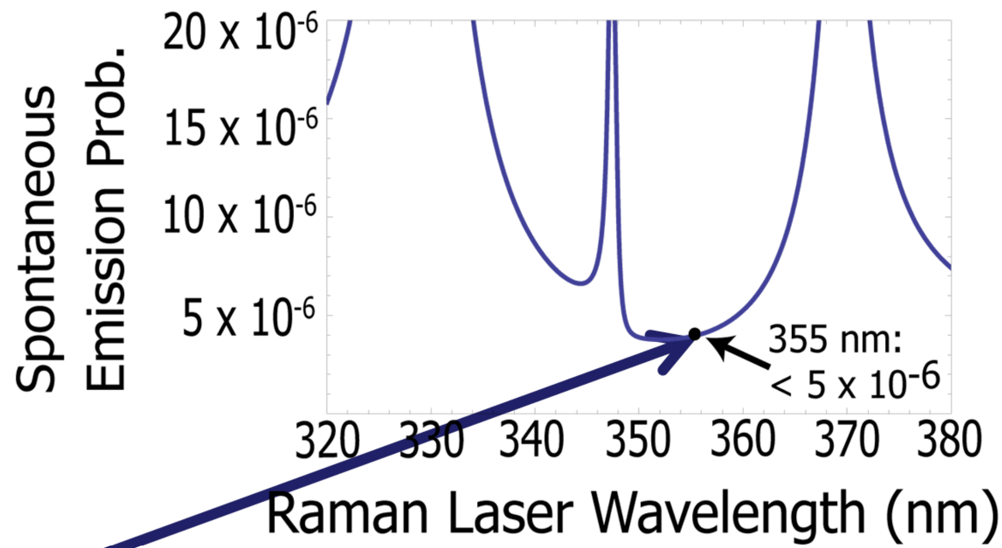
Randomized benchmarking:
Less sensitive to certain errors

Randomized benchmarking
Experimental



355 Raman transitions: $^{171}Yb^{+}$

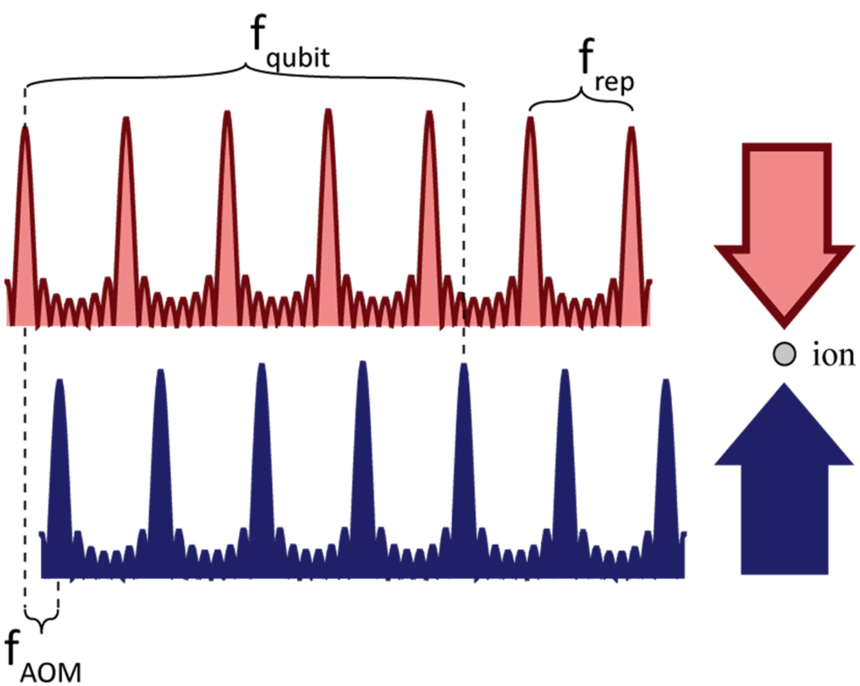




3x $Nd{:}YVO_4$ (355 nm) near minimum in Differential AC Stark Shift and spontaneous emission for $^{171}Yb^{+}$ ($\Delta_{Stark}/\Omega_{Rabi} < 3 \times 10^{-4}$ at 355 nm)

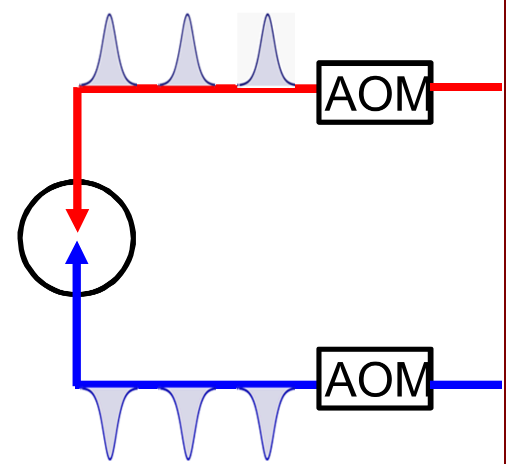
Pulsed laser Raman transitions

- Couple to ions using 355nm frequency comb
- Beat note created by repetition rate and AOM shift
- Get large splitting for free

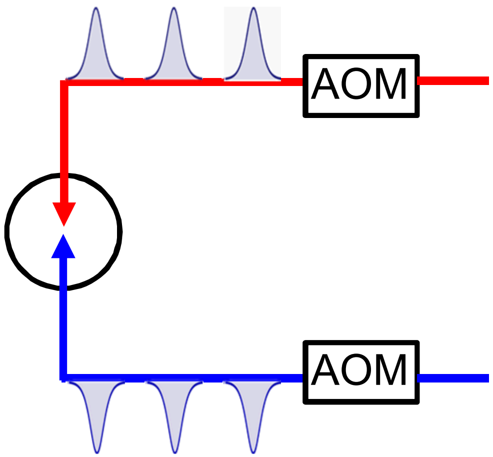


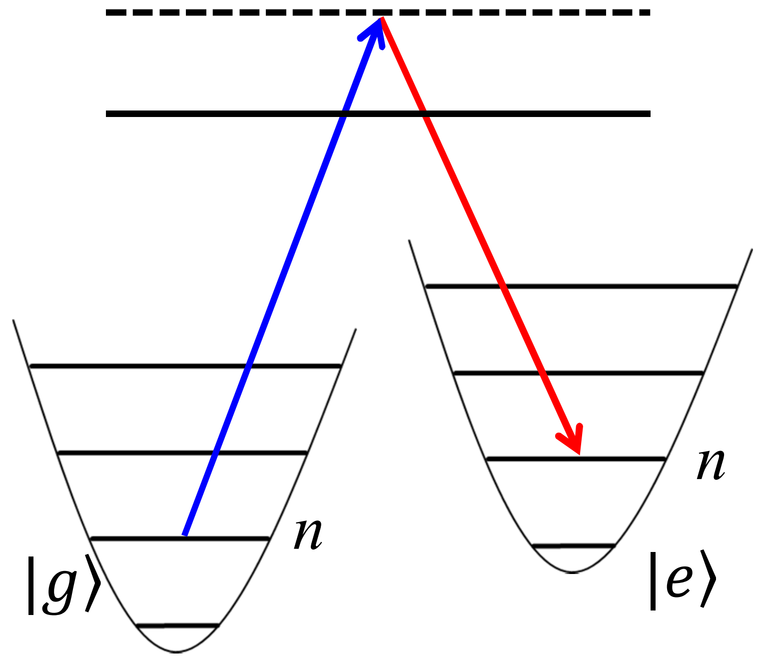
Requirement:

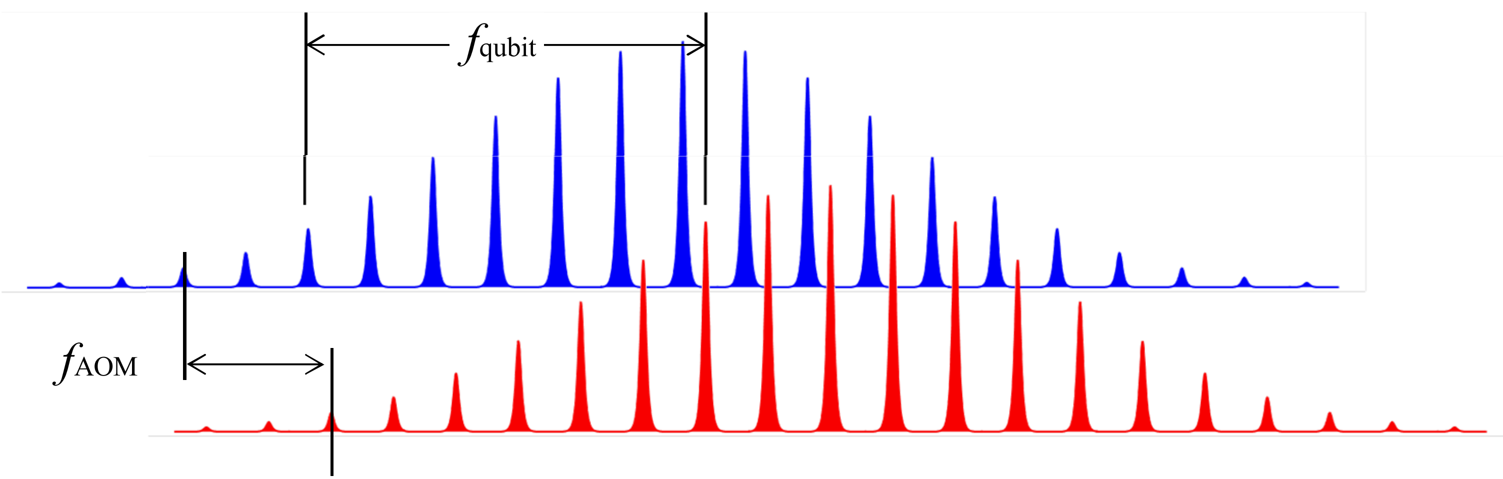
$$f_{qubit} = nf_{rep} \pm f_{AOM}$$



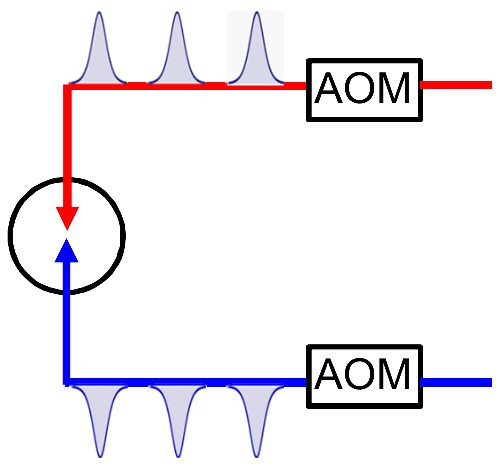
Pulsed laser Raman transitions

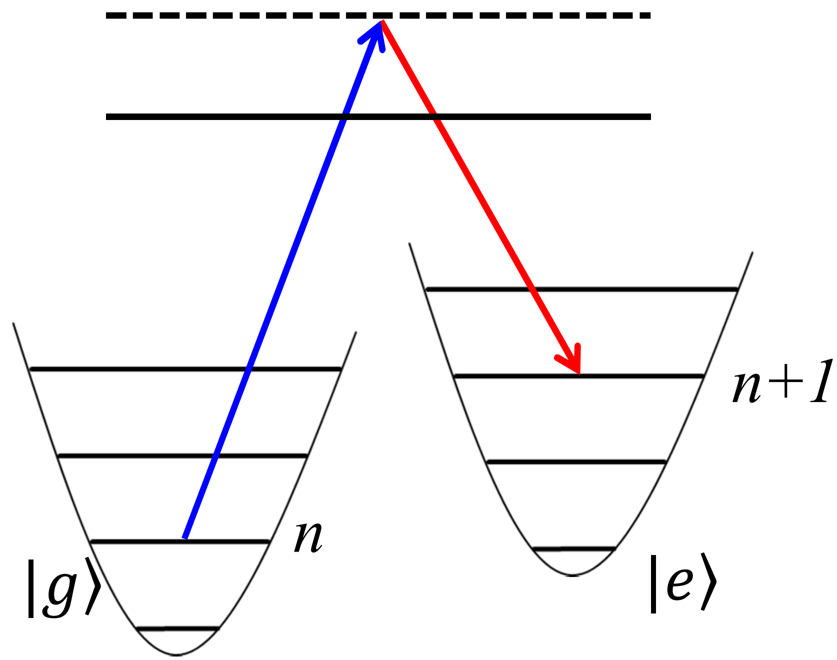


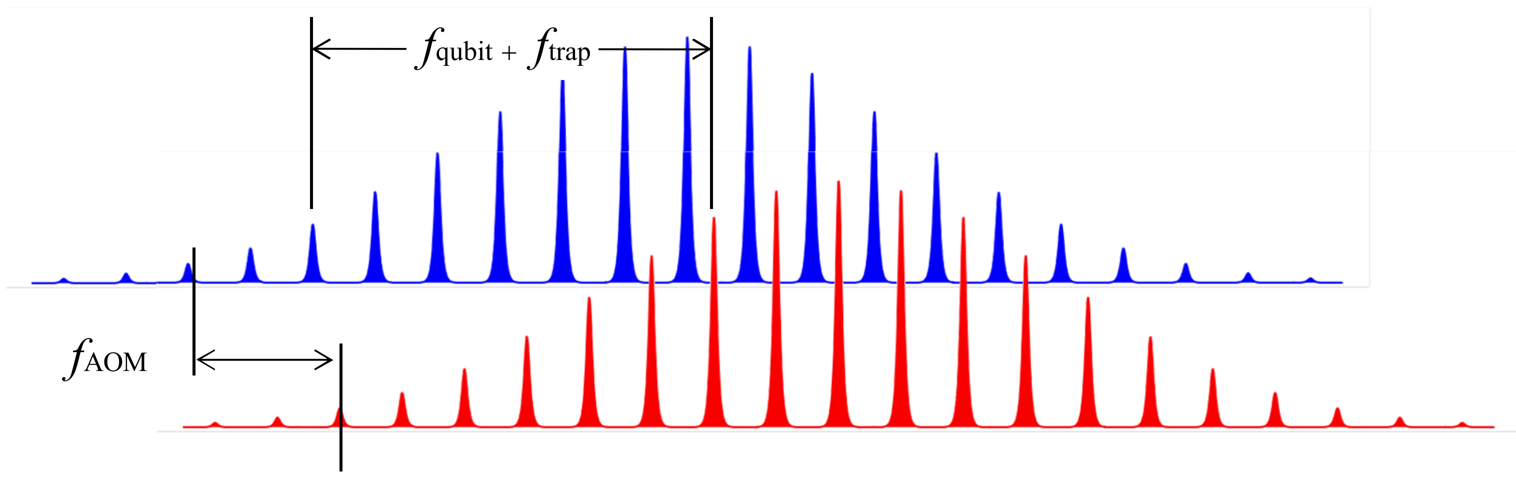




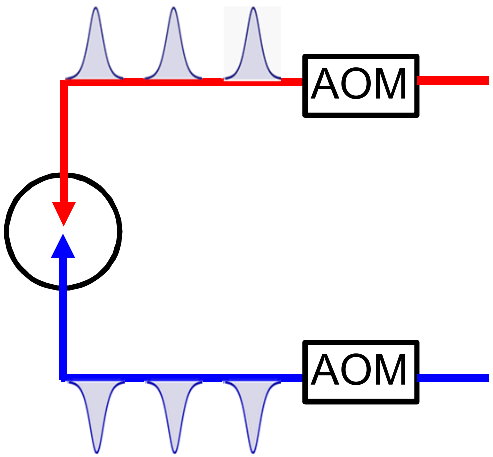
Pulsed laser Raman transitions

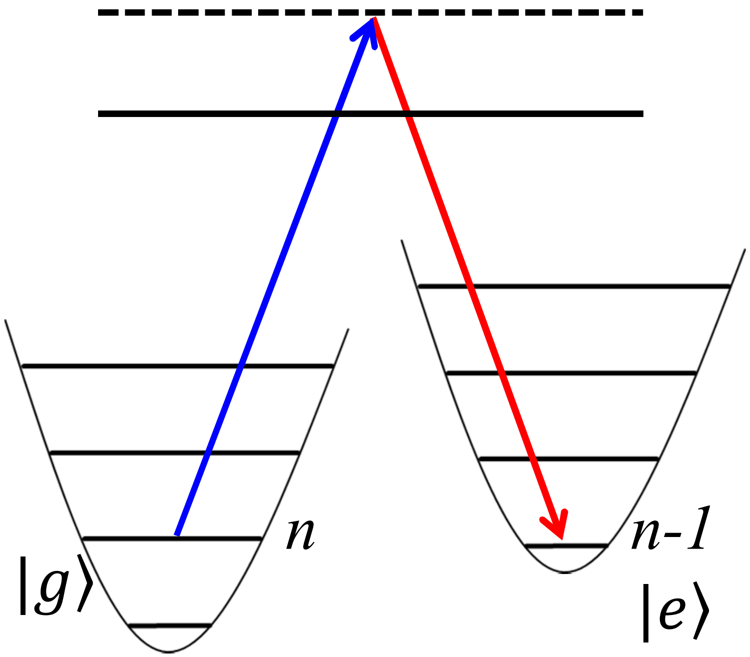


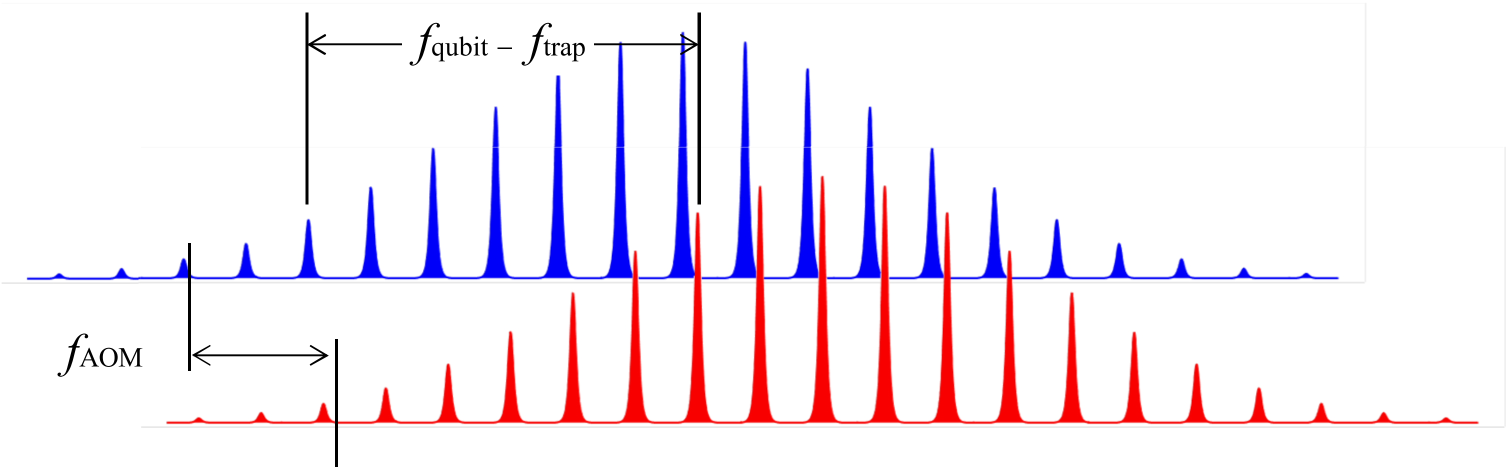




Pulsed laser Raman transitions

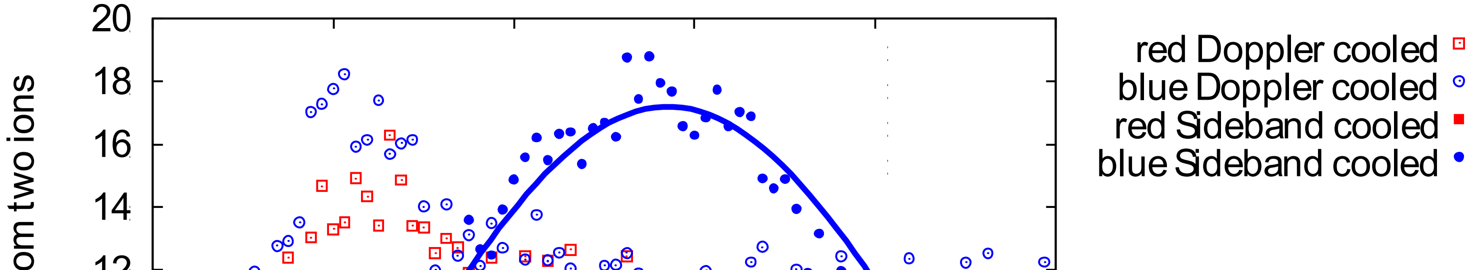


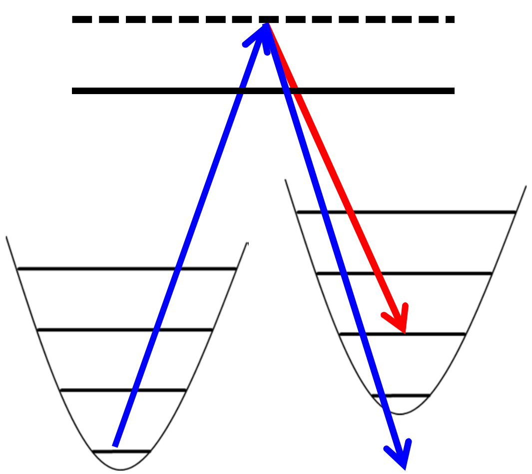




Sideband cooling

- Ground state cooling evident when red sideband cannot be driven
- Data shows ground state cooling of two ion radial tilt mode, $\bar{n} \ll 1$

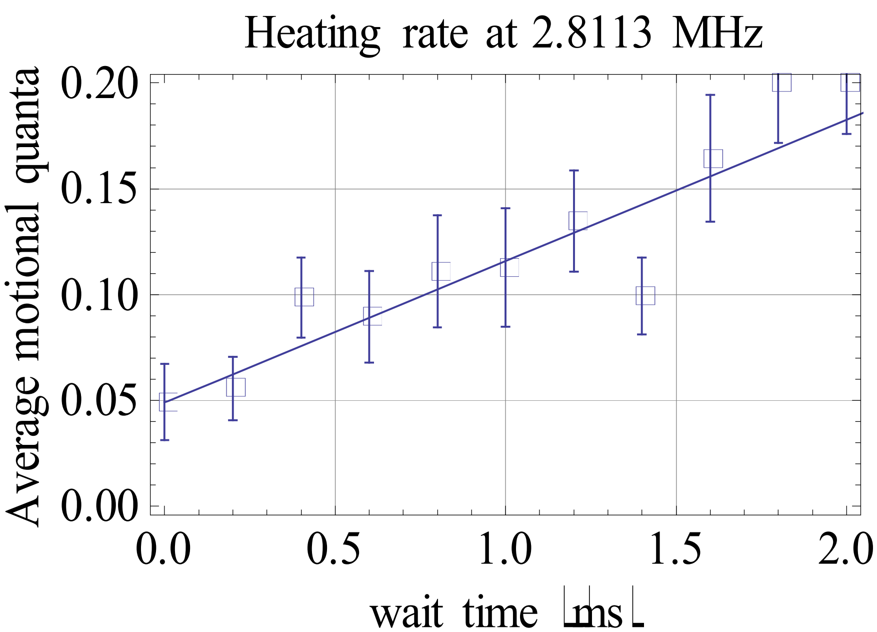




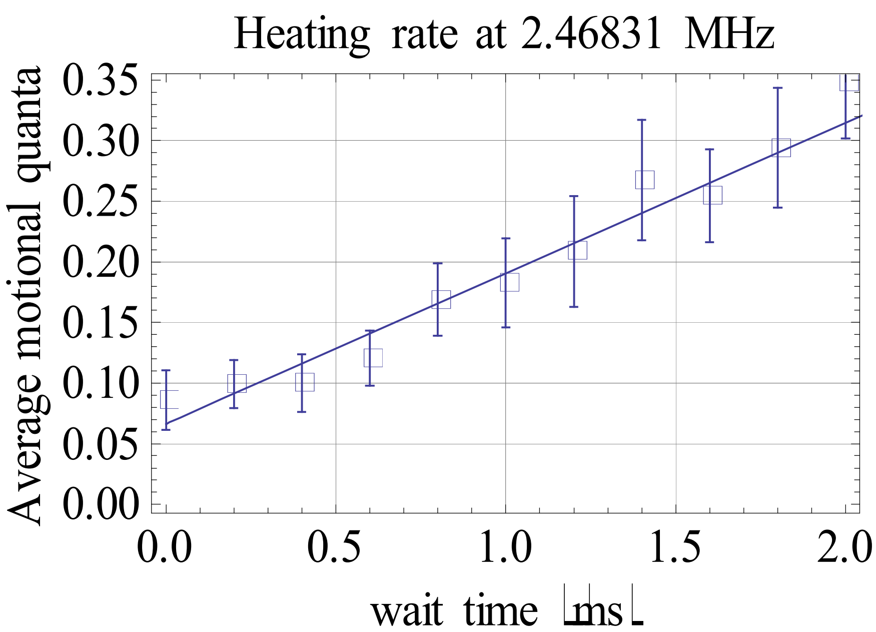
Heating in Two Ion Chain

Transversal Center of Mass | Transversal Tilt | Longitudinal Center of Mass | Longitudinal Stretch

2 modes | 2 modes



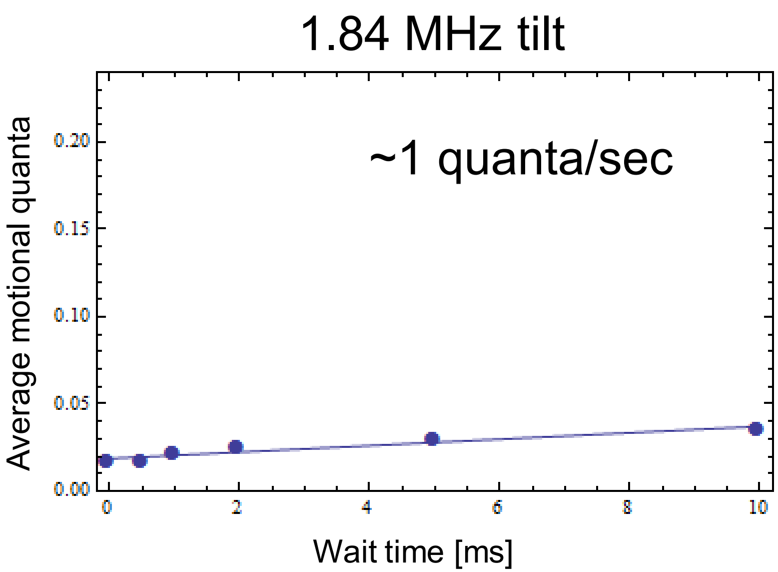
Fit: 67 quanta/s

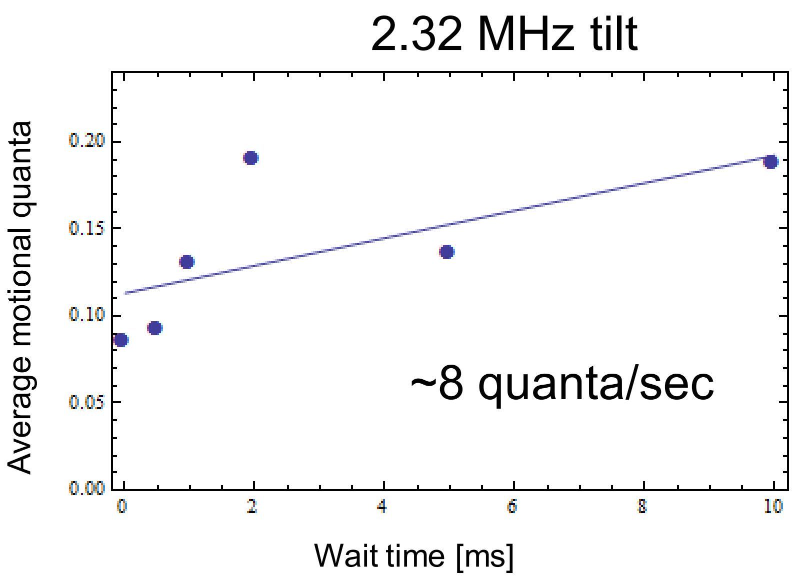


Fit: 124 quanta/s

- Likely to be limited by technical noise

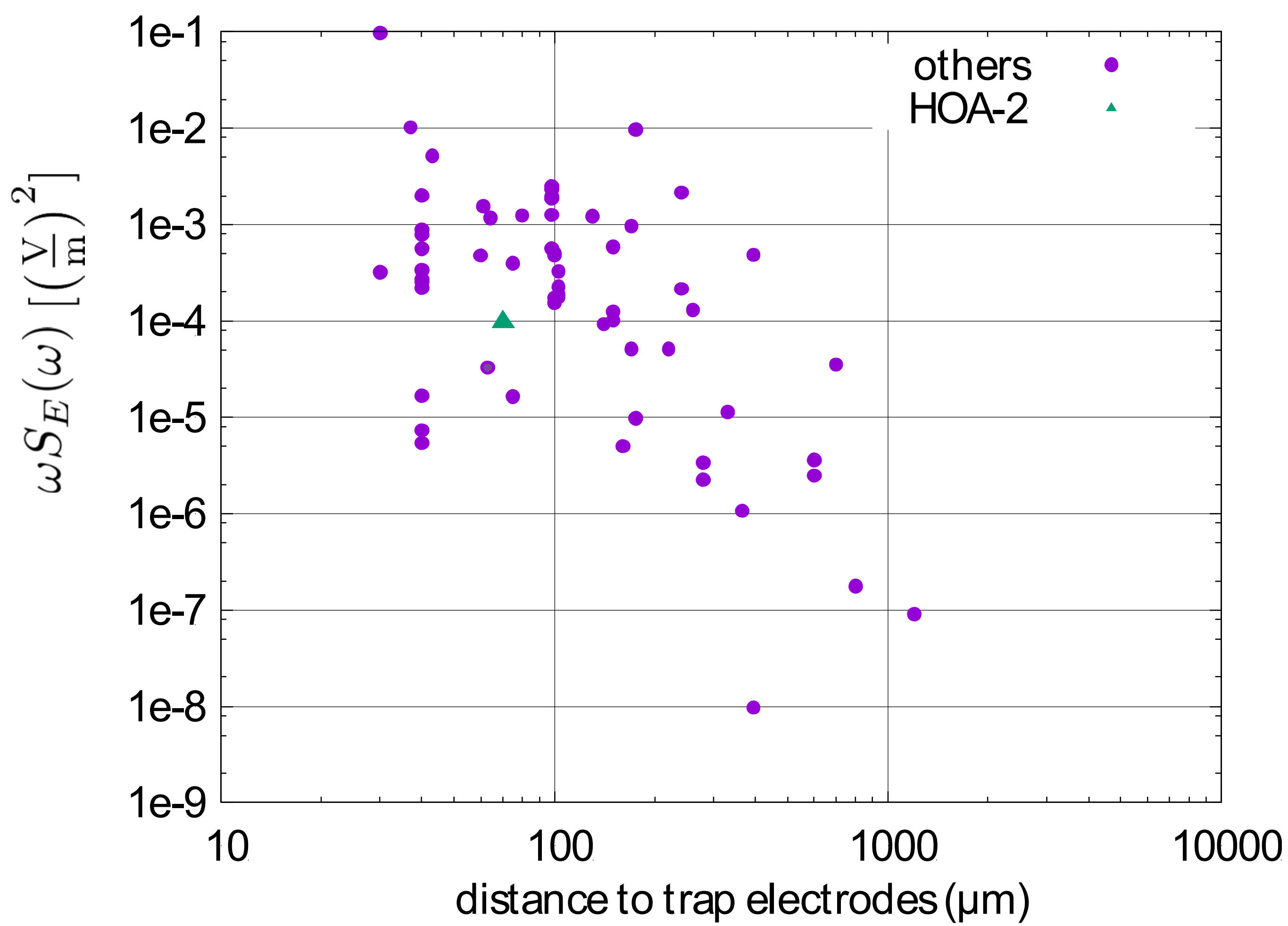
Heating in Two Ion Chain





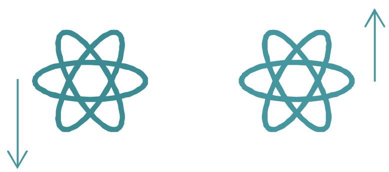
- Using tilt mode near 1.84 MHz for gate
- Lowest heating <1 quanta/sec

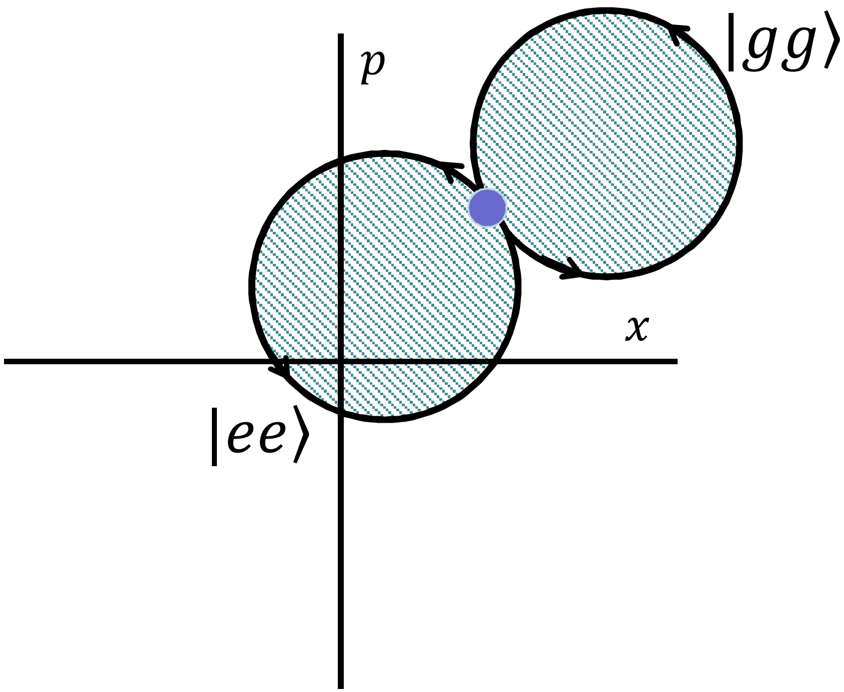
Heating rate in context



Entangling Gate

Basic idea: Use common motion of the ions to mediate entanglement





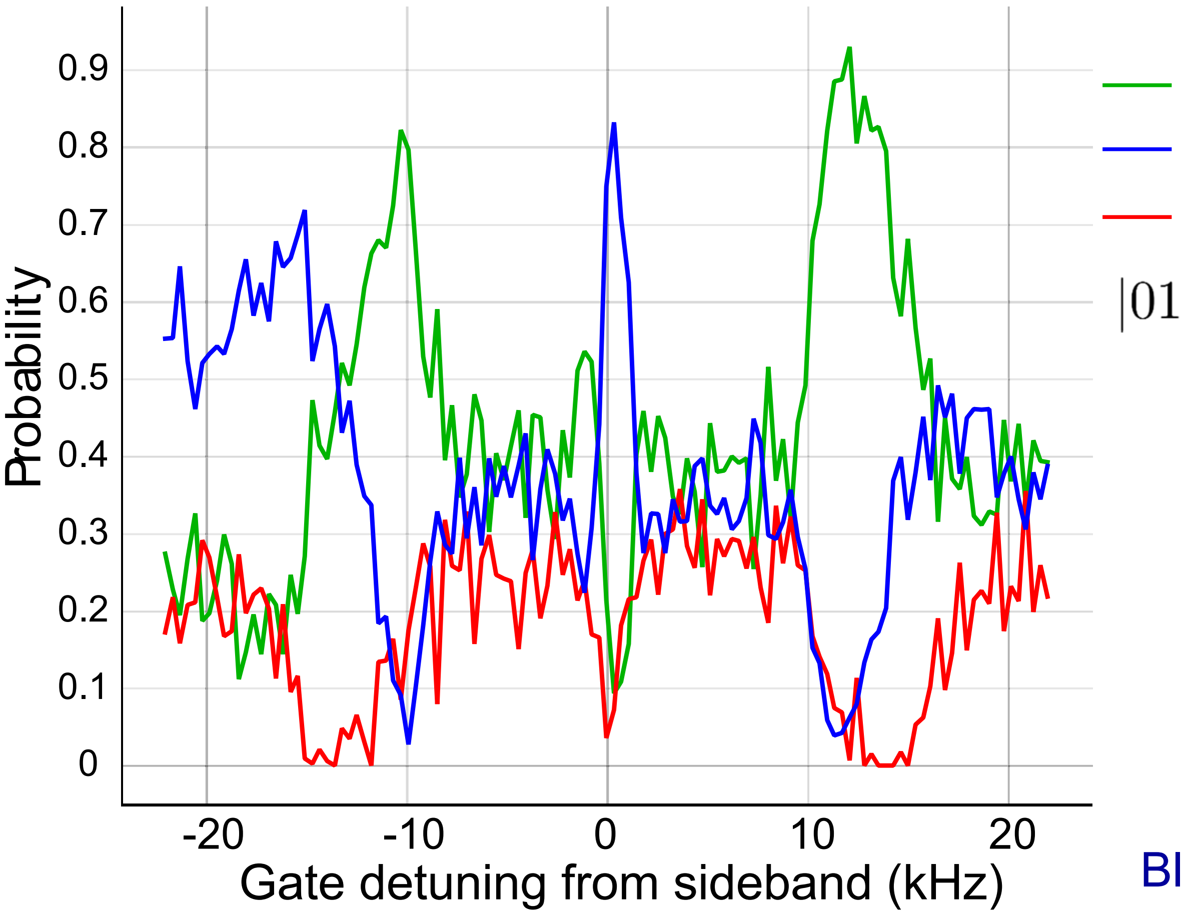
- Raman beams create *spin-dependent force*
- Force drives the ions away from and then back to their starting position

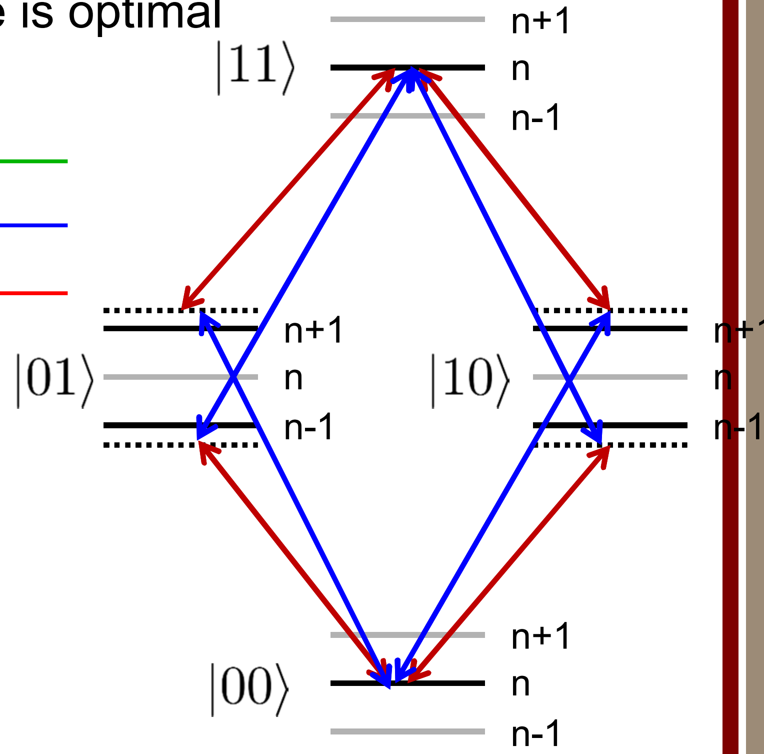
- Spin dependent phase remains

[1] K. Mølmer, A. Sørensen, PRL 82, 1835 (1999)
[2] A. Sørensen, K. Mølmer, PRL 82, 1971 (1999)
[3] A. Sørensen, K. Mølmer, PRA 62, 022311 (2000)

Entangling Gate

- Scanning detuning reveals point where gate is optimal





$$|00\rangle \rightarrow |00\rangle + |11\rangle$$

Blue: Zero ions bright

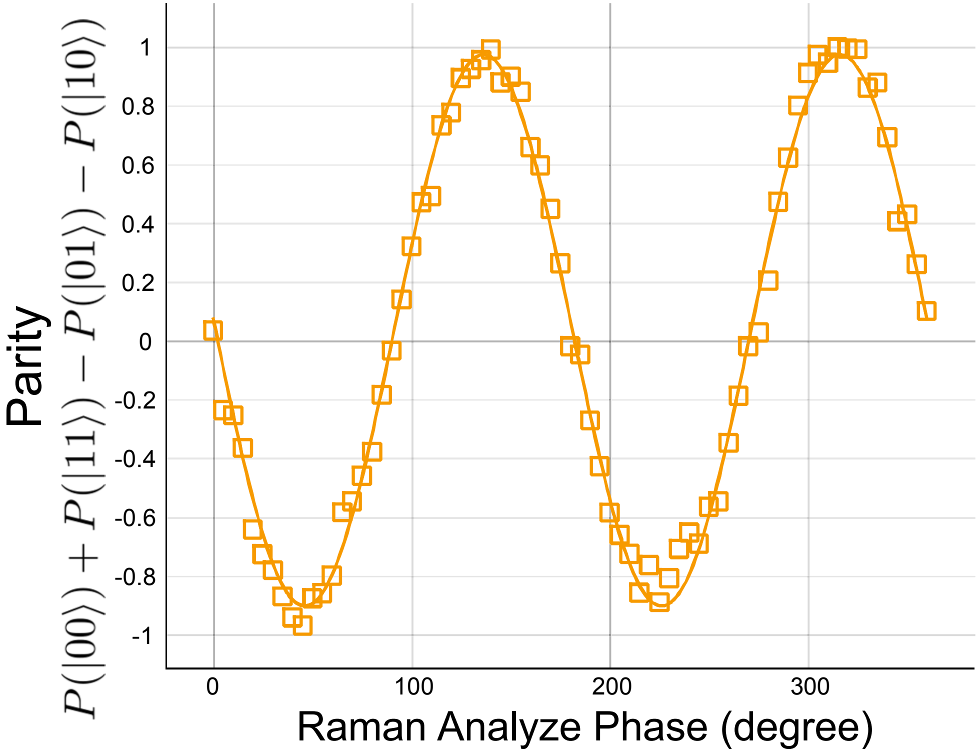
Red: One ion bright

Green: Two ions bright

D. Hayes et al. Phys. Rev. Lett. 109, 020503 (2012)

Entangling Gate – preliminary results

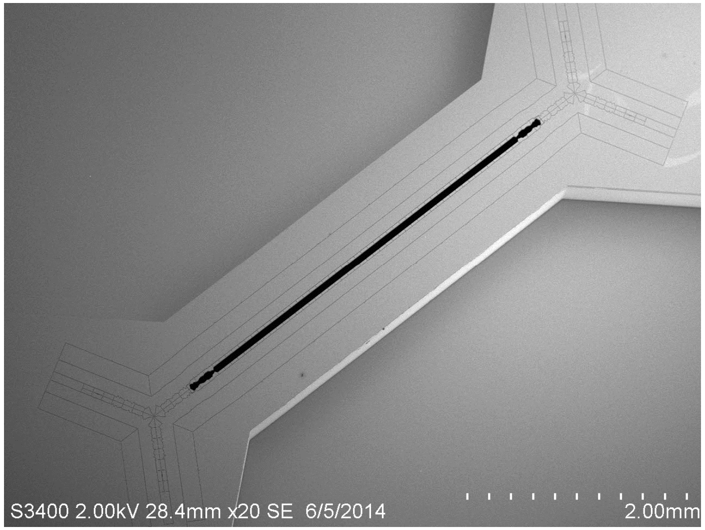
- Populations reveal diagonals of density matrix, parity scan reveals coherences
- Taken together they yield the fidelity



$$\mathcal{F} = \frac{1}{2}(P(|00\rangle) + P(|11\rangle)) + \frac{1}{4}c = 0.97$$

- Gate fidelity 97%
- Have yet to characterize sources of infidelity

Conclusion



Microfabricated traps are ready for QIP

- Experiments were done in HOA-2 and Thunderbird trap

HOA-2 has advantages over Thunderbird:

- Higher trap frequencies
- Better trap characteristics
- Optical access for individual addressing

Thank you

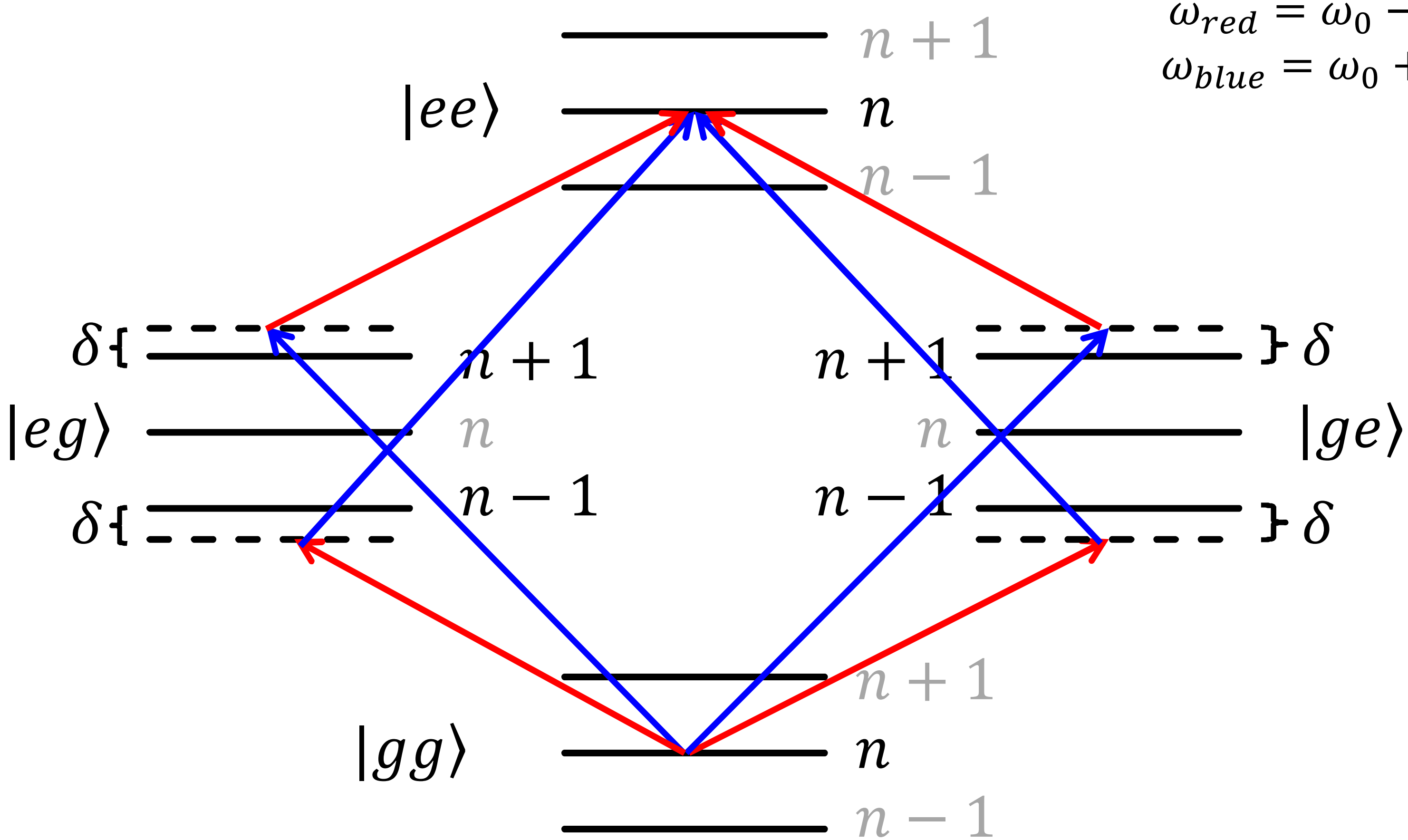
Job openings for postdocs:
http://Sandia.jobs opening 648055

plmaunz@sandia.gov
dlstick@sandia.gov

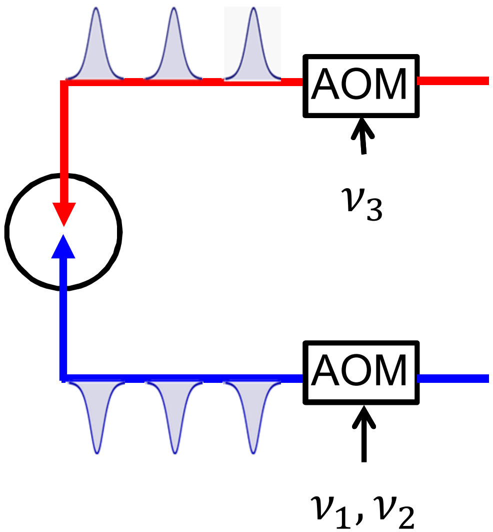
Entangling Gate

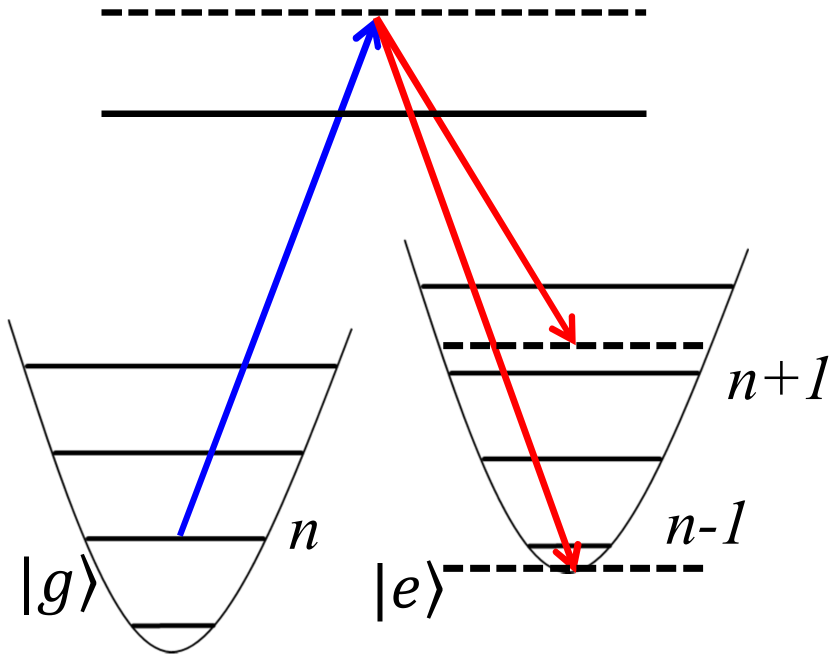
Creating a spin-dependent force with Raman beams:
Apply red and blue detuned sidebands simultaneously

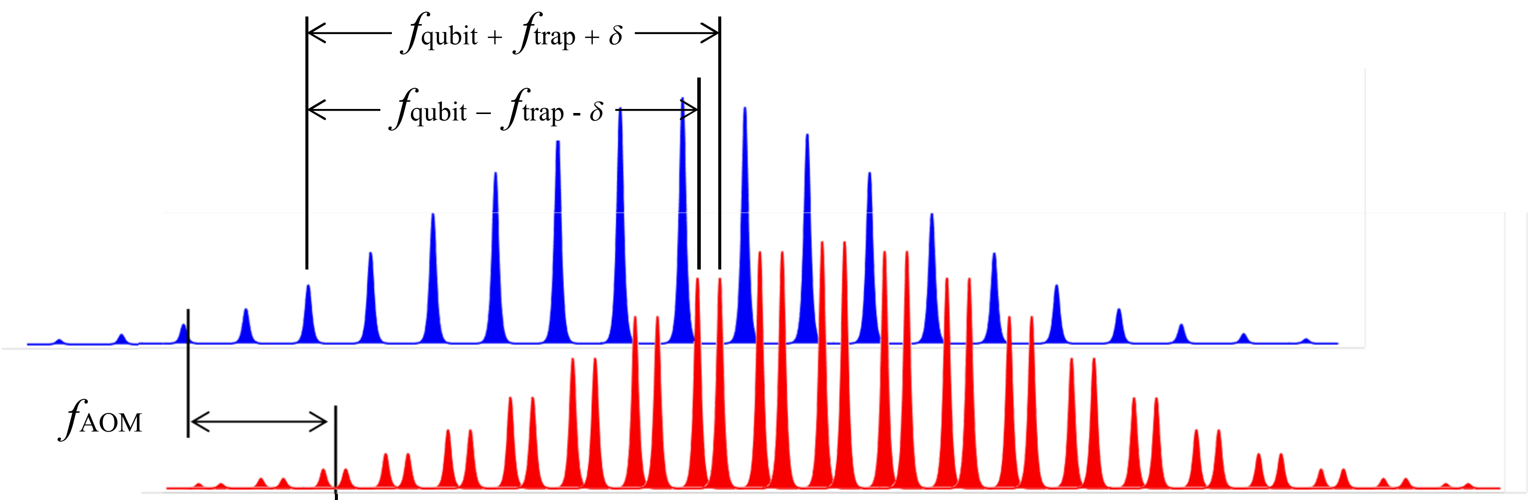
$$\omega_{red} = \omega_0 - \nu - \delta$$
$$\omega_{blue} = \omega_0 + \nu + \delta$$



Entangling Gate

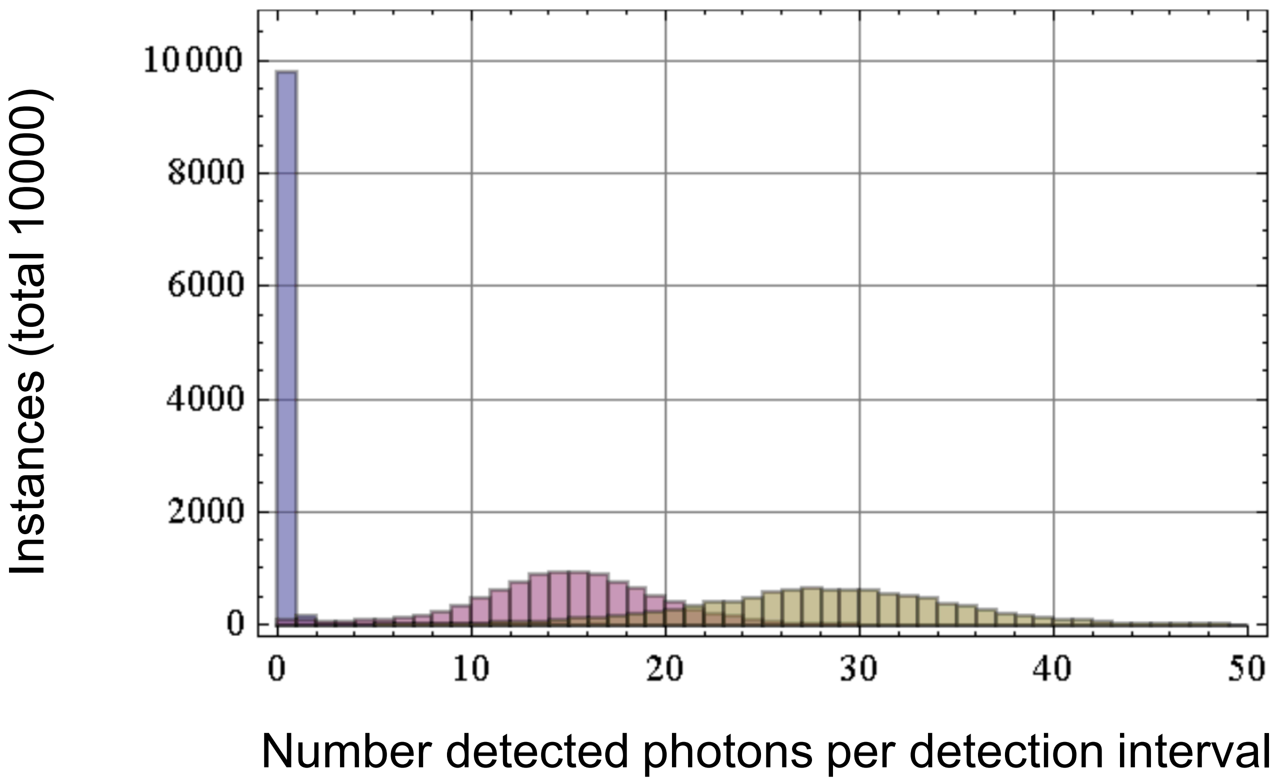






State Detection using Histograms

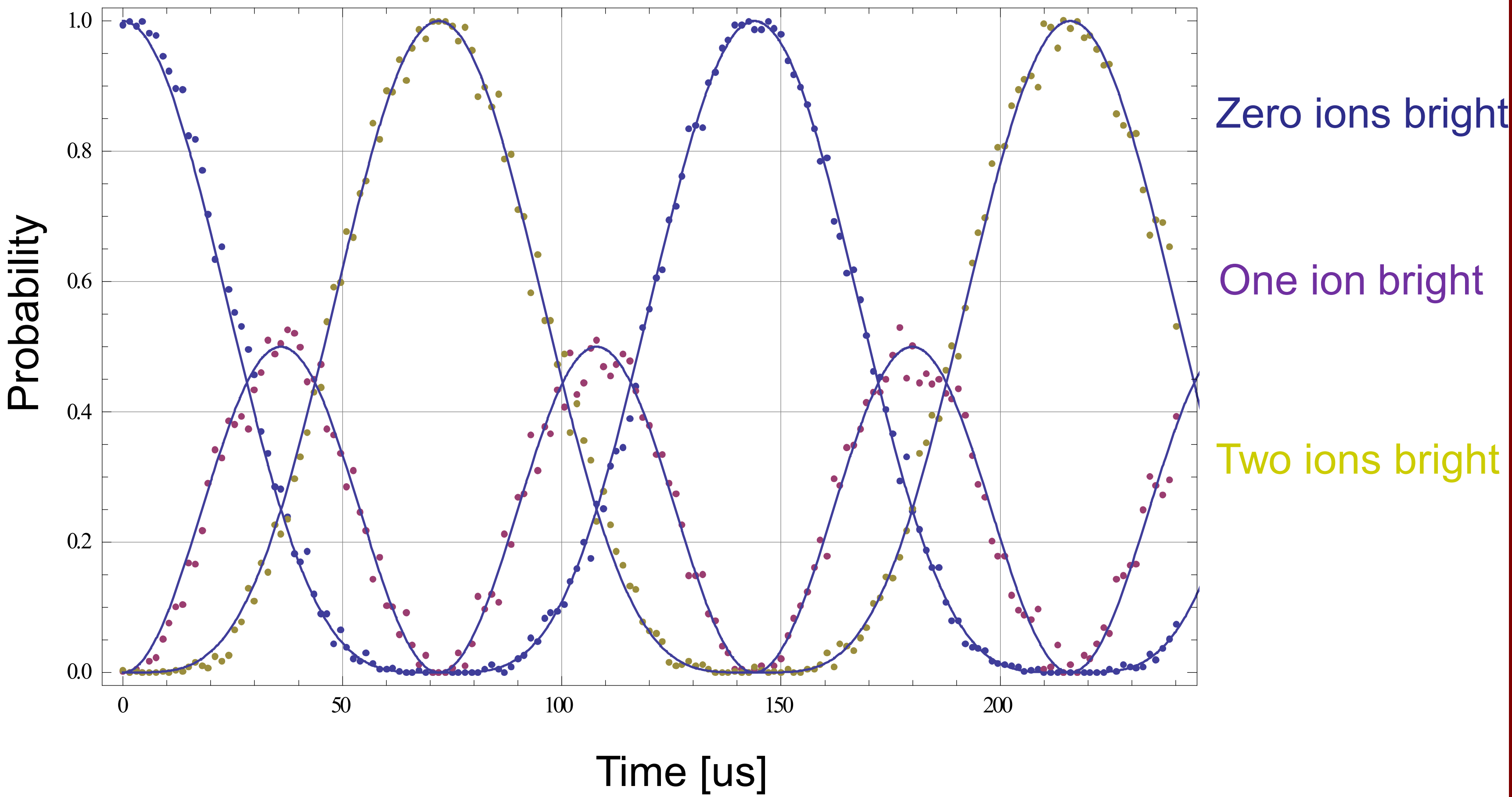
Example histograms



Long term plan: segmented PMT for individual state detection
Currently limited by optical crosstalk

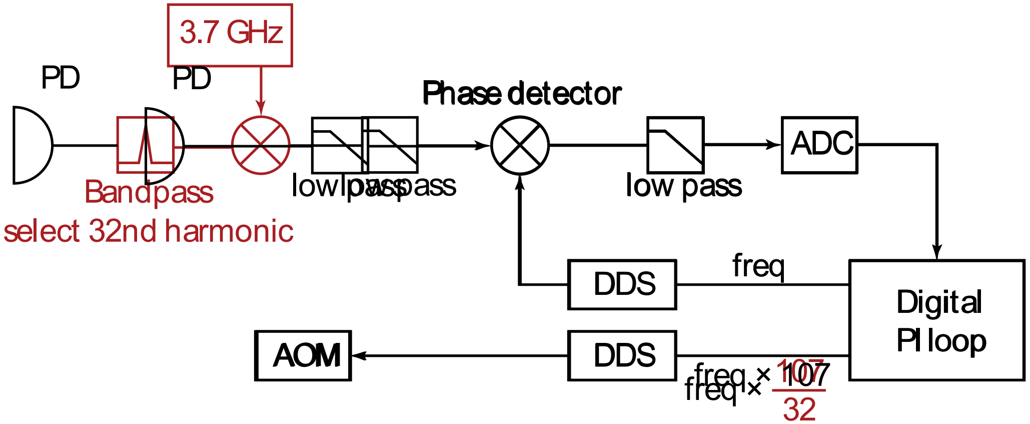
State Detection Using Histograms

Global Rabi Oscillations on two ions



One parameter (Rabi time) is sufficient to simultaneously fit all three curves

Coherence time



Lock at fundamental:

- 85% contrast between 100µs and 1s

Lock at 32nd harmonic

- Coherence time > 2s