Quantum Control of Atomic Qudits

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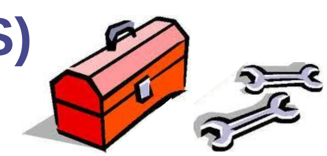
Quantum Control of Atomic Qudits

- **Open Loop Quantum Control**
  - **State-to-state mapping** $\left| y_{initial} \right\rangle \xrightarrow{H(t)} \left| y_{target} \right\rangle$
  - **Unitary maps** $" \; \left| y \right\rangle \hat{I} \; H \; : \; \left| y \right\rangle \xrightarrow{H(t)} U \left| y \right\rangle$
  - **Unitary maps on subspaces, partial isometries**

Quantum Control of Atomic Qudits

- **Open Loop Quantum Control**
  - **State-to-state mapping** $|y_{initial}\rangle \xrightarrow{H(t)} |y_{target}\rangle$
  - **Unitary maps** $" \; |y\rangle \,\hat{\text{I}}\; H \;:\; |y\rangle \xrightarrow{H(t)} U|y\rangle$
  - **Unitary maps on subspaces, partial isometries**

- **Rich toolbox already exists for qubits (NMR, QIS)**
- **Next step: extend to $d > 2$ dimensional systems**
- **Explore: controllability, numerical design, robust control, benchmarking, state/process tomography**



Quantum Control of Atomic Qudits

- **Quantum Information Science**

Physical building blocks are often qudits

– opportunities ? –

(atoms, ions, molecules, SC devices, hybrids)

W. S. Bakr et al., Science (2010)

Example: QIP/Simulation w/cold atoms

- uses atoms as scalar or spin ½ particles
- beyond spin ½ → qubits encoded for storage vs. interaction decoherence free subspaces
- robust and/or addressable control

Quantum Control of Atomic Qudits

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<u>Example</u>: Simplified Toffoli gate using Qtrits and 2-Qubit gates

Simplifying quantum logic using higher-dimensional Hilbert spaces

N. Phys. **5**, 134 (2009)

Benjamin P. Lanyon[1★], Marco Barbieri[1], Marcelo P. Almeida[1], Thomas Jennewein[1,2], Timothy C. Ralph[1], Kevin J. Resch[1,3], Geoff J. Pryde[1,4], Jeremy L. O'Brien[1,5], Alexei Gilchrist[1,6] and Andrew G. White[1]

Quantum computation promises to solve fundamental, yet otherwise intractable, problems across a range of active fields of research. Recently, universal quantum logic-gate sets—the elemental building blocks for a quantum computer—have been demonstrated in several physical architectures. A serious obstacle to a full-scale implementation is the large number of these gates required to build even small quantum circuits. Here, we present and demonstrate a general technique that harnesses multi-level information carriers to significantly reduce this number, enabling the construction of key quantum circuits with existing technology. We present implementations of two key quantum circuits: the three-qubit Toffoli gate and

Quantum Control of Atomic Qudits

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Example: Improved atom-light interface and spin squeezing

Enhanced Squeezing of a Collective Spin via Control of Its Qudit Subsystems

Leigh M. Norris,[1,2,*] Collin M. Trail,[3] Poul S. Jessen,[1,4] and Ivan H. Deutsch[1,2]
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[2]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131-0001, USA*
[3]*Institute for Quantum Information Science, University of Calgary, Calgary, Alberta, Canada T2N 1N4*
[4]*College of Optical Sciences and Department of Physics, University of Arizona, Tucson, Arizona 85721, USA*
(Received 24 May 2012; published 23 October 2012)

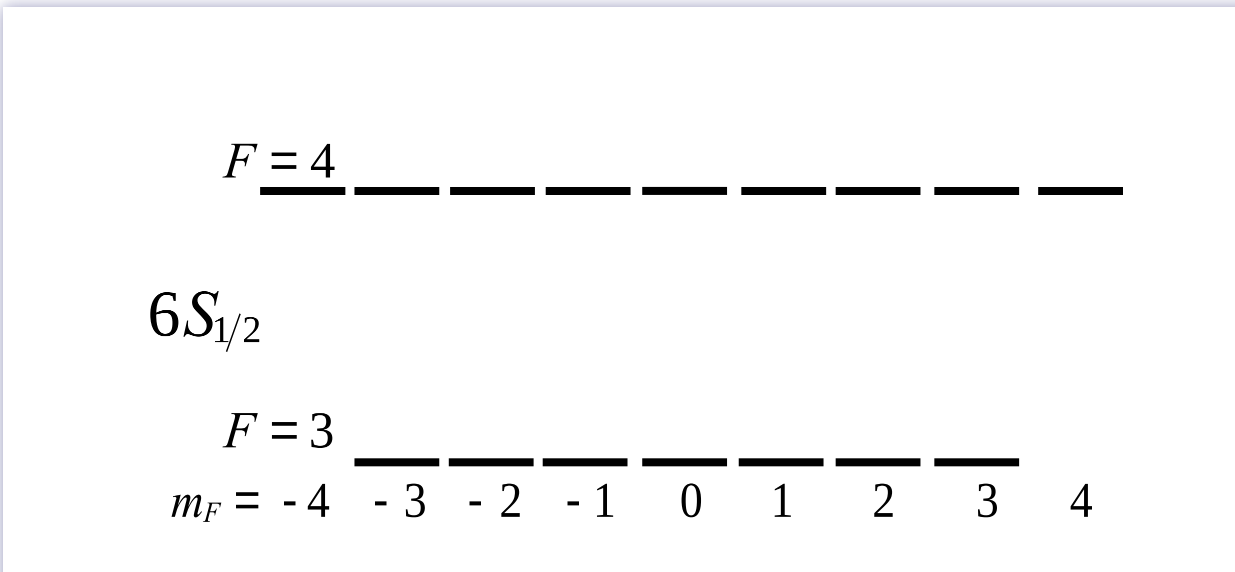
Unitary control of qudits can improve the collective spin squeezing of an atomic ensemble. Preparing the atoms in a state with large quantum fluctuations in magnetization strengthens the entangling Faraday interaction. The resulting increase in interatomic entanglement can be converted into metrologically useful spin squeezing. Further control can squeeze the internal atomic spin without compromising

PRL **109**, 173603 (2012)

Our Platform: The ^{133}Cs Atom

Ground state hyperfine structure

$$\mathbf{F} = \mathbf{S} + \mathbf{I} \qquad \left.\begin{matrix} I = 7/2 \\ S = 1/2 \end{matrix}\right\} \text{ Þ } \quad F = 3, 4$$

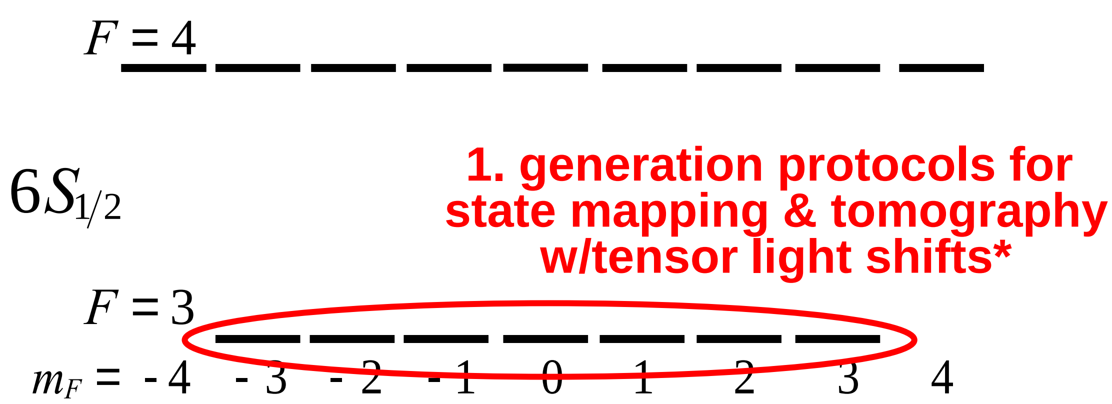


– Naturally long coherence times, limited by background magnetic fields –

Our Platform: The ^{133}Cs Atom

Ground state hyperfine structure

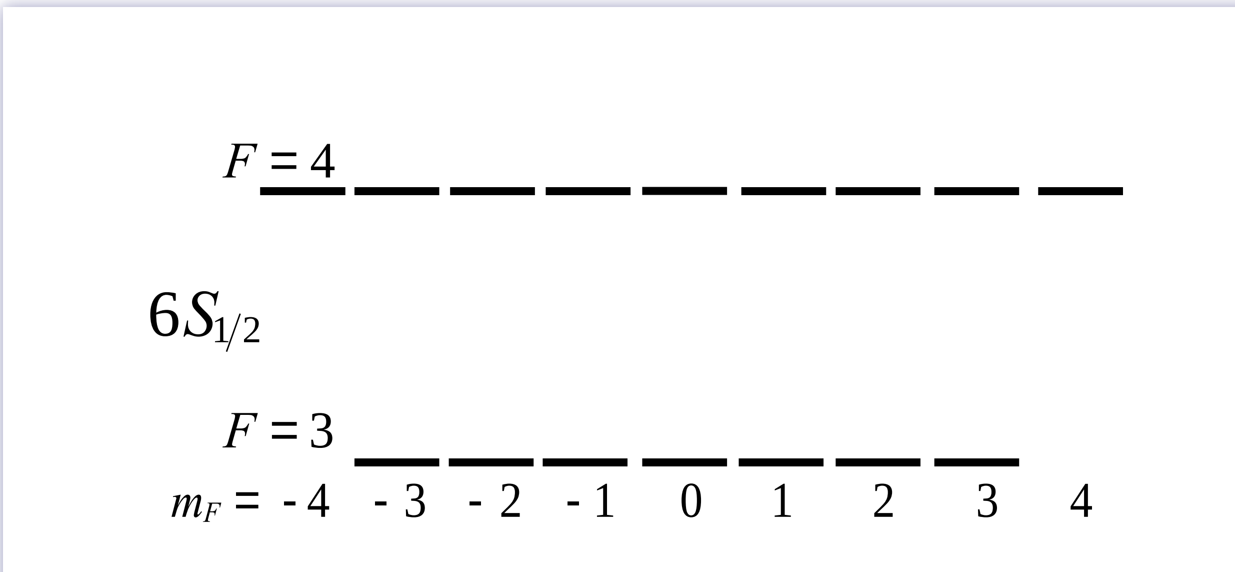
$$\mathbf{F} = \mathbf{S} + \mathbf{I} \qquad \left. \begin{array}{l} I = 7/2 \\ S = 1/2 \end{array} \right\} \Rightarrow \quad F = 3, 4$$



* Smith, Silberfarb, IHD & PSJ, PRL **97**, 180403 (2006)
Chaudhury, Merkel, Herr, Silberfarb, IHD & PSJ, PRL **99**, 163002 (2007)
Chaudhury, Smith, Anderson, Ghose & PSJ, Nature **461**, 768 (2009)
IHD & PSJ, Opt. Comm. **283**, 681 (2010)

Our Platform: The ^{133}Cs Atom

Control Hamiltonian: $H(t) = A\,\mathbf{I}\cdot\mathbf{S} + g_e \mu_B \mathbf{B}(t)\cdot\mathbf{S} + g_N \mu_B \mathbf{B}(t)\cdot\mathbf{I}$



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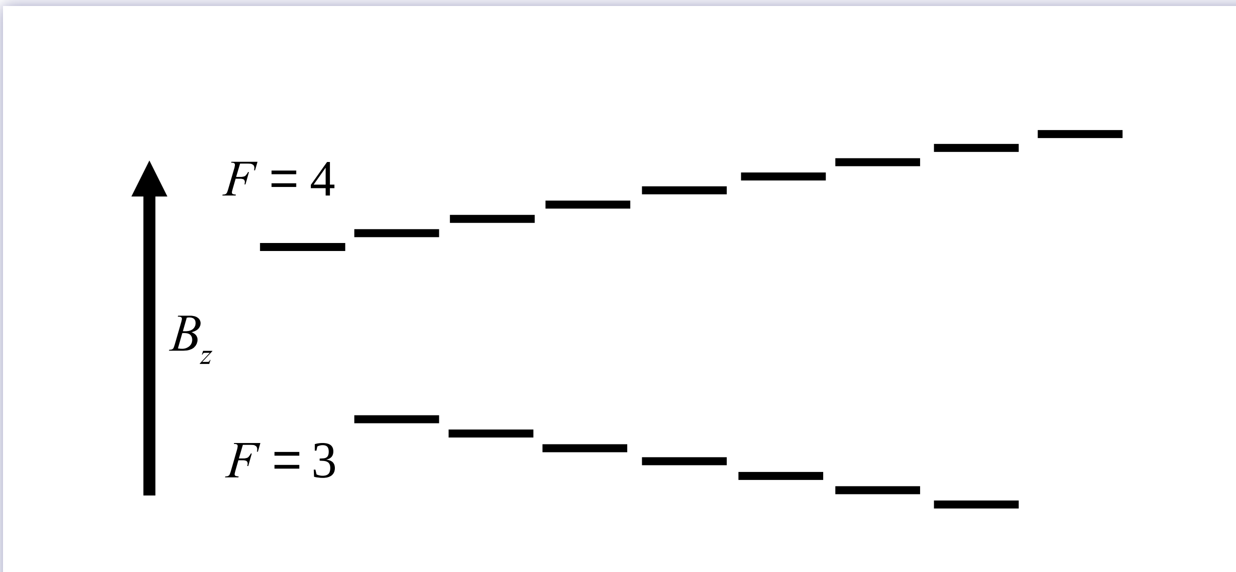
Magnetic Fields: $\mathbf{B}(t) = B_0\mathbf{z}$



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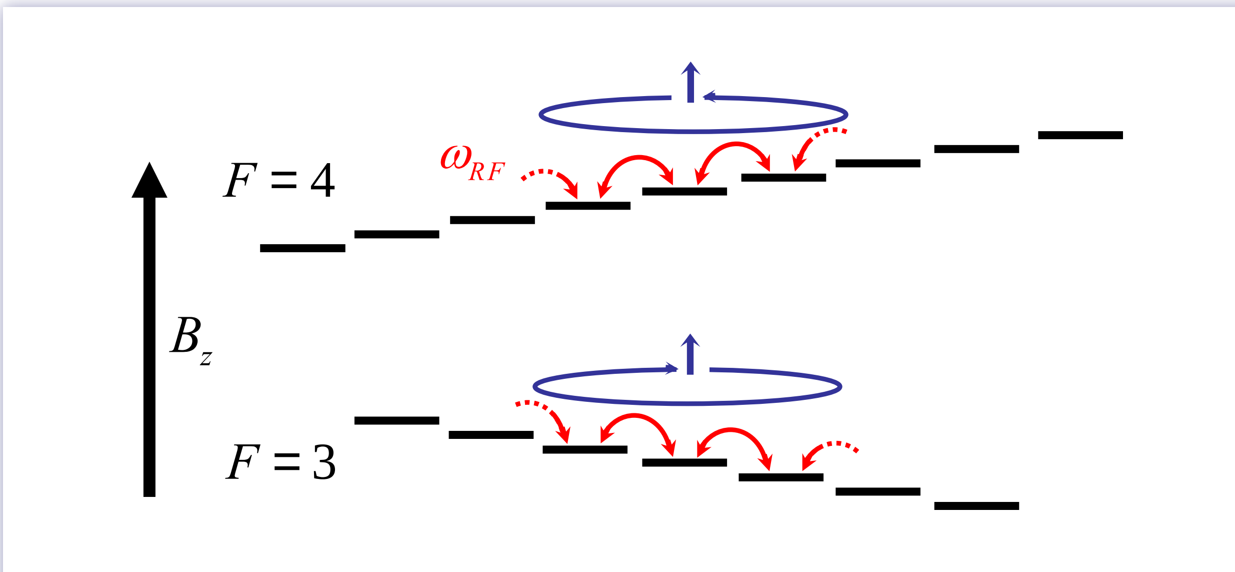

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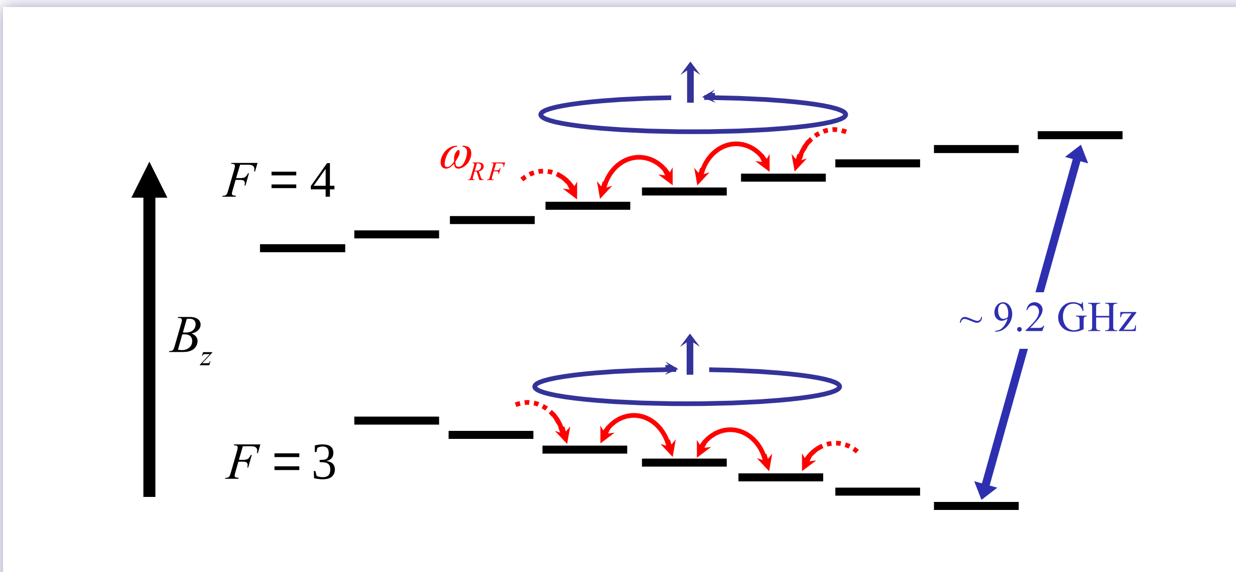

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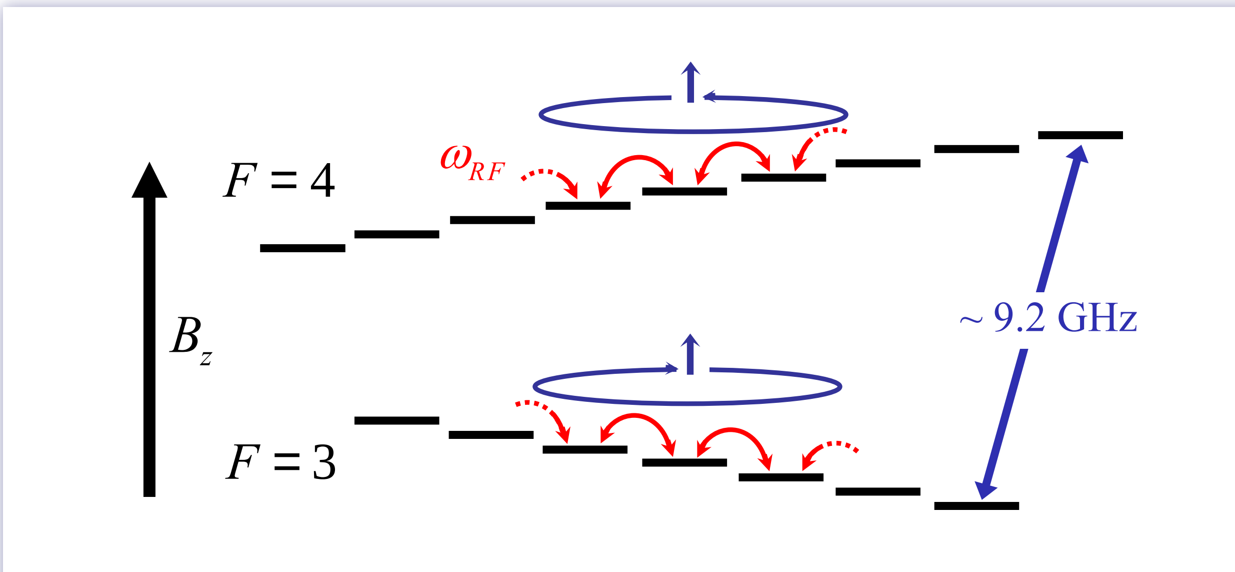

Control Parameters: RF phases $\phi_x(t)$, $\phi_y(t)$ μW phase $\phi_{\mu W}(t)$

Merkel, PSJ & IHD, PRA **78**, 023404 (2008)

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In terms of total spin F, NL Zeeman Effect, Rotating Wave Approximation

$$\begin{aligned}
H_{RWA} =& \left[\frac{3\hbar\Omega_0}{2}(1+g_{\text{rel}}) - \frac{25 g_{\text{rel}}\hbar^2\Omega_0^2}{2\Delta E_{\text{HF}}} - \frac{\hbar}{2}(\Delta_{\mu\text{W}} - 7\Delta_{\text{rf}})\right]\left(P^{(4)} - P^{(3)}\right) \\
&+ \Omega_0(1+g_{\text{rel}})F_z^{(3)} + \frac{g_{\text{rel}}\Omega_0^2}{\Delta E_{\text{HF}}}\left(F_z^{(4)2} - F_z^{(3)2}\right) - \Delta_{\text{rf}}\left(F_z^{(4)} - F_z^{(3)}\right) \\
&+ \frac{\Omega_x}{2}\left[\cos(\phi_x)\left(F_x^{(4)} + g_{\text{rel}}F_x^{(3)}\right) - \sin(\phi_x)\left(F_y^{(4)} - g_{\text{rel}}F_y^{(3)}\right)\right] \\
&+ \frac{\Omega_y}{2}\left[\sin(\phi_y)\left(F_x^{(4)} - g_{\text{rel}}F_x^{(3)}\right) + \cos(\phi_y)\left(F_y^{(4)} + g_{\text{rel}}F_y^{(3)}\right)\right] \\
&+ \frac{\Omega_{\mu\text{W}}}{2}\left[\cos(\phi_{\mu\text{W}})\sigma_x - \sin(\phi_{\mu\text{W}})\sigma_y\right].
\end{aligned}$$

Merkel, PSJ & IHD, PRA **78**, 023404 (2008) Riofrio, PhD Thesis, arXiv:1111.5627 (2011)

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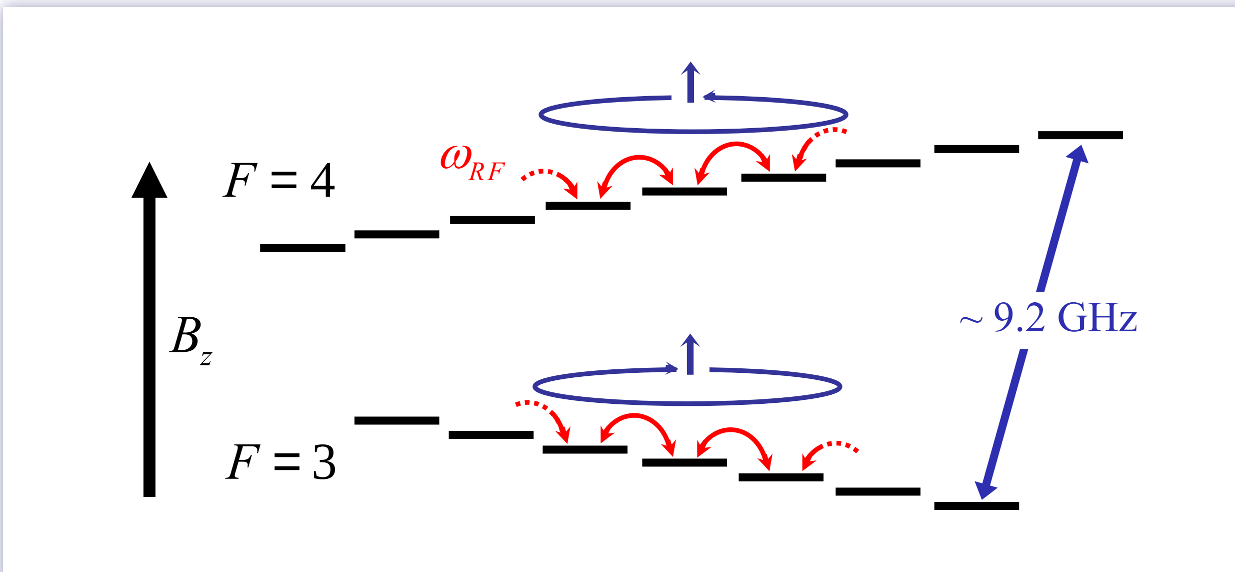
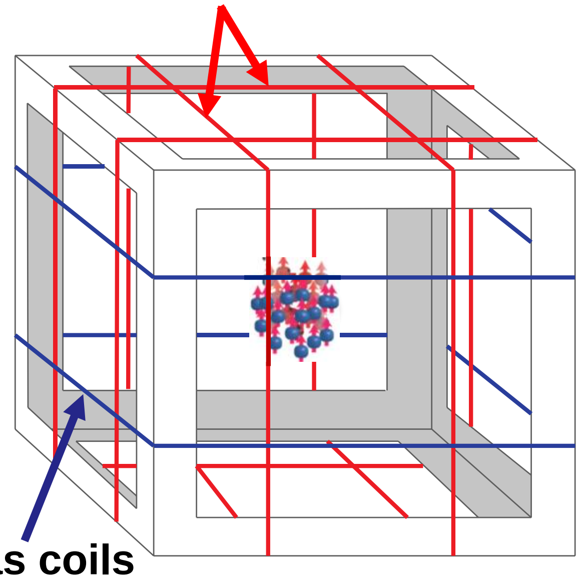
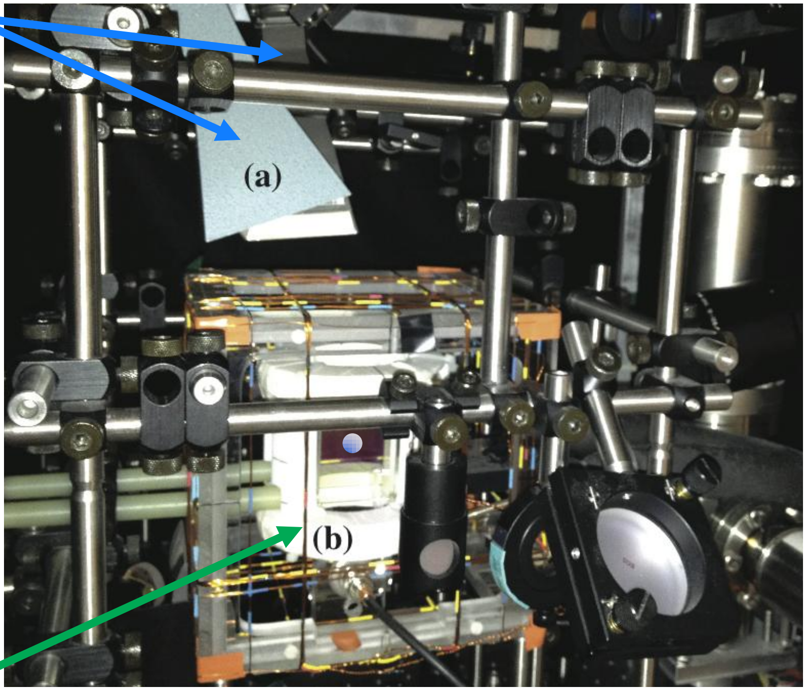


Control Parameters: RF phases $\varphi_x(t)$, $\varphi_y(t)$ μW phase $\varphi_{\mu W}(t)$

Experimental Setup





Internal-state control of ~10^6 laser cooled atoms in free fall

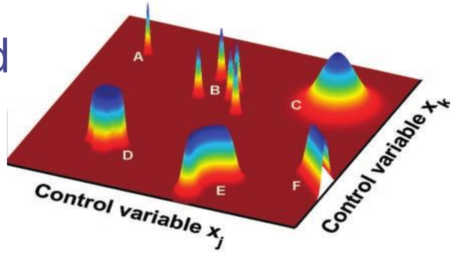
Bias field:	$\sim 3\,Gauss$	**RF Larmor freq:**	$25kHz$
Bias Larmor freq:	$1.0MHz \pm 10Hz$	**μw Rabi freq:**	$27.5kHz$

Numerical Design of Unitary Controls

Control Objective: $" \; |y\rangle : \; |y\rangle \longrightarrow W|y\rangle$ $\quad W$: target unitary

- **Hamiltonian** $\quad H(t) = H_0 + å_j H_j(c_j(t))$
- **Control waveforms** $\quad c_j(t) \to c_j(t_k) = c_{jk}$ $\quad \leftarrow$ vector **c**
- **Cost function** $\quad F[\mathbf{c}] = \frac{1}{d^2}|Tr[W^{+}U(T)]|^2$ $\quad \leftarrow$ Fidelity)
- **Numerics** $\quad$ Find **c** that maximizes $J[\mathbf{c}]$

Challenge:
- search complexity not well understood
- thought to be harder than state maps[+]



* See e. g. Moore et al, PRA **83**, 012326 (2011) $\quad$ + Rabitz et al, Science **303**, 1998 (2004)

Numerical Design of Unitary Controls

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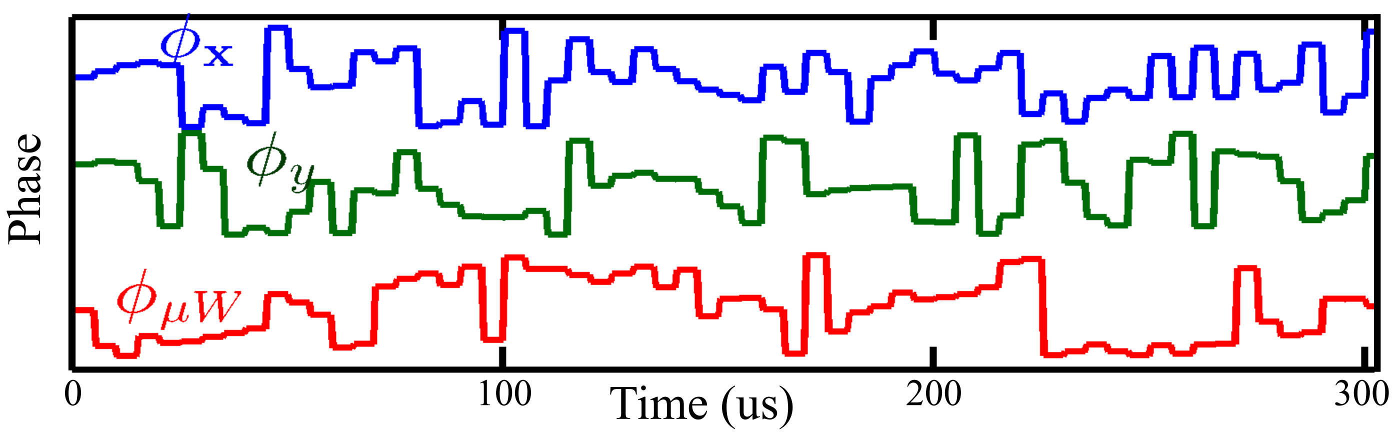
$\Omega_{RF,x} = \Omega_{RF,y} = 25.0\,kHz \qquad \Omega_{\mu W} = 27.5\,kHz$

$\omega_{RF} = 1.0\,MHz \qquad \omega_{\mu W} = 9.2\,GHz$

Control variables: ***phases*** $\mathbf{c} = \{\phi_x(t_i), \phi_y(t_i), \phi_{\mu W}(t_i)\}, \quad i = 1,\ldots,N$



Numerical Design of Unitary Controls

Numerical Search

- Start from random seed, integrate S. E. & compute fidelity
- Calculate gradient w/respect to control variables and take one step in uphill direction, repeat until $F[\mathbf{c}] \sim 1$

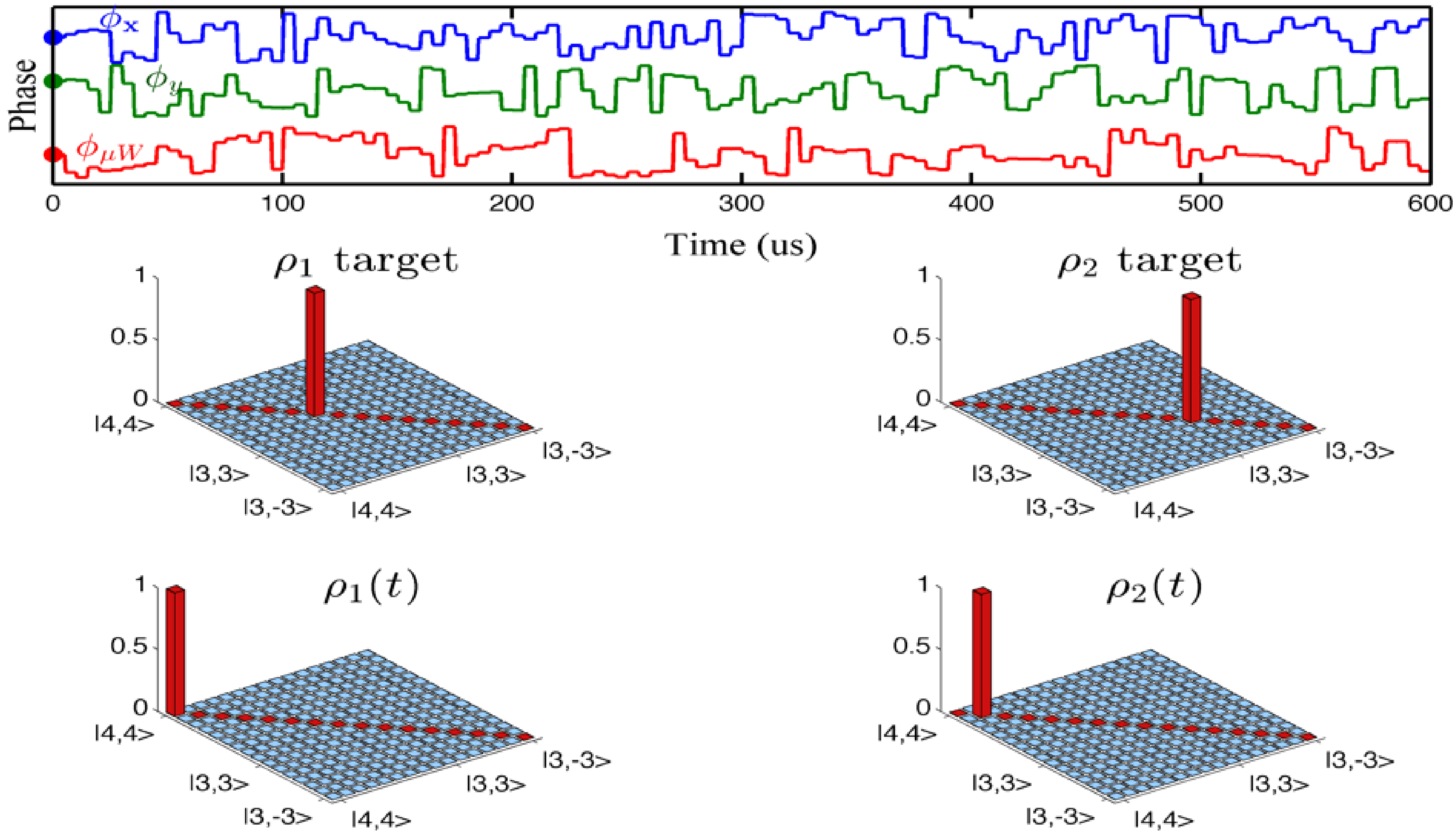
Numerical Design of Unitary Controls

Numerical Search

- Start from random seed, integrate S. E. & compute fidelity
- Calculate gradient w/respect to control variables and take one step in uphill direction, repeat until $F[\mathbf{c}] \sim 1$
- Use RWA with Bloch-Siegert type corrections & piece-wise linear phases to speed up integration of S. E.
- Use variant of the GRAPE algorithm for efficient search
  ➡ computational complexity per iteration ~ # of phases
- Can design a $d = 16$ unitary in ~3 minutes on desktop
- Easy to design many unitaries in parallel on HPC cluster

Numerical Design of Unitary Controls

<u>Example</u> - **permutation of all 16 magnetic eigenstates (two shown)**



Numerical Design of Unitary Controls

Robust control

- Design control waveforms that are insensitive to small errors in the control Hamiltonian*
- Most important in our experiment:
  ~50Hz inhomogeneity in Bias Larmor Frequency
- Greedy search: optimize average fidelity on 2-point grid

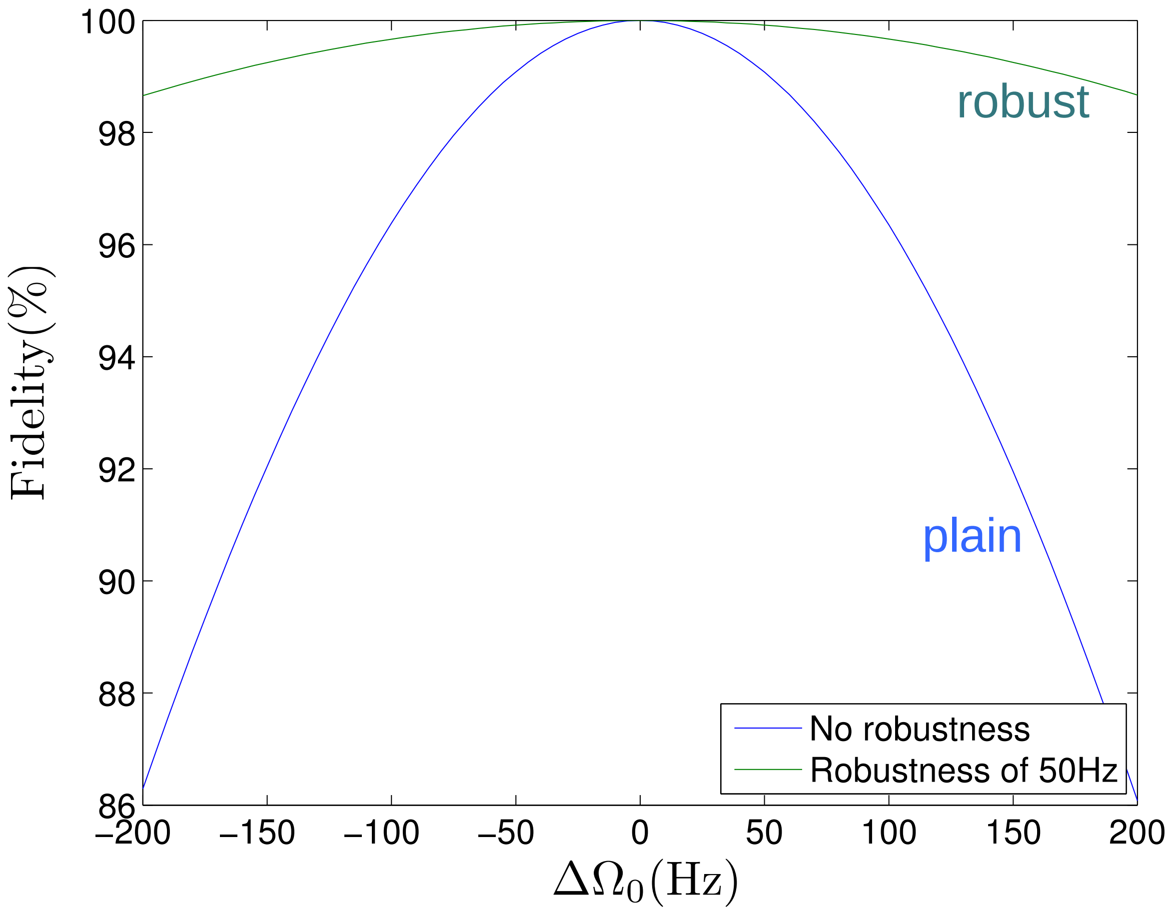
$$\bar{F}[\mathbf{c}] = (F_{+50\,Hz}[\mathbf{c}] + F_{-50\,Hz}[\mathbf{c}])/2$$

* Mischuck, Merkel & IHD, PRA **85**, 022302 (2012)

Numerical Design of Unitary Controls

Robust control

- **Greedy search: optimize average fidelity on 2-point grid**



Quantum Control of Atomic Qudits

Ready to head for the lab

– Not quite…

Randomized Benchmarking

<u>Challenge</u>: **How to determine fidelity in experiment?**

- **Quantum Process Tomography?**
  - **more difficult than unitary control, not accurate enough**
- **Randomized Benchmarking protocol?**
  - **conceptually similar to Randomized Bencharking of qubits**
  - **impractical to do all Clifford Gates in $d=16$ space**
  - **instead benchmark a random sample of unitaries**

* E. Knill et al, Nature **404**, 368 (2000)

Randomized Benchmarking

Protocol

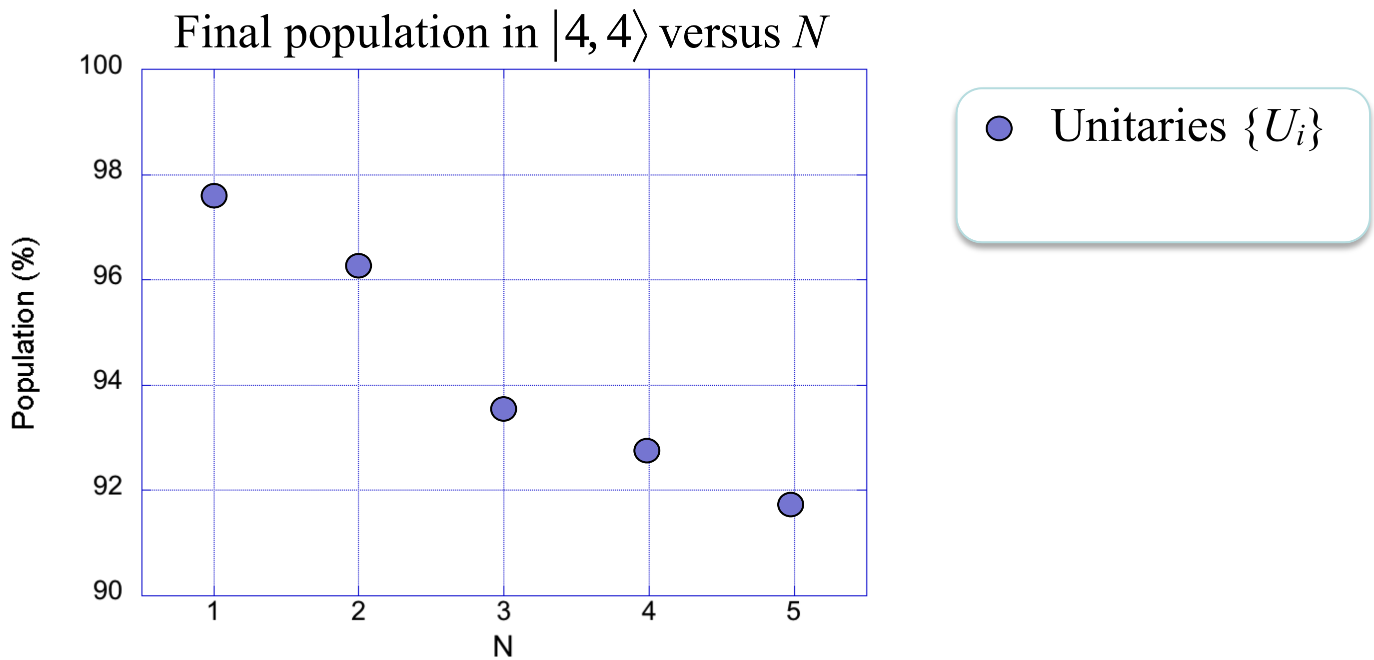
$$|4,4\rangle \rightarrow |\psi_0\rangle \rightarrow |4,4\rangle$$

$$|4,4\rangle \rightarrow |\psi_0\rangle \xrightarrow{U_1} |\psi_1\rangle \rightarrow |4,4\rangle$$

$$|4,4\rangle \rightarrow |\psi_0\rangle \xrightarrow{U_1} |\psi_1\rangle \xrightarrow{U_2} \ldots \xrightarrow{U_N} |\psi_N\rangle \rightarrow |4,4\rangle$$

initialization error | compound error in N unitary maps | readout error

$|\psi_0\rangle$, $\{U_i\}$ chosen at random



Randomized Benchmarking

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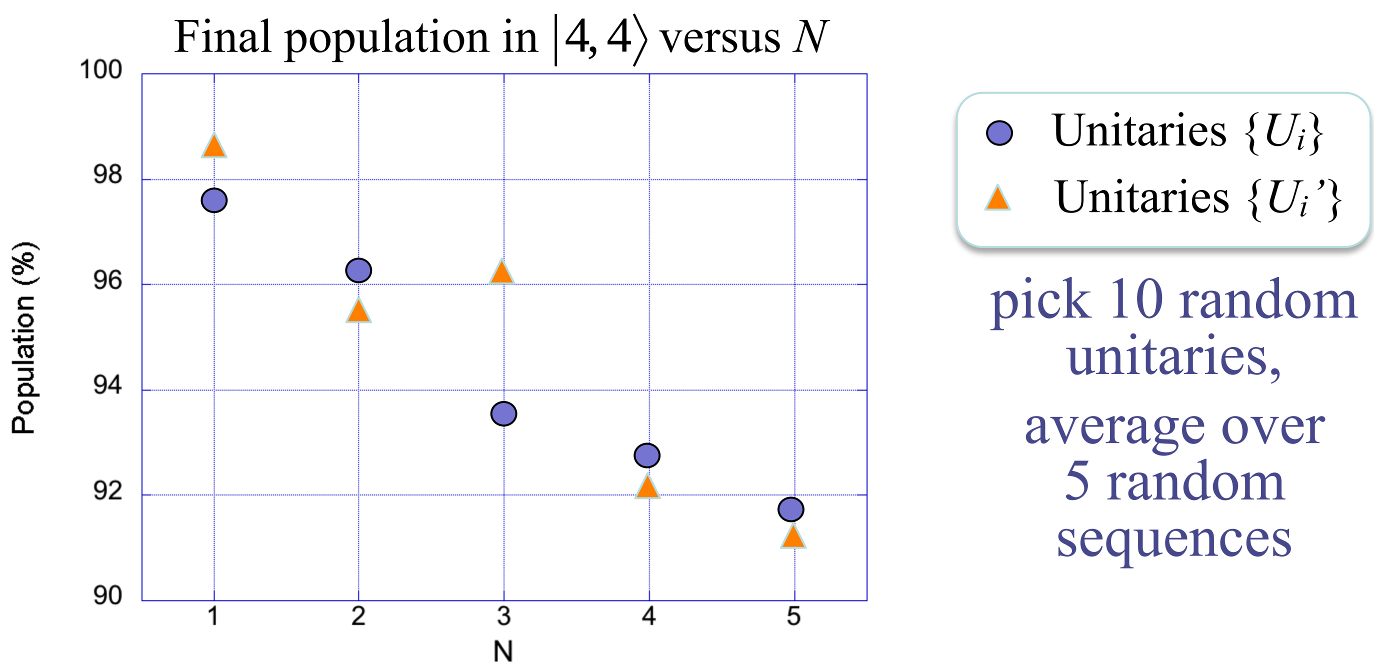


pick 10 random unitaries,

average over 5 random sequences

Randomized Benchmarking

Protocol

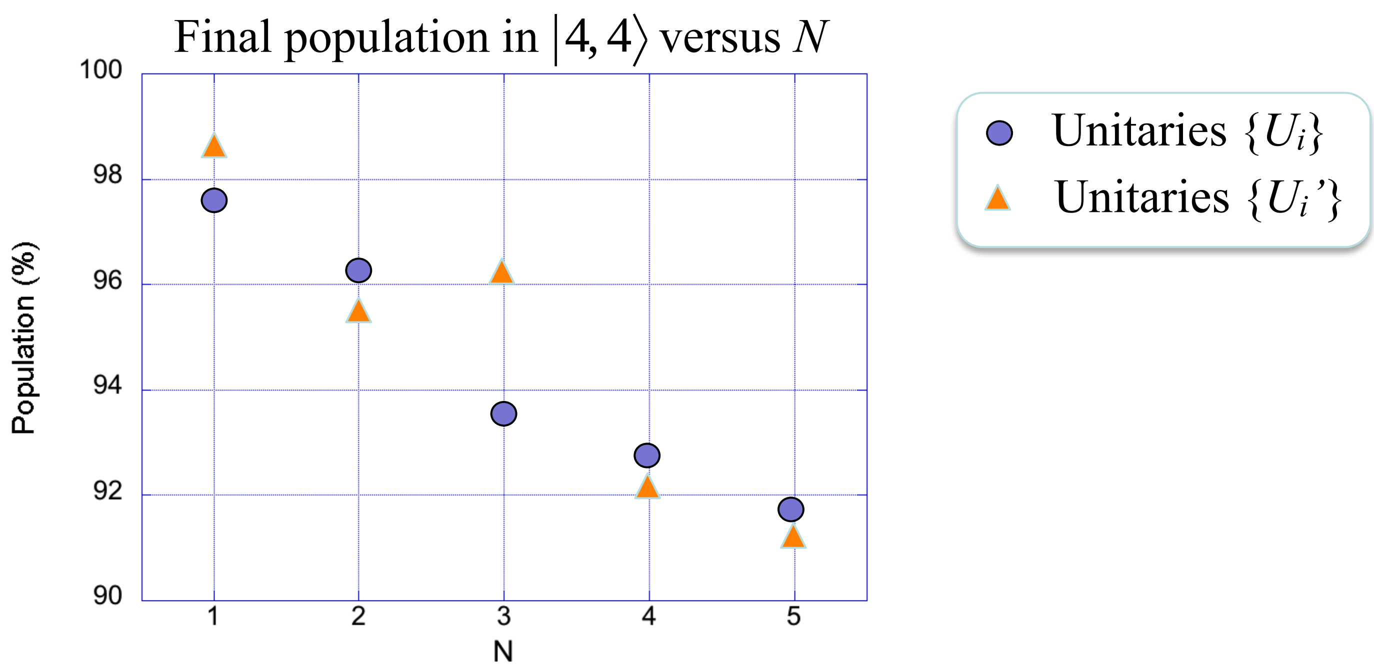
– **average over many such sequences and fit***

$$\bar{F}(N) = \frac{1}{16} + \frac{15}{16}\left(1 - \frac{16}{15}\eta_0\right)\left(1 - \frac{16}{15}\eta\right)^N \approx 1 - \eta_0 - N\eta$$

init & readout error

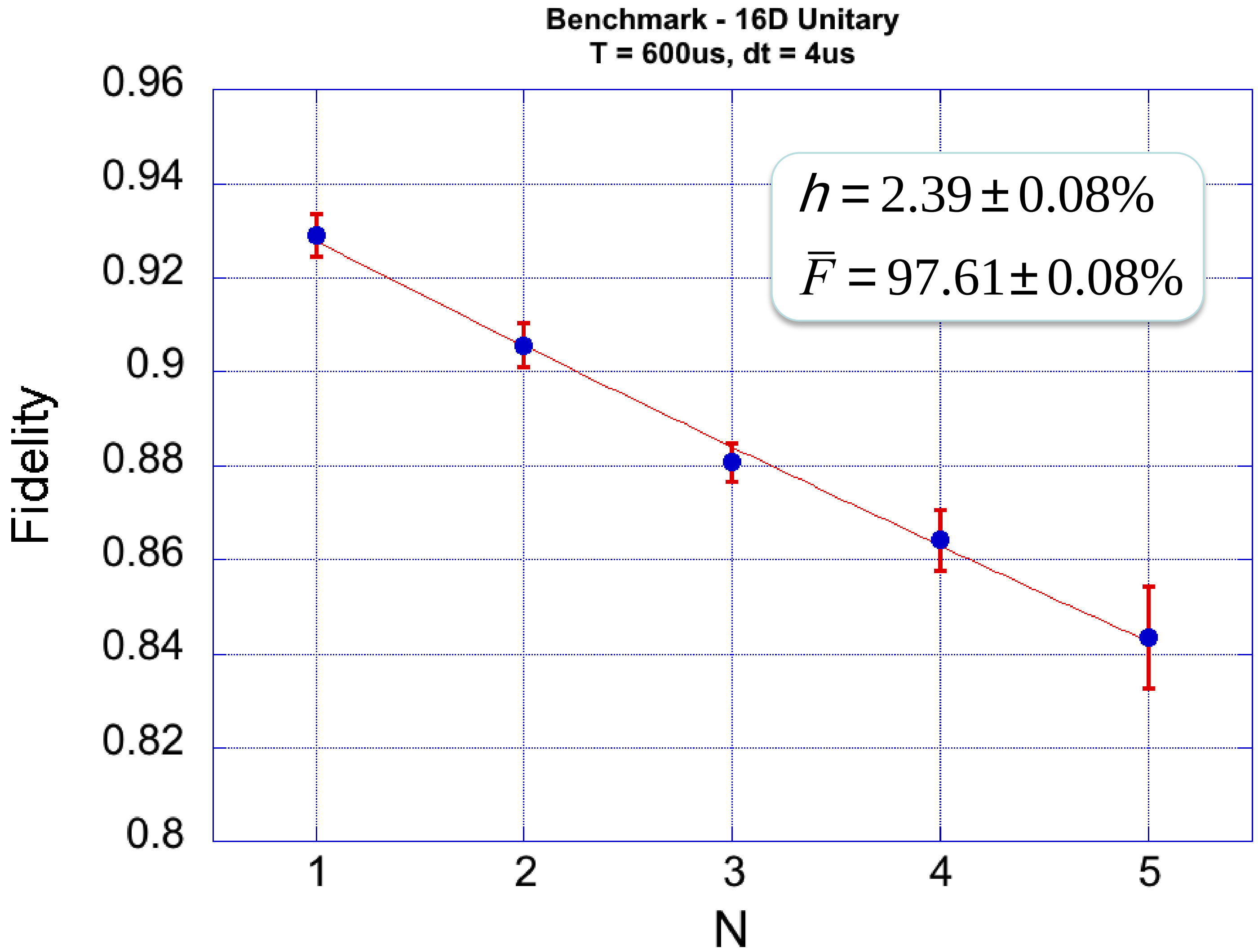
average error per unitary

average fidelity for N unitaries



Randomized Benchmarking

Experimental Data



Randomized Benchmarking

- **But wait – how does this relate to the fidelity of the unitaries?**
  - **no rigorous basis for this, as compared to qubits**

Randomized Benchmarking

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- **We can simulate an experiment with given imperfections**

Fixed parameters in $H(t)$:

$W_0 = 1.0MHz$ **(bias Larmor freq.)**

$W_{RF,x} = W_{RF,y} = 25.0kHz$

$W_{mW} = 27.5kHz$

$w_{RF} = 1.0MHz \quad w_{mW} = 9.2GHz$

Run w/these values ➡ $U(\mathbf{c}) = W$

Run w/deviations from these values (errors) ➡ $U_E(\mathbf{c})\ ^1\ W$

"Real" fidelity

$$\bar{F}_{real}[\mathbf{c}] = \frac{1}{d^2}\left\langle \left| Tr[W^+ U_E(\mathbf{c})] \right|^2 \right\rangle_U$$

Randomized Benchmarking

- But wait – how does this relate to the fidelity of the unitaries?
  - no rigorous basis for this, as compared to qubits

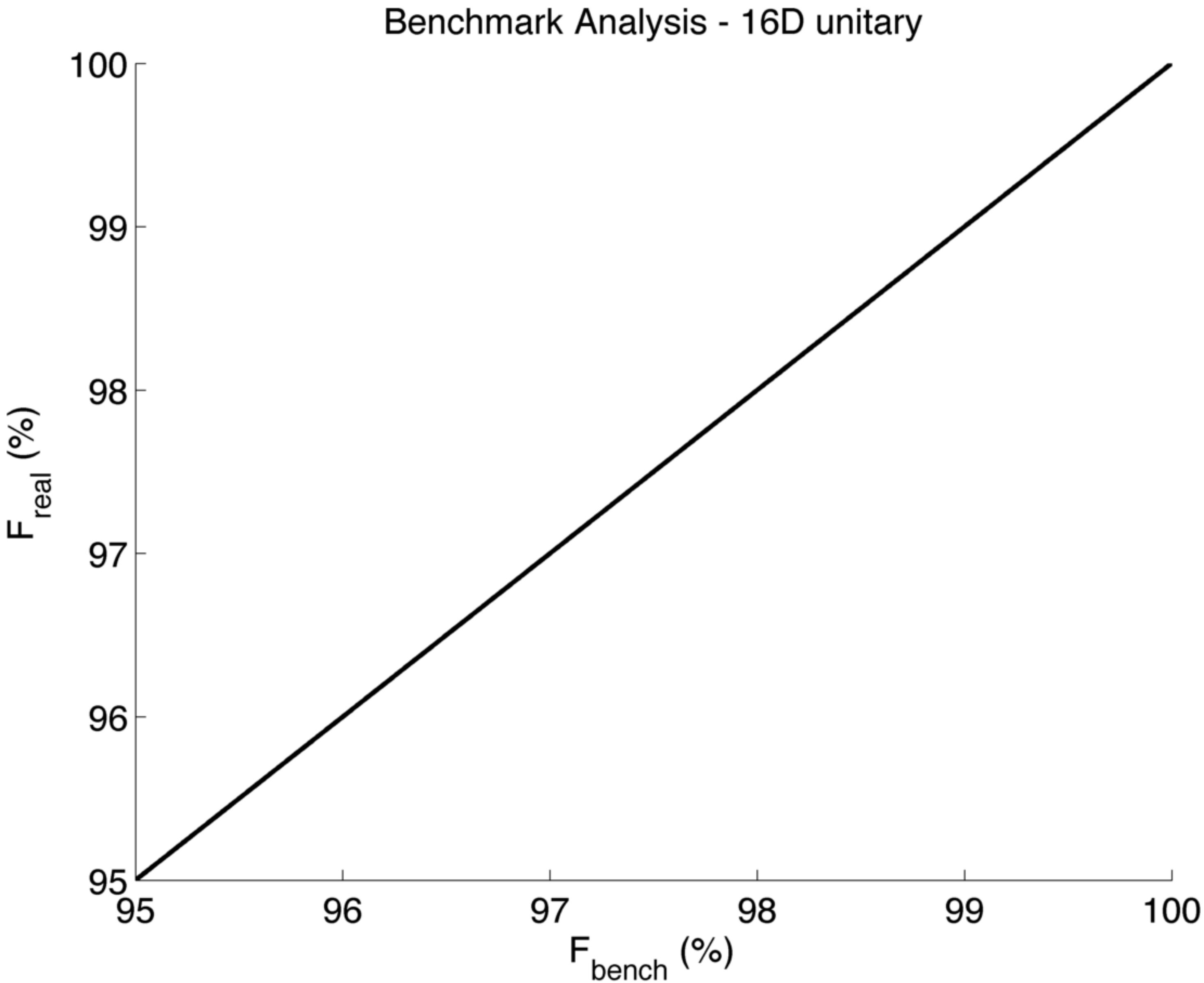
- We can simulate an experiment with given imperfections

$$\Rightarrow \bar{F}_{real}[\mathbf{c}] = \frac{1}{d^2}\left\langle \left| Tr[W^{+}U_E(\mathbf{c})] \right|^2 \right\rangle_U$$

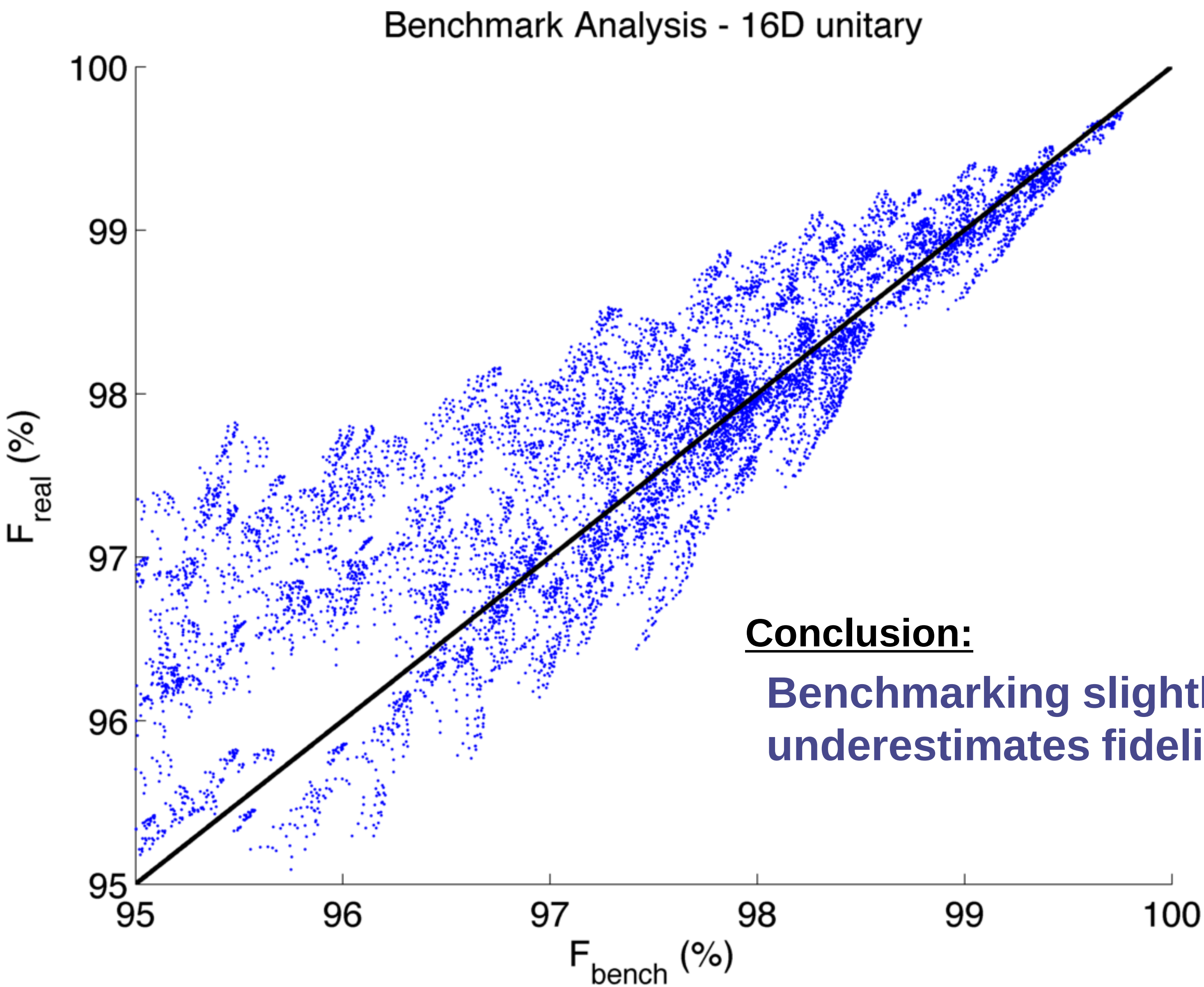
- We can also simulate randomized benchmarking in an experiment with similar imperfections $\Rightarrow \bar{F}_{bench}$

- If these are very similar then Benchmarking is meaningful

Randomized Benchmarking



Randomized Benchmarking



Conclusion:

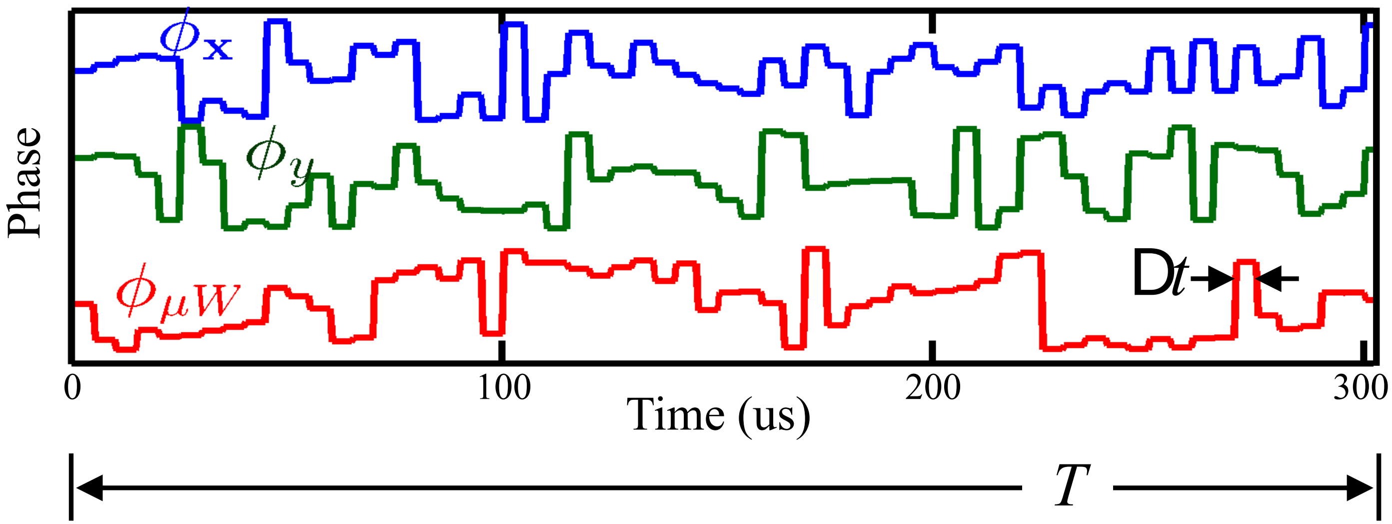
Benchmarking slightly underestimates fidelity

Quantum Control of Atomic Qudits

How well does in work?

Control Time and # of Control Parameters

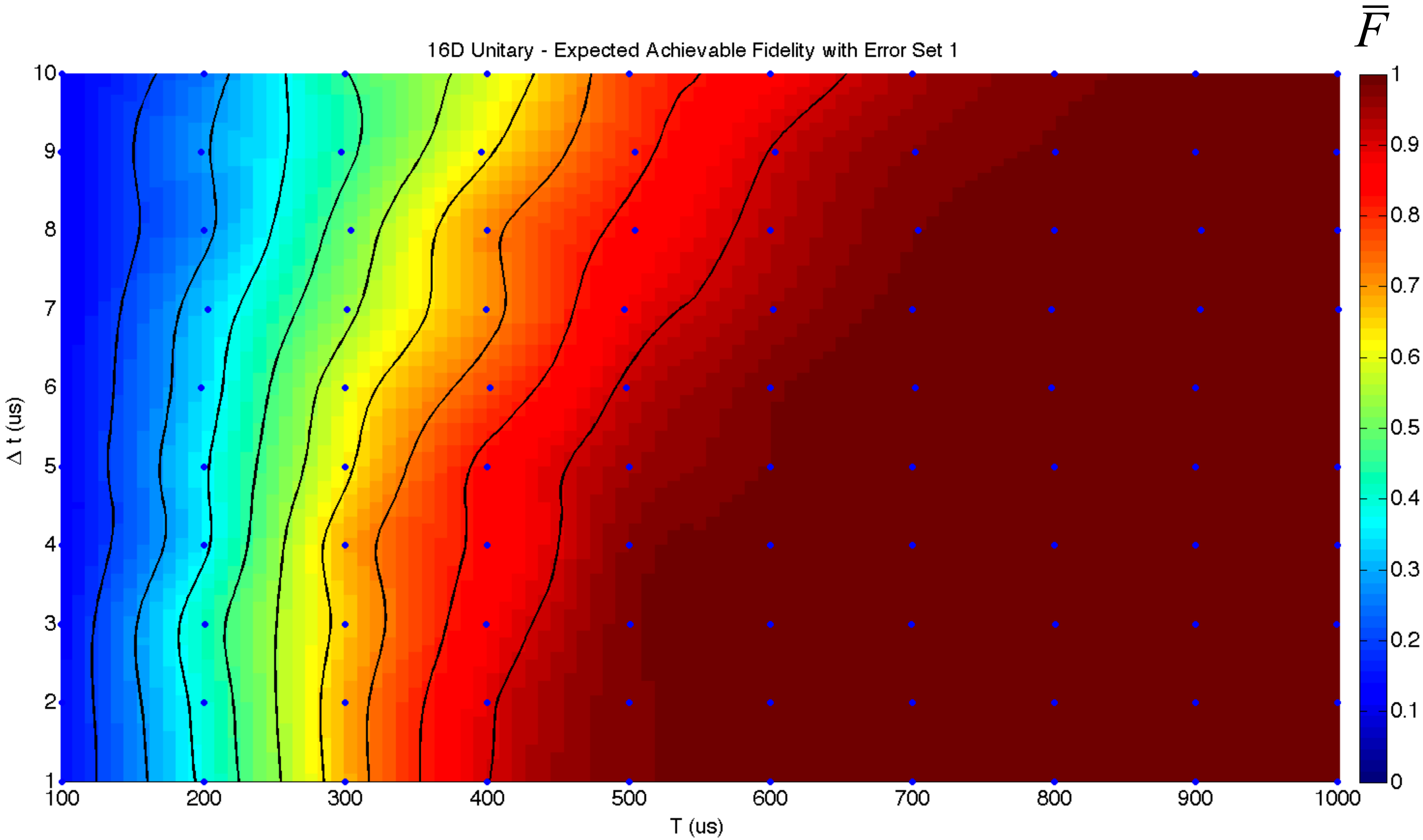
Control variables: *phases* $\mathbf{c} = \{\phi_x(t_i), \phi_y(t_i), \phi_{\mu W}(t_i)\}, \quad i = 1, \ldots, N = \frac{T}{\Delta t}$



- ➢ **Explore tradeoff between fidelity, control time and number of control parameters***

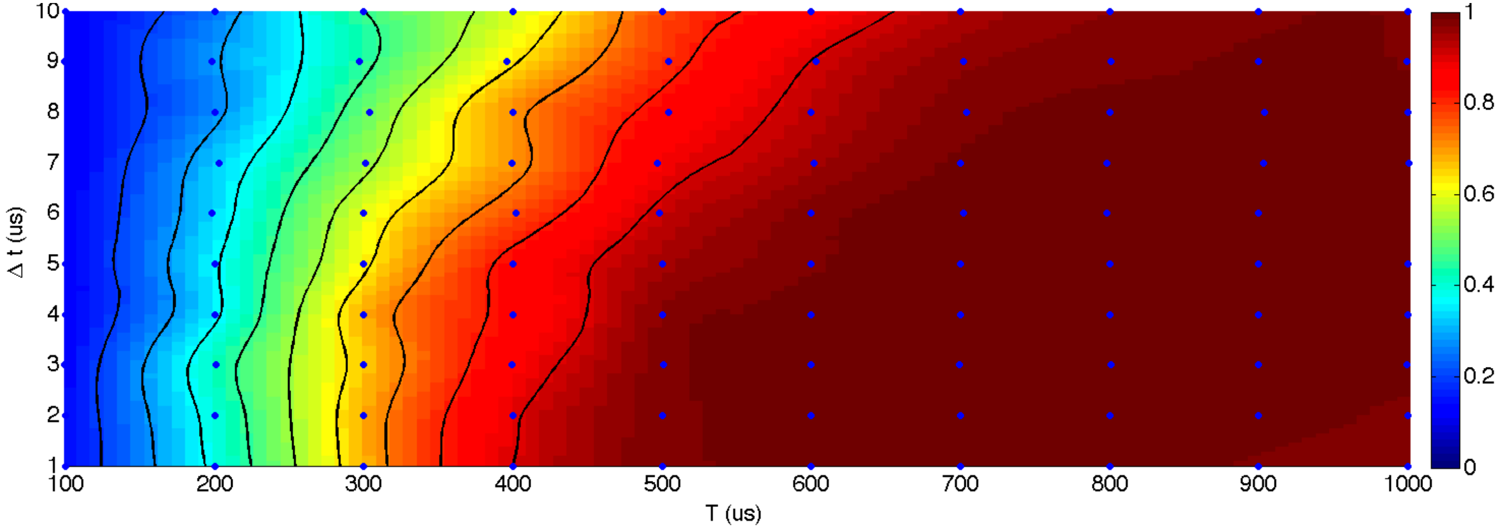
Control Time and # of Control Parameters

- 16D unitaries, robust controls, no additional imperfections

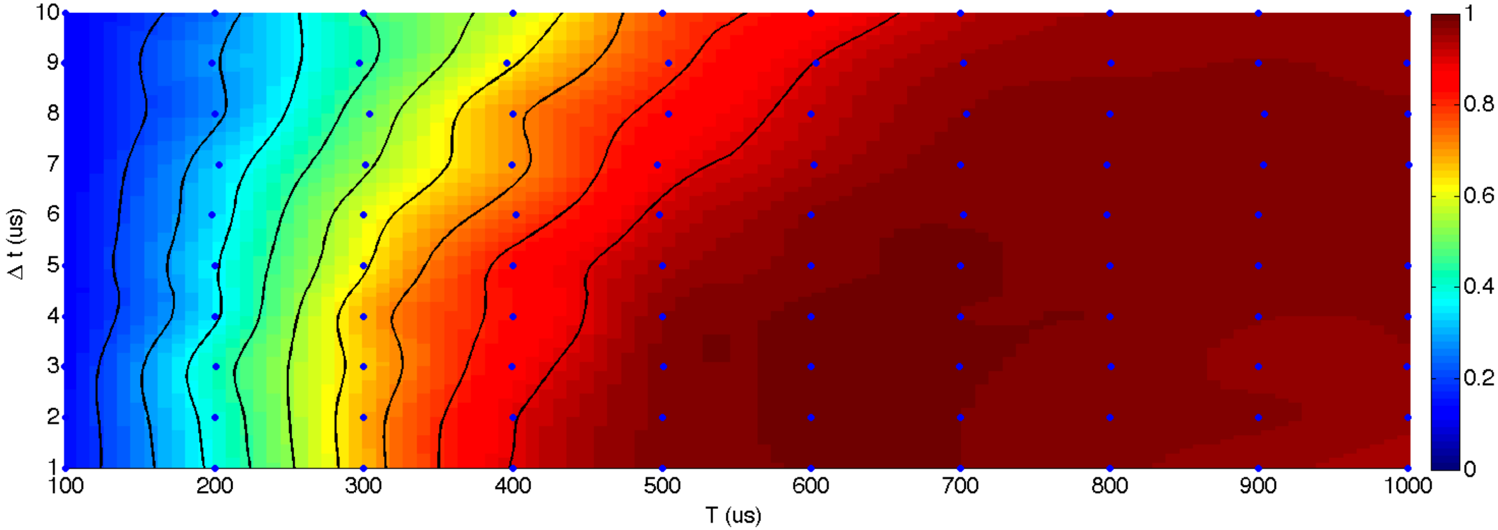


Control Time and # of Control Parameters

➢ **16D unitaries, robust controls, additional imperfections (~ our experiment)**

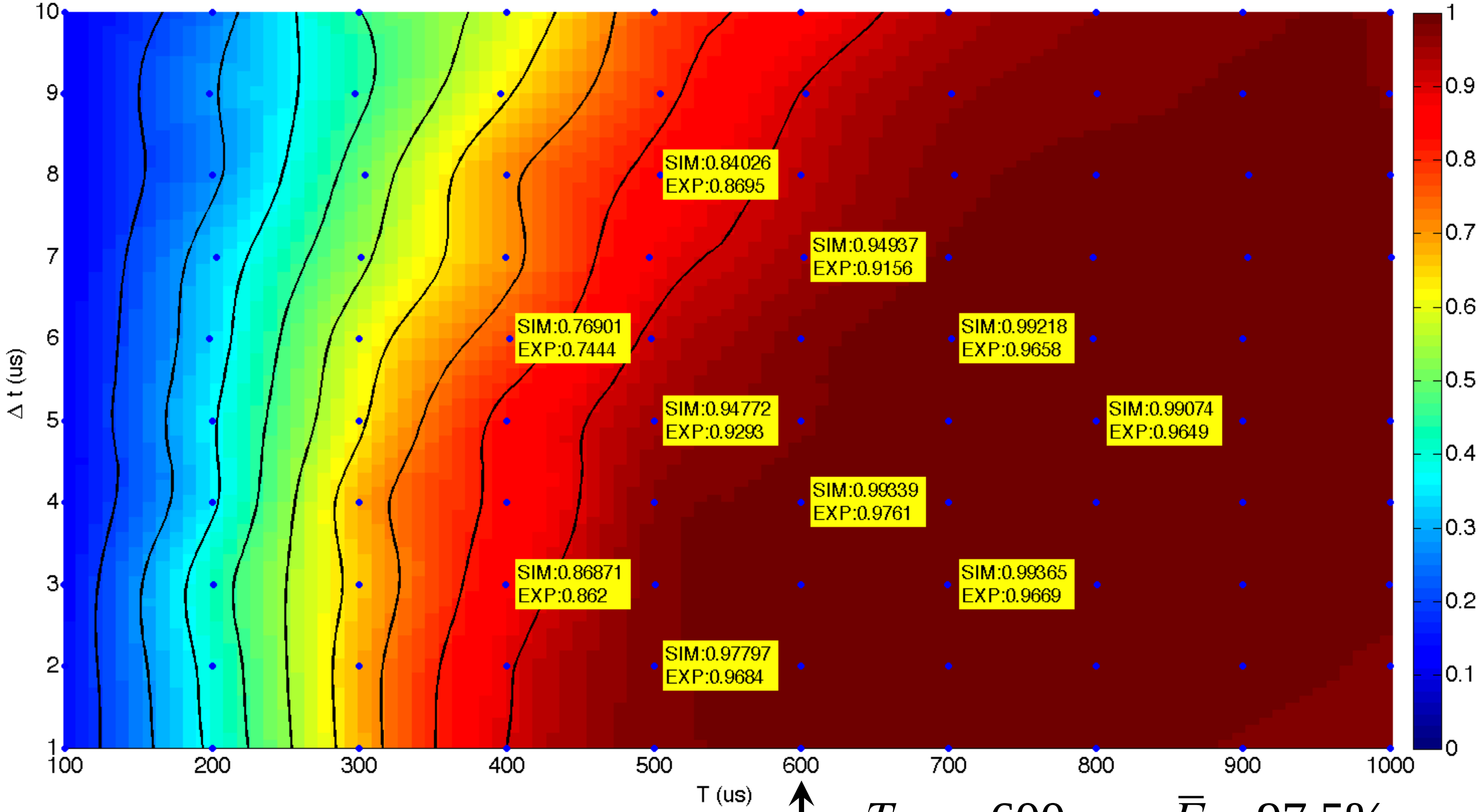


➢ **16D unitaries, Robust controls, additional imperfections (> our experiment**



Control Time and # of Control Parameters

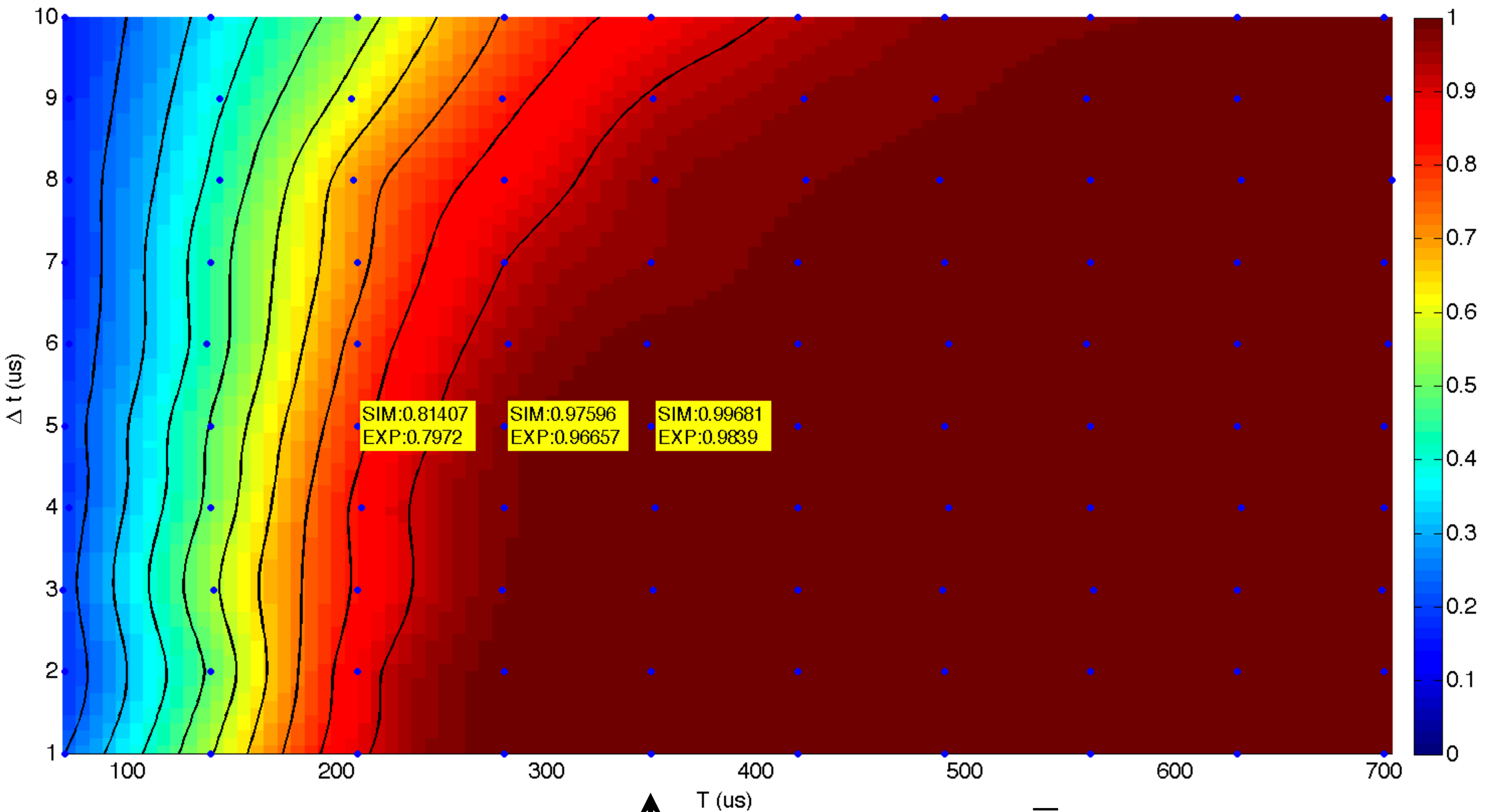
➢ **16D unitaries, robust controls, additional imperfections (~ our experiment)**



$T_{\min} \sim 600\,\mu s, \quad \bar{F} » 97.5\%$

Control Time and # of Control Parameters

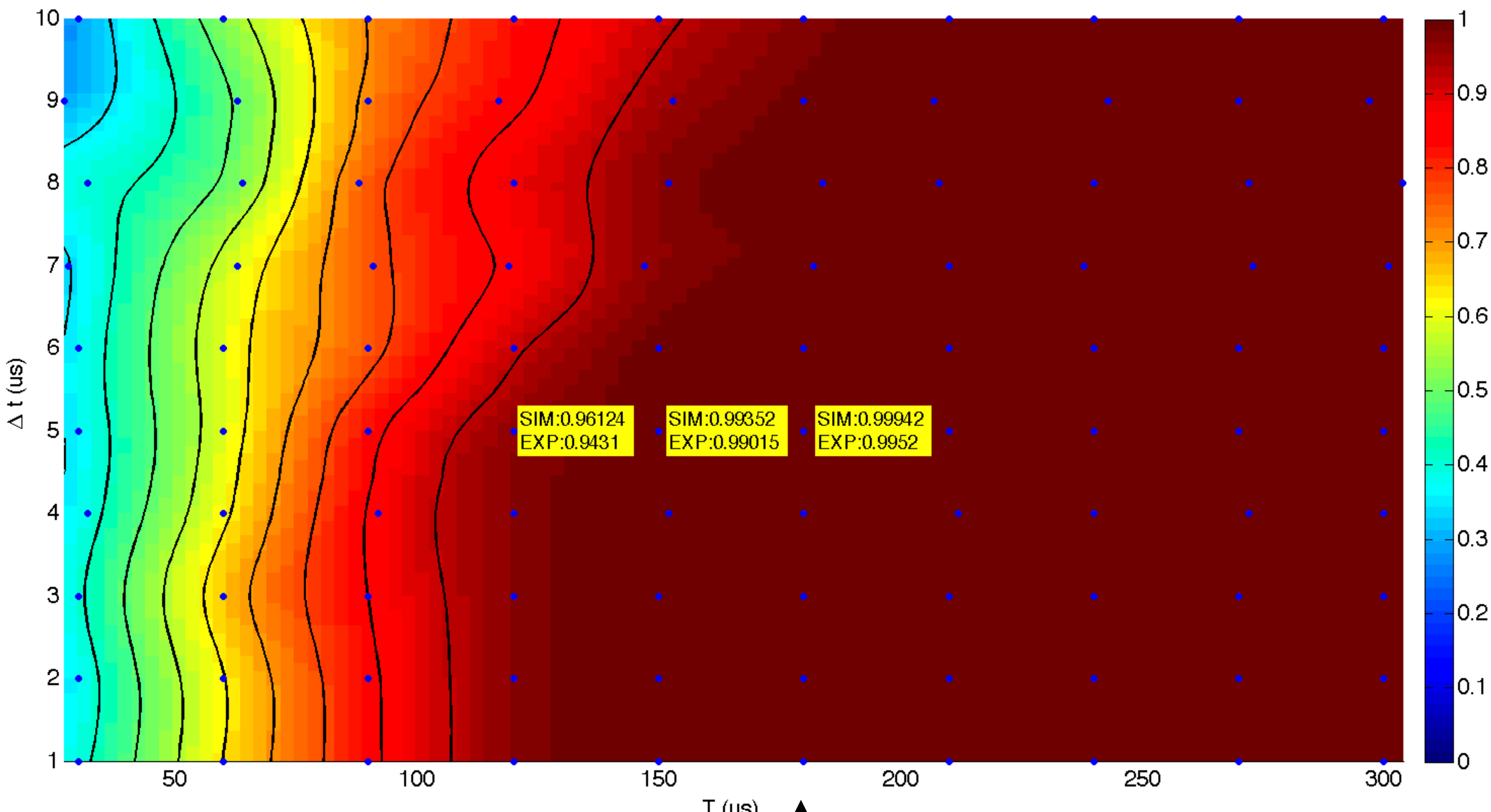
- 9D unitaries on *F* = 4 subspace



$T_{\min} \sim 350\,\mu s, \quad \bar{F} » 98.4\%$

Control Time and # of Control Parameters

- Average over randomly chosen 2D isometries



$T_{\min} \sim 175\mu s, \quad \bar{F} \gg 99.5\%$

Summary

- **Have implemented 16D unitary transformations.**

$$T_{\min} \sim 600\,\mu s, \quad \bar{F} \gg 97.5\%$$

- **Unitaries on 9D subspaces, 2D partial isometries**

$$T_{\min} \sim 350\,\mu s, \quad \bar{F} \gg 98.4\% \qquad T_{\min} \sim 175\,\mu s, \quad \bar{F} \gg 99.5\%$$

- **State-to-state maps** $T_{\min} \sim 150\,\mu s, \quad \bar{F} \gg 99.7\%$

- **Simpler control tasks** ➡ { **shorter control time**, **higher fidelity** }

Qudit Control – Future Goals

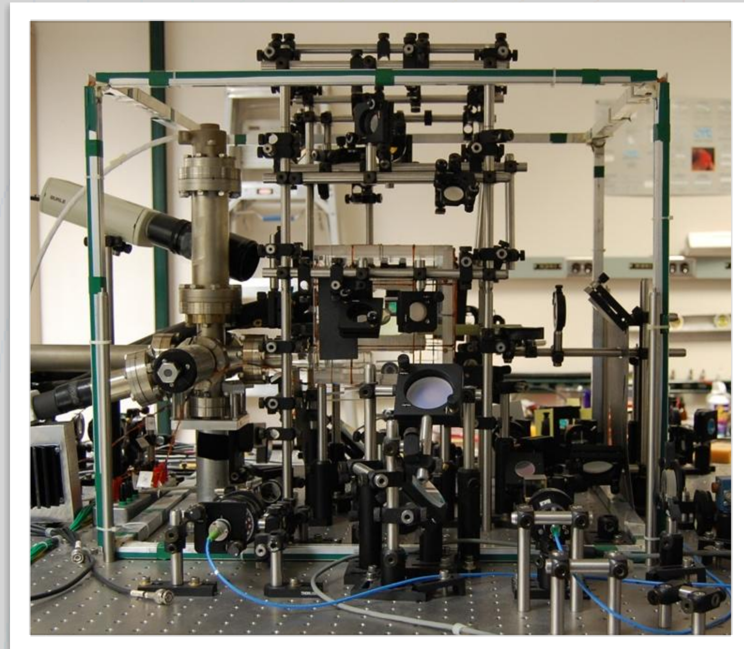
- **Inhomogeneous control***
  – do for Qudits what we can do for Qubits

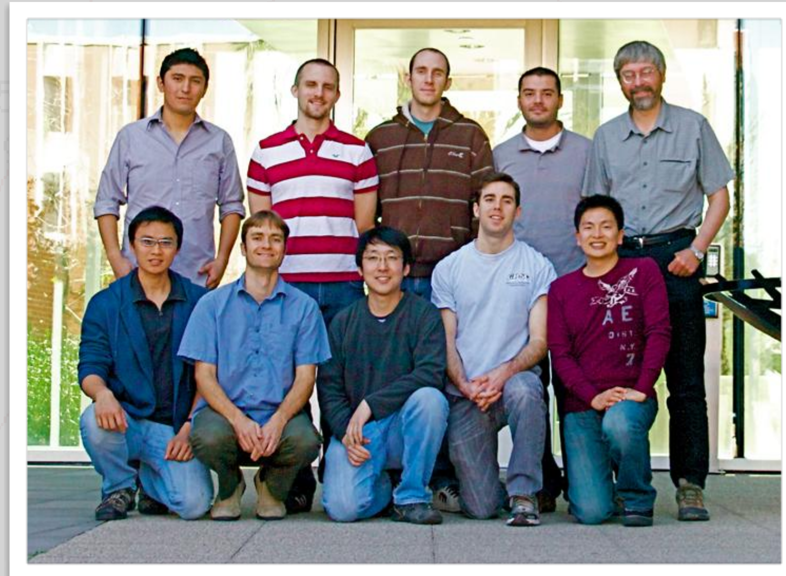
- **Improved atom-light interface and manybody control/spin squeezing****

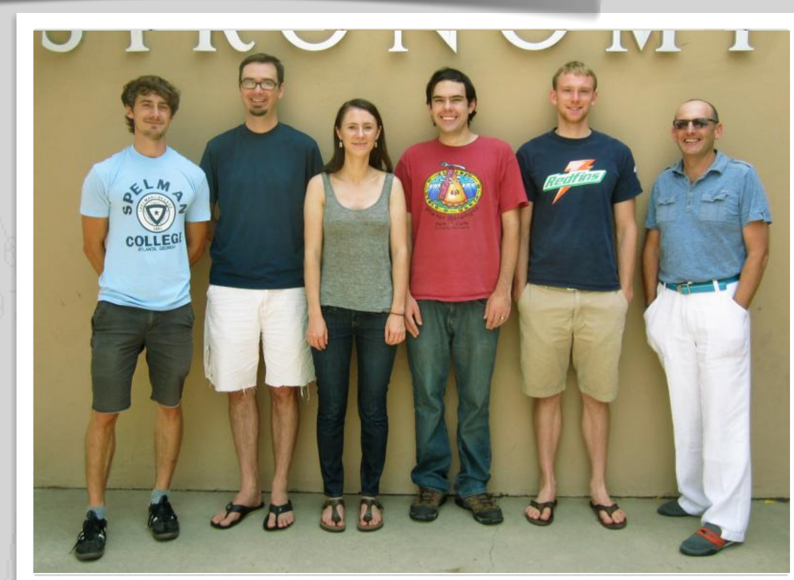
- **Beyond coherent control**
  – mixed-state to mixed-state mapping
  – completely positive maps

*   Mischuck, Merkel and IHD, PRA **85**, 022302 (2012)
** Norris, Trail, PSJ & IHD, PRL **109**, 173603 (2012)

Thank you to the Team







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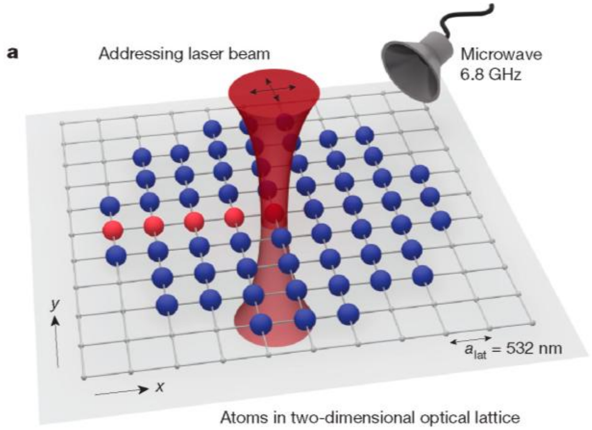
Resonance Addressing in an Optical Lattic

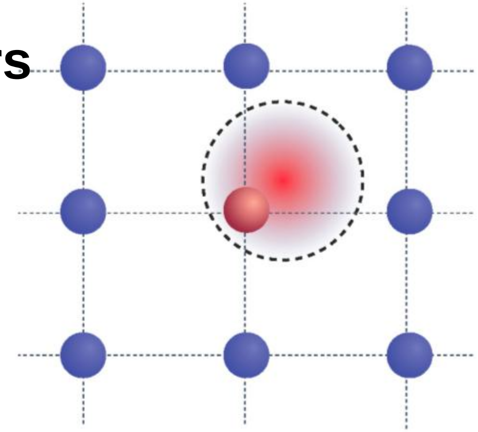
- **Site Resolved Addressing of Atoms in Optical Lattices**

W. S. Bakr et al, Nature **462**, 74 (2009)



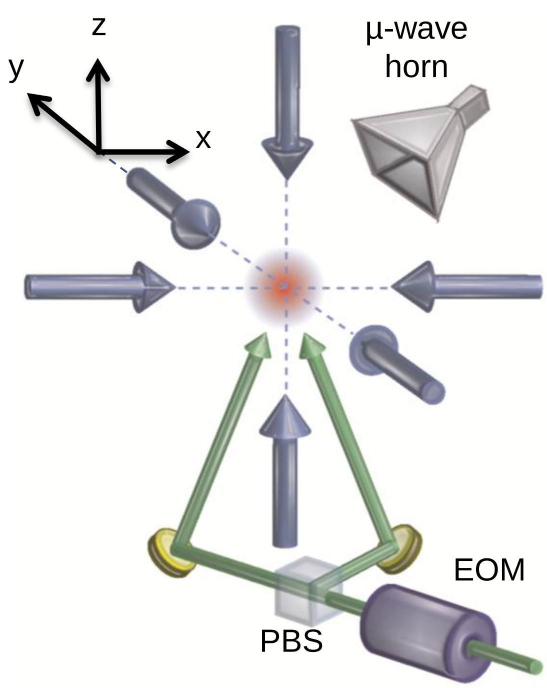
C. Weitenberg et al., Nature **471**, 319 (2011)

Challenge: Pointing errors



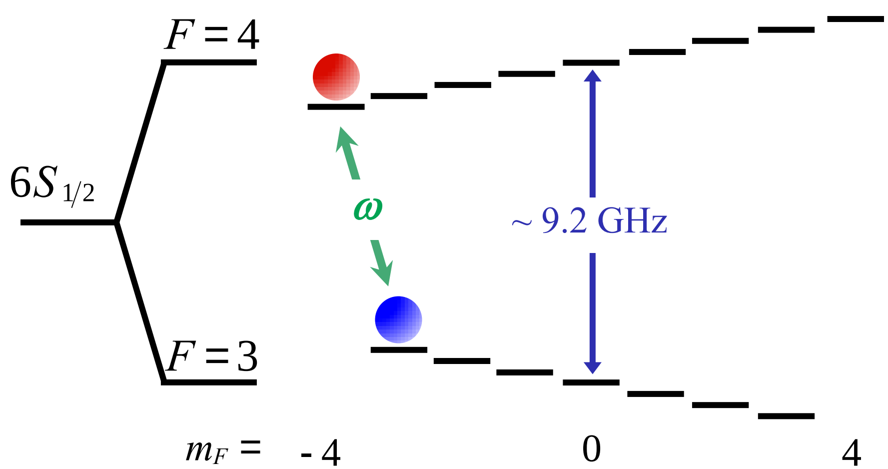
Resonance Addressing in an Optical Lattic

➢ **<u>Our Approach</u>: Use standing wave to address in 1D**



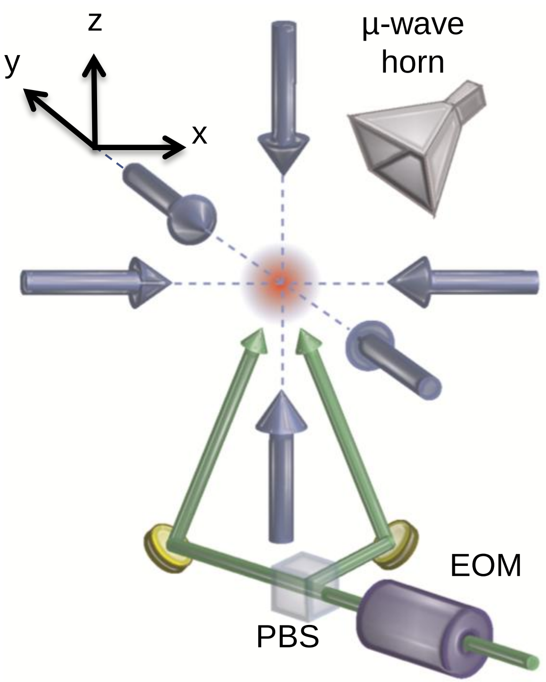
Cesium atom qubit ($\lambda = 852$ nm)

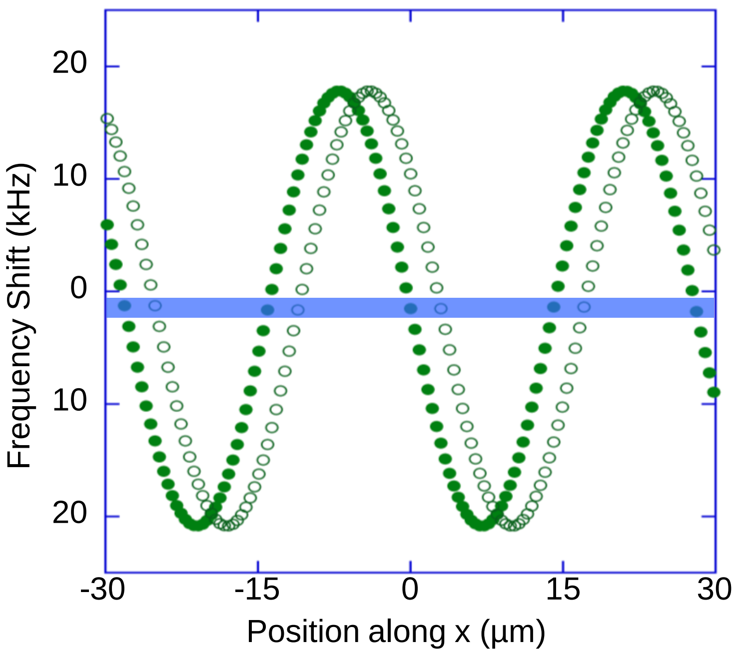
ground manifold



Resonance Addressing in an Optical Lattic

➢ **Our Approach:** **Use standing wave to address in 1D**

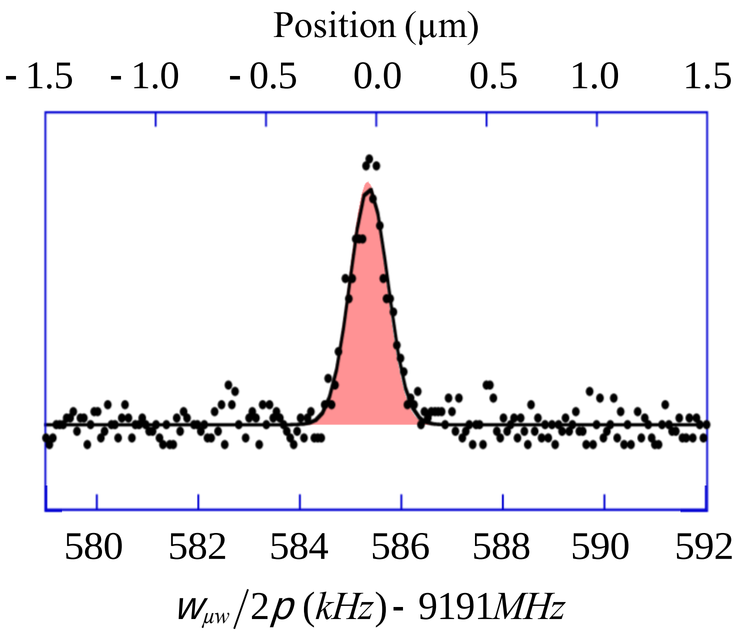


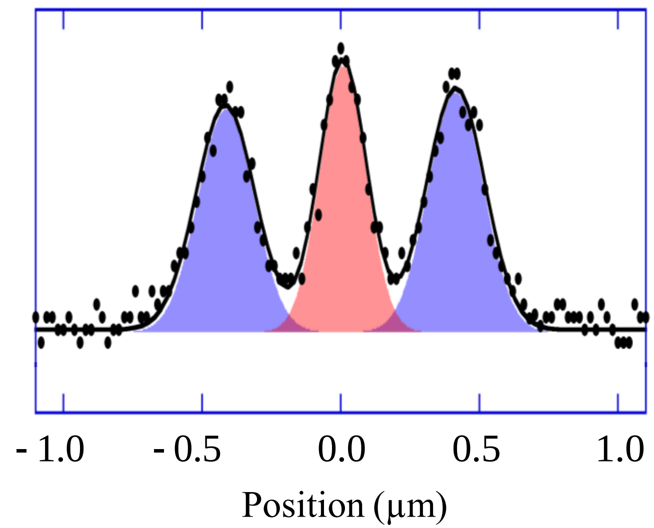


Translate "addressing lattice" by phase shifting ⇨ nm resolution

Resonance Addressing in an Optical Lattic

➢ Preparation and resonance imaging





RMS width of image: 80nm (350Hz)

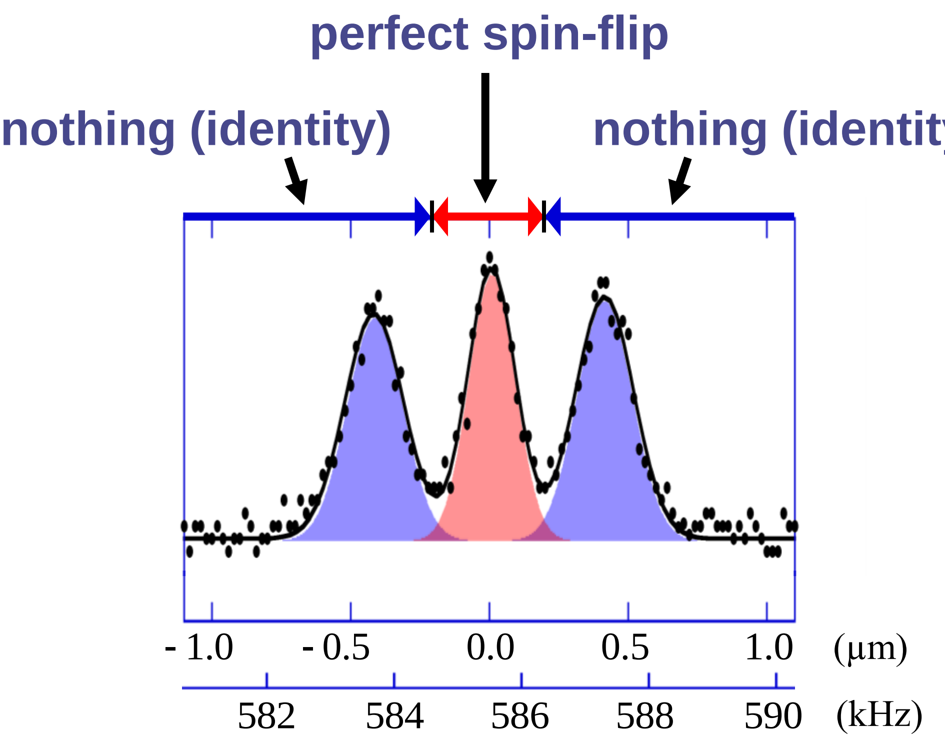
Resolution: 80nm/$\sqrt{2}$ = 57nm

Lattice spacing: λ/2 = 426nm

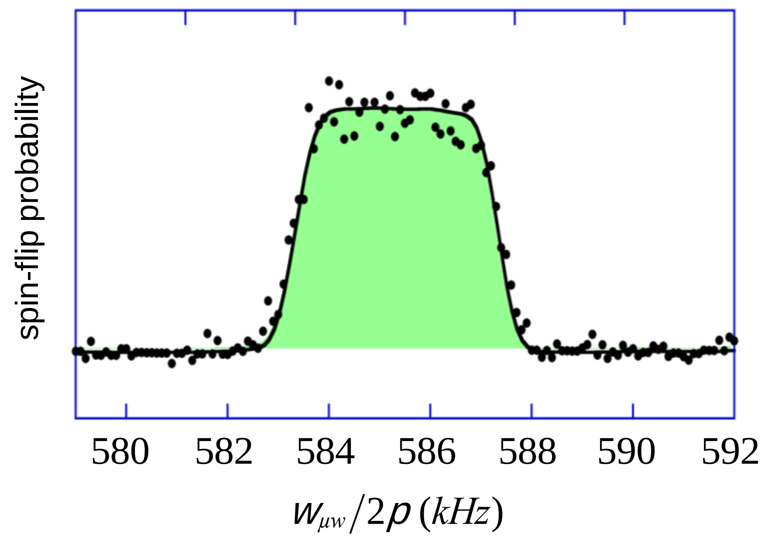
Good resolution of adjacent sites

Resonance Addressing in an Optical Lattic

➢ **Spin-flip at target site without touching neighbors**



example: phase modulated pulse with top-hat response



Resonance Addressing in an Optical Lattic

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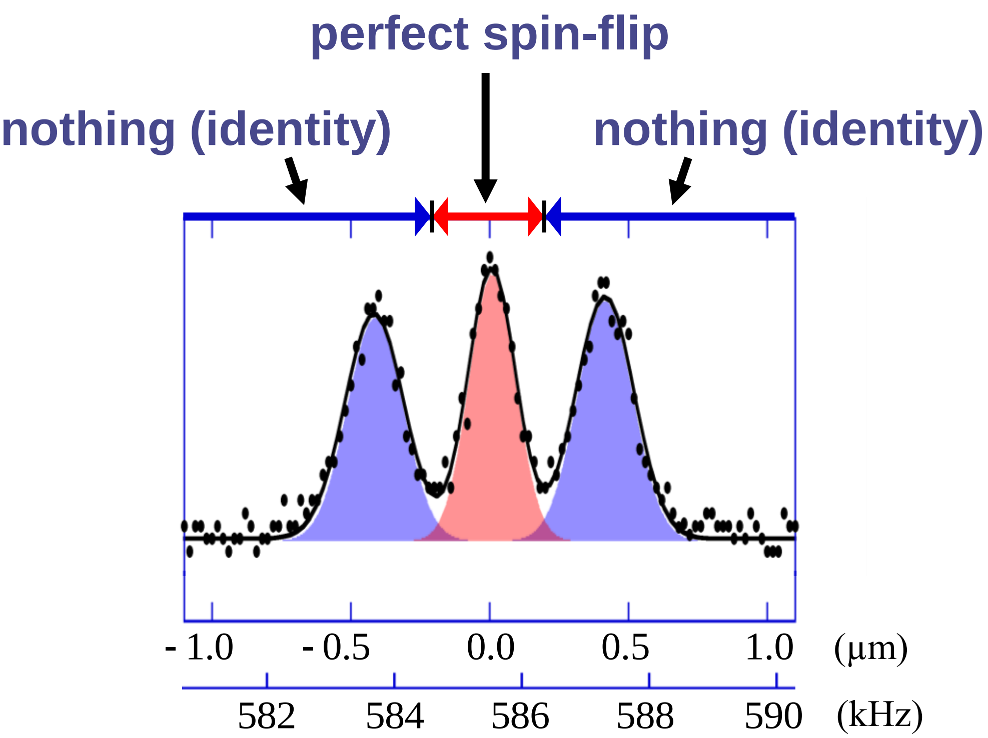
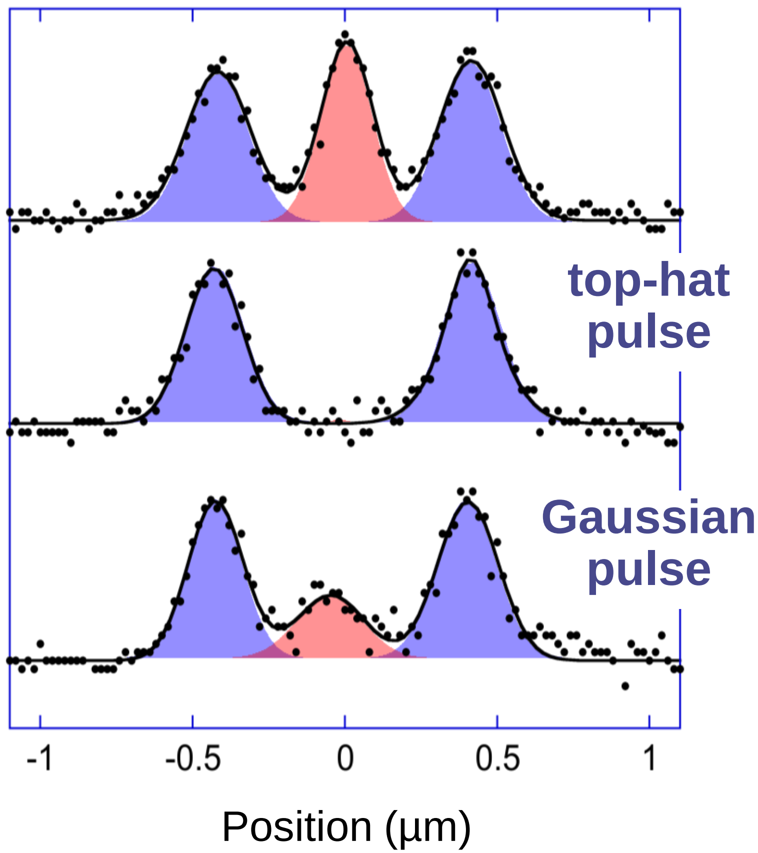
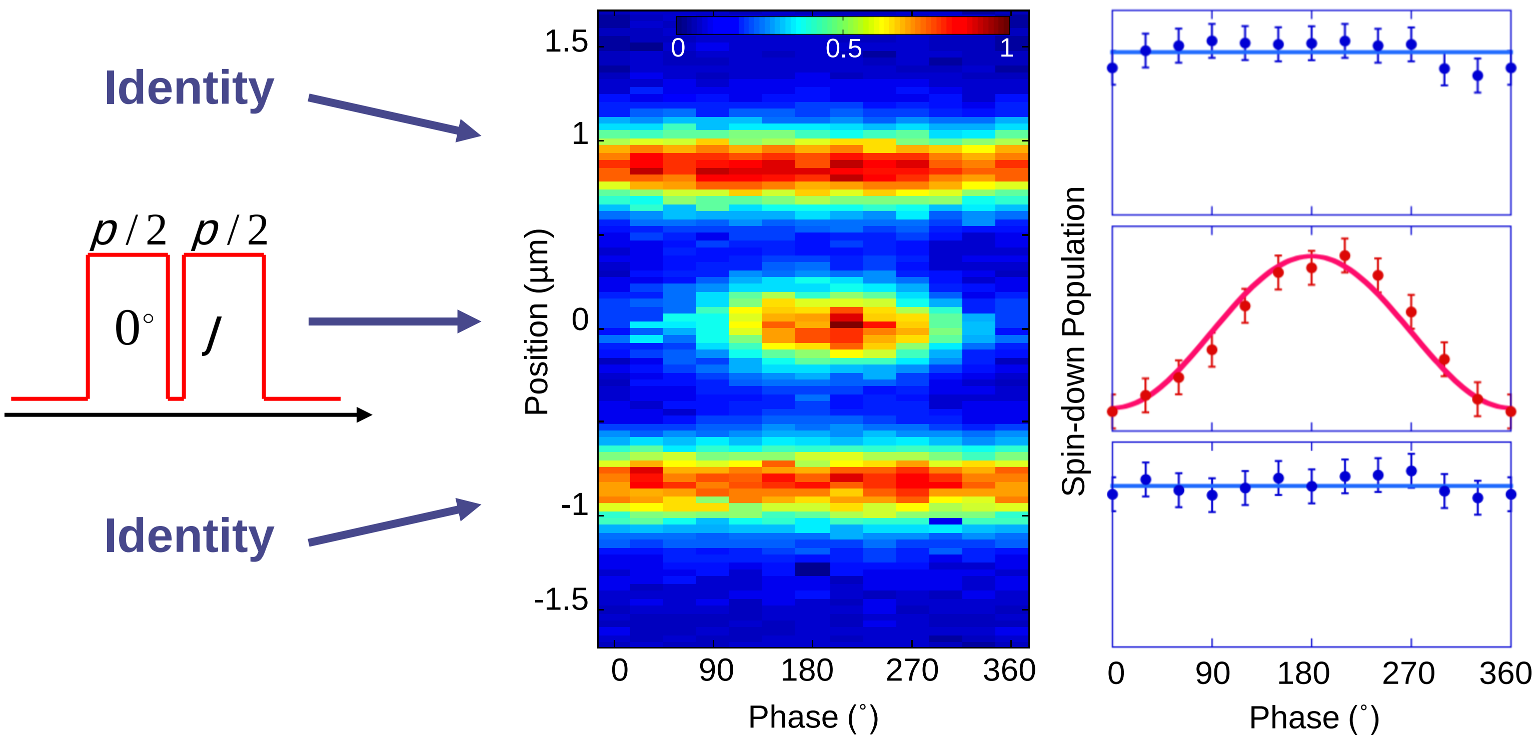




Resonance Addressing in an Optical Lattic

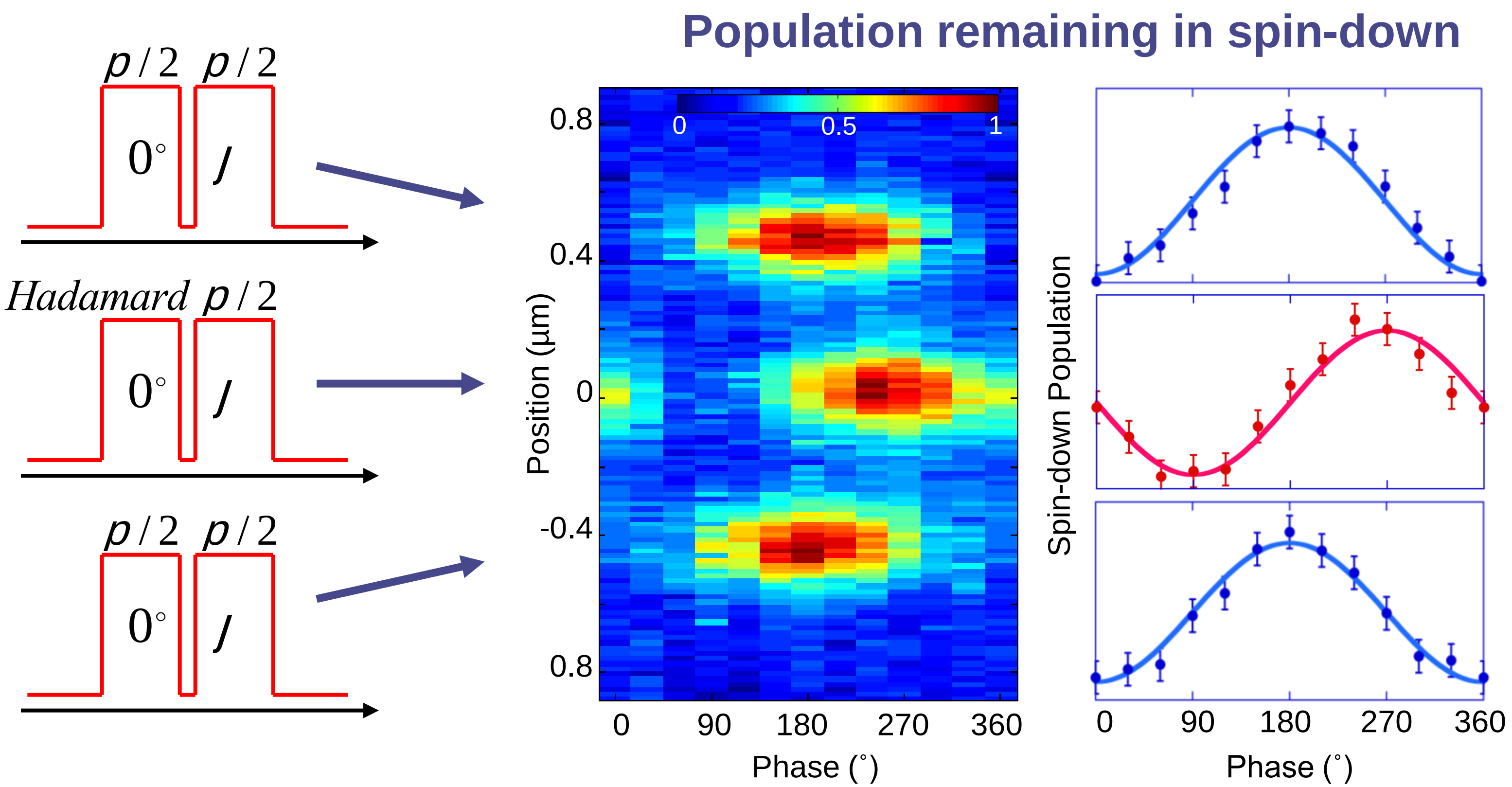
- Site-resolving, coherent quantum gates

Population remaining in spin-down



Resonance Addressing in an Optical Lattic

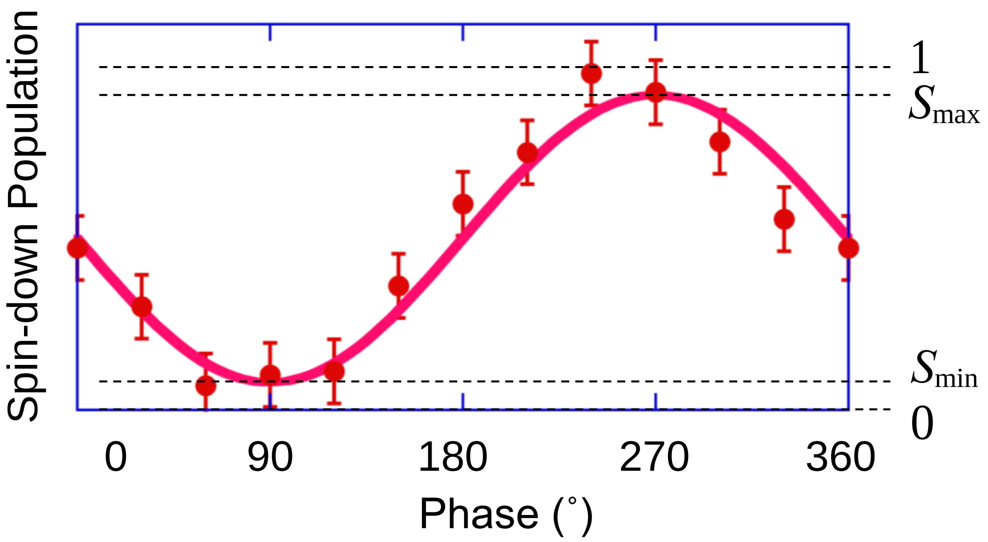
➢ **Site-resolving, coherent quantum gates**



Resonance Addressing in an Optical Lattic

➢ **Site-resolving, coherent quantum gates**

Estimate fidelity from interference fringe



At fringe minimum gates execute

$$|\downarrow_z\rangle \rightarrow |y\rangle \rightarrow |\uparrow_z\rangle$$

with fidelity

$$\mathcal{F}_{pair} = S_{max} / (S_{min} + S_{max})$$

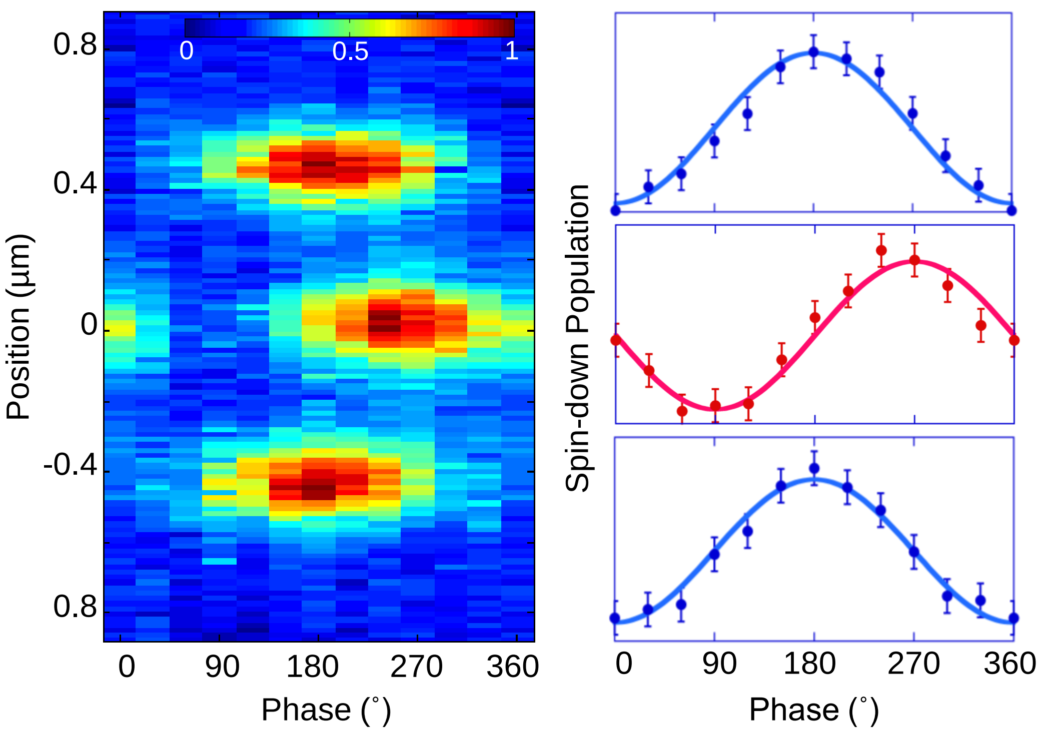
Fidelity per gate:

$$\mathcal{F}_{gate} \approx \sqrt{\mathcal{F}_{pair}}$$

Resonance Addressing in an Optical Lattic

➢ **Site-resolving, coherent quantum gates**

Population remaining in spin-down



$\mathcal{F}_{gate} = 0.973$

$\mathcal{F}_{gate} = 0.959$

$\mathcal{F}_{gate} = 0.947$

average value

$\bar{\mathcal{F}}_{gate} = 96\%$

randomized benchmarking

$\bar{\mathcal{F}}_{gate} = 95 \pm 3\%$

Resonance Addressing in an Optical Lattic

- Site-resolving, coherent quantum gates

J. H. Lee, E. Montano, IHD & PSJ, submitted

- Can we do something similar with qudits?

Enhanced Spin Squeezing w/Qudit Contro

PRL **109,** 173603 (2012) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2012

Enhanced Squeezing of a Collective Spin via Control of Its Qudit Subsystems

Leigh M. Norris,[1,2,*] Collin M. Trail,[3] Poul S. Jessen,[1,4] and Ivan H. Deutsch[1,2]

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[2]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131-0001, USA*
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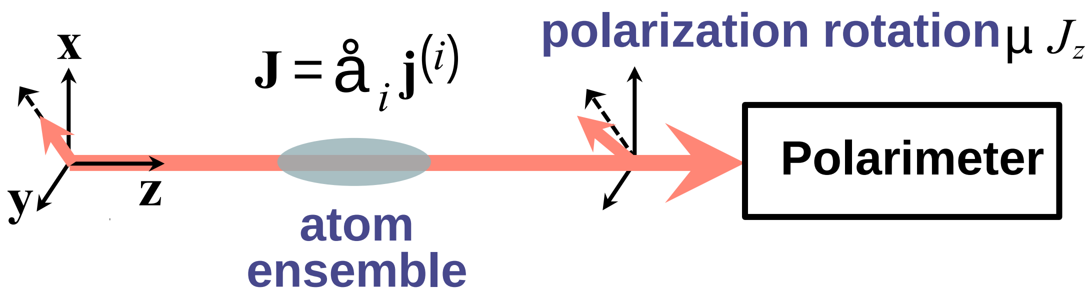
(Received 24 May 2012; published 23 October 2012)

Unitary control of qudits can improve the collective spin squeezing of an atomic ensemble. Preparing the atoms in a state with large quantum fluctuations in magnetization strengthens the entangling Faraday interaction. The resulting increase in interatomic entanglement can be converted into metrologically useful spin squeezing. Further control can squeeze the internal atomic spin without compromising entanglement, providing an overall multiplicative factor in the collective squeezing. We model the effects of optical pumping and study the tradeoffs between enhanced entanglement and decoherence. For realistic parameters we see improvements of ∼10 dB.

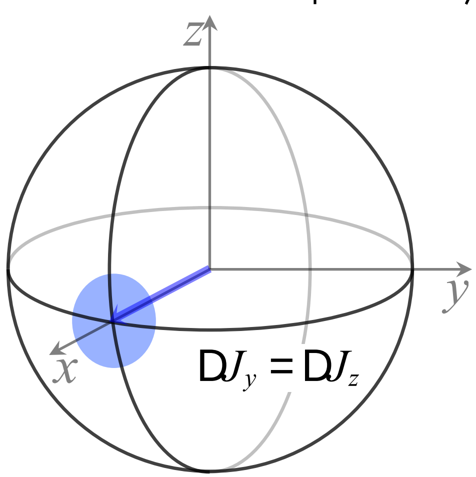
DOI: 10.1103/PhysRevLett.109.173603 PACS numbers: 42.50.Dv, 03.67.Bg, 42.50.Lc

Enhanced Spin Squeezing w/Qudit Contro

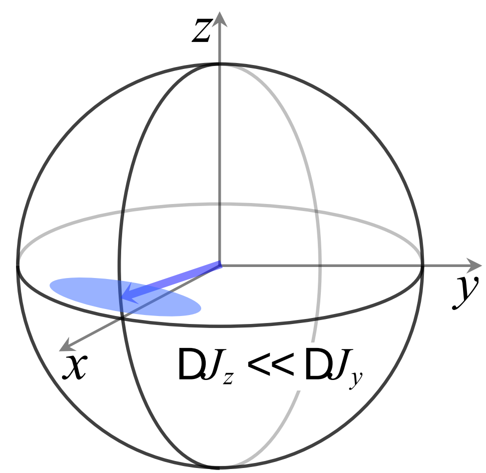
- **Faraday Rotation ➡ QND measurement of a Collective Spi**



Spin-coherent state $|m_x = j\rangle^{\otimes N_A}$



Spin-squeezed, entangled state



Enhanced Spin Squeezing w/Qudit Contro

- Faraday Rotation ➡ QND measurement of a Collective Spi
- Atoms become entangled when QND measurement resolves quantum projection noise ΔJ_z over shot-noise
- More projection noise ΔJ ➡ more entanglement

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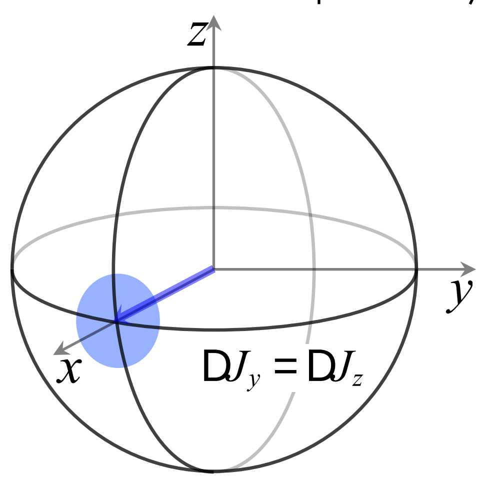

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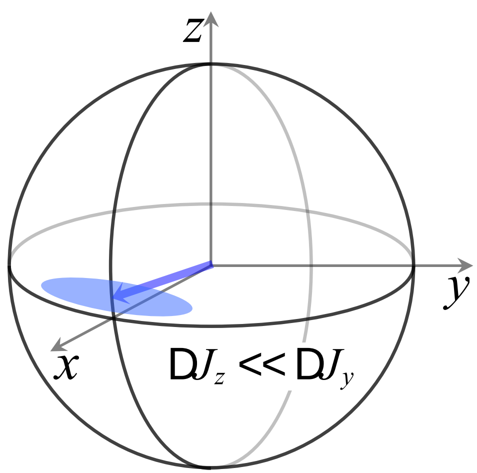

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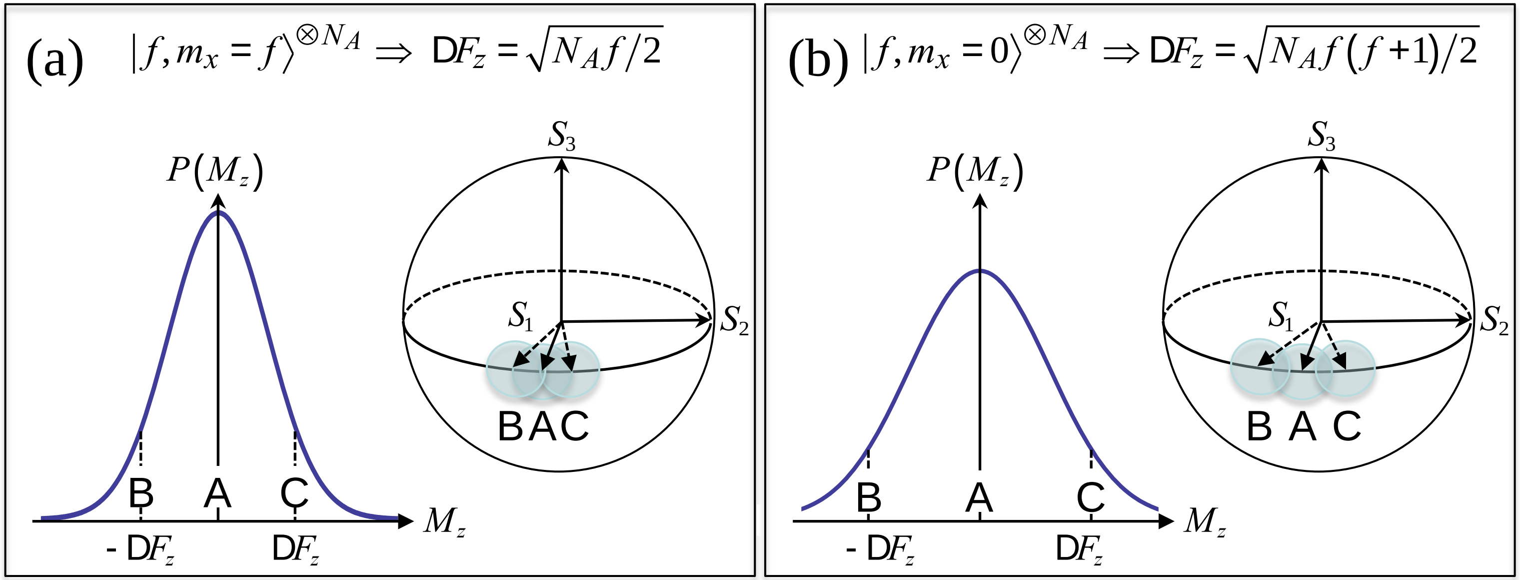

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- Faraday Rotation ➡ QND measurement of a Collective Spi

- Atoms become entangled when QND measurement resolves quantum projection noise ΔJ_z over shot-noise

- More projection noise ΔJ ➡ more entanglement

- If input is not a spin coherent state, entanglement leads to squeezing of a pseudo-spin in some internal state basis

- Pseudo-spin squeezing can be transferred to other bases
  ➡ squeezing of e. g physical spin or clock pseudospin

Enhanced Spin Squeezing w/Qudit Contro

73603 (2012) PHYSICAL REVIEW LETTERS wee
26 OC

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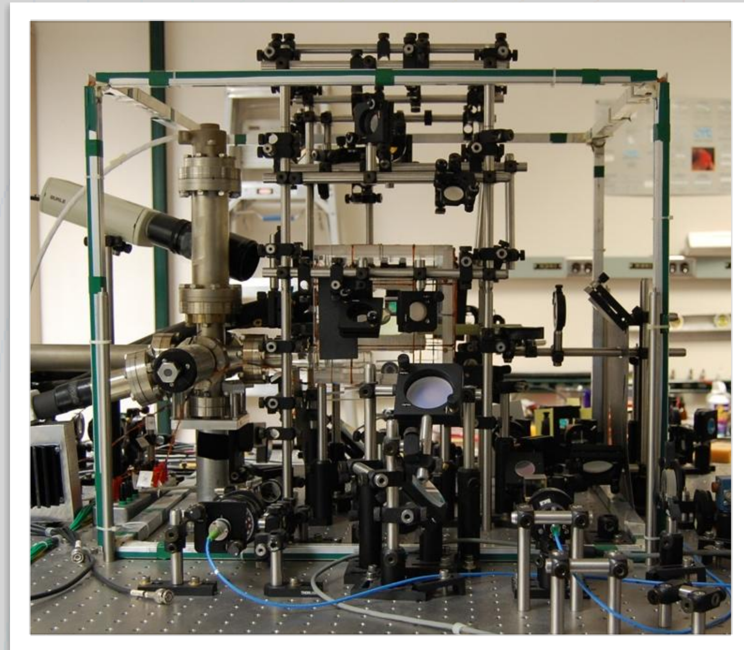

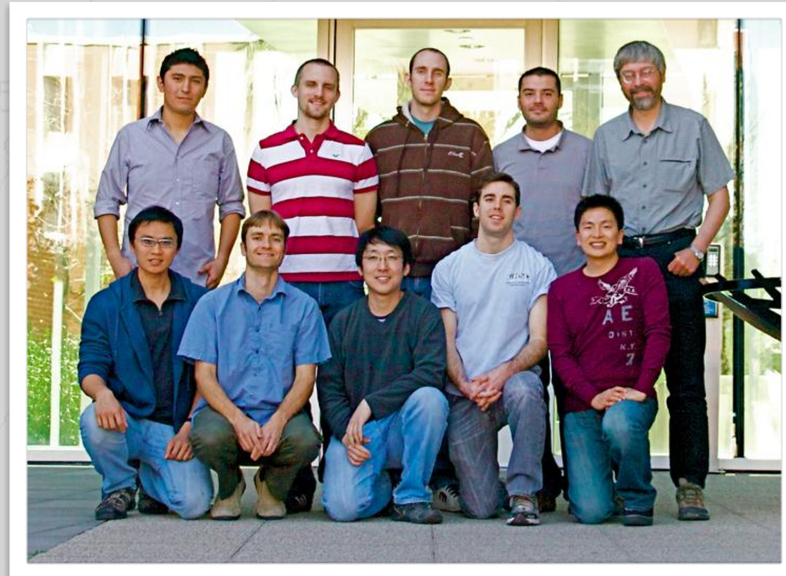

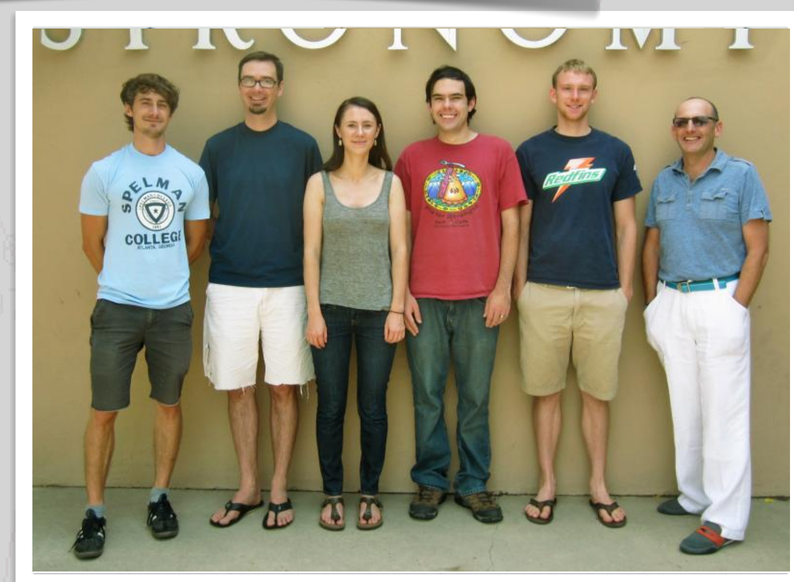

Poul Jessen
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