Practical Quantum Computation

Lecture 1: Trapped Ion Qubit Basics
Lecture 2: Systems and Technology Considerations

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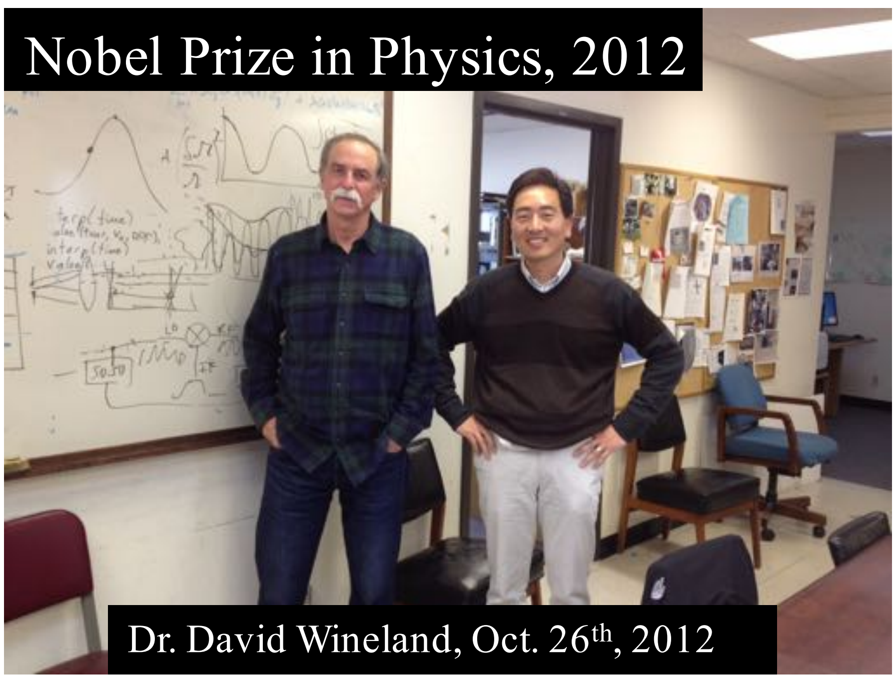
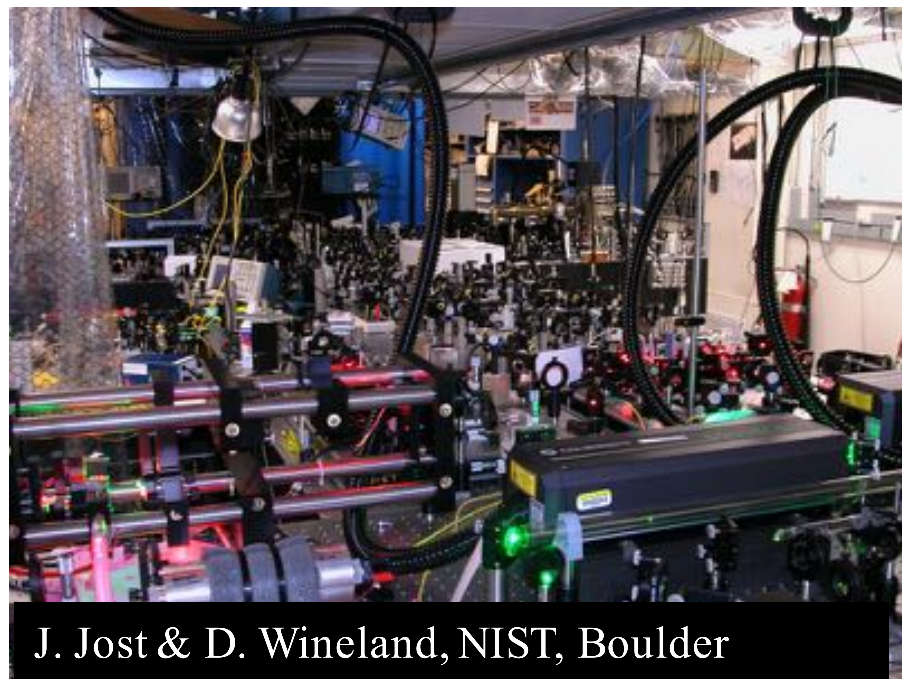
Trapped Ions as QIP Platform

- Trapped Ions are
  - Strongly trapped yet well isolated from environment (atomic clocks)
  - Satisfies all DiVincenzo criteria for scalable QIP
- But, they are NOT
  - Easily integrated into large-scale systems
  - Challenging experimental infrastructure


Nobel Prize in Physics, 2012

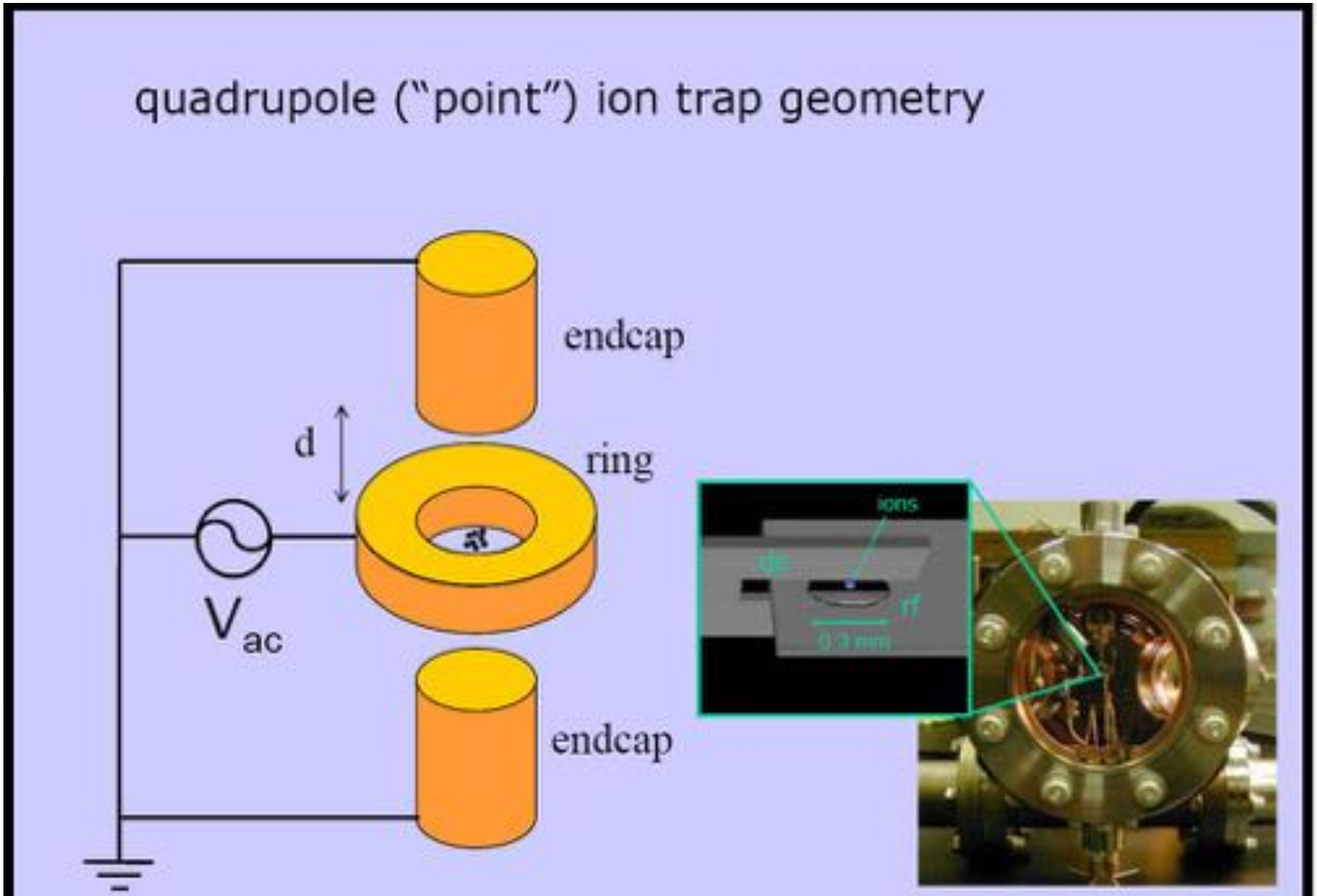
Dr. David Wineland, Oct. 26th, 2012


J. Jost & D. Wineland, NIST, Boulder

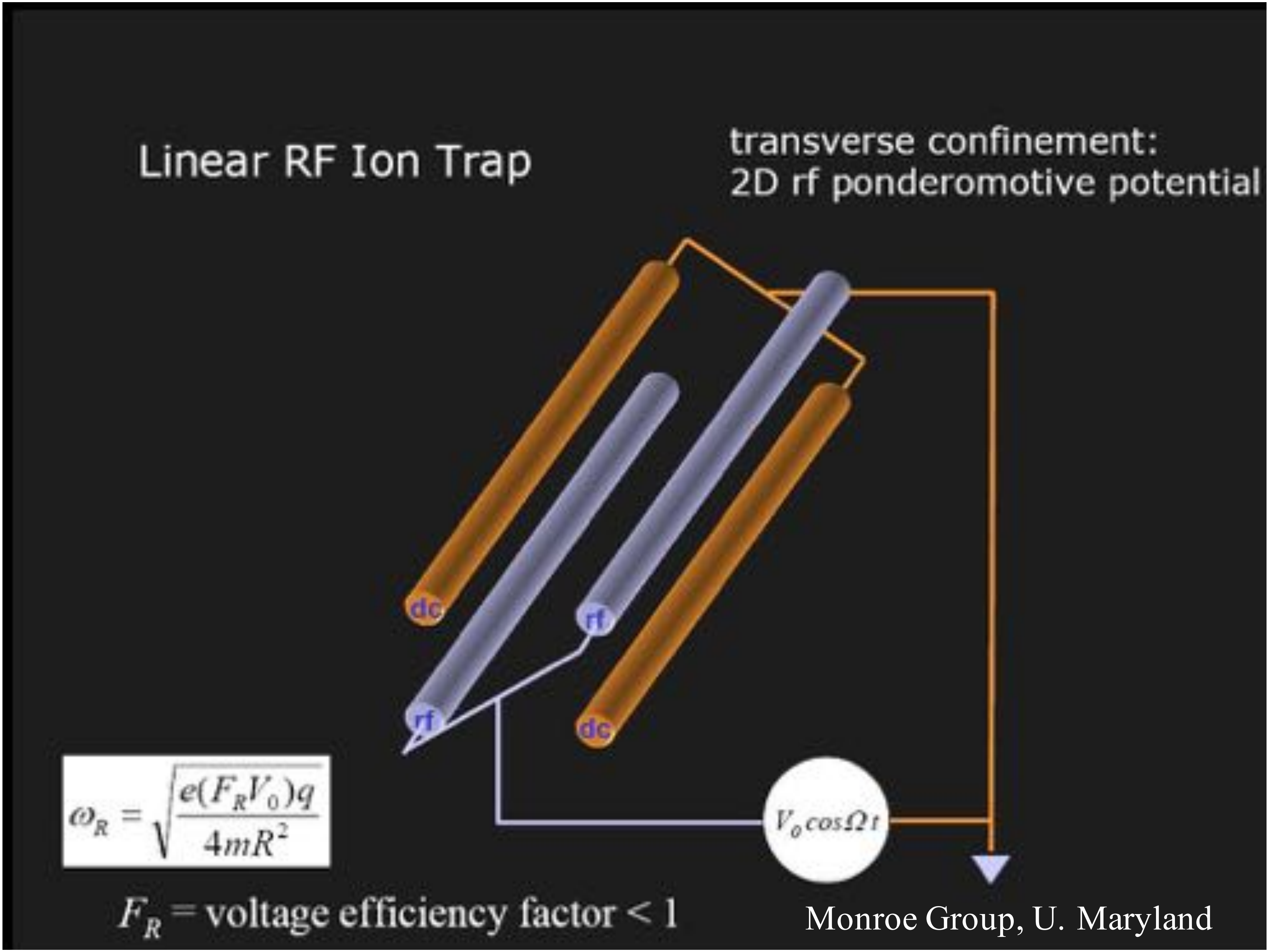
Lecture 1: Trapped Ion Qubit Basics

1. Ion Trapping Basics
2. Trapped Ions as Qubit Platform
3. Concepts for Scalable Ion Trap QC Hardware

Principles of RF Paul Trap

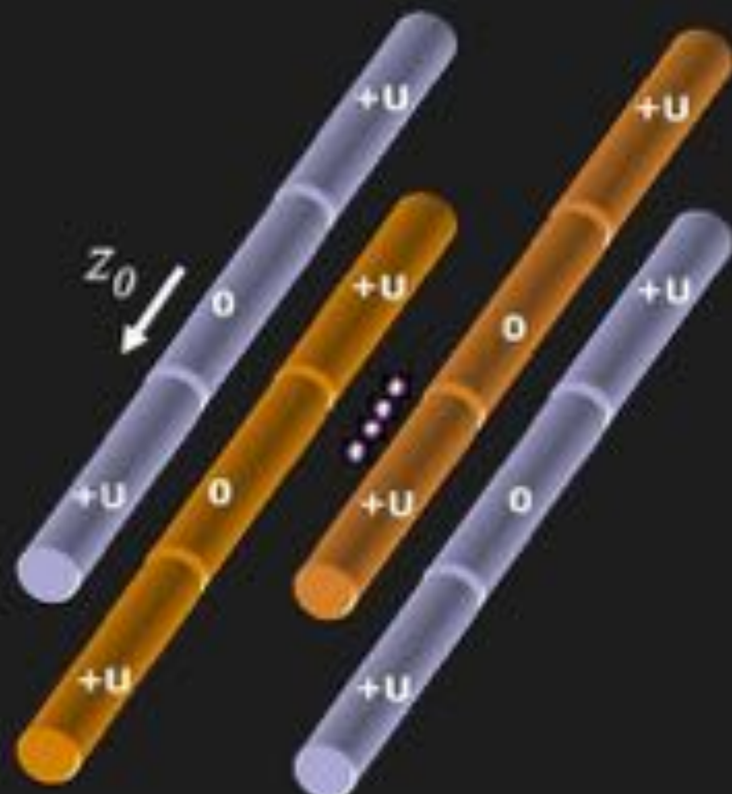


Monroe Group, U. Maryland and Wikipedia


Linear RF Ion Trap
transverse confinement:
2D rf ponderomotive potential
dc
rf
rf
dc
$V_0 \cos \Omega t$
$\omega_R = \sqrt{\dfrac{e(F_R V_0)q}{4mR^2}}$
F_R = voltage efficiency factor < 1
Monroe Group, U. Maryland

Linear RF Ion Trap

axial confinement:
static "endcaps"

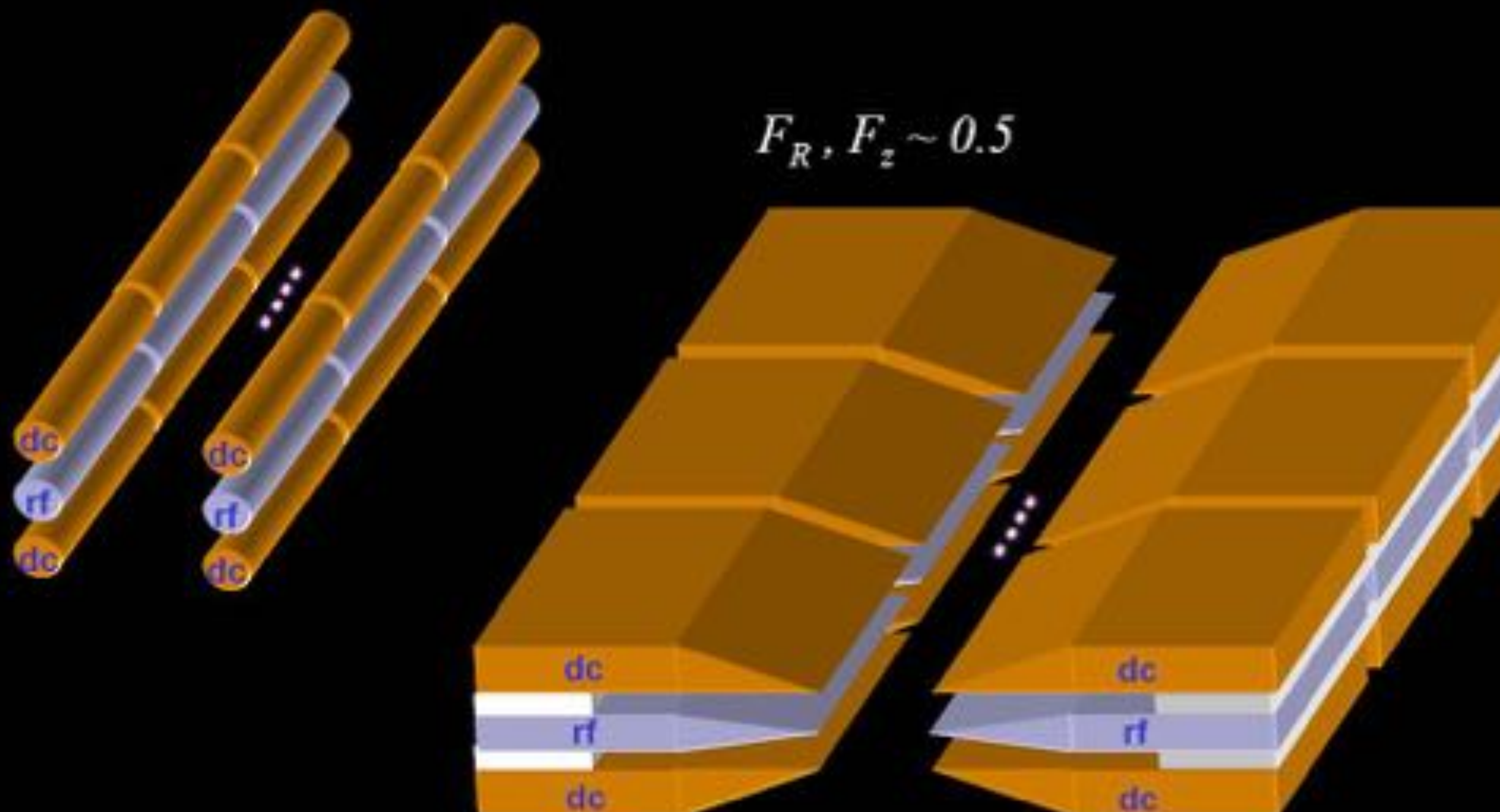


$$\omega_z = \sqrt{\frac{e(F_z U_0)}{m z_0^2}}$$

Monroe Group, U. Maryland

3-layer geometry:

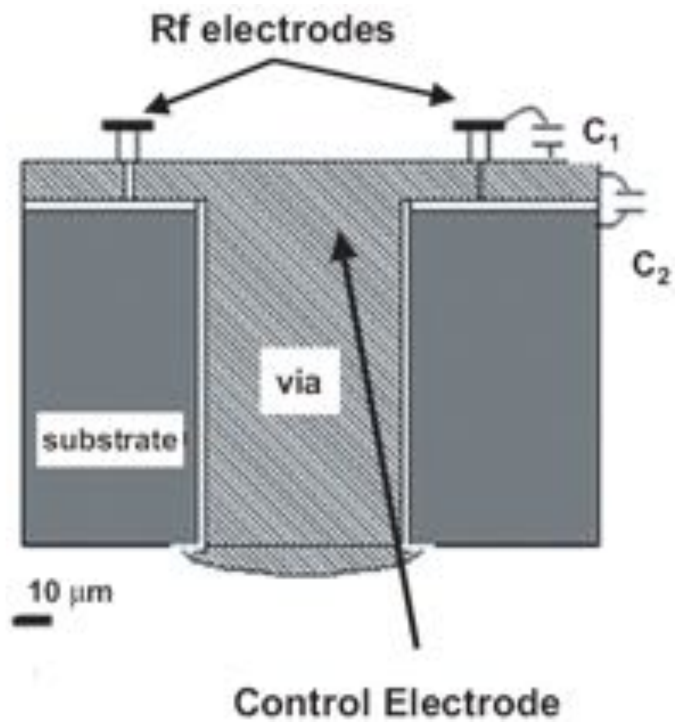
- allows 3D offset compensation
- scalable to larger structures

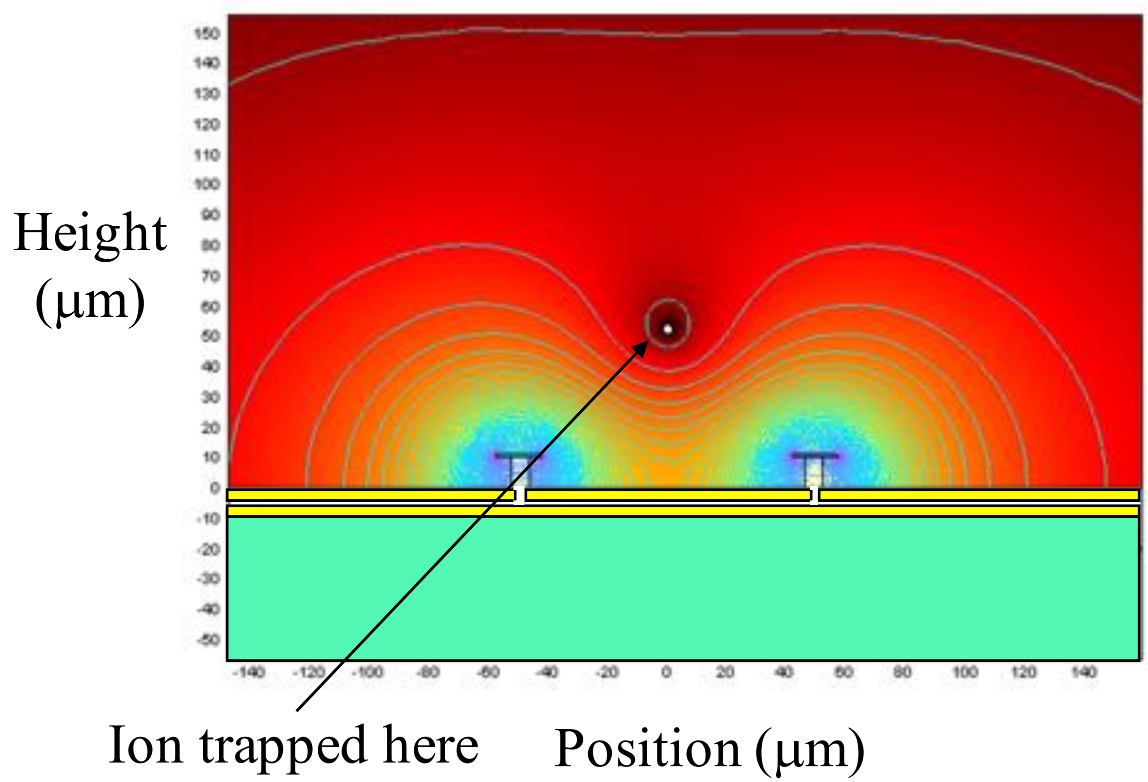


Monroe Group, U. Maryland

Scalable Surface Ion Trap Chip

- **Design and Fabrication of Scalable Surface Ion Trap Chips**



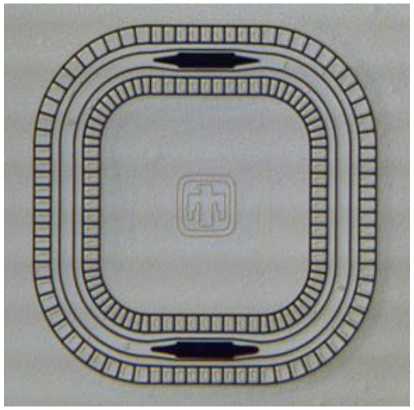


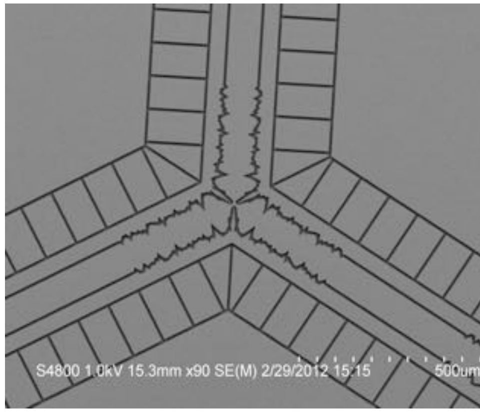
Surface Trap Fabrication: NIST, Georgia Tech, Sandia, MIT, Ulm, …
Surface Trap Operation: NIST, Maryland, MIT, Duke, Innsbruck, Oxford, …

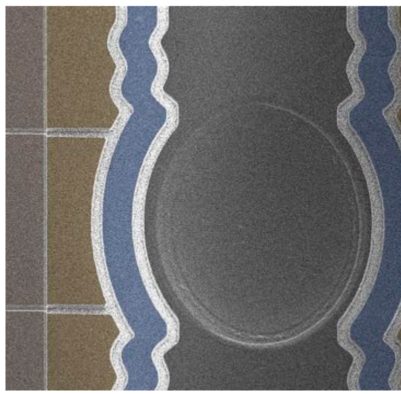
Chiaverini et al., Quant. Inf. Comput. 5, pp 419 (2005)
J. Kim et al., Quant. Inf. Comput. 5, pp 515 (2005)

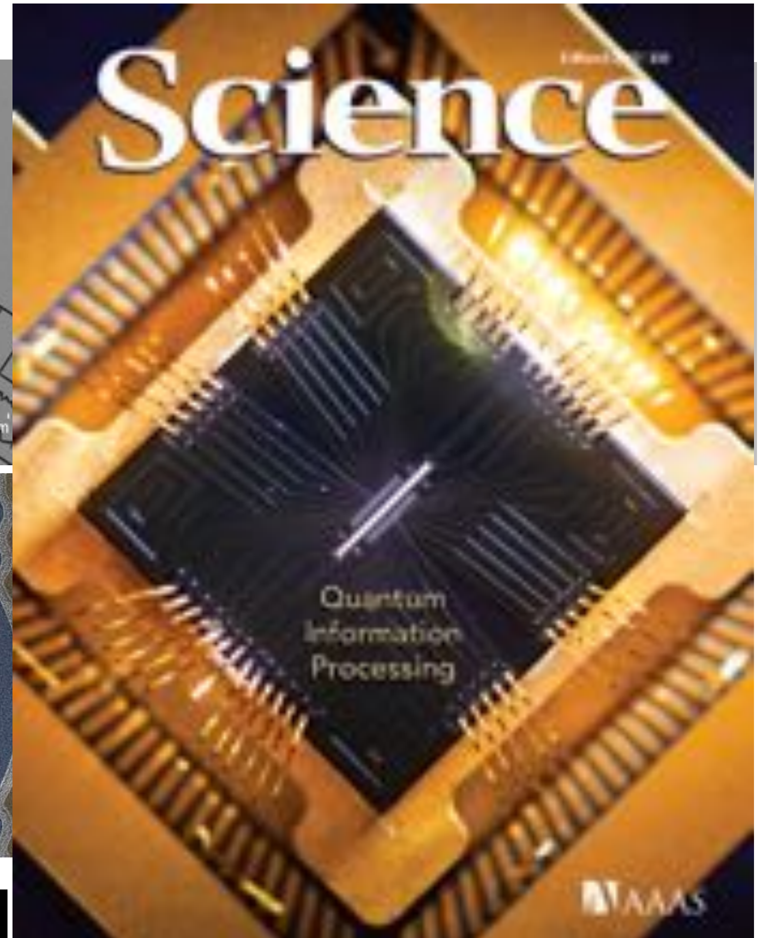
Modern Trap Fabrication Technology

- Microfabricated Ion Traps









NJP 13, 075018 (2011)

NJP 13, 103005 (2011)
NJP 14, 073012 (2012)
NJP 15, 033004 (2013)
NJP 15, 083053 (2013)

Advanced Trap Functionalities

Jason Amini et al., GTRI (2011)

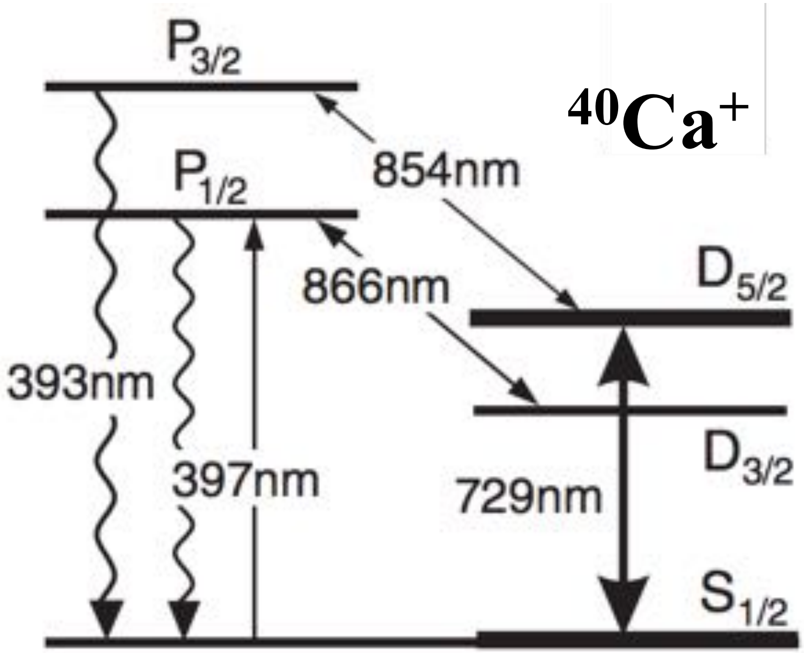
Lecture 1: Trapped Ion Qubit Basics

1. **Ion Trapping Basics**
2. **Trapped Ions as Qubit Platform**
3. **Concepts for Scalable Ion Trap QC Hardware**

Atomic Species for Ion Qubits

Qubit Choices for Trapped Ions

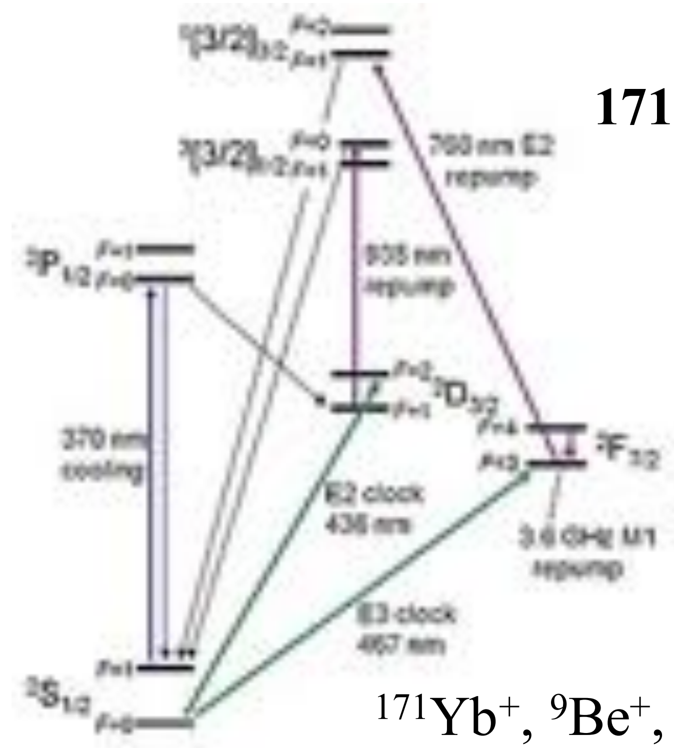
- The “Optical” Qubit



$^{40}Ca^+$, $^{88}Sr^+$, $^{138}Ba^+$, etc.

  – Ground S state and metastable D state qubit
  – Stable laser needed (~1Hz)

- The “Hyperfine” Qubit



$^{171}Yb^+$

$^{171}Yb^+$, $^{9}Be^+$, $^{27}Mg^+$, etc.

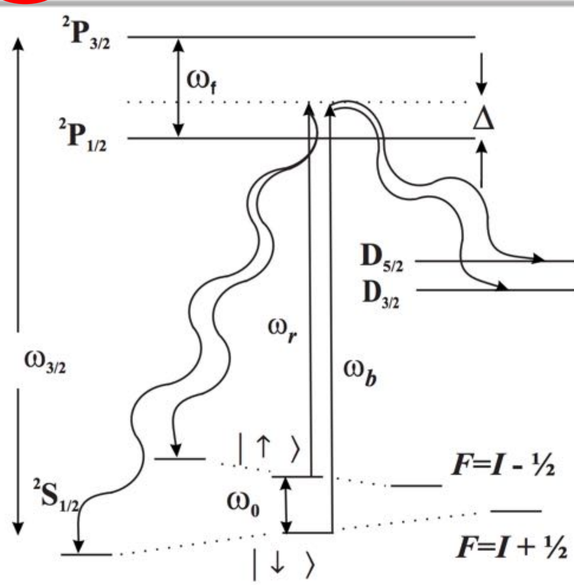
  – Two states from the hyperfine ground state manifold
  – Microwave frequency transitions

F. Schmidt-Kaler et al., J. Phys. B 36, 623 (2003)

http://www.ptb.de

Basic Properties of Hyperfine Qubits

Ion	I	$\gamma/2\pi$ (MHz)	$\omega_0/2\pi$ (GHz)	$\omega_f/2\pi$ (THz)	$\lambda_{1/2}$ (nm)	$\lambda_{3/2}$ (nm)	f^{-1}
$^{9}Be^{+}$	3/2	19.6	1.25	0.198	313.1	313.0	N.A.
$^{25}Mg^{+}$	5/2	41.3	1.79	2.75	280.3	279.6	N.A.
$^{43}Ca^{+}$	7/2	22.5	3.23	6.68	396.8	393.4	17
$^{67}Zn^{+}$	5/2	62.2	7.2	27.8	206.2	202.5	N.A.
$^{87}Sr^{+}$	9/2	21.5	5.00	24.0	421.6	407.8	14
$^{111}Cd^{+}$	1/2	50.5	14.53	74.4	226.5	214.4	N.A.
$^{137}Ba^{+}$	3/2	20.1	8.04	50.7	493.4	455.4	3
$^{171}Yb^{+}$	1/2	19.7	12.64	99.8	369.4	328.9	290
$^{199}Hg^{+}$	1/2	54.7	40.51	273.4	194.2	165.0	700

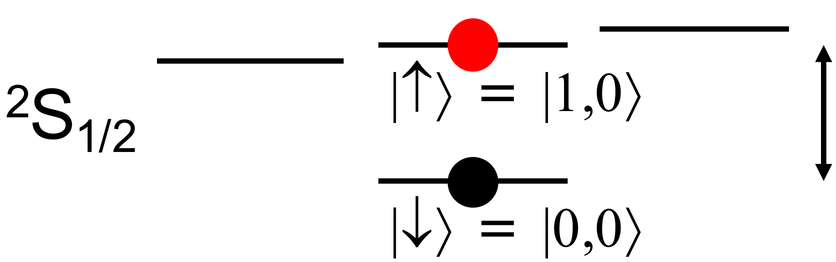


I : Nuclear spin
γ : P state natural linewidth
ω_0 : Ground state hyperfine splitting
ω_f : P state fine structure splitting
λ_n: Transition frequency to P_n state
f : Branching ratio

R. Ozeri et al., PRA 75, 042529 (2007)

The $^{171}Yb^{+}$ Hyperfine Qubit : Coherence

- Qubit states are two internal (clock) states of the atomic ion
- Carefully chosen states have long coherence times
  - $T_2 \approx 1$sec "without trying much"
  - $T_2 \approx 15$ min with "some effort"



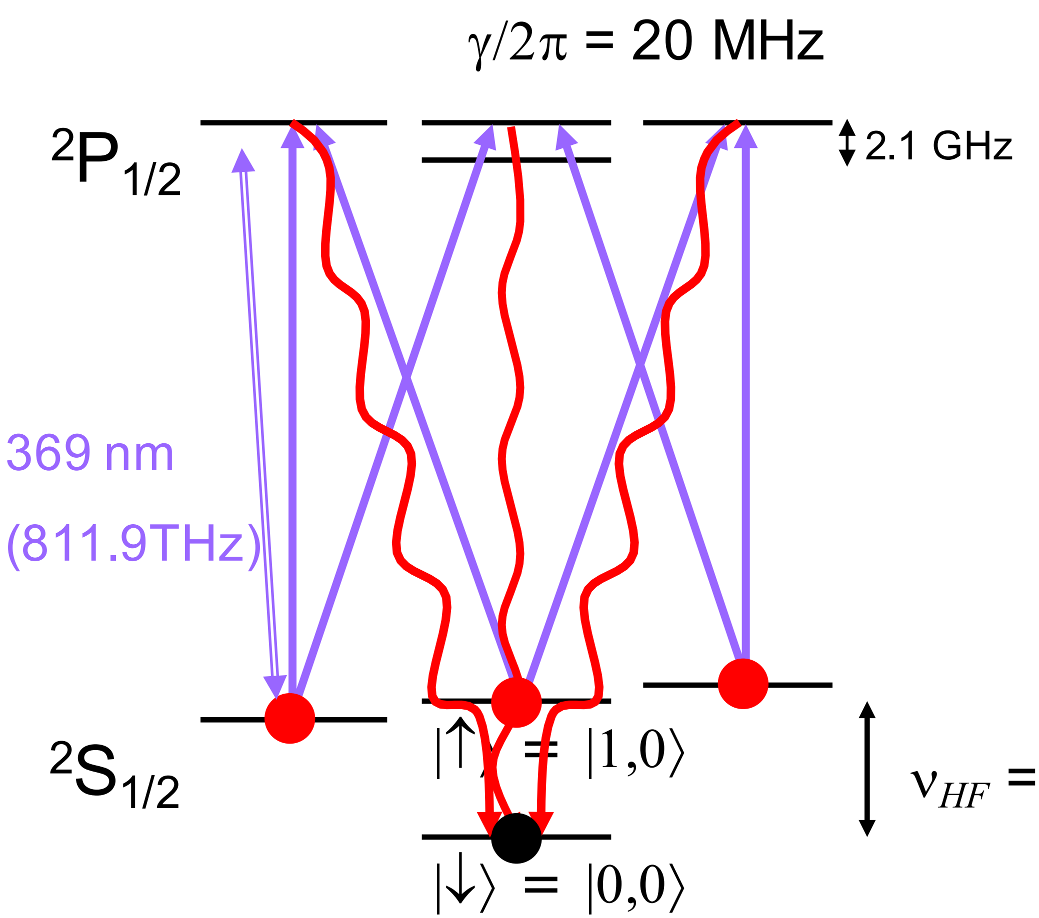
ν_{HF} = 12 642 812 118 + 311B^2 Hz

(600 Hz/G @ 1 G)

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

The $^{171}Yb^{+}$ Hyperfine Qubit: Initialization

- Optical pumping into the dark state prepares initial qubit state
- High preparation fidelity (>99.99% after scattering ≈ 10 photons)



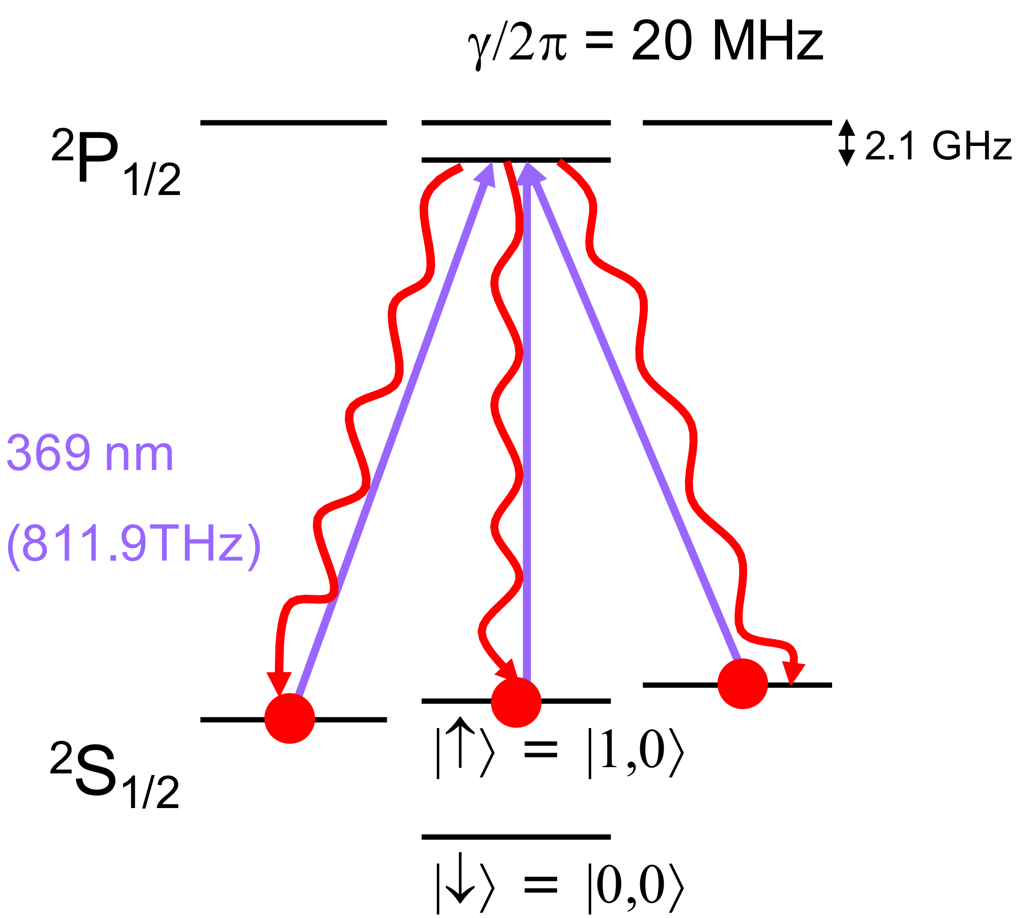
ν_{HF} = 12 642 812 118 + 311B^2 Hz

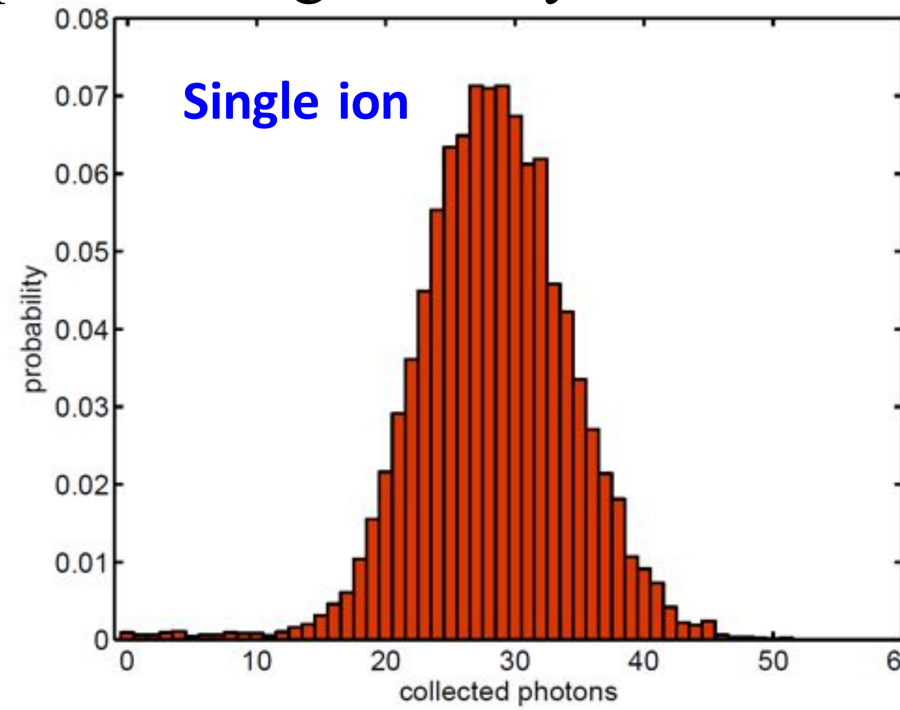
(600 Hz/G @ 1 G)

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

The $^{171}Yb^{+}$ Hyperfine Qubit: State Detection

- State-dependent fluorescence provides high fidelity detection





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

The $^{171}Yb^{+}$ Hyperfine Qubit: State Detection

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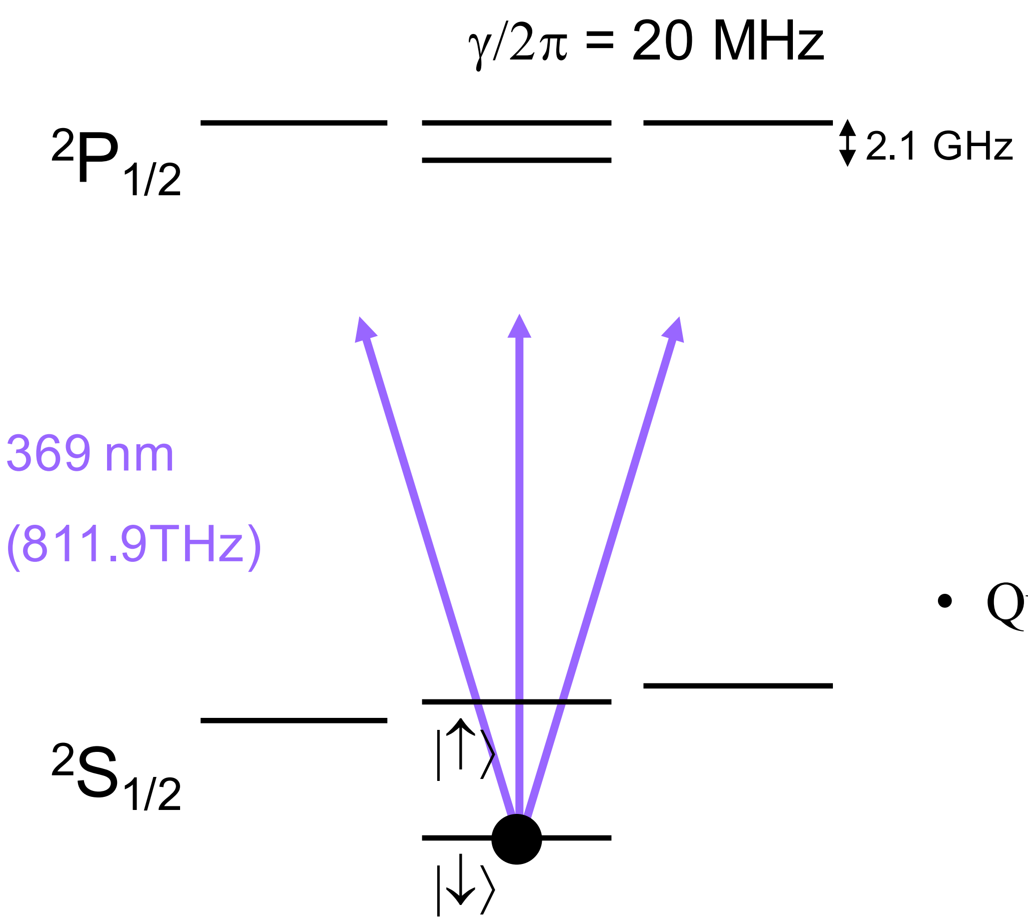
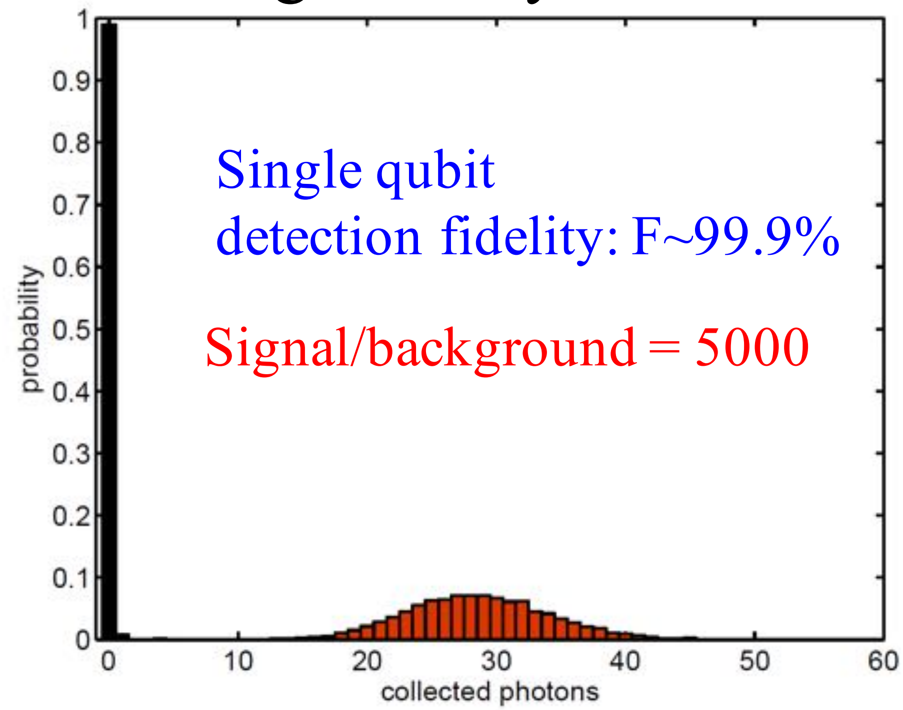




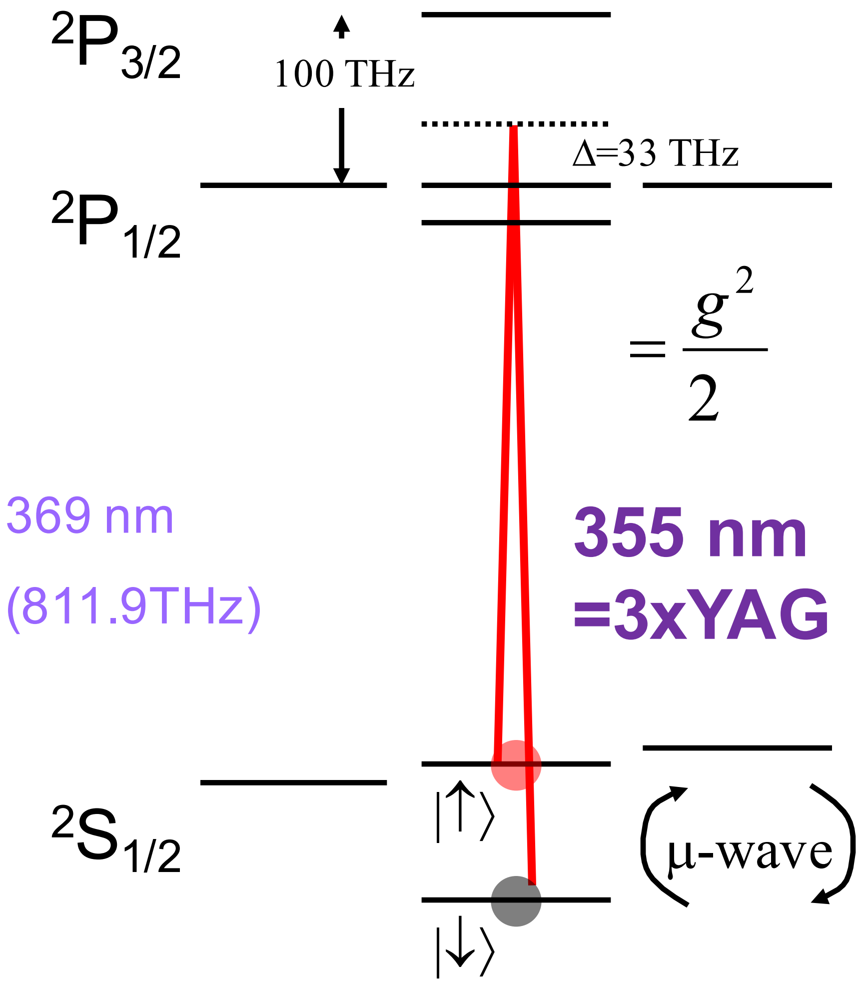
- Qubit state detection takes
  < 30 us for ~99.9% fidelity
  ~ 10 us for ~99% fidelity

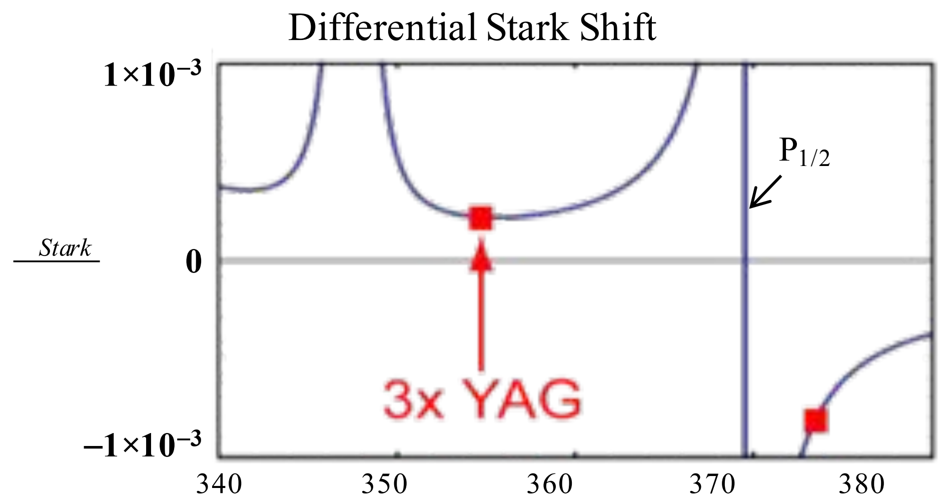
R. Noek et al., Opt. Lett. 38, 4735 (2013)

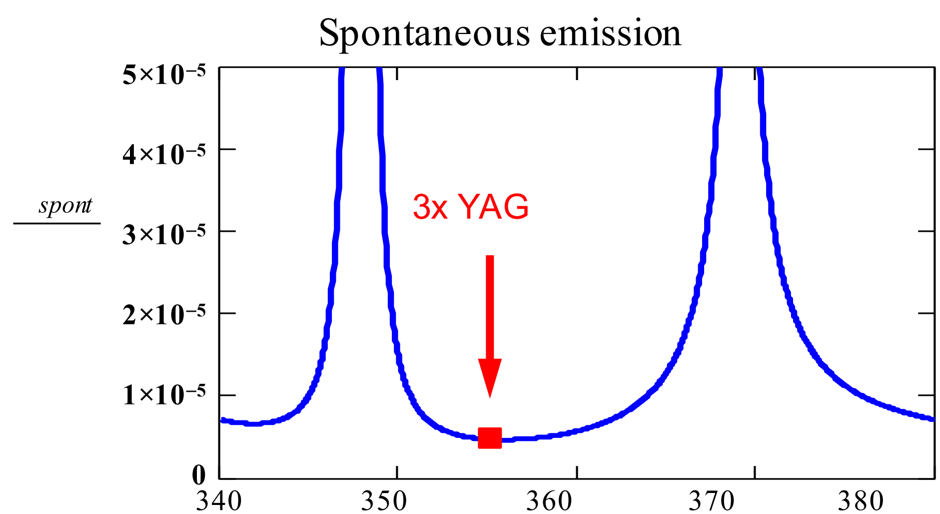
S. Olmschenk et al., PRA 76, 052314 (2007)

The $^{171}Yb^{+}$ Hyperfine Qubit: Single Qubit Gates

- High fidelity gates via Raman transition or microwave transition
- Single qubit fidelity over 99% using ~ μs optical/microwave pulse

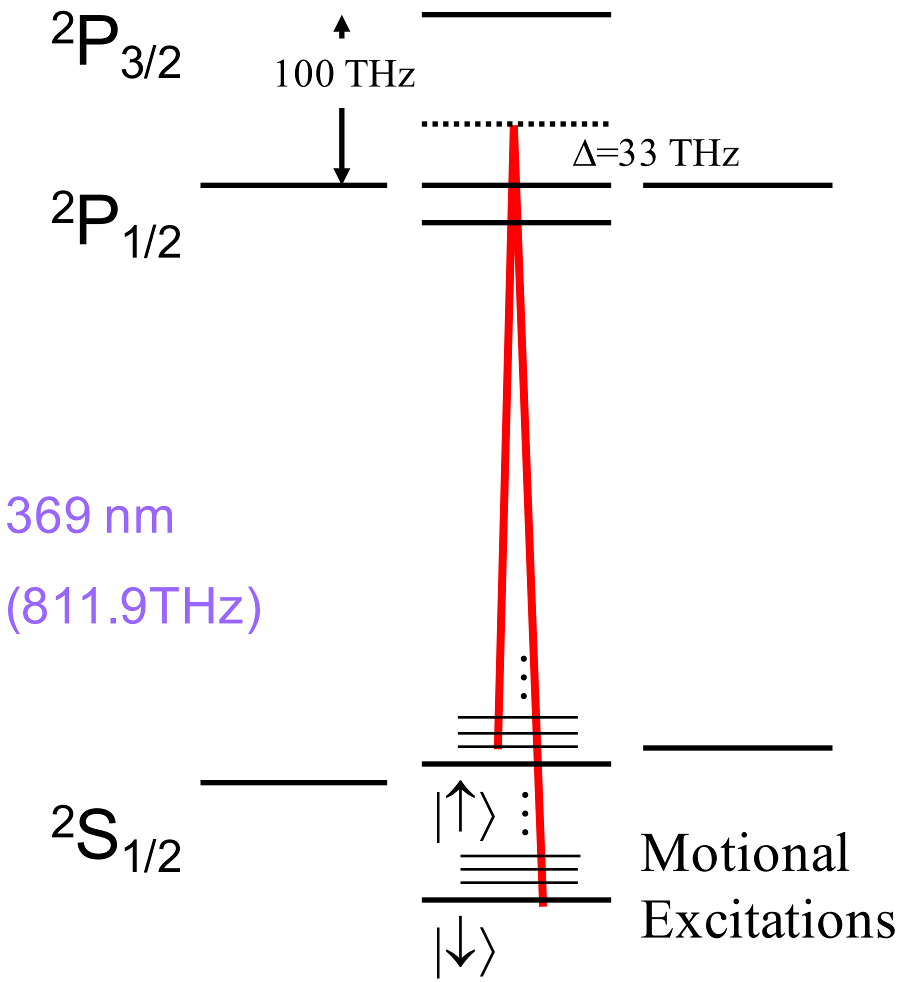


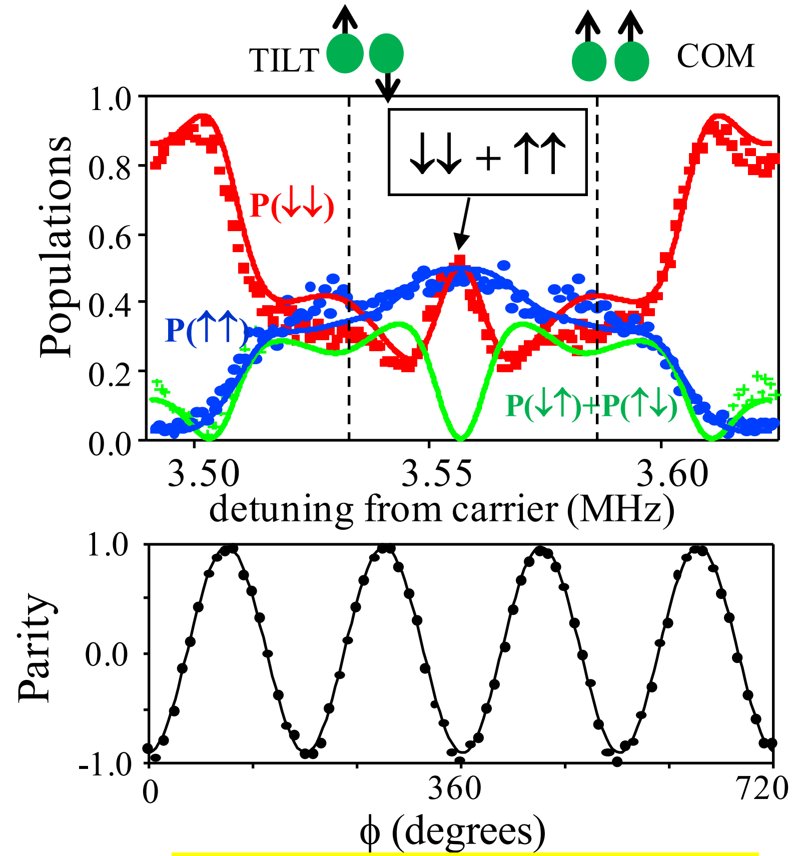




The $^{171}Yb^{+}$ Hyperfine Qubit: Multi-Qubit Gates

- Detuned Raman transition applies spin-dependent forces
- Can lead to robust spin-dependent phase shift (controlled-phase)





$\tau_2 = 40\ \mu s \qquad F_2 > 98\%$

K. Kim et al., Phys. Rev. Lett. **103**, 120502 (2009)

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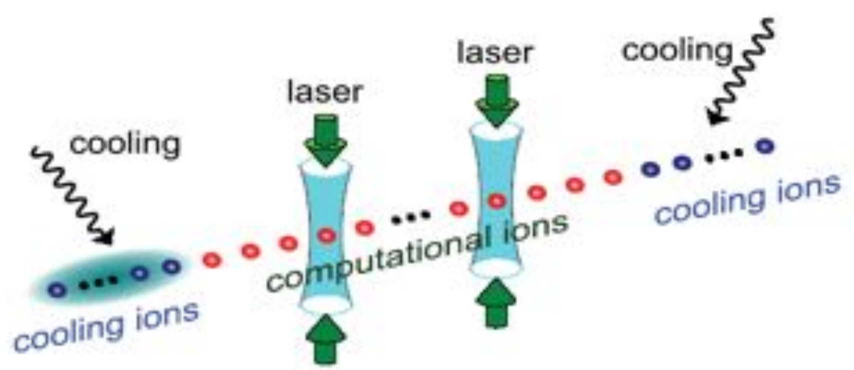
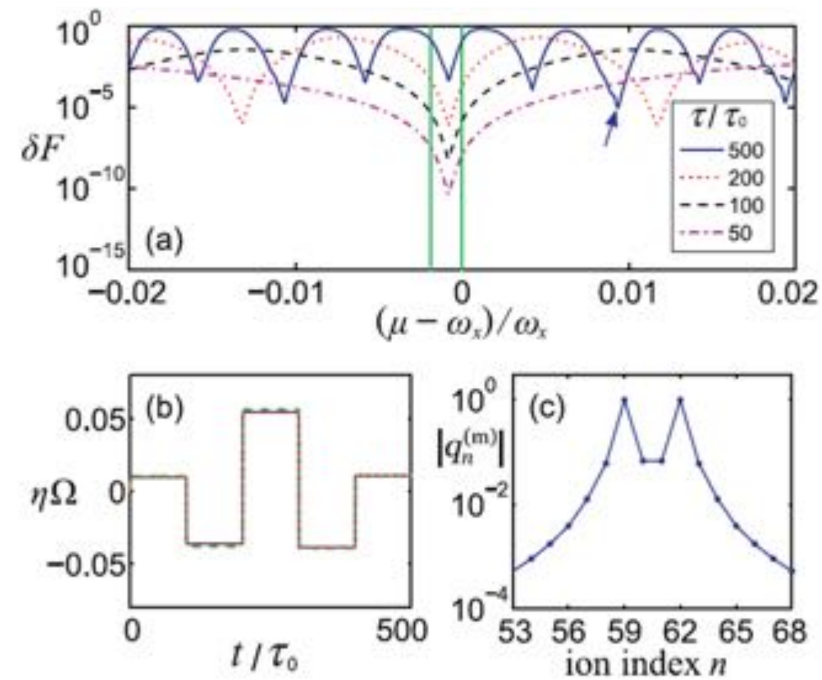
3. **Concepts for Scalable Ion Trap QC Hardware**

Ion Chain Quantum Register

- Equally spaced long ion chain
- Use transverse phonon mode for multi-qubit gates
- Design and control of laser pulses that apply spin-dependent forces at the heart of quantum register operation
- Forms Elementary Logic Unit (ELU) in MUSIQC architecture

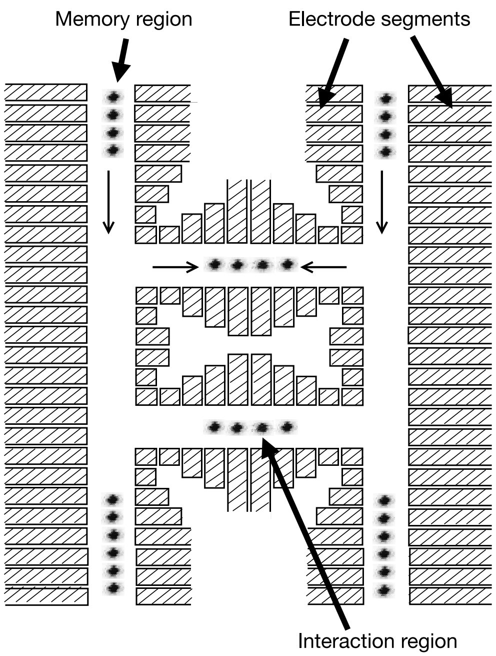




Zhu, Monroe and Duan, PRL 97, 050505 (2006); Europhys. Lett. 73, 485 (2006)

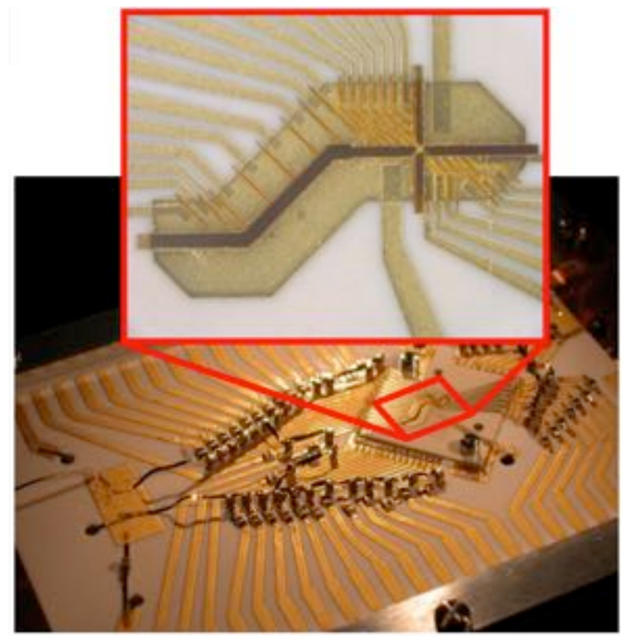
Shuttling of Ions on a Chip Trap

- Changing voltages can move the center of the trap
- Qubit state remain undisturbed through shuttling
- Sympathetic cooling necessary to perform motional gates after ion shuttling
- Noise-free qubit transport performed at NIST-Boulder



Kielpinski, Monroe and Wineland
Nature 417, 709 (2002)

D. Leibfried et al. NIST

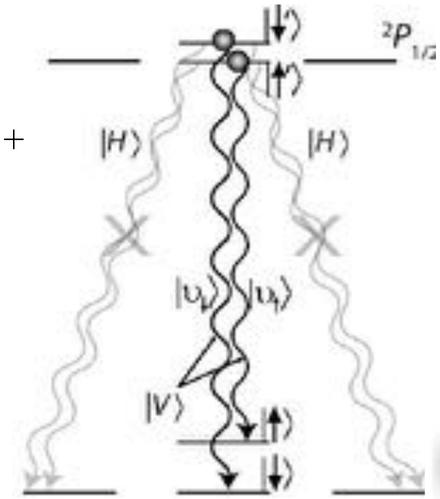


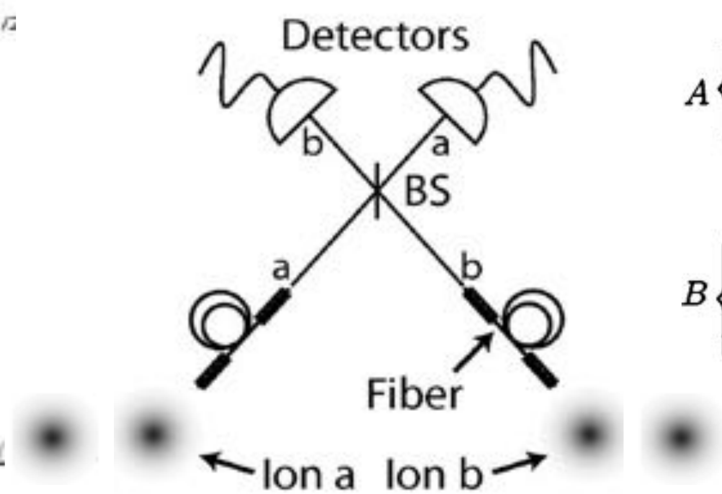
R. B. Blakestad, et al.,
Phys. Rev. Lett. 102, 153002 (2009)

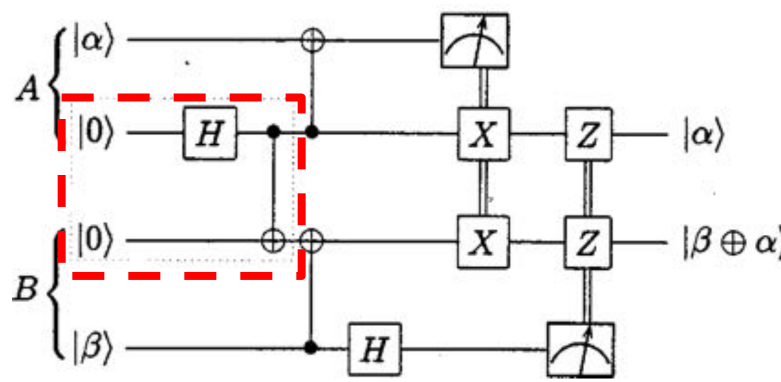
Entangling Remote Memories using Photons

- Remote Entanglement Generation of Quantum Memories
  - Entanglement of internal atomic state and photon (e.g., color)
  - From a pair of such systems, interfere the photons
  - Based on measurement, heralded entanglement is generated probabilistically between ions through entanglement swapping
  - Use the entanglement for logic operation

$^{171}Yb^{+}$







Ion-Photon (2004)
Atom-Photon (2006)
NV-Photon (2010)
QD-Photon (2012)

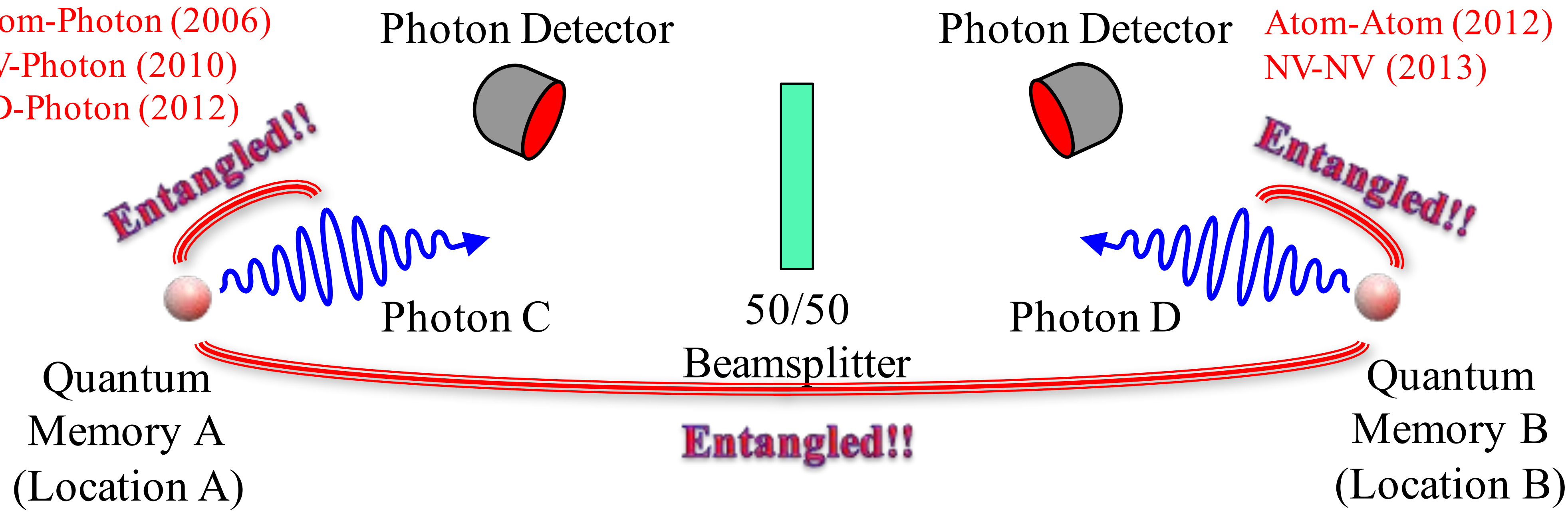
Ion-Ion (2007)
Atom-Atom (2012)
NV-NV (2013)

Duan et al., Quant. Inf. Comput. 4, 165 (2004)
Experiments from C. Monroe group
Gottesman and Chuang, Nature 402, 390 (1999)

Generation of Remotely Entangled Memories

Ion-Photon (2004)
Atom-Photon (2006)
NV-Photon (2010)
QD-Photon (2012)

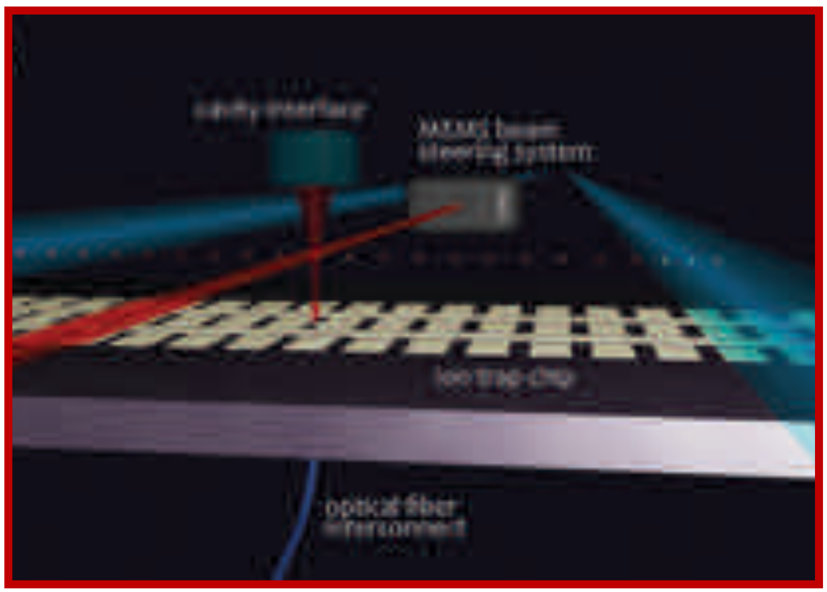
Ion-Ion (2007)
Atom-Atom (2012)
NV-NV (2013)



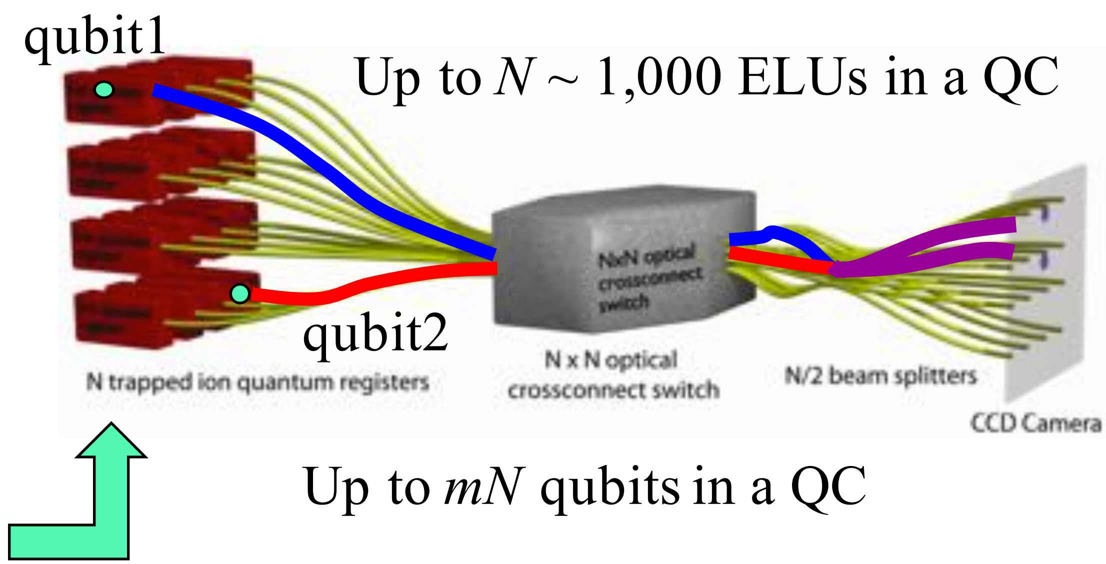
- When both photon detectors click, it signals successful entanglement between A&B
- With a good quantum memory, the generated entanglement can be stored and used for deterministic quantum logic operation
- Opportunities for photonics technology
  - Optical networking to construct quantum networks
  - Manipulation of photonic qubits (frequency conversion, etc.)

MUSIQC: Multi-Tier Approach to Scalability

- Quantum Computation in Small Coulomb Crystals
  - Linear ion chain with 20-100 ions (Elementary Logic Unit, or ELU)
  - Arbitrary quantum logic operation among the qubits in the chain
- Interconnect of Multiple Coulomb Crystals via Photonic Channel
  - Reconfigurable interconnect using optical crossconnect (OXC) switches
  - Efficient optical interface for remote entanglement generation



m ~ 10-100 qubits / ELU

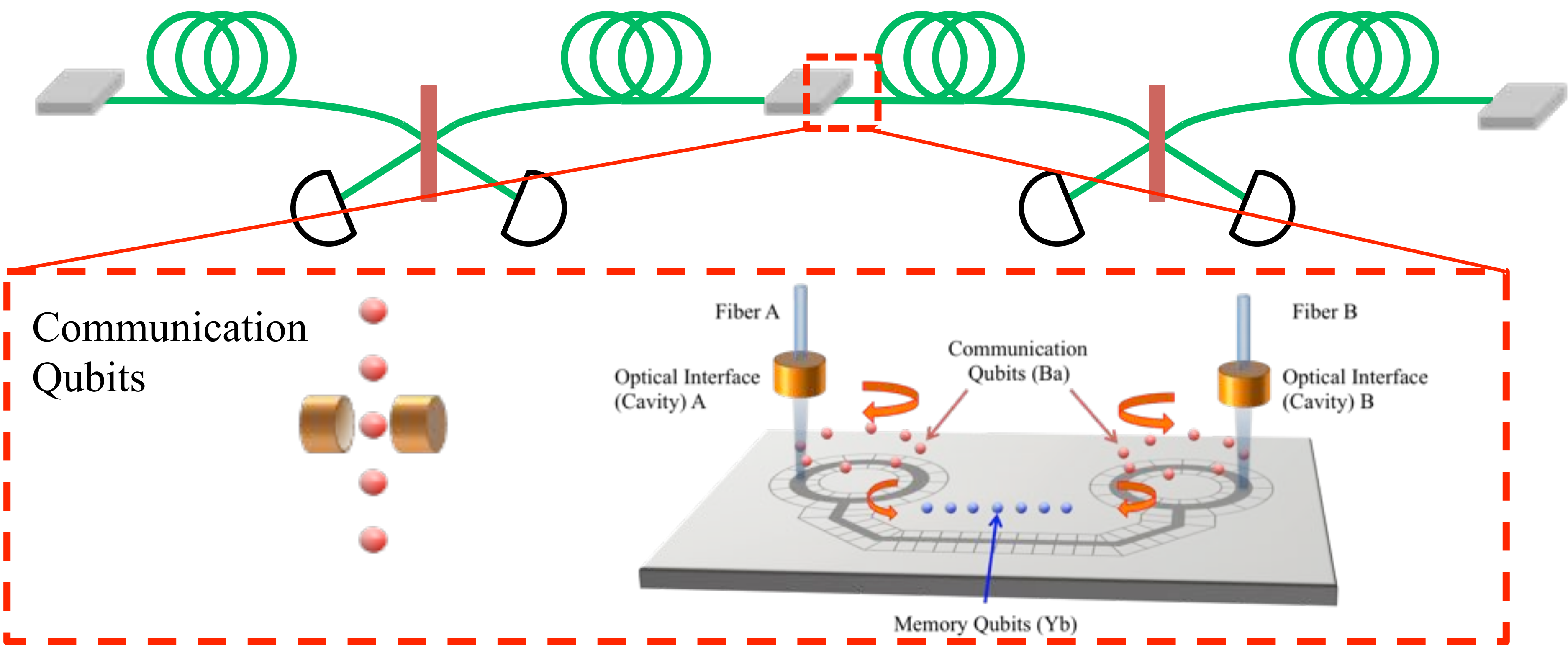


Up to mN qubits in a QC

Monroe, Kim, Duan (2009)
Monroe and Kim, Science 339, 1164 (2013)

SPARQC: Quantum Repeater Platform

- Strategy for Quantum Repeater Realization
  - Trapped-ion quantum information processor with two optical ports can function as a quantum repeater node

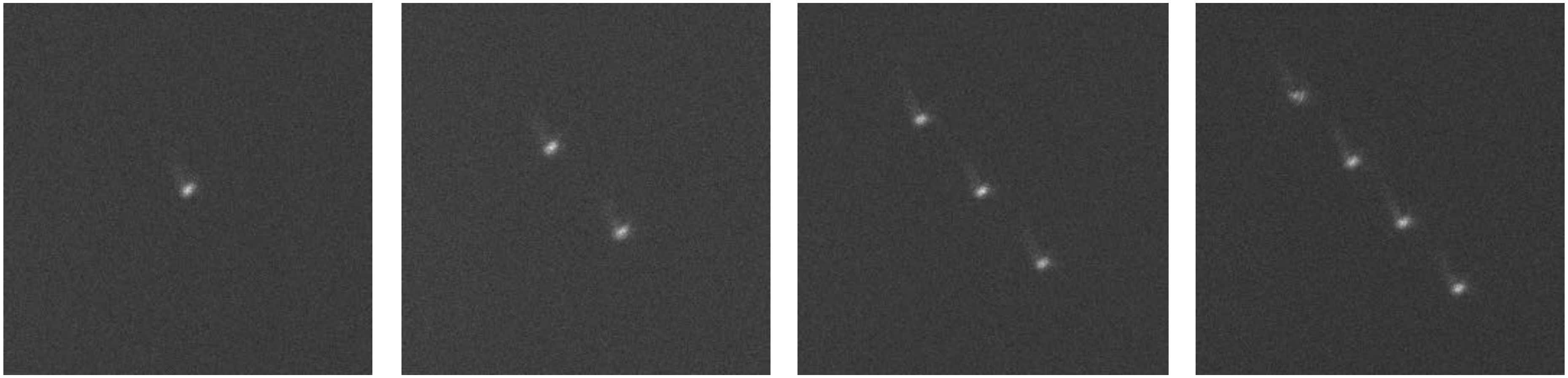


Monroe and Kim, Science 339, 1164 (2013)

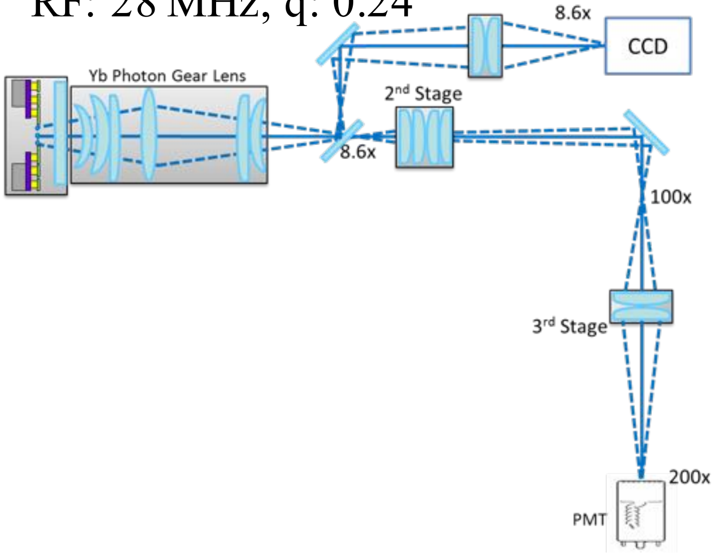
Lecture 2: Systems and Technology Considerations

1. Qubit Gates for Trapped Ions
2. Individual Addressing Strategies
3. Photonic Interconnects for Scaling
4. Architectural Implications

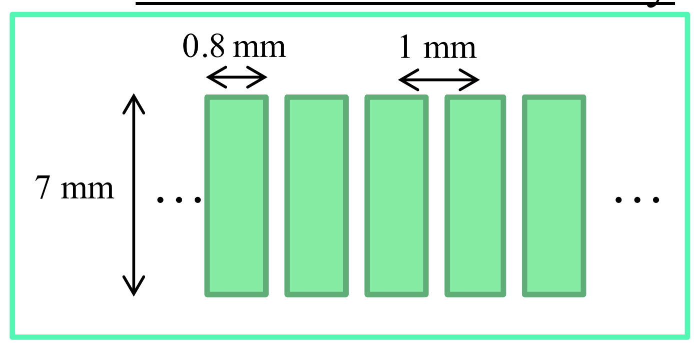
Ion chains in a Surface Trap



- Chains of two ions are held for up to 2 hours.
- RF: 28 MHz, q: 0.24



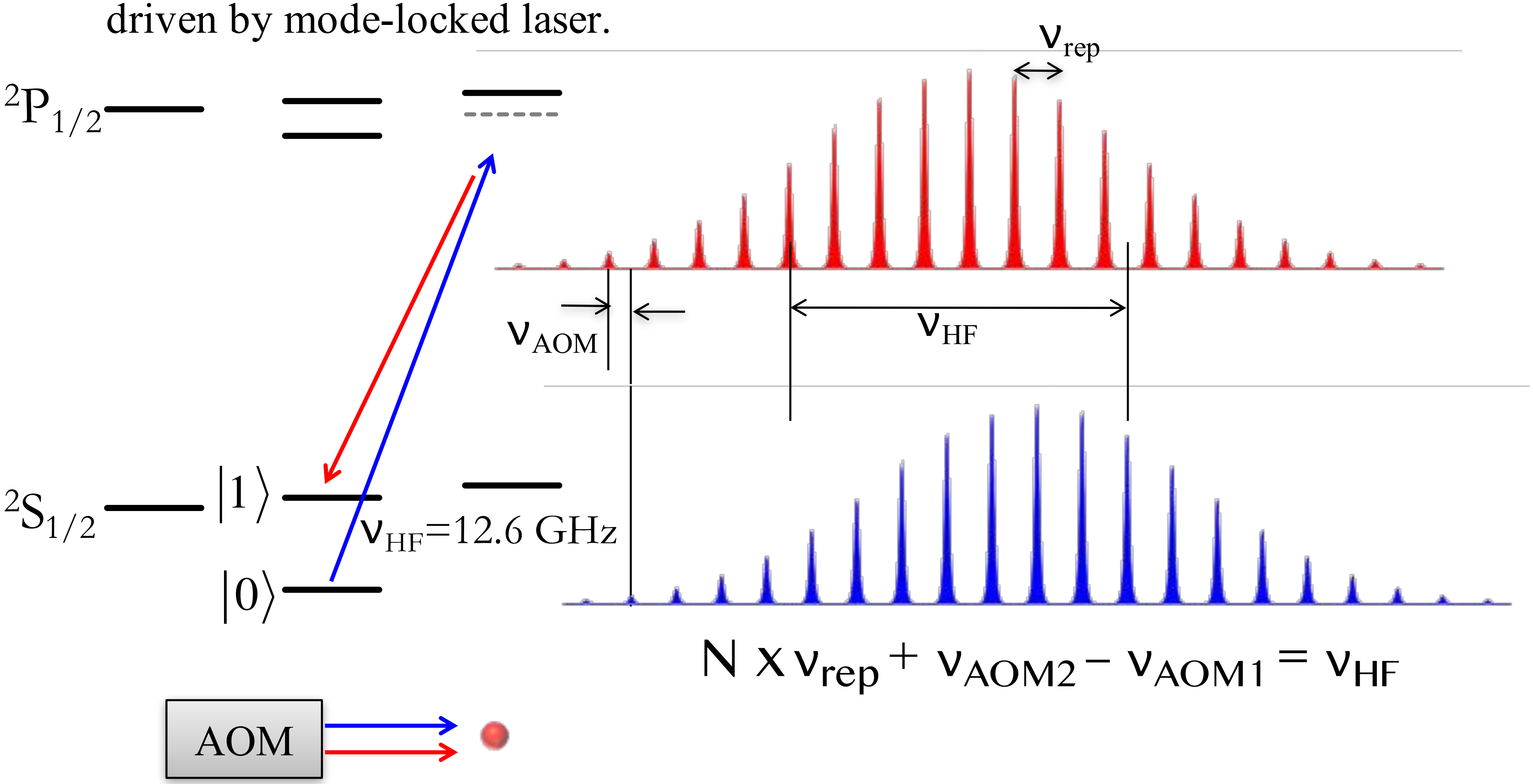
32-Channel PMT Array



1 ions

Raman Single Qubit Gates

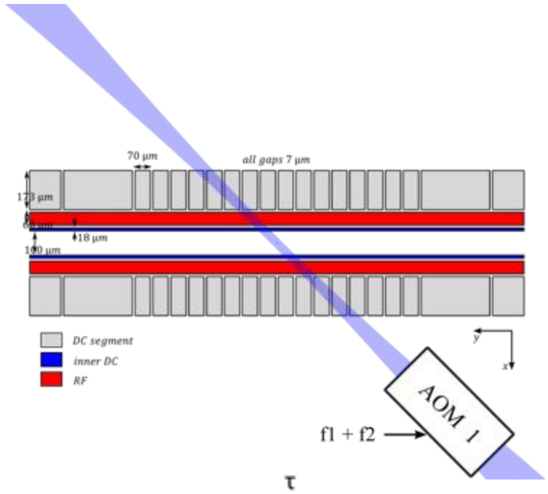
- Global & Individual single qubit gates can be realized by Raman transition driven by mode-locked laser.



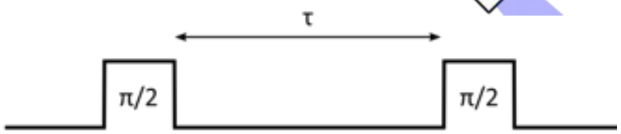
Co-propagating optical frequency combs

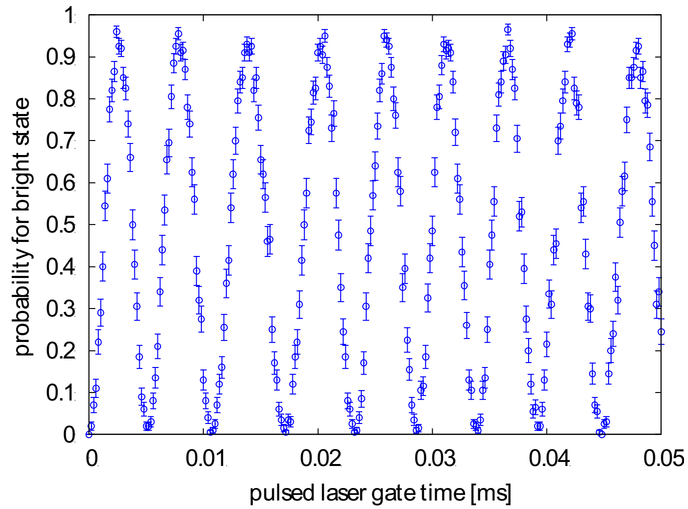
D. Hayes et al., PRL 104, 140501 (2010)

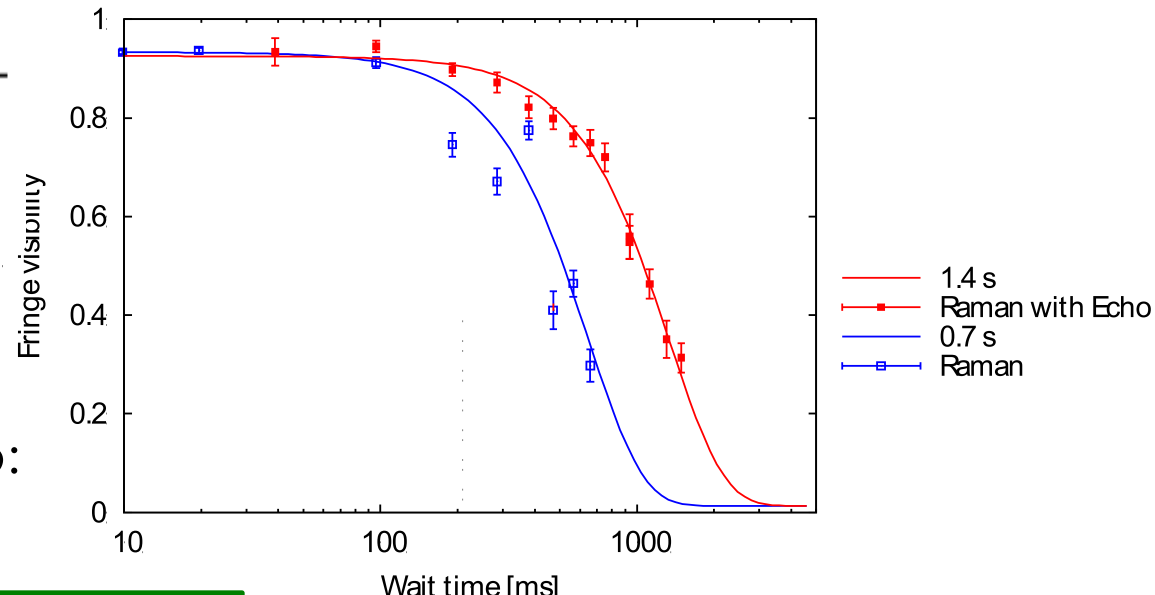
Qubit Manipulation with Raman Beams



No Echo





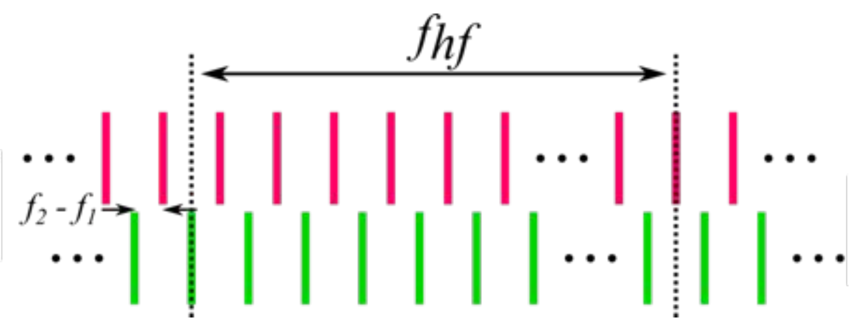


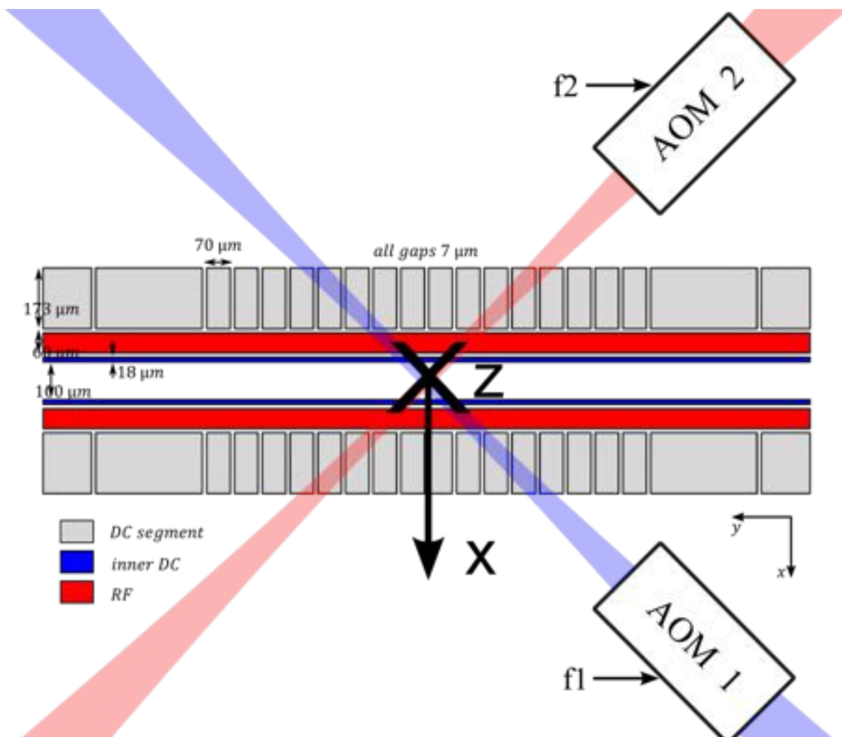
- Ramsey experiment with frequency combs:
- Coherence time without echo: 690 ms

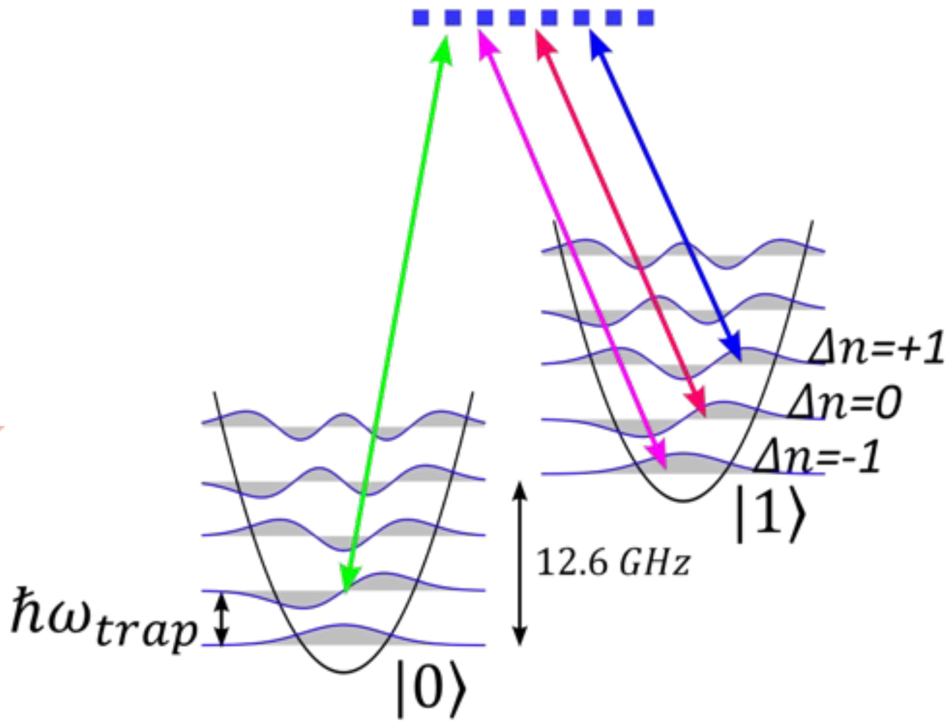
Coherence time with a single echo pulse: 1.4 sec

E. Mount *et al, NJP* **15** 093018 (2013)

Motional Raman transitions



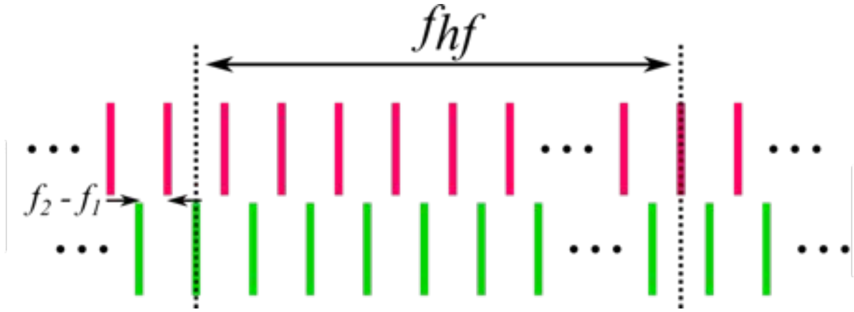


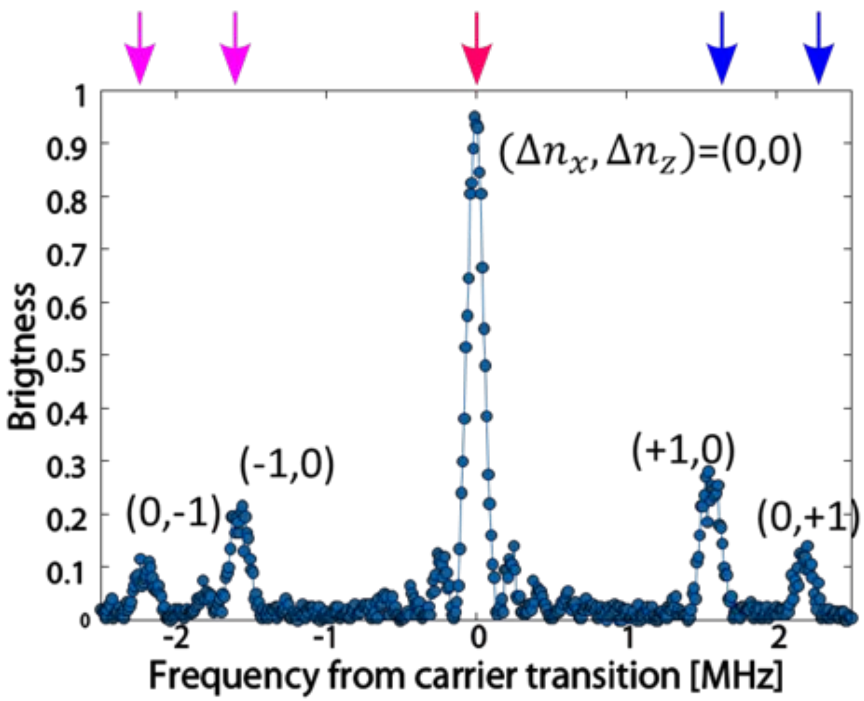


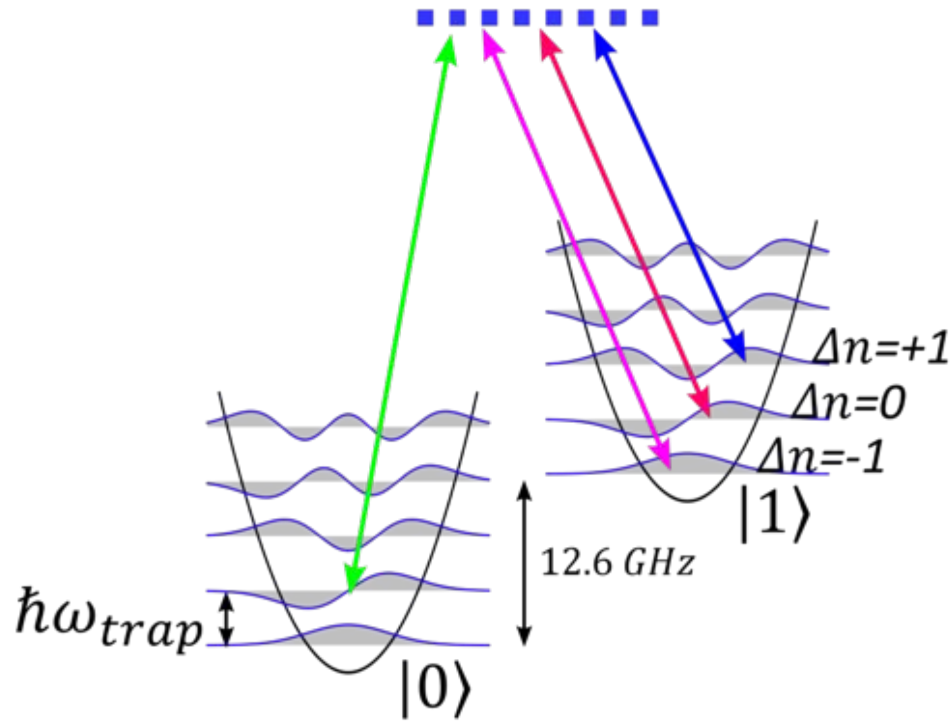
$$n * f_{rep} + (f_2 - f_1) = f_{hf} \pm f_{trap}$$

E. Mount *et al, NJP* **15** 093018 (2013)

Motional Raman transitions



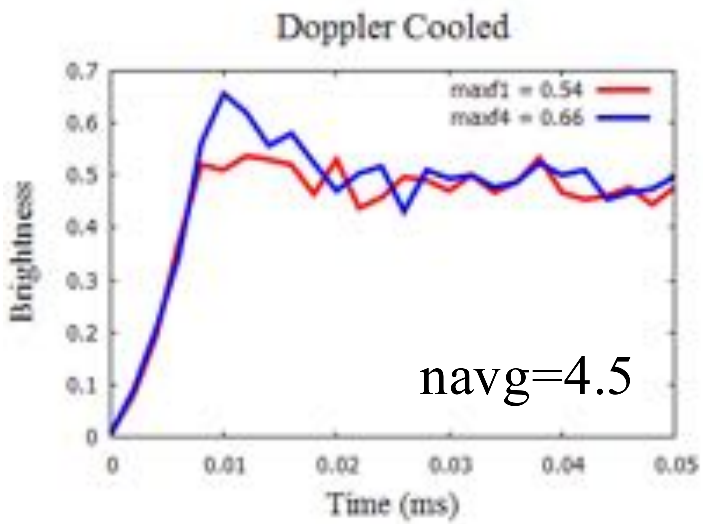


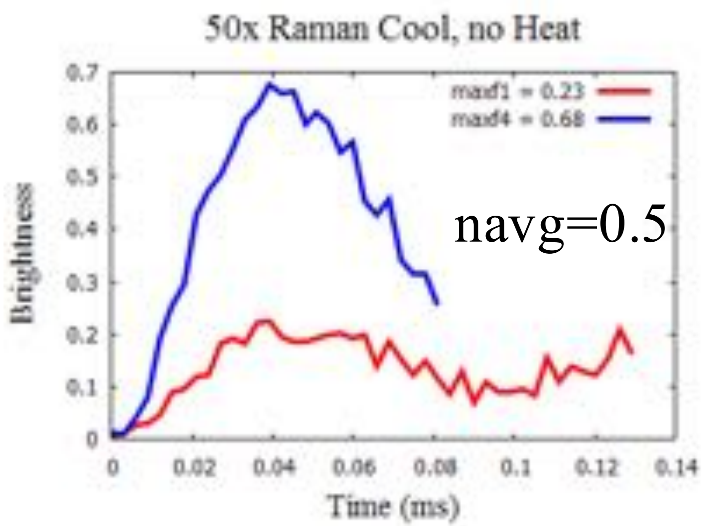


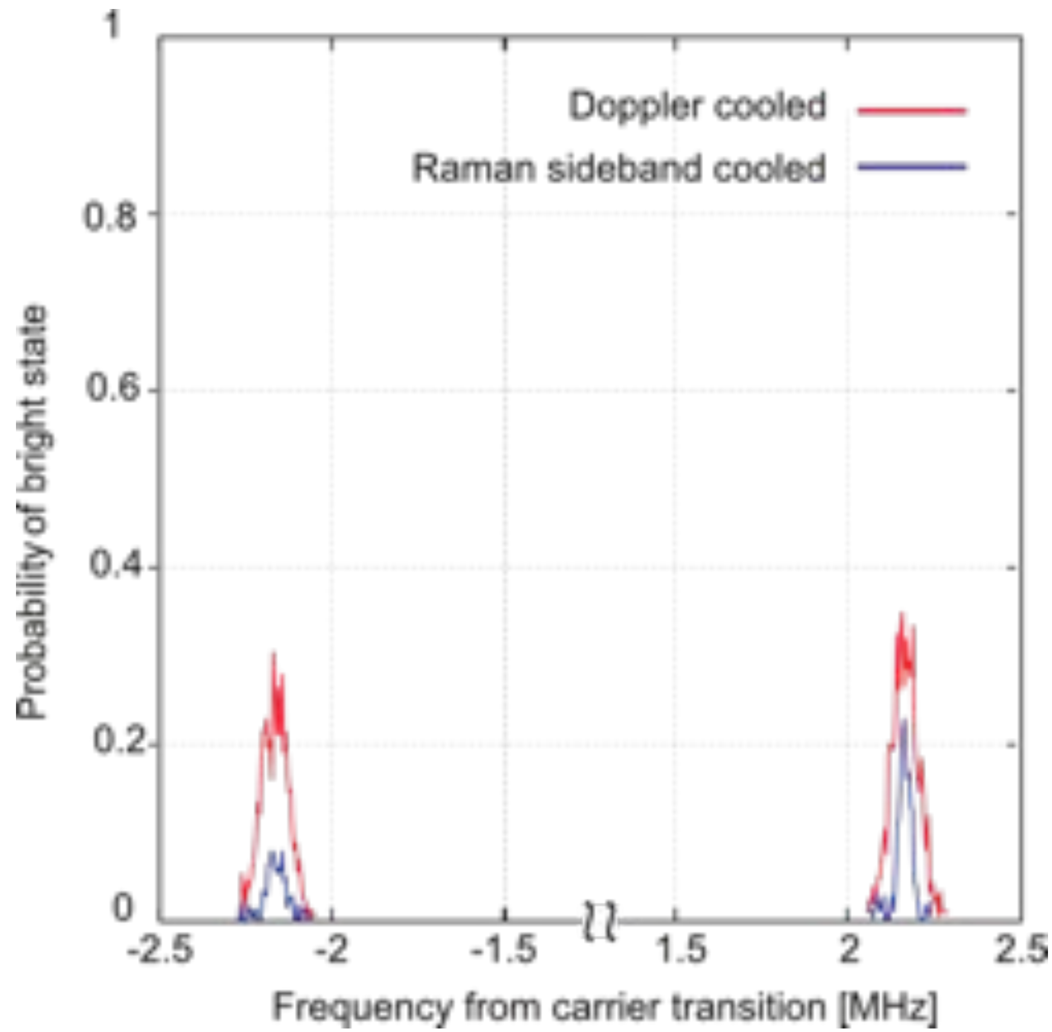
$$n * f_{rep} + (f_2 - f_1) = f_{hf} \pm f_{trap}$$

E. Mount *et al, NJP* **15** 093018 (2013)

Ground state cooling

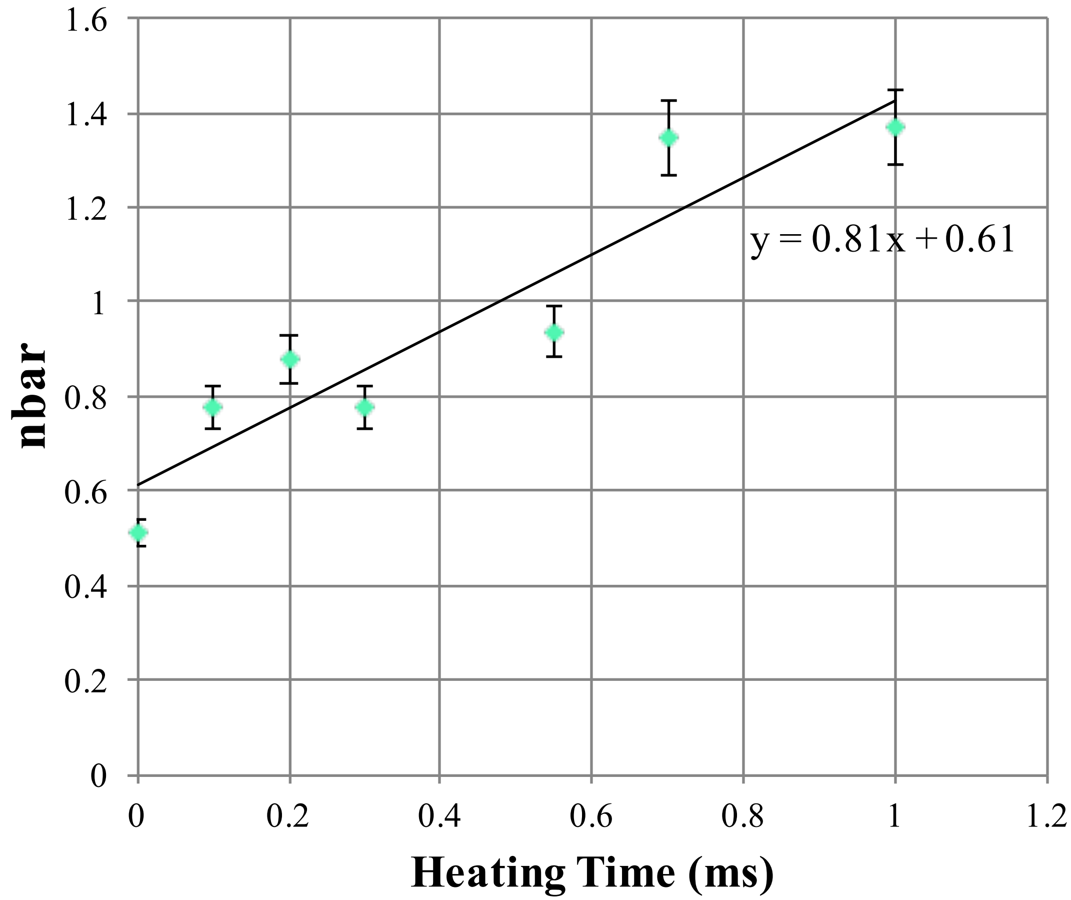






E. Mount *et al, NJP* **15** 093018 (2013)

Heating rate



Heating Rate (transverse mode):
~1 quantum/ms

E. Mount *et al, NJP* **15** 093018 (2013)

Recent results in Surface Traps

- Traps with lower heating rates (Duke, Sandia, NIST, MIT-LL, etc.)
- Reduced heating at cryogenic temp. (MIT, NIST, Lincoln Labs, etc.)
- Surface cleaning to reduce heating (NIST, Berkeley, MIT-LL etc.)

Heating issue is under control!!

D. Hite *et al, PRL* **109** 103001 (2012)
N. Daniilidis *et al, PRB* **89** 245435 (2014)
R. McConnell *et al, PRA* **92** 020302 (2015)
C. Bruzewicz *et al, PRA* **91** 041402 (2015)
J. Labaziewicz *et al, PRL* **100** 013001 (2008)

Lecture 2: Systems and Technology Considerations

1. **Qubit Gates for Trapped Ions**
2. **Individual Addressing Strategies**
3. **Photonic Interconnects for Scaling**
4. **Architectural Implications**

MUSIQC: Multi-Tier Approach to Scalability

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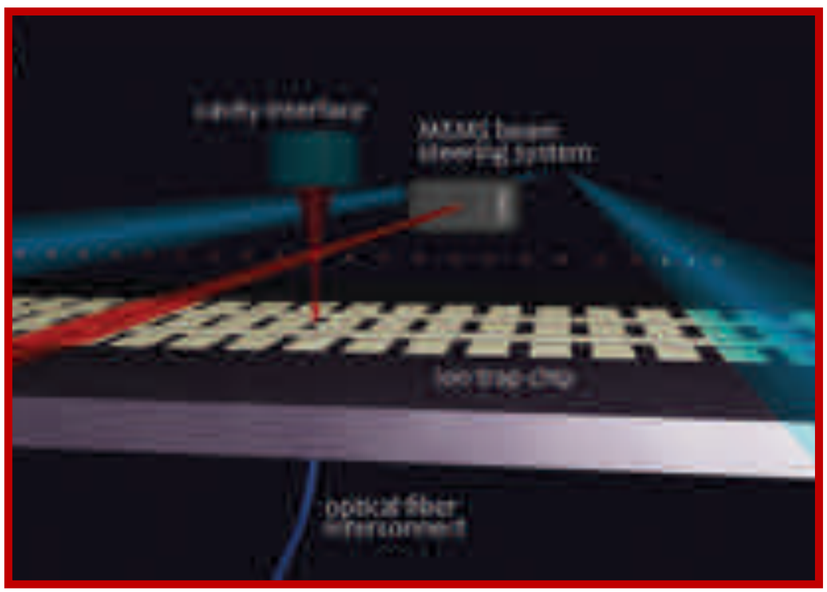
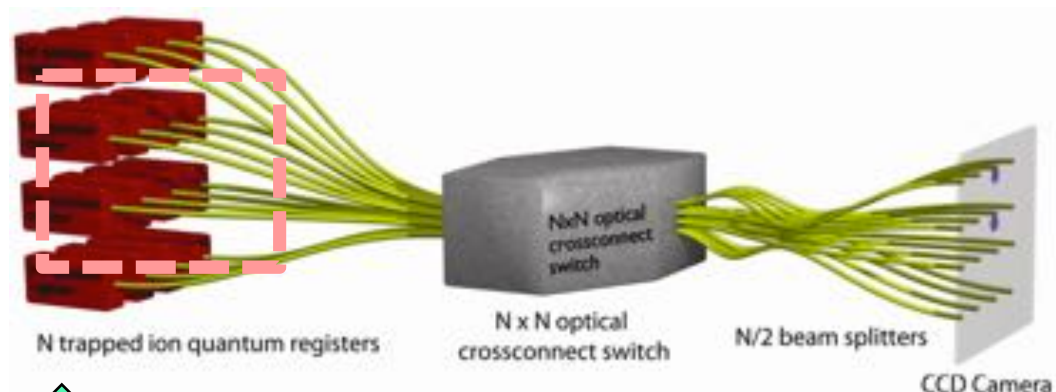
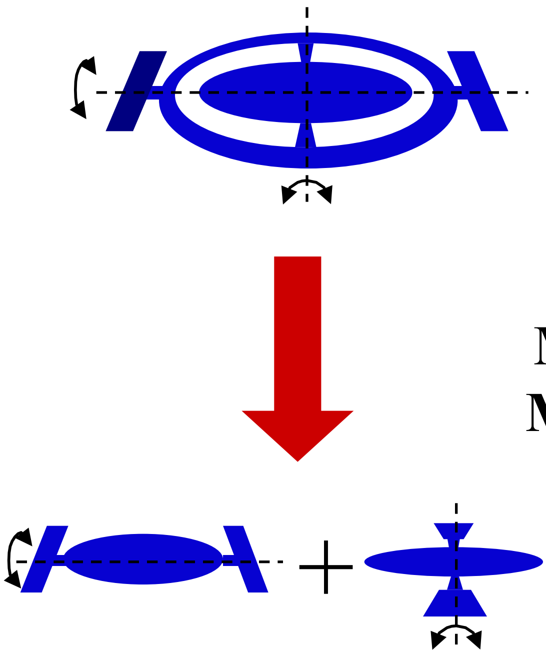




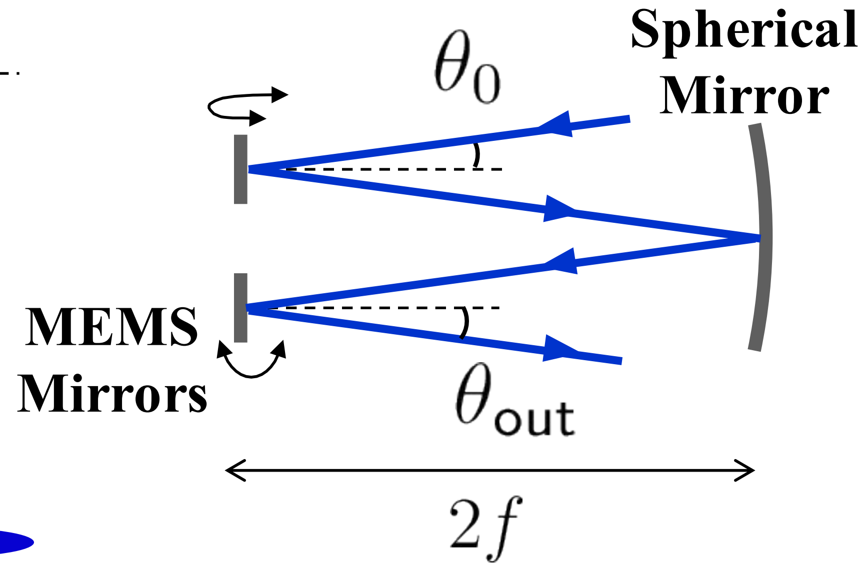
Individual Addressing Strategies

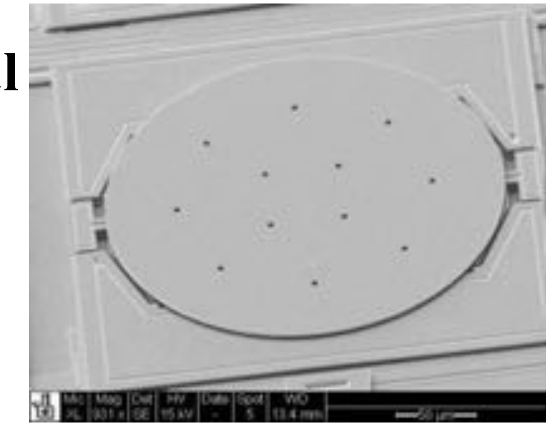
- Options for Individual Addressing of Atoms
  - Frequency discrimination: Siegen (Wunderlich), Penn State (Weiss)
  - Beam Steering: Wisconsin (Saffman, AO), Innsbruck (Blatt, EO)
  - Difficult to scale to parallel Operations
- Scalable MEMS beam steering
  - Scalable fabrication technology
  - Low optical loss over broadband
  - Provide Optical Multiplexing
    - Addressing locations
    - Beam paths
    - Operating wavelengths
- MEMS challenges
  - Speed – 10^3 speedup
  - Stability, reliability and optical performance

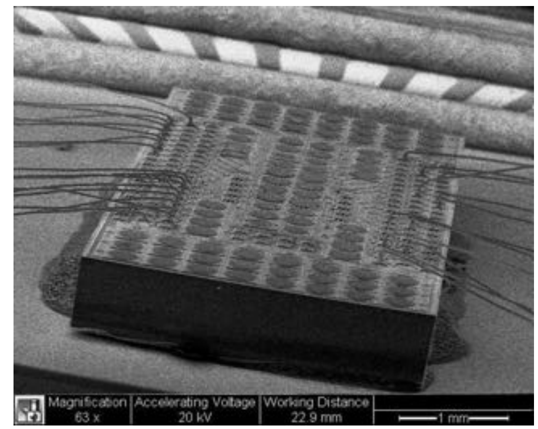
2D Tilt with MEMS Micromirrors

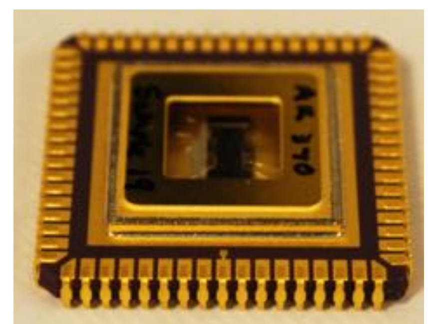


2D decoupled tilt







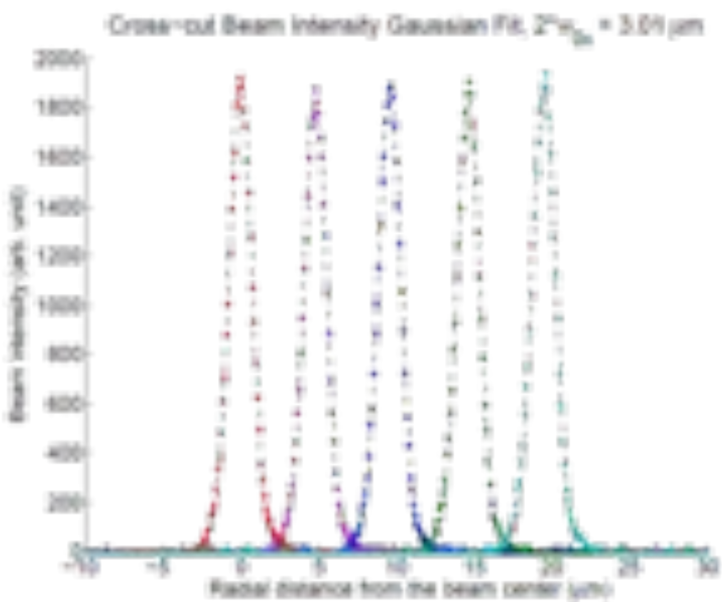


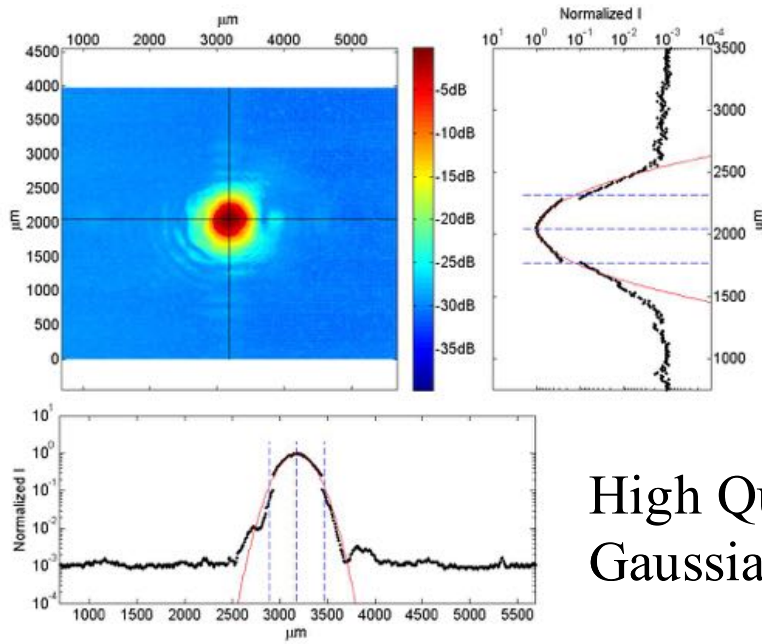
$$\Delta\theta_{\text{out}} = 2\,\alpha$$

α: MEMS mechanical tilt angle

$\Delta\theta_{\text{out}}$: change in beam tilt angle

Beam Steering Capability

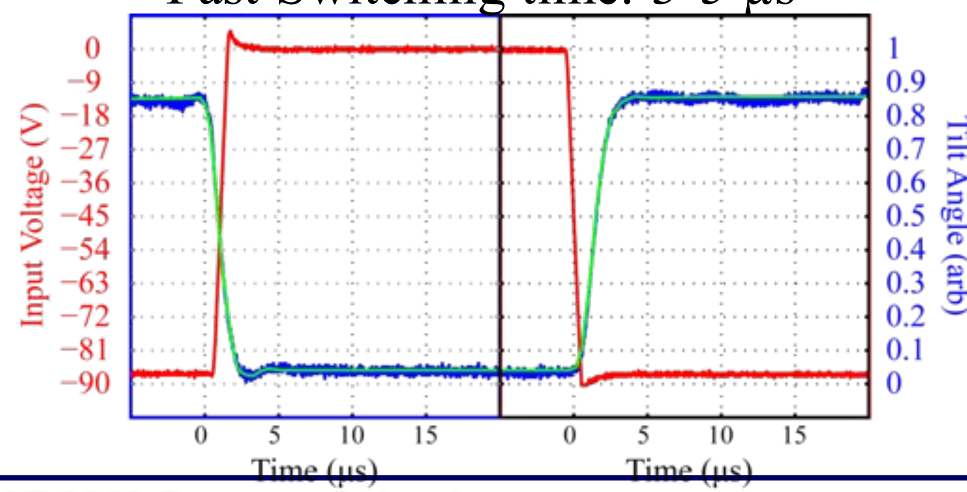




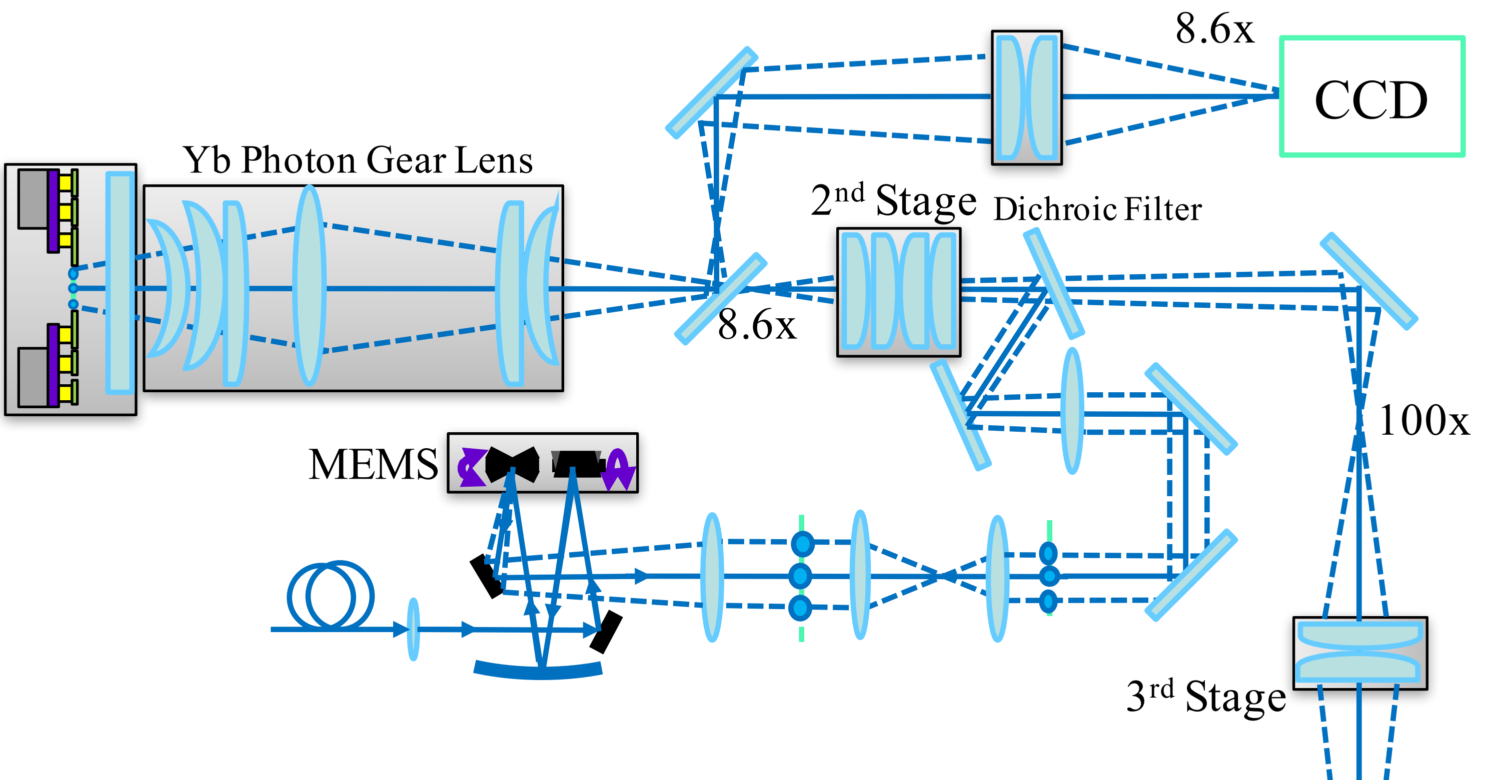
High Quality Beams
Gaussian down to < -30dB

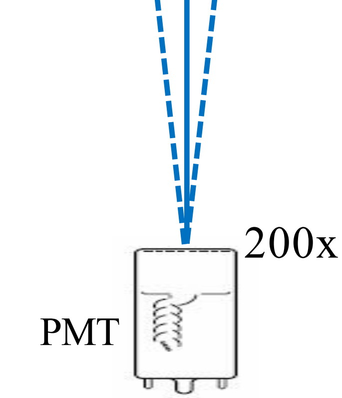
Knoernschild et al.,
Optics Express 17, 7233 (2009)

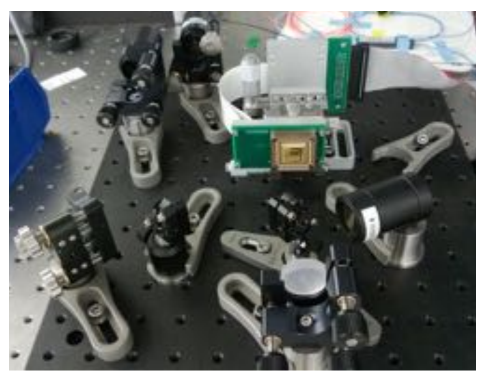
Fast Switching time: 3-5 μs



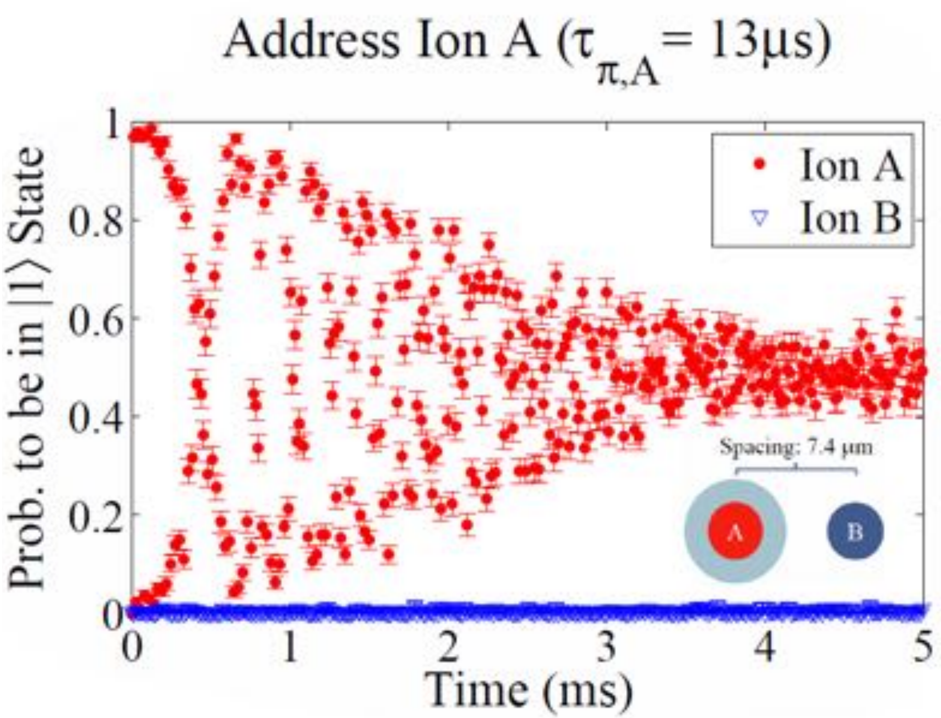
MEMS integration

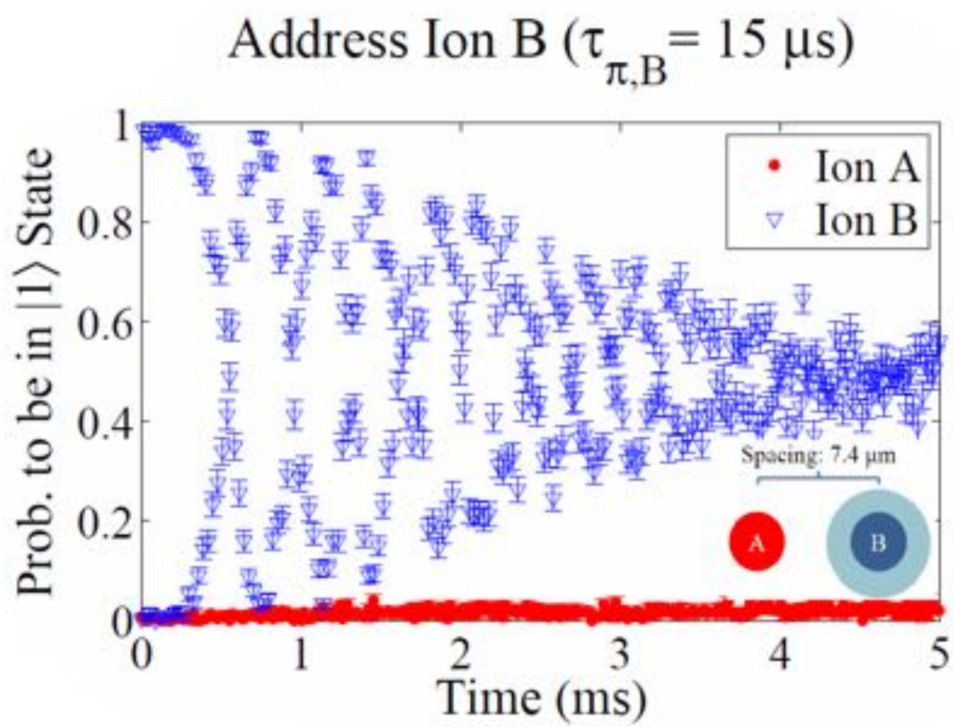






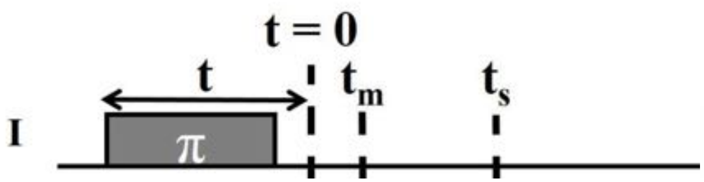
Crosstalk Characterization

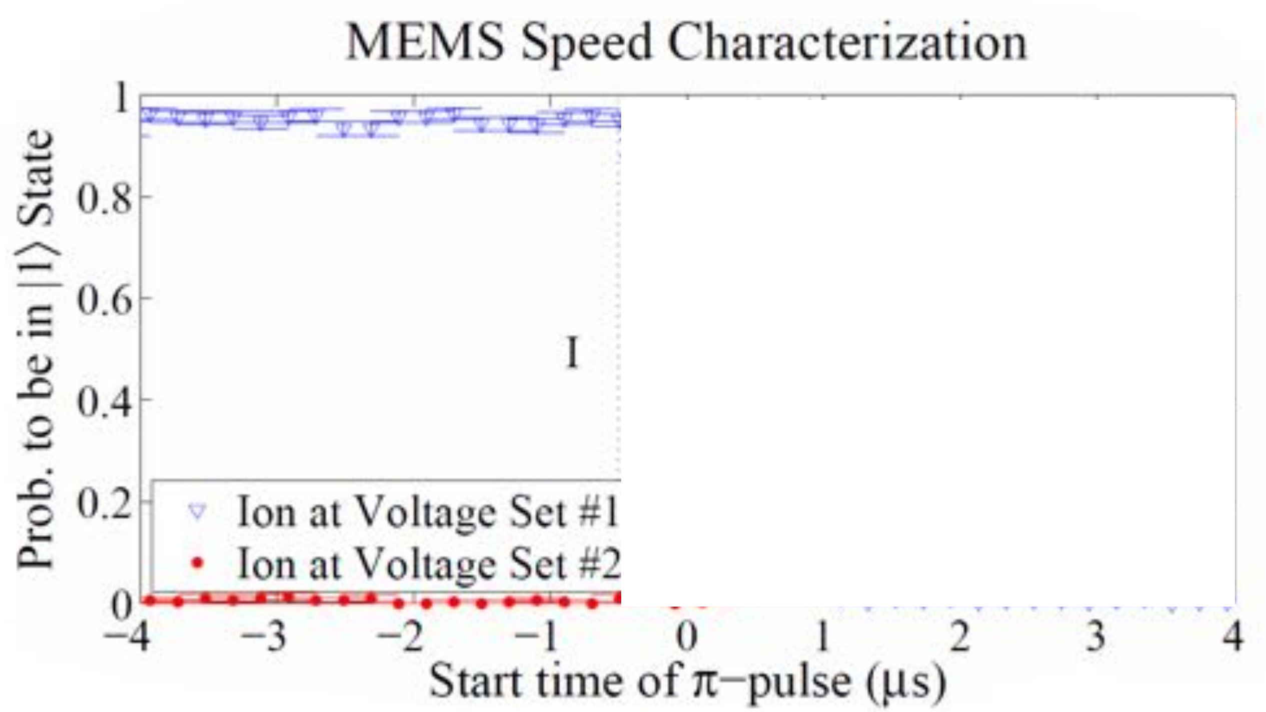




- By comparing the Rabi frequencies of the target and neighboring ion, crosstalk is calculated to be 1.3×10^{-4} on Ion B and 2.9×10^{-4} on Ion A

Switching Speed Characterization





- t_m~ 0.9 us , t_s~ 2 us
- Total switching time ~1.1 us

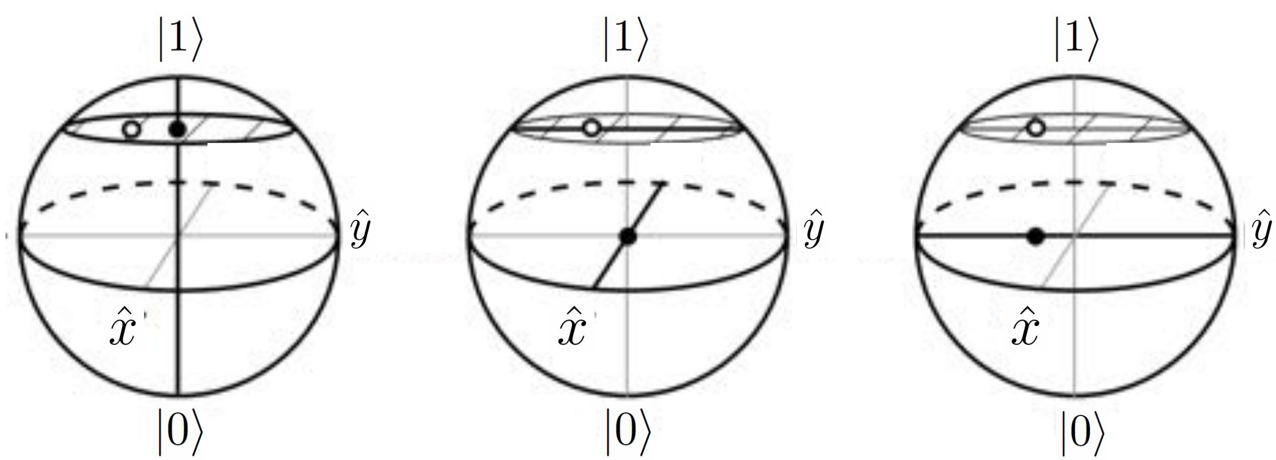
Sequential Single Qubit Gates

- Quantum State Tomography
  - Reconstruct full density matrix
  - Requires measurements in 3 bases for a single qubit state

$$|0\rangle \qquad \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \qquad \frac{1}{\sqrt{2}}(|0\rangle + \imath\,|1\rangle)$$

  - Rotate to one of the three bases by:

$$\mathcal{I} \qquad R_x(\tfrac{\pi}{2}) \qquad R_y(\tfrac{\pi}{2})$$

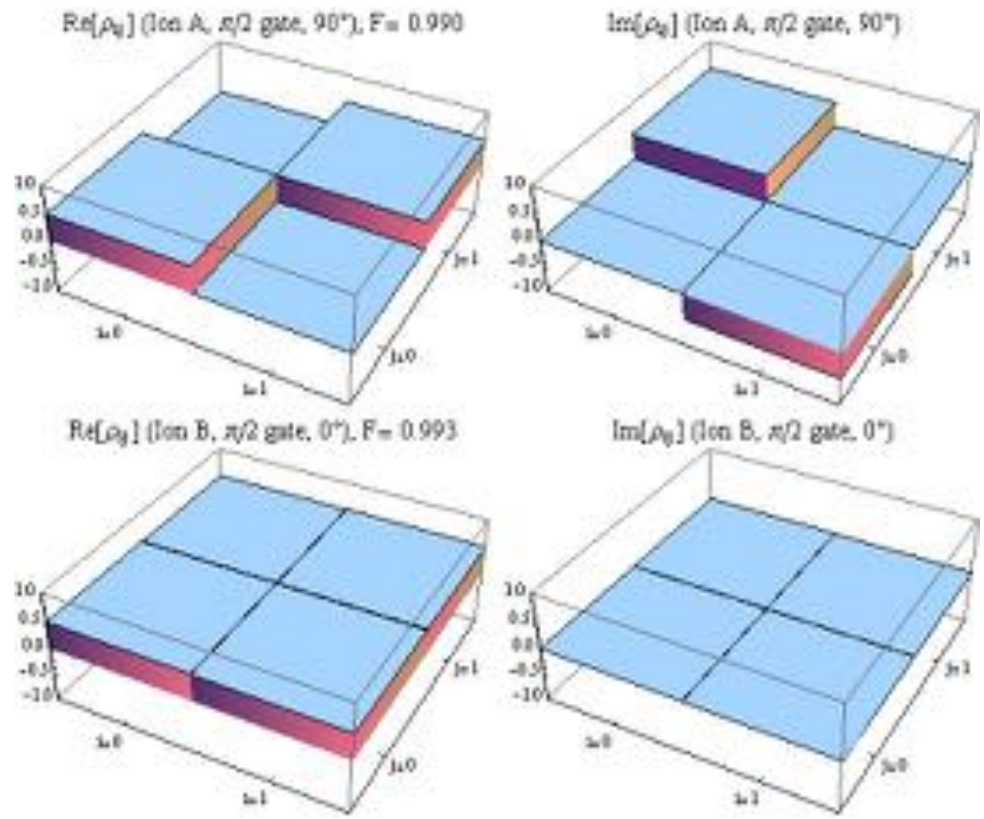


J. Altepeter, E. Jerey, and P. Kwiat, “Photonic state tomography," in Advances In Atomic, Molecular, and Optical Physics, Advances, Vol. 52, edited by P. Berman and C. Lin (Academic Press, Bellingham, 2006) pp. 105-159.

Sequential Single Qubit Gates

- Experimental Procedure:
  - Cool (1.5 ms)
  - Pump to $|0\rangle$ (20 us)
  - Raman pulse on ion A
  - Raman pulse on ion B
  - Analysis pulse on ion A
  - Analysis pulse on ion B
  - Detect (400 us)

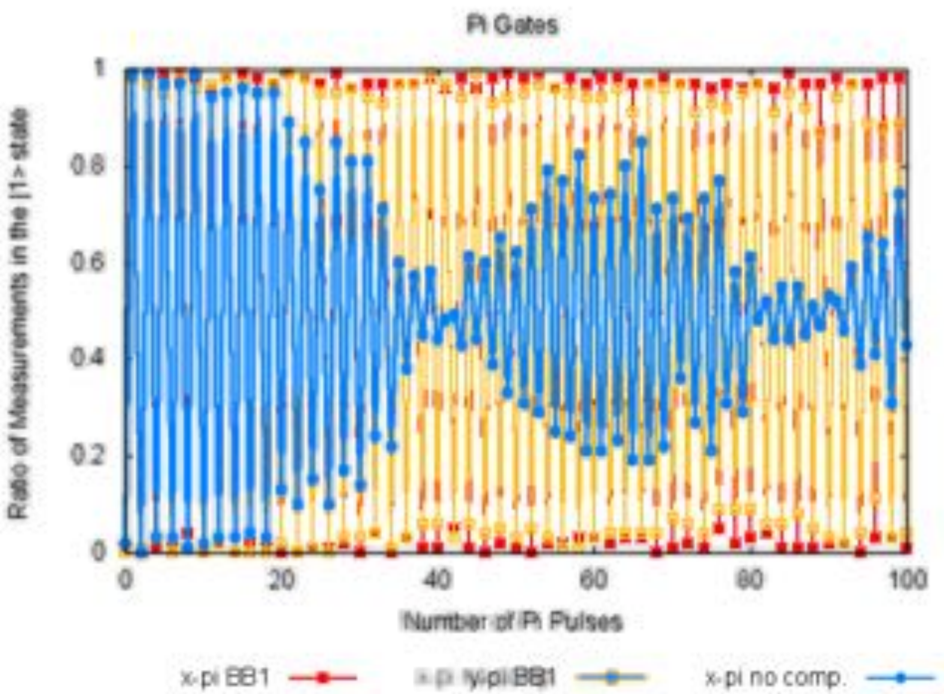
$$R_y(\tfrac{\pi}{2}), R_x(\tfrac{\pi}{2})$$

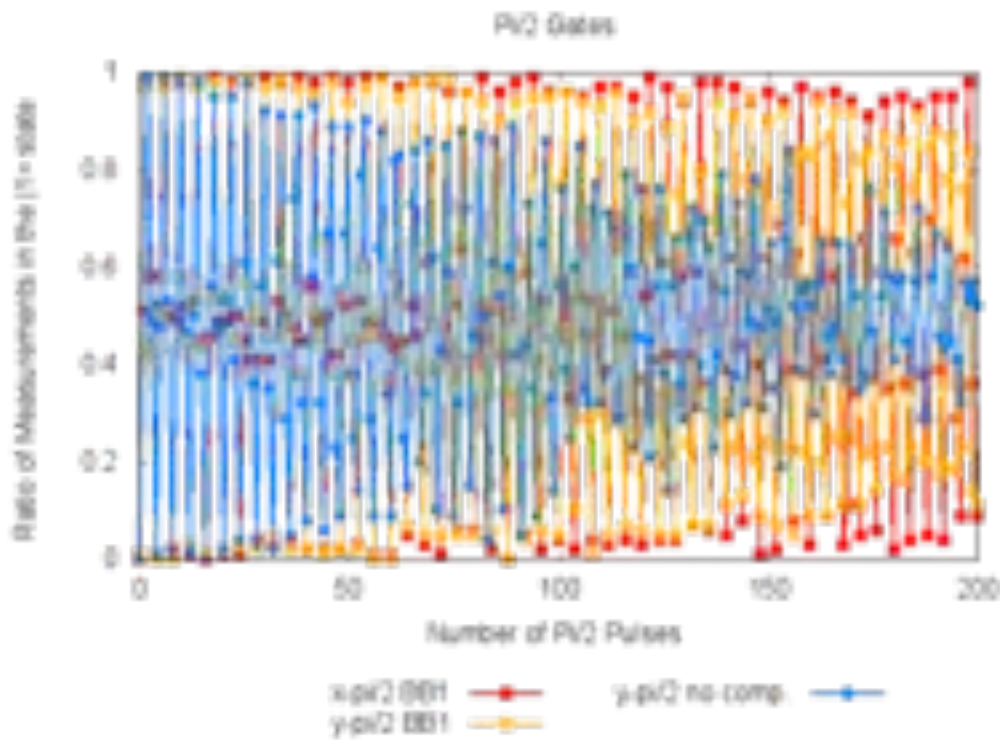


- $|0\rangle$ state preparation/measurement fidelity: 0.998
- $|1\rangle$ state measurement fidelity: 0.991

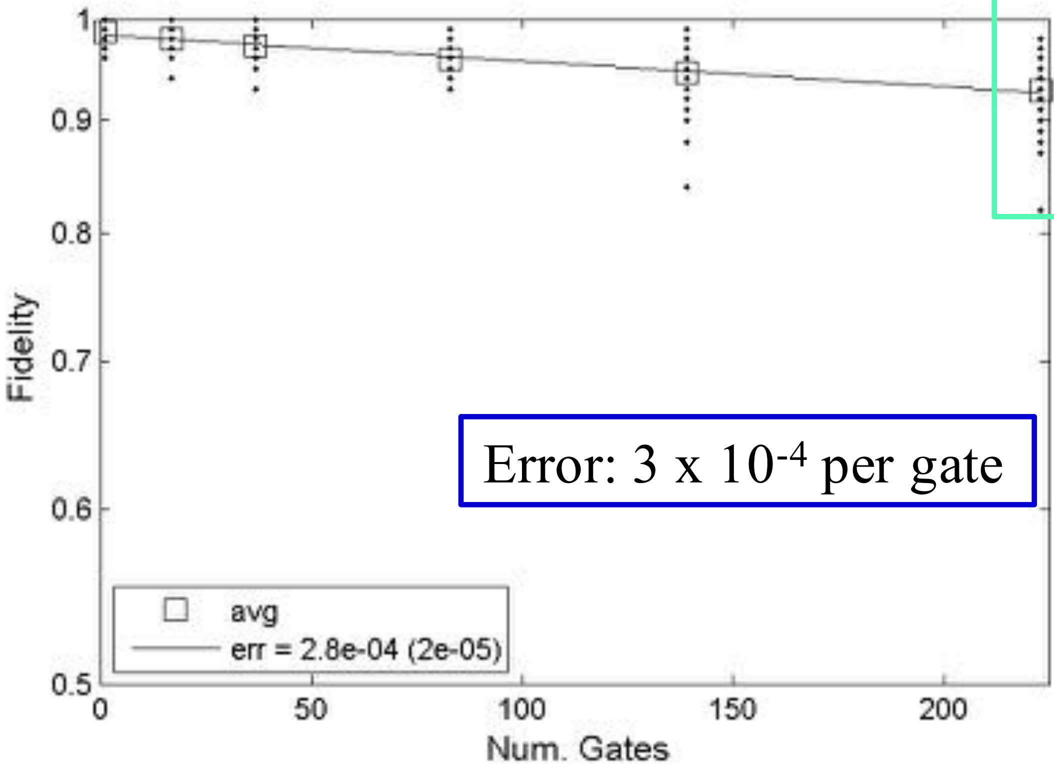
Compensated Pulses

- Sequences of pulses can be used to make gates less sensitive to amplitude fluctuations.
- We use the BB1 compensation sequence here.

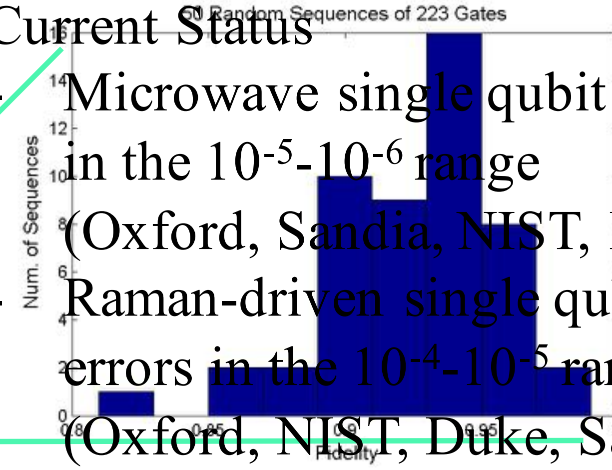




Single Qubit Gate Fidelity



Current Status



- Microwave single qubit gate errors in the 10^{-5}-10^{-6} range (Oxford, Sandia, NIST, Duke, etc.)
- Raman-driven single qubit gate errors in the 10^{-4}-10^{-5} range (Oxford, NIST, Duke, Sandia, etc.)
- Raman-driven two qubit gate errors in the 10^{-3} range (Innsbruck, Oxford, NIST, etc.)

Knill et al, PRA 77, 012307 (2008)
Mount et al., PRA 92, 060301 (2015)

J. Benhelm *et al, Nature Phys.* **4** 463 (2008)
K. Brown *et al, PRA* **84** 030303 (2011)
T. Harty *et al, PRL* **113** 220501 (2014)
C. Ballance *et al, arXiv:1512.04600* (2015)
J. Gaebler *et al, arXiv:1604.00032* (2016)

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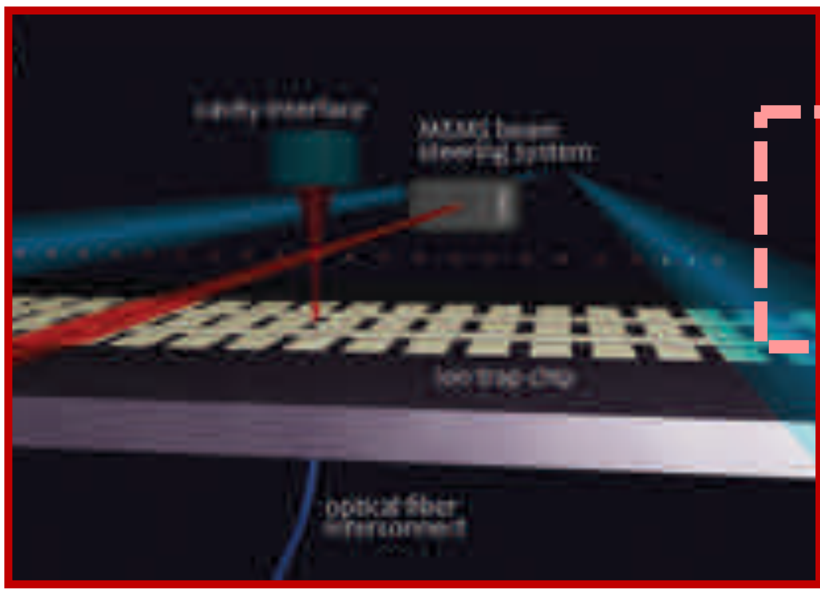
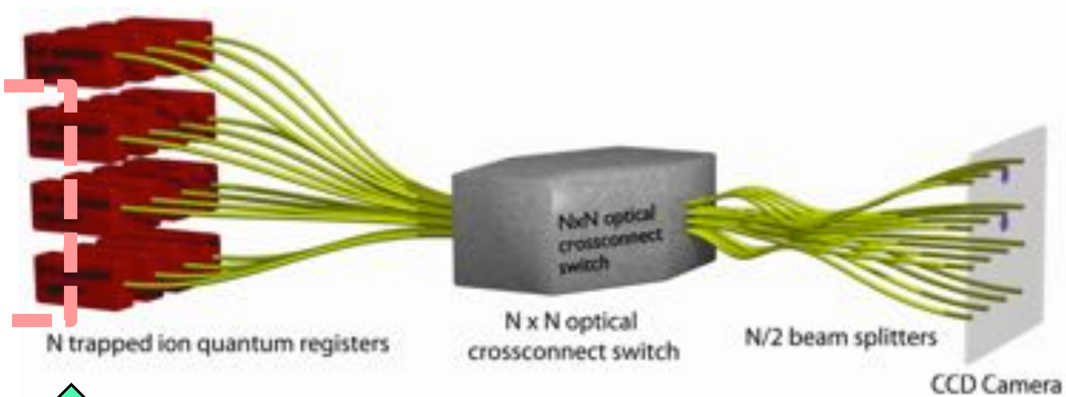
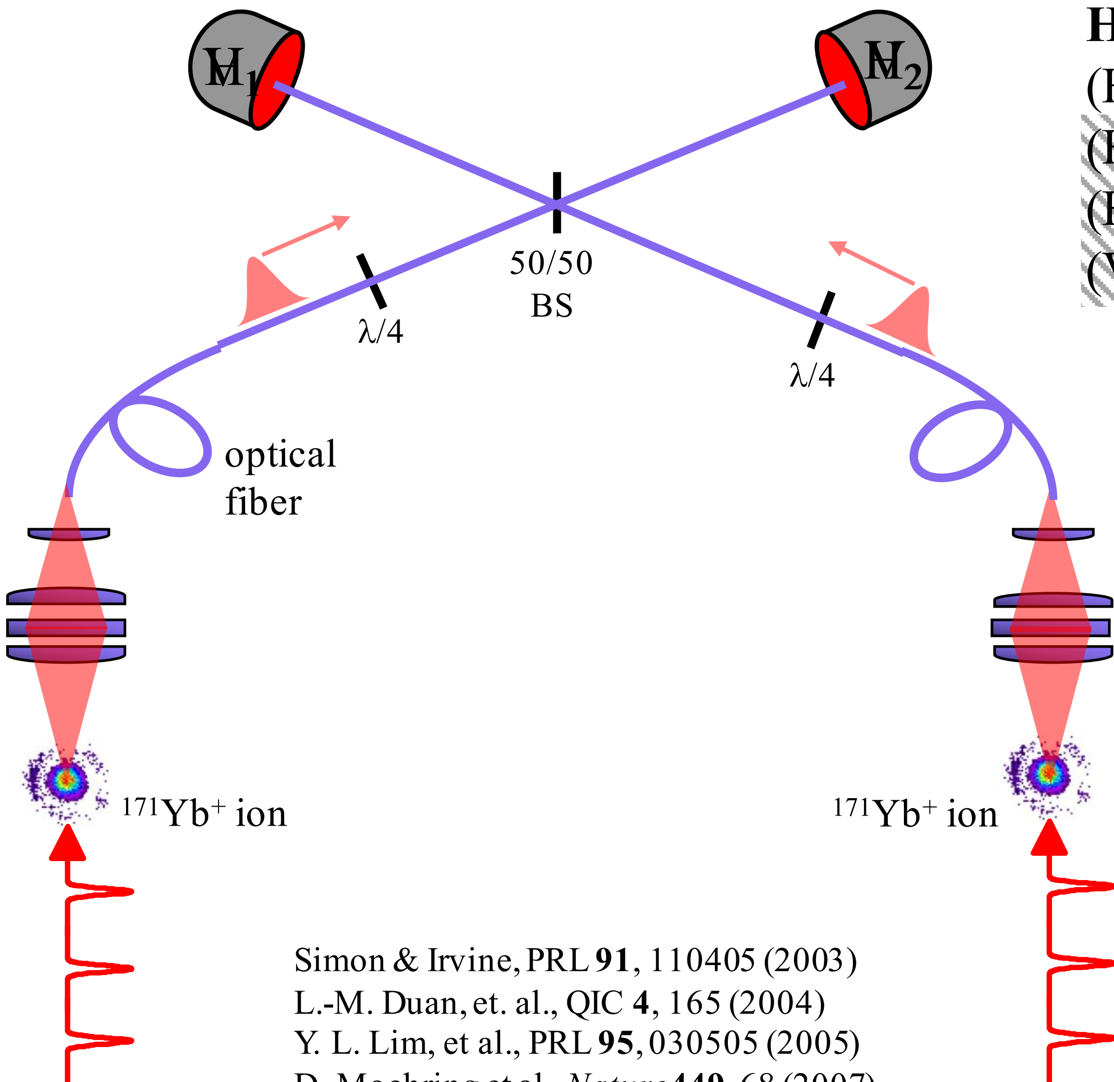




Remote Entanglement Generation



Heralded coincident events (p_{suc}=1/4):

$(H_1 \ \& \ V_2)$ or $(V_1 \ \& \ H_2) \ \rightarrow \ |\downarrow\uparrow\rangle - |\downarrow\uparrow\rangle$

$(H_1 \ \& \ V_1)$ or $(V_2 \ \& \ H_2) \ \rightarrow \ |\downarrow\uparrow\rangle + |\downarrow\uparrow\rangle$

$(H_1 \ \& \ H_1)$ or $(H_2 \ \& \ H_2) \ \rightarrow \ |\downarrow\downarrow\rangle$

$(V_1 \ \& \ V_1)$ or $(V_2 \ \& \ V_2) \ \rightarrow \ |\uparrow\uparrow\rangle$

$$R_{ent} = \frac{1}{2} R \left(\eta_D \cdot F \cdot \frac{d\Omega}{4\pi} \right)^2$$

R: Repetition Rate

η_D: Detector Efficiency

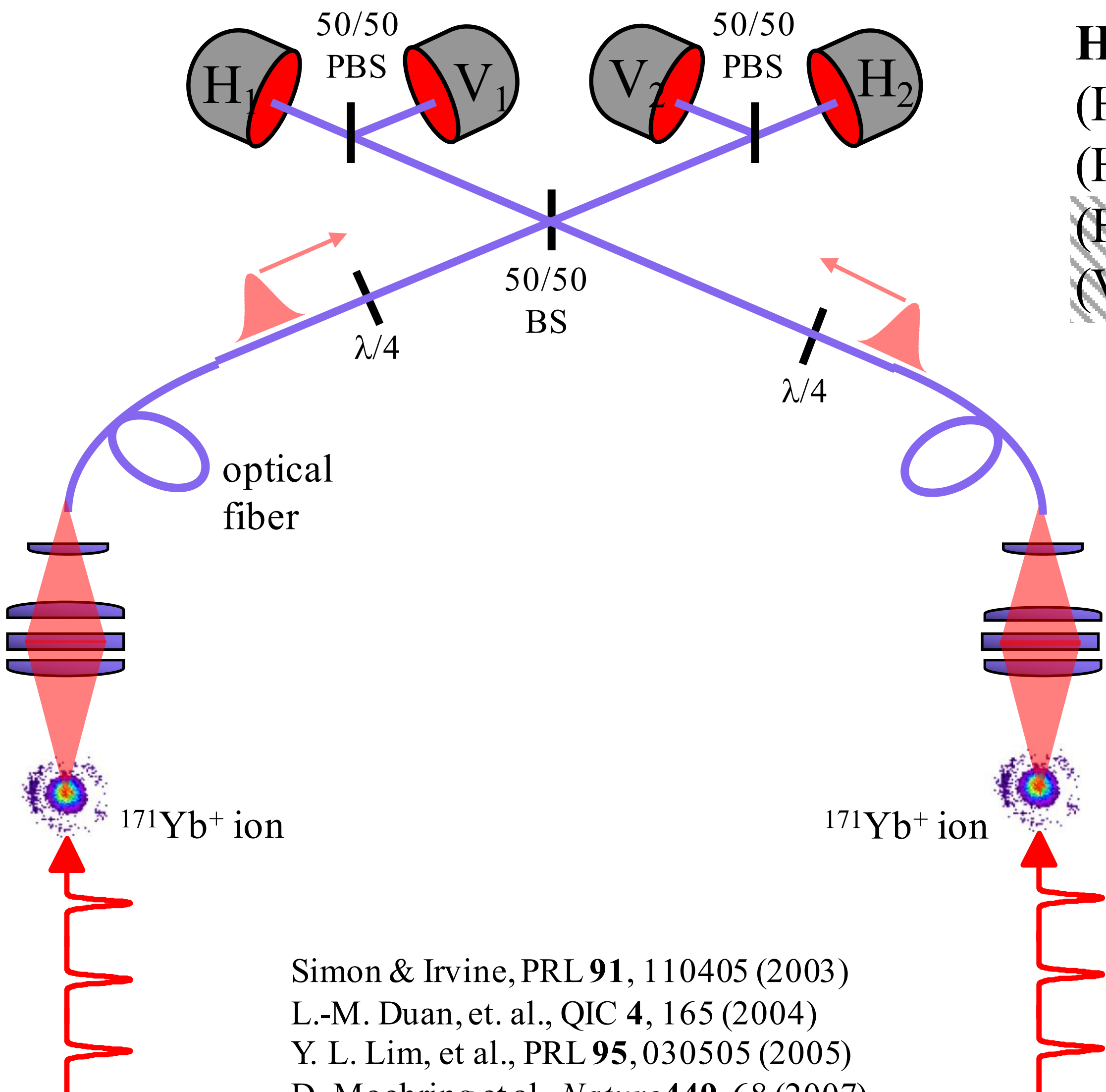
$d\Omega$: Collection Solid Angle

F: Collection Efficiency

$$R_{ent} = 0.001 - 0.025 s^{-1}$$

Simon & Irvine, PRL **91**, 110405 (2003)
L.-M. Duan, et. al., QIC **4**, 165 (2004)
Y. L. Lim, et al., PRL **95**, 030505 (2005)
D. Moehring et al., *Nature* **449**, 68 (2007)

Current Status on Entanglement Generation



Heralded coincident events (p_{suc}=1/2):

$(H_1 \ \& \ V_2)$ or $(V_1 \ \& \ H_2)$ $\rightarrow$ $|\downarrow\uparrow\rangle - |\downarrow\uparrow\rangle$

$(H_1 \ \& \ V_1)$ or $(V_2 \ \& \ H_2)$ $\rightarrow$ $|\downarrow\uparrow\rangle + |\downarrow\uparrow\rangle$

$(H_1 \ \& \ H_1)$ or $(H_2 \ \& \ H_2)$ $\rightarrow$ $|\downarrow\downarrow\rangle$

$(V_1 \ \& \ V_1)$ or $(V_2 \ \& \ V_2)$ $\rightarrow$ $|\uparrow\uparrow\rangle$

$$R_{ent} = \frac{1}{2} R \left(\eta_D \cdot F \cdot \frac{d\Omega}{4\pi} \right)^2$$

Current:

$$R = 470 kHz$$

$$p = \eta_D \cdot F \cdot \frac{d\Omega}{4\pi} = (0.35)(0.14)(0.10)$$

$$\boxed{R_{ent} = 4.5 s^{-1}}$$

Simon & Irvine, PRL **91**, 110405 (2003)
L.-M. Duan, et. al., QIC **4**, 165 (2004)
Y. L. Lim, et al., PRL **95**, 030505 (2005)
D. Moehring et al., *Nature* **449**, 68 (2007)

Kim, Maunz, Kim, PRA 84, 063423 (2011)
Hucul et al, (UMD) arXiv: 1403.3696 (2014)

Cavity Integrated Trap at Duke

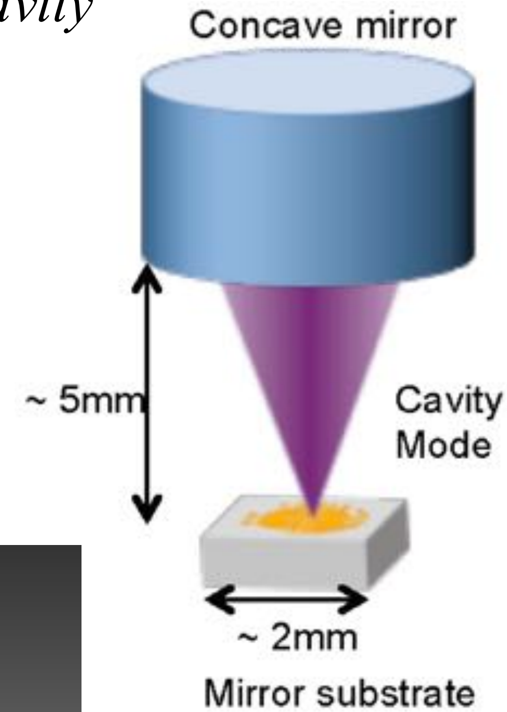
- Small waist, modest length leads to good coupling while lowering requirements for the mirror coatings

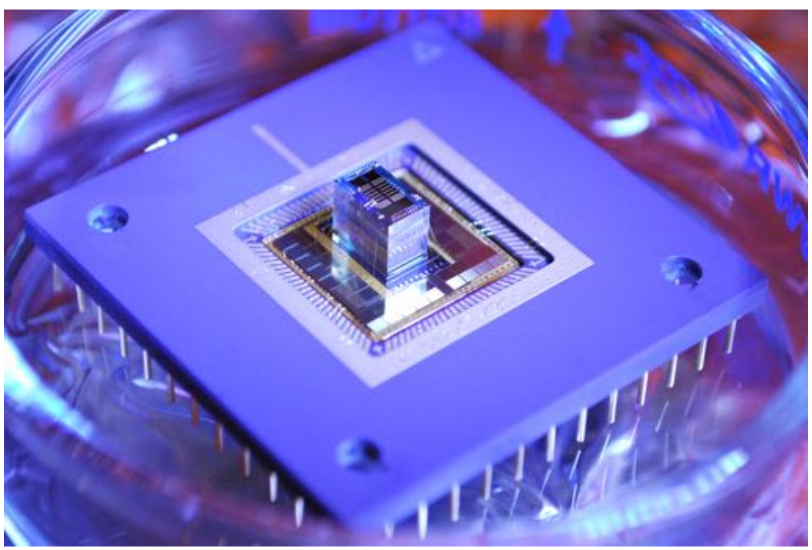
L_{cavity} = 5mm
Z_{ion} =50μm
W_{ion} =4μm

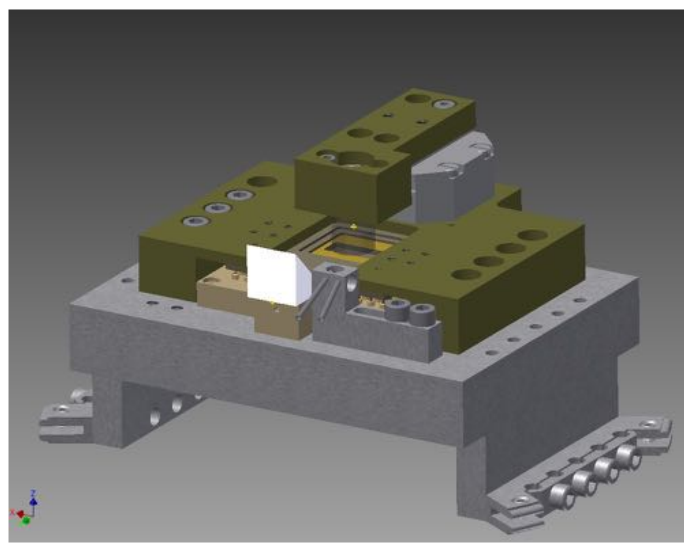
g = 17 MHz
κ = 23 MHz
γ_{Yb}=10 MHz

- Alignment is critical, mirror needs to be positioned to better than 1mm in all directions
- ≥30% collection efficiency expected in a practical system

Planar-concave cavity







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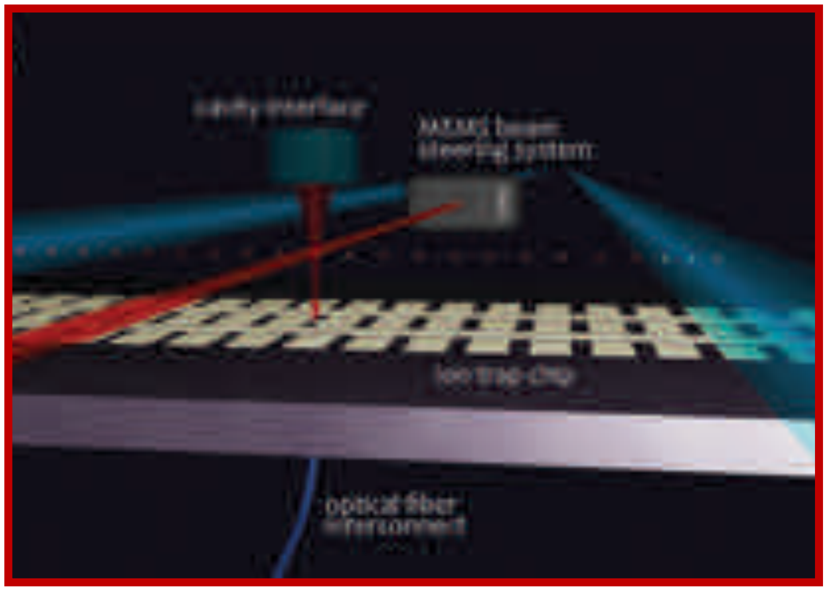
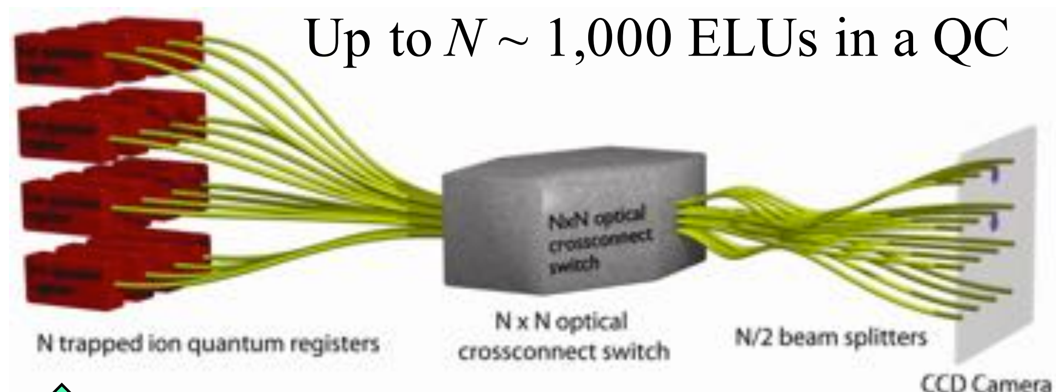


m ~ 10-100 qubits / ELU

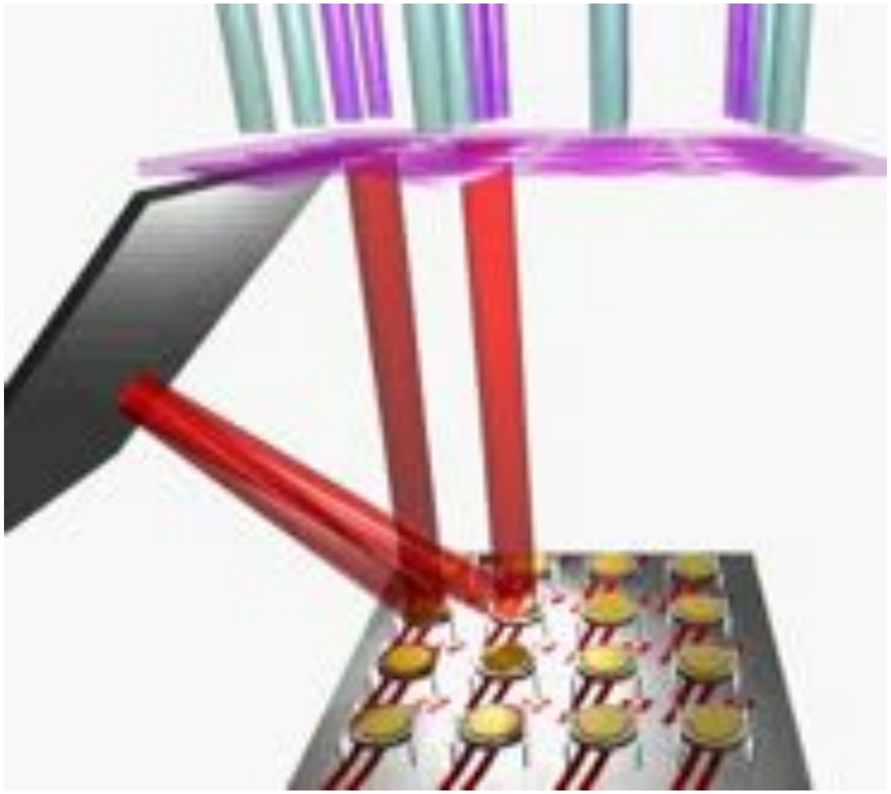
Up to N ~ 1,000 ELUs in a QC



Up to mN qubits in a QC

Monroe, Kim, Duan (2009)
Monroe and Kim, Science 339, 1164 (2013)

Beam Steering Optical Switches

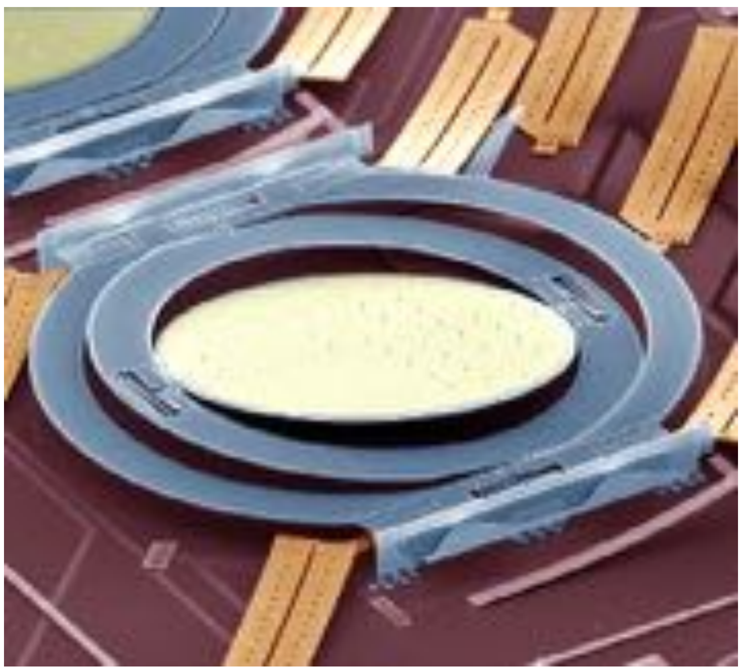


- **Only feasible Technology to scale to Large Portcount**
- **Proper design eliminates path length-dependent loss**

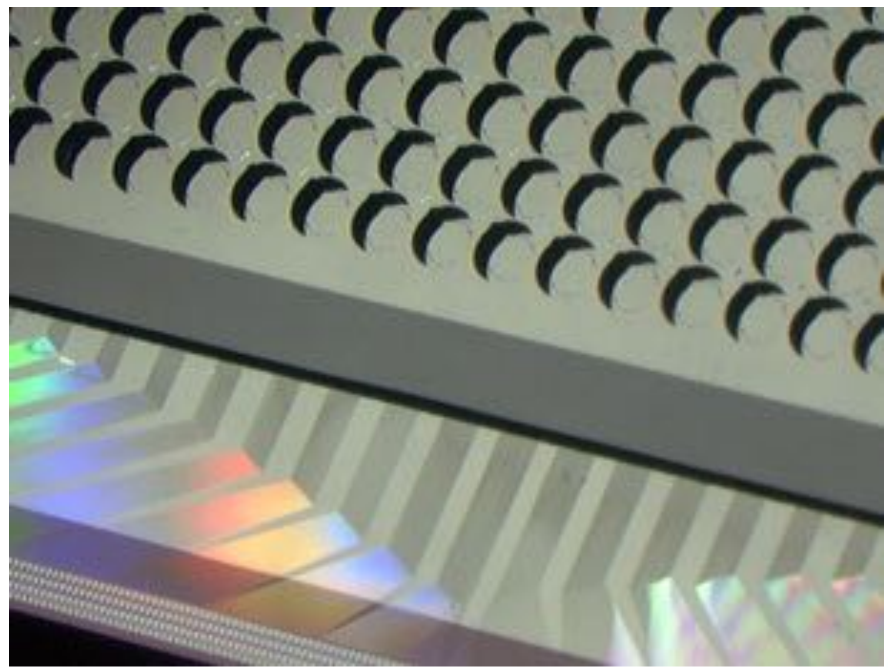
Lucent, Nortel (Xyros), Glimmerglass, Calient, MEMX, Tellium, …

Critical Component - MEMS

- *MEMS Mirrors (Surface & Bulk Micromachined)*
  - Electrostatic Actuation
  - Operation below snapdown – Simple control mechanism
  - Absolute stability required
  - Control of mirror radius of curvature



Surface Micromachined Mirror

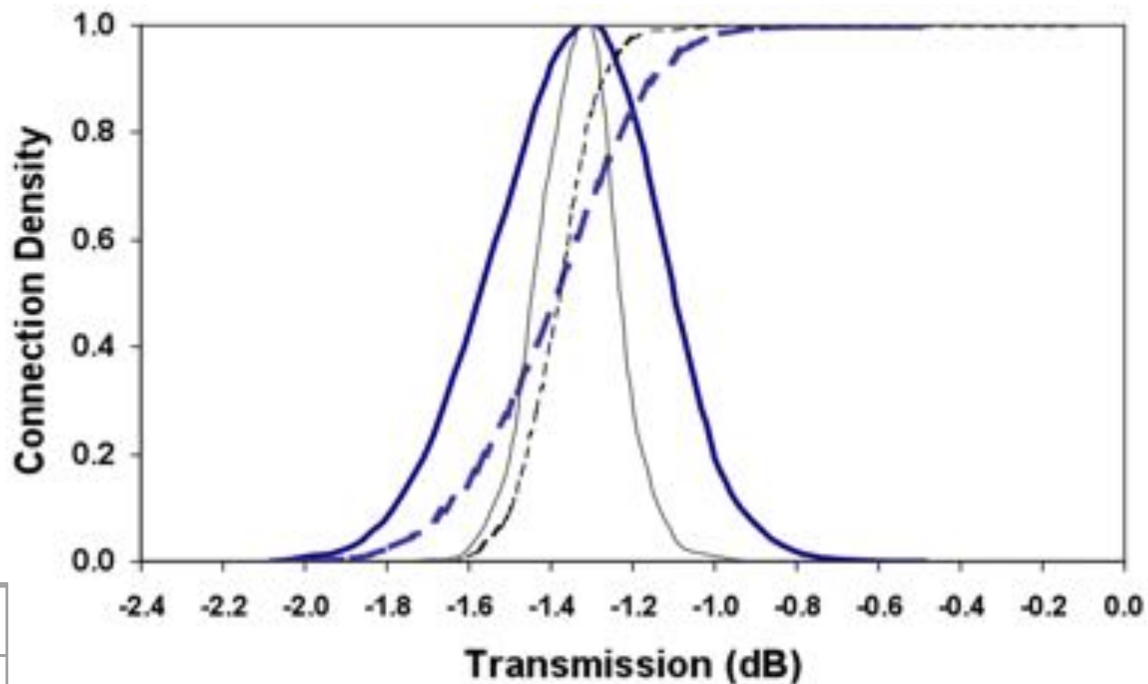


Bulk Micromachined Mirror

Loss and Loss Variations

- **Loss and Loss Variations in 256x256 switch fabric**

238 x 238 OSM with 2dB Max Loss



Loss Distribution for 56,644 Connections

LC Connectors : 0.0dB +/-0.4dB
Microlenses : 0.2+/-0.1dB
Optical Coatings: 0.8+/-0.1dB.
Mirror Curvature : 0.2+/-0.1dB
Beam Clipping: 0.1+/-0.1dB
Total Loss: 1.3dB +/- 0.6dB

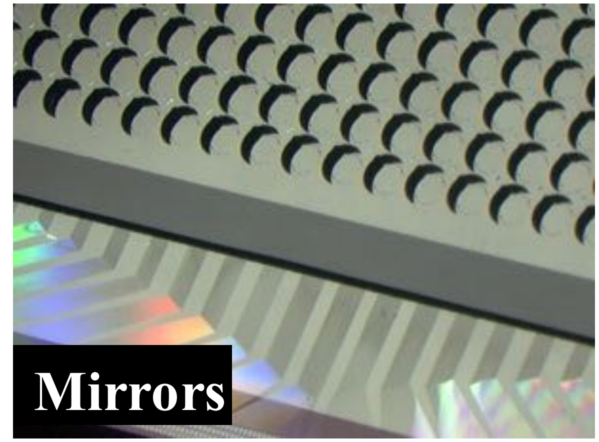
Aksyuk et al.,
Photon. Tech. Lett. 15, 587 (2003)

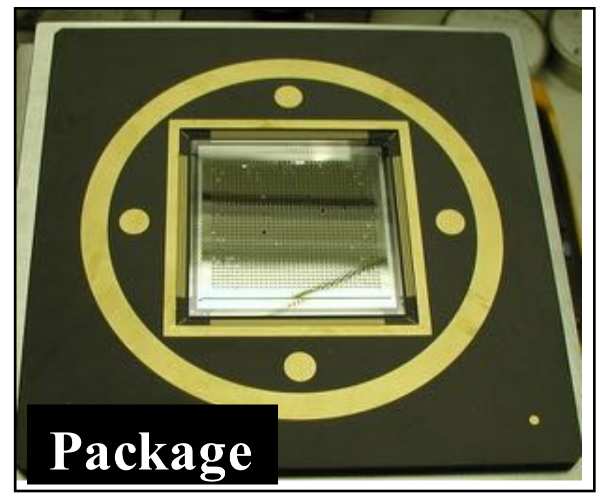
Lucent Technologies
Bell Labs Innovations

Large OXC Switches (1296x1296)

Front

Rear





J. Kim et al., IEEE PTL 15, p 1537 (2003)

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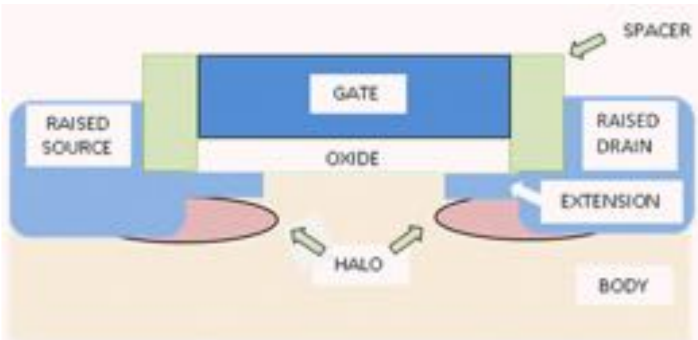
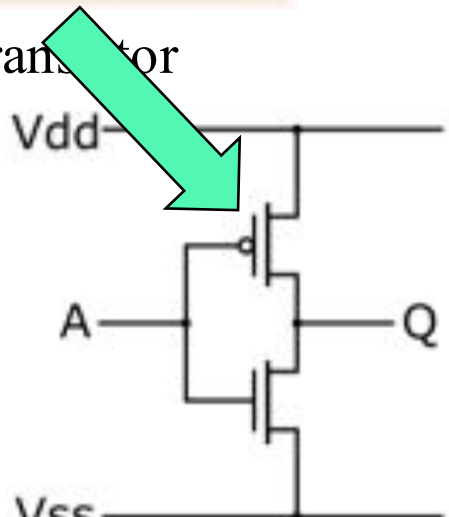
Learning from Classical Computers

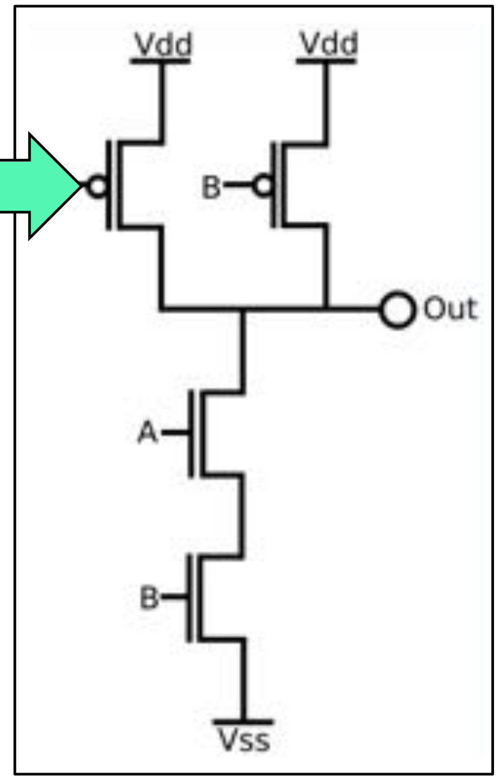
- Computer is a very complicated system!!
  - All systems are designed with an architecture



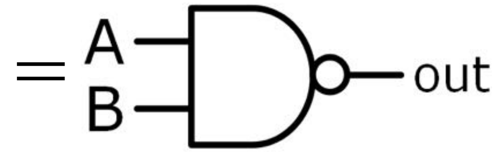
Individual Transistor



CMOS Inverter



CMOS NAND

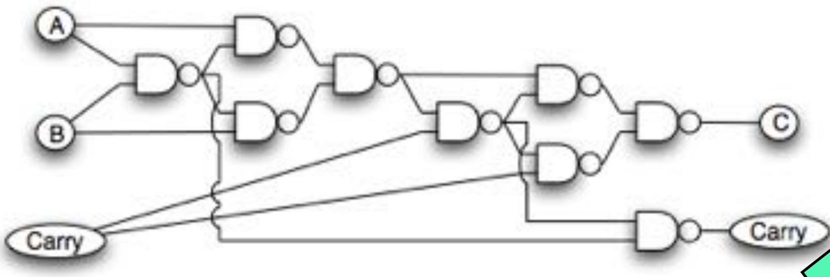


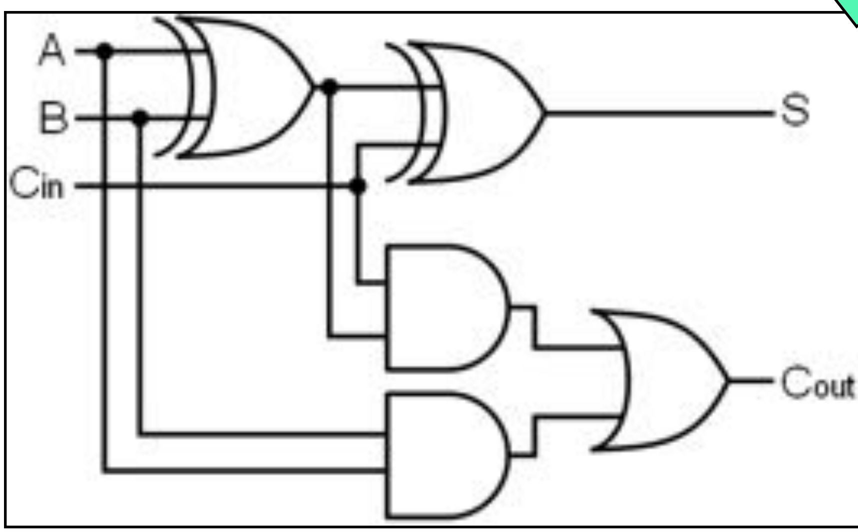
Logic Gate (NAND)

All images from Wikipedia.com

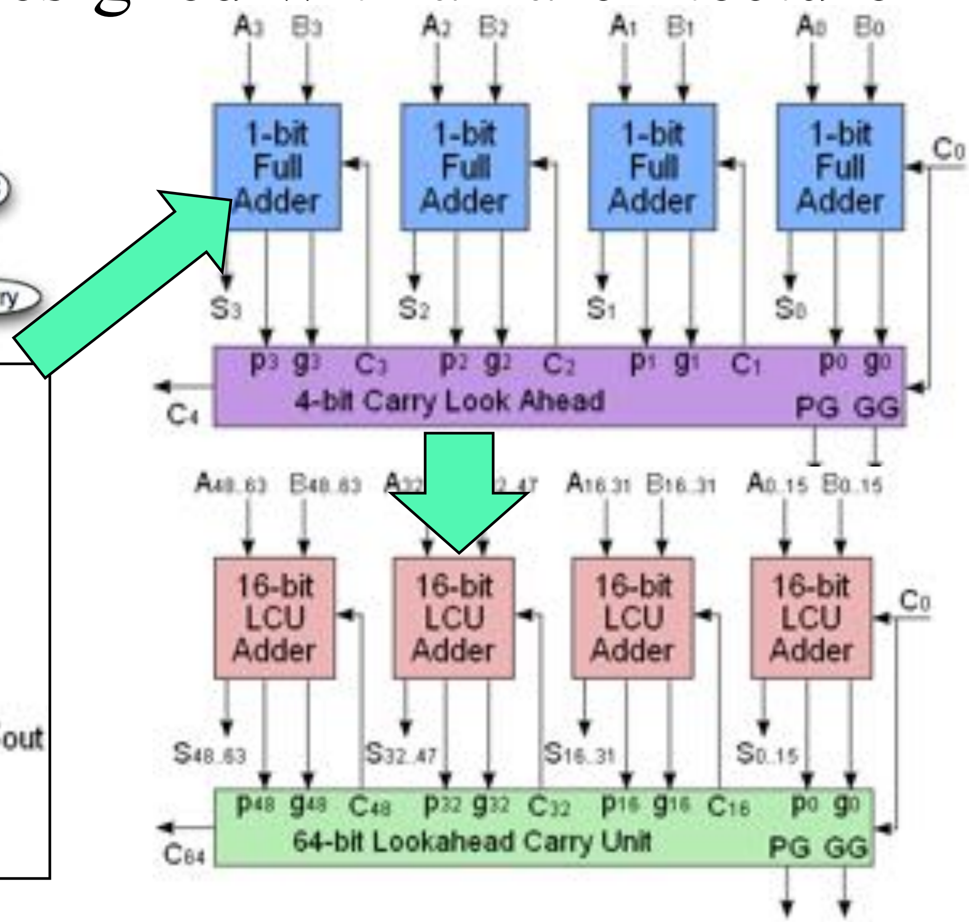
Learning from Classical Computers

- Computer is a very complicated system!!
  - All systems are designed with an architecture





1-bit Full Adder



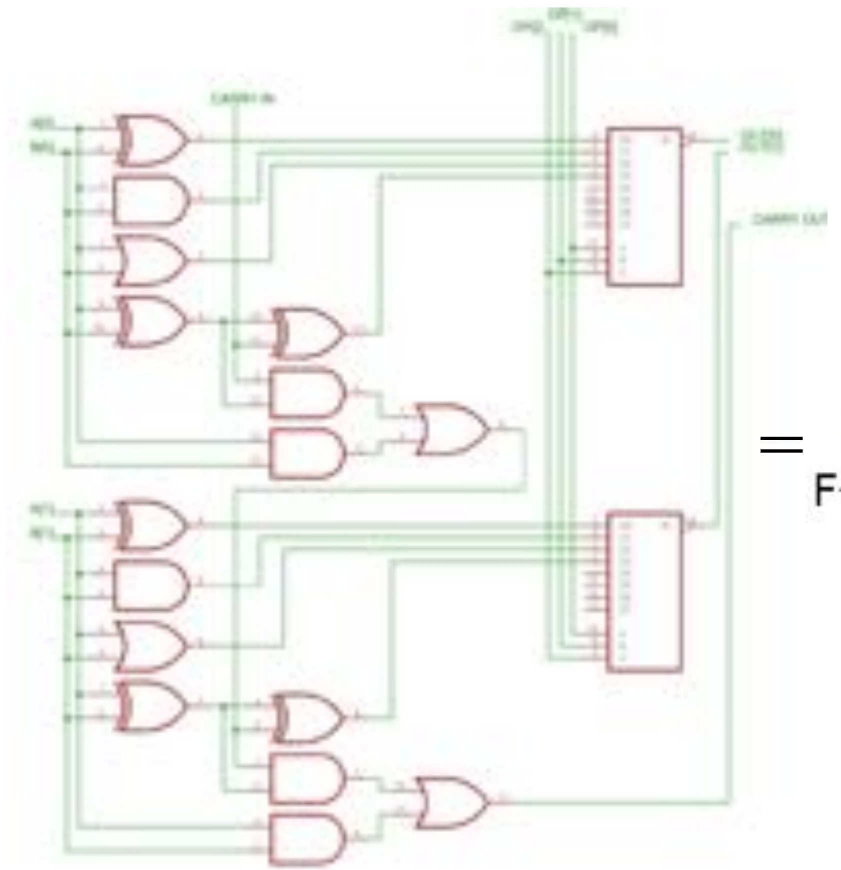
4-bit Adder

64-bit Adder

All images from Wikipedia.com

Learning from Classical Computers

- Computer is a very complicated system!!
  - All systems are designed with an architecture



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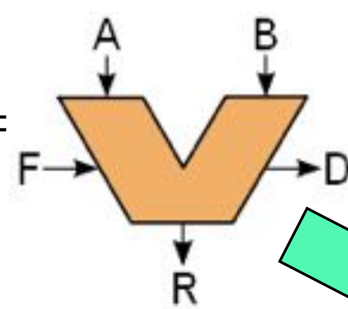
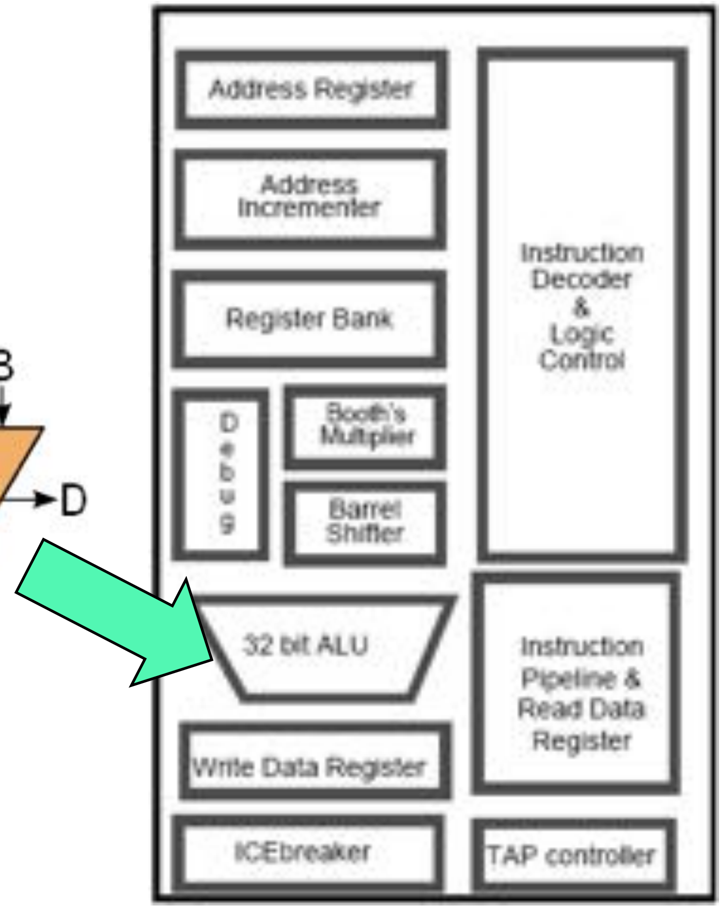




Arithmetic Logic Unit (ALU)

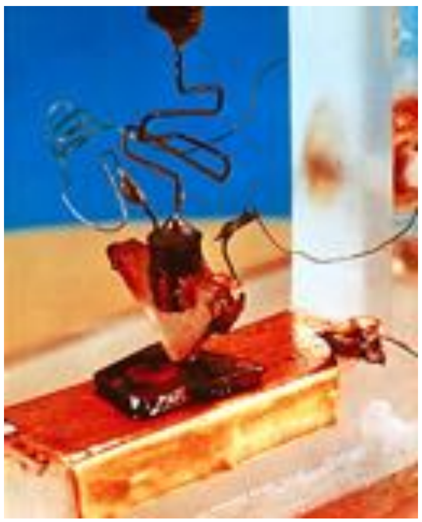
ARM7 Processor Architecture

Learning from Classical Computers

- Computer is a very complicated system!!
  - All systems are designed with an architecture
- Implication for QIP
  - A practical QIP will be very complicated!!
  - Fault-tolerance will be central issue in architecture
  - Architectural optimization will be necessary
  - Evaluation of architectural performance will be crucial (tools will be required)

Technology: Transistor to Processor

- ***Integrated Circuits Technology (Kilby & Noyce, 1958)***
  - ***Scalable technology platform*** **for creating functional circuits**
  - **Reduced the cost and increased the functionality of electronic functions by a factor of a million in last 30 years**



The First Transistor

AT&T Bell Lavs (http://www.britannica.com)

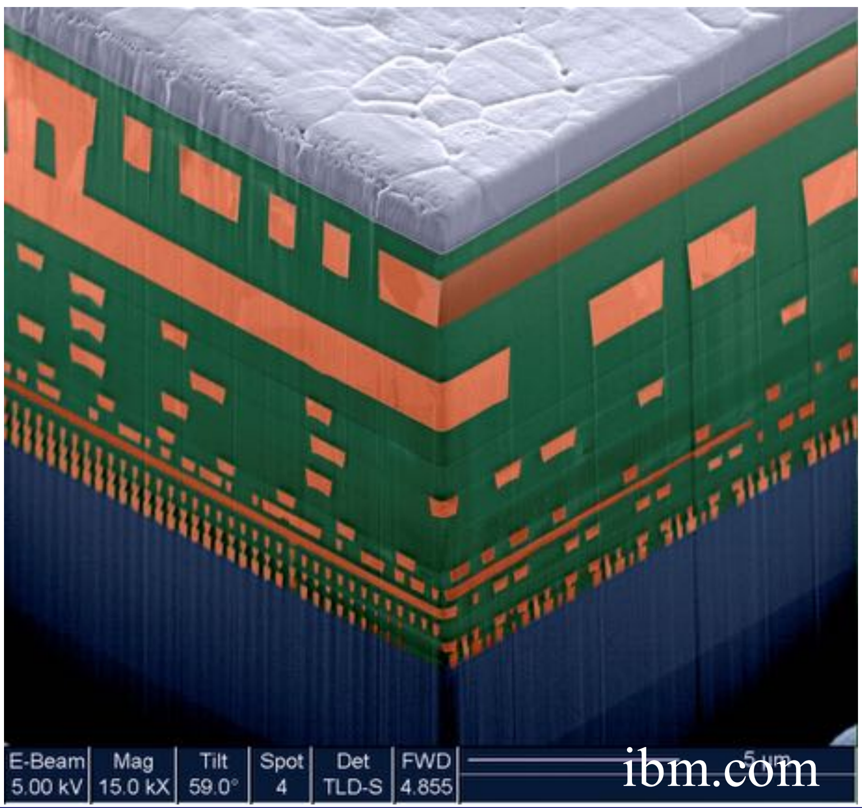
Intel® Microprocessor

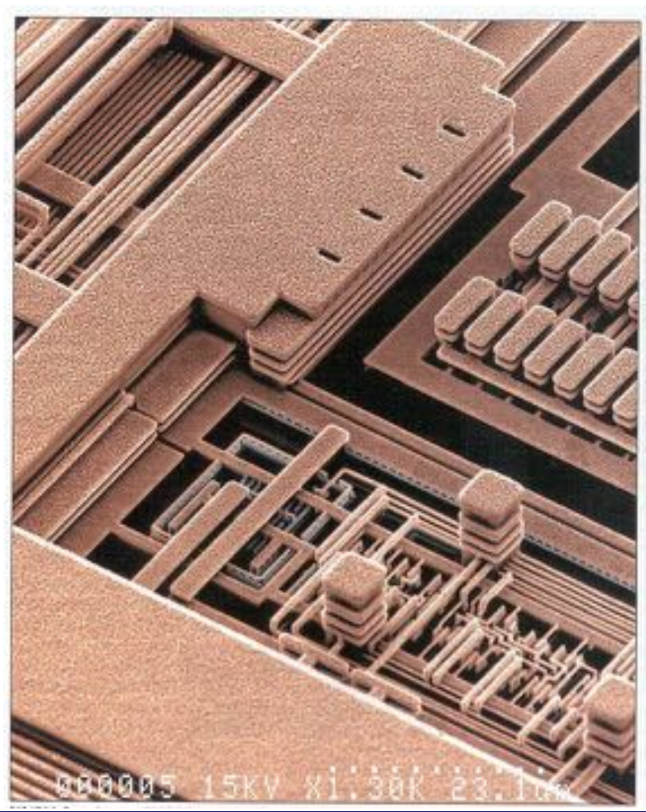
http://education.discovery.com/

Technology to integrate ALL components needed for computation
Ability to control each and every transistor in the processor at will!!

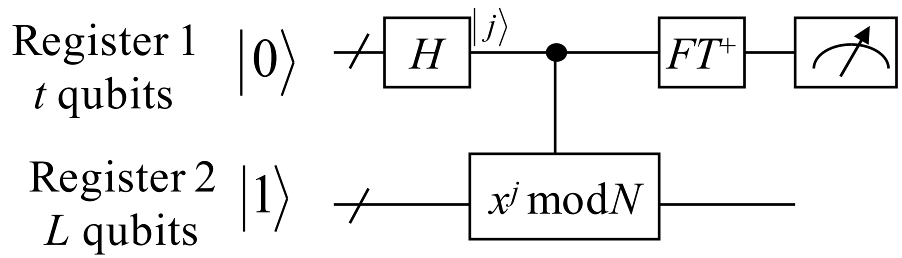
Interconnect Network in Classical IP

- Interconnect is a large portion of IC design
  - 1 layer of transistors, 9-12 layers of metal
  - Interconnect complexity increases dramatically for large scale ICs
  - Quantum wires are non-trivial!!

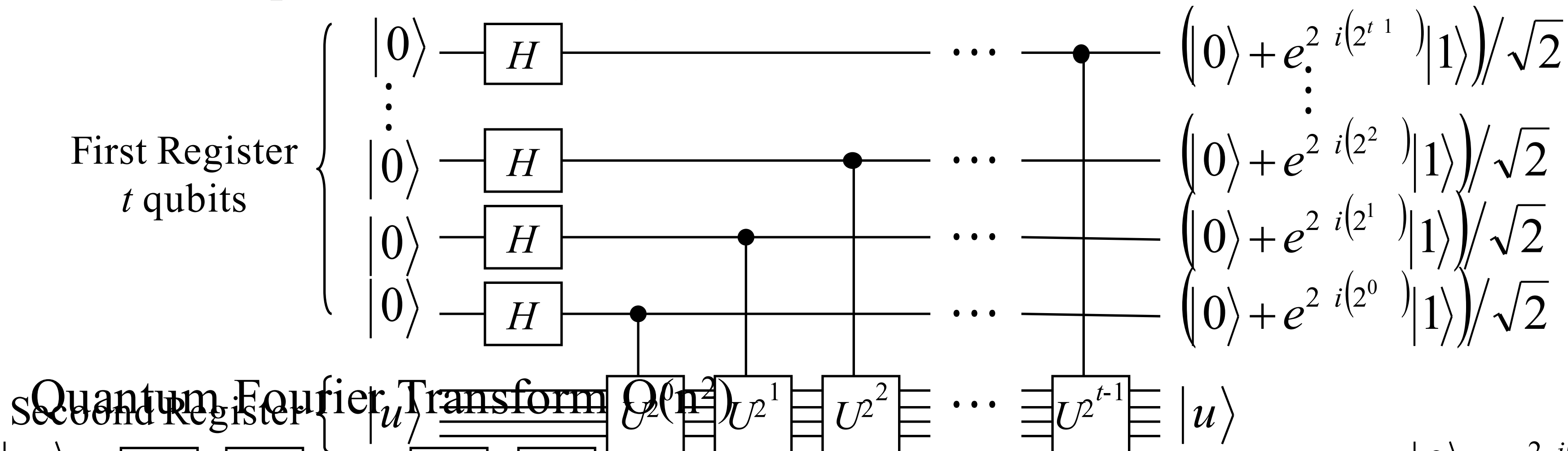




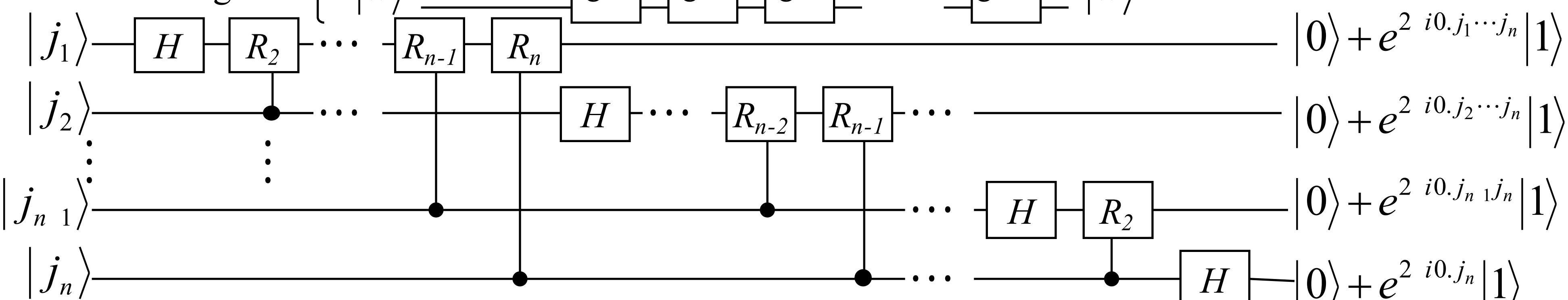
Example: Shor Algorithm



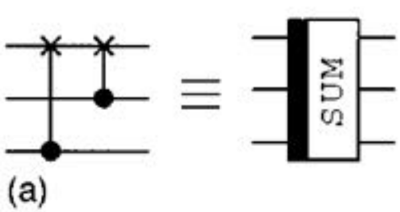
Modular Exponentiation O(n^3)



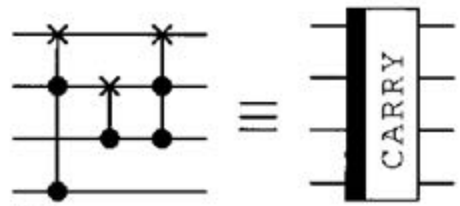
Quantum Fourier Transform O(n^2)



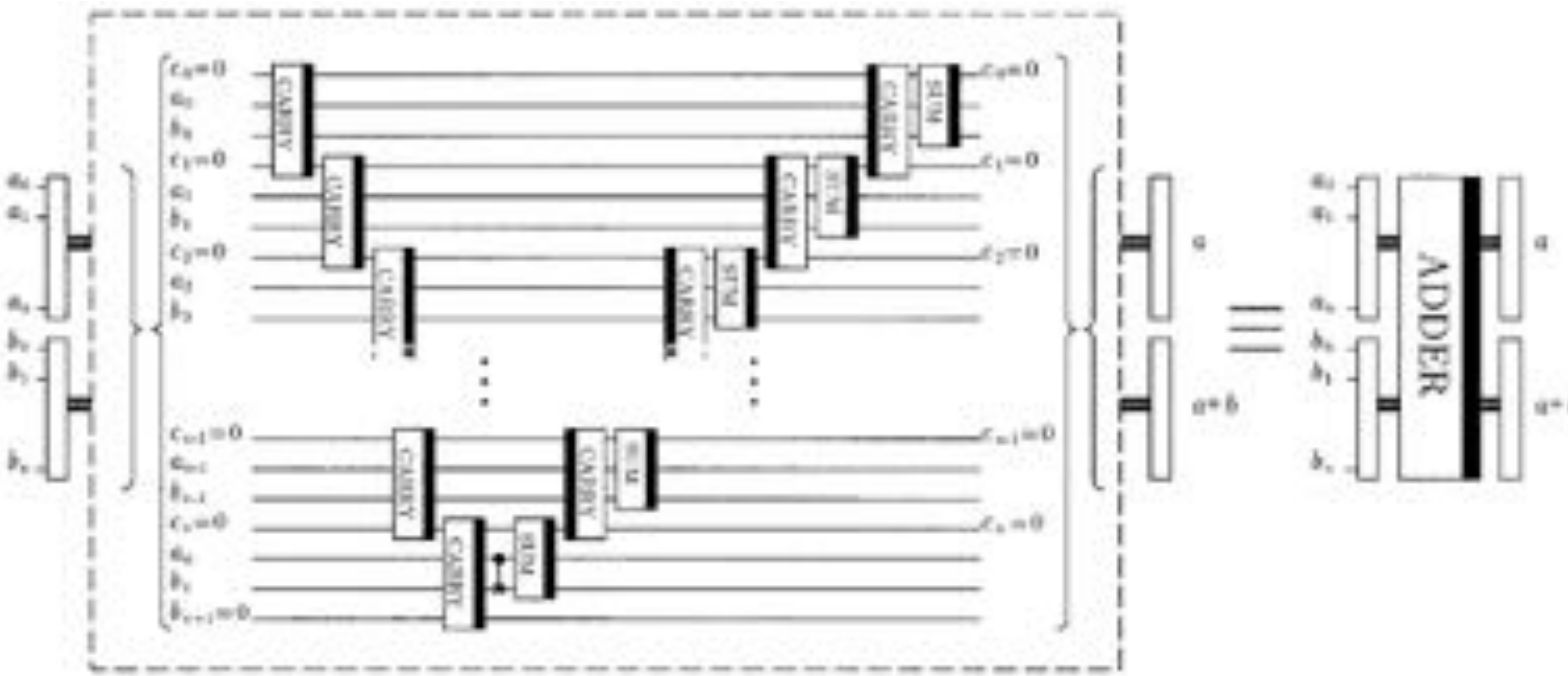
Circuit for Modular Exponentiation



Half Adder



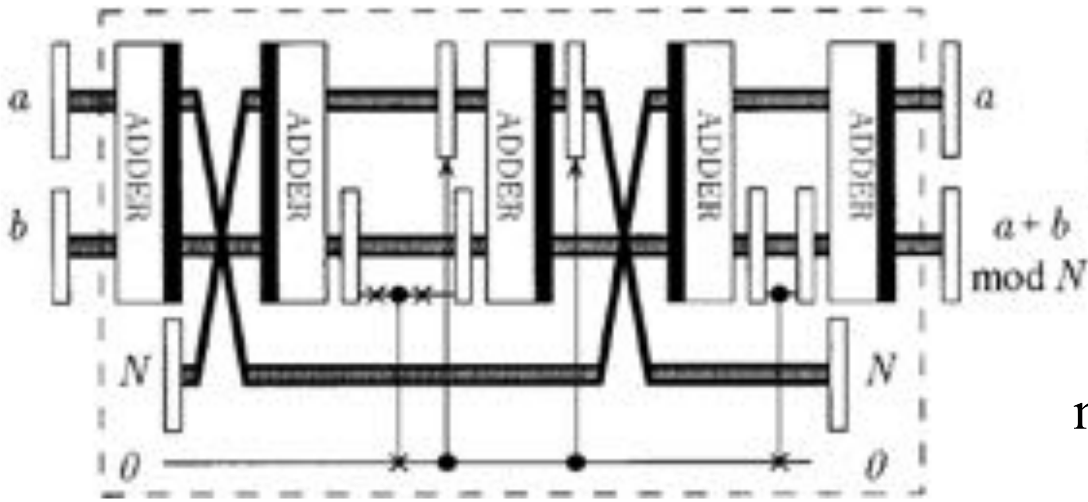
(b) 1-bit Full Adder

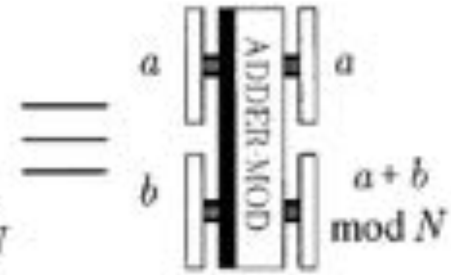


n-bit Full Adder (Carry ripple)

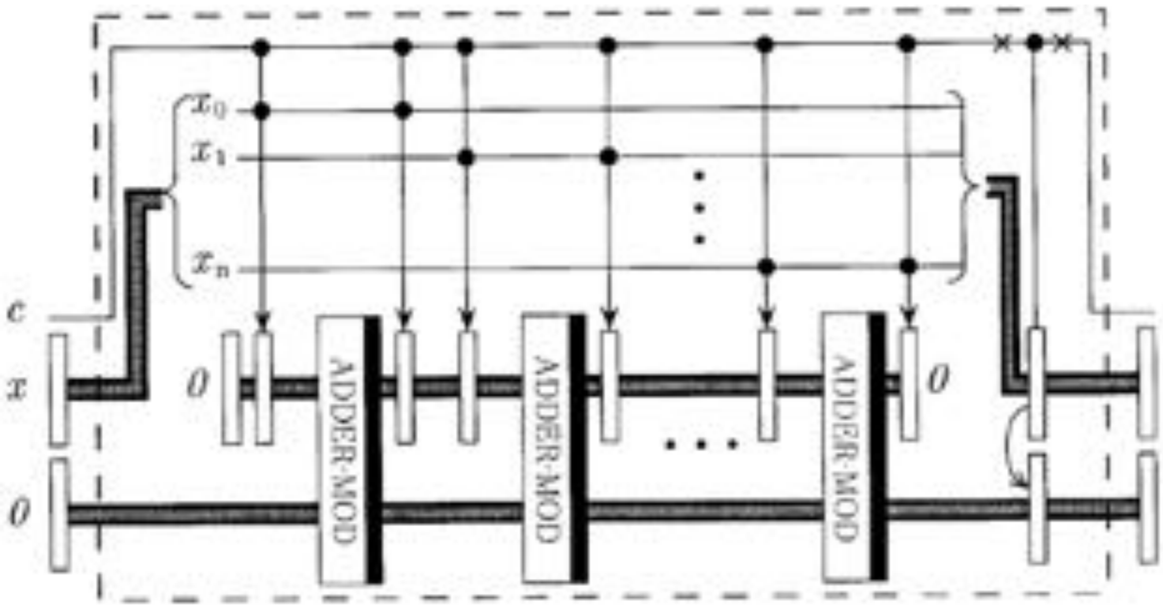
Vedral, Barenco & Ekert, PRA (1996)

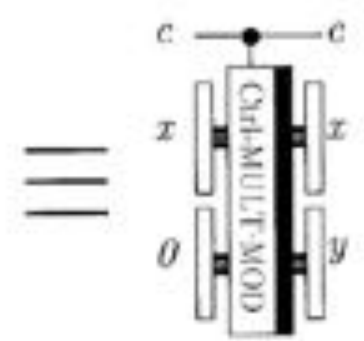
Circuit for Modular Exponentiation





n-bit Adder modulo N

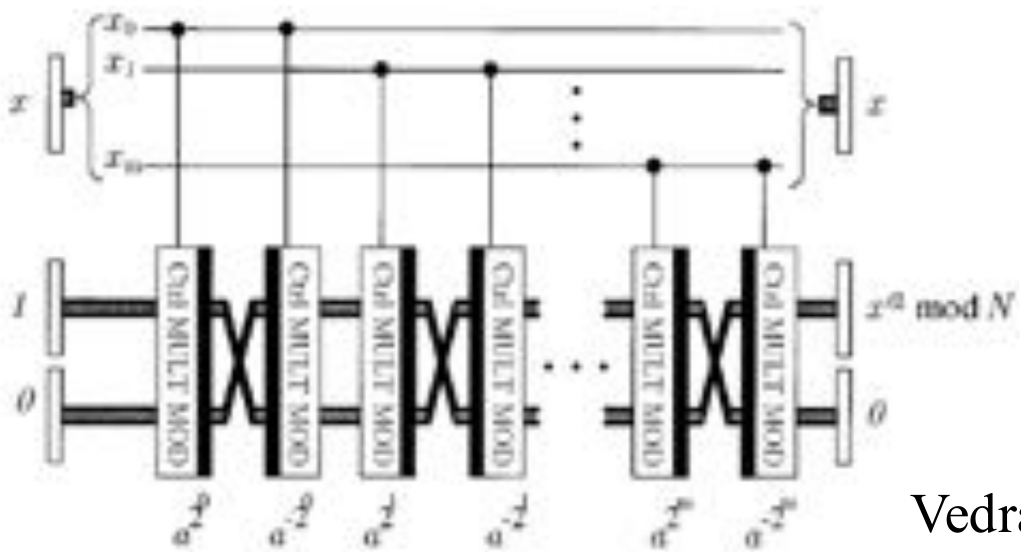




Controlled Multiplication modulo N

Vedral, Barenco & Ekert, PRA (1996)

Circuit for Modular Exponentiation



Controlled modulo-N exponentiation

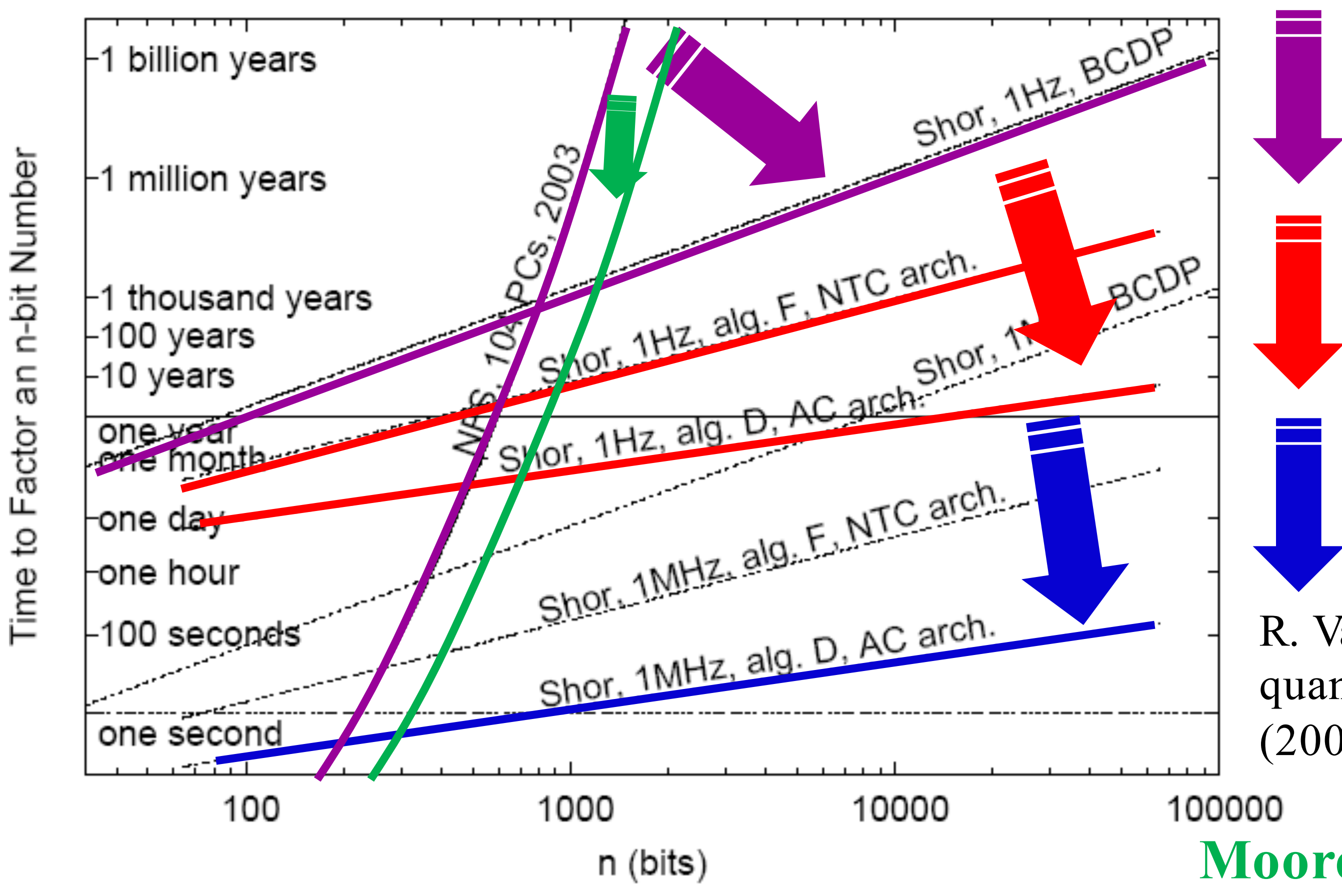
Vedral, Barenco & Ekert, PRA (1996)

- Further Architectural Optimizations to
  - Introduction of concurrency
  - Effective implementation of adders by improved "connectedness"
  - Reducing overhead for modulo operation

Van Meter and Itoh, PRA 71, 052320 (2005)

The Factoring Problem

- Best known classical algorithm: Number Field Sieve
- RSA-640 (193 digits) factored with 30 2.2GHz-Opteron CPU years (5 calendar months) http://www.rsa.com/rsalabs/node.asp?id=2093
- Implementation architecture makes a big difference!!

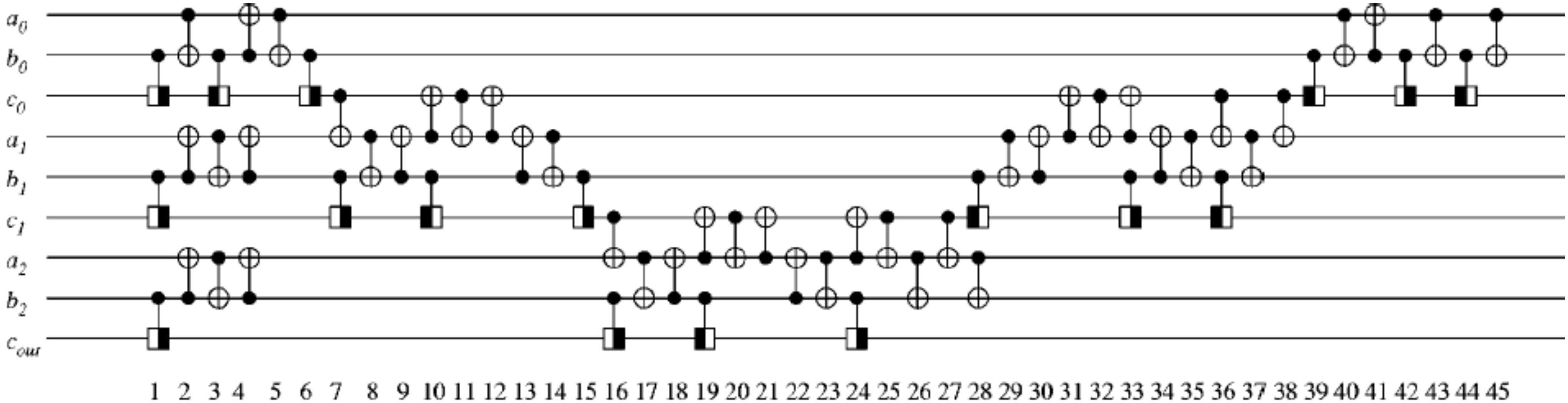


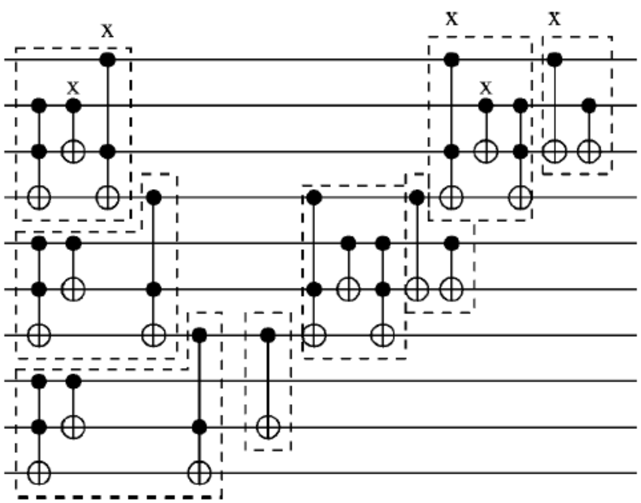
R. Van Meter et al., quant-ph/0507023 (2005)

Moore’s Law

Example of Architectural Advantage

3-bit Vedral, Barenco & Ekert (VBE) Carry-Ripple Adder (PRA 54, 147, 1996)





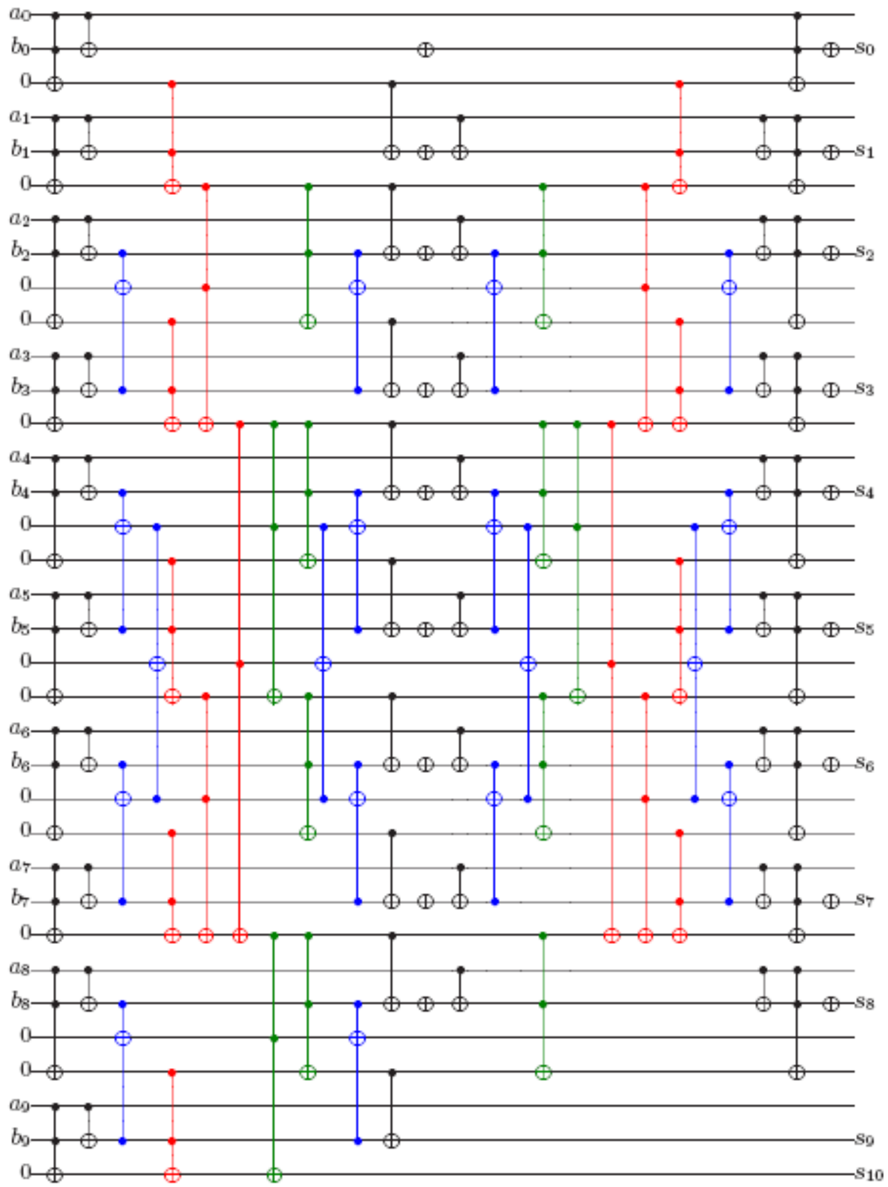
NTC Architecture, 45 steps

$$t_V^{NTC} = \left(400n^3 \quad 400n^2 + 75n\right)T_{CNOT}$$

AC Architecture, 15 steps

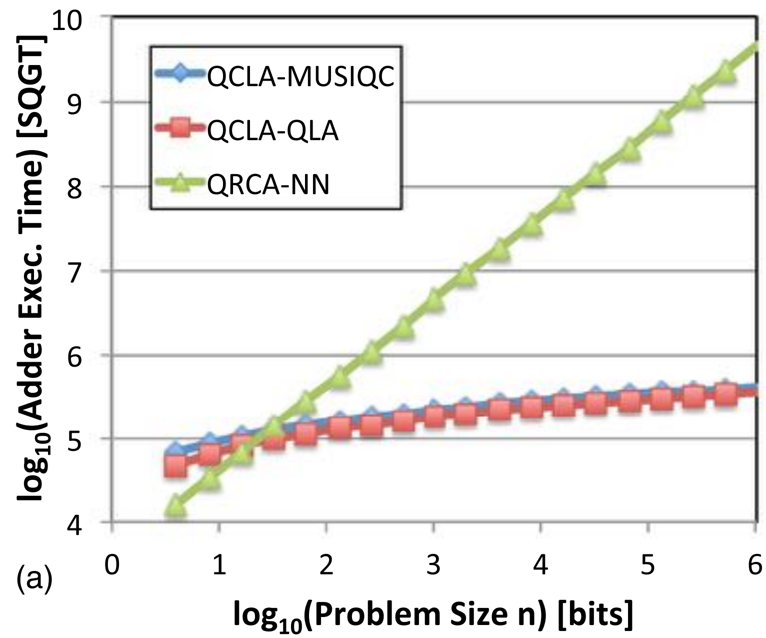
$$t_V^{AC} = \left(60n^3 \quad 75n^2 + 15n\right)T_{Toffoli}$$
$$+ \left(40n^3 \quad 70n^2 + 15n\right)T_{CNOT}$$

More Efficient Architectures



10-bit Carry Lookahead Adder
AC Architecture
Logarithmic Depth (21 steps for 10 bits)
Very efficient adder

Draper et al., quant-ph/0406142

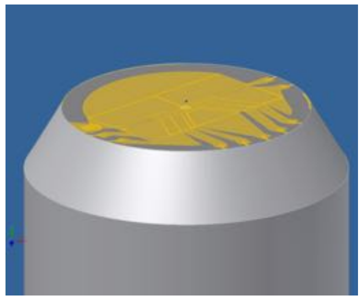


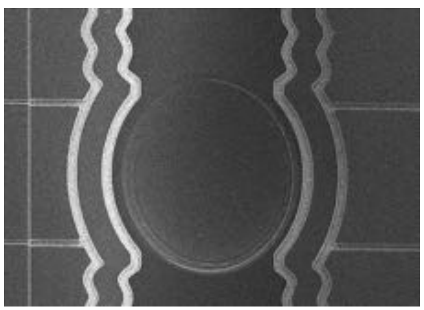
Monroe, Raussendorf, Ruthven, Brown, Maunz, Duan and Kim, PRA 89, 022317 (2014)

Platform for Scalable Quantum Computation

Enabling Technology

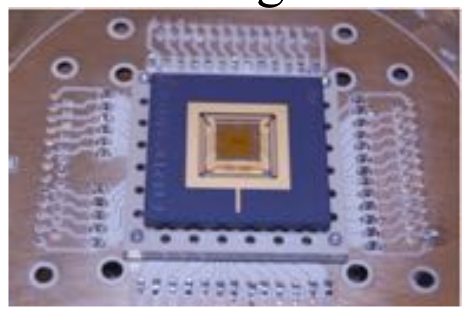
Microfabricated Traps





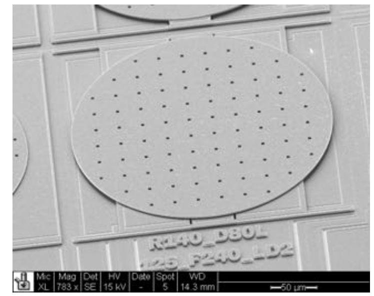
Sandia, GTRI
Duke, etc.

UHV Integration



Maryland, Washington
Duke, Georgia Tech
Sandia, GTRI

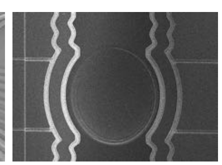
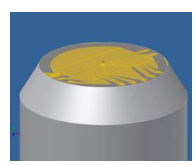
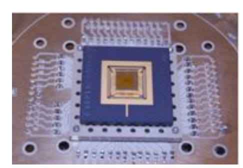
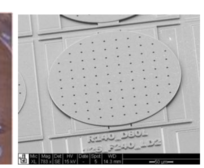
MEMS Technology



Photonic Integration

Duke

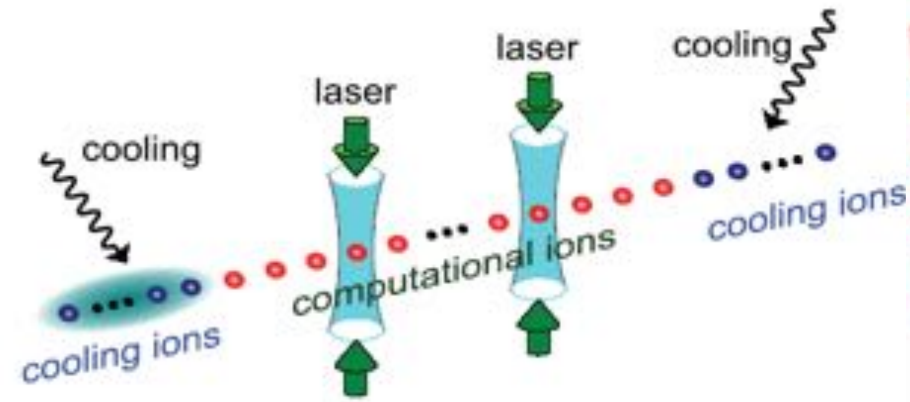
Enabling Technology

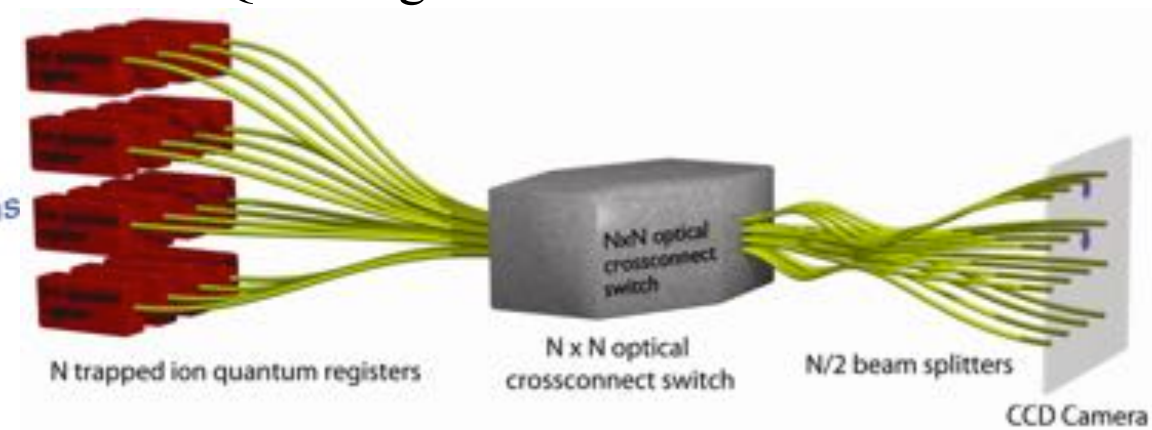

Platform for Scalable Quantum Computation

Qubit Hardware

ELU Implementation

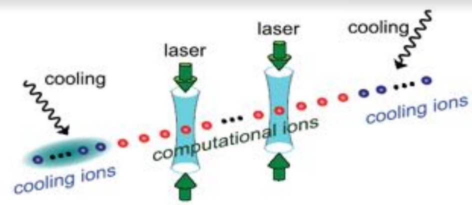


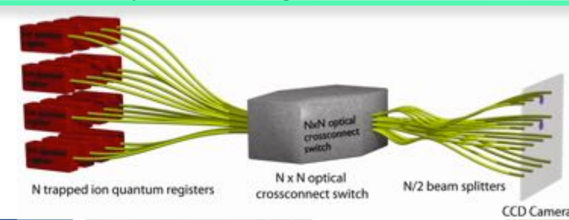
MUSIQC Integration



Protocols: Cooling, gates, error evasion, measurement, state/process verification, etc.

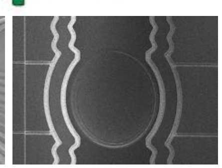
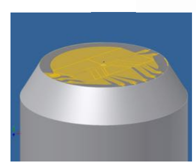
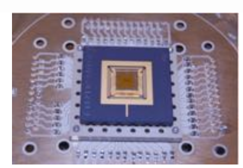
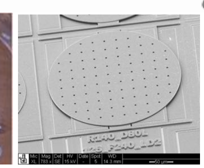
Qubit Hardware





"Hardware"

Enabling Technology

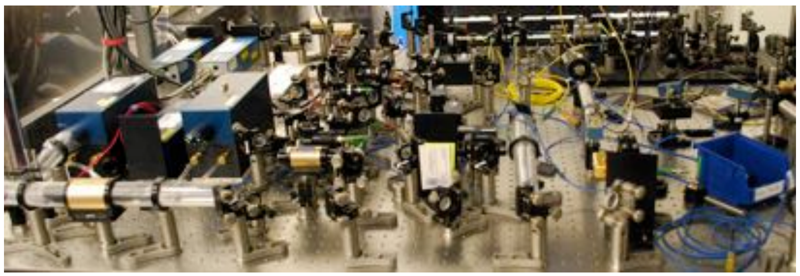

Platform for Scalable Quantum Computation

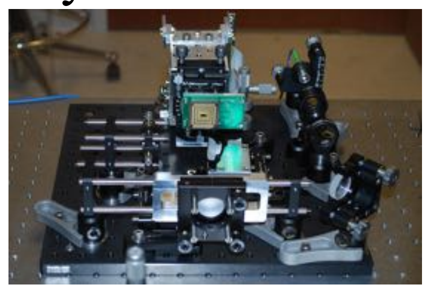
Controller Hardware

Laser Systems

Beam Delivery Systems

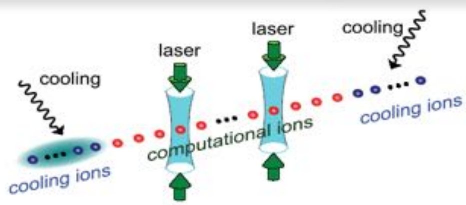
Control Electronics: Custom & Off-the-shelf

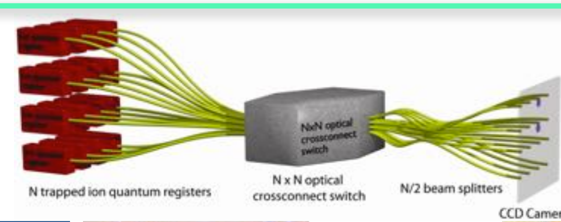




Controller Hardware

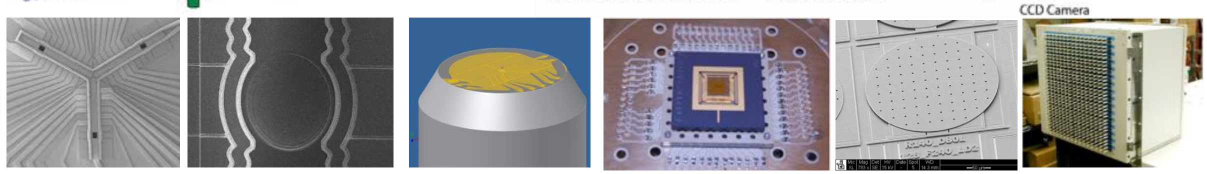
Qubit Hardware





"Hardware"

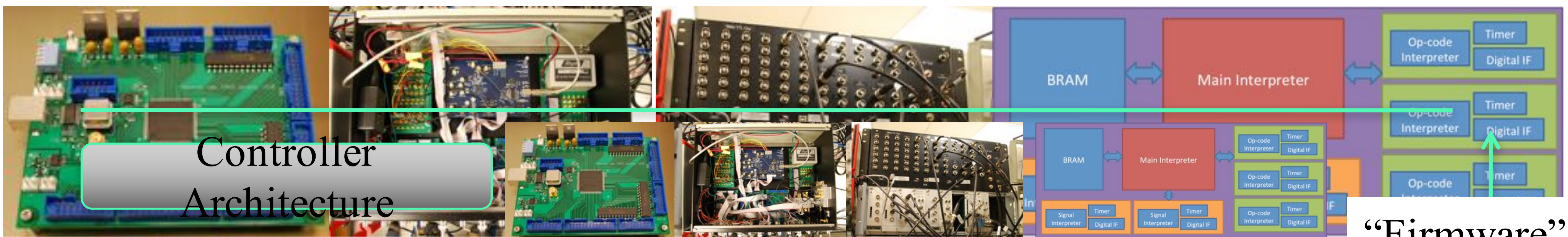
Enabling Technology



Platform for Scalable Quantum Computation

Controller Architecture

FPGAs | Digital Controller Boxes | Digital Controller Architecture

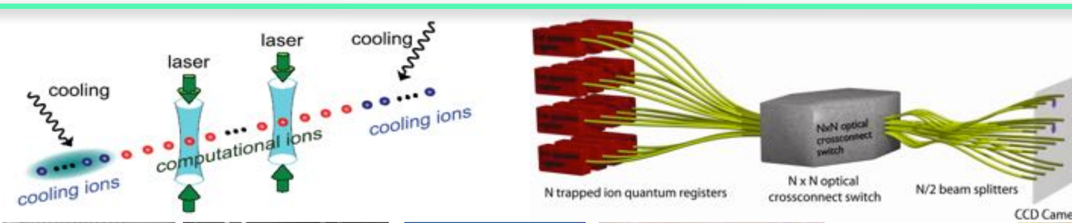


Controller Architecture

"Firmware"

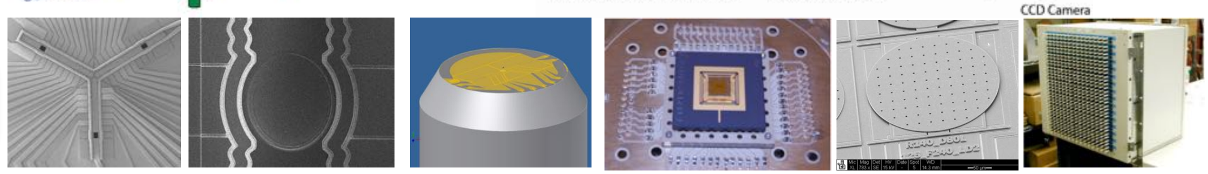
Controller Hardware

Qubit Hardware



"Hardware"

Enabling Technology



Platform for Scalable Quantum Computation

Algorithm

Logical Circuit

Physical Operations

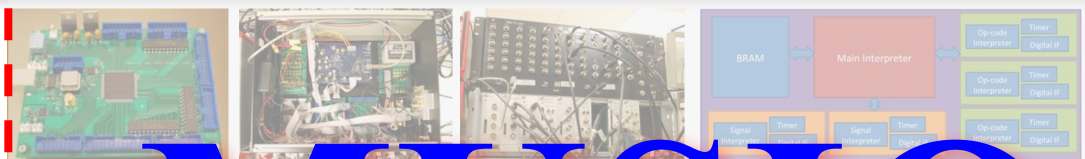
Compiler: Generate sequence of logical operations
Minimize number of resource-intensive gates

Assembler: Generate sequence of physical operations
Error-correcting codes and Fault-tolerant schemes

"Software"

Scheduler: Executes the gate sequence on hardware
Resource, performance and error estimation

Controller Architecture



"Firmware"

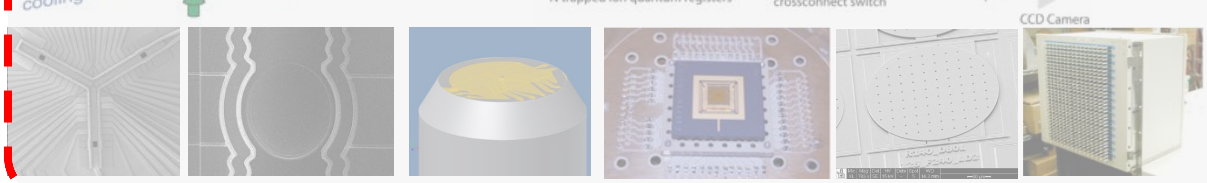
MUSIQC

Controller Hardware

Qubit Hardware

"Hardware"

Enabling Technology



Towards "QC-in-a-Box"

- Constructing a stand-alone, programmable QC
  - QC is no longer scientific experiment, but a generic tool
  - "Users" will dictate the applications and demand
  - Critical requirement in technology transformation
- So, what does it take?
  - Enabling technology
    - Microfabricated traps and reliable operation
    - Compact and stable lasers and efficient optical routing
    - Creating reliable vacuum environment
    - Scalable, fully coherent controllers
    - "Operating system" for software-firmware interface
  - Architectural design for general-purpose QC
  - Multidisciplinary team of talented people!!

Team and Collaboration

- Duke Team

  Peter Maunz, Taehyun Kim[1], So-Young Baek, Byung-Soo Choi, Seo Ho Youn, Jinhyun Cho, Rachel Noek, Emily Mount, Hui Son, Daniel Gaultney, Ryan Clark, Andre van Rynbach, Stephen Crain, Seongphill Moon, Muhammed Ahsan, Caleb Knoernschild[2], Kyle McKay[3]

- MUSIQC Collaborators

  Chris Monroe (U. Maryland)
  Luming Duan (U. Michigan)
  Ken Brown (Georgia Tech)
  Boris Blinov (U. Washington)
  Michael Biercuk (U. Sydney)
  Steven Flammia (U. Sydney)
  Robert Raussendorf (UBC)
  Steve Naboicheck(MagiQ)
  Jason Amini et al. (GTRI)
  Peter Maunz et al. (Sandia)

- SPARQC Collaborators

  Chris Monroe (U. Maryland)
  Misha Lukin, Marko Loncar, Hongkun Park (Harvard)
  Daniel Twitchen, Matthew Markham (Element 6)
  Dan Gauthier (Duke)
  Liang Jiang (Yale)
  Norbert Lutkenhaus (Waterloo)
  Marty Fejer (Stanford)
  Peter Maunz (Sandia)

- Quantum Circuits MURI

  Paul Kwiat (UIUC)
  Ben Lev (Stanford)
  Edo Waks (U. Maryland)
  Duncan Steel (U. Michigan)
  Lu Sham (UCSD)
  Dan Gauthier (Duke)
  Dan Gammon (NRL)
  Jake Taylor (NIST/JQI)

- Other Collaborators

  Felix Lu (AQT)
  Mark Saffman (U. Wisconsin)
  Dave Weiss (Penn State)
  Jaewan Kim (KIAS)

- [1] SK Telecom, Korea
- [2] Raytheon Corporation
- [3] NIST, Boulder CO

http://mist.ee.duke.edu