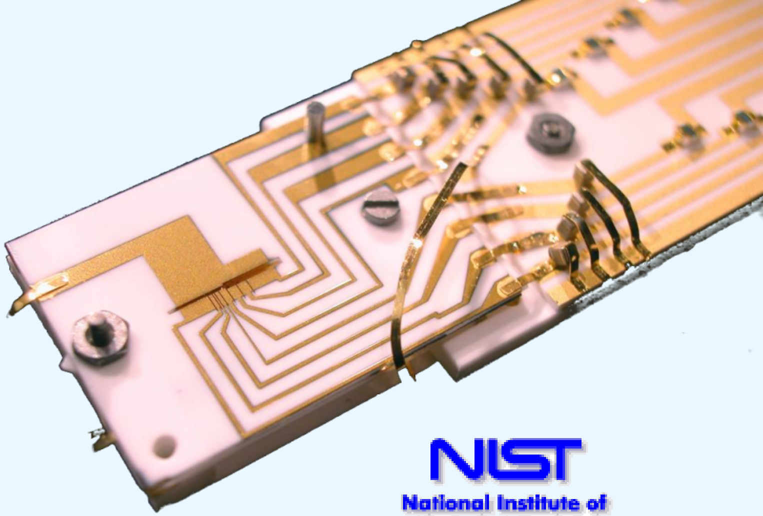
Entangled Mechanical Oscillators and a Programmable Quantum Computer



NIST
National Institute of Standards and Technology

David Hanneke

DARPA

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BE THE FUTURE

Michelson Postdoctoral Prize Lectures

10 May 2010

DEPARTMENT OF THE NAVY
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Science & Technology

Sandia National Laboratories

NATIONAL SECURITY AGENCY
UNITED STATES OF AMERICA

Outline

- Introduction
  - Two-level systems
  - Harmonic oscillators
- Complete methods set for scalable ion-trap QIP
  - Internal state control
  - External state control
- Demonstration experiments
  - Sustained quantum information processing
  - Programmable two-qubit quantum processor
  - Entangled mechanical oscillators

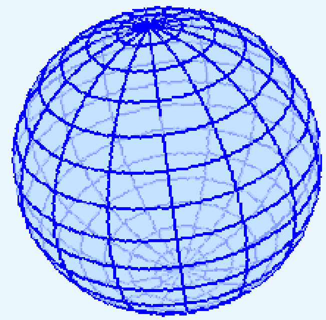
Two-level System

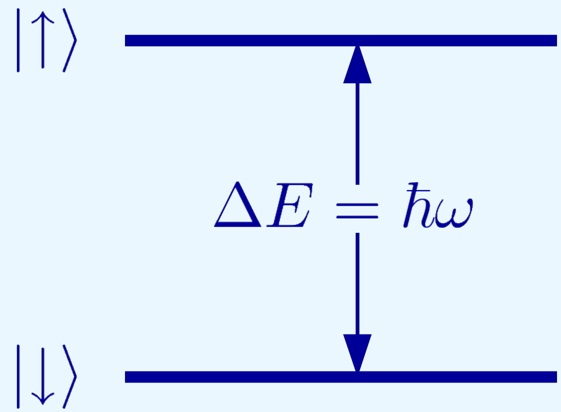
Free precession

$$|\psi\rangle = \alpha\,|\downarrow\rangle + e^{-i\omega t}\beta\,|\uparrow\rangle$$

Coherent drive

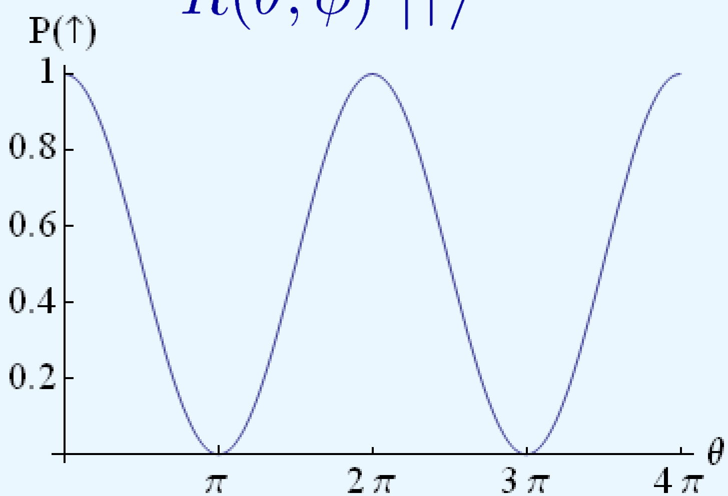
$$H' = V\cos(\omega t + \phi)$$





Rabi "flopping"

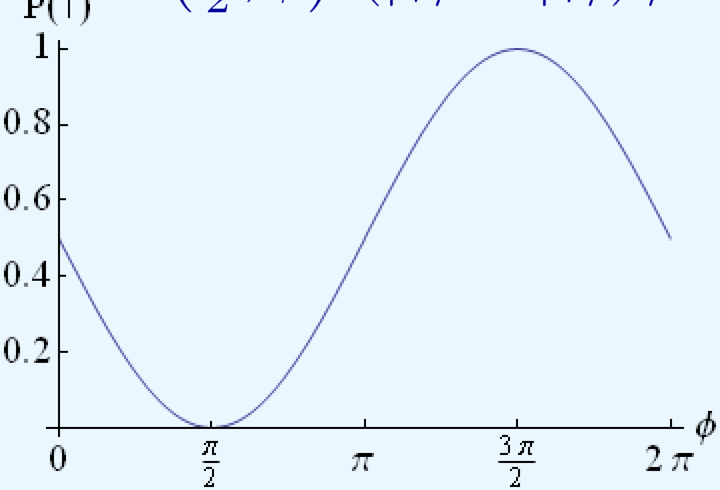
$$R(\theta,\phi)\ |\uparrow\rangle$$



$$\theta = V_{\uparrow,\downarrow}t/\hbar$$

Phase scan

$$R\left(\tfrac{\pi}{2},\phi\right)\ \left(|\downarrow\rangle + |\uparrow\rangle\right)/\sqrt{2}$$

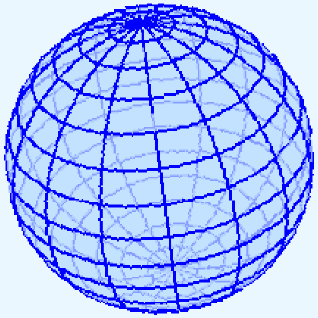


Quantum Information Processing

- Different from classical information processing
  - Bits → qubits (discrete → continuous)
  - No cloning
  - Unitary gates
  - Massive parallelism
  - Measurement ⇒ collapse

$$\alpha \left|\downarrow\right\rangle + \beta \left|\uparrow\right\rangle$$
$$\gamma \left|\downarrow\downarrow\right\rangle + \delta \left|\uparrow\uparrow\right\rangle$$

$\left|\uparrow\right\rangle$



$\left|\downarrow\right\rangle$

- Potential advantages
  - Factoring

    Shor, *IEEE SFCS*, 124 (1994)
  - Search

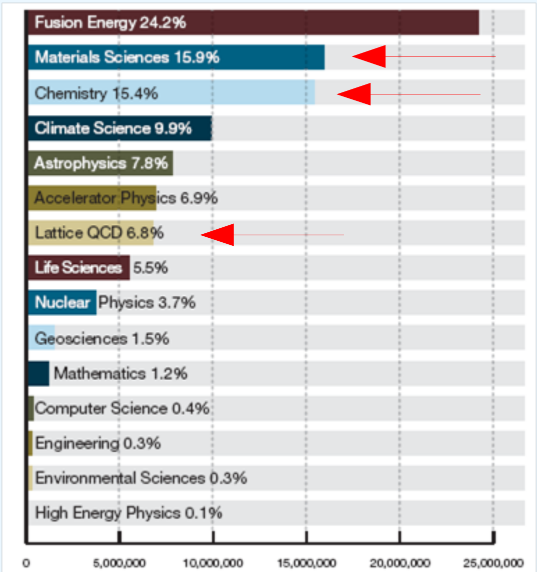
    Grover, *STOC '96*, 212 (1996)
  - Solving linear equations

    Harrow, *et al.*, *Phys. Rev. Lett.* **103** 150502 (2009)
  - Simulation

    Feynman, *Int. J. Theor. Phys.* **21**, 467 (1982)

    Buluta & Nori, *Science* **326** 108 (2009)

Use of DOE supercomputing time:



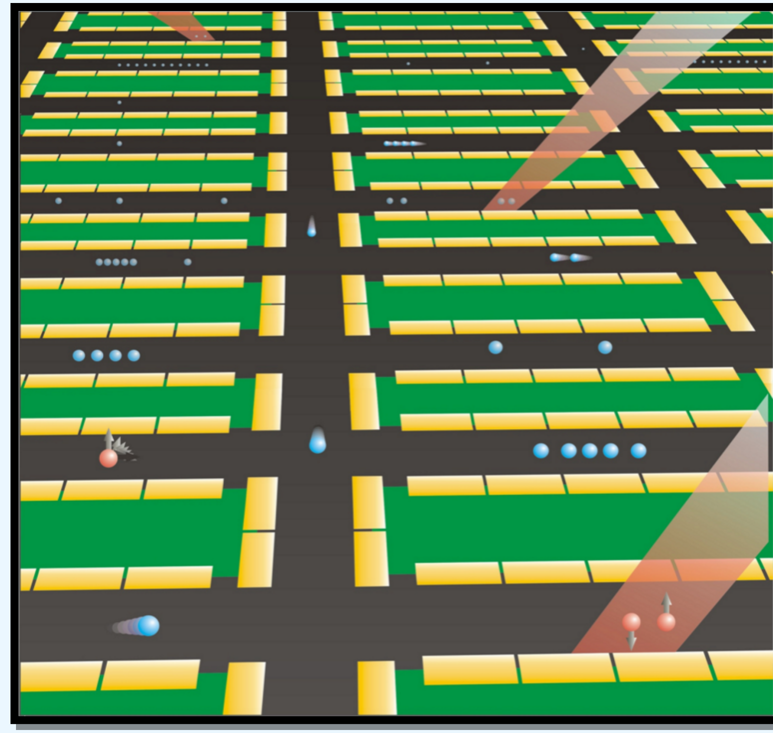
Quantum Information Processors

<u>Methods required of any processor</u>

- Good qubits (initialize, measure, long coherence)
- Universal gate set
- Quantum information transport

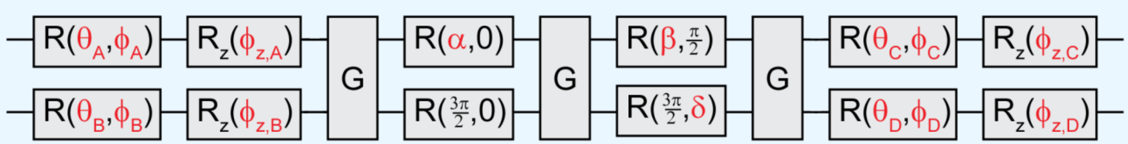
<u>Quantum CCD Architecture</u>

- Qubits stored in ions
- Move the ions in a multizone trap
- One- and two-qubit gates



D. Wineland, *et al*, *J. Res. NIST* **103** 259-328 (1998)
D. Kielpinski, *et al*, *Nature* **417** 709 (2002)

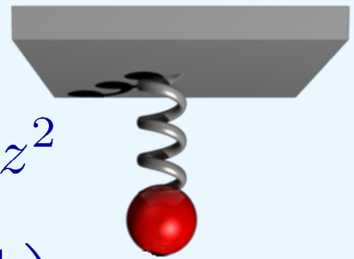
Circuit-based:

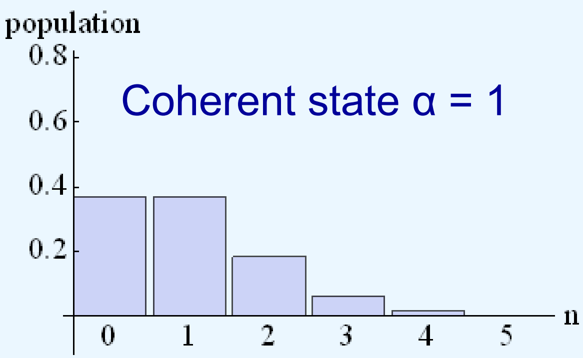


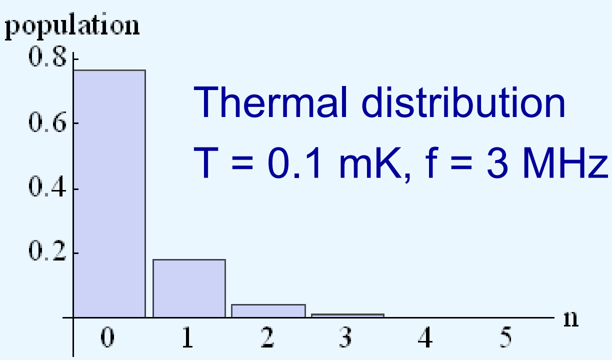
Quantum Harmonic Oscillator

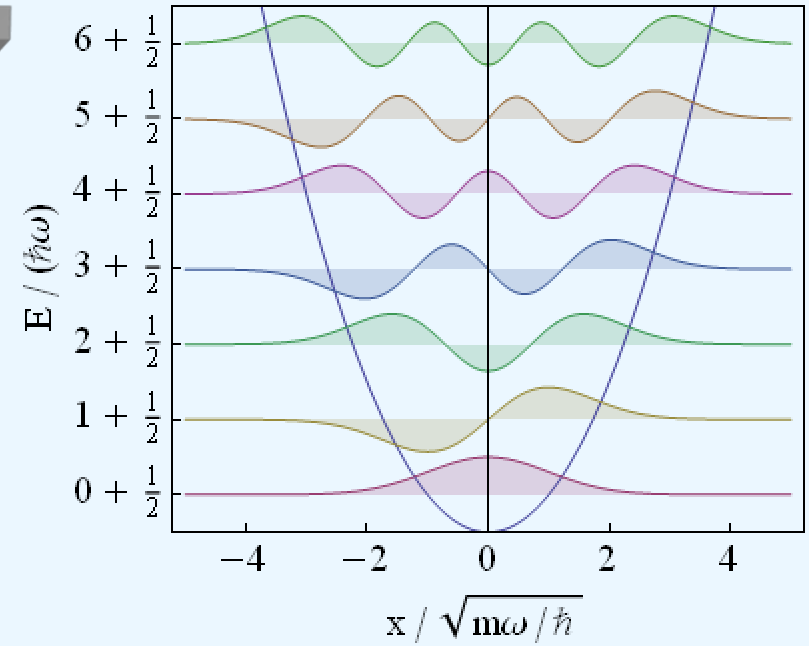
$$H = \frac{p^2}{2m} + \frac{1}{2} m \omega_z^2 z^2$$

$$= \hbar \omega_z \left(a^\dagger a + \frac{1}{2} \right)$$





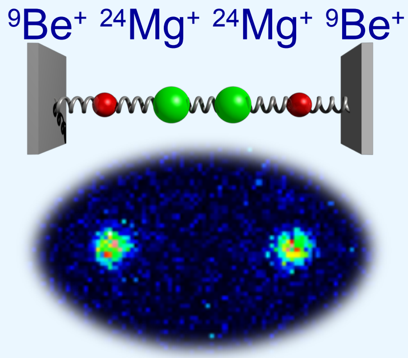




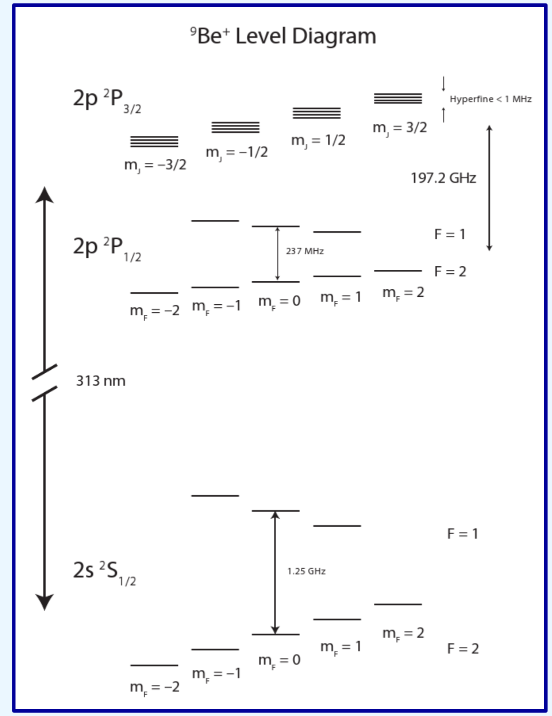
Interesting motional states

- Number states $|n\rangle$
- "Cat" states $\left(|\alpha\rangle + |-\alpha\rangle\right)/\sqrt{2}$
- Entangled states $\left(|00\rangle - |11\rangle\right)/\sqrt{2}$

Trapped Ions



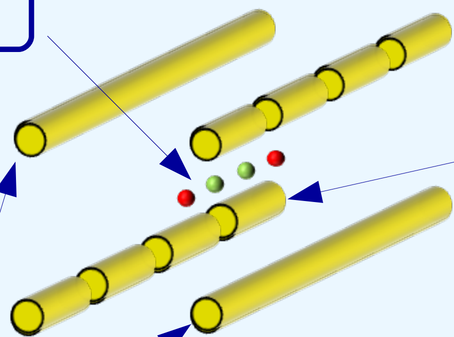
- <u>Internal states</u>: two-level systems
- <u>External states</u>: harmonic oscillators
- Spectroscopically separate systems
- Laser manipulations



C. Langer, Ph.D. Thesis, U. Colorado (2006)

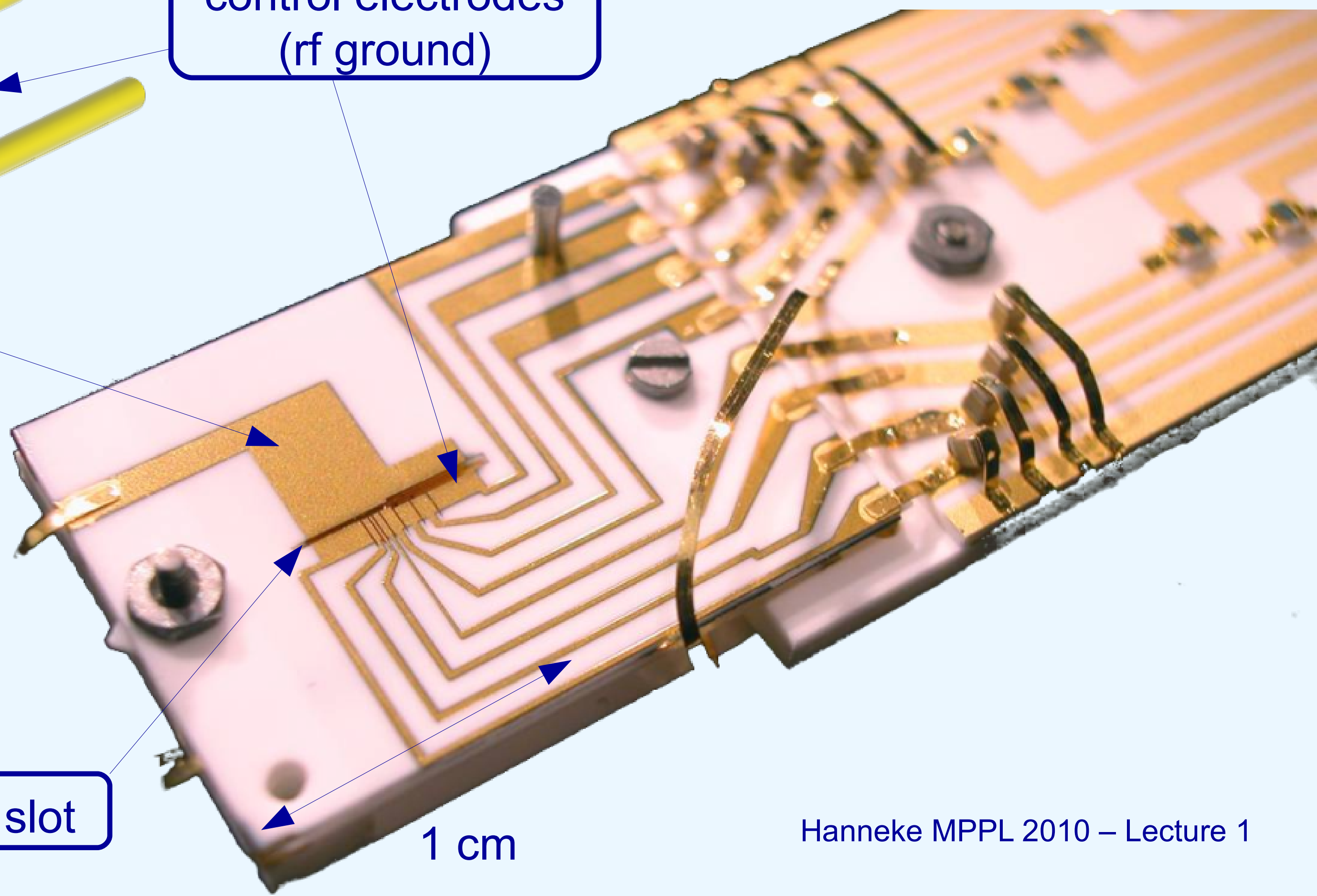
An Ion trap

Ideal linear radiofrequency (Paul) trap



Real trap

- Gold on alumina
- Two wafers
- Multi-zone



Harmonic oscillators

Axial ~ 3 MHz
Radial $\gg$ axial
Radial $\propto$ 1/mass

The quantum processor

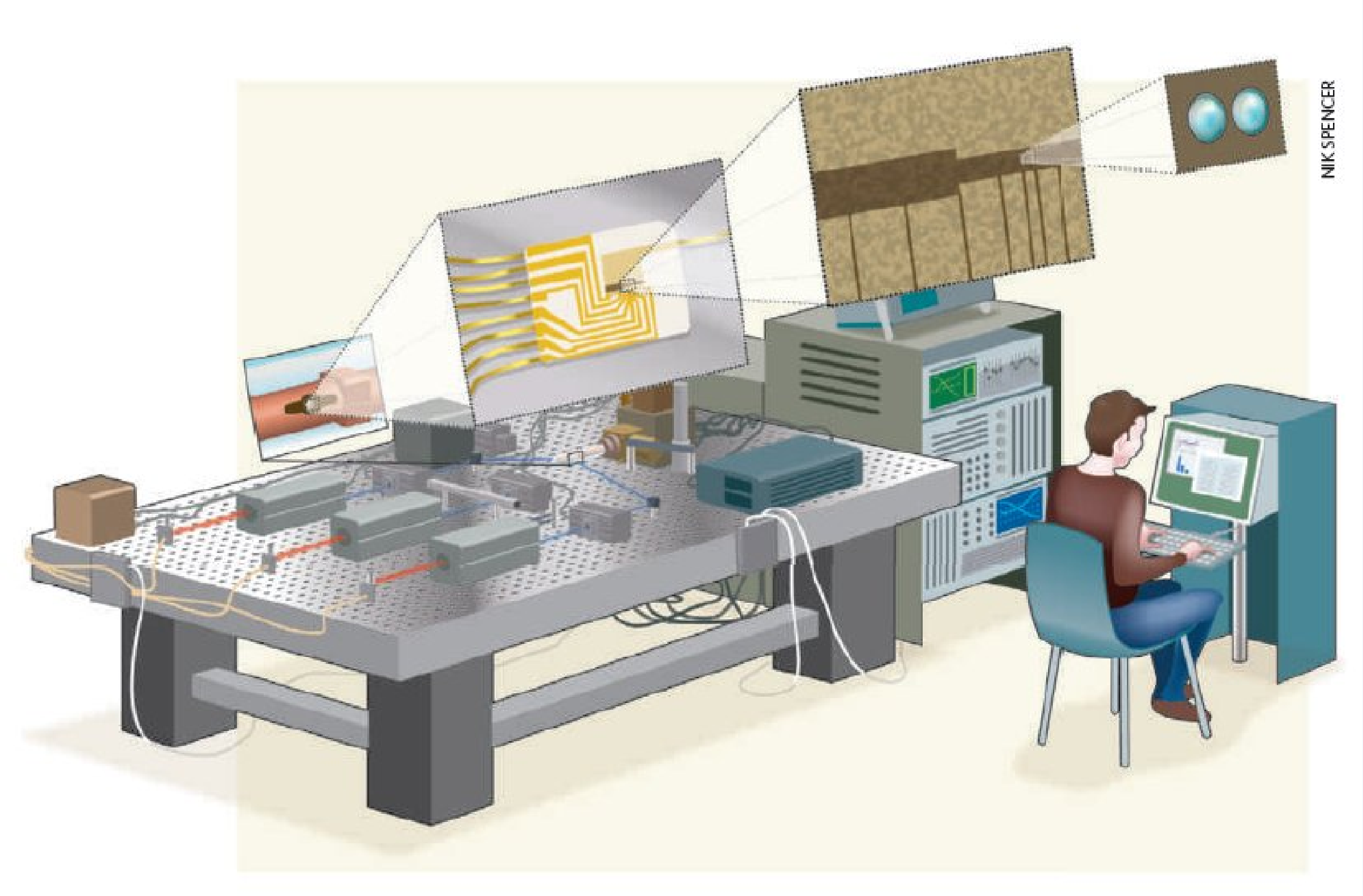
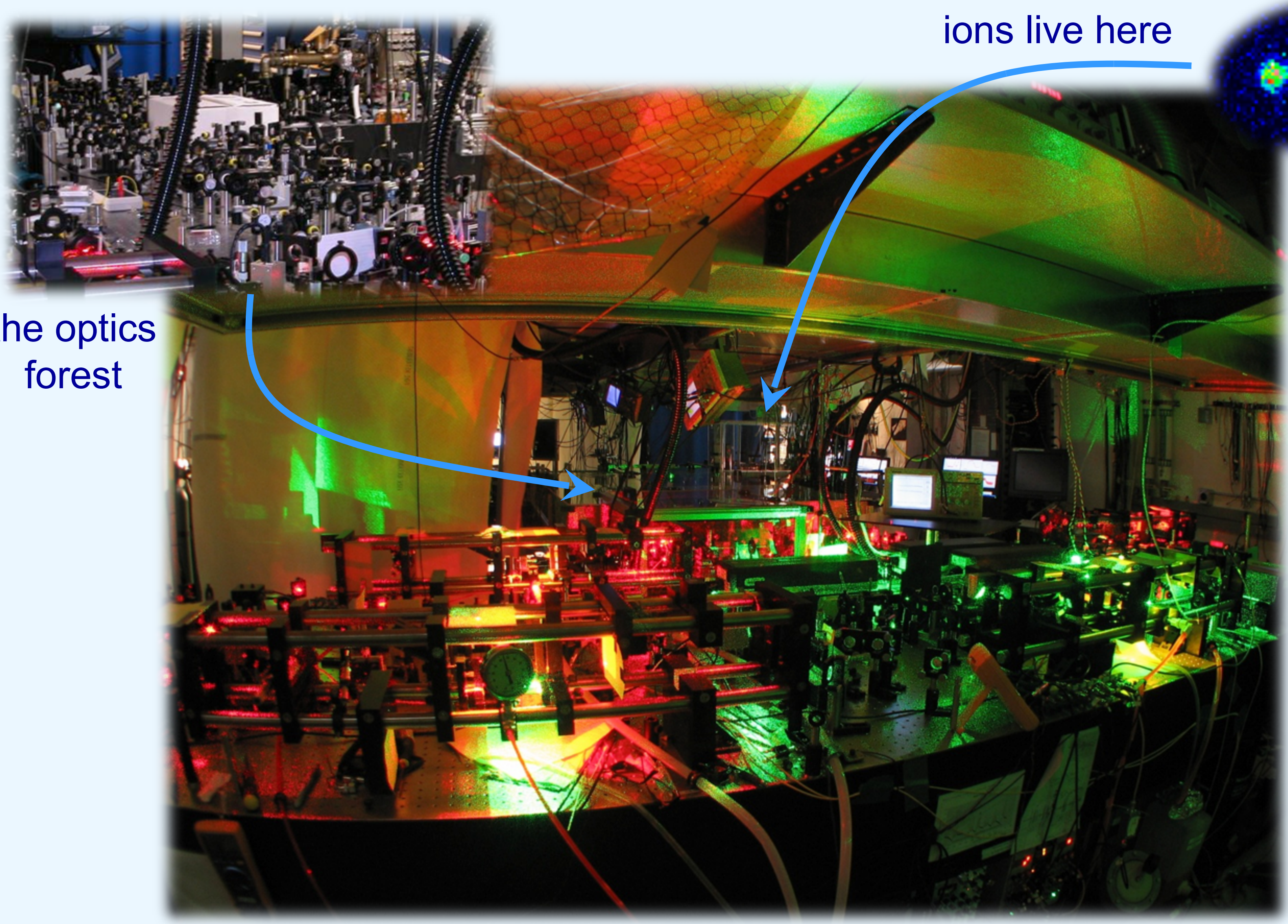
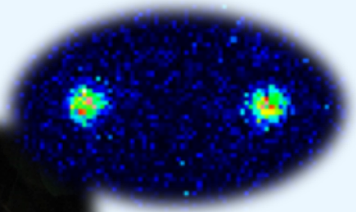


Figure from E. Knill, *Nature* **463** 441-443 (2010)

The quantum processor





ions live here

the optics forest

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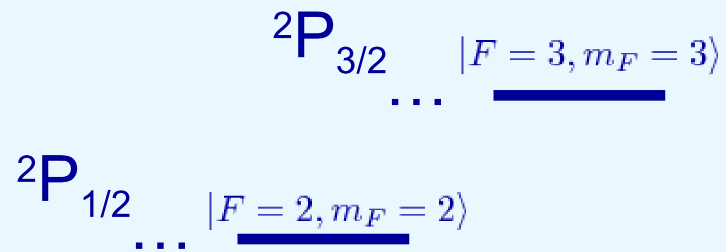
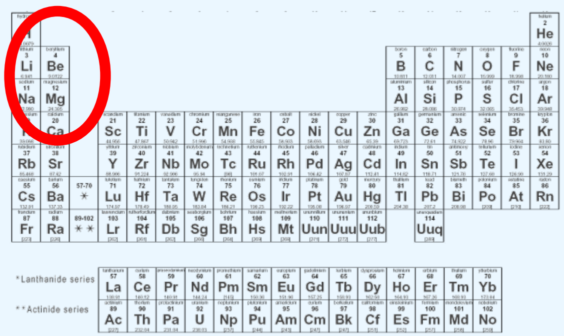
Methods set: State prep and measurement

Qubit ion: $^9Be^+$ (I = 3/2)

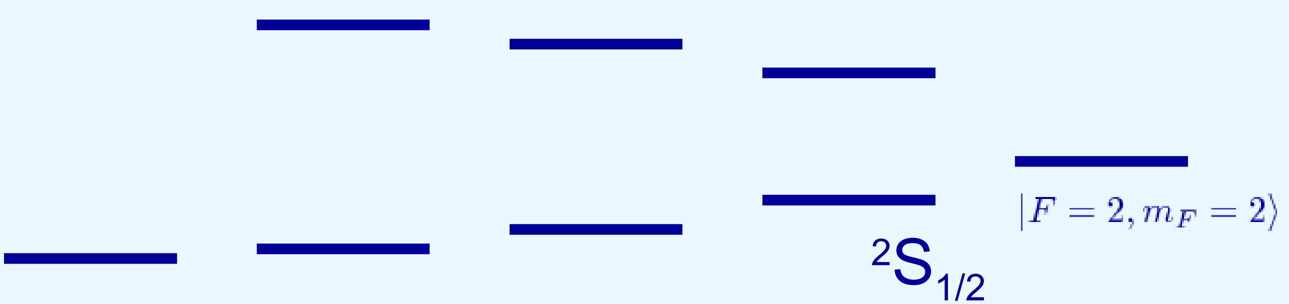


State prep: optical pumping

Measurement: bright vs. dark



313 nm



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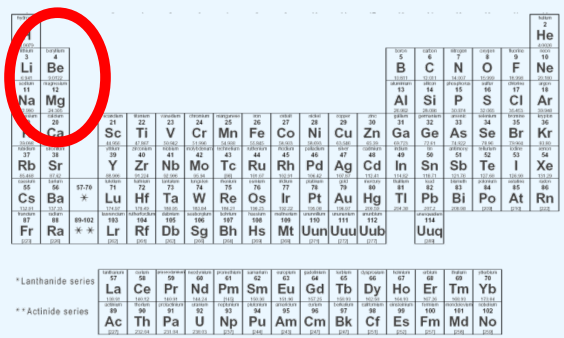

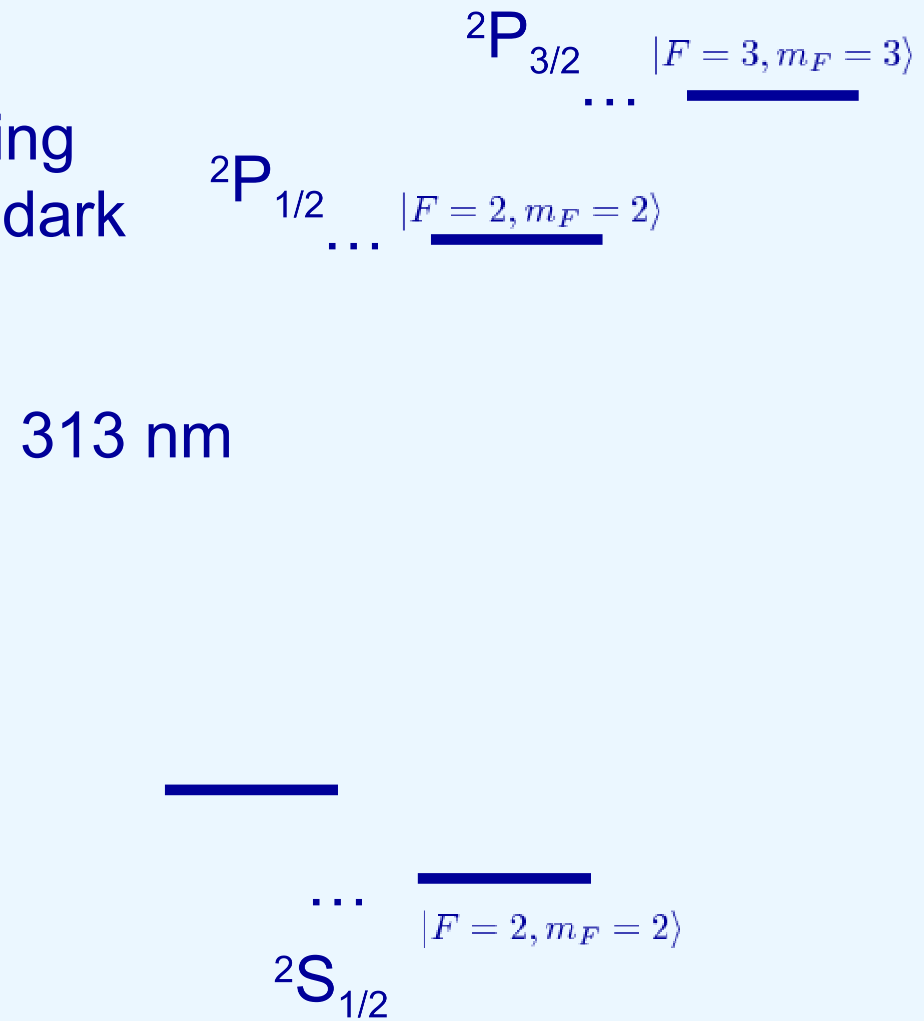

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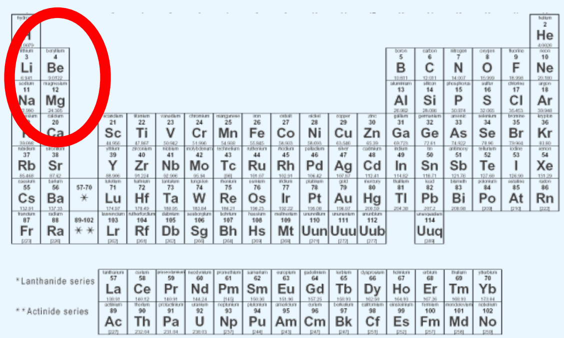

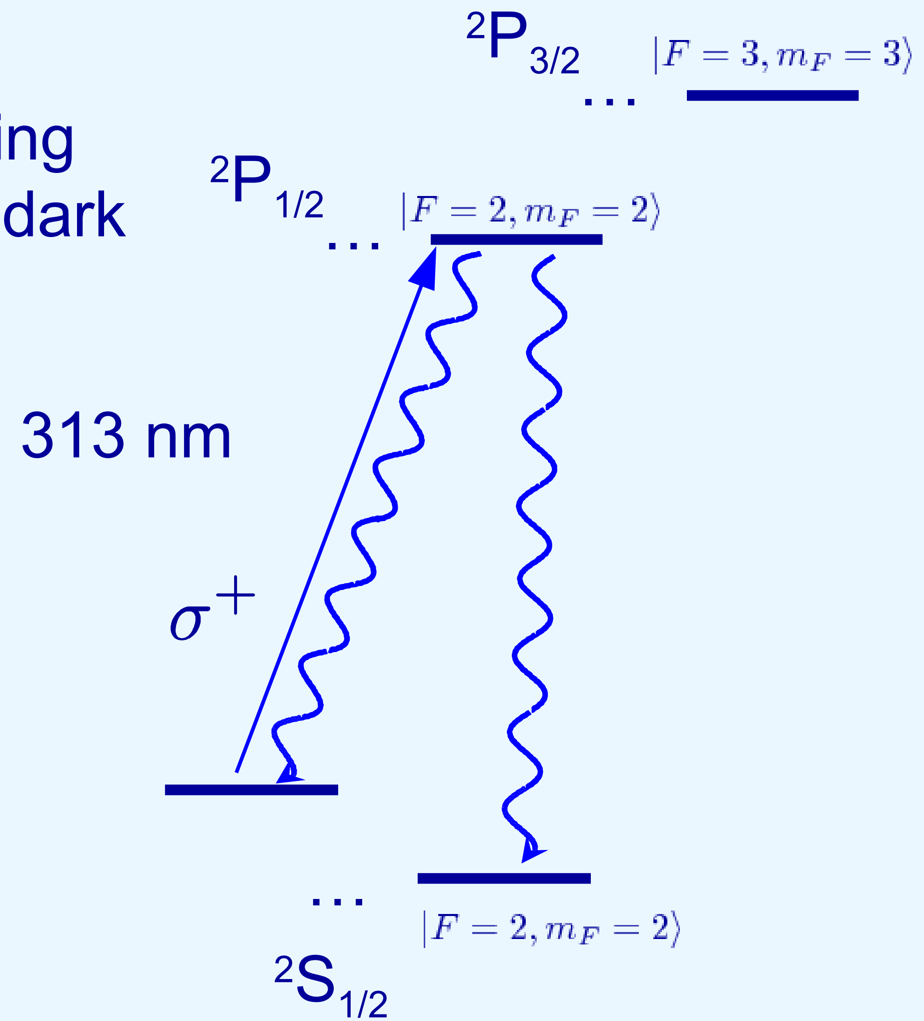

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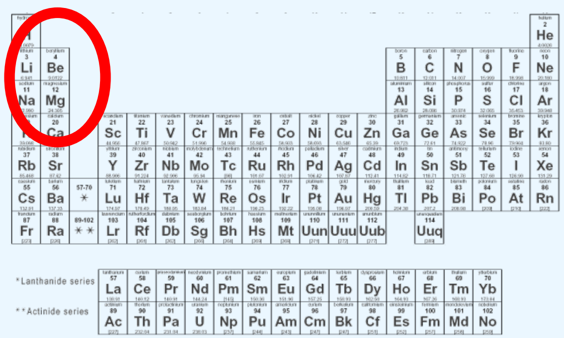
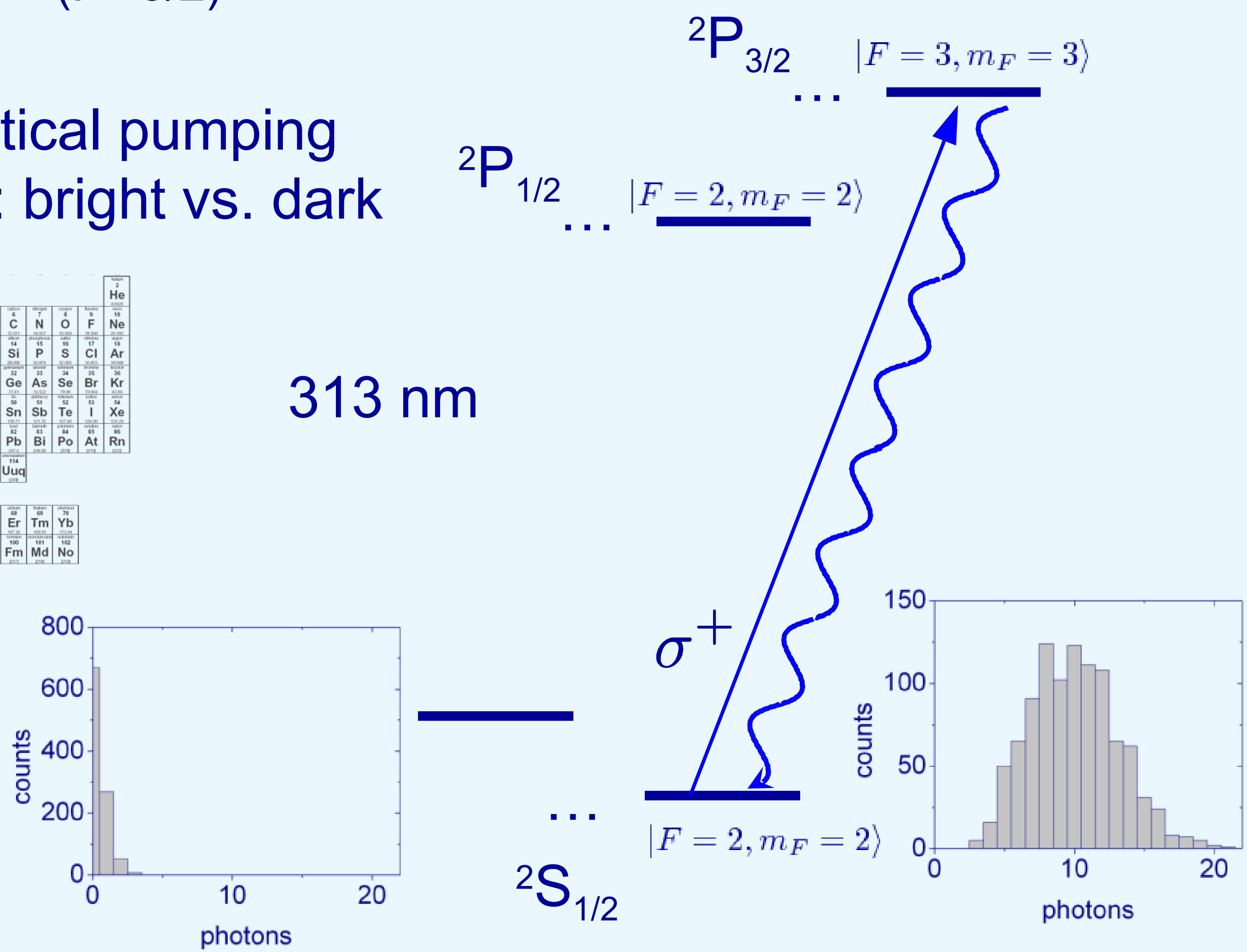




Methods set: Qubit storage

Qubit coherence times much longer than experiment times.

$$\nu = 1.207\,352\,807\,53\ \mathrm{GHz}$$

T_1 > 10^7 years

T_2 ~ 15 s

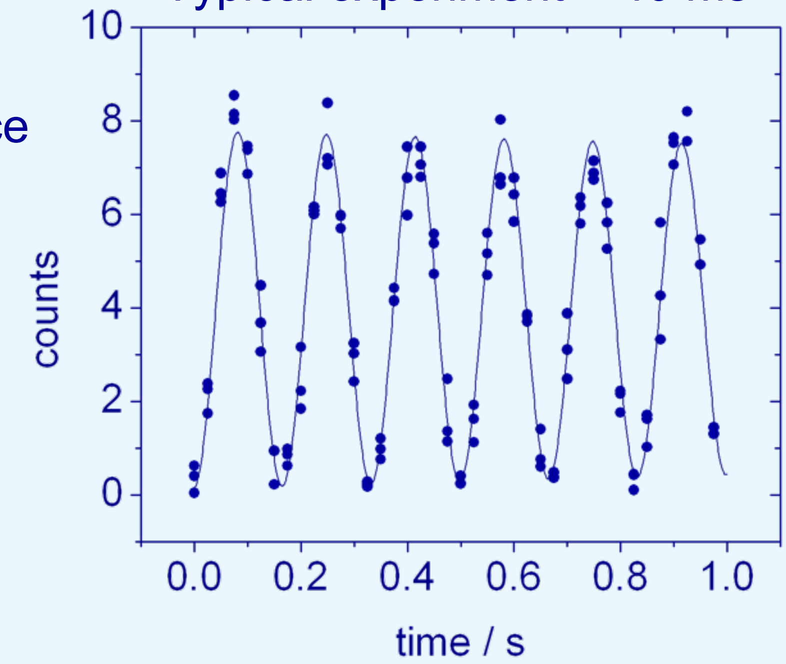
$^9Be^+\ ^2S_{1/2}$

B = 119.64 G

$$|F=1, m_F=0\rangle$$
$$\updownarrow$$
$$|F=2, m_F=1\rangle$$

Typical experiment ~ 40 ms

Ramsey interference fringes

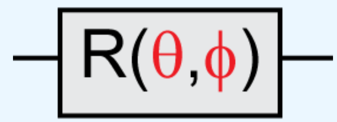


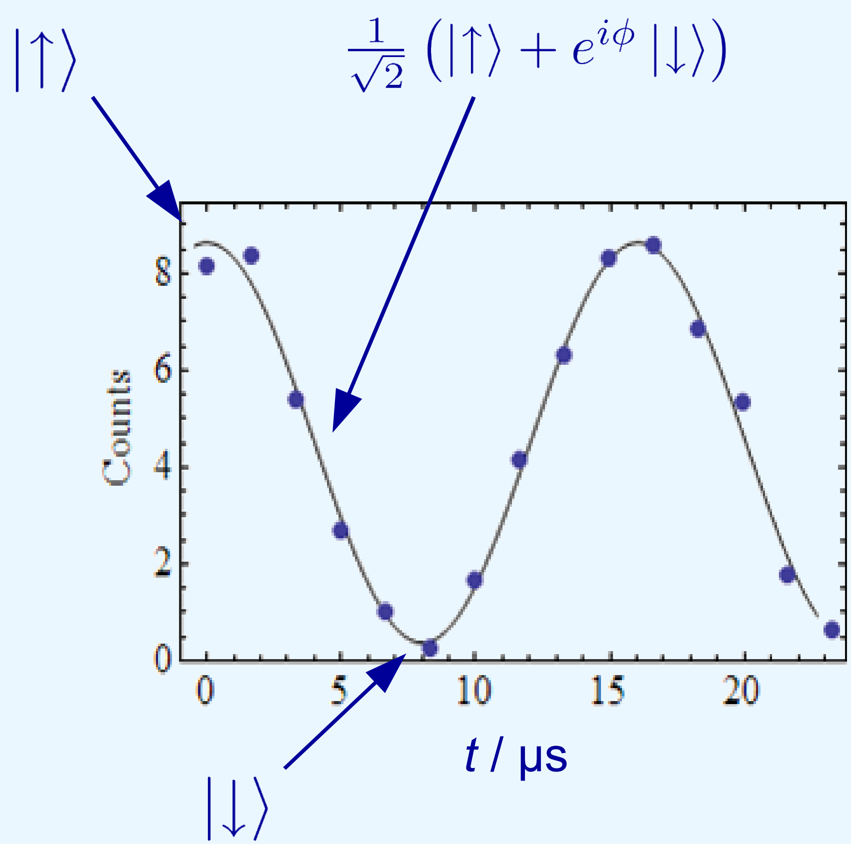
$$\frac{\partial \omega}{\partial B} = 0$$

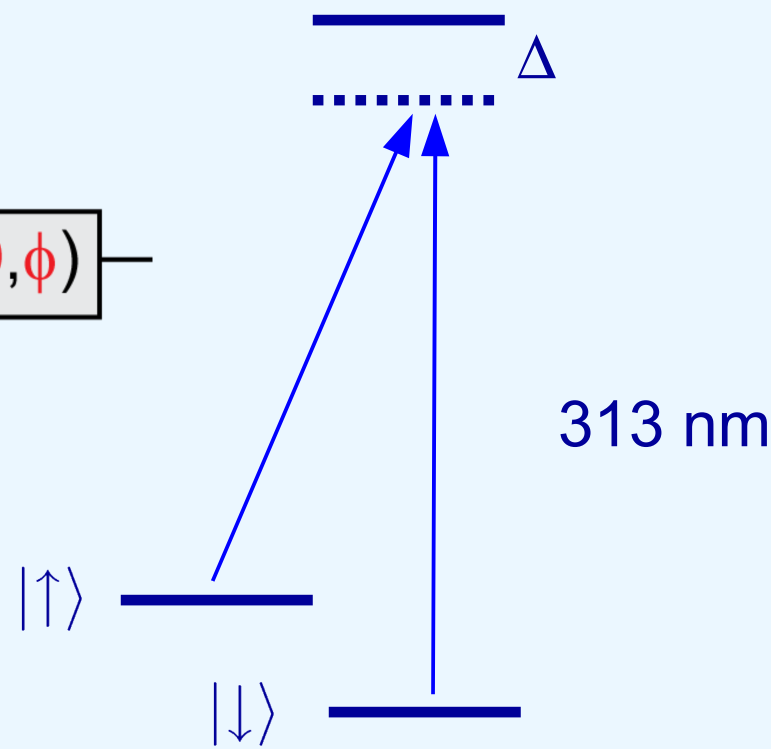
C. Langer, *et al*, *Phys. Rev. Lett.* **95** 060502 (2005)

Methods set: Single-qubit gates

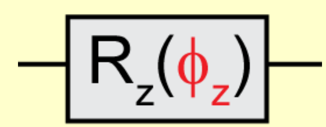
- Stimulated Raman transitions
- Coherent Rabi flopping
- *F* ~ 99.5%







Also *z*-rotations



Methods set: Two-qubit gate

- Coupled motion is an information bus
- Laser-induced, state-dependent motion
- Maximally entangling gate
- *F* ~ 96%

<u>Joint qubit states</u>

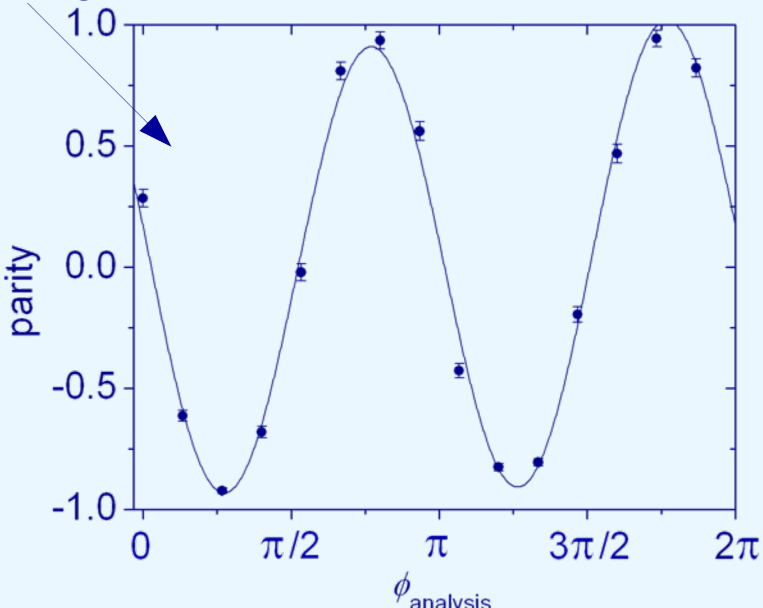
$|\uparrow\rangle\,|\uparrow\rangle$

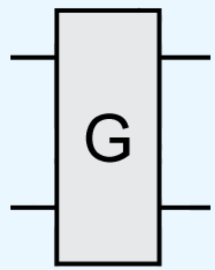
$|\uparrow\rangle\,|\downarrow\rangle$

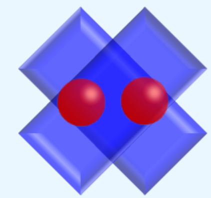
$|\downarrow\rangle\,|\uparrow\rangle$

$|\downarrow\rangle\,|\downarrow\rangle$

Coherence of entangled state





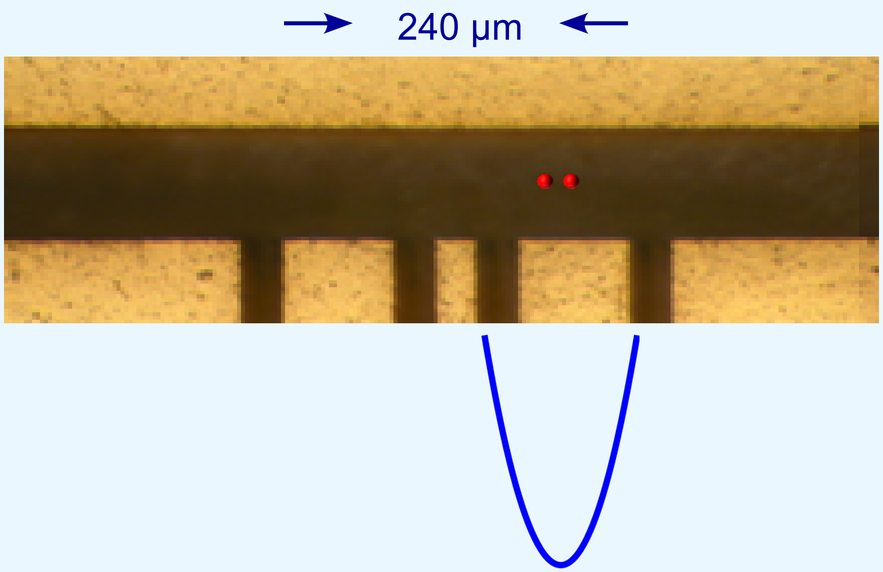


$$G = e^{-i\pi/4} \exp\left(\frac{i\pi}{4}\sigma_z \otimes \sigma_z\right)$$

<u>One mode</u>: D. Leibfried, *et al*, *Nature* **422** 412-415 (2003)
<u>Two modes</u>: J. P. Home, *et al*, *Science* **325** 1227-1230 (2009)

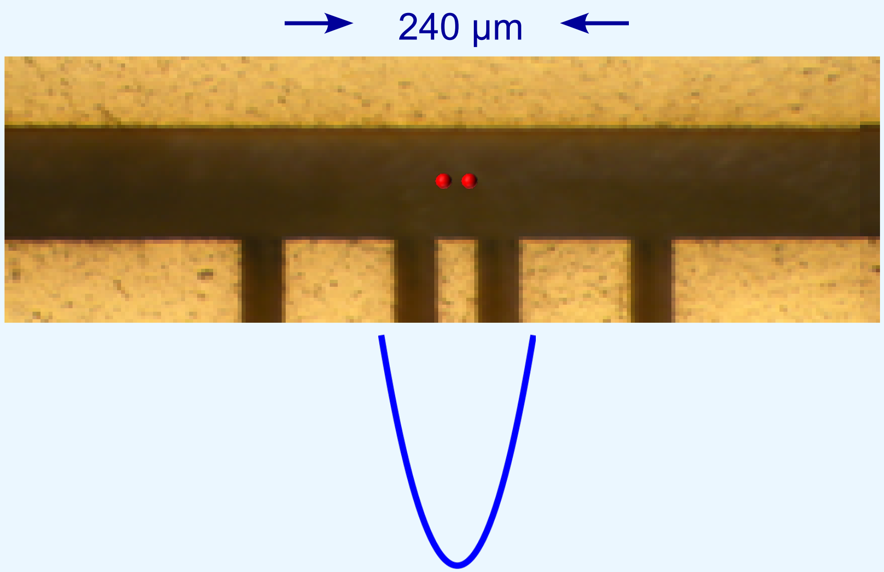
Methods set: Information transfer

Move & Separate Ion Chains



Ions not to scale

Move & Separate Ion Chains



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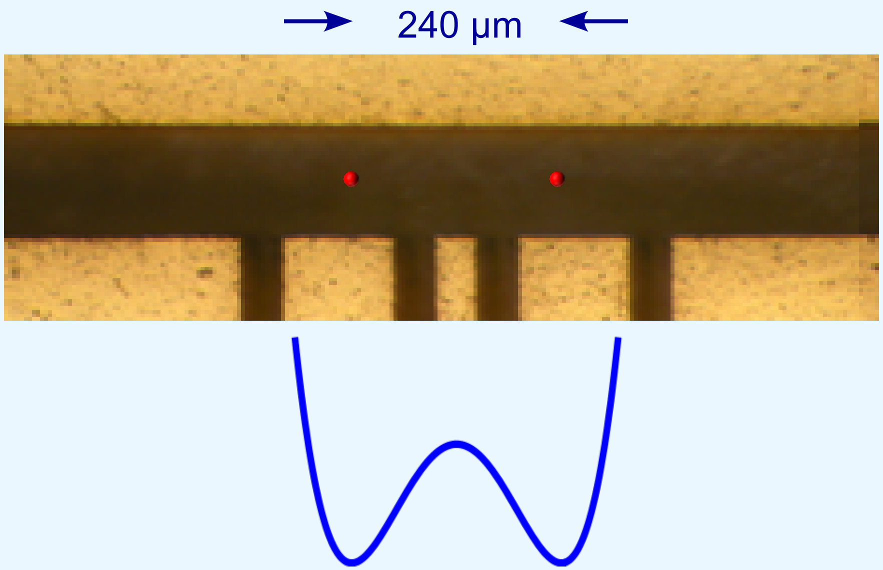

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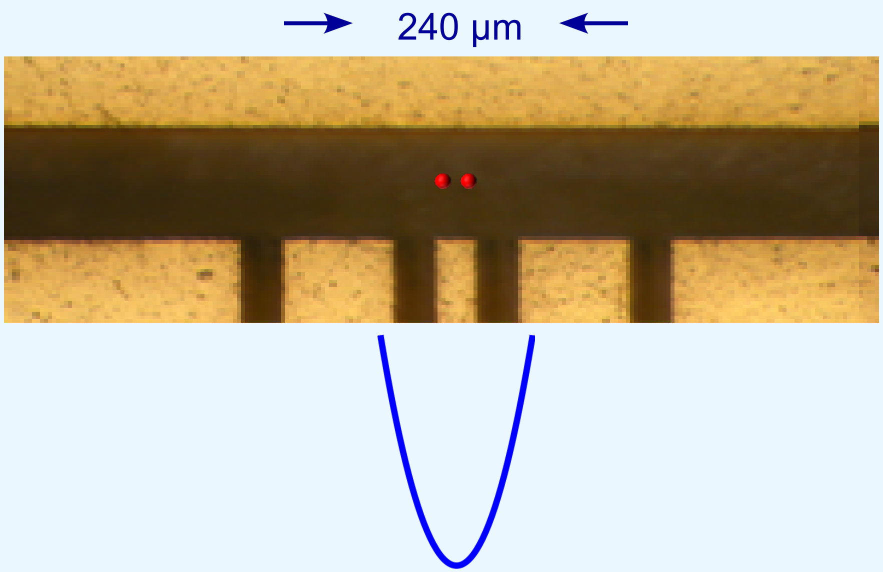

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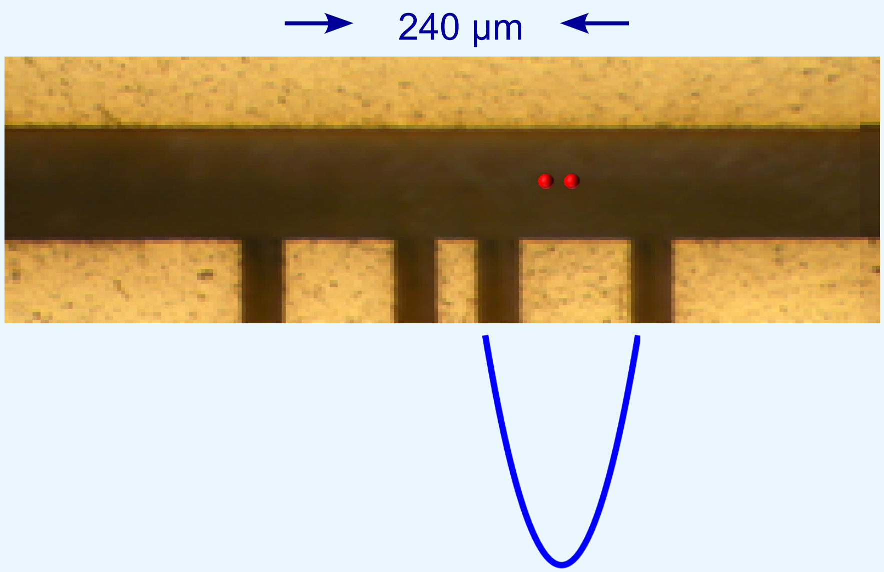

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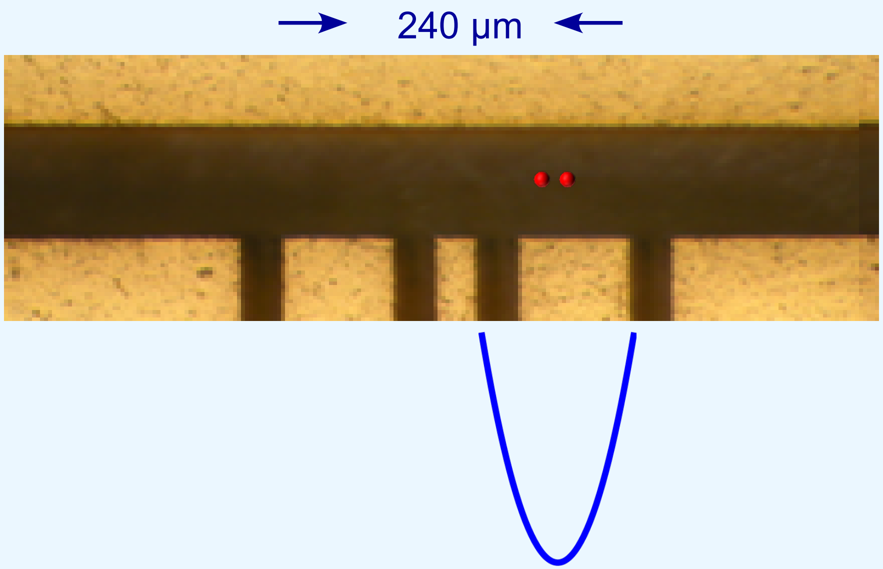
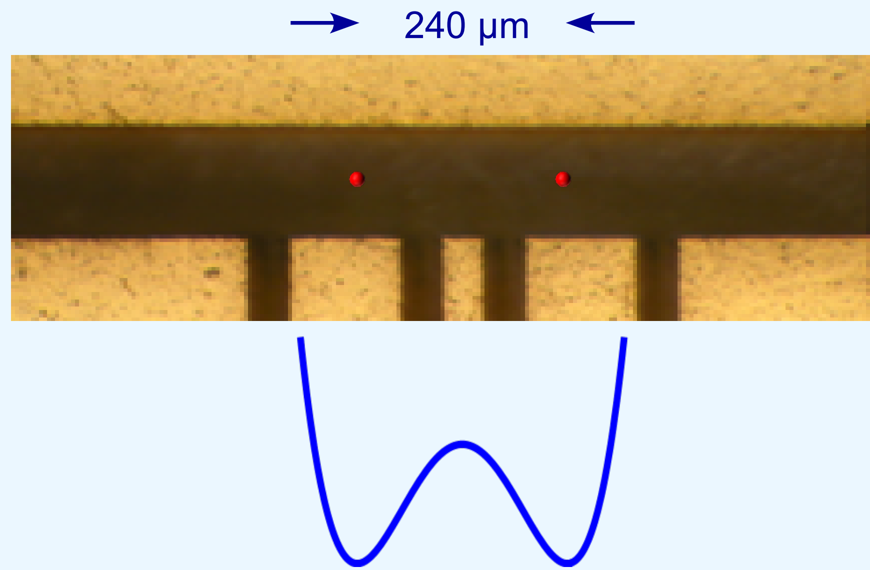




- Two-qubit gates

- Individual addressing
- Single-qubit gates
- Measurement

Ions not to scale

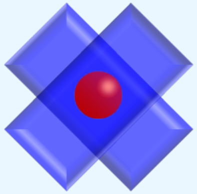
Methods set: Cooling

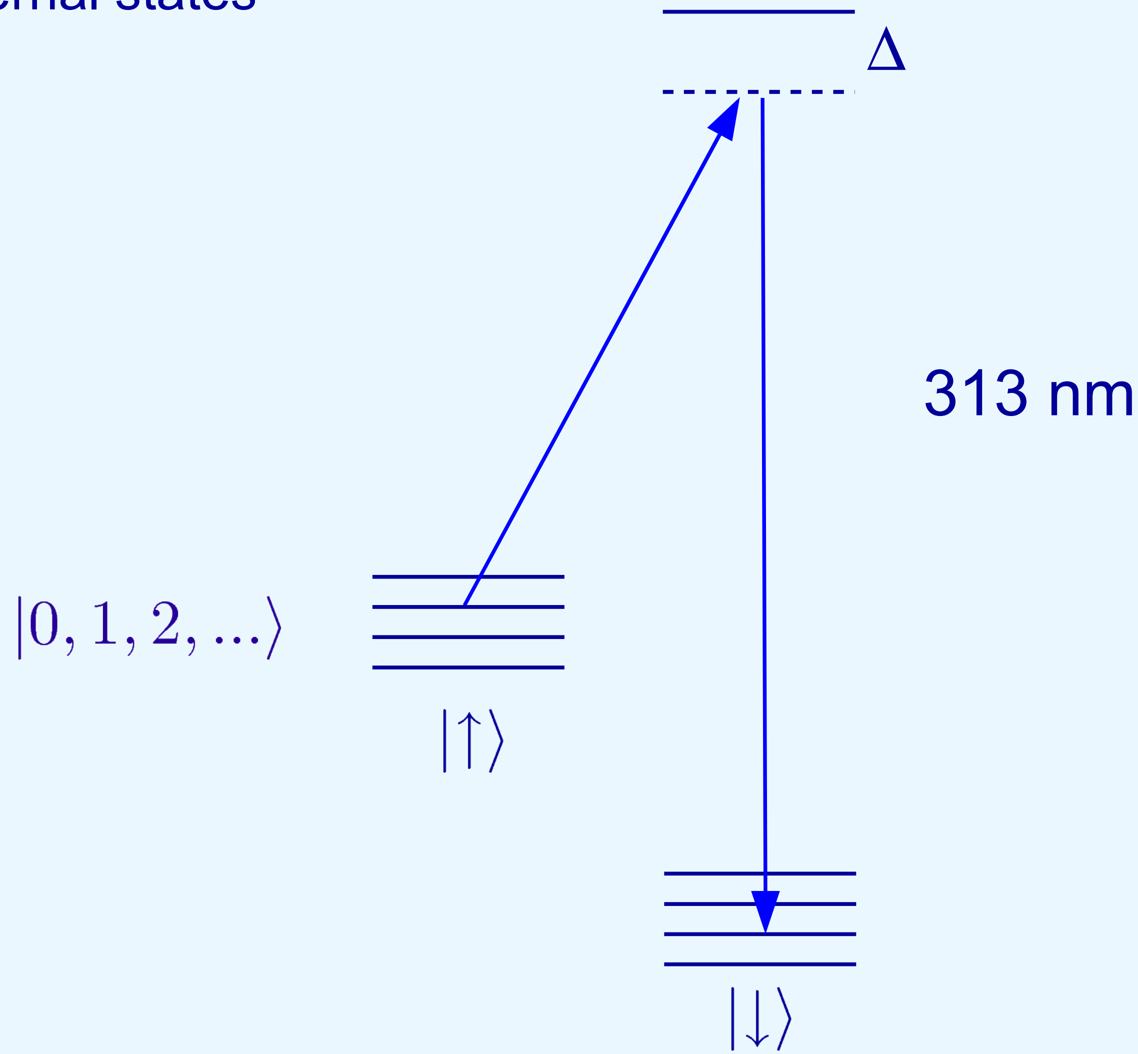
Couple internal and external states

- Doppler cooling
- Raman cooling

<ins>Raman cooling</ins>

1. Sideband pulse
2. Repump





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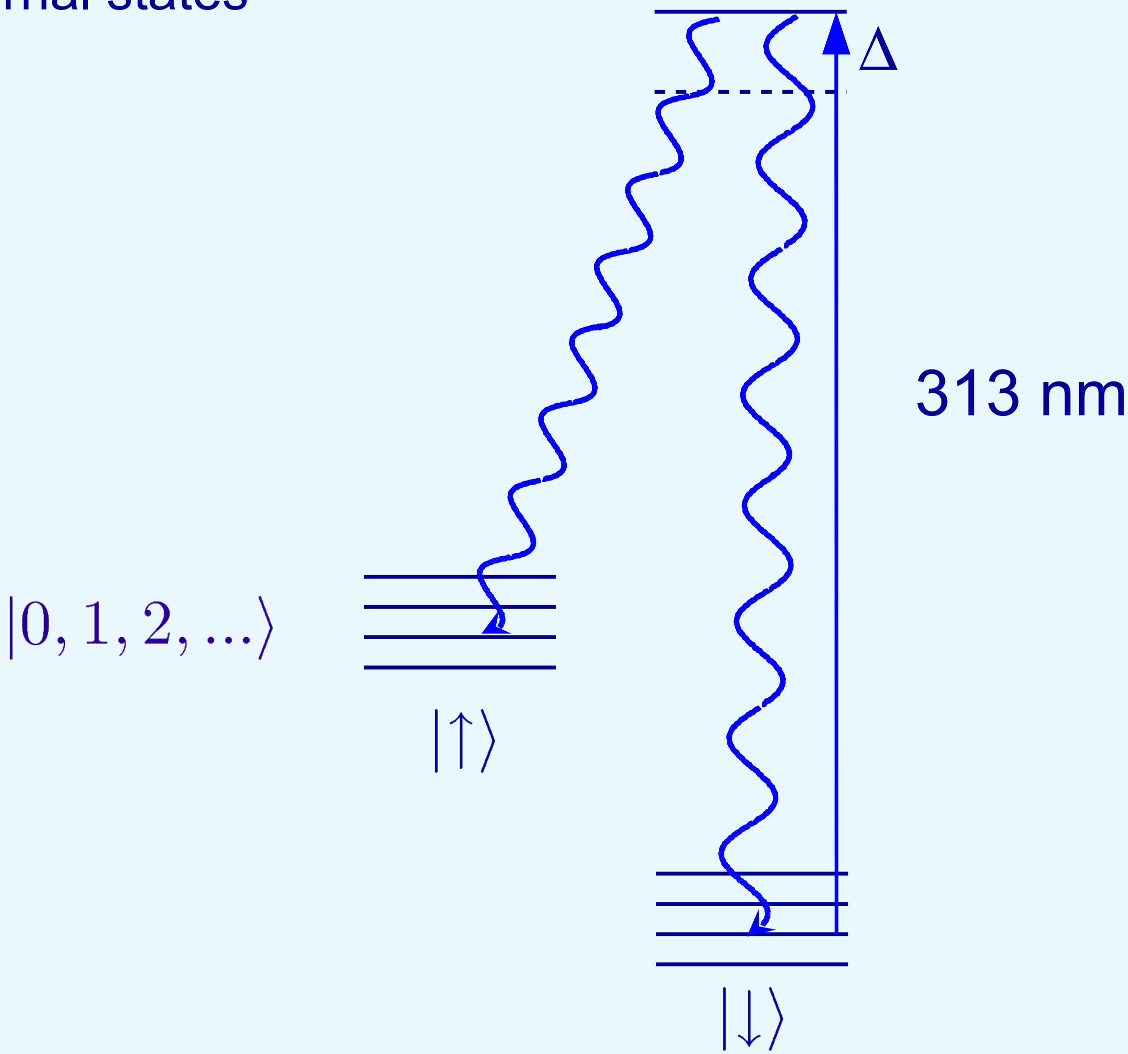

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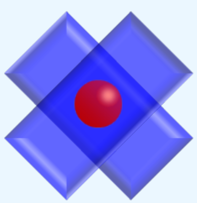

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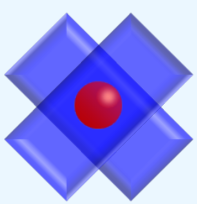

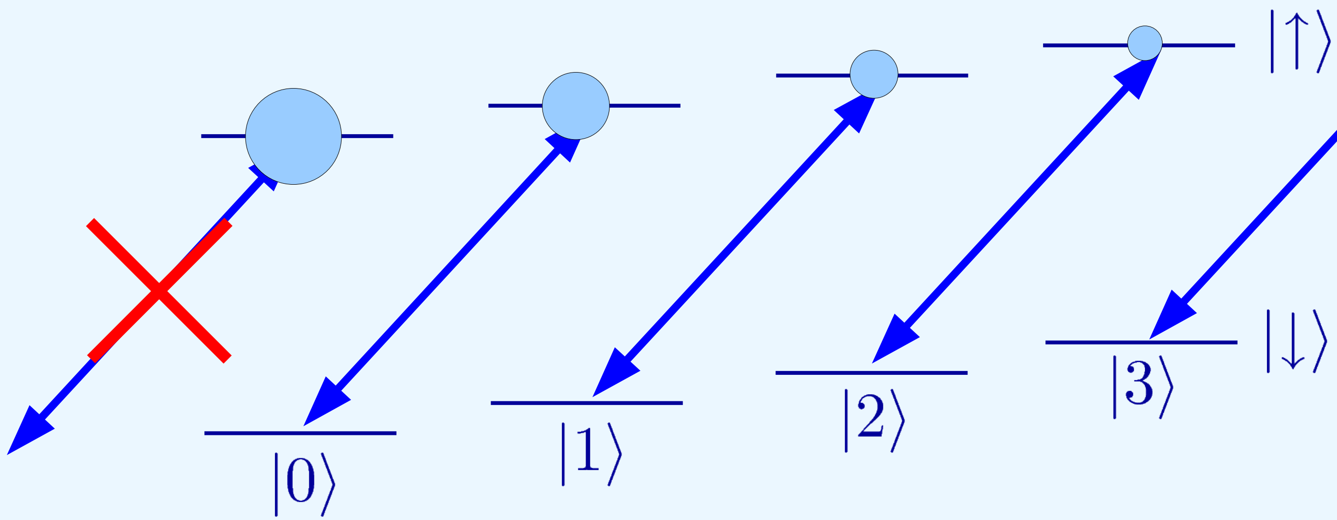

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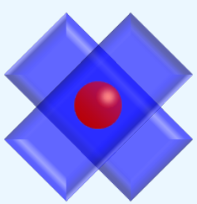

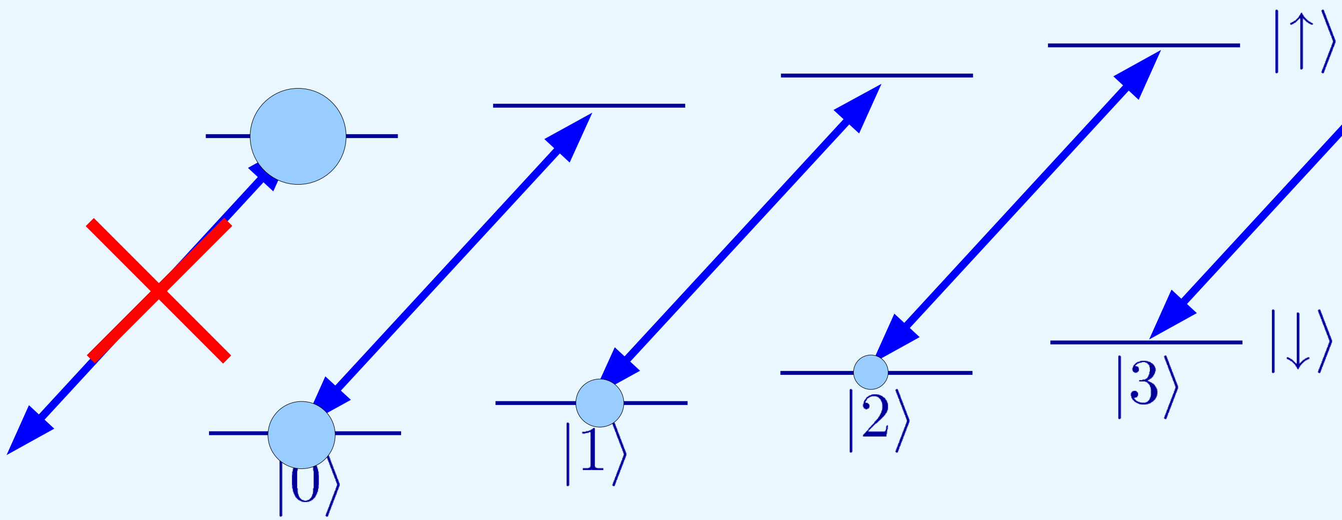

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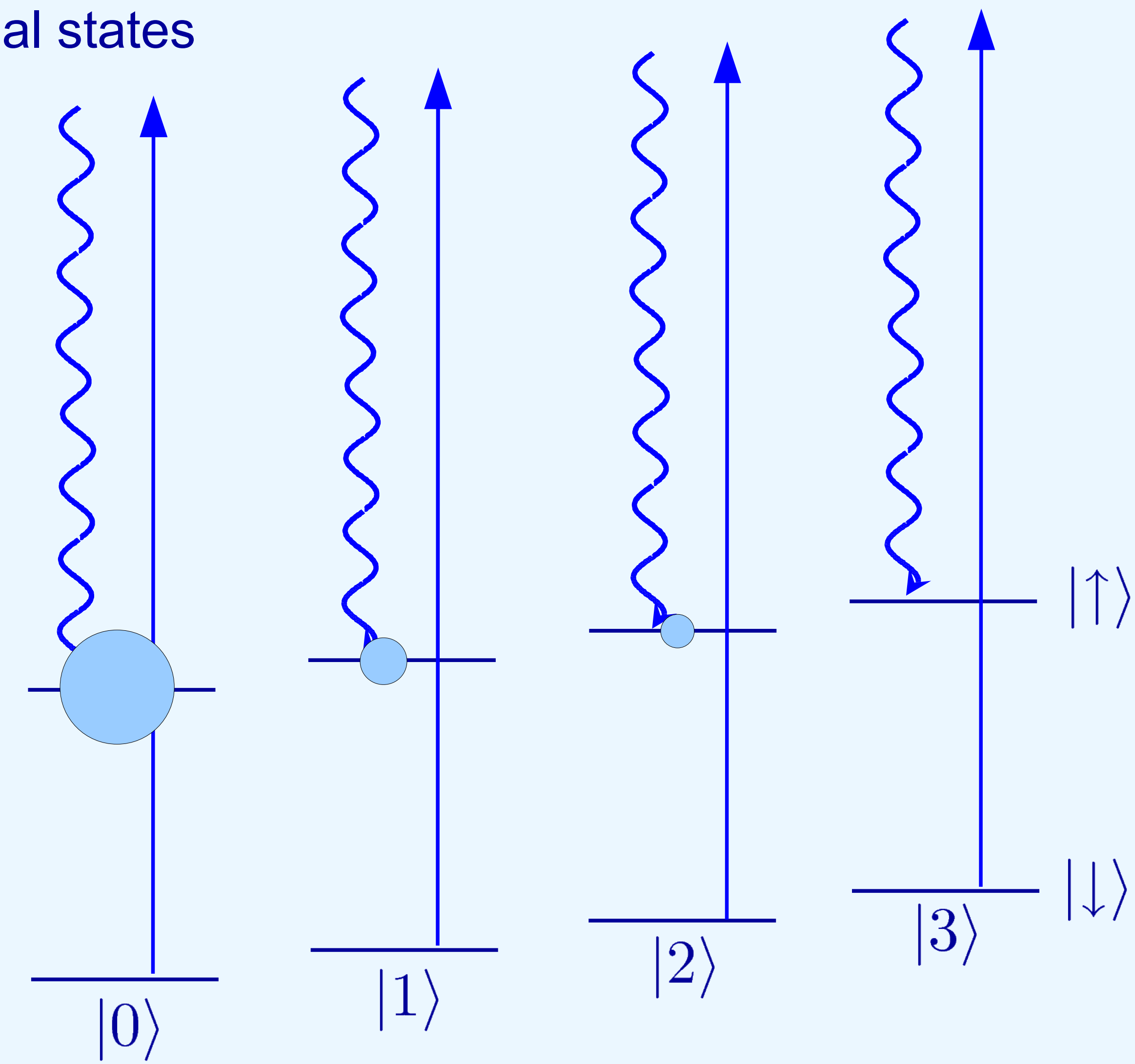

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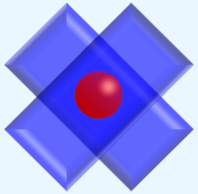

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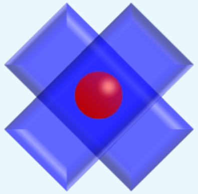

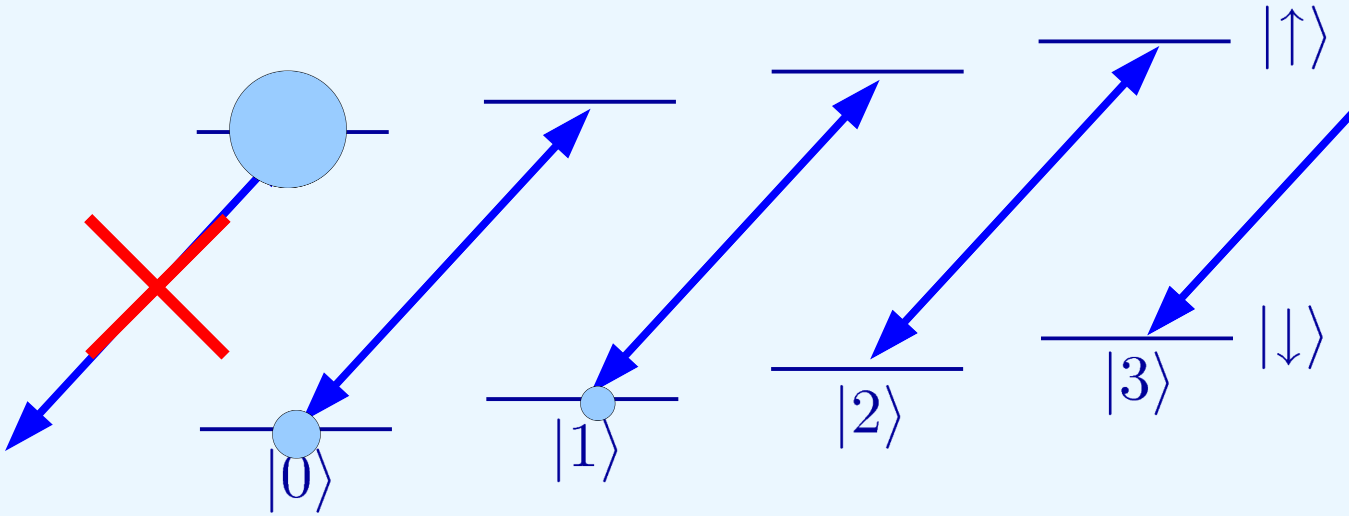

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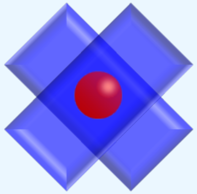
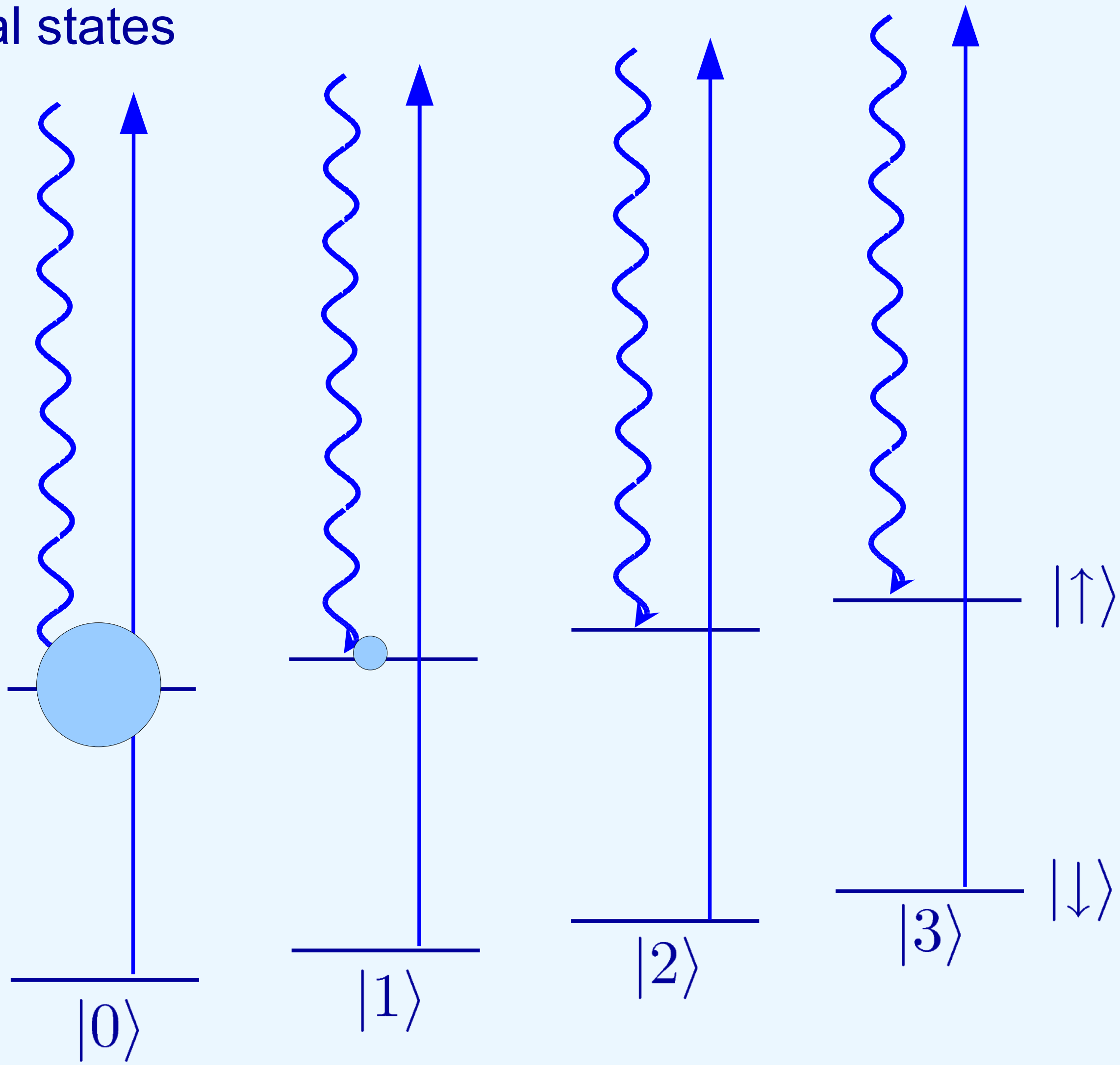
1. Sideband pulse
2. Repump





Methods set: Cooling

Couple internal and external states
- Doppler cooling
- Raman cooling

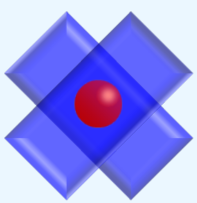
Coherent coupling

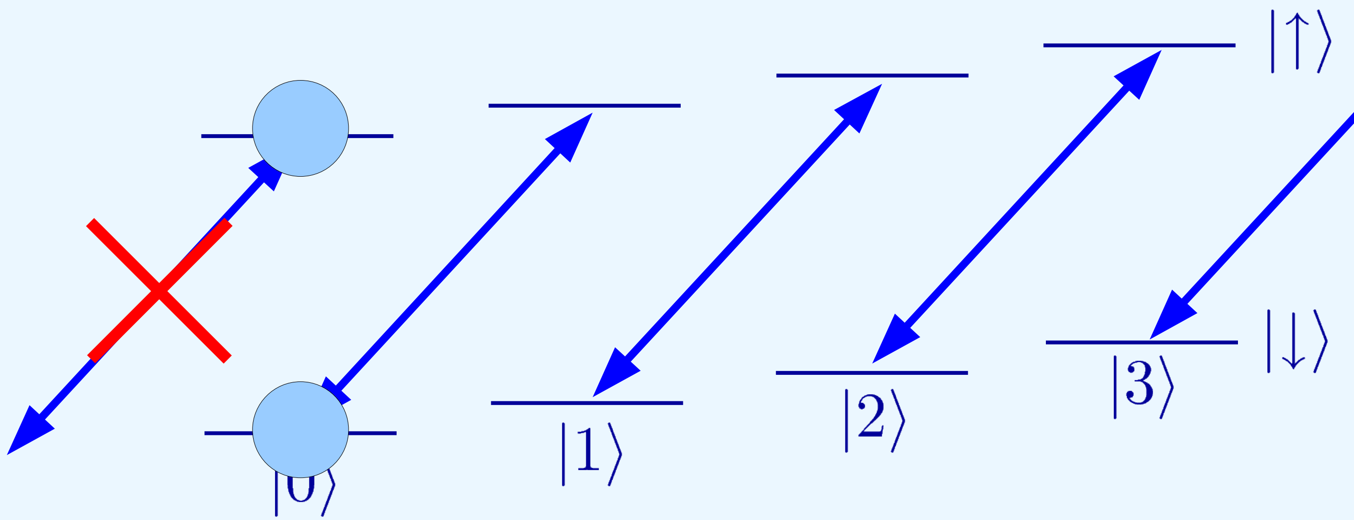
$$\frac{1}{\sqrt{2}}\left(\left|\downarrow\right\rangle + e^{i\phi}\left|\uparrow\right\rangle\right)\left|0\right\rangle$$
$$\Downarrow$$
$$\frac{1}{\sqrt{2}}\left|\uparrow\right\rangle\left(\left|1\right\rangle + e^{i\phi}\left|0\right\rangle\right)$$

<u>Raman cooling</u>

1. Sideband pulse
2. Repump

Cooling: Add dissipation





Methods set: Cooling

Couple internal and external states

- Doppler cooling
- Raman cooling

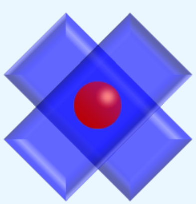
Coherent coupling

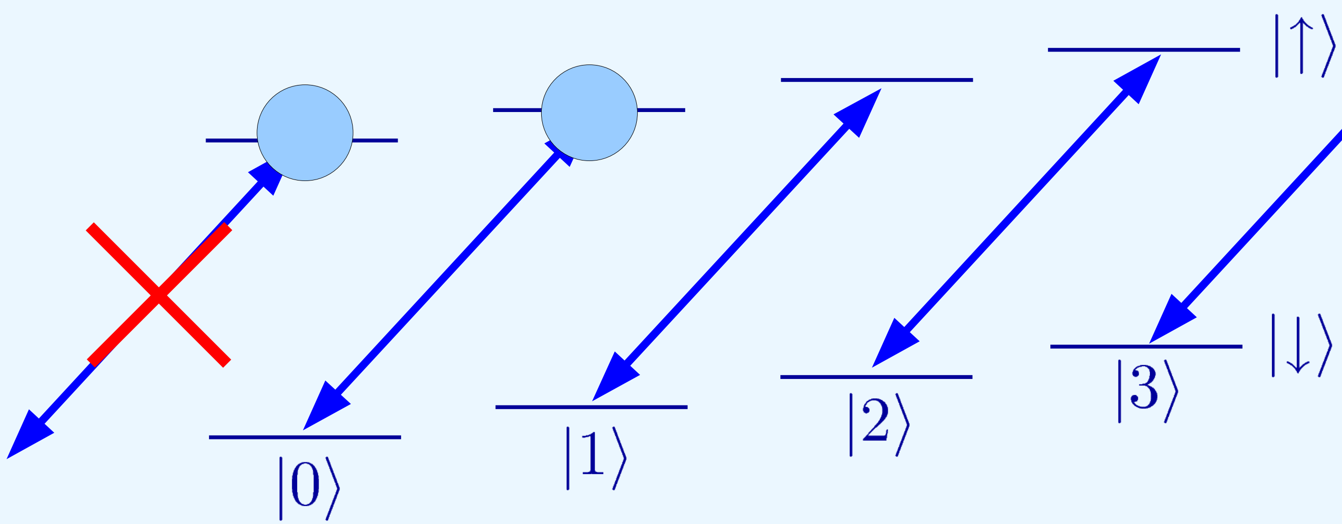
$$\frac{1}{\sqrt{2}}\left(|\downarrow\rangle + e^{i\phi}|\uparrow\rangle\right)|0\rangle$$
$$\Downarrow$$
$$\frac{1}{\sqrt{2}}|\uparrow\rangle\left(|1\rangle + e^{i\phi}|0\rangle\right)$$

<u>Raman cooling</u>

1. Sideband pulse
2. Repump

Cooling: Add dissipation



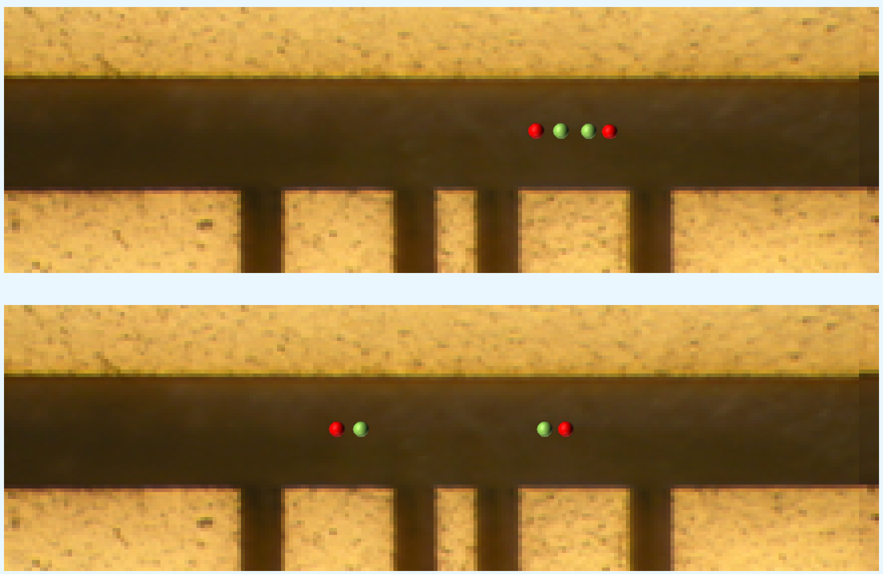


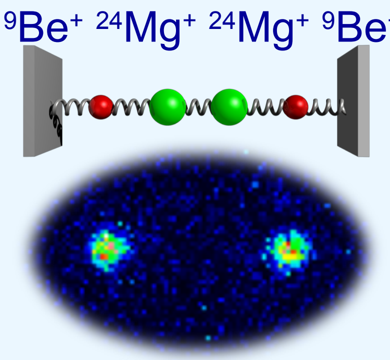
Methods set: Sympathetic cooling

$^{24}Mg^+$ refrigerant ion

- Does not affect qubit coherence (280 nm versus 313 nm)
- Doppler cool before single-qubit gate
- Ground-state cool before each two-qubit gate $\bar{n} \sim 0.06$

→ 240 µm ←





M. Barrett, *et al*, *Phys. Rev. A* **68** 042302 (2003)
J. Jost, *et al*, *Nature* **459** 683-685 (2009)

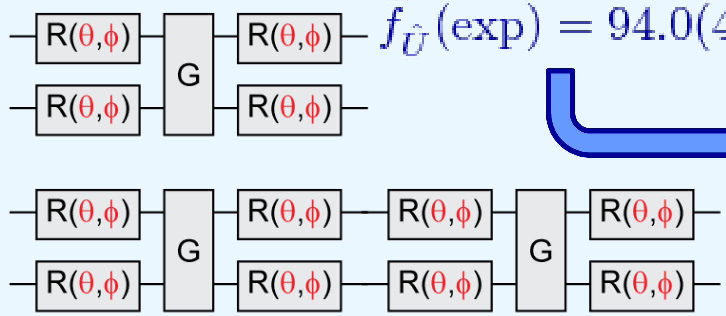
Outline

- Introduction
  - Two-level systems
  - Harmonic oscillators
- Complete methods set for scalable ion-trap QIP
  - Internal state control
  - External state control
- Demonstration experiments
  - Sustained quantum information processing
  - Programmable two-qubit quantum processor
  - Entangled mechanical oscillators

Sustained processing

Put the pieces together

Compare
- Single run
- Repeated run



$\bar{f}_{\hat{U}}(\text{exp}) = 94.0(4)\%$

$\bar{f}_{\hat{U}\hat{U}}(\text{num}) = 88.6(8)\%$

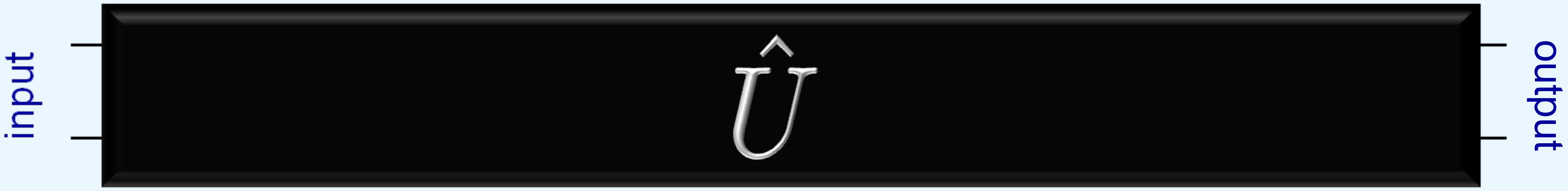
$\bar{f}_{\hat{U}^2}(\text{exp}) = 89.0(4)\%$

Compare experimental repetition to numeric repetition

$$\frac{\bar{f}_{\hat{U}^2}(\text{exp})}{\bar{f}_{\hat{U}\hat{U}}(\text{num})} = 1.004(10)$$

J. P. Home, *et al*, *Science* **325** 1227-1230 (2009)

Programmable quantum processor

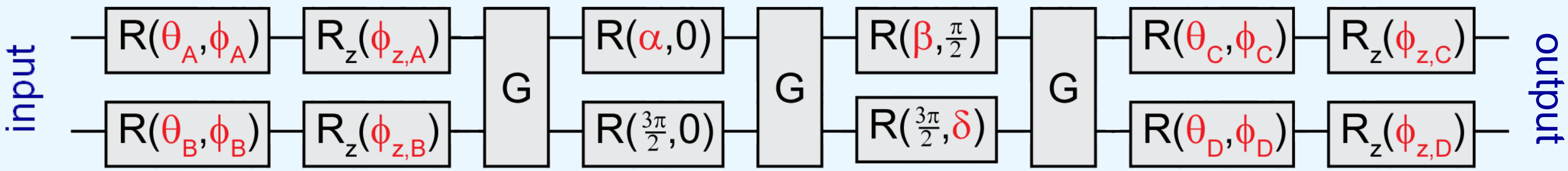


- Universal two-qubit quantum processor
- Implements <u>any</u> two-qubit unitary operation
- Programmed with 15 classical inputs

<u>Prior theory work</u>: B. Kraus & J. I. Cirac, *Phys. Rev. A* **63** 062309 (2001)
G. Vidal & C. M. Dawson, *Phys. Rev. A* **69** 010301(R) (2004)
V. V. Shende, *et al*, *Phys. Rev. A* **69** 062321 (2004)

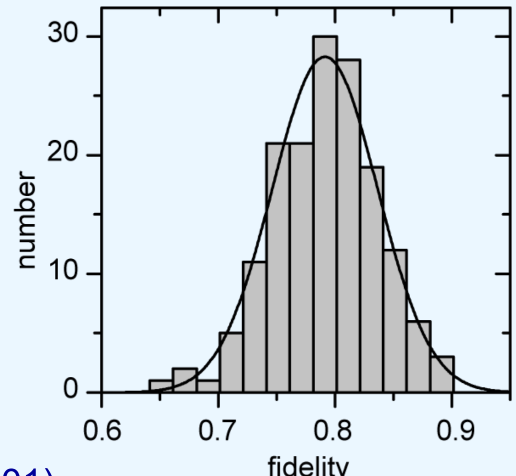
<u>Experiment</u>: D. Hanneke, *et al*, *Nature Phys.* **6** 13-16 (2010)

Programmable quantum processor



- Universal two-qubit quantum processor
- Implements <u>any</u> two-qubit unitary operation
- Programmed with 15 classical inputs

$$\bar{f}_{\Upsilon\in \mathrm{SU}(4)} = 79(5)\%$$



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G. Vidal & C. M. Dawson, *Phys. Rev. A* **69** 010301(R) (2004)
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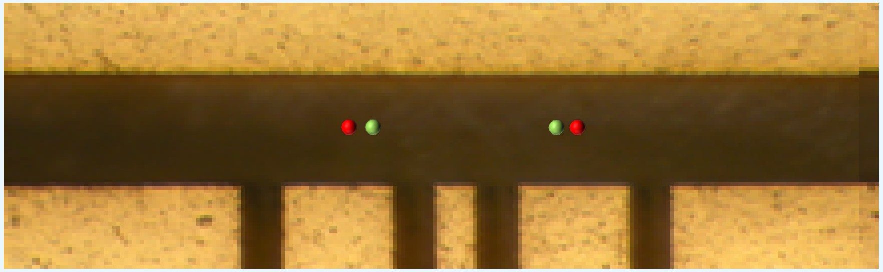
<u>Experiment</u>: D. Hanneke, *et al*, *Nature Phys.* **6** 13-16 (2010)

Entangled Mechanical Oscillators

→ 240 μm ←

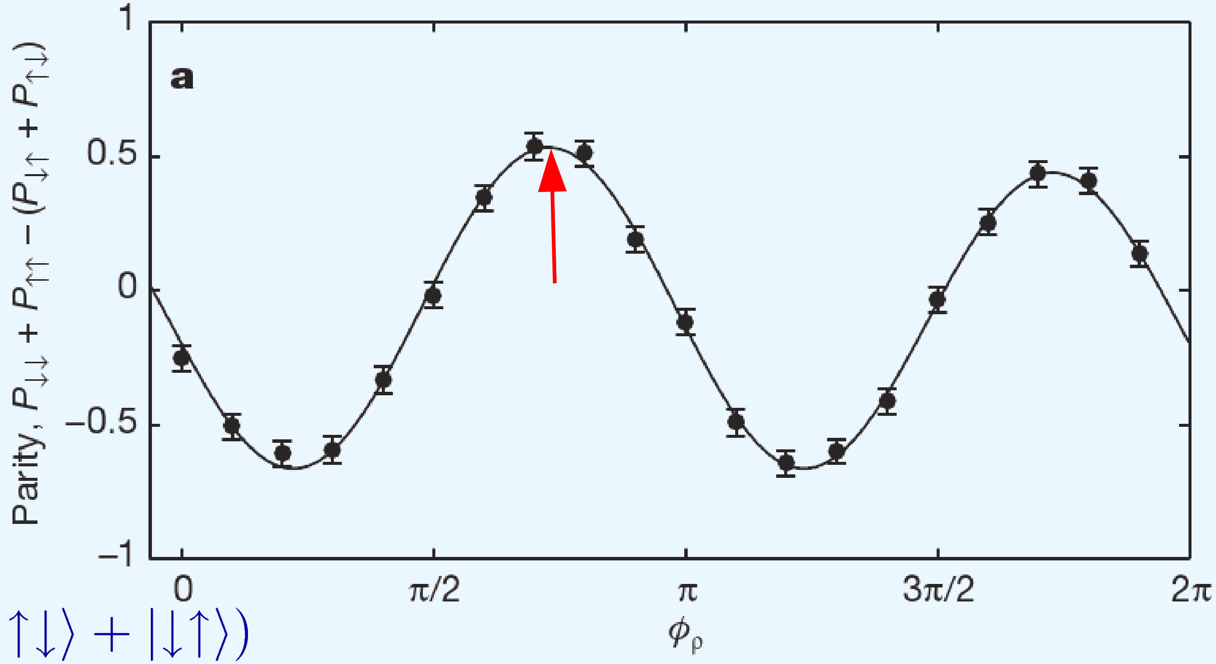


- Entangle the two qubits $\left|\uparrow\downarrow\right\rangle + e^{i\phi}\left|\downarrow\uparrow\right\rangle$
- Separate and cool $\left(\left|\uparrow\downarrow\right\rangle + e^{i\phi}\left|\downarrow\uparrow\right\rangle\right)\left|00\right\rangle$
- Transfer entanglement onto the motion $\left|\uparrow\uparrow\right\rangle\left(\left|00\right\rangle - e^{i\phi}\left|11\right\rangle\right)$
- Measure
  - "Hide" qubit error population
  - Transfer entanglement back to qubit
  - Recombine and analyze

J. D. Jost, *et al*, *Nature* **459** 683-685 (2009)

Entangled Mechanical Oscillators

$\frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle + i\,|\downarrow\downarrow\rangle\right)$ Contrast = 0.57(2) > 50%



$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$

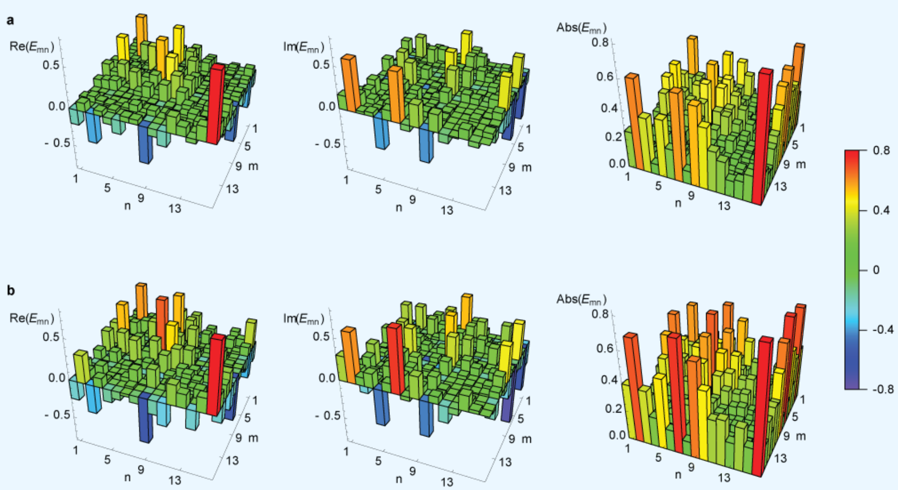
- Map into a known state $\quad |\Psi_f\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle + i\,|\downarrow\downarrow\rangle\right)$
- Measure the coherence of that state $\quad |\rho_{\downarrow\downarrow,\uparrow\uparrow}| = |\langle\downarrow\downarrow|\rho_f|\uparrow\uparrow\rangle| = C_2$

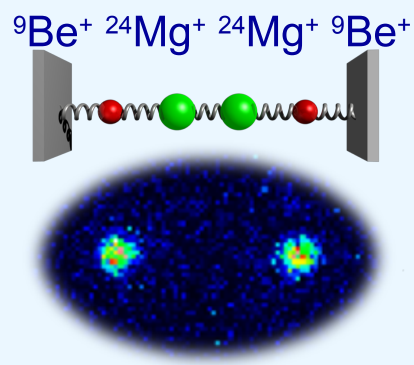
$$R\left(\tfrac{\pi}{2}, \phi_p\right)|\Psi_f\rangle : \;\; \Pi \sim C_2 \cos\left(2\phi_p\right)$$

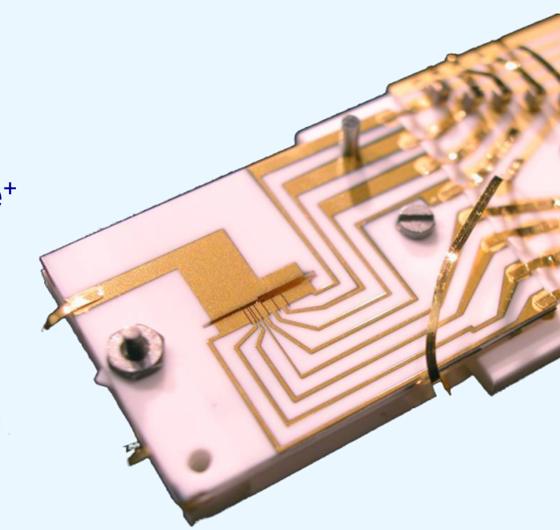
J. D. Jost, *et al*, *Nature* **459** 683-685 (2009)

Conclusions

- “Simple” systems can do interesting science
- Complete methods set for scalable trapped-ion QIP
- Programmable two-qubit quantum processor
- Entangled mechanical oscillators







Acknowledgements

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Ryan Bowler (grad student, CU)
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Kenton Brown (postdoc, Maryland)
James Chou (postdoc, CalTech)
Yves Colombe (postdoc, Paris)
David Hanneke (postdoc, Harvard)
Jonathan Home (postdoc, Oxford)
David Hume (grad student, CU)
John Jost (grad student, CU)
Christian Ospelkaus (postdoc, Hamburg)
Ting Rei Tan (guest researcher, Singapore)
Michael Thorpe (postdoc, CU)
Aaron VanDevender (postdoc, Univ. Illinois)
Ulrich Warring (postdoc, MPIK)

NIST Ion Storage Group
Boulder, CO

Michelson Postdoctoral Prize Lectures

- Entangled Mechanical Oscillators and a Programmable Quantum Computer
  - Monday, May 10, 12:30pm, Miller Room

- Optical Atomic Clocks
  - Tuesday, May 11, 11:30am, Miller Room

- Cavity Control in a Single-Electron Quantum Cyclotron
  - Thursday, May 13, 4:15pm, Rock 301

- High-Energy Physics with Low-Energy Symmetry Studies
  - Friday, May 14, 12:30pm, Miller Room

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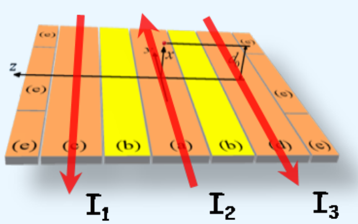
- Towards scaled processing

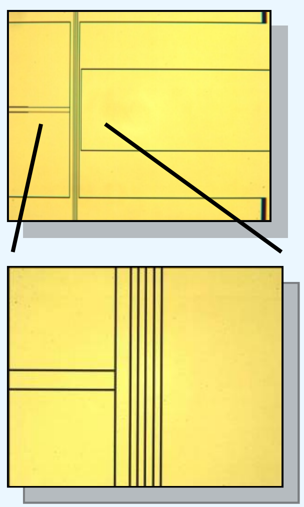
Towards scaled processing

Higher gate fidelities

- We need ~ 99.99%
- How to improve
  - More laser power (reduced spontaneous emission)
  - Laser intensity stabilization
  - Laser position control
  - Different two-qubit gate styles
    - One that works without lasers (e.g. radiofrequency drive)



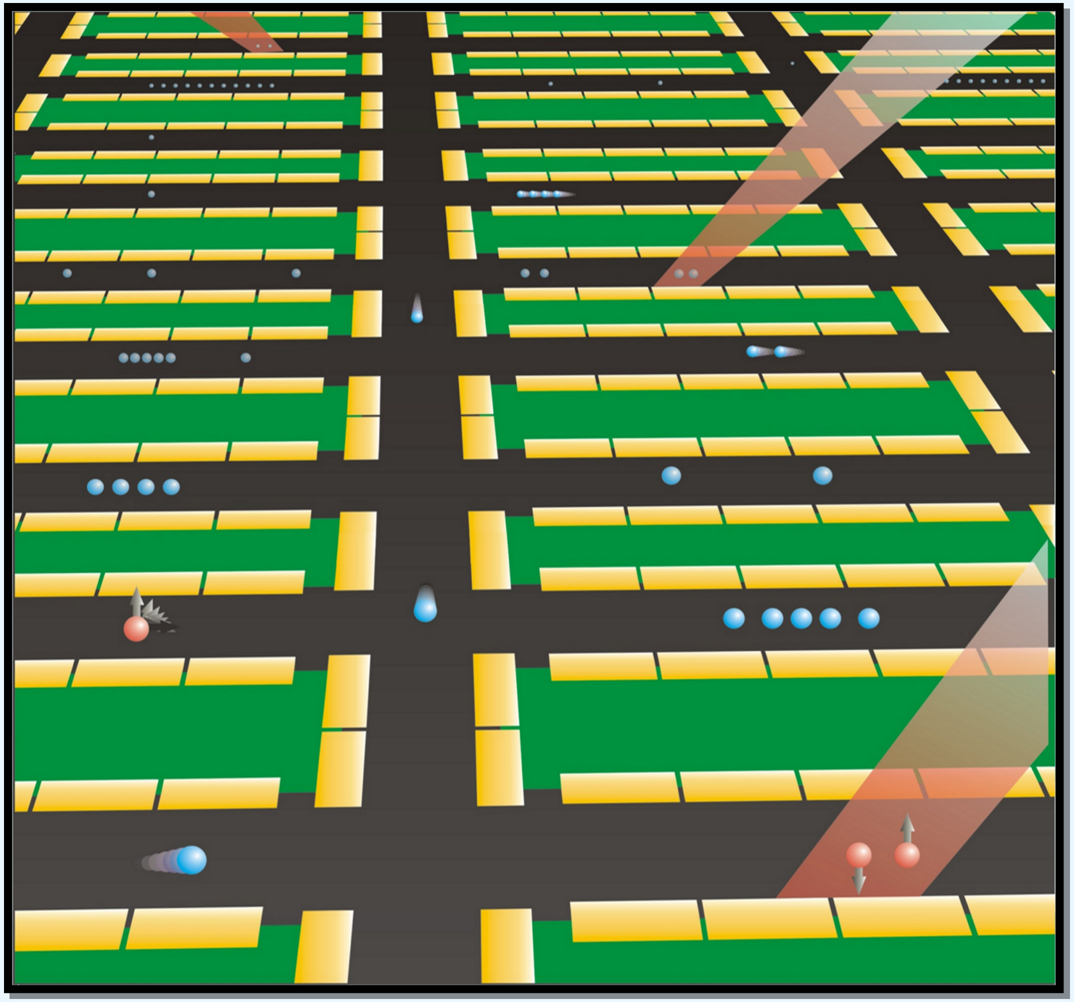
C. Ospelkaus, *et al*, *Phys. Rev. Lett.* **101** 090502 (2008)



More channels of classical control

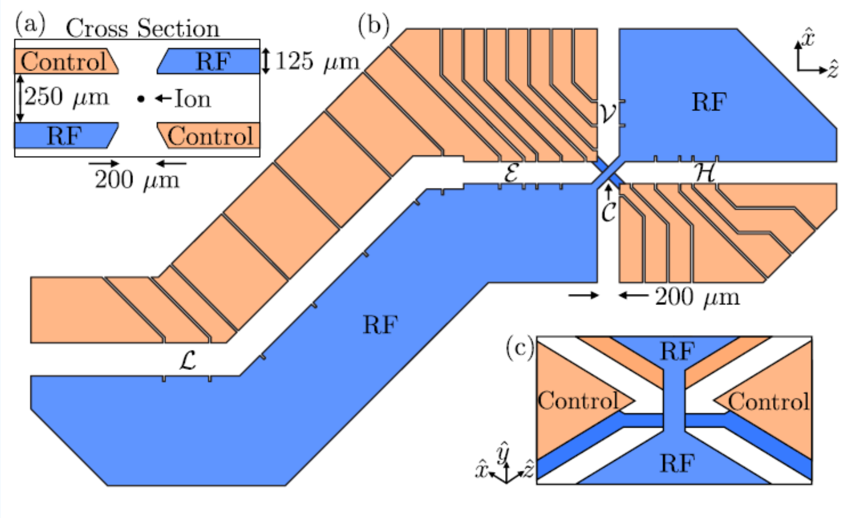
- Frequency sources (rf & laser)
- Analog voltage sources
- Controllers (FPGAs)
- Detectors

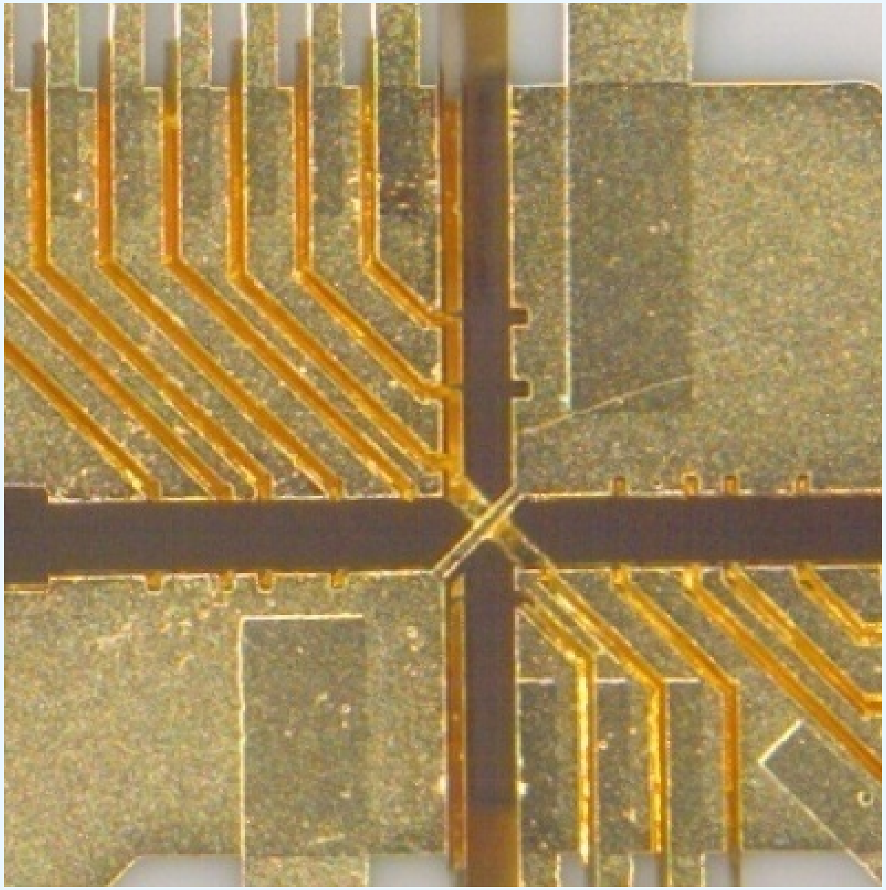
Scaling up ion traps



- Dedicated components
- Fabrication techniques / materials

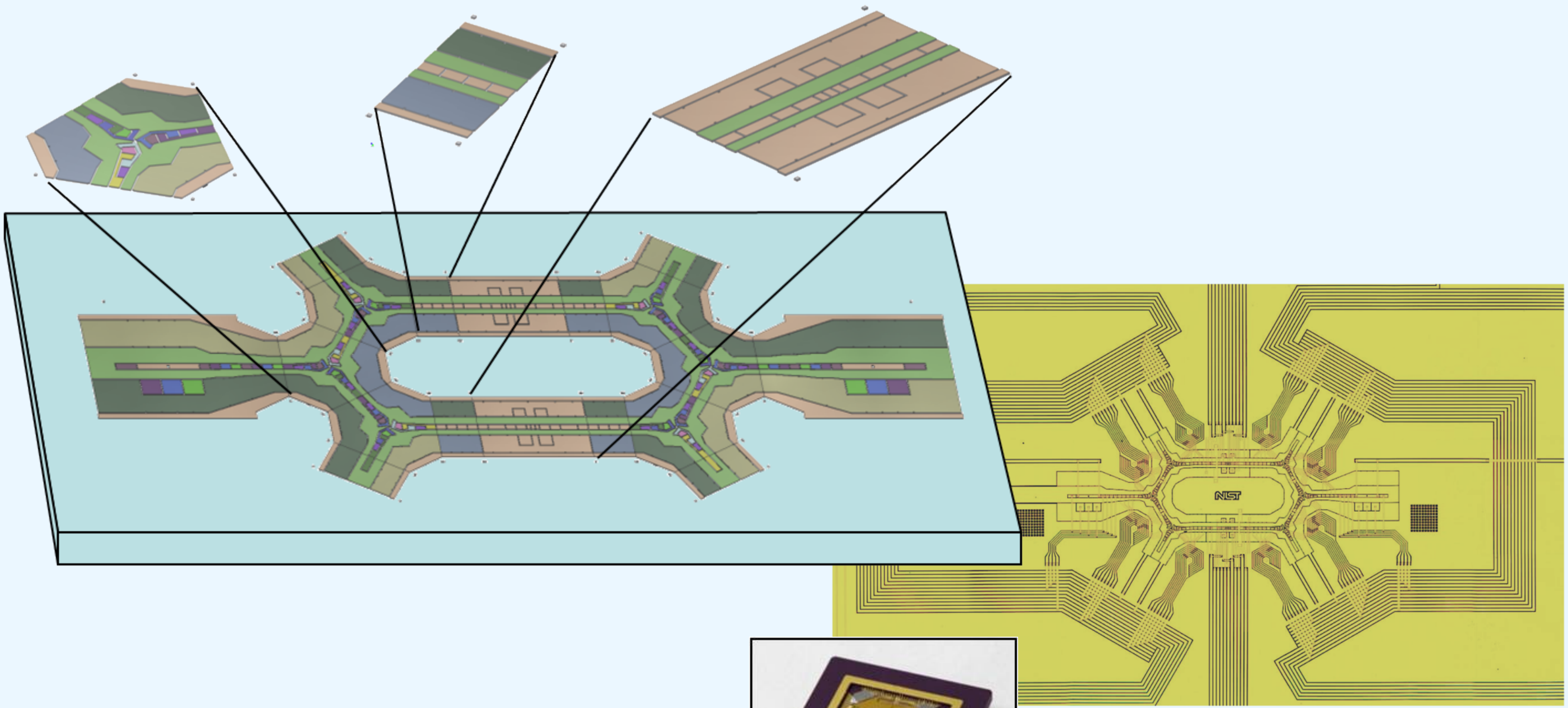
X-junction



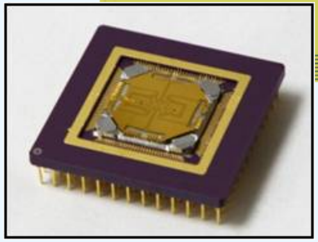


R. B. Blakestad, *et al*, *PRL* **102** 153002 (2009)

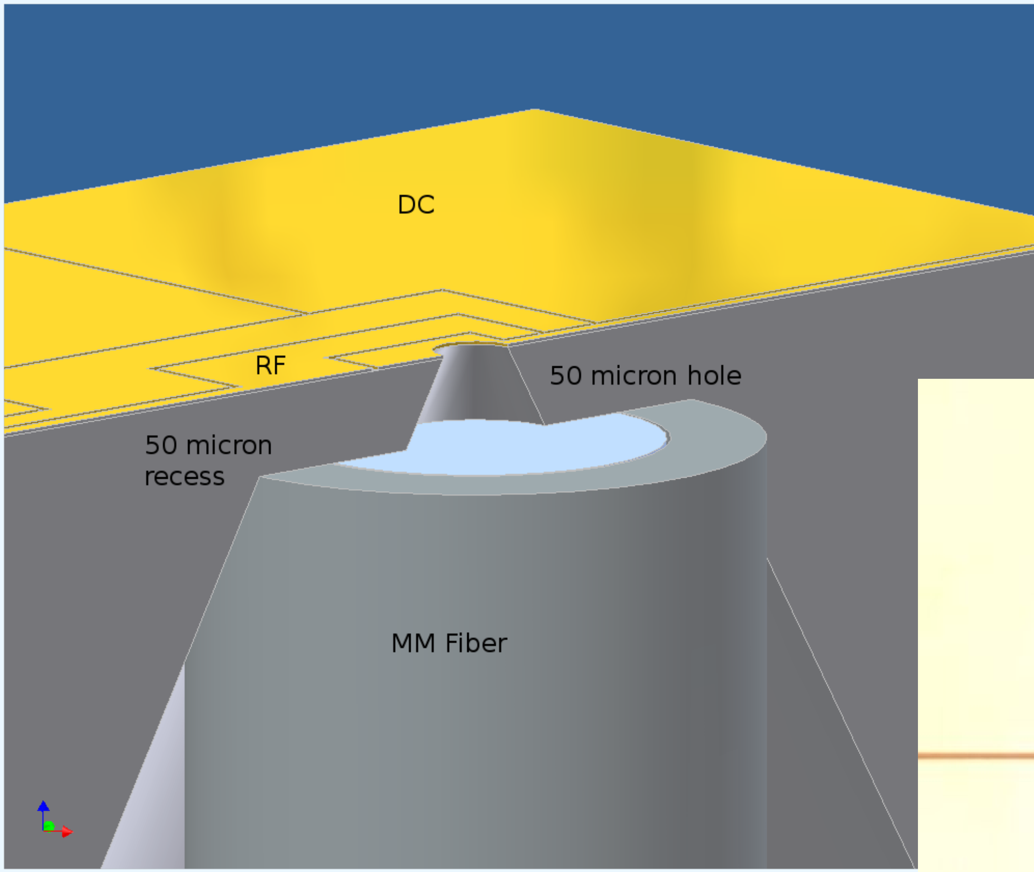
Trap component library



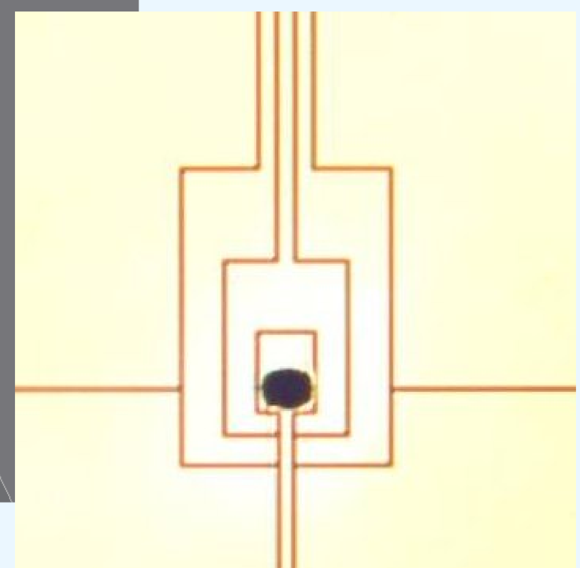
J. M. Amini, *et al*, arXiv:0909.2464



Integrated Fiber Optics

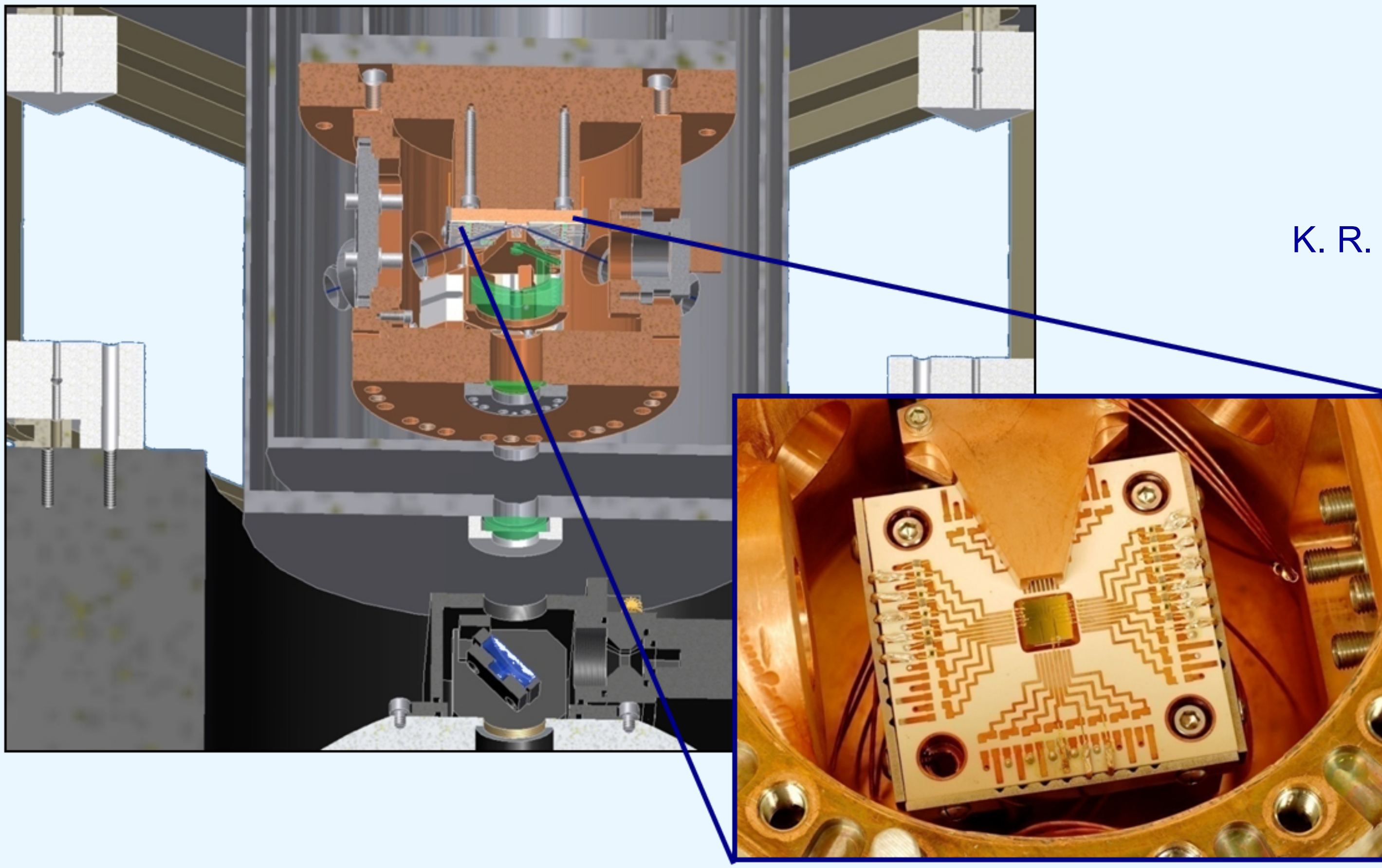


A. P. VanDevender
Y. Colombe



Towards scaled processing

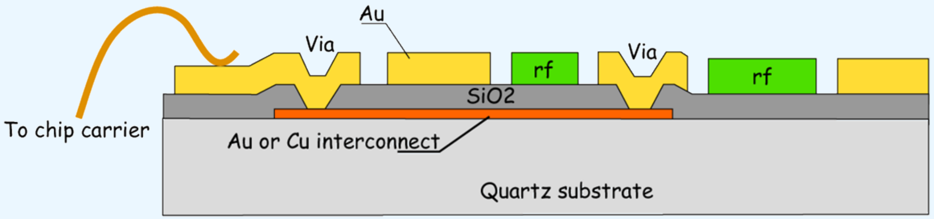
Cryogenic Trap



K. R. Brown

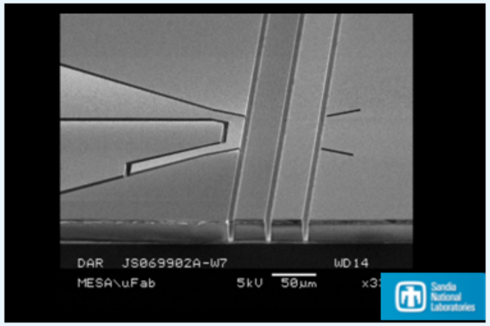
Materials and fab techniques

Multilayer gold on quartz



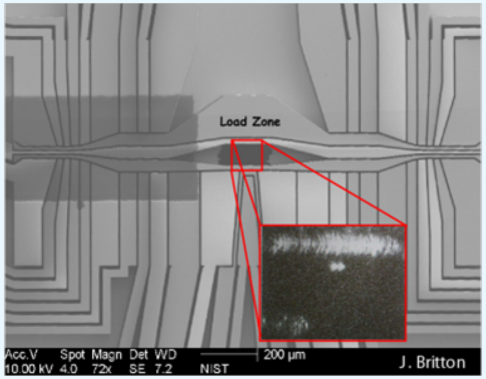
J. M. Amini, *et al*, arXiv:0909.2464

Al, SiO_2 on Si



Collaboration with Sandia National Labs

Doped Si



J. Britton, *et al*, *Appl. Phys. Lett.* **95** 173102 (2009)