Naturwissenschaftlich-Technische Fakultät
Department Physik

UNIVERSITÄT SIEGEN

Quantum Information Science with Atomic Trapped Ions

An Introduction

Christof Wunderlich

PRELUDE

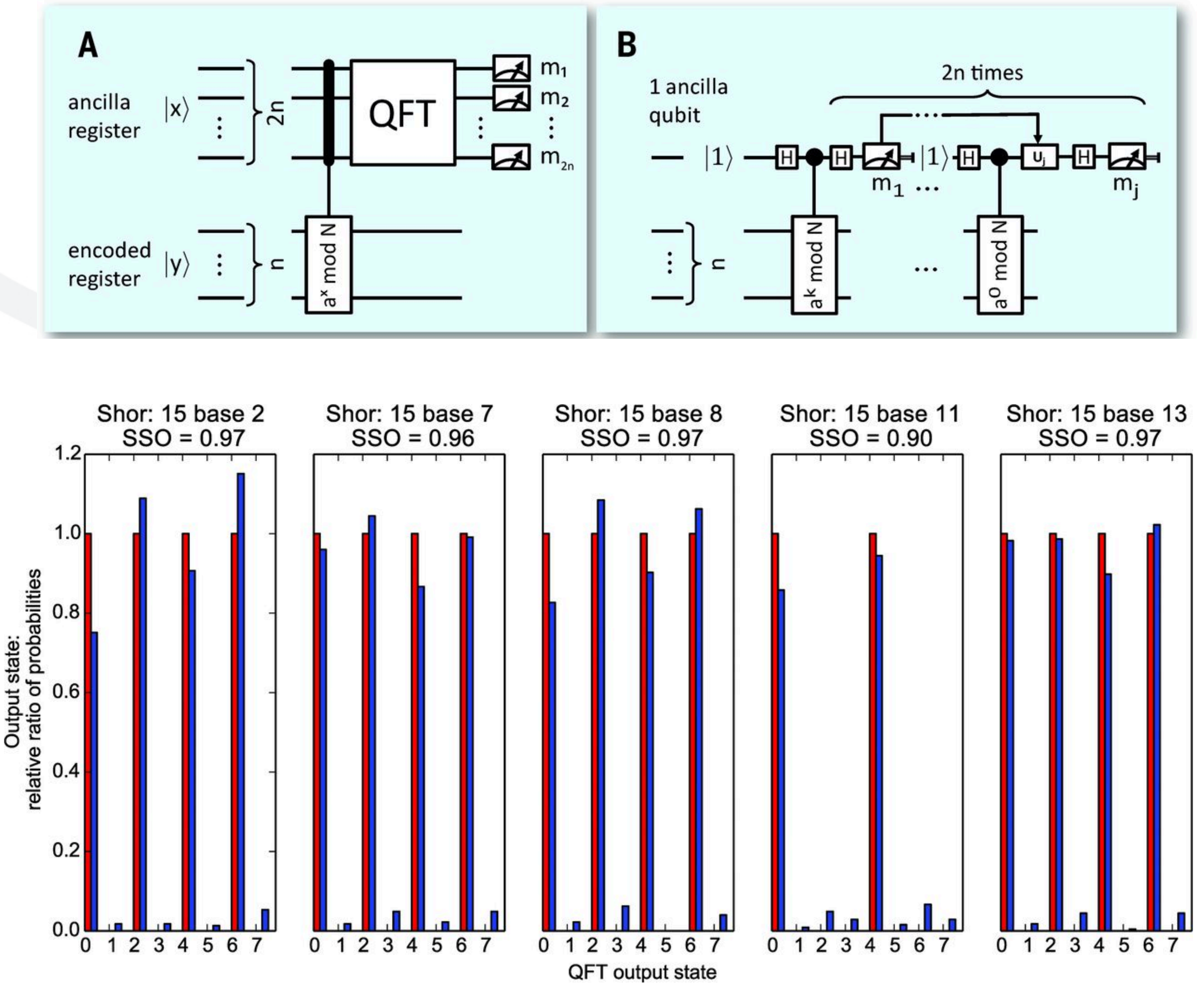
INTRODUCTION

TRAPPING AND QUBITS

INTERACTING IONS

PRELUDE

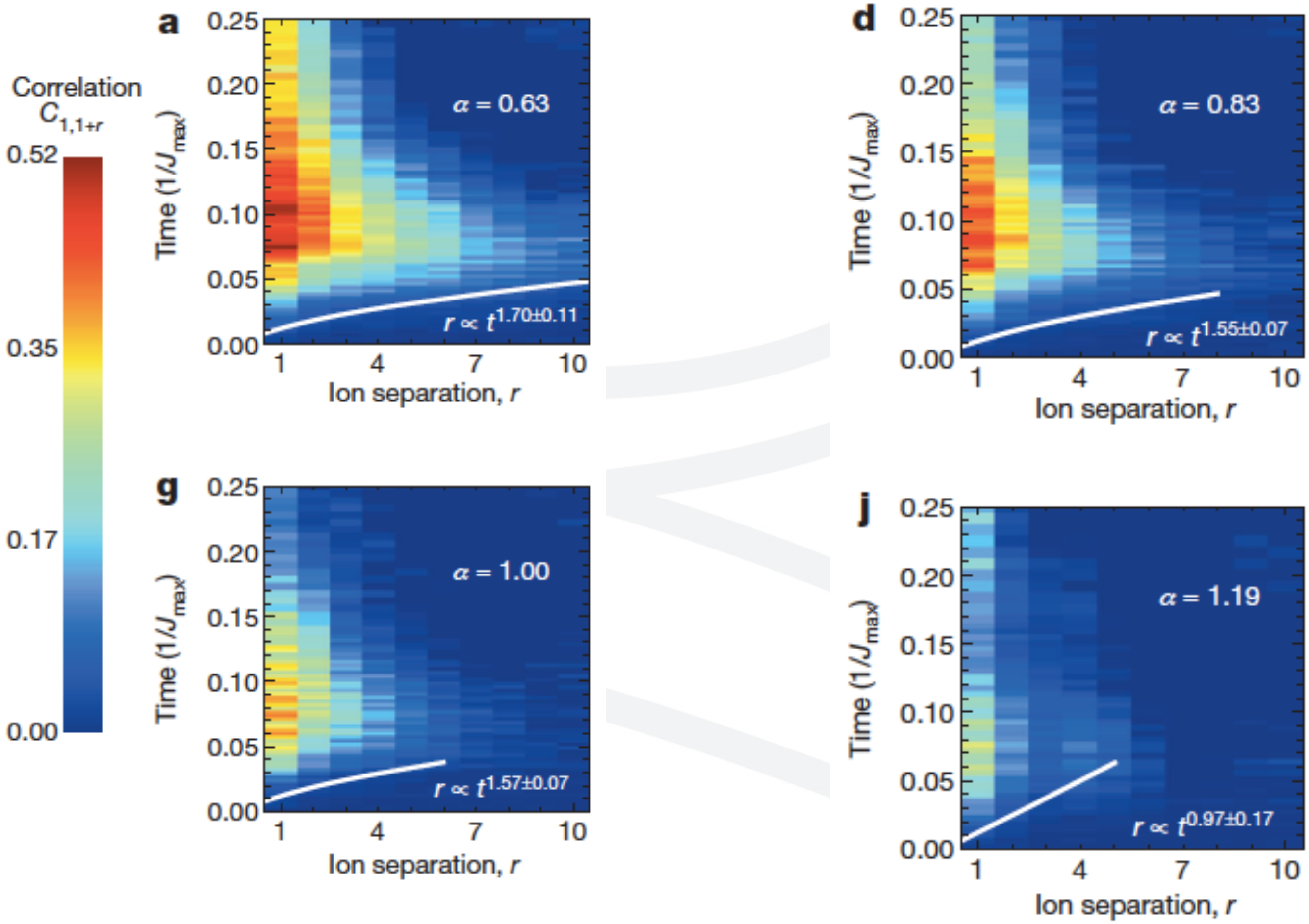
5-Qubit Trapped Ion Quantum Computer
Example



Th. Monz et al., Science **351**, 1068 (2016)

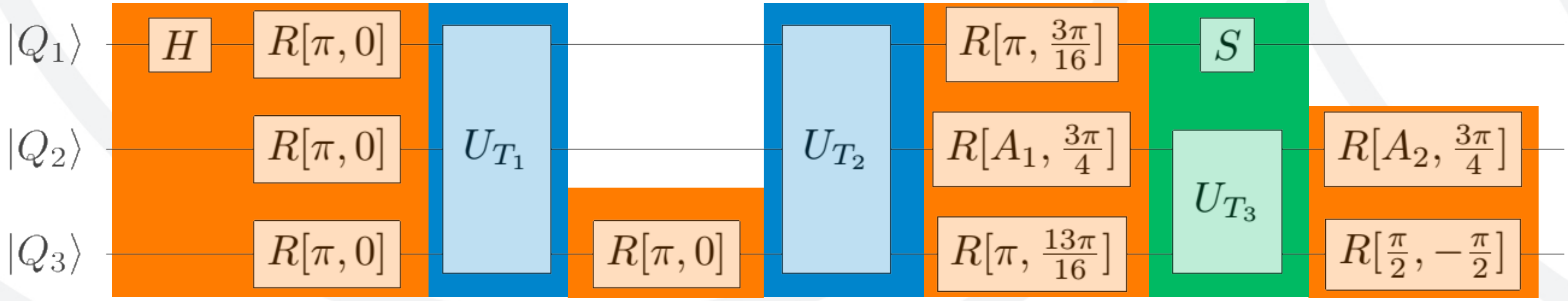
Optical Spin-Spin Interaction

Entanglement Propagation after Global Quench

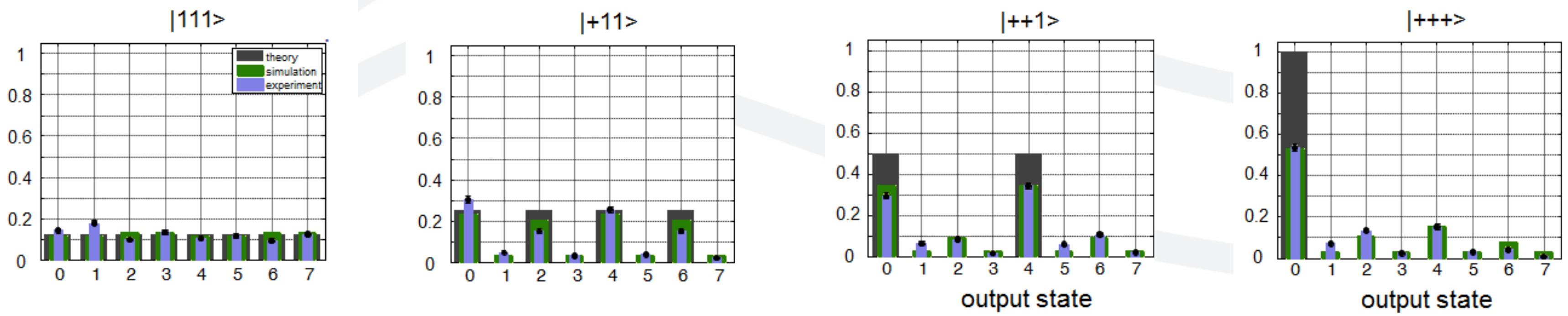


P. Richerme et al., Nature **511** (2014).

Coherent QFT Using MAGIC



- Total time of QFT≈ time for one CNOT gate



Science Advances **2** (2016)

INTRODUCTION

Structure of Matter?

	Atom: Indivisible	**Plenist view**

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≈ 450 – 300 bC	Leukipp, Demokrit	Platon, Aristoteles
≈ 1600 - 1900	Gassendi, Jungius, Newton, Bernoulli, Richter, Dalton, …	Descartes, Leibniz, … Mach, Planck, …

Structure of Matter?

	Atom: Indivisible	**Plenist view**
≈ 450 - 300 bC	Leukipp, Demokrit	Platon, Aristoteles
≈ 1650 - 1900	Gassendi, Jungius, Newton, Bernoulli, Richter, Dalton, …	Descartes, Leibniz, … Mach, Planck, …

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	Atom: Indivisible	**Plenist view**
≈ 450 bC	Leukipp, Demokrit	Platon, Aristoteles
≈ 1650 - ≈1900	Gassendi, Jungius, Newton, Bernoulli, Richter, Dalton, …	Descartes, Leibniz, … Mach, Planck, …
≈ 1910	…, Rutherford, Bohr, …	Mach, …

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≈ 1910	…, Rutherford, Bohr, …	Mach: "Who has seen these atoms?"

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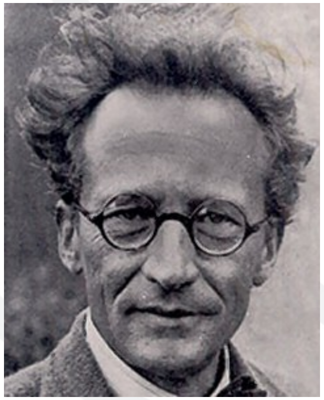
≈ 1910	…, Rutherford, Bohr, …	Mach: "Who has seen these atoms?" („Ham`S scho eins g`sehn?")

A single atom



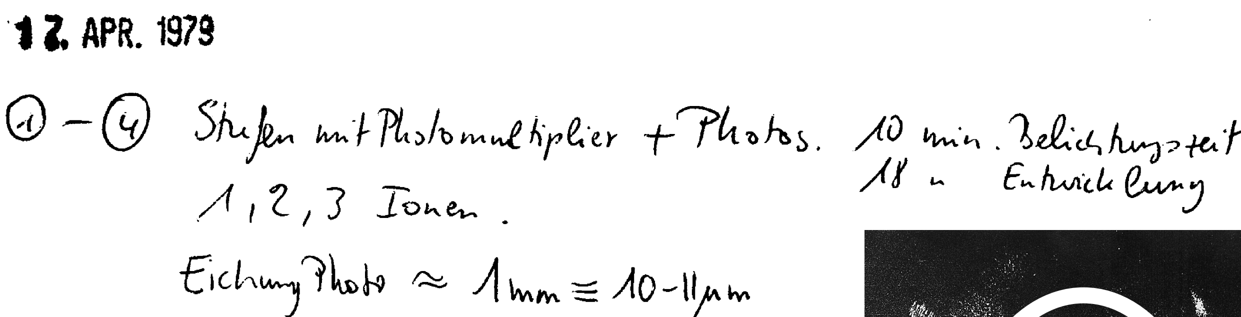
E. Schrödinger:

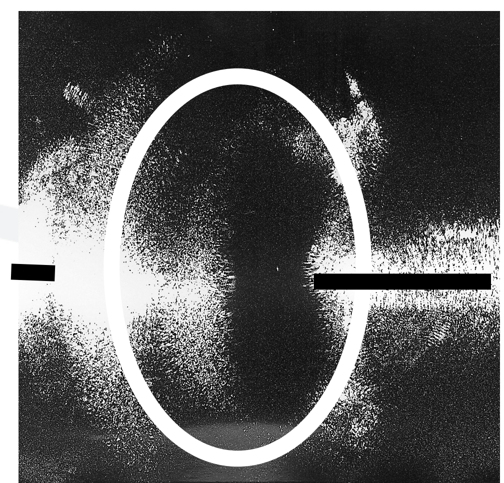
… we *never* experiment with just *one* electron or atom ...

... we are not *experimenting* with single particles, any more than we can raise Ichthyosauria in the zoo.

Br. J. Philos. Sci. III, August 1952.

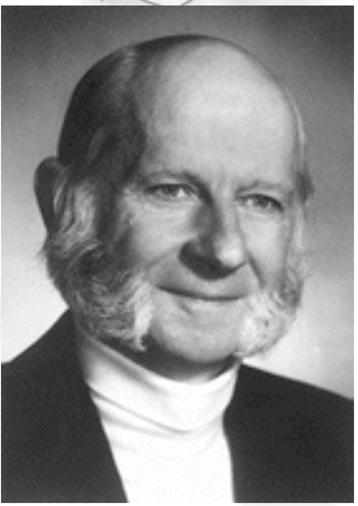
W. Neuhauser *et al.*: Single Barium-Ion





W. Neuhauser, M. Hohenstatt, P. E. Toschek, H.G. Dehmelt, Phys. Rev. A **22**, 1137 (1980).

Trapped Atoms



H. Dehmelt
Nobel Prize 1989

VOLUME 41, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JULY 1978

Optical-Sideband Cooling of Visible Atom Cloud Confined in Parabolic Well

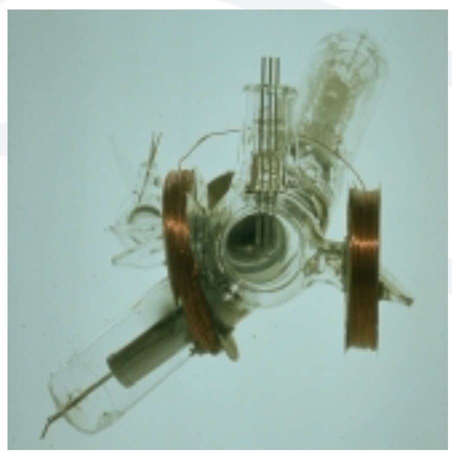
W. Neuhauser, M. Hohenstatt, and P. Toschek
Institut für Angewandte Physik I der Universität Heidelberg, D-69 Heidelberg, West Germany

and

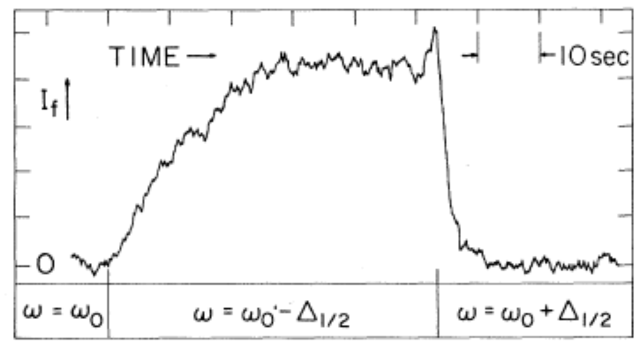
H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 25 April 1978)

An assemblage of < 50 Ba^+ ions, contained in a parabolic well, has been visually observed and cooled by means of near-resonant laser irradiation.

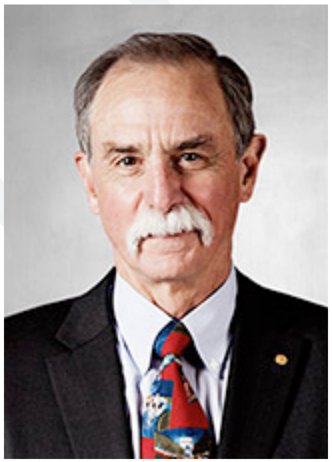
P. E. Toschek



Deutsches Museum Bonn



Trapped Atoms



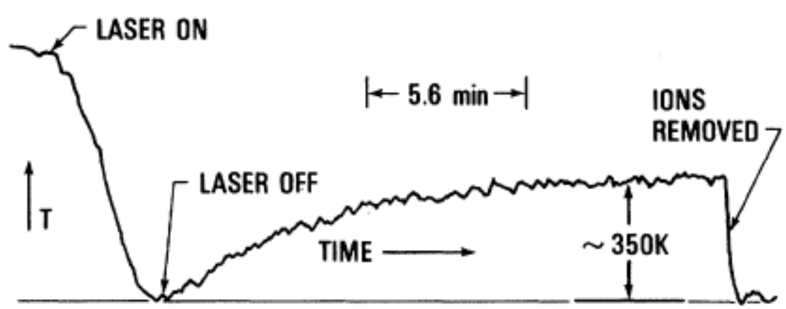
D. Wineland
Nobel Prize 2012

Volume 40, Number 25 PHYSICAL REVIEW LETTERS 19 June 1978

Radiation-Pressure Cooling of Bound Resonant Absorbers

D. J. Wineland, R. E. Drullinger, and F. L. Walls
Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80303
(Received 26 April 1978)

We report the first observation of radiation-pressure cooling on a system of resonant absorbers which are elastically bound to a laboratory fixed apparatus. Mg II ions confined in a Penning electromagnetic trap are cooled to <40 K by irradiating them with the 8-μW output of a frequency doubled, single-mode dye laser tuned to the low-frequency side of the Doppler profile on the $^2S_{1/2} \leftrightarrow {}^2P_{3/2}$ ($M_J = +\frac{1}{2} \leftrightarrow M_J = +\frac{3}{2}$ or $M_J = -\frac{1}{2} \leftrightarrow M_J = -\frac{3}{2}$) transitions. Cooling to approximately 10^{-3} K should be possible.



Individual Trapped Ions

Time and Frequency: Example

- Trapping ⇒ first-order Doppler shift → 0
- Trapping + laser cooling ⇒ time dilation → 0
- High vacuum at low temperature ⇒ environmental perturbations (collisions, black body shifts, ...) → 0

David Wineland
Nobel Prize 2012

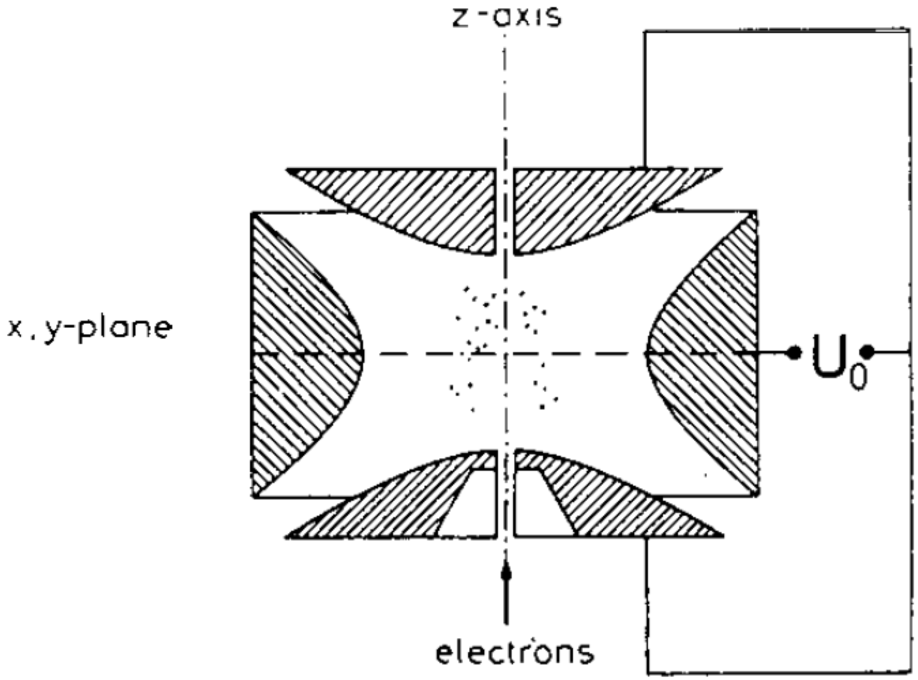
TABLE I. Systematic effects that shift the clock from its ideal unperturbed frequency. Shifts and uncertainties given are in fractional frequency units ($\Delta\nu/\nu$). See text for discussion.

Effect	Shift (10^{-18})	Uncertainty (10^{-18})
Excess micromotion	−9	6
Secular motion	−16.3	5
Blackbody radiation shift	−9	3
Cooling laser Stark shift	−3.6	1.5
Quad. Zeeman shift	−1079.9	0.7
Linear Doppler shift	0	0.3
Clock laser Stark shift	0	0.2
Background-gas collisions	0	0.5
AOM freq. error	0	0.2
Total	−1117.8	8.6

C. W. Chou et al., PRL **104** (2010)

Trapped Atoms

W. Paul
Nobel Prize 1989



First ion trap 1955
W. Paul, Rev. Mod. Phys **6**, 531 (1990).

Individual Trapped Ions

- Localized: ≈ 10 nm
- Laser cooled: μK – mK
- Individual quantum objects prepared deterministically
- Deterministic interaction
- Long Storage Time
- Variable Size

Individual Trapped Ions

Some Research Fields

- Clocks, O(10^{-18})
- Change in time of natural constants?
- Anti-H spectroscopy
- Molecular spectroscopy
- Chemical reactions
- Quantum Information Science
- …

Individual Trapped Ions

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- Clocks, $O(10^{-18})$
- Change in time of natural constants?
- Anti-H spectroscopy
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- Chemical reactions
- **Quantum Information Science**
- ...

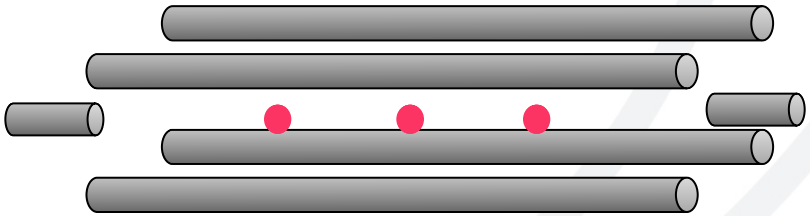
Individual Trapped Ions

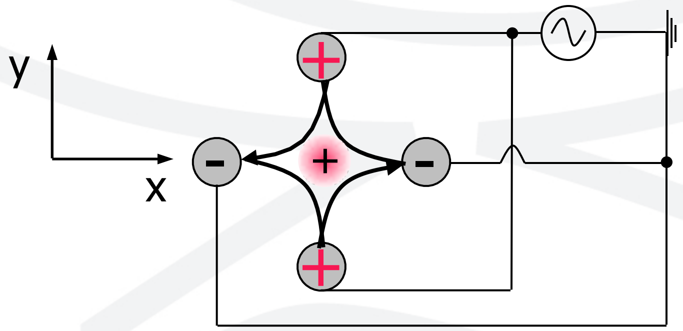
Quantum Information Science

- Fundamental Questions of Quantum Physics
  - Measurement Process
  - Quantum / Classical
  - Entanglement
- Universal Quantum Computation
- Quantum Simulation
- Precision Measurements

TRAPPING AND QUBITS

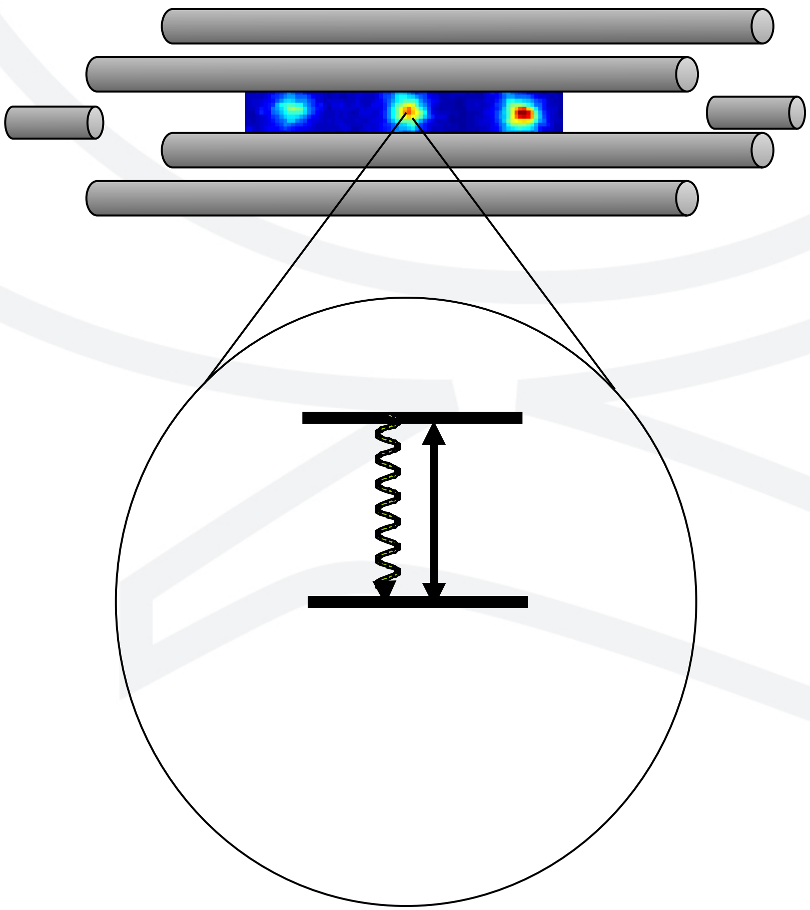
Generic Paul Trap





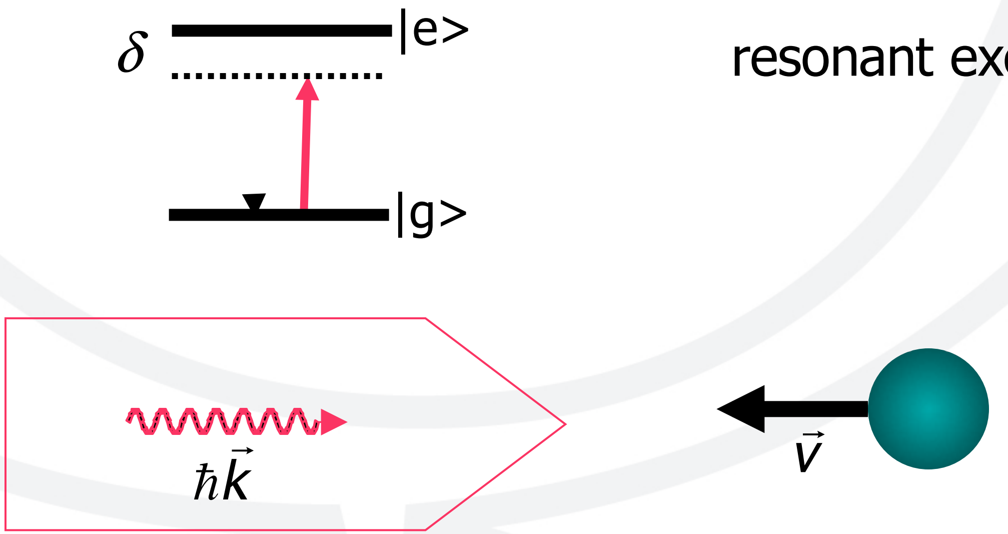
Trapping ions
Cooling and Detection

Yb$^+$ ion crystal



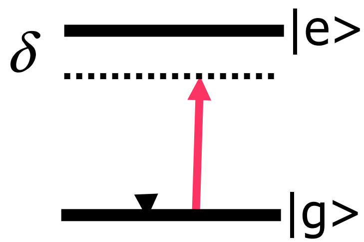
Fast (≈20MHz) dipole transition:
- Detect resonance fluorescence
- Cooling.

Doppler Cooling



resonant excitation for $\delta \cong \vec{k} \bullet \vec{v}$

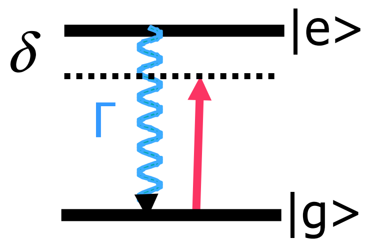
Doppler Cooling



resonant excitation for $\delta \cong \vec{k} \bullet \vec{v}$

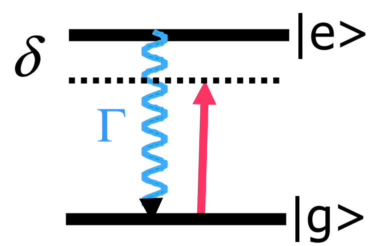
change of velocity $\Delta\vec{v} \cong \hbar\vec{k} / m$

Doppler Cooling

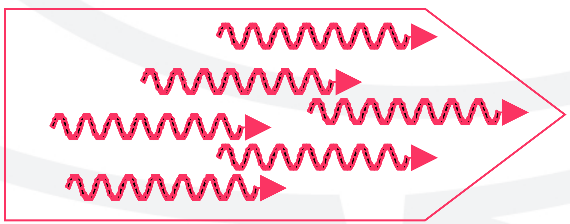


spontaneous emission with rate Γ

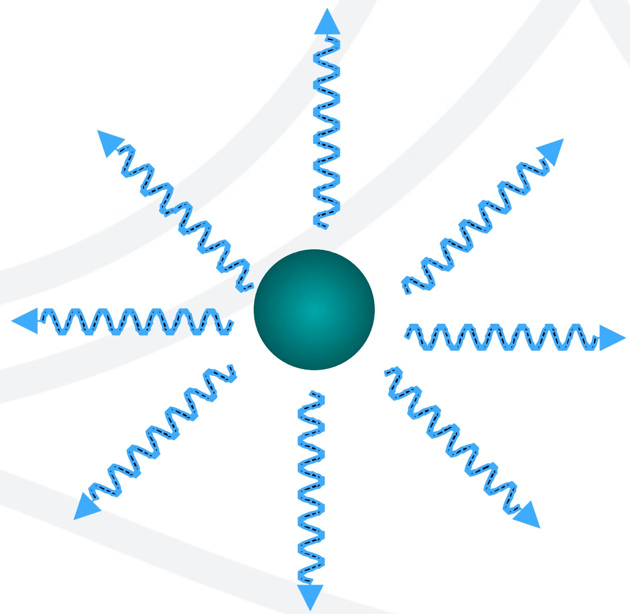
Doppler Cooling $\Gamma \gg \nu$



spontaneous emission with rate Γ



$n \times \hbar\vec{k}, \quad n \in \mathbb{N}$



Absorption: $\Delta\vec{p}_A = n \times \hbar\vec{k}$

Emission: $\langle \Delta\vec{p}_E \rangle = 0$

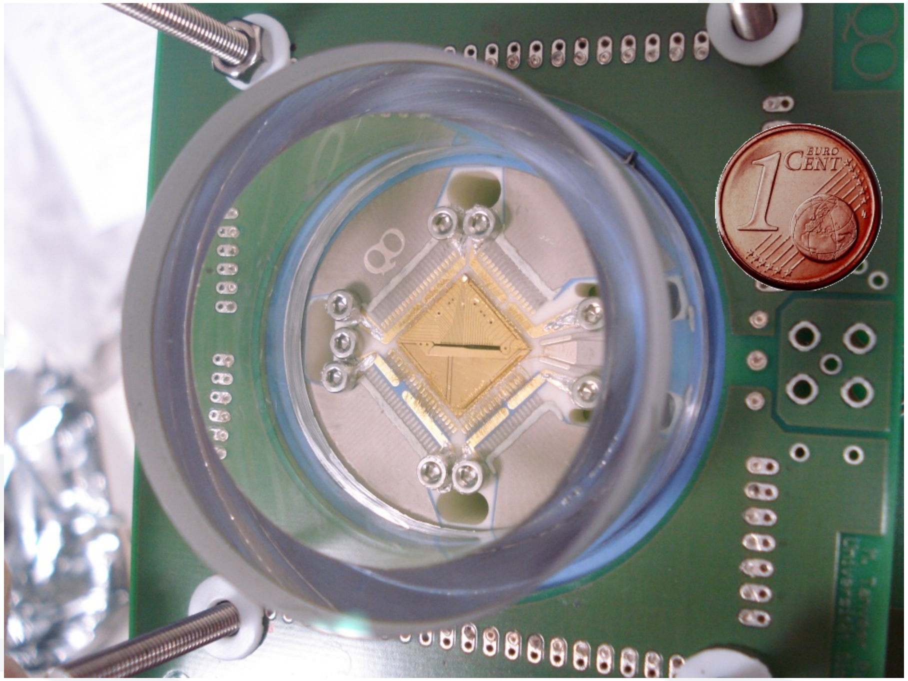
Diffusion in momentum space

limits final temperature: $k_B T = \hbar\Gamma / 2$

Ex.: $\nu = 1\text{MHz}, \ \Gamma = 20\text{MHz} \ \Rightarrow \langle \text{n} \rangle_{\text{thermal}} \approx 10$

S. Stenholm, Rev.Mod. Phys. **58**, 699 (1986).

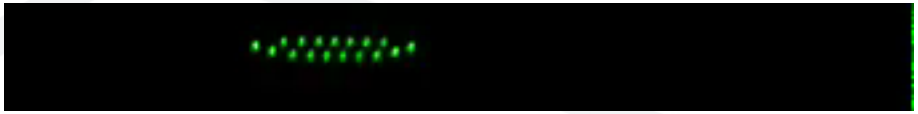
Example: Micro-structured 3-d trap



Appl. Phys. B **107** (2012); also S. A. Schulz et al., NJP **10**, 045007 (2008).

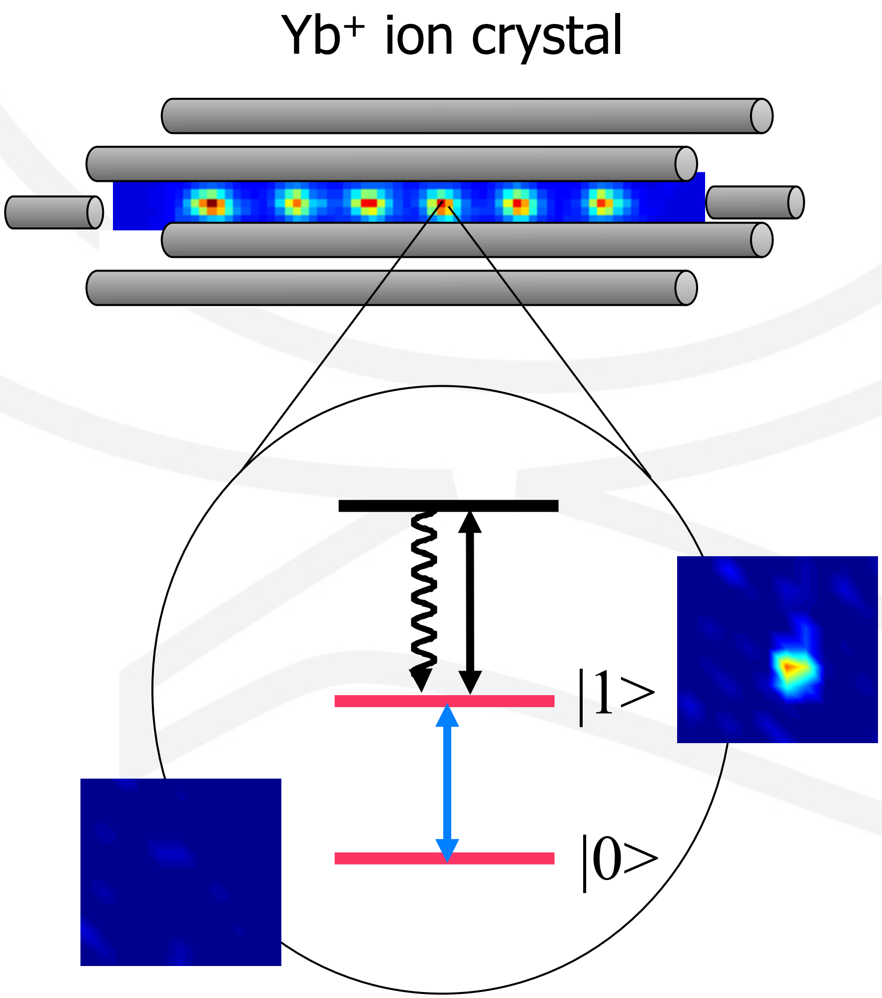
[redacted]

Individual Trapped Ions



Trapped Ions for QIS

Qubits

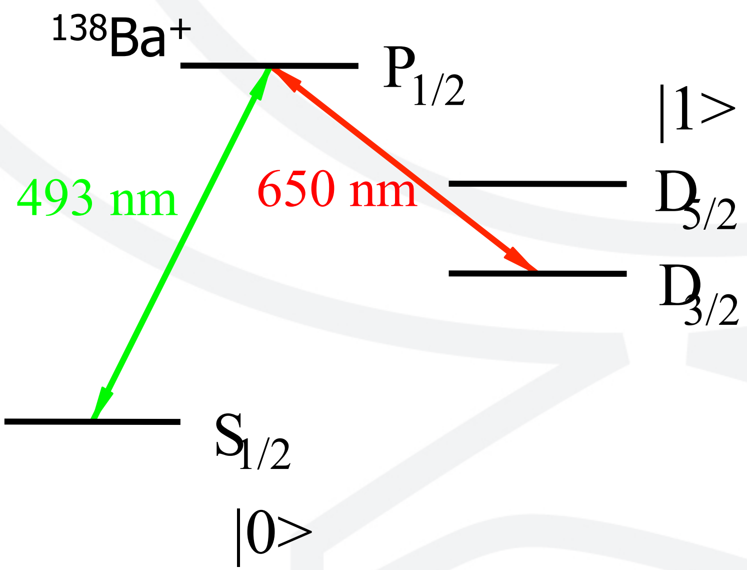


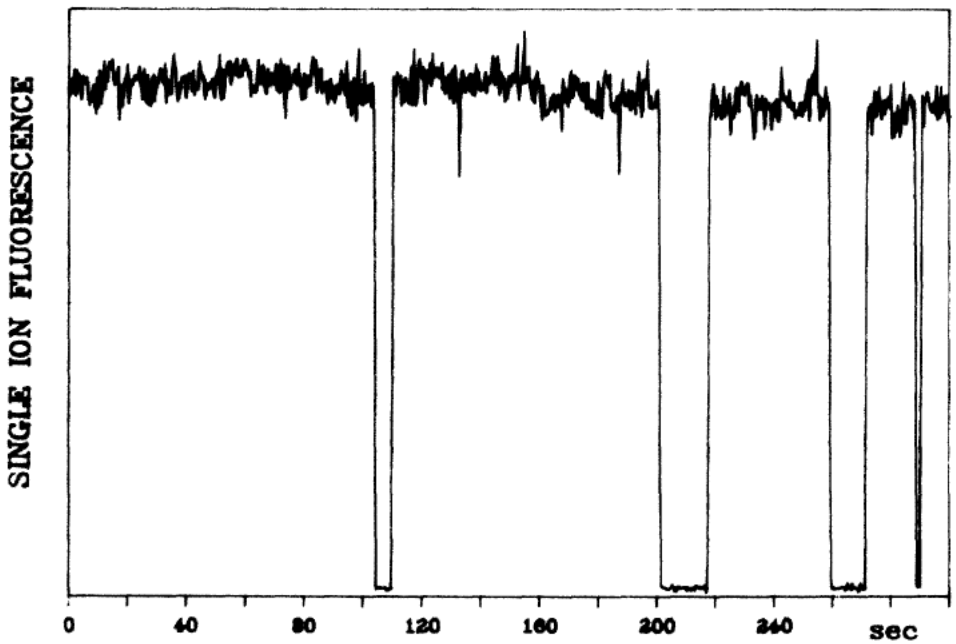
Dipole transition:
- Detect resonance fluorescence
- Cooling.

Long-lived internal states serve as qubits (spin-1/2).

State selective detection:
Projective measurement of *individual* qubits.

State selective detection



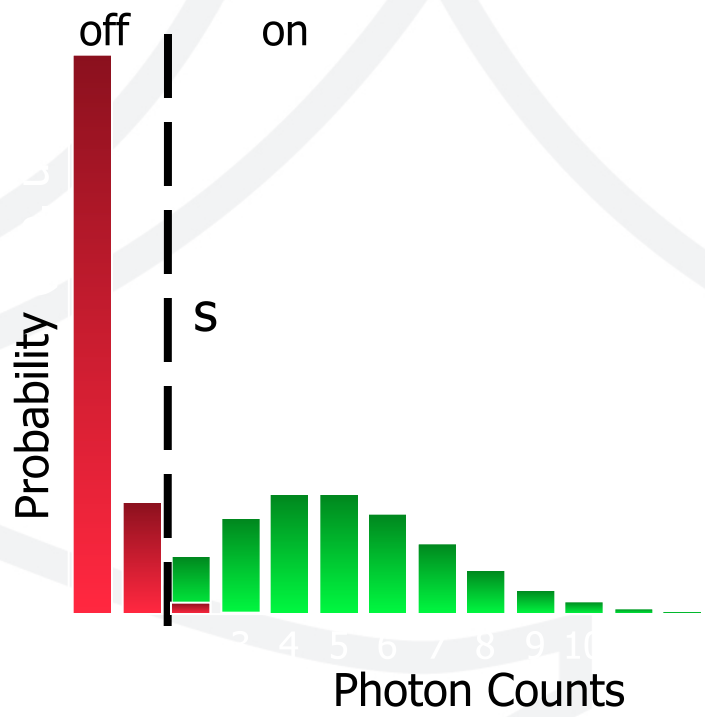


T. Sauter, W. Neuhauser, R. Blatt, P.E. Toschek, PRL **57** (1986).

State selective detection

- Poisson Distribution
- Background Light

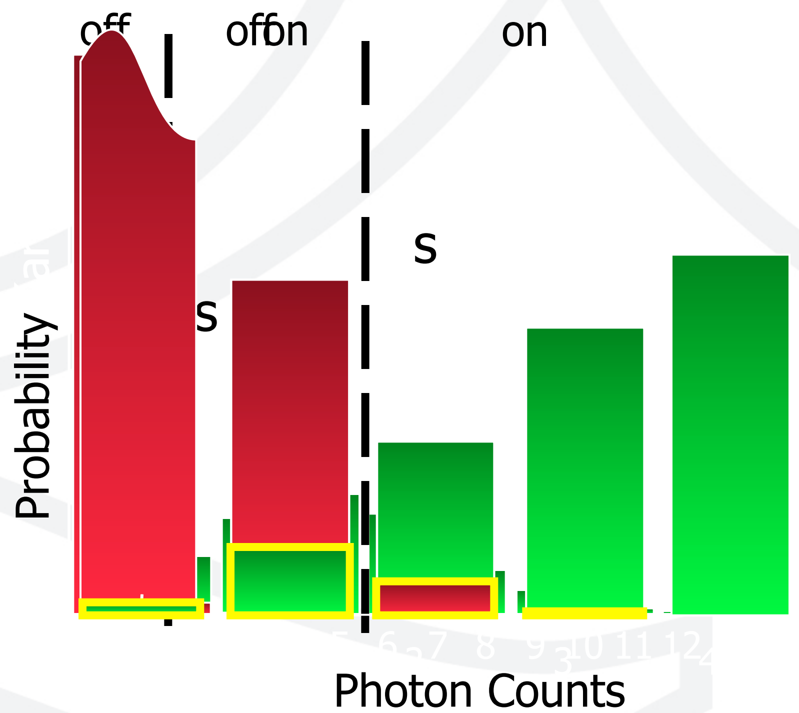
Threshold: s



State selective detection

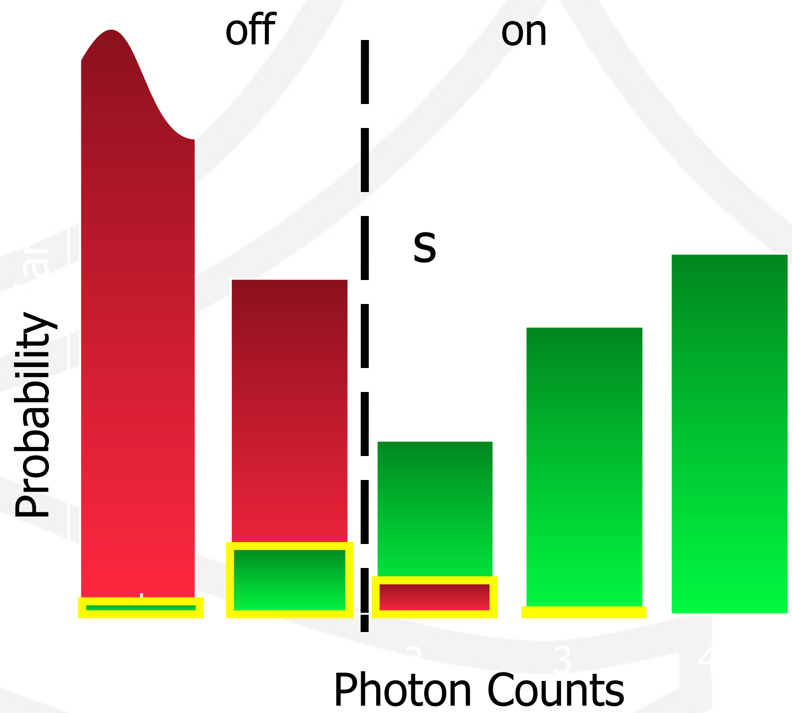
- Poissonian Distribution
- Background Light

Threshold: s



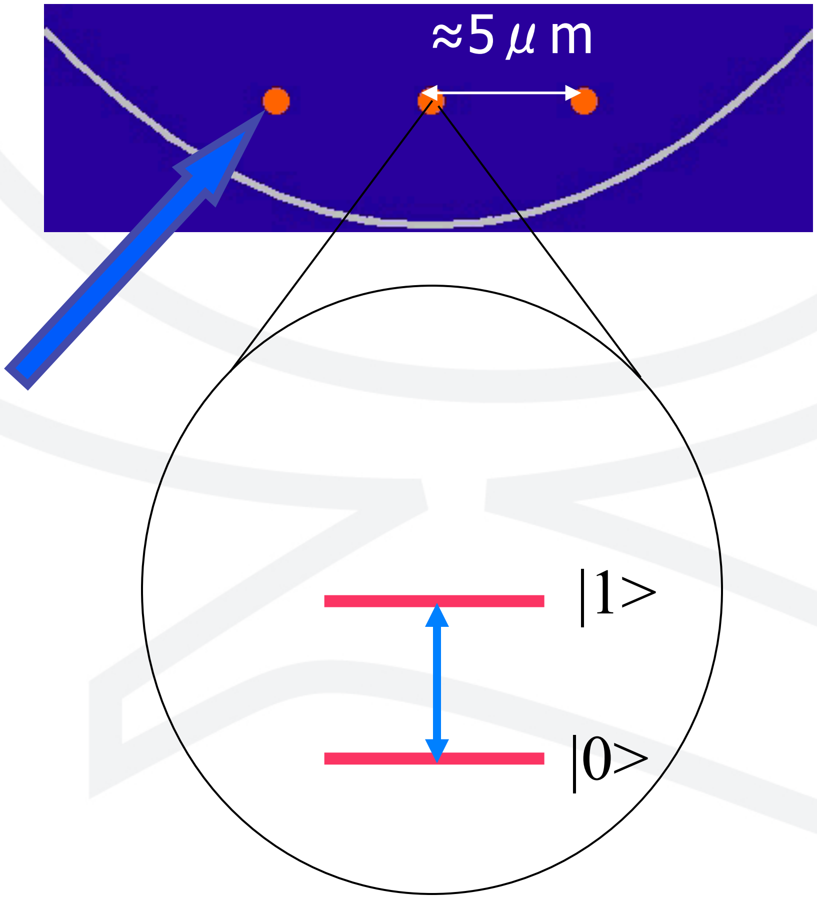
State selective detection

- Wrong Assignments



Trapped Ions for QIS

Single Qubit Gates

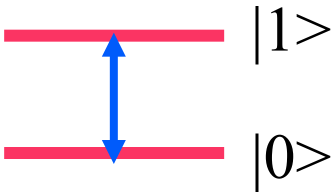


Electromagnetic radiation for ...

- ... **Addressing** individual qubits

$\Rightarrow$ optical wavelengths

Single Qubit Gate



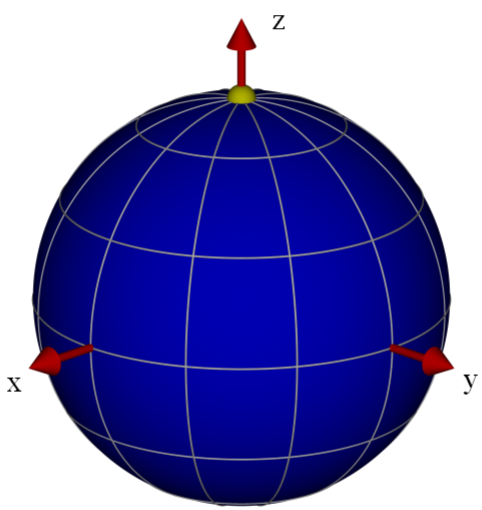
$$\omega_L = \omega$$

$$\Rightarrow \tilde{H}_L = \frac{1}{2}\hbar\Omega_R\left(\sigma_+ e^{i\phi} + \sigma_- e^{-i\phi}\right)$$

Rabi frequency $\Omega_R \equiv d_{eg} \cdot F_0 / \hbar$

Time evolution operator (interaction picture) $U(t) = \exp\left(-\frac{i}{\hbar}\tilde{H}_L t\right)$

With $\phi = 0$: $\mathrm{U}(\vartheta) = \exp(-\mathrm{i}\frac{\vartheta}{2}\sigma_x) = \begin{pmatrix} \cos\vartheta/2 & -\mathrm{i}\sin\vartheta/2 \\ -\mathrm{i}\sin\vartheta/2 & \cos\vartheta/2 \end{pmatrix}$ where $\vartheta \equiv \Omega t$



Single-Qubit Operations

• Single-shot readout fidelity > 99.9 %

Examples: A. H. Myerson et al., PRL **100**, 200502 (2008); R. Noek et al. Optics Lett. **38**, 4735 (2013)

• Single-qubit fidelity > 99.99 %

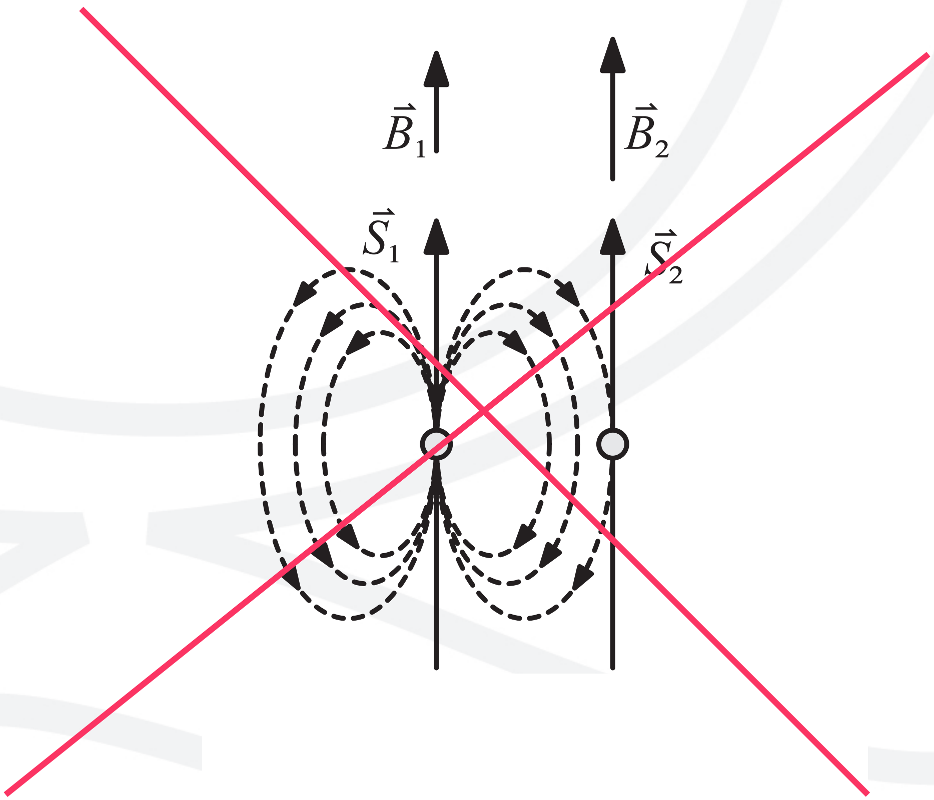
Examples: K. R. Brown et al., PRA **84**, 030303 (2011); T. P. Harty et al., PRL **113**, 220501 (2014)

• Coherence Time > 1 s

Examples: C. Langer, et al., PRL **95**, 060502 (2005), Timoney et al., Nature **476**, 185 (2011)

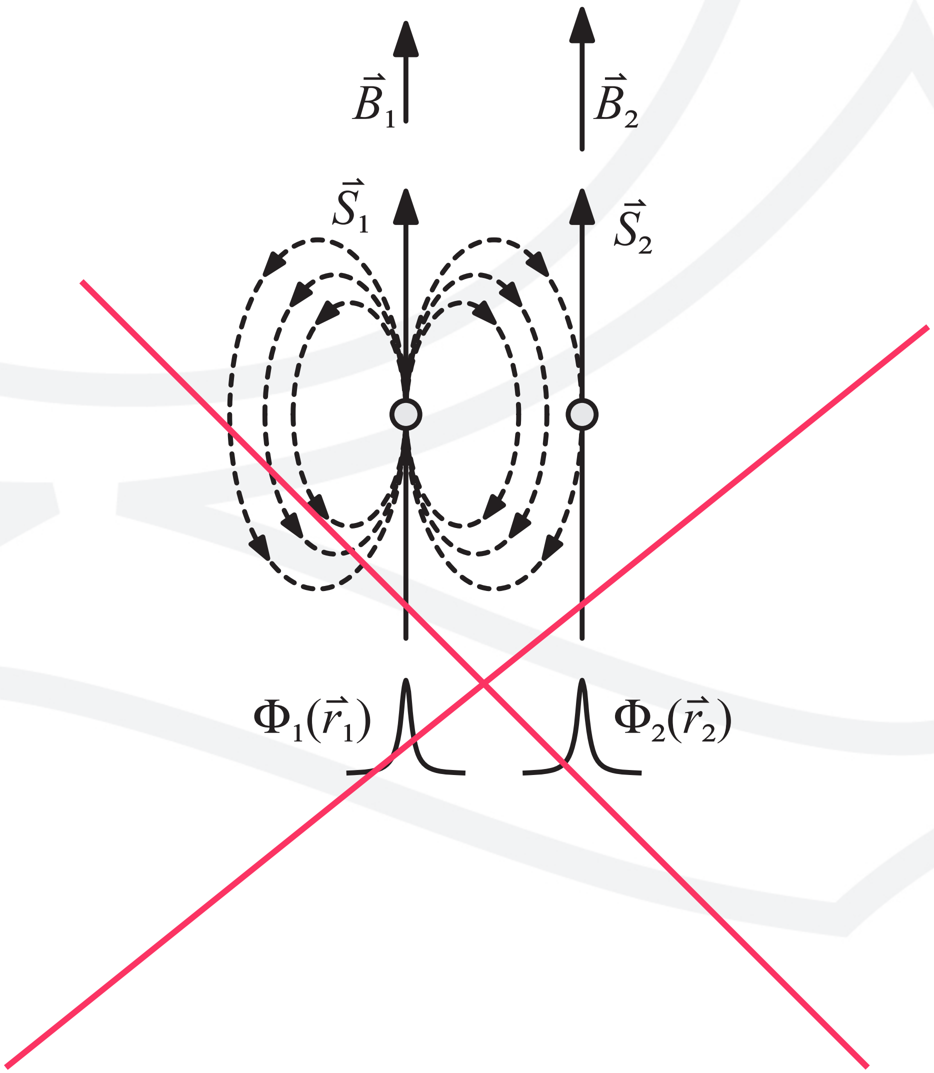
INTERACTING IONS

Direct Spin-Spin Interaction?



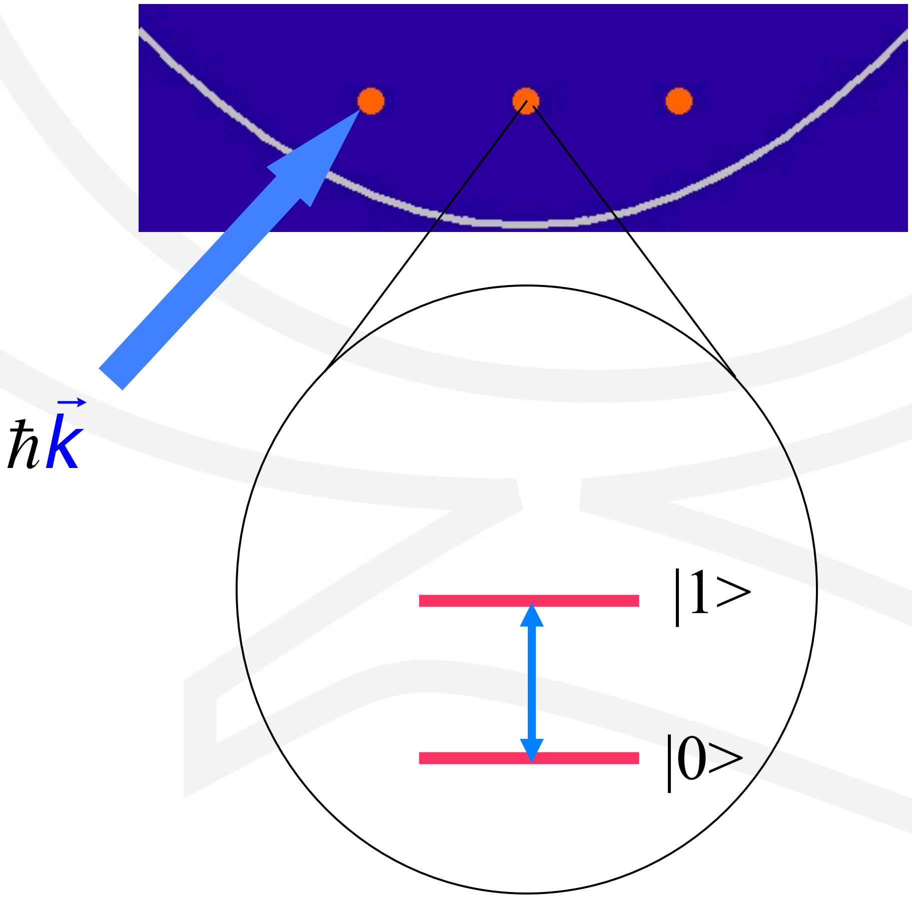
J. Phys. B **42,** 154009 (2009)

Exchange Interaction?



J. Phys. B **42,** 154009 (2009)

Conditional Dynamics using Laser Light



Electromagnetic radiation for

- **Coupling** internal and external degrees of freedom:

$$\text{need } \eta \equiv \frac{\hbar k}{2p_0}$$

$\Rightarrow$ optical wavelengths

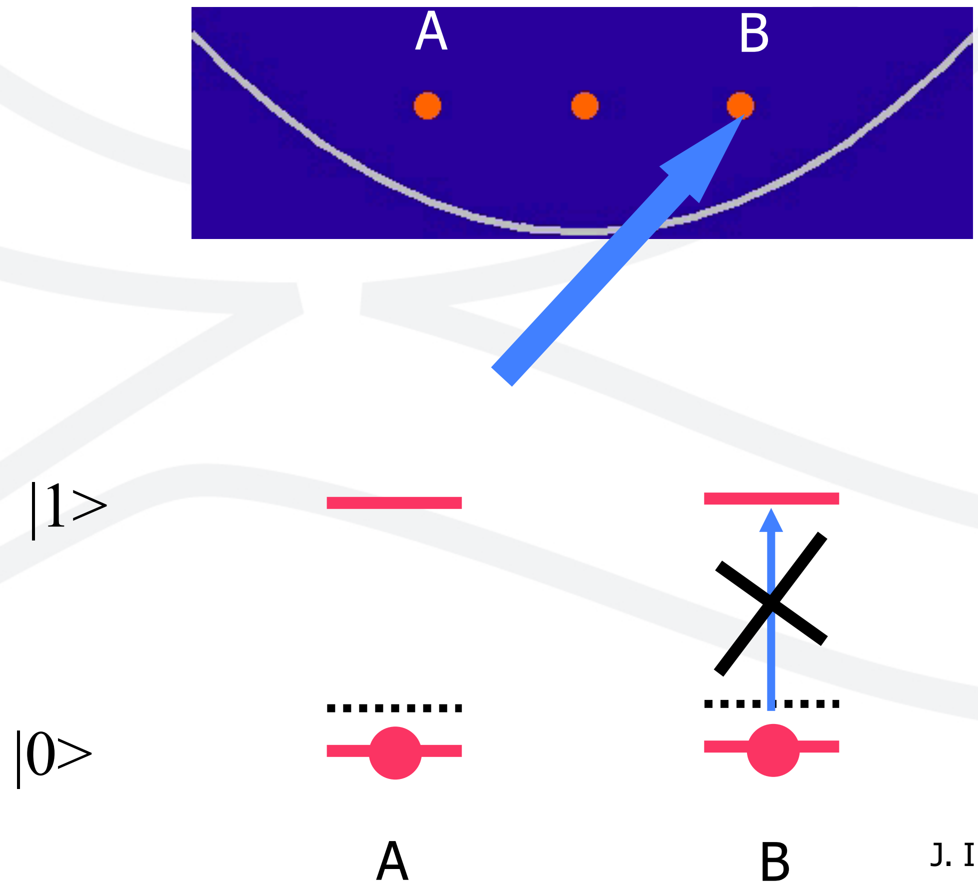
J. I. Cirac, P. Zoller, PRL **74**, 4091 (1995).
Schmidt-Kaler *et al.*, Nature **422**, 408 (2003)
A. Sørensen, and K. Mølmer, PRA **62**, 022311 (2000)
Leibfried *et al.*, Nature **422**, 412 (2003).

Conditional Quantum Dynamics

A	B
0	0
0	1

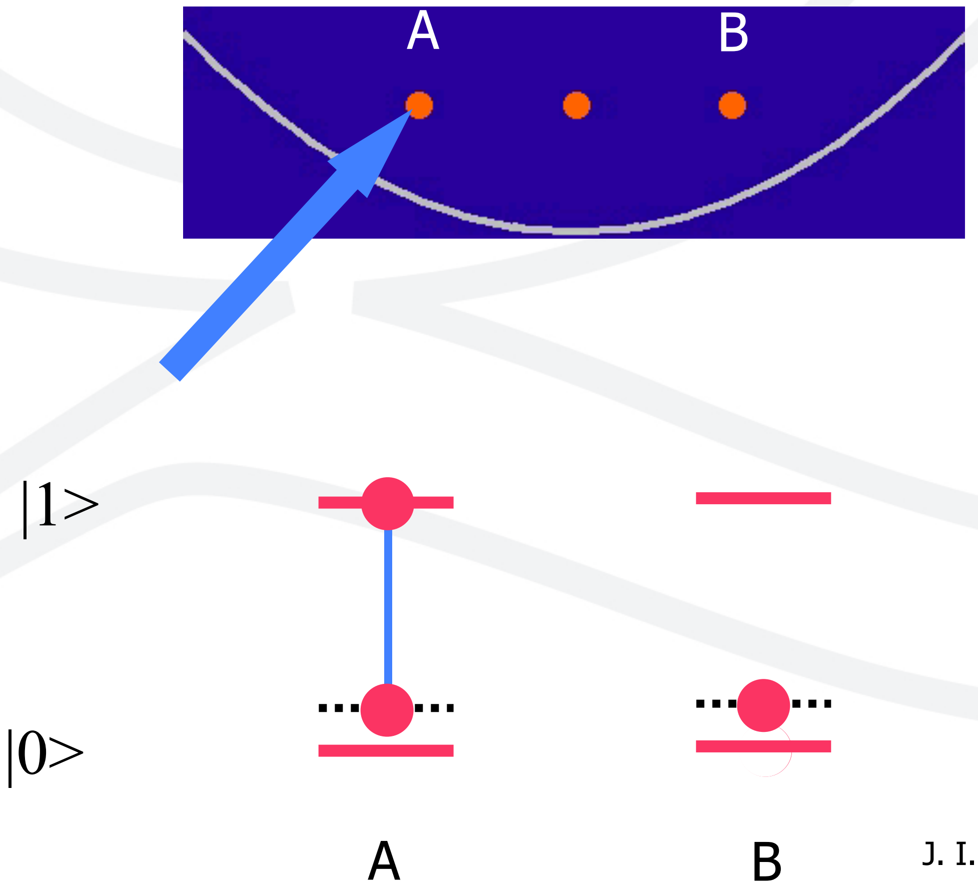
→

A	B
0	0
0	1



J. I. Cirac, P. Zoller, PRL **74**, 4091 (1995).

Conditional Quantum Dynamics



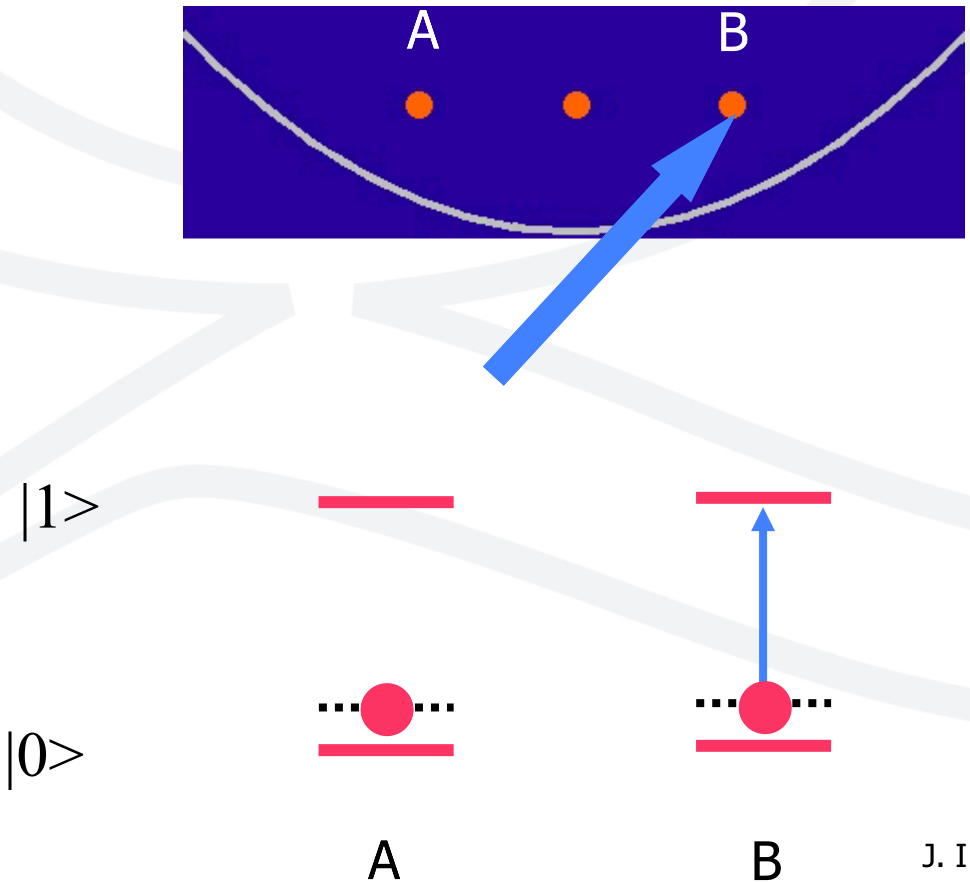
J. I. Cirac, P. Zoller, PRL **74**, 4091 (1995).

Conditional Quantum Dynamics

A	B
0	0
0	1
1	0
1	1

CNOT →

A	B
0	0
0	1
1	1
1	0



J. I. Cirac, P. Zoller, PRL **74**, 4091 (1995).

- First obseravtion of a single atom in 1979
  (after a couple of thousands years of discussion)

- Diverse Research with trapped ions incl. QIS

- Principle of Paul trap

- Physical principles of
  - Doppler cooling
  - State selecvtive detection
  - Single qubit operations
  - Conditional quantum dynamics

SUMMARY PART I