Quantum computation and quantum information

Chapter 7

- Physical Realizations

Ch. 7 – Physical Realizations

- Deviate from the book
- 2 lectures, 4h, 4 parts
  1) Overview, general info on implementations
  2) DiVincenzo criteria + Ion traps
  3) Rare-earth impurities
  4) Other systems (linear optics/superconducting qubits)
- Wrap up and comparisons

Why is it difficult to build a quantum computer?

- The quantum bits must remain in superposition states throughout the calculations
  – Thus the qubits must not interact with the environment
- Quantum logics requires that bits can control each other
  – Thus the qubits must interact with each other

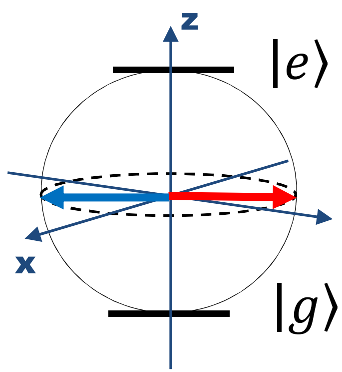
Will there be quantum computers?

- Analog qubit, so do they require infinite accuracy to succeed?
- Error correction algorithms works when the error per operation is $< 10^{-4}$ (later in the course)
- If quantum operations can be performed with an error of less than 10^{-4} we can keep an arbitrary large quantum system coherent for an arbitrary long time!
- So… theoretically posssible but can it really be done?
  – this lecture!

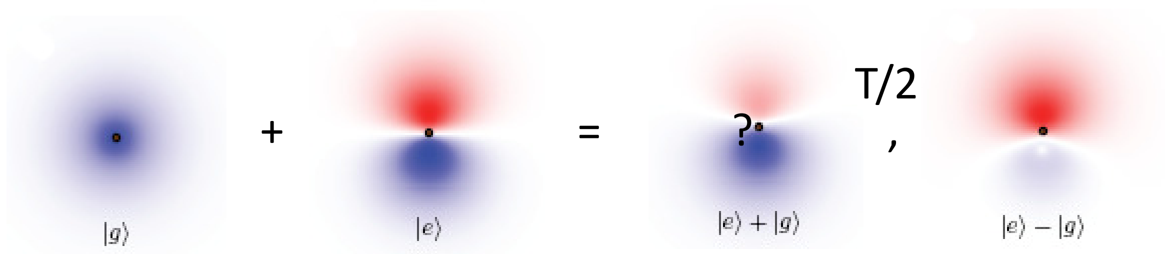
What is a superposition state physically?

- General properites of systems that can encode quantum information

$$|\psi\rangle = \alpha|e\rangle + \beta|g\rangle$$



Example: electron density:



What is a superposition state physically?

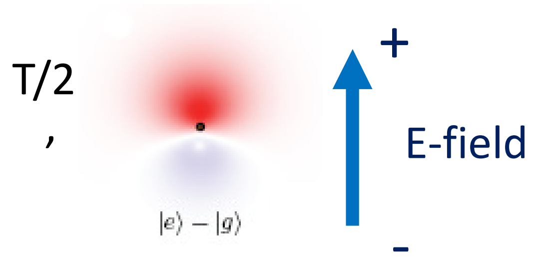
Consider charge distribution ρ as a function of time (and space).
– two-level system with energies E_g and E_e.

$$\psi_g(r,t) = g_g(r)e^{-iE_g t/\hbar}$$
$$\psi_e(r,t) = g_e(r)e^{-iE_e t/\hbar} \qquad , \Delta E = \hbar\omega$$

$$\rho \sim |\psi_{\text{total}}|^2 = |\psi_g + \psi_e|^2 = |g_g|^2 + |g_e|^2 + g_g g_e^* e^{i(\omega_e - \omega_g)t} + g_g^* g_e \; e^{-i(\omega_e-\omega_g)t}$$

$$= |g_g|^2 + |g_e|^2 + 2\tilde{g}_g\tilde{g}_e \cos(\omega_{ge}t - \varphi_{ge})$$

- An atom in a superposition will radiate (oscillating dipole)
- The phase of the electric field (light) changes the interaction

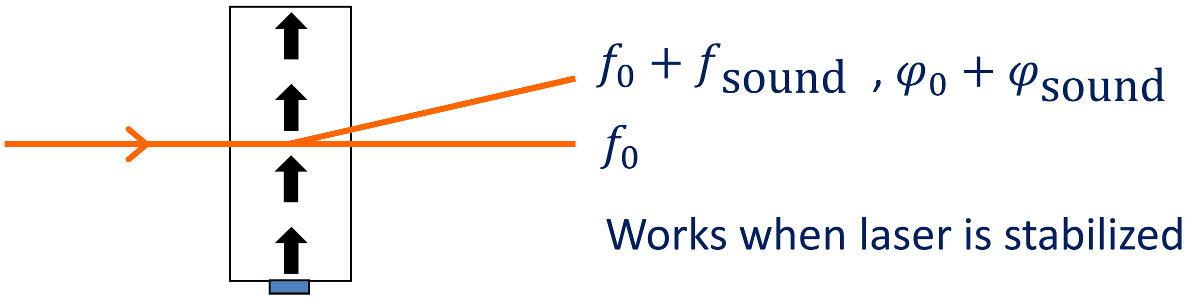


- What is the corresponding physical nature of decoherence?

How can we change the phase of the light field?

- Difficult because the light has a frequency of $\sim 10^{15}$ Hz

Acousto Optic Modulator (AOM):



Works when laser is stabilized!

Beam deflection from grating
or
Photon and phonon collision

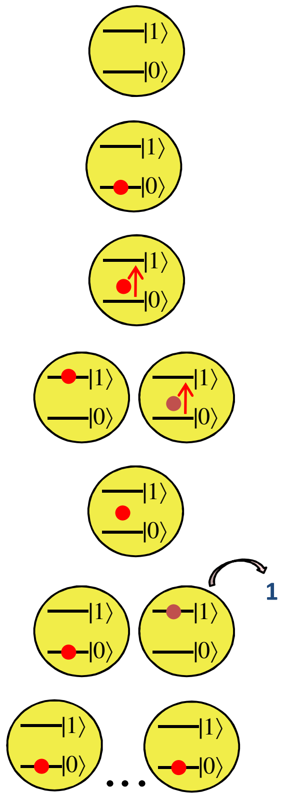
- Momentum conservation
- Energy conservation

$\Rightarrow$

- Beam is deflected
- Frequency of light is changed
- Phase of light is changed

What do you need?

Di Vincenzo criteria



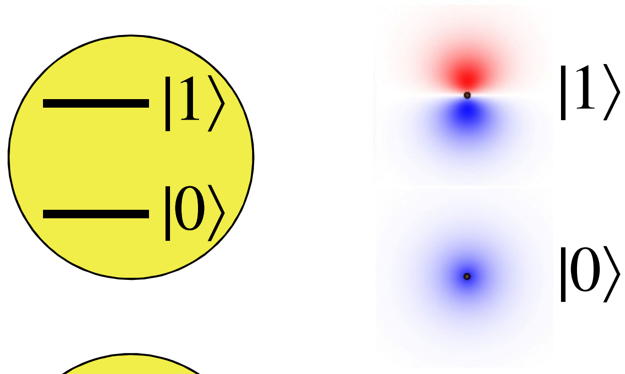
1) **Qubit**
2) **Initialize**
3) **Single qubit gate**
4) **Two qubit gate**
5) **Long coherence time**
6) **Qubit readout**
7) **Scalability**

Reformulated from: D. P. di Vincenzo, *The physical implementation of quantum computation*, Fortschritte der Physik, **48**, 771 (2000) (http://arxiv.org/abs/quant-ph/0002077)

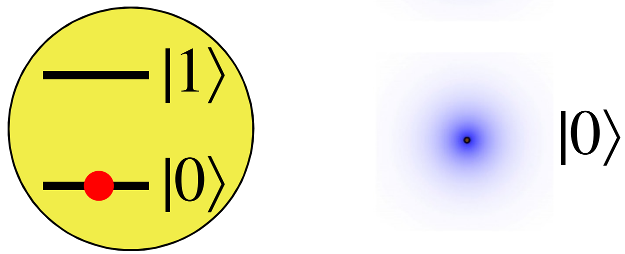
What do you need?

To build a quantum computer

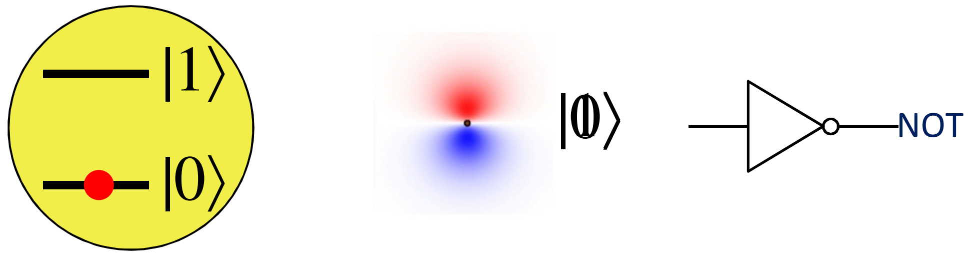
qubit



Initialize



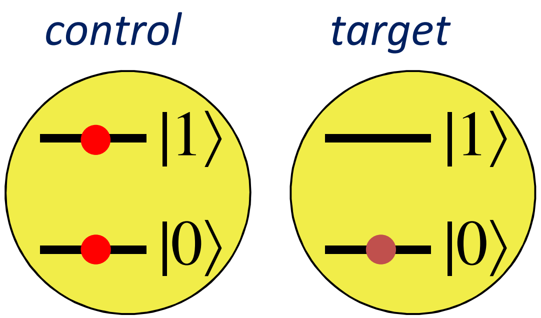
Single qubit gate

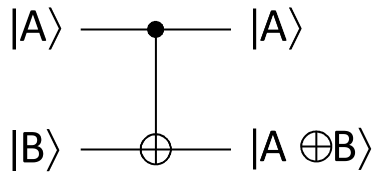


What do you need?

To build a quantum computer

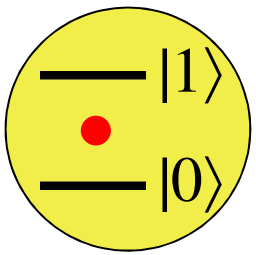
Conditional two qubit gate





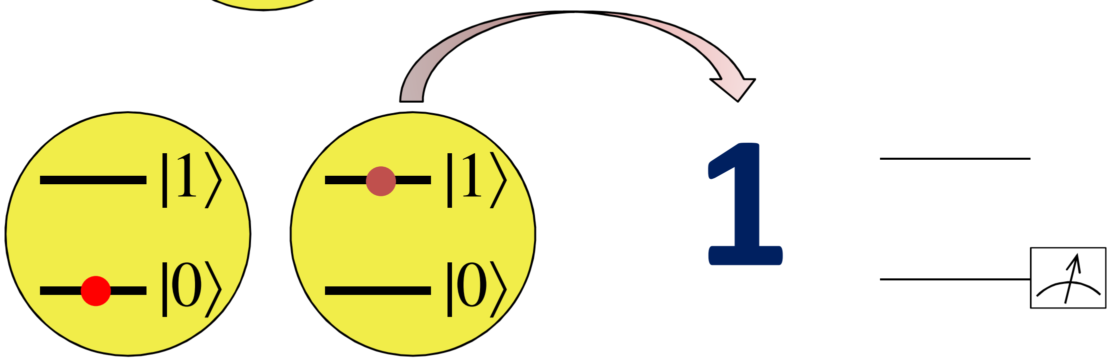
State: $|00\rangle + |11\rangle$

Long coherence time



$$N_{\text{op}} = \frac{T_{\text{coherence}}}{T_{\text{operation}}}$$

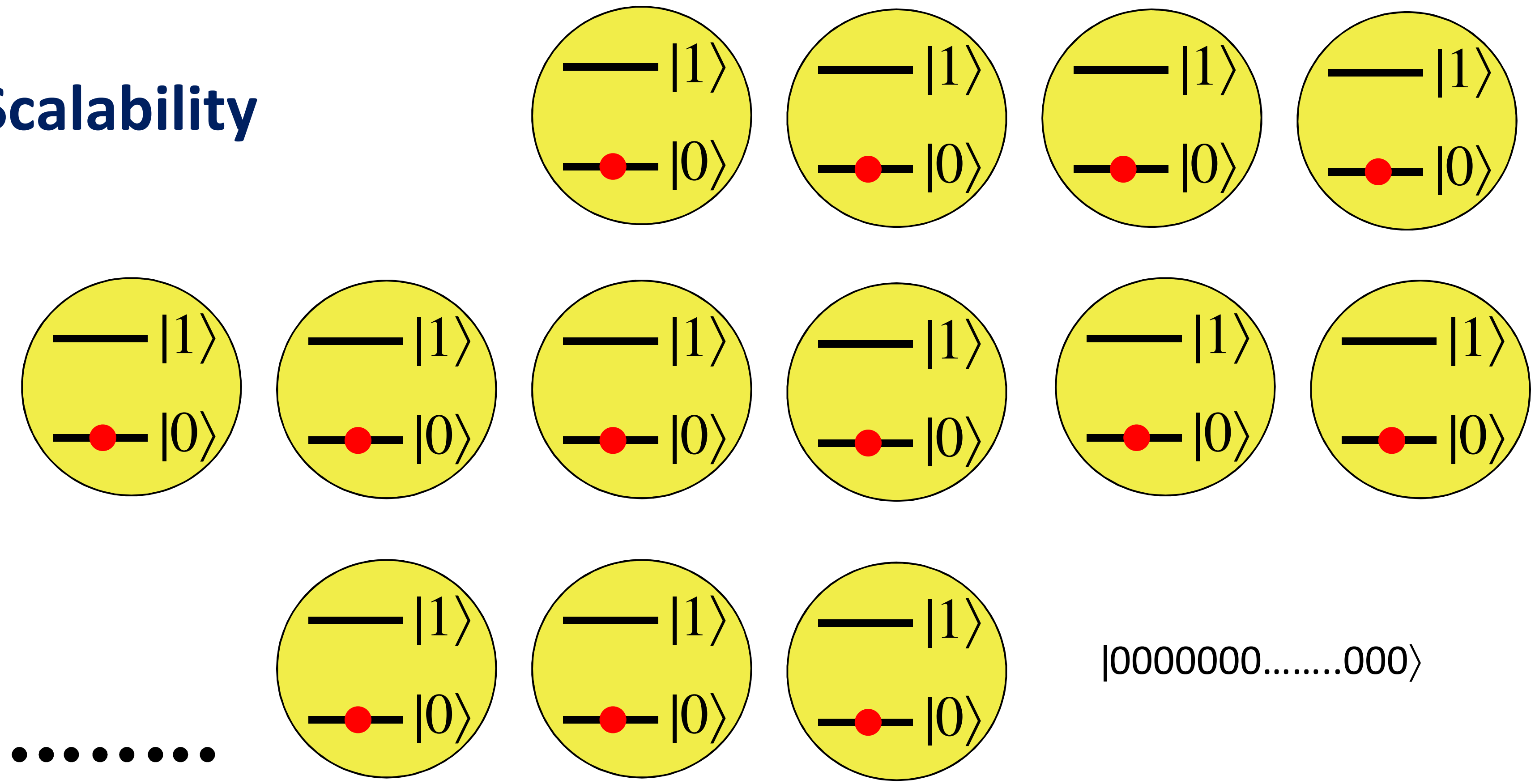
Qubit specific measurement



What do you need?

To build a quantum computer

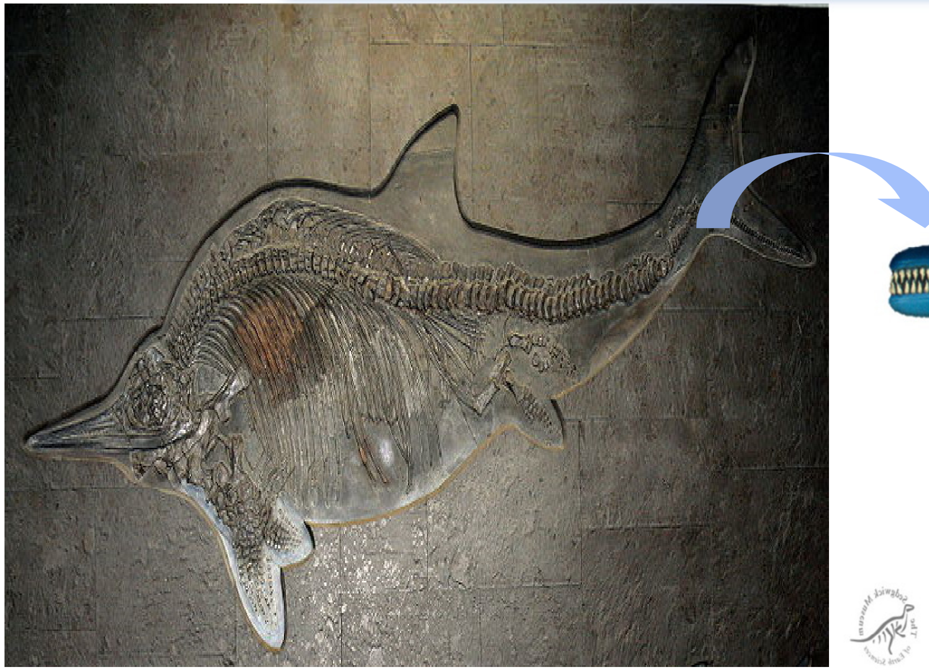
Scalability

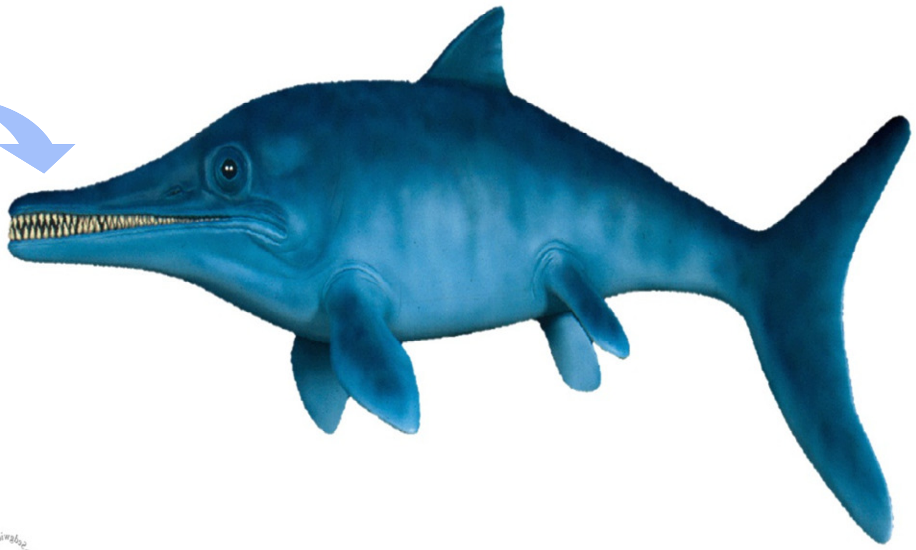


What makes ion traps so useful?

"… it is fair to state that we are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo…" Erwin Schrödinger 1952

But with trapped single ions we can!





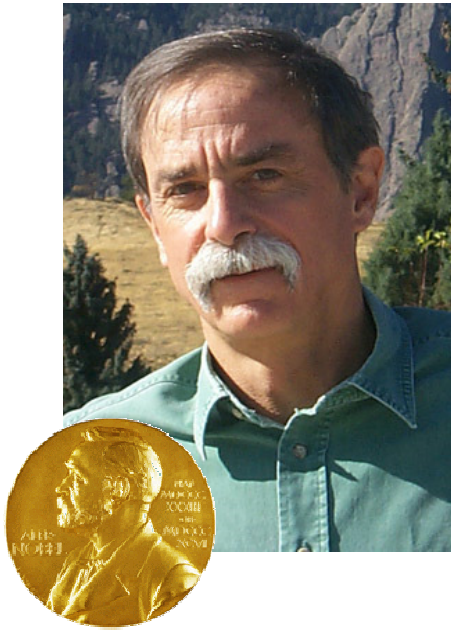
What makes ion traps so useful?

Answer: it offers almost textbook level of system control

- Single atoms with large amounts of control well separated from environment
- Ion traps was an important realistic proposal: Cirac and Zoller 1995

Hot topic:

- Awarded the nobel prize 2012: David Wineland at NIST, Boulder, USA



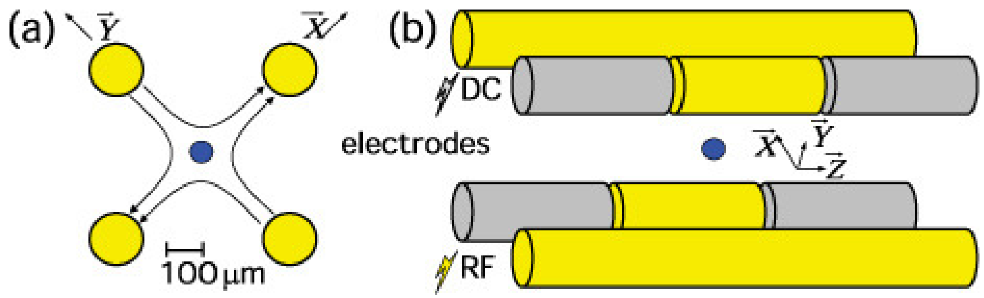
Introduction – How to trap an Ion

Trap in 3D cannot be made from static electric fields only (Earnshaw theorem).

Solutions:

- Use both electric and magnetic fields → Penning trap
- Use both static and dynamic electric fields → Paul Trap

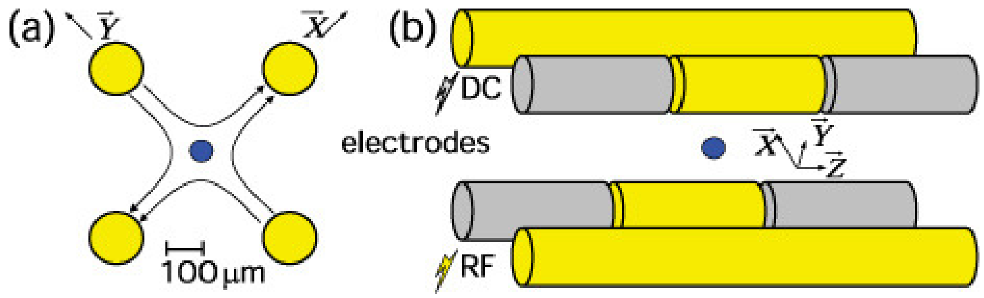
Paul Trap, confinement through a ponderomotive force:



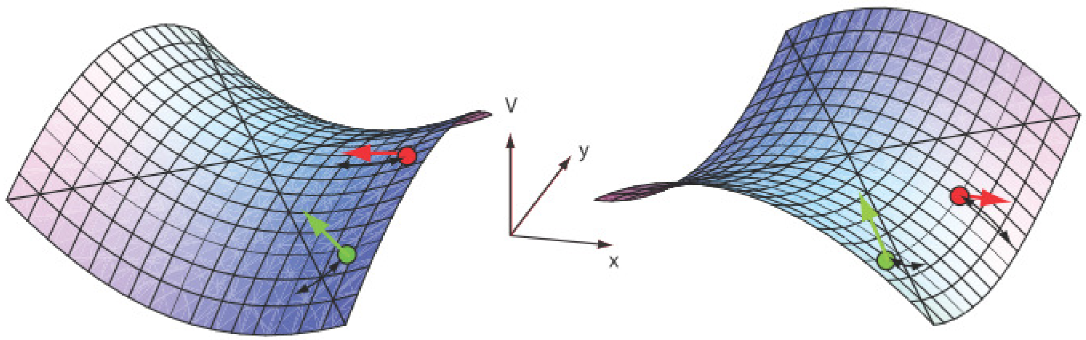
Introduction – How to trap an Ion

Introduction – How to trap an Ion

Paul Trap, confinement through a ponderomotive force:

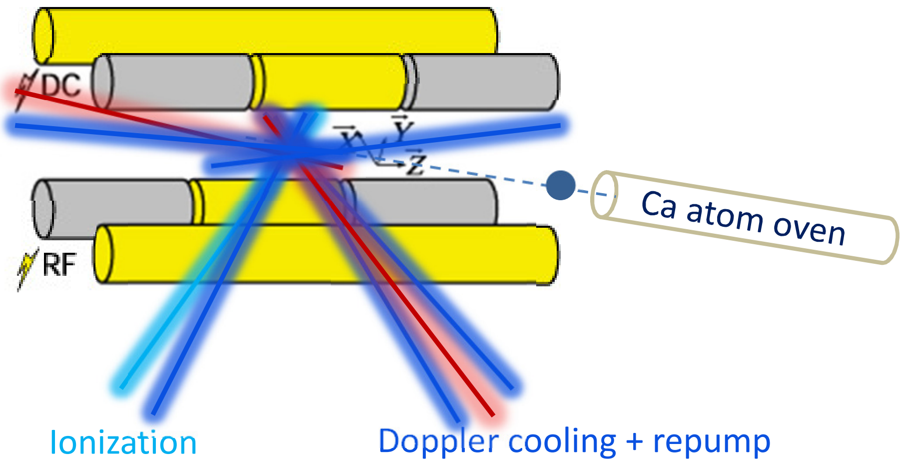


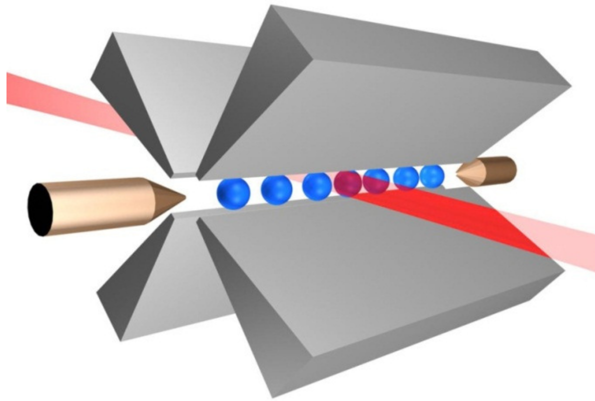
Pseudo potential ensures an average force towards the center

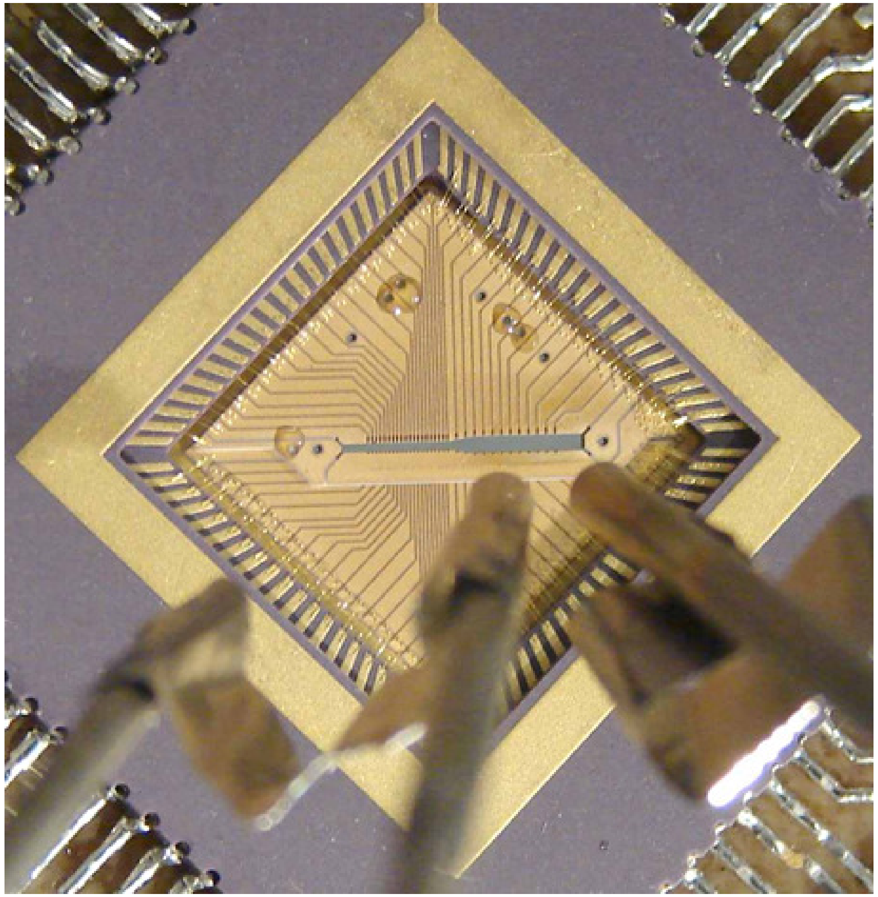


Introduction – How to trap an Ion

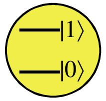
The trapping procedure:





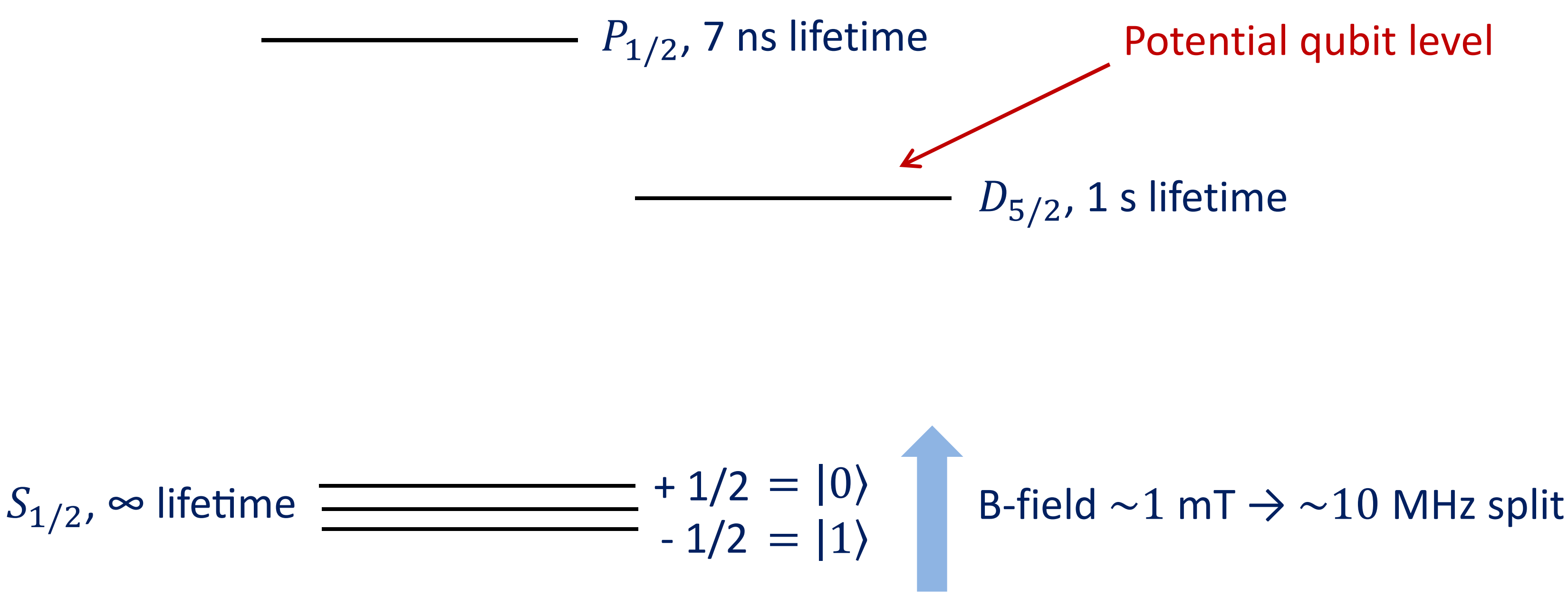


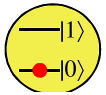
- For full experiment:
  Total of 8 different lasers
  (12 different beams)
- Drawback with ion traps:
  very resource heavy

Ion traps:  1) Qubit

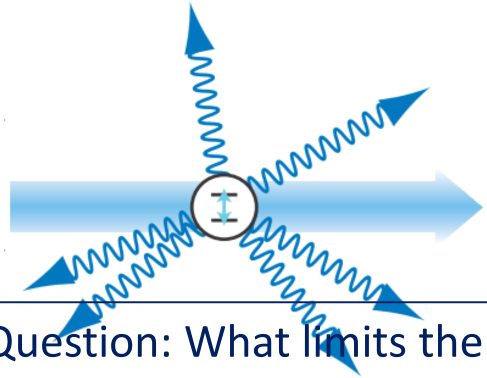
Most used ions for qubits are ^{40}Ca, ^{9}Be and ^{171}Yb. Focus here will be on Calcium.

$^{40}Ca^{+}$ level scheme:

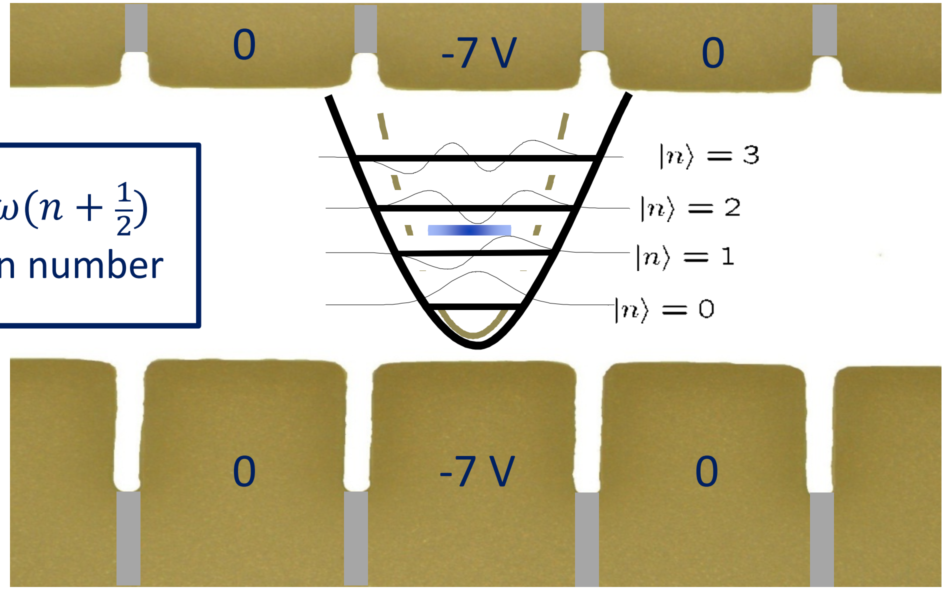


Ion traps: 

2) Initialize
- cooling

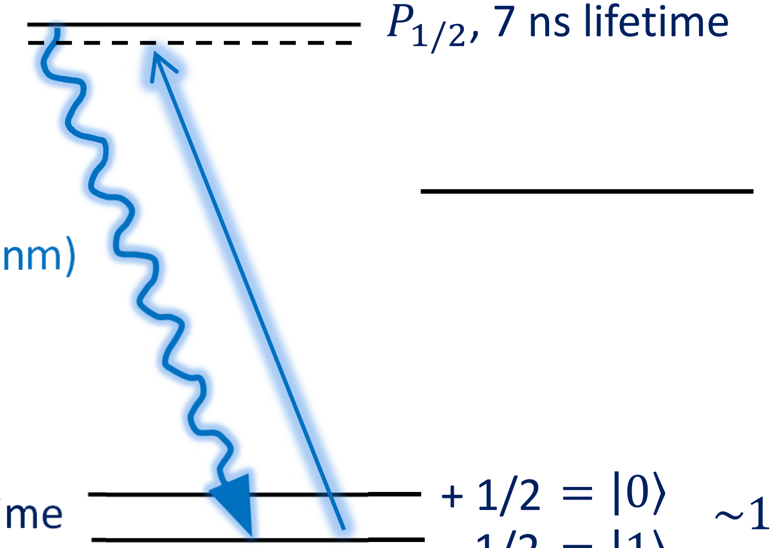


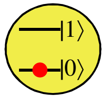
$$E(n) = \hbar\omega(n + \tfrac{1}{2})$$
n = phonon number



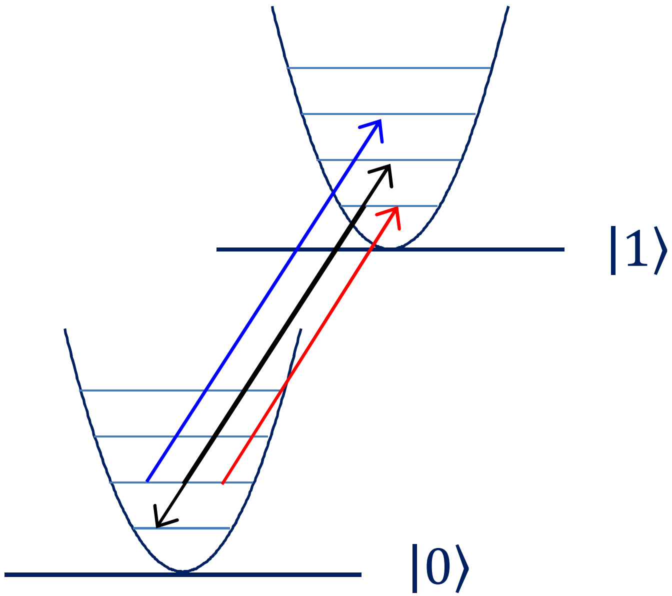
Question: What limits the doppler cooling?

Limit given by single photon recoil $\sim$10 phonons



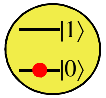
Ion traps:  **2) Initialize**
- cooling

Phonon resolved cooling (sideband cooling):



- Resolved sideband cooling allows cooling down to about 0.1 phonons
- Which corresponds to a temperature of 7 μK
- This is cold enough for good localization!

Ion traps:



2) Initialize

- state selection

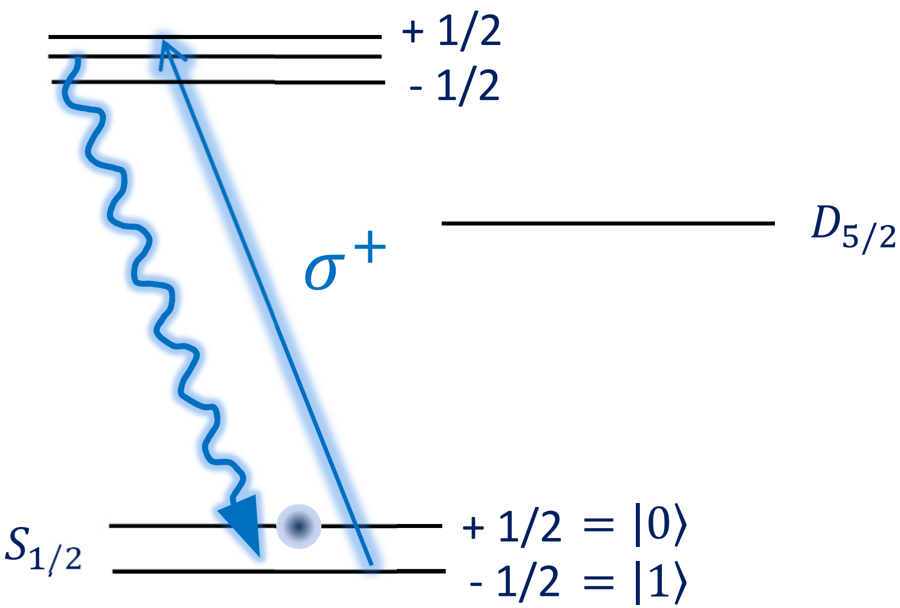
Part two of initialization means deterministically driving the ion into a defined state, for example $|0\rangle$

~~$+1/2 \rightarrow +1/2$~~

~~$+1/2 \rightarrow -1/2$~~

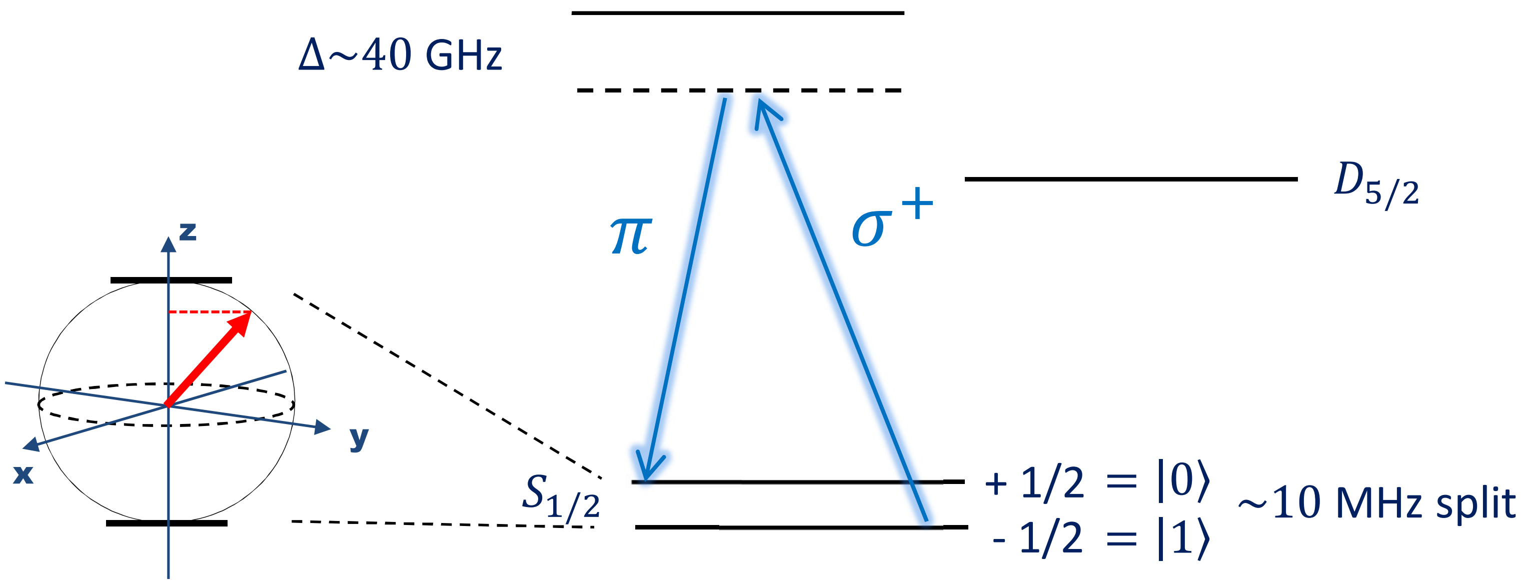
$\boxed{-1/2 \rightarrow +1/2}$

~~$-1/2 \rightarrow -1/2$~~



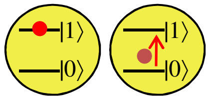
Ion traps: 3) Single qubit gate

Single qubit gate operations performed via 2-photon Raman interactions



- Can accomplish arbitrary Bloch sphere state via relative phase between beams
- Advantage with Raman operations is that the laser does not have to be stabilized!

Ion traps:

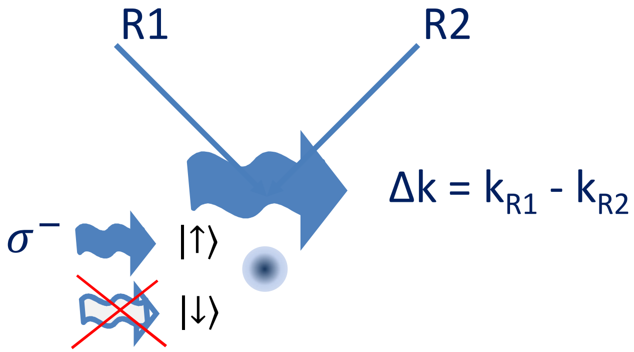


4) Two qubit gate

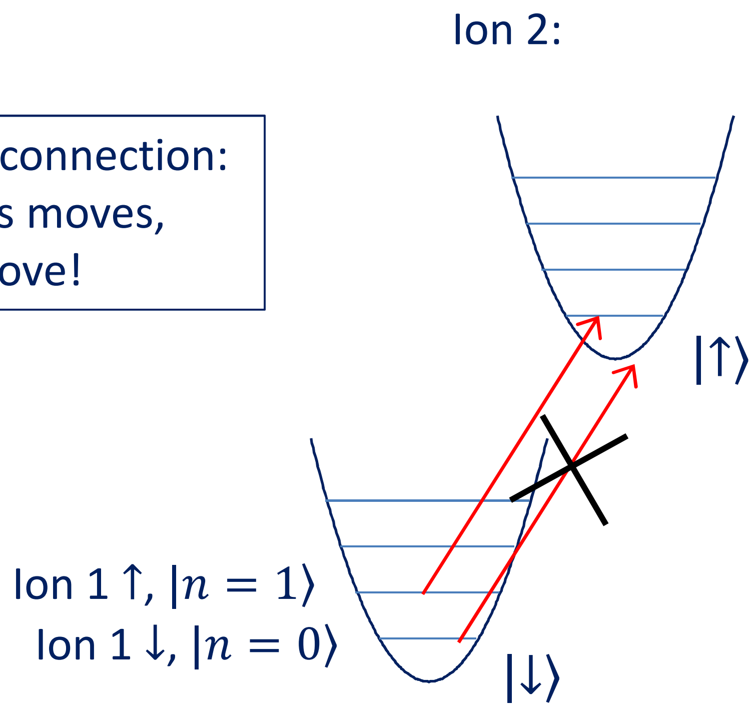
Gate types:

- Original Cirac-Zoller gate (proposed 1995, realized 2003)
- Mølmer-Sørenssen gate (proposed 1998, realized 2008)
- Geometric Phase gate (Leibfried; proposed and realized 2003)

Need a mechanism for creating conditional operations:

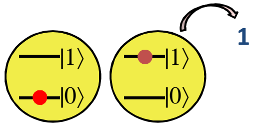


Coulomb connection:
If one ions moves,
all ions move!

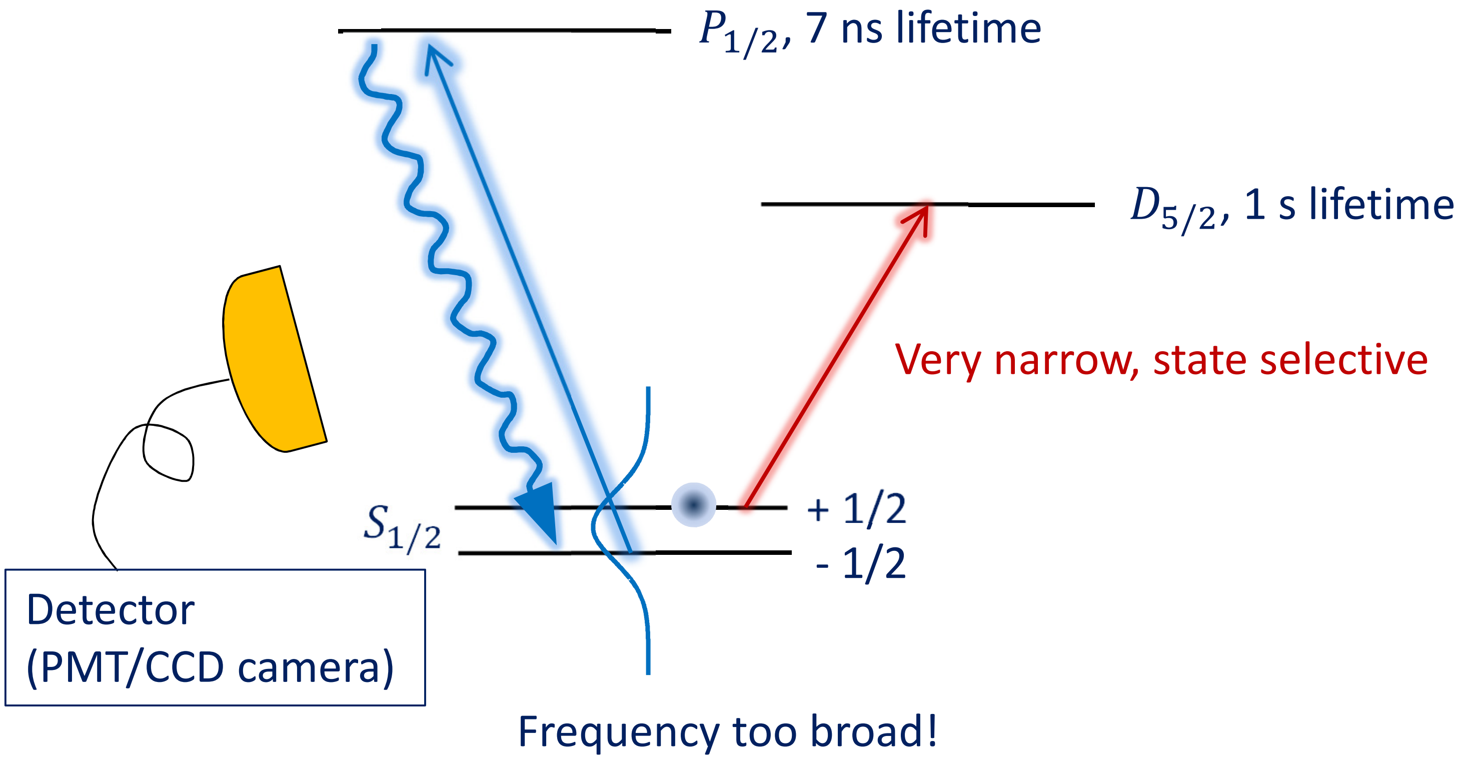


Final state: $|\uparrow, \uparrow\rangle + |\downarrow, \downarrow\rangle$, Entangled Bell state

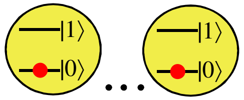
Ion traps:



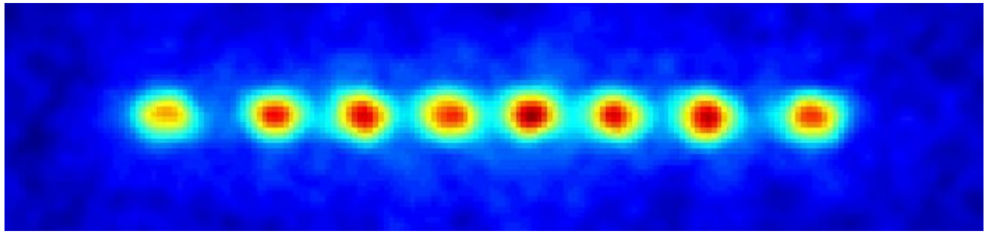
6) Qubit readout

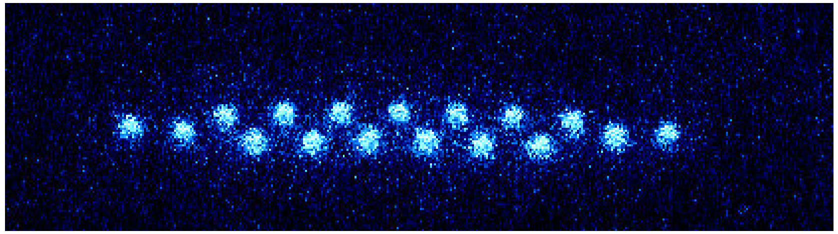


- Ions in state +1/2 gets shelved and does not fluoresce
- Ions in state -1/2 remains and does fluoresce

Ion traps:  7) Scalability

Innsbruck trap, 8 qubits (quantum byte):



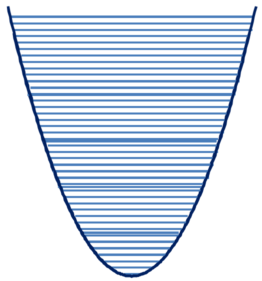


- Ion-ion interaction done via conditional (quantized) motion of ions

Caveats:

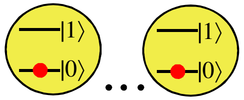
- Must remain near motional ground state
- Too many ions leads to uncontrollable motion
- The number of motional modes increase with the number of ions
  - 1 ion has only *common* mode, 2 ions have both *common* and *stretching* mode

Single ions
Many ions



Individual states distinguishable
NOT distinguishable

Ion traps:

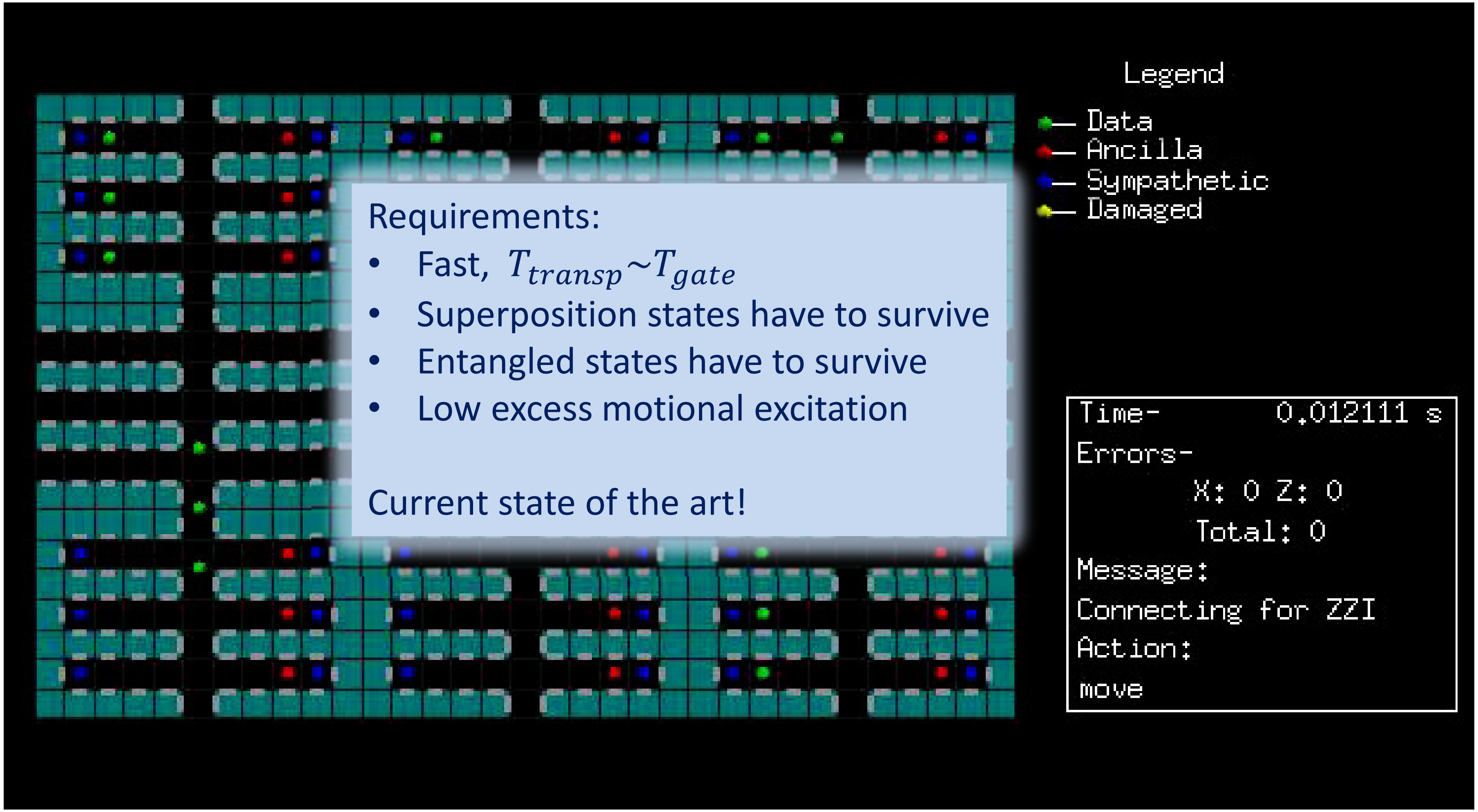


7) Scalability

If we can't put more ions in one trap then we need more traps!

D. Kielpinski, C. Monroe, and D. Wineland, Nature 417, 709 (2002).

Isaac Chuang, video showing 3 qubit error correction recursive:



Requirements:

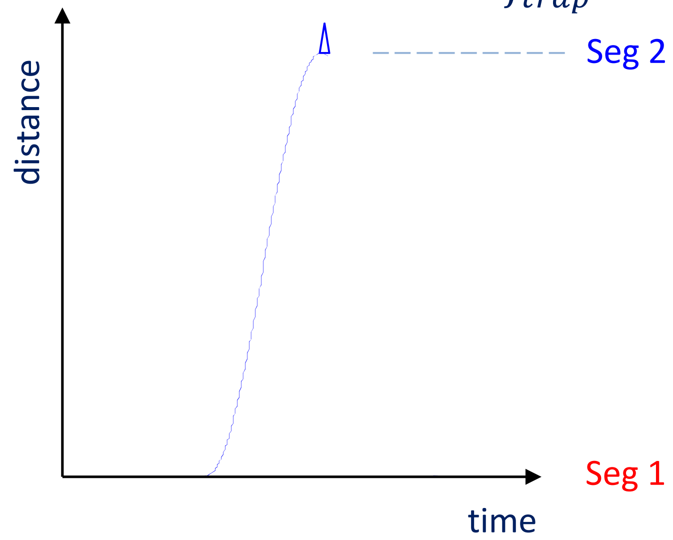
- Fast, $T_{transp} \sim T_{gate}$
- Superposition states have to survive
- Entangled states have to survive
- Low excess motional excitation

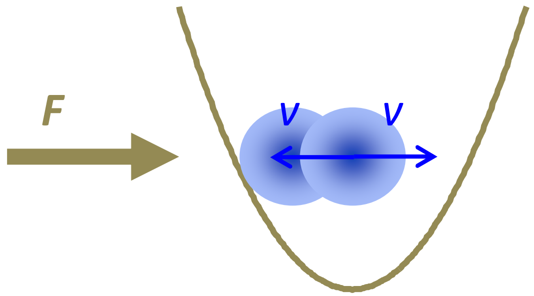
Current state of the art!

Fast single ion transport

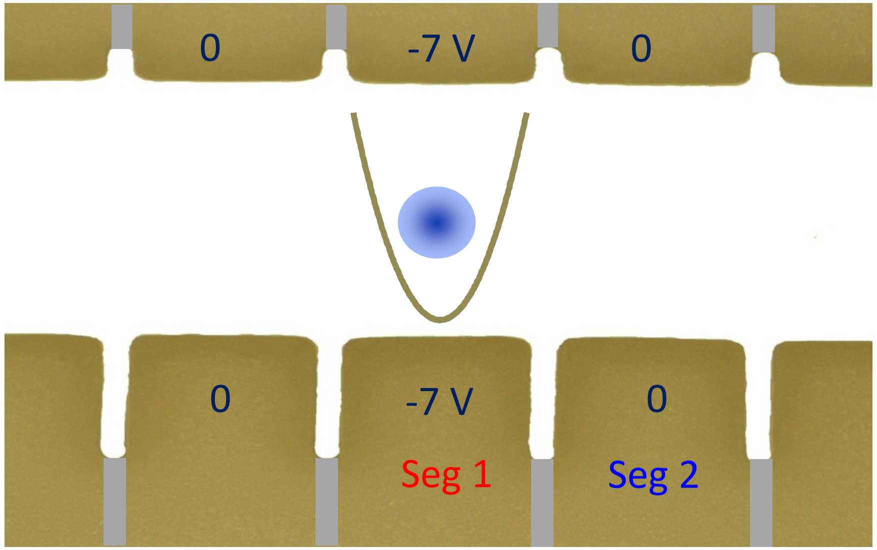
Transport shape: $\sin^2$

$$\tau_{kick} < \frac{1}{f_{trap}} \sim 700\ ns$$





$$f_{harm.\,osc.} = 1.4\ MHz$$

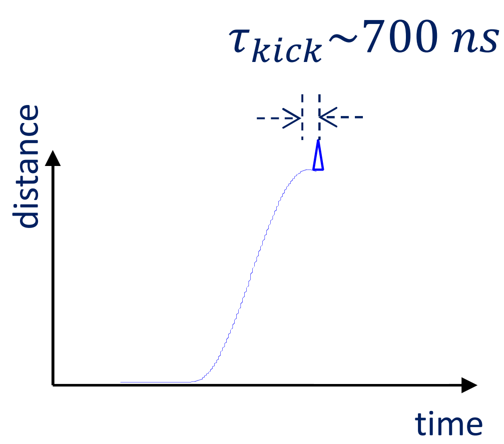


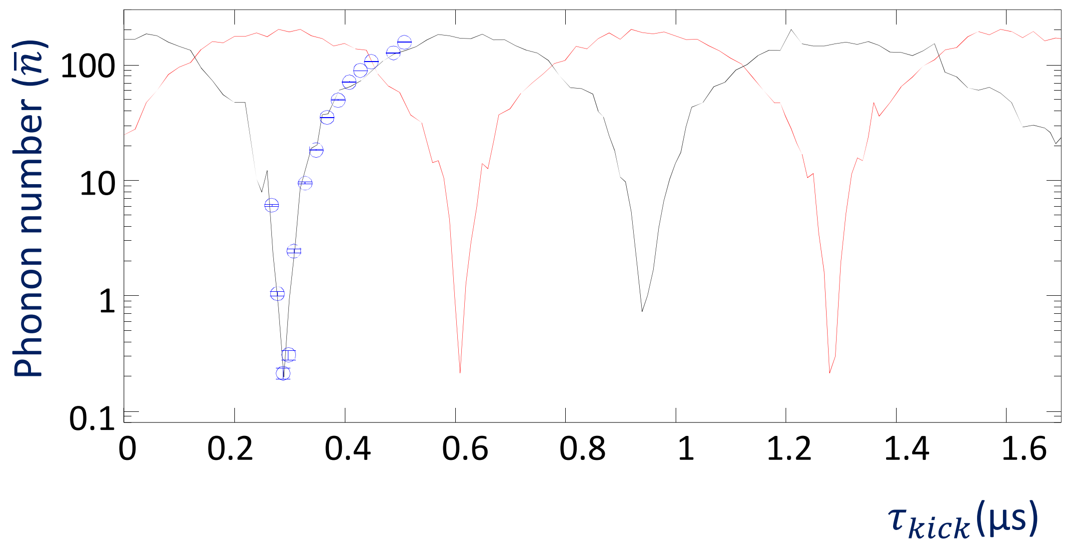
Transport details (each direction):

- 10 sample points
- 3.6 µs → ~5 motion cycles
- 280 µm (one segment), ~30000 times the size of ion wavepacket
- Speed: 6000 wavepackets/cycle
- 280 km/h

Results of ground state cooled transport

We measure the phonon number as function of kick timing





	start	transport	kick	final
Phonon number:	0.1	+ 100	- 99.9	= 0.2

- Well below Lamb-Dicke Limit required for performing gates!
- $T_{transp} \approx 4\mu s \lesssim T_{gate}$

PRL 109, 080501 (2012) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

Controlling Fast Transport of Cold Trapped Ions

A. Walther, F. Ziesel, T. Ruster, S. T. Dawkins, K. Ott, M. Hettrich, K. Singer, F. Schmidt-Kaler, and U. Poschinger*

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Coherent Diabatic Ion Transport and Separation in a Multizone Trap Array

R. Bowler,* J. Gaebler, Y. Lin, T. R. Tan, D. Hanneke,† J. D. Jost, J. P. Home,‡ D. Leibfried, and D. J. Wineland

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Transport of spin-motion entangled states