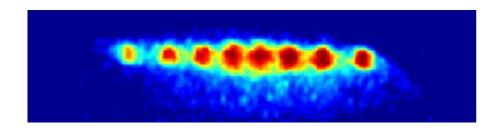
## The trapped-ion qubit tool box

Contemporary Physics, 52, 531-550 (2011)



### Roee Ozeri



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# Physical Implementation of a quantum computer

#### David Divincenzo's criteria:

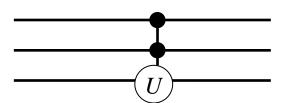
- 1. Well defined qubits.
- 2. Initialization to a pure state
- 3. Universal set of quantum gates.
- 4. Qubit specific measurement.
- 5. Long coherence times (compared with gate & meas. time).

## Universal Gate set

- For N qubits, a general unitary transformation U acts on a  $2^{N}$ - dimension Hilbert space.

- A *finite* set of unitary gates that spans any such U.

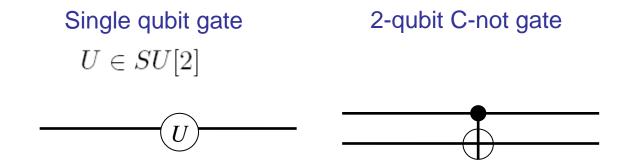
- The Deutsch-Toffoli gate



- D. Deutsch, *Proc. R. Soc. London*, Ser. A, **425**, 73, (1989).

### Universal Gate set

- For *N*-qubits, and unitary transformation U on a  $2^N$ -dimension Hilbert space.
- A *finite* set of unitary gates that spans any such U.



- Rotations can be approximated to  $\varepsilon$  by concatenating k gates, from a finite set  $\{V_i\}$ , where  $k < polylog(1/\varepsilon)$ .
- Barenco et. al. Phys. Rev. A, 52, 3457, (1995).

# Physical Implementation of a quantum computer

David Divincenzo's criteria:

How well???

Well enough to allow for a large scale computation: Fault tolerance

$$F = \langle \Psi | \rho_{\epsilon} | \Psi \rangle$$
  $\epsilon = 1 - F$ 

# Fault-tolerant Quantum Computation

Noisy operations  $\epsilon$ 



One level quantum error-correction codes

$$O((\epsilon/\epsilon_{\theta})^2)$$

concatenation; threshold theorem

k-levels of fault-tolerant encoding

$$O((\epsilon/\epsilon_{\theta})^{2^k}) \to \theta \quad \text{if} \quad \epsilon < \epsilon_{\theta}$$

- $\epsilon_0$  Fault tolerance threshold.
- Heavy resource requirements when  $\epsilon \simeq \epsilon_0$
- Depends on code, noise model, arch. constraints etc.
- Current estimates for  $\epsilon_0 \simeq 10^{-2} 10^{-4}$

### **Tutorial overview**

- 1. The ion-qubit: different ion-qubit choices, Ion traps.
- 2. Qubit initialization.
- 3. Qubit measurement.
- 4. Universal set of quantum gates: single qubit rotations; two-ion entanglement gates
- 5. Memory coherence times

How well???
Benchmarked to current threshold estimates

Disclaimer: non exhaustive; focuses on laser-driven gates

# Different ion-qubit choises

- One electron in the valence shell; "Alkali like" <sup>2</sup>S<sub>1/2</sub> ground state.

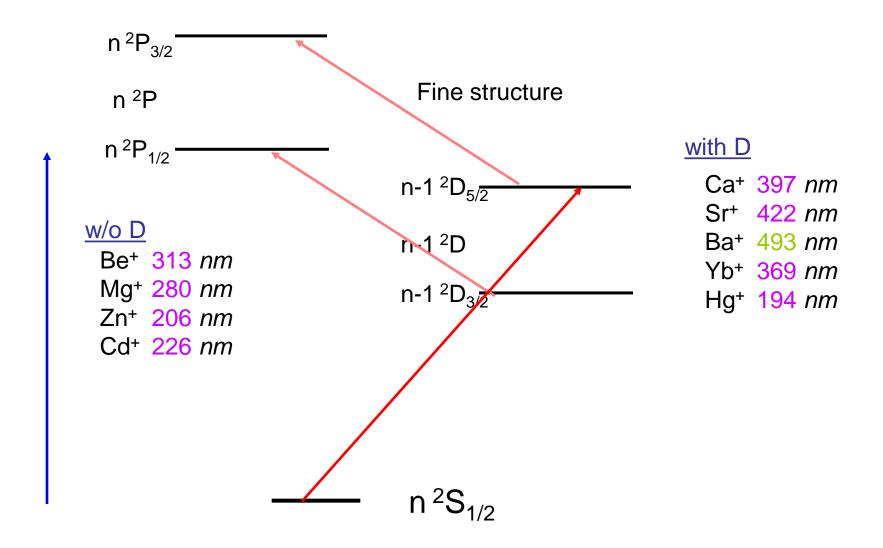
hydrogen 1																		helium 2
H																		He
1.0079 lithium	peryllium											Ī	boron	carbon	nitrogen	oxygen	fluorine	4.0026 neon
3	4												5	6	7	8	9	10
Li	Be												В	C	N	0	F	Ne
6.941	9.0122												10.811	12.011	14.007	15,999	18.998	20.180
sodium 11	magnesium 12												aluminium 13	silicon 14	phosphorus 15	sulfur 16	chlorine 17	argon 18
Na	Mg												Al	Si	Р	S	CI	Ar
22.990	24.305												26.982	28.086	30.974	32.065	35.453	39.948
potassium	calcium		scandium	titanium	vanadium	chromium	manganese	iron 26	cobalt 27	nickel	copper 29	ZINC	gallium	germanium 32	arsenic	selenium	bromine	krypton
19	20		21	22	23	24	25			28		30	31		33	34	35	36
K	Ca		Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
39.098	40.078		44.956	47.867	50.942	51.996	54.938	55.845	58.933	58.693	63.546	65.39	69.723	72.61	74.922	78.96	79.904	83.80
39.098 rubidium	585(555)		44.956 yttrium	47.867 zirconium		51.996 molybdenum		46		58.693 palladium				99-03-03-03-03	The second secon	78.96 tellurium		83,80 xenon
39.098 rubidium <b>37</b>	40.078 strontium <b>38</b>		44.956 yttrium <b>39</b>	47.867 zirconium <b>40</b>	50.942 niobium <b>41</b>	51.996 molybdenum <b>42</b>	54.938 technetium <b>43</b>	55.845 ruthenium <b>44</b>	58.933 rhodium <b>45</b>	58.693 palladium <b>46</b>	63.546 silver <b>47</b>	65,39 cadmium <b>48</b>	69.723 indium <b>49</b>	72.61 tin <b>50</b>	74.922 antimony <b>51</b>	78.96 tellurium <b>52</b>	79.904 iodine	83.80 xenon <b>54</b>
39.098 rubidium	40.078 strontium		44.956 yttrium	47.867 zirconium	50.942 niobium	51.996 molybdenum	54.938 technetium	55.845 ruthenium	58.933 rhodium	58.693 palladium	63.546 silver	65,39 cadmium	69.723 indium	72.61 tin	74.922 antimony	78.96 tellurium	79.904 iodine	83,80 xenon
39,098 rubidium 37 <b>Rb</b> 85,468 caesium	40.078 strontium 38 Sr 87.62 barium	F7 70	44.956 yttrium 39 Y 88.906 lutetium	47.867 zirconium 40 Zr 91.224 hafnium	50.942 niobium 41 Nb 92.906 tantalum	51.996 molybdenum 42 Mo 95.94 tungsten	54.938 technetium 43 TC [98] rhenium	ruthenium 44 Ru 101.07 osmium	58.933 rhodium 45 Rh 102.91 iridium	palladium 46 Pd 106.42 platinum	63.546 silver 47 <b>Ag</b> 107.87 gold	65.39 cadmium 48 Cd 112.41 mercury	69.723 indium 49 In 114.82 thallium	72.61 tin 50 Sn 118.71 lead	74.922 antimony 51 <b>Sb</b> 121.76 bismuth	78.96 tellurium 52 Te 127.60 polonium	79.904 iodine 53 1 126.90 astatine	83.80 xenon 54 <b>Xe</b> 131.29 radon
39.098 rubidium 37 Rb 85.468 caesium 55	40.078 strontium 38 <b>Sr</b> 87.62 barium 56	57-70	44.956 yttrium 39 Y 88.906 lutetium 71	47.867 zirconium 40 Zr 91.224 hafnium 72	50.942 niobium 41 Nb 92.906 tantalum 73	51.996 molybdenum 42 Mo 95.94 tungsten 74	54.938 technetium 43 TC [98] rhenium 75	55.845 ruthenium 44 Ru 101.07 osmium 76	58.933 rhodium 45 Rh 102.91 iridium 77	58.693 palladium 46 Pd 106.42 platinum 78	63.546 silver 47 <b>Ag</b> 107.87 gold 79	65.39 cadmium 48 Cd 112.41 mercury 80	69.723 indium 49 In 114.82 thallium 81	72.61 tin 50 <b>Sn</b> 118.71 lead 82	74.922 antimony 51 <b>Sb</b> 121.76 bismuth 83	78.96 tellurium 52 Te 127.60 polonium 84	79,904 lodine 53 126,90 astatine 85	83.80 xenon 54 Xe 131.29 radon 86
39,098 rubidium 37 <b>Rb</b> 85,468 caesium	40.078 strontium 38 Sr 87.62 barium	57-70 <del>X</del>	44.956 yttrium 39 Y 88.906 lutetium	47.867 zirconium 40 Zr 91.224 hafnium	50.942 niobium 41 Nb 92.906 tantalum	51.996 molybdenum 42 Mo 95.94 tungsten	54.938 technetium 43 TC [98] rhenium	ruthenium 44 Ru 101.07 osmium	58.933 rhodium 45 Rh 102.91 iridium	palladium 46 Pd 106.42 platinum	63.546 silver 47 <b>Ag</b> 107.87 gold	65.39 cadmium 48 Cd 112.41 mercury 80	69.723 indium 49 In 114.82 thallium	72.61 tin 50 Sn 118.71 lead	74.922 antimony 51 <b>Sb</b> 121.76 bismuth	78.96 tellurium 52 Te 127.60 polonium	79.904 iodine 53 1 126.90 astatine	83.80 xenon 54 <b>Xe</b> 131.29 radon
39.098 rubidium 37 <b>Rb</b> 85.468 caesium 55 <b>Cs</b> 132.91	40.078 strontium 38 Sr 87.62 barium 56 Ba 137.33	3885 ACCOUNT	44.956 yttrium 39 Y 88.906 lutetium 71 Lu 174.97	47.867 zirconium 40 Zr 91.224 hafinium 72 Hf 178.49	50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95	51.996 molybdenum 42 MO 95.94 tungsten 74 W 183.84	54.938 technetium 43 TC [98] rhenium 75 Re 186.21	55.845 ruthenium 44 Ru 101.07 osmium 76 Os 190.23	58,933 rhodium 45 <b>Rh</b> 102,91 iridium 77 <b>Ir</b> 192,22	58,693 palladium 46 Pd 106.42 platinum 78 Pt 195.08	63,546 silver 47 <b>Ag</b> 107,87 gold 79 <b>Au</b> 196,97	65.39 cadmium 48 Cd 112.41 mercury 80 Hg 200.59	69.723 indium 49 In 114.82 thallium 81	72.61 tin 50 Sn 118.71 lead 82 Pb 207.2	74.922 antimony 51 <b>Sb</b> 121.76 bismuth 83	78.96 tellurium 52 Te 127.60 polonium 84	79,904 lodine 53 126,90 astatine 85	83.80 xenon 54 Xe 131.29 radon 86
39.098 rubidium 37 <b>Rb</b> 85.468 caesium 55 <b>Cs</b> 132.91 francium	40.078 strontium 38 Sr 87.62 barium 56 Ba 137.33	*	44,956 yttrium 39 Y 88,906 lutetium 71 Lu 174,97 lawrencium	47.867 zirconium 40 Zr 91.224 hafnium 72 Hf 178.49 rutherfordium	50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95 dubnium	51.996 molybdenum 42 Mo 95.94 tungsten 74 W 183.84 seaborgium	technetium 43 TC [98] rhenium 75 Re 186.21 bohrium	55.845 ruthenium 44 Ru 101.07 osmium 76 Os 190.23 hassium	58,933 rhodium 45 Rh 102.91 iridium 77 Ir 192.22 meitnerium	58.693 palladium 46 Pd 106.42 platinum 78 Pt 195.08 ununnilium	63,546 silver 47 <b>Ag</b> 107,87 gold 79 <b>Au</b> 196,97 ununulum	65.39 cadmium 48 Cd 112.41 mercury 80 Hg 200.59	69,723 indium 49 In 114,82 thailium 81	72.61 tin 50 Sn 118.71 lead 82 Pb 207.2	74.922 antimony 51 Sb 121.76 bismuth 83 Bi	78.96 tellurium 52 Te 127.60 polonium 84 Po	79.904 iodine 53	83.80 xenon 54 <b>Xe</b> 131.29 radon 86 <b>Rn</b>
39,098 rubidium 37 <b>Rb</b> 85,468 caesium 55 <b>CS</b> 132,91 francium 87	40.078 strontium 38 Sr 87.62 barium 56 Ba 137.33	<del>X</del> 89-102	44,956 yttrium 39 Y 88,906 lutetium 71 Lu 174,97 lawrencium 103	47.867 zirconium 40 Zr 91.224 hafnium 72 Hf 178.49 rutherfordium 104	50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95 dubnium 105	51.996 molybdenum 42 Mo 95.94 tungsten 74 W 183.84 seaborgium 106	technetium 43 TC [98] rhenium 75 Re 186.21 bohrium 107	ruthenium 44 Ru 101.07 osmium 76 Os 190.23 hassium 108	58.933 rhodium 45 Rh 102.91 iridium 77 Ir 192.22 meitnerium 109	58.693 palladium 46 Pd 106.42 platinum 78 Pt 195.08 ununnilium 110	63,546 silver 47 Ag 107,87 gold 79 Au 196,97 unununium 111	65.39 cadmium 48 Cd 112.41 mercury 80 Hg 200.59	69,723 indium 49 In 114,82 thailium 81	72.61 tin 50 Sn 118.71 lead 82 Pb 207.2 ununquadium 114	74.922 antimony 51 Sb 121.76 bismuth 83 Bi 208.98	78.96 tellurium 52 Te 127.60 polonium 84 Po	79.904 iodine 53	83.80 xenon 54 <b>Xe</b> 131.29 radon 86 <b>Rn</b>
39.098 rubidium 37 <b>Rb</b> 85.468 caesium 55 <b>Cs</b> 132.91 francium	40.078 strontium 38 Sr 87.62 barium 56 Ba 137.33	*	44,956 yttrium 39 Y 88,906 lutetium 71 Lu 174,97 lawrencium	47.867 zirconium 40 Zr 91.224 hafnium 72 Hf 178.49 rutherfordium	50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95 dubnium	51.996 molybdenum 42 Mo 95.94 tungsten 74 W 183.84 seaborgium	technetium 43 TC [98] rhenium 75 Re 186.21 bohrium	55.845 ruthenium 44 Ru 101.07 osmium 76 Os 190.23 hassium	58,933 rhodium 45 Rh 102.91 iridium 77 Ir 192.22 meitnerium	58.693 palladium 46 Pd 106.42 platinum 78 Pt 195.08 ununnilium 110	63,546 silver 47 <b>Ag</b> 107,87 gold 79 <b>Au</b> 196,97 ununulum	65.39 cadmium 48 Cd 112.41 mercury 80 Hg 200.59	69,723 indium 49 In 114,82 thailium 81	72.61 tin 50 Sn 118.71 lead 82 Pb 207.2	74.922 antimony 51 Sb 121.76 bismuth 83 Bi 208.98	78.96 tellurium 52 Te 127.60 polonium 84 Po	79.904 iodine 53	83.80 xenon 54 <b>Xe</b> 131.29 radon 86 <b>Rn</b>

\*Lanthanide series

\* \* Actinide series

lanthanum 57	cerium 58	praseodymium 59	neodymium <b>60</b>	promethium 61	samarium 62	europium 63	gadolinium <b>64</b>	terbium <b>65</b>	dysprosium <b>66</b>	holmium 67	erbium 68	thulium <b>69</b>	ytterbium <b>70</b>
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb
138.91	140.12	140.91	144.24	[145]	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	470.04
actinium 89	thorium 90	protactinium 91	uranium 92	neptunium 93	plutonium 94	americium 95	curium 96	berkelium 97	californium 98	einsteinium 99	fermium 100	mendelevium 101	nobelium 102
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
[227]	232.04	231.04	238.03	[237]	[244]	[243]	[247]	[247]	[251]	[252]	[257]	[258]	[259]

### Electronic levels Structure



# <sup>2</sup>S<sub>1/2</sub> Zeeman qubit

(Isotopes w/o nuclear spin)

#### e.g.

<sup>24</sup>Mg<sup>+</sup>

<sup>64</sup>Zn+

<sup>114</sup>Cd+

<sup>40</sup>Ca+

88Sr+

<sup>138</sup>Ba+

<sup>174</sup>Yb+

<sup>202</sup>Hg+

#### <u>Advantages</u>

- RF separation.
- Tunable.
- Infinite T<sub>1</sub>.

#### **Disadvantages**

- Energy depends linearly on B.
- Transition photon caries no momentum
- -Momentum transfer with offresonance lasers: photon scattering.
- Detection.

$$m = 1/2 \mid \uparrow \rangle$$

 $n^2S_{1/2}$ 

$$m = -1/2 |\downarrow\rangle$$

Turn on small B field 2.8 MHz/G

# <sup>2</sup>S<sub>1/2</sub> Hyperfine qubit



 $^{9}$ Be<sup>+</sup>  $^{25}$ Mg<sup>+</sup>
Hyperfine structure (order depends on the sign of  $A_{hf}$ )  $^{67}$ Zn<sup>+</sup>
Turn on small B field

<sup>111</sup>Cd+

<sup>43</sup>Ca+

87Sr+

137**D**a.

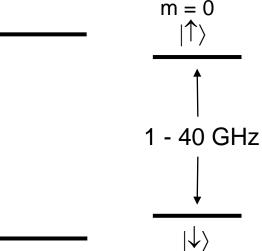
<sup>137</sup>Ba+

<sup>199</sup>Hg+

**Advantages** 

- MW energy separation.
- B-field independent qubit.
- Infinite T<sub>1</sub>.
- State selective fluorescence Detection.

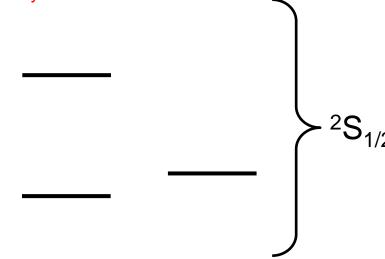
### F = I - 1/2



m = 0

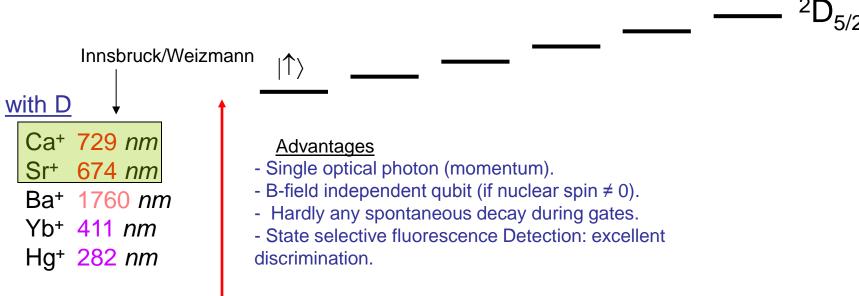
#### **Disadvantages**

- Few GHz energy separation.
- -Transition photon caries no momentum
- Off resonance photon scattering.
- initialization to clock transition can be more tricky



$$F = I + 1/2$$

# Optical qubit



#### <u>Disadvantages</u>

- Finite ( $\sim$  1 sec)  $|\uparrow\rangle$  lifetime.
- Coherence time is limited by laser linewidth.

 $^{2}S_{1/2}$ 

# Trapping

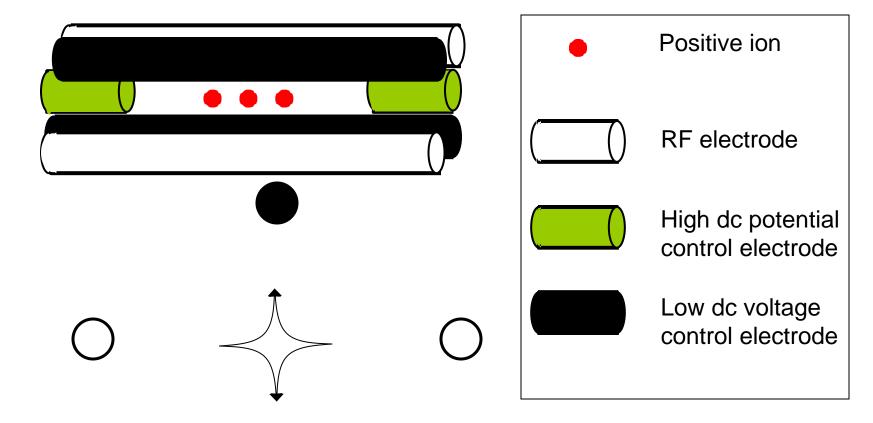
- Trap ions: a minimum/maximum to φ, the electric potential.

- Impossible in all directions; Laplace's equation:

$$\nabla^2 \Phi = 0$$

# **Trapping**

### Linear RF Paul trap



# <u>Dynamic trapping</u> (pondermotive forces)

#### Oscillating electric field:

$$E(x,t) = E_0(x)\cos(w_{rf} + \phi)$$

$$x(t) = X(t) + \xi(t)$$

Large and slow

 $X(t) \gg \xi(t)$ 

small and fast

$$\frac{\partial^2 X(t)}{\partial t^2} \ll \frac{\partial^2 \xi(t)}{\partial t^2}$$

#### Newton's E.O.M:

$$m(\frac{\partial^2 X(t)}{\partial t^2} + \frac{\partial^2 \xi(t)}{\partial t^2}) = eE_0(x)\cos(\omega_{rf}t + \phi)$$

# Dynamic trapping

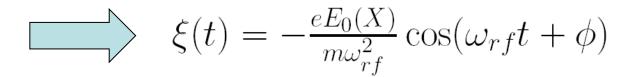
$$m(\frac{\partial^2 X(t)}{\partial t^2} + \frac{\partial^2 \xi(t)}{\partial t^2}) = eE_0(x)\cos(\omega_{rf}t + \phi)$$

#### Field expansion:

$$E_0(x) = E_0(X) + \frac{\partial E_0(X)}{\partial X} \xi + O(\xi^2)$$

To 0<sup>th</sup> order:

$$m\frac{\partial^2 \xi(t)}{\partial t^2} = eE_0(X)\cos(\omega_{rf}t + \phi)$$



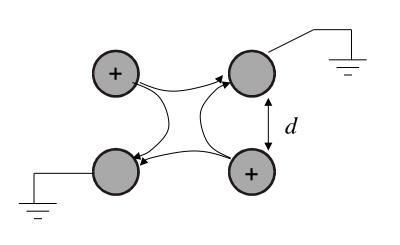
#### Next order:

$$m\frac{\partial^2 X(t)}{\partial t^2} = -\frac{e^2 E_0(x)}{m\omega_{rf}^2} \frac{\partial E_0(X)}{\partial X} \cos^2(\omega_{rf} t + \phi)$$

Average over one period:

$$m\frac{\partial^2 X(t)}{\partial t^2} = -\frac{e^2}{4m\omega_{rf}^2} \frac{\partial E_0^2(X)}{\partial X}$$

# Dynamic trapping



$$m\frac{\partial^2 X(t)}{\partial t^2} = -\frac{e^2}{4m\omega_{rf}^2} \frac{\partial E_0^2(X)}{\partial X}$$

For electric quadruple:

$$E_0(x) = \alpha \left[\frac{V_{rf}}{d}\right] \frac{x}{d}$$

Pseudo-potential: Sign of e 
$$U_{eff}(x) = \left[\frac{\alpha^2 e^2 V_{rf}^2}{4m\omega_{rf} d^4}\right] x^2$$

Harmonic frequency:

$$\omega_{trap} \sim \frac{eV_{rf}}{m\omega_{rf}d^2}$$

# **Trapping**

#### Linear RF Paul trap

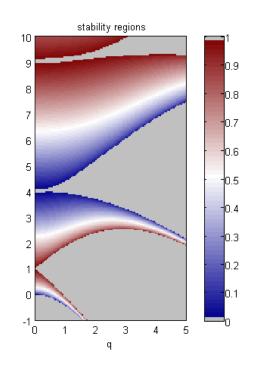
#### **Potential:**

$$\Phi = \sum_{i} (\alpha_{i} + \beta_{i} V_{0} \cos(\omega_{rf} t)) X_{i}^{2}$$

#### Solve E.O.M:

$$M\ddot{\ddot{X}} = F = -e\nabla\Phi$$

(Mathieu eq': 
$$\frac{d^2X_i}{d\tau^2} + [a_i + 2q_i\cos(2\tau)]X_i = 0$$
 )



#### **Stable solution:**

$$\omega_{trap} \sim \frac{eV_{RF}}{m\omega_{rf}d^2}$$

d – the distance between the ion and the electrodes

Drive frequency ~ 20-30 MHz RF amplitude ~ 200-300 V

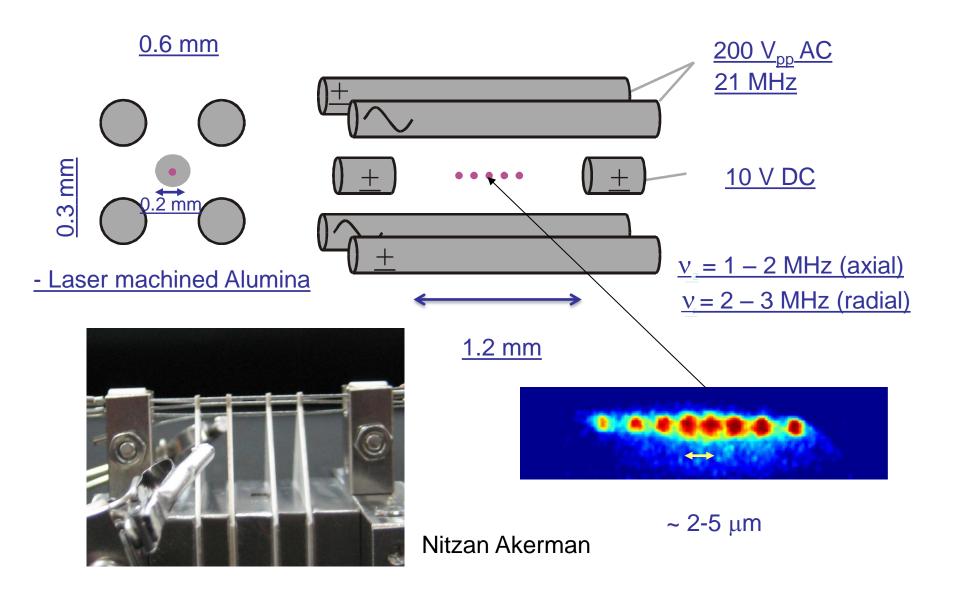
Secular frequency

Radial ~ 2-3 MHz -

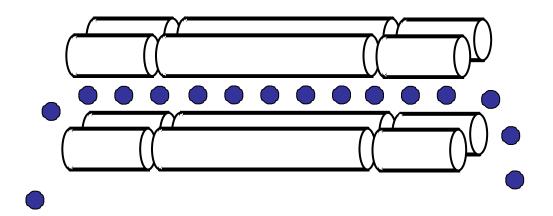
Axial ~ 1 MHz -

•

# Weizmann trap.

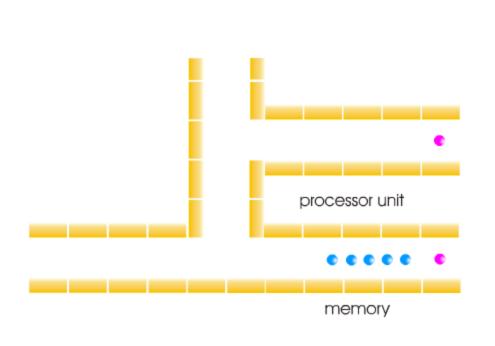


# Scale up?



One (out of many) problem: isolating one mode of motion for gates

# The ion vision: Multiplexed trap array



interconnected multi-trap structure subtraps completely decoupled

routing of ions by controlling electrode voltages

Subtrap for different purpose: Gates, readout, etc.

D. J. Wineland, et al.,

J. Res. Nat. Inst. Stand. Technol. 103, 259 (1998);

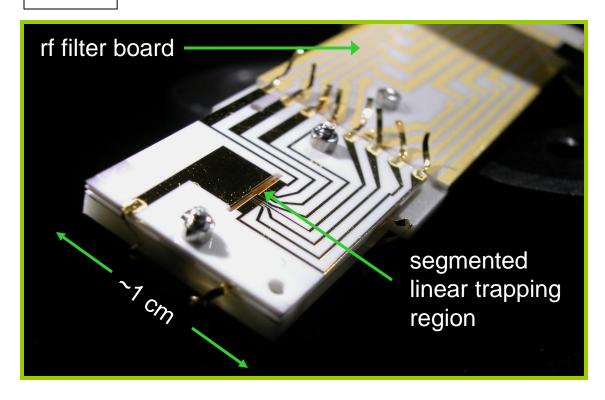
D. Kielpinski, C. Monroe, and D. J. Wineland, Nature **417**, 709 (2002).

Other proposals: DeVoe, Phys. Rev. A **58**, 910 (1998).

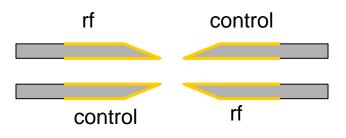
Cirac & Zoller, Nature 404, 579 (2000).

# Multi-zone ion trap

#### **NIST**



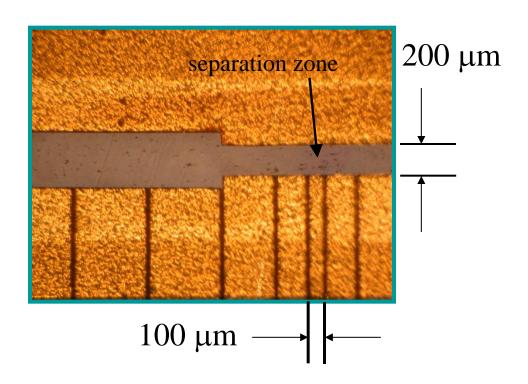
view along axis:



- Gold on alumina construction
  - RF quadrupole realized in two layers
- Six trapping zones
  - Both loading and experimental zones
    - One narrow separation zone
- Closest electrode ~140 µm from ion

# Ion transport

**NIST** 

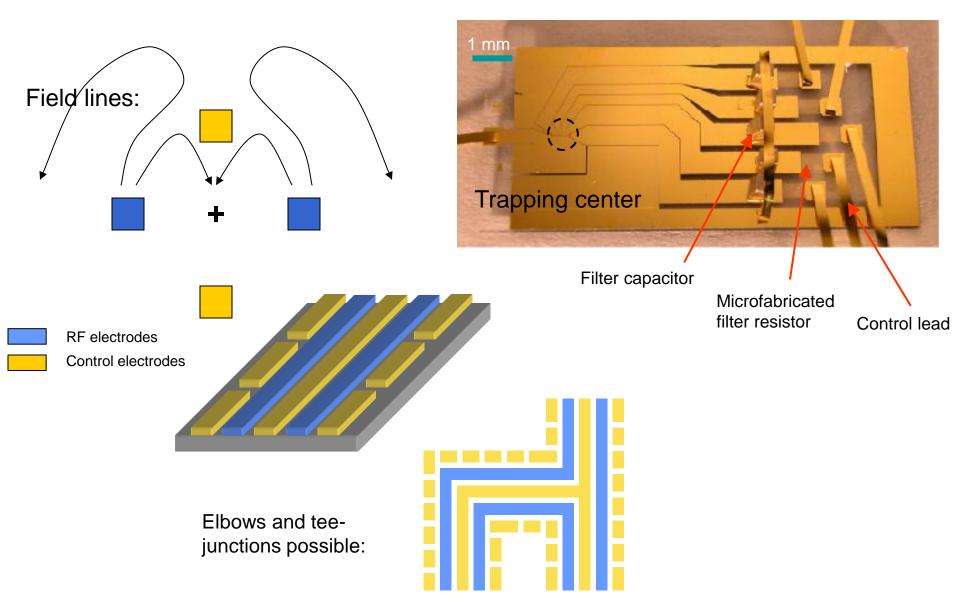


6-zone alumina/gold trap (Murray Barrett, John Jost)

- lons can be moved between traps.
- Electrode potentials varied with time
- Ions can be separated efficiently in sep. zone
  - Small electrode's potential raised
  - Motion (relatively) fast
  - Shuttling (adiabatic): several 10 μs
- Separating: few 100 μs -

### **NIST**

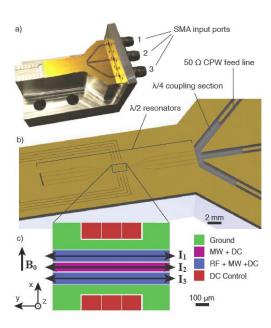
### Surface-electrode traps



J. Chiaverini et al. Quant. Inform. Comp. 5, 419 (2005).

S. Seidelin et al. Phys. Rev. Lett. 96, 253003 (2006).

### Micro-fabricated traps

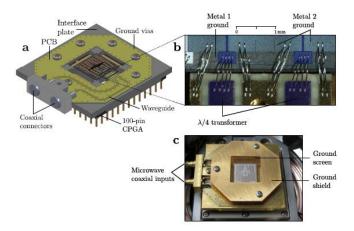


Allcock; Oxford

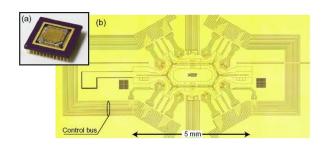
Amini *et al.* New J. Phys. 12, 033031 (2010).

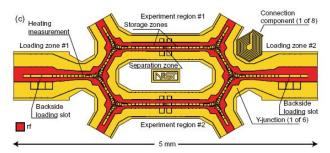
Allcock *et al.* App. Phys. Lett. 102, 044103 (2012).

Shappert *et al.* arXiv quant-ph\1304. 6636 (2013).



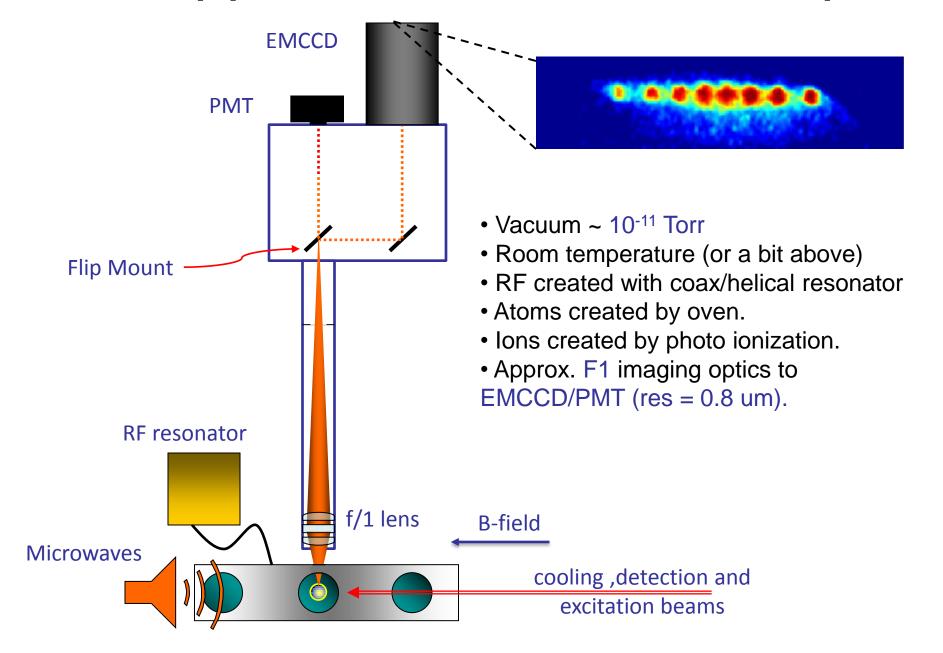
Shappert; Georgia Tech



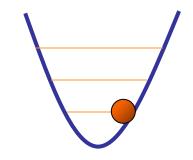


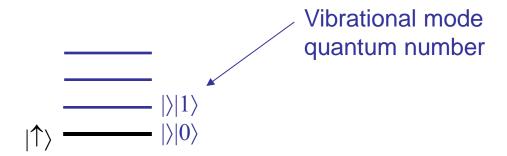
Amini; NIST

# Trapped ions on the tabletop



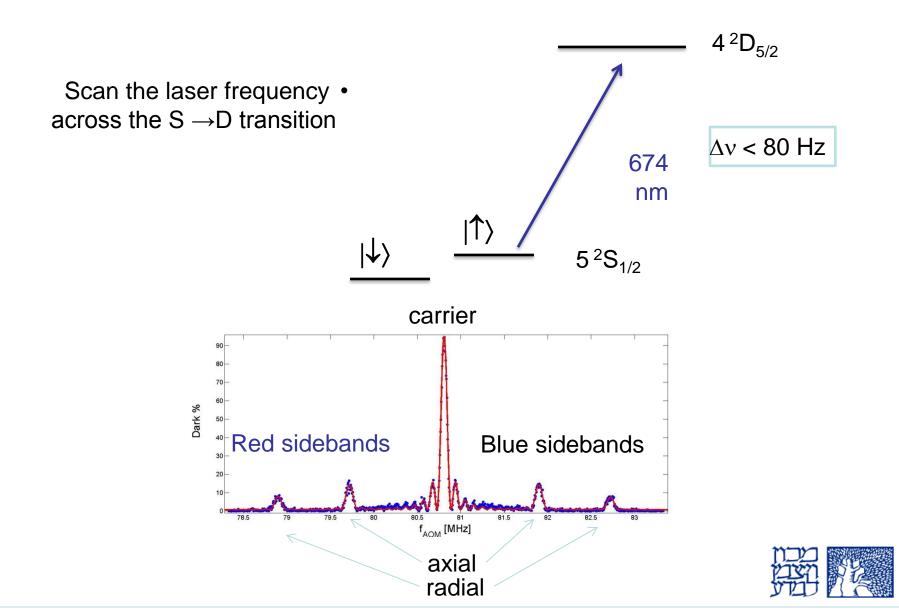
# Harmonic oscillator levels



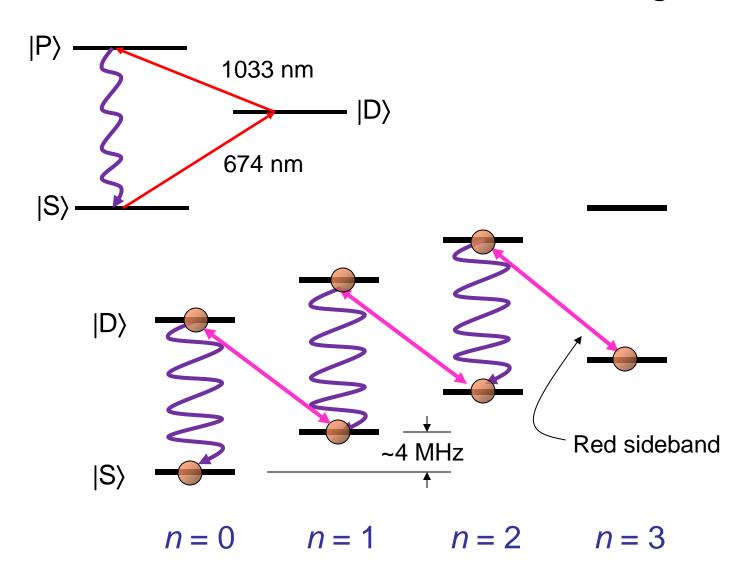


- Doppler cooling.  $\langle n \rangle \sim 3-20$
- Resolved side band cooling.  $\langle n \rangle \sim 0$

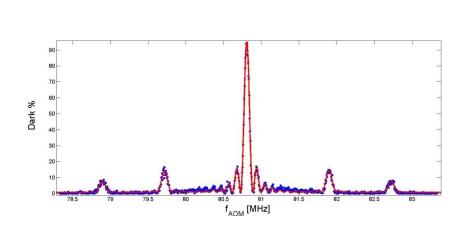
## Sideband Spectroscopy

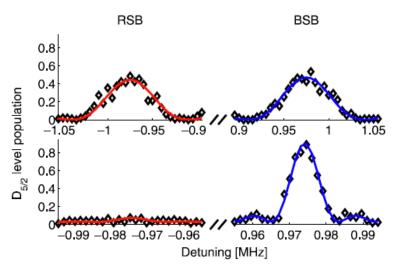


### Resolved-sideband Cooling



# Sideband cooling to the ground state





$$\langle n \rangle < 0.05$$

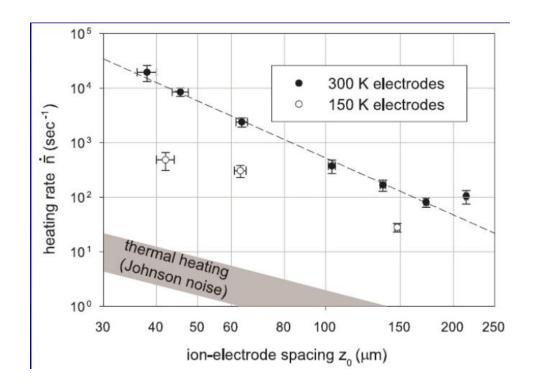
- T  $\approx 2~\mu\text{K}$
- Uncertainty in ion position = ground state extent

$$\sqrt{\frac{\hbar}{2m\omega_{ho}}} = 6nm$$





### **Anomalous heating**

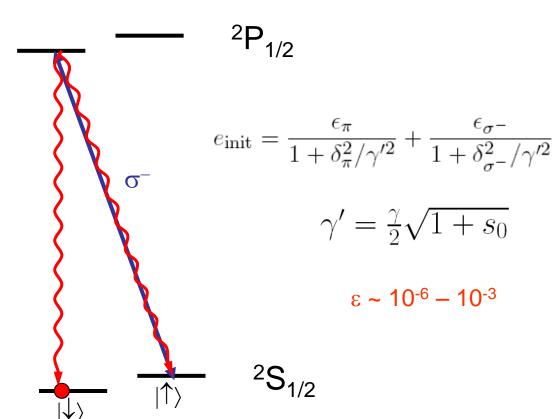


$$\frac{\dot{n}}{z_o} \propto \frac{1}{z_o^{3.5}}$$

- Fluctuating charges
- f<sup>-1.5</sup> noise
- Thermally activated
- Due to monolayer of C on eletrodes: gone after Ar+ ion cleaning

#### Zeeman qubit

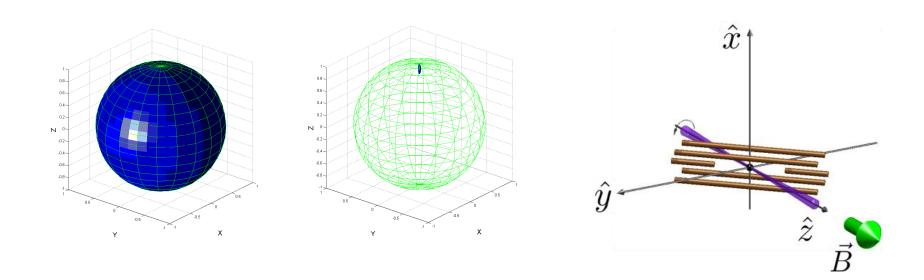
- -Optical pumping into a dark state.
- -CPT possible into any superposition..



#### Error sources:

- Polarization purity.

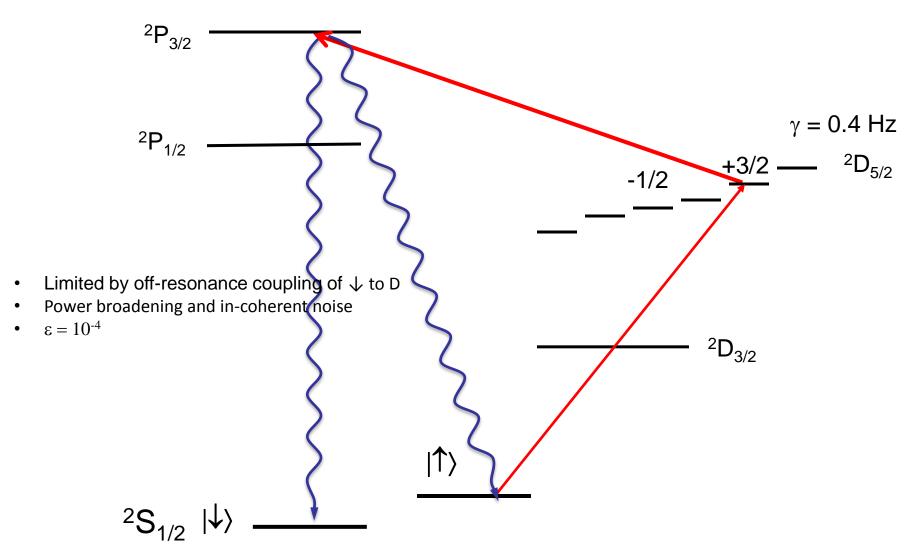
Zeeman qubit



Process tomography of optical pumping

Limited to 10<sup>-3</sup> due to stressinduced birefringence in vacum chamber optical viewports

Zeeman qubit: the D level option



Keselman, Glickman, Akerman, Kotler and Ozeri, New J. of Phys. 13, 073027, (2011)

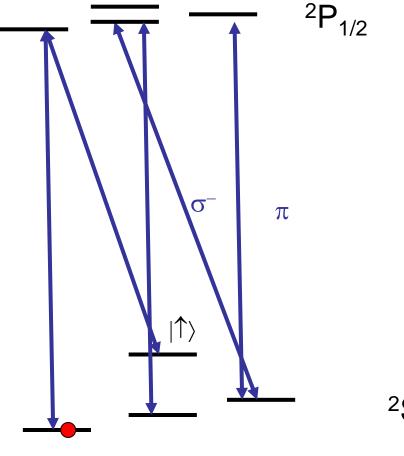
Hyperfine qubit

- Optical pumping into a dark state.

#### **Estimated:**

$$\epsilon \le 2 \times 10^{-5}$$

C. Langer, Ph.D Thesis, University of Colorado, (2006).



 $|\downarrow\rangle$ 

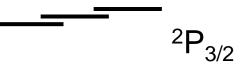
F=0

F=1

 $^{2}S_{1/2}$ 

#### Optical qubit

-  $|\downarrow\rangle$  state initialization: same as previous.



- $|\uparrow\rangle$  state initialization:
  - Rapid adiabatic passage.

$$\epsilon \sim 10^{-2}$$
 (Wunderlich et. al. Journal of Modern Optics 54, 1541 (2007))

-  $\pi$ -pulse.

 $\varepsilon \sim 10^{-2}$ 

