Trapped ion quantum computing, simulation, and sensing

John Bollinger, NIST, Boulder CO

Monday, July 2, 11:00 AM – Trapped ion quantum computing

Tuesday, July 3, 11:00 AM – Trapped ion quantum simulation

Thursday, July 5, 9:00 AM – Trapped ion quantum sensing

Trapped ion quantum computing, simulation, and sensing

John Bollinger, NIST, Boulder CO

Monday, July 2, 11:00 AM – Trapped ion quantum computing

Reviews for basic tools of ion trap quantum computing:

D. J. Wineland, C. Monroe, W. M. Itano, D. Leibfried, B. E. King, and D. M. Meekhof, J. Res. Nat. Inst. Stand. Tech. 103, 259 (1998)

M. Sasura and V. Buzek, J. Mod. Opt. 49, 1593 (2002)

D. Leibfried, R. Blatt, C. Monroe, and D. Wineland, Rev. Mod. Phys. 75, 281 (2003)

H. Häffner, C. F. Roos, and R. Blatt, Physics Reports 469, 155 (2008)

D. Kielpinski, Front. Phys. China 3, 365 (2008)

Thanks to Didi Leibfried, NIST, for the use of some of his slides

Trapped ion quantum computing

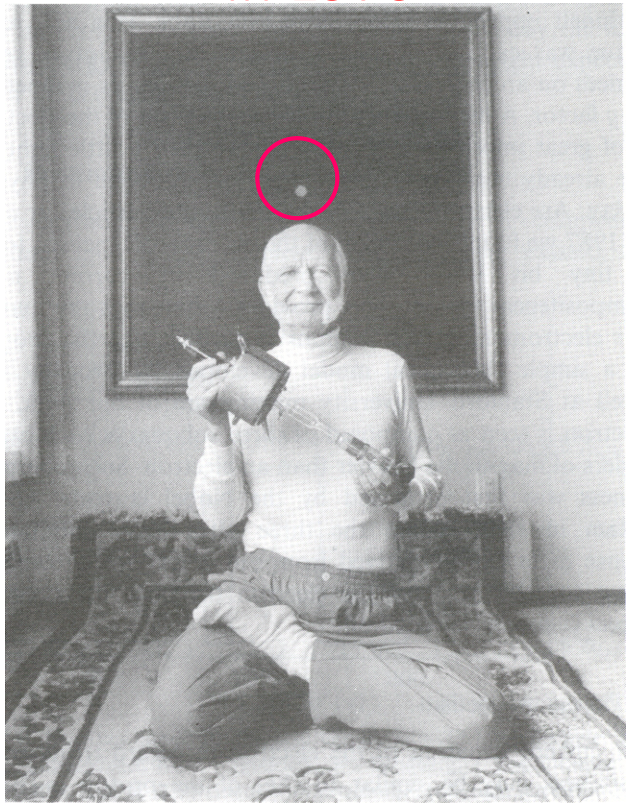
1. Linear rf traps
2. Atomic physics for ion qubits
3. Generating entangled states with spin-dependent forces
4. Example experiments
5. Surface-electrode rf traps

Traps for single charged particles

Paul trap 1956

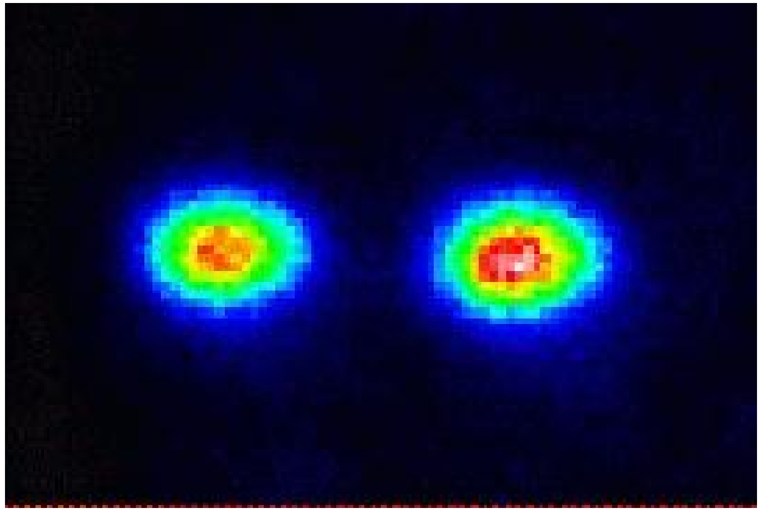
Wolfgang Paul

Penning trap 1959
single electron trapped in 1973



Hans Dehmelt

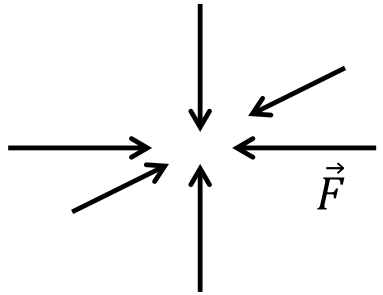
1980/1981 single trapped and laser cooled atomic ions at Univ. of Heidelberg and NIST



CCD image of two trapped and laser cooled $^9Be^+$ ions in a Paul-trap at NIST

Shared 1989 Nobel prize in physics

Paul (or rf) trap – linear rf trap

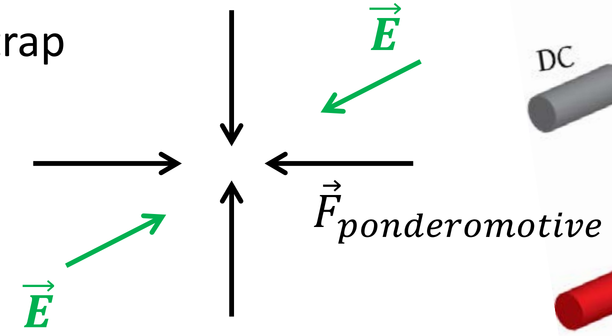


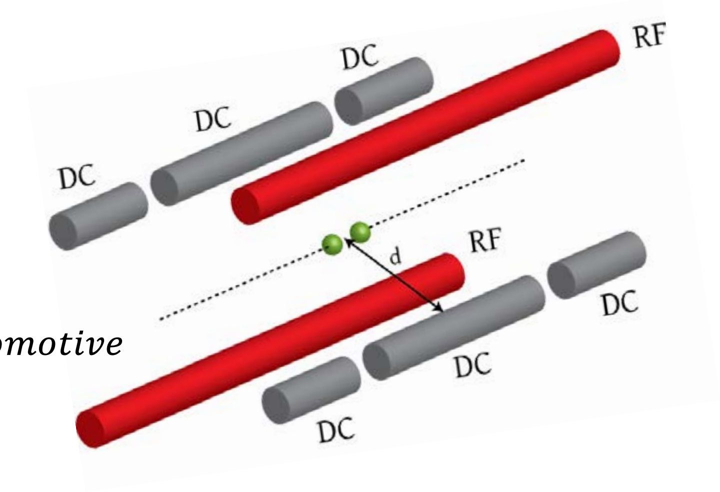
ideal ion trap
desire $\vec{\nabla} \cdot \vec{F} \neq 0$

static confinement axially

$$q\phi_s = \frac{1}{2} m\omega_z^2 \left[z^2 - \frac{1}{2}(x^2 + y^2) \right]$$

linear rf trap





pseudopotential confinement radially

$$q\phi_s = \frac{1}{2} m\omega_r^2 (x^2 + y^2)$$

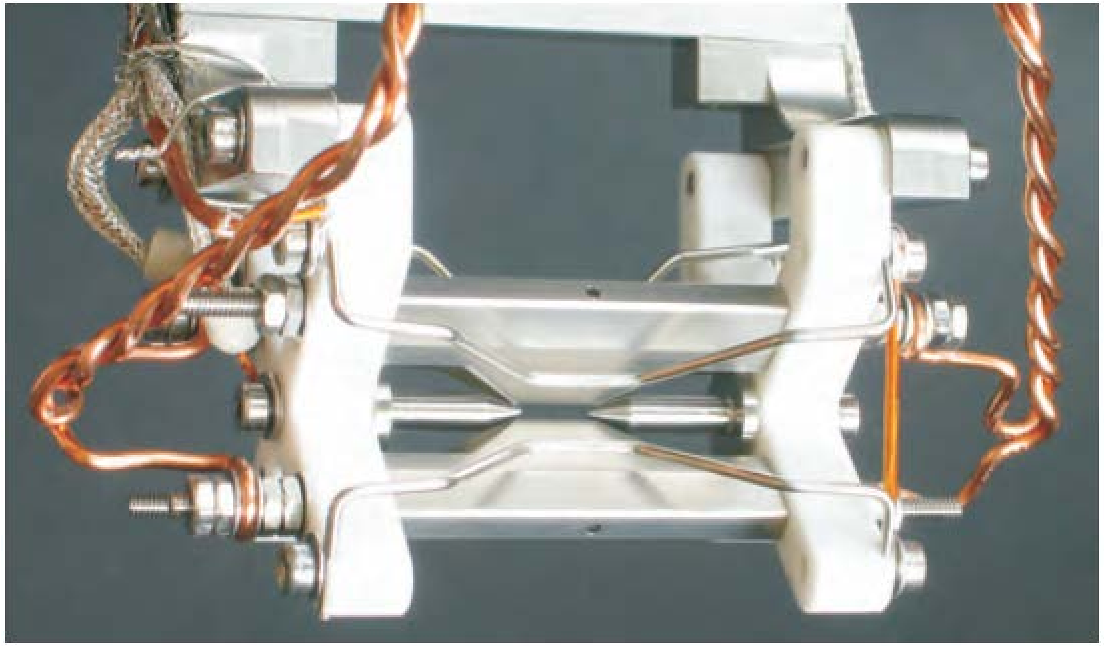
$$\frac{\omega_r}{2\pi}, \frac{\omega_z}{2\pi} \sim 1 - 5 \text{ MHz}$$

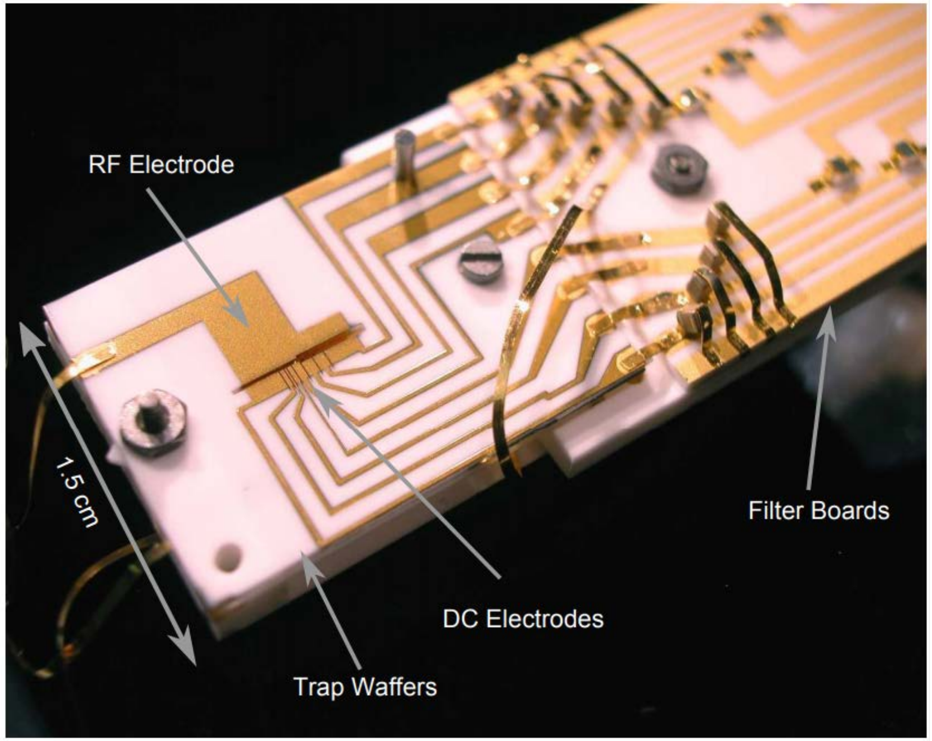
rf drive frequency $\frac{\Omega}{2\pi} \sim 40 - 100$ MHz

pondermotive force $\vec{F}_p = -\frac{e^2}{4m\Omega^2} \vec{\nabla}(E^2)$

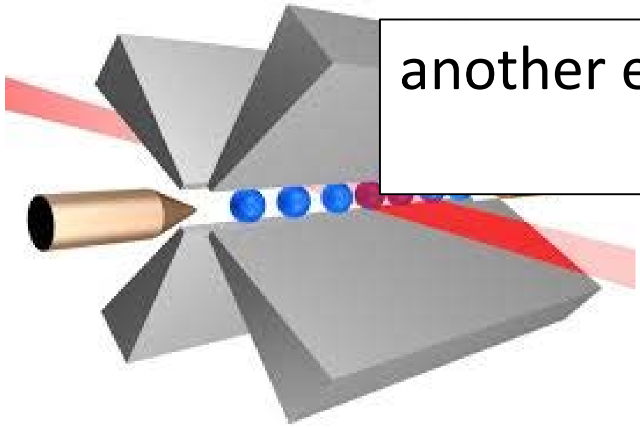
Example linear rf traps

Blade trap, Blatt group, Innsbruck

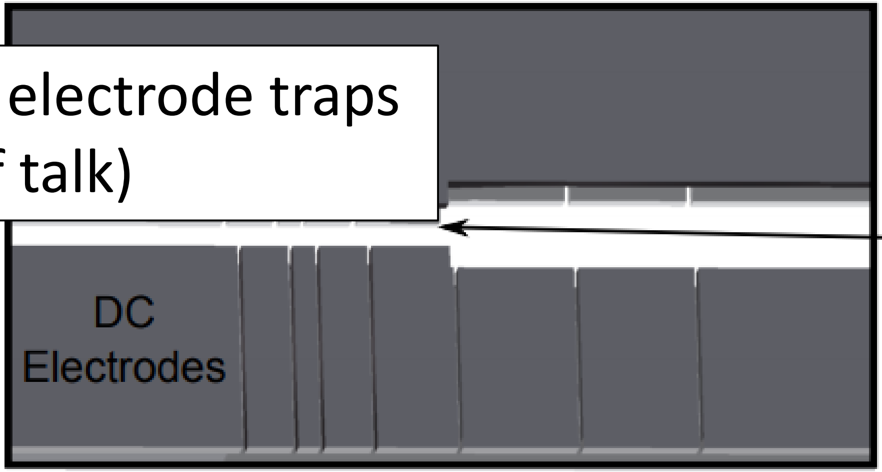




Two wafer trap, NIST



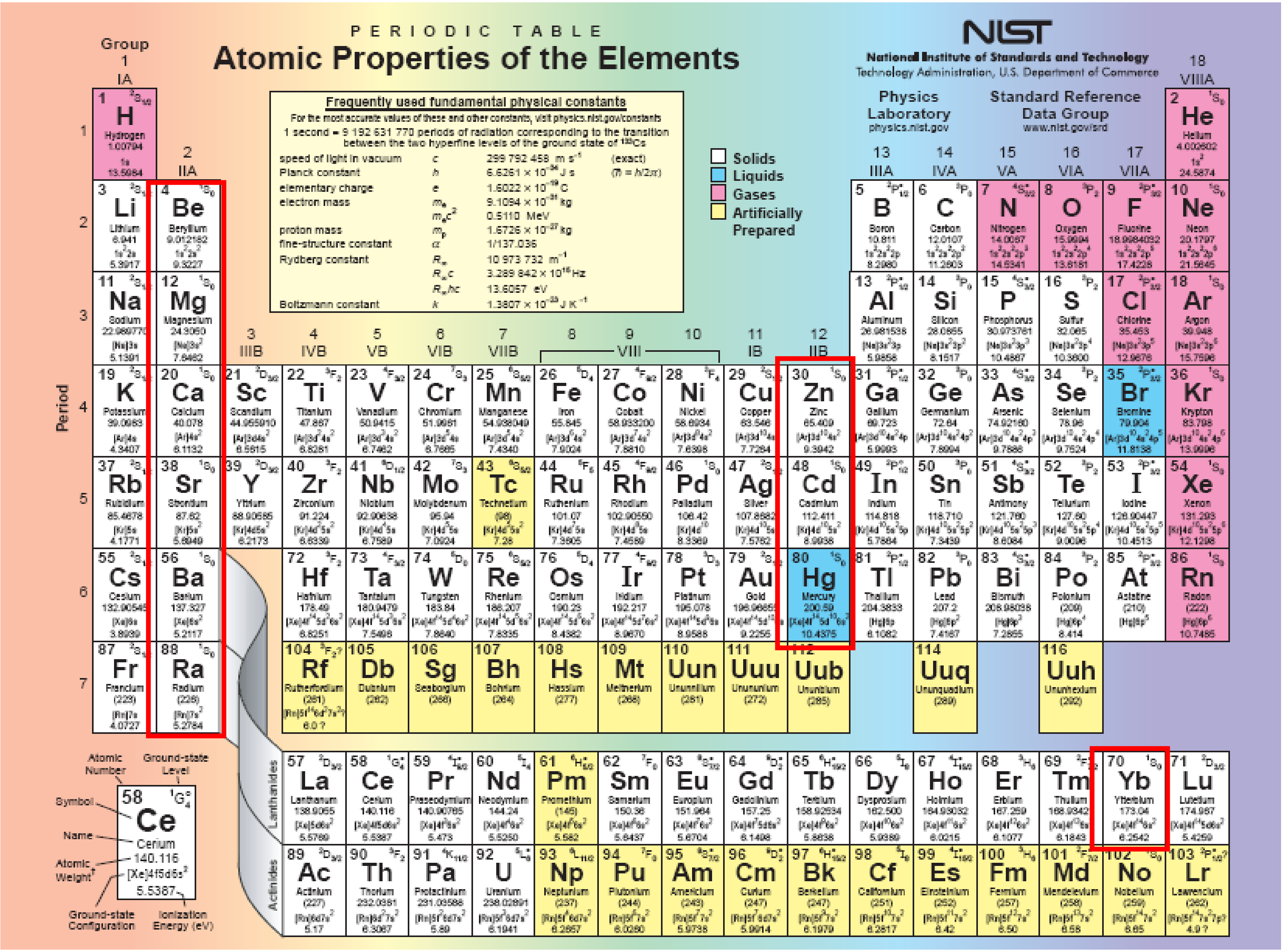
another example: surface electrode traps (see end of talk)



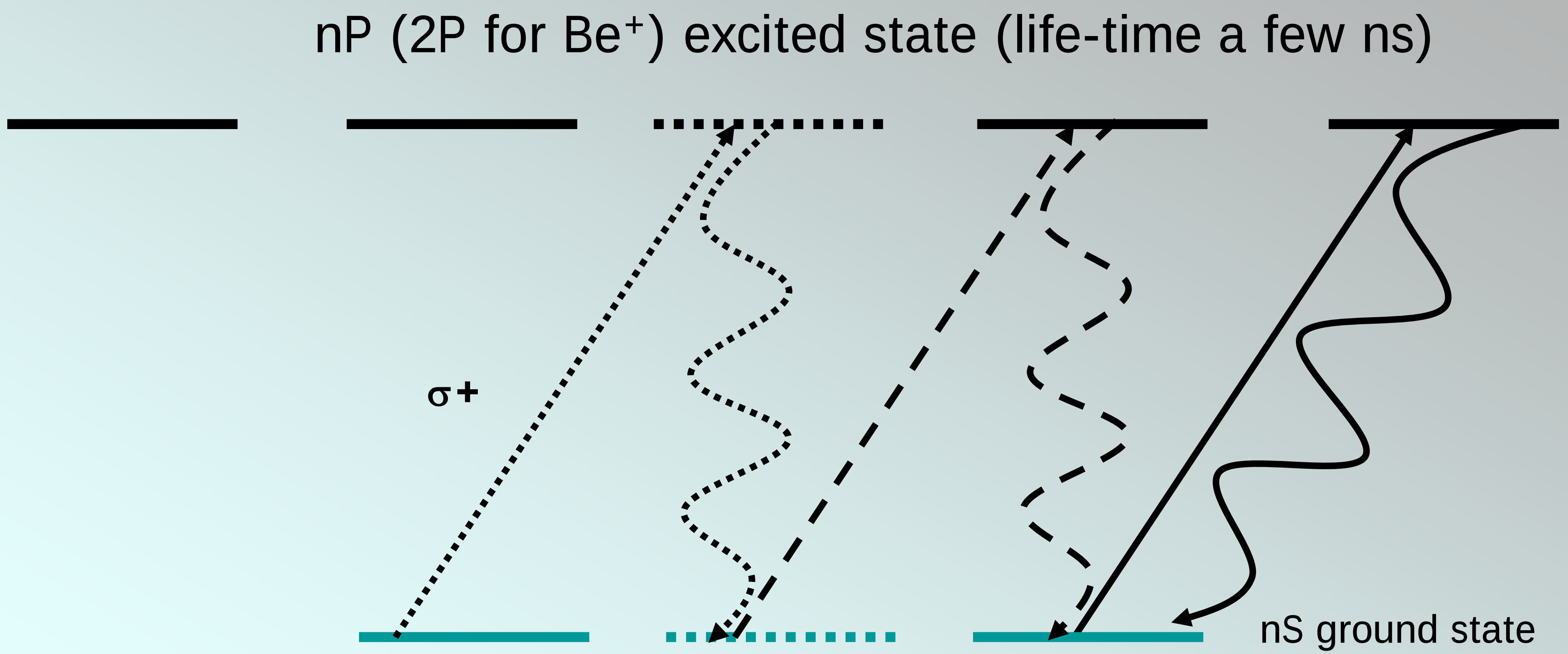
DC Electrodes (on bottom trap wafer)

Atomic physics for ion-qubits

One electron systems



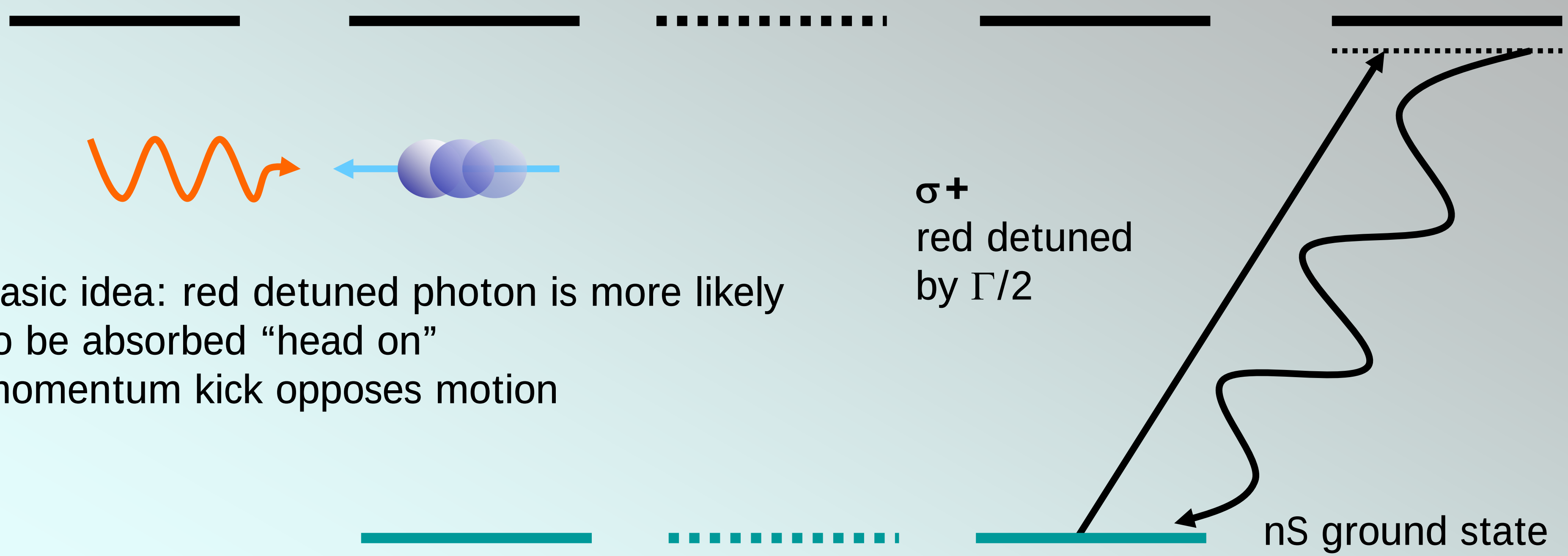
Resonant S → P transition



optically pump for state preparation

Resonant S → P transition

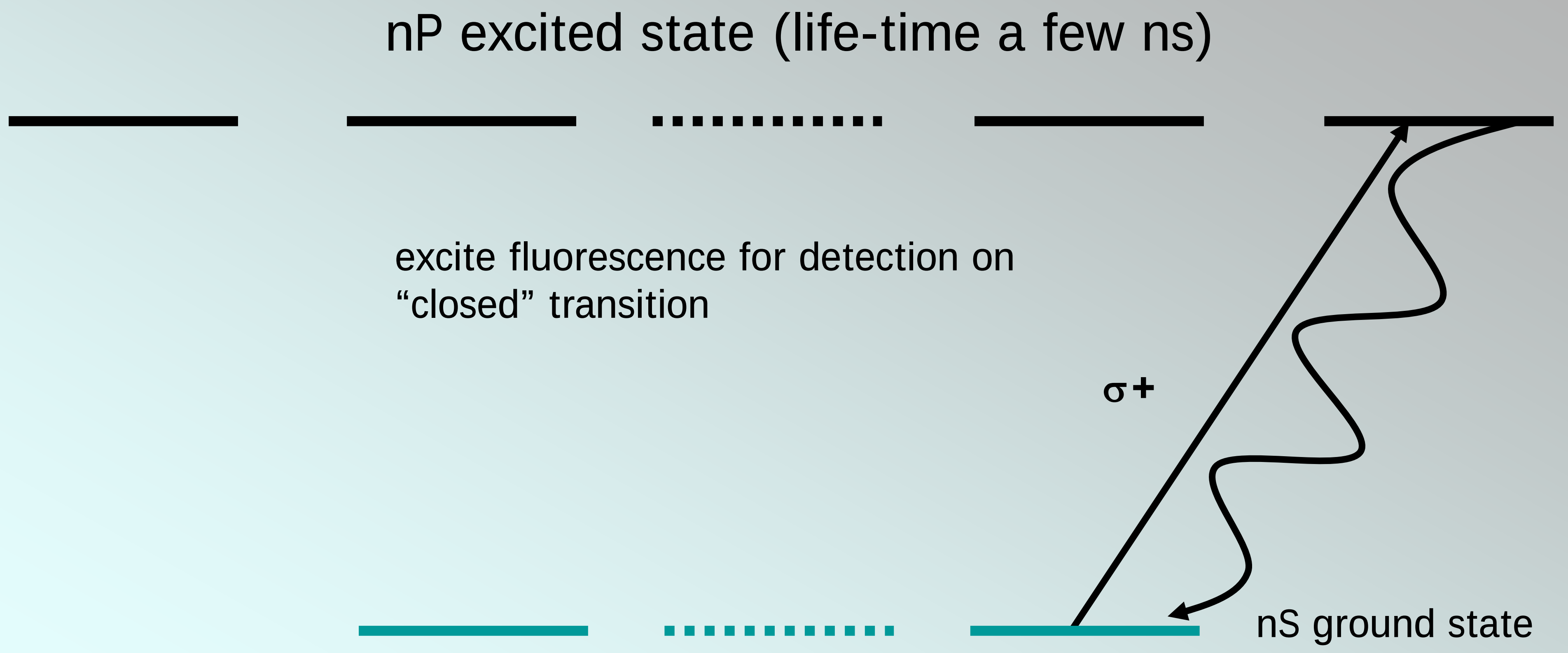
nP excited state (life-time a few ns)



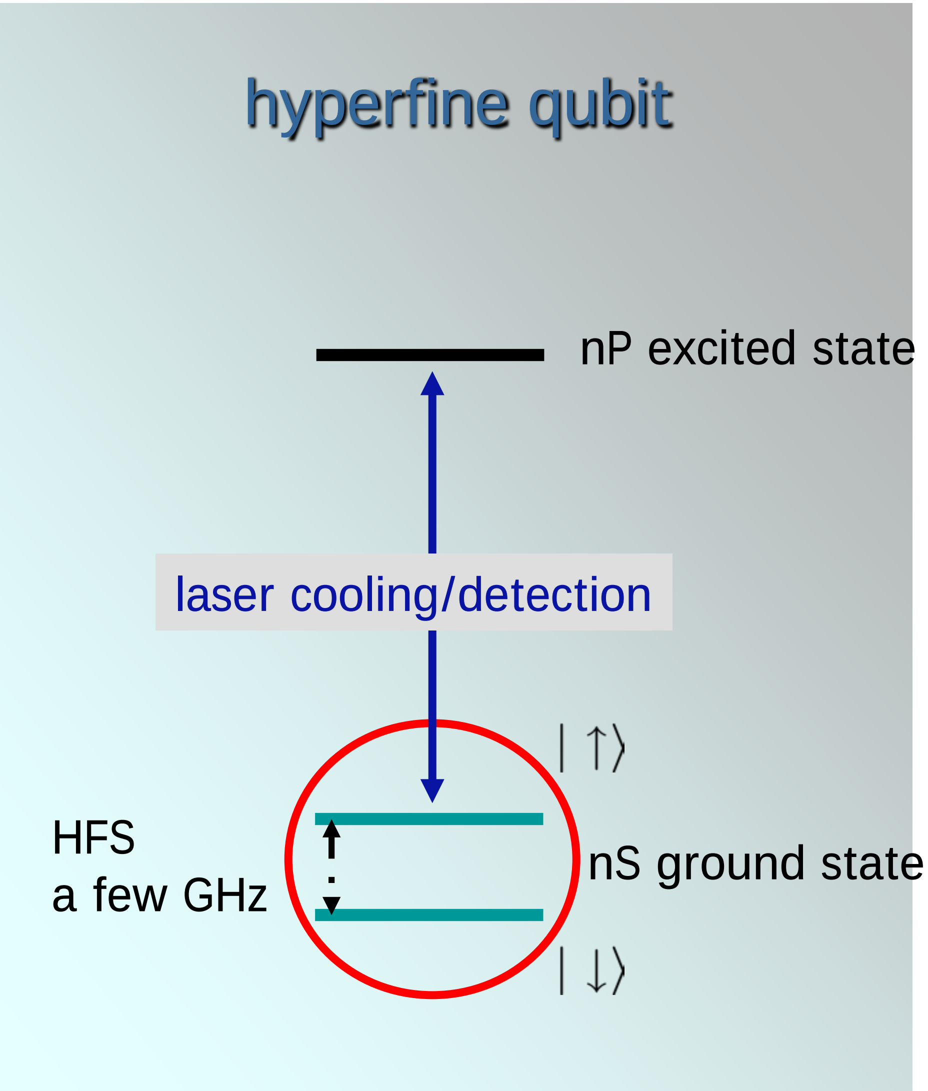
basic idea: red detuned photon is more likely to be absorbed "head on"
momentum kick opposes motion

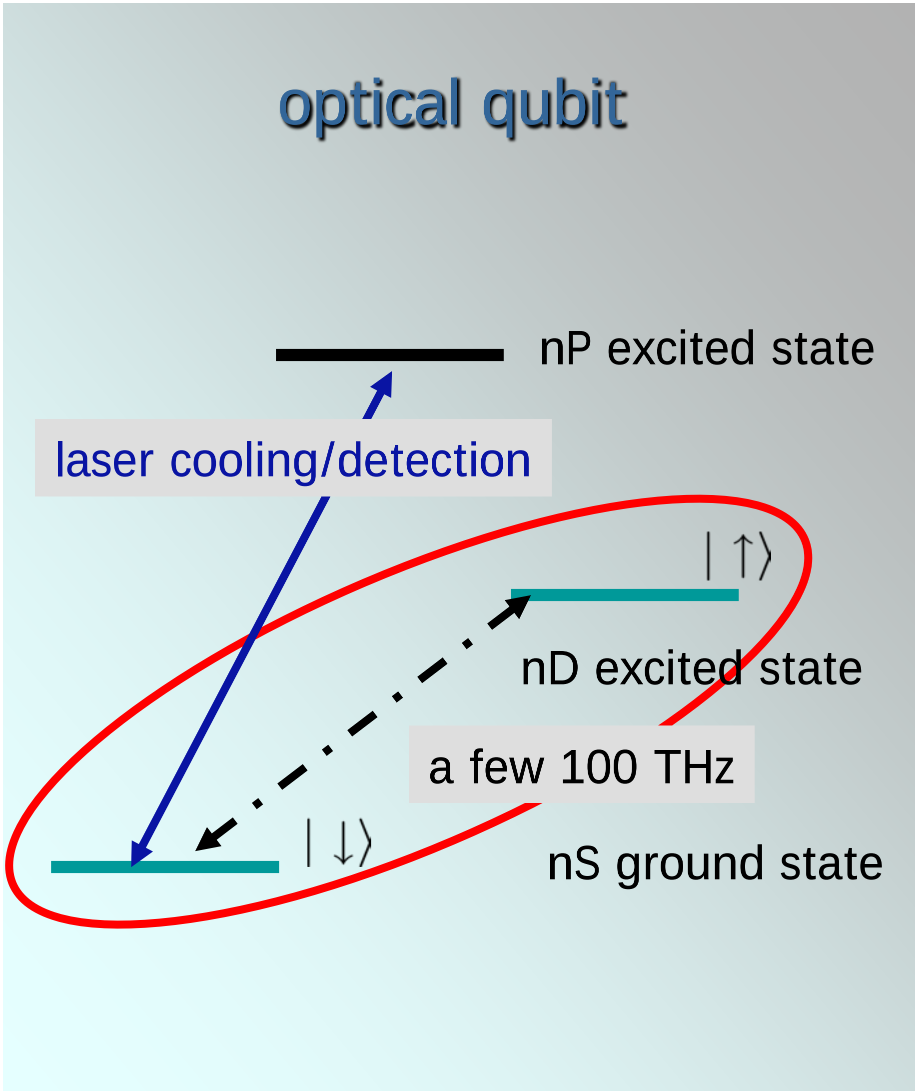
Doppler cooling ⇒ ion crystal forms

Resonant S → P transition

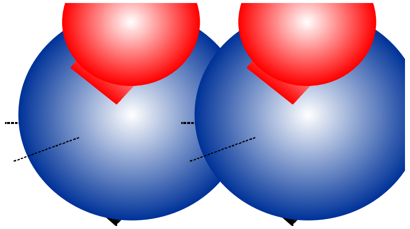


Ion qubits (|↓ ⟩, |↑⟩)


hyperfine qubit
nP excited state
laser cooling/detection
| ↑⟩
HFS
a few GHz
nS ground state
| ↓⟩

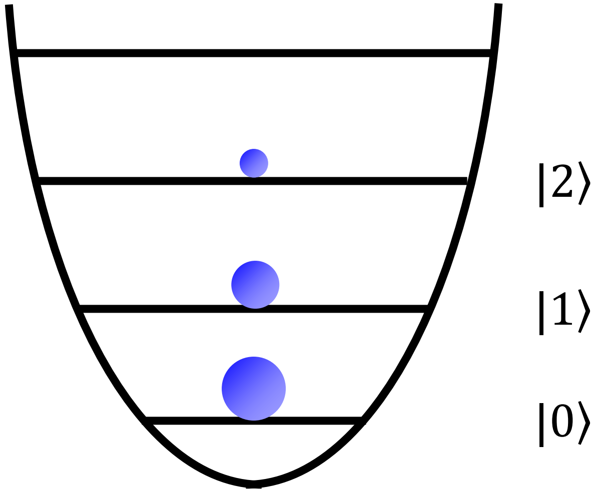

optical qubit
nP excited state
laser cooling/detection
| ↑⟩
nD excited state
a few 100 THz
| ↓⟩
nS ground state

Sideband cooling – cooling to the ground state

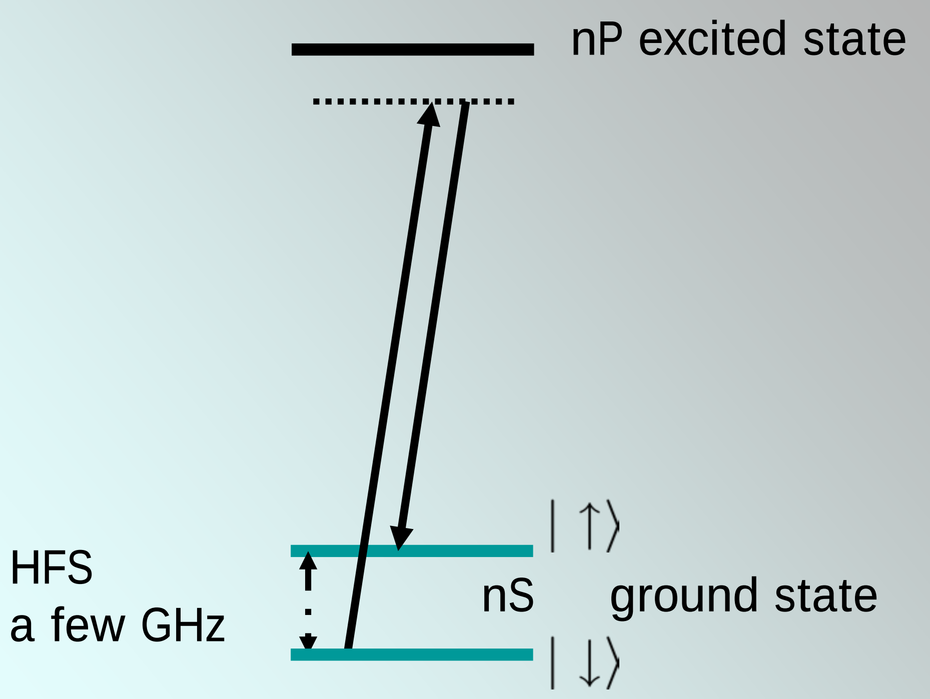


two ions ↔ 6 normal modes

normal mode ↔ harmonic oscillator



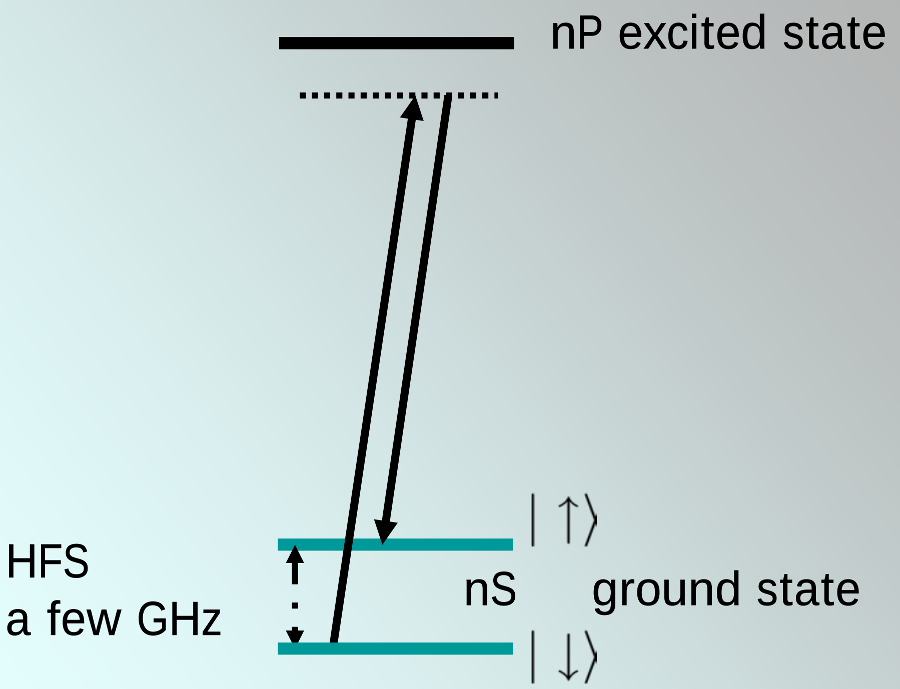
hyperfine qubit



stimulated Raman interaction

Sideband cooling – cooling to the ground state

hyperfine qubit



stimulated Raman interaction

basic coupling, Ω_0 contains details (Raman or optical etc.)

$$H_I = \hbar\Omega_0 e^{-i([\delta_0 - \omega_0]t + \phi)} e^{i\Delta\mathbf{k}\cdot\mathbf{r}} |\uparrow\rangle\langle\downarrow| + \text{h.c.}$$

light detuning and phase

ion motion in trap

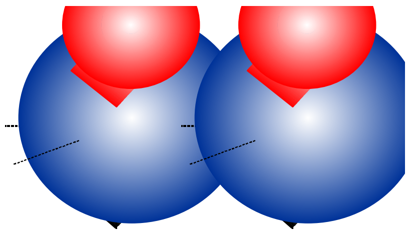
$$e^{i\Delta\mathbf{k}\cdot\mathbf{r}} = e^{i\eta(a_i^\dagger + a_i)} \simeq 1 + i\eta(a_i^\dagger + a_i)$$

Lamb-Dicke approximation

$$\eta = \sqrt{\frac{E_{\text{rec}}}{E_{\text{h.o.}}}} = \sqrt{\frac{\hbar^2 k^2}{2m\hbar\omega}} = 2\pi\frac{a_0}{\lambda} \ll 1$$

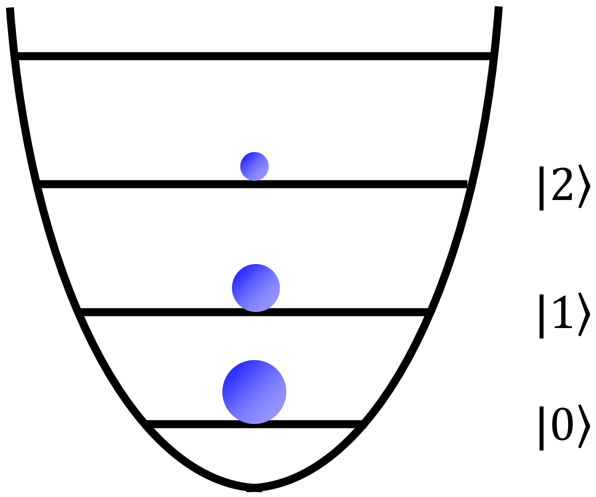
a_0 typically order 10 nm for a few MHz trap frequency, $\lambda \sim$ 200-400nm

Sideband cooling – cooling to the ground state

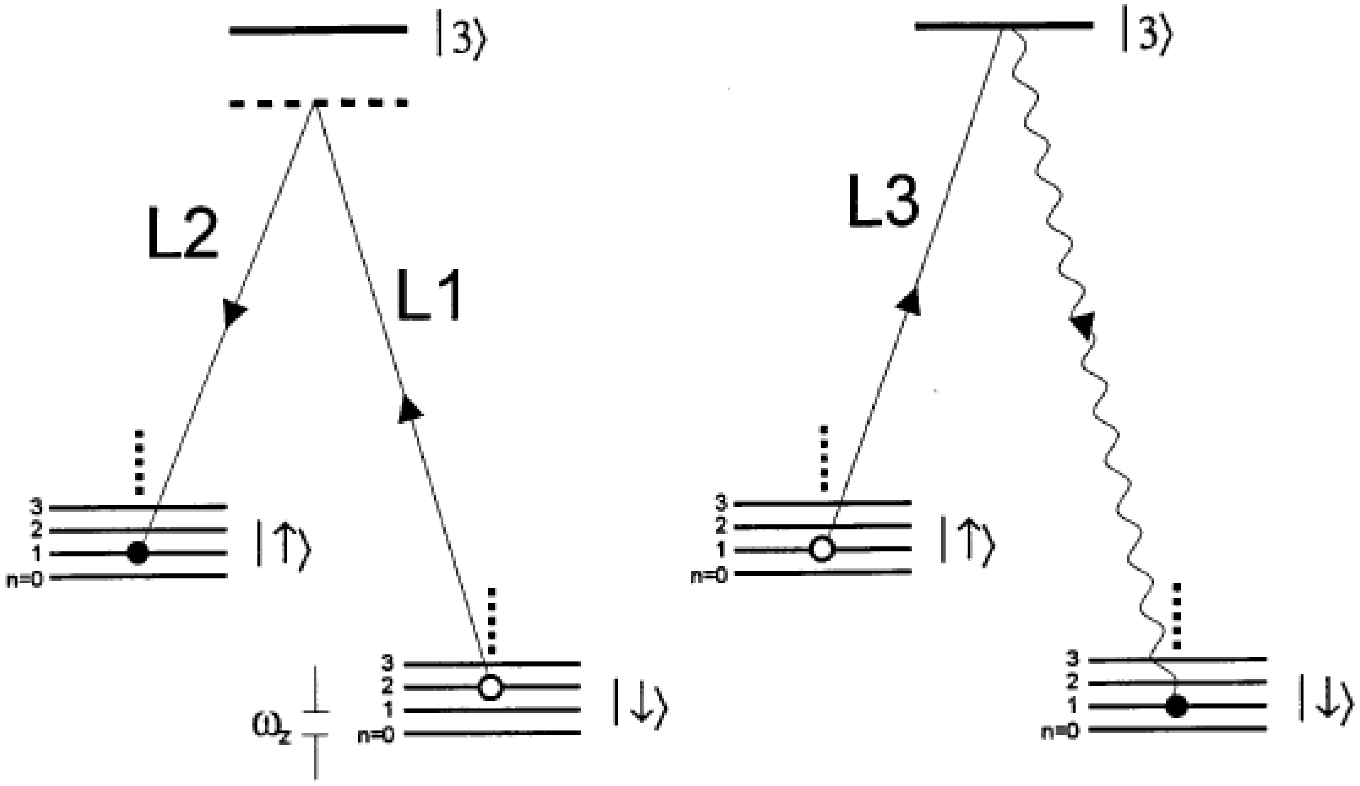


two ions ↔ 6 normal modes

normal mode ↔ harmonic oscillator



From D. J. Wineland, et al., *Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions*
J. Res. Nat. Inst. Stand. Tech. 103, 259 (1998)



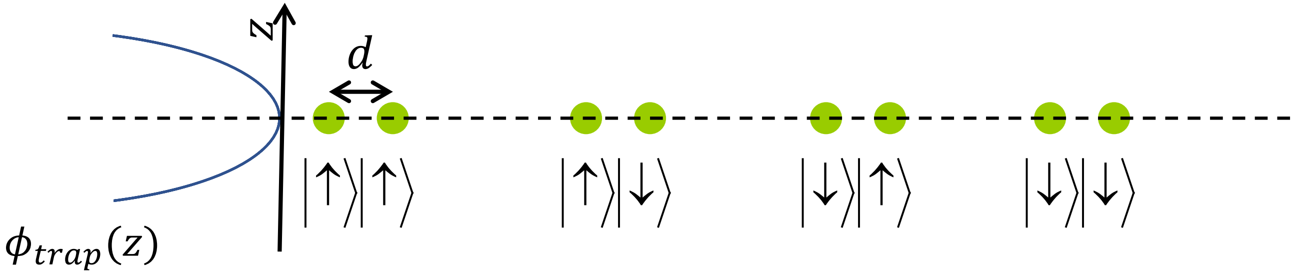
(a) stimulated Raman (Δn = -1)   (b) spontaneous Raman (Δn ≈ 0)

Generating entangled states
(a quantum logic gate)
with spin-dependent forces

Generating entangled states with spin-dependent forces

Simple example – adiabatic spin-dependent force

Calarco, Cirac, Zoller, PRA (2001)

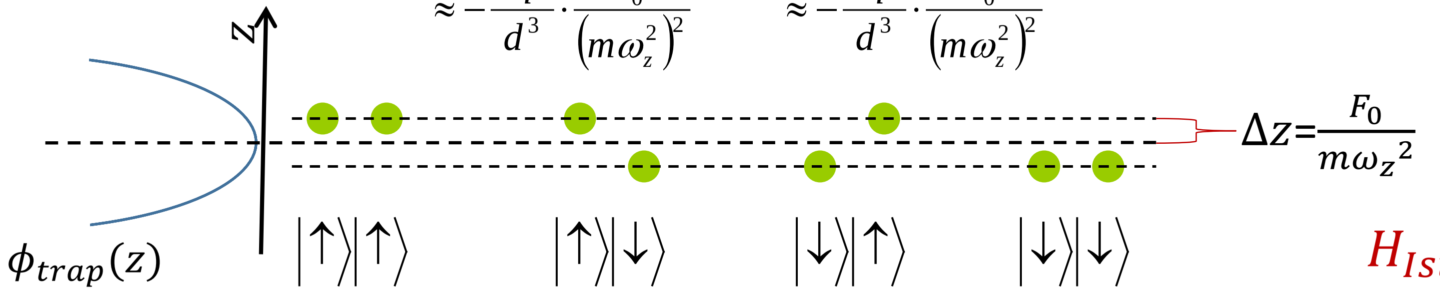


$$E_{Coulomb} \propto q^2/d$$

$$0 \qquad \frac{q^2}{d} - \frac{q^2}{\sqrt{d^2 + (2\cdot\Delta z)^2}} \qquad \frac{q^2}{d} - \frac{q^2}{\sqrt{d^2 + (2\cdot\Delta z)^2}} \qquad 0 \longleftarrow \Delta E_{Coulomb}$$

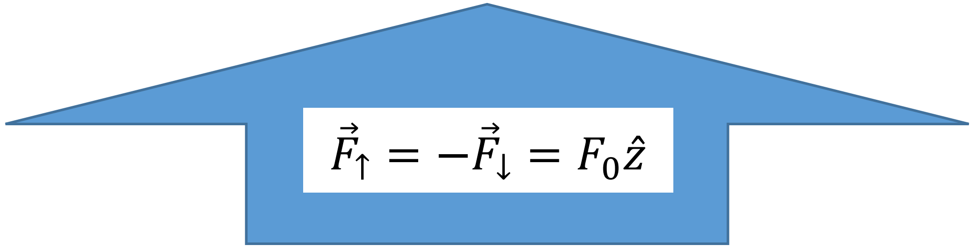
$$\approx -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2} \qquad \approx -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2}$$

$\Delta E_{Coulomb} \leftrightarrow$ **antiferromagnetic Ising interaction**



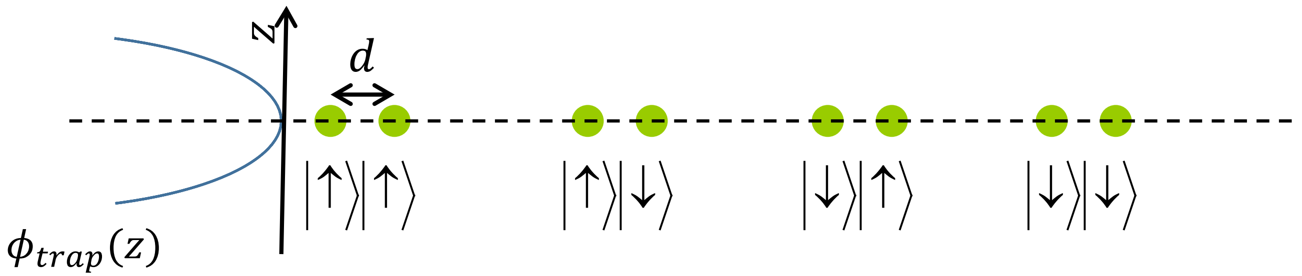
$$H_{Ising} = J\sigma^z{}_1 \cdot \sigma^z{}_2,$$

$$J = \frac{q^2}{d^3}\frac{F_0{}^2}{(m\omega_z{}^2)^2}$$



Generating entangled states with spin-dependent forces

Simple example – adiabatic spin-dependent force

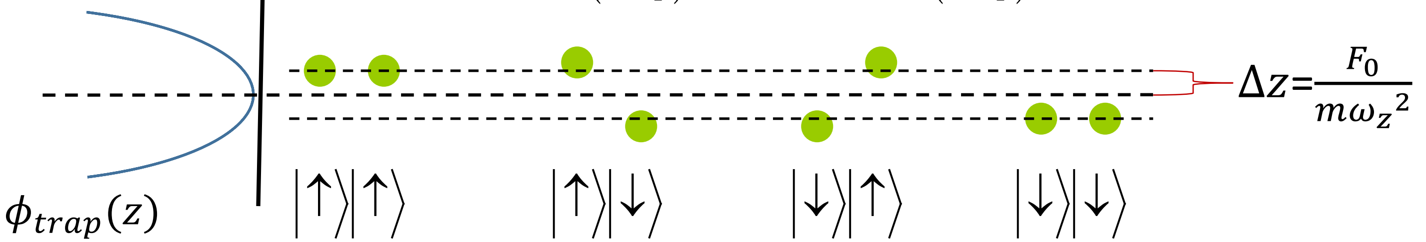


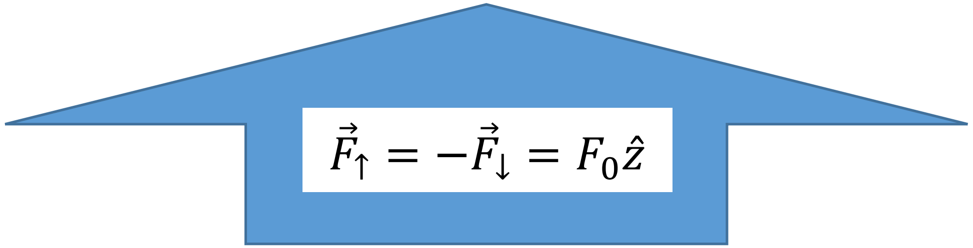
$E_{Coulomb} \propto q^2/d$

Spin-dependent push can be enhanced by the remaining ion!

$$0 \qquad -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2} \qquad -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2} \qquad 0 \quad \longleftarrow \quad \Delta E_{Coulomb}$$

$$\frac{F_0^2}{m\omega_z^2},\ \frac{F_0^2}{m\omega_z^2}+\frac{4q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2},\ \frac{F_0^2}{m\omega_z^2}+\frac{4q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2},\ \frac{F_0^2}{m\omega_z^2} \quad \longleftarrow \quad \Delta E_{Trap}$$





$\Delta E_{Coulomb} + \Delta E_{Trap} \Longrightarrow$ ferromagnetic interaction

$$H_{Ising} = J\sigma^z{}_1 \cdot \sigma^z{}_2,$$

$$J = -\frac{q^2}{d^3}\frac{F_0{}^2}{(m\omega_z{}^2)^2}$$

Generating entangled states with spin-dependent forces

Oscillating spin-dependent force: $\vec{F}_{\uparrow}(t) = -\vec{F}_{\downarrow}(t) = F_0 \cos(\mu t)\,\hat{z}$

- $\mu < \omega_z$, ion oscillation, $\vec{F}_{\uparrow,\downarrow}(t)$ in phase

  $|\uparrow\rangle|\downarrow\rangle, |\downarrow\rangle|\uparrow\rangle$ have larger oscillation amplitude and energy

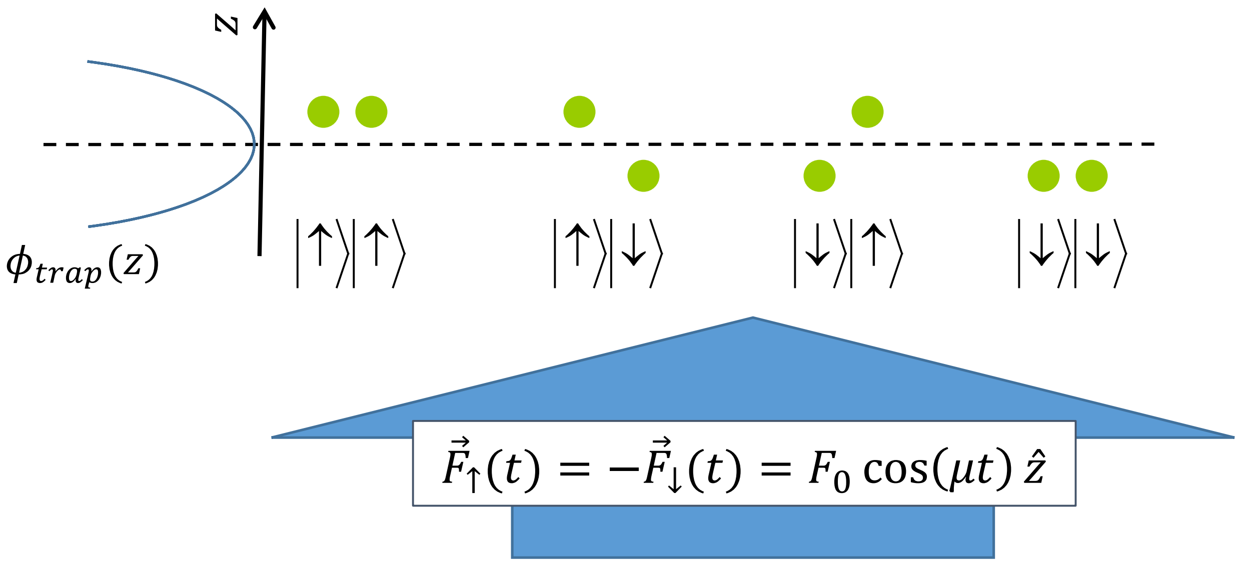
  $\Rightarrow$ ferromagnetic interaction

- $\mu > \omega_z$, ion oscillation, $\vec{F}_{\uparrow,\downarrow}(t)$ 180° out of phase

  Coulomb force opposes $\vec{F}_{\uparrow,\downarrow}(t)$ for $|\uparrow\rangle|\downarrow\rangle, |\downarrow\rangle|\uparrow\rangle$ states,

  $|\uparrow\rangle|\downarrow\rangle, |\downarrow\rangle|\uparrow\rangle$ have smaller oscillation amplitude and energy

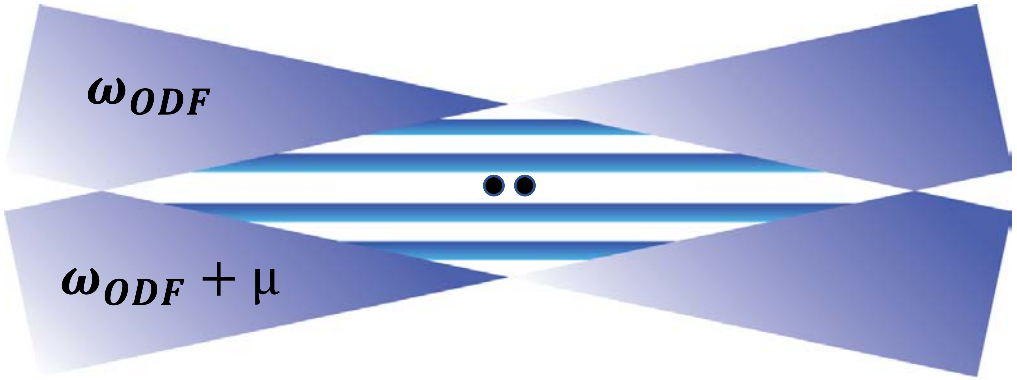
  $\Longrightarrow$ anti-ferromagnetic interaction



Generating entangled states – geometric phase picture

Spin-dependent forces from optical dipole forces

- Rarely turn on adiabatically
- Easier to generate time-dependent force

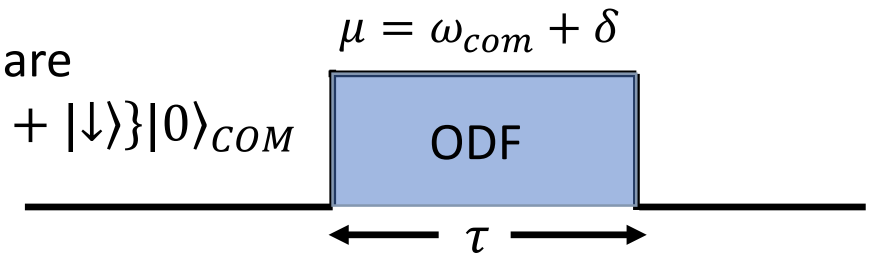


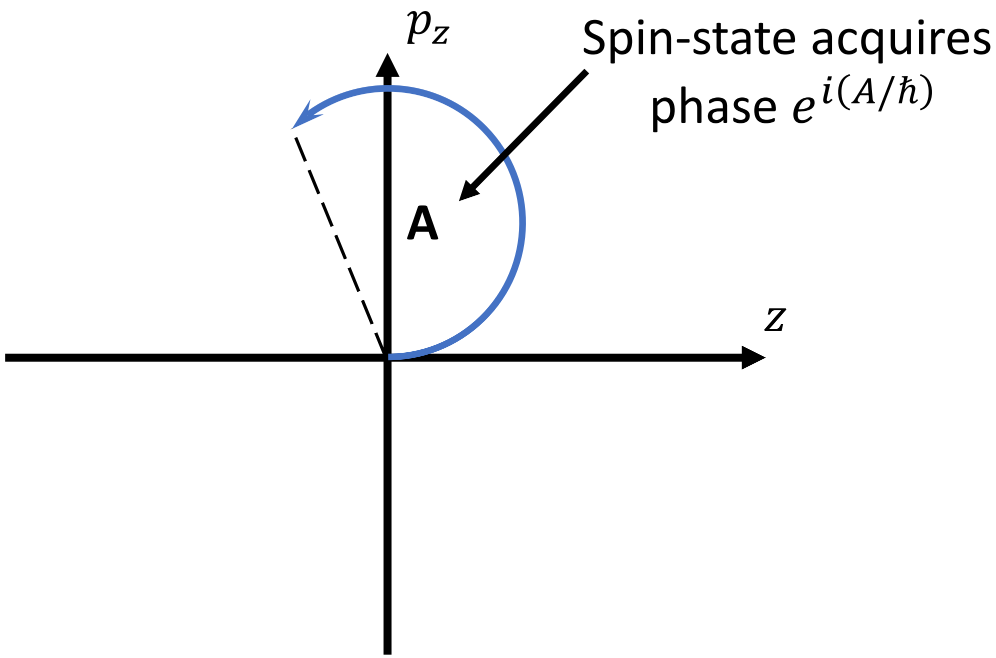
- $F_\uparrow(t) = -F_\downarrow(t)$

  $F_\uparrow(t) = F_0 \cos(\mu t)$

$$\hat{H}_{ODF}(t) = F_0 \cos(\mu t) \sum_{j=1}^{2} \hat{z}_j \cdot \hat{\sigma}_j^z$$

Prepare
$\{|\uparrow\rangle + |\downarrow\rangle\}\{|\uparrow\rangle + |\downarrow\rangle\}|0\rangle_{COM}$





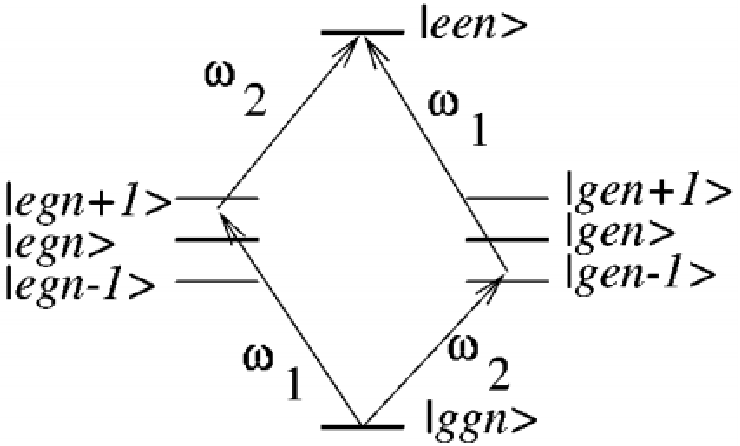
Different spin states acquire different phases
Enables a phase gate, $J\hat{\sigma}_1^z\hat{\sigma}_2^z$
Leibfried et al., Nature **422**, (2003)

Trapped ion entangling gates

- Cirac –Zoller controlled not gate- *Phys Rev Lett* **74** (1995)
  first-order sensitive to ground state cooling

- Geometric phase gate - Leibfried et al., Nature **422**, (2003)
  first-order insensitive to motional temperature
  $\mu = \omega_{com} + \delta$, $\hat{\sigma}_z\hat{\sigma}_z$ interaction

- Molmer-Sorensen gate - Sørensen and Mølmer, Phys. Rev. Lett. 82 (1999)
  first-order insensitive to motional temperature
  $\mu = \omega_{qubit} \pm \omega_{com} \pm \delta$, $\hat{\sigma}_x\hat{\sigma}_x$ or $\hat{\sigma}_y\hat{\sigma}_y$ interaction



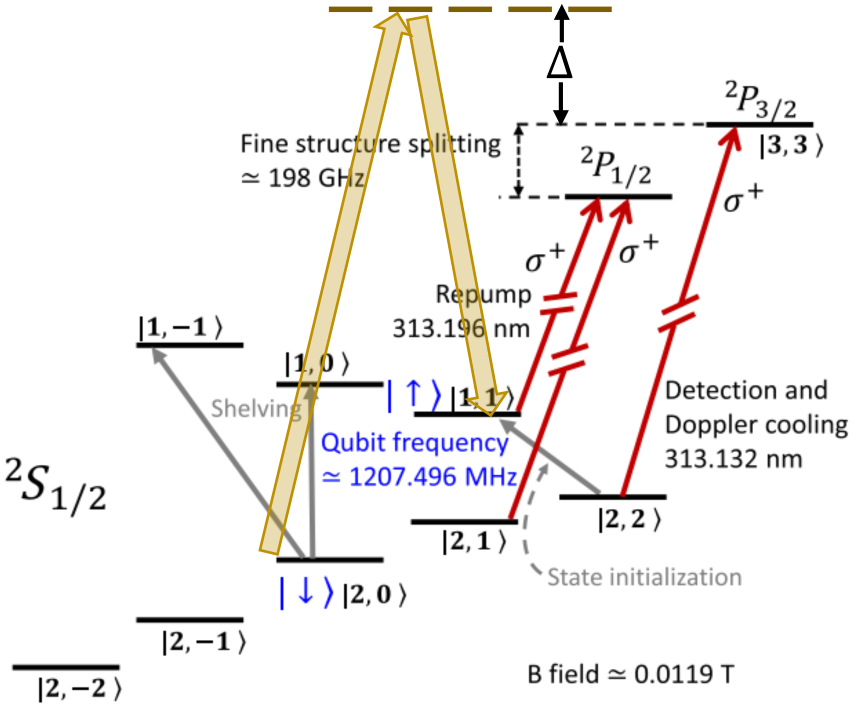
Example experiments

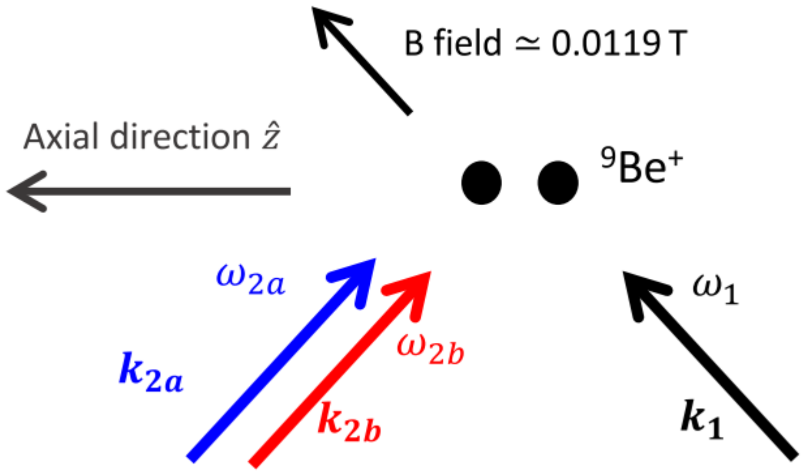
1. High-Fidelity Universal Gate Set for $^{9}Be^{+}$ Ion Qubits
   NIST group, PRL (2016)

2. 14-Qubit Entanglement: Creation and Coherence
   Blatt group, PRL (2011)

3. Demonstration of a small programmable quantum computer
   with atomic qubits, Monroe group, Nature (2016)
   also PRL 120 (2018)

High fidelity gate for ^{9}Be qubits – NIST group

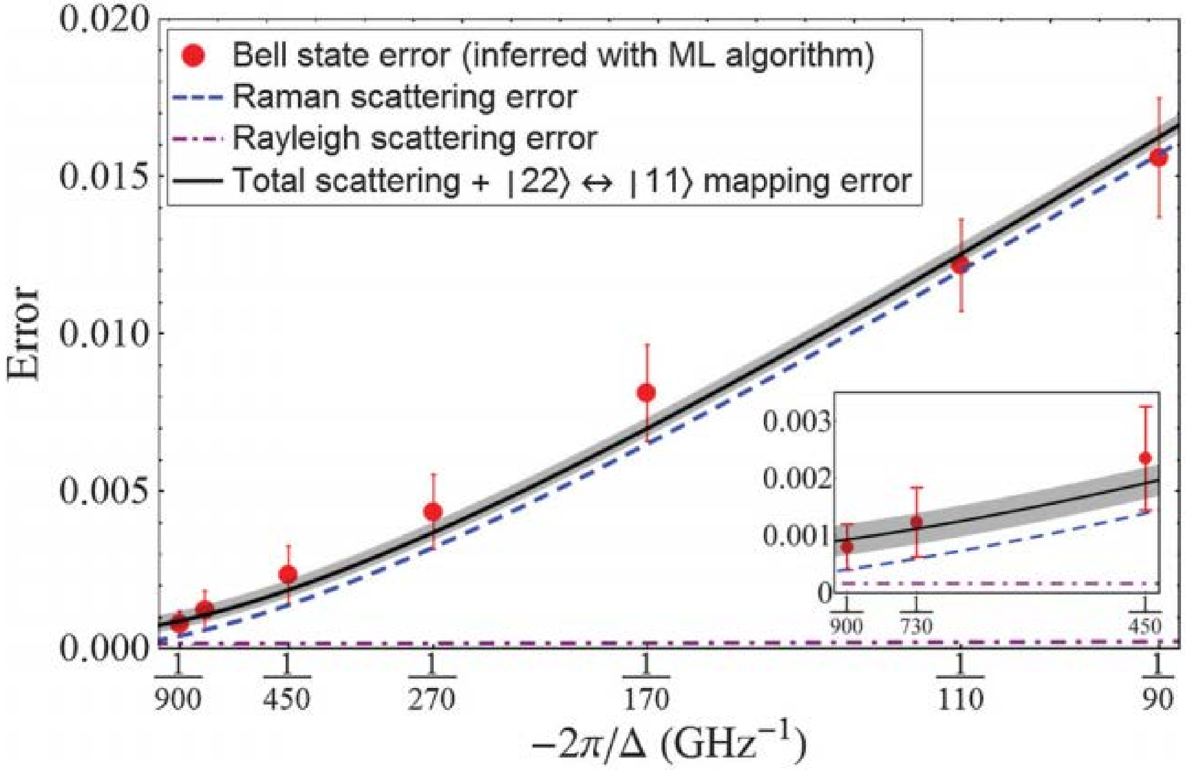




Employ MS gate to prepare Bell state:

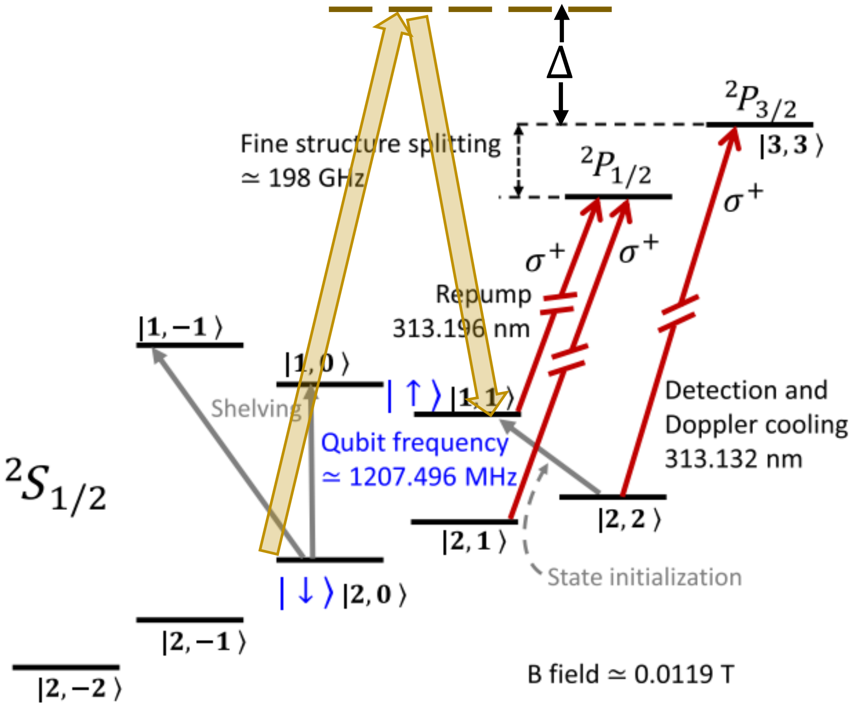
$$|\Phi_+\rangle = (|\uparrow\uparrow\rangle) + |\downarrow\downarrow\rangle)/\sqrt{2}$$

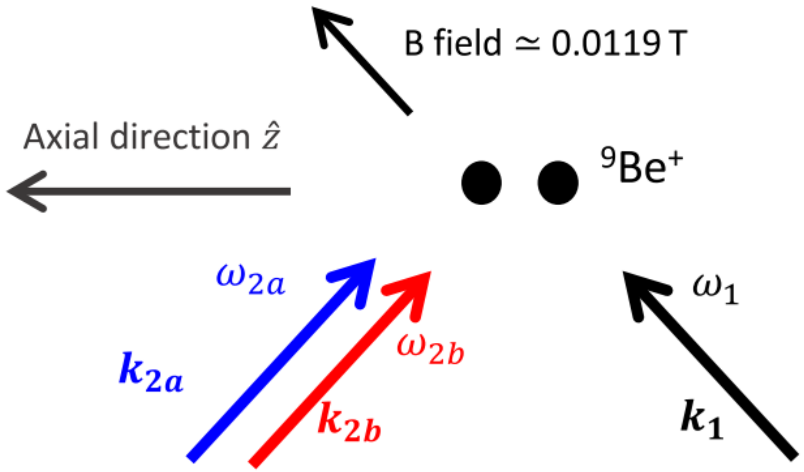
Partial state tomography ⇒ Fidelity



Bell state error vs Raman detuning Δ

High fidelity gate for ^{9}Be qubits – NIST group





Employ MS gate to prepare Bell state:

$$|\Phi_+\rangle = (|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)/\sqrt{2}$$

Individually determined errors for $\frac{\Delta}{2\pi} = 900$ GHz

Errors	$\times 10^{-4}$
Spontaneous emission (Raman)	4.0
Spontaneous emission (Rayleigh)	1.7
Motional mode frequency fluctuations	1
Rabi rate fluctuations	1
Laser coherence	0.2
Qubit coherence	< 0.1
Stretch-mode heating	0.3
Error from Lamb-Dicke approximation	0.2
Off-resonant coupling	< 0.1
$\lvert 2,2\rangle \Leftrightarrow \lvert\uparrow\rangle$ two-way transfer	4

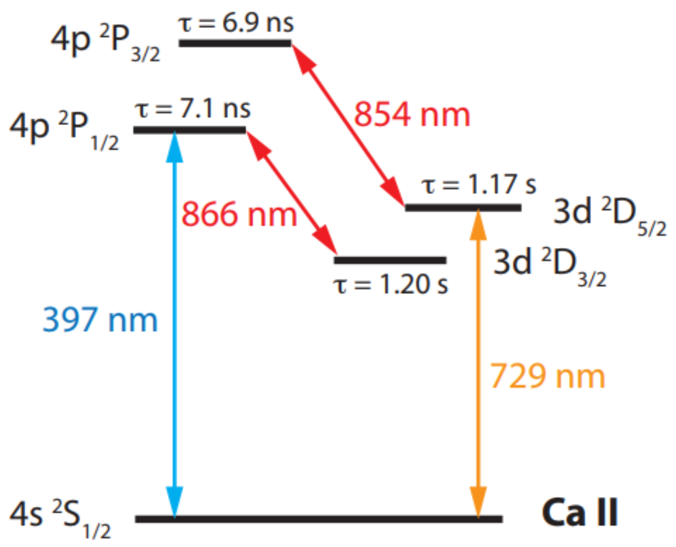
^{9}Be$^+$ hyperfine qubits, NIST group, 99.92(4)%

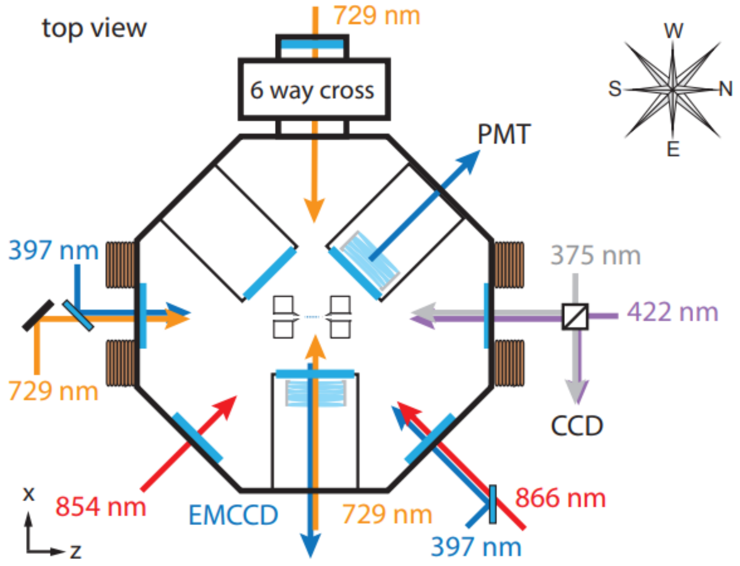
^{43}Ca$^+$ hyperfine qubits, Oxford group, 99.9(1)%

Balance et al., PRL 117 (2016)

14 qubit entanglement – Blatt group, PRL 2011

$^{40}Ca^{+}$ optical qubit





Global application of a MS entangling gate ⇒
GHZ state $(|\underbrace{000\ldots0}_{\text{N qubits}}\rangle + |111\ldots1\rangle)/\sqrt{2}$

GHZ coherence ⇔ parity P oscillation measurements

1. global $\pi/2$ spin rotation with phase ϕ
2. measure parity $P = P_{even} - P_{odd}$

   $P_{even,odd}$ = probability of even, odd excitations

14 qubit entanglement – Blatt group, PRL 2011

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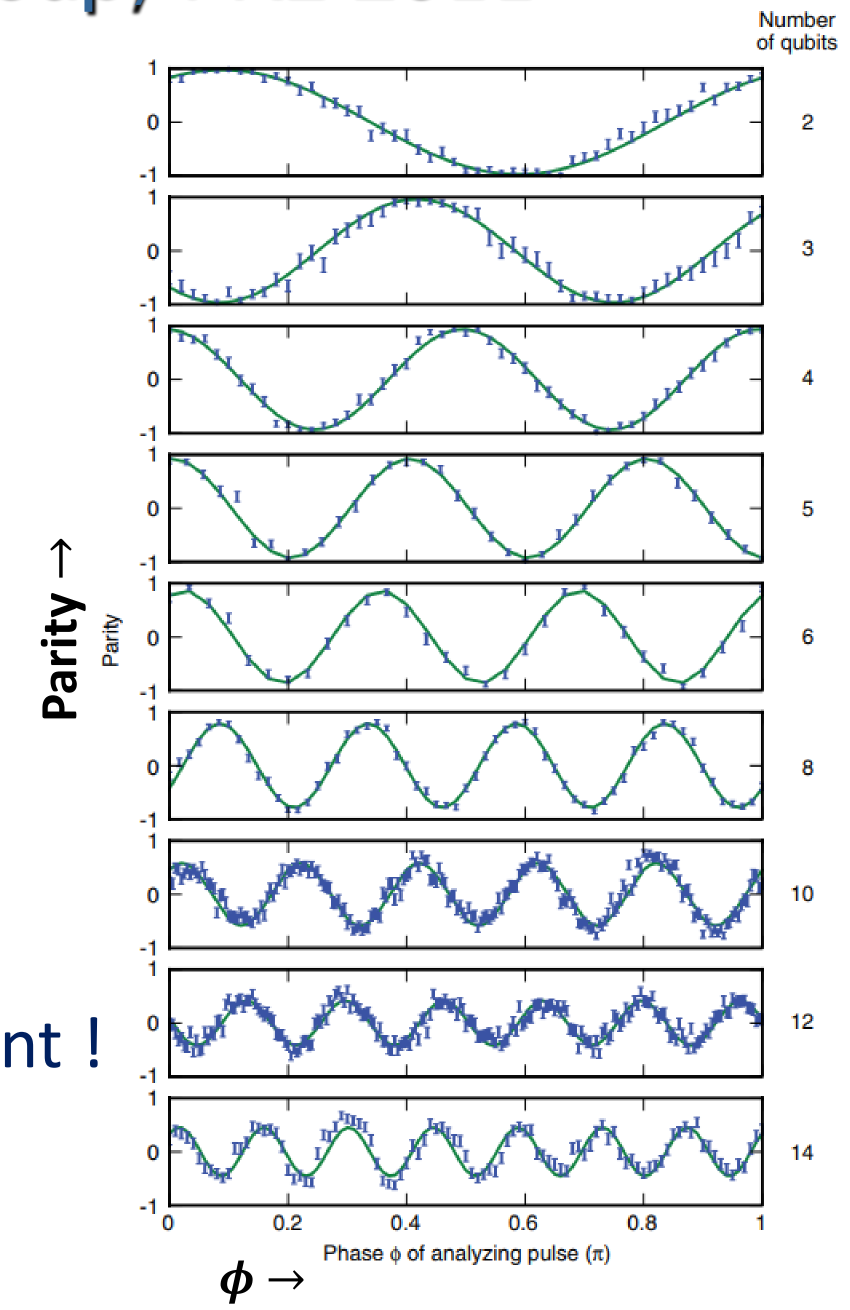
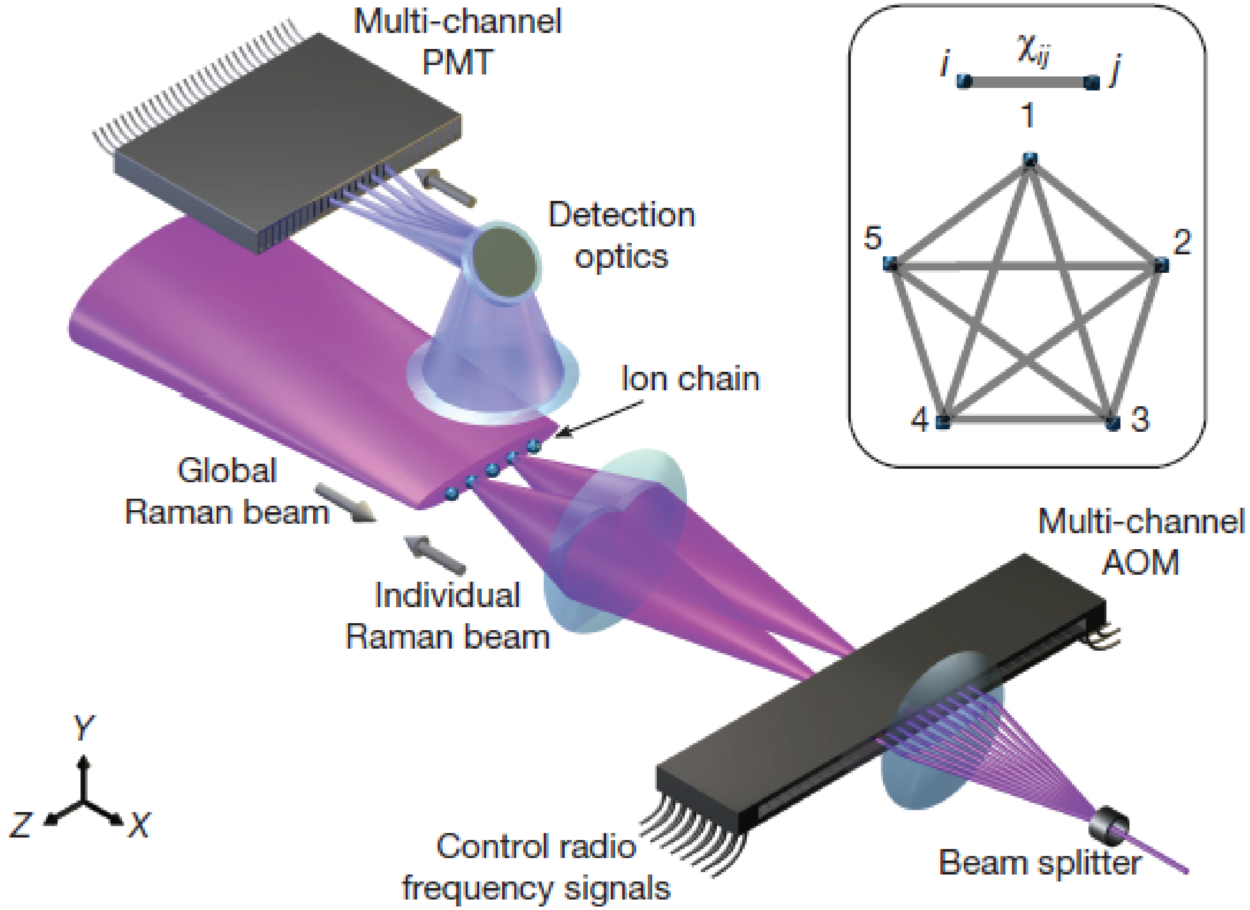
Parity oscillations ⟹ up to 14-particle entanglement !



5-ion programmable quantum computer – Monroe group, Nature 2016

$^{171}Yb^{+}$ hyperfine qubit, ν_0 =12.6 GHz



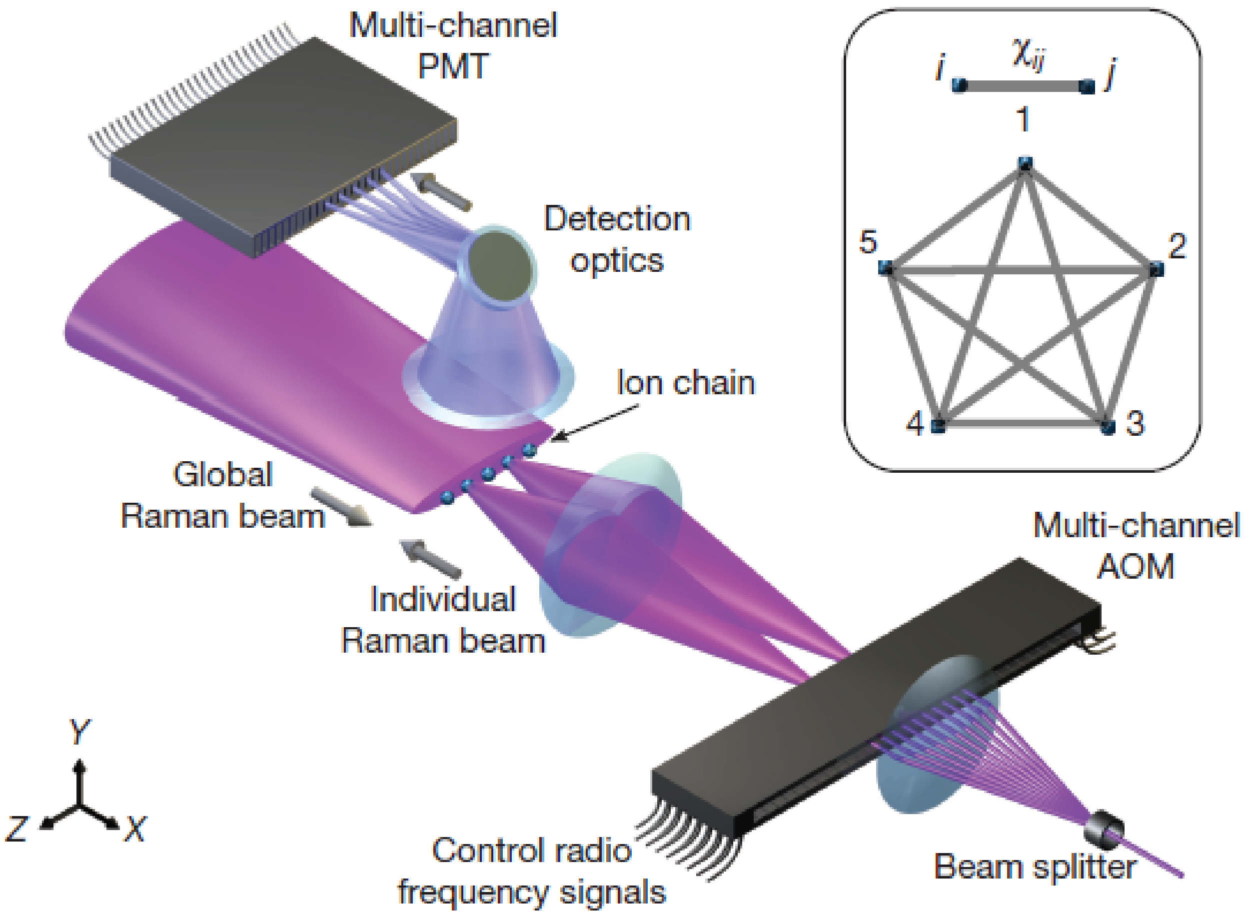
Features:

- very large Raman detuning Δ mitigates spontaneous emission
- Multi-channel AOM provides flexible addressability
- Single qubit rotations, Raman beat note $= \nu_0$
- $\sigma_x \sigma_x$ 2-qubit gates formed with Raman beat notes near $\nu_0 \pm \nu_x$ (MS gate on X-modes)
- all X-modes coupled to spins
- Spin-motion disentangled through amplitude and frequency modulation
- Highest 2-qubit gate fidelities are 98.3(4)%
- Full connectivity of trapped ions ⇒ benefits
- Implement algorithms including QFT, fidelity~ 80%

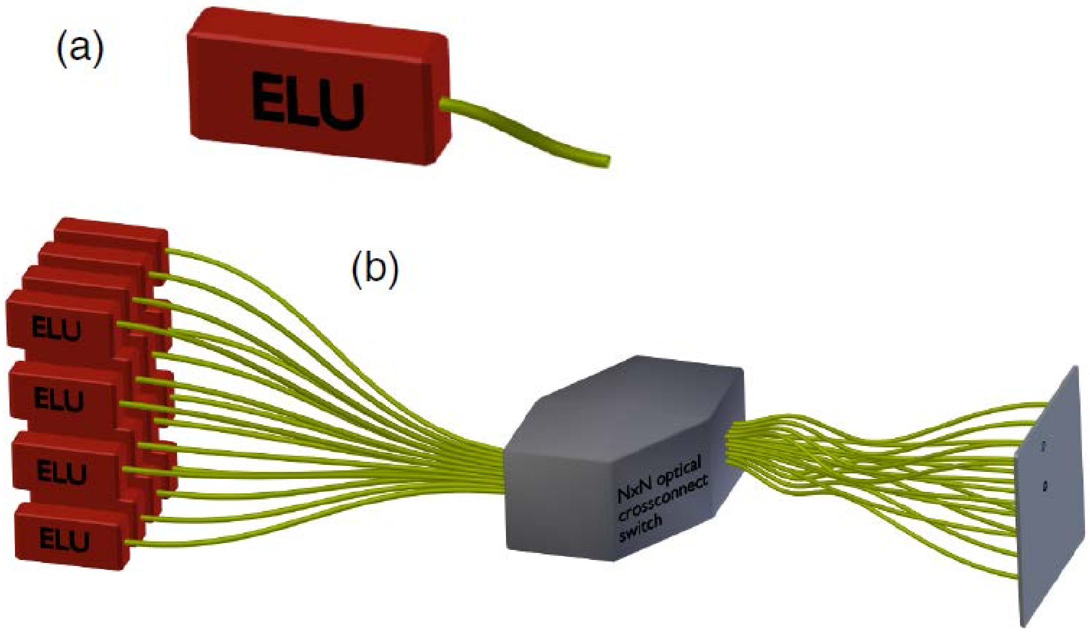
5-ion programmable quantum computer – Monroe group, Nature 2016

$^{171}Yb^{+}$ hyperfine qubit, ν_0 =12.6 GHz

Current efforts to scale from 5 ions → ~32 ions (UMD, IonQ)

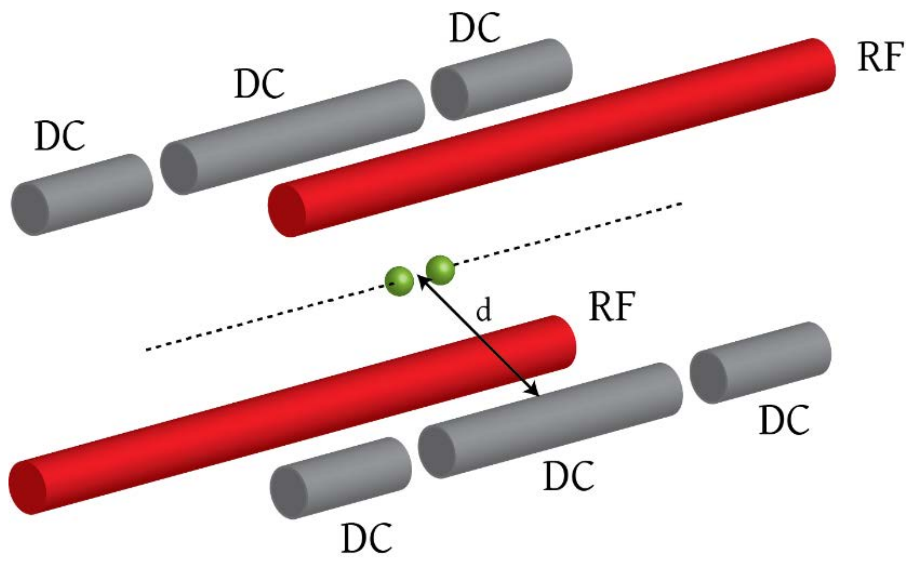


Vision for scaling beyond single linear trap: photonic quantum channels
Monroe, PRA 89 (2014)

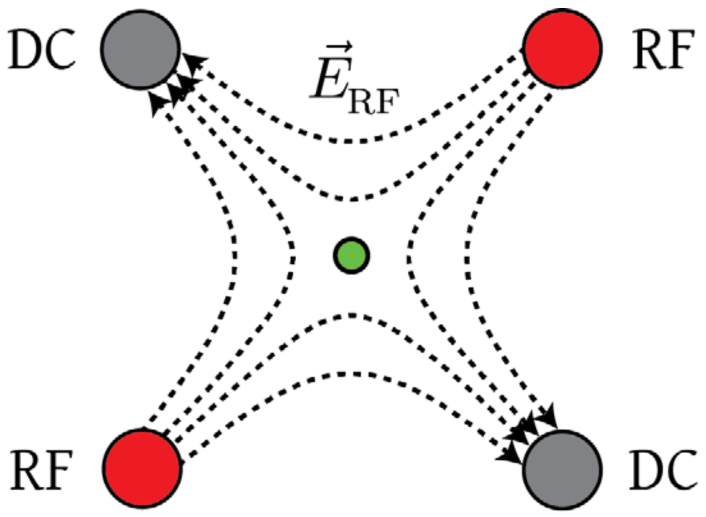


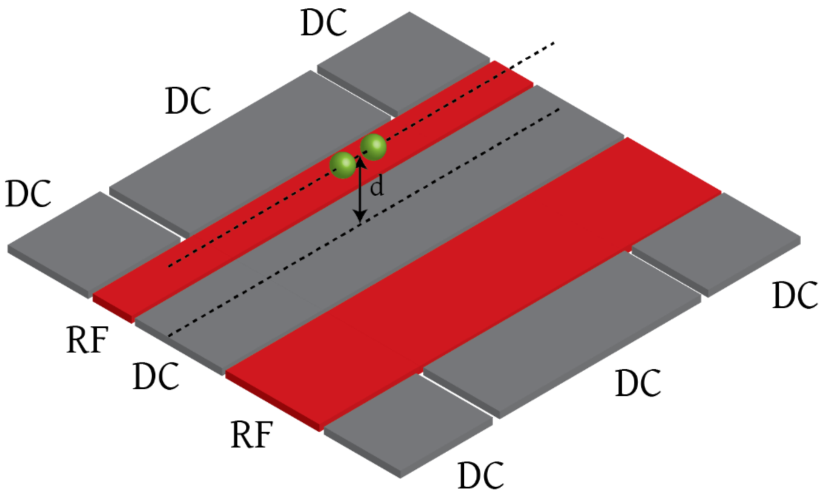
Surface-electrode rf ion traps

Surface-electrode rf ion traps

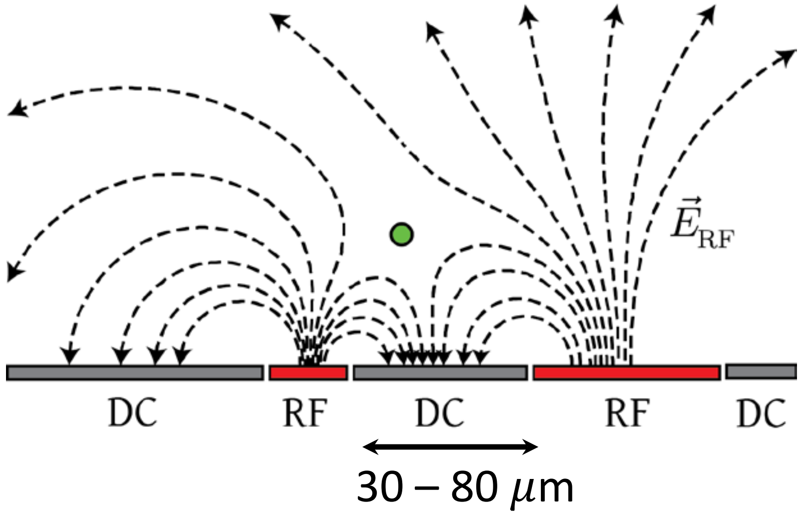


3D linear
Paul (RF) trap





Linear surface-
electrode RF trap



Why surface-electrode rf ion traps?

Pros:

- precisely fabricated with clean room microfabrication techniques
- include on-chip components such as ADC's
- scalable fabrication for making large complicated arrays
- provides path for scaling up ion trap QC via the "Quantum CCD architecture"

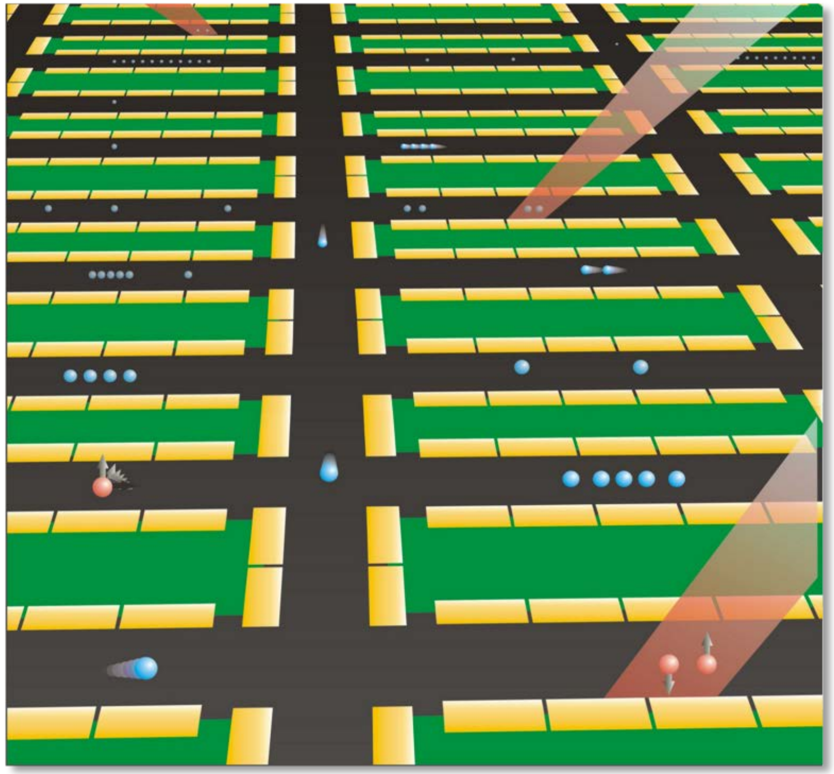
Con:

- small well depth motivates cryogenic operation

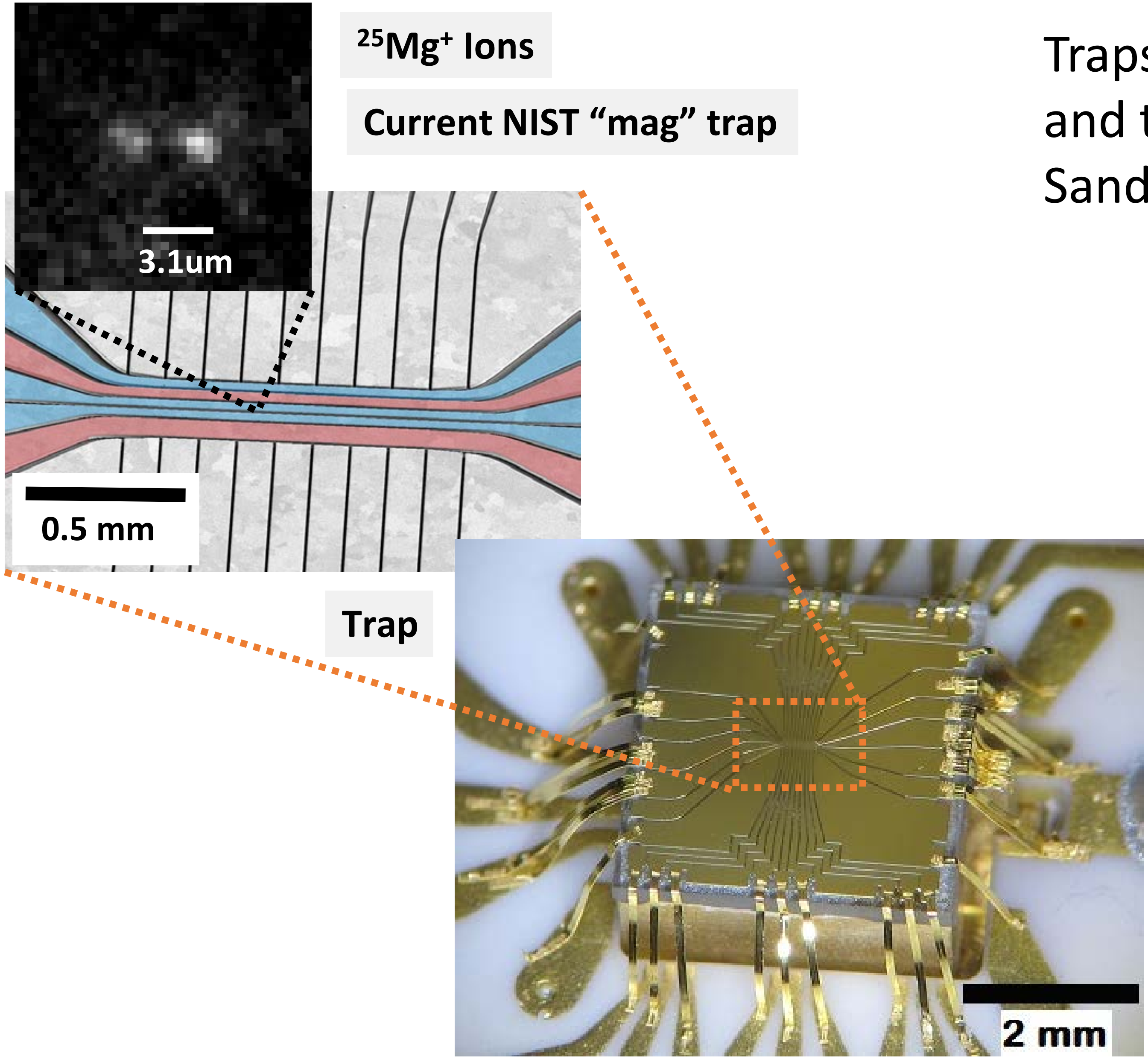
Quantum CCD architecture

Kielpinski, et al., Nature 417 (2002)

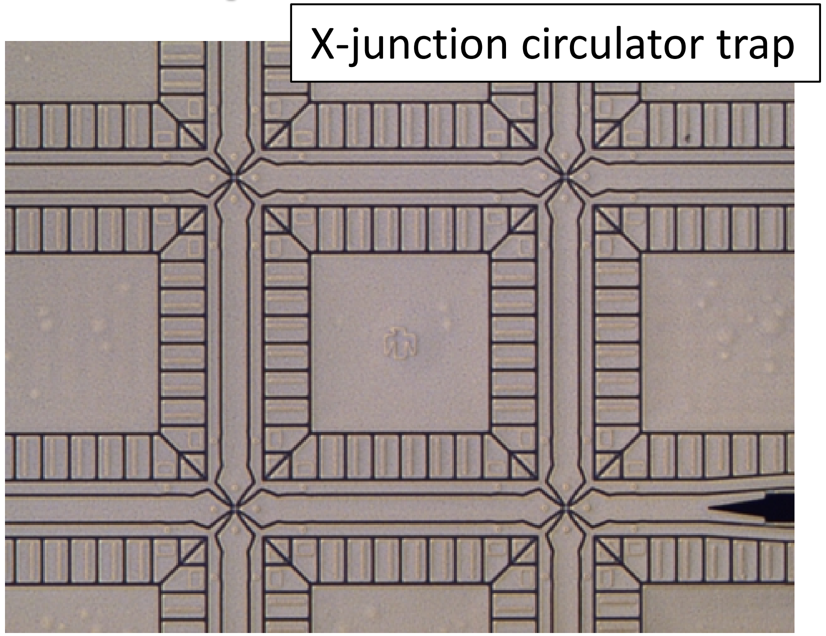
- Ions move between different trap zones (e.g. memory, gate, recooling)
- Laser/microwave access to subset of trap

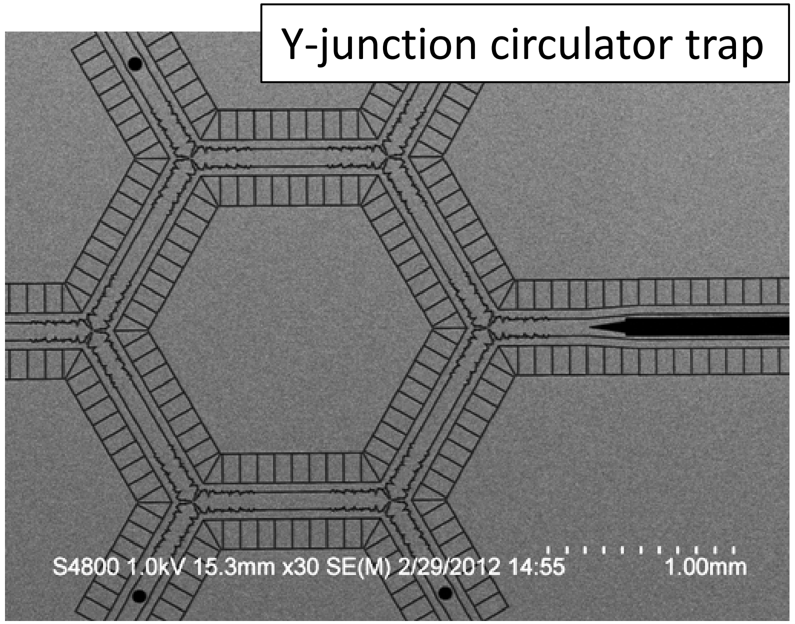


example surface-electrode rf ion traps



Traps fabricated and tested at Sandia Nat. Lab

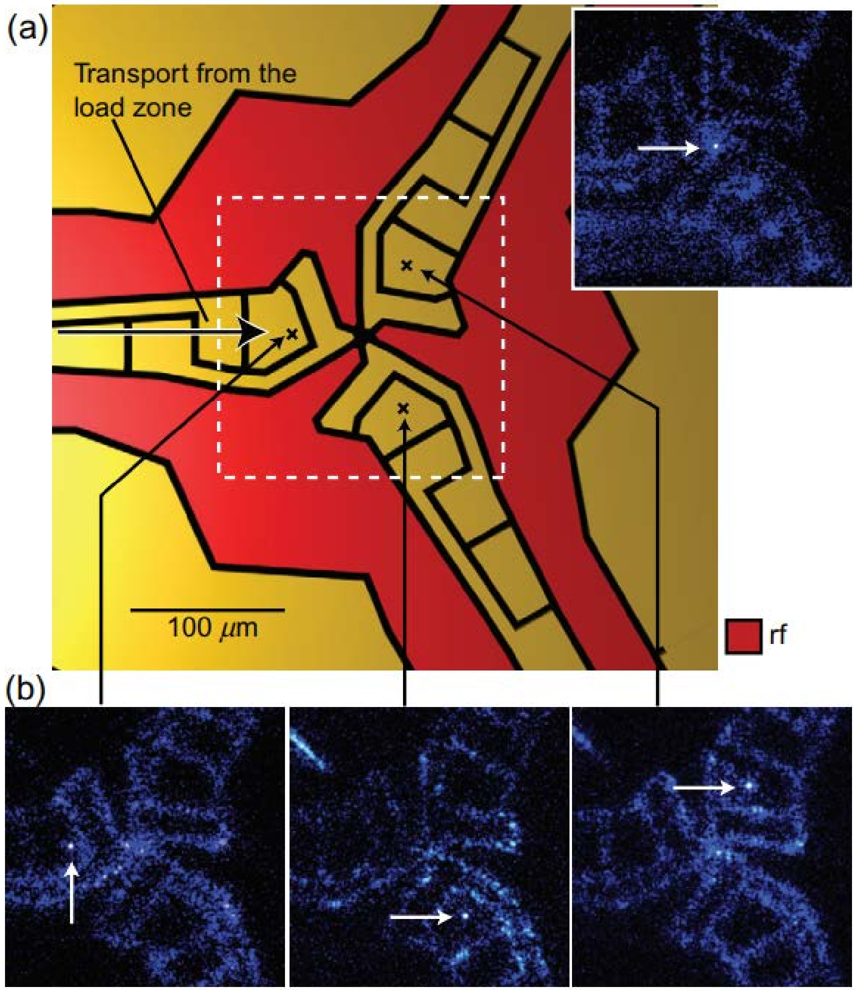


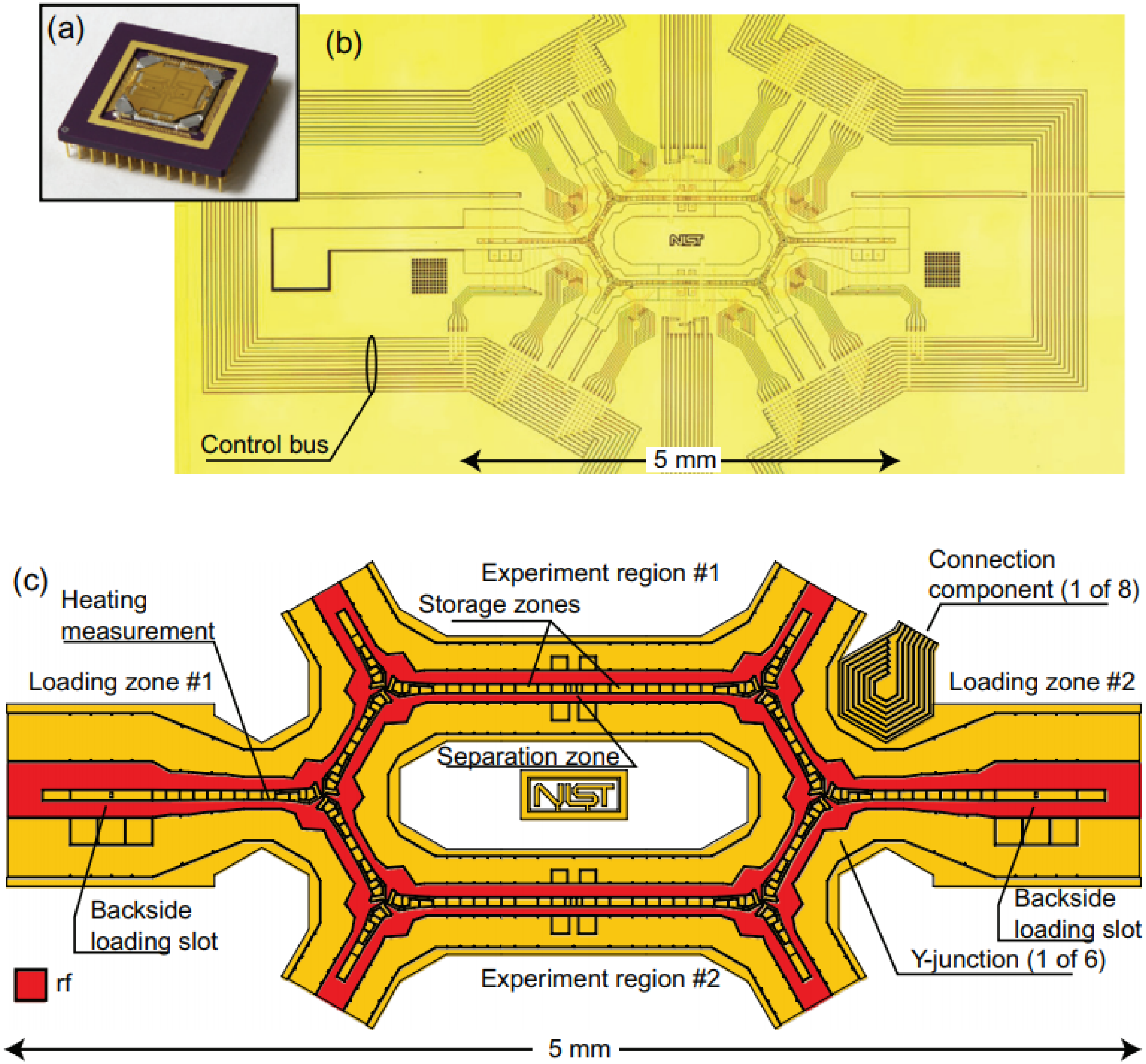


example surface-electrode rf ion traps

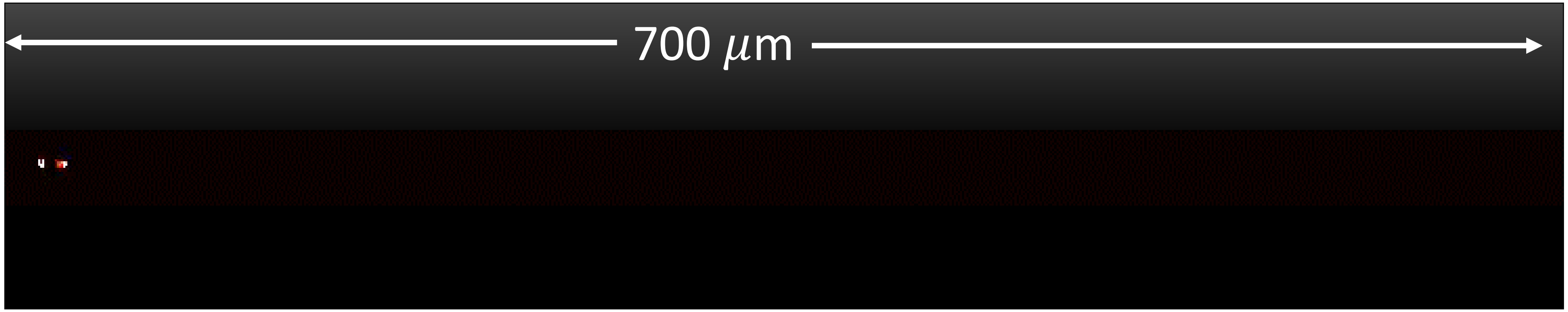
NIST Y-junction trap

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





Acrobatic shuttling – Sandia National Lab



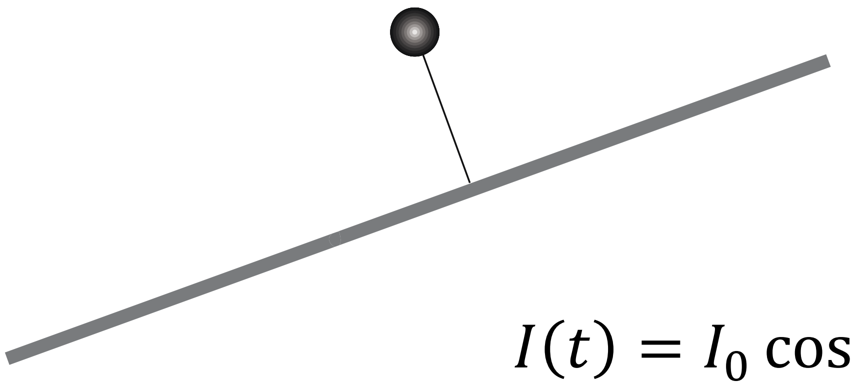
Surface-electrode ion trap demonstrations:

- shuttling, including through junctions
- high fidelity single-qubit gates
- high fidelity two-qubit gates

⋮

Surface-electrode ion traps enable new capabilities !!

Spin-dependent forces from magnetic field gradients



$$I(t) = I_0 \cos(\omega t)$$

$$B \propto \frac{I_0}{d}$$

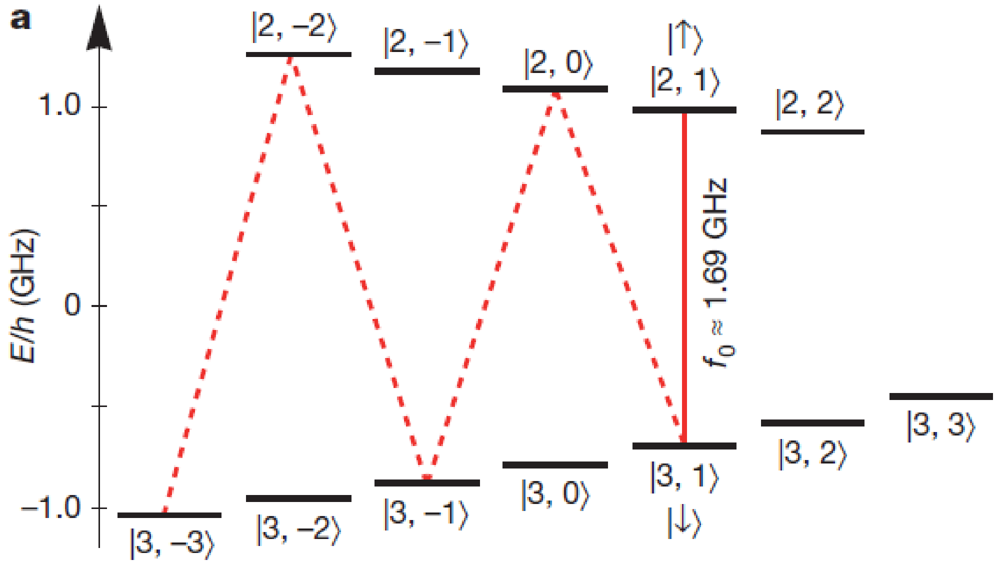
$$\nabla B \propto \frac{I_0}{d^2}$$

Advantages over laser-driven gates:

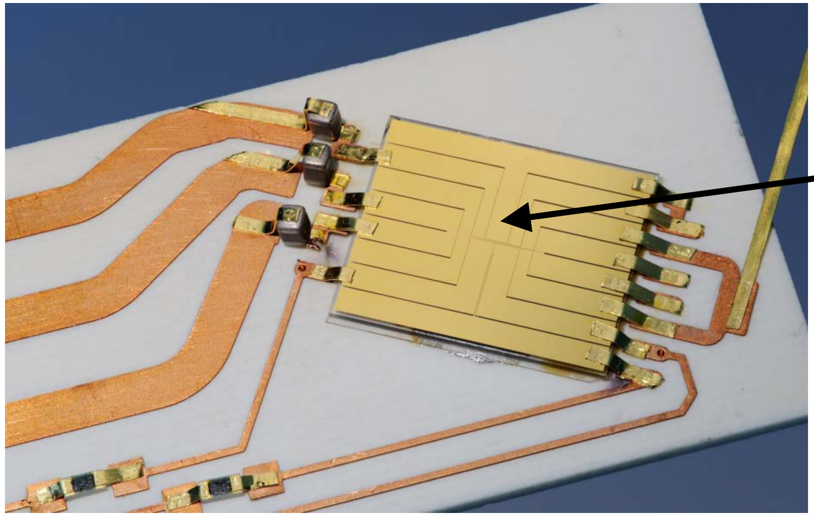
- Electronic sources are more stable, easily controlled, cheaper, and smaller
- Wires are much easier to integrate into ion traps than optics
- Eliminates fundamental photon scattering errors

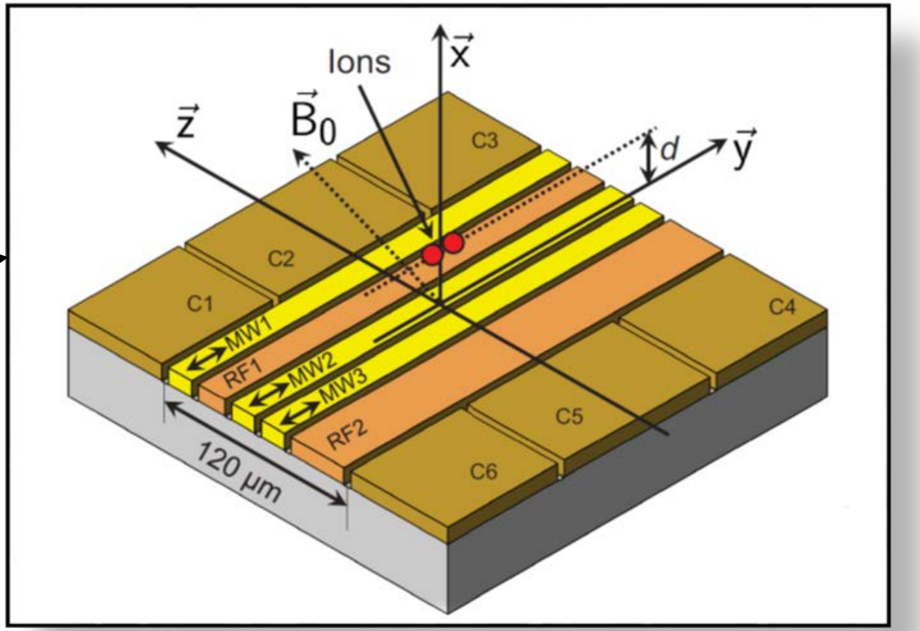
Entangled states with magnetic field gradients

C. Ospelkaus *et al.*, *Nature*, **476**, 181 (2011)



$^{25}Mg^+$, radial trap frequency ≈ 5 MHz,
B_0= 21.3 mT
ion – electrode distance = 30 μm
dB_{uW}/dz ≈ 35 T/m





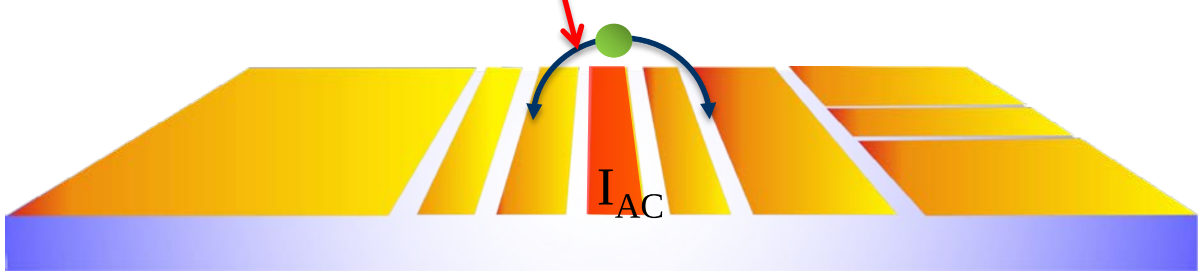
Entangled states with magnetic field gradients

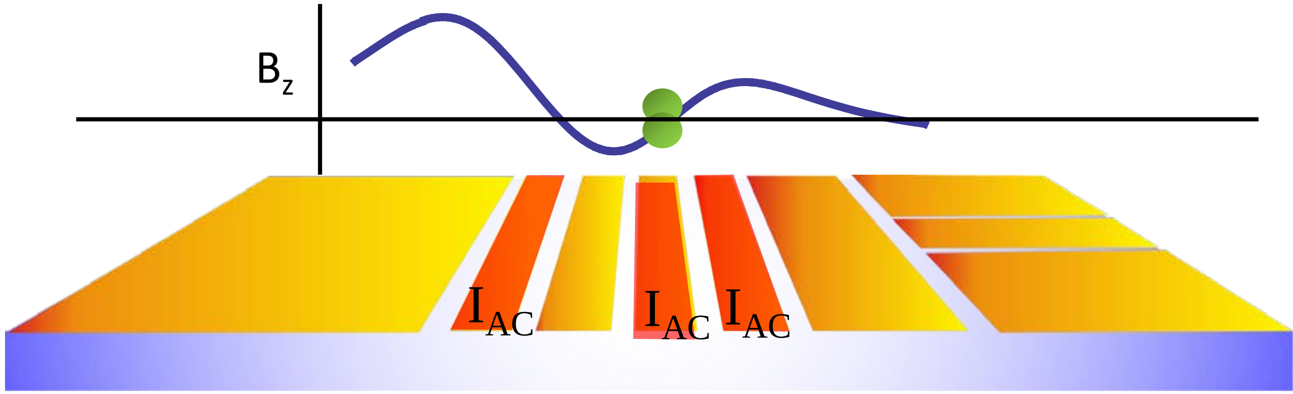
C. Ospelkaus *et al.*, *Nature*, **476**, 181 (2011)

$B = B_1 \cos(2\pi f_0 t)$

$|3,1\rangle \leftrightarrow |2,1\rangle$ transition

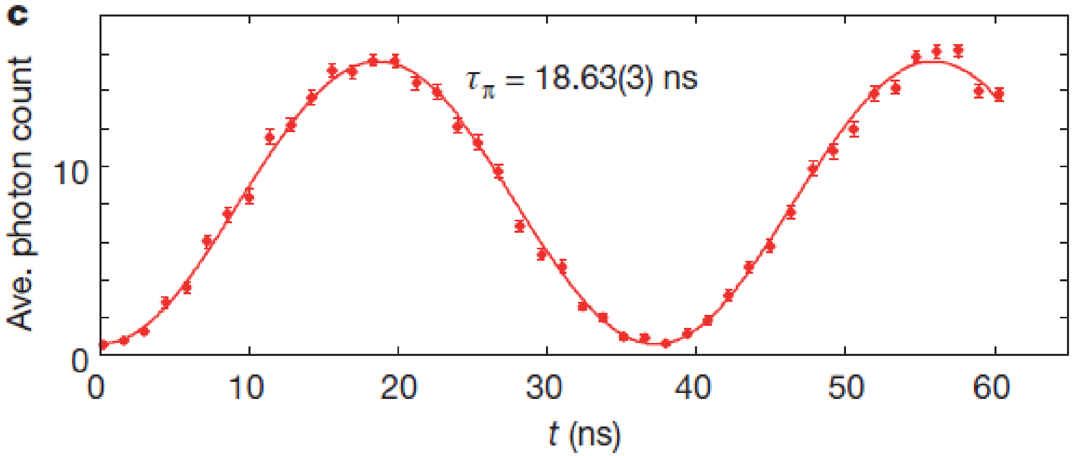
$f_0 \cong 1.69$ GHz, $^{25}Mg^+$)





Rabi flopping

18 ns π –time



- MS gate with gradients at $f_0 \pm (f_r + \delta)$

$$\psi \simeq \left(|\uparrow\uparrow\rangle + e^{i\phi}|\downarrow\downarrow\rangle\right)\sqrt{2},$$

Fidelity = 0.76(3), $T_{gate} = 200\ \mu s$

85 ion trap groups listed at https://quantumoptics.at/en/links.html

There's a lot of activity!

completeness disclaimer – my summary is necessarily biased towards my interests

	Country	Institution	Group	Head	Ions	City
1	Australia	Griffith University	Ion-trap Quantum Computing Laboratory	Eric Streed, Mirko Lobino	Yb+	Brisbane
2	Australia	University of Sydney	Quantum Control Laboratory	Mike Biercuk	Be+, Yb+	Sydney
3	Austria	University of Innsbruck	Quantum Optics and Spectroscopy	Rainer Blatt	Al+, Ba+, Ca+, Sr+	Innsbruck
4	Austria	University of Innsbruck	Molecular Systems	Roland Wester	Molecular ions	Innsbruck
5	Canada	IQC, University of Waterloo	Quantum Information with Trapped Ions	K. Rajibul Islam	?	Waterloo
6	Canada	NRC	Measurement science and standards	John Bernard, Alan Madej	Sr+	Ottawa
7	Canada	Simon Fraser University	Haljan Group	Paul Haljan	Yb+	Burnaby
8	China	Huazhong University of Science and Technology	MOE Key Laboratory	Zehuang Lu	Al+, Mg+	Wuhan
9	China	National University of Defense Technology	Department of Physics	Pingxing Chen	Ca+	Changsha
10	China	Tsinghua University	Center for Quantum Information	Kihwan Kim	Ba+, Yb+	Beijing
11	China	Tsinghua University	Joint institute for Measurement Science	Li-Jun Wang	Ba+, Cd+, In+	Beijing
12	China	University of Science and Technology of China	Key Laboratory of Quantum Information	Guang-Can Guo	Yb+	Hefei
13	China	Wuhan Institute of Physics and Mathematics	Ion Optical Frequency Standard	Xueren Huang	Al+, Ca+	Wuhan
14	China	Wuhan Institute of Physics and Mathematics	Mercury Ion Microwave Frequency Standard	Jiaomei Li	Hg+	Wuhan
15	China	Wuhan Institute of Physics and Mathematics	Quantum Information and Trapped Ion Physics	Mang Feng	Ca+	Wuhan
16	China	Wuhan Institute of Physics and Mathematics	Trapping of Cold Ions	Ke-Lin Gao	Ca+, Li+	Wuhan
17	Czech Republic	Palacký University & ISI	Quantum Optics Lab	Radim Filip, Lukáš Slodička	Ca+	Olomouc & Brno
18	Denmark	Aarhus University	Ion Trap Group	Michael Drewsen	Ca+, molecular ions	Aarhus
19	Finland	Aalto University	MIKES Time and Frequency Group	Mikko Merimaa	Sr+	Helsinki
20	France	Aix-Marseille University	Ion Trapping and Laser Manipulation Group	Martina Knoop, Caroline Champenois	Ca+	Marseille
21	France	FEMTO-ST	Compact Optical Atomic Clock	Clément Lacroûte	Yb+	Besançon
22	France	LKB	Trapped Ions Group	Laurent Hilico	H2+	Paris
23	France	Université Paris Diderot	Trapped Ions and Quantum Information	Luca Guidoni, Samuel Guibal	Sr+	Paris
24	Germany	Mainz University	Cold Ions and Experimental Quantum Information	Ferdinand Schmidt-Kaler	Ca+, Sr+	Mainz
25	Germany	MPI for the Science of Light	Leuchs Division	Gerd Leuchs	Yb+	Erlangen
26	Germany	MPI für Kernphysik	Structure and dynamics of few electron ions in an EBIT	José Ramon Crespo López-Urrutia	Be+, highly charged ions	Heidelberg
27	Germany	MPQ	Trapped Ions Group	Thomas Udem, Ted Hänsch	Be+, Mg+	Garching
28	Germany	PTB	Multi-Ion Clocks	Tanja Mehlstäubler	In+, Yb+	Braunschweig
29	Germany	PTB	Optical Clocks with Trapped Ions	Ekkehard Peik	Th+, Yb+	Braunschweig
30	Germany	PTB	Quantum Logic Spectroscopy Group	Piet Schmidt	Al+, Ca+, Mg+, molecular ions	Braunschweig
31	Germany	PTB & Leibniz University	Trapped-Ion Quantum Engineering	Christian Ospelkaus	Be+	Braunschweig & Ha
32	Germany	Saarland University	Quantum Photonics Group	Jürgen Eschner	Ca+	Saarbrücken
33	Germany	Ulm University	Institute of Quantum Matter	Johannes Hecker Denschlag	Ba+, Rb+	Ulm
34	Germany	University of Bonn	Experimental Quantum Physics	Michael Köhl	Yb+	Bonn
35	Germany	University of Düsseldorf	Quantum Optics and Relativity	Stephan Schiller	Be+, HD+	Düsseldorf
36	Germany	University of Freiburg	Schaetz Division	Tobias Schaetz	Ba+, Mg+	Freiburg
37	Germany	University of Kassel	Light-matter interaction	Kilian Singer	Ca+	Kassel
38	Germany	University of Siegen	Quantum Optics Research Group	Christof Wunderlich	Yb+	Siegen
39	India	Raman Research Institute	Quantum Interactions	Sadiq Rangwala	Rb+	Bangalore
40	Israel	Weizmann Institute	Trapped-Ions Lab	Roee Ozeri	Sr+	Rehovot
41	Israel	Weizmann Institute	Molecular Physics Group	Daniel Zajfman	Molecular ions	Rehovot
42	Japan	Kyoto University	Quantum Optical Engineering	Masao Kitano	Yb+	Kyoto
43	Japan	NICT	Quantum ICT Laboratory	Kazuhiro Hayasaka	Ca+, In+	Kobe
44	Japan	Osaka University	Mukaiyama Laboratory	Takashi Mukaiyama	Ca+, In+	Osaka
45	Japan	University of Tokyo	Hasegawa Laboratory	Shuichi Hasegawa	Ca+	Tokyo
46	Netherlands	VU Amsterdam	HD+ spectroscopy team	Jeroen Koelemeij	Be+, HD+	Amsterdam
47	Netherlands	VU Amsterdam	Ultrafast Laser Physics and Precision Metrology Group	Kjeld Eikema	Ca+	Amsterdam
48	Netherlands	University of Amsterdam	Hybrid atom-ion Quantum Systems	Rene Gerritsma	Yb+	Amsterdam
49	Netherlands	University of Groningen	Research Group Ions	Klaus Jungmann	Ba+, Ra+	Groningen
50	Singapore	CQT	Manas Mukherjee Group	Manas Mukherjee	Ba+	Singapore
51	Singapore	CQT	Microtraps Group	Murray Barrett	Ba+, Lu+	Singapore
52	Singapore	CQT	Trapped molecular ions	Dzmitry Matsukevich	Yb+, SiO+	Singapore
53	South Africa	Stellenbosch University	Quantum Control	Herman Uys	Yb+	Stellenbosch
54	South Korea	Seoul National University	Nano/Micro system & controls Lab	Dan Cho	Yb+	Seoul
55	South Korea	SK telecom	Ion Trap	Taehyun Kim	Yb+	Bundang
56	Spain	Universidad de Granada	Molecules Atoms Ions Nuclei	Daniel Rodriguez	Ca+	Granada
57	Sweden	Stockholm University	Trapped Ion Quantum Technologies	Markus Hennrich	Sr+	Stockholm
58	Switzerland	ETH	Trapped Ion Quantum Information	Jonathan Home	Be+, Ca+	Zurich
59	Switzerland	University of Basel	Willitsch Group	Stefan Willitsch	Ca+, molecular ions	Basel
60	United Kingdom	Imperial College	Ion Trapping Group	Richard Thompson	Ca+	London
61	United Kingdom	NPL	Strontium Ion Optical Frequency Standard	Alastair Sinclair, Patrick Gill	Sr+	Teddington
62	United Kingdom	NPL	Ytterbium Ion Optical Frequency Standard	Rachel Godun	Yb+	Teddington
63	United Kingdom	University of Oxford	Ion Trap Quantum Computing Group	David Lucas, Andrew Steane	Ca+, Sr+	Oxford
64	United Kingdom	University of Oxford	Softley Research Group	Tim Softley	Ca+, molecular ions	Oxford
65	United Kingdom	University of Sussex	Ion Quantum Technology Group	Winni Hensinger	Yb+	Brighton
66	United Kingdom	University of Sussex	ITCM Group	Matthias Keller	Ca+, N2+	Brighton
67	USA	Amherst College	David Hanneke Group	David Hanneke	Be+	Amherst
68	USA	Denison University	Ion Quantum Optics	Steven Olmschenk	Ba+	Granville
69	USA	Duke University	MIST Group	Jungsang Kim	Ba+, Yb+	Durham
70	USA	Georgia Tech	Brown Lab	Kenneth Brown	B+, Ca+, molecular ions	Atlanta
71	USA	Georgia Tech	Chapman Research Lab	Michael Chapman	Ba+, Th3+, molecular ions	Atlanta
72	USA	GTRI	Quantum Systems group	Alexa Harter	Ca+, Yb+	Atlanta
73	USA	Indiana University	Richerme Lab	Phil Richerme	Yb+	Bloomington
74	USA	JQI (UMD / NIST)	Trapped Ion Quantum Information	Chris Monroe	Ba+, Yb+	UMD College Park
75	USA	MIT Center for Ultracold Atoms	Experimental Atomic Physics Group	Vladan Vuletic	Yb+	Cambridge
76	USA	MIT Center for Ultracold Atoms	Quanta Group	Ike Chuang	Sr+	Cambridge
77	USA	MIT Lincoln Laboratory	Lincoln Laboratory	John Chiaverini	Ca+, Sr+	Lexington
78	USA	NIST	Ion Storage Group	Dave Wineland	Al+, Be+, Ca+, Hg+, Mg+, molec	Boulder
79	USA	Northwestern University	Molecular Ion and Atom Trapping Group	Brian Odom	Ba+, molecular ions	Evanston
80	USA	Sandia National Labs	Photonic Microsystem Technologies	Dan Stick, Peter Maunz, Matt Blain	Ca+, Yb+	Albuquerque
81	USA	UC Berkeley	Ion Trap Group	Hartmut Häffner	Ca+	Berkeley
82	USA	UCLA	Campbell Lab	Wes Campbell	Yb+	Los Angeles
83	USA	UCLA	Hudson Lab	Eric Hudson	Ba+, Yb+, molecular ions	Los Angeles
84	USA	University of Connecticut	Atomic and Molecular Spectroscopy Group	Winthrop Smith	Ca+, Na+, Rb+, molecular ions	Storrs
85	USA	University of Washington	Trapped Ion Quantum Computing	Boris Blinov	Ba+, Yb+	Seattle

Trapped ion quantum computing, simulation, and sensing

John Bollinger, NIST, Boulder CO

Monday, July 2, 11:00 AM – Trapped ion quantum computing

Tuesday, July 3, 11:00 AM – Trapped ion quantum simulation

Thursday, July 5, 9:00 AM – Trapped ion quantum sensing