

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

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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

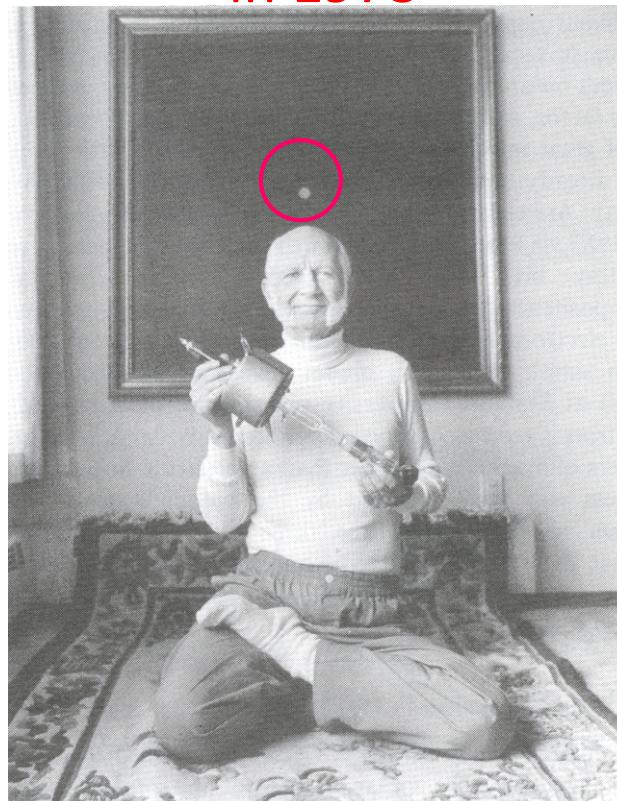
Paul trap 1956



Wolfgang Paul

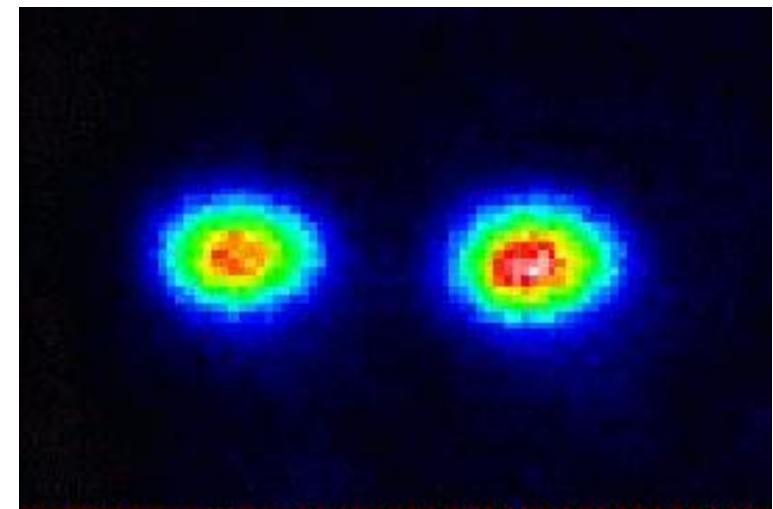
Shared 1989 Nobel prize in physics

Penning trap 1959
single electron trapped
in 1973



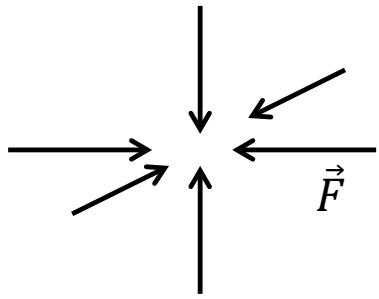
Hans Dehmelt

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



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

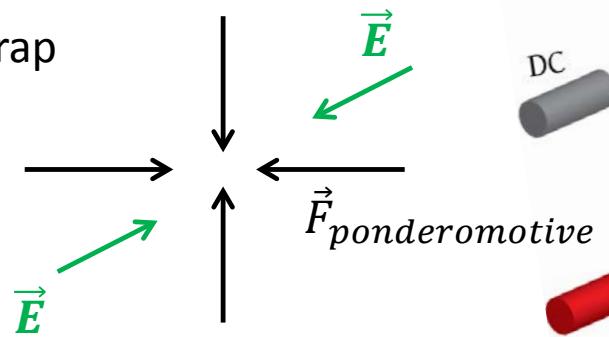
Paul (or rf) trap – linear rf trap



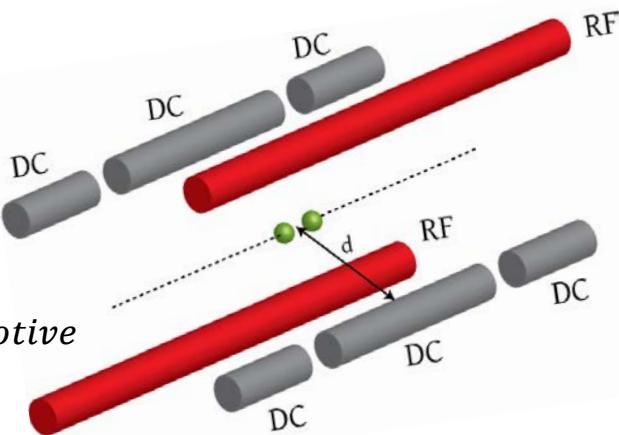
ideal ion trap
desire $\nabla \cdot \vec{F} \neq 0$

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



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



pseudopotential confinement radially

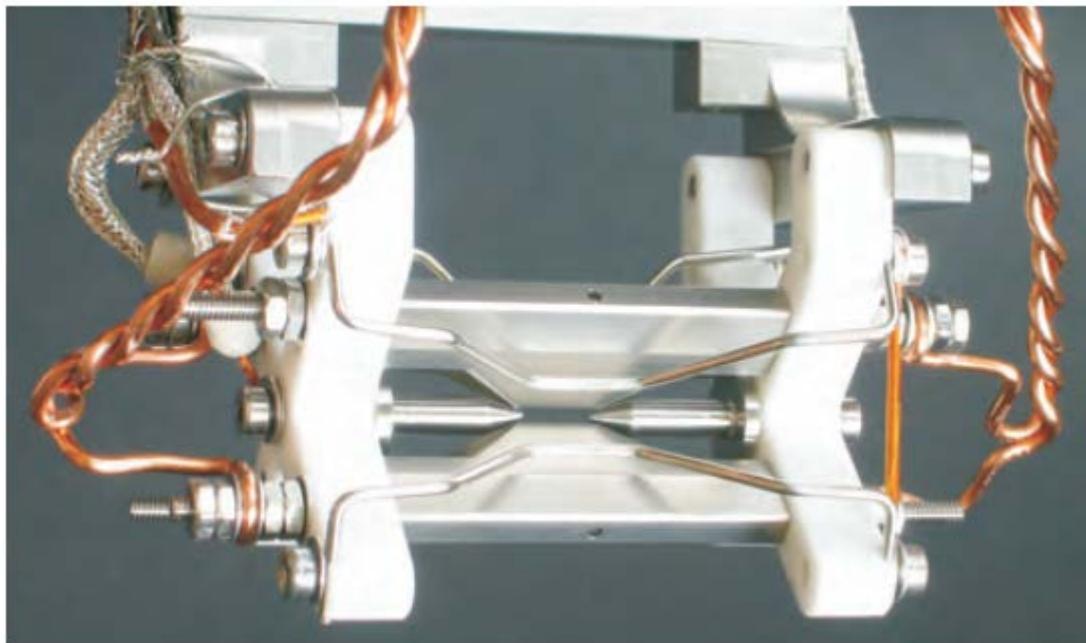
$$q\phi_s = \frac{1}{2}m\omega_r^2(x^2 + y^2)$$

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

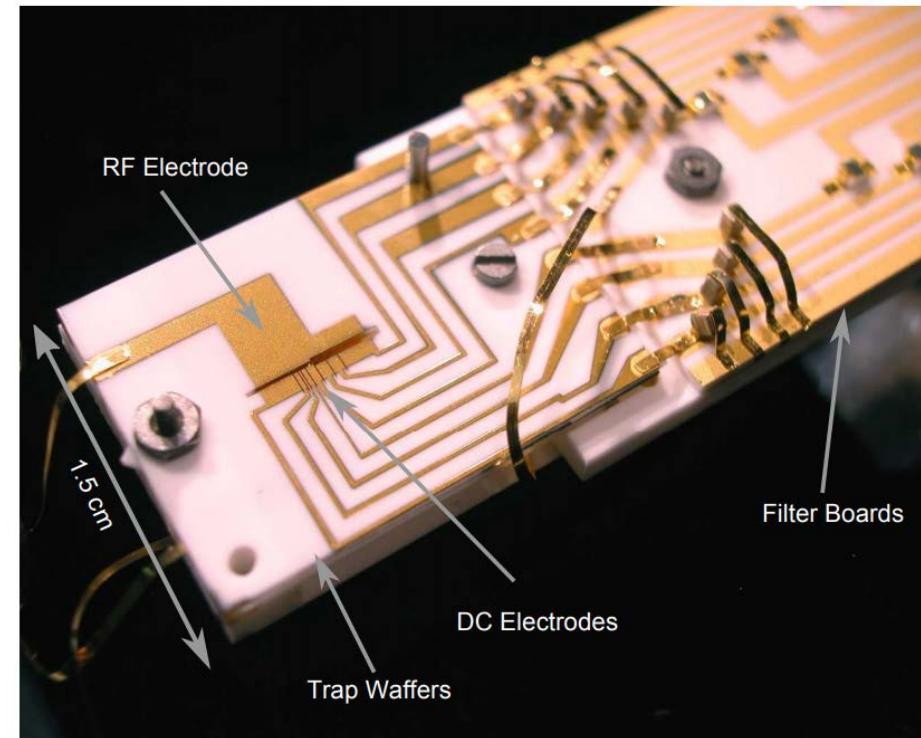
$$\text{rf drive frequency } \frac{\Omega}{2\pi} \sim 40 - 100 \text{ MHz}$$

Example linear rf traps

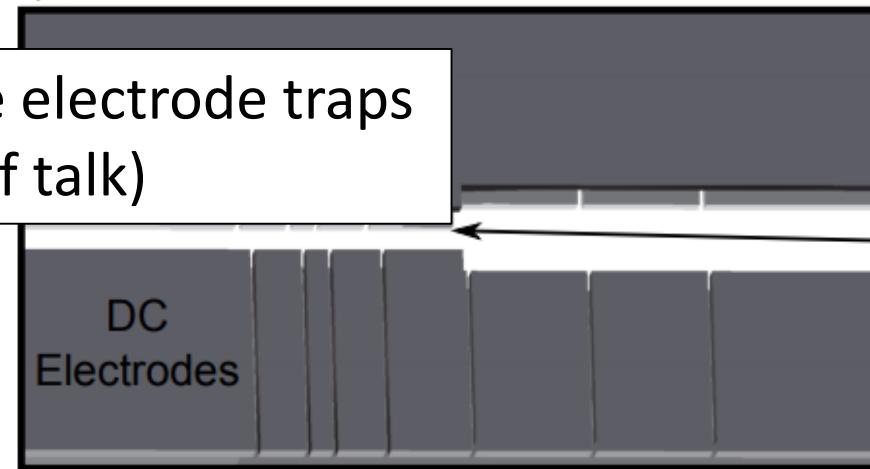
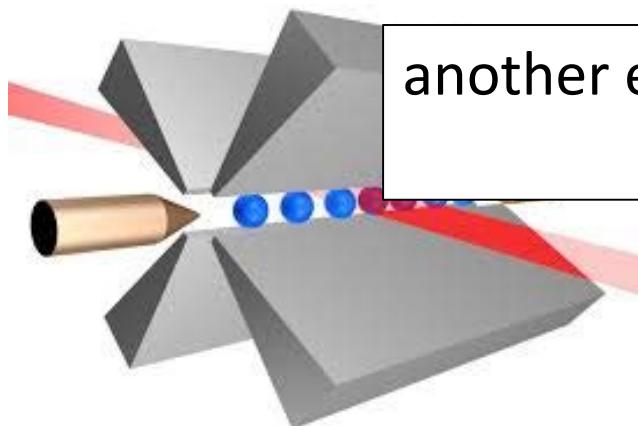
Blade trap, Blatt group, Innsbruck



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

PERIODIC TABLE
Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9.192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum c $299\,792\,458 \text{ m s}^{-1}$ (exact)
Planck constant h $6.6261 \times 10^{-34} \text{ J s}$ ($\hbar = h/2\pi$)
elementary charge e $1.6022 \times 10^{-19} \text{ C}$
electron mass m_e $9.1094 \times 10^{-31} \text{ kg}$
 $m_e c^2$ 0.5110 MeV
proton mass m_p $1.6726 \times 10^{-27} \text{ kg}$
fine-structure constant α $1/137.036$
Rydberg constant R_∞ $10\,973\,732 \text{ m}^{-1}$
 $R_\infty c$ $3.289\,842 \times 10^{16} \text{ Hz}$
 $R_\infty hc$ 13.6057 eV
Boltzmann constant k $1.3807 \times 10^{-23} \text{ J K}^{-1}$

Period

Group

1 IA

2 IIA

3 IIIA

4 IVB

5 VB

6 VIB

7 VIIB

8 VIII

13 IIIA

14 IVA

15 VA

16 VIA

17 VIIA

18 VIIIA

Solids

Liquids

Gases

Artificially Prepared

Physics Laboratory physics.nist.gov

Standard Reference Data Group www.nist.gov/srd

5 $^2\text{P}_{1/2}$ **6 $^3\text{P}_2$** **7 $^4\text{S}_{1/2}$** **8 $^3\text{P}_2$** **9 $^3\text{P}_{2/1}$** **10 $^1\text{S}_0$** **He**

Boron **Carbon** **Nitrogen** **Oxygen** **Fluorine** **Neon**

10.811 12.0107 14.0067 15.0094 18.0084032 4.002802

$1s^2 2s^2$ $1s^2 2s^2 2p^2$ $1s^2 2p^3$ $1s^2 2p^4$ $1s^2 2p^5$ $1s^2$

13 $^2\text{P}_{1/2}$ **14 $^3\text{P}_0$** **15 $^4\text{S}_{3/2}$** **16 $^3\text{P}_2$** **17 $^2\text{P}_{3/2}$** **18 $^1\text{S}_0$** **Ar**

Aluminum **Silicon** **Phosphorus** **Sulfur** **Chlorine** **Argon**

26.981538 28.0865 30.073761 32.065 35.463 39.948

$[\text{Ne}] 3s^2 3p^2$ $[\text{Ne}] 3s^2 3p^3$ $[\text{Ne}] 3s^2 3p^5$ $[\text{Ne}] 3s^2 3p^4$ $[\text{Ne}] 3s^2 3p^5$ $[\text{Ne}] 3s^2 3p^6$

21 $^3\text{D}_{1/2}$ **22 $^3\text{F}_2$** **23 $^4\text{F}_{5/2}$** **24 $^7\text{S}_0$** **25 $^6\text{S}_{1/2}$** **26 $^5\text{D}_4$** **27 $^4\text{F}_{5/2}$** **28 $^5\text{F}_4$** **29 $^5\text{S}_0$** **30 $^5\text{S}_{1/2}$** **31 $^3\text{P}_{1/2}$** **32 $^3\text{P}_0$** **33 $^6\text{S}_{3/2}$** **34 $^3\text{P}_2$** **35 $^3\text{P}_{1/2}$** **36 $^1\text{S}_0$** **Zn**

Scandium **Titanium** **Vanadium** **Chromium** **Manganese** **Iron** **Cobalt** **Nickel** **Copper** **Zinc** **Gallium** **Germanium** **Asenic** **Se** **Br** **Kr**

44.065910 47.887 50.9415 54.998049 56.933200 59.8934 62.8934 65.8034 68.723 72.64 74.92190 76.06 79.004 83.798 13.0006

$[\text{Ar}] 3d^1 4s^2$ $[\text{Ar}] 3d^2 4s^2$ $[\text{Ar}] 3d^3 4s^2$ $[\text{Ar}] 3d^4 4s^2$ $[\text{Ar}] 3d^5 4s^2$ $[\text{Ar}] 3d^6 4s^2$ $[\text{Ar}] 3d^7 4s^2$ $[\text{Ar}] 3d^8 4s^2$ $[\text{Ar}] 3d^9 4s^2$ $[\text{Ar}] 3d^10 4s^2$ $[\text{Ar}] 3d^1 4p^2$ $[\text{Ar}] 3d^2 4p^2$ $[\text{Ar}] 3d^3 4p^2$ $[\text{Ar}] 3d^4 4p^2$ $[\text{Ar}] 3d^5 4p^2$

38 $^1\text{S}_0$ **39 $^3\text{D}_{1/2}$** **40 $^3\text{F}_2$** **41 $^3\text{D}_{1/2}$** **42 $^3\text{G}_{3/2}$** **43 $^3\text{G}_{5/2}$** **44 $^3\text{F}_6$** **45 $^4\text{F}_{9/2}$** **46 $^1\text{S}_0$** **47 $^3\text{G}_{3/2}$** **48 $^3\text{P}_{1/2}$** **49 $^3\text{P}_{1/2}$** **50 $^3\text{P}_0$** **51 $^4\text{S}_{3/2}$** **52 $^3\text{P}_{2/1}$** **53 $^3\text{P}_{1/2}$** **54 $^1\text{S}_0$** **Y** **Zr** **Nb** **Tc** **Ru** **Rh** **Pd** **Ag** **Cd** **In** **Sn** **Sb** **Te** **I** **Xe**

Rubidium **Samarium** **Yttrium** **Zirconium** **Niobium** **Molybdenum** **Technetium** **Ruthenium** **Rhodium** **Palladium** **Silver** **Cadmium** **Indium** **Antimony** **Tellurium** **Iodine** **Xenon**

85.4678 87.62 88.9085 89.0058 89.9638 90.94 91.94 92.90590 93.9059 94.9059 95.9059 96.9059 97.9059 98.9059 99.9059 101.9059 102.9059 103.9059 104.9059 105.9059 106.9059 107.9059 108.9059 109.9059 110.9059 111.9059 112.9059 113.9059 114.9059 115.9059 116.9059 117.9059 118.9059 119.9059 120.9059 121.9059 122.9059 123.9059 124.9059 125.9059 126.9059 127.9059 128.9059 129.9059 130.9059 131.9059 132.9059 133.9059 134.9059 135.9059 136.9059 137.9059 138.9059 139.9059 140.9059 141.9059 142.9059 143.9059 144.9059 145.9059 146.9059 147.9059 148.9059 149.9059 150.9059 151.9059 152.9059 153.9059 154.9059 155.9059 156.9059 157.9059 158.9059 159.9059 160.9059 161.9059 162.9059 163.9059 164.9059 165.9059 166.9059 167.9059 168.9059 169.9059 170.9059 171.9059 172.9059 173.9059 174.9059 175.9059 176.9059 177.9059 178.9059 179.9059 180.9059 181.9059 182.9059 183.9059 184.9059 185.9059 186.9059 187.9059 188.9059 189.9059 190.9059 191.9059 192.9059 193.9059 194.9059 195.9059 196.9059 197.9059 198.9059 199.9059 200.9059 201.9059 202.9059 203.9059 204.9059 205.9059 206.9059 207.9059 208.9059 209.9059 210.9059 211.9059 212.9059 213.9059 214.9059 215.9059 216.9059 217.9059 218.9059 219.9059 220.9059 221.9059 222.9059 223.9059 224.9059 225.9059 226.9059 227.9059 228.9059 229.9059 230.9059 231.9059 232.9059 233.9059 234.9059 235.9059 236.9059 237.9059 238.9059 239.9059 240.9059 241.9059 242.9059 243.9059 244.9059 245.9059 246.9059 247.9059 248.9059 249.9059 250.9059 251.9059 252.9059 253.9059 254.9059 255.9059 256.9059 257.9059 258.9059 259.9059 260.9059 261.9059 262.9059 263.9059 264.9059 265.9059 266.9059 267.9059 268.9059 269.9059 270.9059 271.9059 272.9059 273.9059 274.9059 275.9059 276.9059 277.9059 278.9059 279.9059 280.9059 281.9059 282.9059 283.9059 284.9059 285.9059 286.9059 287.9059 288.9059 289.9059 290.9059 291.9059 292.9059 293.9059 294.9059 295.9059 296.9059 297.9059 298.9059 299.9059 300.9059 301.9059 302.9059 303.9059 304.9059 305.9059 306.9059 307.9059 308.9059 309.9059 310.9059 311.9059 312.9059 313.9059 314.9059 315.9059 316.9059 317.9059 318.9059 319.9059 320.9059 321.9059 322.9059 323.9059 324.9059 325.9059 326.9059 327.9059 328.9059 329.9059 330.9059 331.9059 332.9059 333.9059 334.9059 335.9059 336.9059 337.9059 338.9059 339.9059 340.9059 341.9059 342.9059 343.9059 344.9059 345.9059 346.9059 347.9059 348.9059 349.9059 350.9059 351.9059 352.9059 353.9059 354.9059 355.9059 356.9059 357.9059 358.9059 359.9059 360.9059 361.9059 362.9059 363.9059 364.9059 365.9059 366.9059 367.9059 368.9059 369.9059 370.9059 371.9059 372.9059 373.9059 374.9059 375.9059 376.9059 377.9059 378.9059 379.9059 380.9059 381.9059 382.9059 383.9059 384.9059 385.9059 386.9059 387.9059 388.9059 389.9059 390.9059 391.9059 392.9059 393.9059 394.9059 395.9059 396.9059 397.9059 398.9059 399.9059 400.9059 401.9059 402.9059 403.9059 404.9059 405.9059 406.9059 407.9059 408.9059 409.9059 410.9059 411.9059 412.9059 413.9059 414.9059 415.9059 416.9059 417.9059 418.9059 419.9059 420.9059 421.9059 422.9059 423.9059 424.9059 425.9059 426.9059 427.9059 428.9059 429.9059 430.9059 431.9059 432.9059 433.9059 434.9059 435.9059 436.9059 437.9059 438.9059 439.9059 440.9059 441.9059 442.9059 443.9059 444.9059 445.9059 446.9059 447.9059 448.9059 449.9059 450.9059 451.9059 452.9059 453.9059 454.9059 455.9059 456.9059 457.9059 458.9059 459.9059 460.9059 461.9059 462.9059 463.9059 464.9059 465.9059 466.9059 467.9059 468.9059 469.9059 470.9059 471.9059 472.9059 473.9059 474.9059 475.9059 476.9059 477.9059 478.9059 479.9059 480.9059 481.9059 482.9059 483.9059 484.9059 485.9059 486.9059 487.9059 488.9059 489.9059 490.9059 491.9059 492.9059 493.9059 494.9059 495.9059 496.9059 497.9059 498.9059 499.9059 500.9059 501.9059 502.9059 503.9059 504.9059 505.9059 506.9059 507.9059 508.9059 509.9059 510.9059 511.9059 512.9059 513.9059 514.9059 515.9059 516.9059 517.9059 518.9059 519.9059 520.9059 521.9059 522.9059 523.9059 524.9059 525.9059 526.9059 527.9059 528.9059 529.9059 530.9059 531.9059 532.9059 533.9059 534.9059 535.9059 536.9059 537.9059 538.9059 539.9059 540.9059 541.9059 542.9059 543.9059 544.9059 545.9059 546.9059 547.9059 548.9059 549.9059 550.9059 551.9059 552.9059 553.9059 554.9059 555.9059 556.9059 557.9059 558.9059 559.9059 560.9059 561.9059 562.9059 563.9059 564.9059 565.9059 566.9059 567.9059 568.9059 569.9059 570.9059 571.9059 572.9059 573.9059 574.9059 575.9059 576.9059 577.9059 578.9059 579.9059 580.9059 581.9059 582.9059 583.9059 584.9059 585.9059 586.9059 587.9059 588.9059 589.9059 590.9059 591.9059 592.9059 593.9059 594.9059 595.9059 596.9059 597.9059 598.9059 599.9059 600.9059 601.9059 602.9059 603.9059 604.9059 605.9059 606.9059 607.9059 608.9059 609.9059 610.9059 611.9059 612.9059 613.9059 614.9059 615.9059 616.9059 617.9059 618.9059 619.9059 620.9059 621.9059 622.9059 623.9059 624.9059 625.9059 626.9059 627.9059 628.9059 629.9059 630.9059 631.9059 632.9059 633.9059 634.9059 635.9059 636.9059 637.9059 638.9059 639.9059 640.9059 641.9059 64

Resonant S → P transition

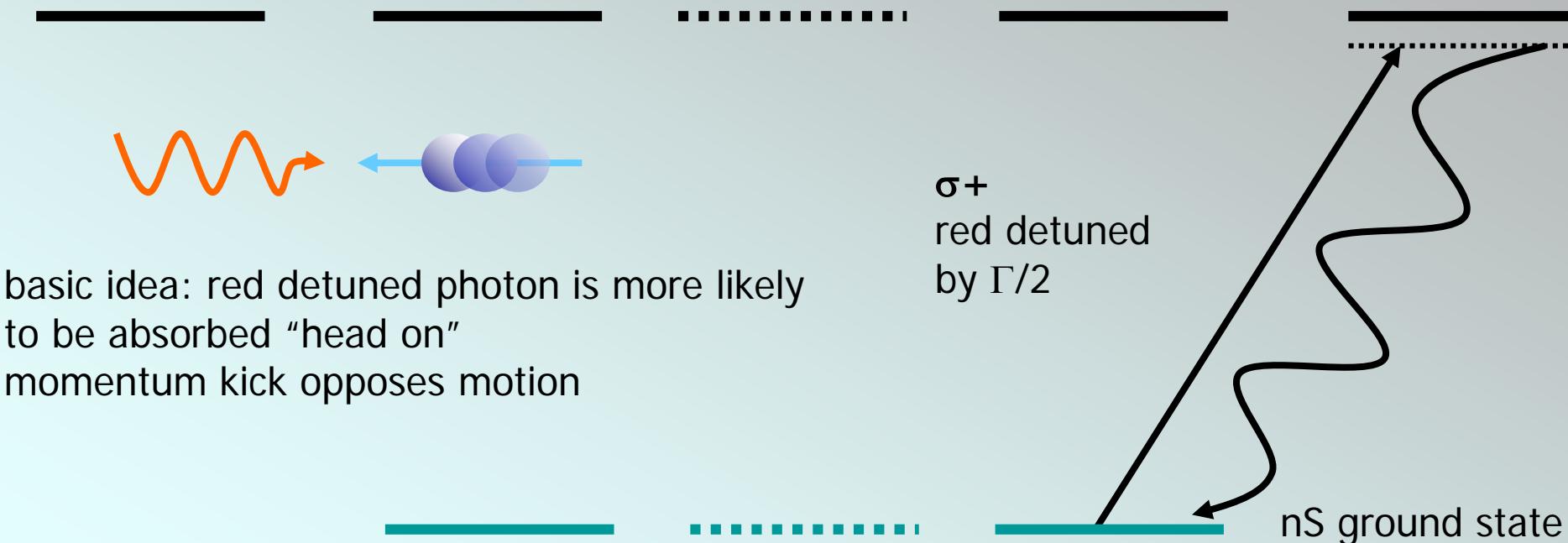
nP (2P for Be⁺) excited state (life-time a few ns)



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

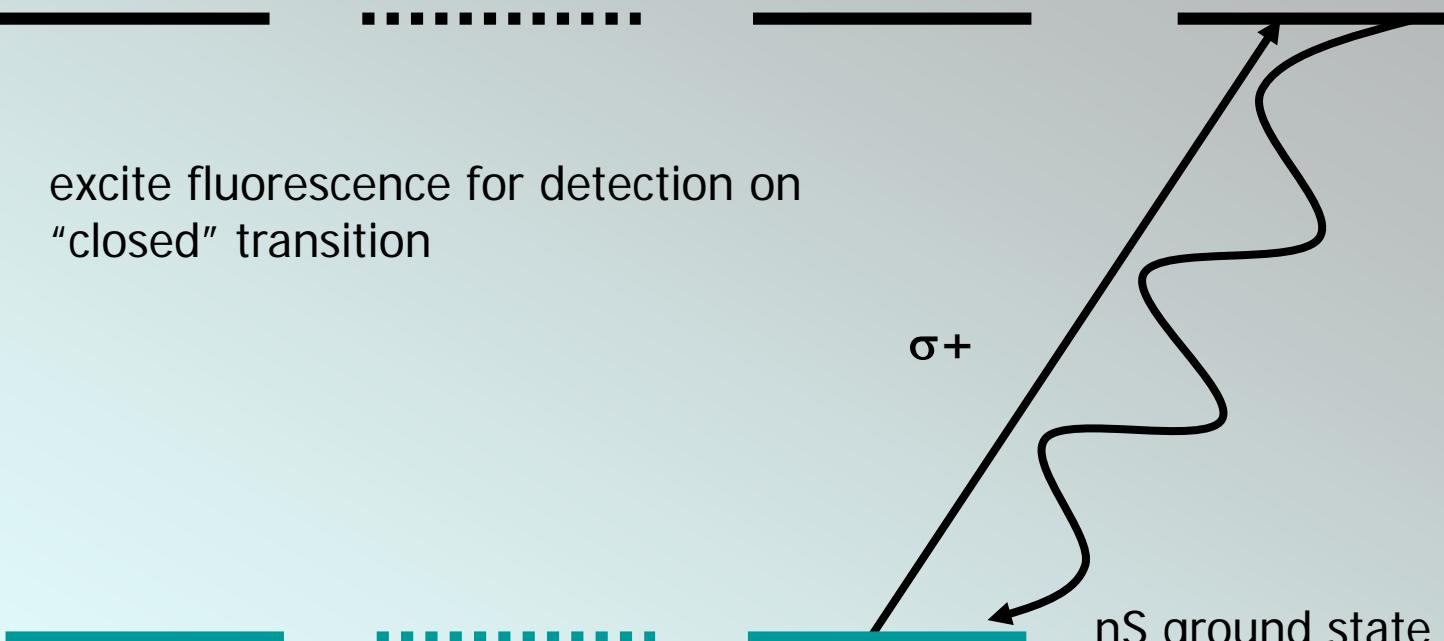
Resonant S → P transition

nP excited state (life-time a few ns)

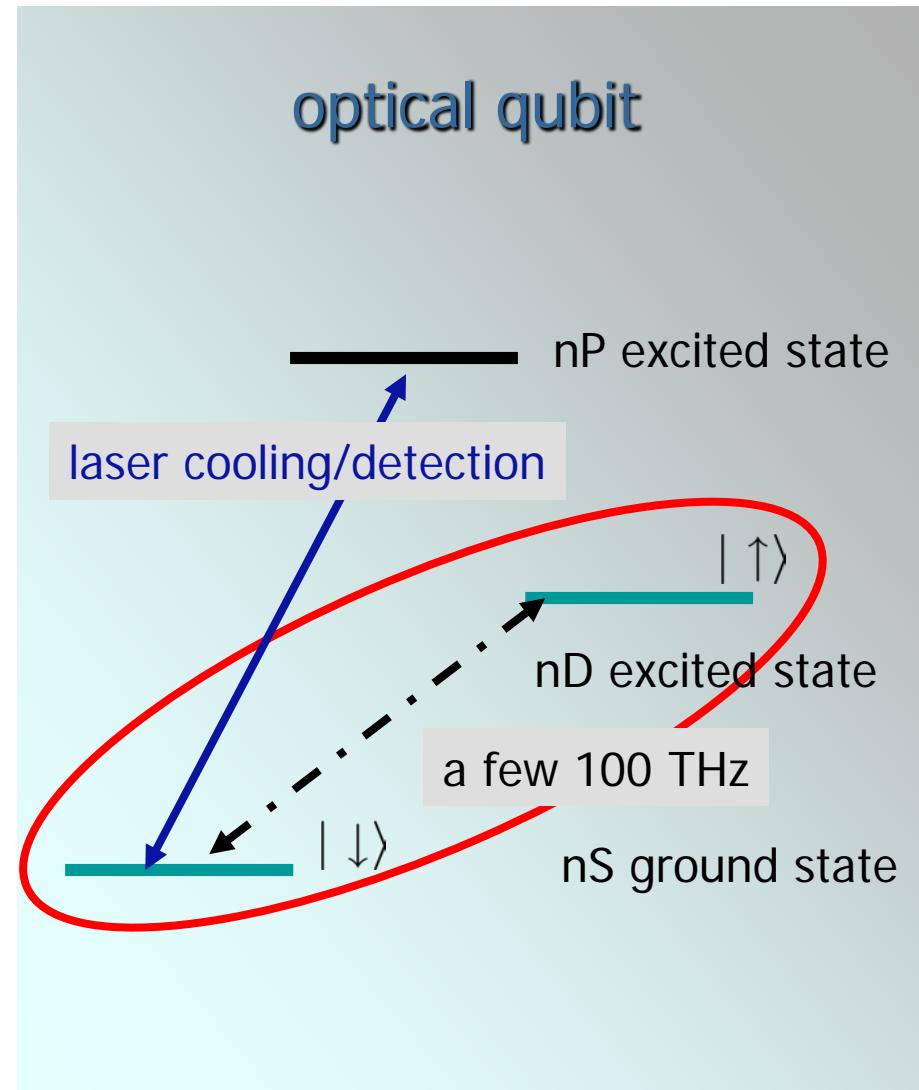
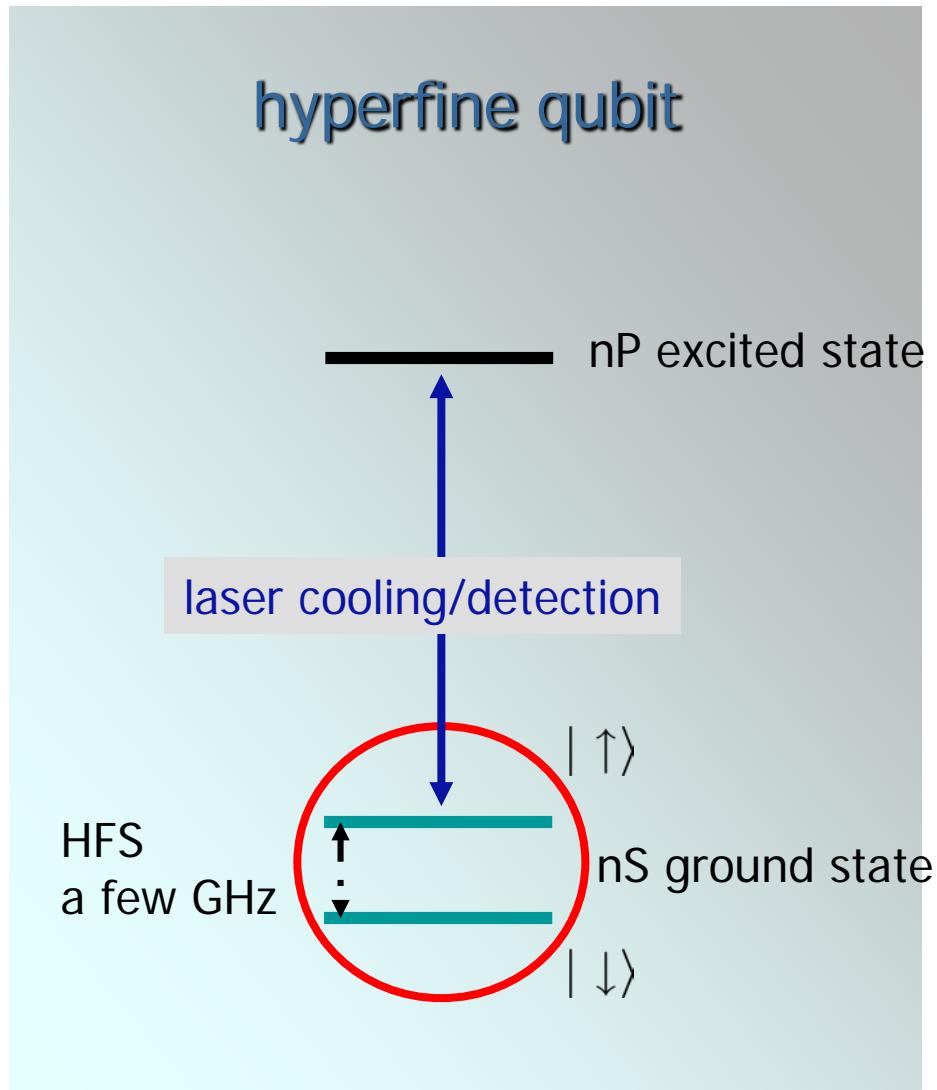
excite fluorescence for detection on
“closed” transition

$\sigma+$

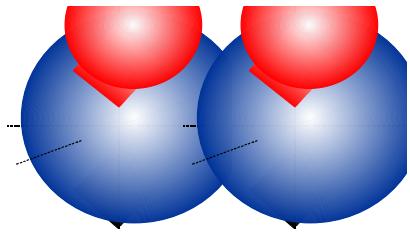
nS ground state



Ion qubits ($| \downarrow \rangle$, $| \uparrow \rangle$)

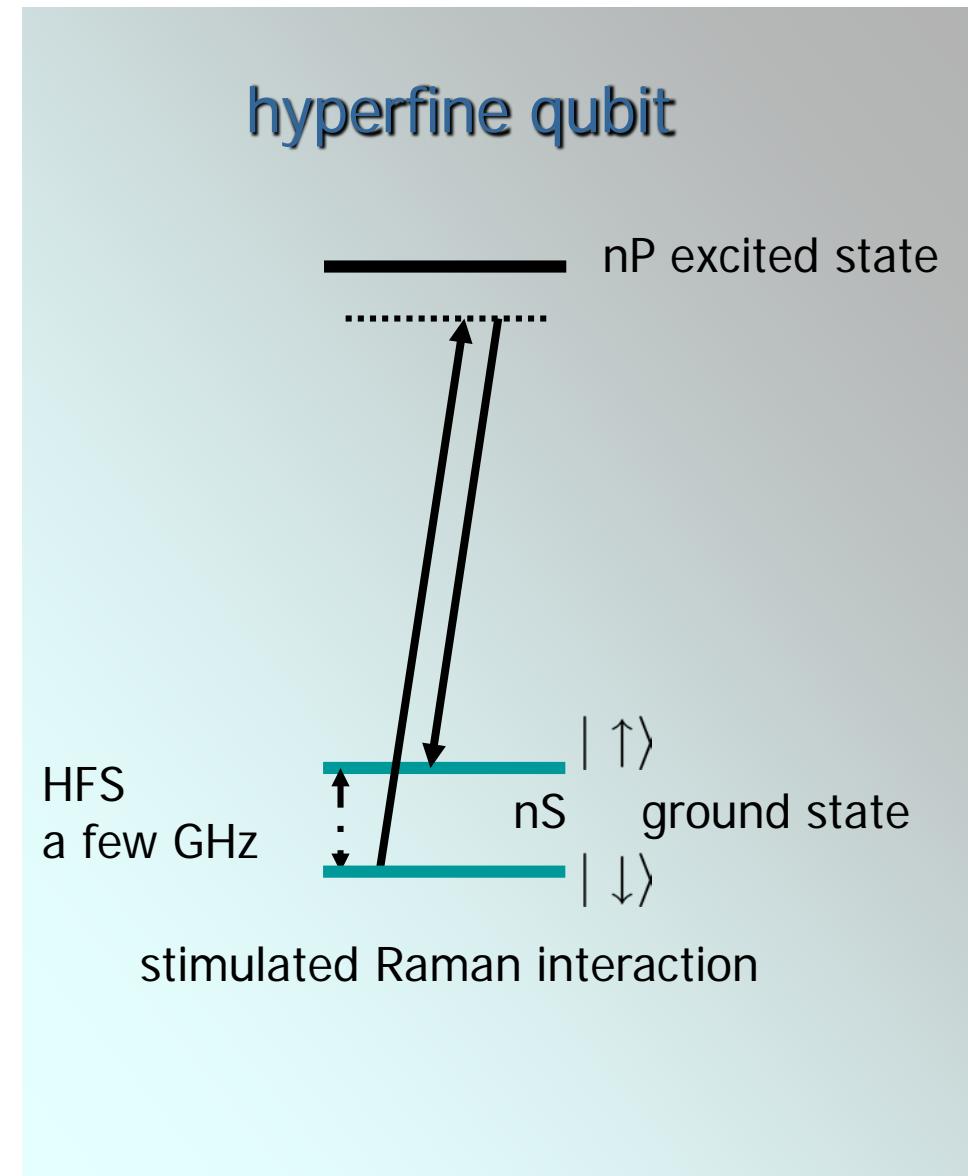
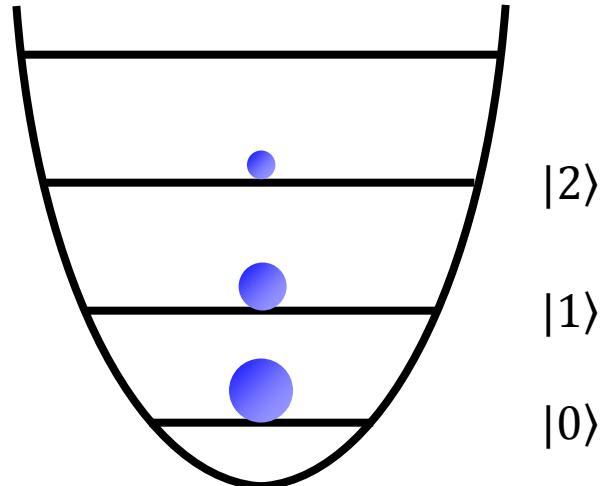


Sideband cooling – cooling to the ground state



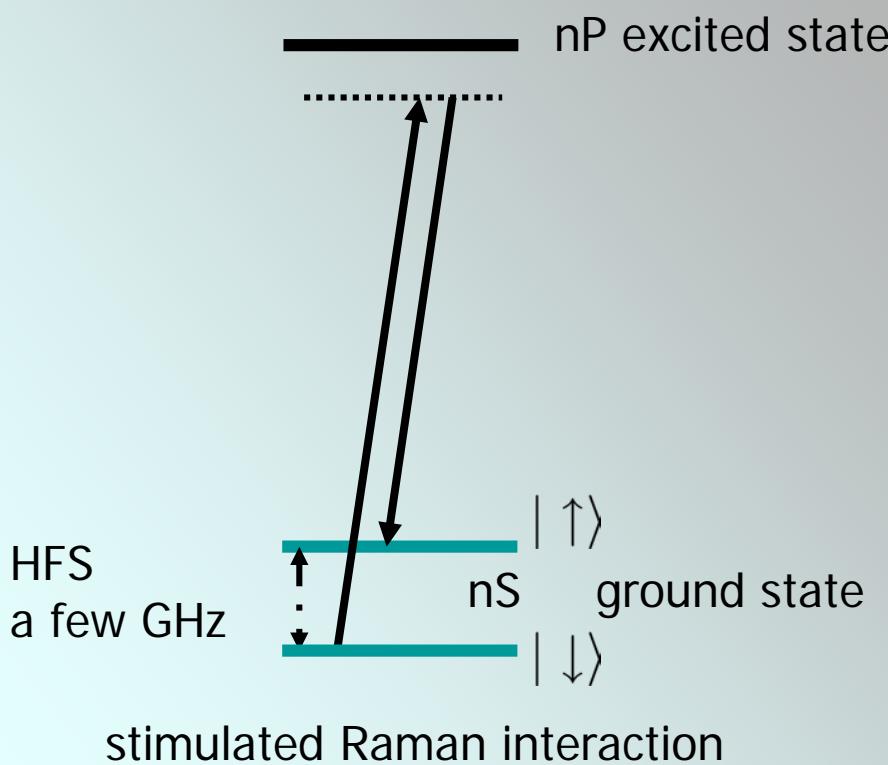
two ions \leftrightarrow 6 normal modes

normal mode \leftrightarrow harmonic oscillator



Sideband cooling – cooling to the ground state

hyperfine qubit



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

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

light detuning and phase ion motion in trap

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

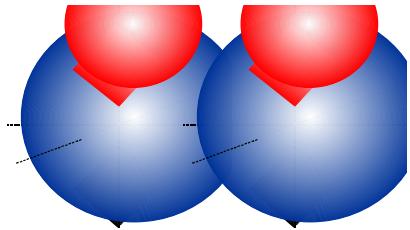
Lamb-Dicke approximation

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

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

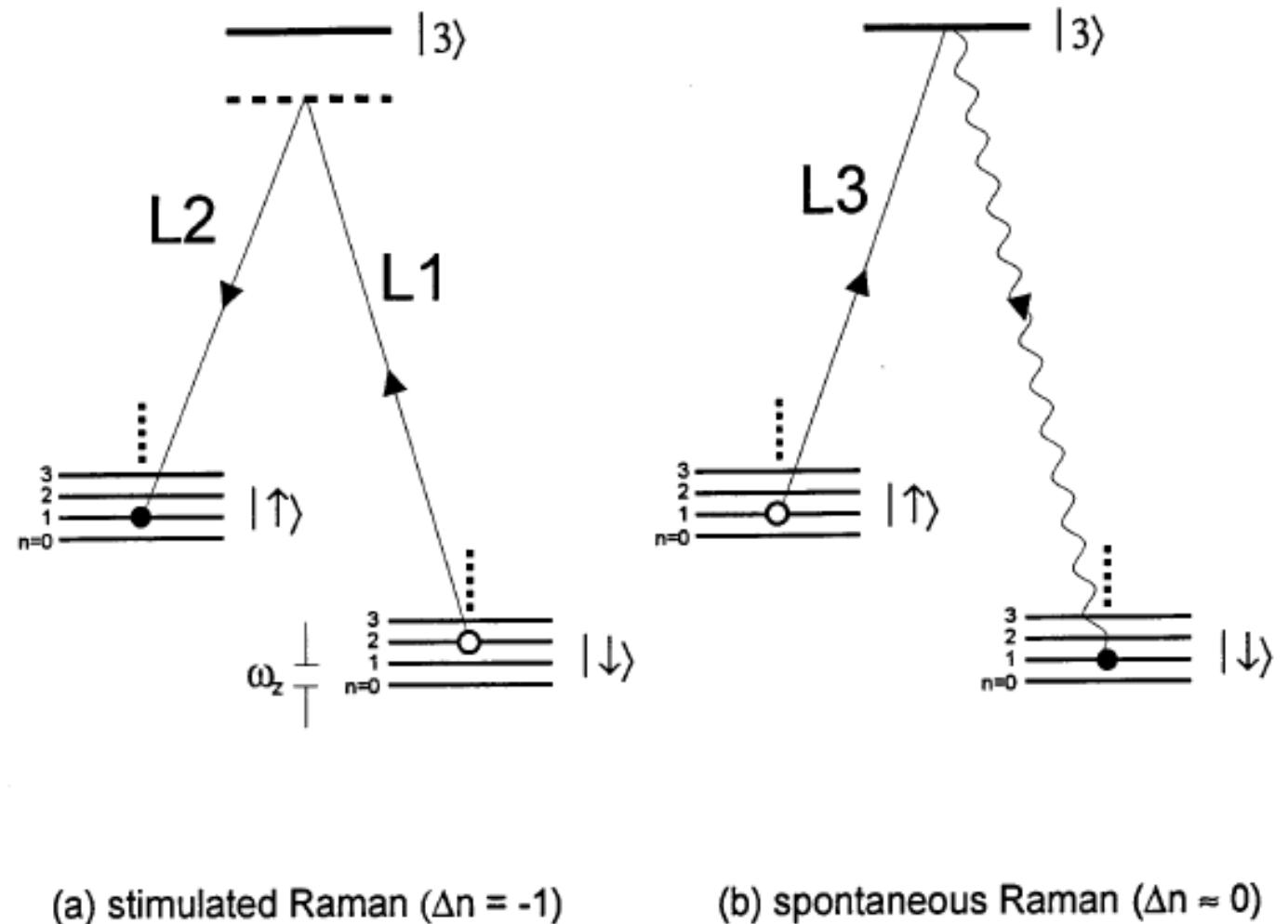
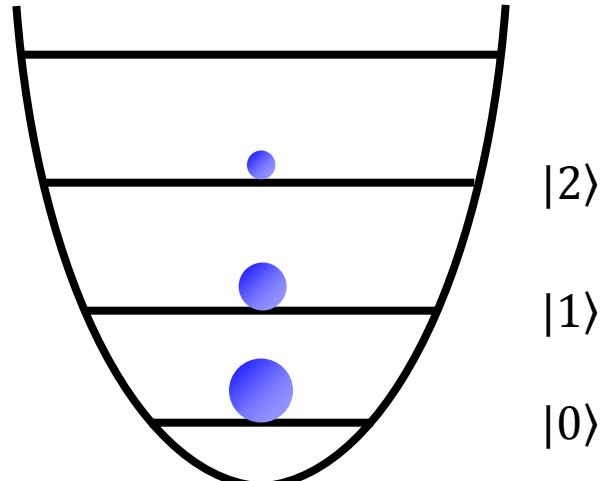
Sideband cooling – cooling to the ground state

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



two ions \leftrightarrow 6 normal modes

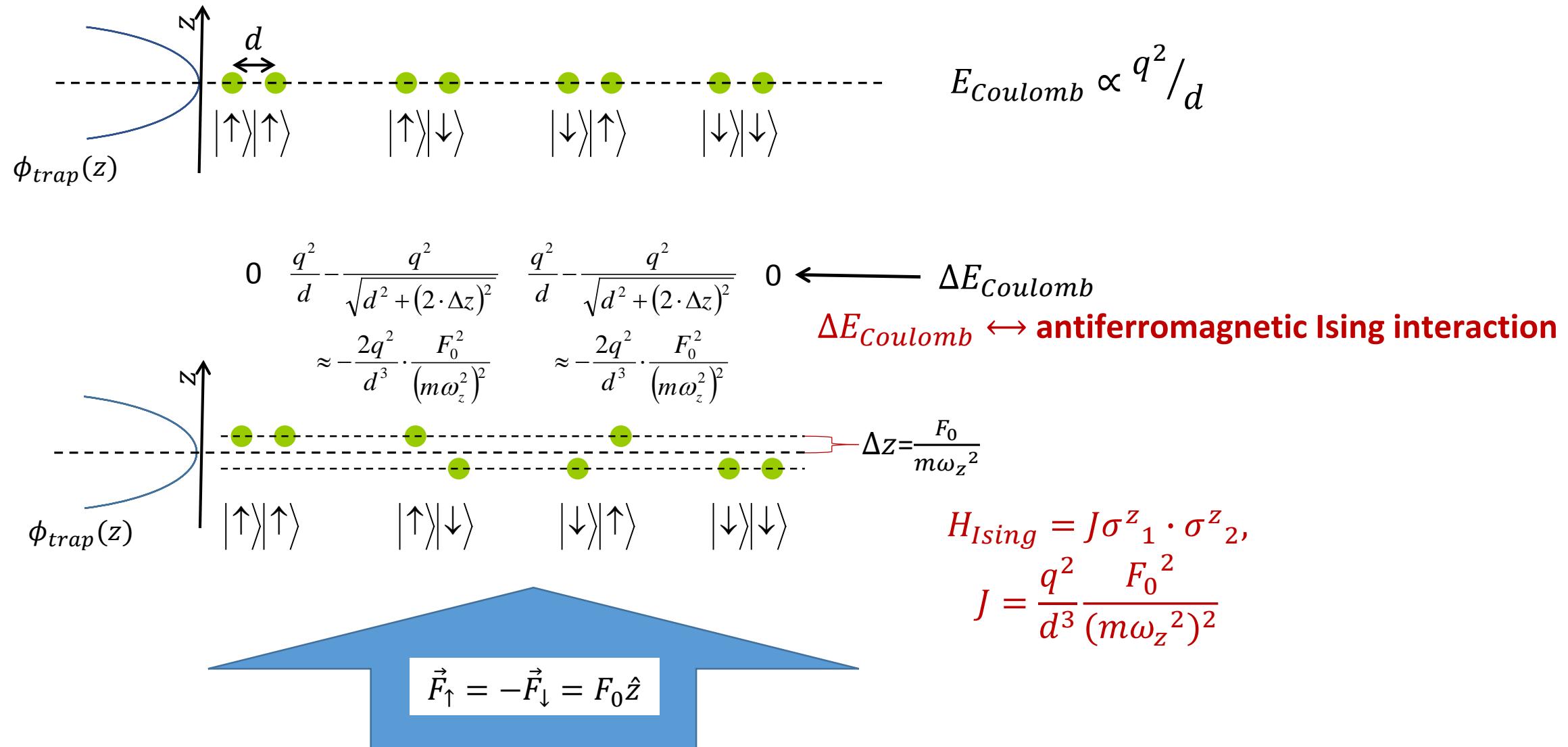
normal mode \leftrightarrow harmonic oscillator



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

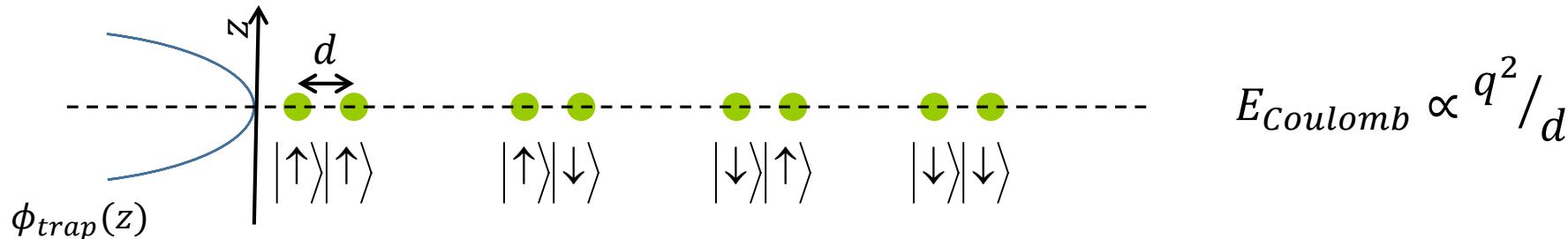
Generating entangled states with spin-dependent forces

Simple example – adiabatic spin-dependent force Calarco, Cirac, Zoller, PRA (2001)

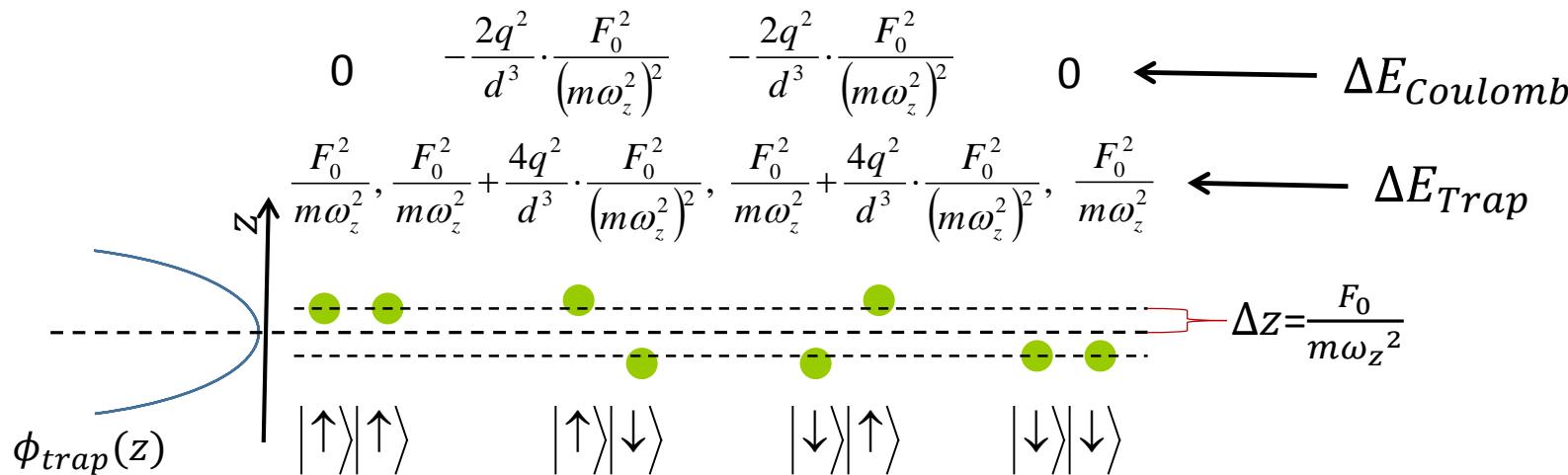


Generating entangled states with spin-dependent forces

Simple example – adiabatic spin-dependent force



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



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

$$H_{Ising} = J \sigma^z_1 \cdot \sigma^z_2,$$
$$J = -\frac{q^2}{d^3} \frac{F_0^2}{(m\omega_z^2)^2}$$

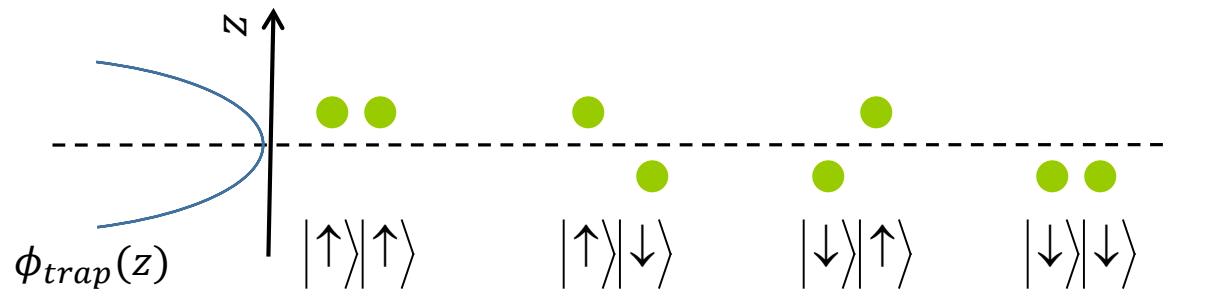
$$\vec{F}_\uparrow = -\vec{F}_\downarrow = F_0 \hat{z}$$

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
⇒ 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
⇒ anti-ferromagnetic interaction

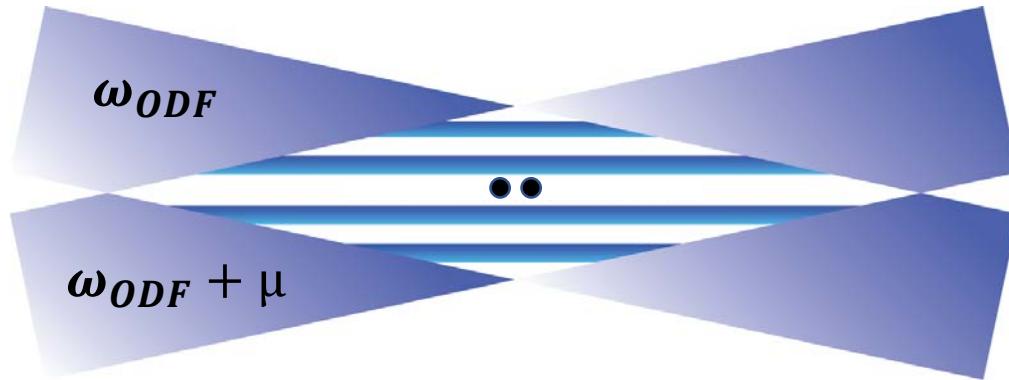


$$\vec{F}_\uparrow(t) = -\vec{F}_\downarrow(t) = F_0 \cos(\mu t) \hat{z}$$

Generating entangled states – geometric phase picture

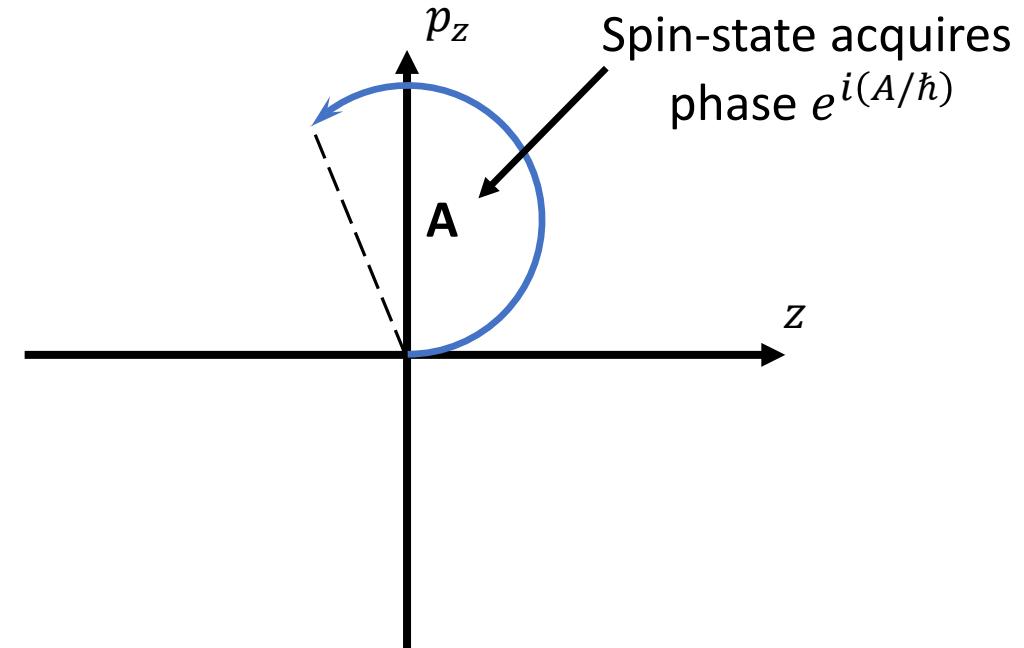
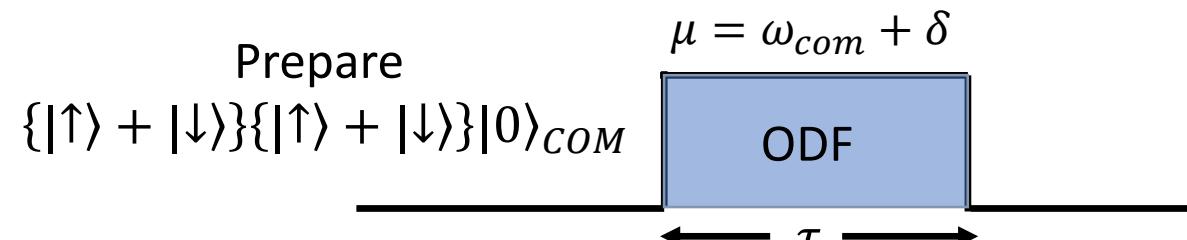
Spin-dependent forces from optical dipole forces

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



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

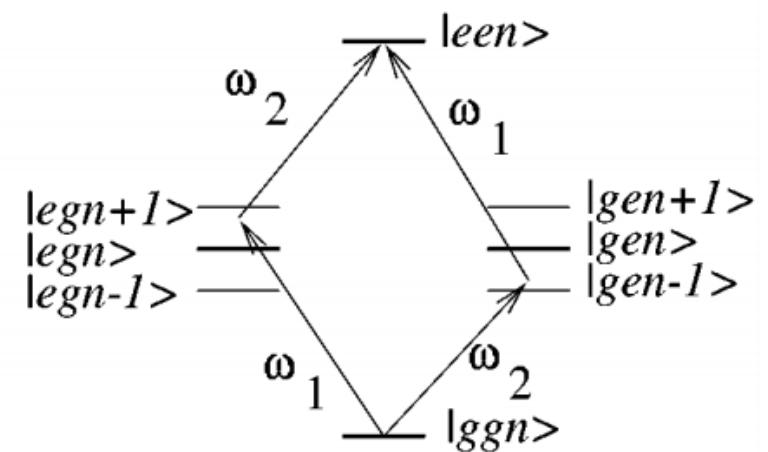
$$\hat{H}_{ODF}(t) = F_0 \cos(\mu t) \sum_{j=1}^2 \hat{z}_j \cdot \hat{\sigma}_j^z$$



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

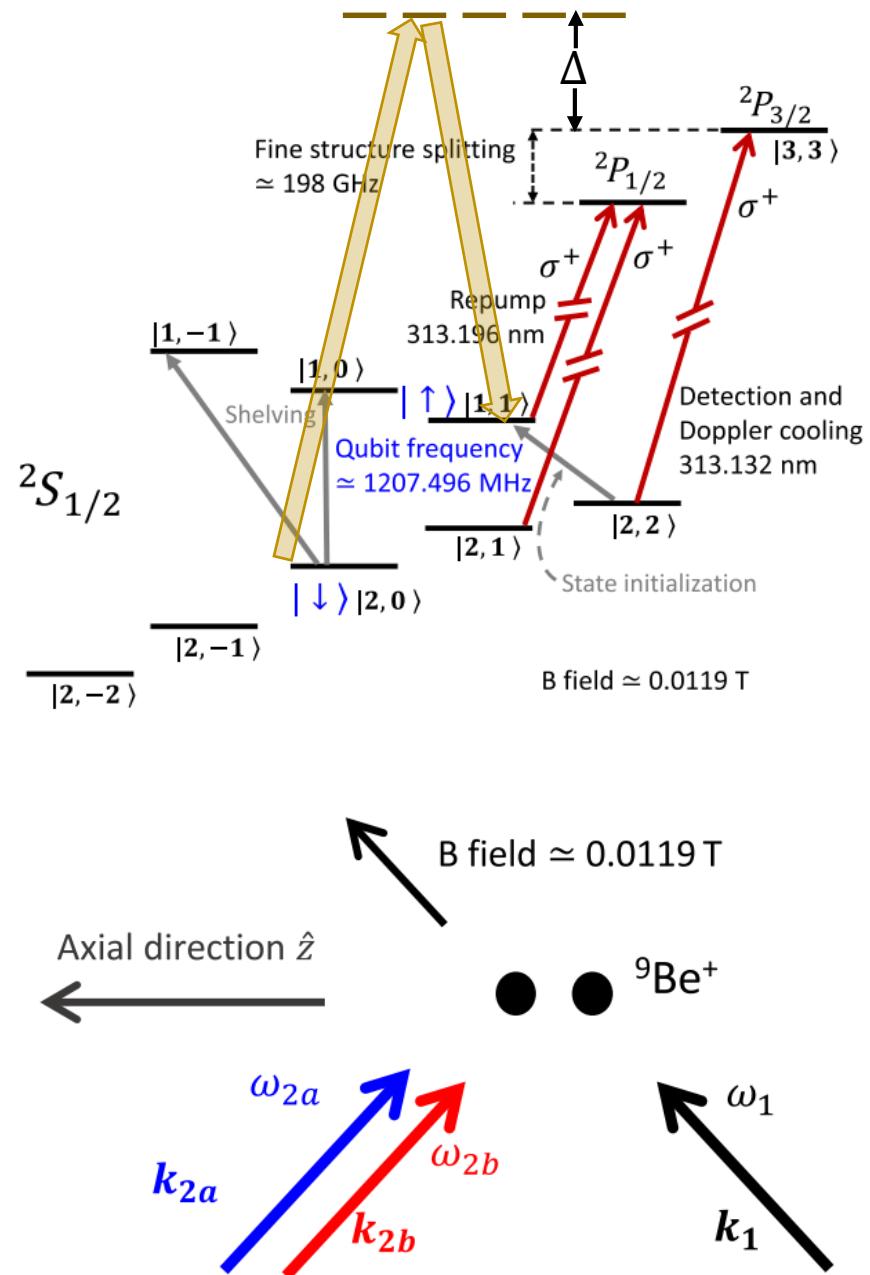
- Cirac –Zoller controlled not gate- *Phys Rev Lett* **74** (1995)
first-order sensitive to ground state cooling
- Geometric phase gate - Leibfried et al., *Nature* **422**, (2003)
first-order insensitive to motional temperature
 $\mu = \omega_{com} + \delta$, $\hat{\sigma}_z\hat{\sigma}_z$ interaction
- 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 ${}^9\text{Be}^+$ 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)

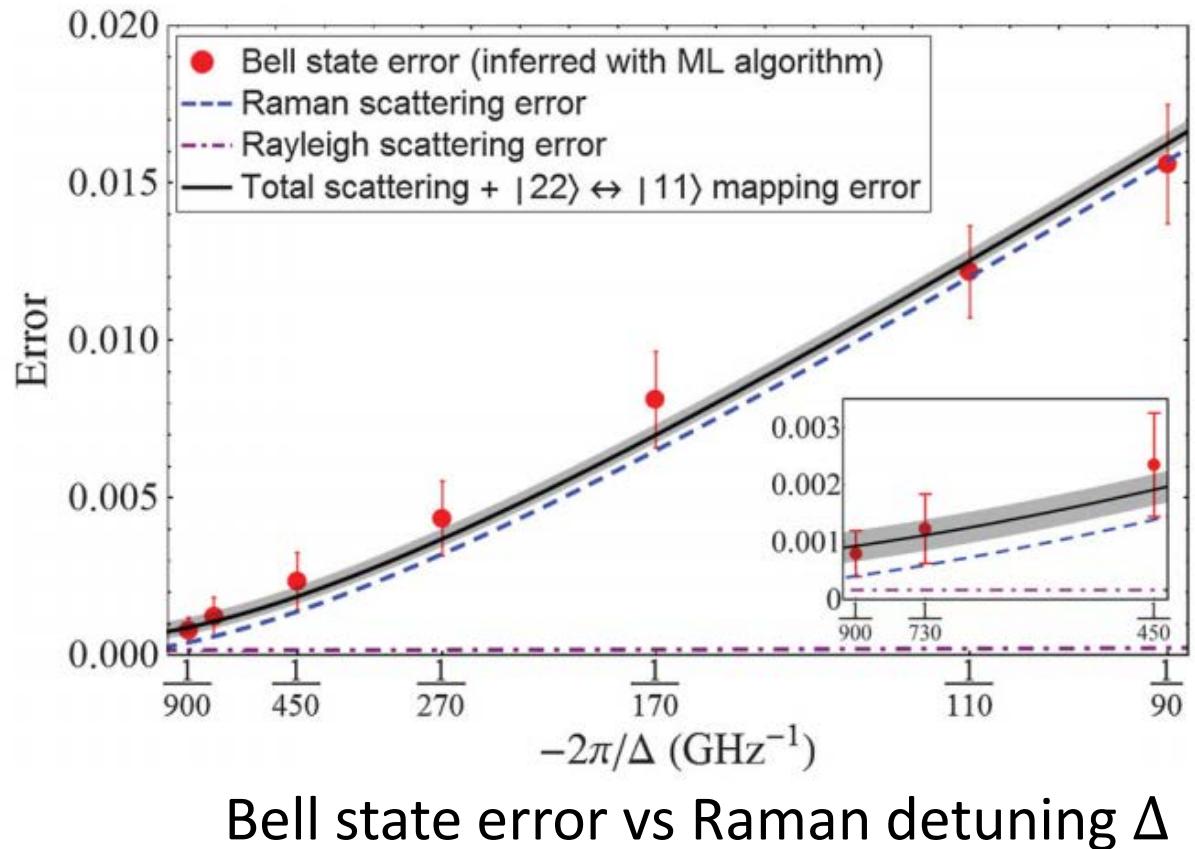
High fidelity gate for ${}^9\text{Be}$ qubits – NIST group



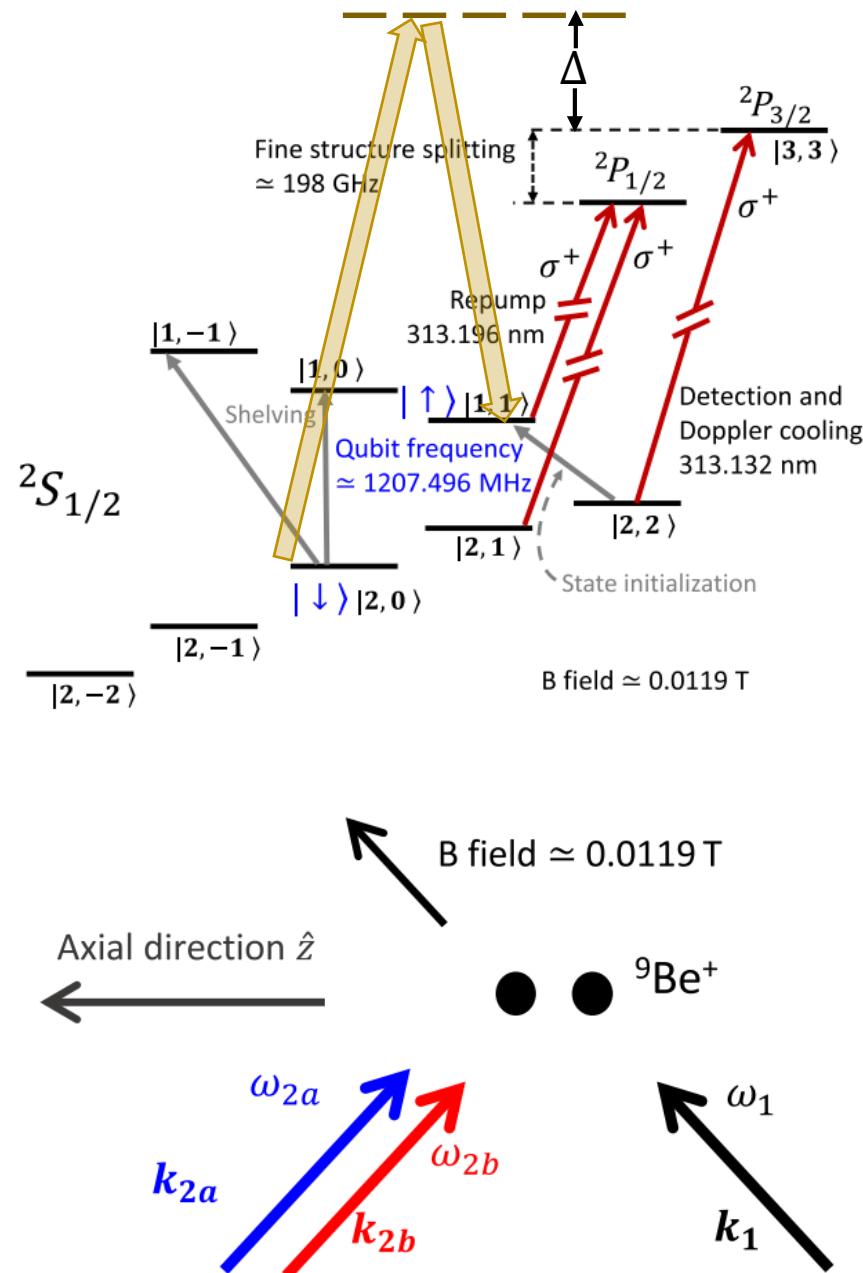
Employ MS gate to prepare Bell state:

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

Partial state tomography \Rightarrow Fidelity



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



Employ MS gate to prepare Bell state:

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

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

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
$ 2, 2\rangle \Leftrightarrow \uparrow\rangle$ two-way transfer	4

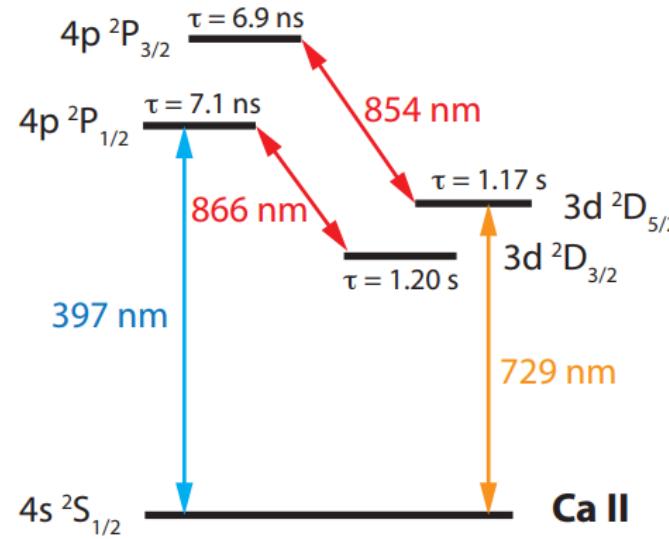
${}^9\text{Be}^+$ hyperfine qubits, NIST group, 99.92(4)%

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

Balance et al., PRL 117 (2016)

14 qubit entanglement – Blatt group, PRL 2011

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

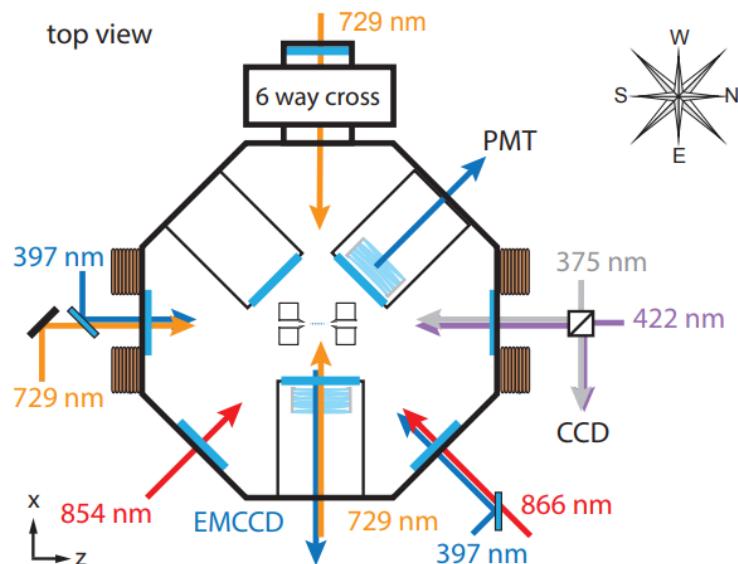


Global application of a MS entangling gate \Rightarrow
GHZ state $(|000\dots0\rangle + |111\dots1\rangle)/\sqrt{2}$

$\underbrace{|000\dots0\rangle + |111\dots1\rangle}_{N \text{ qubits}}/\sqrt{2}$

GHZ coherence \Leftrightarrow 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

Global application of a MS entangling gate \Rightarrow

$$\text{GHZ state } (\lvert 000 \dots 0 \rangle + \lvert 111 \dots 1 \rangle)/\sqrt{2}$$

$\underbrace{}_{N \text{ qubits}}$

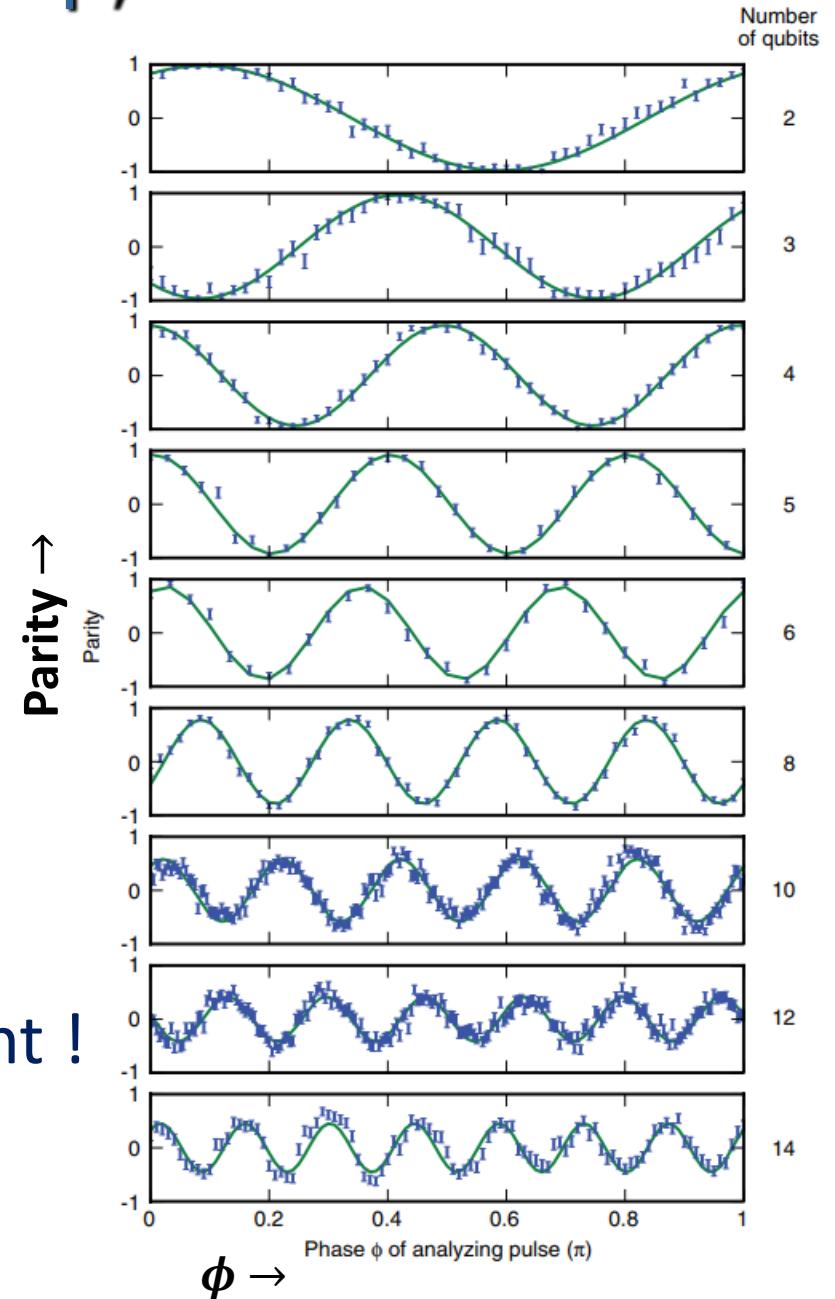
GHZ coherence \Leftrightarrow parity P oscillation measurements

1. global $\pi/2$ spin rotation with phase ϕ

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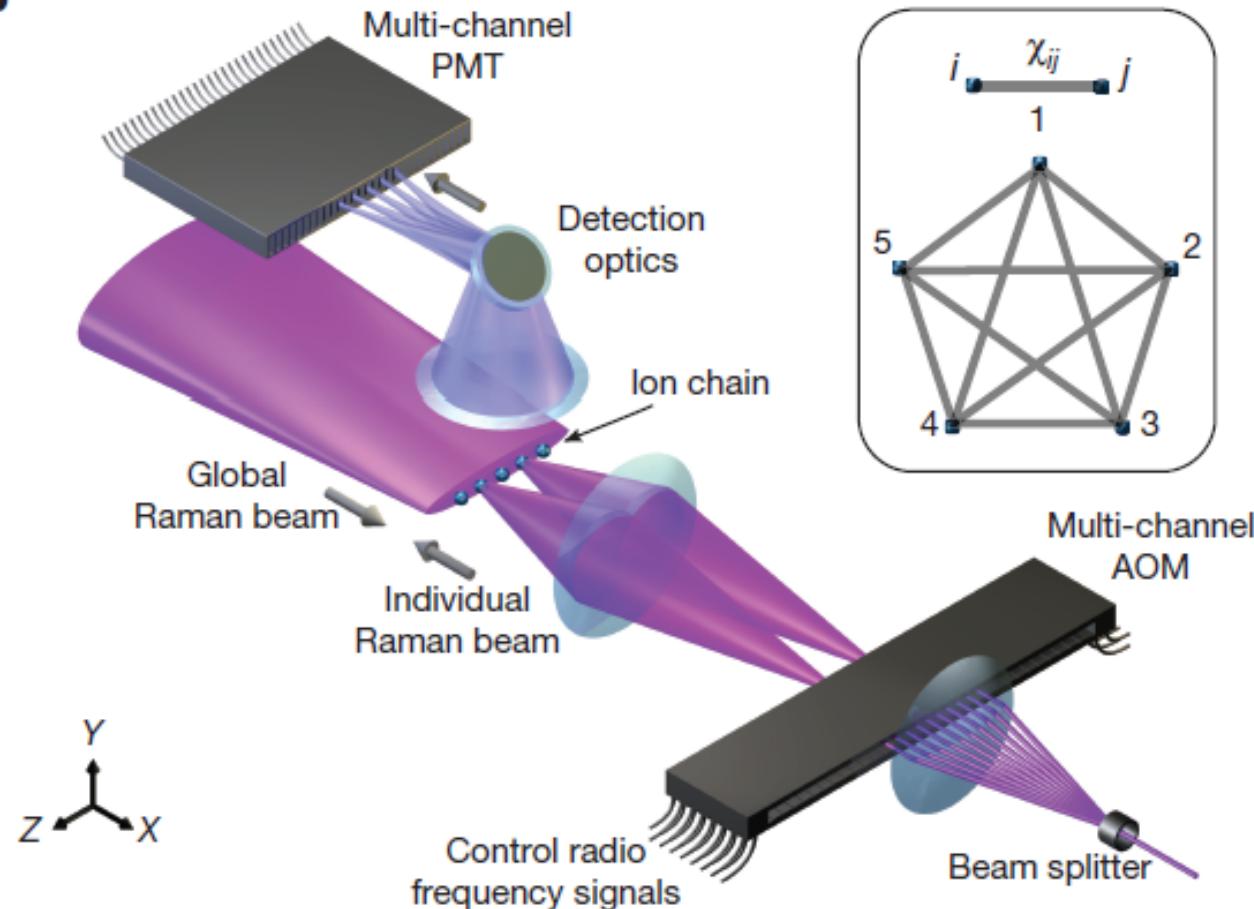
$P_{even,odd}$ = probability of even, odd excitations

Parity oscillations \Rightarrow up to 14-particle entanglement !



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

$^{171}\text{Yb}^+$ hyperfine qubit, $\nu_0 = 12.6 \text{ GHz}$

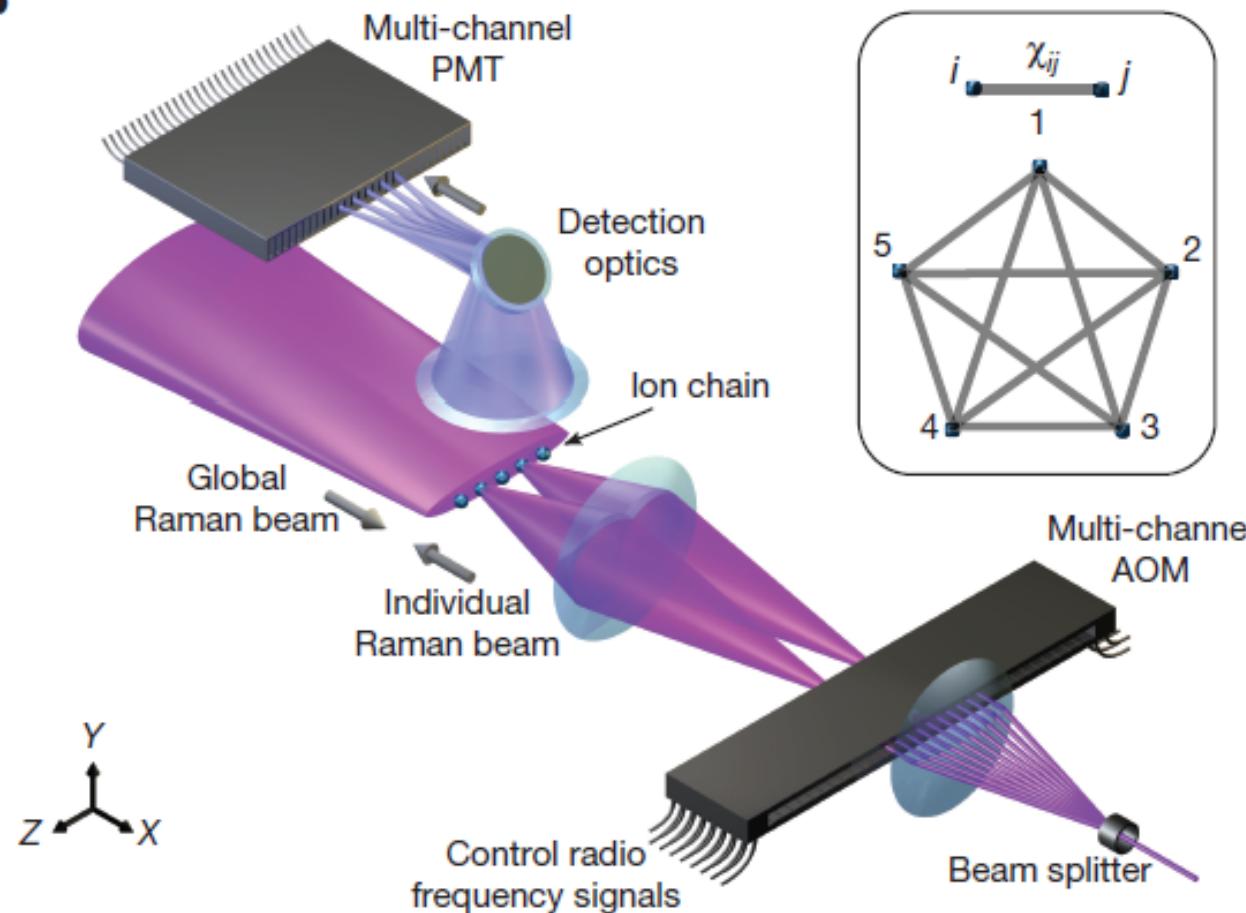


Features:

- 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 \Rightarrow benefits
- Implement algorithms including QFT, fidelity $\sim 80\%$

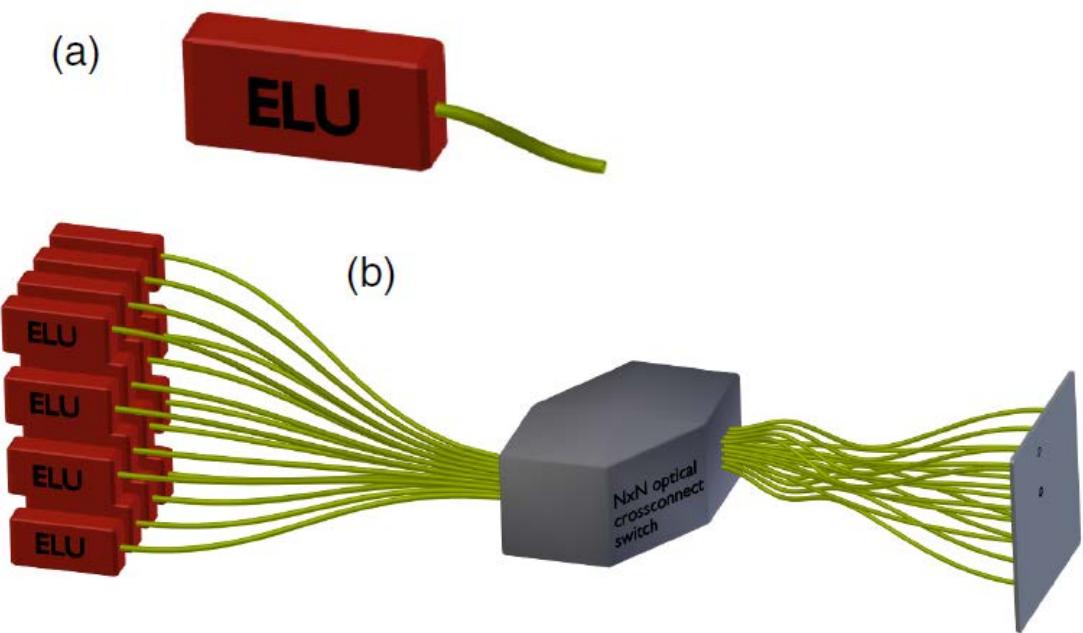
5-ion programmable quantum computer – Monroe group, Nature 2016

$^{171}\text{Yb}^+$ hyperfine qubit, $\nu_0 = 12.6 \text{ GHz}$



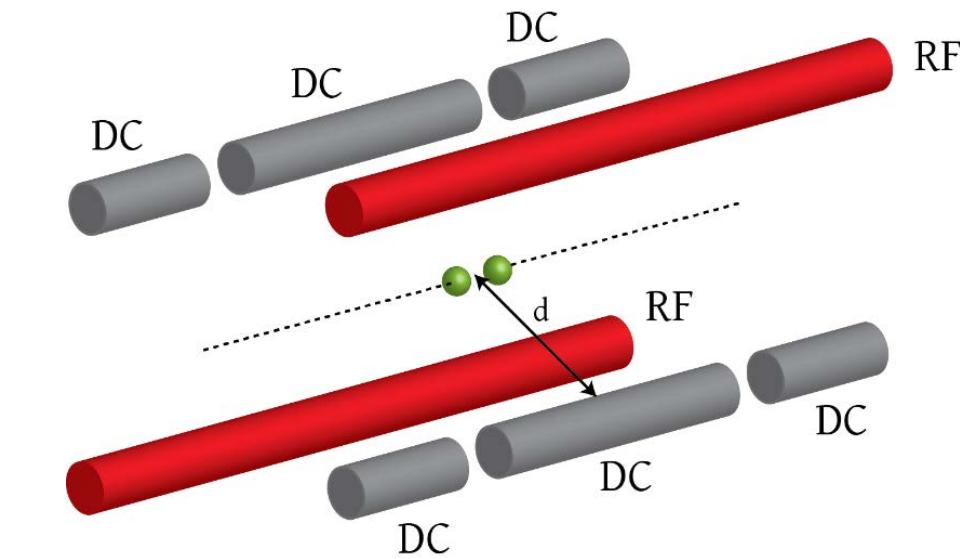
Current efforts to scale from 5 ions $\rightarrow \sim 32$ ions
(UMD, IonQ)

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

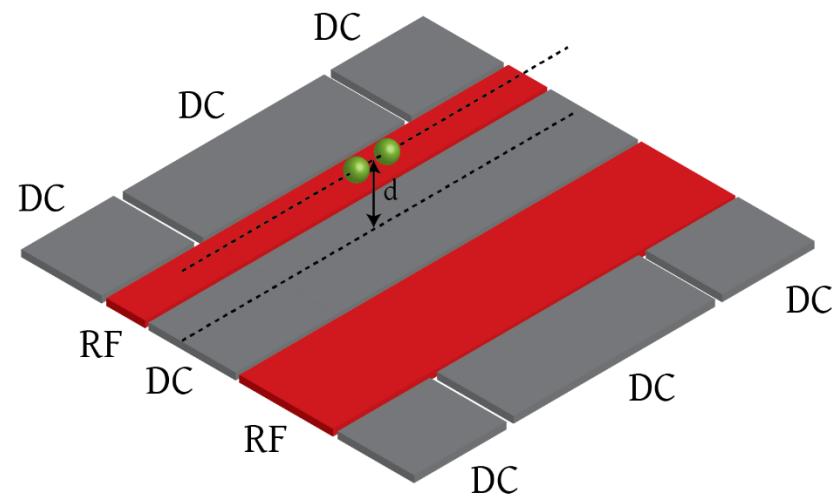


Surface-electrode rf ion traps

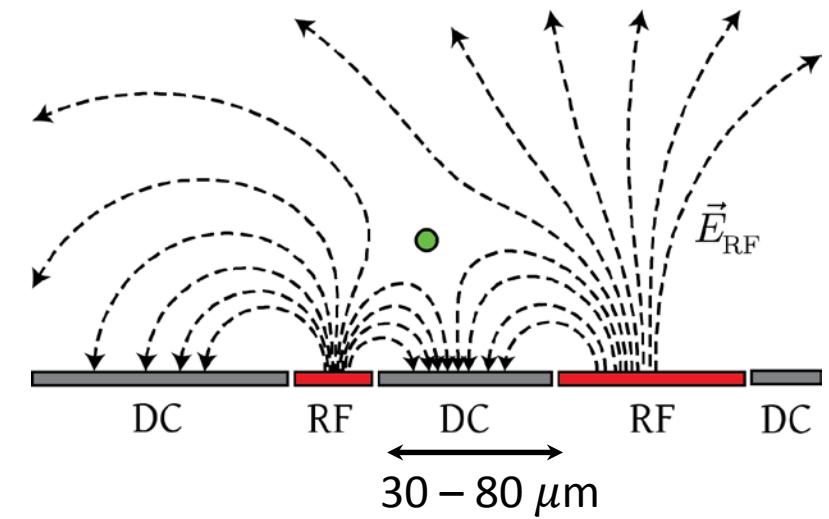
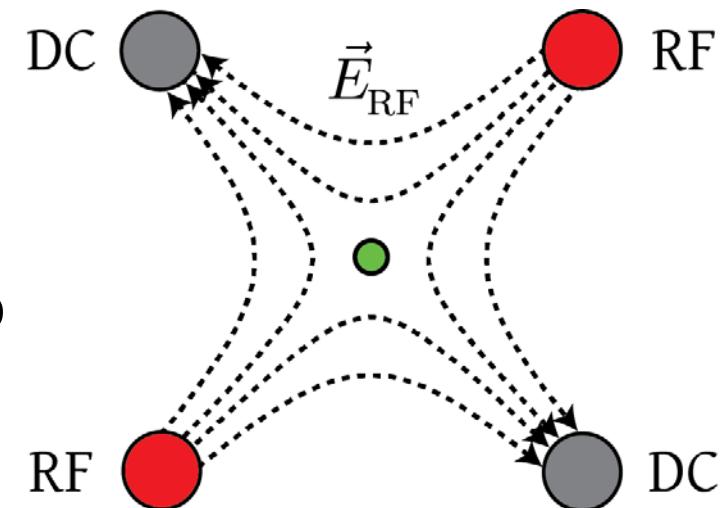
Surface-electrode rf ion traps



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"

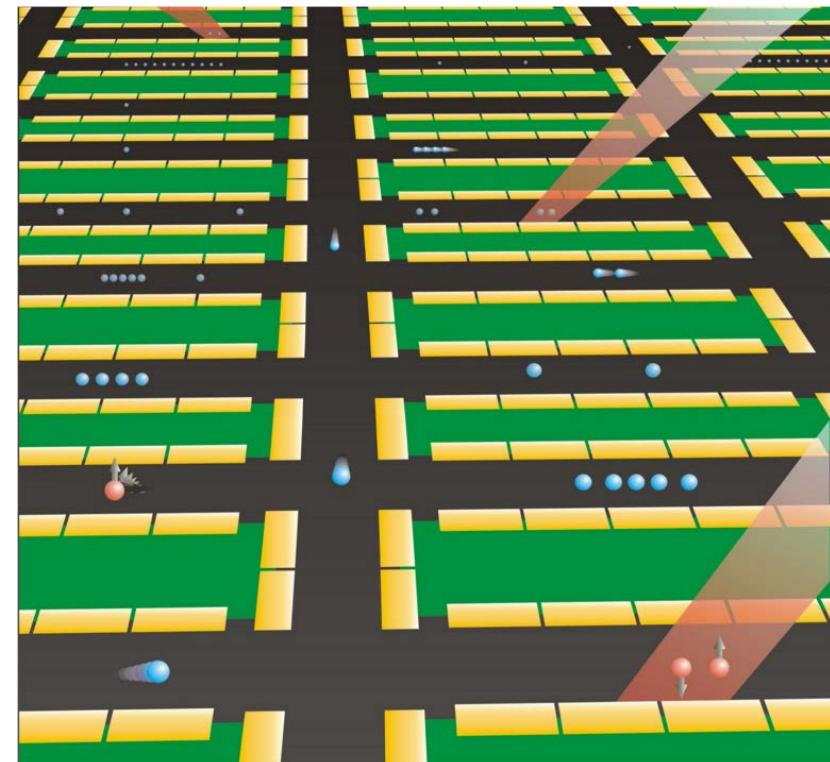
Con:

- small well depth motivates cryogenic operation

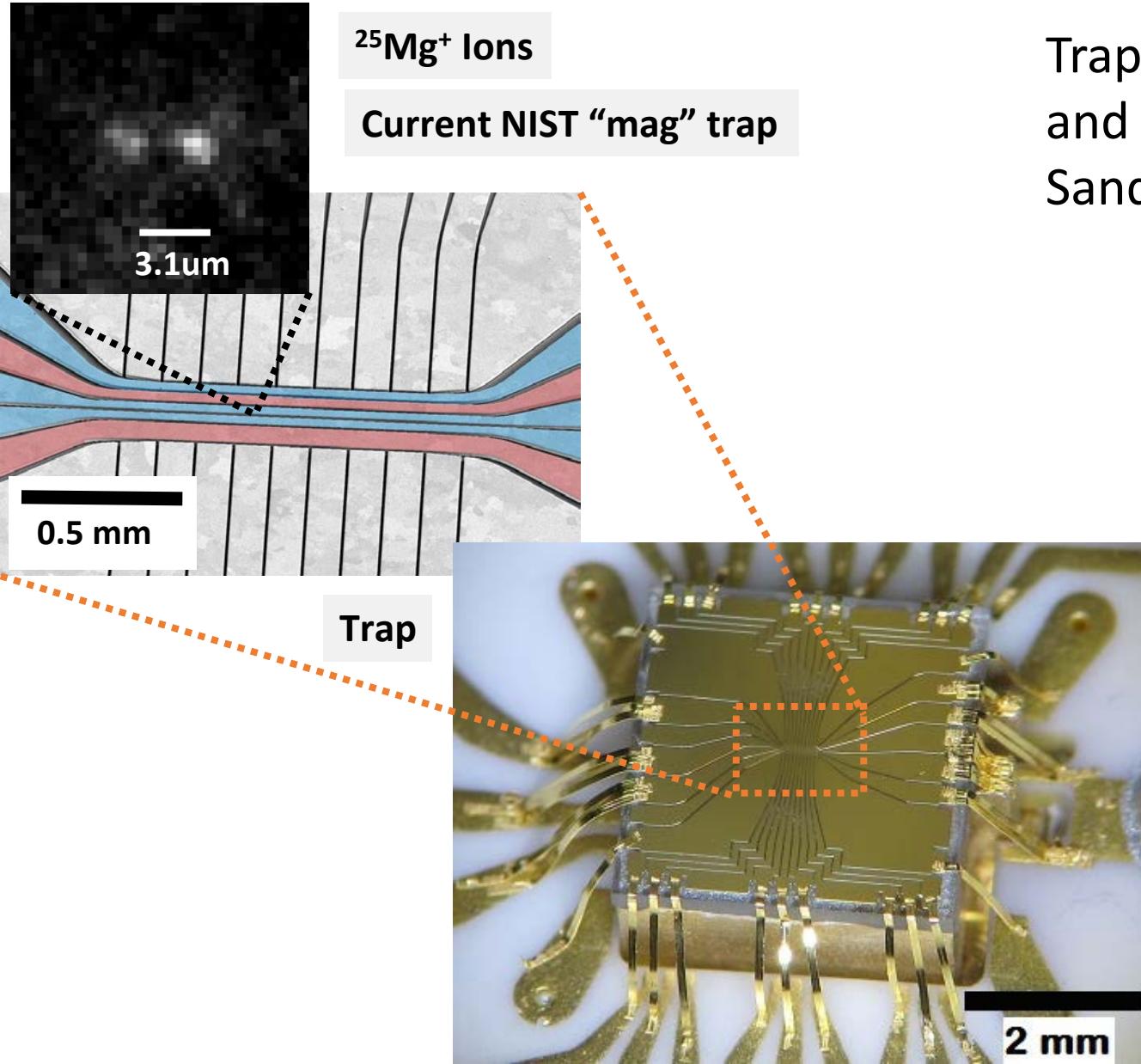
Quantum CCD architecture

Kielpinski, et al., Nature 417 (2002)

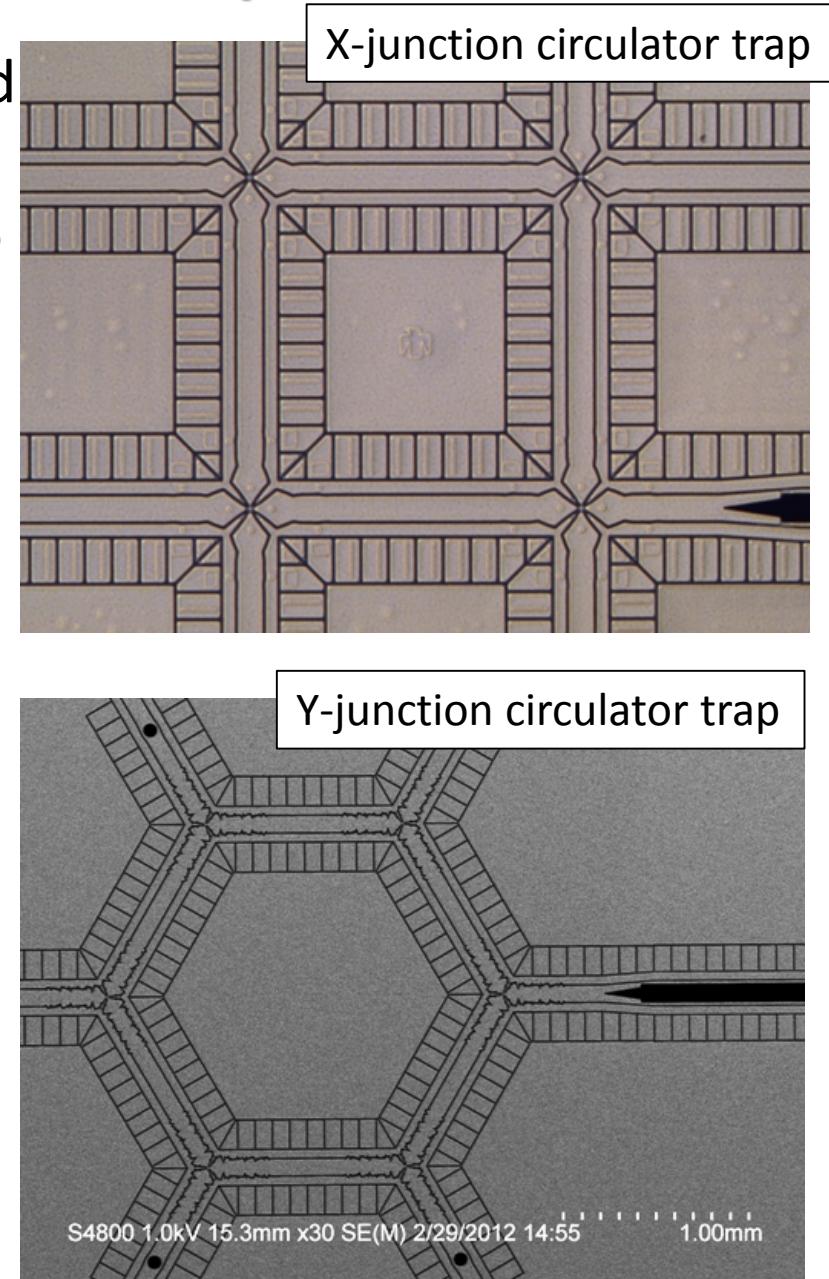
- Ions move between different trap zones (e.g. memory, gate, recooling)
- Laser/microwave access to subset of trap



example surface-electrode rf ion traps



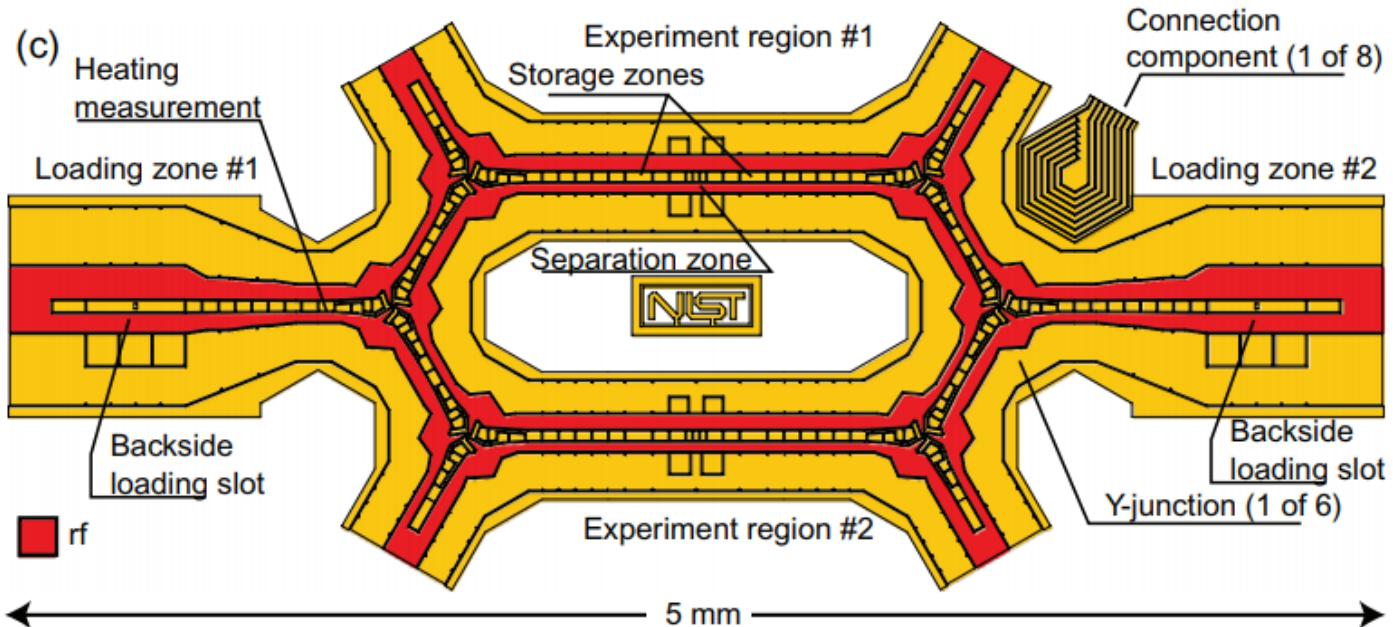
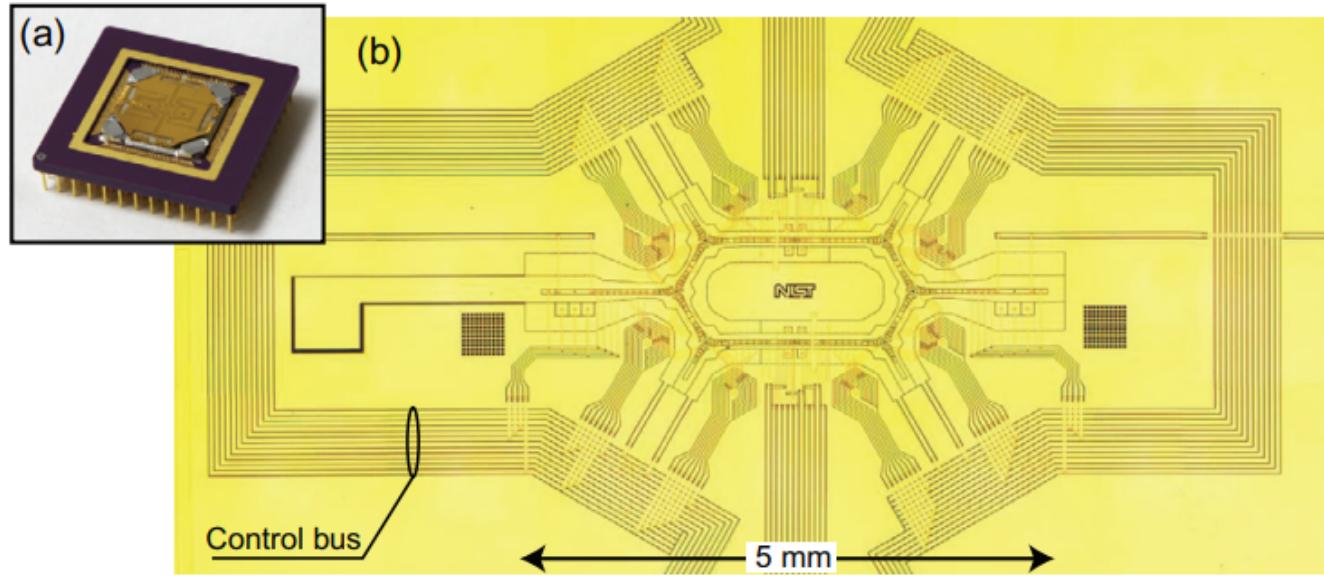
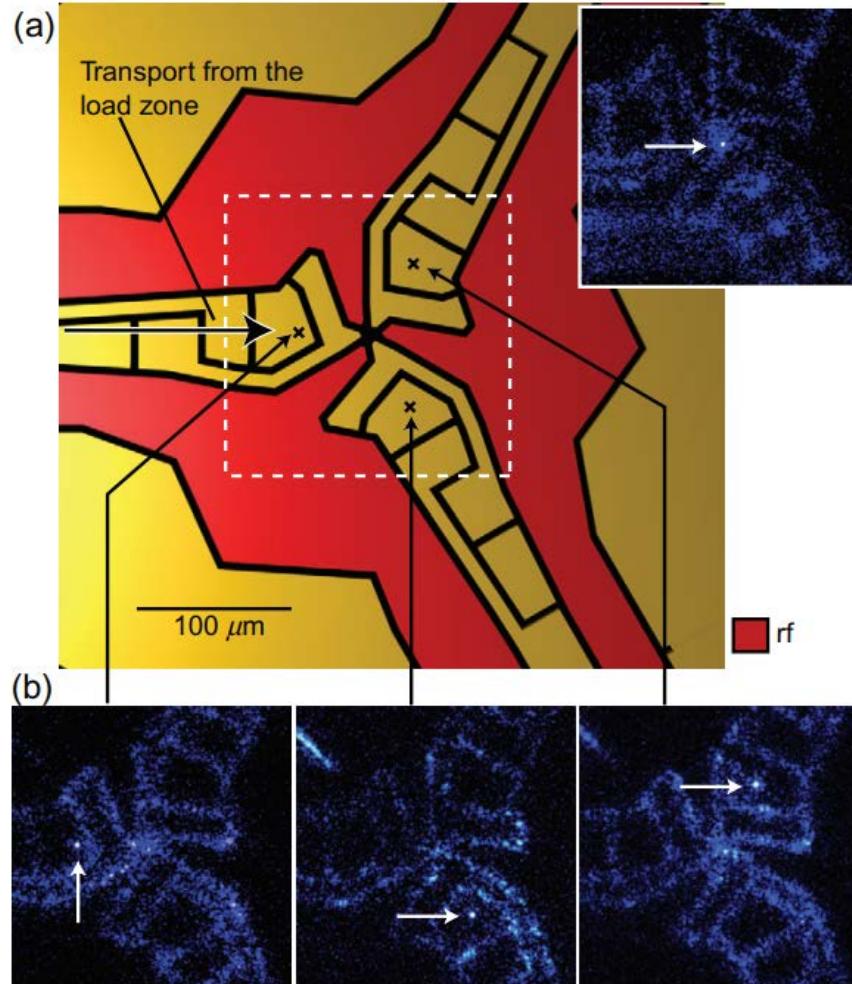
Traps fabricated
and tested at
Sandia Nat. Lab



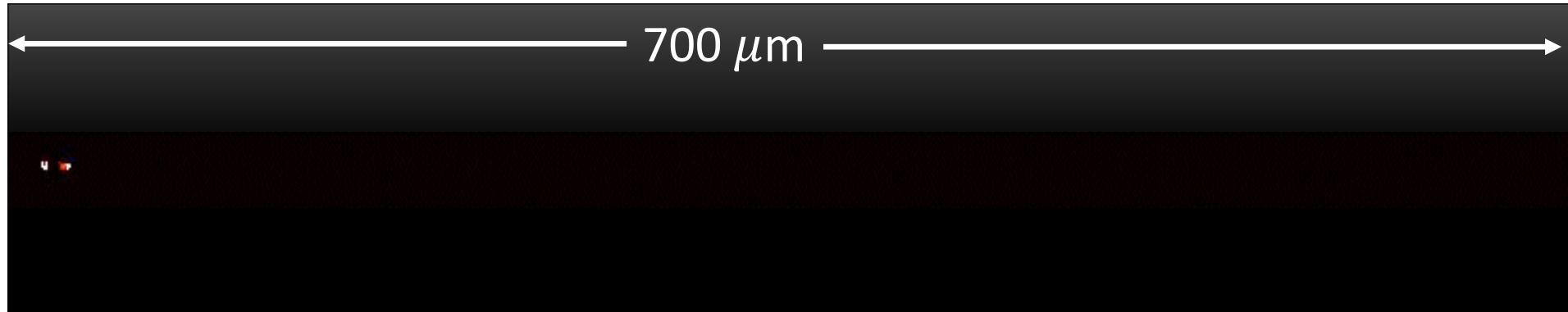
example surface-electrode rf ion traps

NIST Y-junction trap

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



Acrobatic shuttling – Sandia National Lab

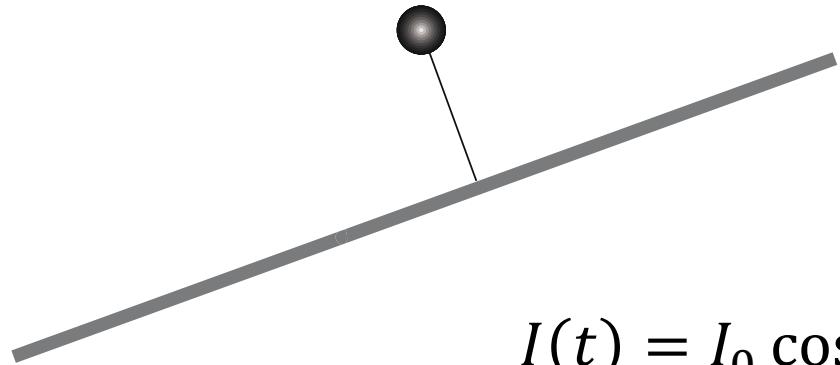


Surface-electrode ion trap demonstrations:

- 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



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

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

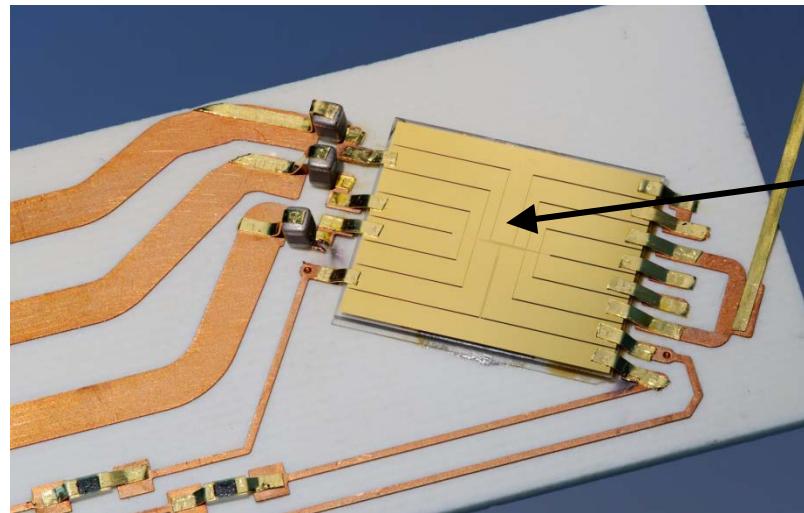
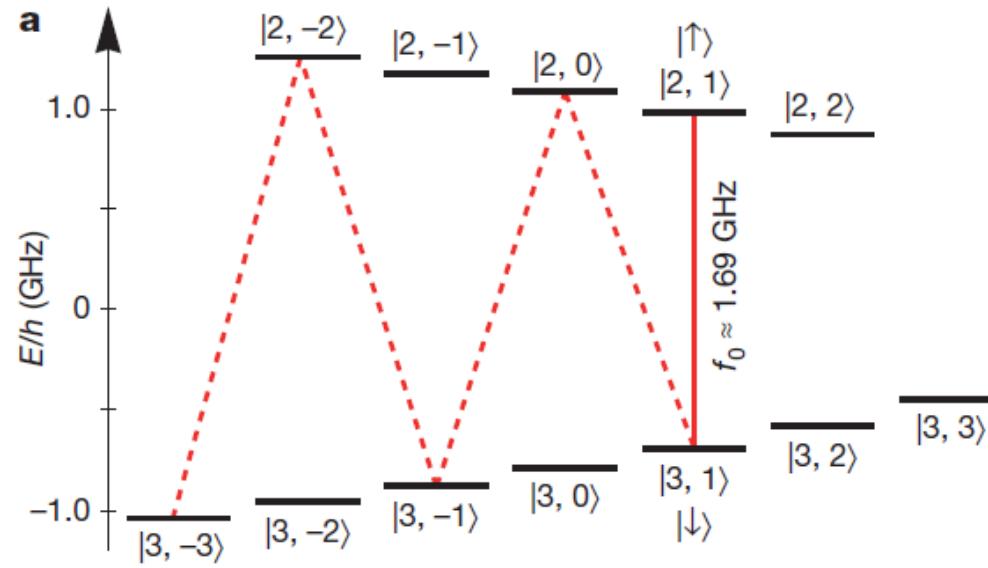
$$\nabla B \propto \frac{I_0}{d^2}$$

Advantages over laser-driven gates:

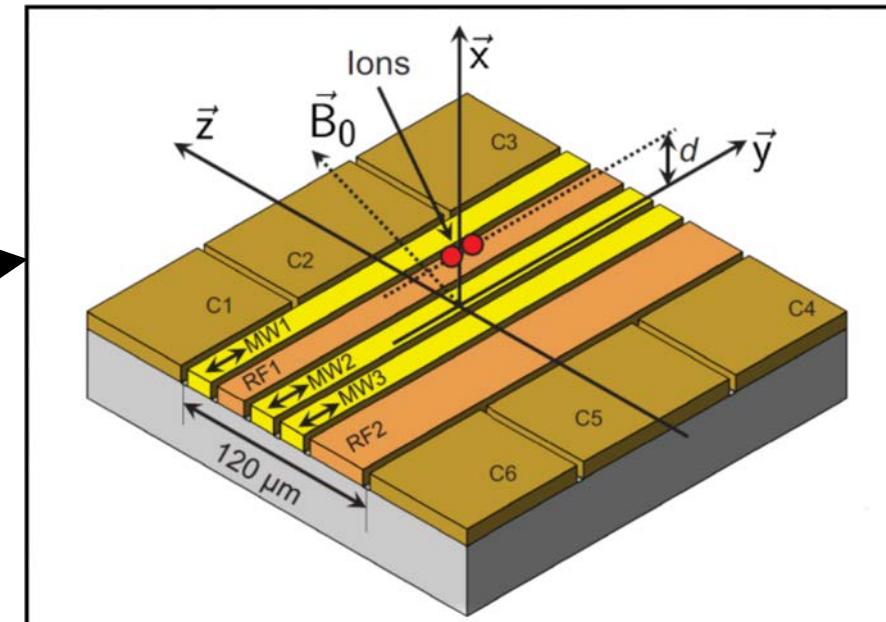
- Electronic sources are more stable, easily controlled, cheaper, and smaller
- Wires are much easier to integrate into ion traps than optics
- Eliminates fundamental photon scattering errors

Entangled states with magnetic field gradients

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



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



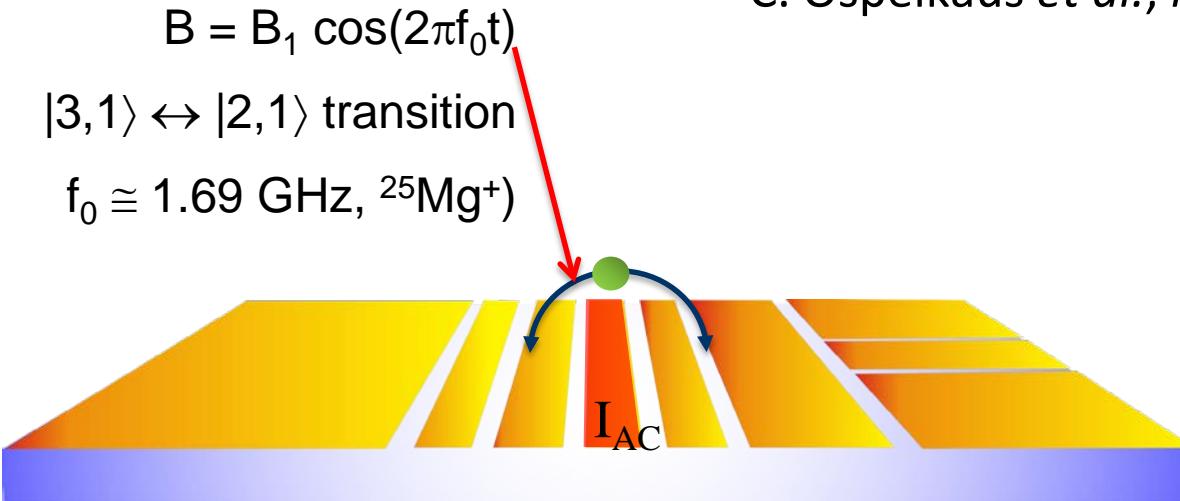
Entangled states with magnetic field gradients

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

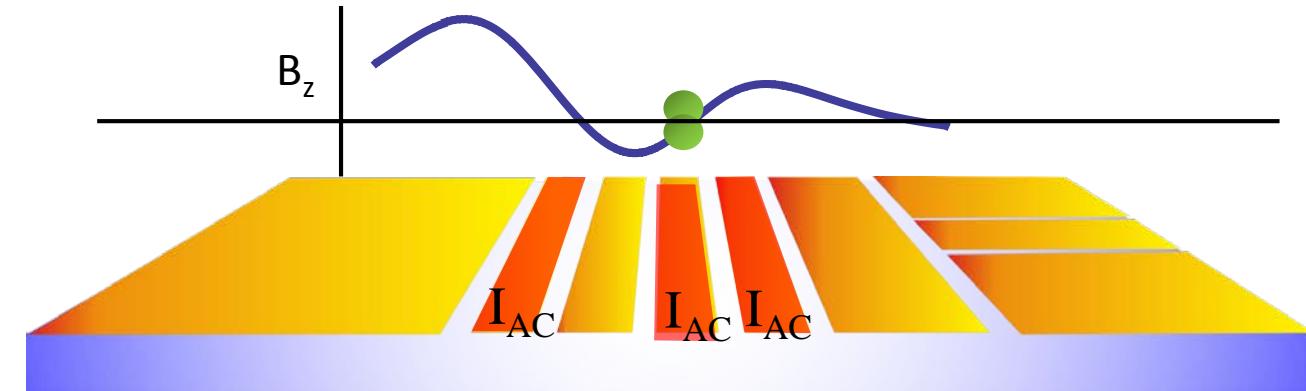
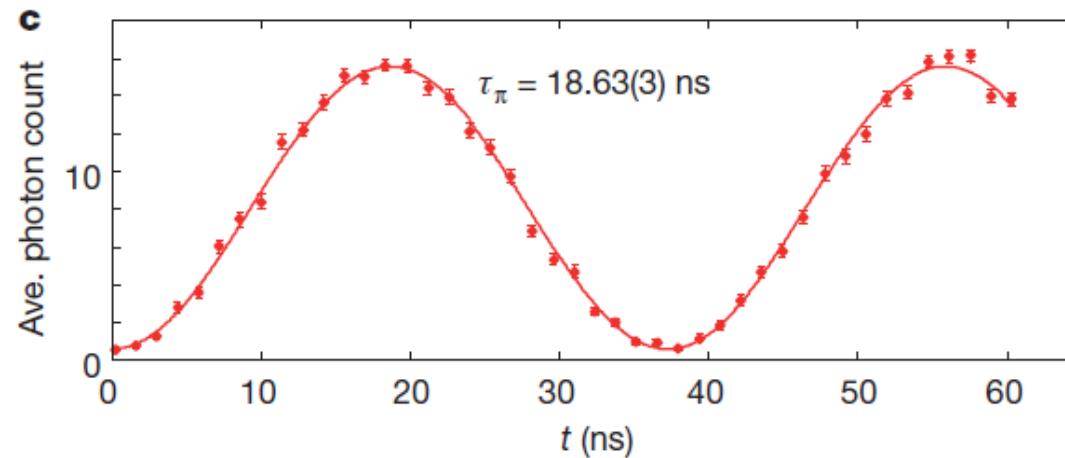
$$B = B_1 \cos(2\pi f_0 t)$$

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

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



Rabi
flopping 18 ns π –time



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

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

Fidelity = 0.76(3), $T_{gate} = 200$ μ 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	Pingping 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	Palacky University & IISI	Quantum Optics Lab	Radim Illy, Lukáš Slodička	Ca+	Olomouc & Brno
18 Denmark	Aarhus University	Ion Trap Group	Michael Dresen	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 Kropp, Caroline Champenois	Ca+	Marseille
21 France	FEMTO-ST	Compact Optical Atomic Clock	Clément Lacoste	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	MPG für the Science of Light	Leuchs Division	Gerd Leuchs	Yb+	Erlangen
26 Germany	MPG für Kernphysik	Structure and dynamics of few electron ions in an EBIT	José Ramón 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 Mehlstäbler	In+, Yb+	Braunschweig
29 Germany	PTB	Optical Clocks with Trapped Ions	Elkehard 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 & Hannover
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	Roei 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 Koelman	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	Dmitry 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	Tae hyun 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 Henrich	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	Be+, 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	JOI (JMD / 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+, molecular ions	Boulder
79 USA	Northwestern University	Molecular Ion and Atom Trapping Group	Brian Odum	Ba+, molecular ions	Evanson
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