Quantum logic gates between trapped ions

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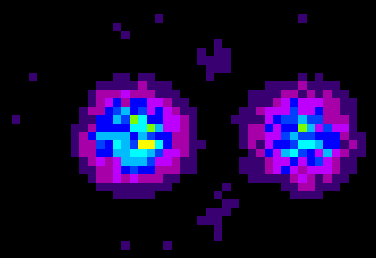
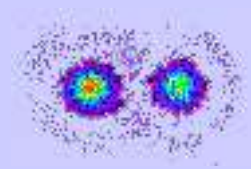


Quantum Information and Trapped Ions

$$H = \sum_{i=1}^{N} \frac{1}{2} \omega_i(t) \hat{\vec{\sigma}}^{(i)} + \sum_{i,j=1}^{N} g_{ij}(t) \hat{\vec{\sigma}}^{(i)} \cdot \hat{\vec{\sigma}}^{(j)}$$

N qubits

controlled coupling



2-10 μm

<u>phonons</u>: Coulomb interaction
photons: Linear optics, cavity-QED

PERIODIC TABLE

Atomic Properties of the Elements

Physics Laboratory physics.nist.gov — NIST www.nist.gov — Standard Reference Data Program www.nist.gov/srd

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

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 m s^{-1}	(exact)
Planck constant	h	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	$m_e c^2$	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,84 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

Group: IA, IIA, IIIA, IVA, VA, VIA, VIIA, VIIIA, IB, IIB, IIIB, IVB, VB, VIB, VIIB, VIII

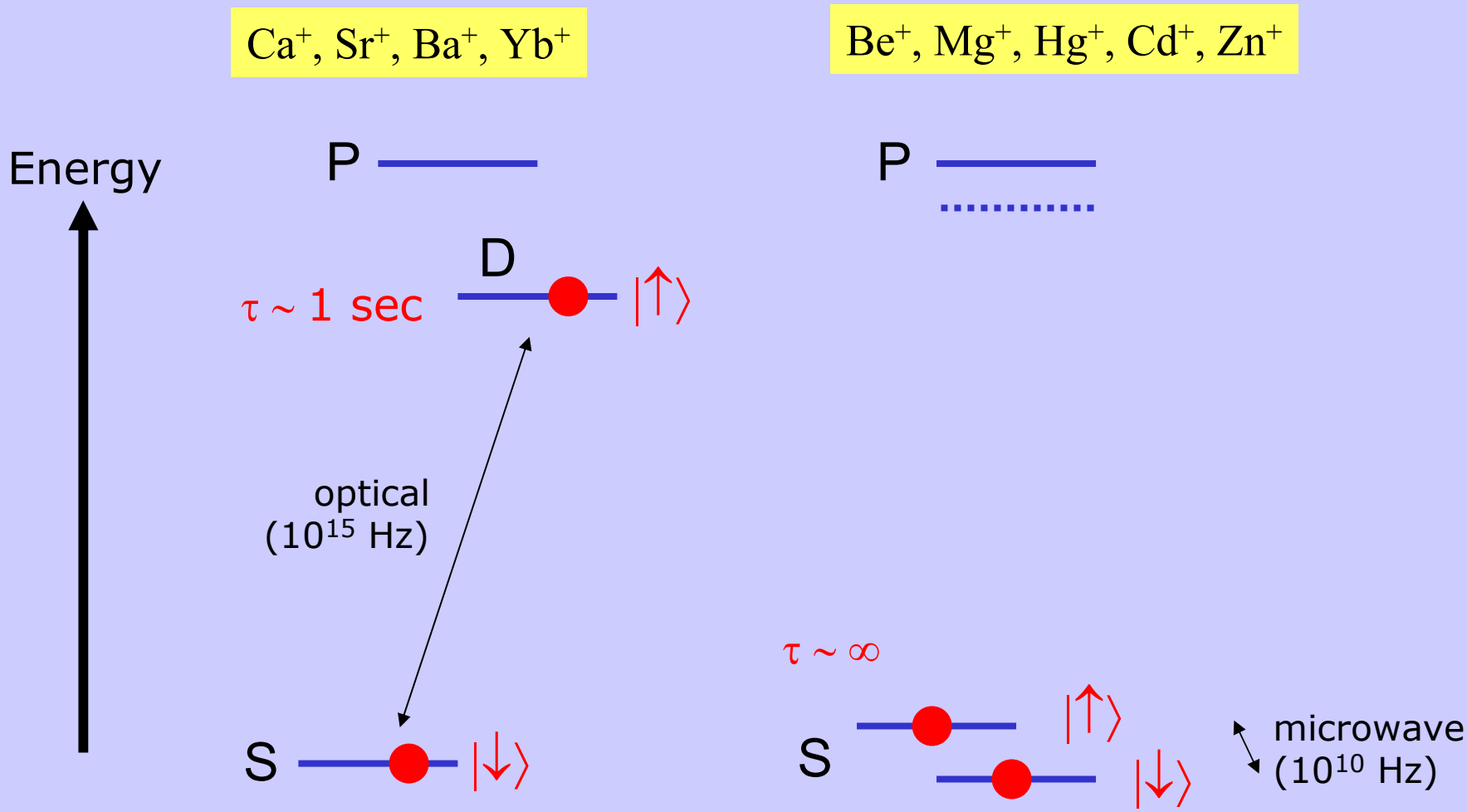
Period: 1, 2, 3, 4, 5, 6, 7

Atomic Number	Symbol	Name	Ground-state Level	Atomic Weight[1]	Ground-state Configuration	Ionization Energy (eV)
1	H	Hydrogen	$^2S_{1/2}$	1.00794	$1s$	13.5984
2	He	Helium	$^1S_0$	4.00260	$1s^2$	24.5874
3	Li	Lithium	$^2S_{1/2}$	6.941	$1s^2 2s$	5.3917
4	Be	Beryllium	$^1S_0$	9.01218	$1s^2 2s^2$	9.3227
5	B	Boron	$^2P^o_{1/2}$	10.811	$1s^2 2s^2 2p$	8.2980
6	C	Carbon	$^3P_0$	12.0107	$1s^2 2s^2 2p^2$	11.2603
7	N	Nitrogen	$^4S^o_{3/2}$	14.00674	$1s^2 2s^2 2p^3$	14.5341
8	O	Oxygen	$^3P_2$	15.9994	$1s^2 2s^2 2p^4$	13.6181
9	F	Fluorine	$^2P^o_{3/2}$	18.99840	$1s^2 2s^2 2p^5$	17.4228
10	Ne	Neon	$^1S_0$	20.1797	$1s^2 2s^2 2p^6$	21.5646
11	Na	Sodium	$^2S_{1/2}$	22.98977	[Ne]$3s$	5.1391
12	Mg	Magnesium	$^1S_0$	24.3050	[Ne]$3s^2$	7.6462
13	Al	Aluminum	$^2P^o_{1/2}$	26.98154	[Ne]$3s^2 3p$	5.9858
14	Si	Silicon	$^3P_0$	28.0855	[Ne]$3s^2 3p^2$	8.1517
15	P	Phosphorus	$^4S^o_{3/2}$	30.97376	[Ne]$3s^2 3p^3$	10.4867
16	S	Sulfur	$^3P_2$	32.066	[Ne]$3s^2 3p^4$	10.3600
17	Cl	Chlorine	$^2P^o_{3/2}$	35.4527	[Ne]$3s^2 3p^5$	12.9676
18	Ar	Argon	$^1S_0$	39.948	[Ne]$3s^2 3p^6$	15.7596
19	K	Potassium	$^2S_{1/2}$	39.0983	[Ar]$4s$	4.3407
20	Ca	Calcium	$^1S_0$	40.078	[Ar]$4s^2$	6.1132
21	Sc	Scandium	$^2D_{3/2}$	44.95591	[Ar]$3d4s^2$	6.5615
22	Ti	Titanium	$^3F_2$	47.867	[Ar]$3d^2 4s^2$	6.8281
23	V	Vanadium	$^4F_{3/2}$	50.9415	[Ar]$3d^3 4s^2$	6.7462
24	Cr	Chromium	$^7S_3$	51.9961	[Ar]$3d^5 4s$	6.7665
25	Mn	Manganese	$^6S_{5/2}$	54.93805	[Ar]$3d^5 4s^2$	7.4340
26	Fe	Iron	$^5D_4$	55.845	[Ar]$3d^6 4s^2$	7.9024
27	Co	Cobalt	$^4F_{9/2}$	58.93320	[Ar]$3d^7 4s^2$	7.8810
28	Ni	Nickel	$^3F_4$	58.6934	[Ar]$3d^8 4s^2$	7.6398
29	Cu	Copper	$^2S_{1/2}$	63.546	[Ar]$3d^{10} 4s$	7.7264
30	Zn	Zinc	$^1S_0$	65.39	[Ar]$3d^{10} 4s^2$	9.3942
31	Ga	Gallium	$^2P^o_{1/2}$	69.723	[Ar]$3d^{10} 4s^2 4p$	5.9993
32	Ge	Germanium	$^3P_0$	72.61	[Ar]$3d^{10} 4s^2 4p^2$	7.8994
33	As	Arsenic	$^4S^o_{3/2}$	74.92160	[Ar]$3d^{10} 4s^2 4p^3$	9.7886
34	Se	Selenium	$^3P_2$	78.96	[Ar]$3d^{10} 4s^2 4p^4$	9.7524
35	Br	Bromine	$^2P^o_{3/2}$	79.904	[Ar]$3d^{10} 4s^2 4p^5$	11.8138
36	Kr	Krypton	$^1S_0$	83.80	[Ar]$3d^{10} 4s^2 4p^6$	13.9996
37	Rb	Rubidium	$^2S_{1/2}$	85.4678	[Kr]$5s$	4.1771
38	Sr	Strontium	$^1S_0$	87.62	[Kr]$5s^2$	5.6949
39	Y	Yttrium	$^2D_{3/2}$	88.90585	[Kr]$4d5s^2$	6.2171
40	Zr	Zirconium	$^3F_2$	91.224	[Kr]$4d^2 5s^2$	6.6339
41	Nb	Niobium	$^6D_{1/2}$	92.90638	[Kr]$4d^4 5s$	6.7589
42	Mo	Molybdenum	$^7S_3$	95.94	[Kr]$4d^5 5s$	7.0924
43	Tc	Technetium	$^6S_{5/2}$	(98)	[Kr]$4d^5 5s^2$	7.28
44	Ru	Ruthenium	$^5F_5$	101.07	[Kr]$4d^7 5s$	7.3605
45	Rh	Rhodium	$^4F_{9/2}$	102.90550	[Kr]$4d^8 5s$	7.4589
46	Pd	Palladium	$^1S_0$	106.42	[Kr]$4d^{10}$	8.3369
47	Ag	Silver	$^2S_{1/2}$	107.8682	[Kr]$4d^{10} 5s$	7.5762
48	Cd	Cadmium	$^1S_0$	112.411	[Kr]$4d^{10} 5s^2$	8.9938
49	In	Indium	$^2P^o_{1/2}$	114.818	[Kr]$4d^{10} 5s^2 5p$	5.7864
50	Sn	Tin	$^3P_0$	118.710	[Kr]$4d^{10} 5s^2 5p^2$	7.3439
51	Sb	Antimony	$^4S^o_{3/2}$	121.760	[Kr]$4d^{10} 5s^2 5p^3$	8.6084
52	Te	Tellurium	$^3P_2$	127.60	[Kr]$4d^{10} 5s^2 5p^4$	9.0096
53	I	Iodine	$^2P^o_{3/2}$	126.90447	[Kr]$4d^{10} 5s^2 5p^5$	10.4513
54	Xe	Xenon	$^1S_0$	131.29	[Kr]$4d^{10} 5s^2 5p^6$	12.1298
55	Cs	Cesium	$^2S_{1/2}$	132.90545	[Xe]$6s$	3.8939
56	Ba	Barium	$^1S_0$	137.327	[Xe]$6s^2$	5.2117
57	La	Lanthanum	$^2D_{3/2}$	138.9055	[Xe]$5d6s^2$	5.5769
58	Ce	Cerium	$^1G^o_4$	140.116	[Xe]$4f5d6s^2$	5.5387
59	Pr	Praseodymium	$^4I^o_{9/2}$	140.90765	[Xe]$4f^3 6s^2$	5.473
60	Nd	Neodymium	$^5I_4$	144.24	[Xe]$4f^4 6s^2$	5.5250
61	Pm	Promethium	$^6H^o_{5/2}$	(145)	[Xe]$4f^5 6s^2$	5.582
62	Sm	Samarium	$^7F_0$	150.36	[Xe]$4f^6 6s^2$	5.6436
63	Eu	Europium	$^8S^o_{7/2}$	151.964	[Xe]$4f^7 6s^2$	5.6704
64	Gd	Gadolinium	$^9D^o_2$	157.25	[Xe]$4f^7 5d6s^2$	6.1501
65	Tb	Terbium	$^6H^o_{15/2}$	158.92534	[Xe]$4f^9 6s^2$	5.8638
66	Dy	Dysprosium	$^5I_8$	162.50	[Xe]$4f^{10} 6s^2$	5.9389
67	Ho	Holmium	$^4I^o_{15/2}$	164.93032	[Xe]$4f^{11} 6s^2$	6.0215
68	Er	Erbium	$^3H_6$	167.26	[Xe]$4f^{12} 6s^2$	6.1077
69	Tm	Thulium	$^2F^o_{7/2}$	168.93421	[Xe]$4f^{13} 6s^2$	6.1843
70	Yb	Ytterbium	$^1S_0$	173.04	[Xe]$4f^{14} 6s^2$	6.2542
71	Lu	Lutetium	$^2D_{3/2}$	174.967	[Xe]$4f^{14} 5d6s^2$	5.4259
89	Ac	Actinium	$^2D_{3/2}$	(227)	[Rn]$6d7s^2$	5.17
90	Th	Thorium	$^3F_2$	232.0381	[Rn]$6d^2 7s^2$	6.3067
91	Pa	Protactinium	$^4K_{11/2}$	231.03588	[Rn]$5f^2 6d7s^2$	5.89
92	U	Uranium	$^5L^o_6$	238.0289	[Rn]$5f^3 6d7s^2$	6.1941
93	Np	Neptunium	$^6L_{11/2}$	(237)	[Rn]$5f^4 6d7s^2$	6.2657
94	Pu	Plutonium	$^7F_0$	(244)	[Rn]$5f^6 7s^2$	6.0262
95	Am	Americium	$^8S^o_{7/2}$	(243)	[Rn]$5f^7 7s^2$	5.9738
96	Cm	Curium	$^9D^o_2$	(247)	[Rn]$5f^7 6d7s^2$	5.9915
97	Bk	Berkelium	$^6H^o_{15/2}$	(247)	[Rn]$5f^9 7s^2$	6.1979
98	Cf	Californium	$^5I_8$	(251)	[Rn]$5f^{10} 7s^2$	6.2817
99	Es	Einsteinium	$^4I^o_{15/2}$	(252)	[Rn]$5f^{11} 7s^2$	6.42
100	Fm	Fermium	$^3H_6$	(257)	[Rn]$5f^{12} 7s^2$	6.50
101	Md	Mendelevium	$^2F^o_{7/2}$	(258)	[Rn]$5f^{13} 7s^2$	6.58
102	No	Nobelium	$^1S_0$	(259)	[Rn]$5f^{14} 7s^2$	6.65
103	Lr	Lawrencium	$^2P^o_{1/2}$	(262)	[Rn]$5f^{14} 7s^2 7p$	4.9?
104	Rf	Rutherfordium	$^2F_{3/2}$?	(261)	[Rn]$5f^{14} 6d^2 7s^2$?	6.0 ?
105	Db	Dubnium		(262)		
106	Sg	Seaborgium		(263)		
107	Bh	Bohrium		(264)		
108	Hs	Hassium		(265)		
109	Mt	Meitnerium		(268)		
110	Uun	Ununnilium		(269)		
111	Uuu	Unununium		(272)		
112	Uub	Ununbium				

Solids
Liquids
Gases
Artificially Prepared

For a description of the atomic data, visit physics.nist.gov/atomic

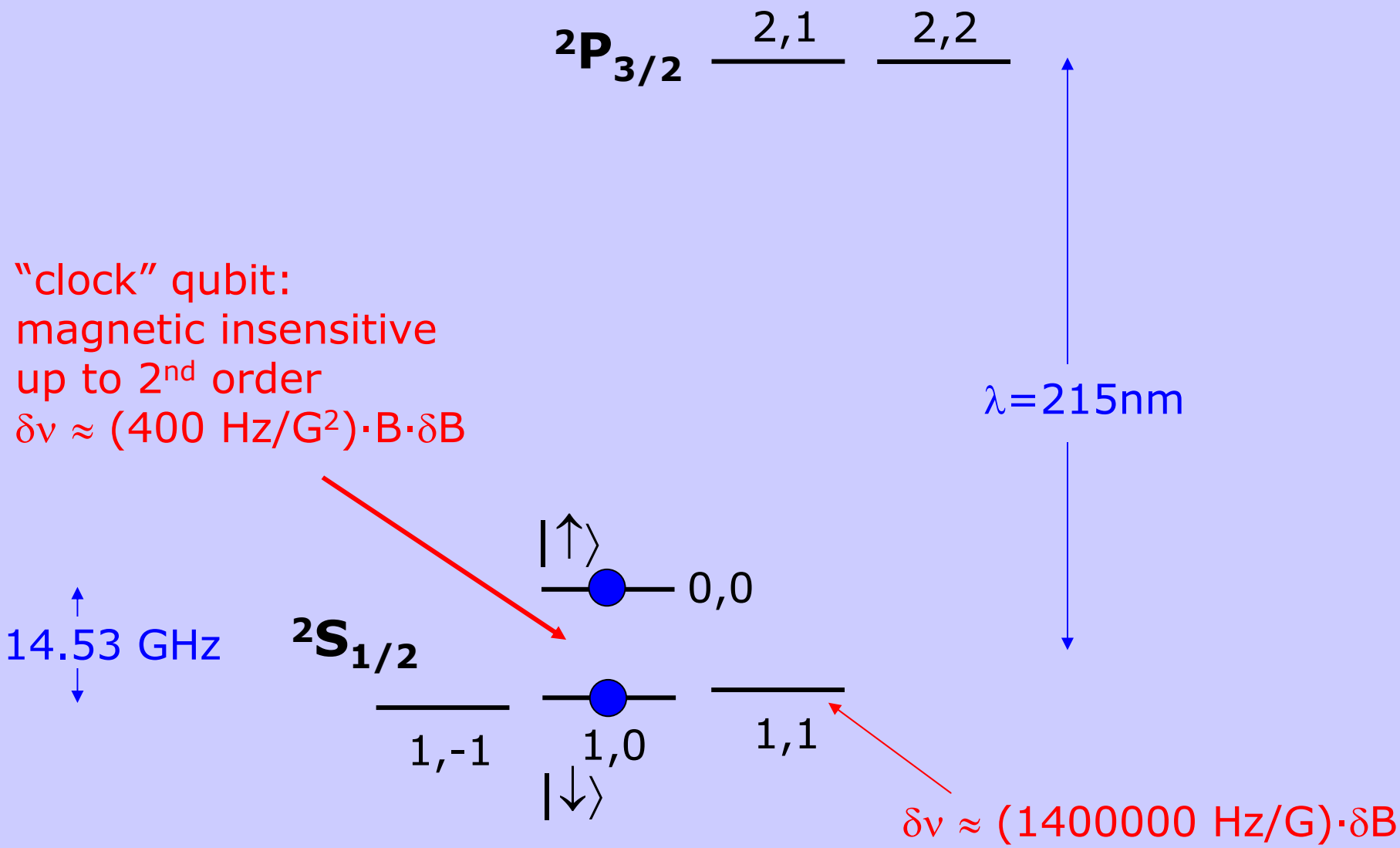
Atomic Ion Internal Energy Levels



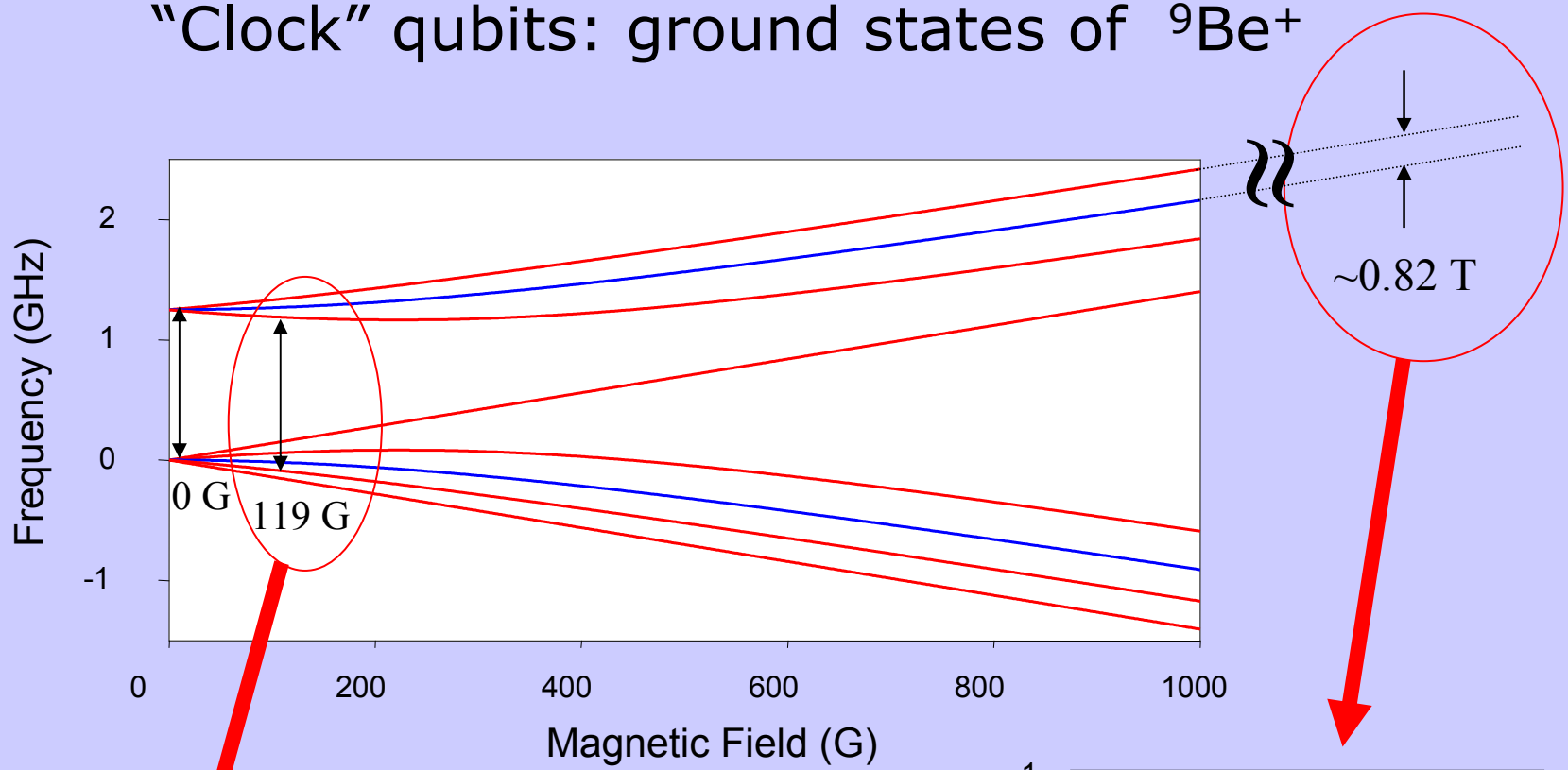
optical qubit levels

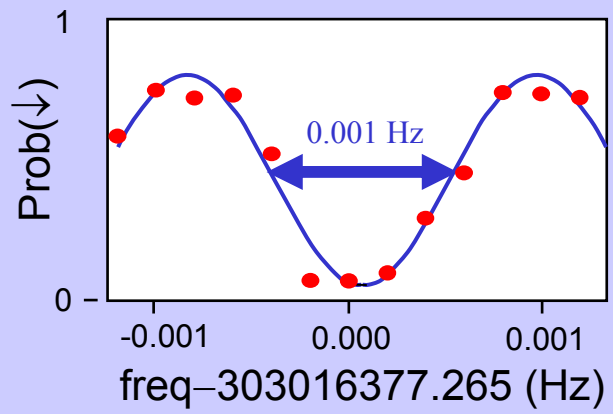
hyperfine qubit levels

$^{111}Cd^{+}$ atomic structure



"Clock" qubits: ground states of $^{9}Be^{+}$



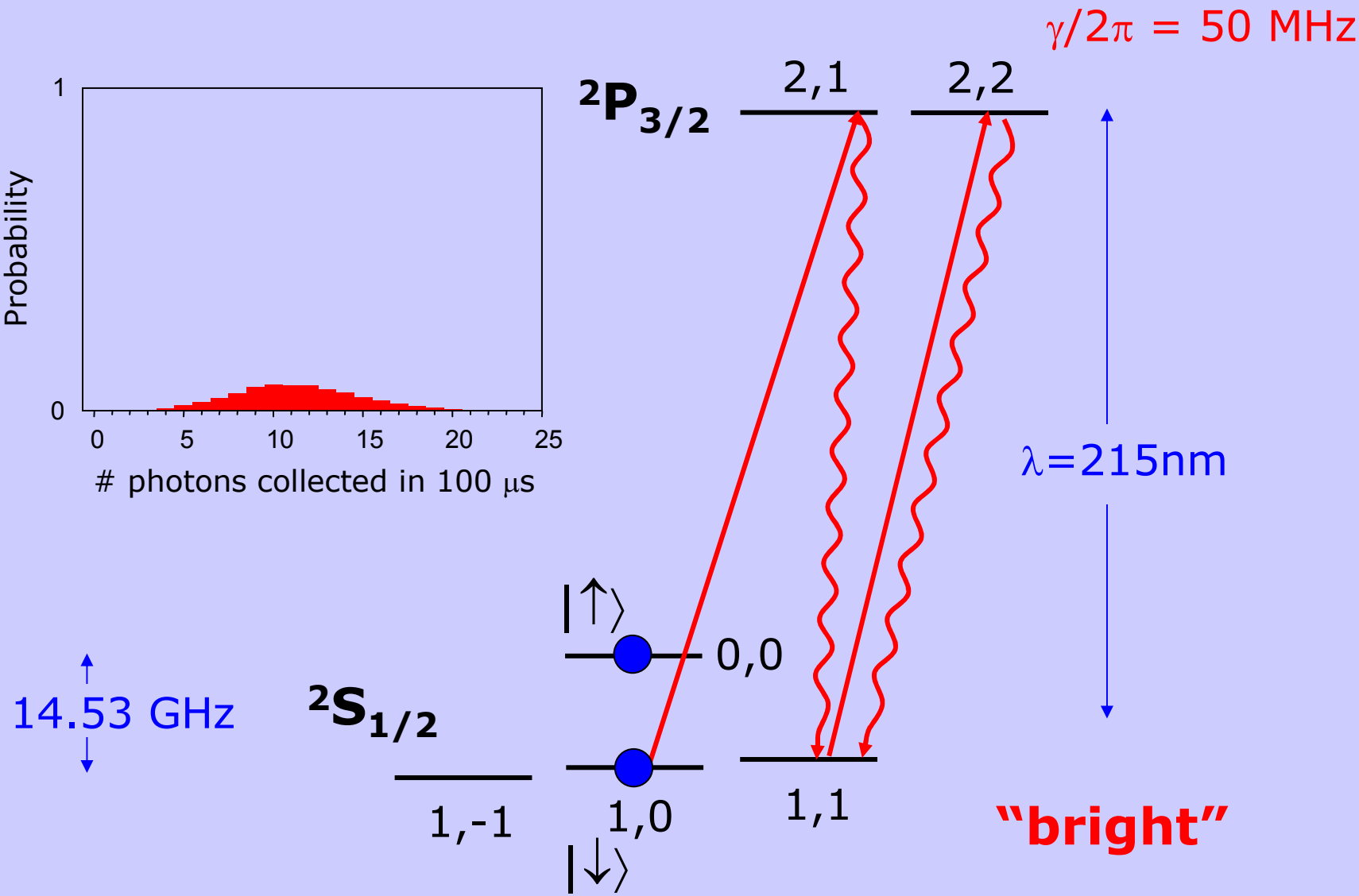


>10 sec coherence time observed

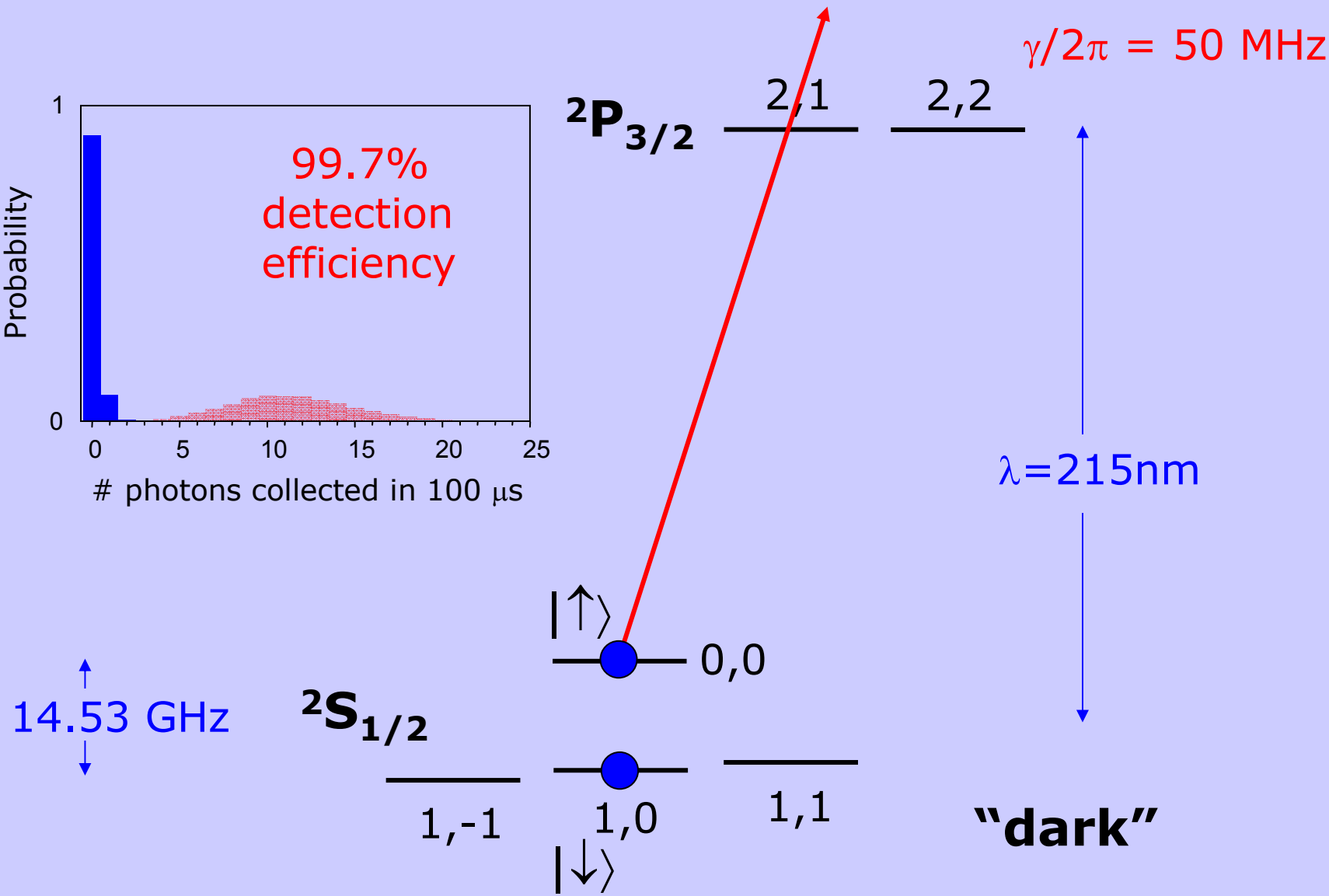
Langer, et al., PRL **95**, 060502 (2005)
POSTERS M01,M08,M14,M21

Bollinger, et al.,
IEEE Trans. Inst. Meas. **40**, 126 (1991)

qubit measurement



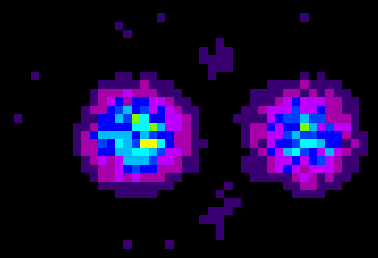
qubit measurement



Entangling Gate Schemes for Trapped Ion

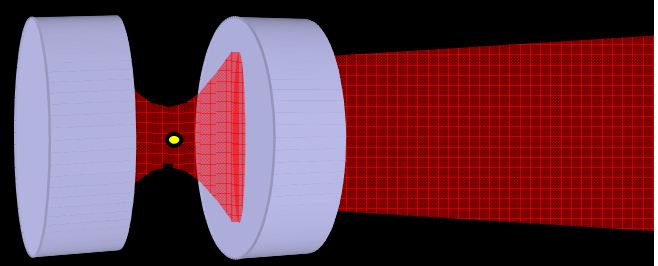
MOTIONAL GATES

- Direct Phonon Coupling
- Spin-dependent Forces



PHOTONIC GATES

- Linear Optics (probabilistic)
- Cavity-QED



Optical Raman transitions

$\Delta < \Delta_{FS}$

$$\Omega = \frac{g_1 g_2}{\Delta}$$

$$N = \frac{\Omega}{\gamma_{sp}} \sim \frac{\Delta}{\gamma}$$

$$\gamma_{sp} = \frac{\gamma(g_1^2 + g_2^2)}{\Delta^2}$$

Heinzen, et al., PRA **42**, 2977 (1990)
C.M., et al., PRL **75**, 4011 (1995)

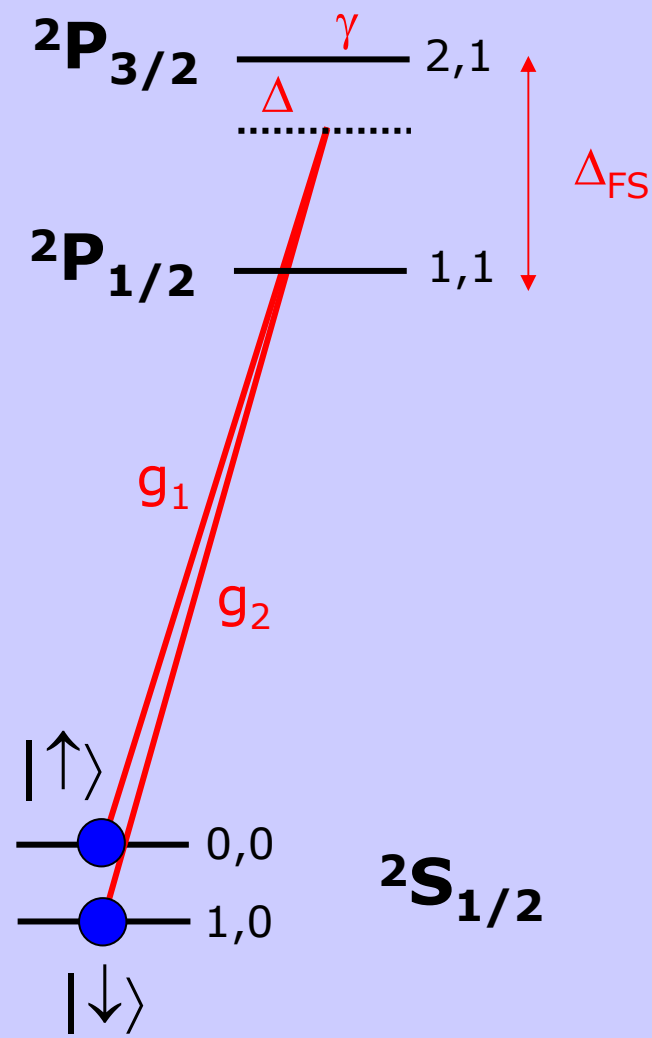
$\Delta >> \Delta_{FS}$

$$\Omega = \frac{g_1 g_2 \Delta_{FS}}{\Delta^2}$$

$$N = \frac{\Omega}{\gamma_{sp}} \sim \frac{\Delta^2}{\gamma \Delta_{FS}}$$

$$\gamma_{sp} = \frac{\gamma(g_1^2 + g_2^2)\Delta_{FS}^2}{\Delta^4}$$

Ozeri, et al., PRL **95**, 030403 (2005)
POSTER M20



Spin-motion coupling: some math

$$H = \hbar\omega_0\hat{\sigma}_z + \underbrace{\frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega^2\hat{x}^2}_{\hbar\omega(a^+a+1/2)} - \hat{\mu}\cdot E(\hat{x})$$

frequency of applied radiation

$$-\mu_0\cdot\frac{E_0}{2}(\hat{\sigma}_+ + \hat{\sigma}_-)(e^{ik\hat{x}-i\omega_L t} + e^{-ik\hat{x}+i\omega_L t})$$

interaction frame; "rotating wave approximation"

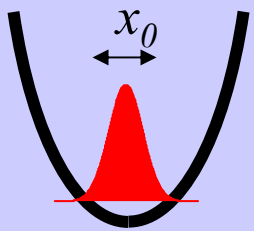
$$H = \hbar g(\hat{\sigma}_+ e^{ik\hat{x}-i\delta t} + \hat{\sigma}_- e^{-ik\hat{x}+i\delta t})$$

$\delta = (\omega_2 - \omega_1) - \omega_{HF}$ = *detuning of beat note*

$k = k_2 - k_1$ = *wavevector difference*

$$\hat{x} = x_0(ae^{-i\omega t} + a^+e^{i\omega t})$$

$$x_0 = \sqrt{\frac{\hbar}{2m\omega}}$$



$$H = \hbar g\left[\hat{\sigma}_+ e^{i\eta(ae^{-i\omega t}+a^+e^{i\omega t})-i\delta t} + \hat{\sigma}_- e^{-i\eta(ae^{-i\omega t}+a^+e^{i\omega t})+i\delta t}\right]$$

$\eta \equiv kx_0$ = "Lamb-Dicke" parameter

$\eta\sqrt{n+1} << 1$: "Lamb-Dicke limit"

stationary terms arise in H at particular values of δ (for g<<ω):

$\delta = 0$ $\quad H_0 = \hbar g(\hat{\sigma}_+ + \hat{\sigma}_-) \longrightarrow \langle\downarrow,n|H_0|\uparrow,n\rangle = \hbar g$

"CARRIER"

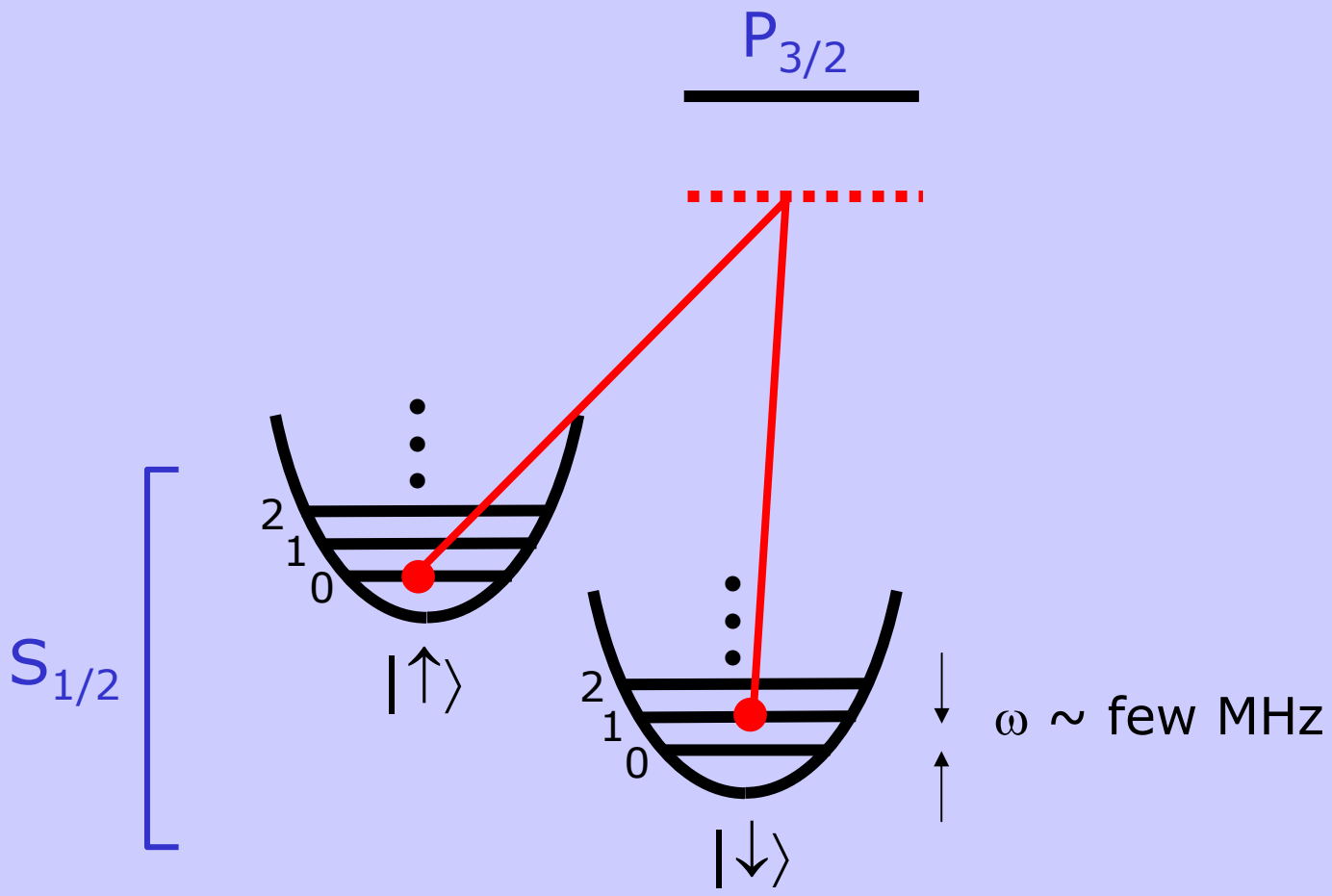
$\delta = -\omega$ $\quad H_{-1} = \hbar g\eta(\hat{\sigma}_+ a^+ + \hat{\sigma}_- a) \longrightarrow \langle\downarrow,n+1|H_{+1}|\uparrow,n\rangle = \hbar g\eta\sqrt{n+1}$

"1ST RED SIDEBAND"

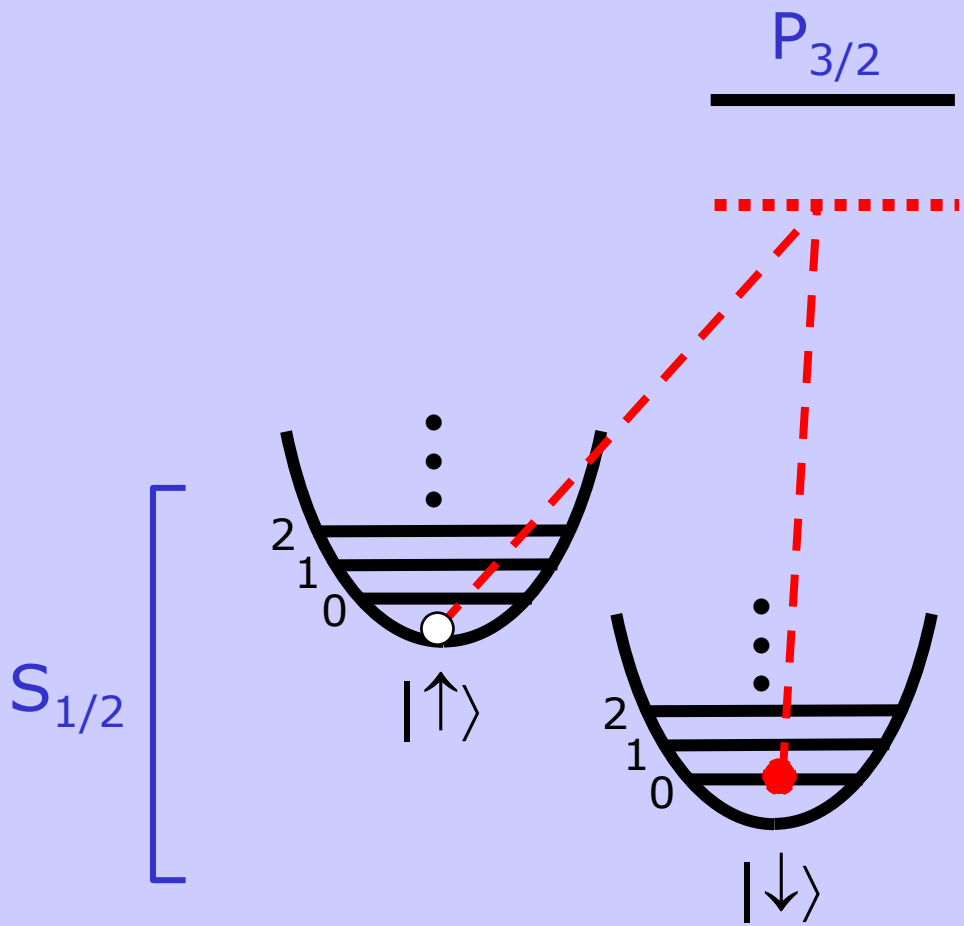
$\delta = +\omega$ $\quad H_{+1} = \hbar g\eta(\hat{\sigma}_+ a + \hat{\sigma}_- a^+) \longrightarrow \langle\downarrow,n-1|H_0|\uparrow,n\rangle = \hbar g\eta\sqrt{n}$

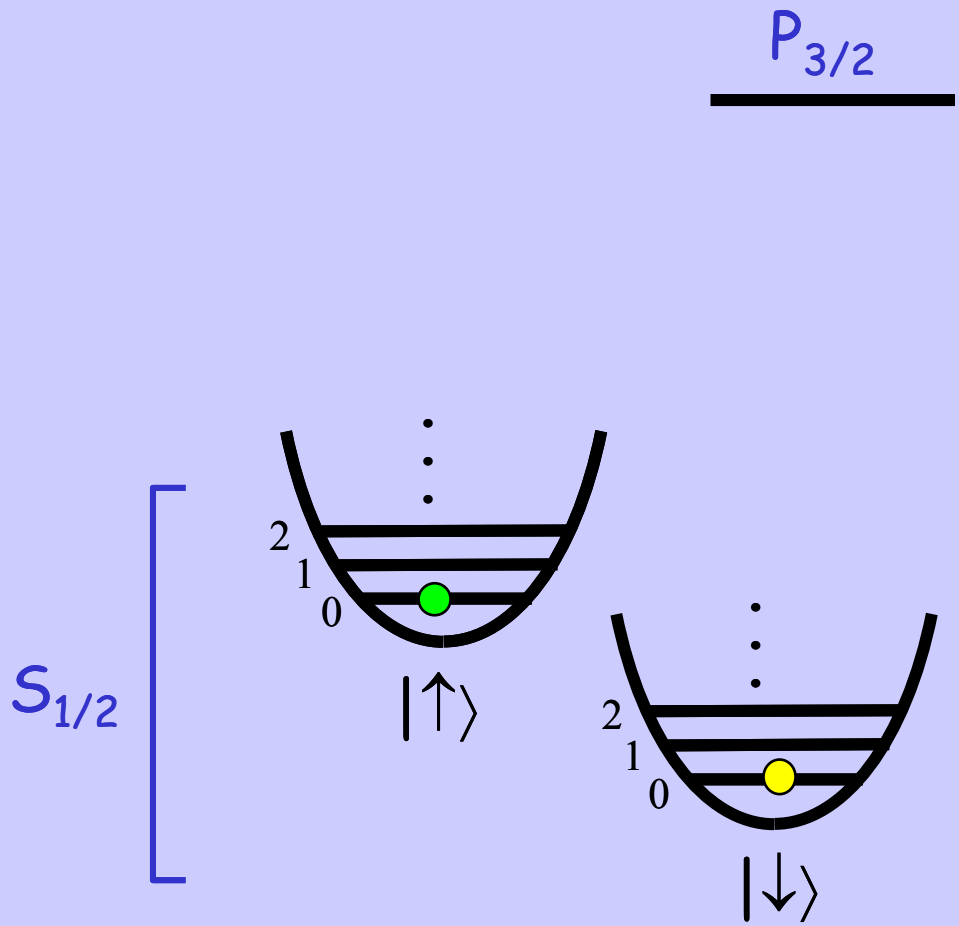
"1ST BLUE SIDEBAND"

excitation on 1st lower ("red") motional sideband (n=0)

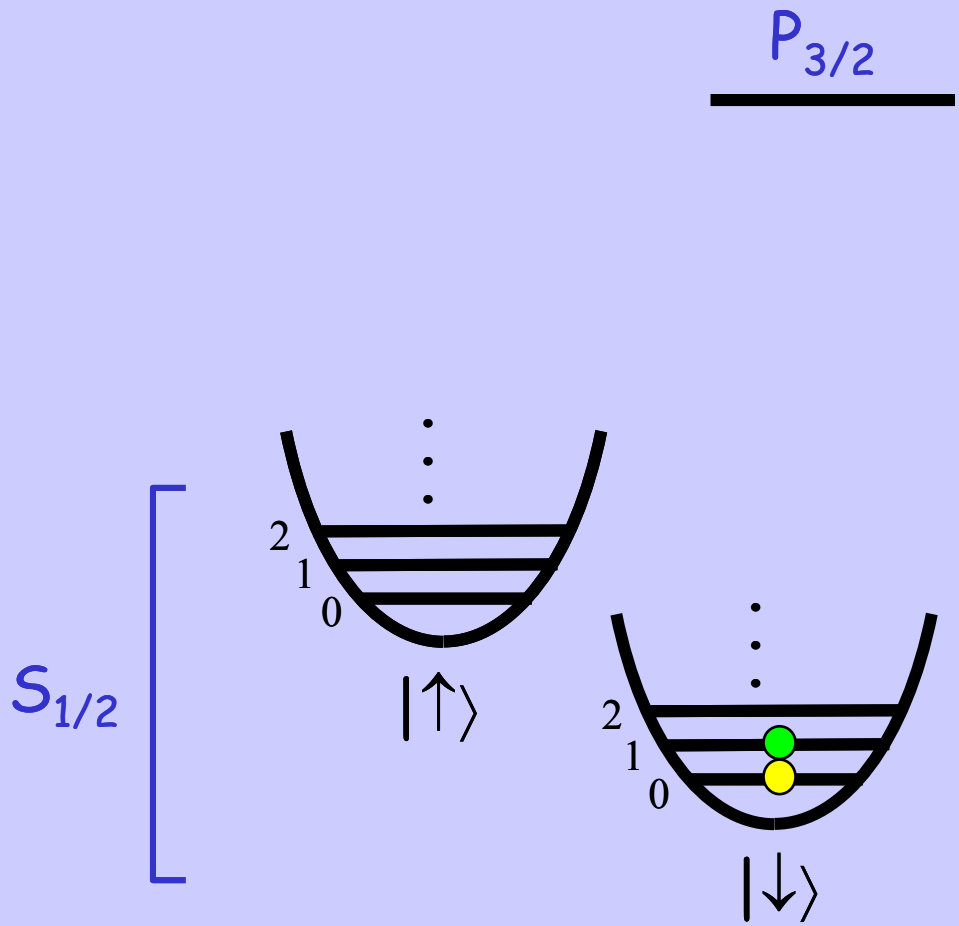


excitation on 1st lower ("red") motional sideband (n=0)





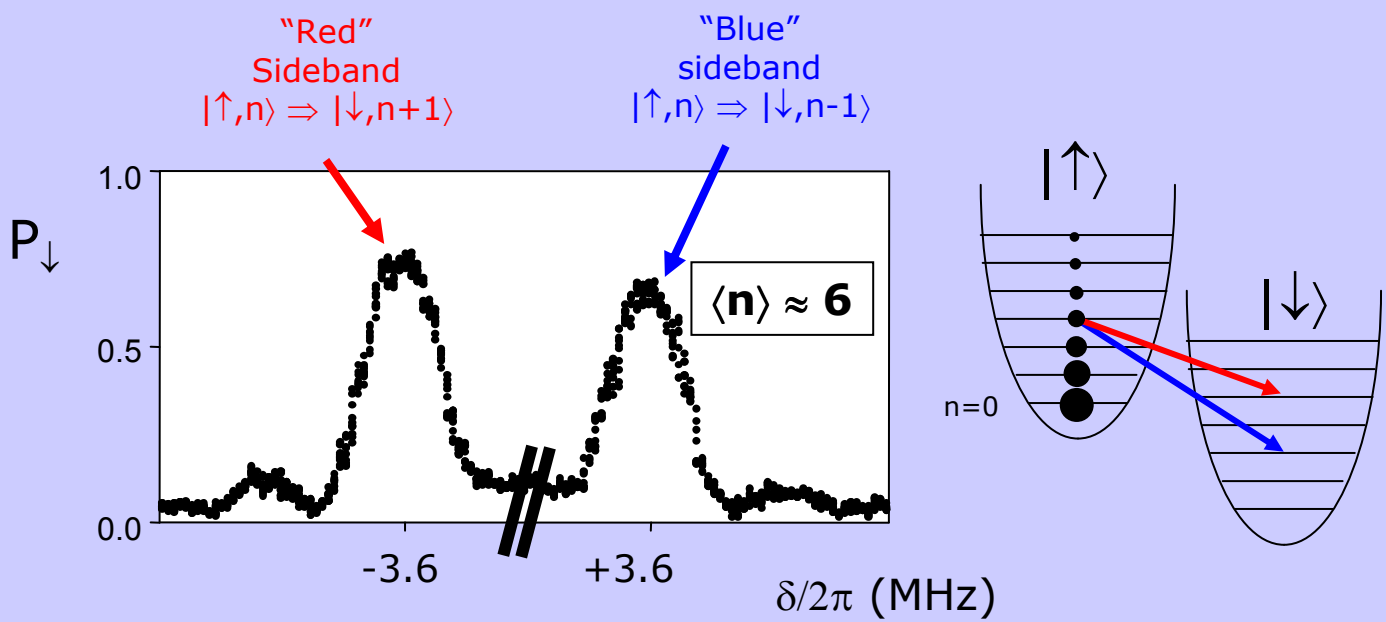
Mapping: $\boxed{(\alpha|\downarrow\rangle + \beta|\uparrow\rangle)}\,|0\rangle_m \;\rightarrow\; |\downarrow\rangle\,(\alpha|0\rangle_m + \beta|1\rangle_m)$



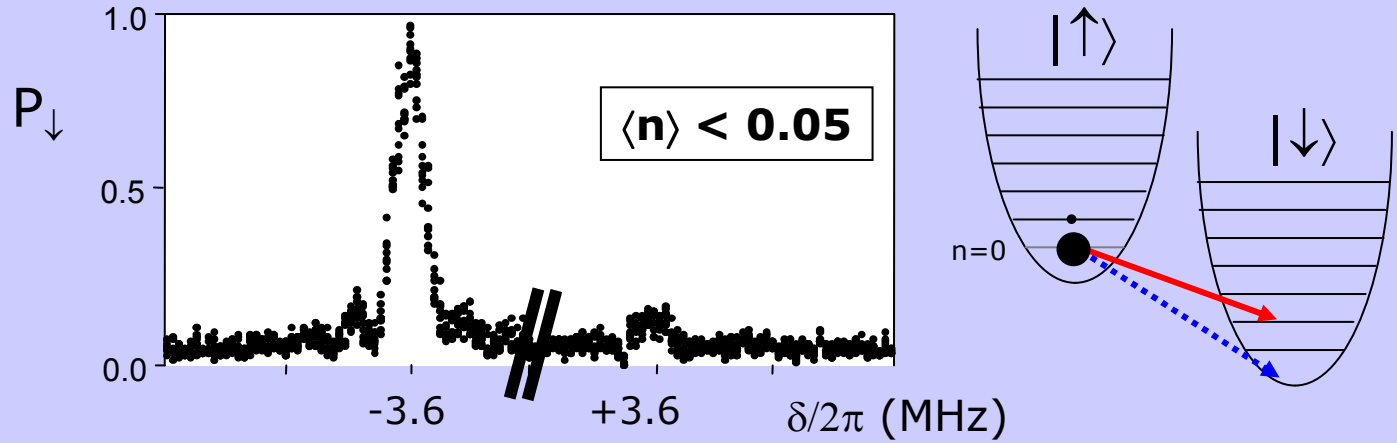
Mapping: $(\alpha|\downarrow\rangle + \beta|\uparrow\rangle)\,|0\rangle_m \;\rightarrow\; |\downarrow\rangle\boxed{(\alpha|0\rangle_m + \beta|1\rangle_m)}$

Raman spectrum of single $^{111}Cd^+$ ion (3.6 MHz trap)

Doppler Cooling



Doppler + Raman Cooling



$x_0 \sim 3$ nm

L. Deslauriers *et al.*, *Phys. Rev. A* **70**, 043408 (2004)

Universal Quantum Logic Gates with Trapped Ions

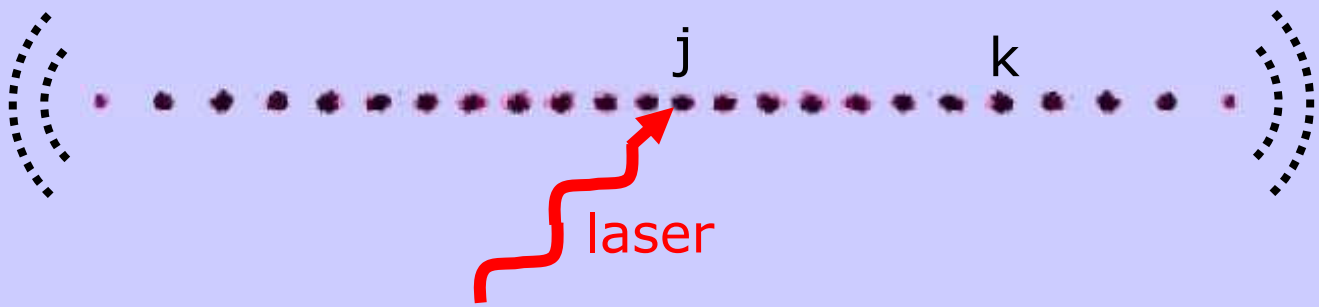
Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)

n=0

Step 1 Laser cool collective motion to rest

Universal Quantum Logic Gates with Trapped Ions

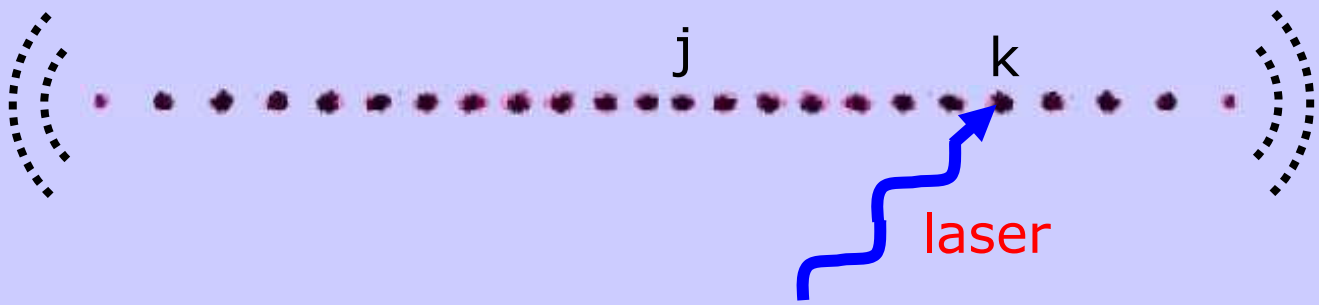
Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)



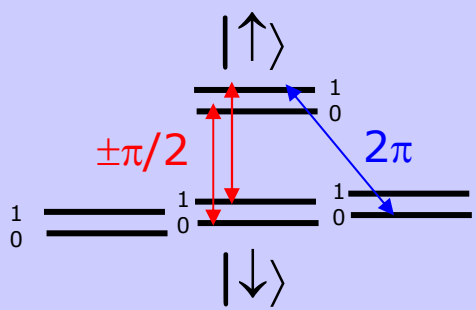
Step 2 Map j^{th} qubit to collective motion

Universal Quantum Logic Gates with Trapped Ions

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)



Step 3 Flip k^{th} qubit depending upon motion

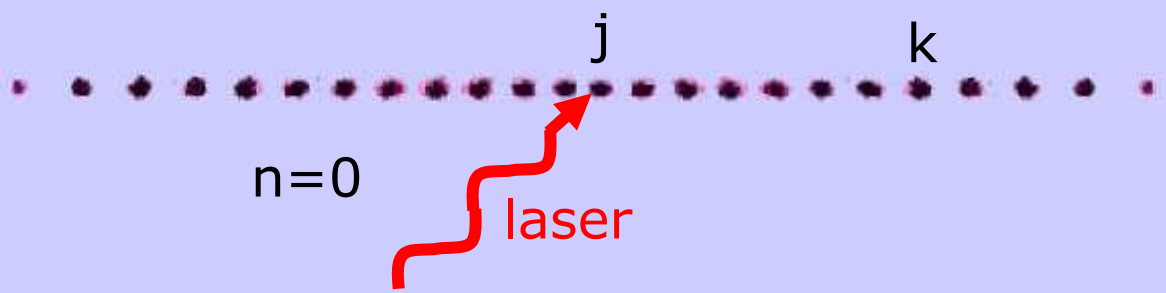


$\pi/2$, 2π, $-\pi/2$

sign flip $|\uparrow\rangle|n=1\rangle$ only !

Universal Quantum Logic Gates with Trapped Ions

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)



Step 4 Remap collective motion to j^{th} qubit (reverse of Step 1)

Net result: $[|\downarrow\rangle_j + |\uparrow\rangle_j]\, |\downarrow\rangle_k \rightarrow |\downarrow\rangle_j\, |\downarrow\rangle_k + |\uparrow\rangle_j |\uparrow\rangle_k$

Demonstrations of Cirac-Zoller '95 Gates

- CNOT between motion and spin (1 ion)

  C.M., et al., *Phys. Rev. Lett.* **75**, 4714 (1995)

- CNOT between spins of 2 ions

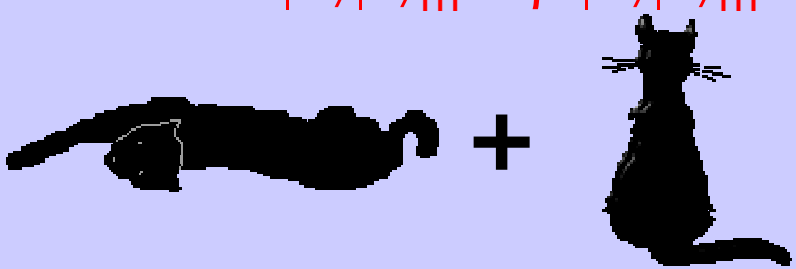
  Schmidt-Kaler, et al., *Nature* **422**, 408-411 (2003).

- Entangled "W-states" between 3-8 ions

  Roos, et al., Science **304**, 1478 (2004)
  Häffner, et al., Nature **438**, 643 (2005)

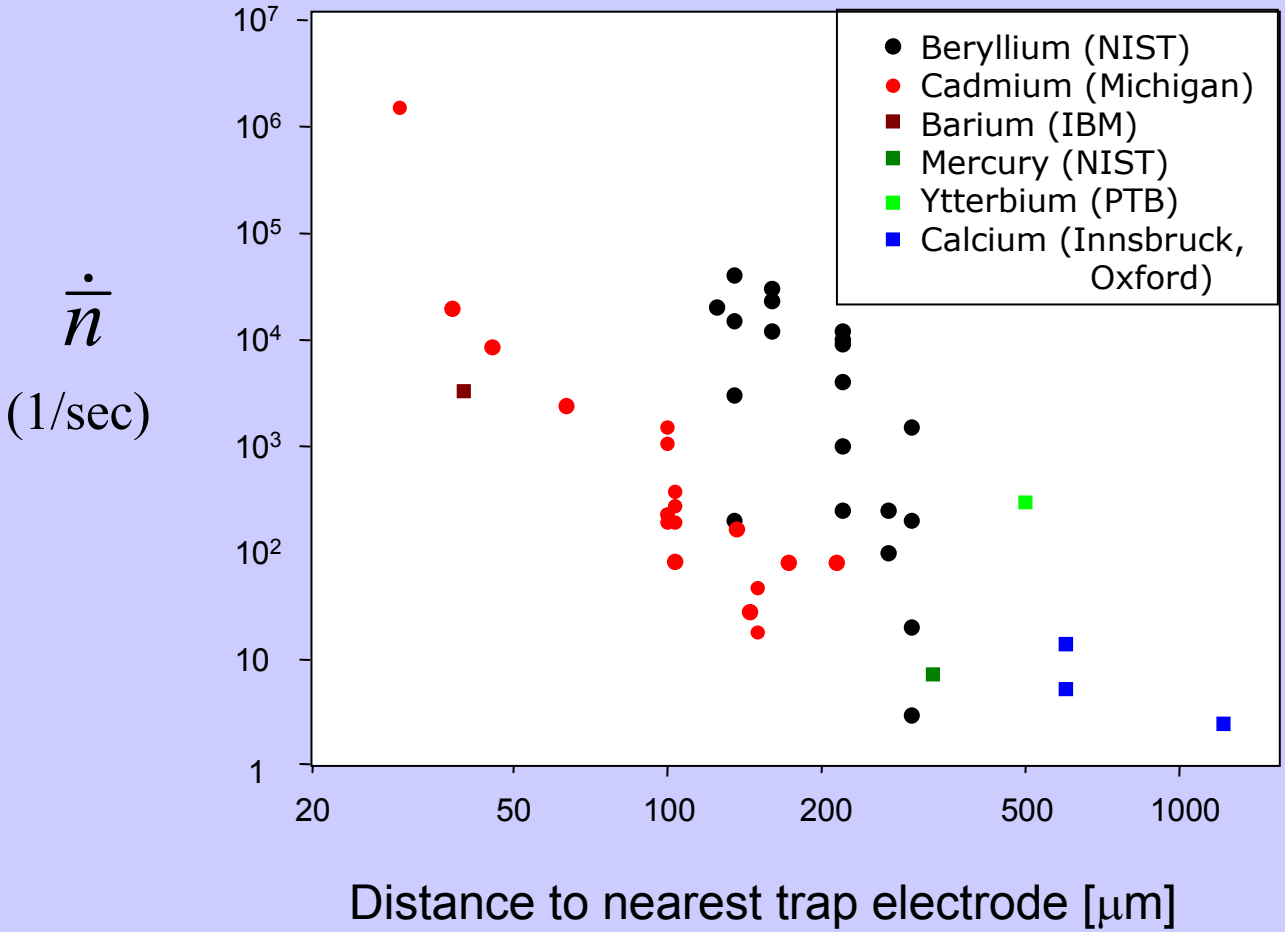
BIG PROBLEM: during the gate (at some point),
the state of an ion qubit and motional bus state is:

$$\Psi = \alpha|\downarrow\rangle|0\rangle_m + \beta\,|\uparrow\rangle|1\rangle_m$$

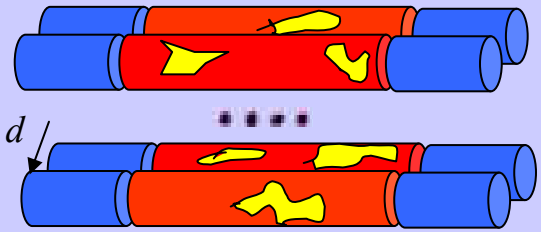


Decoherence Kills the Cat

Heating history in 0.6-6.0 MHz traps



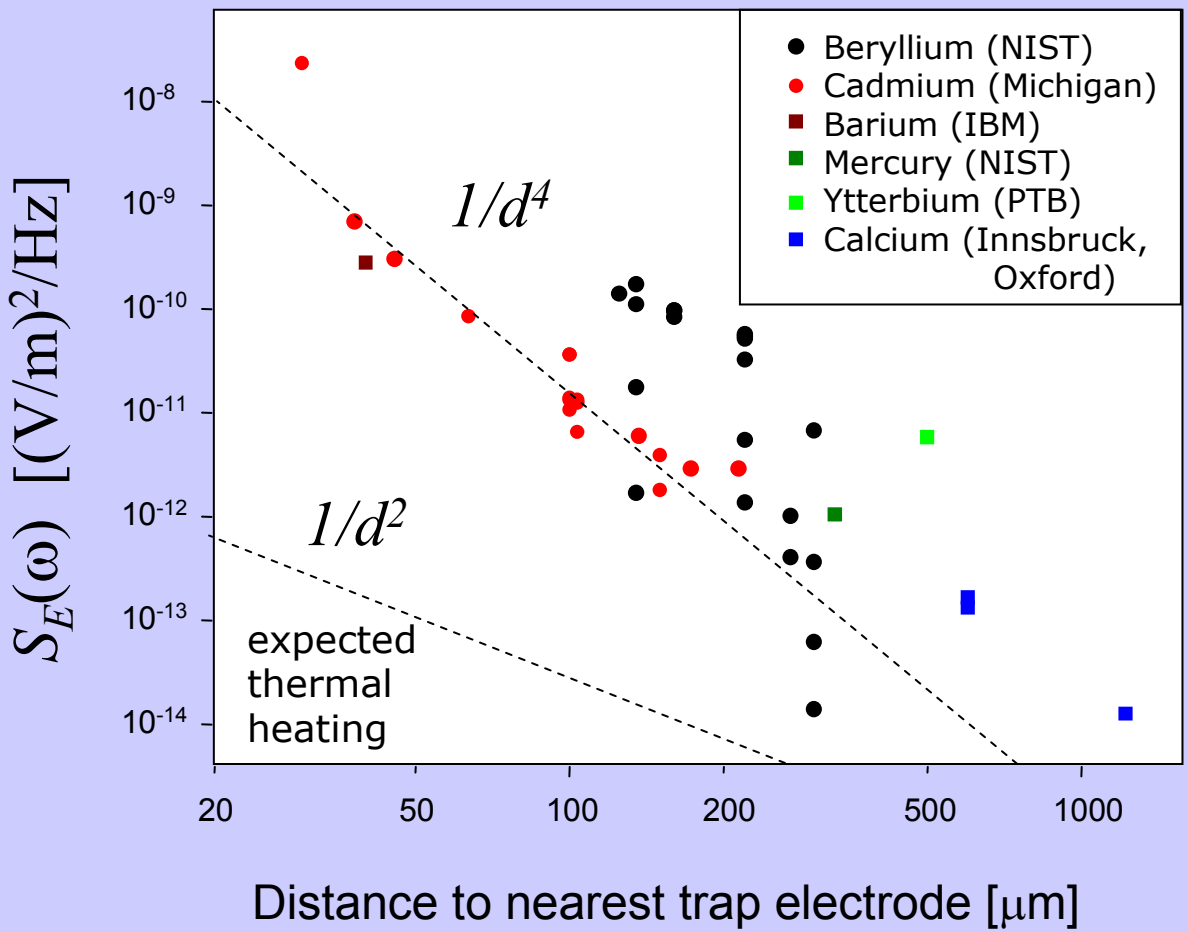
Heating due to fluctuating patch potentials (?)



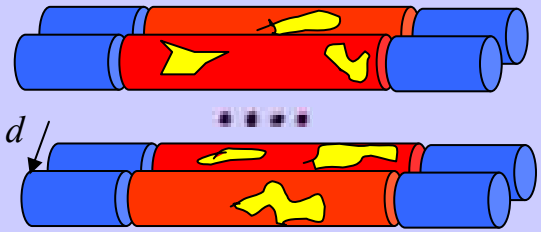
$$\dot{\bar{n}} = \frac{e^2}{4m\hbar\omega} S_E(\omega)$$

$$\sim 1/d^4$$

Electric Field Noise History in 0.6-6.0 MHz traps



Heating due to fluctuating patch potentials (?)



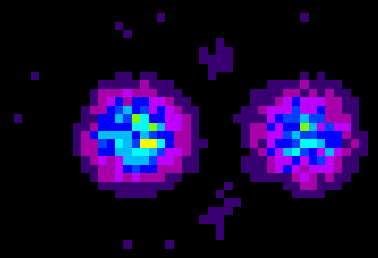
$$\dot{\bar{n}} = \frac{e^2}{4m\hbar\omega} S_E(\omega)$$

$$\sim 1/d^4$$

Entangling Gate Schemes for Trapped Ion

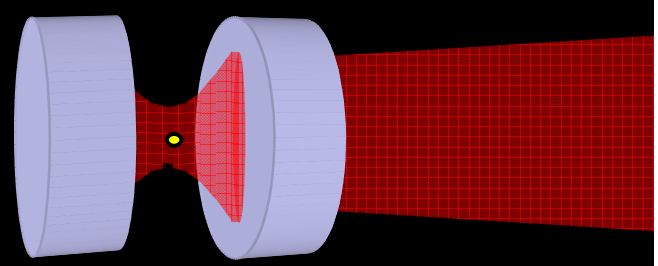
MOTIONAL GATES

- Direct Phonon Coupling
- Spin-dependent Forces



PHOTONIC GATES

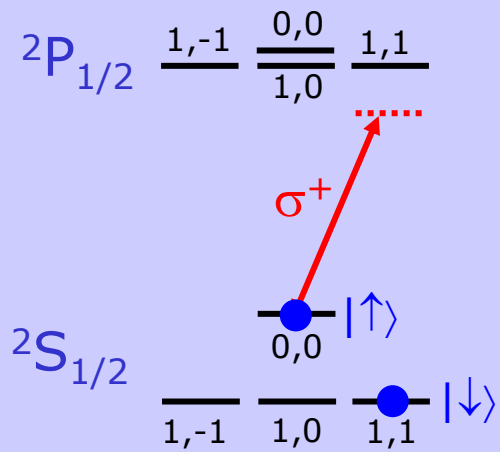
- Linear Optics (probabilistic)
- Cavity-QED



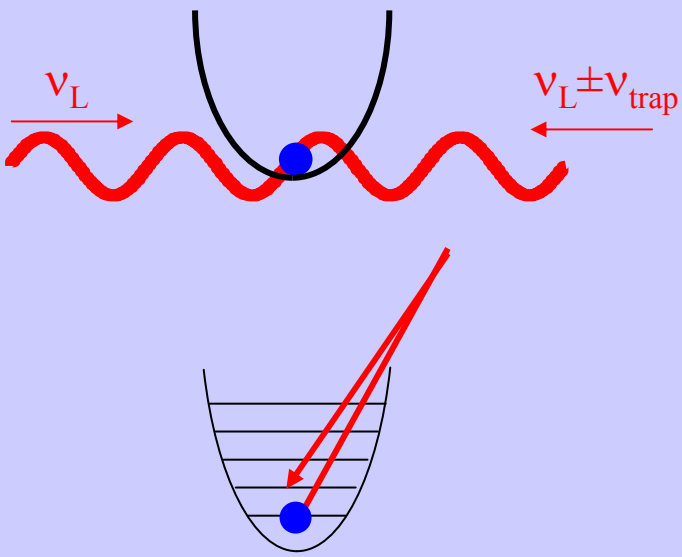
BETTER: Indirect use of motion for quantum gates

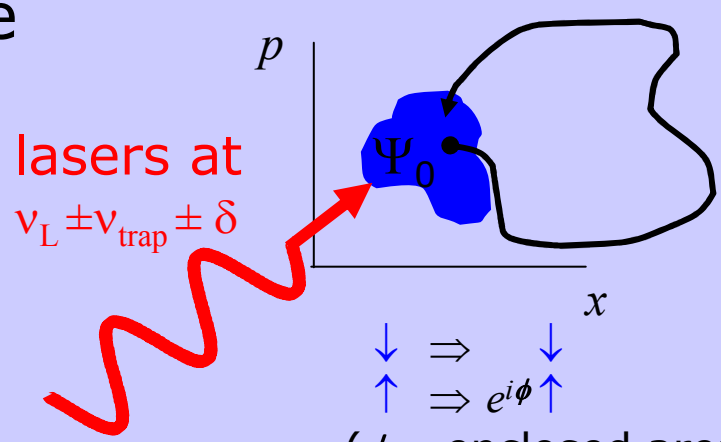
spin-dependent force:

$$\text{Force} = F_0 |\uparrow\rangle\langle\uparrow|$$



(a) near-resonant dipole force





$\downarrow \Rightarrow \downarrow$

$\uparrow \Rightarrow e^{i\phi}\uparrow$

($\phi \propto$ enclosed area)

Independent of initial state but requires Lamb-Dicke limit

N=2 ions

e.g., force on stretch mode only

$$\downarrow\downarrow \Rightarrow \downarrow\downarrow$$
$$\downarrow\uparrow \Rightarrow e^{i\phi}\downarrow\uparrow$$
$$\uparrow\downarrow \Rightarrow e^{i\phi}\uparrow\downarrow$$
$$\uparrow\uparrow \Rightarrow \uparrow\uparrow$$

$$H = \hbar\Omega\hat{\sigma}_z^2$$

$\phi = \pi/2$: π-phase gate

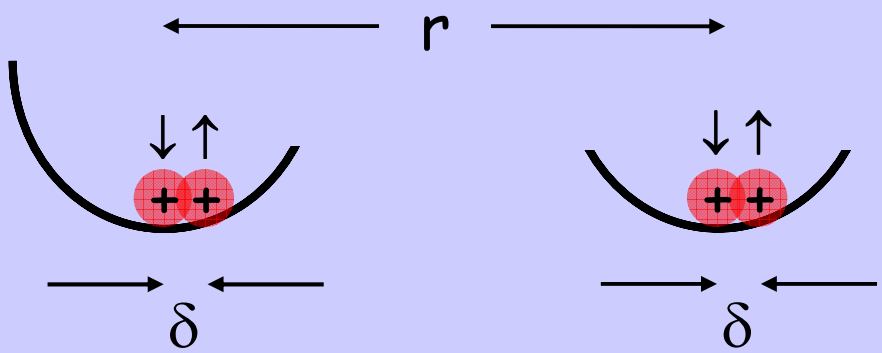
Mølmer and Sørensen, PRL **82**, 1835 (1999)
Solano, de Matos Filho, Zagury, PRA **59**, R2539 (1999)
Milburn, Schneider, James, Fortschr. Phys. (2000)

Leibfried *et al.*, Nature **422**, 412 (2003)
Lucas, Steane, *et al*. (2005)

N=6 ions $\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow + \downarrow\downarrow\downarrow\downarrow\downarrow\downarrow$

Leibfried *et al.*, Nature **438**, 639-642 (2005)
POSTER M25

(b) spin-dependent "push" force



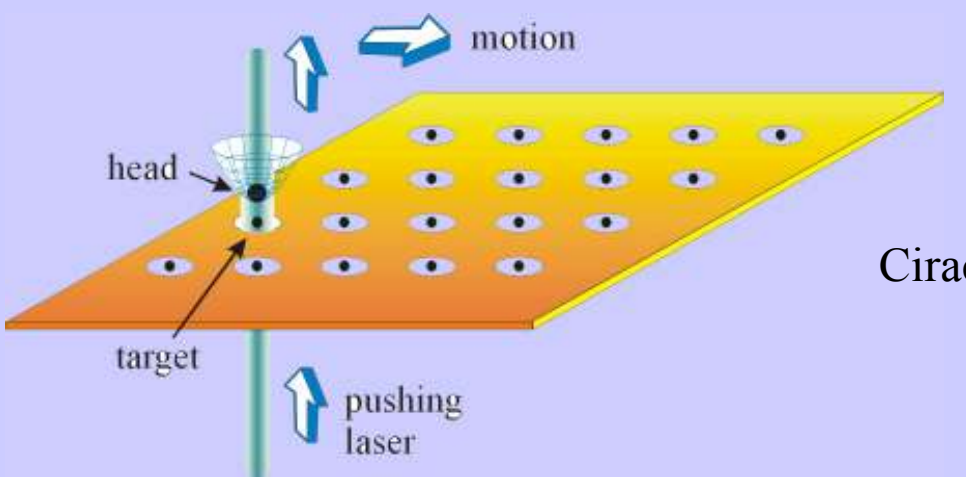
$$U_{dd} = \mu_1\mu_2/r^3 = (e\delta)^2/r^3$$

quantum phase gate

$$|\downarrow\downarrow\rangle \rightarrow \quad |\downarrow\downarrow\rangle = |\downarrow'\downarrow'\rangle$$
$$|\downarrow\uparrow\rangle \rightarrow e^{+i\kappa - i\phi/2}\,|\downarrow\uparrow\rangle = |\downarrow'\uparrow'\rangle$$
$$|\uparrow\downarrow\rangle \rightarrow e^{-i\kappa - i\phi/2}\,|\uparrow\downarrow\rangle = |\uparrow'\downarrow'\rangle$$
$$|\uparrow\uparrow\rangle \rightarrow \quad |\uparrow\uparrow\rangle = e^{i\phi}\,|\uparrow'\uparrow'\rangle$$

κ = *linear shift*

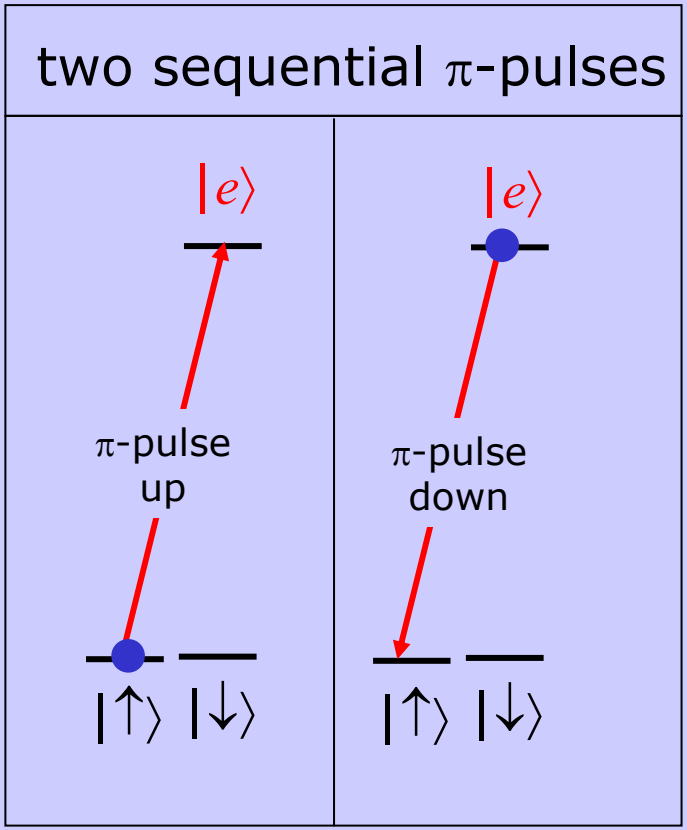
ϕ = *nonlinear shift* = $2U_{dd}\tau/\hbar$

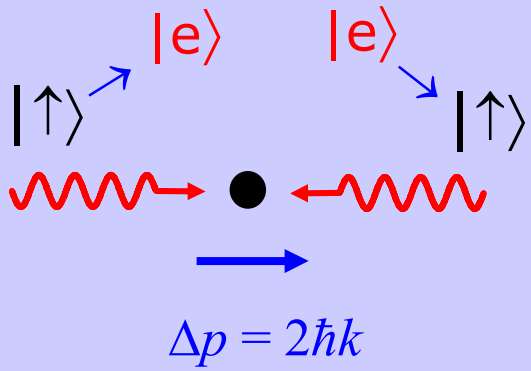


Cirac & Zoller *Nature* **404**, 579-581 (2000)

(c) Impulsive spin-dependent forces

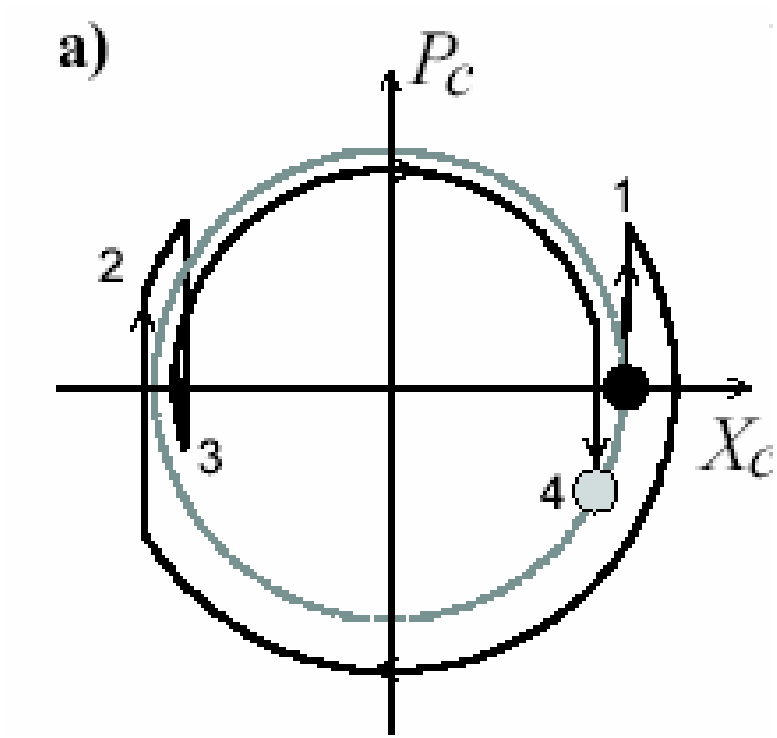
Poyatos, Cirac, Blatt & Zoller, *PRA* **54**, 1532 (1996)
Garcia-Ripoll, Zoller, & Cirac, *PRL* **91**, 157901 (2003)





$$U = |\uparrow\rangle\langle\uparrow| e^{2i\eta(a+a^\dagger)}$$

spin-dependent impulse

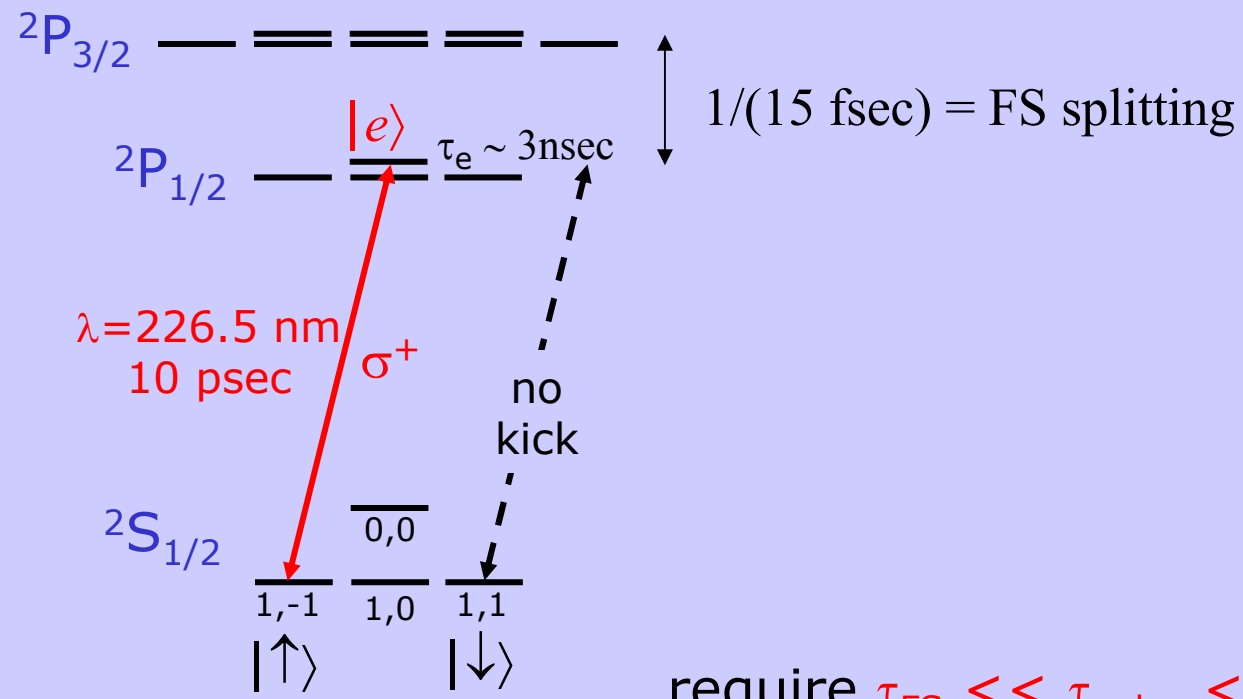


The trajectory of a normal motional mode of two ions in phase space under the influence of four photon kicks. Gray curve: free evolution. Black curve: four impulses kick the trajectory in phase space, with an ultimate return to the free trajectory after ~1.08 revolutions.

Fast version of σ_z phase gate

does not require Lamb-Dicke regime!

e.g. $^{111}Cd^+$



require $\tau_{FS} << \tau_{pulse} << \tau_e$

requires ultrafast laser control

Problem with σ_Z gates:

With "clock" state qubits
(no differential Zeeman shift),…

cannot realize a spin-dependent force
(no differential AC Stark shift)

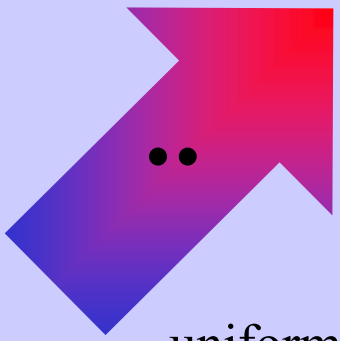
P. J. Lee, et al., Journal of Optics B **7**, S371 (2005).

Solution:

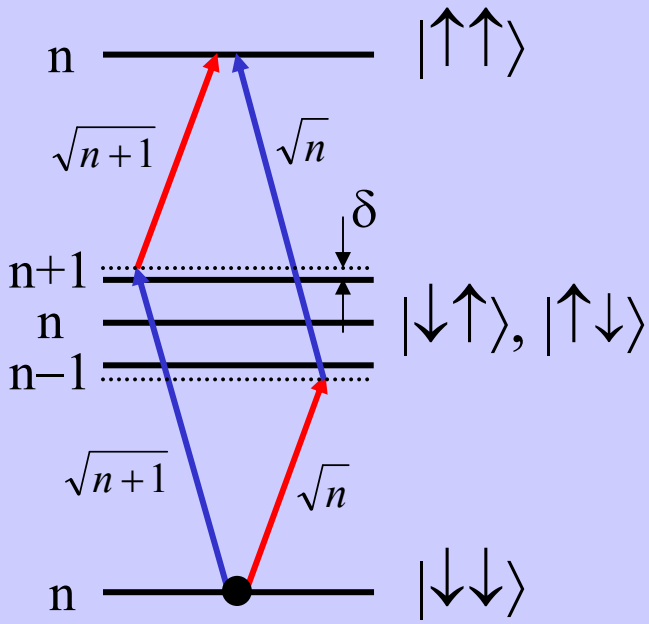
Apply spin-dependent forces in a diferent basis

Mølmer and Sørensen, PRL **82**, 1835 (1999)
Solano, de Matos Filho, Zagury, PRA **59**, R2539 (1999)
Milburn, Schneider, James, Fortschr. Phys. (2000)

Bichromatic coupling to *sidebands*
"Molmer-Sorensen gate"



uniform
illumination



$$\Omega = \text{Rabi Freq} = \frac{(kx_0 g\sqrt{n+1})^2}{\delta} + \frac{(kx_0 g\sqrt{n})^2}{-\delta}$$

$$= \frac{(kx_0 g)^2}{\delta}$$

independent of motion !

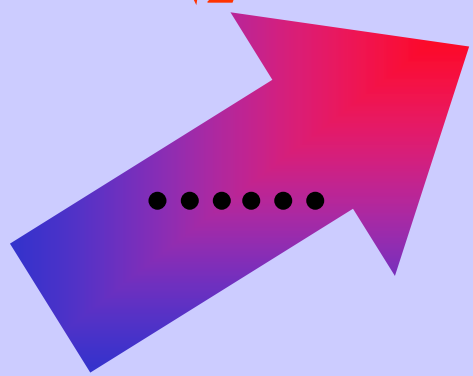
$$H = \hbar\Omega\hat{\sigma}_x^2$$

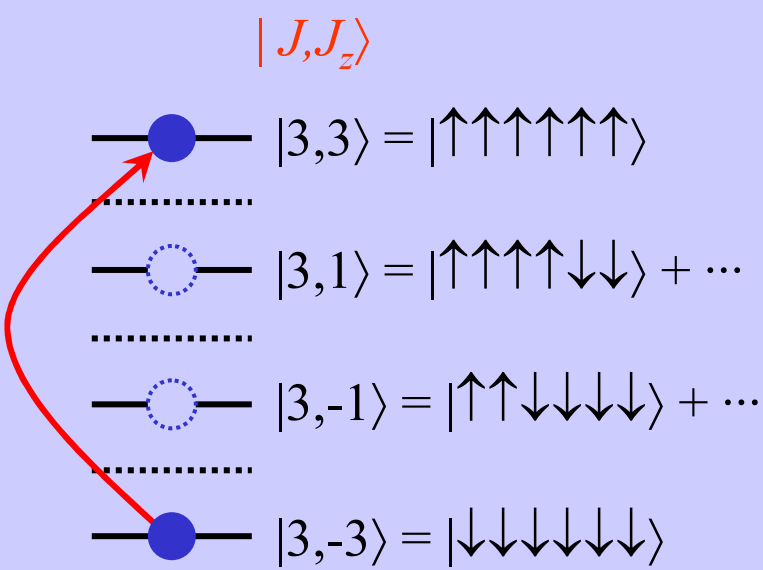
(as long as $kx_0\sqrt{n+1} << 1$: "Lamb-Dicke regime")

Can scalable to arbitrary N

$$|\downarrow\downarrow\downarrow\cdots\downarrow\rangle \Rightarrow \frac{|\downarrow\downarrow\downarrow\cdots\downarrow\rangle + |\uparrow\uparrow\uparrow\cdots\uparrow\rangle}{\sqrt{2}}$$

e.g., 6 ions





N=4 ions

Sackett, et al., *Nature* **404**, 256 (2000)

N=2 ions (clock qubits)

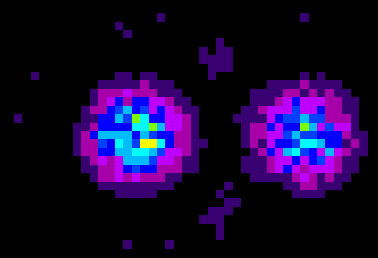
Haljan, et al, PRA **72**, 062316 (2005)

POSTER M21

Entangling Gate Schemes for Trapped Ion

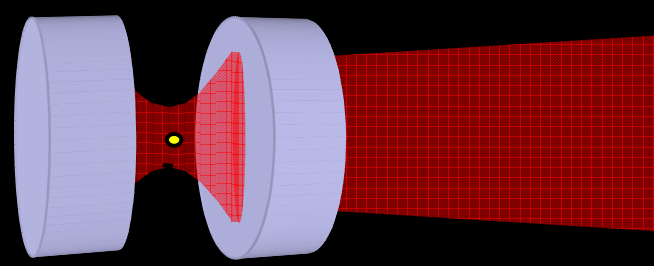
MOTIONAL GATES

- Direct Phonon Coupling
- Spin-dependent Force

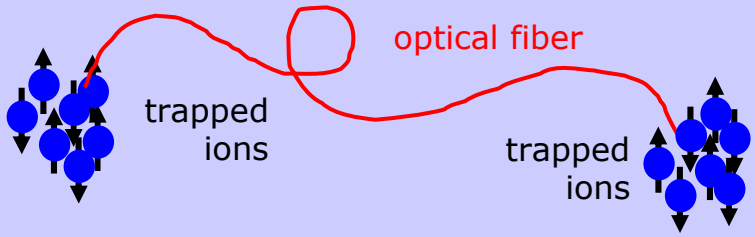


PHOTONIC GATES

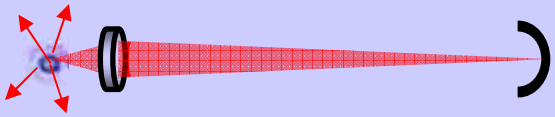
- Linear Optics (probabilistic)
- Cavity-QED



Interfacing Trapped Ions and Photons



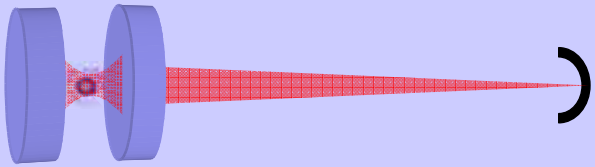
- Free space (probabilistic $p<<1$)



$$p = \eta\, d\Omega \sim 10^{-3}$$

- "Bad" cavities (probabilistic $p\sim 0.3$)

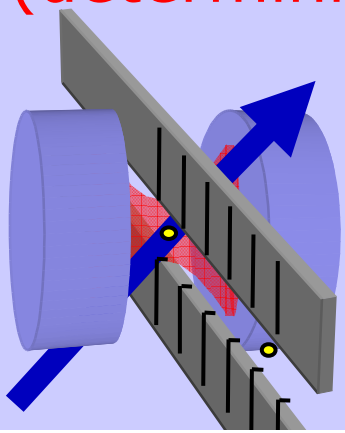
$$C = \frac{g^2}{\kappa\gamma} \approx 1$$



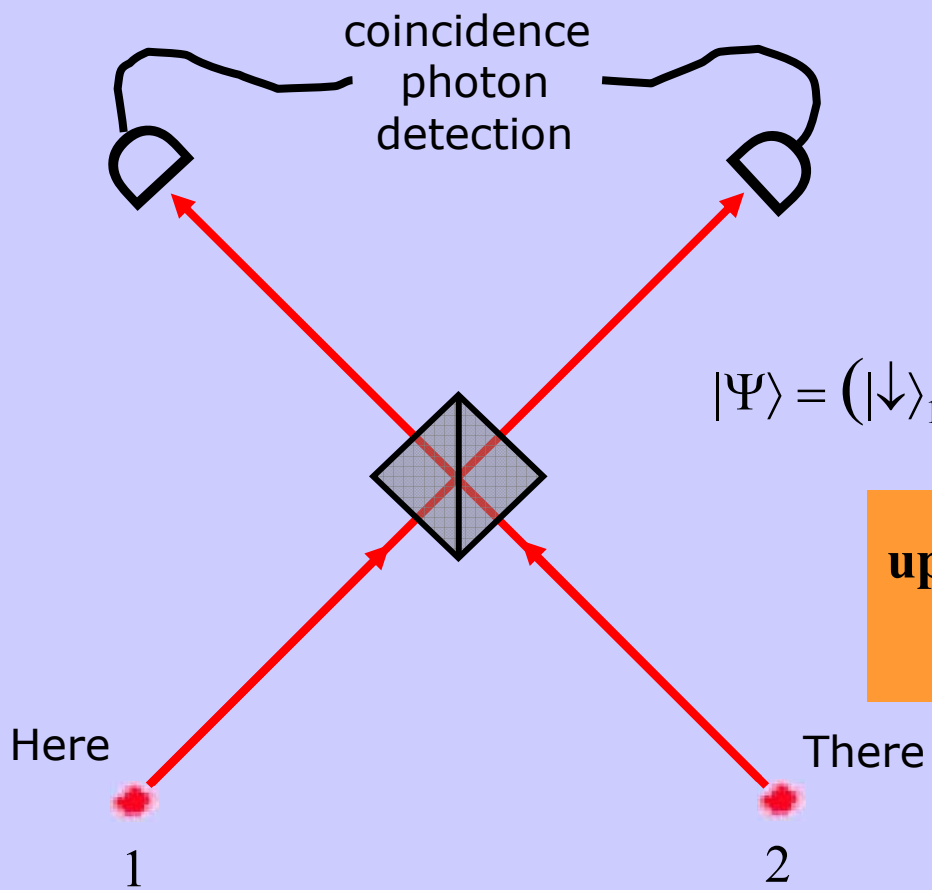
$$p = \eta\left(\frac{C}{C+1}\right) \approx 0.1 - 0.3$$

- Strong coupling (deterministic cavity-QED)

$$C = \frac{g^2}{\kappa\gamma} >> 1$$



Networking distant ions



$$|\Psi\rangle = \left(|\downarrow\rangle_1|V\rangle_1 + |\uparrow\rangle_1|H\rangle_1\right)\otimes\left(|\downarrow\rangle_2|V\rangle_2 + |\uparrow\rangle_2|H\rangle_2\right)$$

upon coincidence photon detection

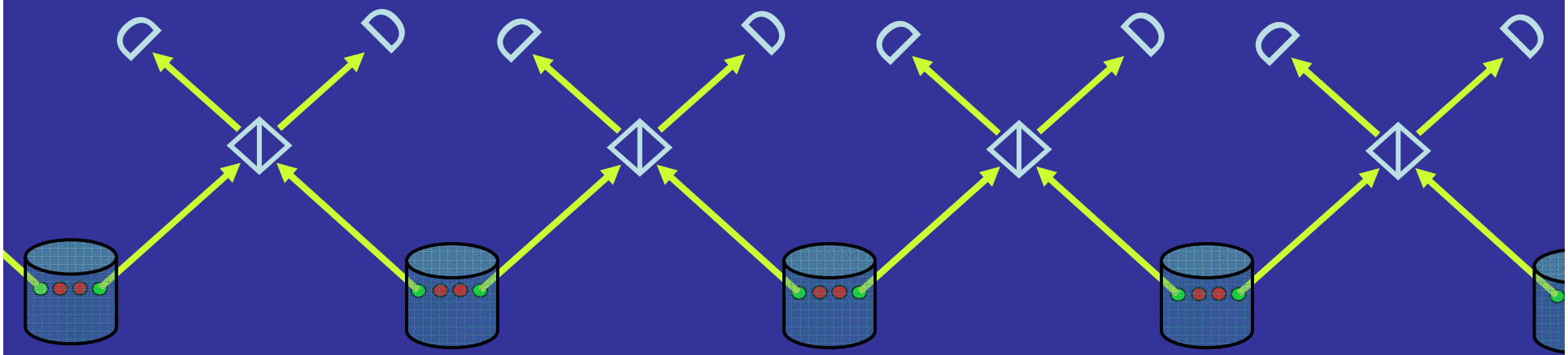
$$|\Psi\rangle \Rightarrow |\downarrow\rangle_1|\uparrow\rangle_2 - |\uparrow\rangle_2|\downarrow\rangle_2$$

insensitive to interferometric phase noise
insensitive to ion motion

Simon & Irvine, PRL **91**, 110405 (2003)
Blinov, et al., Nature 428, 153 (2004)
Duan, et. al., *QIC* **4**, 165 (2004)

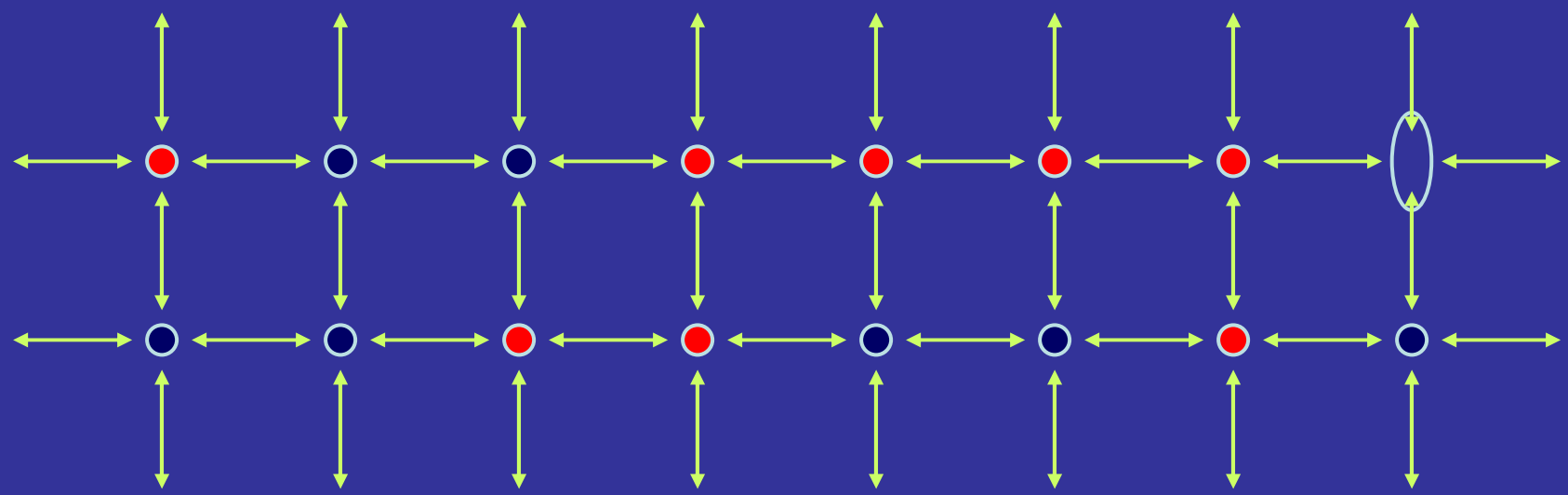
POSTERS M04, M17, M18

Quantum networking with probabalistic entanglement



Quantum repeater network

Briegel *et al.*, PRL **81**, 5932 (1998)

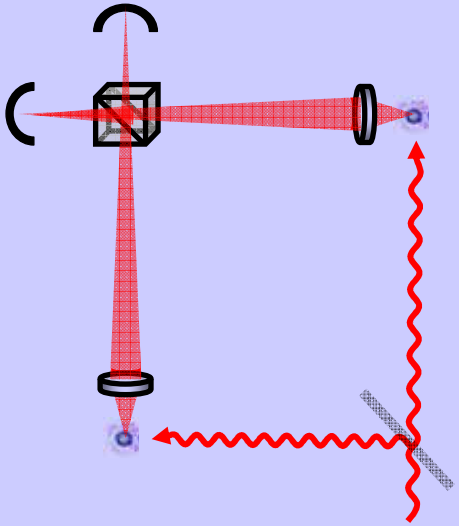


Cluster state quantum computing

Raussendorf and Briegel, PRL **86**, 910 (2001)

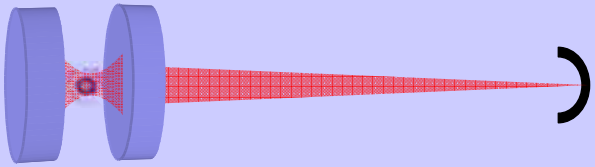
Duan and Raussendorf, PRL 95, 080503 (2005)

- Free space (probabilistic $p<<1$)



Pair entanglement rate $= Rp^2 \sim 1$ *Hz*

- Optical Cavities around ions

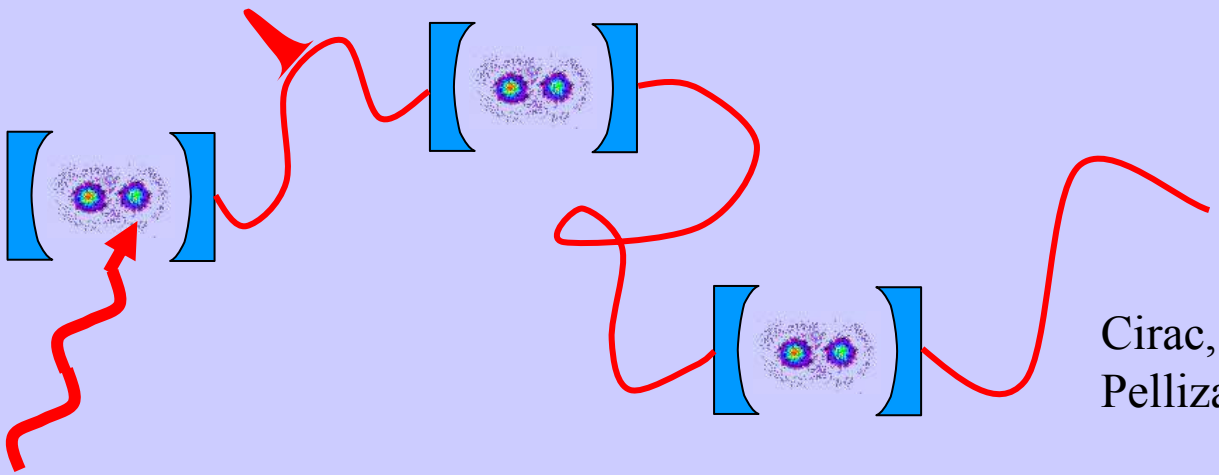


$$C = \frac{g^2}{\kappa\gamma} >> 1 \qquad g = \frac{\mu E}{\hbar} \sim \frac{1}{\sqrt{Vol}}$$

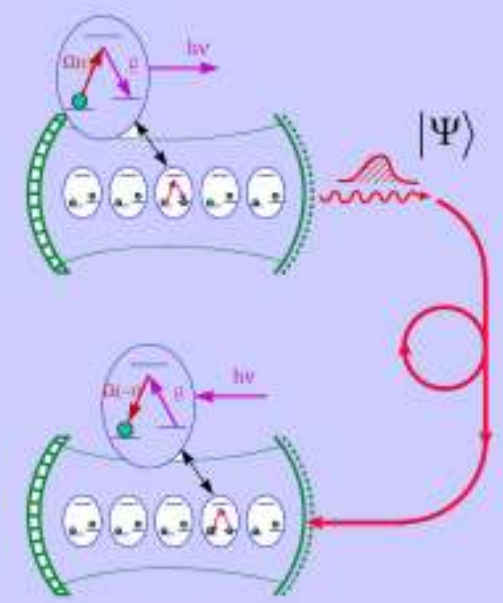
G. Guthorlein, M. Keller, K. Hayasaka, W. Lange, and H. Walther,
"A single ion as a nanoscopic probe of an optical field"
Nature **414**, 49 (2001).

Mundt, A. Kreuter, C. Becher, D. Leibfried, J. Eschner, F. Schmidt-Kaler, R. Blatt,
"Coupling a Single Atomic Quantum Bit to a High Finesse Optical Cavity"
Phys. Rev. Lett. **89**, 103001 (2002).

Deterministic coupling of atoms to a single-mode cavity



Cirac, Zoller, Pellizarri, PRL (1995)
Pellizarri, PRL **79**, 5242 (1997)



Cirac, Zoller, Kimble, Mabuchi, PRL **78**, 3221 (1997).

Entangling Gate Schemes for Trapped Ion

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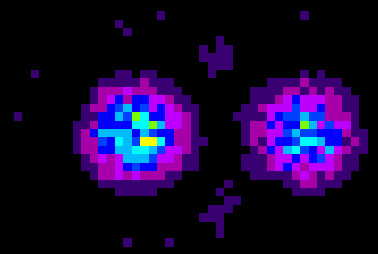
- Spin-dependent Force



PHOTONIC GATES

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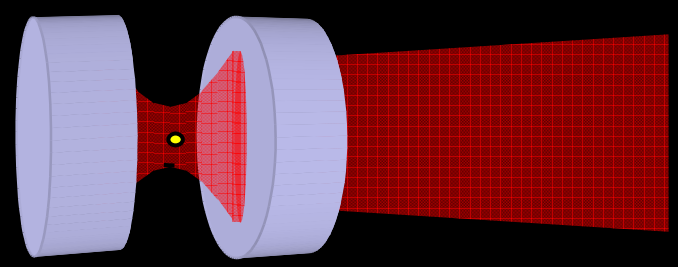

COUPLING TO SOLID-STATE?

- superconducting
- quantum dots