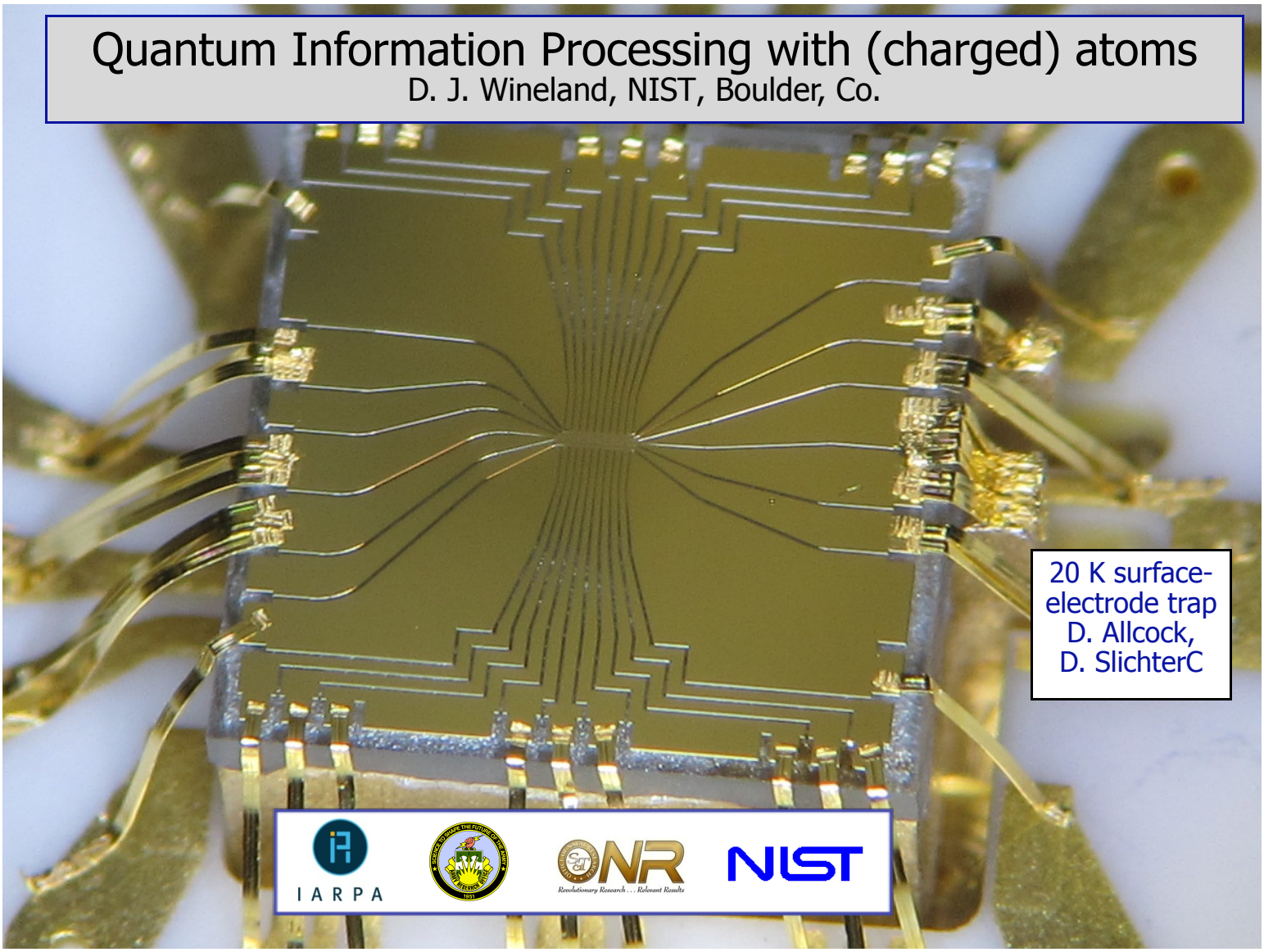
Quantum Information Processing with (charged) atoms

D. J. Wineland, NIST, Boulder, Co.



20 K surface-electrode trap
D. Allcock,
D. SlichterC

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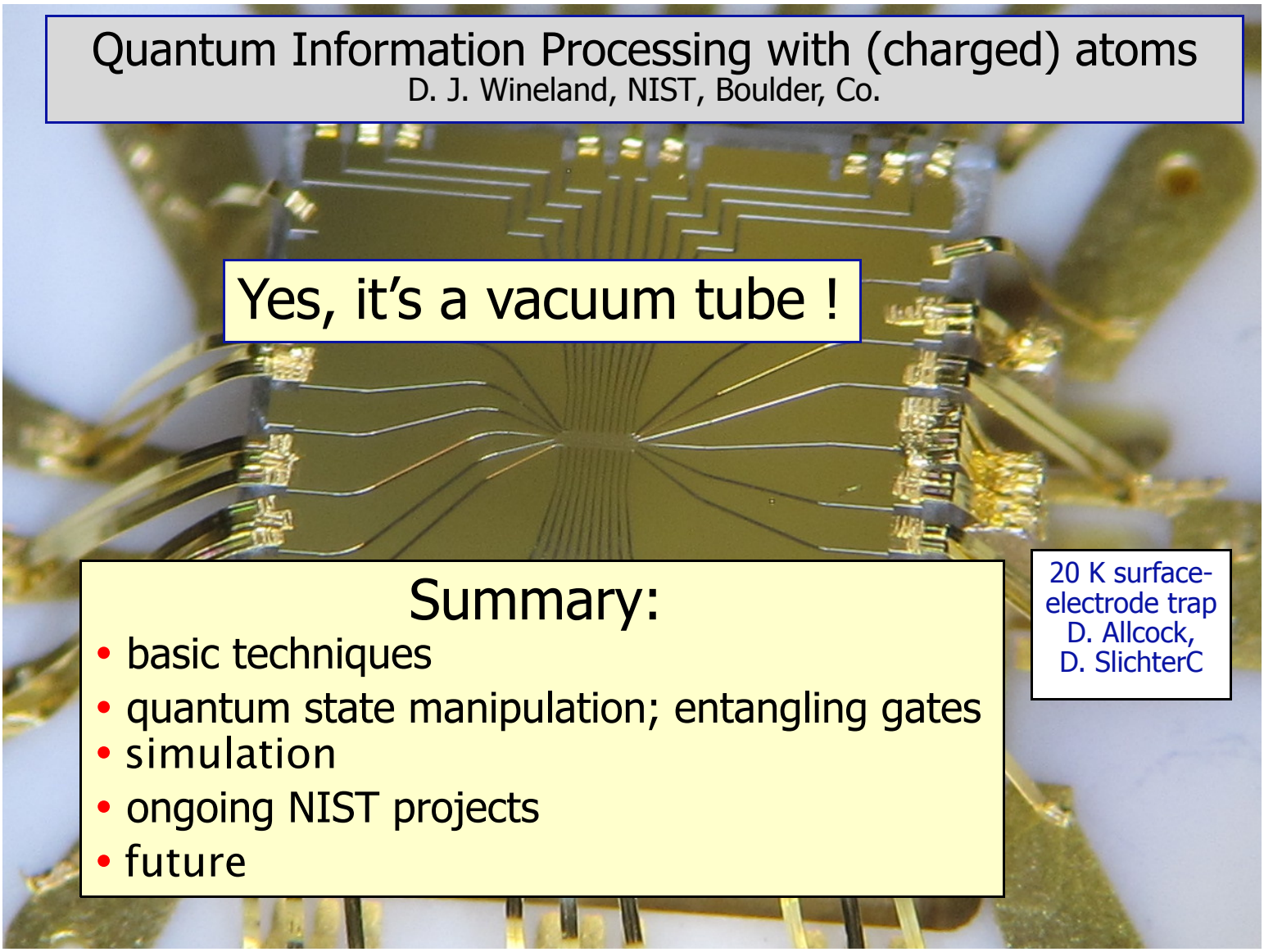


Yes, it's a vacuum tube !

20 K surface-electrode trap
D. Allcock,
D. SlichterC

Summary:

- basic techniques
- quantum state manipulation; entangling gates
- simulation
- ongoing NIST projects
- future

Atomic ion experimental groups pursuing Quantum Information Processing:

Aarhus
Amherst
The Citadel
Tsinghua (Bejing)
U.C. Berke
U.C.L.A.
Duke
ETH (Züric
Freiburg
Garching (
Georgia Te
Griffiths
Hannover
Innsbruck
JQI (U. Ma
Lincoln La
Imperial (L
Mainz

MIT
NIST
Northwestern
NPL

aris)

b

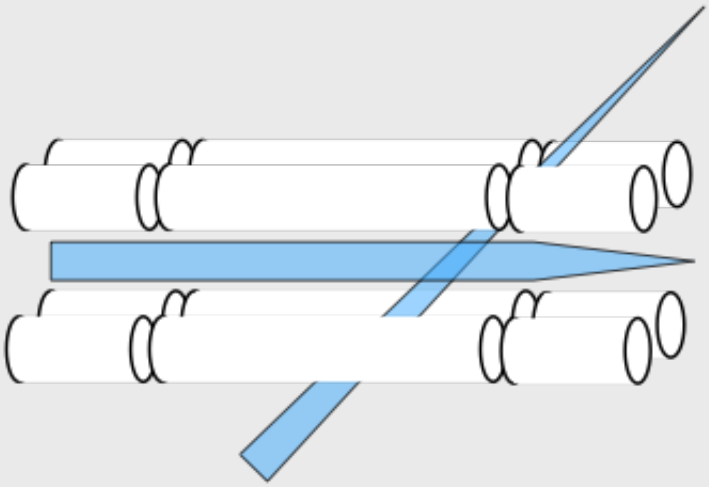
rea

U. Washington
Weizmann Institute

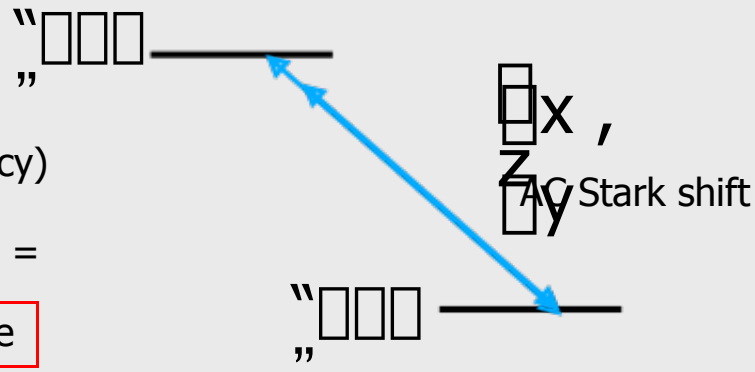
Peter Zoller Ignacio Cirac

(1995 proposal for trapped-ion quantum information processing)

Basic setup:

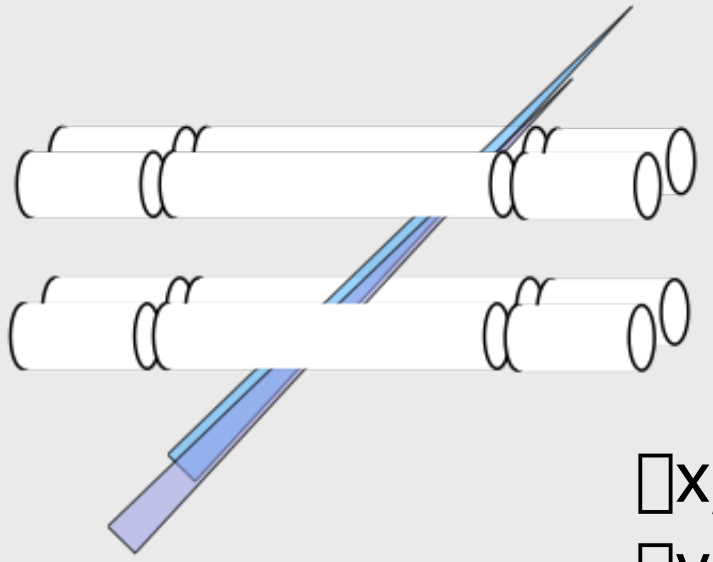


linear quadrupole Paul trap
RF + DC potentials
 3-D harmonic well
(motion frequencies ~ few MHz)



Optical qubit:
(E - E)/ħ = 0 (optical frequency)
e.g.,
Ca+ | 2S1/2, | 2D5/2, = 729 nm

need high-stability optical source



2P3/2

2P1/2

two-photon stimulated-Raman

□x,

□y

□(9Be+) □ 313 nm
□(25Mg+) □ 280 nm
□(Yb+) □ 369 nm

"□□□"

2S1/2

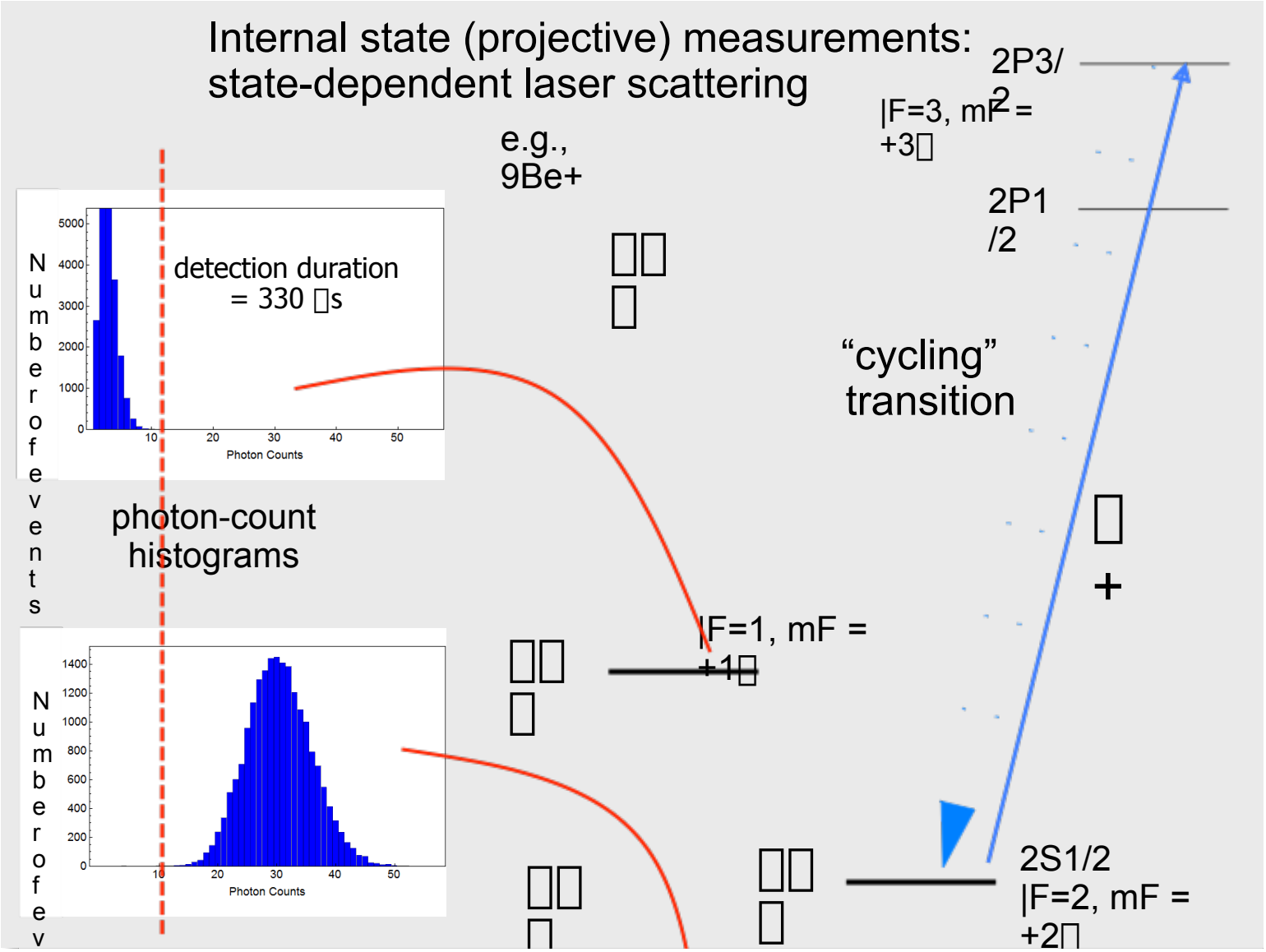
"□□□"

Hyperfine/Zeeman qubit:
□0 = RF/microwave frequency
e.g.,
9Be+, 25Mg+, 171Yb+, ...

need high-stability □-wave source

problem: spontaneous Raman scattering

Internal state (projective) measurements: state-dependent laser scattering



Two qubit gates:

Cirac/Zoller gate:
(use of discrete motional states)

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

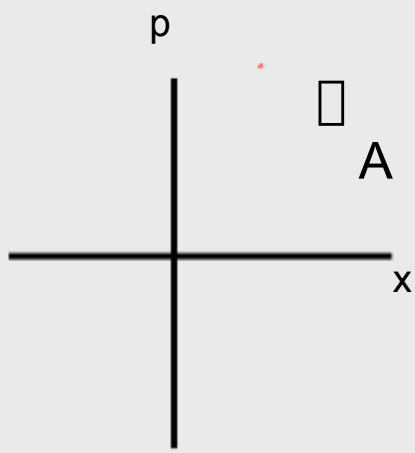
Geometric phase gates:
insensitive to motion if z2½ << effective wavelength ("Lamb-Dicke regime")

A. Sørensen and K. Mølmer, Phys. Rev. Lett. **82**, 1971 (1999).
E. Solano, R. L. de Matos Filho, and N. Zagury, Phys. Rev. A **59**, 2539 (1999).
G. J. Milburn, S. Schneider, and D. F. V. James, Fortschr. Physik **48**, 801 (2000).
A. Sørensen and K. Mølmer, Phys. Rev. A **62**, 02231 (2000).
X.Wang, A. Sørensen, and K. Mølmer, Phys. Rev. Lett. **86**, 3907 (2001).

Summary: P. Lee et al., J. Opt B: Quantum Semiclass. Opt. **7**, s371 (2005)

Geometric phase gates:

phase-space diagram for motional mode:



□ □ ei□ □

□ □ enclosed area A

$$D(\alpha+\beta) = D(\alpha)D(\beta)\exp\{-i\,\mathrm{Im}(\alpha\beta^*)\}$$

concatenate steps

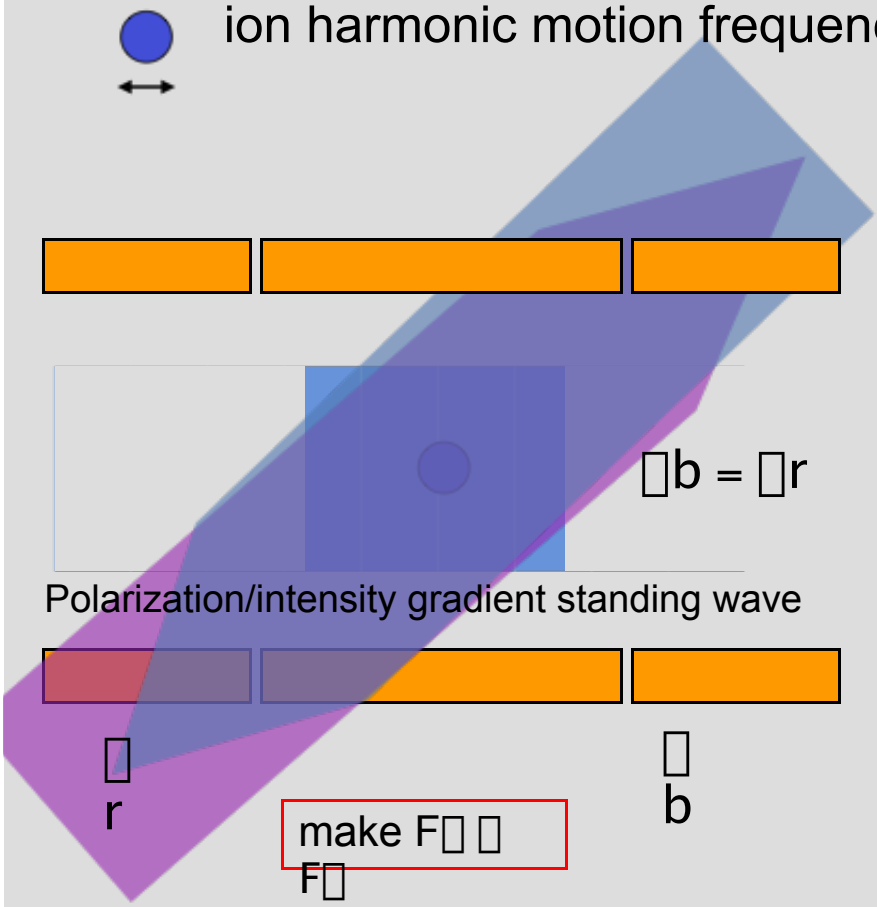
- make force state-dependent to realize phase gate, e.g,:

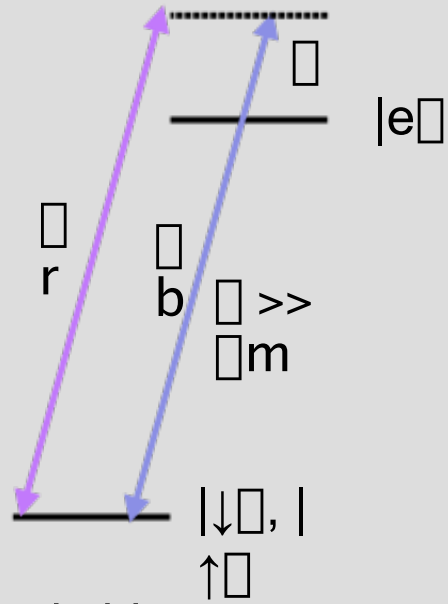
□□□1□□□2 □ □□□1□□□2 □□□1□□□2 □ i□□□1□□□2

□□□1□□□2 □ i□□□1□□□2 □□□1□□□2 □ □□□1□□□2

- use optical dipole forces

Optical dipole forces

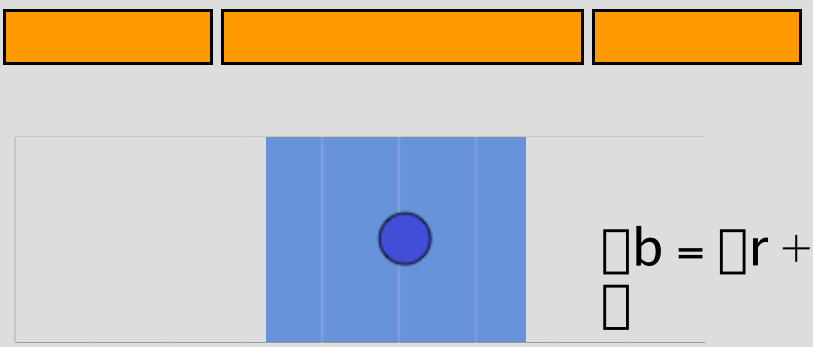




basic idea: use gradient of Stark shift to apply forces F□, F□ to |↓□ and |↑□

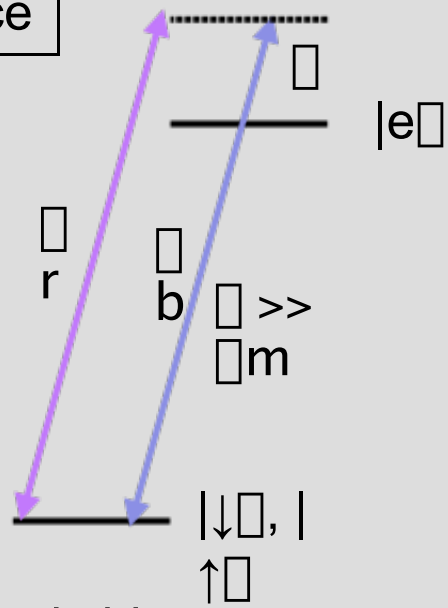
Dipole forces to displace ions in phase space

ion harmonic motion frequency □m



□b = □r + □m + □

“walking” standing wave



basic idea: use gradient of Stark shift to apply forces to |↓□ and |↑□

example: make F□ = − F□

2-ion phase-space displacement (e.g., stretch mode):

□b – □a = □stretch + □

apply forces for t = 2□/□

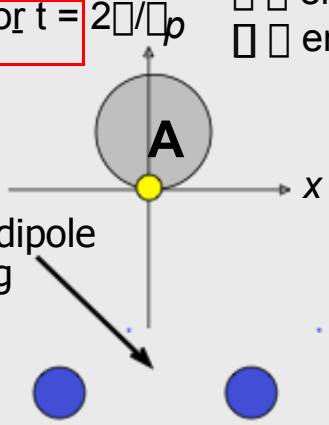
assume F□ = F□

□ □ ei□ □

□ □ enclosed area A

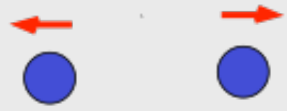
|□□|□□:

moving optical-dipole potential grating



|□□|□□ □ i |□□|□□

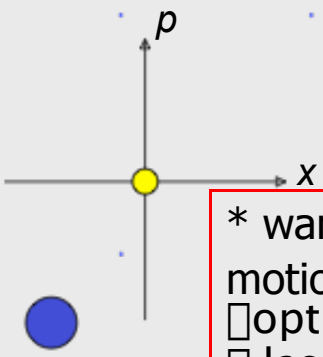
|□□|□□ □ i |□□|□□



U(t= tgate) = exp[-i(□/4)□z1□z2] = □z1□z2 phase gate

(up to Z rotation)

|□□|□□:



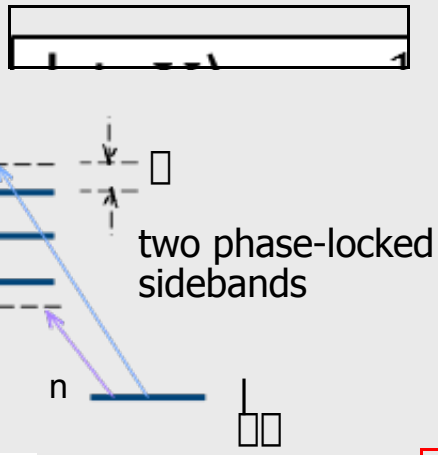
|□□|□□ □ |□□|□□

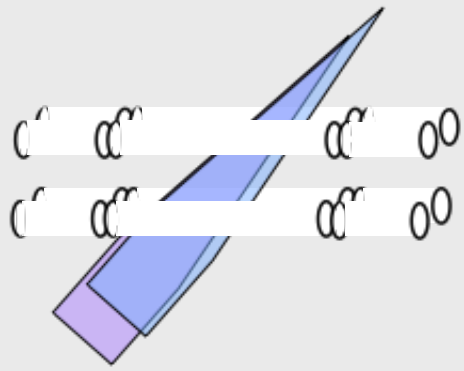
* want linear excitation/de-excitation □ motion amplitude << effective wavelength ~ □optical

□ laser cooling

* won't work on "B-field-independent" qubits

"Mølmer-Sørensen" (phase gate in □+X□,□−X□ basis) □x□x gate





optical qubits

$|\downarrow\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle)$

F = 0.993(1); 40Ca+, □ = 729 nm |S□ = |□□, |D□ = |□□

J. Benhelm et al., Nature Phys. **4**, 463 (2008)

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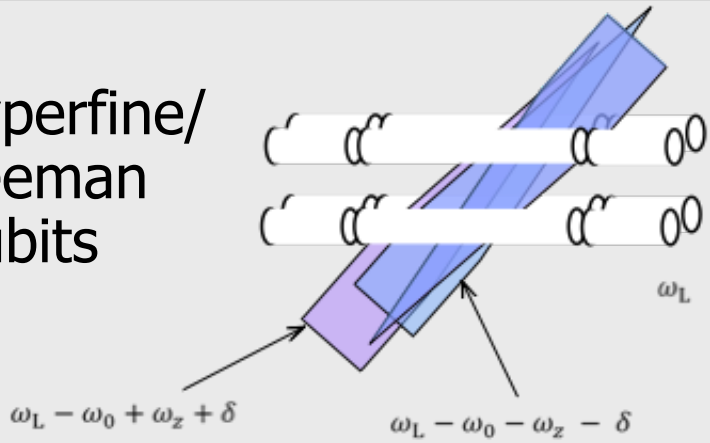
hyperfine/ Zeeman qubits



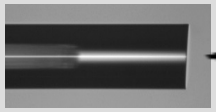
□x□x gate

beam pairs separated by

~ hyperfine frequency □0

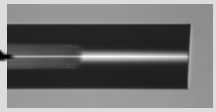
UV fibers: Y. Colombe, D. Slichter, A. Wilson et al.

fused quartz solid core fiber, length 1-3 m



collapsed and angle cleaved end

Input



collapsed and angle cleaved end

Output

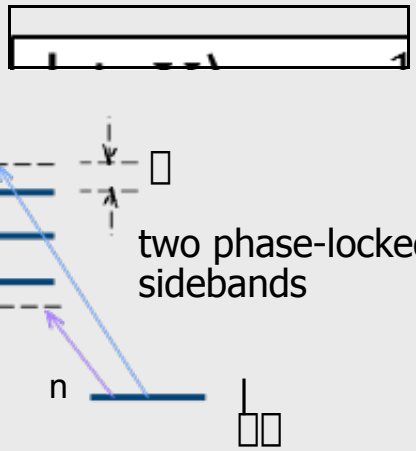
0.13±0.04 dB/m

98% TEM00

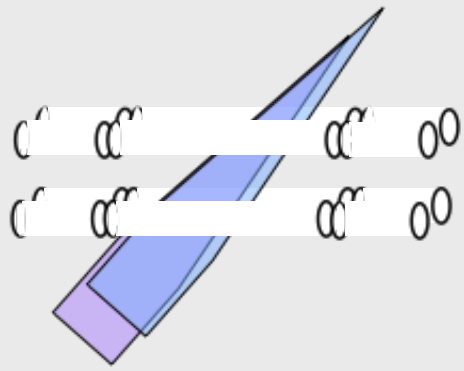
cross section with propagating mode (8-10 mm mode diameter, solid core)

- hydrogen loading at 100 atm. + UV curing suppresses UV "solarization"
- > 300 mW continuous @313 nm, 100 mW average power of 355 nm 10 ps-pulses (Duke)
- single mode over large range of wavelengths, tested at 313 nm, 280 nm, 285 nm, 355 nm
- no signs of deterioration (T > 1 yr)
- Y. Colombe *et al.*, Optics Express **22**, 19783 (2014)
- Recipe: D. Slichter, http://www.nist.gov/pml/div688/grp10/index.cfm

"Mølmer-Sørensen" (C-phase gate in□+X□,□−X□ basis) □x□x gate



optical qubits



$|\downarrow\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle)$ F = 0.993(1); J. Benhelm et al., Nature Phys. **4**, 463 (2008)

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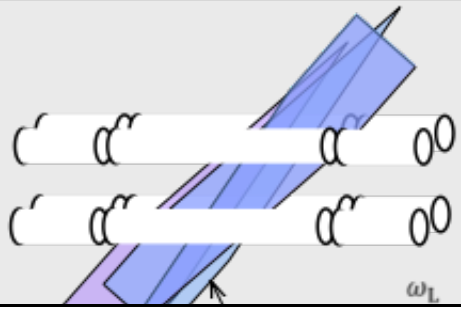
hyperfine/ Zeeman qubits

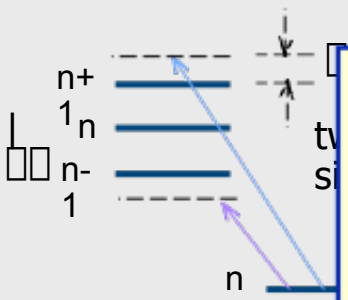


□x□x gate
beam pairs separated by
~ hyperfine frequency □0

Stimulated-Raman laser gates:
□z□z gate: F = 0.999(1); □x gate: F = 0.999934(3) (Ca+, □ =397 nm Oxford arXiv:1512.04600)
□x□x gate: F = 0.999(2), □x gate: F = 0.999963(3) (Be+, □ = 313 nm, NIST)

"Mølmer-Sørensen" (C-□–phase gate in□+X□,□–X□ basis) □x□x gate

optical qubits

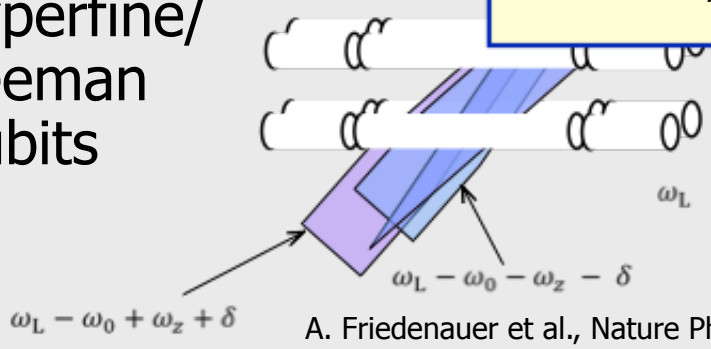


$|\downarrow\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle)$

Chris Monroe
U. Maryland

Rainer Blatt
U. Innsbruck

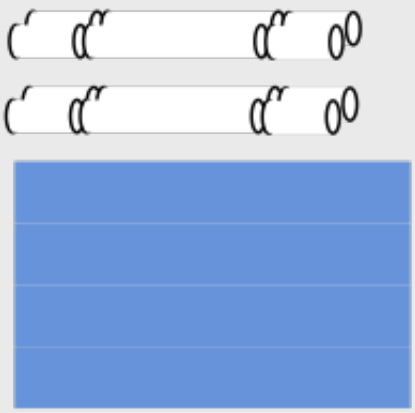
hyperfine/ Zeeman qubits



□x□x gate □ Ising model (2 spins)

A. Friedenauer et al., Nature Phys. **4**, 757 (2008) (Schätz group, Freiburg)

> 2 qubits



e.g., 9 (Yb+) Ions: R. Islam et al. Nature Commun. **2**, 377 (2011) (JQI, U. Md.)

COM (center of mass) mode

"tilt" or "rocking"mode

transverse mode spectrum (detuning from carrier, MHz)

for □force □ □COM

□ spin squeezing, GHZ states

add magnetic field:

for larger detunings (□force > □COM)

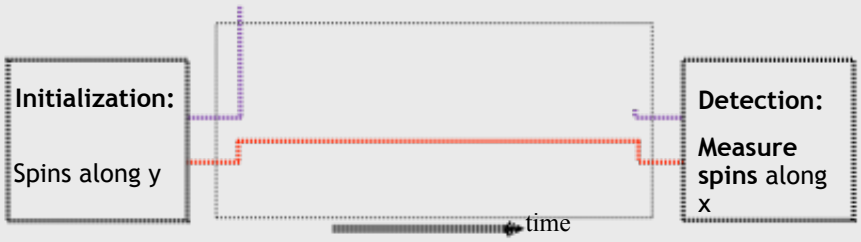
($J_{i,j} > 0$, anti-ferromagnetic)

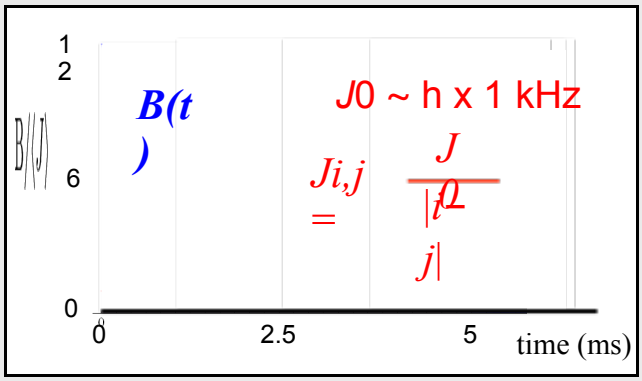
Transverse Ising model

vary □ by varying detuning

Adiabatic Quantum Simulation Protocol

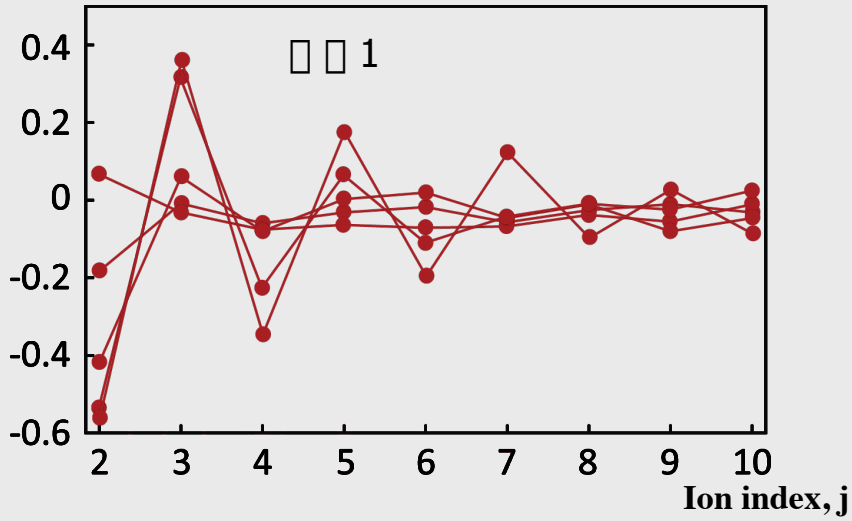
10 ions: Monroe group





Demonstrate coherence by reversing ramp and measuring

measured pair correlation



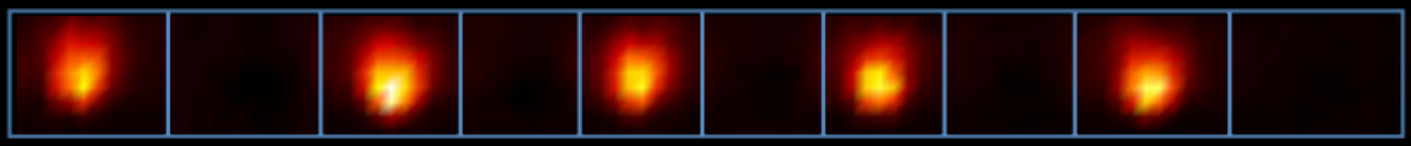
R. Islam et al., *Science* **340**, 583 (2013)

Detection:

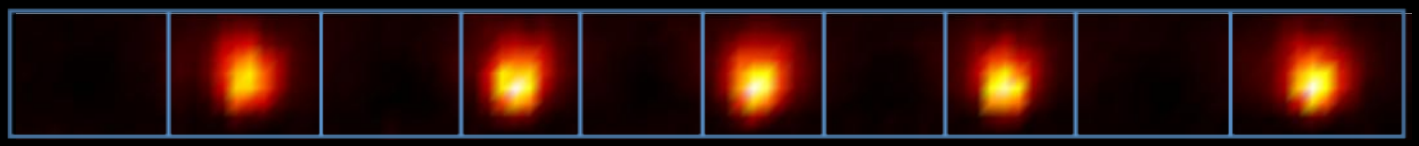
All in state

All in state |-

Anti-ferromagnetic ground state order

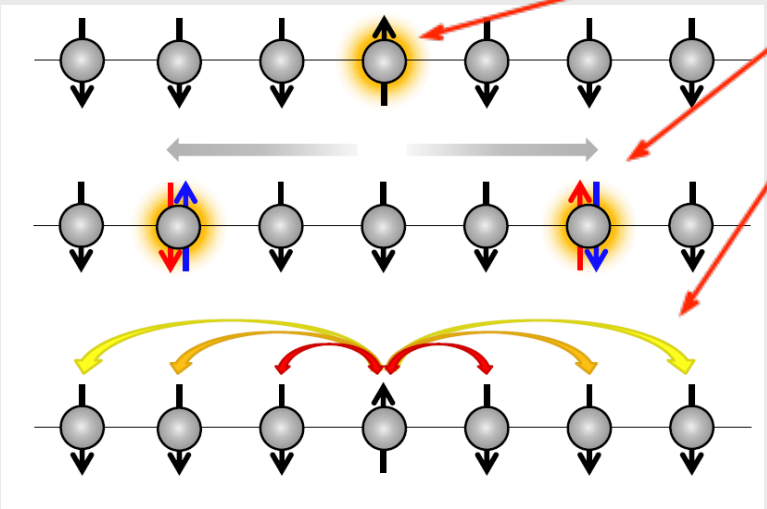


or:

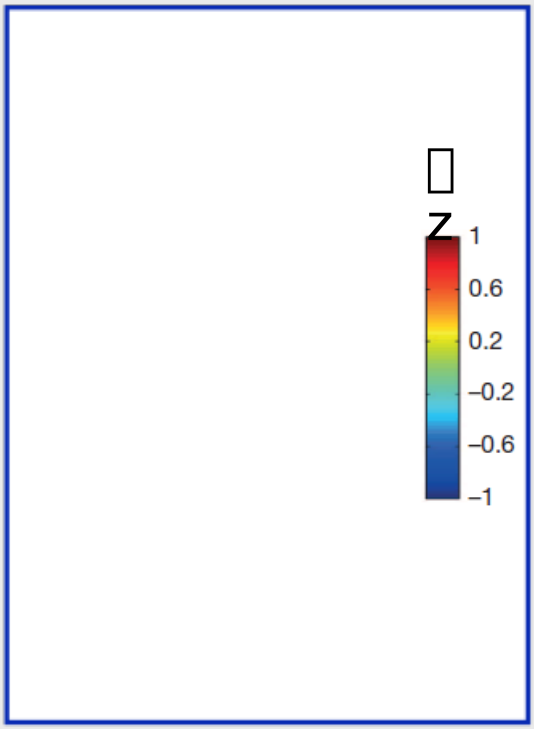


Quasiparticle dynamics

from: P. Jurcevic et al., *Nature* **511**, 202 (2014)



- prepare ground state,
- flip one spin (local quench),
- simulate interaction,
- measure quasiparticle dynamics



Propagation faster than Lieb – Robinson bound
(nearest neighbor interactions)
E.H. Lieb and D.W. Robinson,
"*The finite group velocity of quantum spin systems*,"
Comm. Math. Phys. 28, 251–257 (1972).

see also: P. Richerme *et. al.*, *Nature* **511**, 198 (2014)

Digital quantum simulation:

R. Blatt, C. Roos, Nature Physics **8**, 277 (2012)
B. Lanyon et al., Science **334**, 6052 (2011)

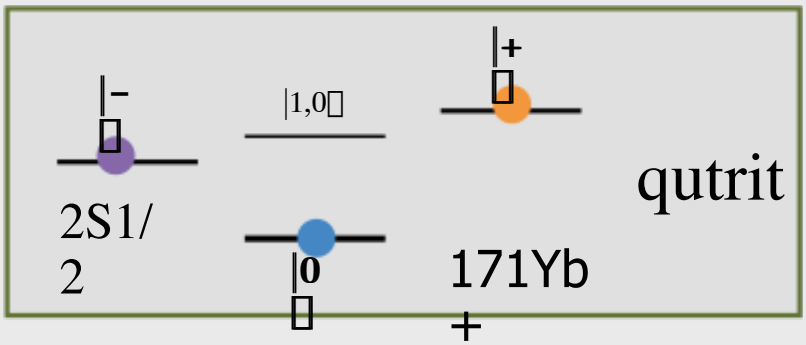
$$H = H_1 + H_2 + \ldots + H_k$$

"Trotterize"

$$e^{-\frac{i}{\hbar}H\,t} = \left(e^{-\frac{i}{\hbar}H_1\,t/n} e^{-\frac{i}{\hbar}H_2\,t/n} \ldots e^{-\frac{i}{\hbar}H_k\,t/n}\right)^n$$

efficient for local computations, S. Lloyd, Science **273**, 1073 (1996)

Spin-1



C. Senko, et al.,
Phys. Rev. X 5, 021026 (2015)

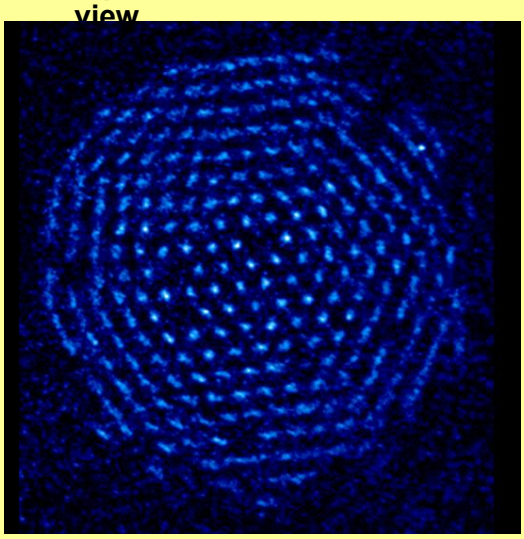
Spectroscopy of excited states

* C. Senko, J. Smith, P. Richerme, A. Lee, W. C. Campbell, C. Monroe, Science **345**, 430 (2014)
* P. Jurcevic, P. Hauke, C. Maier, C. Hempel, B. P. Lanyon, R. Blatt, C. F. Roos, Phys. Rev. Lett. 115, 100501 (2015)

> 20 ions

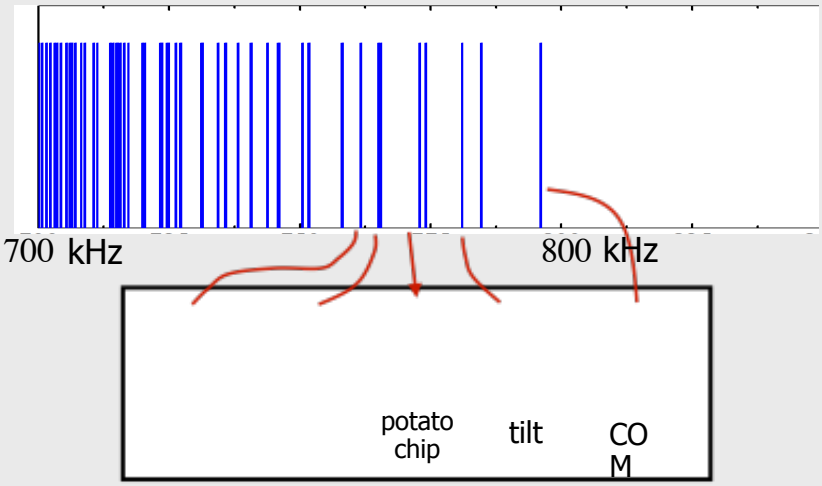
2-D array (Penning trap)
Wigner crystal
(J. Bollinger *et al.*, NIST)

top view



- N □ 100 spins
- "self assembled" triangular lattice

transverse mode spectrum: N □ 200

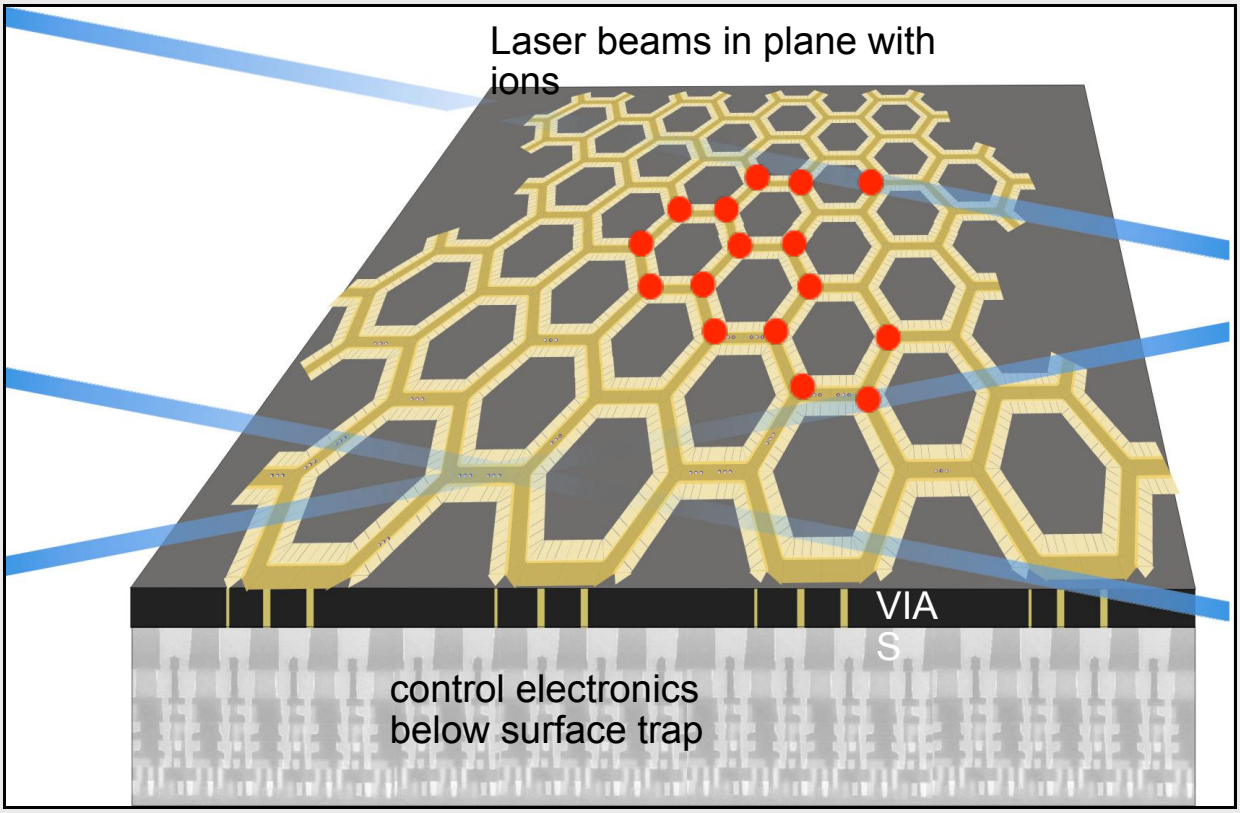


J. Britton et. al., Nature **484**, 489 (2012)
B. Sawyer et al., Phys. Rev. Lett. **108**, 213003 (2012)

Spin squeezing on ~ 200 ions arXiv:1512.03756

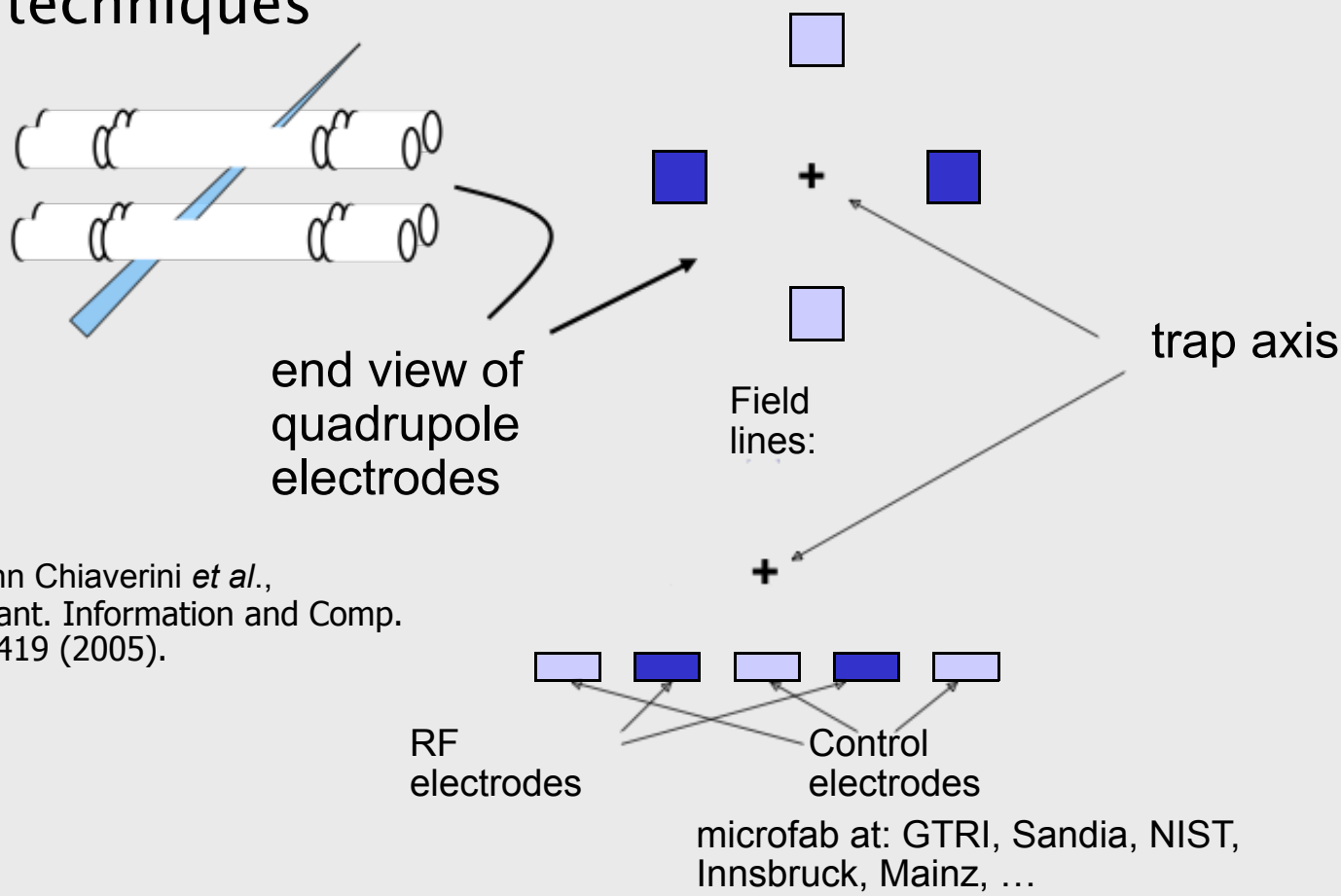
- Observe Ising coupling through dynamics of □Jtotal□
- □ = 0.01 – 2.72 (vary □)
  J0 ~ 1 kHz (□ = 1)

Engineered geometry for simulations



Chiaverini and Lybarger, PRA 77, 022324 (2008)
Schmied, Wesenberg, Leibfried, PRL **102**, 233002 (2009)
Schmied, Wesenberg, Leibfried, New J. Phys. 13 115011 (2011)

surface-electrode traps
→ use lithographic techniques

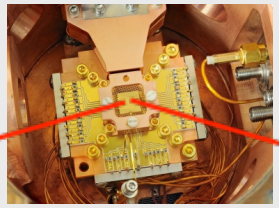


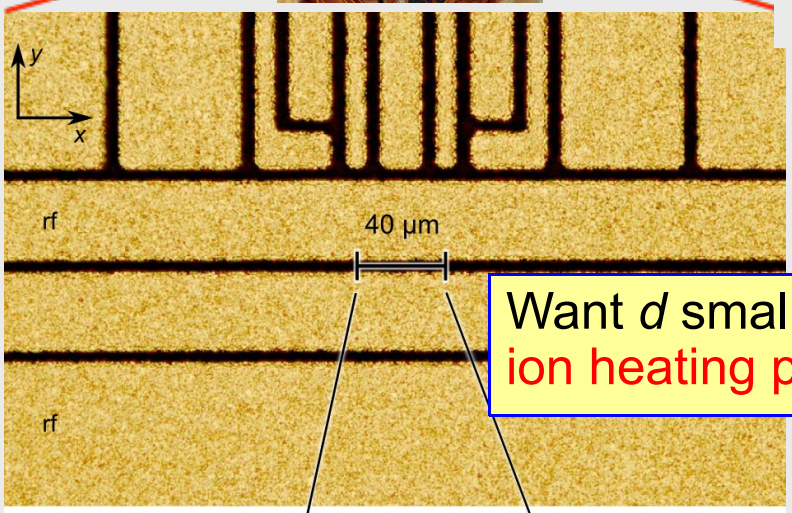
John Chiaverini *et al.*, Quant. Information and Comp. **5**, 419 (2005).

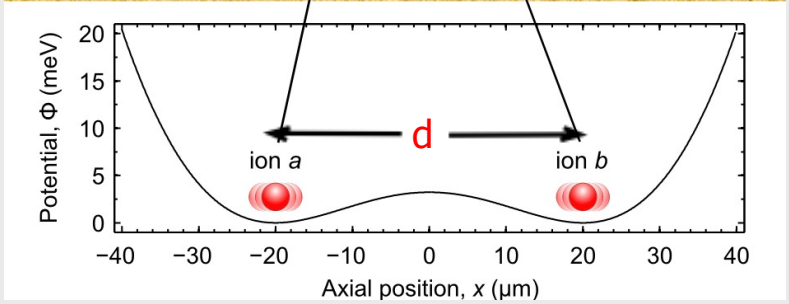
microfab at: GTRI, Sandia, NIST, Innsbruck, Mainz, …

Step 0.1 to engineered geometry: couple ions in separate traps

9Be+ T = 4 K







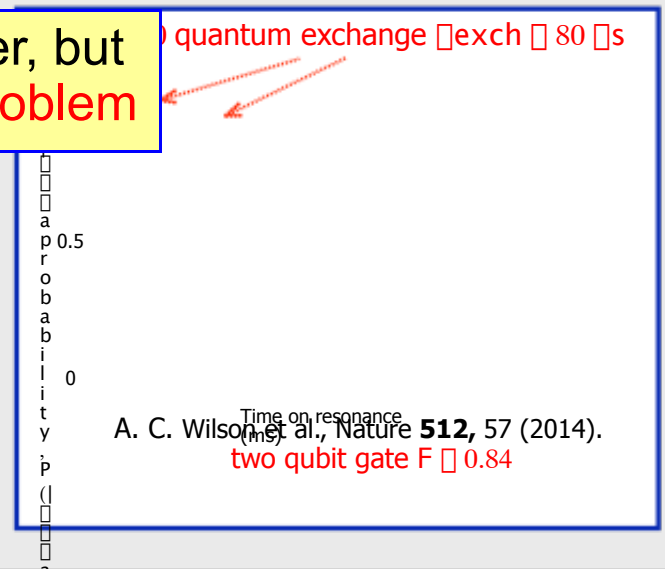
$$H' = \hbar R_{exch}(ab^\dagger + a^\dagger b)$$

$$\frac{\pi}{2\tau_{exch}} = R_{exch} \equiv \frac{q_a q_b}{4\pi\epsilon_0 d^3 \omega_m \sqrt{m_a m_b}}$$

d = 40 μm $\omega_m/2\pi \simeq 4$ MHz

K. R. Brown et al., Nature, **471**, 196 (2011)
M. Harlander et al., ibid, p. 200 (Innsbruck)

Want *d* smaller, but ion heating problem



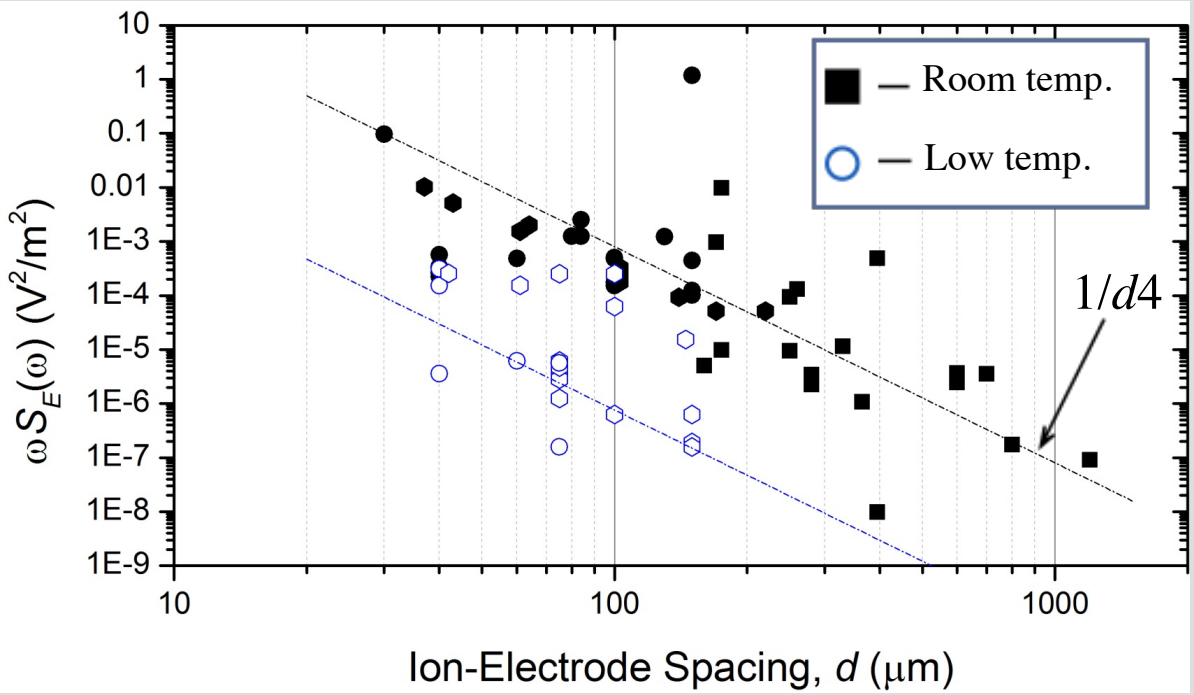
A. C. Wilson et al., Nature **512,** 57 (2014).
two qubit gate F 0.84

Ongoing NIST ion projects:

- "anomalous" electric-field noise heating
- scaling:
  - multi-zone trap arrays
  - fast ion-qubit transport
- inhomogeneous microwave-field 1- and 2-qubit gates
- multi-species logic (e.g. $^{9}Be^{+}$ & $^{25}Mg^{+}$)
- entanglement through dissipation
- entanglement via "quantum-zeno dynamics"
- quantum-logic clock
- SNSPD's

(Superconducting Nanowire Single-Photon transition-edge Detectors)

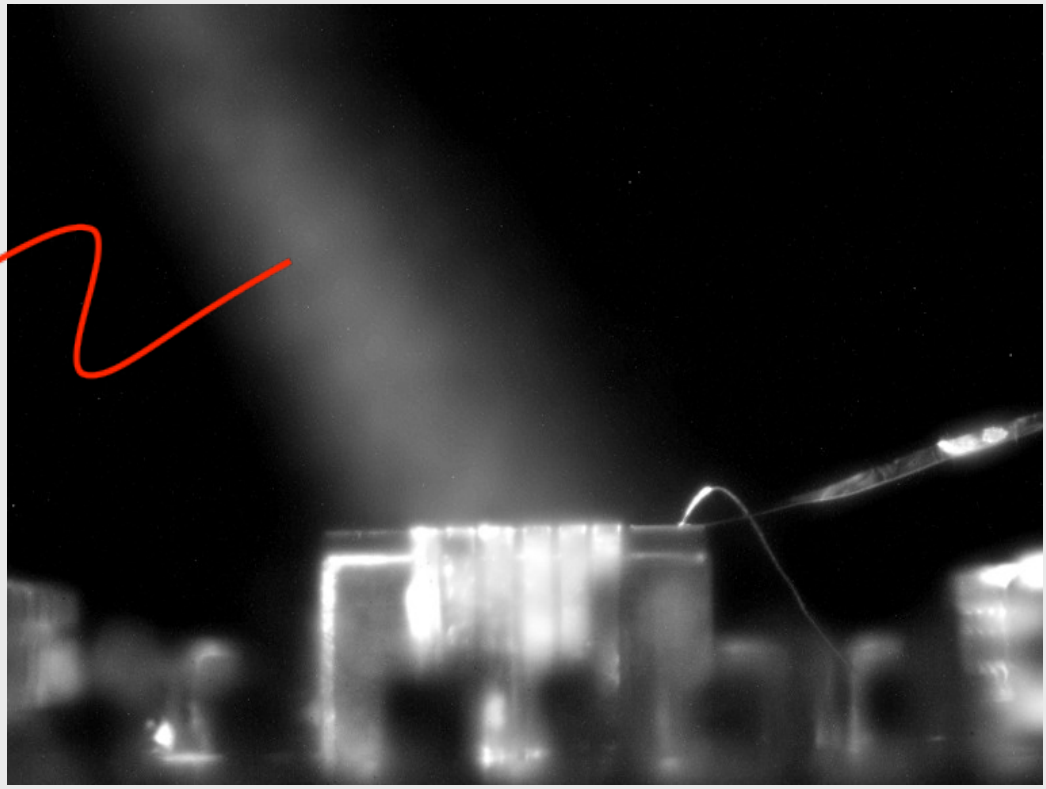
Perennial problem
"anomalous" ion heating



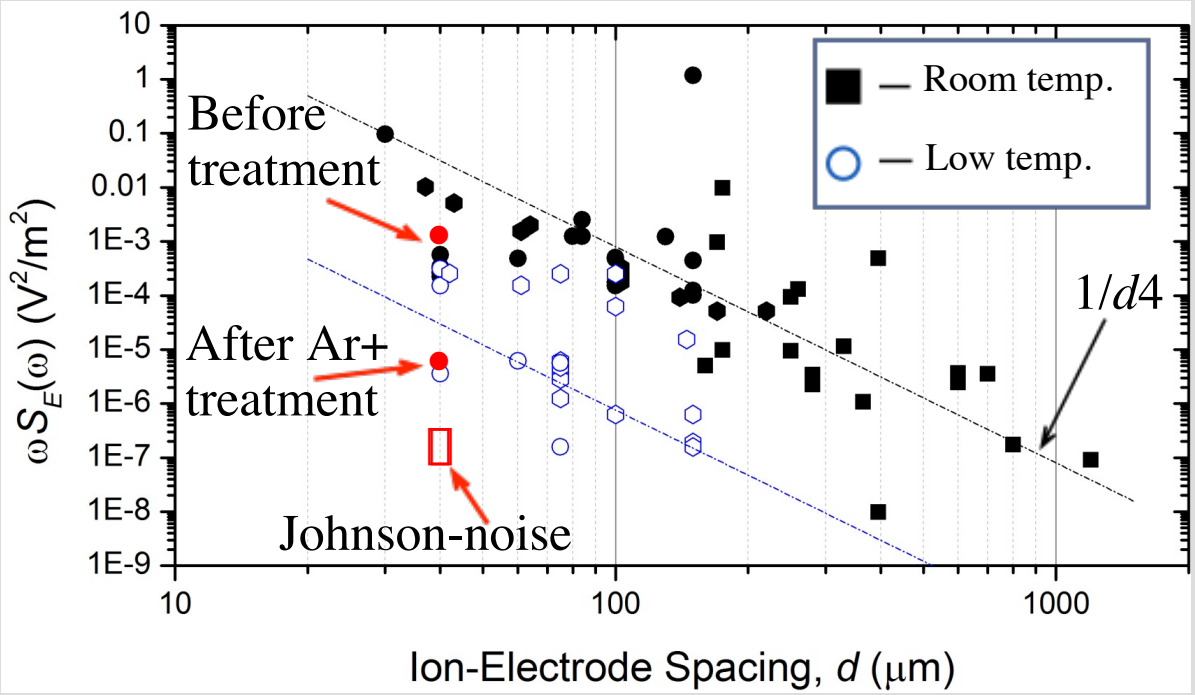
Enter surface science techniques:

collaboration with D. Hite, K. McKay, D. Pappas (NIST, Boulder)

Ar+ beam cleaning



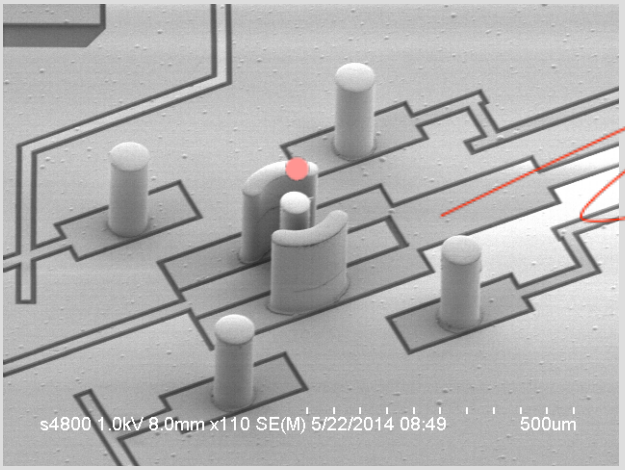
“anomalous” ion heating

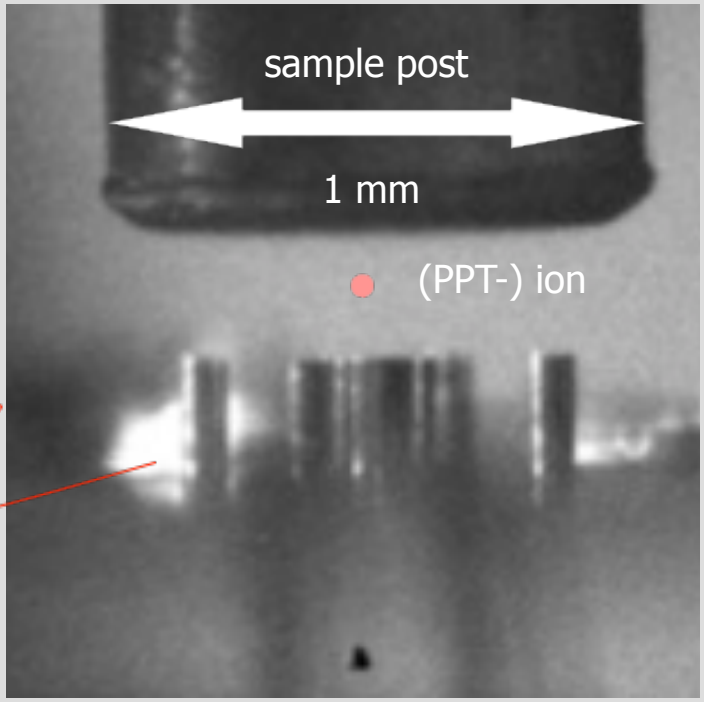


D. A. Hite et al., PRL **109**, 103001 (2012) (Ar+ beam sputtering)
N. Daniilidis et al., PRB **89**, 245435 (2013) (H. Haeffner group, Berkeley, similar improvement)

“Anomalous” heating studies

- target heating rate dn/dt < 10-4/tgate
- noble gas sputtering reduces heating from gold/Cu-Al surfaces by factor 100
- try to find root causes
- stylus trap/surface science experiments

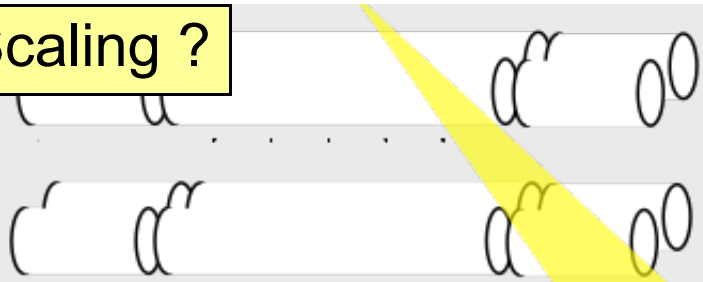




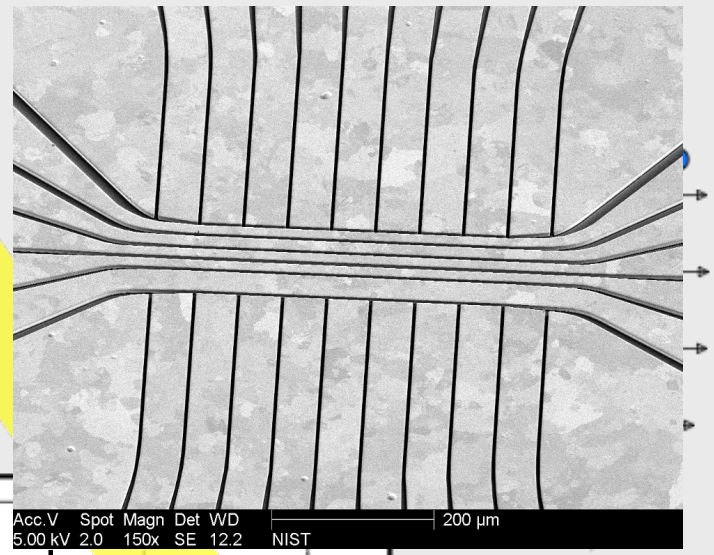
collaboration with D. Hite, K. McKay, D. Pappas (NIST),
Chris Arrington et al. (Sandia), Hossein Sadeghpour et al. (ITAMP/Harvard)

Scaling ?

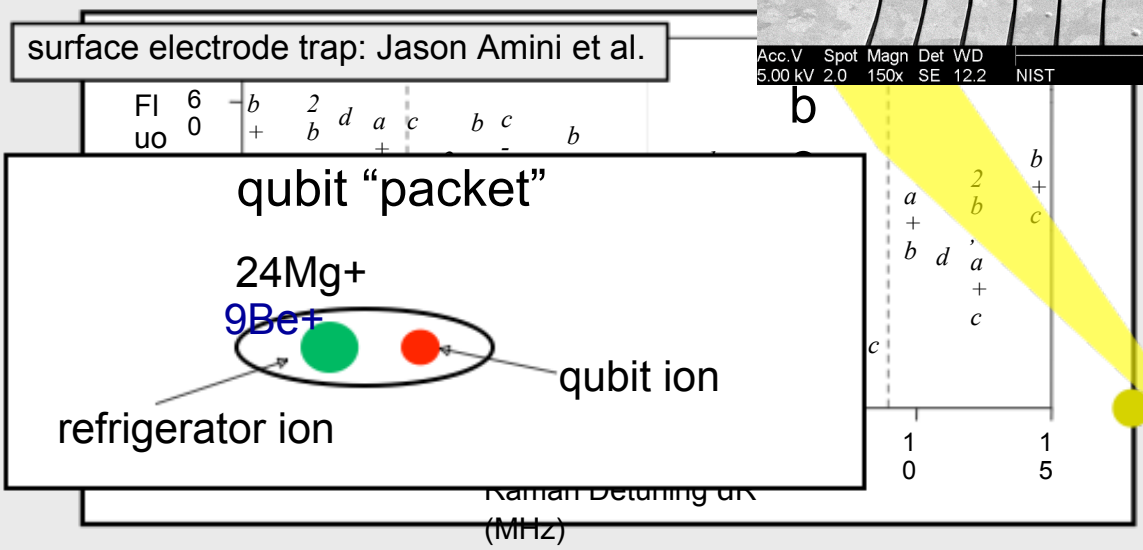
Scale up?



Mode competition –
example: axial modes, N = 4 ions



surface electrode trap: Jason Amini et al.



qubit "packet"

24Mg+

9Be+

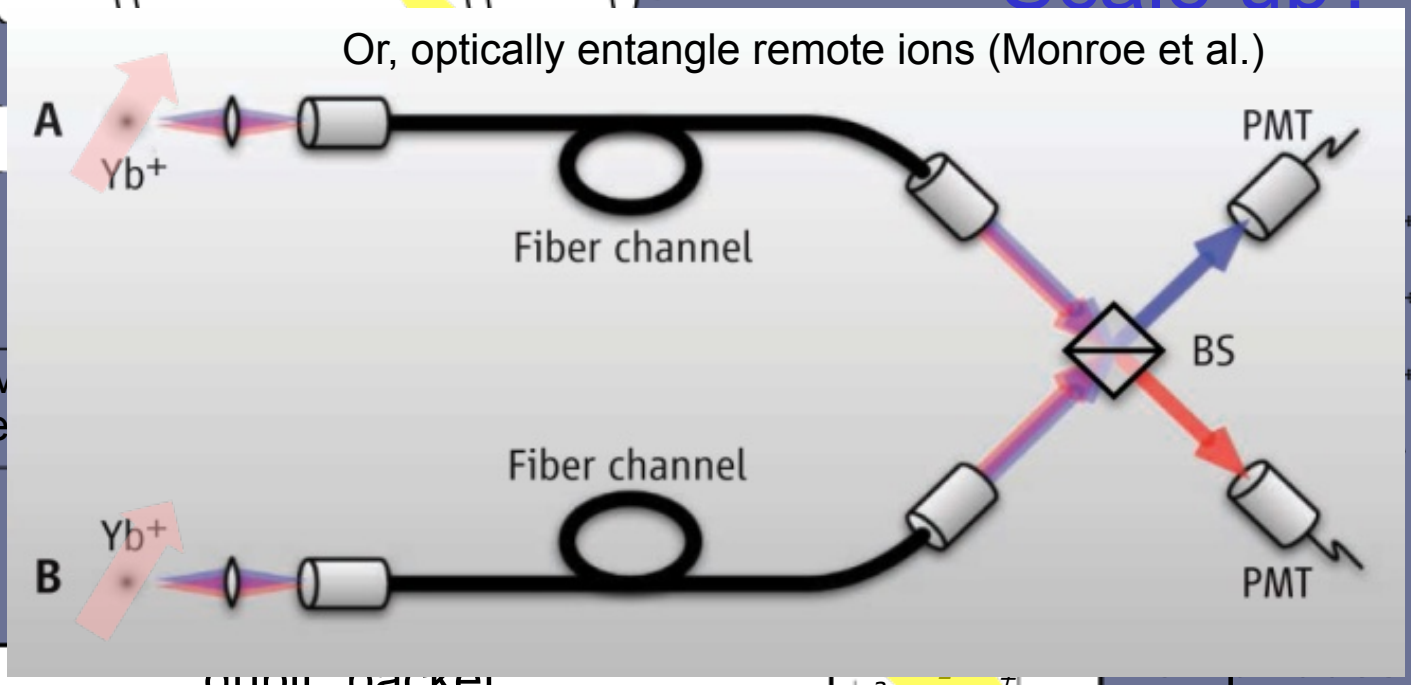
qubit ion

refrigerator ion

Scaling ?

Scale up?

Or, optically entangle remote ions (Monroe et al.)



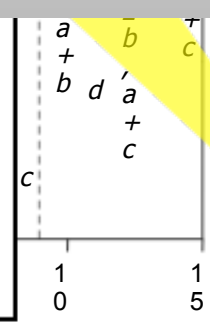
qubit packet

24Mg+

9Be+

qubit ion

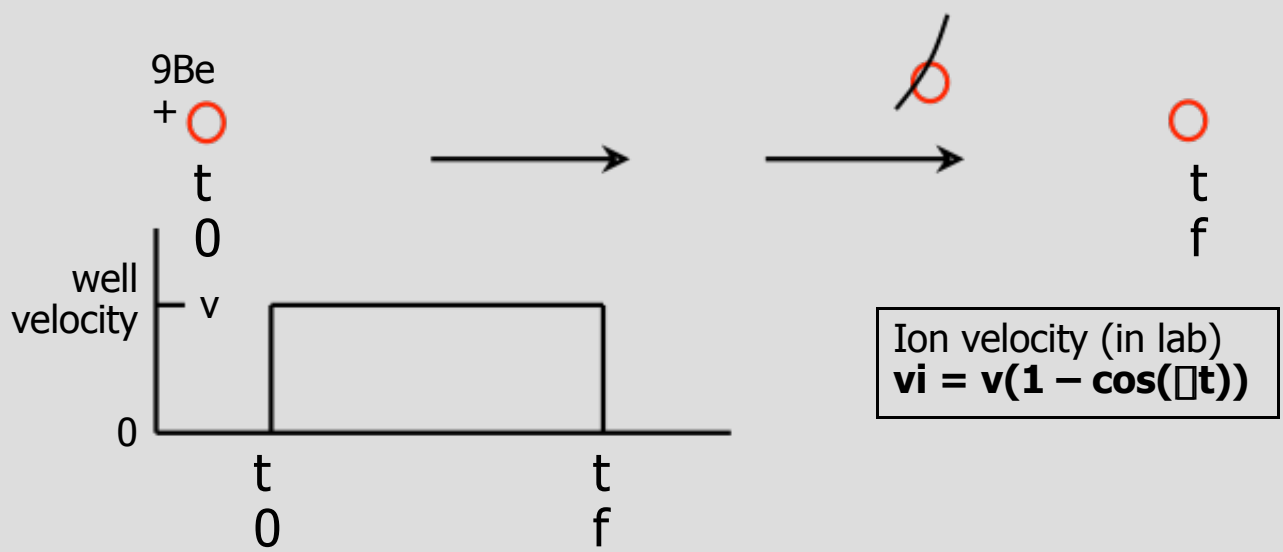
refrigerator ion



Raman Detuning dR (MHz)

Diabatic transport

Basic idea:



Ion velocity (in lab)
vi = v(1 – cos(□t))

- ion at rest for tf = = N x 2□/□
- can move arbitrarily fast and keep ion(s) near ground state

R. Bowler et al., Phys. Rev. Lett. **109**, 080502 (2012).
A. Walther et al., Phys. Rev. Lett. **109**, 080501 (2012) (Schmidt-Kaler group; Mainz)

Future:

- More and better: more qubits; better fidelity
  - use cleaning techniques, make smaller traps
  - incorporate optical fibers
- simulation
- atomic ion, molecular ion spectroscopy
- hybrid systems?
- ?????

Back row:
Dave Leibrandt, John Bollinger, Christoph Kurz, Kevin Gilmore, Shon Cook, Raghu Srinivas,
Dave Hume, David Allcock, Shaun Burd, Jwo-Sy Chen, Jim Bergquist, Sam Brewer, Dave Wineland
Front row:
Justin Bohnet, Kyle McKay, Yao Huang, James Chou, Susanna Todaro, Katie McCormick, Daniel Slichter,
Didi Leibfried, Aaron Hankin, Stephen Erickson, Andrew Wilson, Yong Wan, Ting Rei Tan