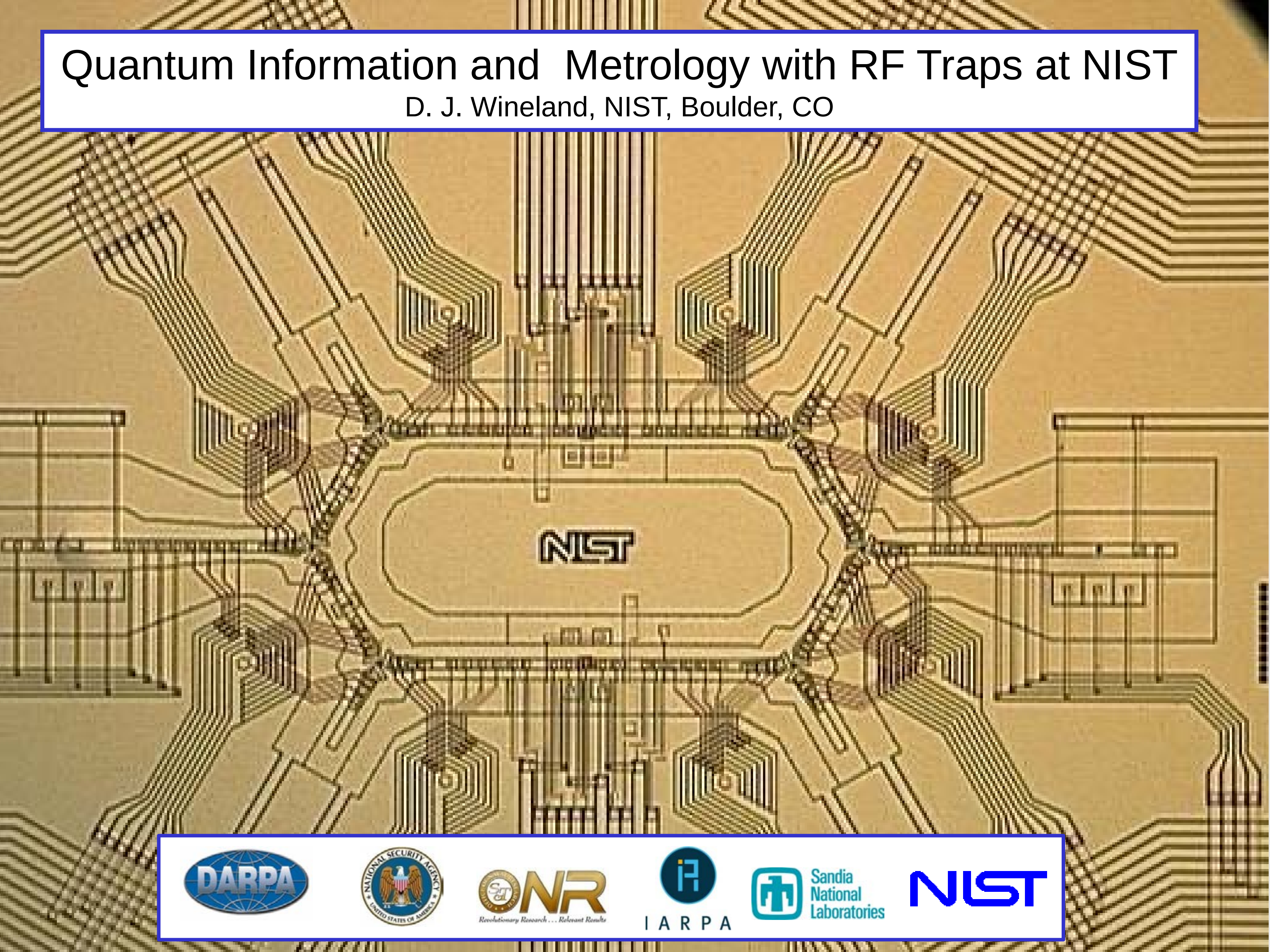
Quantum Information and Metrology with RF Traps at NIST

D. J. Wineland, NIST, Boulder, CO



DARPA
ONR
Revolutionary Research . . . Relevant Results
IARPA
Sandia National Laboratories
NIST

NIST- Boulder ions:

J. Amini (PostDoc, Berkeley)‡
J. C. Bergquist (NIST)
S. Bickman (PostDoc, Yale) &
M. Biercuk (GTRI) %
R. B. Blakestad (student, CU)♣
J. J. Bollinger (NIST)
R. Bowler (student, CU)
J. Britton (PostDoc, CU)
K. Brown (PostDoc, U. Md.)
J. Chou (PostDoc, Cal Tech)
Y. Colombe (PostDoc, ENS)
D. Hanneke (PostDoc, Harvard)
J. Home (PostDoc, Oxford) @
D. Hume (student, CU) †

W. Itano (NIST)
J. D. Jost (PostDoc, CU)
E. Knill (NIST)*
D. Leibfried (NIST)
D. Leibrandt (PostDoc, MIT)
Y. Lin (student , CU)
C. Ospelkaus (PD, Hamburg)
T. Rosenband (NIST)

T –R Tan (Student, CU)
M. Thorpe (PostDoc, CU)
H. Uys (PostDoc, U. Arizona) #
A. VanDevender (PD, U. Illinois)
U. Warring (PD, Heidelberg)
A. Wilson (guest researcher)
D. J. Wineland (NIST)
J. Yao (student , CU)

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‡ Current address: Georgia Tech. Res. Inst.
# Current address: CSIR, South Africa
% Current address: University of Sydney
& Current address: Vescent Photonics, Denver
@ Current address: ETH, Zürich
♣ Current address: JQI, U. Md.

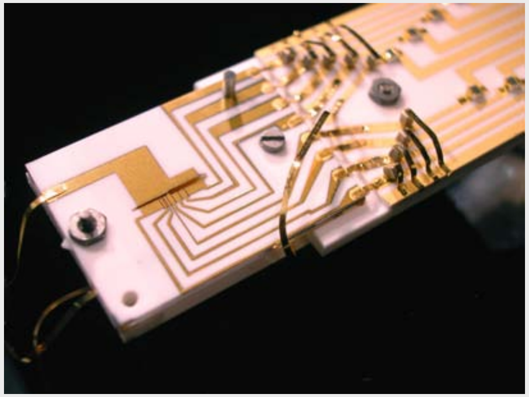
Summary:

- scaling to larger systems (increase fidelity and number)
  - best 2-qubit gates (Innsbruck) $\varepsilon < 0.01$
  - ion arrays
    - * transporting quantum information
    - * trap fabrication & steps toward simulation
    - * qubit detection (integrated optics)
    - * low-temperature traps
    - * scaling with gates
  - alternate strategies?, e.g., microwave gates
- metrology, e.g. atomic clocks
- prospects

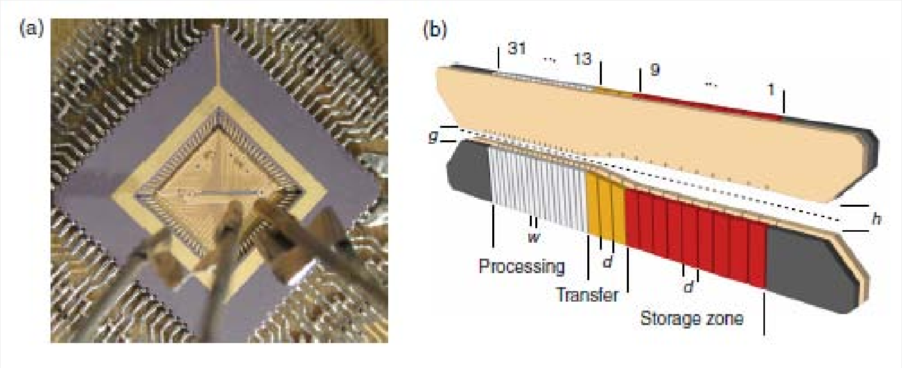
Multiplexed trap arrays

Examples:

Linear arrays:

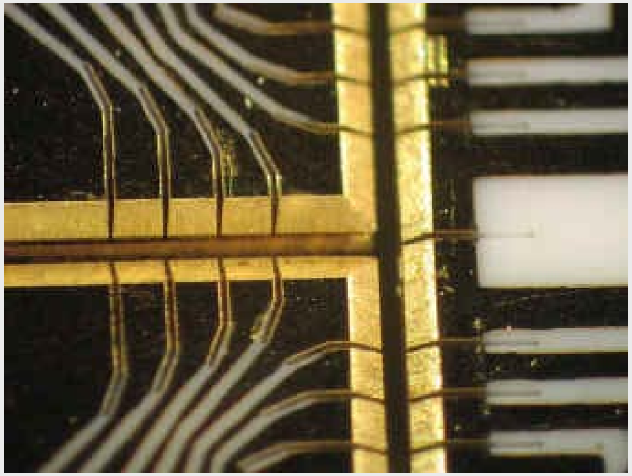


NIST (M. Rowe *et al.,*
Quant. Inf. Comp. **2**, 257 (2002))

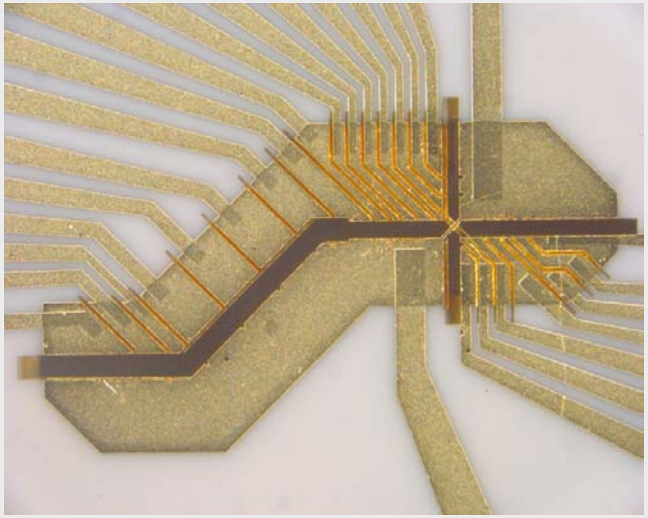


S. A. Schulz *et al*., New J. Phys. **10,** 045007 (2008)
Schmidt-Kaler group

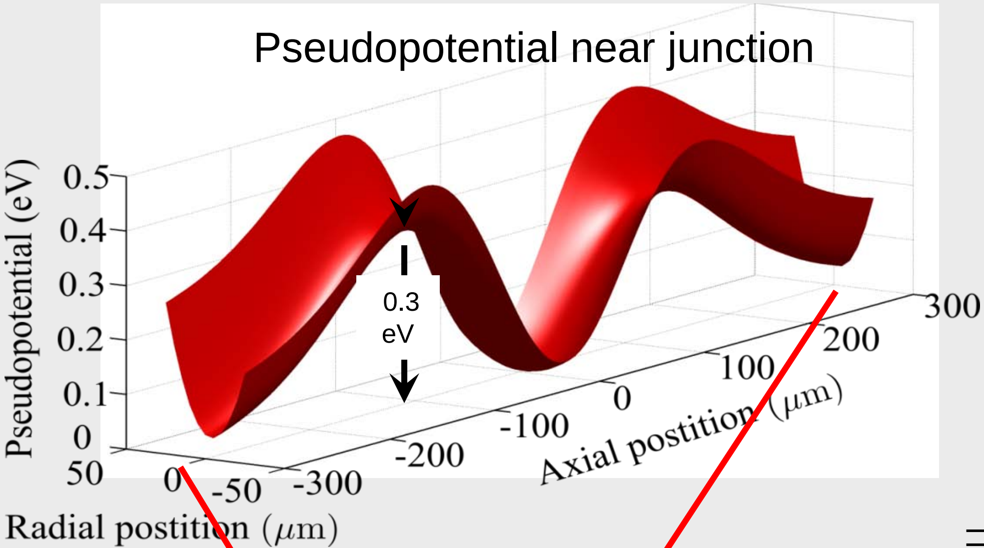
Traps with junctions (2-D):



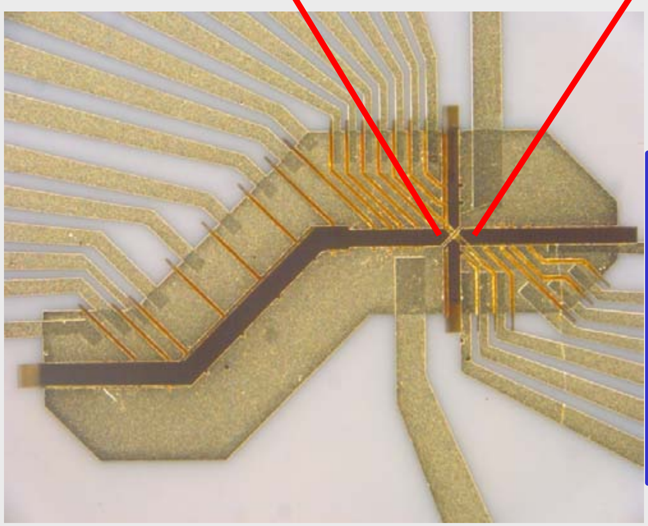
W. Hensinger *et al.*, (Monroe group)
Appl. Phys. Lett. **88**, 034101 (2006)



R. Blakestad et al., (NIST)
PRL **102**, 153002 (2009)



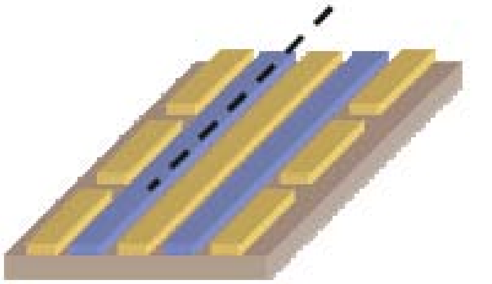
Maxwell:
harmonic confinement
⇒ pseudopotential bumps
(J. H. Wesenberg, PRA 78, 063410 (2008))



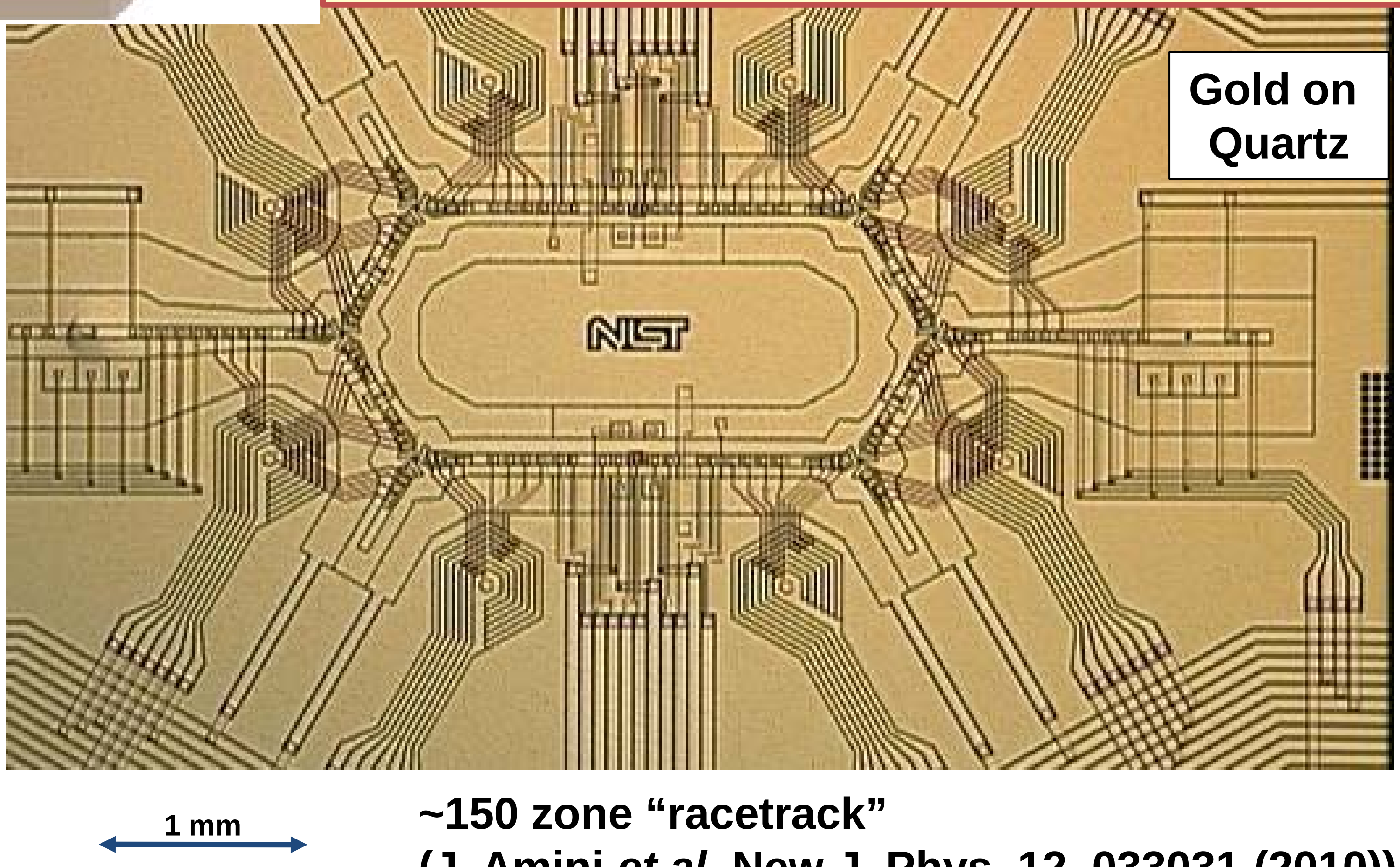
- primary heating mechanisms identified
  - ◊ RF noise at $\Omega_{RF} \pm \omega_z$
  - ◊ DAC updating rate
- heating < 1 quantum/transfer

(R. Blakestad et al.,
PRL **102**, 153002 (2009))

Surface-electrode traps



- repeatable component library
- two-layer construction with vias
- “backside” loading
- transport in linear sections and through “Y” junctions

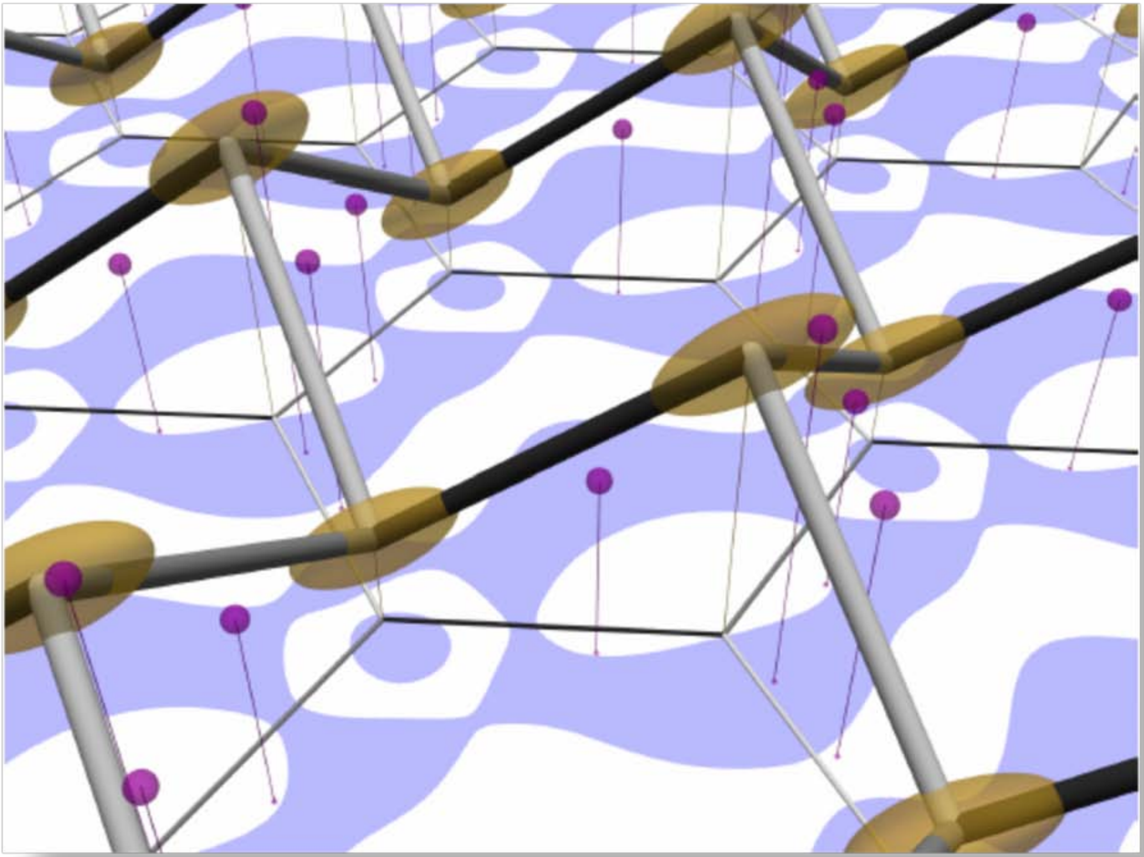


~150 zone “racetrack”
(J. Amini *et al.* New J. Phys. 12, 033031 (2010))

Surface traps ⇒ one route to complex simulations

More general Heisenberg/Ising-type couplings :

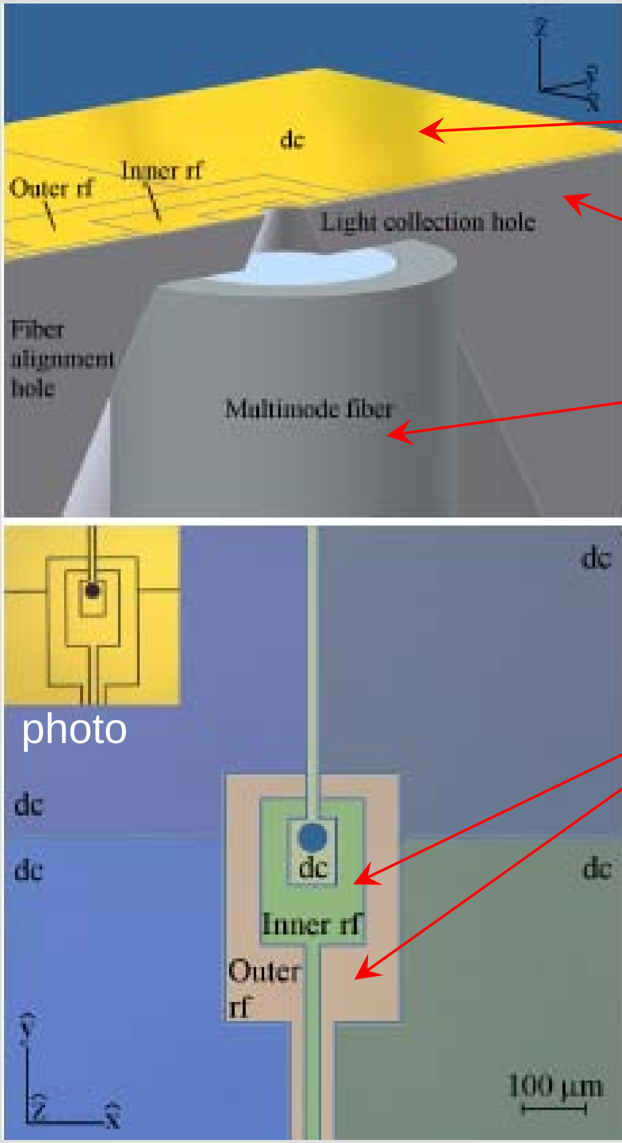
$\sigma_x^{(i)}\sigma_x^{(j)}, \sigma_y^{(i)}\sigma_y^{(j)}, \sigma_z^{(i)}\sigma_z^{(j)}$ like two qubit-gates



R. Schmied, J. Wesenberg, D. Leibfried
PRL **102**, 233002 (2009)

Integrated Optics

Problem with ions: charging of optics



evaporated gold

quartz substrate

quartz fiber NA = 0.37, 2.1% collection

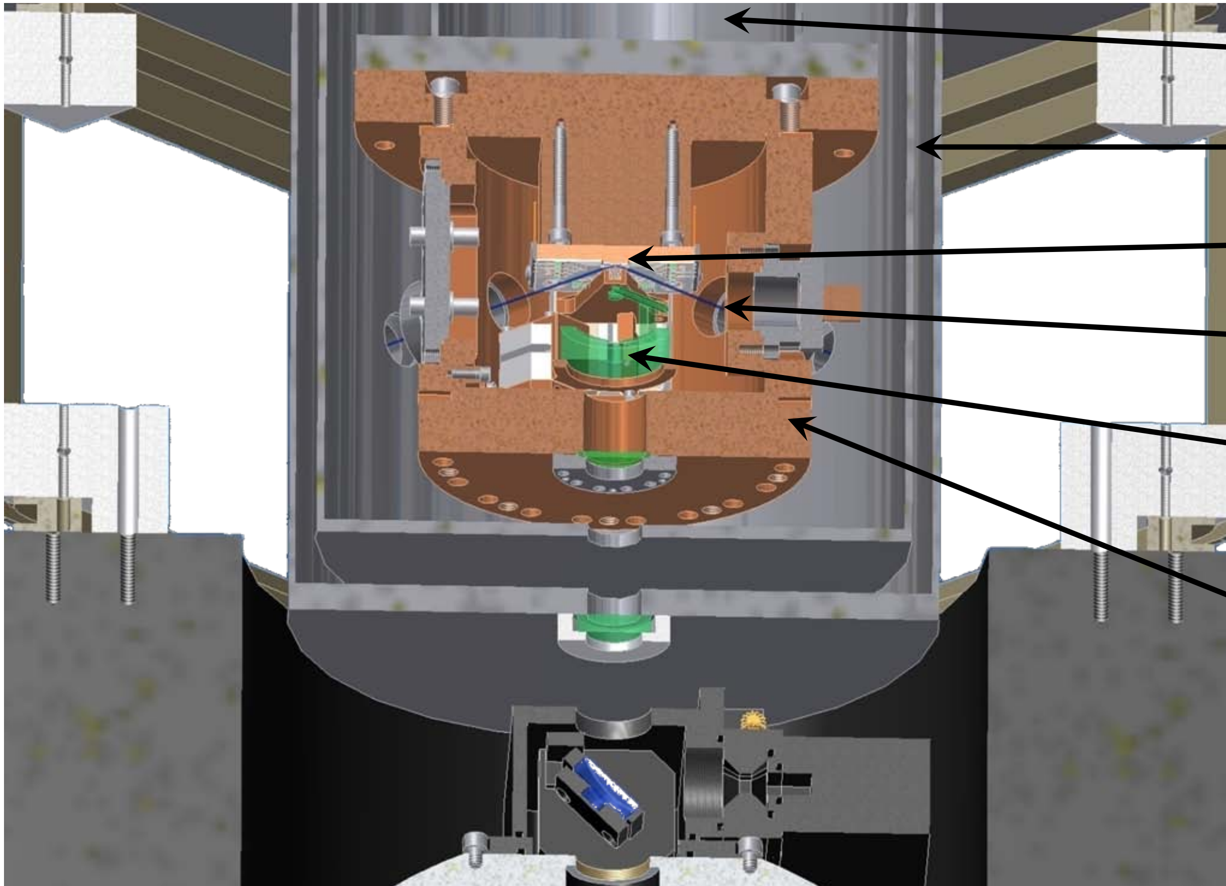
η(fiber) = 0.3 x η(multi-element lens, NA = 0.5)

Control height
with differential RF

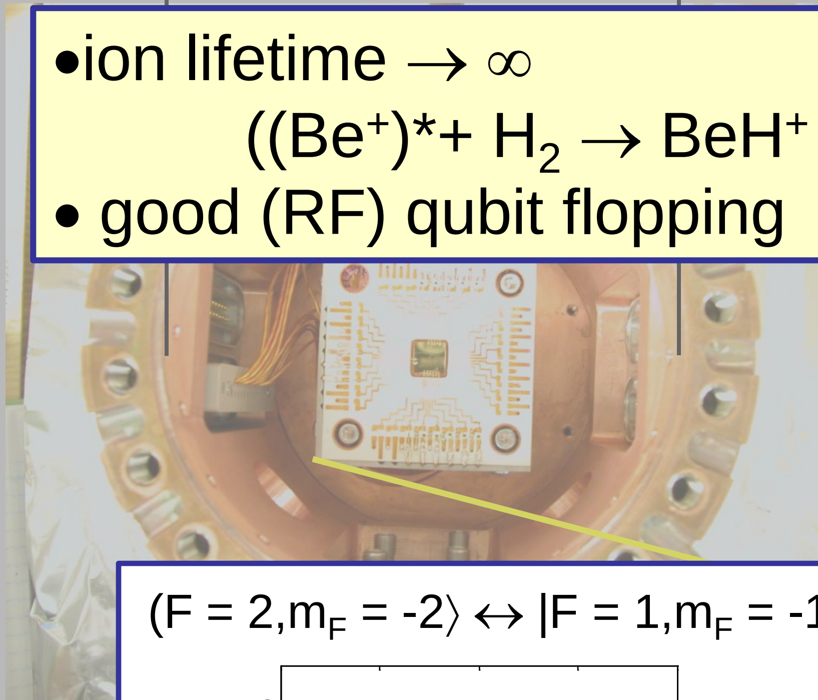
Aaron VanDevender, Yves Colombe *et al.*,
PRL **105**, 023001 (2010)
(in collaboration with Sandia National Labs)

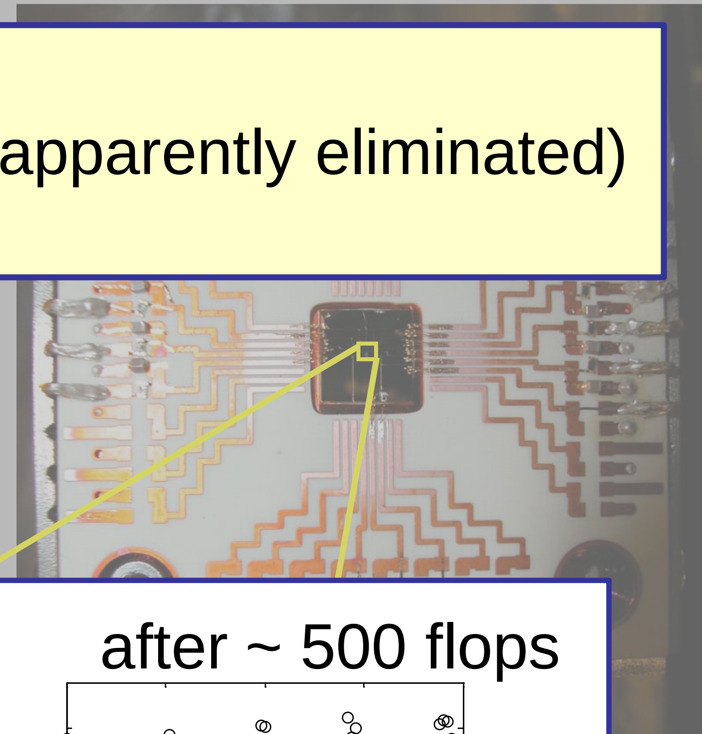
Cold Trap (4 K)

Kenton Brown, Christian Ospelkaus, Yves Colombe, Andrew Wilson



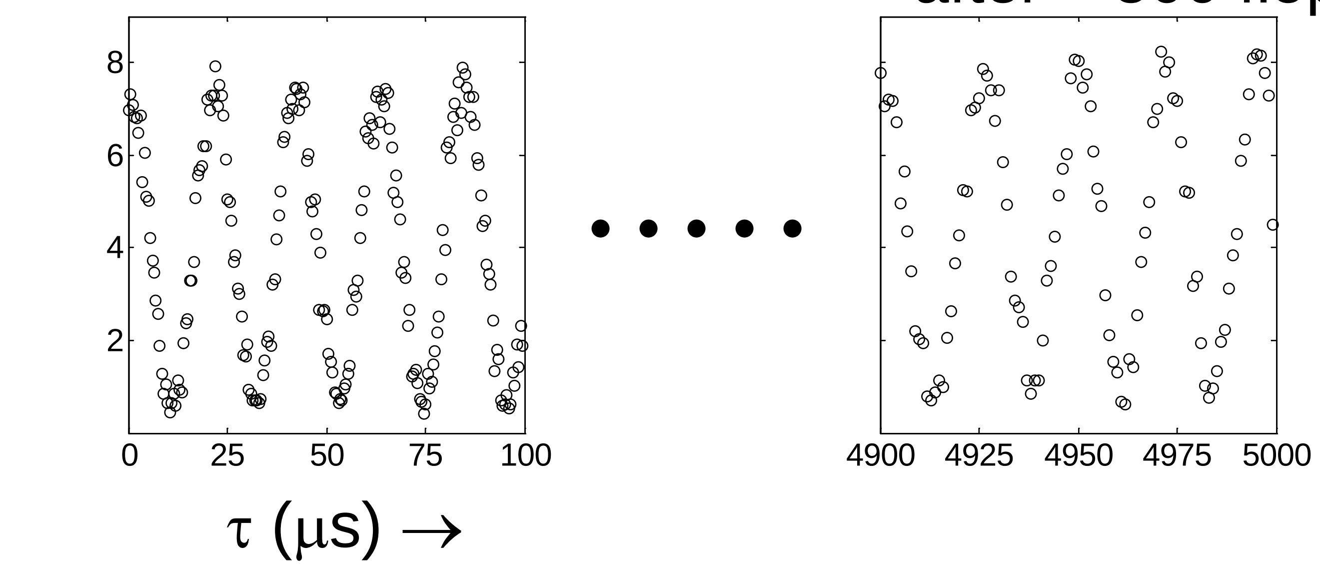
~ 20 cm





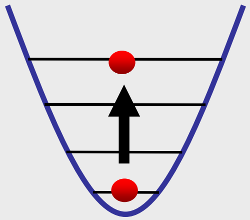
- ion lifetime $\rightarrow \infty$

  $((Be^+)^* + H_2 \rightarrow BeH^+ + H$ apparently eliminated)
- good (RF) qubit flopping

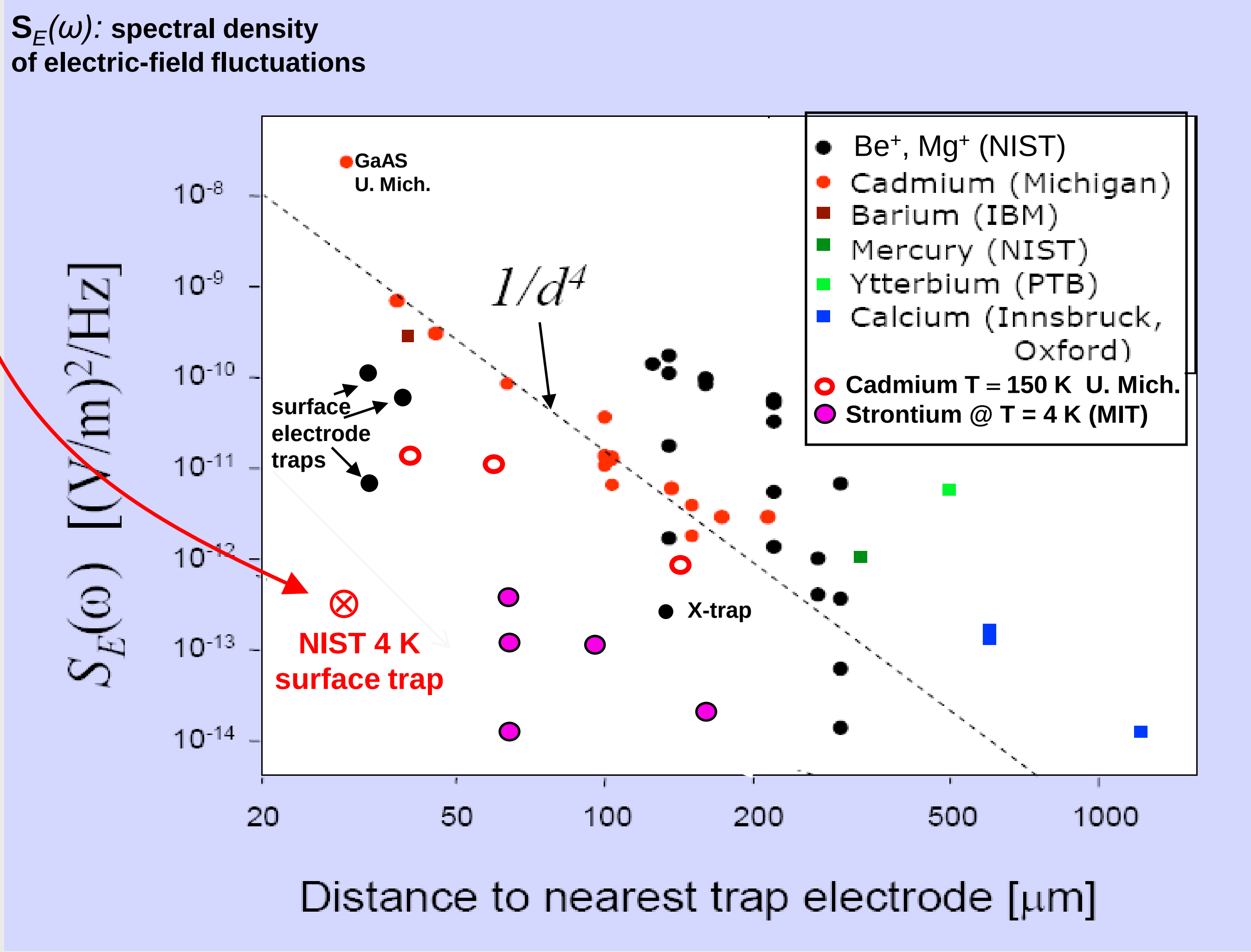


(backside illumination)

Low heating (sometimes)



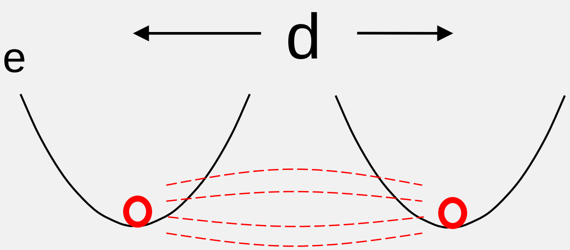
$$\dot{\bar{n}} = \frac{e^2}{4m\hbar\omega} S_E(\omega)$$



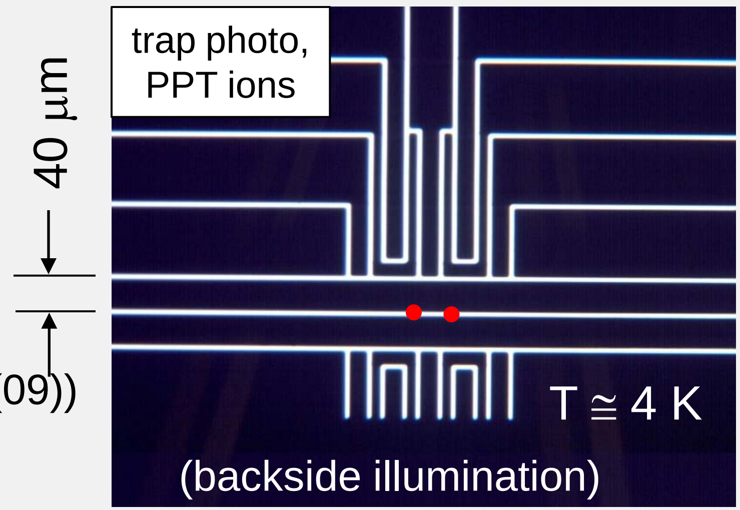
Deslauriers *et al.* PRL **97** (2006) and R. J. Epstein, *et al.* PRA **76** 033411-1 (2007)

Coupling ions in separate wells

$\tau_{exchange} \propto d^3$

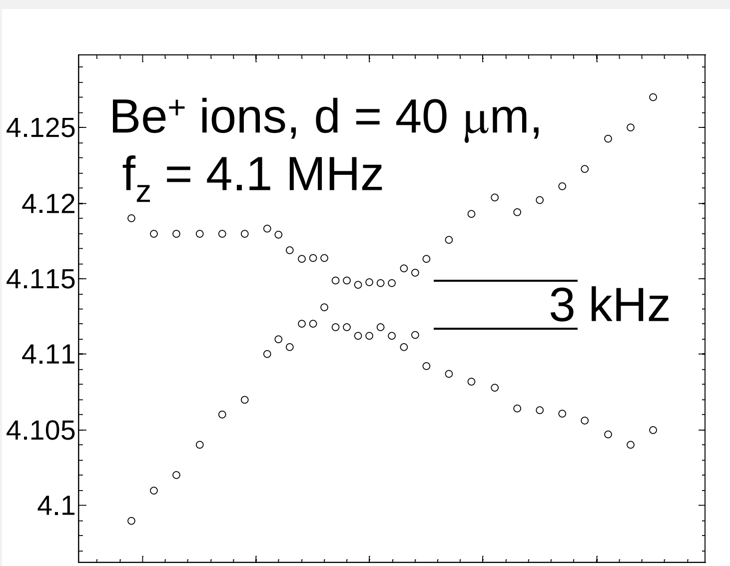


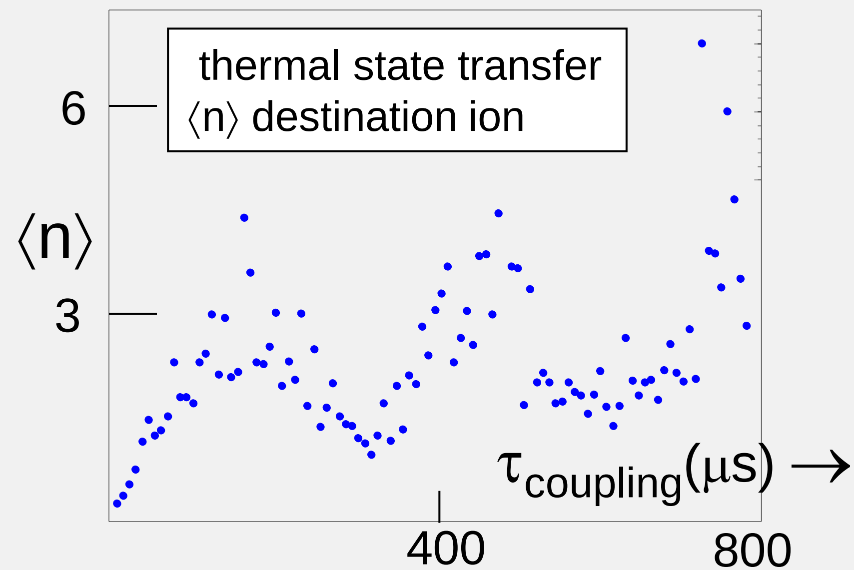
5-zone "4-wire" surface-electrode test trap (Au on crystaline quartz)



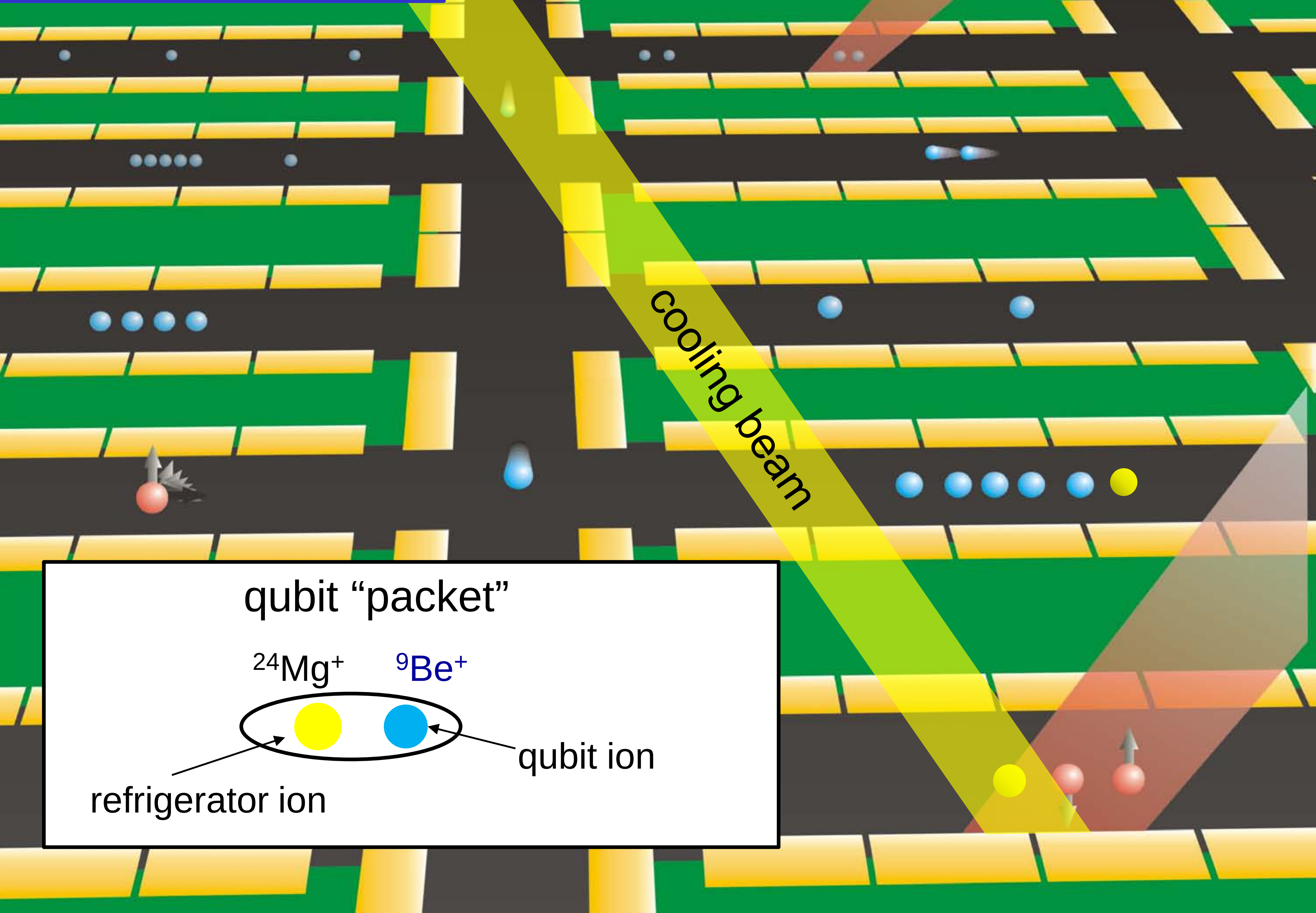
- generalization of quantum-logic spectroscopy (D. Heinzen, DJW, PRA **42** 2977 (1990))
- step towards coupling to other quantum systems
- new entanglement schemes
- precursor to arrays for simulation

(e.g. Schmied, Wesenberg, Leibfried PRL **102**, 233002 (09))

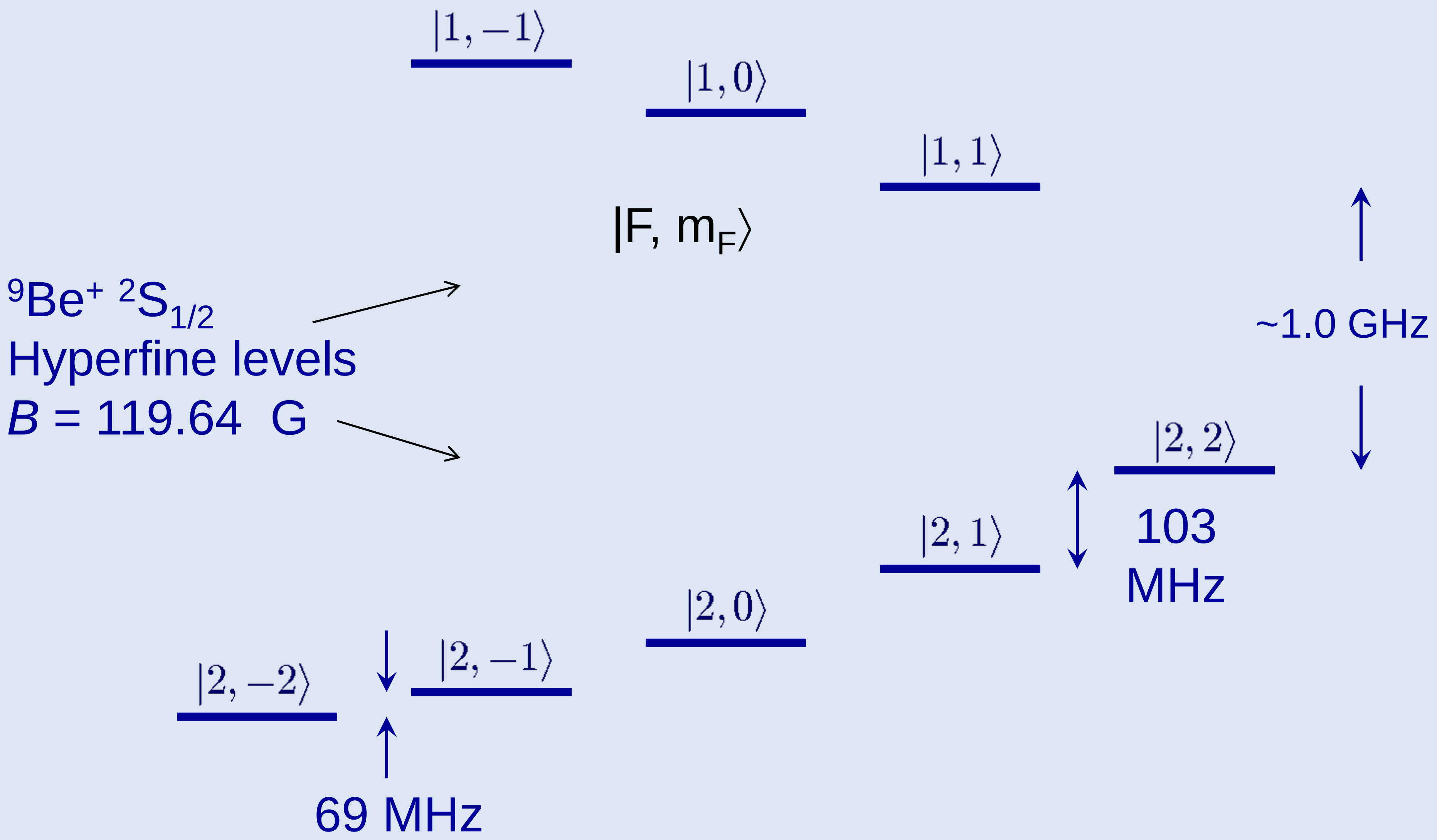




Scaling with gates



"hybrid" qubit system



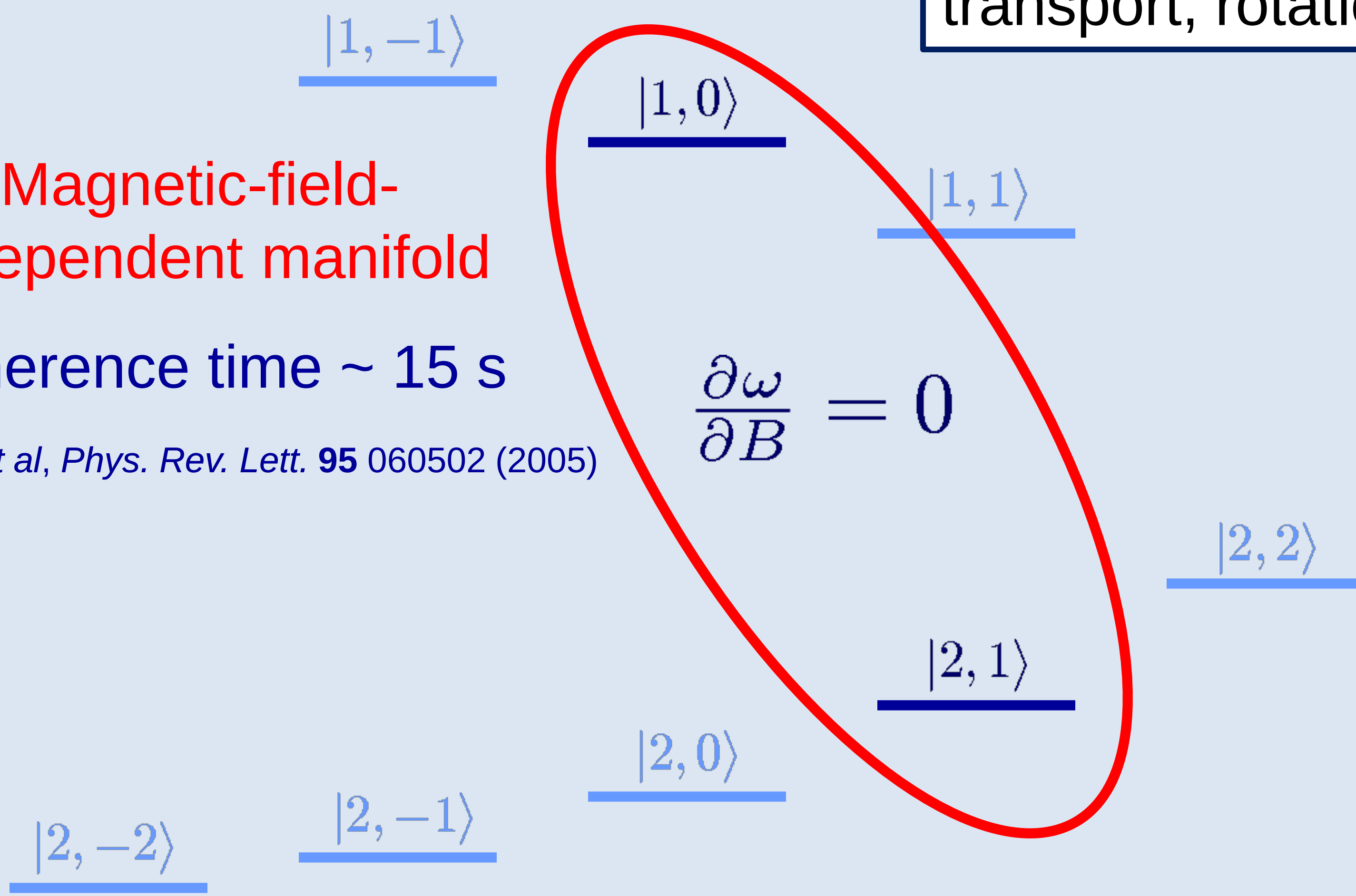
“hybrid” qubit system

qubit for memory, transport, rotations

Magnetic-field-independent manifold

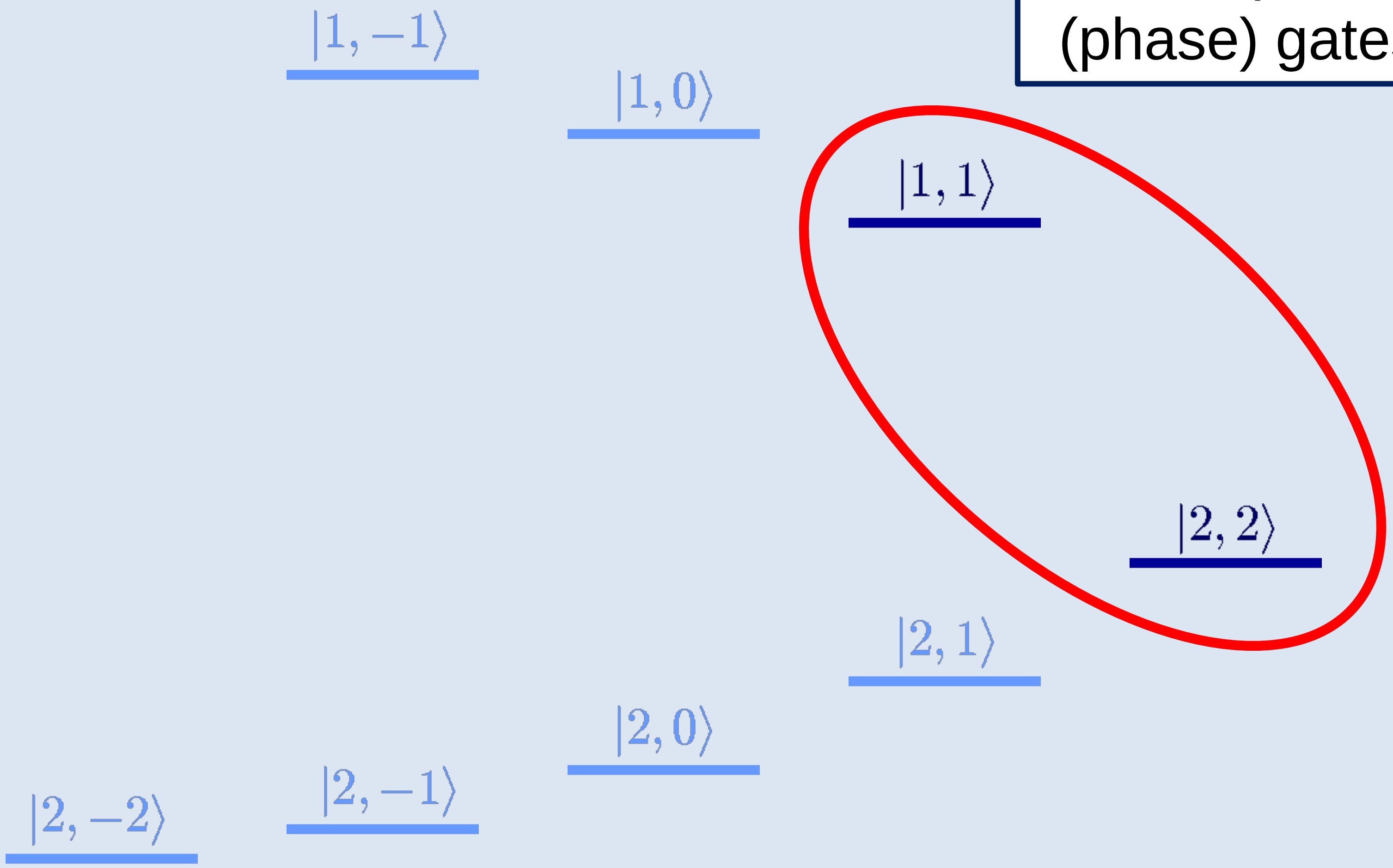
Coherence time ~ 15 s

C. Langer, *et al*, *Phys. Rev. Lett.* **95** 060502 (2005)



“hybrid” qubit system

qubit for
two-qubit
(phase) gates

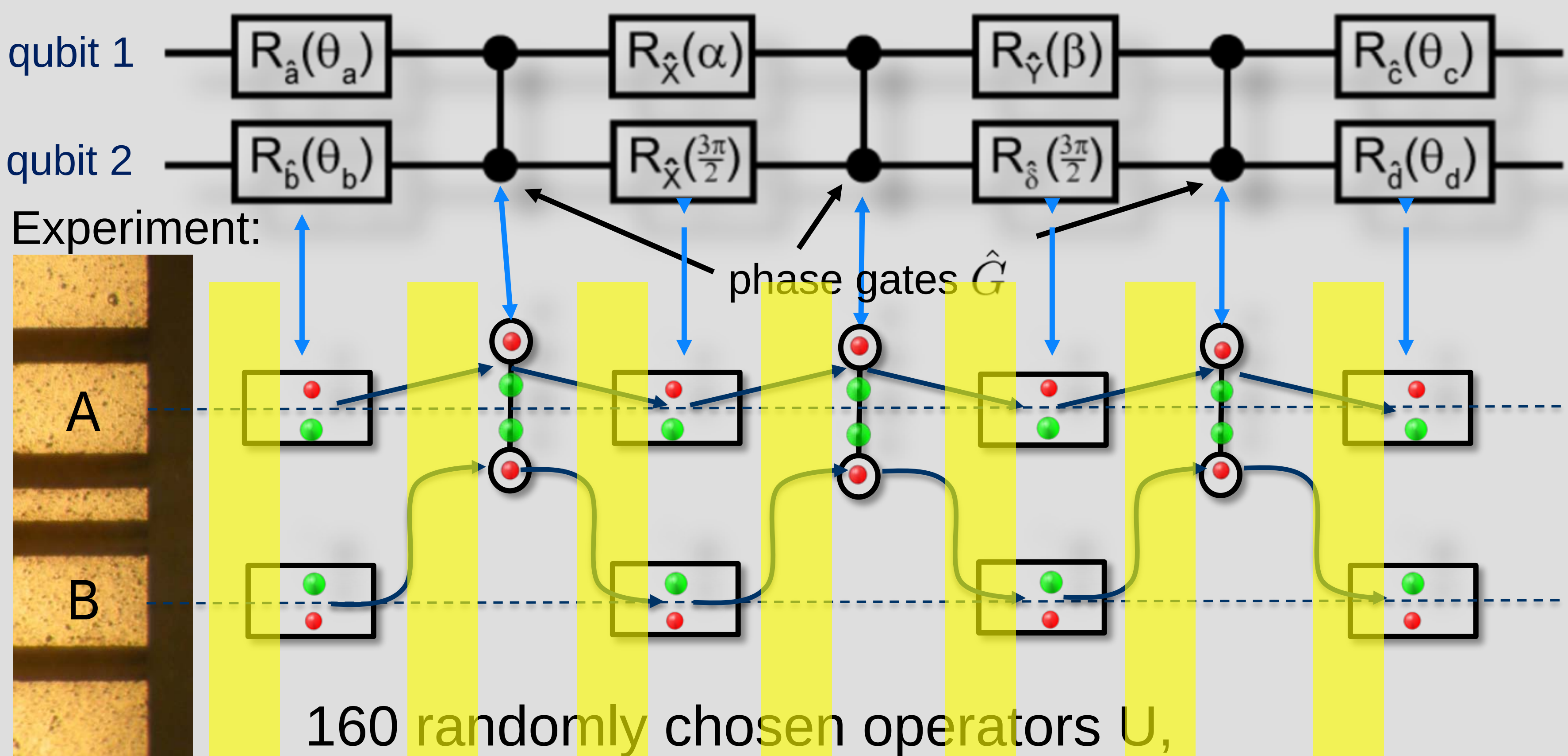


Programmable (universal) 2-qubit quantum processor

(David Hanneke, Jonathan Home, John Jost *et al.*, *Nature Physics* **6**, 13 (2010).)

Theory: arbitrary unitary U (SU4):

B. Kraus and J. I. Cirac, Phys. Rev. A **63** 062309 (2001)
V. V. Shende, *et al*, Phys. Rev. A **69** 062321 (2004)



160 randomly chosen operators U,

apply to $\Psi_1 \otimes \Psi_2, \quad \Psi_i \in \{|0\rangle, |1\rangle, \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle), \frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)\}$

average final state fidelity = 79.1(4.5)

plus,
laser cooling

$$\hat{G} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

extension: entangled mechanical oscillators

$$\frac{1}{\sqrt{2}}\left[|\uparrow\rangle_{\mathrm{A}}|\downarrow\rangle_{\mathrm{B}}+\mathrm{e}^{i\xi(t)}|\downarrow\rangle_{\mathrm{A}}|\uparrow\rangle_{\mathrm{B}}\right]|0\rangle_{\mathrm{A}}|0\rangle_{\mathrm{B}} \longrightarrow \frac{1}{\sqrt{2}}|\uparrow\rangle_{\mathrm{A}}|\uparrow\rangle_{\mathrm{B}}\left[|0\rangle_{\mathrm{A}}|0\rangle_{\mathrm{B}}-\mathrm{e}^{i\xi(t)}|1\rangle_{\mathrm{A}}|1\rangle_{\mathrm{B}}\right]$$

John Jost, Jonathan Home, Jason Amini, David Hanneke *et al., Nature*, **459**, 683 (2009)

Alternateive strategies: RF magnetic field gates?

Why? Get rid of the lasers!

<u>static magnetic field gradient:</u>

Wunderlich group (Siegen):

Adv. At. Mol. Opt. Phys. **49**, 295 (2003)

M. Johanning *et* al., PRL **102**, 073004 (2009)

Chuang group (MIT):

S. Wang *et al.*, Appl. Phys. Lett. **94,** 094103 (2009)

Meschede group (Bonn):

L. Förster *et al.*, PRL **103**, 233001 (2009)

<u>AC magnetic field gradient</u>

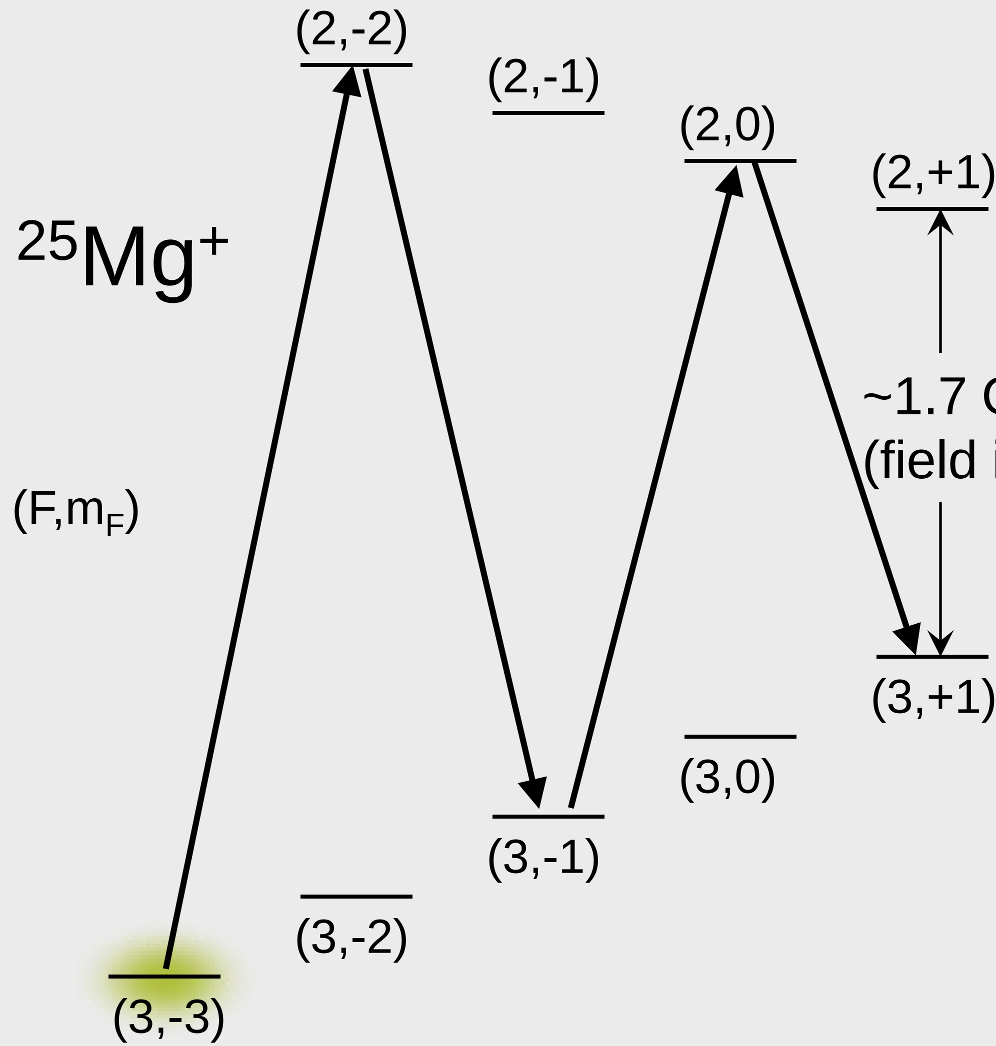
Dehmelt – g-2 “AC Stern Gerlach effect”

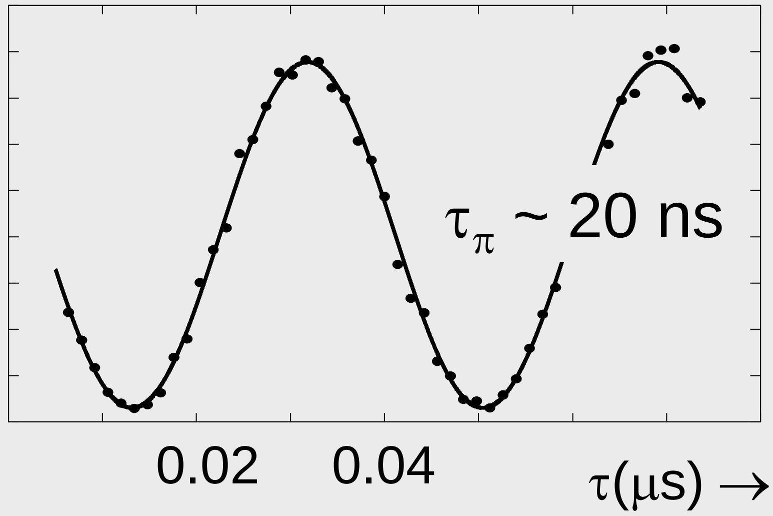
NIST:

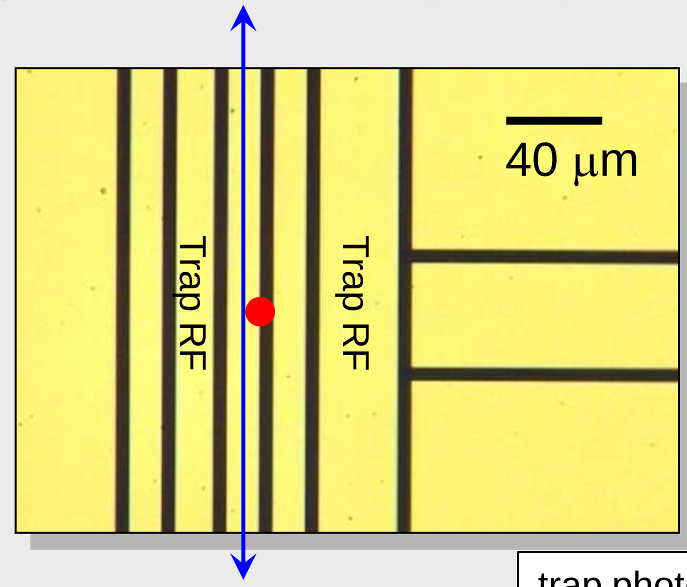
Christian Ospelkaus *et al.*, PRL **101**, 090502 (2008)

“5-wire” surface-electrode trap

(Christian Ospelkaus, Ulrich Warring, …)





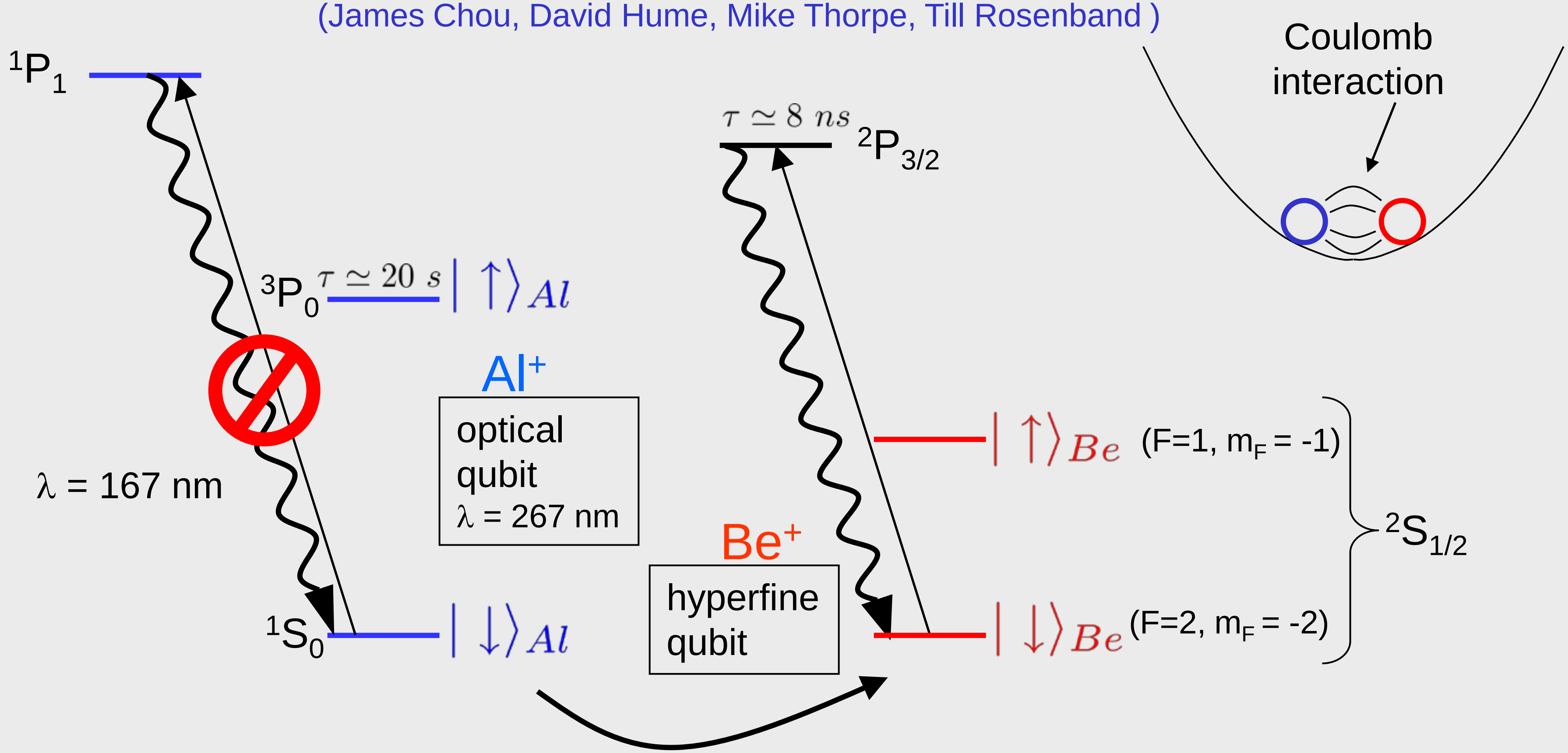


trap photo, PPT ion

Lamb-Dicke parameter $\eta \sim 1/3000$

Applications to metrology: Al^+ "quantum-logic clock"

(James Chou, David Hume, Mike Thorpe, Till Rosenband)



$$\Psi = \alpha|^1S_0\rangle_{Al} + \beta|^3P_0\rangle_{Al} \rightarrow \text{motion} \rightarrow \alpha|^1S_0\rangle_{Al}|\uparrow\rangle_{Be} + \beta|^3P_0\rangle_{Al}|\downarrow\rangle_{Be}$$

Shopping list:

- “More and better”
  - ♦ reduce gate errors further
  - ♦ scale to many qubits
- couple ion qubits to other quantum systems
  - * e.g., macroscopic systems
- simulations, applications in spectroscopy
- smaller structures ⇒ everything gets better
  - ♦ but, solve heating problem!

Ion “trapology” workshop (NIST Boulder, February 16, 17, 2011))

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