# Elements of quantum information processing and quantum computers
(with trapped ion examples)

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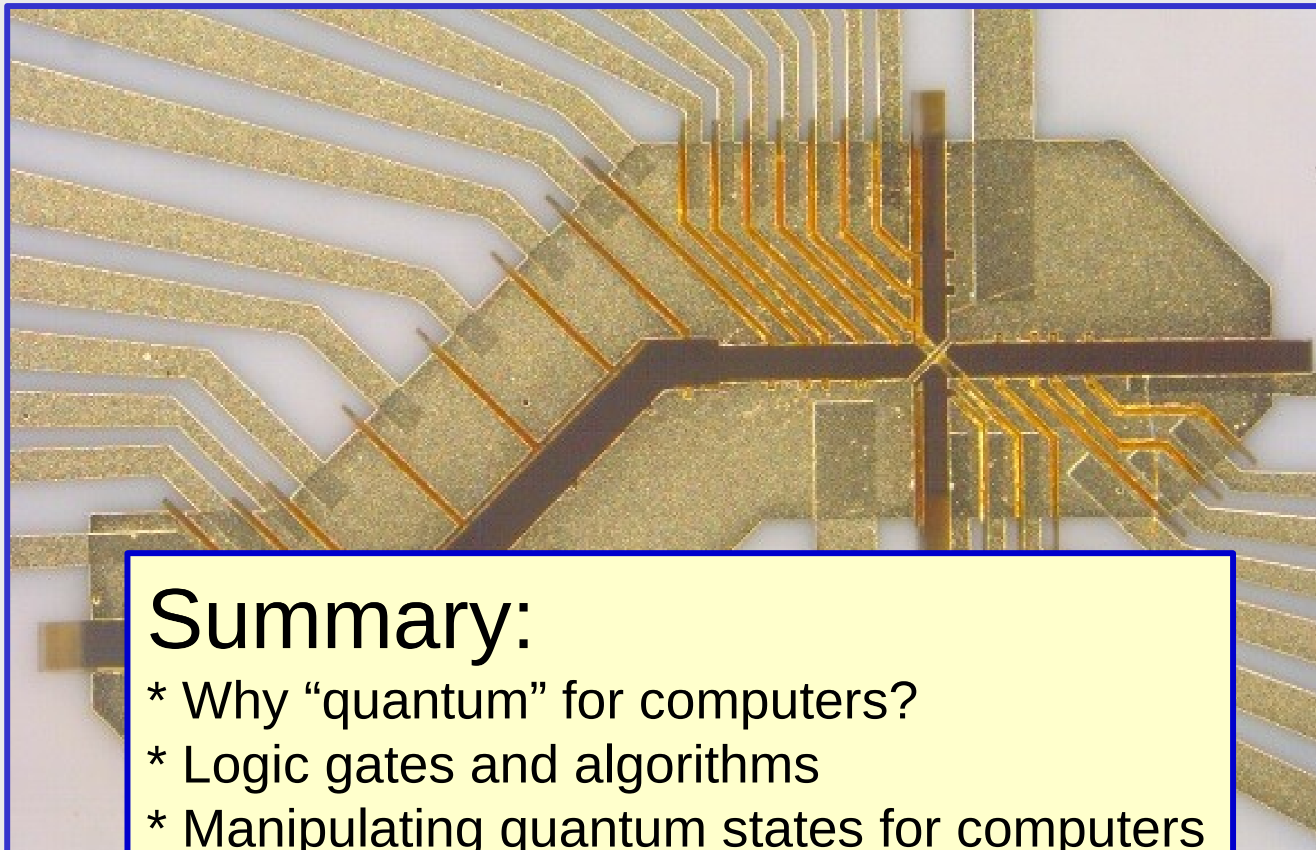

## Summary:
* Why “quantum” for computers?
* Logic gates and algorithms
* Manipulating quantum states for computers
* Quantum computers and Schrödinger’s cat

e quantum computer

**Data storage**:

- classical: computer bit: (0) or (1)
- quantum: "qubit" $\Psi = \alpha_0|0\rangle + \alpha_1|1\rangle$

superposition: $|0\rangle$ **AND** $|1\rangle$

**Scaling**: Consider 3-bit register (N = 3):

Classical register: (example): (101)

Quantum register: (3 qubits):

$\Psi = \alpha_0|0,0,0\rangle + \alpha_1|0,0,1\rangle + \alpha_2|0,1,0\rangle + \alpha_3|1,0,0\rangle + \alpha_4|0,1,1\rangle + \alpha_5|1,0,1\rangle + \alpha_6|1,1,0\rangle + \alpha_7|1,1,1\rangle$ (represents $2^3$ numbers simultaneously)

For N = 300 qubits, store $2^{300} \approx 10^{90}$ numbers simultaneously
(more than all the classical information in universe!)

**Parallel processing**: single gate operates on all $2^N$ inputs simultaneously

e quantum computer

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measurement:
$\alpha_0|0\rangle + \alpha_1|1\rangle$ "collapses" to
$|0\rangle$ **OR** $|1\rangle$
with probabilities $|\alpha_0|^2$ and $|\alpha_1|^2$

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e quantum computer

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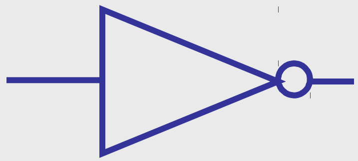
**Factoring**: Peter Shor's Algorithm (1994)

# Logic gates for Universal computation

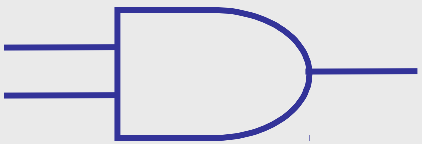
- Classical:

1-bit NOT



0 → 1
1 → 0

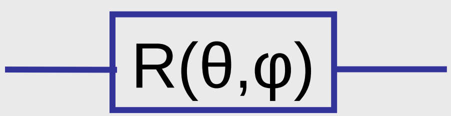
2-bit AND



00 → 0
01 → 0
10 → 0
11 → 1

- Quantum:

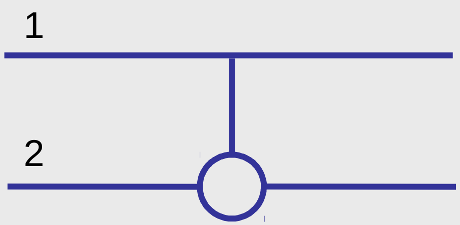
"rotation"




e.g.,
$|0\rangle \rightarrow \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle$
$|1\rangle \rightarrow -e^{-i\phi}\sin(\theta/2)|0\rangle + \cos(\theta/2)|1\rangle\rangle$

like rotating a spin-1/2 particle states: $|\downarrow\rangle$ (= $|0\rangle$) and $|\uparrow\rangle$ (= $|1\rangle$)

2-qubit logic gate




$U_{1,2}(\pi)$

$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$
$|0\rangle|1\rangle \rightarrow |0\rangle|1\rangle$
$|1\rangle|0\rangle \rightarrow |1\rangle|0\rangle$
$|1\rangle|1\rangle \rightarrow - |1\rangle|1\rangle$

phase gate

# Universal logic gates for processing

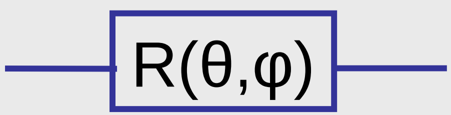
$$\Psi = \psi_1 \otimes \psi_2 = \tfrac{1}{2}\big(|0\rangle + |1\rangle\big)\big(|0\rangle + |1\rangle\big) \rightarrow U_{1,2}(\pi) \rightarrow$$

$$\tfrac{1}{2}\big(|0\rangle|0\rangle + |0\rangle|1\rangle + |1\rangle|0\rangle - |1\rangle|1\rangle\big) \neq \psi_1 \otimes \psi_2$$

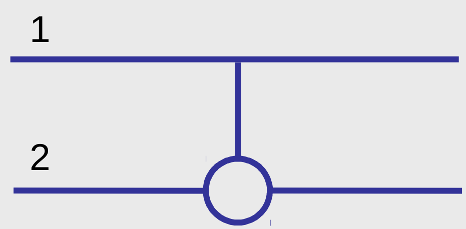
entanglement!

- Quantum:

"rotation"




2-qubit logic gate




$U_{1,2}(\pi)$

e.g.,
$|0\rangle \rightarrow \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle$
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like rotating a spin-1/2 particle
states: $|\downarrow\rangle$ (= $|0\rangle$) and $|\uparrow\rangle$ (= $|1\rangle$)

$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$
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phase gate

Quantum computer algorithm
to efficiently factorize large numbers

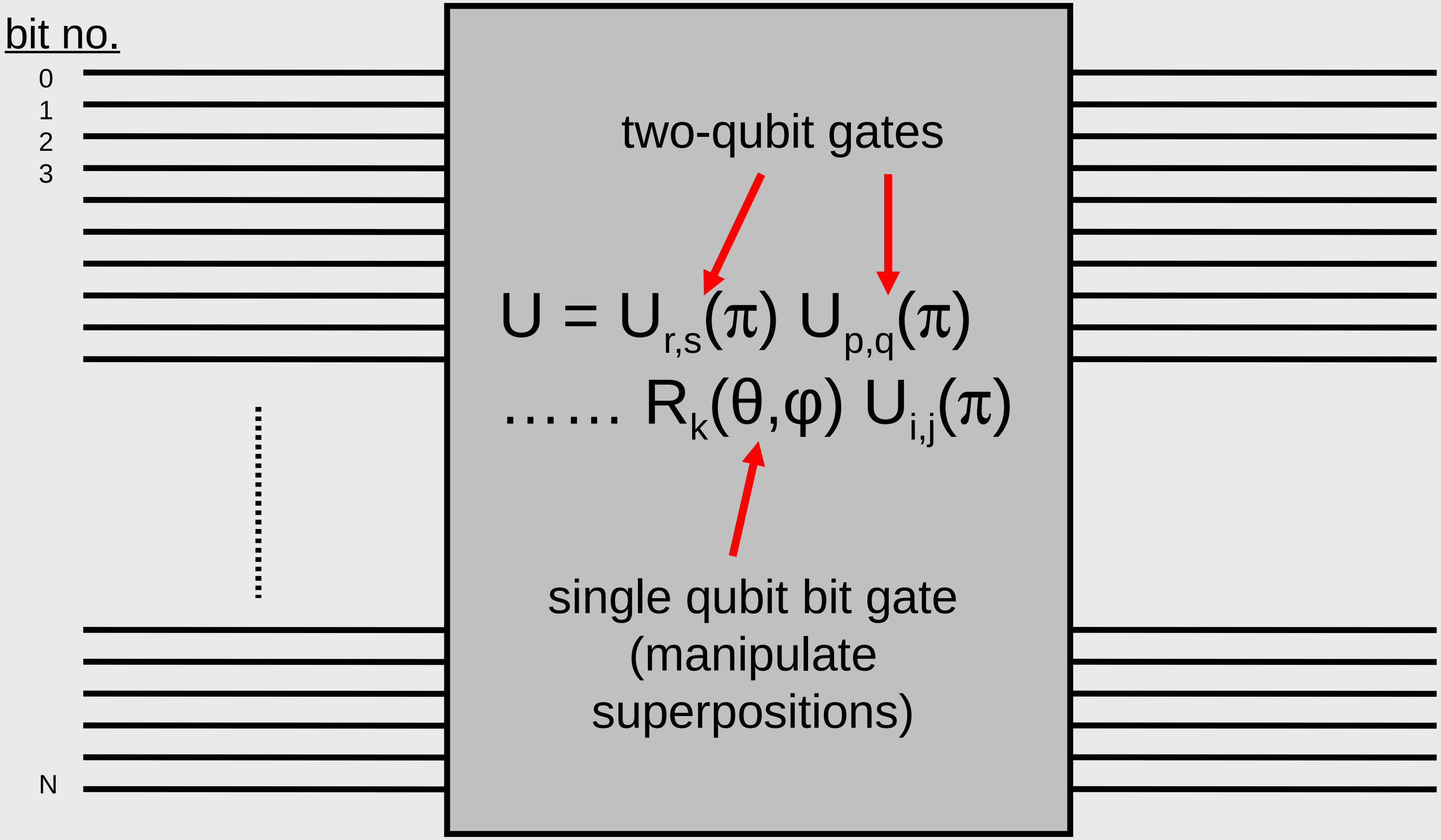
Peter Shor
(1994)

N-qubits:

$$\psi_{in} = \sum_{i=0}^{2^N-1} |i\rangle$$

e.g., for N = 3, $\Psi_{in} = C_N \big[|0,0,0\rangle + |0,0,1\rangle + |0,1,0\rangle + |1,0,0\rangle + |0,1,1\rangle + |1,0,1\rangle + |1,1,0\rangle + |1,1,1\rangle\big]$

Process all inputs simultaneously



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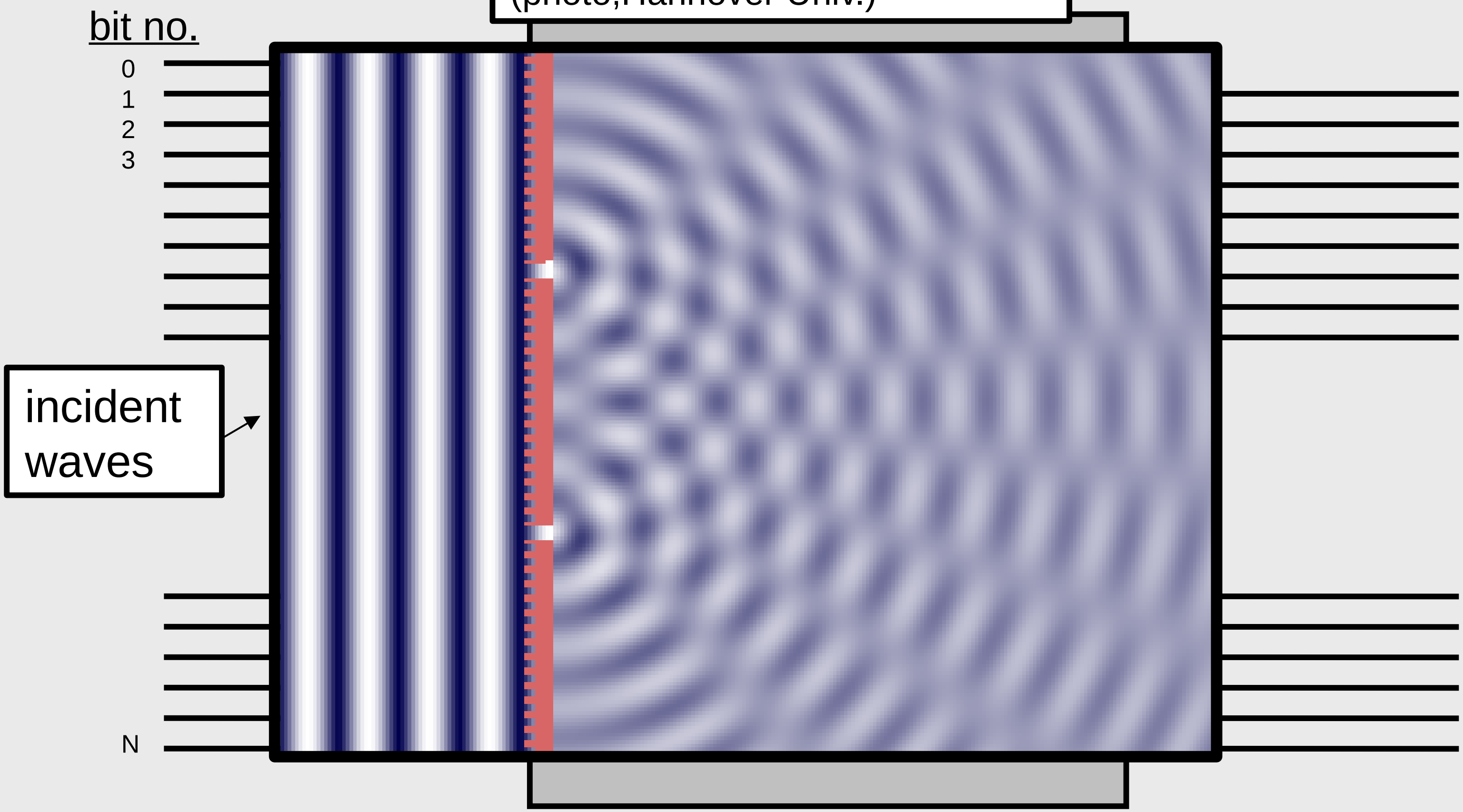
$+ |0,1,1\rangle + |1,0,1\rangle + |1,1,0\rangle + |1,1,1\rangle \big]$

Process all inputs si

analogous to
waterwave interference
(photo,Hannover Univ.)



Quantum computer algorithm
to efficiently factorize large numbers

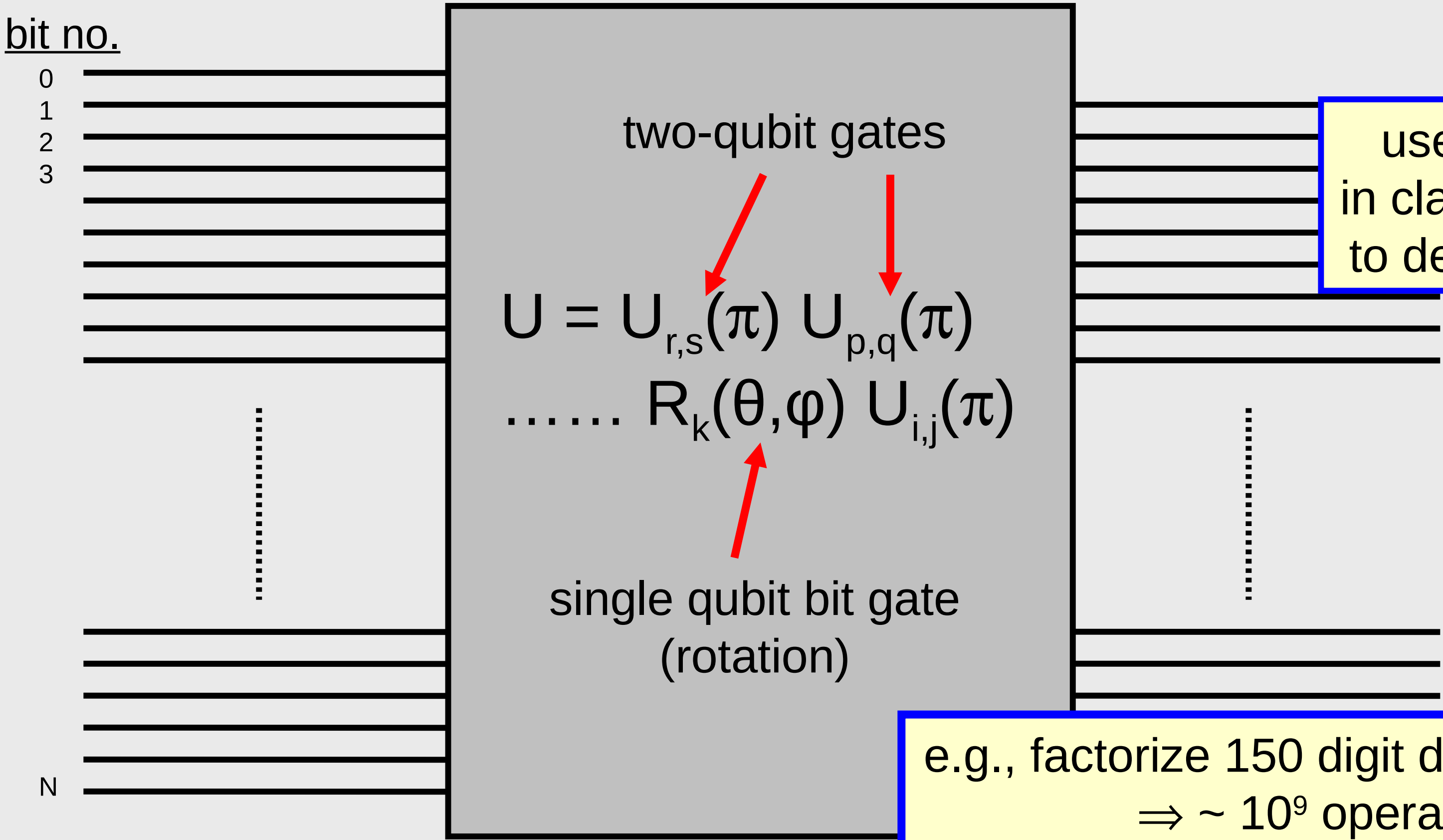
Peter Shor
(1994)

$$\psi_{in} = \sum_{i=0}^{2^N-1} |i\rangle$$

Process all possible
inputs simultaneously

$$\psi_{out} = \sum_{\text{small selection}} |i\rangle$$

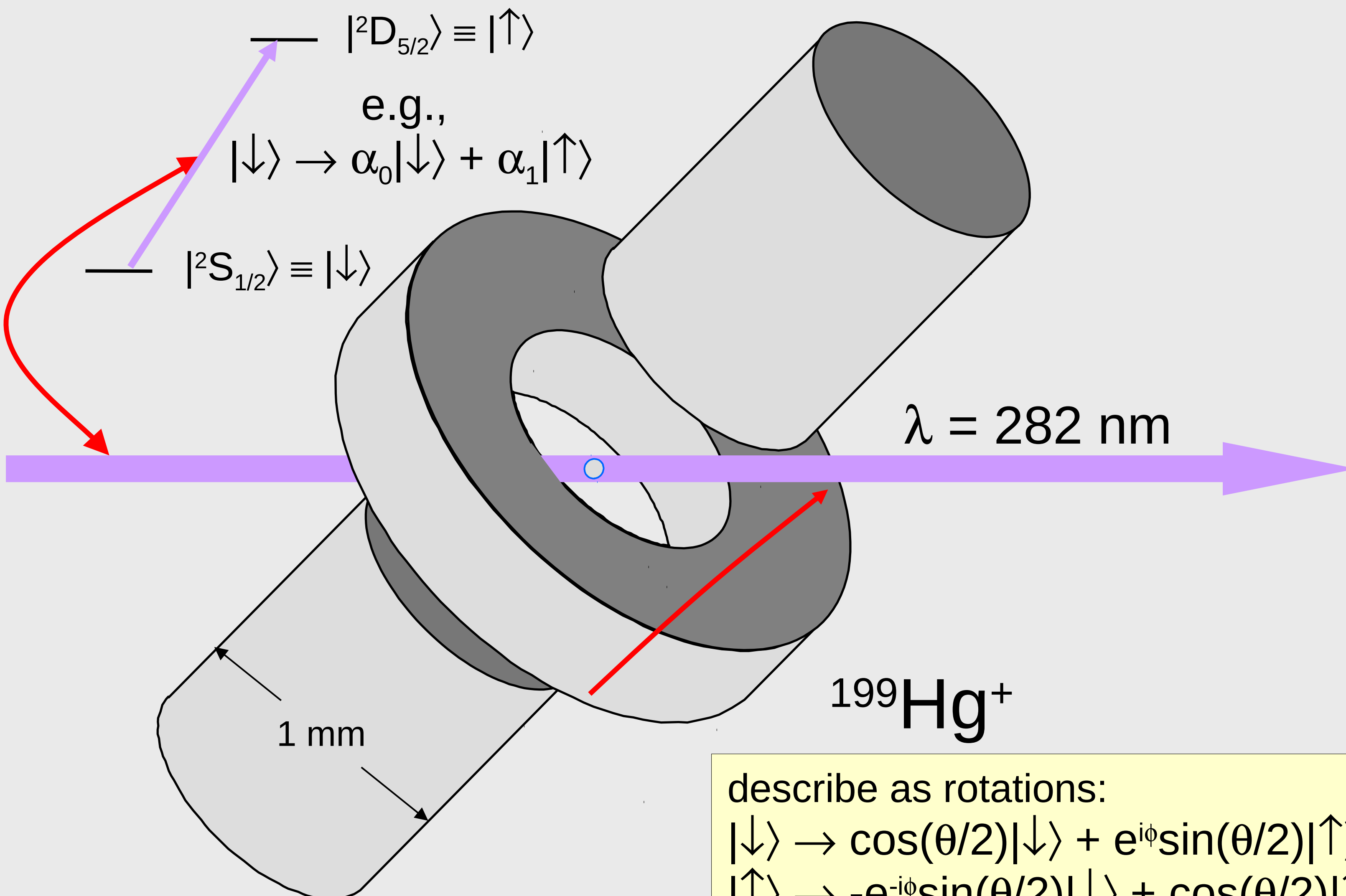
measure
qubits




use measured “i”
in classical algorithm
to determine factors

e.g., factorize 150 digit decimal number
$\Rightarrow \sim 10^9$ operations

# “spin” rotations
## (superpositions of internal energy states of ion)



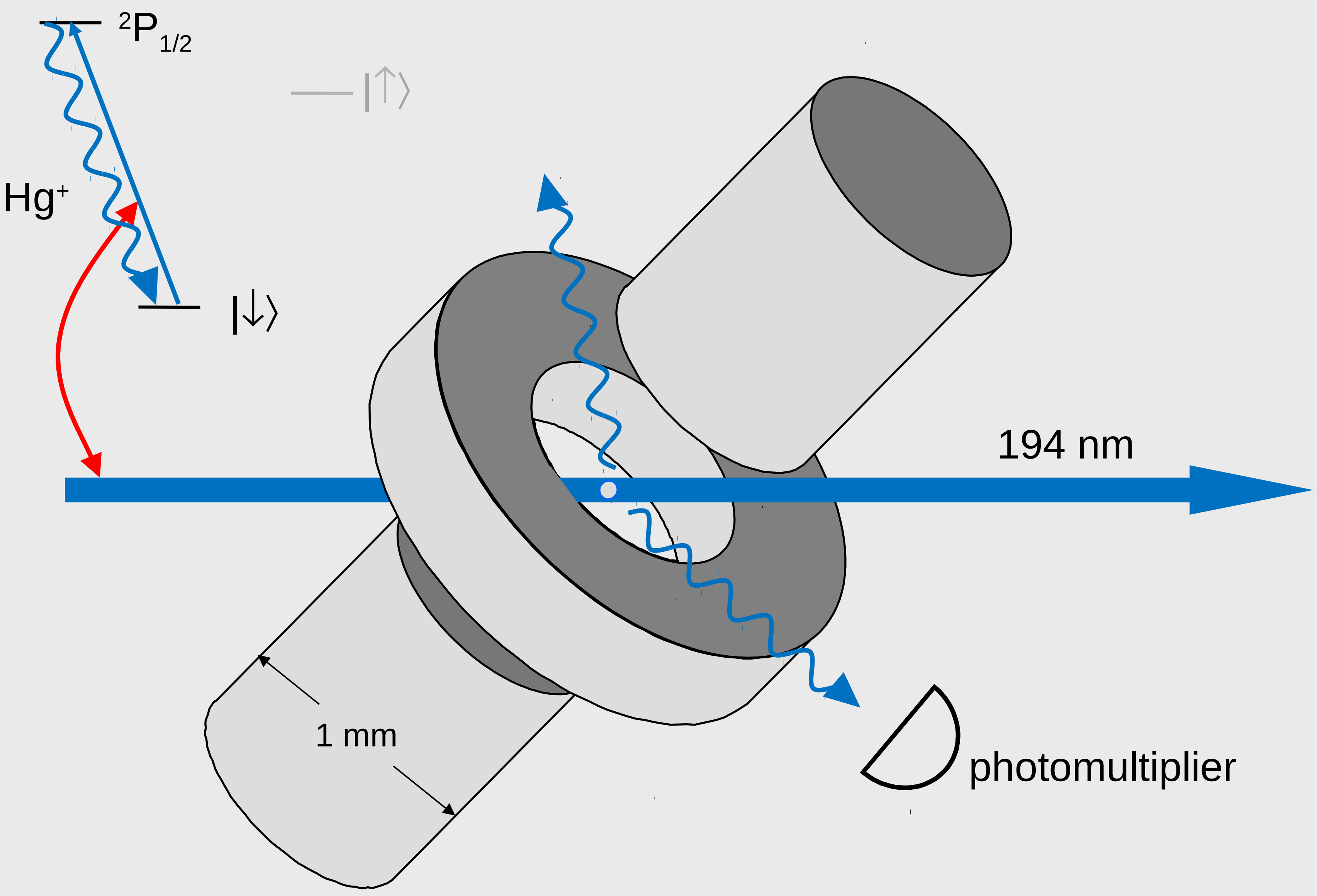

describe as rotations:

$|\downarrow\rangle \rightarrow \cos(\theta/2)|\downarrow\rangle + e^{i\phi}\sin(\theta/2)|\uparrow\rangle$

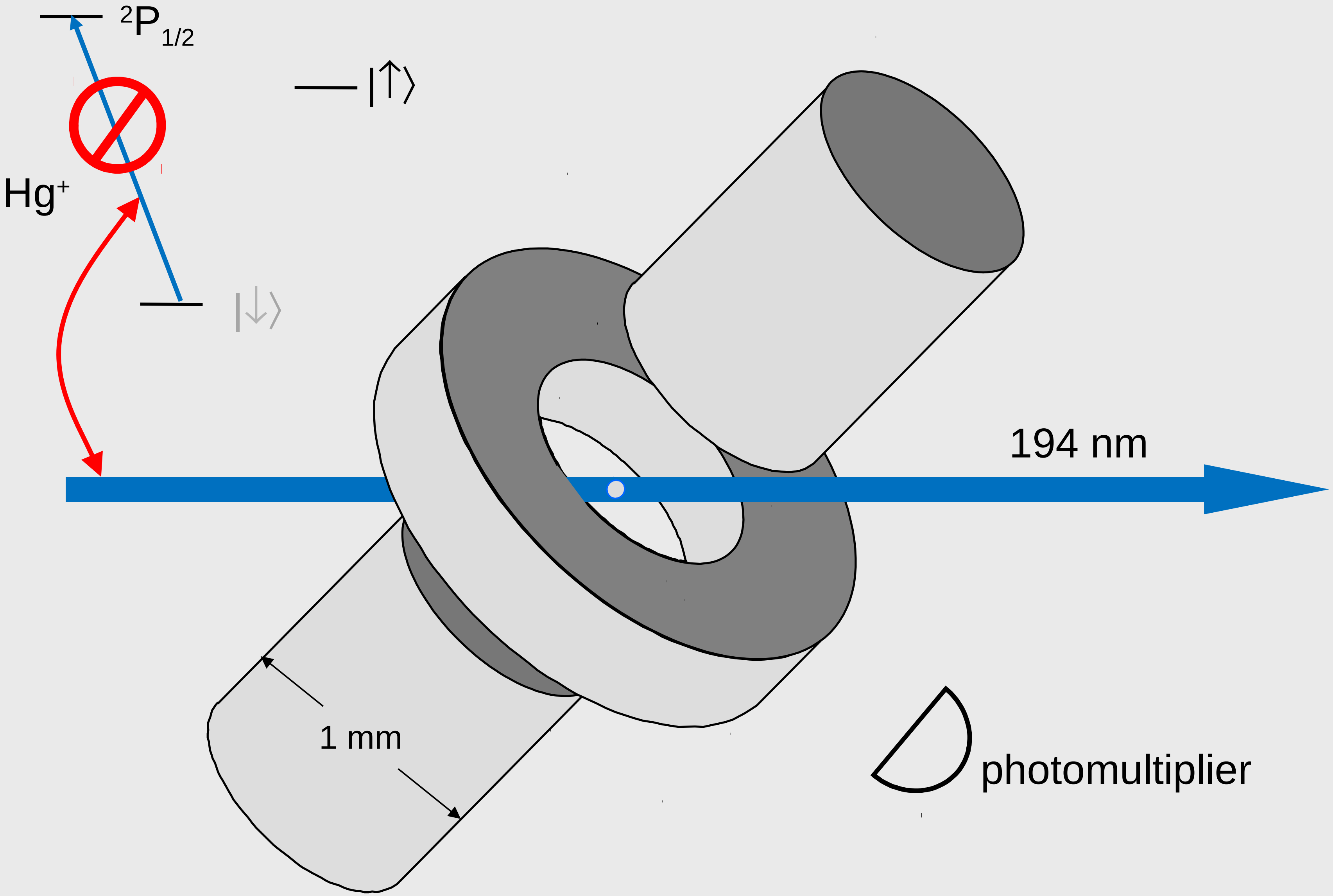
$|\uparrow\rangle \rightarrow -e^{-i\phi}\sin(\theta/2)|\downarrow\rangle + \cos(\theta/2)|\uparrow\rangle\rangle$

detection:

$$\alpha_0|\downarrow\rangle + \alpha_1|\uparrow\rangle \rightarrow |\downarrow\rangle$$



$$\alpha_0|\downarrow\rangle + \alpha_1|\uparrow\rangle \rightarrow |\uparrow\rangle$$



# Hyperfine qubits: e.g. $^9Be^+$

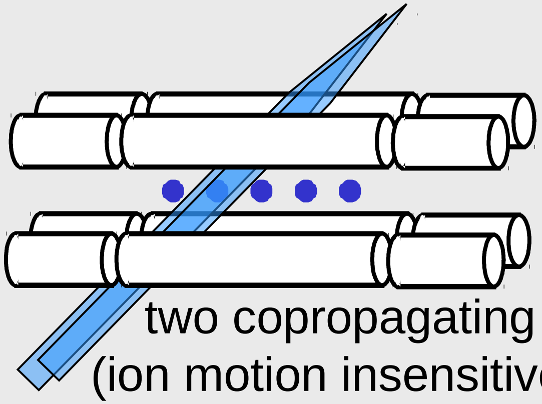
$^2S_{1/2}$ electronic ground level

hyperfine states

$|\downarrow\rangle \equiv |F = 2, m_F = 0\rangle$

$|\uparrow\rangle \equiv |F = 1, m_F = -1\rangle$

B ≅ 119 G (coherence time > 10 s)



two copropagating beams
(ion motion insensitive)

$^2P_{3/2}$

$^2P_{1/2}$

two-photon coherent stimulated-Raman transitions

- focused beams

⇒ individual ion addressability

$|\uparrow\rangle$

~1.21 GHz

$|\downarrow\rangle$

e.g., rotations

$|\downarrow\rangle \rightarrow \cos(\theta/2)|\downarrow\rangle + e^{i\phi}\sin(\theta/2)|\uparrow\rangle$

$|\uparrow\rangle \rightarrow -e^{-i\phi}\sin(\theta/2)|\downarrow\rangle + \cos(\theta/2)|\uparrow\rangle\rangle$

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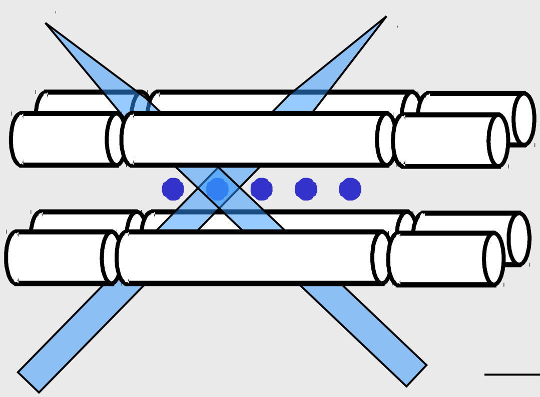
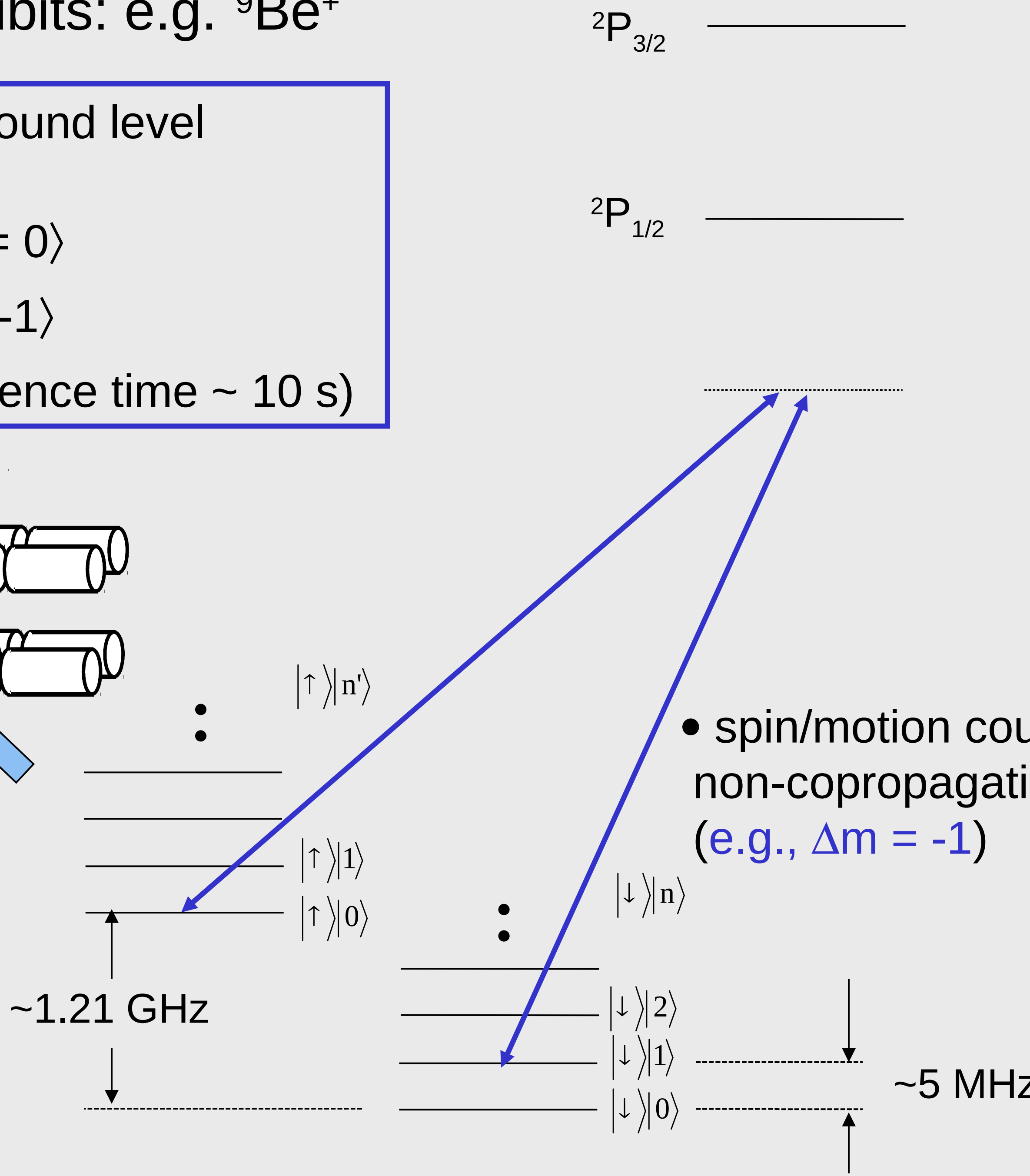





- spin/motion coupling with non-copropagating beams. (e.g., $\Delta m = -1$)

# A bit more history:

Peter Shor: algorithm for efficient number factoring on a quantum computer (~ 1994)

Artur Ekert: presentation at the 1994 International Conference on Atomic Physics Boulder, Colorado

# Atomic ion quantum computer:

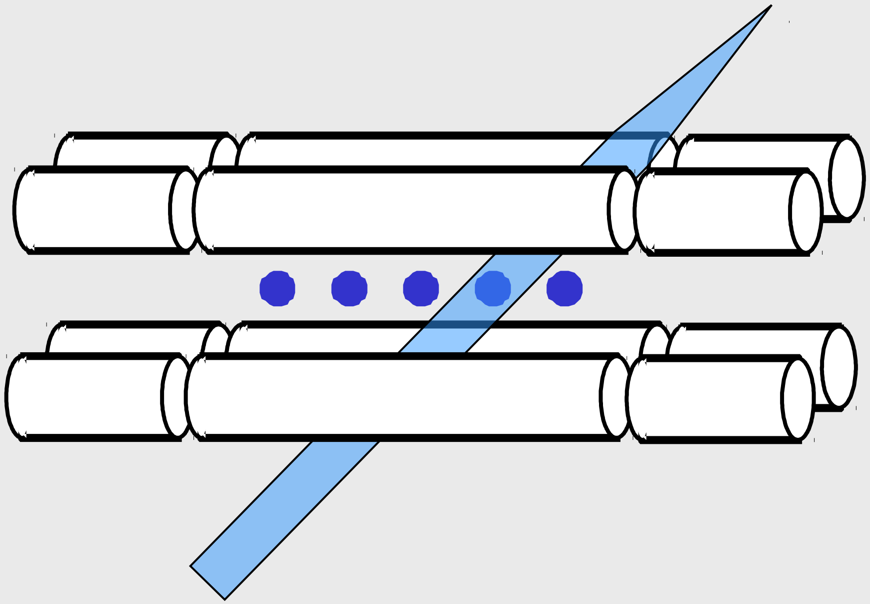
J. I. Cirac, P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995)

Ignacio Cirac

Peter Zoller

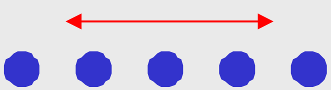
1. START MOTION IN GROUND STATE

2. SPIN → MOTION MAP

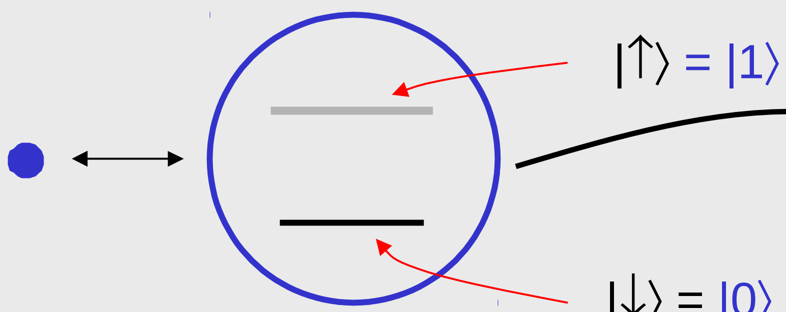


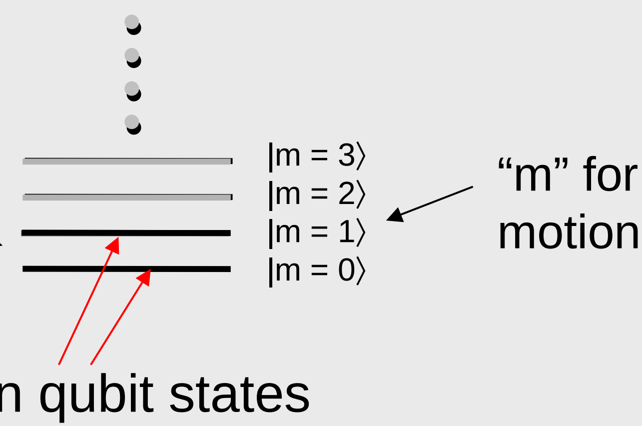
MOTION “DATA BUS”

(e.g., center-of-mass mode)



INTERNAL STATE “**SPIN**” QUBIT



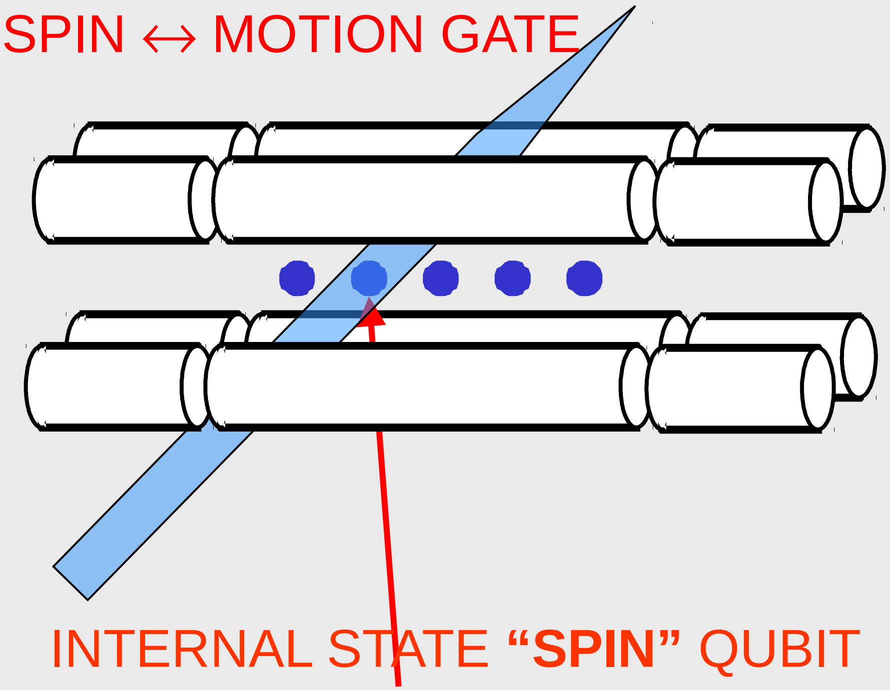
# Atomic ion quantum computation:

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

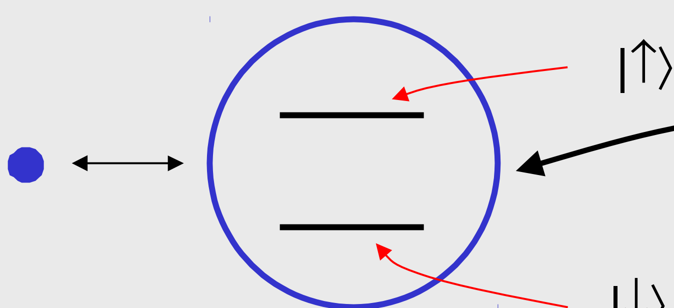
Ignacio Cirac

Peter Zoller

1. START MOTION IN GROUND STATE
2. SPIN → MOTION MAP
3. SPIN ↔ MOTION GATE

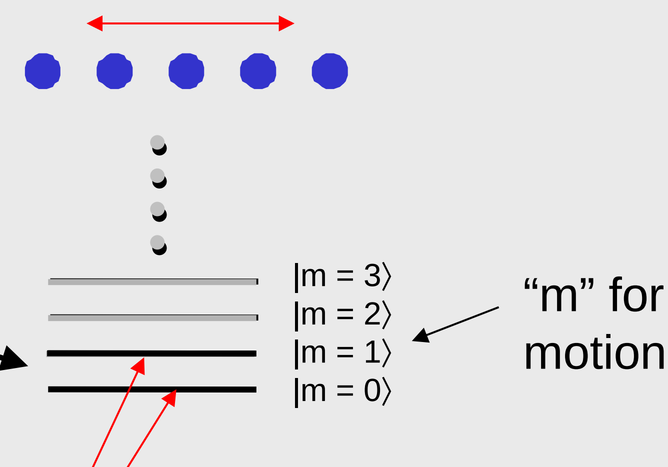


INTERNAL STATE **“SPIN”** QUBIT




MOTION “DATA BUS”

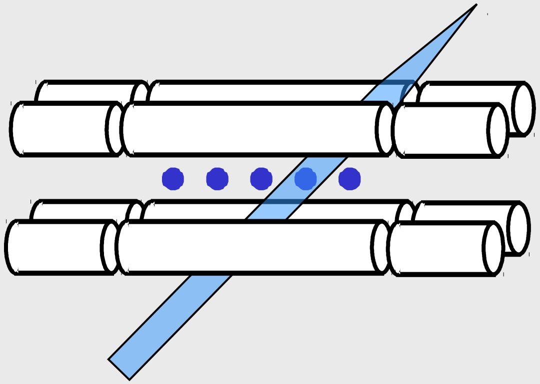
(e.g., center-of-mass mode)

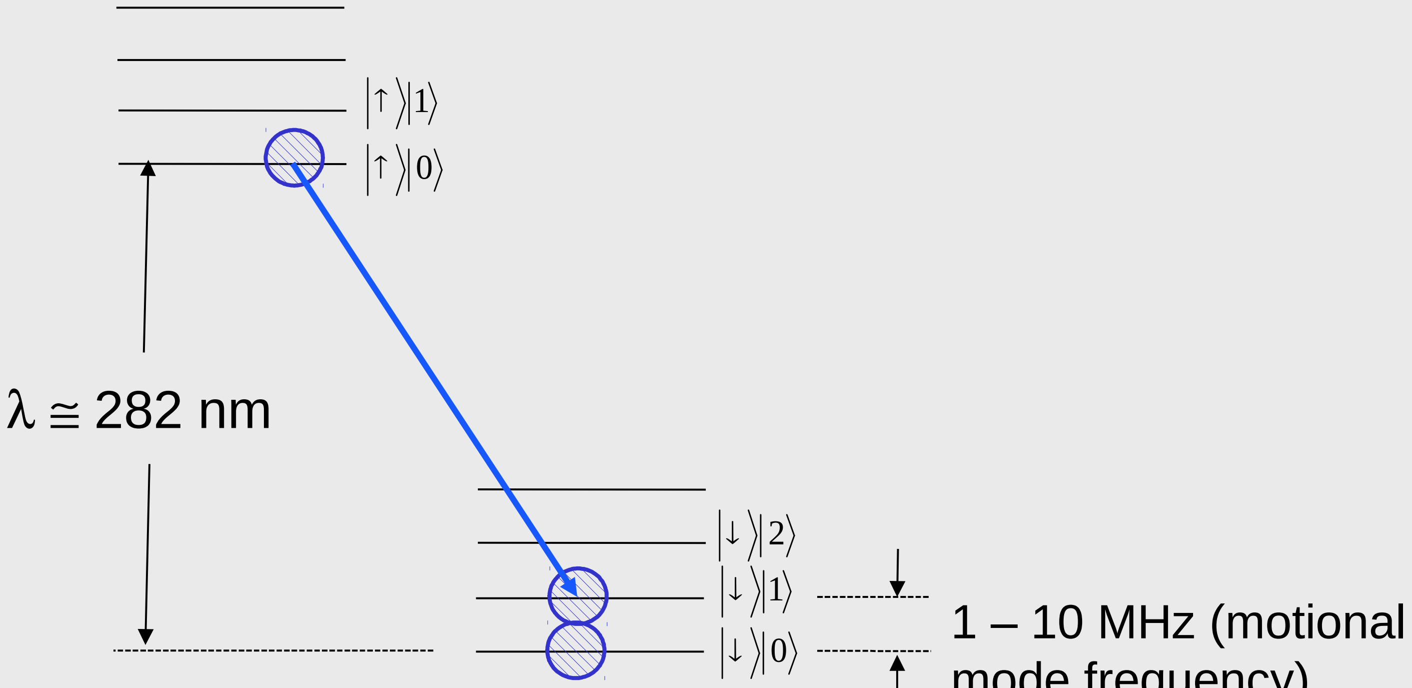



Motion qubit states

# Step 2. Spin → motion map

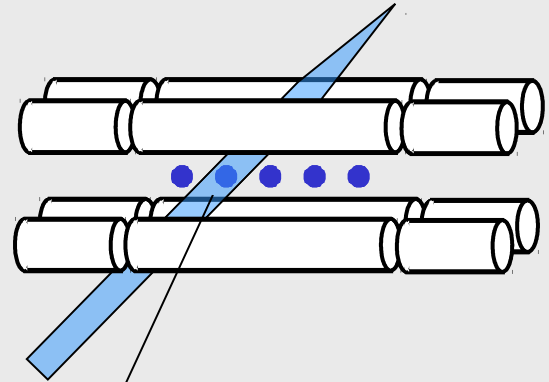
$$(\alpha|\downarrow\rangle + \beta|\uparrow\rangle)|0\rangle \rightarrow |\downarrow\rangle(\alpha|0\rangle + \beta|1\rangle)$$





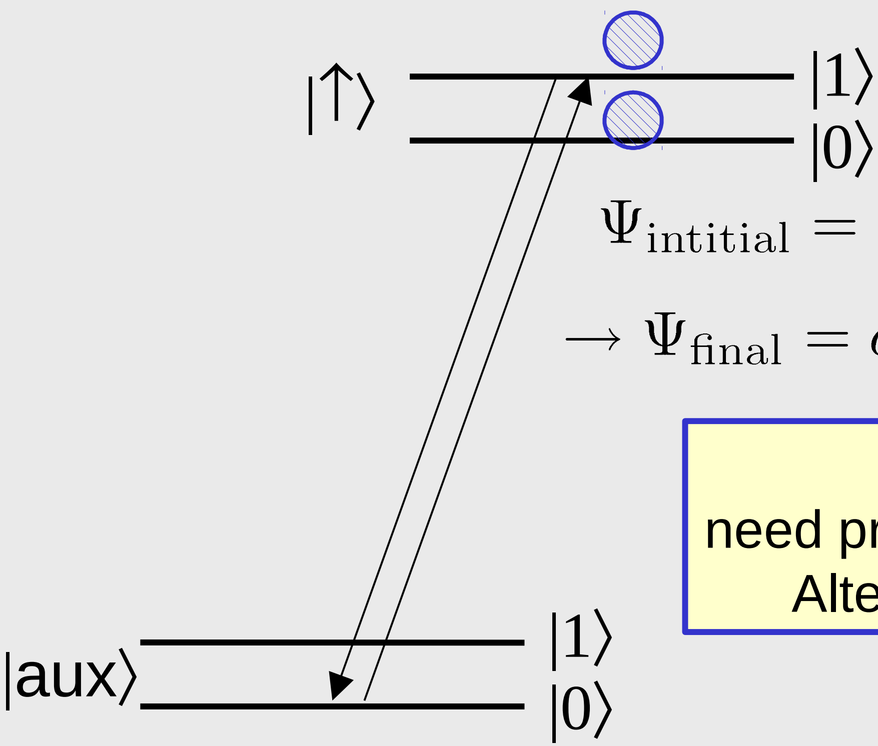
# Step 2: Spin-qubit/motion-qubit logic gate

(Chris Monroe et al., Phys. Rev. Lett. **75**, 4714 (1995)).
Hyperfine states of $^9Be^+$ coupled with stimulated-Raman transitions



## Complete Cirac-Zoller gate (two ions):

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

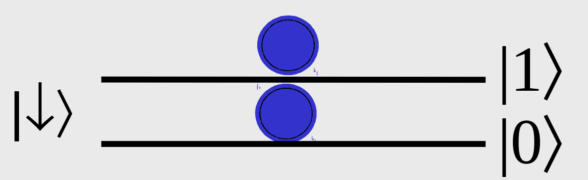



π phase shift, |↑⟩|1⟩ → - |↑⟩|1⟩

$$\Psi_{\text{intitial}} = \alpha|\downarrow\rangle|0\rangle + \beta|\downarrow\rangle|1\rangle + \gamma|\uparrow\rangle|0\rangle + \delta|\uparrow\rangle|1\rangle$$

$$\rightarrow \Psi_{\text{final}} = \alpha|\downarrow\rangle|0\rangle + \beta|\downarrow\rangle|1\rangle + \gamma|\uparrow\rangle|0\rangle - \delta|\uparrow\rangle|1\rangle$$

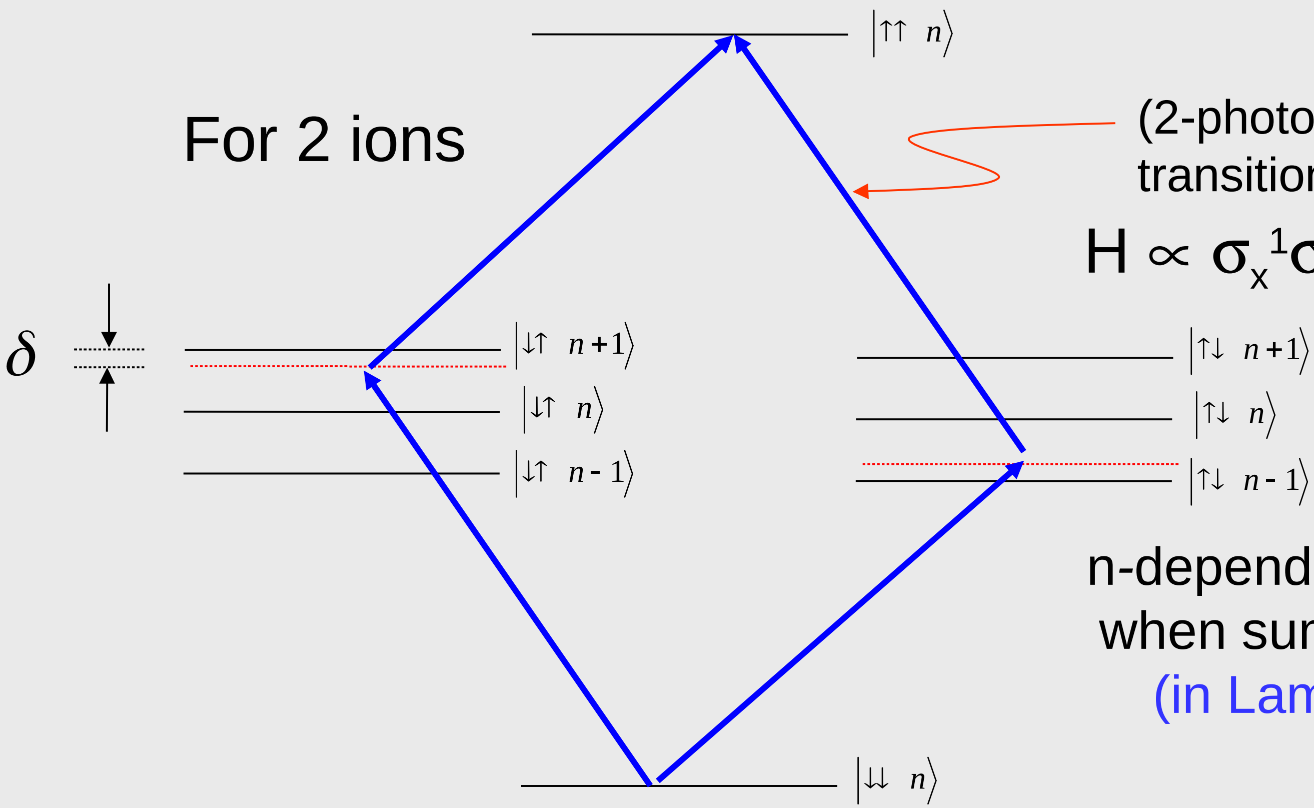
Cirac – Zoller gates:
need precise control of motion quantum states.
Alternative gates suppress this problem.



# “Motion-insensitive” gates (in Lamb-Dicke limit: wave function << λ)


K. Mølmer and A. Sørensen, Phys. Rev. Lett. **82**, 1835 (1999).
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).
A. Sørensen and K. Mølmer, Phys. Rev. A **62**, 02231 (2000).
G. J. Milburn, S. Schneider, and D. F. V. James, Fortschr. Physik **48**, 801 (2000).
X.Wang, A. Sørensen, and K. Mølmer, Phys. Rev. Lett. **86**, 3907 (2001).


For 2 ions



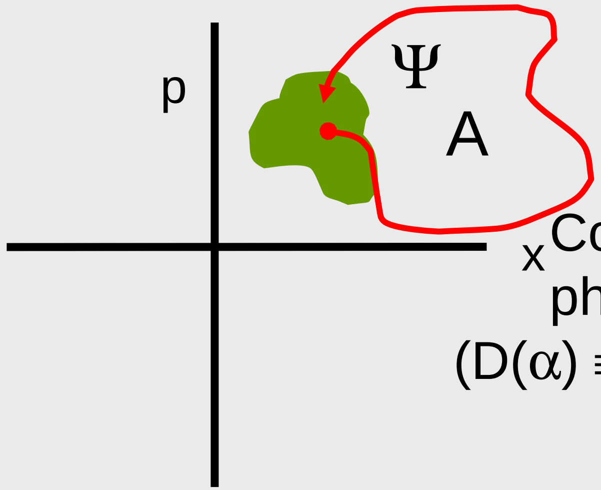

(2-photon stimulated-Raman transitions for hyperfine qubits)

$H \propto \sigma_x^1 \sigma_x^2$

n-dependence disappears when summing the paths (in Lamb-Dicke limit)

# Can view gates in terms of geometric phases:

phase-space diagram for selected motional mode:




$\Psi \rightarrow e^{i\phi}\Psi$

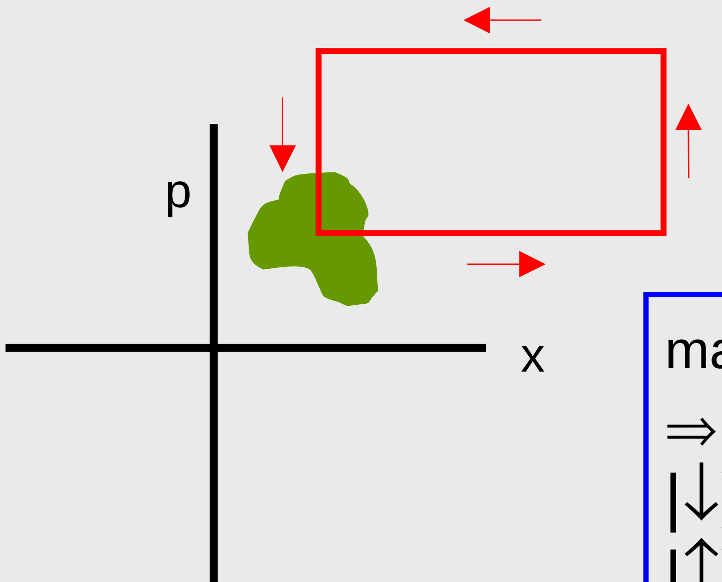
$\phi \propto$ enclosed area A

Consider successive displacements D in phase space where

$(D(\alpha) \equiv \exp[\alpha a^\dagger - \alpha^* a]$ with $\alpha = (\Delta x + i\Delta p/m\omega_x)/(2x_0))$

For closed loops concatenate small steps

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




resonant displacements **can be fast!**

G. J. Milburn, S. Schneider, D. F. V. James Fortschr. Physik **48**, 801 (2000).

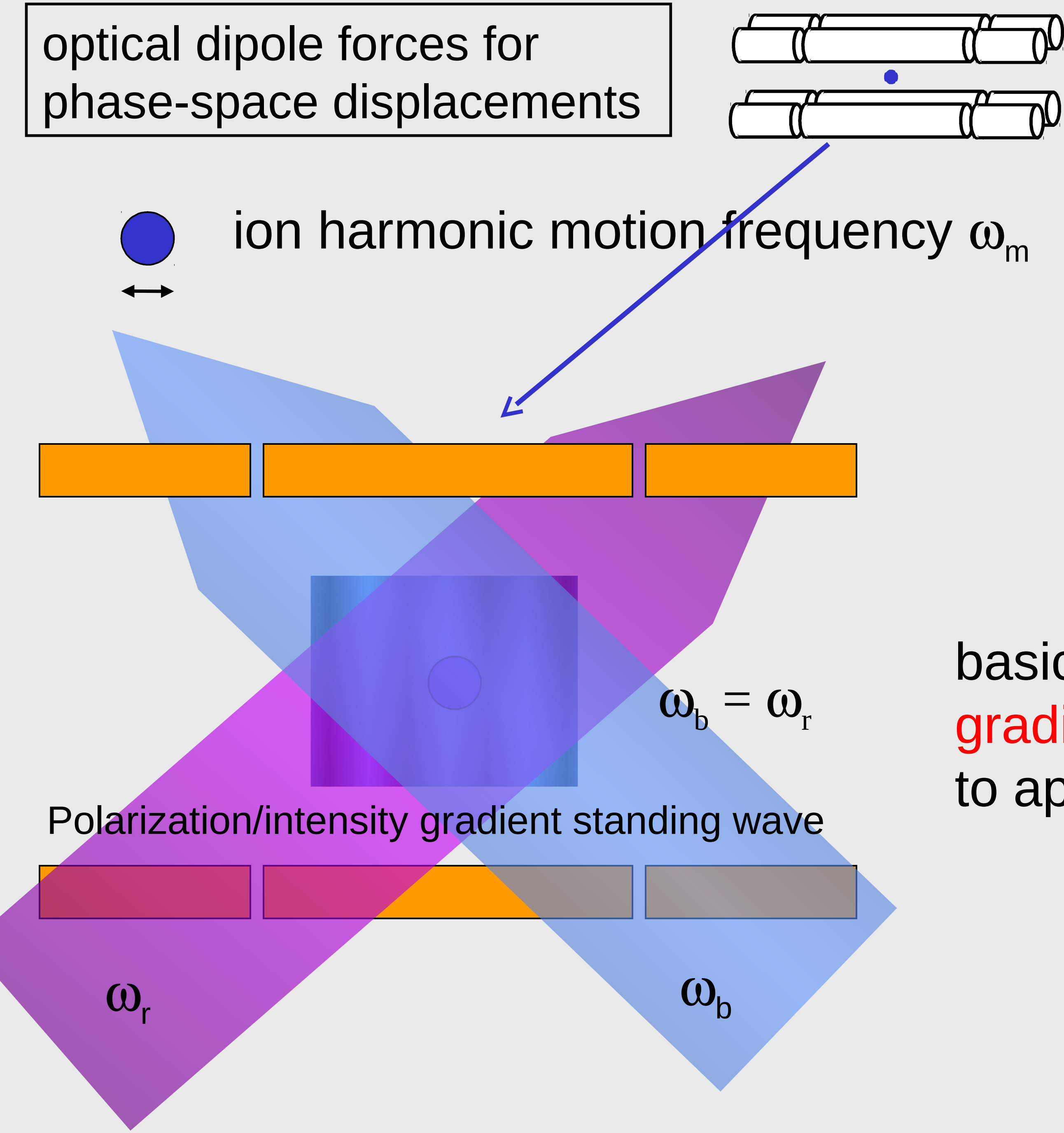
make force state-dependent, e.g. $F \propto \sigma_z$,

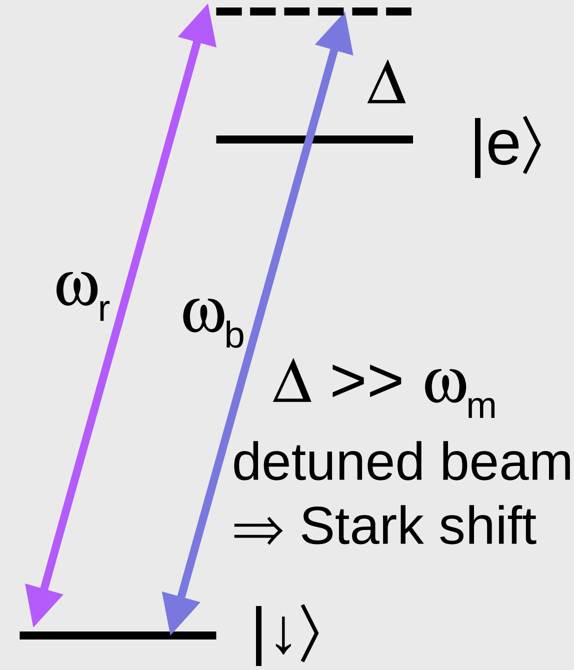
$\Rightarrow$ realize two qubit phase gate, e.g,:

$|\downarrow\rangle|\downarrow\rangle \rightarrow |\downarrow\rangle|\downarrow\rangle$, $|\downarrow\rangle|\uparrow\rangle \rightarrow i|\downarrow\rangle|\uparrow\rangle$

$|\uparrow\rangle|\downarrow\rangle \rightarrow i|\uparrow\rangle|\downarrow\rangle$, $|\uparrow\rangle|\uparrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$

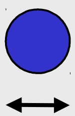
optical dipole forces for phase-space displacements



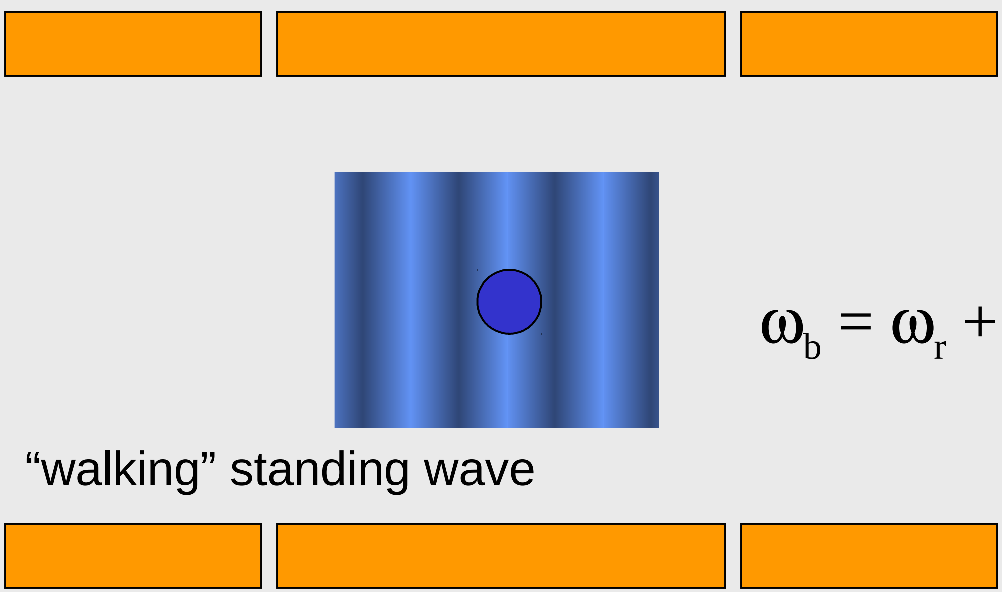




basic idea: use
gradient of Stark shift
to apply force

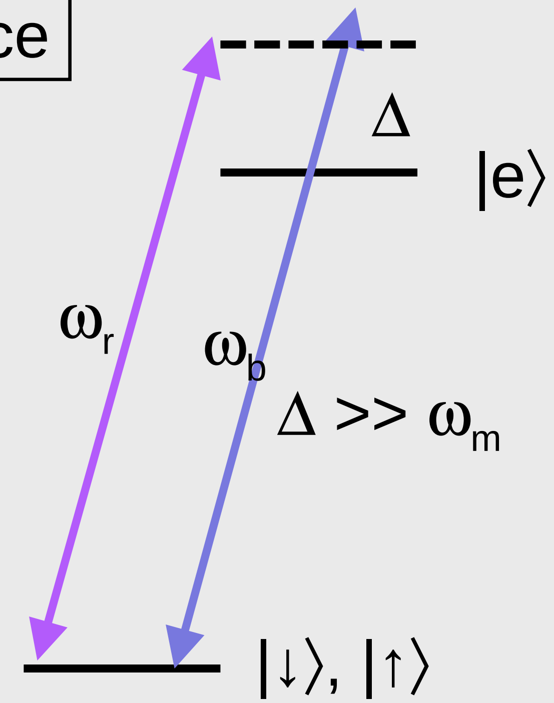
# Dipole forces to displace ions in phase space



ion harmonic motion frequency $\omega_m$

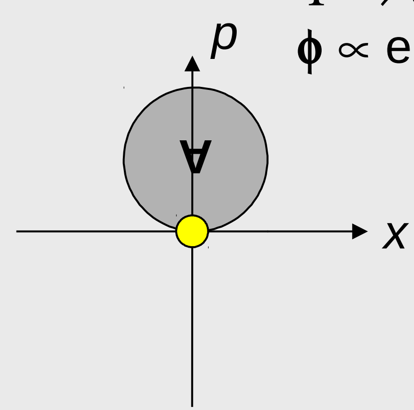



$$\omega_b = \omega_r + \omega_m + \delta$$




$\Psi \rightarrow e^{i\phi}\Psi$

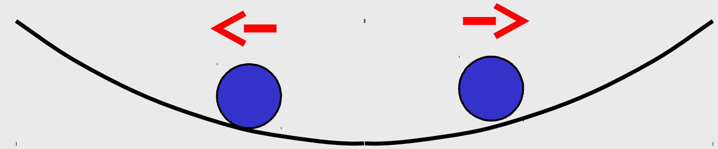
$\phi \propto$ enclosed area A



2-ion phase-gate example (e.g., stretch mode, $F_\uparrow = - F_\downarrow$ (i.e., $F \propto \sigma_z$ ))

$\omega_b - \omega_a = \omega_{stretch} + \delta$

apply forces for $t = 2\pi/\delta$



$\Psi \rightarrow e^{i\phi}\Psi$

$\phi \propto$ enclosed area A

*p*

movi

poten

Strengths:

- individual ion addressing not required
- Doesn't depend on initial motion wave function, <u>but</u> we want:
  - spread of wave function << $\lambda_{eff}$
  - amplitude of excitation << $\lambda_{eff}$

  ] Lamb-Dicke regime

- Same picture for $\sigma_{z1}\sigma_{z2}$ and $\sigma_{x1}\sigma_{x2}$ gates (just different basis states)

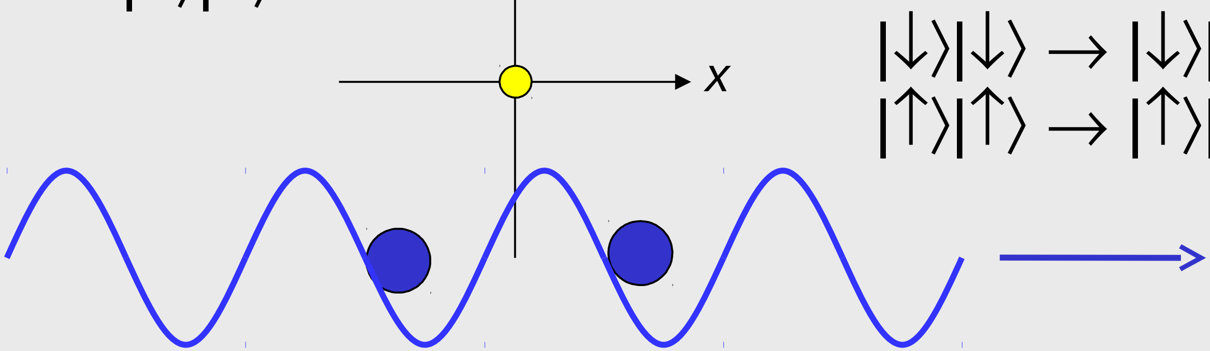
(P. J. Lee et al., J. Opt. B: Quantum Semiclass. Opt. **7**, S371 (2005))

$_2$]

te

hifts)

$|\downarrow\rangle|\downarrow\rangle$:




$|\downarrow\rangle|\downarrow\rangle \rightarrow |\downarrow\rangle|\downarrow\rangle$

$|\uparrow\rangle|\uparrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$

# Apply gate to selected ions in linear array

(Chris Monroe group, U. Md.
and Rainer Blatt group, Innsbruck)


$$G = e^{-i\sigma_x^{(1)}\sigma_x^{(2)}\varphi}$$

Ising interaction

# Simulation

$$H = \sum_{i<j} J_{i,j} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)} + B \sum_i \hat{\sigma}_y^{(i)}$$

etc.

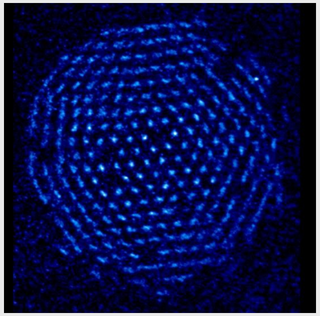
Chris Monroe

JQI, Maryland
e.g., P. Richerme et al.,
*Nature* **511**, 198 (2014)

Rainer Blatt

Innsbruck
e.g., P. Jurcevic et al.,
*Nature* **511**, 202 (2014)

John Bollinger

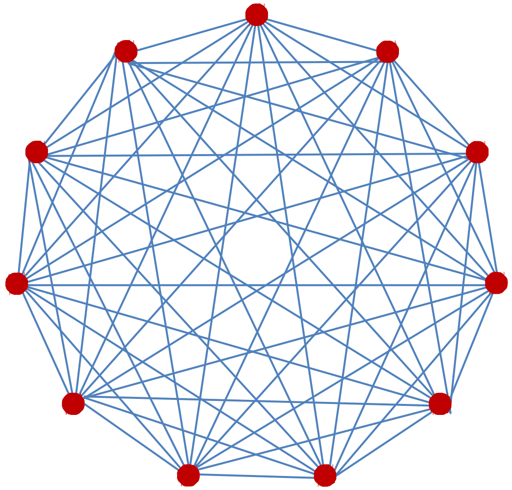


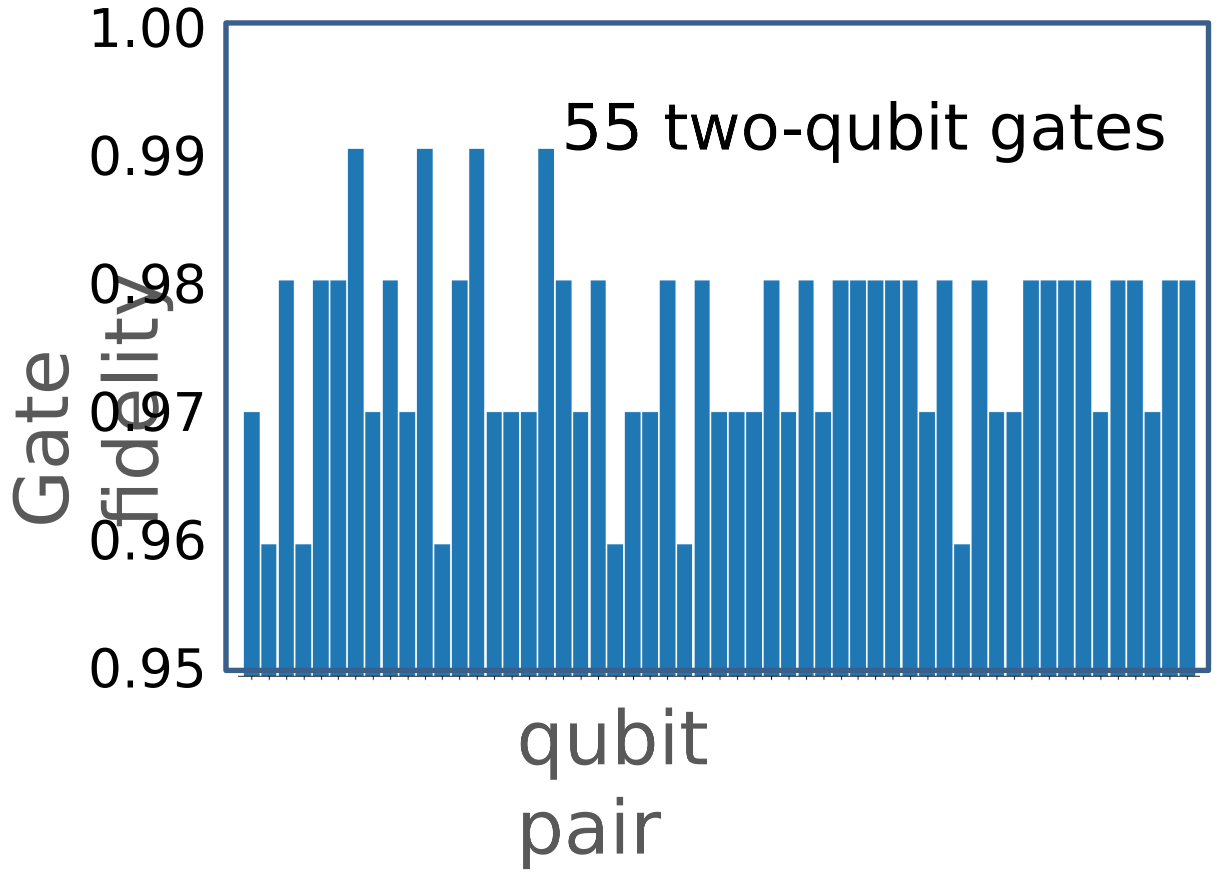
2D Wigner crystal

NIST
e.g., J. G. Bohnet et al,
*Sci.* **352**, 1297 (2016)

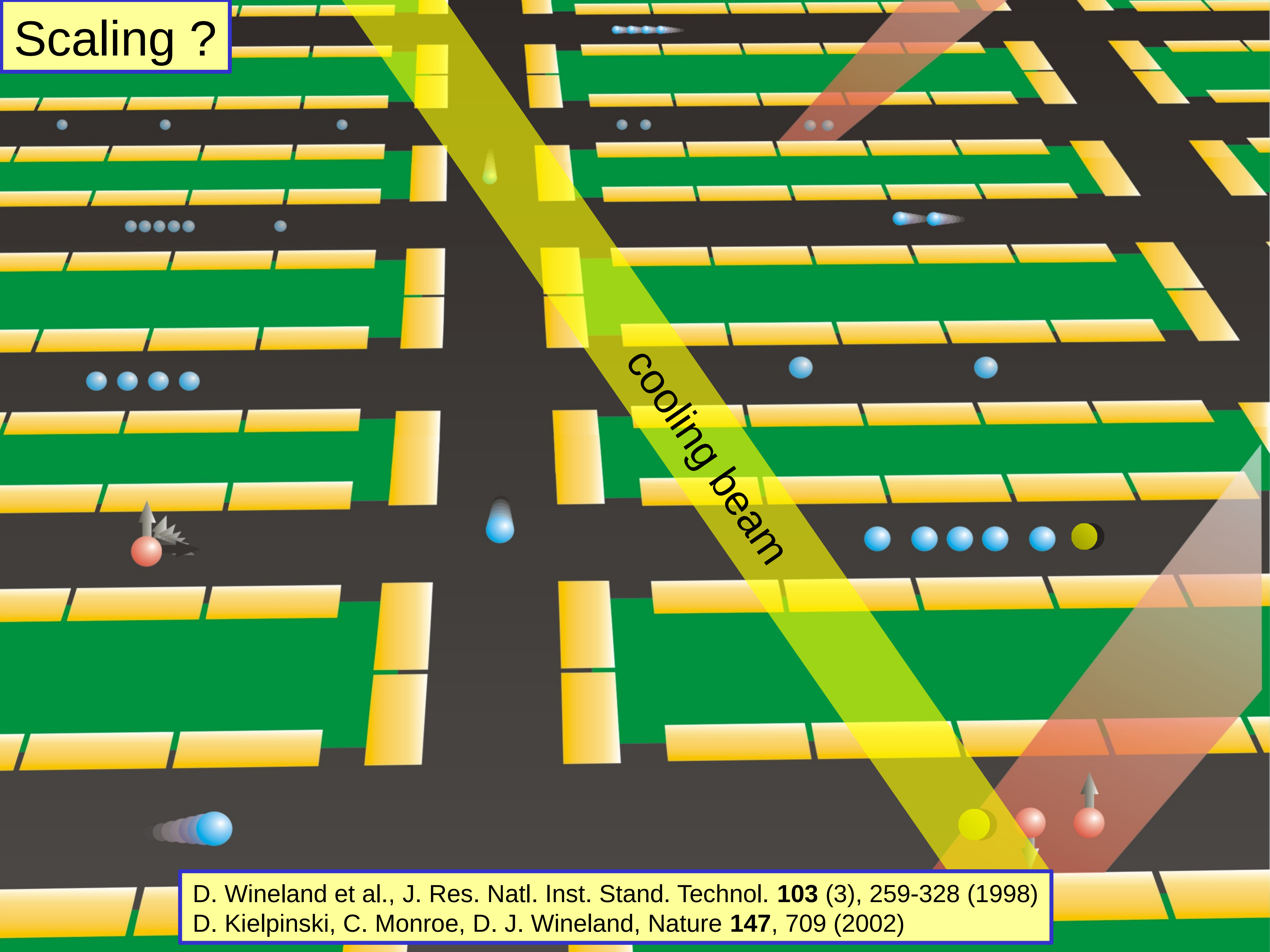
# “Full connectivity” (11 qubits)

K. Wright et al., arXiv:1903.08181





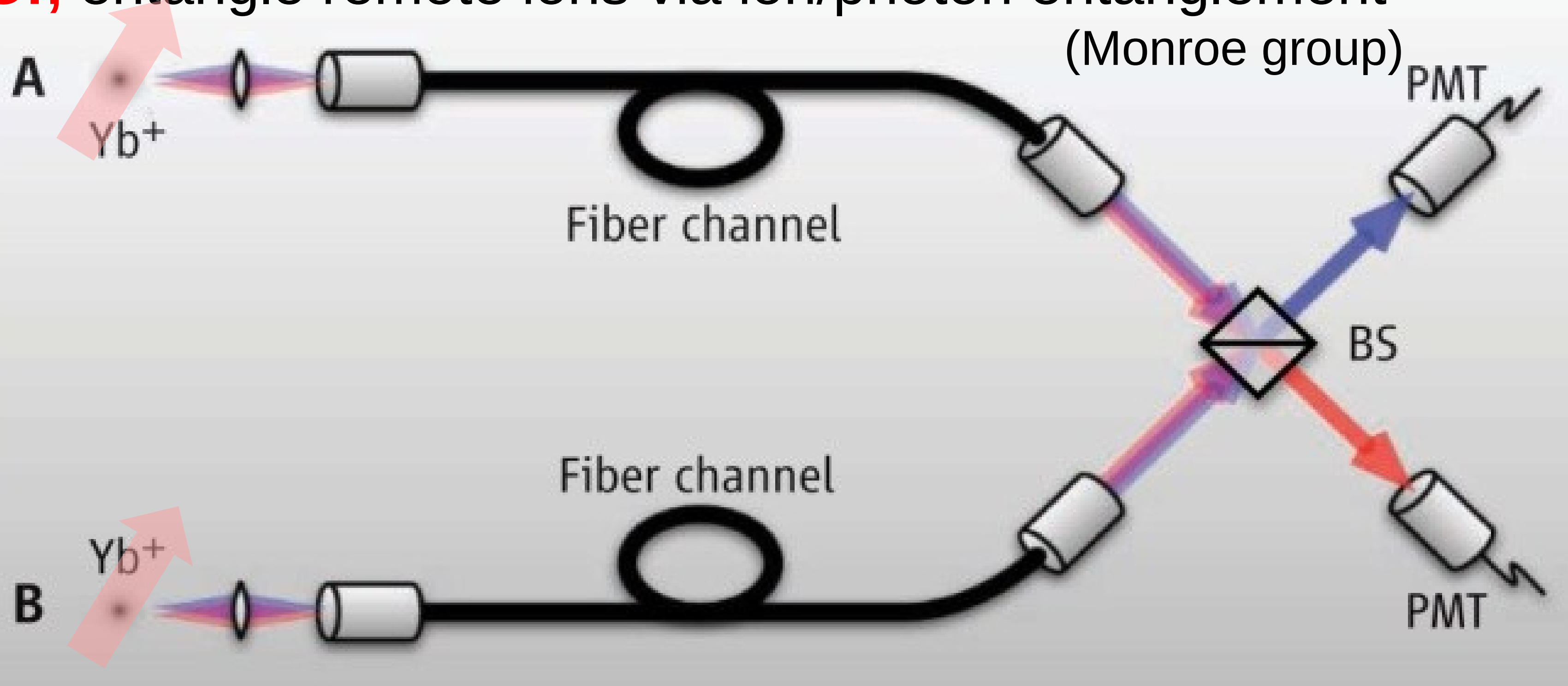
# Scaling ?




D. Wineland et al., J. Res. Natl. Inst. Stand. Technol. **103** (3), 259-328 (1998)
D. Kielpinski, C. Monroe, D. J. Wineland, Nature **147**, 709 (2002)

**Or,** entangle remote ions via ion/photon entanglement

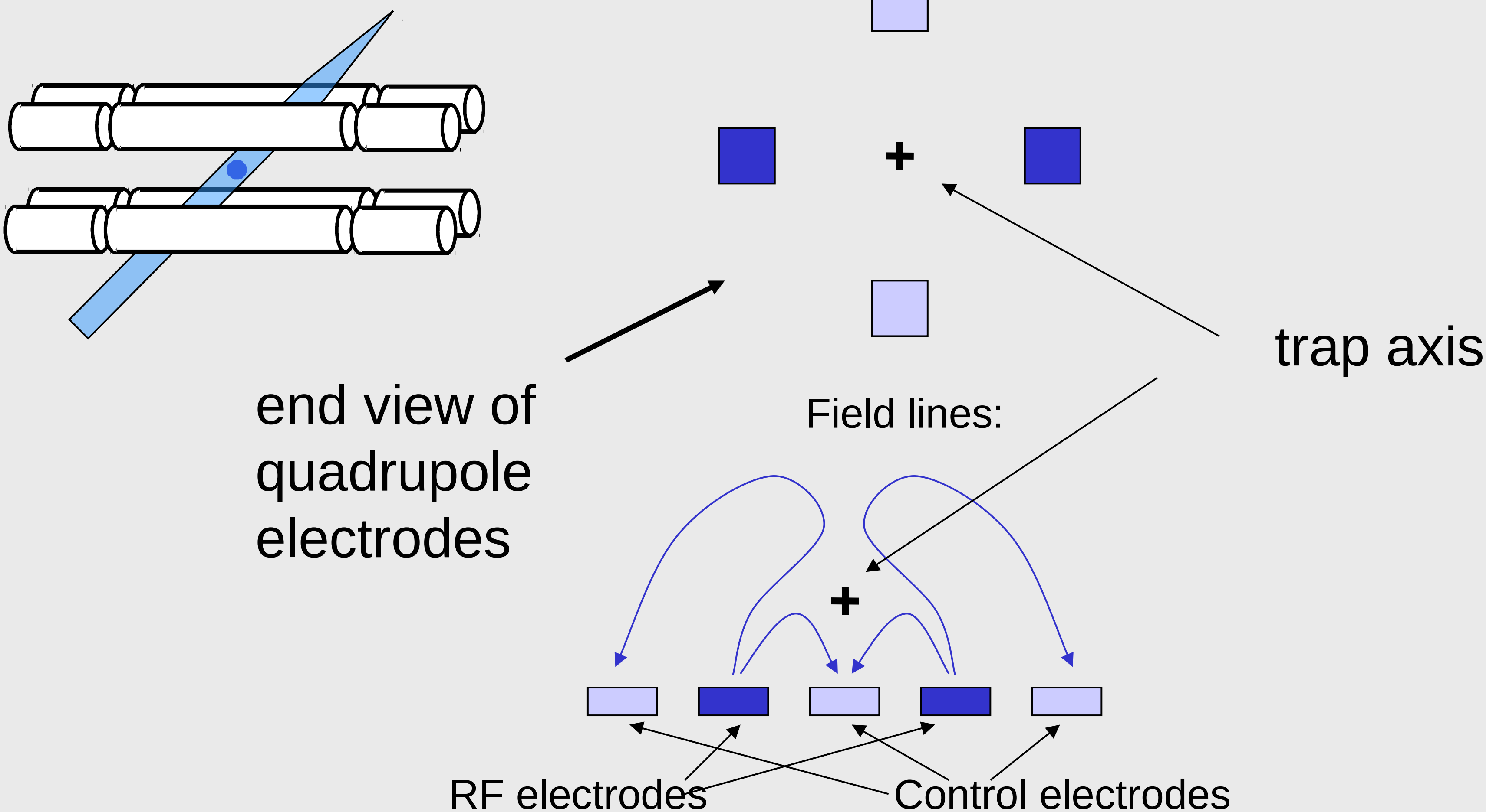
(Monroe group)



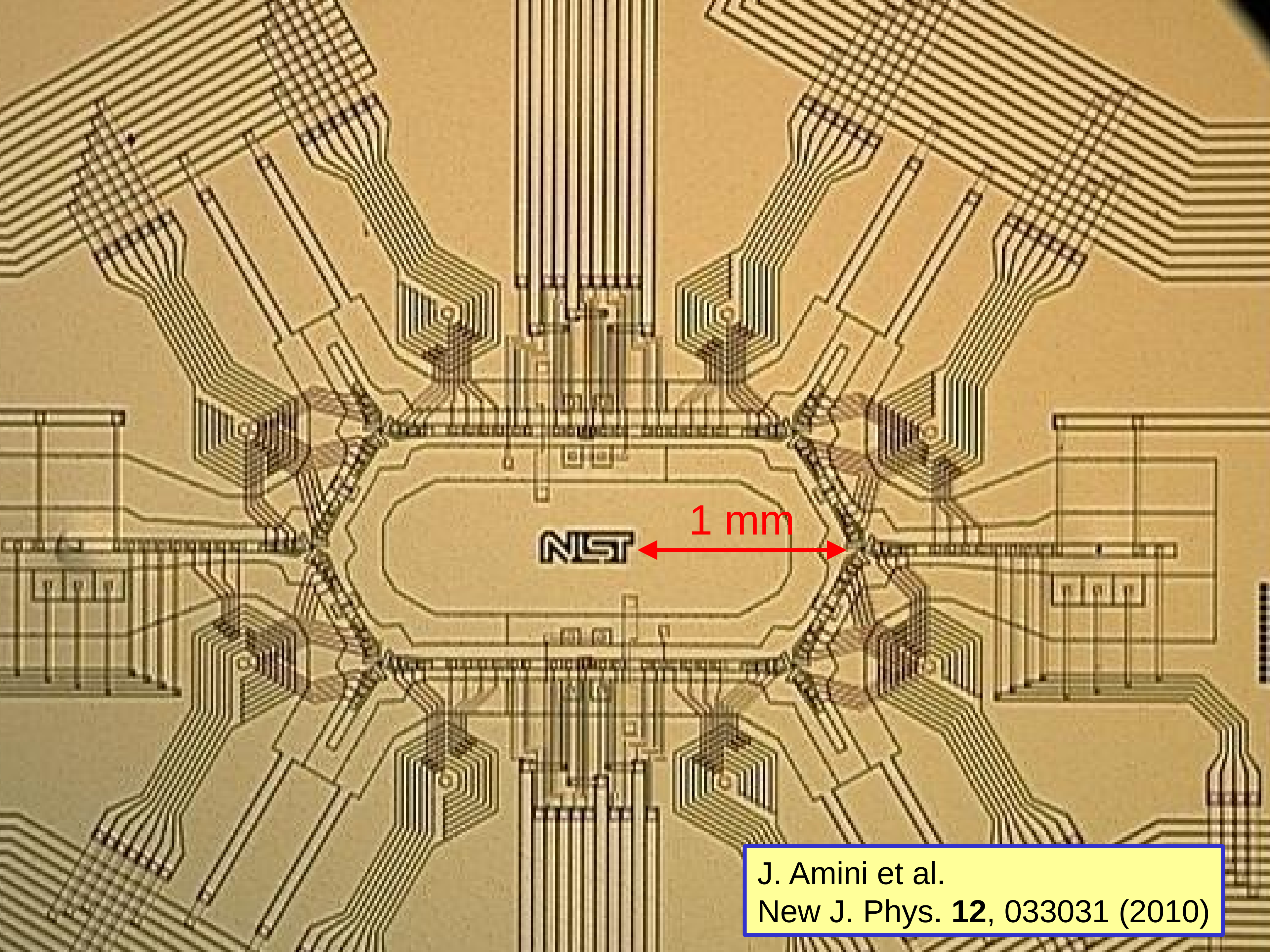

- teleport qubits and logic gates between sites in quantum processor
- connect nodes in quantum communication network

C. Monroe and J. Kim, *Science* **339**, 1164 (2013)

# Surface-electrode traps




J. Chiaverini *et al*., Quant. Information and Comp. **5**, 419 (2005).
S. Seidelin et al. Phys. Rev. Lett. **96**, 253003 (2006)


1 mm
NIST
J. Amini et al.
New J. Phys. **12**, 033031 (2010)

# Atomic ion experimental groups pursuing quantum information & metrology

Aarhus
AFRL-Rome
Amherst
ARL-Adelphi
Basel
Berkeley
Bonn
Buenos Aires
Freiburg
Georgia Tech
GTRI
Griffith
Hannover
Honeywell
Imperial (London)
Indiana
Innsbruck
IonQ
Lincoln Labs
Marseille

MIT
Munich/Garching
NIST, Boulder
Northwestern
NPL
Osaka
Oxford
Paris (Université Paris)
Singapore
SK Telecom, S. Korea
Sussex
Sydney
Tsinghua (Bejing)
UCLA
U. Oregon
U. Washington
Waterloo
Weizmann Institute
Williams

**+ many other platforms: neutral atoms, Josephson junctions, quantum dots, NV centers in diamond, single photons, …**

031 (2010)

# Future?

- Computers
  ◊ "More and better" (more qubits, smaller gate errors)
  2 qubit gate errors ~ $10^{-3}$, want < $10^{-4}$
  ◊ problem areas: e.g., for ions – "anomalous heating"
  ◊ need error correction!
- Factoring machine?
- Simulation
  ◊ mimic the dynamics of another quantum system of interest
- Metrology
  ◊ "quantum-logic" spectroscopy
  ◊ improve beyond standard quantum limit for phase measurements
- Commercial: D-wave, IBM, Google, Microsoft, Rigetti Computing, Quantum Circuits, IonQ, AQT,… (quantumcomputingreport.com)
- ???

# COMMERCIAL INTEREST (IONS)

honeywell.com/quantumsolutions

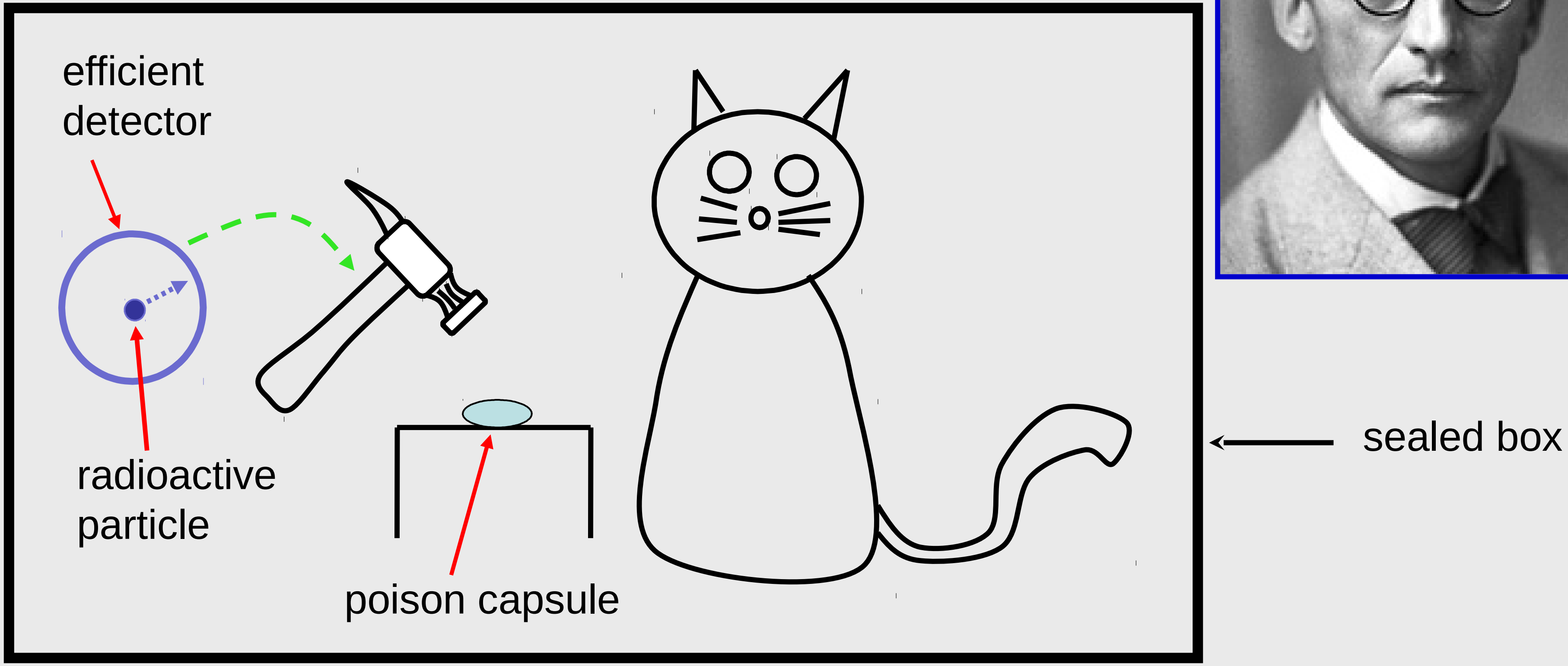
## STARTUPS

ionq.co (C. Monroe, J. Kim, …)

Alpine Quantum Technologies, aqt.eu
(R. Blatt, P. Zoller, T. Monz…)

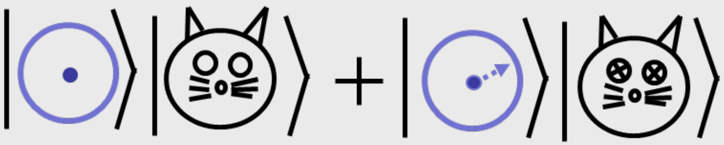
# Erwin Schrödinger’s Cat (1935)

(extrapolating ideas of quantum mechanics
from microscopic to macroscopic world)



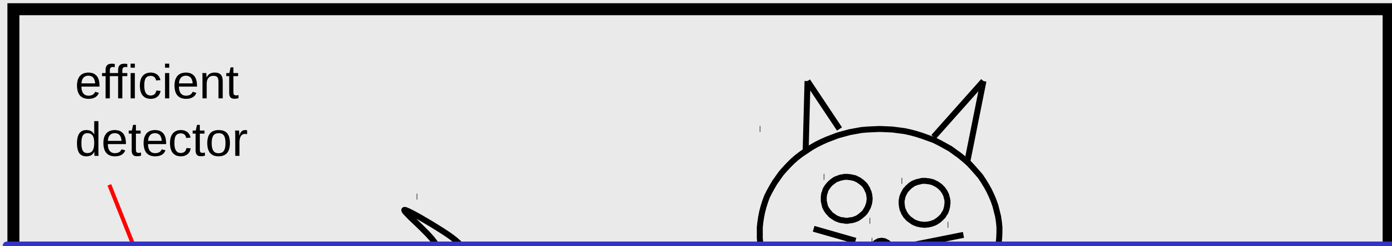

At “half-life” of particle, quantum mechanics says
cat is simultaneously dead and alive!

“entangled” superposition $\Psi$ =



# Erwin Schrödinger's Cat (1935)

(extrapolating ideas of quantum mechanics from microscopic to macroscopic world)

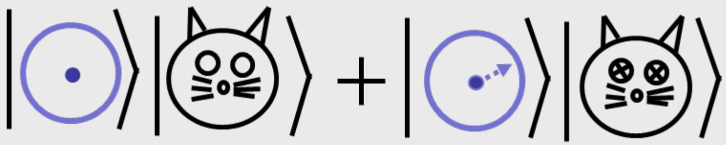



**Schrödinger (1952):**

"We never experiment with just one electron or atom or (small) molecule.  In thought experiments, we sometimes assume that we do; this invariably entails ridiculous consequences…"

At "half-life" of particle, quantum mechanics says cat is simultaneously dead and alive!

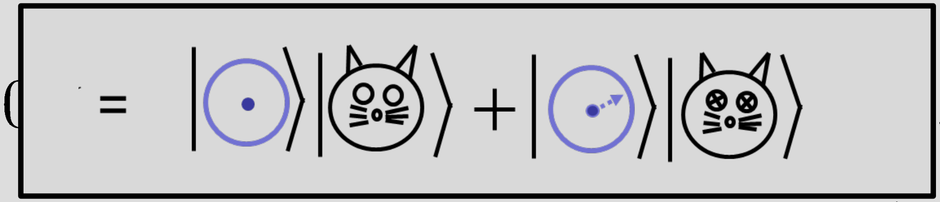
"entangled" superposition $\Psi$ =



# Special superposition state made with quantum computer:

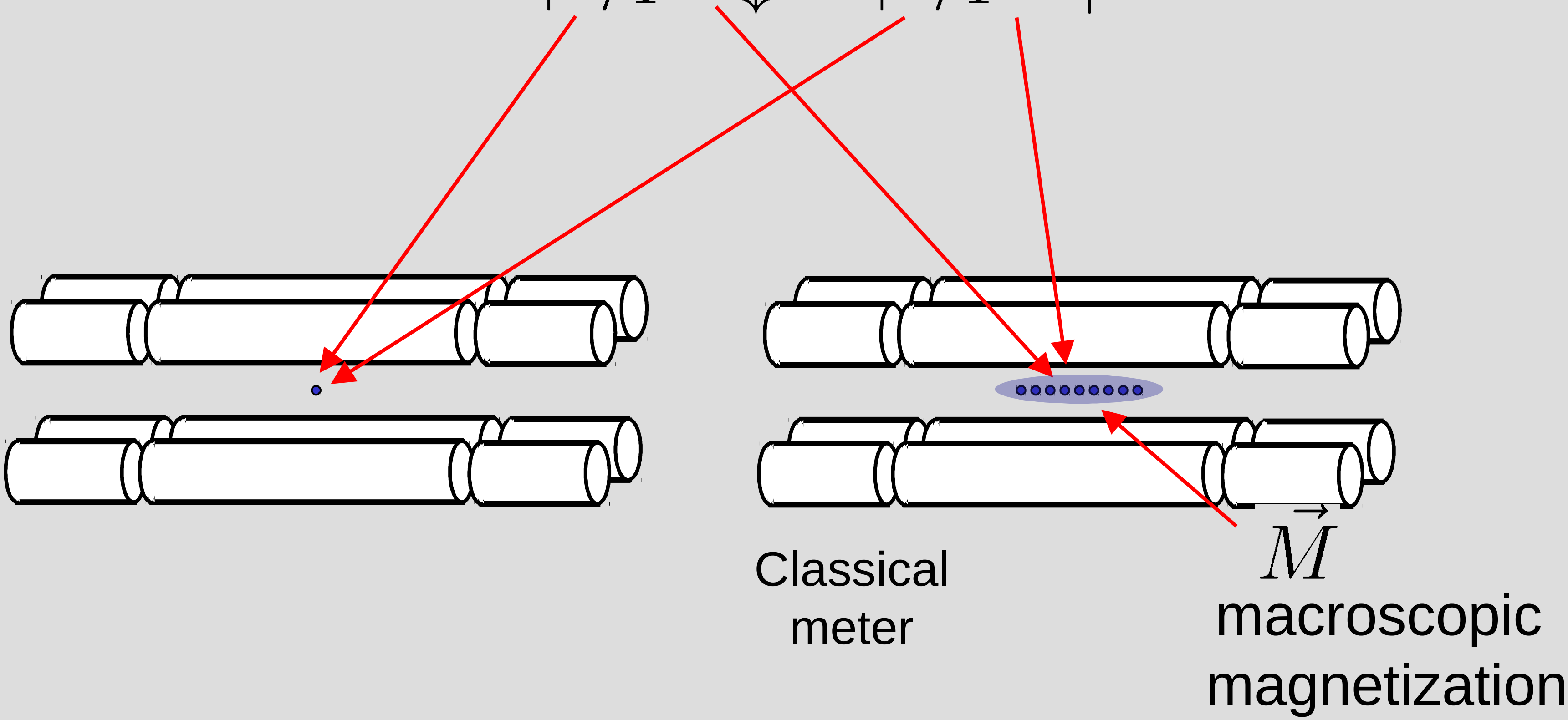
Schrödinger's cat?

$\Psi(t) = |0\rangle_1|0$



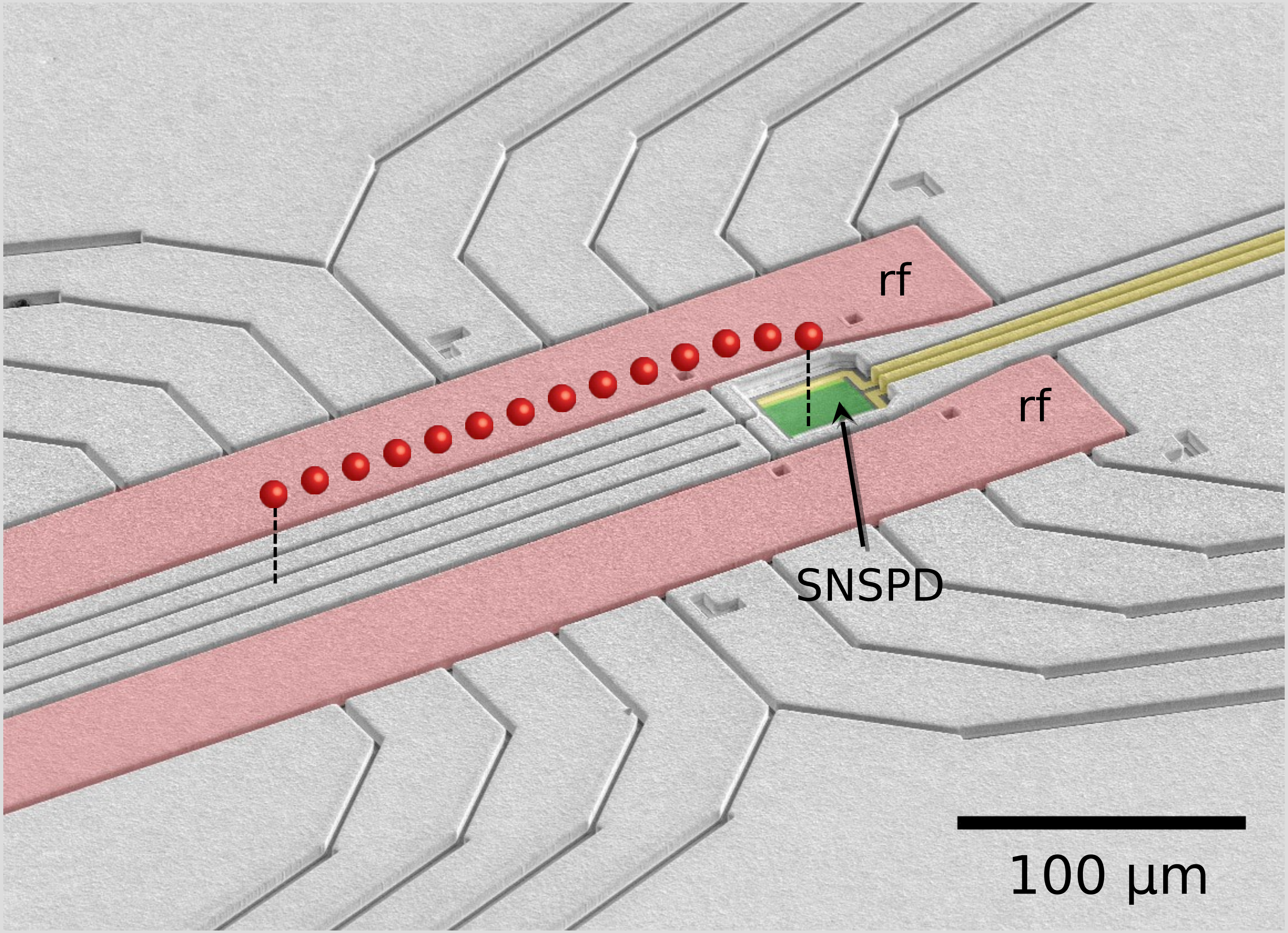

$\ldots|1\rangle_N$

For large N $\Psi = |0\rangle_1 \vec{M}_\downarrow + |1\rangle_1 \vec{M}_\uparrow$



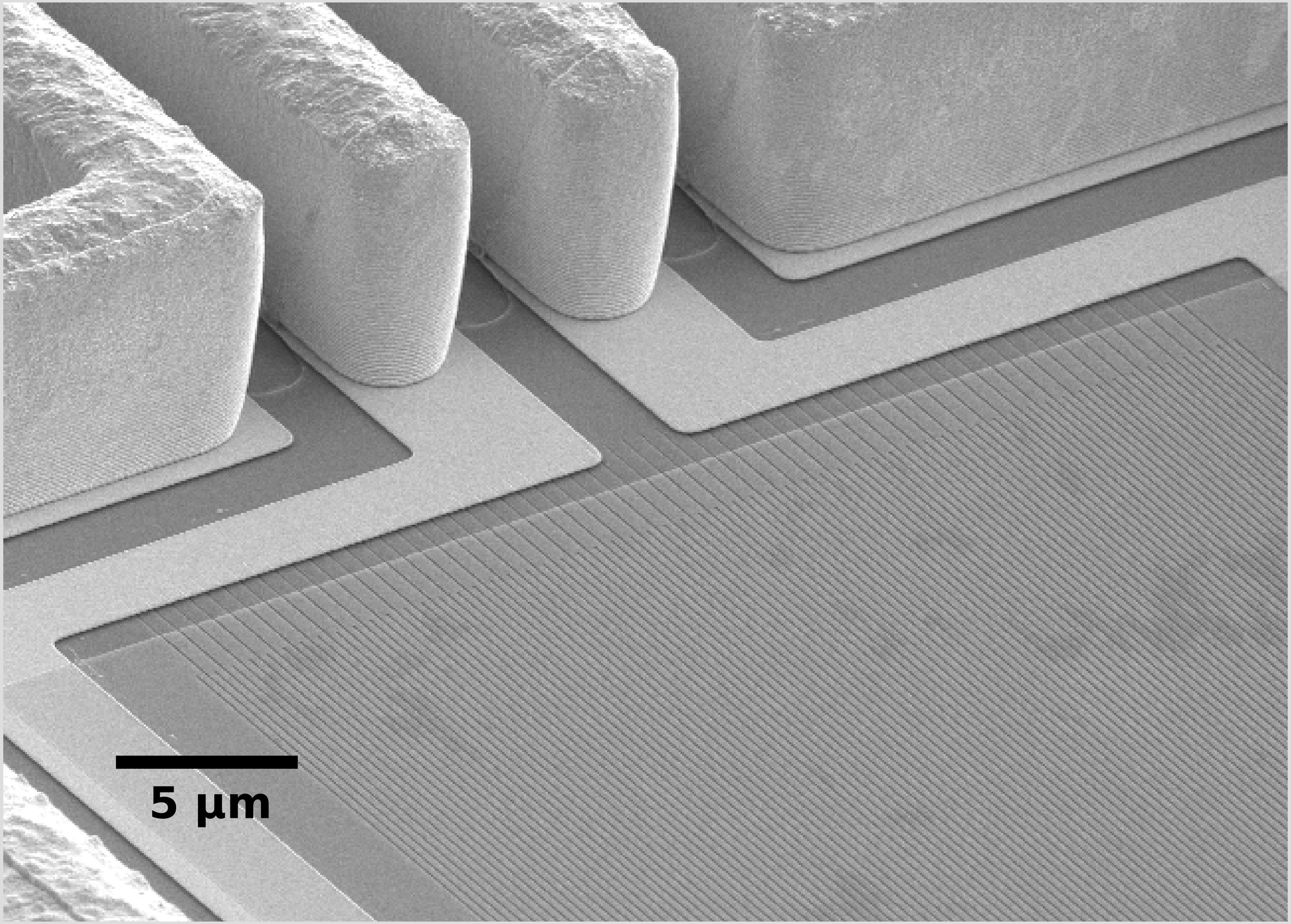

NIST IONS, December 2018

# Linear RF trap with integrated SNSPD (D. Slichter et al., NIST)



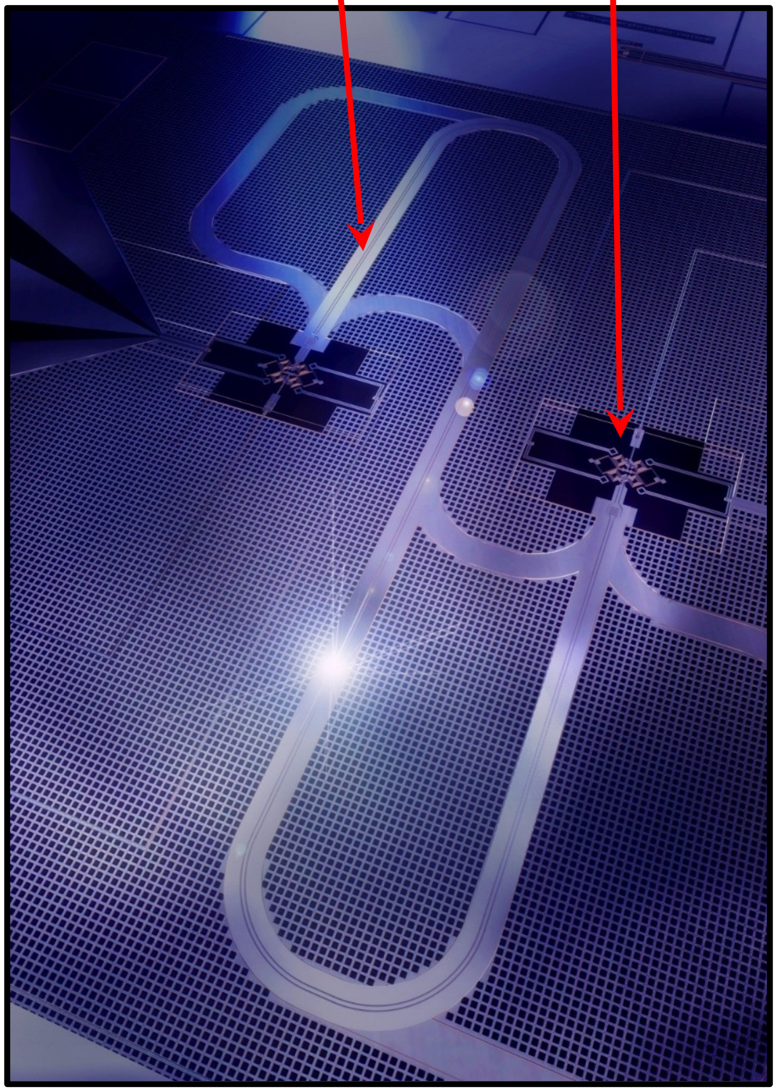

Detector NA =
0.34(2)

# Superconducting nanowire meander (MoSi)



# Superconducting qubits

e.g., Josephson-junction qubits coupled with stripline cavities



UCSB/Google – J. Martinis
Yale – M. Devoret, R. Schoelkopf
UC Berkeley – I. Siddiqi, J. Clarke
IBM
BBN
CEA Saclay
Ecole Normale Superieure – B. Huard
U Chicago – D. Schuster, A. Cleland
Princeton – A. Houck
NIST – R. Simmonds, J. Aumentado, J. Teufel, D. Pappas
IQC (Waterloo) – A. Lupascu, C. Wilson, M. Mariantoni
Colorado – K. Lehnert
Wisconsin – R. McDermott
Syracuse – B. Plourde
Washington U. in St. Louis – K. Murch
Tata Institute – R. Vijay
U Pittsburgh – M. Hatridge
Kansas – S. Han
MIT/Lincoln Labs – W. Oliver, T. Orlando
Delft – L. DiCarlo, H. Mooij
ETH Zurich – A. Wallraff
U Grenoble – O. Buisson
U. Tokyo – Y. Nakamura
NEC – J. Tsai
NTT – K. Semba
Royal Holloway – O. Astafiev
Maryland/JQI – F. Wellstood, K. Osborn, B. Palmer, V. Manucharyan
Innsbruck – G. Kirchmair
Chalmers – P. Delsing
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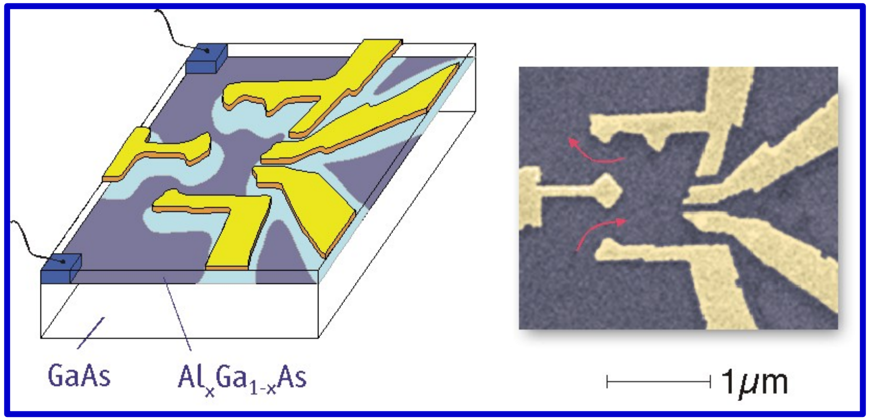
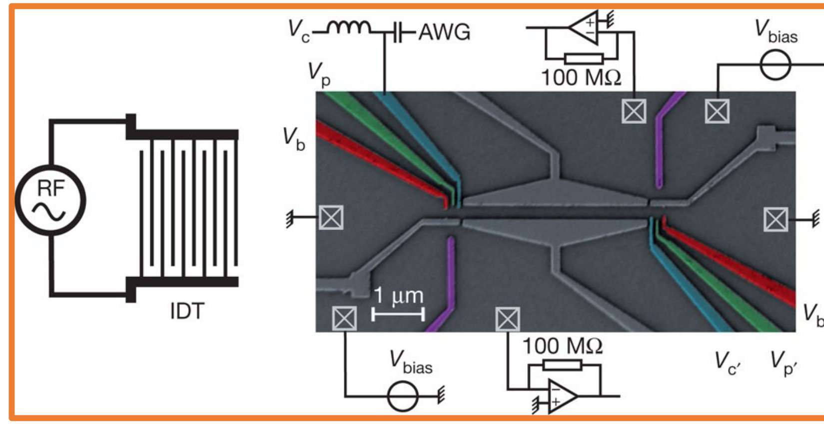
# Quantum dots/NV centers/SiC centers/P donors in Si

e.g., 2DEG GaAs Qubits




C. Marcus et al.




S. Hermelin et al., Nature **447**, 435 (2011)

HRL
Niels Bohr Institute – C. Marcus …
U. Chicago – D. Awschalom…
Oxford – J. Morton…
U. New South Wales – A. Morello,
A. Dzurak, M. Simmons, S. Rogge
U. Sydney – D. Reilly …
OIST (Okinawa) – Y. Kubo …
ETH Zurich – K. Ensslin, A. Imamoglu
Harvard – M. Lukin,
A. Yacoby, R. Walsworth
UCSB – A. Gossard …
MIT – D. Englund …

NRC, Canada, A. Sachrajda …
Princeton – J. Petta, S. Lyon, J. Thompson …
Stanford – Y. Yamamoto, J. Vukovic …
IQC (Waterloo) – M. Bajcsy …
McGill – L. Childress …
UC Berkeley – E. Yablonovitch, J. Bokor …
LBNL – T. Schenkel …
UCLA – H. Jiang …
Delft – L. Kouwekhoven,
L. Vandersypen, R. Hanson …
Wisconsin – M. Eriksson …
TU-Munich – G. Abstreiter …
Dortmund – M. Bayer …
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