Quantum Information Science
(NIST trapped ion group)

Dilbert confronts Schrödinger's cat, 4/17/12

The quantum computer

Data storage:

- classical: computer bit: (0) or (1)
- quantum: "qubit" $\alpha|0\rangle + \beta|1\rangle$ superposition

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

Classical register: (example): (101)

Quantum register: (3 qubits):

$$\Psi = C_{000}|0,0,0\rangle + C_{001}|0,0,1\rangle + C_{010}|0,1,0\rangle + C_{011}|0,1,1\rangle$$

$$+ C_{100}|1,0,0\rangle + C_{101}|1,0,1\rangle + C_{110}|1,1,0\rangle + C_{111}|1,1,1\rangle$$

(represents 2^3 numbers simultaneously)

For N = 300 qubits, store $2^{300} \approx 10^{90}$ numbers simultaneously

(> classical information in universe!)

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

But!: quantum measurement rule: measured register gives only one number

Factoring: Shor's Algorithm (1994)

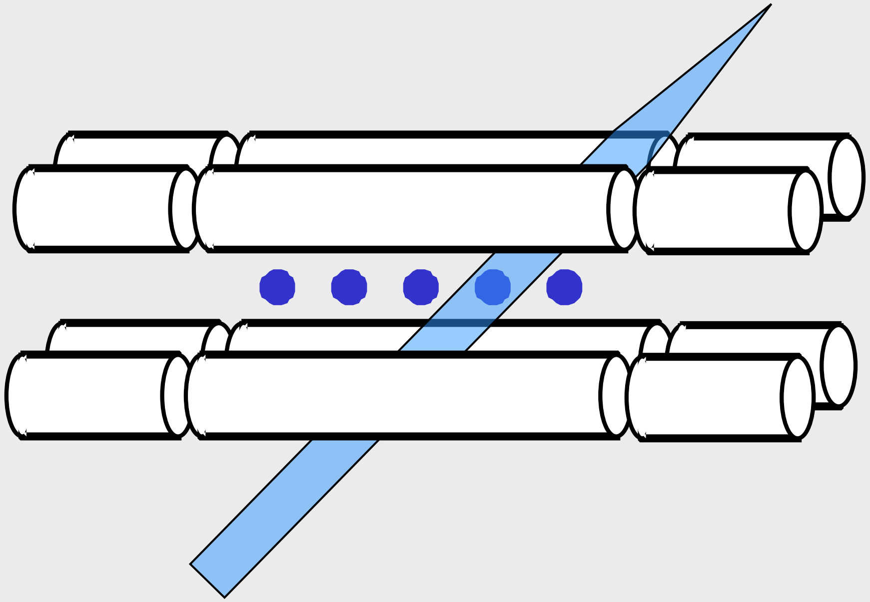
Atomic ion quantum computation:

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

Ignacio Cirac   Peter Zoller

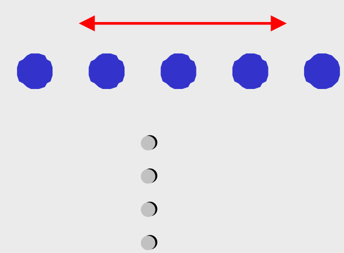
1. START MOTION IN GROUND STATE

2. SPIN → MOTION MAP

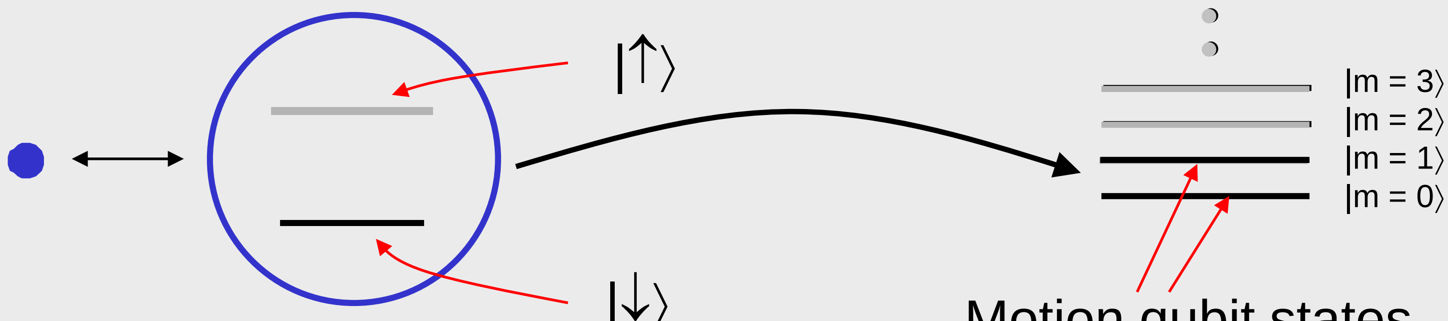


MOTION “DATA BUS”

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



INTERNAL STATE **“SPIN”** QUBIT



Atomic ion quantum computation:

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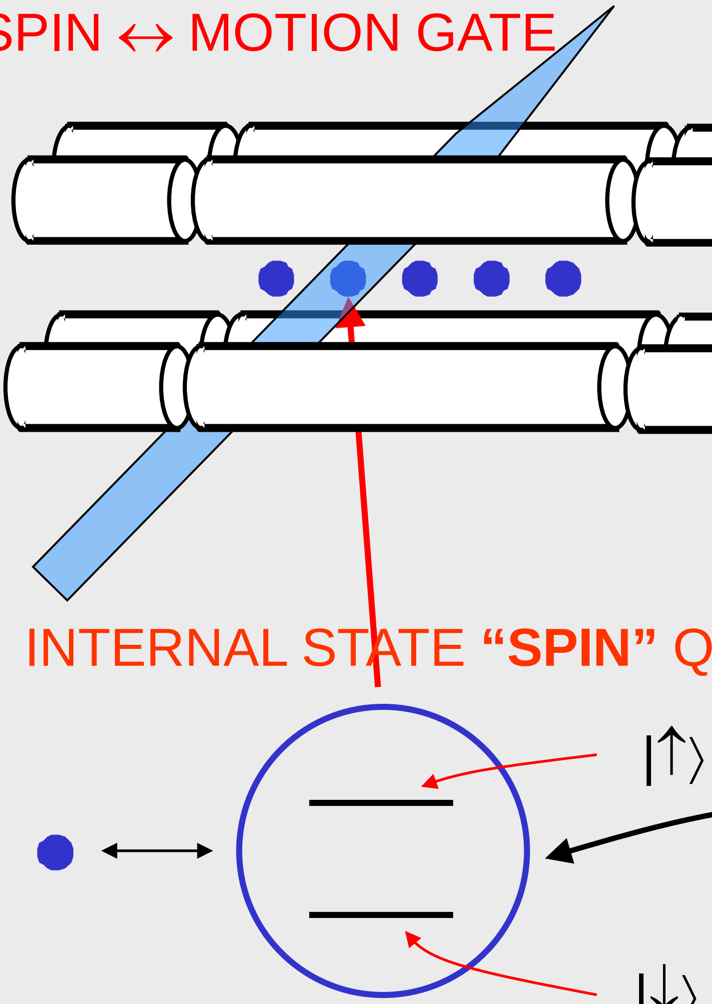
Ignacio Cirac

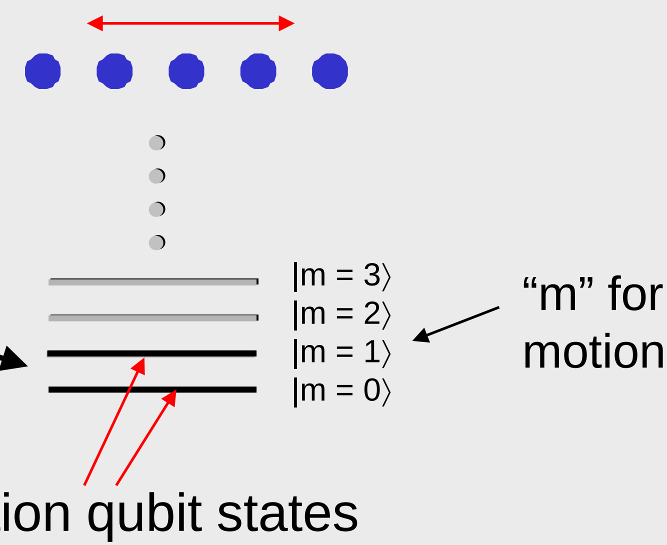
Peter Zoller

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

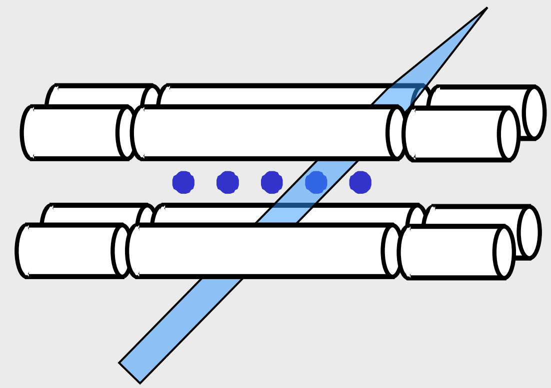


MOTION "DATA BUS"

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



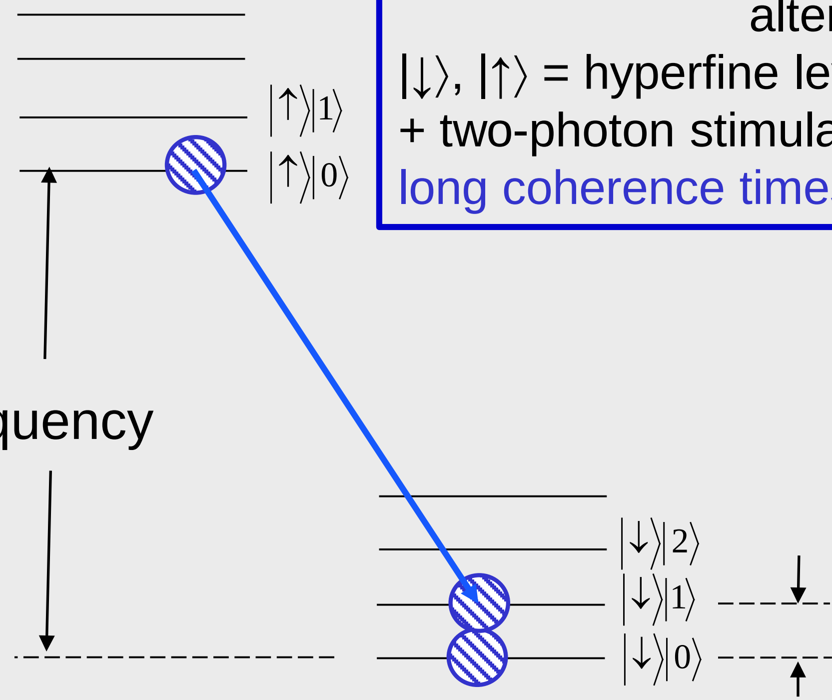
Interactions with laser beams :



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

information transfer

alternative:
$|\downarrow\rangle$, $|\uparrow\rangle$ = hyperfine levels,
+ two-photon stimulated-Raman transitions
long coherence times ~ 30 min

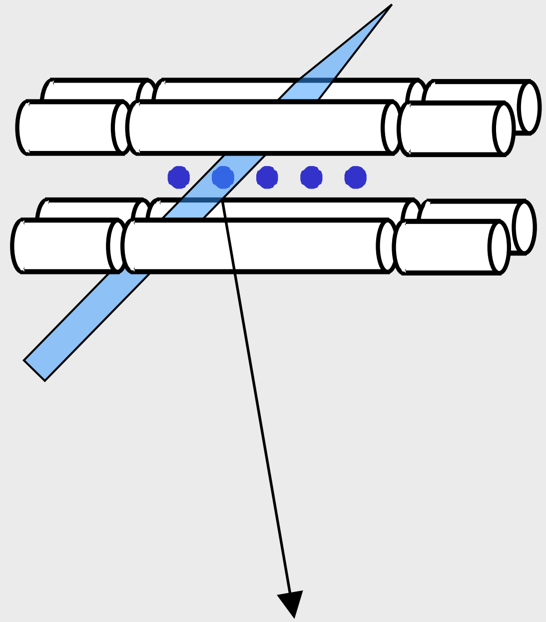


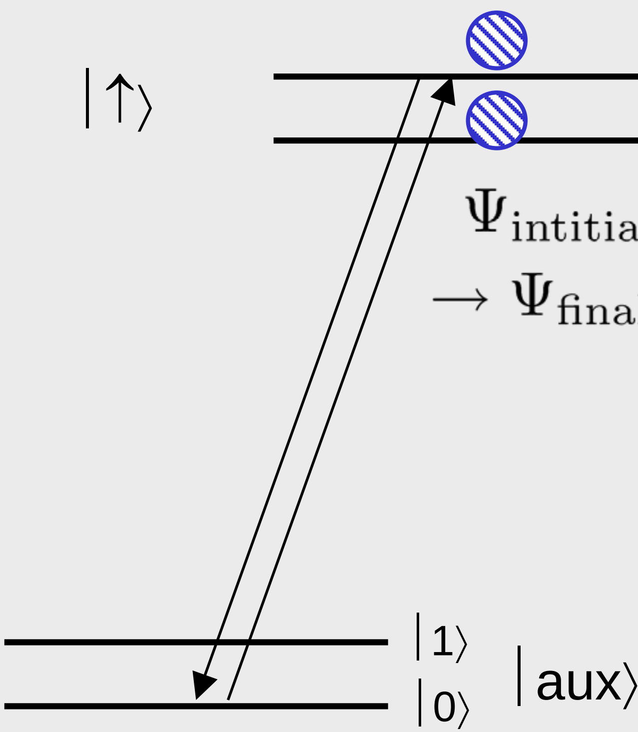
optical frequency

1 – 10 MHz (motional mode frequency)

SPIN-MOTION GATE:

(Chris Monroe et al. PRL, '95)

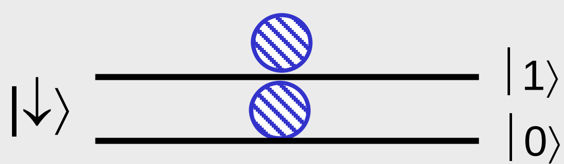




$$\Psi_{\text{intitial}} = \alpha|\downarrow\rangle|0\rangle + \beta|\downarrow\rangle|1\rangle + \gamma|\uparrow\rangle|0\rangle + \delta|\uparrow\rangle|1\rangle$$

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

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \sim G = \sigma_1^z \sigma_2^z$$



Quantum computer algorithm
to efficiently factorize large numbers

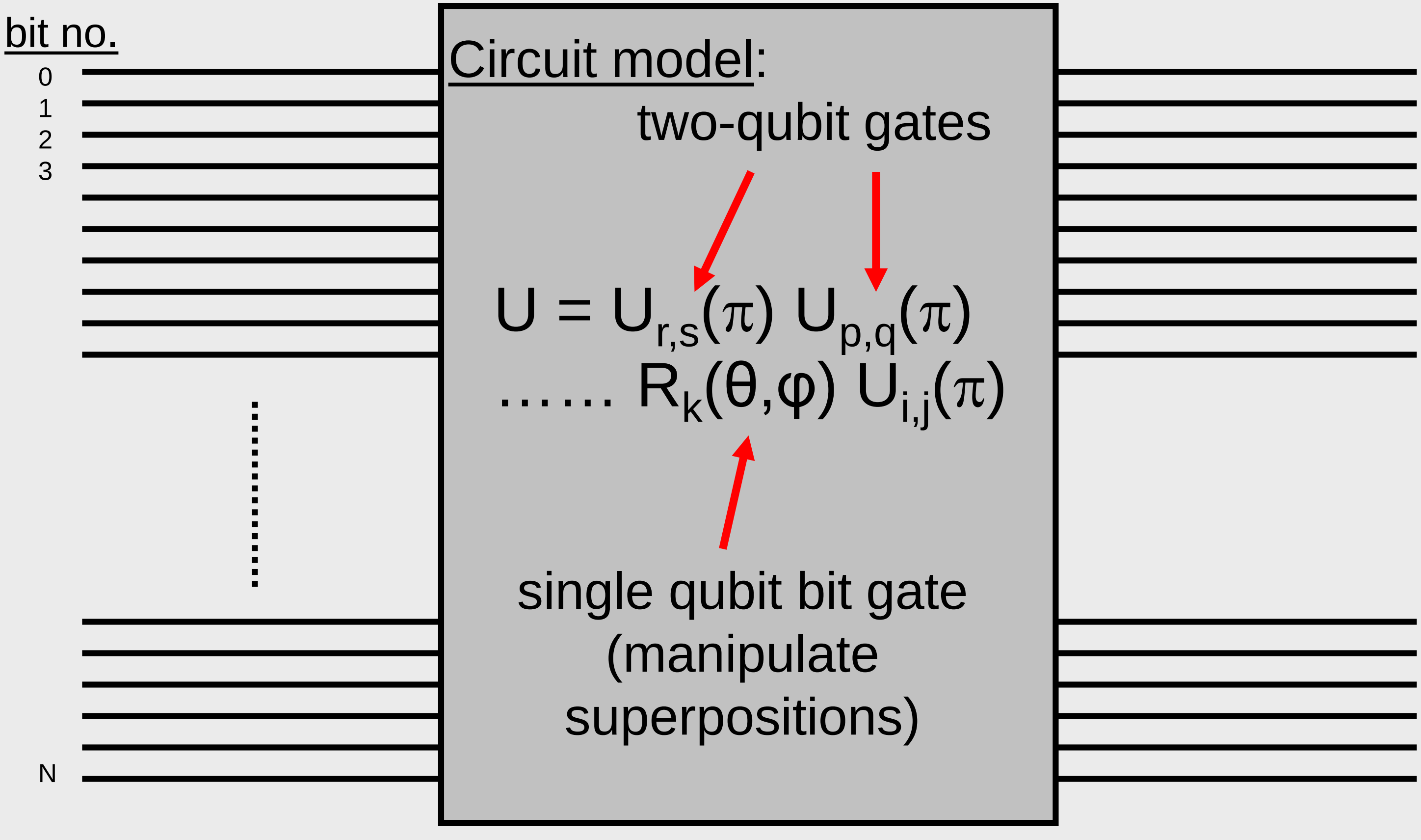
Peter Shor (~ 1994)

N-qubits:

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

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

Process all possible
inputs simultaneously



Quantum computer algorithm
to efficiently factorize large numbers

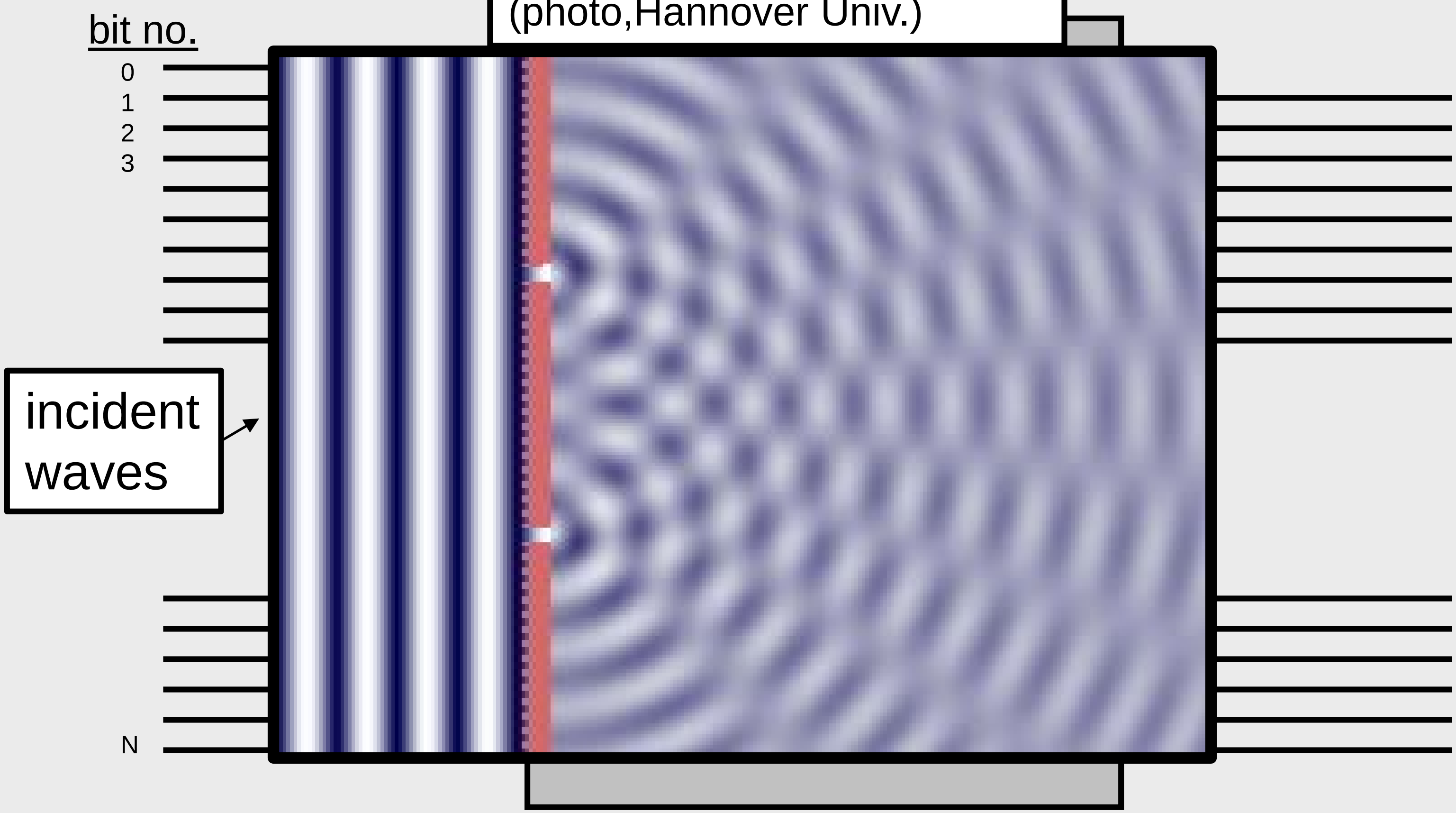
Peter Shor (~ 1994)

N-qubits:

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

Process all possible
inputs simultaneous

analogous to
waterwave interference
(photo,Hannover Univ.)



Quantum computer algorithm to efficiently factorize large numbers

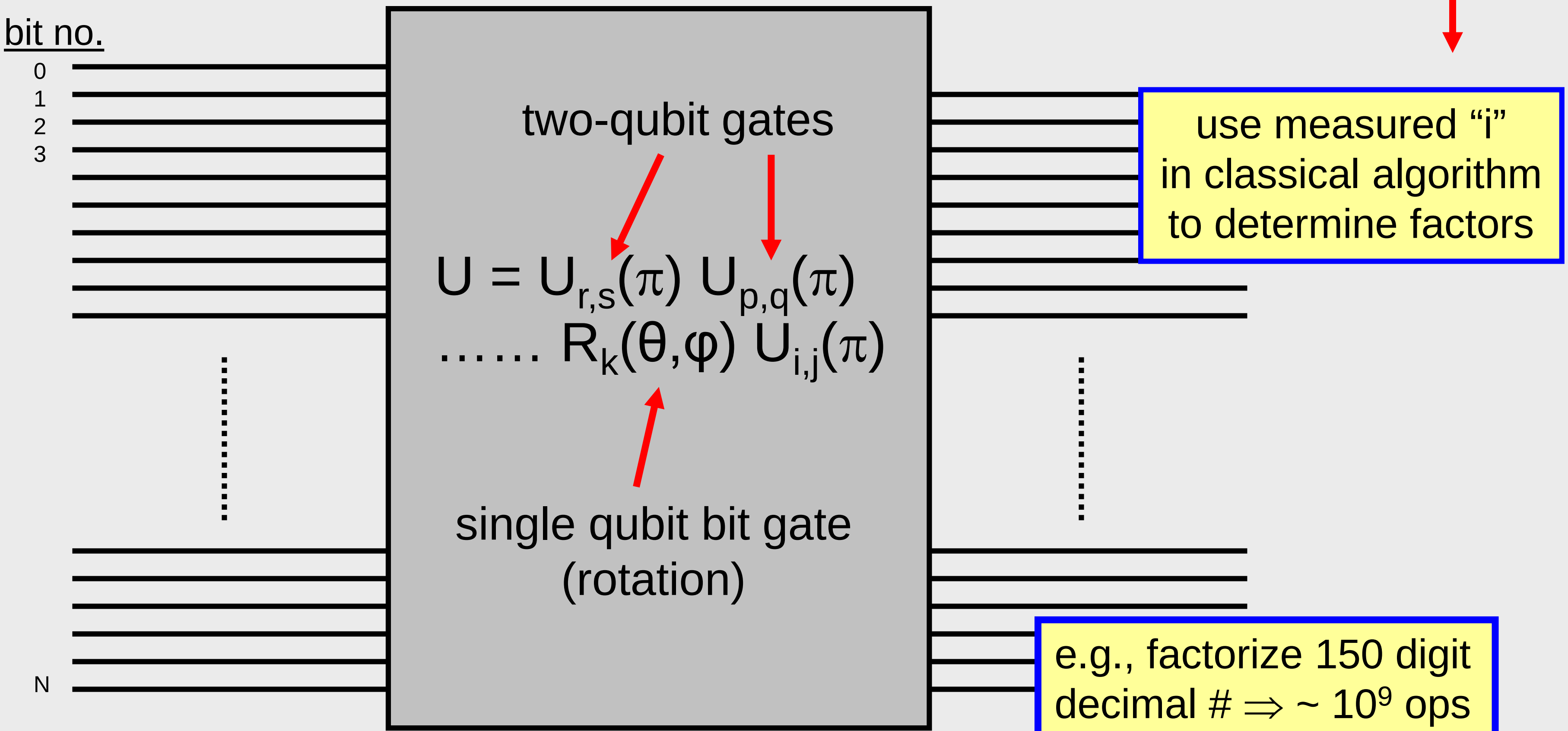
Peter Shor (~ 1994)

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

Process all possible inputs simultaneously

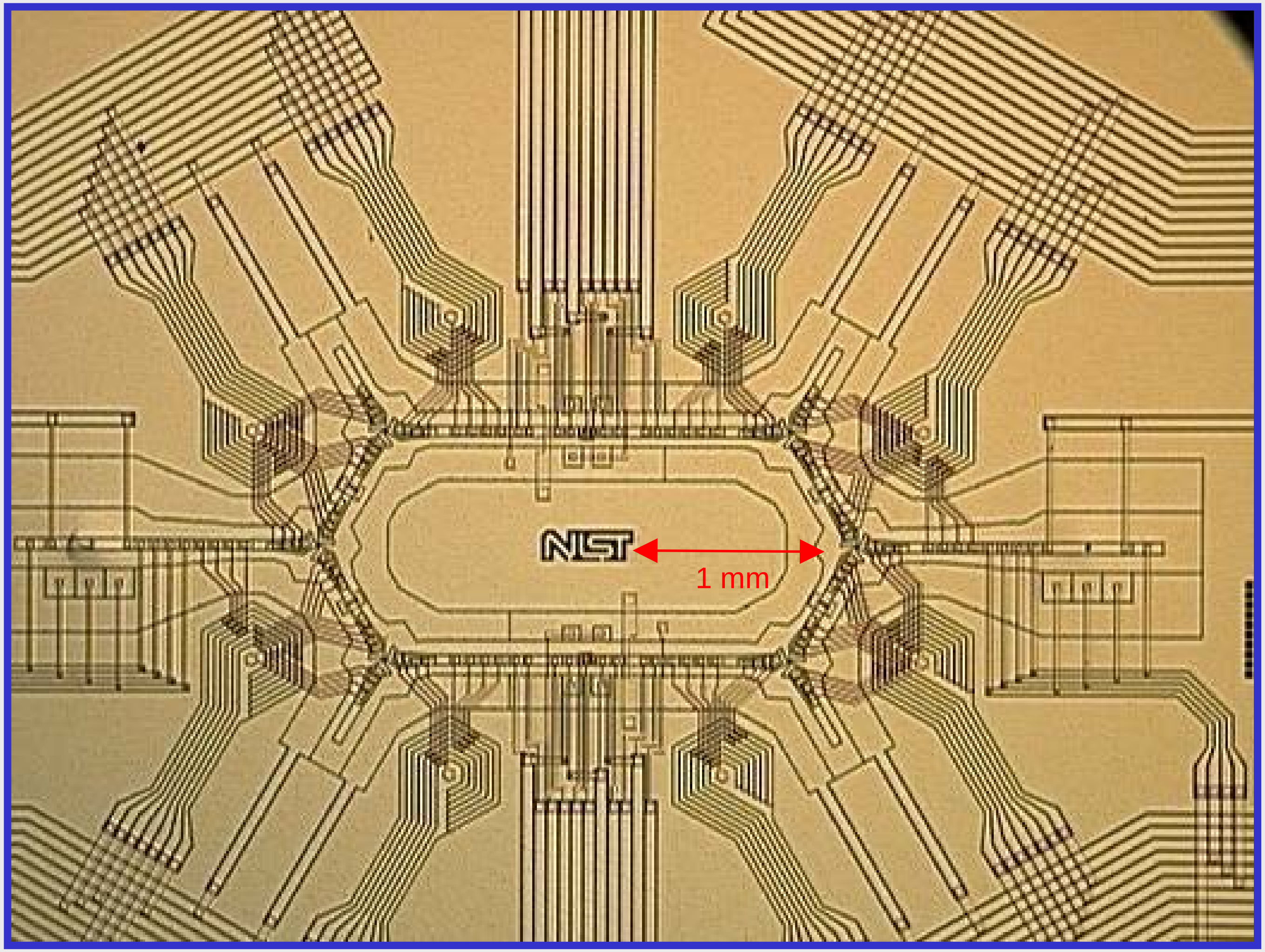
$$\psi_{out} = \sum_{\text{small selection}} |i\rangle$$

measure qubits



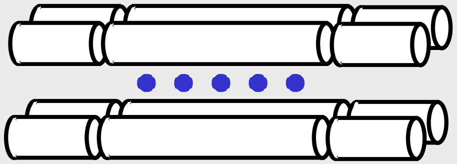
Scale up qubit numbers?

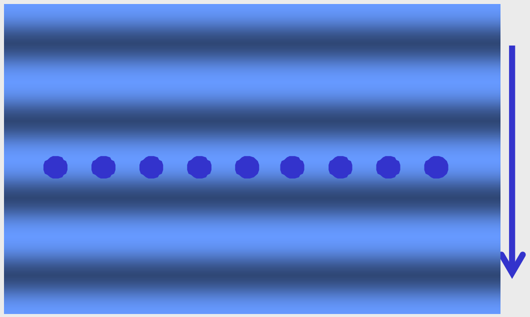
- small electrodes: use lithographic techniques
- move ions in multi-zone arrays for scaling



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

Quantum simulation:



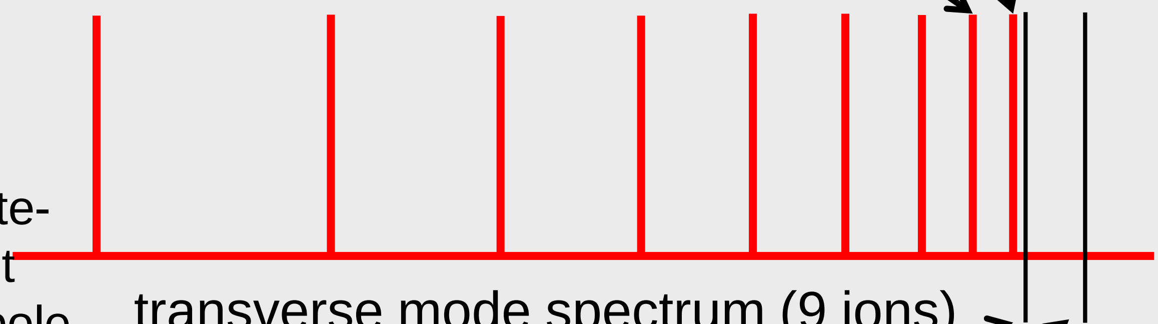


"moving standing wave" state-dependent optical-dipole forces

Center-of-mass mode

tilt mode

mode frequency →



transverse mode spectrum (9 ions)

add magnetic field:

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

Transverse Ising model
(JQI, Innsbruck)

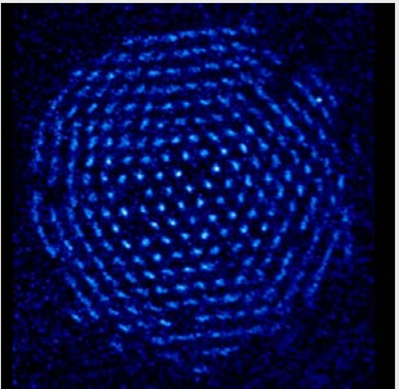
for $\omega_{force} \cong \omega_{COM}$

$$H = J \sum_{i<j} \hat{\sigma}_z^i \hat{\sigma}_z^j$$

($\omega_{force} > \omega_{COM}$)

$$H = \sum_{i<j} J_{i,j} \hat{\sigma}_z^i \hat{\sigma}_z^j$$

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



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

$$J_{i,j} \sim \frac{+J_0}{|i-j|^\alpha}$$

vary α by
varying detuning
α = 0 - ~3

Atomic ion experimental groups pursuing Quantum Information Processing:

- Aarhus
- Amherst
- The Citadel
- Tsinghua (Bejing)
- U.C. Berkeley
- U.C.L.A.
- Duke
- ETH (Zürich)
- Freiburg
- Garching (MPQ)
- Georgia Tech
- Griffiths
- Hannover
- Innsbruck
- JQI (U. Maryland)
- Lincoln Labs
- Imperial (London)
- Mainz
- MIT
- NIST
- Northwestern
- NPL
- Osaka
- Oxford
- Paris (Université Paris)
- Pretoria, S. Africa
- PTB
- Saarland
- Sandia National Lab
- Siegen
- Simon Fraser
- Singapore
- SK Telecom, S. Korea
- Sussex
- Sydney
- U. Washington
- Weizmann Institute

Atomic ion experimental groups pursuing Quantum Information Processing:

Aarhus
Amherst
The Citadel
Tsinghua (Bejing)
U.C. Berkeley

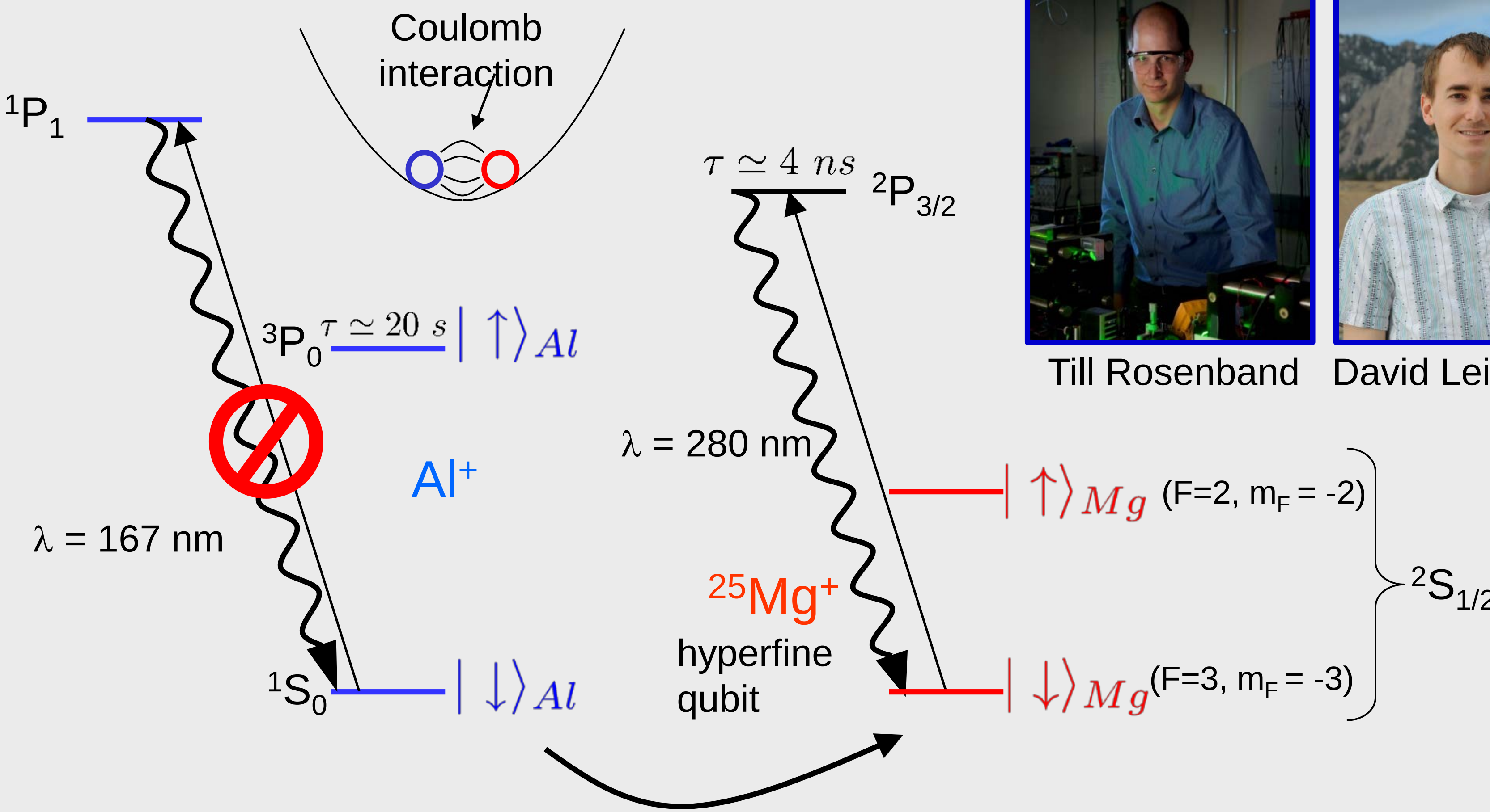
+ many other platforms:
neutral atoms, Josephson junctions, quantum dots, NV centers in diamond, single photons, …

Griffiths
Hannover
Innsbruck
JQI (U. Maryland)
Lincoln Labs
Imperial (London)
Mainz

MIT
NIST
Northwestern
NPL
Osaka

Siegen
Simon Fraser
Singapore
SK Telecom, S. Korea
Sussex
Sydney
U. Washington
Weizmann Institute

Applications: Al^+ "quantum-logic clock"



Till Rosenband

David Leibrandt

$\alpha|\downarrow\rangle_{Al} + \beta|\uparrow\rangle_{Al} \rightarrow$ motion superposition $\rightarrow \alpha|\downarrow\rangle_{Mg} + \beta|\uparrow\rangle_{Mg}$

- ◊ laser-cooled Mg^+ keeps Al^+ cold
- ◊ Mg^+ helps to calibrate $\langle B^2 \rangle$ from all sources
- ◊ collisions observed by ions switching places
- ◊ ……

⇒ Systematic uncertainty = 0.8×10^{-17}

Future:

now 10^{-3} per 2-qubit gate, need $\leq 10^{-4}$ for error correction

improve hardware: e.g., optical fibers for UV

- More and better (more qubits, smaller gate errors)
  - dirty laundry: ion heating

collaborate with NIST surface group, D. Pappas et al.

- Simulation
  - ◊ quantum logic gates emulate spin-spin coupling

    Example: transverse Ising model

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

useful simulations can tolerate higher errors

  - ◊ Universal digital quantum simulation
- Metrology
  - ◊ "quantum-logic" spectroscopy — extend to molecules
  - ◊ improve beyond standard quantum limit for phase measurements
- Factoring machine?
- ???

Jim Bergquist, John Bollinger, Joe Britton, Justin Bonet, Ryan Bowler, John Gaebler, Andrew Wilson, Dave Wineland, David Leibrandt, Peter Burns, Raghu Srinivas, Shon Cook, Robert Jordens

David Hume   Ting Rei Tan

Shlomi Kotler, Dustin Hite, Katie McCormick,Susanna Todaro, Leif Waldner, Yiheng Lin, Daniel Slichter, James Chou, David Allcock, Didi Leibfried, Jwo-Sy Chen, Sam Brewer, Kyle McKay

Not pictured: Brian Sawyer, Yong Wan, Aaron Hankin,
Till Rosenband, Wayne Itano, Dave Pappas, Bob Drullinger