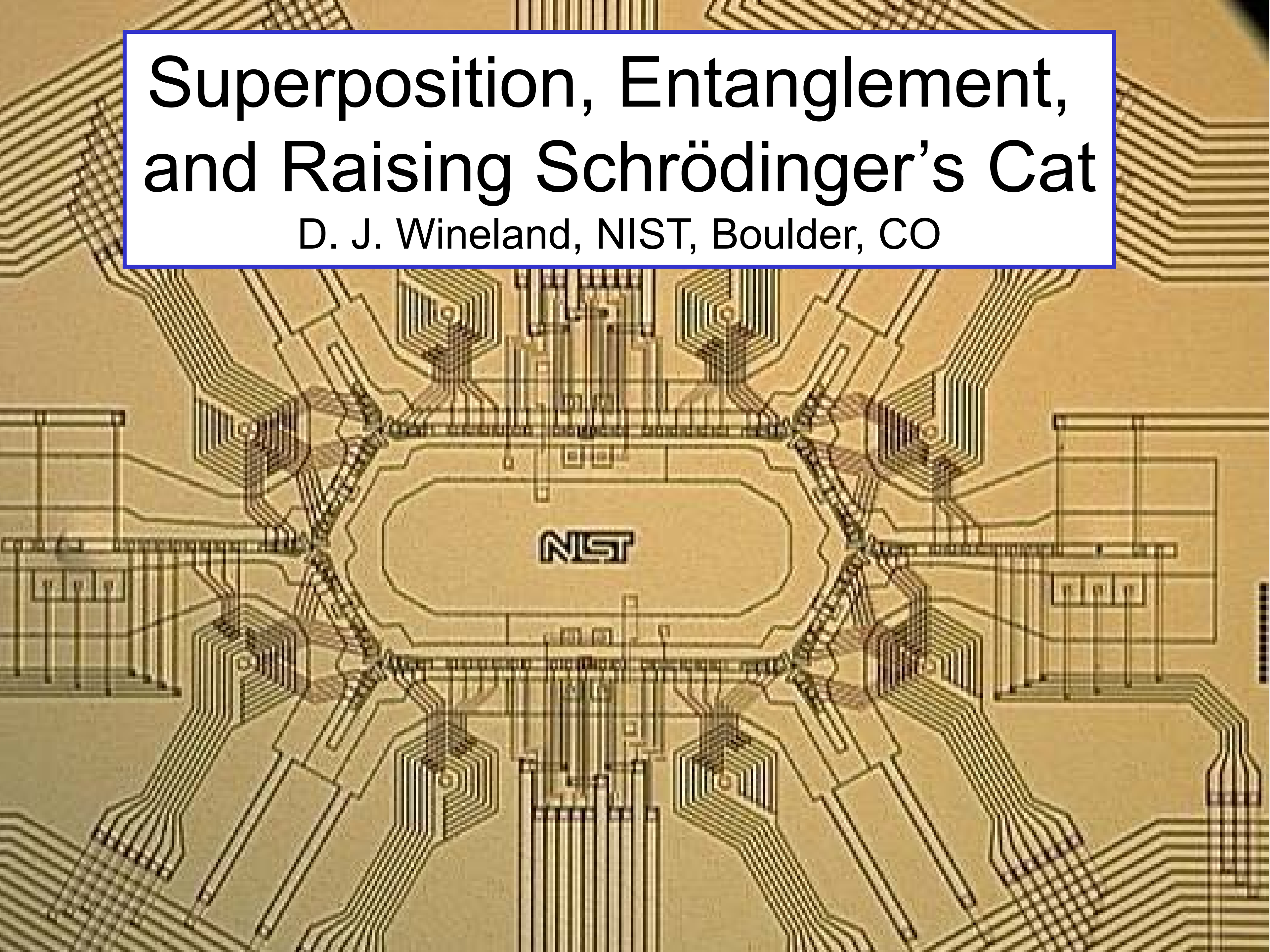
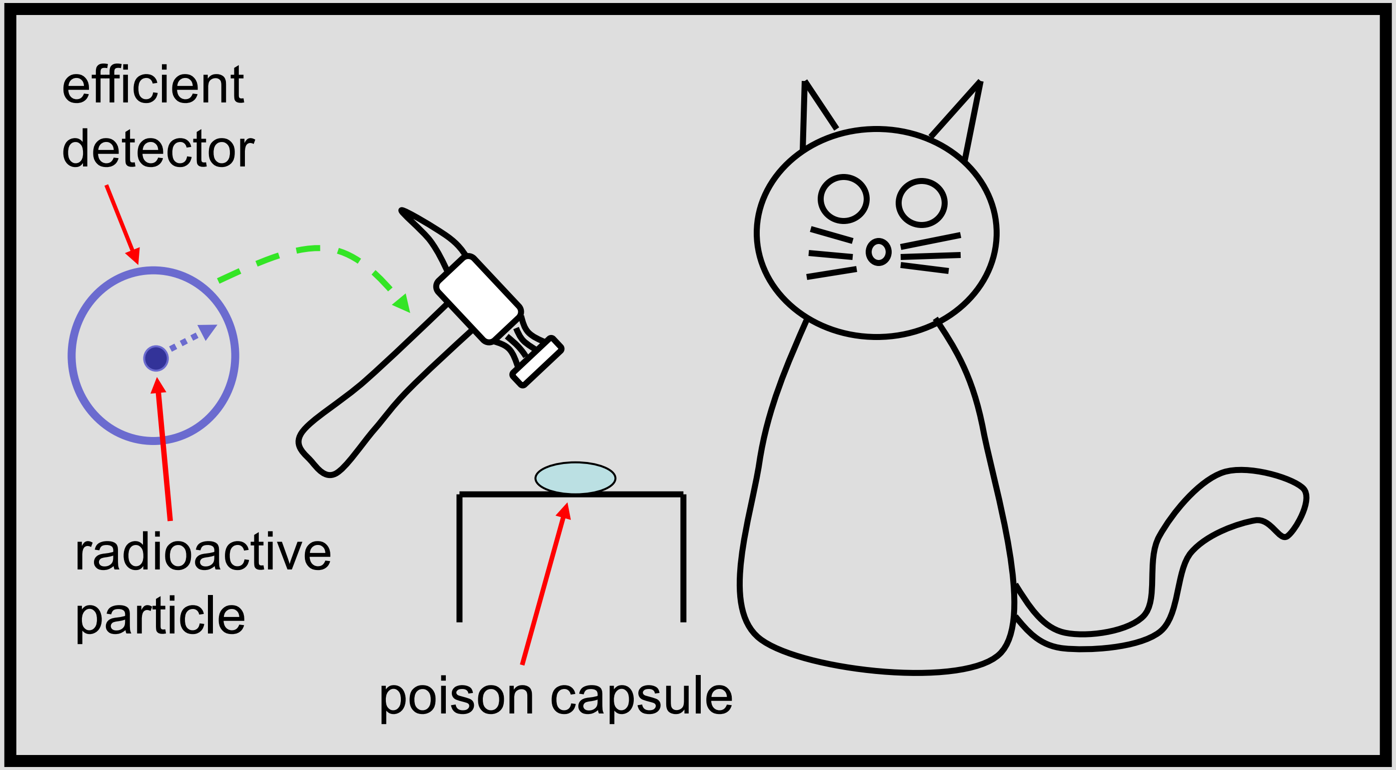
Superposition, Entanglement, and Raising Schrödinger's Cat

D. J. Wineland, NIST, Boulder, CO



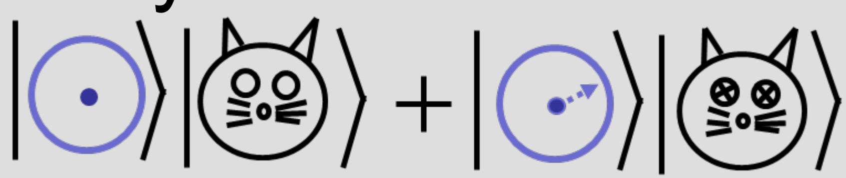
Erwin Schrödinger's Cat (1935)



← sealed box

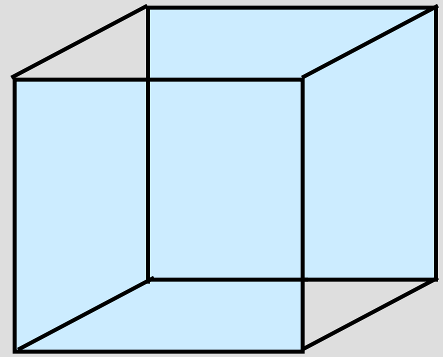
At "half-life of particle, quantum mechanics says cat is simultaneously dead and alive!

"superposition"

$\Psi =$ 

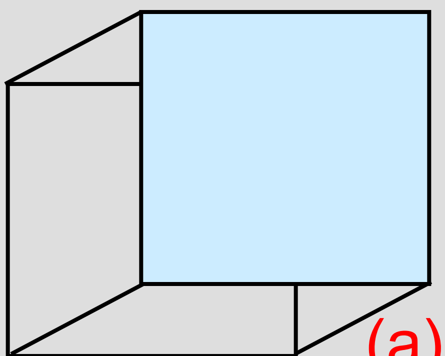
Analog of quantum superposition

two “states” of a box

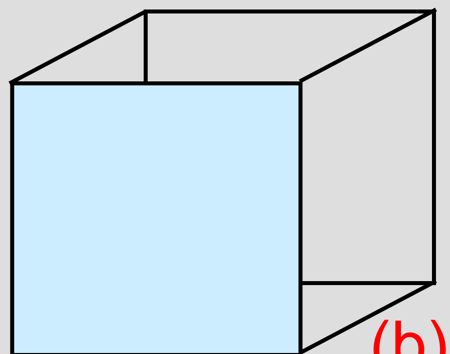


?

(a) <u>and</u> (b)



(a)



(b)

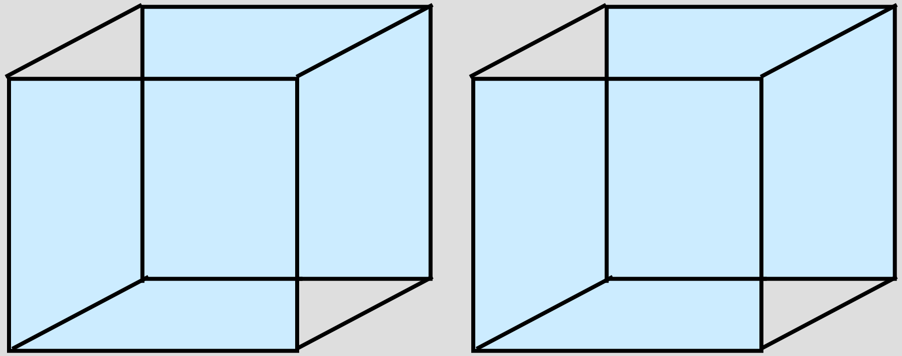
1. ambiguity about which state the box is in.
Box possesses <u>both properties simultaneously</u>

2. quantum measurement: collapse or “projection” into either state (a) or (b)

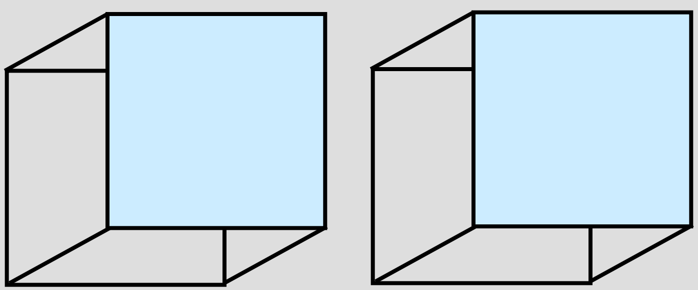
Fred Alan Wolf, "Taking the Quantum Leap" (Harper & Row, San Francisco, 1981)

Analog of quantum entanglement

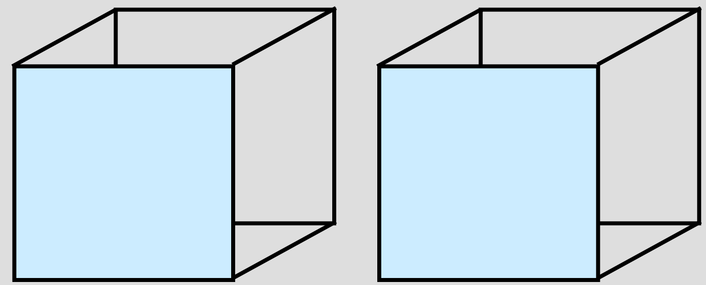
two entangled boxes:



tend to see:

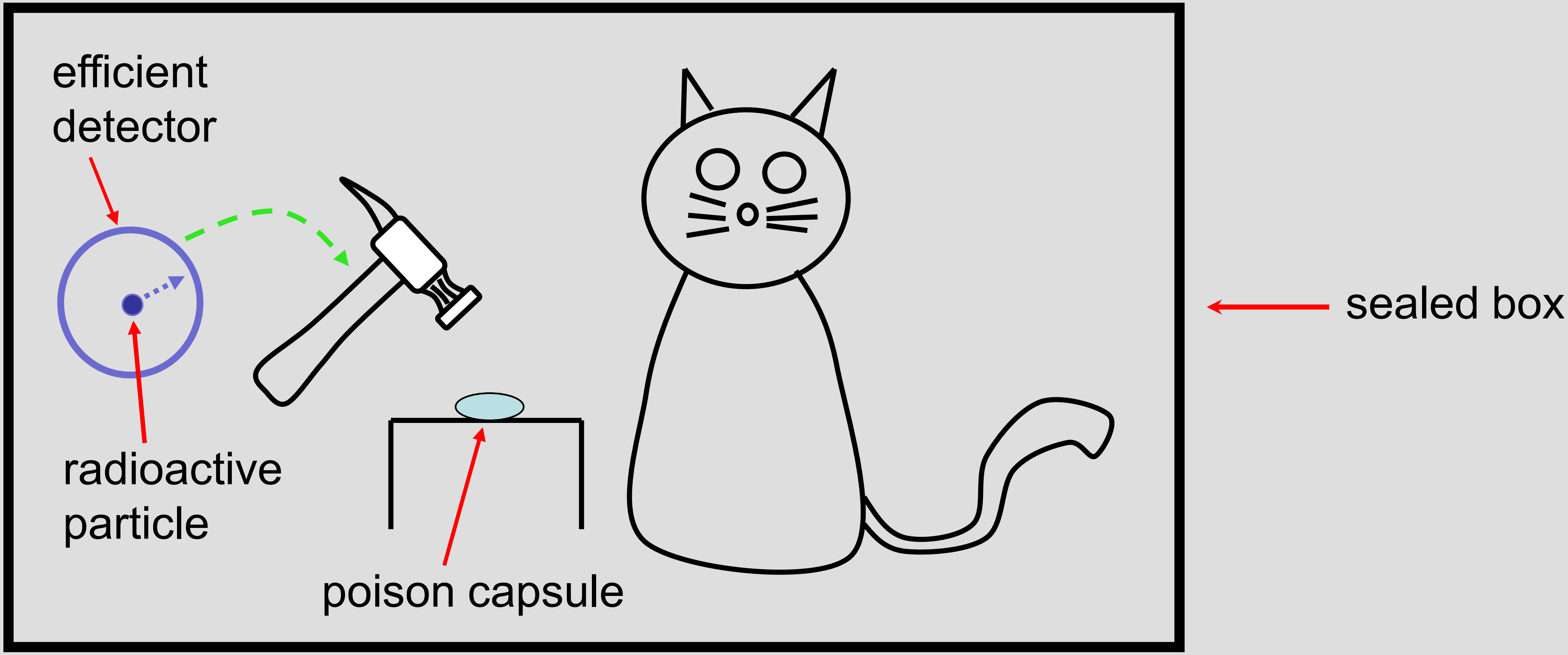


or:

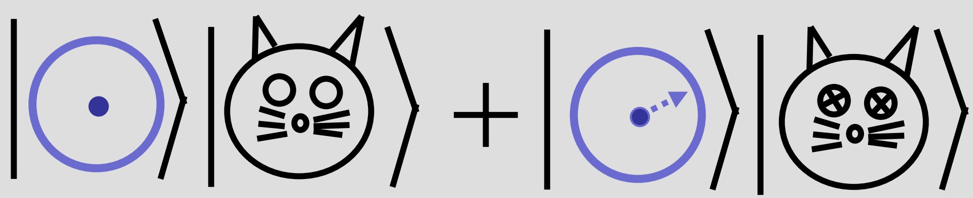


"measured" states of boxes are correlated

Erwin Schrödinger's Cat (1935)



at half-life: $\Psi =$



- state of cat is "entangled" with state of radioactive particle
- measured states are correlated

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…”

But now we can enter this world!

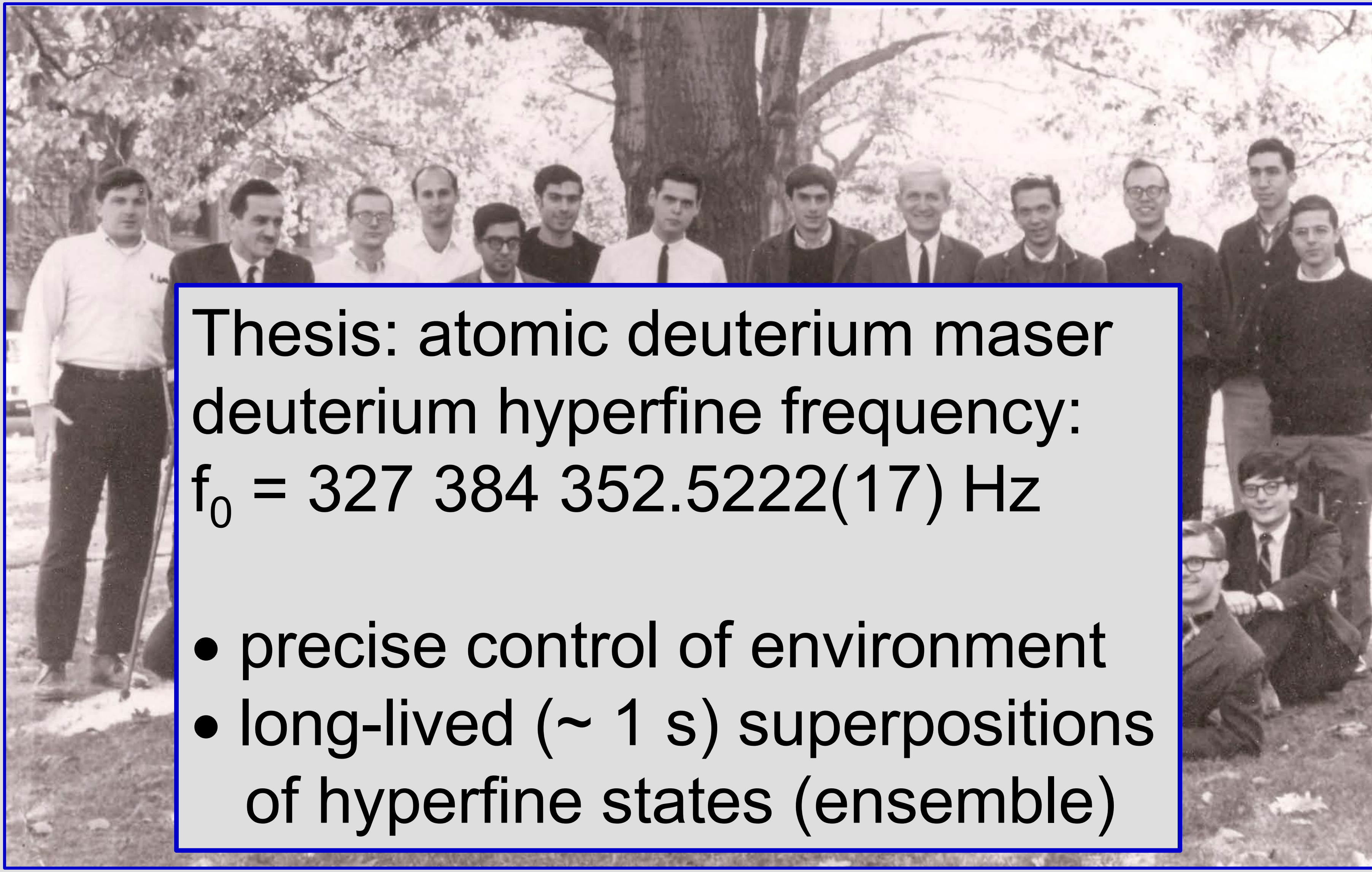
Need:

* precise control + isolation from environment
* simple small systems
  e.g., single or small groups of particles

The development:

* personal story + the work of <u>many</u> others

Norman Ramsey's group, Harvard,1966



Thesis: atomic deuterium maser
deuterium hyperfine frequency:
f_0 = 327 384 352.5222(17) Hz

- precise control of environment
- long-lived (~ 1 s) superpositions of hyperfine states (ensemble)

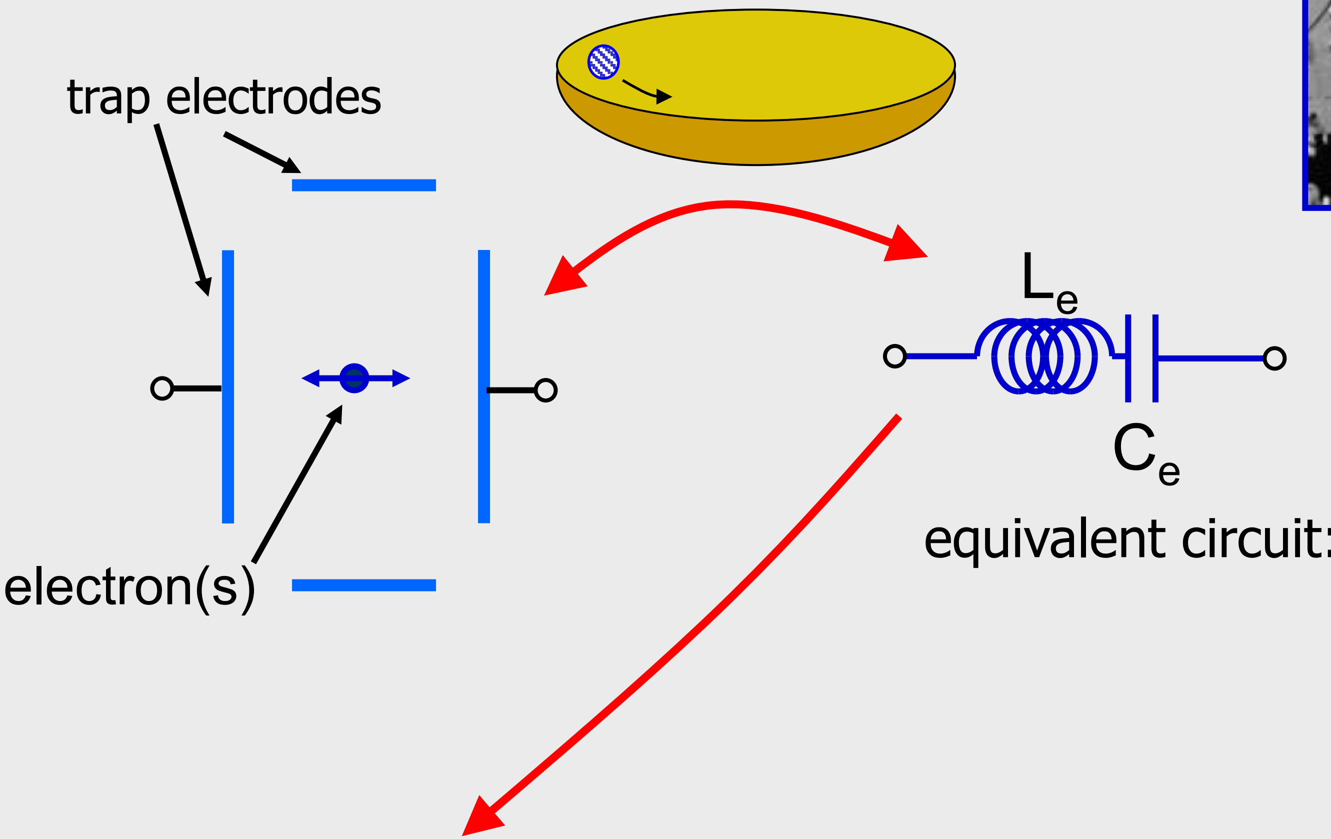
Ed Uzgiris   Andrew Chakulski   Tom English   Doug Brenner   Ashok Kosha   Tom Follett   Dave Wineland   Norman   Pat Gibbons   Paul Zitzewitz   Bill Edelstein   Roger Hegstrom

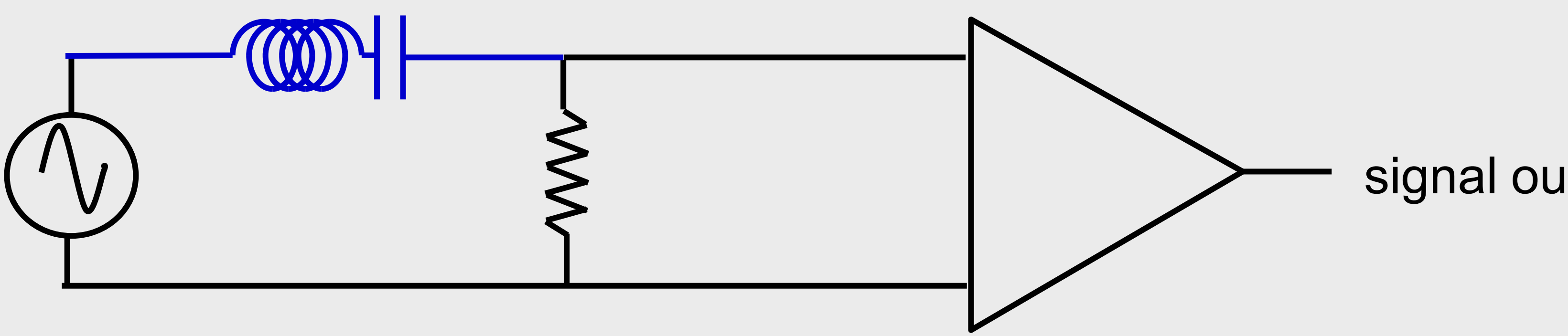
Keith McAdam   Peter Moulton   Bob Hilborn   Peter Valberg

Frank Winkler   Fraser Code

On to Hans Dehmelt's lab: trapped electrons/ions

Hans Dehmelt

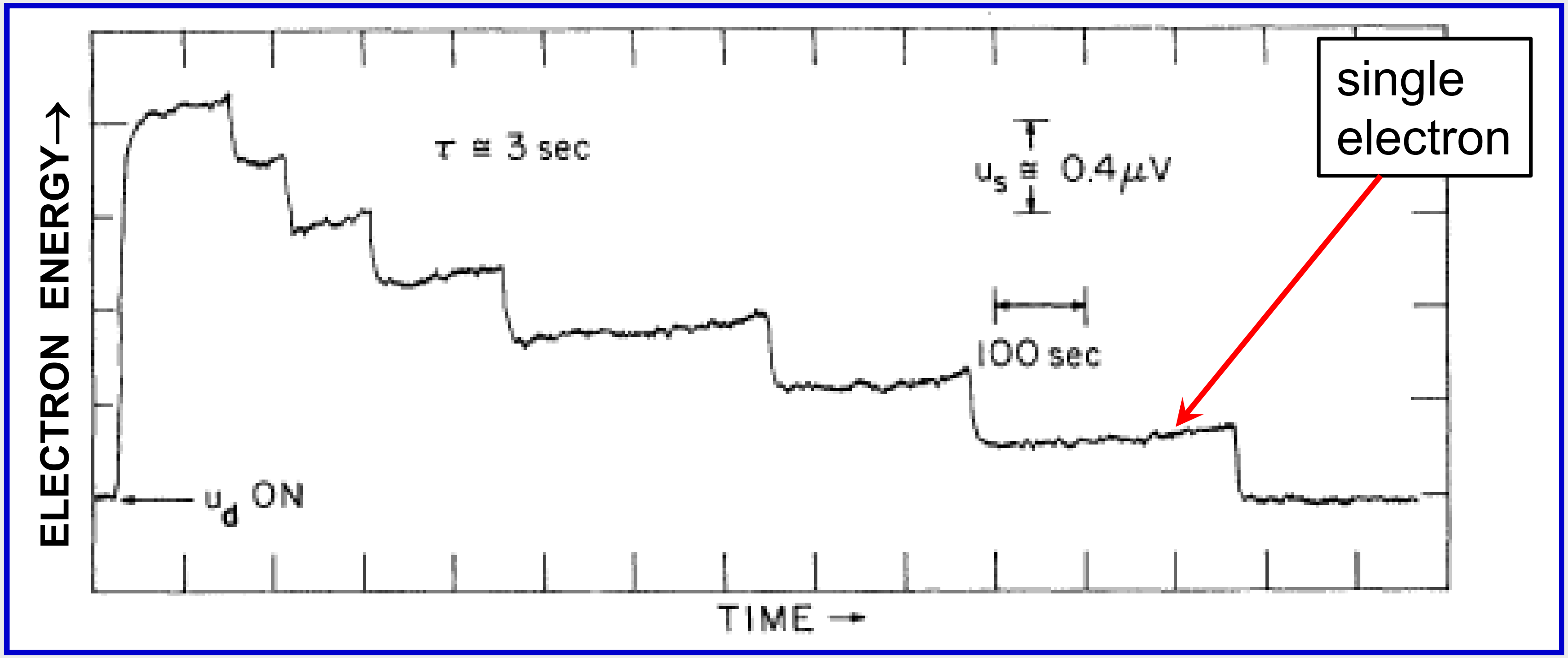




Single electrons

precursor to measurement of $\mu_{electron}$

R. S. Van Dyck, P. Ekstrom, H. Dehmelt, Phys. Rev. Lett. **38**, 310 (1977)



D. Wineland, P. Ekstrom, and H. Dehmelt, Phys. Rev. Lett. 31, 1279 (1973).

Single electrons

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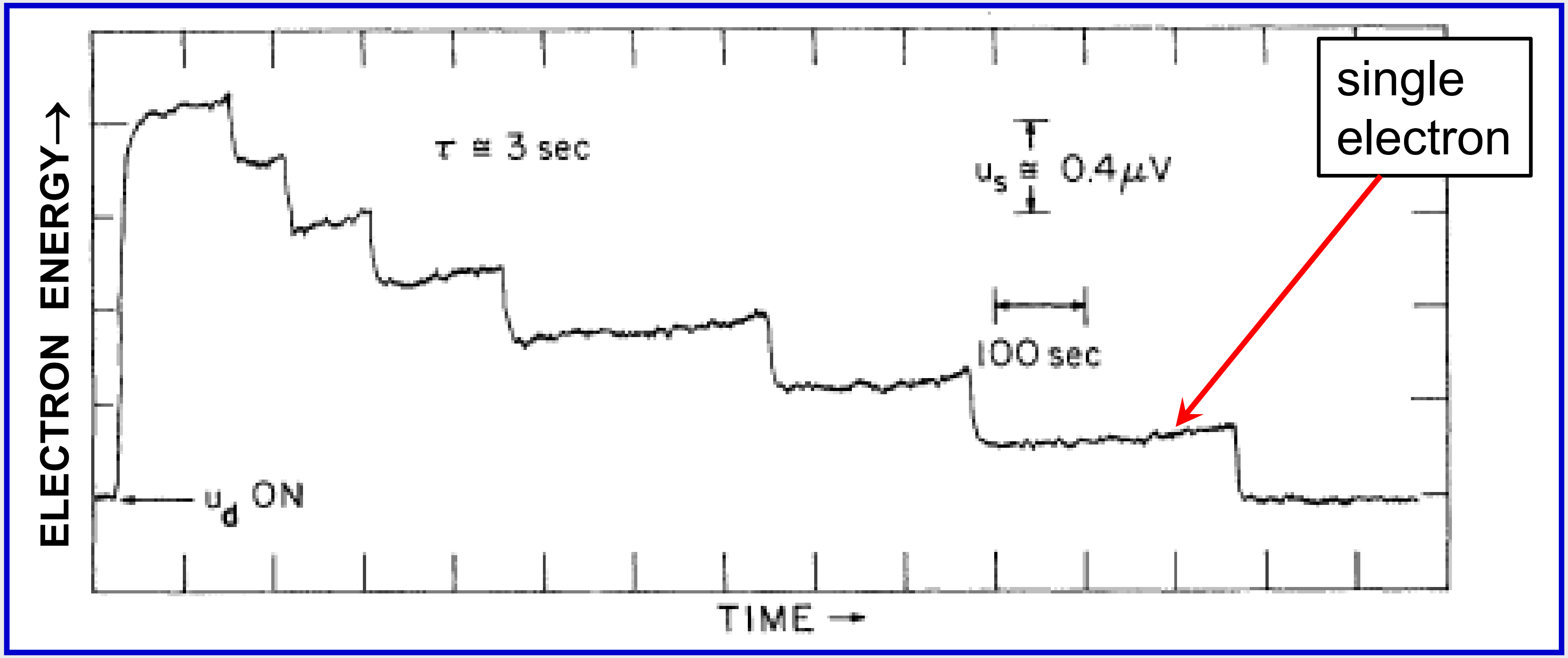
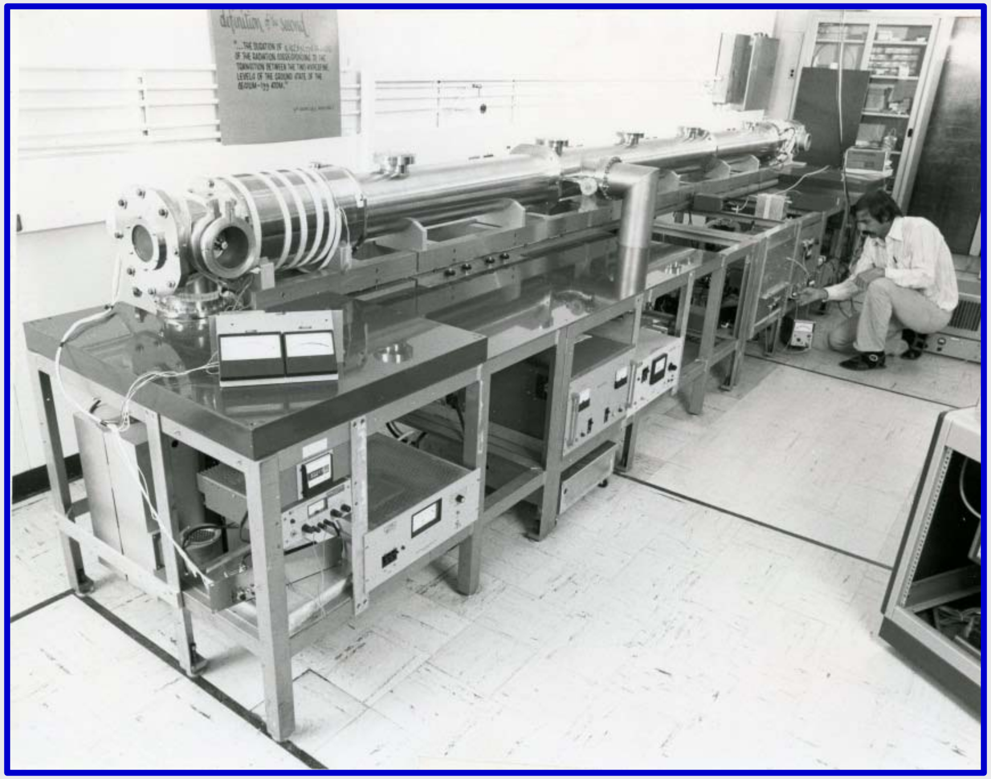


D. Wineland, P. Ekstrom, and H. Dehmelt, Phys. Rev. Lett. 31, 1279 (1973).

and, some ideas about laser cooling
D.J.Wineland and H. Dehmelt, Bulletin, Am. Phys. Soc. **20**, 637 (1975)

concurrently,
T. W. Hänsch and A. L. Schawlow, Opt. Comm. **13**, 68 (1975)

On to NIST
(then NBS, National Bureau of Standards)



Cs beam frequency standard
"NBS-6"

Helmut Hellwig

41, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JULY 1978

Optical-Sideband Cooling of Visible Atom Cloud Confined in Parabolic Well

W. Neuhauser, M. Hohenstatt, and P. Toschek
Institut für Angewandte Physik I der Universität Heidelberg, D-69 Heidelberg, West Germany

and

H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 25 April 1978)

An assemblage of < 50 Ba^+ ions, contained in a parabolic well, has been visually observed and cooled by means of near-resonant laser irradiation.

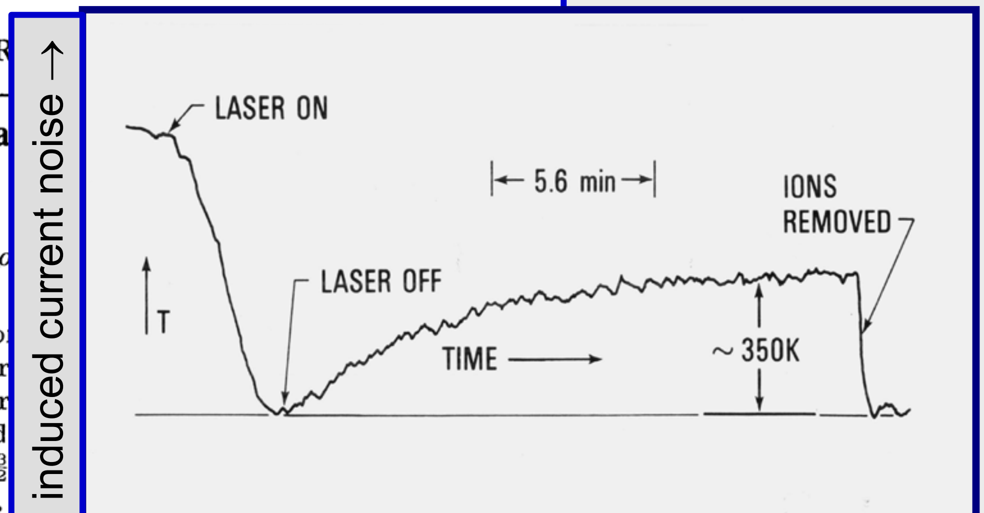
Peter Toschek

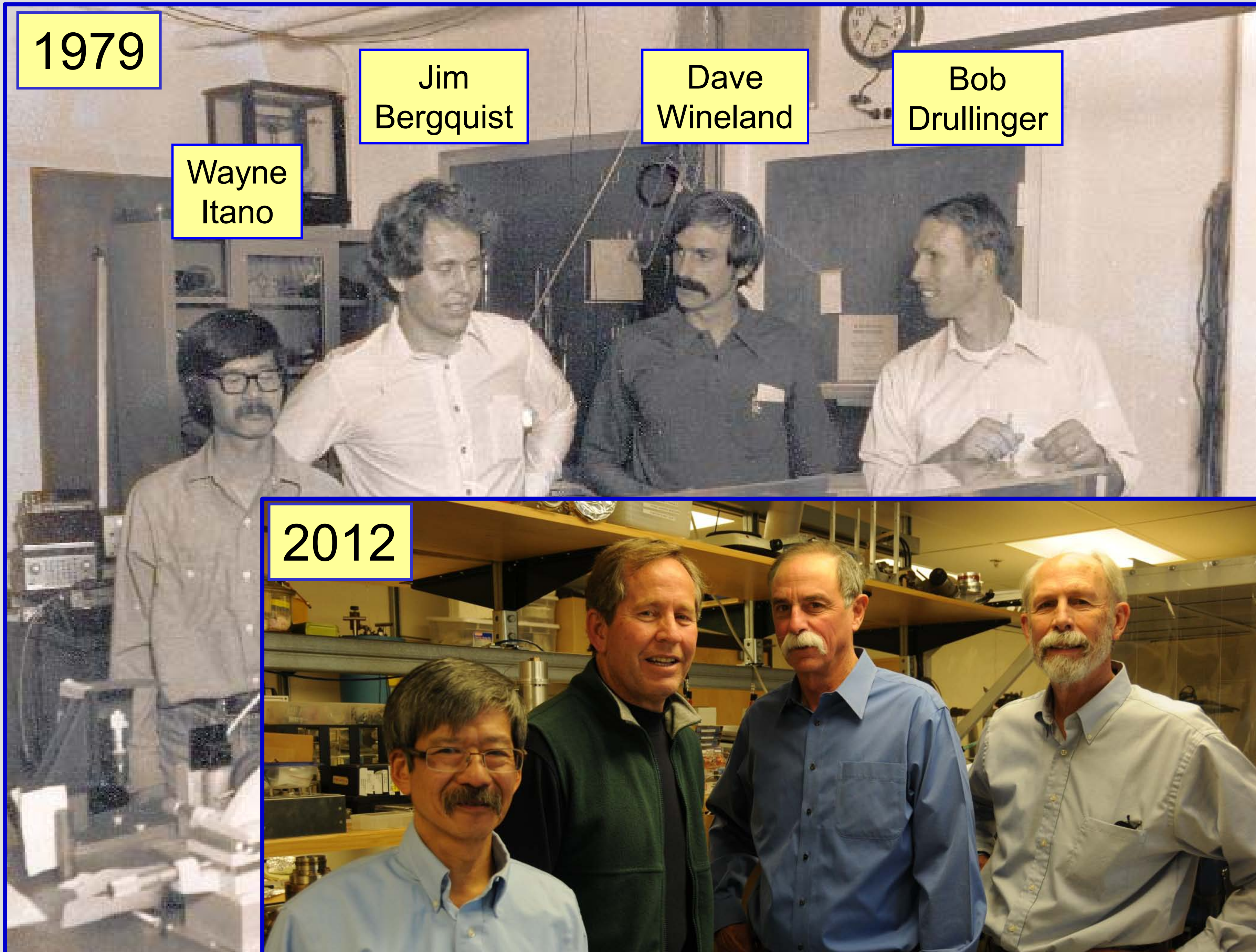
), NUMBER 25 PHYSICAL REVIEW LETTER

Radiation-Pressure Cooling of Bound Resona

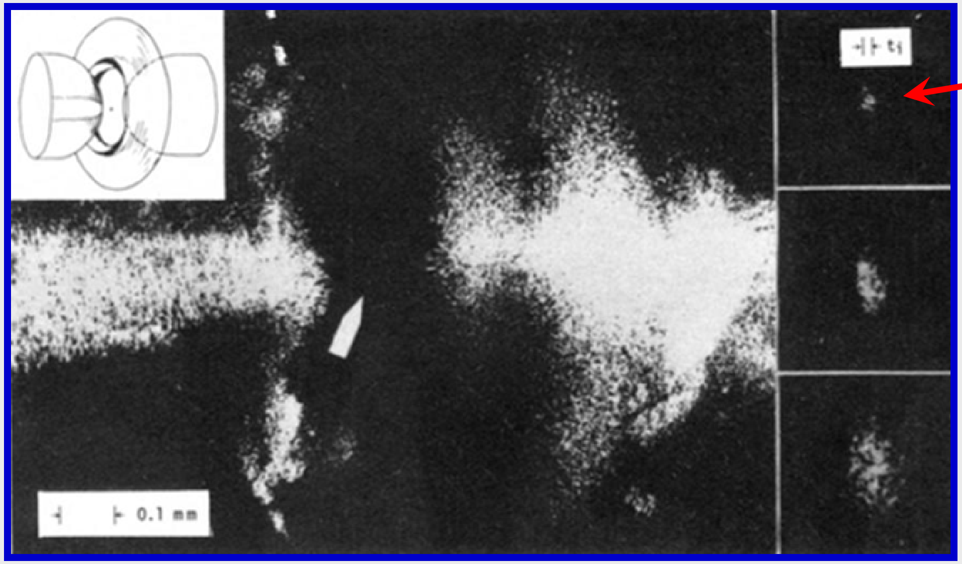
D. J. Wineland, R. E. Drullinger, and F. L.
Time and Frequency Division, National Bureau of Standards, Bo
(Received 26 April 1978)

We report the first observation of radiation-pressure cooling o
absorbers which are elastically bound to a laboratory fixed appar
fined in a Penning electromagnetic trap are cooled to <40 K by ir
8-μW output of a frequency doubled, single-mode dye laser tuned
side of the Doppler profile on the $^2S_{1/2} \longleftrightarrow {}^2P_{3/2}$ ($M_J = +\frac{1}{2} \longleftrightarrow M_J = +\frac{3}{2}$
transitions. Cooling to approximately 10^{-3} K should be possible.



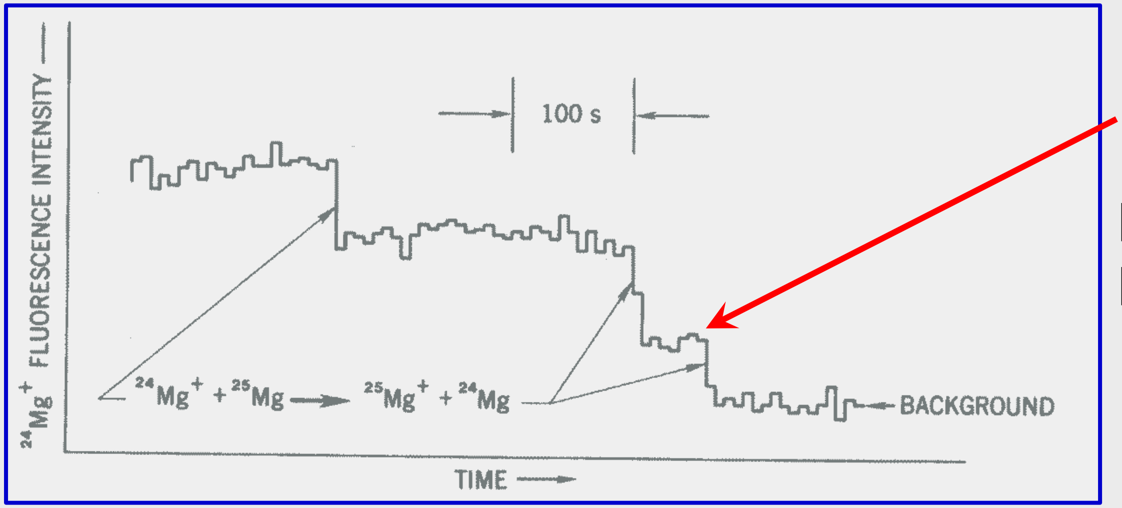

1979
Wayne Itano
Jim Bergquist
Dave Wineland
Bob Drullinger
2012

Individual ions:



single Ba^+ ion

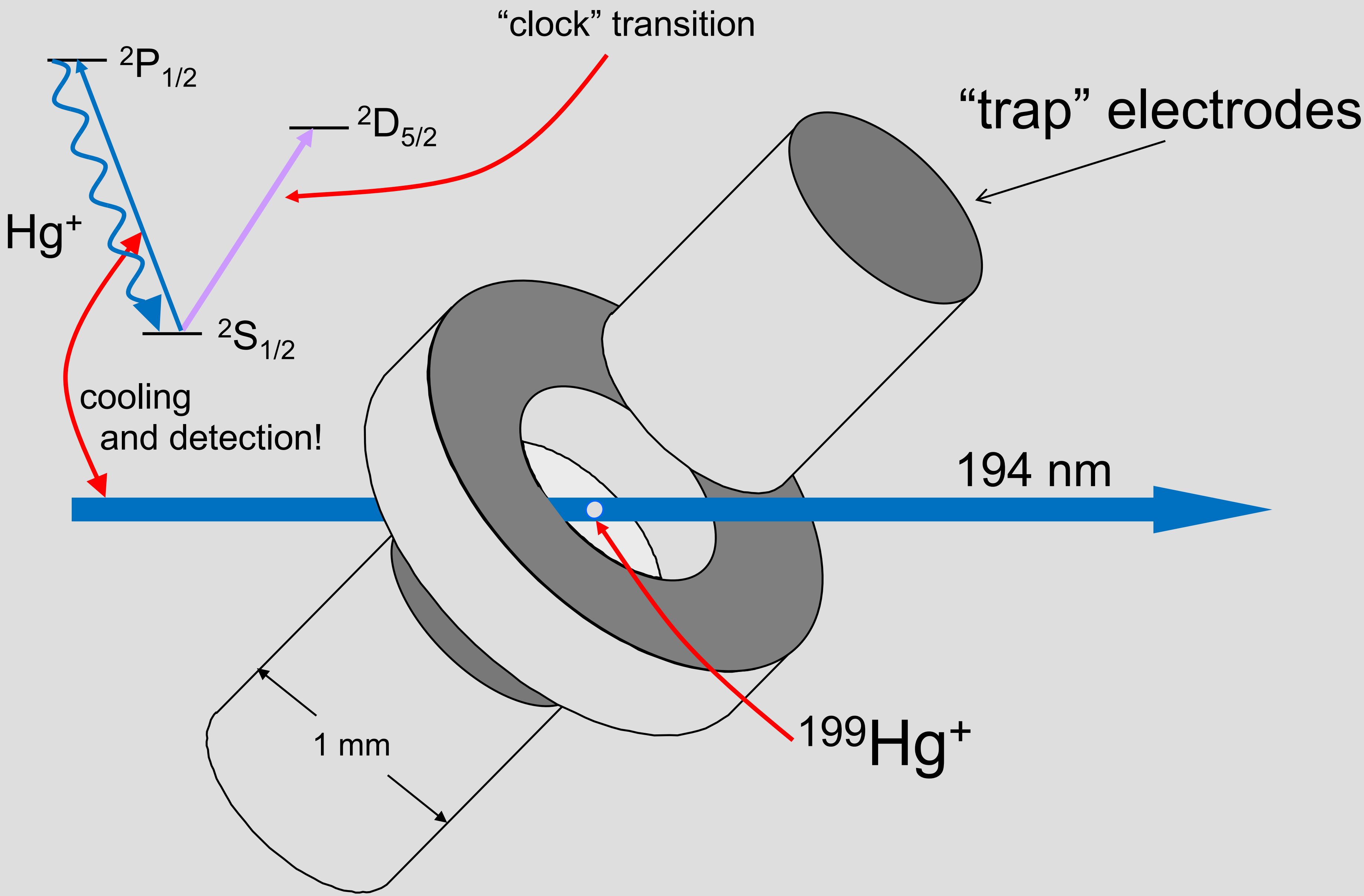
W. Neuhauser, M. Hohenstatt, P. Toschek, H. Dehmelt, Phys. Rev. A**22**, 1137 (1980).

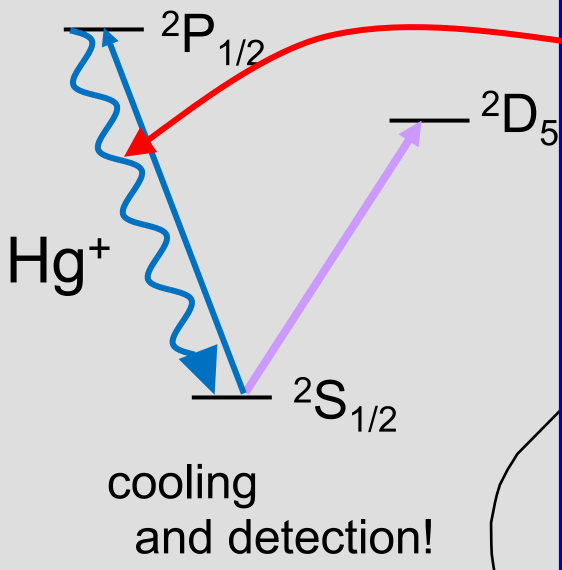


single $^{24}Mg^+$ ion

D.J. Wineland and W. M. Itano, Phys. Lett. 82A, 75-78 (1981).

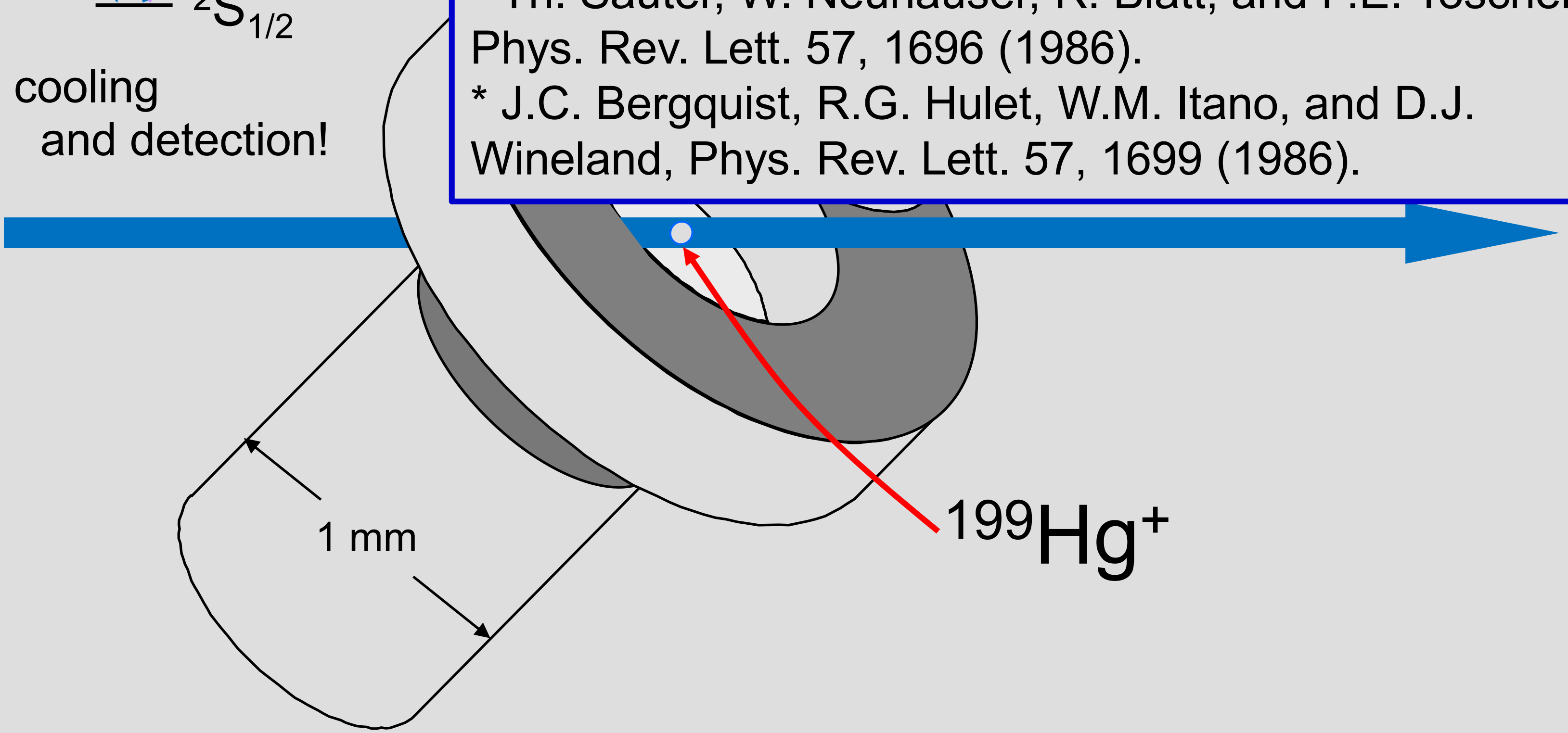
Single Hg^+ ion experiments at NIST

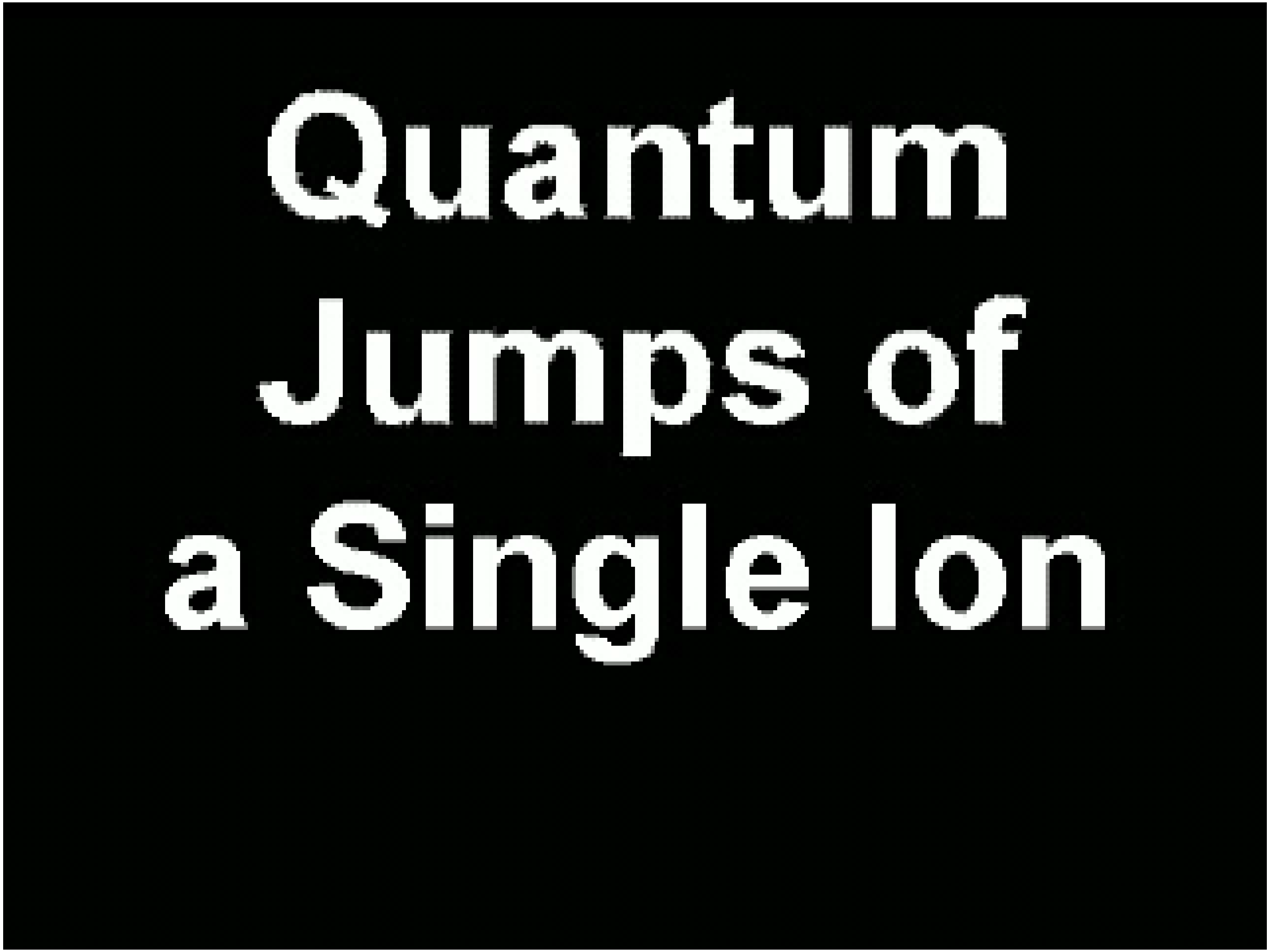




"Quantum jumps"
See abrupt changes in scattered light (fluorescence) when ion changes clock states

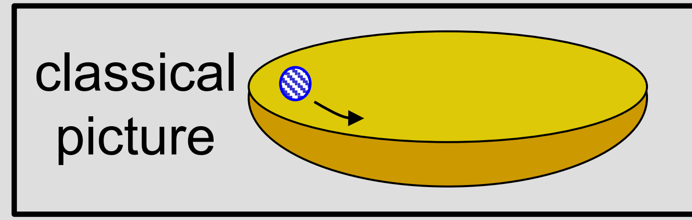
* W. Nagourney, J. Sandberg, and H. Dehmelt, Phys. Rev. Lett. 56, 2797 (1986).
* Th. Sauter, W. Neuhauser, R. Blatt, and P.E. Toschek, Phys. Rev. Lett. 57, 1696 (1986).
* J.C. Bergquist, R.G. Hulet, W.M. Itano, and D.J. Wineland, Phys. Rev. Lett. 57, 1699 (1986).

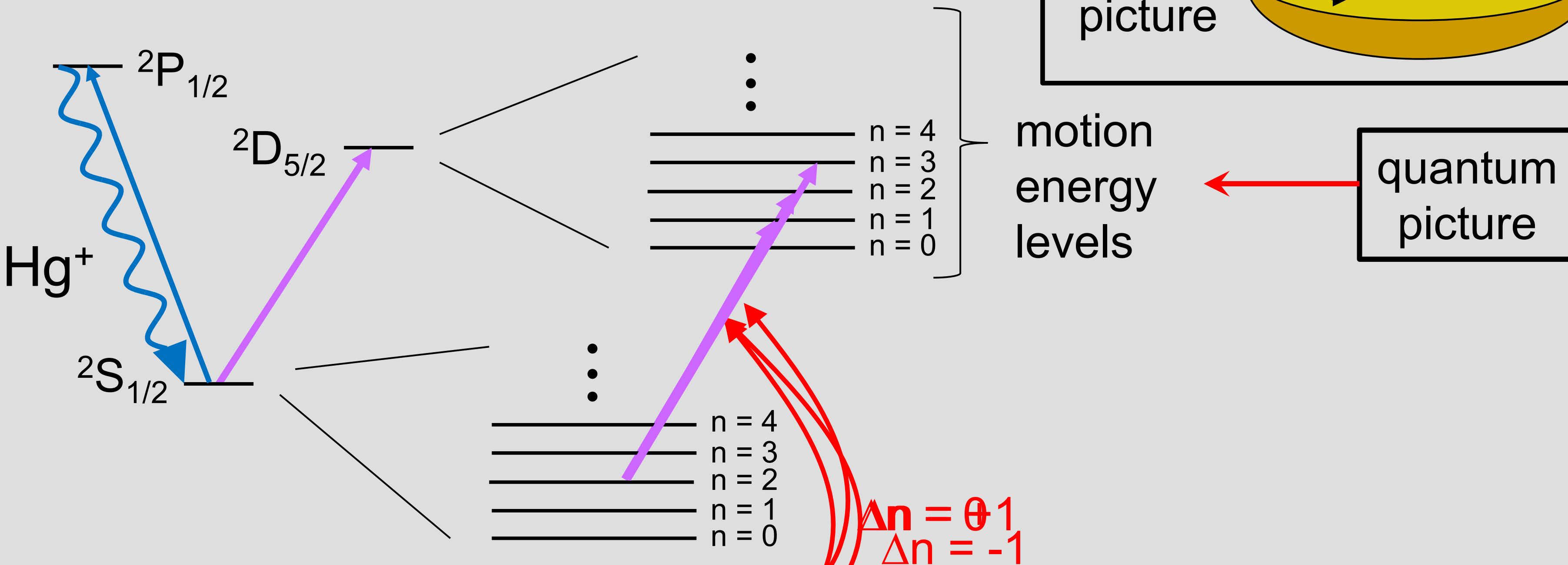




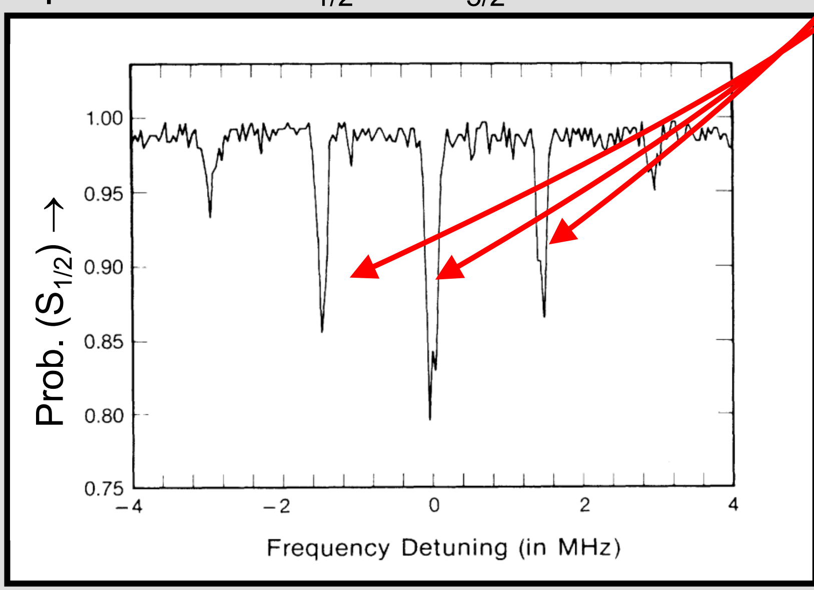
"Quantum Jumps I" (1986 release)

Quantized motion?:



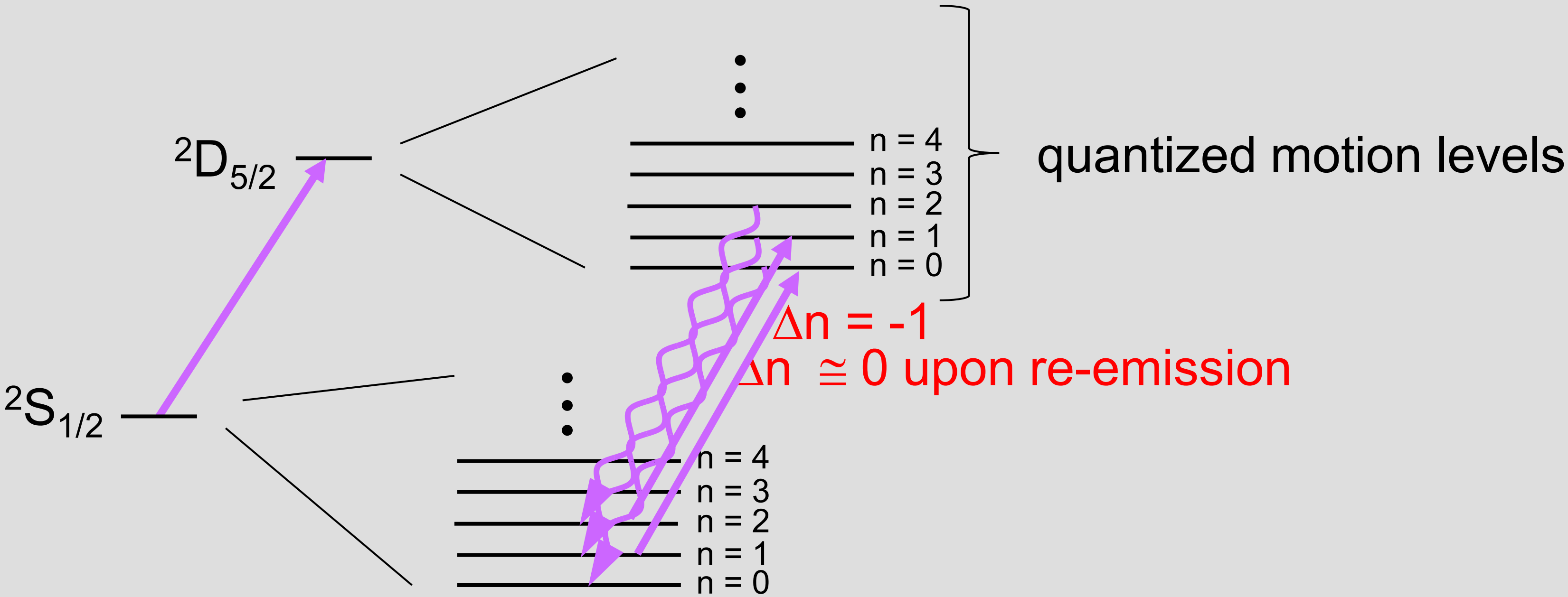


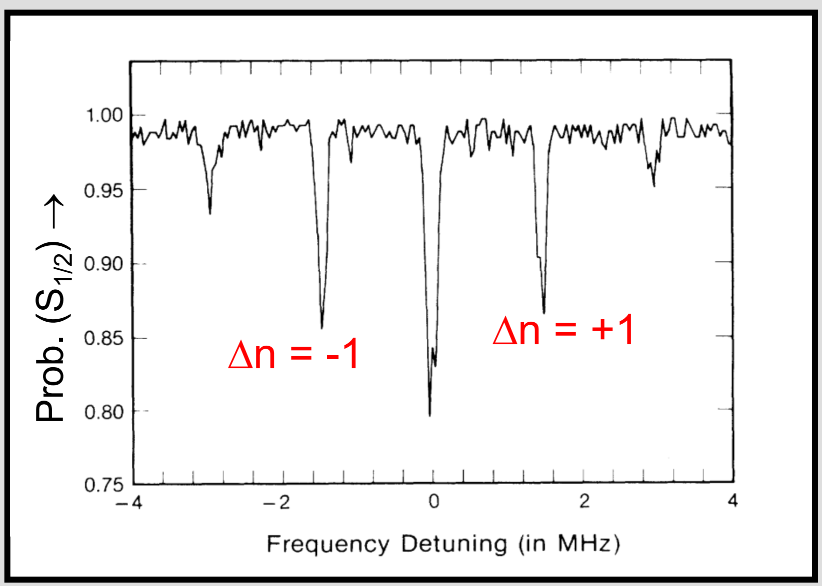
spectrum of $^2S_{1/2} \rightarrow {}^2D_{5/2}$ clock transition



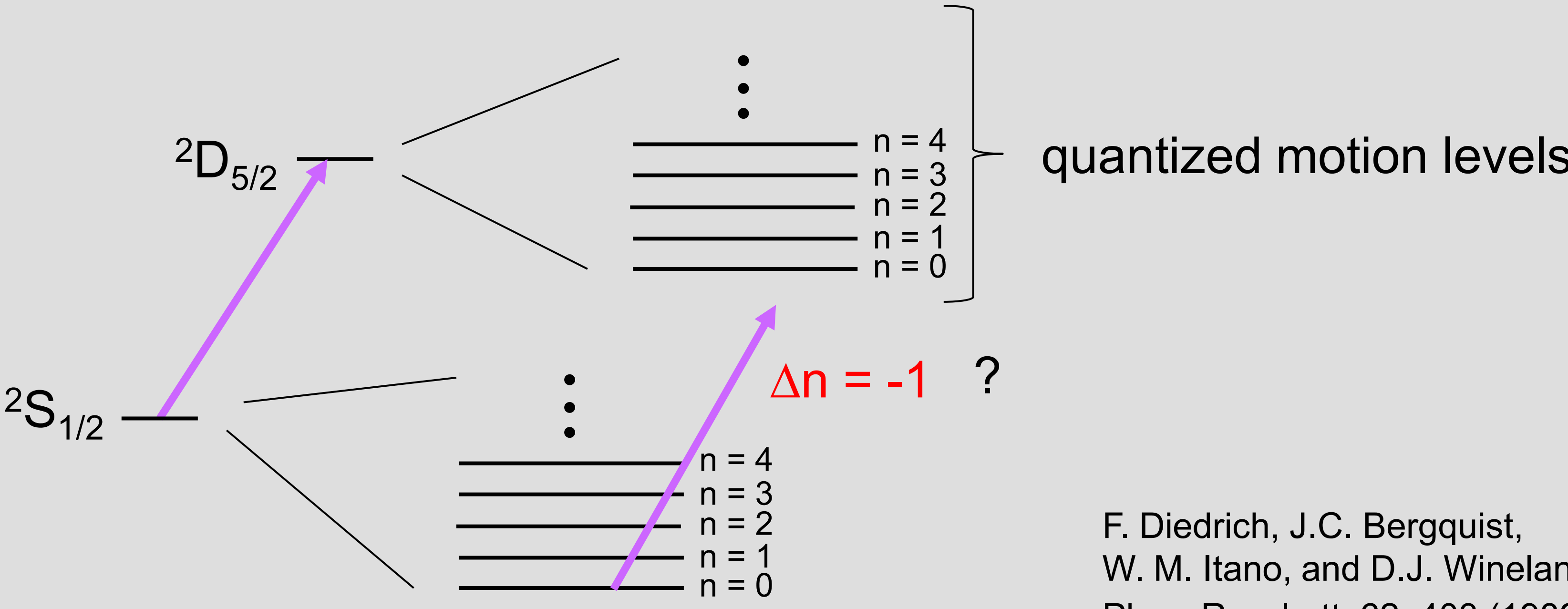
J. C. Bergquist, W. M. Itano, D. J. Wineland, Phys. Rev. A**36**, 428 (1987).

Cooling to the ground state of motion

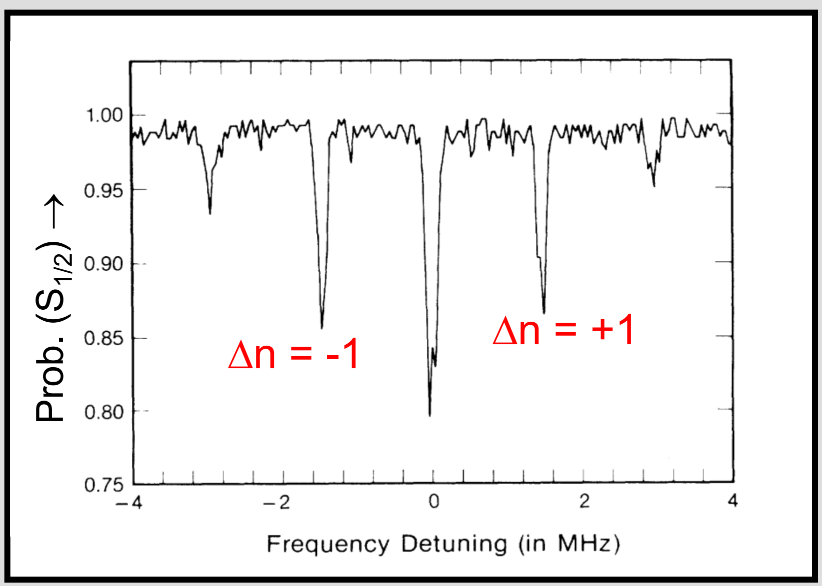


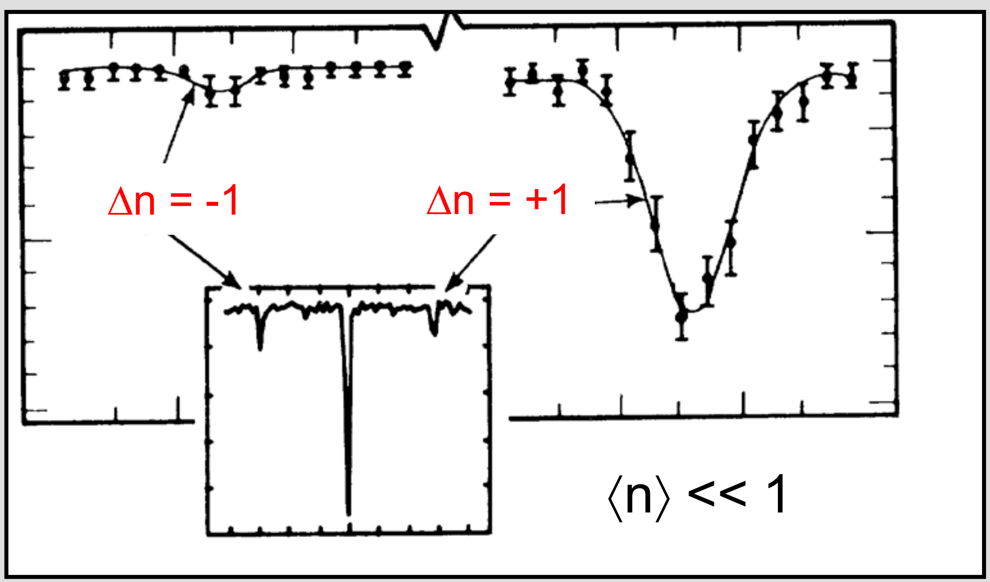


Cooling to the ground state of motion



F. Diedrich, J.C. Bergquist, W. M. Itano, and D.J. Wineland, Phys. Rev. Lett. 62, 403 (1989).

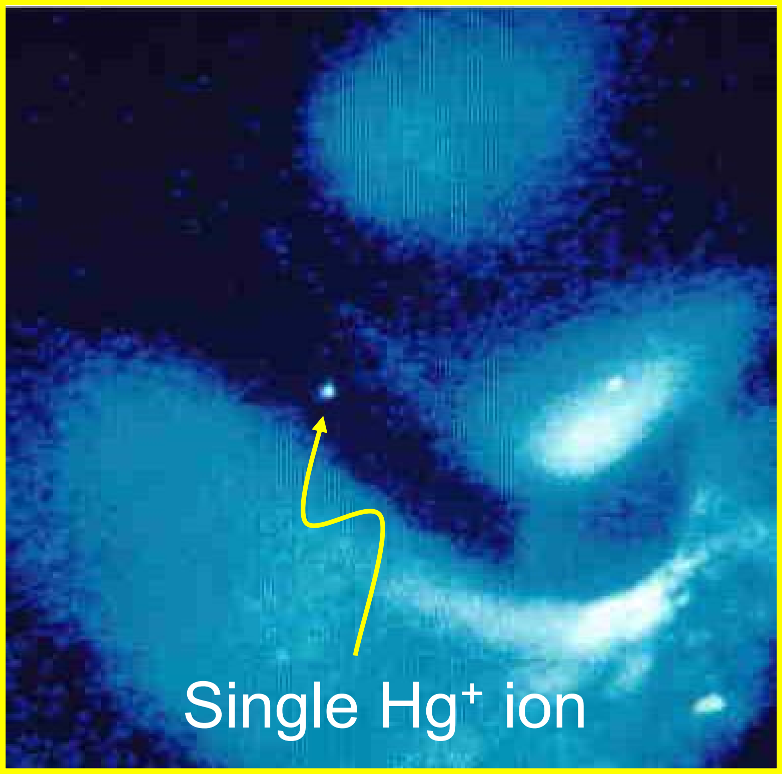




Single ions for (optical) clocks:

J. C. Bergquist et al., 1981 $\rightarrow$

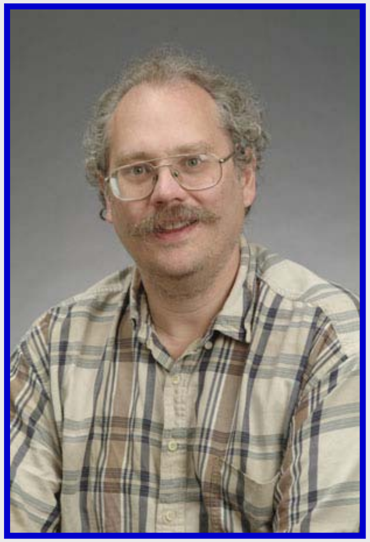
Jim Bergquist



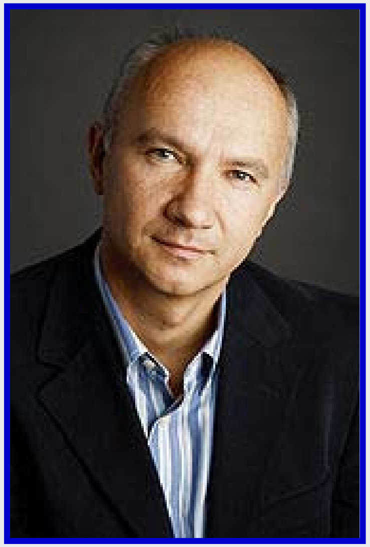
- trapping $\Rightarrow$ first-order Doppler shift $\rightarrow$ 0
- trapping + laser cooling $\Rightarrow$ time dilation $\rightarrow$ 0
- trapping in high vacuum at low temp
  $\Rightarrow$ environmental perturbations (collisions, black body shifts, etc.) $\rightarrow$ 0

Enter quantum information processing

Richard Feynman, David Deutsch, Paul Benioff,…(1980's)



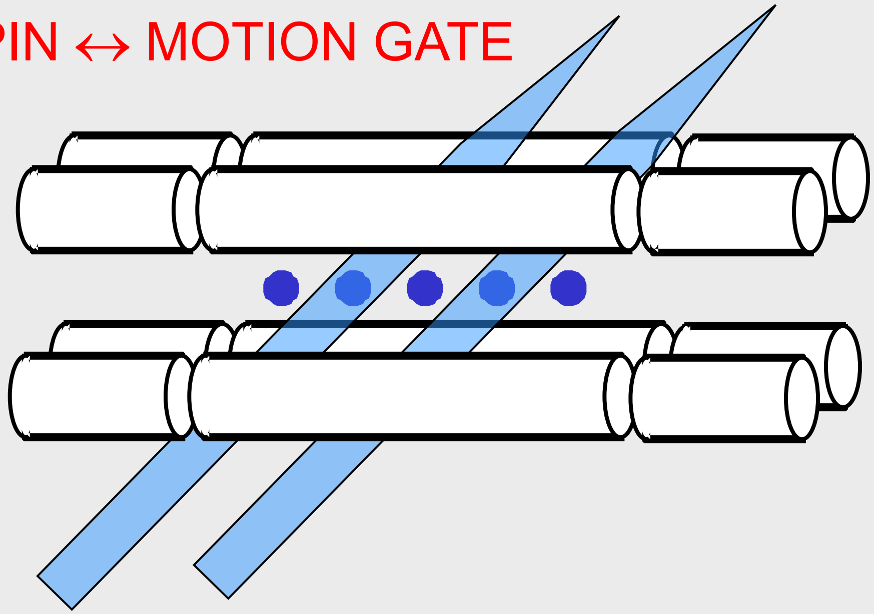
Peter Shor: algorithm for efficient number factoring on a quantum computer (~ 1994)



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

Atomic Ion Quantum Computation:

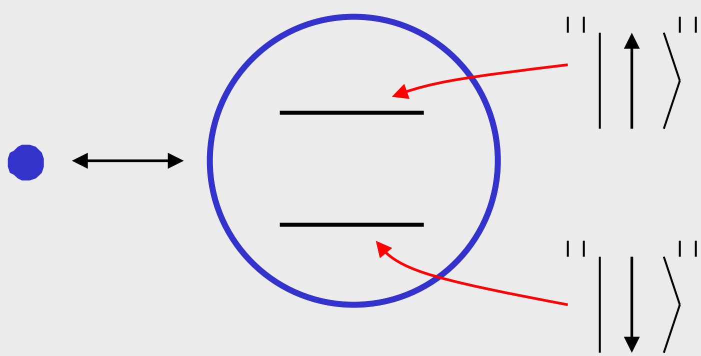
(J. I. Cirac, P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995)



Ignacio Cirac

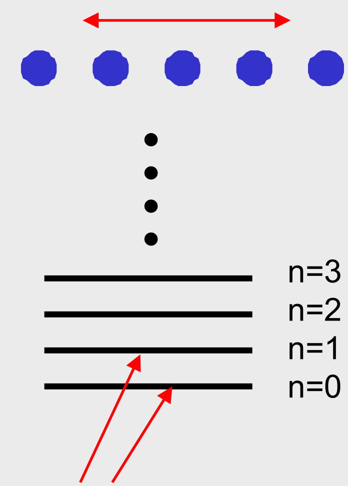
Peter Zoller

INTERNAL STATE “QUBIT”



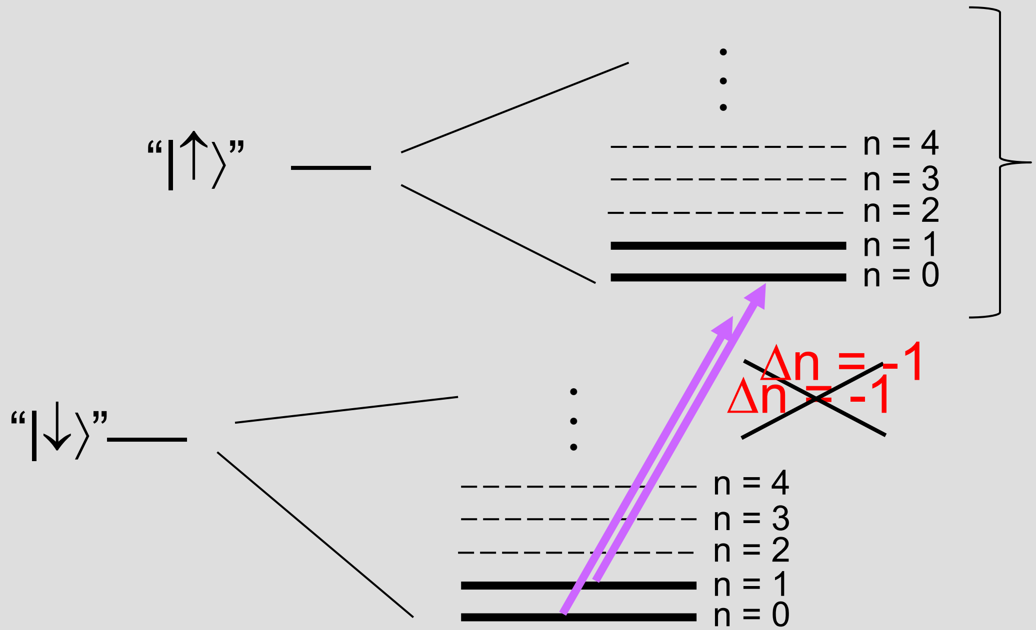
MOTION “DATA BUS”

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



Motion qubit states

Quantum logic gates?



Chris Monroe

Simple example of quantum logic:

control bit (motion state)	target bit (atomic internal state)
n = 1	$\|\downarrow\rangle \rightarrow \|\uparrow\rangle$
n = 0	$\|\downarrow\rangle \rightarrow \|\downarrow\rangle$

“Controlled-NOT” gate between motion and atom’s internal state

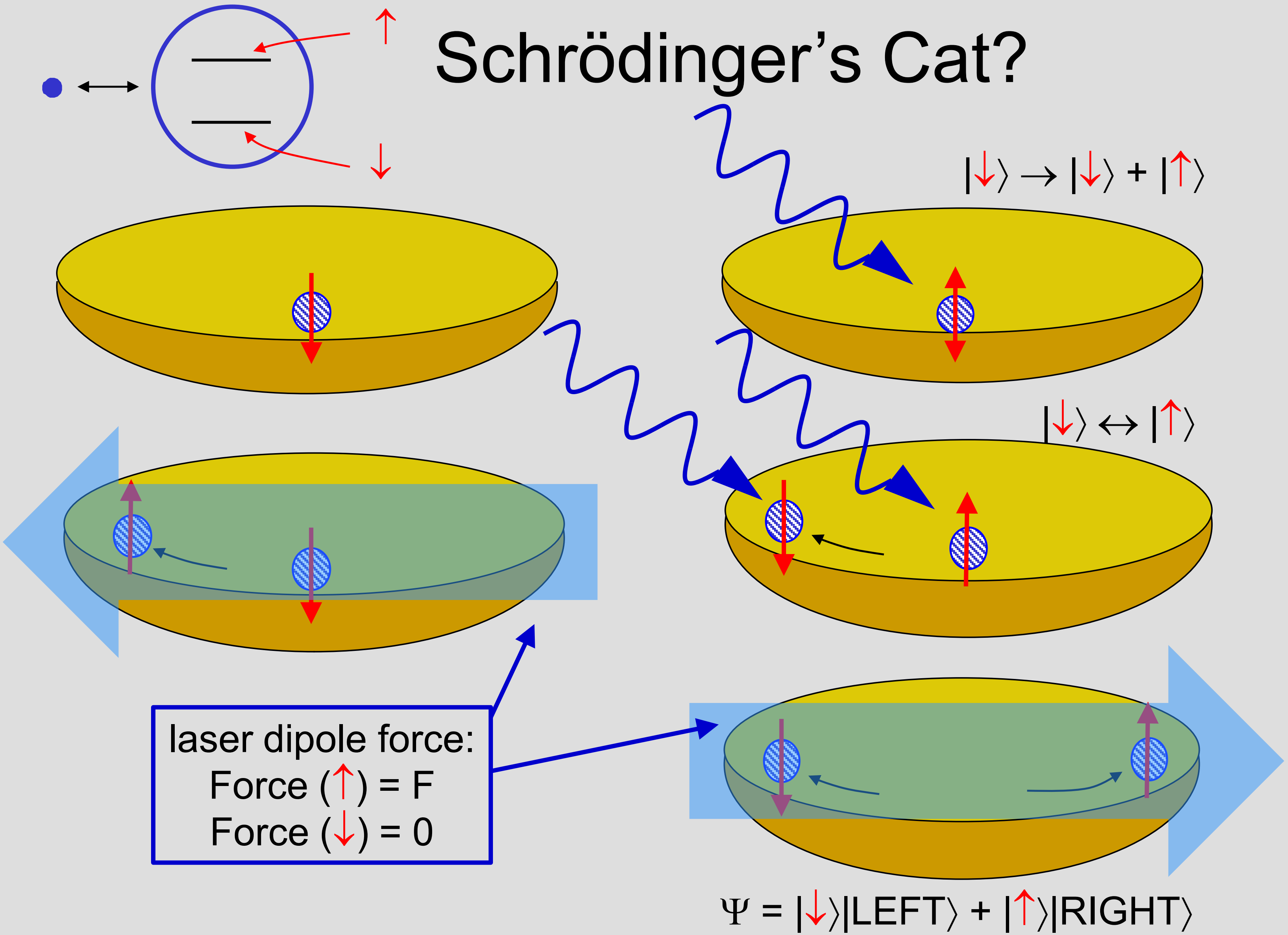
C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. 75, 4714 (1995).

Atomic ion experimental groups pursuing Quantum Information Processing:

Aarhus
Amherst
Bejing (Tsinghua)
Berkeley
Duke
ETH (Zürich)
Freiburg
Garching (MPQ)
Georgia Tech
Griffiths University
Hannover
Innsbruck
JQI (U. Maryland)
Lincoln Labs
London (Imperial)
Mainz

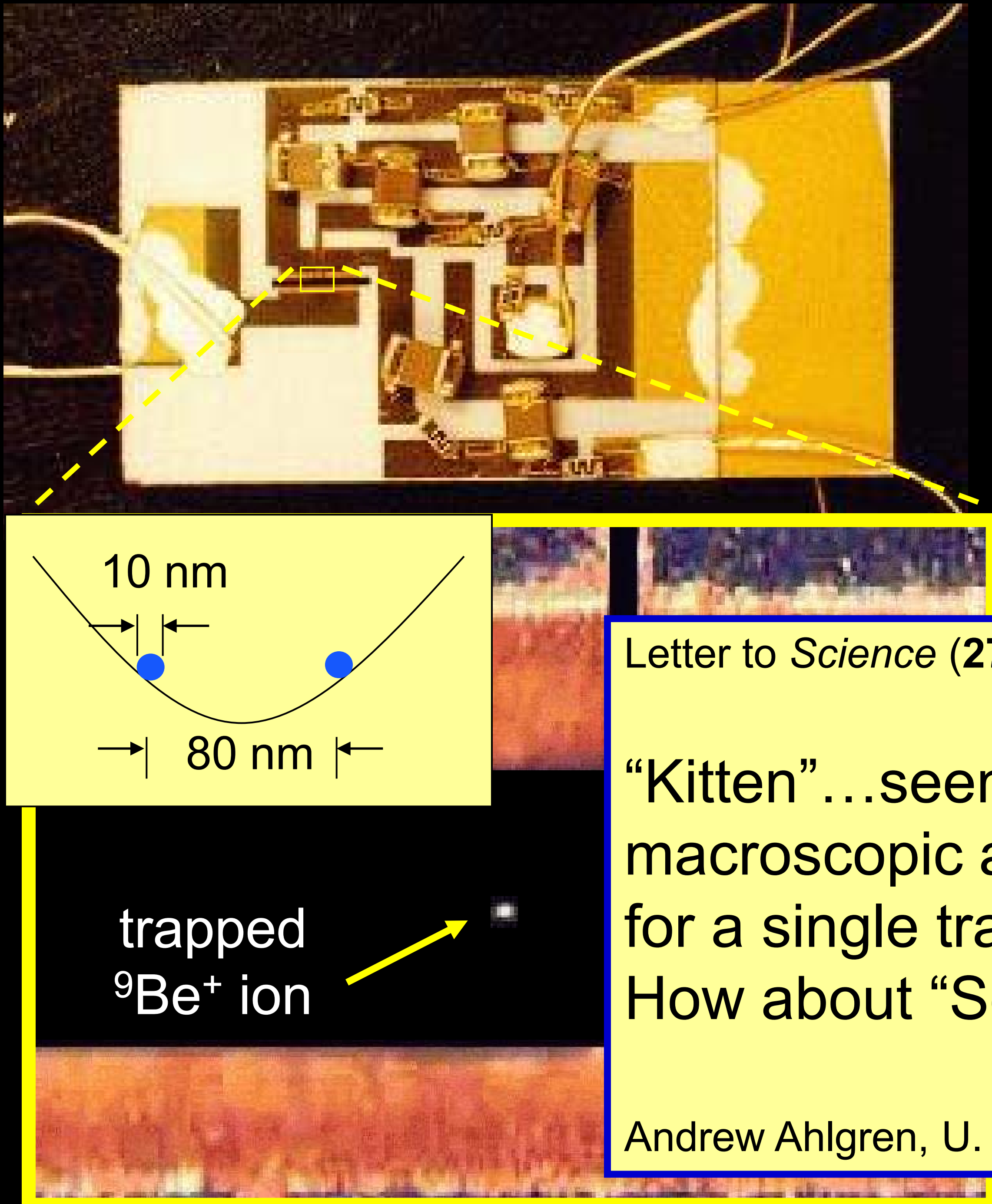
MIT
NIST
NPL
Osaka University
Oxford
Paris (Université Paris)
PTB, Braunschweig
Saarland
Sandia National Lab
Siegen
Simon Fraser University
Singapore
Sussex
Sydney
U. Washington
Weizmann Institute

Schrödinger's Cat?



C. Monroe, D. M. Meekhof, B. E. King, and D. J. Wineland, Science **272**, 1131 (1996).

atomic Schrödinger "kitten"



Letter to *Science* (**273**, 860 (1996)):

"Kitten"…seems needlessly macroscopic as a metaphor for a single trapped atom. How about "Schrödinger's furrball?"

Andrew Ahlgren, U. of Minnesota, Minneapolis, MN

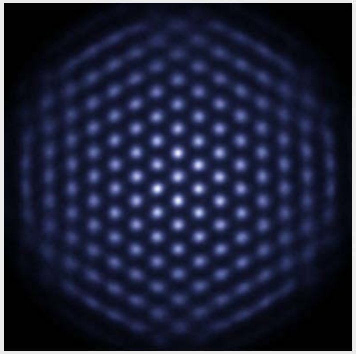
Quantum Information Processing with ions

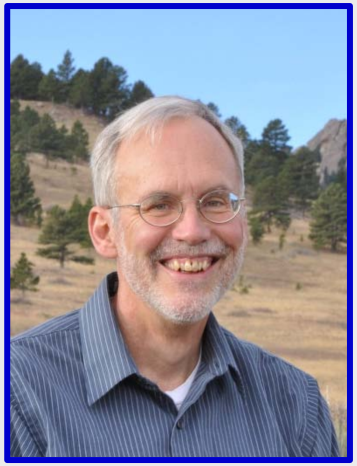
Didi Leibfried

- gates, simple algorithm implementations
  many groups including NIST
- simulations of other quantum systems (S. Lloyd,…)

◊ e.g., interacting oscillating ion dipoles
  simulate quantum magnets

C. Monroe et al., U. Maryland
T. Schätz et al., Freiburg;
J. Bollinger et al., NIST
• • • • •





John Bollinger

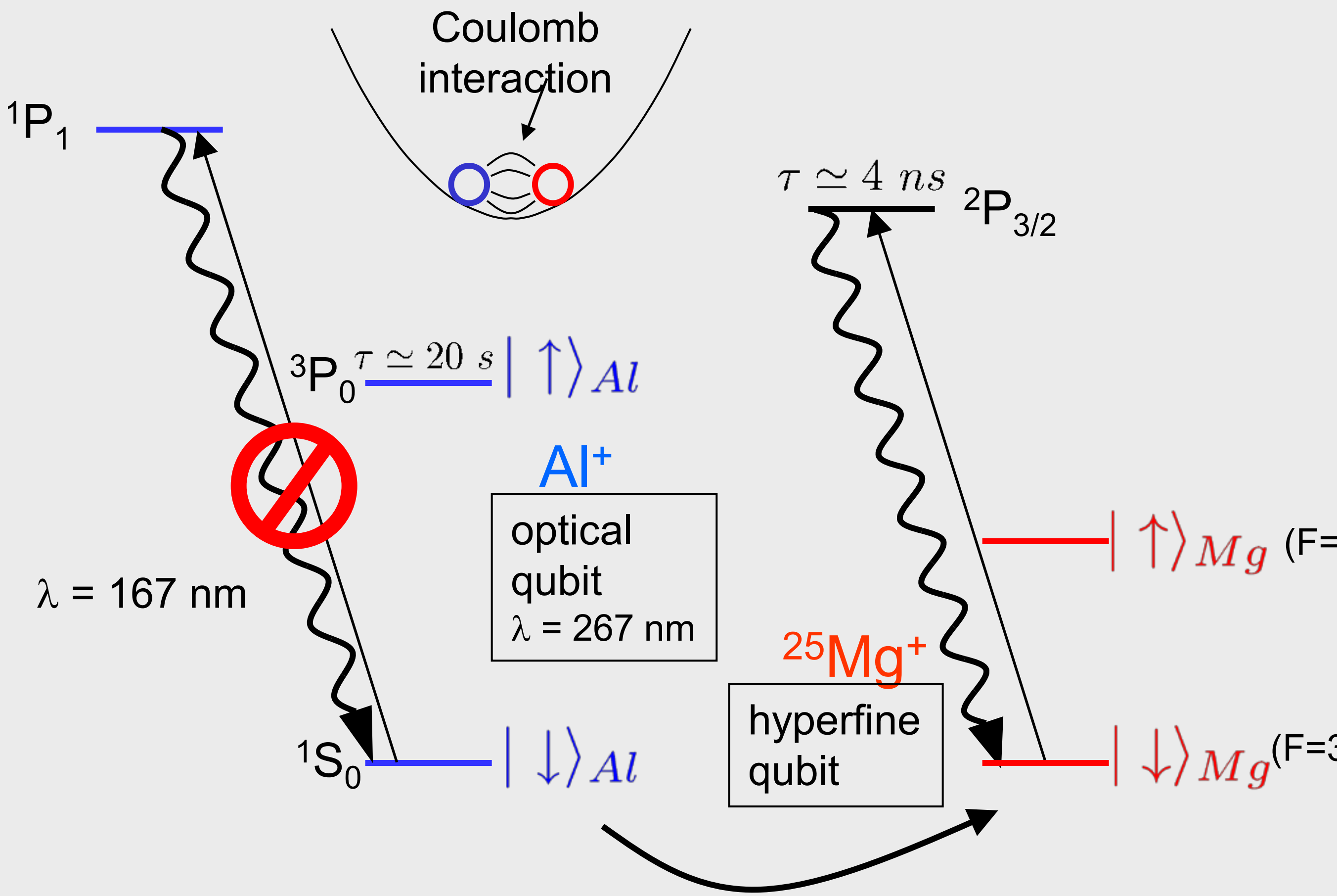
- universal (digital) quantum simulator

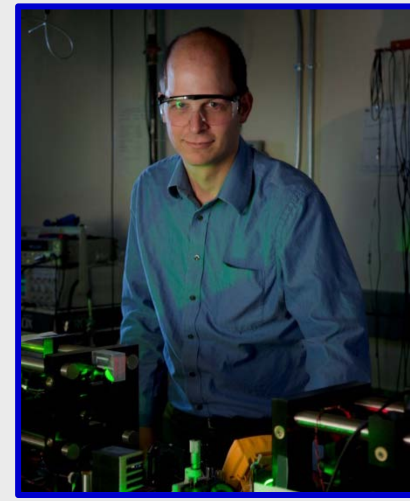
R. Blatt et al., Innsbruck

Rainer Blatt

and many more…

Al$^+$ "quantum-logic clock" (T. Rosenband et al.)





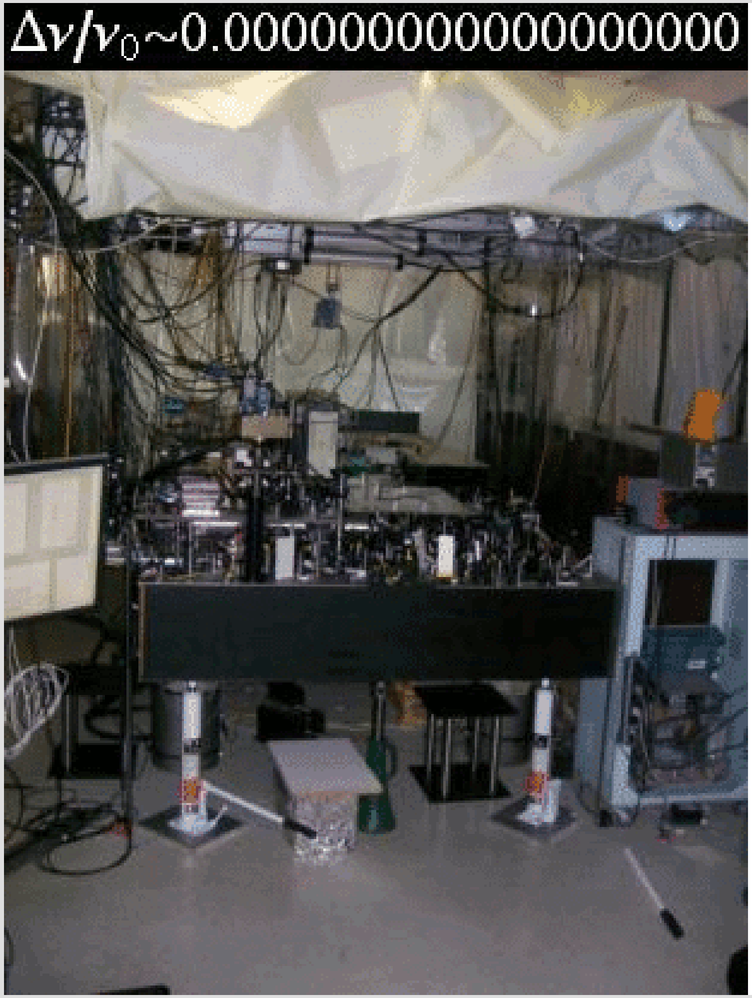
Till Rosenband

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

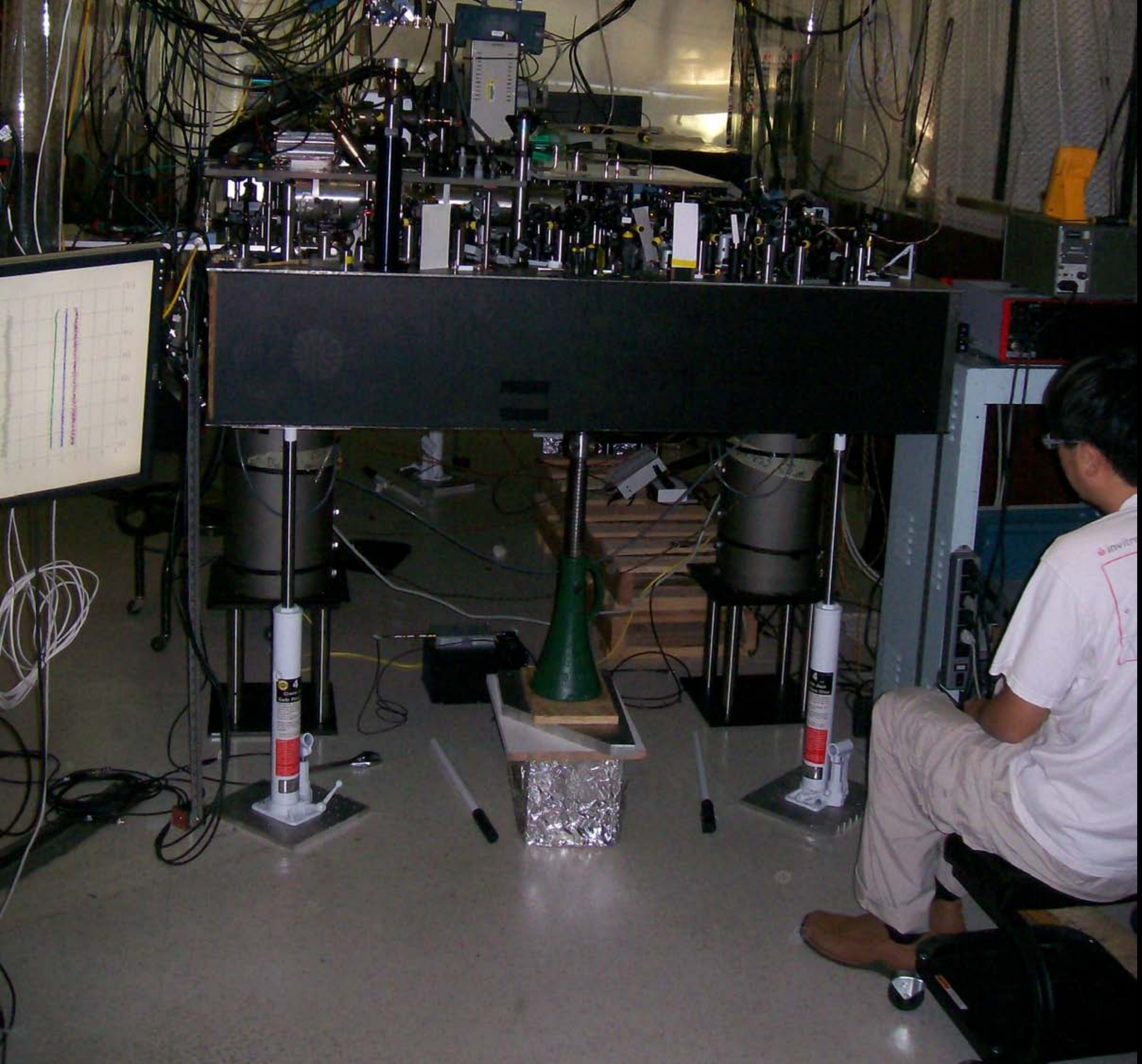
◊ laser-cooled Mg$^+$ keeps Al$^+$ cold
◊ Mg$^+$ used to calibrate $\langle B^2 \rangle$ from all sources
◊ collisions observed by ions switching places
◊ ……

$\Rightarrow$ systematic uncertainty $\approx 10^{-17}$

James Chou with "portable" Al^+ clock



measure
gravitational potential
red shift



Δh = 33 cm

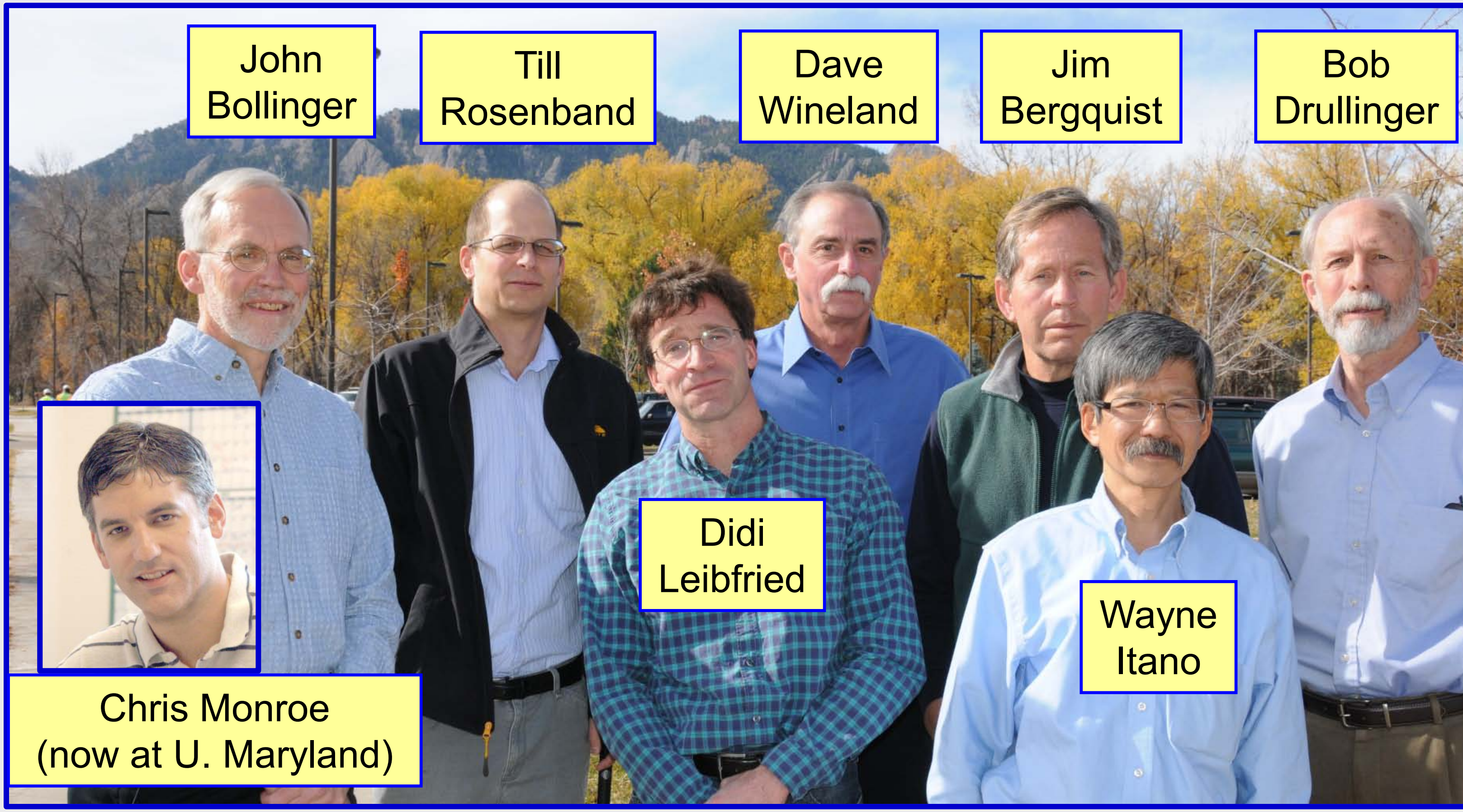
predict

36×10^{-18}

measure

$41 \pm 16 \times 10^{-18}$

NIST group: collaboration of many people

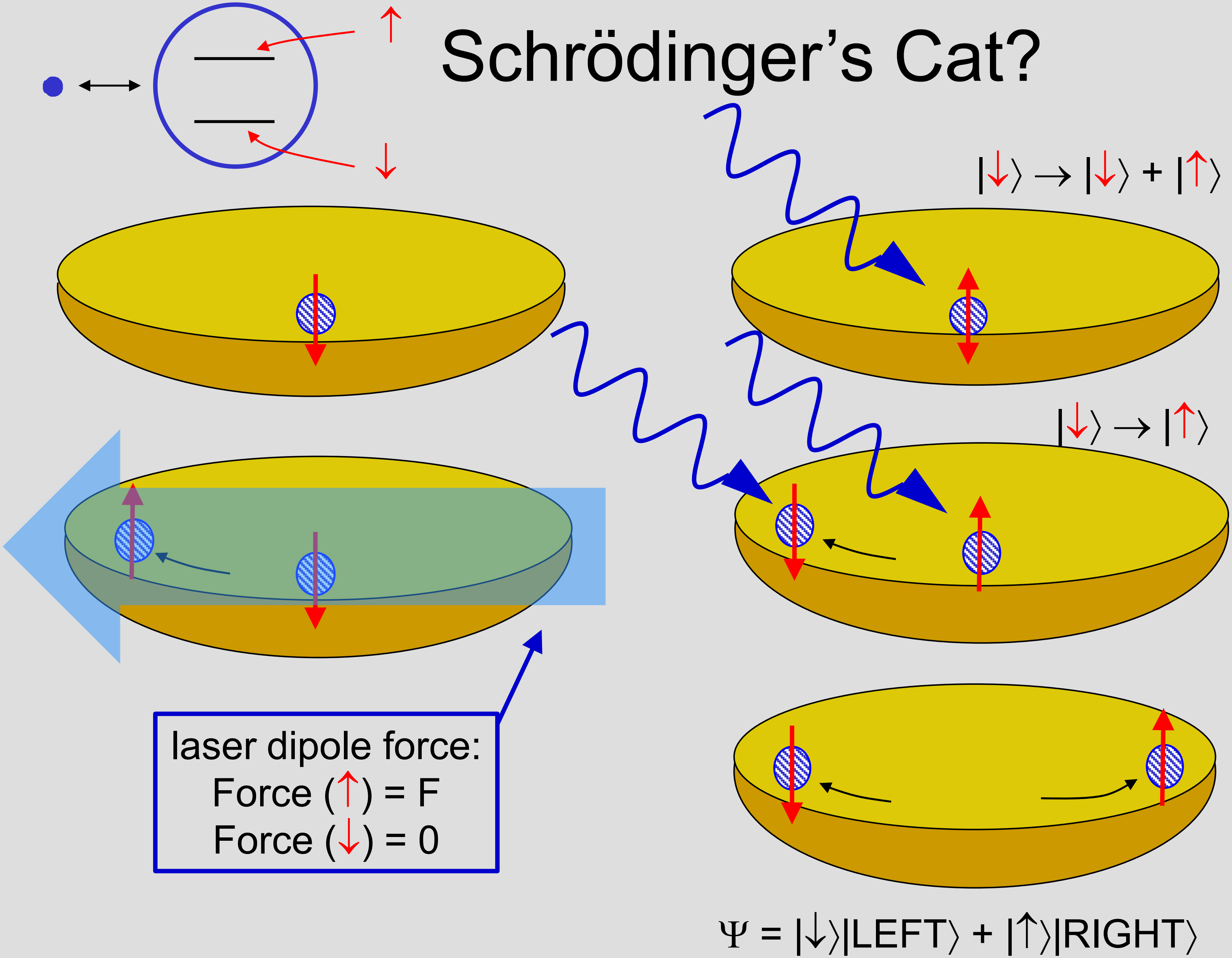


- plus students, postdocs, visitors (> 100)
- institutional support

Helmut Hellwig, Sam Stein, Don Sullivan, Tom O’Brian, Katharine Gebbie…

And good friends along the way!

Schrödinger's Cat?



C. Monroe, D. M. Meekhof, B. E. King, and D. J. Wineland, Science **272**, 1131 (1996).

On to Hans Dehmelt's lab: trapped electrons/ions

Hans Dehmelt