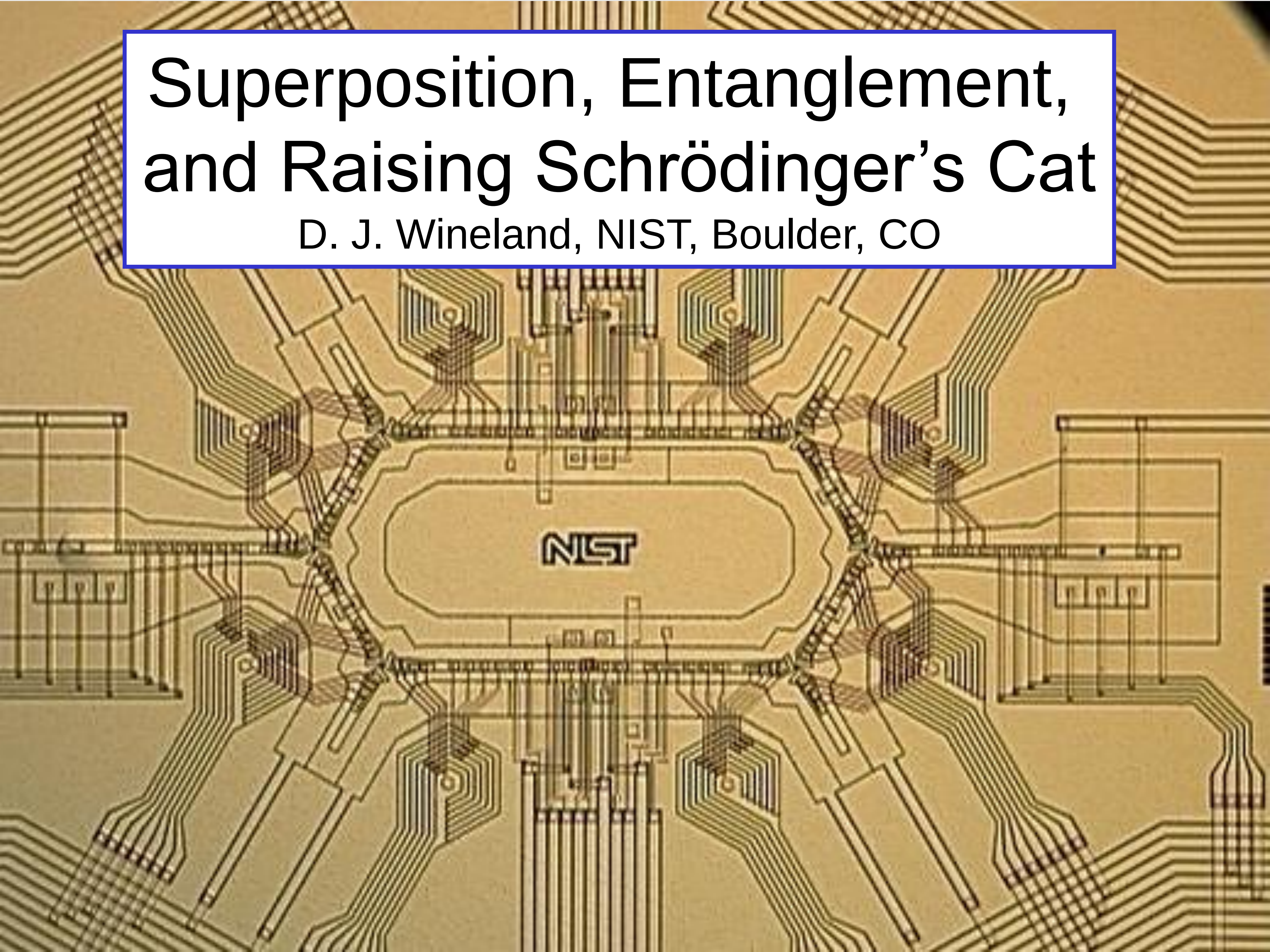
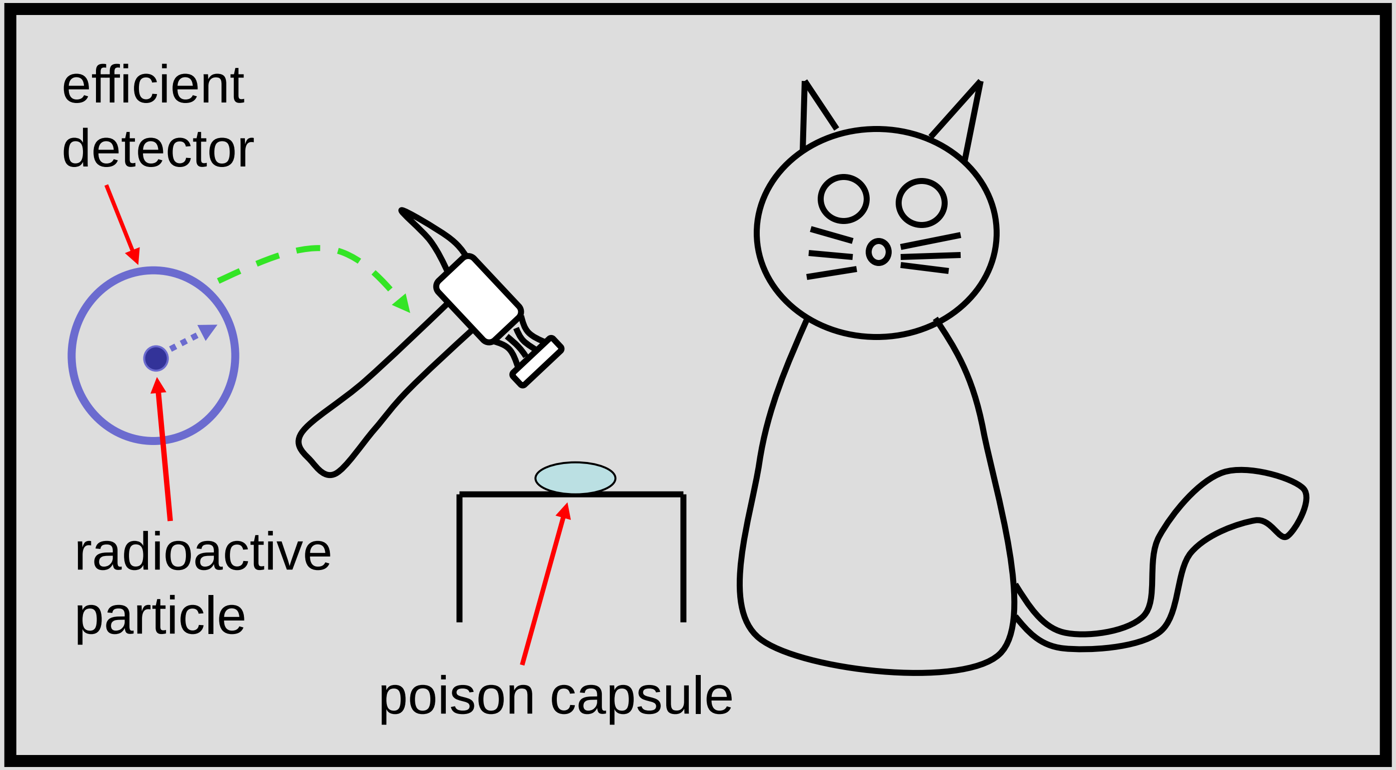
Superposition, Entanglement, and Raising Schrödinger's Cat

D. J. Wineland, NIST, Boulder, CO

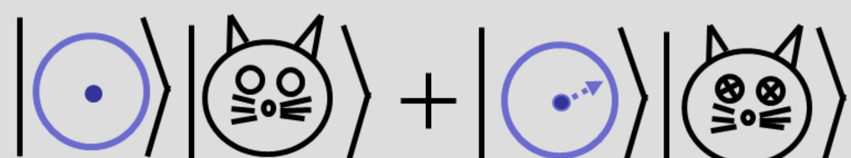


Erwin Schrödinger's Cat (1935)



At "half-life of particle, cat is dead <u>and</u> alive!

"superposition"

$\Psi =$ 

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!

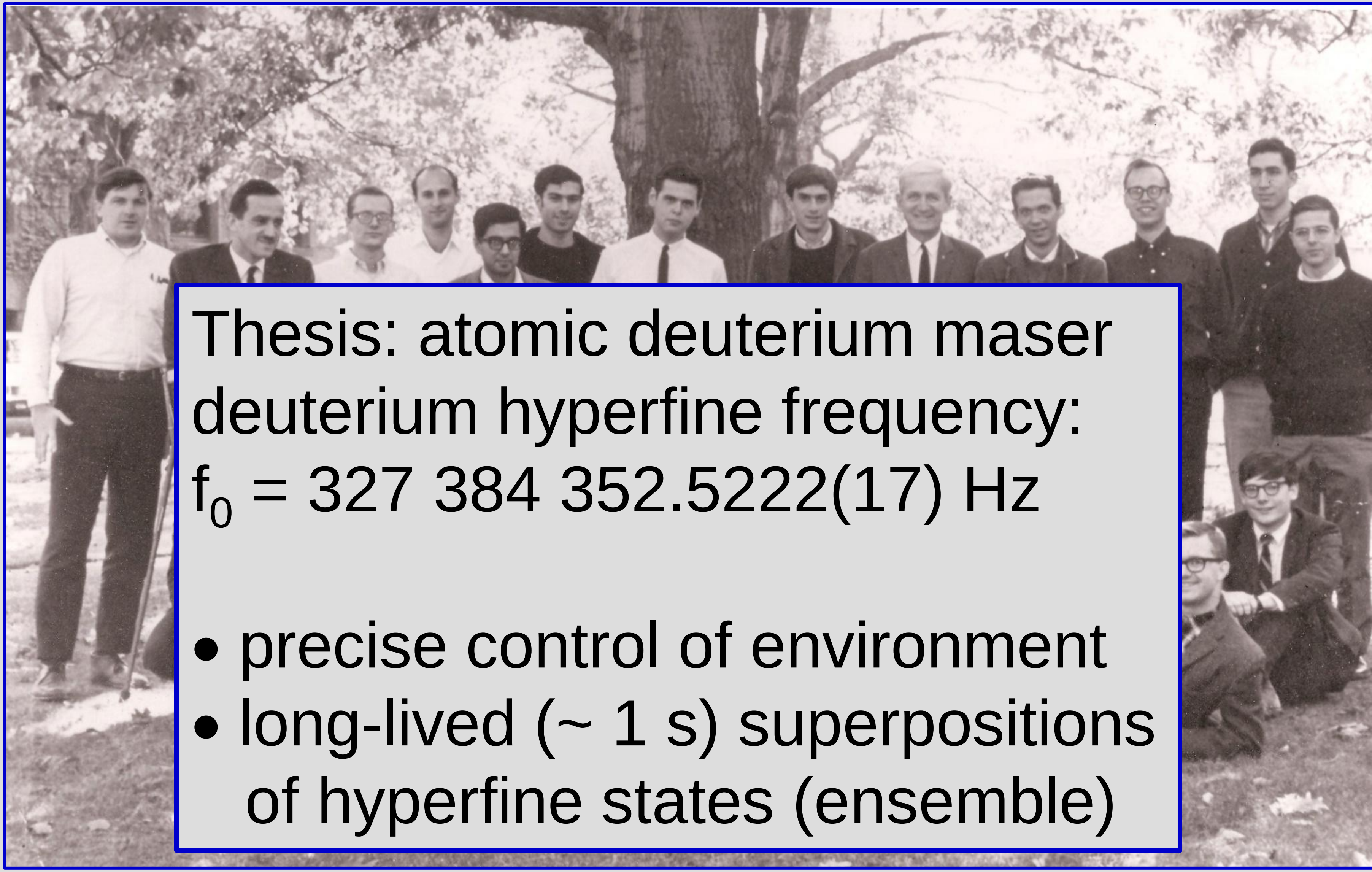
Need:

* 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)

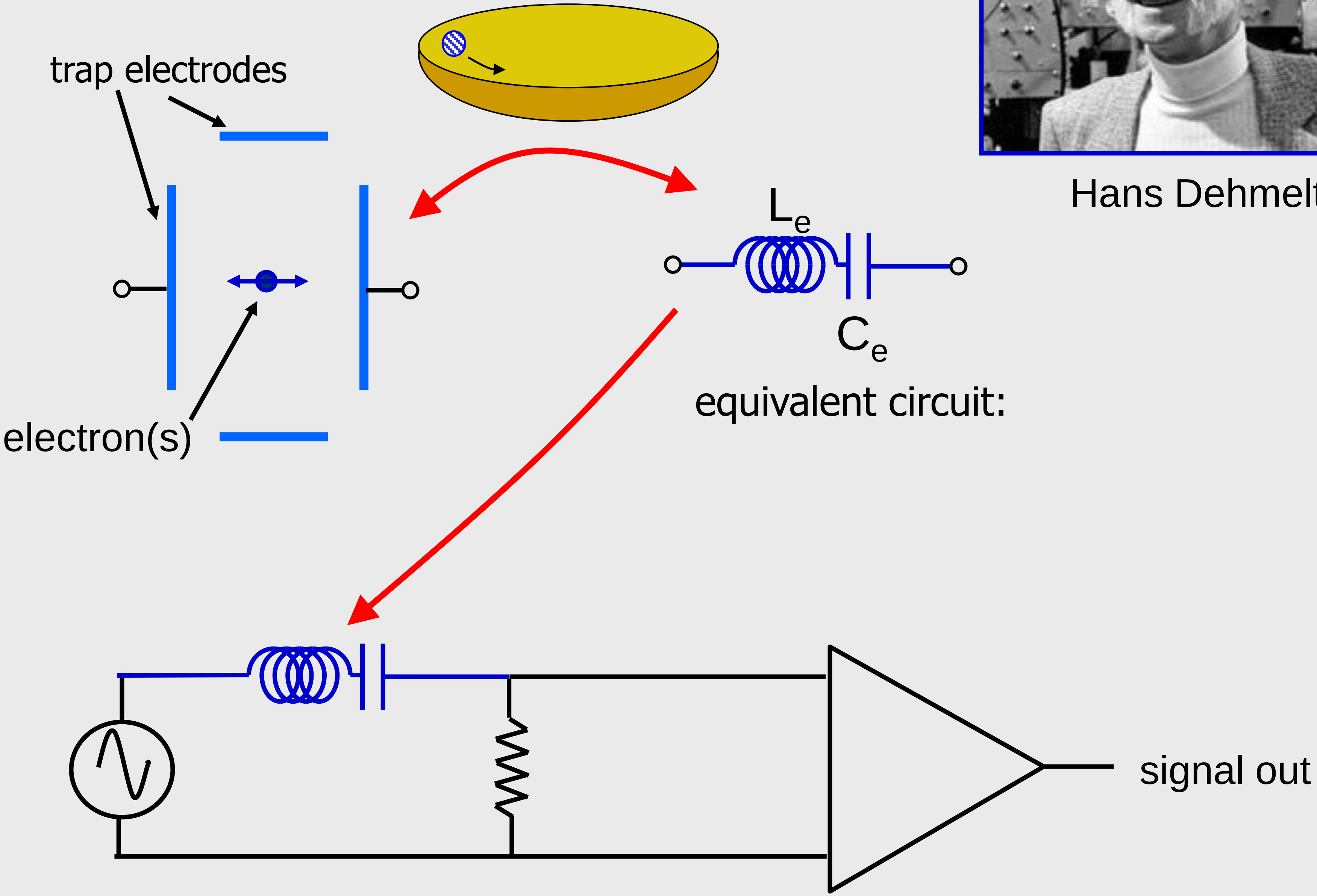
Ed Uzgiris Andrew Chakulski Tom English Doug Brenner Ashok Kosha Tom Follett Dave Wineland Norman Pat Gibbons Paul Zitzewitz Bill Edelstein Roger Hegstrom

Keith McAdam Peter Moulton Bob Hilborn Peter Valberg

Frank Winkler Fraser Code

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

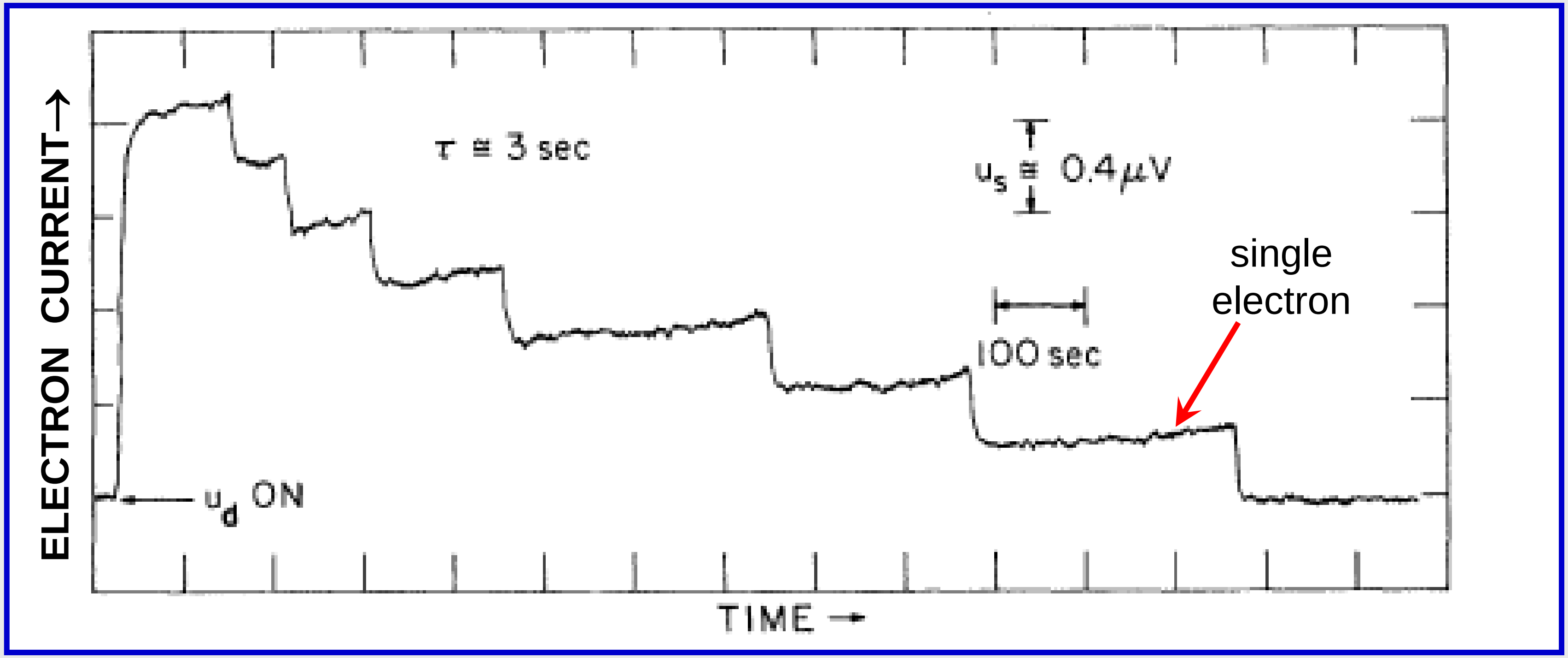
Hans Dehmelt



Single electrons

precursor to measurement of $\mu_{electron}$

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



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

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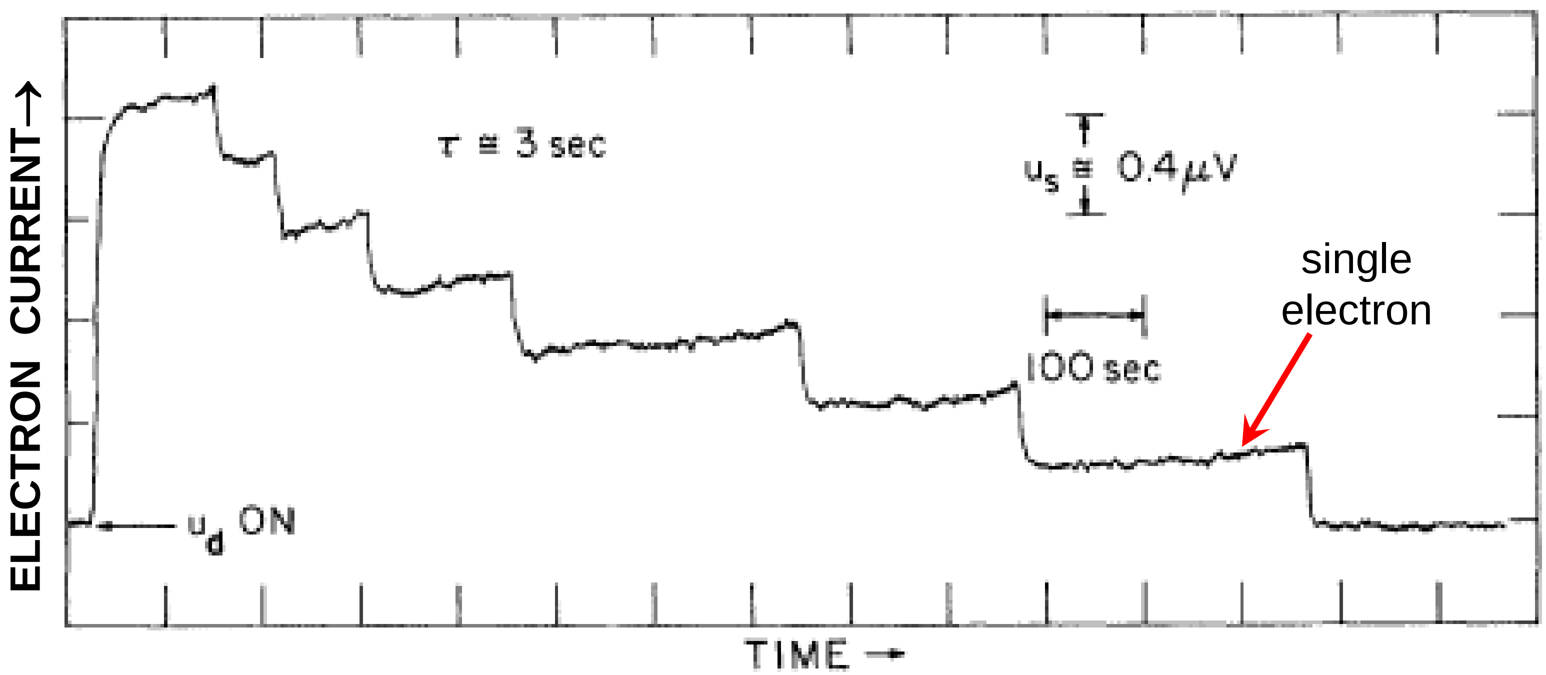


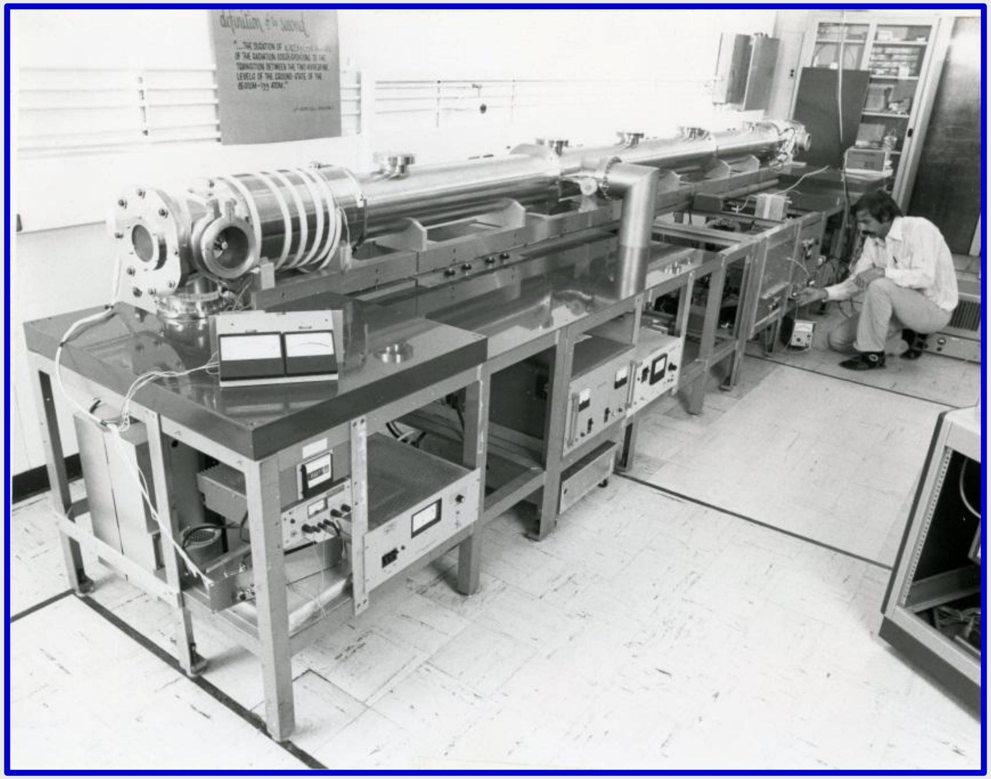
D. Wineland, P. Ekstrom, and H. Dehmelt, Phys. Rev. Lett. 31, 1279 (1973).

and, some ideas about laser cooling

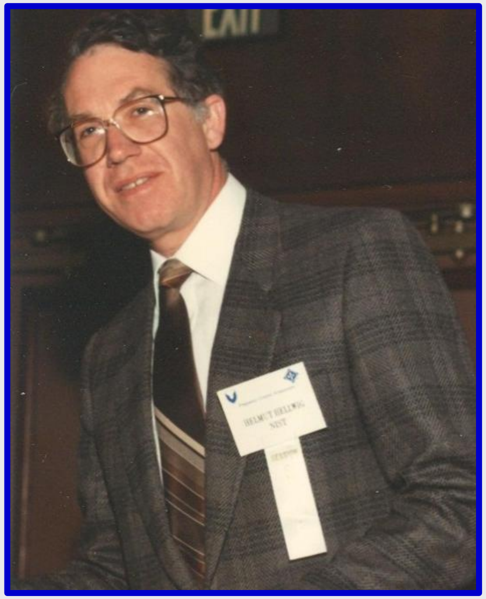
D.J.Wineland and H. Dehmelt, Bulletin, Am. Phys. Soc. **20**, 637 (1975)

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

On to NIST (National Institute of Standards and Technology) (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.

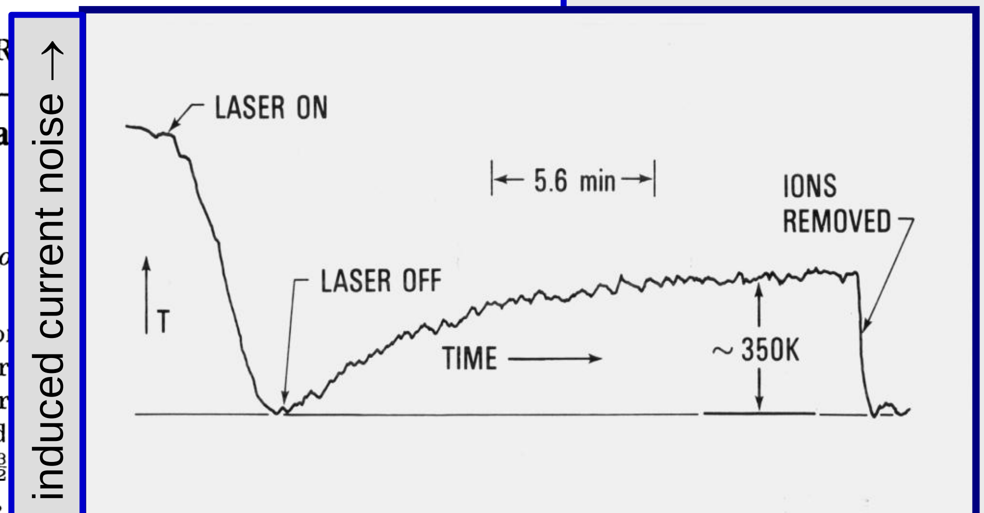
Peter Toschek

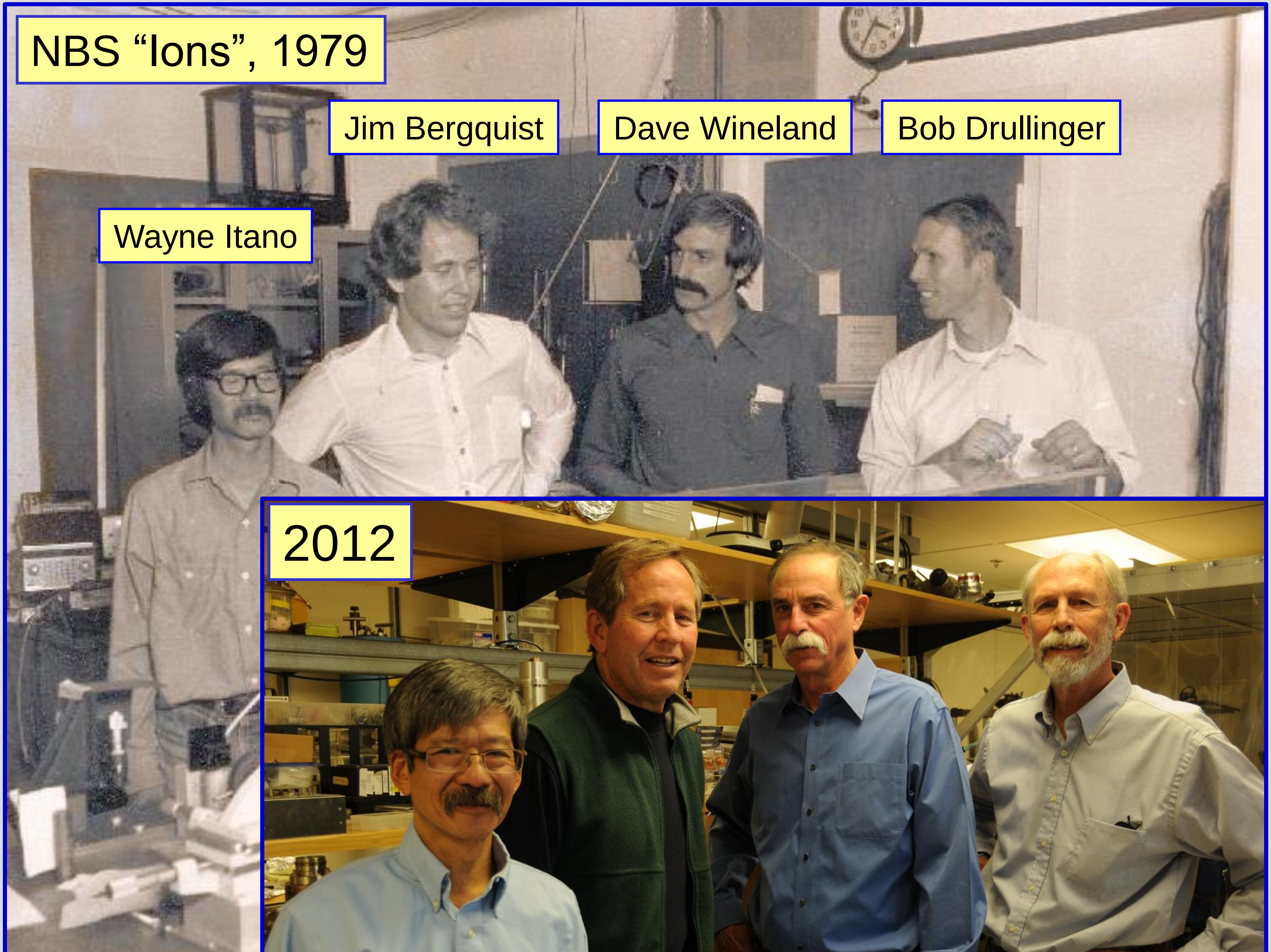
), NUMBER 25 PHYSICAL REVIEW LETTER

Radiation-Pressure Cooling of Bound Resona

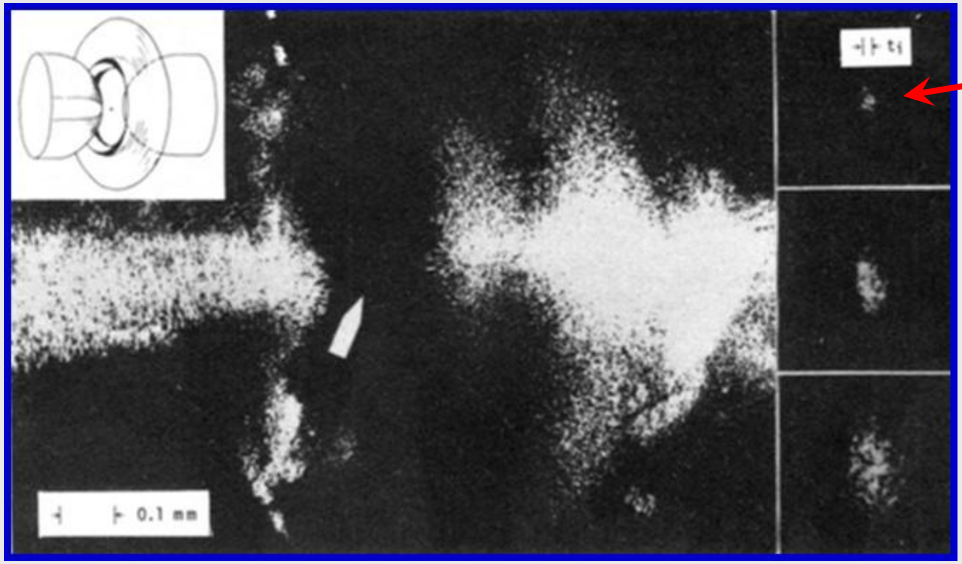
D. J. Wineland, R. E. Drullinger, and F. L.
Time and Frequency Division, National Bureau of Standards, Bo
(Received 26 April 1978)

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 i
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.



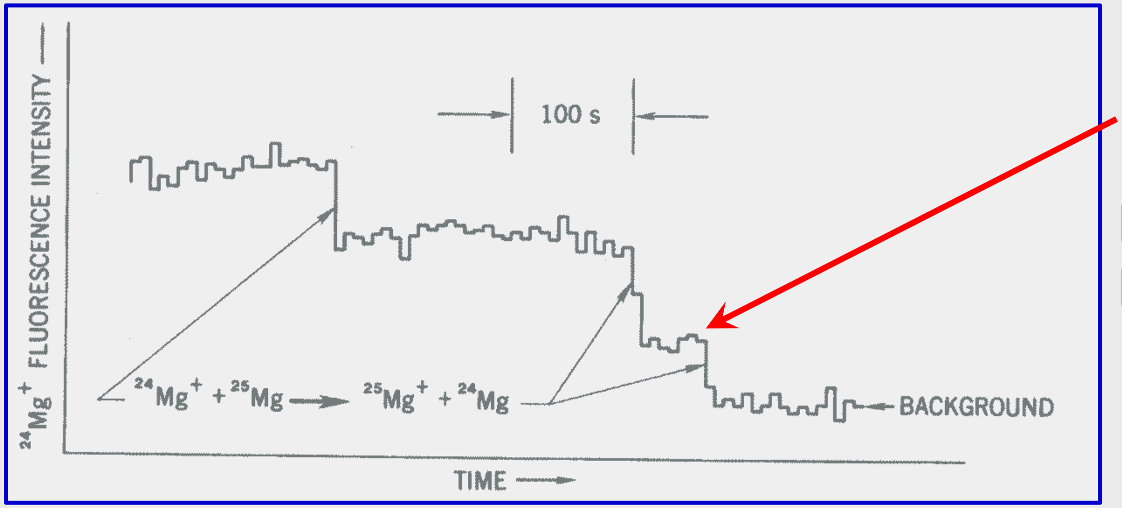

NBS "Ions", 1979
Jim Bergquist
Dave Wineland
Bob Drullinger
Wayne Itano
2012

Isolating individual ions:



single Ba^{+} ion

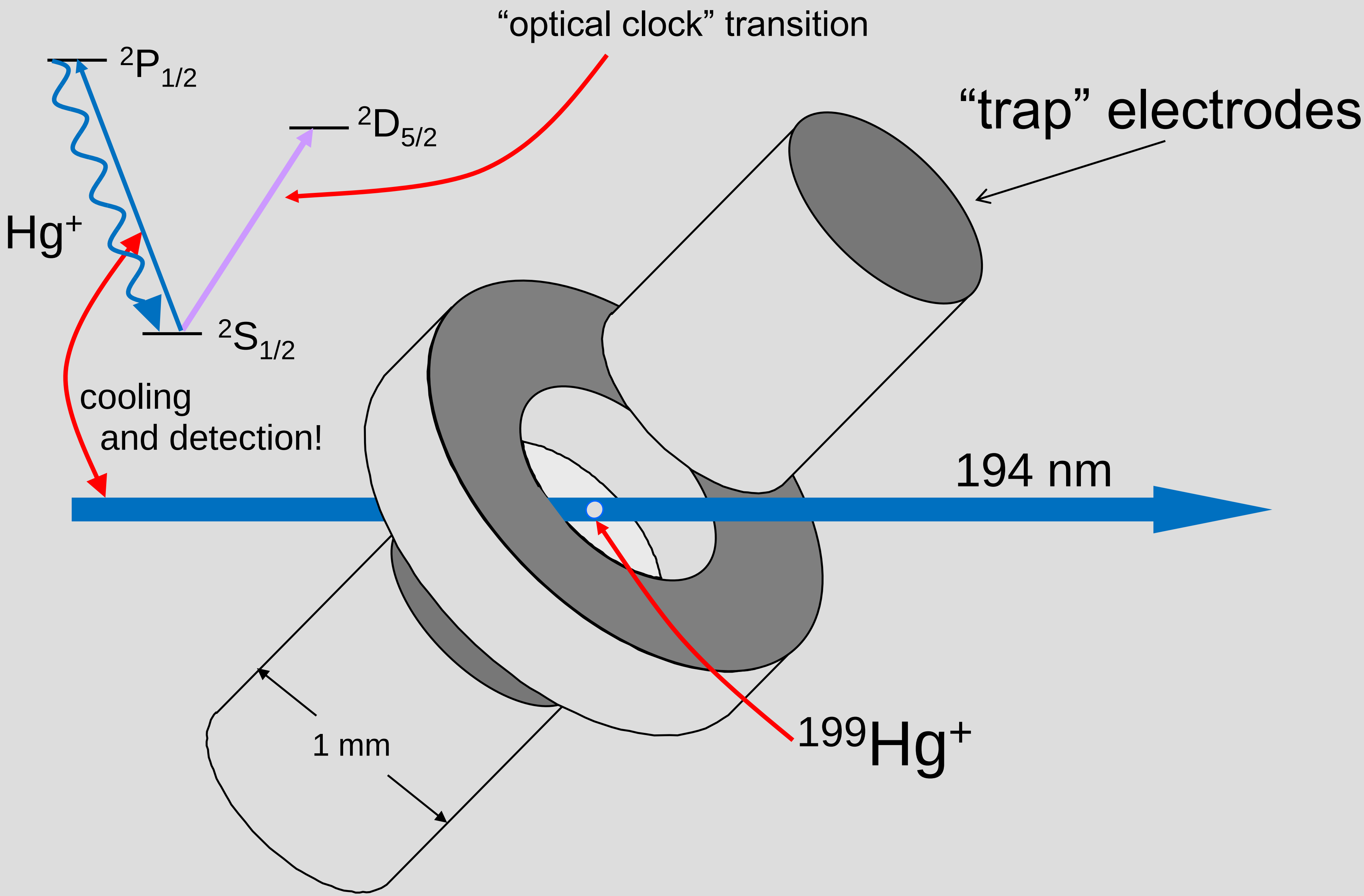
W. Neuhauser, M. Hohenstatt, P. Toschek, H. Dehmelt, Phys. Rev. A**22**, 1137 (1980).



single $^{24}Mg^{+}$ ion

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

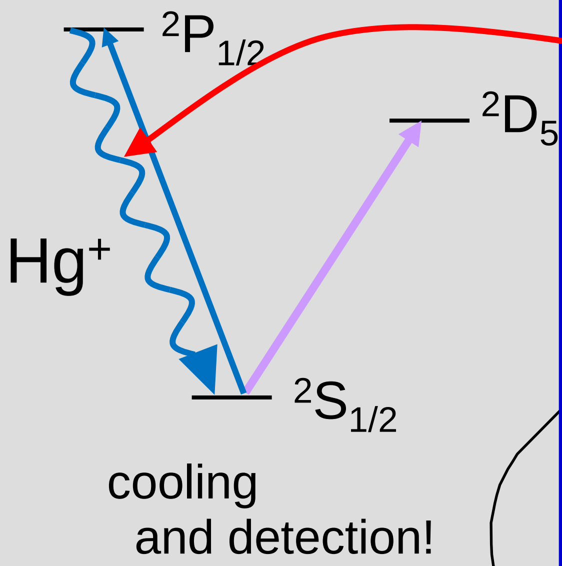
Single Hg^+ ion experiments at NIST (1981 →)

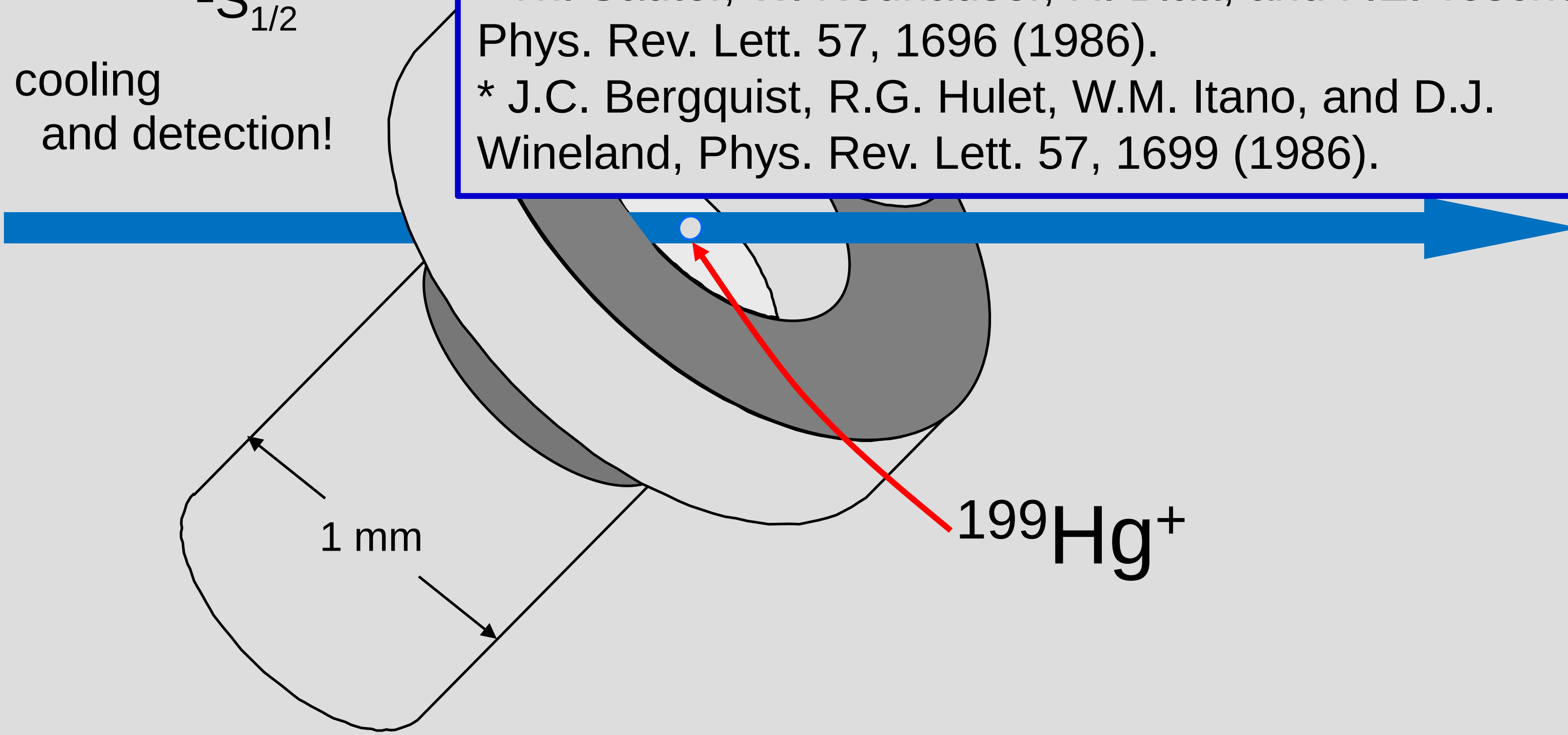


“Quantum jumps”

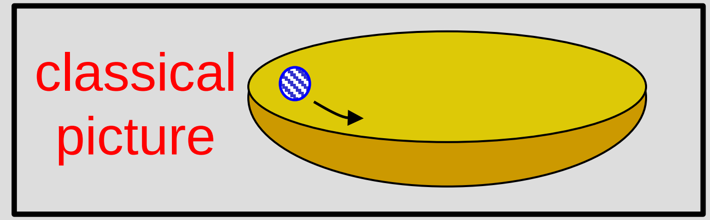
See abrupt changes in scattered light (fluorescence) when ion changes clock states

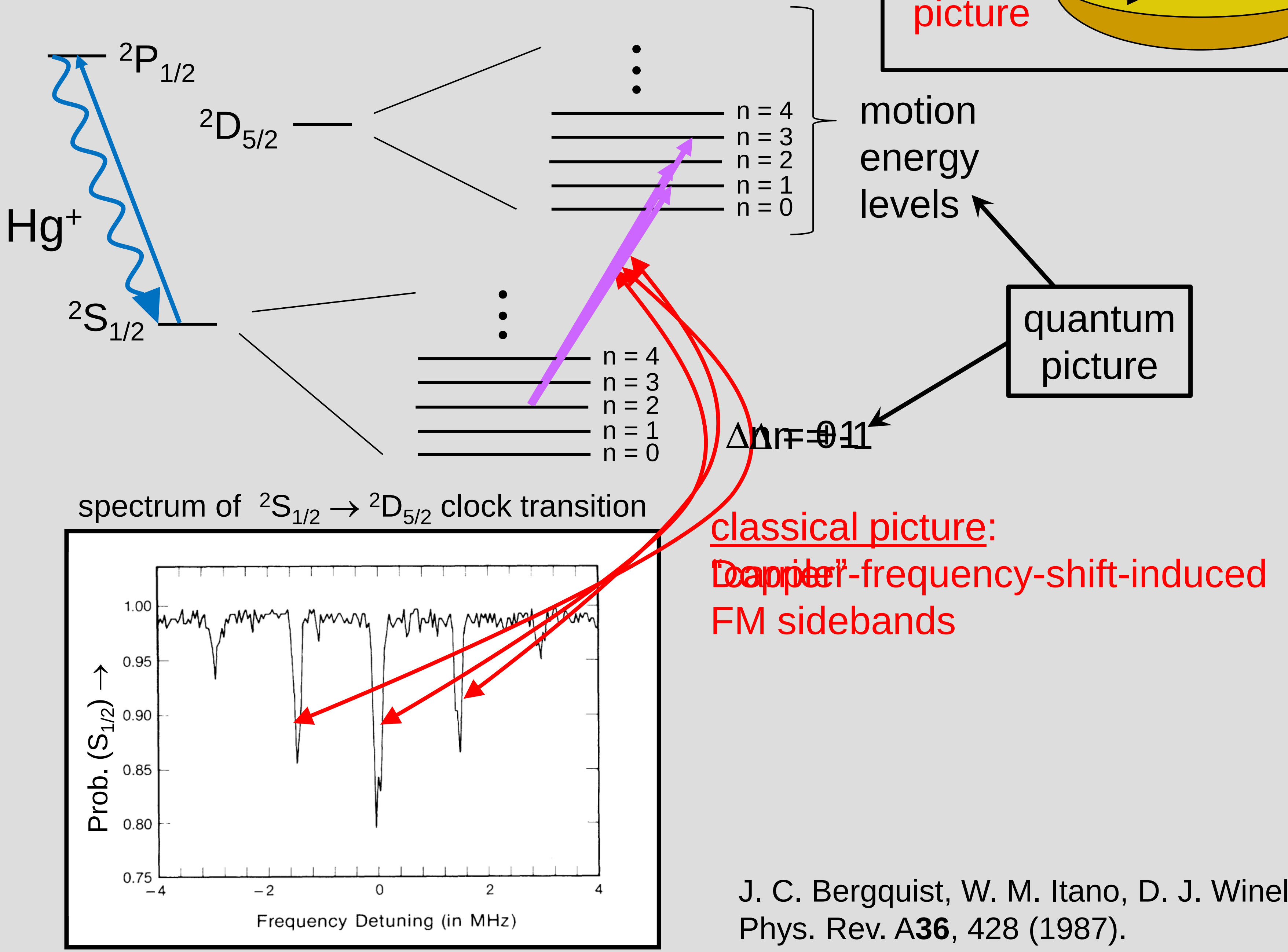
* W. Nagourney, J. Sandberg, and H. Dehmelt, Phys. Rev. Lett. 56, 2797 (1986).
* Th. Sauter, W. Neuhauser, R. Blatt, and P.E. Toschek, Phys. Rev. Lett. 57, 1696 (1986).
* J.C. Bergquist, R.G. Hulet, W.M. Itano, and D.J. Wineland, Phys. Rev. Lett. 57, 1699 (1986).





On to quantized motion:

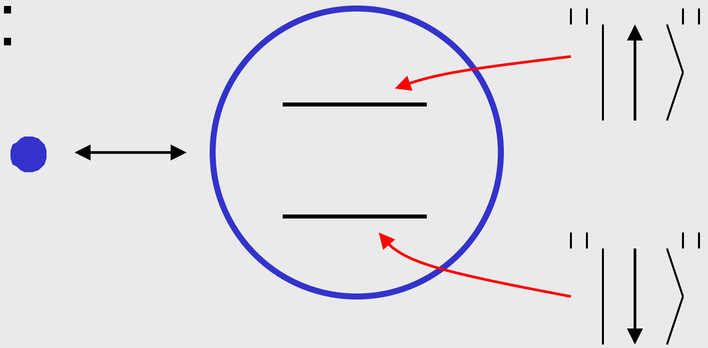




J. C. Bergquist, W. M. Itano, D. J. Wineland, Phys. Rev. A**36**, 428 (1987).

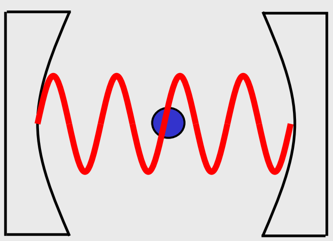
Connections to cavity QED:

atomic two-level system:



atom-oscillator coupling:

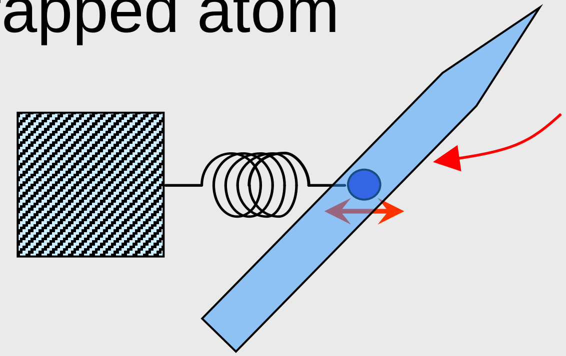
Cavity-QED



quantized oscillator =
mode of electromagnetic field

• atom/oscillator coupling
⇔ dipole coupling

Trapped atom

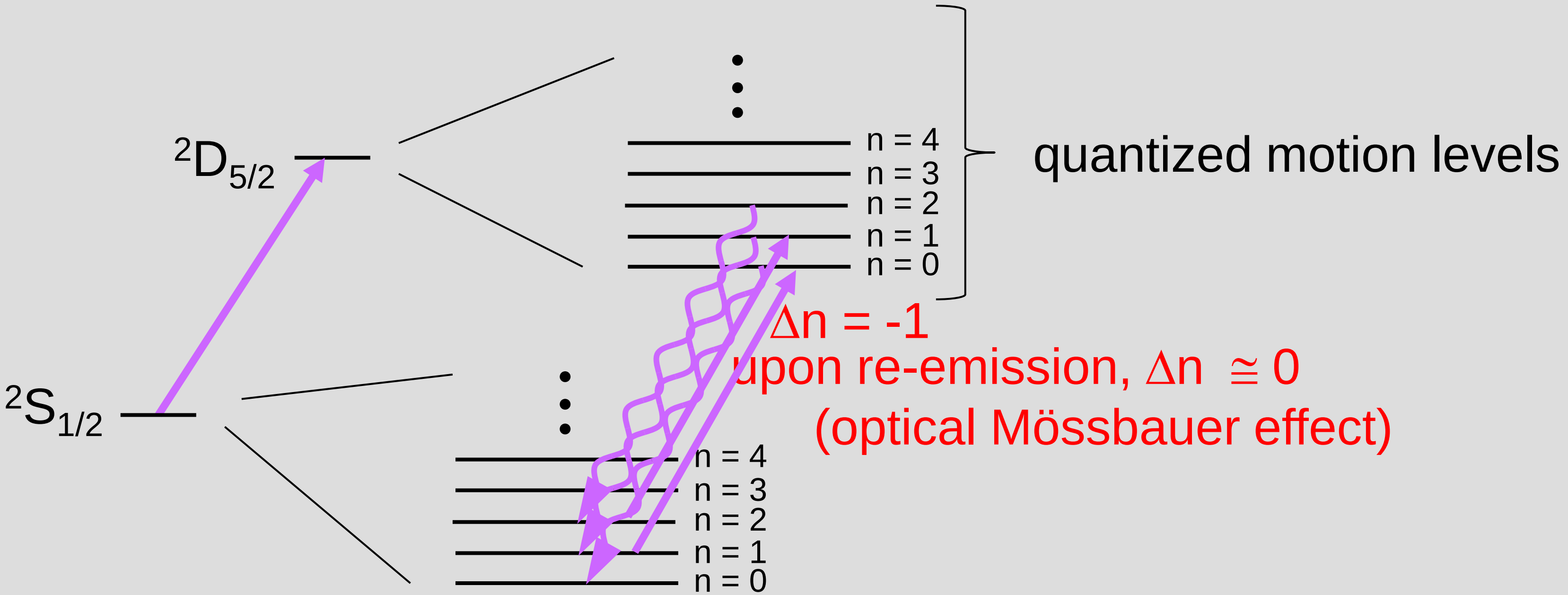


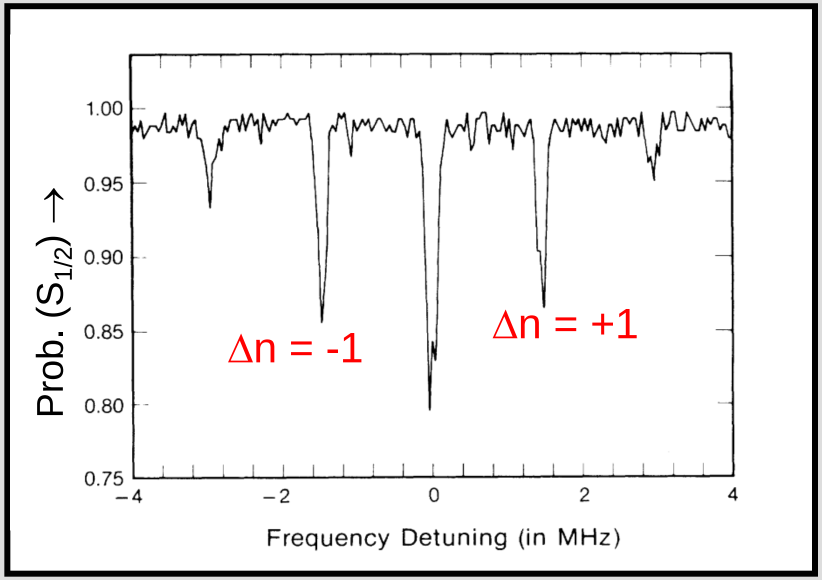
quantized oscillator =
mode of motion

• atom/oscillator coupling
⇔ dipole coupling
modulated by motion

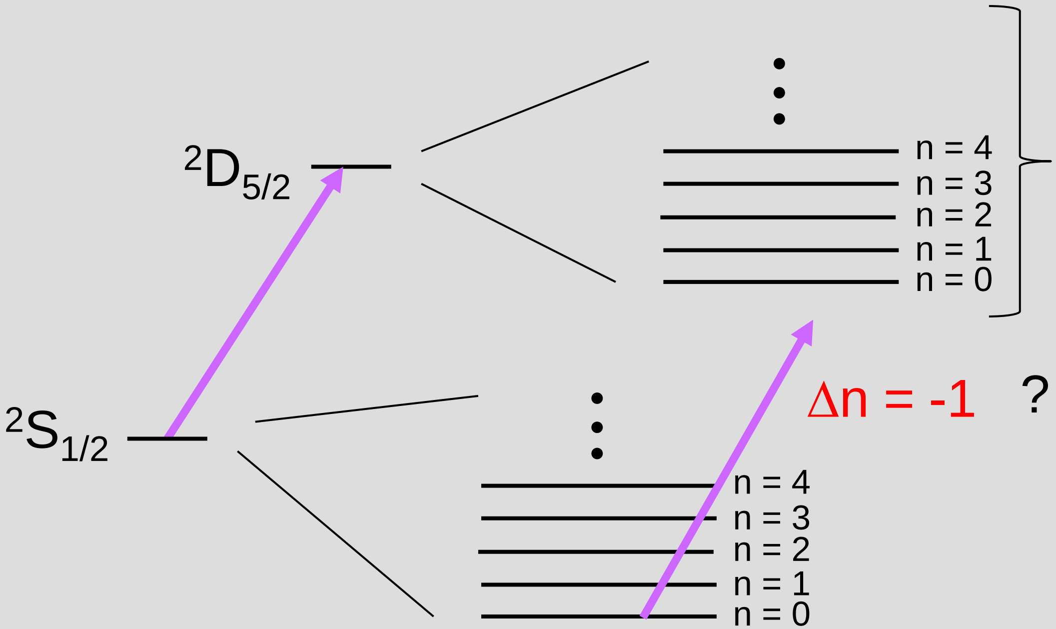
for both, $H_I = \hbar g\,(\sigma_+ a + \sigma_- a^\dagger)$ Jaynes-Cummings coupling

Cooling to the ground state of motion:

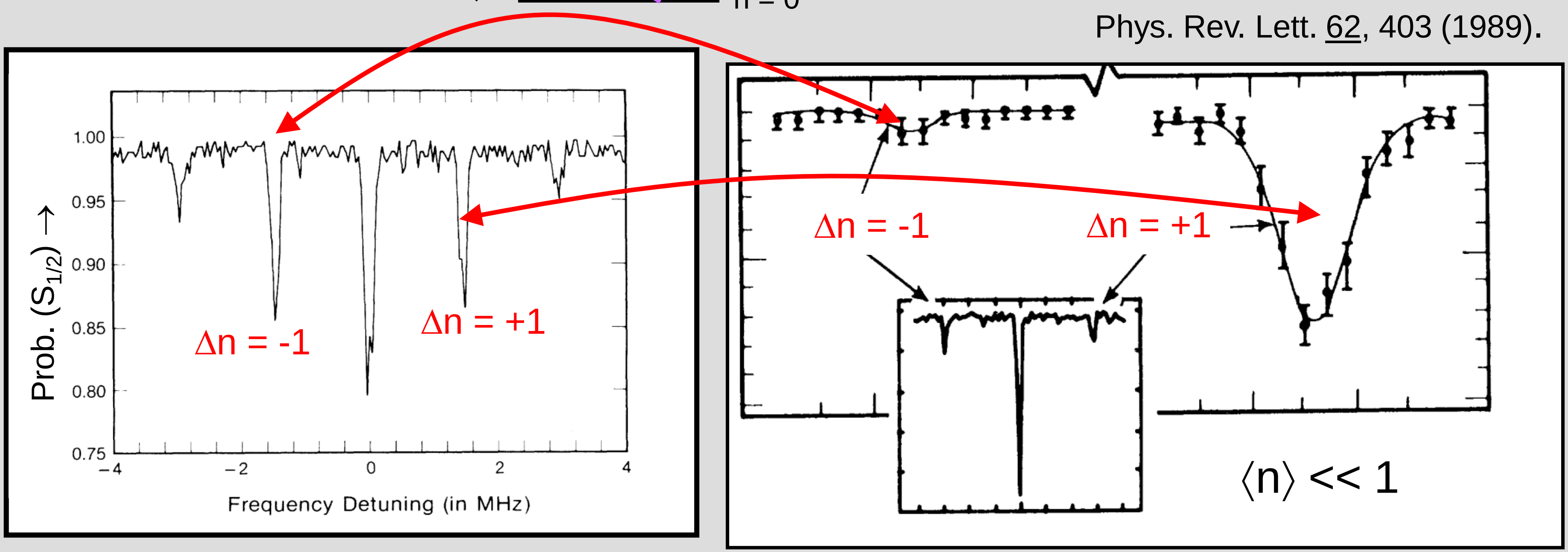




Cooling to the ground state of motion



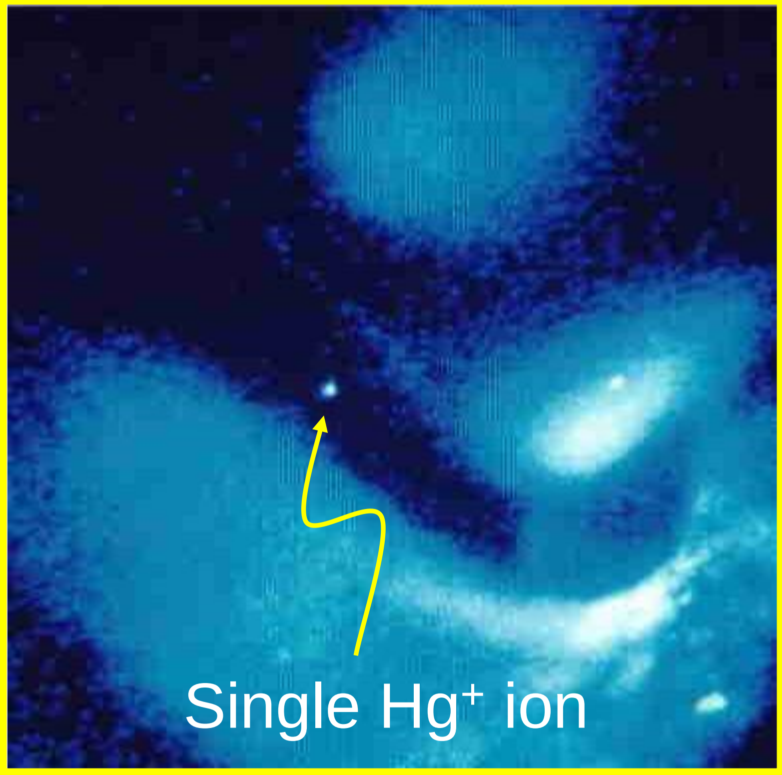
F. Diedrich, J.C. Bergquist,
W. M. Itano, and D.J. Wineland,
Phys. Rev. Lett. 62, 403 (1989).



Single ions for (optical) clocks:

J. C. Bergquist et al., 1981 →

Jim Bergquist



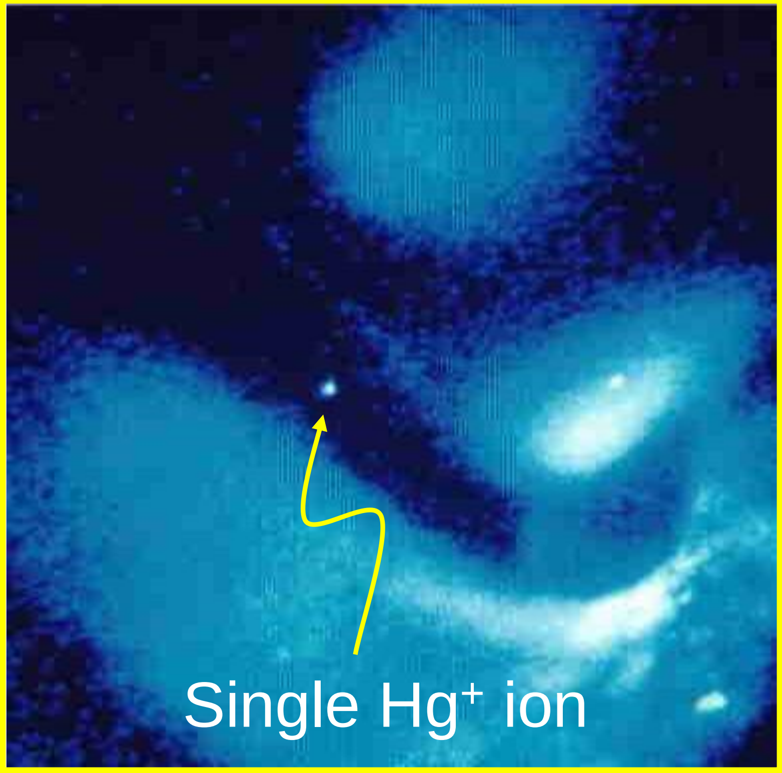
- trapping ⇒ first-order Doppler shift → 0
- laser cooling ⇒ time dilation small
- trapping in high vacuum at 4 K
  ⇒ environmental perturbations (collisions, black body shifts, etc.) small

⇒ first clock with systematic uncertainly ($7x10^{-17}$) below Cesium
- W. H. Oskay et al., Phys. Rev. Lett. **97**, 020801 (2006)

Single ions for (optical) clocks:

J. C. Bergquist et al., 1981 →

Jim Bergquist



Plus many other ion species:

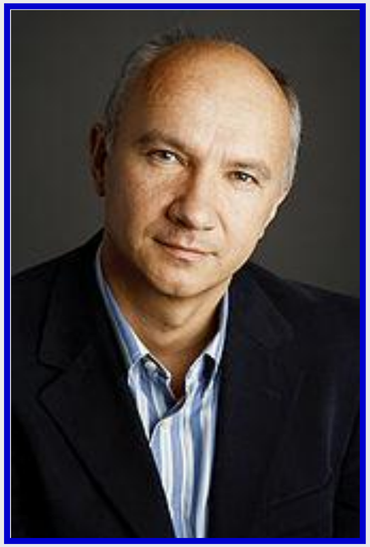
$^{88}Sr^{+}$, $^{171}Yb^{+}$, $^{27}Al^{+}$, $^{40}Ca^{+}$, $^{115}In^{+}$

see, e.g., P. Gill, Phil. Trans. R. Soc. A **369**, 4109 (2011)

Enter quantum information processing

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

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

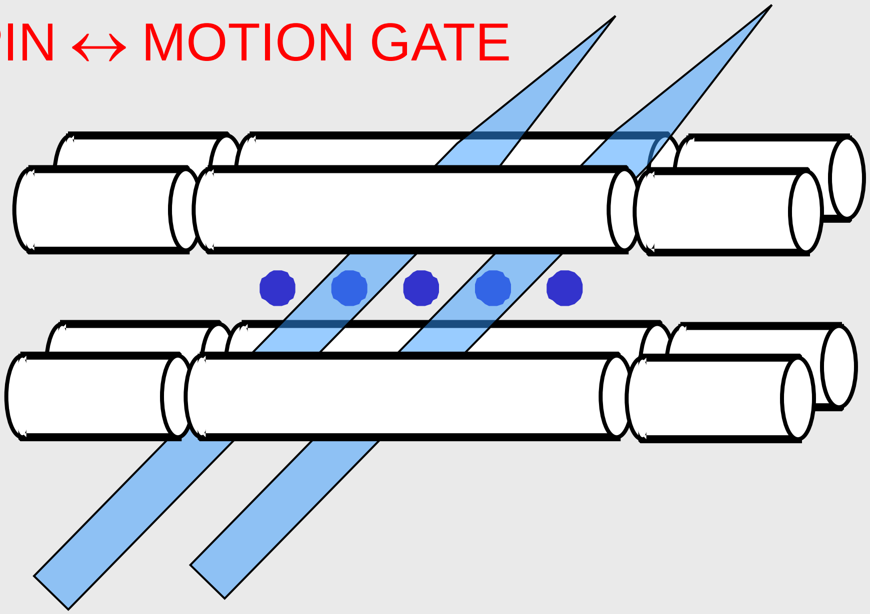


Artur Ekert: presentation at the 1994 International Conference on Atomic Physics Boulder, Colorado

Atomic Ion Quantum Computation:
(J. I. Cirac, P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995)

SPIN → MOTION MAP

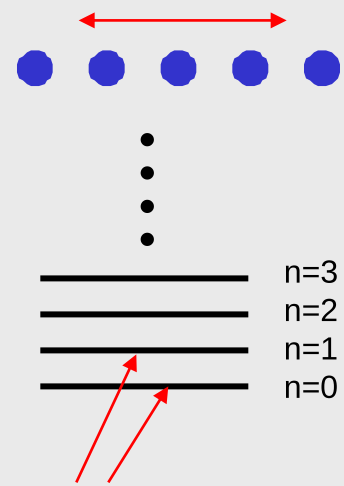
SPIN ↔ MOTION GATE



Ignacio Cirac

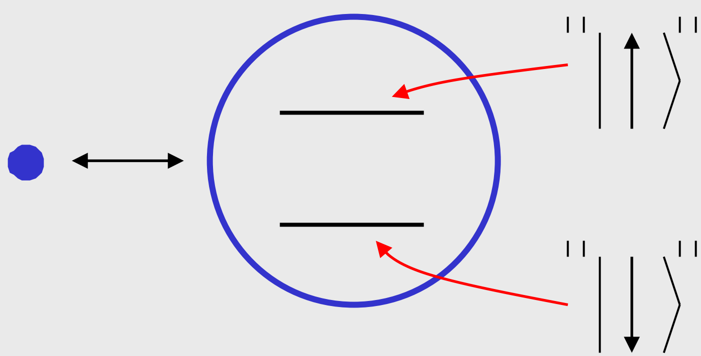
Peter Zoller

MOTION "DATA BUS"
(e.g., center-of-mass mode)



Motion qubit states

INTERNAL STATE "QUBIT"



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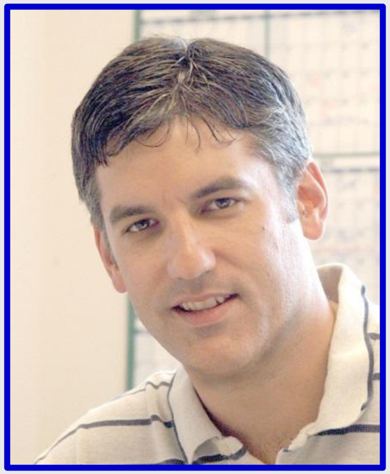
(J. I. Cirac, P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995)

Ignacio Cirac

Peter Zoller

SPIN → MOTION MAP

SPIN ↔ MOTION GATE



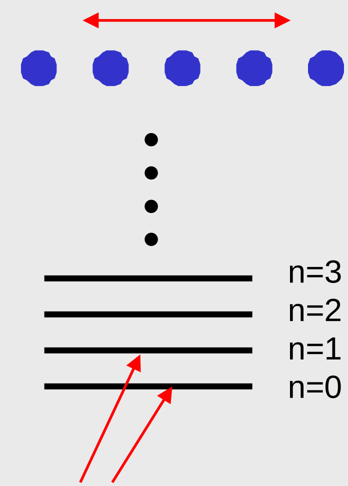
Chris Monroe

"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).

MOTION "DATA BUS"

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



Motion qubit states

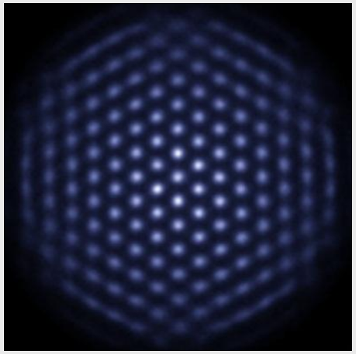
Some examples:

Didi Leibfried

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

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

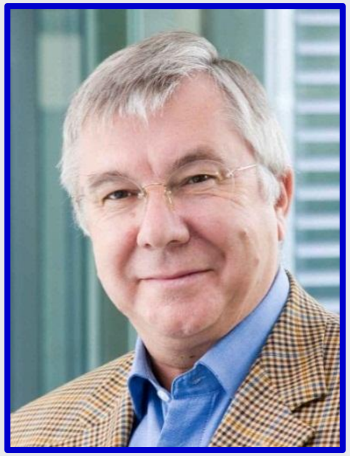
C. Monroe et al., U. Maryland
T. Schätz et al., Freiburg;
J. Bollinger et al., NIST
…..



John Bollinger

- universal (digital) quantum simulator
  R. Blatt et al., Innsbruck

Rainer Blatt



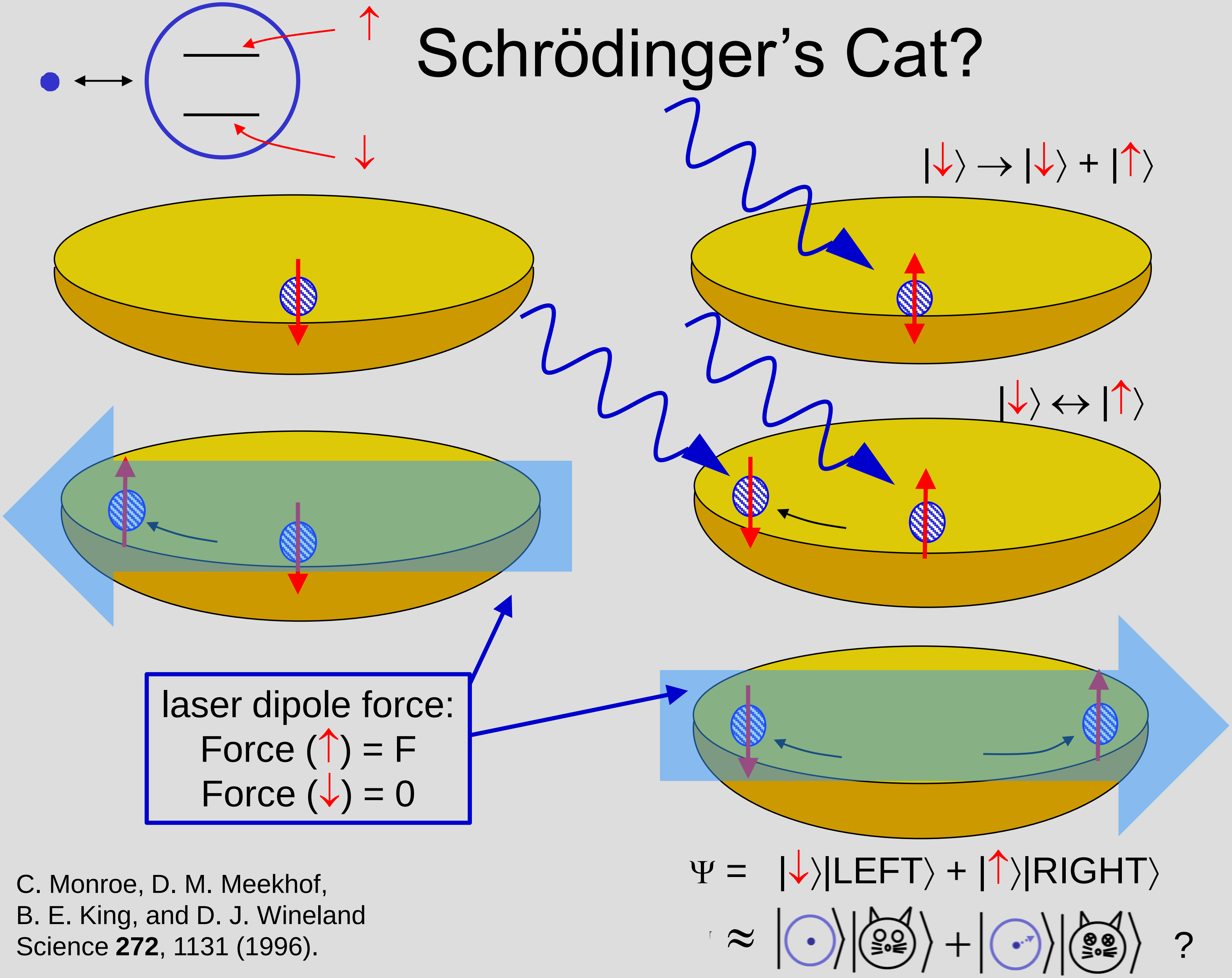
and many more…

Atomic ion experimental groups pursuing Quantum Information Processing:

Aarhus
Amherst
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

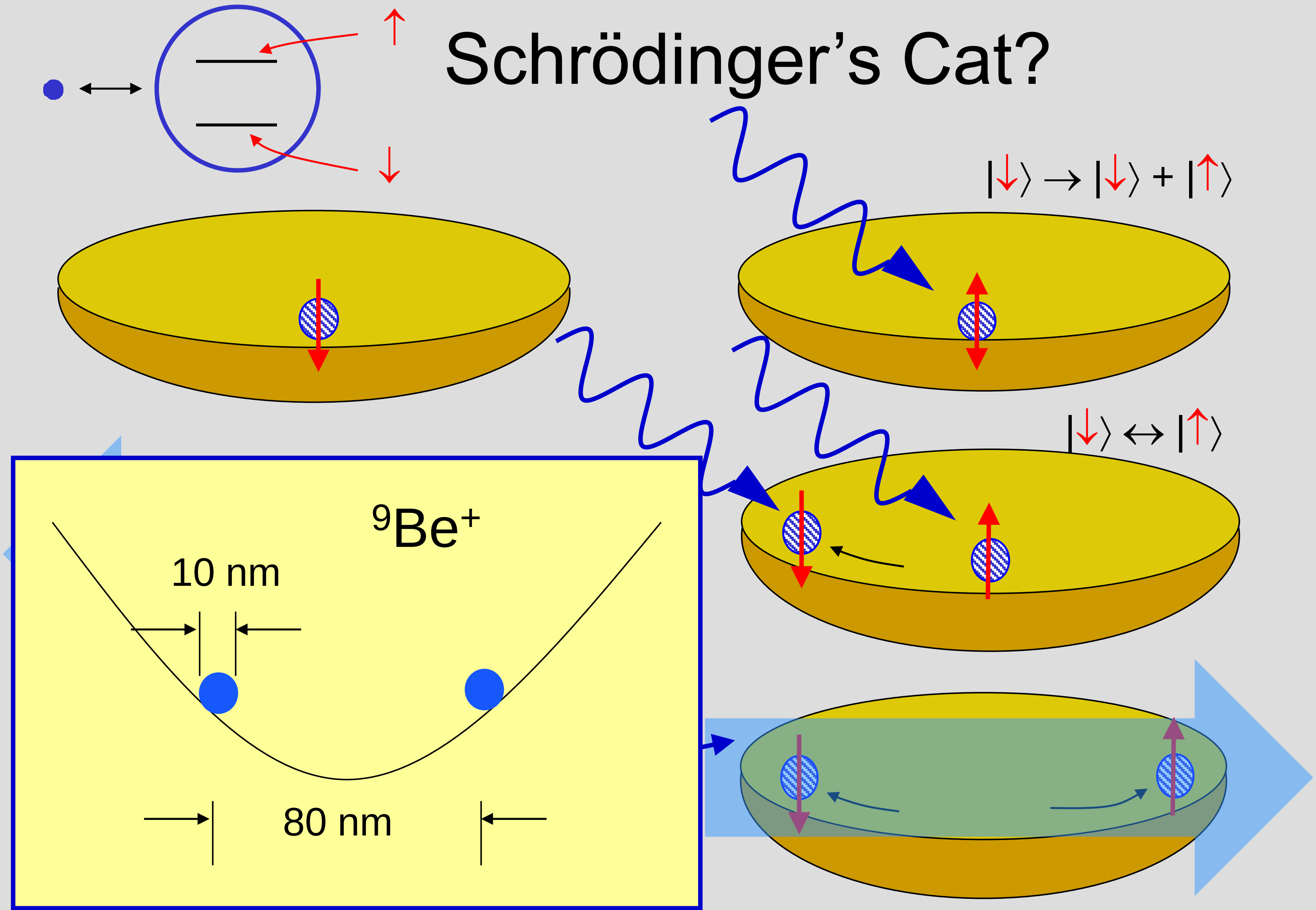
MIT
NIST
NPL
Osaka
Oxford
Paris (Université Paris)
PTB
Saarland
Sandia National Lab
Siegen
Simon Fraser
Singapore
Sussex
Sydney
U. Washington
Weizmann Institute

Schrödinger's Cat?

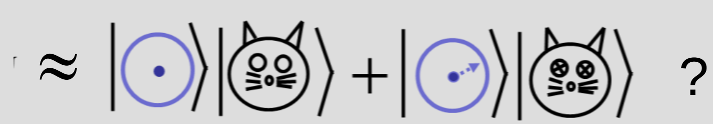


C. Monroe, D. M. Meekhof,
B. E. King, and D. J. Wineland
Science **272**, 1131 (1996).

Schrödinger’s Cat?



$\Psi = \; |\downarrow\rangle|\text{LEFT}\rangle + |\uparrow\rangle|\text{RIGHT}\rangle$



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

Is there a quantum/classical boundary and what defines it?

- Well-known discussions:
  - Ghirardi, Rimini, Weber, (A. Bassi, G. Ghirardi, Phys. Rep. **379**, 257 (2003))
  - A. J. Leggett (J. Phys.: Condens. Matter **14**, R415 (2002))
  - R. Penrose (Gen. Relativ. Gravit. **28**, 581 (1996))

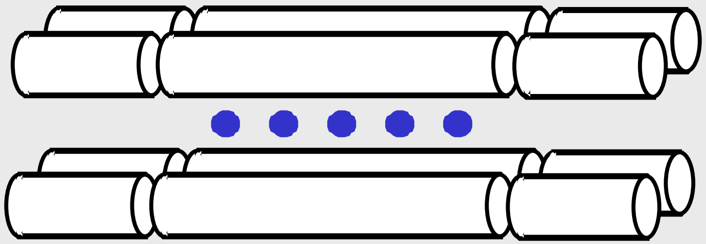
- Does it depend on size and what means "size"?
  - mass? (look at decoherence of mesoscopic mechanical oscillators)
  - physical dimensions?
    - ◊ optics - entanglement extends over km
    - ◊ mechanical system dimensions?
  - number of elementary constituents?
    - ◊ e.g. electrons in super conducting circuits (A. J. Leggett, B. Whaley, …)
  - number of particles or degrees of freedom entangled?
    - ◊ $N_{entangled} \cong 100$ atoms

      (C. Gross et al., **464**, 1165 (2010) – M. Oberthaler group)

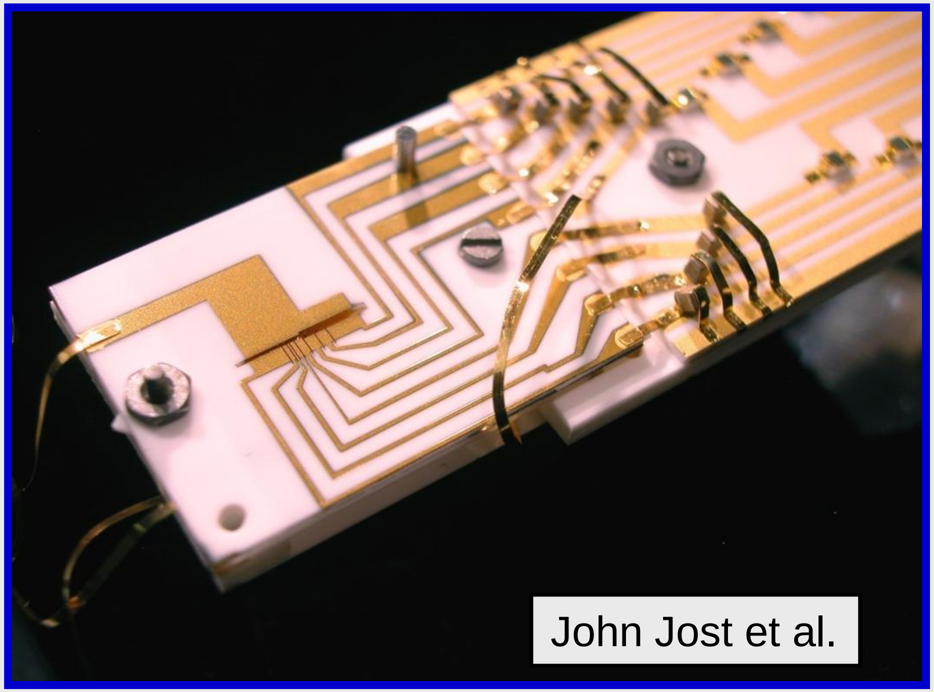
- Interesting to explore all regimes!

Hardware

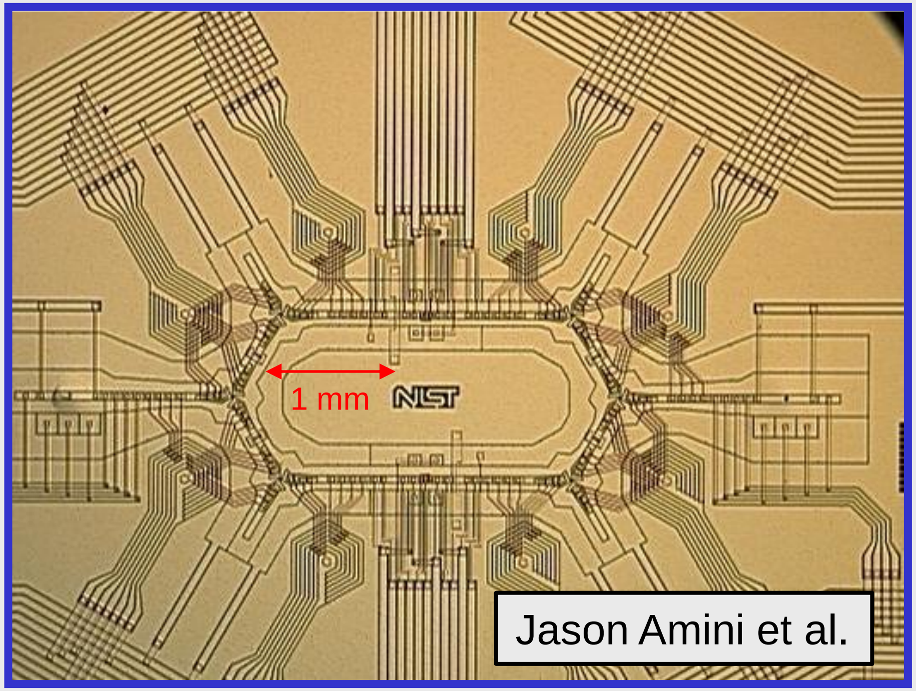
“ideal” trap



want small traps (for speed) ⇒ lithographic techniques



John Jost et al.



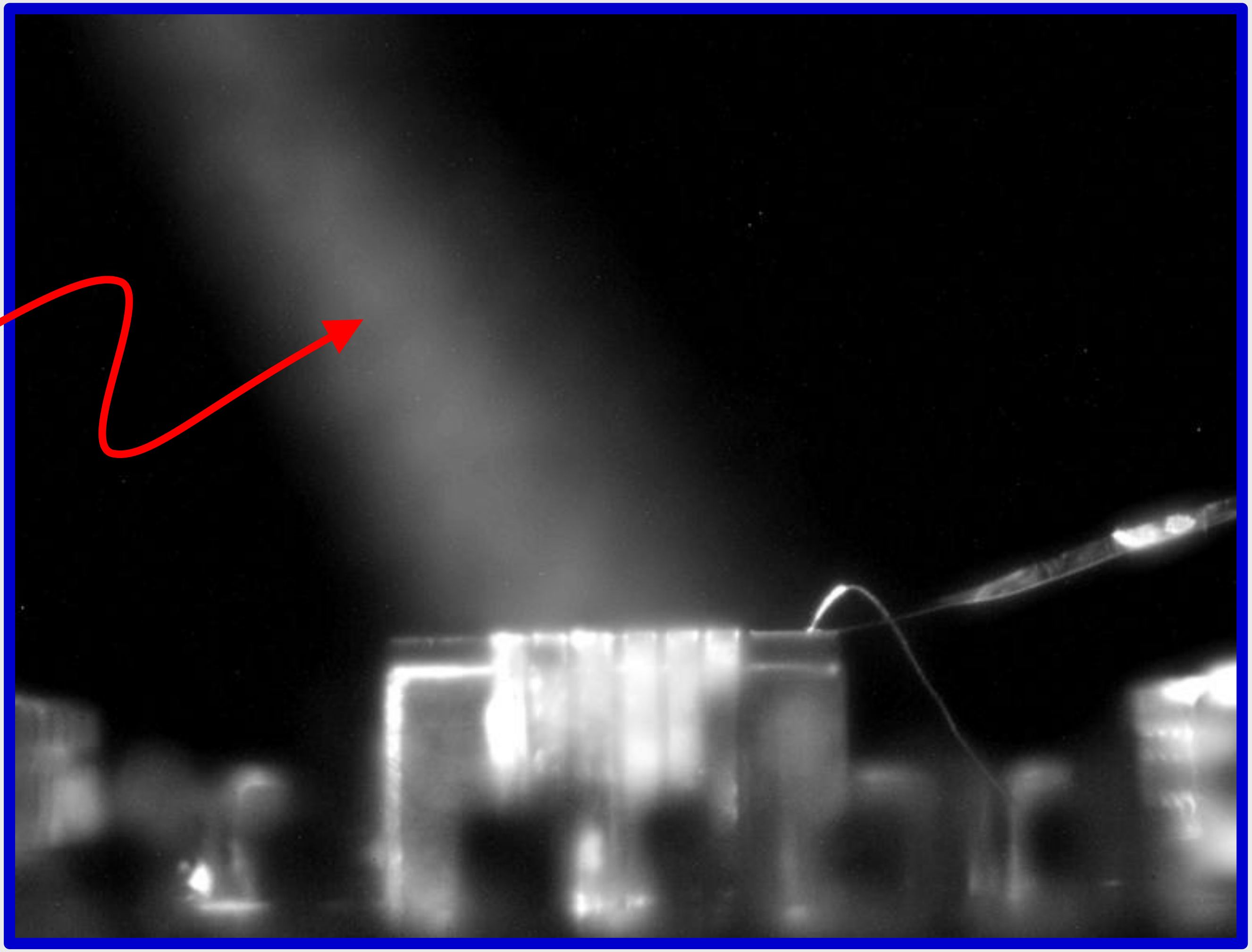
Jason Amini et al.

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

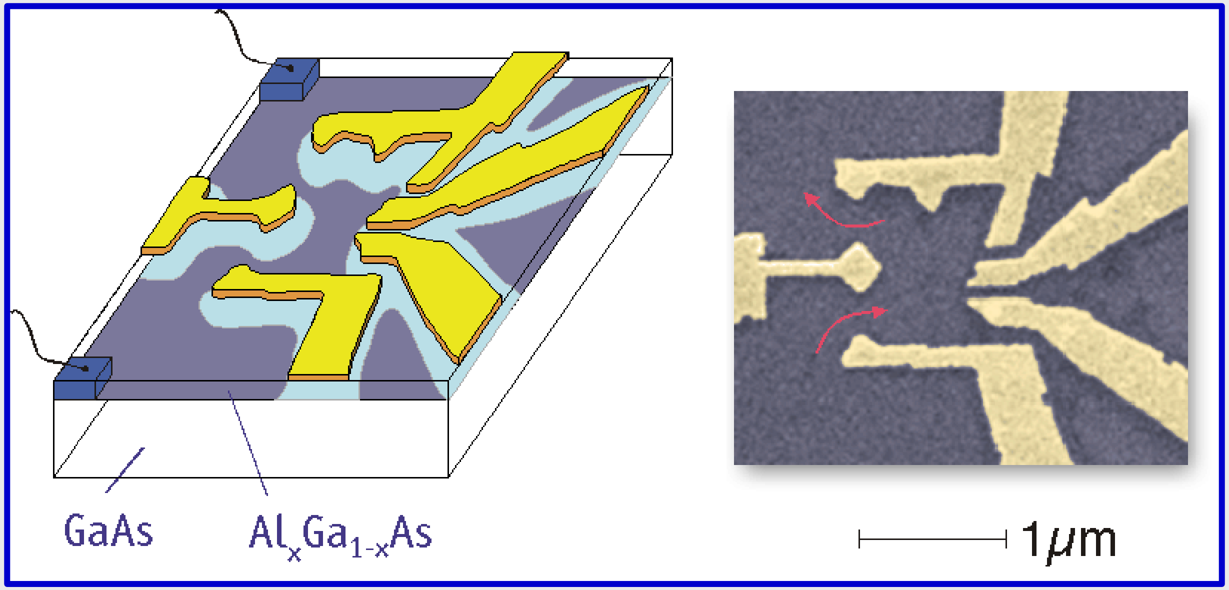
Dirty laundry: “anomalous” ion heating

Collaboration with Dustin Hite, Kyle McKay, Dave Pappas (Div. 686)

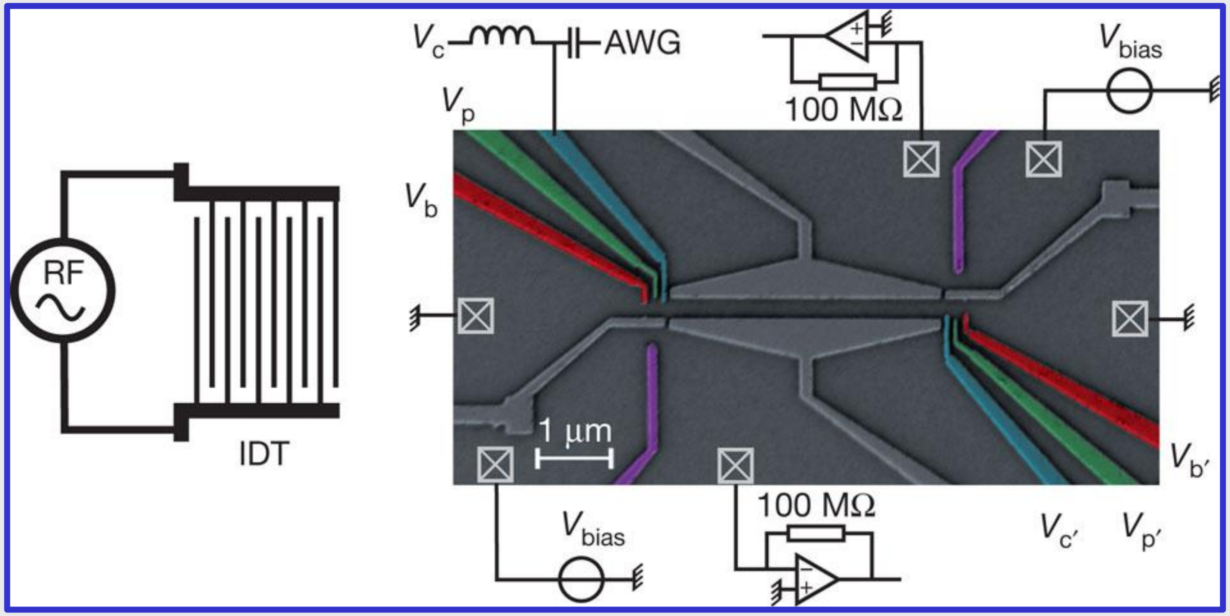
Ar^+ beam cleaning



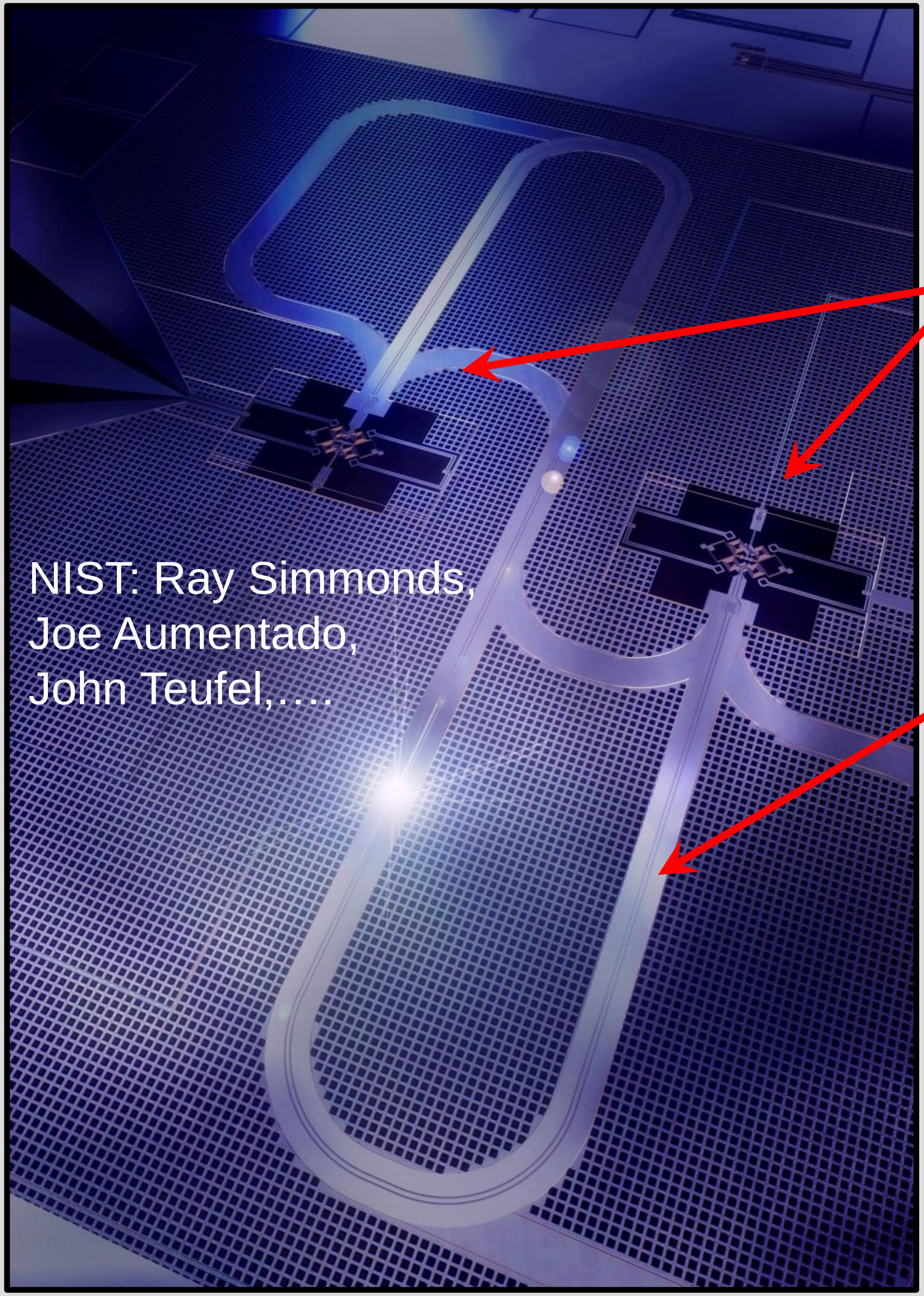
Many other qubits: e.g., 2DEG GaAs Qubits



C. Marcus group

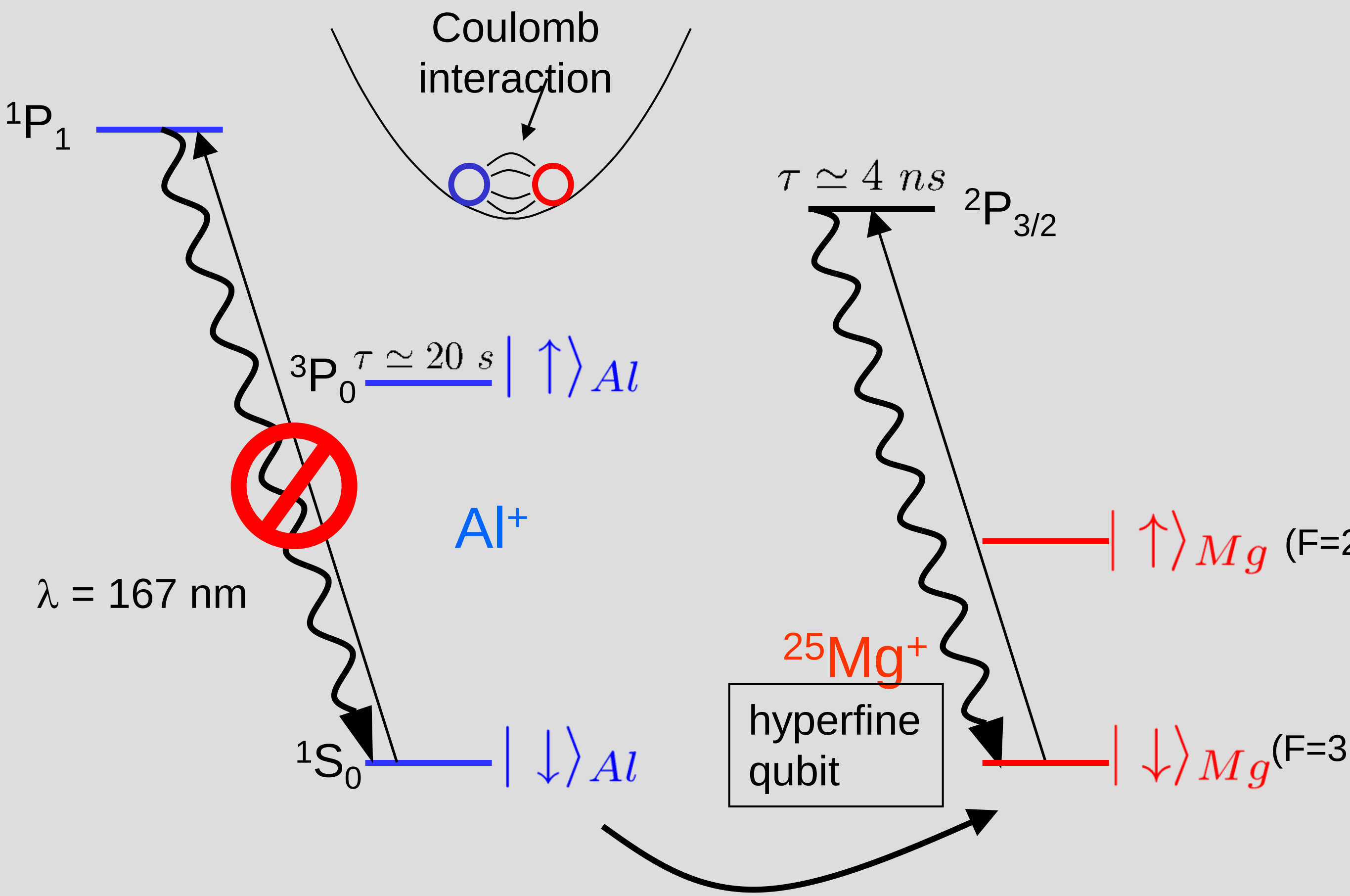


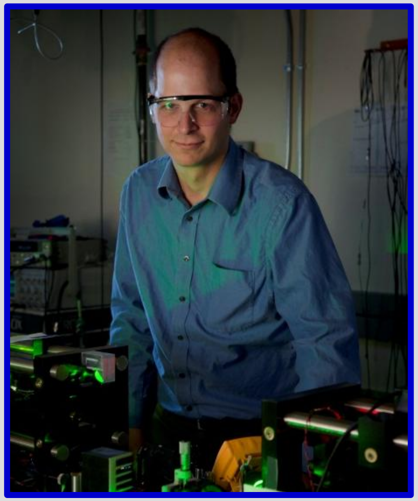
S. Hermelin et al., Nature **447**, 435 (2011)



Josephson-junction qubits coupled with strip-lines

Al^+ “quantum-logic clock” (T. Rosenband et al.)





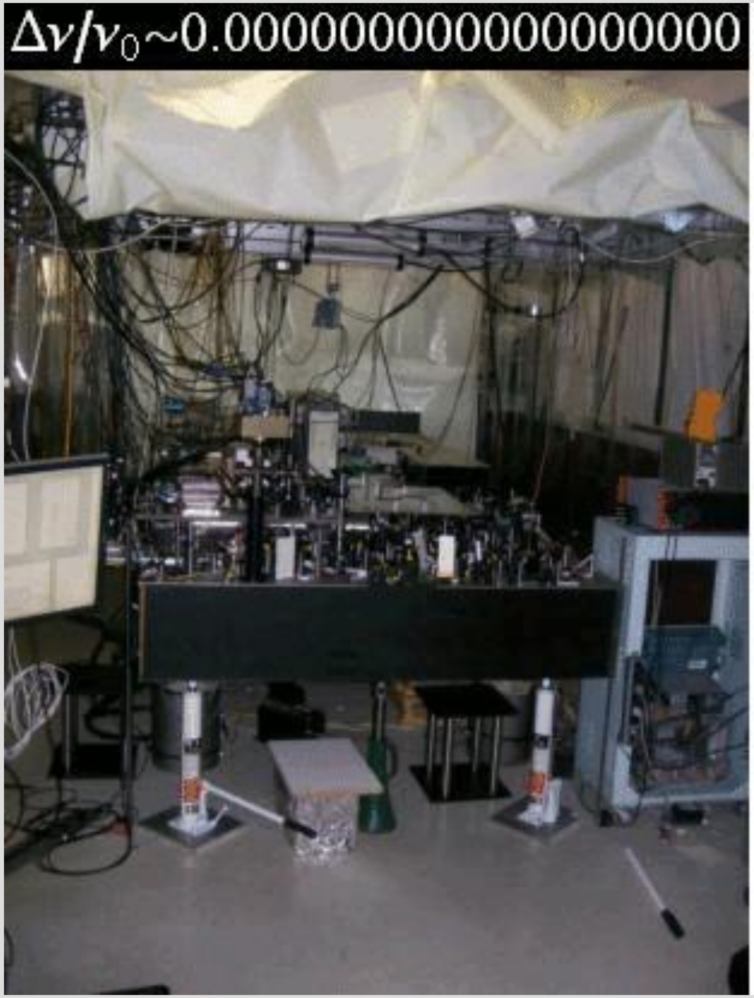
Till Rosenband

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

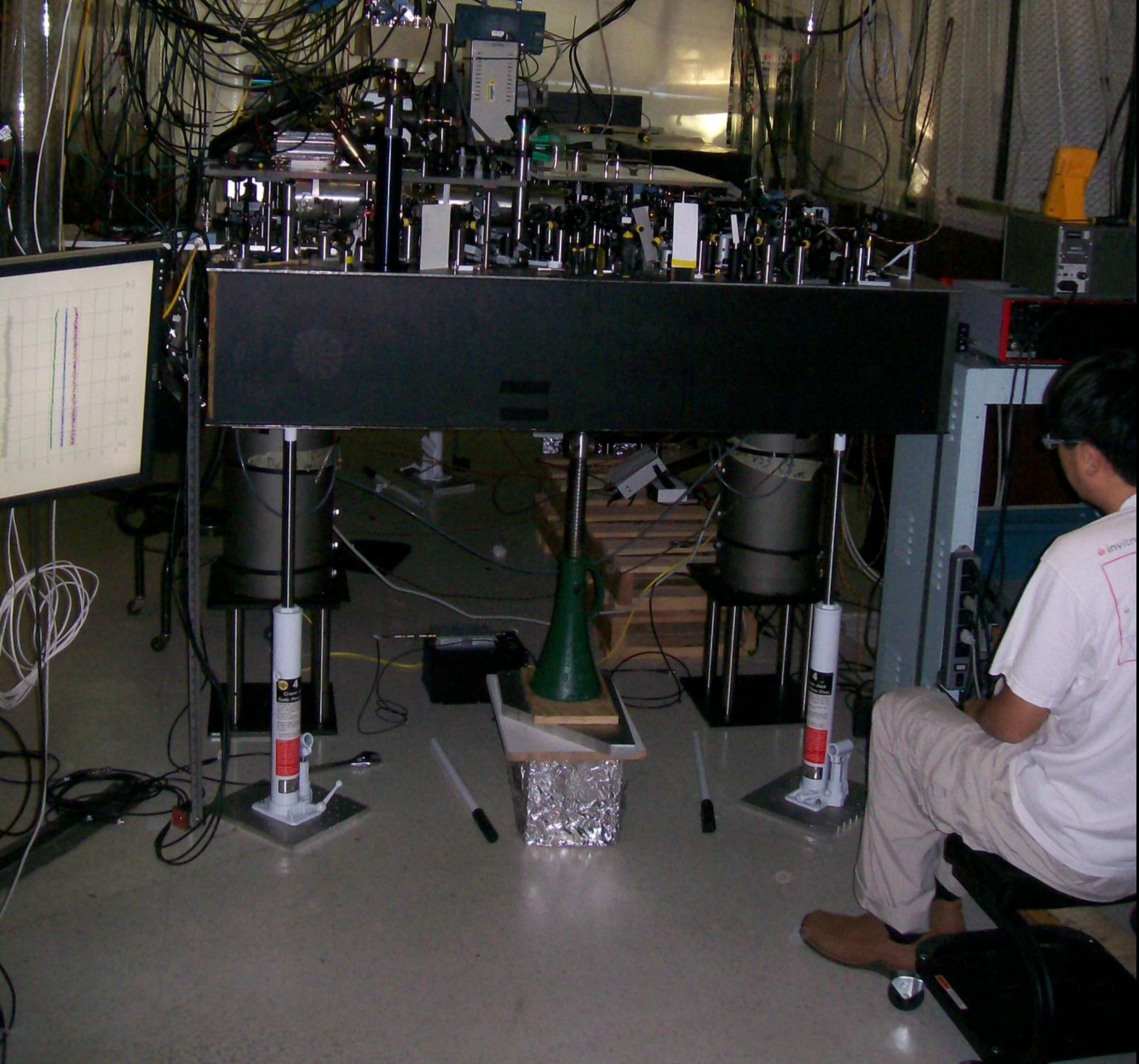
◊ laser-cooled Mg^+ keeps Al^+ cold
◊ Mg^+ helps to calibrate $\langle B^2 \rangle$ from all sources
◊ collisions observed by ions switching places
◊ ……

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

James Chou with "portable" Al^+ clock



measure
gravitational potential
red shift



Δh = 33 cm

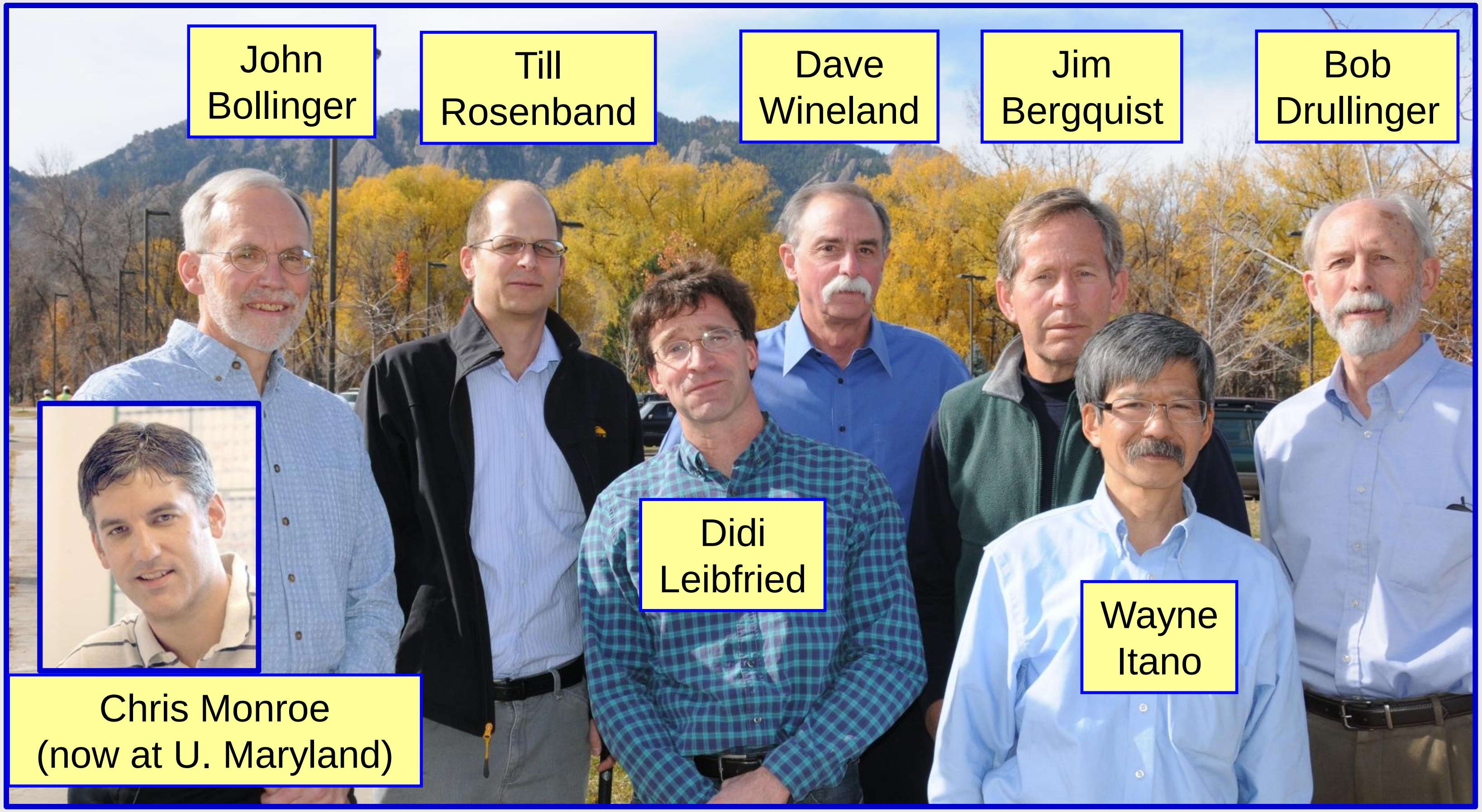
predict

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, Carl Williams, Katharine Gebbie…

Nobel award ceremony

Banquet

And good friends along the way!