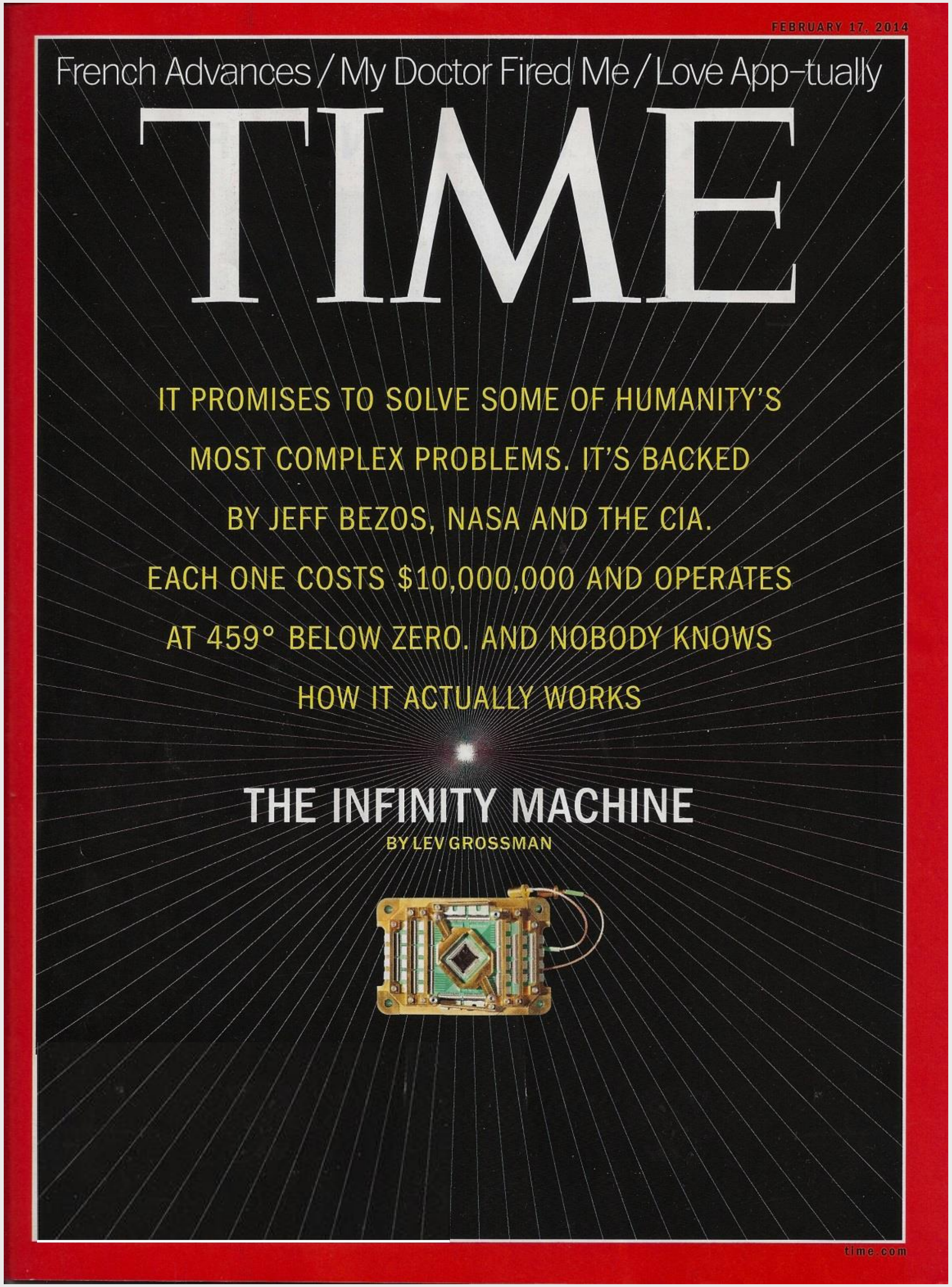
Superposition, entanglement and raising Schrödinger's cat

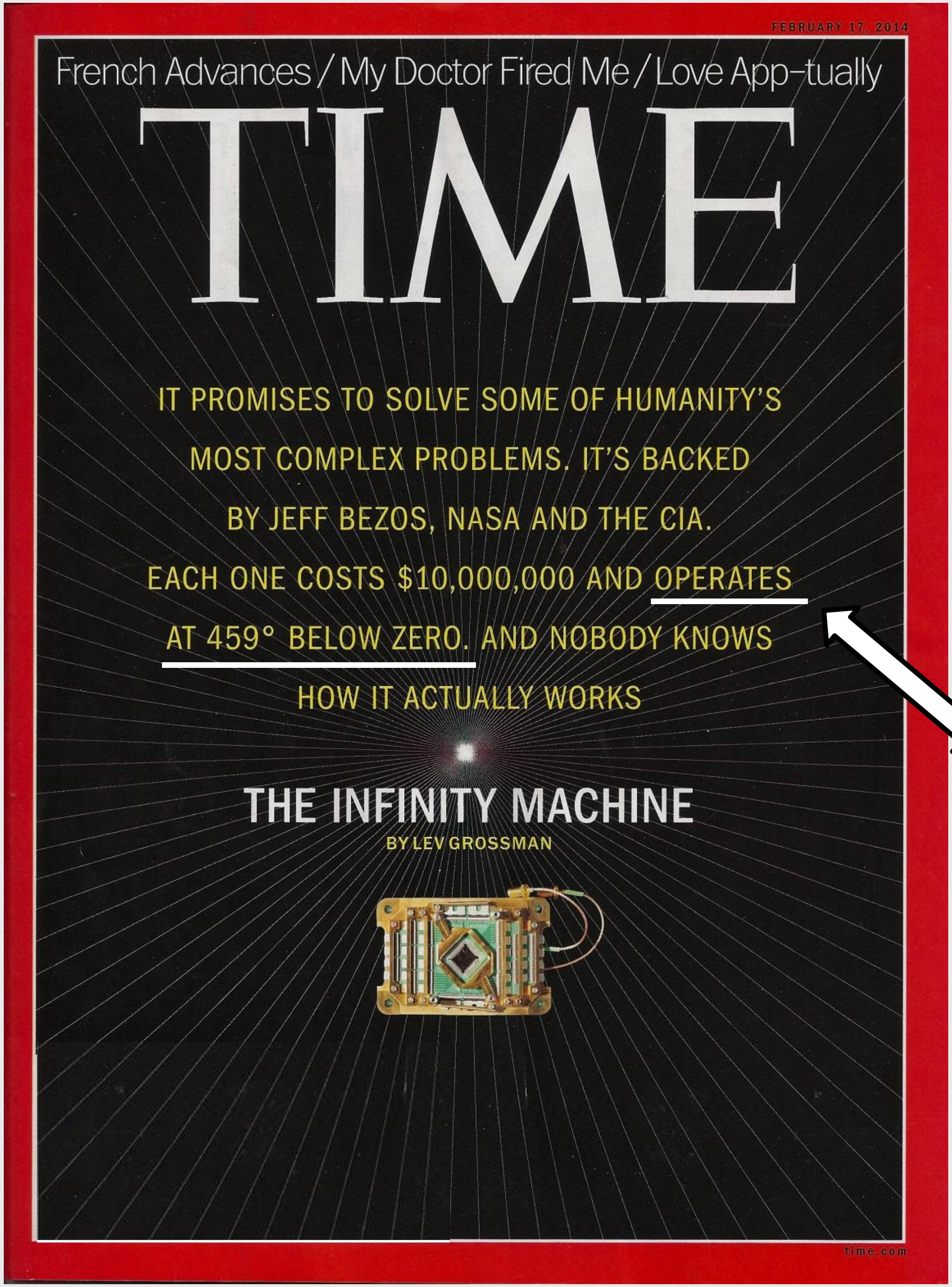
D. J. Wineland, NIST, Boulder, Colorado

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



Time magazine

(February 17, 2014)
Article about D-Wave
“quantum computer”

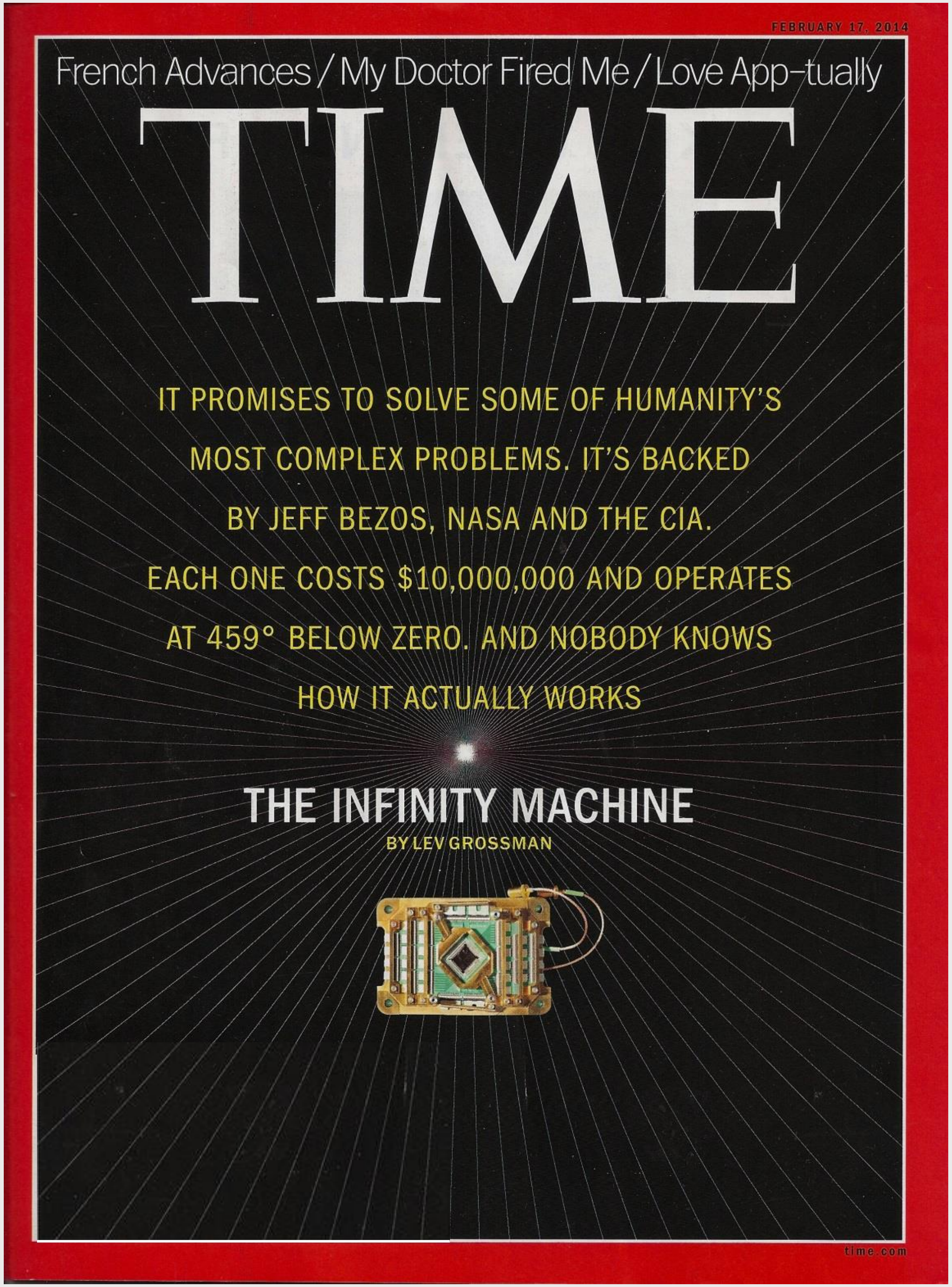


Time magazine

(February 17, 2014)
Article about D-Wave
“quantum computer”

Take note
neutral atom trappers!

“The coldest place in the universe [20 milliKelvins] is actually in a small city directly east of Vancouver…”



Time magazine

(February 17, 2014)
Article about D-Wave
"quantum computer"

<u>A quantum computer can</u>:

"HELP CARS DRIVE THEMSELVES Google is using a quantum computer to design software that can distinguish cars from landmarks"

"BOOST GDP Hyperpersonalized advertising, based on quantum computation, will simulate consumer spending"

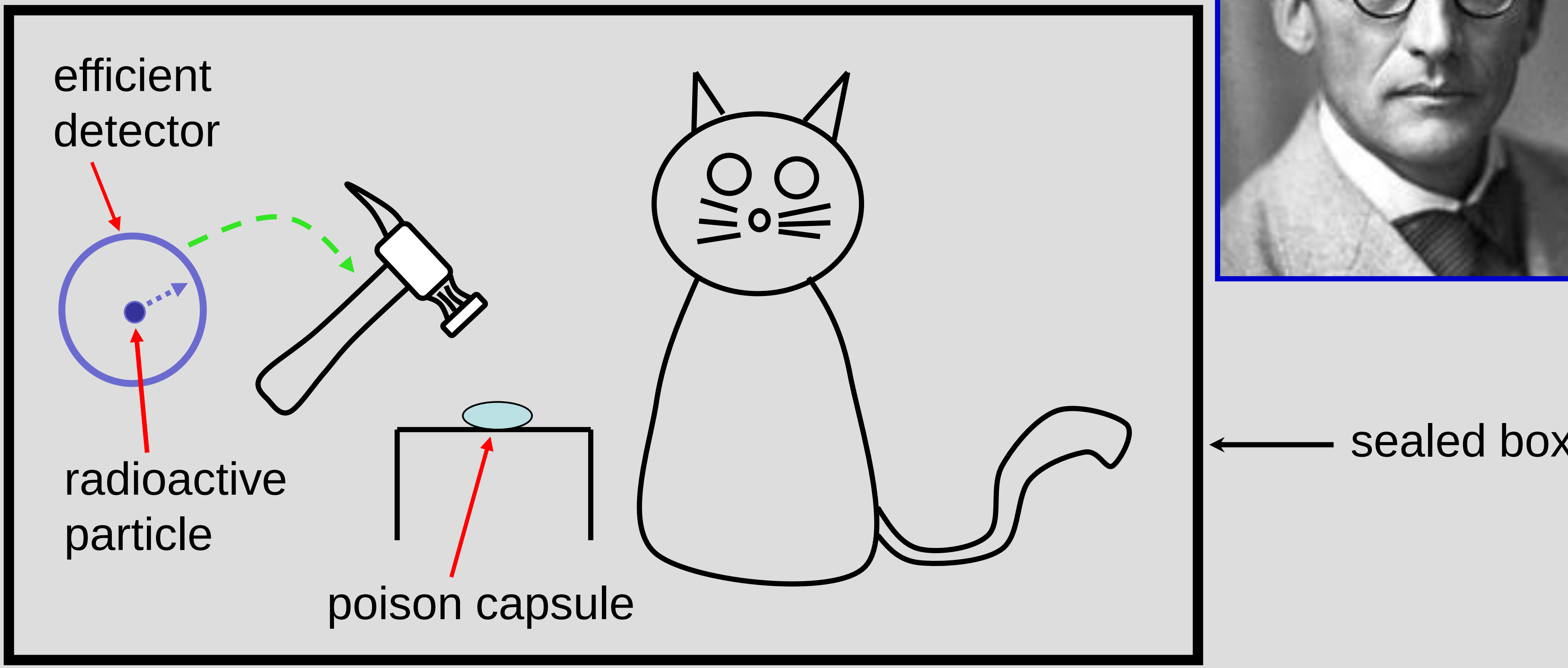
Wow!

Summary:

- ♦ Schrödinger’s cat
- ♦ one person’s path
- ♦ spectroscopy, clocks
- ♦ quantum information
  - ◊ elements of quantum computing
  - ◊ quantum simulation
- ♦ many people & many groups worldwide

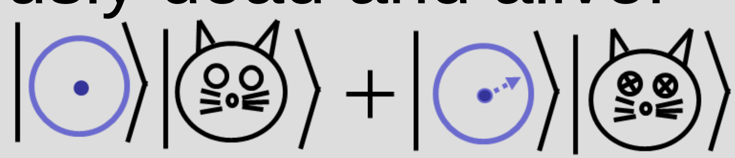
Erwin Schrödinger's Cat (1935)

(extrapolating quantum mechanics from microscopic to macroscopic world)



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

"superposition"

$\Psi =$ 

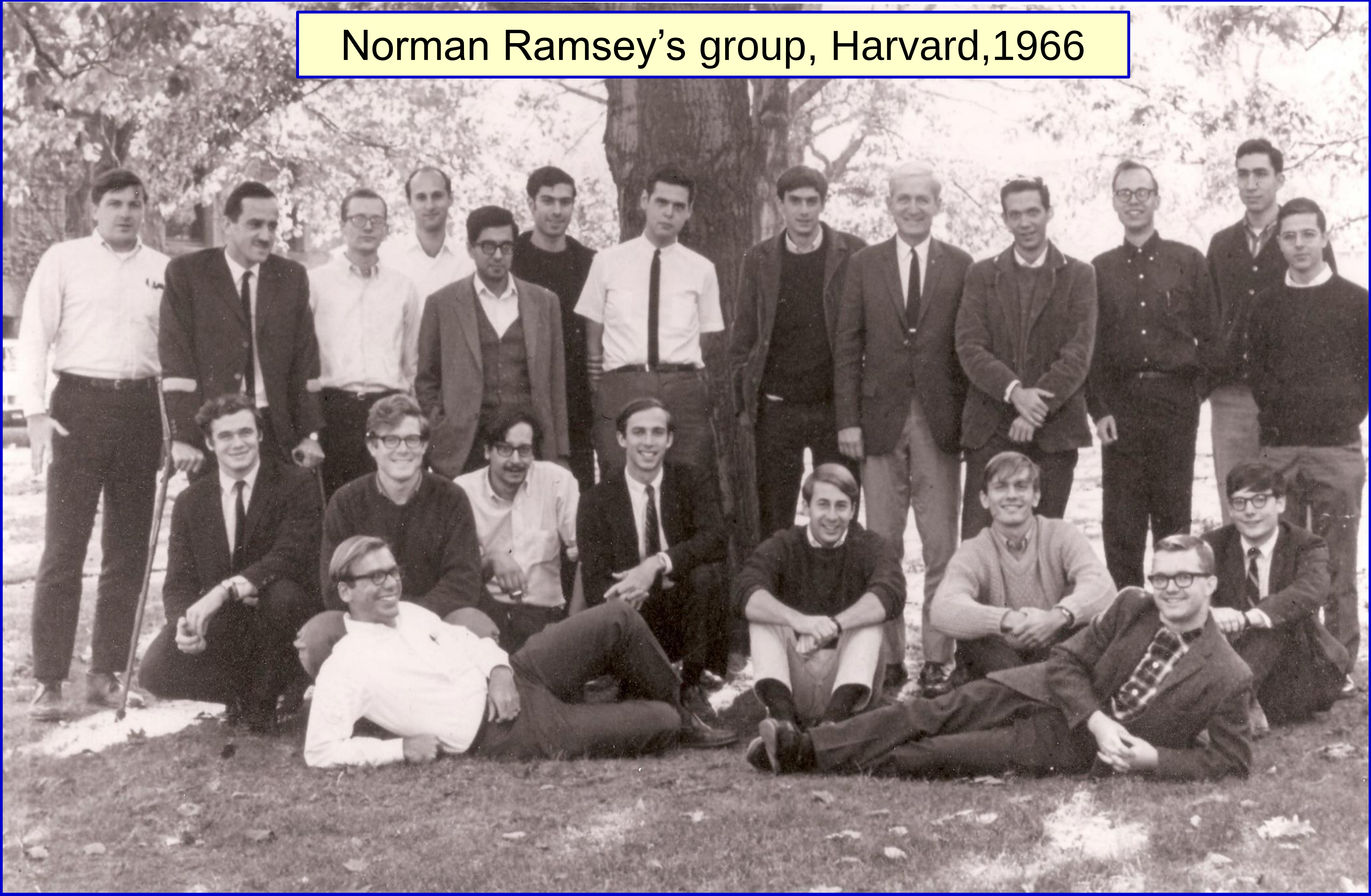
Schrödinger (1952):

"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 this is now our world!

* at least for at least for small systems; e.g., atoms
* precise control + isolation from environment
* macroscopic systems: why not?

Norman Ramsey's group, Harvard,1966



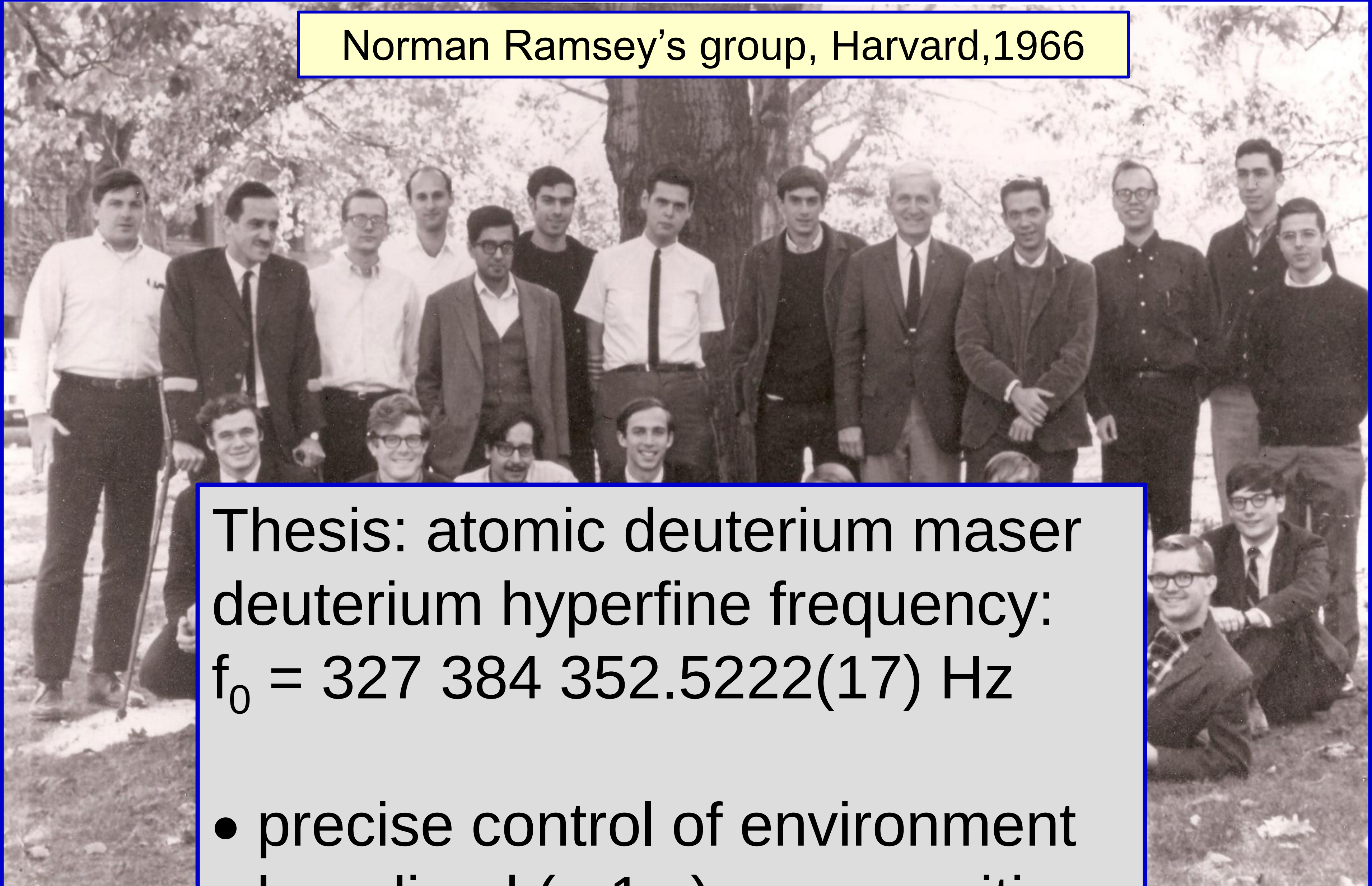
Doug Brenner Randy Wolfe

Ed Uzgiris Andrzej Chachulski Tom English Ashok Khosla Tom Follett Dave Wineland Norman Pat Gibbons Paul Zitzewitz Bill Edelstein Roger Hegstrom

Keith MacAdam Peter Moulton Bob Hilborn Peter Valberg Charles Minter

Frank Winkler Fraser Code

Norman Ramsey's group, Harvard,1966



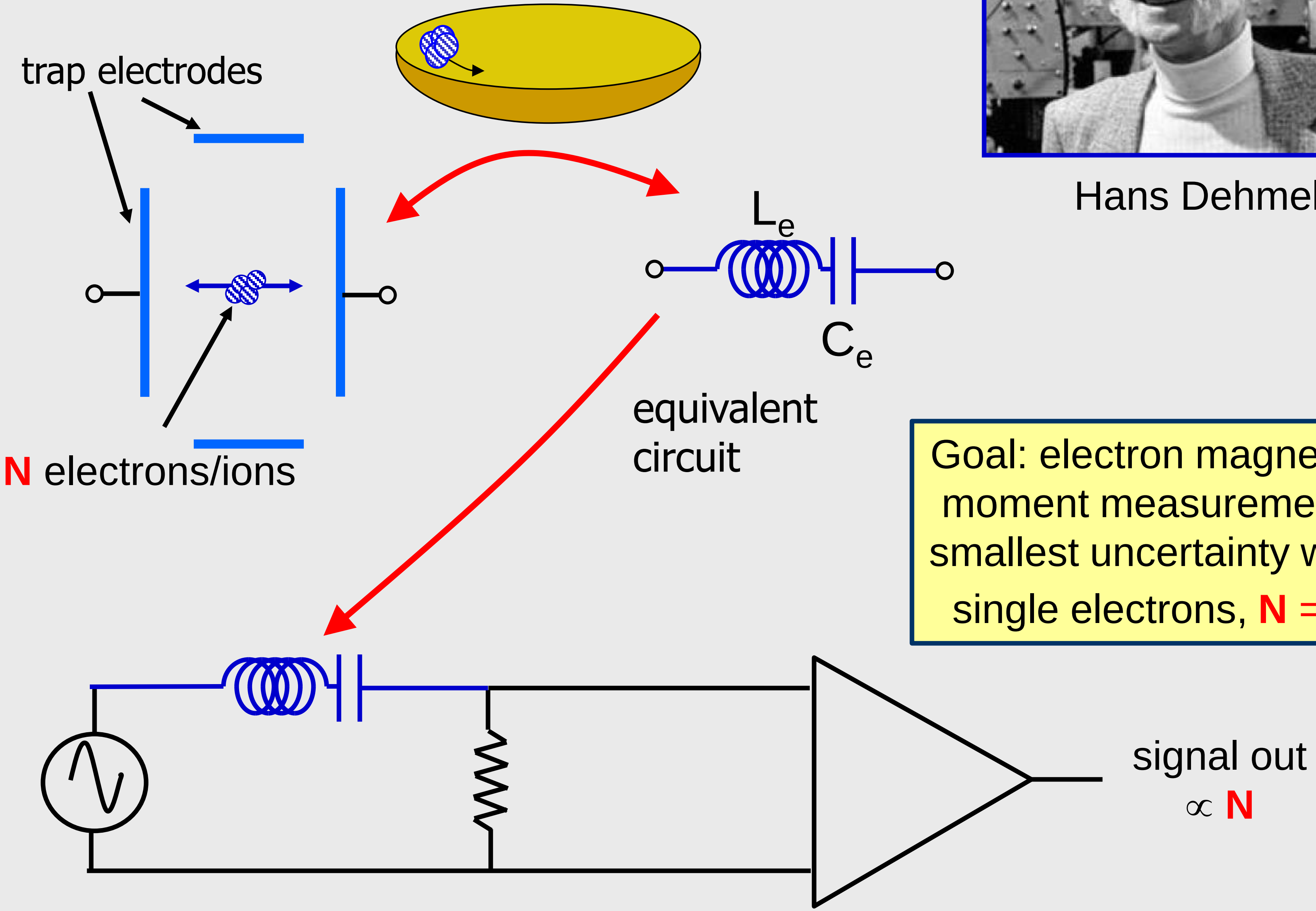
Thesis: atomic deuterium maser
deuterium hyperfine frequency:
$f_0 = 327\ 384\ 352.5222(17)$ Hz

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

Ed Uzgiris Andrzej Cha … delstein Roger Hegstrom
Charles Minter

On to Hans Dehmelt's lab (Univ. Washington) - trapped electrons/ions

Hans Dehmelt

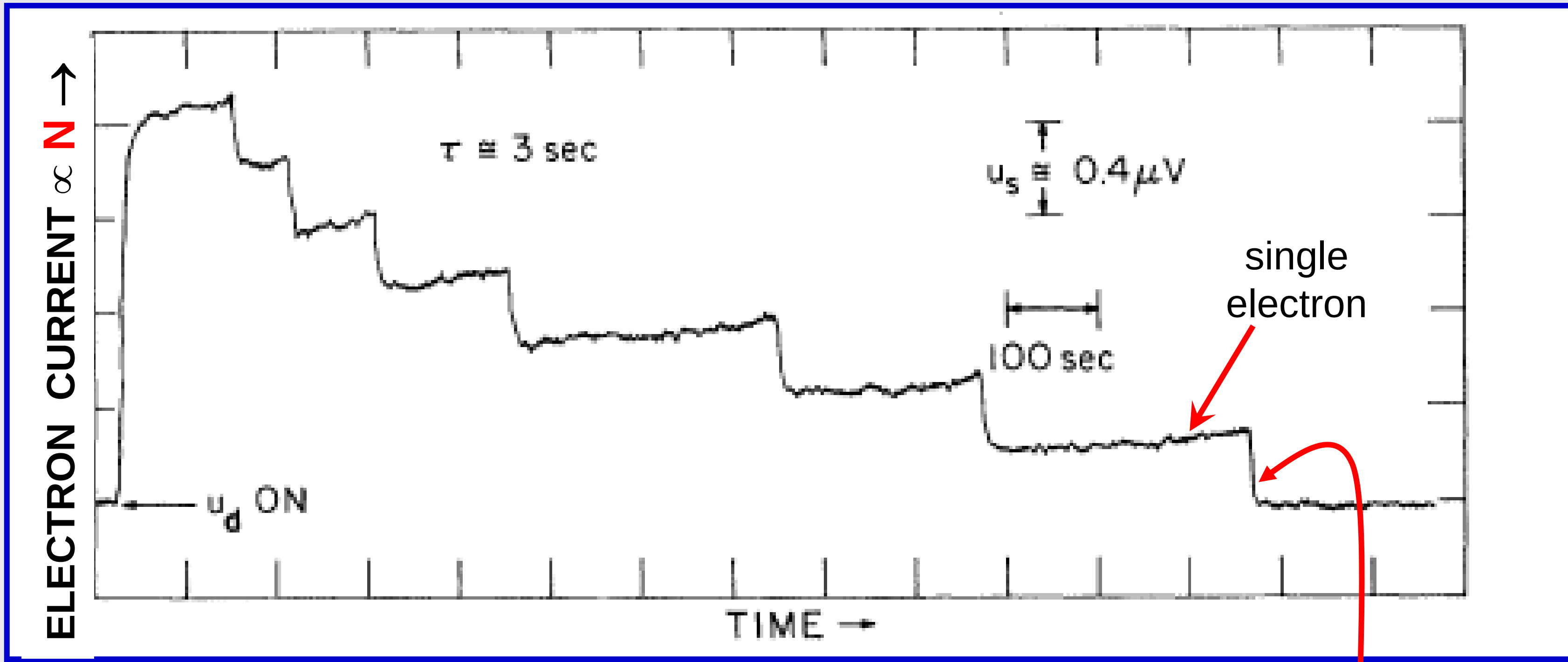


Goal: electron magnetic moment measurement: smallest uncertainty with single electrons, **N** = 1

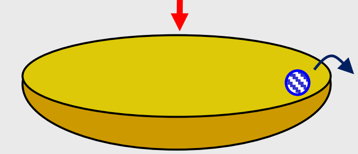
Single electrons

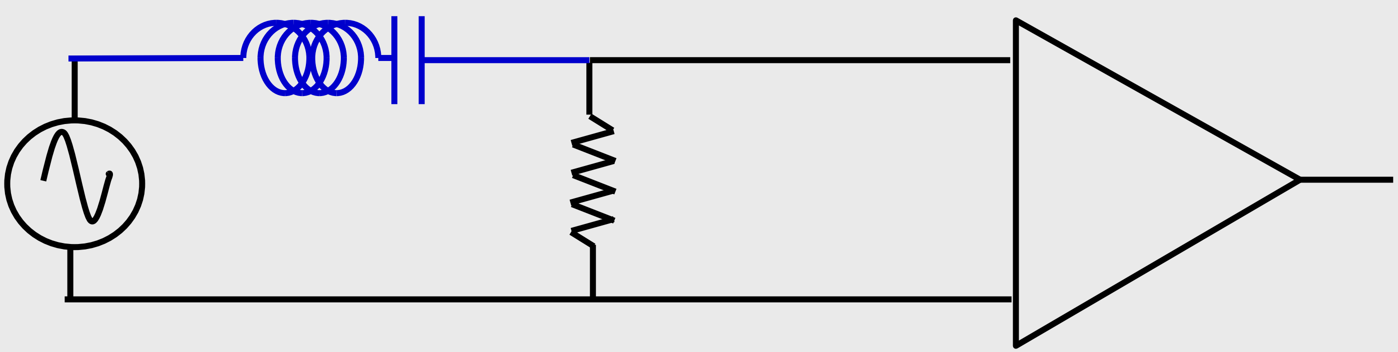
precursor to measurement of $\mu_{electron}$

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).





Single electrons

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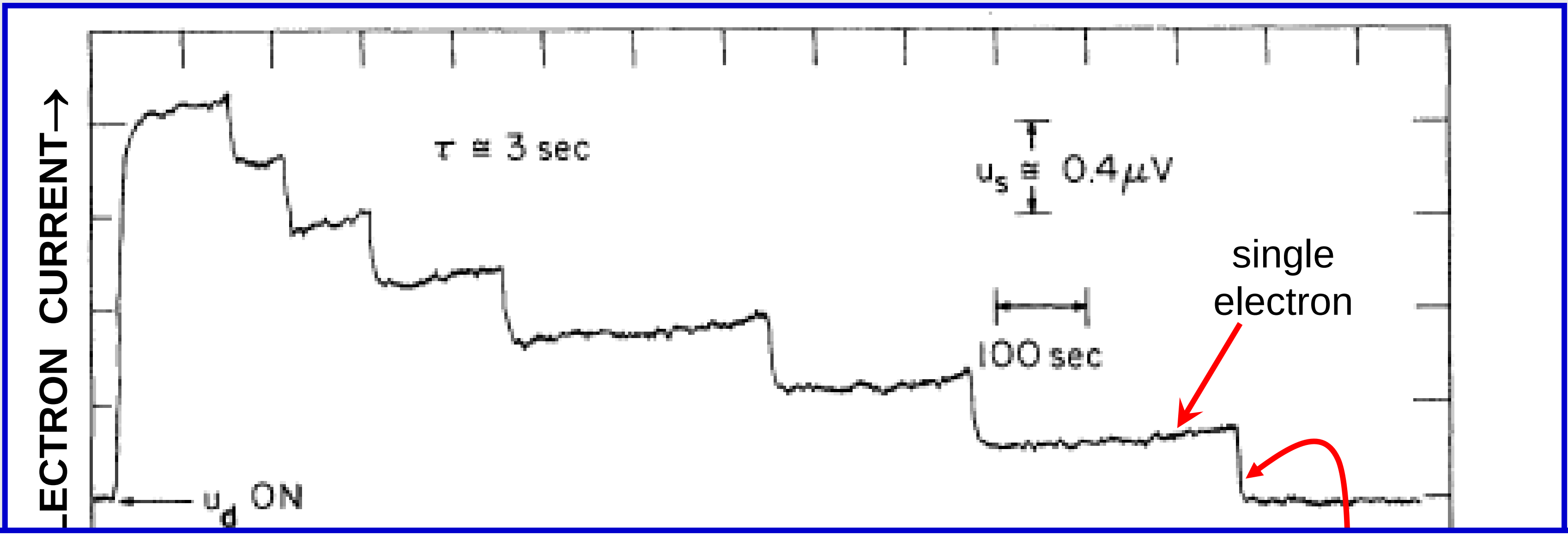
R. S. Van Dyck, P. Schwinberg, H. Dehmelt, Phys. Rev. Lett. **38**, 310 (1977)



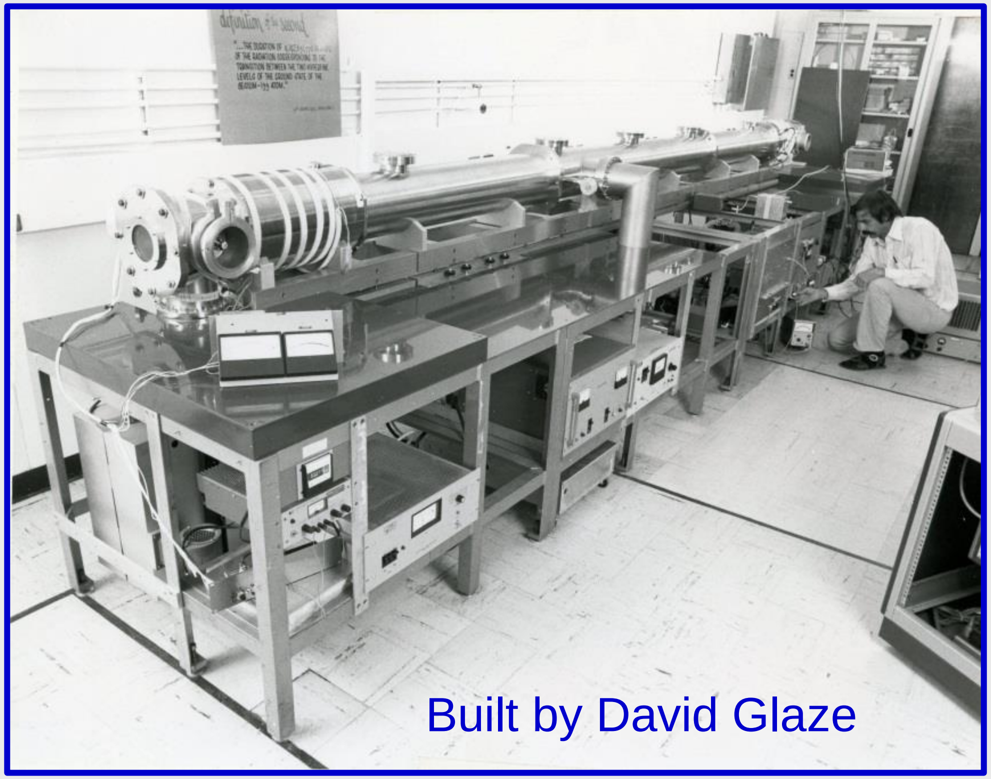
and, some ideas about laser cooling

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

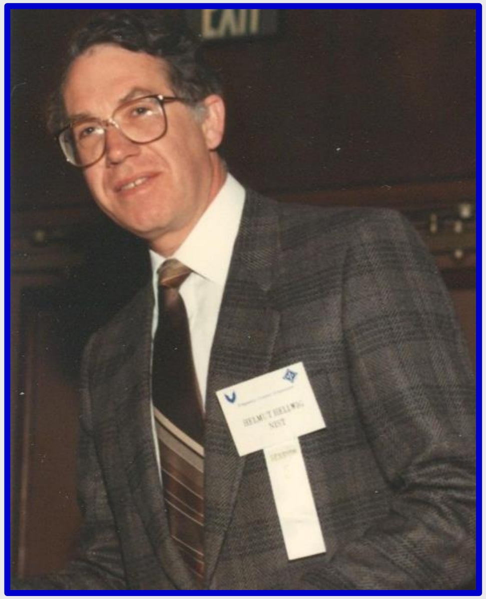
T. W. Hänsch and A. L. Schawlow, Opt. Comm. **13**, 68 (1975)

laser cooling suppresses time-dilation shifts in spectroscopy & atomic clocks

On to NIST, 1975 (National Institute of Standards and Technology)
(then NBS, National Bureau of Standards)



Cs beam frequency standard
"NBS-6"



Group leader:
Helmut Hellwig
(pursuaded NBS
to support research
on laser cooling)

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.

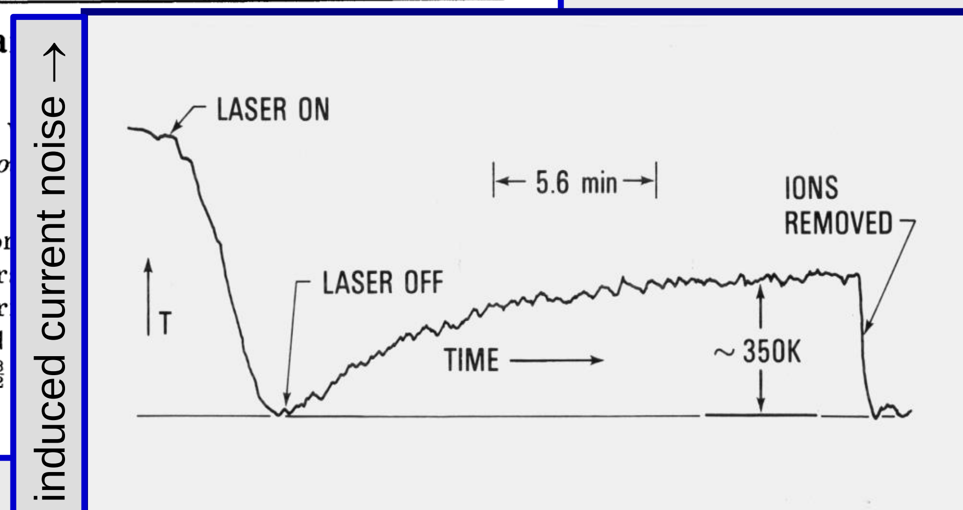
Peter Toschek

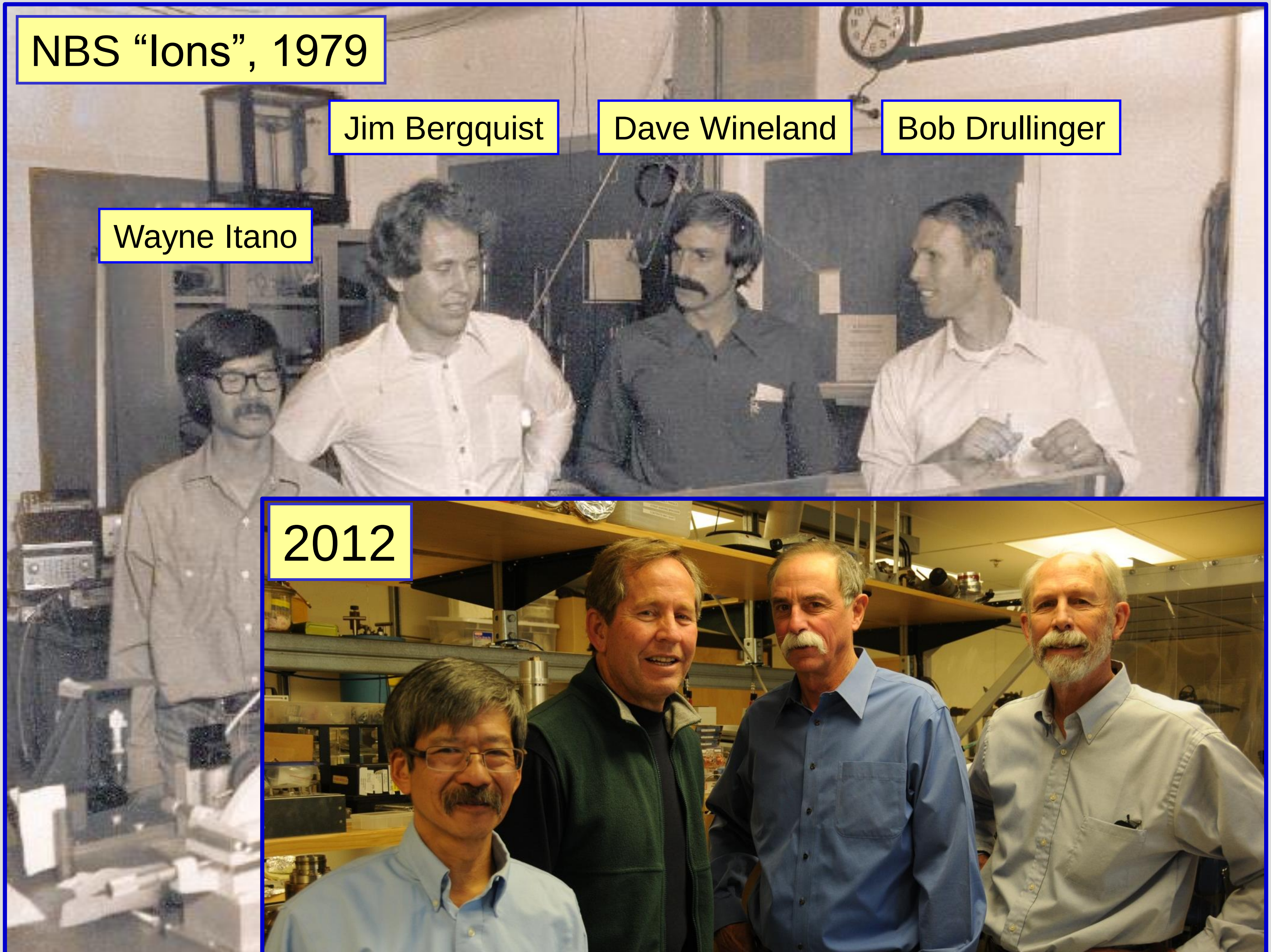
), NUMBER 25 PHYSICAL REVIEW LETTERS 19 JUNE 1978

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.

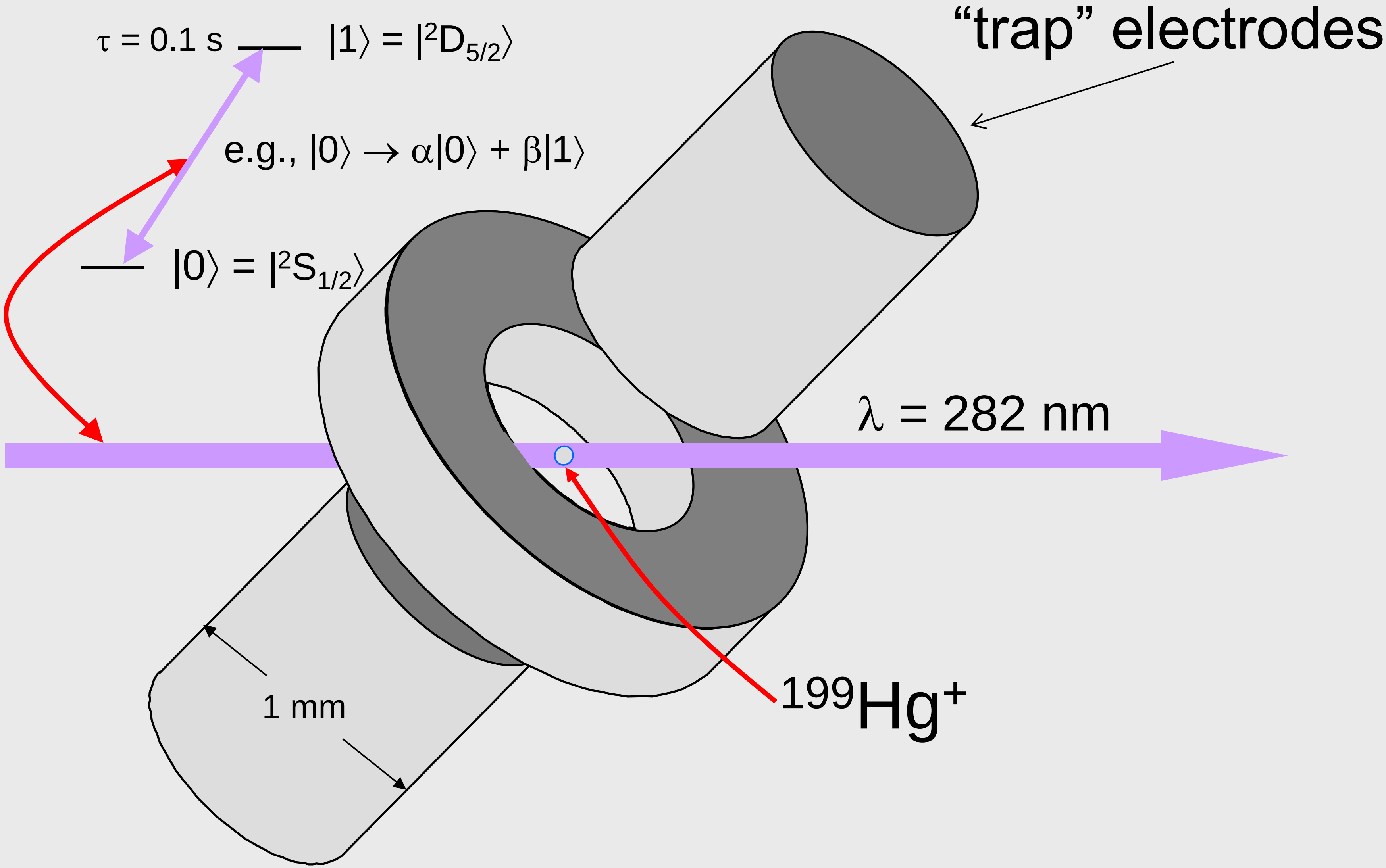



NBS “Ions”, 1979
Jim Bergquist
Dave Wineland
Bob Drullinger
Wayne Itano
2012

Mercury ion (Hg^+) experiments at NIST, 1981 →

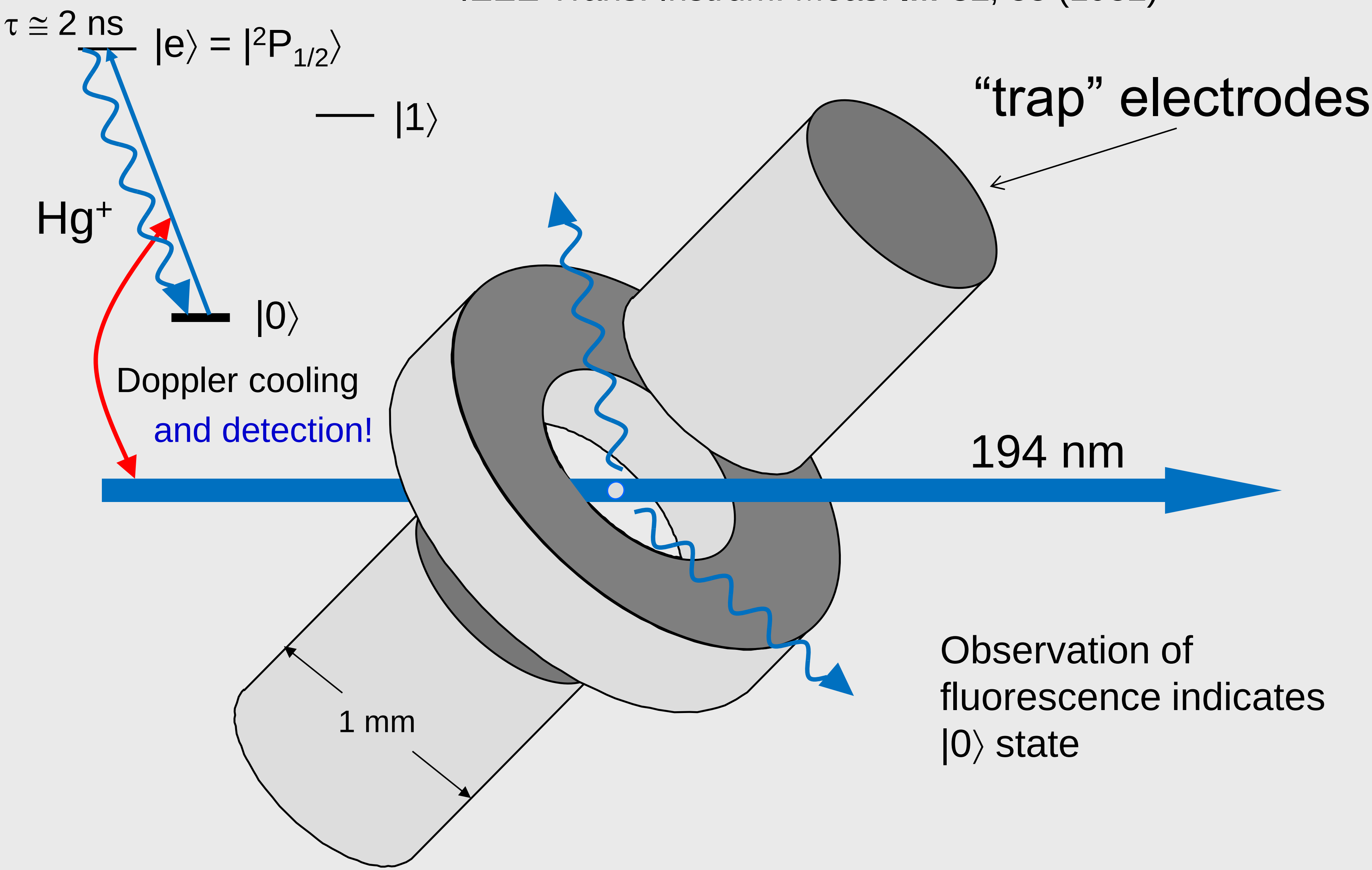
40 GHz hyperfine transition

+ 282 nm narrow optical transition



“Electron shelving amplifier” detection (Hans Dehmelt)

- Bulletin APS **20**, 60 (1975)
- IEEE Trans. Instrum. Meas. **IM-31**, 83 (1982)



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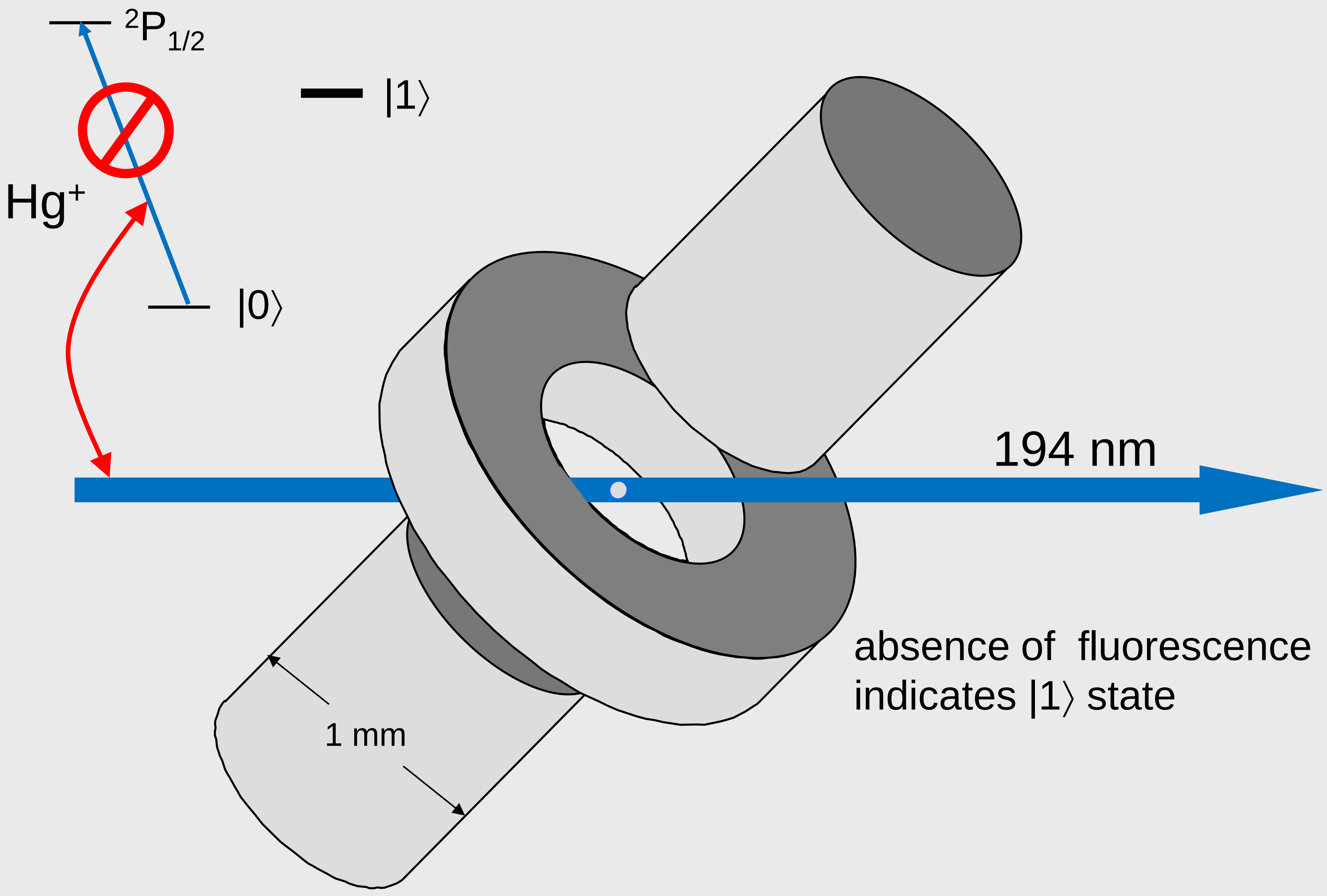
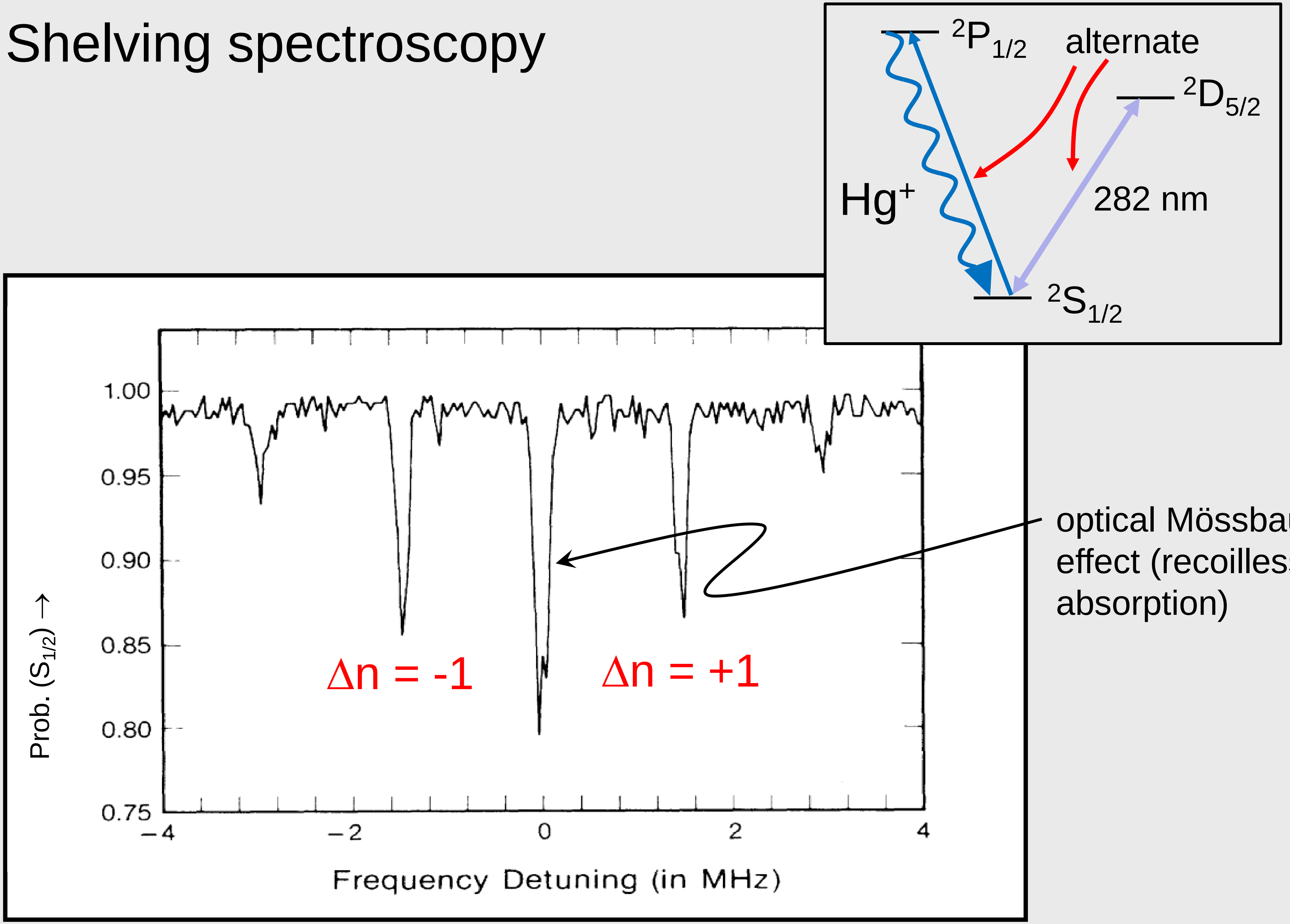


Shelving spectroscopy

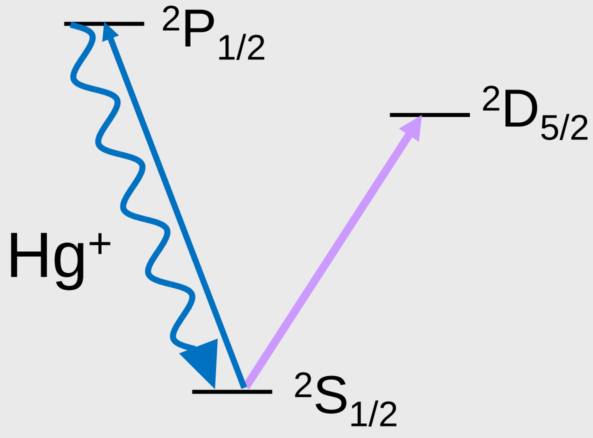


optical Mössbauer effect (recoilless absorption)

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

Single $^{199}Hg^{+}$ ions for (optical) clocks:

J. C. Bergquist et al., (NIST)1981 →



Jim Bergquist

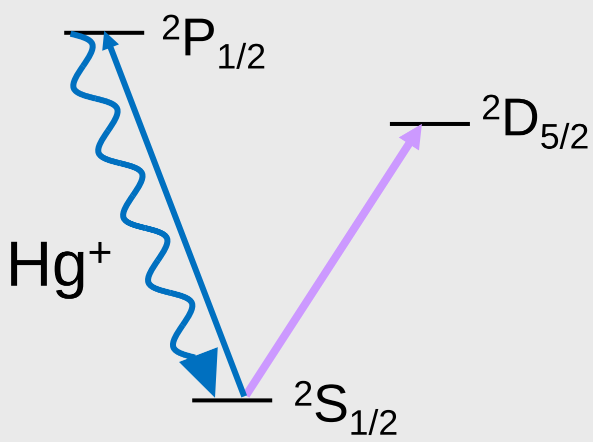
- trapping ⇒ first-order Doppler shift → 0
- laser cooling ⇒ time dilation small
- trapping in high vacuum at 4 K
  ⇒ small environmental perturbations (collisions, black body shifts, etc.)

⇒ first clock with systematic uncertainly ($7x10^{-17}$) below Cesium

- W. H. Oskay et al., Phys. Rev. Lett. **97**, 020801 (2006)

Single $^{199}Hg^{+}$ ions for (optical) clocks:

J. C. Bergquist et al., (NIST)1981 →



Jim Bergquist

Plus several other ion species: $^{229}Th^{3+}$

$^{88}Sr^{+}$, $^{171}Yb^{+}$, $^{27}Al^{+}$, $^{40}Ca^{+}$, $^{115}In^{+}$ (PTB, UCLA Kuzmich group)

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

Atomic ion quantum computation:

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

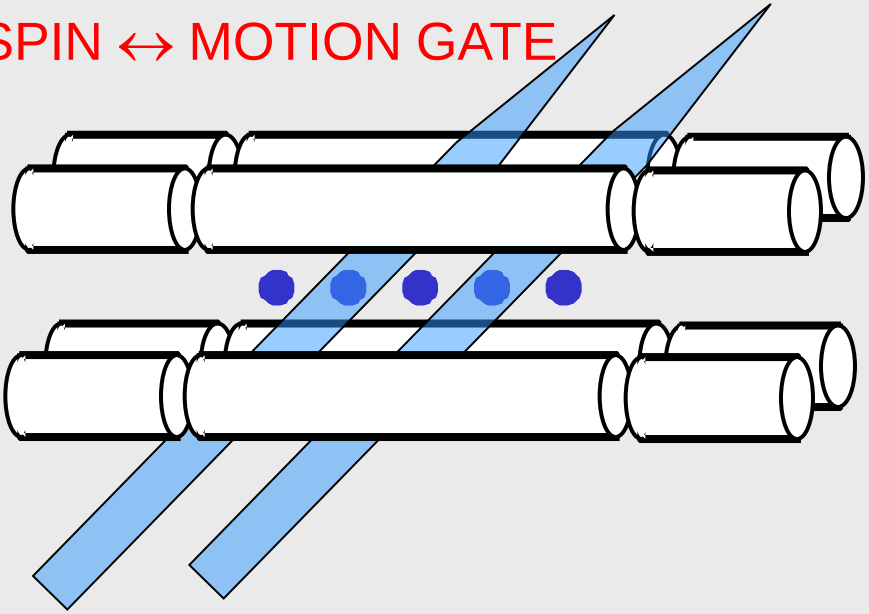
Ignacio Cirac

Peter Zoller

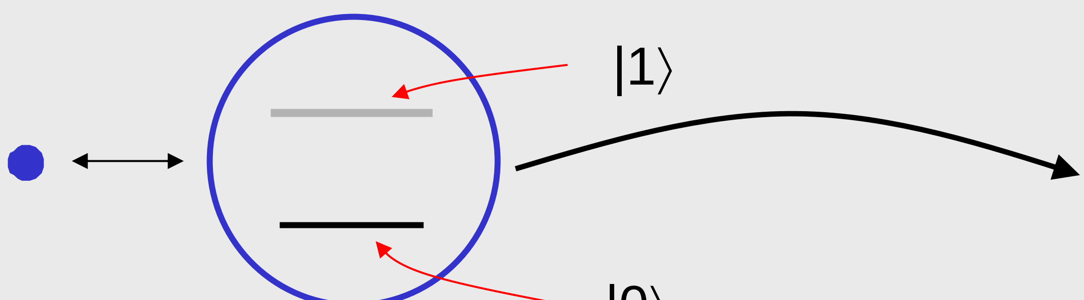
1. START MOTION IN GROUND STATE

2. SPIN → MOTION MAP

3. SPIN ↔ MOTION GATE

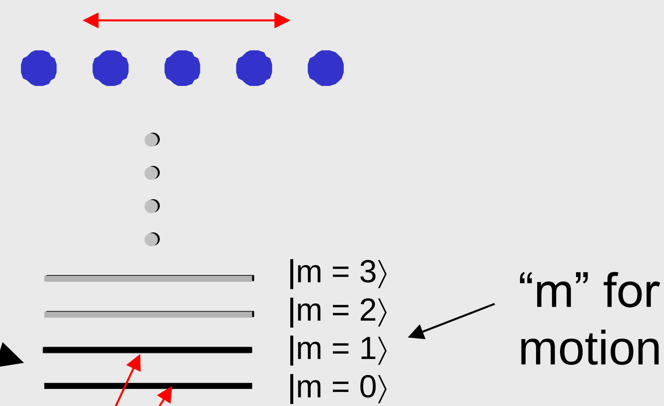


INTERNAL STATE “**SPIN**” QUBIT



MOTION “DATA BUS”

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



Motion qubit states

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

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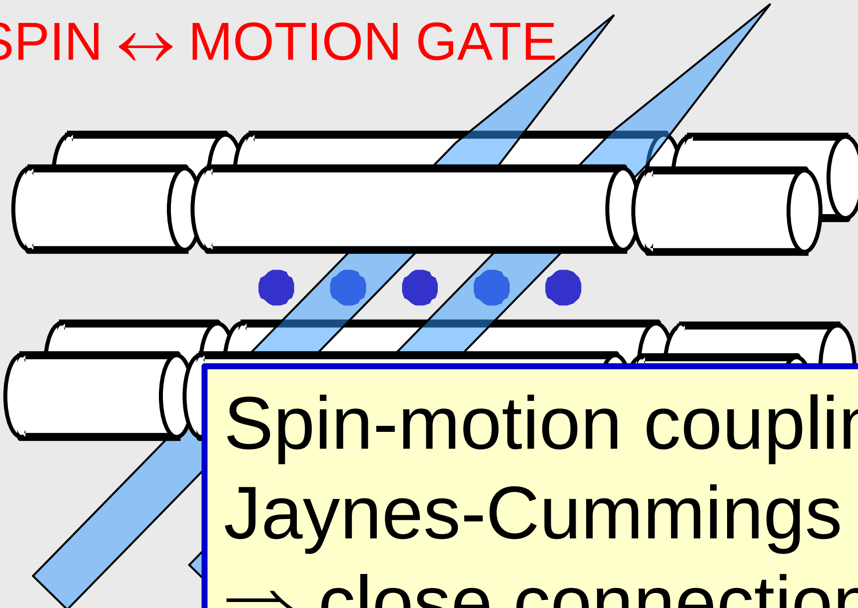
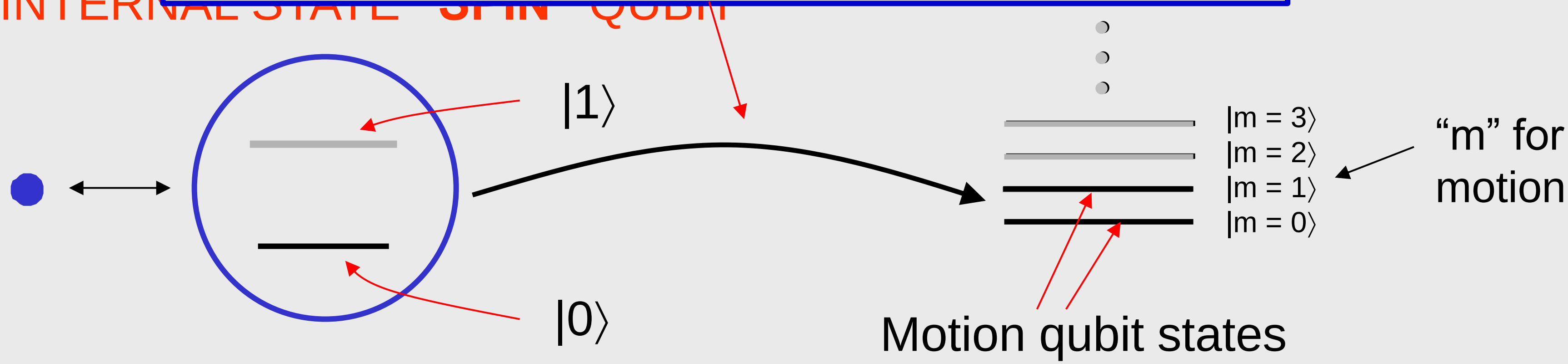


US”

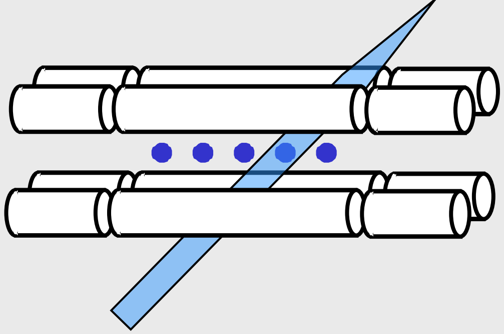
ass mode)

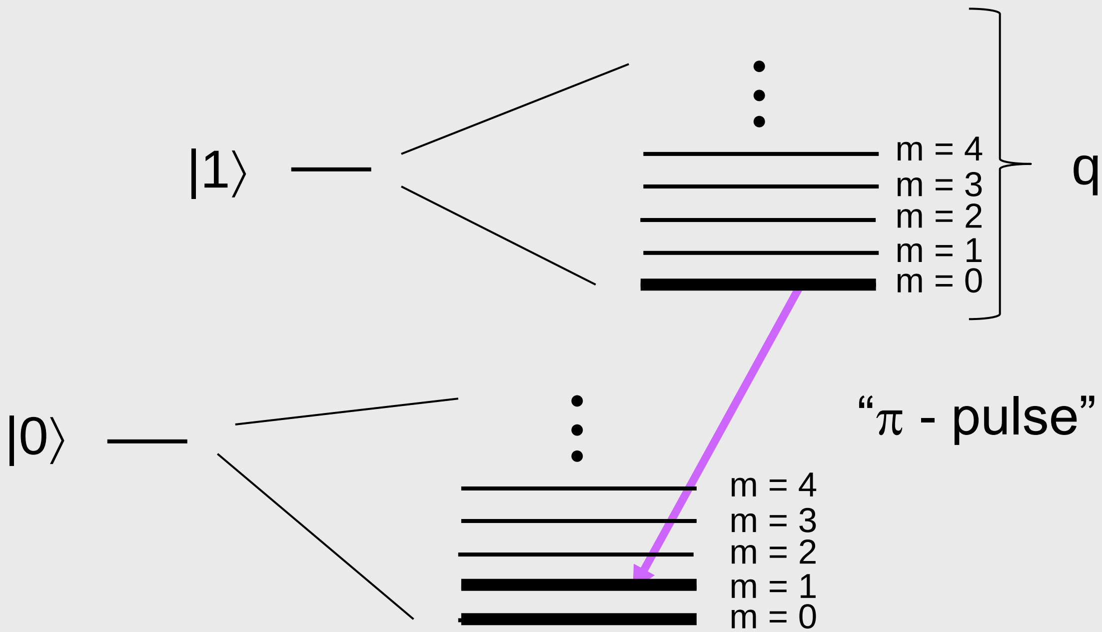
Spin-motion coupling through Jaynes-Cummings type Interaction ⇒ close connections to Cavity-QED

INTERNAL STATE “SPIN” QUBIT



SPIN → MOTION MAP



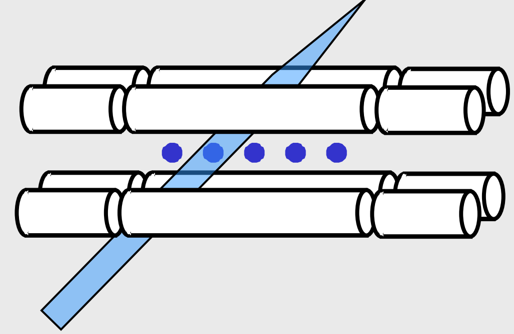


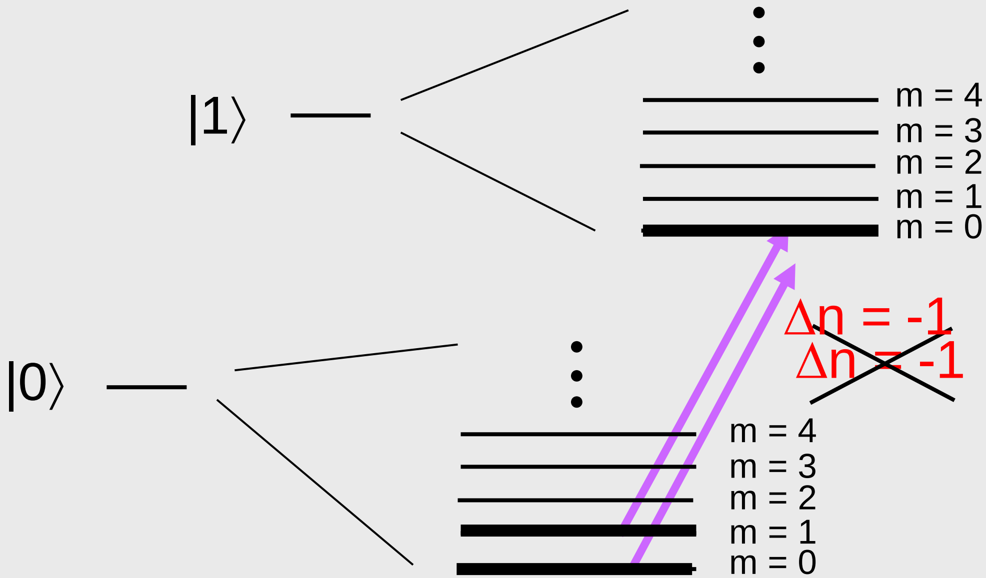
$$(\alpha|0\rangle + \beta|1\rangle)\,|m=0\rangle \;\rightarrow\; |0\rangle\,(\alpha|m=0\rangle + \beta|m=1\rangle)$$

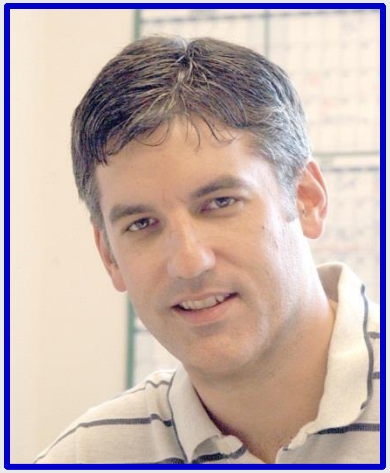
initial state

transfer information onto motion

SPIN ↔ MOTION GATE







Chris Monroe

Conditional dynamics for quantum logic

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

"Controlled-NOT" gate between motion and atom's internal state

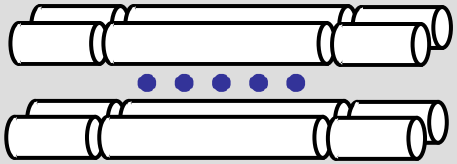
C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. 75, 4714 (1995).

Atomic ion experimental groups pursuing Quantum Information Processing:

Aarhus
Amherst
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
Sussex
Sydney
U. Washington
Weizmann Institute

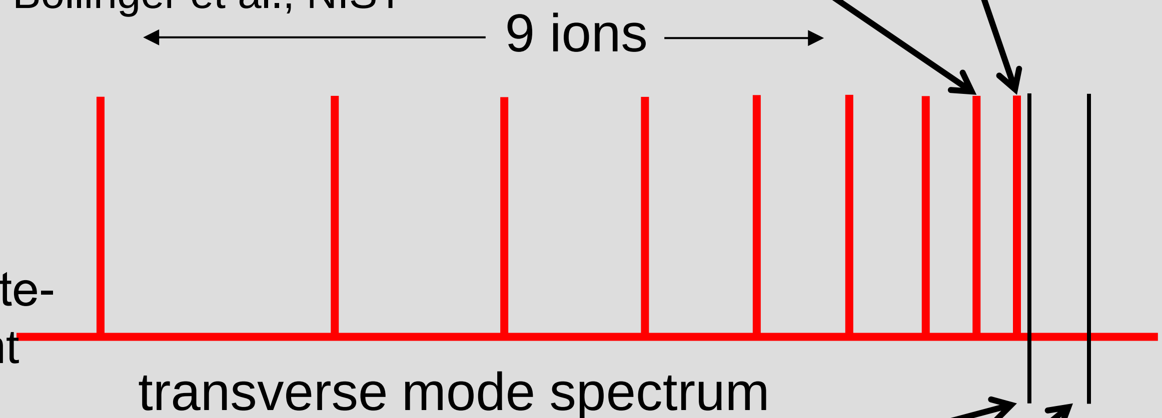
Simulation:

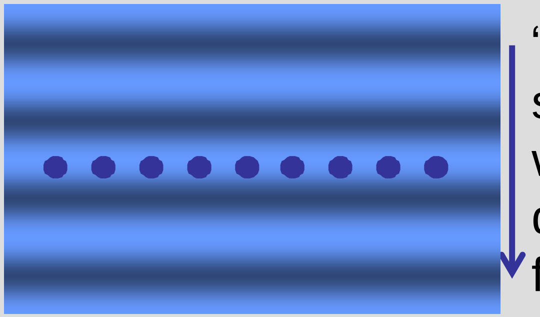


Exps: Shätz group, Freiburg
Monroe group, U. Maryland
Blatt group, Innsbruck
Bollinger et al., NIST

Center-of-mass)mode

tilt mode





“moving standing wave” state-dependent forces

add magnetic field:

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

Transverse Ising model

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

$$H = J\sum_{i<j}\hat{\sigma}_z^i\hat{\sigma}_z^j \quad \Rightarrow \text{GHZ states}$$

for larger detunings ($\omega_{force} > \omega_{COM}$)

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

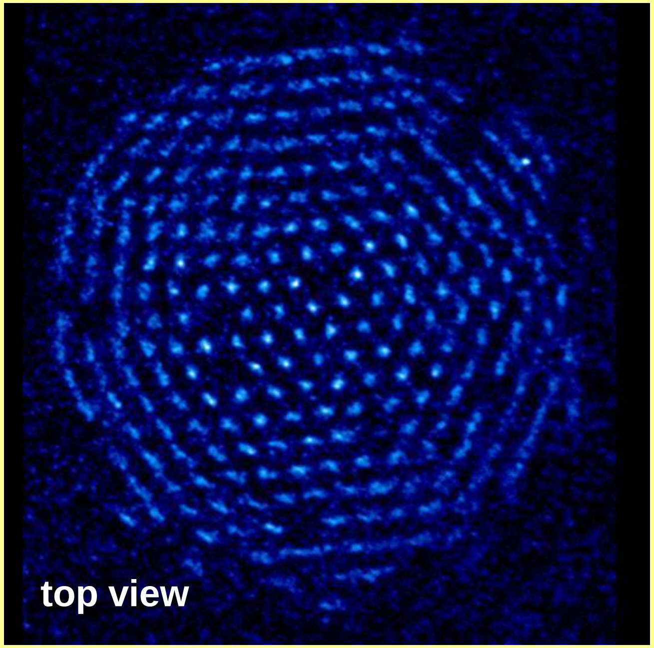
($J_{i,j} > 0$, anti-ferromagnetic)

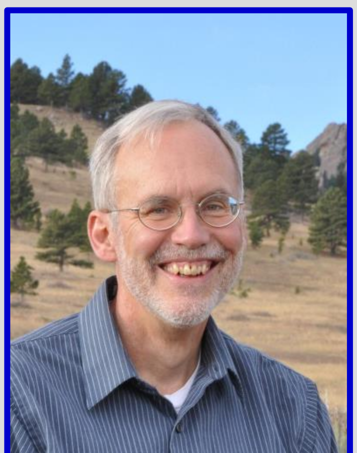
$$J_{i,j} \sim \frac{+J_0}{|i-j|^\alpha}$$

vary α by varying detuning

Porras and Cirac, PRL **92**, 207901 (2004)
Porras and Cirac, PRL **96**, 250501 (2006)
Deng, Porras, Cirac, PRA **7782**, 063407 (2005)
Taylor and Calarco, PRA , 062331 (2008)
Johanning et al., J. Phys. B **42**, 154009 (2009)
Schneider, Porras, Schätz, Rep. Prog. Phys. **75**, 024401(2012)

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

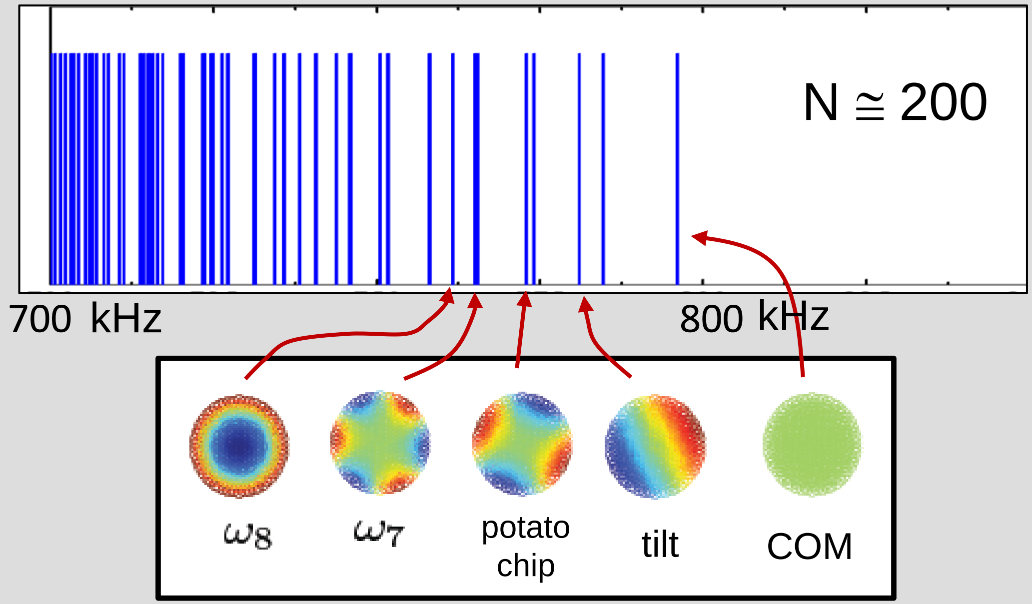




John Bollinger

- N > 100 spins
- "self assembled" triangular lattice

transverse mode spectrum (modes out of plane)



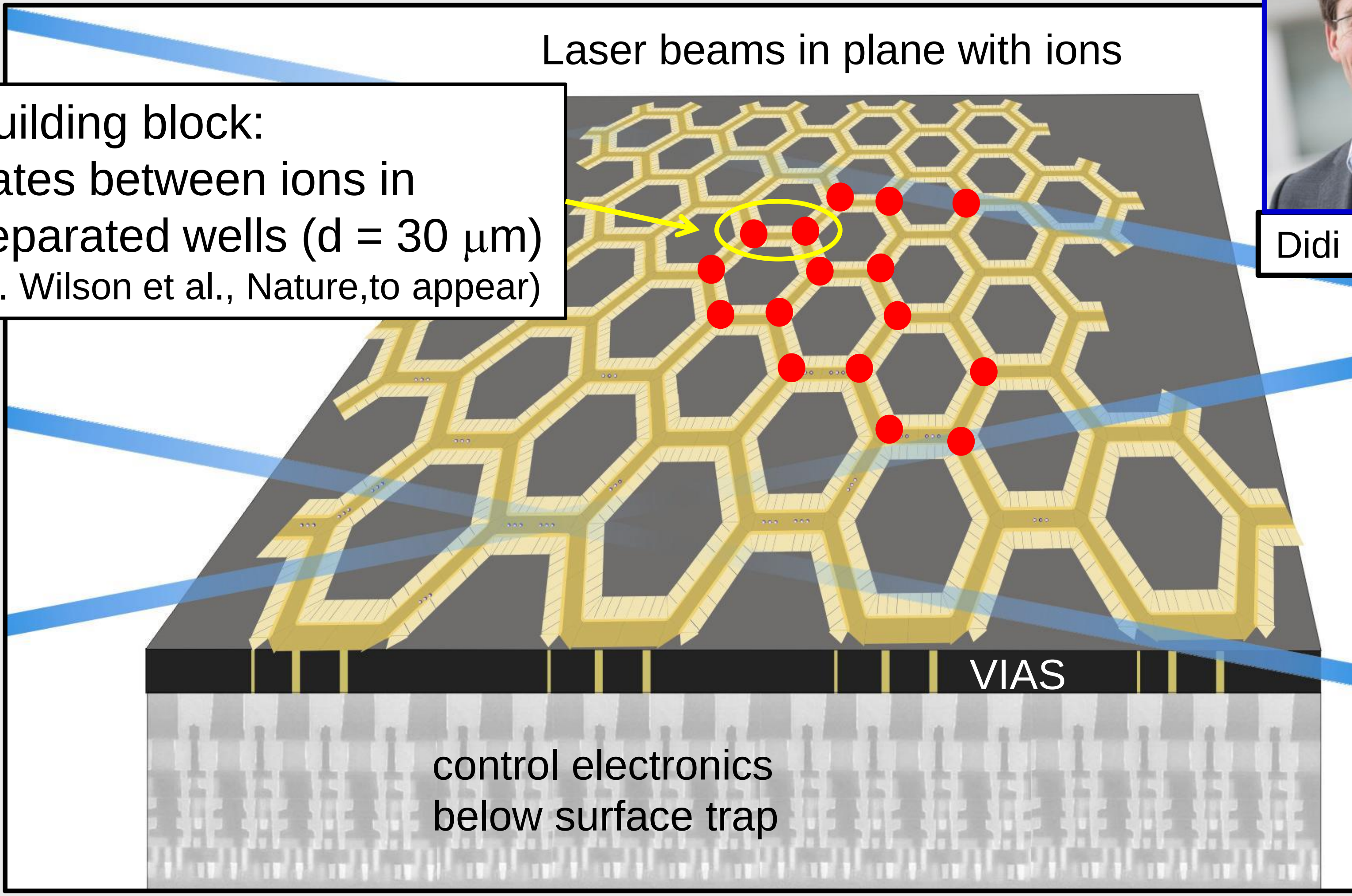
$$J_{i,j} \sim \frac{+J_0}{|i-j|^{\alpha}}$$

- Observe Ising coupling
- α = 0.01 – 2.72 (vary δ)
  J_0 ~ 1 kHz (α = 1)

J. Britton et. al., Nature **484**, 489 (2012)
B. Sawyer et al., Phys. Rev. Lett. **108**, 213003 (2012)

Engineered geometry for simulations

D. Leibfried et al.

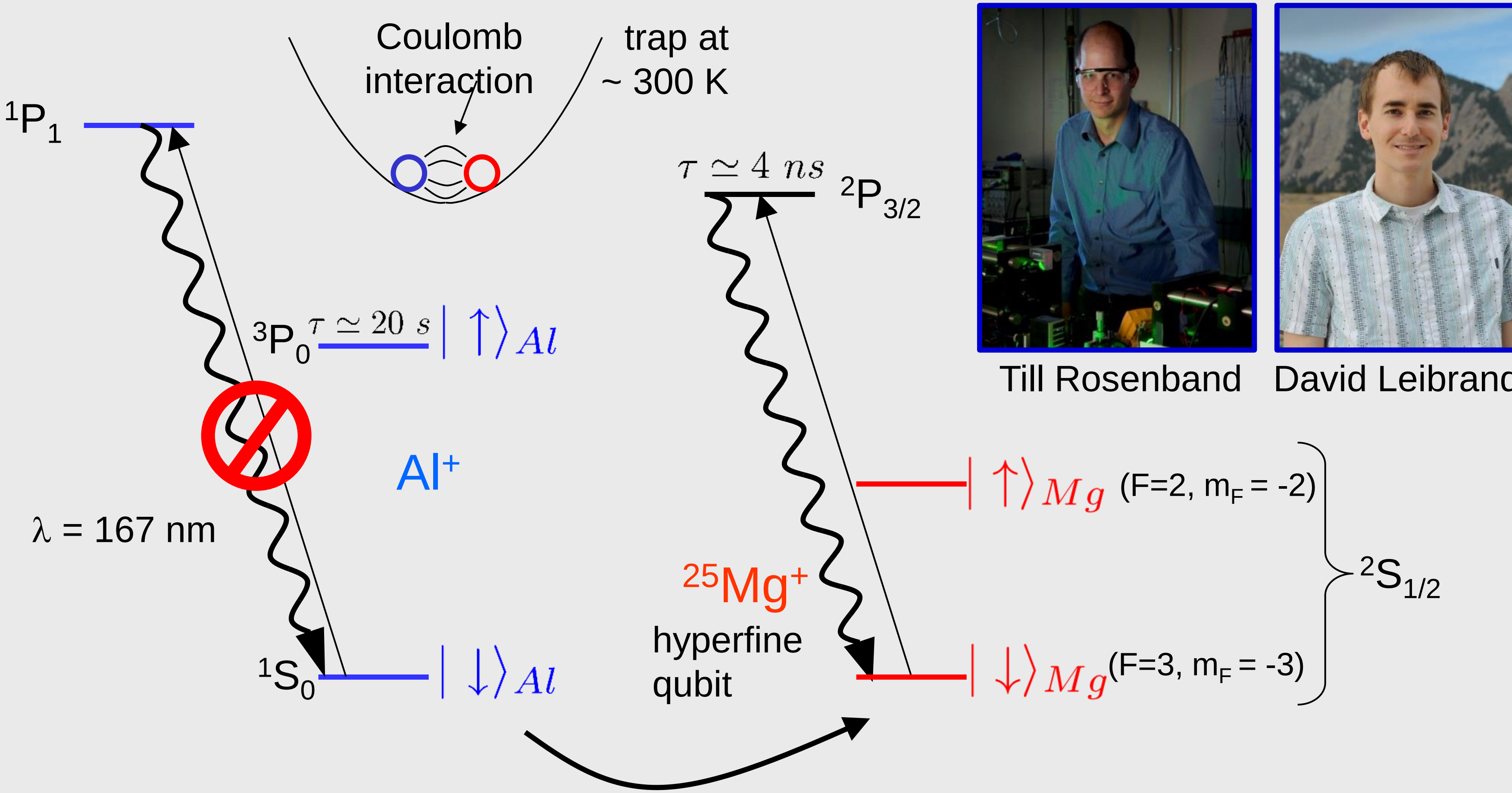


Building block:
gates between ions in
separated wells (d = 30 μm)
(A. Wilson et al., Nature,to appear)

Didi Leibfried

Chiaverini and Lybarger, PRA 77, 022324 (2008)
Schmied, Wesenberg, Leibfried, PRL **102**, 233002 (2009)
Schmied, Wesenberg, Leibfried, New J. Phys. 13 115011 (2011)

Al^+ "quantum-logic clock" (T. Rosenband, P. Schmidt, C.-W. Chou, D. Hume, D. Leibrandt, et al.)



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
◊ ……

$\Delta f/f_0$(systematic) = 8.0×10^{-18}

Moving target!

Jun Ye's group (JILA), Sr neutral atoms in optical lattice:

$\Delta f/f_0$(systematic) = 6.4×10^{-18}

(B. J. Bloom et al., *Nature* **506**, 71 (2014))

$\Delta T \approx 30$ mK

PTB, Braunschweig, Germany

$\Delta f/f_0$(systematic) = 3.9×10^{-18}

(unpublished)

weak (octupole) transition, laser Stark shifts, …

H. Katori group (Riken) Sr neutral atoms in optical lattice

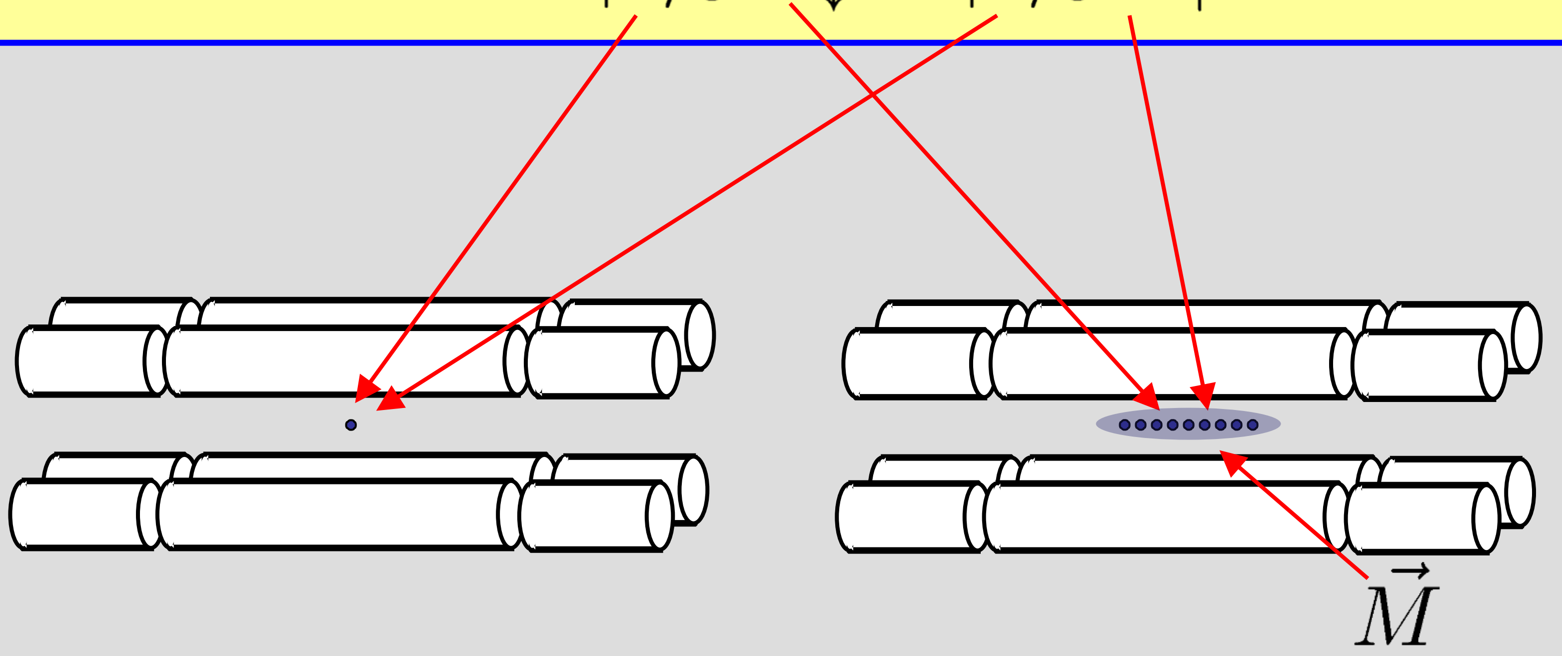
$\Delta f/f_0$(systematic) = 7.2×10^{-18} (arXiv:1405.4071)

record low instabilities: Sr (JILA,Riken), Yb (NIST) ~ 2×10^{-18} ($\tau = 10^4$ s)

Schrödinger's cat?

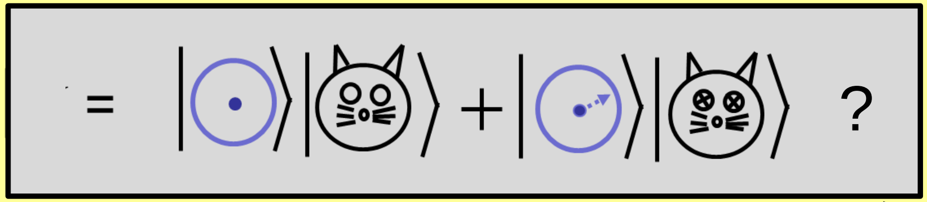
$$\Psi(t) = |0\rangle_0 \big[|0\rangle_1 |0\rangle_2 ......|0\rangle_{N-1}\big] + |1\rangle_0 \big[1\rangle_1 |1\rangle_2 ......|1\rangle_{N-1}\big]$$

For large N $\Psi = |0\rangle_0 \vec{M}_{\downarrow} + |1\rangle_0 \vec{M}_{\uparrow}$



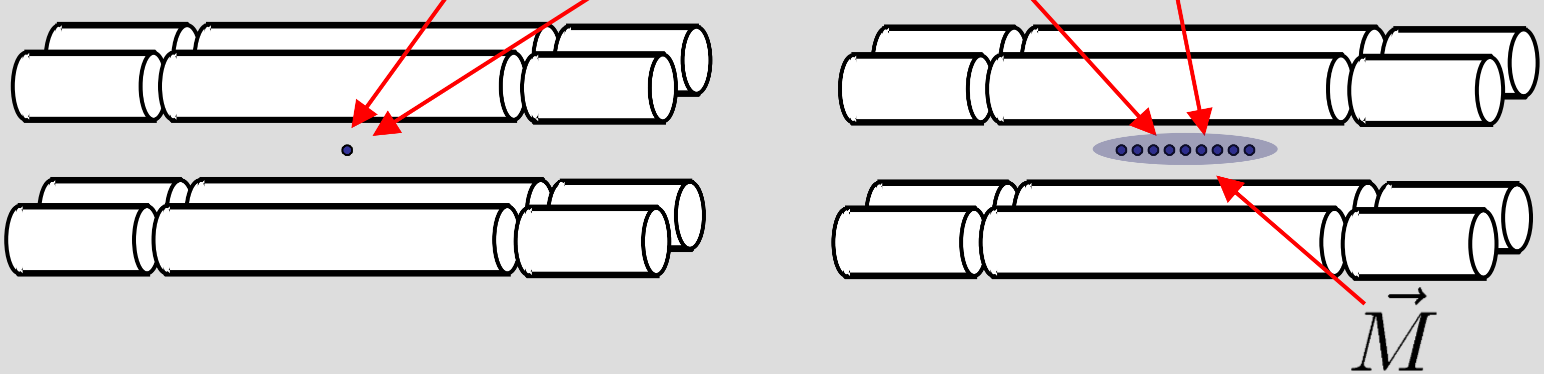
Schrödinger's cat?

$$\Psi(t) = |0\rangle_0 \big[|0\rangle_1$$



$$\ldots\ldots |1\rangle_{N-1} \big]$$

For large N $\Psi = |0\rangle_0 \vec{M}_{\downarrow} + |1\rangle_0 \vec{M}_{\uparrow}$



macroscopic magnetization

- plus students, postdocs, visitors (> 100)
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IARPA ONR DARPA NIST


Katharine Gebbie

And good friends along the way!