Title: Atomic Physics in the Era of Control: What every physicist should know about the 2012 Physics Nobel Prize

Date: Aug 16, 2013 03:45 PM

URL: http://pirsa.org/13080042

Abstract: To say that atomic, molecular, and optical (AMO) physics underwent a revival in the 80s and 90s is to acknowledge that it was in need of reviving. Prior to this rebirth, high-quality research was being done in many labs, but it was primarily passive with respect to atomic motion. The demonstration of laser cooling in 1978 ushered in a new era where the full quantum states (internal and external) of atoms would be precisely controlled in the following decades. This control has essentially given todayâ€™s AMO physicist the power to â€œrealize the gedankenâ€• and build experiments that exploit quantum mechanics to perform computations, simulations, and measurements with tremendous speed and precision. I will discuss some of the current challenges and potential of this exciting time in the field of AMO physics through the lens of a case study of some of the work of this yearâ€™s Nobel Laureates, Dave Wineland and Serge Haroche.


PERIMETER
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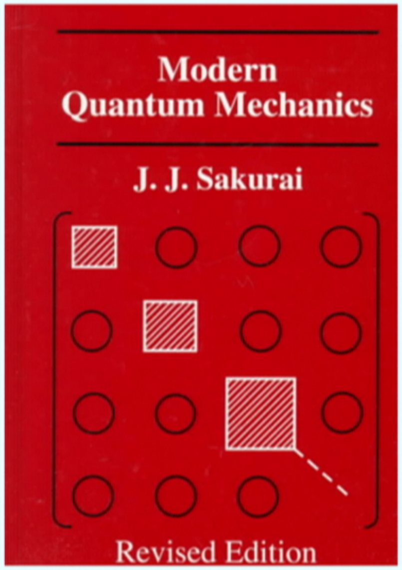
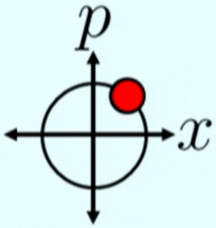
Individual Quantum Systems

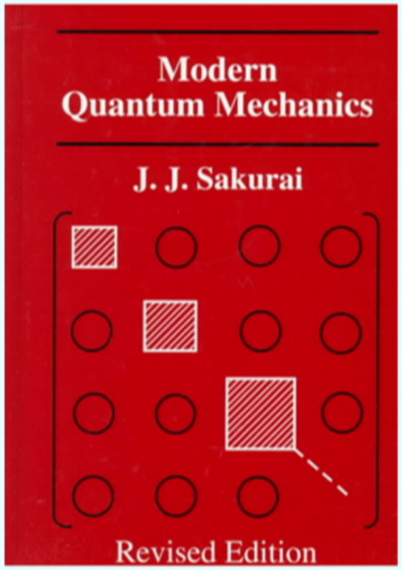


- **harmonic oscillators**



$\hat{a}^\dagger \quad \hat{a}$

Individual Quantum Systems

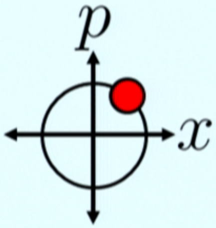


Modern
Quantum Mechanics

J. J. Sakurai

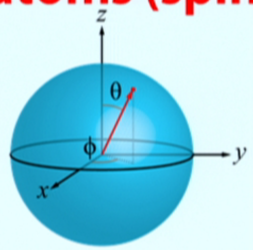
Revised Edition

- harmonic oscillators



$\hat{a}^\dagger \quad \hat{a}$

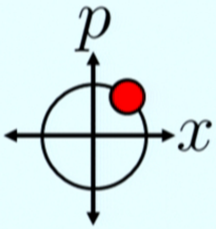
- atoms (spin ½ particles)



$\hat{\sigma}_+ \quad \hat{\sigma}_-$

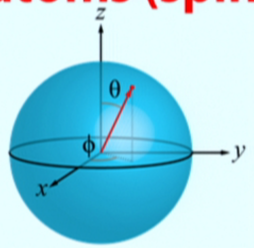
Jaynes-Cummings Hamiltonian

harmonic oscillators

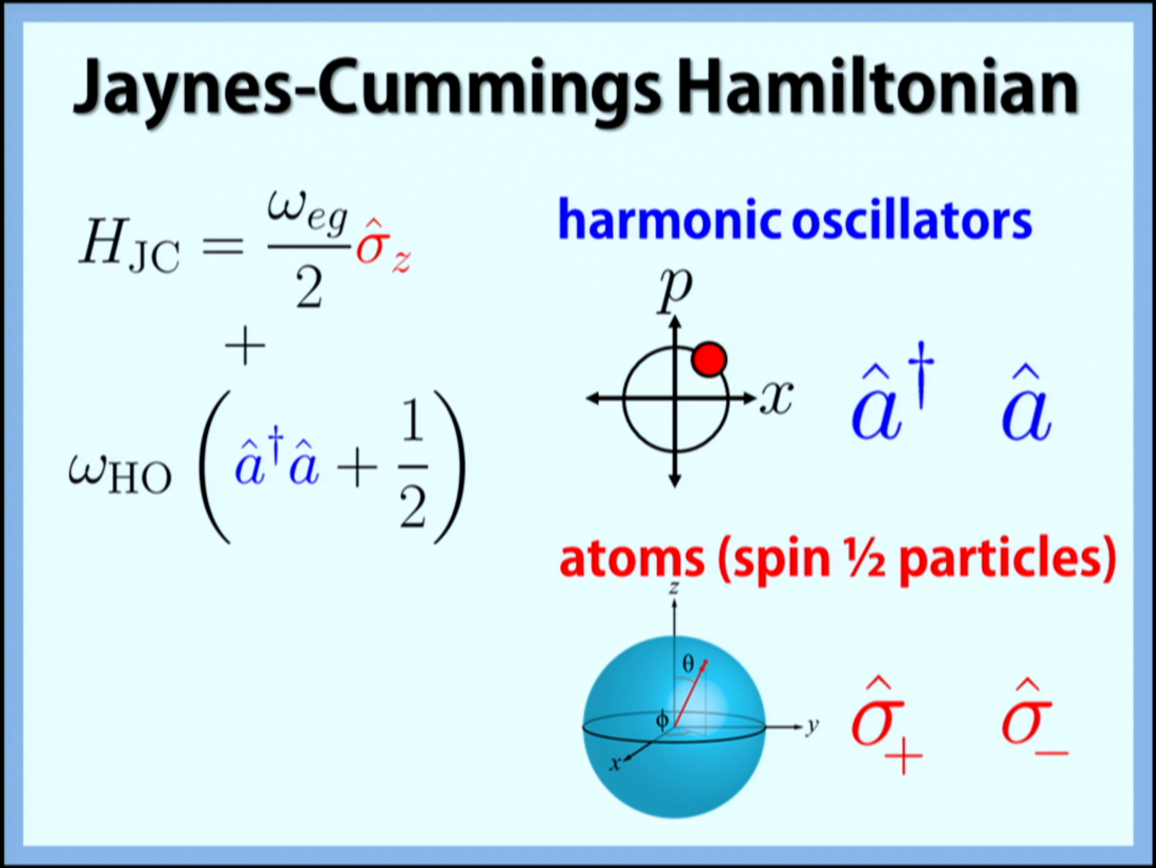


$\hat{a}^\dagger \quad \hat{a}$

atoms (spin ½ particles)



$\hat{\sigma}_+ \quad \hat{\sigma}_-$



Jaynes-Cummings Hamiltonian

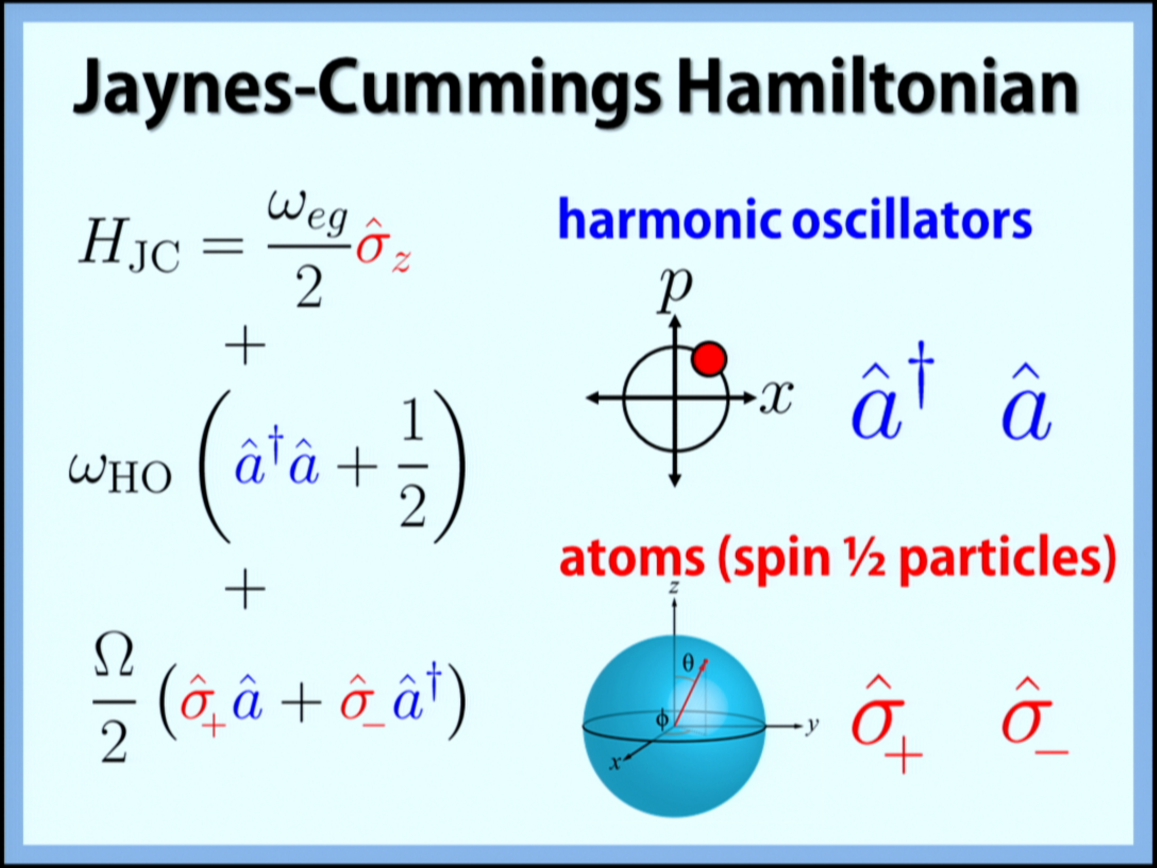
$$H_{\mathrm{JC}} = \frac{\omega_{eg}}{2}\hat{\sigma}_z + \omega_{\mathrm{HO}}\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right)$$

harmonic oscillators

$\hat{a}^\dagger$ $\hat{a}$

atoms (spin ½ particles)

$\hat{\sigma}_+$ $\hat{\sigma}_-$



Jaynes-Cummings Hamiltonian

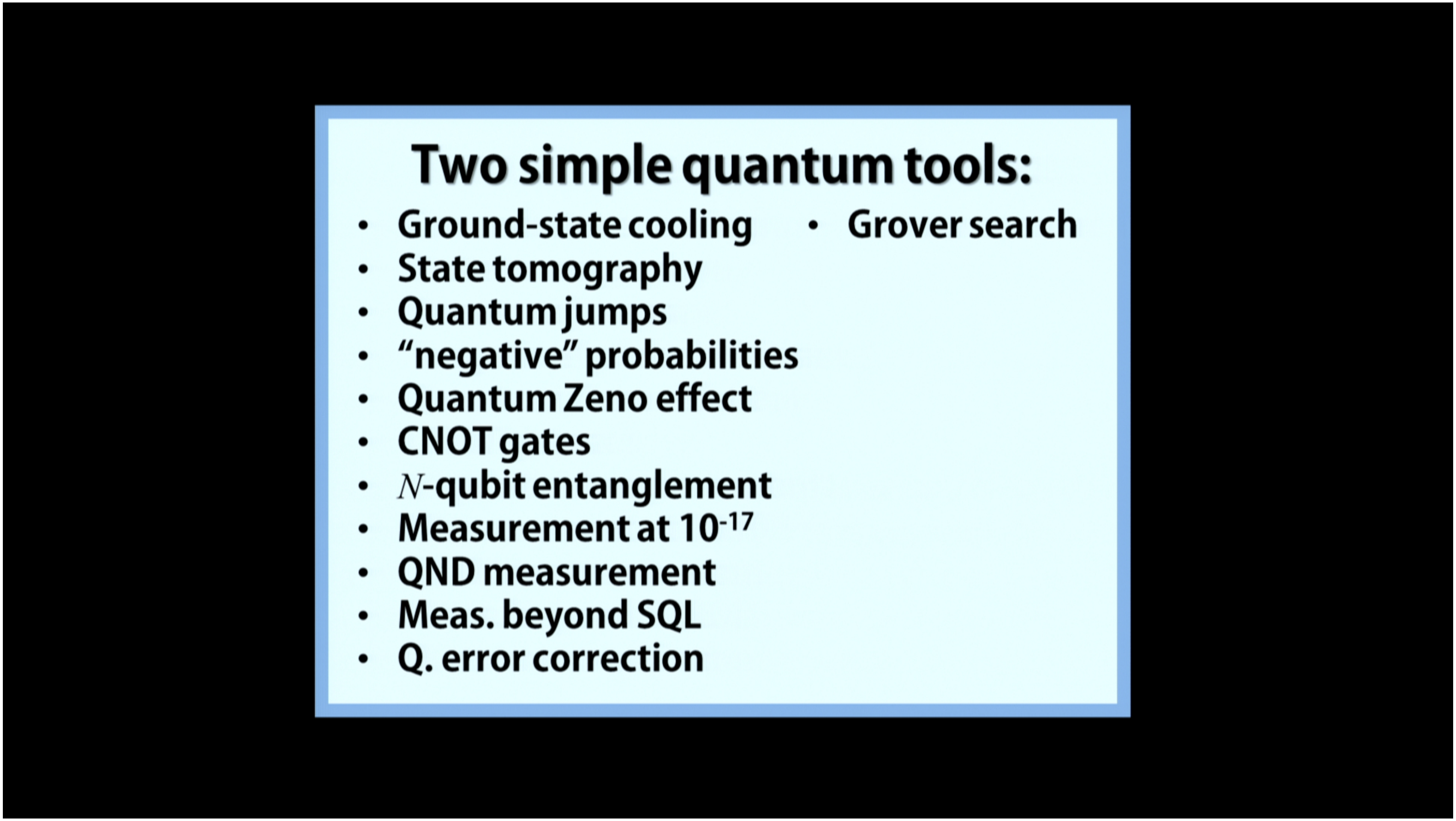
$$
\begin{aligned}
H_{\mathrm{JC}} = {} & \frac{\omega_{eg}}{2}\hat{\sigma}_z \\
& + \\
& \omega_{\mathrm{HO}}\left(\hat{a}^{\dagger}\hat{a}+\frac{1}{2}\right) \\
& + \\
& \frac{\Omega}{2}\left(\hat{\sigma}_{+}\hat{a}+\hat{\sigma}_{-}\hat{a}^{\dagger}\right)
\end{aligned}
$$

harmonic oscillators

$\hat{a}^{\dagger}$ $\hat{a}$

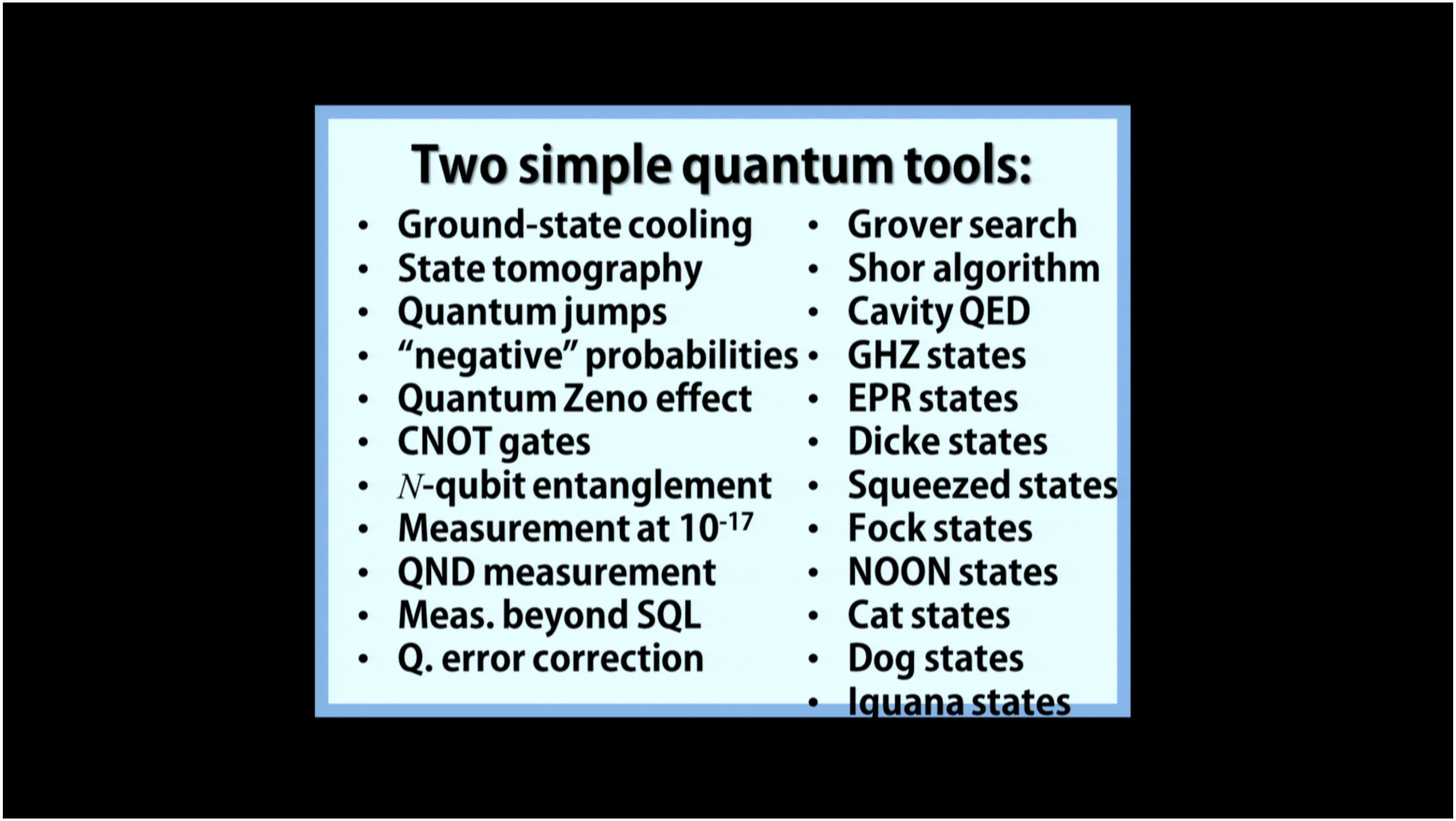
atoms (spin ½ particles)

$\hat{\sigma}_{+}$ $\hat{\sigma}_{-}$



Two simple quantum tools:

- Ground-state cooling
- State tomography
- Quantum jumps
- “negative” probabilities
- Quantum Zeno effect
- CNOT gates
- N-qubit entanglement
- Measurement at 10^{-17}
- QND measurement
- Meas. beyond SQL
- Q. error correction
- Grover search



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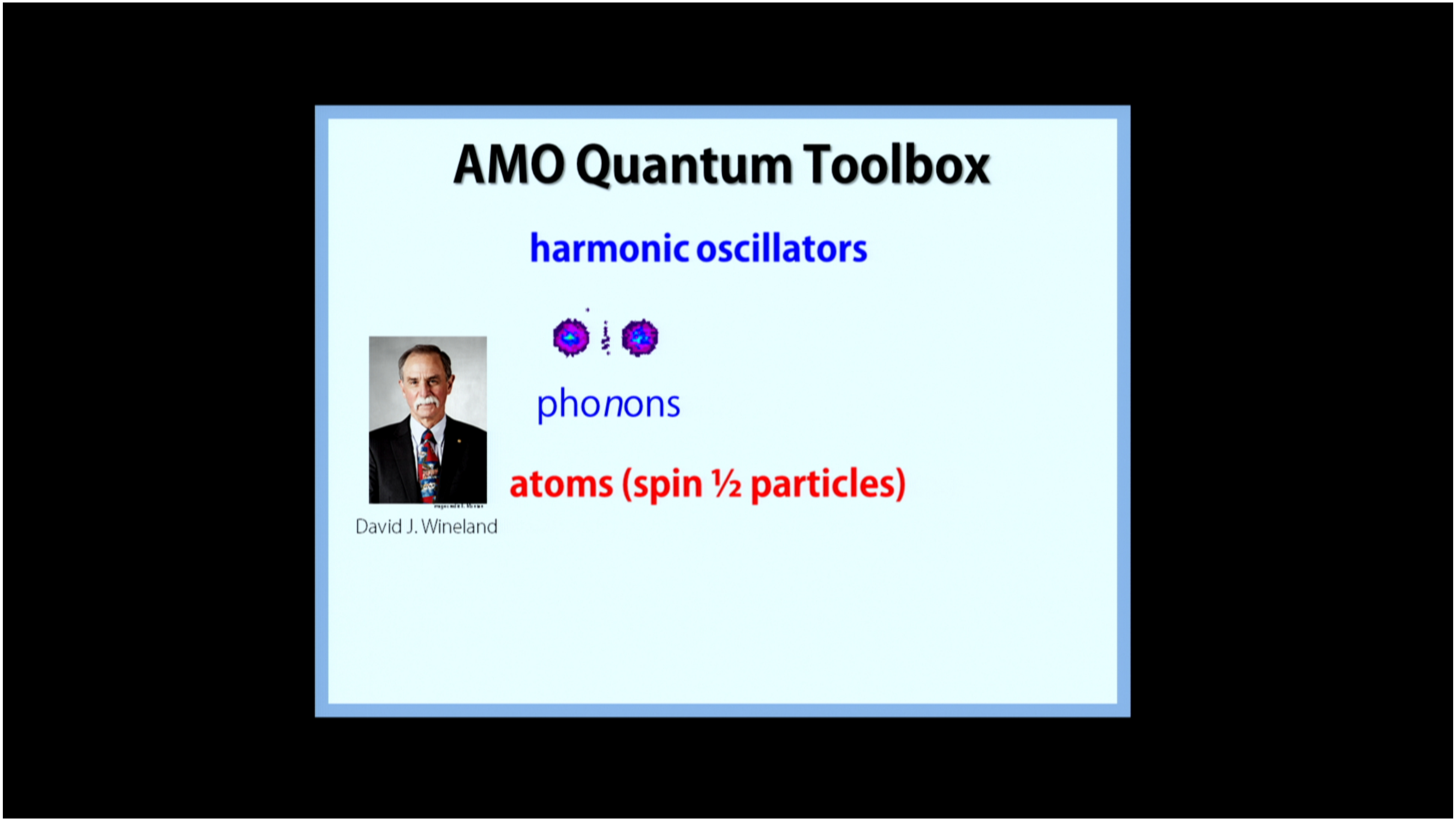
- Grover search
- Shor algorithm
- Cavity QED
- GHZ states
- EPR states
- Dicke states
- Squeezed states
- Fock states
- NOON states
- Cat states
- Dog states
- Iguana states



AMO Quantum Toolbox

harmonic oscillators

pho*n*ons

atoms (spin ½ particles)

David J. Wineland

AMO Quantum Toolbox

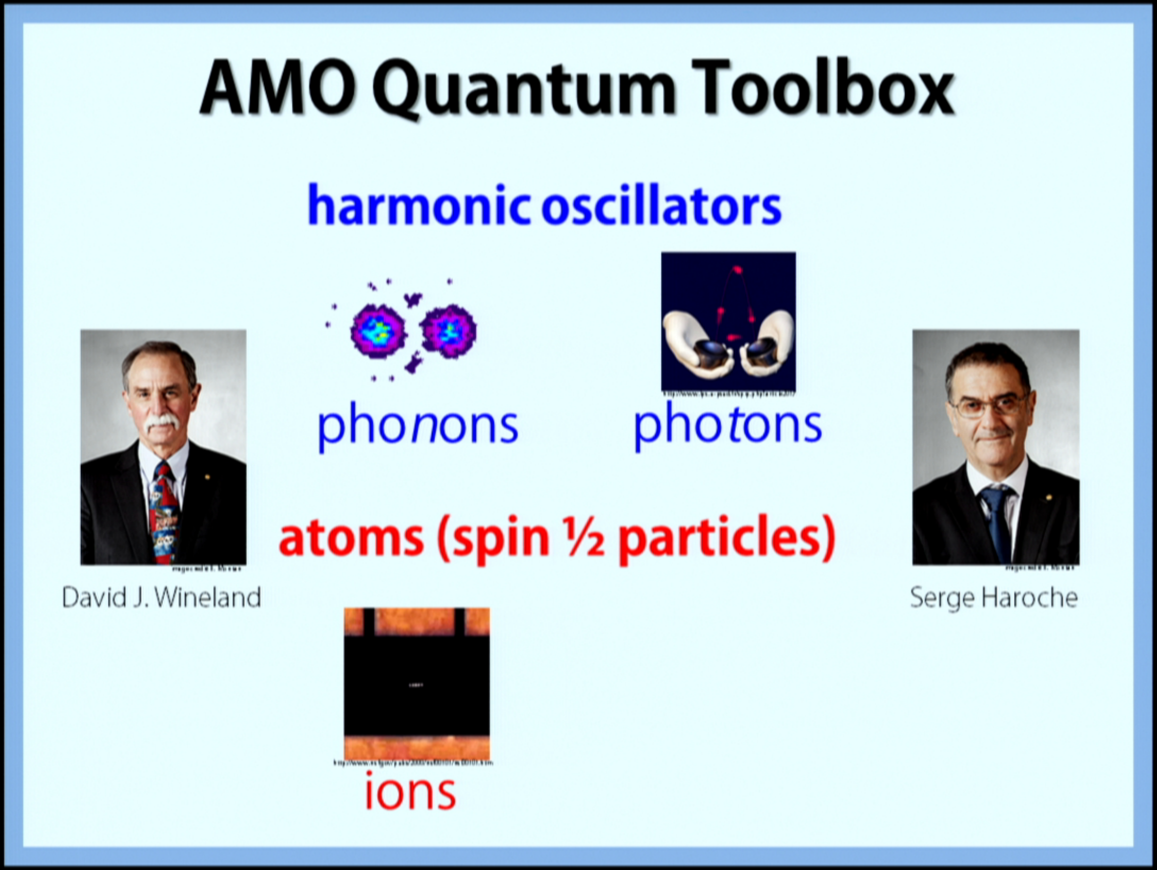
harmonic oscillators

David J. Wineland

phonons

atoms (spin ½ particles)

ions



AMO Quantum Toolbox

harmonic oscillators

pho*n*ons

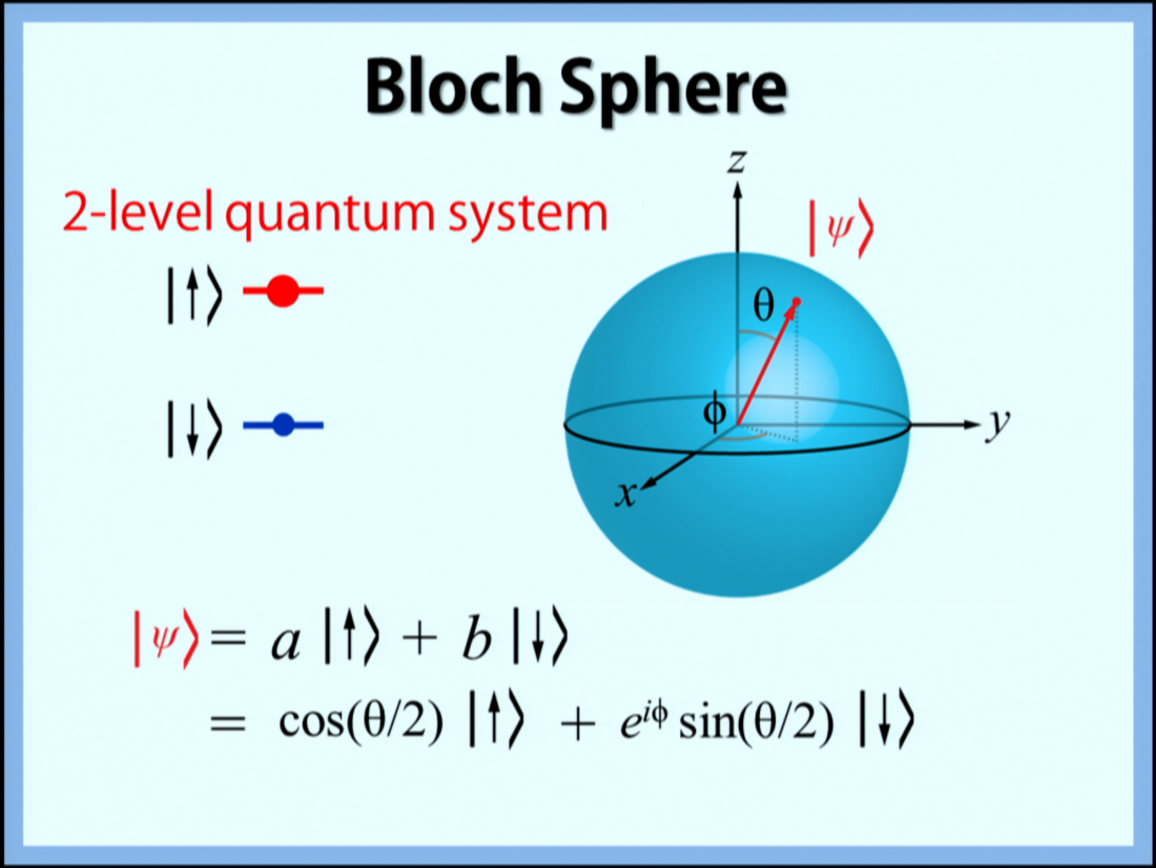
pho*t*ons

atoms (spin ½ particles)

ions

David J. Wineland

Serge Haroche



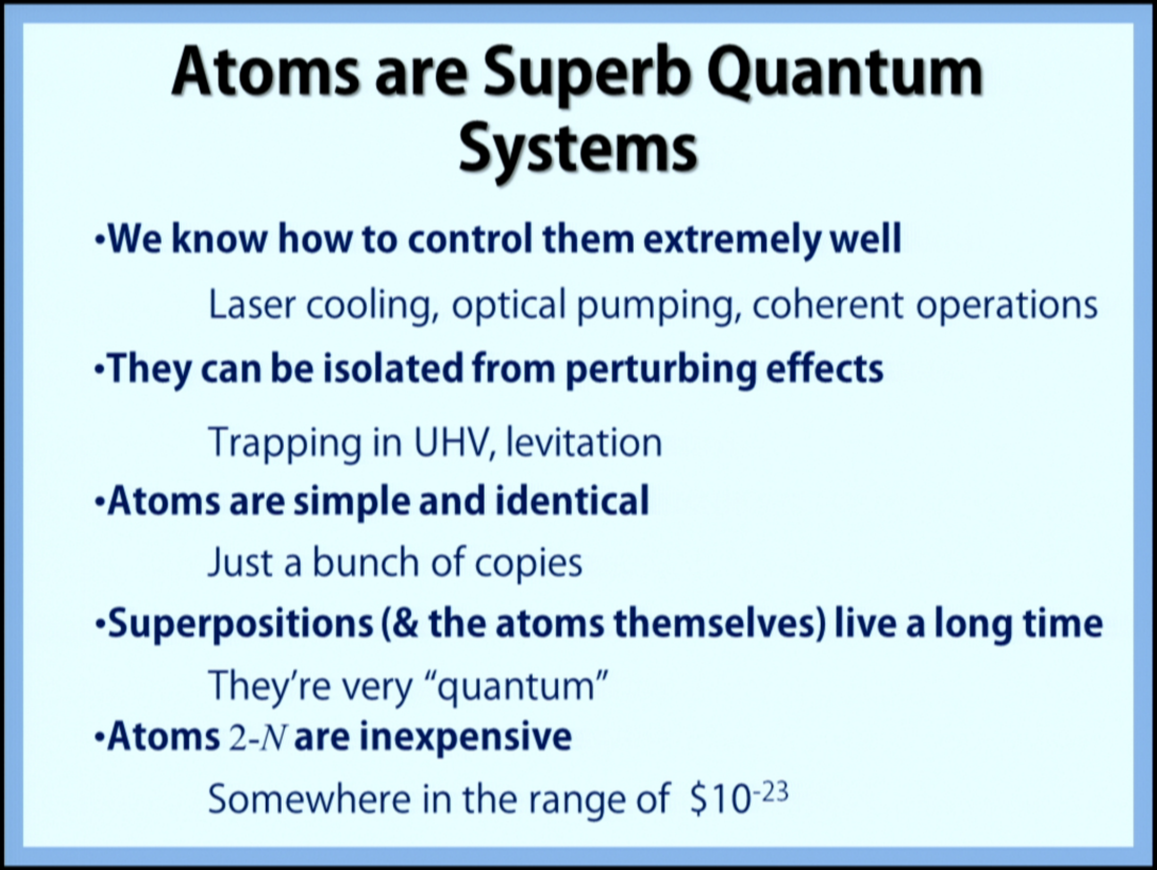
Bloch Sphere

2-level quantum system

$|\uparrow\rangle$

$|\downarrow\rangle$

$$\begin{aligned} |\psi\rangle &= a\,|\uparrow\rangle + b\,|\downarrow\rangle \\ &= \cos(\theta/2)\,|\uparrow\rangle + e^{i\phi}\sin(\theta/2)\,|\downarrow\rangle \end{aligned}$$



Atoms are Superb Quantum Systems

- **We know how to control them extremely well**
  - Laser cooling, optical pumping, coherent operations
- **They can be isolated from perturbing effects**
  - Trapping in UHV, levitation
- **Atoms are simple and identical**
  - Just a bunch of copies
- **Superpositions (& the atoms themselves) live a long time**
  - They’re very “quantum”
- **Atoms** 2-N **are inexpensive**
  - Somewhere in the range of \$$10^{-23}$

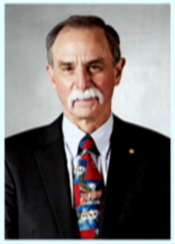
Which atoms?

- **Effective spin ½ particle**

    Two long-lived states

- **Control over atomic motion**

    One short-lived state

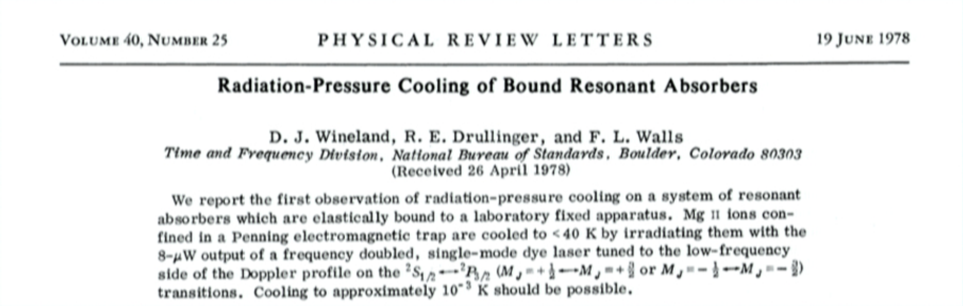


David J. Wineland

Laser cooling!

(1978)

Which atoms?

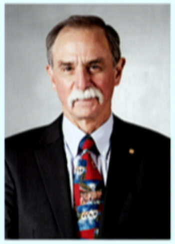


Volume 40, Number 25 PHYSICAL REVIEW LETTERS 19 June 1978

Radiation-Pressure Cooling of Bound Resonant Absorbers

D. J. Wineland, R. E. Drullinger, and F. L. Walls
Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80303
(Received 26 April 1978)

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



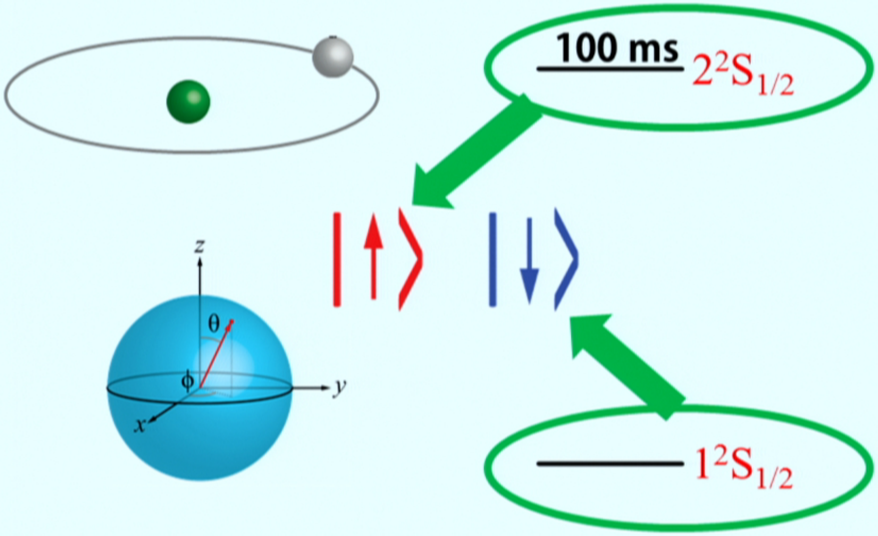
David J. Wineland

Also: Neuhauser, Hohenstatt, Toschek, & Dehmelt

Laser cooling!

(1978)

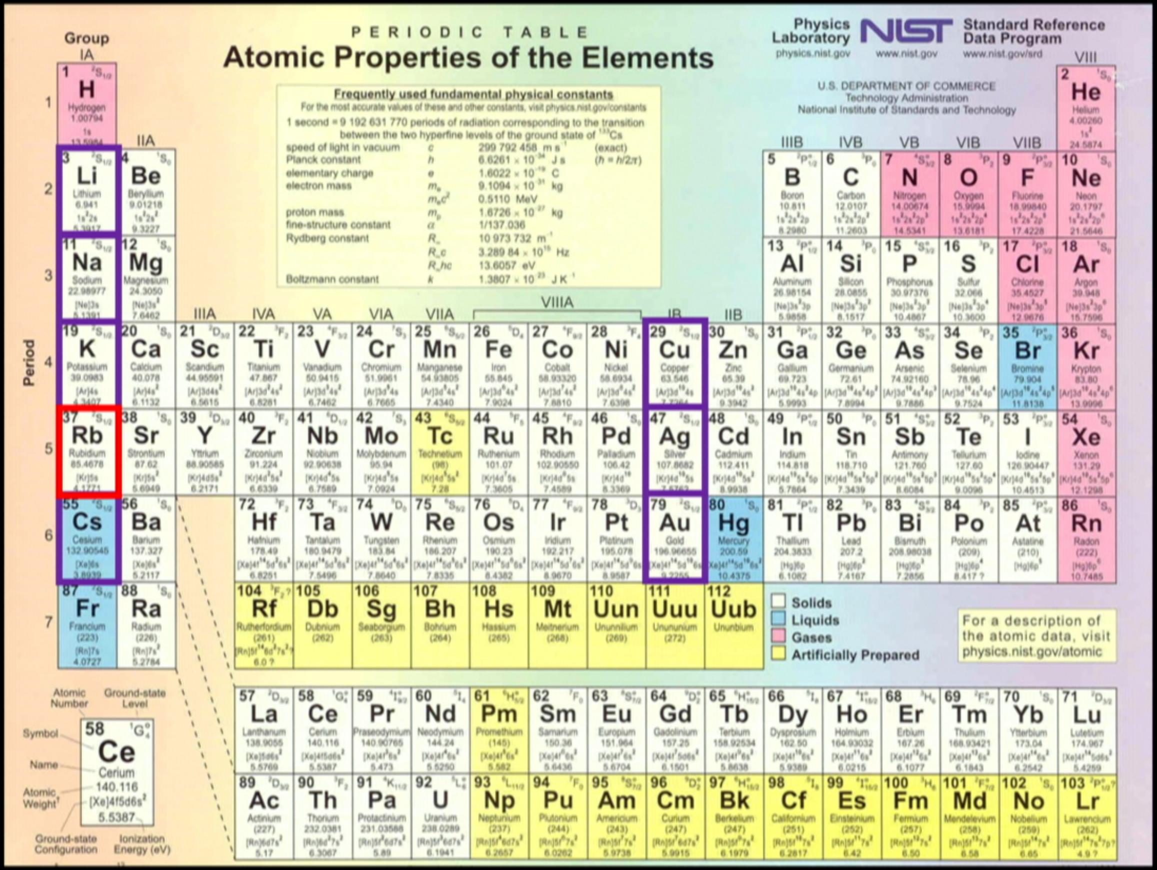
Example: Atomic Hydrogen



100 ms $2^2S_{1/2}$

$|\uparrow\rangle$ $|\downarrow\rangle$

$1^2S_{1/2}$



Physics Laboratory
physics.nist.gov

NIST
www.nist.gov

Standard Reference Data Program
www.nist.gov/srd

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

PERIODIC TABLE

Atomic Properties of the Elements

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	m_ec^2	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,84 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

Period	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 H Hydrogen																	2 He Helium
2	3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
3	11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
4	19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
5	37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
6	55 Cs Cesium	56 Ba Barium		72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
7	87 Fr Francium	88 Ra Radium		104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Uun Ununnilium	111 Uuu Unununium	112 Uub Ununbium						

57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

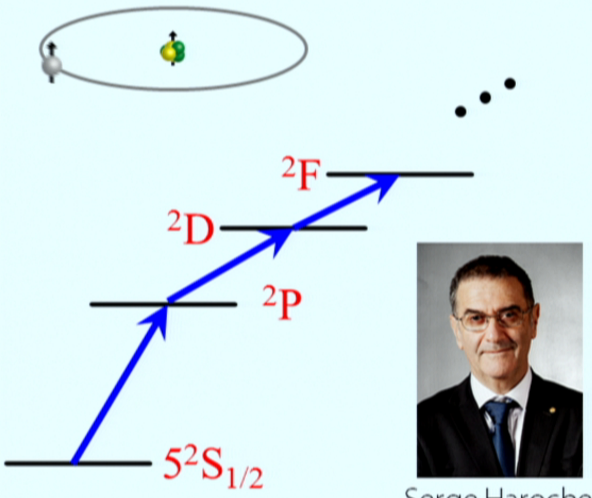
- ☐ Solids
- ☐ Liquids
- ☐ Gases
- ☐ Artificially Prepared

For a description of the atomic data, visit physics.nist.gov/atomic

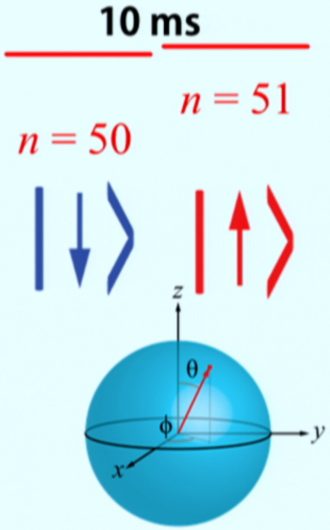
Atomic Number — 58
Ground-state Level — $^1G^\circ_4$
Symbol — Ce
Name — Cerium
Atomic Weight† — 140.116
Ground-state Configuration — [Xe]4f5d6s^2
Ionization Energy (eV) — 5.5387

Circular Rydberg states

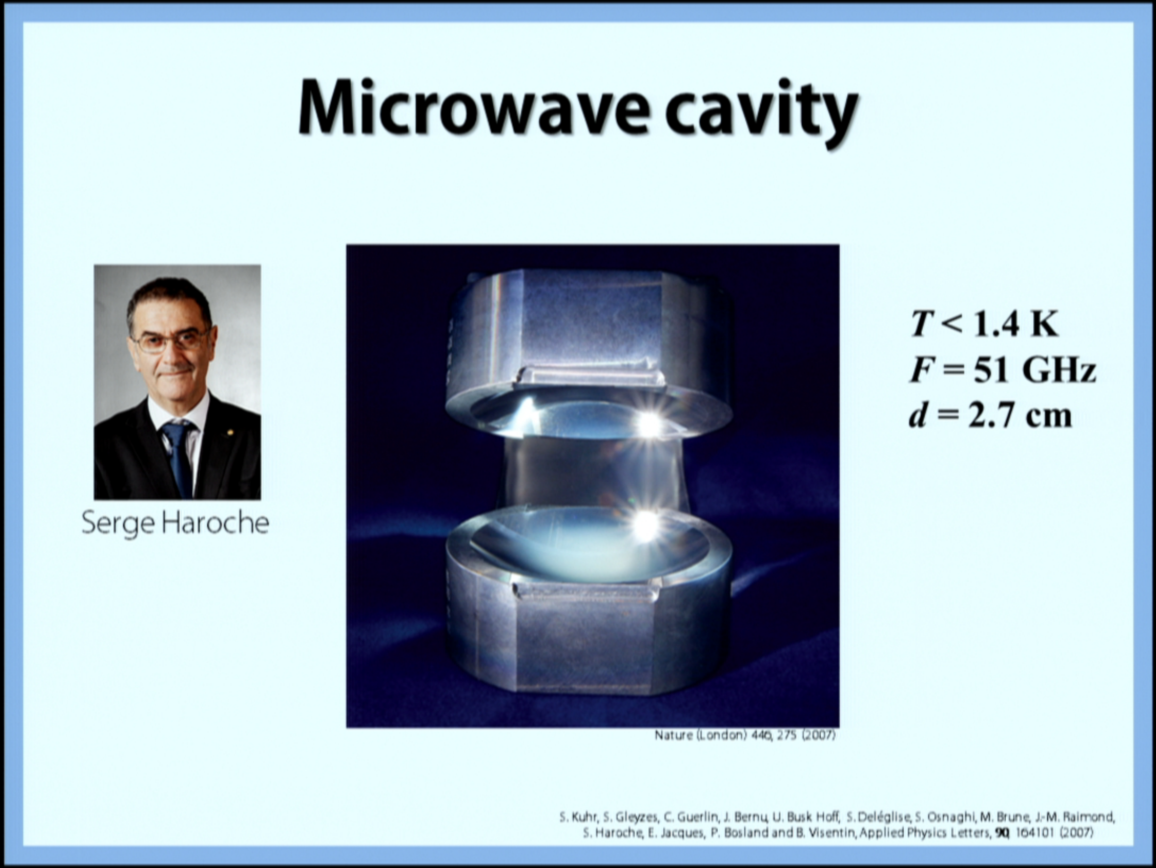
Ionization threshold



Serge Haroche



Nussenzveig, Bernardot, Brune, Hare, Raimond, Haroche, and Gawlik, PRA **48**, 3991 (1993)



Microwave cavity

Serge Haroche

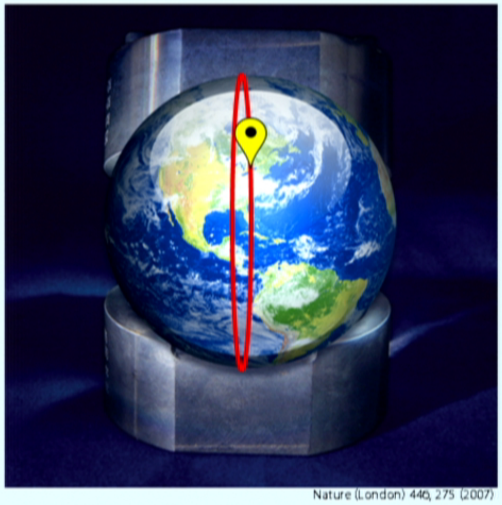
$T < 1.4$ K
$F = 51$ GHz
$d = 2.7$ cm

Nature (London) 446, 275 (2007)

S. Kuhr, S. Gleyzes, C. Guerlin, J. Bernu, U. Busk Hoff, S. Deléglise, S. Osnaghi, M. Brune, J.-M. Raimond, S. Haroche, E. Jacques, P. Bosland and B. Visentin, Applied Physics Letters, **90**, 164101 (2007)

Microwave cavity

Serge Haroche

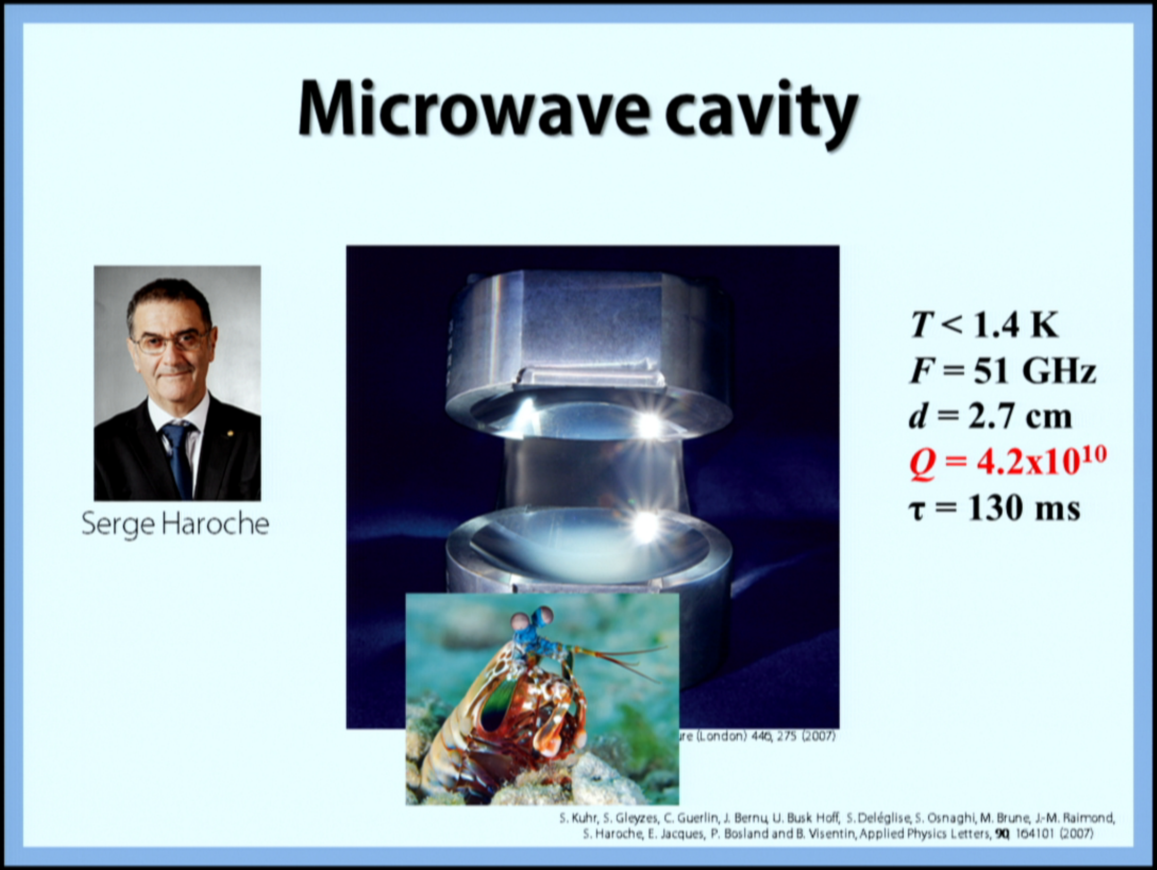


Nature (London) 446, 275 (2007)

$T < 1.4$ K
$F = 51$ GHz
$d = 2.7$ cm
$Q = 4.2\text{x}10^{10}$
$\tau = 130$ ms

$c\tau = 39\ 000$ km!

S. Kuhr, S. Gleyzes, C. Guerlin, J. Bernu, U. Busk Hoff, S. Deléglise, S. Osnaghi, M. Brune, J.-M. Raimond, S. Haroche, E. Jacques, P. Bosland and B. Visentin, Applied Physics Letters, **90** 164101 (2007)



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Jaynes-Cummings Interaction

$|\downarrow\rangle$

$n_p = 0$

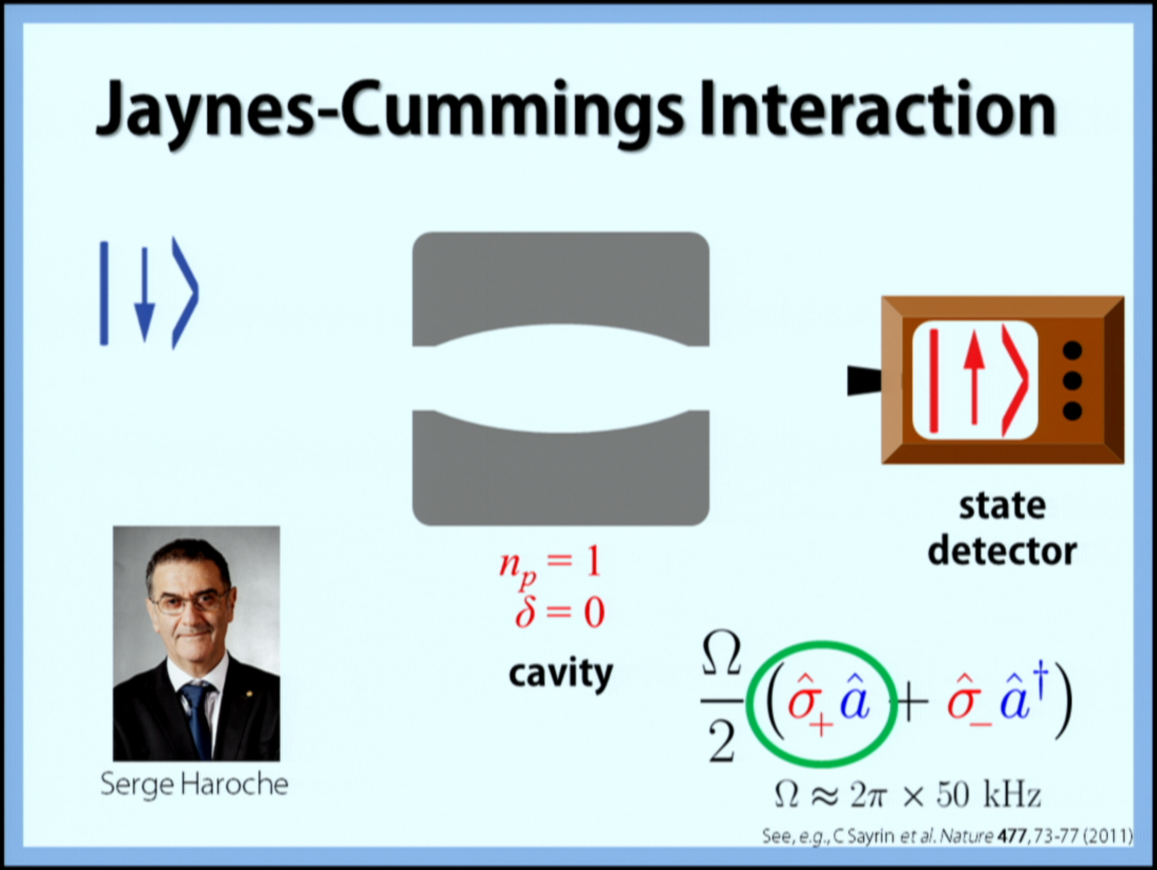
$\delta = 0$

cavity

state detector

Serge Haroche

See, *e.g.*, C Sayrin *et al. Nature* **477**, 73-77 (2011)



Jaynes-Cummings Interaction

$|\downarrow\rangle$

$n_p = 1$
$\delta = 0$
cavity

$|\uparrow\rangle$

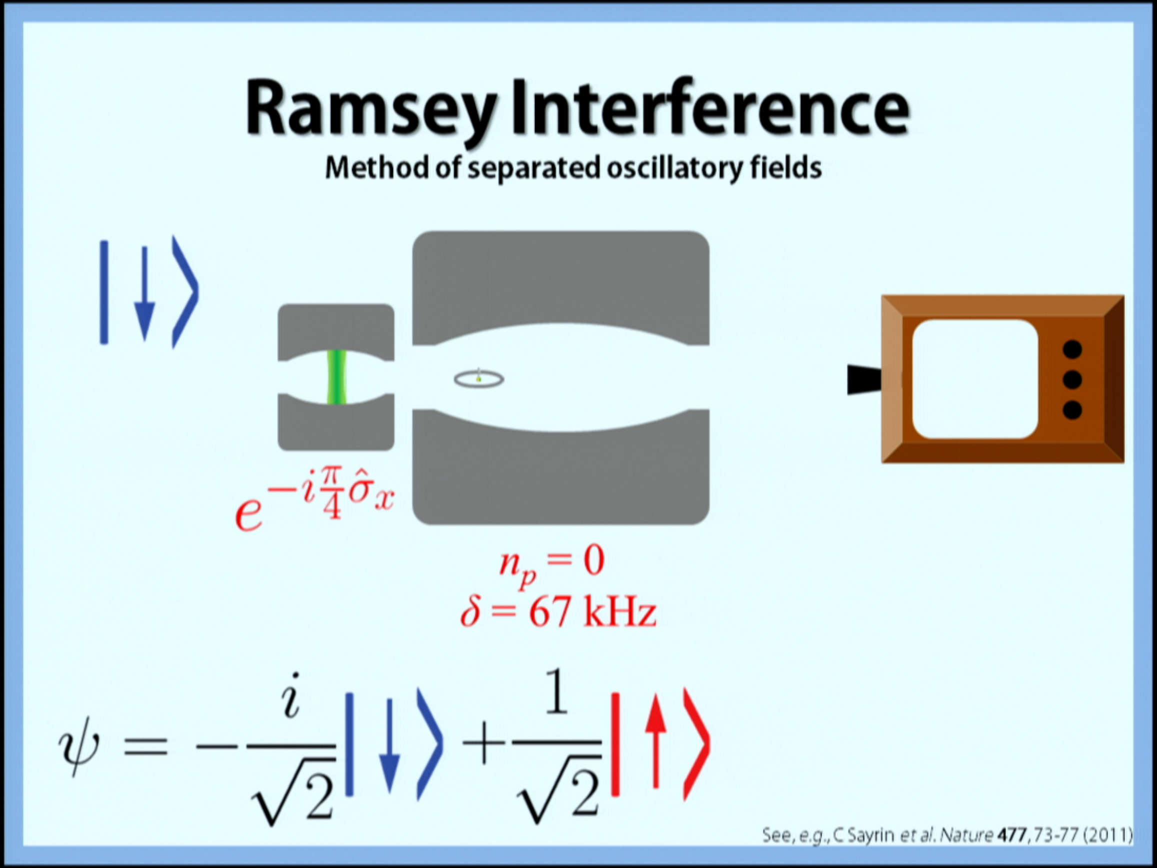
state detector

Serge Haroche

$$\frac{\Omega}{2}\left(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger\right)$$

$$\Omega \approx 2\pi \times 50\ \text{kHz}$$

See, *e.g.*, C Sayrin *et al.* *Nature* **477**, 73-77 (2011)



Ramsey Interference

Method of separated oscillatory fields

$|\downarrow\rangle$

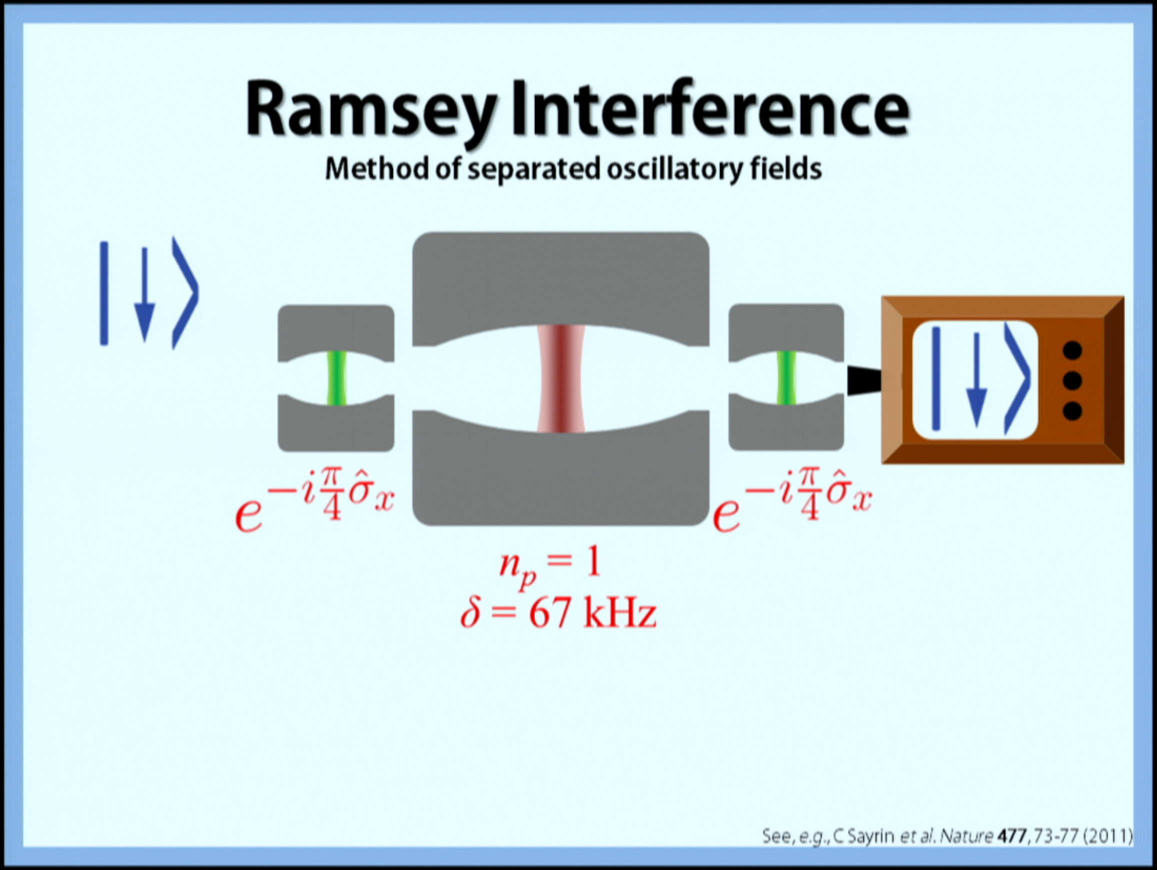
$e^{-i\frac{\pi}{4}\hat{\sigma}_x}$

$n_p = 0$

$\delta = 67$ kHz

$$\psi = -\frac{i}{\sqrt{2}}|\downarrow\rangle + \frac{1}{\sqrt{2}}|\uparrow\rangle$$

See, *e.g.*, C Sayrin *et al. Nature* **477**, 73-77 (2011)



Ramsey Interference

Method of separated oscillatory fields

$|\downarrow\rangle$

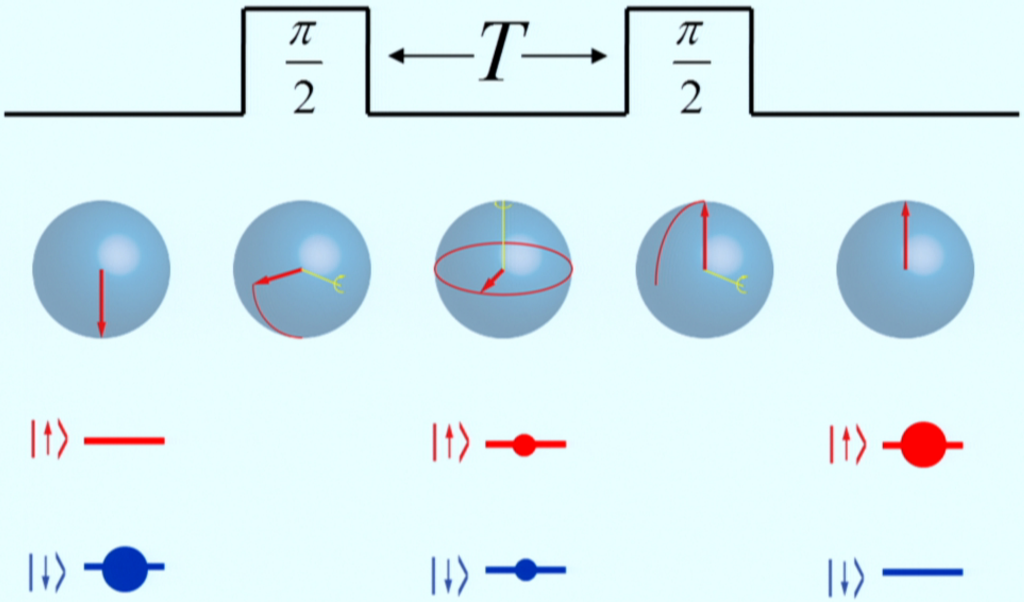
$e^{-i\frac{\pi}{4}\hat{\sigma}_x}$ $e^{-i\frac{\pi}{4}\hat{\sigma}_x}$

$n_p = 1$

$\delta = 67\ \mathrm{kHz}$

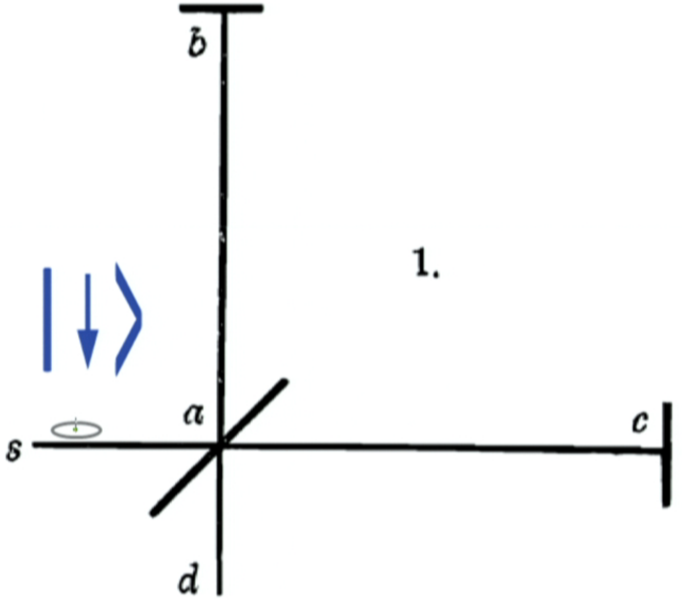
See, *e.g.*, C Sayrin *et al.* *Nature* **477**, 73-77 (2011)

Ramsey Sequence: Bloch Sphere

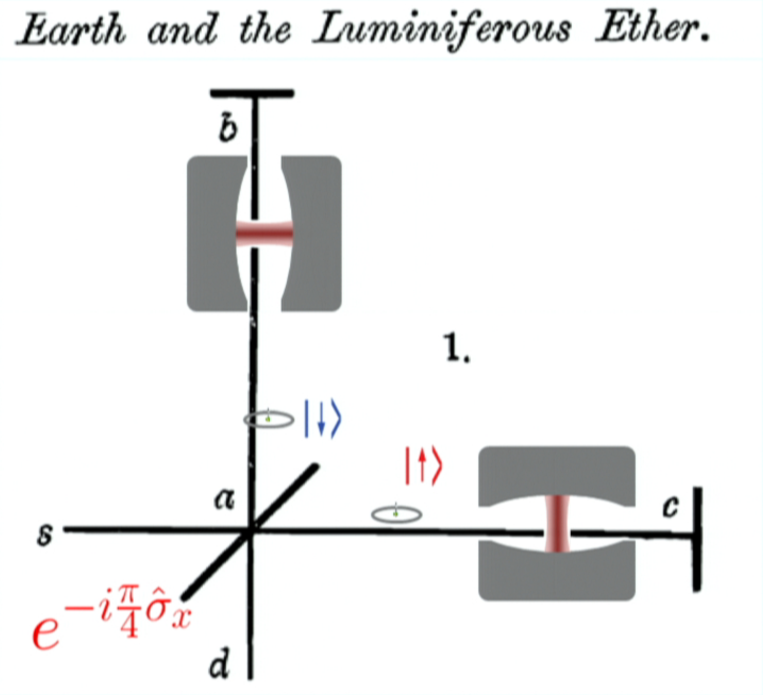


Michelson Interferometer

Earth and the Luminiferous Ether.



Michelson Interferometer



Recent Results

Serge Haroche

LETTER

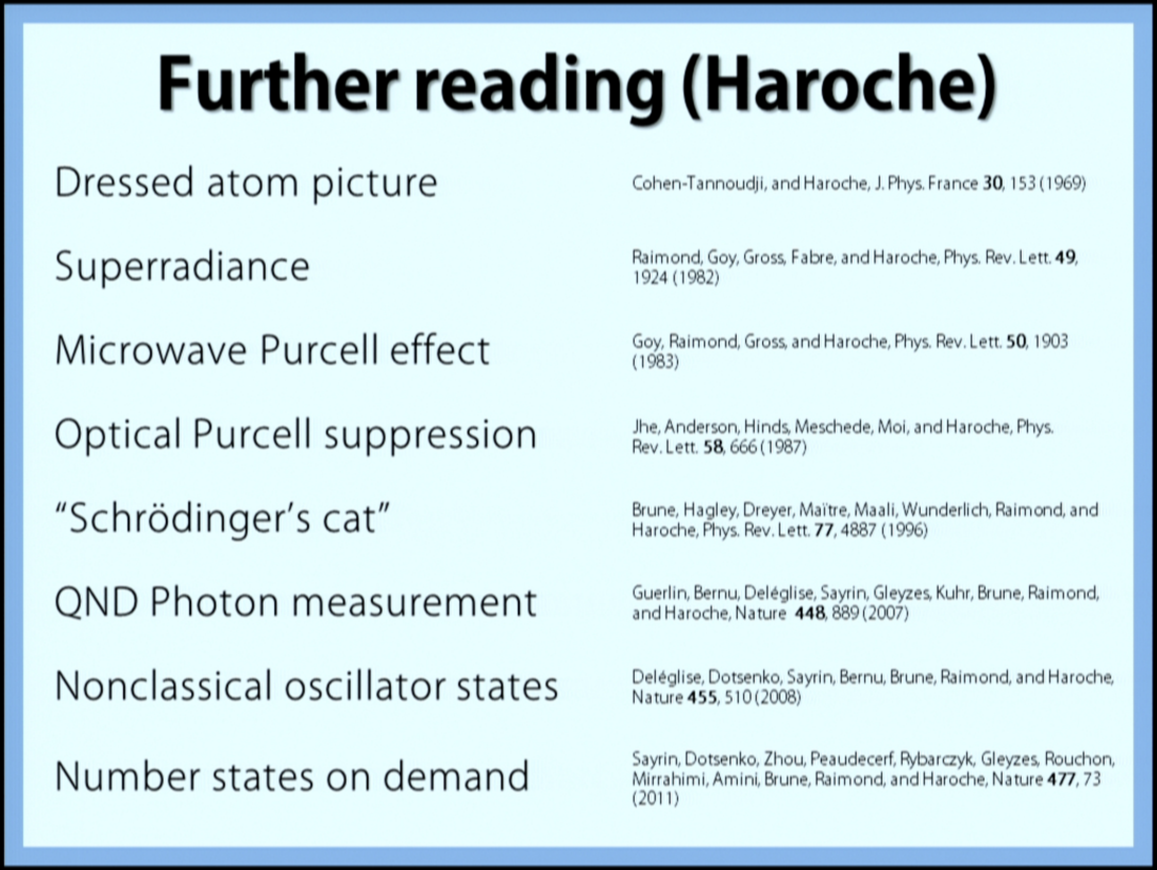
1 SEPTEMBER 2011 | VOL 477 | NATURE | 73

doi:10.1038/nature10376

Real-time quantum feedback prepares and stabilizes photon number states

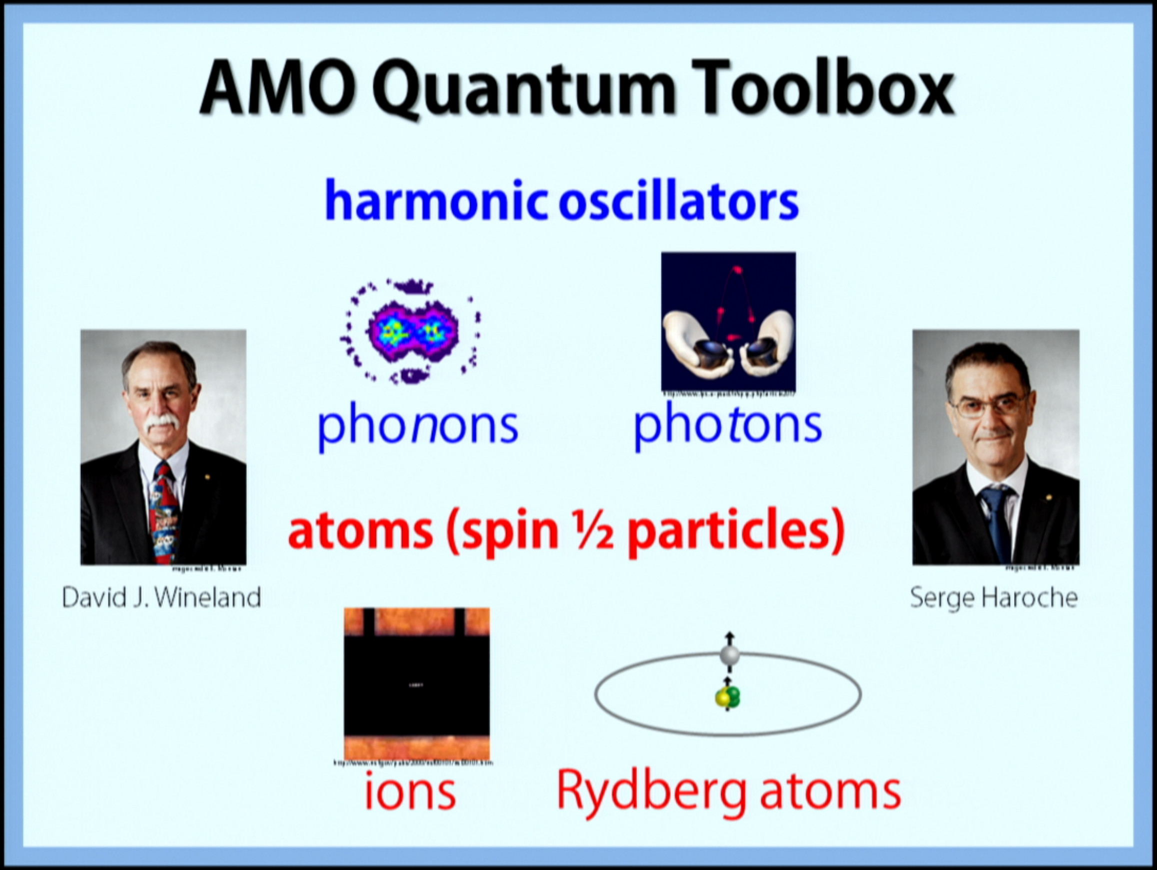
Clément Sayrin[1], Igor Dotsenko[1], Xingxing Zhou[1], Bruno Peaudecerf[1], Théo Rybarczyk[1], Sébastien Gleyzes[1], Pierre Rouchon[2], Mazyar Mirrahimi[3], Hadis Amini[2], Michel Brune[1], Jean-Michel Raimond[1] & Serge Haroche[1,4]

Stabilized photon number states on demand!



Further reading (Haroche)

Dressed atom picture	Cohen-Tannoudji, and Haroche, J. Phys. France **30**, 153 (1969)
Superradiance	Raimond, Goy, Gross, Fabre, and Haroche, Phys. Rev. Lett. **49**, 1924 (1982)
Microwave Purcell effect	Goy, Raimond, Gross, and Haroche, Phys. Rev. Lett. **50**, 1903 (1983)
Optical Purcell suppression	Jhe, Anderson, Hinds, Meschede, Moi, and Haroche, Phys. Rev. Lett. **58**, 666 (1987)
"Schrödinger's cat"	Brune, Hagley, Dreyer, Maître, Maali, Wunderlich, Raimond, and Haroche, Phys. Rev. Lett. **77**, 4887 (1996)
QND Photon measurement	Guerlin, Bernu, Deléglise, Sayrin, Gleyzes, Kuhr, Brune, Raimond, and Haroche, Nature **448**, 889 (2007)
Nonclassical oscillator states	Deléglise, Dotsenko, Sayrin, Bernu, Brune, Raimond, and Haroche, Nature **455**, 510 (2008)
Number states on demand	Sayrin, Dotsenko, Zhou, Peaudecerf, Rybarczyk, Gleyzes, Rouchon, Mirrahimi, Amini, Brune, Raimond, and Haroche, Nature **477**, 73 (2011)



AMO Quantum Toolbox

harmonic oscillators

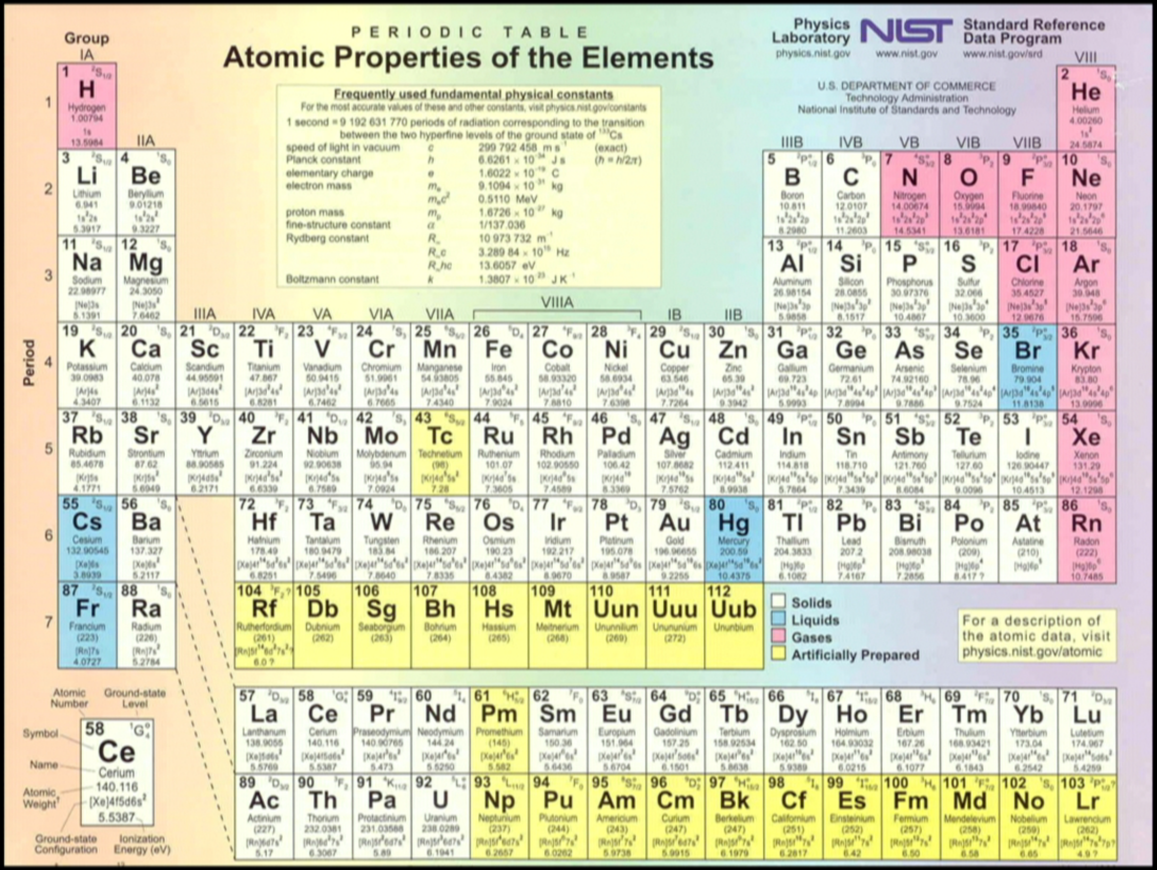
pho*n*ons pho*t*ons

atoms (spin ½ particles)

ions Rydberg atoms

David J. Wineland

Serge Haroche



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Standard Reference Data Program
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U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	m_ec^2	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,84 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

☐ Solids
▨ Liquids
▨ Gases
▨ Artificially Prepared

For a description of the atomic data, visit physics.nist.gov/atomic

Ion Traps

- levitate atoms in vacuo for isolation from environment

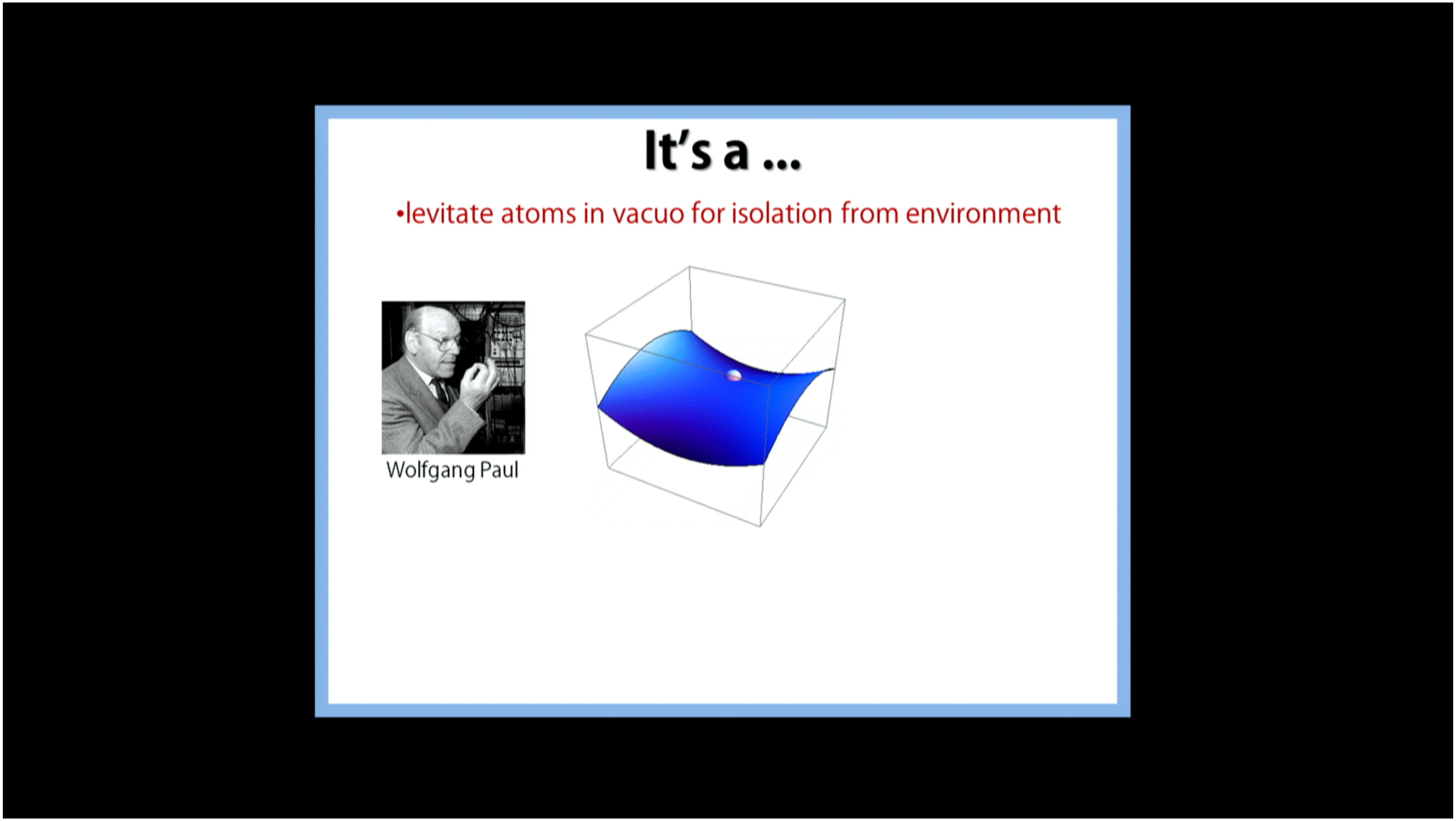
charged particles & static fields:

Earnshaw's theorem,
Maxwell's equations,
(Gauss's Law)

$$\nabla \cdot \mathbf{E} = 0$$

- use time-dependent (RF) fields

Wolfgang Paul



It's a ...

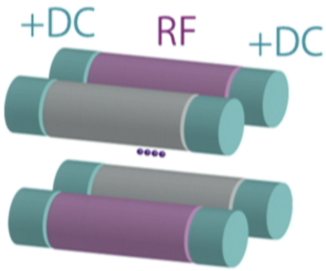
- levitate atoms in vacuo for isolation from environment

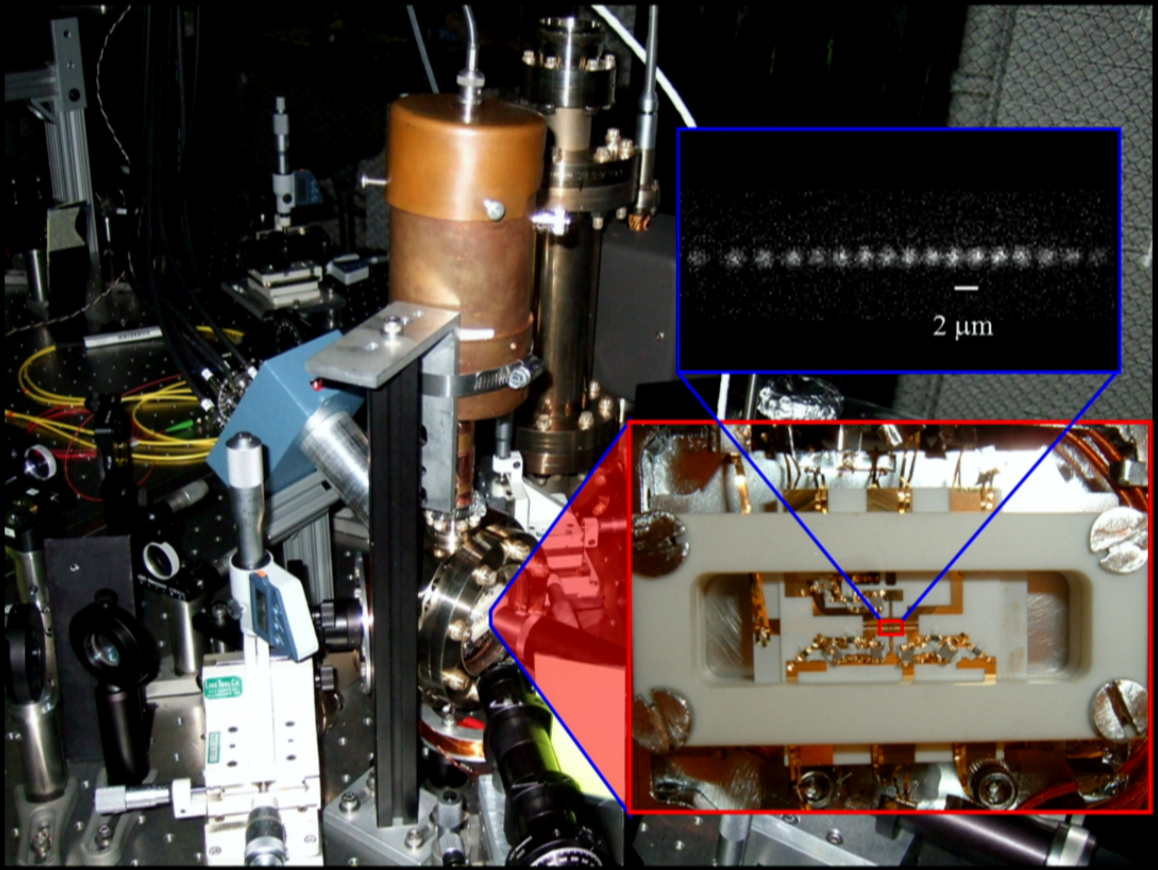
Wolfgang Paul

It’s a ...

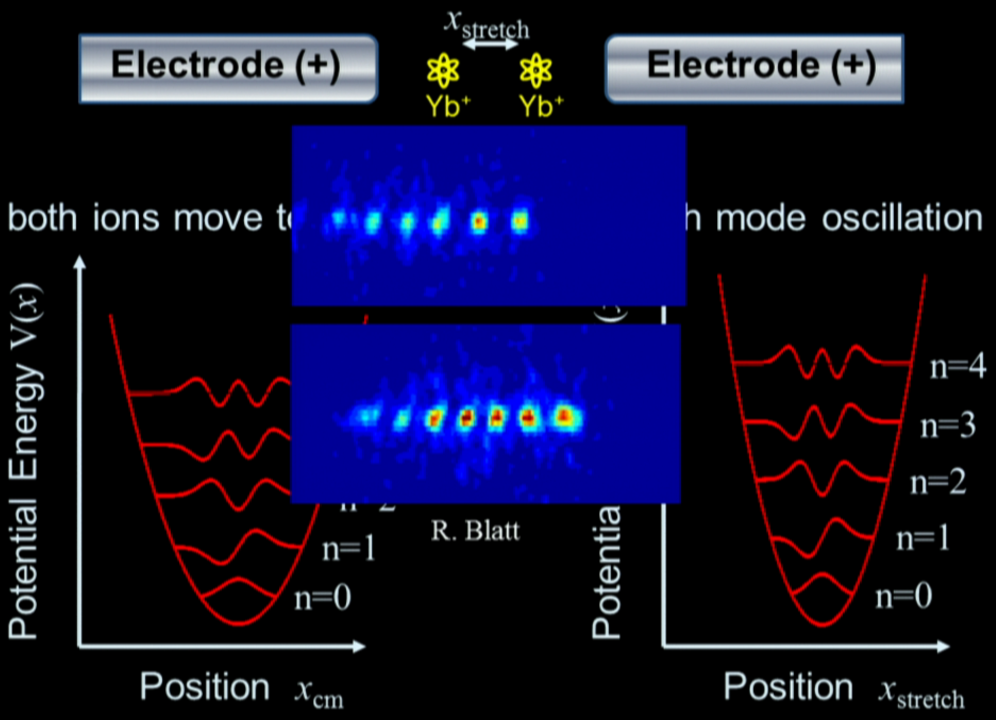
- levitate atoms in vacuo for isolation from environment

Wolfgang Paul

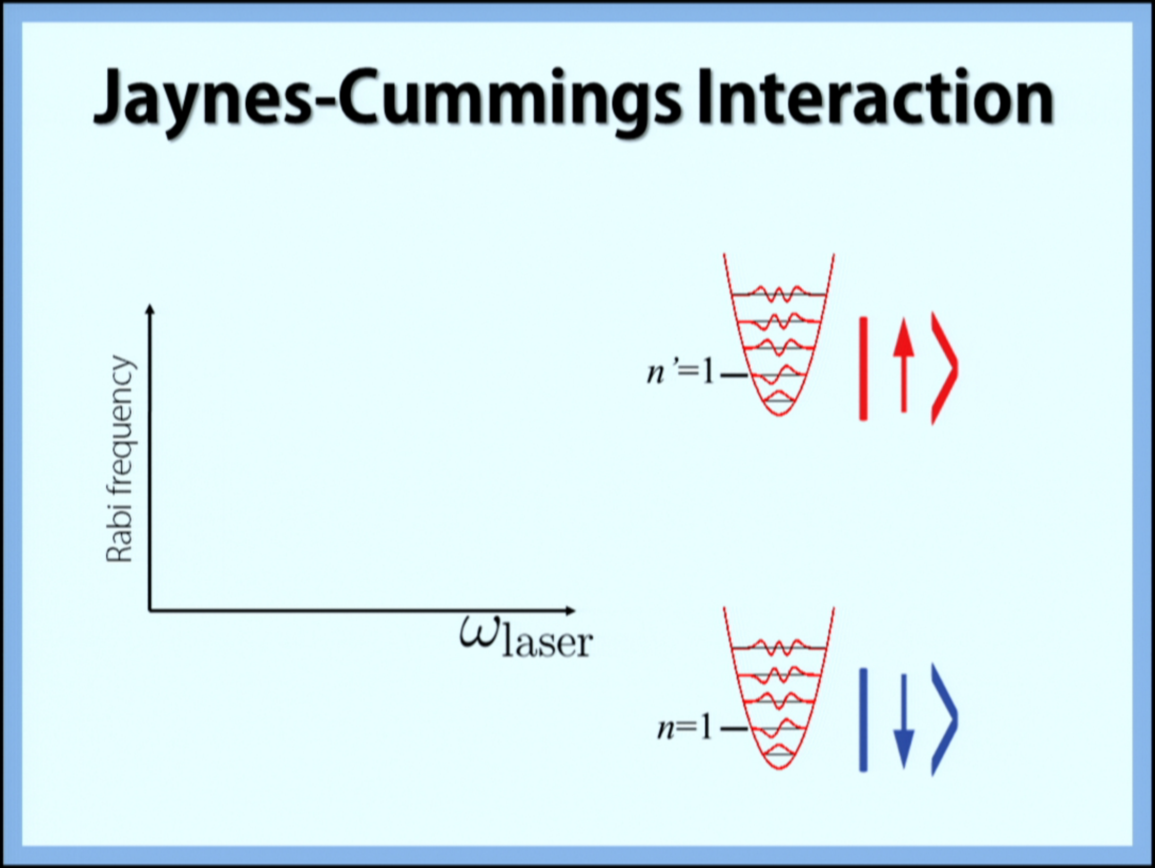



2 μm

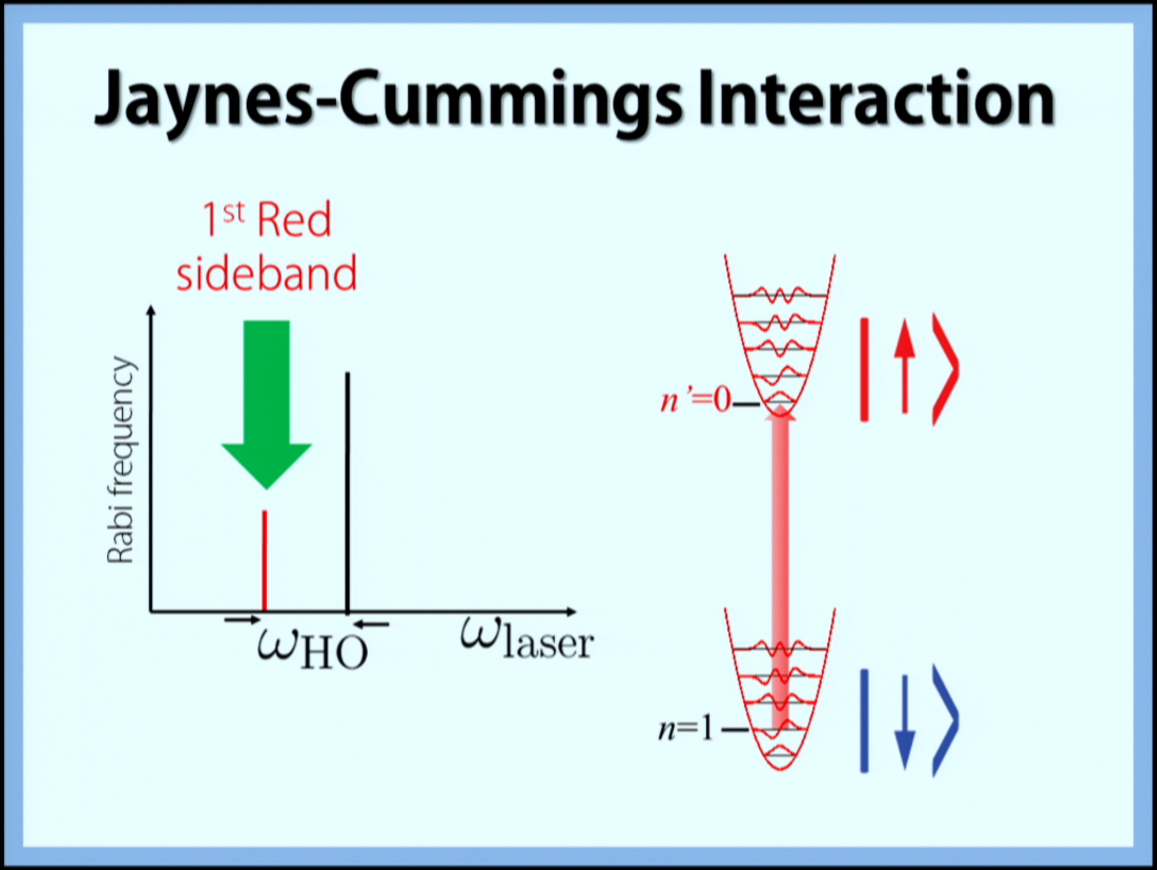
Trapped Ion Motion



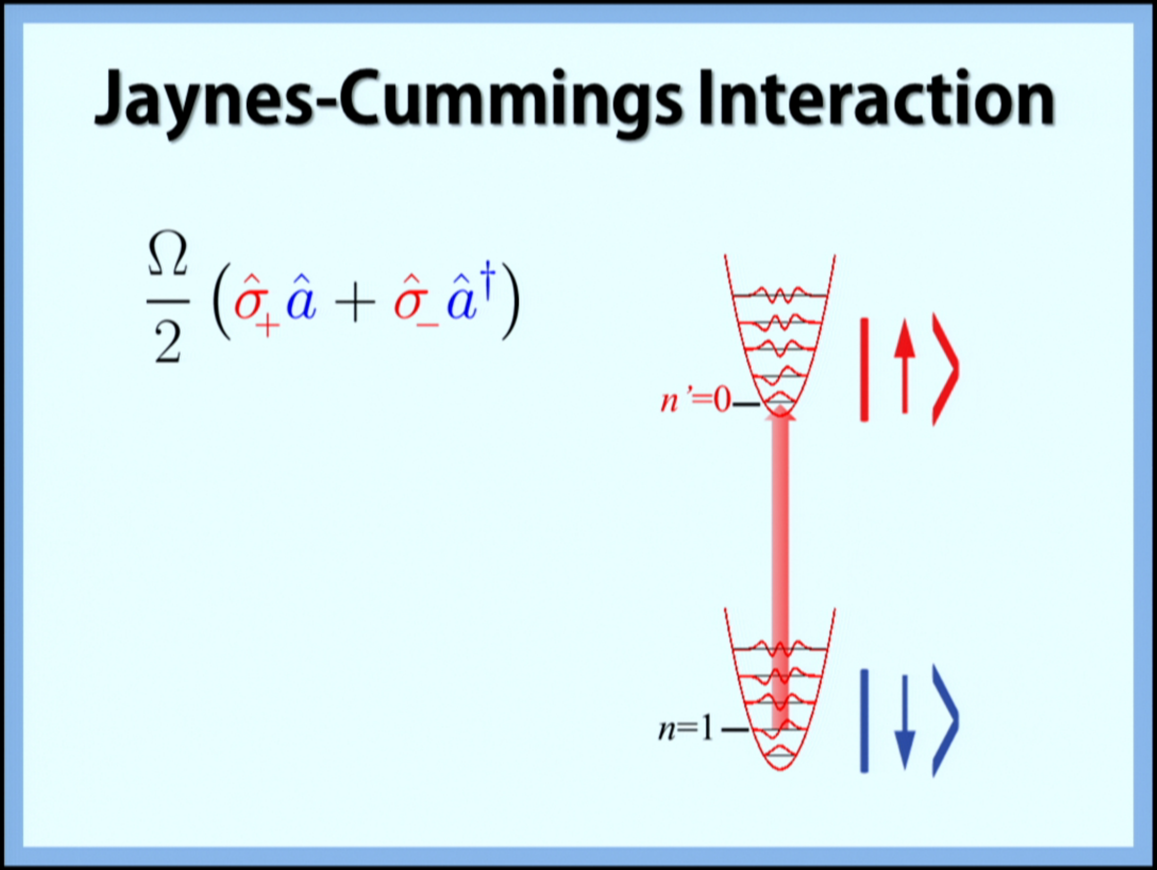
R. Blatt



Jaynes-Cummings Interaction

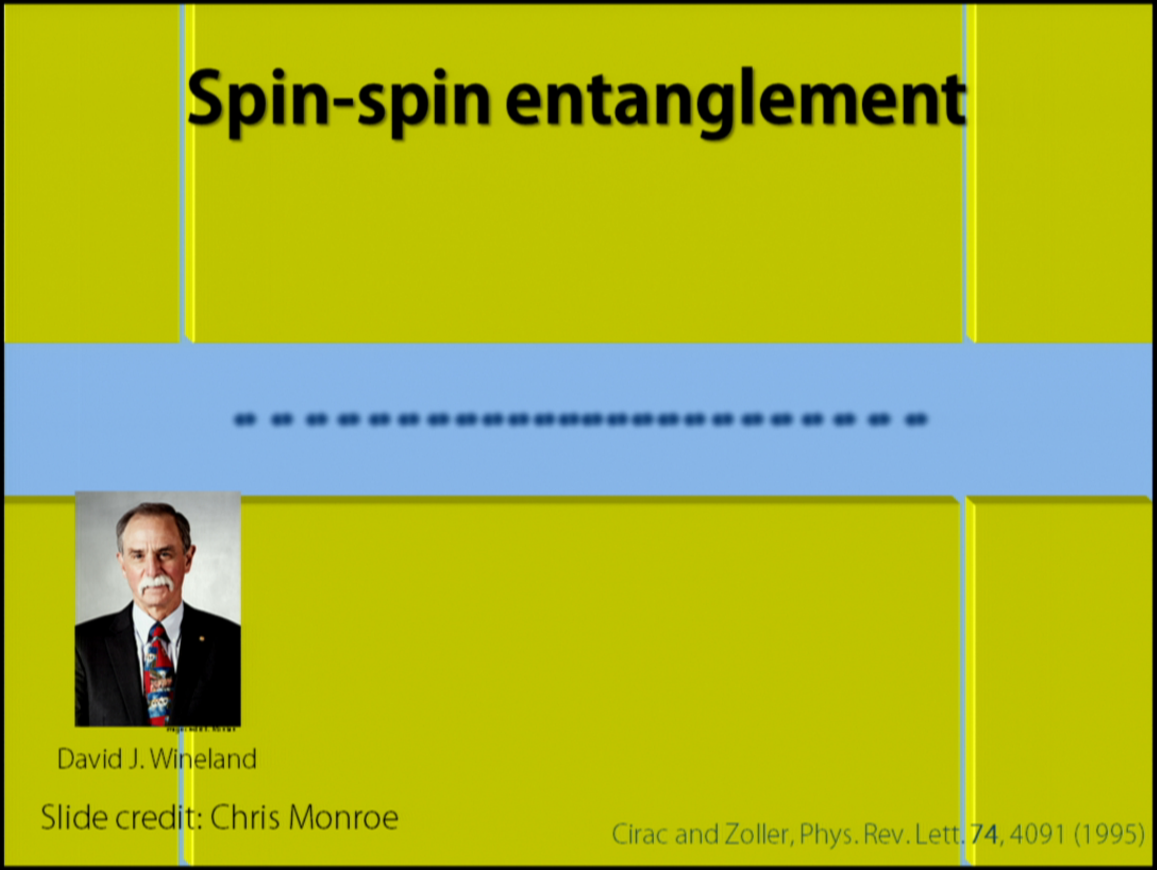


Jaynes-Cummings Interaction



Jaynes-Cummings Interaction

$$\frac{\Omega}{2}\left(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger\right)$$

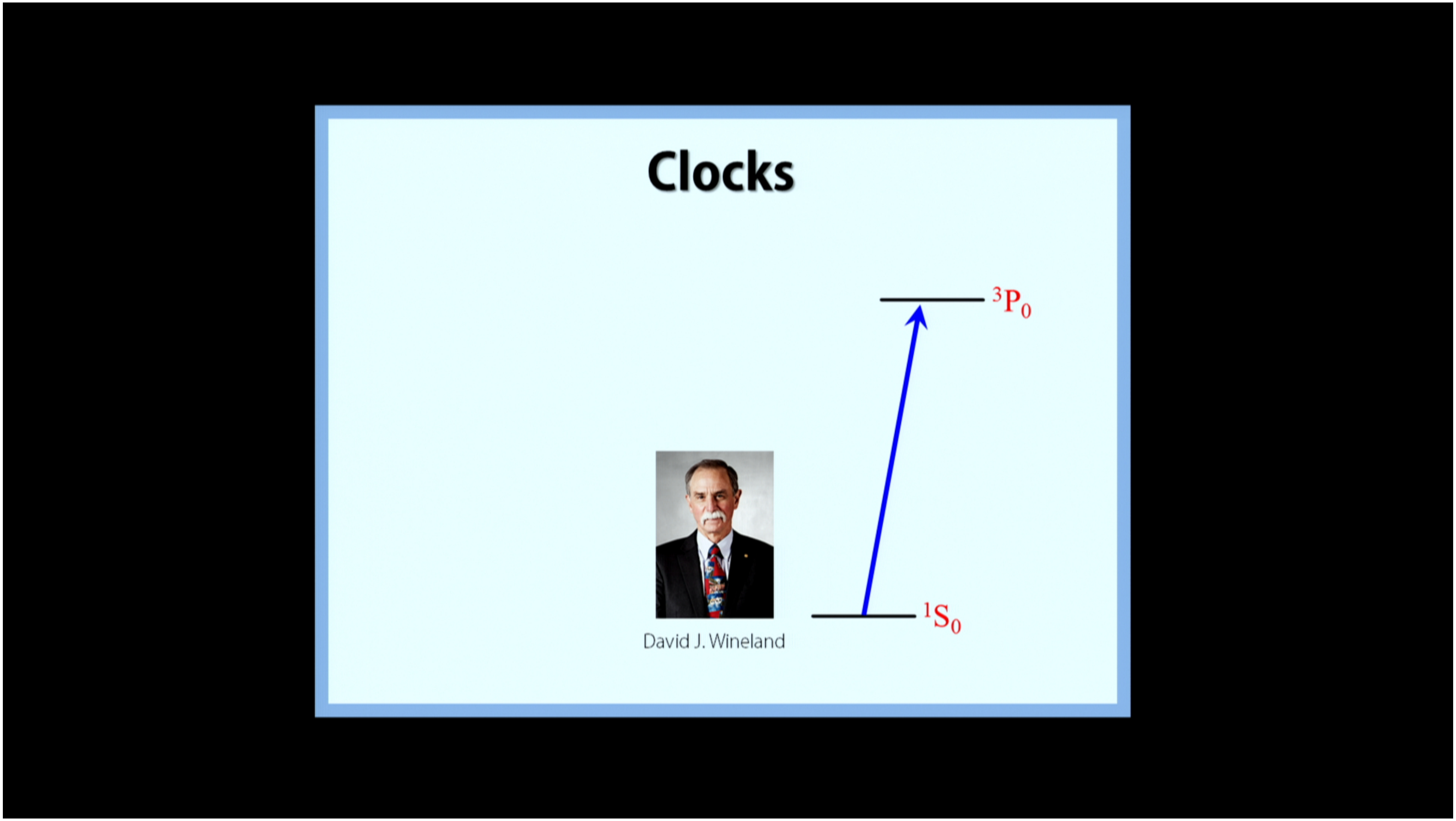


Spin-spin entanglement

David J. Wineland

Slide credit: Chris Monroe

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)

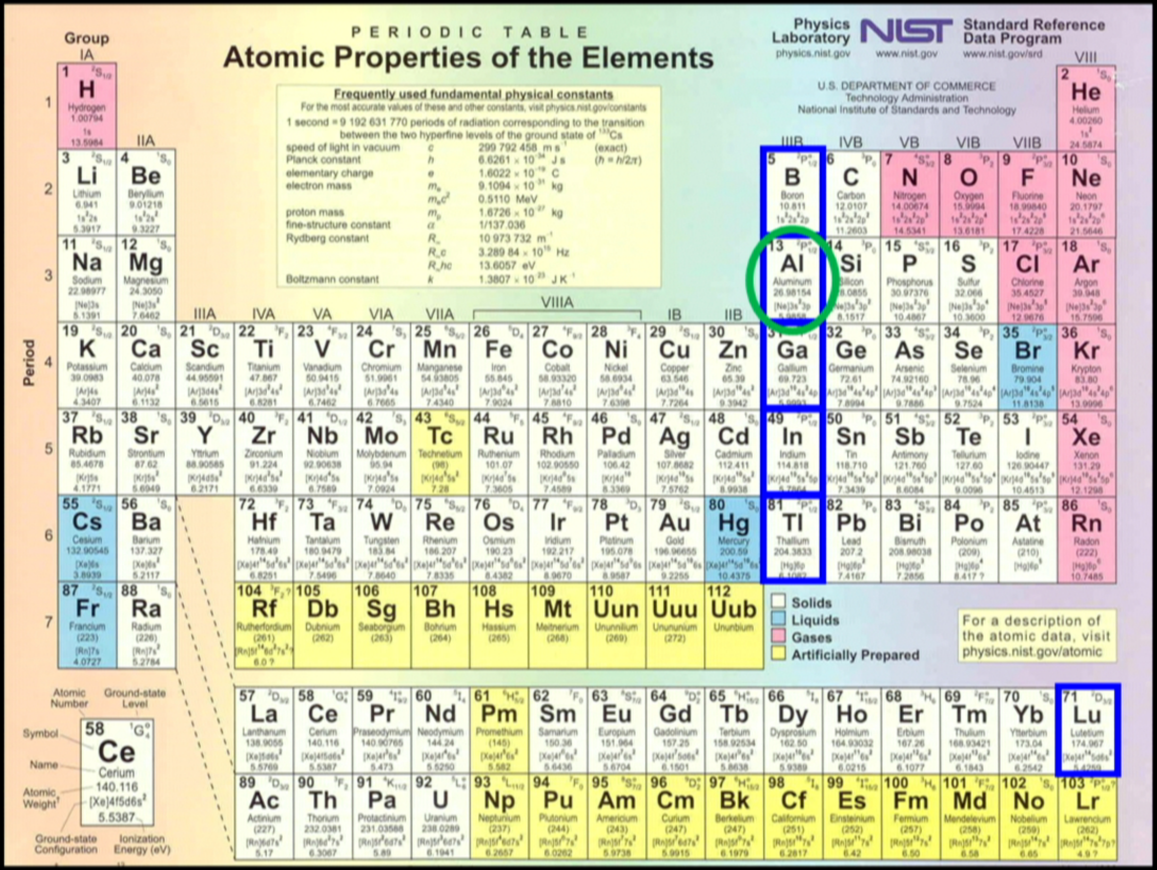


Clocks

$^3P_0$

$^1S_0$

David J. Wineland



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PERIODIC TABLE

Atomic Properties of the Elements

Frequently used fundamental physical constants

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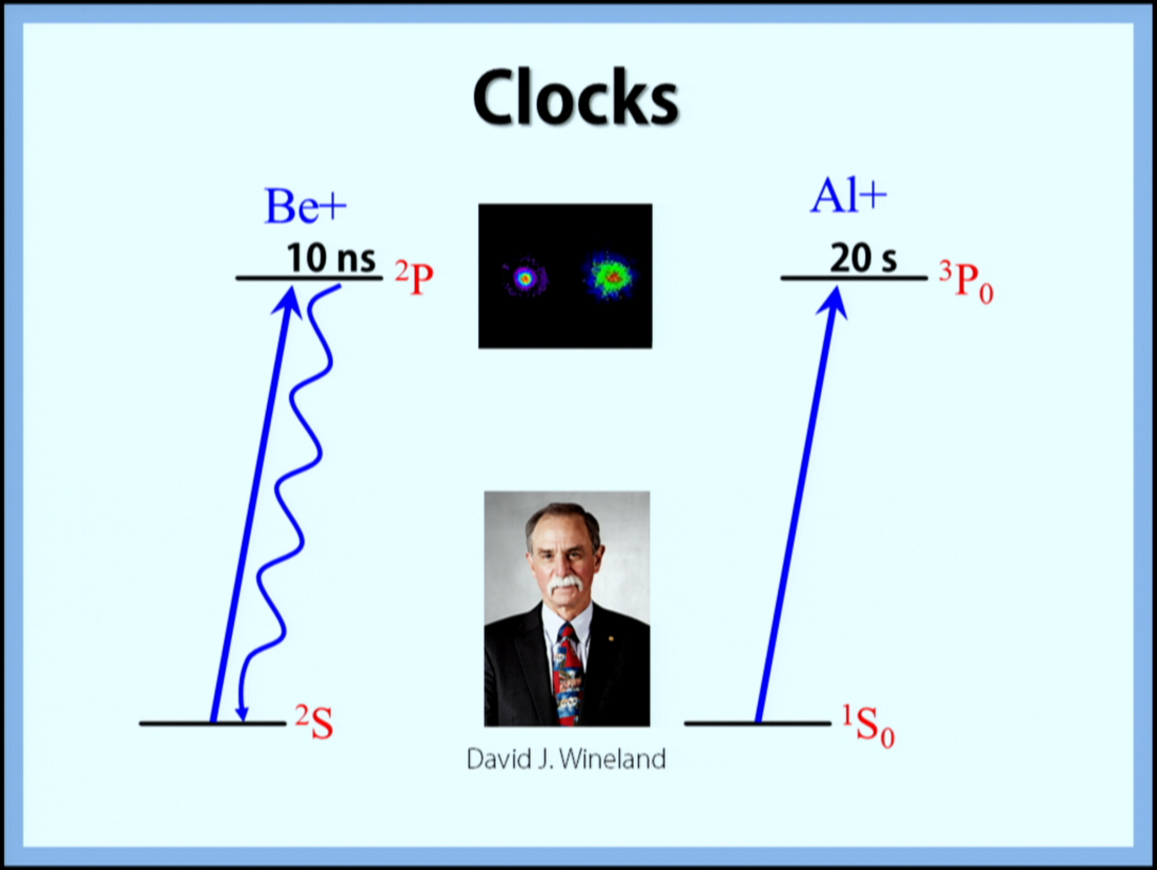
Period	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub						

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

- ☐ Solids
- ☐ Liquids
- ☐ Gases
- ☐ Artificially Prepared

For a description of the atomic data, visit physics.nist.gov/atomic



Clocks

Be+

10 ns ^2P

^2S

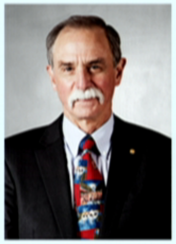
Al+

20 s $^3P_0$

$^1S_0$

David J. Wineland

Precision Measurement



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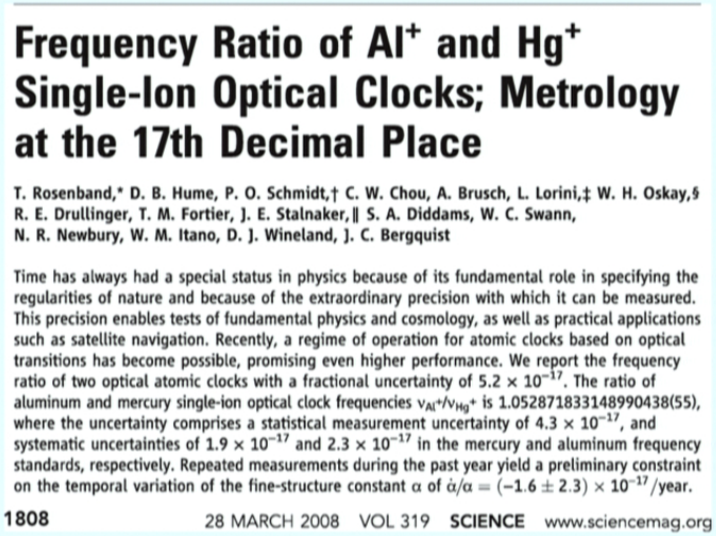
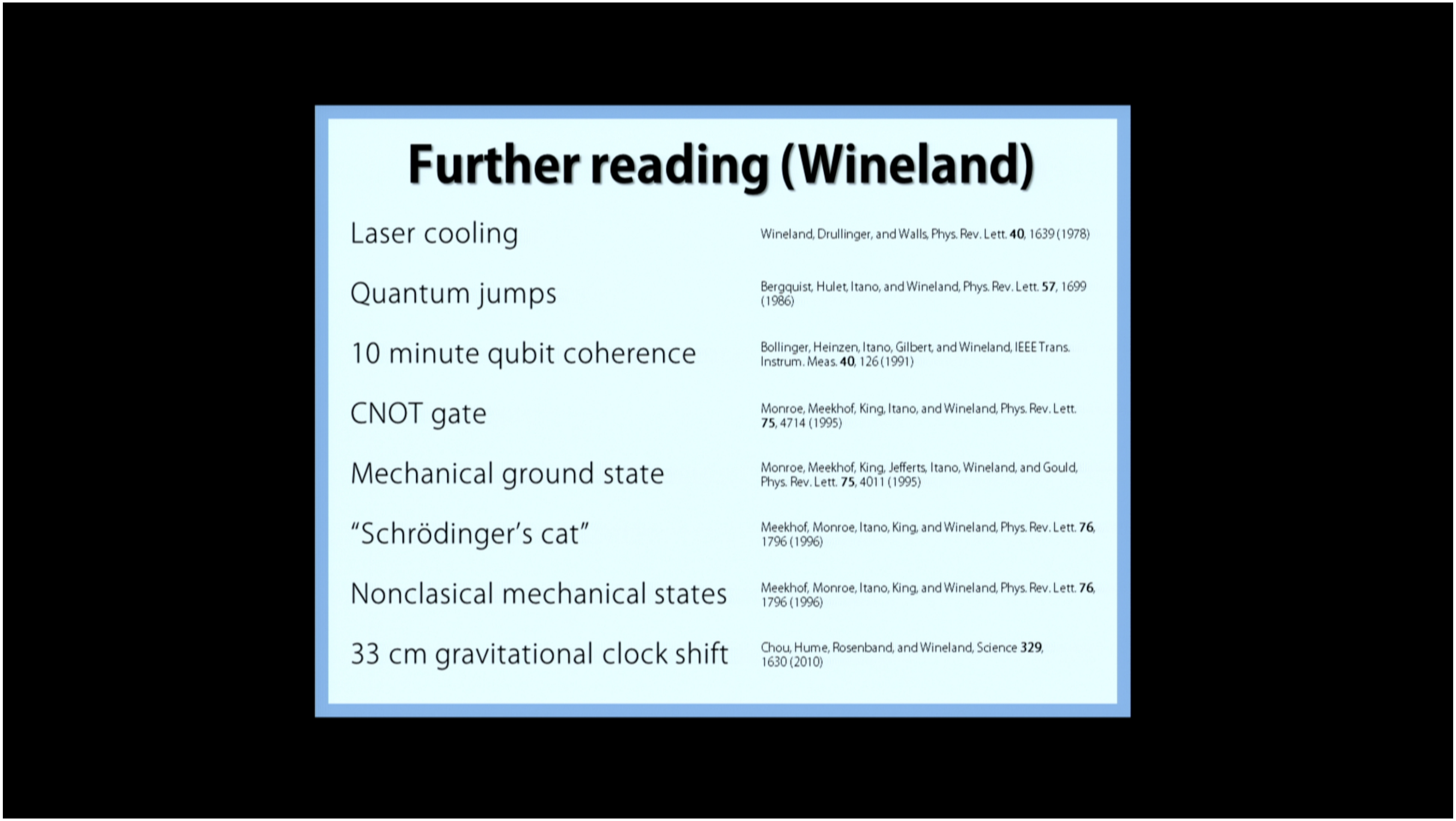


Frequency Ratio of Al^+ and Hg^+ Single-Ion Optical Clocks; Metrology at the 17th Decimal Place

T. Rosenband,* D. B. Hume, P. O. Schmidt,† C. W. Chou, A. Brusch, L. Lorini,‡ W. H. Oskay,§
R. E. Drullinger, T. M. Fortier, J. E. Stalnaker,‖ S. A. Diddams, W. C. Swann,
N. R. Newbury, W. M. Itano, D. J. Wineland, J. C. Bergquist

Time has always had a special status in physics because of its fundamental role in specifying the regularities of nature and because of the extraordinary precision with which it can be measured. This precision enables tests of fundamental physics and cosmology, as well as practical applications such as satellite navigation. Recently, a regime of operation for atomic clocks based on optical transitions has become possible, promising even higher performance. We report the frequency ratio of two optical atomic clocks with a fractional uncertainty of 5.2×10^{-17}. The ratio of aluminum and mercury single-ion optical clock frequencies ν_{Al^+}/ν_{Hg^+} is 1.052871833148990438(55), where the uncertainty comprises a statistical measurement uncertainty of 4.3×10^{-17}, and systematic uncertainties of 1.9×10^{-17} and 2.3×10^{-17} in the mercury and aluminum frequency standards, respectively. Repeated measurements during the past year yield a preliminary constraint on the temporal variation of the fine-structure constant α of $\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}$/year.

1808 28 MARCH 2008 VOL 319 **SCIENCE** www.sciencemag.org



Further reading (Wineland)

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Quantum jumps	Bergquist, Hulet, Itano, and Wineland, Phys. Rev. Lett. **57**, 1699 (1986)
10 minute qubit coherence	Bollinger, Heinzen, Itano, Gilbert, and Wineland, IEEE Trans. Instrum. Meas. **40**, 126 (1991)
CNOT gate	Monroe, Meekhof, King, Itano, and Wineland, Phys. Rev. Lett. **75**, 4714 (1995)
Mechanical ground state	Monroe, Meekhof, King, Jefferts, Itano, Wineland, and Gould, Phys. Rev. Lett. **75**, 4011 (1995)
“Schrödinger’s cat”	Meekhof, Monroe, Itano, King, and Wineland, Phys. Rev. Lett. **76**, 1796 (1996)
Nonclasical mechanical states	Meekhof, Monroe, Itano, King, and Wineland, Phys. Rev. Lett. **76**, 1796 (1996)
33 cm gravitational clock shift	Chou, Hume, Rosenband, and Wineland, Science **329**, 1630 (2010)