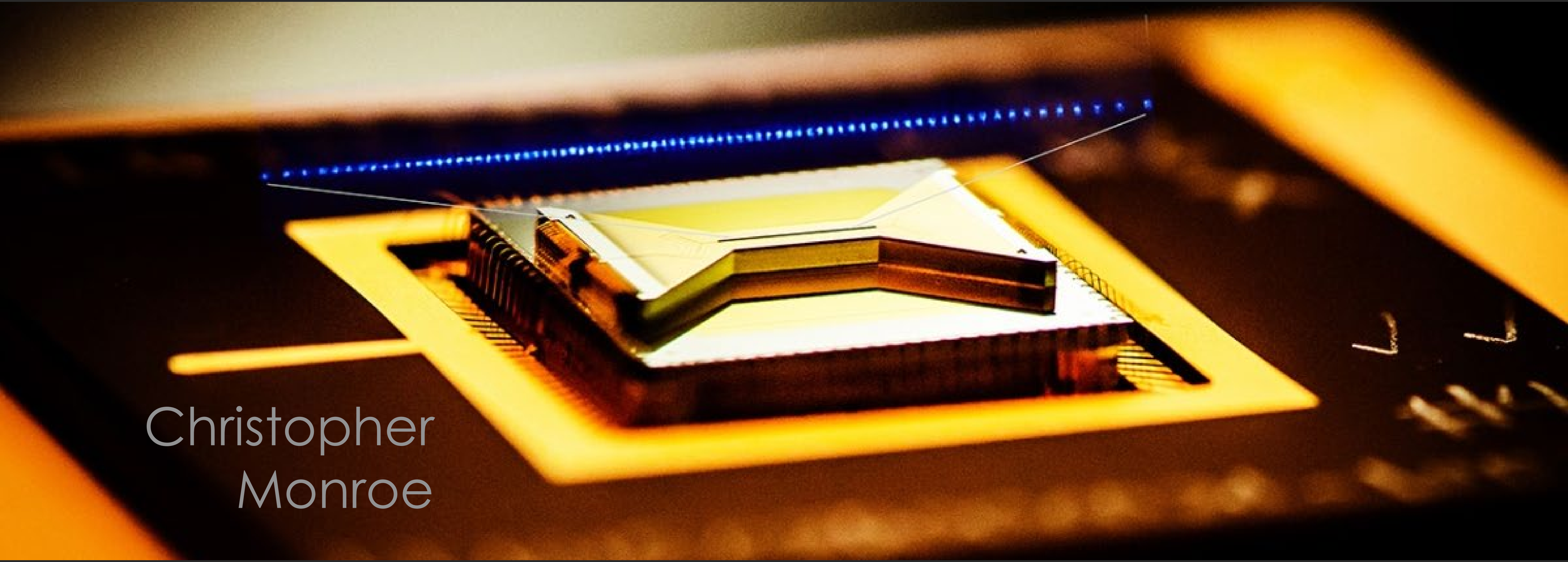
Quantum Simulation and Computing with Atomic Ions



Christopher Monroe

UNIVERSITY OF MARYLAND

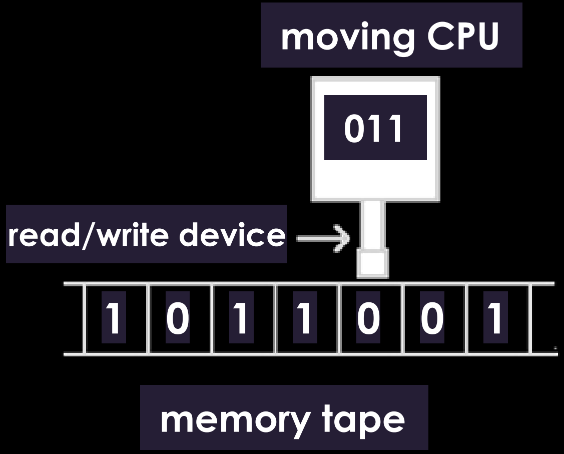
Duke UNIVERSITY

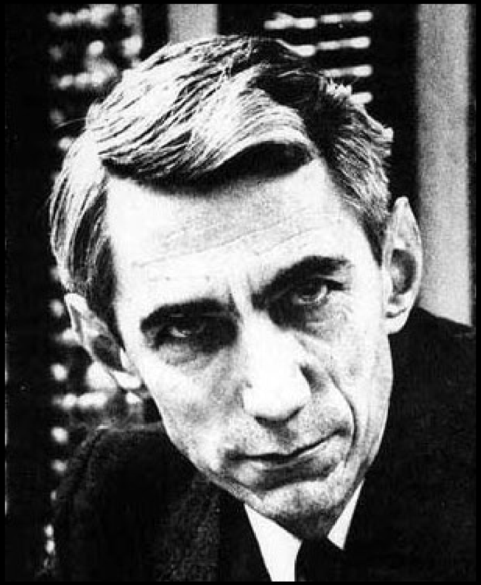
Duke Quantum Center

IONQ

Computing and Information

Alan Turing (1912-1954)
universal computing machines



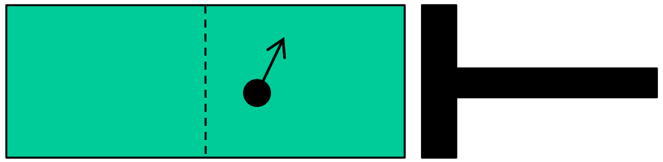


Claude Shannon (1916-2001)
quantify information: the bit

$$H = -\sum_{i=1}^{k} p_i log_2 p_i$$

Quantum Information Theory

Classical Information Entropy $S = -\sum_{i=1}^{k} p_i \log_2 p_i$



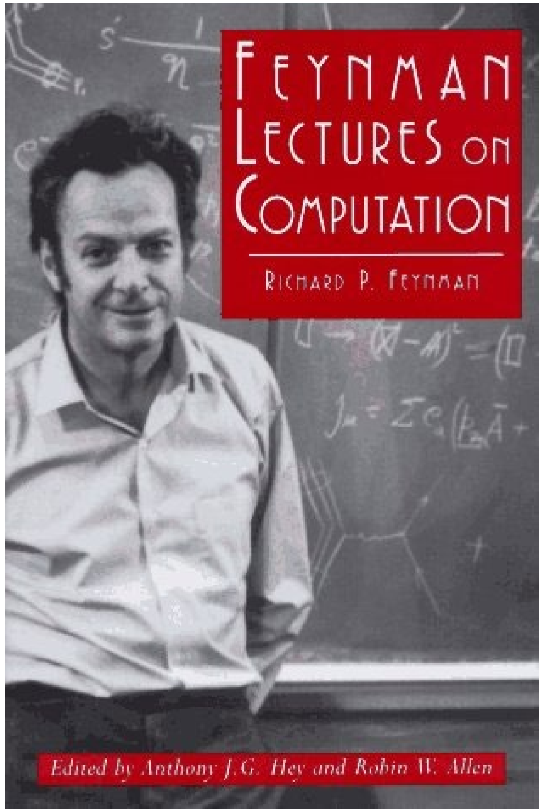
single atom “ideal gas”

Classical Information: $S(AB) \geq S(A) + S(B)$

Entangled qubits: $\psi_{AB} = |\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle$

$S(AB) = \mathbf{0}$ but.... $S(A) > 0$
$S(B) > \mathbf{0}$

$S(AB) < S(A) + S(B)$!



Quantum Error Correction

CLASSICAL: Shannon (1948)
Calderbank, Shor, Steane (1995)
Bravyi, Kitaev (1998)

$$\alpha|0\rangle + \beta|1\rangle \quad \Longrightarrow$$

error
prob. p

Decoherence

error prob. p (per qubit)

$$\alpha\begin{pmatrix} |00000\rangle + |10010\rangle + |01001\rangle + |10100\rangle \\ +|01010\rangle - |11011\rangle - |00110\rangle - |11000\rangle \\ -|11101\rangle - |00011\rangle - |11110\rangle - |01111\rangle \\ -|10001\rangle - |01100\rangle - |10111\rangle + |00101\rangle \end{pmatrix} + \beta\begin{pmatrix} |11111\rangle + |01101\rangle + |10110\rangle + |01011\rangle \\ +|10101\rangle - |00100\rangle - |11001\rangle - |00111\rangle \\ -|00010\rangle - |11100\rangle - |00001\rangle - |10000\rangle \\ -|01110\rangle - |10011\rangle - |10111\rangle + |11010\rangle \end{pmatrix}$$

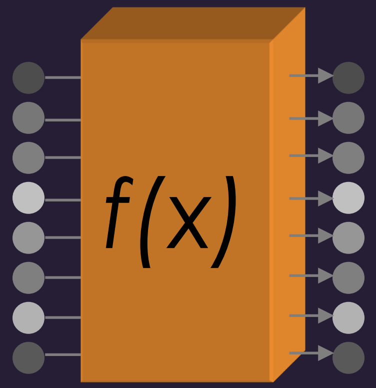
$$\boxed{p \Longrightarrow Cp^2}$$

Improved performance (so long as $p < 1/C$)

Good News...

parallel processing
on 2^N inputs

e.g., *N*=3 qubits

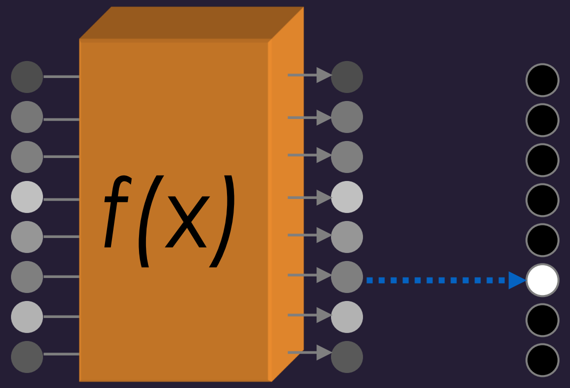


$$a_0\,|000\rangle + a_1|001\rangle + a_2\,|010\rangle + a_3\,|011\rangle$$
$$a_4\,|100\rangle + a_5|101\rangle + a_6\,|110\rangle + a_7\,|111\rangle$$

N=300 qubits have more configurations than there are particles in the universe!

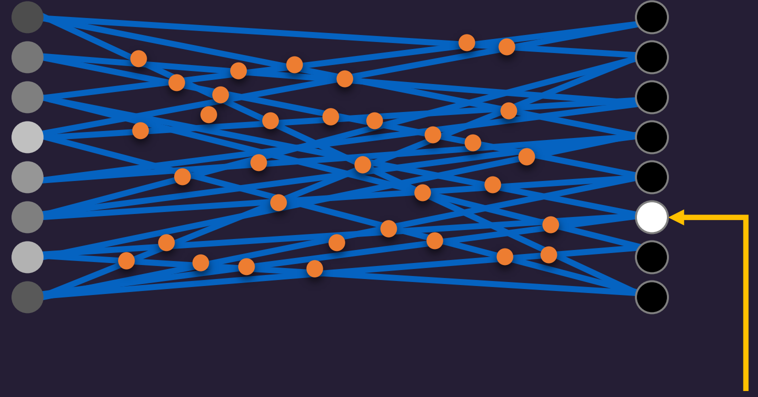
...Bad News...

measurement gives
random result



...Good News!

quantum interference



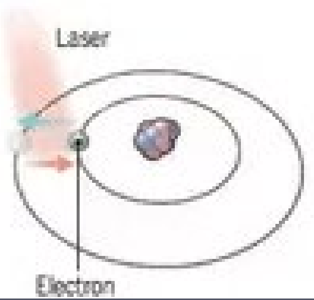
**depends
on *all* inputs**

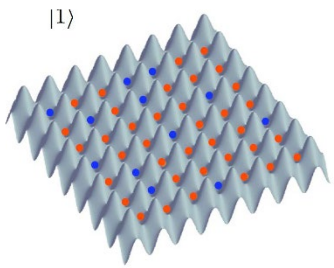
Why is Quantum Computing Interesting to Physics (and Ultracold Matter)?

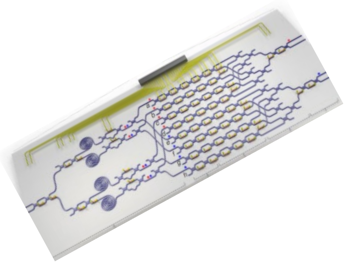
1. Entanglement is the root of all difficulty in many-body physics (see condensed-matter, nuclear, cosmology)

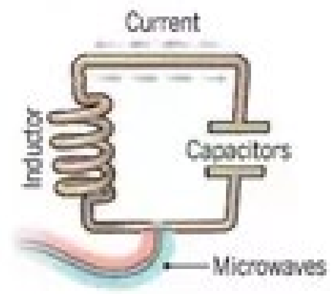
2. Ultracold matter is the basis for all well-performing qubits

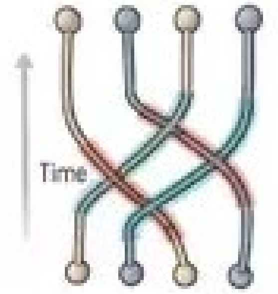
Quantum Computer Technologies

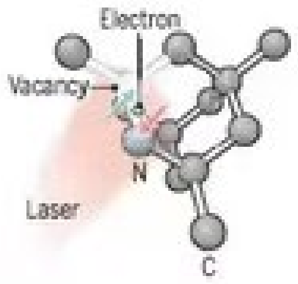












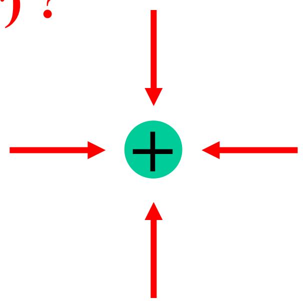
	Natural Qubits			Synthetic Qubits			
	Trapped Ions	**Neutral Atoms**	**Photonics**	**Superconducting Loops**	**Silicon Quantum Dots**	**Topological Qubits**	**Diamond Vacancies**
	Electrically charged atoms, or ions, are held in place with electric fields. Qubits are stored in electronic states. Ions are pushed with laser beams to allow the qubits to interact.	Neutral atoms, like ions, store qubits within electronic states. Laser activates the electrons to create interaction between qubits.	Photonic qubits (light particles) are sent through a maze of optical channels on a chip to interact. At the end of the maze, the distribution of photons is measured as an output.	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Qubit Coherence Time (sec)	>1000	1	--	0.00005	0.03	N/A	10
Fidelity	99.9%	97%	--	99.4%	~99%	N/A	99.2%
Qubits Connected	High	Very high; low individual control	--	High	Very Low	N/A	Low
Company Support	IONQ, AQT, Honeywell, Oxford Ionics	Atom Computing, ColdQuanta, QuEra	Psiquantum, Xanadu	Google, IBM, QCI, Rigetti	HRL, Intel, SQC	Microsoft	Quantum Diamond Technologies
Pros	Very stable. Highest achieved gate fidelities.	Many qubits, 2D and maybe 3D.	Linear optical gates, integrated on-chip.	Can lay out physical circuits on chip.	Borrows from existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Slow operation. Many lasers are needed.	Hard to program and control individual qubits; prone to noise.	Each program requires its own chip with unique optical channels. No memory.	Must be cooled to near absolute zero. High variability in fabrication. Lots of noise.	Only a few connected. Must be cooled to near absolute zero. High variability in fabrication.	Existence not yet confirmed.	Difficult to create high numbers of qubits, limiting compute capacity.

Source: Science, Dec. 2016

Ion Traps

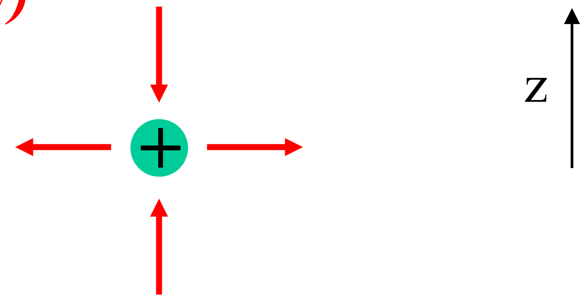
How to trap an ion

E(r) ?



NO! $\nabla\cdot\mathbf{E} = 0$

E(r)



quadrupole: $\mathbf{E}(\boldsymbol{r}) = \varepsilon(\boldsymbol{x} + \boldsymbol{y} - 2\boldsymbol{z})$

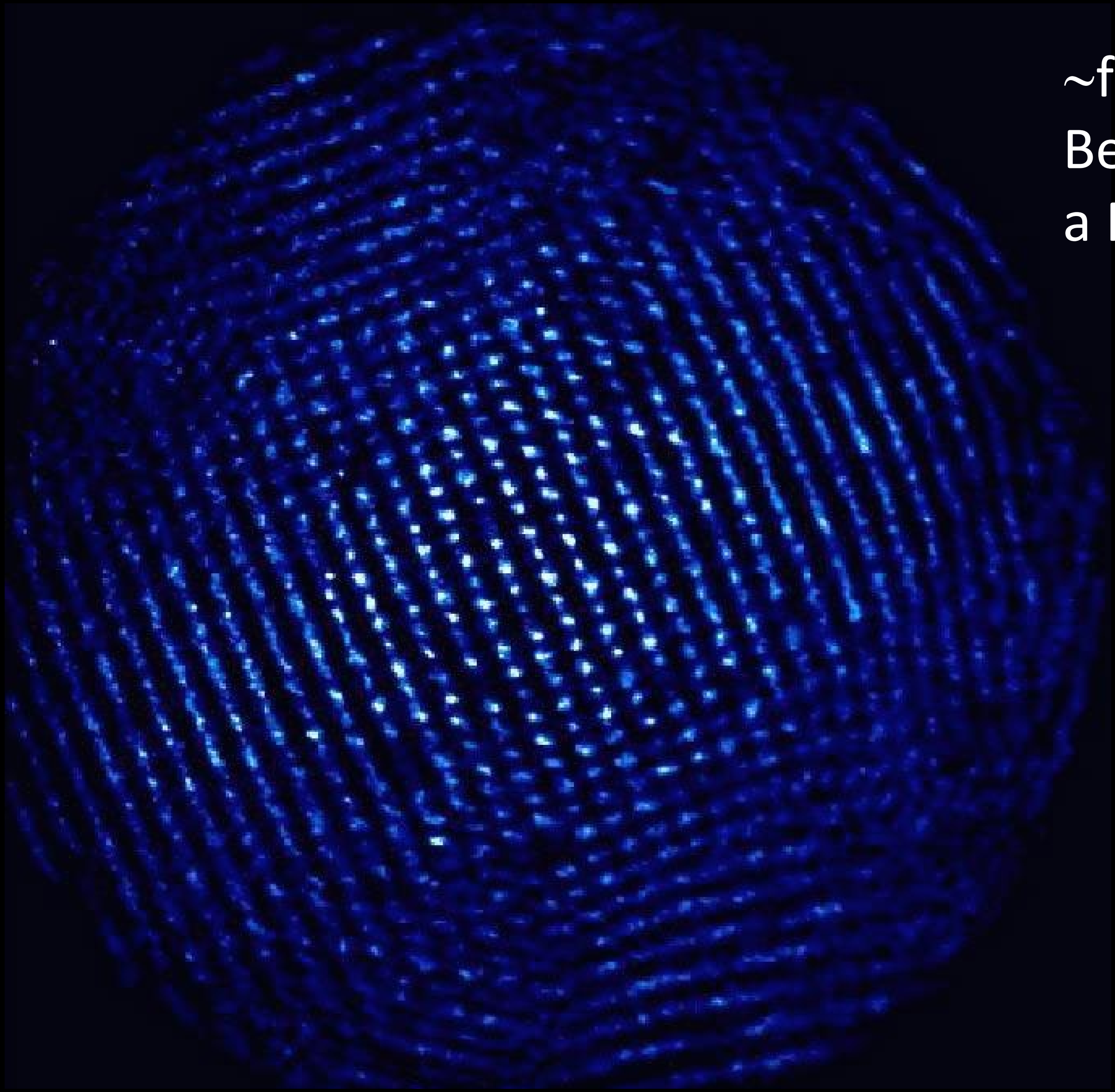
Ion Trap Tricks to "get around" $\nabla\cdot\mathbf{E} = 0$:

(1) Apply magnetic field along z; e$\mathbf{v}\times\mathbf{B}$ Lorentz force confines in xy plane

PENNING TRAP

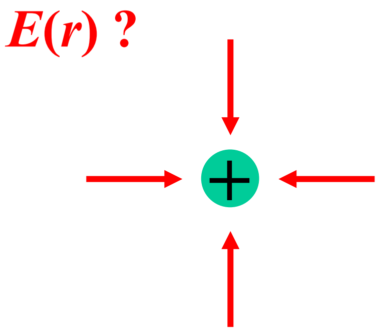
- large capacity (1-10^8)
- ions rotate around z
- confinement frequency limited by $\omega_c = \dfrac{eB}{mc}$

$m = 9$ amu
$B = 1$ T
$\boldsymbol{\omega_c = 2\pi(1\ \mathrm{MHz})}$

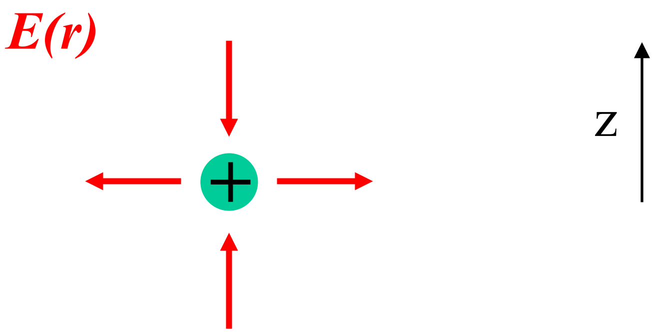


~few 1000
Be^{+} ions in
a Penning Trap

J. Bollinger, NIST
A. M. Rey, JILA



NO! $\nabla\cdot\mathbf{E} = 0$



quadrupole: $\mathbf{E}(\boldsymbol{r}) = \varepsilon(\boldsymbol{x} + \boldsymbol{y} - 2\boldsymbol{z})$

Ion Trap Tricks to "get around" $\nabla\cdot\mathbf{E} = 0$:

(1) Apply magnetic field along z; e$\mathbf{v}\times\mathbf{B}$ Lorentz force confines in xy plane

PENNING TRAP

- large capacity (1-10^8)
- ions rotate around z
- confinement limited by eB/mc

(2) Apply sinusoidal electric field quadrupole (like rotating saddle)

RF (PAUL) TRAP

- ions stationery (on average)
- strong confinement

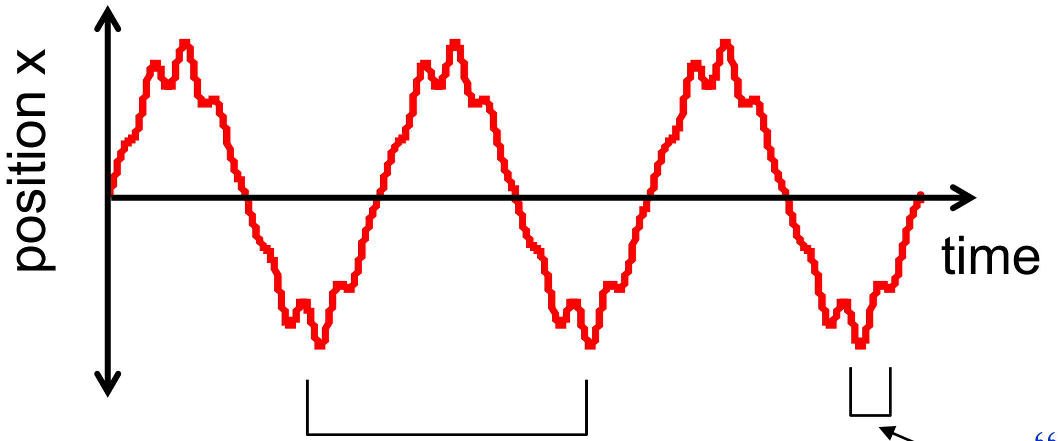
W. Paul & H. Dehmelt
Adv. At. Mol. Phys. 3, 53 (1967)
Rev. Mod. Phys, 62, 531 (1990)

Dynamics of a single ion in a rf trap

$$\ddot{x} + (\kappa^2 \cos\Omega t)x = 0 \qquad \kappa^2 = \frac{eV_0}{mR^2}$$

R = "characteristic" distance from ion to electrode

Mathieu Equation: $x(t)$ bounded for $\kappa \ll \Omega$ $\quad x(t) = x_0\left(1 + \frac{\kappa^2}{\Omega^2}\cos\Omega t\right)\cos\omega t$



"micromotion" at frequency Ω

"secular" motion at frequency $\omega = \frac{\kappa^2}{\sqrt{2}\Omega}$

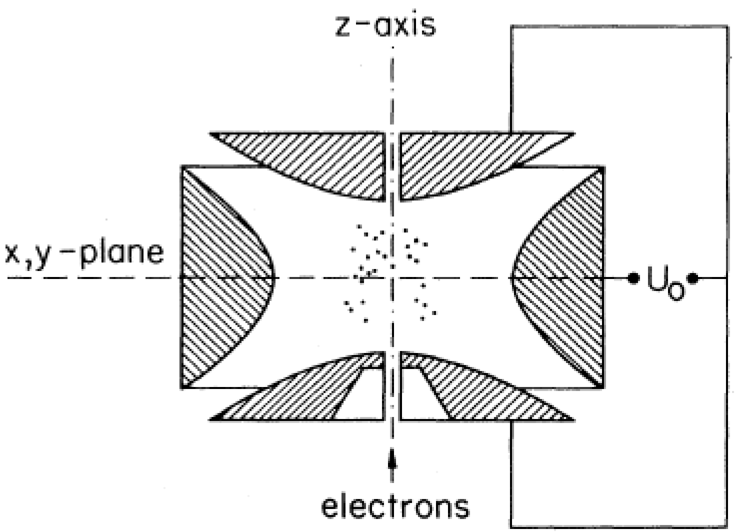
"ponderomotive potential"

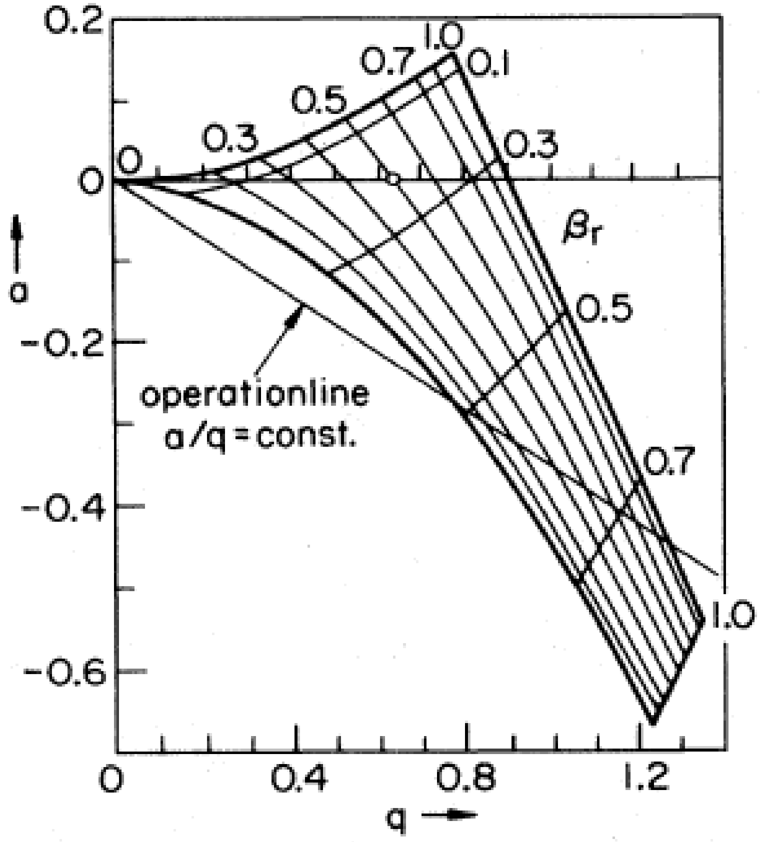
Electromagnetic traps for charged and neutral particles

Wolfgang Paul

Physikalisches Institut, Universität Bonn, Bonn, Germany

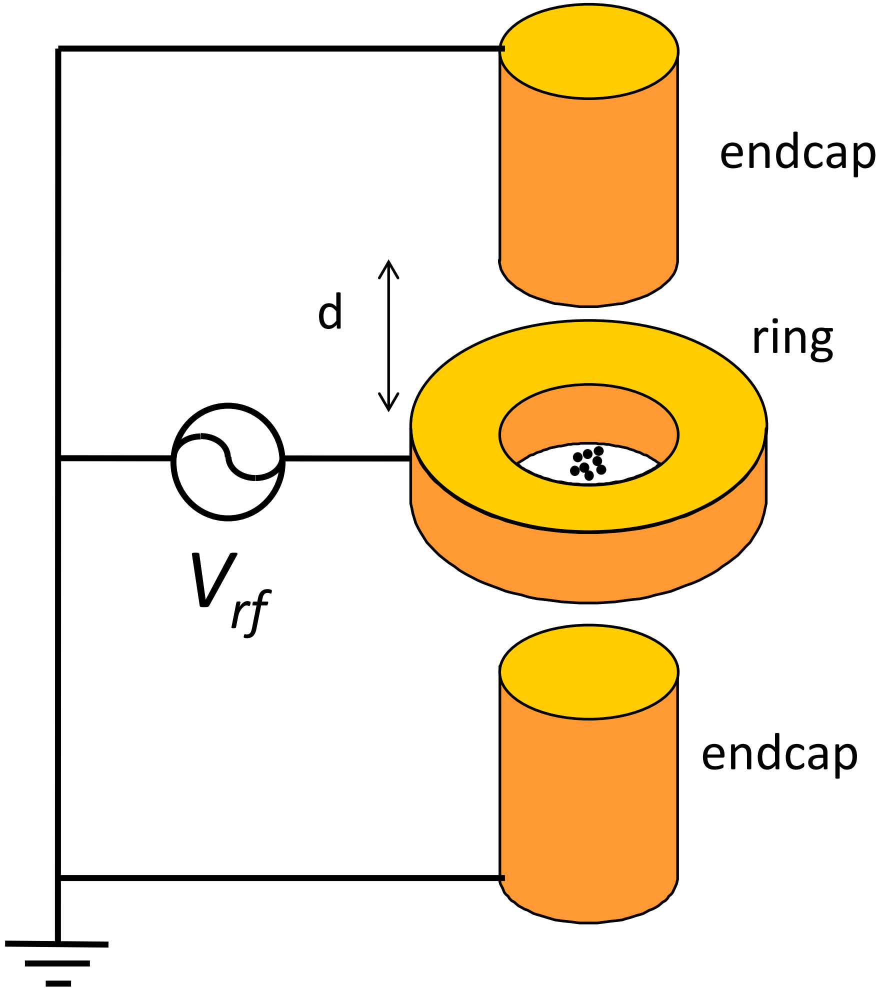
Reviews of Modern Physics, Vol. 62, No. 3, July 1990

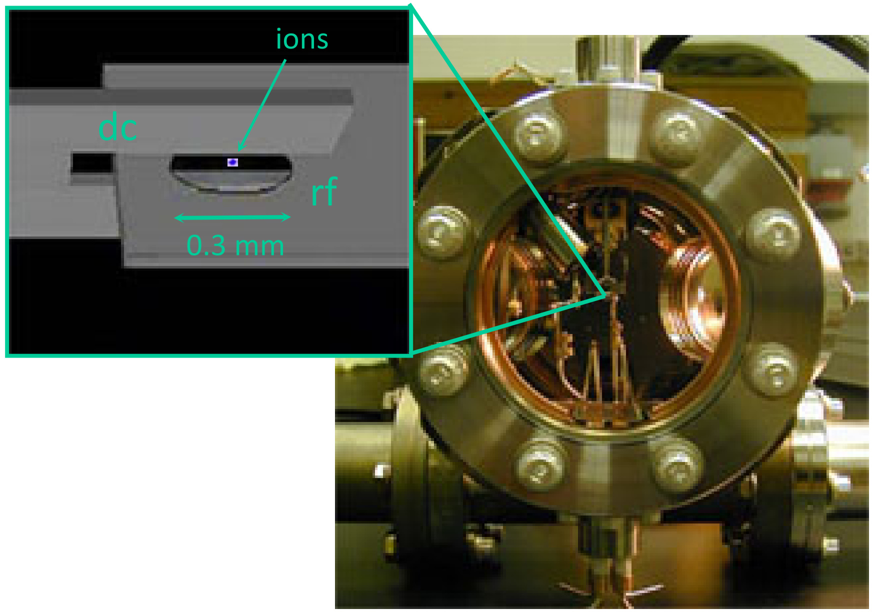




$$\ddot{x} + (a + 2q\cos 2\tau)x = 0$$

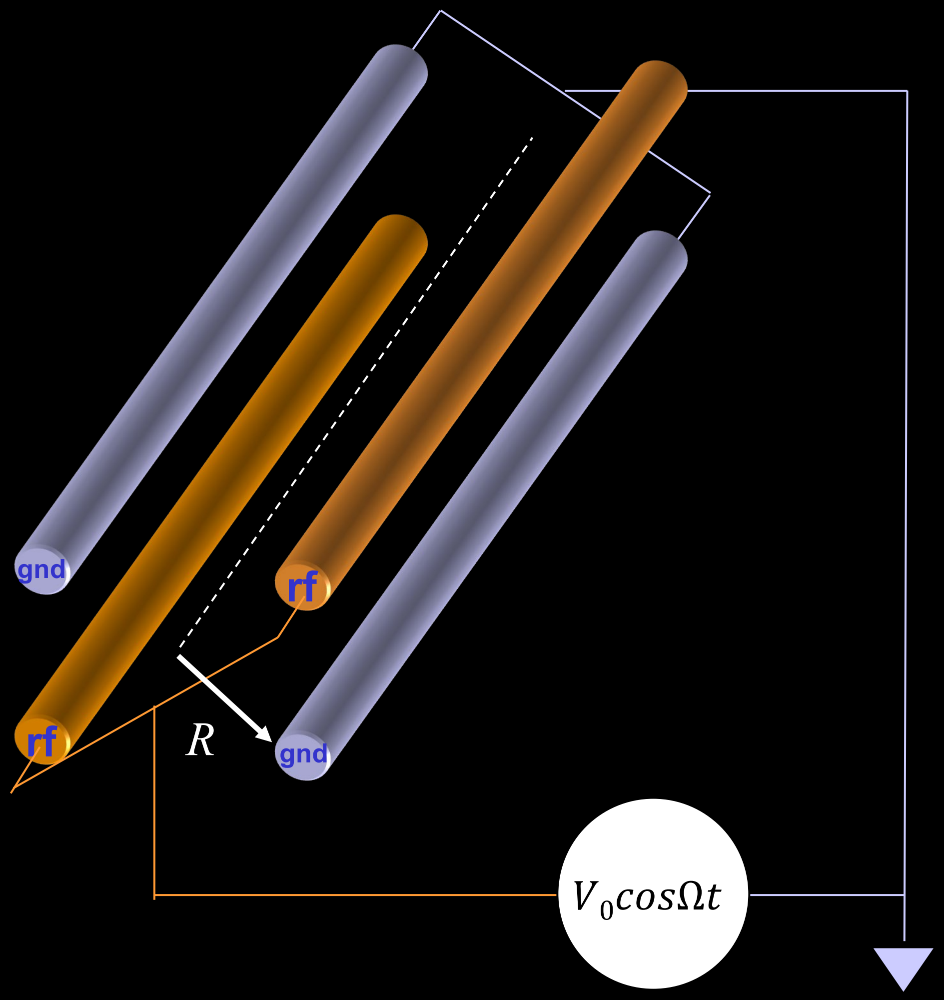
3D ion trap geometry





"Linear" hybrid RF/DC Ion Trap

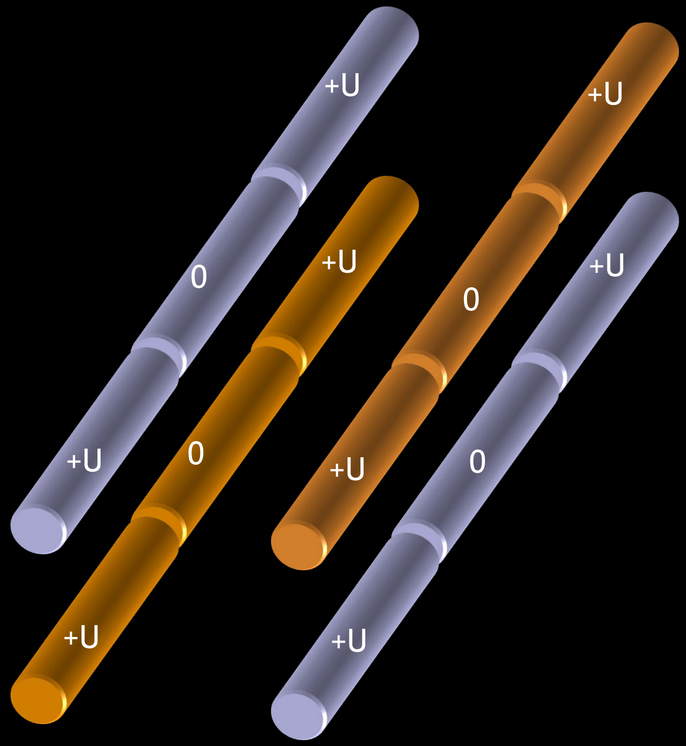
transverse confinement:
2D rf ponderomotive potential

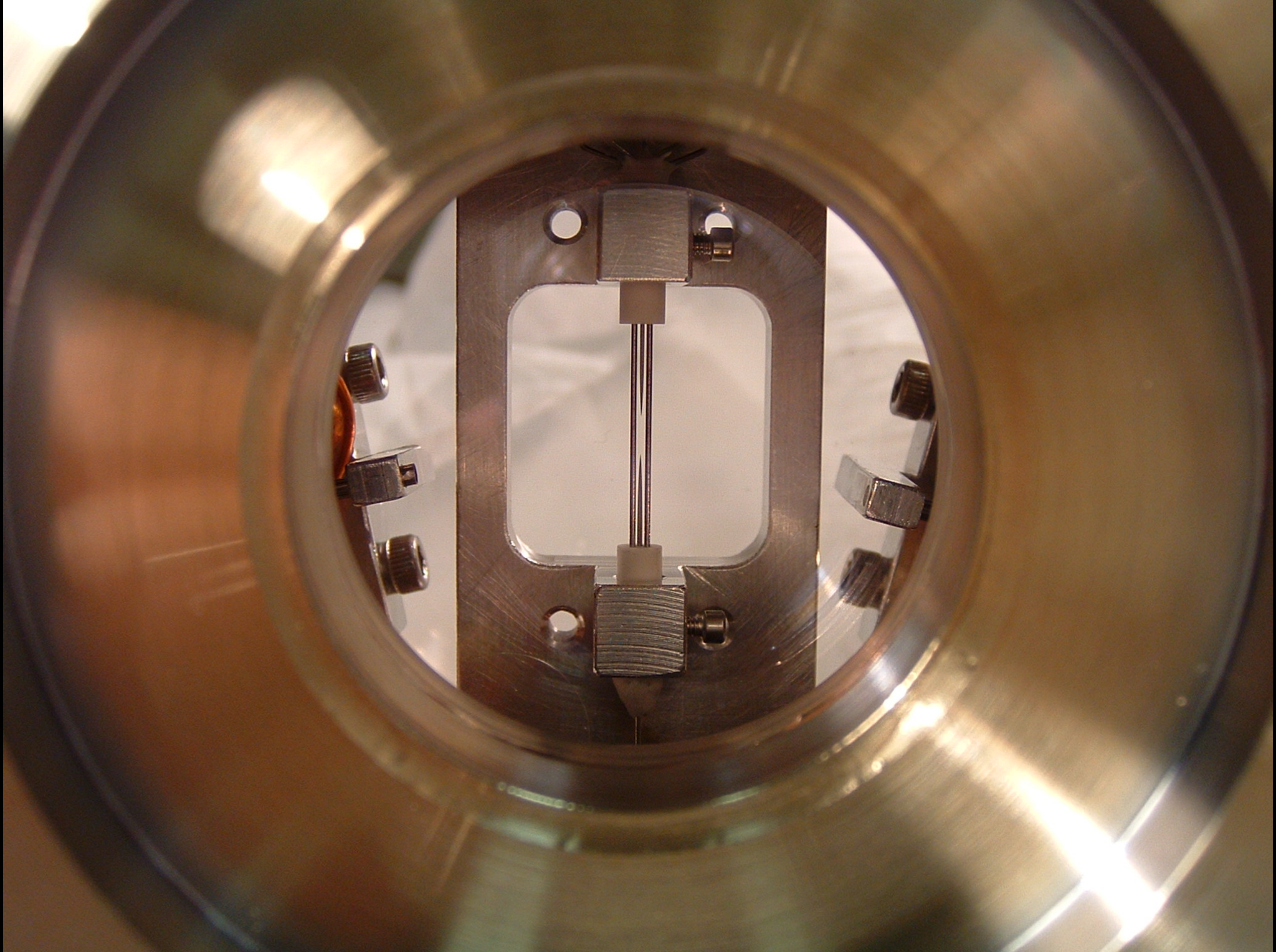


$$\omega_r = \frac{2\sqrt{2}eV_0}{m\Omega R^2} = \sqrt{\frac{qeV_0}{mR^2}}$$

“Linear” hybrid RF/DC Ion Trap

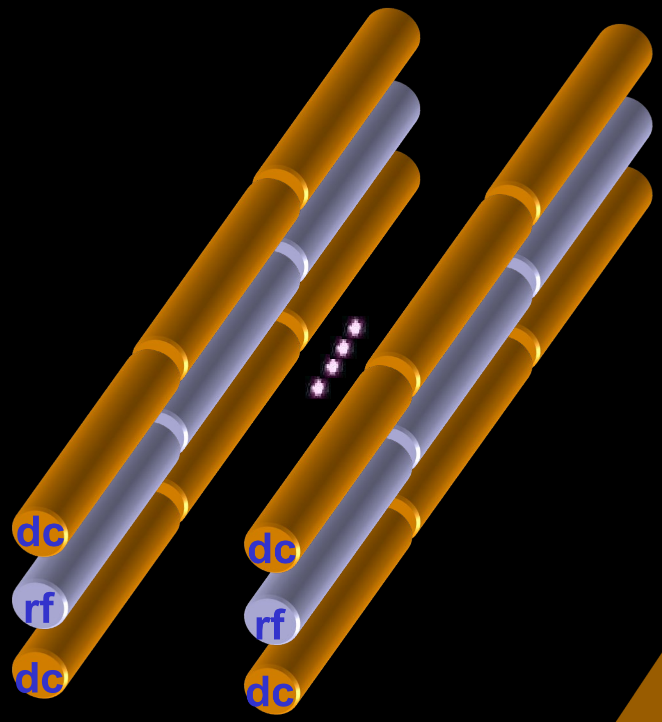
axial confinement:
static “endcaps”

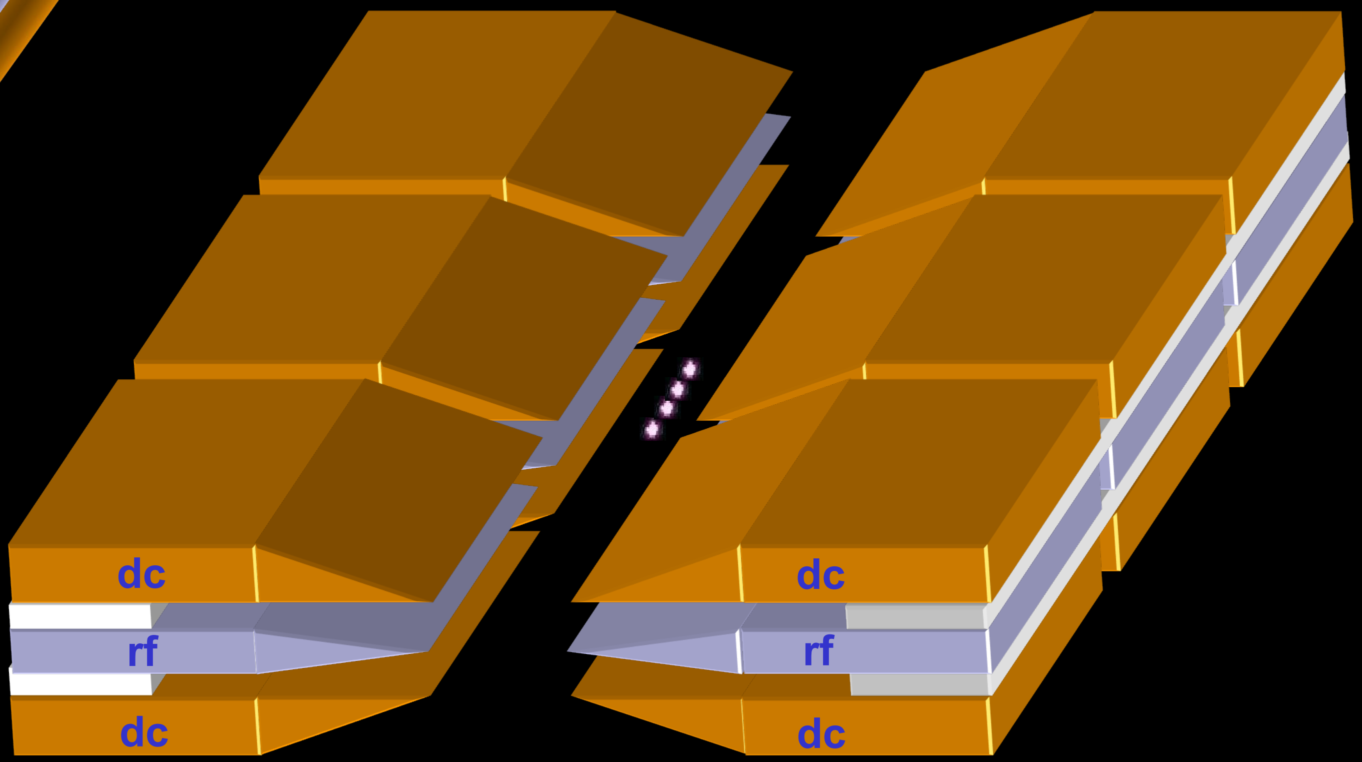


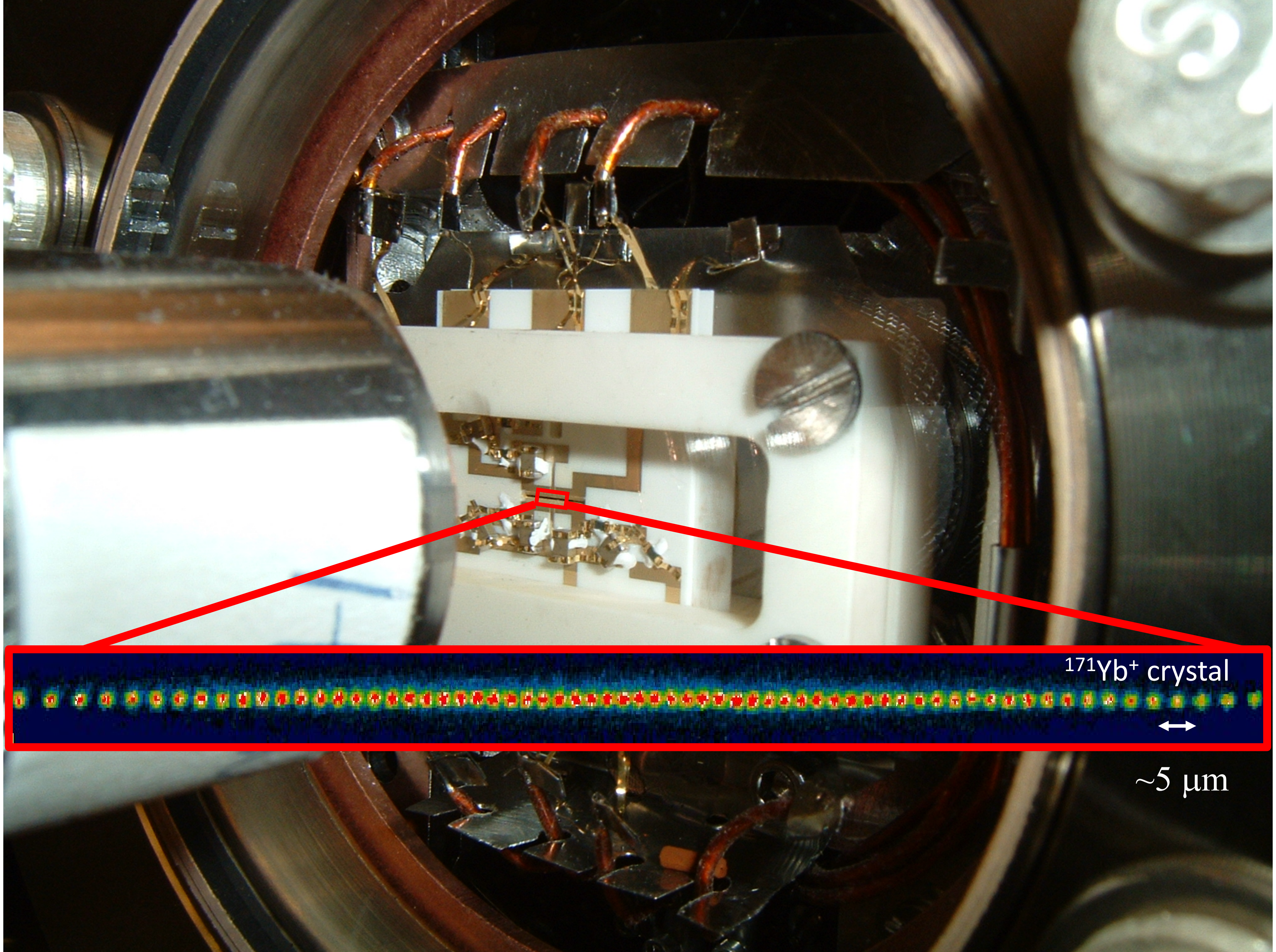


3-layer geometry:

- allows 3D offset compensation
- scalable to larger structures

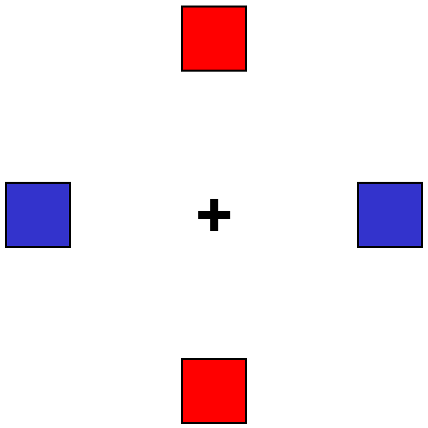




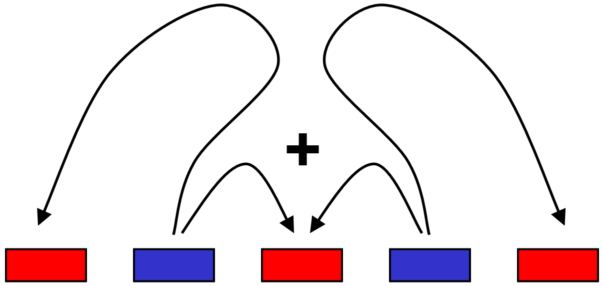


$^{171}Yb^{+}$ crystal
~5 μm

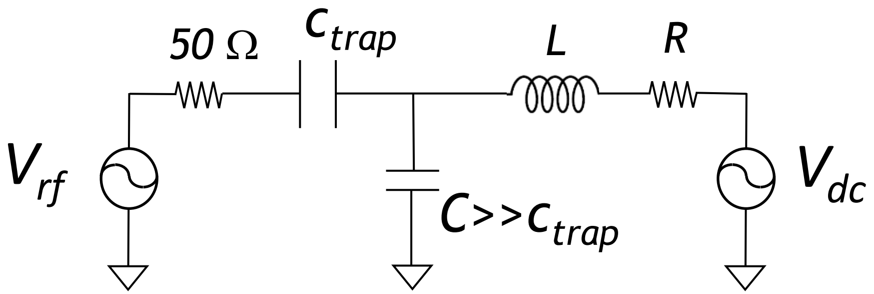
Planar Geometry Niceties

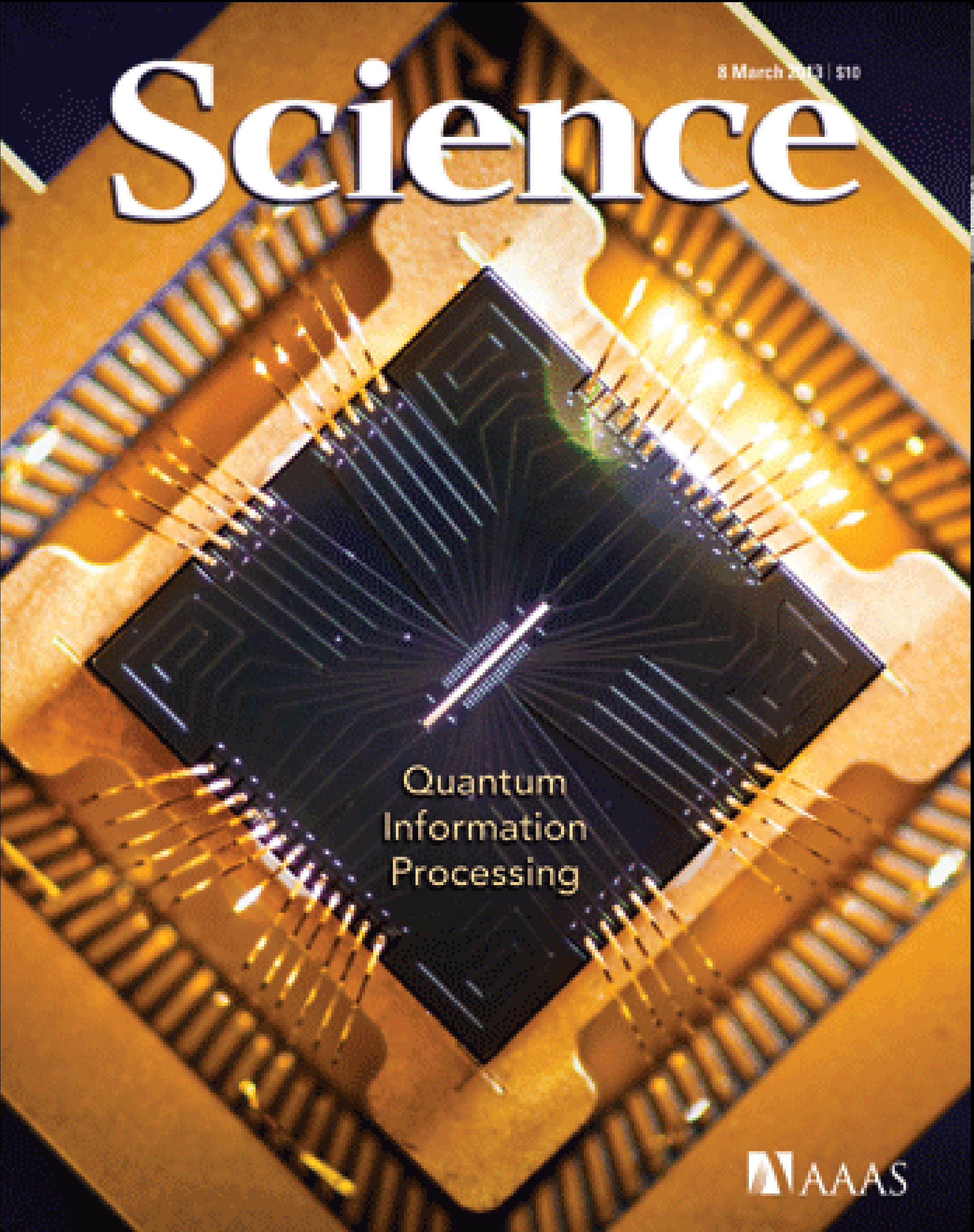


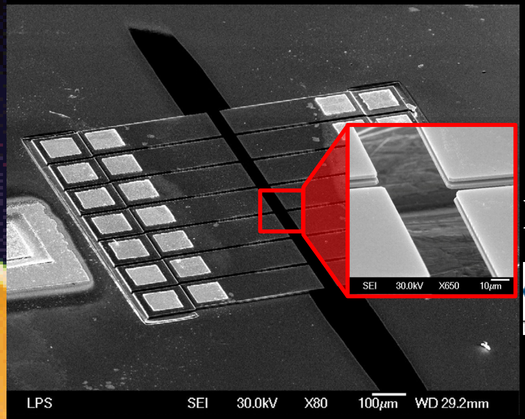
Field lines:



- Leverage semiconductor fabrication processes
  - need low-loss substrate
  - must support high E-fields
- control electrodes through backplane: scalable to lots of electrodes
- on-chip filtering of dc electrodes

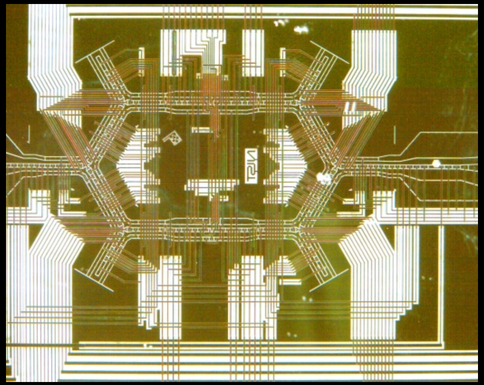




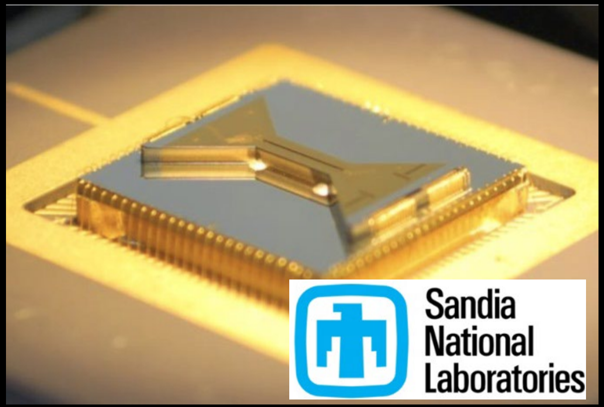


Univ. of Maryland

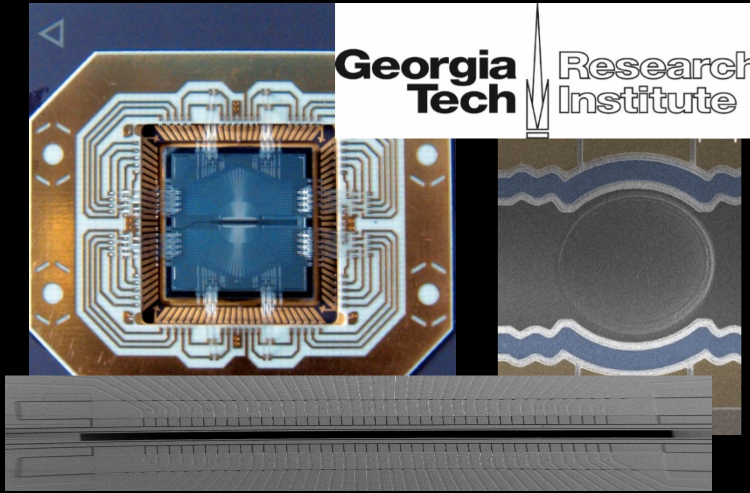
LPS
The Laboratory for Physical Sciences



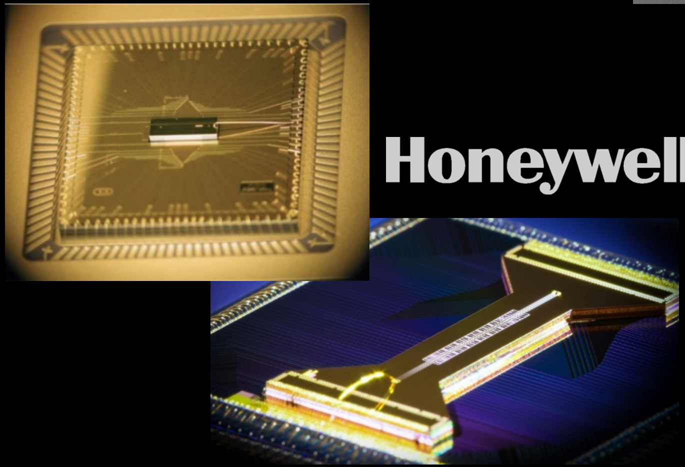
NIST
Boulder



Sandia National Laboratories



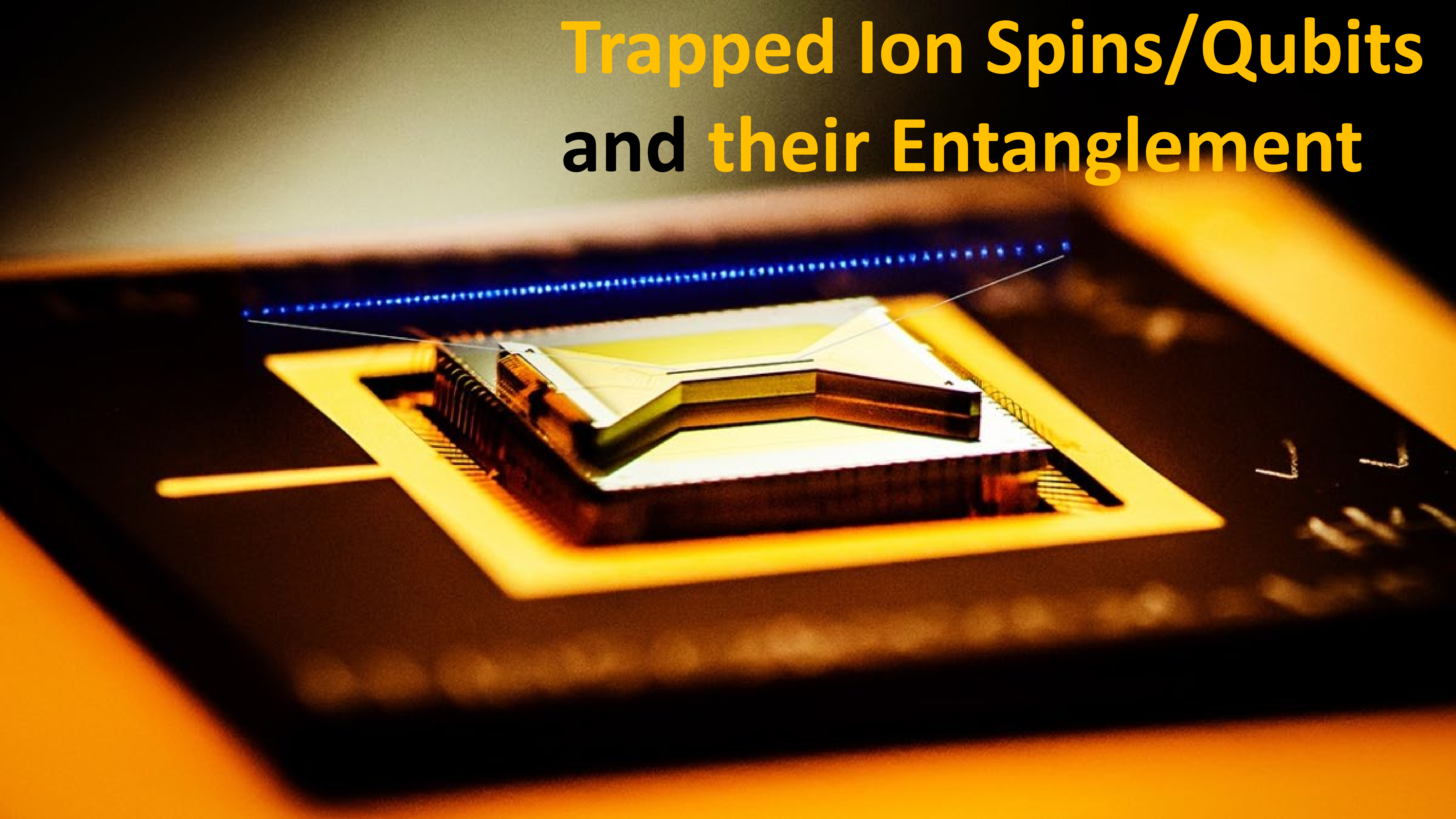
Georgia Tech Research Institute

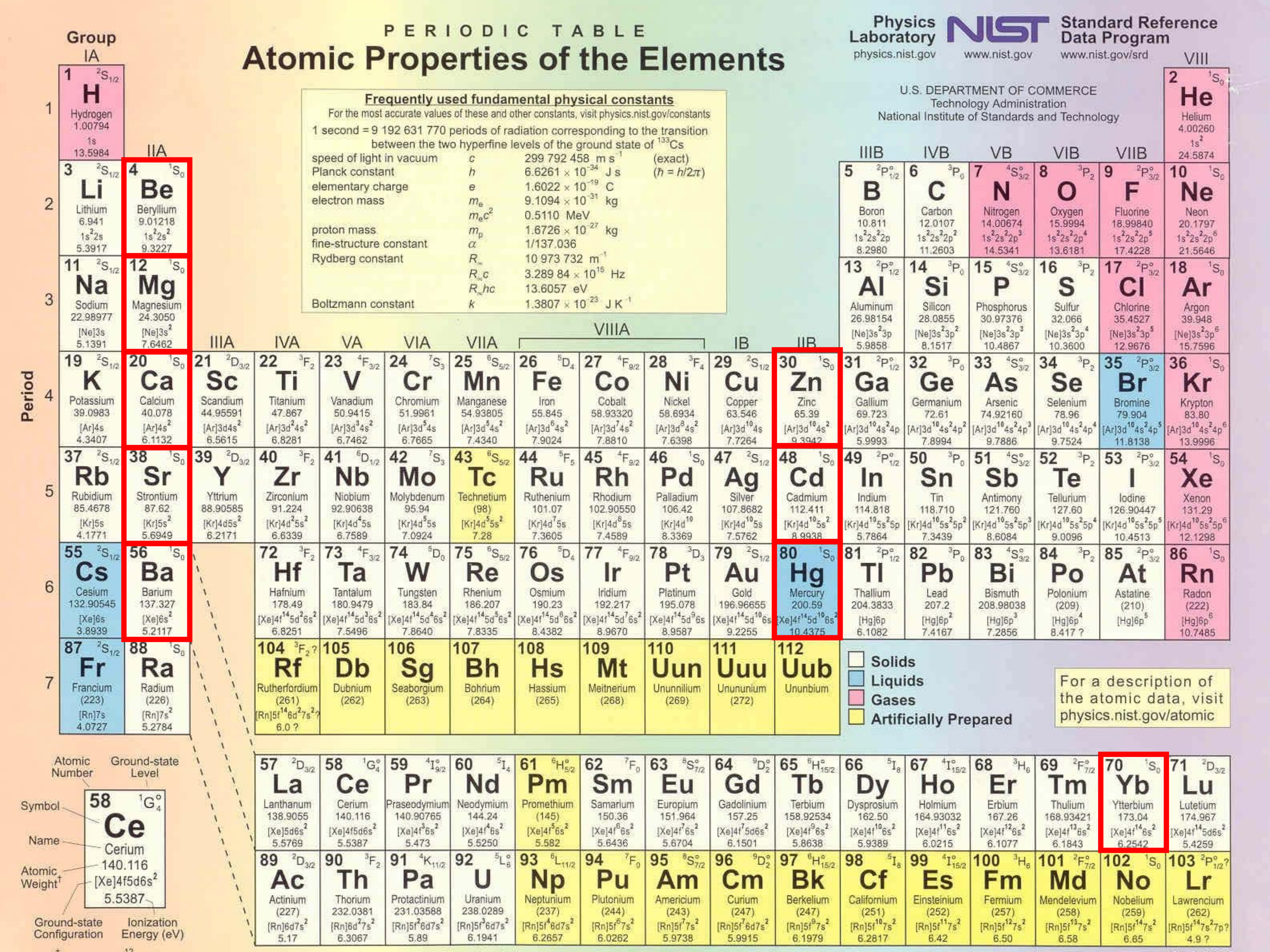


Honeywell

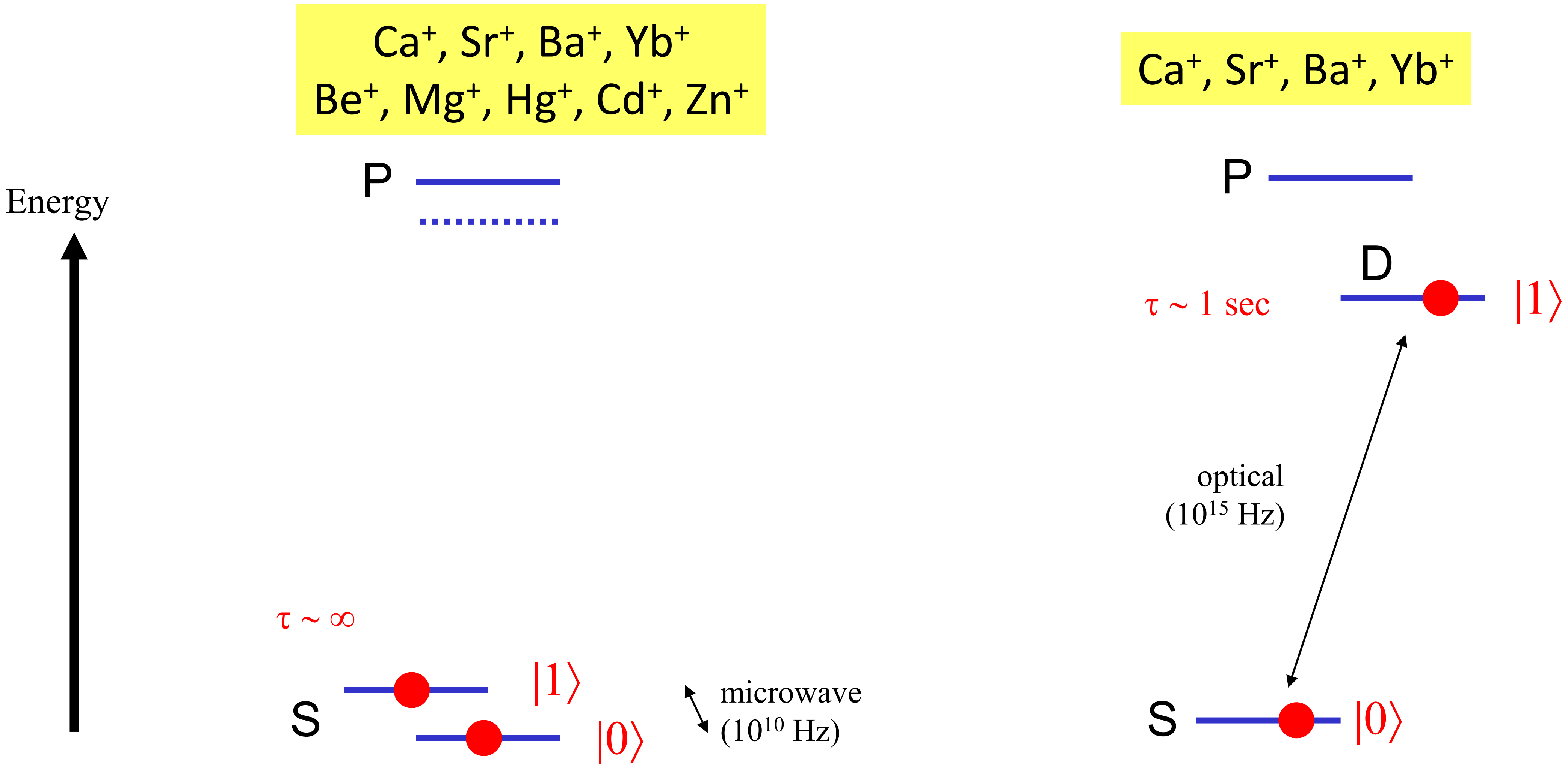
IONQ

Trapped Ion Spins/Qubits and their Entanglement




PERIODIC TABLE
Atomic Properties of the Elements
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
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 × 10^{15} Hz
$R_\infty hc$ 13.6057 eV
Boltzmann constant k 1.3807 × 10^{-23} J K^{-1}
Group IA IIA IIIA IVA VA VIA VIIA VIIIA IB IIB IIIB IVB VB VIB VIIB VIII
Period 1 2 3 4 5 6 7
1 H Hydrogen 1.00794
2 He Helium 4.00260
3 Li Lithium 6.941
4 Be Beryllium 9.01218
5 B Boron 10.811
6 C Carbon 12.0107
7 N Nitrogen 14.00674
8 O Oxygen 15.9994
9 F Fluorine 18.99840
10 Ne Neon 20.1797
11 Na Sodium 22.98977
12 Mg Magnesium 24.3050
13 Al Aluminum 26.98154
14 Si Silicon 28.0855
15 P Phosphorus 30.97376
16 S Sulfur 32.066
17 Cl Chlorine 35.4527
18 Ar Argon 39.948
19 K Potassium 39.0983
20 Ca Calcium 40.078
21 Sc Scandium 44.95591
22 Ti Titanium 47.867
23 V Vanadium 50.9415
24 Cr Chromium 51.9961
25 Mn Manganese 54.93805
26 Fe Iron 55.845
27 Co Cobalt 58.93320
28 Ni Nickel 58.6934
29 Cu Copper 63.546
30 Zn Zinc 65.39
31 Ga Gallium 69.723
32 Ge Germanium 72.61
33 As Arsenic 74.92160
34 Se Selenium 78.96
35 Br Bromine 79.904
36 Kr Krypton 83.80
37 Rb Rubidium 85.4678
38 Sr Strontium 87.62
39 Y Yttrium 88.90585
40 Zr Zirconium 91.224
41 Nb Niobium 92.90638
42 Mo Molybdenum 95.94
43 Tc Technetium (98)
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.90550
46 Pd Palladium 106.42
47 Ag Silver 107.8682
48 Cd Cadmium 112.411
49 In Indium 114.818
50 Sn Tin 118.710
51 Sb Antimony 121.760
52 Te Tellurium 127.60
53 I Iodine 126.90447
54 Xe Xenon 131.29
55 Cs Cesium 132.90545
56 Ba Barium 137.327
72 Hf Hafnium 178.49
73 Ta Tantalum 180.9479
74 W Tungsten 183.84
75 Re Rhenium 186.207
76 Os Osmium 190.23
77 Ir Iridium 192.217
78 Pt Platinum 195.078
79 Au Gold 196.96655
80 Hg Mercury 200.59
81 Tl Thallium 204.3833
82 Pb Lead 207.2
83 Bi Bismuth 208.98038
84 Po Polonium (209)
85 At Astatine (210)
86 Rn Radon (222)
87 Fr Francium (223)
88 Ra Radium (226)
104 Rf Rutherfordium (261)
105 Db Dubnium (262)
106 Sg Seaborgium (263)
107 Bh Bohrium (264)
108 Hs Hassium (265)
109 Mt Meitnerium (268)
110 Uun Ununnilium (269)
111 Uuu Unununium (272)
112 Uub Ununbium
57 La Lanthanum 138.9055
58 Ce Cerium 140.116
59 Pr Praseodymium 140.90765
60 Nd Neodymium 144.24
61 Pm Promethium (145)
62 Sm Samarium 150.36
63 Eu Europium 151.964
64 Gd Gadolinium 157.25
65 Tb Terbium 158.92534
66 Dy Dysprosium 162.50
67 Ho Holmium 164.93032
68 Er Erbium 167.26
69 Tm Thulium 168.93421
70 Yb Ytterbium 173.04
71 Lu Lutetium 174.967
89 Ac Actinium (227)
90 Th Thorium 232.0381
91 Pa Protactinium 231.03588
92 U Uranium 238.0289
93 Np Neptunium (237)
94 Pu Plutonium (244)
95 Am Americium (243)
96 Cm Curium (247)
97 Bk Berkelium (247)
98 Cf Californium (251)
99 Es Einsteinium (252)
100 Fm Fermium (257)
101 Md Mendelevium (258)
102 No Nobelium (259)
103 Lr Lawrencium (262)
Solids
Liquids
Gases
Artificially Prepared
For a description of the atomic data, visit physics.nist.gov/atomic
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight
Ground-state Configuration
Ionization Energy (eV)
58 Ce Cerium 140.116 [Xe]4f5d6s^2 5.5387

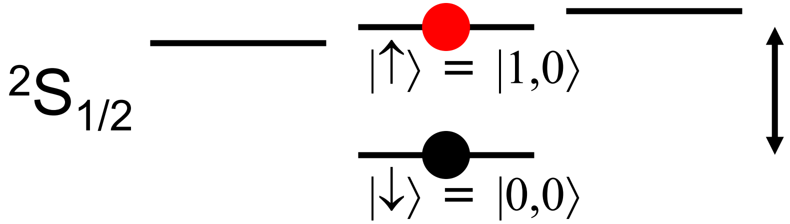
Trapped ion qubits



“hyperfine” qubit levels

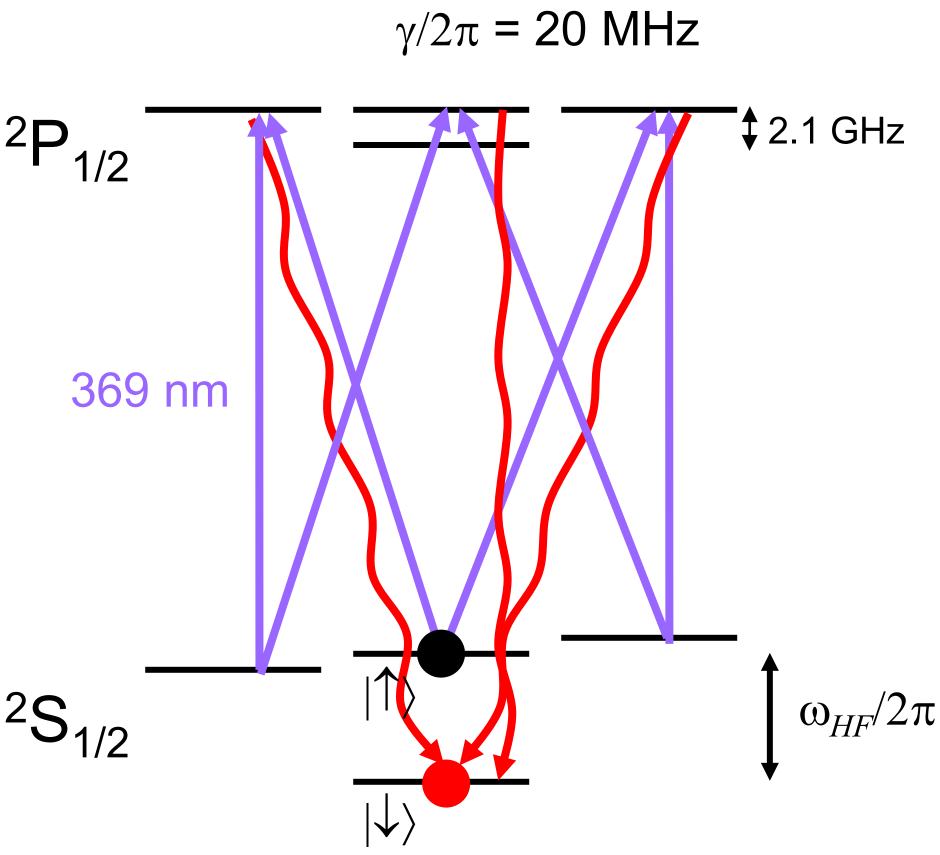
“optical” qubit levels

Atomic Qubit ($^{171}Yb^{+}$)



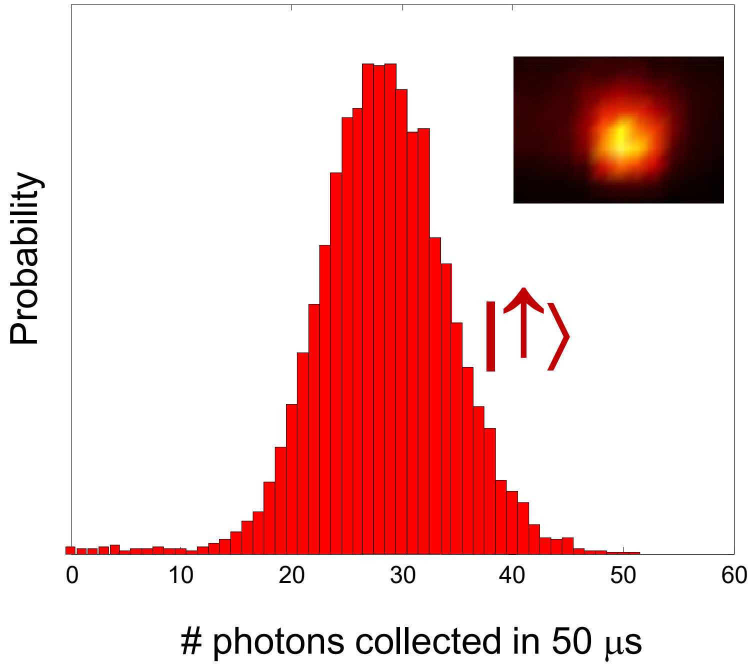
$\omega_{HF}/2\pi = \mathbf{12{,}642{,}812{,}118 + 311\ B^2\ Hz}$

$^{171}Yb^+$ Qubit Initialization



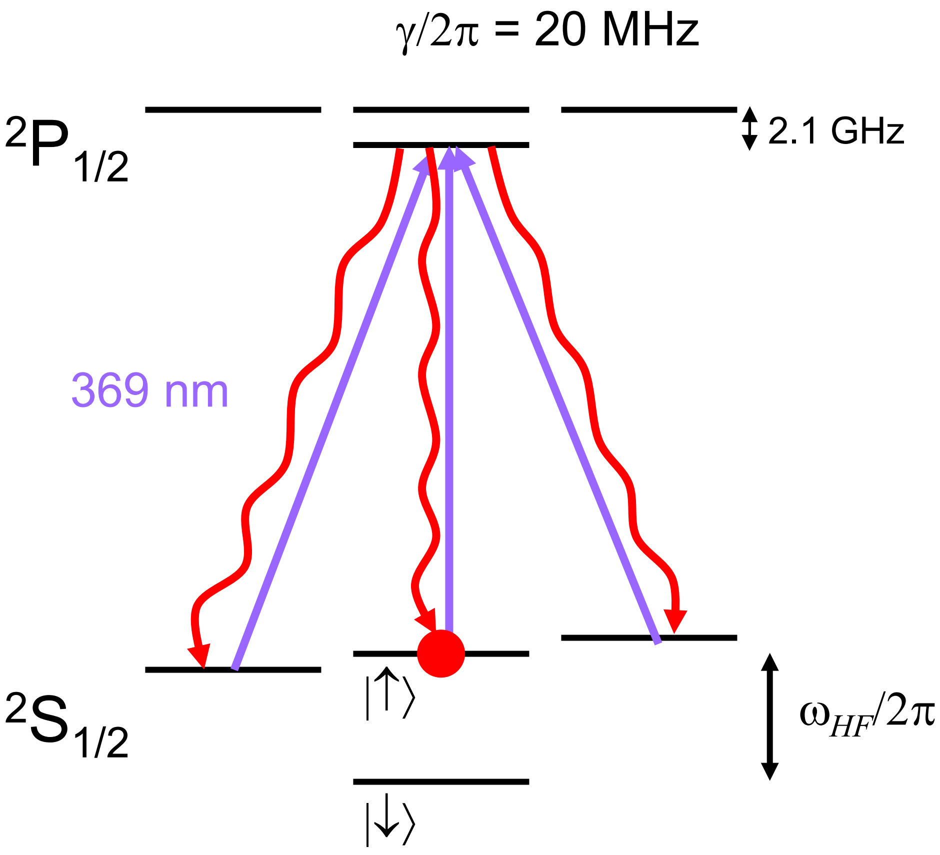
$$\omega_{HF}/2\pi = \mathbf{12{,}642{,}812{,}118 + 311\ B^2\ Hz}$$

atom emits 1 photon every ~10ns
detector clicks every ~1 μs

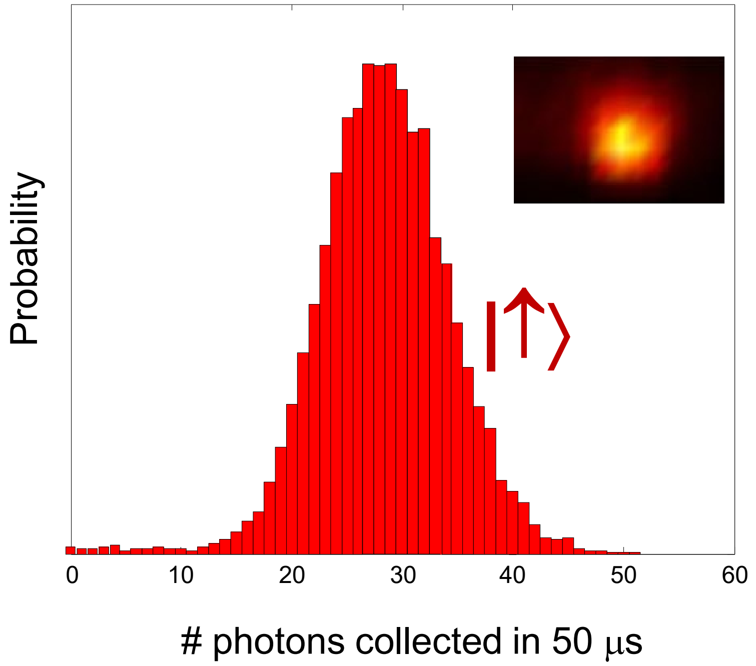


$^{171}Yb^{+}$ Qubit Detection

atom emits 1 photon every ~10ns
detector clicks every ~1 μs



$\omega_{HF}/2\pi$ = **12,642,812,118 + 311 B^2 Hz**



$^{171}Yb^{+}$ Qubit Detection

High-NA collection + SNSPD (J. Kim, Duke)
- 6.5% of fluoresce… detected
- 99.93% q… in 12 μs

$\gamma/2\pi$ = 20 MHz

$^2P_{1/2}$

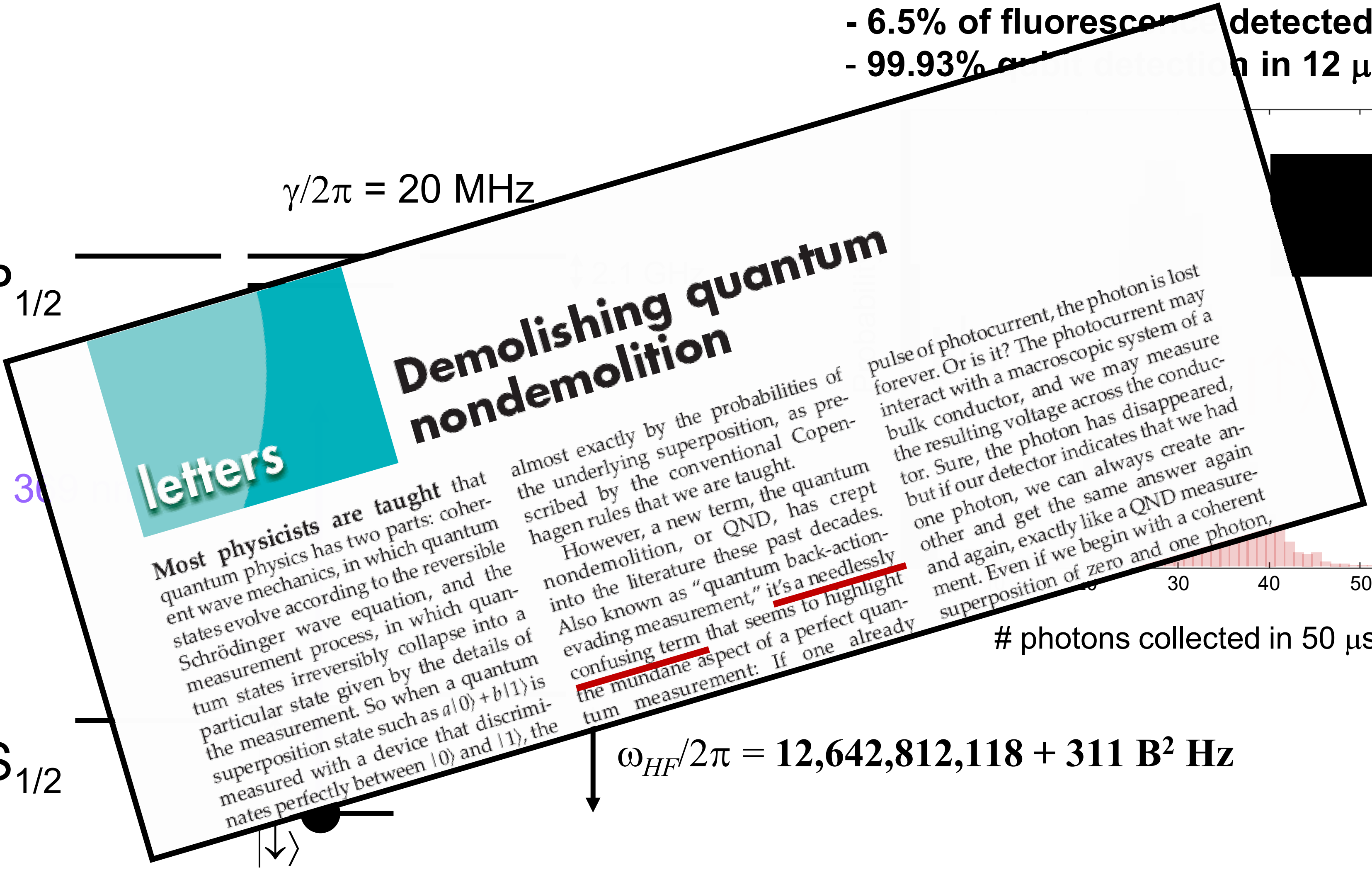
$^2S_{1/2}$

$|\downarrow\rangle$

$\omega_{HF}/2\pi$ = **12,642,812,118 + 311 B² Hz**

30 40 50 60

photons collected in 50 μs



letters

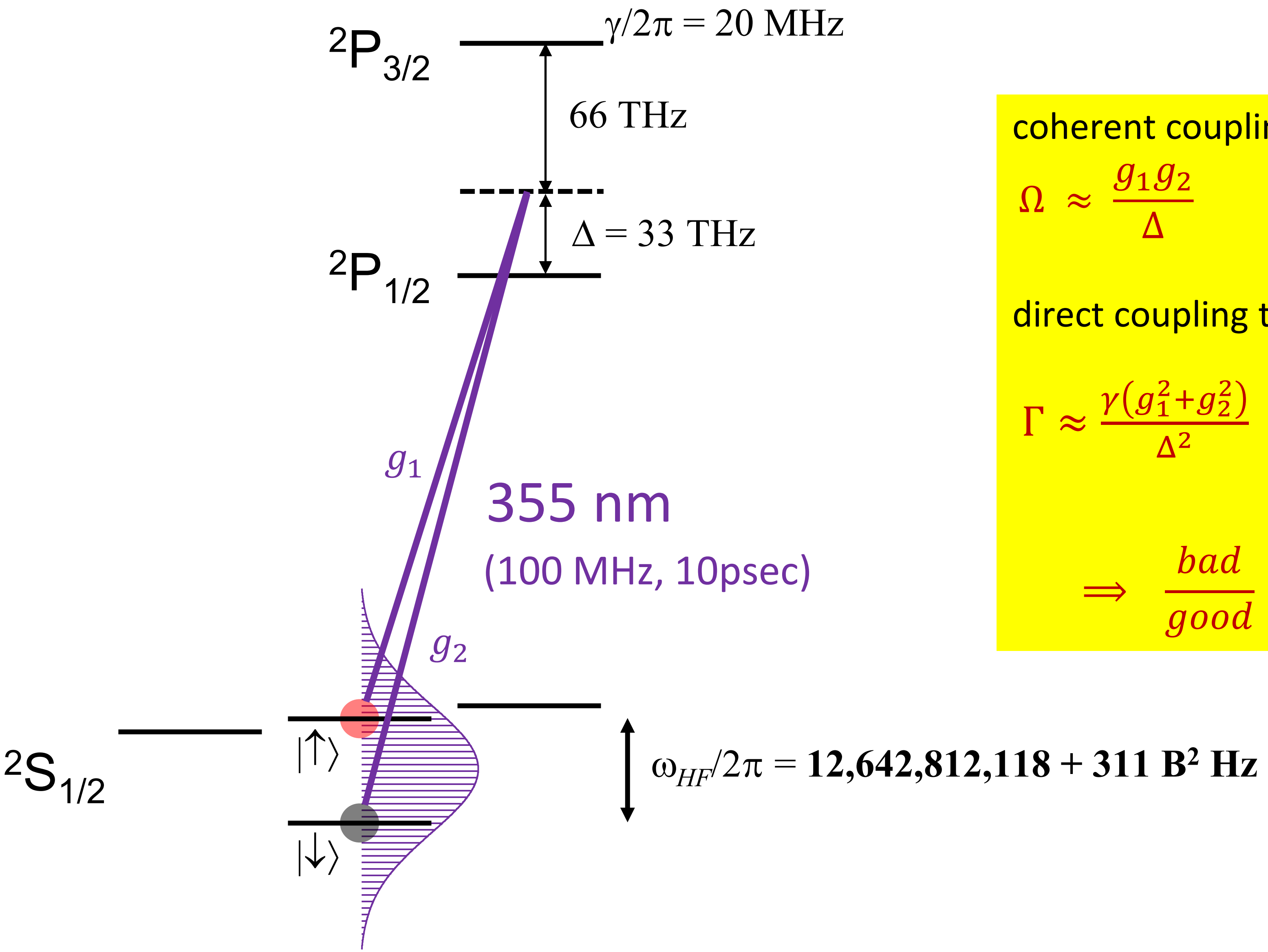
Demolishing quantum nondemolition

Most physicists are taught that quantum physics has two parts: coherent wave mechanics, in which quantum states evolve according to the reversible Schrödinger wave equation, and the measurement process, in which quantum states irreversibly collapse into a particular state given by the details of the measurement. So when a quantum superposition state such as $a|0\rangle + b|1\rangle$ is measured with a device that discriminates perfectly between $|0\rangle$ and $|1\rangle$, the almost exactly by the probabilities of the underlying superposition, as prescribed by the conventional Copenhagen rules that we are taught.

However, a new term, the quantum nondemolition, or QND, has crept into the literature these past decades. Also known as "quantum back-action-evading measurement," it's a needlessly confusing term that seems to highlight the mundane aspect of a perfect quantum measurement: If one already

pulse of photocurrent, the photon is lost forever. Or is it? The photocurrent may interact with a macroscopic system of a bulk conductor, and we may measure the resulting voltage across the conductor. Sure, the photon has disappeared, but if our detector indicates that we had one photon, we can always create another and get the same answer again and again, exactly like a QND measurement. Even if we begin with a coherent superposition of zero and one photon,

$^{171}Yb^+$ Qubit Manipulation



coherent coupling rate (good):

$$\Omega \approx \frac{g_1 g_2}{\Delta}$$

direct coupling to P states (bad):

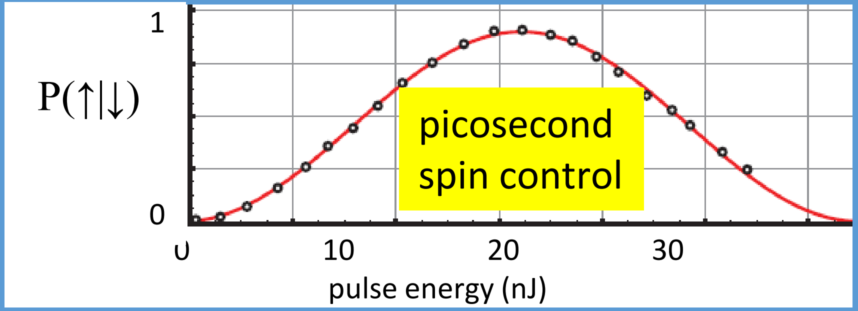
$$\Gamma \approx \frac{\gamma(g_1^2+g_2^2)}{\Delta^2} \sim \Omega\frac{\gamma}{\Delta} \quad \text{(for } g_1 \sim g_2\text{)}$$

$$\Rightarrow \quad \frac{bad}{good} \approx 10\frac{\gamma}{\Delta} \sim 10^{-5}$$

D. Hayes et al., PRL 104, 140501 (2010)

National Ignition Facility: 351nm (Livermore National Laboratory)

P_{avg} ~ 5W at 355nm
10 psec pulses, 120 MHz rep rate



J. Mizrahi, et al., *Phys. Rev. Lett.* 110, 203001 (2013).

Measuring a single qubit (real data)