INTRO TO QUANTUM COMPUTING
LECTURE #23

Quantum Hardware: Trapped ion qubits

David Wong-Campos

04/25/2021

Short bio:

- Born in Peru
- Undergrad in Mexico
- PhD in Physics, quantum computing (University of Maryland)
- Worked for two years at IonQ (a quantum computing startup)
- Currently a Postdoc in neuroscience at Harvard

tldr: Trapped ion qubits

Take mother nature's qubits (atoms) and engineer around them

Why atomic ions?

The most ideal and clean quantum system. Based on well understood Physics

- Best detection fidelity: **99.995(6)%**
- Best single qubit gate fidelity: **99.9934(3)%**
- Best Two qubit gate fidelity: **99.9(1)%**
- Excellent coherence* **(>10 min)**
- Reconfigurable: computation, simulation etc.
- Full connectivity

* Time it takes before it stops having quantum properties

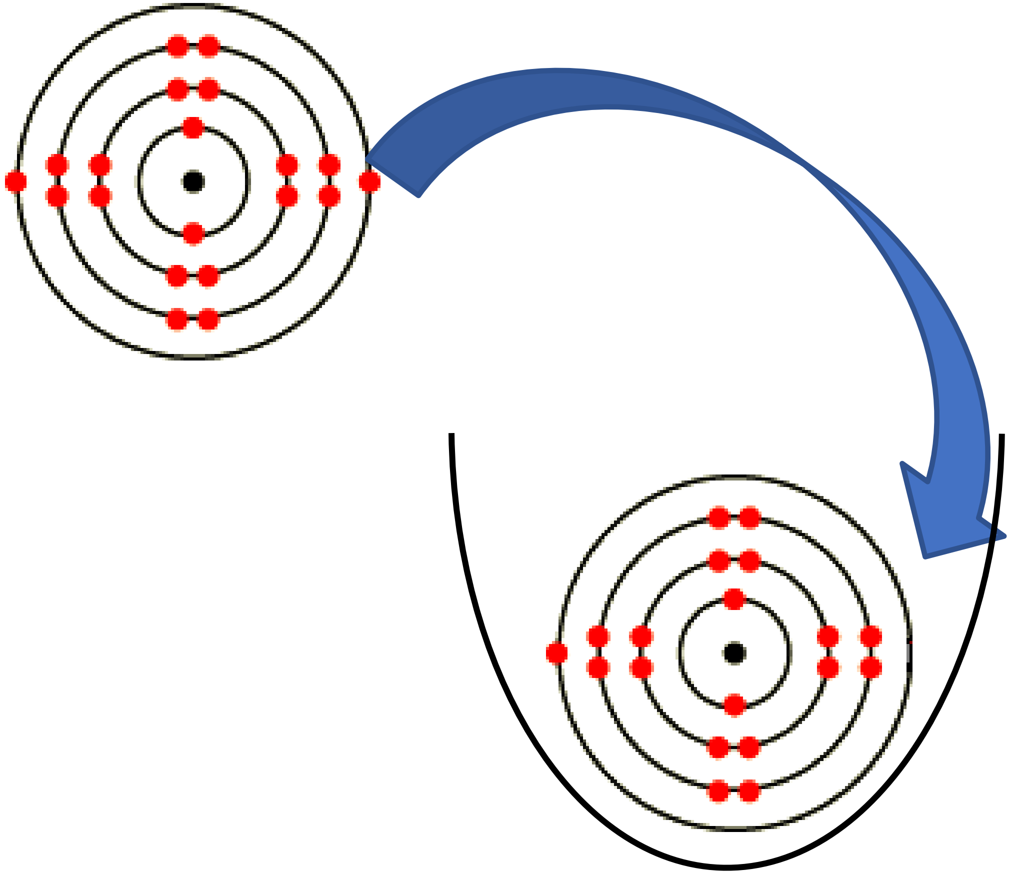
What is an atomic qubit

Trapping charged atoms is relatively easy (done since the 50’s)

Step 1: Find an atom with two outer electrons

Step 2: Ionize it

Step 3: Confine it in an electromagnetic trap



How do the traps work?

Positively charged particles are repelled by electric fields

Electric field

Force

+q

Certain configurations do a better job:

Electric field

Electric field

+q

… but not quite

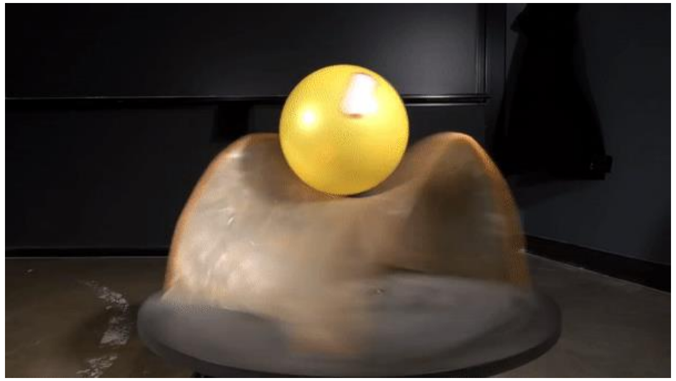
Reality:

Electric field

Electric field

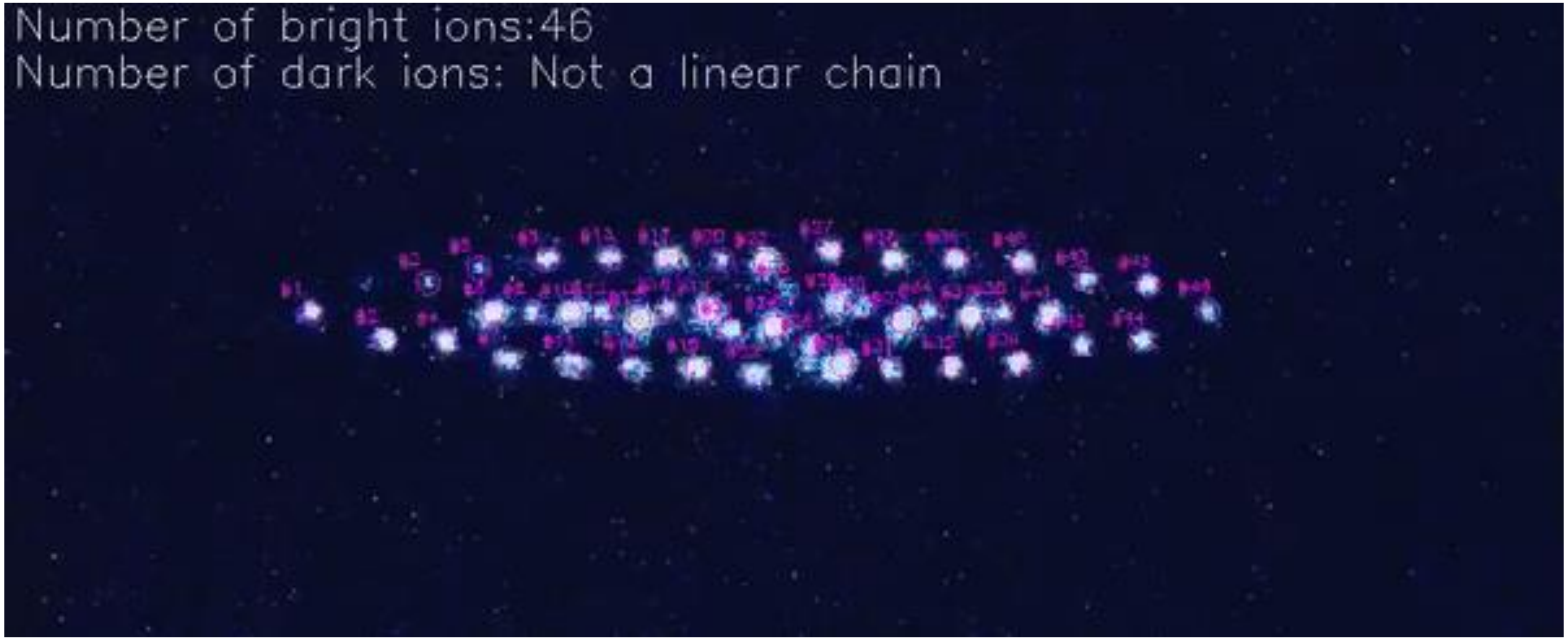
+q

Solution: Make them **rotate/oscilate** !

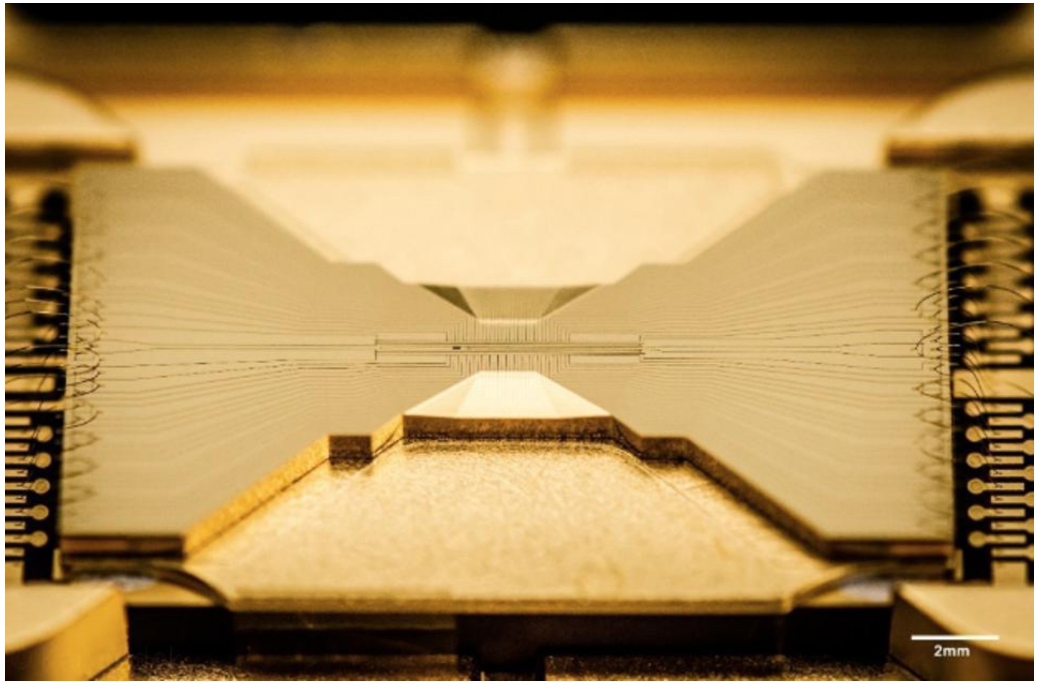


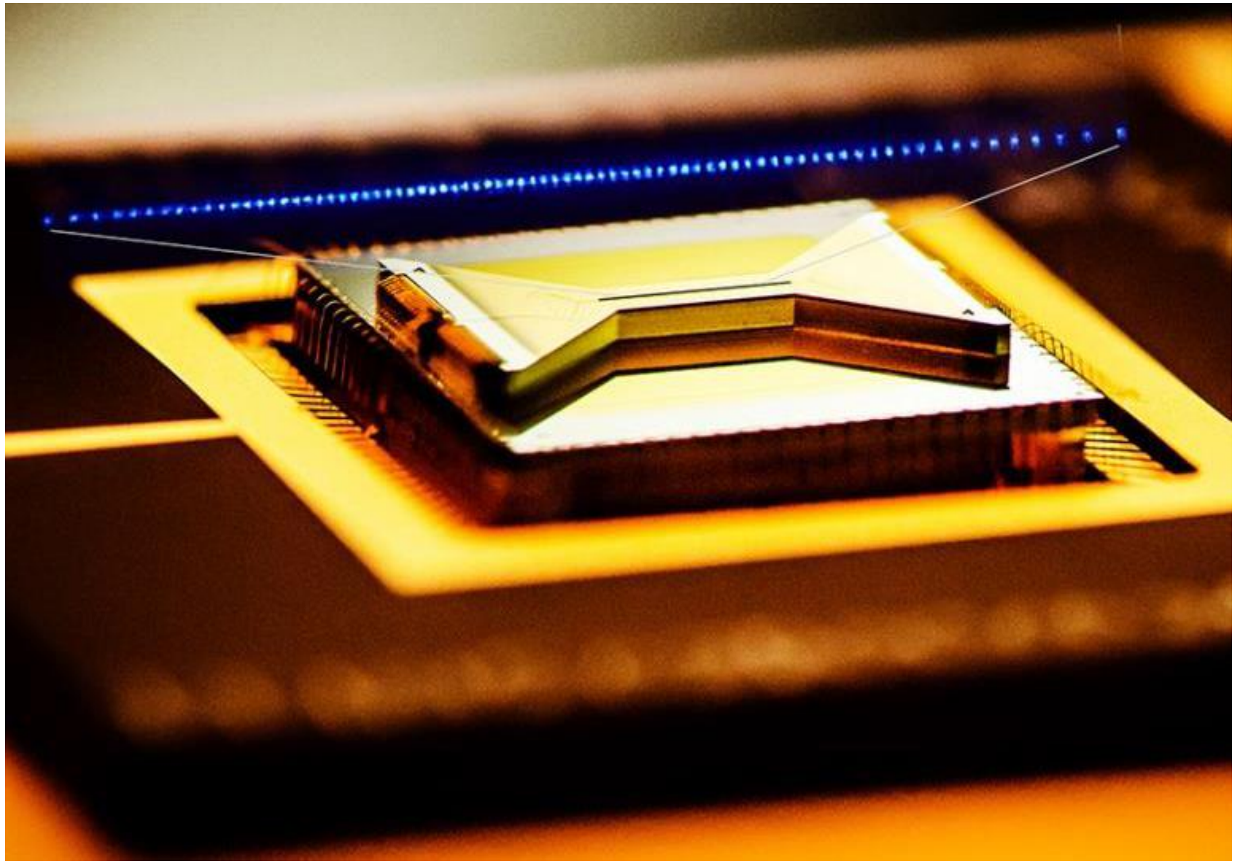
How to get more qubits

One could use the same principle for trapping many of them:



How they look like in *real* life





An analogy

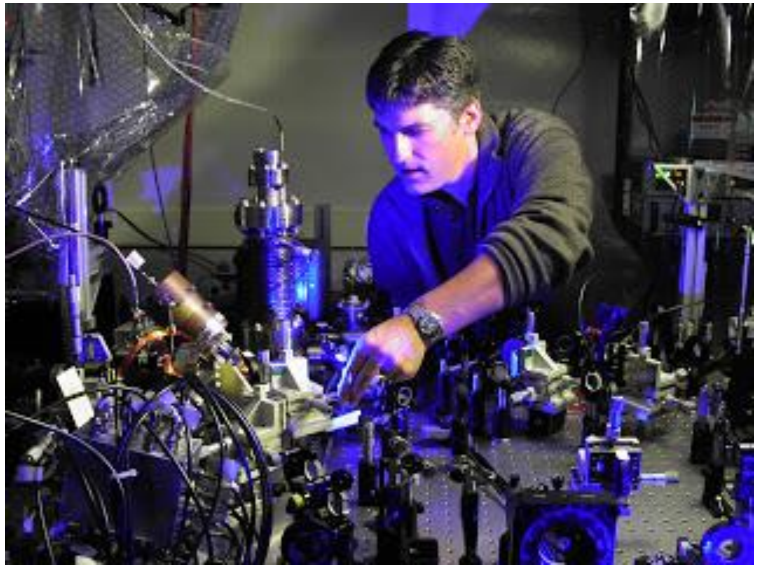
ACTUALLY:

How do we operate the qubits?

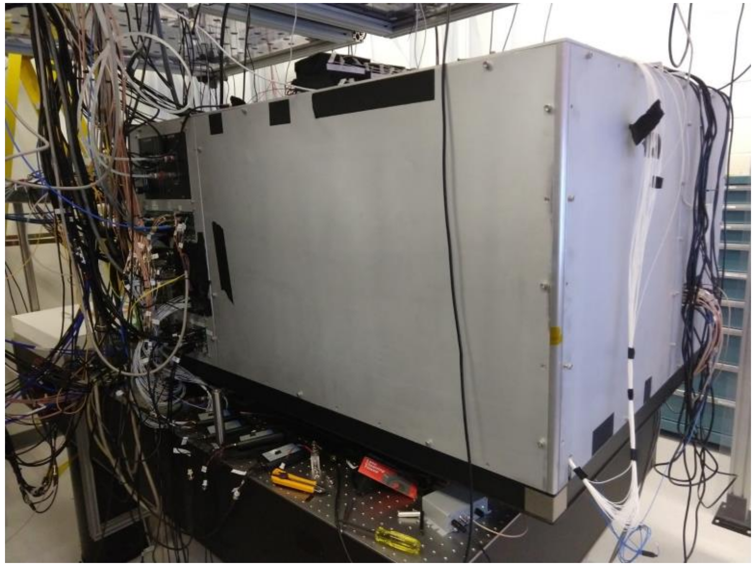
Equipment:

Vacuum chambers

Lasers!

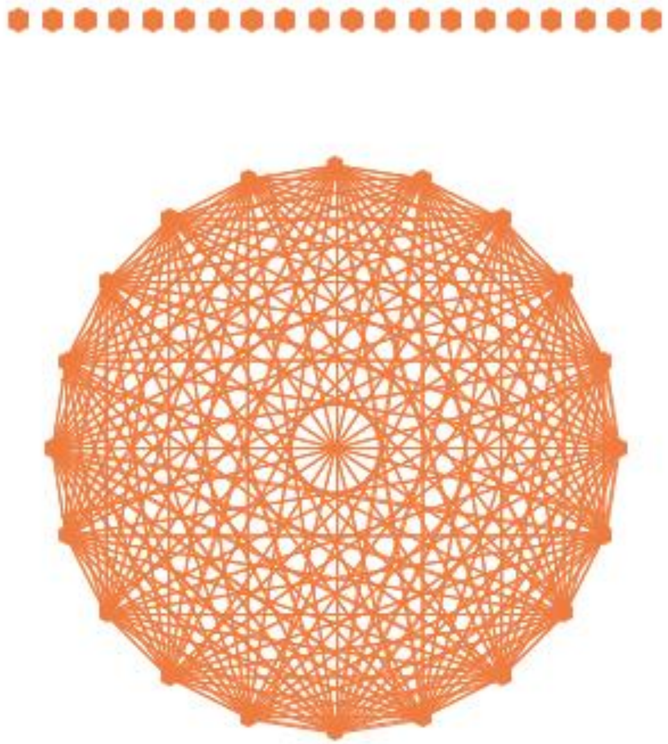


Control electronics



How are the qubits connected

All the atoms “feel” everybody else → They are charged*



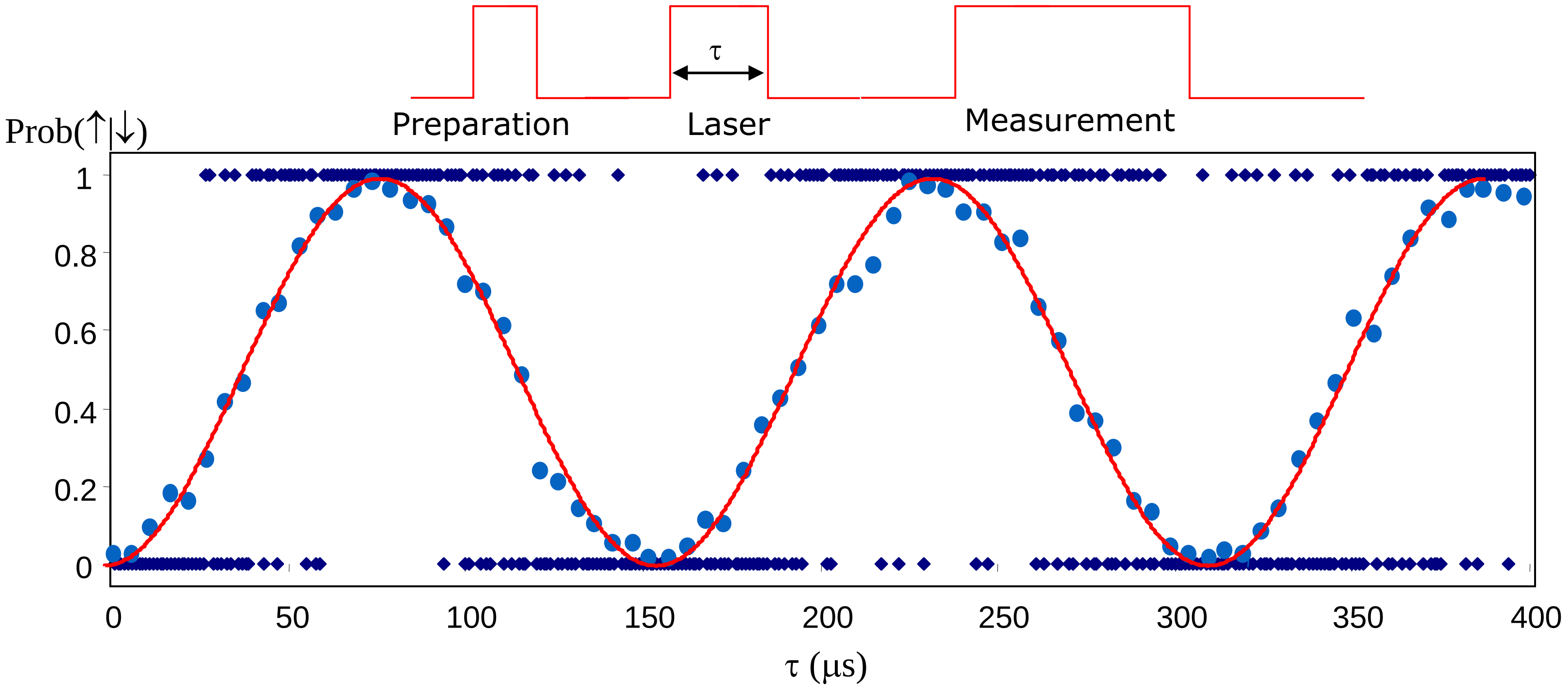
*Like charges repel each other

How do you control them?

Single qubit gates allows the control of “how much” 0 or 1 each qubit have.

Trapped ion qubits are pretty much two level systems for practical purposes*

$$|\Psi\rangle = a_0|0\rangle + a_1|1\rangle$$

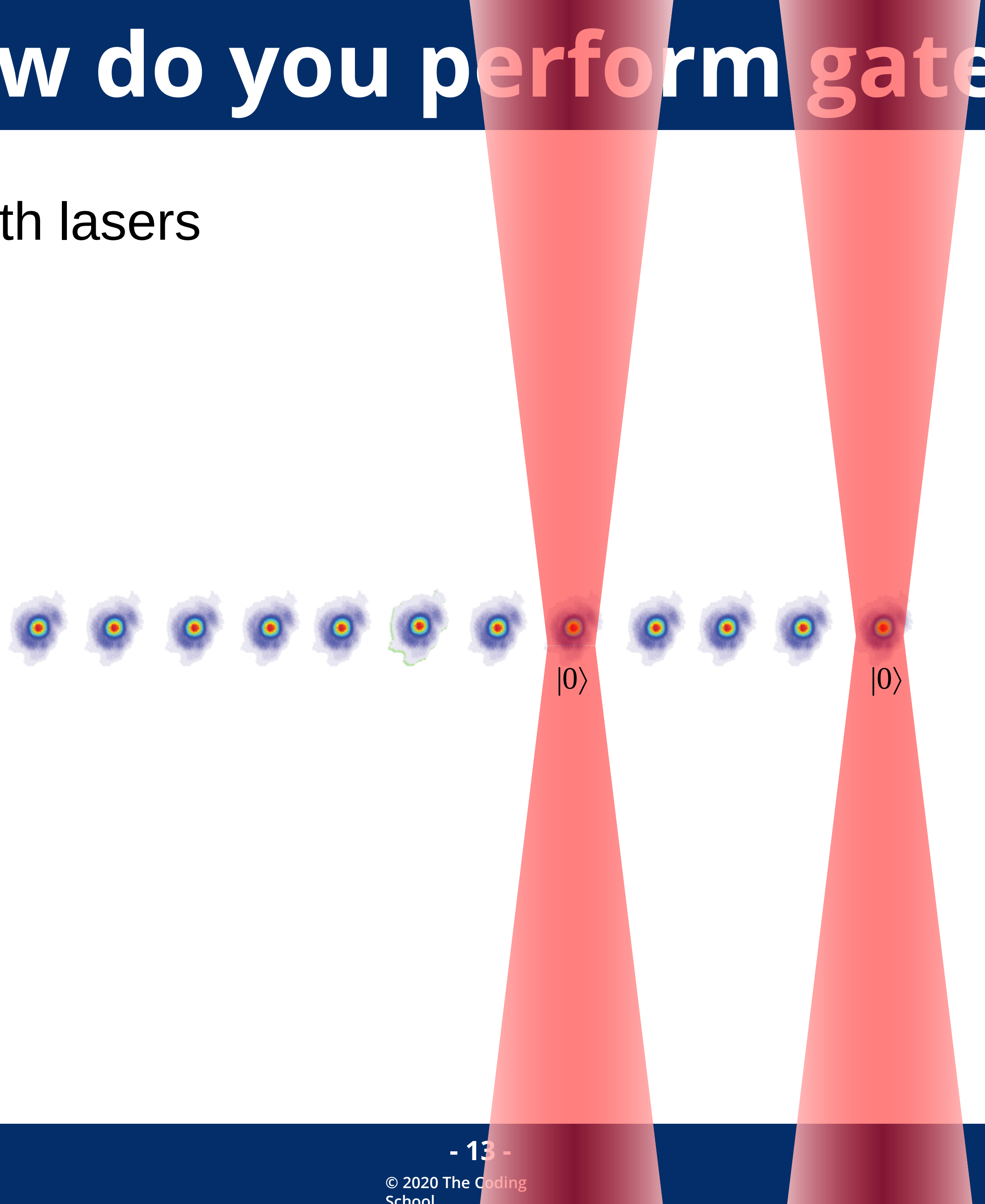


Up to really good approximations!

Fastest gates are usually around 5 microseconds

How do you perform gates?

Push individual ions with lasers



How do you perform gates?

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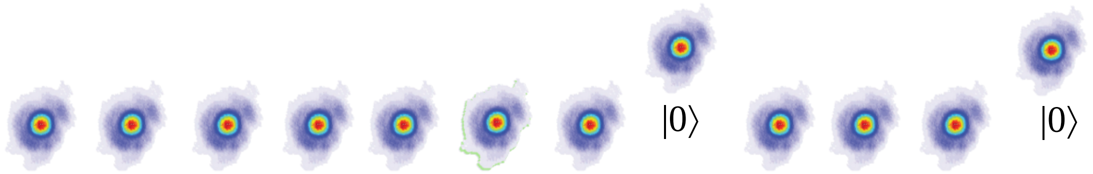
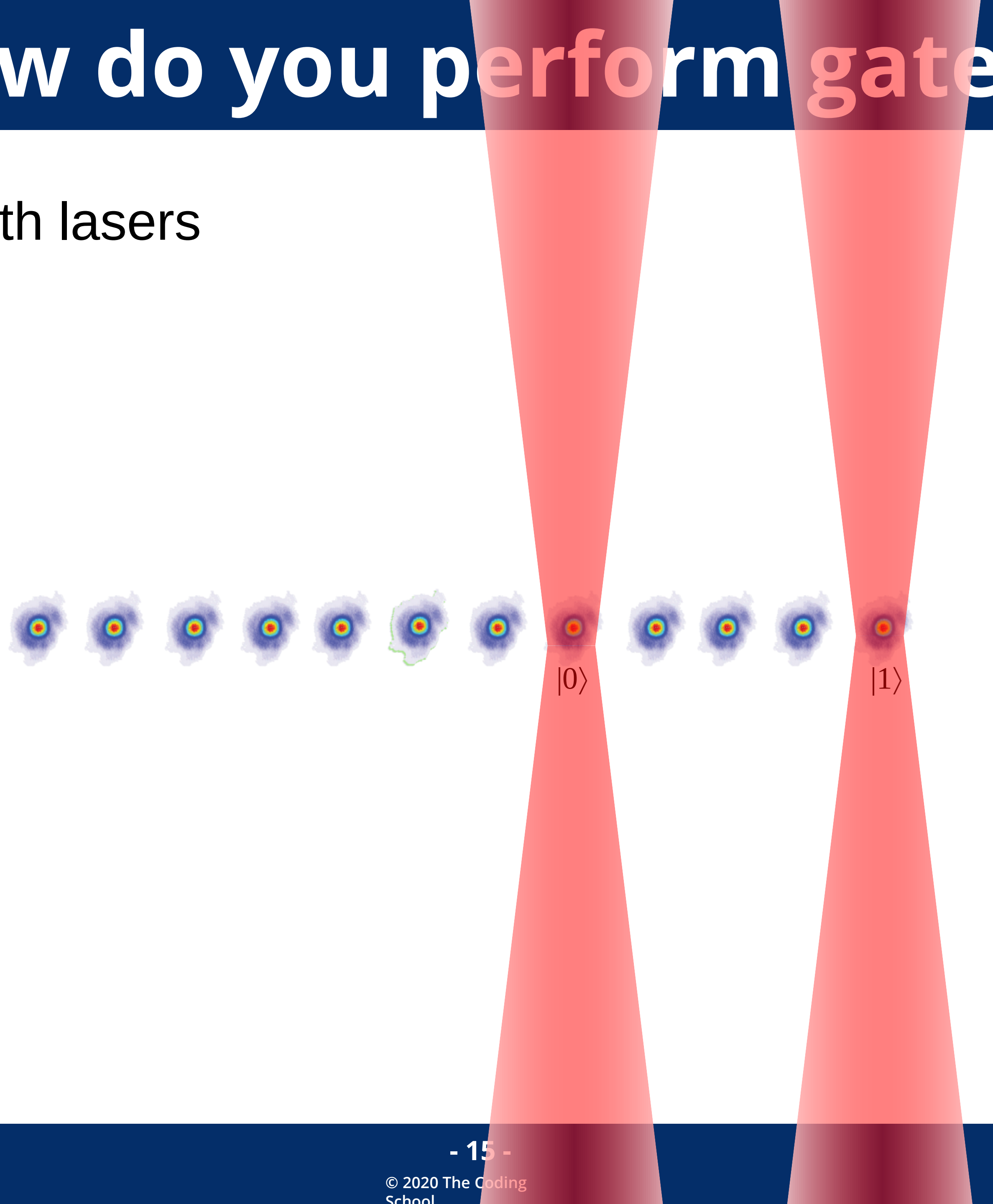


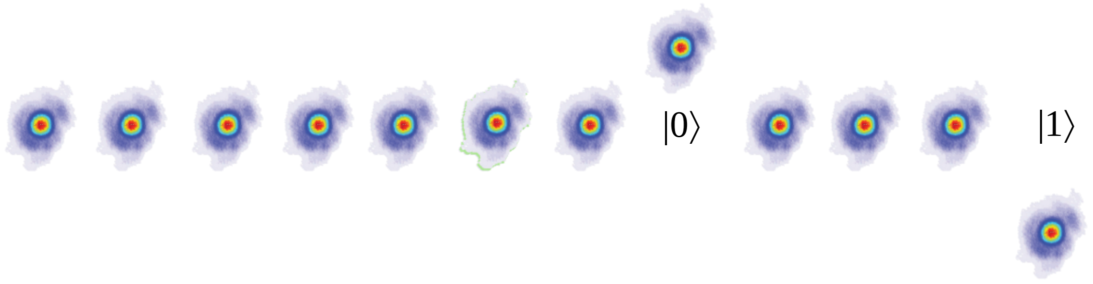
How do you perform gates?

Push individual ions with lasers



How do you perform gates?

Push individual ions with lasers



Average gate time: 5-25 microseconds

If that push depends on whether the ion is in the 0 or 1 state, it allows quantum gates!

EXTRA CREDIT: WHAT HAPPENS IF THE ATOMS ARE IN A SUPERPOSITION OF $|0\rangle$ AND $|1\rangle$??

Pros and Cons

Pros:

- Excellent quantum properties
- Traps are made with known techniques
- Laser and photonics technology is mature enough
- High quality gates and readout

Cons:

- Slow operations (for now)
- Needs vacuum

Breakthroughs

Article

Demonstration of the trapped-ion quantum CCD computer architecture

https://doi.org/10.1038/s41586-021-03318-4
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Check for updates

J. M. Pino[1], J. M. Dreiling[1], C. Figgatt[1], J. P. Gaebler[1], S. A. Moses[1], M. S. Allman[1], C. H. Baldwin[1], M. Foss-Feig[1], D. Hayes[1], K. Mayer[1], C. Ryan-Anderson[1] & B. Neyenhuis[1]

The trapped-ion quantum charge-coupled device (QCCD) proposal[1,2] lays out a blueprint for a universal quantum computer that uses mobile ions as qubits. Analogous to a charge-coupled device (CCD) camera, which stores and processes imaging information as movable electrical charges in coupled pixels, a QCCD computer stores quantum information in the internal state of electrically charged ions that are transported between different processing zones using dynamic electric fields. The promise of the QCCD architecture is to maintain the low error rates demonstrated in small trapped-ion experiments[3–5] by limiting the quantum interactions to multiple small ion crystals, then physically splitting and rearranging the constituent ions of these crystals into new crystals, where further interactions occur. This approach leverages transport timescales that are fast relative to the coherence times of the qubits, the insensitivity of the qubit states of the ion to the electric fields used for transport, and the low crosstalk afforded by spatially separated crystals. However, engineering a machine capable of executing these operations across multiple interaction zones with low error introduces many difficulties, which have slowed progress in scaling this architecture to larger qubit numbers. Here we use a cryogenic surface trap to integrate all necessary elements of the QCCD architecture—a scalable trap design, parallel interaction zones and fast ion transport—into a programmable trapped-ion quantum computer that has a system performance consistent with the low error rates achieved in the individual ion crystals. We apply this approach to realize a teleported CNOT gate using mid-circuit measurement[6], negligible crosstalk error and a quantum volume[7] of $2^6 = 64$. These results demonstrate that the QCCD architecture provides a viable path towards high-performance quantum computers.

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez[1]*, Christine A. Muschik[2,3]*, Philipp Schindler[1], Daniel Nigg[1], Alexander Erhard[1], Markus Heyl[2,4], Philipp Hauke[2,3], Marcello Dalmonte[2,3], Thomas Monz[1], Peter Zoller[2,3] & Rainer Blatt[1,2]

Benchmarking an 11-qubit quantum computer

K. Wright[1]*, K.M. Beck[1], S. Debnath[1], J.M. Amini[1], Y. Nam[1], N. Grzesiak[1], J.-S. Chen[1], N.C. Pisenti[1], M. Chmielewski[1,2], C. Collins[1], K.M. Hudek[1], J. Mizrahi[1], J.D. Wong-Campos[1], S. Allen[1], J. Apisdorf[1], P. Solomon[1], M. Williams[1], A.M. Ducore[1], A. Blinov[1], S.M. Kreikemeier[1], V. Chaplin[1], M. Keesan[1], C. Monroe[1,2] & J. Kim[1,3]

The field of quantum computing has grown from concept to demonstration devices over the past 20 years. Universal quantum computing offers efficiency in approaching problems of scientific and commercial interest, such as factoring large numbers, searching databases, simulating intractable models from quantum physics, and optimizing complex cost functions. Here, we present an 11-qubit fully-connected, programmable quantum computer in a trapped ion system composed of 13 $^{171}Yb^+$ ions. We demonstrate average single-qubit gate fidelities of 99.5%, average two-qubit-gate fidelities of 97.5%, and SPAM errors of 0.7%. To illustrate the capabilities of this universal platform and provide a basis for comparison with similarly-sized devices, we compile the Bernstein-Vazirani and Hidden Shift algorithms into our native gates and execute them on the hardware with average success rates of 78% and 35%, respectively. These algorithms serve as excellent benchmarks for any type of quantum hardware, and show that our system outperforms all other currently available hardware.

Mar. 8, 2021 6:54 pm

Quantum computing company IonQ plans to go public. Here's what it could mean for College Park

Realization of a scalable Shor algorithm

Thomas Monz,[1]* Daniel Nigg,[1] Esteban A. Martinez,[1] Matthias F. Brandl,[1] Philipp Schindler,[1] Richard Rines,[2] Shannon X. Wang,[2] Isaac L. Chuang,[2] Rainer Blatt[1,3]

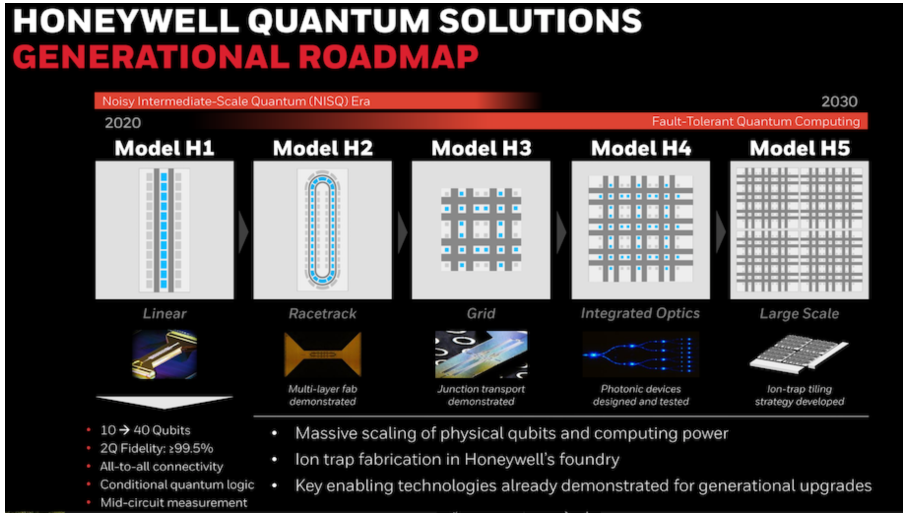
Certain algorithms for quantum computers are able to outperform their classical counterparts. In 1994, Peter Shor came up with a quantum algorithm that calculates the prime factors of a large number vastly more efficiently than a classical computer. For general scalability of such algorithms, hardware, quantum error correction, and the algorithmic realization itself need to be extensible. Here we present the realization of a scalable Shor algorithm, as proposed by Kitaev. We factor the number 15 by effectively employing and controlling seven qubits and four "cache qubits" and by implementing generalized arithmetic operations, known as modular multipliers. This algorithm has been realized scalably within an ion-trap quantum computer and returns the correct factors with a confidence level exceeding 99%.

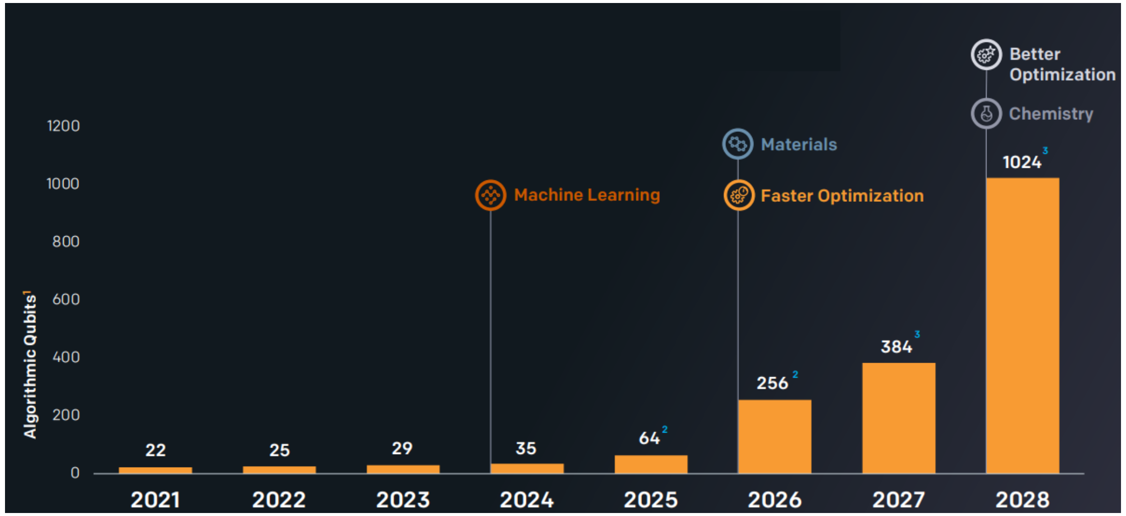
Entanglement of single-atom quantum bits at a distance

D. L. Moehring[1], P. Maunz[1], S. Olmschenk[1], K. C. Younge[1], D. N. Matsukevich[1], L.-M. Duan[1] & C. Monroe[1,2]

Ongoing research and developments

- Scaling to more qubits
- Achieving error correction and fault tolerance
- First quantum Unicorn!





INTRO TO QUANTUM COMPUTING
LECTURE #23

Quantum Hardware: Solid-state defects centers

Eric Bersin, MIT PhD Student

04/25/2021

tldr: Solid-state defect centers

Take a solid material, and add a defect –

ok for quantum computing, *great* for quantum internet

Who am I

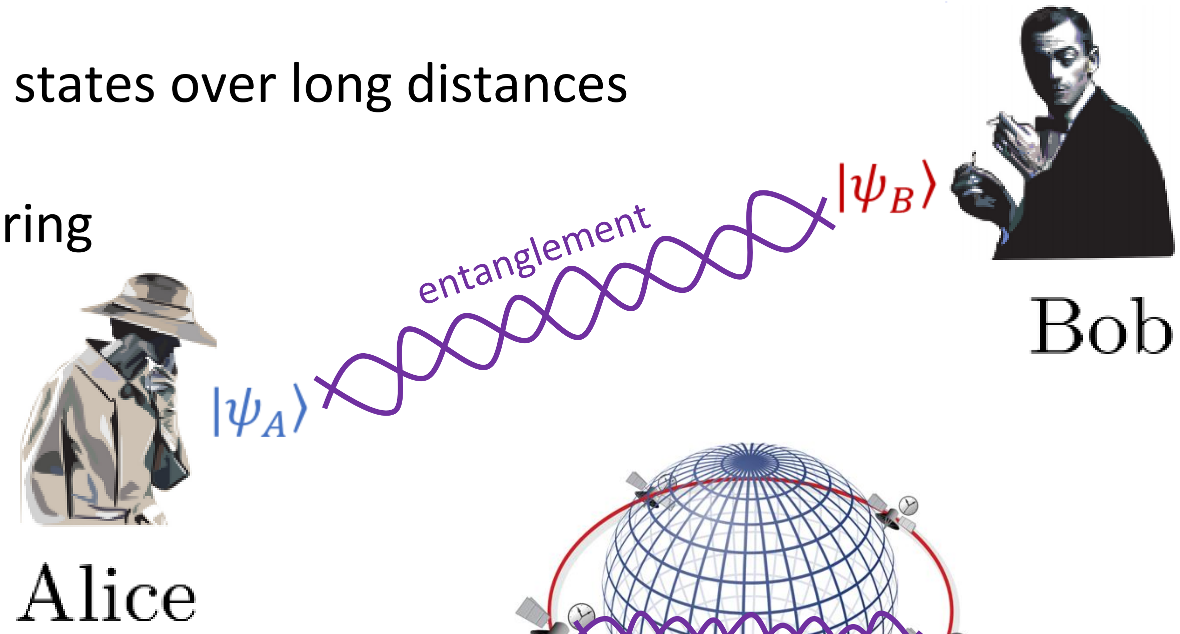
- From Long Grove, Illinois
- Studied biomedical engineering in college
- Found out quantum mechanics super cool AND useful!
- Now MIT grad student in electrical engineering

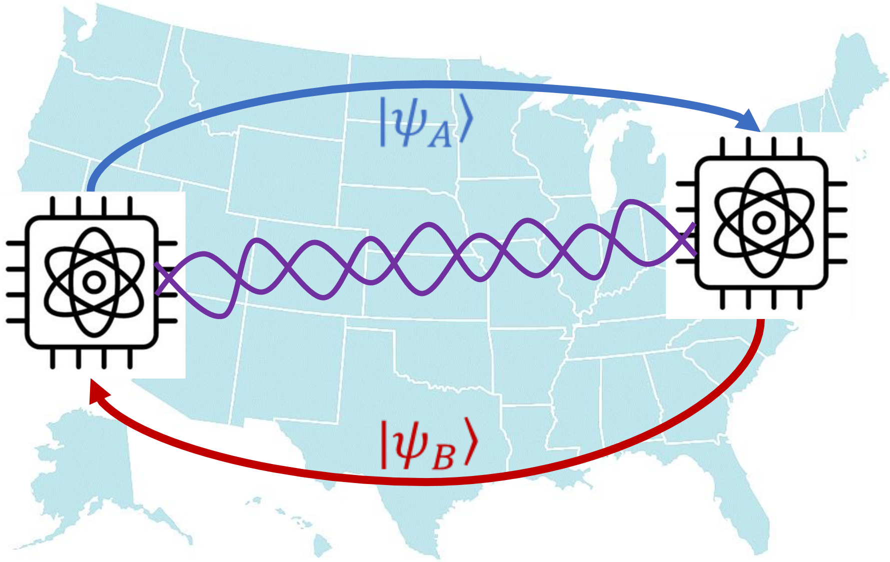
My dog, who likes hiking

MIT Dome!

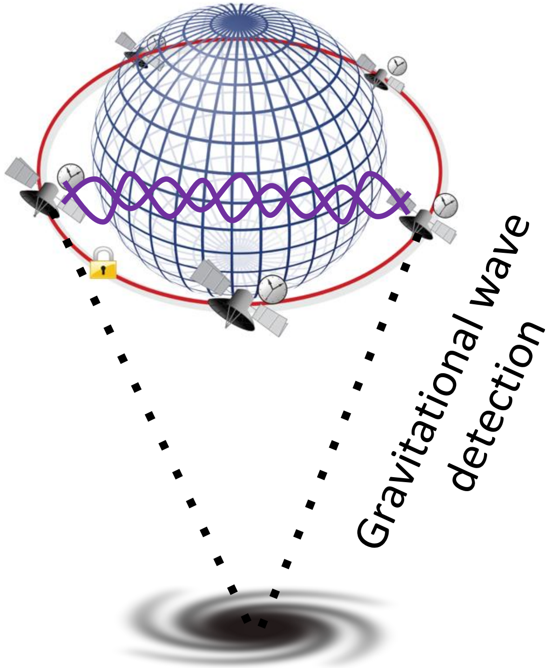
What is the quantum internet?

- Quantum internet/networking = sending quantum states over long distances
- Quantum cryptography 100% secure secret sharing
- Quantum-enhanced sensing
- Connecting quantum computers!



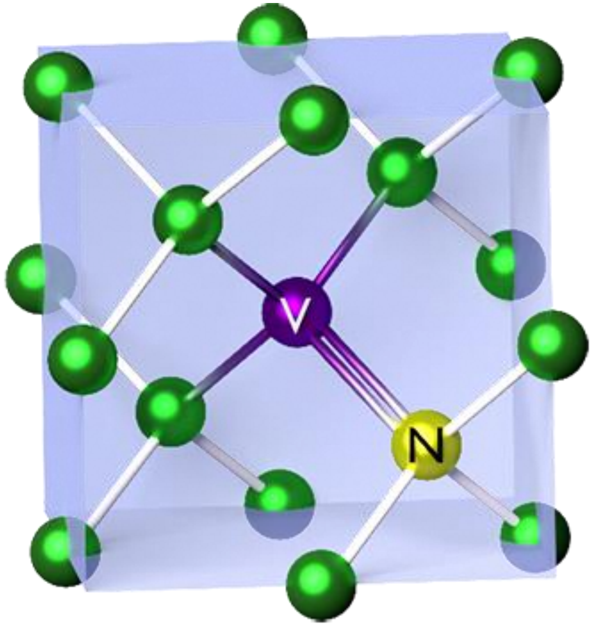


Quantum information can be sent long distances using light pulses – called photons



What is a defect center

- Materials like diamond have a crystal structure
- Defect center qubit: make a “defect” – replace one of the atoms with something else
- Acts like a trapped ion, but protected by the surrounding material



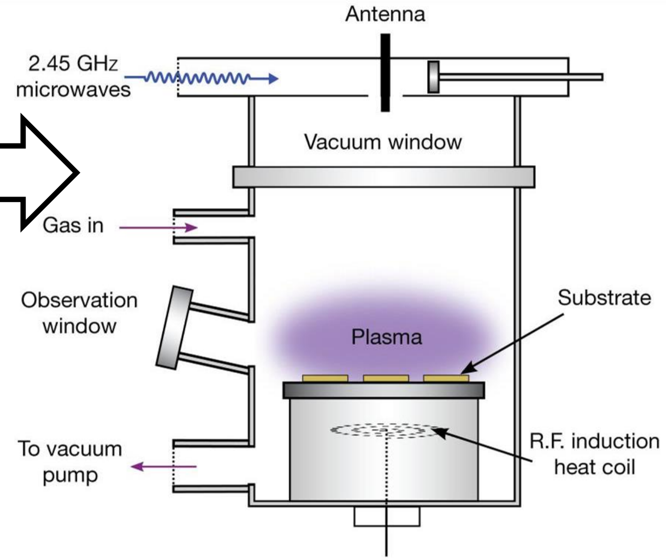
- Lots of different “species” of defects, in lots of different materials!
- **Most popular of these is the “nitrogen vacancy” defect in diamond**

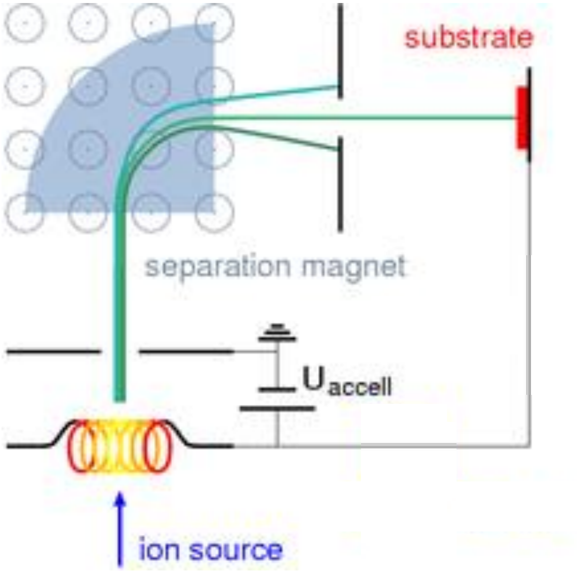
How do we make them

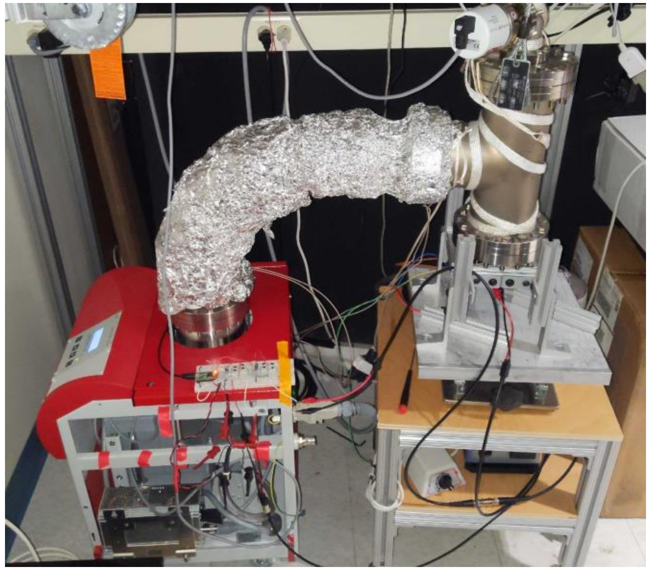
Step 1) Grow a diamond

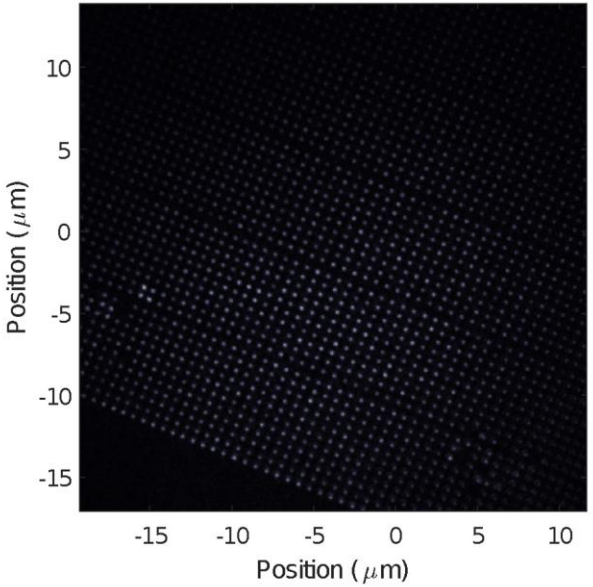
Step 2) Implant ions

Step 3) Heat up diamond (called “annealing”) to form defects!



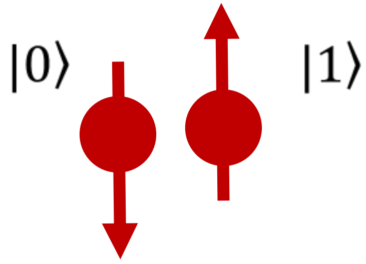


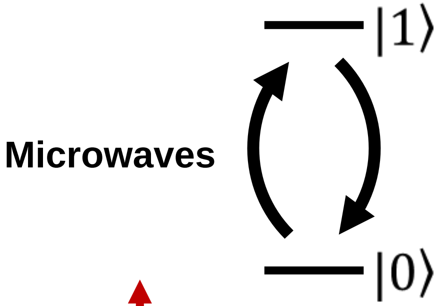


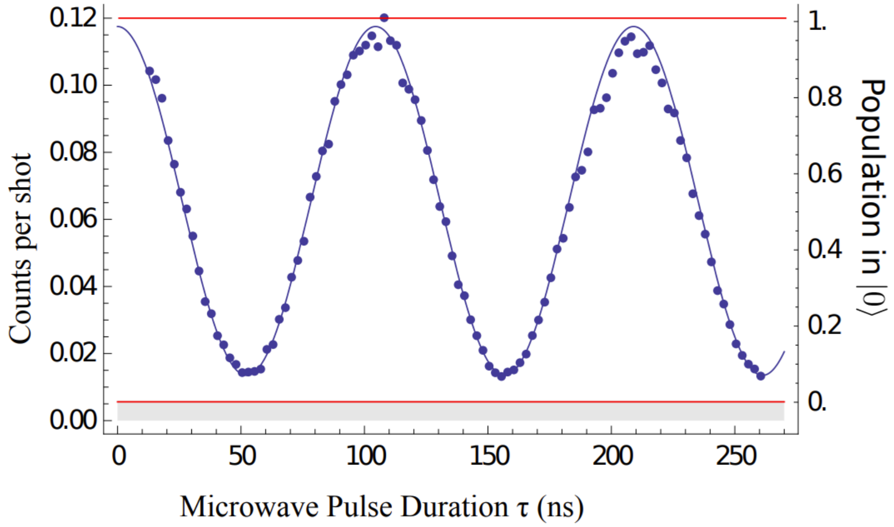


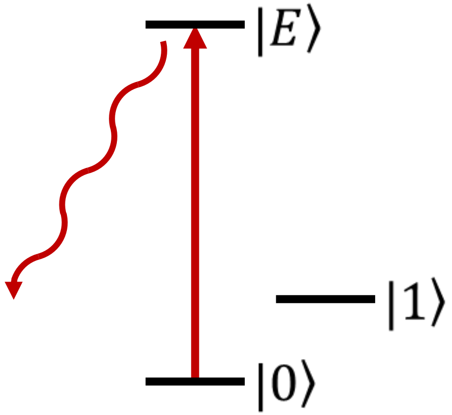
How do we use them as qubits

- Spin of electron forms our qubit
- Read qubit state with **lasers**
- Control qubit with **microwaves**
  $F \approx 99.99\%$, takes ~ 50 ns

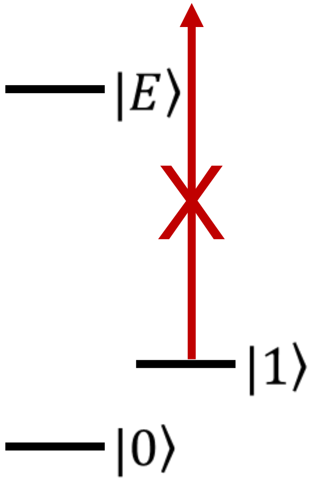








BRIGHT



DARK

Bonus: What happens if we prepare a superposition, then apply a laser?

$$(|0\rangle + |1\rangle)/\sqrt{2}$$

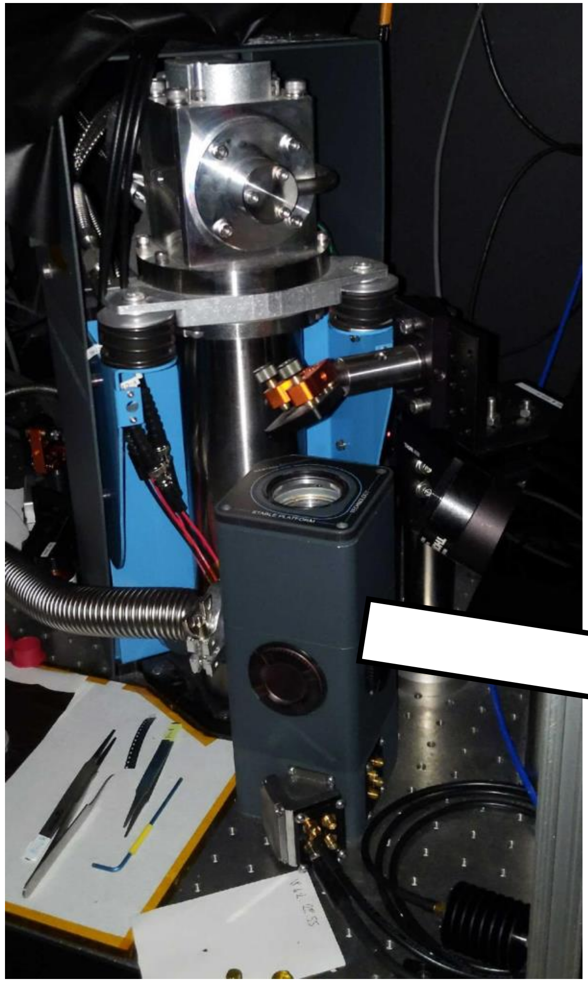
$$\Downarrow$$

$$(|0\rangle|\text{BRIGHT}\rangle + |1\rangle|\text{DARK}\rangle)/\sqrt{2}$$

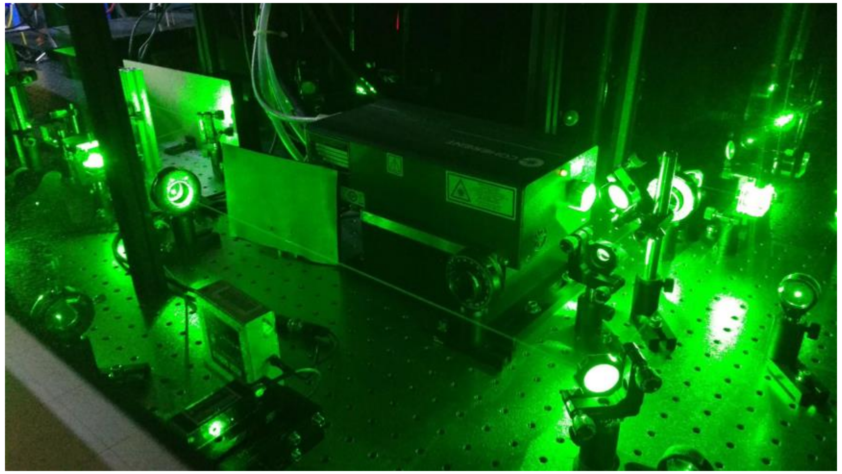
Entanglement between spin and light!

How do we operate the qubits

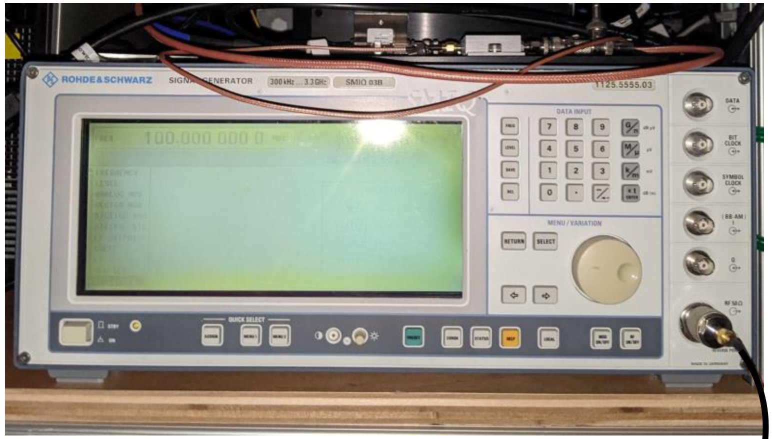
Cryostat for ~kelvin temps

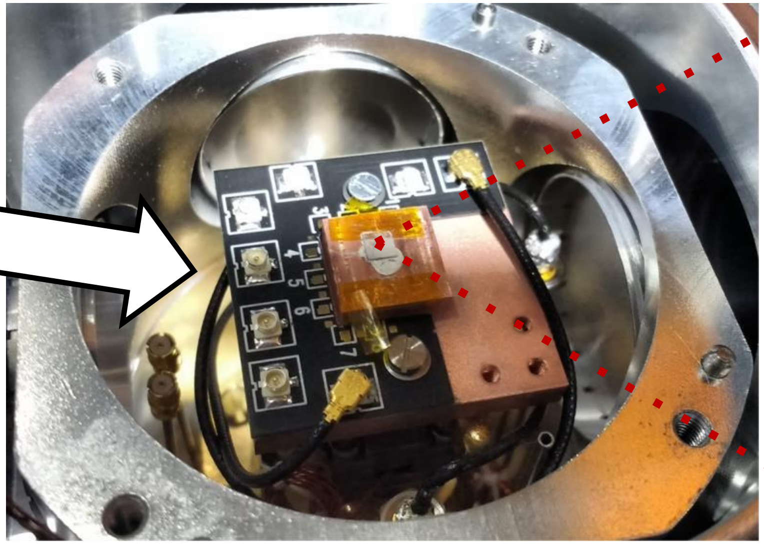


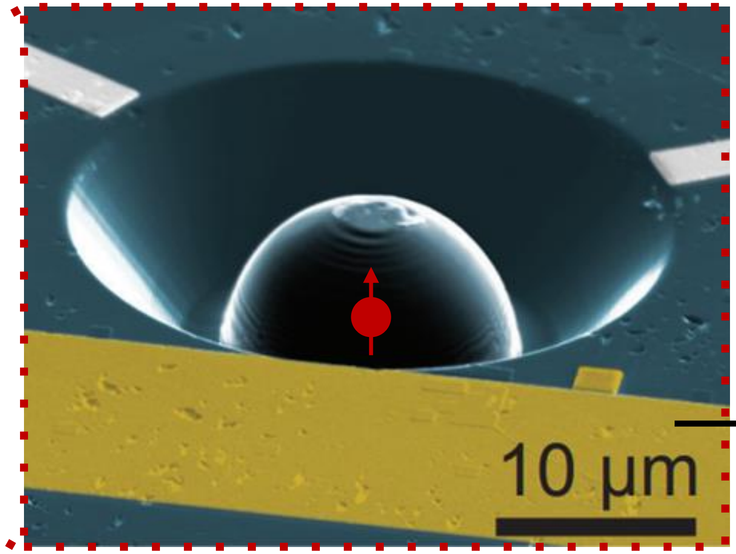
Lasers for reading qubits



Microwaves to control qubits

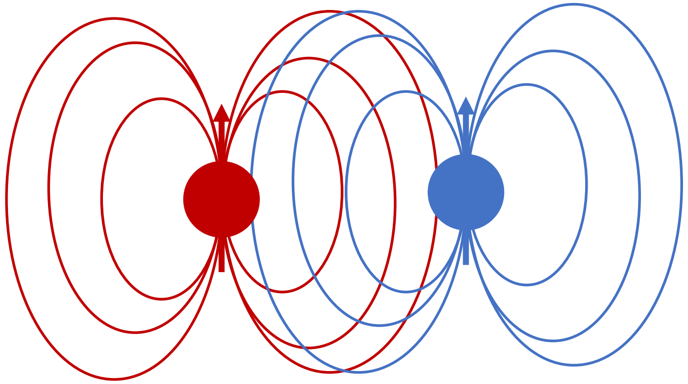






How do we entangle the qubits

Close qubits: Magnetic field interaction



Low Energy

High Energy

$(|0\rangle + |1\rangle)/\sqrt{2} \longrightarrow (|0\rangle - |1\rangle)/\sqrt{2}$

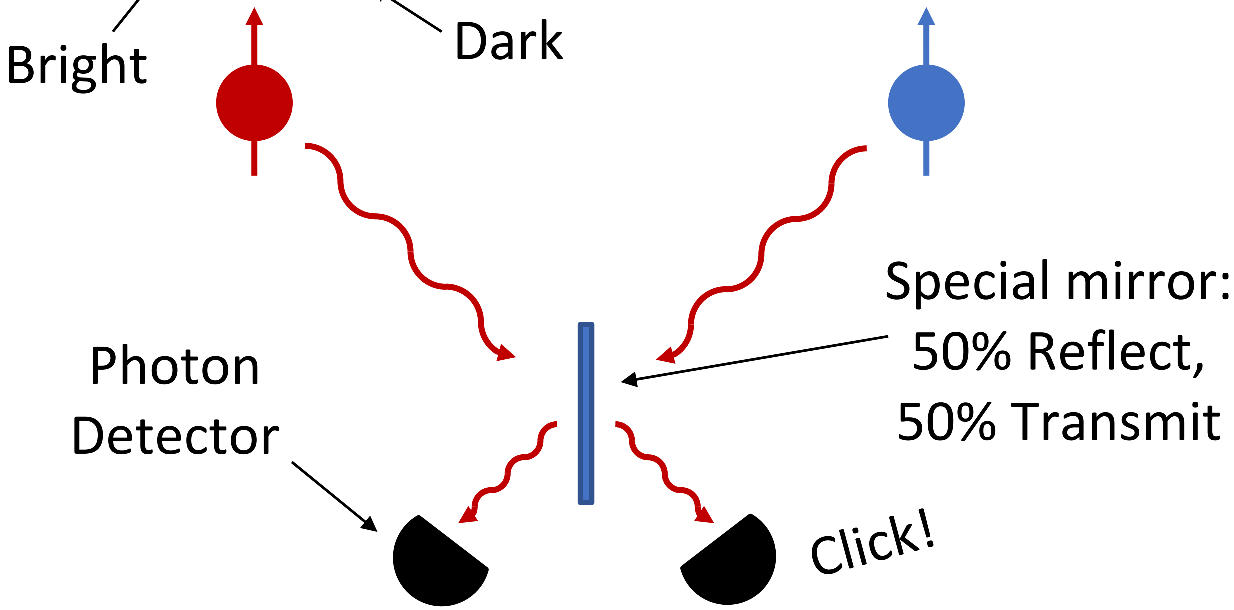
CZ Gate

Pros: Fast ($\sim 1\ \mu s$), high fidelity ($F \approx 99.3\%$)

Cons: Always-on – can't turn off!

Far qubits: Light-mediated gate

$(|0\rangle|B\rangle + |1\rangle|D\rangle)/\sqrt{2}$ $(|0\rangle|B\rangle + |1\rangle|D\rangle)/\sqrt{2}$



One click = $(|0\rangle|1\rangle + |1\rangle|0\rangle)/\sqrt{2}$

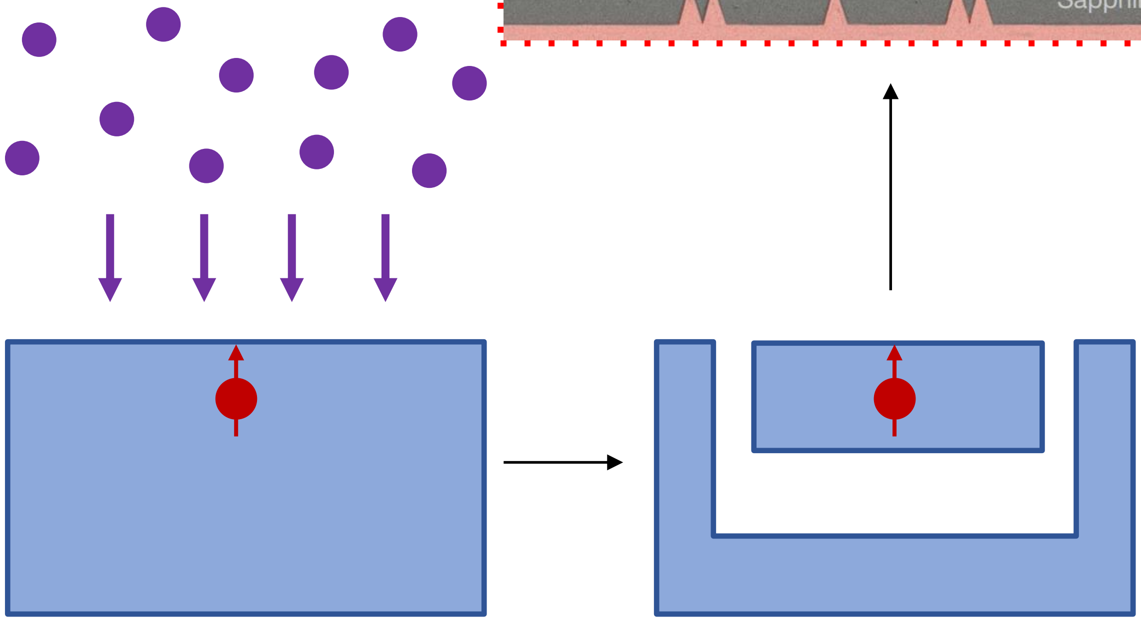
Pros: Connect qubits that are km apart!

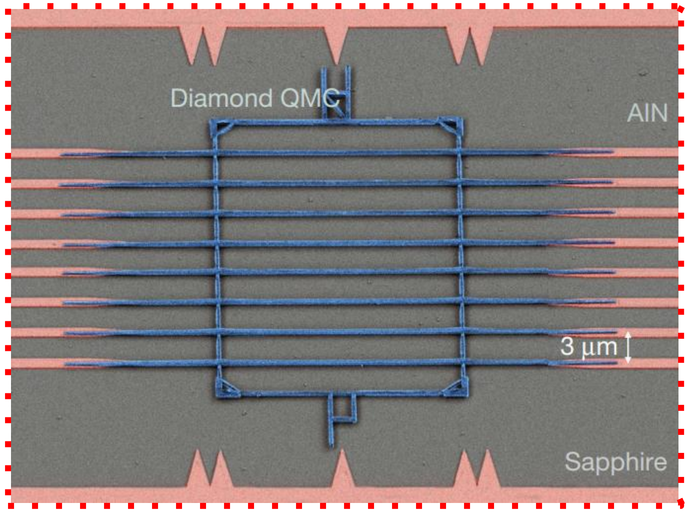
Cons: Slow (0.1 sec), probabilistic ($F \approx 92\%$)

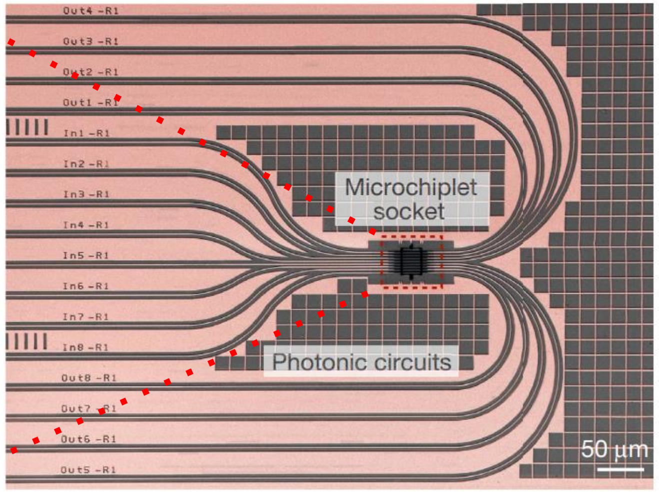
Putting them on a chip – fabrication!

- Qubits already in material
- Can carve wires out for making integrated circuits

Oxygen Plasma

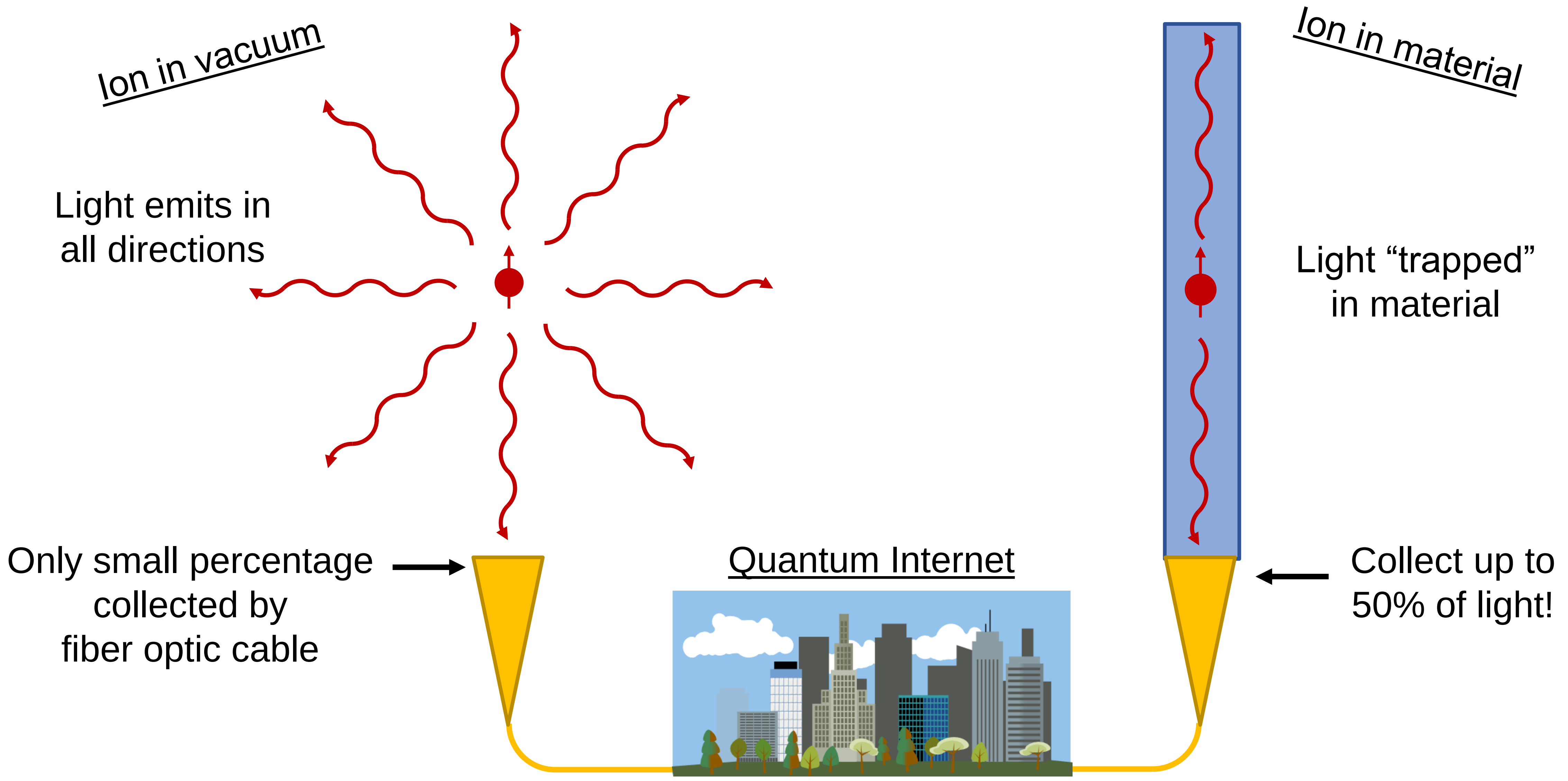






- Can easily put many qubits on a chip
- Can collect light and route on chip, just like electrical circuits

Collecting light for quantum internet



Pros and Cons

Pros:

- Easily integrated on a chip
- Long coherence times
  $T_2 \approx 1$ ms – 1.9 min
- Can do gates between distant qubits

Cons:

- Requires cooling to mK – K temperatures
- Connecting lots of qubits challenging
- Materials sometimes inconsistent

Breakthroughs

LETTER

doi:10.1038/nature15759

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen[1,2], H. Bernien[1,2]†, A. E. Dréau[1,2], A. Reiserer[1,2], N. Kalb[1,2], M. S. Blok[1,2], J. Ruitenberg[1,2], R. F. L. Vermeulen[1,2], R. N. Schouten[1,2], C. Abellán[3], W. Amaya[3], V. Pruneri[3,4], M. W. Mitchell[3,4], M. Markham[5], D. J. Twitchen[5], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]

Realization of a multinode quantum network of remote solid-state qubits

M. Pompili[1,2]†, S. L. N. Hermans[1,2]†, S. Baier[1,2]†‡, H. K. C. Beukers[1,2], P. C. Humphreys[1,2]§, R. N. Schouten[1,2], R. F. L. Vermeulen[1,2], M. J. Tiggelman[1,2]¶, L. dos Santos Martins[1,2], B. Dirkse[1,2], S. Wehner[1,2], R. Hanson[1,2]*

The distribution of entangled states across the nodes of a future quantum internet will unlock fundamentally new technologies. Here, we report on the realization of a three-node entanglement-based quantum network. We combine remote quantum nodes based on diamond communication qubits into a scalable phase-stabilized architecture, supplemented with a robust memory qubit and local quantum logic. In addition, we achieve real-time communication and feed-forward gate operations across the network. We demonstrate two quantum network protocols without postselection: the distribution of genuine multipartite entangled states across the three nodes and entanglement swapping through an intermediary node. Our work establishes a key platform for exploring, testing, and developing multinode quantum network protocols and a quantum network control stack.

Article

Experimental demonstration of memory-enhanced quantum communication

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M. K. Bhaskar[1], R. Riedinger[1], B. Machielse[1], D. S. Levonian[1], C. T. Nguyen[1], E. N. Knall[2], H. Park[1,3], D. Englund[4], M. Lončar[2], D. D. Sukachev[1] & M. D. Lukin[1]✉

The ability to communicate quantum information over long distances is of central importance in quantum science and engineering[1]. Although some applications of quantum communication such as secure quantum key distribution[2,3] are already being successfully deployed[4–7], their range is currently limited by photon losses and cannot be extended using straightforward measure-and-repeat strategies without compromising unconditional security[8]. Alternatively, quantum repeaters[9], which utilize intermediate quantum memory nodes and error correction techniques, can extend the range of quantum channels. However, their implementation remains an outstanding challenge[10–16], requiring a combination of efficient and high-fidelity quantum memories, gate operations, and measurements. Here we use a single solid-state spin memory integrated in a nanophotonic diamond resonator[17–19] to implement asynchronous photonic Bell-state measurements, which are a key component of quantum repeaters. In a proof-of-principle experiment, we demonstrate high-fidelity operation that effectively enables quantum communication at a rate that surpasses the ideal loss-equivalent direct-transmission method while operating at megahertz clock speeds. These results represent a crucial step towards practical quantum repeaters and large-scale quantum networks[20,21].

Article

Large-scale integration of artificial atoms in hybrid photonic circuits

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Check for updates

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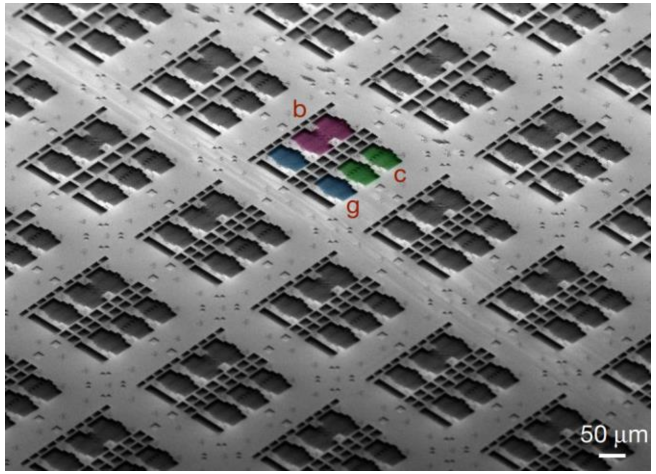
A central challenge in developing quantum computers and long-range quantum networks is the distribution of entanglement across many individually controllable qubits[1]. Colour centres in diamond have emerged as leading solid-state 'artificial

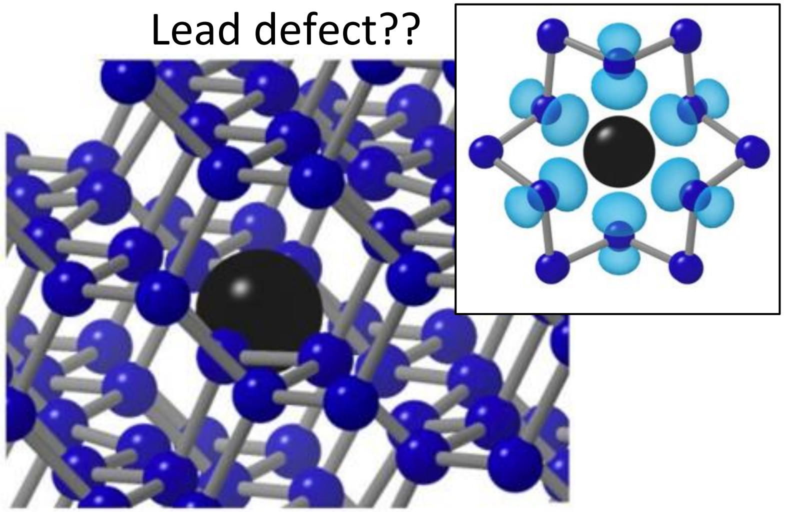
Ongoing research

- Hunt for new species of defects in new materials
- Improvements in host materials (to further improve coherence)
- New fabrication – better light-controlling circuitry
- Faster, higher fidelity two-qubit gates
- Putting even more qubits on one chip

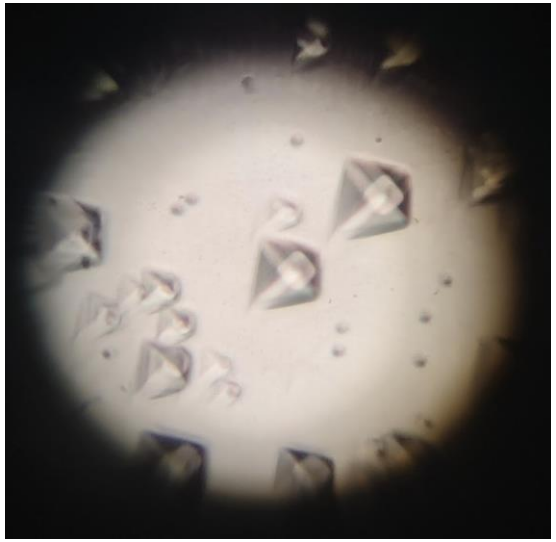


- Thousands of qubits on one chip!

Lead defect??



We grew a very ugly diamond



Additional Reading

- Quantum internet: A vision for the road ahead: https://science.sciencemag.org/content/362/6412/eaam9288

- The Quantum Internet, J. Kimble: https://arxiv.org/abs/0806.4195

- Quantum network is step towards ultrasecure internet: https://www.nature.com/articles/d41586-021-00420-5

- Toward an unhackable quantum internet: https://news.harvard.edu/gazette/story/2020/04/researchers-demonstrate-the-missing-link-for-a-quantum-internet/

- Scaling up the quantum chip: https://news.mit.edu/2020/scaling-quantum-chip-0708

INTRO TO QUANTUM COMPUTING
LECTURE #23

Quantum Hardware: Photonic qubits

Stefan Krastanov

04/25/2021

tldr: Photonic qubits

Use small packets of light to carry quantum information.

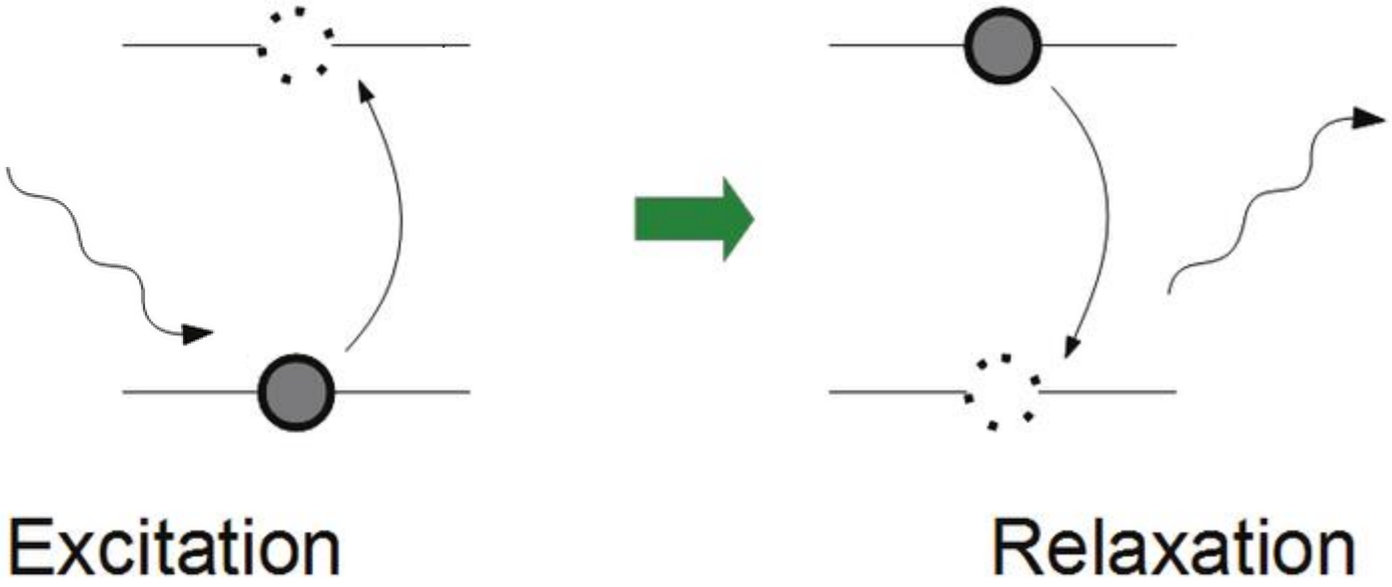
They are resilient to noise, but difficult to work with.

The Good Things About Photons

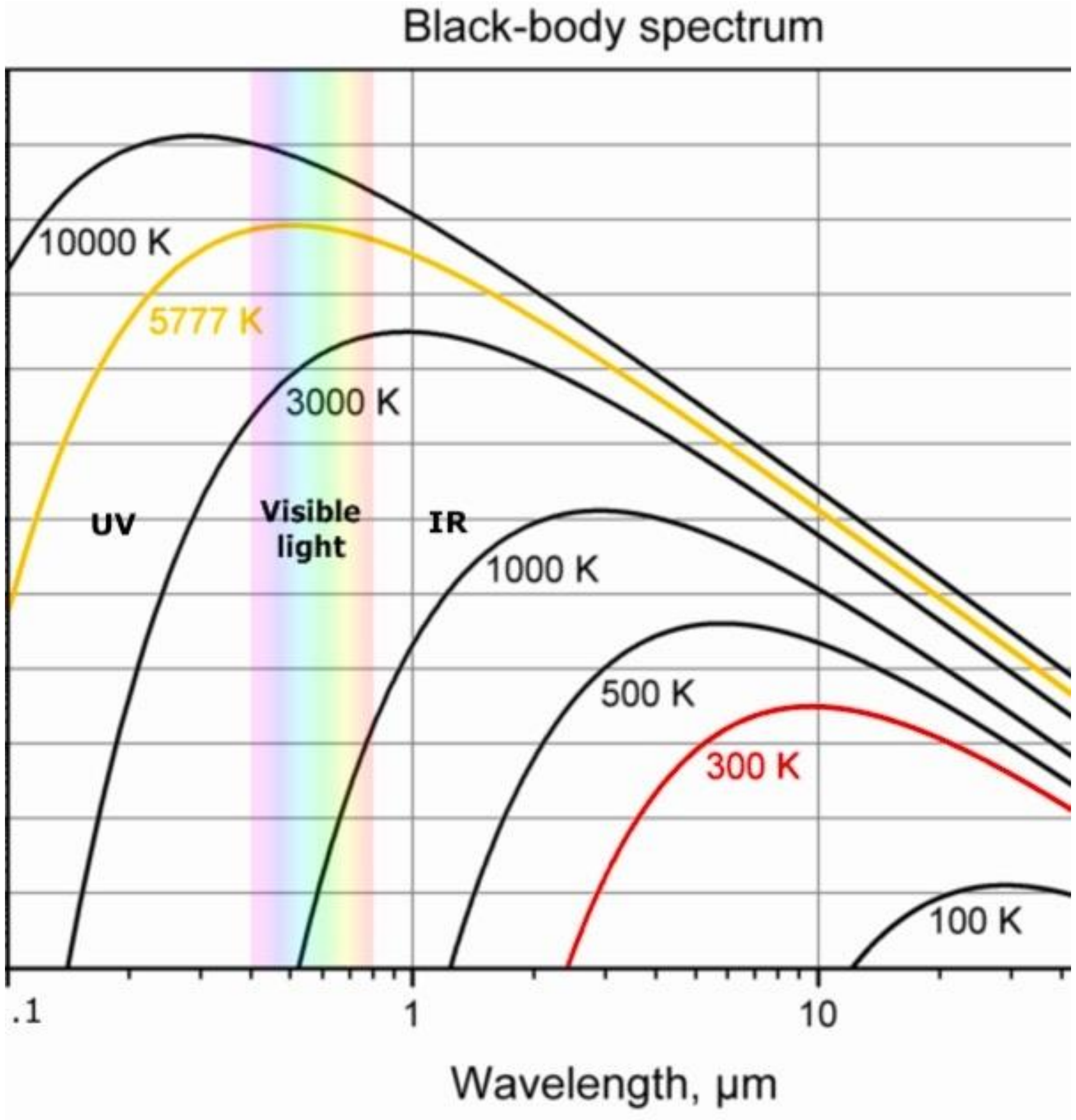
Optical hardware does not need to be cooled.

It also happens to be ridiculously fast.

Thermal noise is a problem



Thermal noise vs Photonic qubits

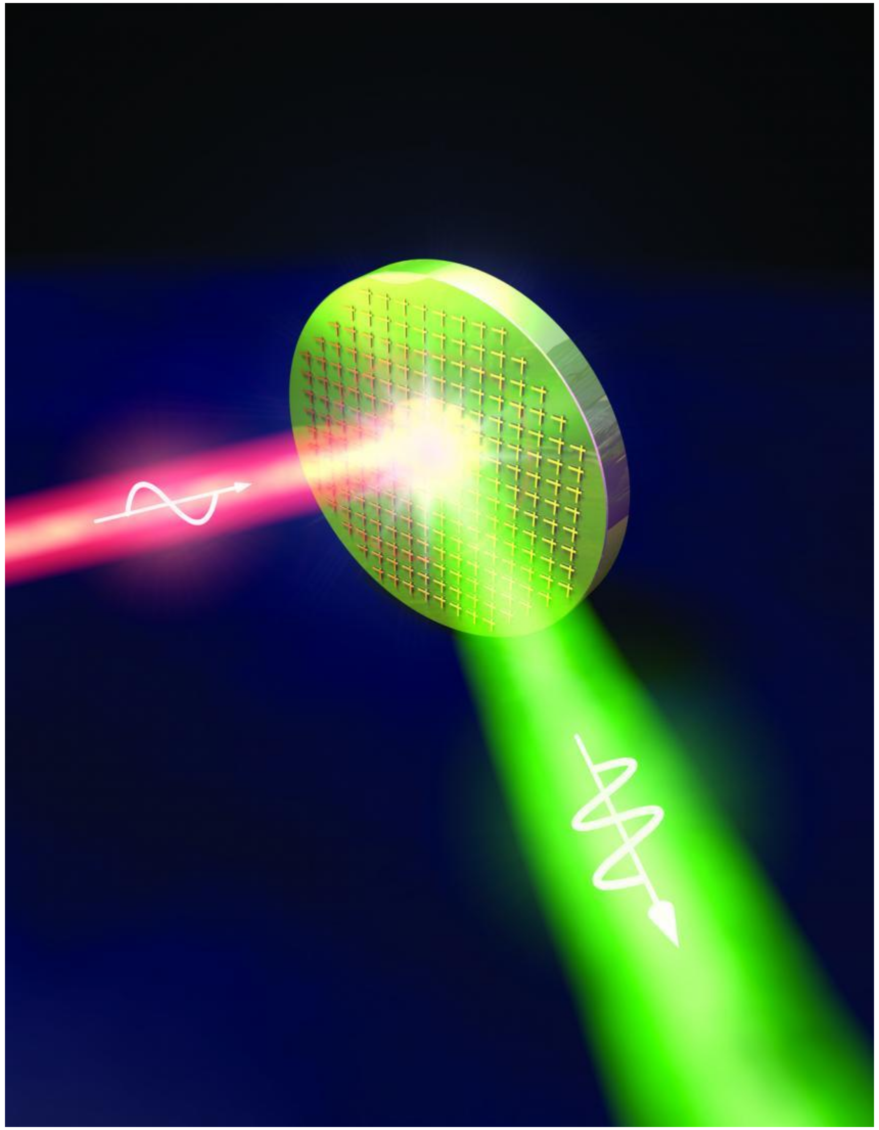


The Bad Things About Photons

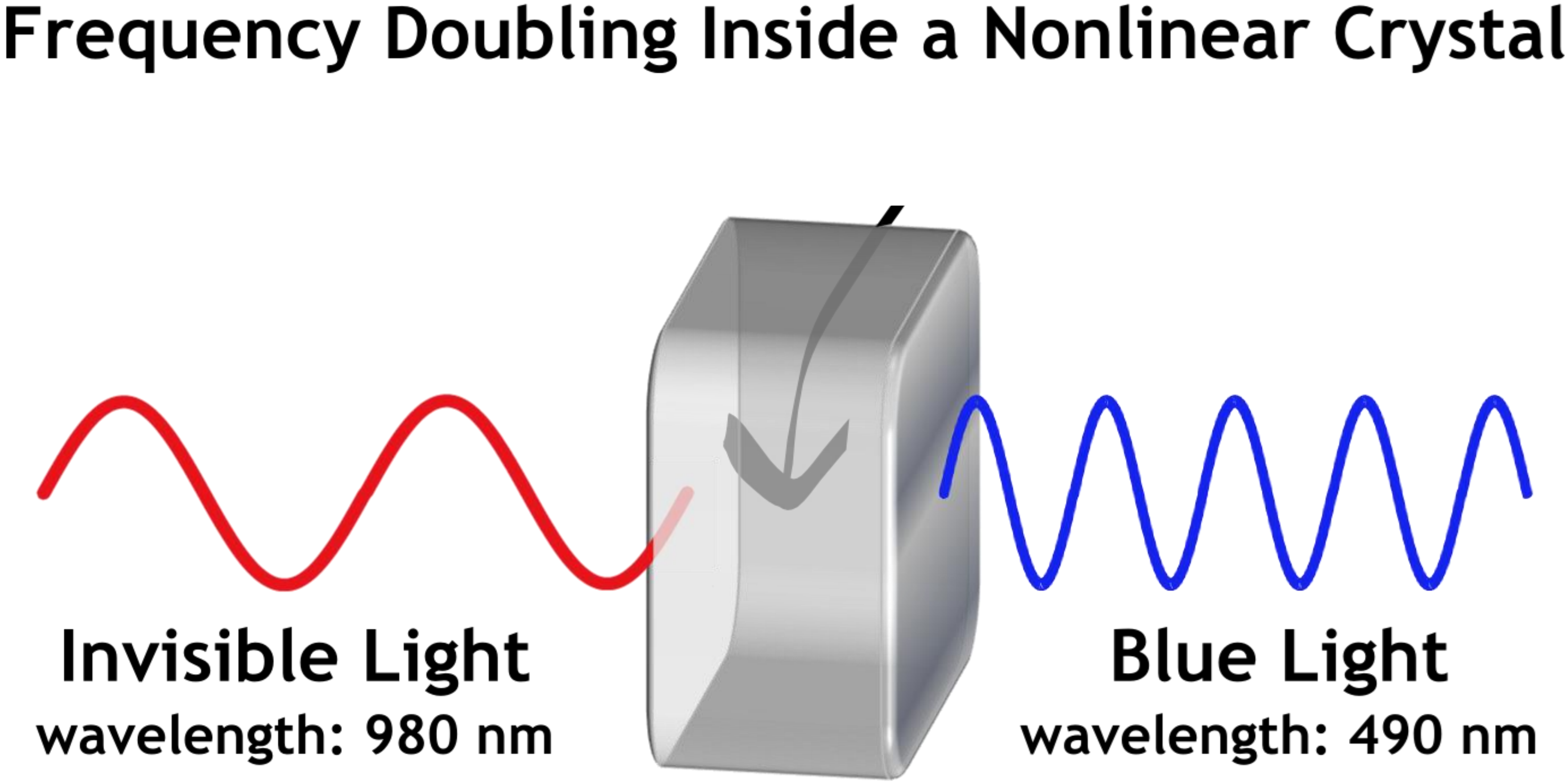
They really do not want to interact with each other.

Light does not interact with itself

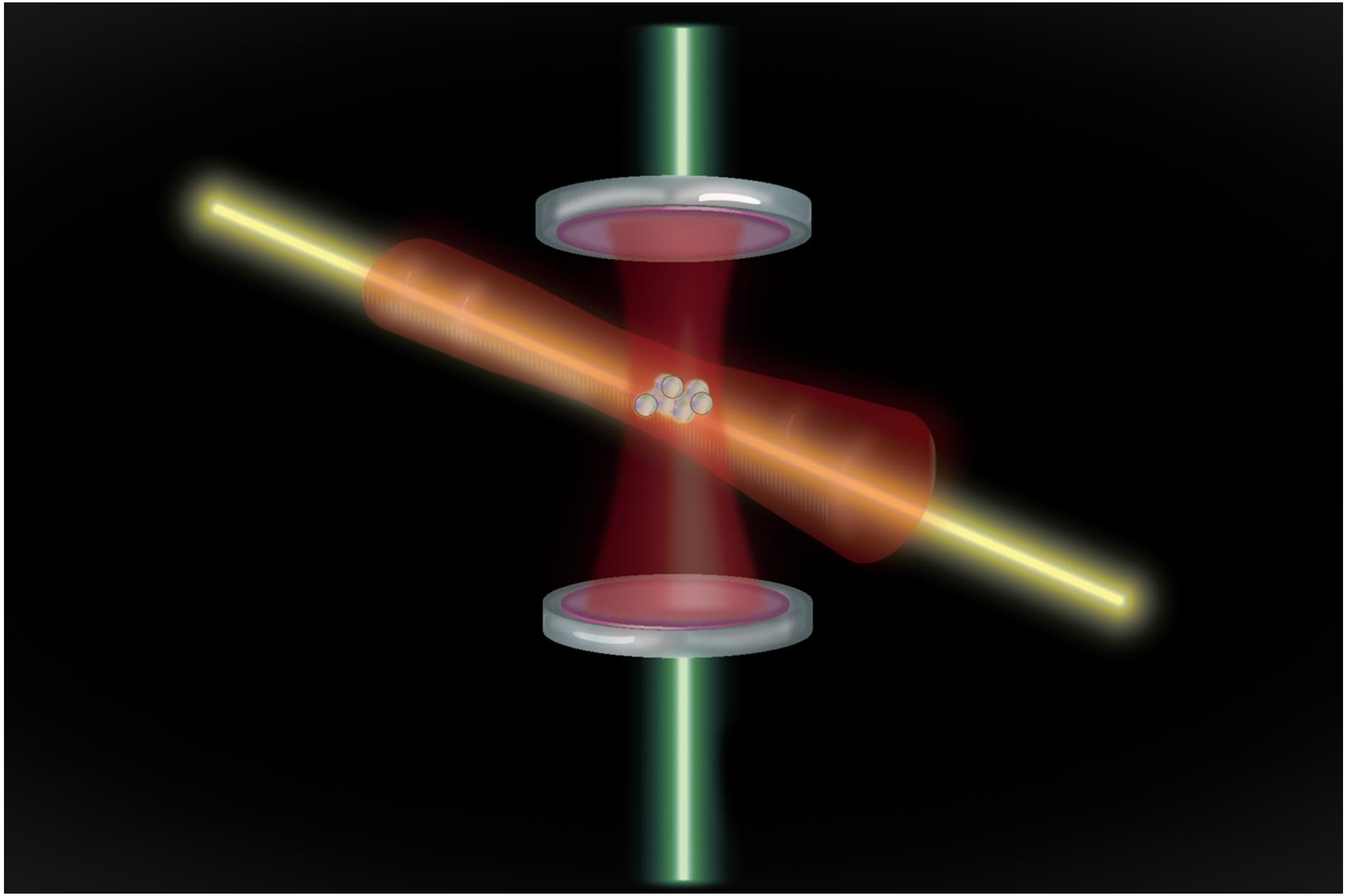
Nonlinear optics in special materials



Nonlinear optics in special materials



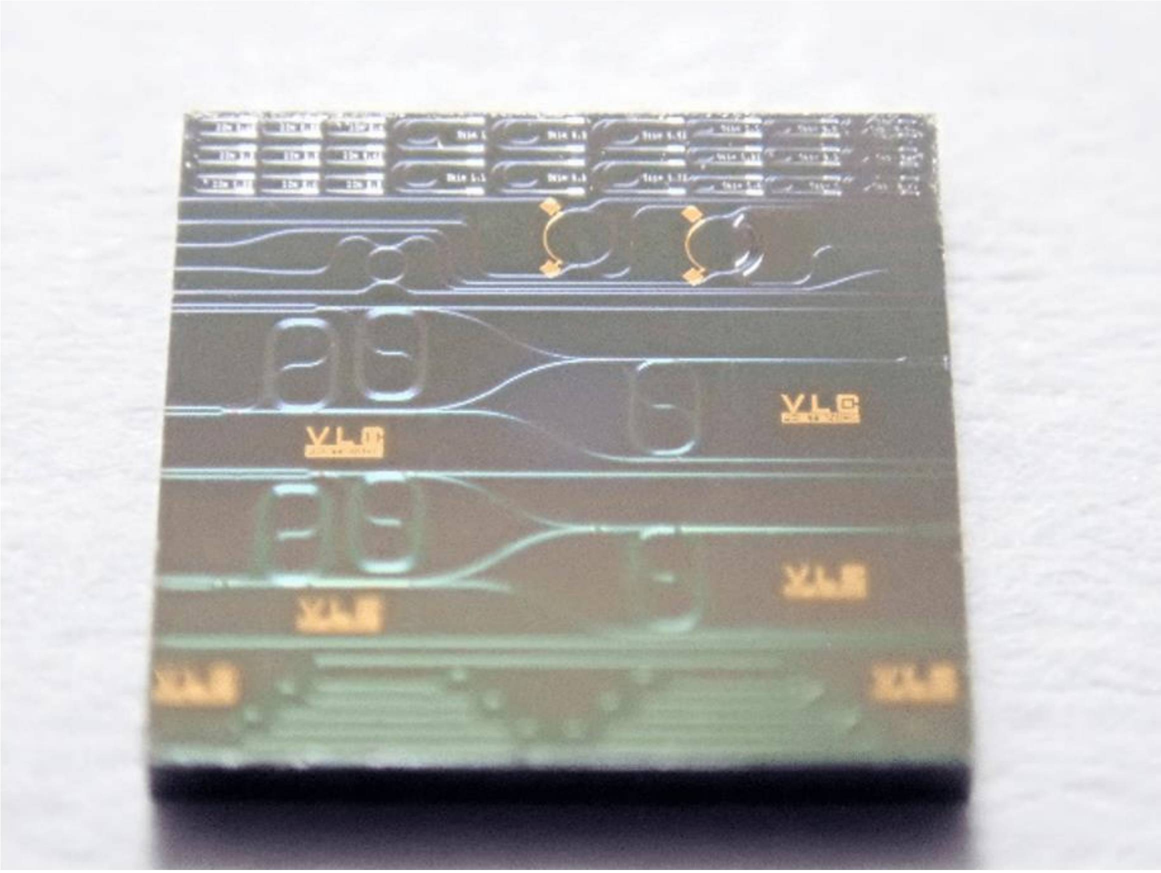
We might just end using atoms/defects

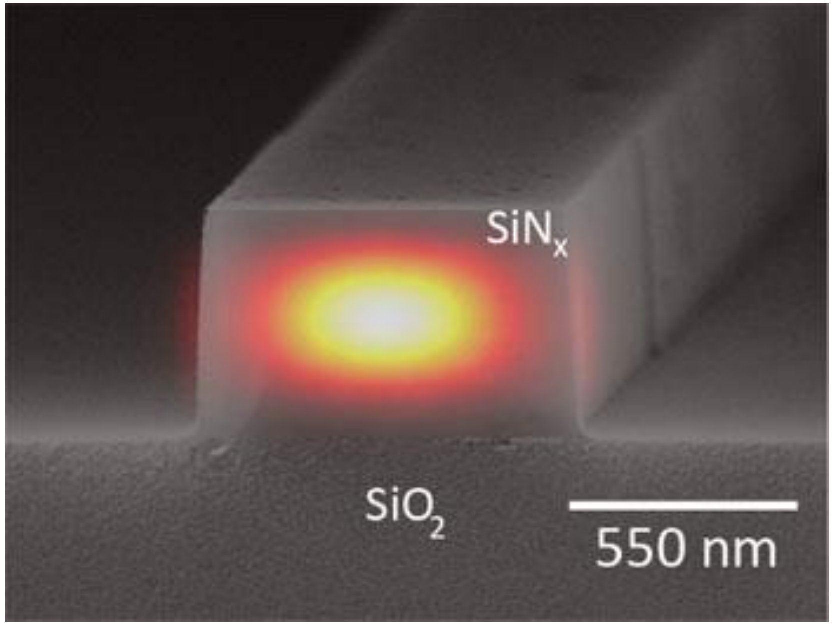


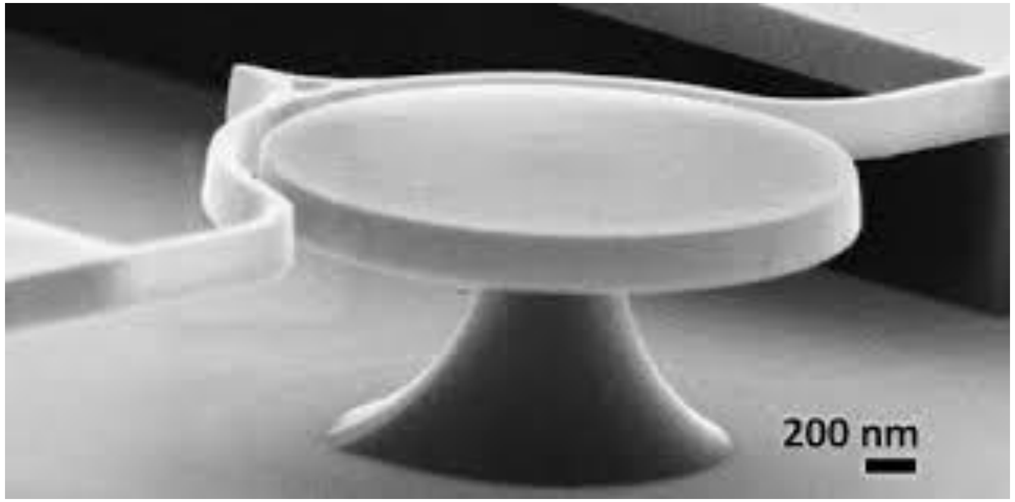
Photonic Chips

To manipulate states of light.

A chip with waveguides instead of wires







Storing light on a chip

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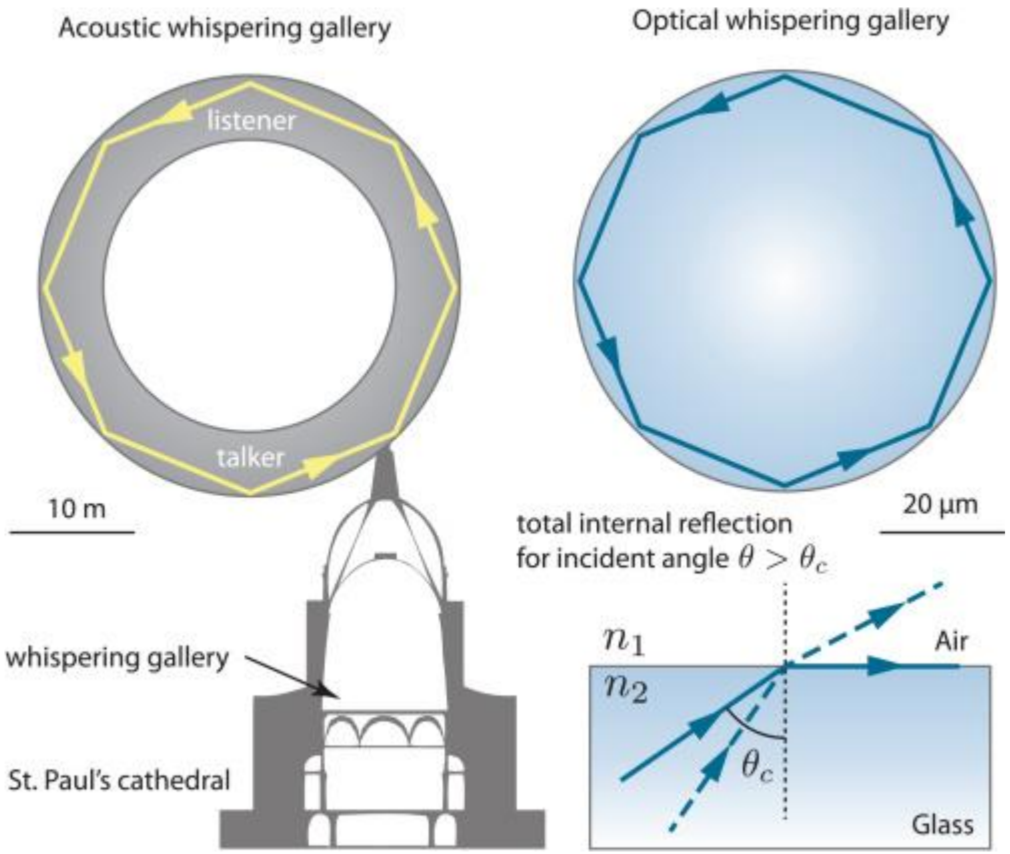
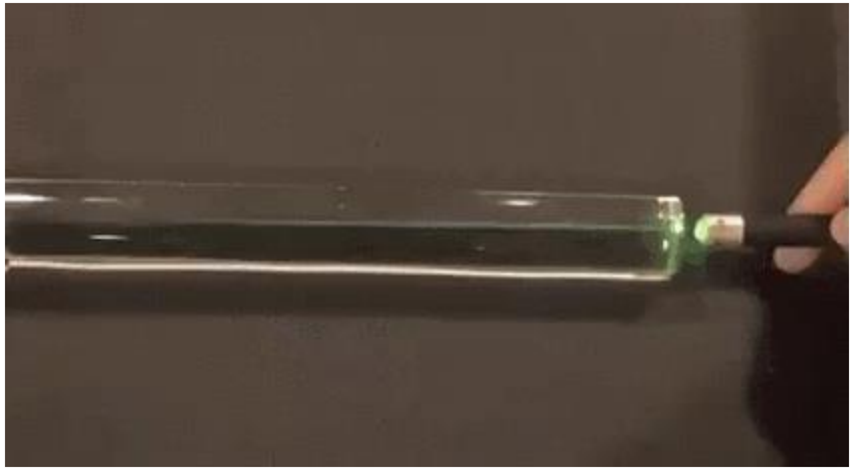
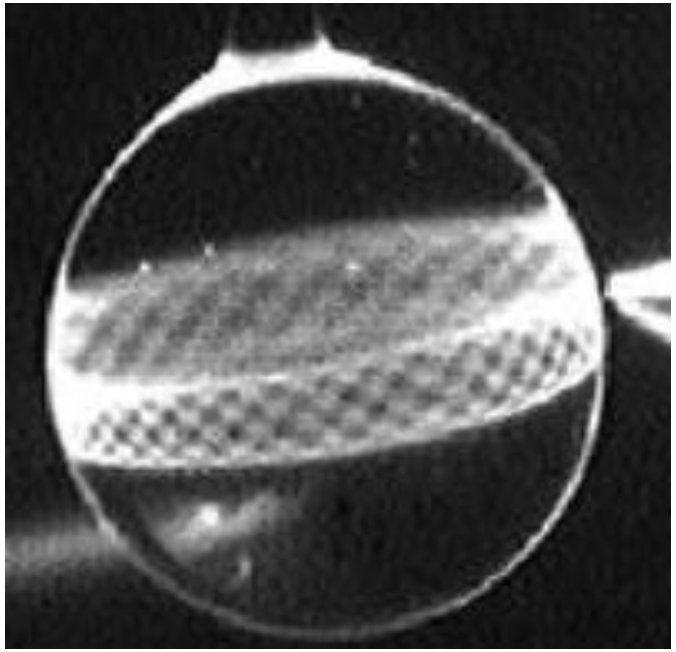
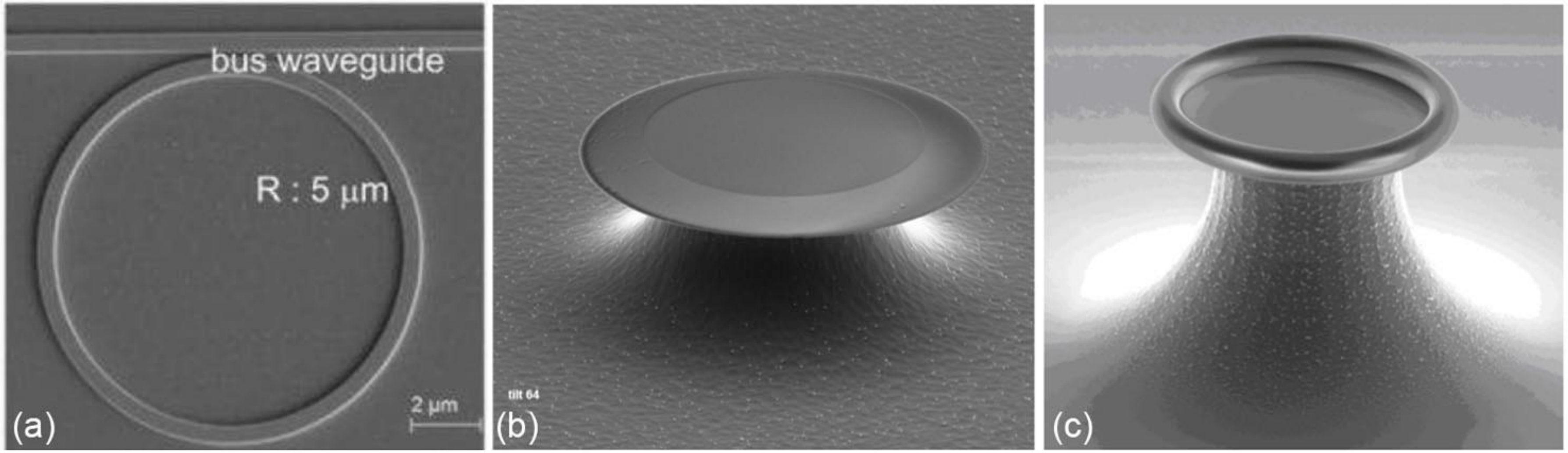




Storing light on a chip





Pros and Cons

Pros:

- Comes on a chip
- Compatible with existing fabrication infrastructure
- Extremely fast
- Room temperature
- The only way to send quantum states between distant devices

Cons:

- Gates between qubits are very difficult as photons simply do not interact with each other