Technologies for Quantum Computing

A bird's eye view

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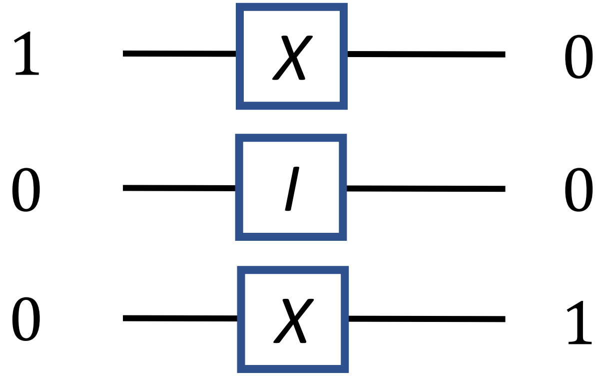
AEAI webinar, Dec 1st 2020

WEIZMANN INSTITUTE OF SCIENCE

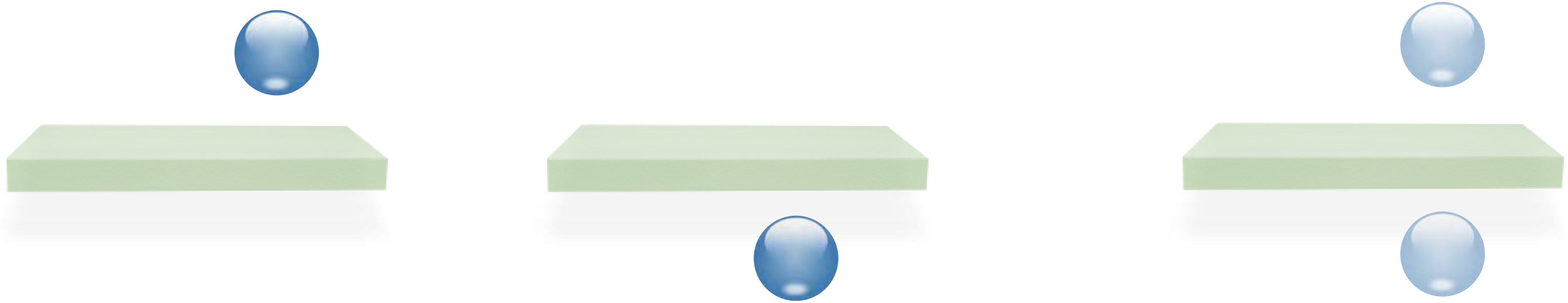
ROSEN BLUM LAB
Quantum Circuits

Back to basics: Classical Bits



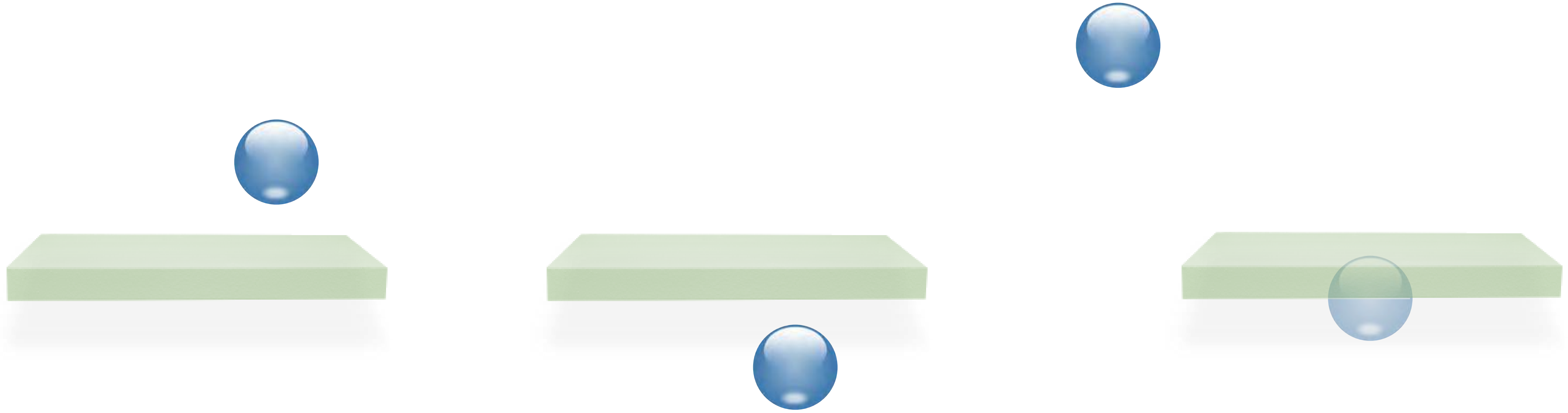
Describing n bits : n numbers

Quantum Bits



$|0\rangle$ $|1\rangle$ $|0\rangle + |1\rangle$

Quantum Bits



$|0\rangle$ $|1\rangle$ $|0\rangle + |1\rangle$

Quantum Bits

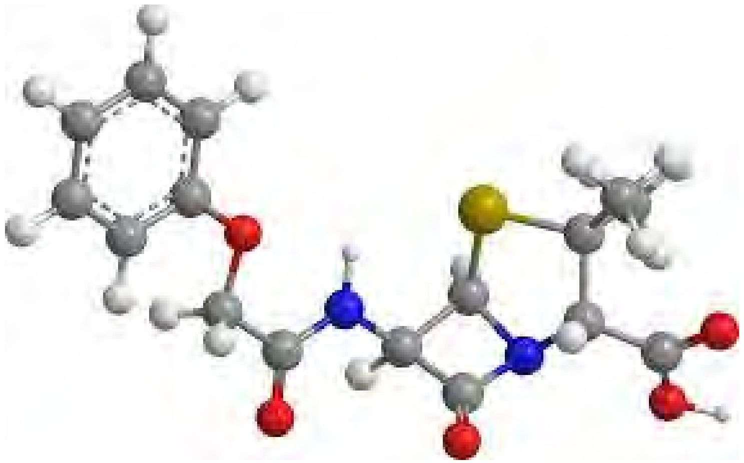
$|1\rangle$ — H — $|0\rangle - |1\rangle$

$|0\rangle$ — H — $|0\rangle + |1\rangle$

$|0\rangle$ — H — $|0\rangle + |1\rangle$

$$|100\rangle \quad \rightarrow \quad +|000\rangle - |100\rangle + \; ... - \; |111\rangle$$

$$a_1|000\,...\rangle + a_2|100\,...\rangle + a_{2^N}|111\,...\rangle$$



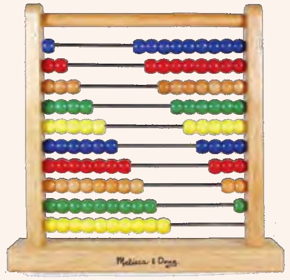
300 electrons $\sim 10^{90}$ numbers

Describing n qubits : 2^n numbers

Quantum Computers are fundamentally different

Classical computers

Quantum computers



abacus

laptop

supercomputer

DNA computer

superconducting quantum chip

mathematician

*Some computational problems are hard for **all** computers, except quantum computers.*

Quantum computers —NOT just a faster version of today's computers

Quantum Computing companies (full stack)

SUPERCONDUCTING

- Google
- IBM
- qci
- intel
- rigetti
- Alibaba
- ALICE & BOB
- IQM

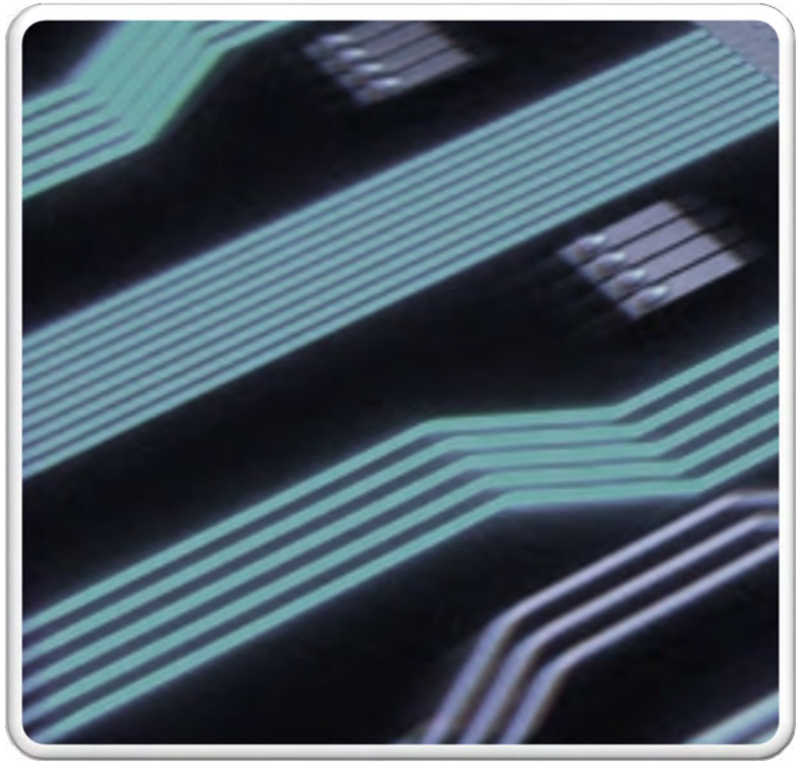
ATOMIC

- IONQ
- Honeywell
- AQT
- PASQAL
- |QuEra〉
- ColdQuanta
- ATOM COMPUTING

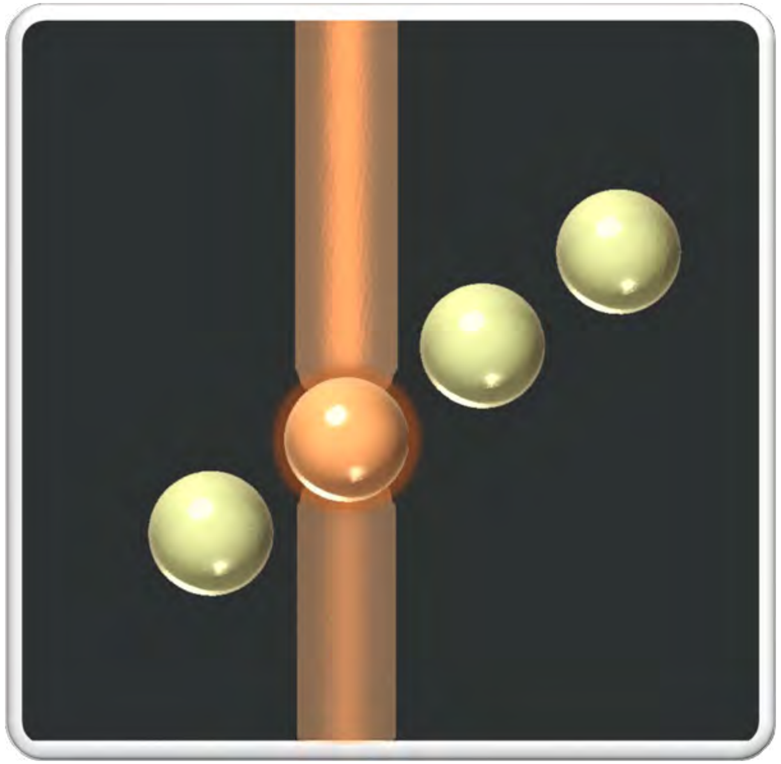
PHOTONICS

- XANADU
- PsiQuantum

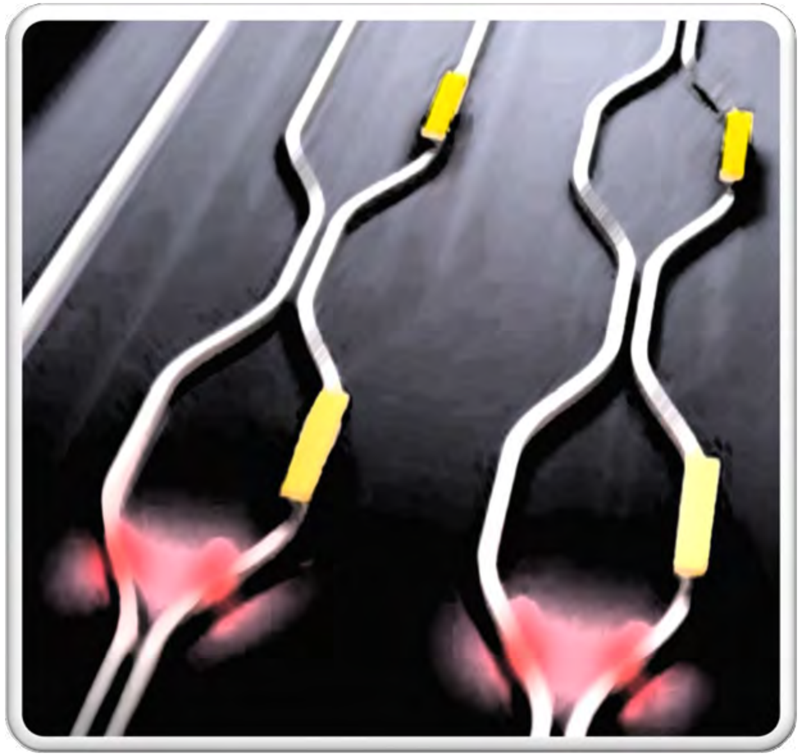
Leading candidate technologies for QC (today)



Superconductors



Atoms / Ions



Optical photons

Also: Quantum Dots, impurities in silicon/diamond, topological anyons, NMR, …

Minimal requirements — DiVincenzo Criteria

1. **Well-defined qubits**

   $$|\psi\rangle = a|0\rangle + b|1\rangle$$

2. **Low error rates**

   How long does the qubit state stay alive?

3. **Initialization**

   How well/fast can you reset your qubits to $|0\rangle$?

4. **Universal set of logical gates**

   Enough control to generate any quantum state?

5. **Measurement**

   How fast/precise is the qubit measurement? Does it ruin the qubit?

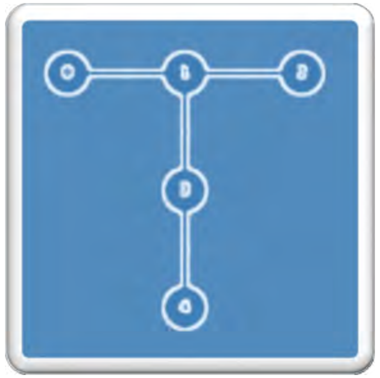
What makes a powerful Quantum Computer?

#1 Number of Qubits

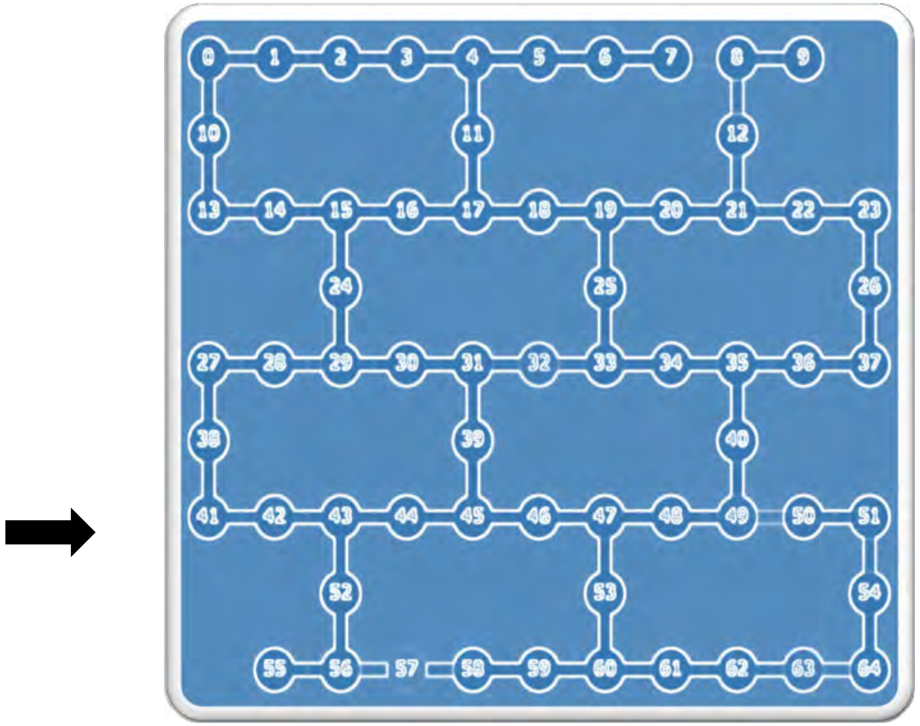
- More qubits = more complex problems

- up to $N \sim 50$ qubits can be simulated on classical computer.

2^{50} numbers $\sim$ 1 Petabyte

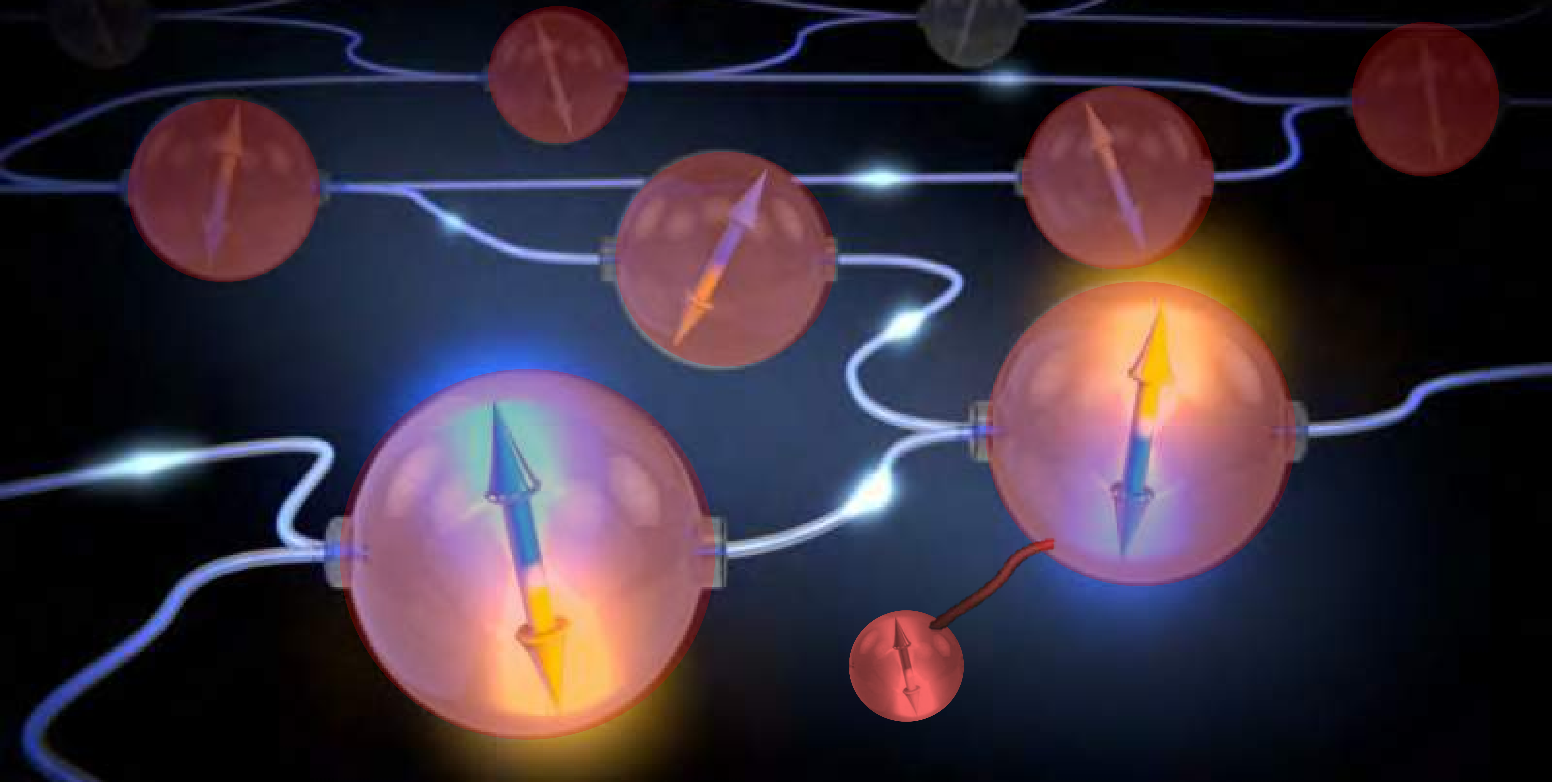


5 qubits - IBM 2016

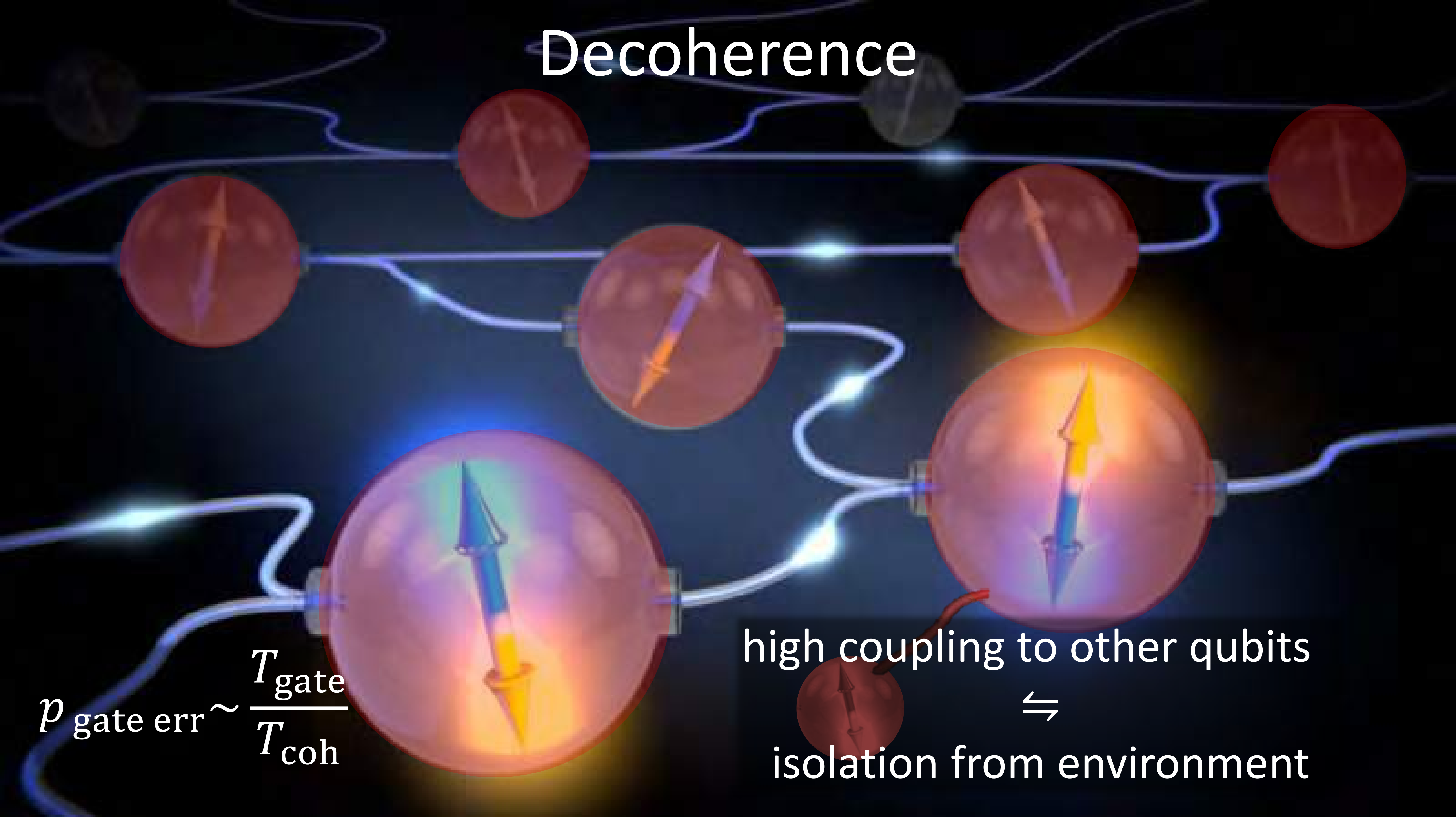


65 qubits - IBM 2020

Decoherence



Decoherence



$$p_{\text{gate err}} \sim \frac{T_{\text{gate}}}{T_{\text{coh}}}$$

high coupling to other qubits

⇋

isolation from environment

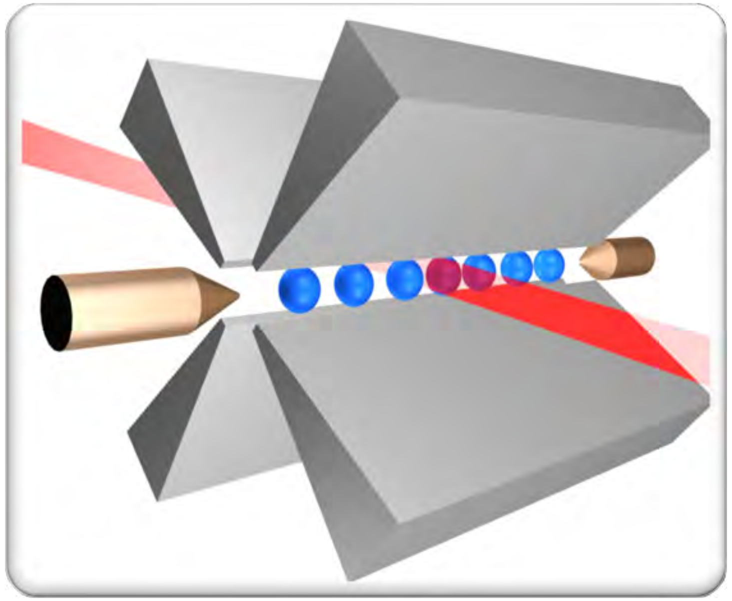
What makes a powerful Quantum Computer?

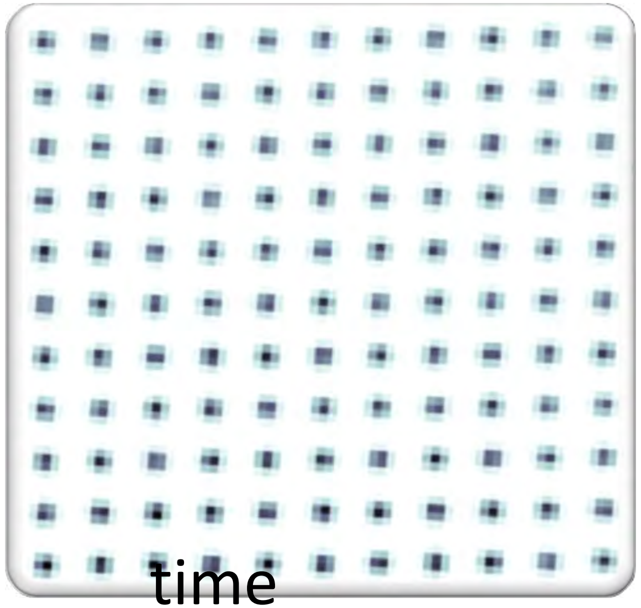
#2 Quality of Qubits

d = circuit depth

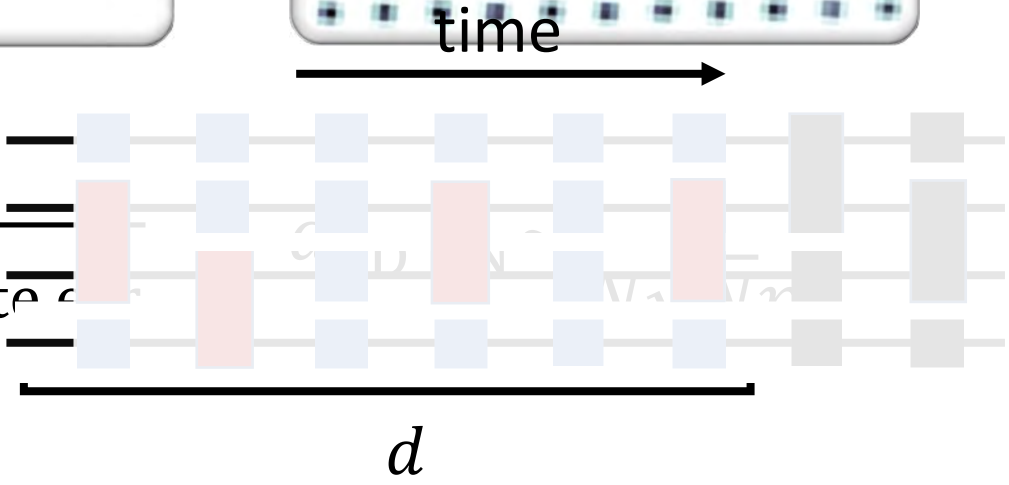
How many computational steps before error happens?

$$d \sim \frac{1}{N p_{\text{gate err}}}$$





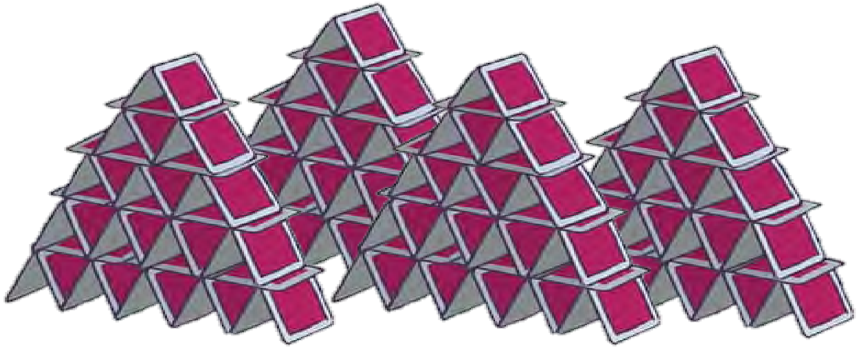
$$d_{\text{1D NN}} \sim \frac{1}{N^2 p_{\text{gate err}}}$$



For QC technology to progress…

… the **qubit number** and **qubit error** must improve *at the same time.*

High N, low *d*

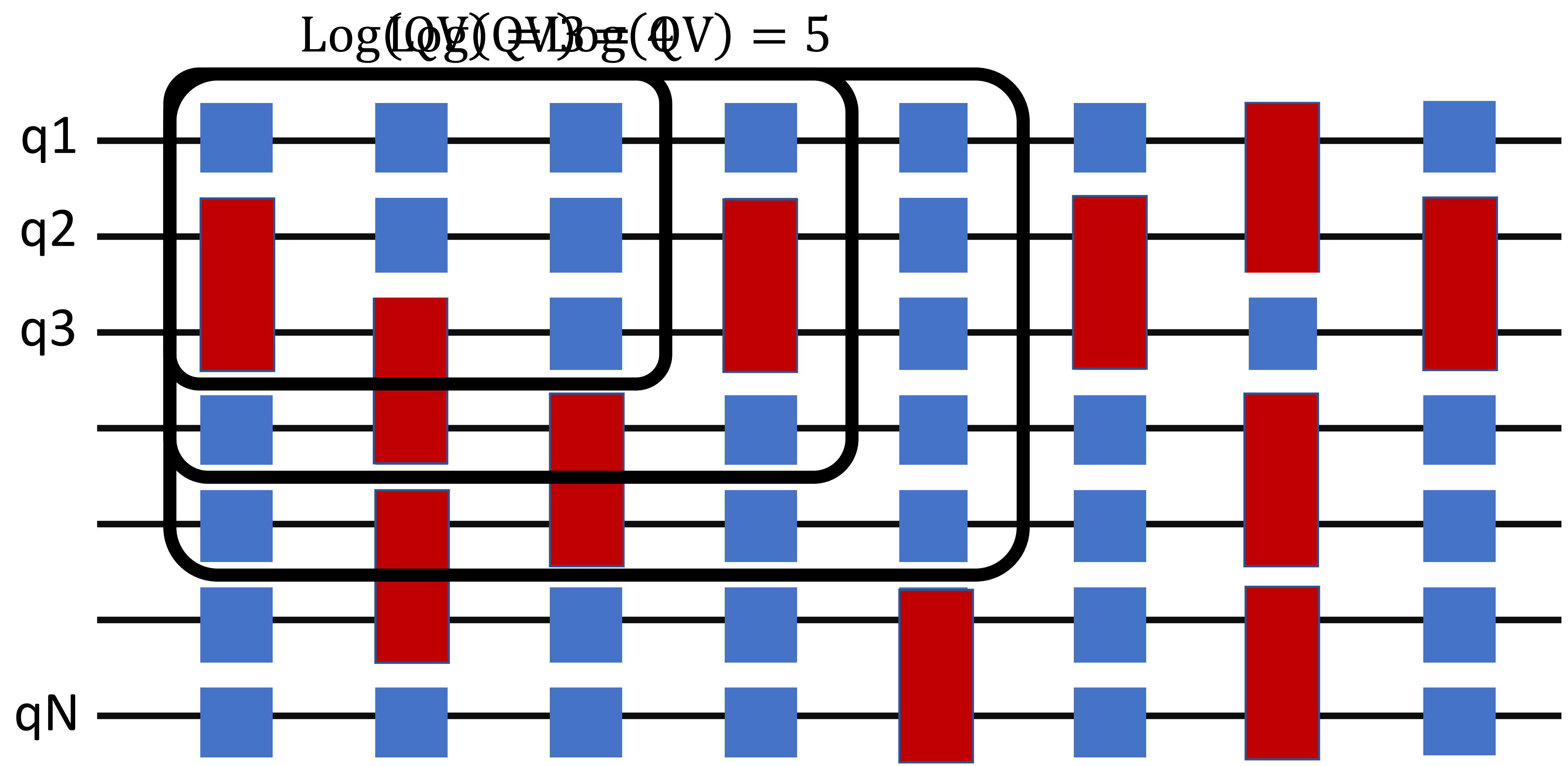


Low N, high *d*

High N, high *d*

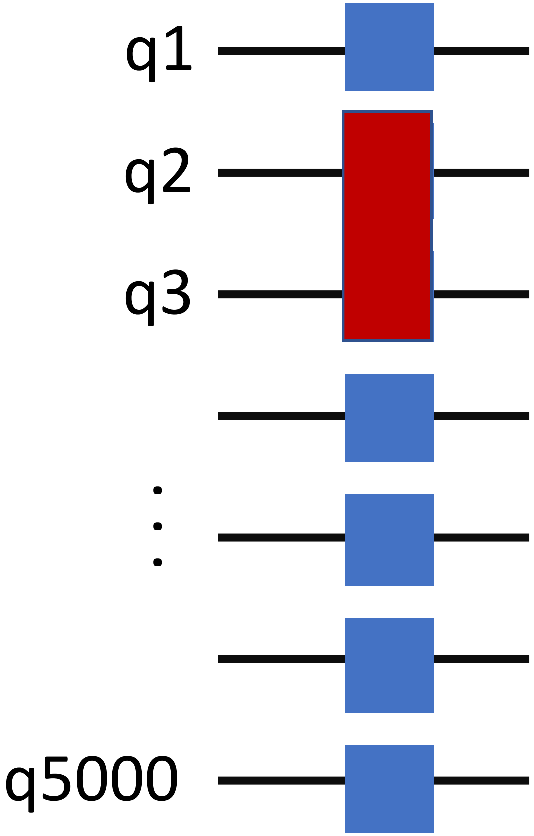
Quantum Volume

$\mathrm{Log(QV)} = \min\big(N, d(N)\big) =$ The largest **square** quantum circuit you can run successfully.

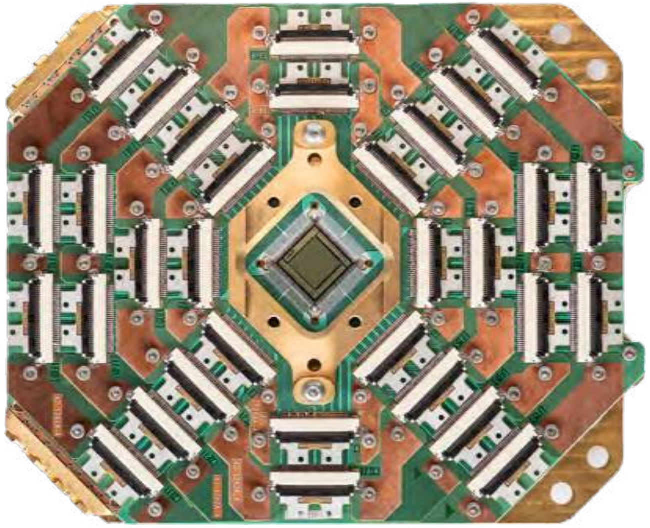


Quantum Volume

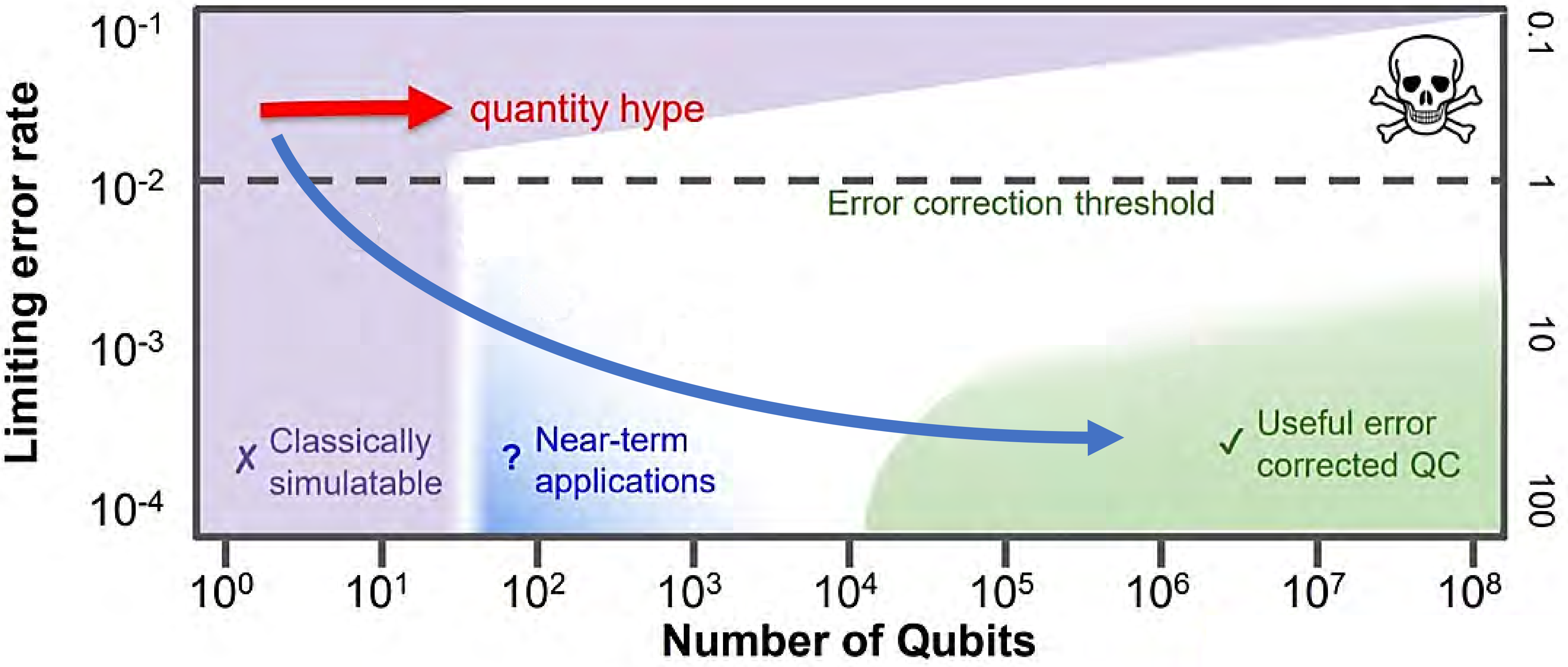
Log(**QV**) = 1



D:Wave
The Quantum Computing Company™



Quantum volume makes sense up to a point



Google strategy

There are other criteria

- **Scalability**

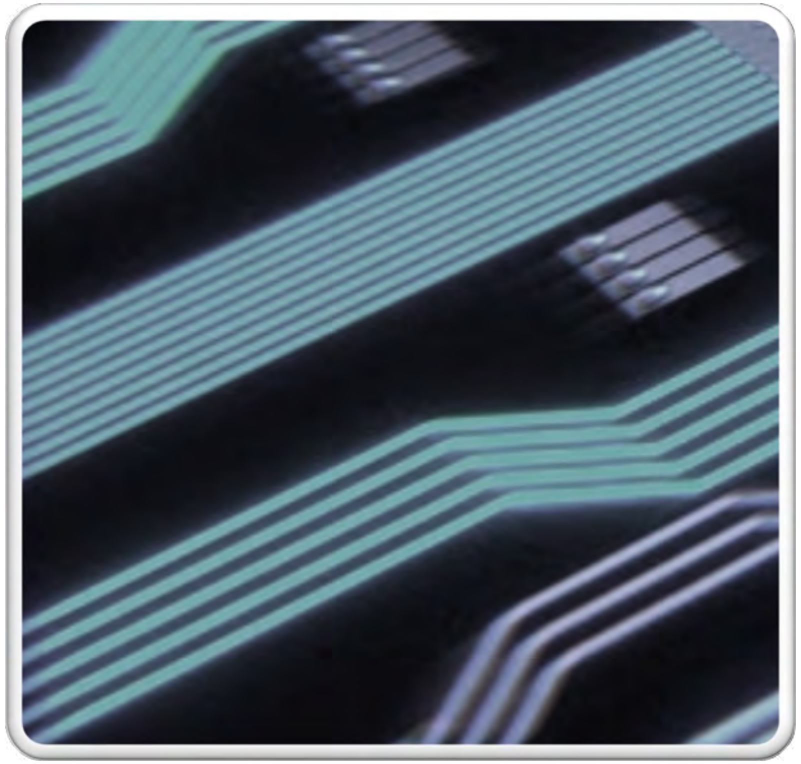
  Is there a clear plan how to increase system size to hundreds / thousands / millions of qubits?

- **Clock speed**

  How fast are the gates?

- **Communication**

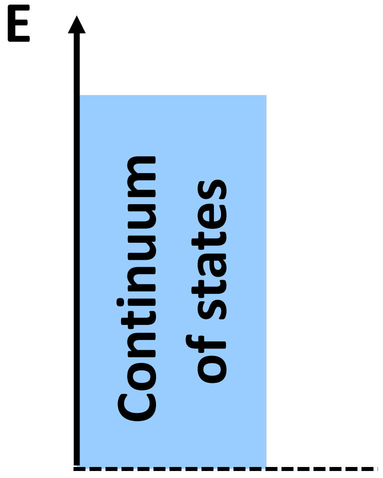
  Can quantum computers interface?

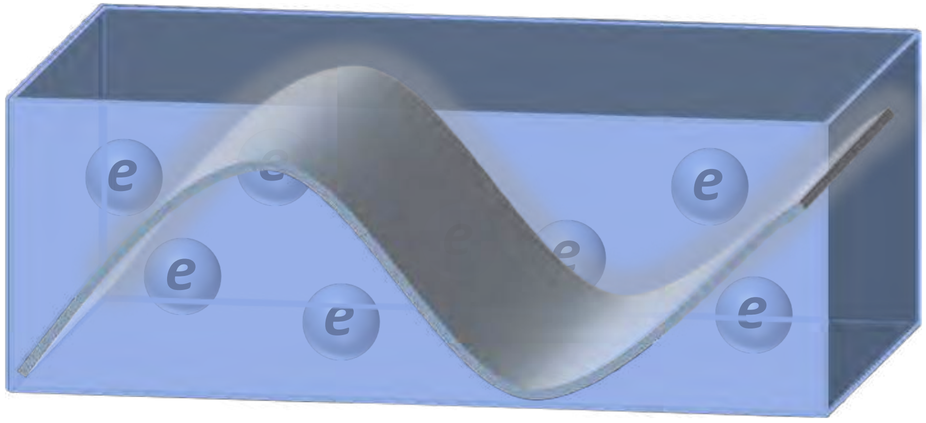


Superconductors

Macroscopic quantum systems

Myth: The smaller an object, the more pronounced its quantum behavior.



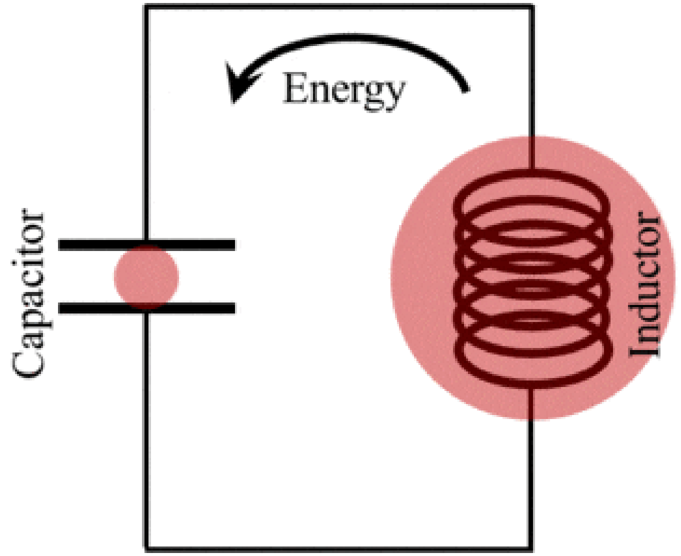


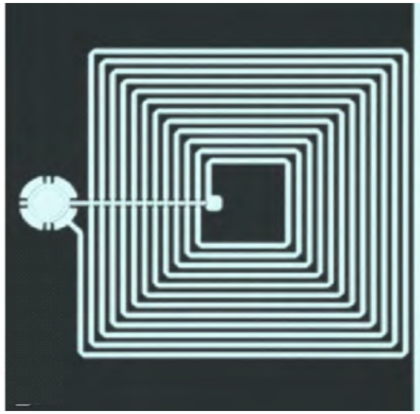
normal metal superconductor

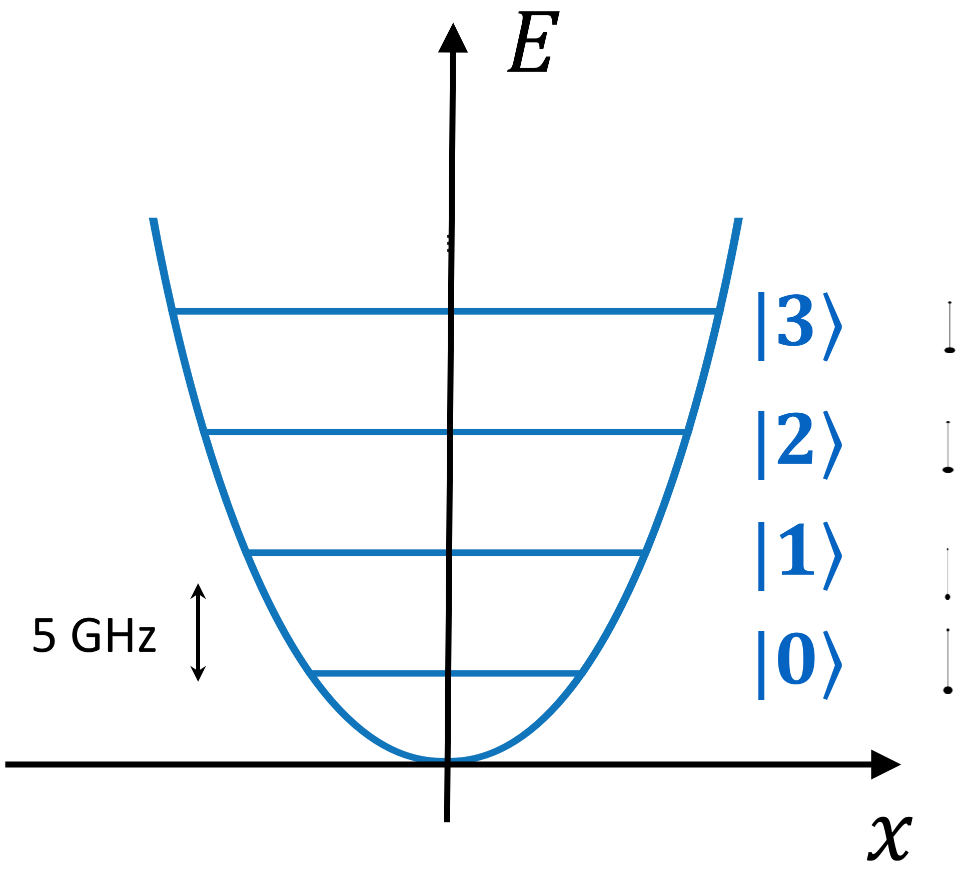
- Macroscopic number of electrons pair up and condense into **single** quantum object

Superconducting microwave resonators

5 GHz LC resonator (Radio frequency)

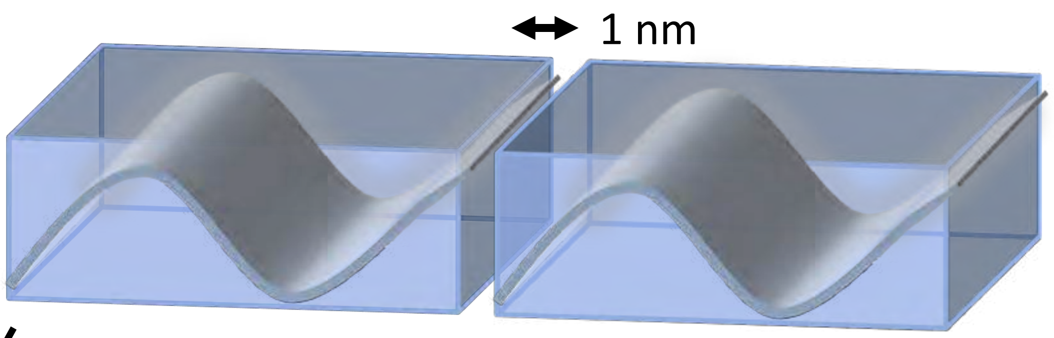




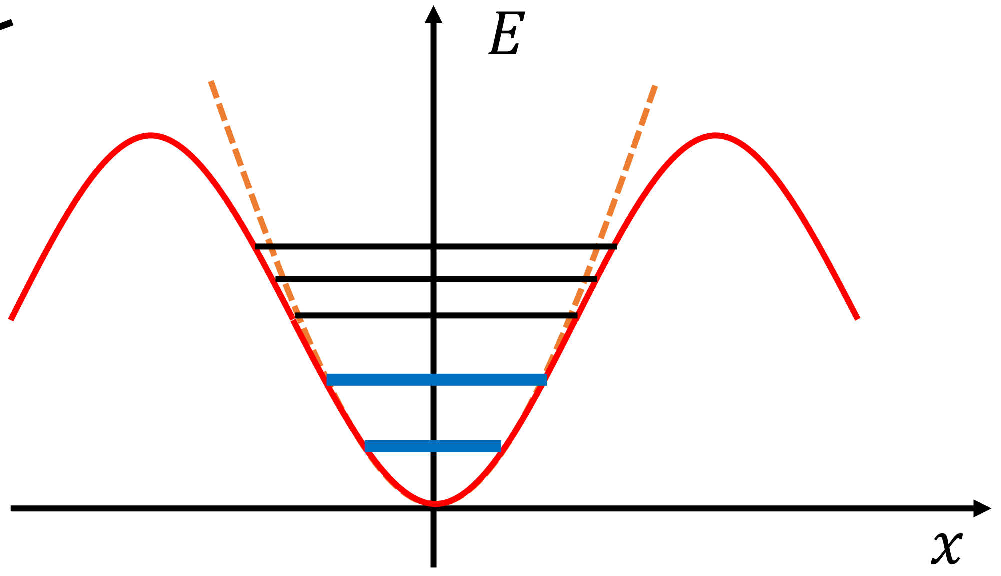


Josephson junctions : artificial atoms

Josephson Junction = 2 superconducting regions separated by thin insulator



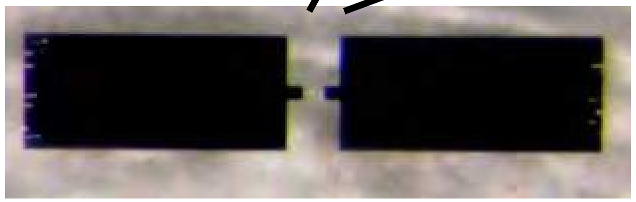
Electrons can tunnel through the link, deforming the potential



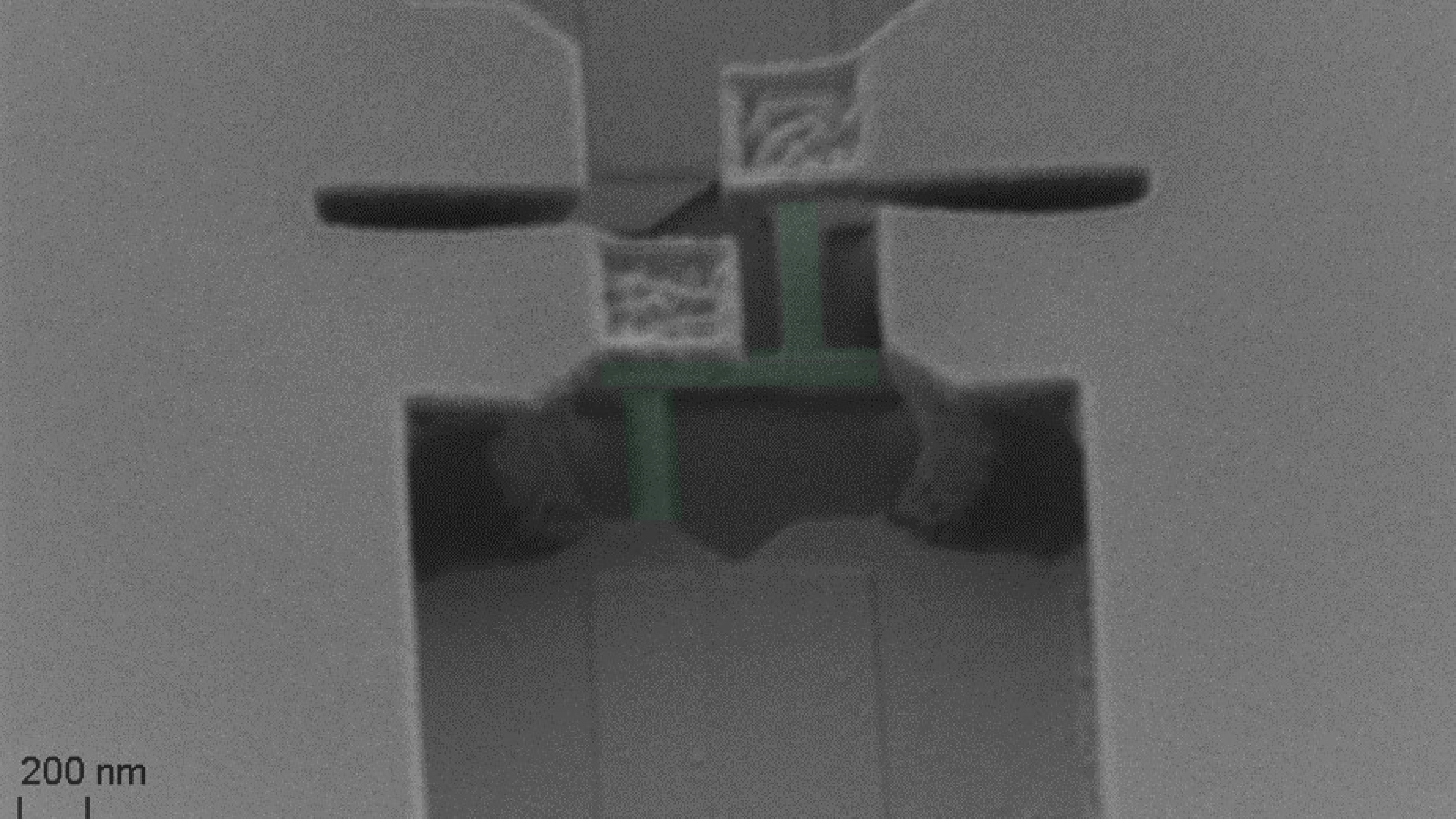
Transmon qubits

=

JJ with wings

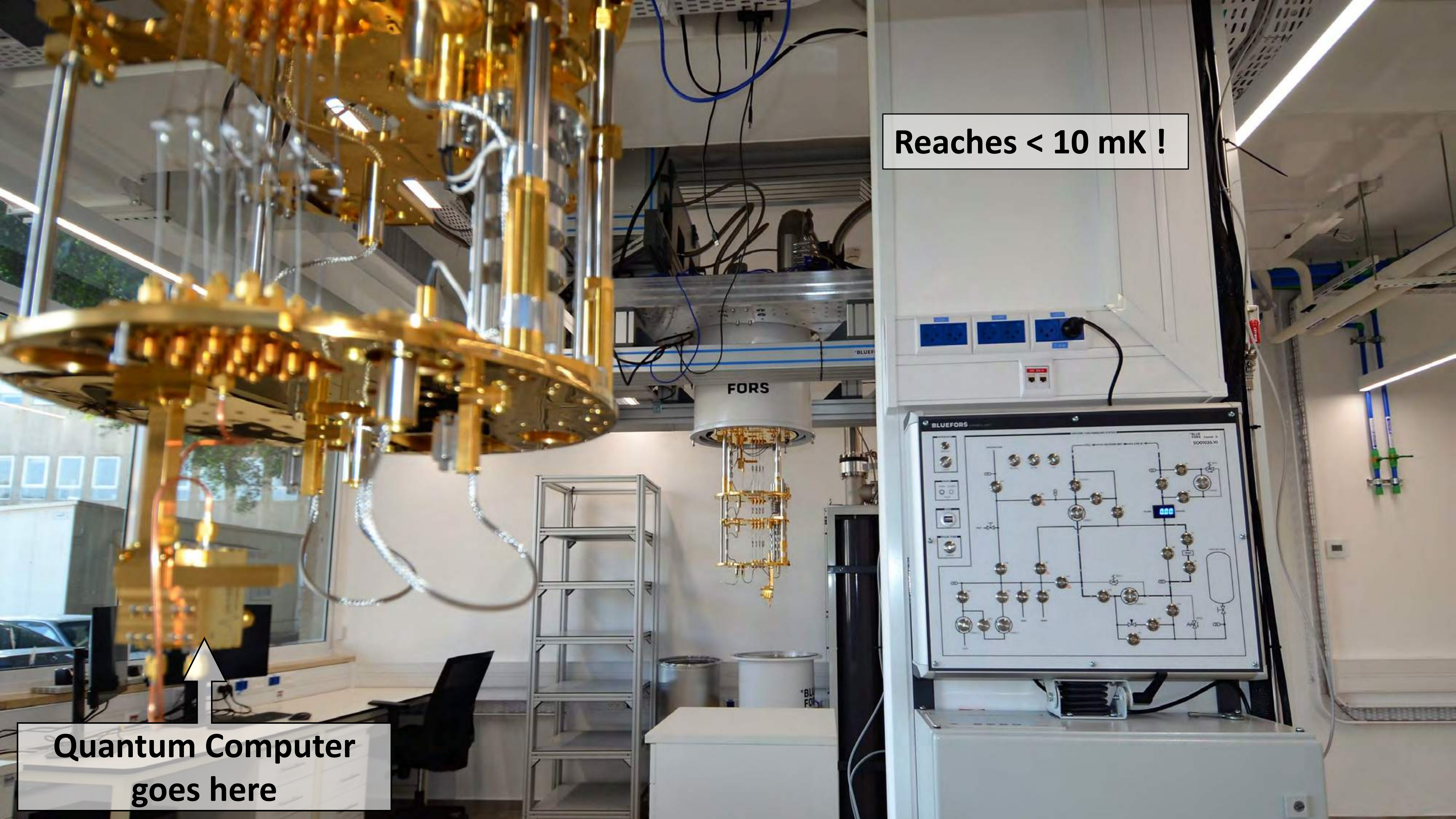


~ 1 mm

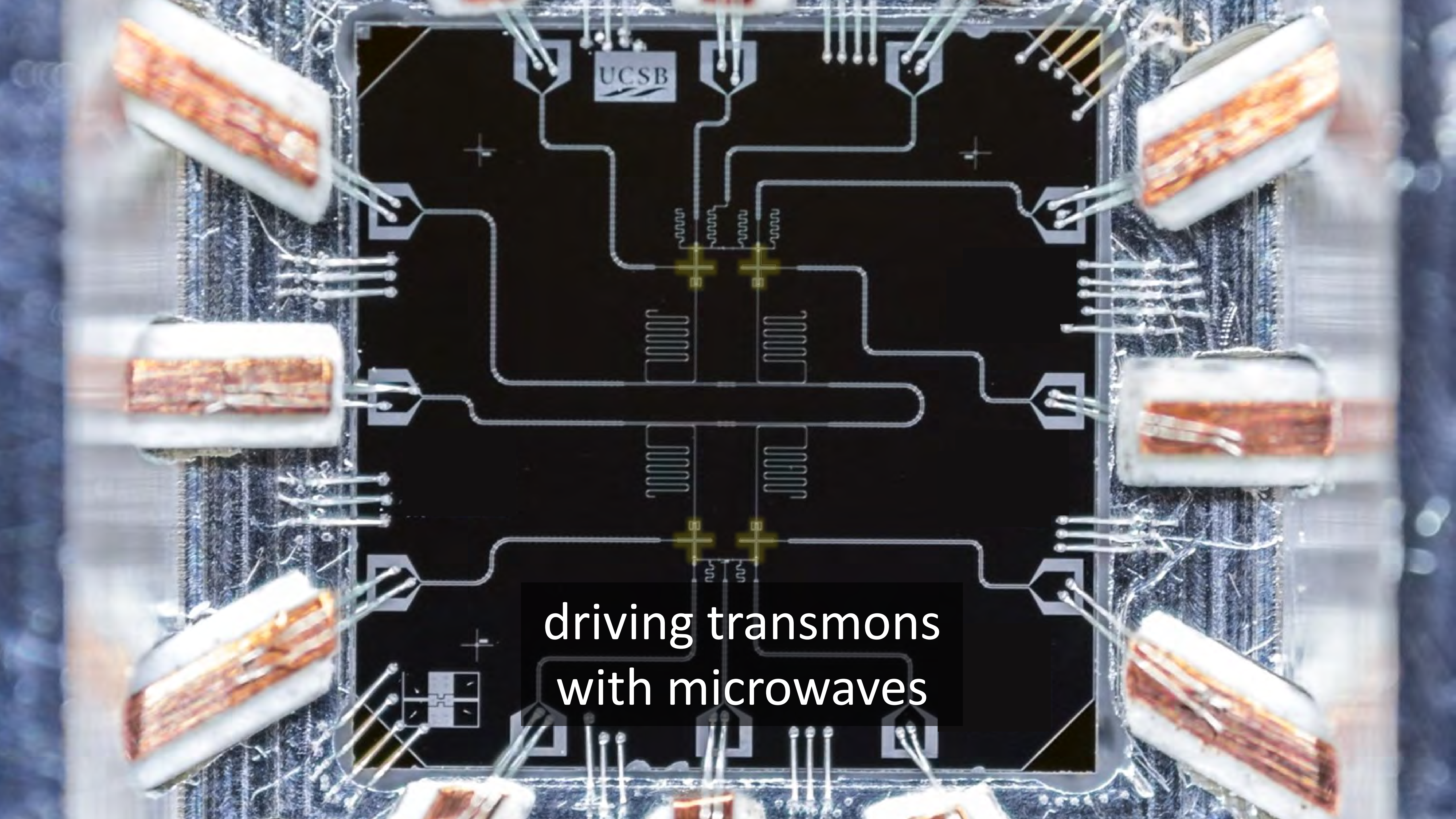

200 nm

How cold does a quantum circuit need to be?

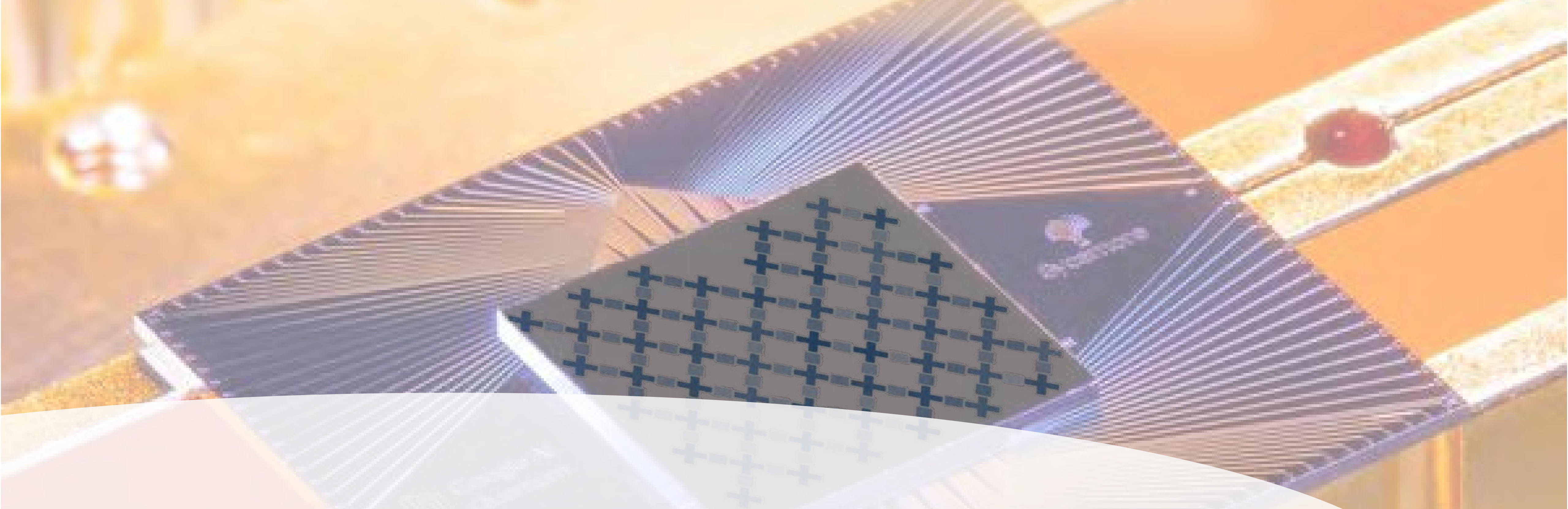
- We need to go superconducting — below 1K (critical T of Al)
- We need to get rid of thermal photons (with 1-10 GHz frequency) — below 100 mK



Reaches < 10 mK !
FORS
BLUEFORS
Quantum Computer goes here


UCSB
driving transmons
with microwaves

2019 - Quantum supremacy demonstrated



- *"After a quarter century of effort, we are now, finally, in the early vacuum tube era of quantum computing."* Scott Aaronson
- large-scale quantum computing is FEASIBLE.

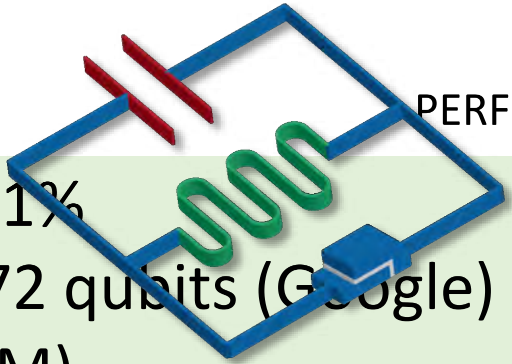
Superconducting quantum computers

+

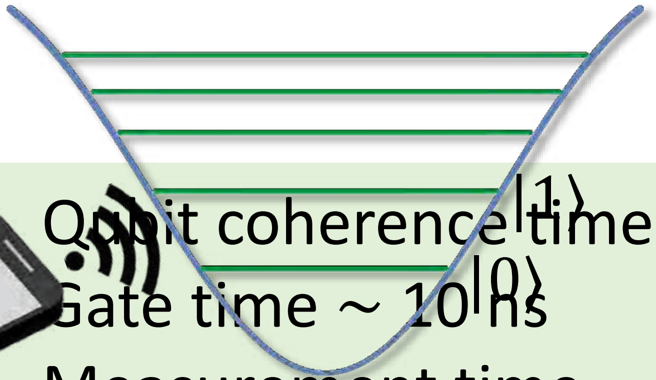
- Mature fabrication methods ⟶ flexible and scalable
- Macroscopic elements ⟶ fast gates

−

- Requires cryogenic temperatures
- Qubits on a chip ⟶ hard to get good quality qubits

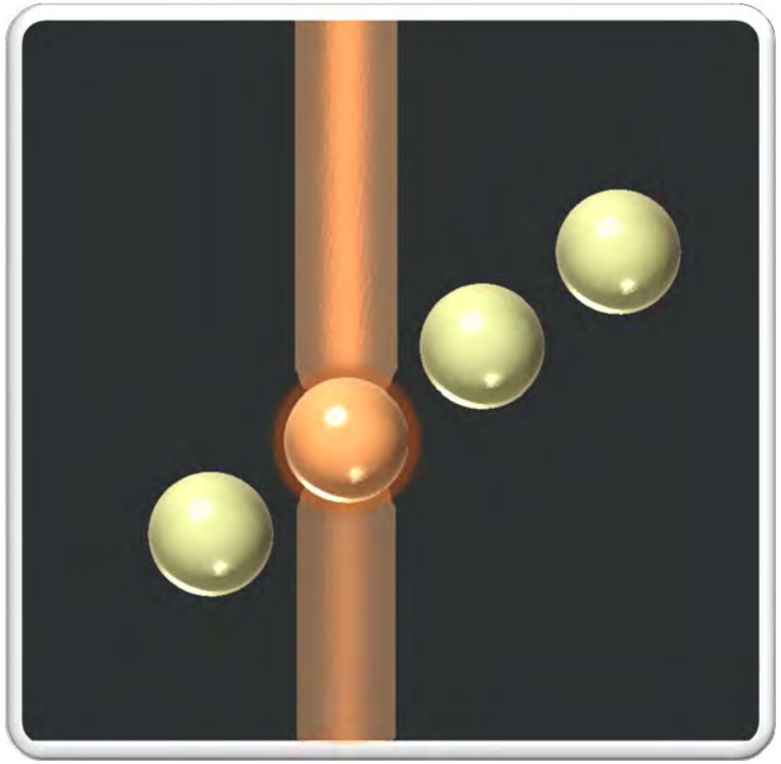


PERFORMANCE



- Gate error ~ 0.1%
- Largest chip = 72 qubits (Google)
- Log(QV) = 7 (IBM)

- Qubit coherence time ~ 100 μs
- Gate time ~ 10 ns
- Measurement time ~ 100 ns



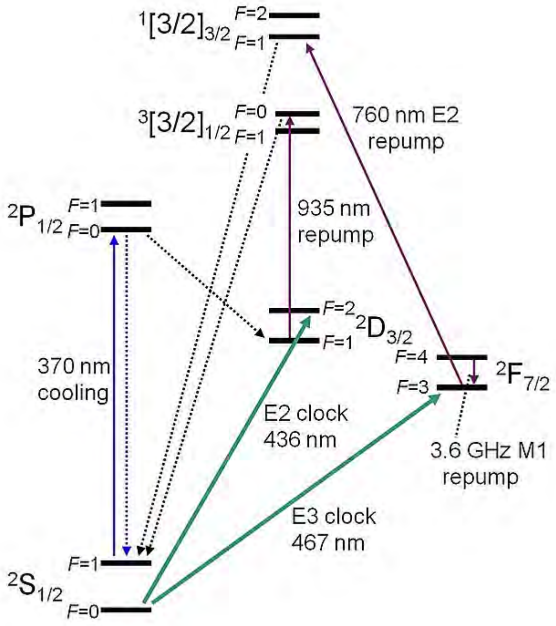
Atoms / Ions

Atom / ion qubits

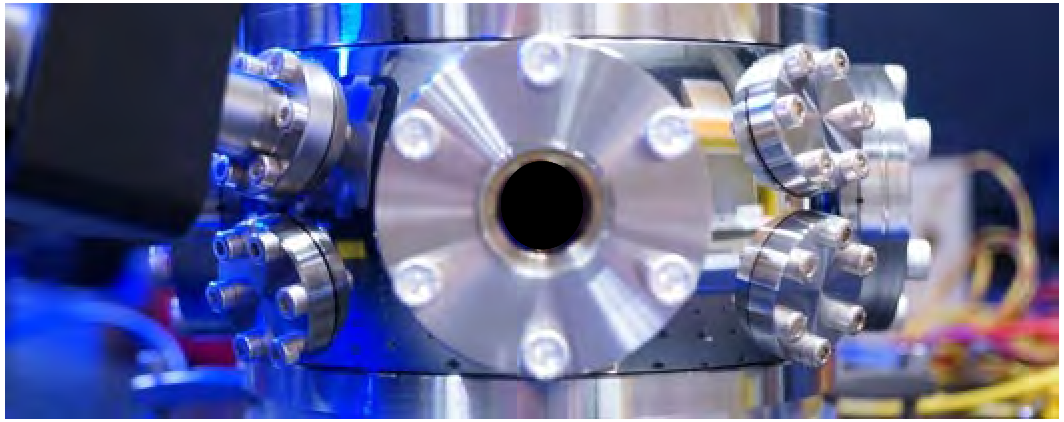
- Qubit encoded in electronic levels (orbit / spin)

  Be^+, Sr^+, Mg^+, Yb^+, Rb, Sr

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



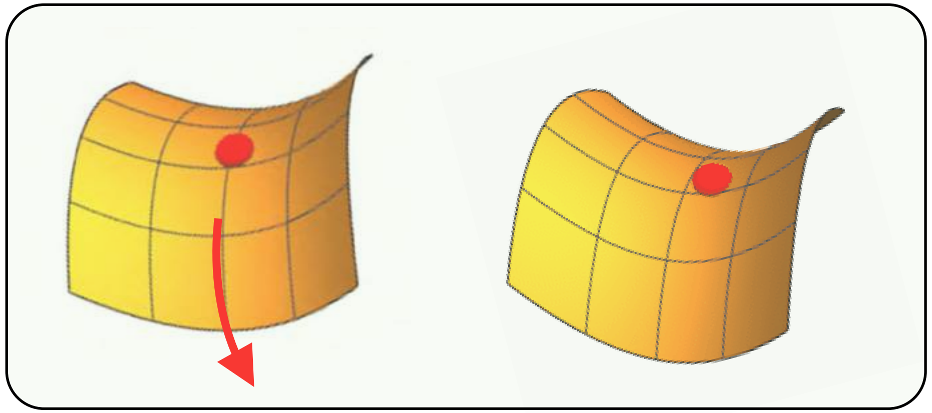
- Atoms protected by ultra-high vacuum



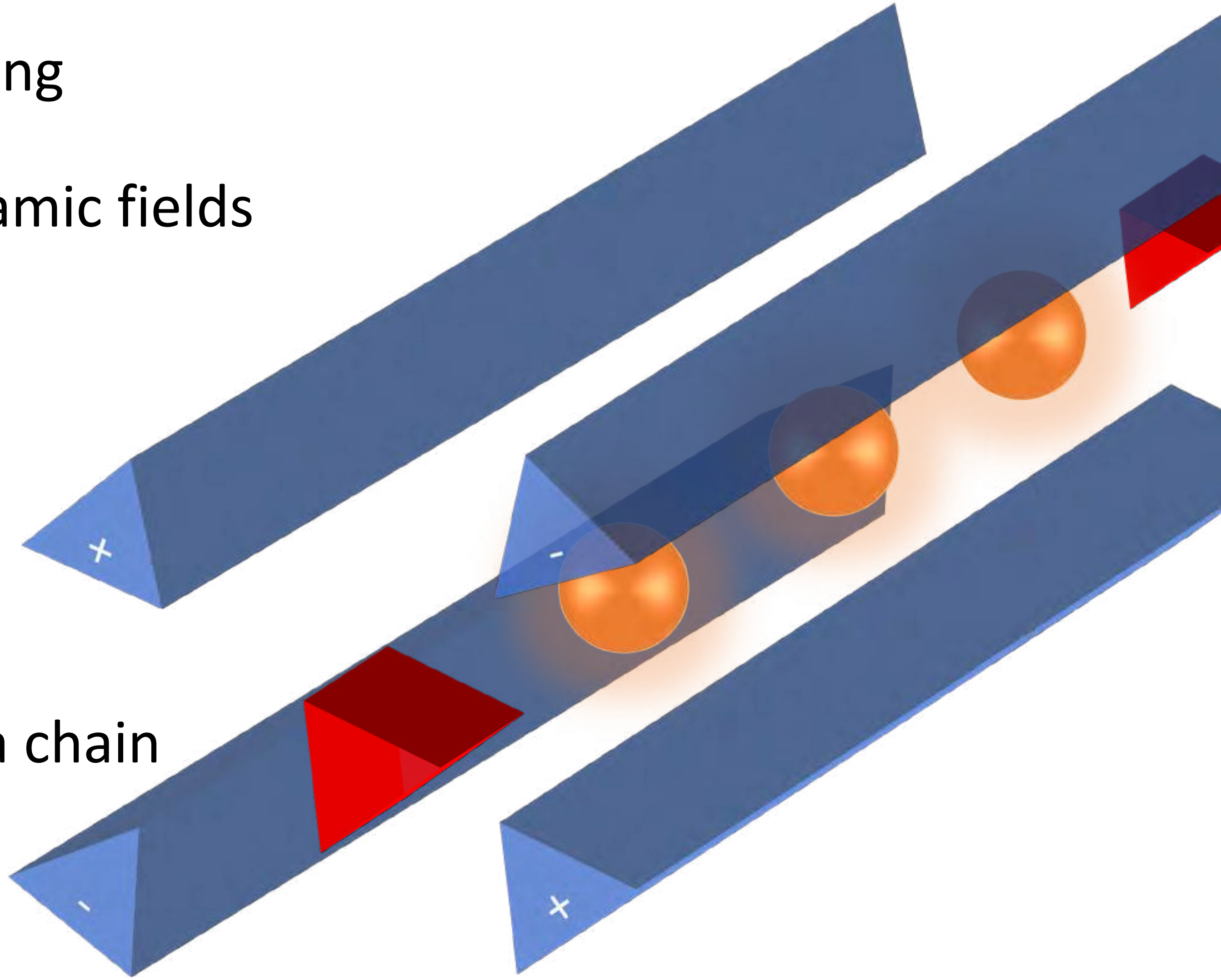
Ion trapping

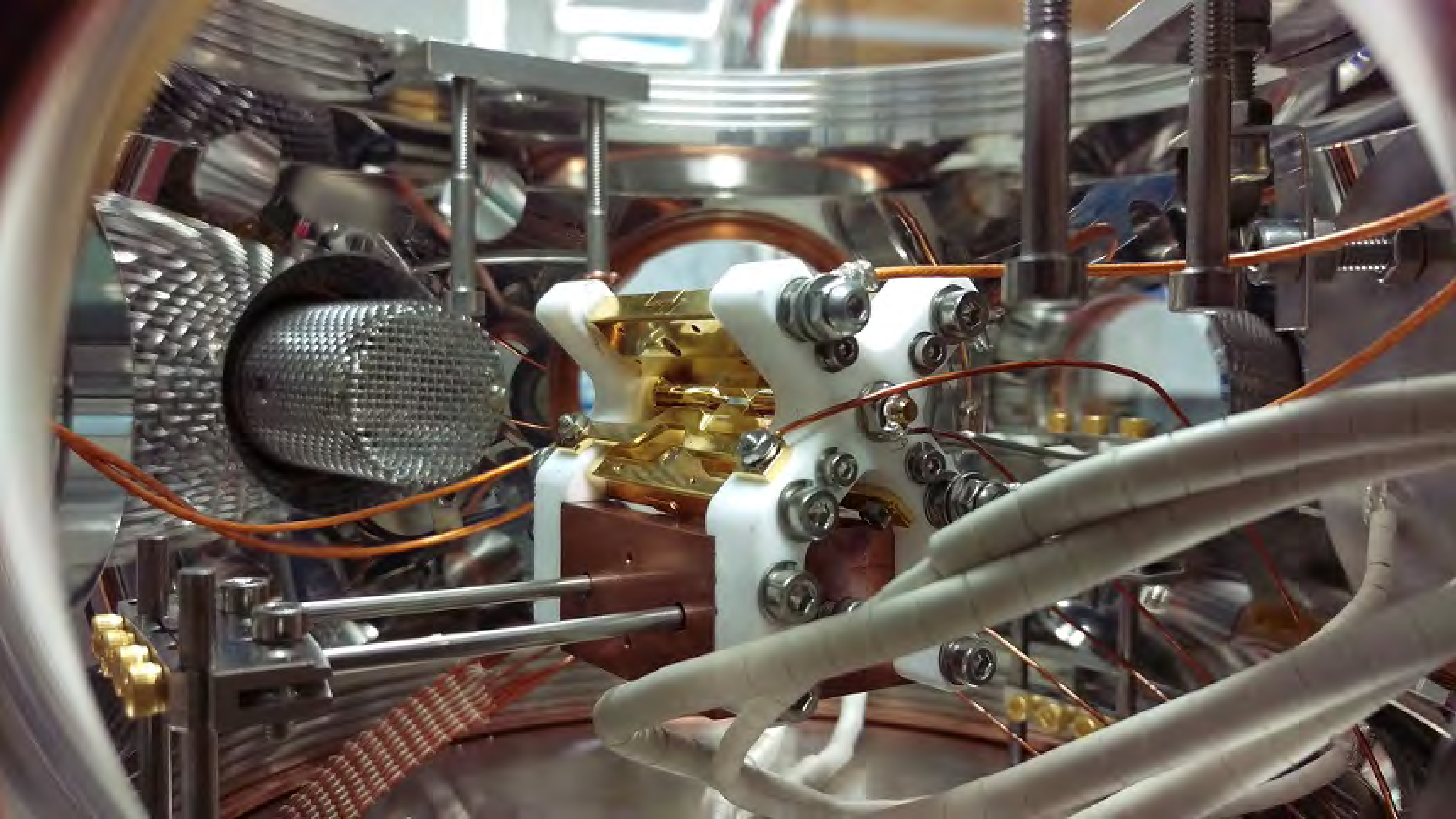
Ions are charged ⟶ electric field trapping

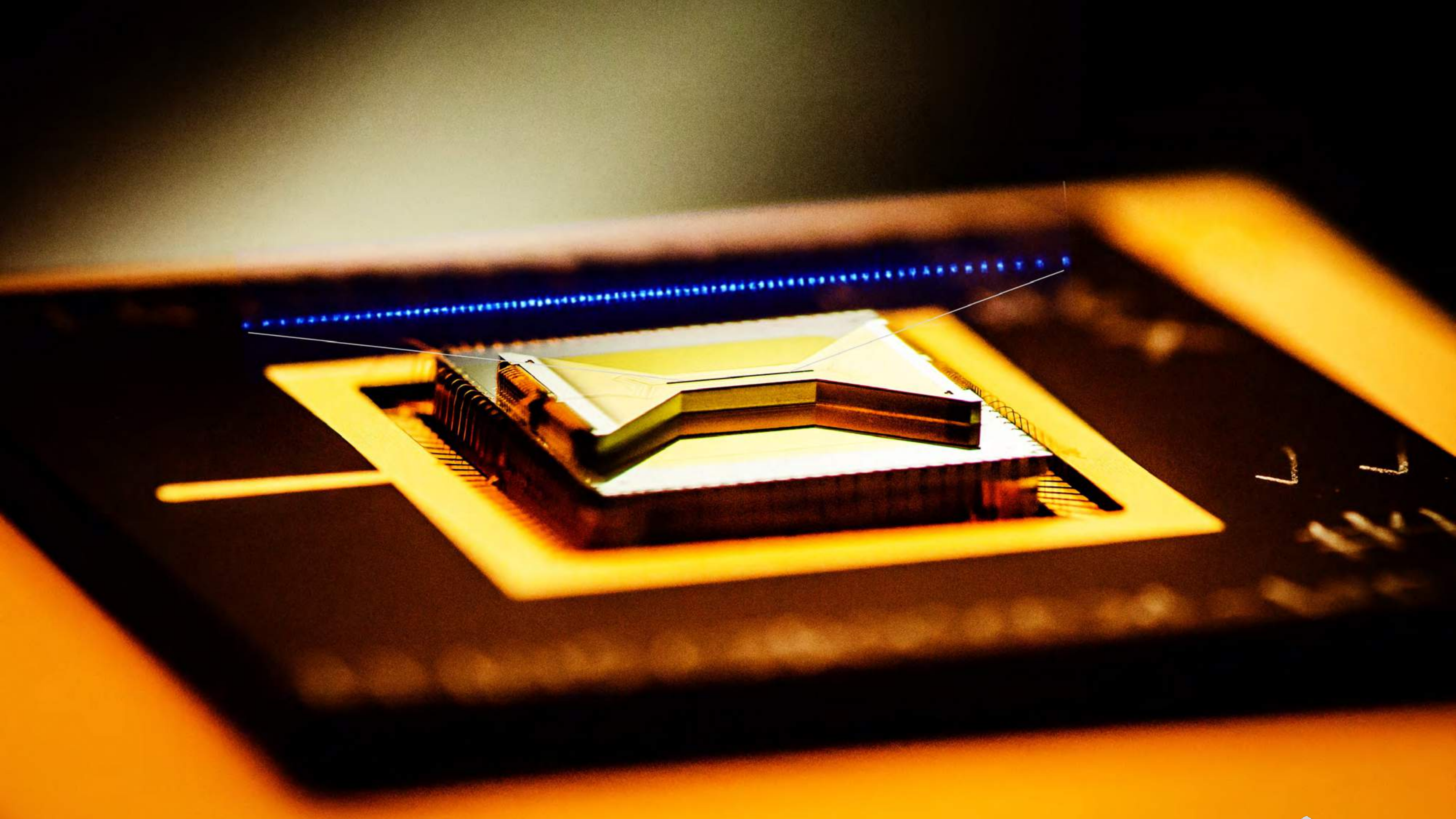
static electric trap impossible ⟶ dynamic fields



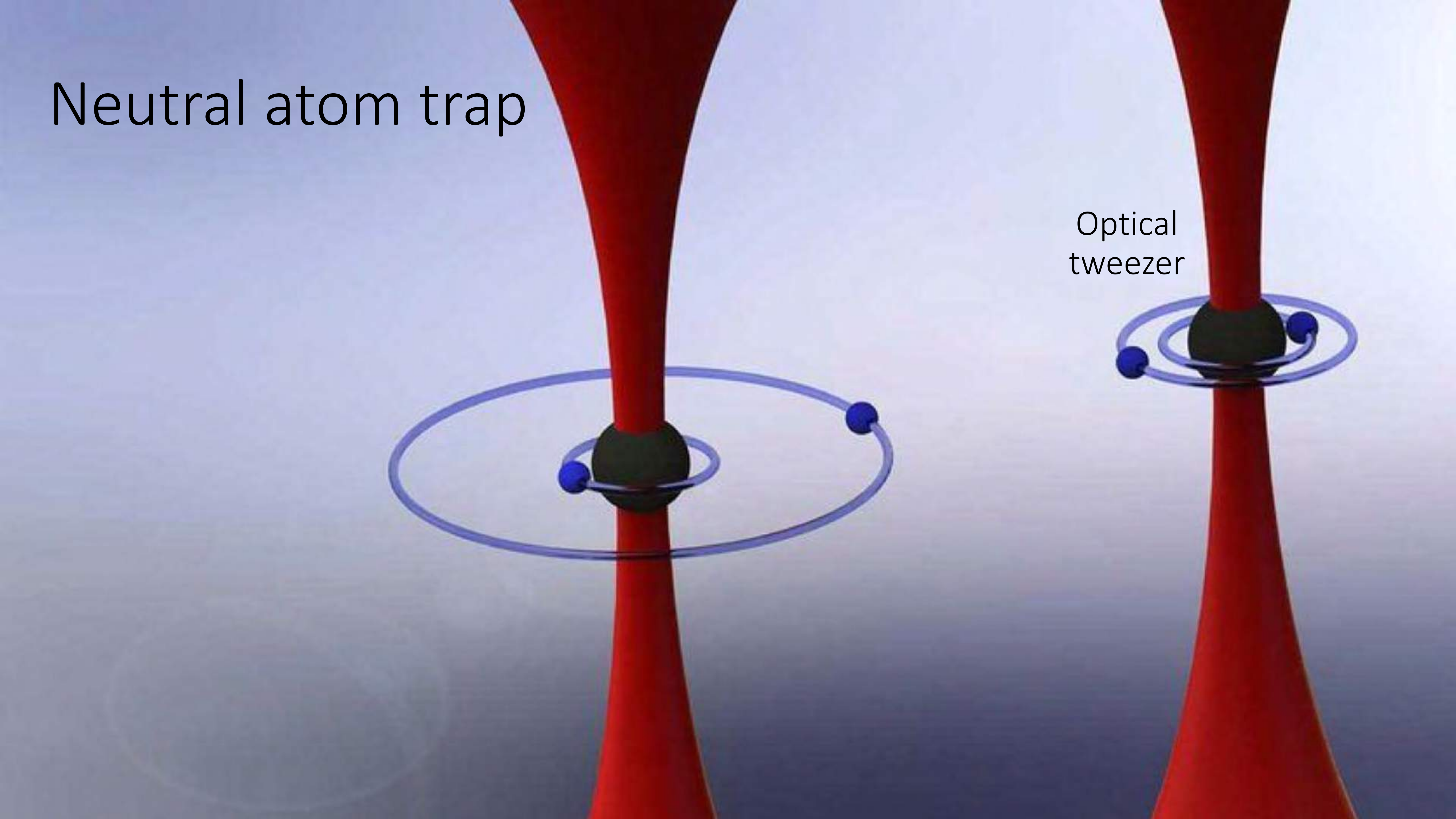
Coulomb repulsion ⟶ ions line up in a chain



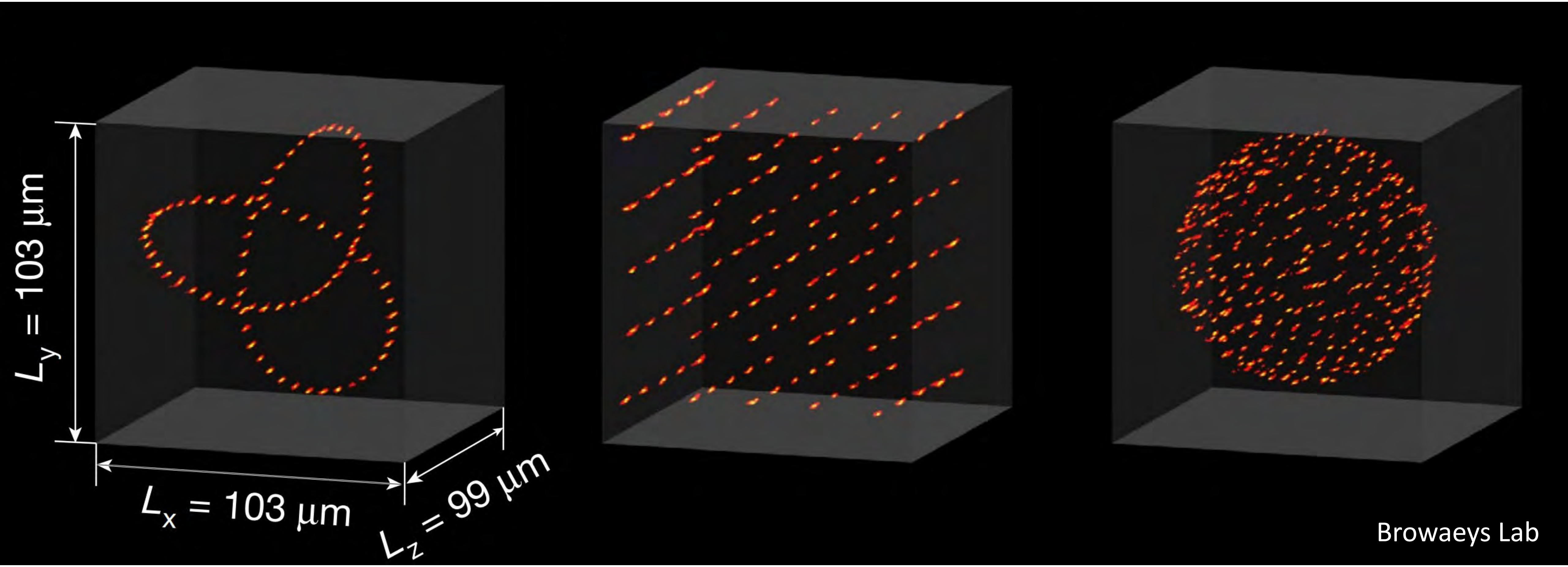




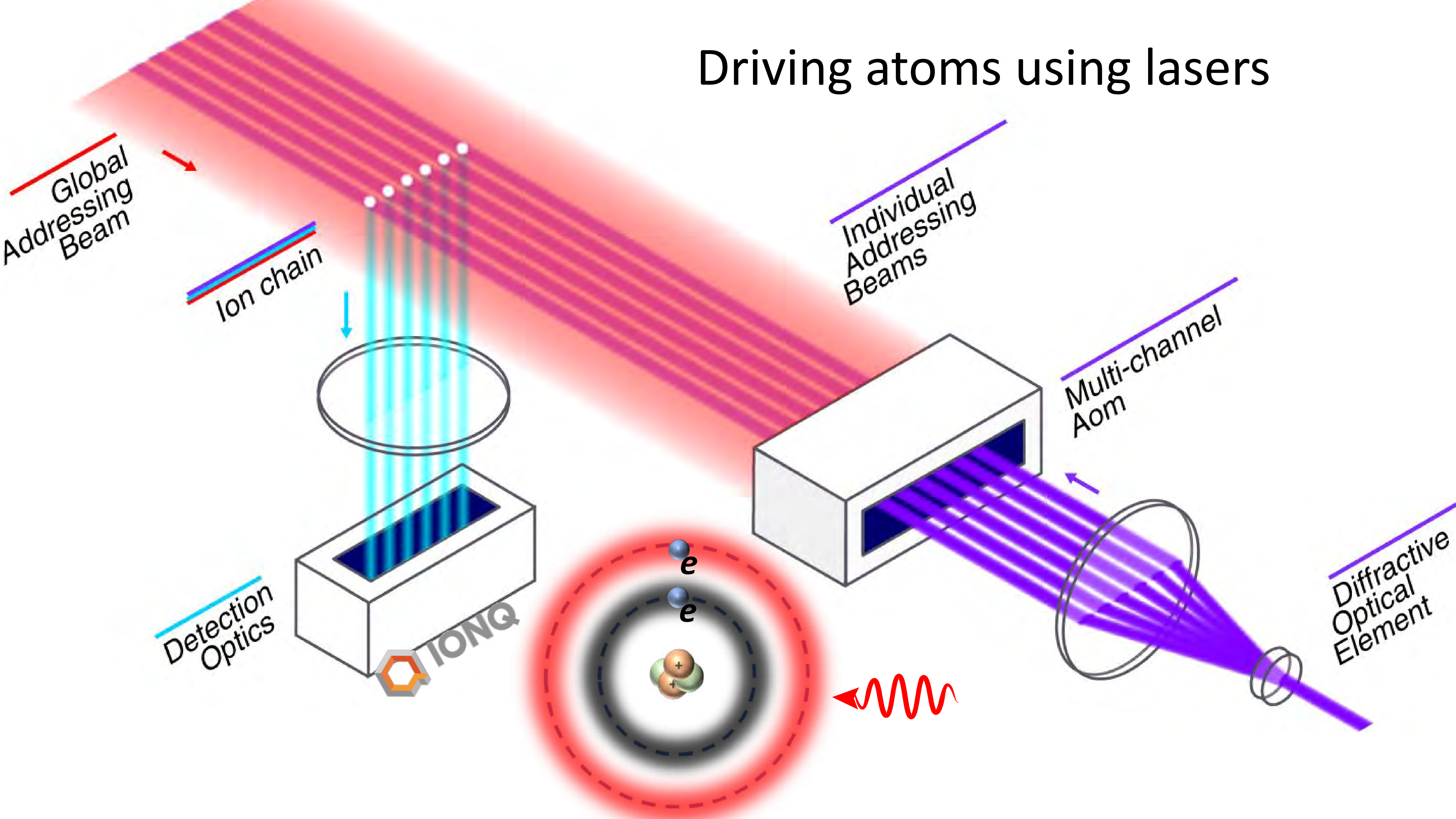
Neutral atom trap

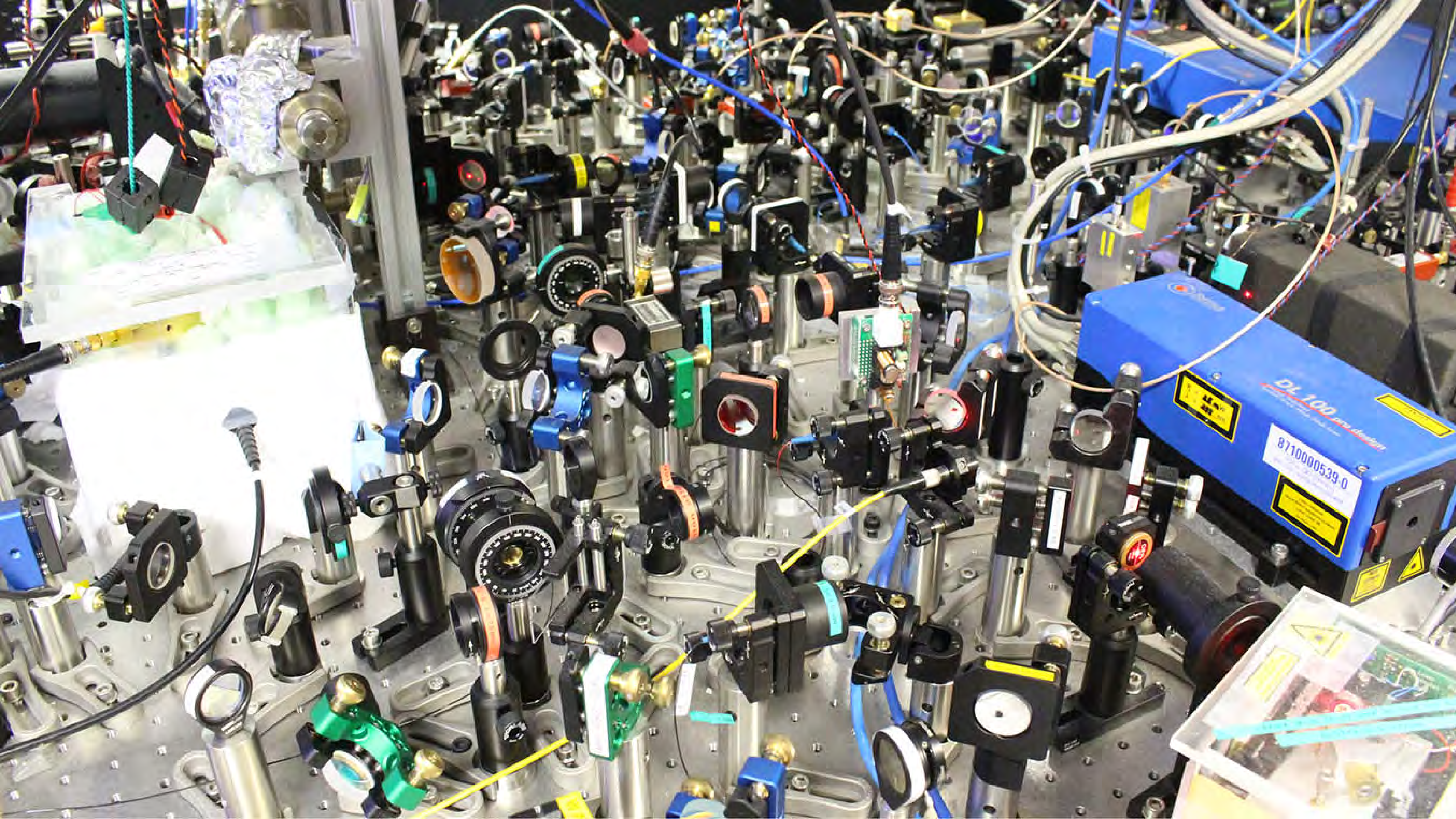


Reconfigurable tweezer array



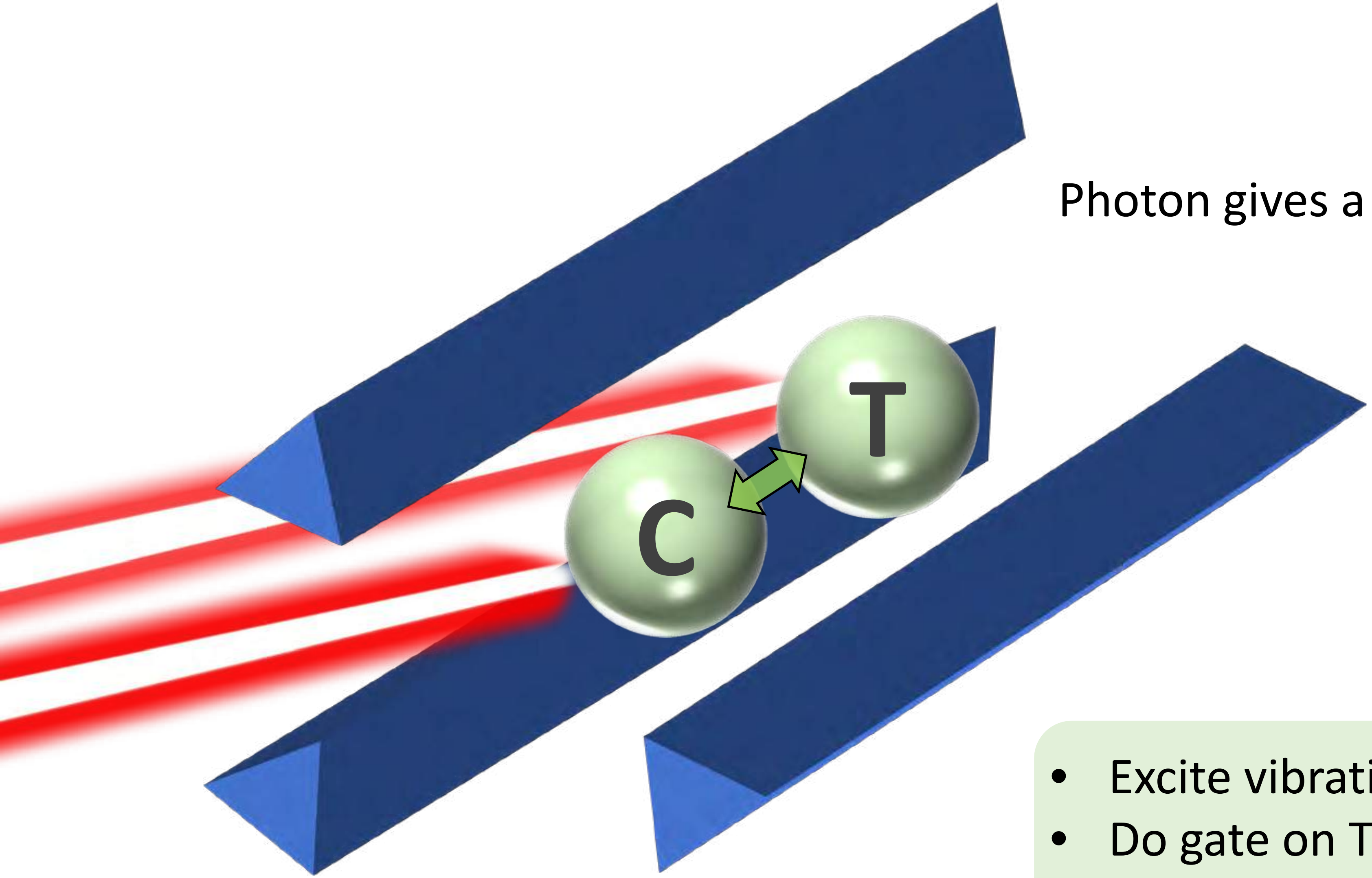
Driving atoms using lasers




DL 100 pro design
8710000539-0


AQT

Gates between ions

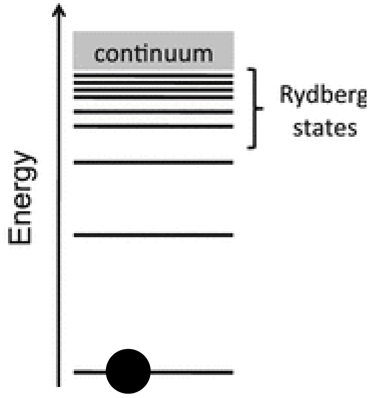


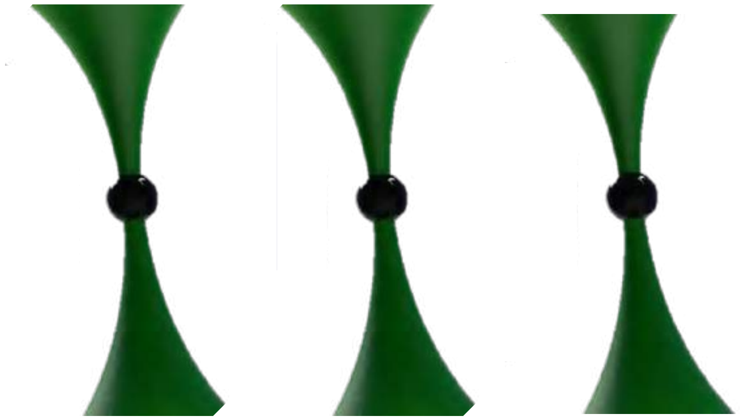
Photon gives a kick to collective motion of ions

- Excite vibration if Control is in $|1\rangle$
- Do gate on Target **conditioned** on vibration
- De-excite vibration

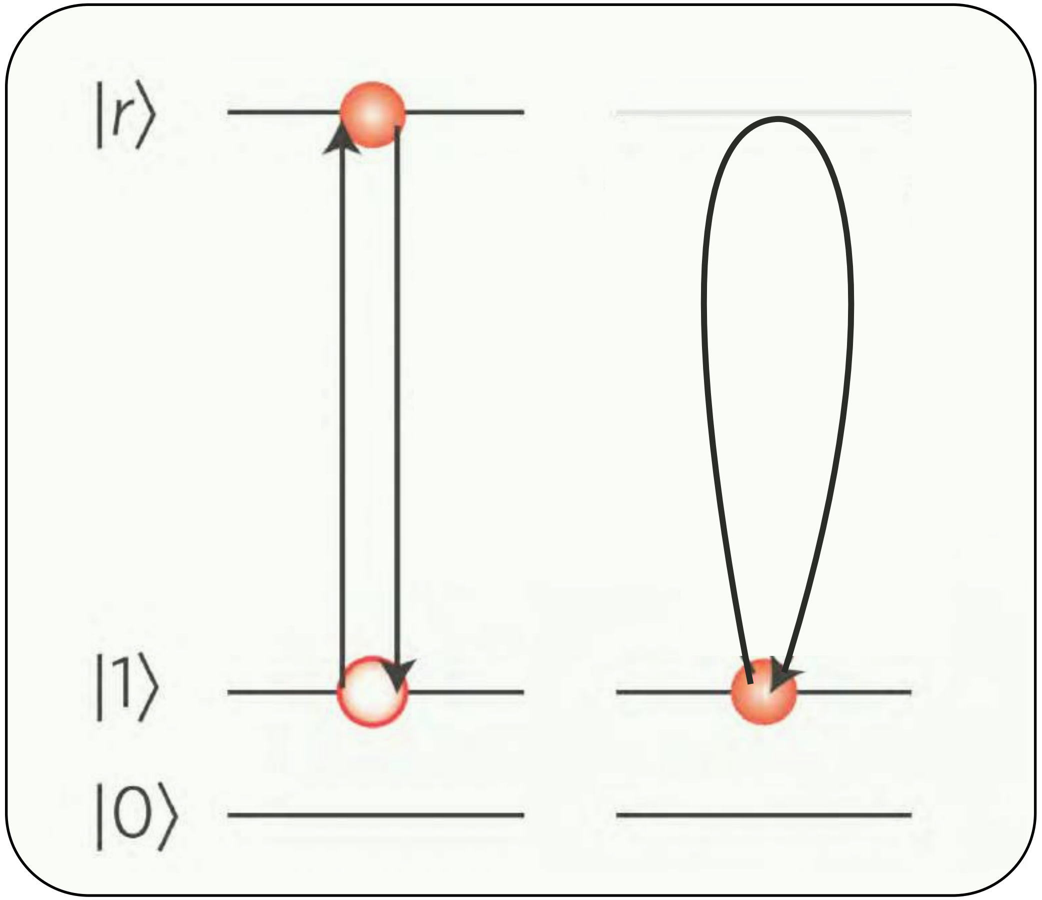
Gates between neutral atoms

Ryberg atom – making an atom 1000 times larger





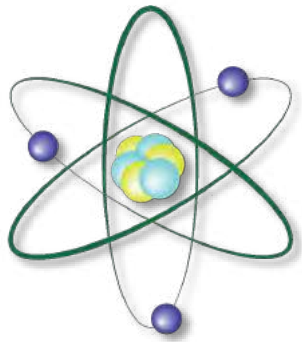
Control Target

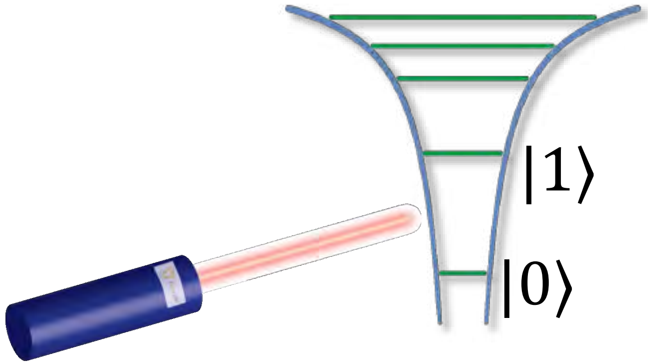


Ion quantum computers

- High quality identical qubits
- All-to-all connectivity

- Hard to scale up
- Slow operations

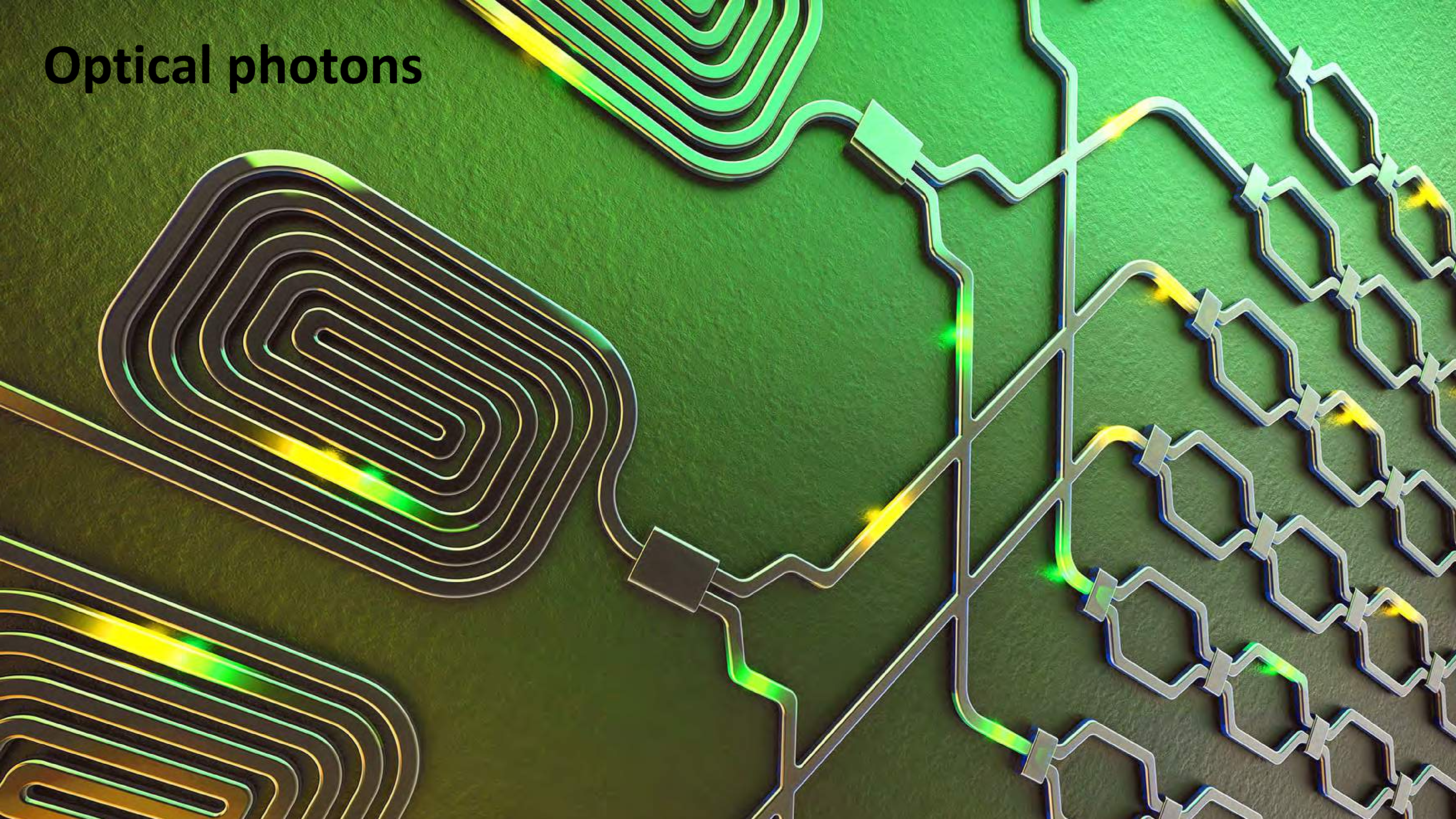


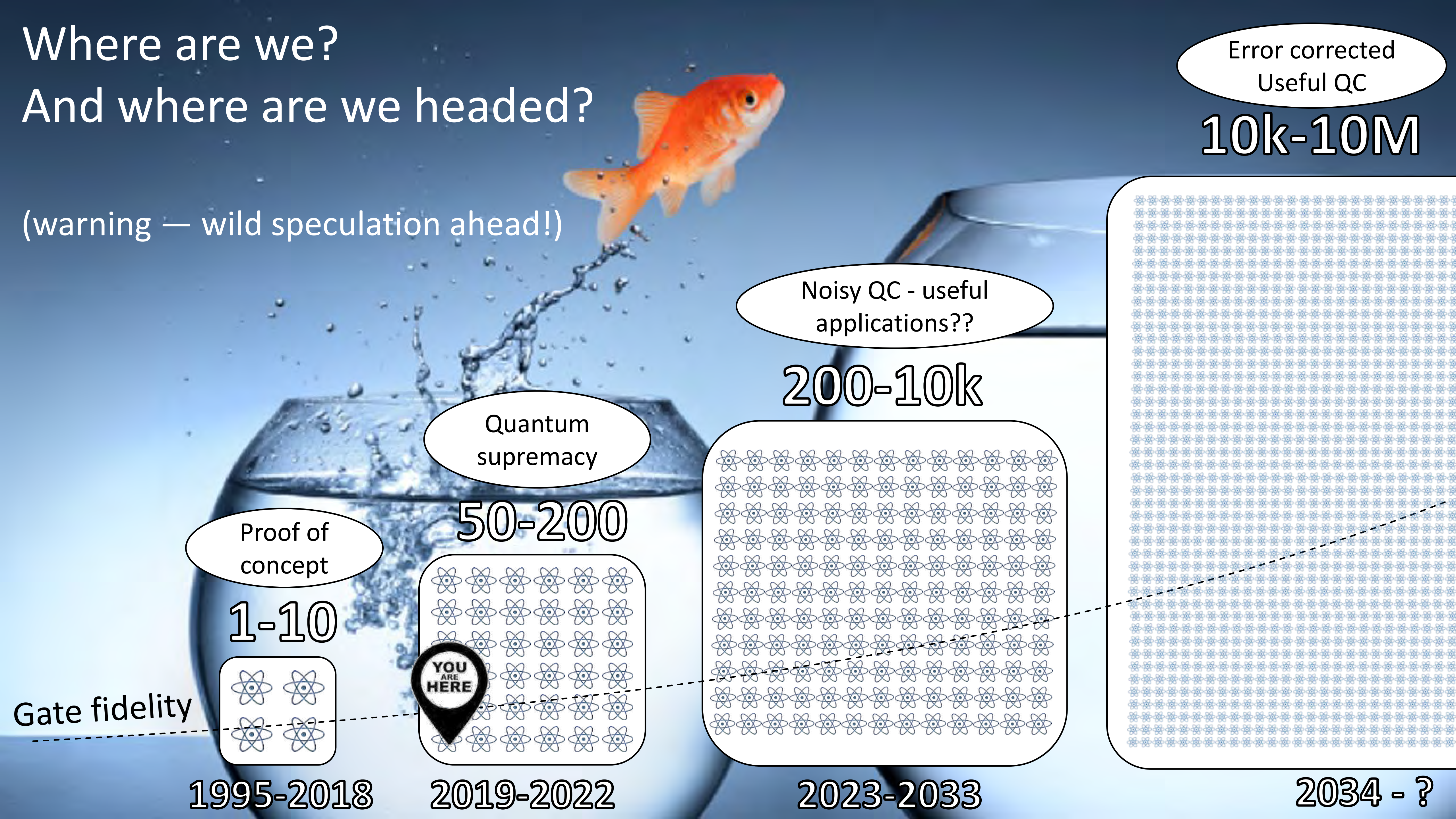


PERFORMANCE

- Qubit errors < 0.1%
- Largest computer = 32 ions (Ion Q)
- Log(QV) = 7 (Honeywell)
- Qubit coherence time $\sim$ hours
- Gate time $\sim$ 10 μs
- Measurement time $<$ 1 ms

Optical photons




Where are we?
And where are we headed?
(warning — wild speculation ahead!)
Error corrected
Useful QC
10k-10M
Noisy QC - useful
applications??
200-10k
Quantum
supremacy
50-200
Proof of
concept
1-10
YOU
ARE
HERE
Gate fidelity
1995-2018
2019-2022
2023-2033
2034 - ?

WEIZMANN INSTITUTE OF SCIENCE

Thank you

- We are looking for brilliant physicists & engineers who are passionate about Quantum.

- If you want to join us, email serge.rosenblum@weizmann.ac.il

ROSEN BLUM LAB