Developing practical large scale quantum computers using trapped ions

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Controlled Quantum Dynamics

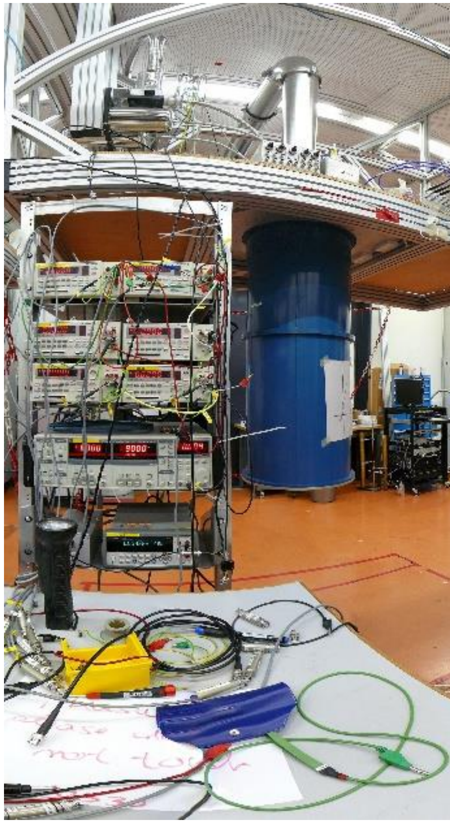
Why we work with trapped ions

Trapped ions:

- Works at room temperature or mild cooling to liquid Nitrogen temperature
- Lots of cooling power available at that temperature
- Two different modular designs are available permitting a modular quantum computer capable of reaching billions of qubits
- Qubits are atoms and as such fully identical

Superconducting qubits:

- -273°C requires a dilution refrigerator
- Very little cooling power available at that temperature
- No proven modular design available allowing to connect one dilution refrigerator to another
- Qubits are not identical but are fabricated individually

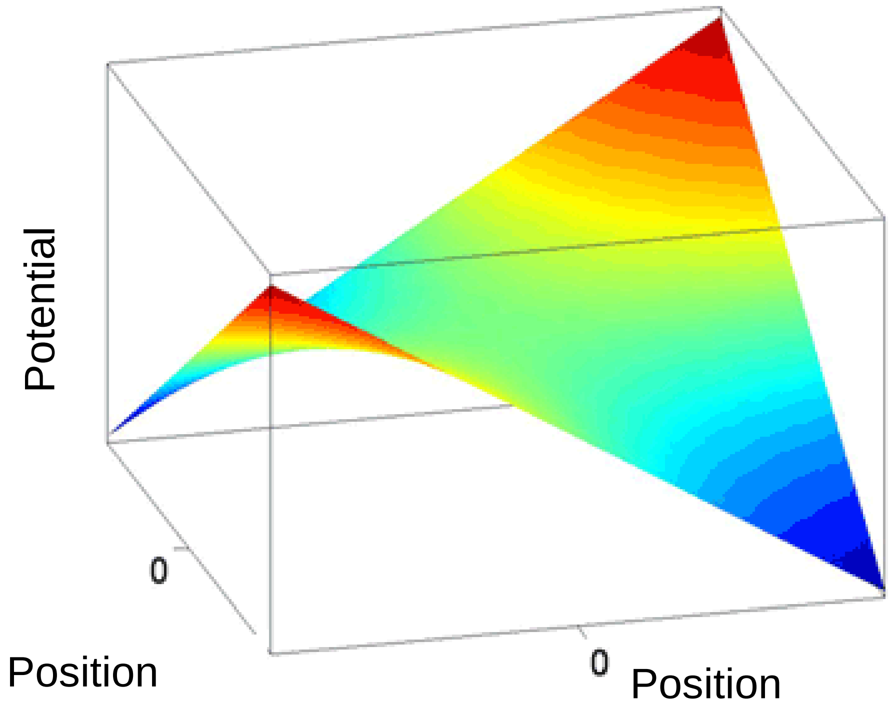


Dilution refrigerator in Andreas Wallraff's superconducting qubit laboratory at ETH Zurich

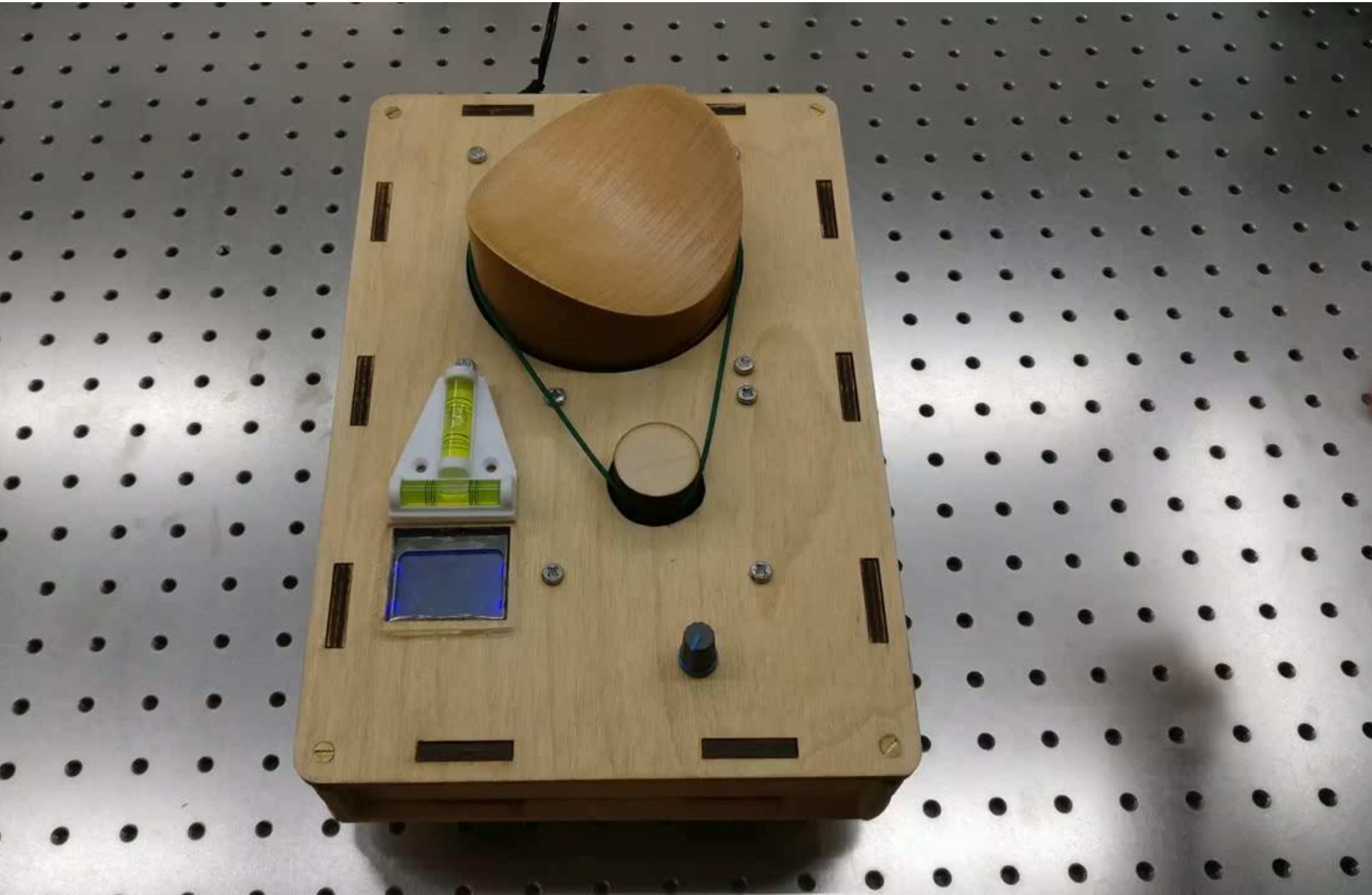
Many platforms have been tried (and are still being developed).

How to trap an ion

An ion is a charged atom
→ need electric field minimum to trap it

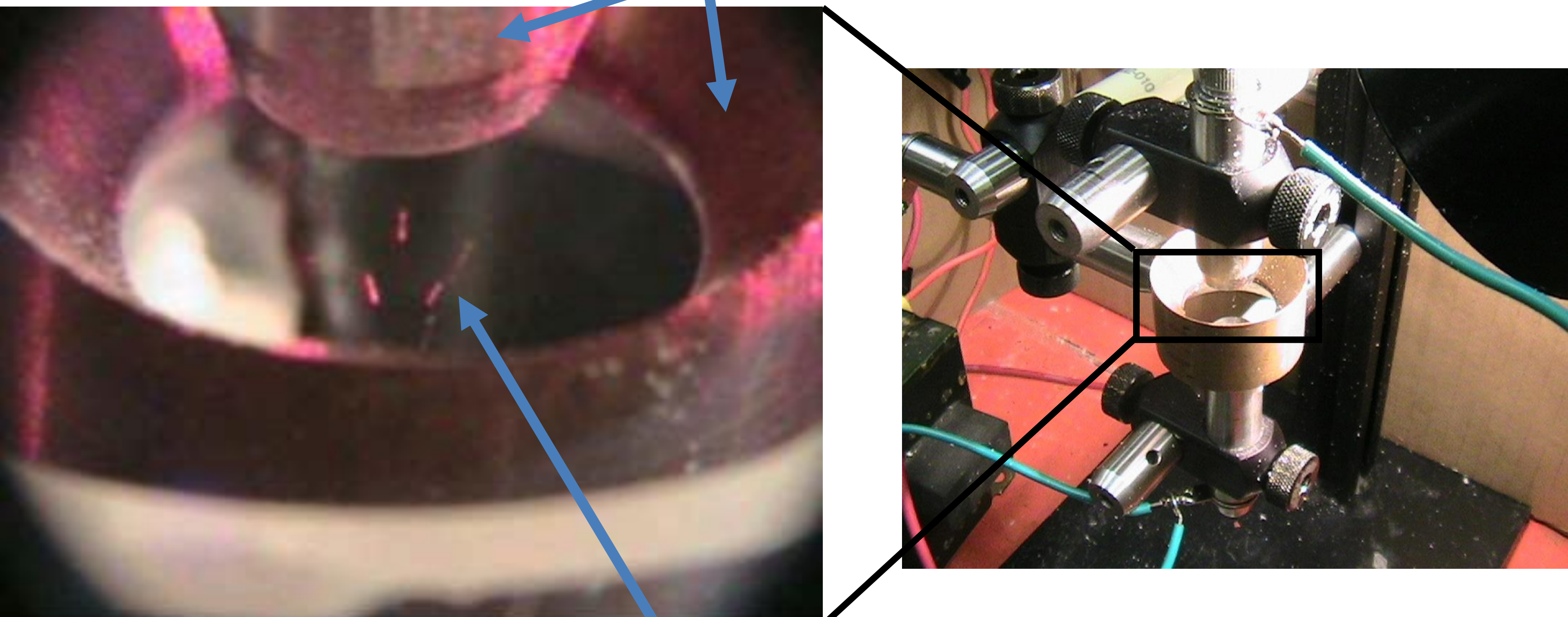


How to trap an ion



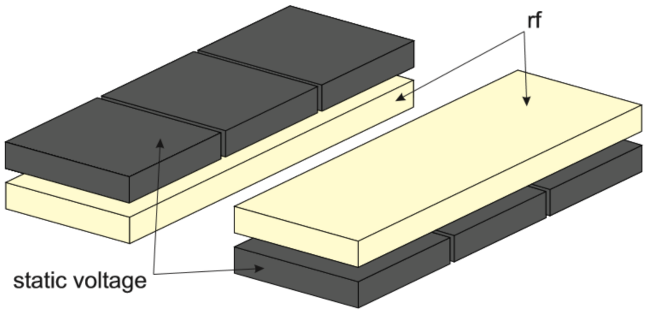
Charged particle trap

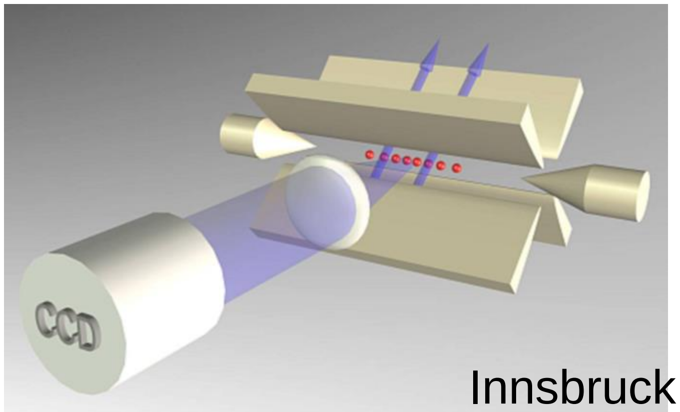
Electrodes emitting oscillating electric field

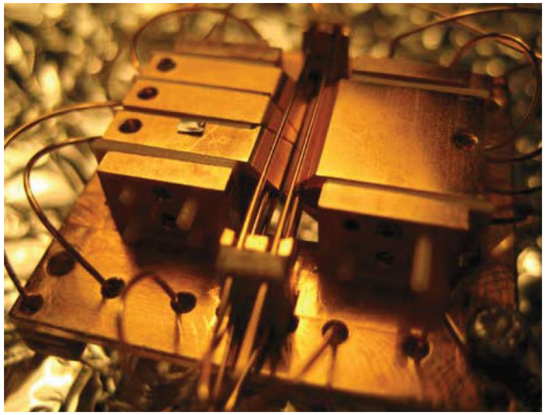


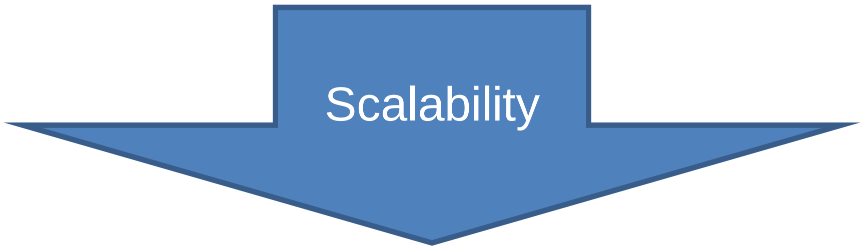
Dust particles that have been rubbed to attract a charge

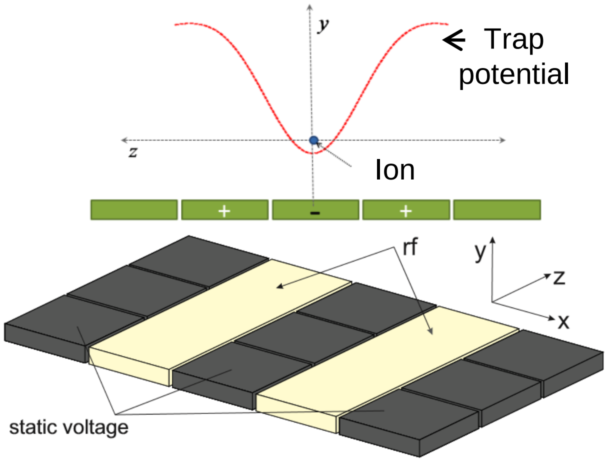
How to trap an ion

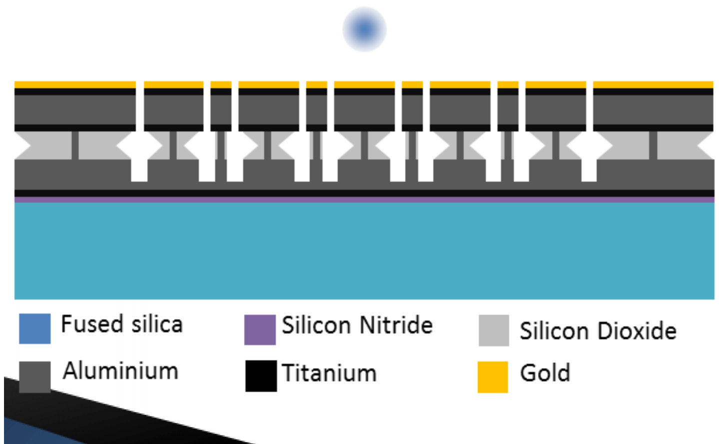


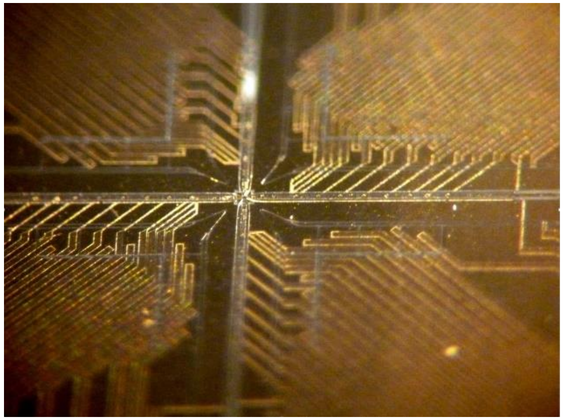


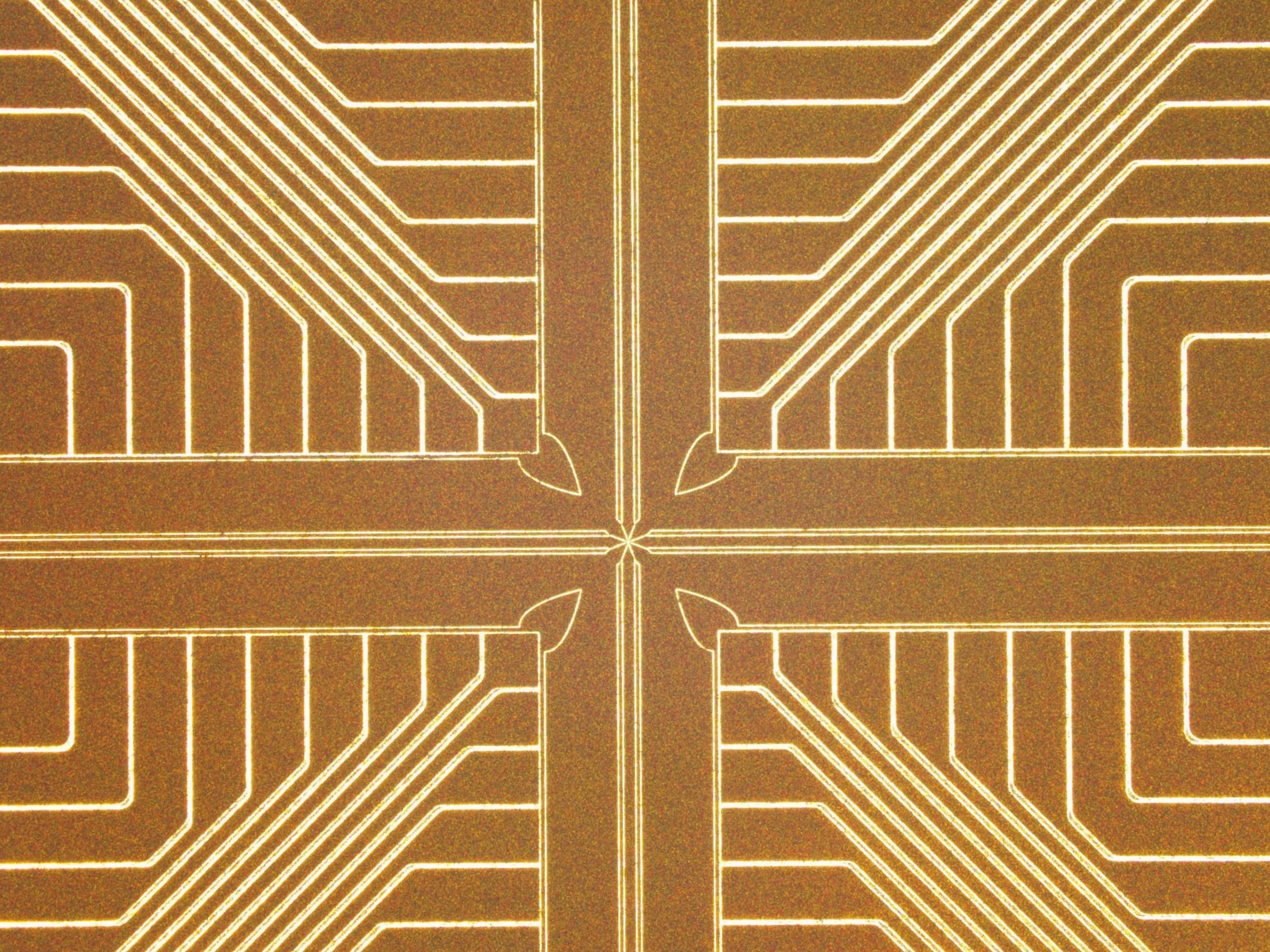




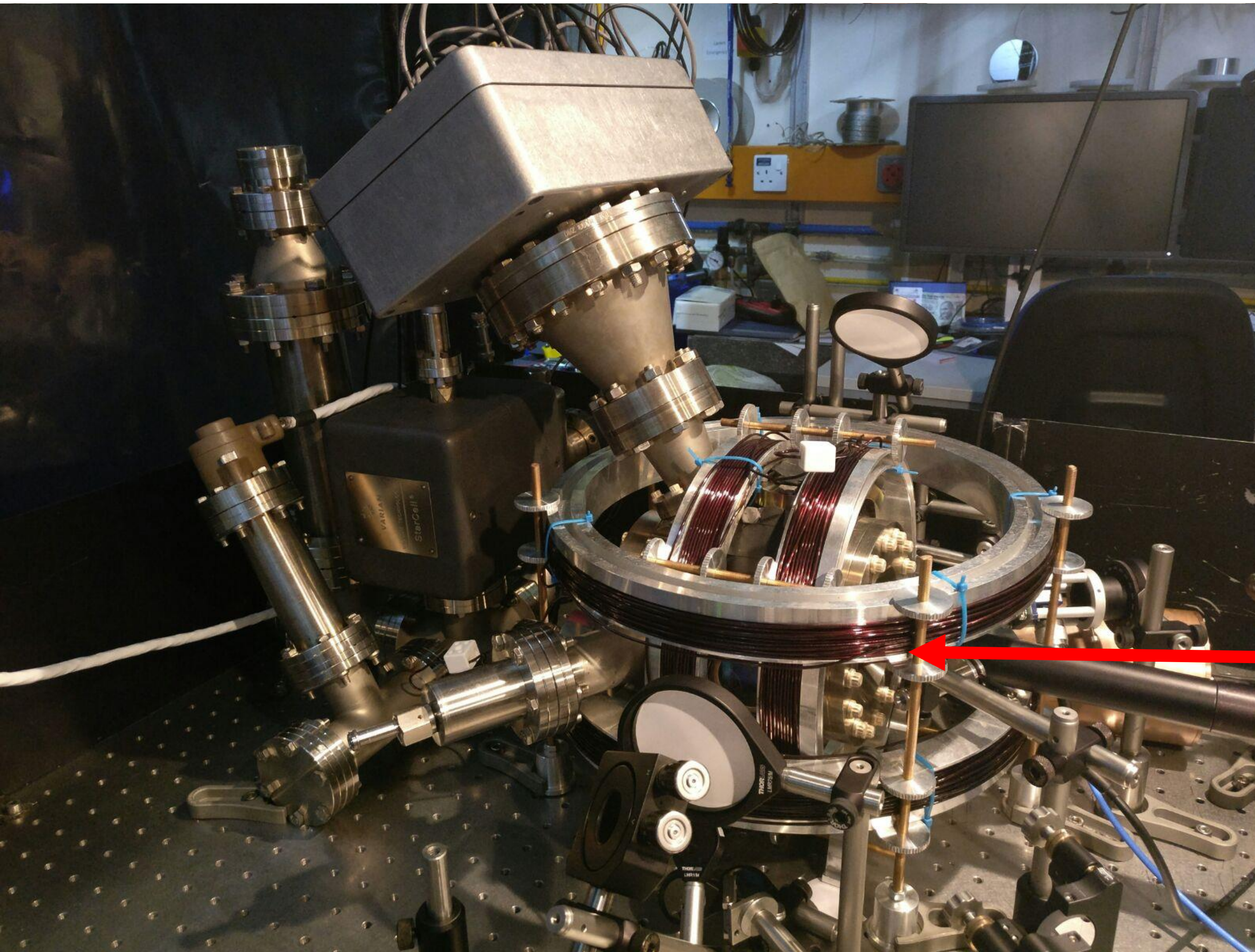








Vacuum system

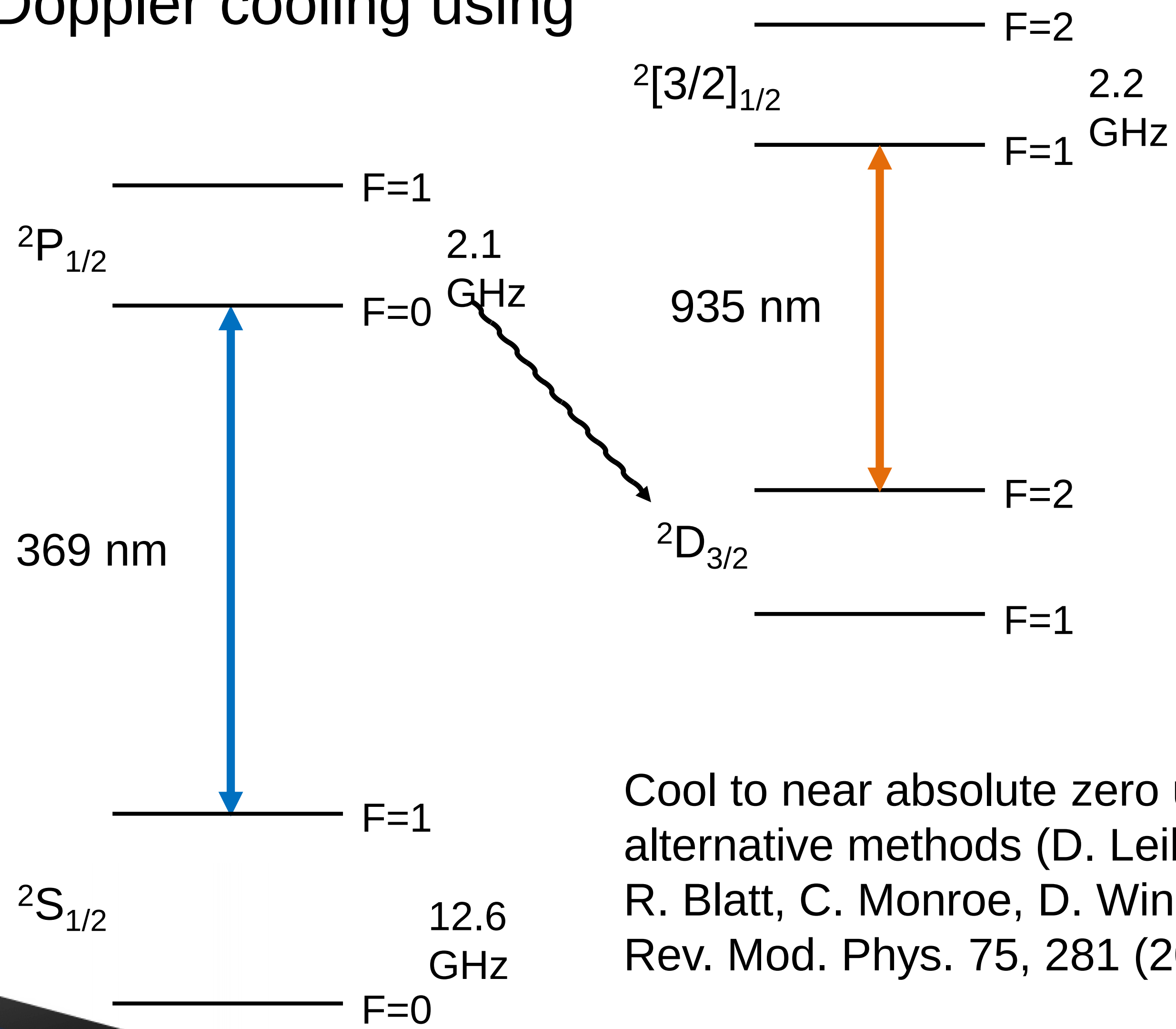


Better vacuum than if you were to step out of a space shuttle ($<10^{-11}$ mbar)

Trapped ions

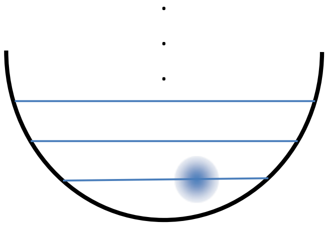
Ionisation and cooling

- Ionisation and Doppler cooling using lasers

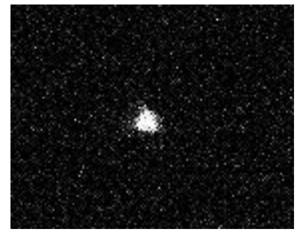


Cool to near absolute zero using alternative methods (D. Leibfried, R. Blatt, C. Monroe, D. Wineland, Rev. Mod. Phys. 75, 281 (2003))

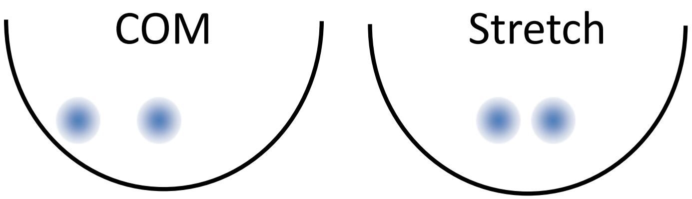
Single Yb ions

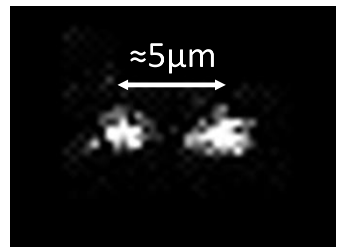


$$H_m = \sum_{k=1}^{N} \hbar \nu_k a_k^\dagger a_k$$

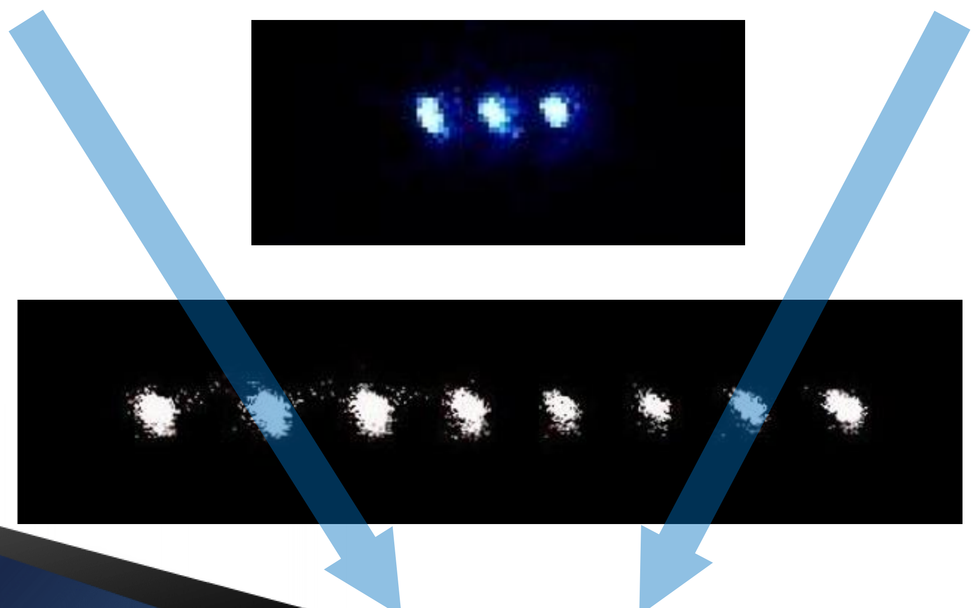


- Axial and radial normal modes of motion
- Quantize harmonic oscillator

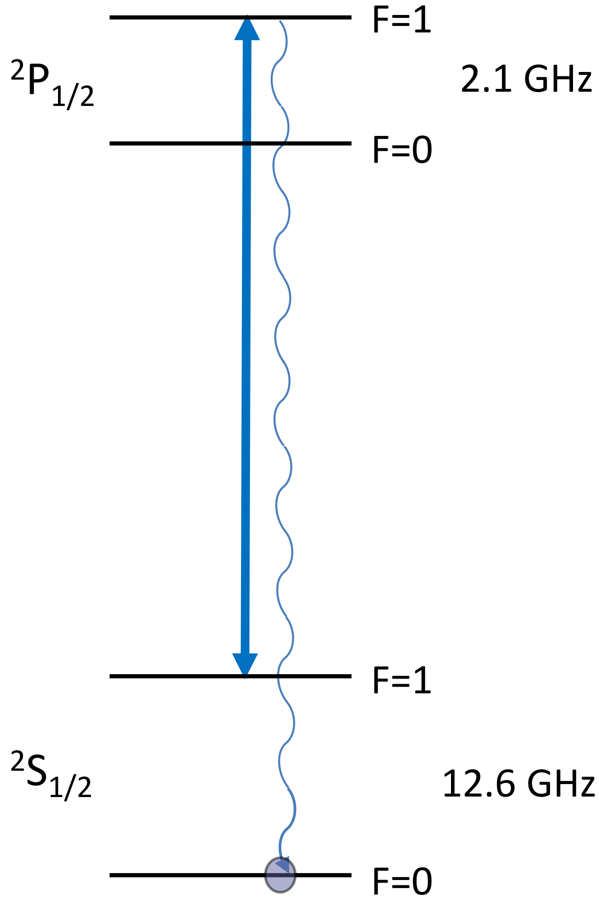




- Strongly coupled motion through Coulomb force

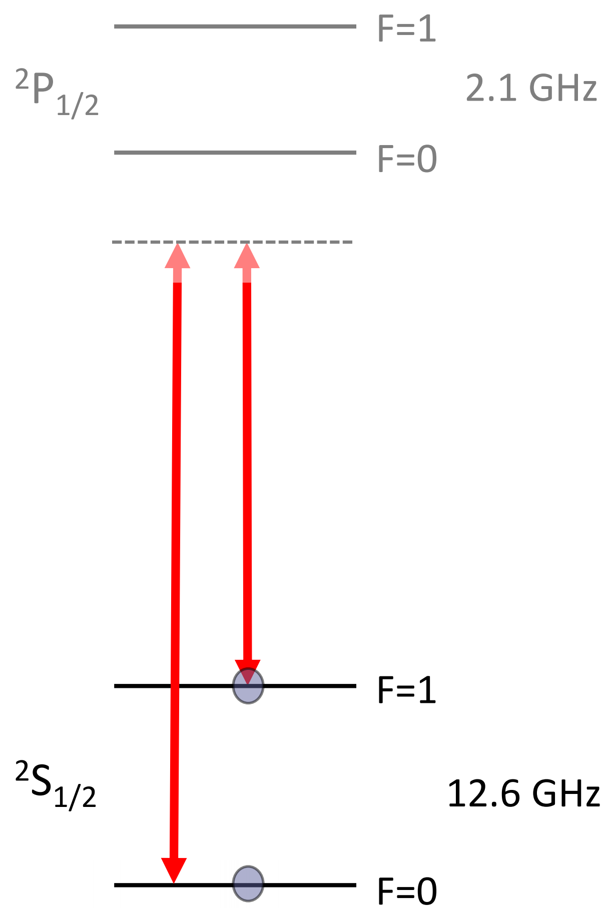


Qubit initialisation – $^{171}Yb^{+}$



Fast optical pumping into known state with near unit fidelity

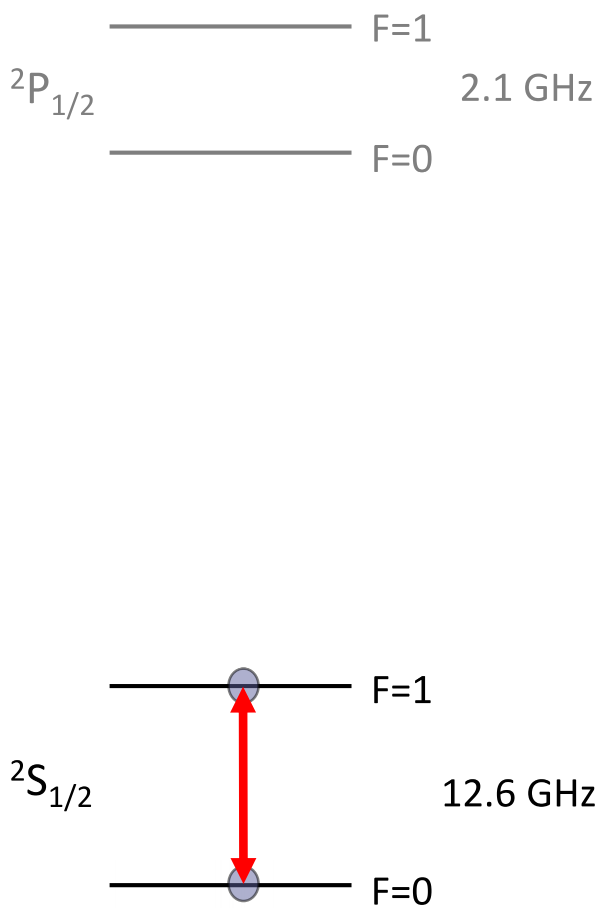
Qubit – $^{171}Yb^{+}$

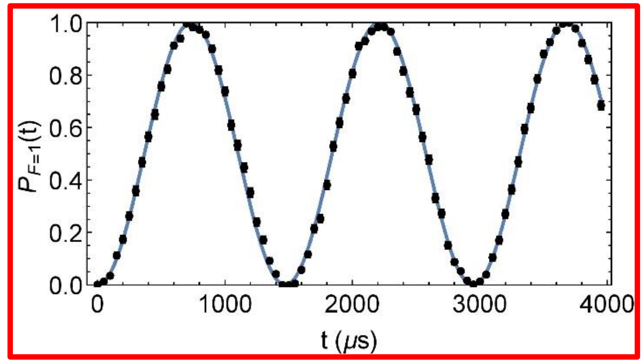


Pair of Raman laser beams for single and multi-qubit gates

Hyperfine qubit: Two-ground state hyperfine or Zeeman sublevels

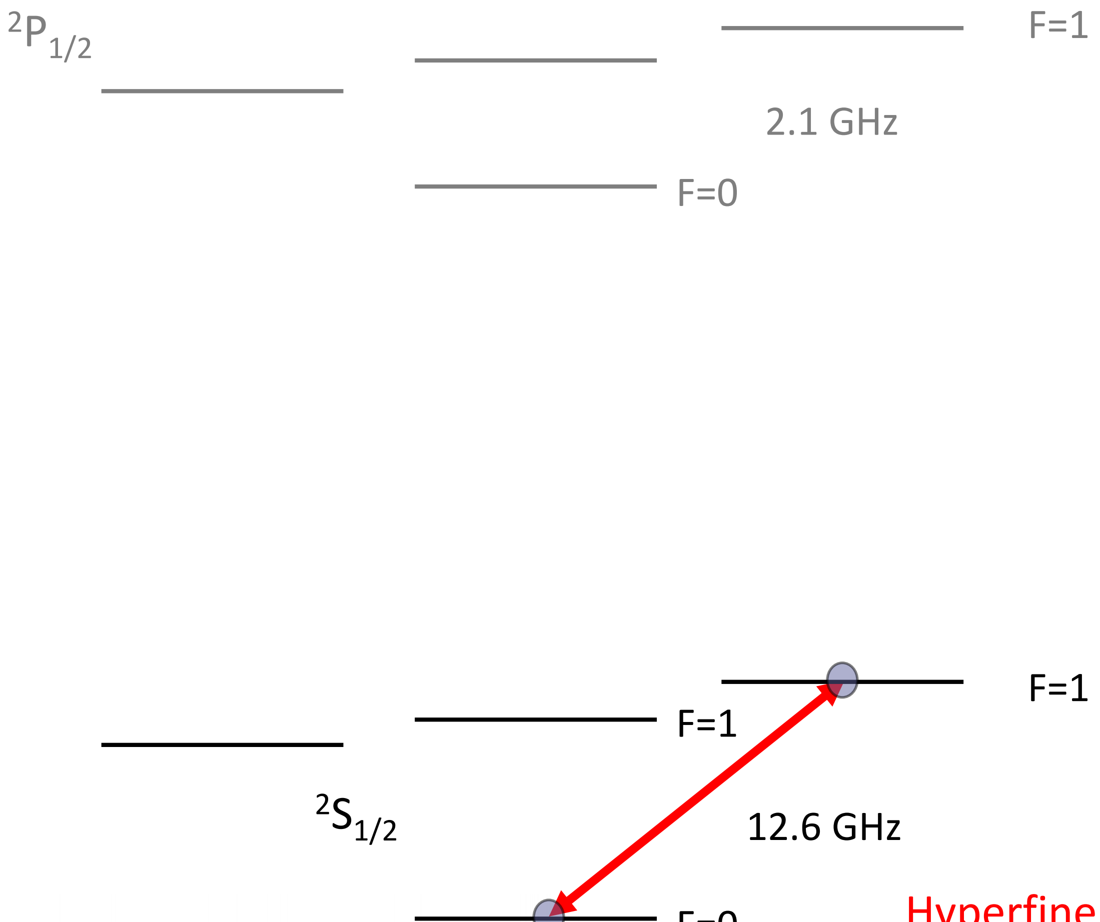
Qubit – $^{171}Yb^{+}$





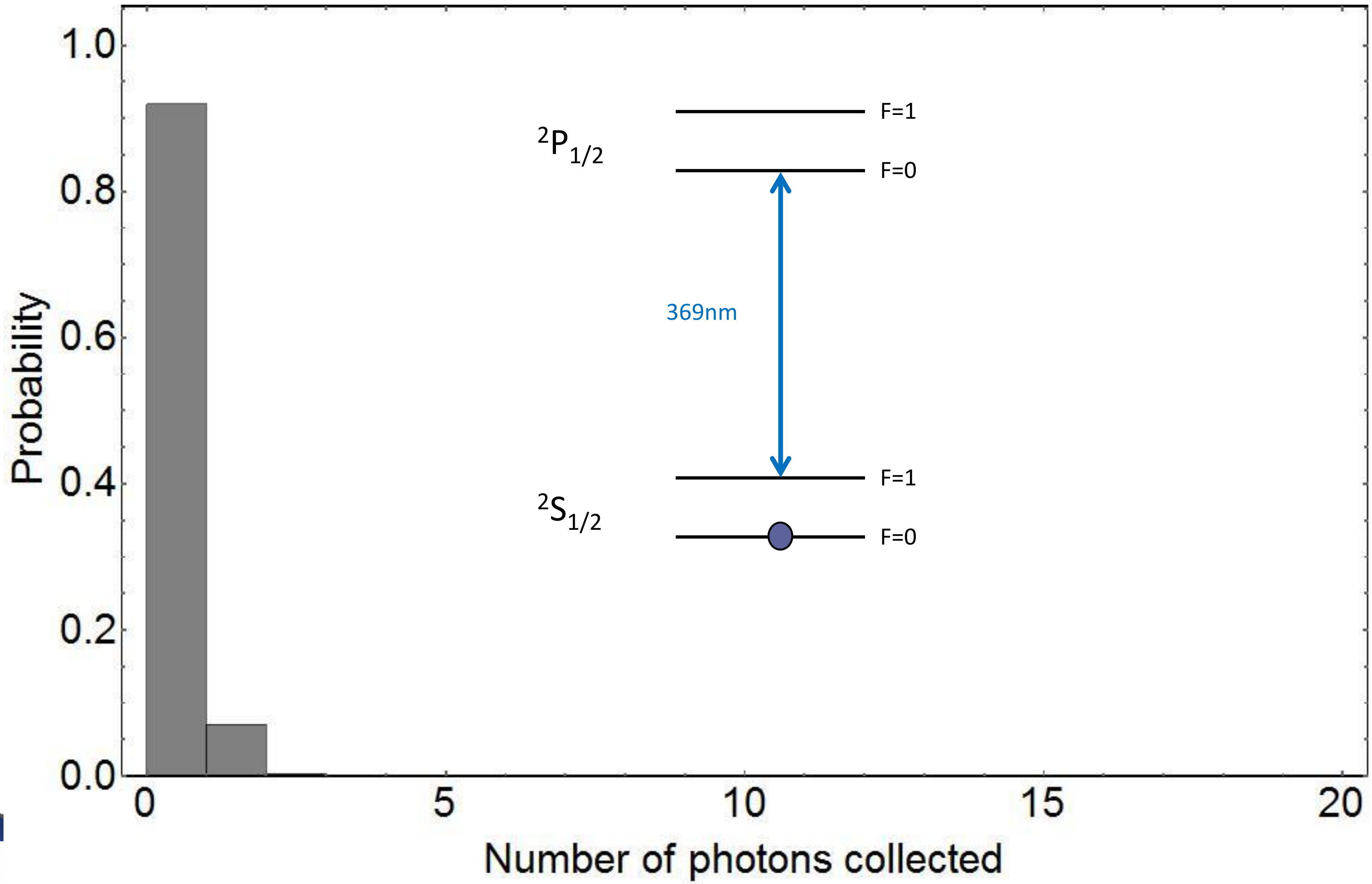
Hyperfine qubit: Two-ground state hyperfine or Zeeman sublevels

Qubit – $^{171}Yb^{+}$

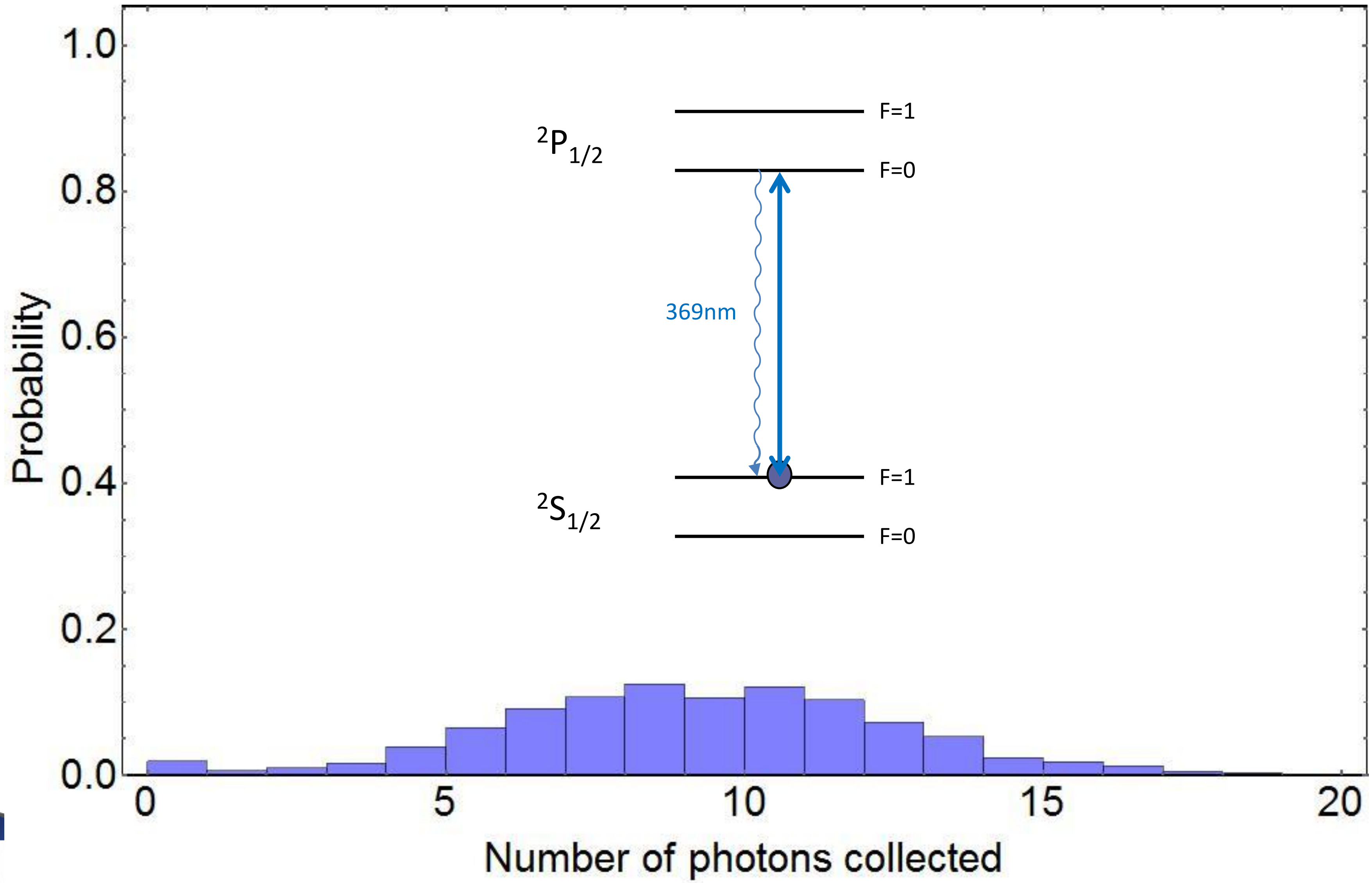


Hyperfine qubit: Two-ground state hyperfine or Zeeman sublevels

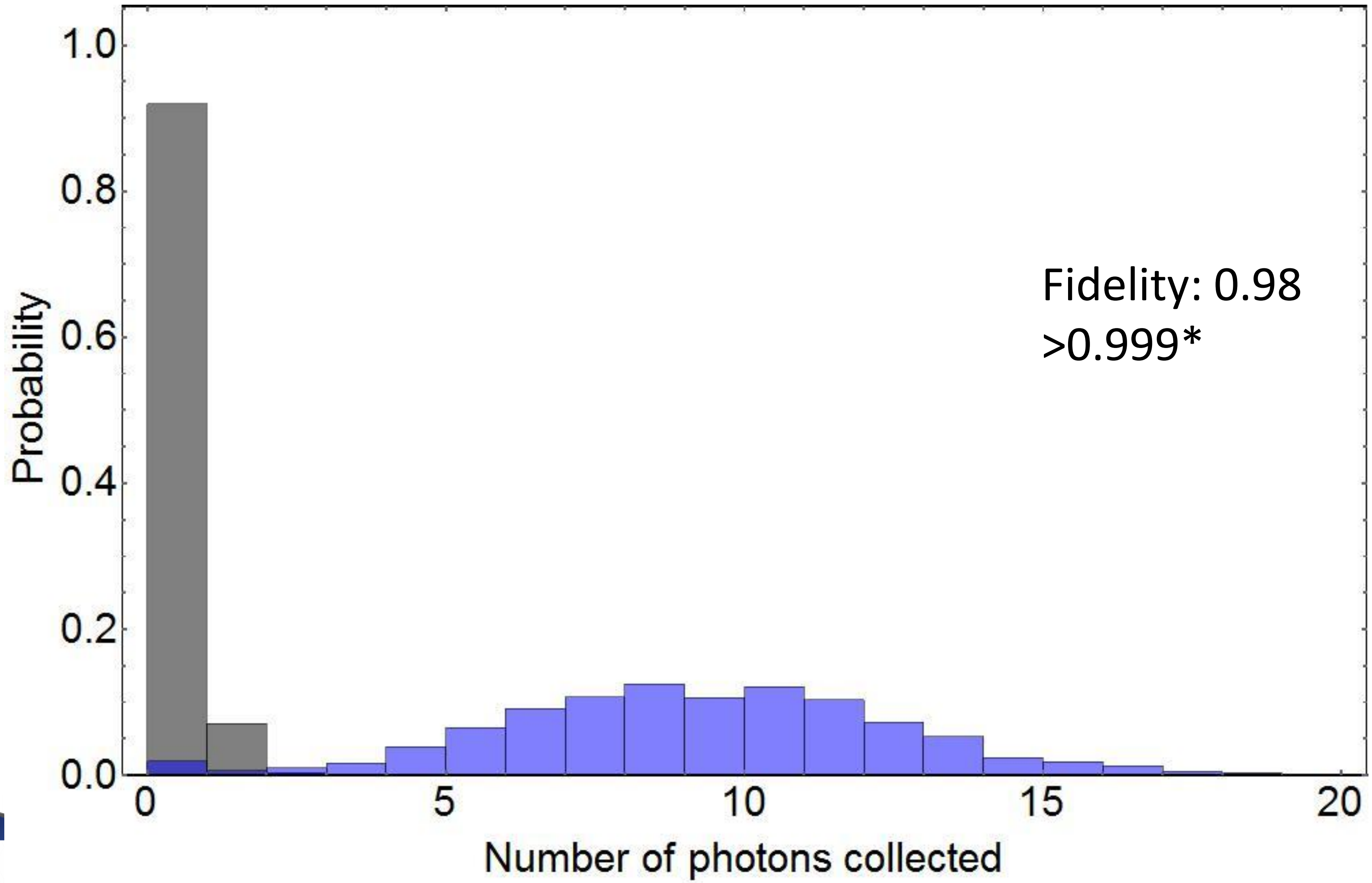
Qubit detection



Qubit detection



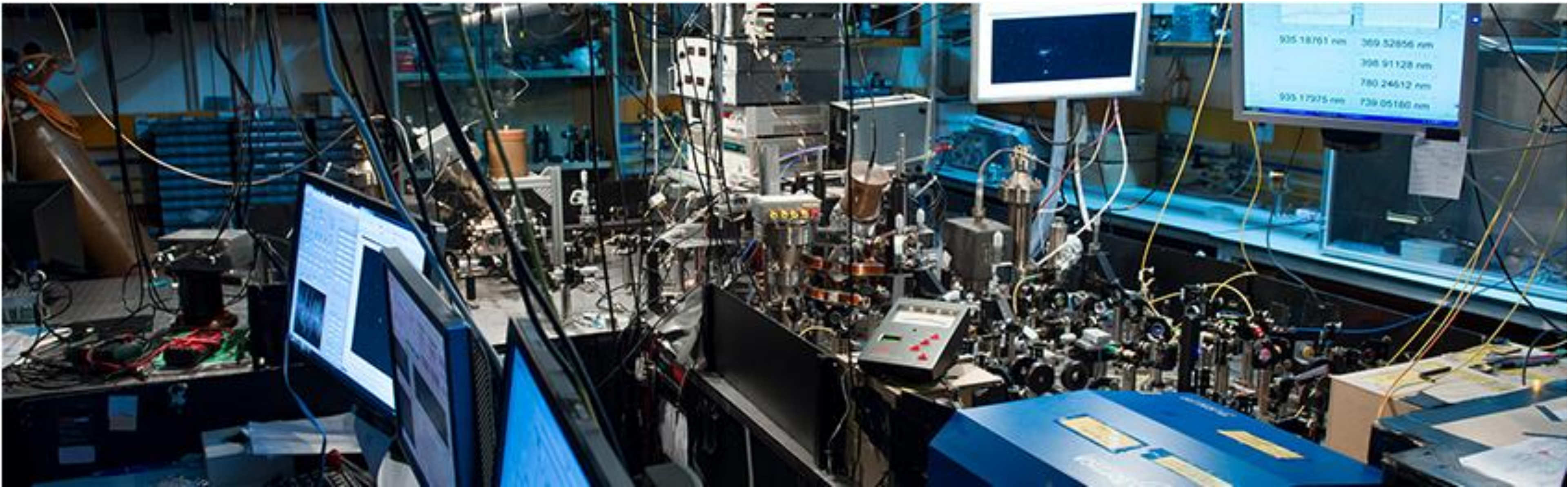
Qubit detection



*Harty et al Phys. Rev. Lett. 113, 220501 (2014)

Trapped ions

- Identical
- Well isolated with coherence times >1000s
- Can be controlled extremely well with logic gate success rates >99.9%
- Technically demanding



What’s missing?

Fault-tolerant quantum computing

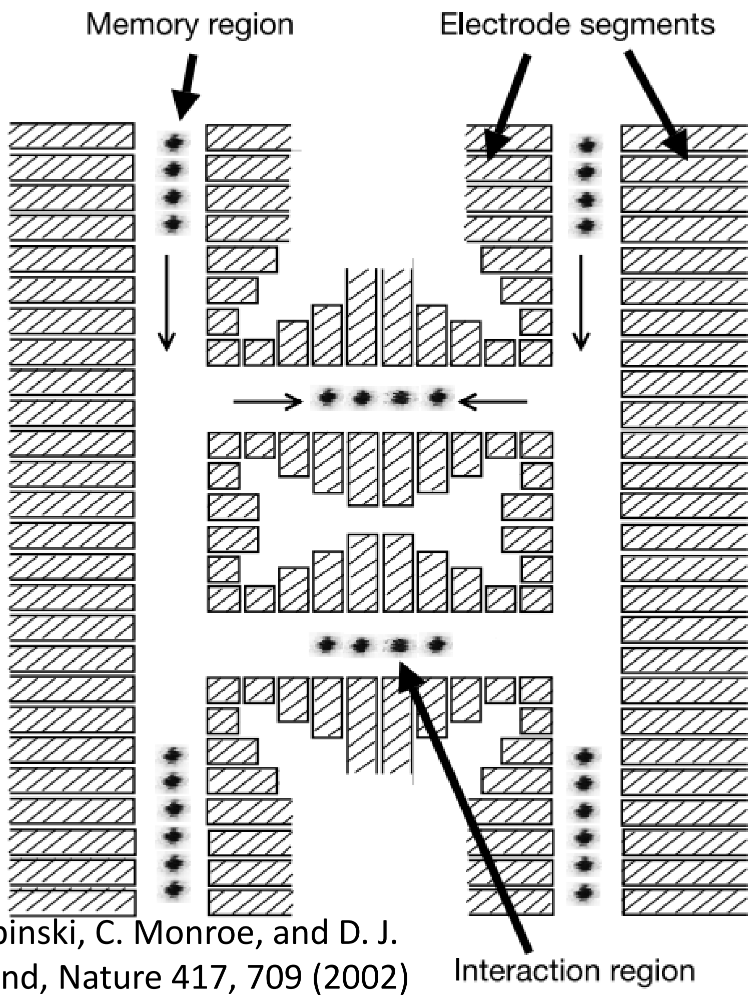
- It can be shown that a system can scale to arbitrary sizes and computations of arbitrary length can be executed given individual operations can be carried out with noise below the fault-tolerant threshold.
- Using a Kitaev surface code one can tolerate an error of around 1% to build a fault-tolerant quantum computer.
- When the error approaches the fault-tolerant threshold, the number of additional 'protection' qubits required explodes, so it is important to remain well below the fault-tolerant threshold.
- Require > million qubits!

So how do we go from a few to many more???

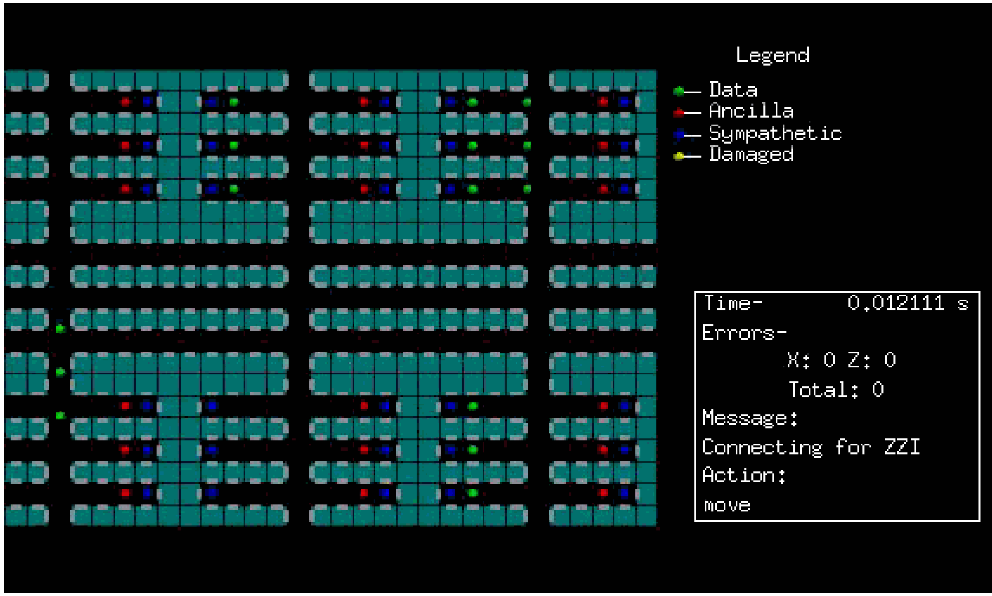
See for example: Surface code quantum computing with error rates over 1%, David S. Wang, Austin G. Fowler, and Lloyd C. L. Hollenberg, PRA 83, 020302(R) (2011)

Scalability (from a few to many)

Number of required gate radiation fields scales with the number of qubits to be used in the quantum computer.



D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002)



Ike Chuang, MIT

How to implement a quantum gate?

Traditionally this is done by interacting two ions with laser beams for each trapped ion qubit.

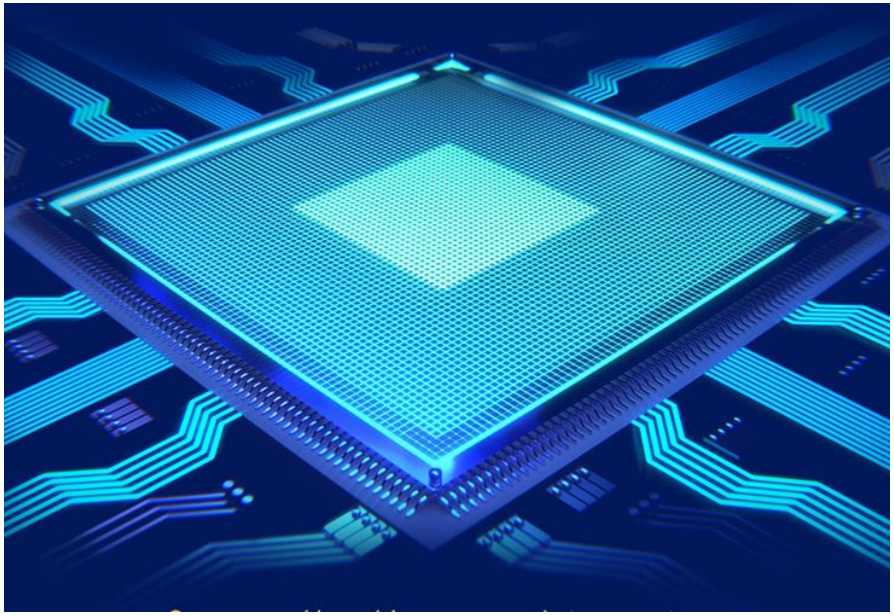
Not easy with lots of qubits

However, remember there will be millions of trapped ions, so this means **millions of laser beams** that need to be **aligned as good as 1/100 of a millimetre!**

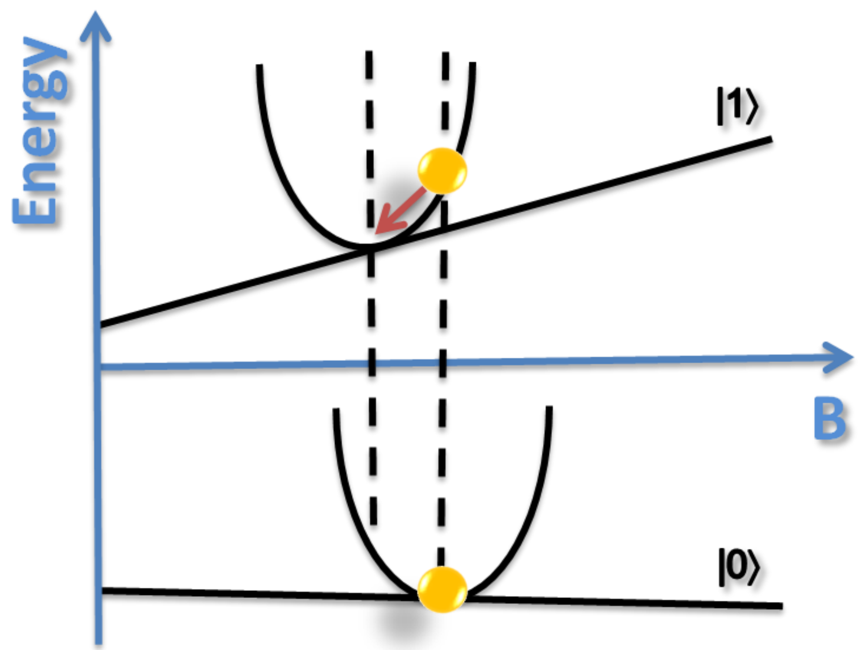
Not easy!

But there is another way…

There is another way – apply voltages to a microchip, analogous to a conventional computer chip



Motional coupling with a magnetic field gradient



Magnetic field gradient gives rise to a state dependent force.

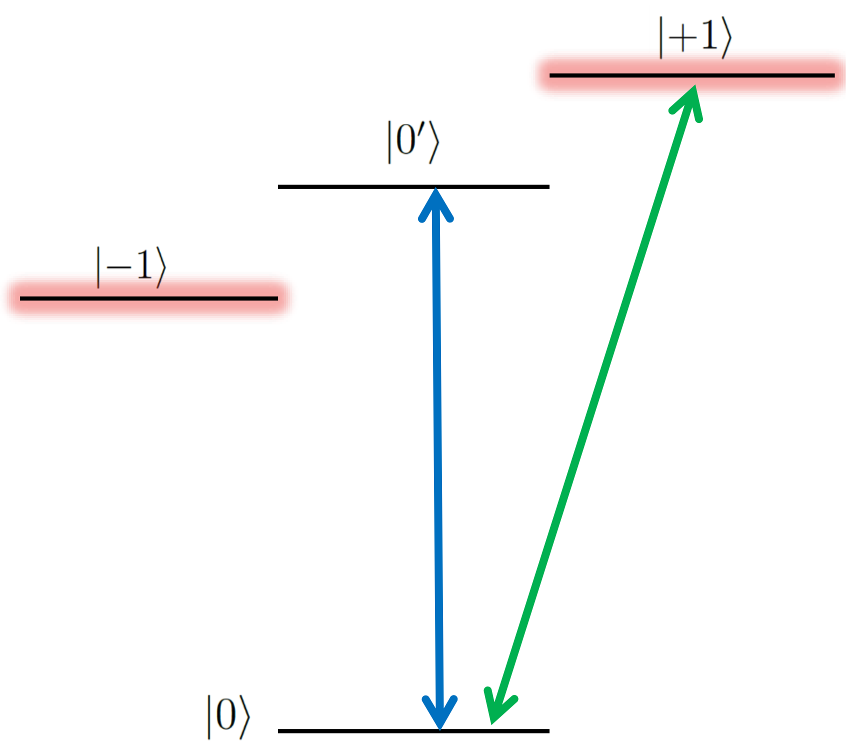
Effective Lamb-Dicke parameter:

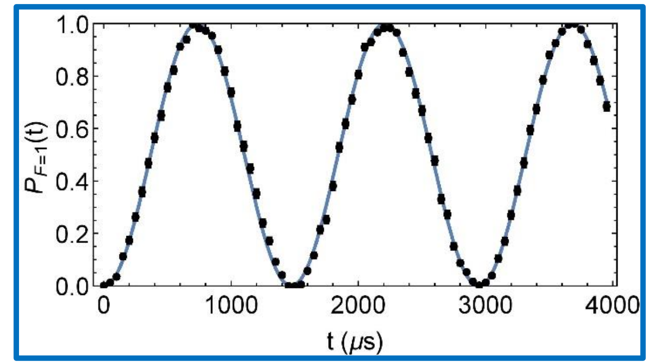
$$\eta_{eff} = \left(1.19 \times 10^6 ms^{-\frac{3}{2}} T^{-1}\right) \frac{\partial_z B}{{v_z}^{\frac{3}{2}}}$$

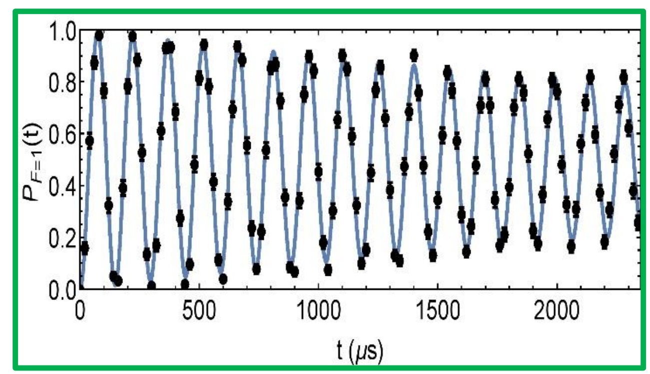
Requires the use of magnetic field sensitive states.

F. Mintert and C. Wunderlich, Phys. Rev. Lett. 87, 257904 (2001)
A. Khromova *et al.*, Phys. Rev. Lett. 108, 220502 (2012)

Challenge: B-field sensitive states







Fluctuations in the magnetic field causes dephasing

Gives rise to short coherence times

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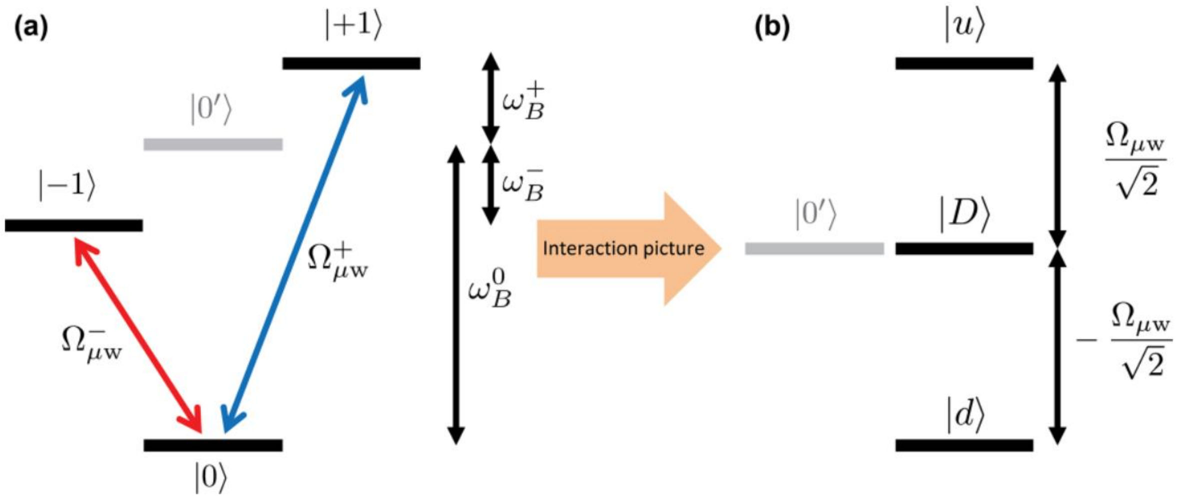
Solution: Microwave dressed-states



Three eigenstates:

$$|D\rangle = \frac{1}{\sqrt{2}}(|+1\rangle - |-1\rangle)$$

$$|u\rangle = \frac{1}{\sqrt{2}}|0\,\rangle + \frac{1}{2}|+1\rangle + \frac{1}{2}|-1\rangle$$

$$|d\rangle = \frac{1}{\sqrt{2}}|0\,\rangle - \frac{1}{2}|+1\rangle - \frac{1}{2}|-1\rangle$$

Two microwave dressing fields

$$H_{\mu w}^I = \frac{\hbar\Omega_{\mu w}}{2}(|+1\rangle\langle 0| + |-1\rangle\langle 0| + h.c)$$

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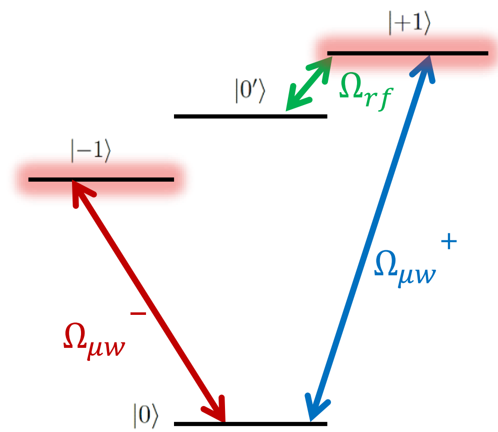
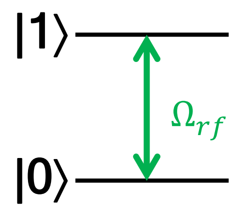
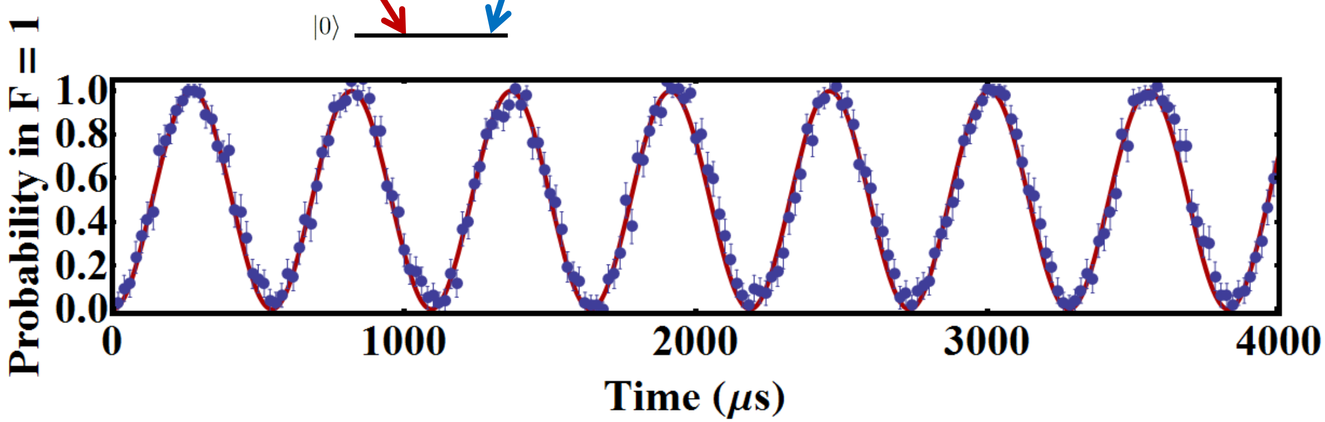
N. Timoney, I. Baumgart, M. Johanning, A. F. Varon, M. B. Plenio, A. Retzker, and C. Wunderlich, Nature 476, 185 (2011)

Single qubit gates

Quantum engineered qubit - extremely robust to noise with useful feature





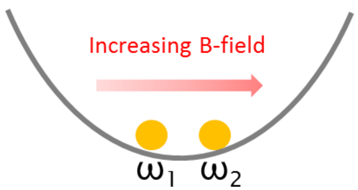


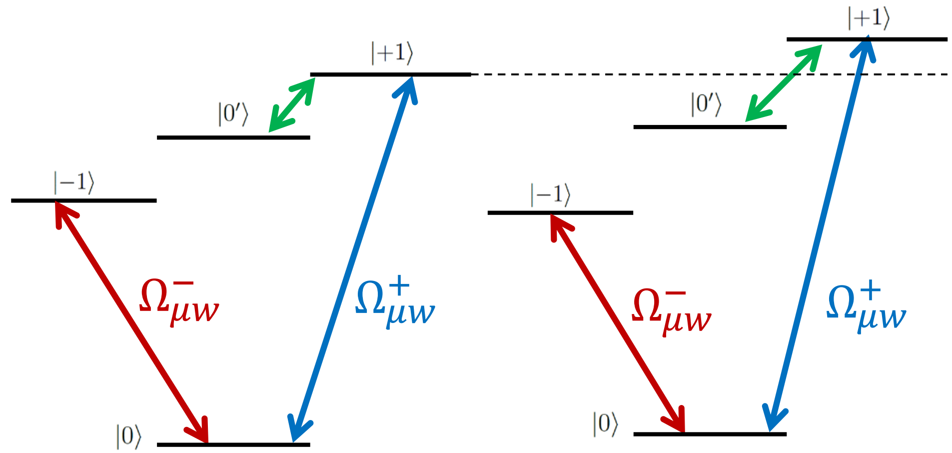
Tuneable 'clock' qubit

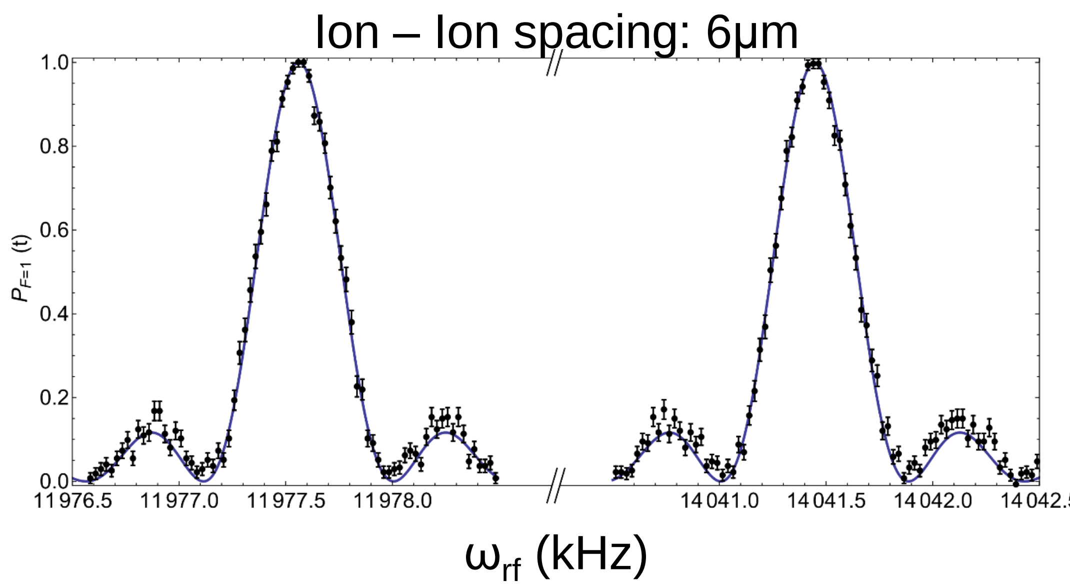
S. C. Webster, S. Weidt, K. Lake, J. J. McLoughlin and W. K. Hensinger, Phys. Rev. Lett. 111, 140501 (2013)

J. Randall, S. Weidt, E. D. Standing, K. Lake, S. C. Webster, D. F. Murgia, T. Navickas, K. Roth, and W. K. Hensinger, Phys. Rev. A 91, 012322 (2015)

Fault-tolerant individual addressing







Δω = frequency splitting
Ω = Rabi frequency

Cross-talk: $\Omega^2 / 2(\Omega^2 + \Delta\omega^2) <$ **10^{-8}**

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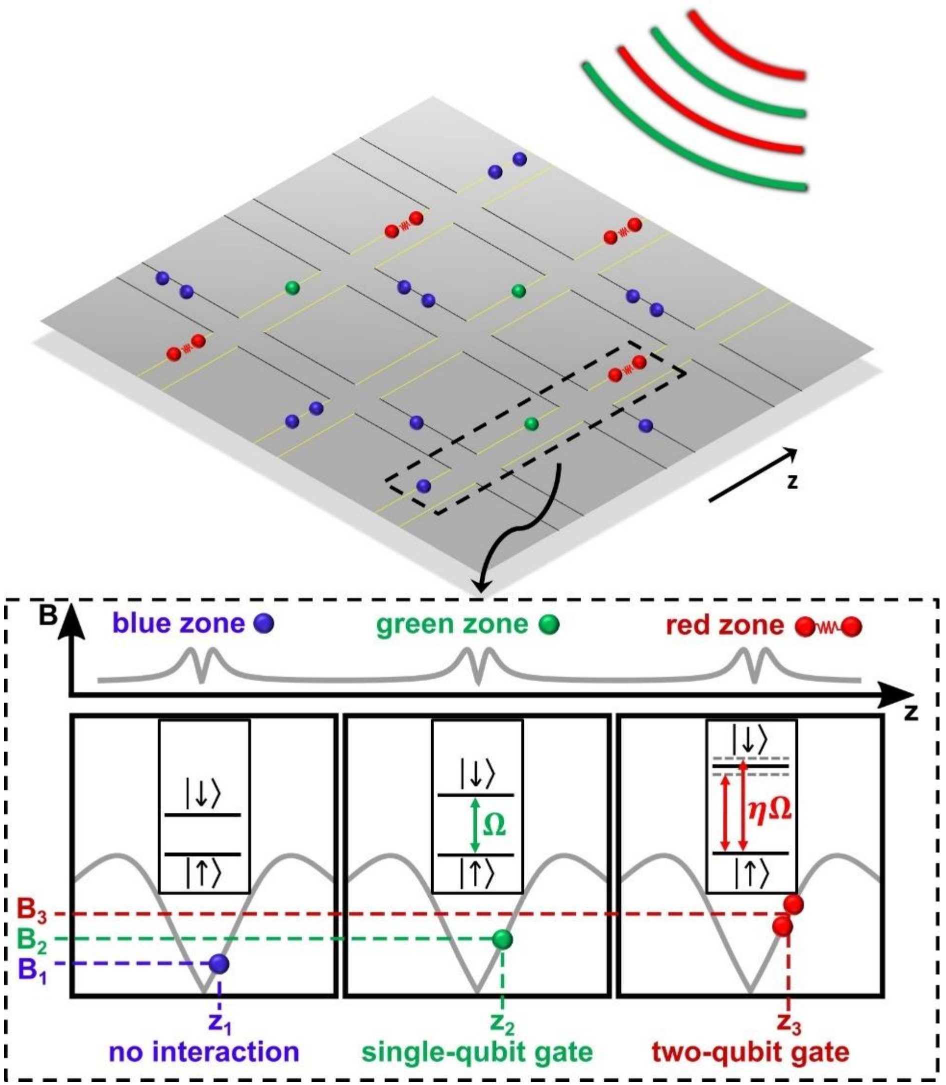
Quantum computing with global fields

Concept:

- Quantum gate selection via the application of voltages to local trap electrodes.
- Single sets of gate specific global fields combined with local gradients perform required operations on large scale.



The number of gate fields required usually scales with the number of qubits.

This scaling vanishes for this new scheme.

S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Phys. Rev. Lett. 117, 220501 (2016)

Initial experimental results for the gate

- Maximally entangled Bell-state:

$$|0'0'\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0'0'\rangle - i\,|DD\rangle\right)$$

$$F = \frac{1}{2}\left(P_{0'0'} + P_{DD}\right) + \rho_{0'0',DD}$$

A/4

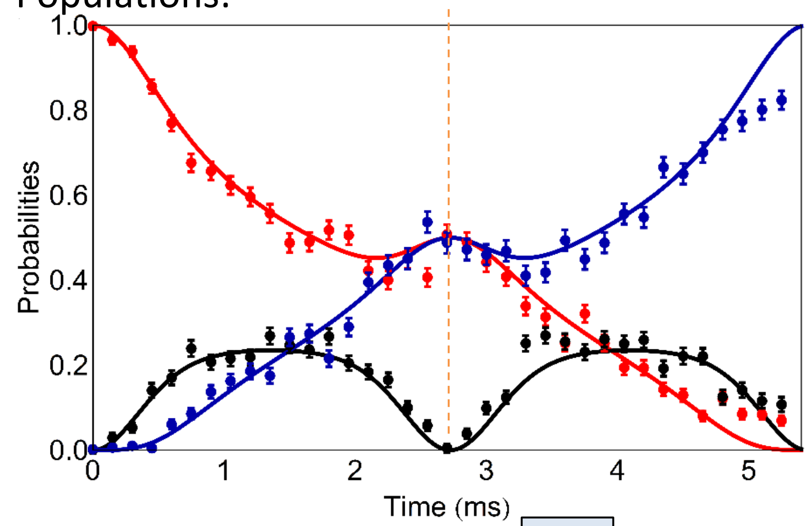
$\Omega/2\pi$	45.4 kHz
$\nu_{STR}/2\pi$	459.3 kHz
η_{eff}	0.0041
$\bar{n}$	0.1
$\delta/2\pi$	0.37 kHz
τ_{gate}	2.7 ms

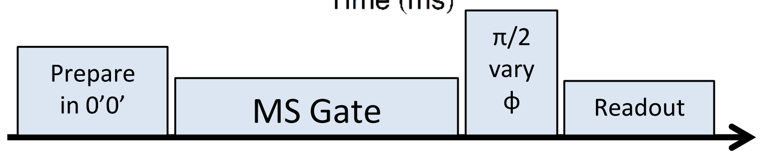
Fidelity: 0.985(12)

Error budget:

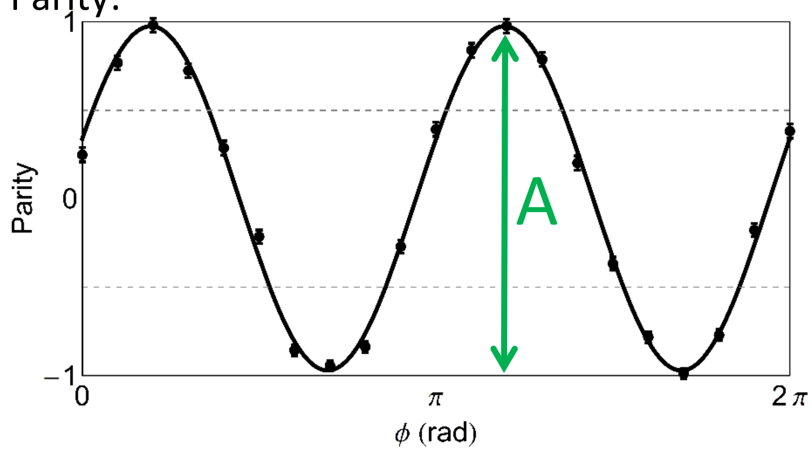
- Motional heating: 1 x 10^{-2}
- Dephasing: 4 x 10^{-3}

Populations:





Parity:



Trapped-ion quantum logic with global radiation fields, S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Phys. Rev. Lett. 117, 220501 (2016)

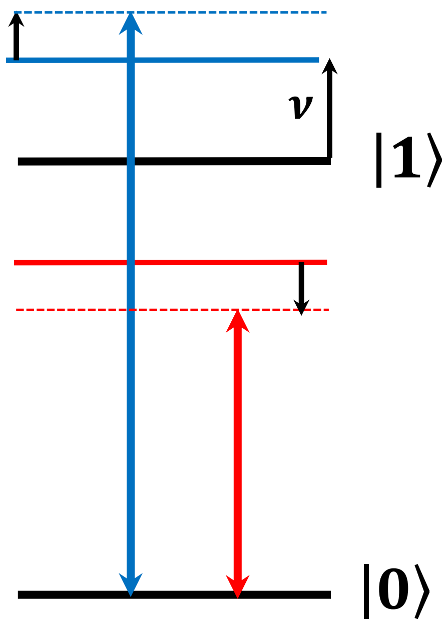
What about a realistic environment with noise?

- Noise in electrical components
- Stray magnetic fields
- A bus driving by the lab
- ….

Resilient two qubit gates: Multi-tone Gates

Standard Mølmer-Sørensen:

Tones applied at $(\omega_0 \pm (\nu + \delta))$

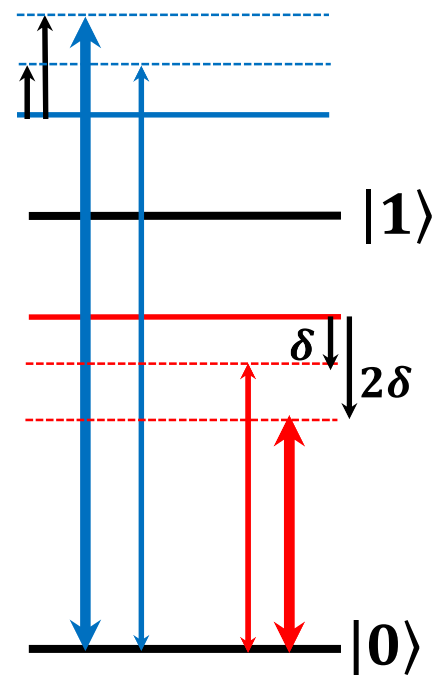


$\Omega_1 = \Omega_0$

Two-tone Mølmer-Sørensen:

Tones applied at

$(\omega_0 \pm (\nu + \delta)), (\omega_0 \pm (\nu + 2\delta))$

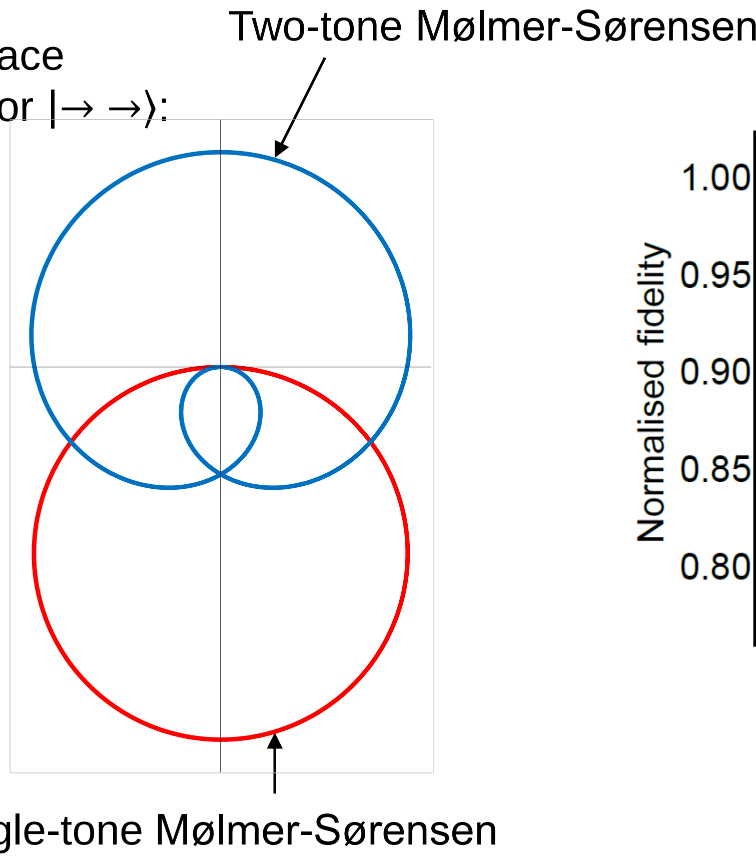


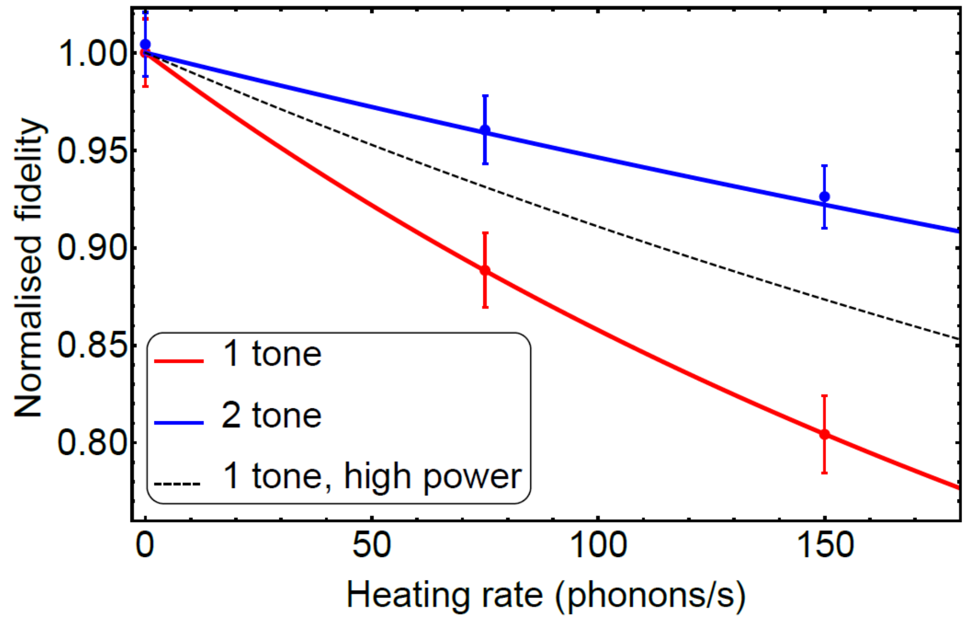
$\Omega_1 = 0.576\Omega_0, \Omega_2 = 1.152\Omega_0$

Resilient entangling gates for trapped ions, A. E. Webb, S. C. Webster, S. Collingbourne, D. Bretaud, A. M. Lawrence, S. Weidt, F. Mintert and W. K. Hensinger, Phys. Rev. Lett. 121, 180501 (2018)

Protection against motional heating

Phase space diagram for $|\rightarrow\rightarrow\rangle$:



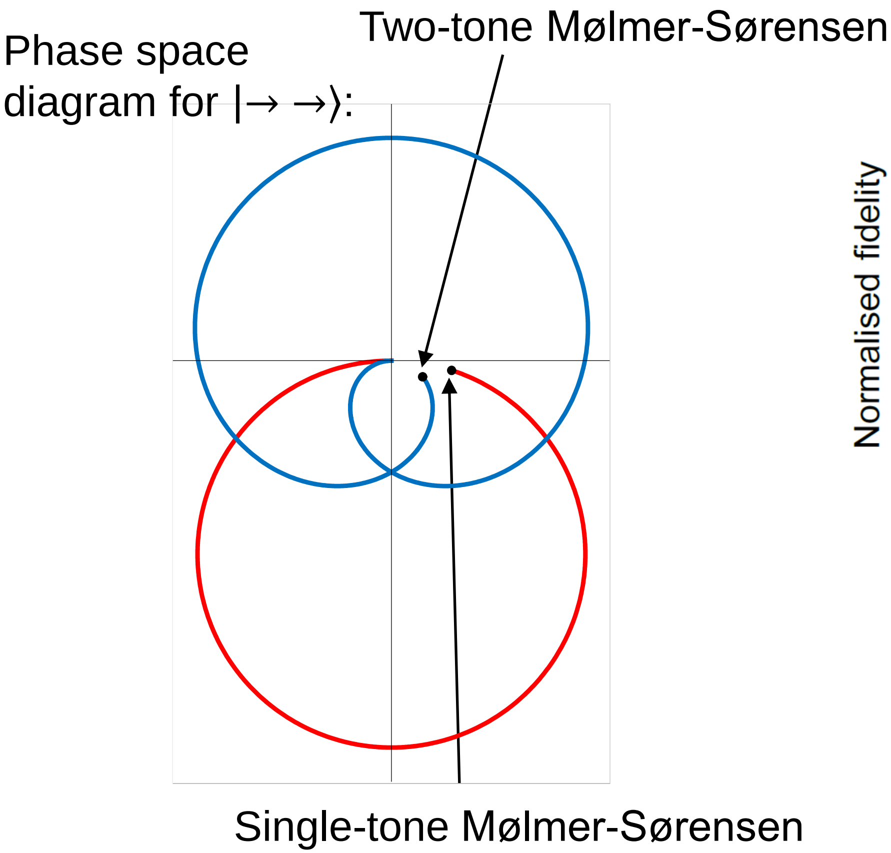


Infidelity due to heating being worse for larger separations in phase space - two-tone MS gate stays closer to the origin during gate

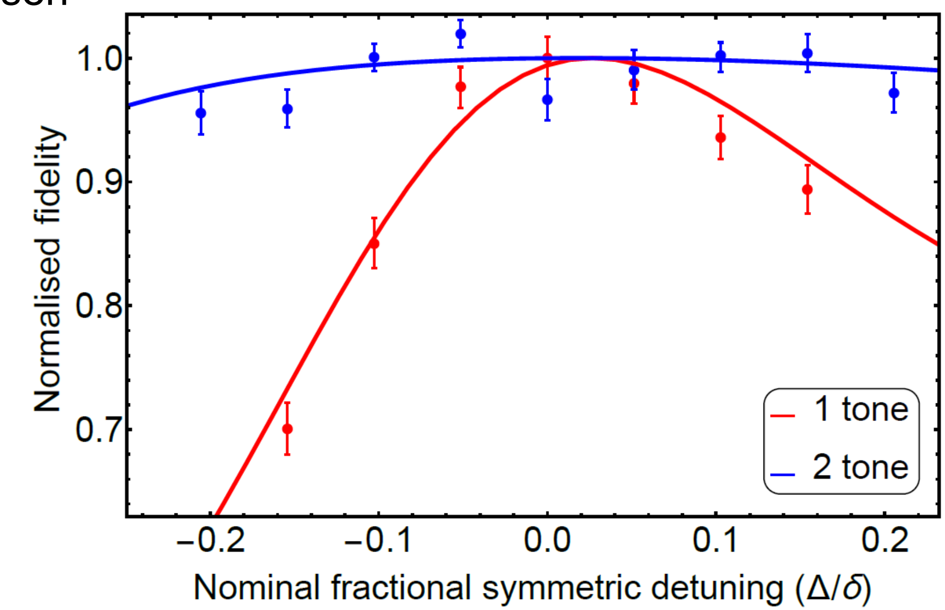
Gate time	3.4ms
Detuning δ	292Hz
$\Omega_0/2\pi$	36kHz
Stretch mode freq	461kHz
Lamb-Dicke	0.0041

Resilient entangling gates for trapped ions, A. E. Webb, S. C. Webster, S. Collingbourne, D. Bretaud, A. M. Lawrence, S. Weidt, F. Mintert and W. K. Hensinger, Phys. Rev. Lett. 121, 180501 (2018)

Protection against parameter error



Error caused by drift in trap frequency



Gate time	3.4ms
Detuning δ	292Hz
$\Omega_0/2\pi$	36kHz
Stretch mode freq	461kHz
Lamb-Dicke	0.0041

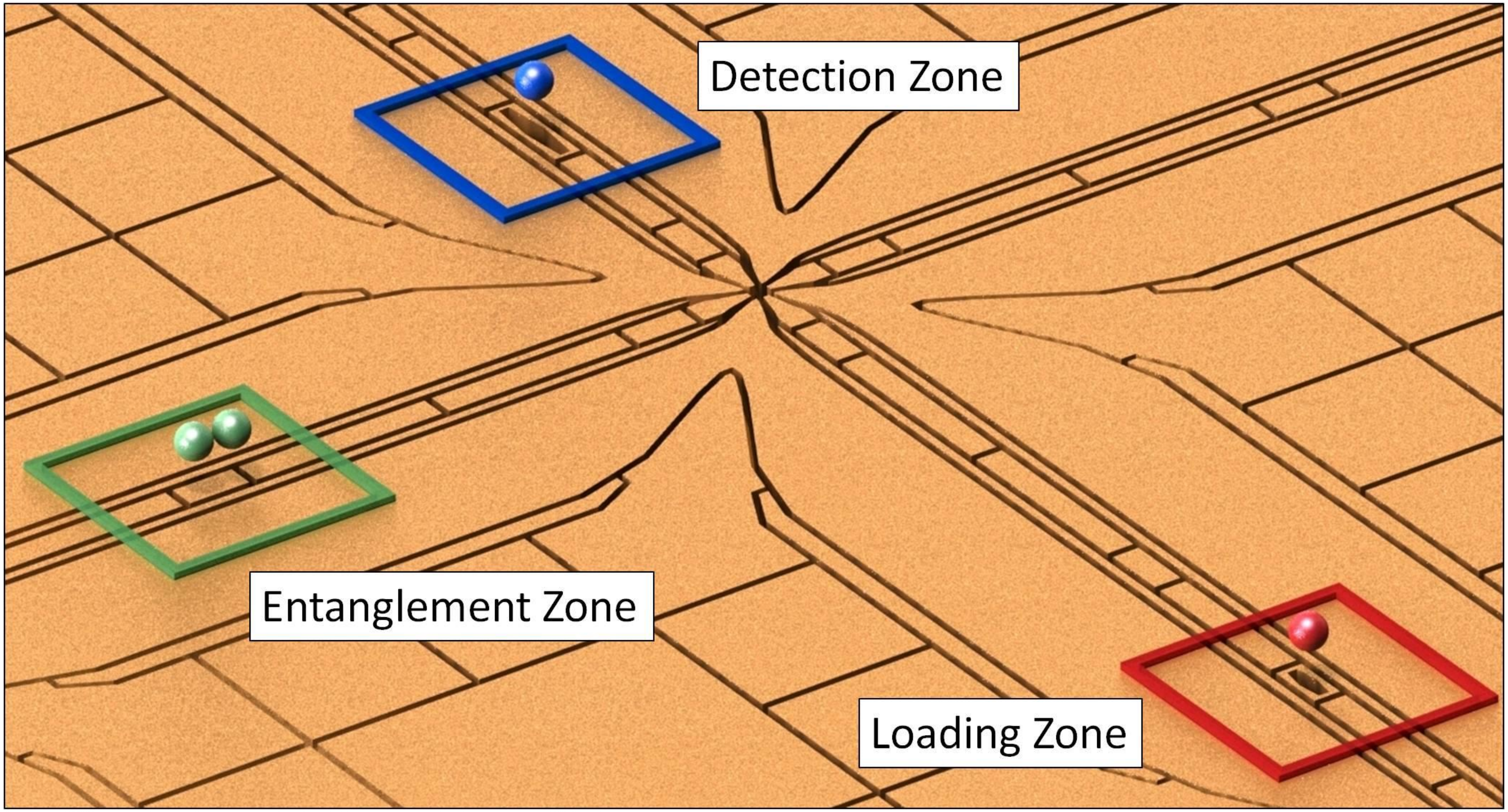
Resilient entangling gates for trapped ions, A. E. Webb, S. C. Webster, S. Collingbourne, D. Bretaud, A. M. Lawrence, S. Weidt, F. Mintert and W. K. Hensinger, Phys. Rev. Lett. 121, 180501 (2018)

Constructing a large scale microwave trapped-ion quantum computer

Blueprint for a microwave trapped ion quantum computer, B. Lekitsch, S. Weidt, A. G. Fowler, K. Mølmer, S.J. Devitt, Ch. Wunderlich, and W. K. Hensinger, Science Advances 3, e1601540 (2017)

Scalable microwave based architecture

- X-Junctions



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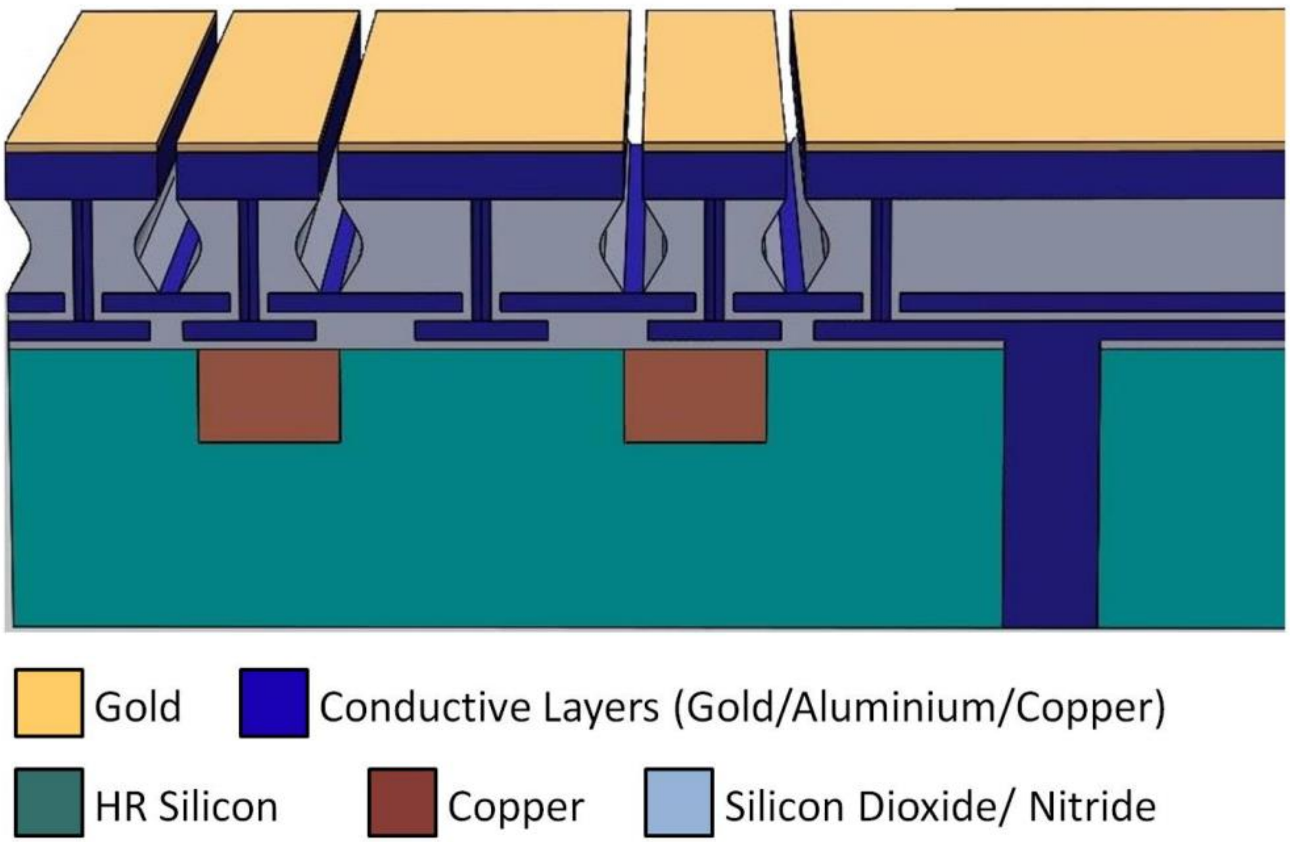
Microchip cross-section



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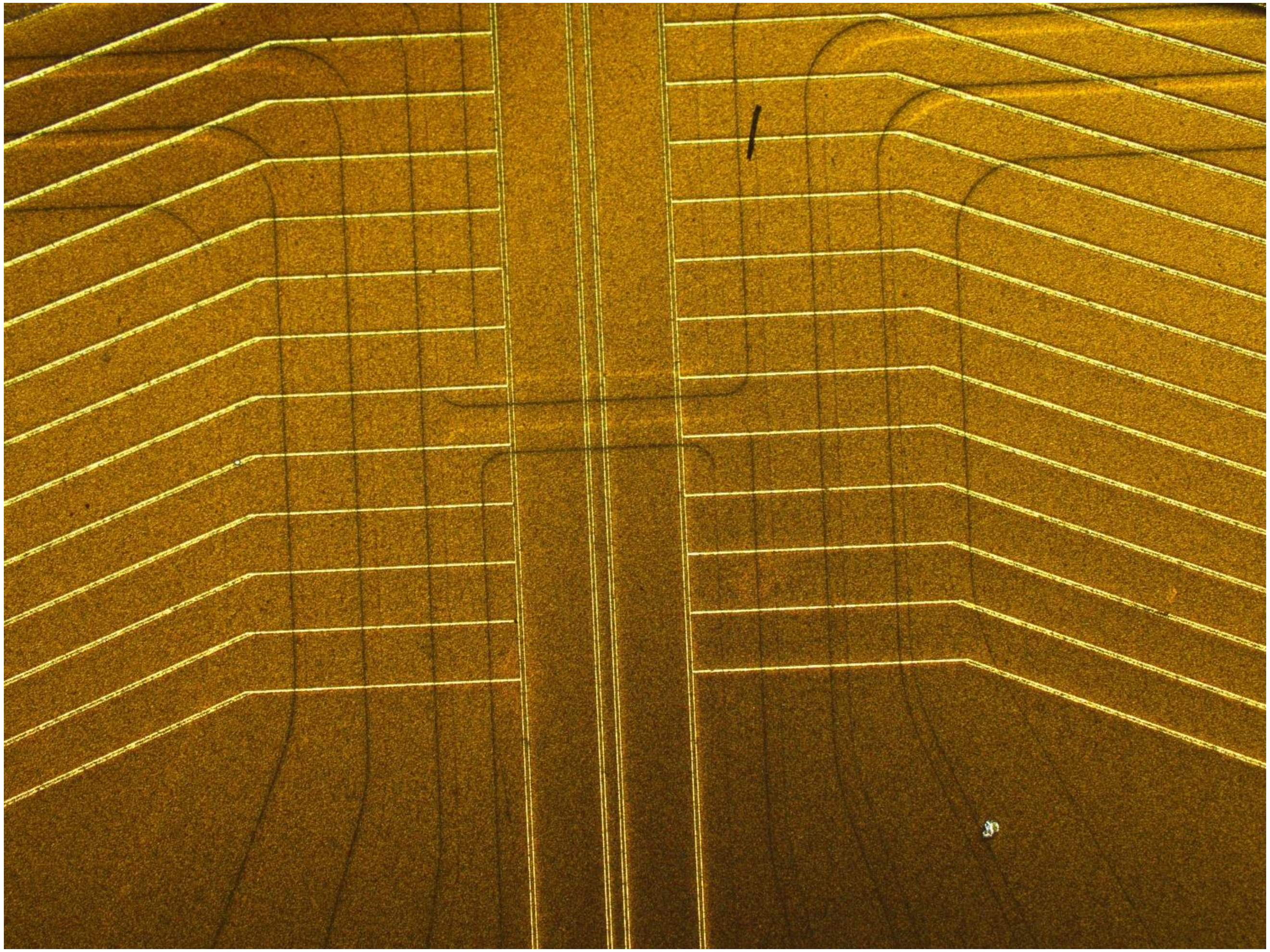
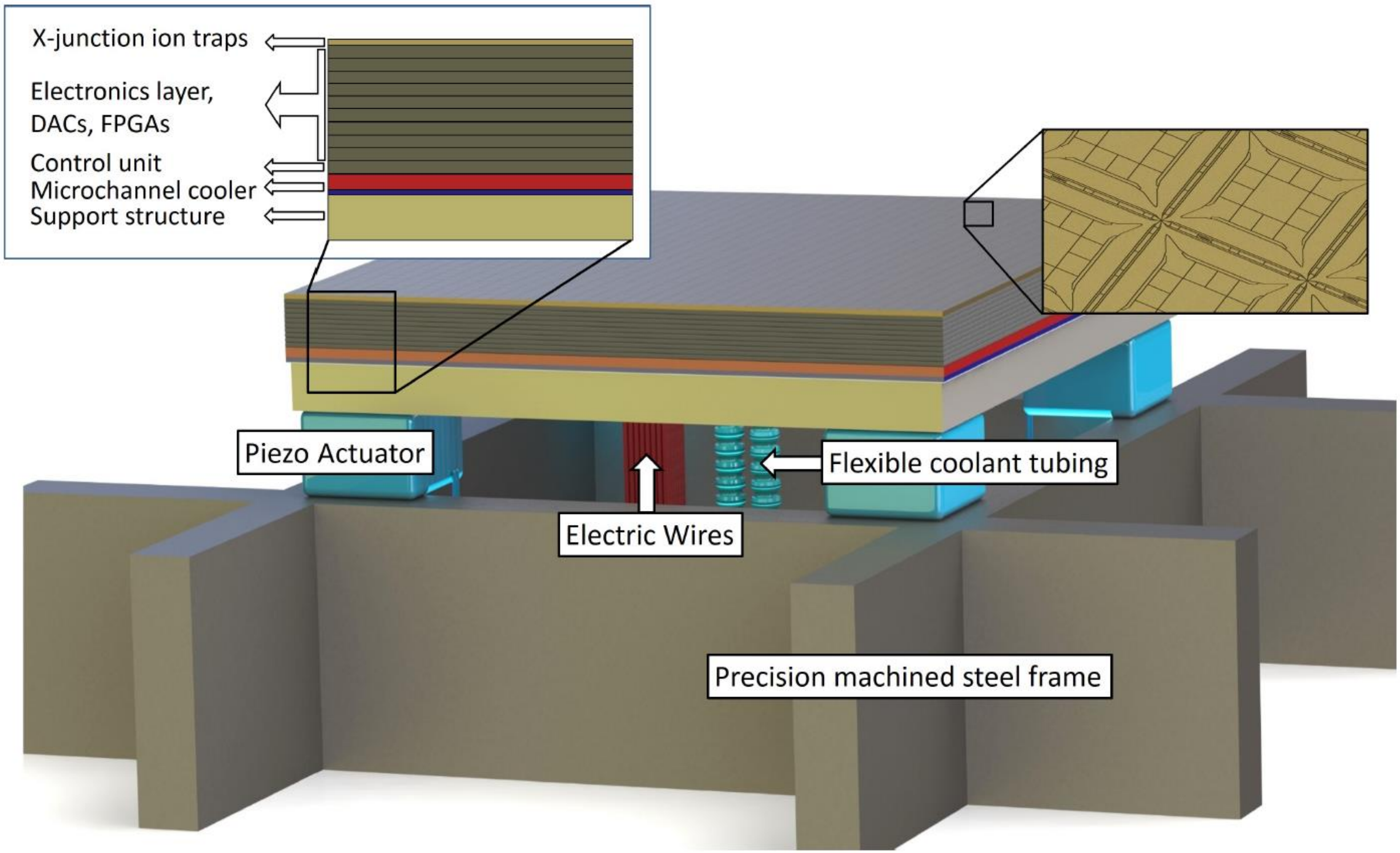
Microchip with integrated gate zone



Electronic Quantum Computer Module



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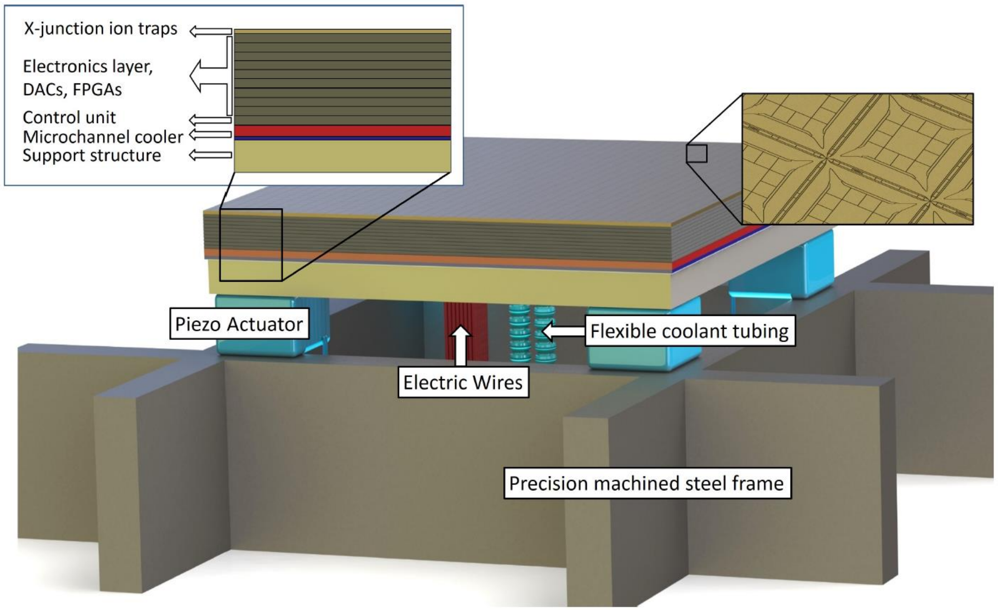
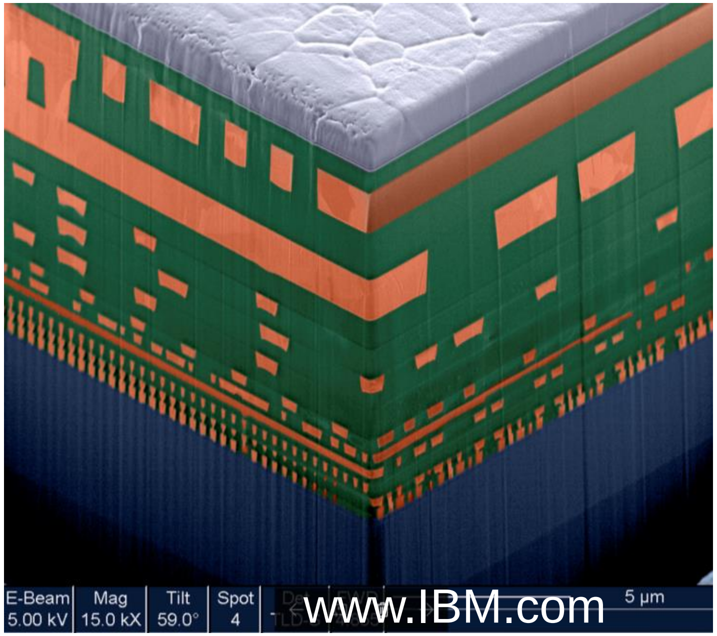
Scalable microwave-based architecture

Quantum computer architecture

Classical computer architecture





Quantum computer module:
Layer of trapped ion qubits controlled via multiple layers of electronics

IBM microprocessor chip:
Layer of transistors connected via multiple layers of wiring

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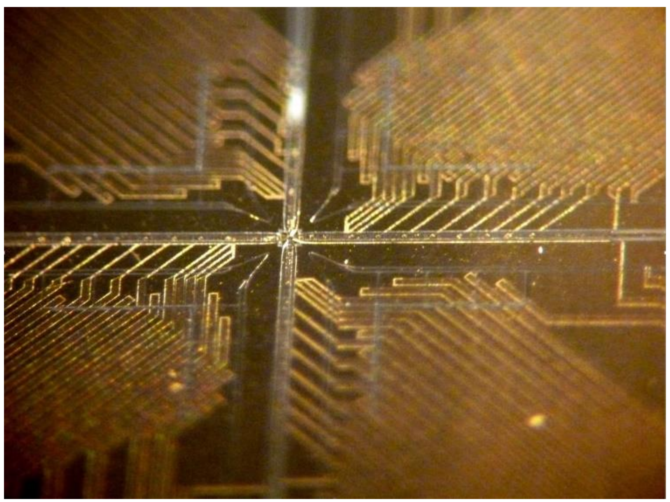
Scalability (from many to many more)

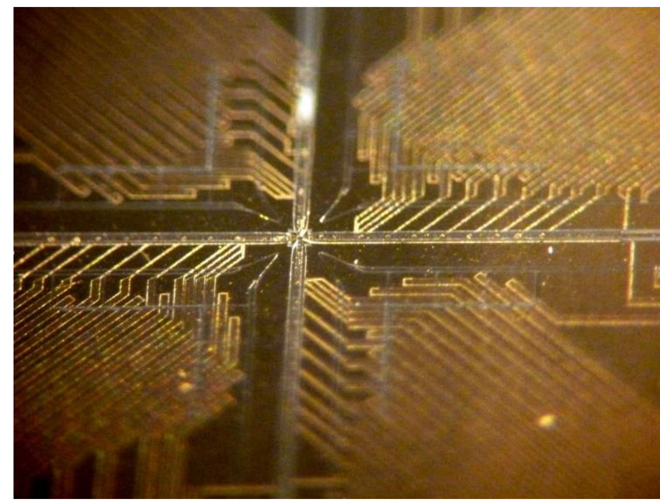
Modular approach:

Module A



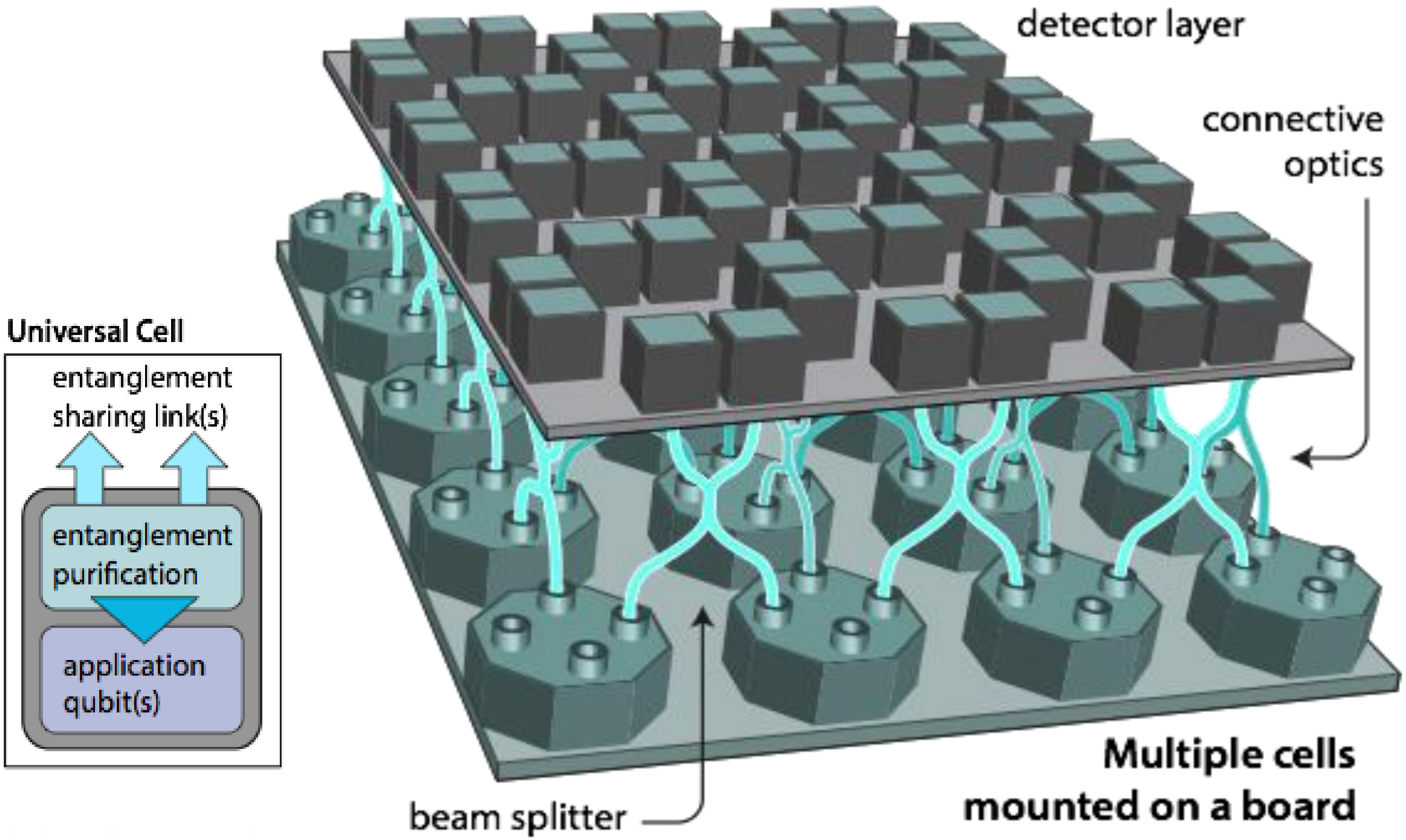
Connection?

Module B



Option 1: Connect modules using photonic interconnects

Optically linked array of quantum computing modules…



Oxford 20:20 engine

C. Monroe et al., Phys. Rev. A 89, 022317 (2014)

Option 2: Use electric fields to connect modules

- Much simpler engineering

- High connection speeds between modules are readily achievable

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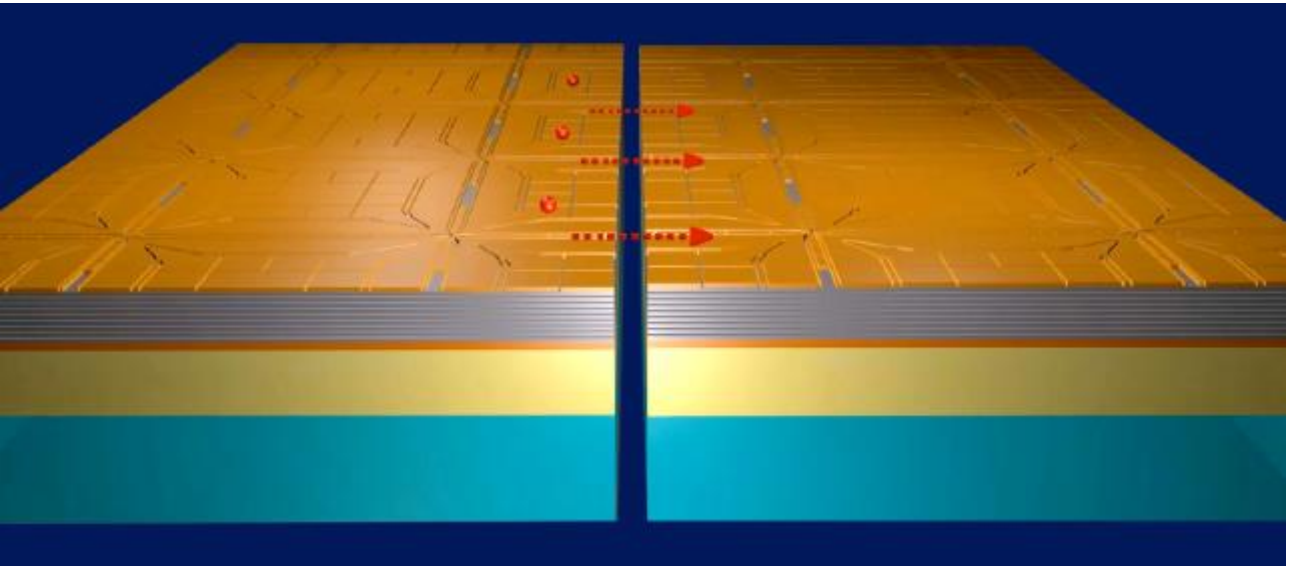
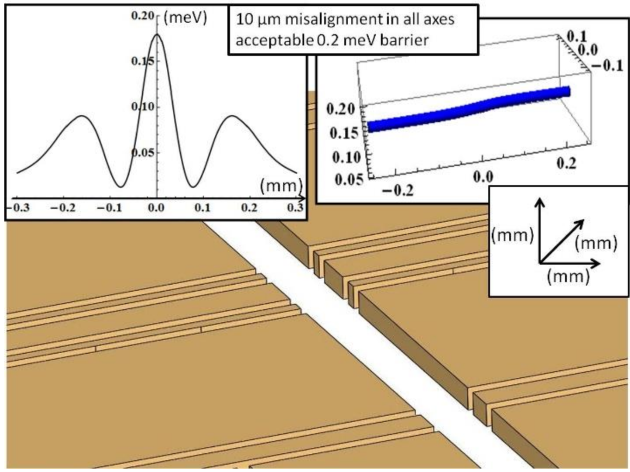
Modularity:
Connecting modules with electric fields





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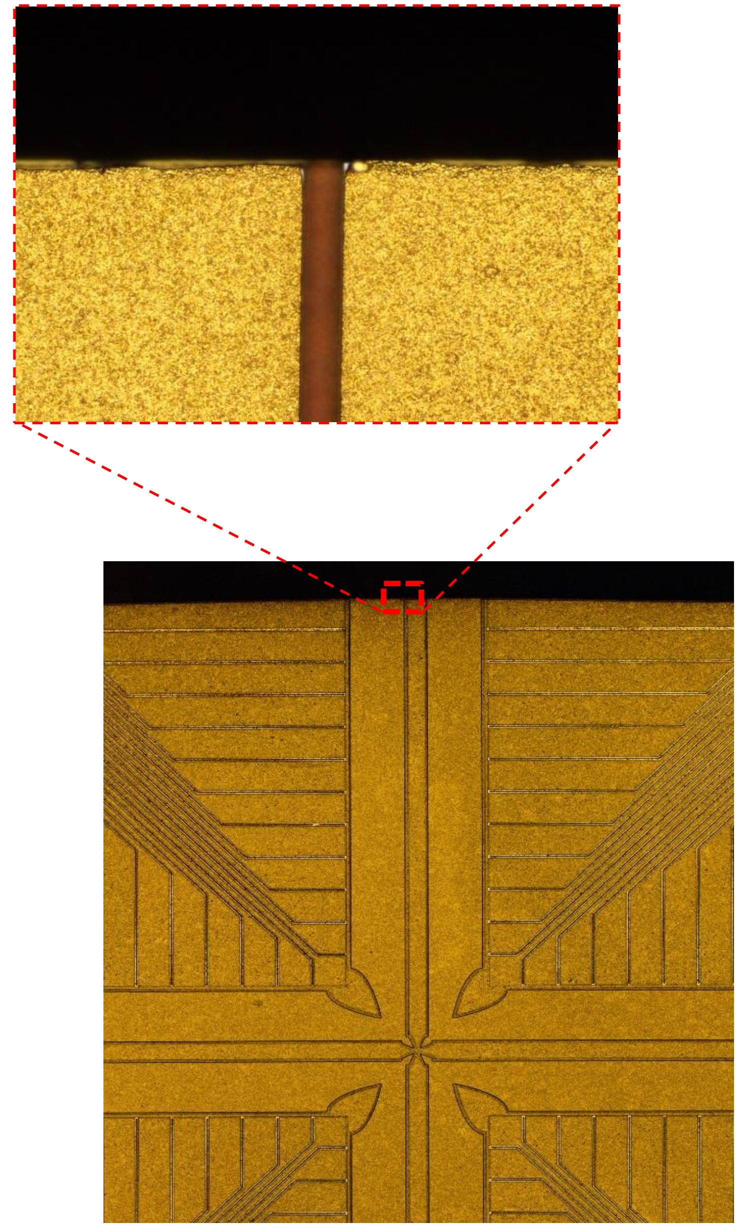
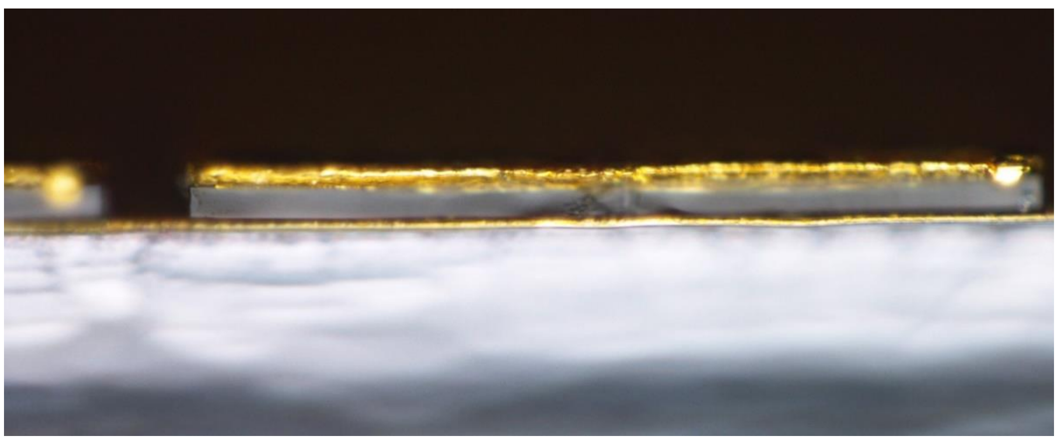
Module interface for shuttling between modules

- Successfully fabricated X-junction edge trap
- Preliminary results on achieving 'smooth edge'
- More testing to be carried out on creating optimum edge geometry





Cross section view of cut edge

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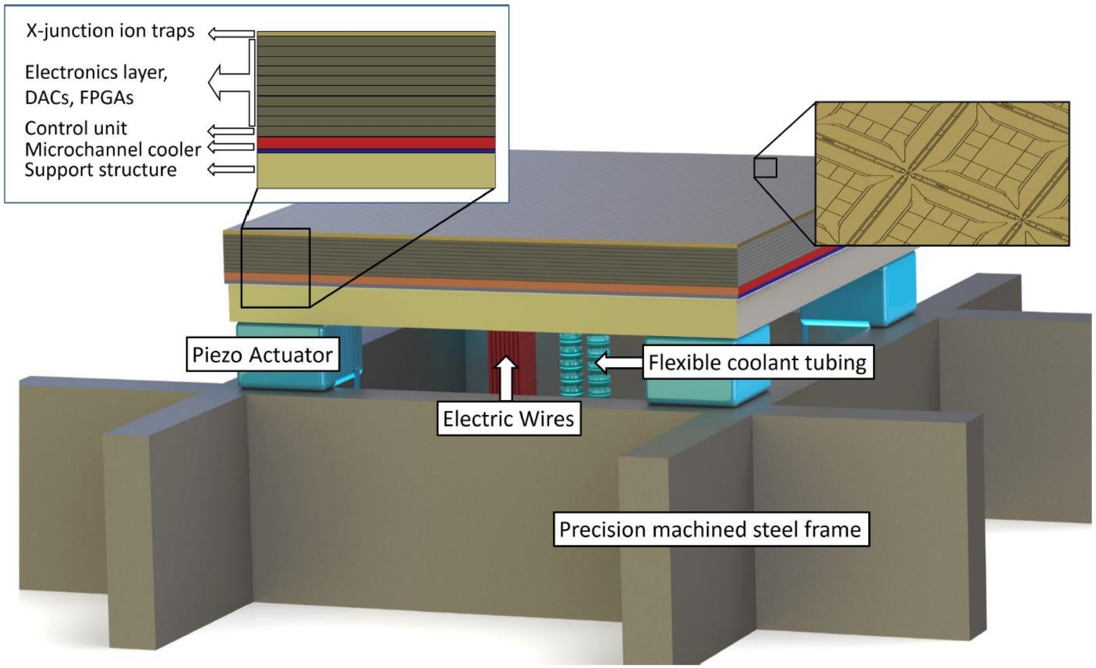
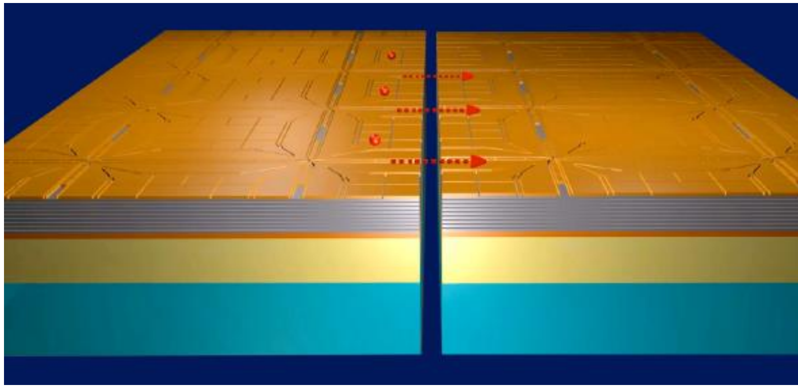
Sussex Modular Microwave Engine

Gates by application of voltages, modules connected using electric fields

Microwave technology is being used for quantum gate execution





Modules are connected via electric fields

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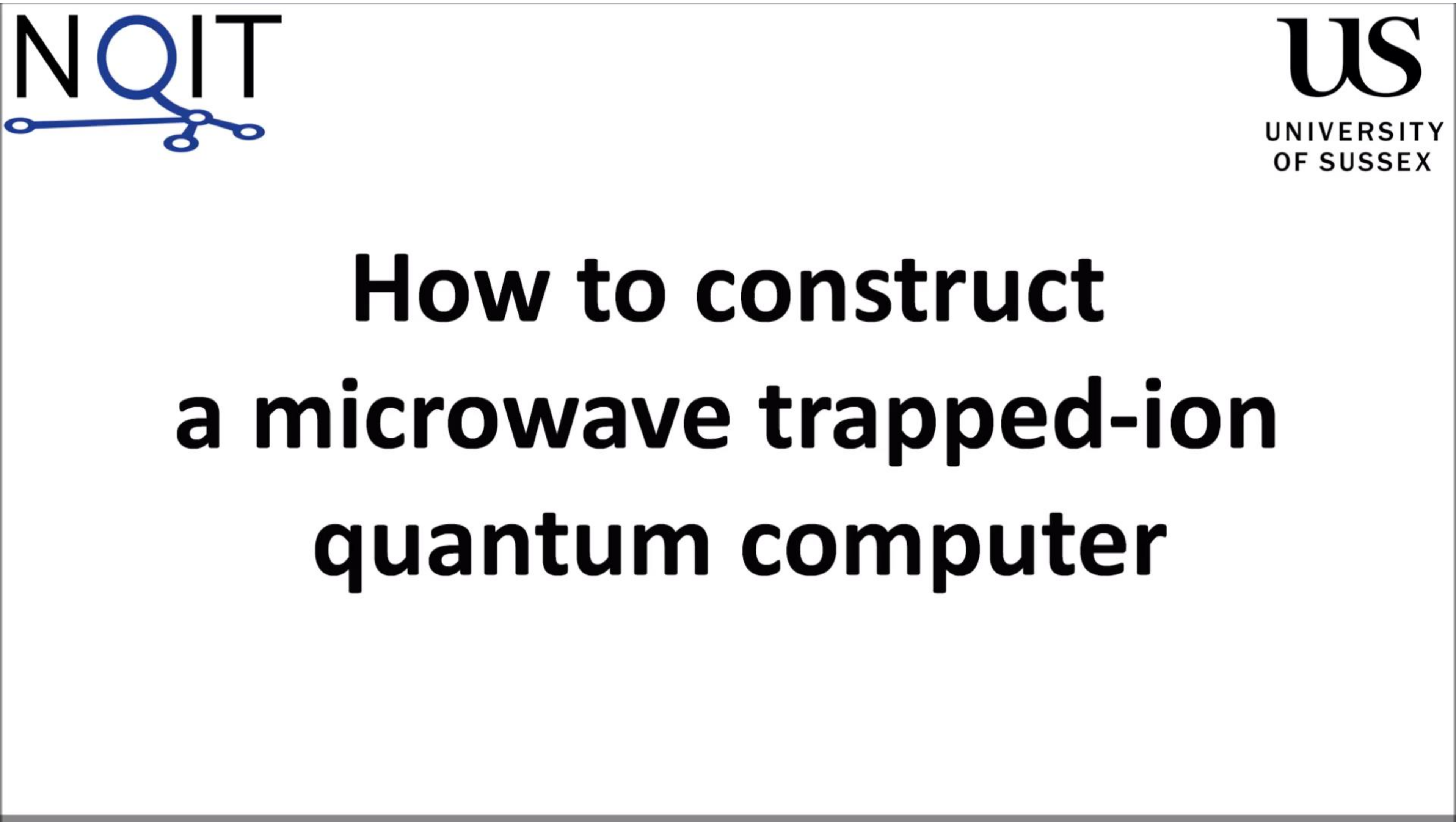
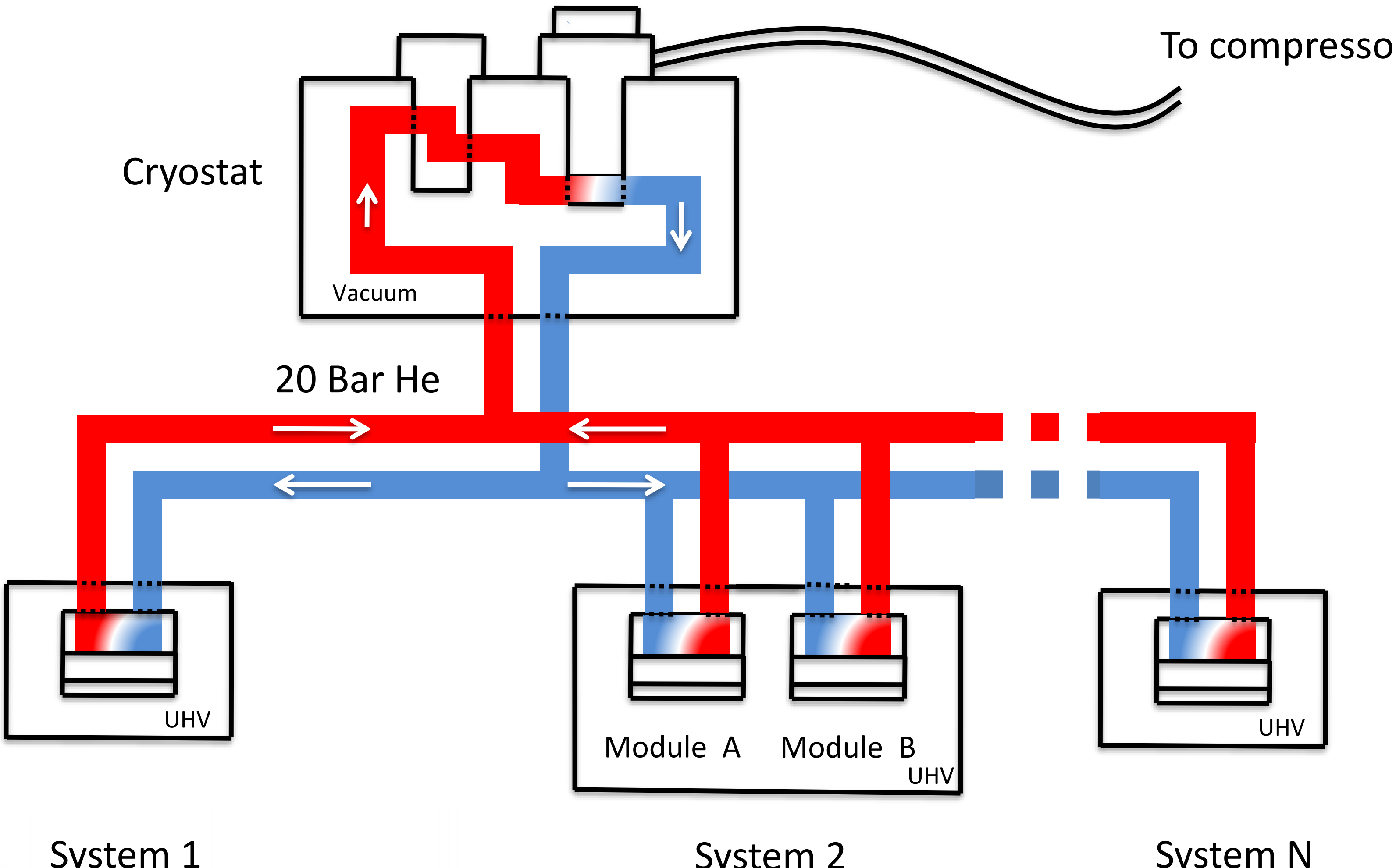
How to construct a large scale quantum computer



Scalable helium gas circulation system for 70K operation



Cooling system is required to cool relevant classical electronics

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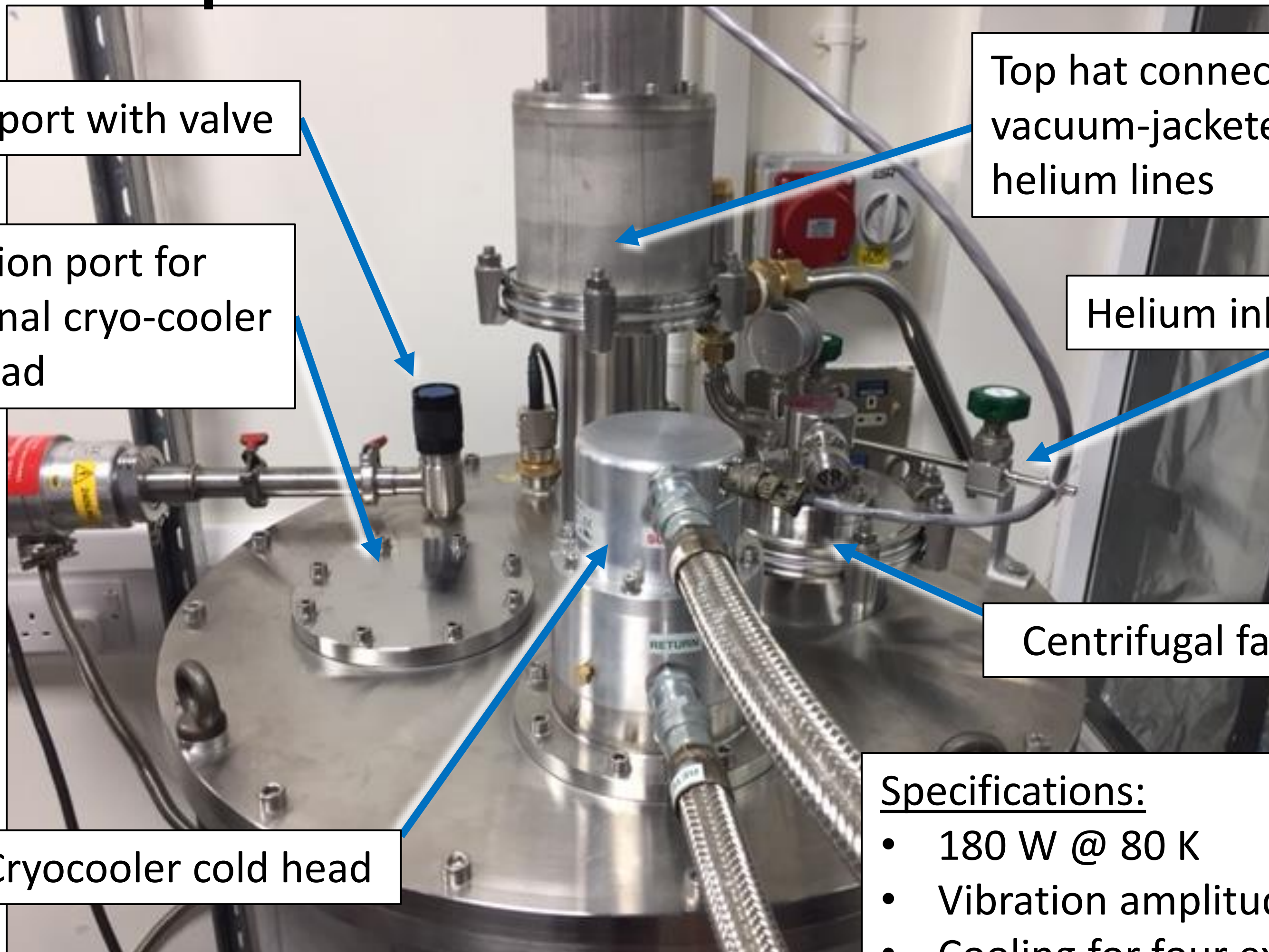
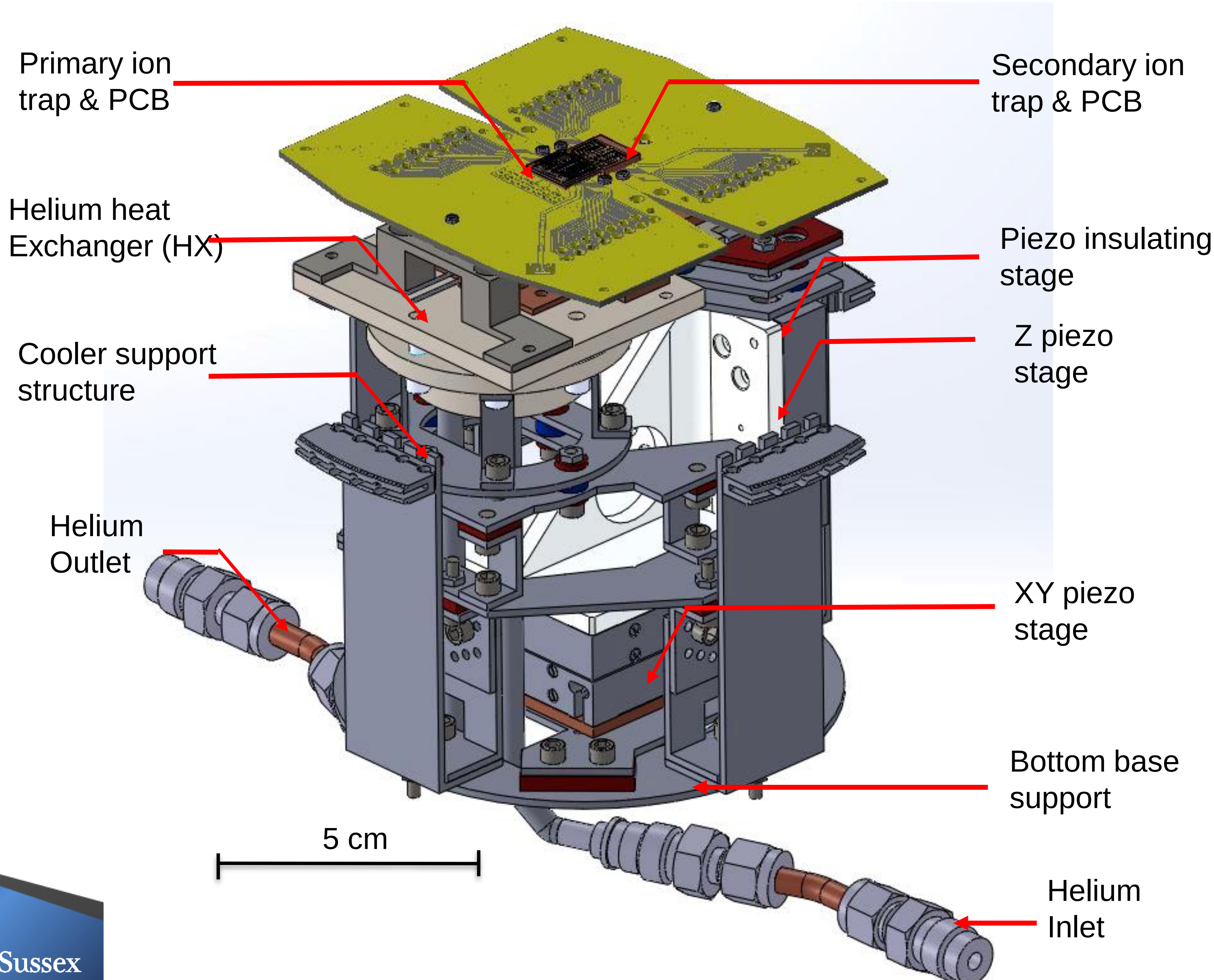
Scalable helium gas circulation system for 70K operation



Specifications:

- 180 W @ 80 K
- Vibration amplitude < 100 nm
- Cooling for four experiments

Two module alignment mechanics



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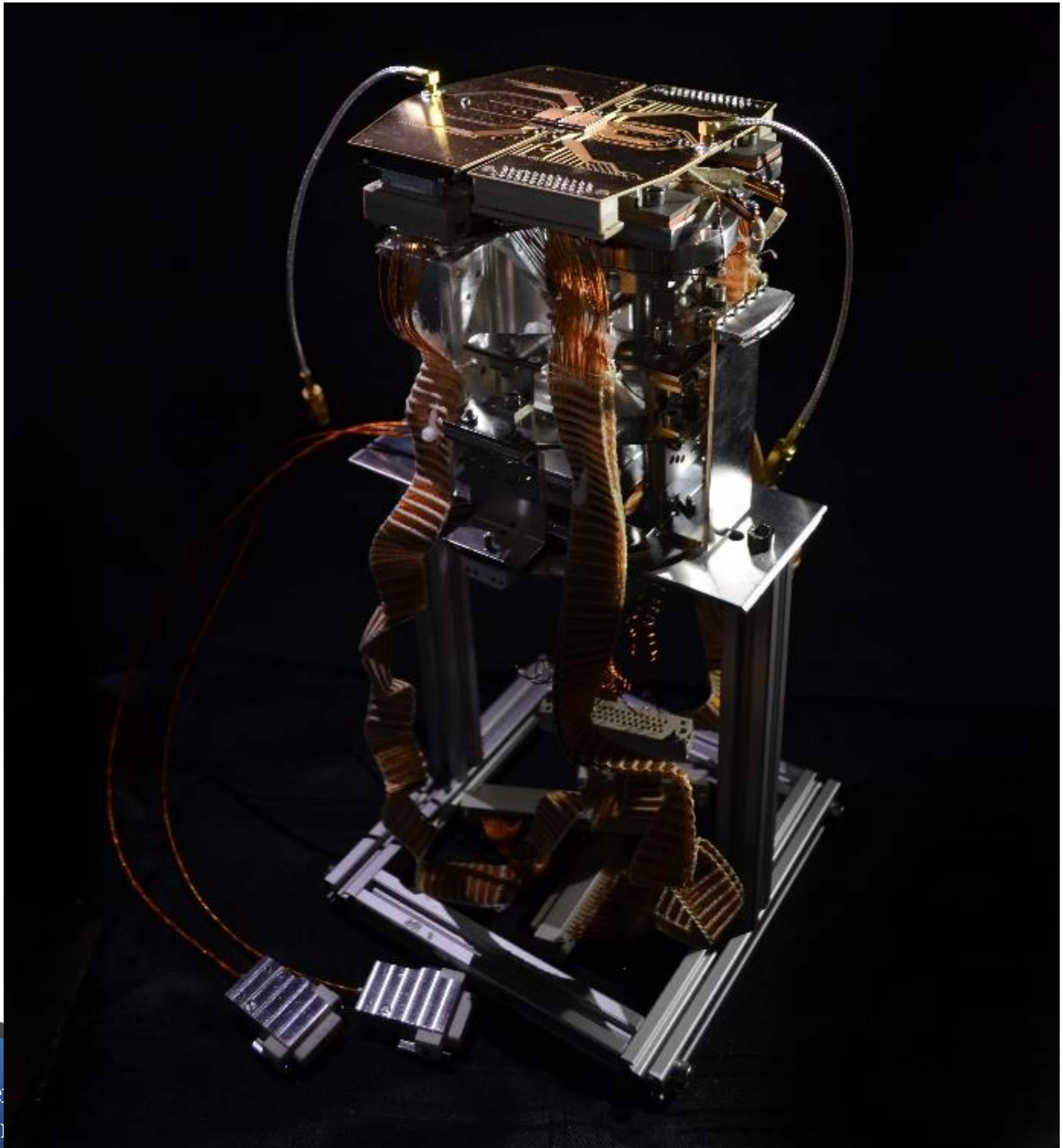

The prototype

How are we going about building practical quantum computers?

Universal Quantum
a new quantum computing company

- Universal Quantum is a quantum computing company with a mission to develop practical commercial large scale quantum computers based on trapped ions

- Complimentary to work carried out in research group

- We are looking for talent across a wide range (quantum physics, engineering, software…).
  - Please get in touch if you are interested: sebastian@universalquantum.com

So what do we know?

- It is possible to build a quantum computer with trapped ions
- However, still highly challenging with lots of engineering required and at a significant cost.
- Time scales:
  - Demonstrator device constructed at Sussex (6 months)
  - Large scale universal quantum computer (10+ years)
- Quantum computers will transform science and society
- Quantum computing hardware development is no longer confined to academia