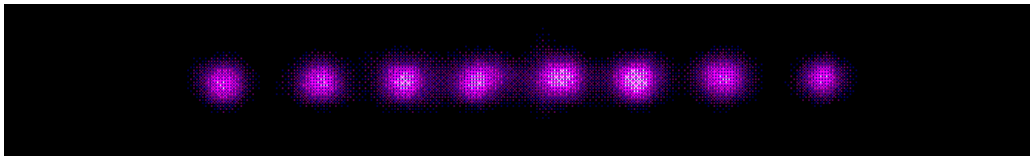
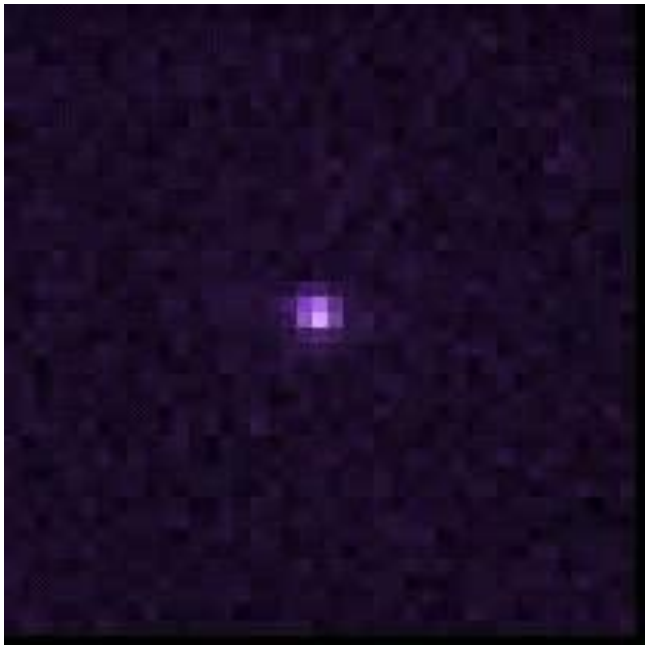
Quantum logic with trapped-ion qubits

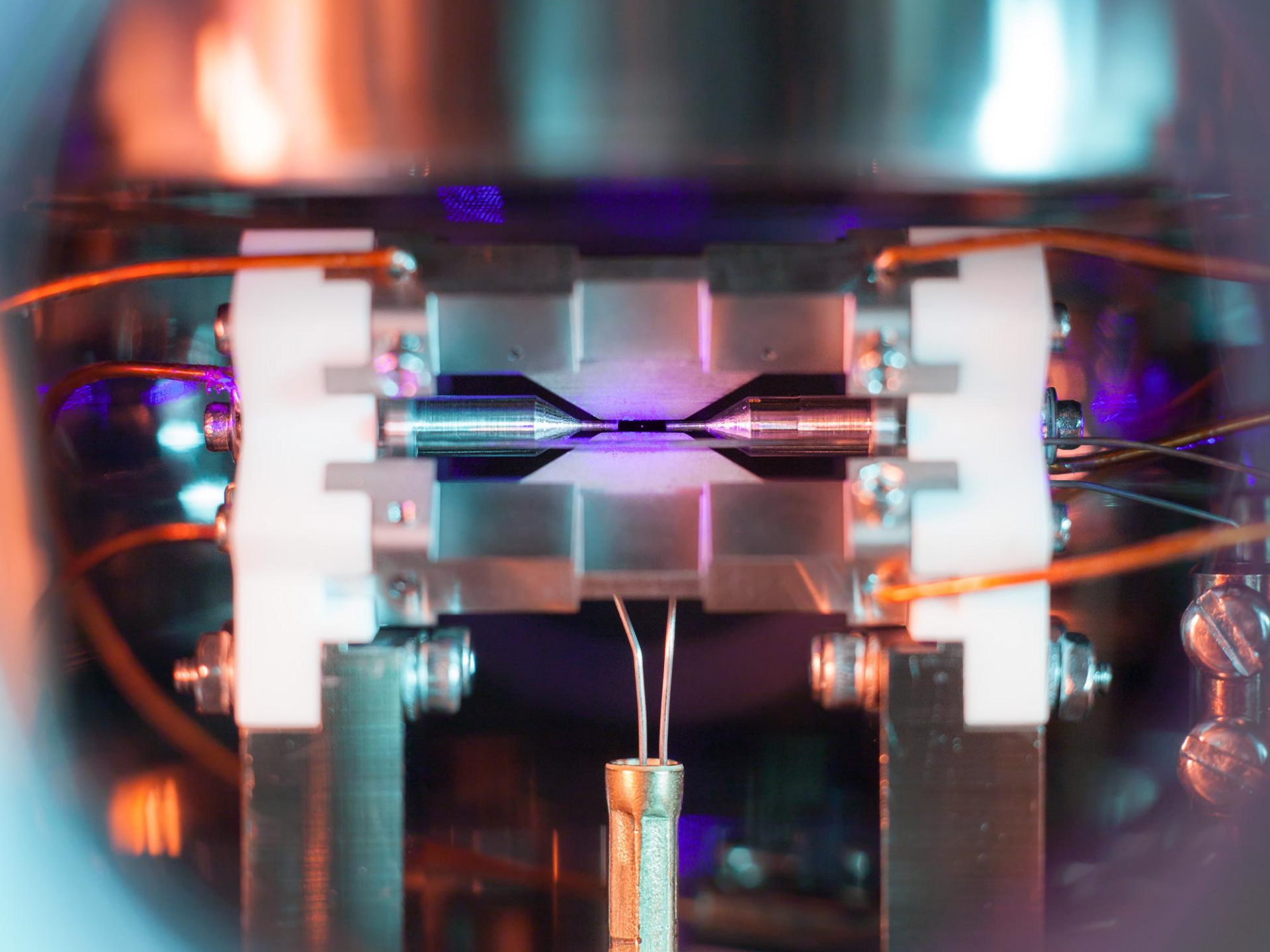
David Lucas

Clarendon Laboratory & Balliol College
Oxford University



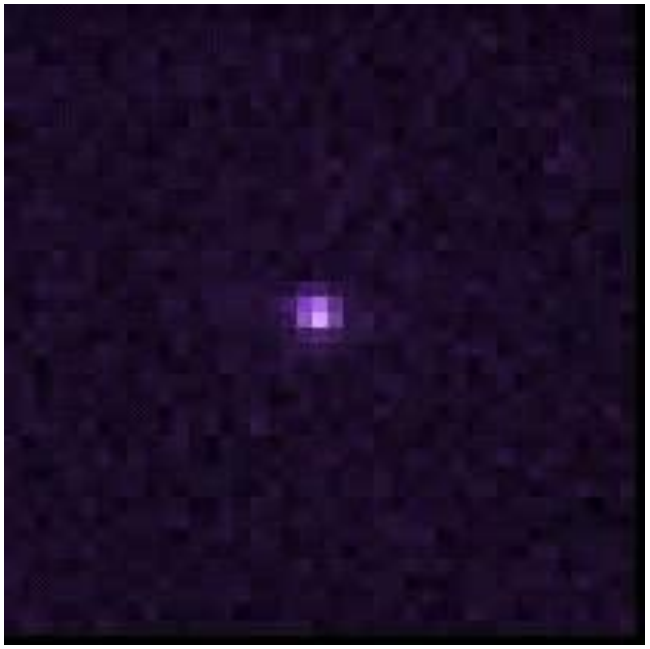
www.physics.ox.ac.uk/users/iontrap





A quantum bit ("qubit")

- single $^{40}Ca^{+}$ ion
- confined in an ion trap
- laser-cooled to <0.001K



$^{40}Ca^{+}$ ground state:
$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^1$

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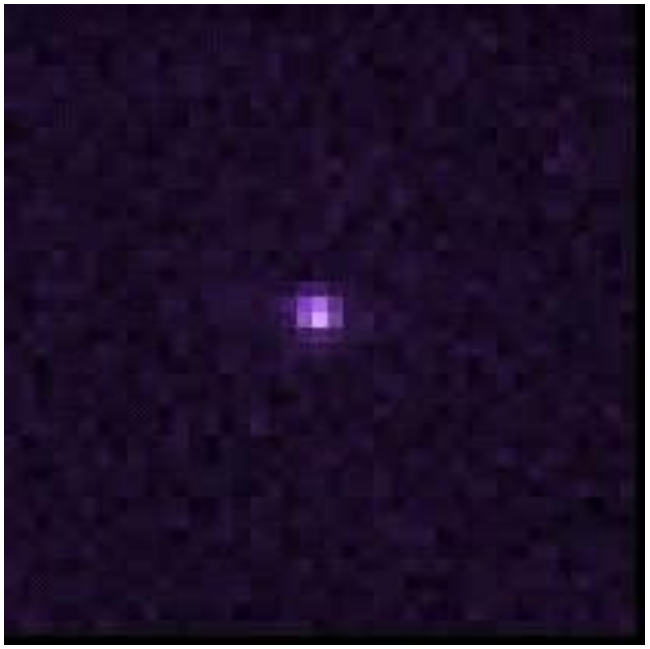

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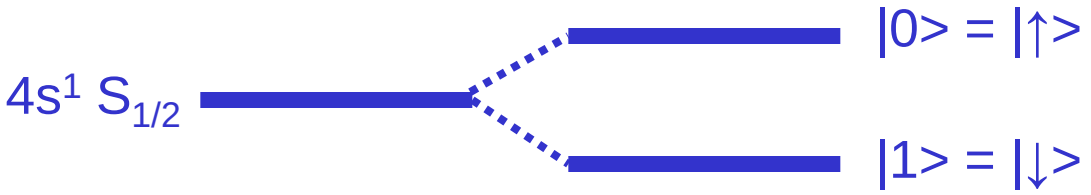

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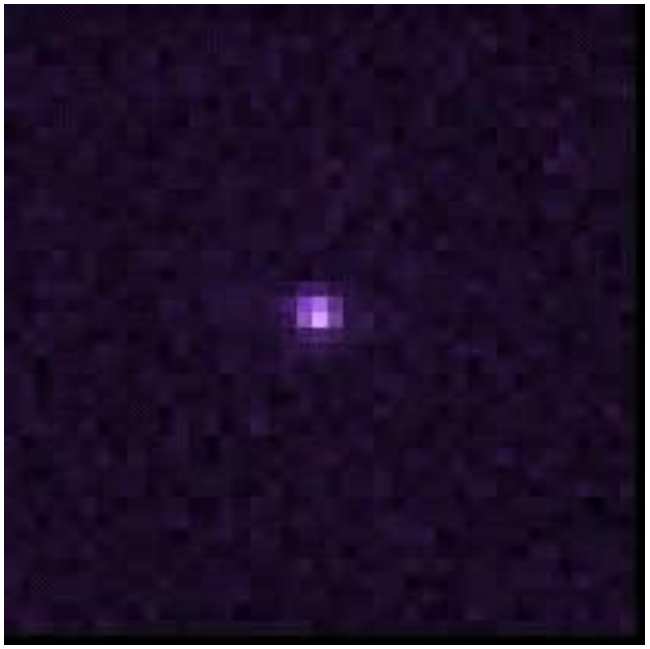

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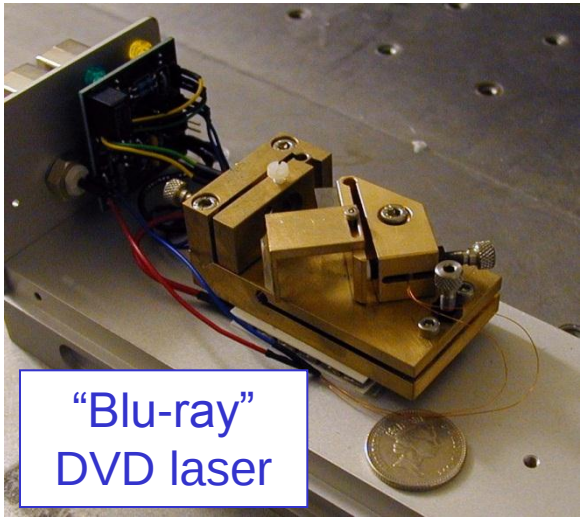

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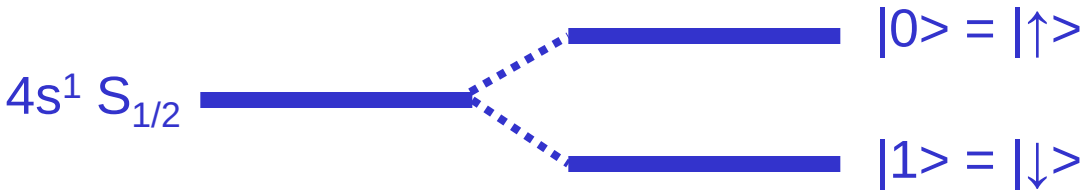
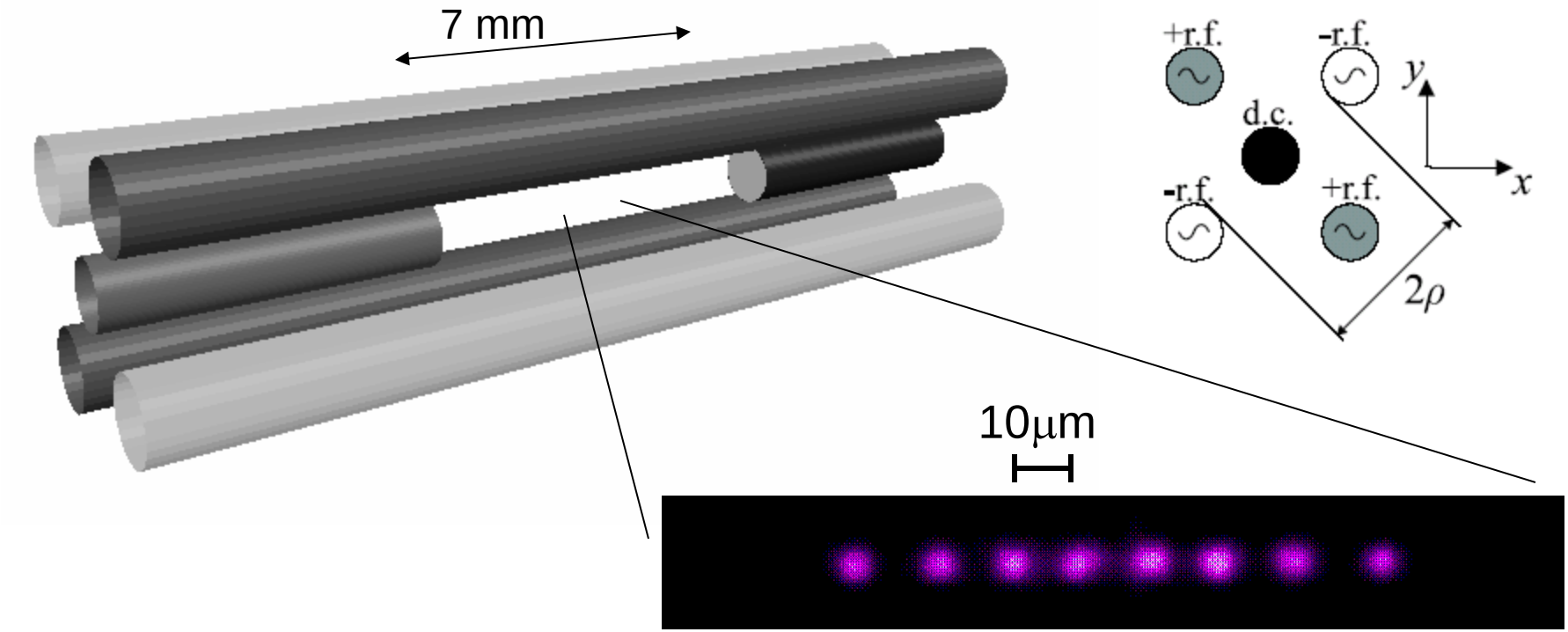
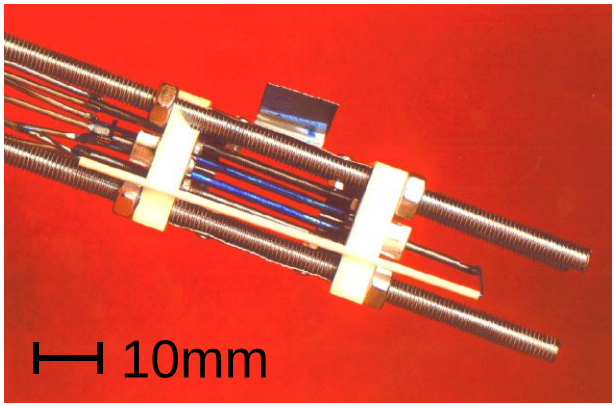


Ion trap "quantum abacus"



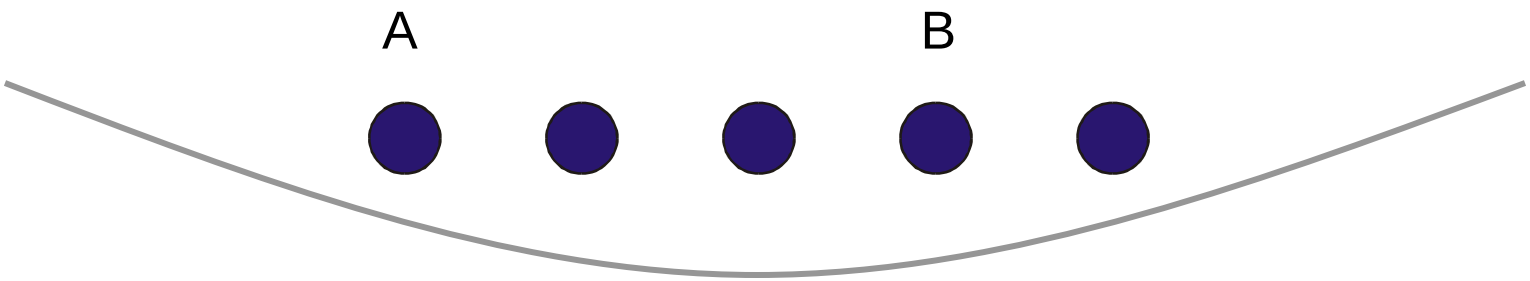


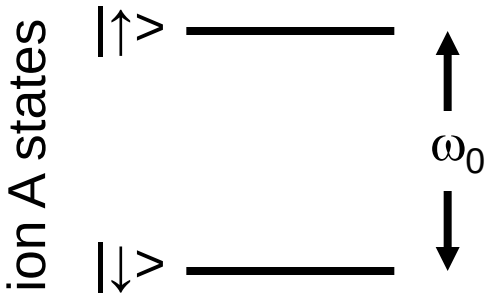
ion-electrode distance = 1.2 mm
motional frequencies ~ 1 MHz

Real atoms!

Quantum logic gate

"Controlled-NOT" gate:
flip ion B between states $|\uparrow\rangle \leftrightarrow |\downarrow\rangle$
if and only if ion A is in state $|\uparrow\rangle$





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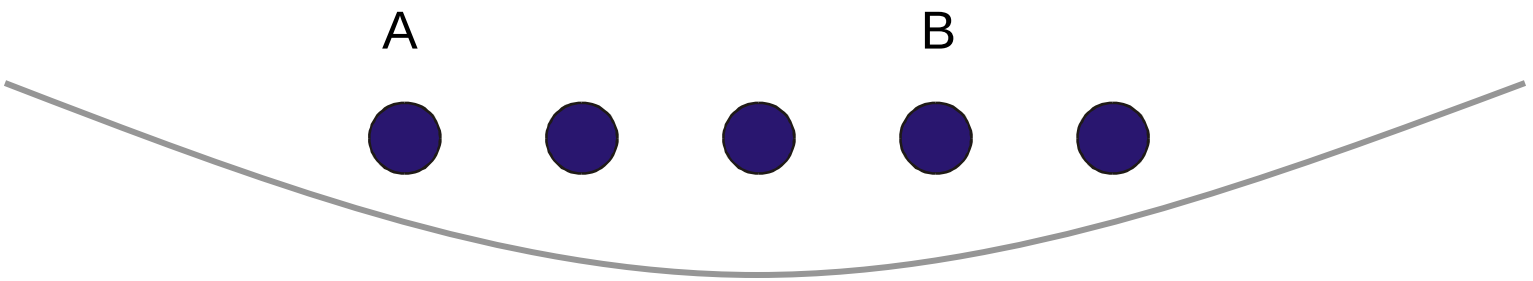

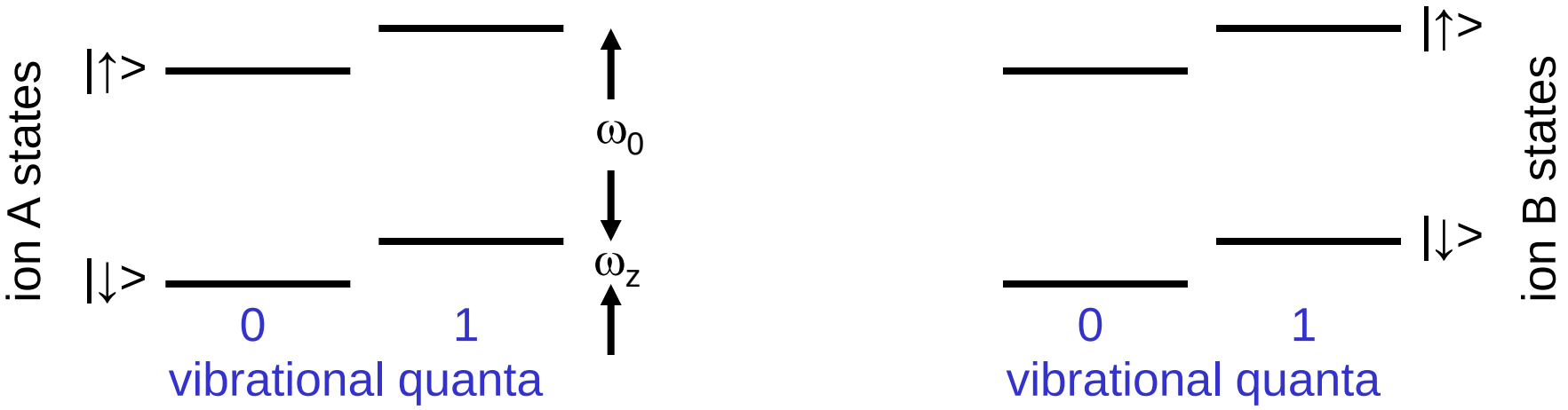

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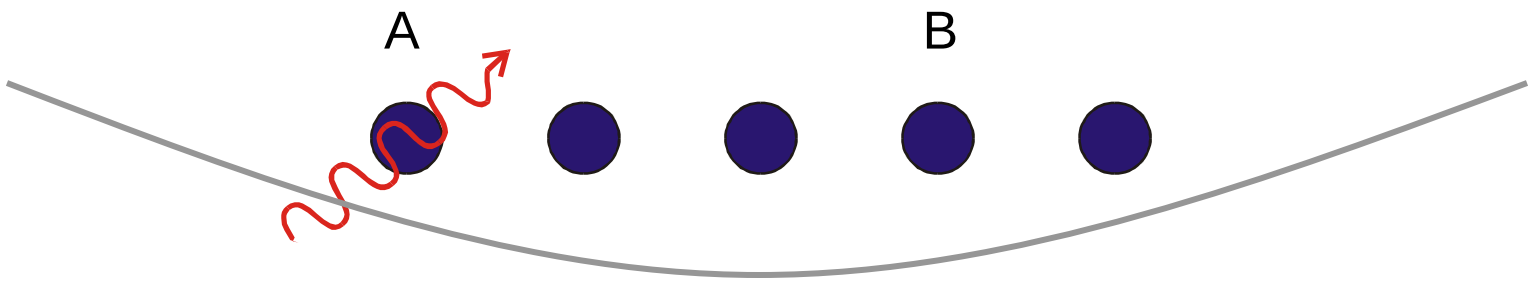
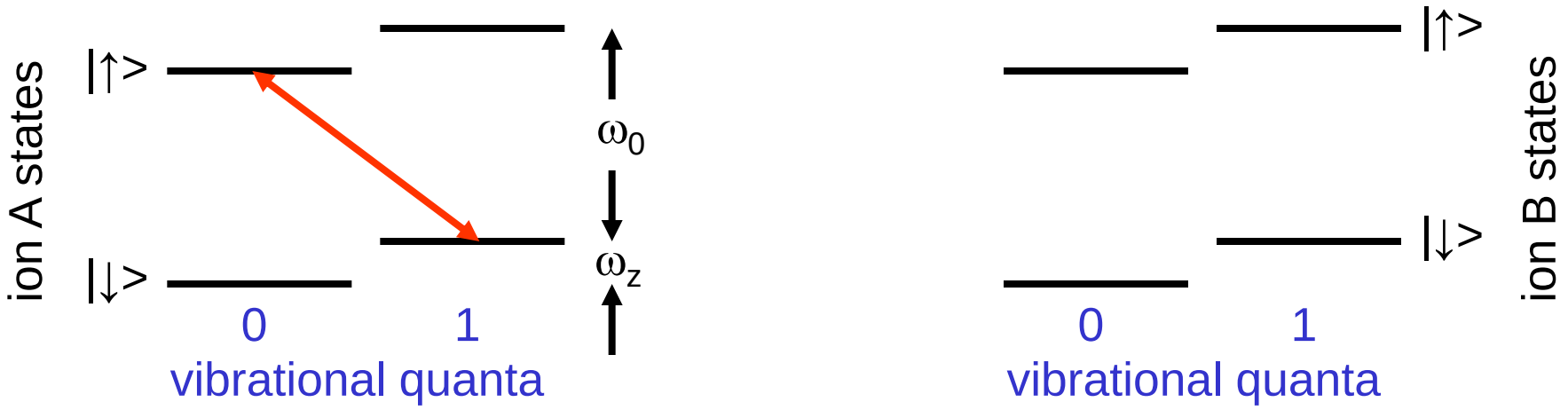


STEP (i): ω_0-ω_z



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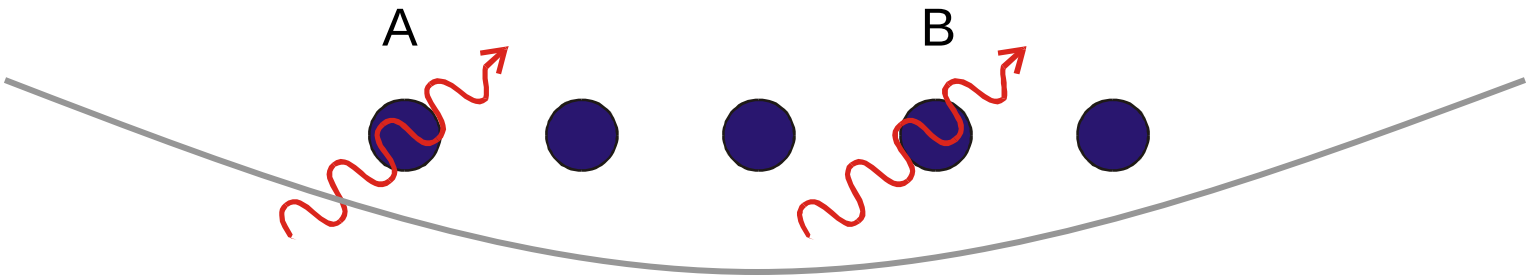
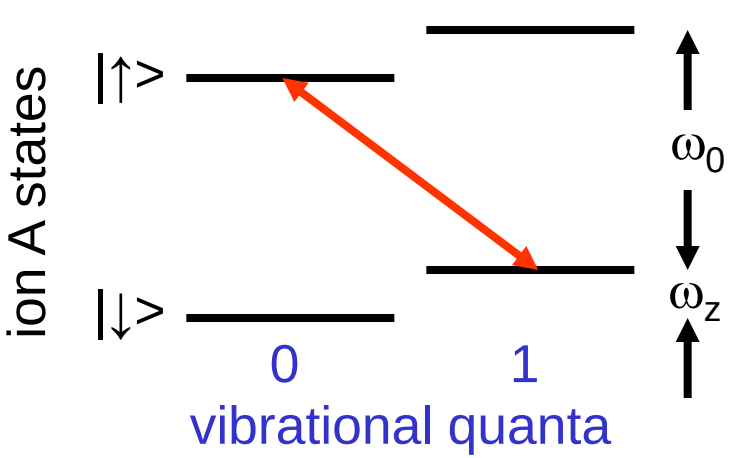
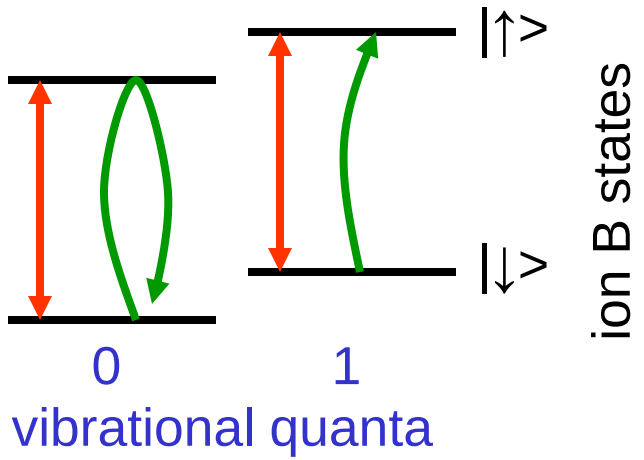


STEP (i): ω_0-ω_z

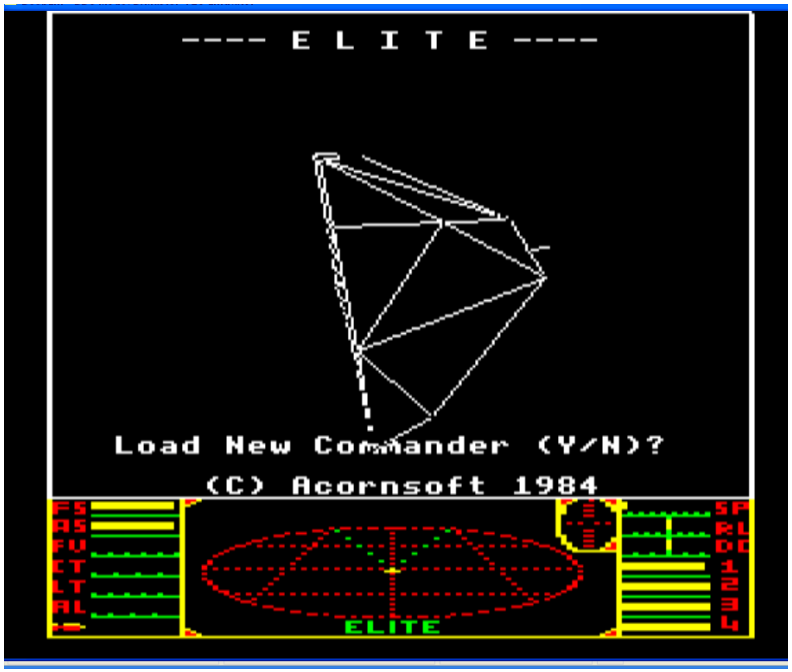
STEP (ii): ω_0





A bit of history

1985 Idea of quantum computer (Deutsch, Oxford; Feynman, Cal.Tech.)

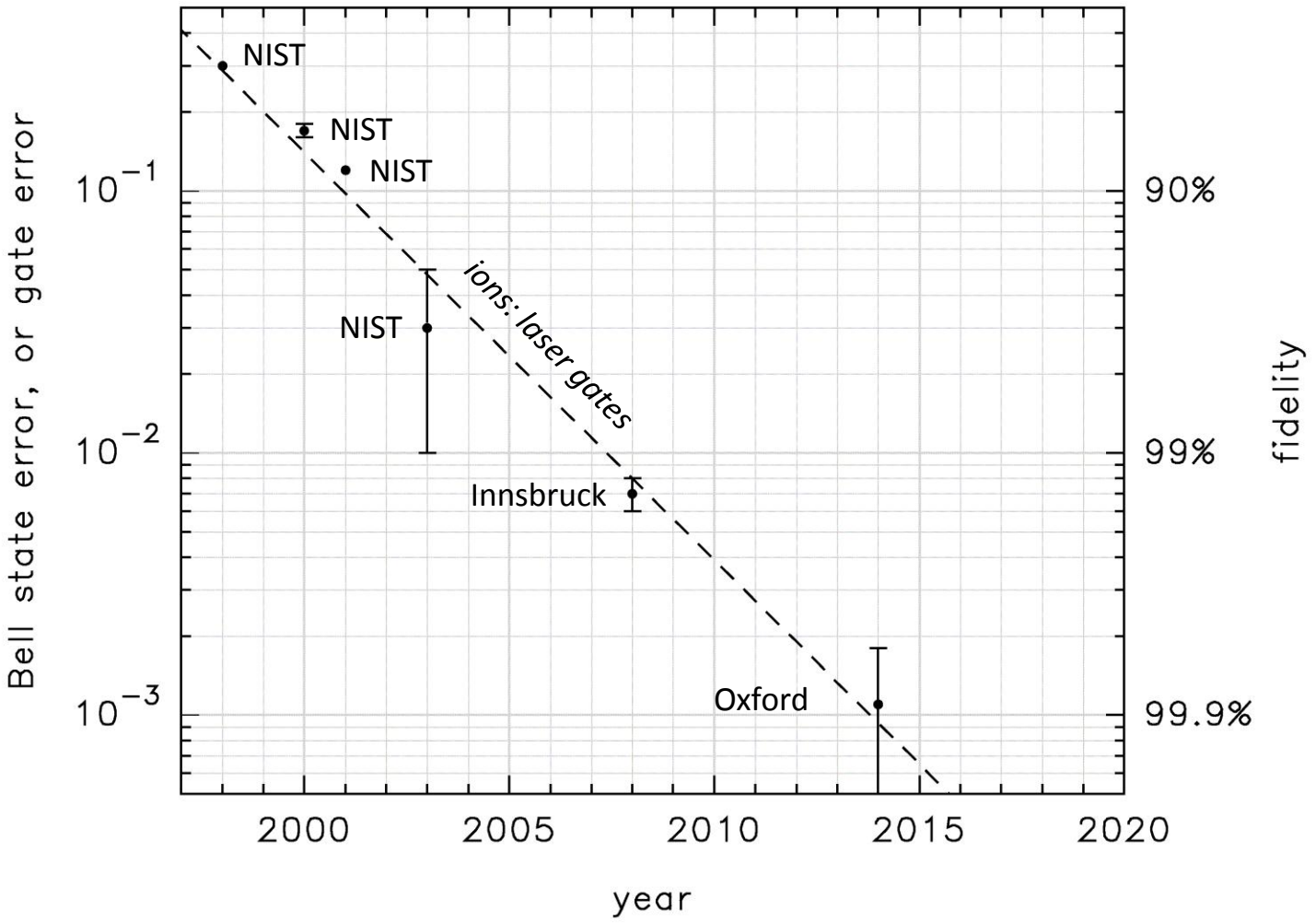


BBC microcomputer 1984

32 kbytes RAM
2 MHz clock speed

1995 Quantum error-correction invented (Shor, IBM; Steane, Oxford)
1998 First quantum logic gate demonstrated (Wineland group, NIST)

History of 2-qubit logic gates



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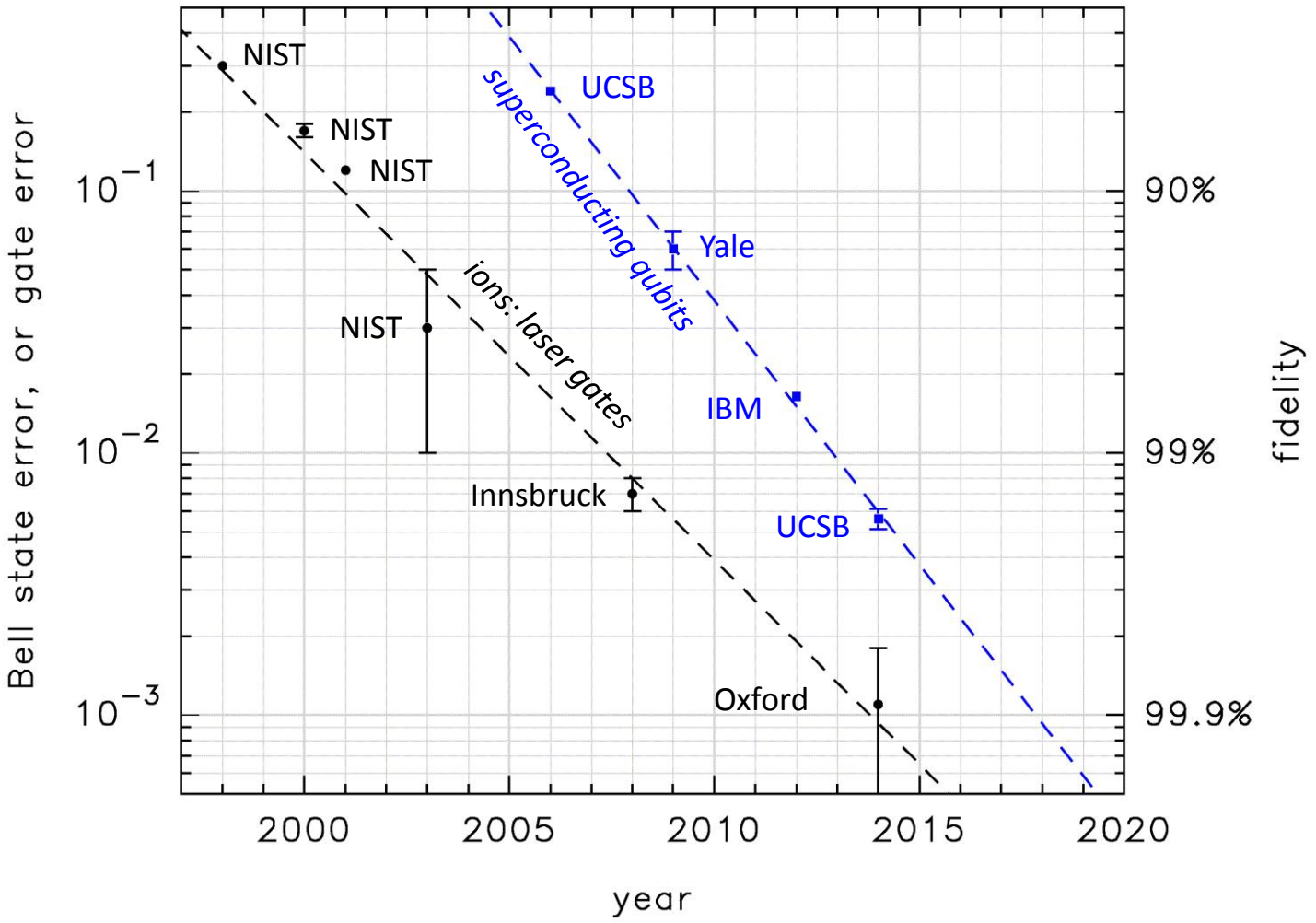

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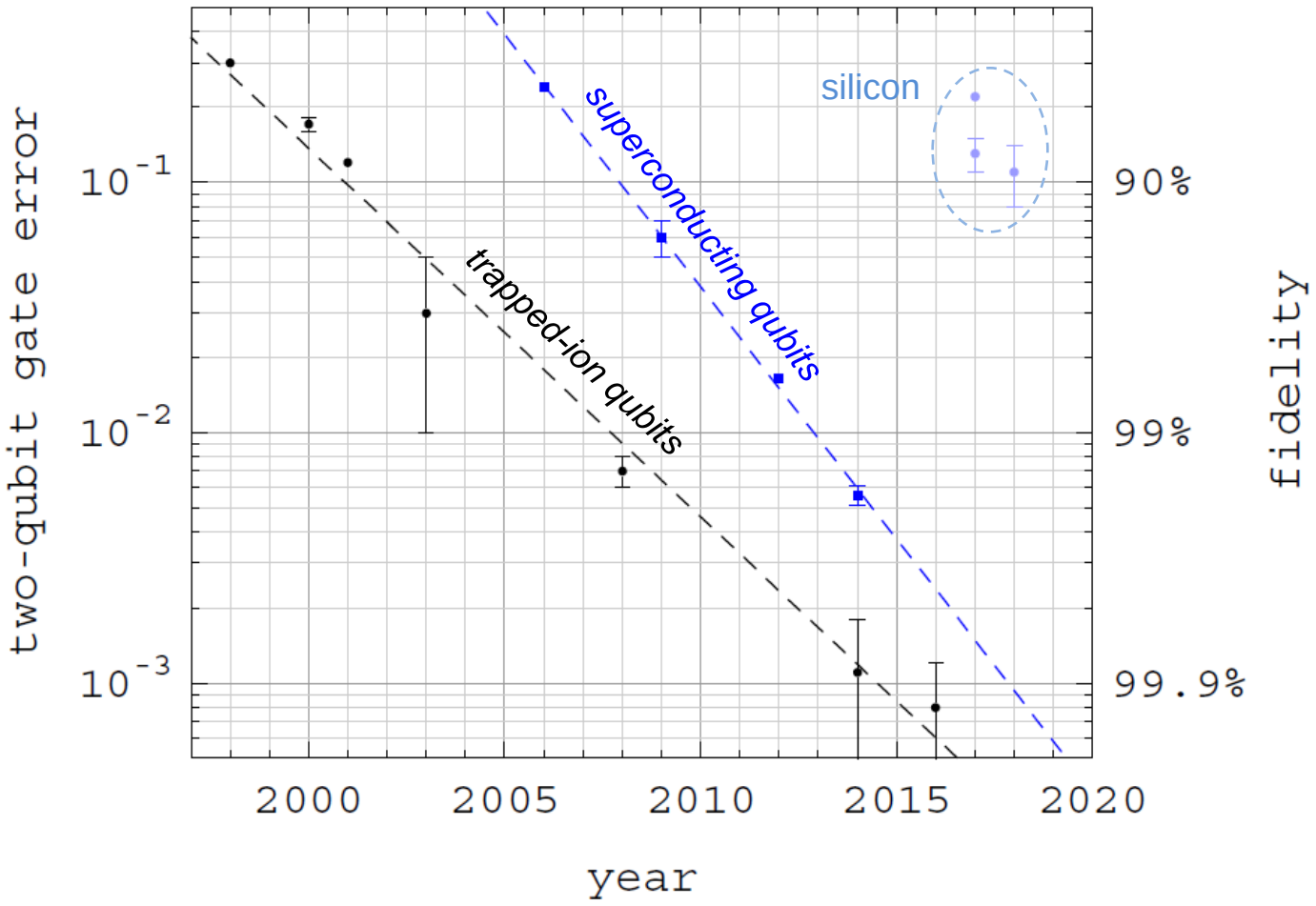
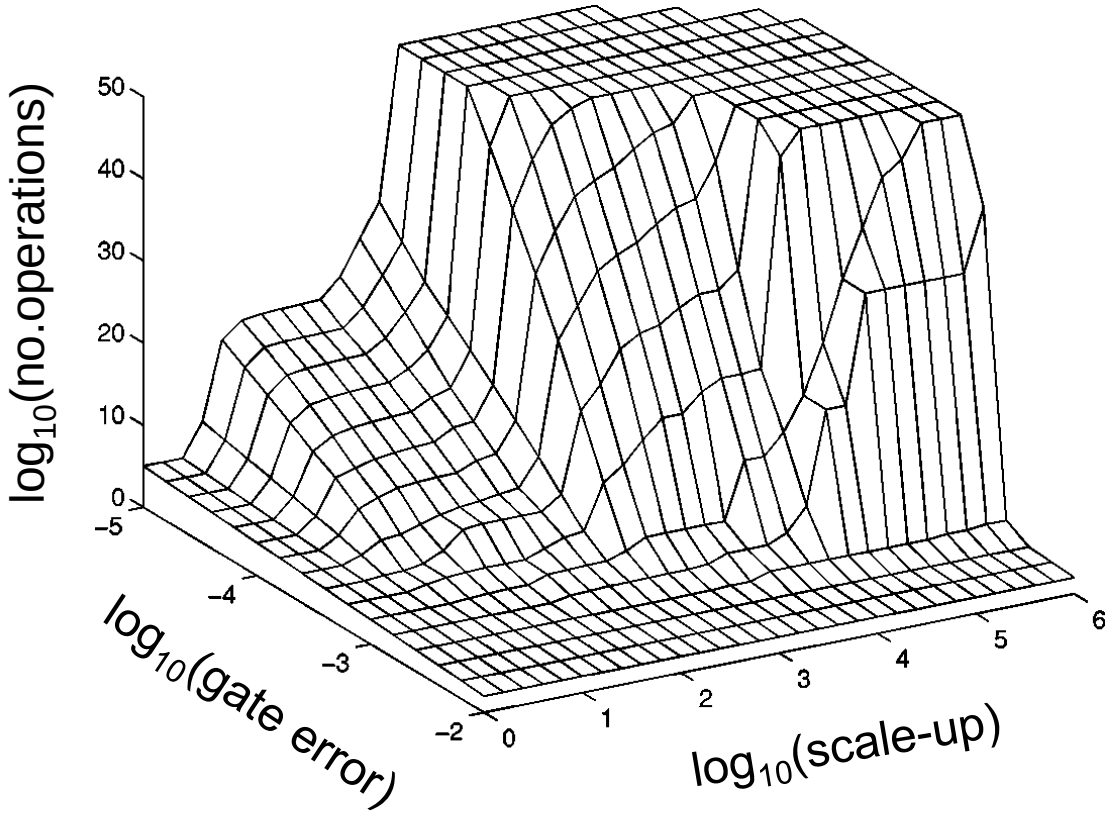


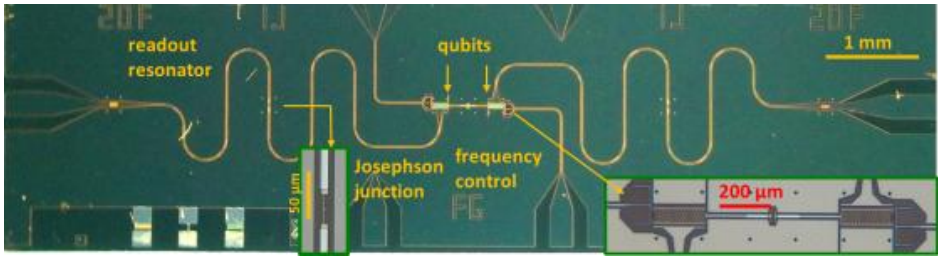
The challenge: quantum error correction

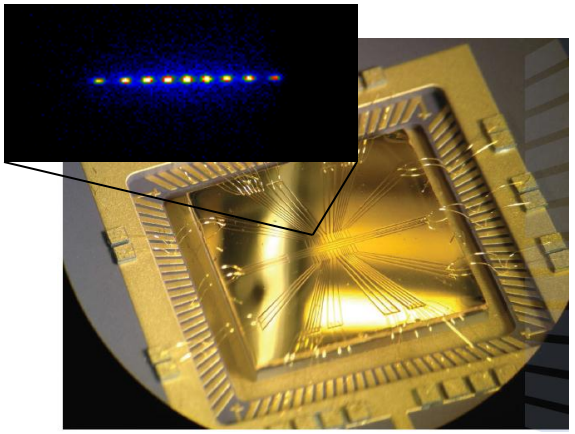


Overhead and noise threshold of fault-tolerant quantum error correction,
A.M.Steane, PRA 2003

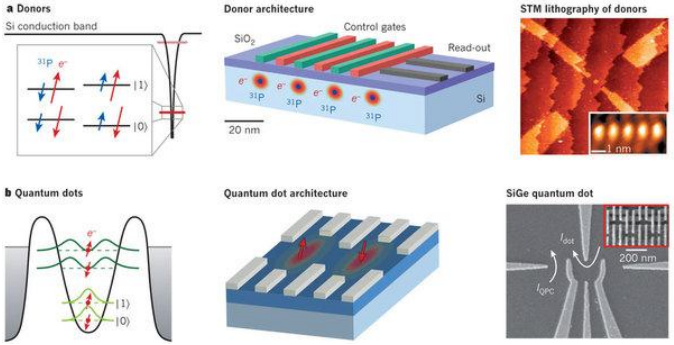
Example qubit hardware platforms

superconducting circuits

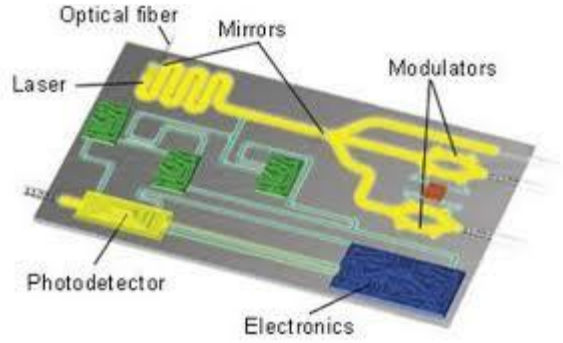




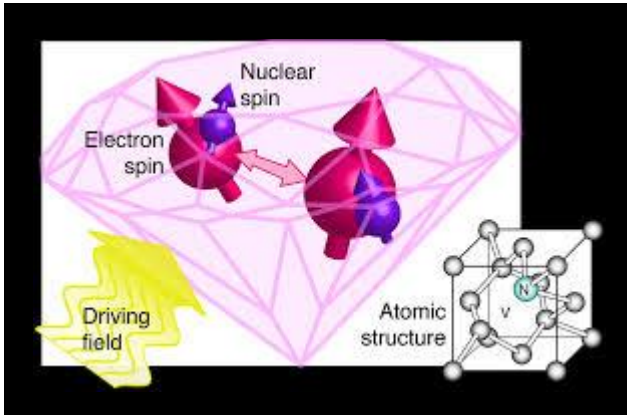
ion traps



electronic
semiconductor
qubits



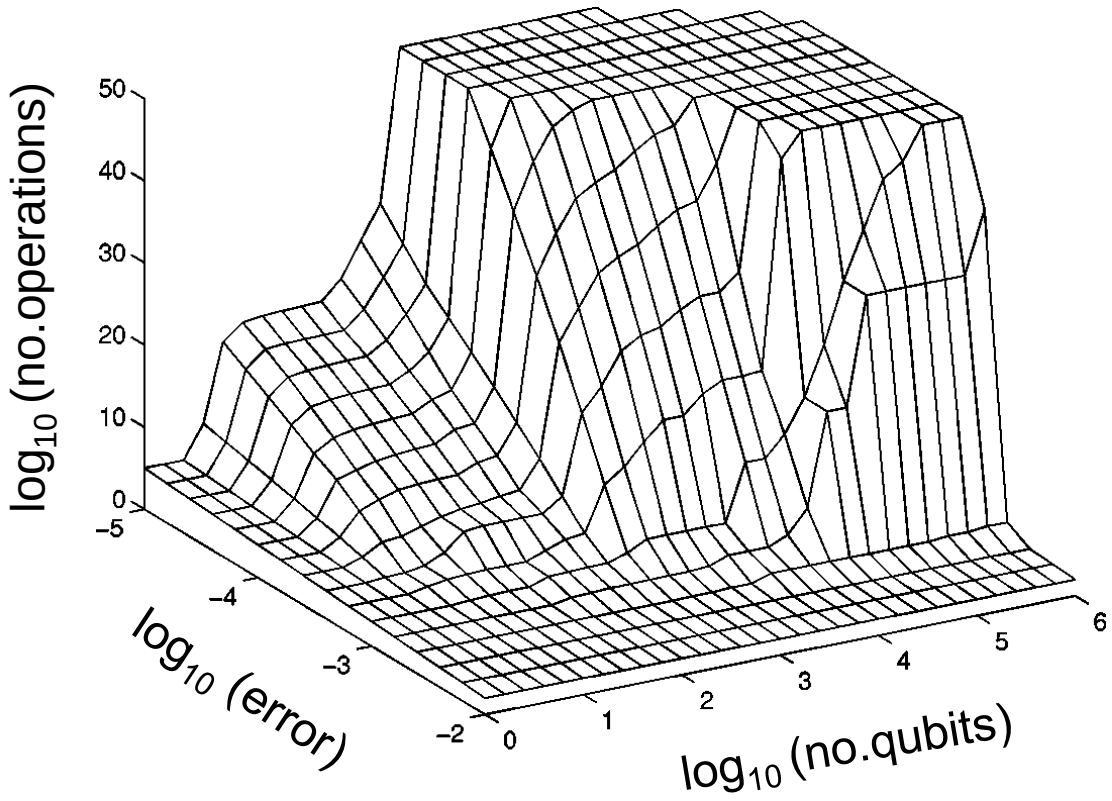
linear optics



impurity spins
in solids
(e.g. NV centres)

blue: *usually* cryogenic
red: *usually* room temp.

Some examples of state-of-the-art



- superconducting circuits (cryo.)
- semiconductor qubits (cryo.)
- trapped ions (room temp.)

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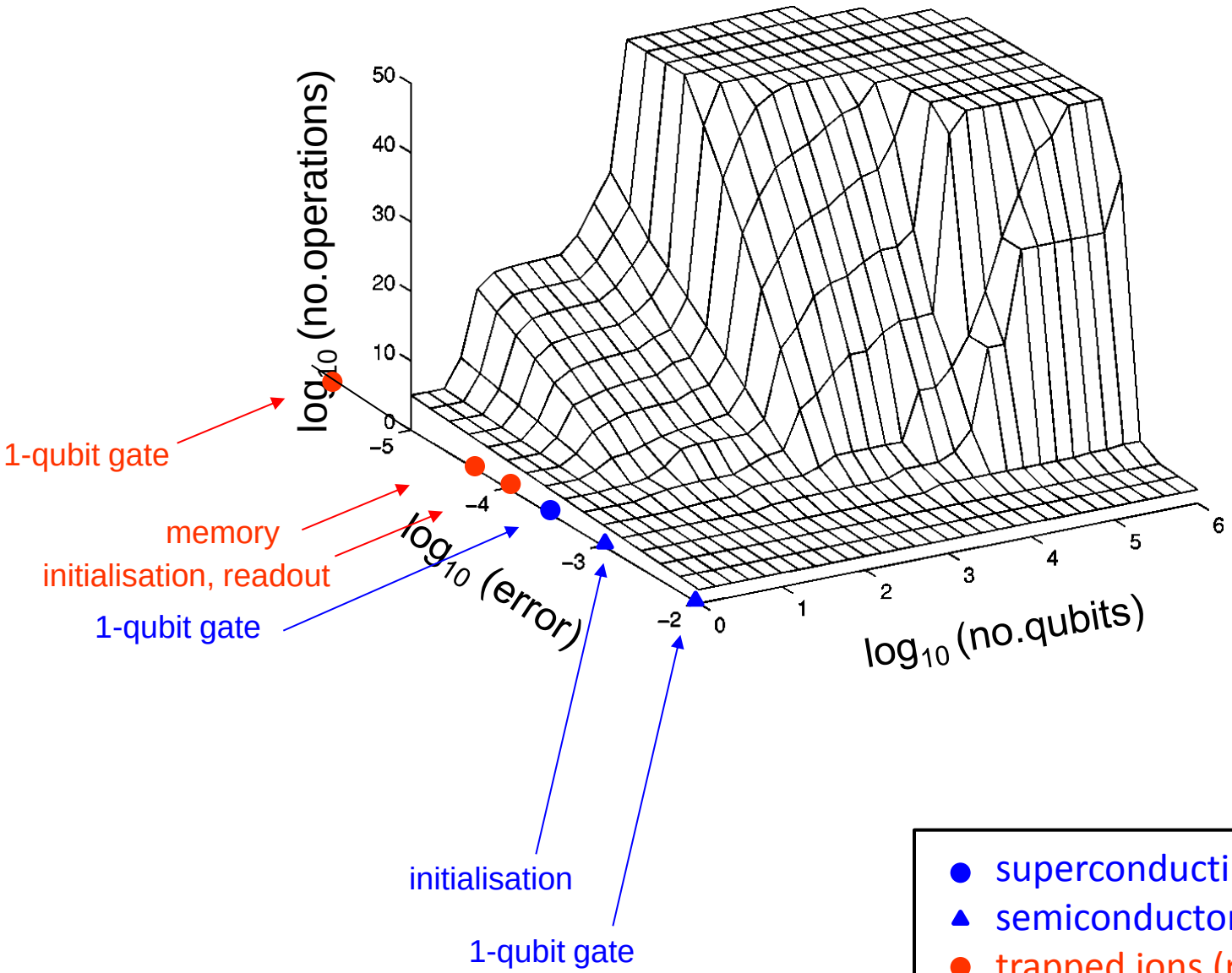

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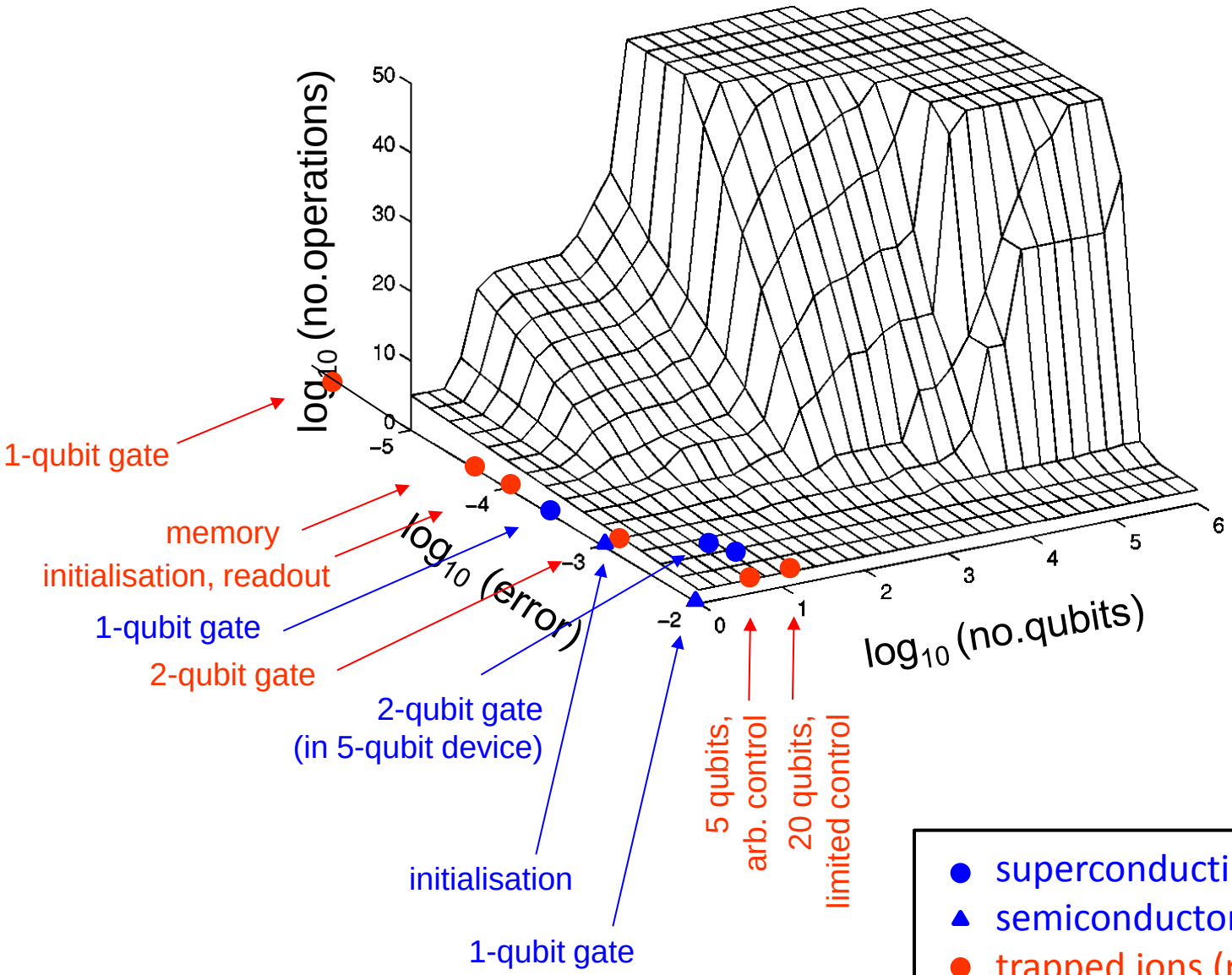
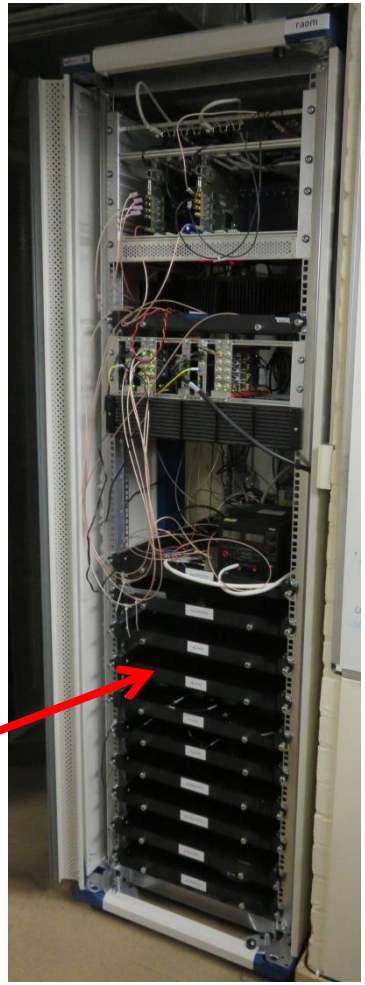
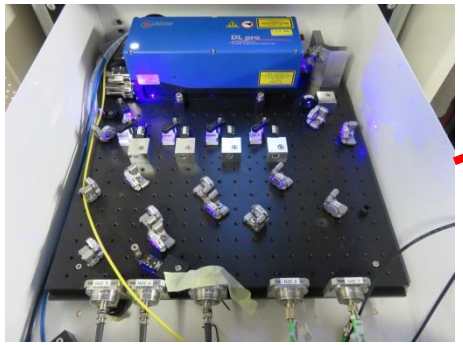


Meanwhile, in the basement…

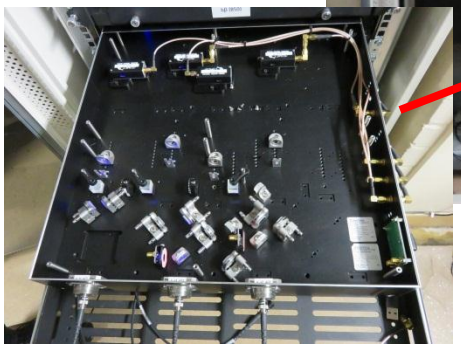
OLD: “traditional” optical table laser setup

NEW: rackmount laser system



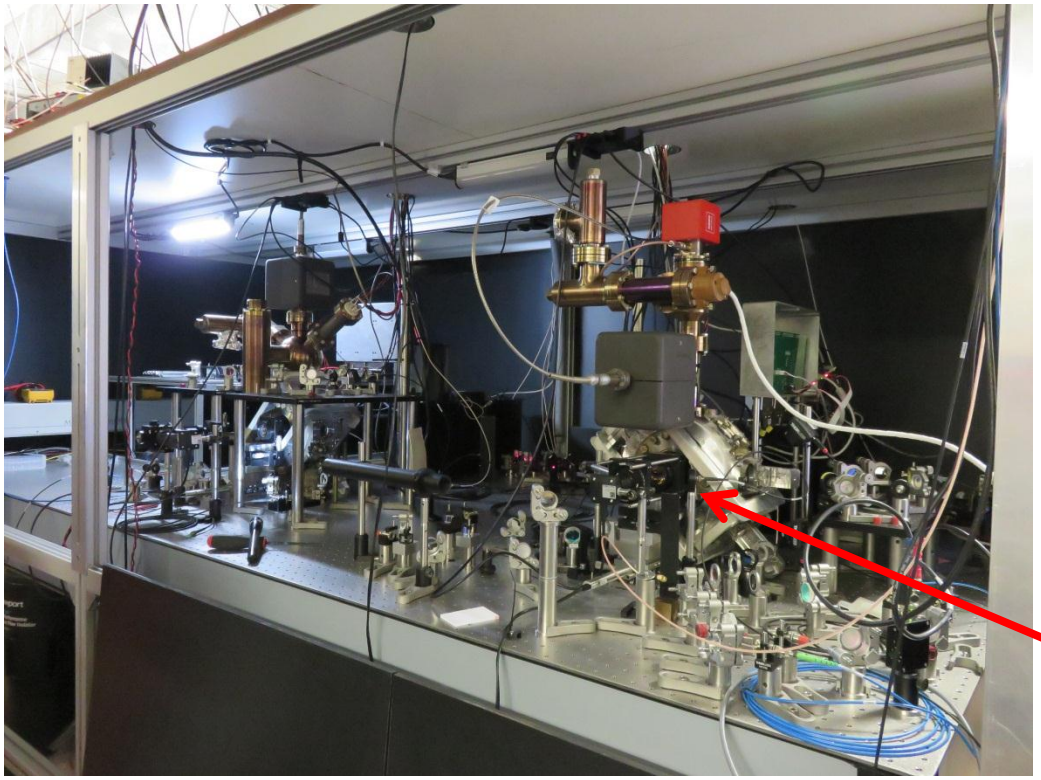


laser subsystem



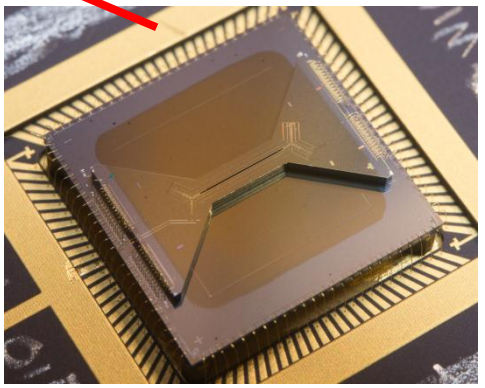
AOM subsystem

Optically-linked ion traps



Node #2 “Bob”

Node #1 “Alice”



HOA-2 surface trap
(Sandia National Labs, USA)