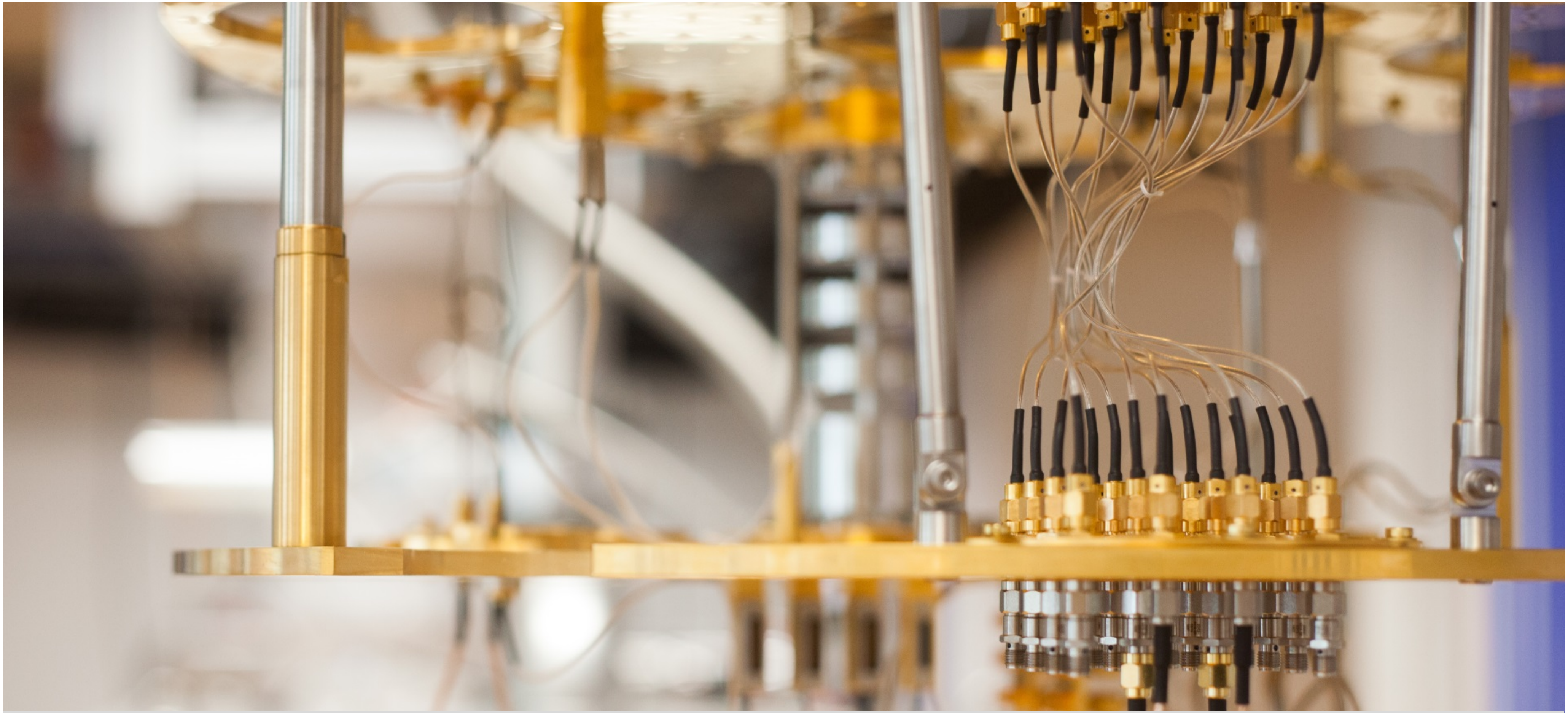


The Grand Challenge and Promise of Quantum Computing

GOTO Amsterdam 2019

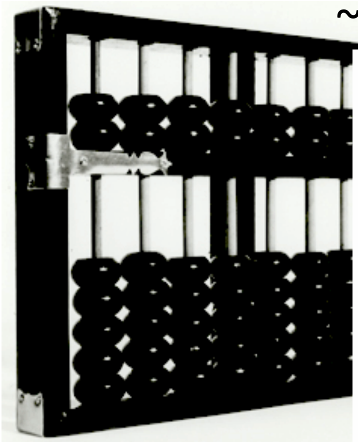
17-20 June 2019

Lieven Vandersypen

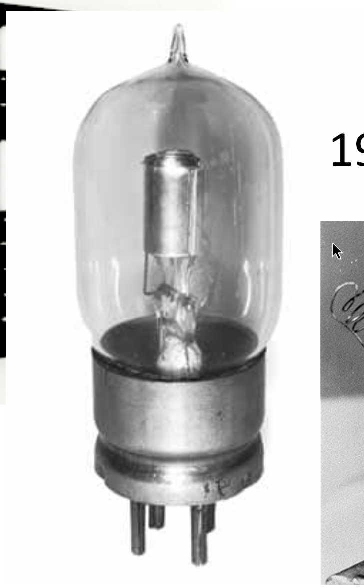
TU Delft
Delft University of Technology
QUTech
TNO
intel
KAVLI INSTITUTE of Nanoscience Delft

The physics of computation

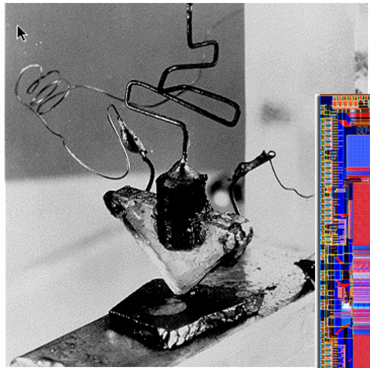
2500 BC abacus



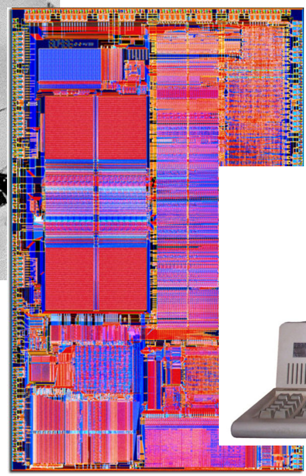
~1910 vacuum tube



1947 transistor



integrated circuit

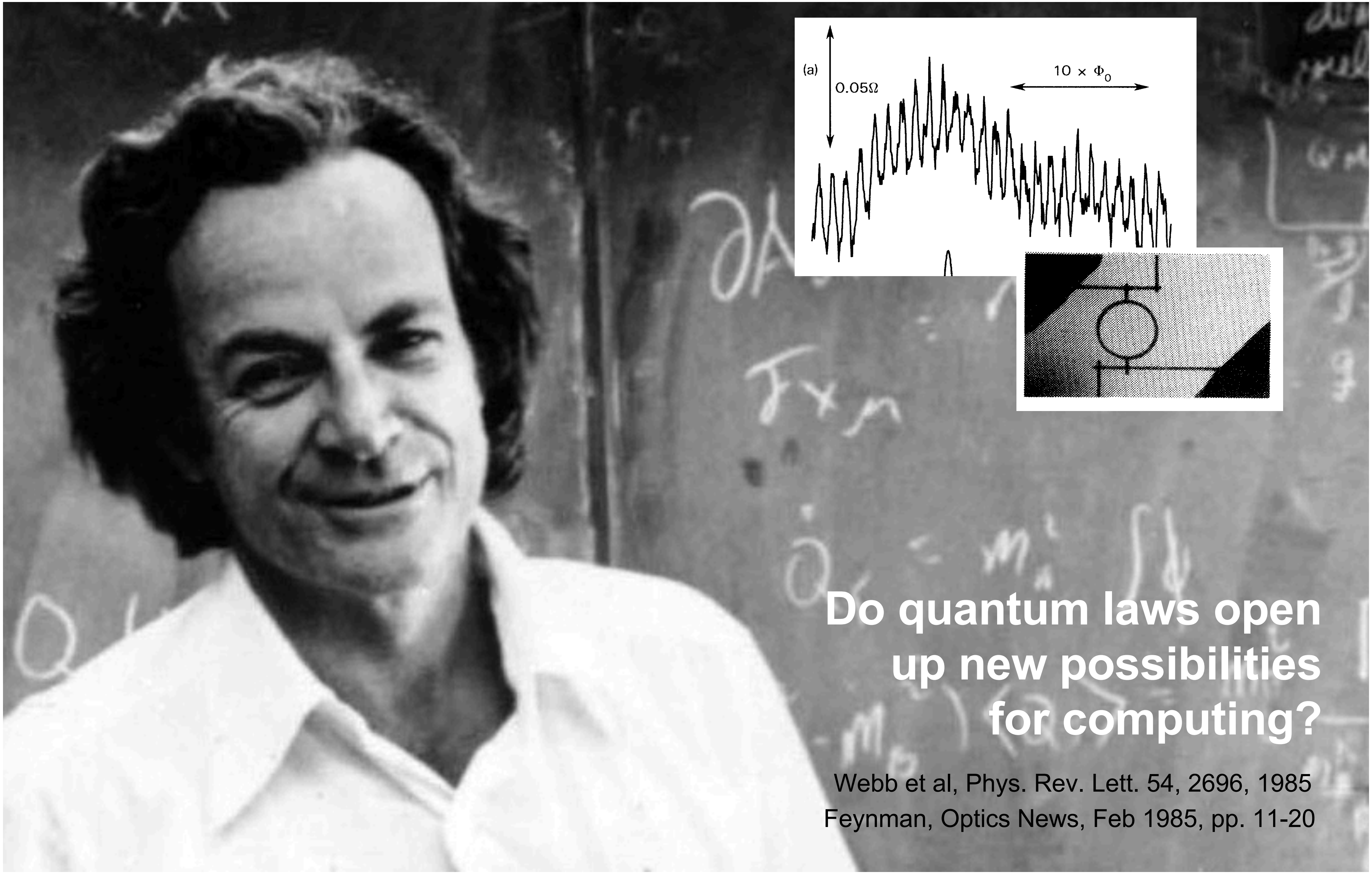


1980’s PC

Supercomputer

Classical bits (0 or 1)
Classical physics

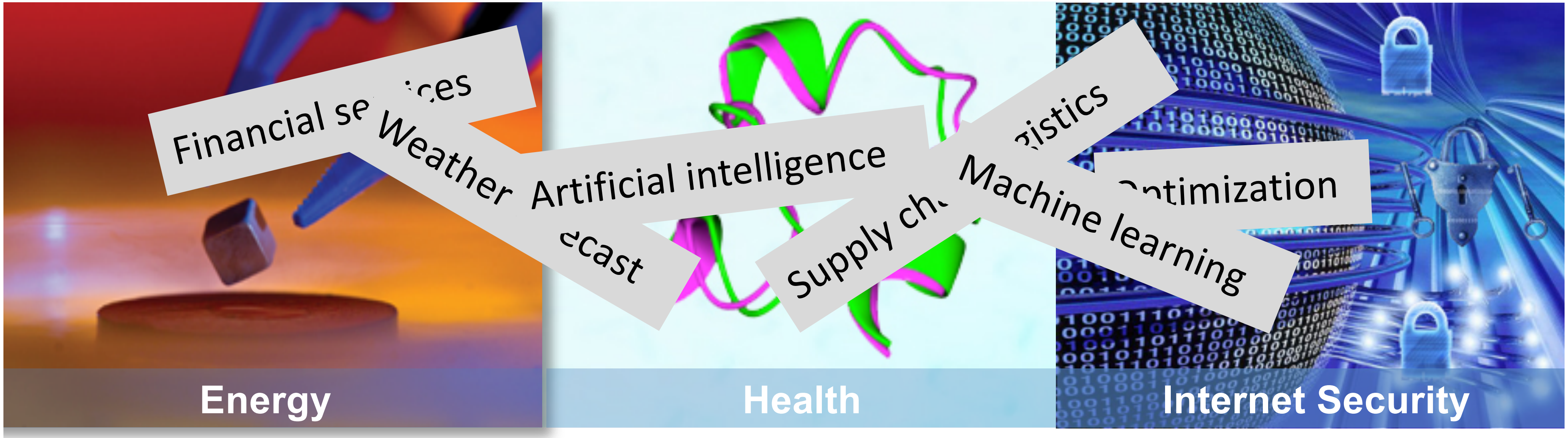
Can we do better?



Do quantum laws open up new possibilities for computing?

Webb et al, Phys. Rev. Lett. 54, 2696, 1985
Feynman, Optics News, Feb 1985, pp. 11-20

Far-reaching potential applications

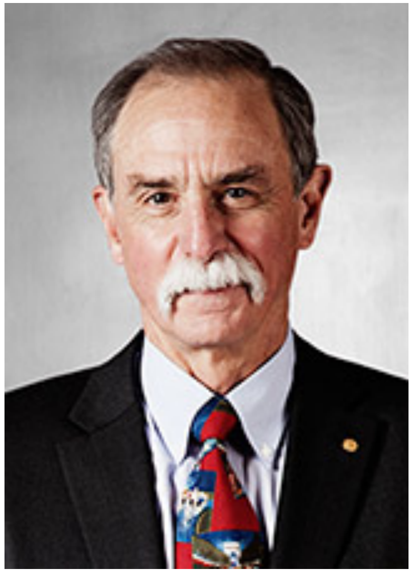


More on http://math.nist.gov/quantum/zoo/

“The quantum computer may change our everyday lives in this century in the same radical way as the classical computer did in the last century.” (Nobel citation 2012)

Controlling individual quanta

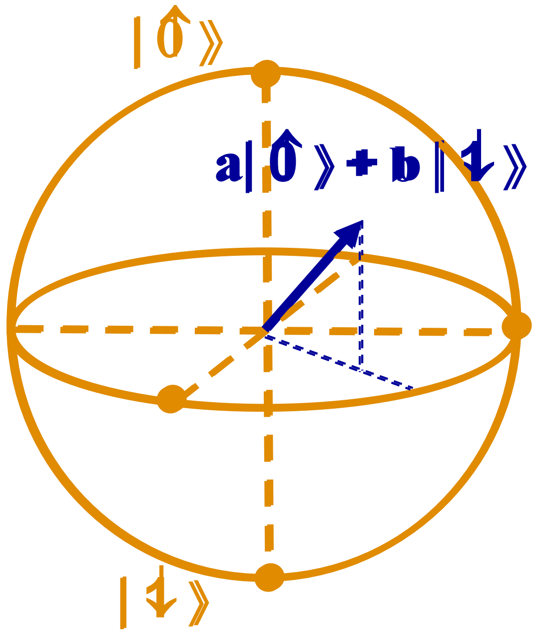
Serge Haroche (ENS Paris)



David Wineland (NIST)

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Physics Nobel Prize 2012



|0⟩
a|0⟩ + b|1⟩
|1⟩

Exponential complexity of quantum bits

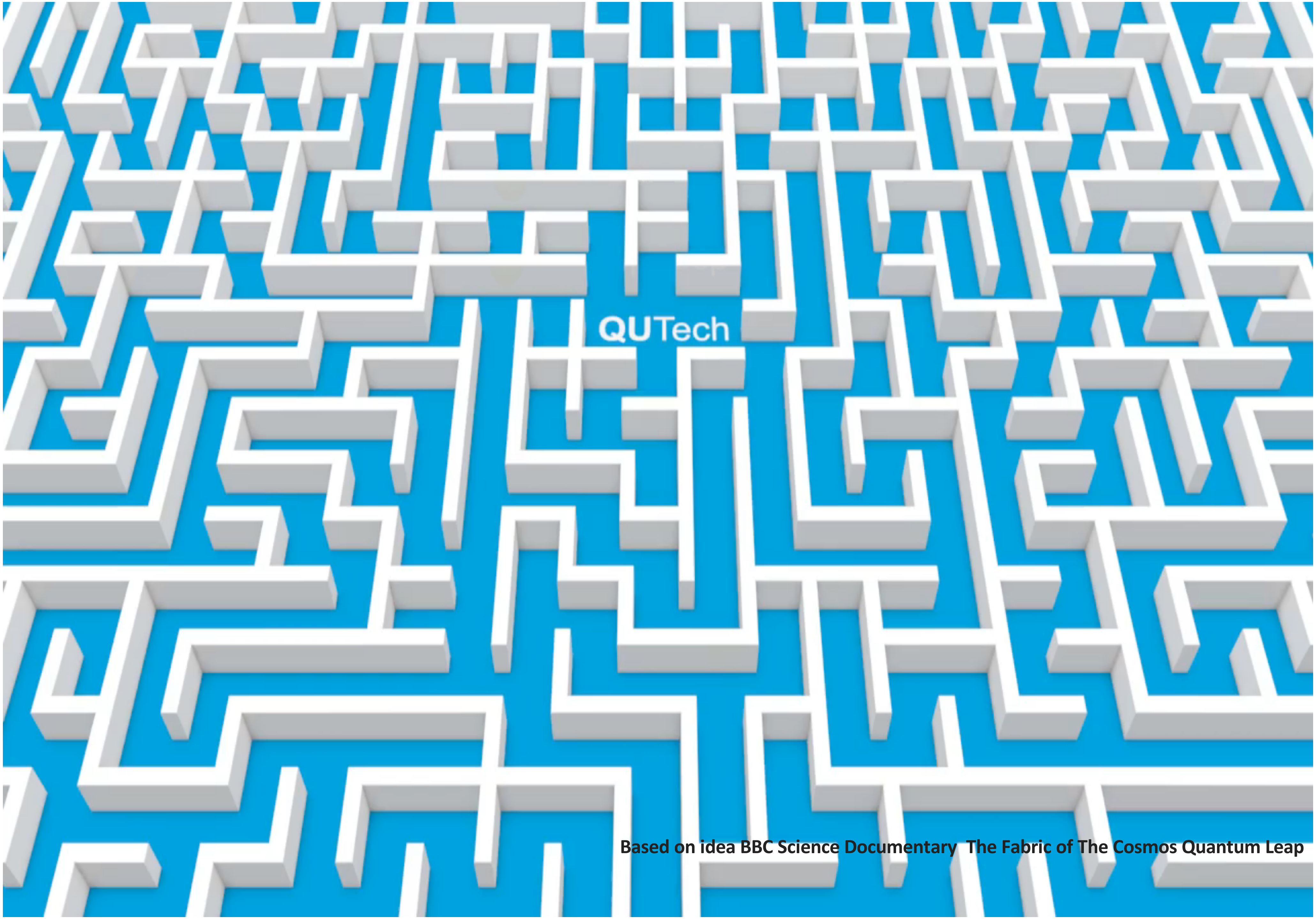
0 & 1

00 & 01 & 10 & 11

000 & 001 & 010 & 011 & 100 & 101 & 110 & 111

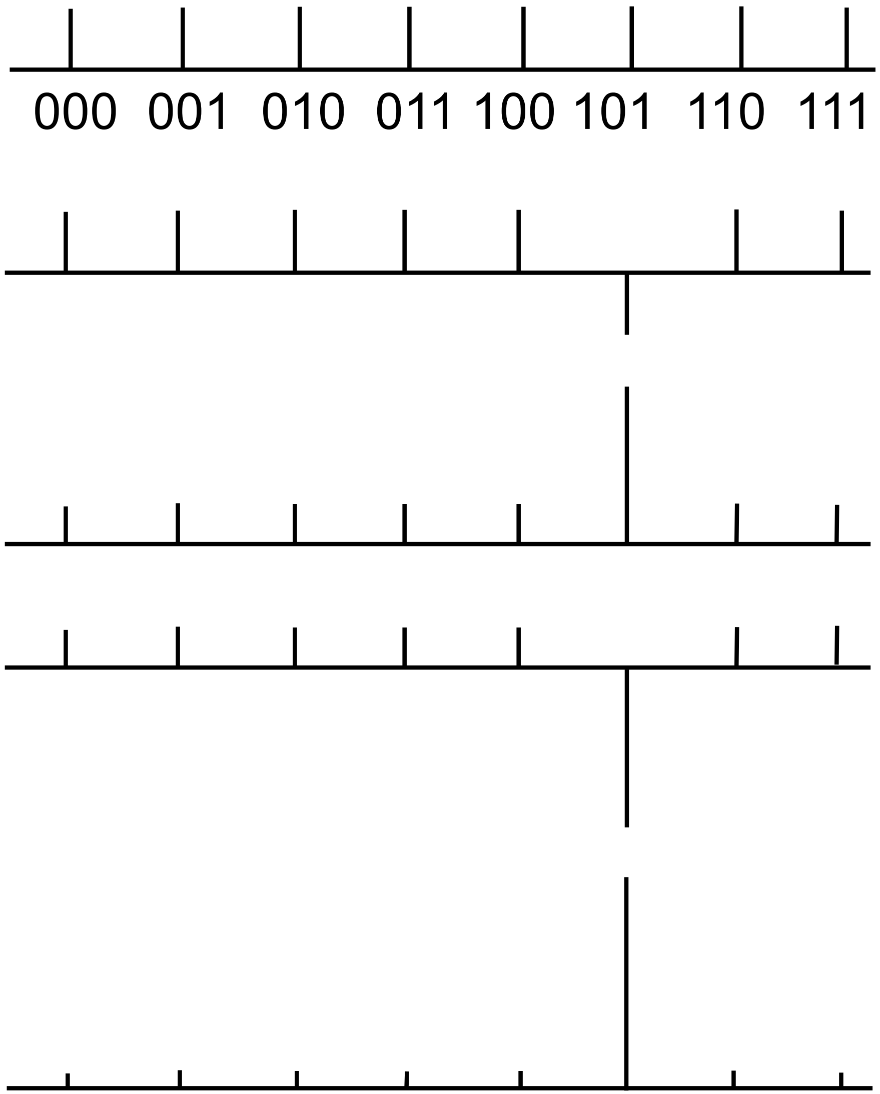
0000 & 0001 & 0010 & 0011 & 0100 & 0101 & 0110 & 0111 & 1000 & 1001 & 1010 & 1011 & 1100 & 1101 & 1110 & 1111

50 qubits (2^{50} ***complex*** amplitudes)
exceed memory of largest supercomputer


QUTech
Based on idea BBC Science Documentary The Fabric of The Cosmos Quantum Leap

How quantum computers compute

Example: Grover's search algorithm



Create equal superposition

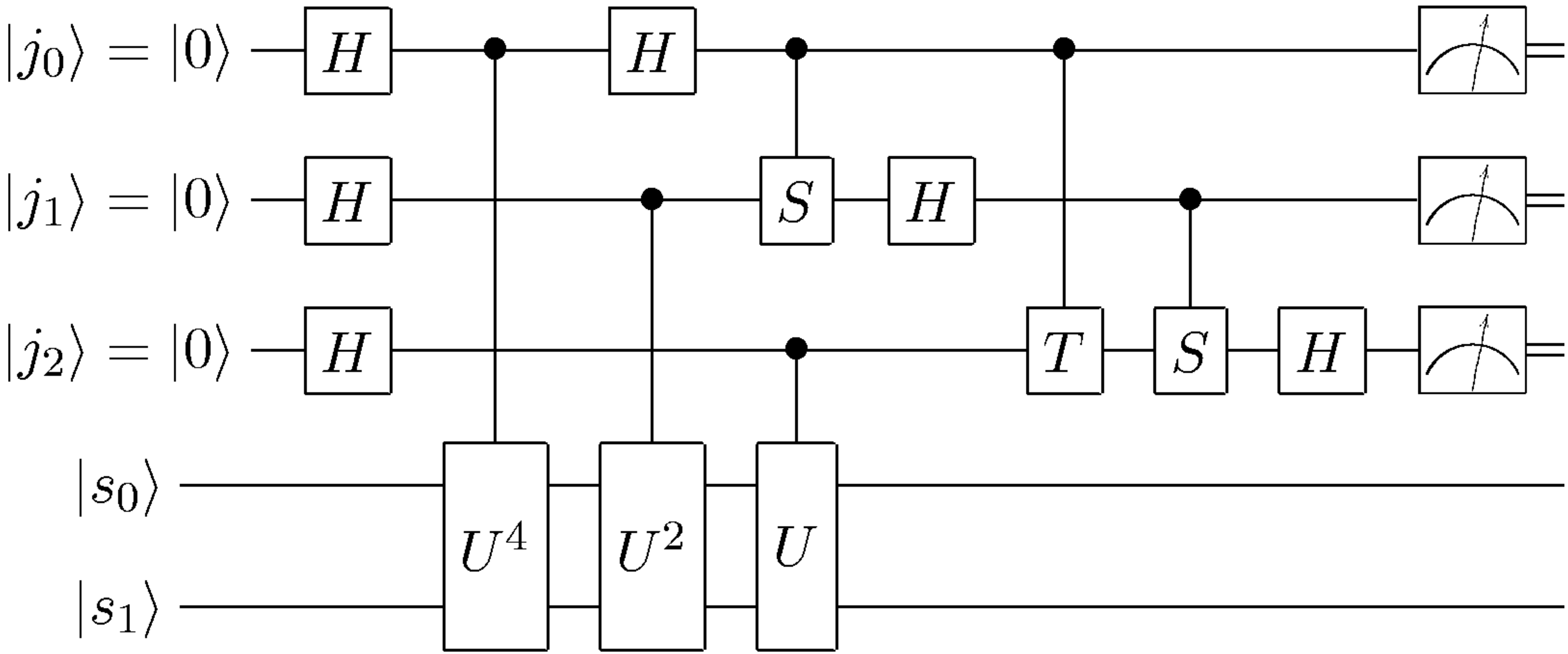
Unitary transformations

Desired answer emerges through interference

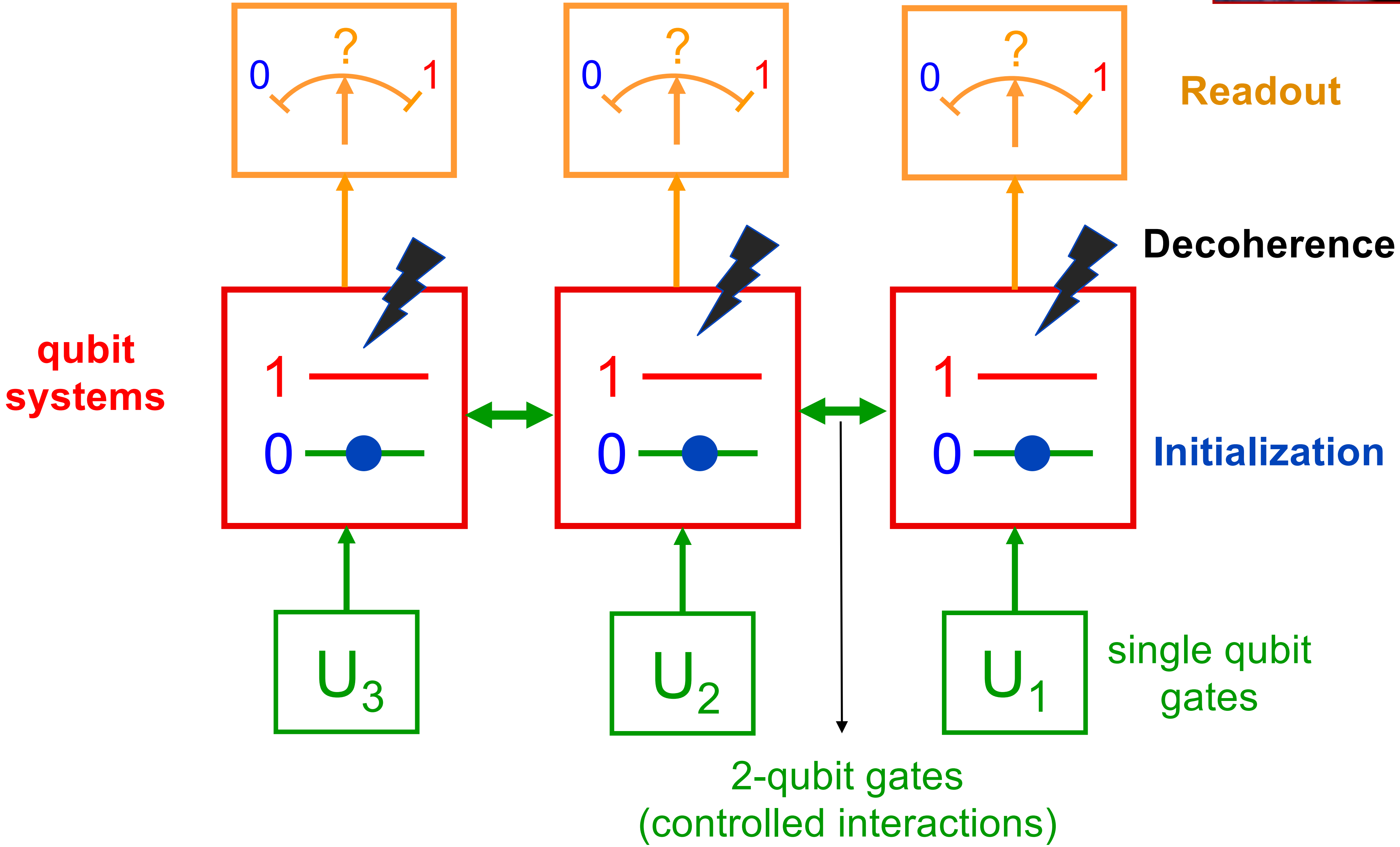
L.K. Grover, Proc STOC 1996

How quantum computers compute

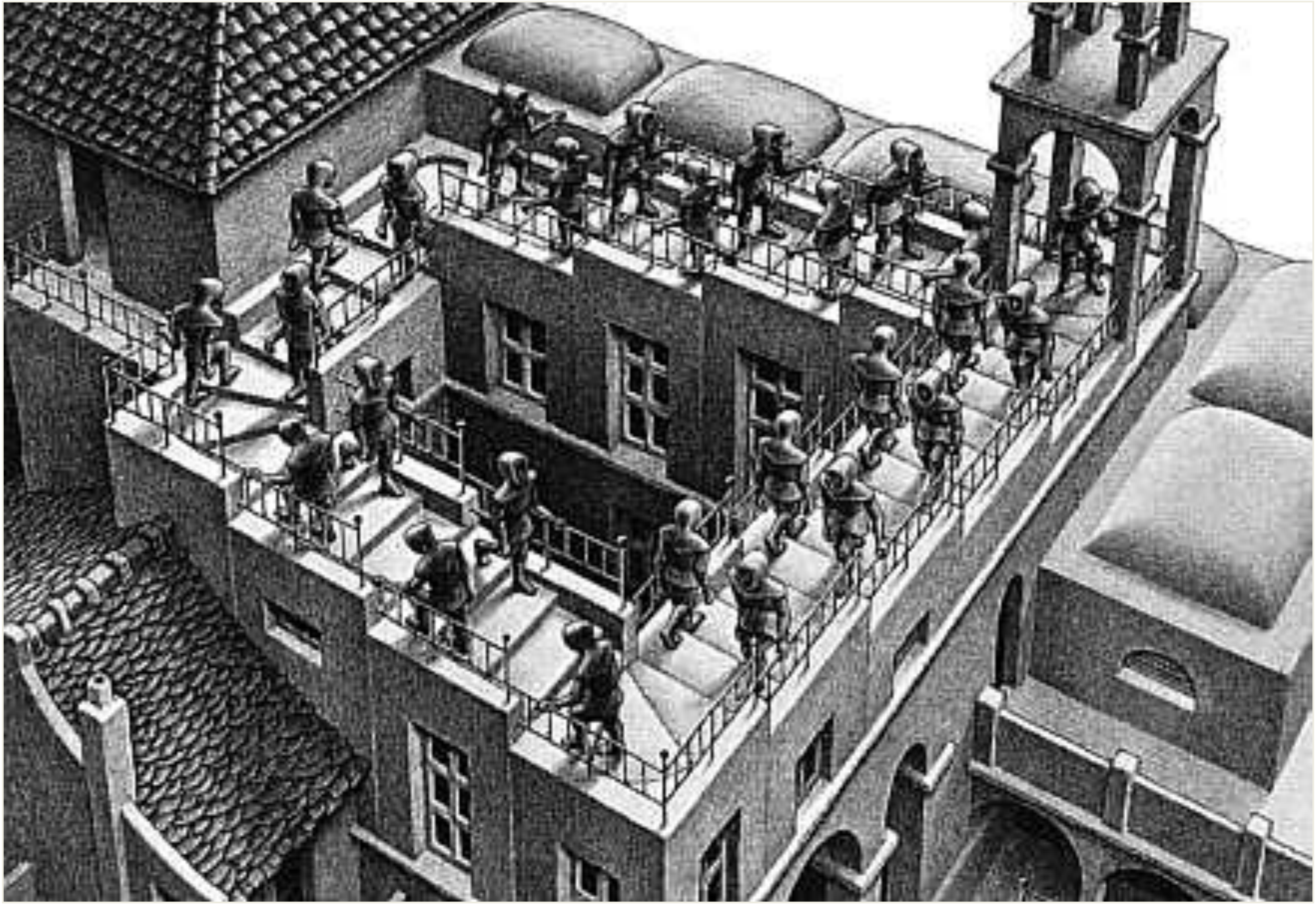
Example quantum circuit



Building a quantum computer
(DiVincenzo criteria)



The Grand Challenge: keeping qubits alive … in a scalable system



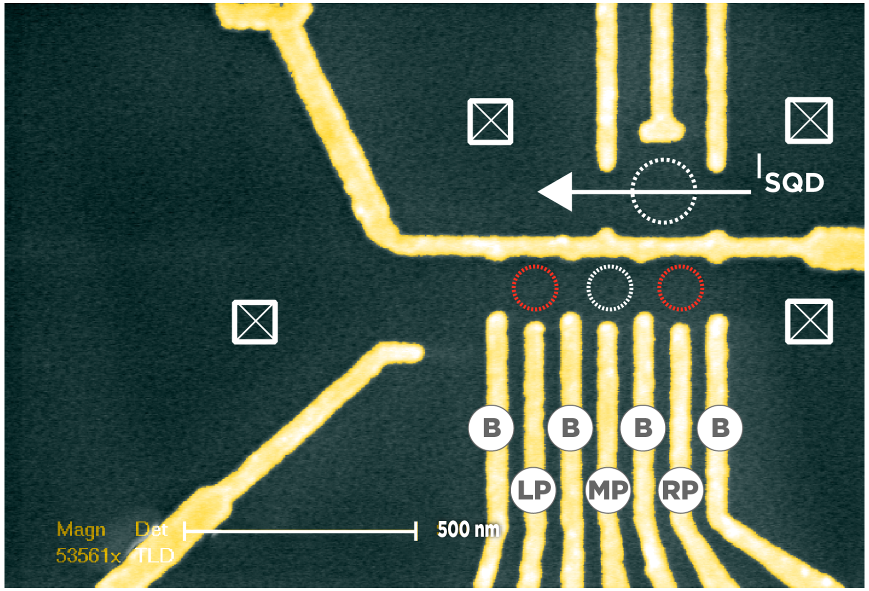
Escher, Eternal Staircase

Why I became optimistic

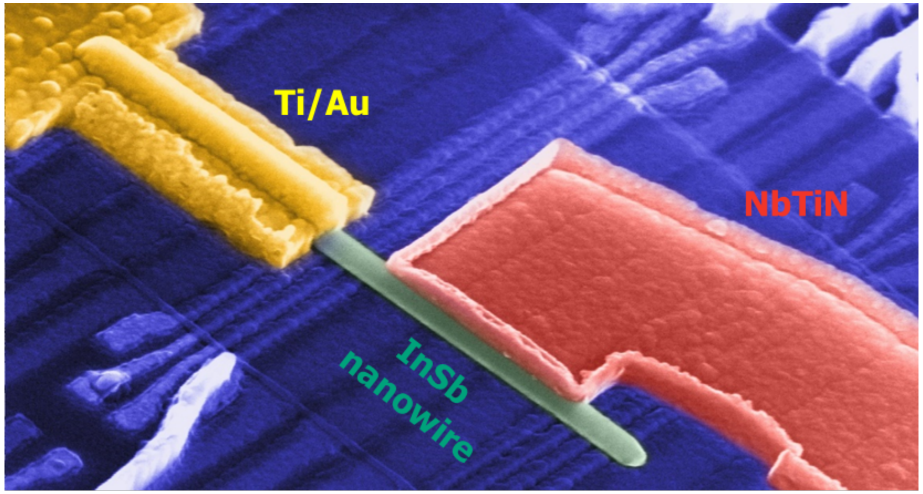
Advance 1: Qubits can be built on a chip!

(Delft examples)

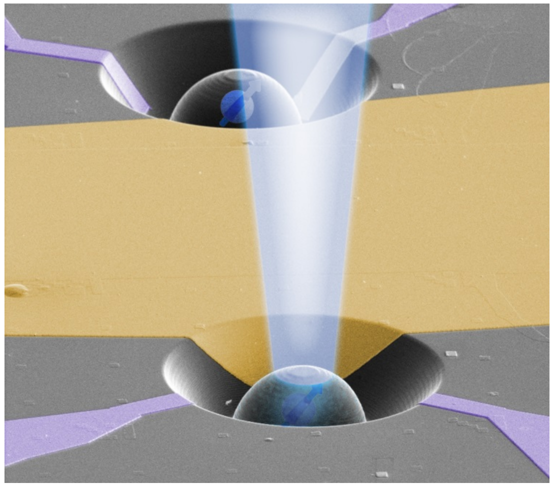
Semiconductor quantum dots



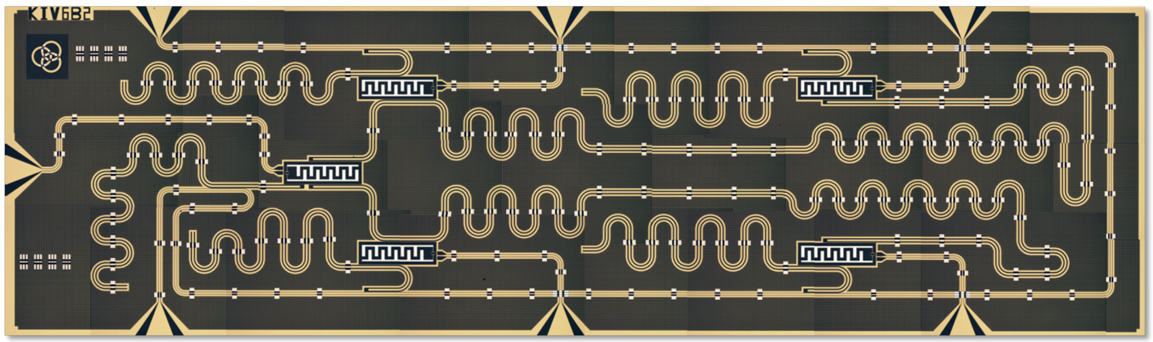
Semiconductor-superconductor hybrids



Impurities in diamond or silicon



Superconducting circuits



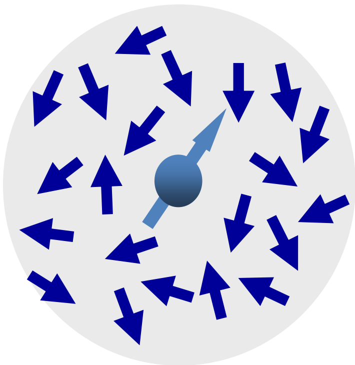
Advance 2: Extending quantum coherence

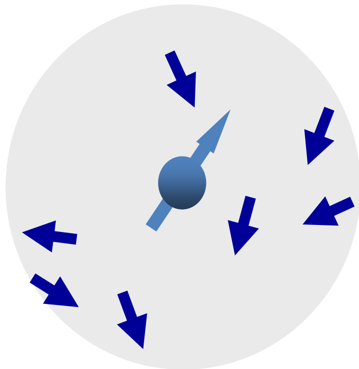
Example: Spin qubits in semiconductor quantum dots

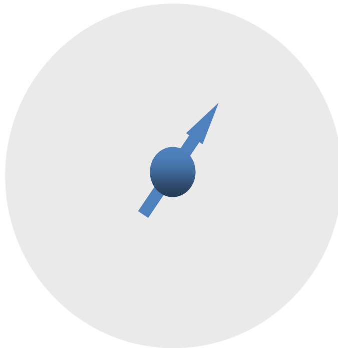
GaAs

Si

^{28}Si







$T_2^* \sim 0.01\ \mu s$

$T_2^{DD} < 0.2$ ms

Petta et al,
Science 2005

$T_2^* \sim 1\ \mu s$

$T_2^{DD} > 0.5$ ms

Kawakami, Scarlino, et al,
Nature Nano 2014

$T_2^* \sim 100\ \mu s$

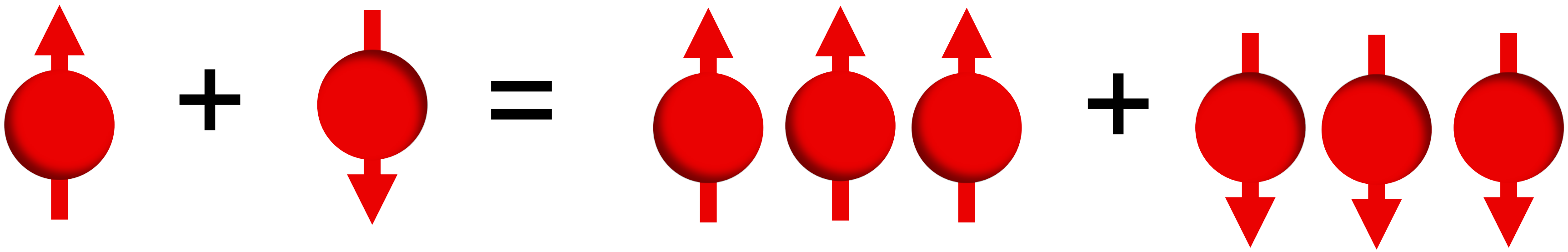
$T_2^{DD} \sim 28$ ms

Veldhorst, et al,
Nature Nano 2014

Quantum state lifetimes boosted by four orders of magnitude

Advance 3: Quantum error correction

Use redundancy to remove errors faster than they occur



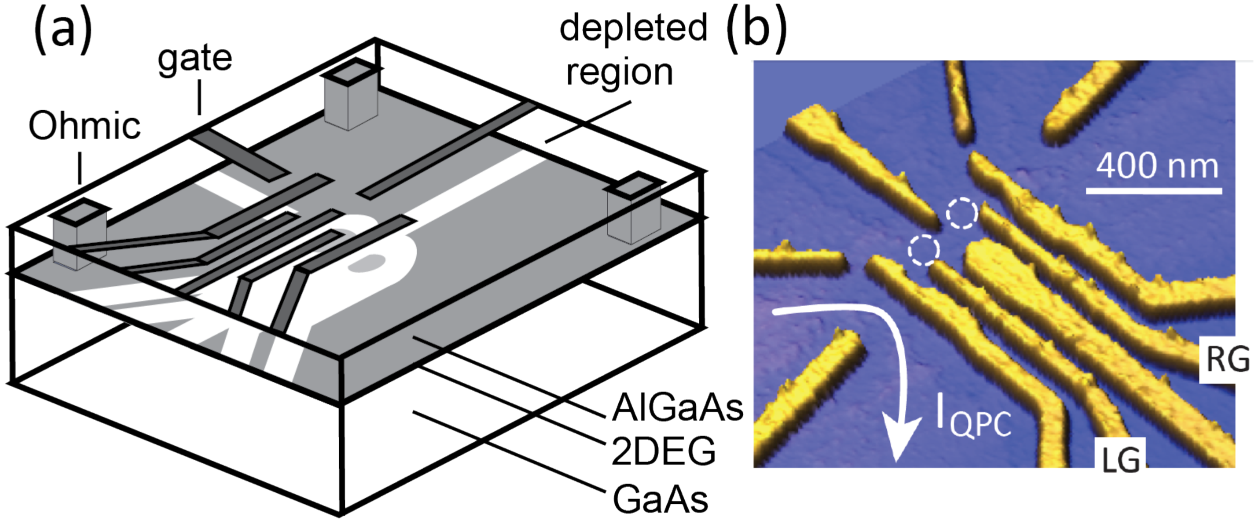
Requires: error probability per step below 1% (previously below 0.01%)
large redundancy (100x to 10,000x)

Can preserve quantum states for as long as is needed!

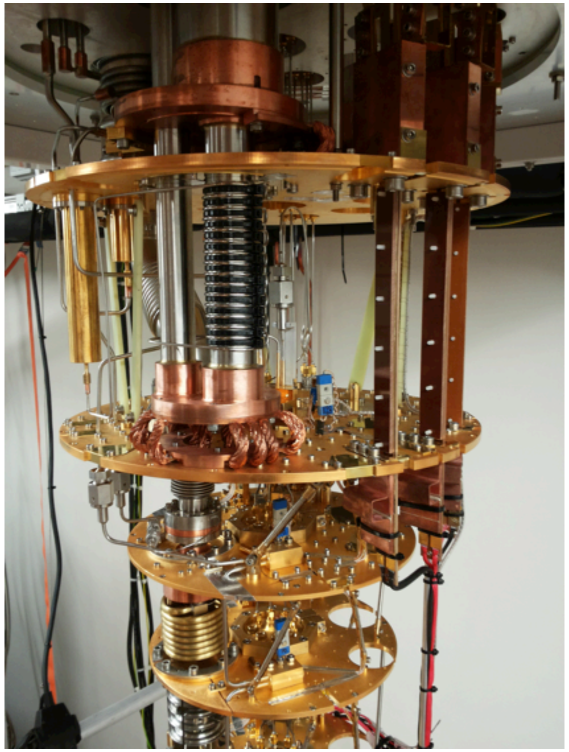
Raussendorf and Briegel, Phys. Rev. Lett. 2007

Intermezzo – making things physical

All-electrical semiconductor quantum dots



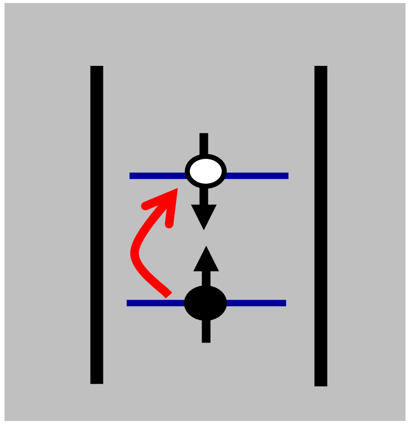
Artificial atoms and molecules



Discrete # charges, quantized orbitals

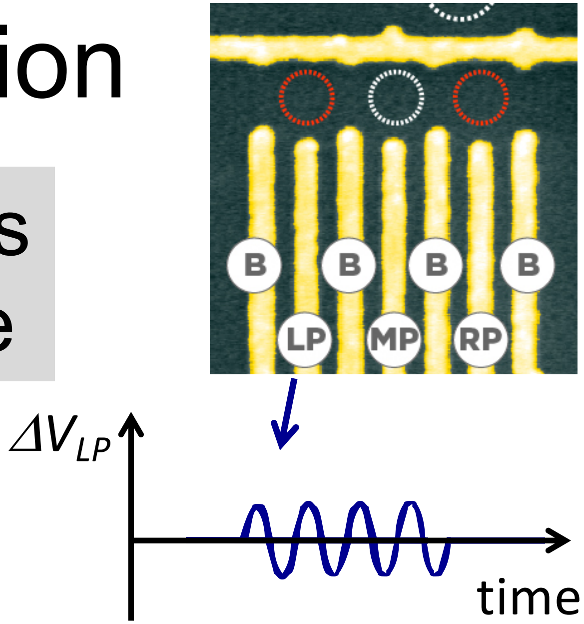
Electrical control and detection

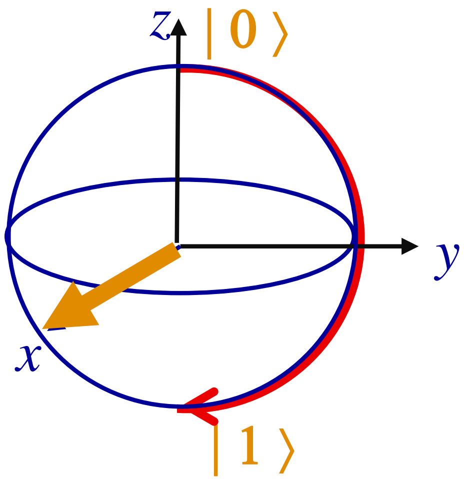
- Tunable # of electrons
- Tunable tunnel barriers
- Electrical contacts

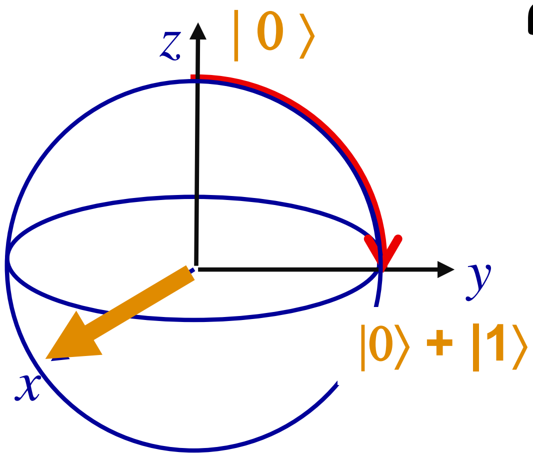


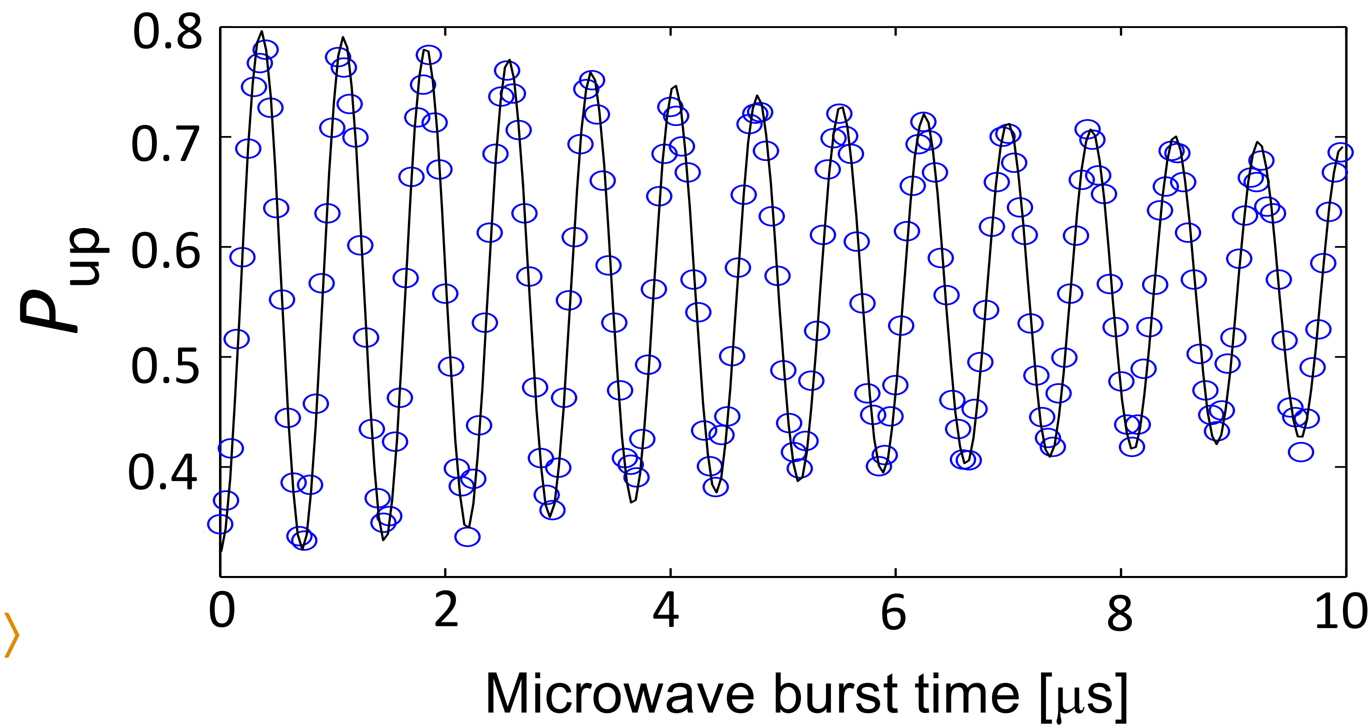
Single-qubit operation

Control individual spins using microwave drive



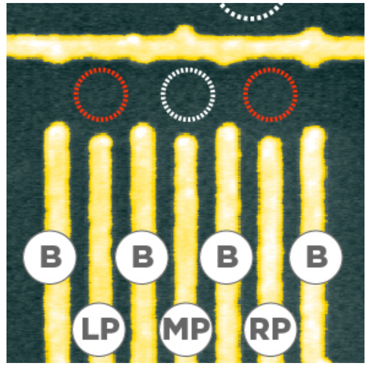


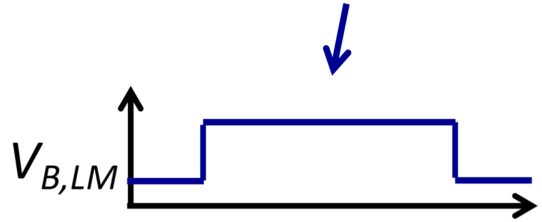




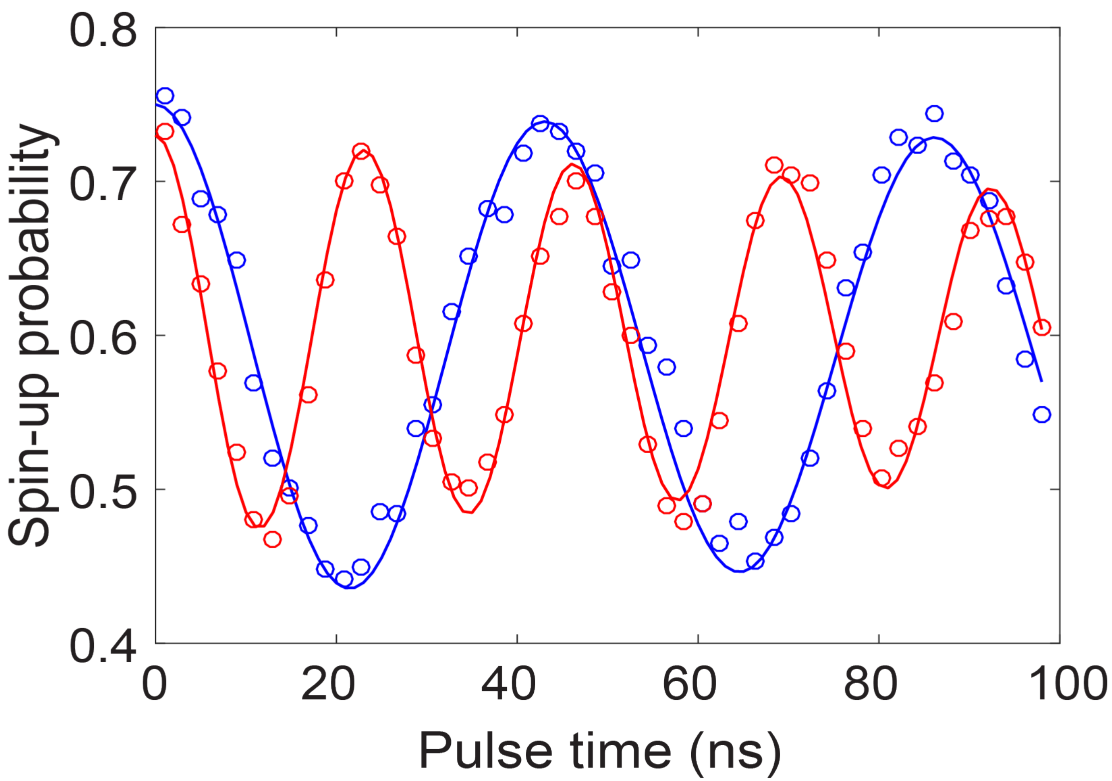
Two-qubit operation

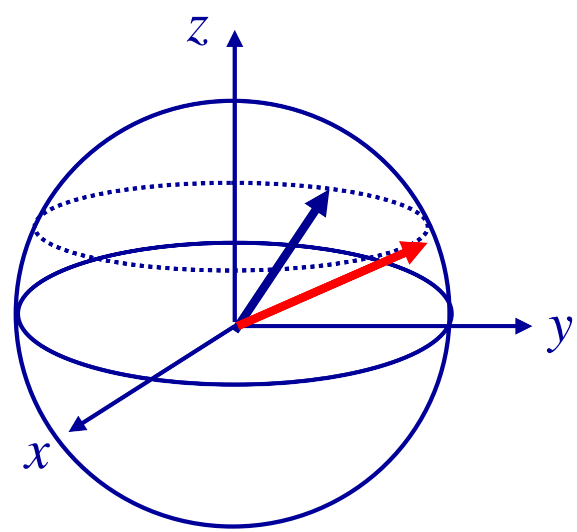
Electrical control of the coupling between neighbouring spins





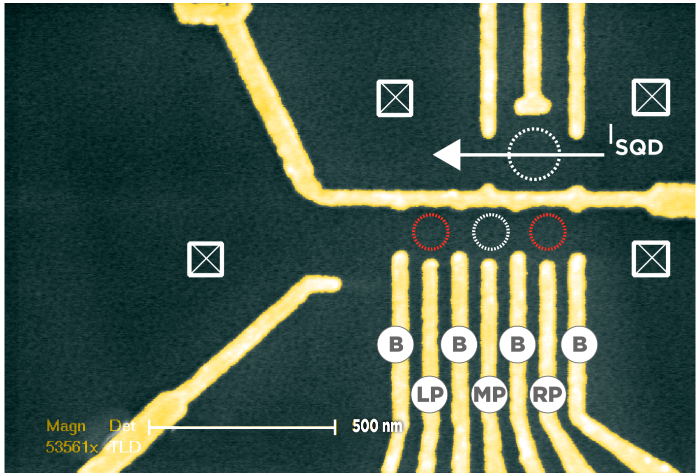
Evolution of spin 2 conditional on spin 1

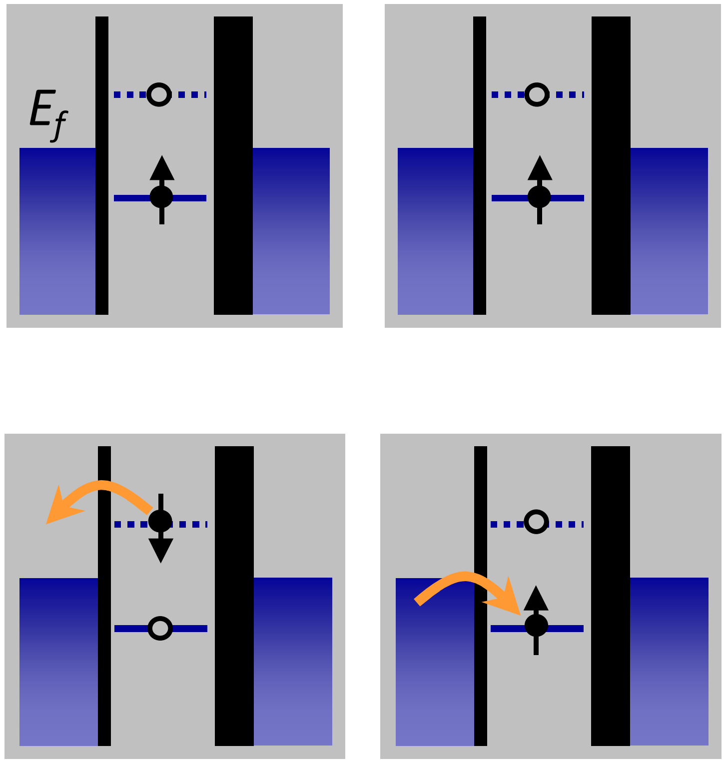


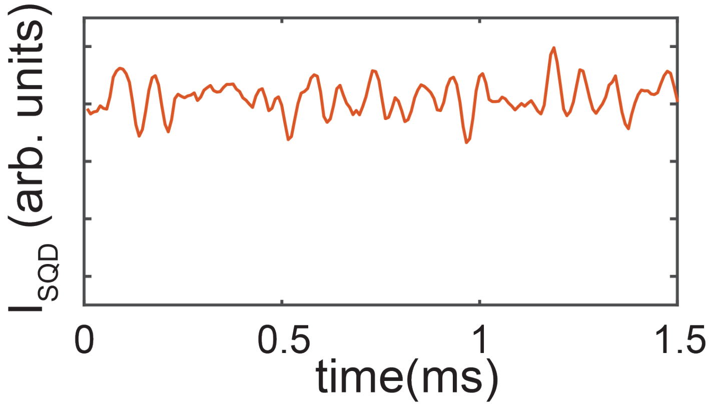


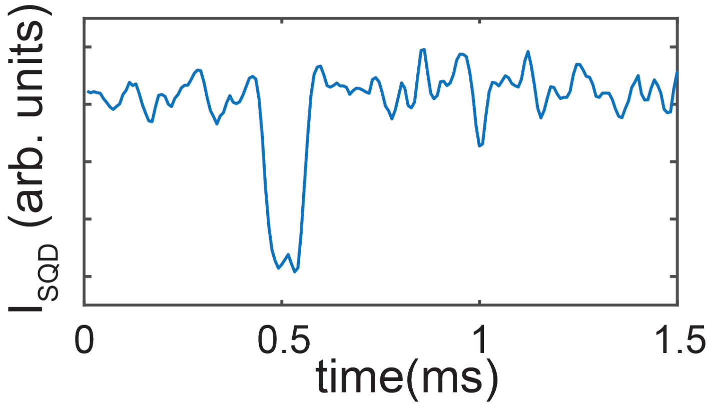
Read-out

Spin-selective tunneling + charge detection



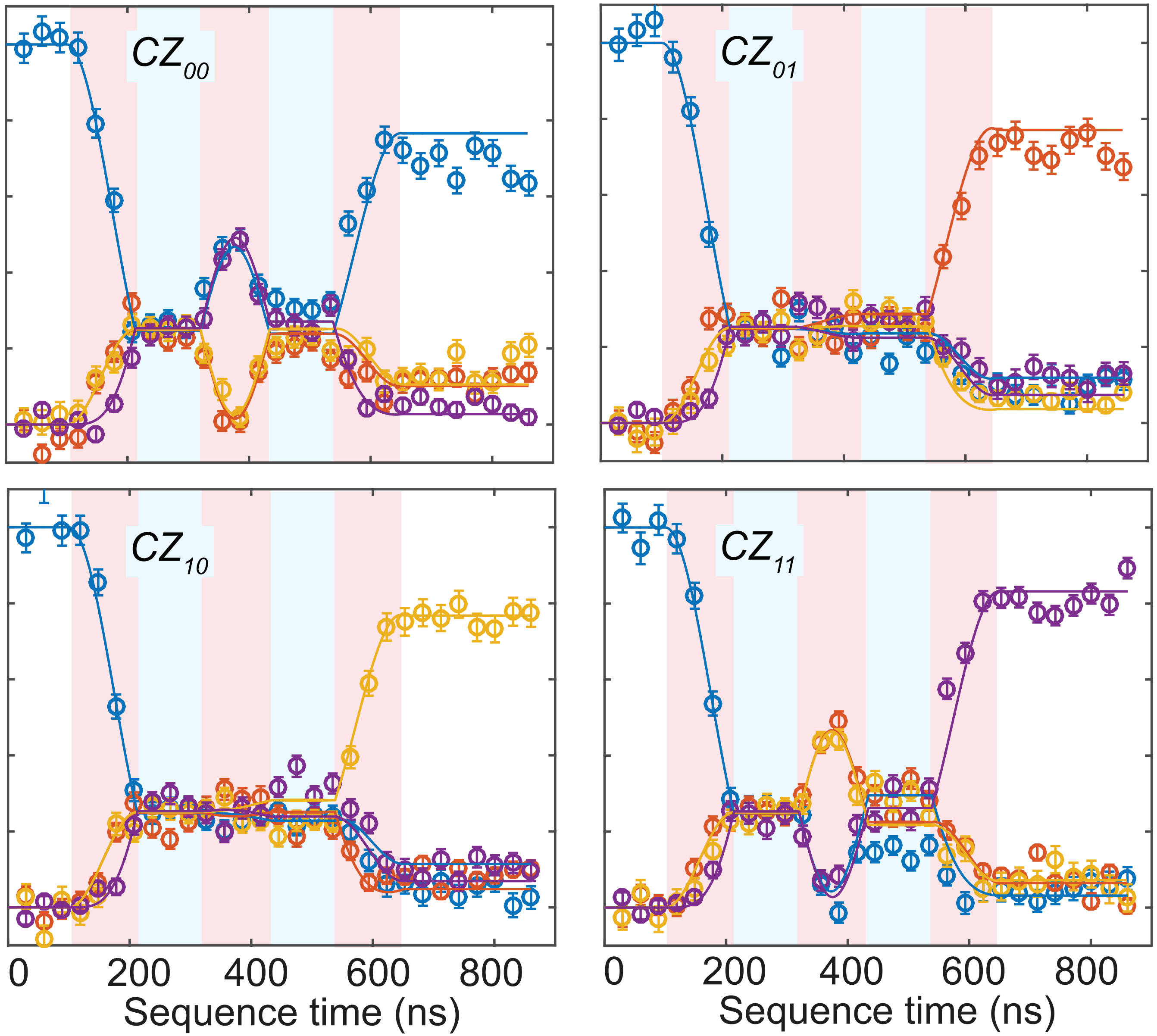






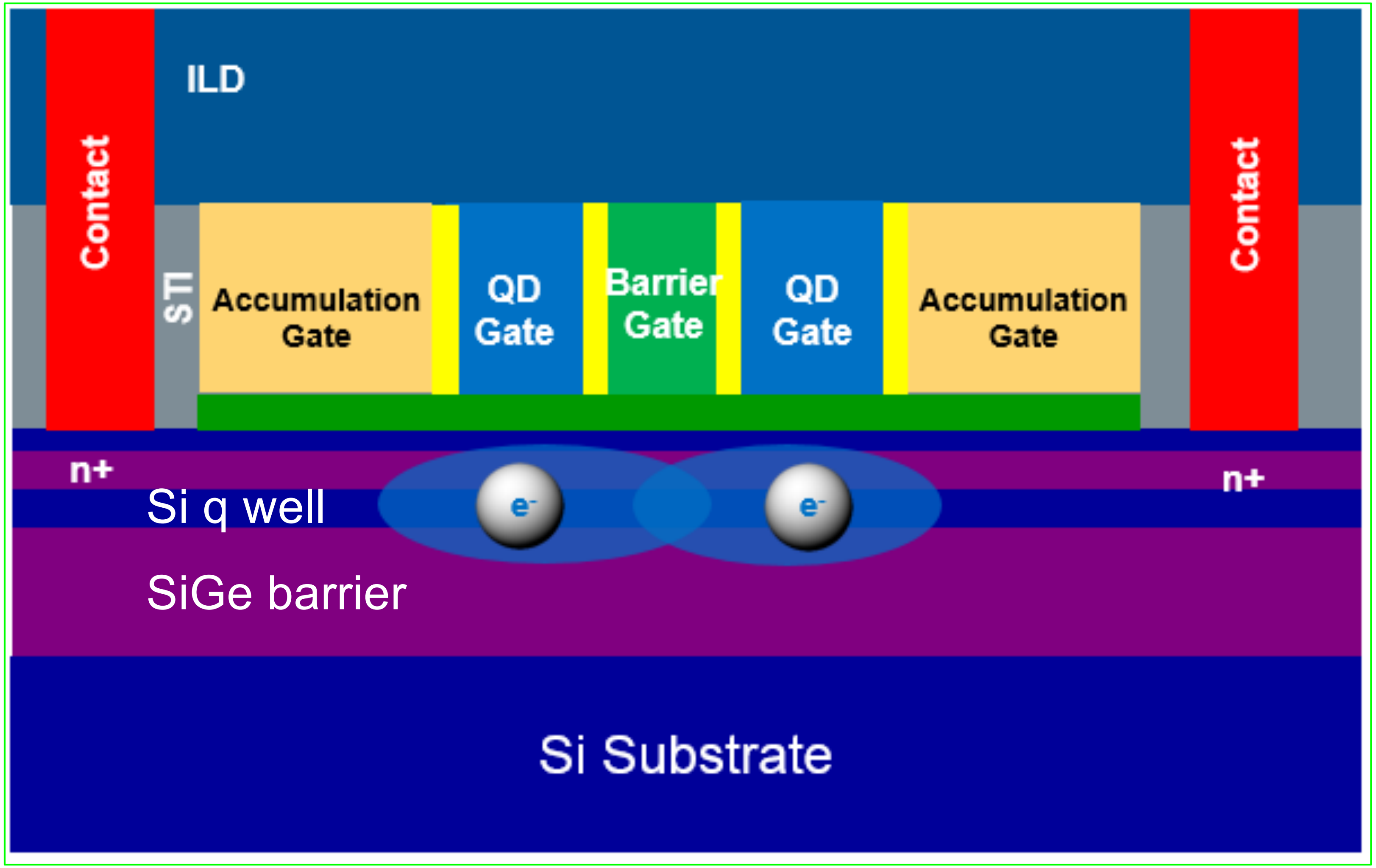
Grover's algorithm in silicon

T. Watson et al, Nature 2018



What stops us from having a quantum computer today?

Challenge 1: Qubits have personalities

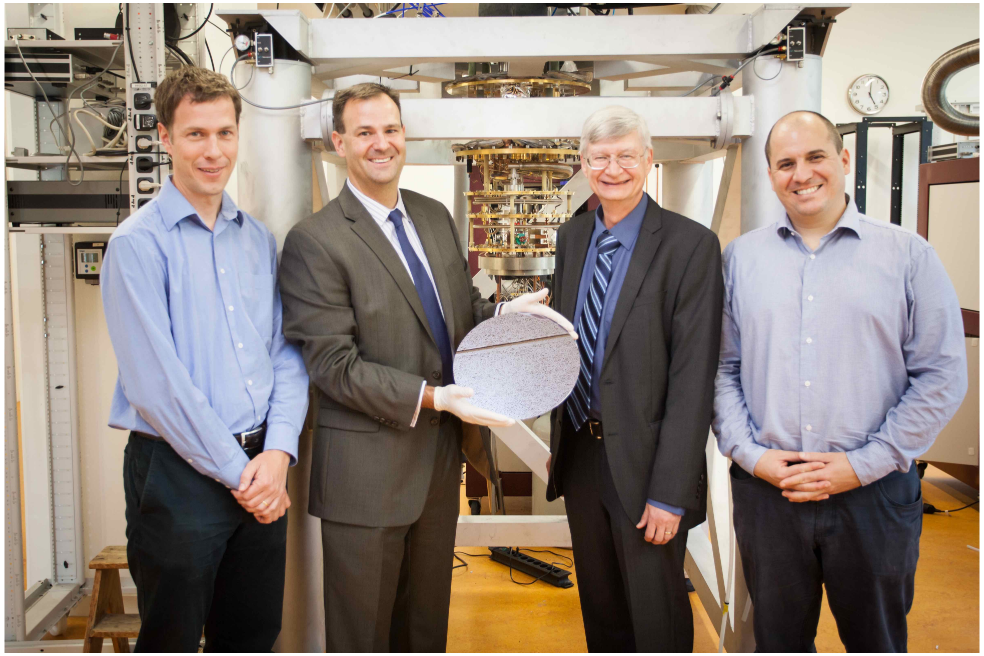


Qubit is highly sensitive to patterning variations and microscopic defects

Way forward 1: Use industry cleanrooms

Tailor-made devices and circuits. Leverage known processes

QuTech-Intel collaboration

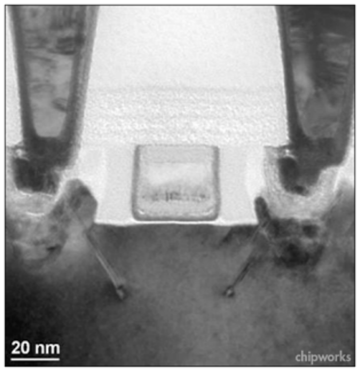


10 years, 50 M$

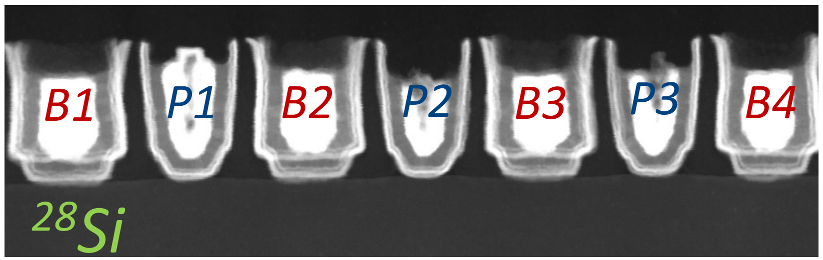
Silicon spin qubits
Transmon qubits

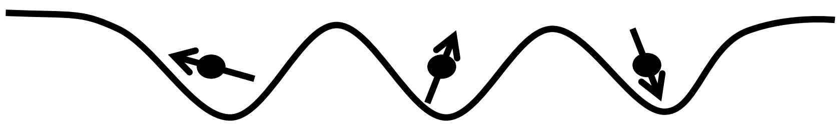
Architecture, Cryo-CMOS, interconnects

Transistor



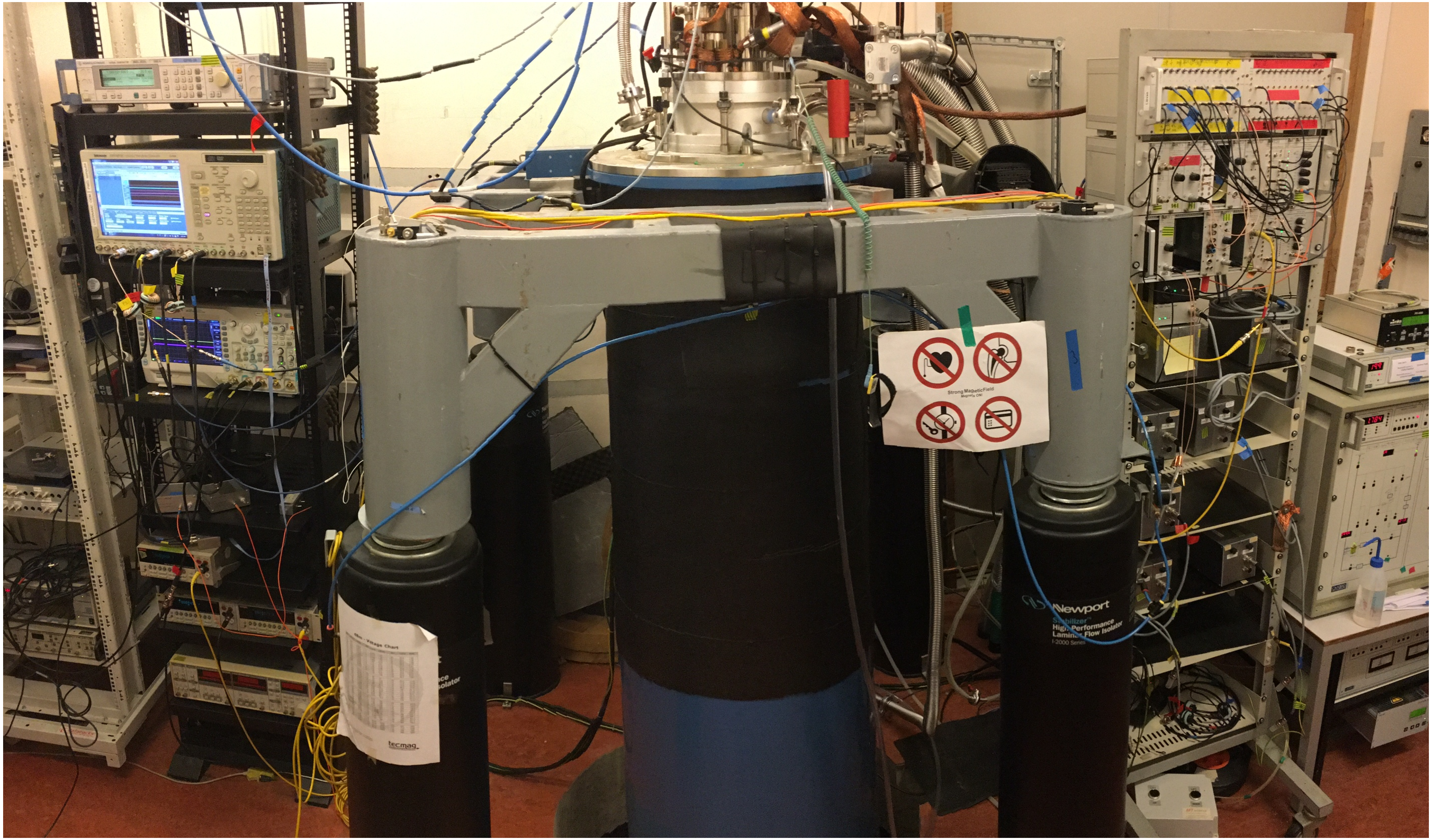
Quantum dot array





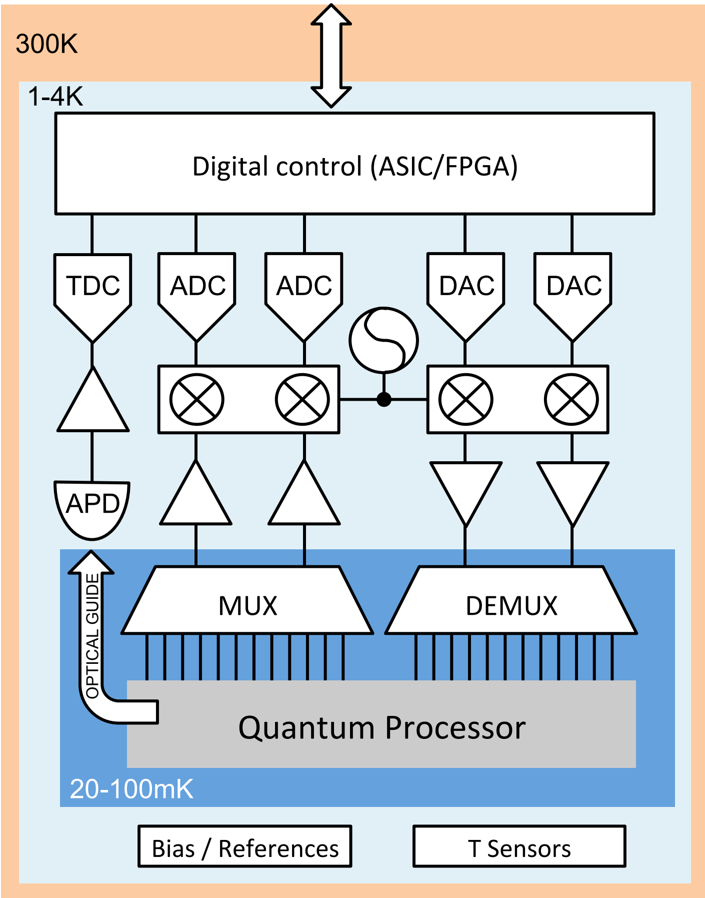
Challenge 2: Scalable wiring & control

Today: bulky, expensive equipment



Way forward 2 : Integrated control architecture

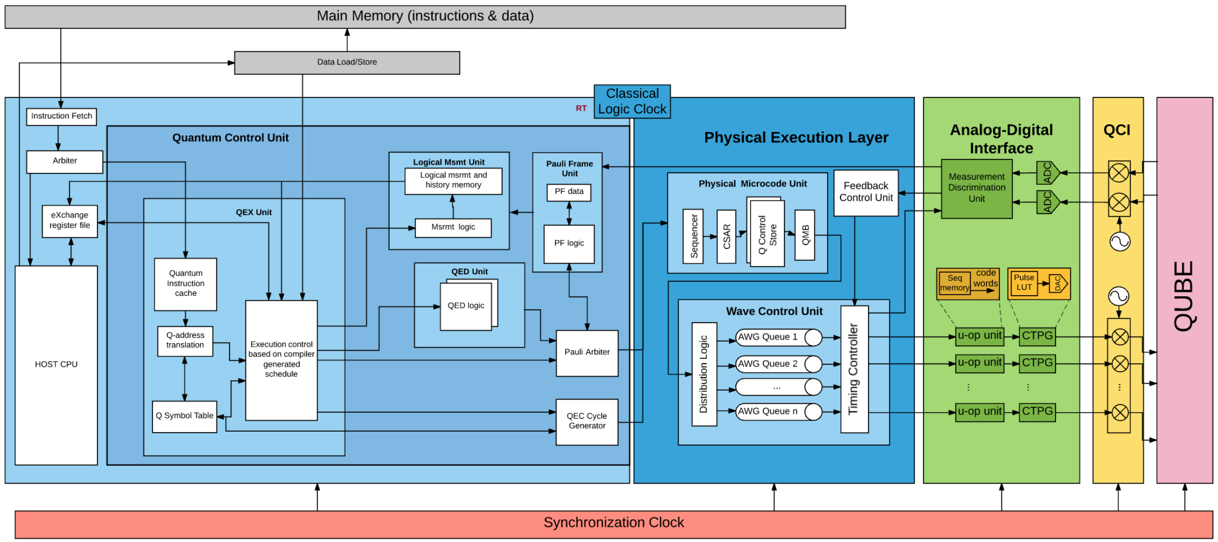
Cryo-CMOS control electronics
Quantum computer archicture



60 K

4 K
2 W

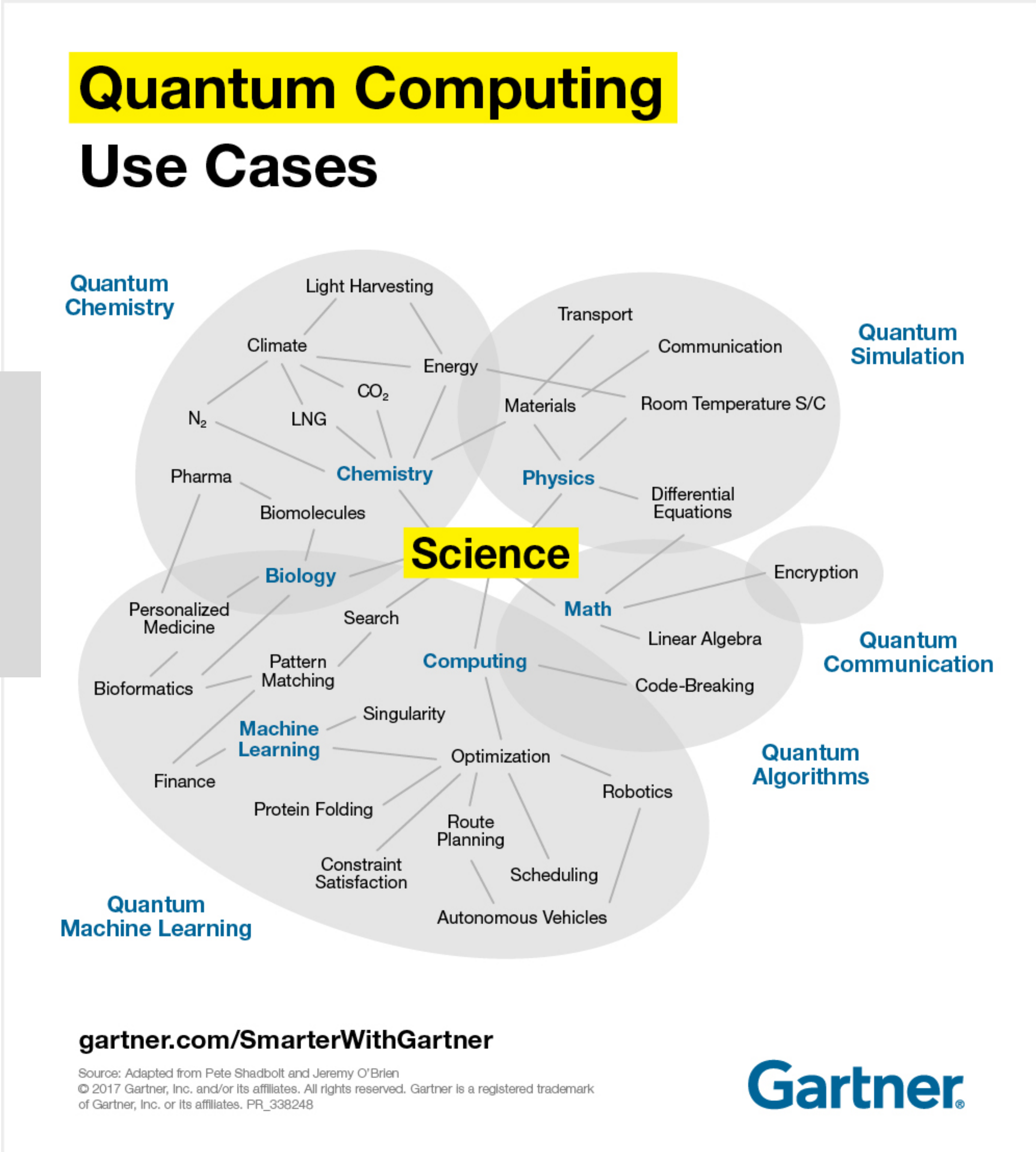
100 mK
0.5 mW



E. Charbon et al., “Cryo-CMOS for Quantum Computing”, IEDM 2016.
X. Fu et al, A microarchitecture for a superconducting quantum processor, IEEE Micro 2018

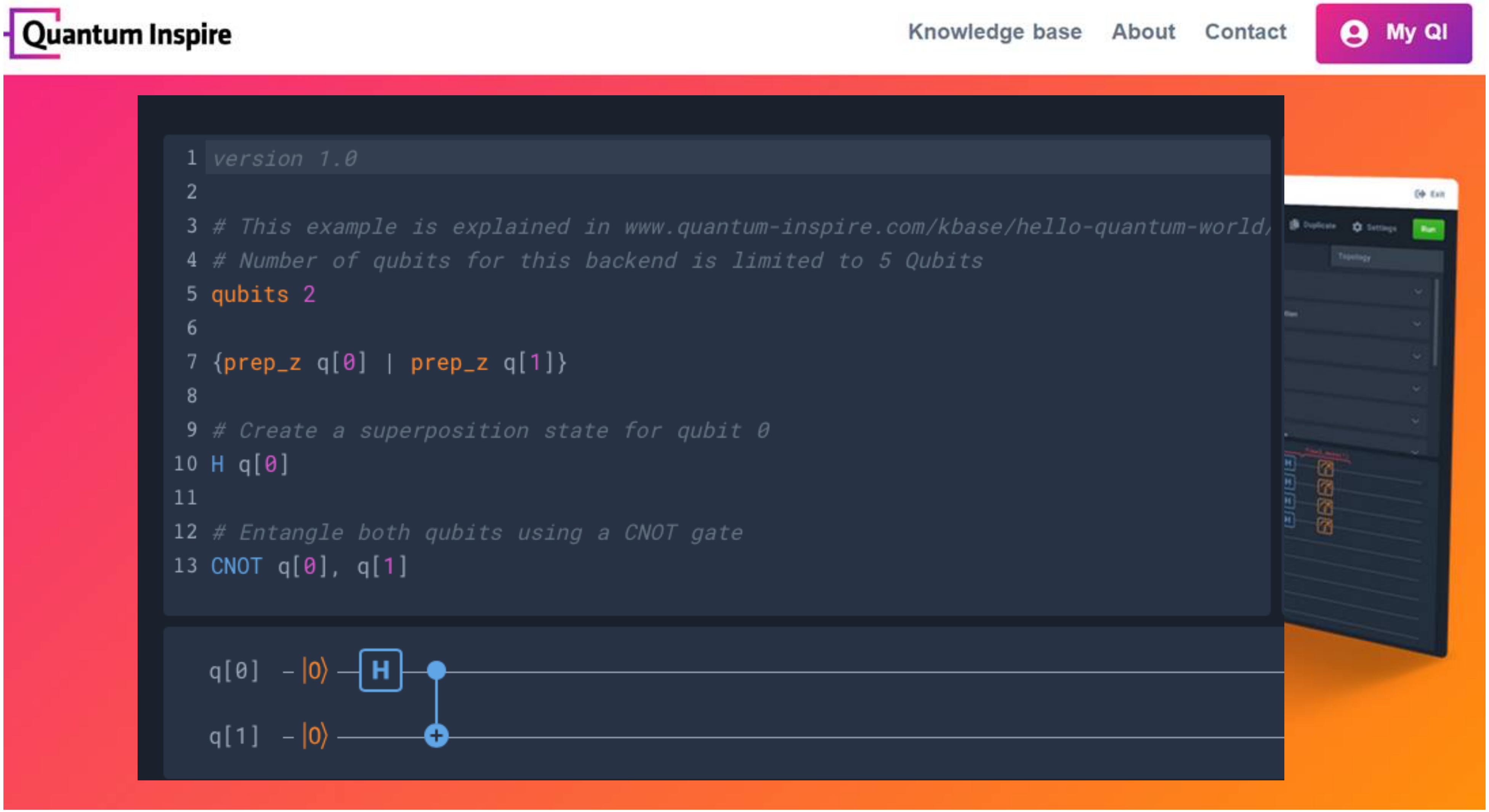
Challenge 3: What is it good for”?

Lots of speculation, high expectations
Little shown.



Way forward 3 – Cloud based platforms

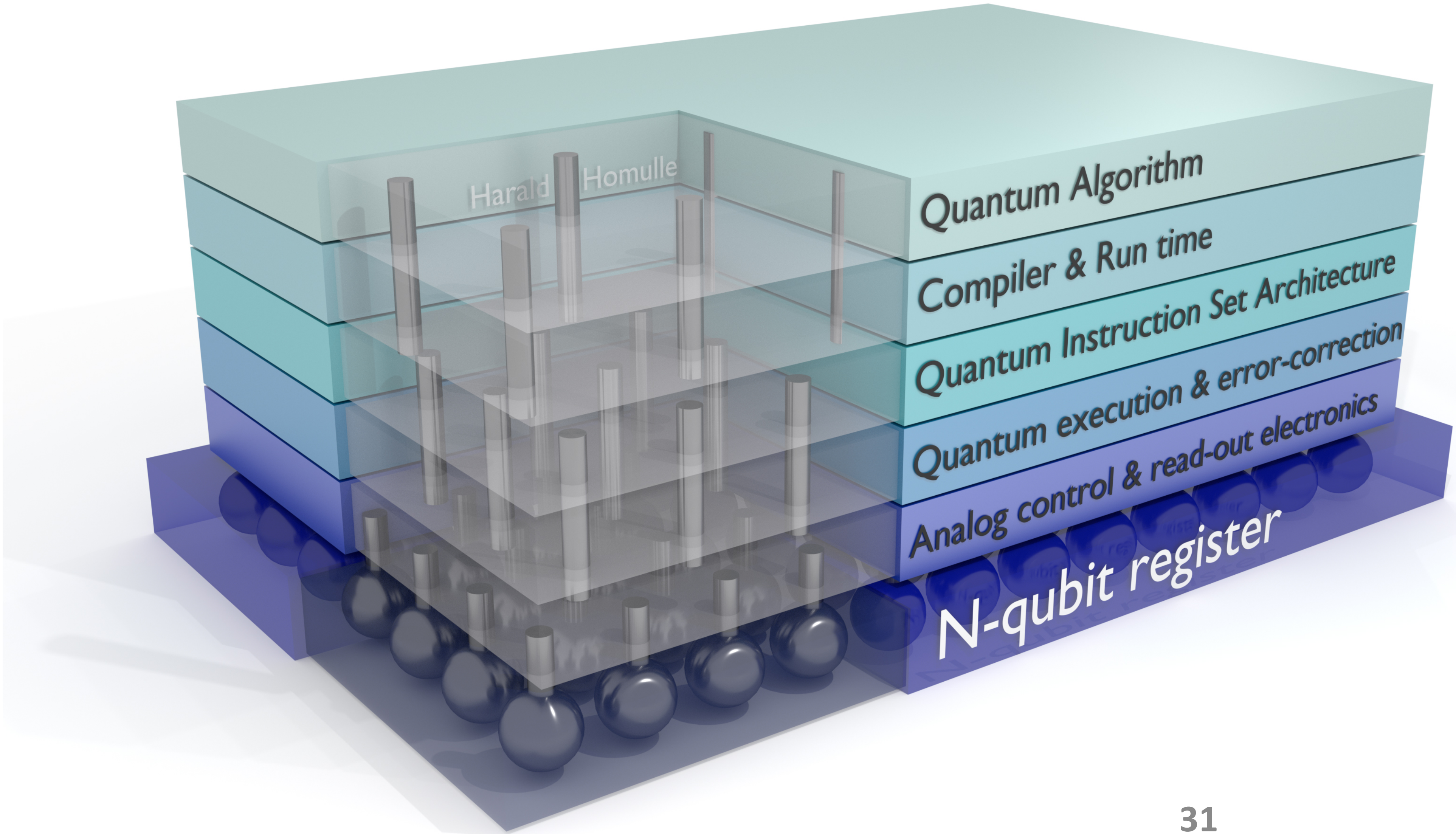
http://quantum-inspire.com - Launched Sept. 4, 2018.
Access to perfect (simulated) qubits. Real qubits coming.
See also IBM Q Experience



Systems approach needed

Challenges in each layer

Layers are highly interrelated



QuTech partnership @ Delft

Quantum technology will not be built by physicists alone

TUDelft
Delft University of Technology

TNO

With support from: NWO FOM STW

QUTech

Currently at ~ 200 fte,
rapidly growing to 350 fte

When will there be a quantum computer?

INDEPENDENT

Quantum computing breakthrough ould 'change life completely'

SciTechDaily

New Achievement Could Lead to More-Eff… Computing

THE WALL STREET JOURNAL.

Podcast: The A… of Quantum Computing Is (Almost) Here

SCIENTIFIC AMERICAN

How Close Are We—Really—to Building a Quantum Computer?

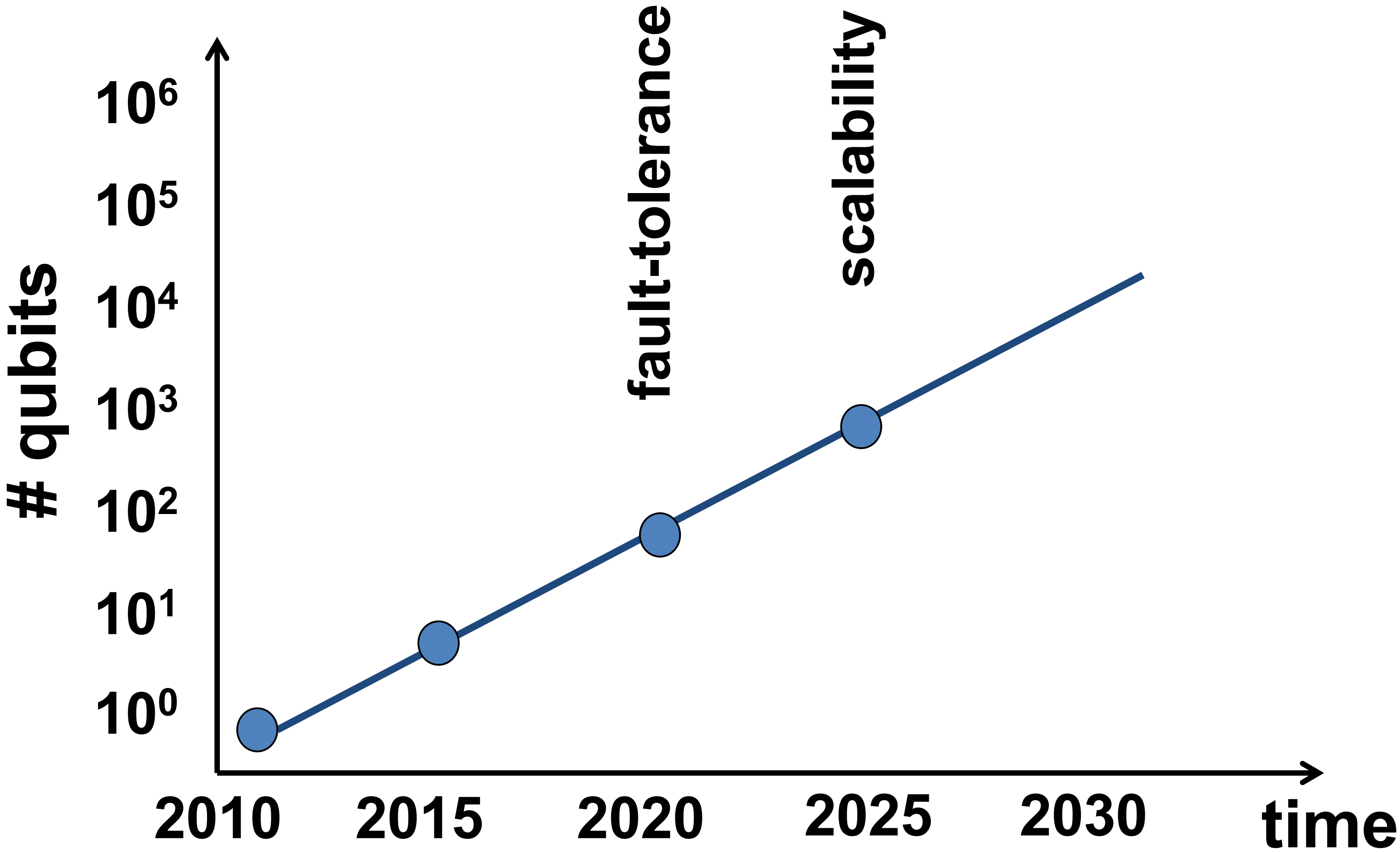
INDEPENDENT

Google sees success with …perimental quantum computer

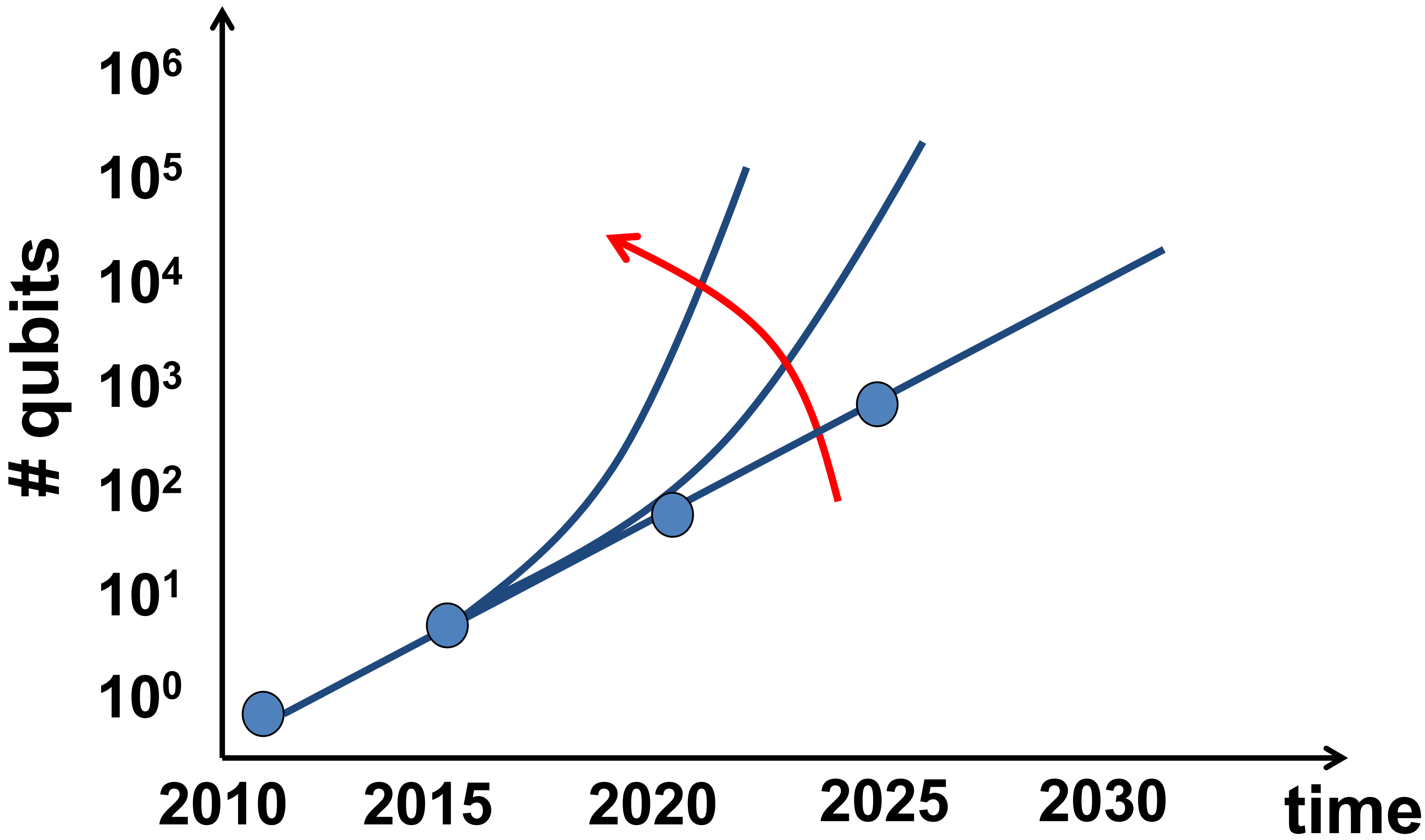
New Scientist

Is the quantum computer revol… really just five years away?

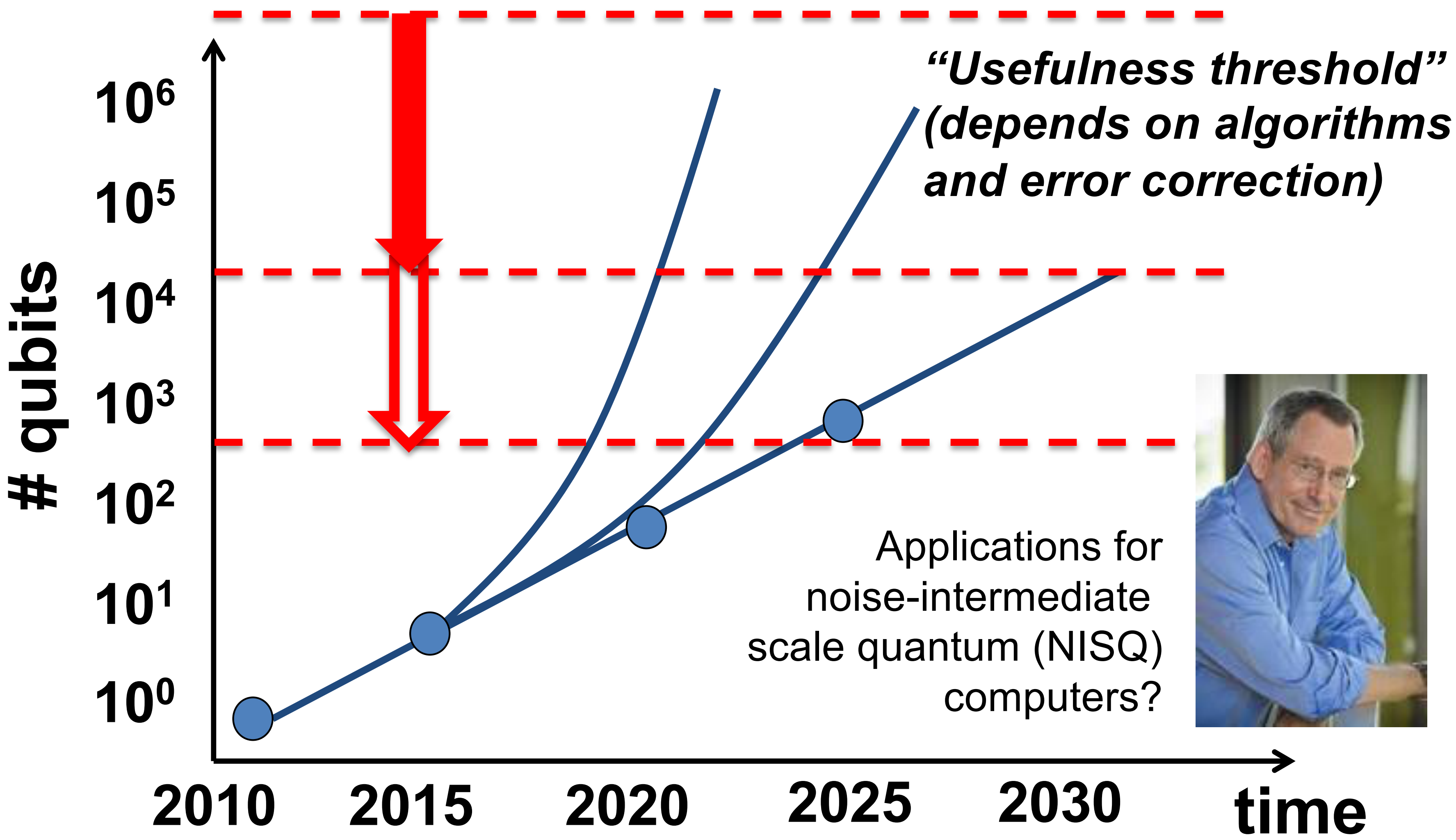
Projecting quantum progress



Can we accelerate hardware development?



Can we accelerate software development?



The quantum computer –
Coming to stores near you (soon?)

intel Google Microsoft IBM

HRL LABORATORIES D-Wave The Quantum Computing Company rigetti

A team effort!