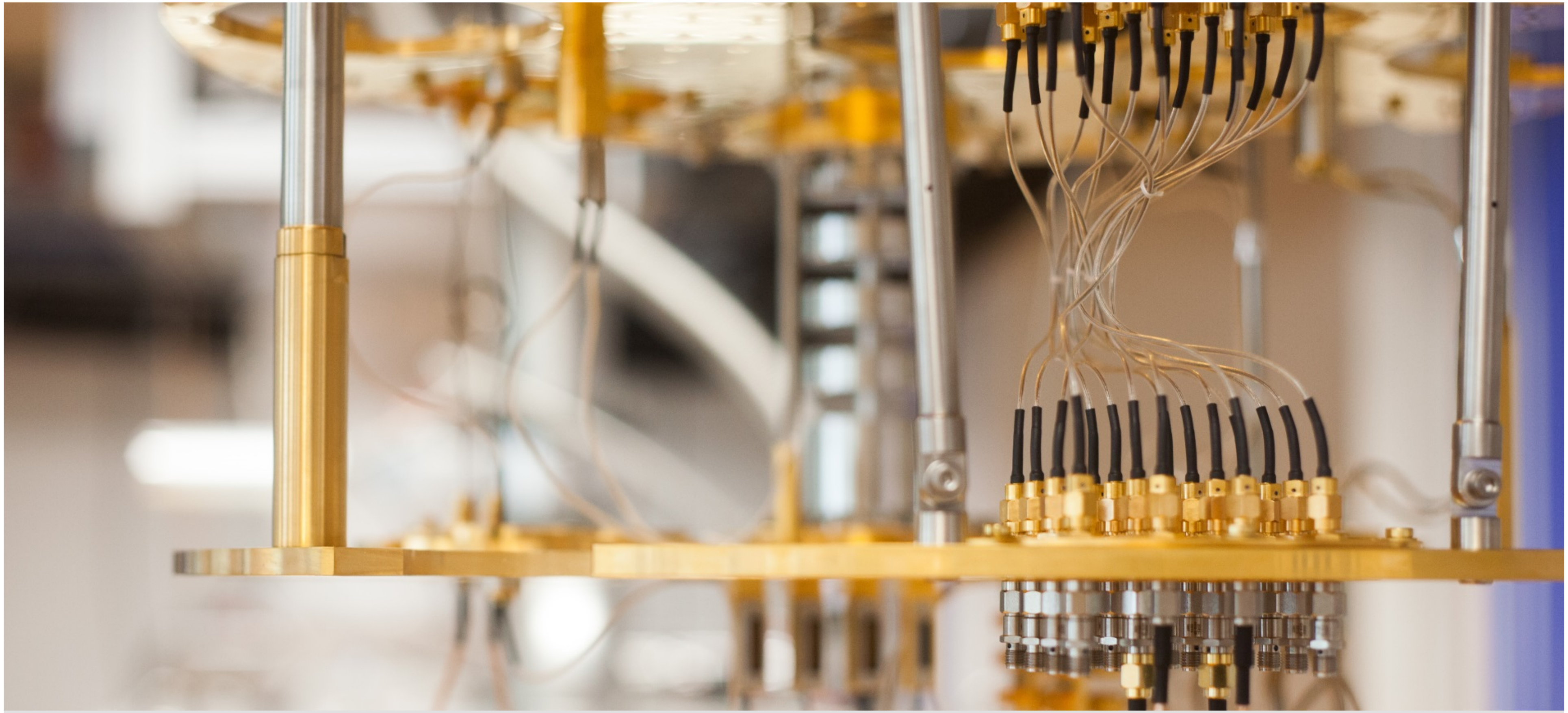


A "Spins–inside" Quantum Processor

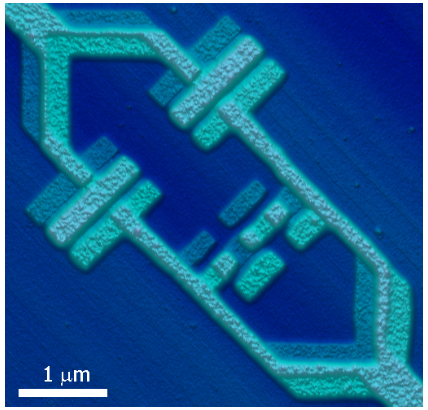
8th Intl. Conf. on Post-Quantum Cryptography

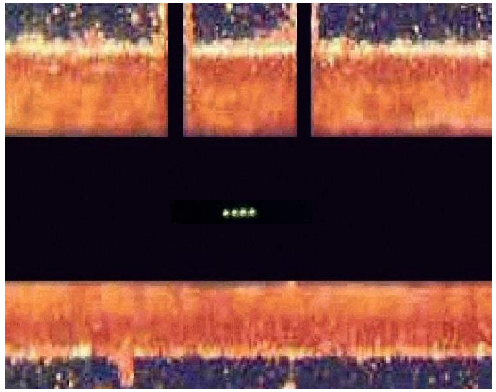
26-28 June 2017, Utrecht, Netherlands

Lieven Vandersypen

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

Can a quantum computer be built?

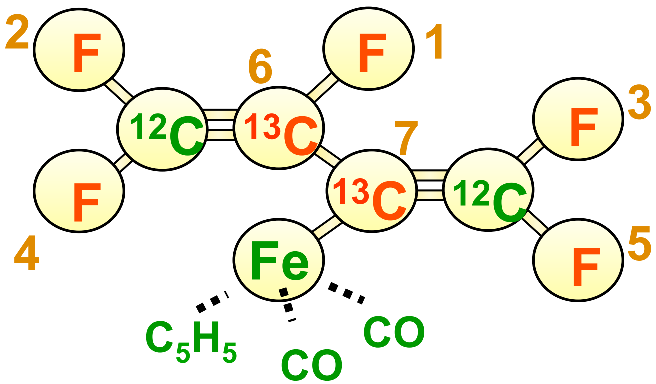


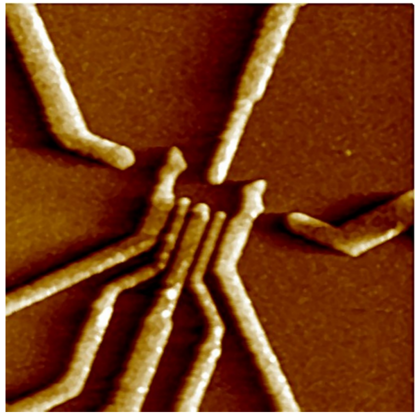


Post Quantum Cryptography workshop

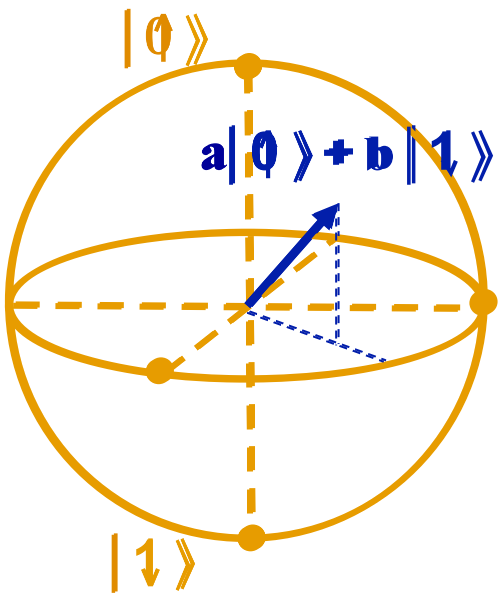
Leuven, 23-26 May 2006

Lieven Vandersypen





TU Delft
Delft University of Technology
Faculty Of Applied Sciences


|0⟩
a|0⟩ + b|1⟩
|1⟩

Exponential complexity of quantum bits

0 & 1

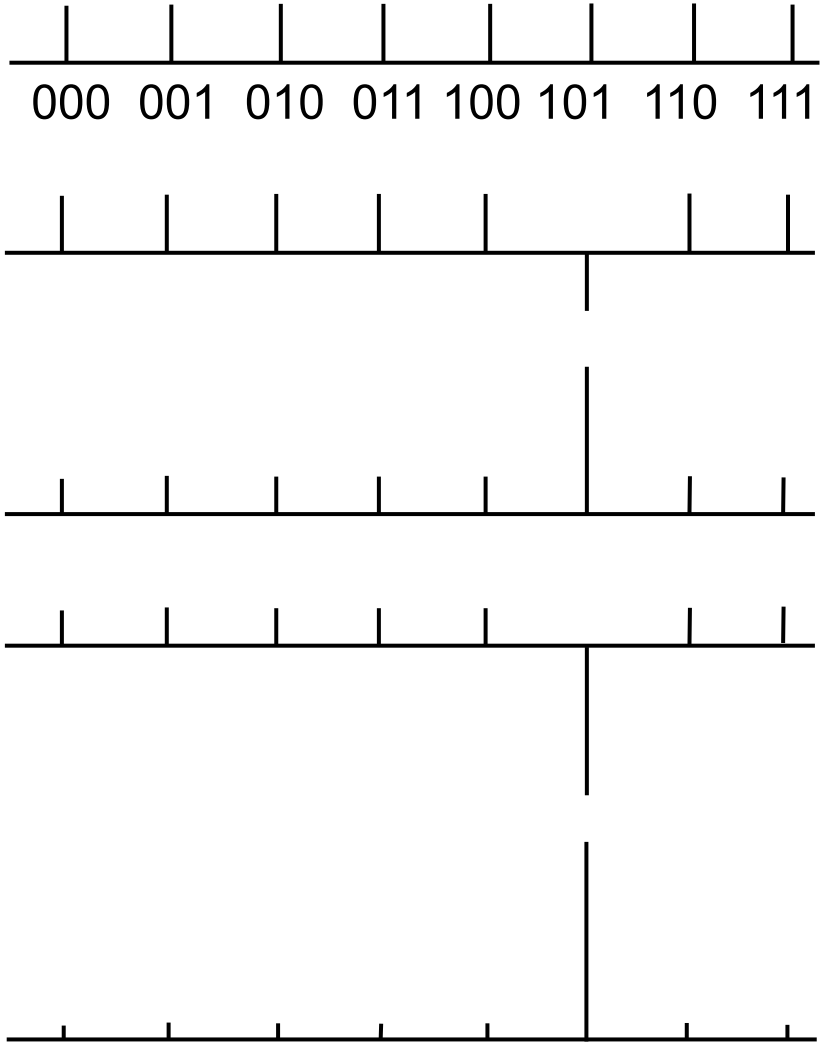
00 & 01 & 10 & 11

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

How quantum computers compute



Create equal superposition

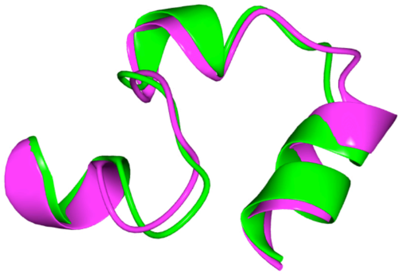
Unitary transformations

Desired answer emerges through interference

L.K. Grover, Proc STOC 1996

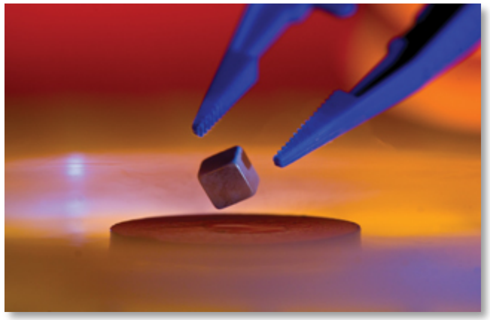
What quantum computers can do

Model complex molecules



Health: Quantum chemistry for medicine

Model complex materials



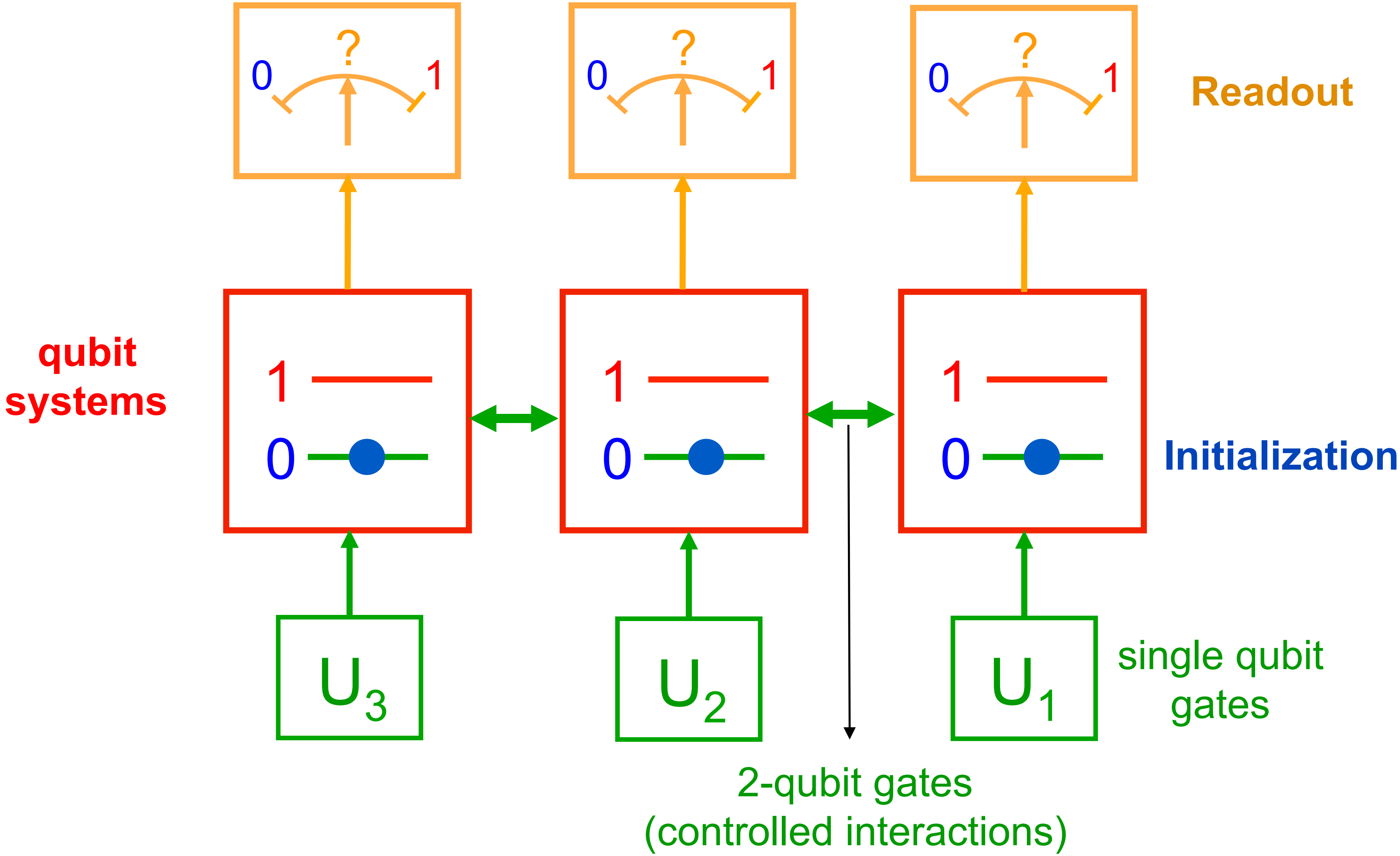
Energy: Room-temperature superconductivity

Solve complex math problems

Security: factoring **and code breaking**

Nobel 2012 citation: *"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."*

What does it take?
(DiVincenzo criteria)

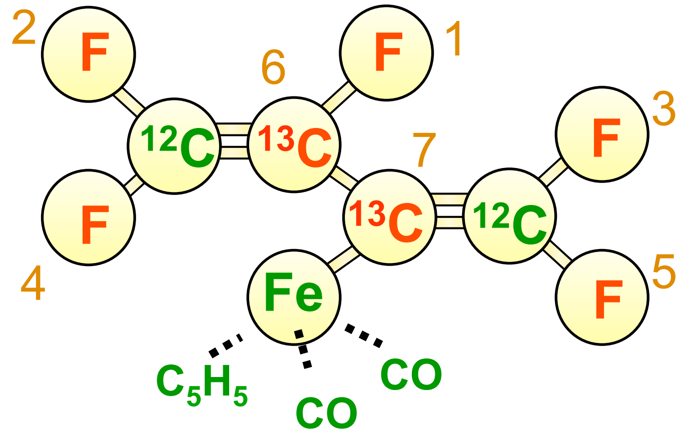


Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

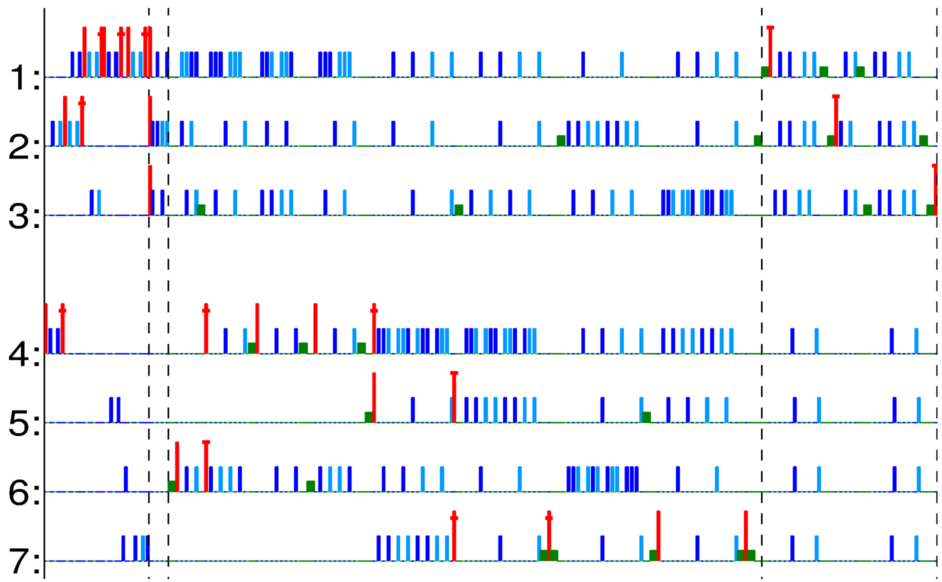
Lieven M. K. Vandersypen*†, Matthias Steffen*†, Gregory Breyta*, Costantino S. Yannoni*, Mark H. Sherwood* & Isaac L. Chuang*†

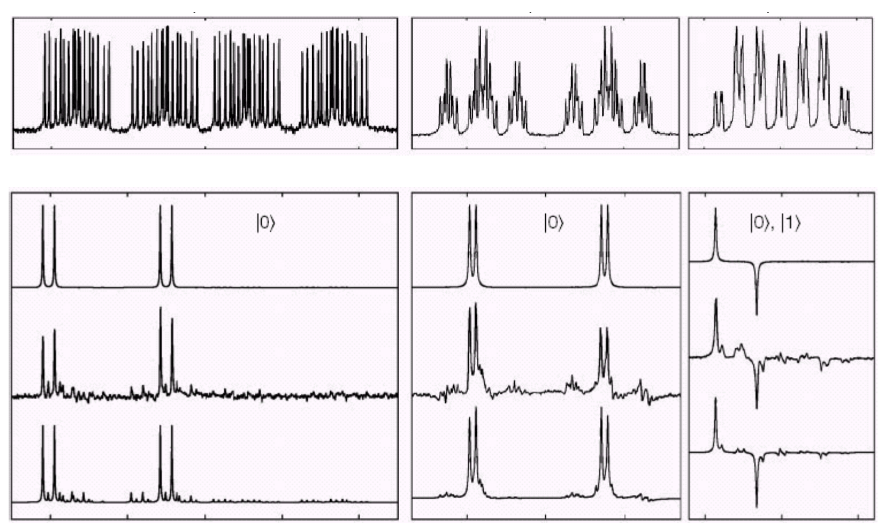
** IBM Almaden Research Center, San Jose, California 95120, USA*
† Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305-4075, USA

NATURE | VOL 414 | 20/27 DECEMBER 2001

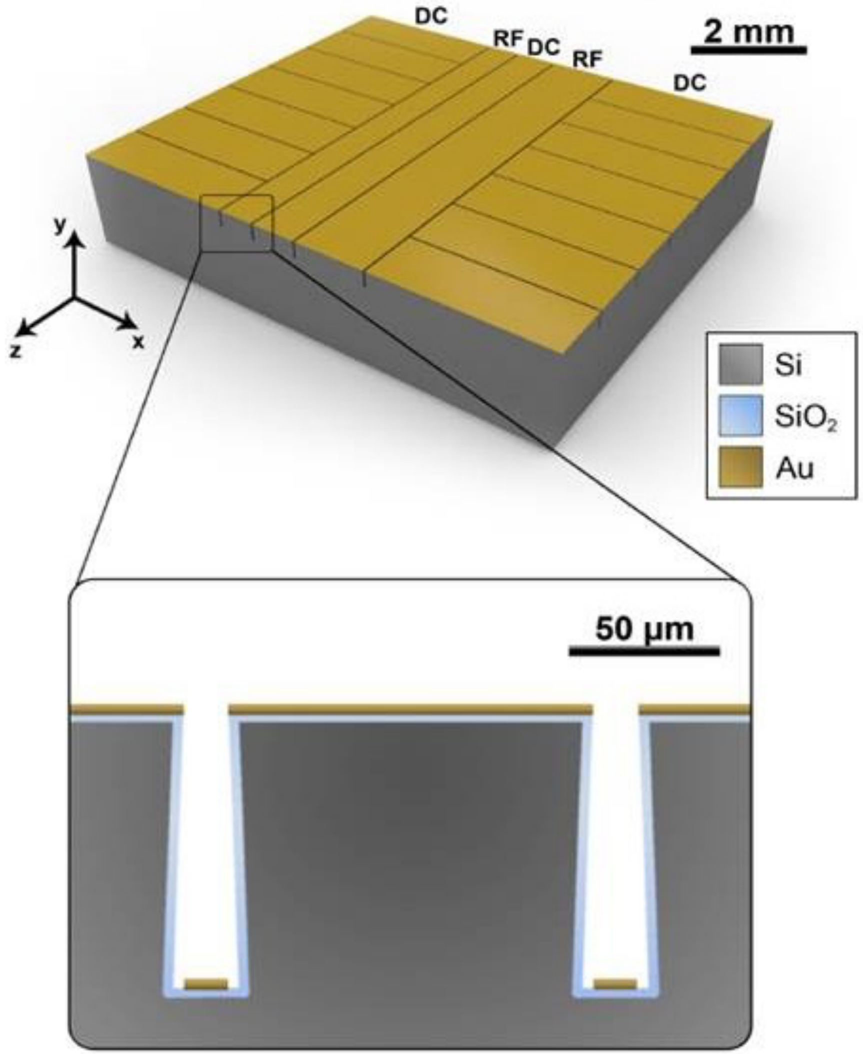


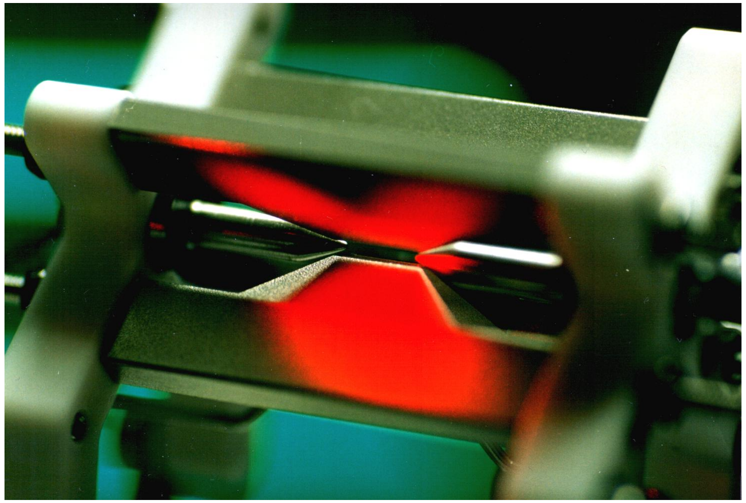
15 = 3 x 5 ...

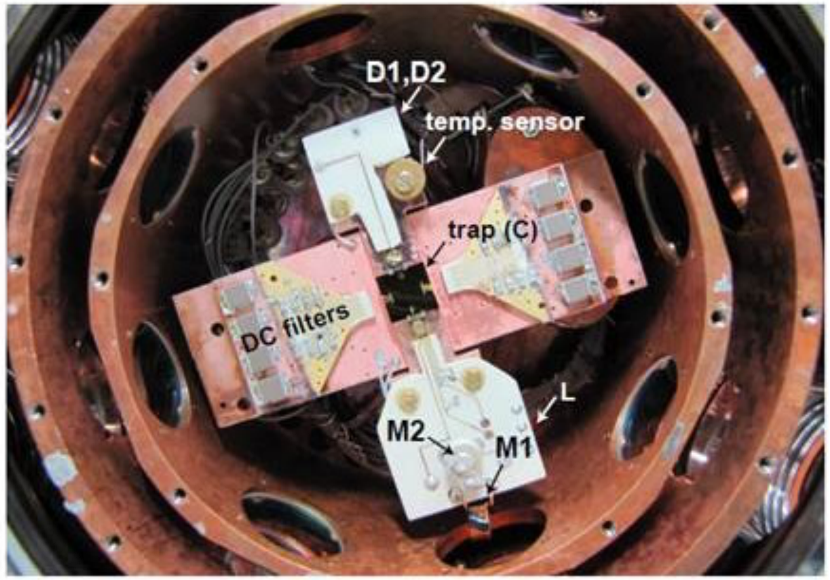




Trapped ions



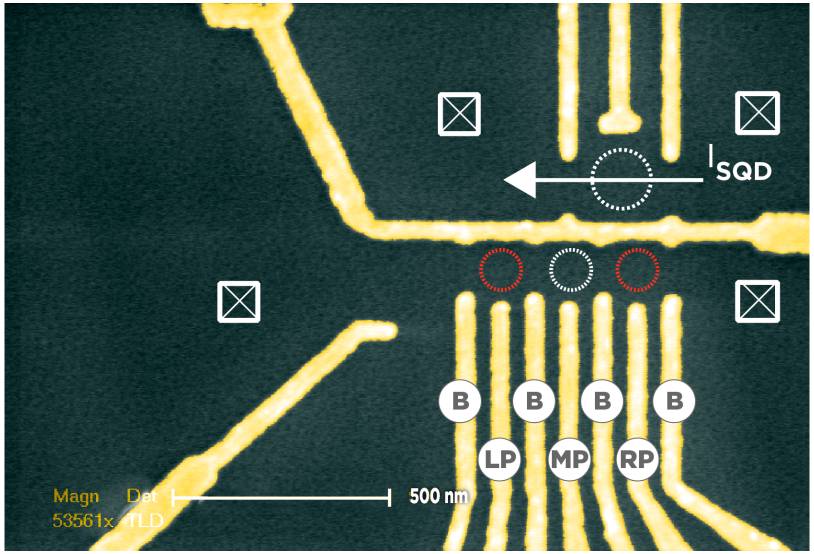




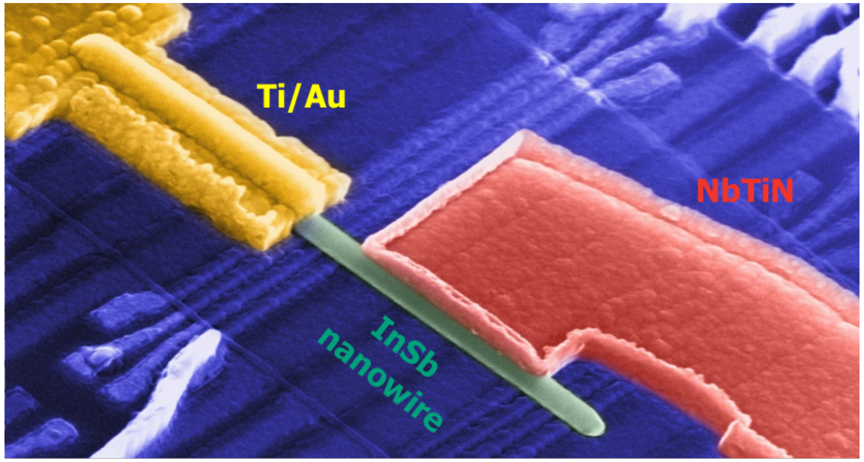
Advance 1: Qubits can be built on a chip!

(Delft examples)

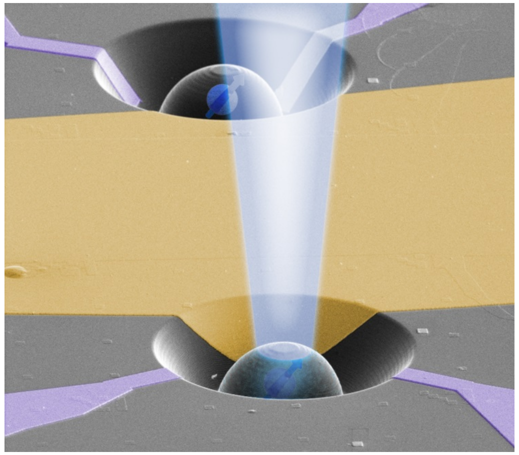
Semiconductor quantum dots



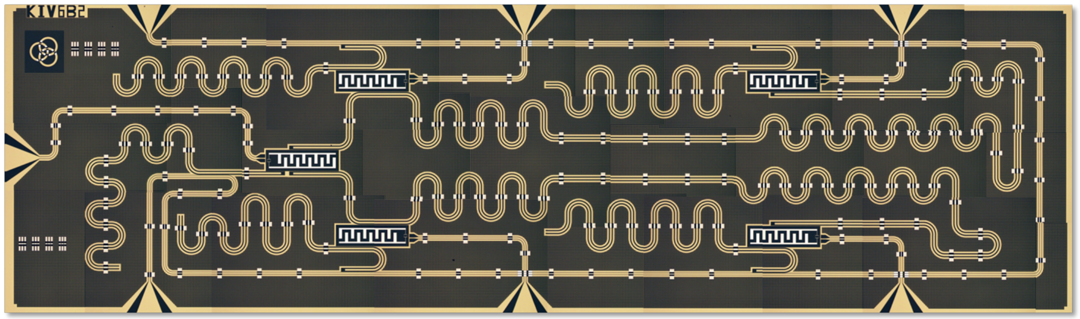
Semiconductor-superconductor hybrids



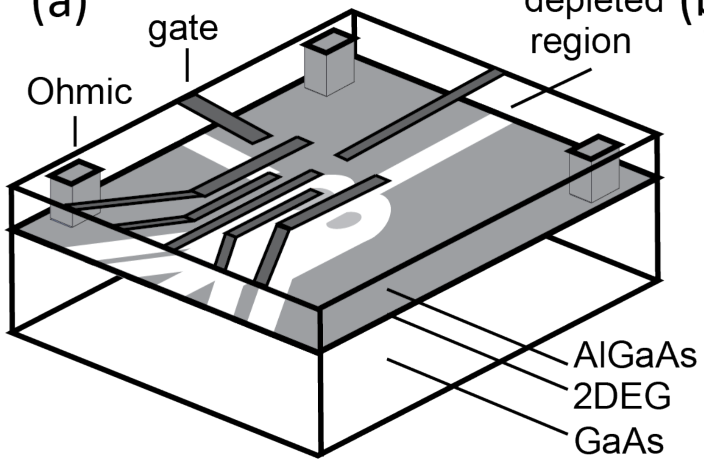
Impurities in diamond or silicon

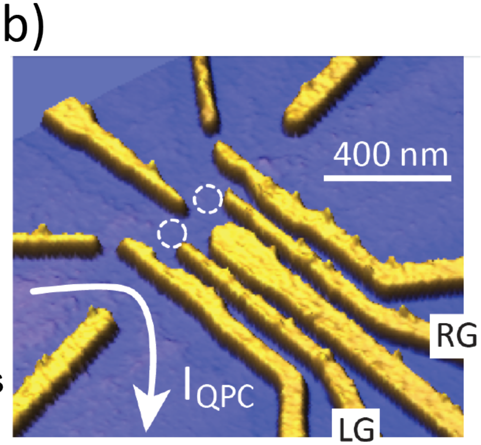


Superconducting circuits



All-electrical semiconductor quantum dots



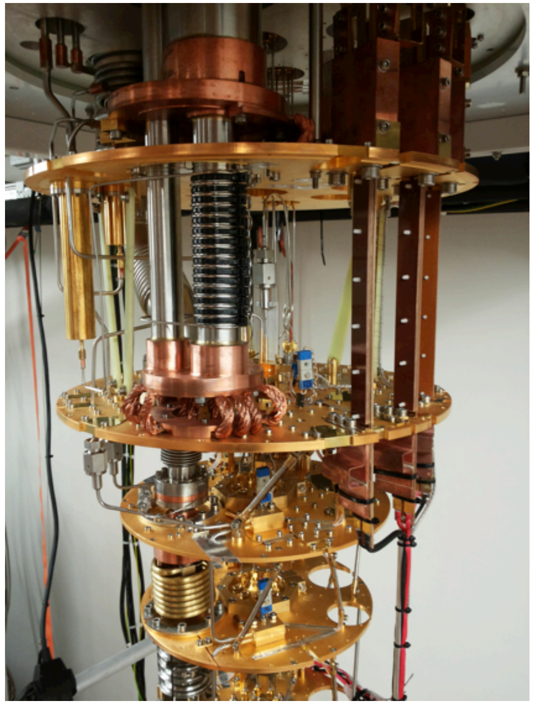


Artificial atoms and molecules

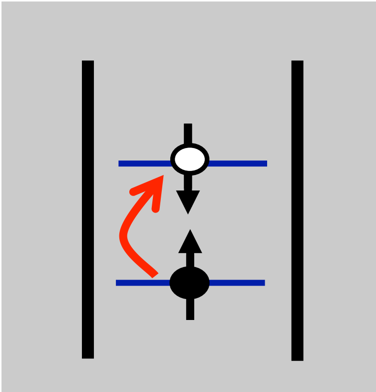
Discrete # charges, quantized orbitals

Electrical control and detection

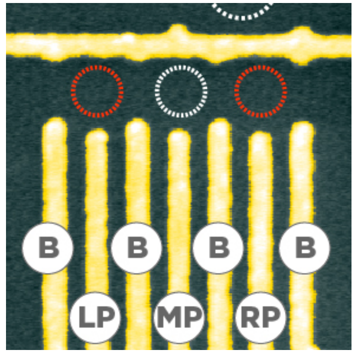
- Tunable # of electrons
- Tunable tunnel barriers
- Electrical contacts

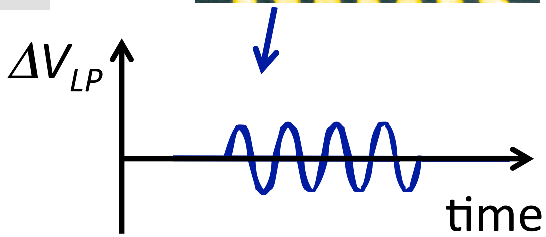


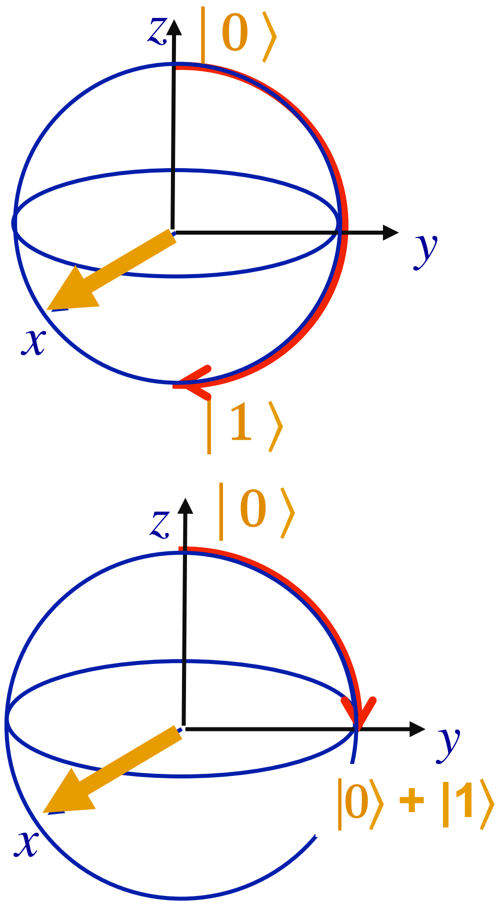
Single-qubit operation

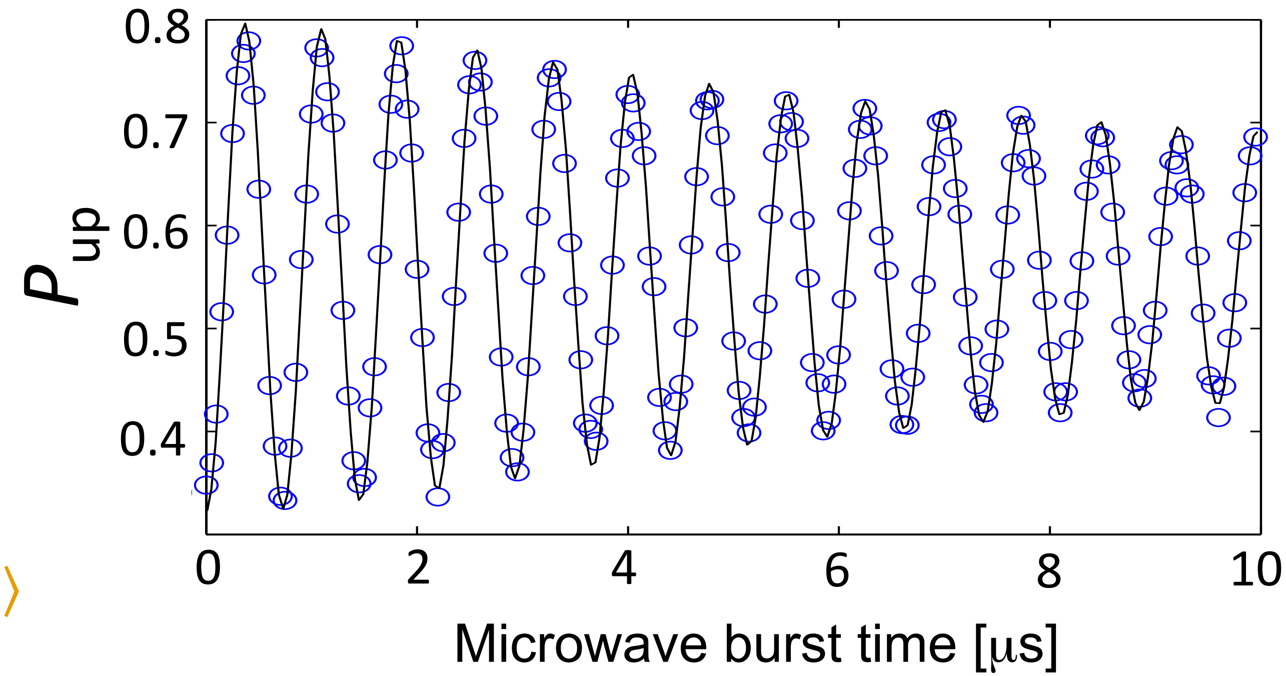


Control individual spins using microwave drive



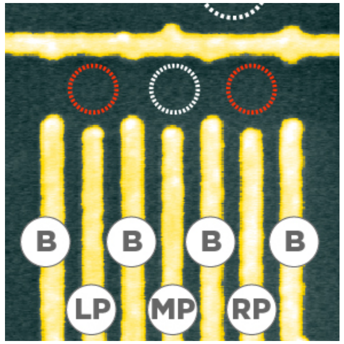


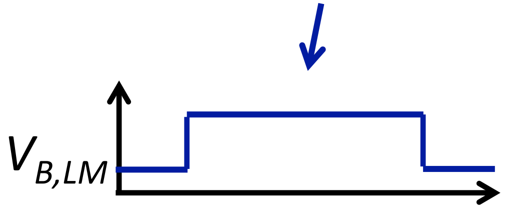




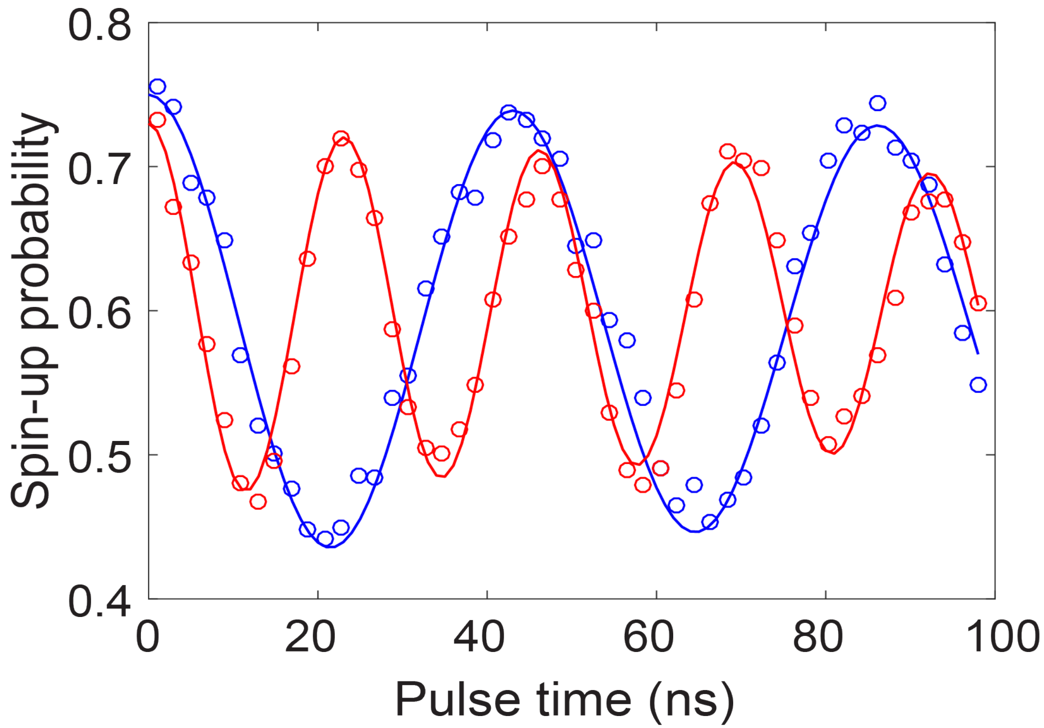
Two-qubit operation

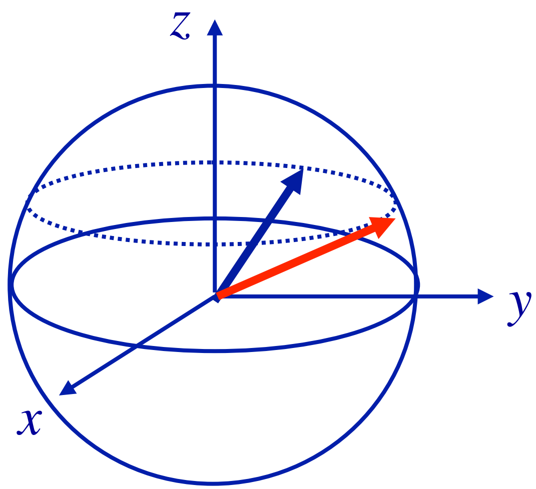
Electrical control of the coupling between neighbouring spins





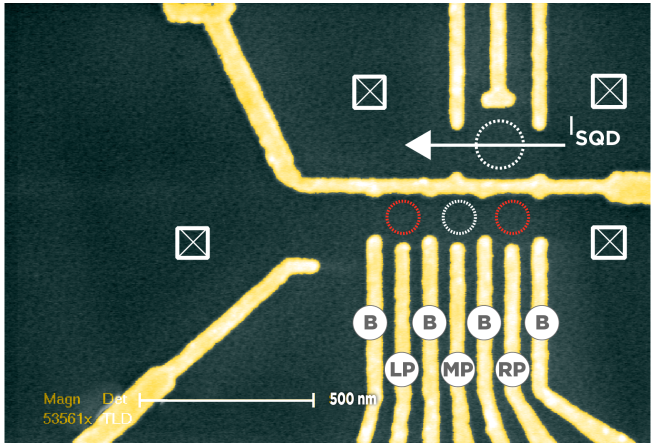
Evolution of spin 2 conditional on spin 1

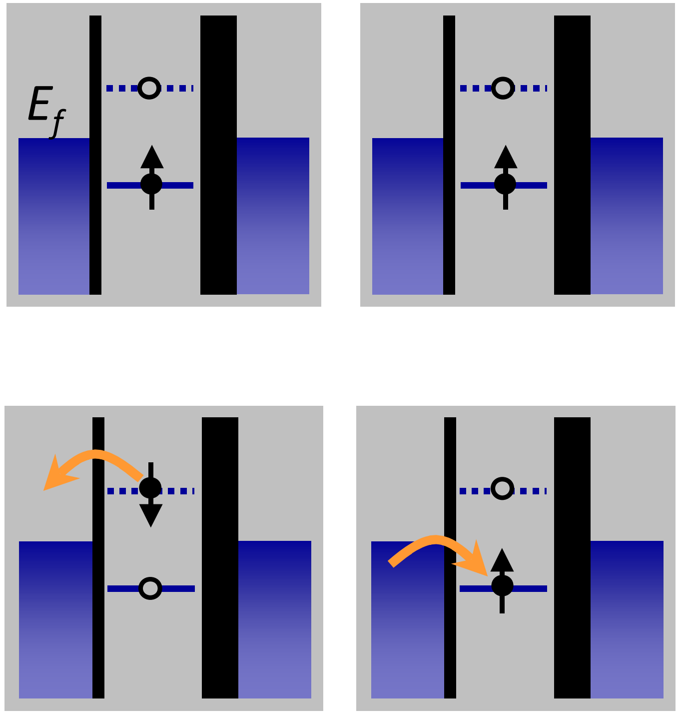


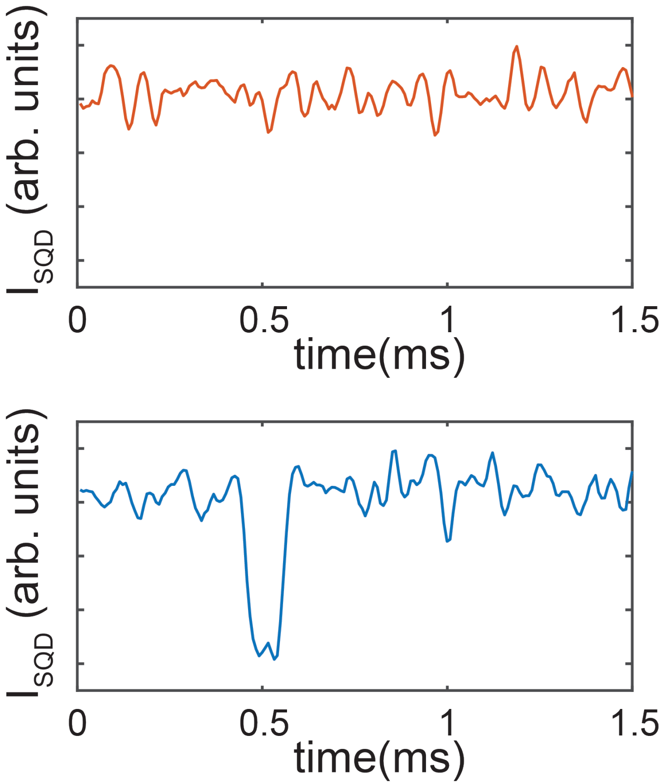


Read-out

Spin-selective tunneling + charge detection

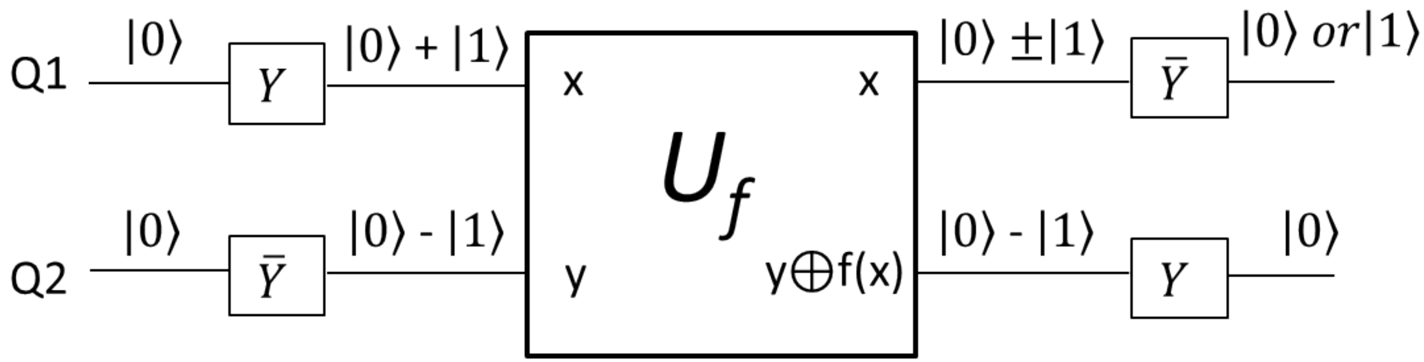


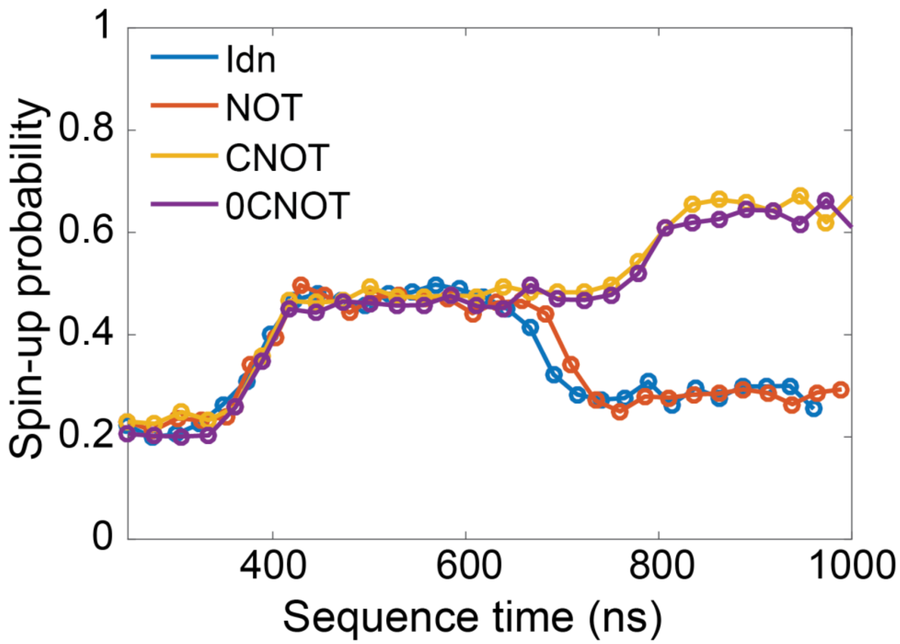


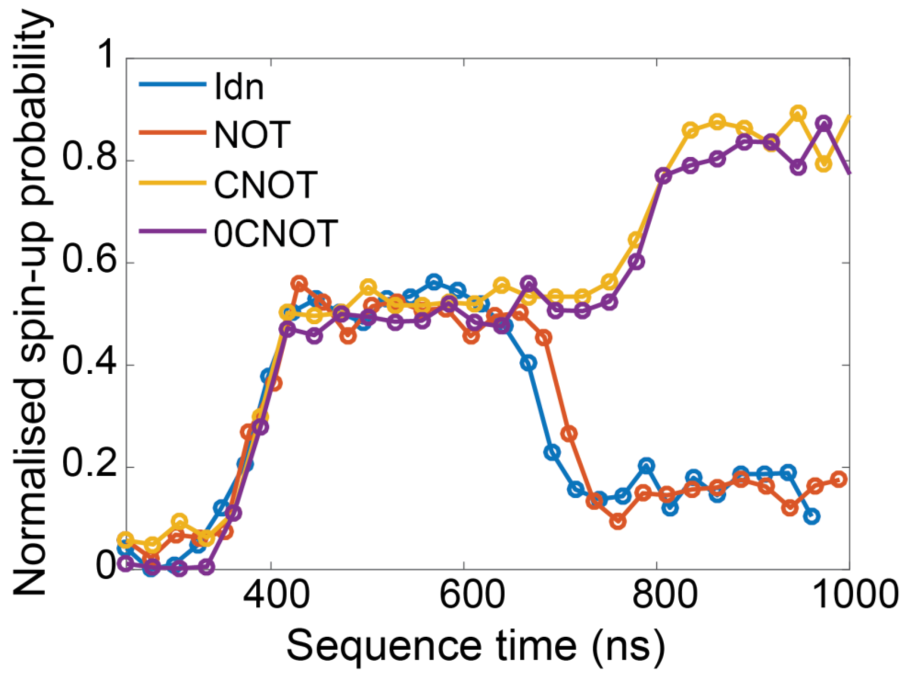


Deutsch-Jozsa algorithm in silicon

T. Watson et al, unpublished

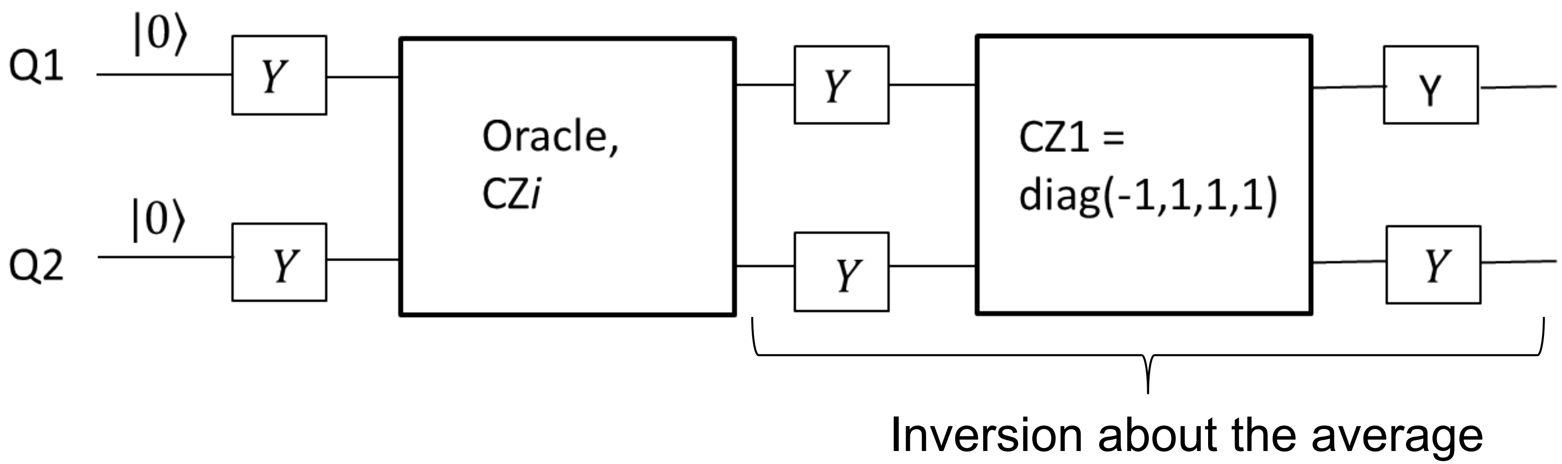


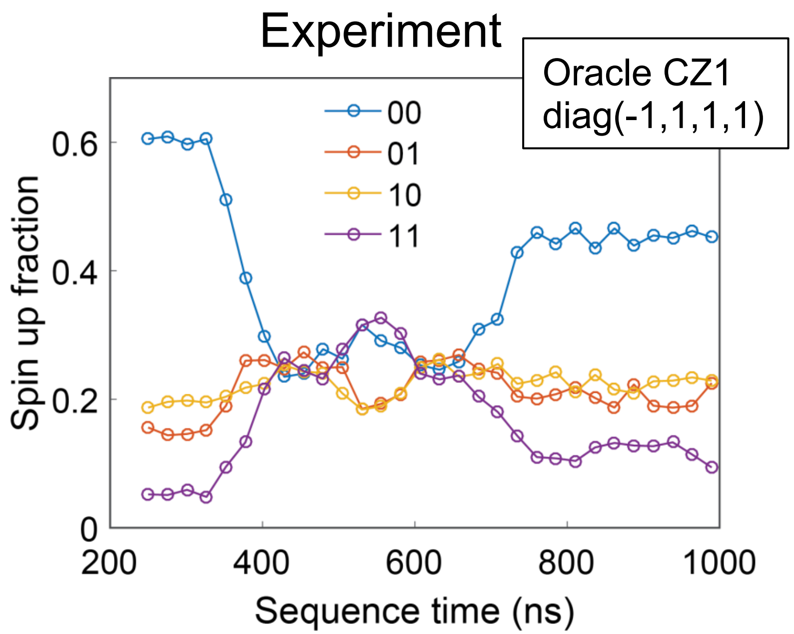


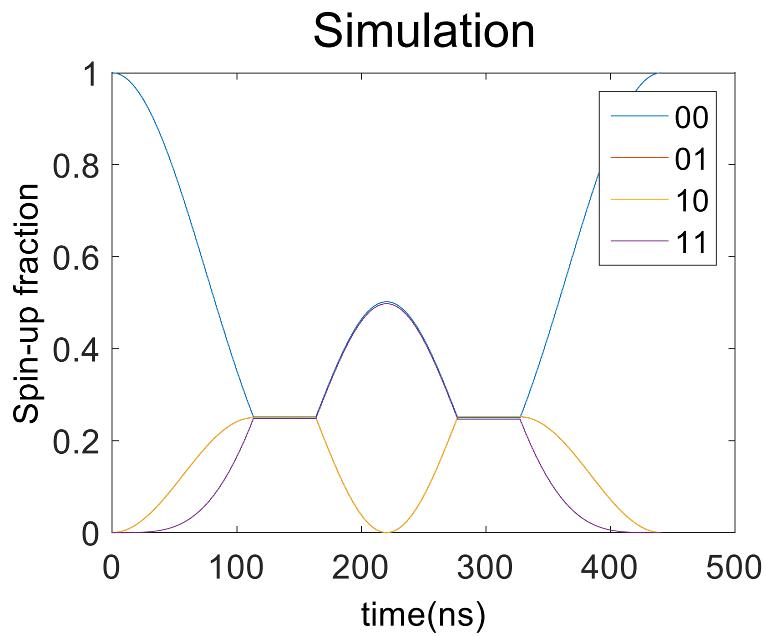


Grover's algorithm in silicon

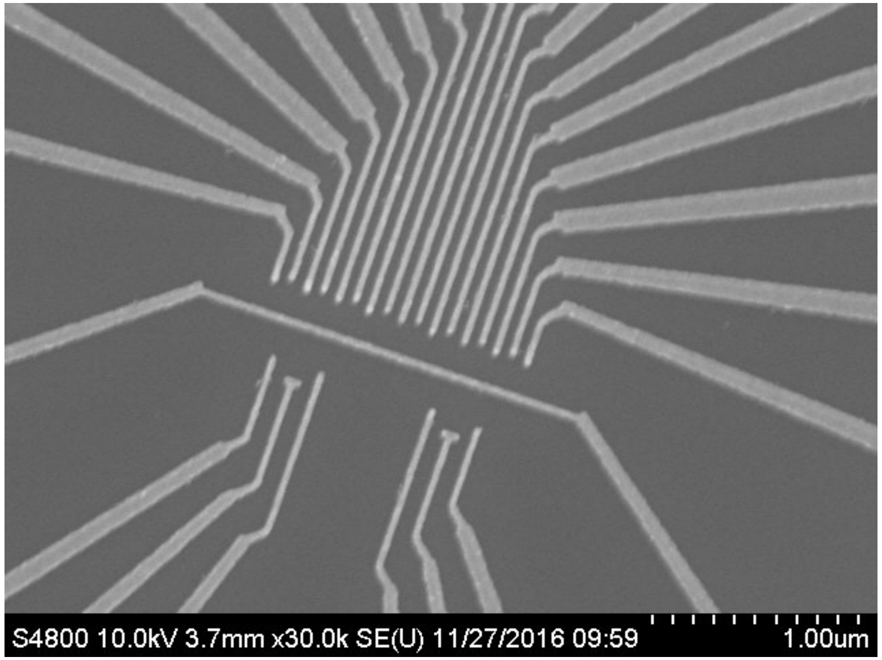
T. Watson et al, unpublished

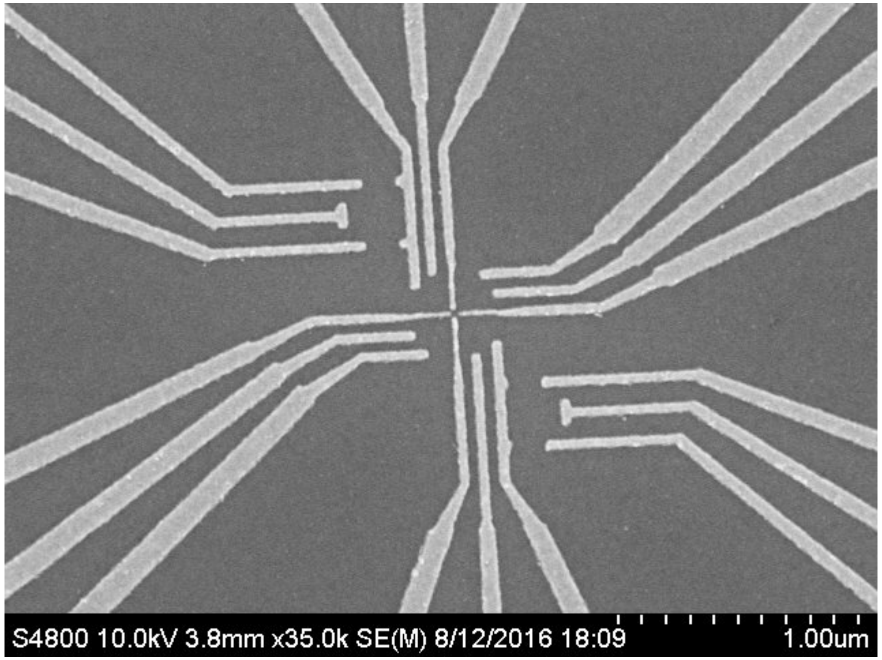






Ongoing – 1D and beyond



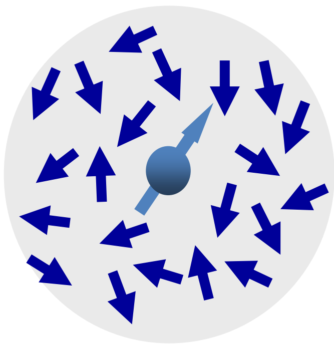


U. Mukhopadhyay, J.P. Dehollain

We can now program and read out
electron spin qubits
in silicon all-electrically

Advance 2: Extending quantum coherence

GaAs

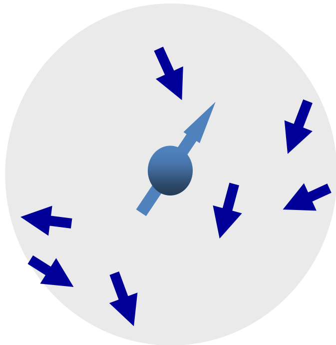


$T_2^* \sim 0.01\ \mu s$

$T_2^{DD} < 0.2\ ms$

Petta et al,
Science 2005

Si

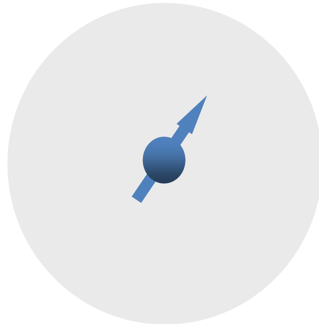


$T_2^* \sim 1\ \mu s$

$T_2^{DD} > 0.5\ ms$

Kawakami, Scarlino, et al,
Nature Nano 2014

^{28}Si



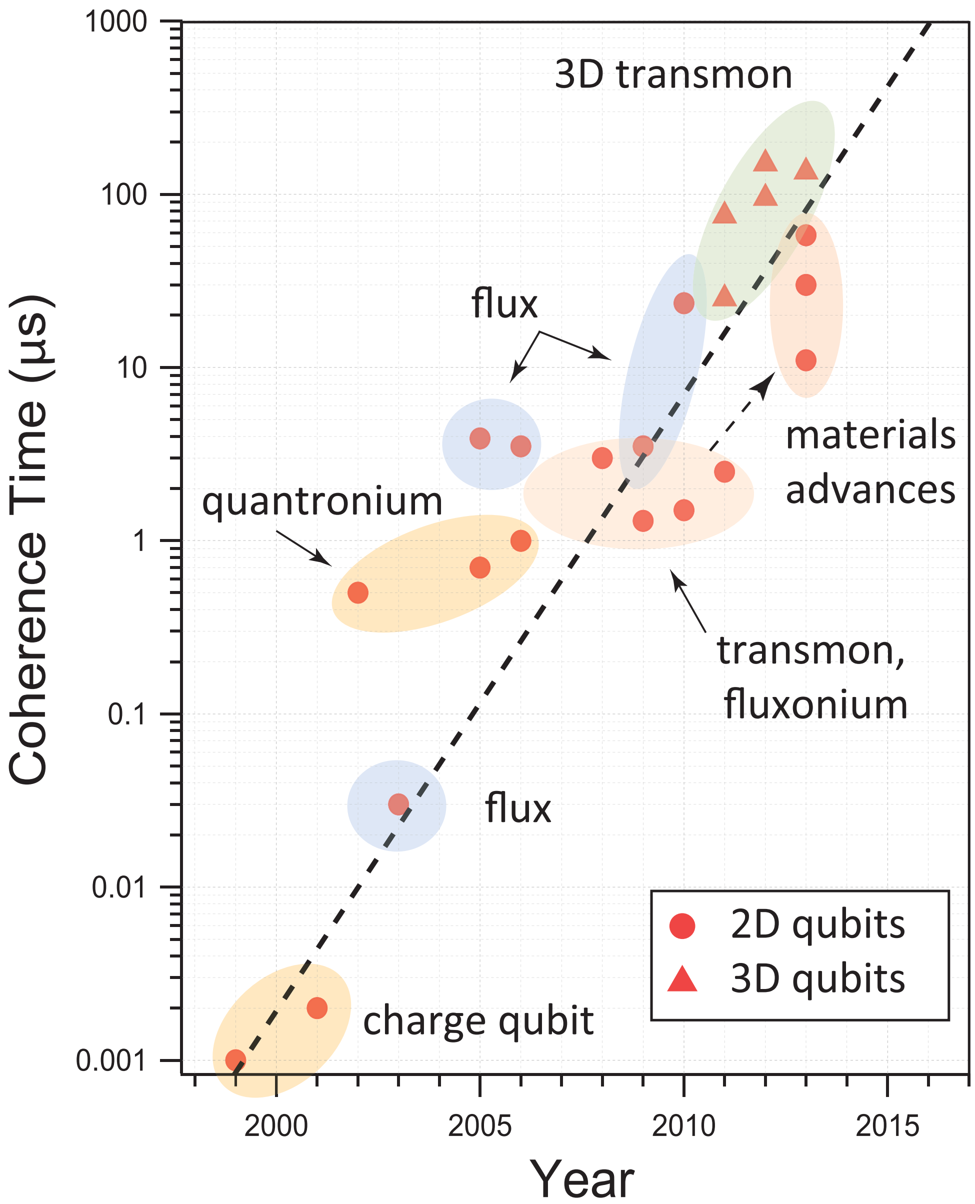
$T_2^* \sim 100\ \mu s$

$T_2^{DD} \sim 28\ ms$

Veldhorst, et al,
Nature Nano 2014

Quantum state lifetimes boosted by four orders of magnitude

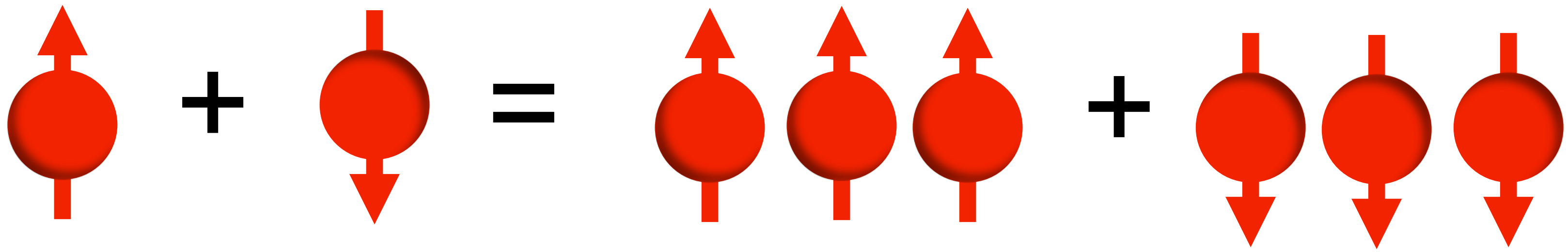
Coherence for superconducting qubits



Oliver and Welander,
MRS Bulletin 2013

Advance 3: Quantum error correction

Use redundancy to remove errors faster than they occur



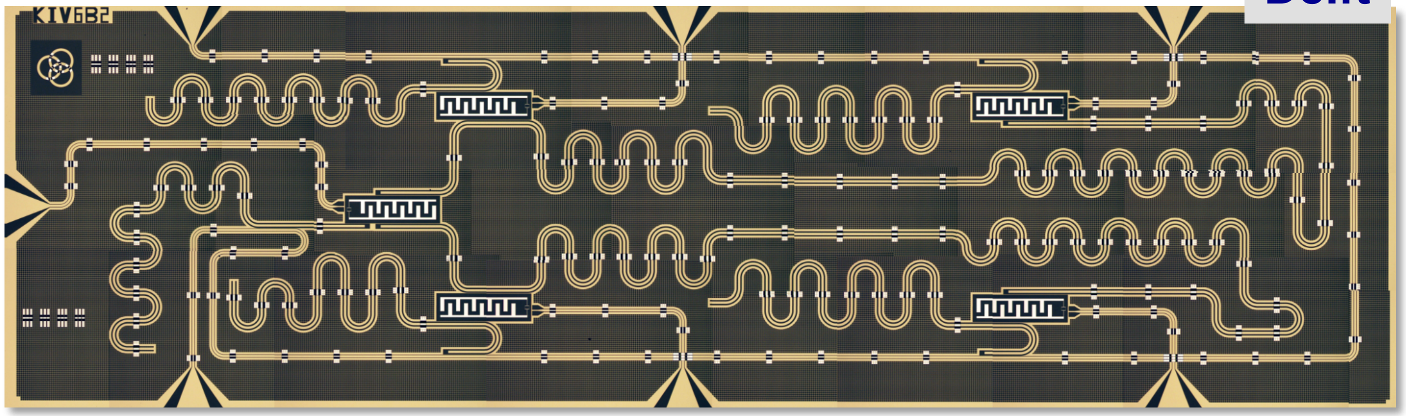
Requires: error probability per step below 1% (previously below 0.01%)
large redundancy (100x to 10,000x)

Can preserve quantum states for as long as is needed!

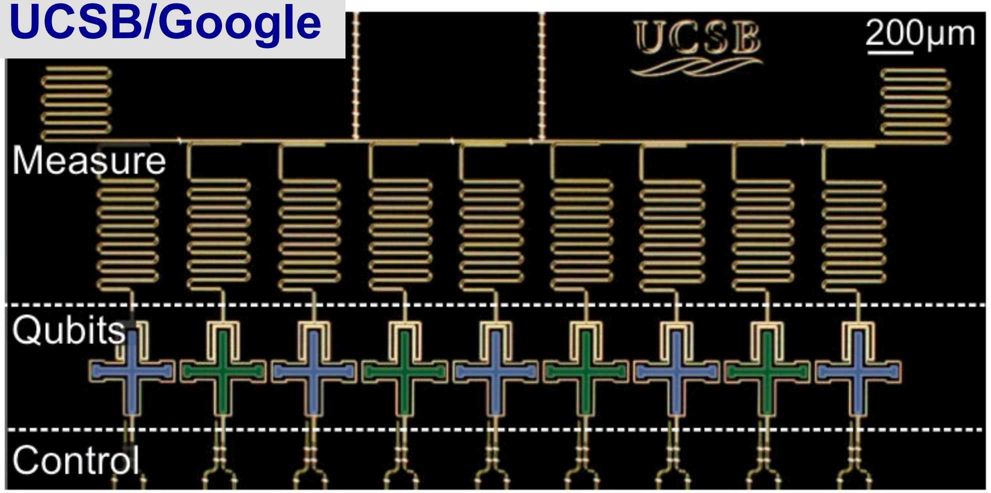
Raussendorf and Briegel, Phys. Rev. Lett. 2007

Quantum error correction demonstrated using superconducting qubits

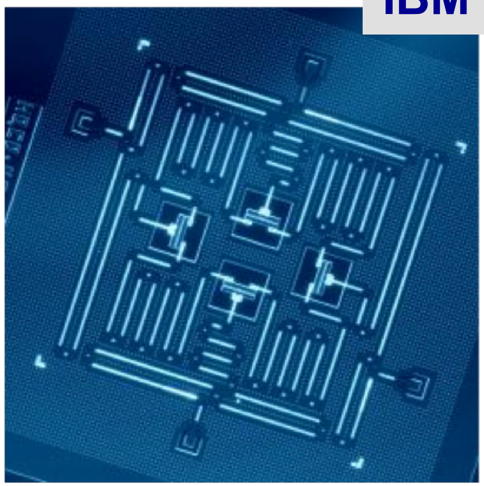
Delft



UCSB/Google

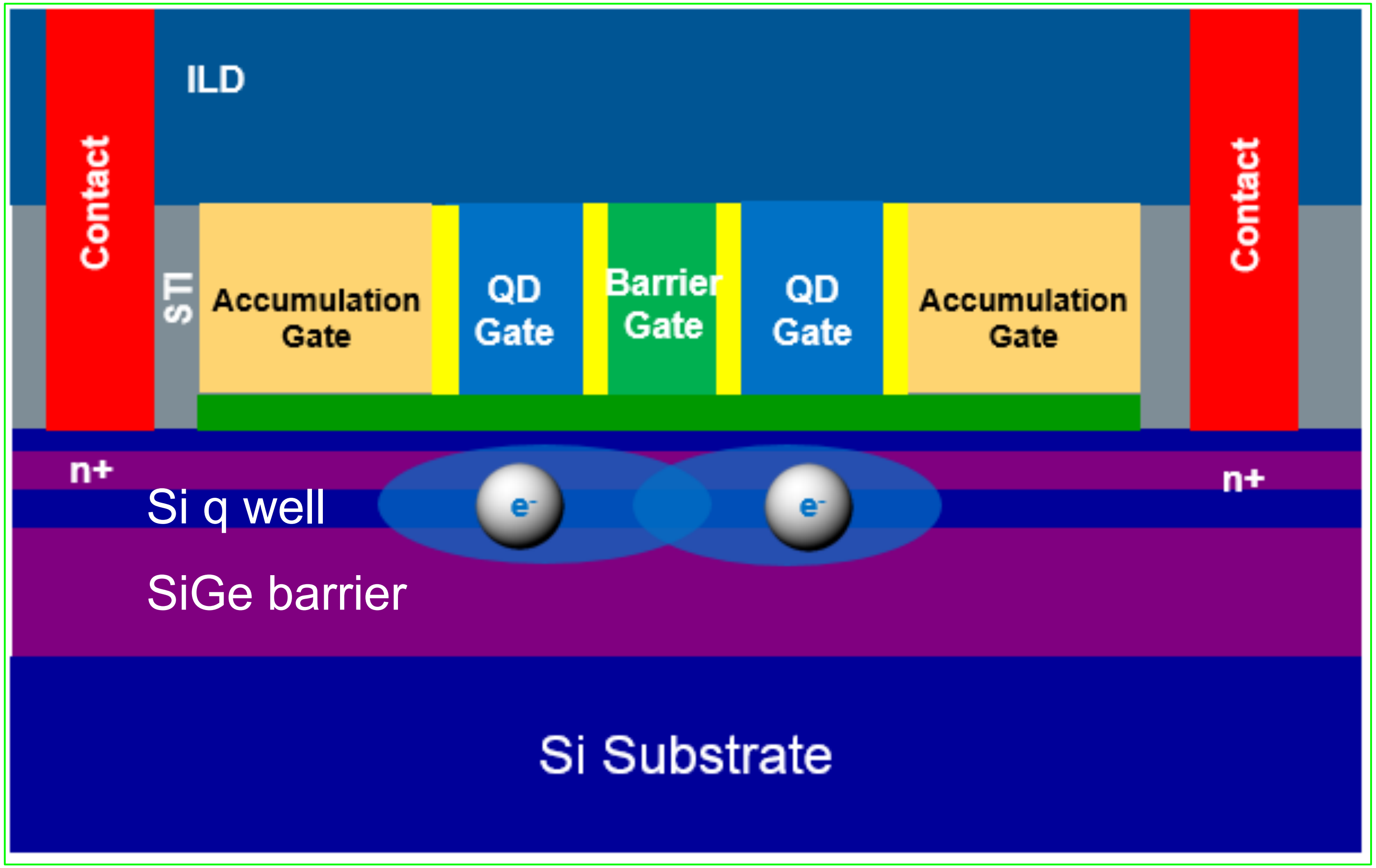


IBM



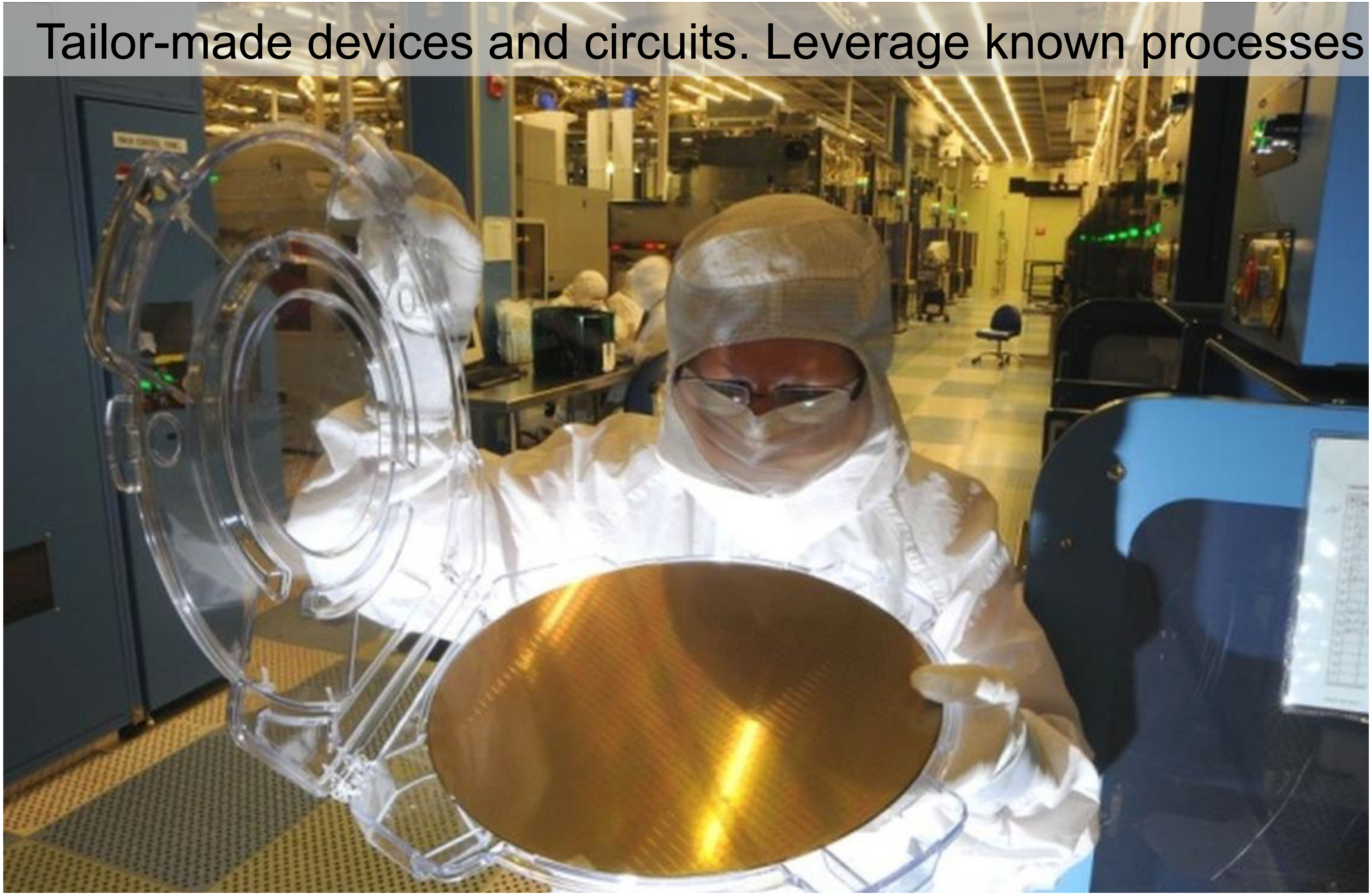
What stops us from having a quantum computer today?

Challenge 1: Qubits have personalities

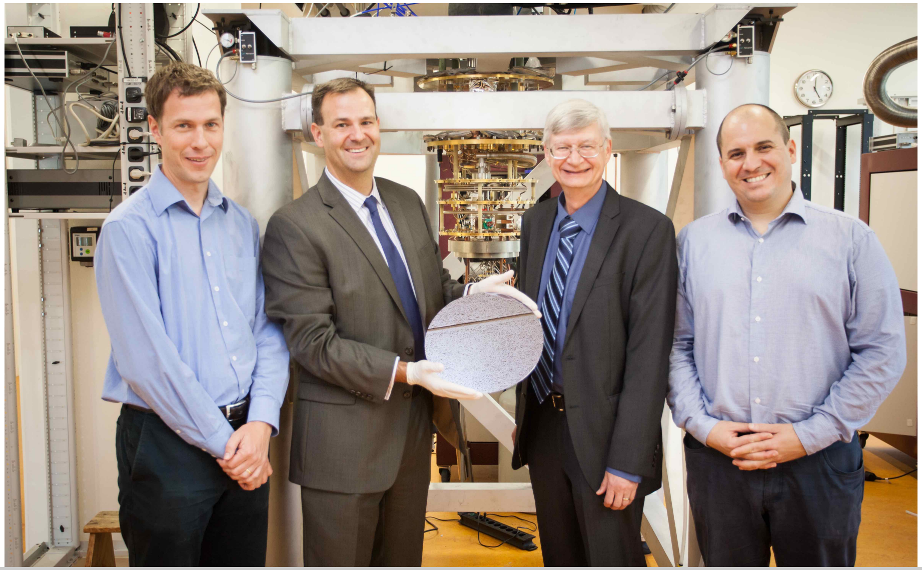


Qubit is much more sensitive to CD variations, scattering, defects, charge noise and even nuclear spins

Way forward 1: Use industry cleanrooms



QuTech-Intel collaboration

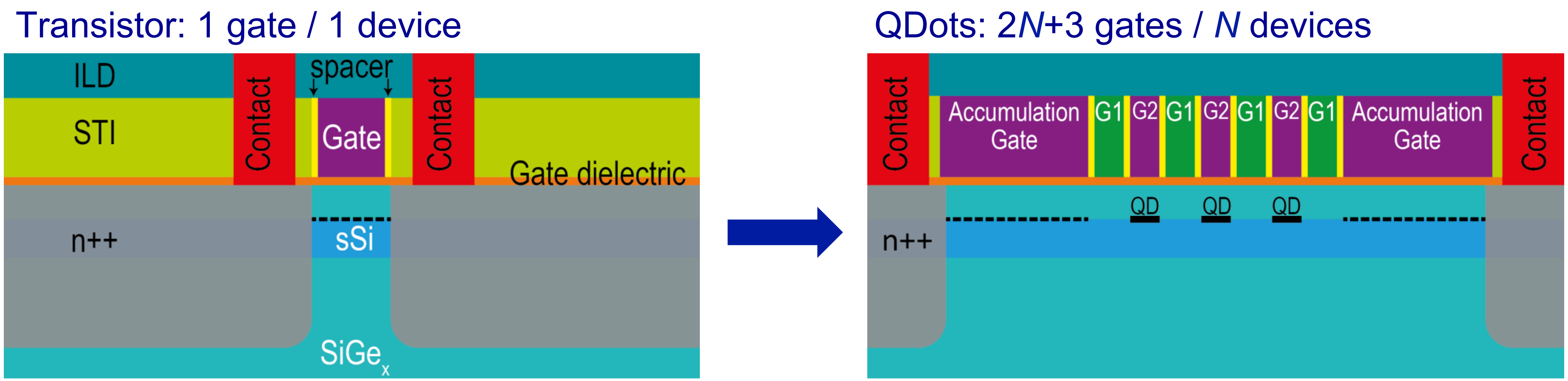


10 years, 50 M$

Silicon spin qubits
Transmon qubits

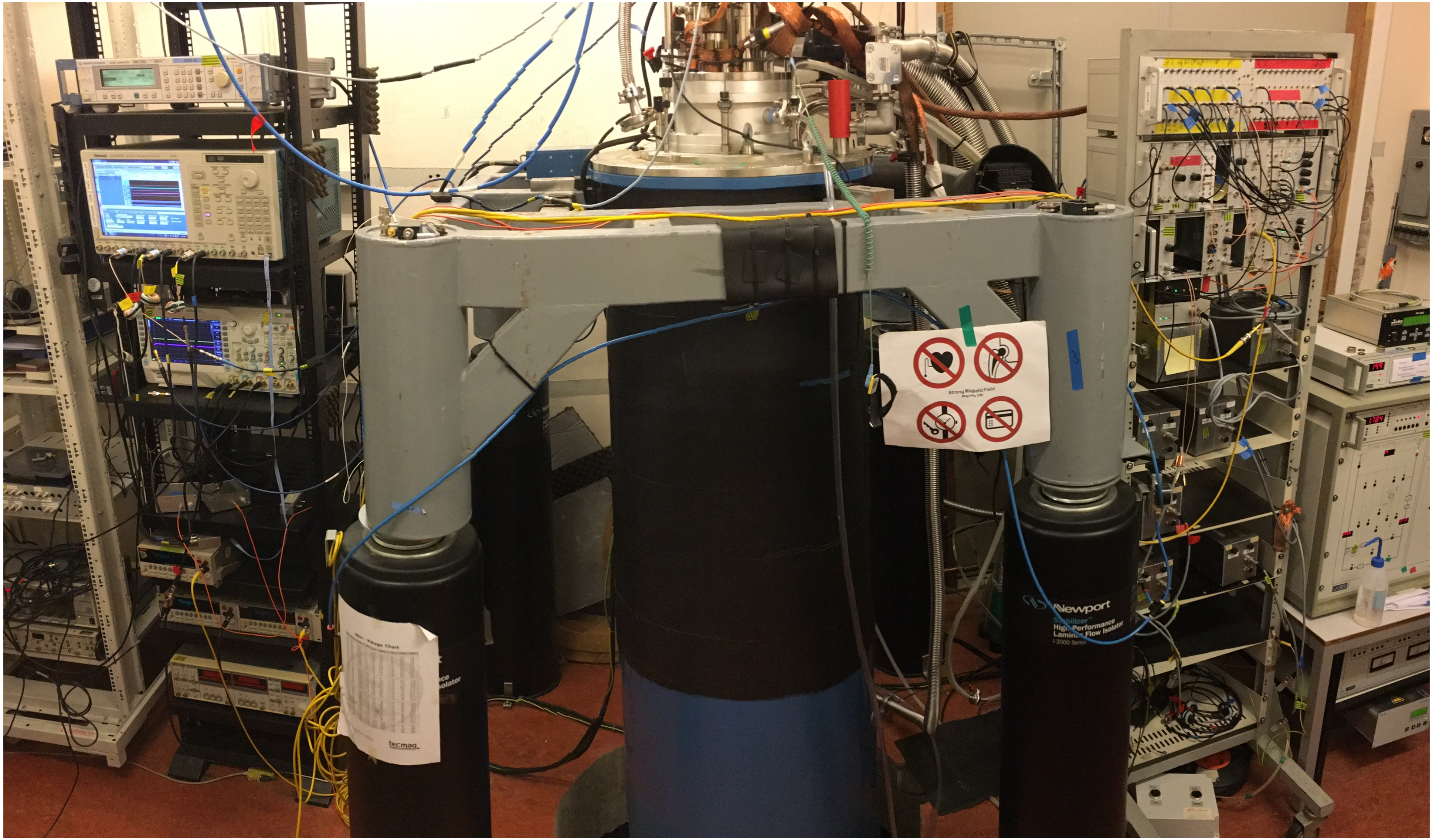
Architecture, Cryo-CMOS, interconnects

Coming this year: quantum dot arrays made @ Intel 300 mm cl



Challenge 2: Scalable control circuits

Today: bulky, expensive equipment



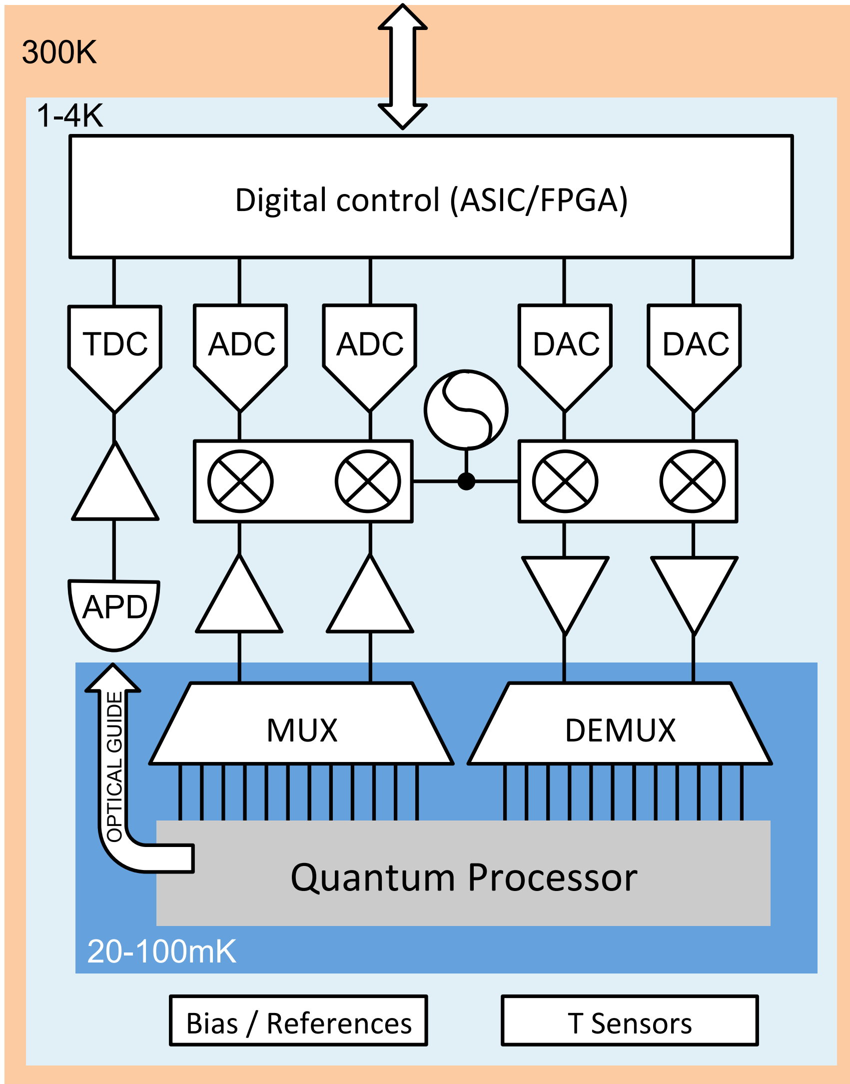
Way forward 2 : Tailored (cryo-)electronics

Integrated electronics
1% accuracy in all parameters

60 K

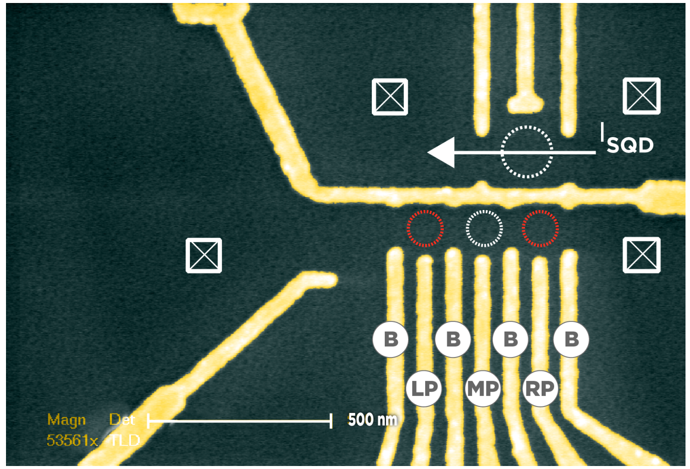
4 K
2 W

100 mK
0.5 mW



E. Charbon et al., “Cryo-CMOS for Quantum Computing”, IEDM 2016.
See ISSCC 2017, Paper 15.5 (Tuesday)

Challenge 3: Wiring up qubits



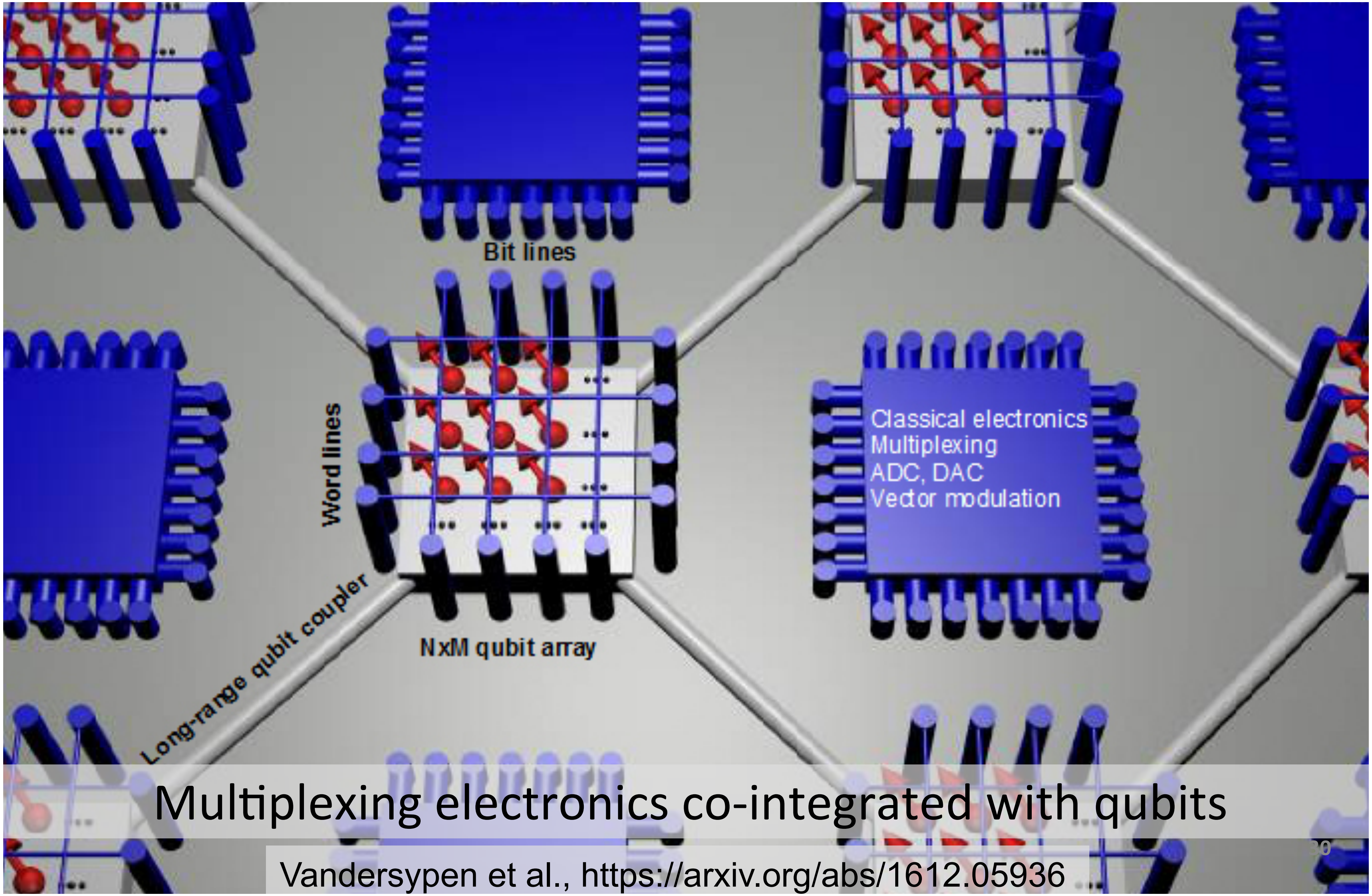
Processor
- 10^9 transistors
- 10^3 pins

Memory
- 10^{12} bytes
- 10^2 pins

Quantum dots
- 3 qubits
- 16 pins

Require signals to/from every single qubit

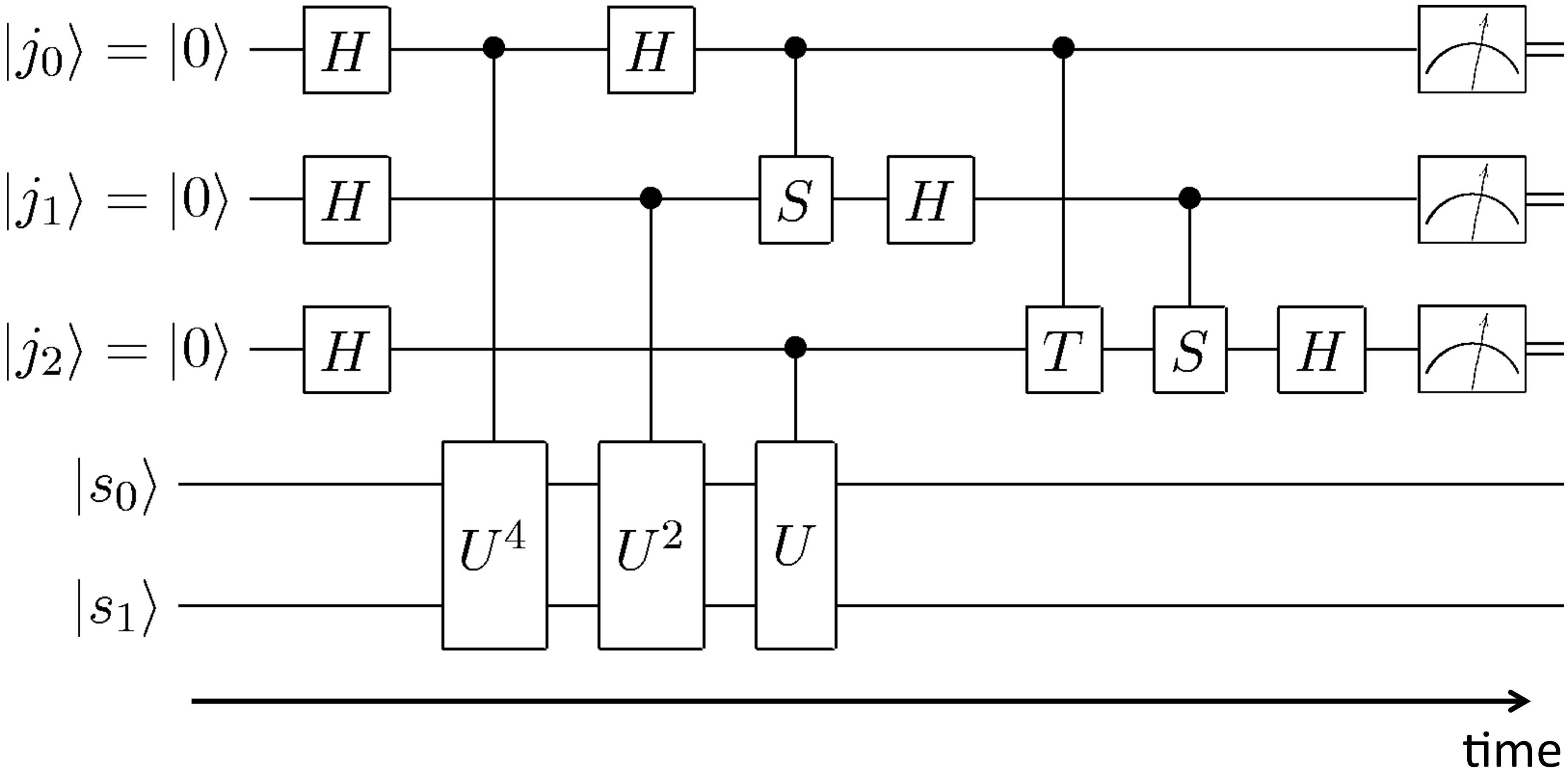
Way forward 3: Quantum version of Rent's rule



Multiplexing electronics co-integrated with qubits

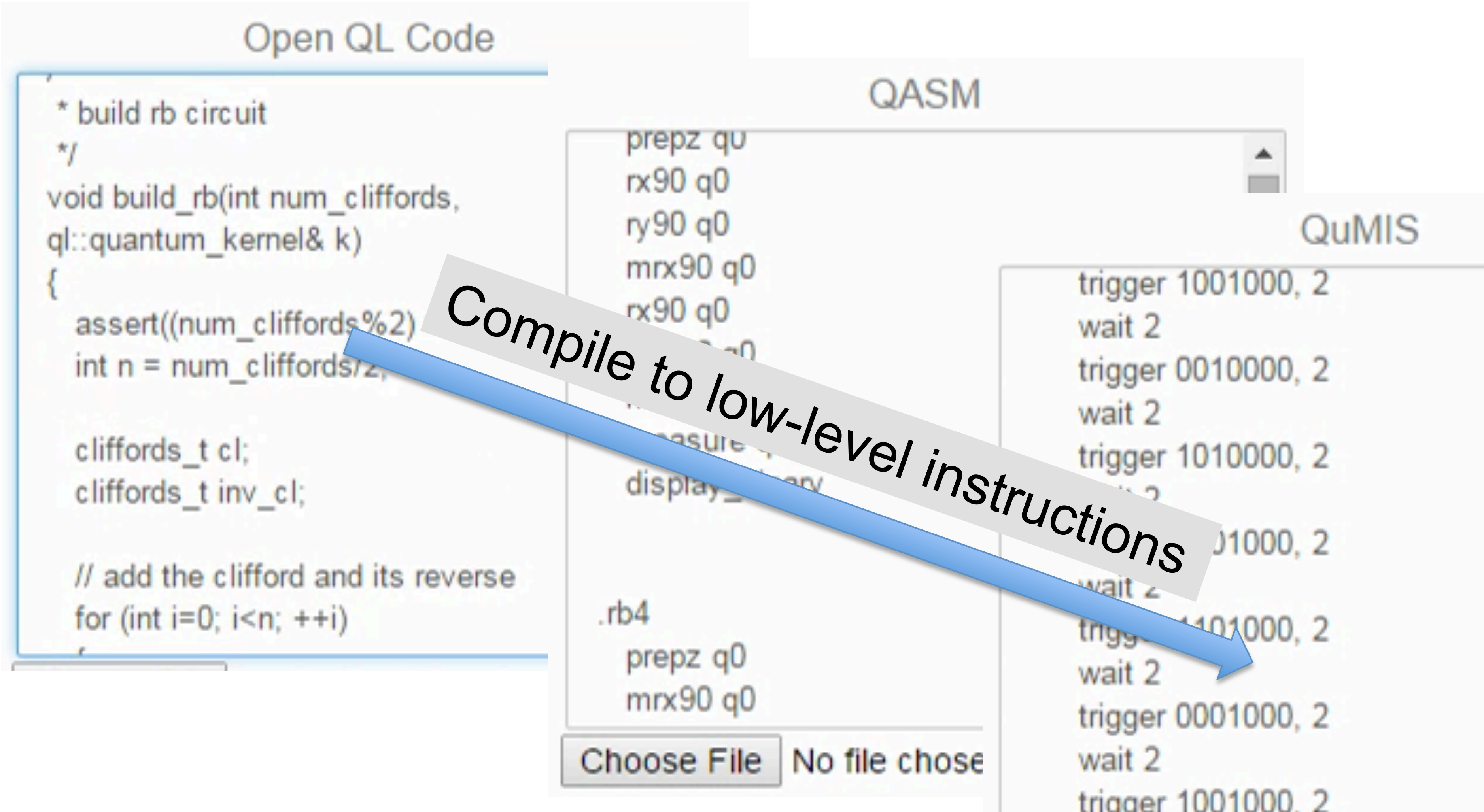
Vandersypen et al., https://arxiv.org/abs/1612.05936

Challenge 4: Architecture



Does not map to any established architecture

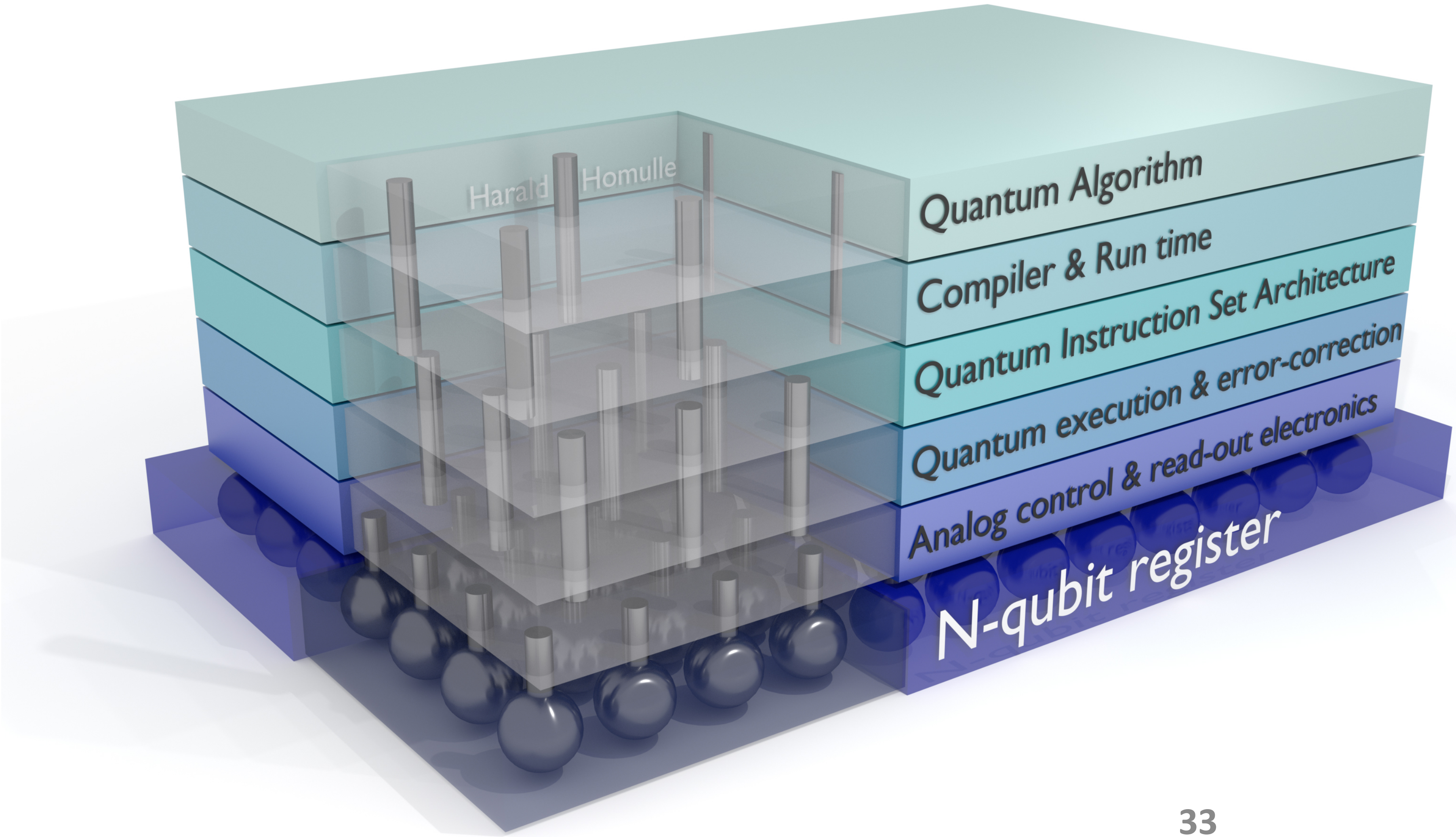
Way forward 4: Quantum architecture



Recycle ideas where possible
Rethink where needed

Systems approach needed

Challenges in each layer **Layers are highly interrelated**



QuTech partnership @ Delft

Quantum technology will not be built by physicists alone

TU Delft

Delft University of Technology

TNO

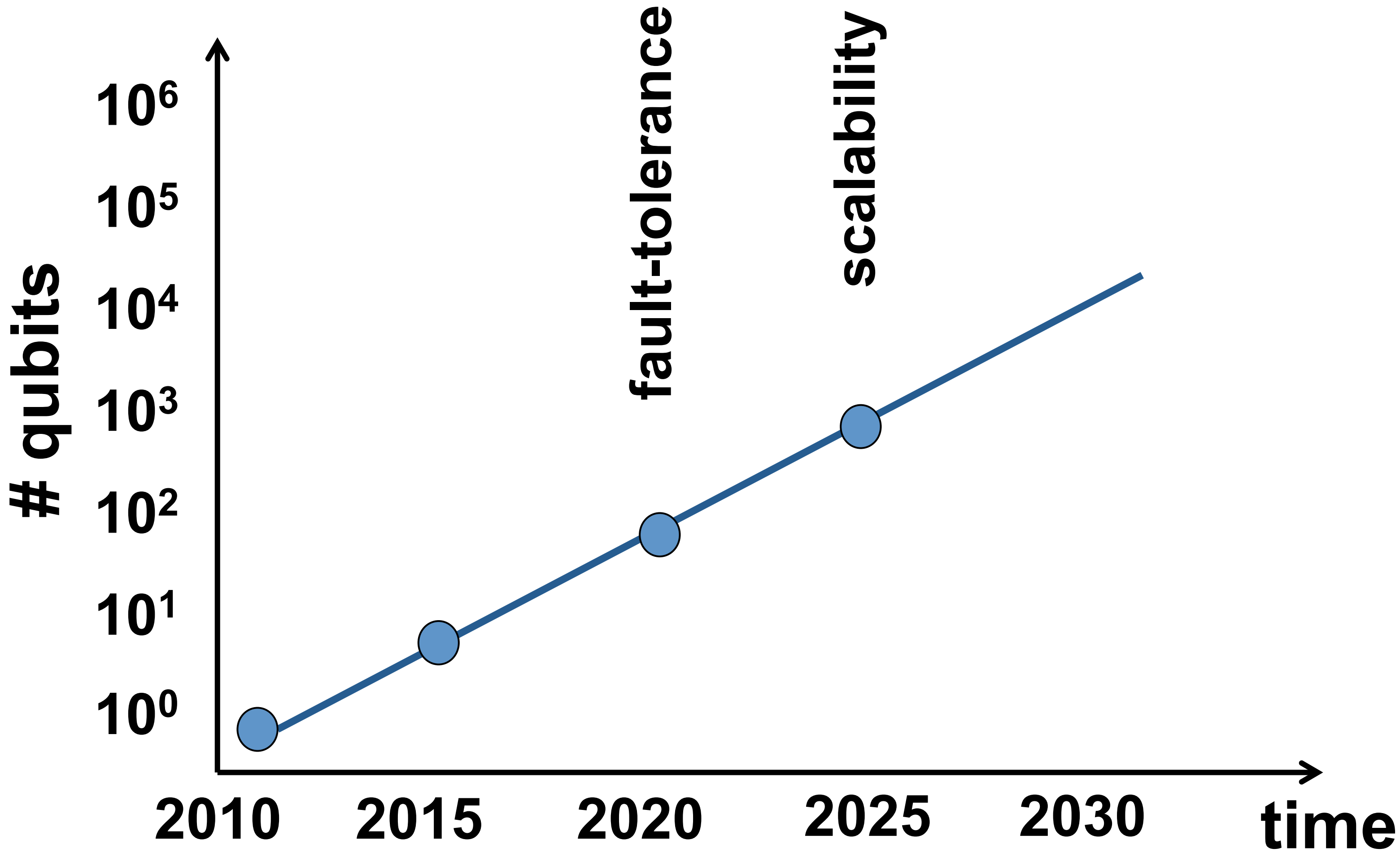
With support from: NWO FOM STW

5 engineering faculty, 5 physics faculty
20 senior scientists
20 technicians
10 administrative staff
building renovation, nanofab facilities, equipment

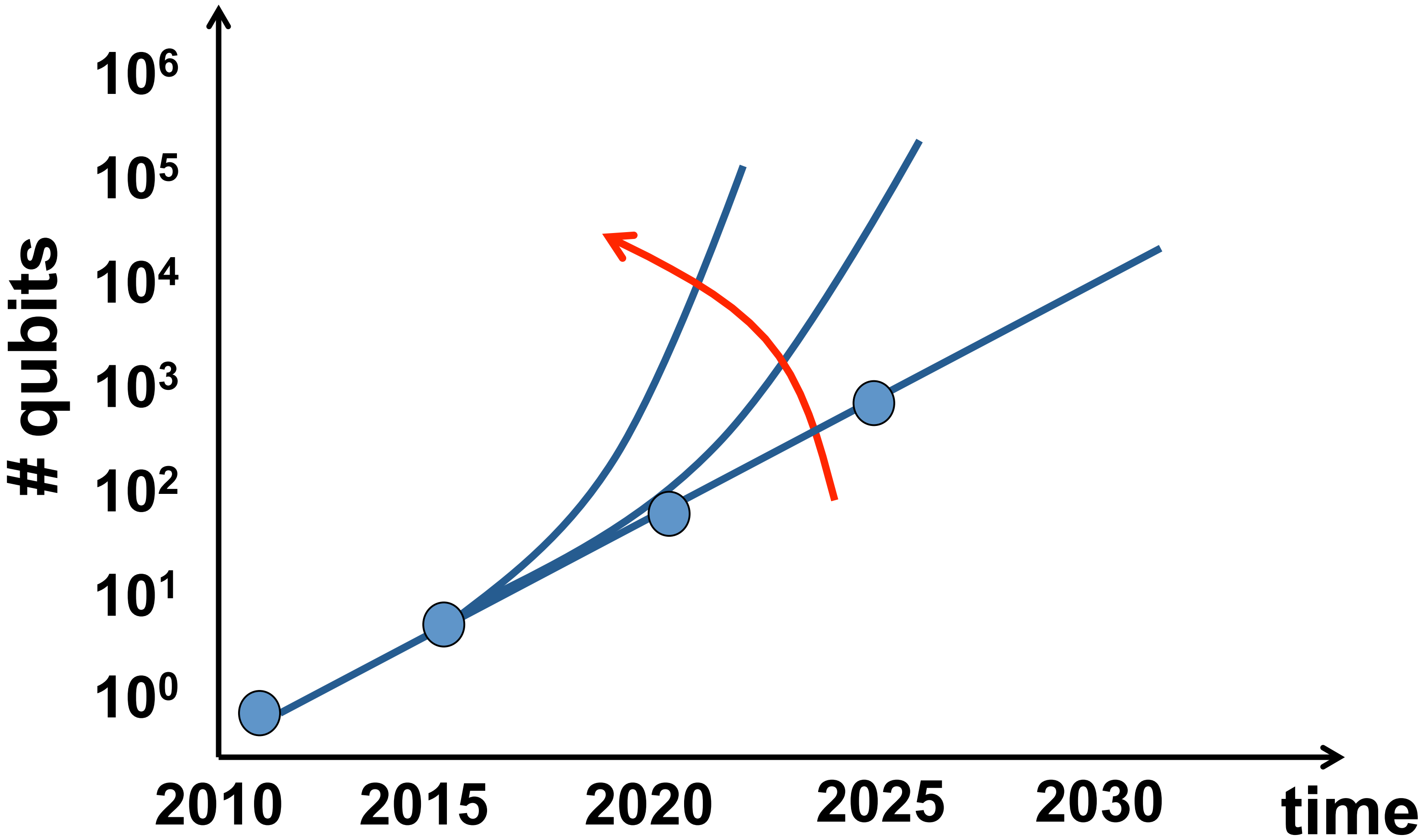
PhD students and postdocs to be funded through external sources


Requires a team effort

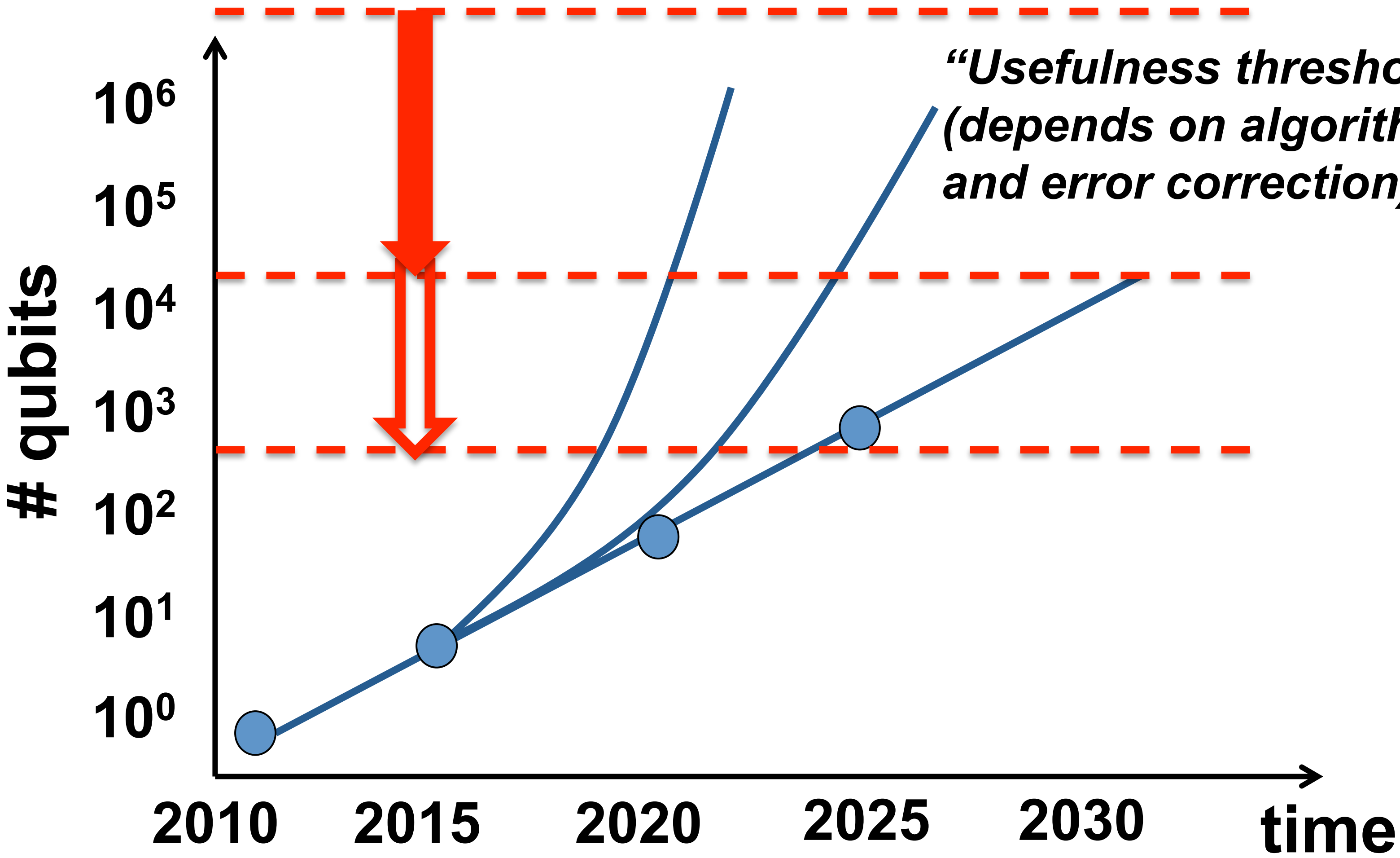
Projecting quantum progress



Can we accelerate hardware development?

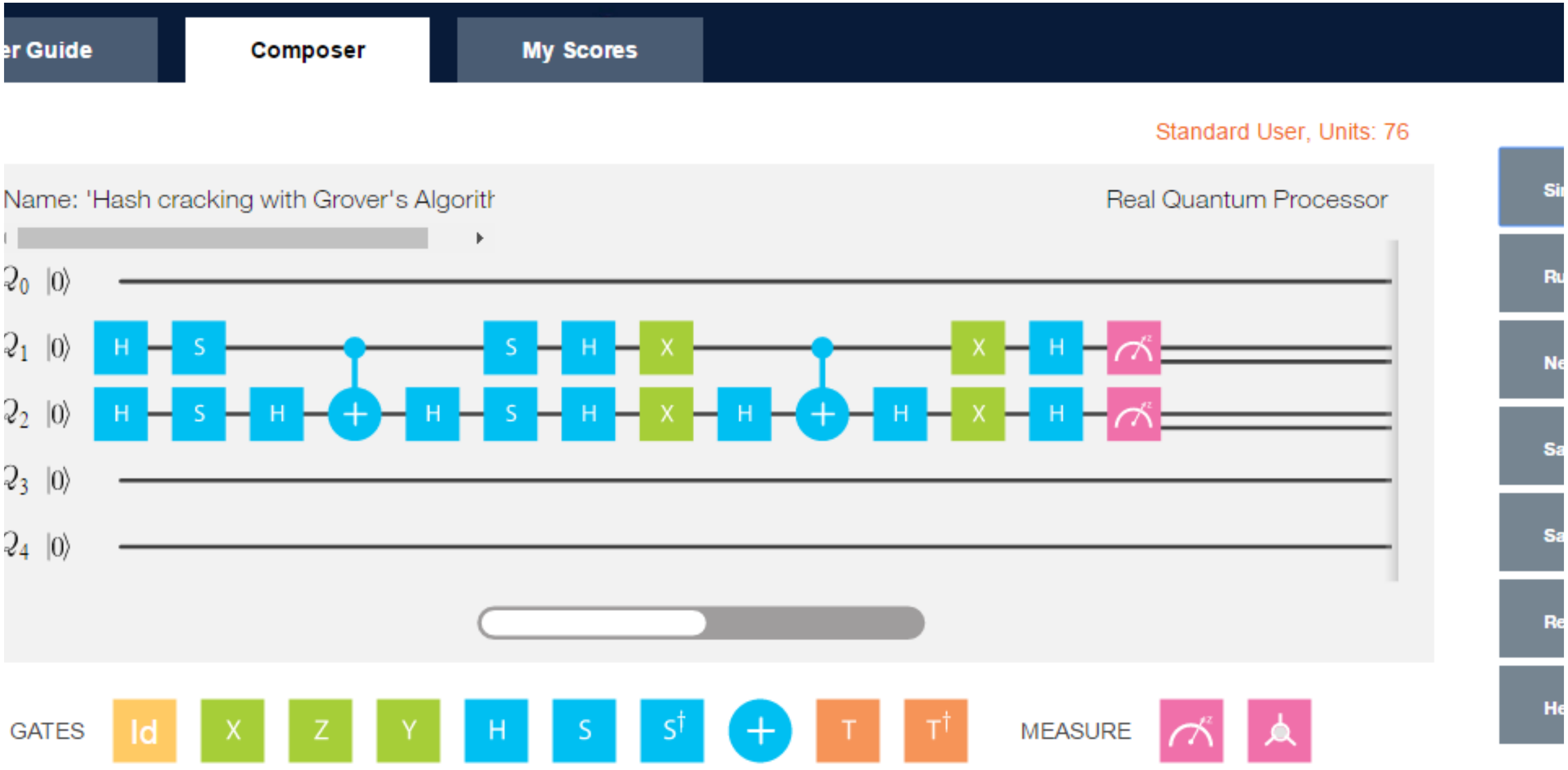


Can we accelerate software development?



IBM Quantum Experience

Accessible to anyone through the cloud



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

http://qutech.nl/vandersypenlab

intel
erc
IARPA
FOM
NWO
SEVENTH FRAMEWORK PROGRAMME