Katere probleme lahko rešujemo?

- vsi klasični algoritmi
- algebrajski problemi

(razcep na prafaktorje, izračun diskretnih logaritmov, razcep Abelovih grup,..)

- iskanje po neurejenih seznamih

(Groverjev algoritem)

- določanje topoloških invariant

(Jonesov polinom)

- reševanje linearnih sistemov enačb

(reševanje enačb, metoda najmanjših kvadratov, strojno učenje)

- simulacije kvantnih sistemov

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

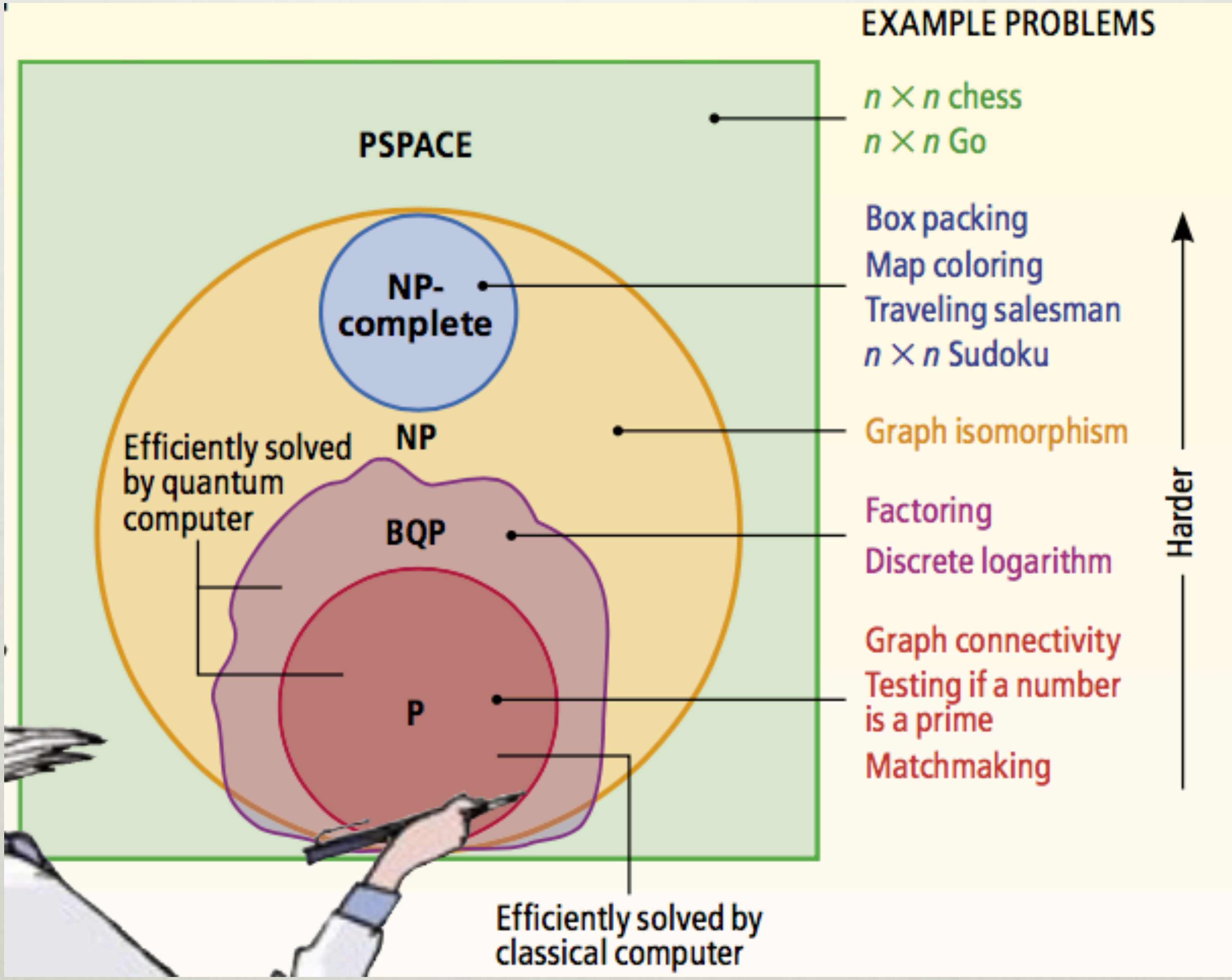
Kaj kvantni računlanik *ni*?

Kvantni računalnik ni klasični računalnik z visokim taktom.

Kvantni računalnik ne more vzporedno preizkusiti vseh možnosti in poiskati pravilne.

Verjetno ni učinkovitih kvantnih algoritmov za NP-polne probleme.

BQP = bounded-error, quantum, polynomial time



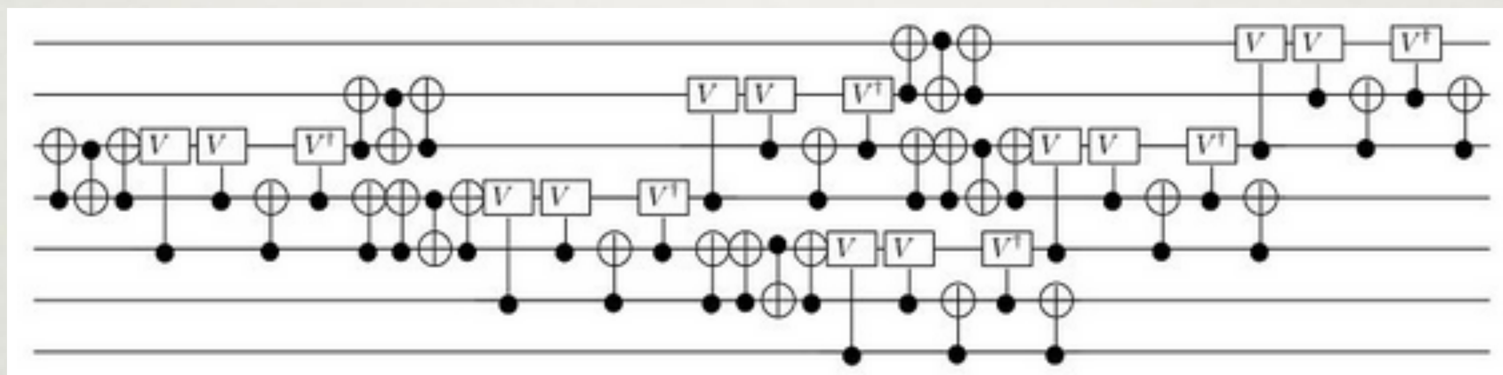
Scott Aaronson, Sci. Am. 62, marec 2008

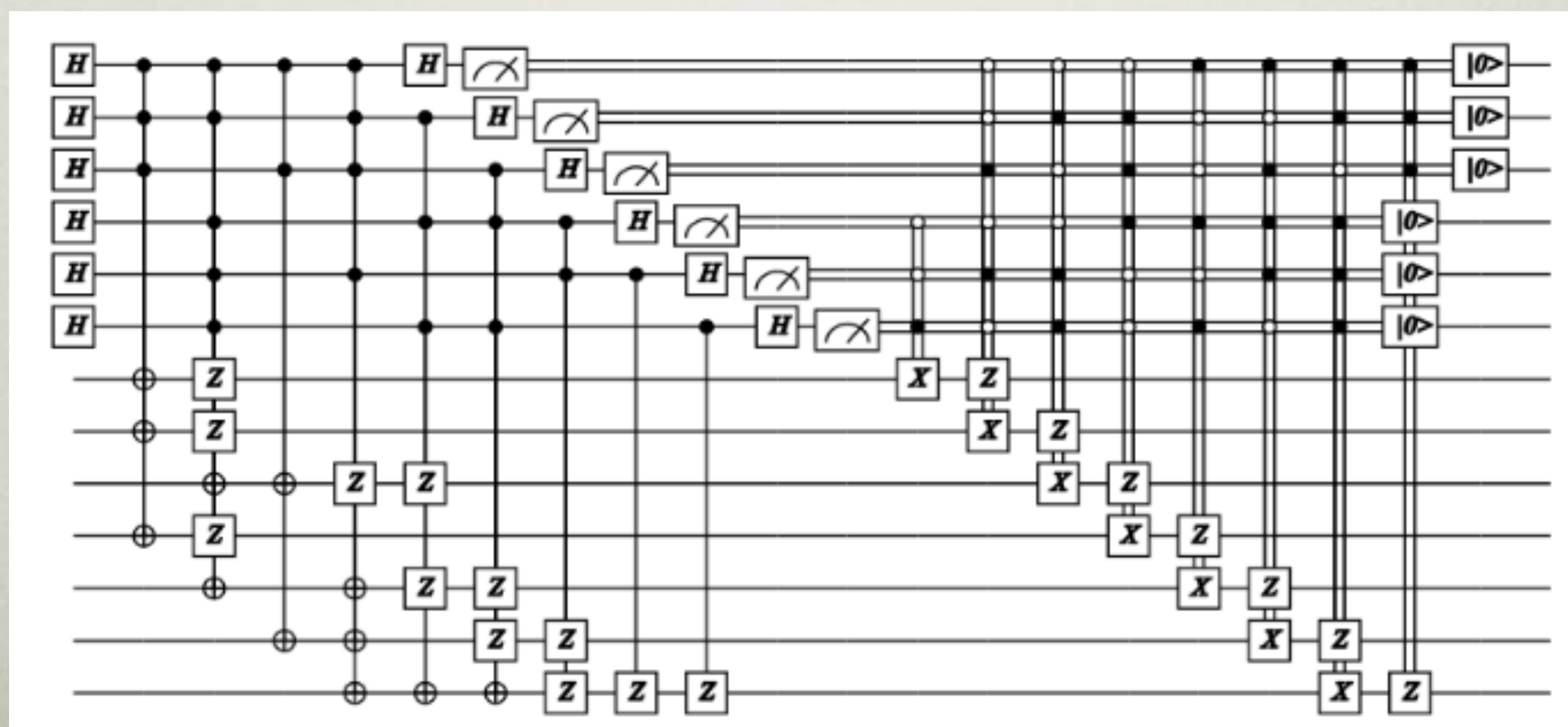
Main QC paradigms

1. Quantum circuit model (Google, IBM, IonQ, IQM, Pasqual,...)
2. Quantum Turing machine
3. Topological quantum computing (Microsoft, Bell Labs)
4. Adiabatic quantum computing (D-Wave)

Quantum circuit model

Sequence of quantum gates (unitary transformations) performed on a quantum register.



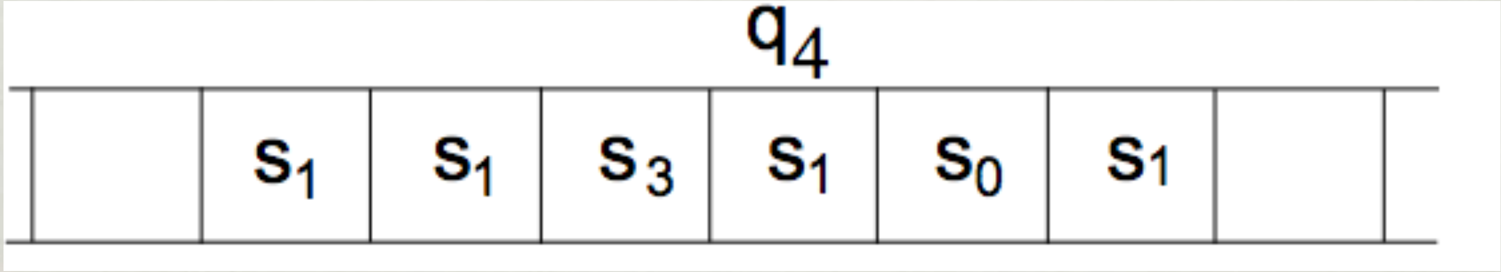


Quantum Turing machines

Tape alphabet: states from a Hilbert space

Internal state: state from a (different) Hilbert space

Transition: collection of unitary matrices



D. Deutsch (1985)

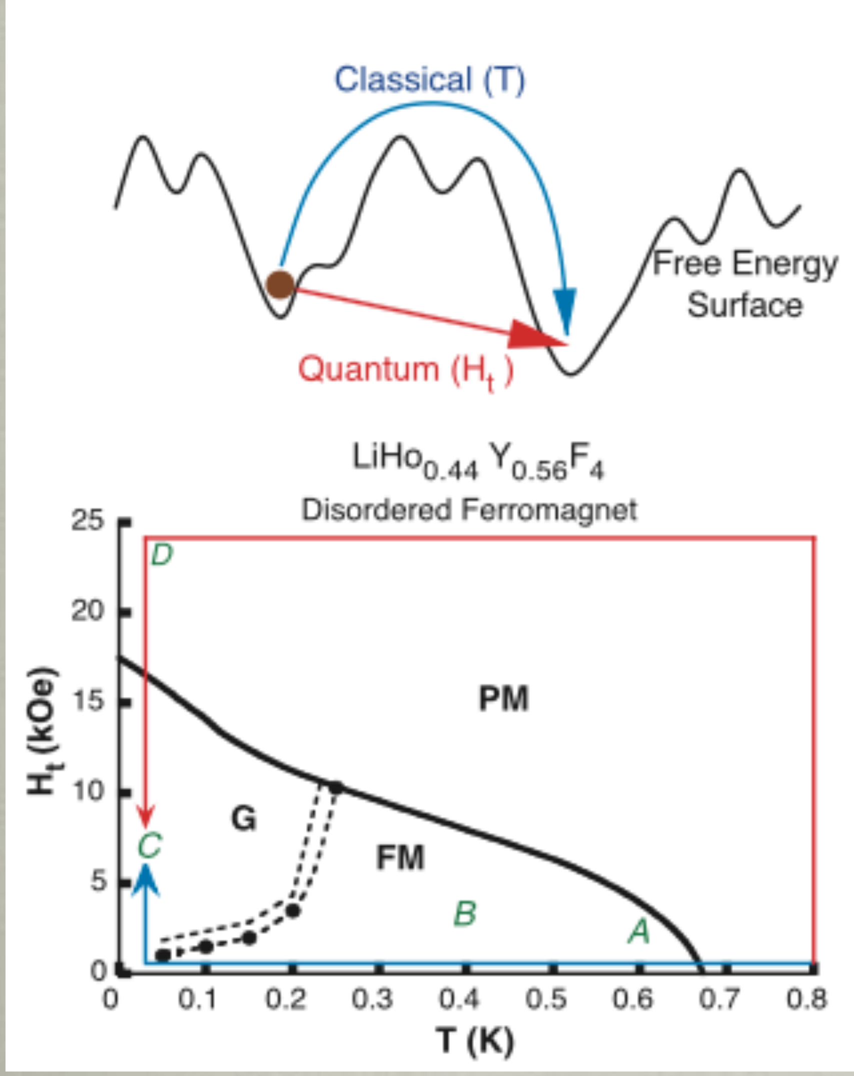
Topological QC

Many-body system with an N-fold degenerate ground state

Manipulation of the system such that the operations correspond to unitary transformations U(N) on the ground-state manifold

Adiabatic QC

Map the problem to a quantum system Hamiltonian H, so that the ground state of H contains the solution of the problem.



classical spin problem
+ transverse field terms

solve via quantum annealing

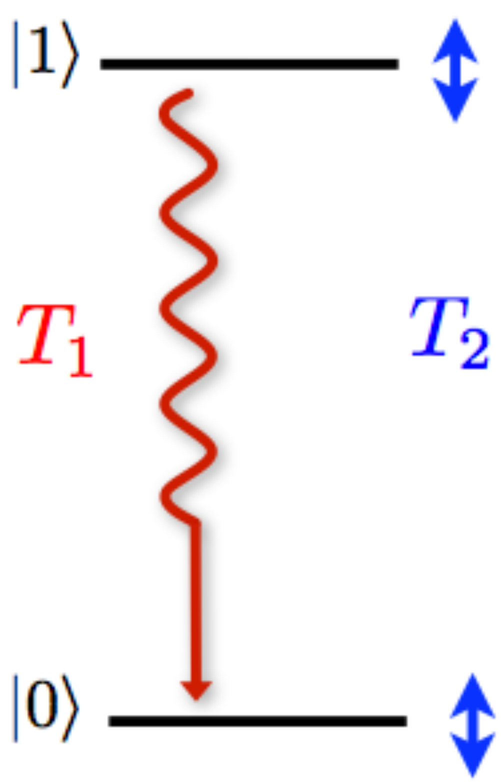
works well for combinatorial optimization problems

Example: D-Wave,
Ising Hamiltonian, 2000 qubits

Brooke, Bitko, Rosenbaum, Aeppli, Science **284**, 779 (1999)

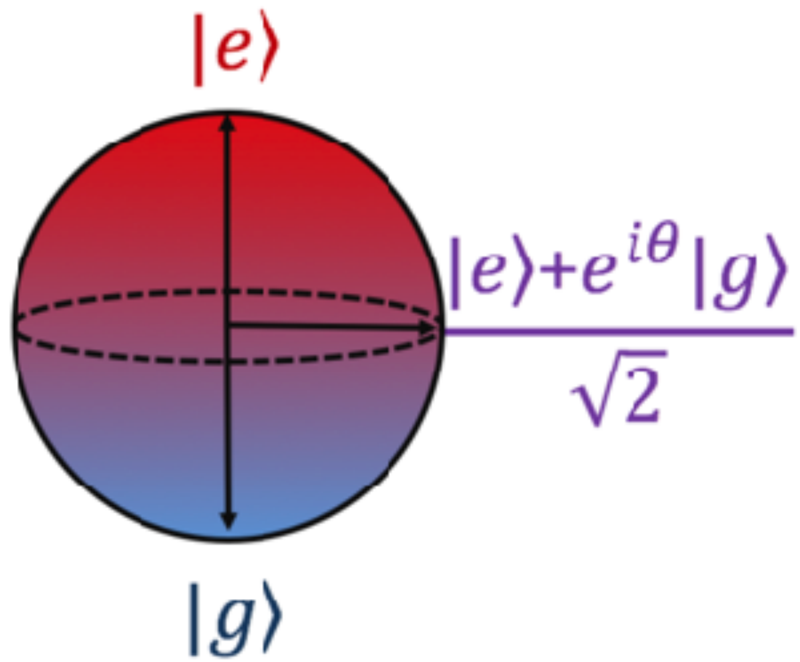
Dekoherenca (kvantni šum)

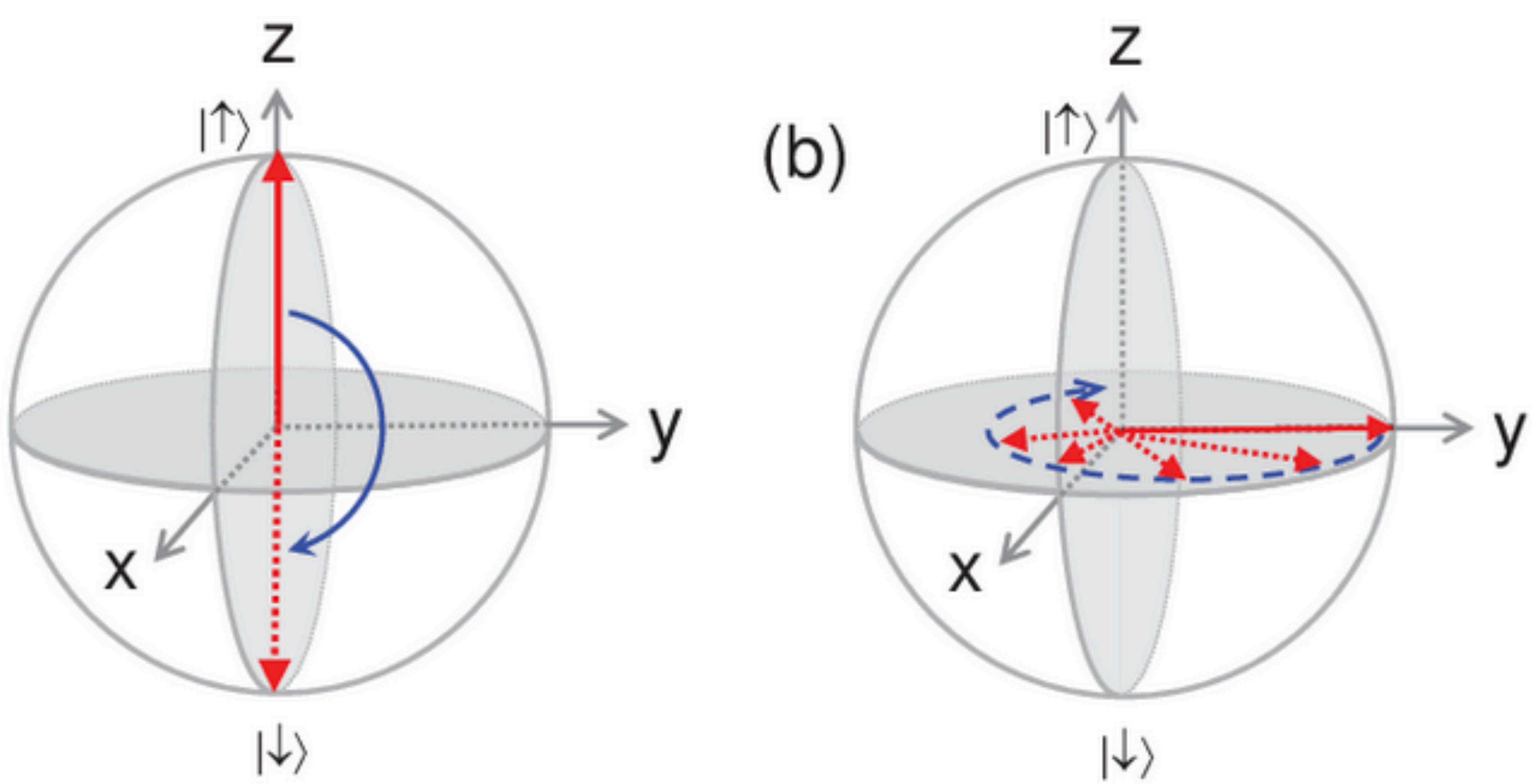
Relaksacijski ali
dekoherenčni čas:



T_1 meri prehode med nivojema.

T_2 meri izgubo čistosti stanja.
(izgubljanje koherence faze)


$|e\rangle$
$\frac{|e\rangle+e^{i\theta}|g\rangle}{\sqrt{2}}$
$|g\rangle$

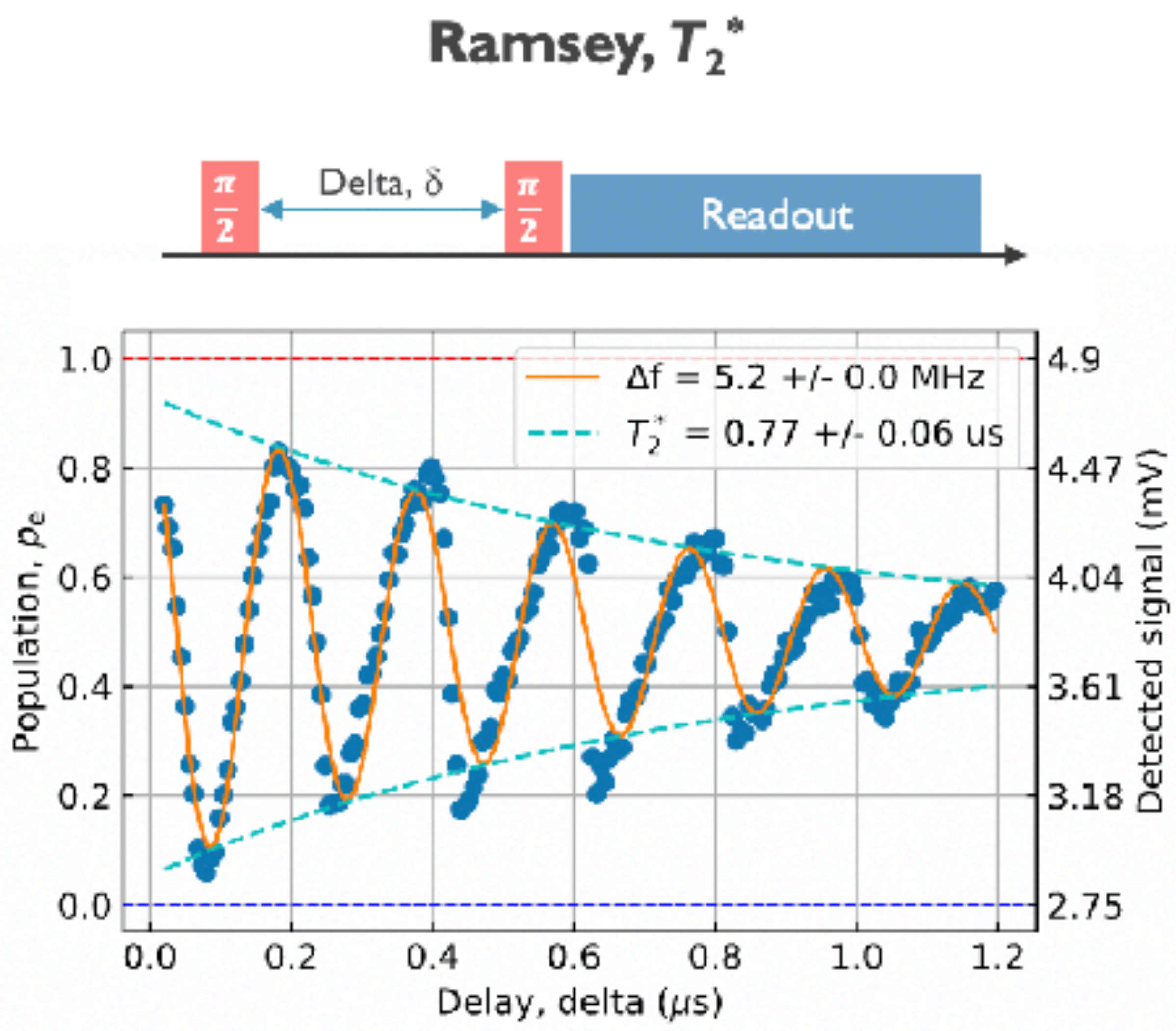

z
$|\uparrow\rangle$
y
x
$|\downarrow\rangle$
(b)
z
$|\uparrow\rangle$
y
x
$|\downarrow\rangle$

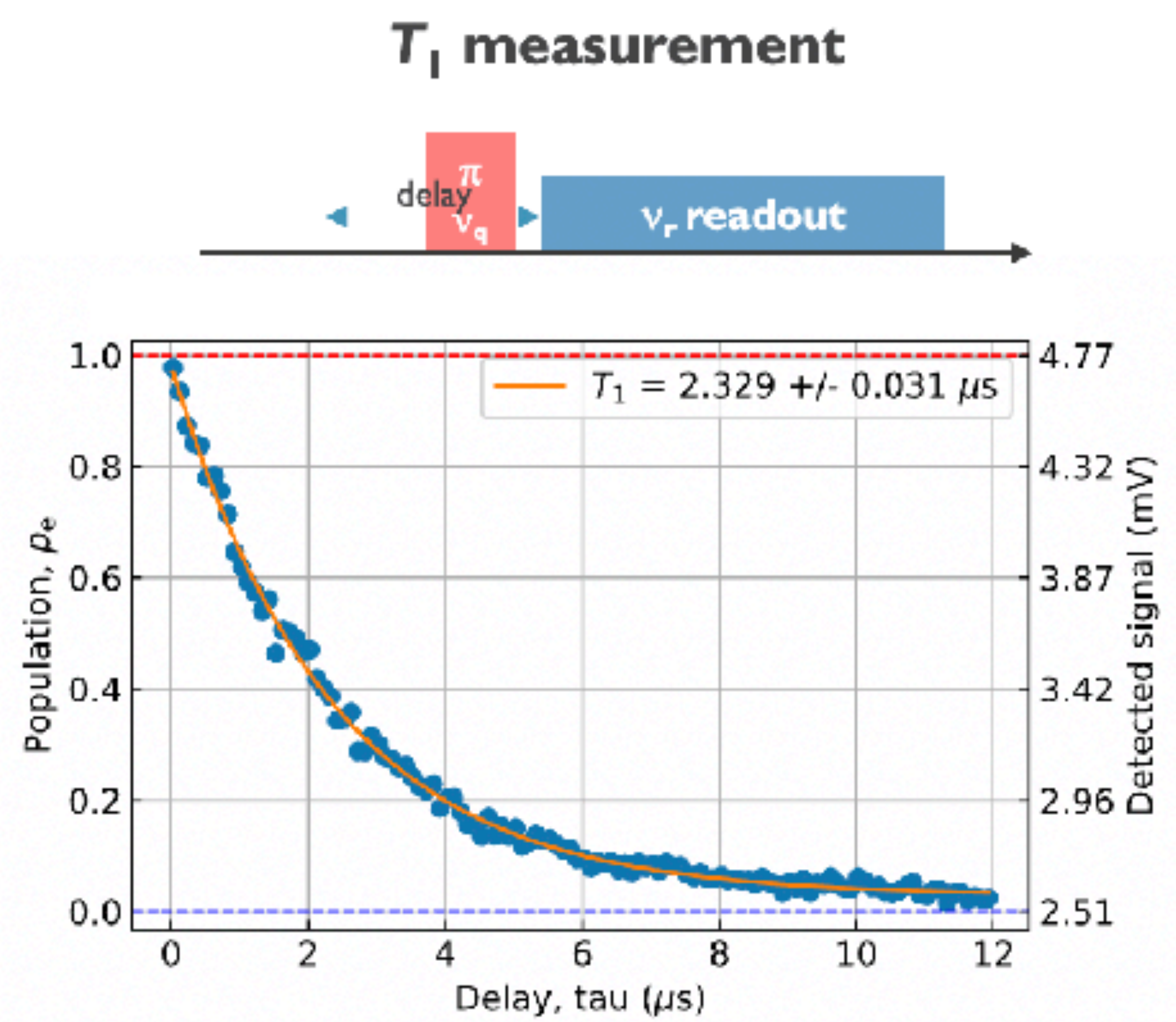
izvajanje kvantnih vrat

dekoherenčni čas

System	τ_Q	τ_{op}	$n_{op} = \lambda^{-1}$
Nuclear spin	$10^{-2} - 10^{8}$	$10^{-3} - 10^{-6}$	$10^{5} - 10^{14}$
Electron spin	10^{-3}	10^{-7}	10^{4}
Ion trap (In^{+})	10^{-1}	10^{-14}	10^{13}
Electron – Au	10^{-8}	10^{-14}	10^{6}
Electron – GaAs	10^{-10}	10^{-13}	10^{3}
Quantum dot	10^{-6}	10^{-9}	10^{3}
Optical cavity	10^{-5}	10^{-14}	10^{9}
Microwave cavity	10^{0}	10^{-4}	10^{4}

300 mm integrated Transmon qubit





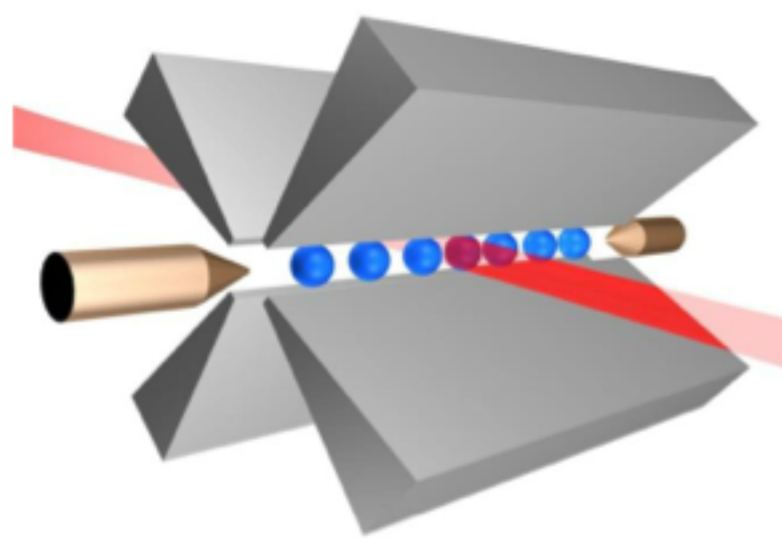
Verjauw, AP *et al.* in preparation.

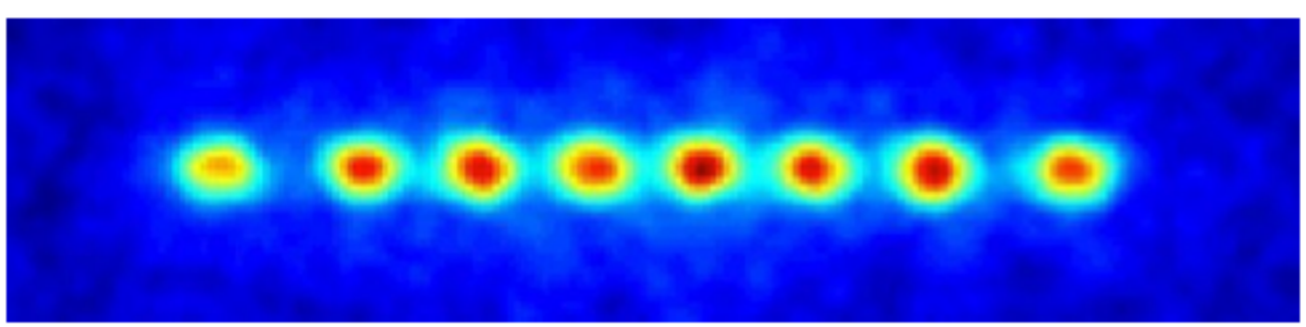
A. Potočnik, 2. 4. 2021

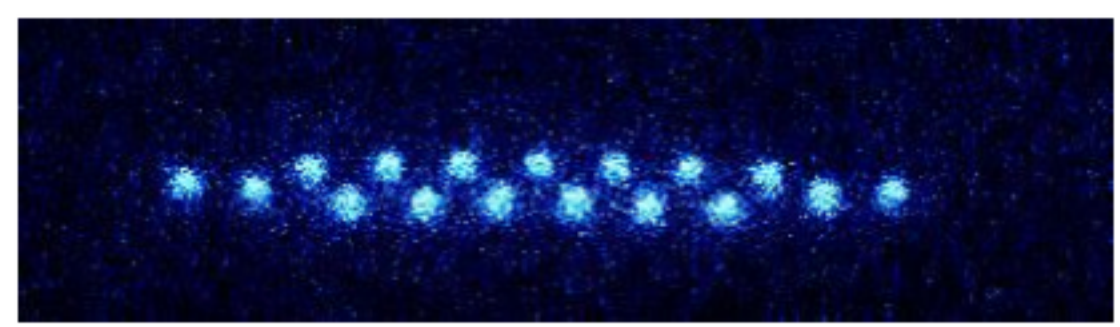
ionske pasti

Ionska past

Dolg koherenčni čas: >20 sekund
Hitra vrata: 0.01ms
Preprosto naslavljanje

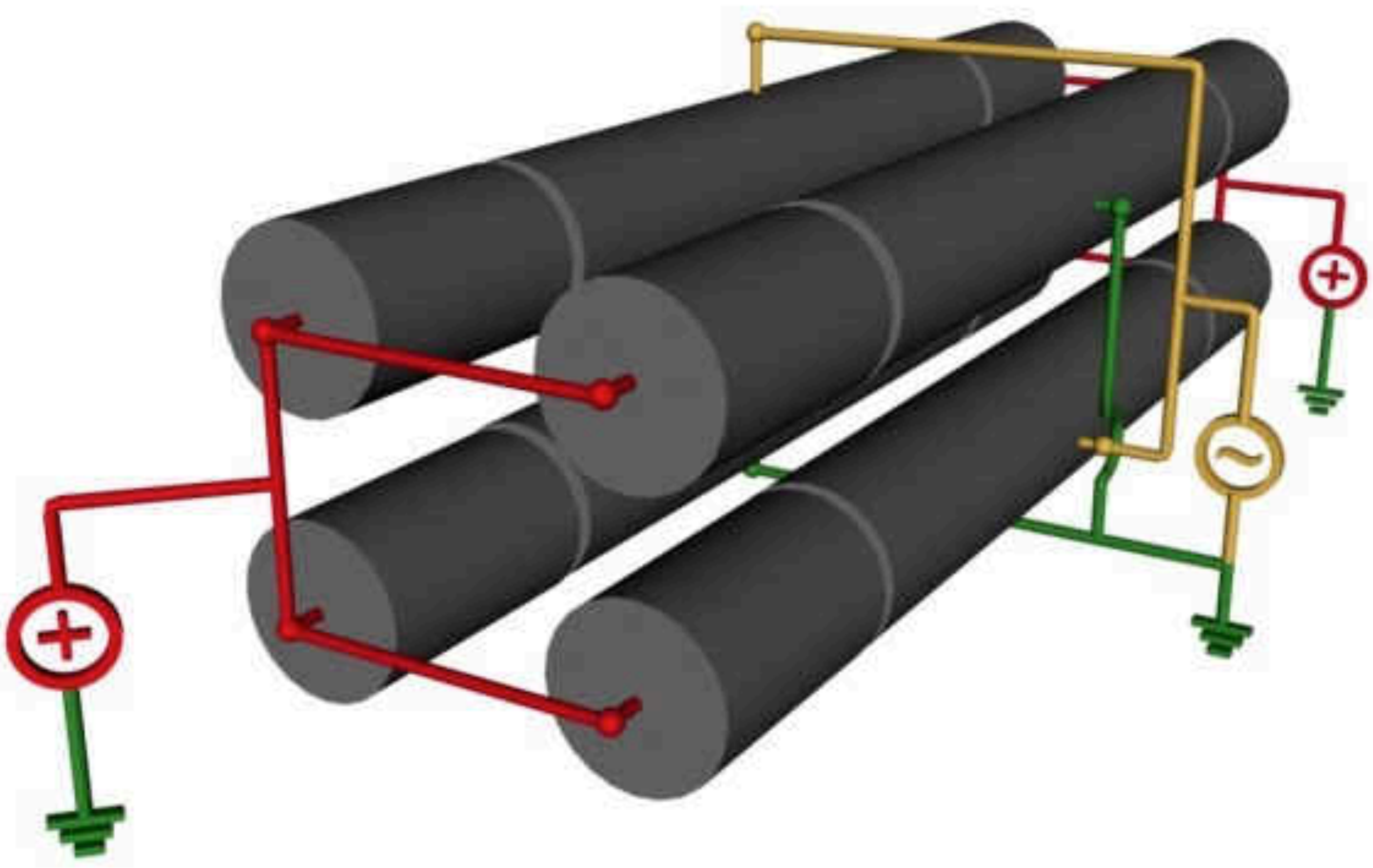






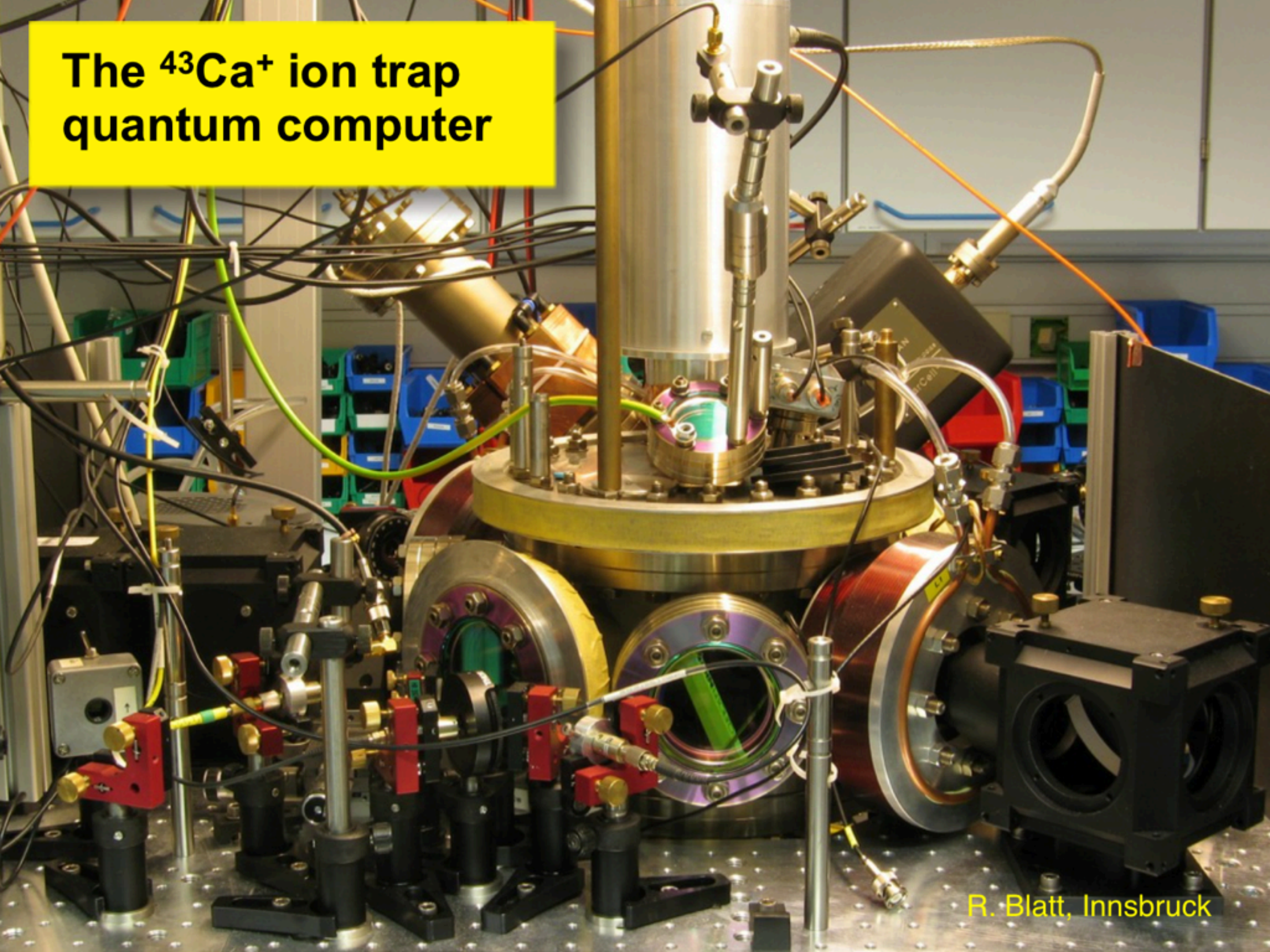
Wolfgang Paul

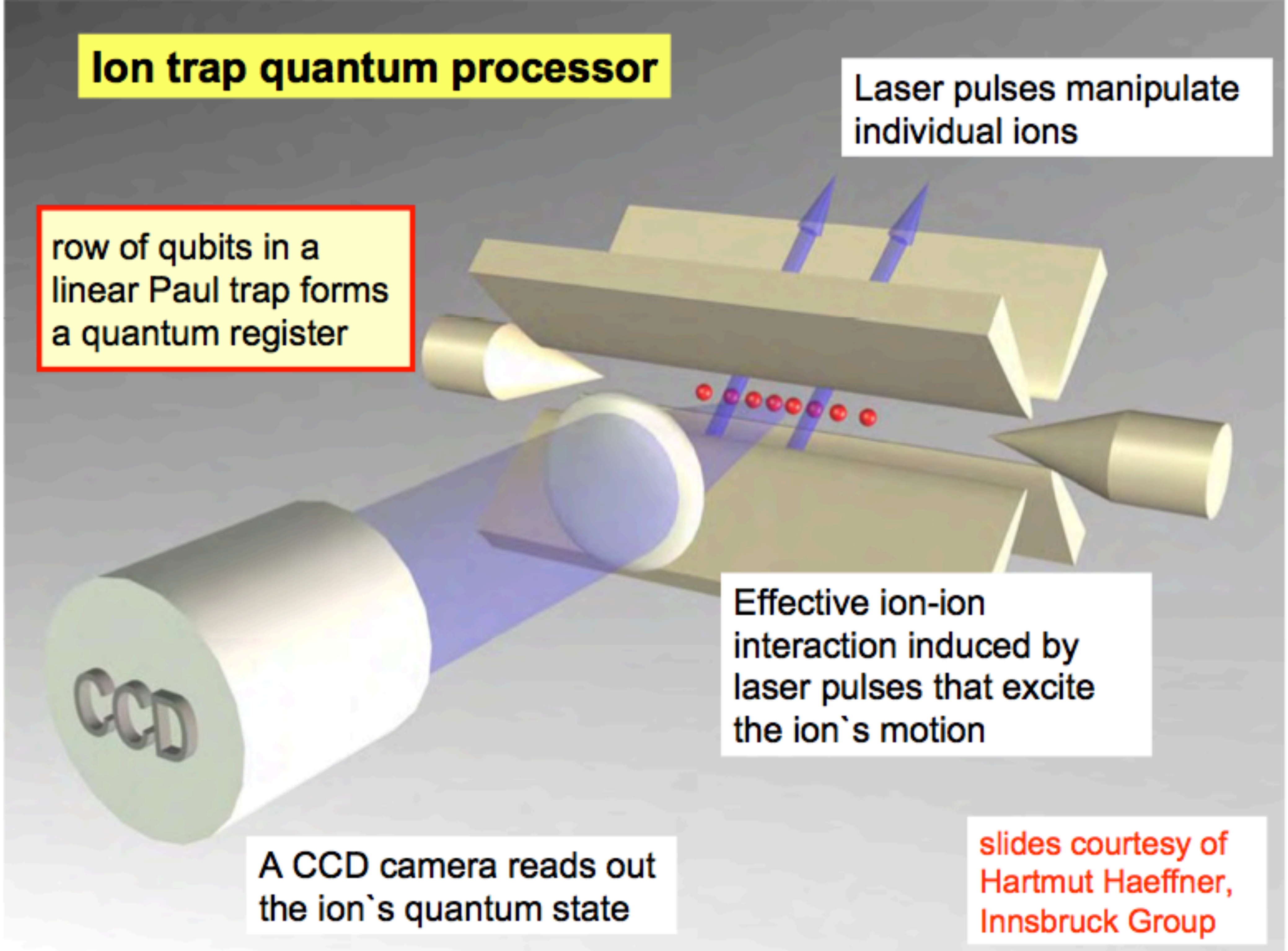
Nobelova 1989

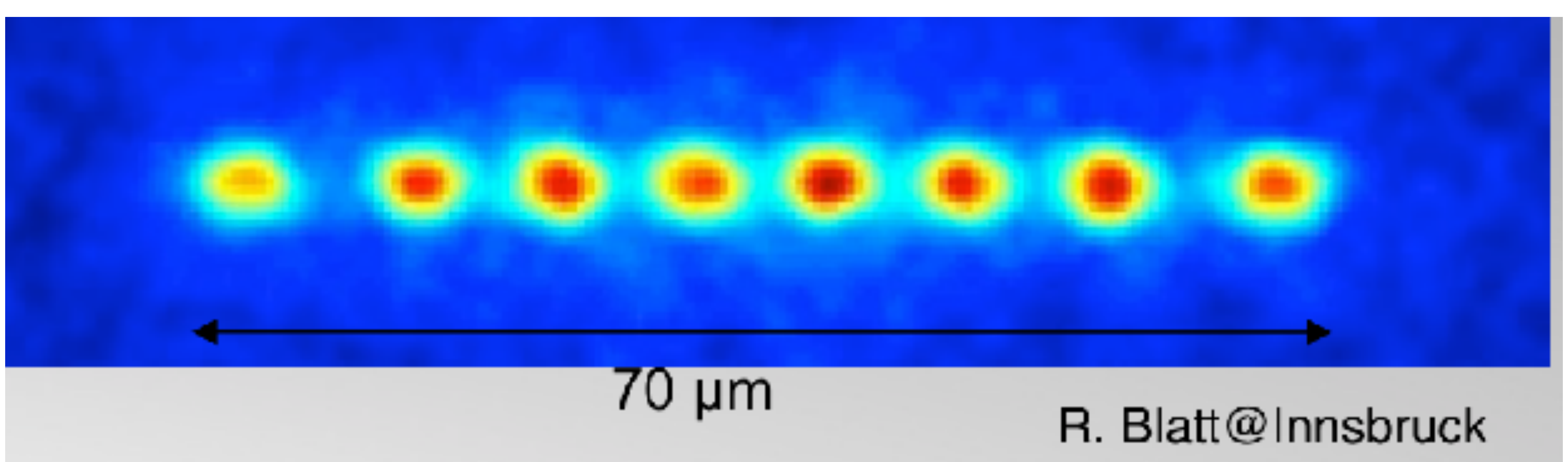


https://www.youtube.com/watch?v=XTJznUkAmIY

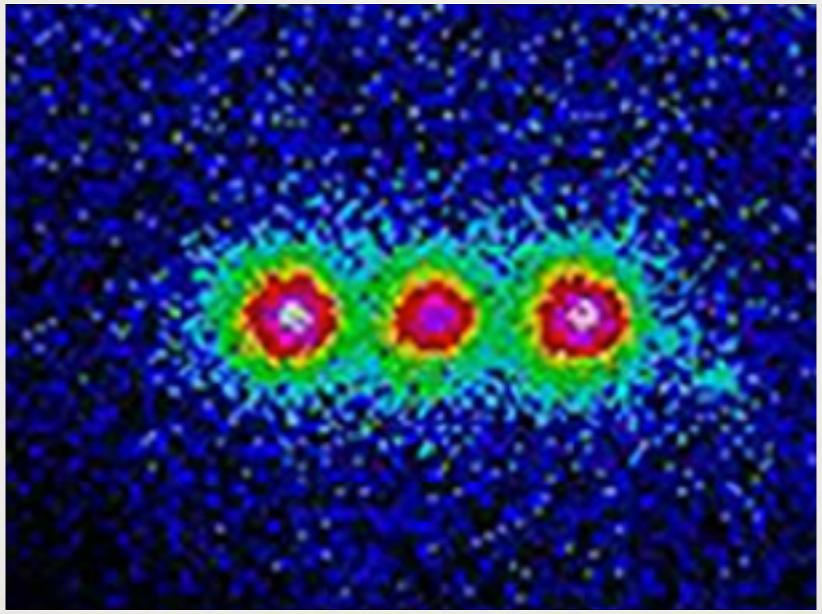
The $^{43}Ca^{+}$ ion trap quantum computer

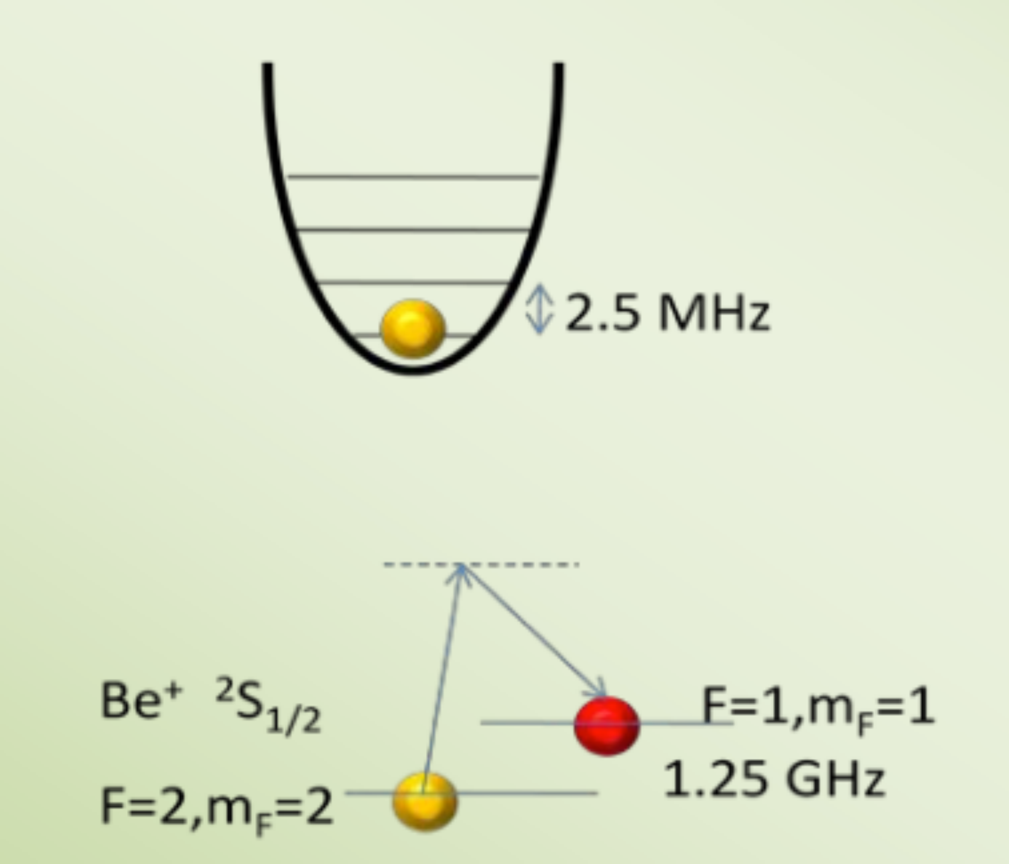



Ion trap quantum processor
Laser pulses manipulate individual ions
row of qubits in a linear Paul trap forms a quantum register
CCD
Effective ion-ion interaction induced by laser pulses that excite the ion`s motion
A CCD camera reads out the ion`s quantum state
slides courtesy of Hartmut Haeffner, Innsbruck Group


70 μm
R. Blatt@Innsbruck

Ionska past

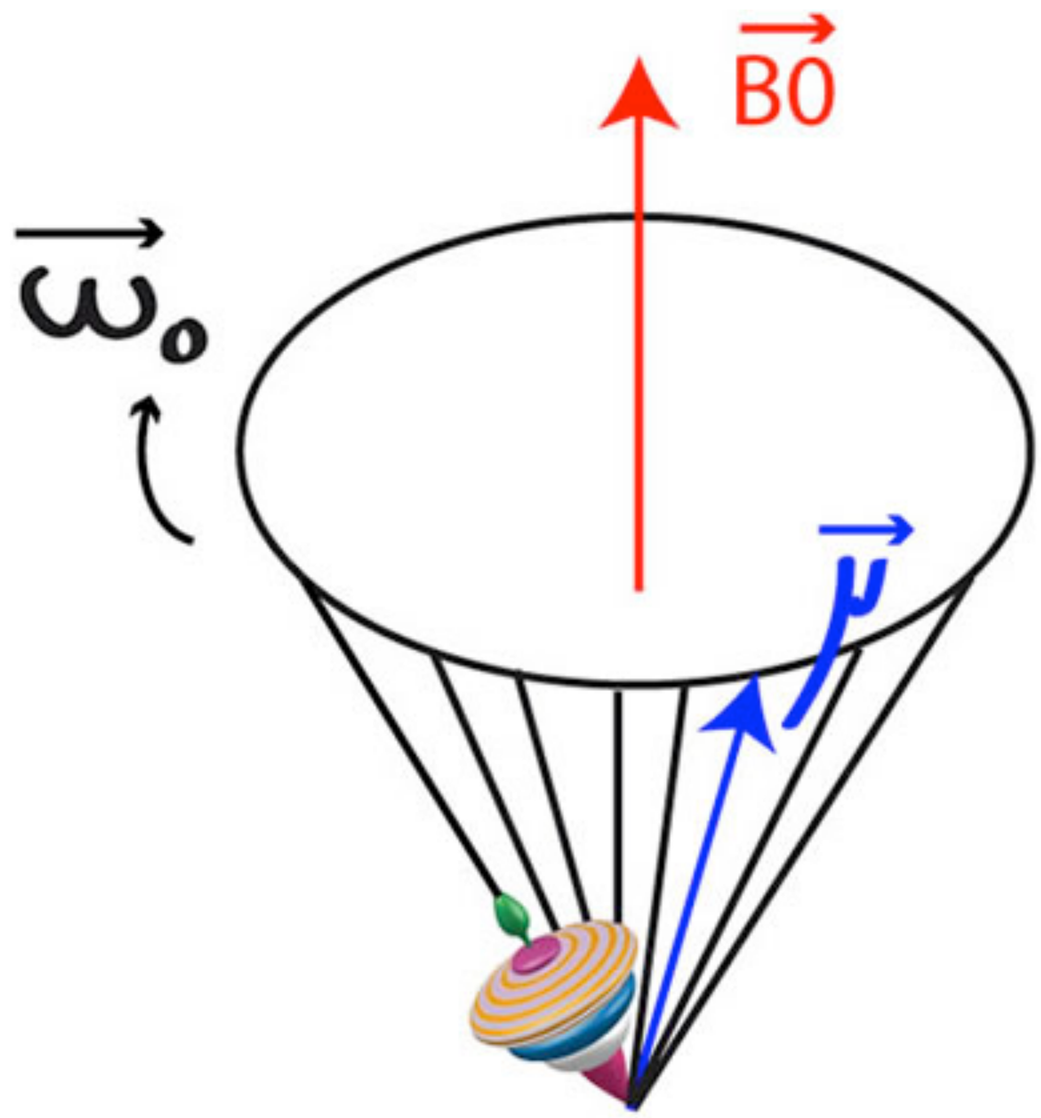




dvonivojski
sistem

Weinland (1978, 1981)

magnetna resonanca

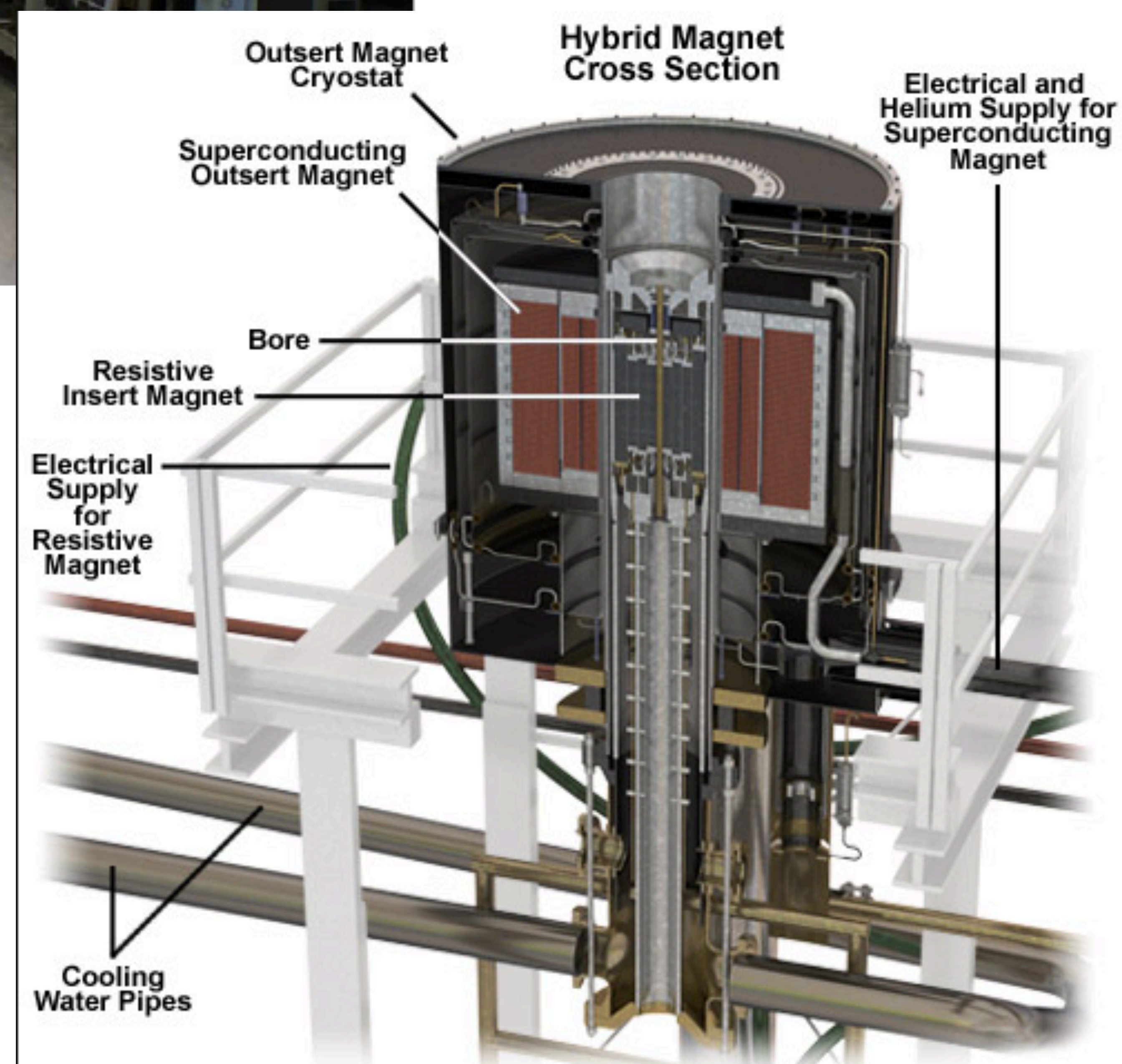


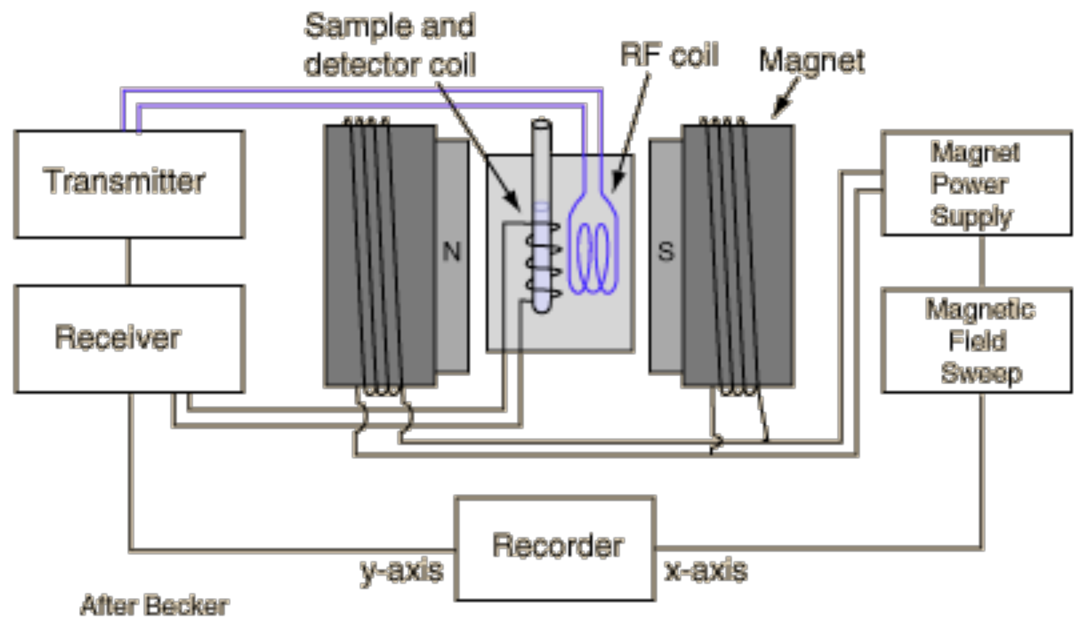
$\vec{B0}$
$\vec{\omega_0}$
$\vec{\mu}$


BRUKER
600
UltraShield™


VARIAN


CELL 15
45T HYBRID
MAGNET SYSTEM


Hybrid Magnet
Cross Section
Outsert Magnet
Cryostat
Superconducting
Outsert Magnet
Electrical and
Helium Supply for
Superconducting
Magnet
Bore
Resistive
Insert Magnet
Electrical
Supply
for
Resistive
Magnet
Cooling
Water Pipes



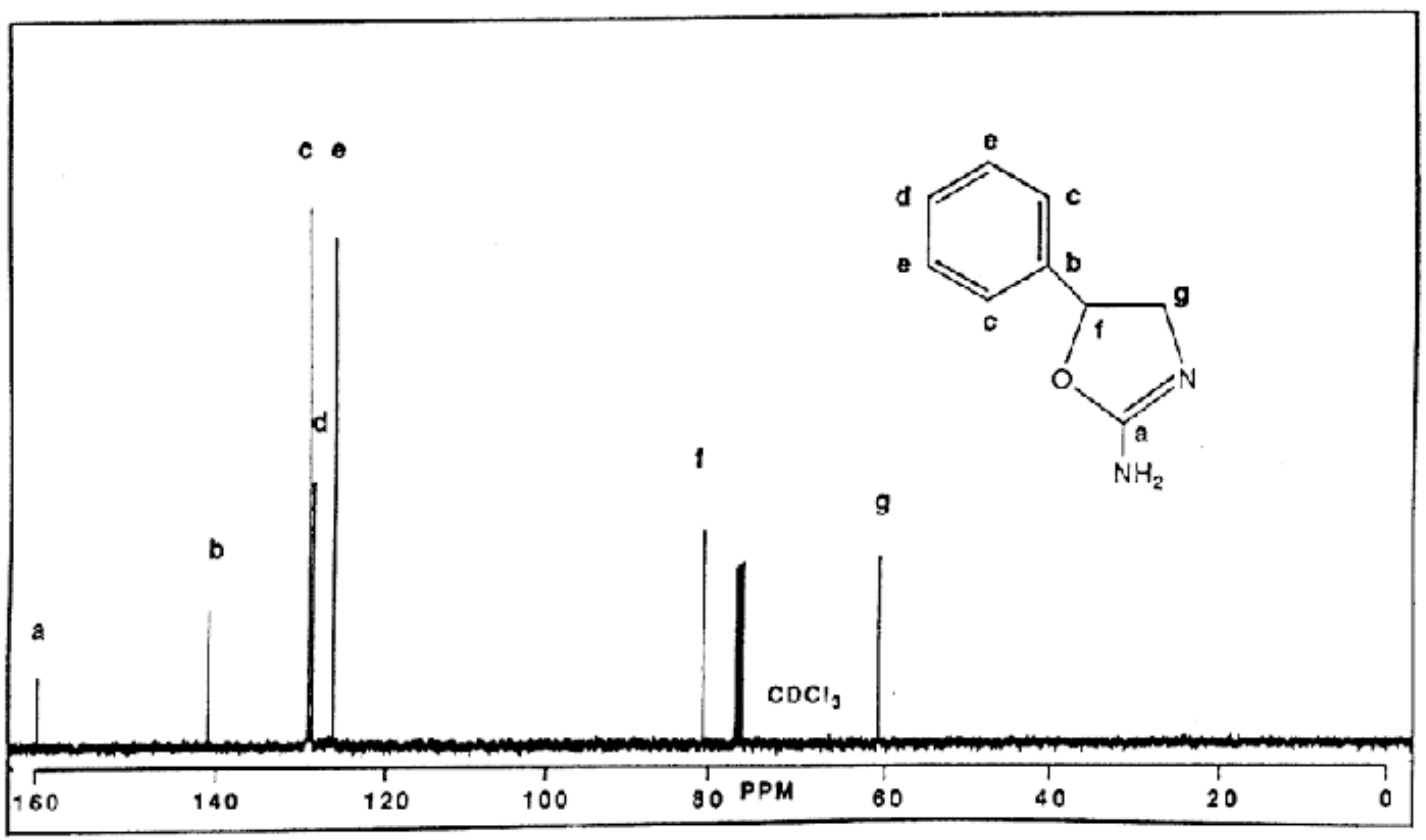
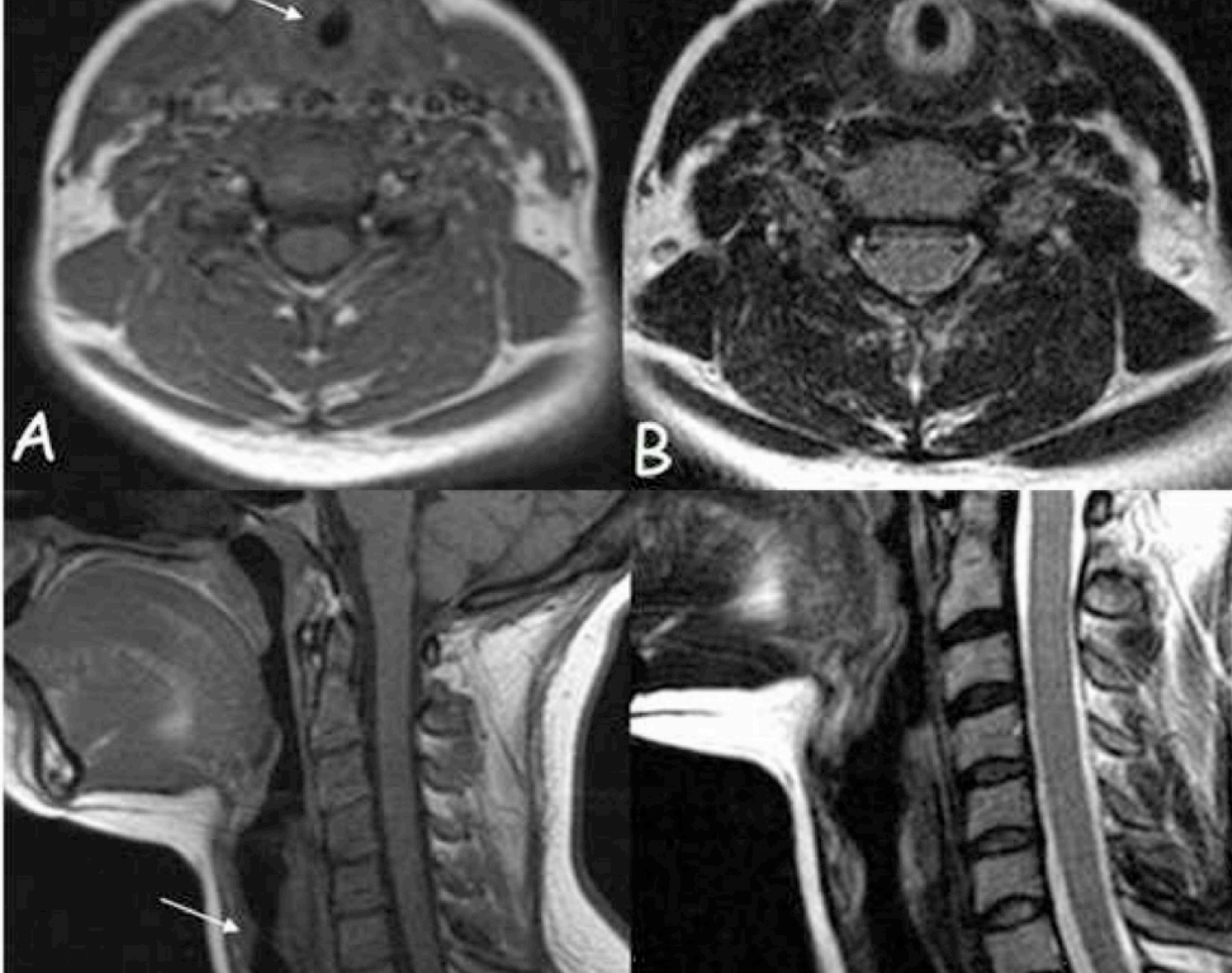


FIG. 3—*Carbon (75-mHz) NMR spectrum for aminorex with interpretation.*

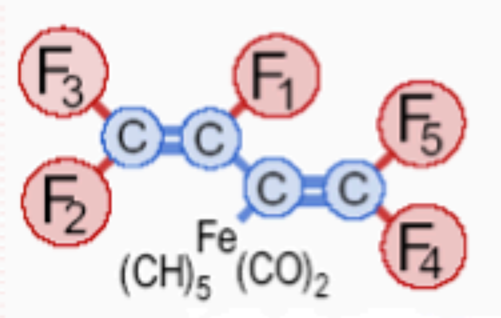

PHILIPS


A
B

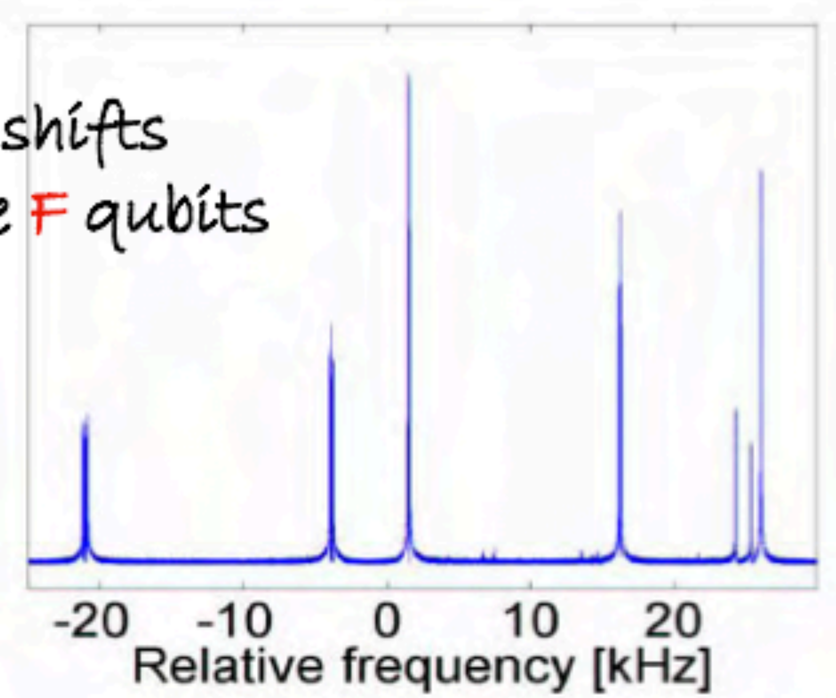
Nuclear spin Hamiltonian
Multiple spins

without qubit/qubit coupling

$$\mathcal{H}_0 = -\sum_{i=1}^{n} \hbar\,(1-\tilde{\sigma}_i)\gamma_i B_0\; I_z^i = -\sum_{i=1}^{n} \hbar\,\omega_0^i\; I_z^i$$



chemical shifts of the five F qubits



	MHz	
^{1}H	500	~ 25 mK
^{13}C	126	
^{15}N	-51	
^{19}F	470	
^{31}P	202	

(at 11.7 Tesla)

qubit level separation

Nuclear spin Hamiltonian

Coupled spins

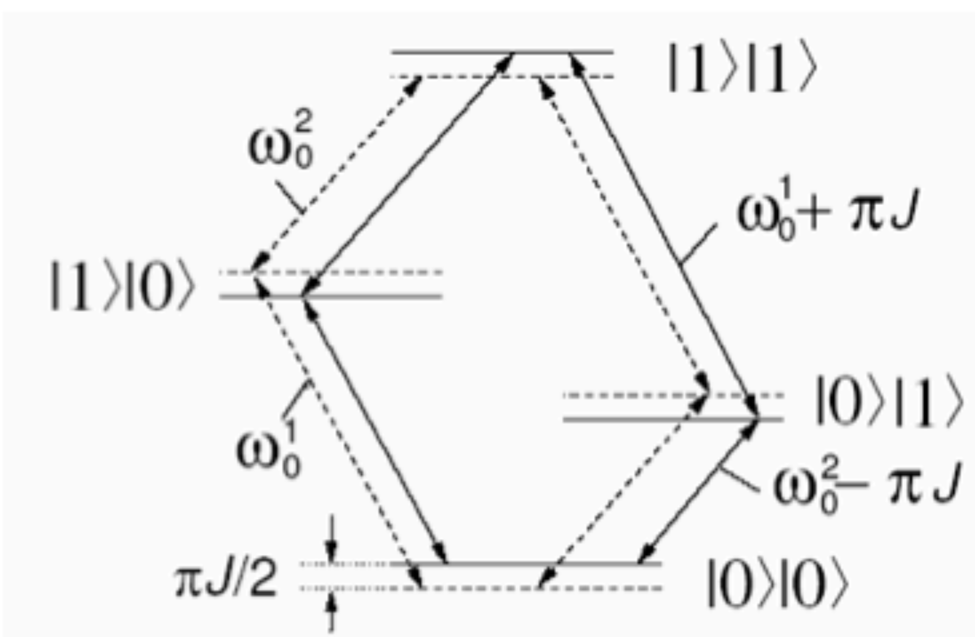
J>0: antiferro mag.

J<0: ferro-mag.

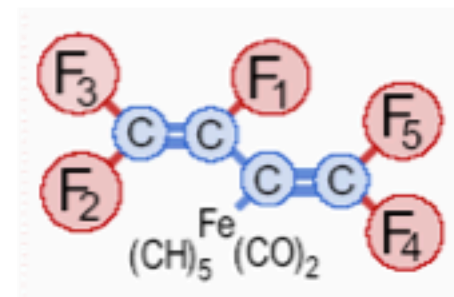
coupling term

$$\mathcal{H}_J = \hbar \sum_{i<j}^{n} 2\pi J_{ij} I_z^i I_z^j$$

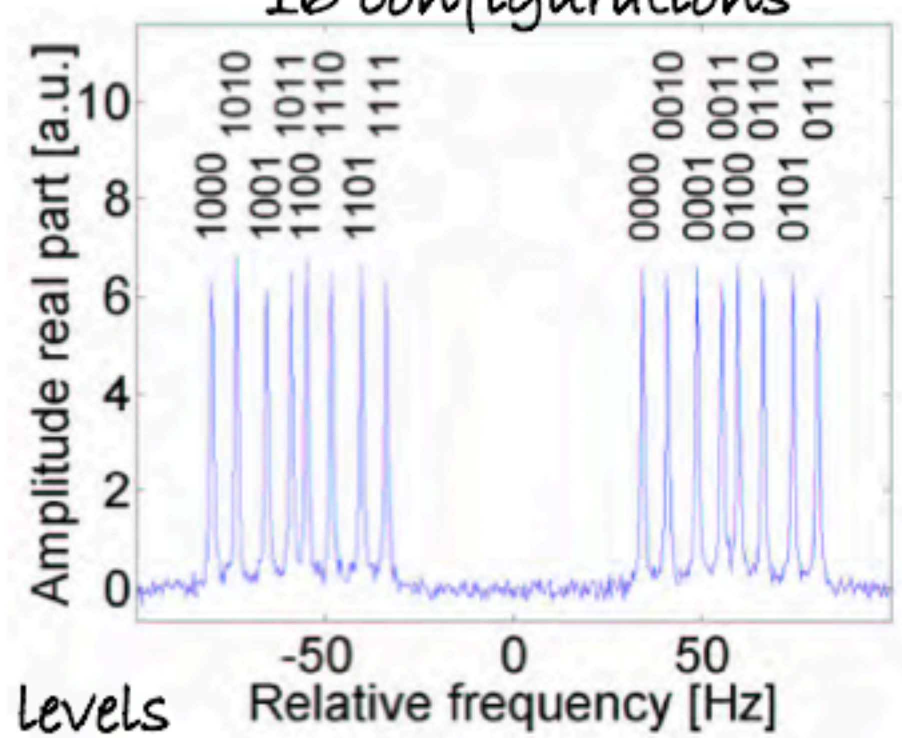
Typical values: *J* up to few 100 Hz



solid (dashed) lines are (un)coupled levels



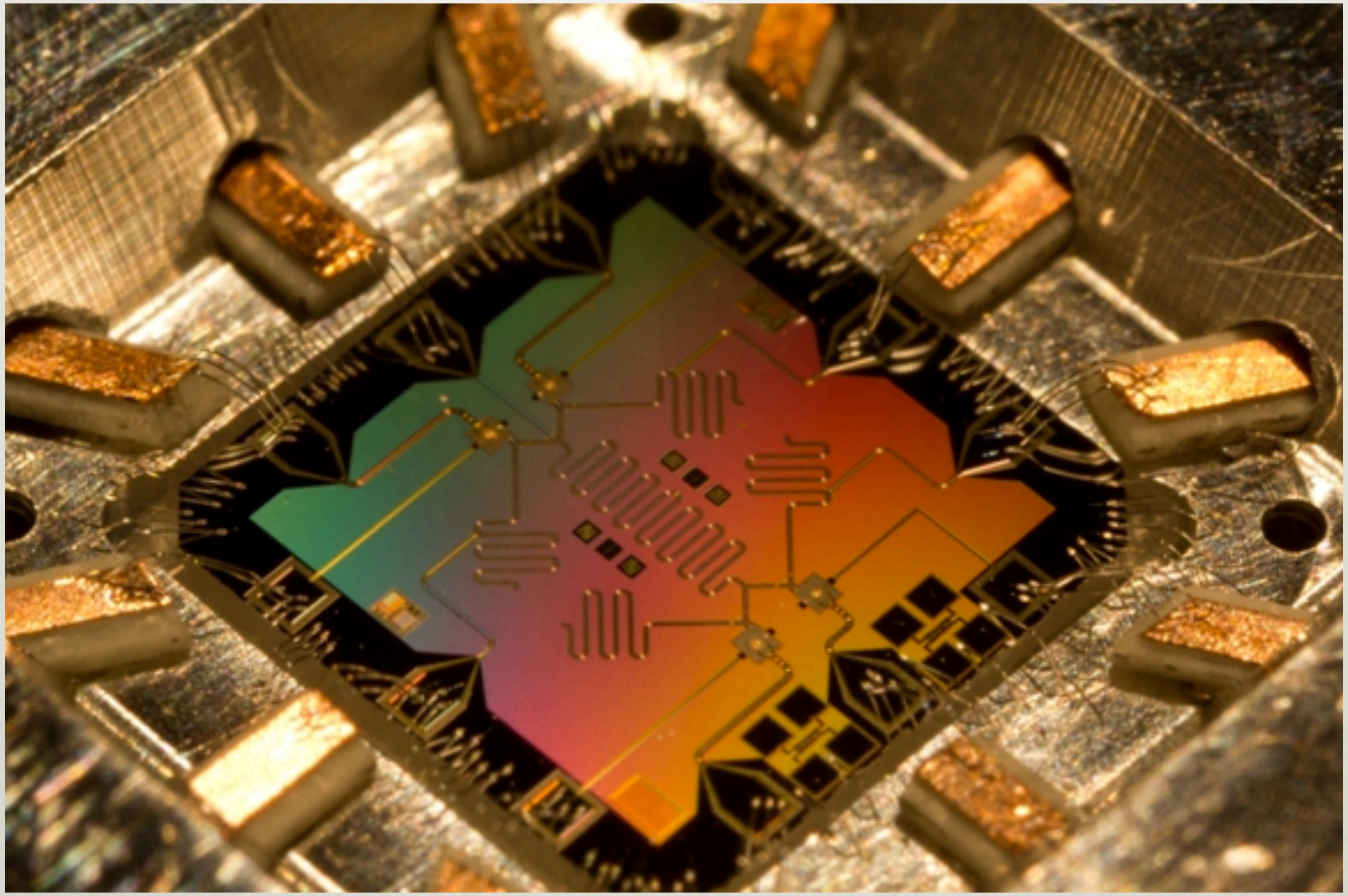
16 configurations



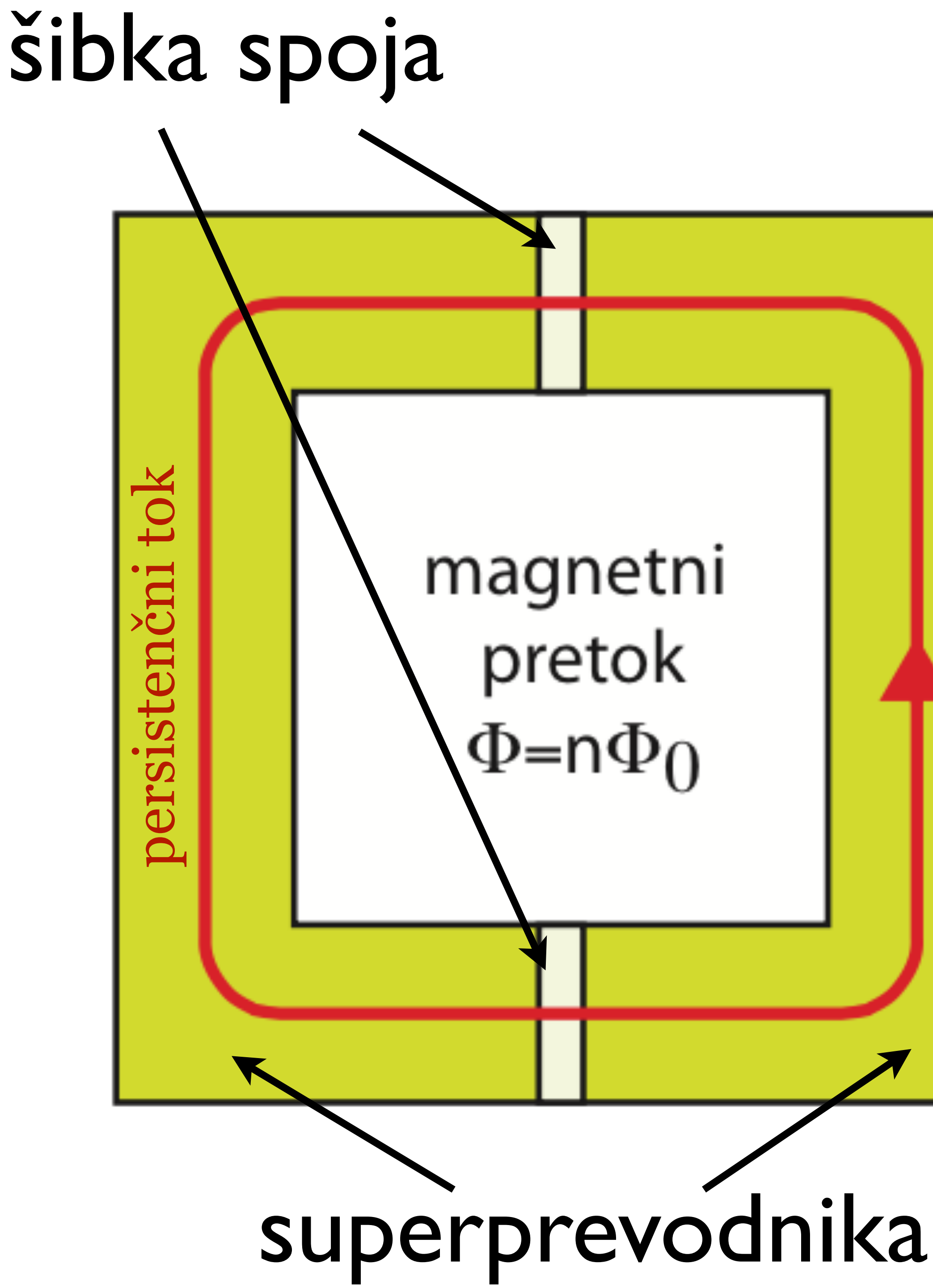
superprevodne naprave

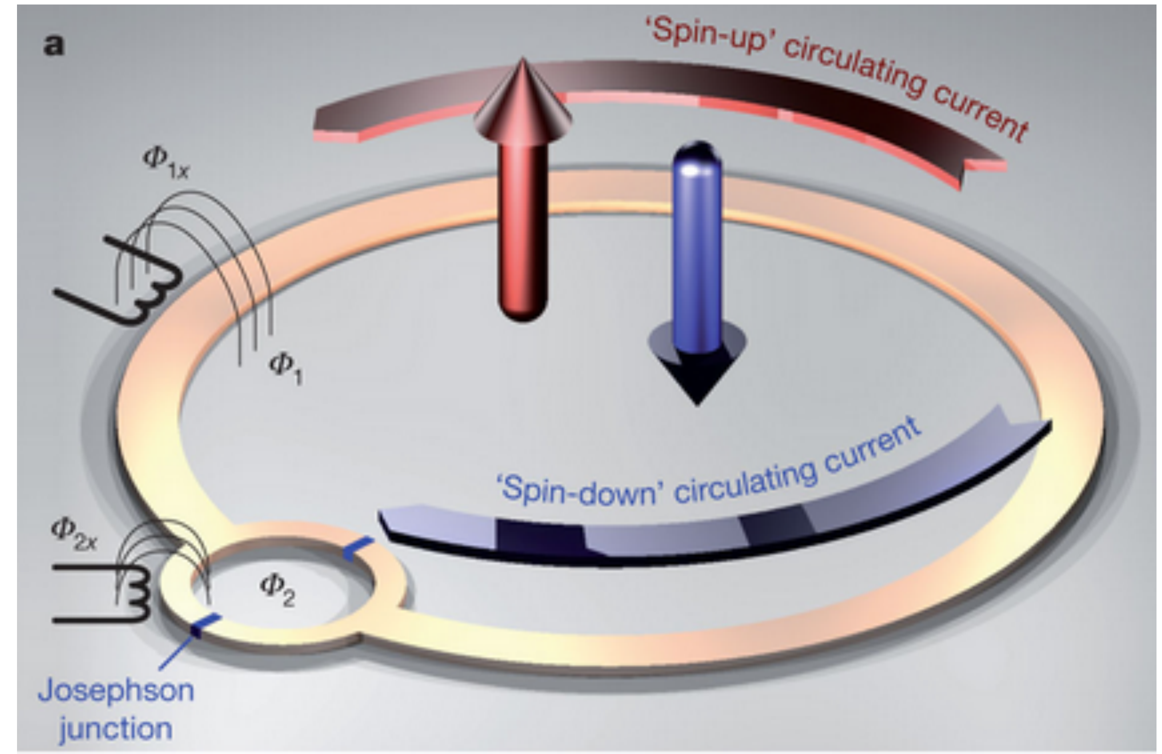
Kvantni procesor z gradniki SQUID

SQUID = superprevodniška interferenčna naprava



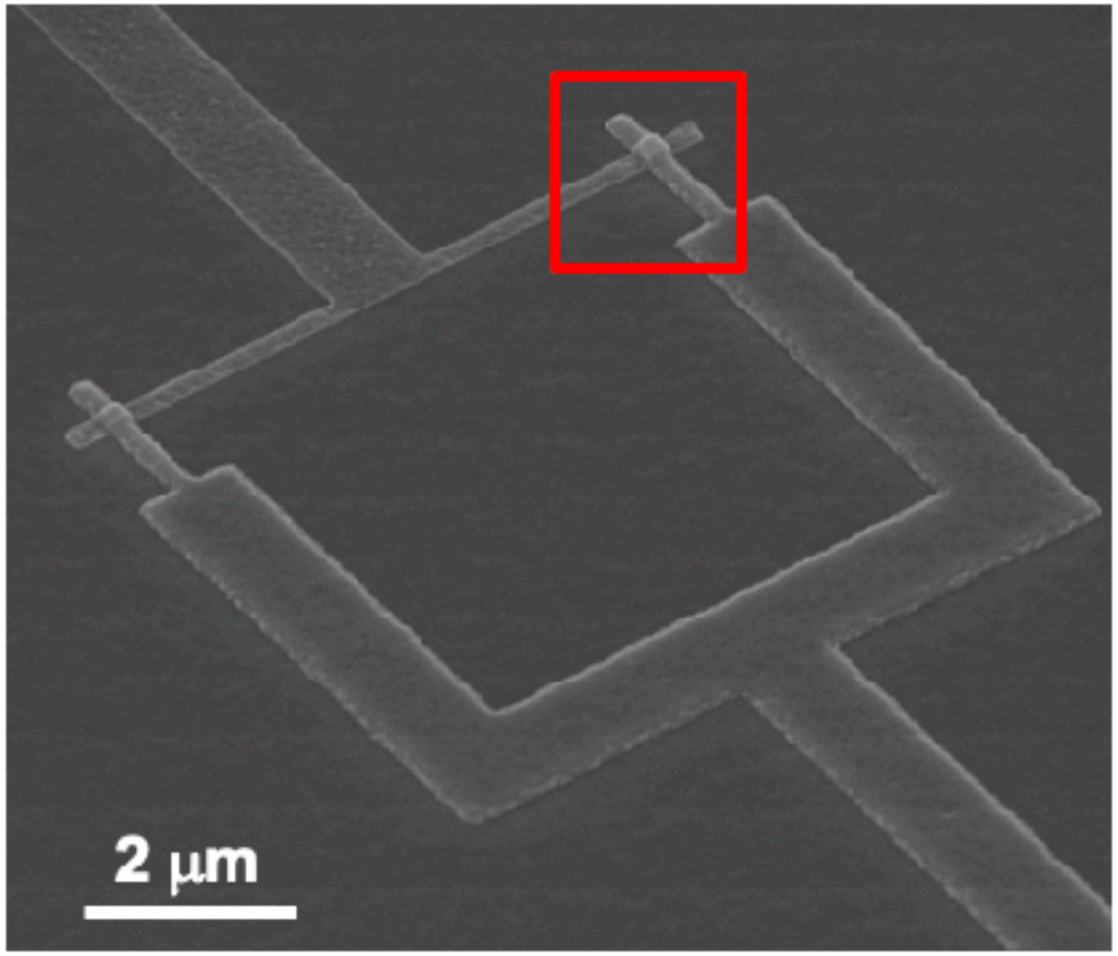
skupina Johna Martinisa,
Univerza v Kaliforniji v Santa Barbari in **Google**

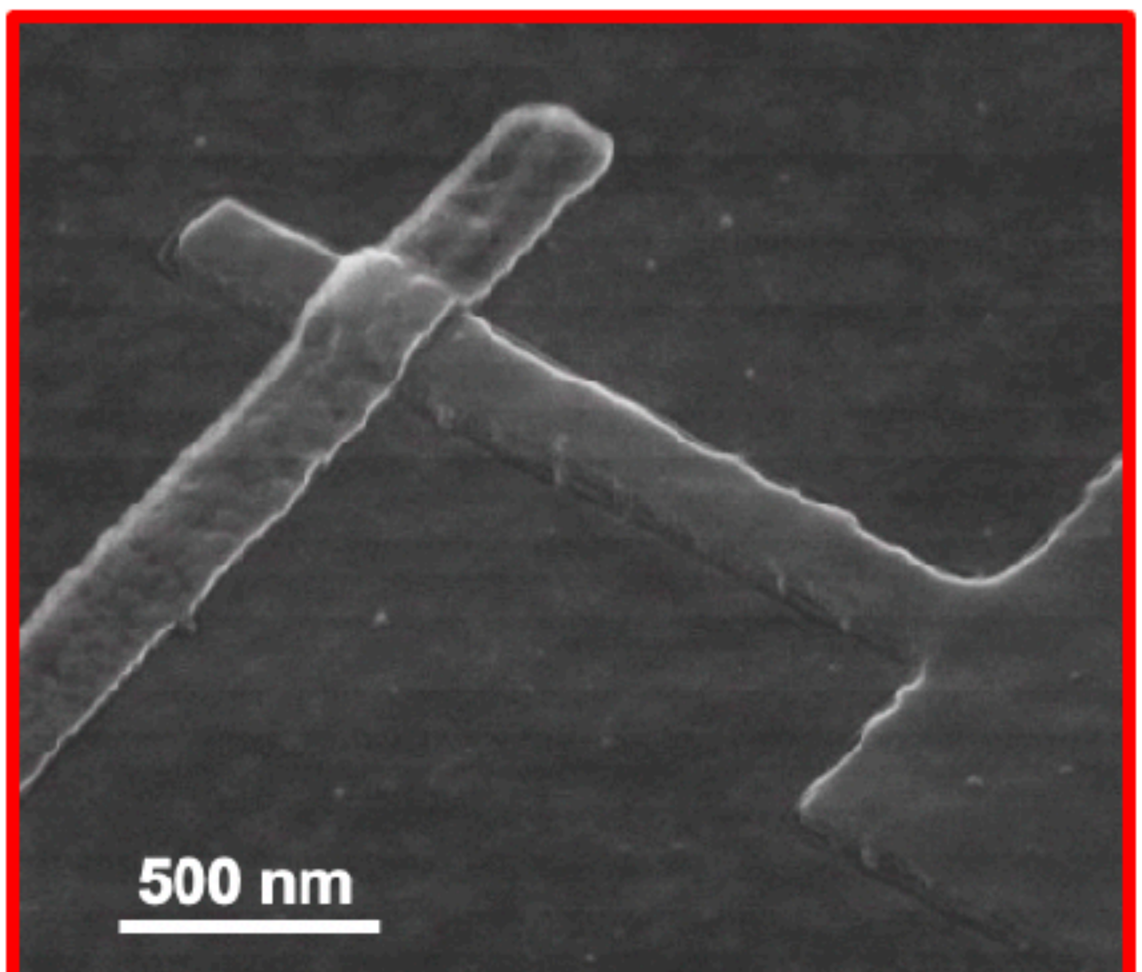




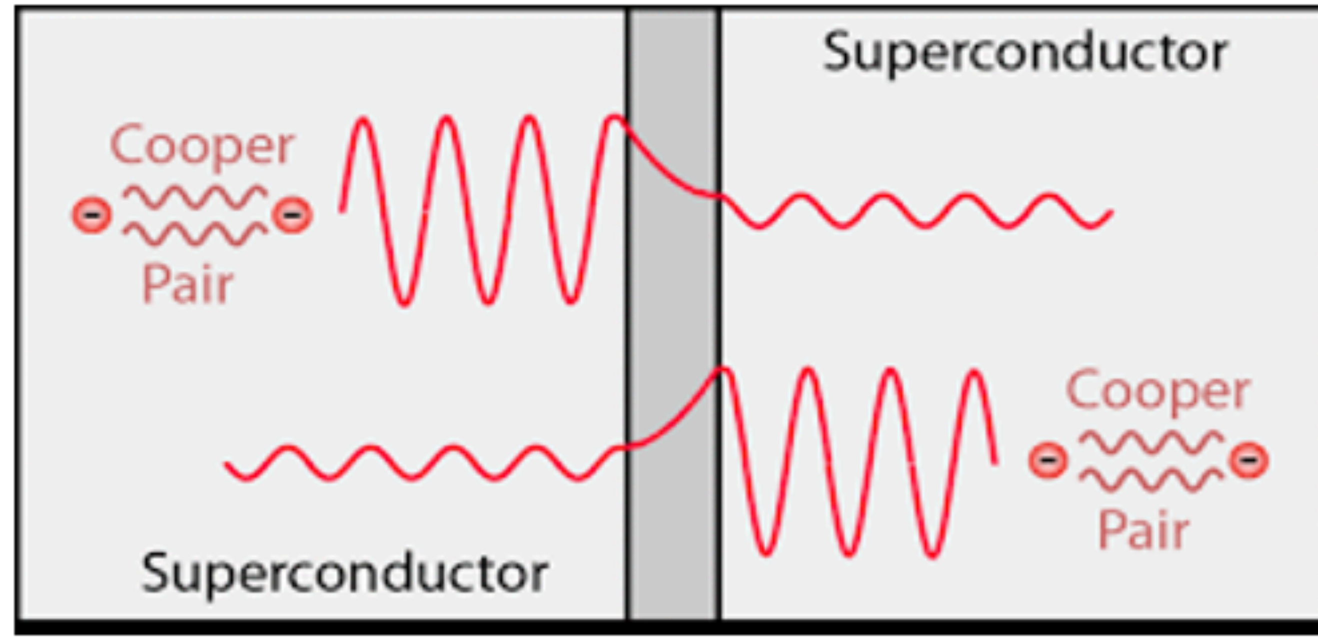
$$\Phi = B \times S$$

$$\Phi_0 = \frac{h}{2e}$$ kvant fluksa





S – I – S

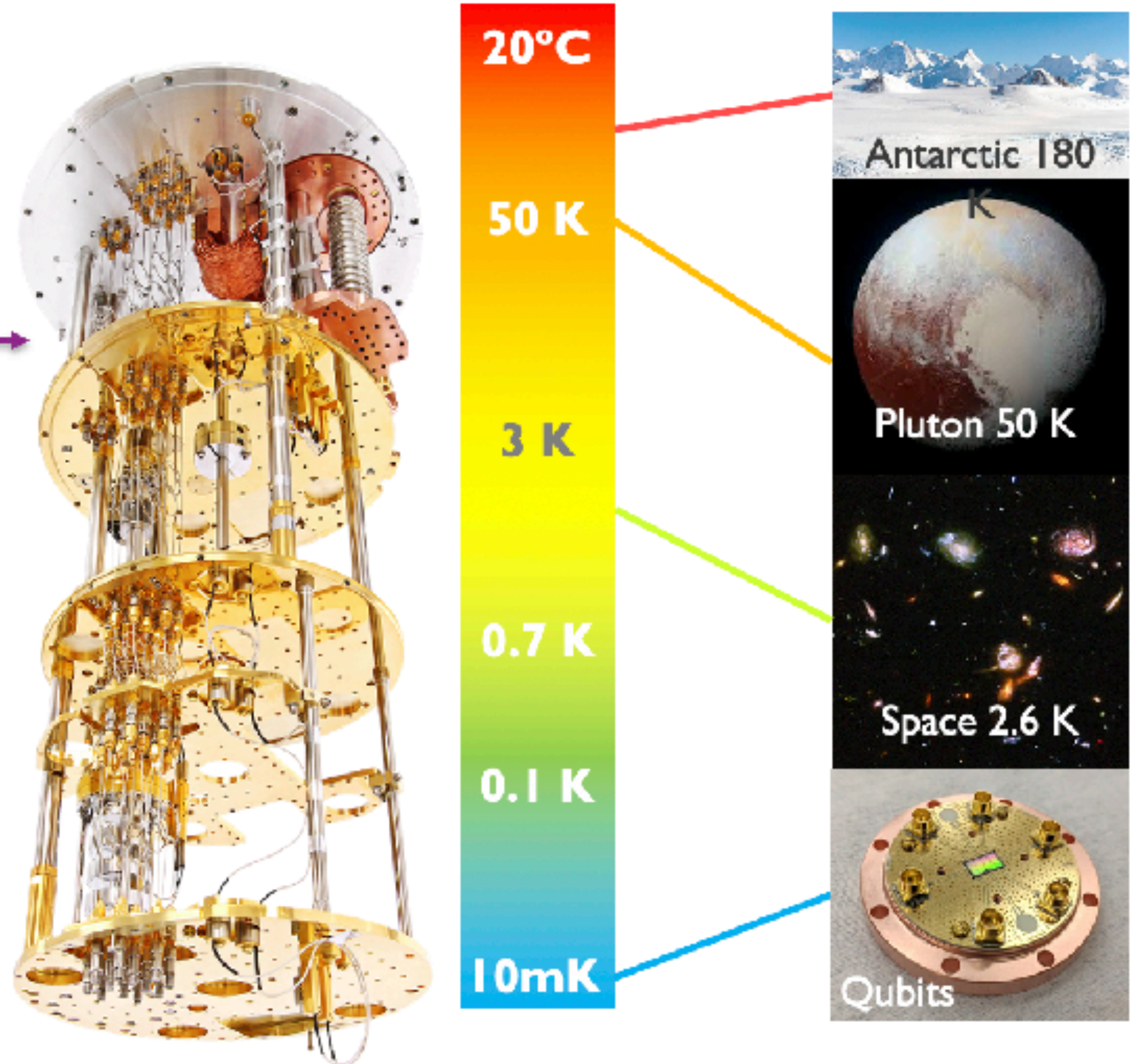


Al	AlO_x	Al
30 nm	1-2 nm	50 nm

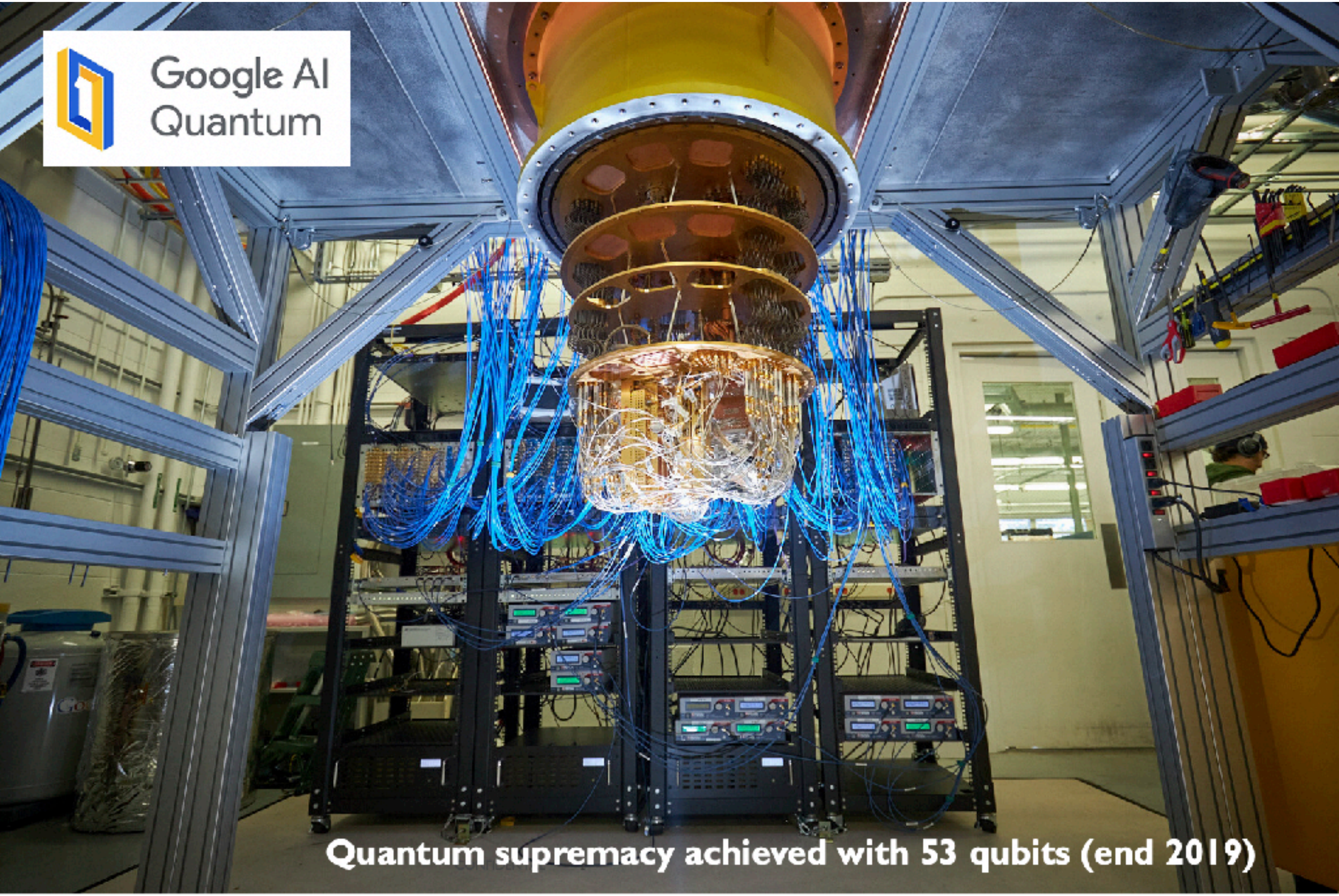
Periphery

He3/He4 REFRIGERATOR

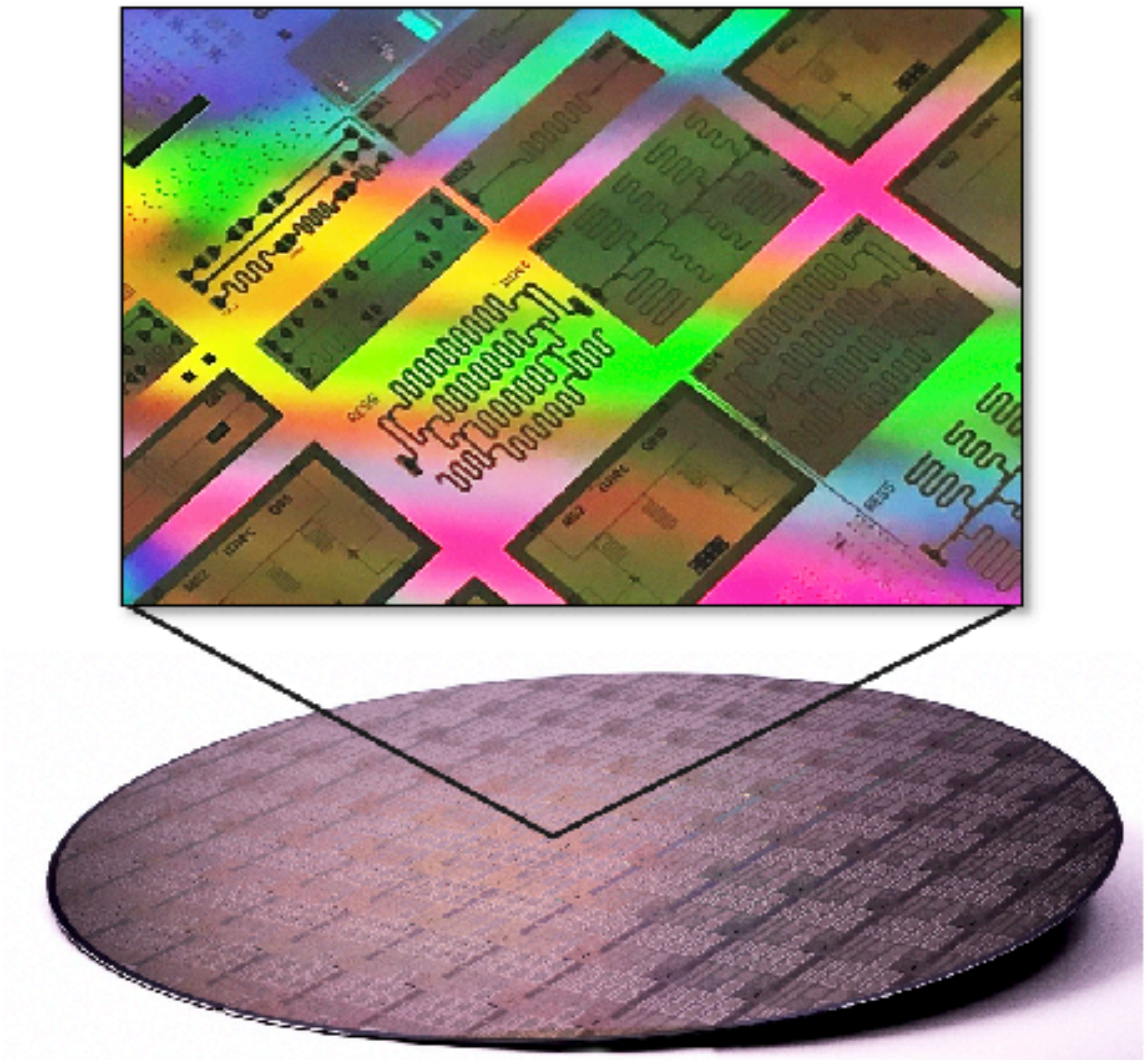
Control Unit, Gas Handling System, and cryostat in mounting frame.

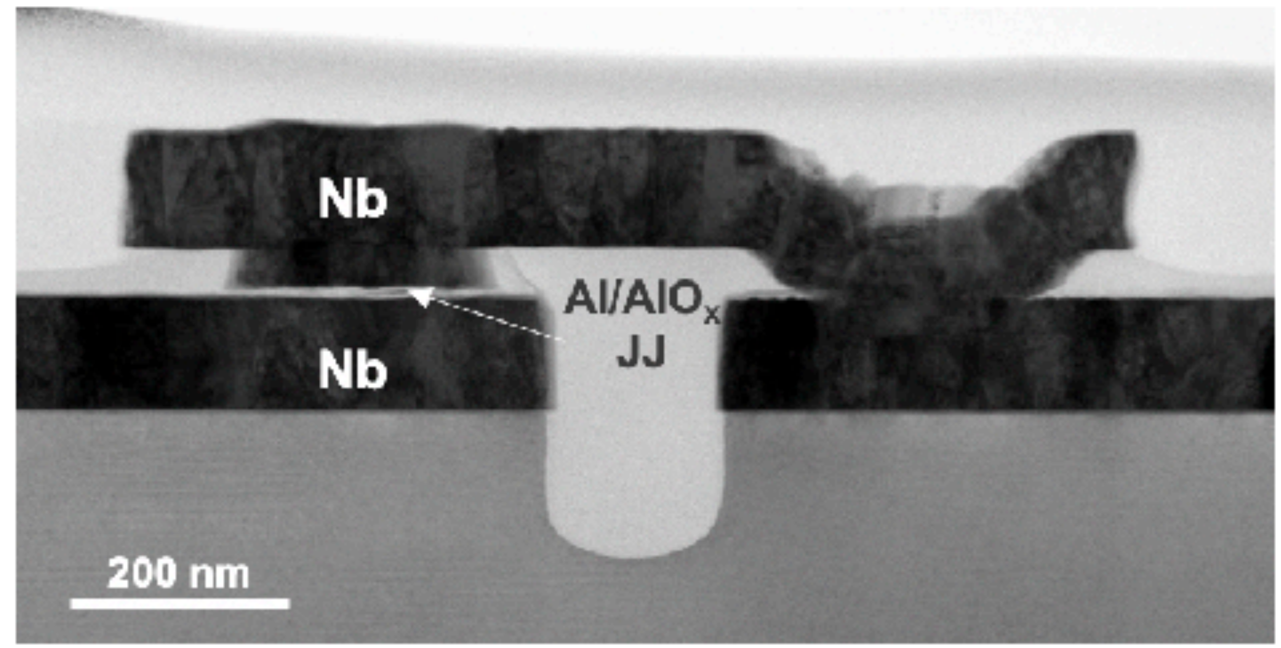


A. Potočnik


Google AI
Quantum
Quantum supremacy achieved with 53 qubits (end 2019)

Shadow evaporation vs Trilayer JJ



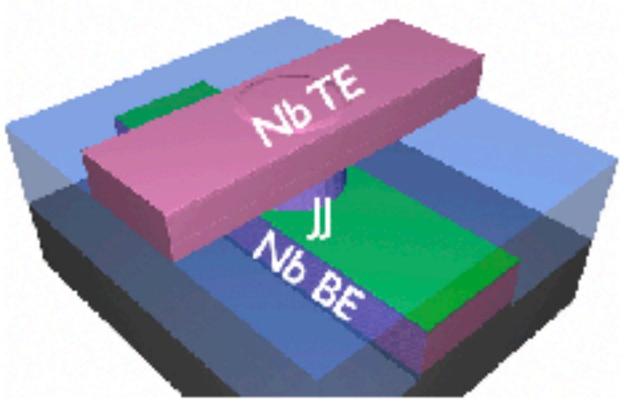


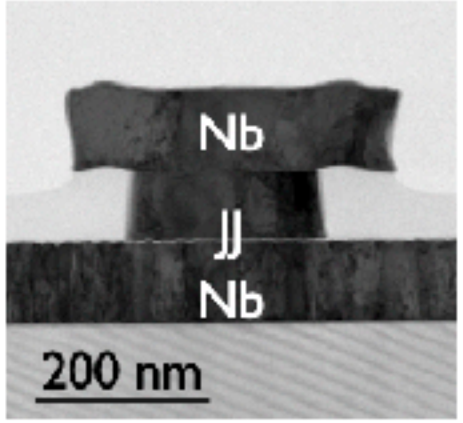
	Shadow ev.	Trilayer
Wafer size	< 200 mm	300 mm
Technology	E-beam	optical
Environment	Laboratory	Industrial
JJ variability	4-10%	~1%*

* Other developed junctions at imec

Room temperature trilayer junction testing

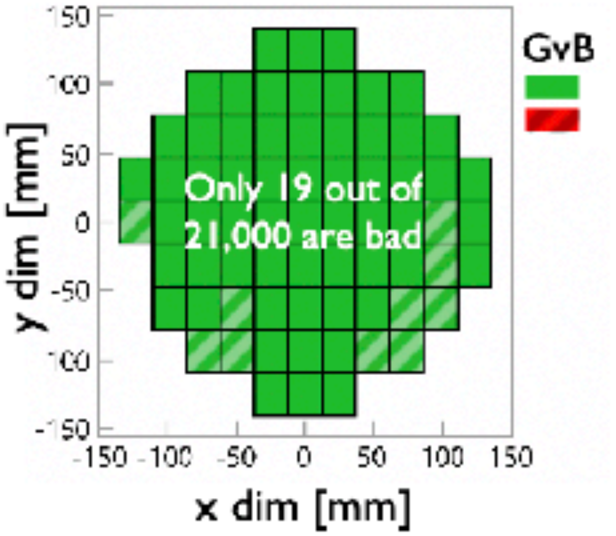
Junction resistance



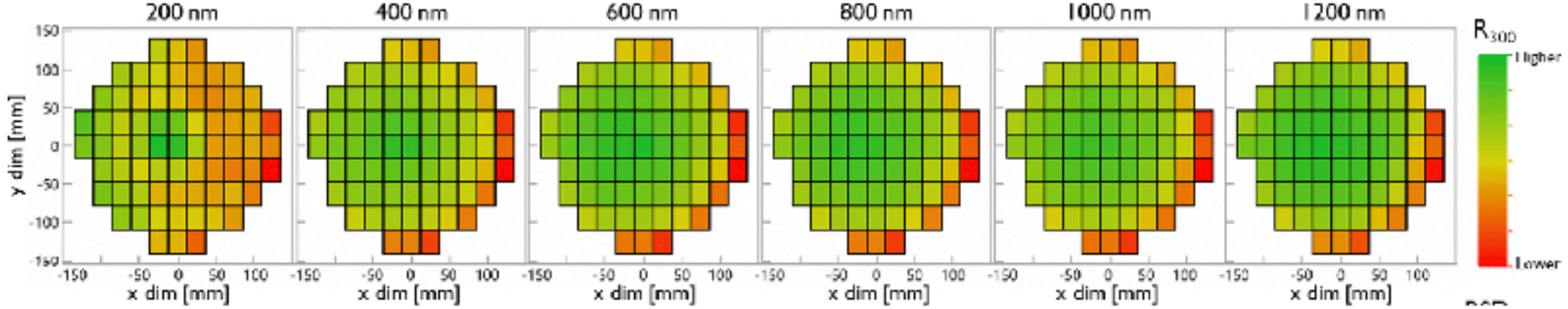


21,000 junctions tested

Junction yield map



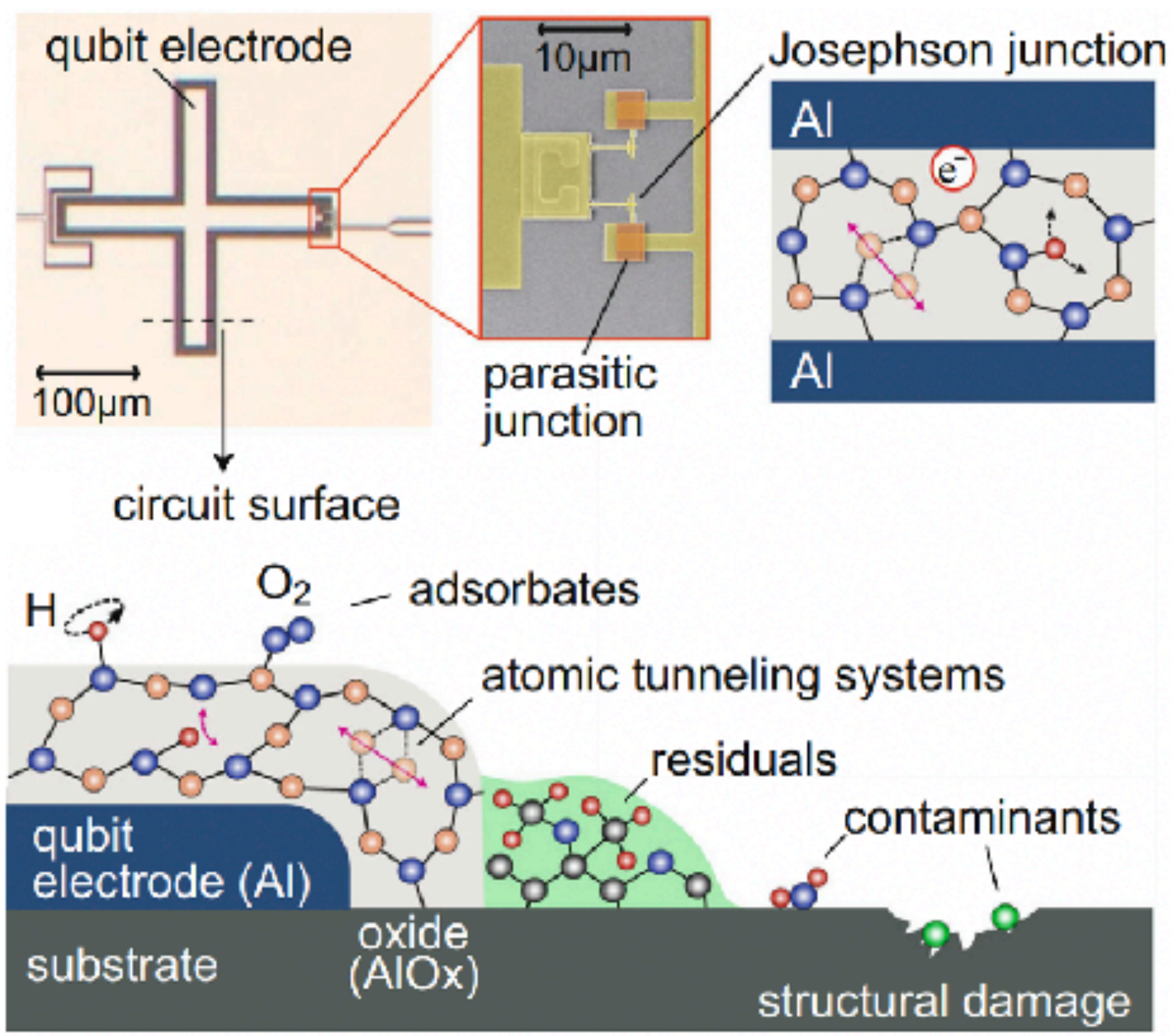
Ambegaokar-Baratoff relation: $R_{300K} \propto \sqrt{f_{01}}$



300mm wafer results: high JJ yield > 99.9%

Wan, AP *et al.* JJAP 60 SBBI04 (2021).

Microwave losses and decoherence

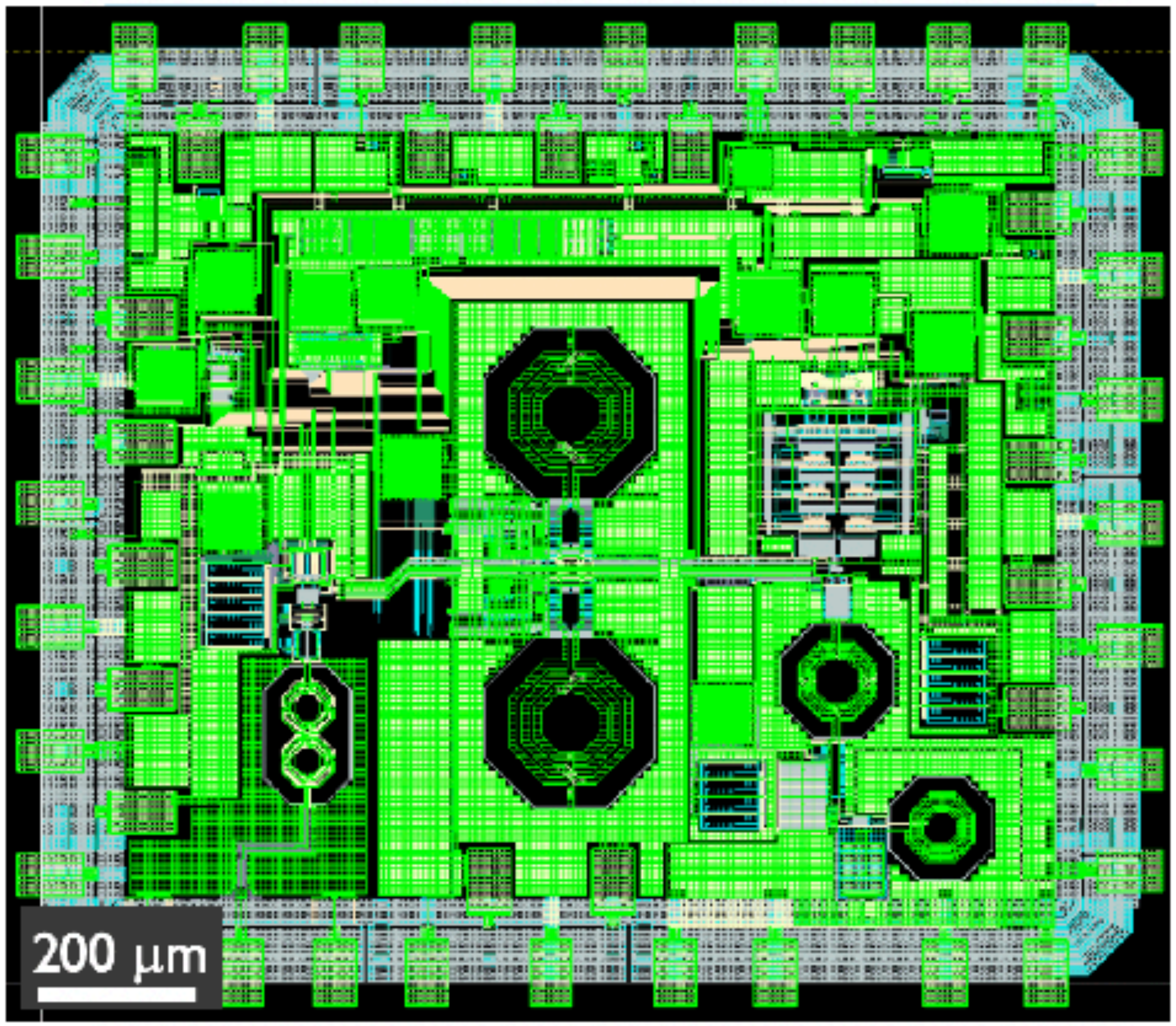


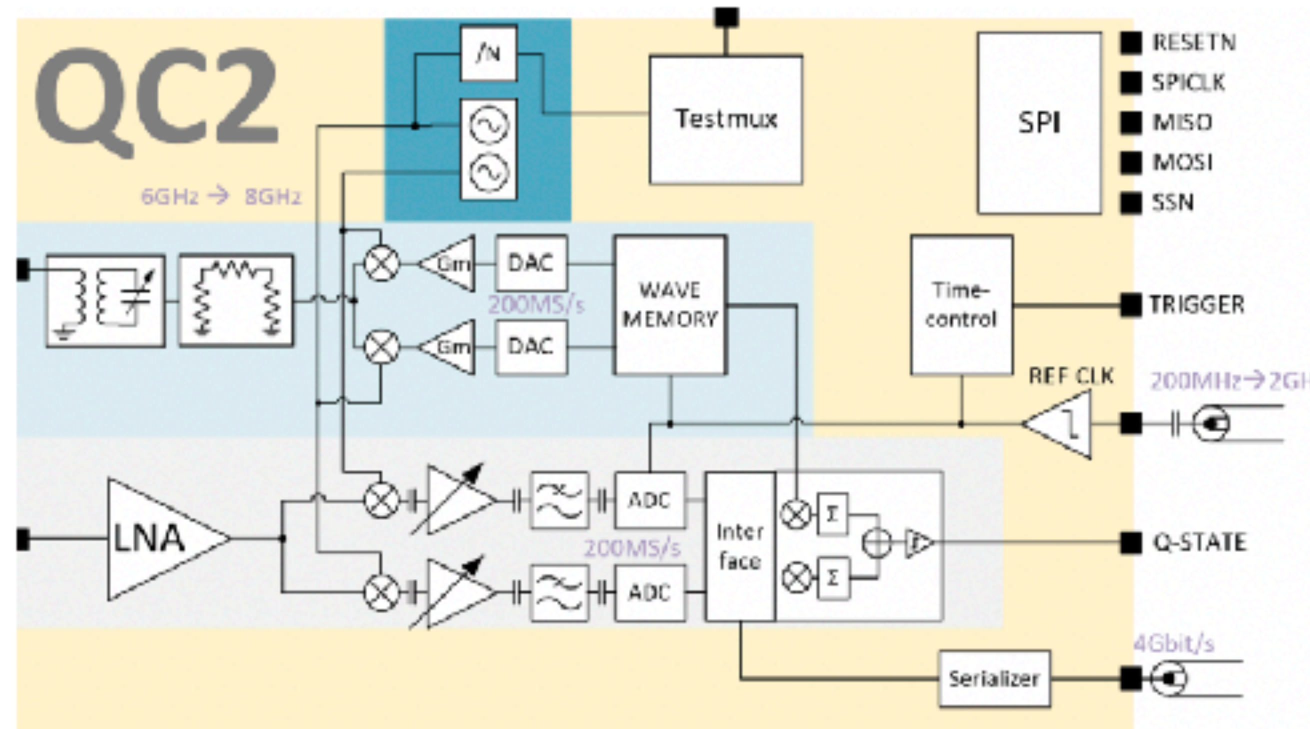
Lisenfeld, *et al.* Npj Quantum Inf. 5, 105 (2019).
Müller *et al.* Rep. Prog. Phys. 82 124501 (2019).

- TLS found in amorphous interfaces are main source of dielectric loss
- Visible <100 mK and low MW powers
- >60% of loss in the capacitor

- Search for materials with lowest TLS loss tangent.
- Search for new deposition conditions

Custom designed Cryo-CMOS control and readout



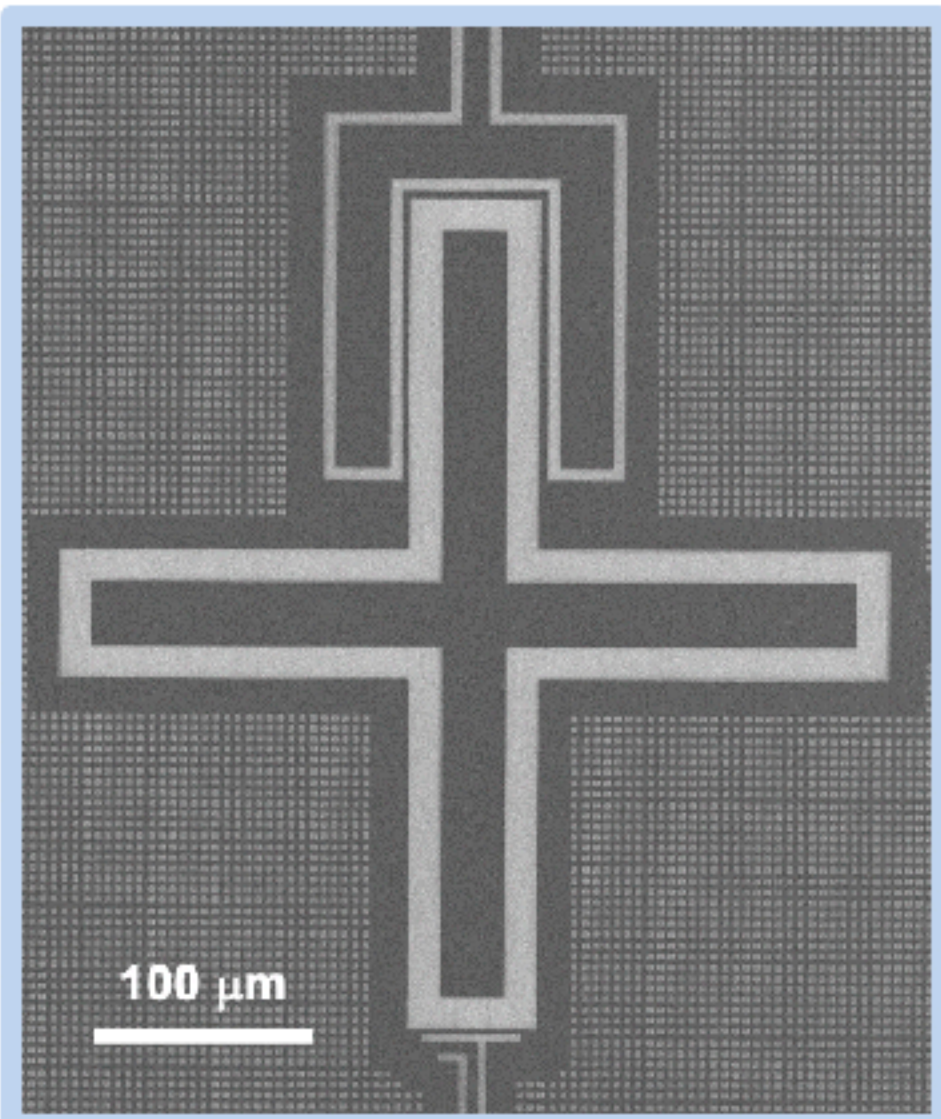


- Lower power consumption per qubit
- Lower latency
- Smaller footprint

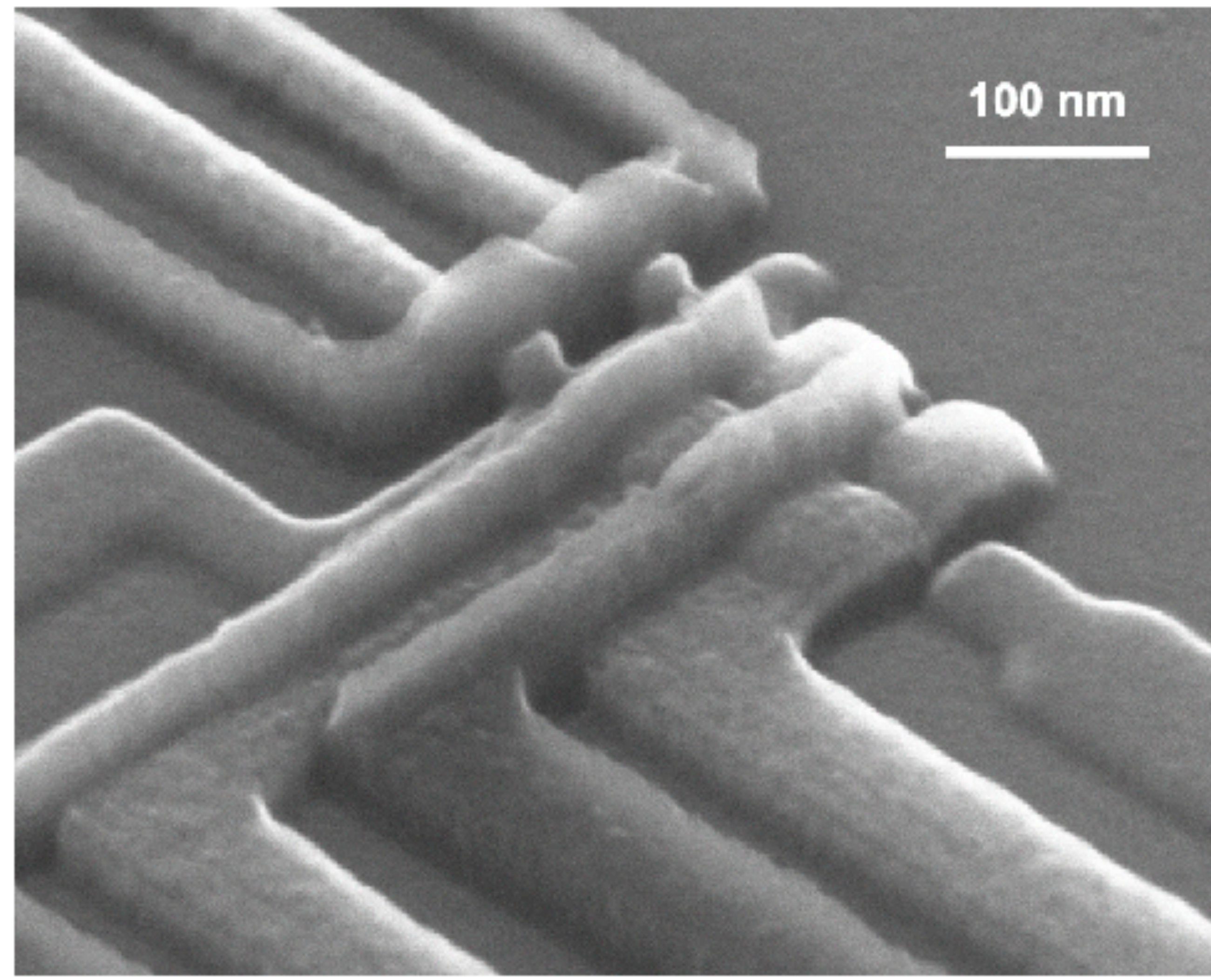
 J. Craninckx AP et al IEDM (2020)., S. Van Winkel, AP et al. *in preparation*

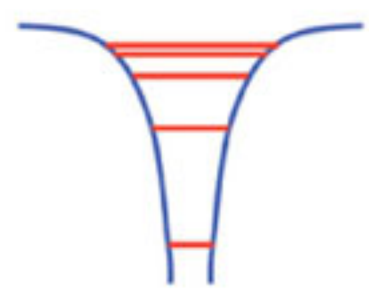
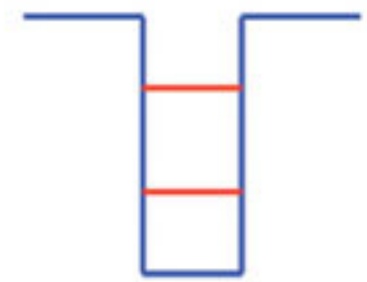
spinski kubiti

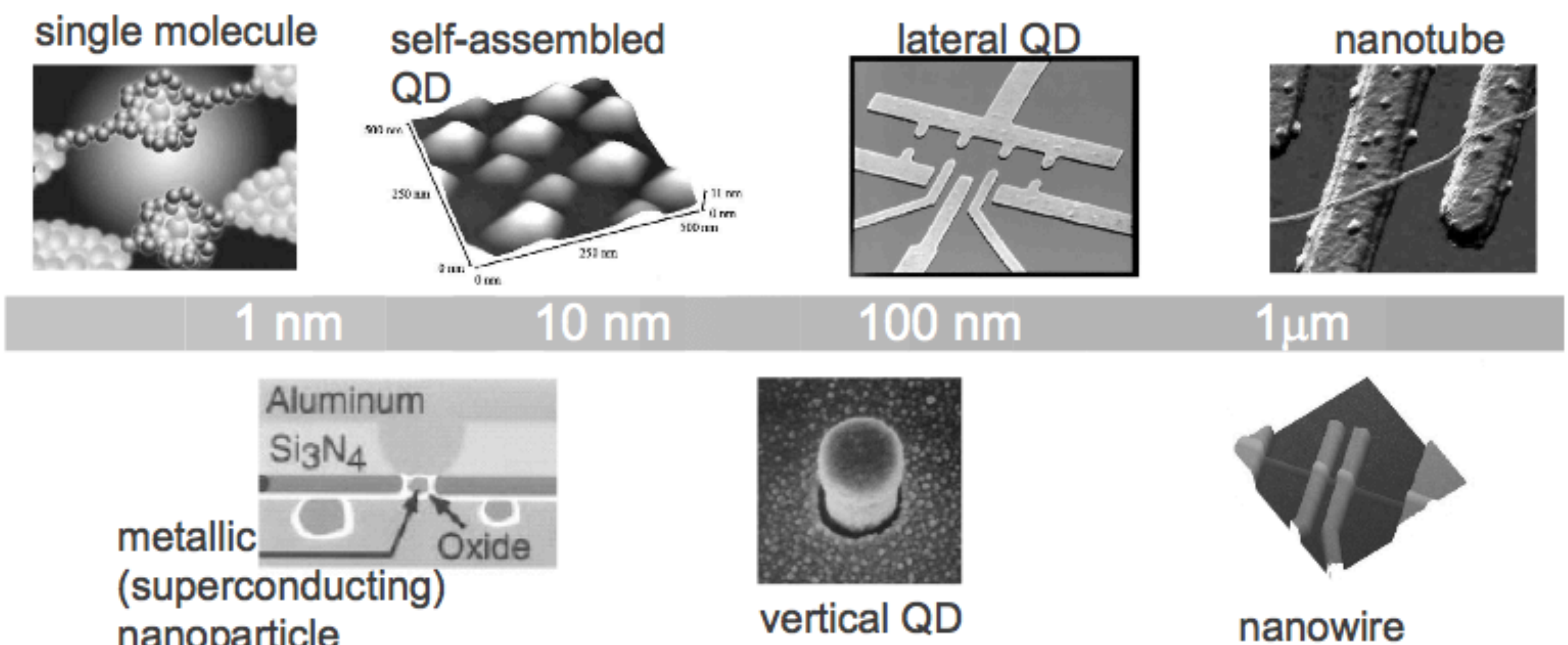
Superconducting qubits

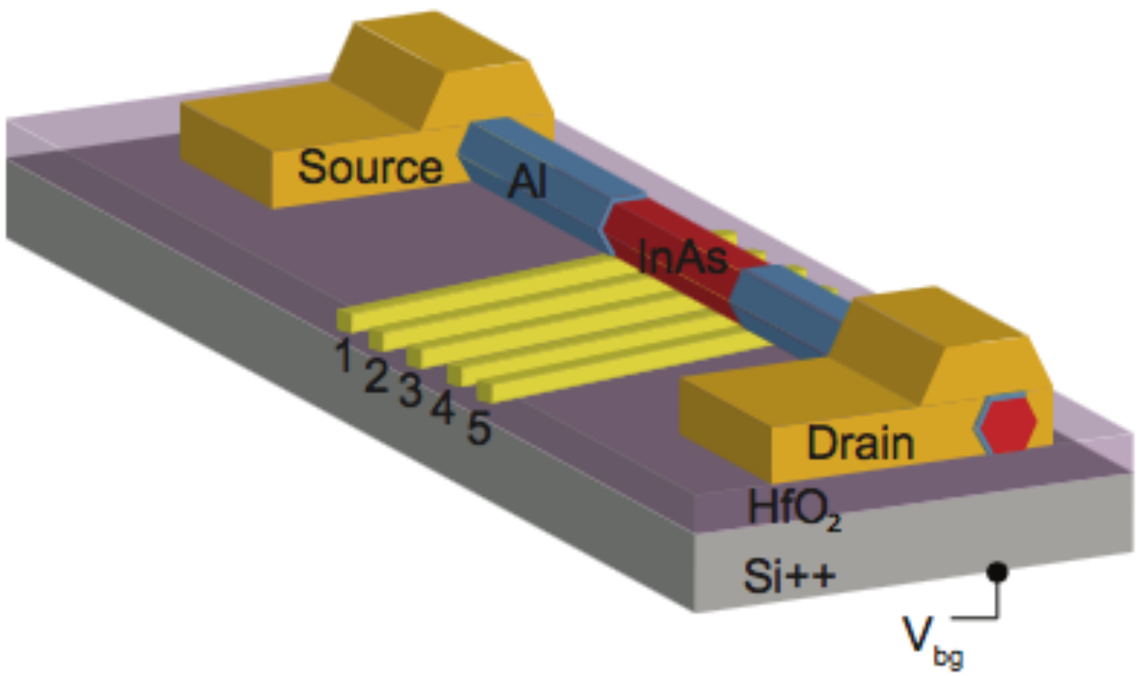


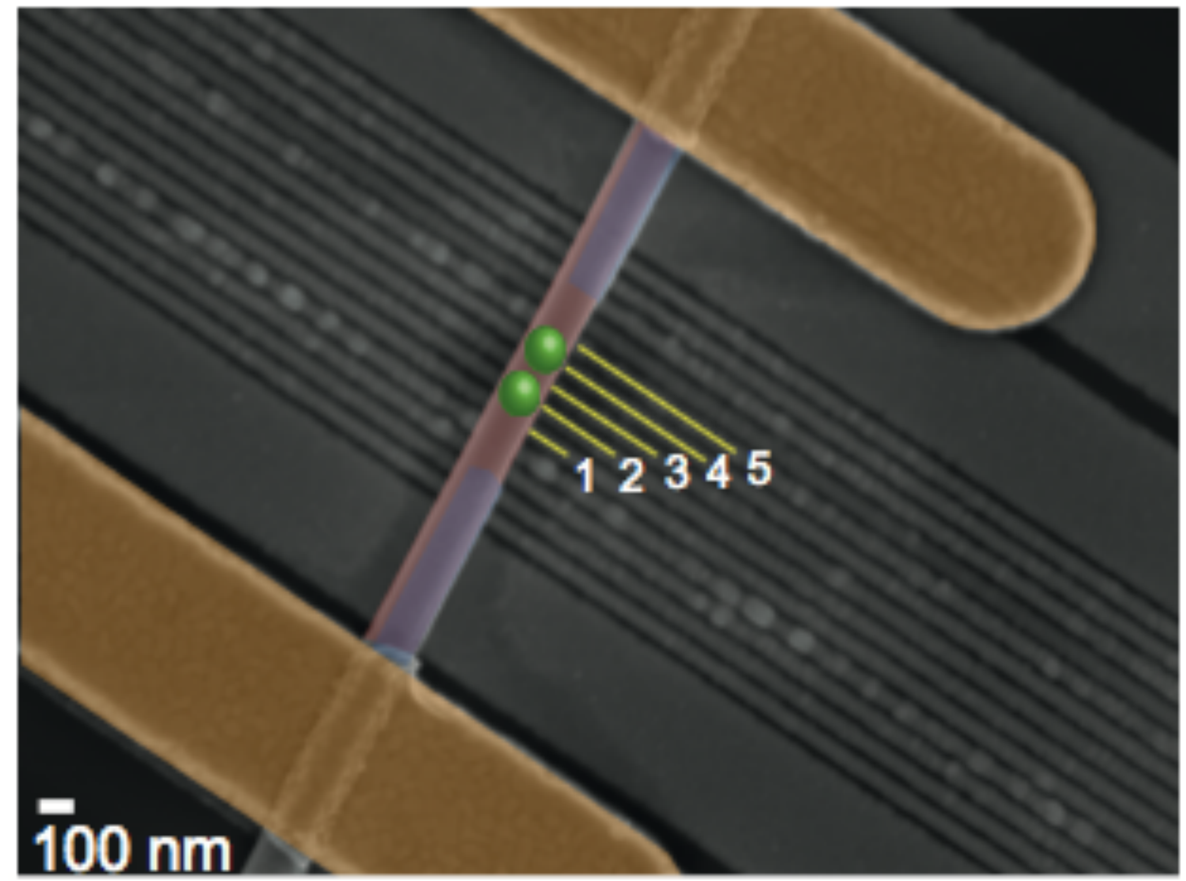
Spin qubits



Atom	Quantum dot
	




Source
Al
InAs
1
2
3
4
5
Drain
HfO_2
Si++
V_{bg}

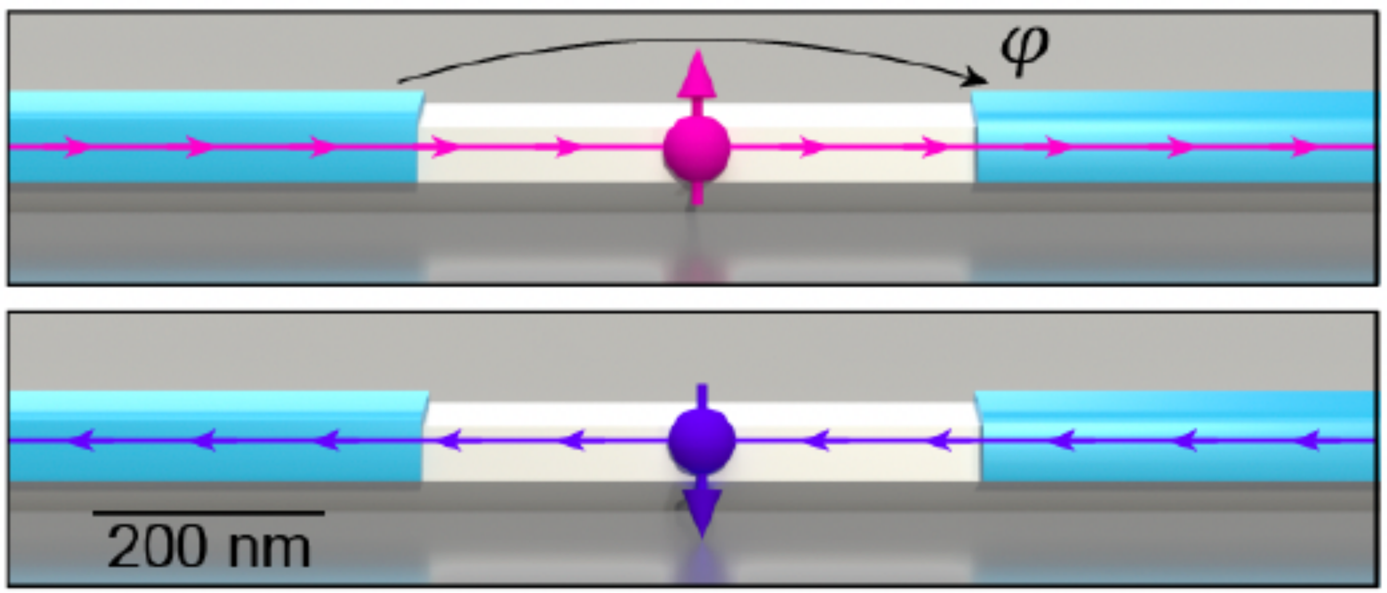

1 2 3 4 5
100 nm

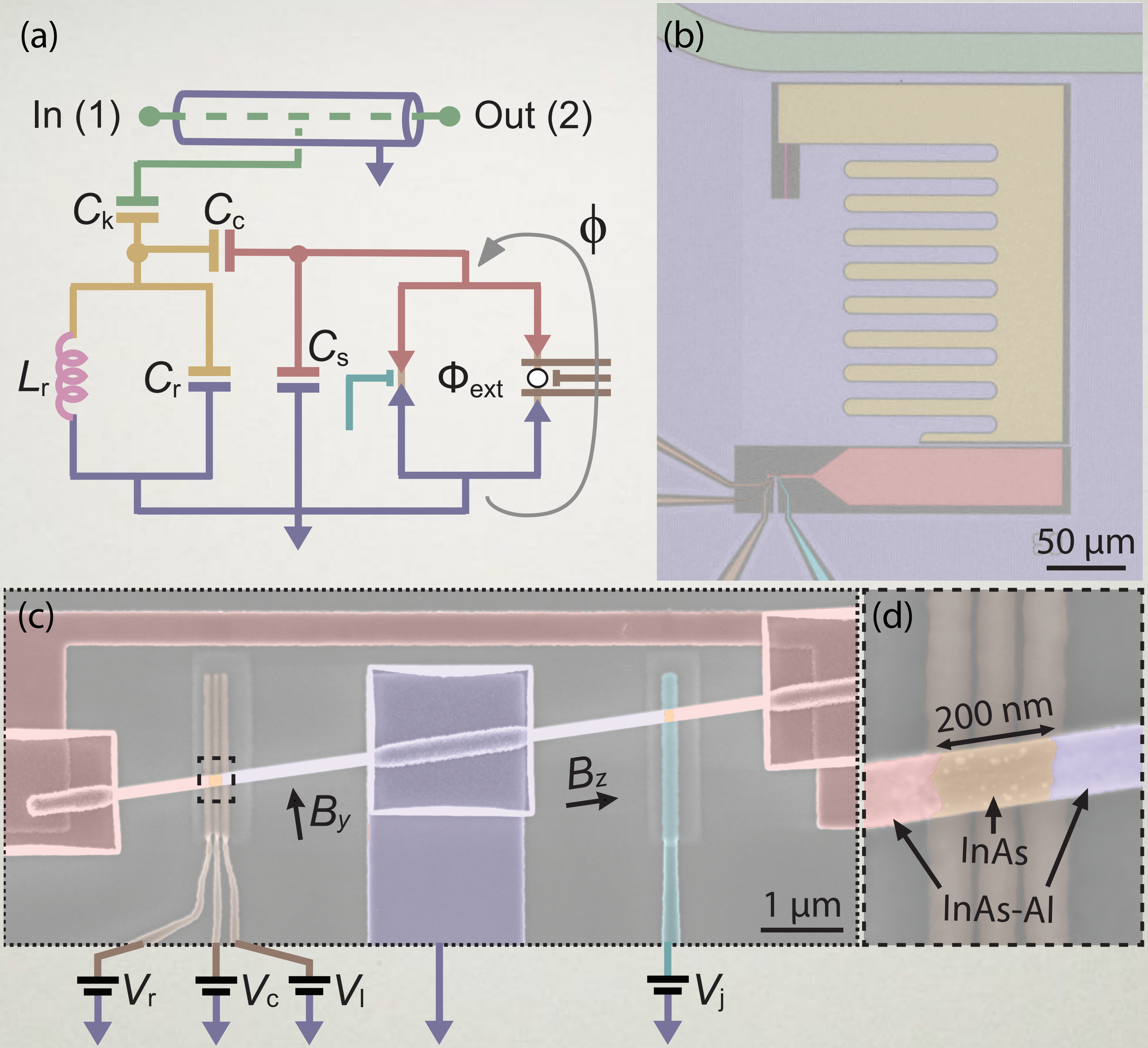
Andreevi spinski kubiti

Coherent manipulation of an Andreev spin qubit

M. Hays,[1,*] V. Fatemi,[1,†] D. Bouman,[2,3] J. Cerrillo,[4,5] S. Diamond,[1] K. Serniak,[1,6] T. Connolly,[1] P. Krogstrup,[7] J. Nygård,[7] A. Levy Yeyati,[5,8] A. Geresdi,[2,3,9] and M. H. Devoret[1,‡]

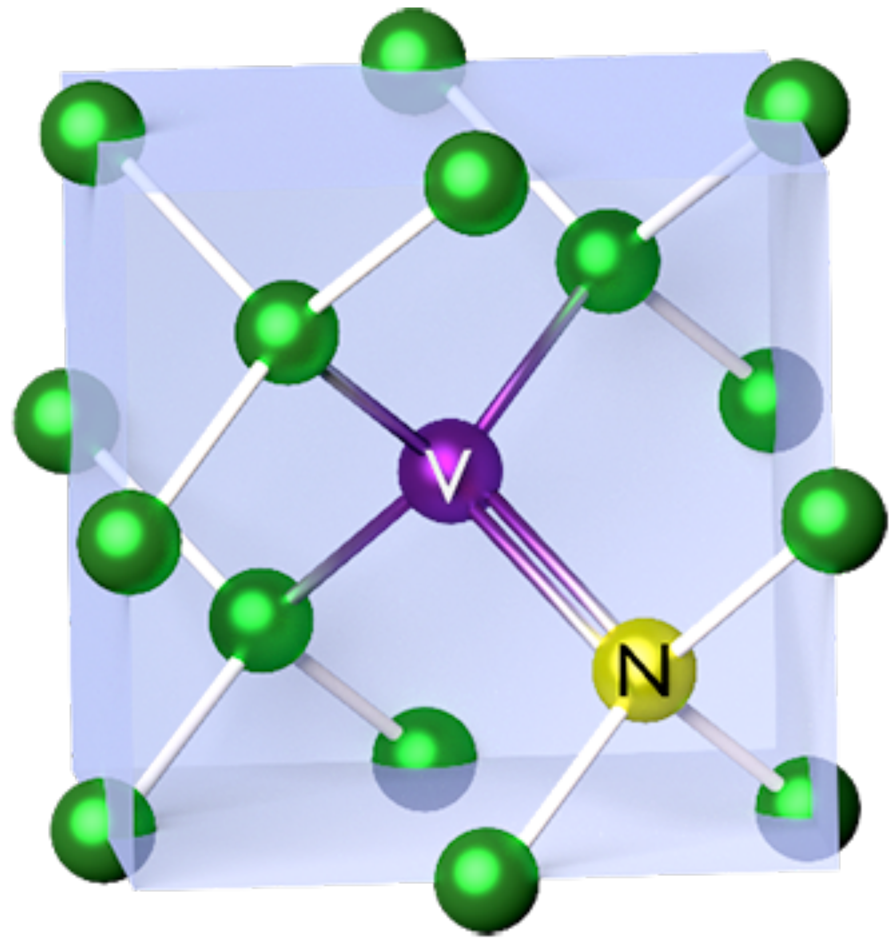
(a)





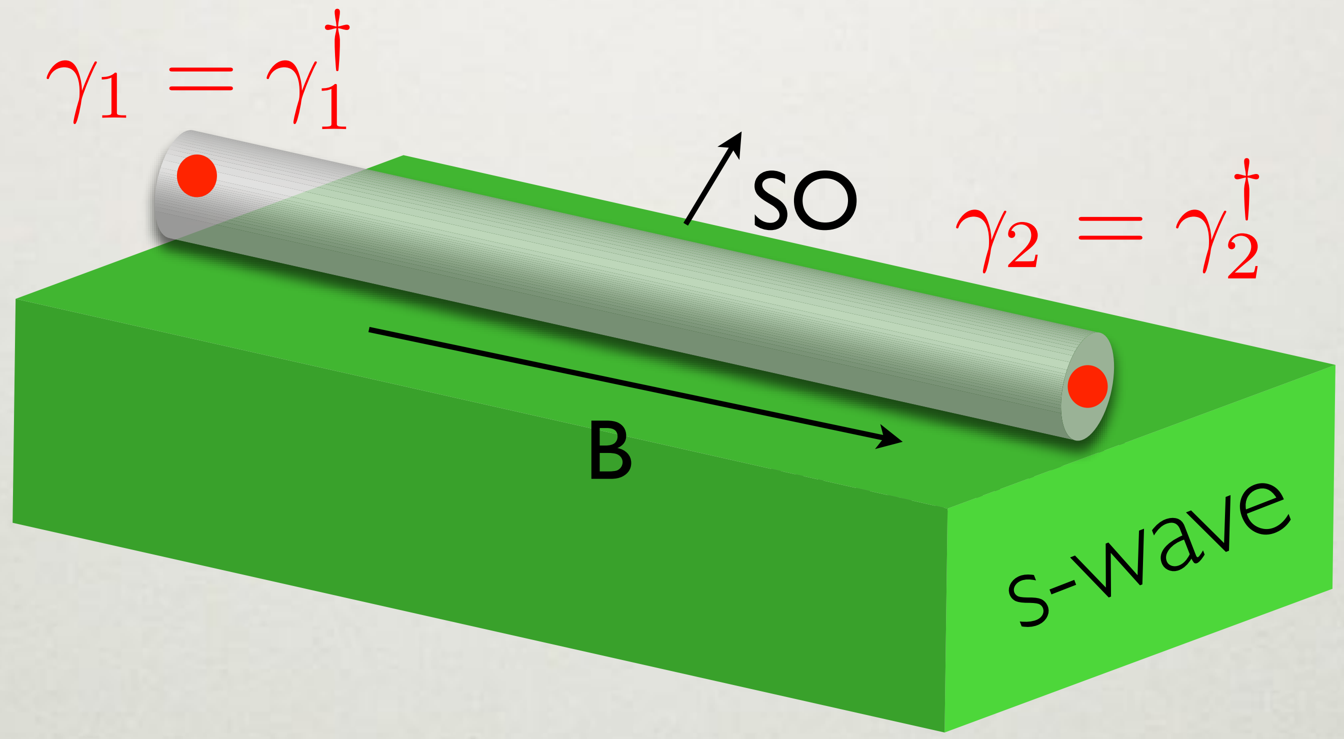
QuTech and Kavli Institute of Nanoscience, Delft University of Technology (TU Delft)
Bargerbos, Pita-Vidal, Žitko, Ávila, Splitthoff, Grünhaupt, Wesdorp, Andersen, Liu, Kouwenhoven, Aguado, Kou, van Heck,
PRX Quantum (2022)

defekti v kristalih


V
N

topološke naprave

Majoranova stanja v nanožicah



Ettore Majorana (/maɪəˈrɑːnə/,[2] Italian: [ˈɛttore majoˈraːna]; born on 5 August 1906 – probably died after 1959[1]) was an Italian theoretical physicist who worked on neutrino masses. On 25 March 1938, he disappeared under mysterious circumstances while going by ship from Palermo to Naples. The Majorana equation and Majorana fermions are named after him. In 2006, the Majorana Prize was established in his memory.

Several possible explanations for his disappearance have been proposed, including:

Hypothesis of suicide

proposed by his colleagues Amaldi, Segrè and other[9]

Hypothesis of escape to Argentina

proposed by Erasmo Recami and Carlo Artemi (who has developed a detailed hypothetical reconstruction of Majorana's possible escape and life in Argentina)[*citation needed*]

Hypothesis of escape to Venezuela

Rai 3 talk show "*Chi l'ha Visto?*" published a statement stating that Majorana was alive between 1955 and 1959, living in Valencia, Venezuela under the surname of "Bini".[10]

Hypothesis of escape to a monastery

proposed by Sciascia (putatively the Charterhouse of Serra San Bruno)[*citation needed*]

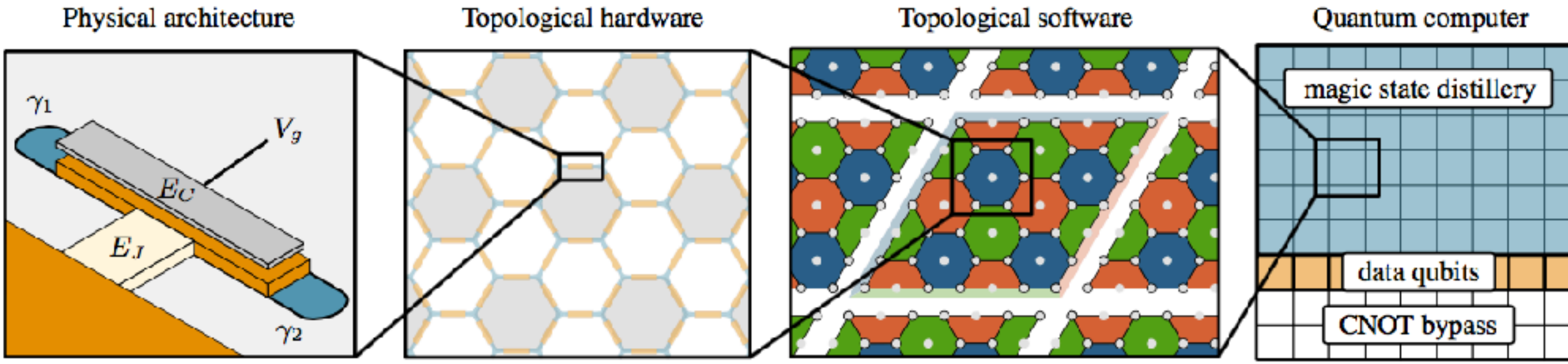
Hypothesis of kidnapping or murder

by Bella, Bartocci, and others, to avoid his participation in the construction of an atomic weapon[*citation needed*]

Hypothesis of escape to become a beggar

by Bascone and Venturini (called the "*omu cani*" or "dog man" hypothesis)[11]

Topološko kvantno računalništvo



a) Majorana Cooper pair box *b*) Physical qubits: hexagonal cells *c*) Logical qubits: diamond color code *d*) Qubit arrangement

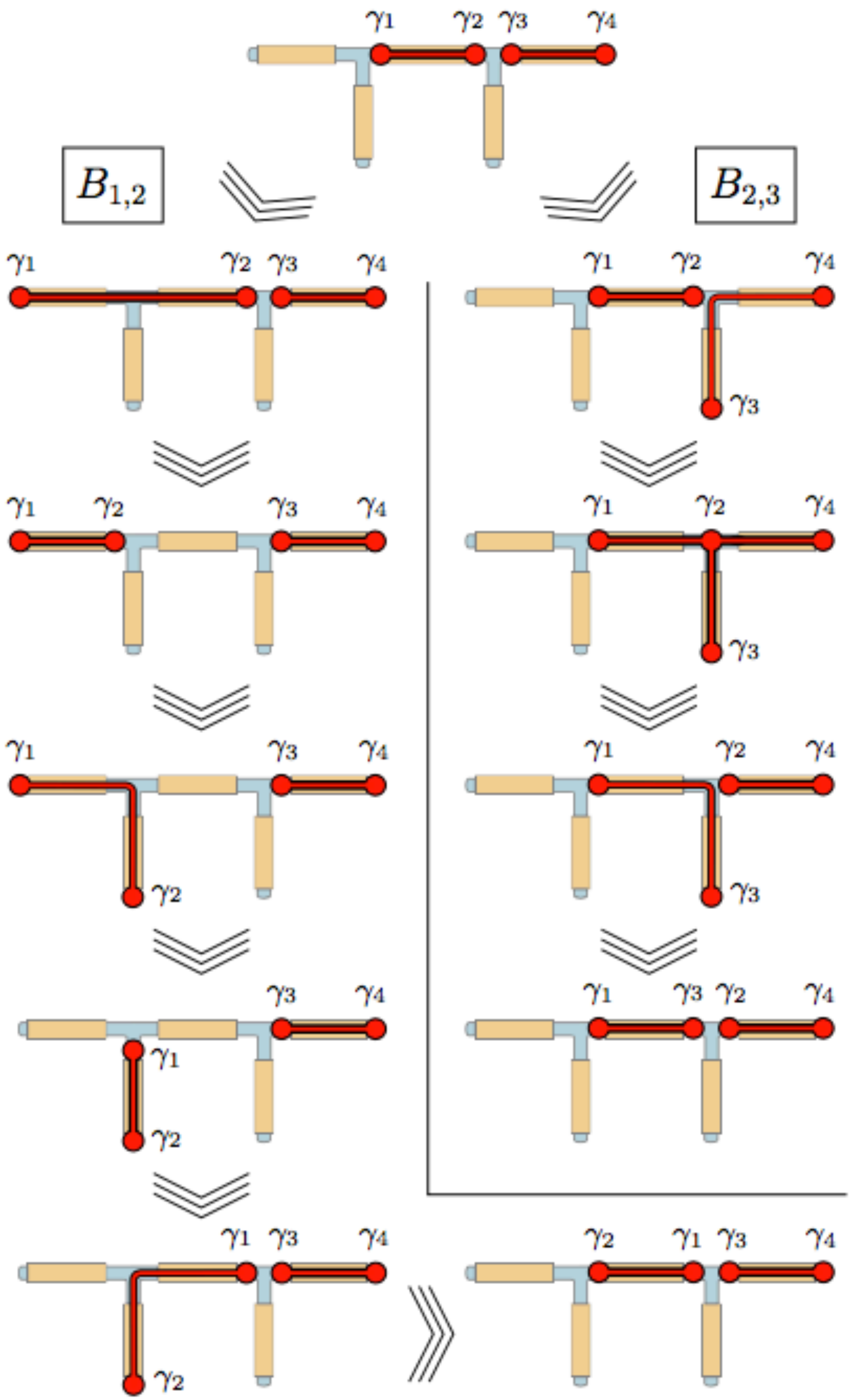
Cliffordova grupa: Hadamard, CNOT, π/4 fazna vrata S (topološko zaščiteno na strojnem nivoju)

π/8 fazna vrata T niso zaščitena, potrebno je energijsko razcepiti stanja (fine tuning!).

Combining Topological Hardware and Topological Software:
Color Code Quantum Computing with Topological Superconductor Networks

Daniel Litinski, Markus S. Kesselring, Jens Eisert, and Felix von Oppen
Dahlem Center for Complex Quantum Systems and Fachbereich Physik,
Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany

Prepletanje v dvojnem spoju T

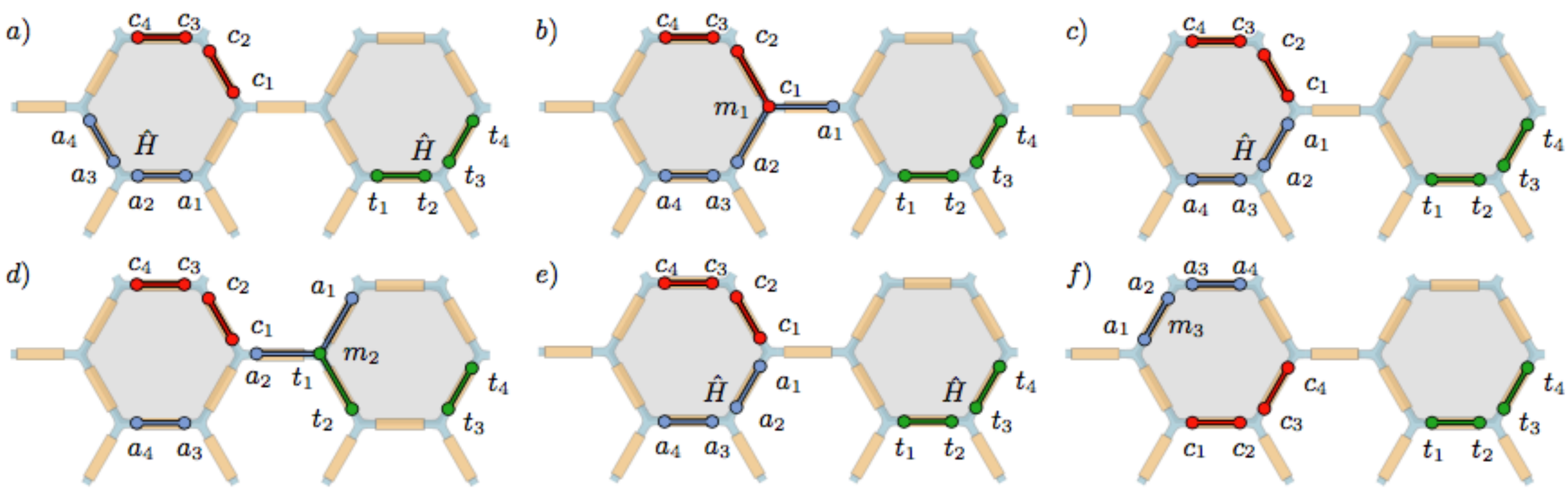


$$B_{i,j} = \frac{1}{\sqrt{2}}(1 + i\eta_i\eta_j)$$

$$S = B_{1,2}$$

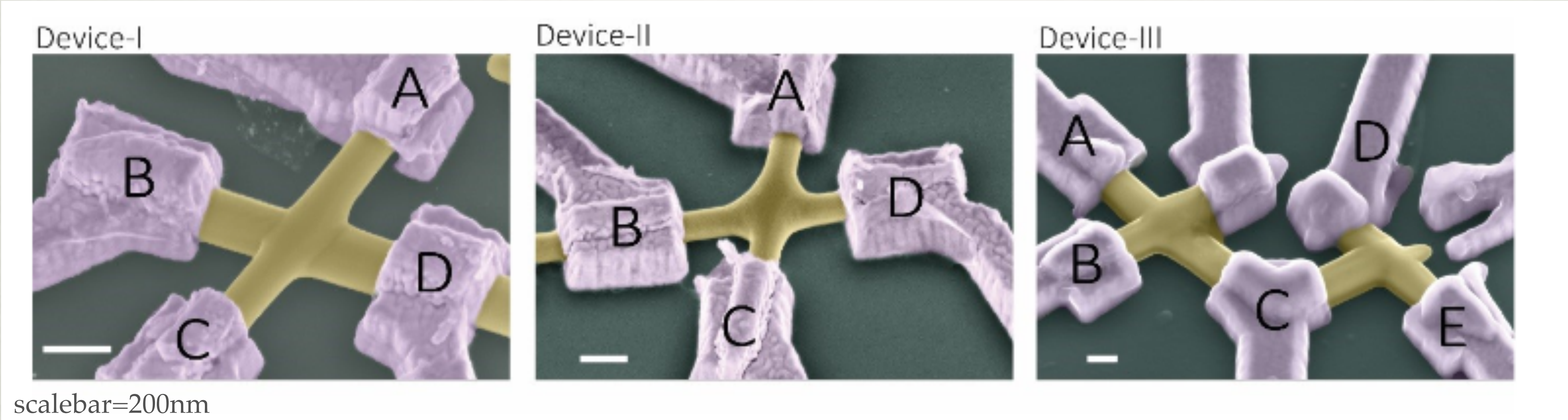
$$H = iB_{1,2}B_{2,3}B_{1,2}$$

Vrata CNOT

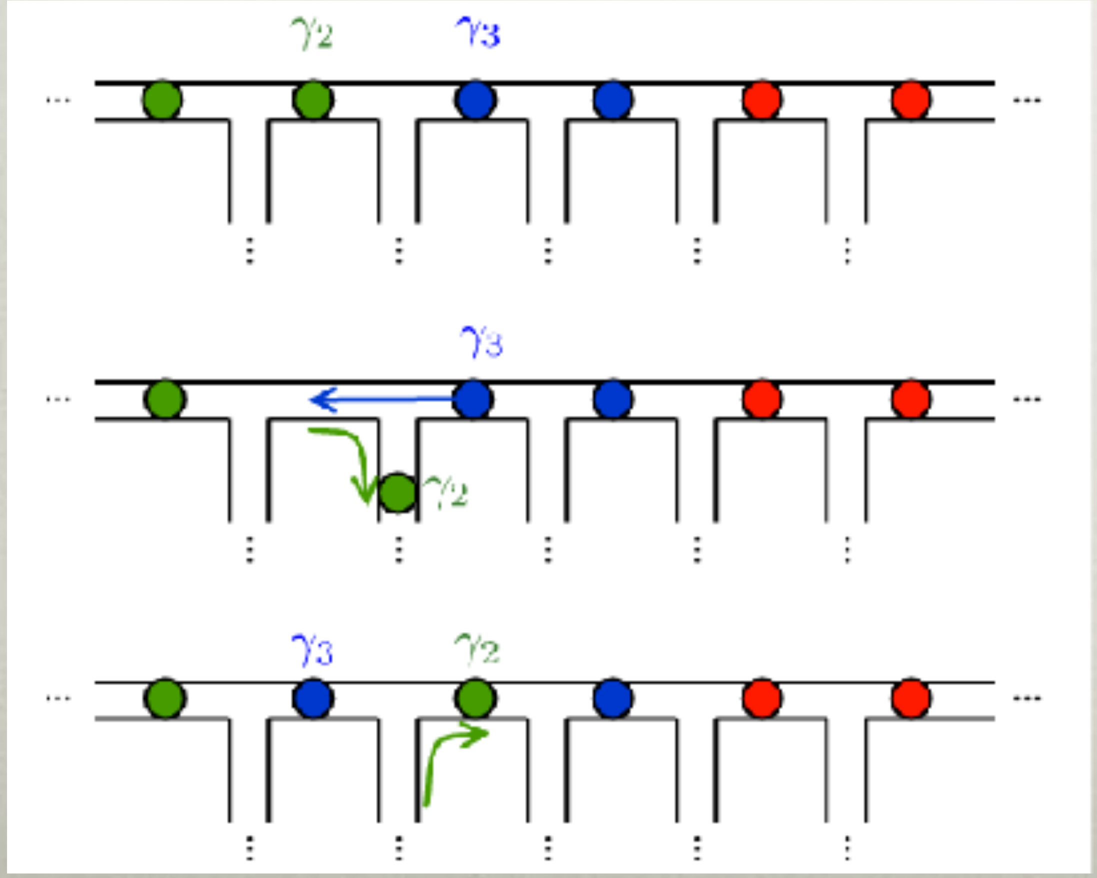


a)
c4 c3 c2 c1
a4 a3 a2 a1
Ĥ
Ĥ
t4 t3 t1 t2
b)
c4 c3 c2 c1
m1
a1 a2 a4 a3
t4 t3 t1 t2
c)
c4 c3 c2 c1
Ĥ
a1 a2 a4 a3
t4 t3 t1 t2
d)
c4 c3 c2 c1
a1
m2
a2 t1 t2
a4 a3
t4 t3
e)
c4 c3 c2 c1
Ĥ
a1 a2 a4 a3
Ĥ
t4 t3 t1 t2
f)
a2 a3 a4
a1 m3
c4 c3 c1 c2
t4 t3 t1 t2

Razvejane nanožice



Kouwenhoven, Bakkers, 2017



Cilj: prepletanje v nanožičkah do konca tega desetletja?