How to Build a Quantum Computer (Putting Strangeness to Work)

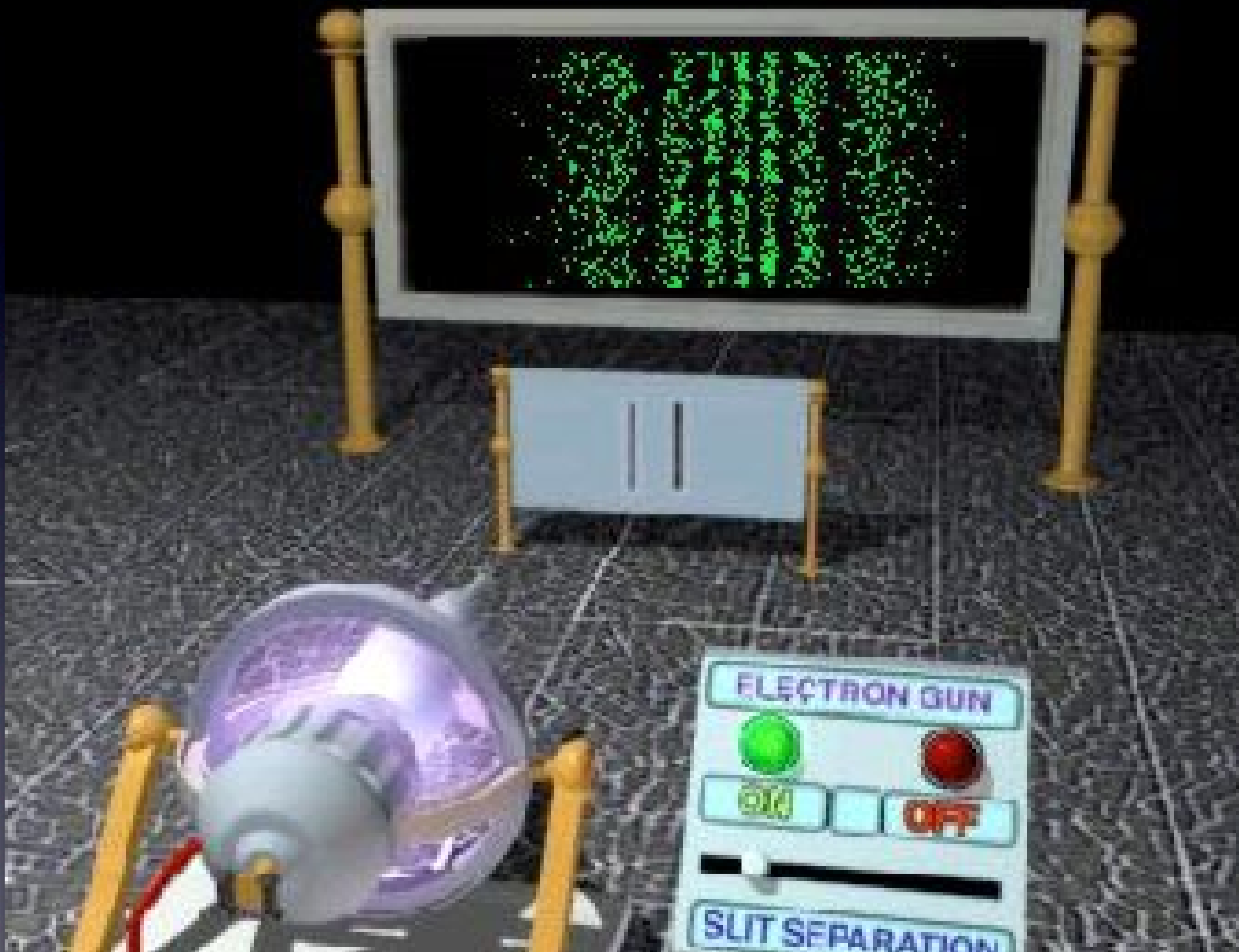
http://qdev.dk

Charles Marcus

Center for Quantum Devices
Niels Bohr Institute
University of Copenhagen

Microsoft Faculty Summit
July 16, 2013

Quantum Strangeness I:
Superposition – Measurement determines state

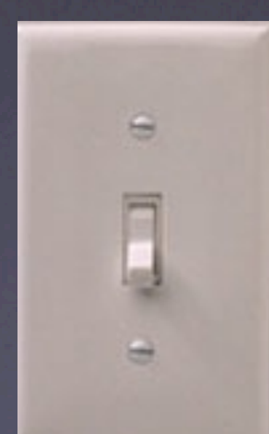


notation

|  ⟩ $= |1\rangle = \uparrow$

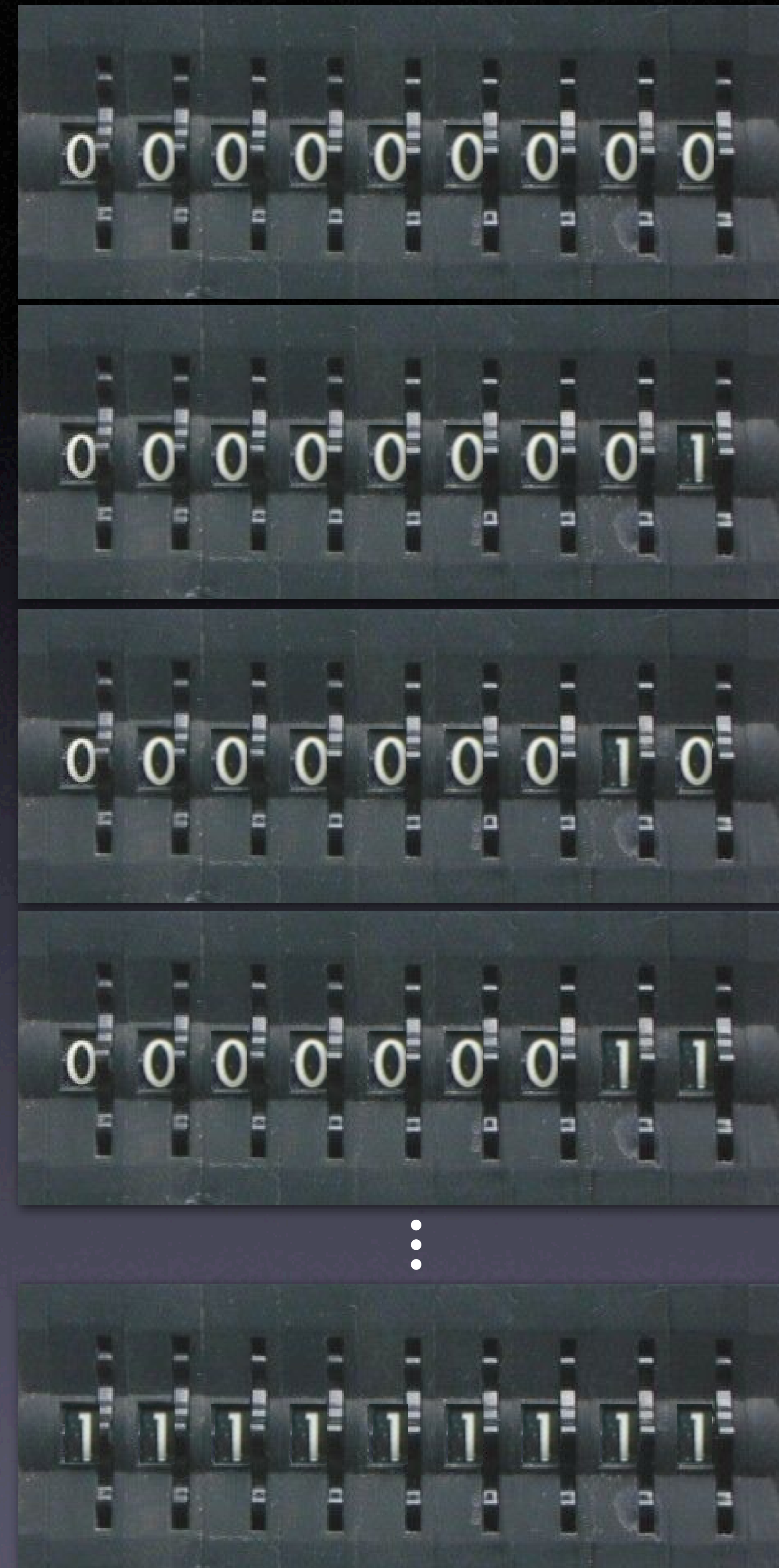
|  ⟩ $= |0\rangle = \downarrow$

a quantum state:

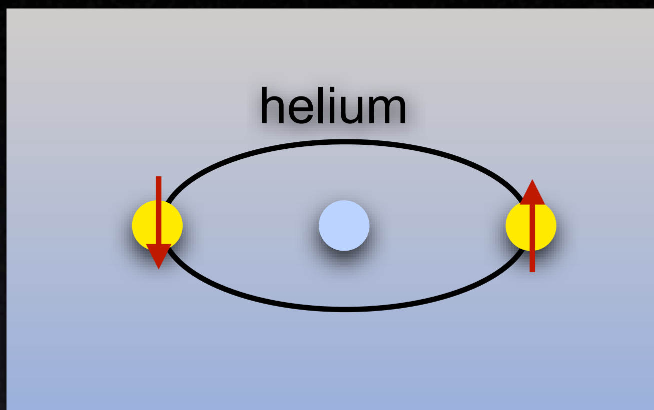
$\psi =$ |  ⟩ $+$ |  ⟩

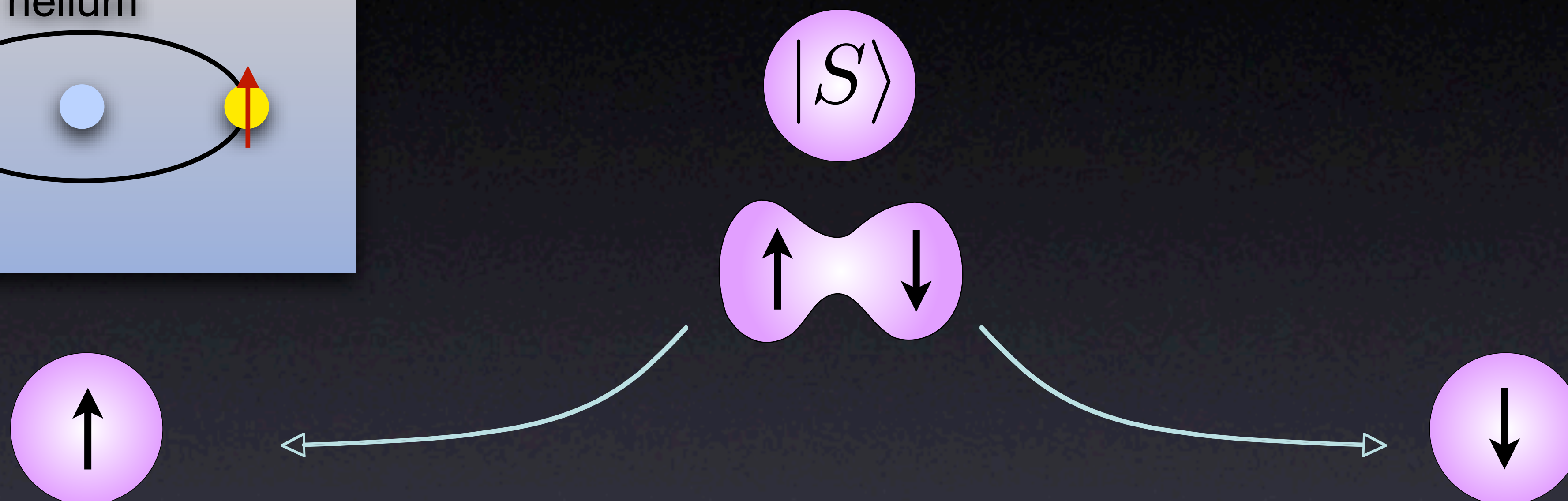
superposition as quantum parallelism

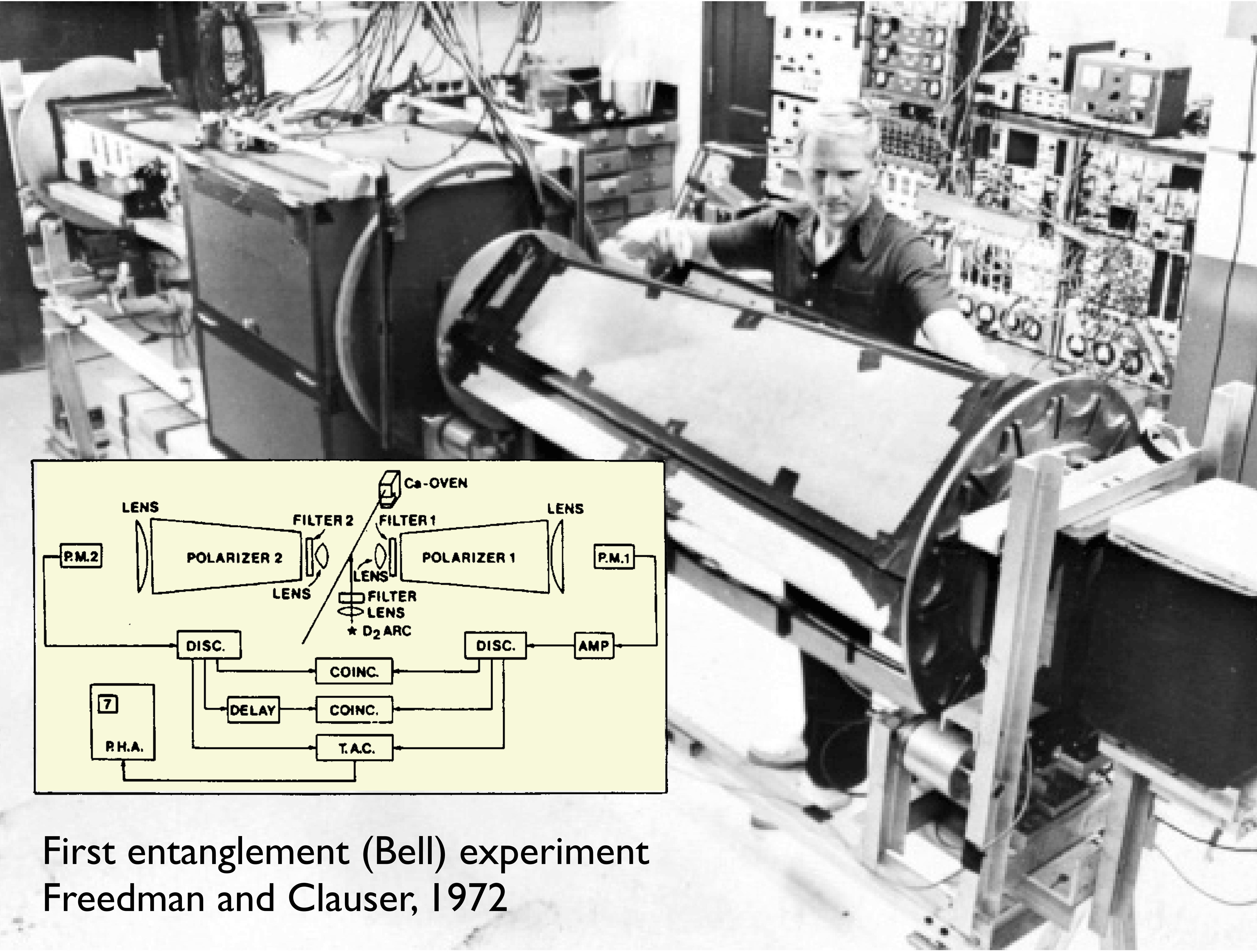
$$|\psi\rangle = \left\{ \right.$$



Quantum Strangeness II:
Entanglement – nonlocal correlations







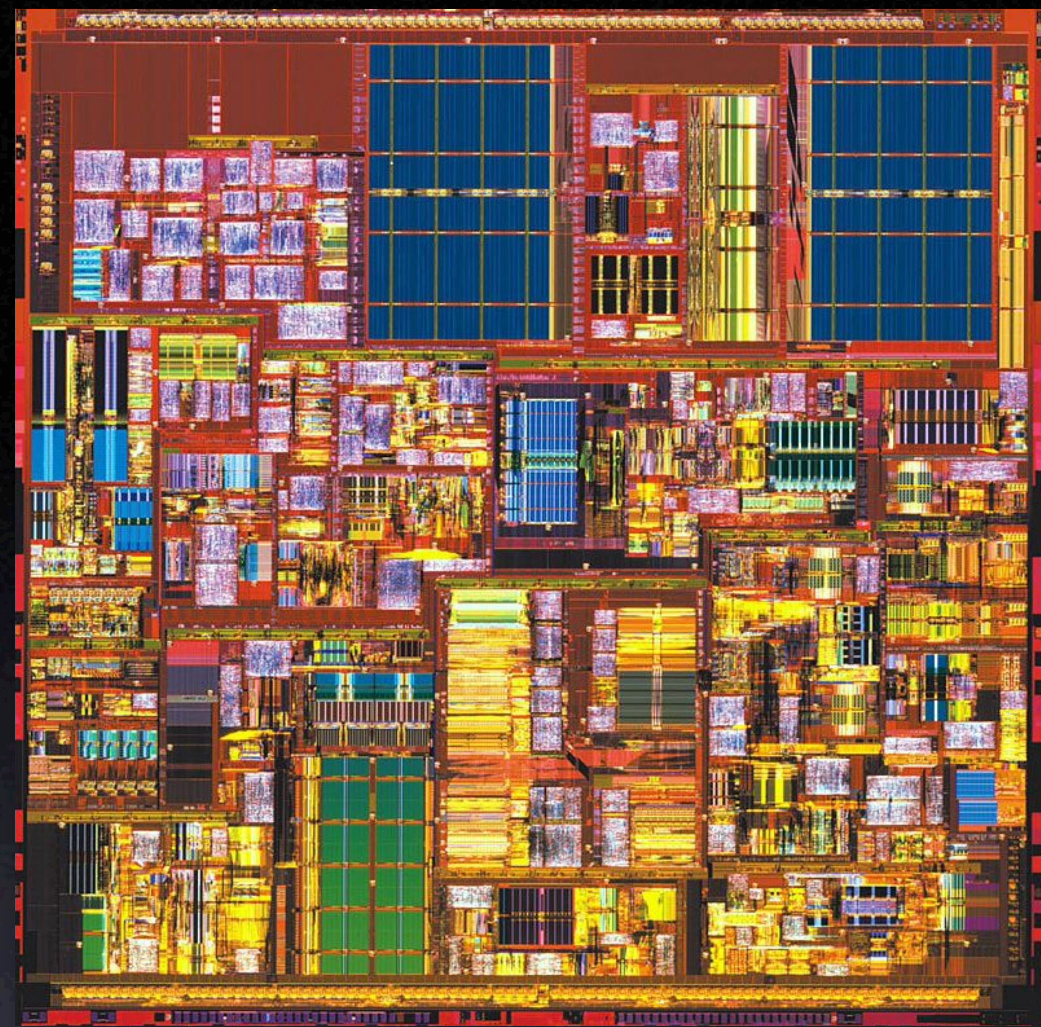
First entanglement (Bell) experiment
Freedman and Clauser, 1972

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with ... a Geiger counter [and] a tiny bit of radioactive substance.

Perhaps ... one of the atoms decays; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid.

The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed ... in equal parts.

- E. Schrödinger, 1935 (translated by J. Trimmer)



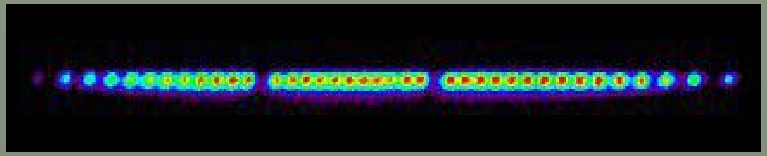
One can even set up quite ridiculous cases. A ~~cat~~ computer chip is penned up in a steel chamber, along with ... a Geiger counter [and] a tiny bit of radioactive substance.

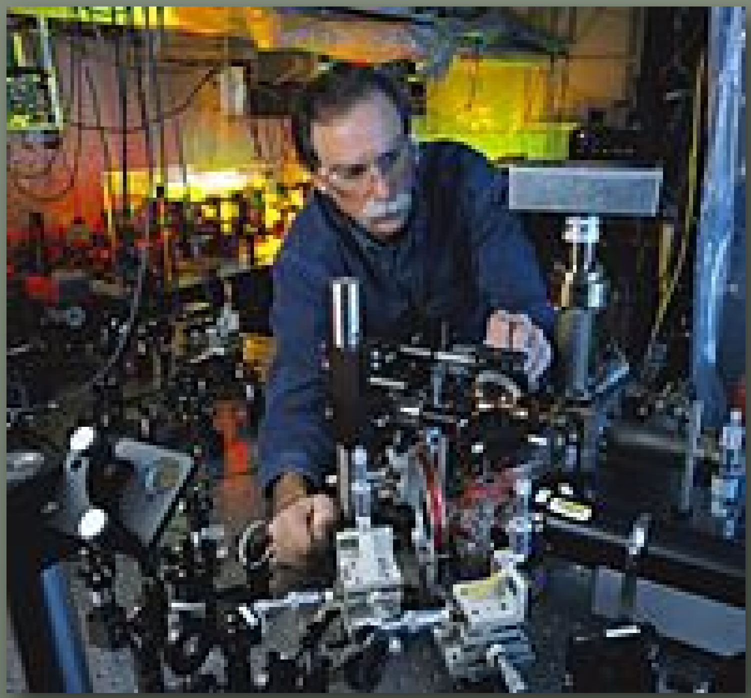
Perhaps ... one of the atoms decays; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid.

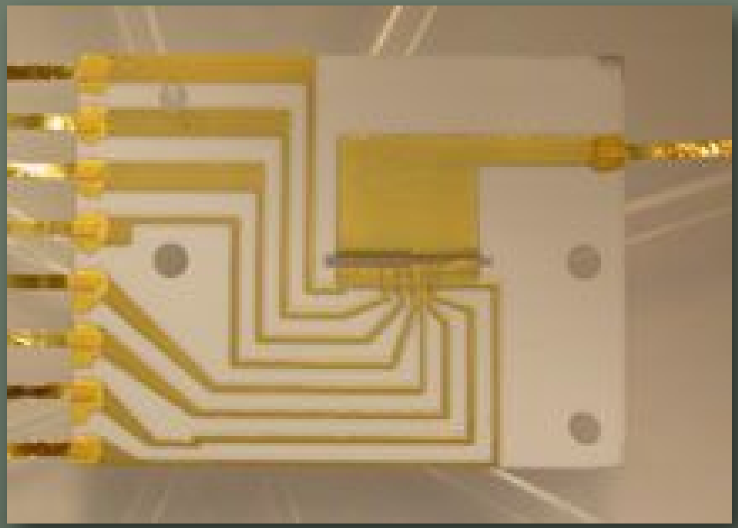
The psi-function of the entire system would express this by having in it the living and dead ~~cat~~ chip (pardon the expression) mixed ... in equal parts.

conventional qubits approaches

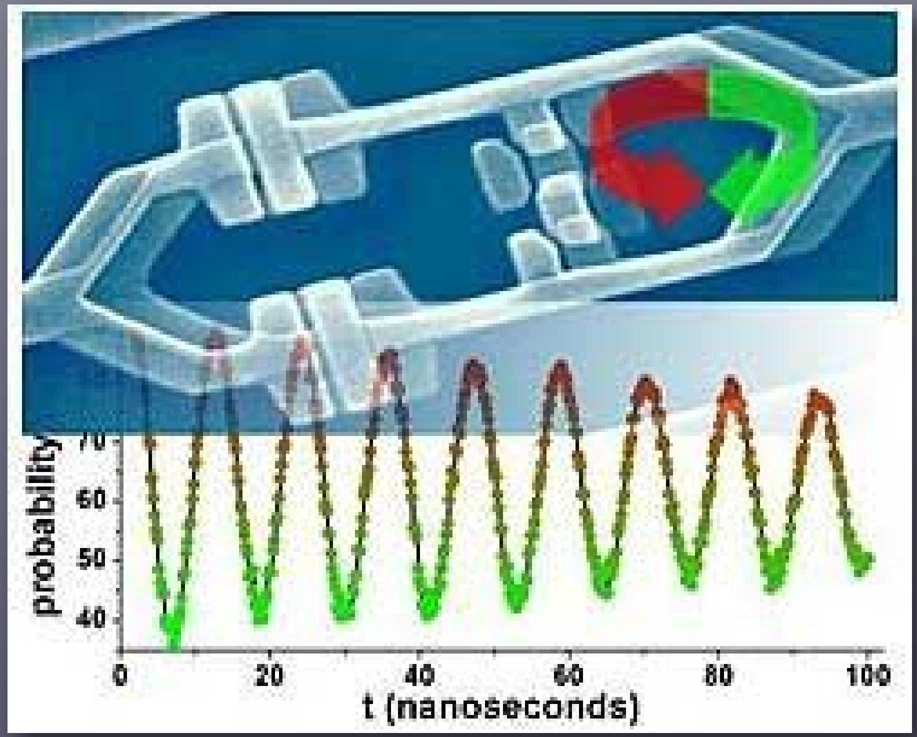
ion traps



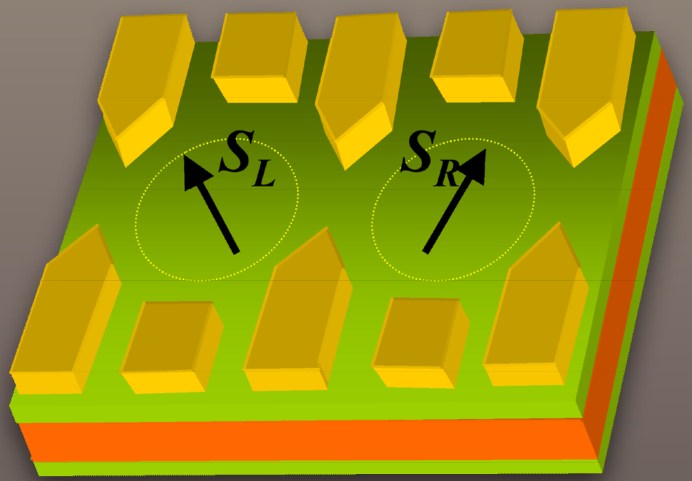




Josephson devices



Electron Spins in Dots



Quantum computation with quantum dots

Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]

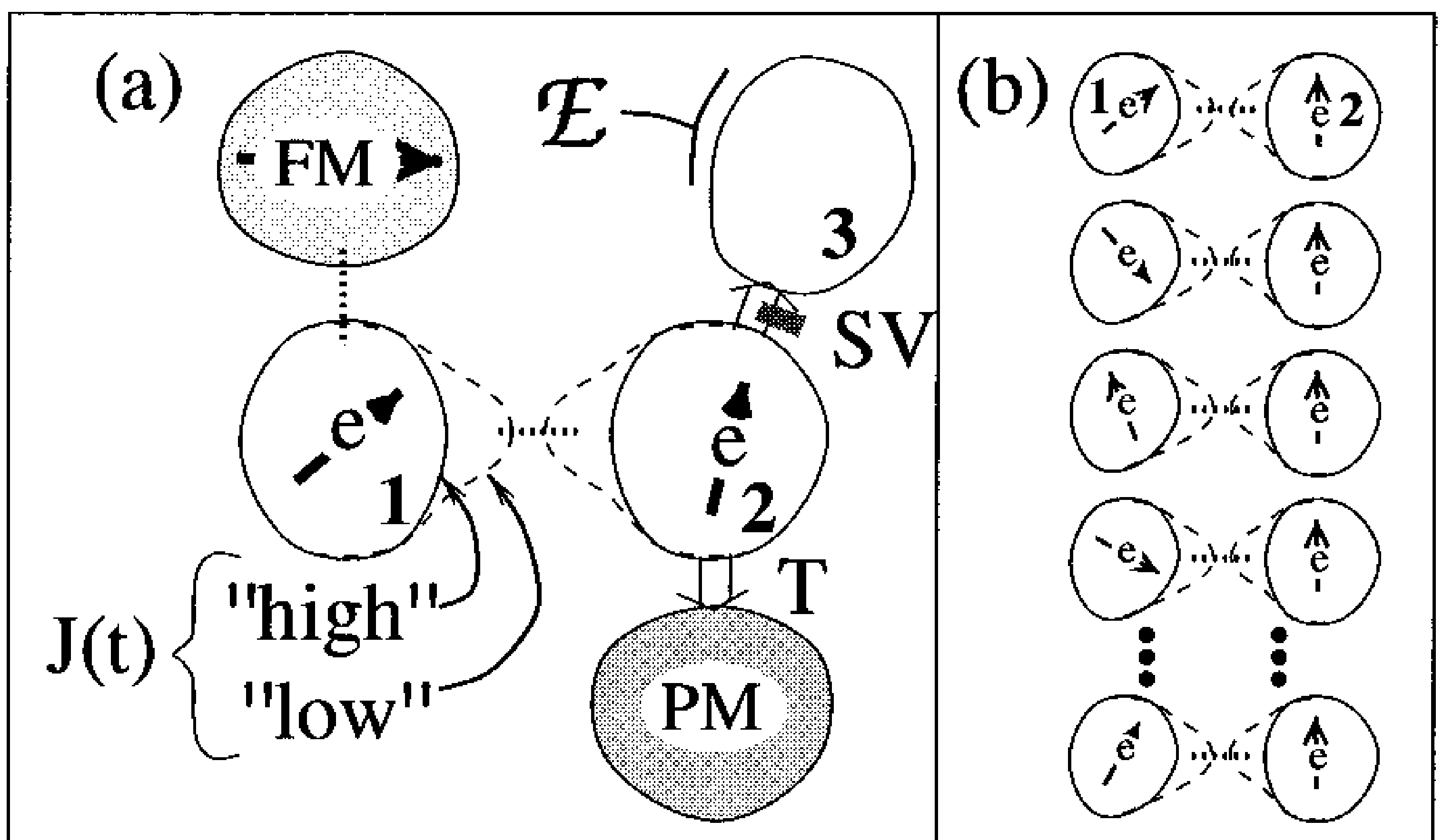
[1]*Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106-4030*

[2]*Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

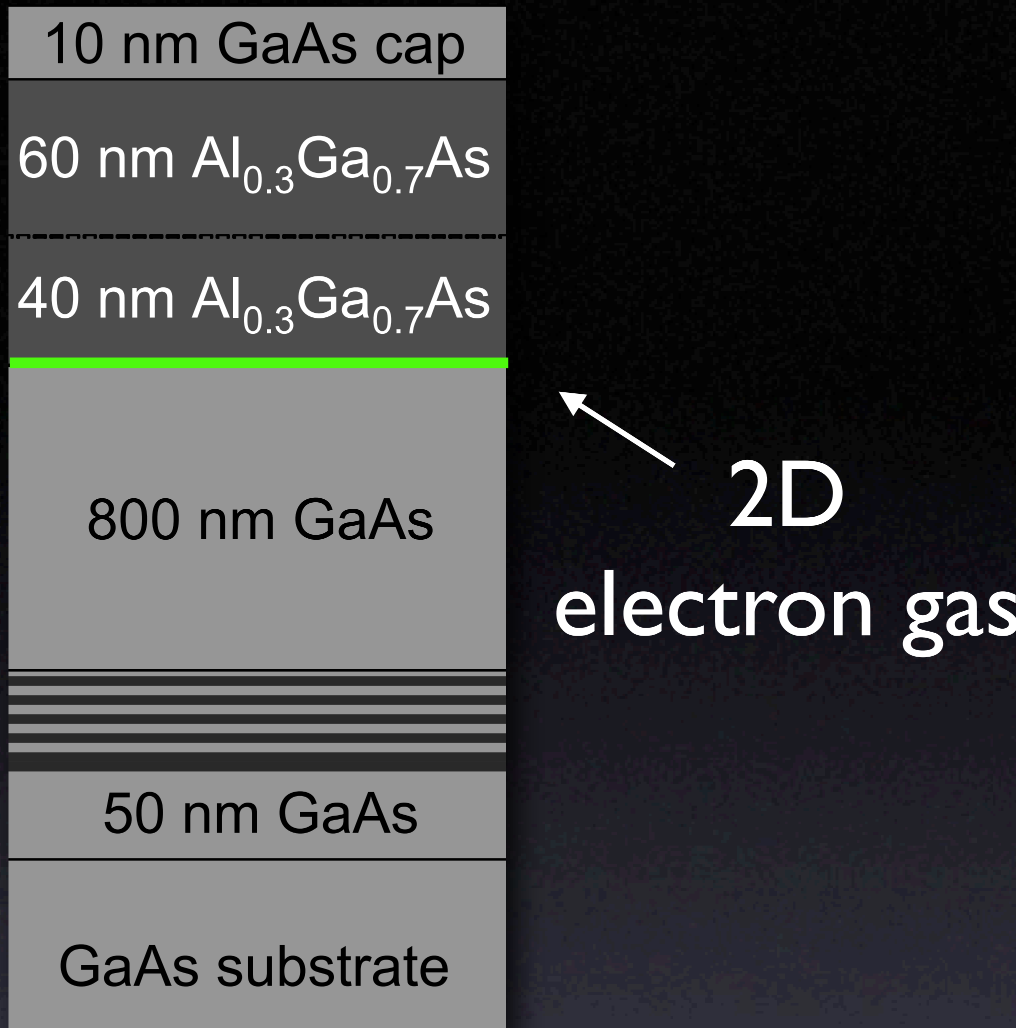
[3]*IBM Research Division, T.J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598*

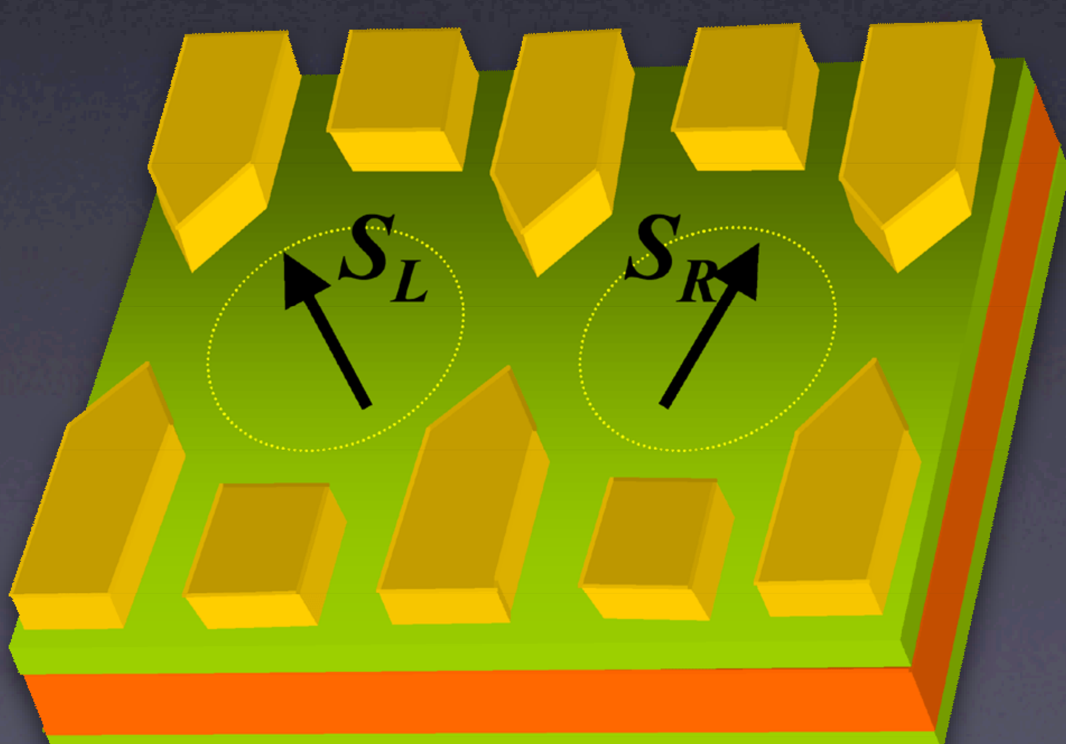
(Received 9 January 1997; revised manuscript received 22 July 1997)

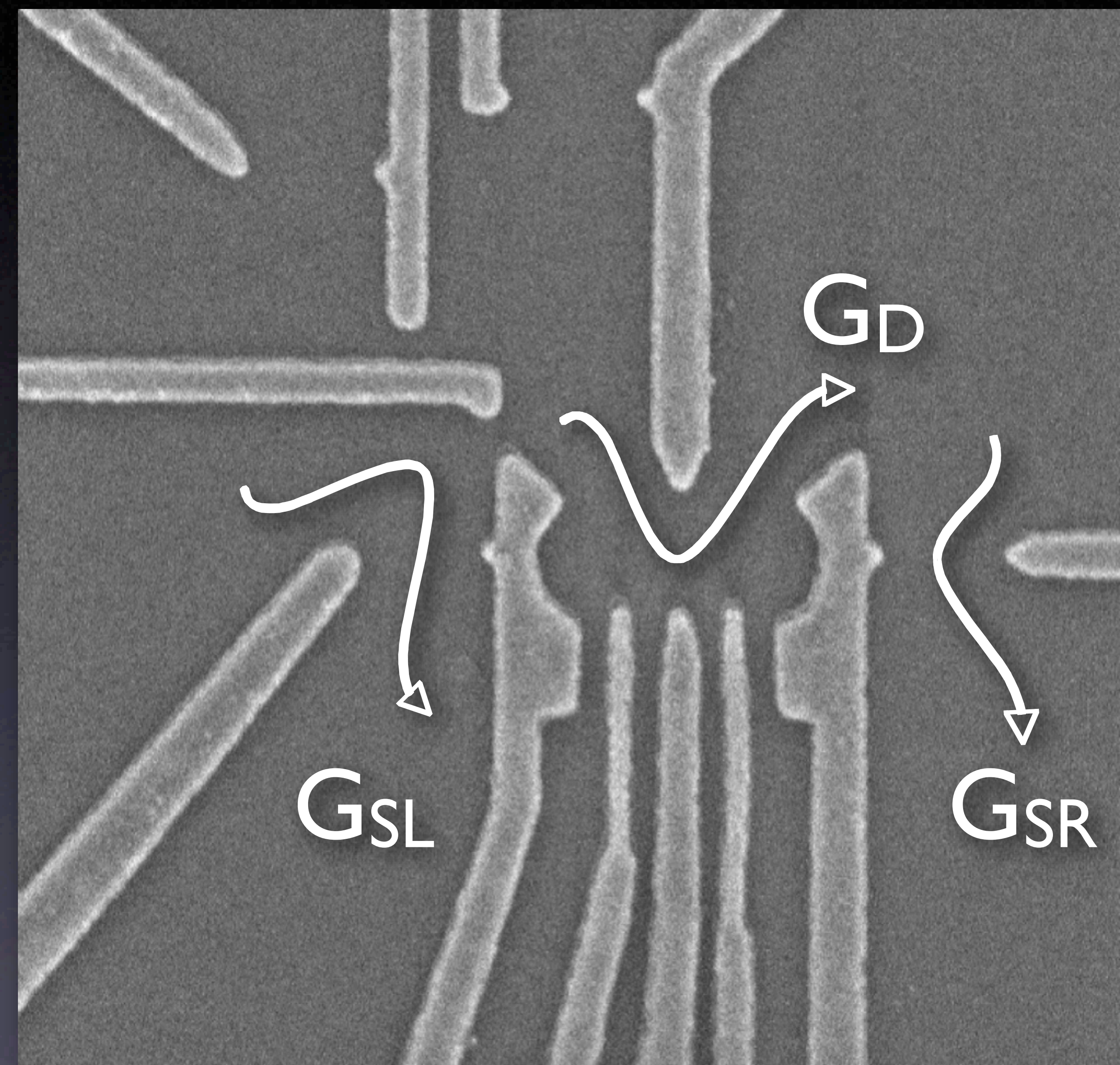
We propose an implementation of a universal set of one- and two-quantum-bit gates for quantum computation using the spin states of coupled single-electron quantum dots. Desired operations are effected by the gating of the tunneling barrier between neighboring dots. Several measures of the gate quality are computed within a recently derived spin master equation incorporating decoherence caused by a prototypical magnetic environment. Dot-array experiments that would provide an initial demonstration of the desired nonequilibrium spin dynamics are proposed. [S1050-2947(98)04501-6]



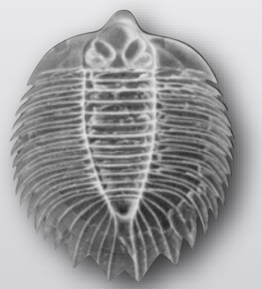
Semiconductor Double Dot Device





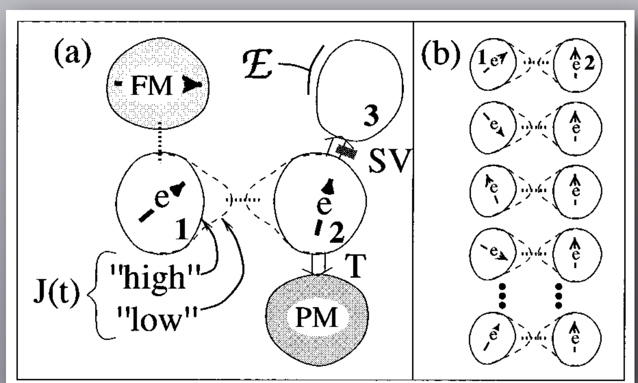


Timeline for spin qubits



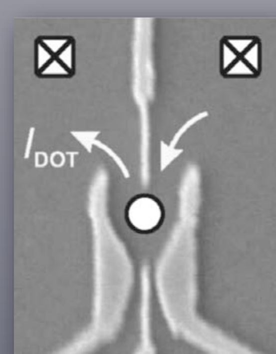
1998

Loss-DiVincenzo proposal



2000

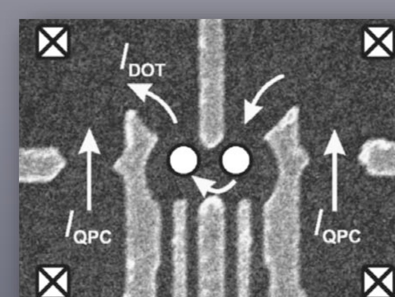
first
few-electron
lateral dot



Ciorga, et al.

2003

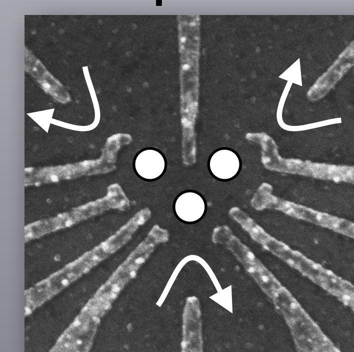
first
few-electron
double dot



Elzerman, et al.

2009

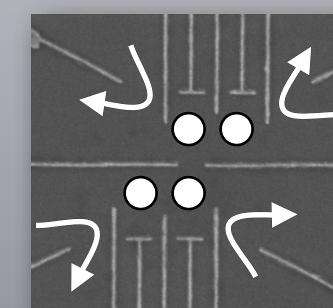
few-electron
triple dot



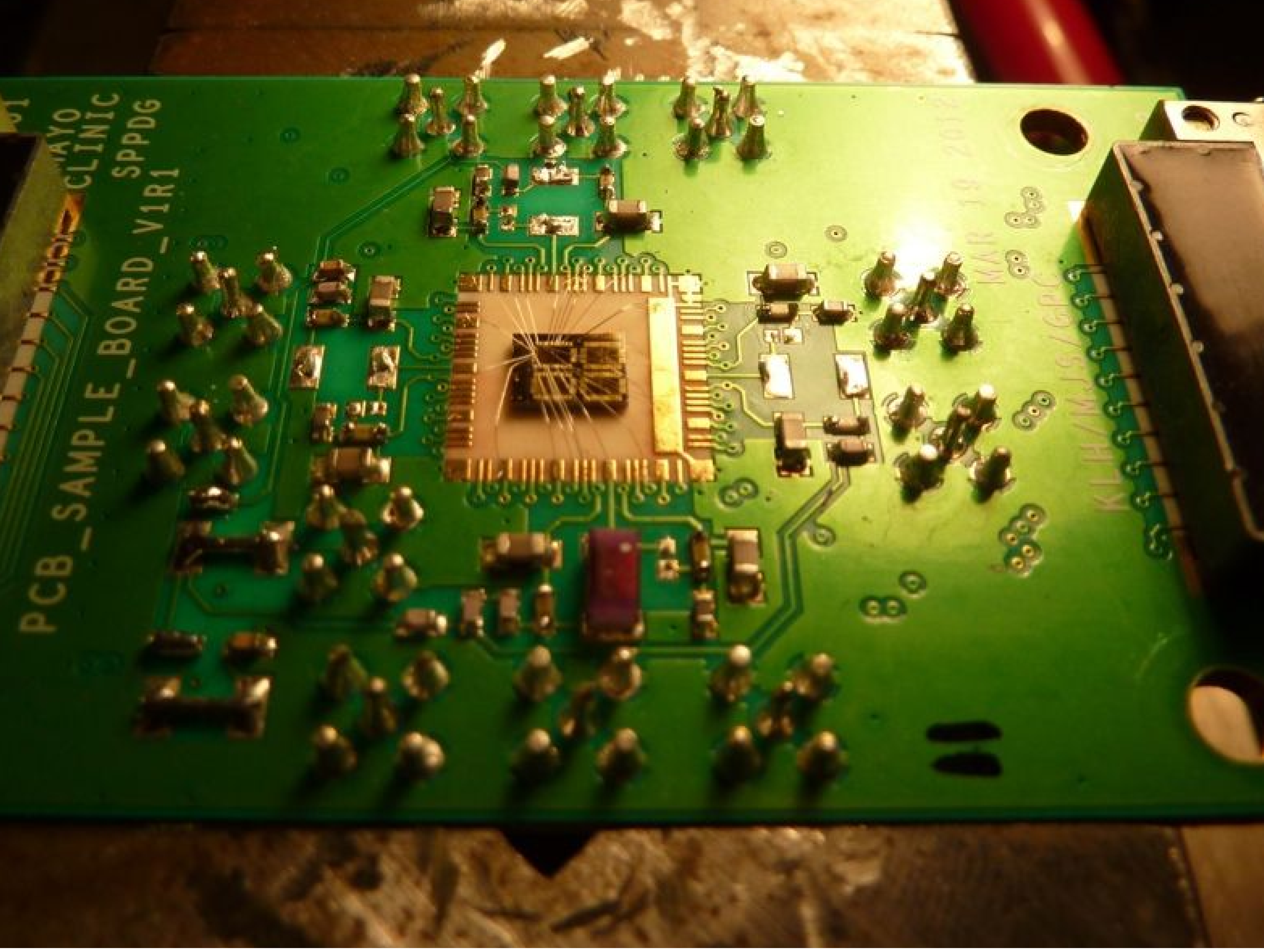
Laird, Folleti, et al.

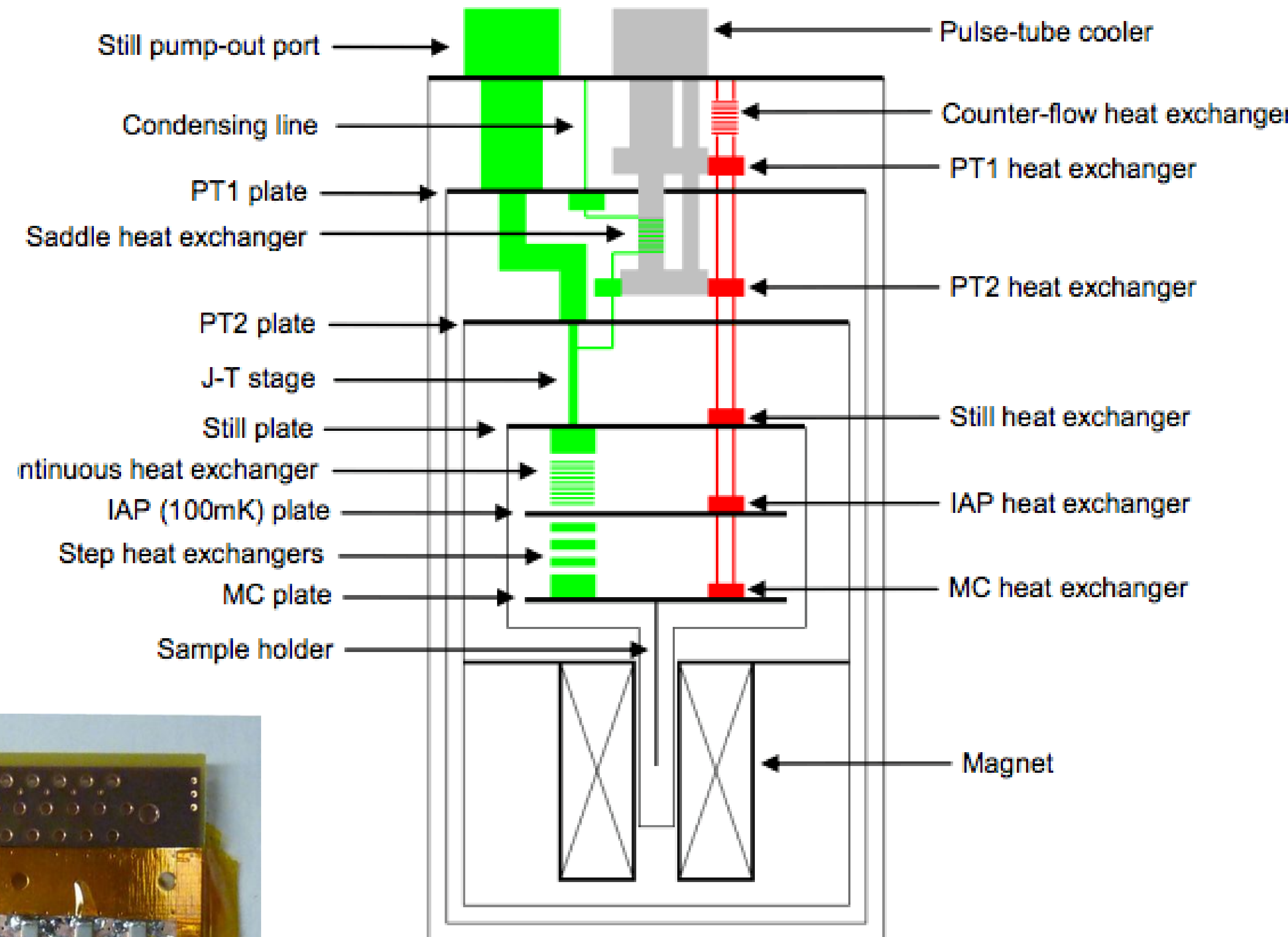
2010

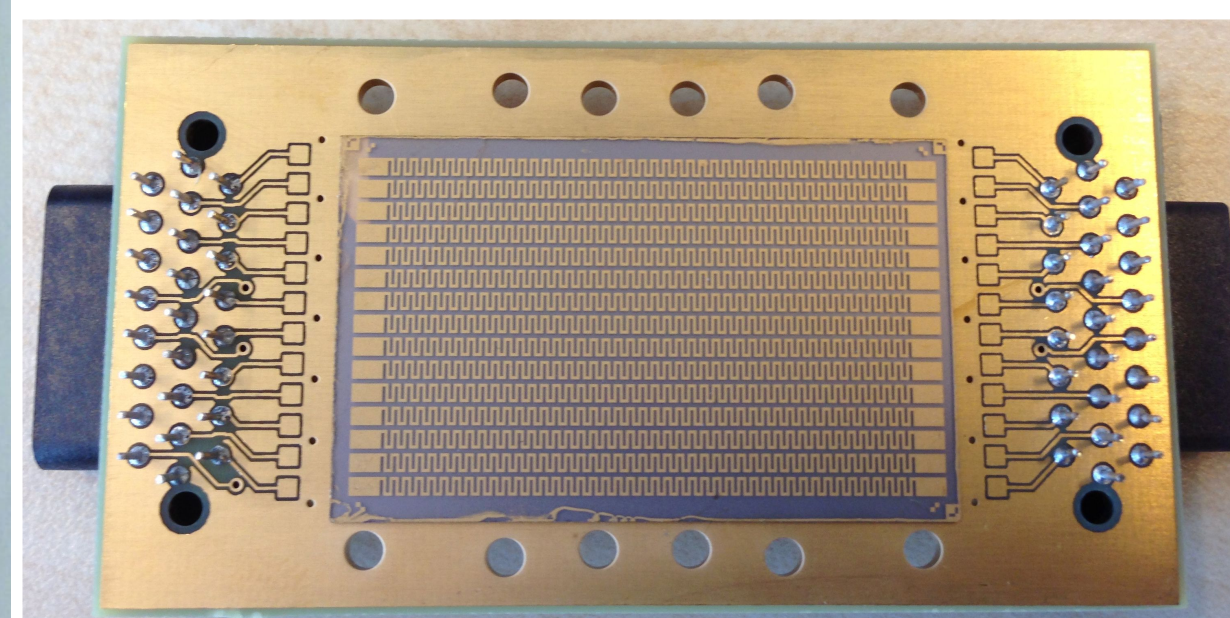
few-electron
double
double dot



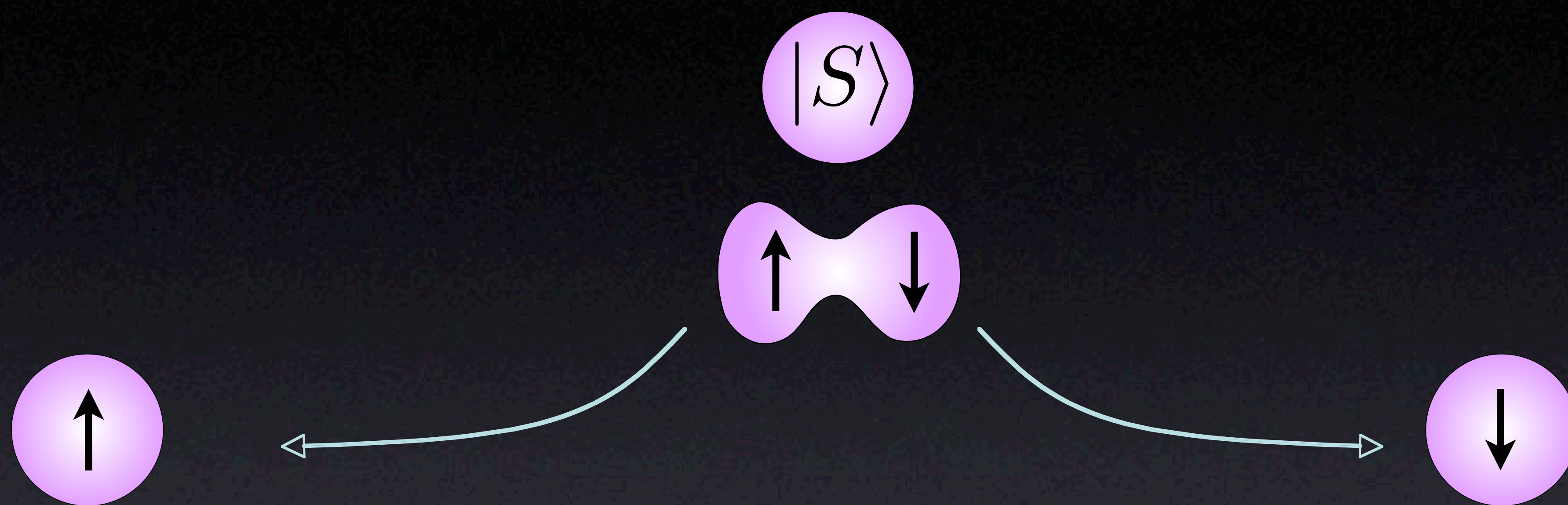
Laird, et al.


CLINIC
SPPDG
PCB_SAMPLE_BOARD_V1R1

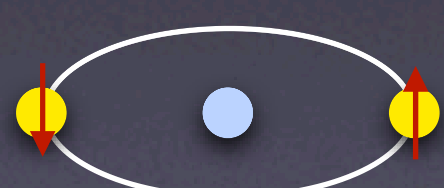

Still pump-out port
Condensing line
PT1 plate
Saddle heat exchanger
PT2 plate
J-T stage
Still plate
ntinuous heat exchanger
IAP (100mK) plate
Step heat exchangers
MC plate
Sample holder
Pulse-tube cooler
Counter-flow heat exchanger
PT1 heat exchanger
PT2 heat exchanger
Still heat exchanger
IAP heat exchanger
MC heat exchanger
Magnet



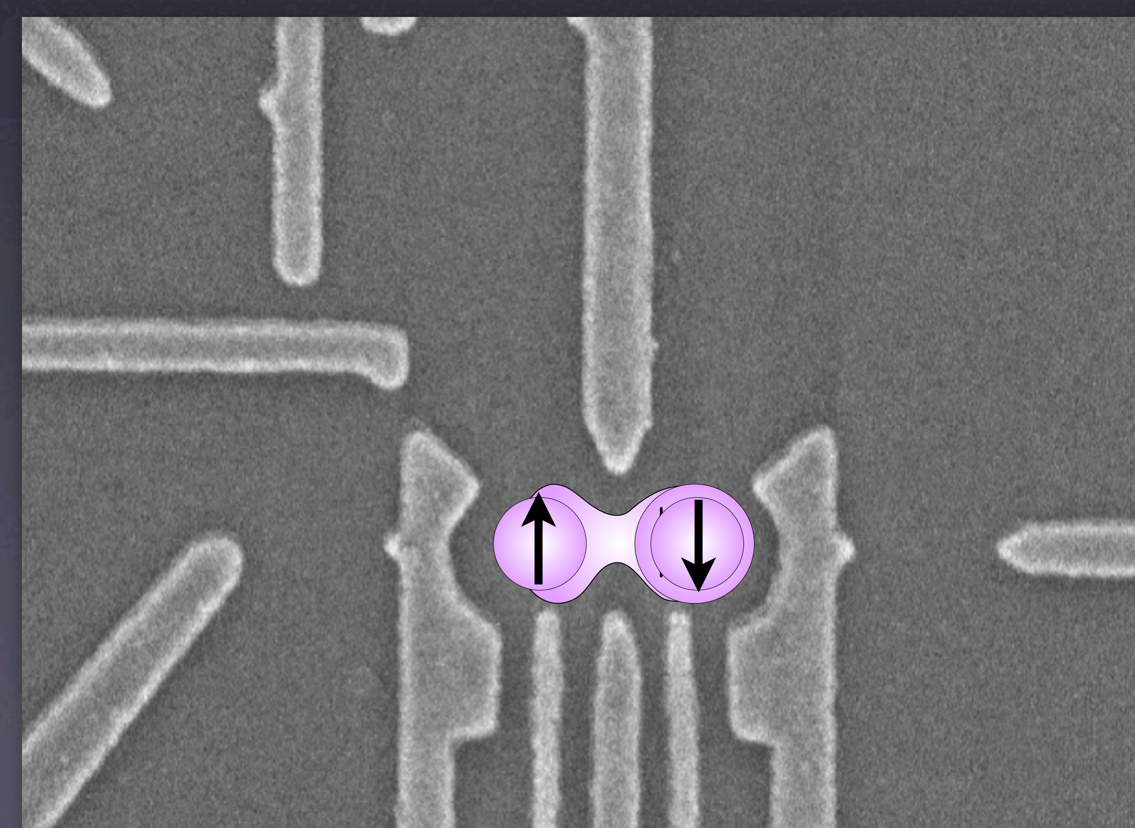
Double Quantum Dot as Entanglement Generator



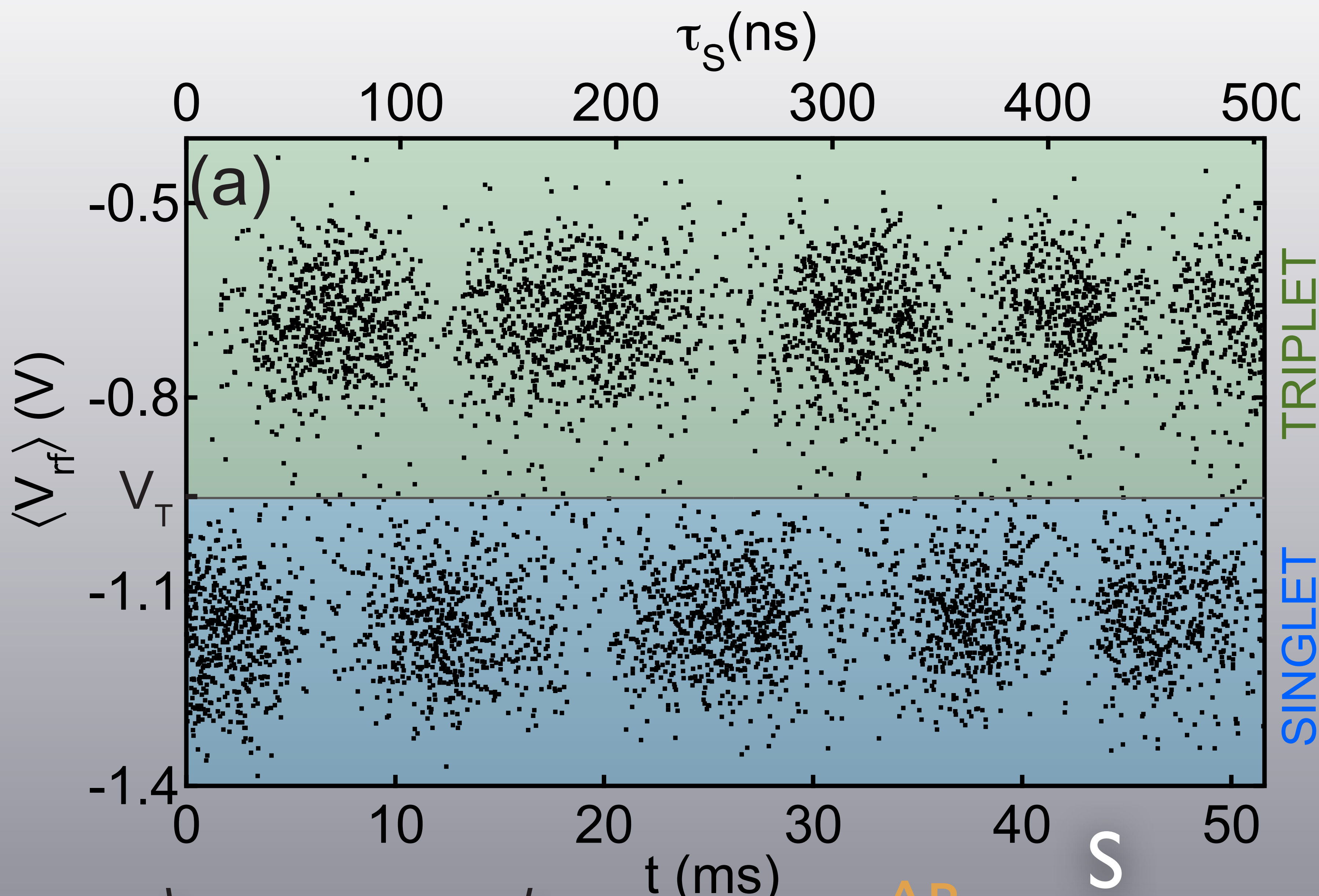
helium

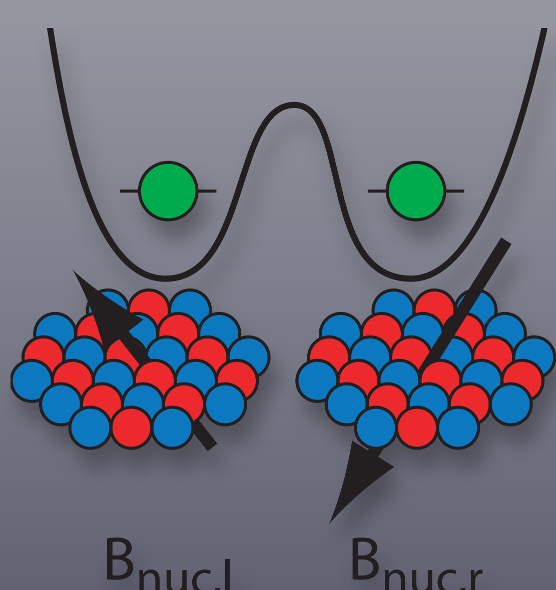


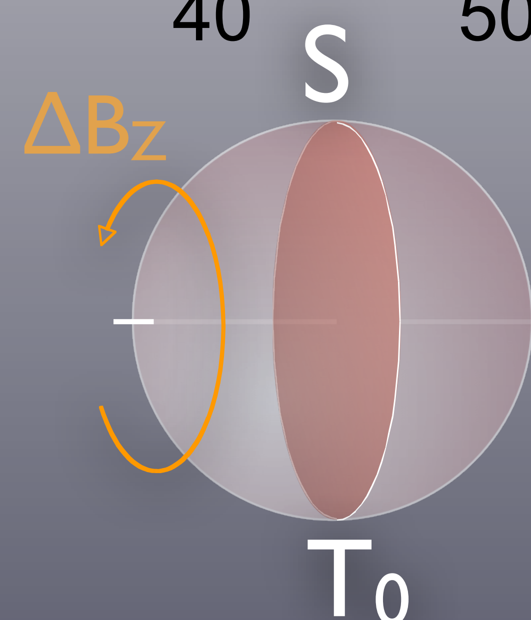
$$|S\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

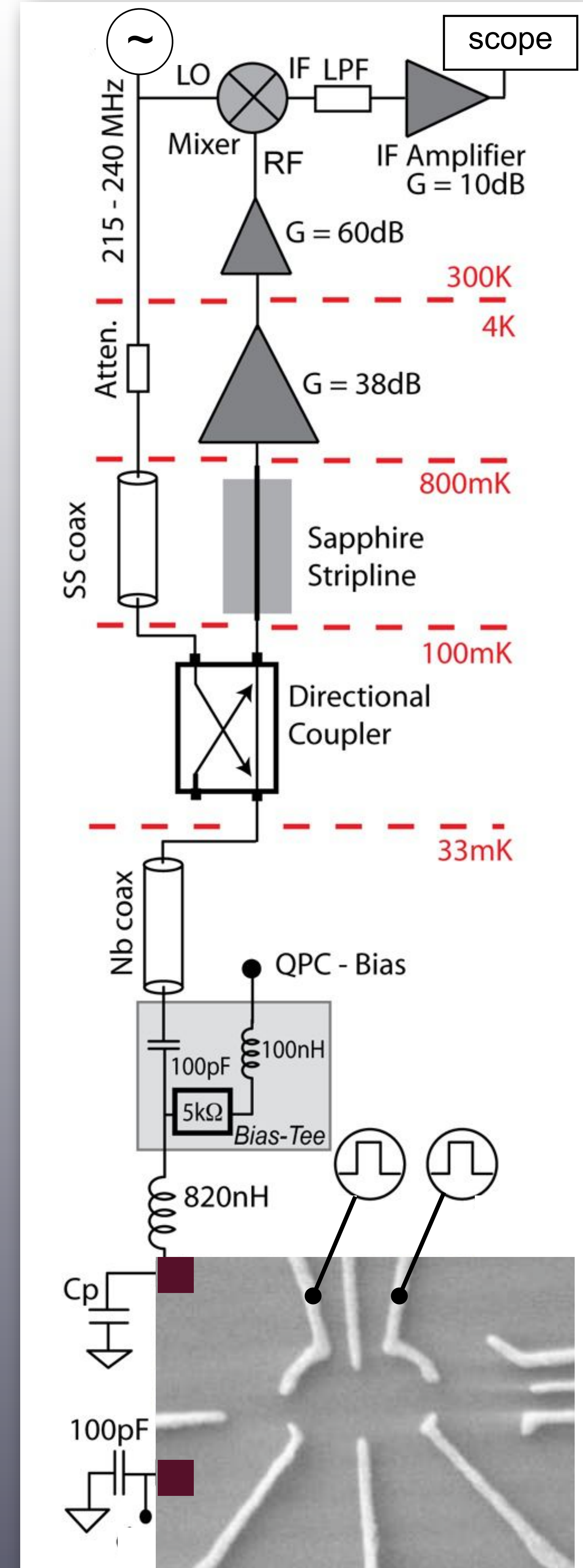


Fast Detection: Unexpected Oscillations





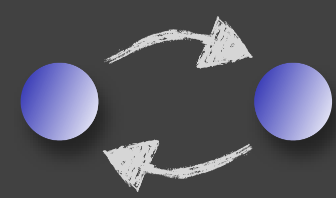




C. Barthel et al., Phys. Rev. Lett. 103, 160503 (2009).

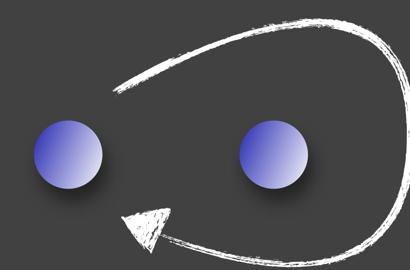
Quantum Strangeness III: Particle Statistics and Topology

3 dimensions



$$|\psi\rangle \longrightarrow |\psi\rangle$$ Bosons

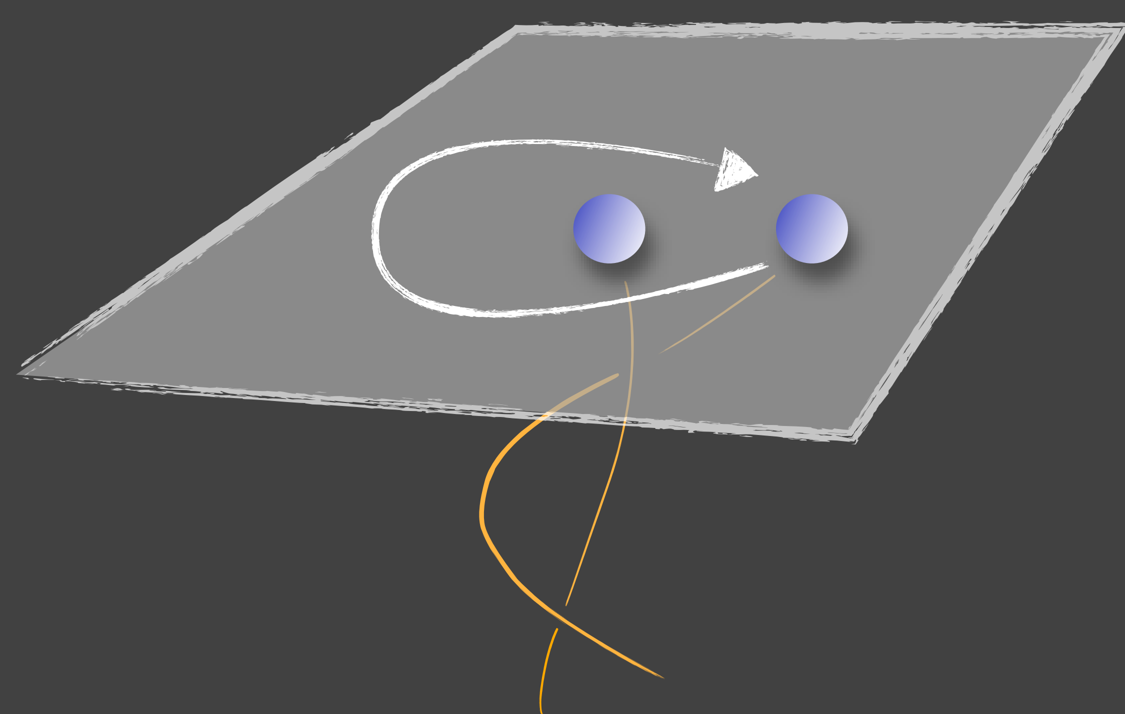
$$|\psi\rangle \longrightarrow -|\psi\rangle$$ Fermions



$$|\psi\rangle \longrightarrow |\psi\rangle$$

---

2 dimensions



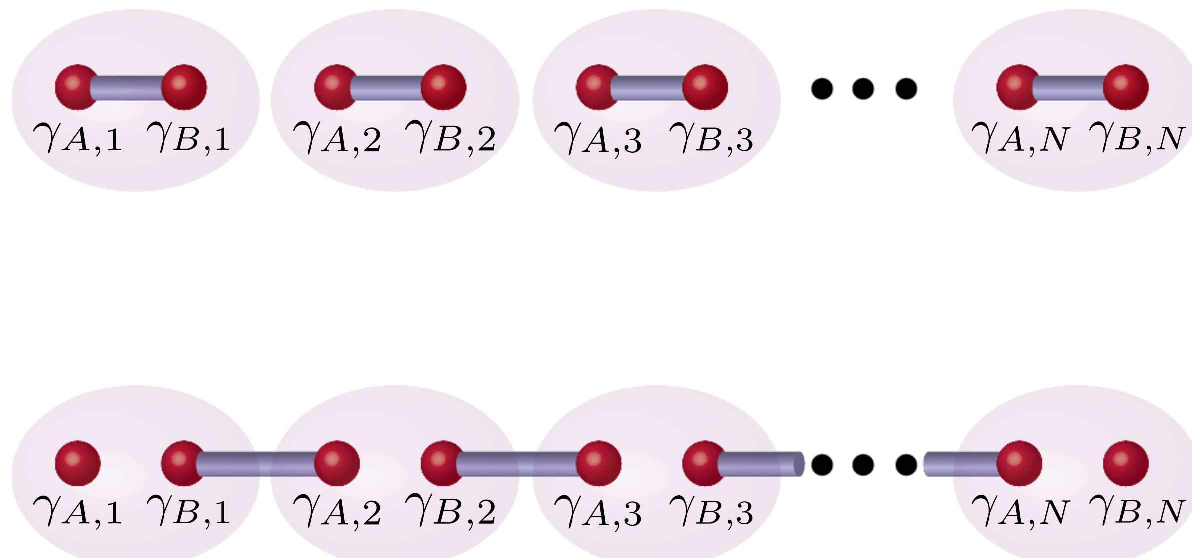
$$|\psi_1\rangle \longrightarrow |\psi_2\rangle$$

New directions in the pursuit of Majorana fermions in solid state systems

Jason Alicea[1]

[1]*Department of Physics and Astronomy, University of California, Irvine, California 92697*

(Dated: February 8, 2012)



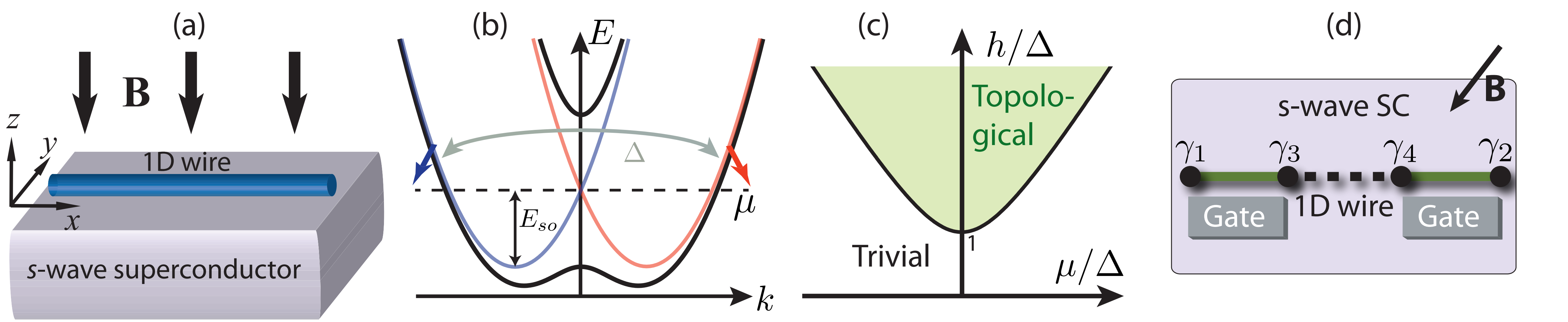


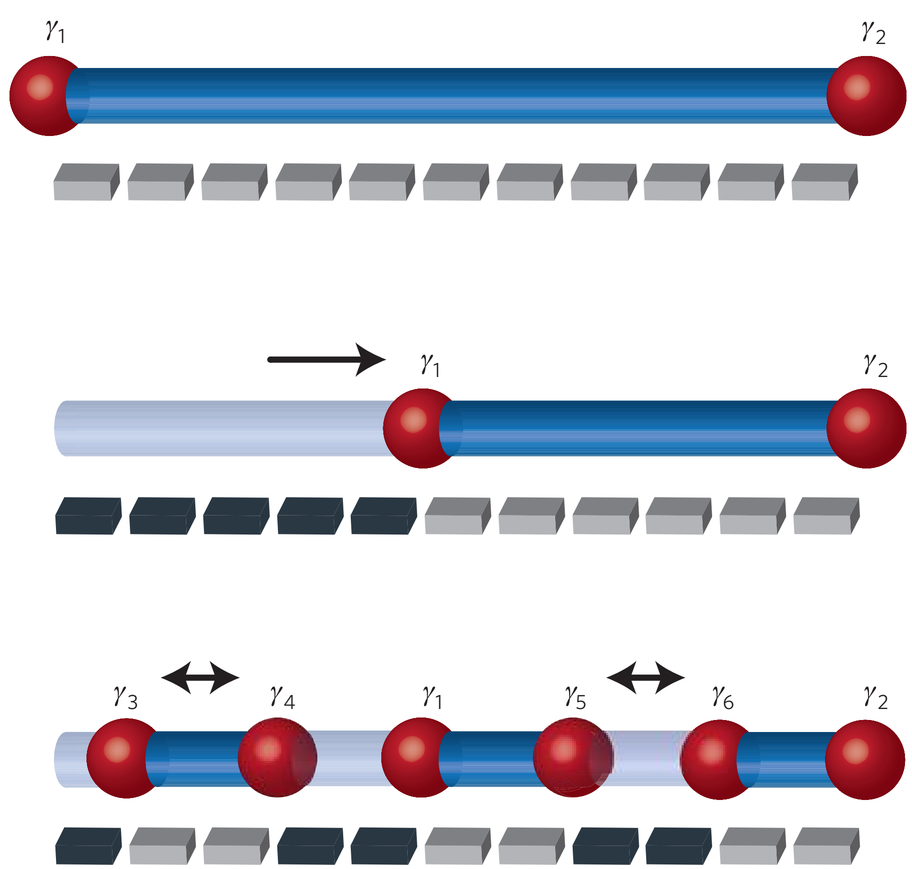
FIG. 6. (a) Basic architecture required to stabilize a topological superconducting state in a 1D spin-orbit-coupled wire. (b) Band structure for the wire when time-reversal symmetry is present (red and blue curves) and broken by a magnetic field (black curves). When the chemical potential lies within the field-induced gap at $k = 0$, the wire appears 'spinless'. Incorporating the pairing induced by the proximate superconductor leads to the phase diagram in (c). The endpoints of topological (green) segments of the wire host localized, zero-energy Majorana modes as shown in (d).

nature physics
ARTICLES
PUBLISHED ONLINE: 13 FEBRUARY 2011 | DOI: 10.1038/NPHYS1915

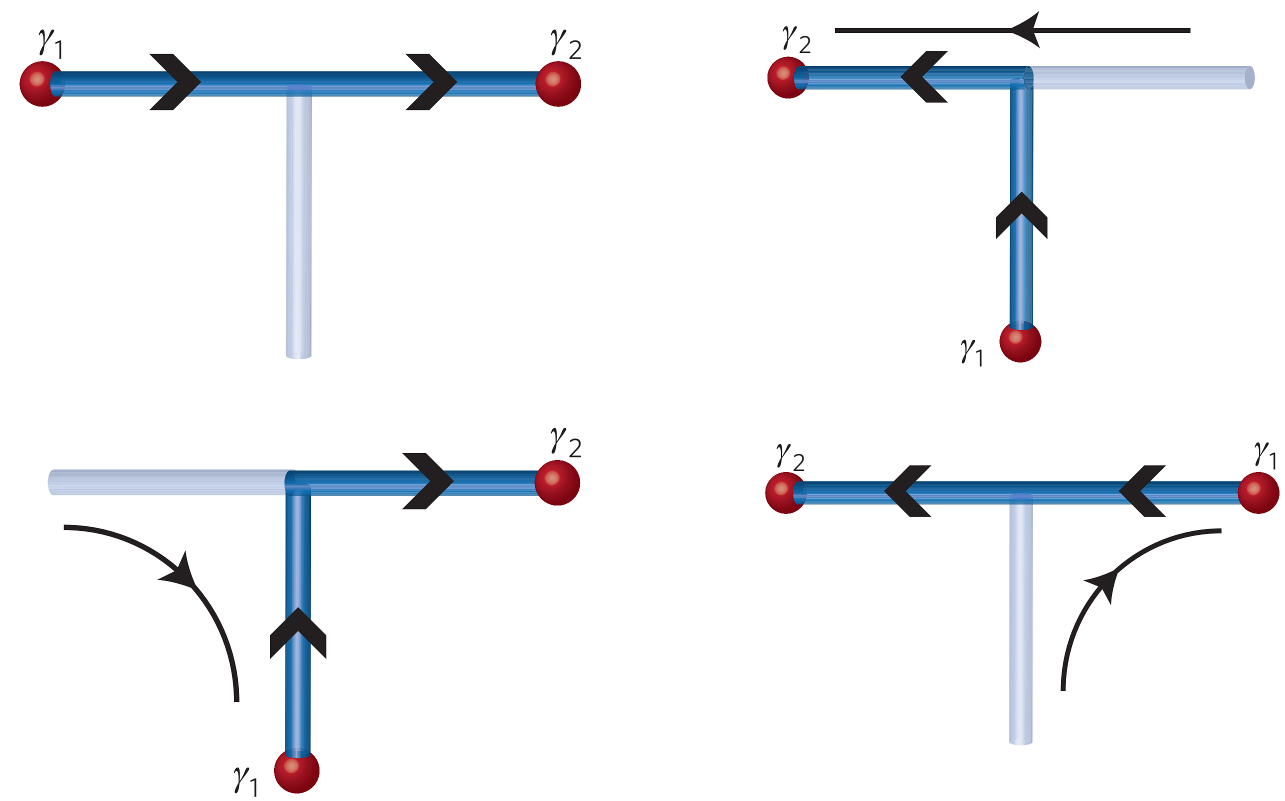
Non-Abelian statistics and topological quantum information processing in 1D wire networks

Jason Alicea[1]*, Yuval Oreg[2], Gil Refael[3], Felix von Oppen[4] and Matthew P. A. Fisher[3,5]

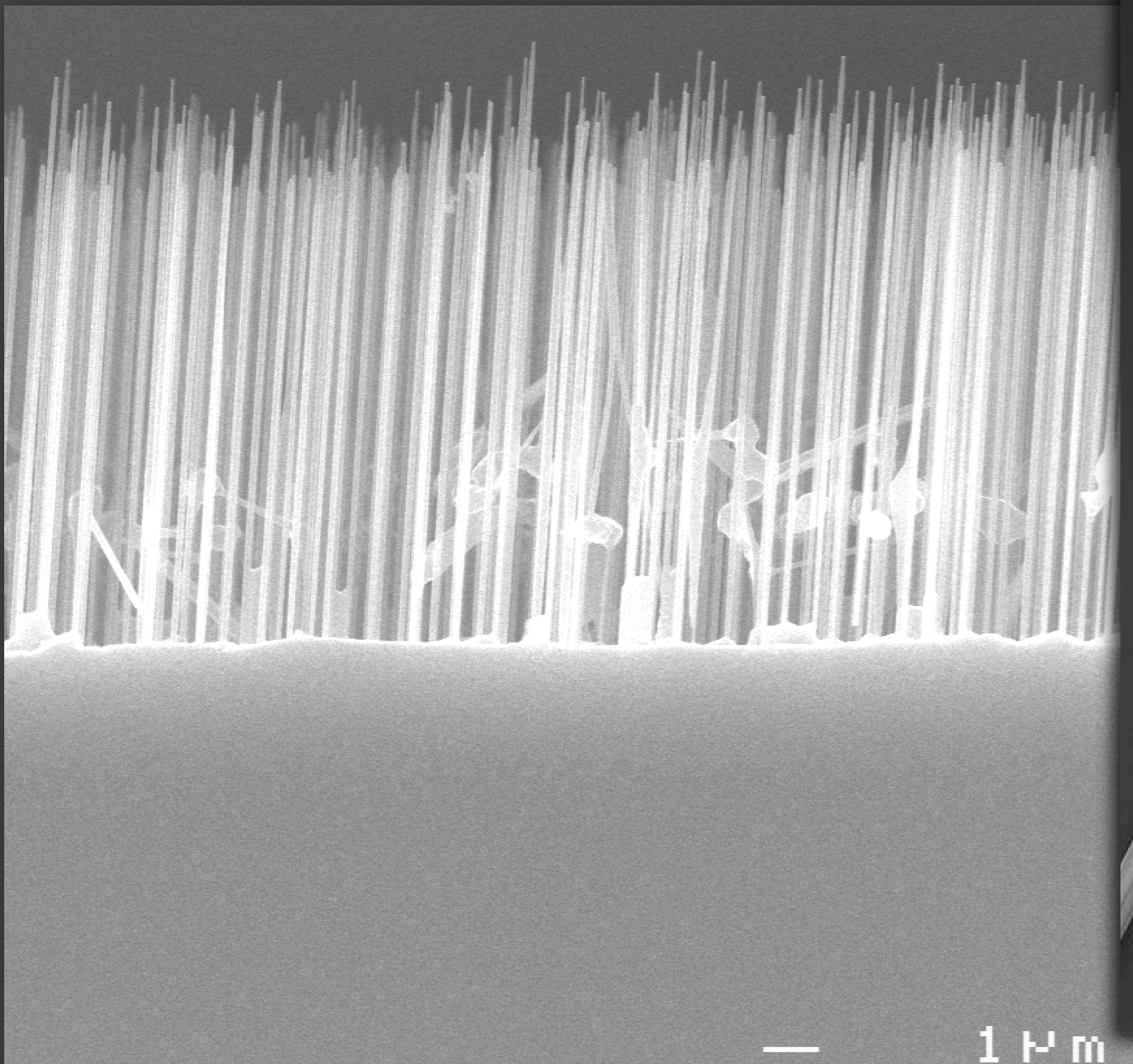
creation and movement

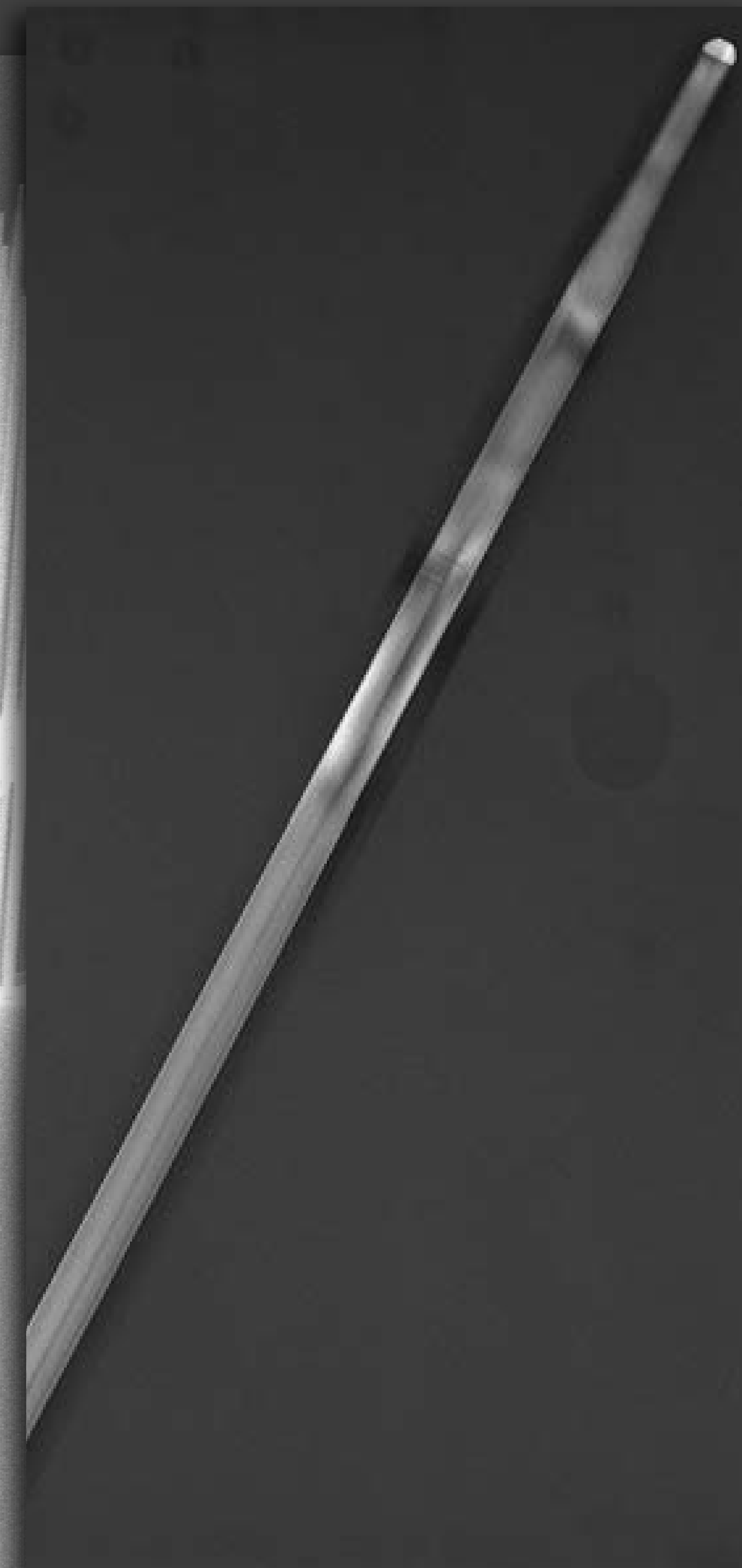


braiding



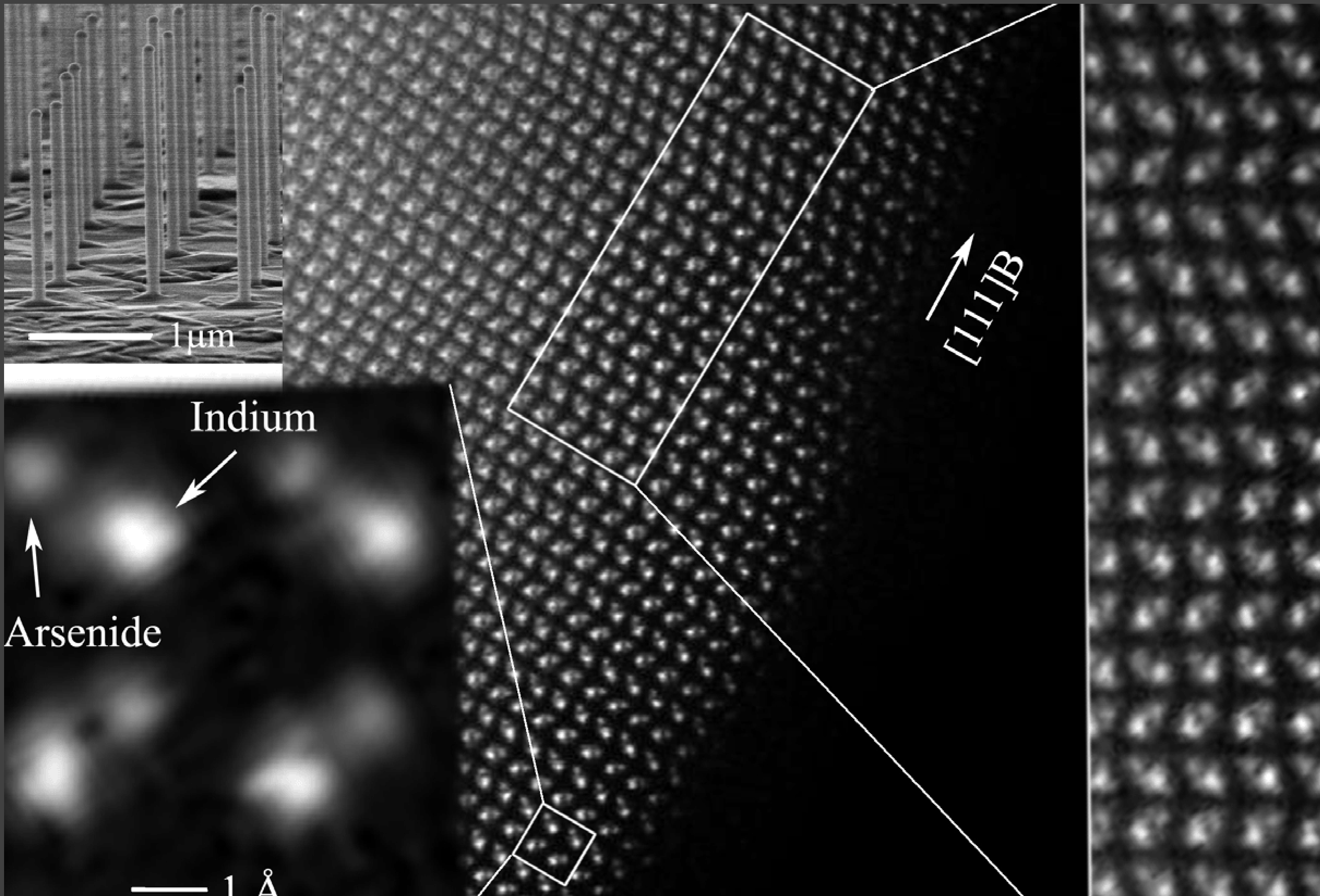
10 µm wires, pure wurzite structure





M.H. Madsen, P. Krogstrup, J. Nygård, Univ. of Copenhagen

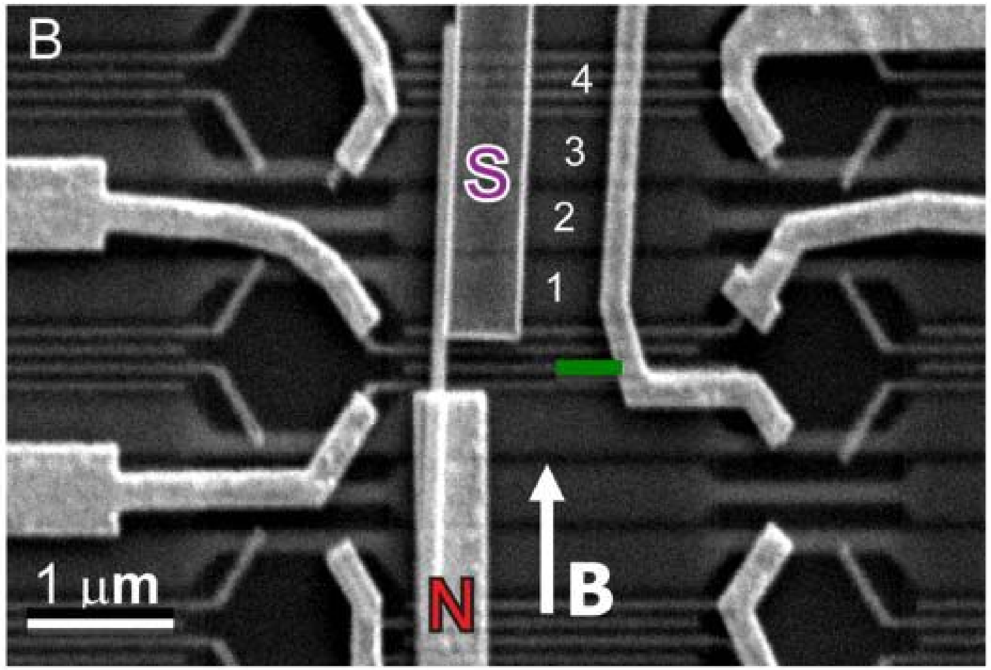
Epitaxial growth of InAs nanowires

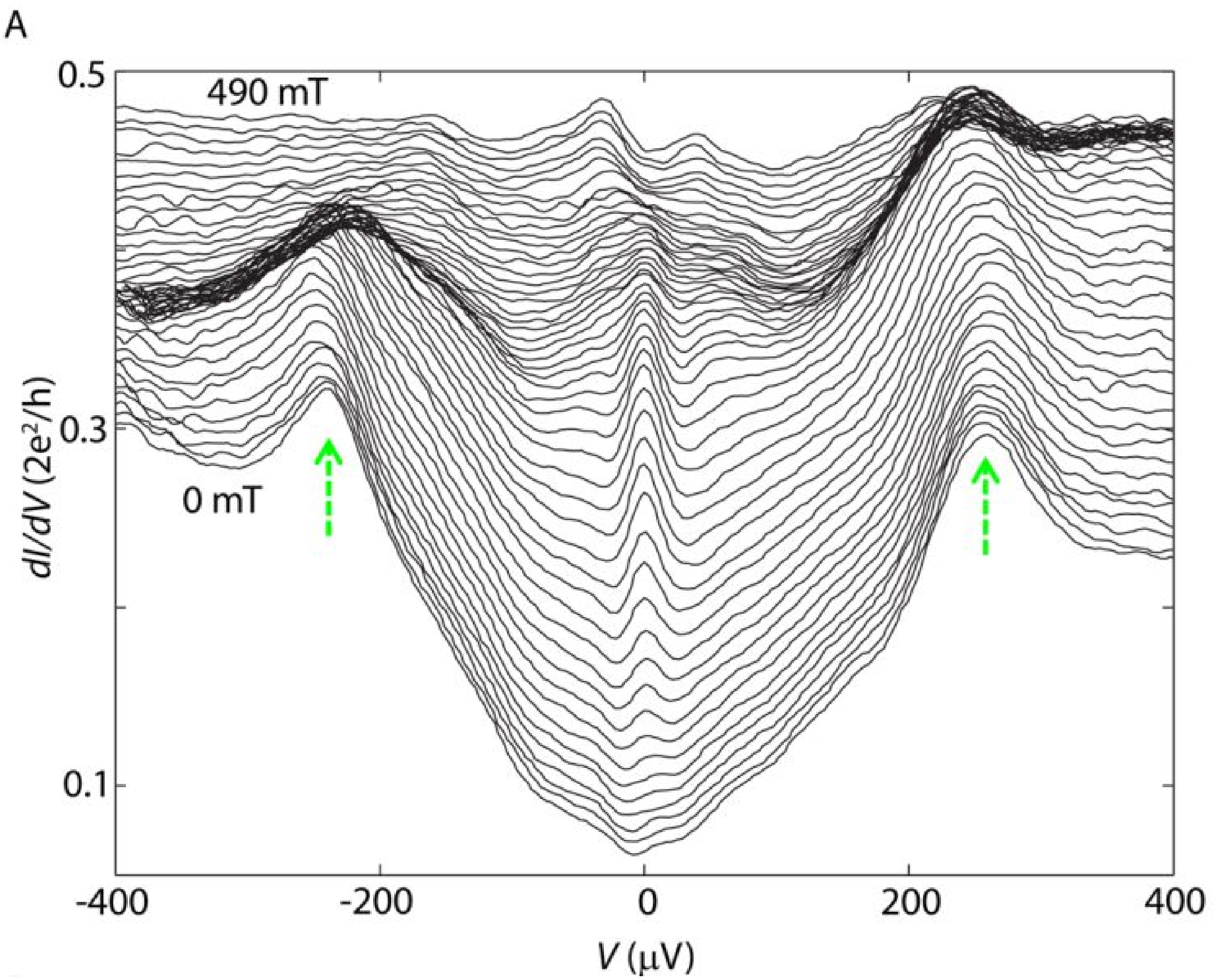


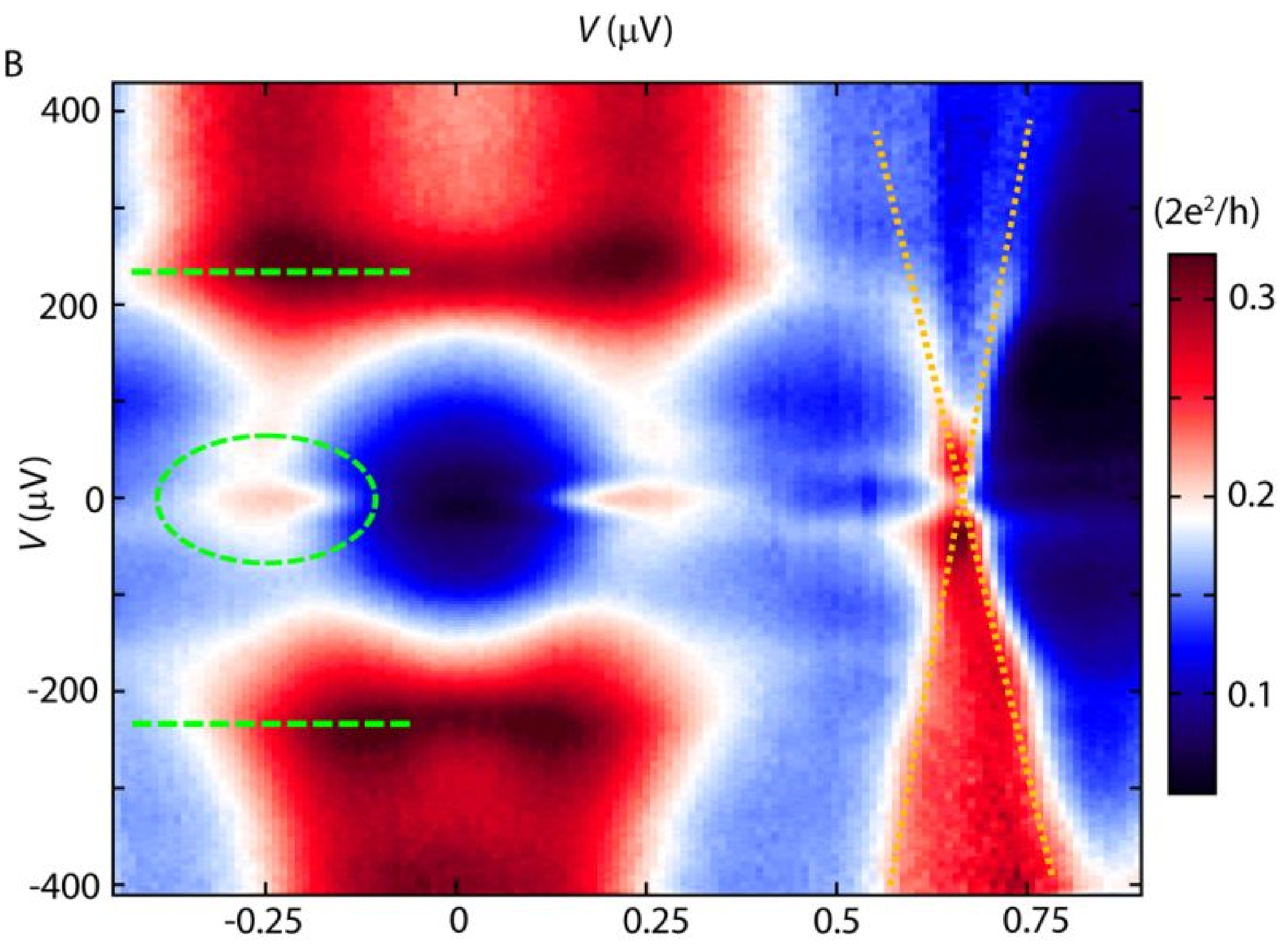
P. Krogstrup, J. Nygård, Univ. of Copenhagen

Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1]* K. Zuo,[1]* S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†







PHYSICAL REVIEW B **87**, 241401(R) (2013)

Superconductor-nanowire devices from tunneling to the multichannel regime: Zero-bias oscillations and magnetoconductance crossover

H. O. H. Churchill,[1,2] V. Fatemi,[2] K. Grove-Rasmussen,[3] M. T. Deng,[4] P. Caroff,[4] H. Q. Xu,[4,5] and C. M. Marcus[3,*]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[3]*Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen Ø, Denmark*
[4]*Division of Solid State Physics, Lund University, Box 118, S-221 00 Lund, Sweden*
[5]*Department of Electronics and Key Laboratory for the Physics and Chemistry of Nanodevices, Peking University, Beijing 100871, China*
(Received 9 March 2013; published 6 June 2013)

Device #1: one-sided (N-wire-S)

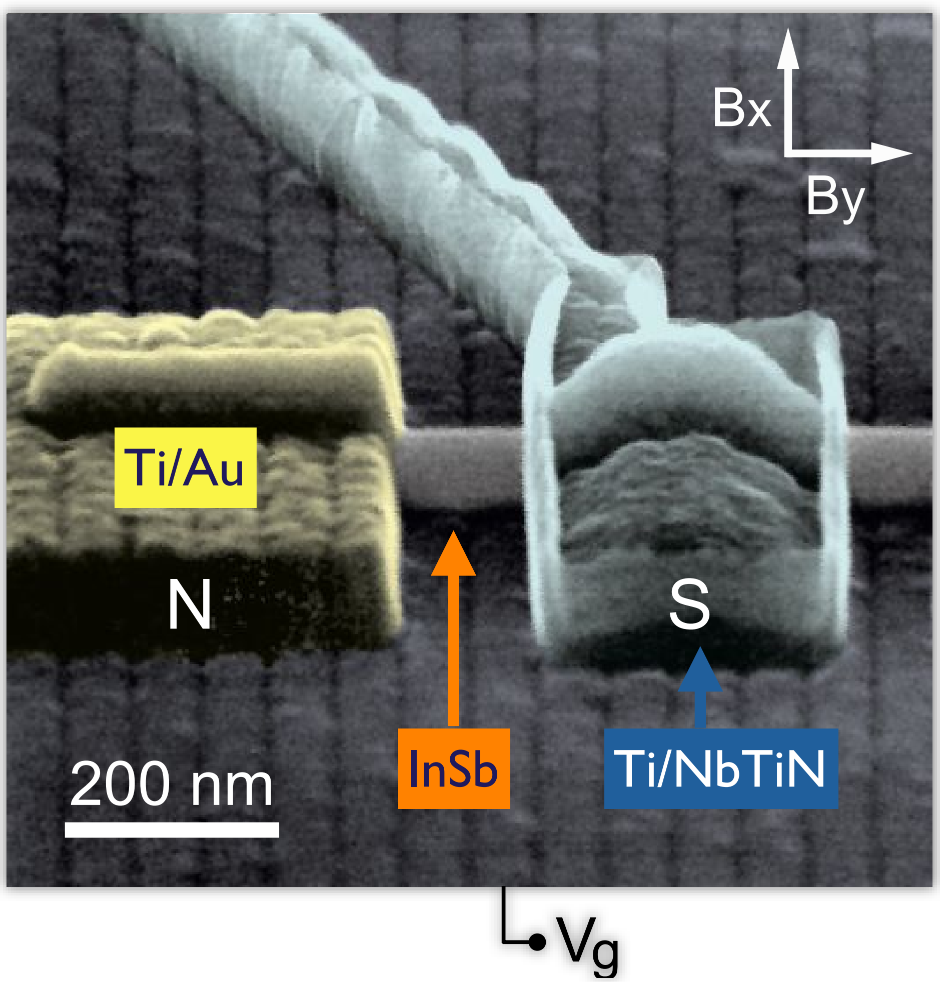
150 nm wide uncovered region

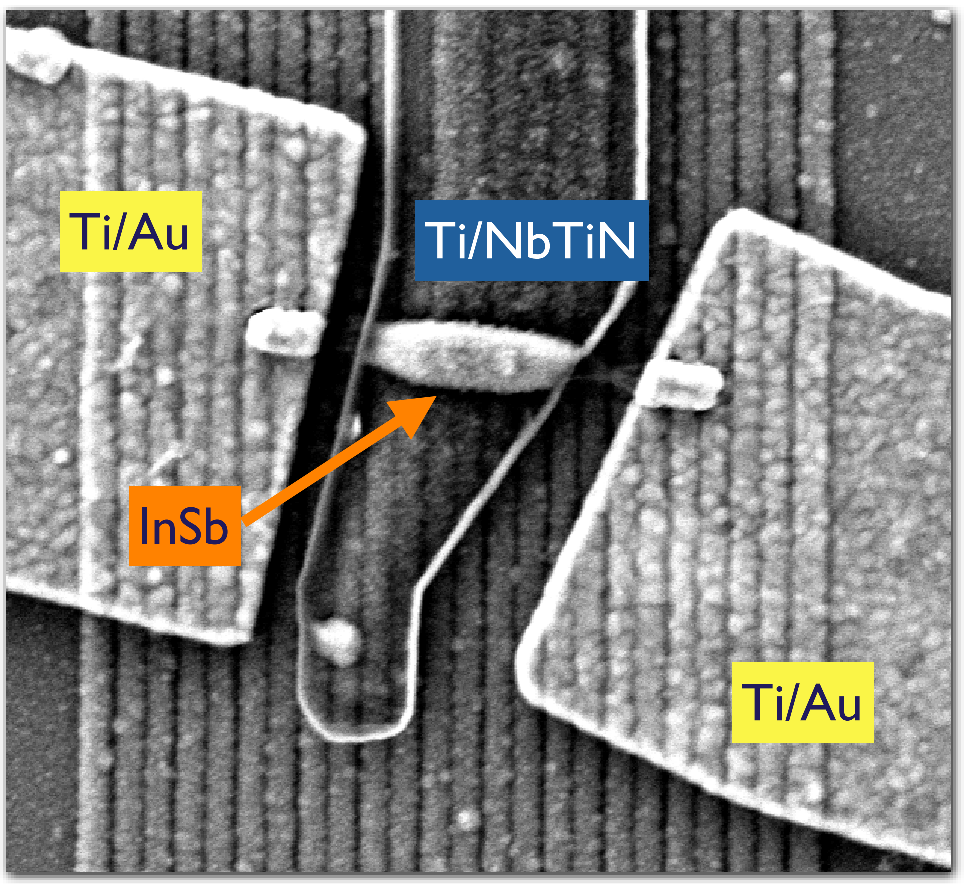
350 nm wide superconducting contact

Device #2: two-sided (N-wire-S-wire-N)

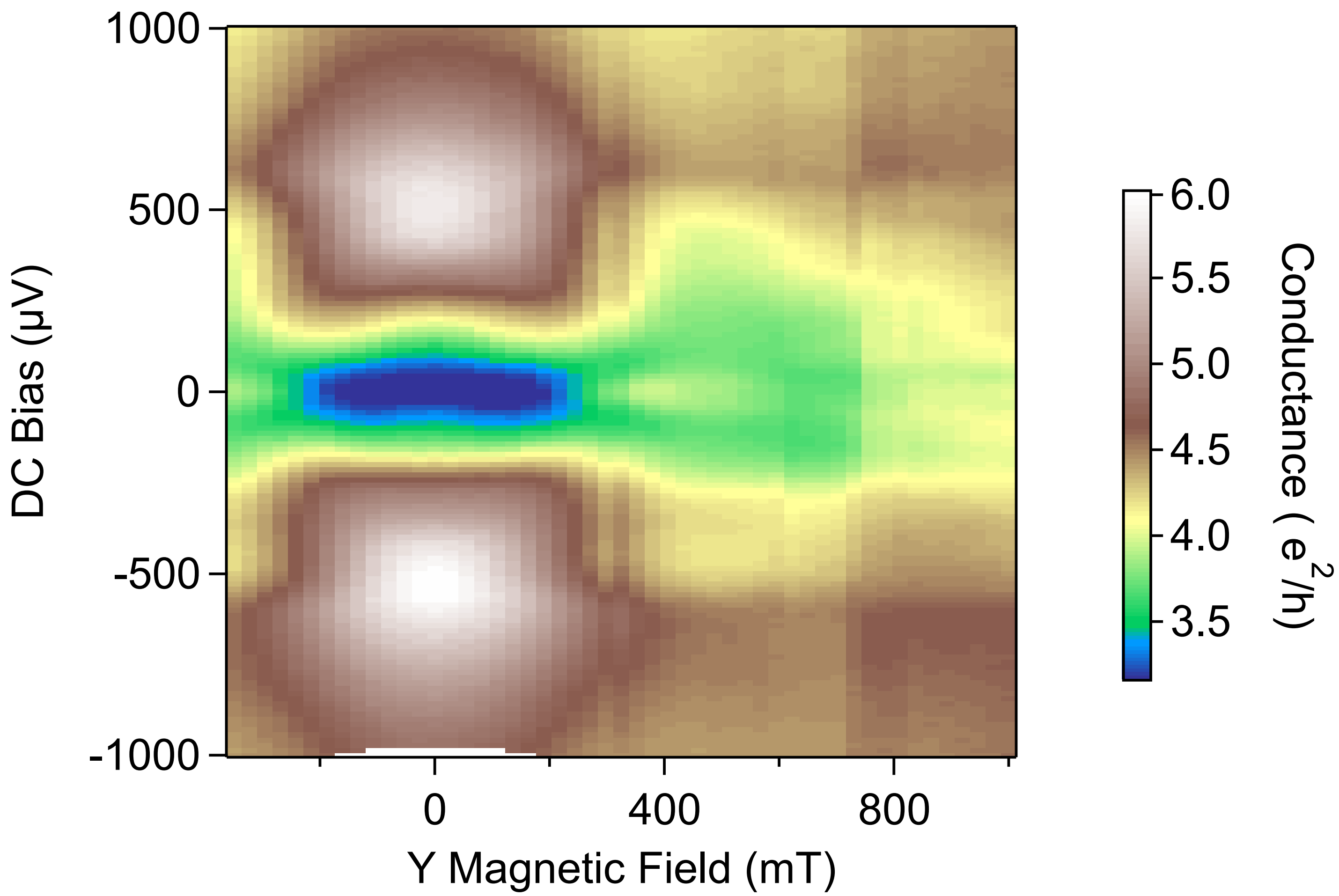
200 nm wide uncovered regions

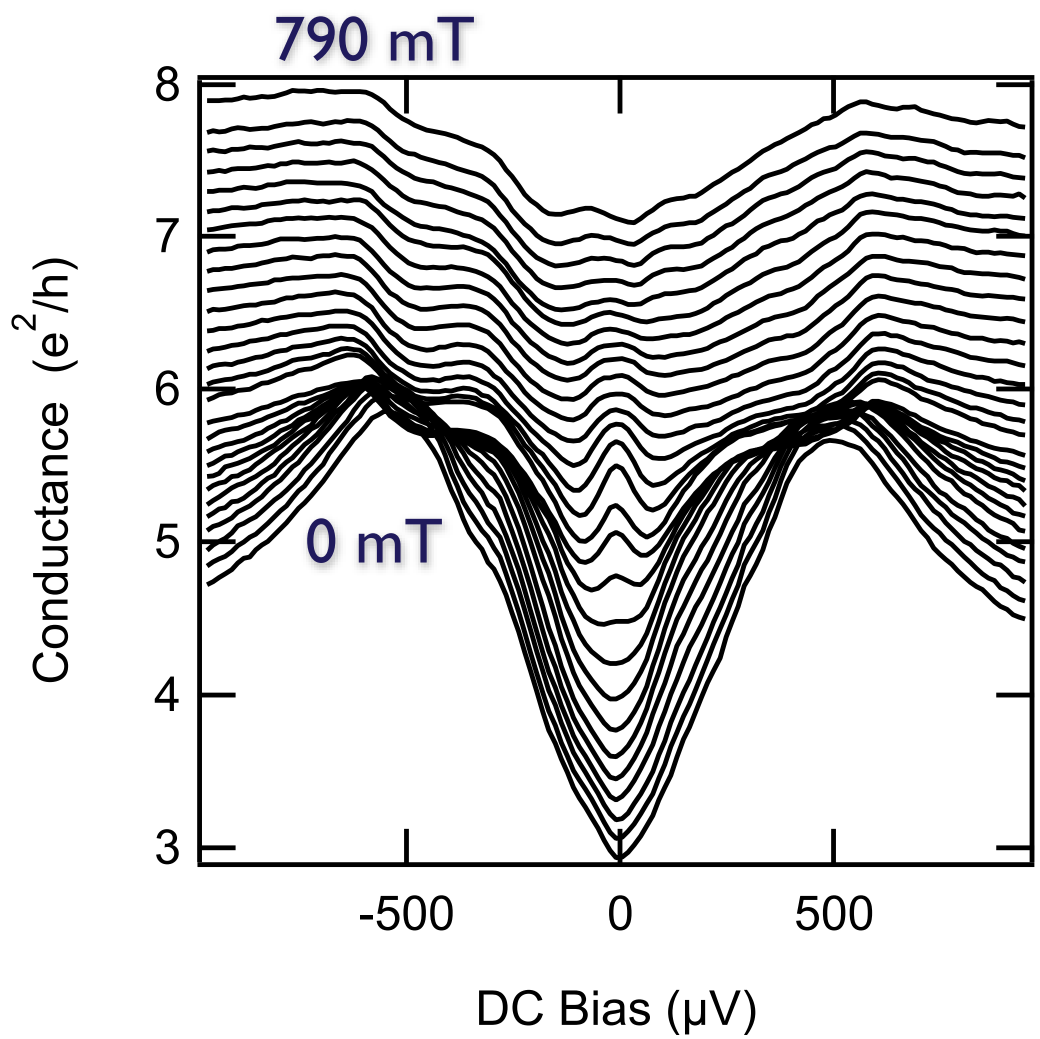
250 nm wide superconducting contacts

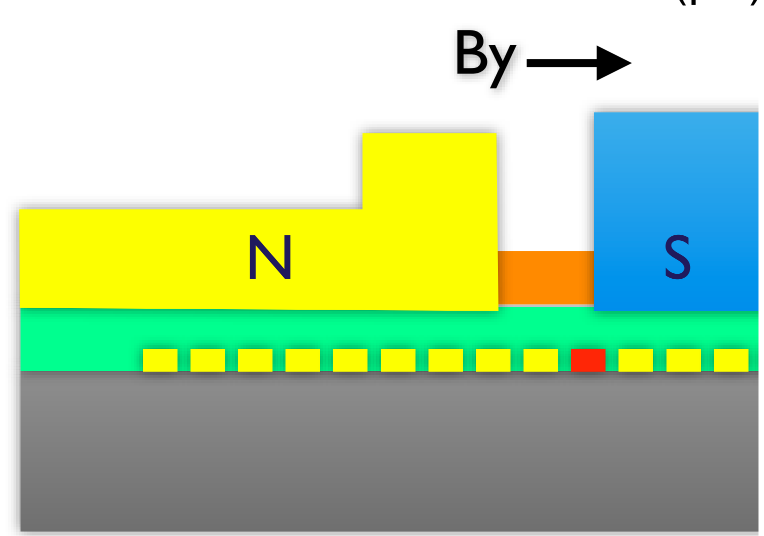




Important check:
Reproduce previously observed behavior



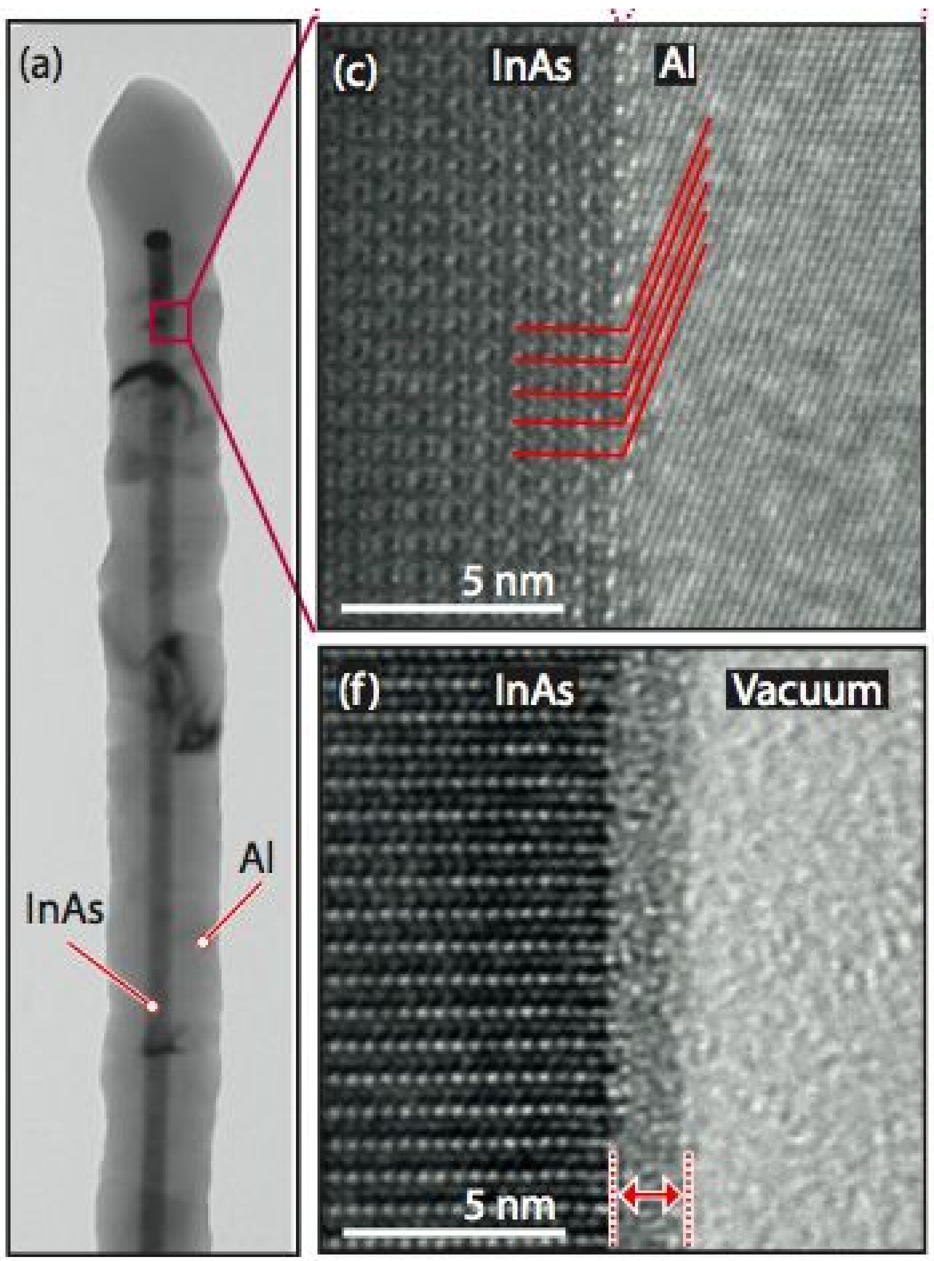


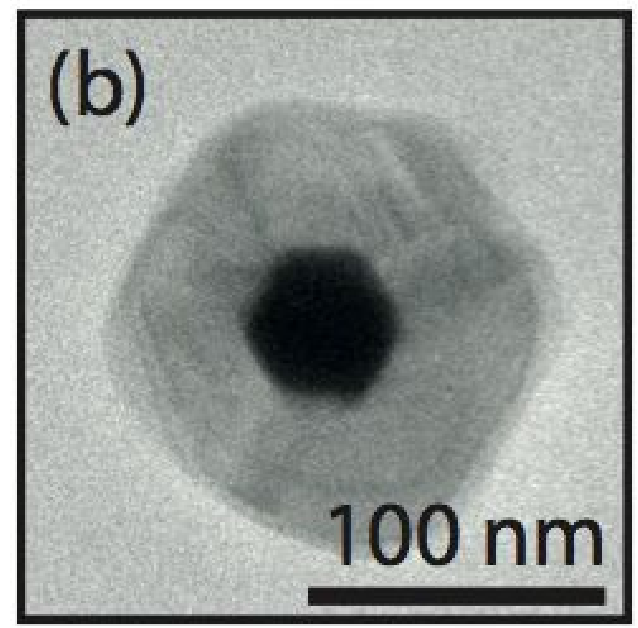


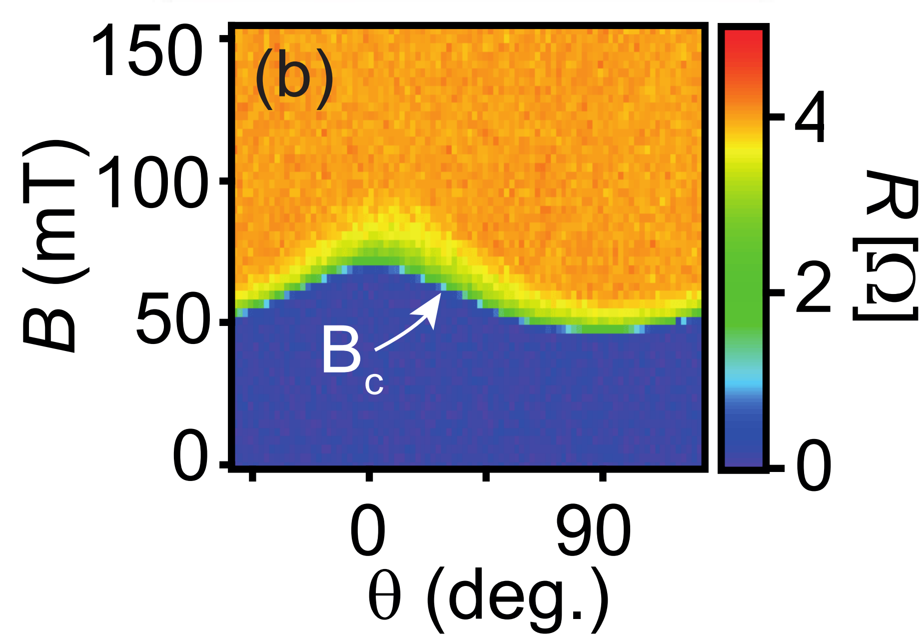
Epitaxial Aluminum contacts to InAs nanowires

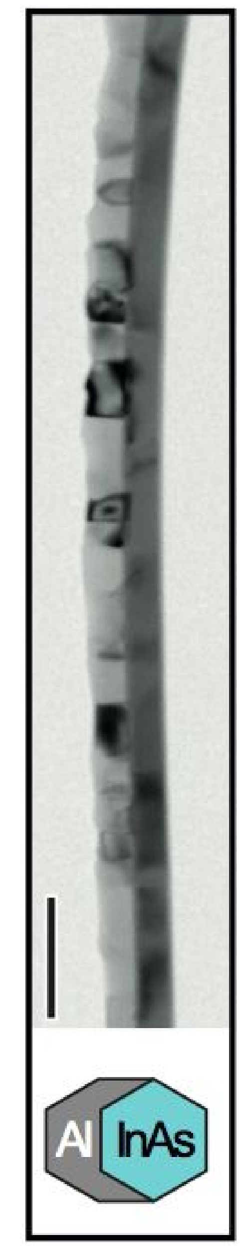
N. L. B. Ziino[1], P. Krogstrup[1], M. H. Madsen[1], E. Johnson[1,2], J. Wagner[3], C. M. Marcus[1], J. Nygård[1], T. S. Jespersen[1]*
[1] Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, Denmark
[2] Department of Materials Research, Ris National Laboratory, Technical University of Denmark, DK-4000 Roskilde, Denmark
[3] Center for Electron Nanoscopy, Technical University of Denmark, Denmark,

Thick coating

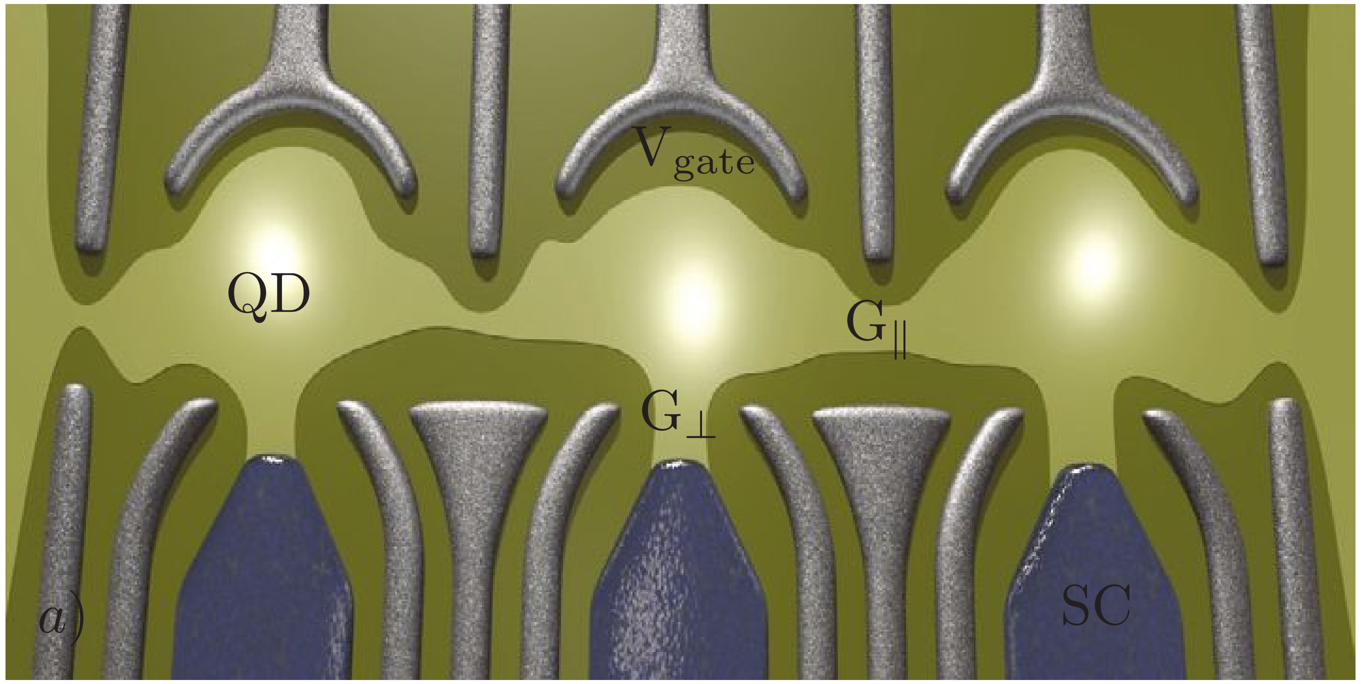




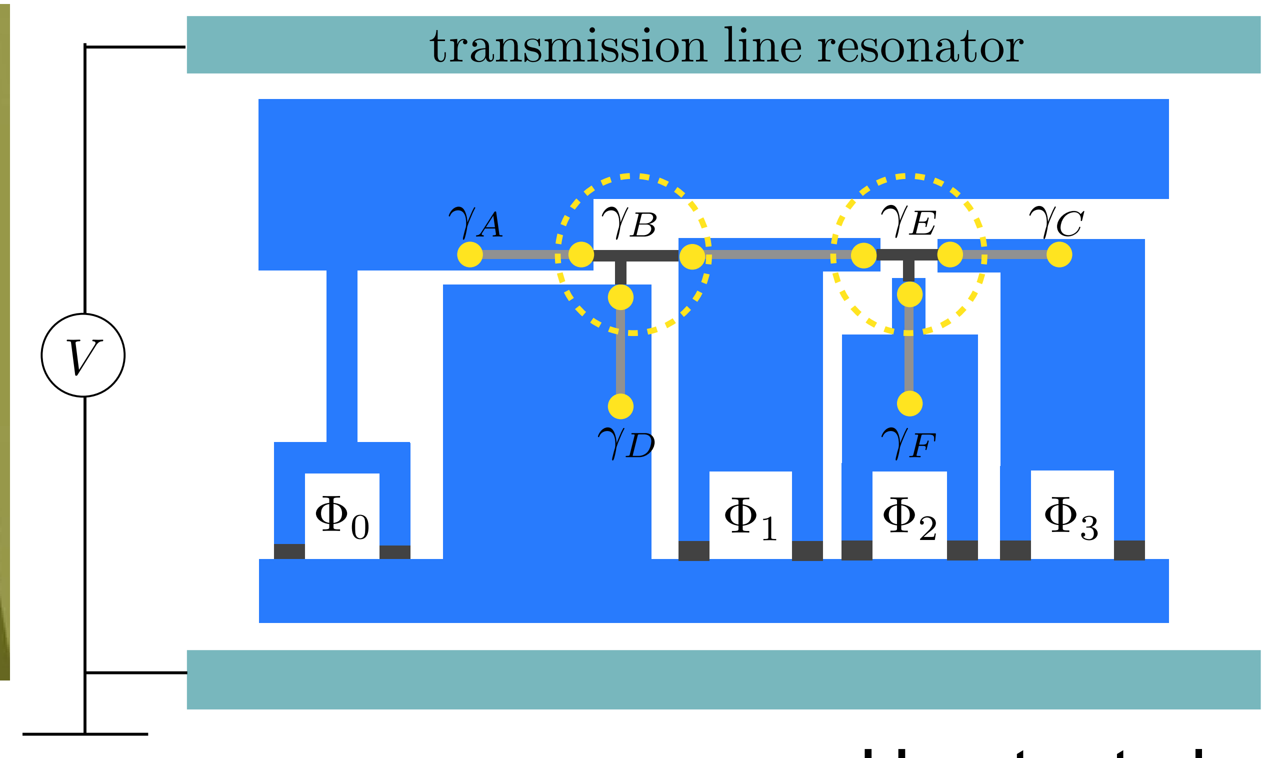




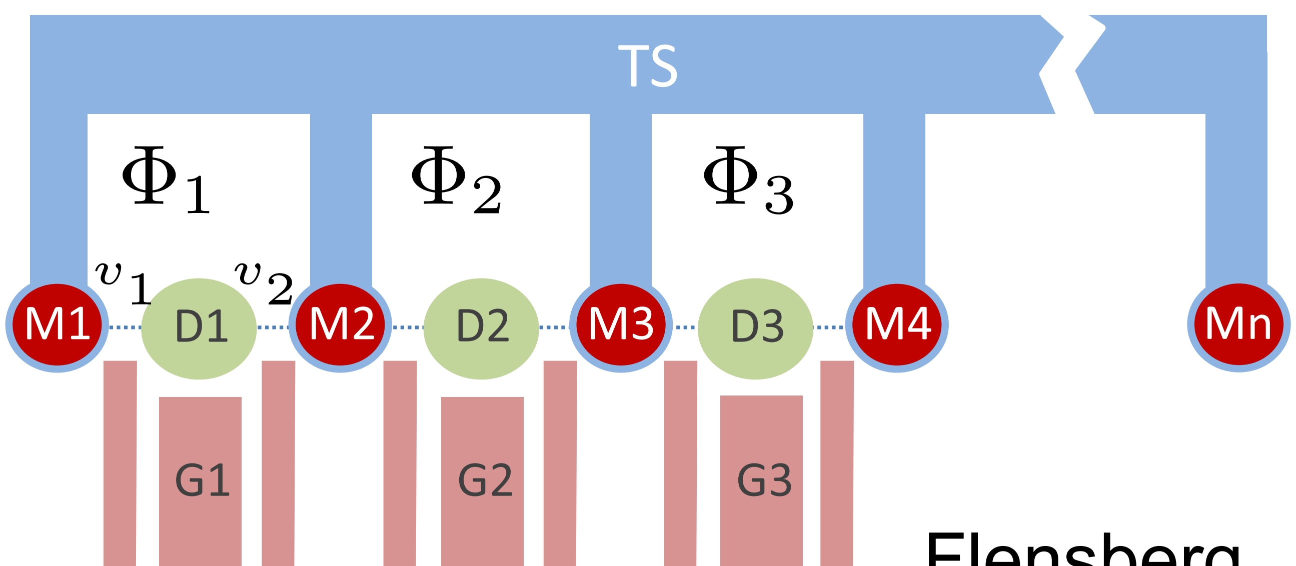
Approaches benefitting from 2D top-down fabrication



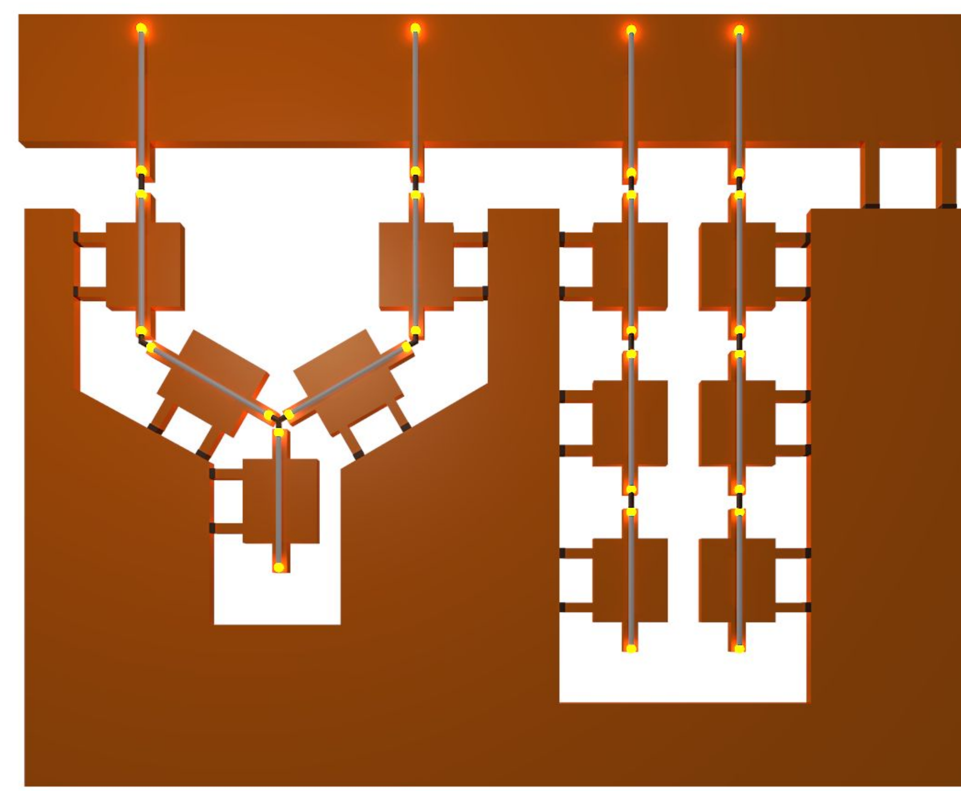
Fulga, et al.



Hyart, et al.



Flensberg



van Heck, et al.

Proximity effect in InSb quantum well