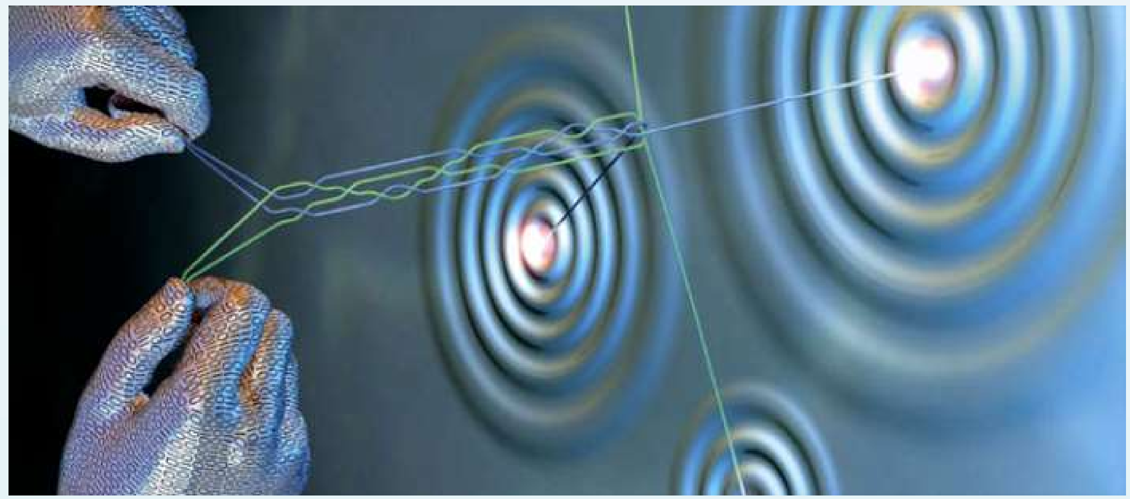
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2013
Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

Let's twist (again) !

Developments related to topology in superconducting electronics



Source: Scientific American

Hans Hilgenkamp
University of Twente &
Leiden University
The Netherlands

11th European Conference on Applied Superconductivity
September 15-19 2013 - Genova, Italy
Eucas 2013

Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

My intentions for this talk:

Convey in accessible words developments in (quantum)-information processing using superconducting devices, with topological quantum computation as the most far-out concept.

This talk will not be a comprehensive review, nor a complete account for all the groups working on these topics, and I will avoid all kinds of detail.

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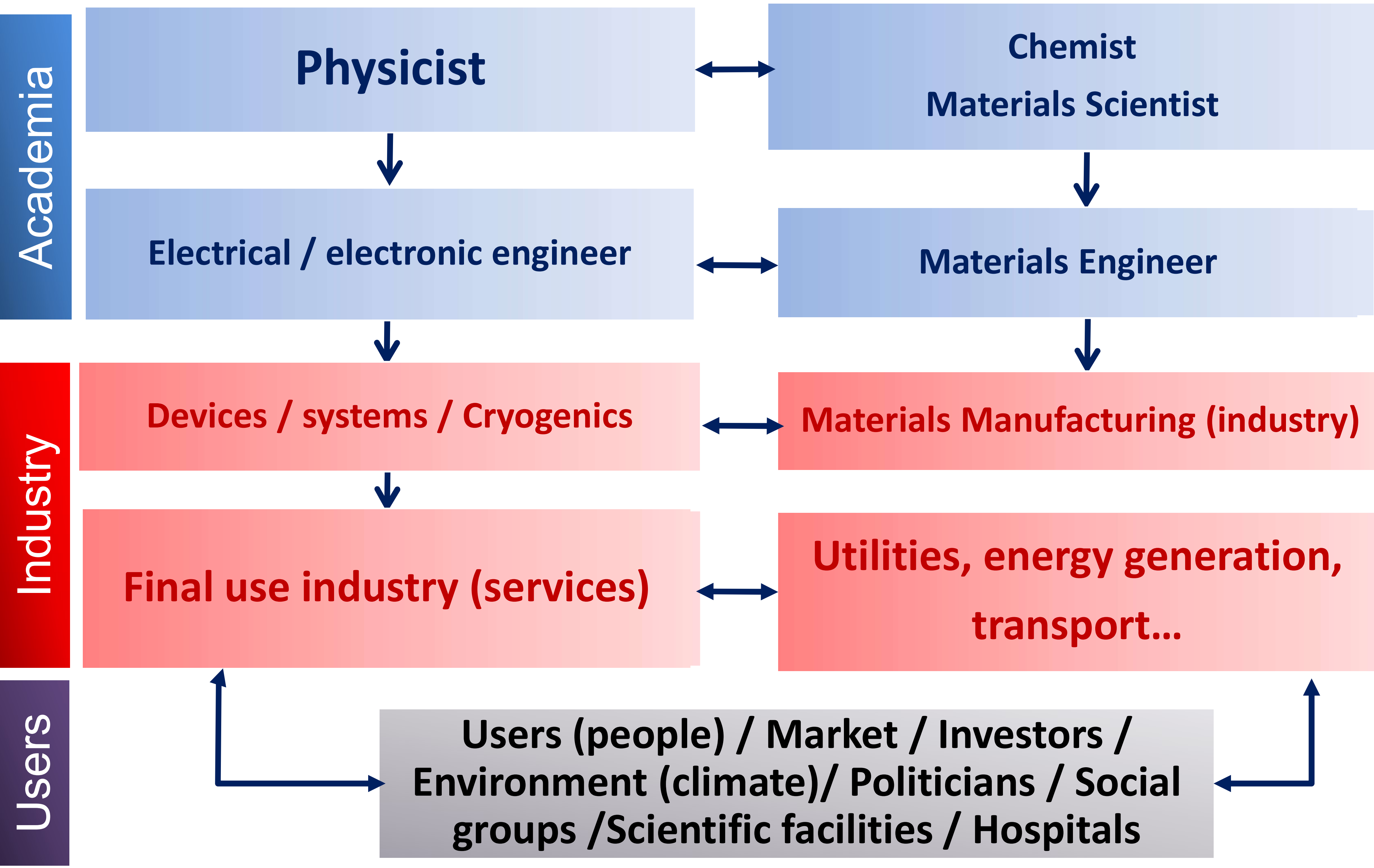
ICMAB

CSIC

The long and winding road: from discovery to applications



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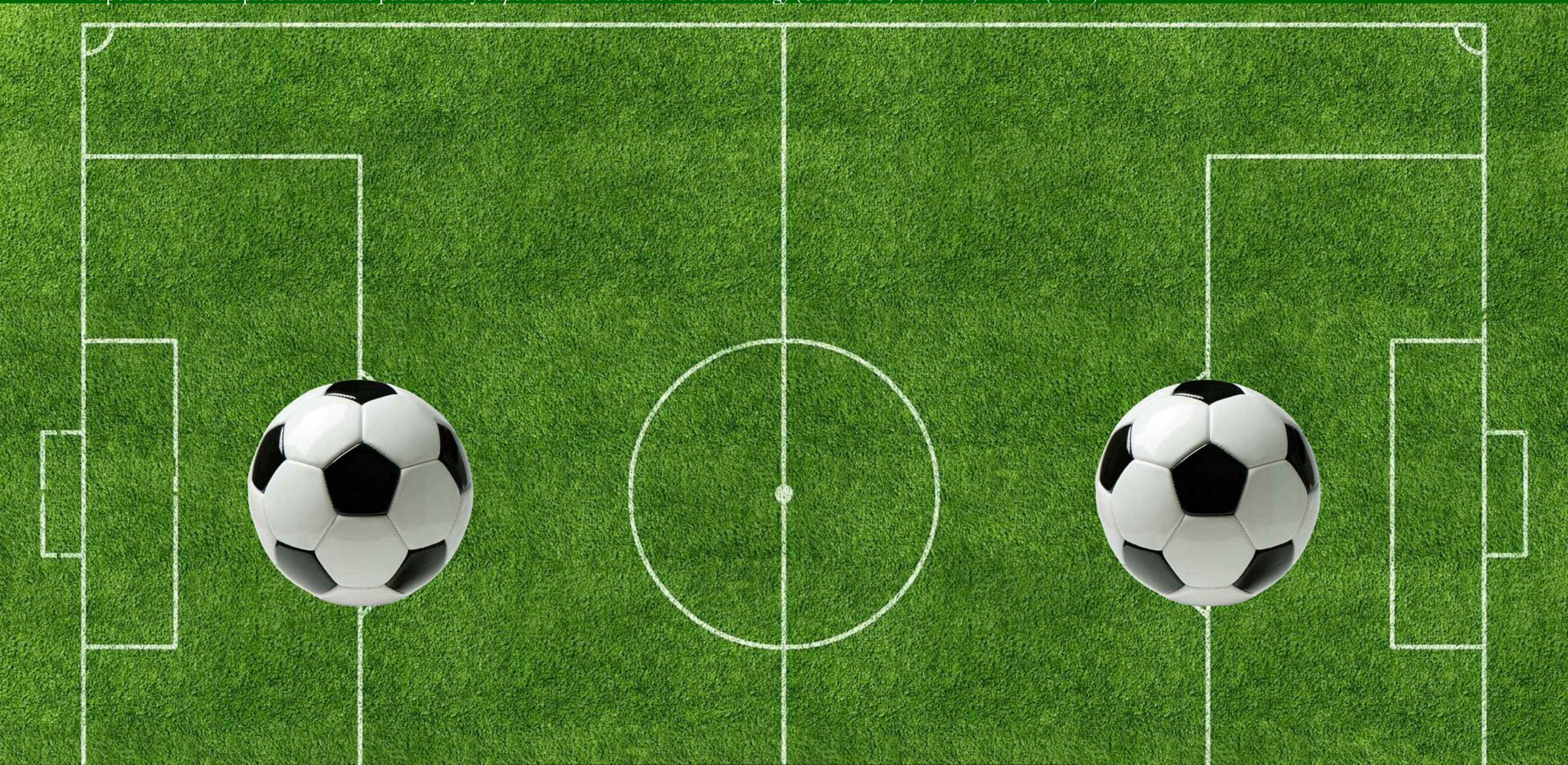

$$\Psi(r_2,r_1) = \Psi(r_1,r_2)$$

Holds for soccer balls, and for bosons such as photons, ^{4}He atoms and Cooperpairs

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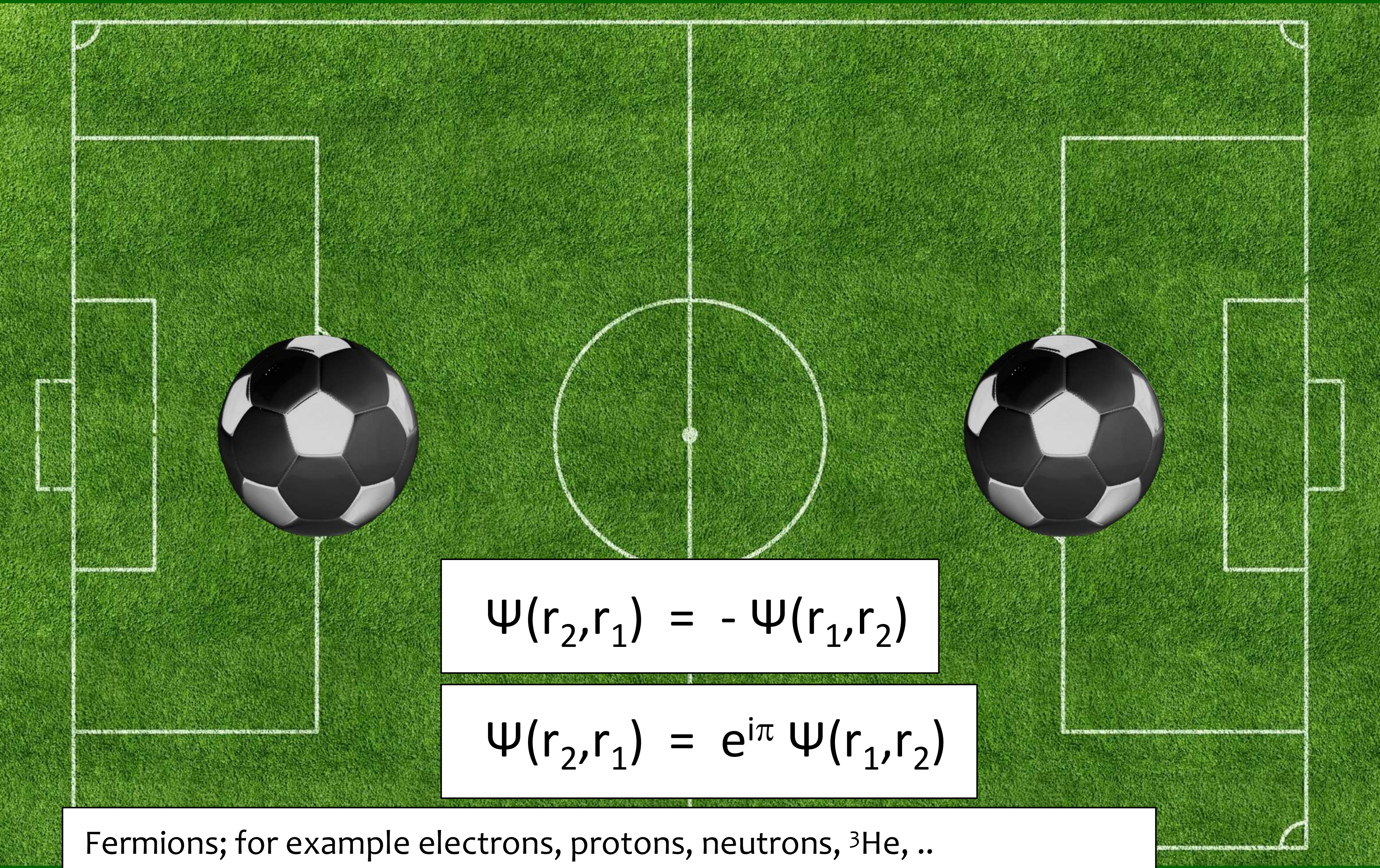

$$\Psi(r_2,r_1) = -\Psi(r_1,r_2)$$

$$\Psi(r_2,r_1) = e^{i\pi}\,\Psi(r_1,r_2)$$

Fermions; for example electrons, protons, neutrons, ^{3}He, ..

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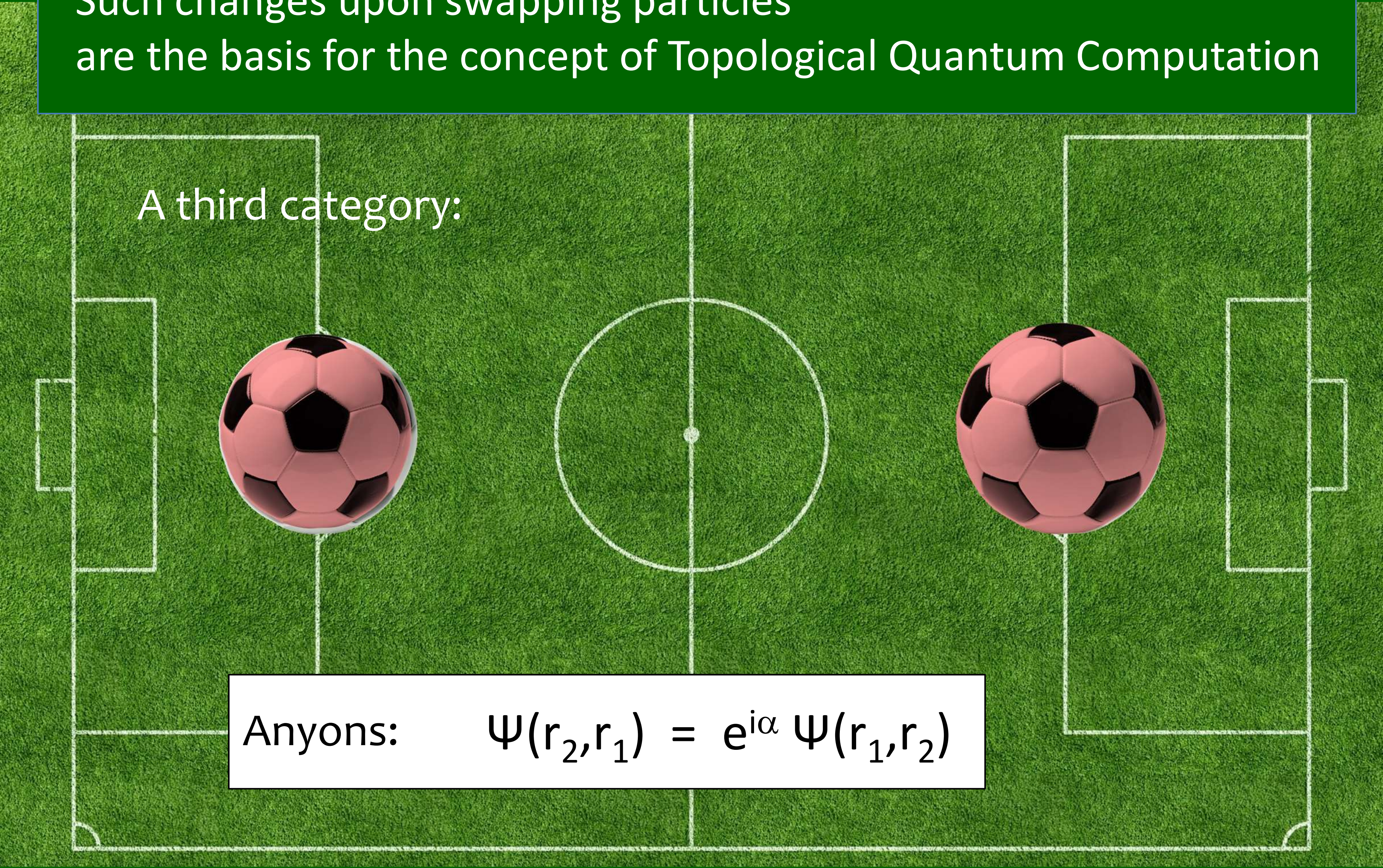
Such changes upon swapping particles are the basis for the concept of Topological Quantum Computation



A third category:

Anyons: $\Psi(r_2,r_1) = e^{i\alpha}\,\Psi(r_1,r_2)$

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Wikipedia on topology:

Topology as a branch of mathematics can be formally defined as the study of qualitative properties of certain objects (called 'topological spaces') that are invariant under a certain kind of transformations (called a continuous map), especially those properties that are invariant under a certain kind of equivalence (called homeomorphism).

●●●

Notable examples of topological defects are obs
Lamdba transition universality class systems incl
screw/edge-dislocations in liquid crystals, magne
tubes in superconductors, vortices in superfluids

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Magnetic flux quanta as topological objects

A.A. Abrikosov

THE DIRECT OBSERVATION OF INDIVIDUAL FLUX LINES IN TYPE II SUPERCONDUCTORS

U. ESSMANN and H. TRÄUBLE

Institut für Physik am Max-Planck-Institut für Metallforschung, Stuttgart and Institut für theoretische und angewandte Physik der Technischen Hochschule Stuttgart

Received 4 April 1967

Triangular flux line lattices have been observed by electron microscopy on Pb-4at% In and niobium specimens in the remanent state. These lattices contain various kinds of defects.

The Abrikosov solution [1] of the Ginsburg-Landau equations [2] for the mixed state of type II superconductors predicts a periodic arrangement of flux lines (flux line lattice) penetrating the specimen parallel to the applied field. Neutron diffraction studies [3,4] on niobium and nuclear magnetic resonance studies on vanadium [5] give evidence for the existence of a close packed arrangement of flux lines.

In this paper we present results on the flux line arrangement obtained by sirect observation of individual flux lines. As was shown in previous papers [6-8], the magnetic structures on the surfaces of ferromagnets and superconductors can be revealed with a resolution of about 500 Å or better by depositing small ferromagnetic particles on the specimen and observing the resulting patterns in the electron microscope by means of a replica technique.

We report here the magnetic structures of Pb-4at%In (κ = 1.35 at 1.1°K [8]) and niobium in the remanent state at 1.1°K based on observations on the end surfaces of well-annealed mono- or polycrystalline rods (4 mm diameter, 50 mm length) that had been magnetized parallel to the rod axis in a field of 3000 Oe. Parts of the surfaces exhibited a quite well defined triangular lattice of "points of exit" of the magnetic flux (fig. 1). In polycrystalline Pb-4at%In the lattice parameter (nearest neighbour separation) is a = 3500 Å. If each of the indivudual spots is as-

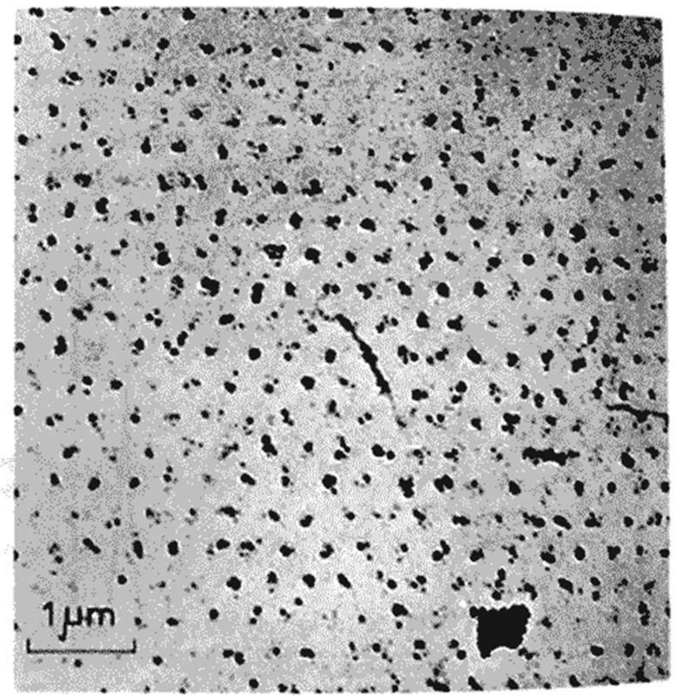

Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

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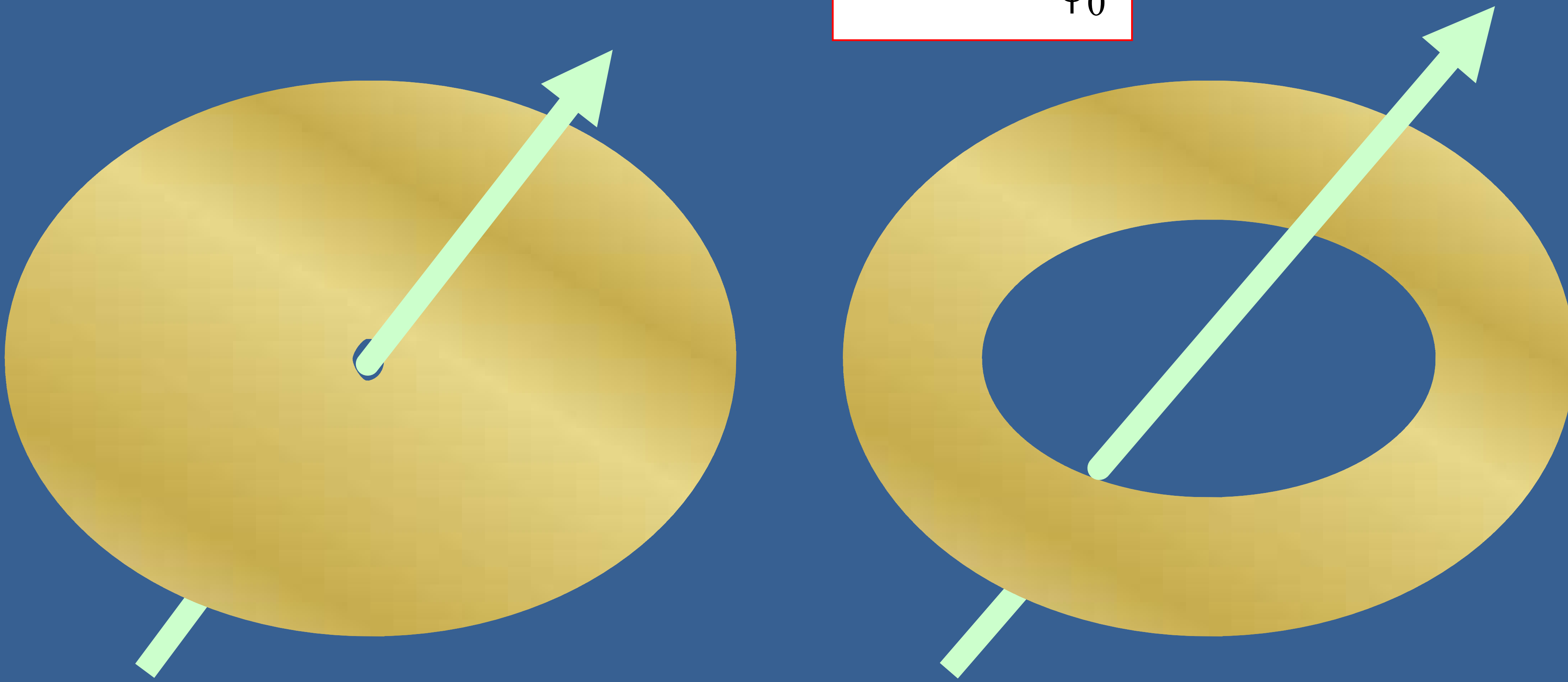
Flux-quantization in Abrikosov vortices and superconducting rings

$$\Psi(\vec{r}) = \Psi_o(\vec{r})\, e^{i\varphi(\vec{r})}$$

$$\Delta\varphi = 2\pi \frac{\phi}{\phi_0}$$



Single-valuedness of the wave function requires $\Delta\varphi = 2n\pi$ around the ring. This provides a form of ‘topological protection’ -> flux cannot be 0.8 ϕ_0 or 1.3 ϕ_0

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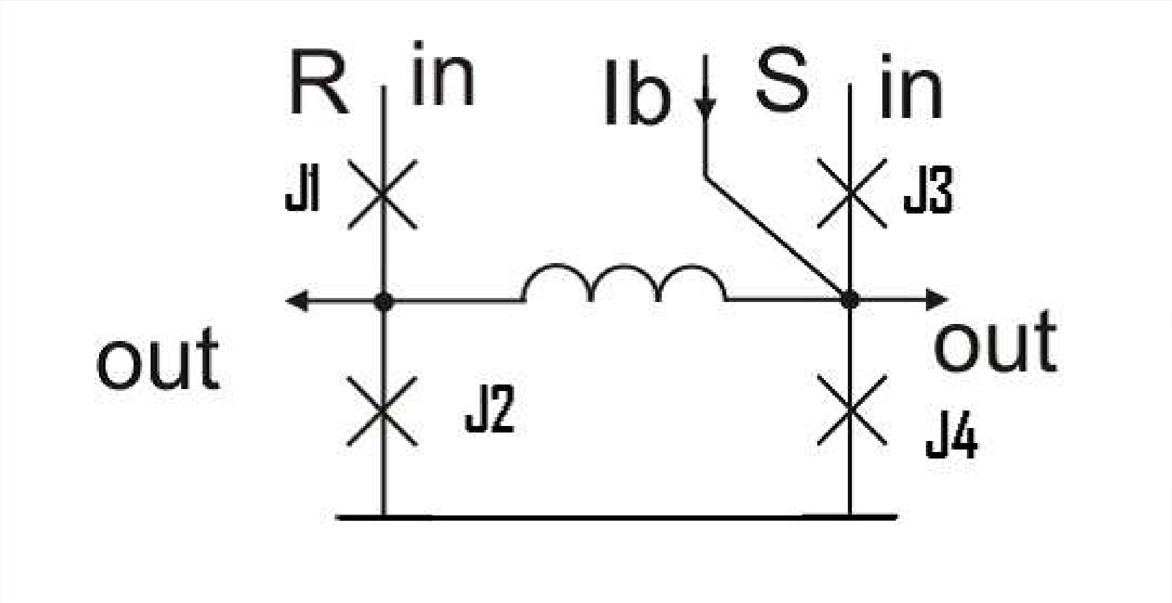
Flux quantization is the basis for many superconducting electronics / sensing devices

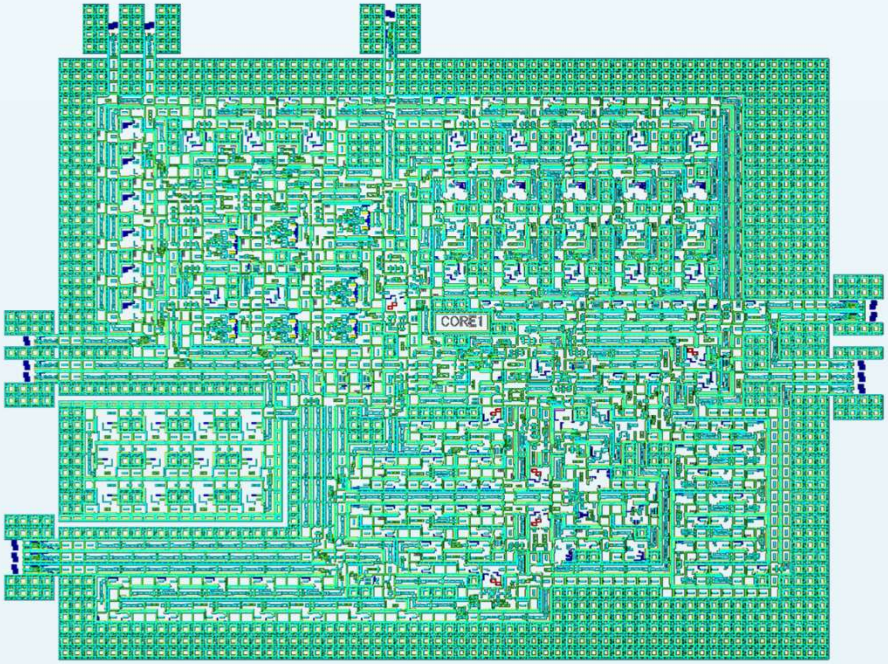


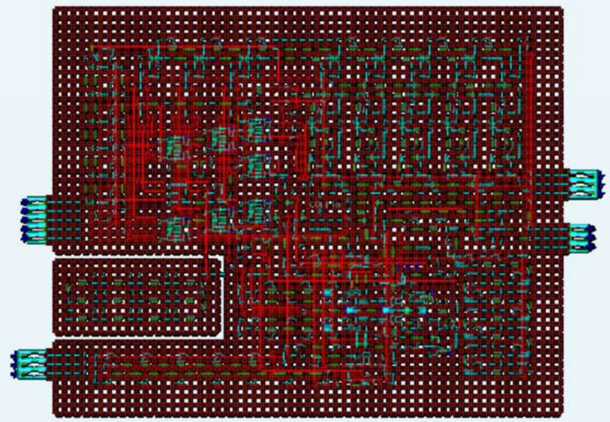
RSFQ Flip Flop
(adapted from S. Narayana & V. Semenov)

Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

Lowered Power Consumption of Microprocessor with Low-Voltage RSFQ Circuit

(from Prof. A. Fujimaki – Nagoya)





Multilayered PTLs introduced
JJ count: -23%, area: -50%

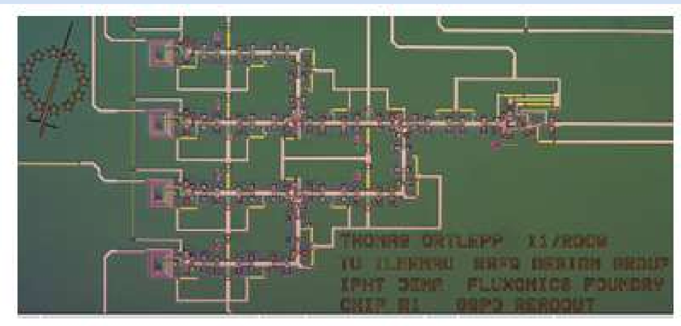
	CORE1α Prototype with Conventional RSFQ (2003) [1]	CORE1α with Low-Voltage RSFQ (2013) [2]
Technology	ISTEC 2.5-kA/cm^2 STP	AIST 10-kA/cm^2 ADP
Size, JJ Count	2.56 mm x 2.12 mm, 4999 JJs	1.38 mm x 1.71 mm, 3869 JJs
Bias Voltage	2.5 mV	**0.5 mV**
Power	1.6 mW	**0.23 mW**

[1] M. Tanaka, et al., "A single-flux-quantum logic prototype microprocessor," ISSCC Dig. Tech. Papers, p. 298, Feb. 2004.
[2] M. Tanaka, Y. Hayakawa, K. Takata, and A. Fujimaki, "Design of Low-Voltage RSFQ Microprocessor Prototypes," to be presented at EUCAS, Genova, Italy, Sep. 2013.

Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

SFQ examples

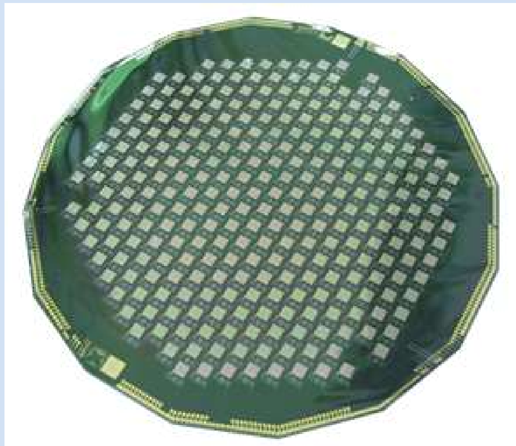
4 channel SNSPD readout and multiplexer circuit
15 JJ/channel



Photograph – T. Ortlepp, Ilmenau University of Technology, Germany

T. Ortlepp et al., Optics Express, 19 (2011) 18593

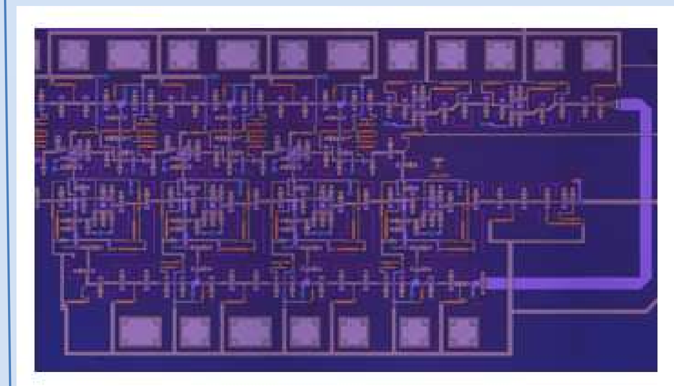
300 pixel TES array with integrated SQUID multiplexer for Atacama Pathfinder experiment (APEX) in Chili



Photograph – T. May
IPHT Jena, Germany

T. May et al. *Proceedings of SPIE 6949 (2008), 69490C*

Digital magnetometer decimation filter
4 GHz operation
360 JJs



Photograph – R. Stolz
IPHT Jena, Germany

**J. Kunert at al.
IEEE TAS, 23, (2013) 1101707**

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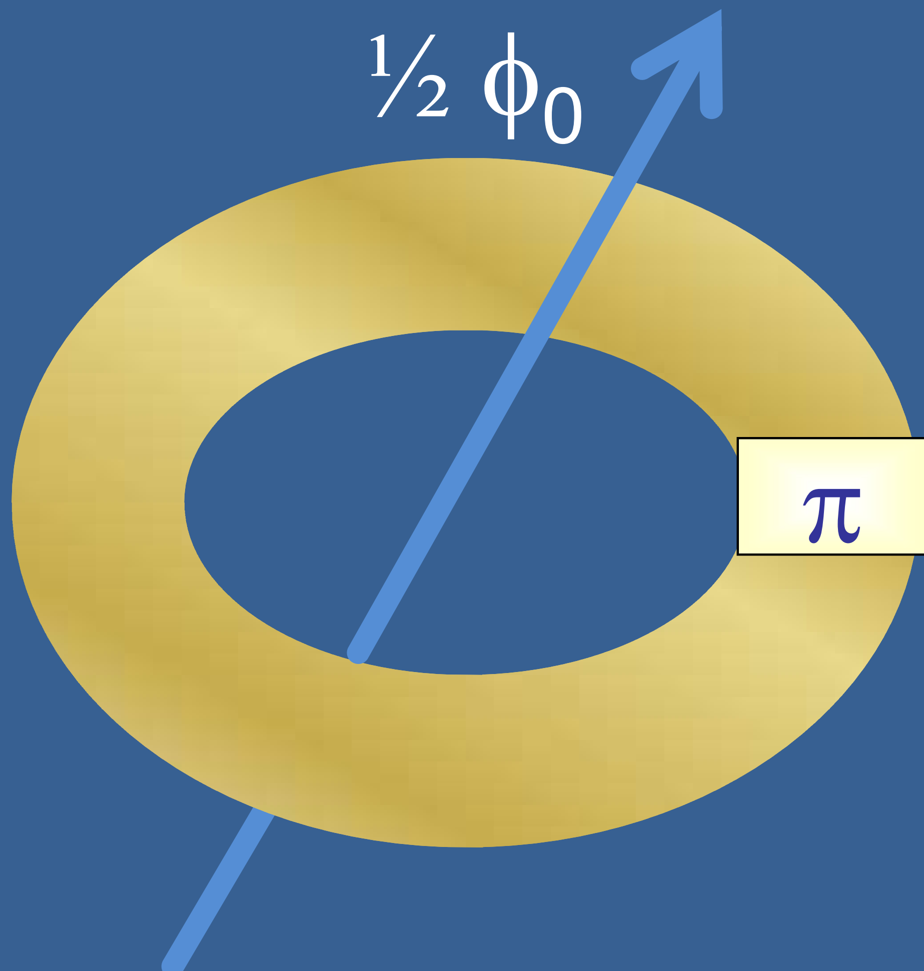

H. Hilgenkamp, EUCAS Brussels 2007
'Pi-phase shift Josephson structures',
Supercond. Science & Techn. 21, 034011 (2008)

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2013
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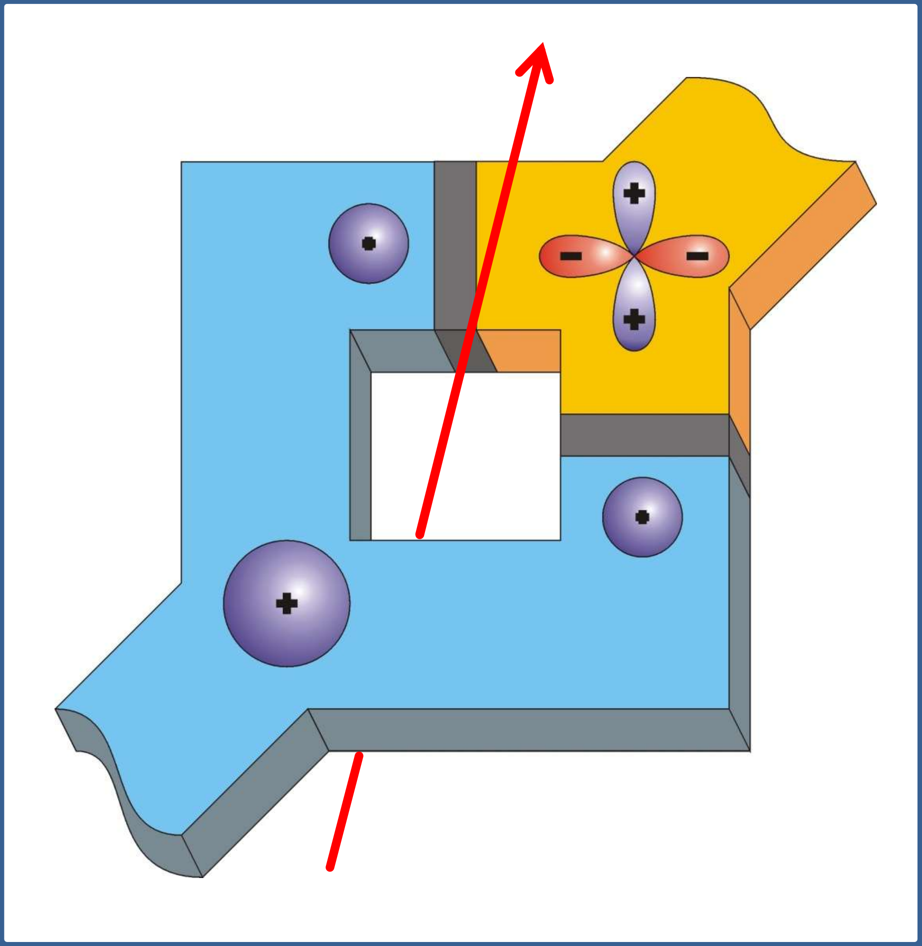
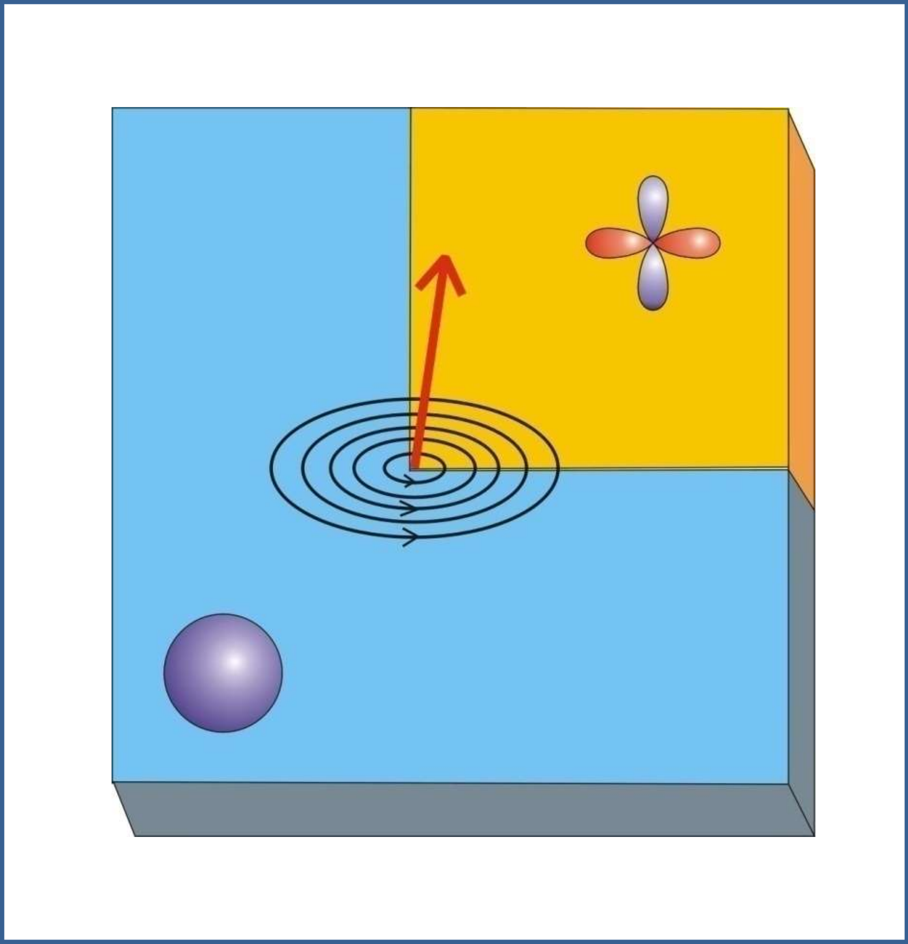
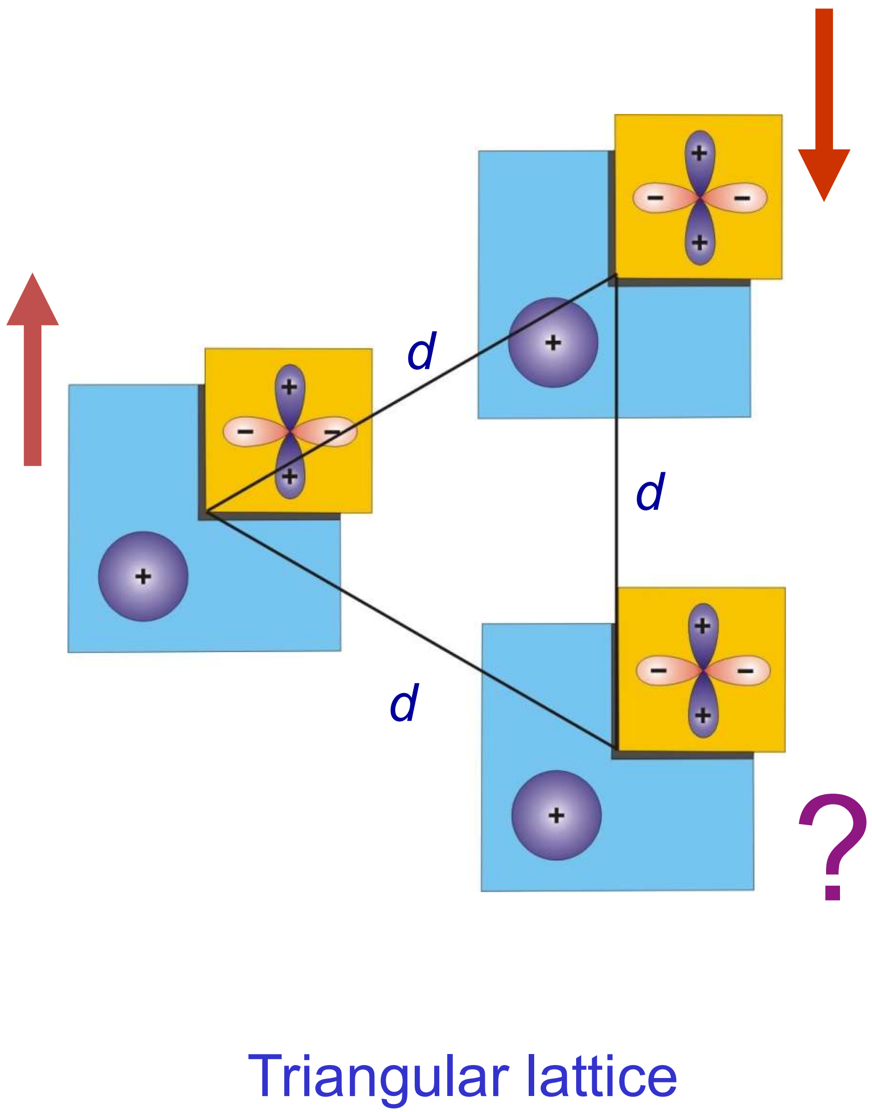
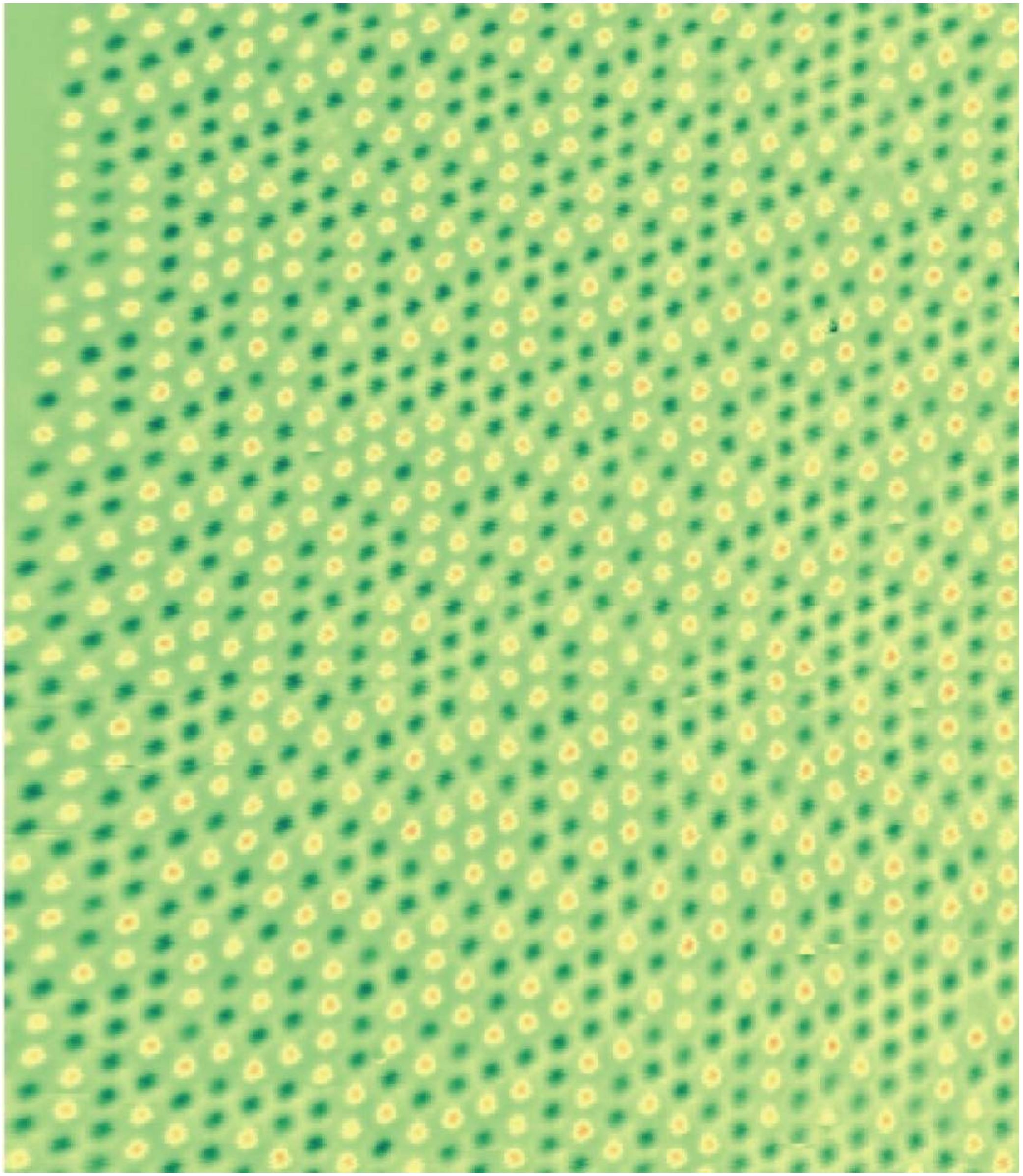
π-ring based on a combination of high-T_c and low-T_c superconductors





Triangular Ising lattice of half-integer flux quanta





Hilgenkamp, Ariando, Smilde, Blank, Rijnders, Rogalla, Kirtley & Tsuei, *Nature* 422, 50-53 (2003)

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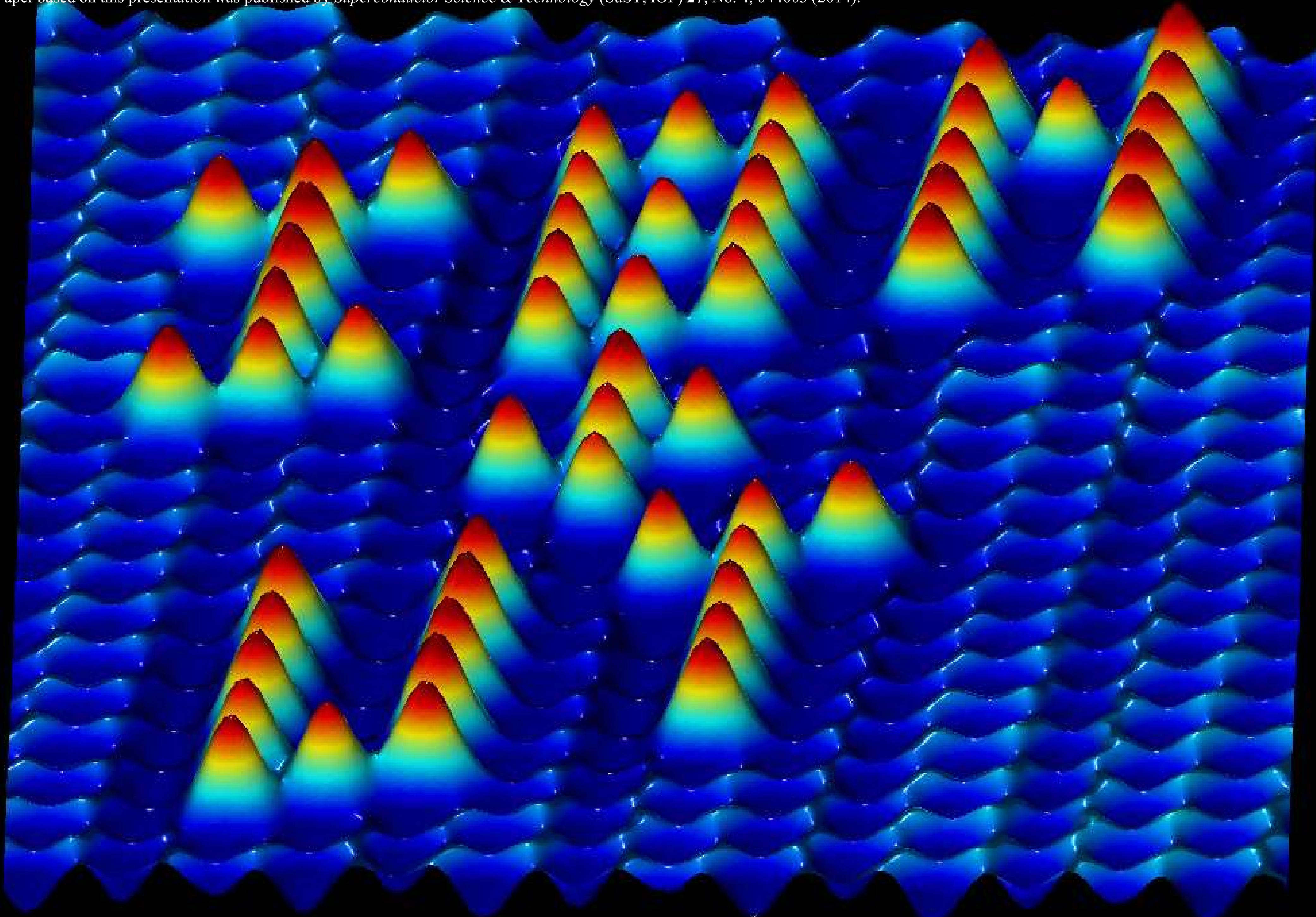
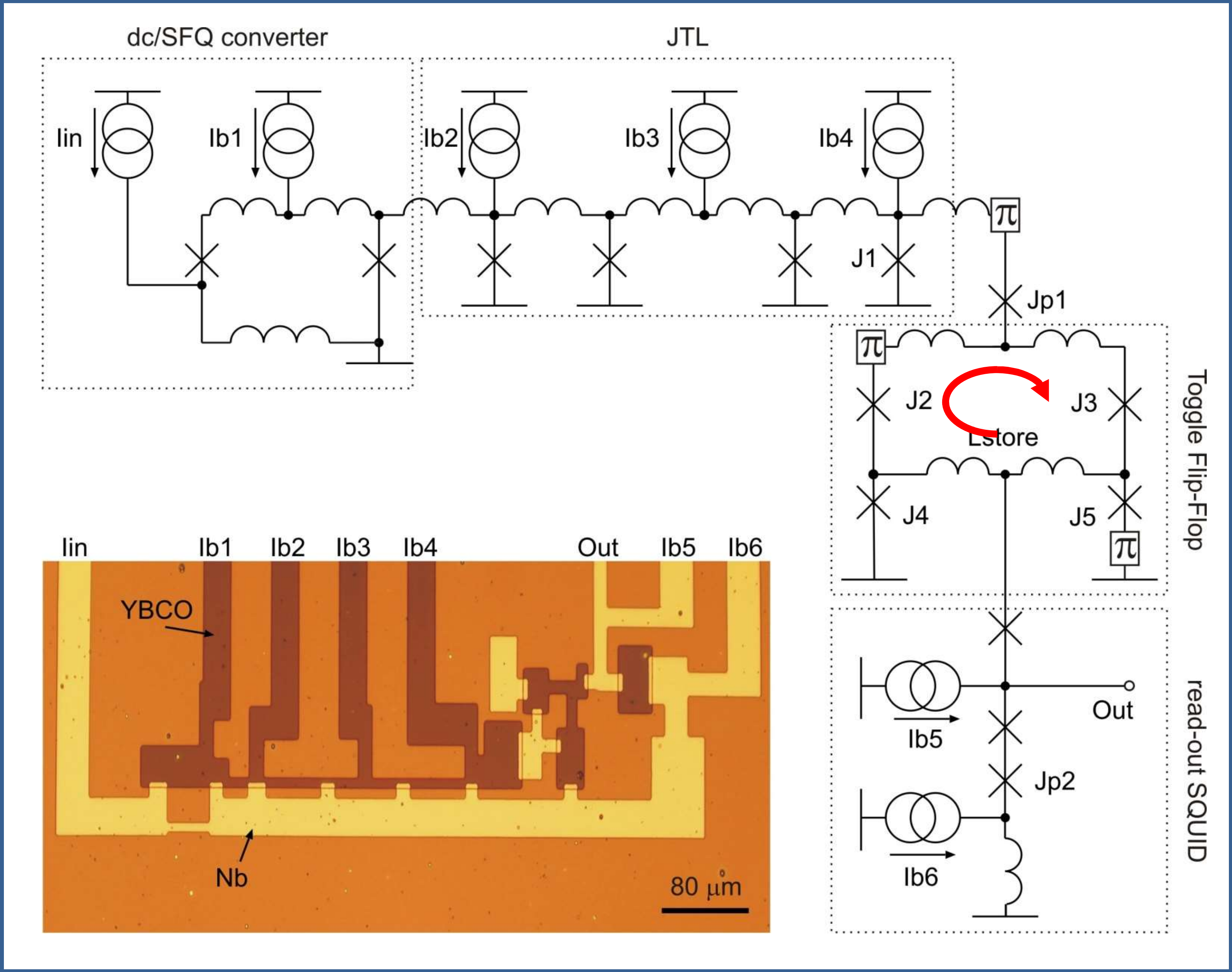
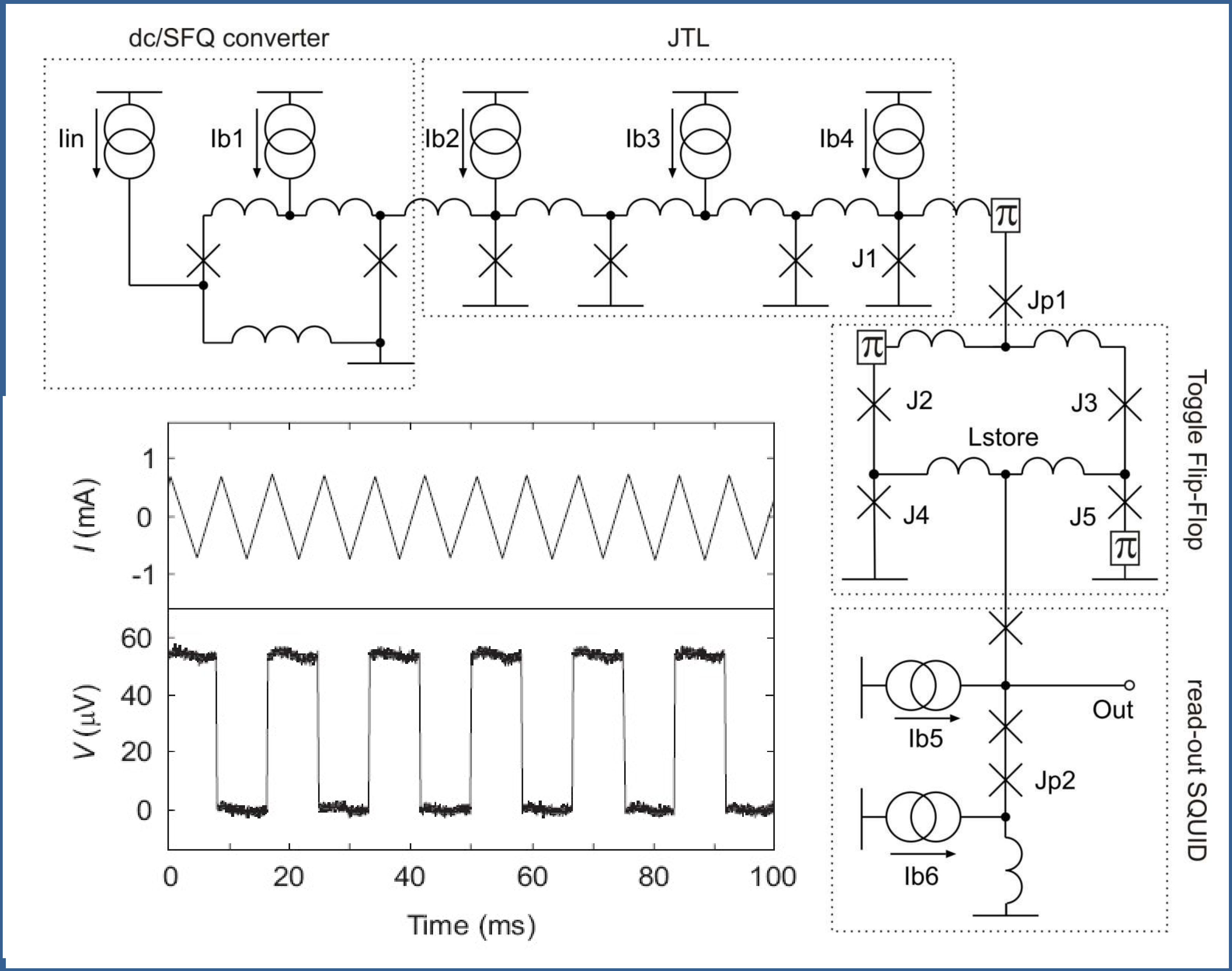


RSFQ circuit using half-integer flux quanta



Ortlepp, Ariando, Mielke, Verwijs, Foo, Rogalla, Uhlmann & Hilgenkamp, *Science* 312, 1495 (2006)

RSFQ circuit using half-integer flux quanta



Ortlepp, Ariando, Mielke, Verwijs, Foo, Rogalla, Uhlmann & Hilgenkamp, *Science* 312, 1495 (2006)

Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

From computation with flux quanta

to

quantum computation

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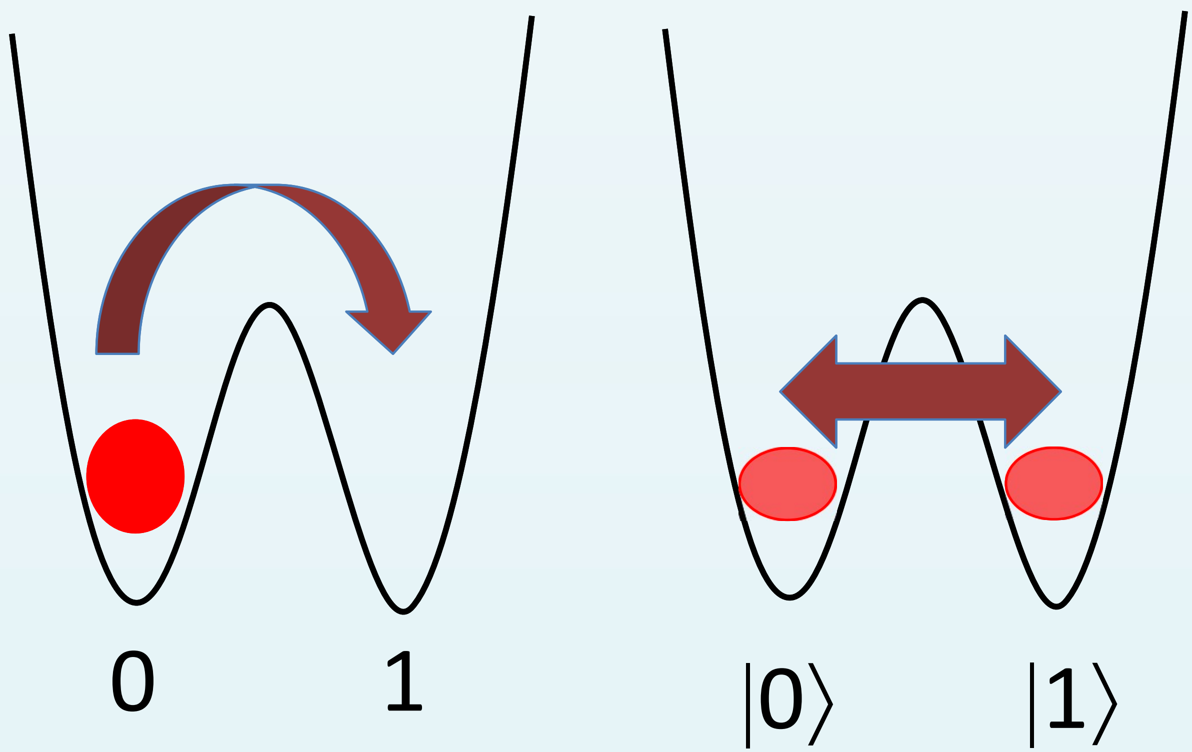
Bits and qubits:

Classical bits   Quantum bits (qubits)



$\Psi = 0$ or
$\Psi = 1$

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

with

$$|\alpha|^2 + |\beta|^2 = 1$$

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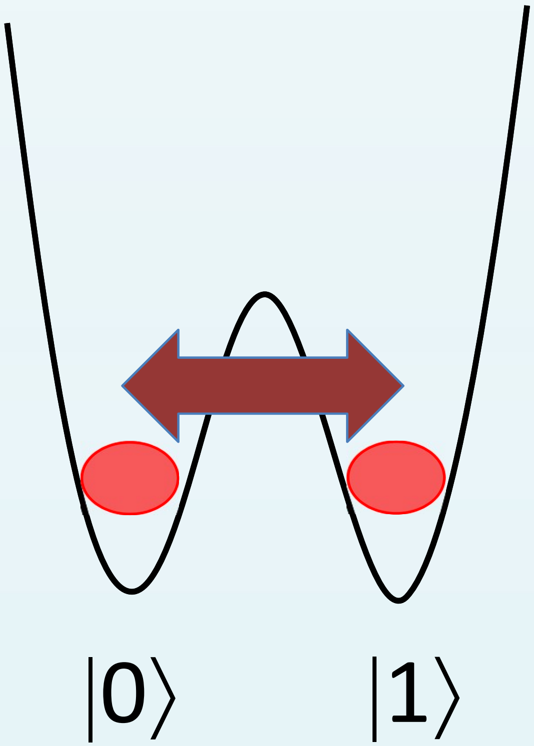
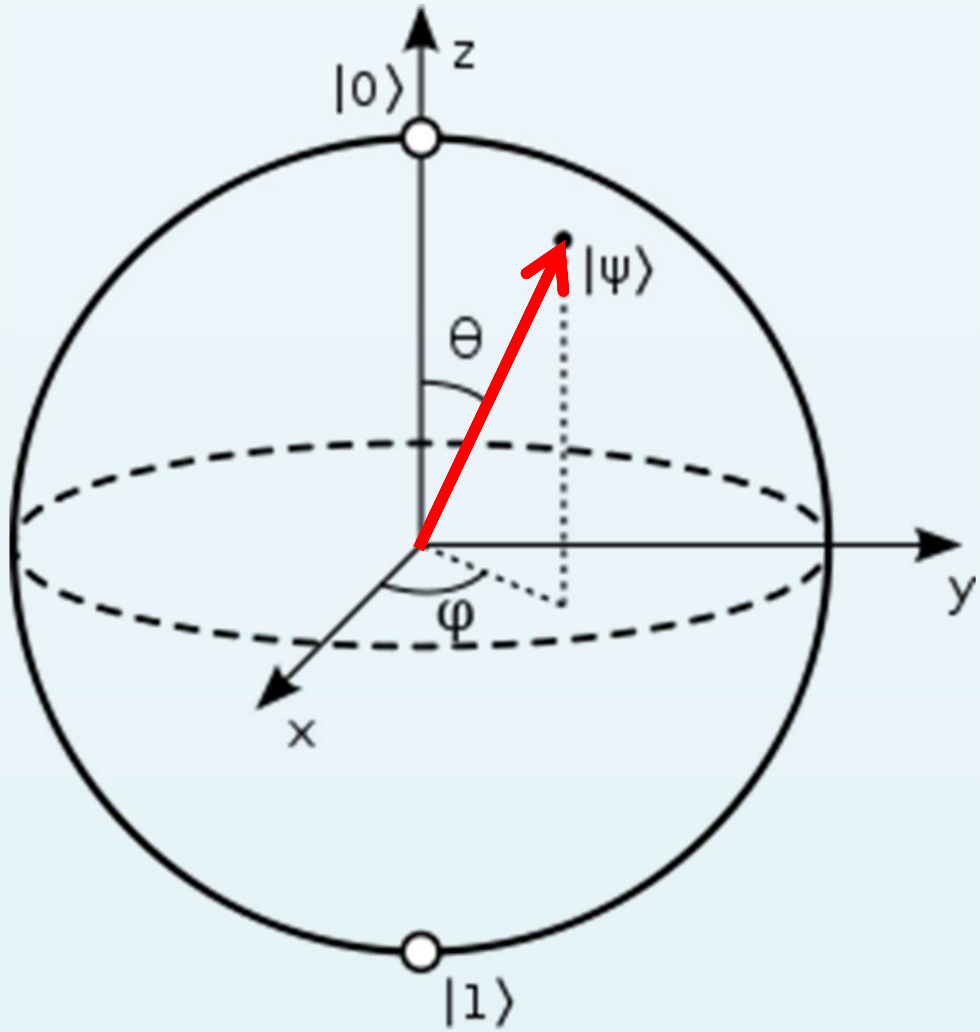
Two attributes: Probability and Phase -> Bloch sphere representation

Quantum bits (qubits)





'Bloch sphere'

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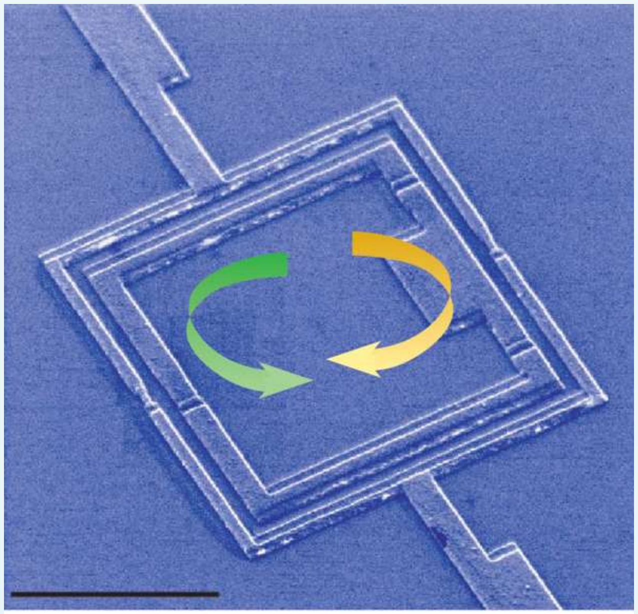
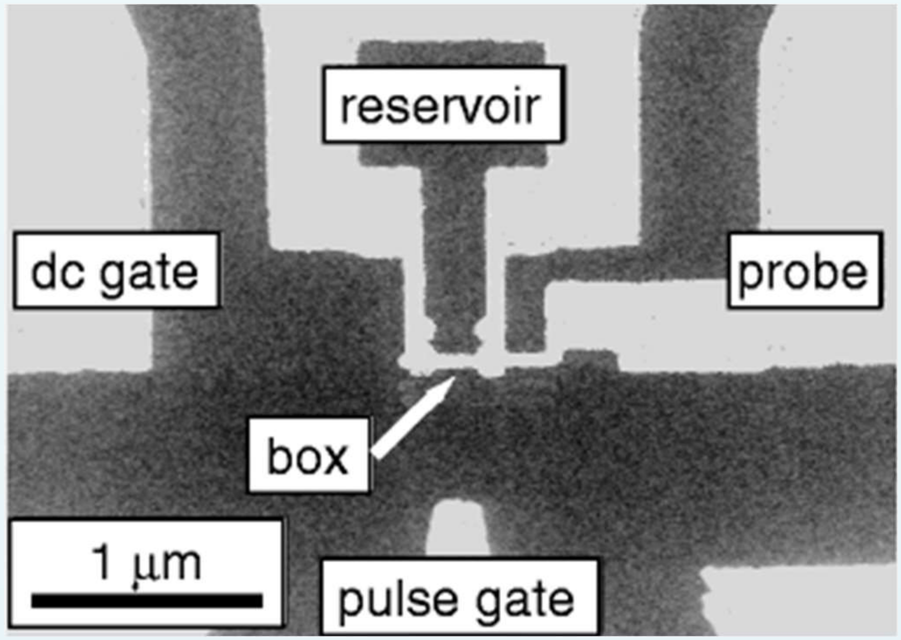
Superconducting qubits

Flux qubit

Charge qubit



J.E. Mooij *et al.*, *Science* 1999



Y. Nakamura *et al.*, *Nature* 1999

In addition:

Phase qubit
'cQED'
'Transmon'
'Quantronium'
'Fluxonium'
...

Good reads:

M.H. Devoret and R.J. Schoelkopf, *Science* 339, 1169 (2013)

J. Clarke and F.K. Wilhelm, *Nature* 453, 1031 (2008)

Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

Opportunities with qubits:

Faster calculations of complex problems, using dedicated algorithms
(best known example: Shor algorithm for integer factorization into prime numbers)

Quantum simulators for quantum materials

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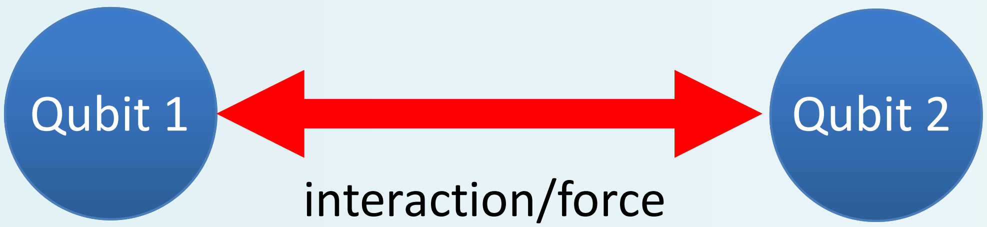
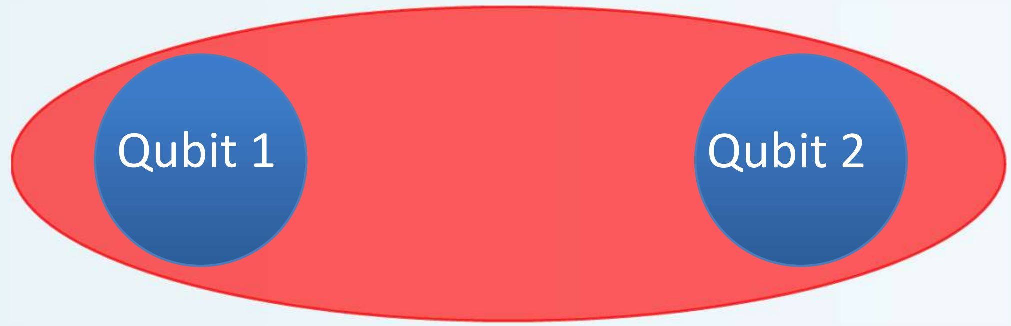
Coupling vs. Entanglement



interaction/force
(with speed of light)



One quantum state
(with instantanous interactions)

$|\psi\rangle = \{ \alpha|0\rangle + \beta|1\rangle \} \times \{ \gamma|0\rangle + \delta|1\rangle \}$

with $|\alpha|^2+|\beta|^2 = 1$ and $|\gamma|^2+|\delta|^2 = 1$

N qubits: N 3-dimensional Bloch spheres

$|\psi\rangle = \{ \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle \}$

with $|\alpha|^2+|\beta|^2+ |\gamma|^2 + |\delta|^2 = 1$

N qubits:
One (4N – 1) dimensional Bloch sphere

To enjoy the full benefits of quantum computation, entanglement is required

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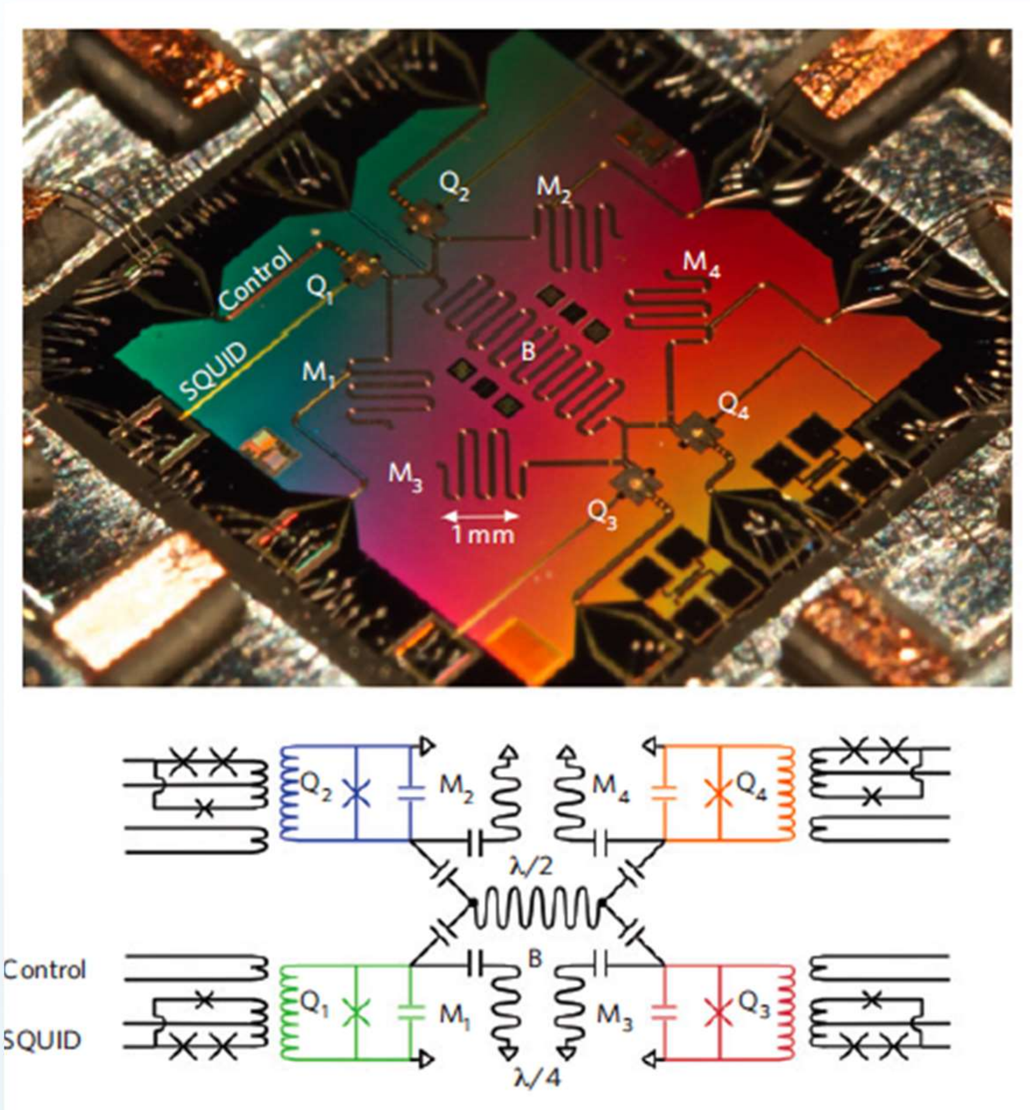
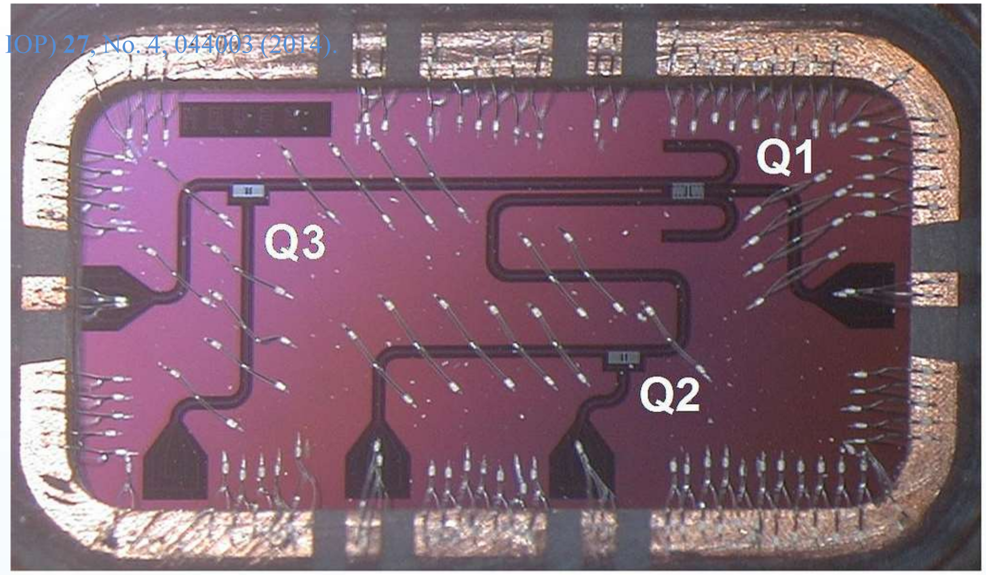
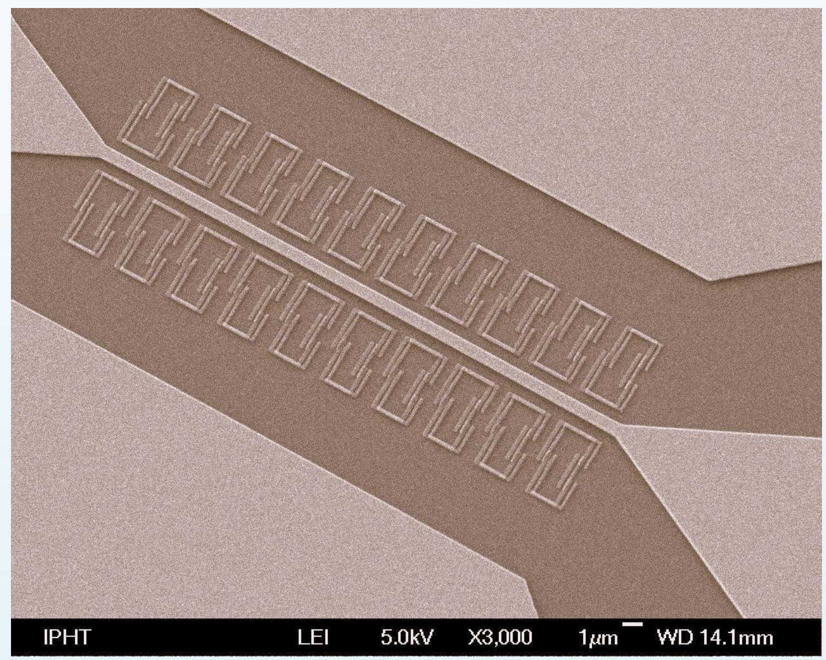
Coupling and entangling qubits



E. Lucero et al. (UC Santa Barbara)
Nature Physics 8, 719 (2012)

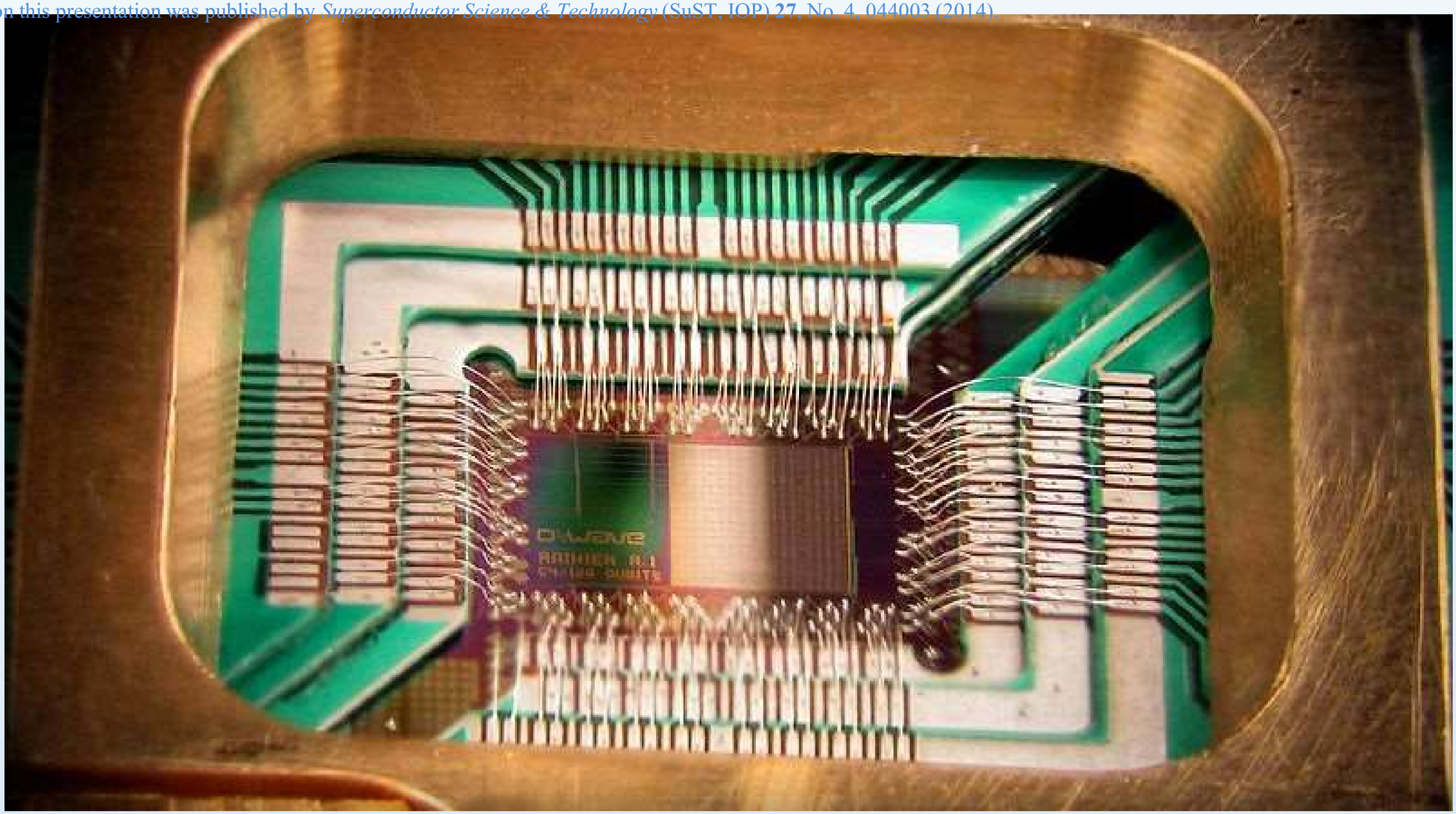


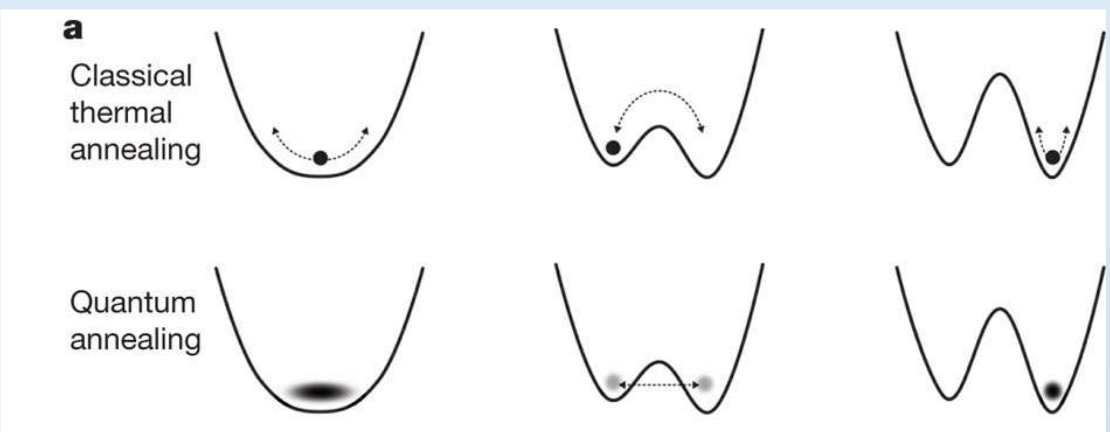
M. Steffen et al. (IBM)
Phys. Rev. B 86, 100506 (2012)



IPHT Jena + Karlsruhe, unpublished
(with thanks to E. Il'ichev)

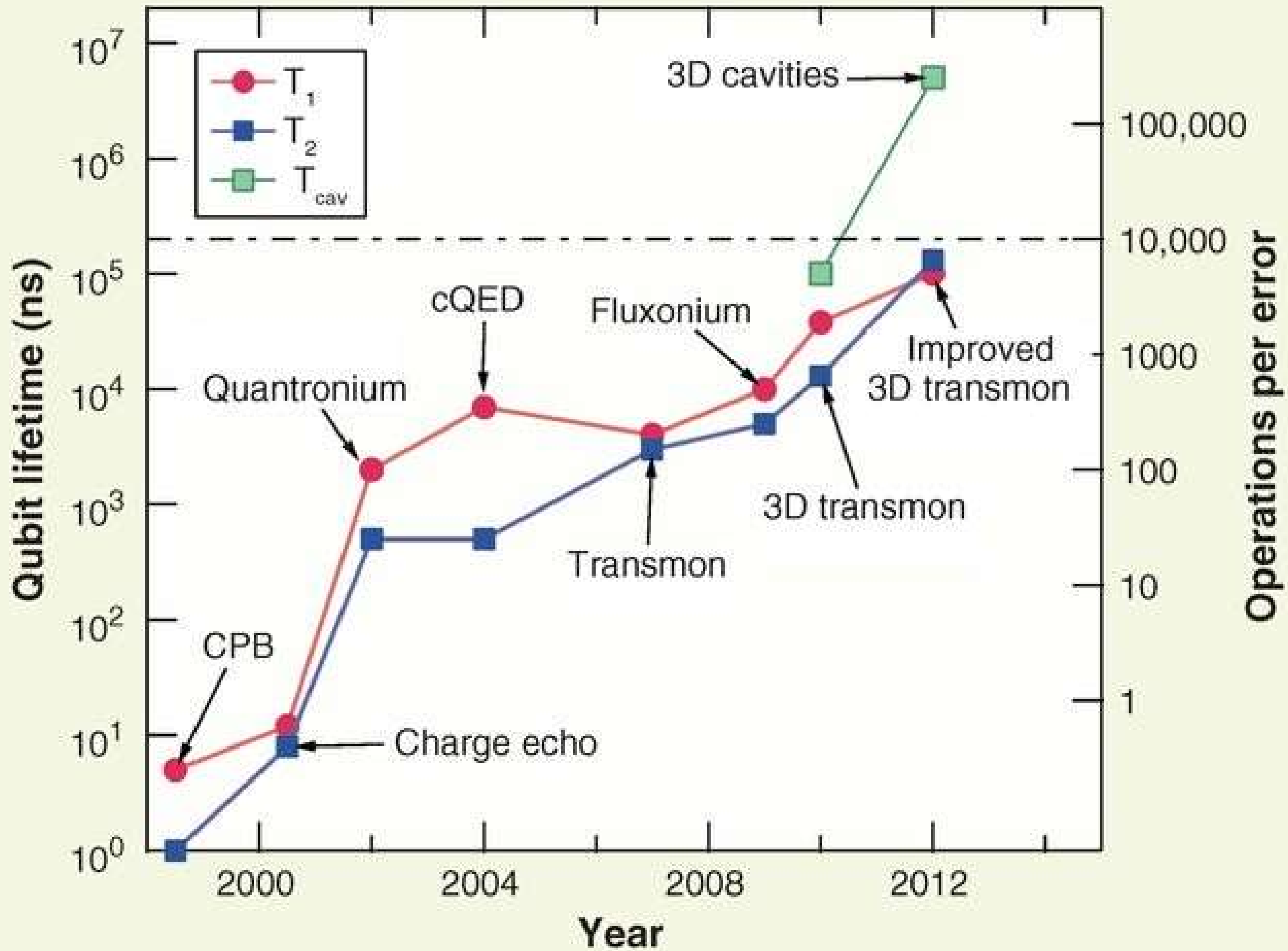
Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).





M.W. Johnson *et al.*, (D-Wave)
Nature 473, 194 (2011)

Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).



M.H. Devoret and R.J. Schoelkopf, *Science* 339, 1169 (2013)

Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

Status of superconducting qubits

Great progress has been achieved with various types of superconducting qubits, regarding extending coherence times, coupling/entangling via e.g. resonators, and inventing useful read-out and error-correction techniques.

However, the sensitivity to decoherence remains a major complication.
This sensitivity on the other hand provides prospects for sensing applications.

Making (more) use of topological protection may be a way to overcome this problem.

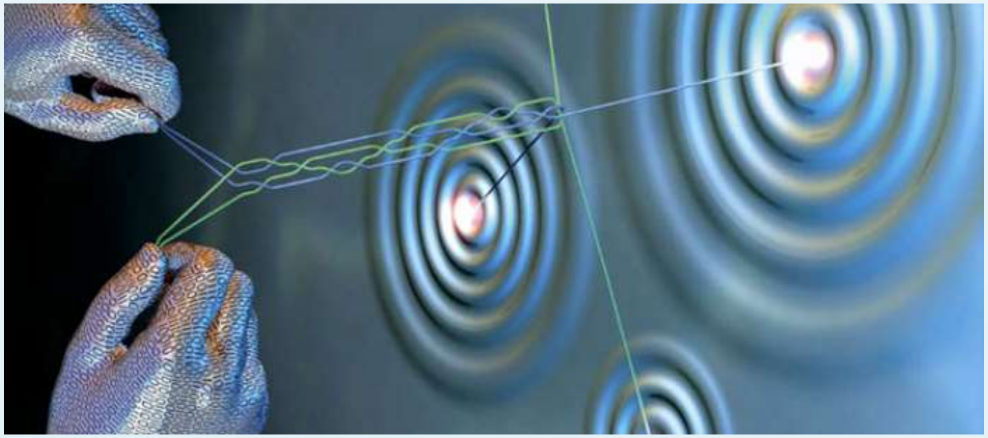
Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

The basic idea of topological quantum computation:

Split qubit into two parts, well separated from each other.
The information is encoded only in the combination of these states, which by themselves are much less sensitive to decoherence.

These two parts are anyons, which means that rotating them around each other changes their composite wave-function.

The anyons also have 'non-Abelian' character, meaning that the order of the rotations matters for the final outcome. This leads to the concept of 'braiding' as a method for topological quantum computations.

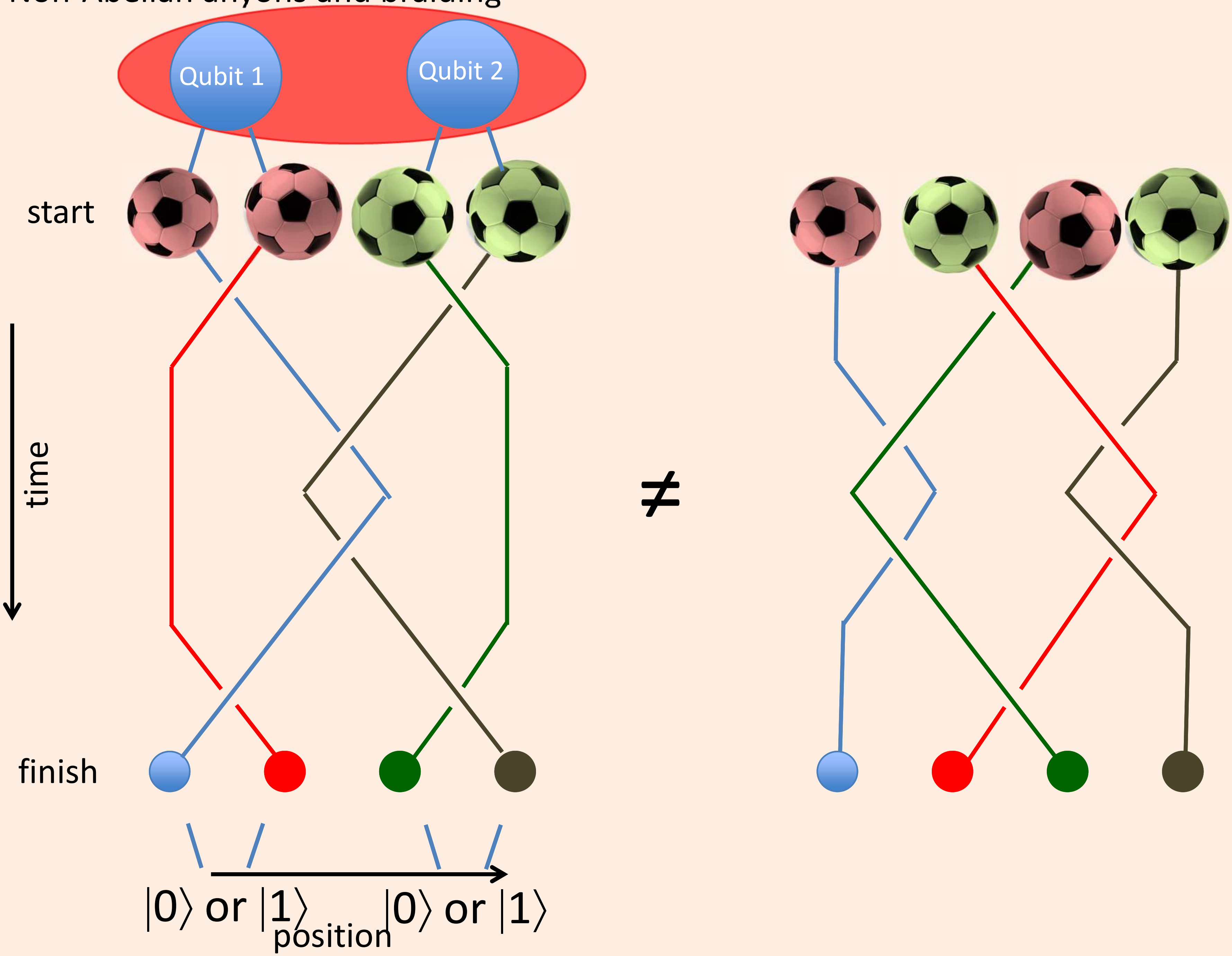


Recent intro-review on
topological quantum computation:

A. Stern & N.H. Lindner,
Science 339, 1179 (2013)

Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

Non-Abelian anyons and braiding



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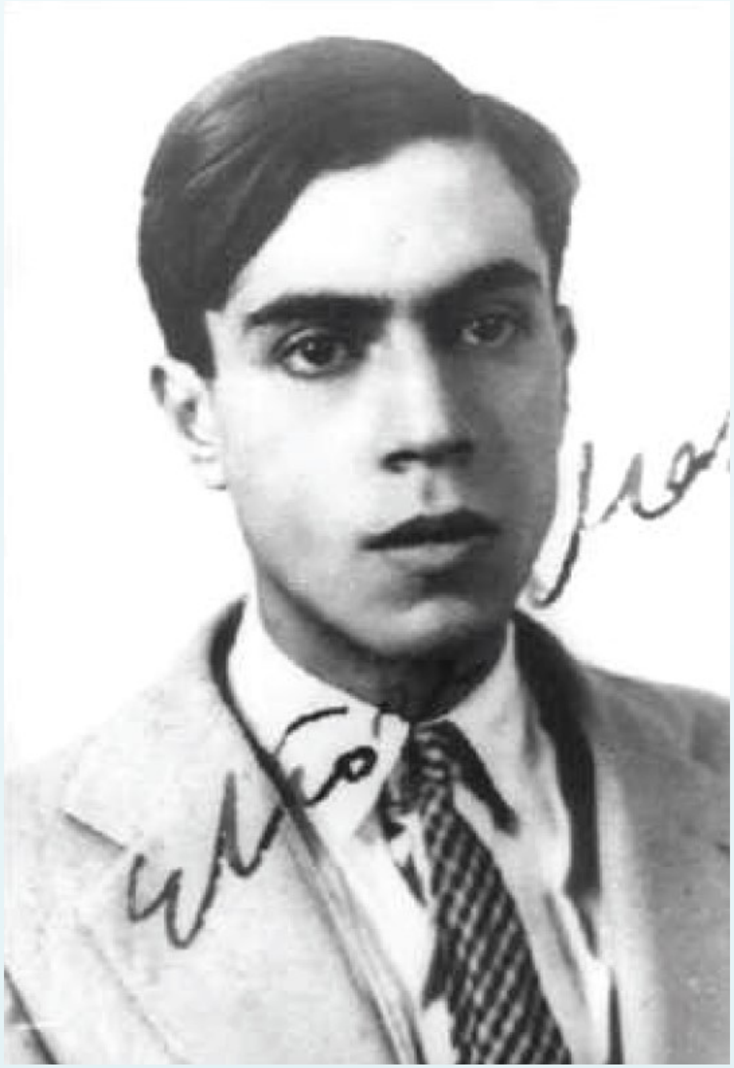
Possible practical realizations of such non-Abelian anyons: Majorana bound states



Ettore Majorana, 1906–1938(?)

A Majorana particle is it's own antiparticle

$$\nu = \bar{\nu}$$

It cannot have energy (E = 0)
It cannot have a charge degree of freedom
It cannot have a spin degree of freedom

Very well protected against decoherence,
and therefore of interest for quantum computation

Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

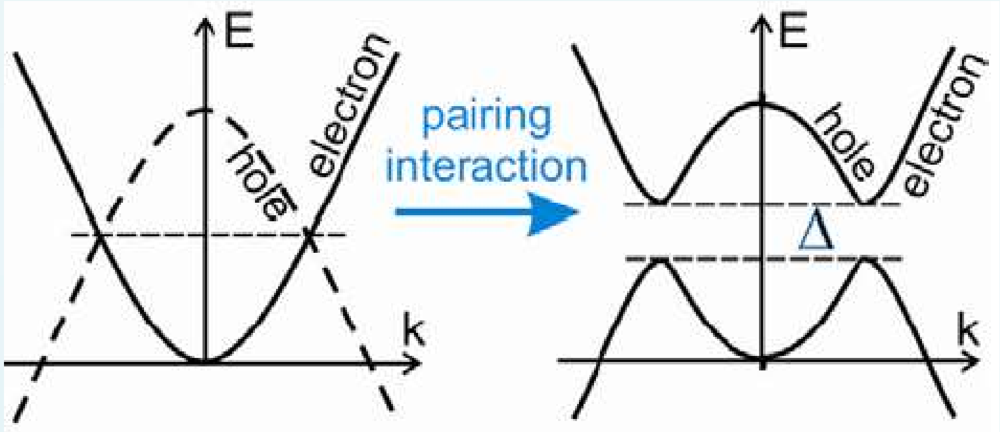
Requirements for the formation of Majorana bound states:

I: They cannot have a spin degree of freedom

Use materials in which the spin of the electrons is fixed.
Every electron can have only one spin value.

II: They cannot have a charge degree of freedom

Use the electron-hole symmetry in superconductors



III: They cannot have energy (E = 0)

Use points where gap closes (at edges or in vortex cores)

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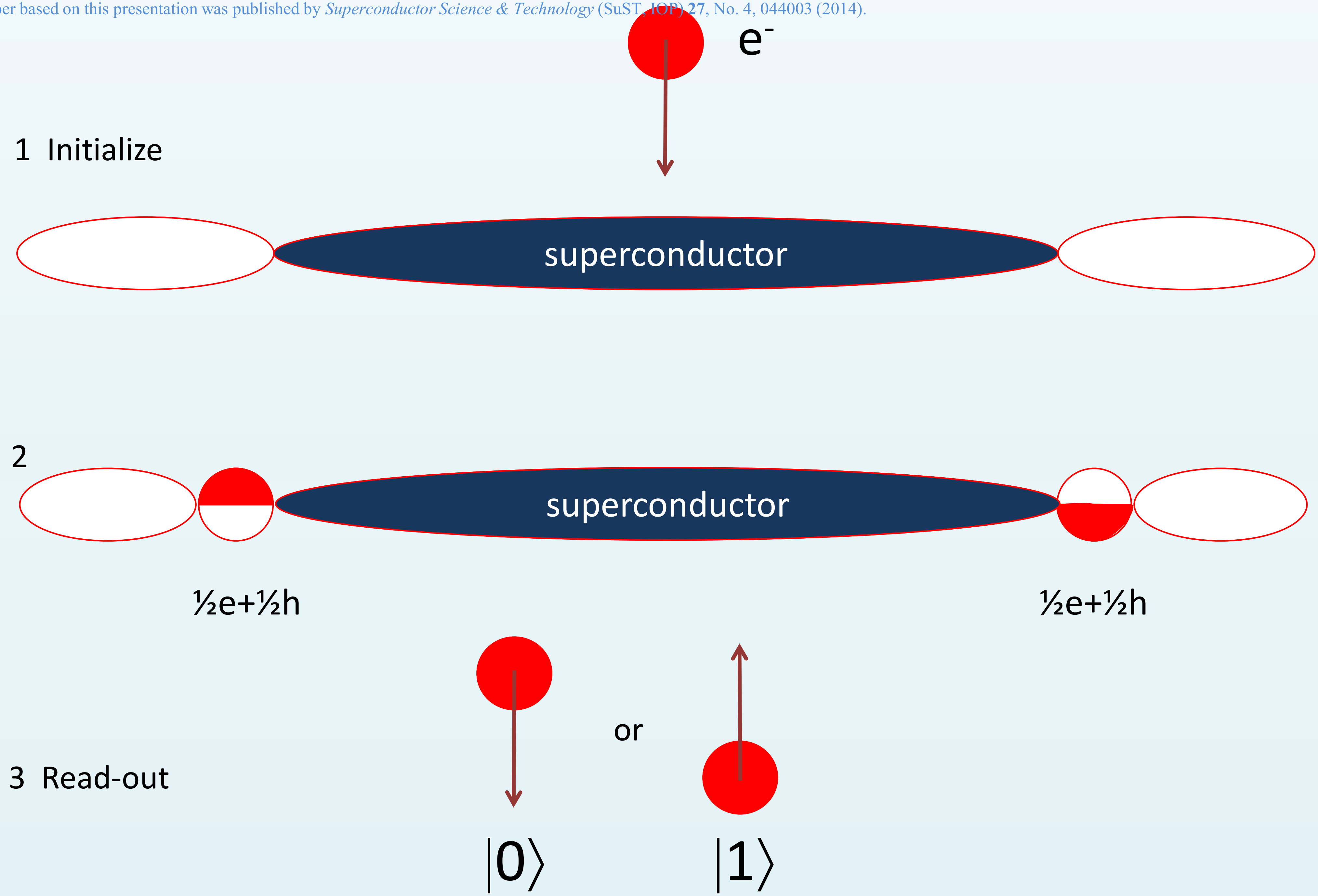

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Possible systems in which Majorana bound states can be realized

Topological (*p*-wave) superconductors ($Cu_xBi_2Se_3$, Sr_2RuO_4 ?)

➔ Superconductors + topological insulators

Superconductors + semiconductors + magnetic fields

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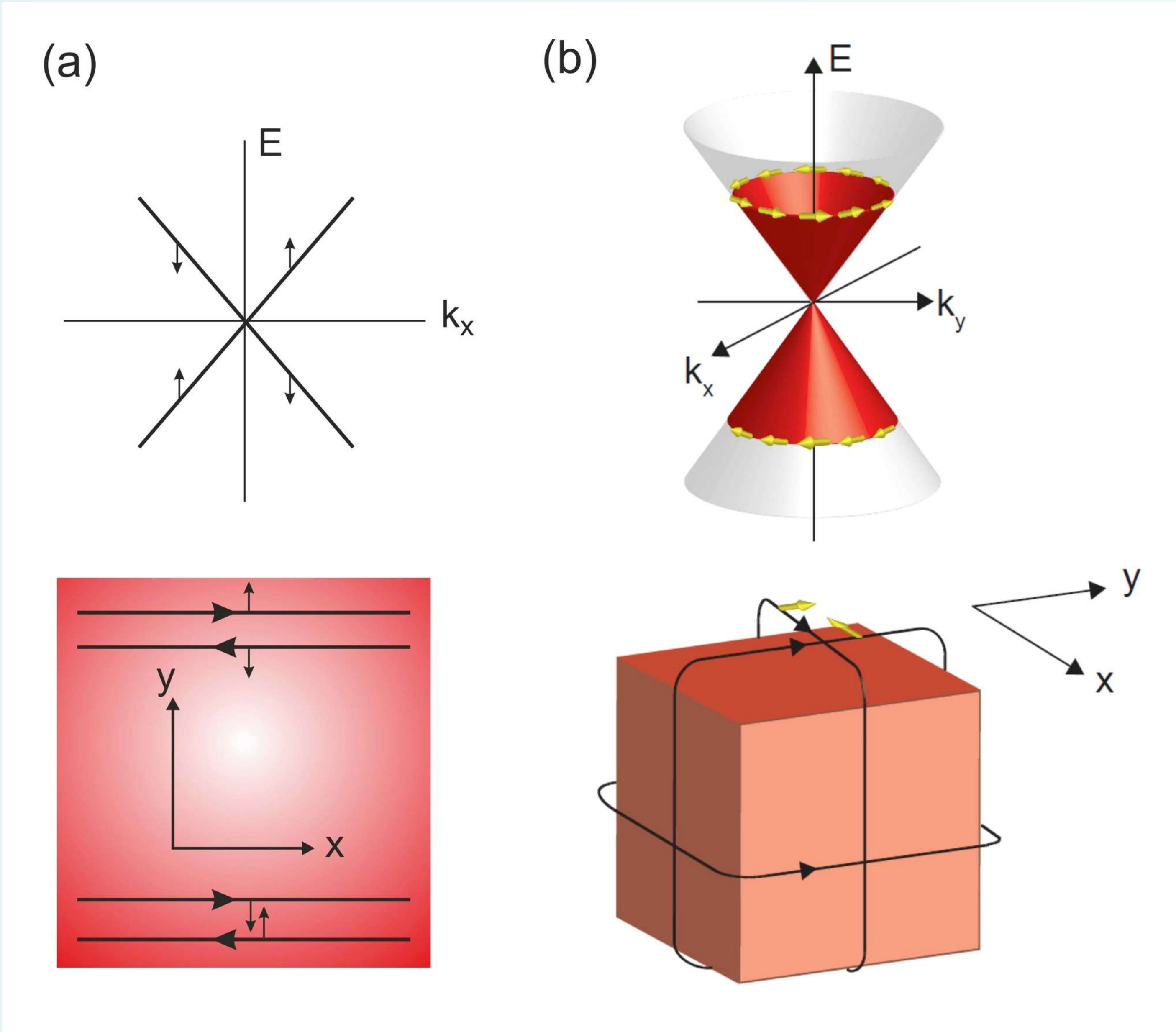
2D and 3D topological insulators



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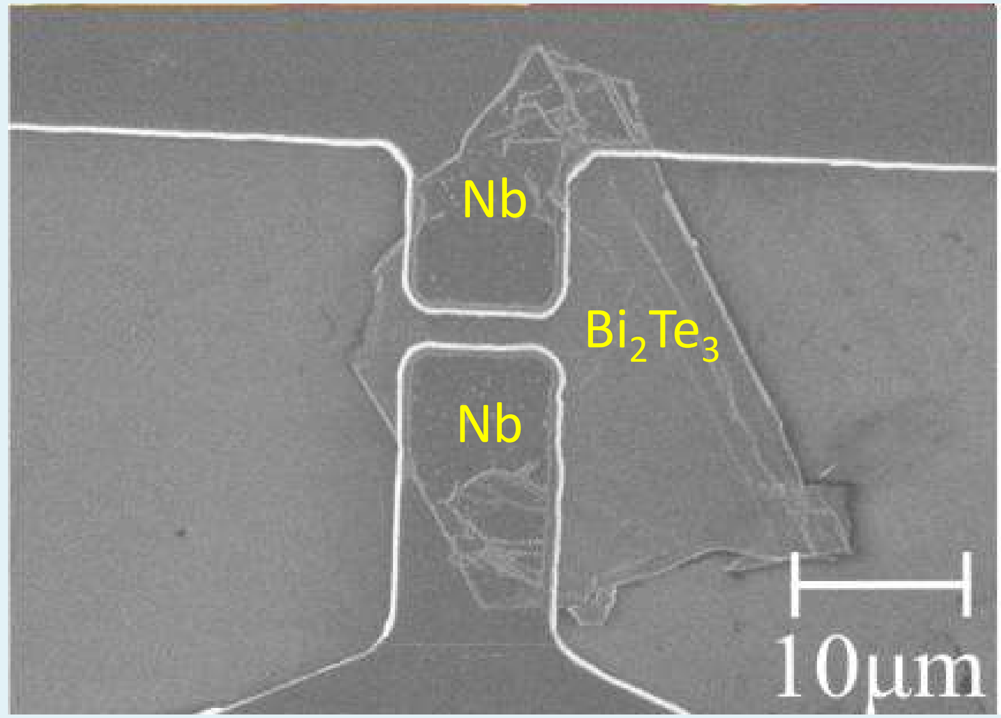
Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

Coupling superconductors to topological insulators



M. Veldhorst[1], M. Snelder[1], M. Hoek[1], T. Gang[1], X. L. Wang[3], V. K. Guduru[2], U. Zeitler[2], W. v.d. Wiel[1], A. A. Golubov[1], H. Hilgenkamp[1,4], A. Brinkman[1]

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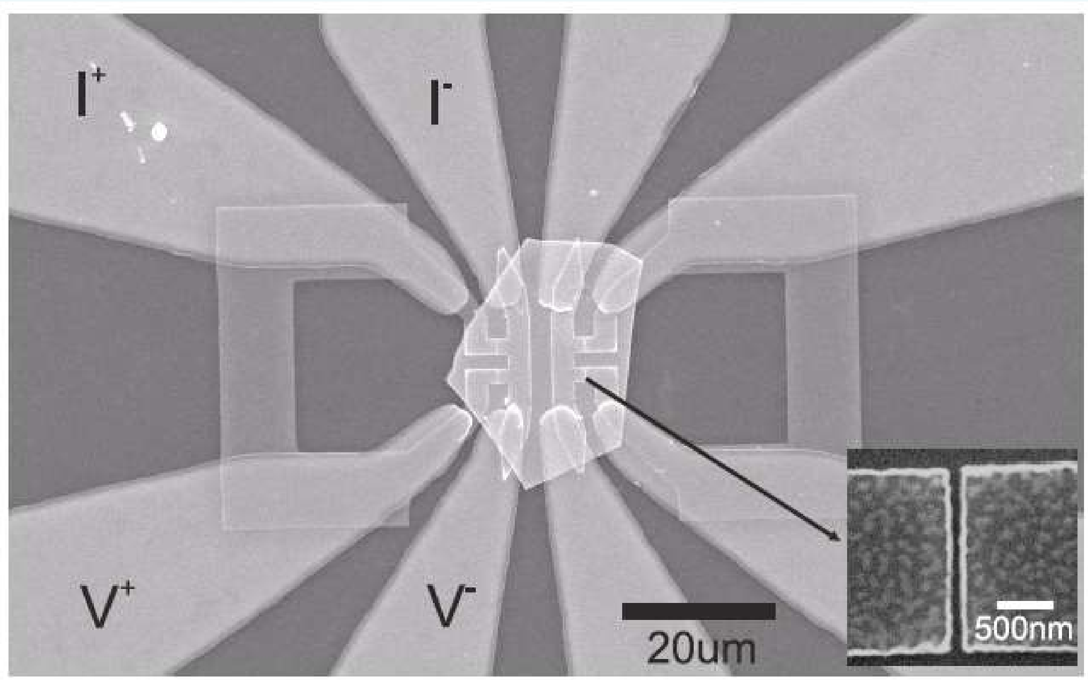
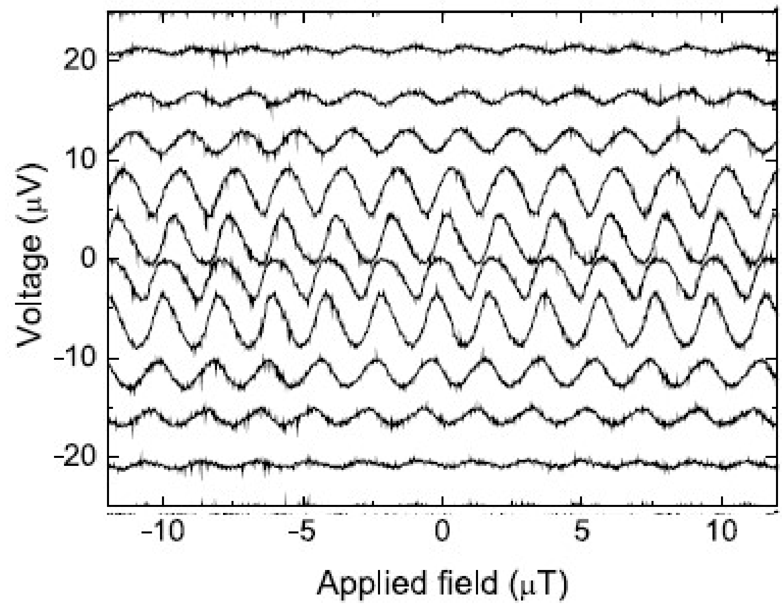
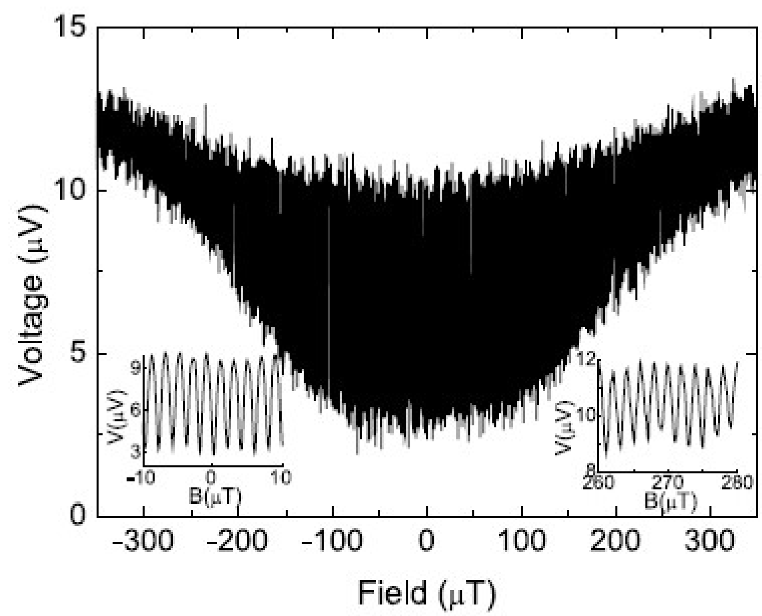
SQUID Modulation







Experimental realization of superconducting quantum interference devices with topological insulator junctions

M. Veldhorst, C.G. Molenaar, X.L. Wang, H. Hilgenkamp, and A. Brinkman
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See also: M. Veldhorst et al., *PRB* (2012)

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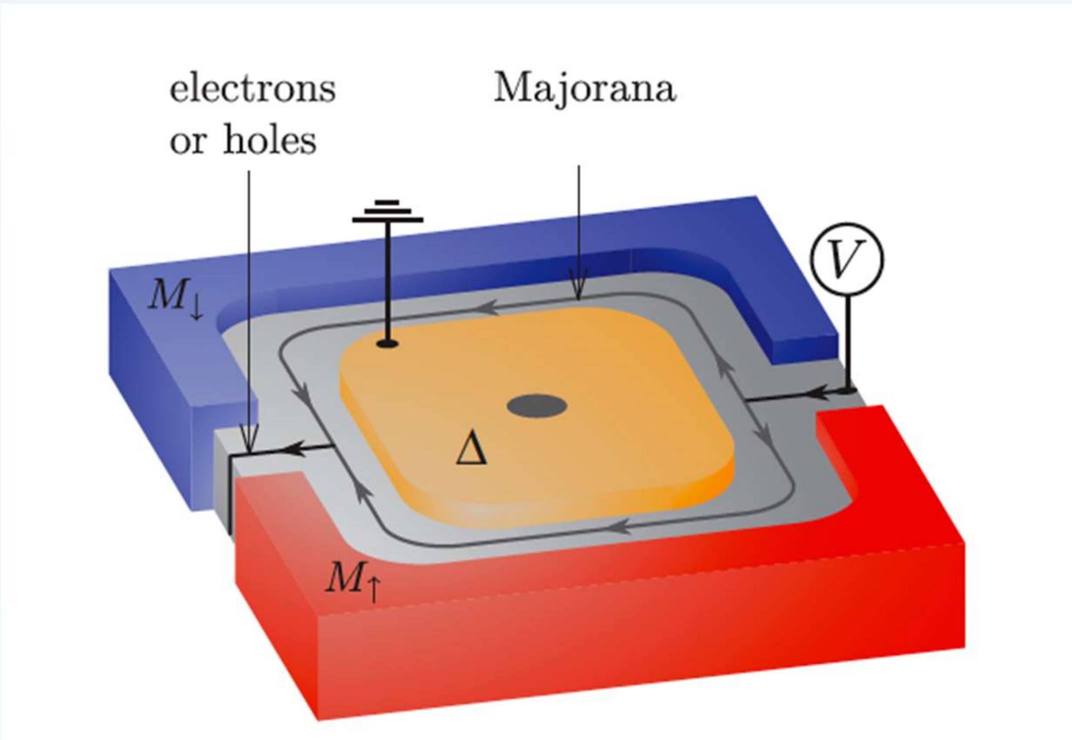
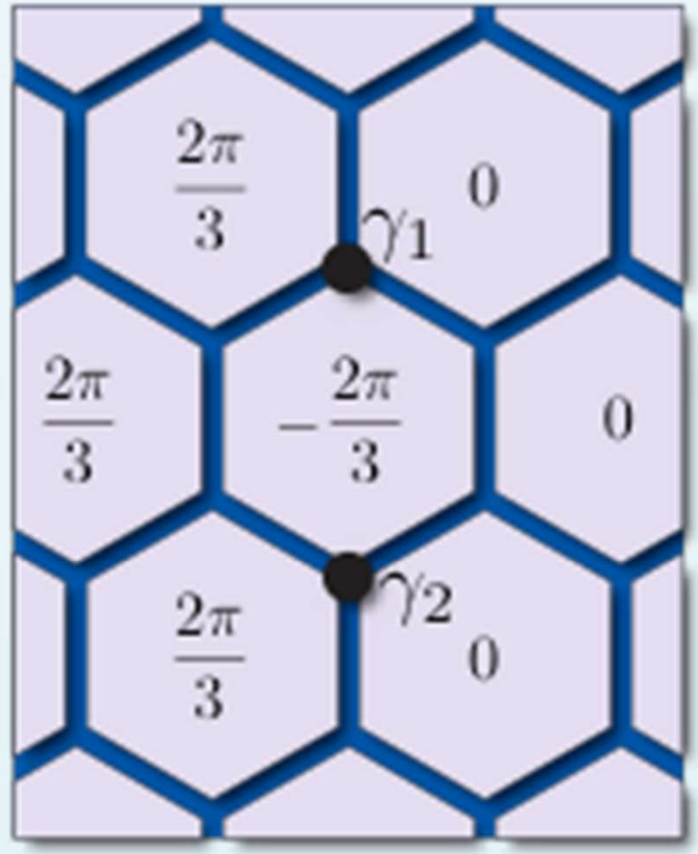
Creating and manipulating Majorana bound states in 3D Ti – Superconducting structures





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Possible systems in which Majorana bound states can be realized

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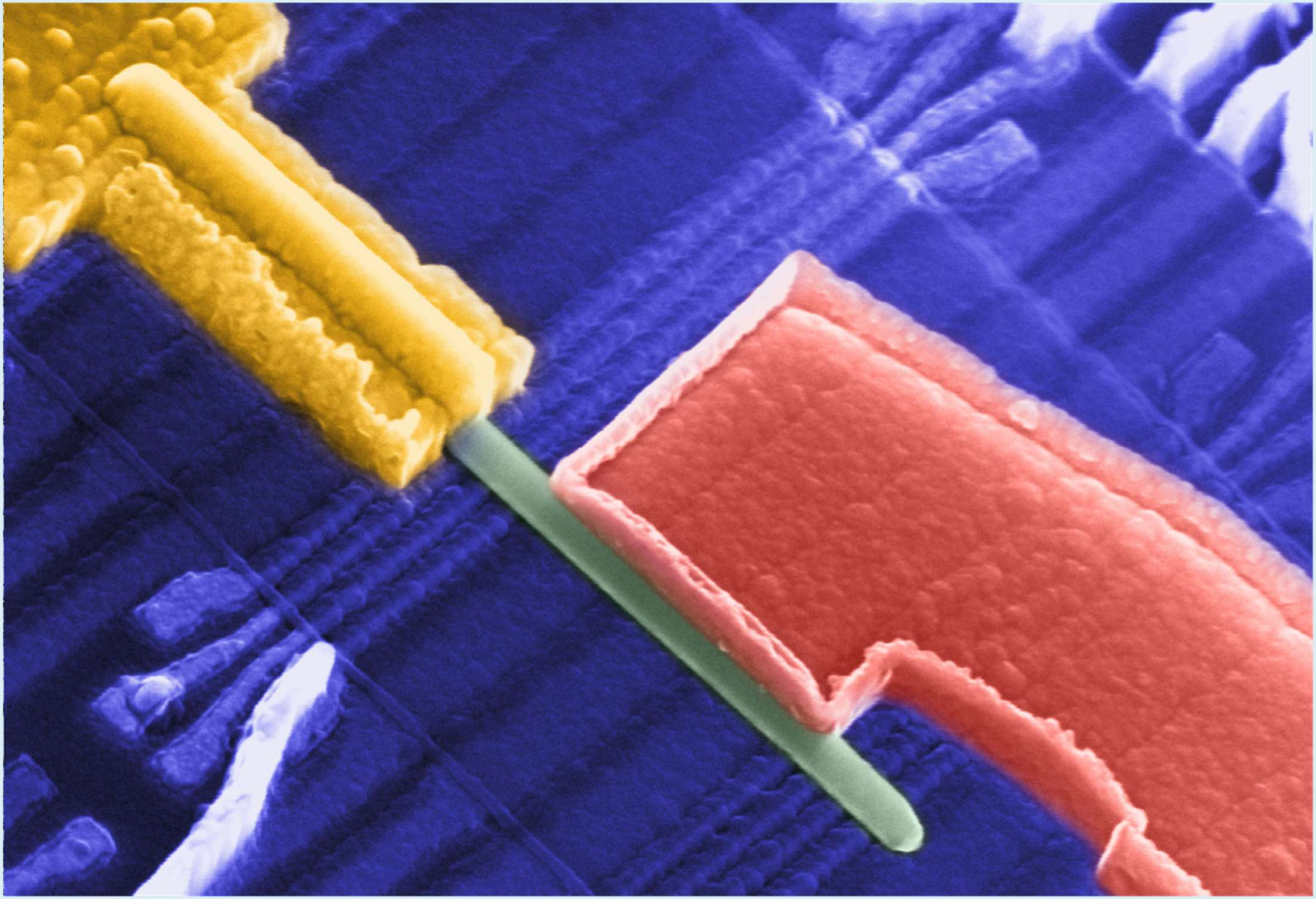

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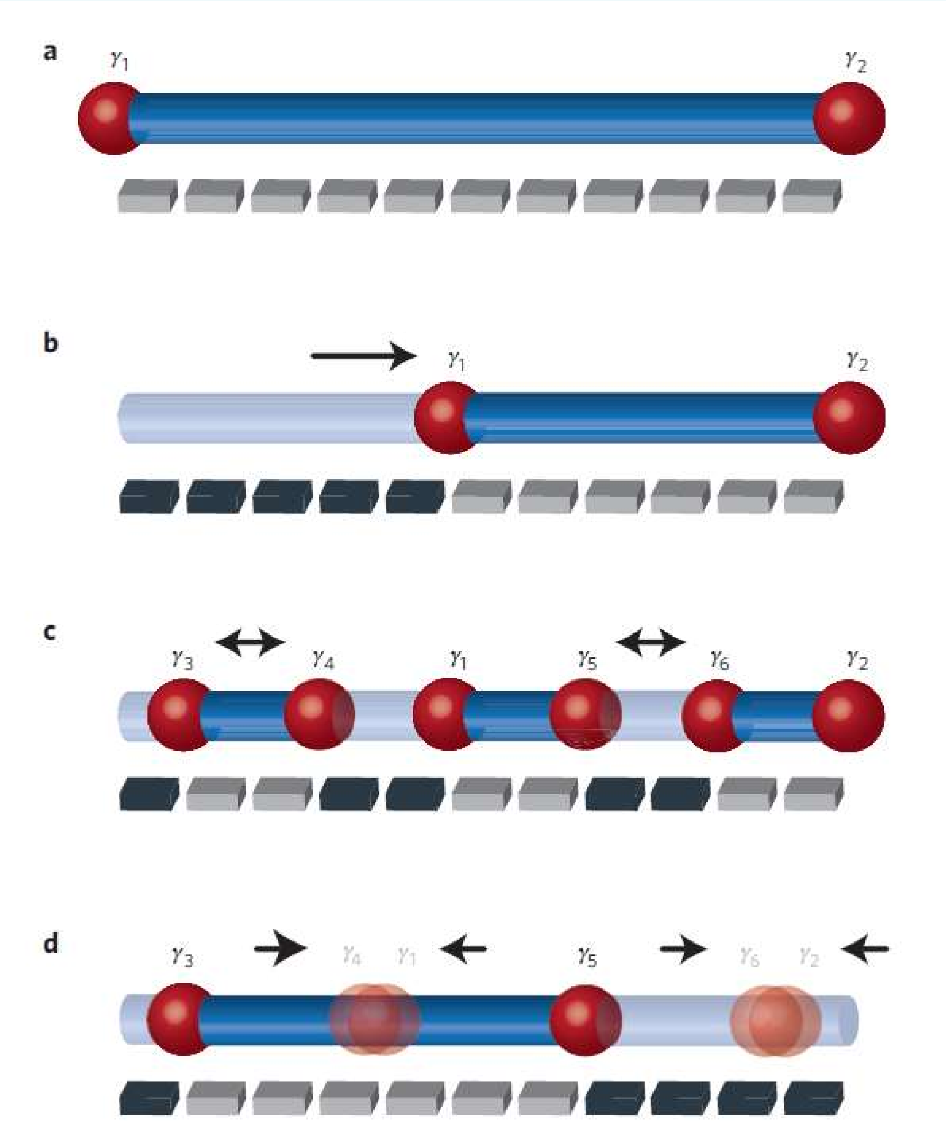
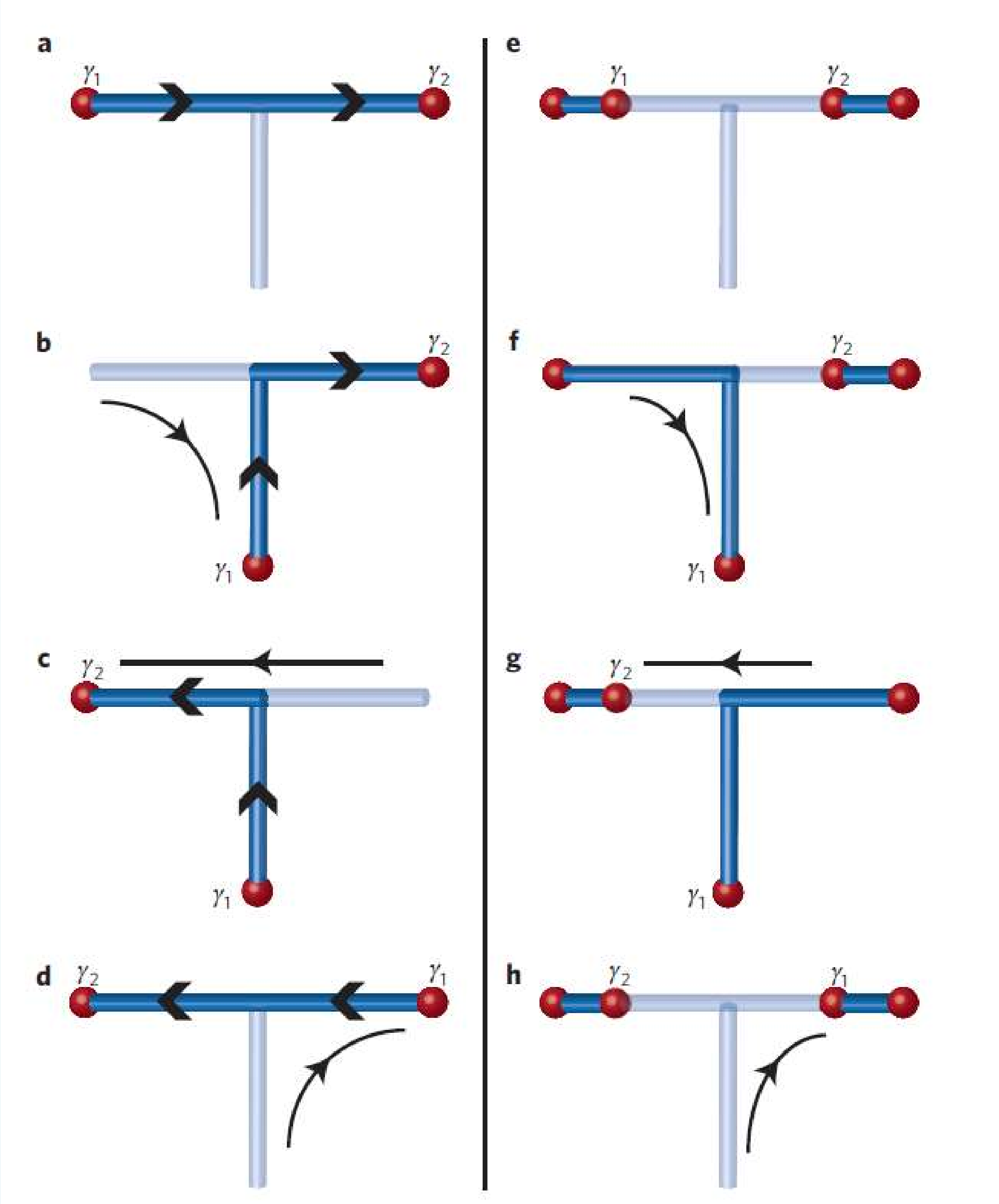
Braiding operations in nanowire-based systems





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Paper based on this presentation was published by *Superconductor Science & Technology* (SuST, IOP) **27**, No. 4, 044003 (2014).

Conclusions:

Topology has been a key topic in applied superconductivity already for a long time.

Great current attention due to developments on topological insulators and Majorana's, in which superconductivity already plays a pivotal role.

Further developments on topological quantum computation to be expected, which may help to overcome decoherence problems.

But also with that, there is still a long way to go for quantum computers.

Time, patience, and devotion ...