Applied Superconductivity

Josephson Effects, Superconducting Electronics, and Quantum Circuits

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Lecture Notes
Summer Semester 2020

R. Gross and K. Fedorov

"Superconductivity and Low Temperature Physics"

The following lectures are offered on a regular basis:

1. **Superconductivity and Low Temperature Physics I (WS)**
   → Foundations of Superconductivity

2. **Superconductivity and Low Temperature Physics II (Thursday 12:00, HS 3)**
   → Foundations of Low Temperature Physics and Techniques

3. **Applied Superconductivity (Mon 14:15\ Wed 14:15)**
   → Josephson-Effects, Superconducting Electronics, Quantum Circuits

4. **Tutorial for Applied Superconductivity (Wednesday 16:00, WMI Raum 128)**

5. **Several Seminars (see announcements)**

   Advances in Solid-State Physics
   Tue. 10:15 – 11:30h
   Seminar room 128, WMI

   Superconducting Quantum Circuits
   Tue. 14:30 – 16:00h
   Library, WMI

Documents and Hints (download):

http://www.wmi.badw.de → Teaching → Lecture notes
download available lecture notes and slides

Contents of Lecture

Contents of Lecture

II Applications of the Josephson Effect

4 SQUIDs

4.1 The dc-SQUID
4.2 The rf-SQUID
4.3 Additional Topic: Other SQUID Configurations
4.4 Instruments Based on SQUIDs
4.5 Applications of SQUIDs

5 Digital Electronics

5.1 Superconductivity and Digital Electronics
5.2 Voltage State Josephson Logic
5.3 RSFQ Logic
5.4 Analog-to-Digital Converters

Contents of Lecture

III Superconducting Quantum Circuits

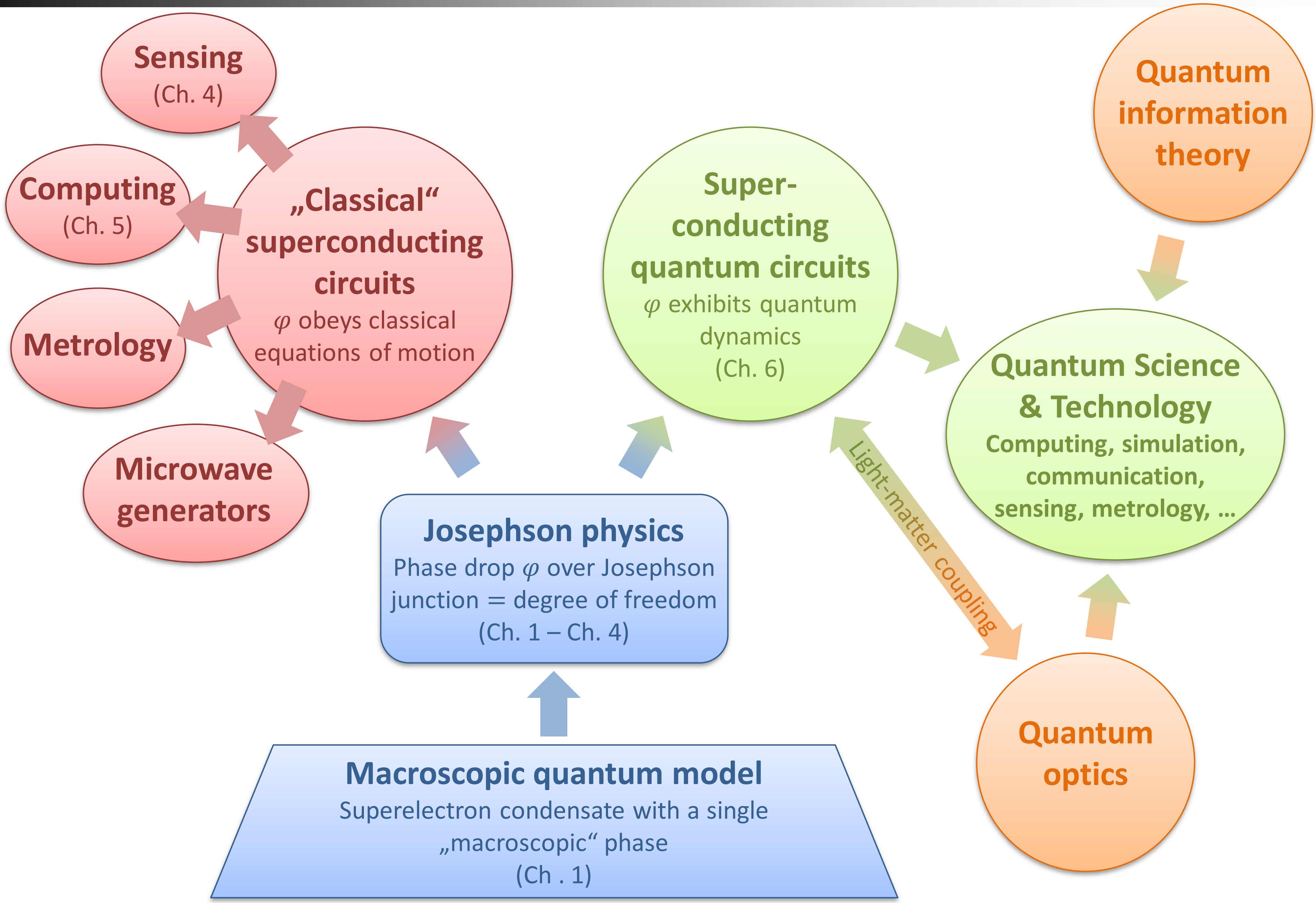
6 Superconducting Quantum Circuits

Bibliography

- Werner Buckel, Reinhold Kleiner,
  Supraleitung – Grundlagen und Anwendungen
  VCH-Verlag, Weinheim (2012).
- R. Gross, A. Marx
  Festkörperphysik, Oldenbourg-Verlag (2012).
- V. V. Schmidt,
  The physics of superconductors
  Springer (1997).
- M. Tinkham,
  Introduction to Superconductivity
  McGraw-Hill, New York (1975).
- K. K. Likharev,
  Dynamics of Josephson Junctions and Circuits
  Gordon and Breach Science Publishers, New York (1986).
- T. P. Orlando, K. A. Delin,
  Foundations of Applied Superconductivity
  Addison-Wesley, New York (1991).
- Lecture notes & slides: R. Gross, A. Marx, http://www.wmi.badw.de/teaching/Lecturenotes/index.html
- M. A. Nielsen, I. L. Chuang
  Quantum Computation and Quantum Information
  Cambridge University Press
- D. E. Walls, G. J. Milburn
  Quantum Optics
  2nd edition, Springer

Introduction

Applied Superconductivity



Superconducting Technology

Microwave Technology
Filters, antennas, cavities
mixers, sources, receivers

Electronics
Sensors (e.g. SQUIDs), RSFQ Logic, quantum electronics (computing, simulation, communication etc.)

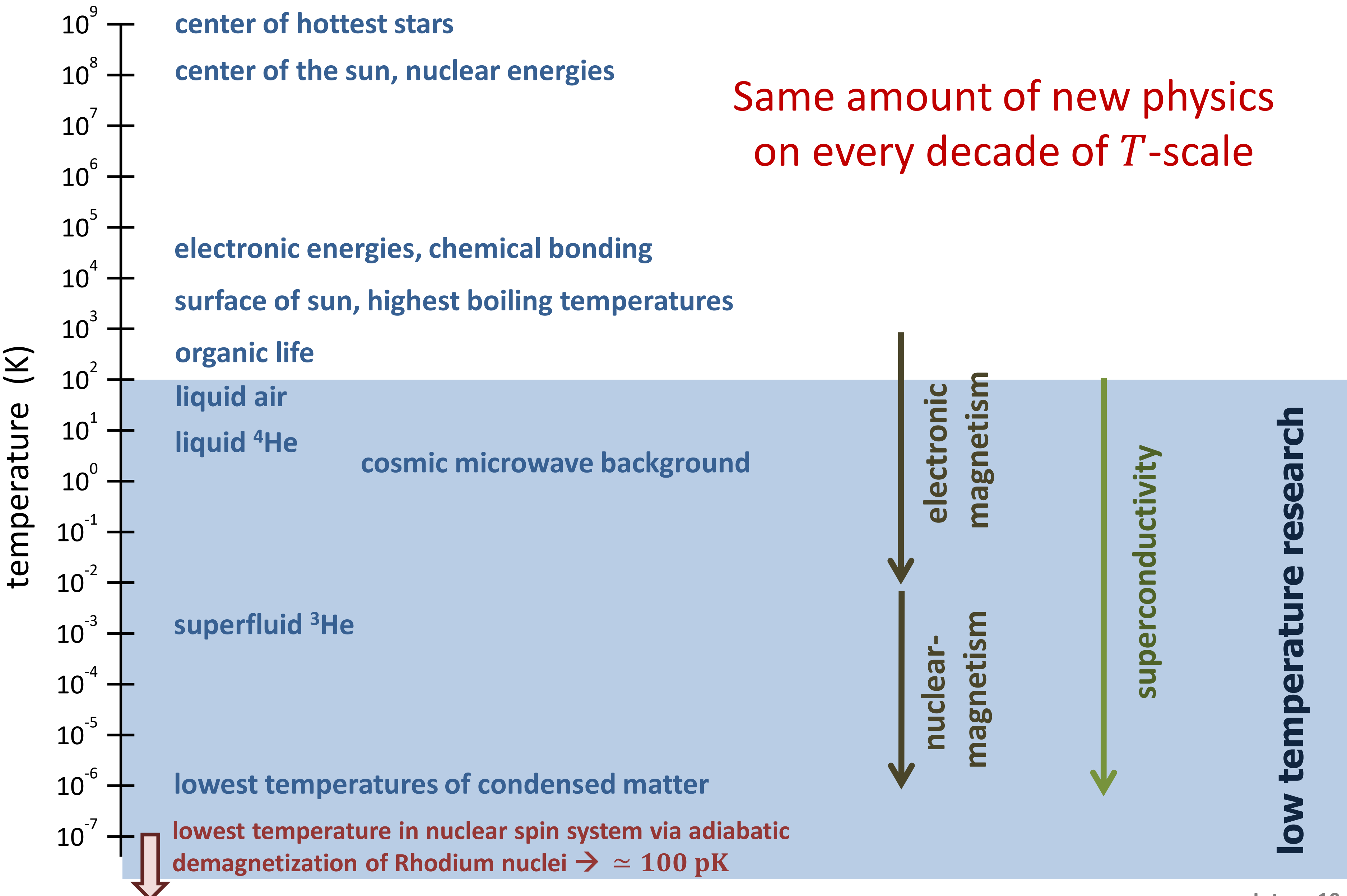
Traffic
Ship motors, Superconducting levitation trains

Medical Technology
Magnetic resonance imaging, magneto-encephalography, magneto-cardiography

Material processing
Separation of ore, water treatment

Energy Technology
Generators, motors, transformers, fault current limiters, magnetic energy storage, cables

Low temperature physics



Low Temperature Technology in Germany

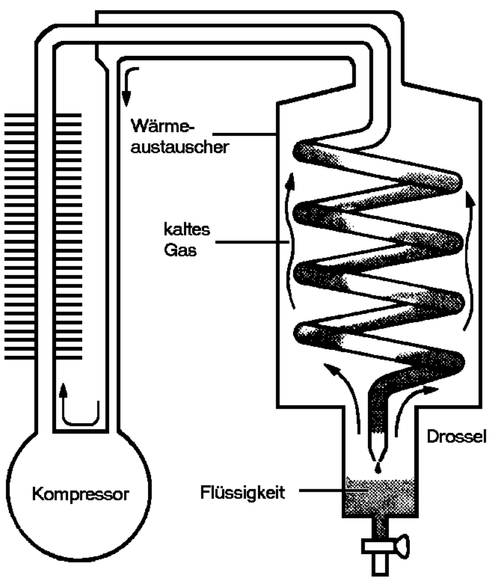
1868 Offered a chair at the Polytechnische Schule München (now TUM)

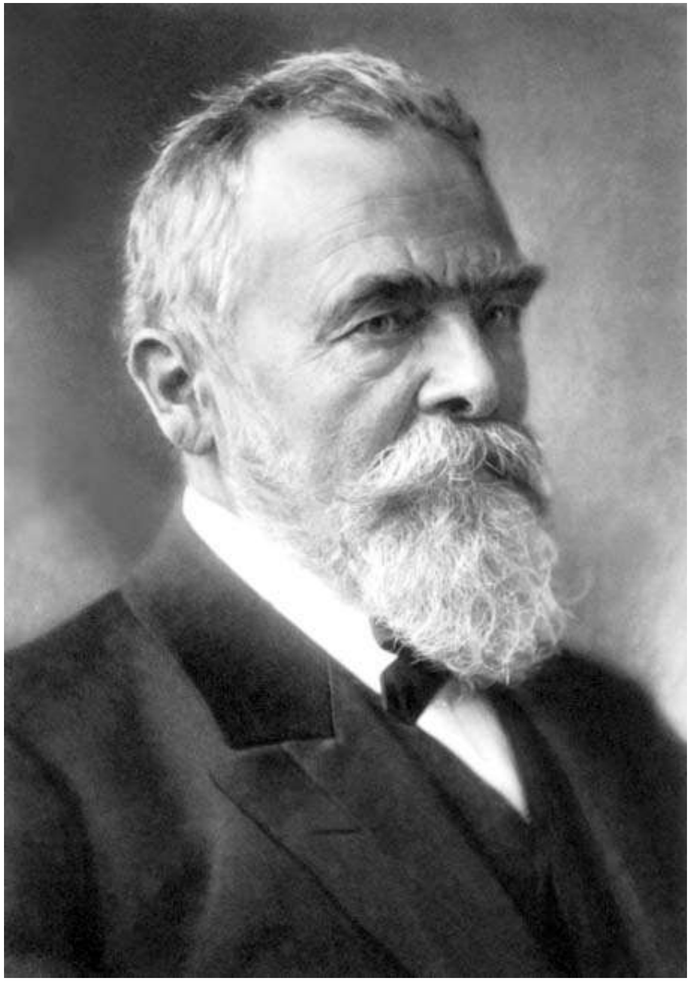
1873 Development of cooling machine allowing the temperature stabilization in beer brewing

21.6.1879 Foundation of „***Gesellschaft für Linde's Eismaschinen AG***" together with two beer brewers and three other co-founders

1892 - 1910 Re-establishment of professorship

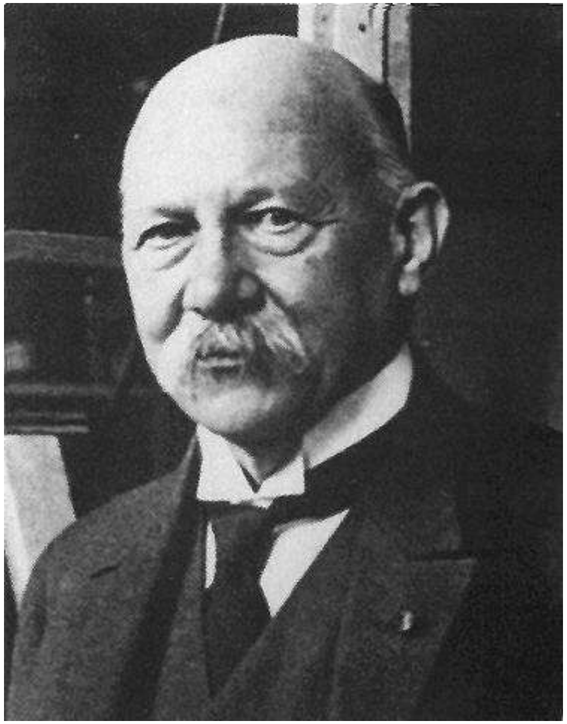
12.5.1903
patent application:
„***Lindesches Gegenstrom-verfahren***"
liquefaction of oxygen
(-182°C = 90 K)



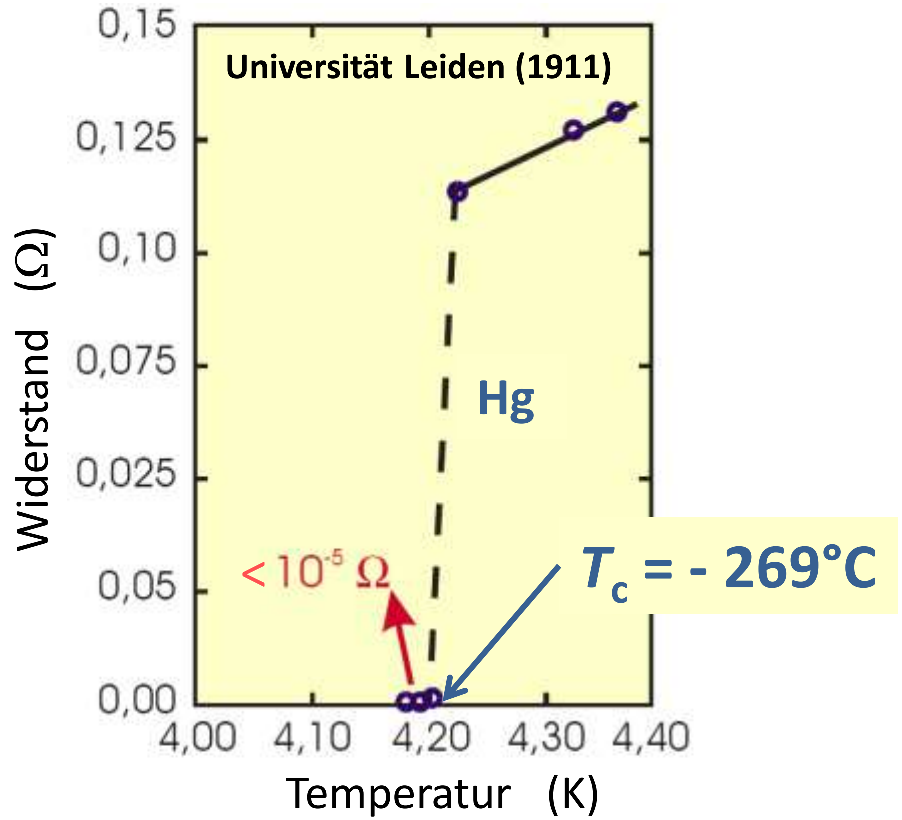


Carl Paul Gottfried von Linde
* 11. Juni 1842 in Berndorf, Oberfranken
† 16. November 1934 in Munich

Discovery of Superconductivity (1911)



Heike Kammerlingh Onnes (1853-1926)



H. K. Onnes, Comm. Leiden 120b (1911)

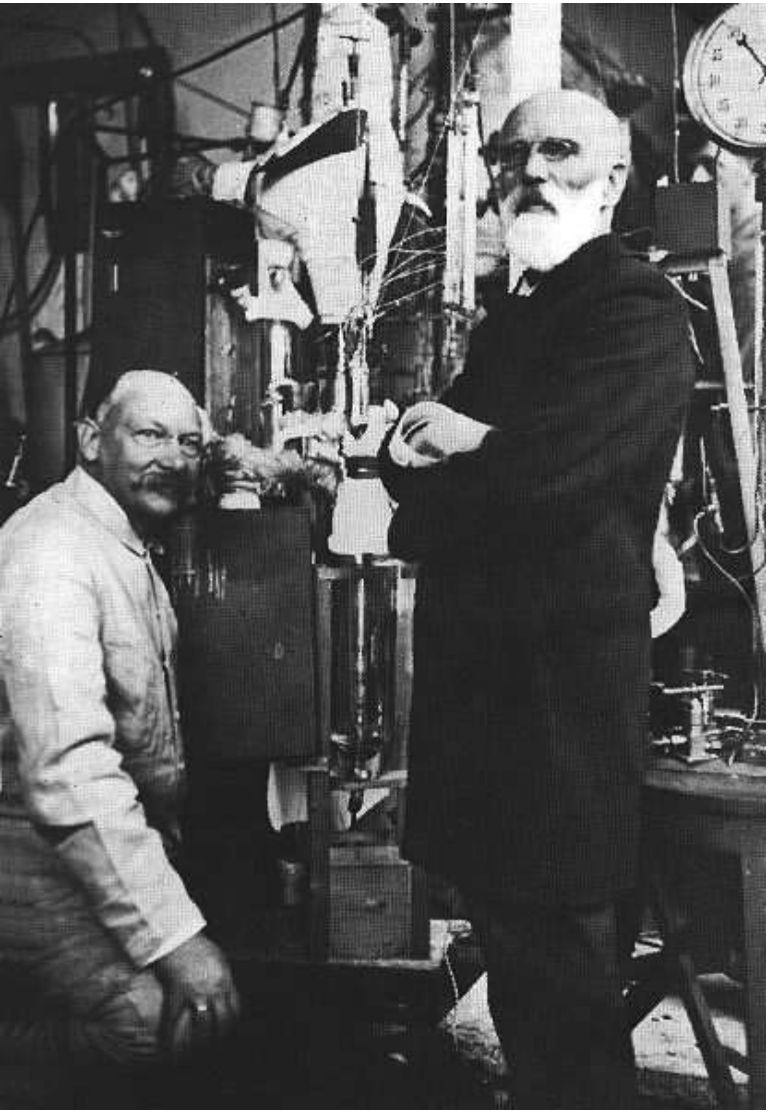
- Helium liquefaction: 1908
- discovery of superconductivity: 1911

Nobel Prize in Physics 1913

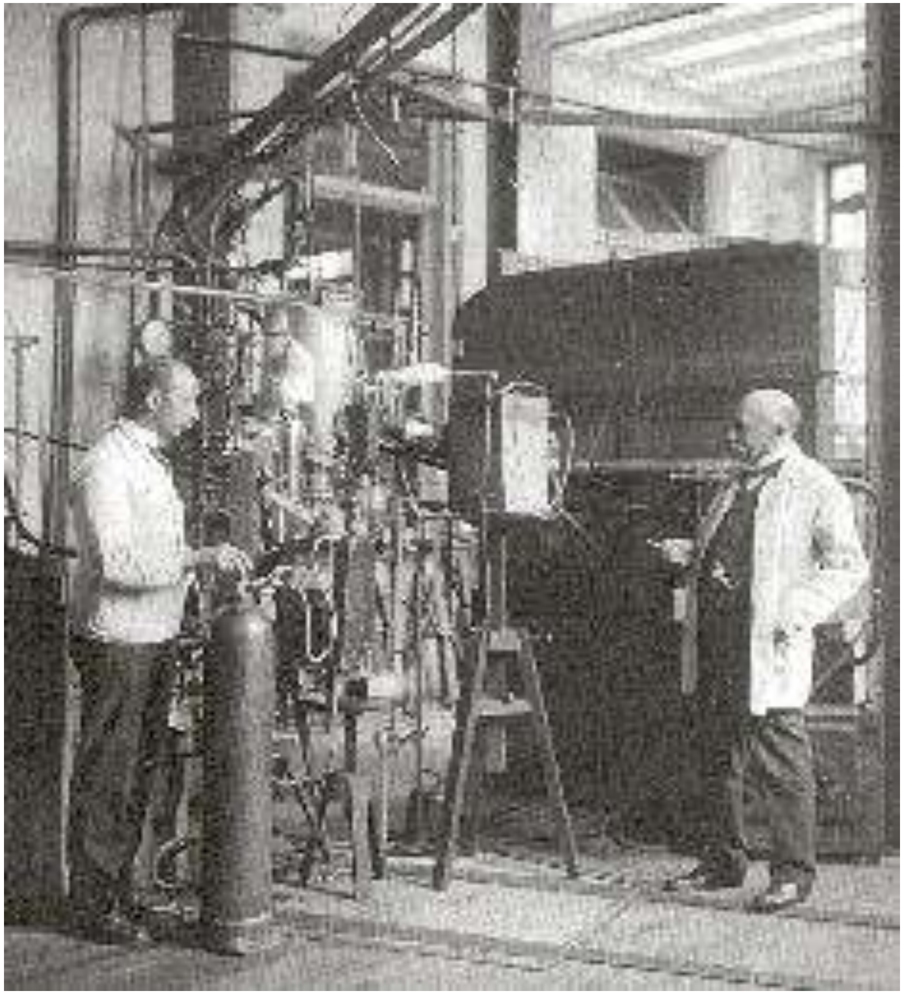
„… for his investigations on the properties of matter at low temperatures which led, inter alia to the production of liquid helium"

Infinite electrical conductivity → „Superconductivity"

Discovery of Superconductivity (1911)



Kammerlingh Onnes and van der Waals



Kammerlingh Onnes and technician Flim

Walther Meißner (1882 – 1974)

1913 – 1934
Building and heading of low temperature laboratory at the Physikalisch-Technischen-Reichsanstalt, liquefaction of H_2 (20K)

7.3.1925 First liquefaction of He in Germany (4.2 K, 200 ml), 3rd system world-wide besides Leiden and Toronto

1933 Discovery of perfect diamagnetism of superconductors together with Ochsenfeld
→ **Meißner-Ochsenfeld Effect**

1934 offer of chair at the Technische Hochschule München (now TUM)

1946 – 1950
president of the Bayerischen Akademie der Wissenschaften

1946 foundation of the commission for Low Temperature Research
→ **Walther-Meißner-Institut**

Walther Meißner

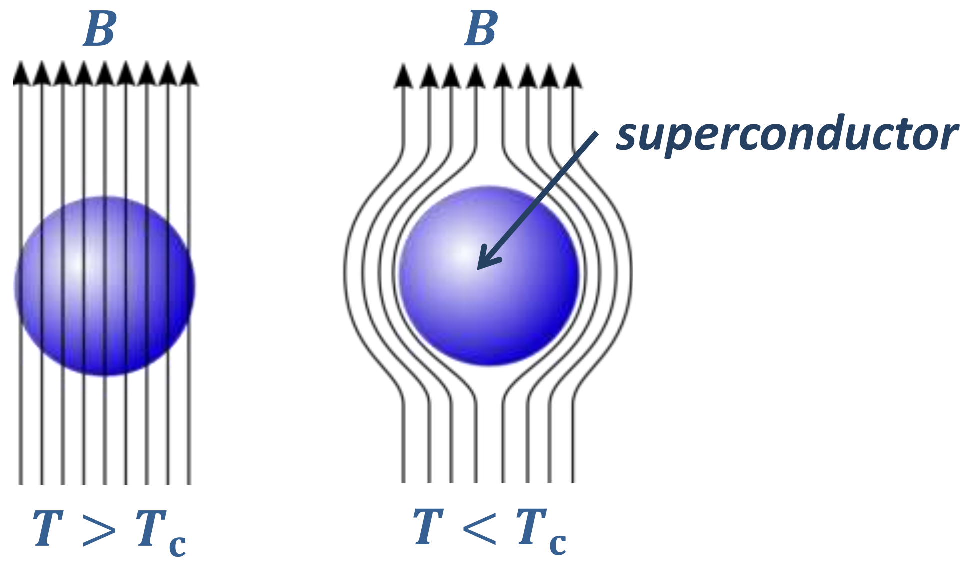
* 16. Dezember 1882 in Berlin

† 15. November 1974 in Munich

Walther Meißner - der Mann, mit dem die Kälte kam
W. Buck, D. Einzel, R. Gross, Physik Journal, Mai 2013

Discovery of the Meißner-Ochsenfeld Effect (1933)

Walther Meißner (1882 – 1974)



Superconductors perfectly expel magnetic field

$$B_{\text{in}} = (1+\chi)\, B_{\text{ex}} = 0$$

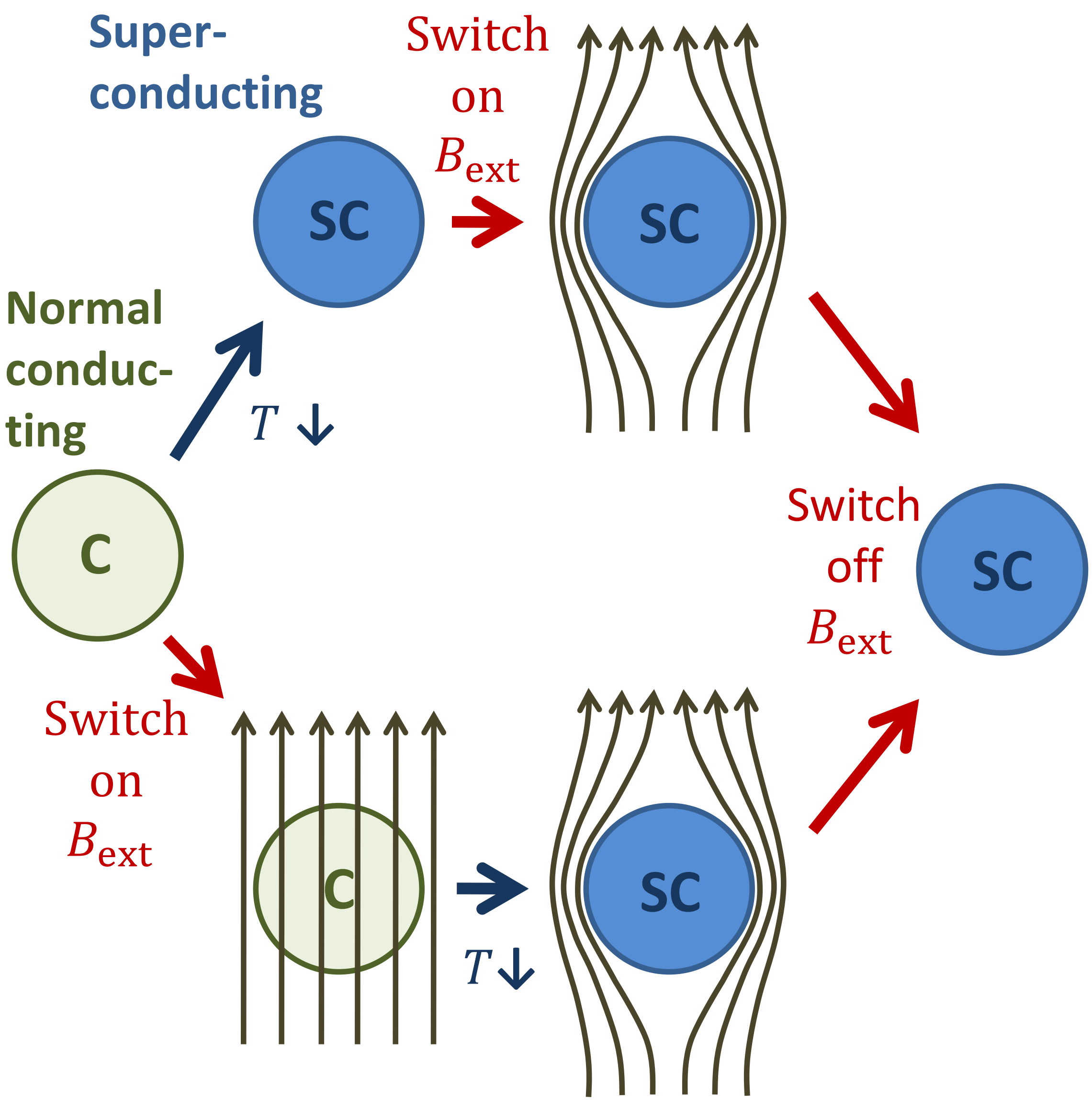
→ **Perfect diamagnetism, $\chi = -1$**

(χ = magnetic susceptibility)

→ Meißner-Ochsenfeld effect

WMI

Superconductor in magnetic field



Path-independent final state of the superconductor

Superconducting state is a thermodynamic phase

Meißner-Ochsenfeld-Effect (Perfect diamagnetism)

1935 **Fritz and Heinz London**

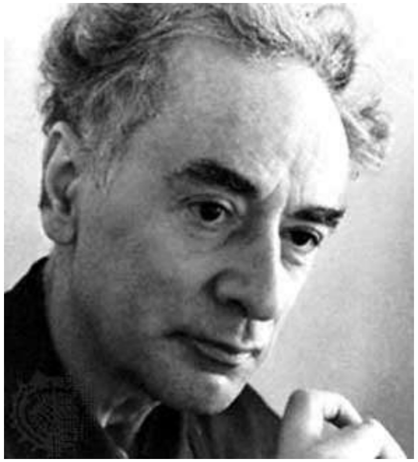
first „quantum mechanical“ theory of superconductivity (phenomenological)

→ Macroscopic wave function

→ London equations

Fritz London
(1900 – 1954)

Ginzburg-Landau Theory (1952)



Lev Landau

Nobel Prize 1962

Vitaly Ginzburg

Nobel Prize 2003

Alexei Abrikosov

Nobel Prize 2003

Lev Davidovich Landau

Nobel Prize in Physics 1962

„… for his pioneering theories for condensed matter, especially liquid helium"

Vitaly Ginzburg, Alexei Abrikosov

Nobel Prize in Physics 2003

(together with Anthony Leggett)

"… for their pioneering contributions to the theory of superconductors and superfluids"

Microscopic (BCS) Theory (1957)

J. Bardeen

L. N. Cooper

R. Schrieffer

Nobel Prize in Physics 1972

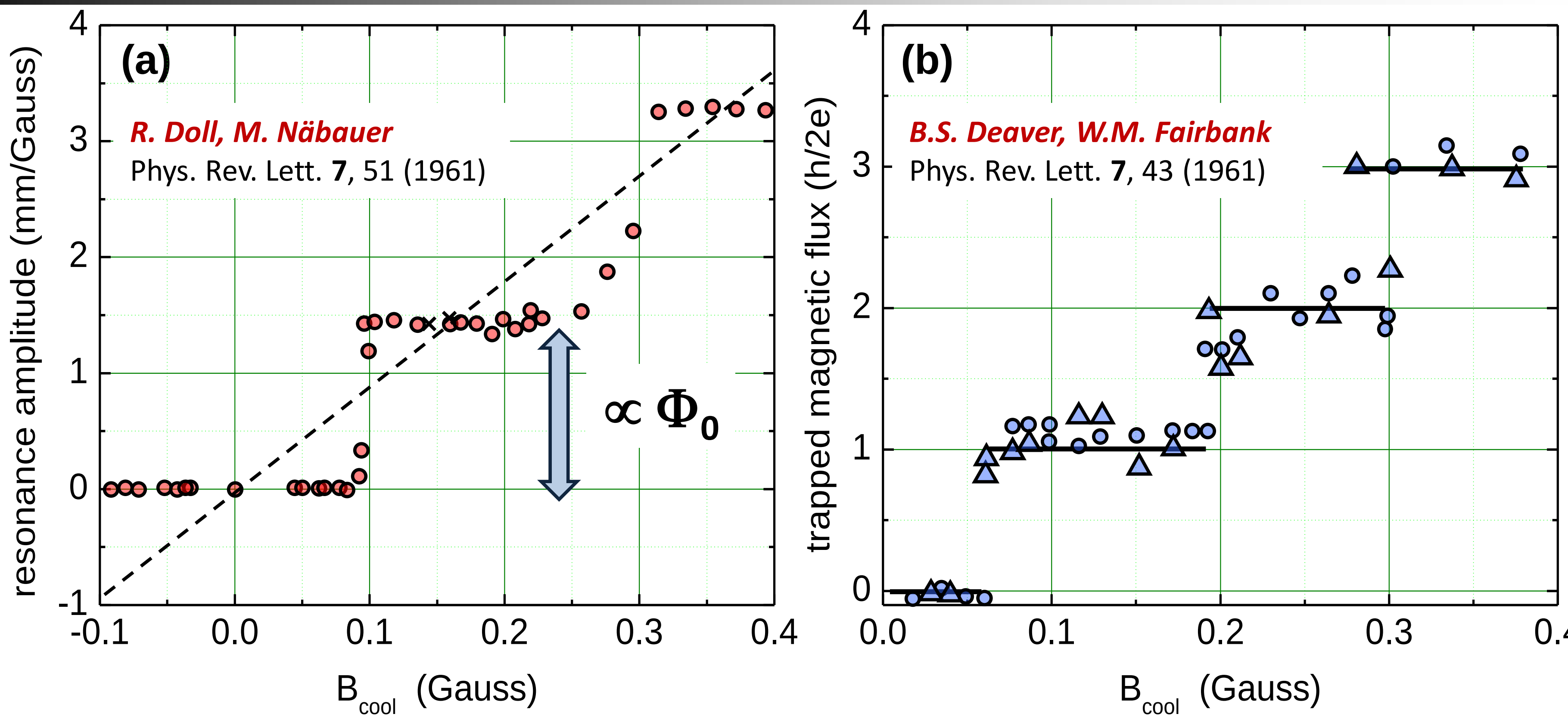
„… for their jointly developed theory of superconductivity, usually called the BCS-theory"

Flux Quantization (1961)

- **Robert Doll**
  Martin Näbauer
  (Wather-Meißner-Institut)

- **Bascom S. Deaver**
  William Martin Fairbanks
  (Stanford University)

Flux Quantization (1961)



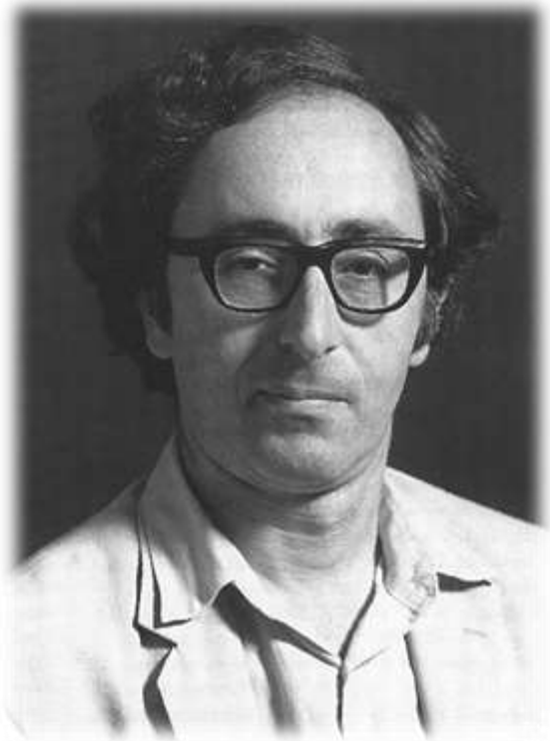
$$\Phi_0 = \frac{h}{2e}$$

Prediction by Fritz London: h/e

→ **First experimental evidence for the existence of Cooper pairs**

Paarweise im Fluss, D. Einzel and R. Gross, Physik Journal **10**, No. 6, 45-48 (2011)

Prediction of the Josephson Effect (1962)



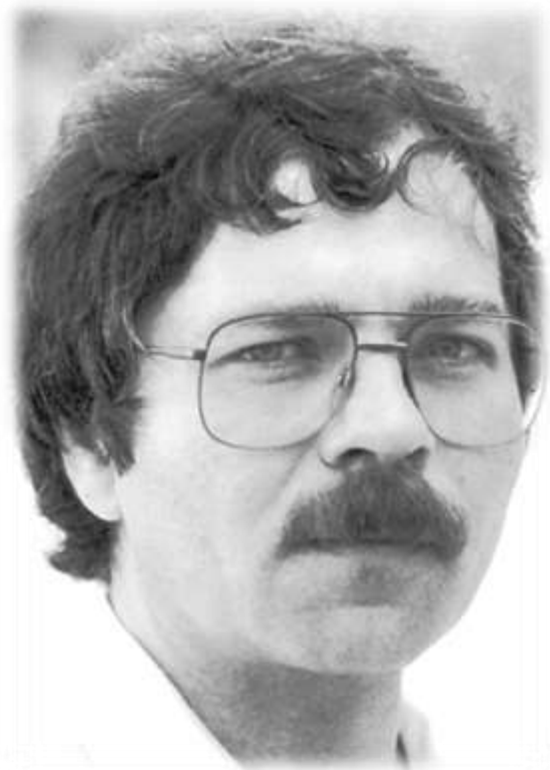
Brian David Josephson (geb. 04. 01. 1940)

Nobel Prize in Physics 1973

„... for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects"

(together with Leo Esaki and Ivar Giaever)

Discovery of high-T_c superconductivity (1986)



J. Georg Bednorz (b. 1950)

K. Alexander Müller (b. 1927)

Nobel Prize in Physics 1987

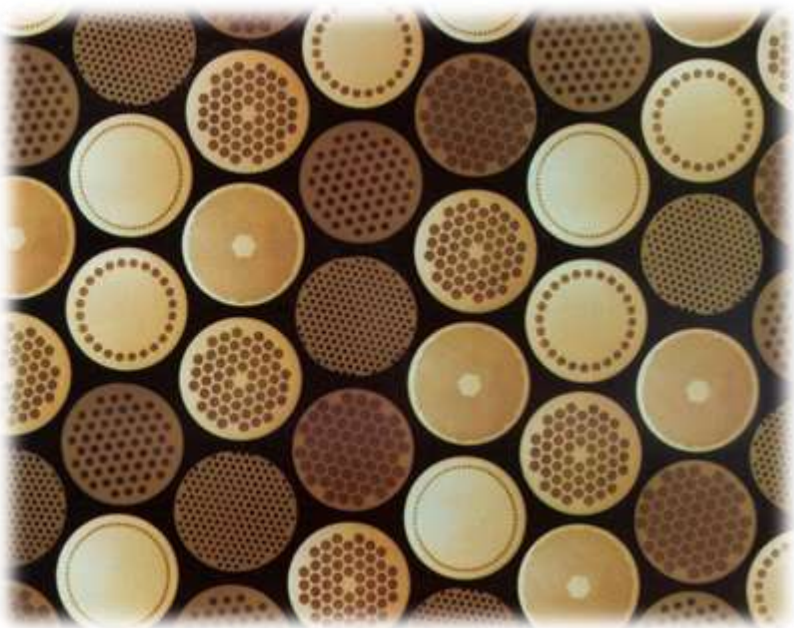
„… for their important breakthrough in the discovery of superconductivity in ceramic materials"

Discovery of high-T_c superconductivity (1986)

Karl Alexander Müller
*20. April 1927 in Basel

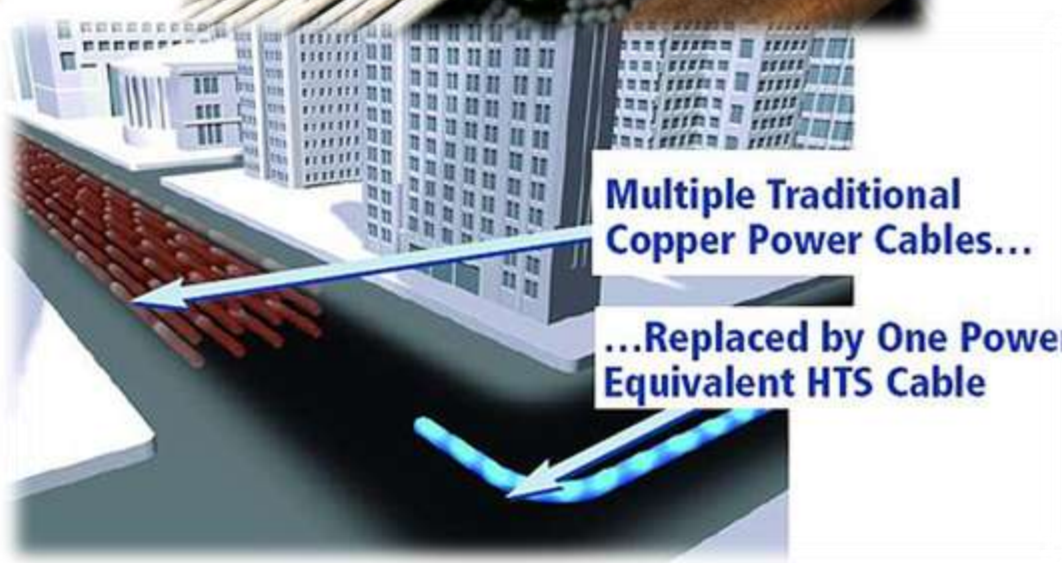
Johannes Georg Bednorz
* 16. Mai 1950 in Neuenkirchen
im Kreis Steinfurt

Superconducting Wires, Tapes, and Cables



Superconducting Wires:
NbTi, Nb_3Sn in Cu-matrix

HTS tapes

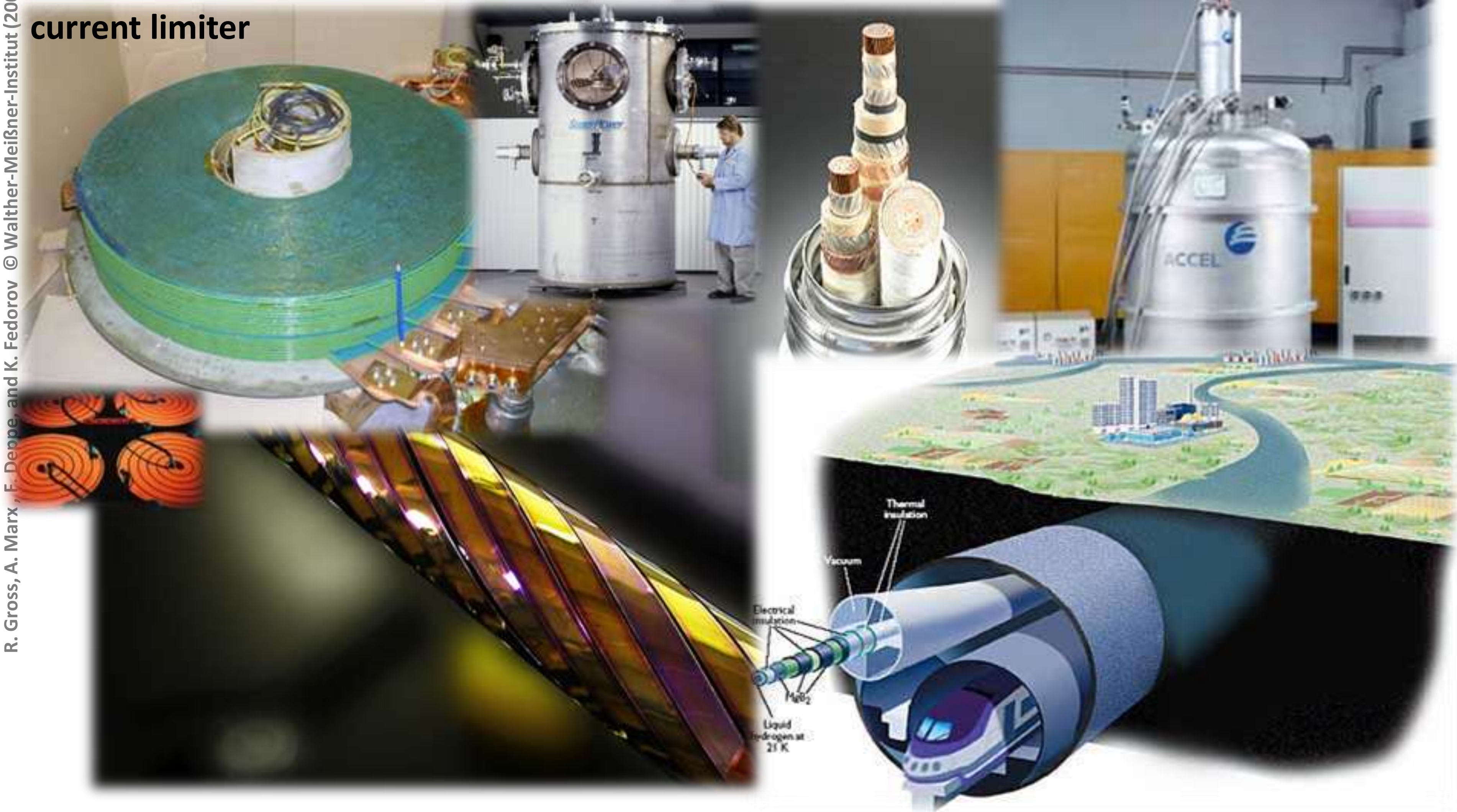


Applications of superconductivity

- ***power applications*** *(transport and storage of energy)*

current limiter

energy storage (2 MJ)



Fault Current Limiters

Superconducting fault current limiter in the power station Boxberg of Vattenfall

(Source: Physik Journal 6, 2011)

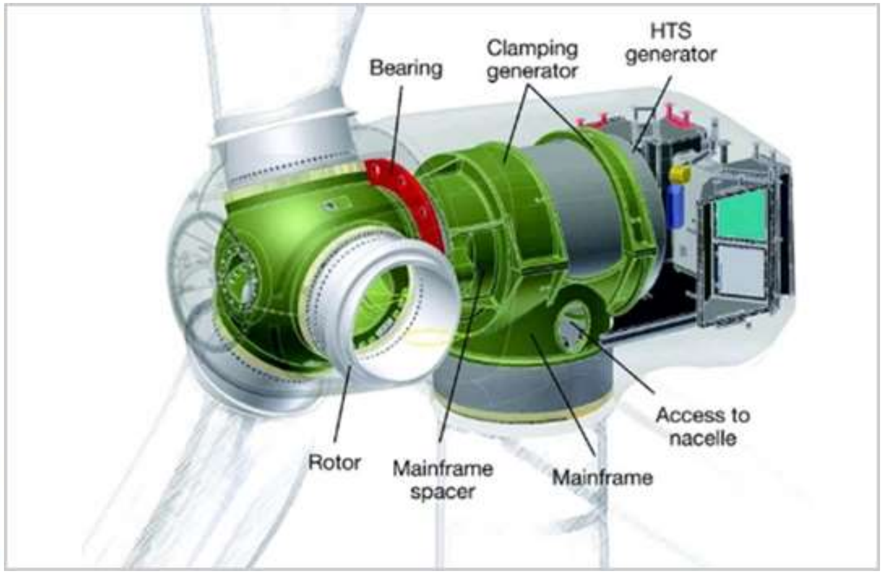
Generators

(Source: Physik Journal 6, 2011)

Superconducting rotor for hydroelectric power station

Zenergy Power GmbH

High-temperature superconducting rotor for wind power station



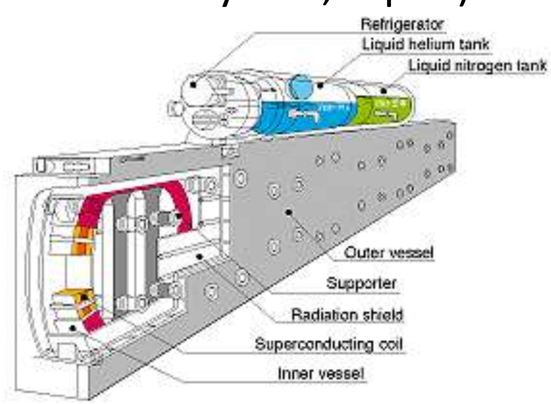
(Source: MAGLEV Off Shore Wind Turbines)

Applications of superconductivity

Transportation systems and traffic

Yamanashi MAGLEV-System

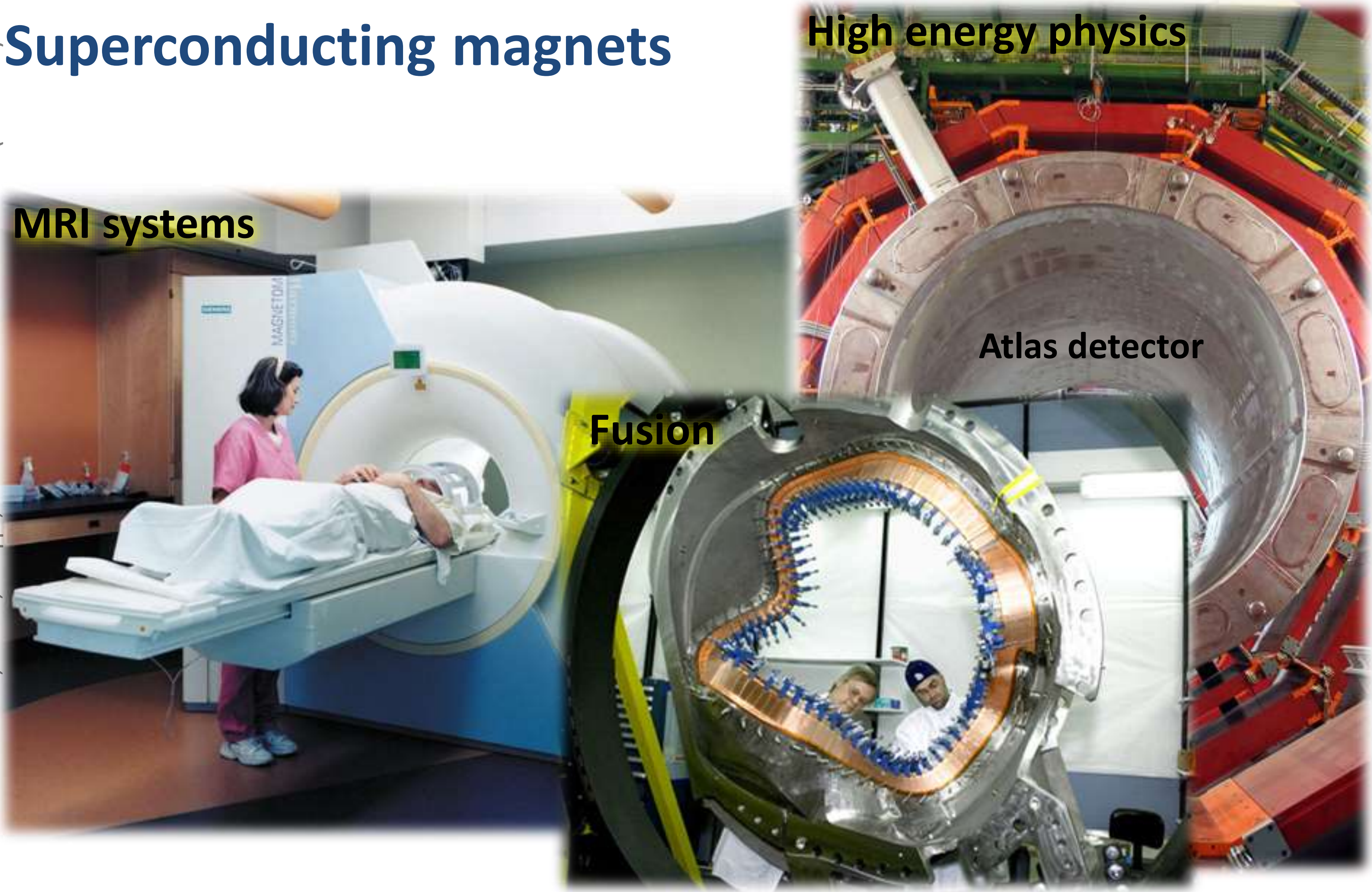
(42.8 km long test track between Sakaigawa and Akiyama, Japan)



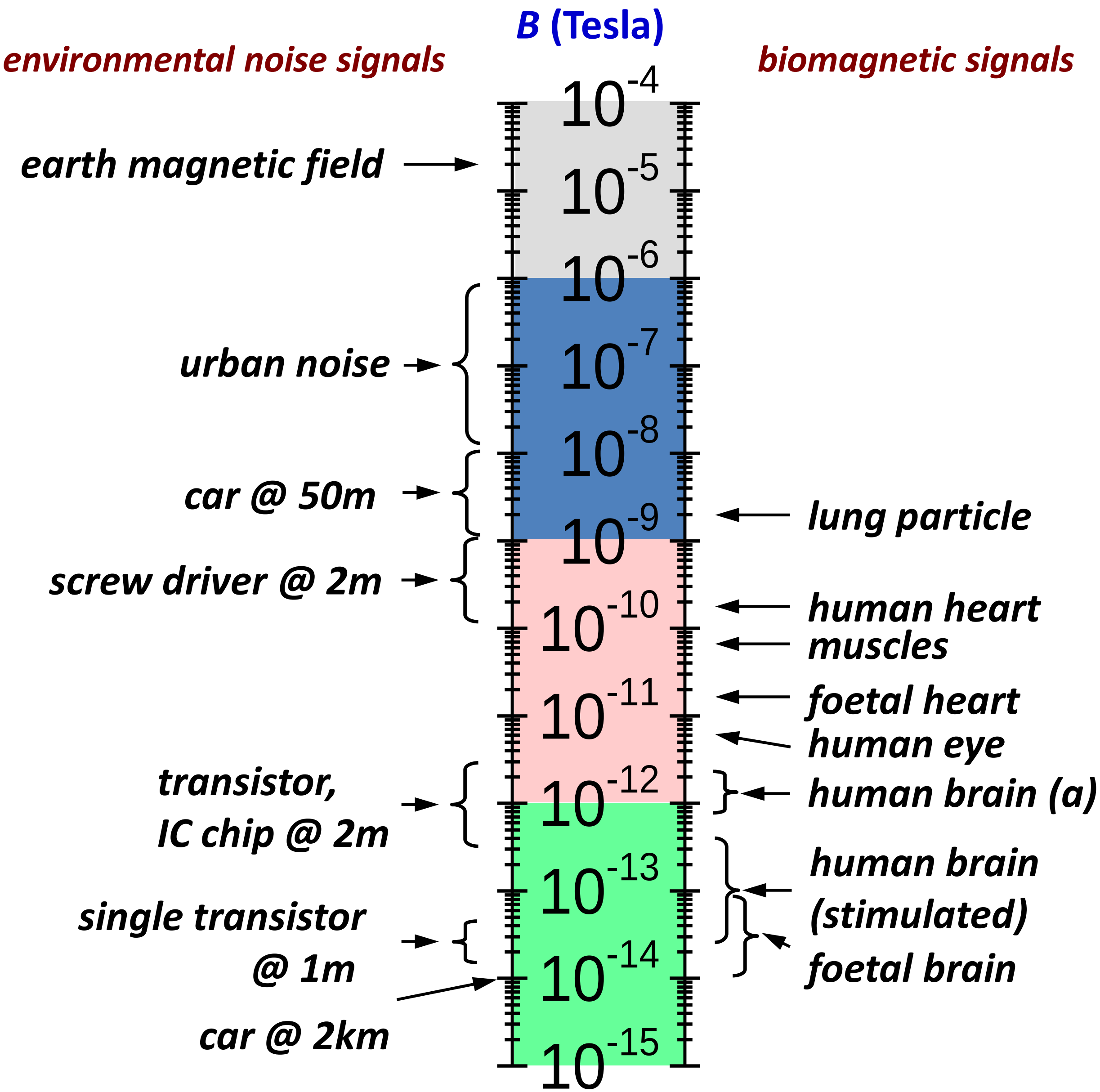
Maximum velocity:
581 km/h (02. 12. 2003)

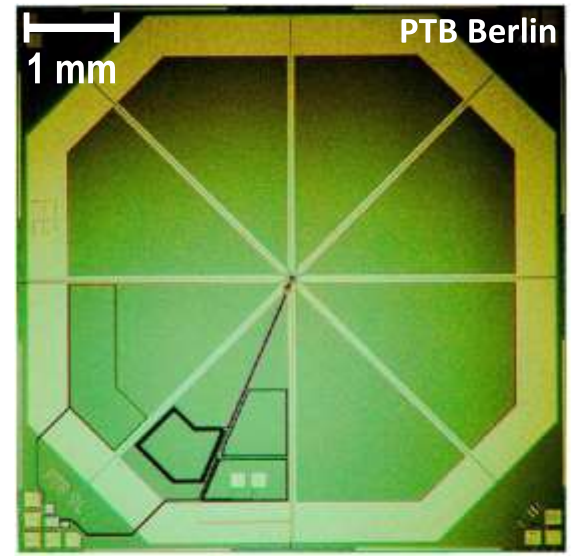
Applications of superconductivity

Superconducting magnets



Biomagnetism

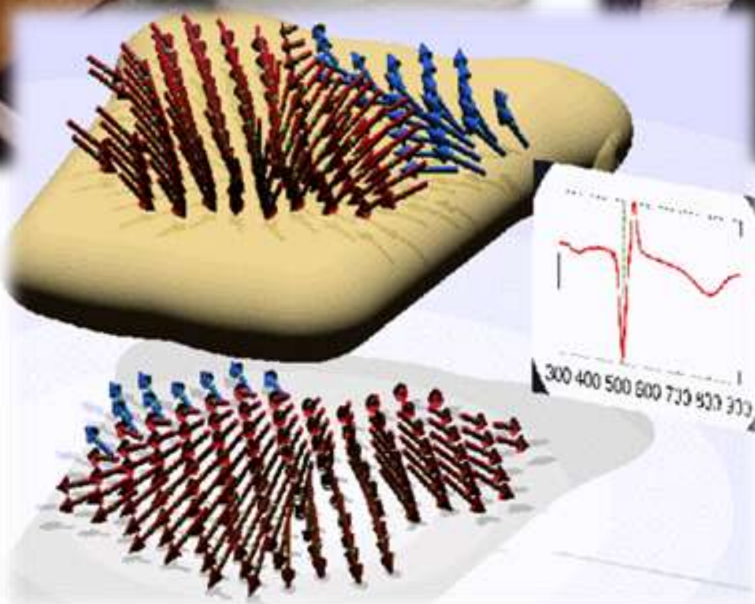




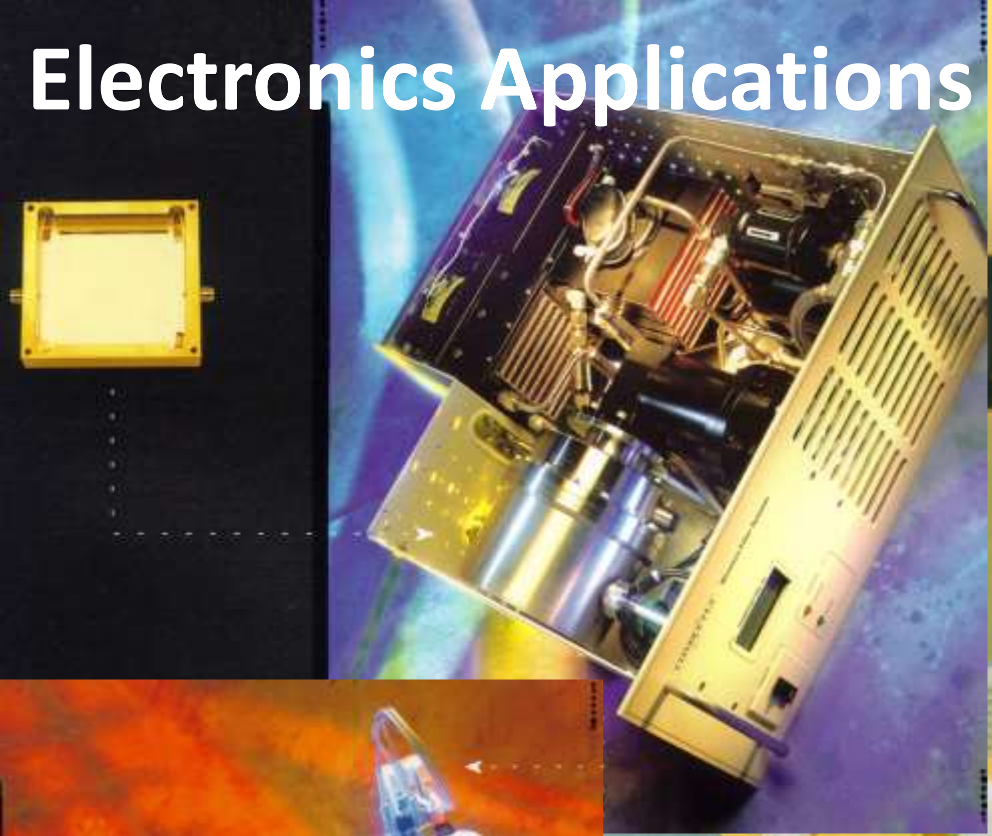
Superconducting Quantum Interference Detector (SQUID)

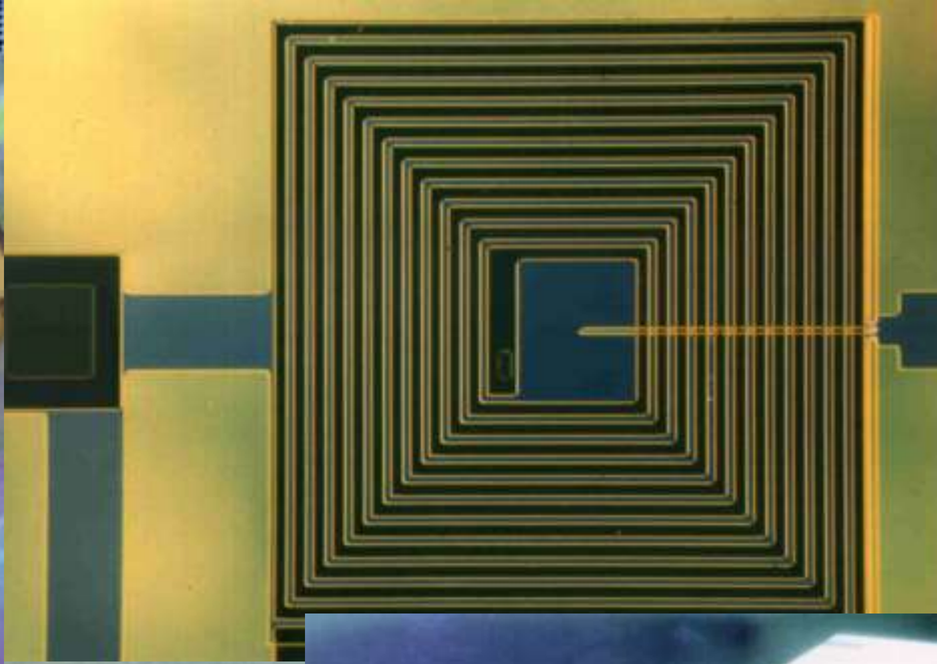
sensitivity:
a few fT/√Hz

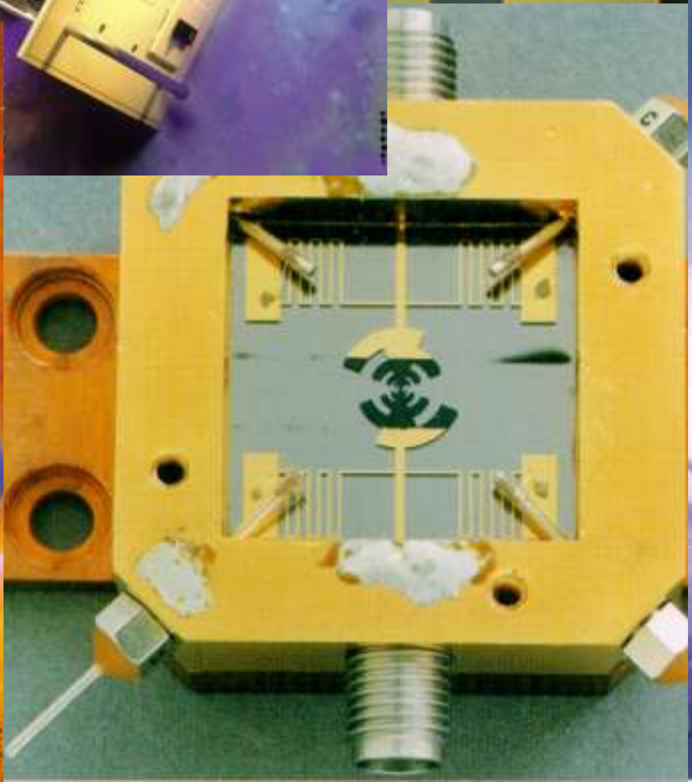
Biomagnetism



Electronics Applications

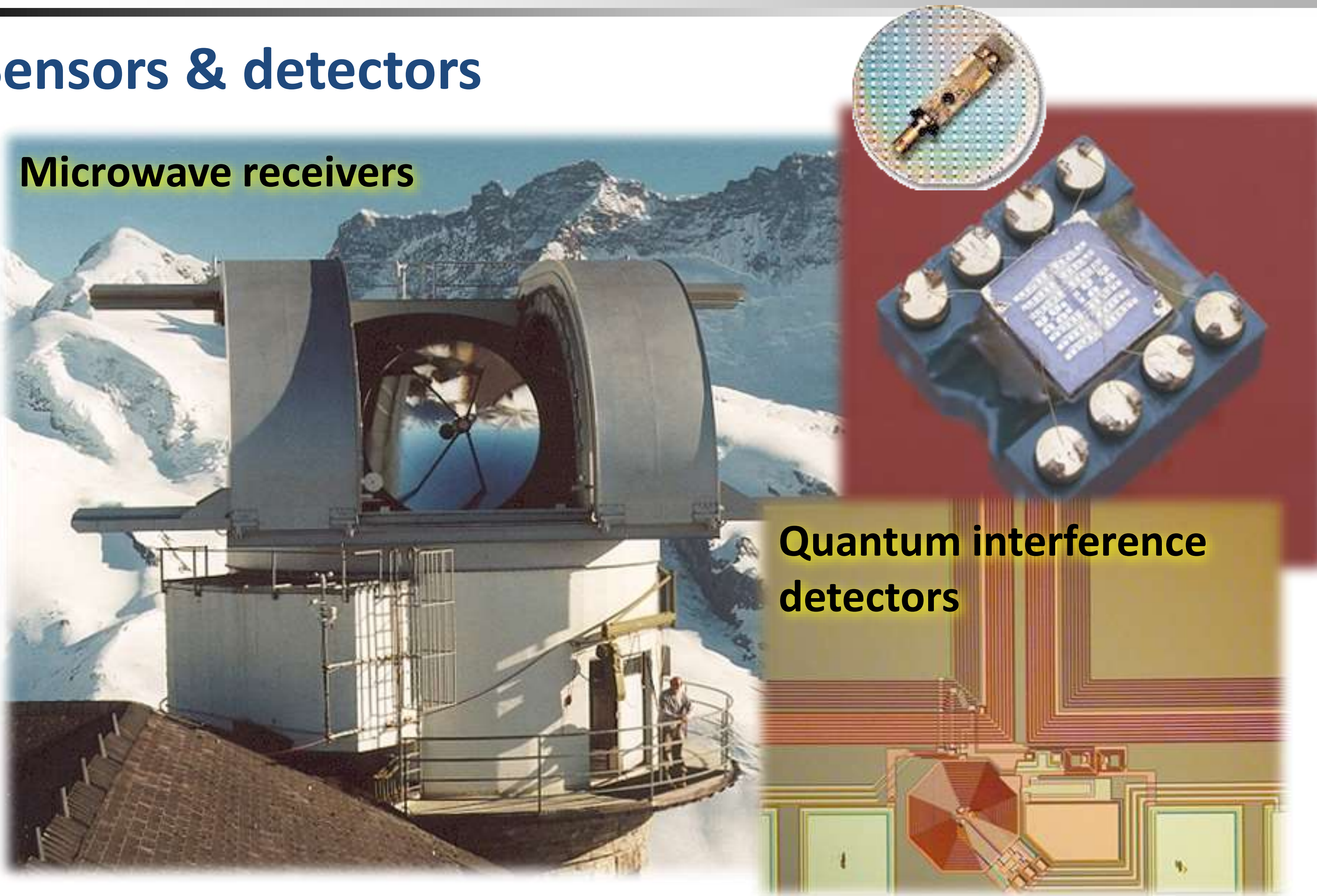




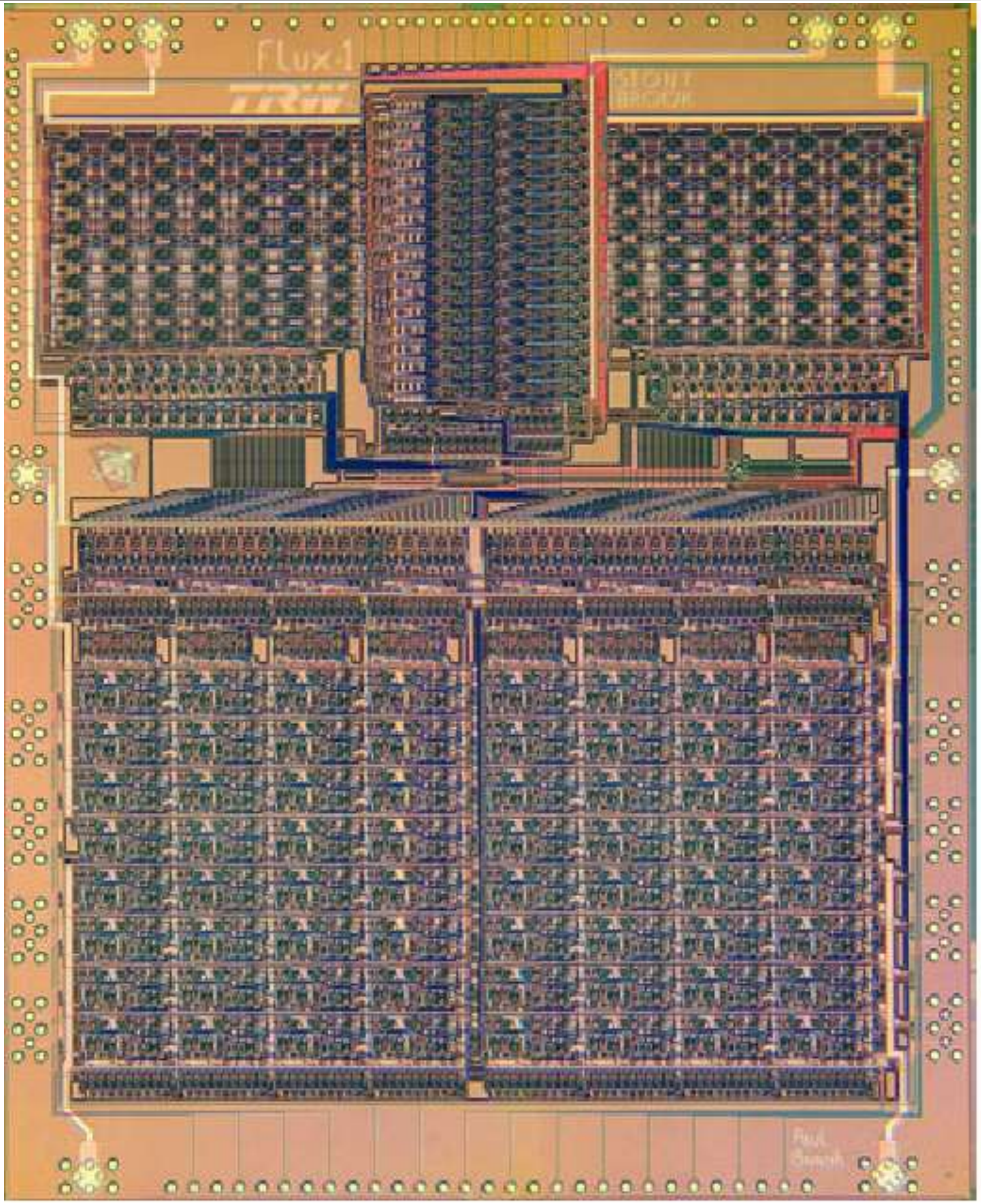


Applications of superconductivity

Sensors & detectors



Josephson Computing



FLUX-1

- the first RSFQ MPU
- 8 bit ALU array
- 16 word instruction memory
- 70,000 JJs
- 14 mW
- 20-22 GHz @ F = 2.0 um
  (⇒ 120-140 GHz @ 0.3 um)
- TRW's 4-metal process

Source: K. K. Likharev, SUNY Stony Brook

Rapid Single Flux Quantum (RSFQ) Logic

PetaFLOPS Scale Computing:

Speed and Power Scales (Year 2006)

	Semiconductors (CMOS)		Superconductors (RSFQ)
Performance:	> 10^5 chips @ 10 GFLOPS each	**Performance:**	$4\cdot10^3$ processors @ 256 GFLOPS each
Power:	≈ 150 W per chip ⇒ total > 15 MW	**Power:**	≈ 0.05 W per PE node ⇒ total 250 W @ 5 K (100 kW @ 300 K)
Footprint:	>30 x 30 m^2 ⇒ latency > 3 ms	**Footprint:**	1 x 1 m^2 ⇒ latency 20 ns

Source: K. K. Likharev, SUNY Stony Brook

Quantum Science and Technology

Quantum Science

→ Fundamental light-matter coupling („Microwave quantum optics“)

→ Ultrastrong coupling

→ Microwave photonics

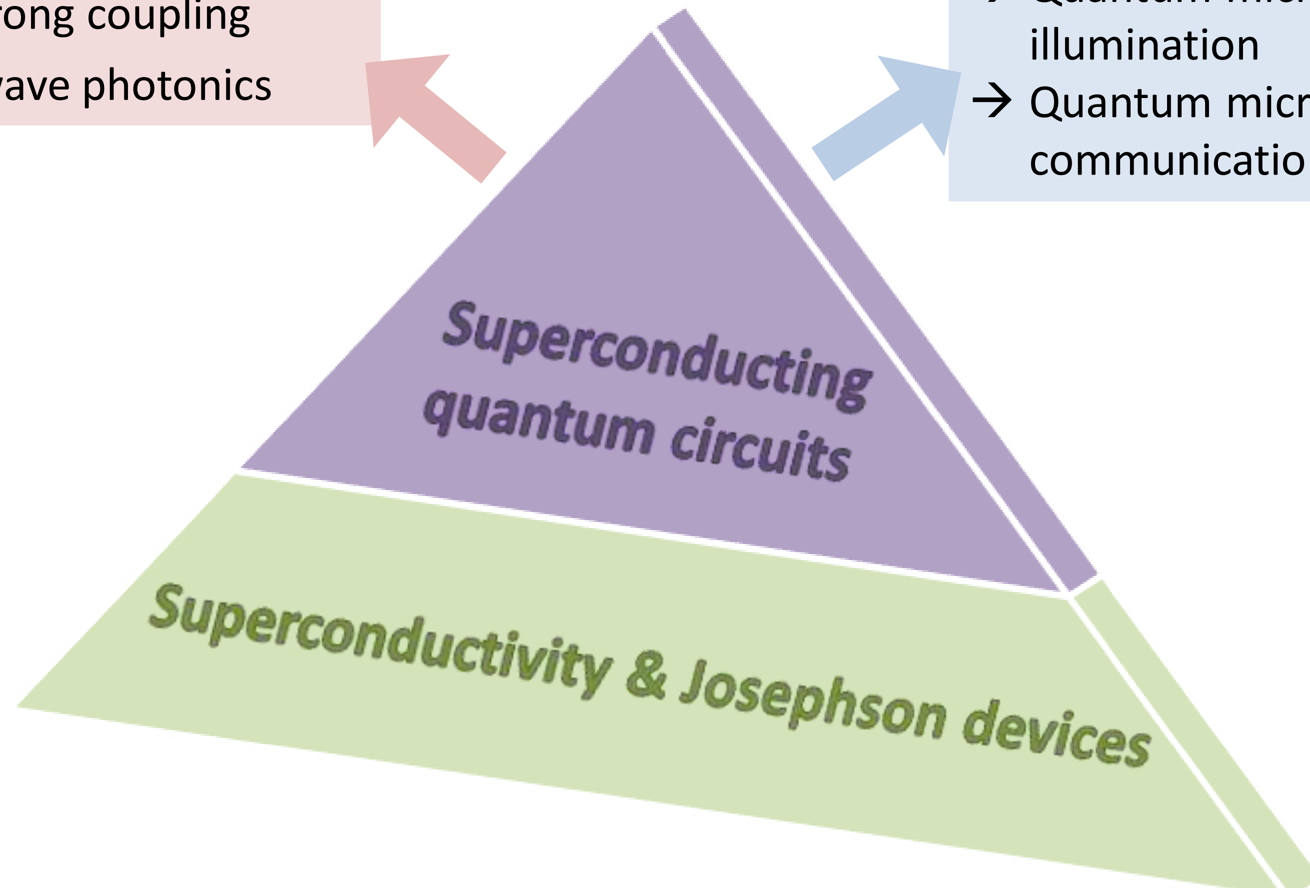
Quantum Technology

→ Quantum information processing (Google, IBM …)

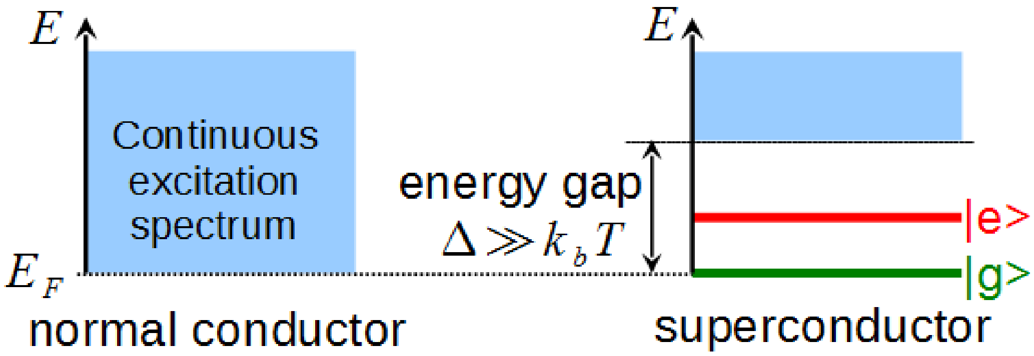
→ Quantum simulation

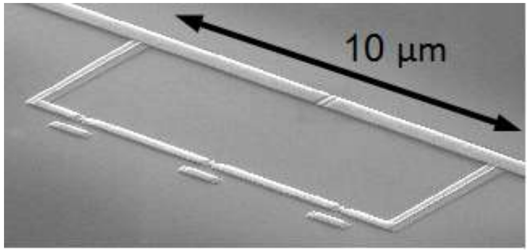
→ Quantum microwave illumination

→ Quantum microwave communication



Quantum circuits: Experimental challenges





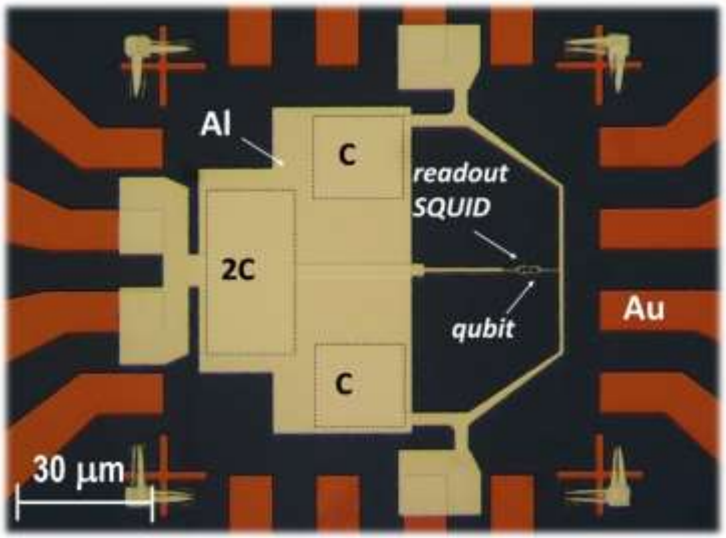
Al: $\Delta/h \simeq 50$ GHz

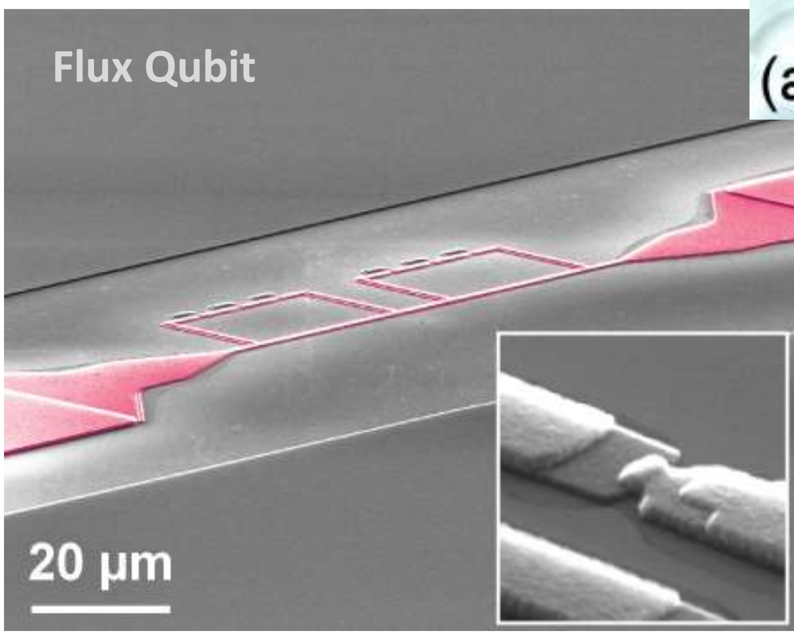
Millikelvin temperatures

$1\mathrm{GHz} \Leftrightarrow 50\ \mathrm{mK}$

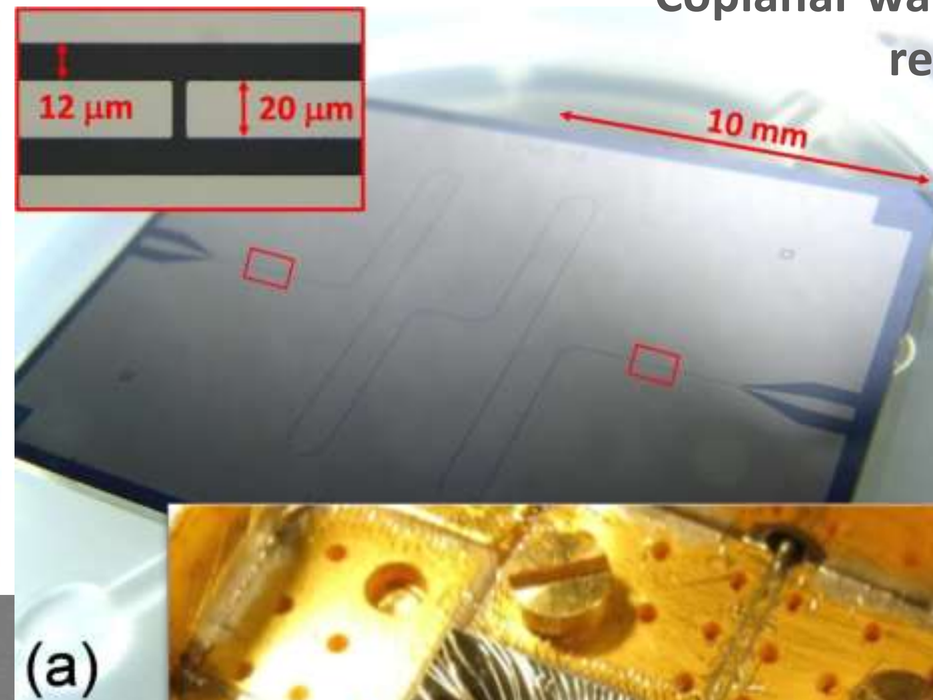
- → Complex nanofabrication
- → Ultralow-power measurements
- → millikelvin cryotechnology

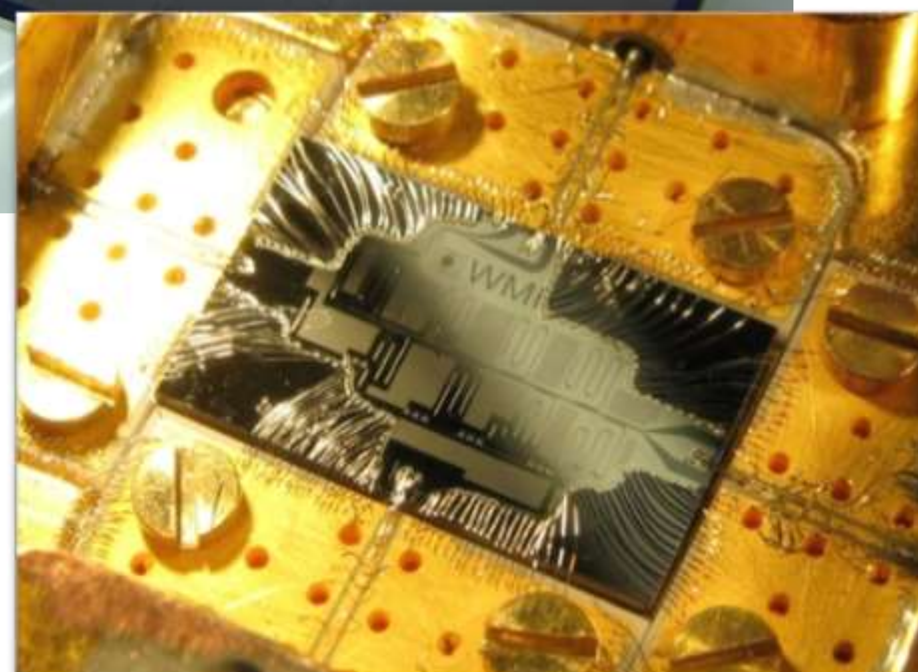
Superconducting Quantum Circuits





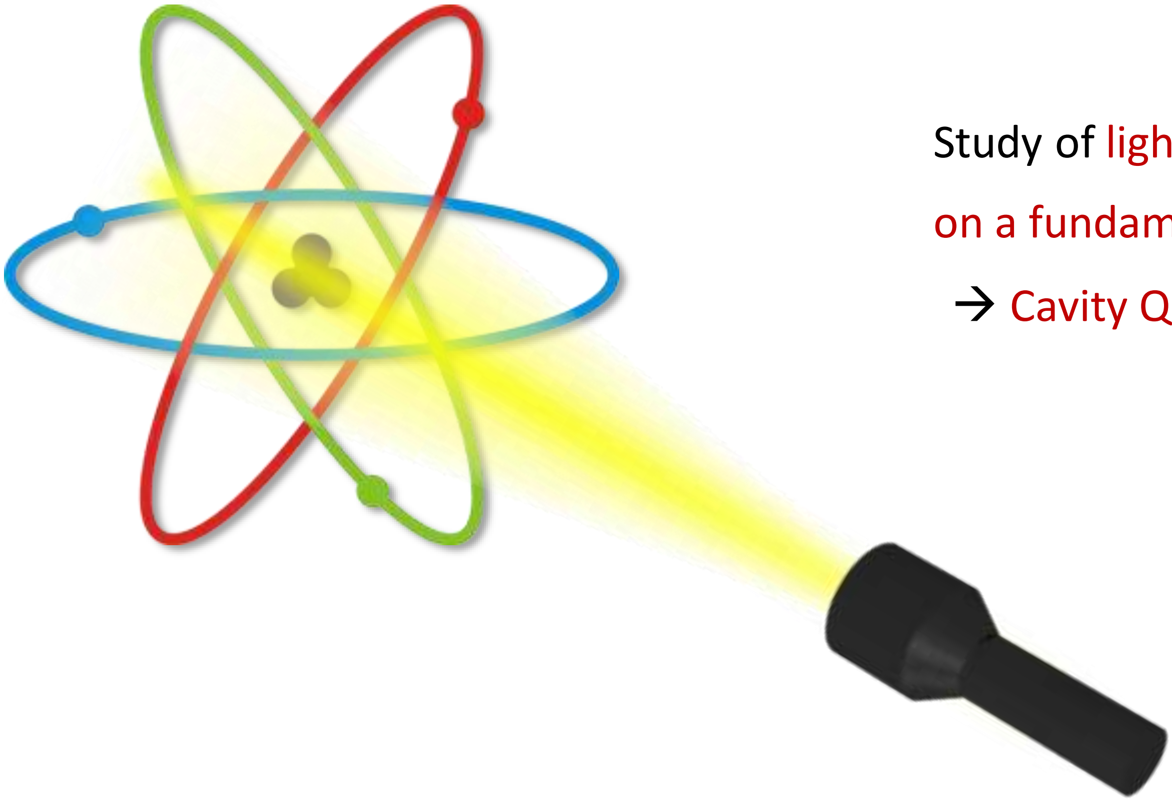
Coplanar waveguide resonator





circuit QED chips

Cavity quantum electrodynamics (QED)



Study of light-matter interaction on a fundamental quantum level

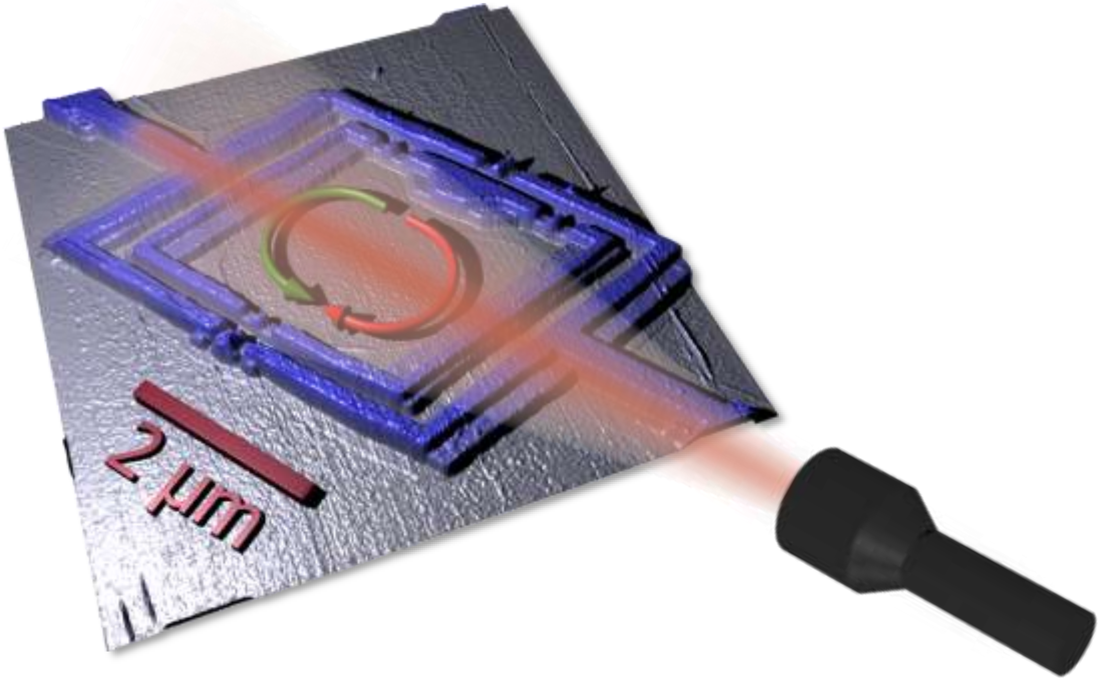
→ Cavity QED (quantum optics)

- → Study consequences of quantum nature of light on light-matter interaction
- → Quantum mechanical control and manipulation of light and matter
- → Basis for (future) quantum information technology
- → How about superconducting circuits?

Circuit quantum electrodynamics

Circuit QED

→ Cavity QED with circuits as quantized light sources and artificial atoms



Why artificial atoms?

→ Tunability of (by design & in experiment)

   → Transition frequency

   → Selection rules / symmetry

   → (Ultra)strong light-matter coupling

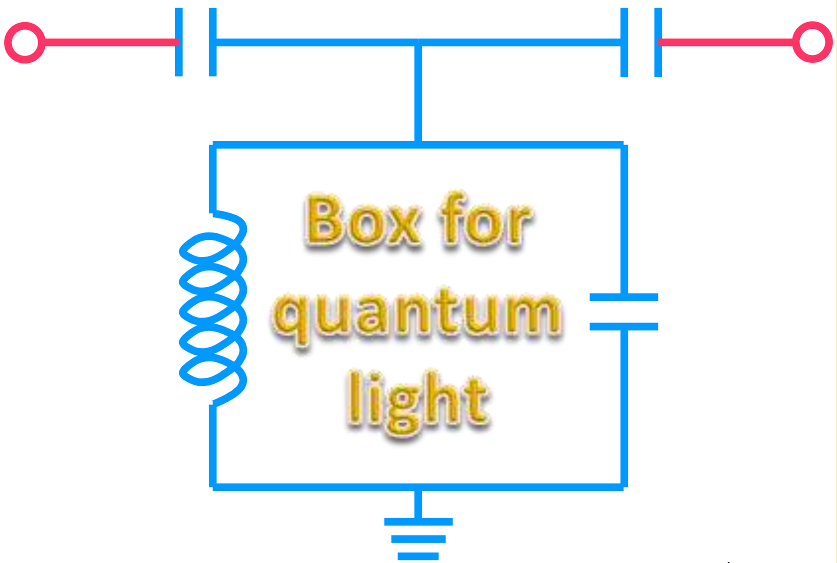
→ Quantum engineering

→ Quantum science

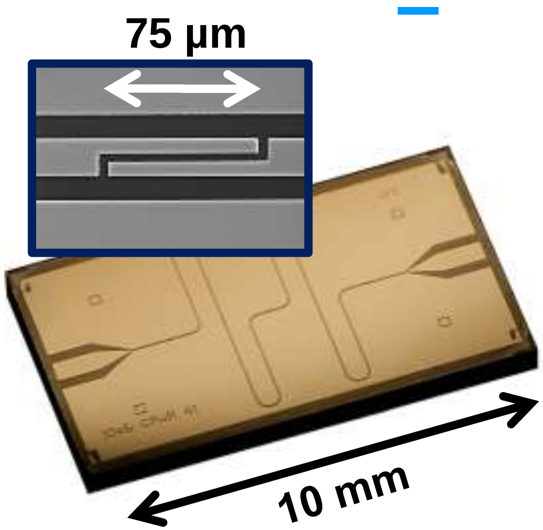
F. Deppe et al. , *Nature Physics 4, 686 (2008)*
T. Niemczyk et al., arXiv:1107.0810v1

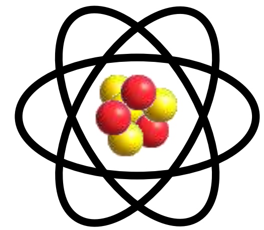
T. Niemczyk et al., *Nature Physics 6, 772 (2010)*

Circuit quantum electrodynamics

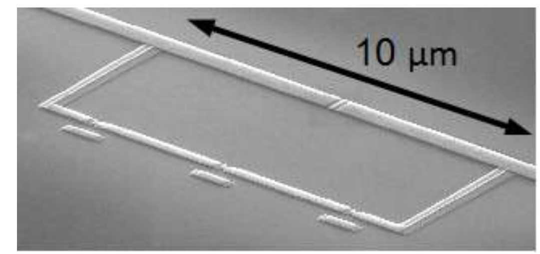


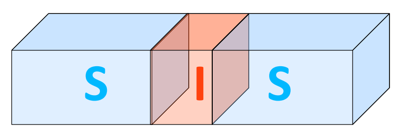
Box for quantum light



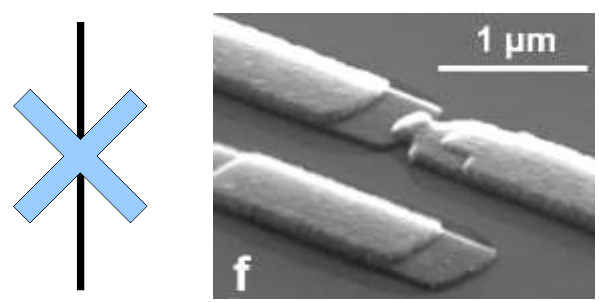


Engineered quantum matter



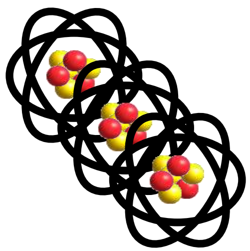


$L_J(\Phi)$

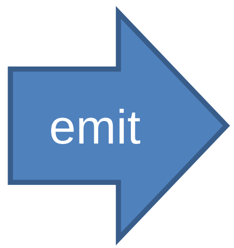


Unusual coupling

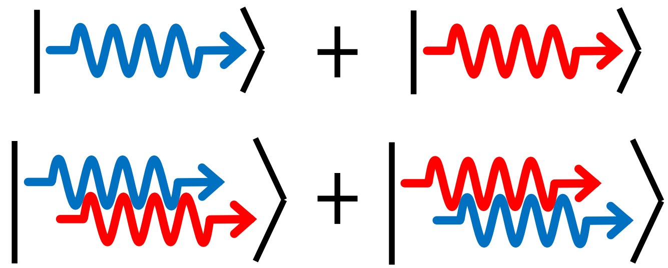
Propagating quantum microwaves

Quantum - 

Superconducting
quantum circuits



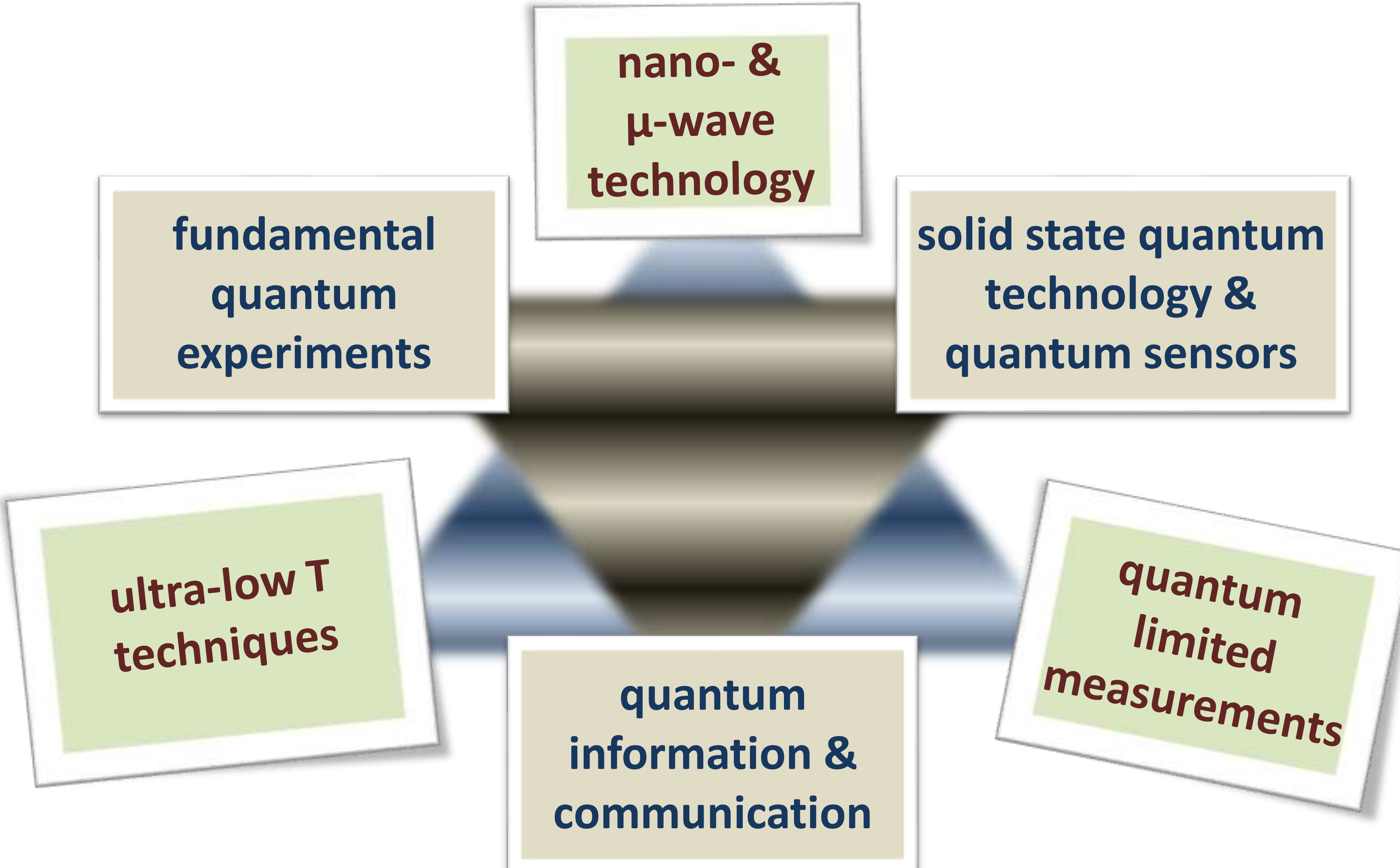
Quantum -  - 



→ Investigate quantum properties (superposition, squeezing, entanglement)
entanglement along the propagation path
→ Pioneered by WMI!

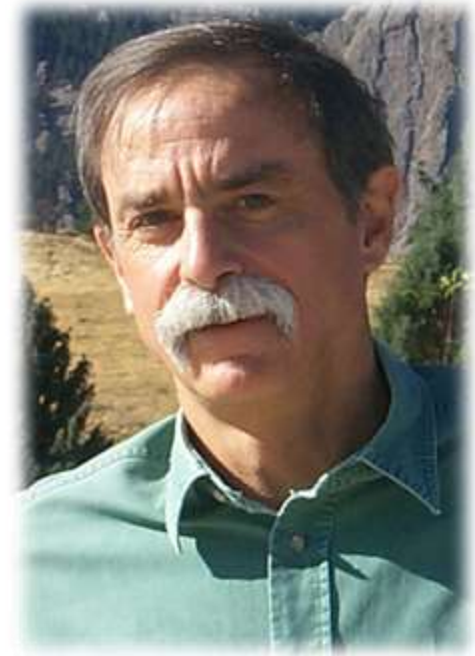
J. Goetz *et al.*, Phys. Rev. Lett. **121**, 060503 (2018)
P. Eder *et al.*, Supercond. Sci. Technol. **31**, 115002 (2018)
K. G. Fedorov *et al.*, Sci. Rep. **8**, 6416 (2017).
K. G. Fedorov *et al.*, Phys. Rev. Lett. **117**, 020502 (2016).
L. Zhong *et al.*, New. J. Phys. **15**, 125013 (2013).
E. P. Menzel *et al.*, Phys Rev. Lett **109**, 250502 (2012).
E. P. Menzel *et al.*, Phys. Rev. Lett. **105**, 100401 (2010).
M. Mariantoni *et al.*, Phys. Rev. Lett. **105**, 133601 (2010).

Prospects of superconducting quantum circuits



The Nobel Prize in Physics 2012

Serge Haroche



David J. Wineland

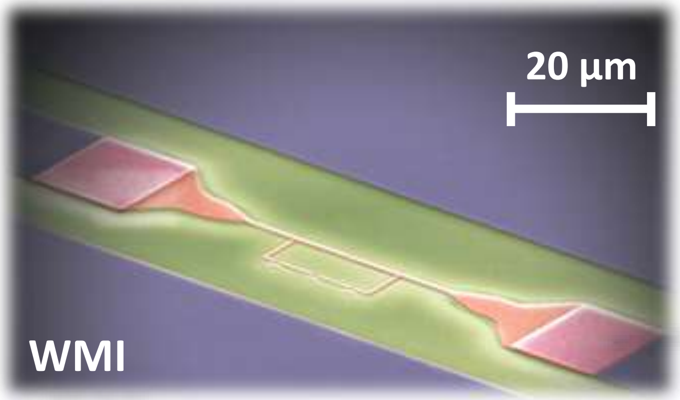
Nobel Prize in Physics 2012

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

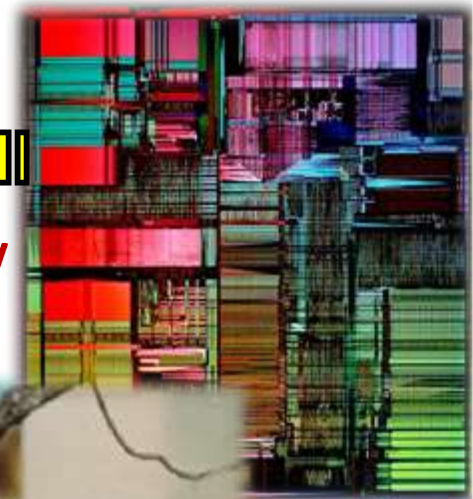
Quantum opticians, but deeply related to superconducting quantum circuits!

From mechanical to quantum mechanical IP

Superconducting Qubit



Intel dual-core **45 nm** (2007)



Science

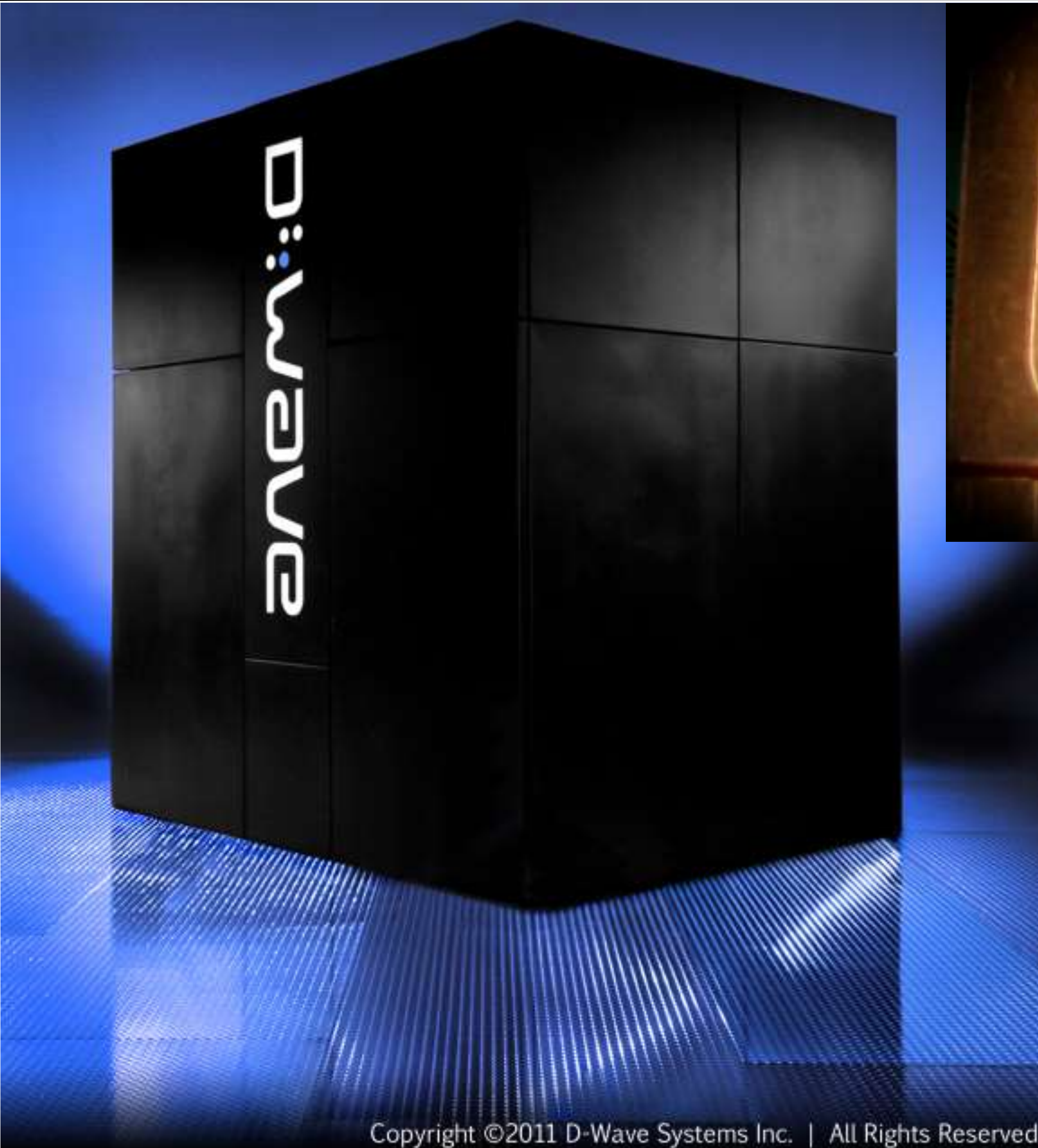
Technology

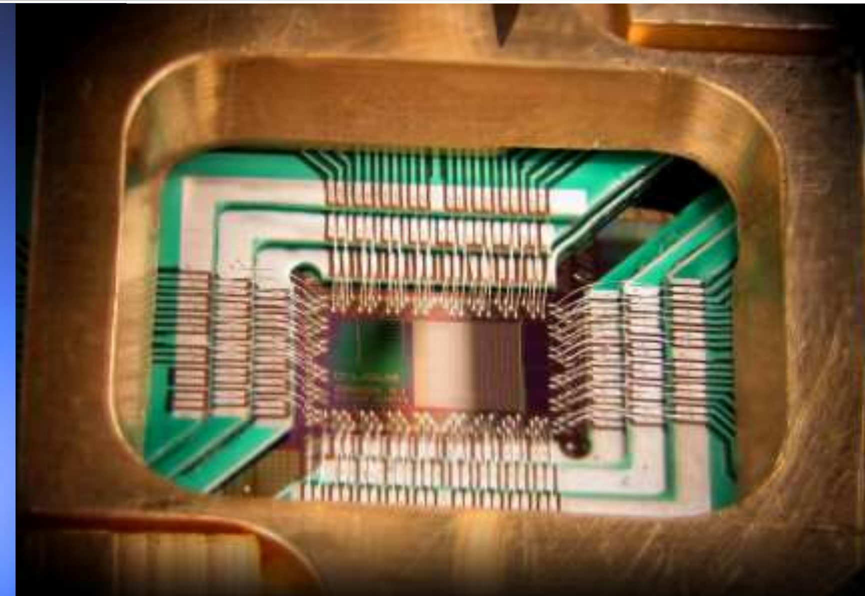
Enigma (1940)

Vacuum tubes
ENIAC (1946)

First transistor (1947)
Bardeen, Brattain, & Shockley

Quantum computing- all done?





No!

- → No quantum coherence
- → Real „Quantumness“ highly doubted!
- → No quantum speedup

State of the art with coherent qubits
→ Order of 10 Qubits
→ Order of 1000 gates

Quantum computing vs. quantum simulation

Classical computer

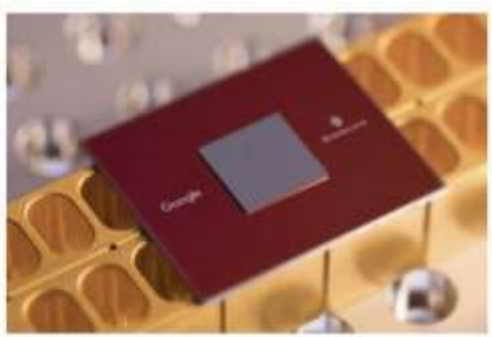
→ Current semiconductor-based implementation highly successful
→ Nevertheless inefficient for certain problems, including
  → Prime number factorization
  → Simulating other quantum systems

Quantum computer

→ **Universal** machine to efficiently solve many types of problems
→ Example: the simulation of quantum systems themselves
→ Always digital
→ **Stringent hardware requirements**

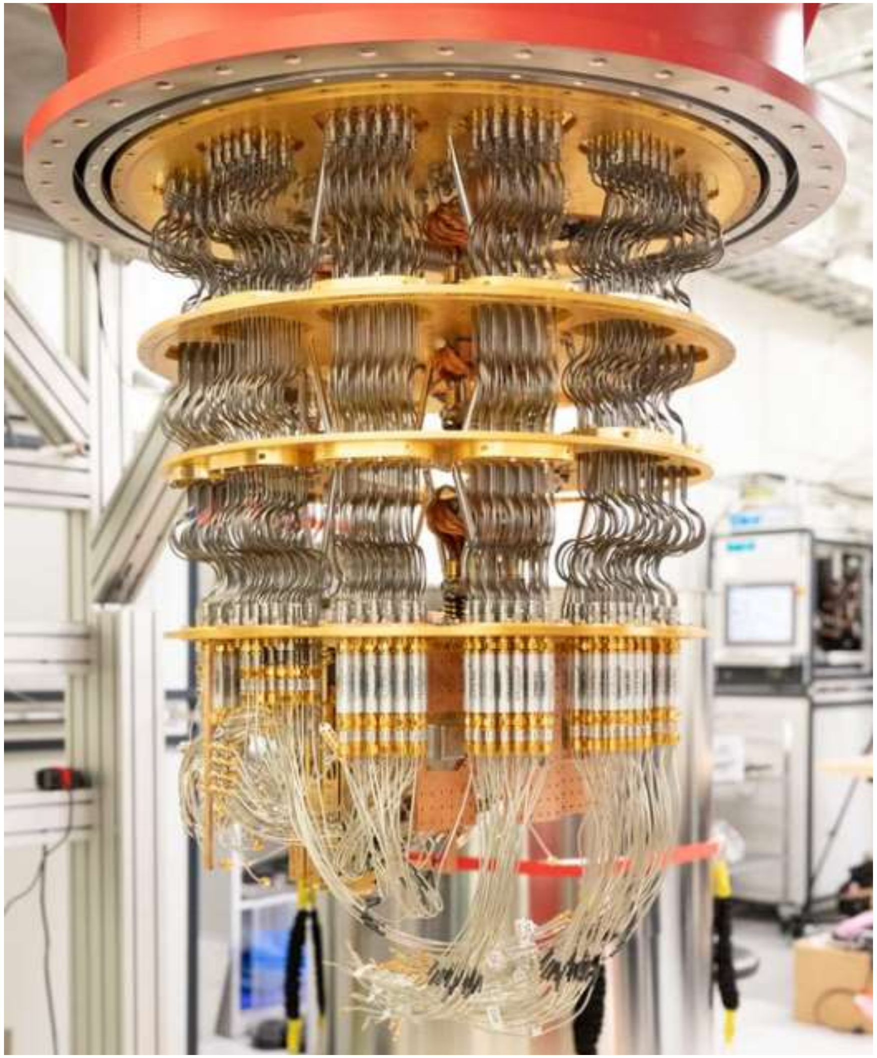
Quantum simulator

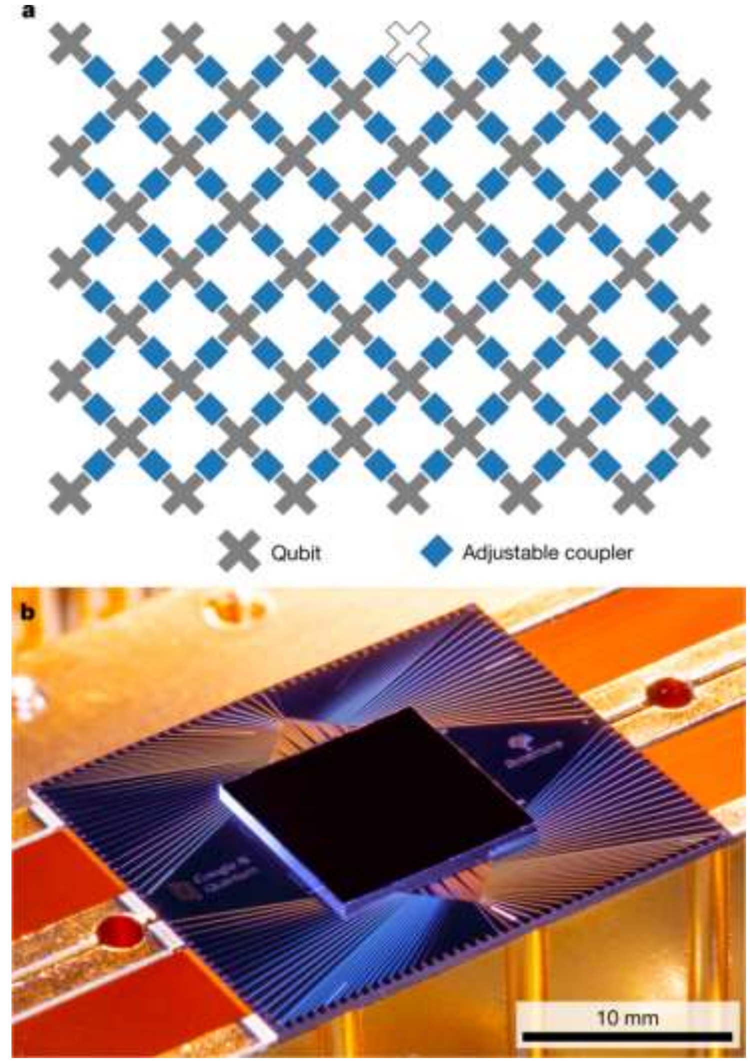
→ Encode one hard-to-access quantum system in an easier-to-access one
→ **Specialized**, not universal
→ Analog or digital variants
→ Dramatically **less stringent hardware requirements**



Google "Bristlecone"
72-qubit prototype

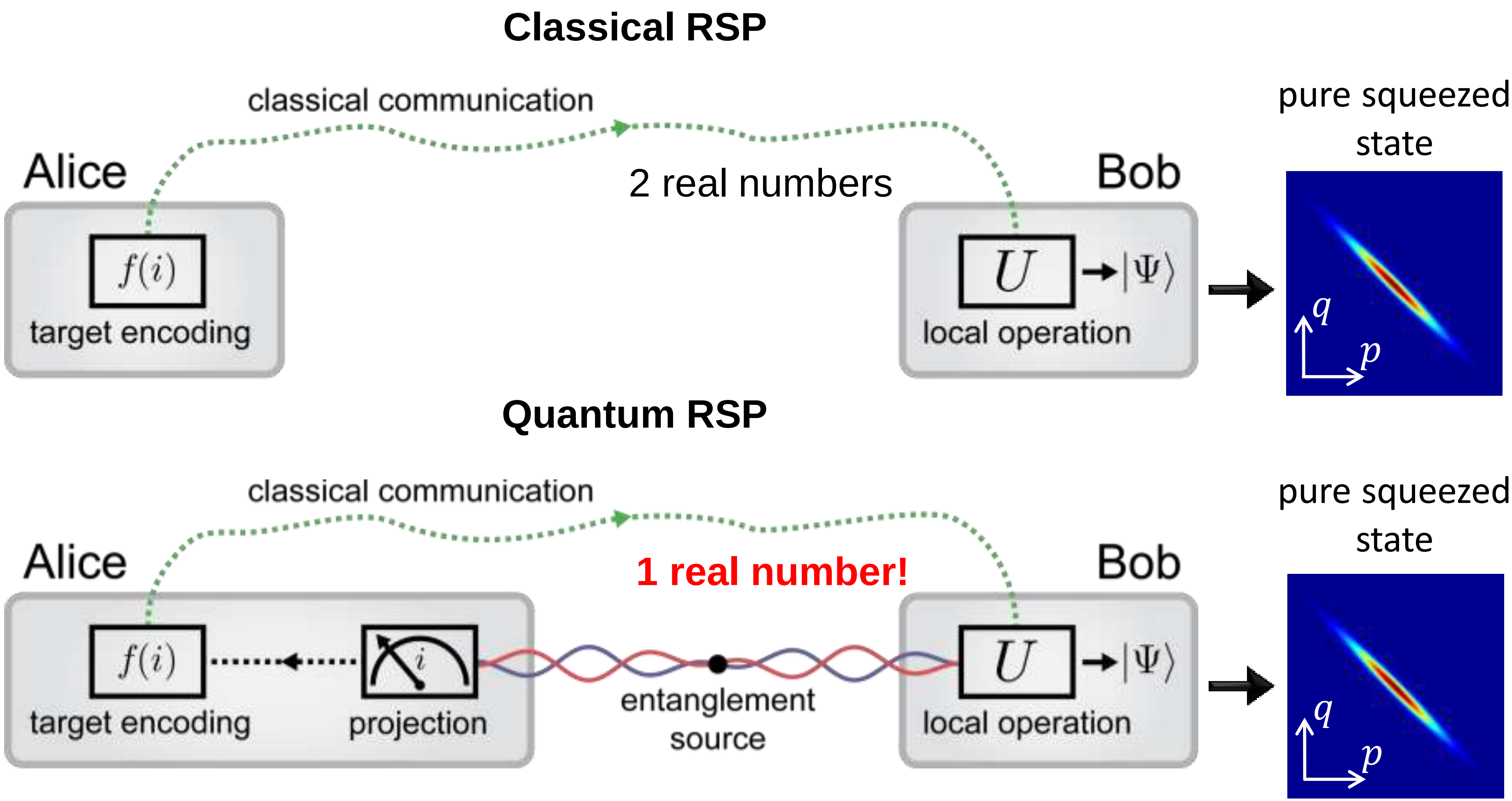
Quantum supremacy





Quantum supremacy using a programmable superconducting processor, Nature **574**, 505 (2019)

Quantum microwave communication



Secure quantum remote state preparation,
Nat. Comm. **10**, 2604 (2019)