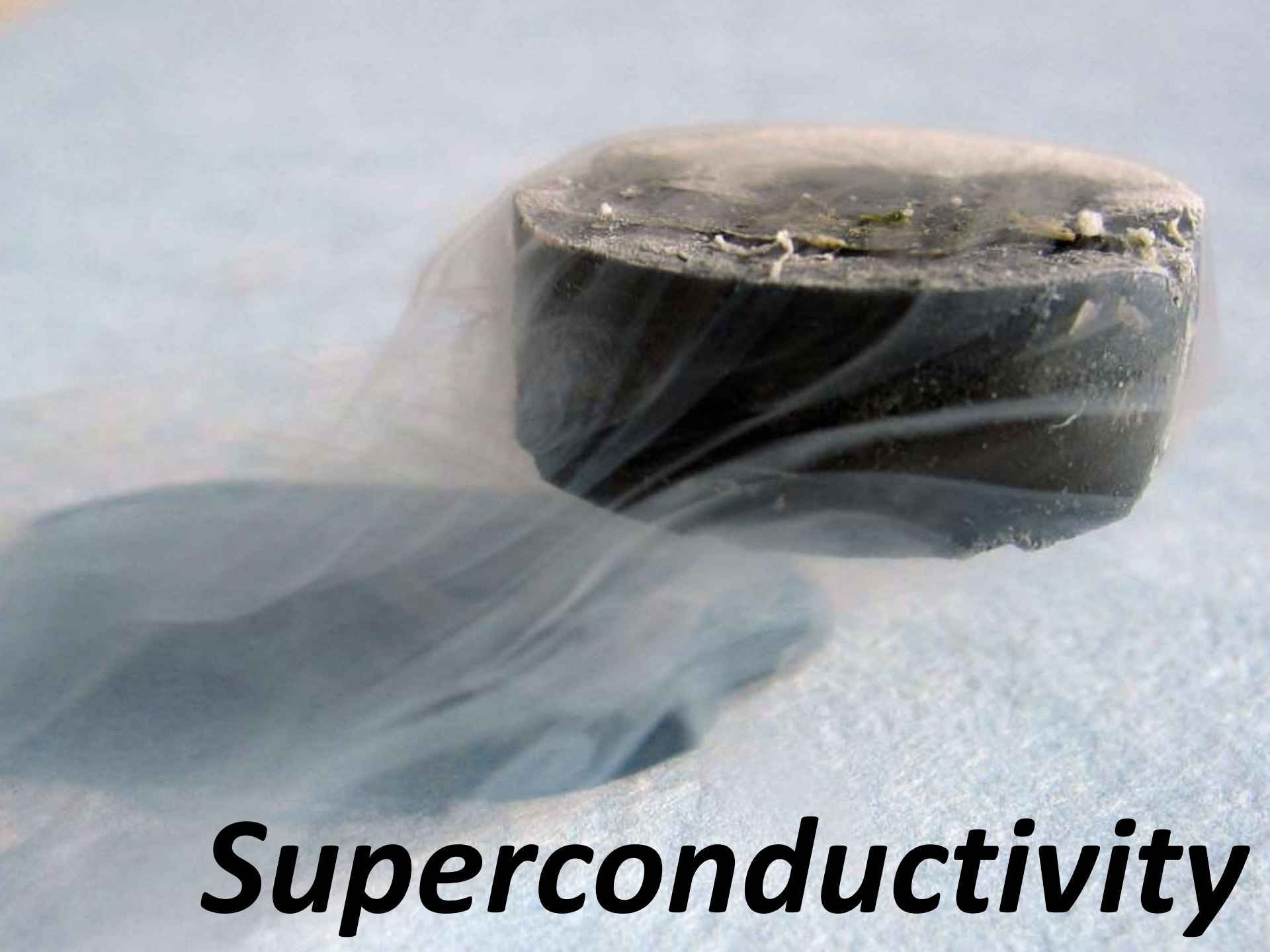


Superconductivity and Low Temperature Physics I



Lecture Notes
Winter Semester 2021/2022

R. Gross
© Walther-Meißner-Institut



Superconductivity



1. Superconductivity and Low Temperature Physics I + II

- Part I (WS 2021/2022): Foundations of Superconductivity
- Part II (SS 2022): Foundations of Low Temperature Physics and Techniques

This lecture

2. Applied Superconductivity I + II

- WS 2021/22 and SS 2022, 2 hrs lecture + 2 hrs exercises
- Josephson-Effect, Superconducting Electronics, Qubits, Quantum Circuits,

3. Seminars (WS 2021/2022, WMI seminar room)

- Advances in Solid State Physics (TUE 10:15-11:30)
- Superconducting Quantum Circuits (TUE 14:30-16:00)

Topics available

Further information: <https://www.wmi.badw.de/teaching>

- announcement of lectures
- downloads of lecture notes, handouts...
- seminar topics

Nobel Prizes in Physics related to LT Physics

year	name	discovery
1913	Heike Kamerlingh Onnes	"For his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium "
1972	John Bardeen , Leon Neil Cooper and Robert Schrieffer	"for their jointly developed theory of superconductivity , usually called the BCS-theory "
1973	Brian David Josephson	"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 effect "
1978	Piotr Kapiza	"for his basic inventions and discoveries in the area of low-temperature physics"
1985	Klaus von Klitzing	"for the discovery of the quantized Hall effect "
1987	Johannes Georg Bednorz und Karl Alex Müller	"for their important break-through in the discovery of superconductivity in ceramic materials "
1996	David M. Lee , Douglas D. Osheroff und Robert C. Richardson	"for their discovery of superfluidity in helium-3 "
1997	Steven Chu , Claude Cohen-Tannoudji and William D. Phillips	"for development of methods to cool and trap atoms with laser light" See Laser cooling .
1998	Robert B. Laughlin , Horst Ludwig Störmer and Daniel Chee Tsui	"for their discovery of a new form of quantum fluid with fractionally charged excitations". See Quantum Hall effect .
2001	Eric A. Cornell , Wolfgang Ketterle and Carl E. Wieman	"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"
2003	Alexei Abrikosov , Witali Ginsburg and Anthony James Leggett	"for pioneering contributions to the theory of superconductors and superfluids"
2016	David J. Thouless , F. Duncan M. Haldane , J. Michael Kosterlitz	"for theoretical discoveries of topological phase transitions and topological phases of matter"

Superconductivity and Low Temperature Physics I

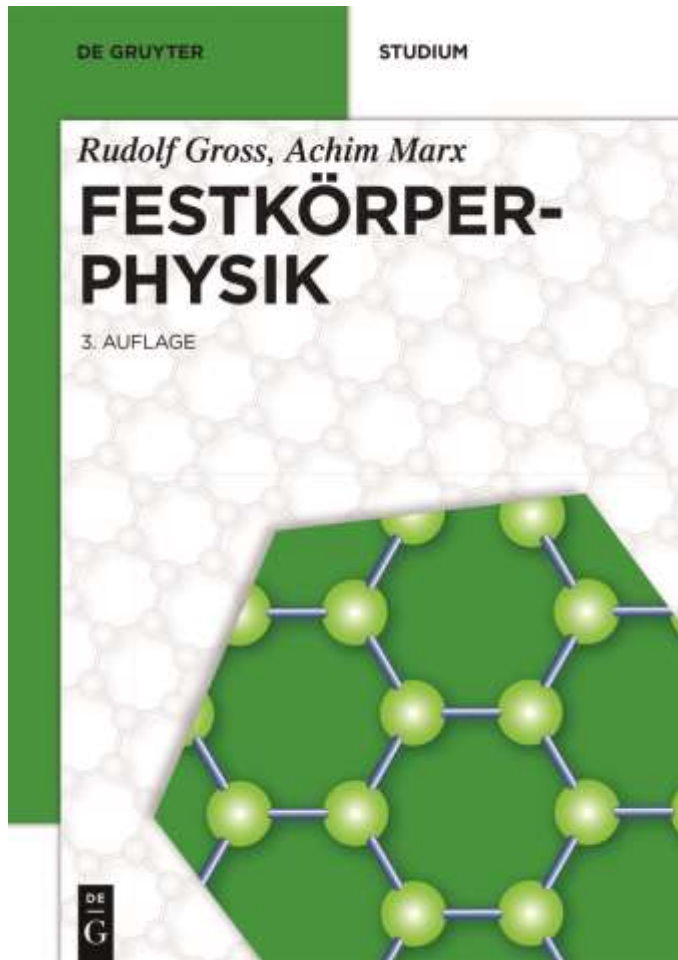
Introduction

1. Basic Properties of Superconductors
2. Phenomenological Models of Superconductivity :
 - London equations
 - macroscopic quantum model
 - Ginzburg-Landau theory
3. Thermodynamics
4. Microscopic (BCS) theory
5. Flux pinning and critical currents
6. High Temperature Superconductivity
7. Applications

Superconductivity and Low Temperature Physics II

1. Bose-Einstein condensation
2. Superfluid Helium (^4He and ^3He)
3. Quantum Interference Effects in Mesoscopic Conductors
4. Low Temperature Techniques
(generation and measurement of low temperatures)

- Werner Buckel, Reinhold Kleiner, *Supraleitung – Grundlagen und Anwendungen*, VCH-Verlag, Weinheim (2013).
- Fossheim, Sudbo, *Superconductivity*, Wiley (2005)
- M. Tinkham, *Introduction to Superconductivity*, McGraw-Hill, New York (1975).
- J.F. Annett, *Superconductivity, Superfluids and Condensates* (2004)
- V.V. Schmidt, *The Physics of Superconductors* (1997)
- J. R. Waldram, *Superconductivity of Metals and Cuprates* (1996)
- D.R. Tilley and J. Tilley, *Superfluidity and Superconductivity*
- P. Komarek, *Hochstromanwendungen der Supraleitung* (1995)
- T. P. Sheathen, *Introduction to High T_c Superconductivity* (1994)
- M. Acquarone, *High Temperature Superconductivity* (1996)
- WMI Lecture Notes <https://www.wmi.badw.de/teaching/Lecturenotes>



Rudolf Gross, Achim Marx

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Published: January 2018

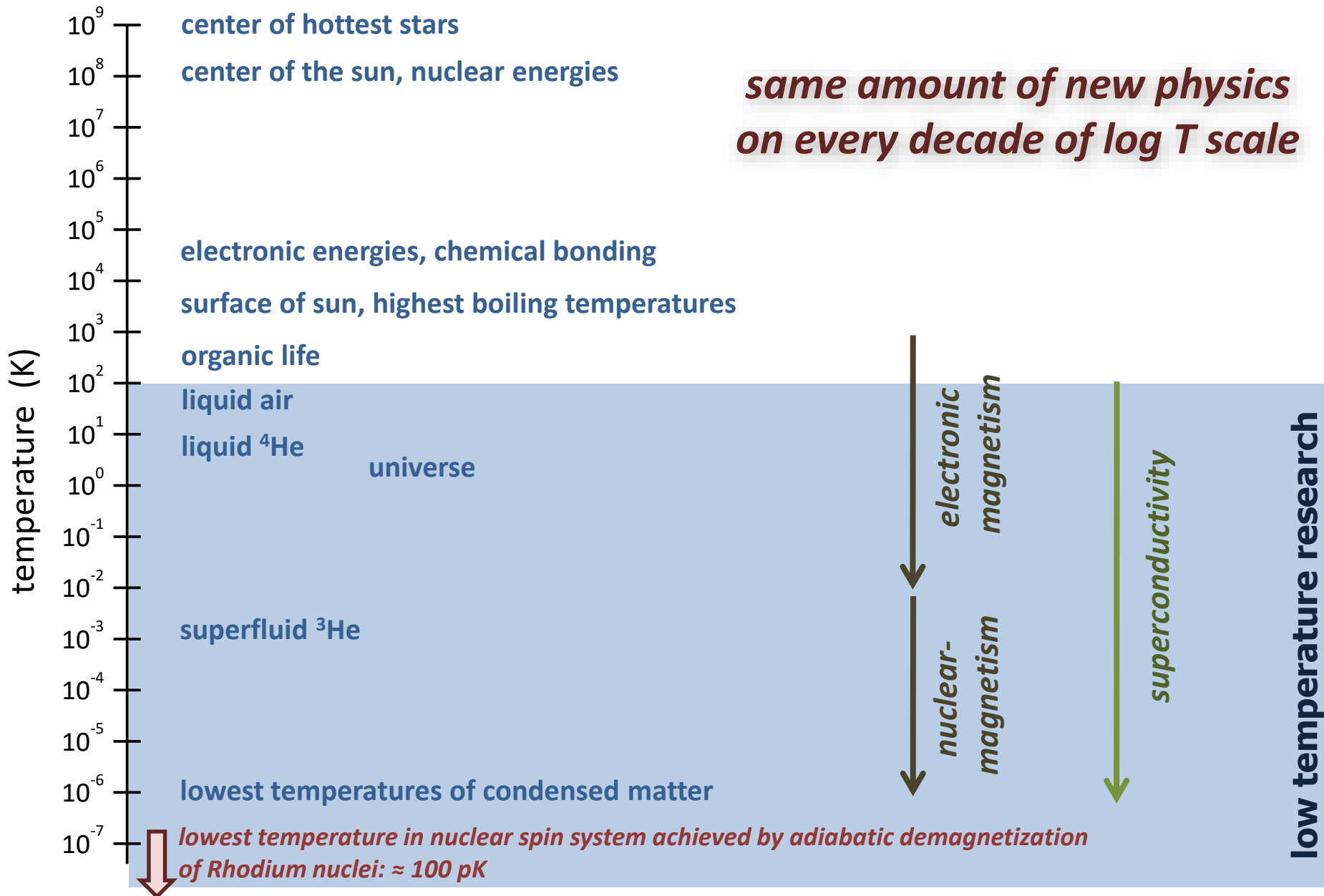
Language: German

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Introduction

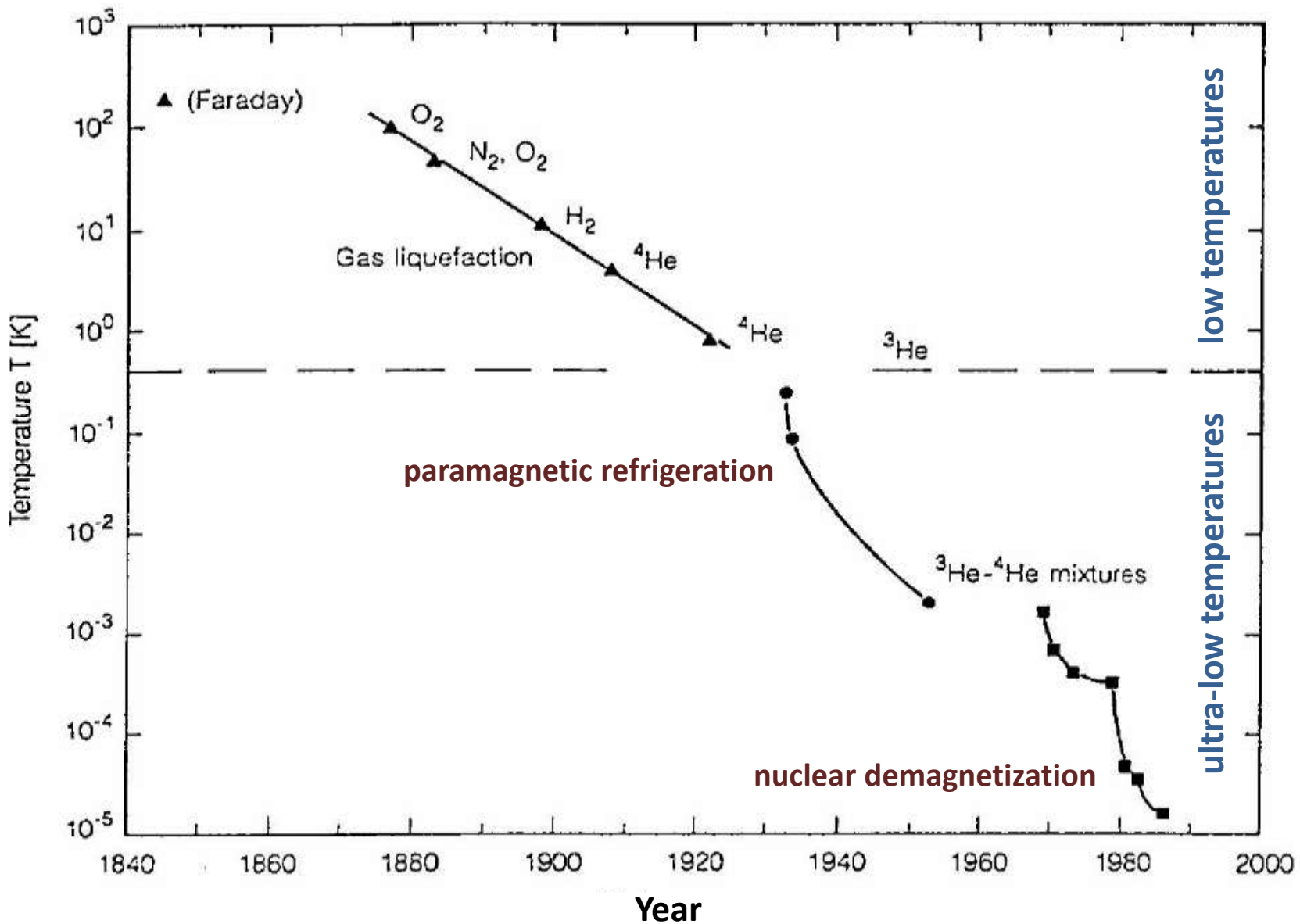
Temperature Scale



same amount of new physics on every decade of log T scale

R. Gross and A. Marx, © Walther-Meißner-Institut (2004 - 2021)

Generation of Low Temperatures



R. Gross and A. Marx, © Walther-Meißner-Institut (2004 - 2021)

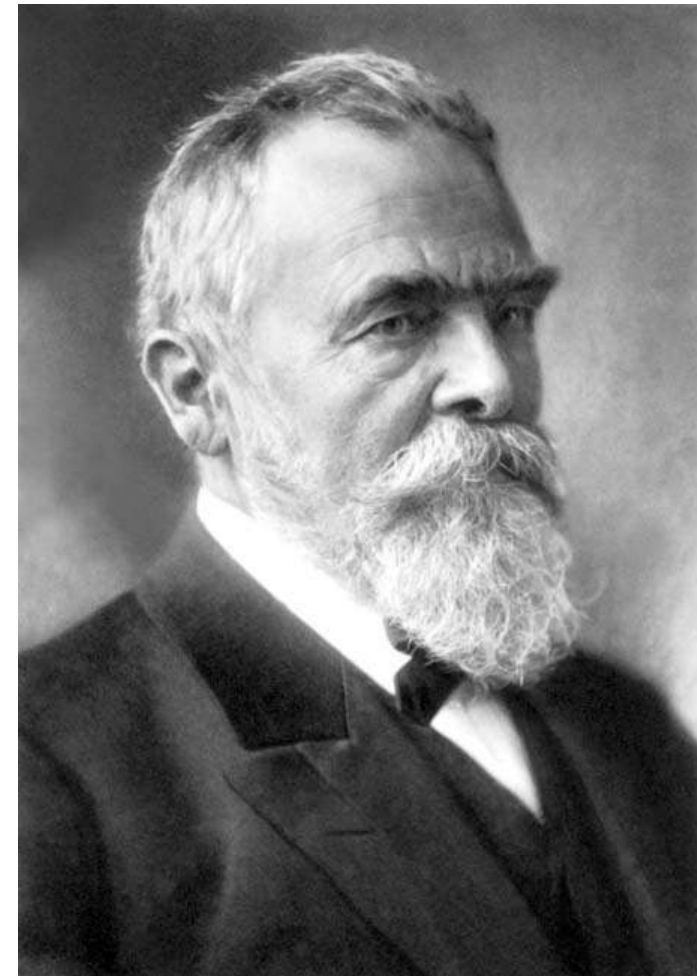
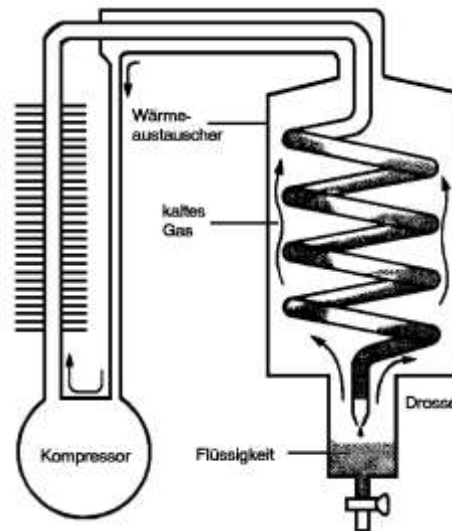
1868 offer of chair at the Polytechnische Schule München (now TUM)

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 Gegenstromverfahren*“
 liquefaction of oxygen
 ($-182^{\circ}\text{C} = 90\text{ K}$)



Carl Paul Gottfried von Linde

* 11. Juni 1842 in Berndorf, Oberfranken
 † 16. November 1934 in Munich

1930 Linde AG uses the first cooling turbines for the generation of low temperatures

turbines have higher efficiency and therefore are used today in all larger liquefaction machines

e.g. He liquefier at the Walther-Meißner-Institut

1947 first commercial He liquefier (design by engineer Collins, therefore denoted as „Collins“ machine)

Arthur D. Little Inc. (today CTI)

1966 **Hall** et al. and **Neganov** et al. develop $^3\text{He}/^4\text{He}$ dilution refrigerators, generation of temperatures down to 2 mK

Discovery of Superconductivity (1911)

Heike Kamerlingh Onnes (1853-1926)

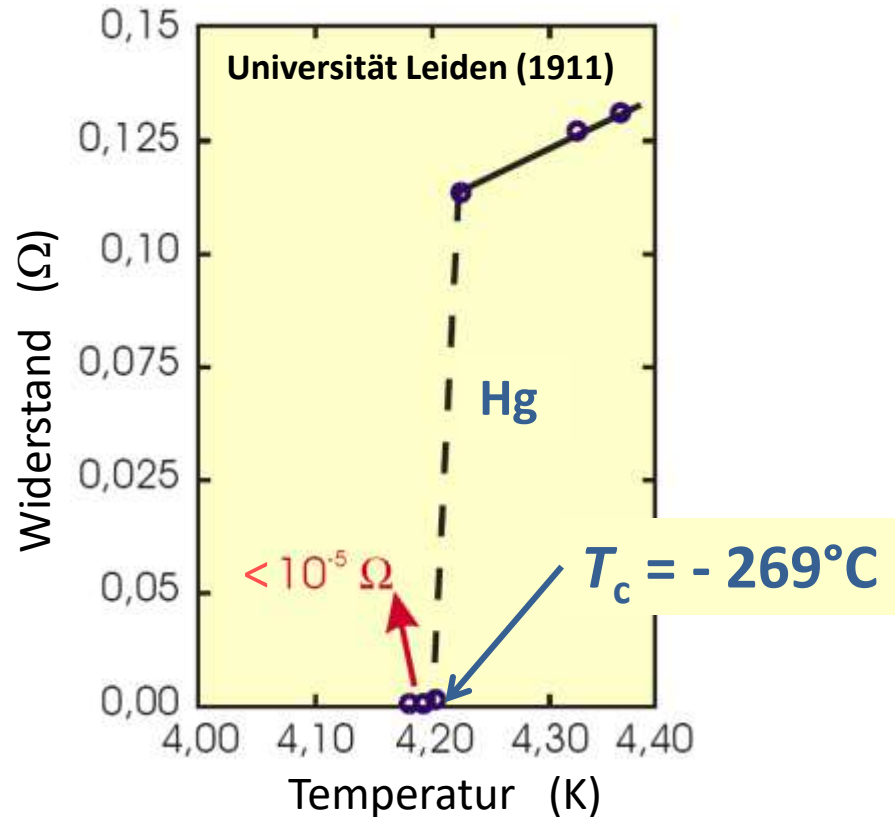


- Helium liquefaction: 1908
- discovery of superconductivity: 1911

Nobel Price in Physics 1913

choice of name:

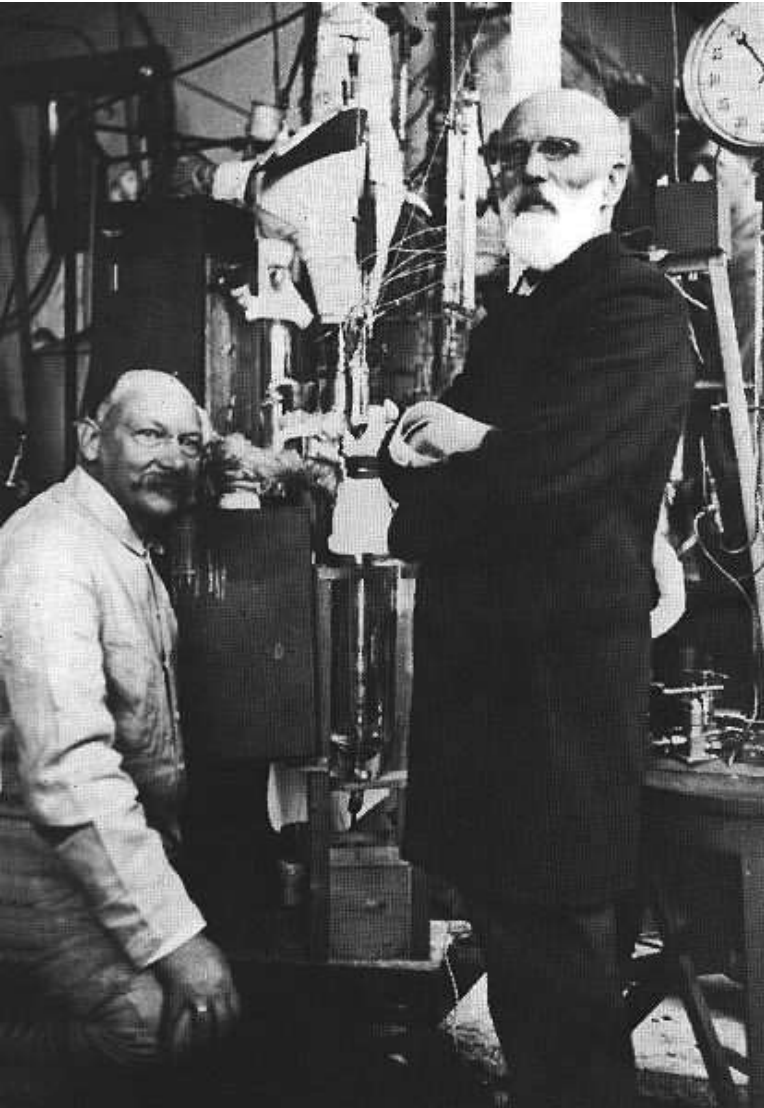
infinite electrical conductivity → **superconductivity**



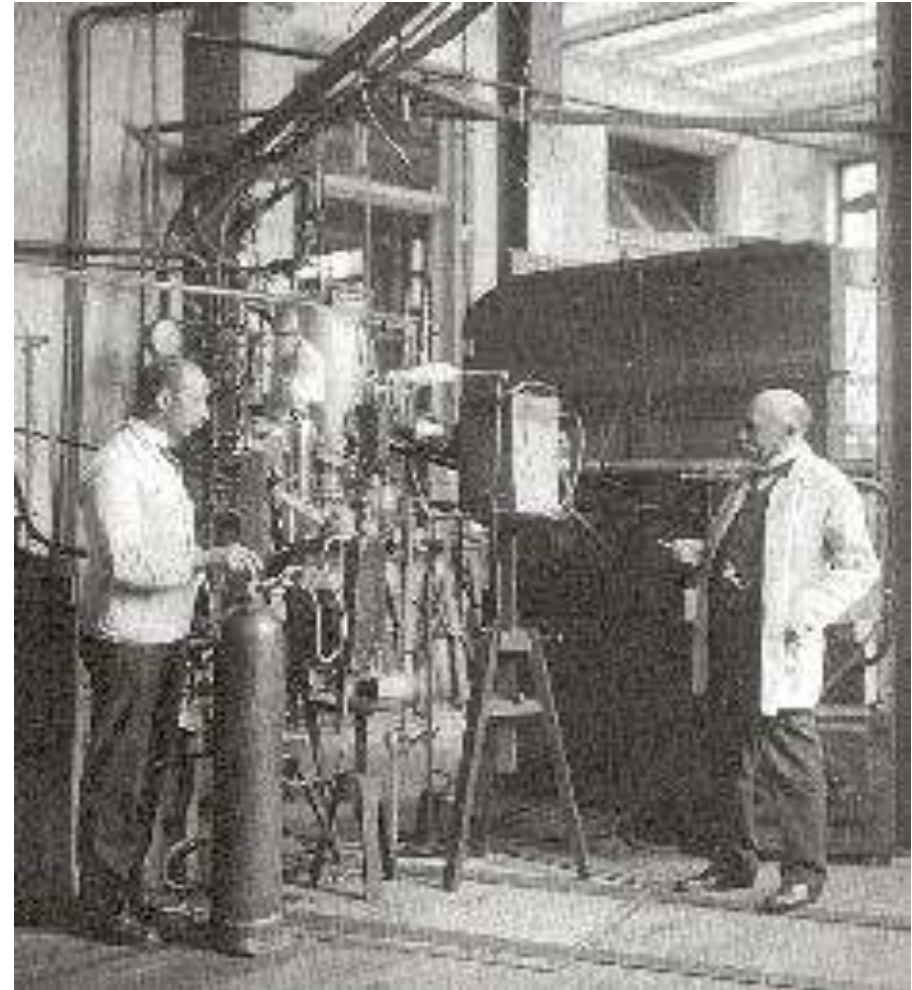
H. K. Onnes, Comm. Leiden 120b (1911)

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

Discovery of Superconductivity (1911)



Kammerlingh Onnes and van der Waals



Kammerlingh Onnes and Techniker Flim



perfect diamagnetism



Dr. Walther Meißner
a. Prof. für technische Physik. Präsident 1946-50

**Walther Meißner
(1882 – 1974)**

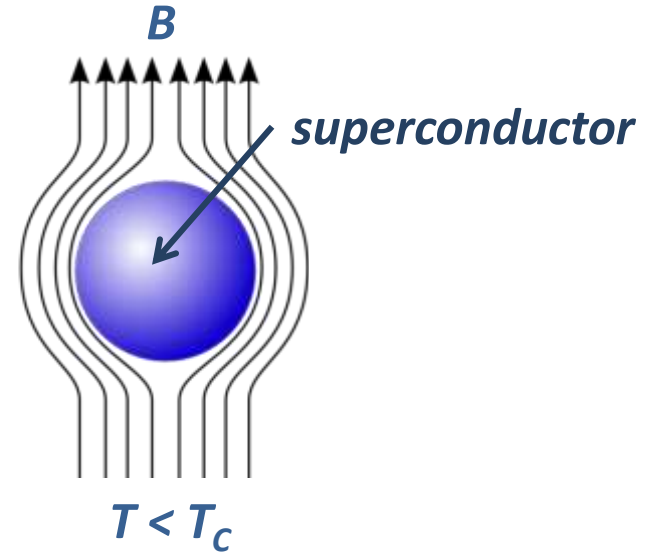
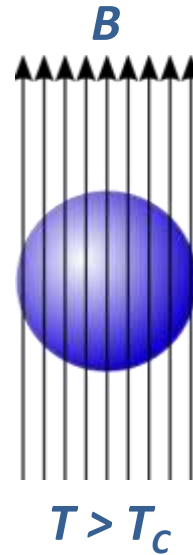
**Robert Ochsenfeld
(1901 – 1993)**

*W. Meißner, R. Ochsenfeld,
Ein neuer Effekt bei Eintritt der Supraleitfähigkeit,
Naturwissenschaften 21, 787 (1933).*

Walther Meißner (1882 – 1974)



R. Gross and A. Marx, © Walther-Meißner-Institut (2004 - 2021)



superconductors perfectly expel magnetic field

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

(χ = magnetic susceptibility)

➔ ideal diamagnetism, $\chi = -1$

choice of name for perfect diamagnetism:

Meißner-Ochsenfeld Effect



1913 – 1934

building and heading of low temperature laboratory at the Physikalisch-Technischen-Reichsanstalt, liquefaction of H₂ (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*



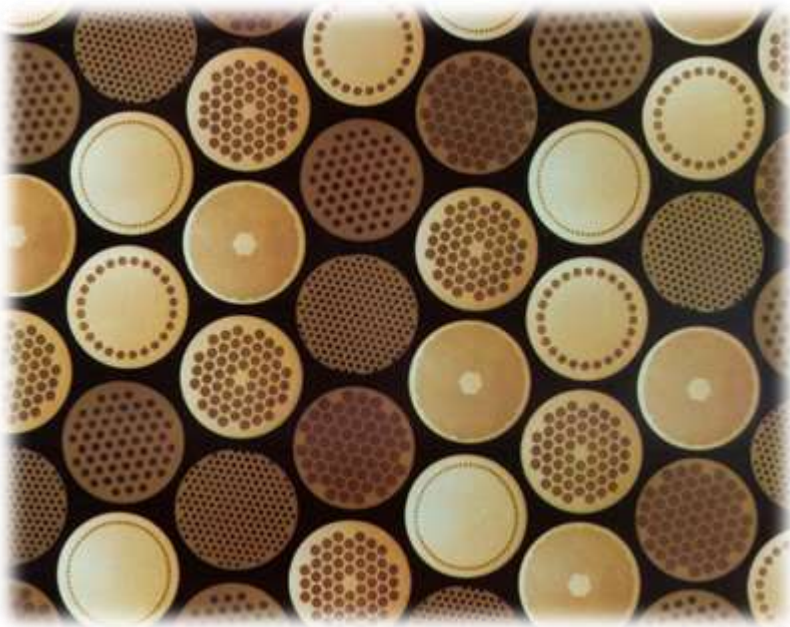
Walther Meißner

* 16. Dezember 1882 in Berlin
 † 15. November 1974 in Munich

Applications Of Superconductivity

Superconducting Wires, Tapes, and Cables

Superconducting Wires:
NbTi, Nb₃Sn in Cu-matrix

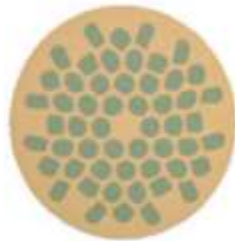


HTS tapes



**Multiple Traditional
Copper Power Cables...**

**...Replaced by One Power
Equivalent HTS Cable**

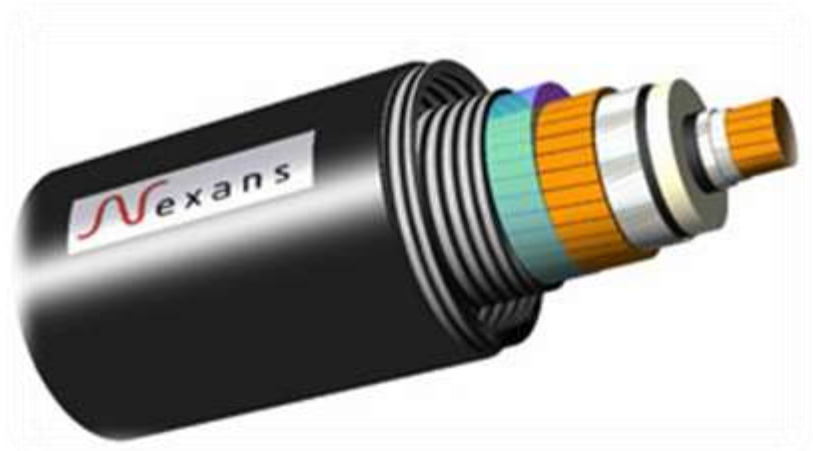
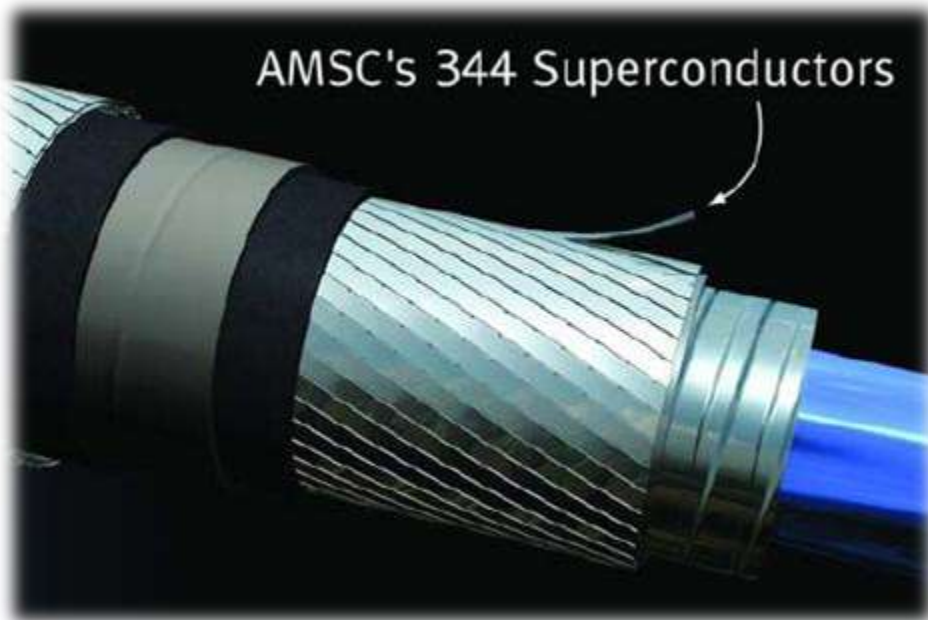
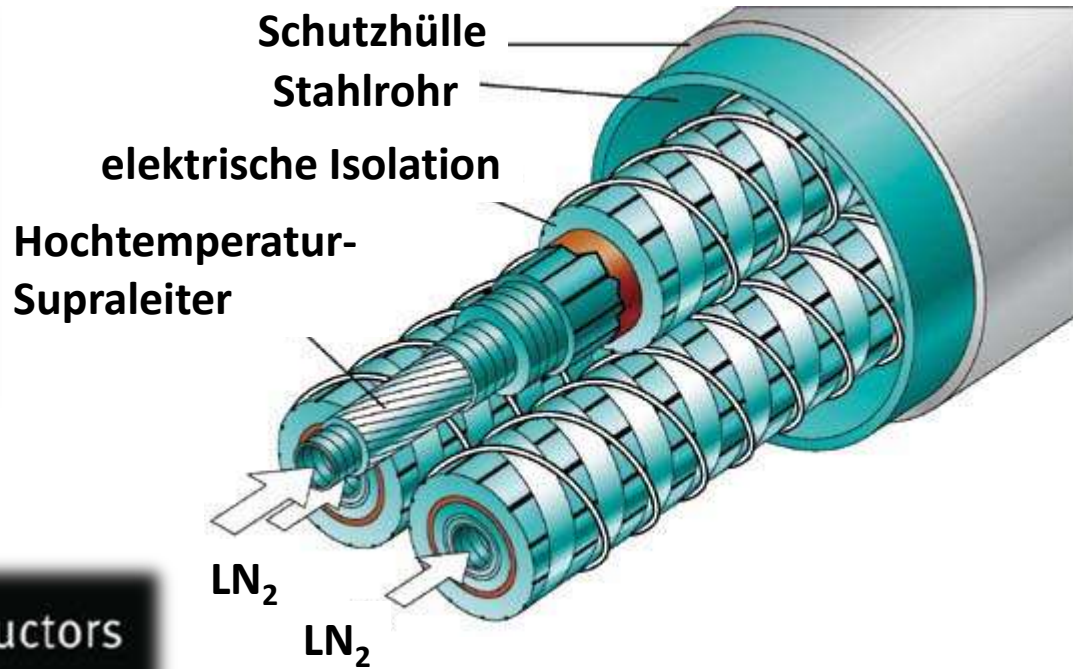


Bruker EST



Von Hand werden bei Bruker EST in Hanau Stangen aus NbTi und Kupferrohre gebündelt. Daraus entstehen dünne supra- leitende Drähte, die zahlreiche NbTi-Filamente in einer Kupfer- matrix enthalten (links).

Superconducting HTS cables



Fabrication of superconducting tapes

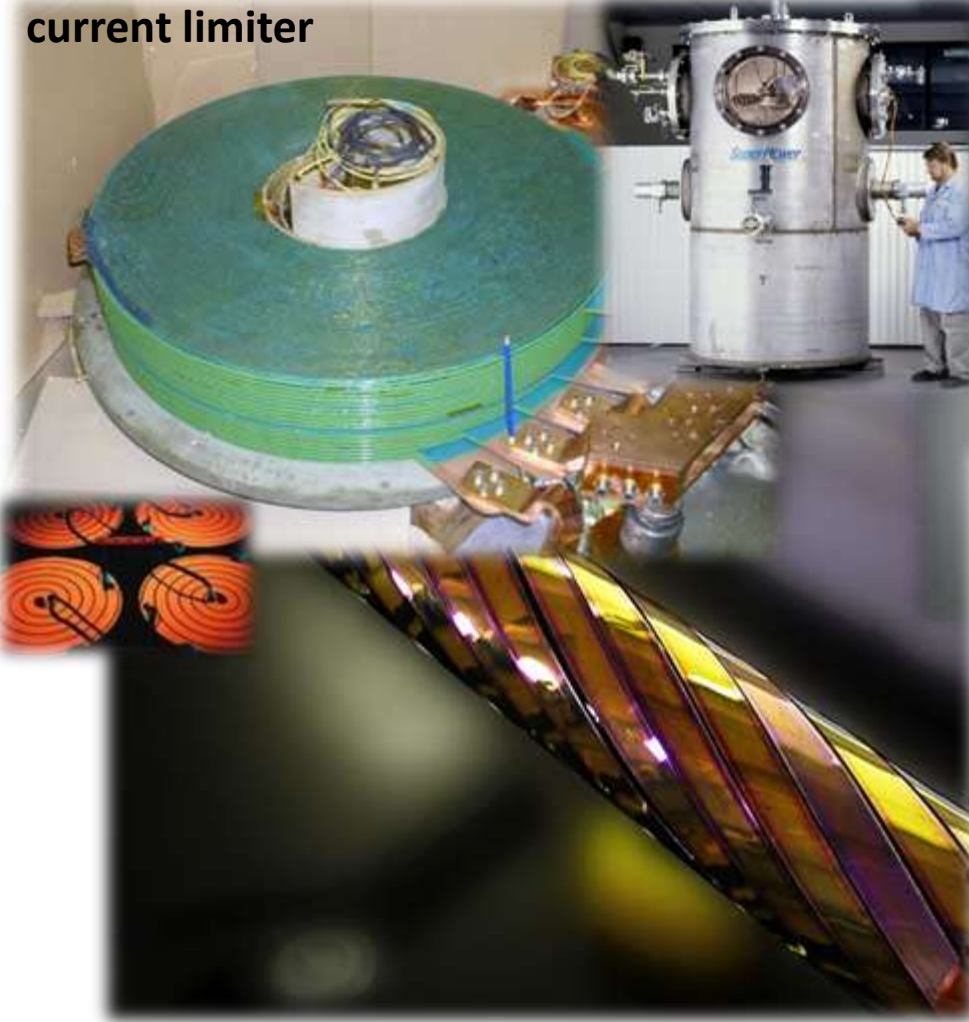
SuperPower Inc.



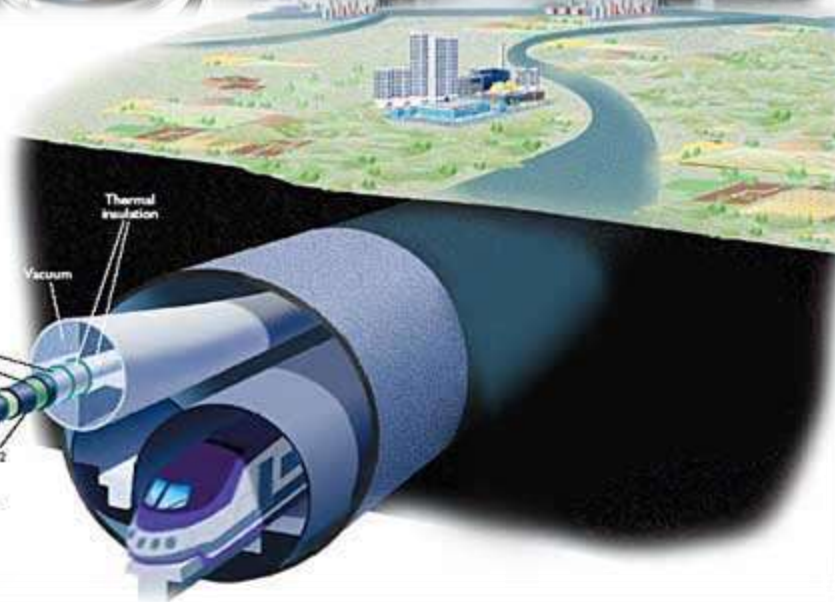
Applications of superconductivity

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

current limiter



energy storage
(2 MJ)



Fault Current
Limiter in the
power station
Boxberg of
Vattenfall

Nexans Superconductors GmbH



(Source: Physik Journal 6, 2011)



Zenergy Power GmbH

superconducting
rotor to be used
in hydroelectric
power station

(Source: Physik Journal 6, 2011)

Superconducting Magnets



(Source: Physik Journal 6, 2011)

Applications of superconductivity

- *transportation systems and traffic*

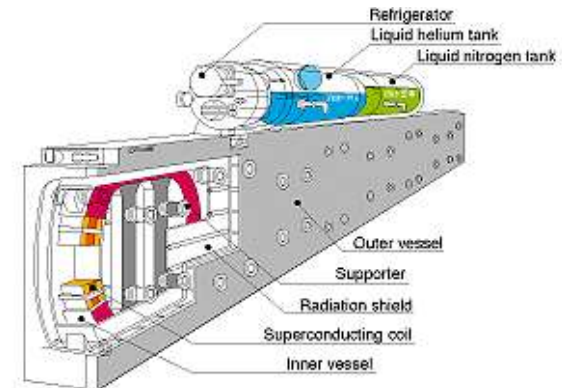


MLX01

Jap. 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*

MRI systems



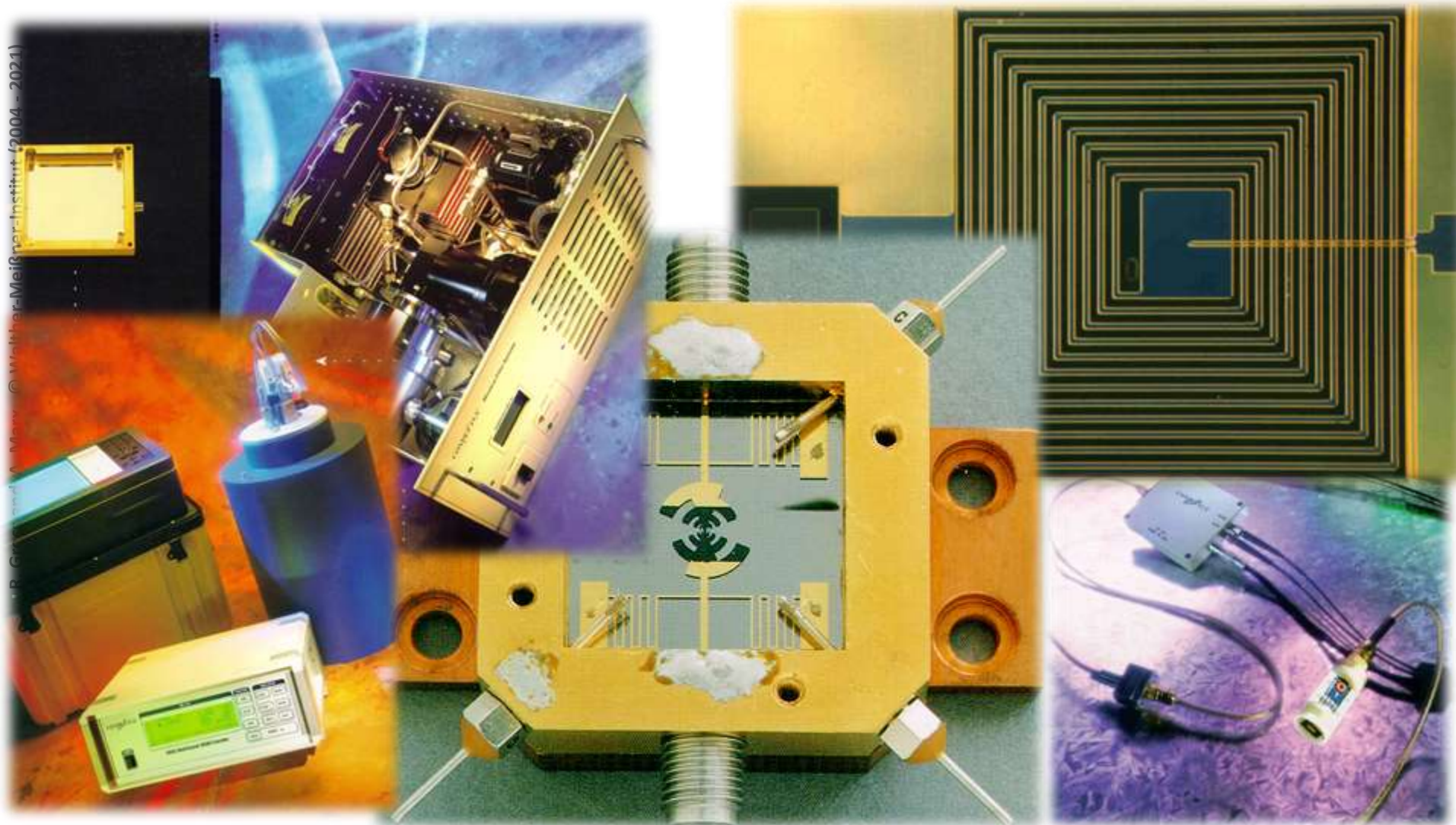
high energy physics



fusion

Applications of superconductivity

- *information and communication systems*

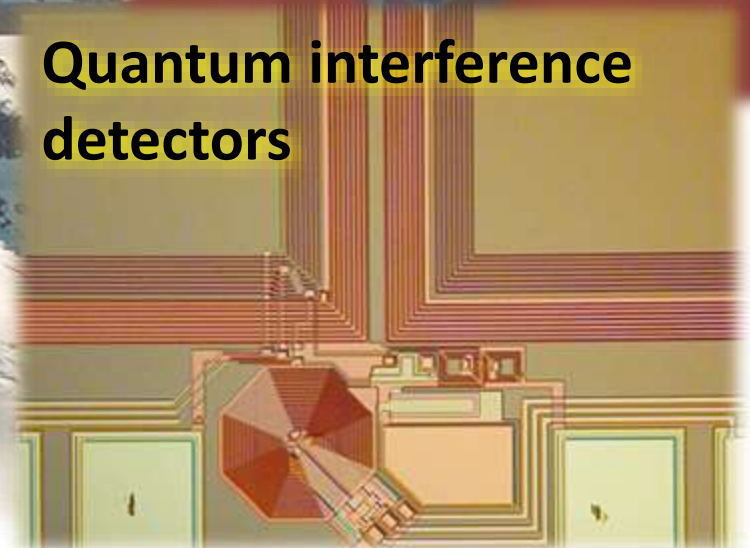


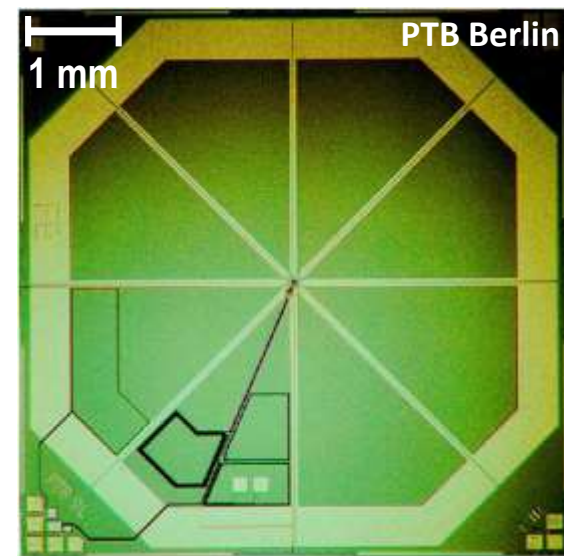
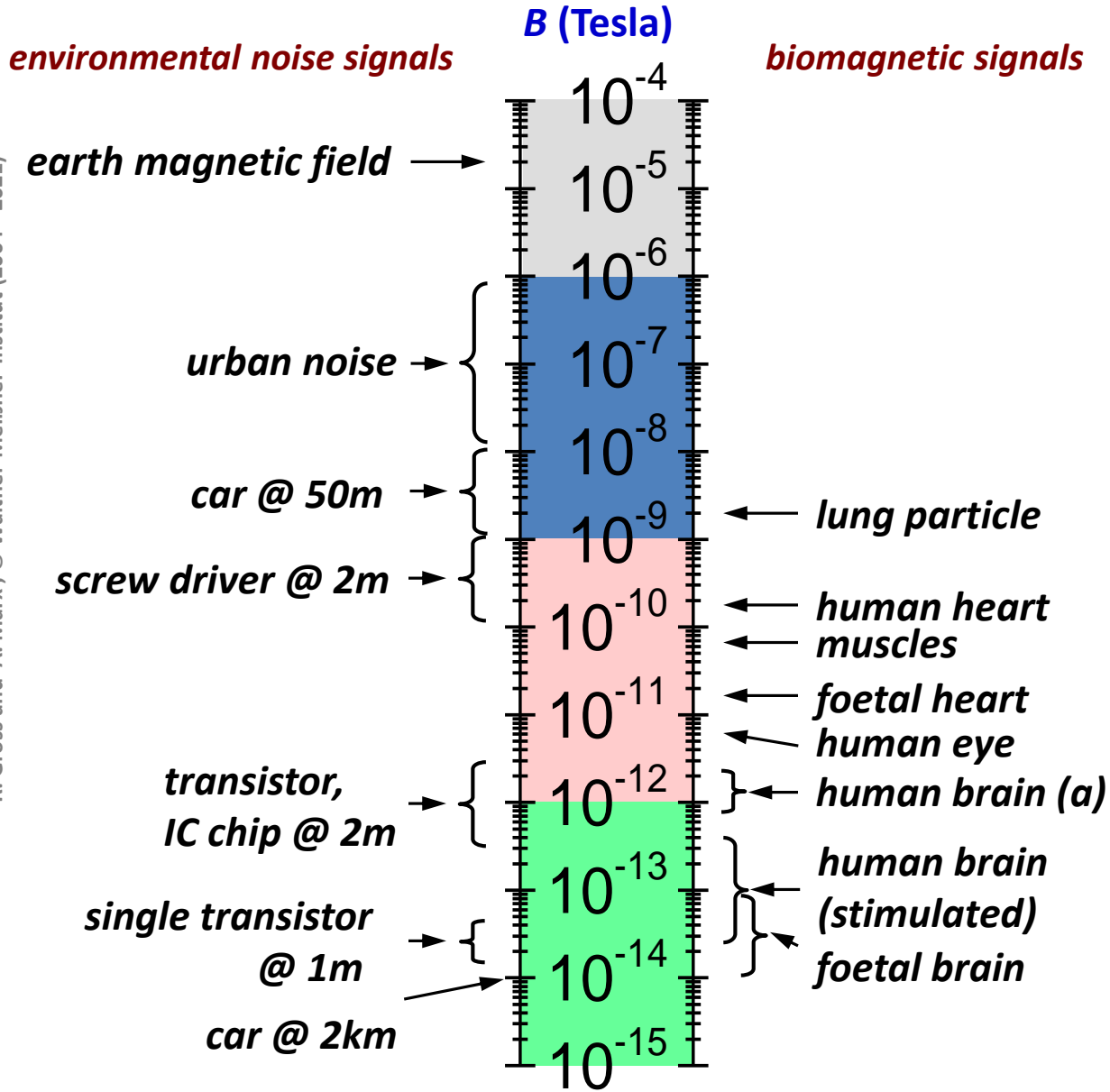
- *sensors and detectors*

microwave receivers



Quantum interference detectors



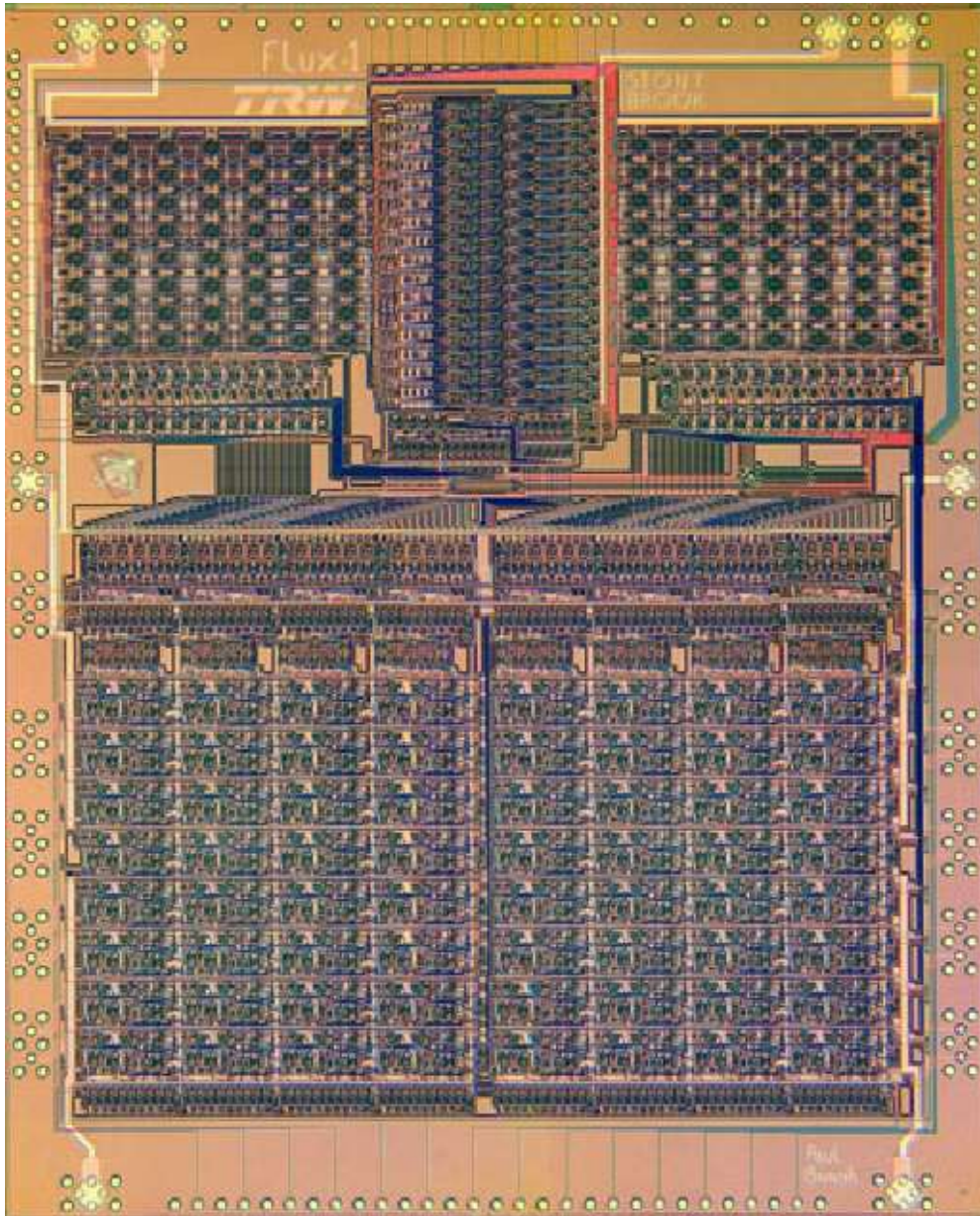


Superconducting Quantum Interference Detector (SQUID)

sensitivity:
a few fT/VHz

R. Gross and A. Marx, © Walther-Meißner-Institut (2004 - 2021)





FLUX-1

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

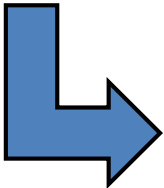
K. K. Likharev, SUNY Stony Brook

From mechanical to quantum mechanical IP

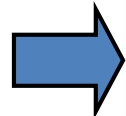
R. Gross and A. Marx, © Walther-Meißner-Institut (2004 - 2021)



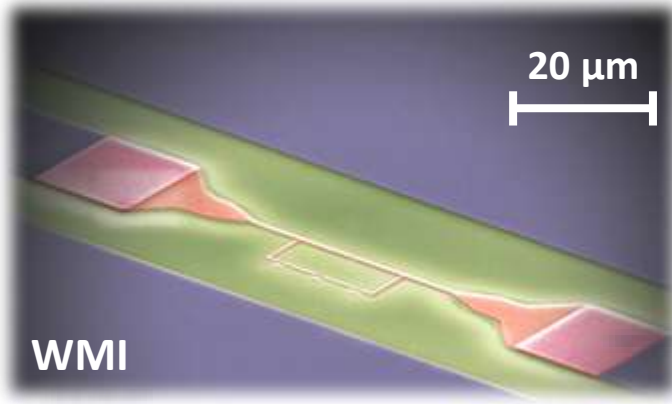
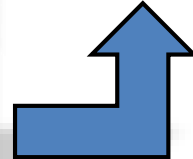
Enigma (1940)



vacuum tubes
ENIAC (1946)

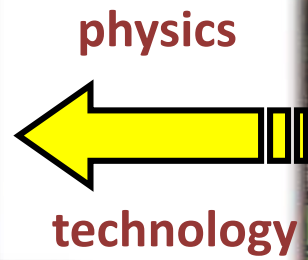


first transistor (1947)
Bardeen, Brattain, & Shockley

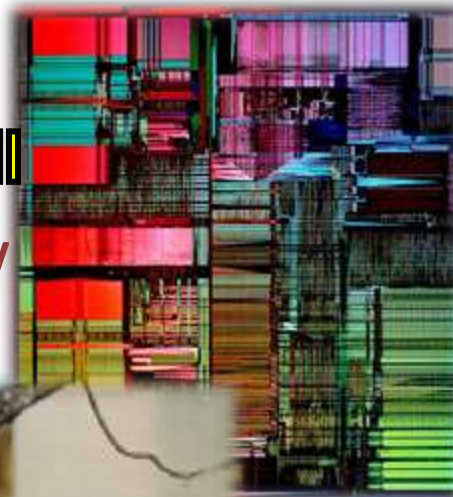


superconducting Qubit

WMI

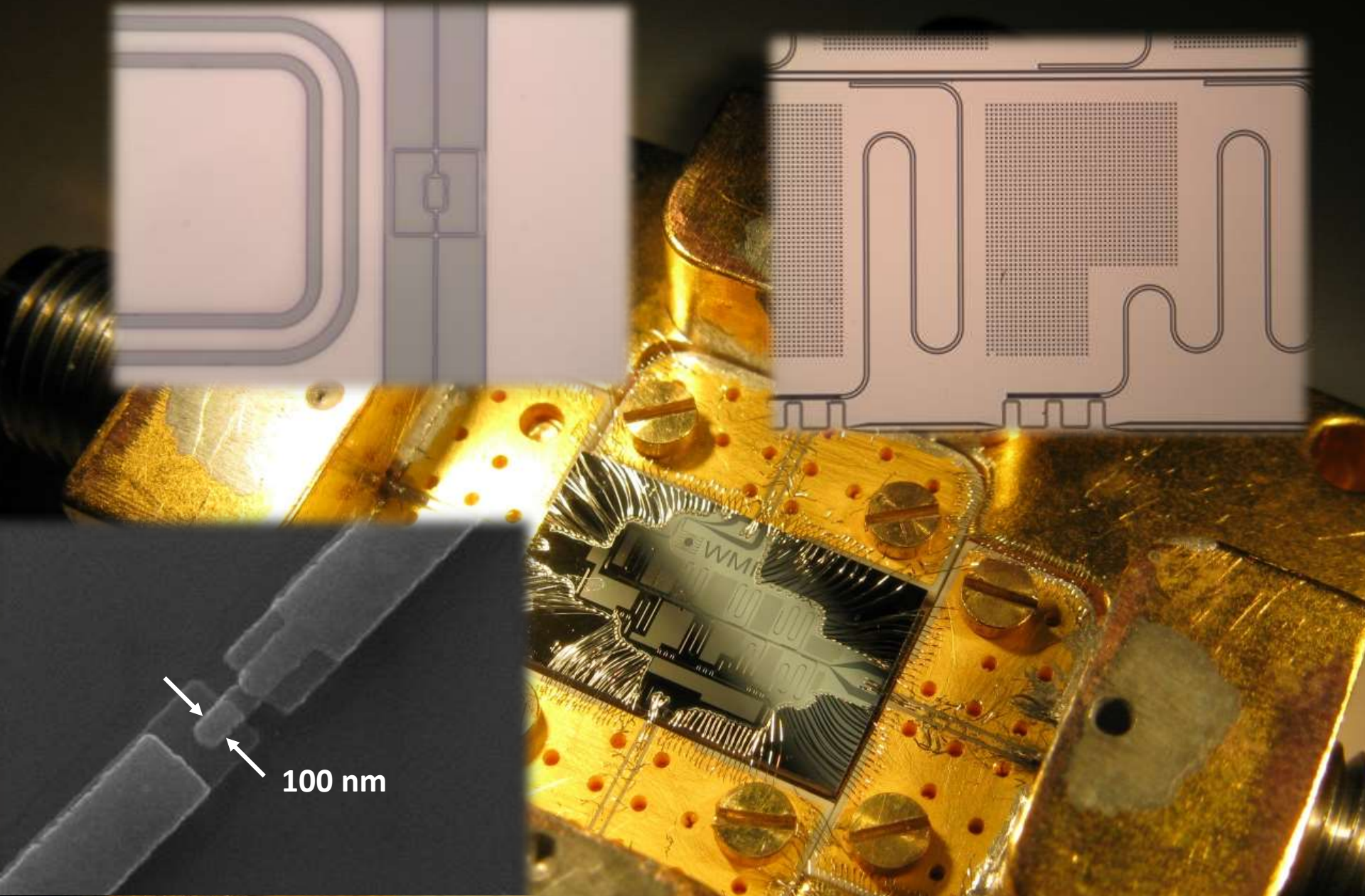


Intel dual-core 45 nm
(2007)

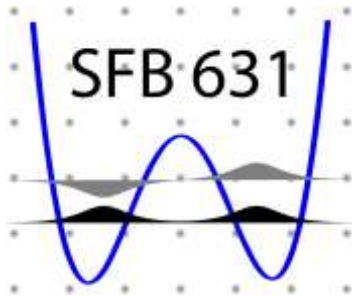




Superconducting Quantum Circuits



100 nm



Collaborative Research Center 631 (2003-2015)
Solid State Quantum Information Processing
spokesperson: R. Gross



Cluster of Excellence
Nanosystems Initiative Munich (2006-2019)
coordinator of RA on Quantum Nanophysics: R. Gross



Cluster of Excellence
Munich Center for Quantum Science & Technology (since 2019)
spokerspersons: I. Bloch, I. Cirac, R. Gross



Munich Quantum Valley (since 2021)