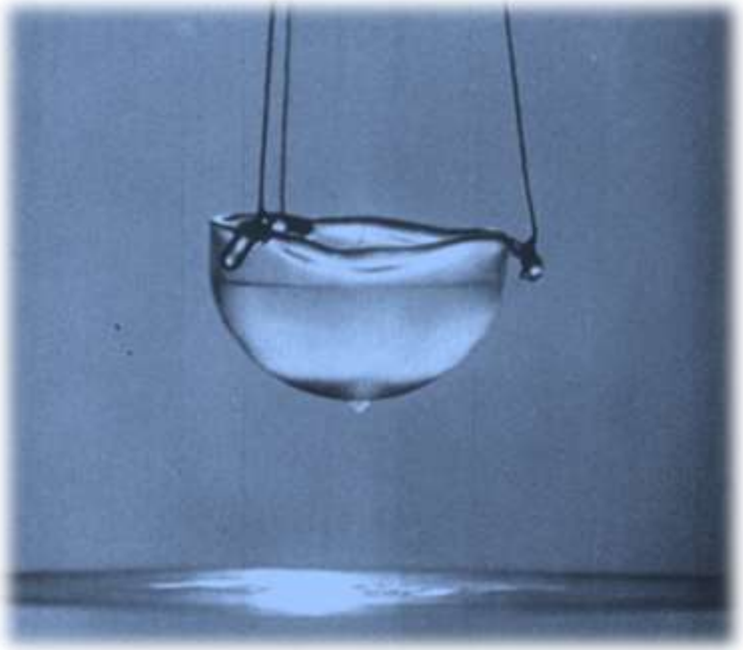
Walther Meißner Institut

BAdW | BAYERISCHE AKADEMIE DER WISSENSCHAFTEN

Technische Universität München

Superconductivity and Low Temperature Physics II



Lecture Notes
Summer Semester 2023

R. Gross

Superconductivity,
Superfluidity, Condensates, Quantum Liquids

General Remarks on the Courses to the Field
Superconductivity and Low Temperature Physics

This lecture

1. **Superconductivity and Low Temperature Physics I + II**
   ➔ Part I (WS 2022/2023): Foundations of Superconductivity
   ➔ Part II (SS 2023): Quantum Liquids, BECs, Quantum Interference Effects, Foundations of Low Temperature Physics and Techniques

2. **Applied Superconductivity I + II**
   Note
   ➔ WS 2022/23 and SS 2023, 2 hrs lecture + 2 hrs exercises
   ➔ Josephson-Effect, Superconducting Electronics, Qubits, Quantum Circuits, ….

3. **Seminars (SS 2023, 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	Pjotr 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”

Contents of Lecture

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. Quantum Gases & Liquids: Bose-Einstein condensation, Superfluid Helium (^{4}He and ^{3}He)
2. Quantum Interference Effects in Mesoscopic Conductors
3. Low Temperature Techniques

   (generation and measurement of low temperatures)

Contents Part I: Quantum Liquids

I.1 Foundations and General Properties
- I.1.1 Quantum Gases & Liquids
- I.1.2 Helium
- I.1.3 Van der Waals Bonding
- I.1.4 Zero-Point Fluctuations
- I.1.5 Helium under Pressure
- I.1.6 pT-Phase Diagram of ^{4}He and ^{3}He
- I.1.7 Characteristic Properties of ^{4}He and ^{3}He
- I.1.8 Specific Heat of ^{4}He and ^{3}He

I.2 ^{4}He as an Ideal Bose Gas
- I.2.1 Bose-Einstein Condensation
- I.2.2 Ideal Bose Gas
- I.2.3 Bose Gas with Interactions
- I.2.4 Bose-Einstein Condensation of ^{4}He

I.3 Superfluid ^{4}He
- I.3.1 Two-Fluid Model
- I.3.2 Experimental Observations
- I.3.3 Two-Fluid Hydrodynamics
- I.3.4 Excitation Spectrum of ^{4}He

I.4 Vortices
- I.4.1 Quantization of Circulation
- I.4.2 Experimental Study of Vortices

I.5 ^{3}He
- I.5.1 normal fluid ^{3}He
- I.5.2 solid ^{3}He and Pomeranchuk effect
- I.5.3 superfluid ^{3}He

I.6 ^{3}He / ^{4}He mixtures

Contents Part II: Quantum Transport in Nanostructures

II.1 Introduction

II.1.1 General Remarks
II.1.2 Mesoscopic Systems
II.1.3 Characteristic Length Scales
II.1.4 Characteristic Energy Scales
II.1.5 Transport Regimes

II.2 Description of Electron Transport by Scattering of Waves

II.2.1 Electron Waves and Waveguides
II.2.2 Landauer Formalism
II.2.3 Multi-terminal Conductors
II.2.4 Statistics of Charge Transport

II.3 Quantum Interference Effects

II.3.1 Double Slit Experiment
II.3.2 Two Barriers – Resonant Tunneling
II.3.3 Aharonov-Bohm Effect
II.3.4 Weak Localization
II.3.5 Universal Conductance Fluctuations

II.4 From Quantum Mechanics to Ohm's Law

II.5 Coulomb Blockade

Contents Part III:

III.1 Generation of Low Temperatures

III.1.1 Introduction
III.1.2 Expansion Machine
III.3 Regenerative Machine
III.1.4 Joule-Thomson Cooling
III.1.5 Summary
III.1.6 Evaporation Cooling
III.1.7 Dilution Cooling
III.1.8 Pomeranchuk Cooling
III.1.9 Adiabatic Demagnetization

III.2 Thermometry

III.2.1 Introduction
III.2.2 Primary Thermometers
III.2.3 Secondary Thermometers

Literature

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  The Physics of Liquid and Solid Helium I and II, Wiley 1978
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- Supriyoto Datta
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- Thomas Heinzel
  Mesoscopic Electronic in Solid State Nanostructures, Wiley VCH, Weinheim (2003)
- Thomas Ihn
  Semiconductor Nanostructures, Oxford University Press (2010)

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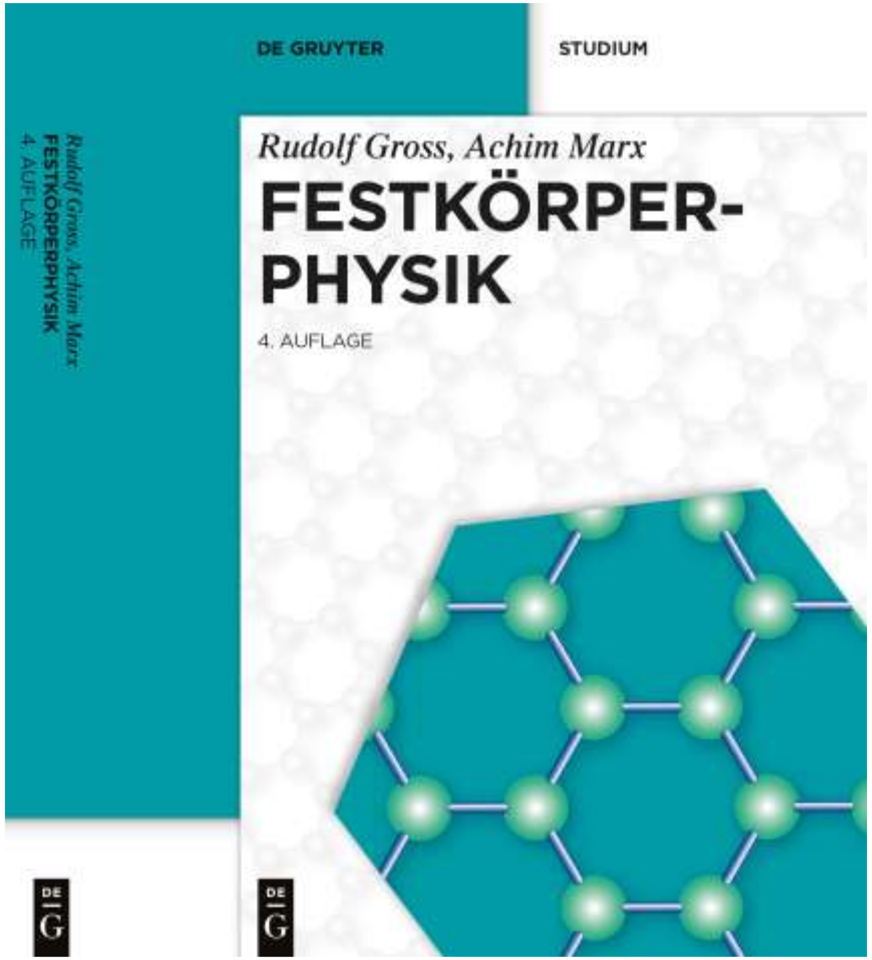


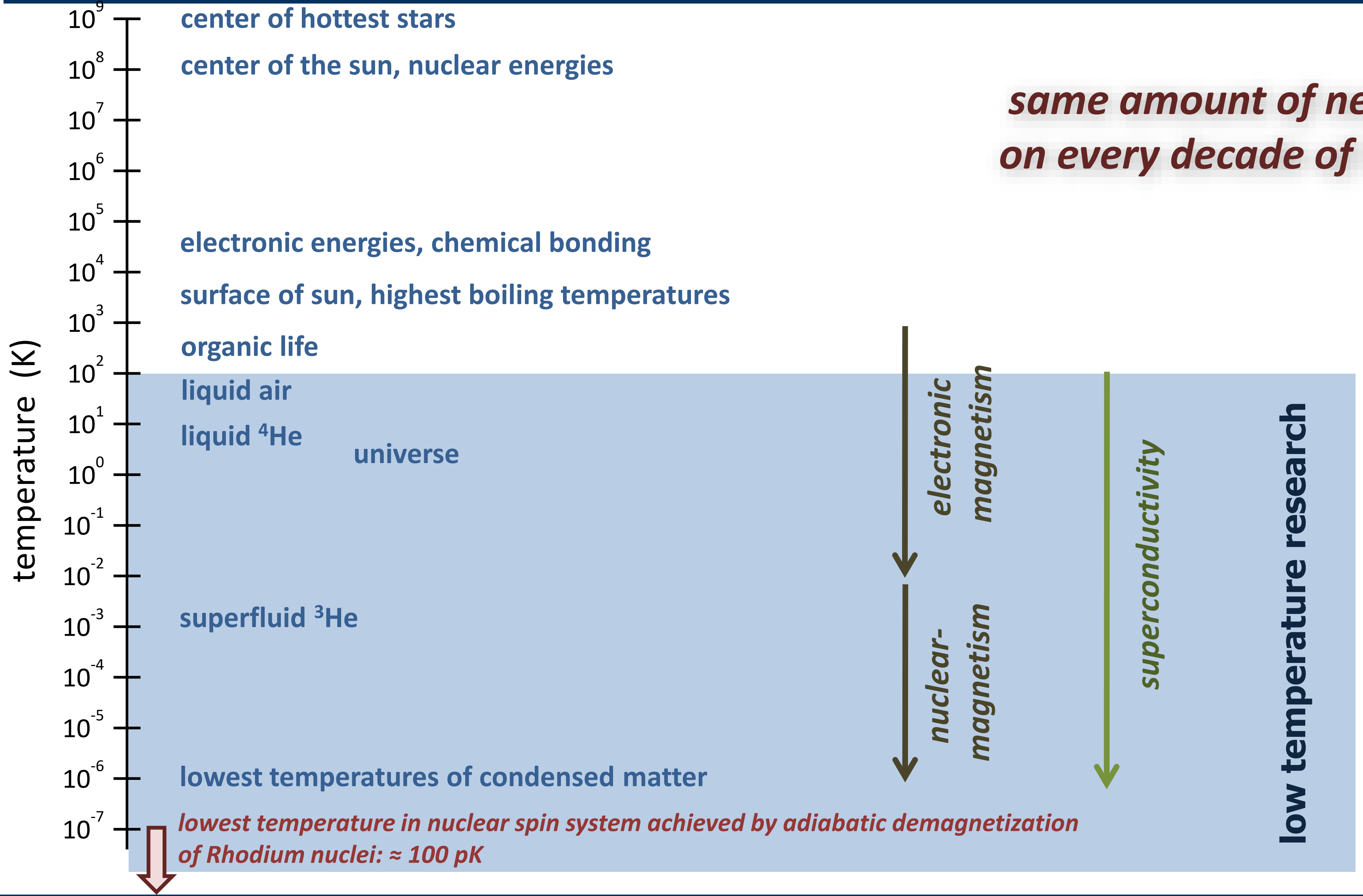
Rudolf Gross, Achim Marx

Title: Festkörperphysik, 4th revised and extended edition
Publisher: Walter de Gruyter GmbH, Berlin/Boston
Published: January 2023
Language: German
9783110782349 (hardcover), ISBN 9783110782394 (eBook)

13	**Supraleitung**	769
13.1	Geschichte und grundlegende Eigenschaften	772
13.1.1	Geschichte der Supraleitung	772
13.1.2	Supraleitende Materialien	780
13.1.3	Sprungtemperaturen	783
13.1.4	Grundlegende Eigenschaften	784
13.2	Thermodynamische Eigenschaften von Supraleitern	792
13.2.1	Typ-I Supraleiter im Magnetfeld	792
13.2.2	Typ-II Supraleiter im Magnetfeld	797
13.3	Phänomenologische Modelle	798
13.3.1	London-Gleichungen	798
13.3.2	Verallgemeinerte London Theorie – Supraleitung als makroskopisches Quantenphänomen	801
13.3.3	Die Ginzburg-Landau-Theorie	813
13.4	Typ-I und Typ-II Supraleiter	825
13.4.1	Mischzustand und kritische Felder	826
13.4.2	Supraleiter-Normalleiter Grenzflächenenergie	827
13.4.3	Vertiefungsthema: Zwischenzustand und Entmagnetisierungseffekte	829
13.4.4	Kritische Felder	830
13.4.5	Vertiefungsthema: Nukleation an Oberflächen	834
13.4.6	Vertiefungsthema: Shubnikov-Phase und Flussliniengitter	835
13.4.7	Vertiefungsthema: Flusslinien in Typ-II Supraleitern	838
13.4.8	Kritische Stromdichte	843
13.5	Mikroskopische Theorie	847
13.5.1	Attraktive Elektron-Elektron-Wechselwirkung und Cooper-Paare	849
13.5.2	Der BCS-Grundzustand	858
13.5.3	Energielücke und Anregungsspektrum	873
13.5.4	Quasiteilchentunneln	875
13.5.5	Thermodynamische Größen	879
13.6	Josephson-Effekt	883
13.6.1	Die Josephson-Gleichungen	883
13.6.2	Josephson-Kontakt mit Wechselspannung	888
13.6.3	Josephson-Kontakt im Magnetfeld	889
13.6.4	Supraleitende Quanteninterferometer	893
13.7	Kritische Ströme in Typ-II Supraleitern	895
13.7.1	Stromtransport im Mischzustand	896
13.7.2	Lorentz-Kraft	898
13.7.3	Reibungskraft	900
13.7.4	Haftkraft	901
13.8	Unkonventionelle Supraleitung	903
13.9	Kuprat-Supraleiter	905
13.9.1	Strukturelle Eigenschaften	906
13.9.2	Elektronische Eigenschaften	907
13.9.3	Supraleitende Eigenschaften	912
	Literatur	921

Introduction

Temperature Scale



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

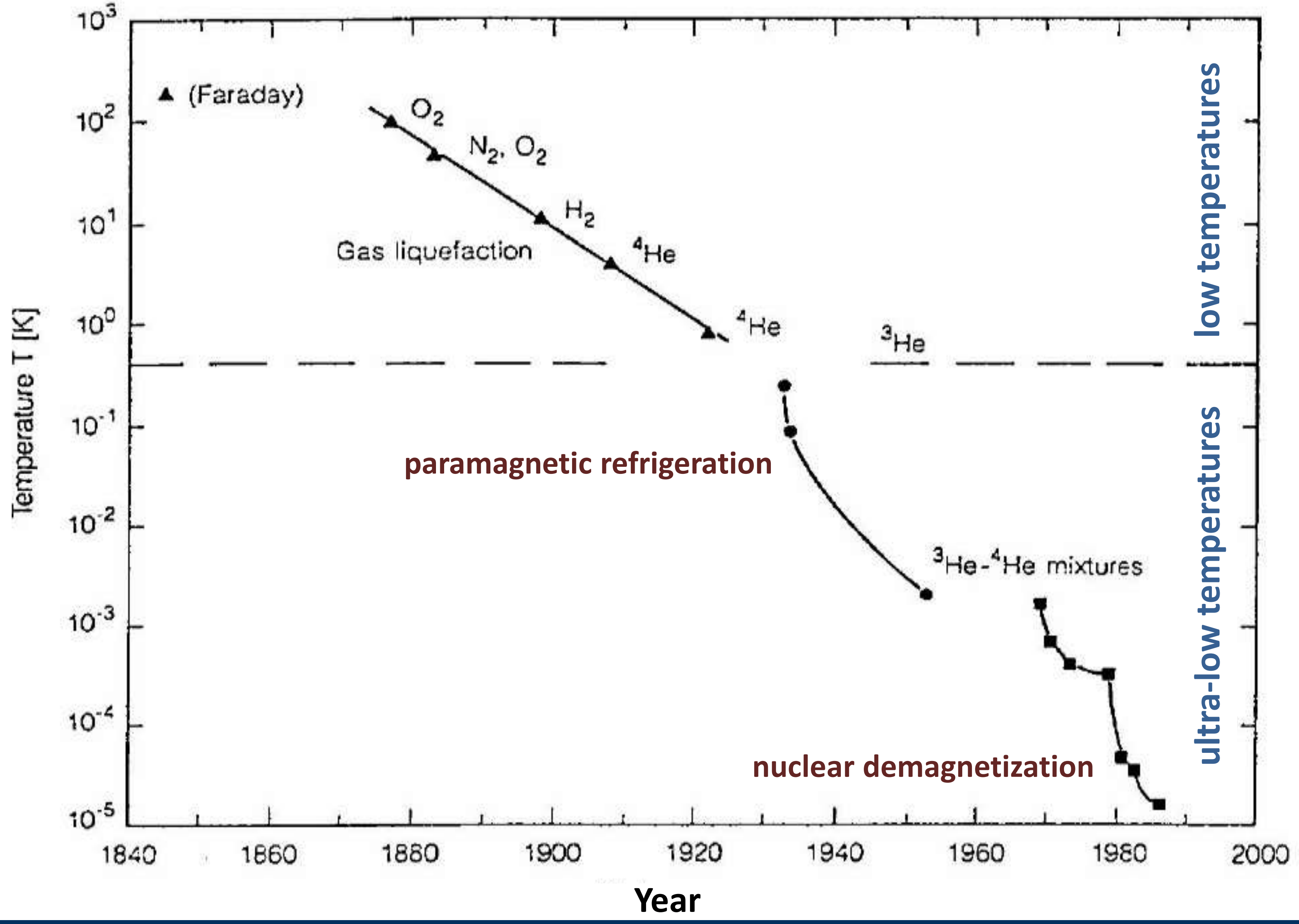
Low Temperature Phenomena

- **many direct implications of quantum mechanics only show up at low temperatures**

  e.g. magnetism, superconductivity

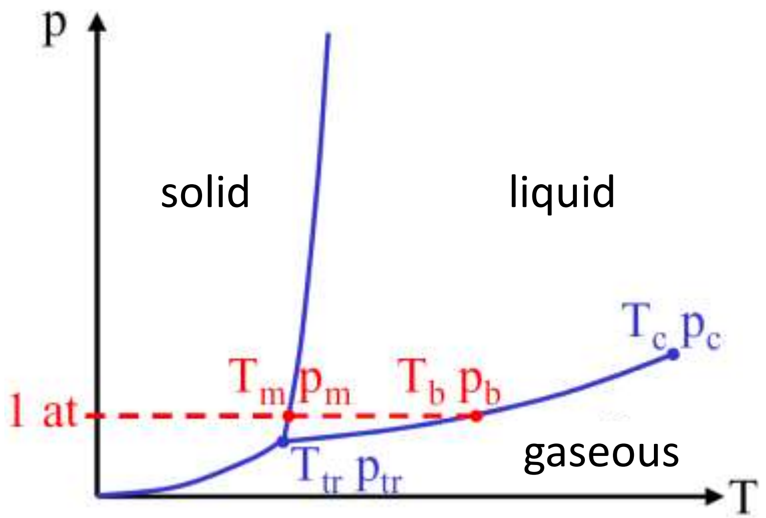
- **particularly interesting are quantum phenomena manifesting themselves on a macroscopic length scale**
  ➔ ***macroscopic quantum phenomena***
  – Superconductivity
  – **Superfluidity** } this lecture
  – **Bose-Einstein Condensation** } this lecture

Generation of Low Temperatures



Generation of Low Temperatures

Substance	T_b [K]	T_m [K]	T_{tr} [K]	P_{tr} [bar]	T_c [K]	P_c [bar]
	@ 1 bar					
H_2O	373.15	273.15	273.16	0.06	647.3	220
Xe	165.1	161.3	161.4	0.82	289.8	58.9
Kr	119.9	115.8	114.9	0.73	209.4	54.9
O_2	90.2	54.4	54.36	0.016	154.3	50.4
Ar	87.3	83.8	83.81	0.67	150.9	48.7
N_2	77.4	63.3	63.15	0.12	126.0	33.9
Ne	27.1	24.5	24.56	0.43	44.5	27.2
D_2	23.7	18.7	18.72	0.17	38.3	16.6
H_2	20.3	14.0	13.80	0.07	33.3	13.0
^4He	4.21	--	--	--	5.20	2.28
^3He	3.19	--	--	--	3.32	1.16



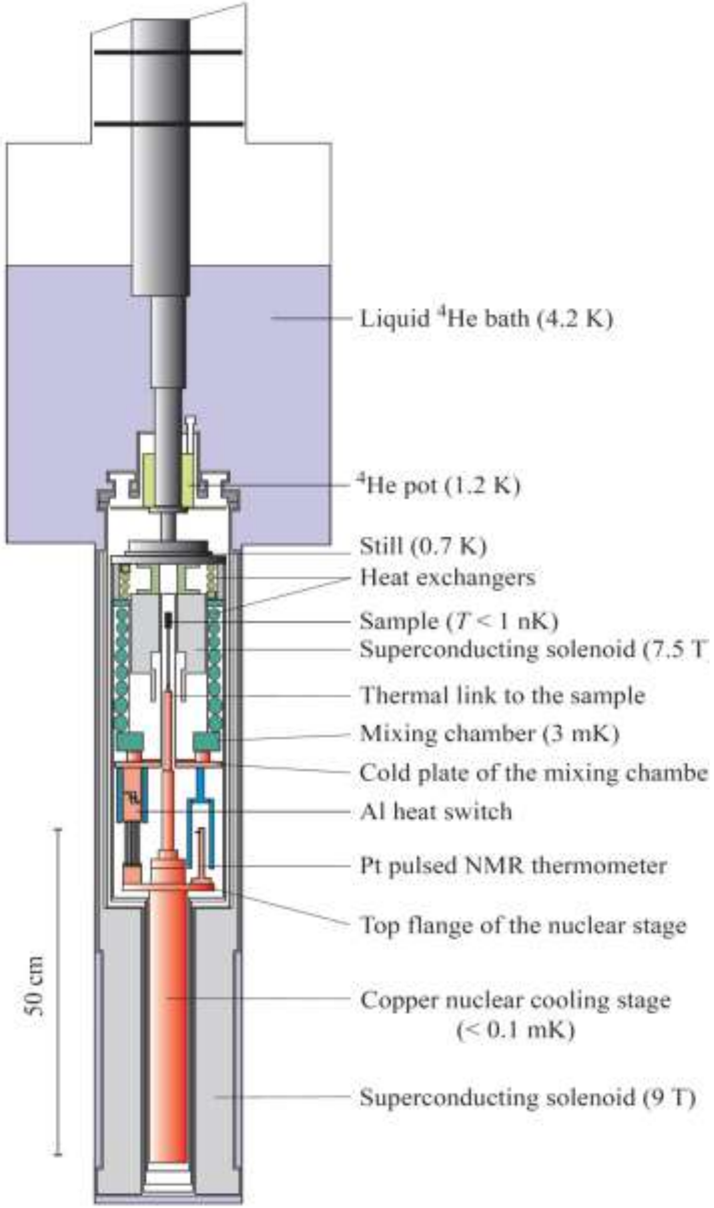
Generation of Low Temperatures

- **nuclear demagnetization**

experimental setup according to
Tauno Knuuttila (2000)

lowest temperature of nuclear spin system:
about **100 pK**
by demagnetization of Rhodium nuclei

PhD Thesis,
Helsinki University of Technology
(Espoo, Finland)



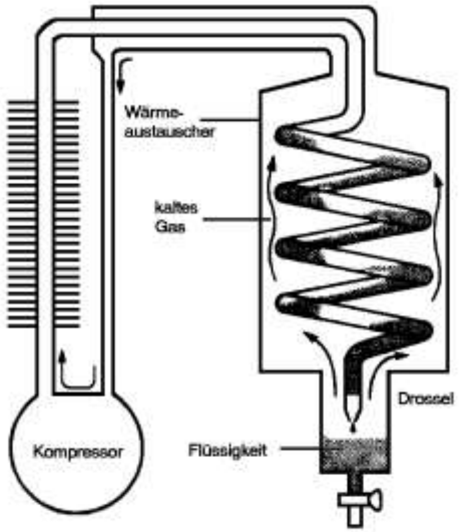
1868 offer of chair at the Polytechnische Schule München (now TUM)

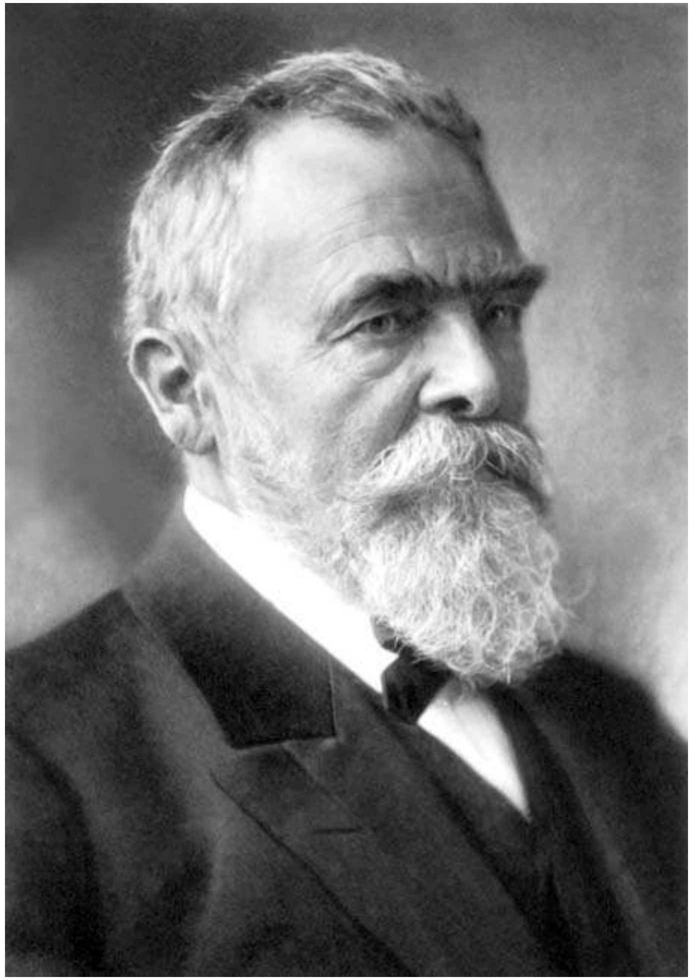
1873 development of cooling machine allowing the temperature stabilization in beer brewing

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 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

Low Temperature Technology

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

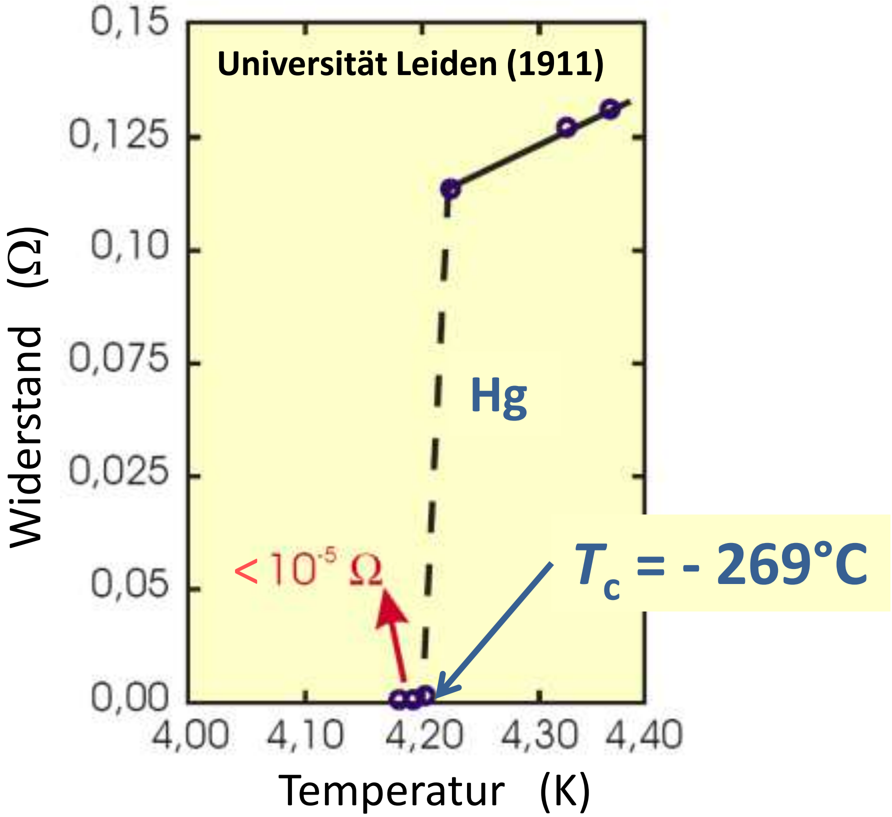
e.g. He liquefier at the Walther-Meißner-Institut

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}He/^{4}He dilution refrigerators, generation of temperatures down to 2 mK

Discovery of Superconductivity (1911)



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

- Helium liquefaction: 1908
- discovery of superconductivity: 1911

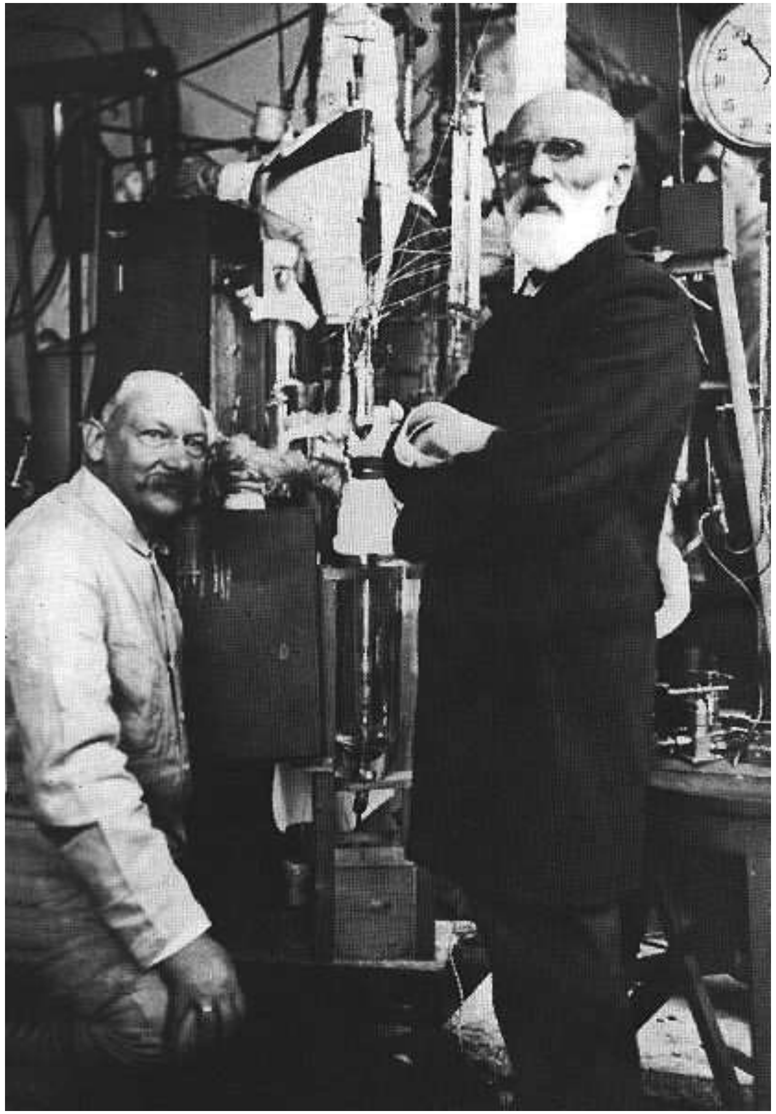
Nobel Price in Physics 1913

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

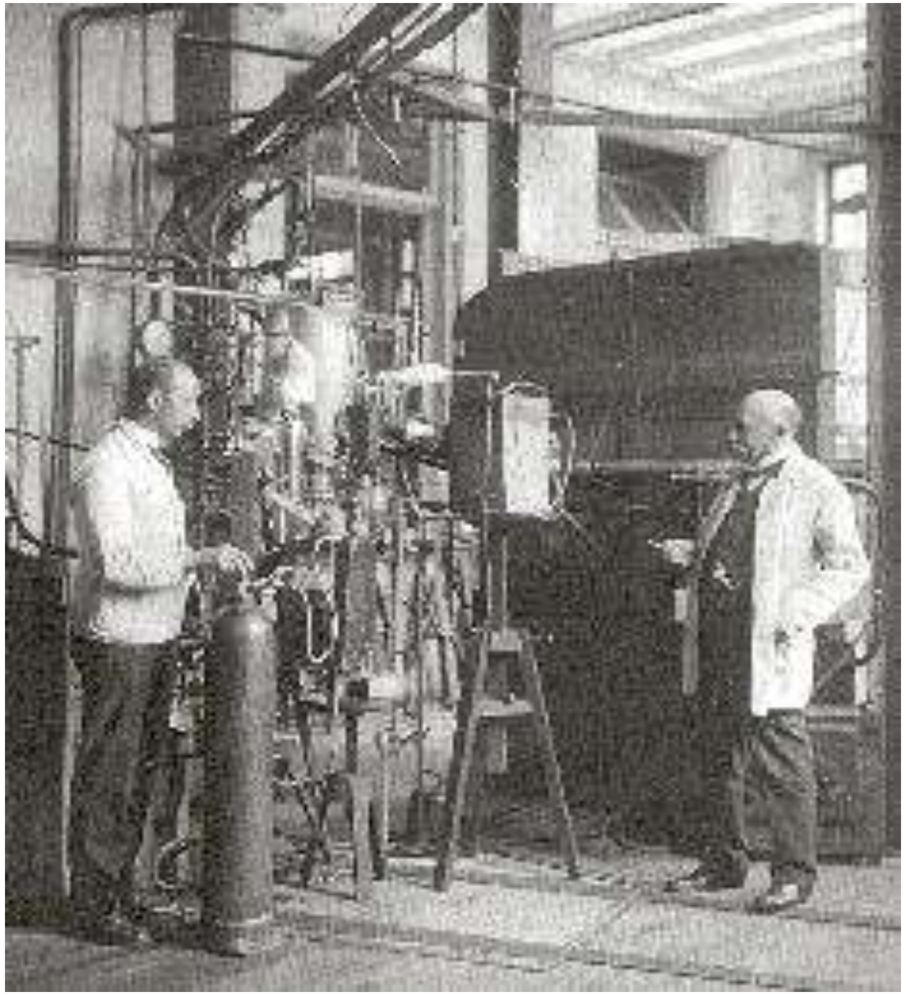
choice of name:

infinite electrical conductivity ➔ **superconductivity**

Discovery of Superconductivity (1911)



Kammerlingh Onnes and van der Waals



Kammerlingh Onnes and Technician Flim

Discovery of the Meißner-Ochsenfeld Effect (1933)

Robert Ochsenfeld
(1901 – 1993)

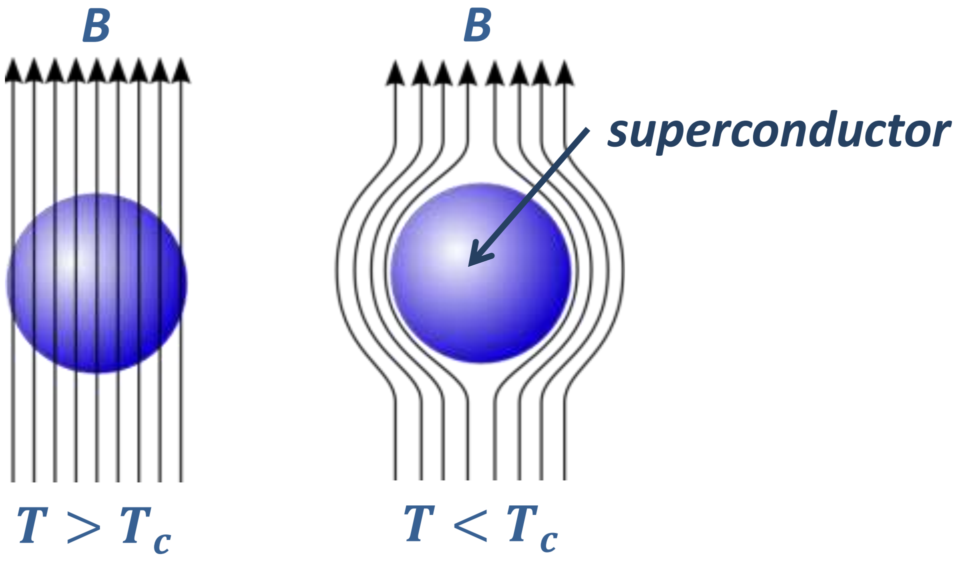
perfect diamagnetism

Walther Meißner
(1882 – 1974)

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

Discovery of the Meißner-Ochsenfeld Effect (1933)

Walther Meißner (1882 – 1974)



superconductors perfectly expel magnetic field

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

χ = magnetic susceptibility

⇨ **ideal diamagnetism, $\chi = -1$**

choice of name for perfect diamagnetism:

Meißner-Ochsenfeld Effect

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 Bavarian Academy of Sciences and Humanities

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

Low Temperature Physics

at

WMI

Low Temperature Physics at WMI

- **superconductivity and superfluidity**
- **magnetism and spintronics**
- **nanoscale superconducting and spintronic devices**
- **solid-state based quantum systems**
- **superconducting quantum circuits for quantum computing**
- **quantum microwave communication and sensing**
- **………**

an appetizer

Low Temperature Physics at WMI

innovative cryoengineering

.....WMI develops first dry dilution fridge

K. Uhlig, Cryogenics 42, 73 – 77 (2002)

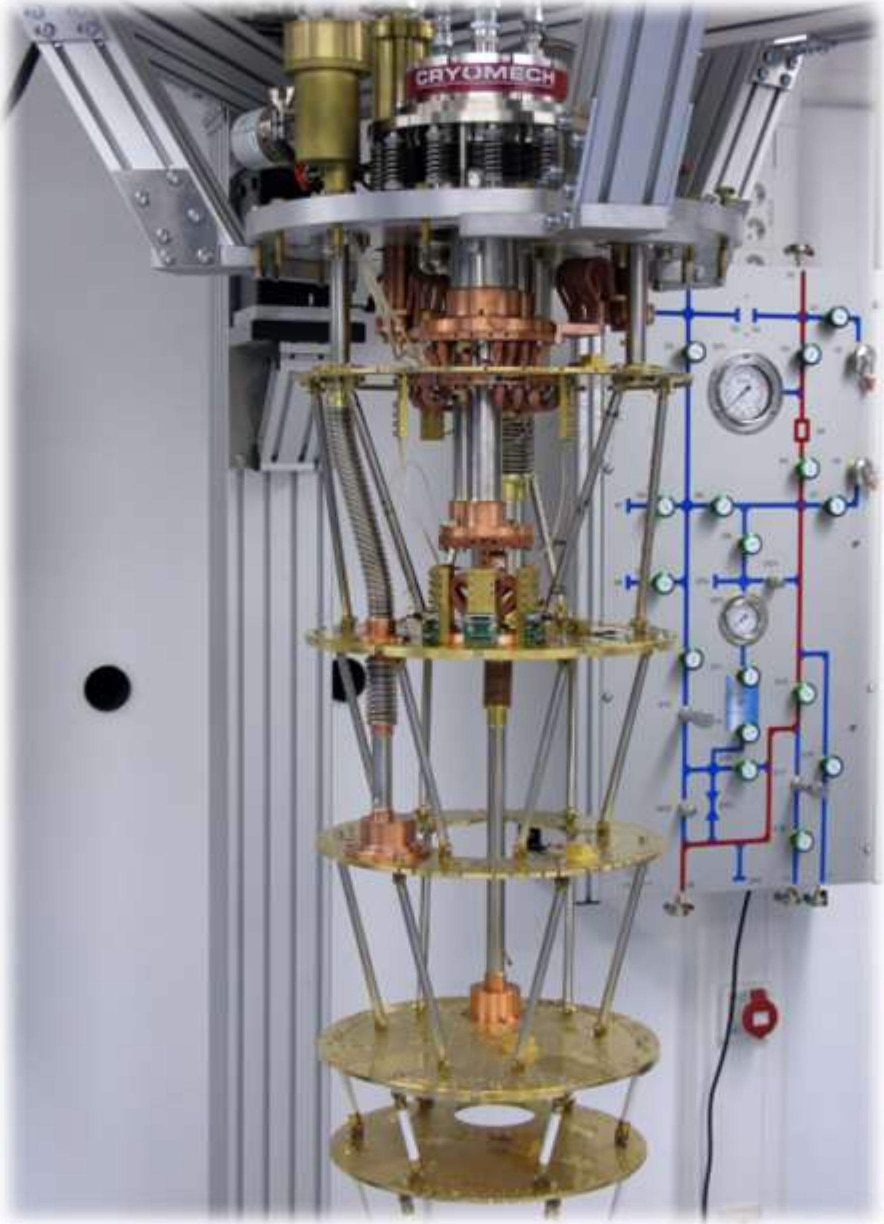
WMI inside

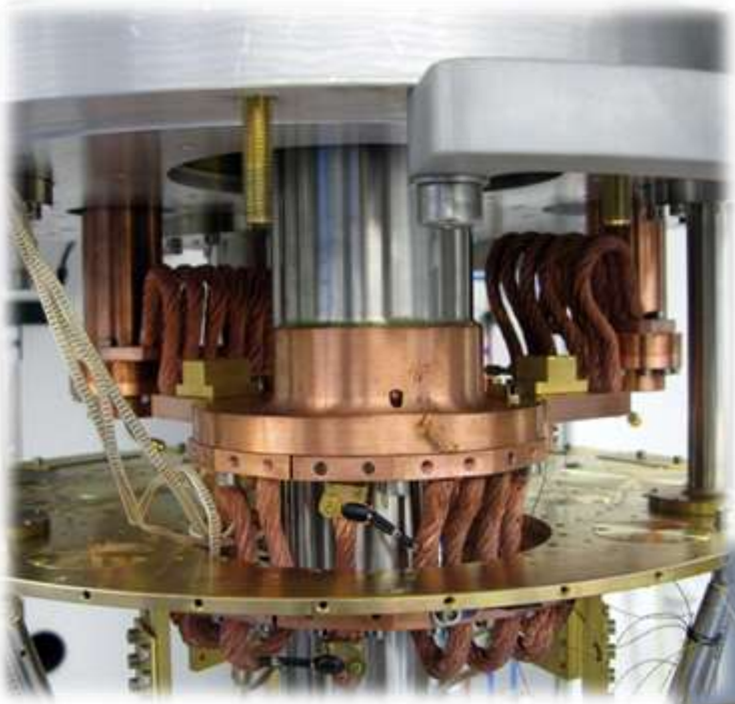
Oxford Instruments Triton family

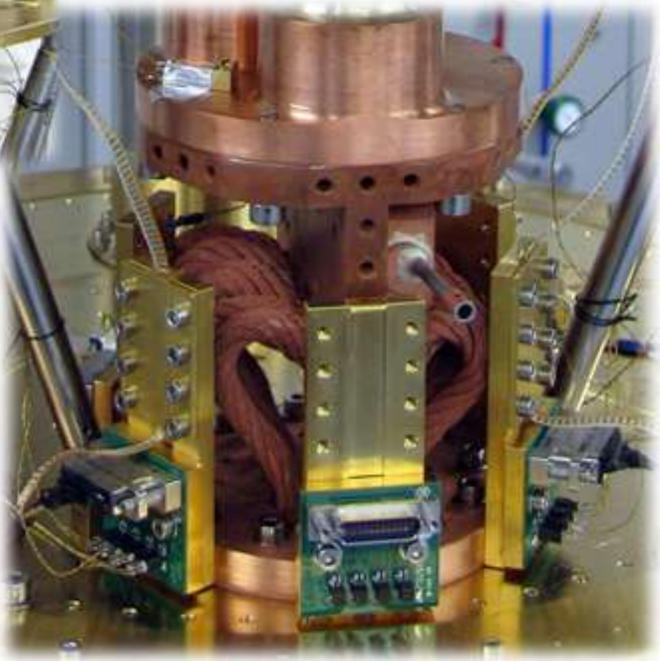
market share of dry dilution fridges: > 95 %

28

Low Temperature Physics at WMI



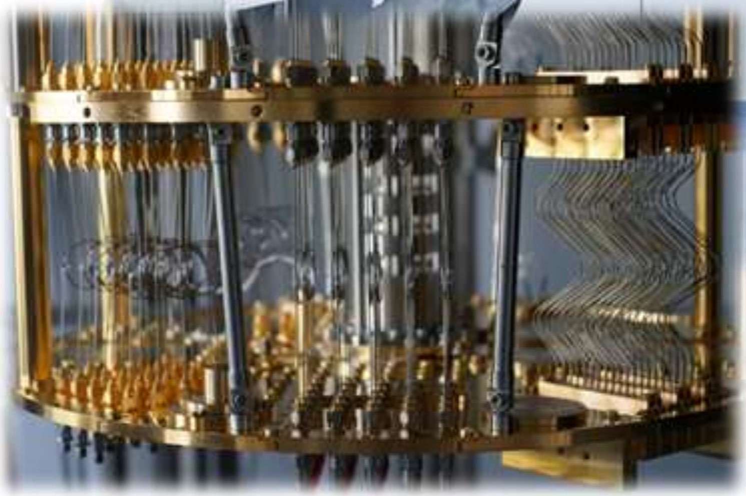




dry dilution fridge designed and fabricated at WMI

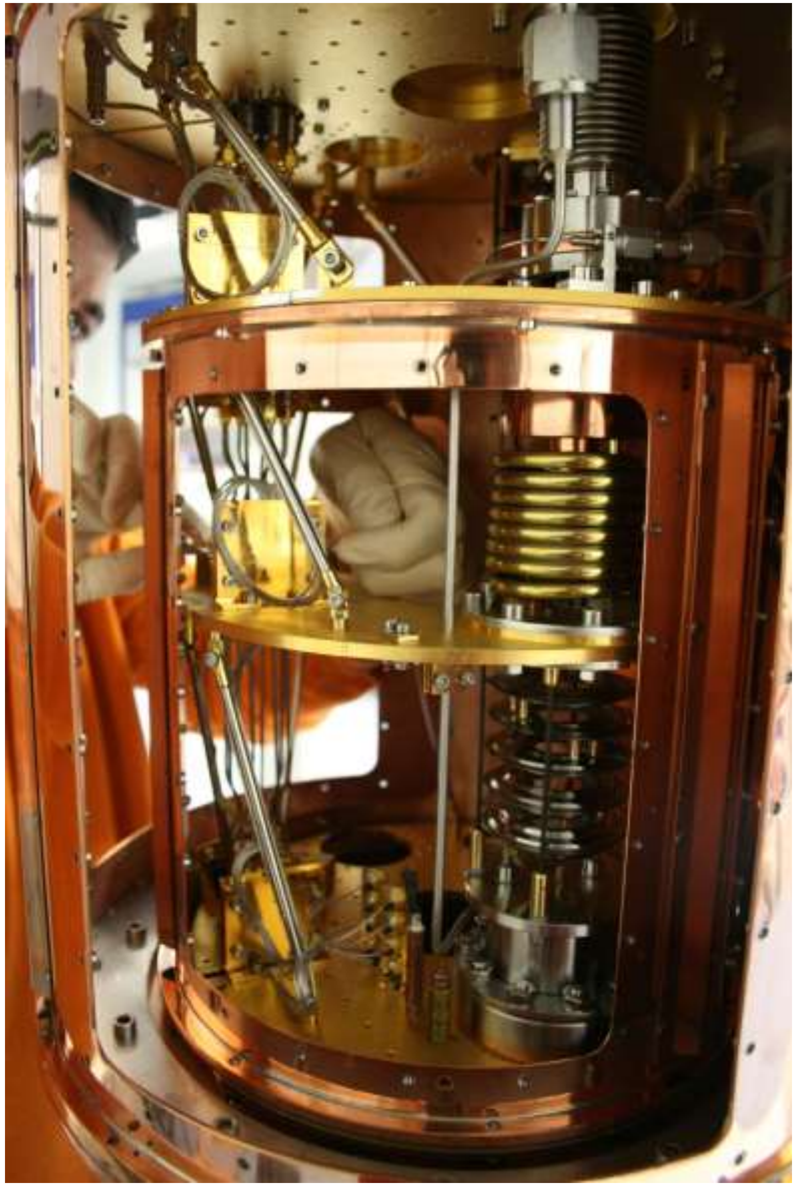
Low Temperature Physics at WMI

- **BlueFors XLD Dilution Fridge (2020)**




Low Temperature Physics at WMI

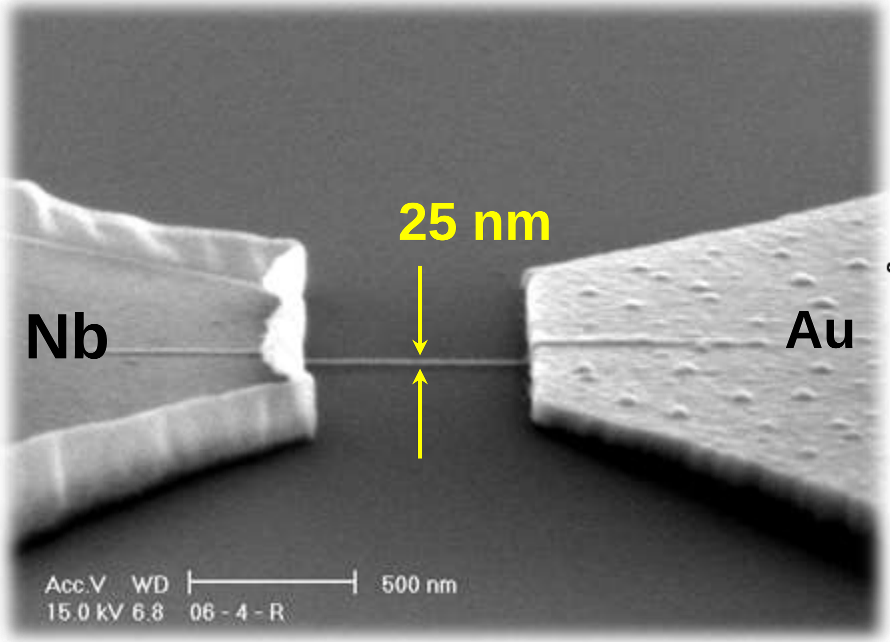
- Oxford Instruments Dilution Fridge (2011)
  (with 3D vector magnet)

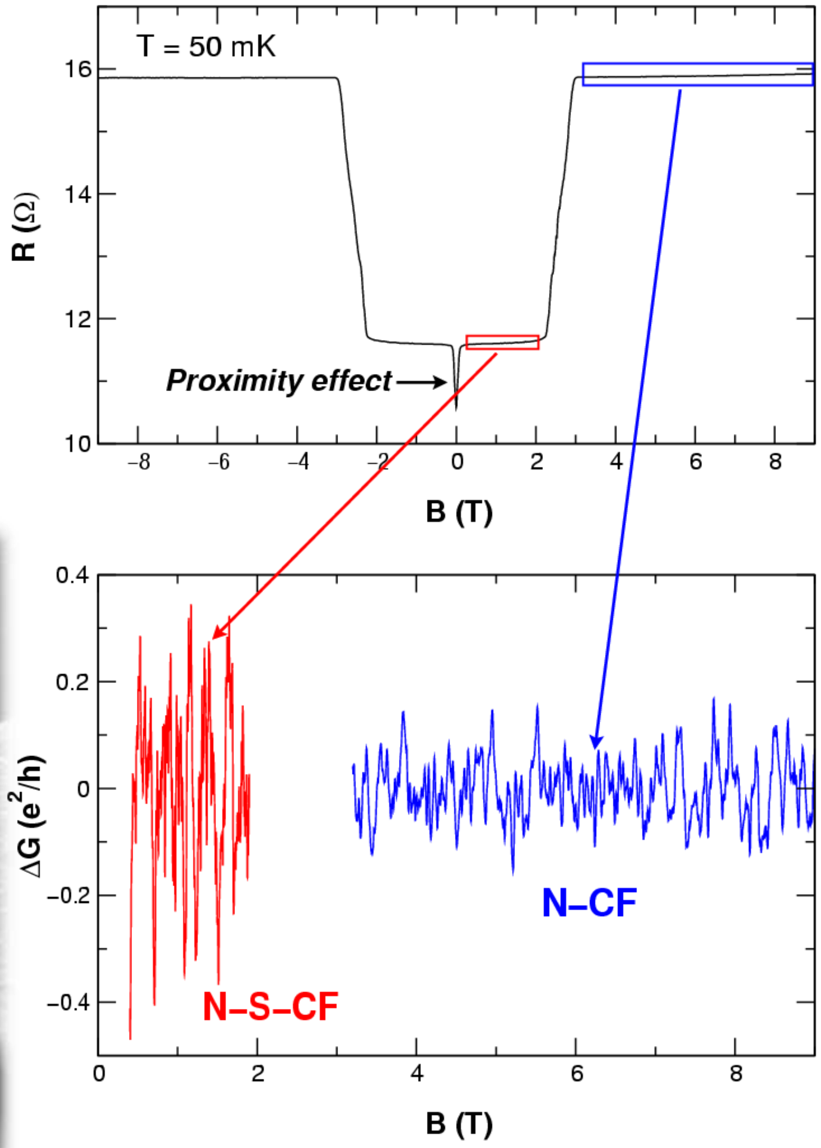


Helium Liquefaction

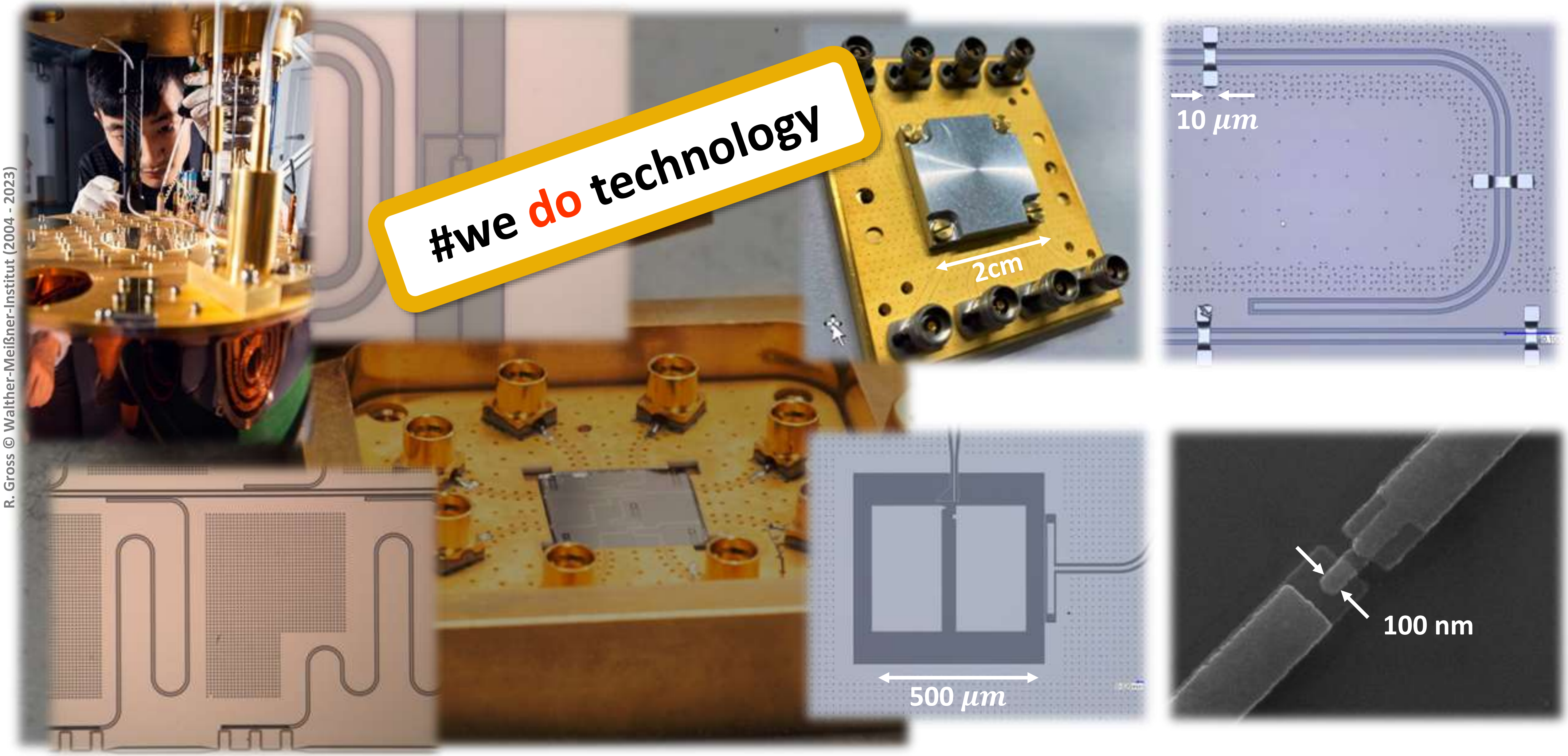
- ***Helium liquefier at WMI:***
  Linde TCF 20
- ***supply of LHe to both Munich Universities***
- ***liquefaction power:***
  > 150 000 l/year
- ***market price:***
  about 2 Mio. €

Low Temperature Physics at WMI

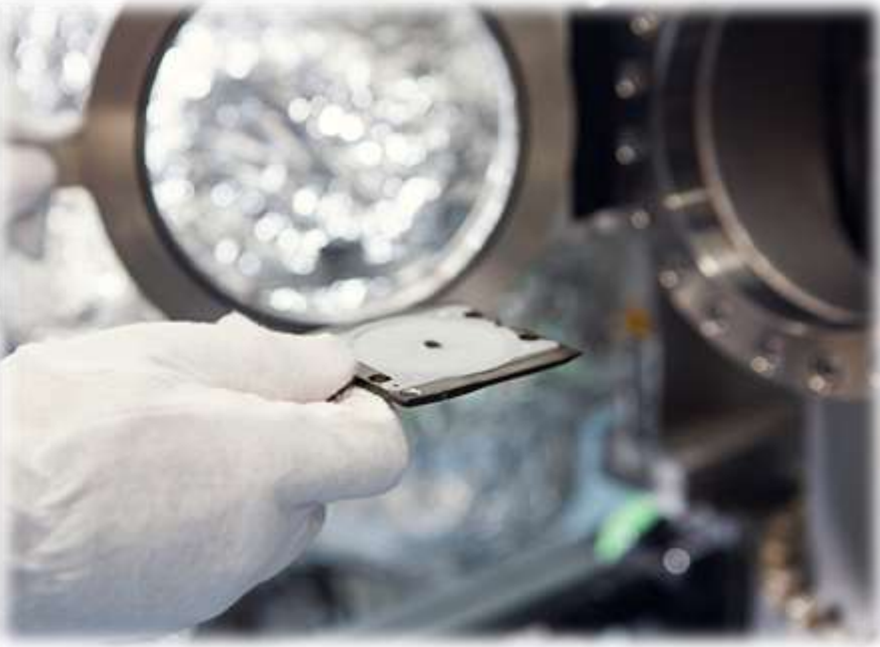




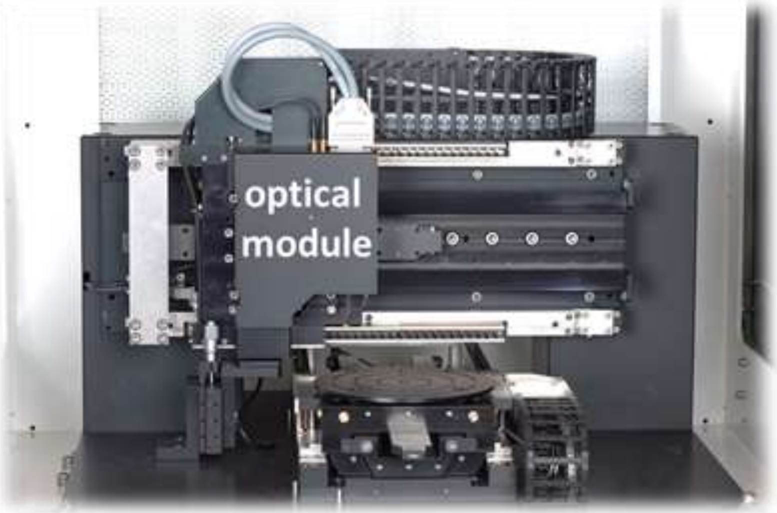
Competence Center for SC Quantum Technology



Hub for Nano-, Thin Film and Cryotechnology





Quantum Technology Projects @ WMI

Bayerisches Staatsministerium für Wissenschaft und Kunst

GeQCoS (BMBF)
MQV-SQQC (StMWK Bayern)
MUNIQC-SC (BMBF)

Bundesministerium für Bildung und Forschung

Bundesministerium für Bildung und Forschung

QuaRaTe

QuaMToMe

DFG Deutsche Forschungsgemeinschaft

MCQST

Demonstrator-QC ~ 10 Qubits → NISQ-QC ~ 100 Qubits → FT-QC ~ 10^6 Qubits

BMW
ROHDE & SCHWARZ
infineon
kiutra
OXFORD INSTRUMENTS

QUANTUM FLAGSHIP
Funded by the European Union
QMiCS
OpenSuperQ / QuSCo
QUSTEC
MOQS Molecular Quantum Simulations
Quromorphic

Have
Fun !!