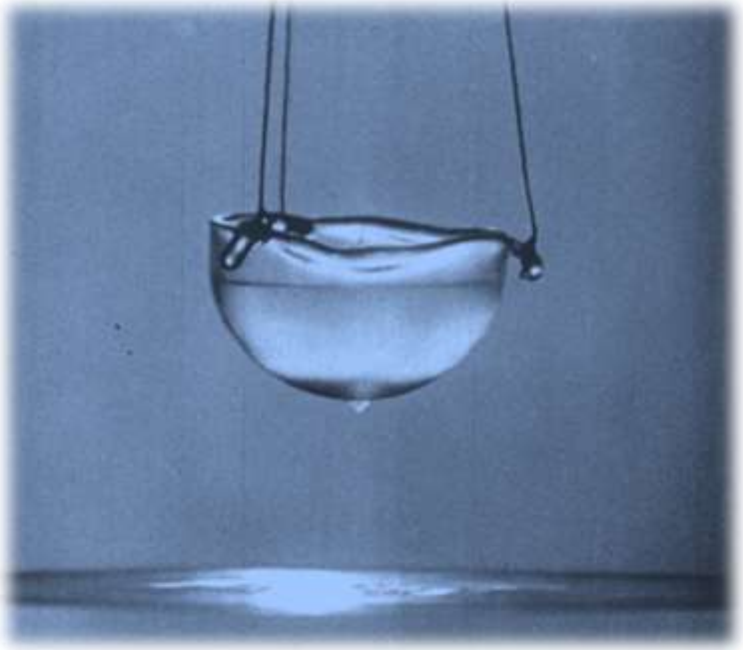
Walther
Meißner
Institut

BAdW BAYERISCHE AKADEMIE DER WISSENSCHAFTEN

Technische Universität München

Superconductivity and Low Temperature Physics II



Lecture Notes
Summer Semester 2022

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

2. **Applied Superconductivity I + II**
   Note
   → WS 2021/22 and SS 2022, 2 hrs lecture + 2 hrs exercises
   → Josephson-Effect, Superconducting Electronics, Qubits, Quantum Circuits, ...

3. **Seminars (SS 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	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

Superconductivity and Low Temperature Physics II

Contents Part I: Quantum Fluids

Contents Part II: Quantum Transport in Nanostructures

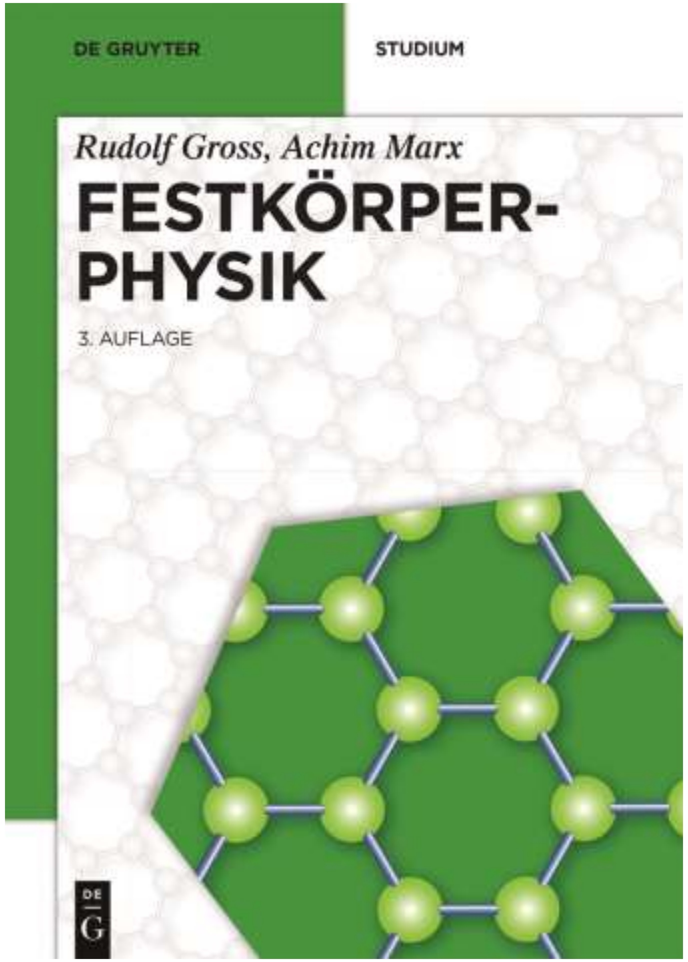
Contents Part IV:

Literature

WMI

- F. Pobell
  Matter and Methods at Low Temperatures, Springer 1996
- D.R. Tilley and J. Tilley
  Superfluidity and Superconductivity, Adam Hilger 1990
- C. Enss and S. Hunklinger
  Low-Temperature Physics, Springer 2005
- P.V.E. McClintock, D.J. Meredith, J.K. Wigmore
  Matter at Low Temperatures, Blackie 1984
- J. Wilks, D.S. Betts
  Introduction to Liquid Helium, Oxford 1987
- A. Kent
  Experimental Low Temperarure Physics, MacMillan, New York
- G.K. White, P.J. Meeson
  Experimental Techniques in Low Temperature Physics, Oxford University Press, 2002
- K.H. Bennemann, J.B. Ketterson
  The Physics of Liquid and Solid Helium I and II, Wiley 1978
- H. Frey, R.A. Haefer
  Tieftemperaturtechnologie, VDI-Verlag, Düsseldorf 1981
- Yoseph Imry
  Introduction to Mesoscopic Physics, Oxford University Press, Oxford (1997)
- Supriyoto Datta
  Electronic Transport in Mesoscopic Systems, Cambridge University Press, Cambridge (1995)
- Thomas Heinzel
  Mesoscopic Electronic in Solid State Nanostructures, Wiley VCH, Weinheim (2003)
- Thomas Ihn
  Semiconductor Nanostructures, Oxford University Press (2010)

Literature

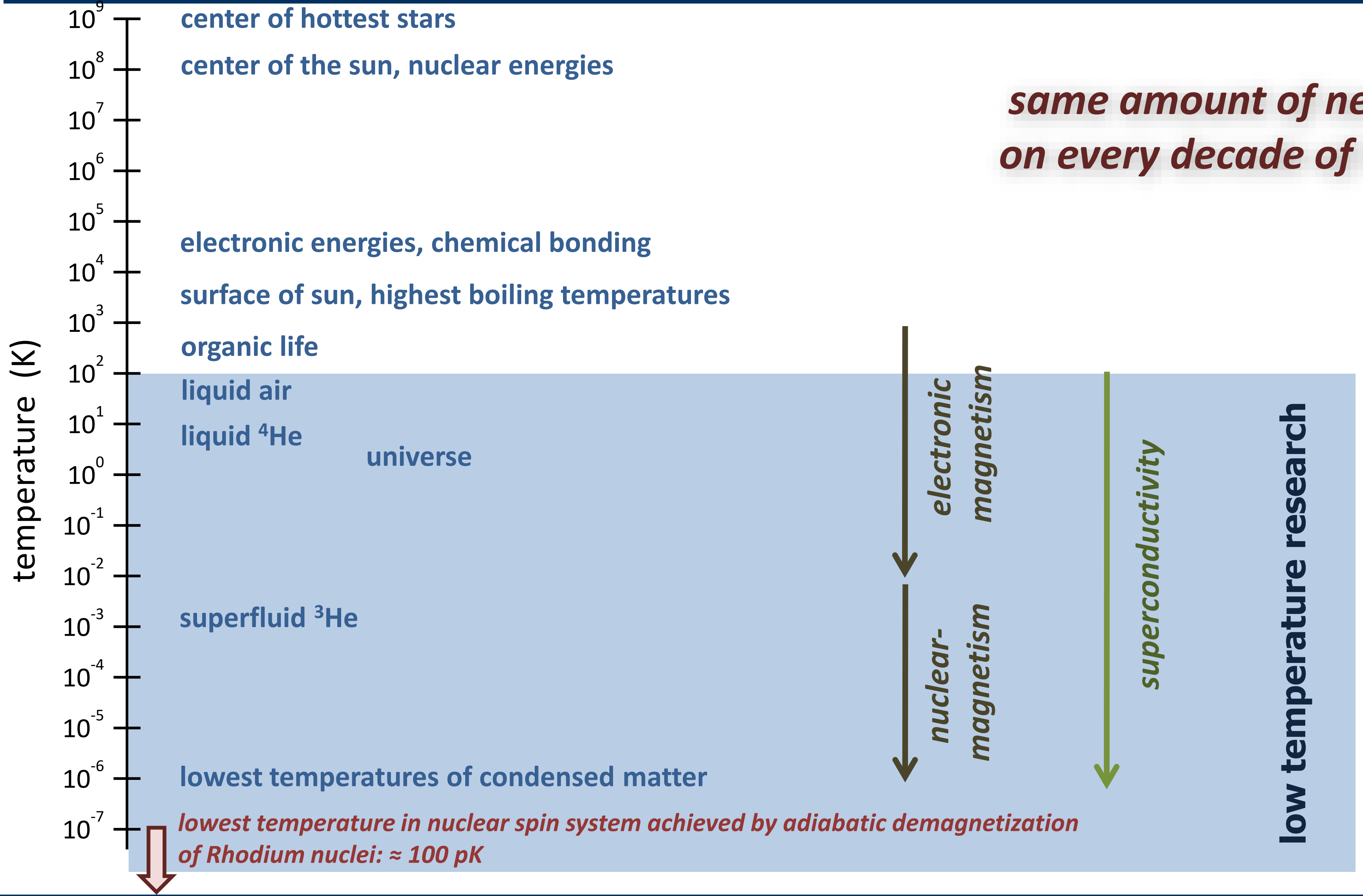


Rudolf Gross, Achim Marx

Title: Festkörperphysik, 3rd revised and extended edition
Publisher: Walter de Gruyter GmbH, Berlin/Boston
Published: January 2018
Language: German
ISBN 978-3-11-055822-7, ISBN 978-3-11-055918-7

Introduction

Temperature Scale



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

Low Temperature Phenomena

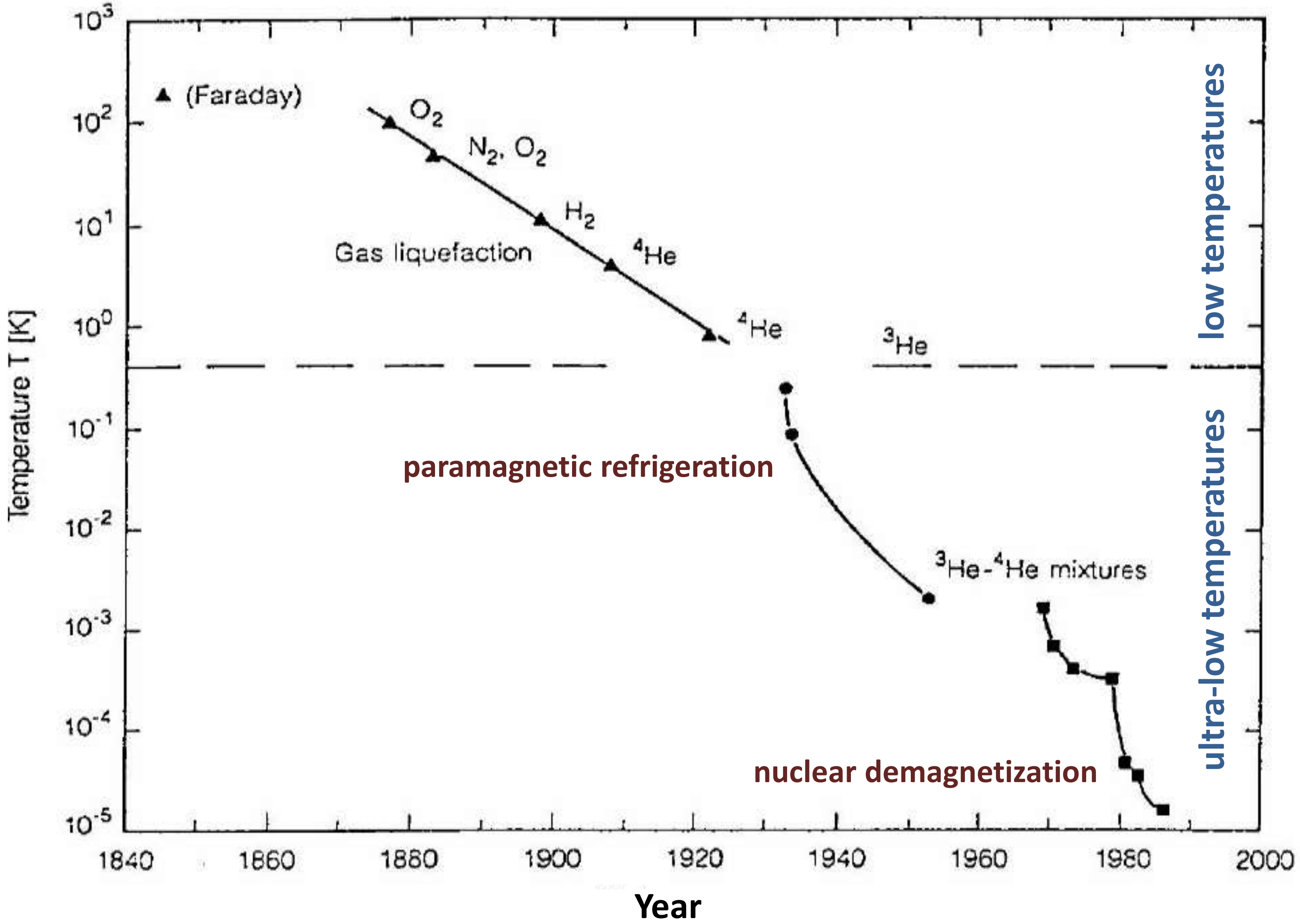
- **many direct implications of quantum mechanics only show up at low temperatures**

  e.g. magnetism, superconductivity

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

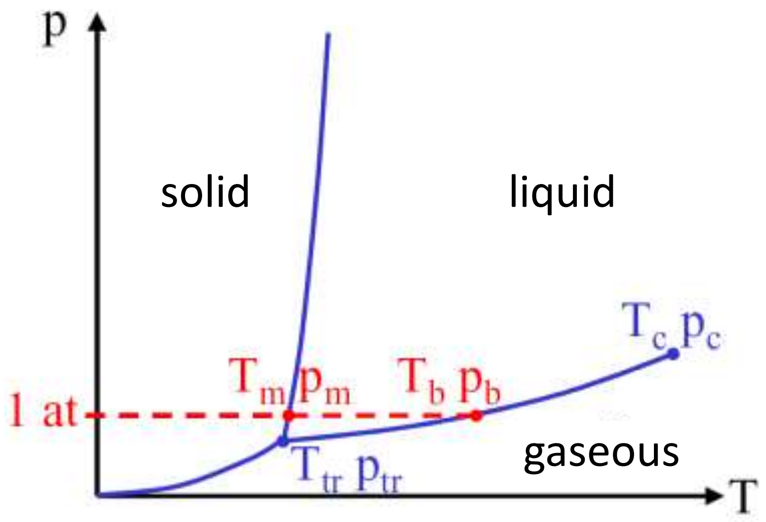
  } this lecture (Superfluidity, Bose-Einstein Condensation)

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



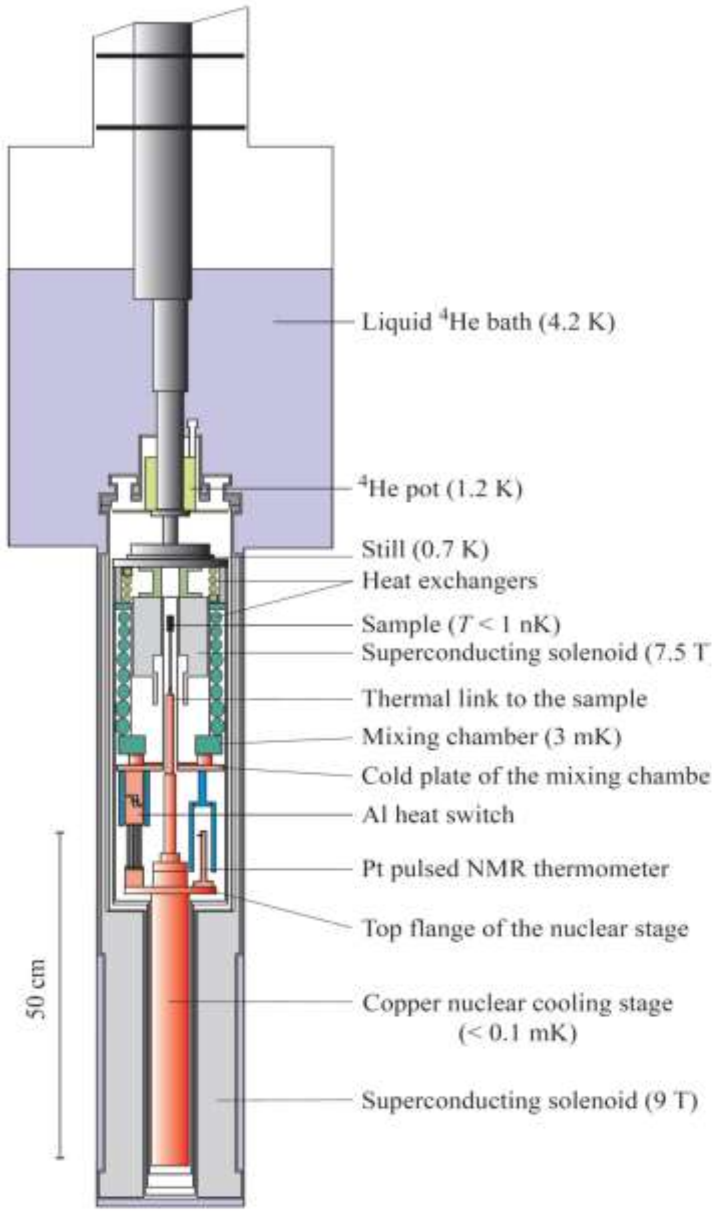
Generation of Low Temperatures

- **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)



Low Temperature Technology

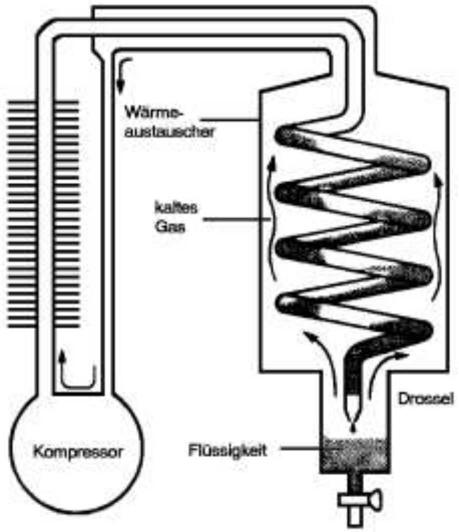
1868 offer of chair at the Polytechnische Schule München (now TUM)

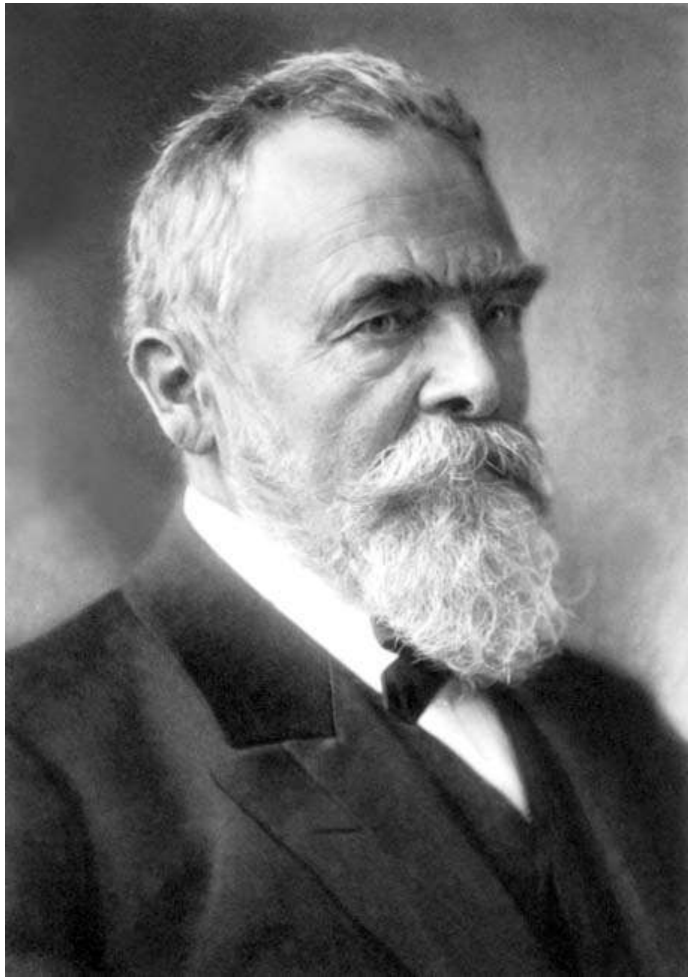
1873 development of cooling machine allowing the temperature stabilization in beer brewing

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

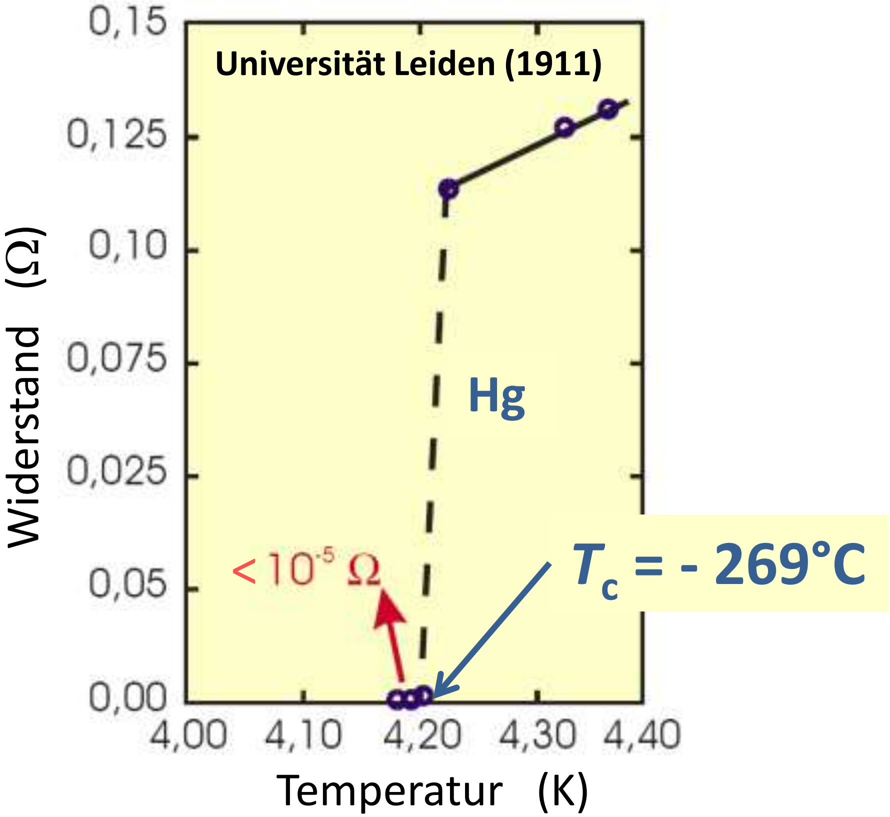
1947 first commercial He liquefier (design by engineer Collins, therefore denoted as „Collins“ machine)

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)

Heike Kammerlingh Onnes (1853-1926)



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

- **Helium liquefaction: 1908**
- **discovery of superconductivity: 1911**

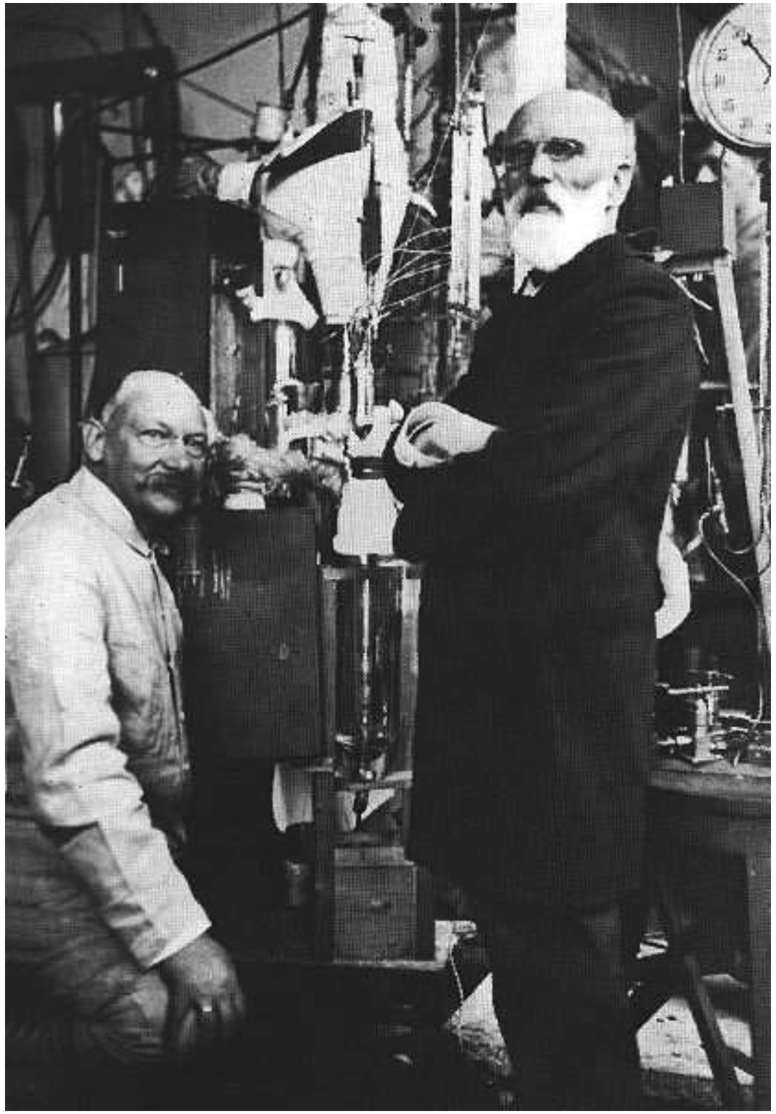
Nobel Price in Physics 1913

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

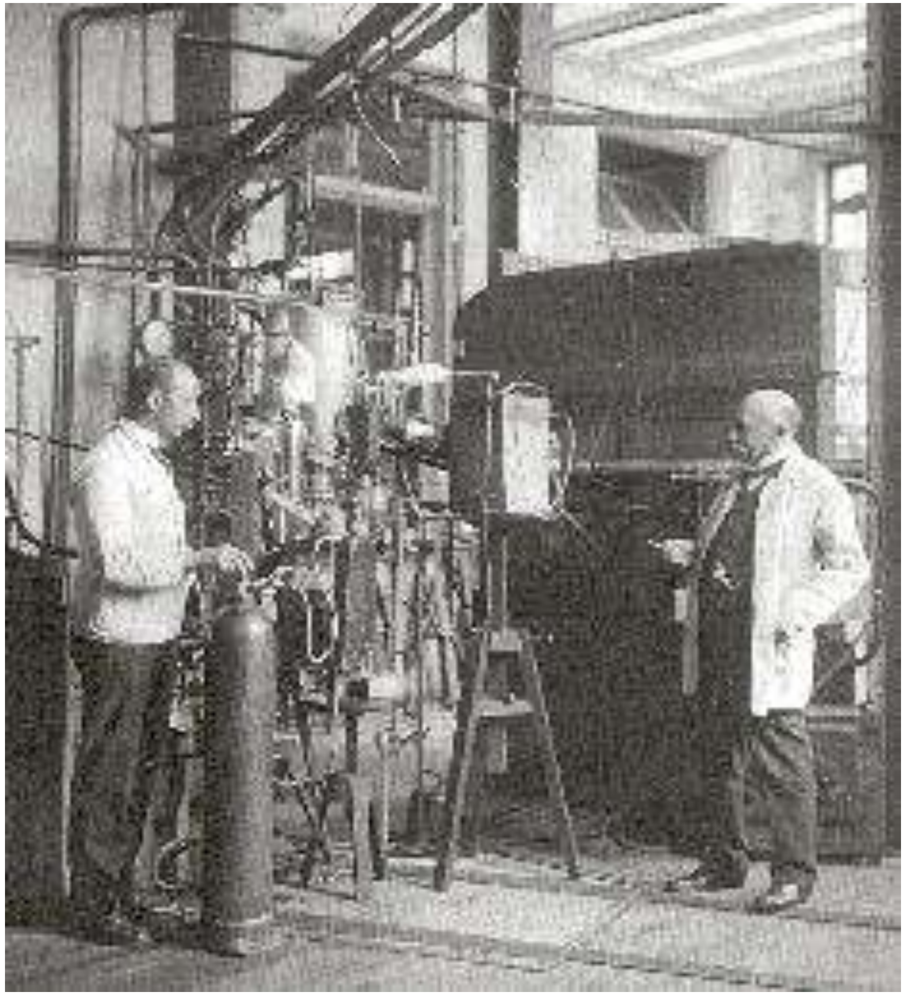
choice of name:

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)

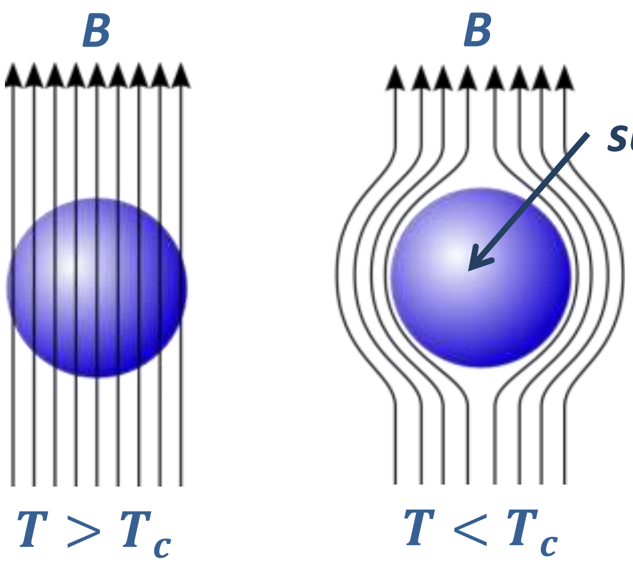
perfect diamagnetism

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

Walther Meißner
(1882 – 1974)

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)

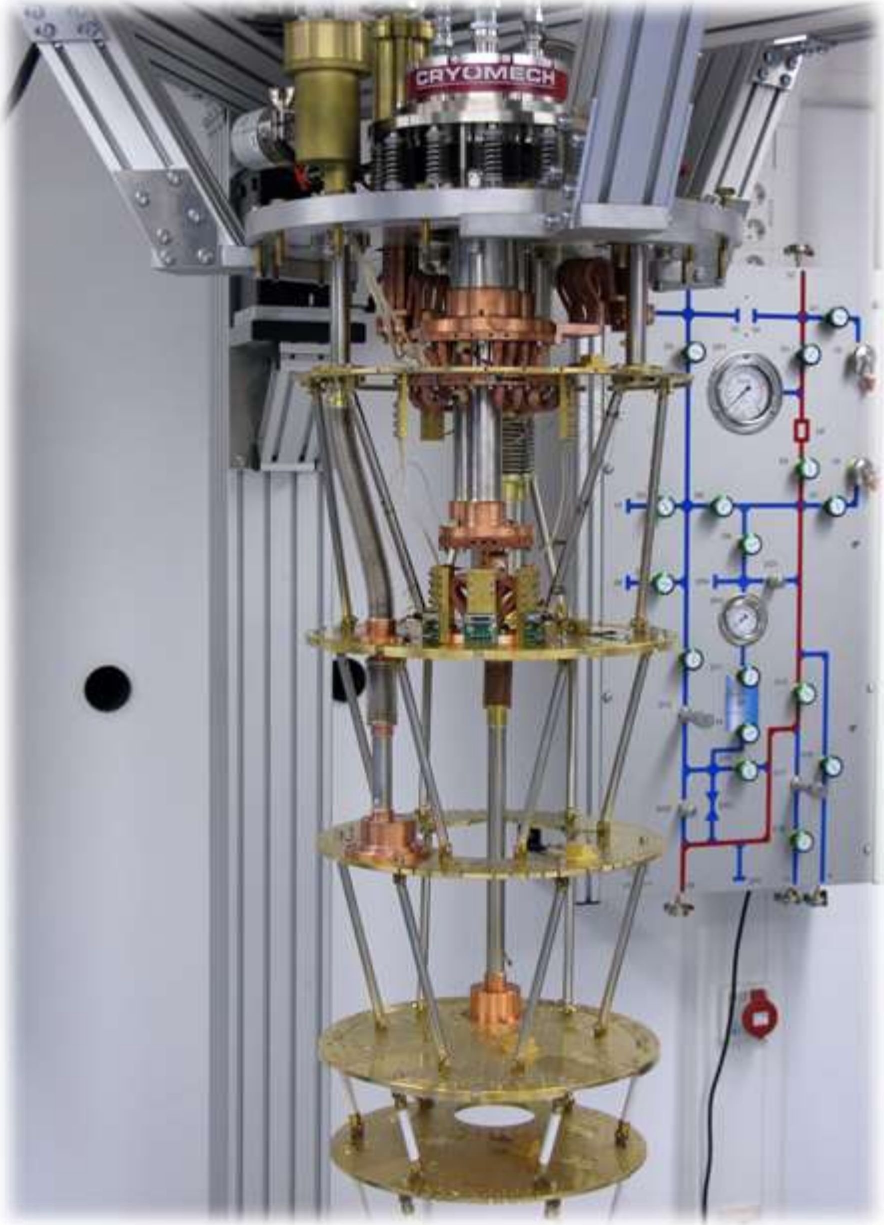
WMI inside

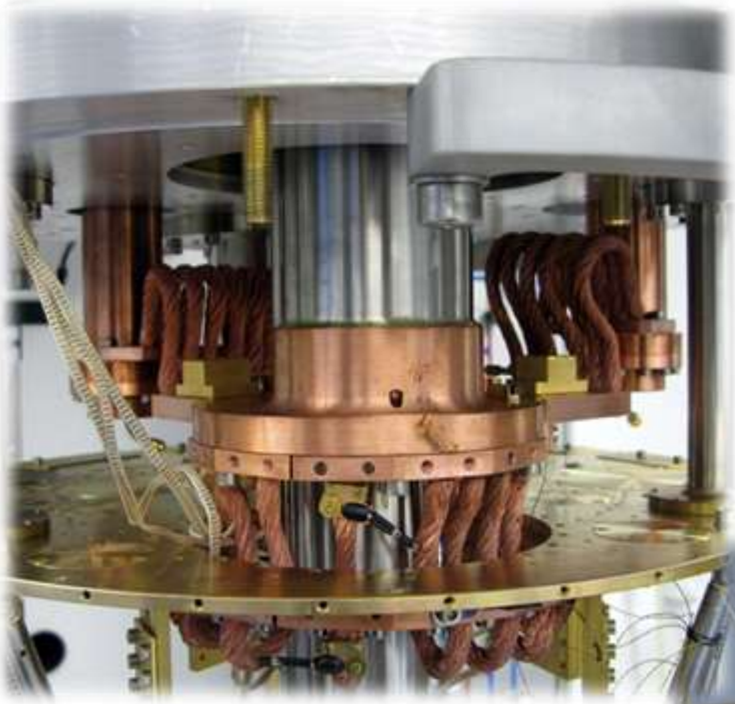
Oxford Instruments Triton family

market share of dry dilution fridges: > 95 %

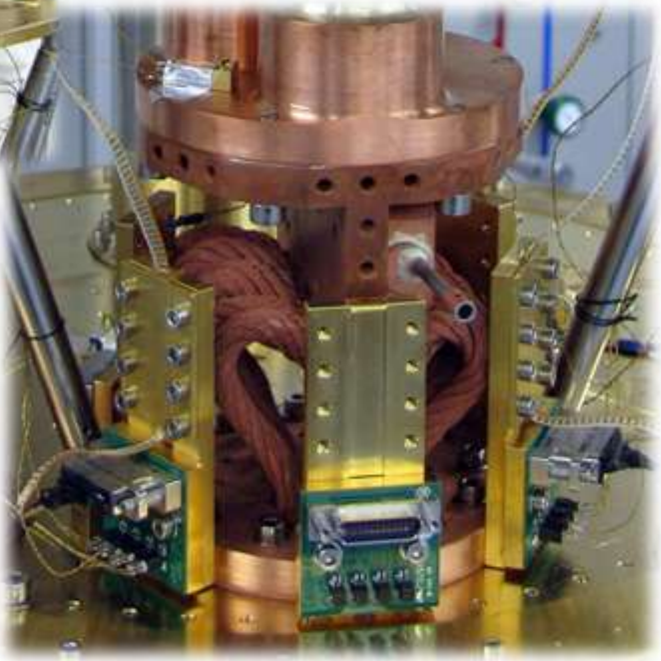
28

Low Temperature Physics at WMI



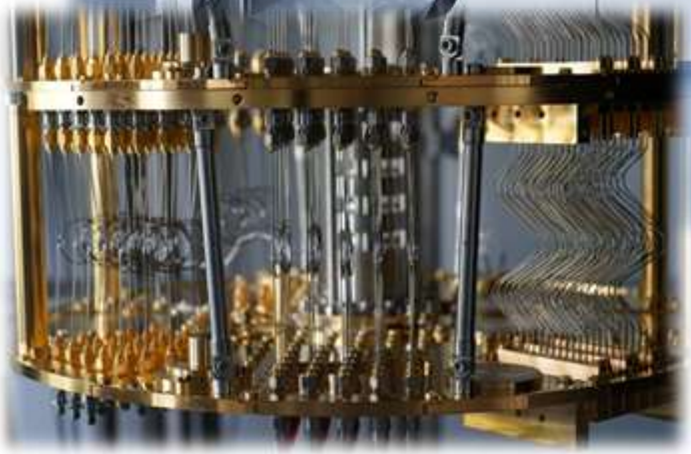


dry dilution fridge designed and fabricated at WMI



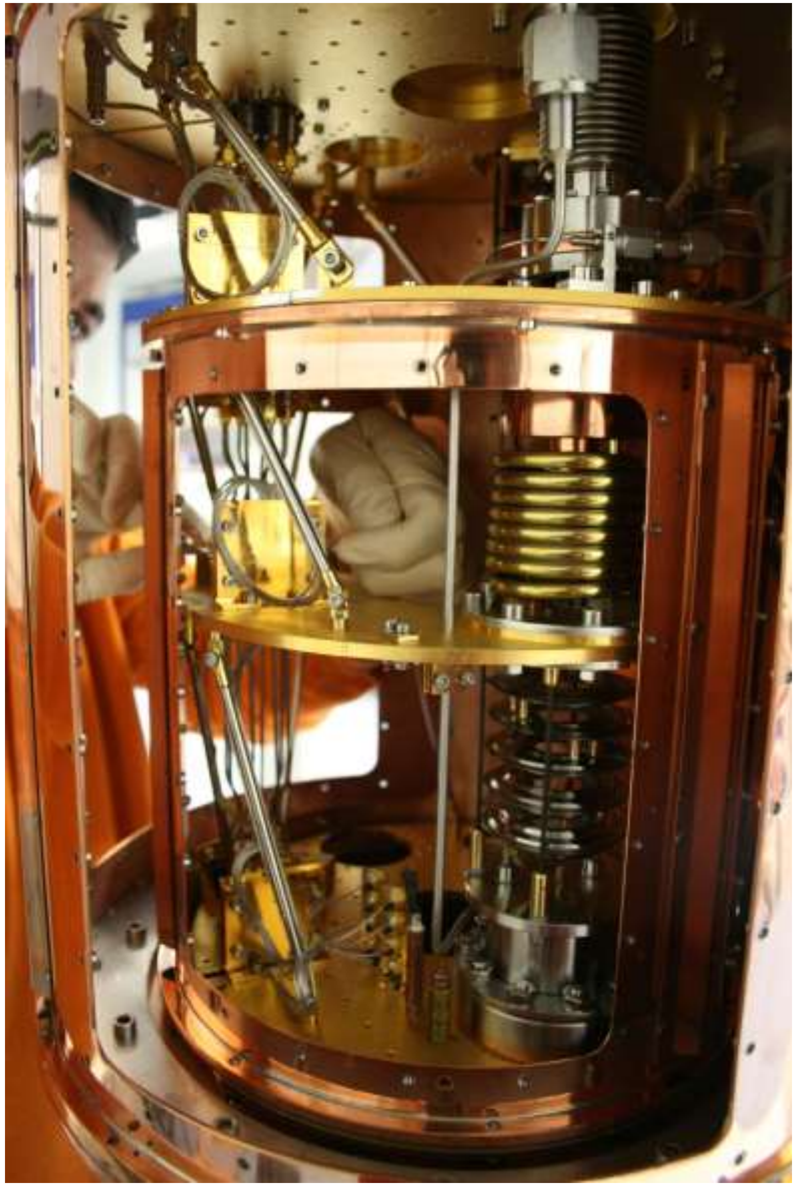
Low Temperature Physics at WMI

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



Low Temperature Physics at WMI

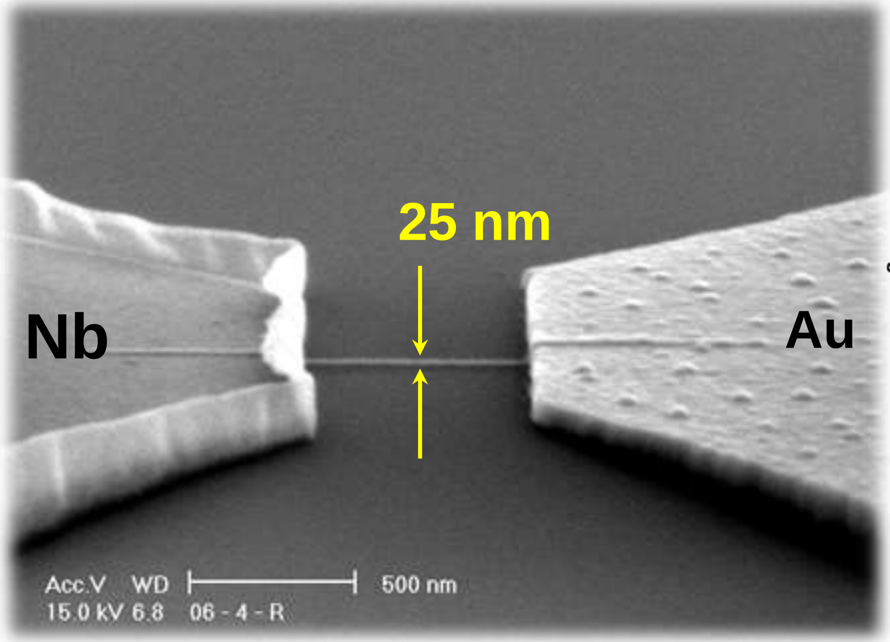
- **Oxford Instruments Dilution Fridge (2011) (with 3D vector magnet)**

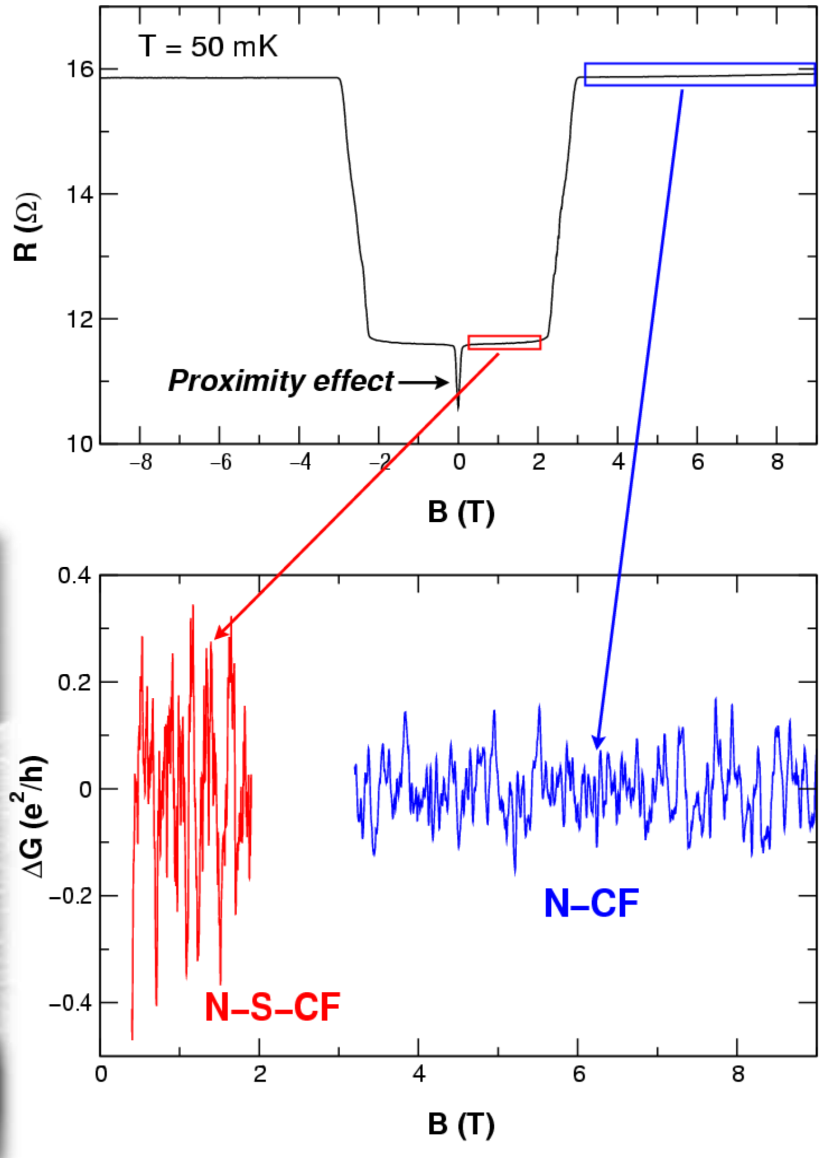


Helium Liquefaction

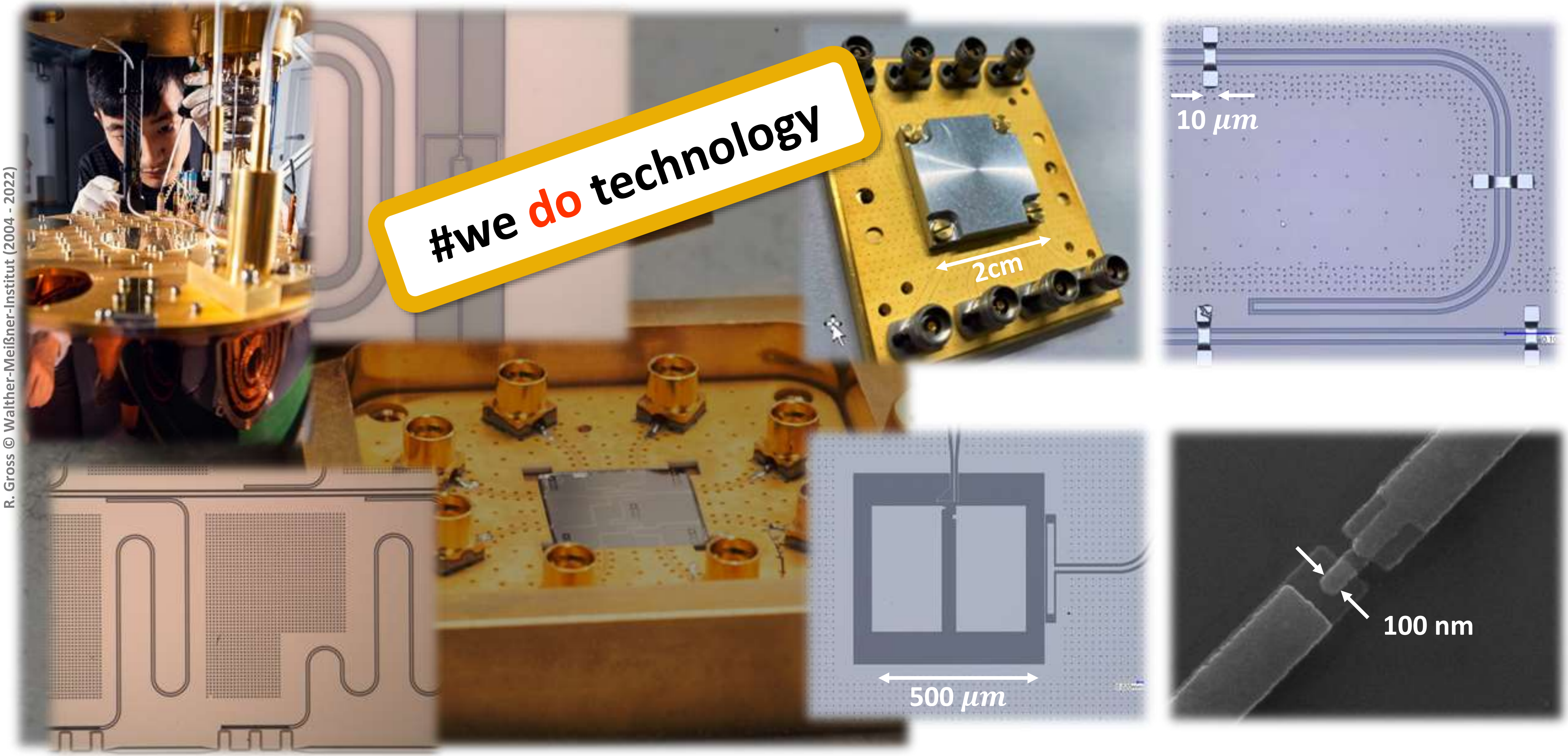
- ***Helium liquefier at WMI:***
  Linde TCF 20
- ***supply of LHe to both Munich Universities***
- ***liquefaction power:***
  > 150 000 l/year
- ***market price:***
  about 2 Mio. €

Low Temperature Physics at WMI

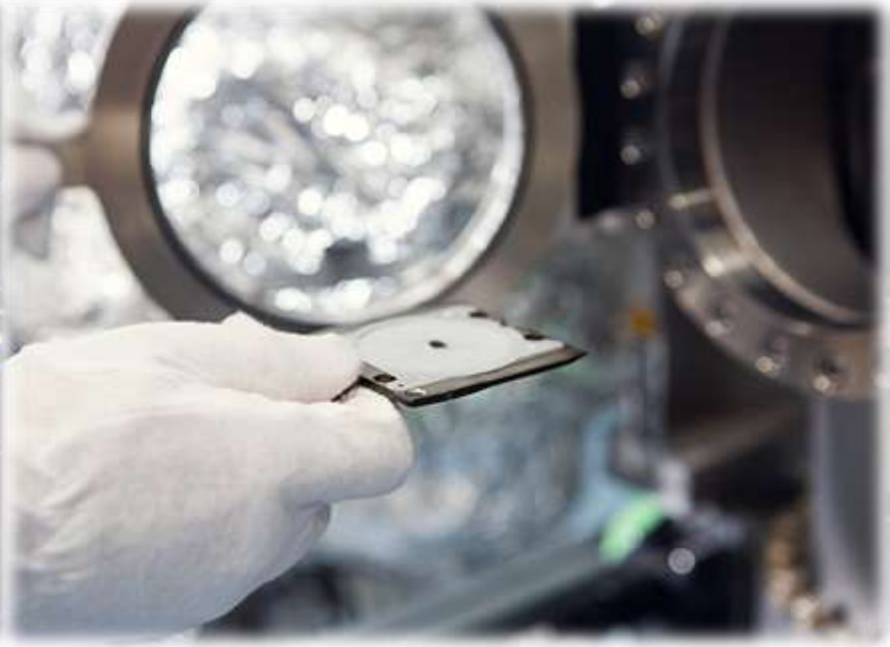




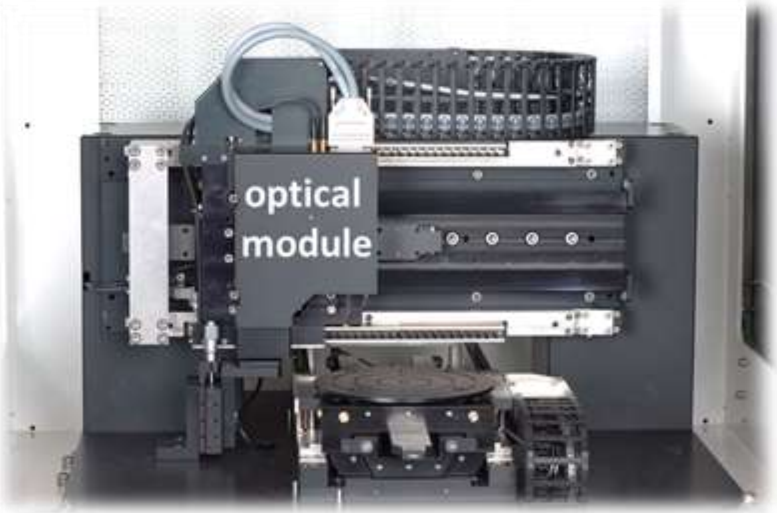
Competence Center for SC Quantum Technology



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

QUANTUM FLAGSHIP

Funded by the European Union

QMiCS

OpenSuperQ / QuSCo

QUSTEC

MOQS Molecular Quantum Simulations

Quromorphic

BMW

ROHDE & SCHWARZ

infineon

kiutra

OXFORD INSTRUMENTS

Have
Fun !!