# Superconductivity and Low Temperature Physics I

Lecture Notes
Winter Semester 2023/2024

R. Gross

# Chapter 1

# Basic Properties of Superconductors

# 1.1 History of Superconductivity

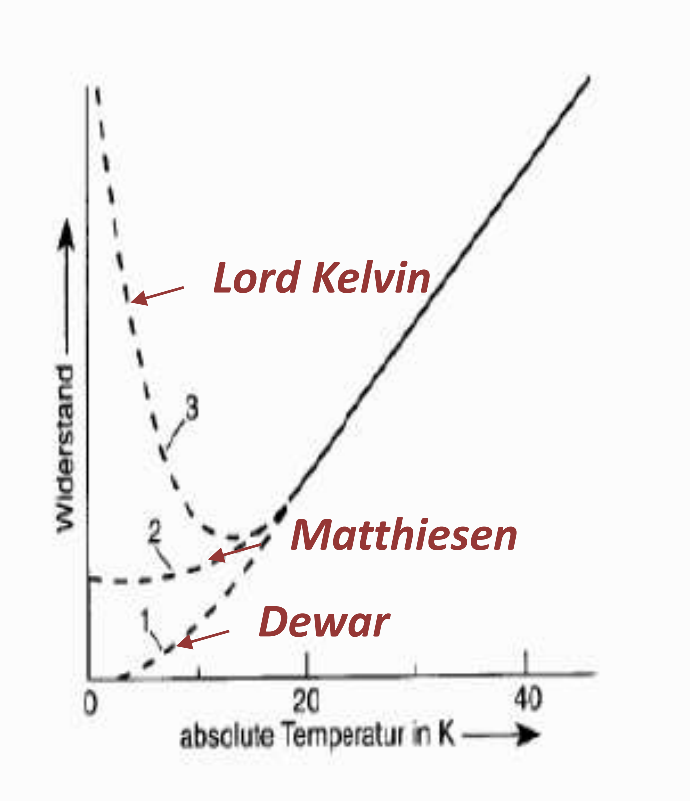
## Discovery and explanation of the phenomena of superconductivity and superfluidity was honored by many Nobel Prizes

| | |
|---|---|
| 1908 | Liquefaction of Helium, 4.2 K (Kamerlingh Onnes) |
| 1911 | Discovery of zero resistance (Kamerlingh Onnes) |
| 1933 | Discovery of the Meißner-Ochsenfeld effect (Meißner & Ochsenfeld) |
| 1935 | London theory (Fritz & Heinz London) |
| 1936 | type-II superconductivity (Shubnikov) |
| 1939 | Discovery of superfluid $^4$Helium (Kapitza, Allen, and Misener) |
| 1952 | Ginzburg-Landau theory (Ginzburg & Landau) |
| 1957 | Abrikosov theory of type-II superconductivity (Abrikosov) |
| 1957 | Bardeen-Cooper-Schrieffer (BCS) theory (Bardeen, Cooper & Schrieffer) |
| 1961 | Discovery of flux quantization (Doll/Näbauer & Deaver/Fairbank) |
| 1962 | Cooper pair tunneling: Josephson effect (Josephson, Giaever) |
| 1966 | Development of Superconducting Quantum Interference Devices (Clarke) |
| 1971 | Discovery of superfluid $^3$Helium (Lee, Richardson, Osheroff) |
| 1975 | Theory of superfluid $^3$Helium (Leggett) |
| 1979 | Discovery of heavy fermion superconductors (Steglich) |
| 1981 | Discovery of organic superconductors (Bechgaard) |
| 1986 | Discovery of high-temperature superconductivity (Bednorz, Müller) |
| 2006 | Discovery of superconductivity in iron pnictides (Hosono) |

blue:
Nobel Prize winners

# 1.1 Discovery of Superconductivity (1911)

- what was the basic interest ?




***temperature dependence of very pure metals for*** $T \rightarrow 0$ ***??***

- $R \rightarrow 0$
- $R \rightarrow const.$
- $R \rightarrow \infty$

***use of Hg, since very pure Hg was available***

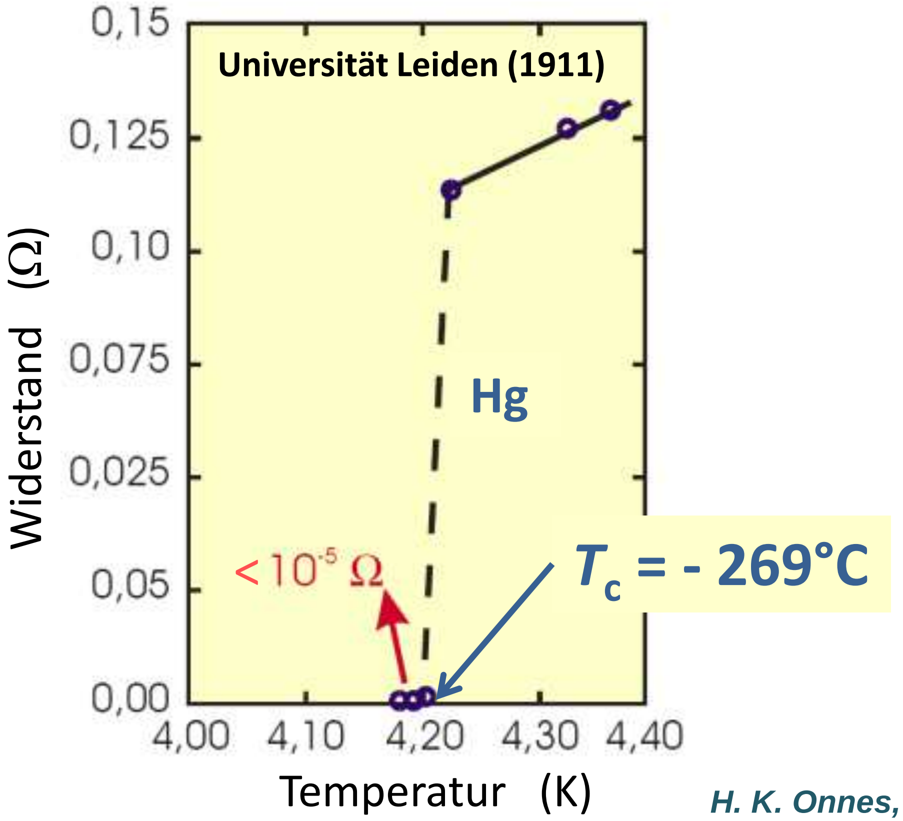
**H. K. Onnes**

*".. Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state"*

# 1.1 Discovery of Superconductivity (1911)


***note***: Heike = first name, Kammerlingh = „Hofrat“

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




*H. K. Onnes,*
*Comm. Leiden 120b, 122b, 124c (1911)*

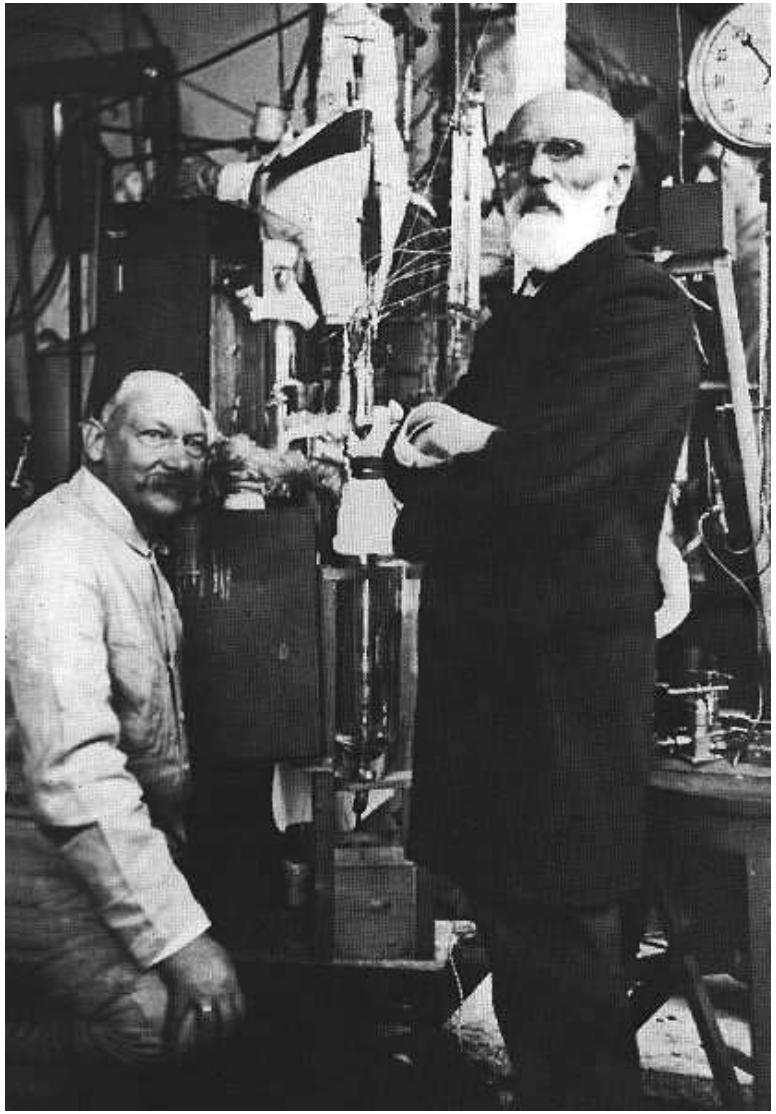
**Nobel Price in Physics 1913**

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

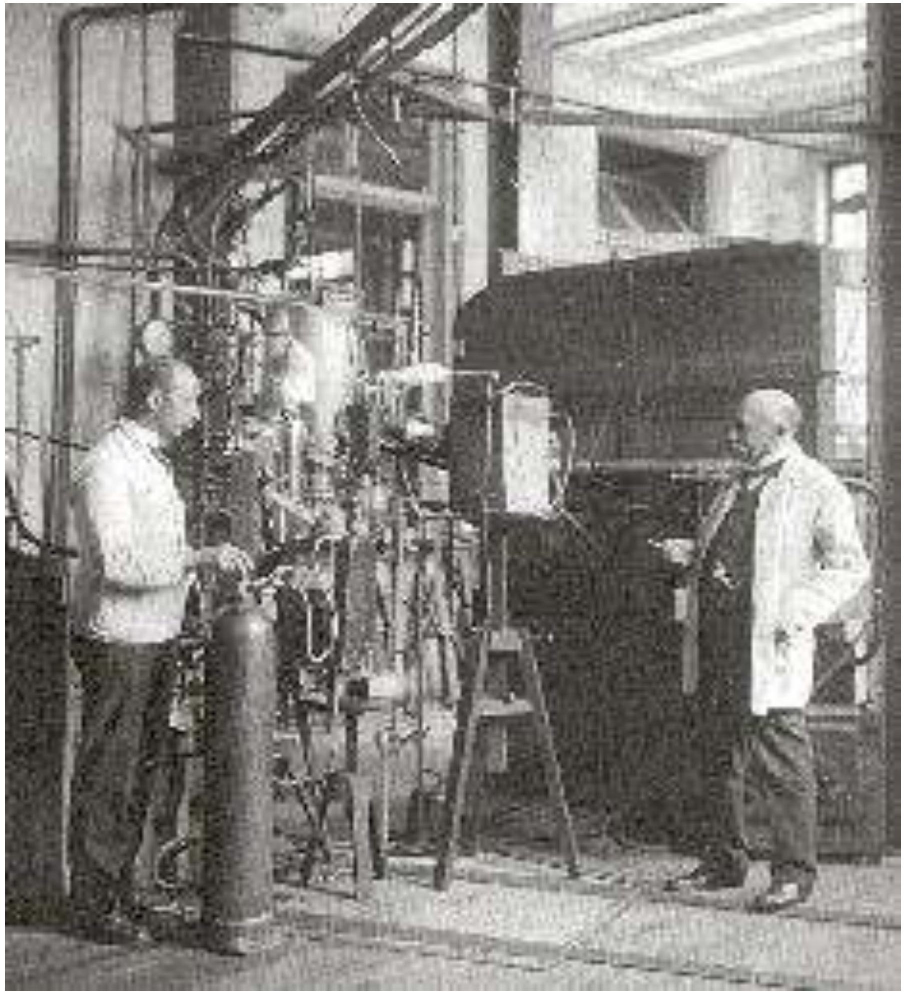
choice of name: *infinite electrical conductivity* ➔ **superconductivity**

# 1.1 Discovery of Superconductivity (1911)





Kammerlingh Onnes and van der Waals



Kammerlingh Onnes and Technician Flim

# 1.1 Discovery of Superconductivity (1911)

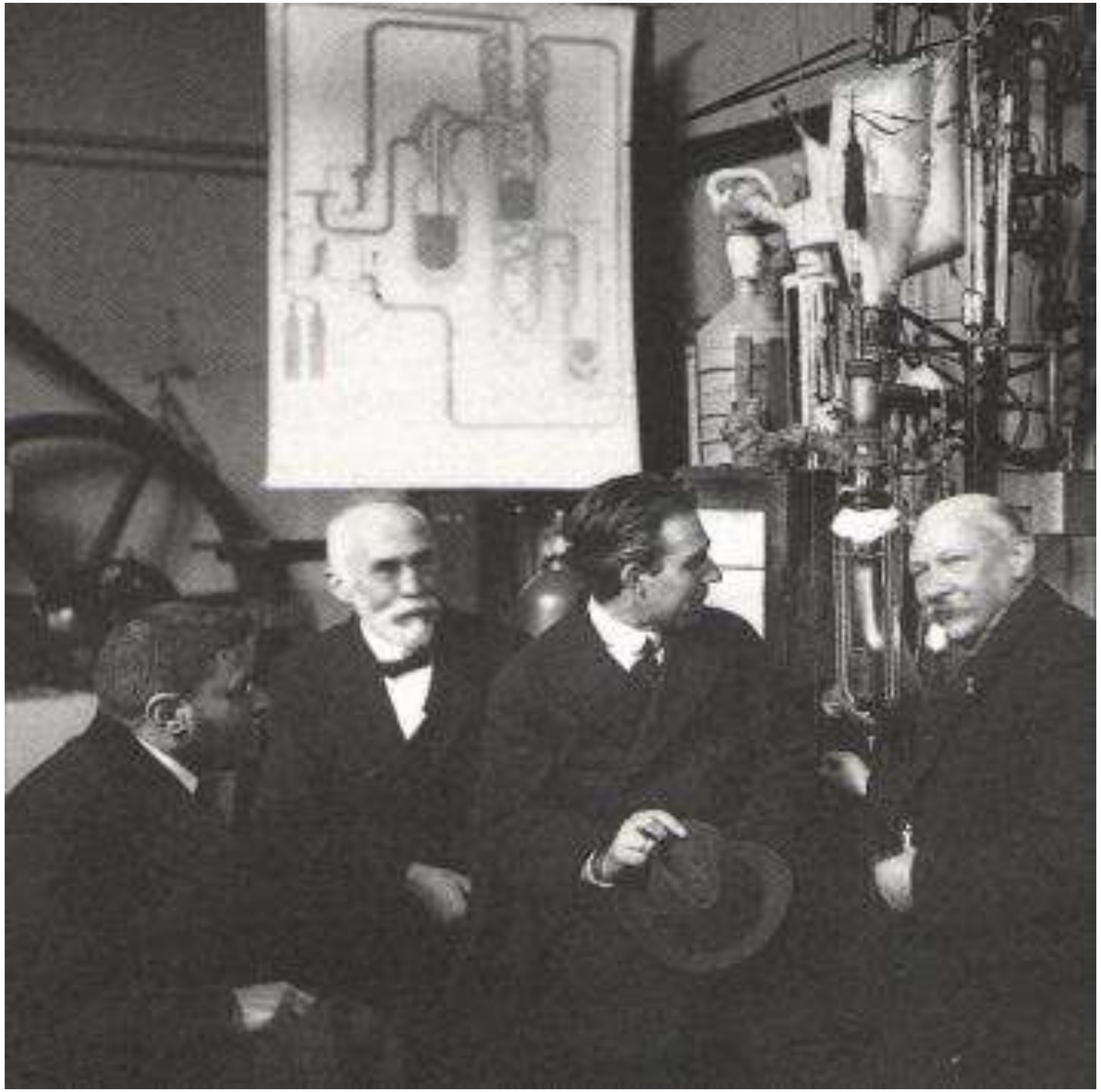


an early picture of the Onnes Laboratory

Kamerlingh Onnes Laboratory, 1924

# 1.1 Discovery of Superconductivity (1911)





**Heike Kamerlingh Onnes** (*far right*) shows his helium liquefactor to three theoretical physicists: Niels Bohr (visiting from Kopenhagen), Hendrik Lorentz, and Paul Ehrenfest (*far left*).

# 1.1 Discovery of Superconductivity (1911)

Prof. Heike Kamerlingh Onnes and his wife with some colleagues among them their friend Albert Einstein (*standing behind Mrs. Kamerlingh Onnes*), ca. 1920.

# 1.1 Discovery of the Meißner-Ochsenfeld Effect (1933)



**Robert Ochsenfeld**
**(1901 – 1993)**

**perfect diamagnetism**

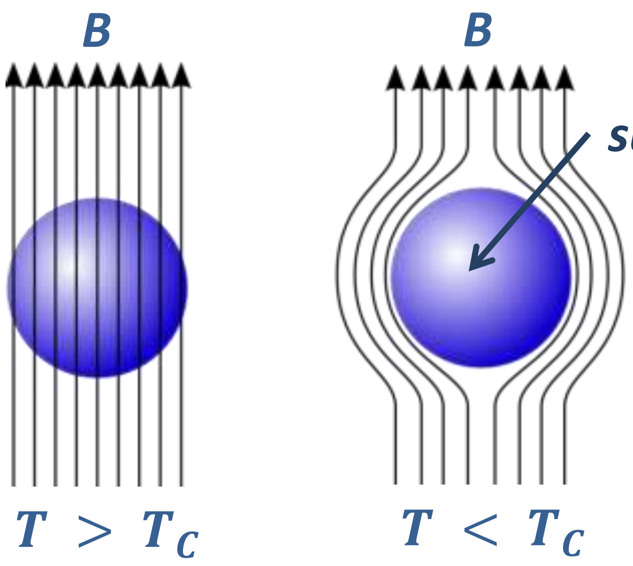

**Walther Meißner**
**(1882 – 1974)**

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

# 1.1 Discovery of the Meißner-Ochsenfeld Effect (1933)



Walther Meißner (1882 – 1974)




**superconductors perfectly expel magnetic field**

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

# London Theory of Superconductivity (1935)



**1935 Fritz and Heinz London**

**first „quantum mechanical“ theory of superconductivity**
(*purely phenomenological*)

→ ***macroscopic wave function***

**Fritz London**
**(1900 – 1954)**

# Shubnikov Phase, Type-I and Type-II SCs (1936)



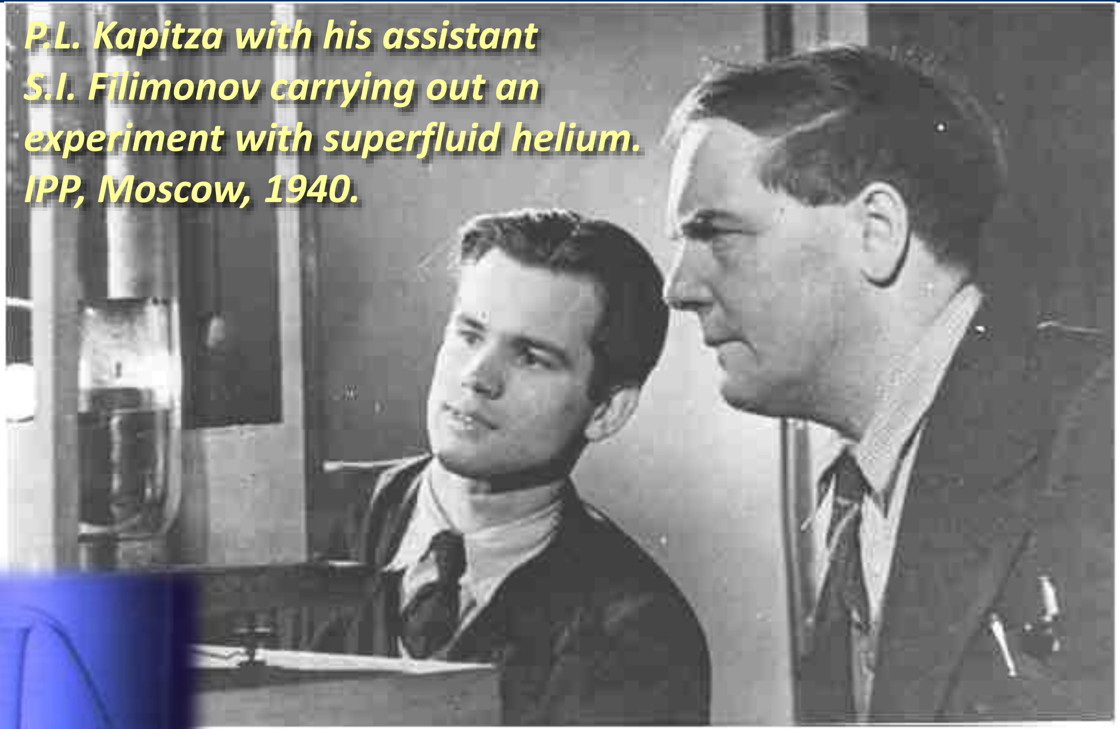
**1936 Lev W. Shubnikov**

**discovery of the Shubnikov phase in superconductors**

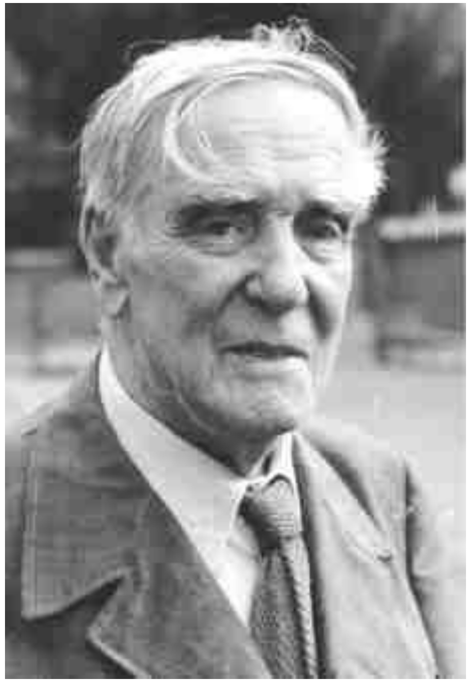
**→ *type-I and type-II superconductivity***

**Lev Wassiljevitsch Shubnikov**
**(1901 – 1937)**

# Discovery of Superfluid $^4$Helium (1939)




*phenomenon analogous to superconductivity is found in an uncharged system*

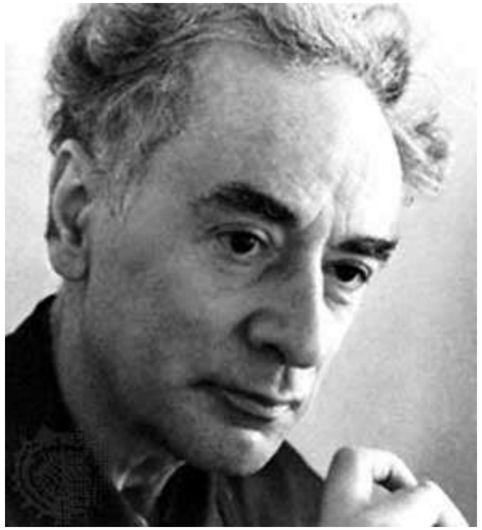


**Pyotr Leonidovich Kapitza (1894-1984)**


## Nobel Prize in Physics 1978

*„for his basic inventions and discoveries in the area of low-temperature physics"*

# Ginzburg-Landau Theory (1952)



Lev Landau

Vitaly Ginzburg

*application of Landau's theory for phase transitions to superconductors using a complex order parameter*

**Lev Davidovich Landau**

**Nobel Prize in Physics 1962**

*"for his pioneering theories for condensed matter, especially liquid helium"*

**Vitaly Ginzburg**

**Nobel Prize in Physics 2003**

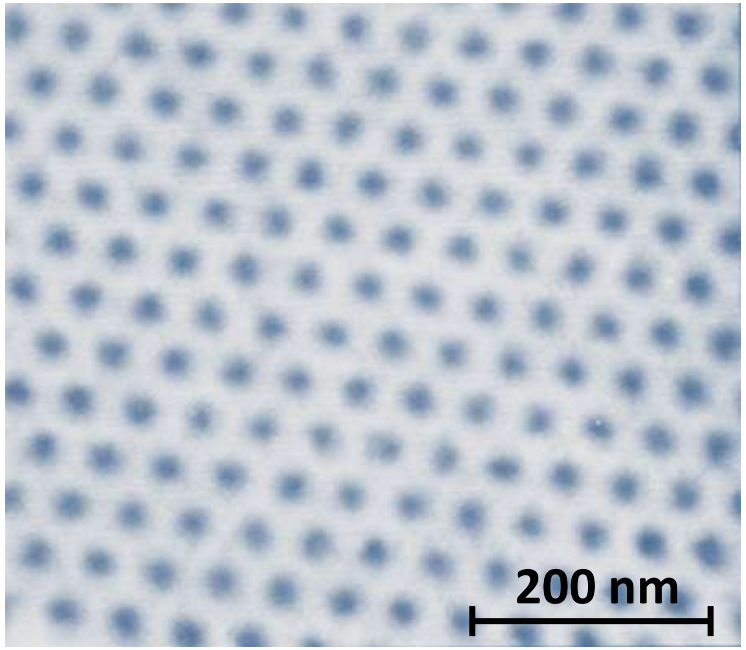
(together with Alexei Abrikosov and Anthony Leggett)

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

# Abrikosov Theory of Type-II Superconductivity (1957)


**Alexei Abrikosov**

***Abrikosov used the Ginzburg-Landau phenomenology to derive the existence of a "mixed-state"***



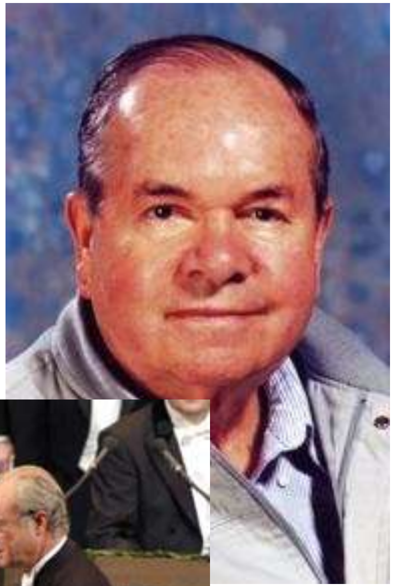

**Alexei Abrikosov**

**Nobel Prize in Physics 2003**

(together with Vitaly Ginzburg and Anthony Leggett)

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

# Alexei A. Abrikosov



# The Nobel Prize in Physics 2003

Alexei A. Abrikosov

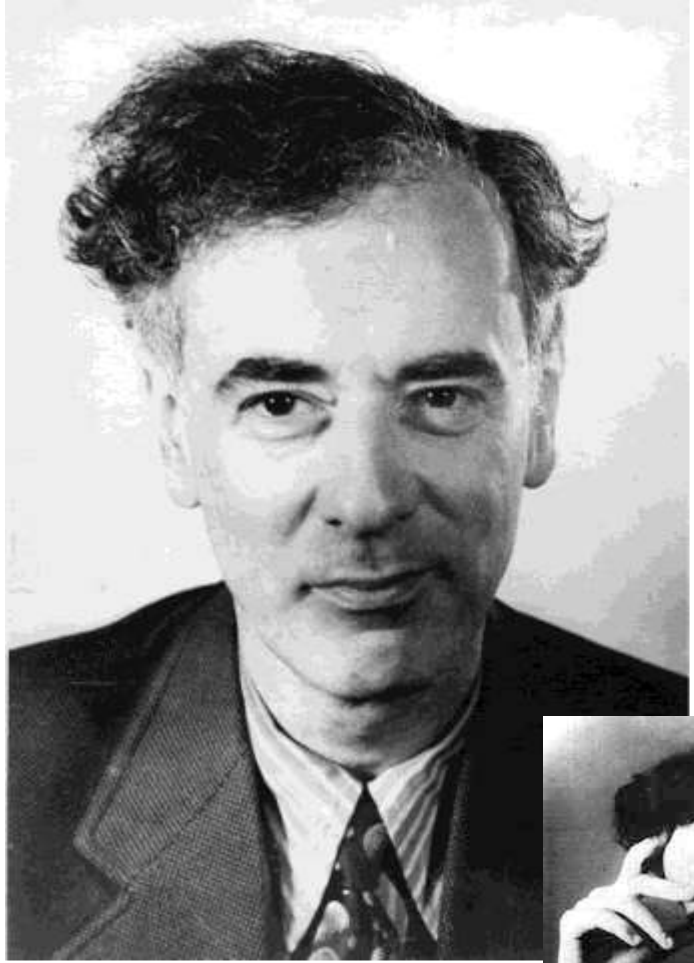
Vitaly L. Ginzburg

Anthony J. Leggett

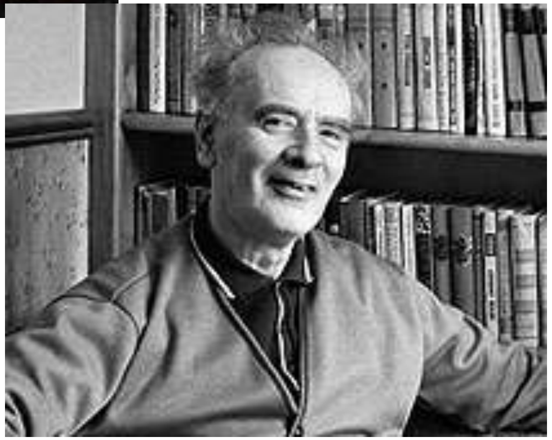
***….. for their pioneering contributions to the theory of superconductors and superfluids.***

# Lev Landau

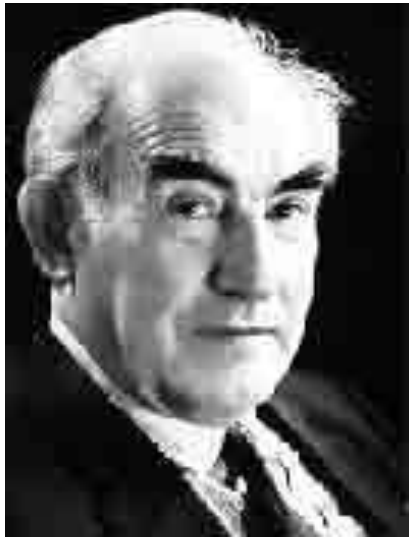


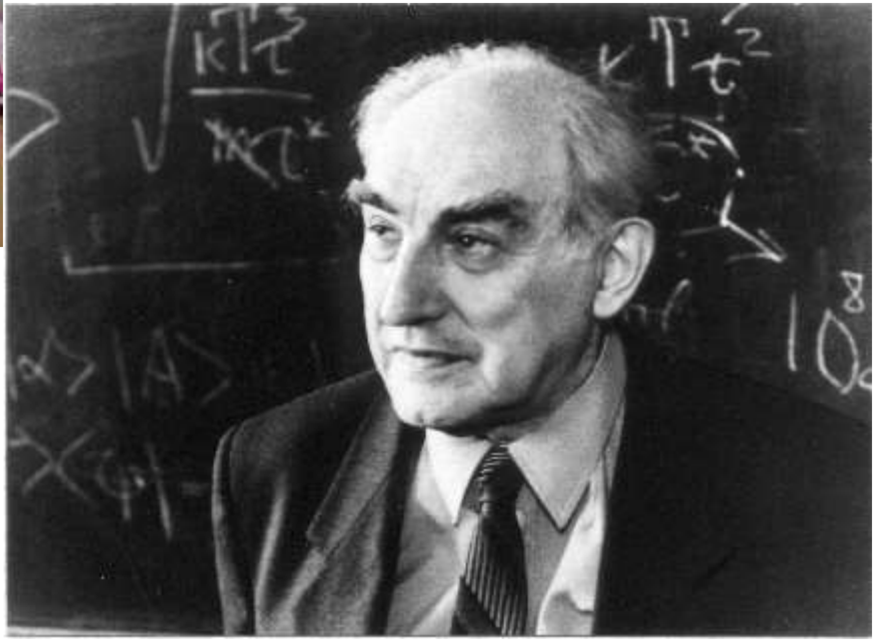




# Vitaly L. Ginzburg





**Tag der Physik**

**07. 07. 2000**

# Microscopic (BCS) Theory (1957)

J. Bardeen

L. N. Cooper

R. Schrieffer

**Nobel Prize in Physics 1972**

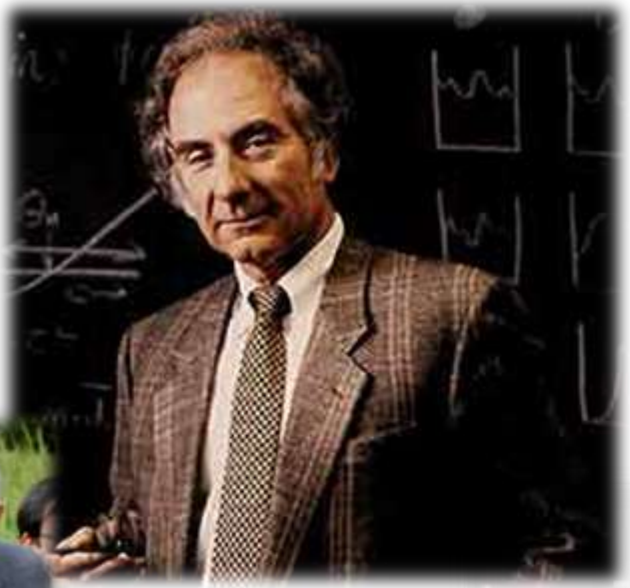
*"for their jointly developed theory of superconductivity, usually called the BCS-theory"*

# John Bardeen


* 23 May 1908, Madison, Wisconsin
† 30 January 1991, Boston
two-times Nobel Price winner

# Leon Neil Cooper

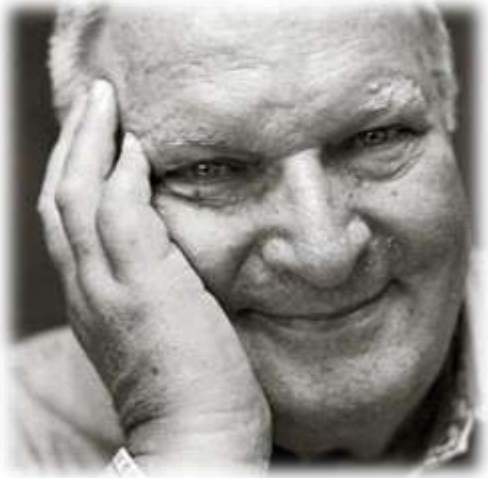
* 28 February 1930, New York
Nobel Prize in Physics 1972



Pioneers of superconductivity honored at BCS@50
From left: Dale J. Van Harlingen, Lev Gor'kov, Charles P. Slichter, Leo Kadanoff, David Pines, Leon Cooper, Marvin Cohen, Michael Tinkham

# John Robert Schrieffer

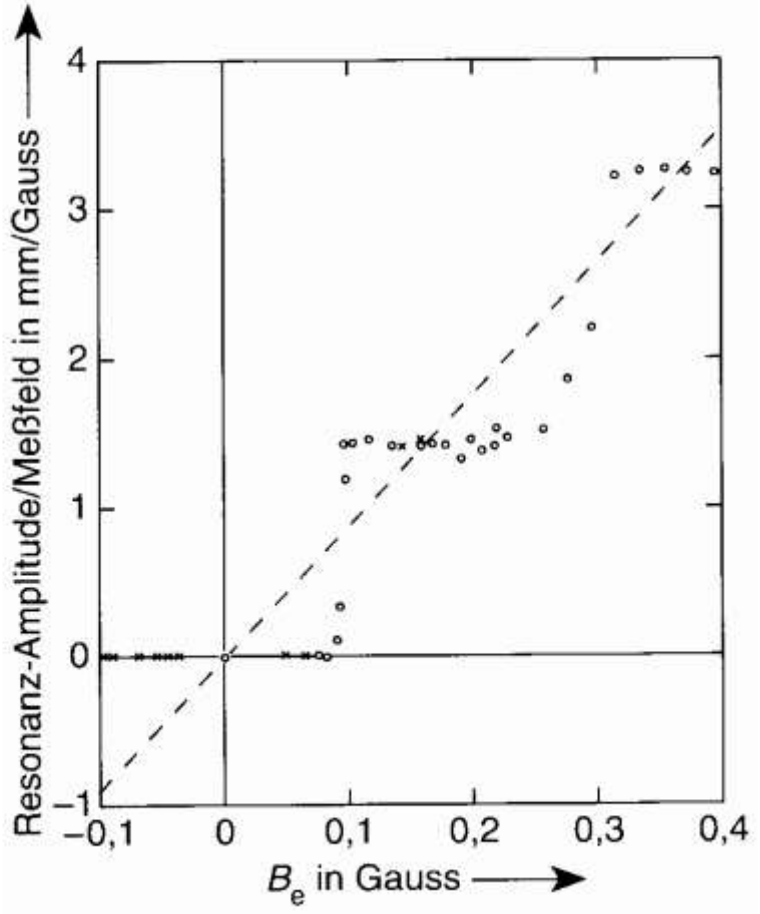


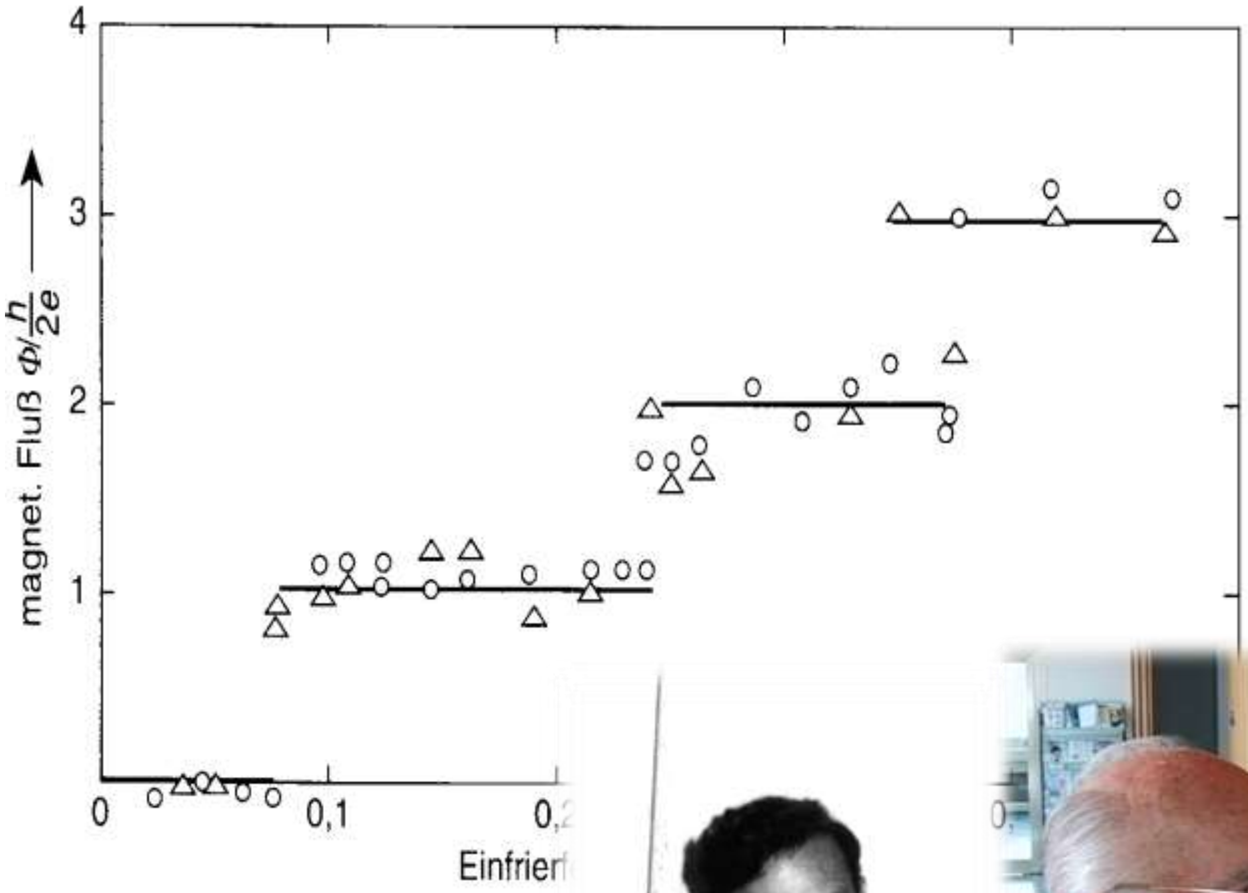


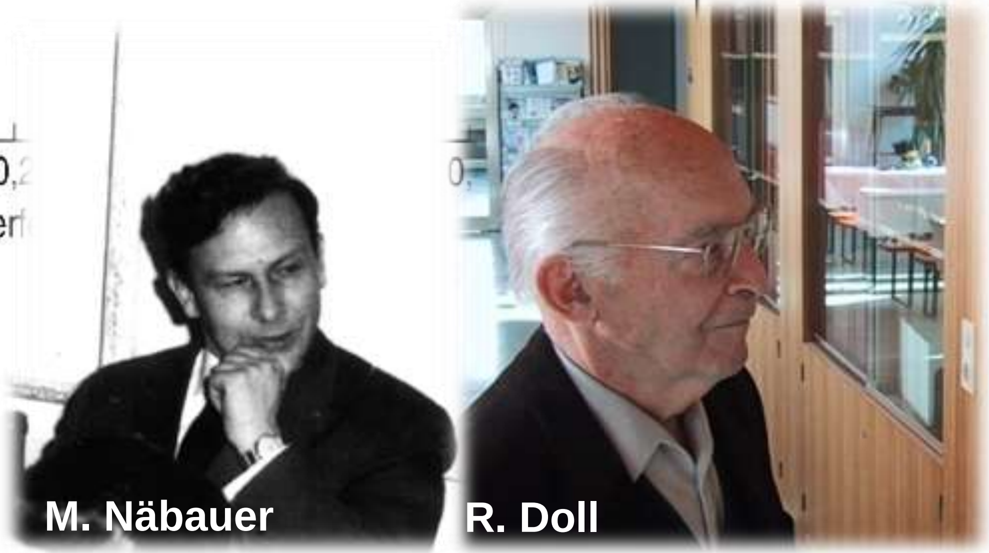
* 31 May 1931, Oak Park, Illinois
Nobel Prize in Physics 1972

# Discovery of Flux Quantization (1961)






**Robert Doll and Martin Näbauer, WMI**

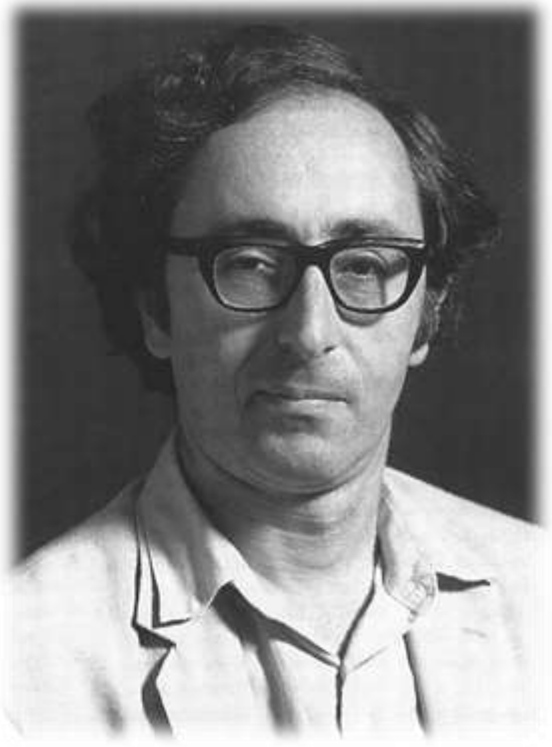
R. Doll, M. Näbauer, Phys. Rev. Lett. 7, 51 (1961).
B.S. Deaver Jr., W.M. Fairbank, Phys. Rev. Lett. 7, 43 (1961).

# Discovery of Flux Quantization (1961)



**Measuring the flux quantum.** Graduate student Bascom Deaver refills his apparatus with liquid nitrogen at Stanford University in 1961, a necessary step in maintaining a superconductor at liquid helium temperature. He and William Fairbank used this setup to show that the magnetic field threading a superconducting loop is always quantized. [Credit: J. Mercado/Stanford News Service]

# Prediction of the Josephson Effect (1962)



**Brian David Josephson (geb. 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 Superfluid $^3$Helium (1971/72)



**Douglas D. Osheroff,**
Stanford University,
Stanford, California, USA

**David M. Lee,**
Cornell University, Ithaca,
New York, USA

**Robert C. Richardson,**
Cornell University, Ithaca,
New York, USA

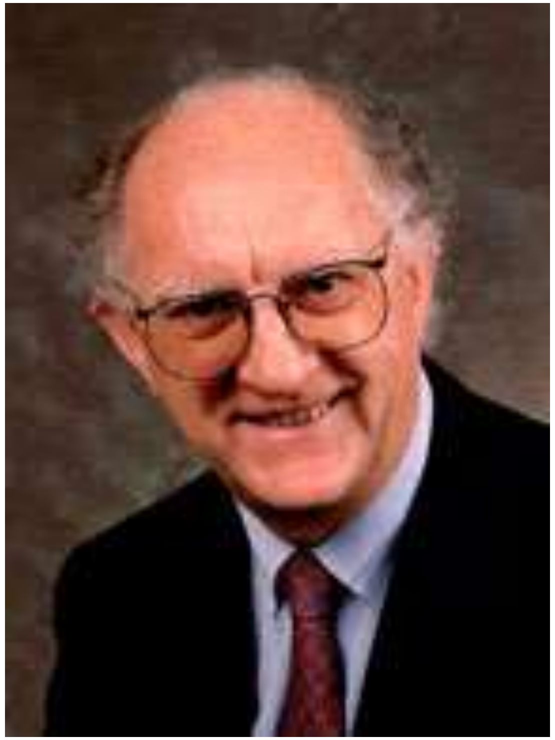
**Nobel Prize in Physics 1996**

***"for their discovery of superfluidity in helium-3"***

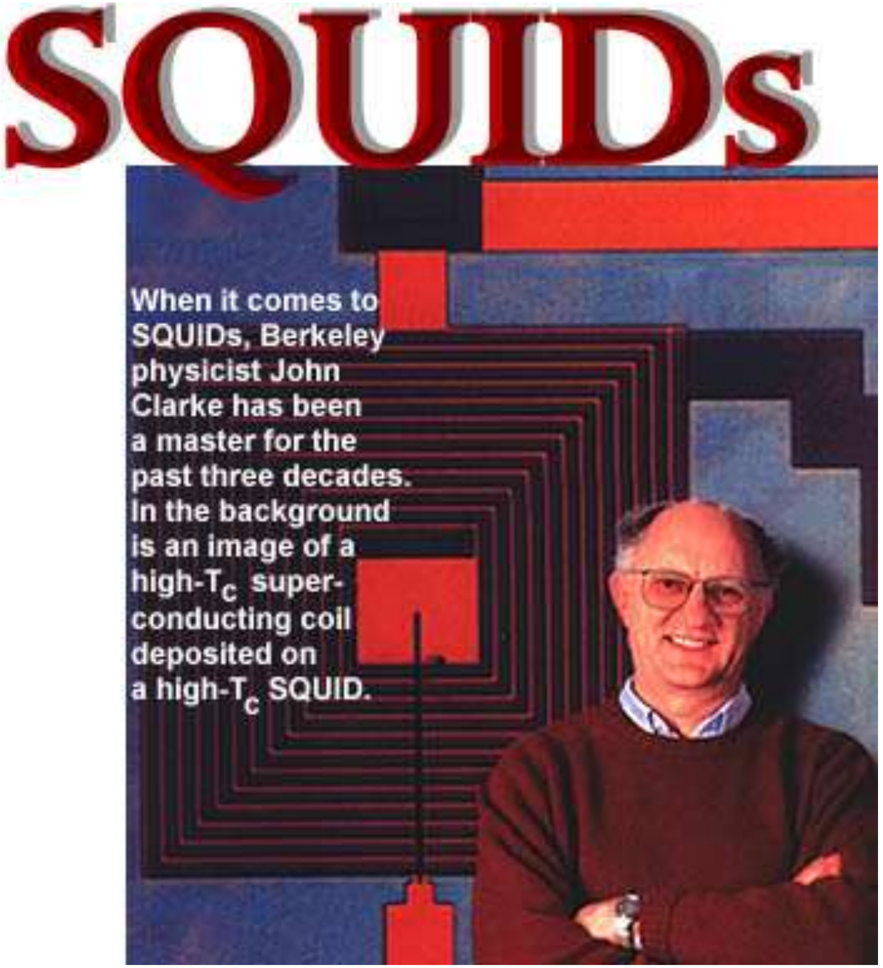
$T_c = 2.6$ mK

**1966 $^3$He/$^4$He dilution refrigerator: Hall, Neganov 2 mK .... 500 mK**

# Development of SQUID (1966)



John Clarke




## Superconducting Quantum Interference Devices

# Theory of Superfluid $^3$Helium (1975)



**Anthony J. Leggett**

**Nobel Prize in Physics 2003**

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

(together with Alexey A. Abrikosov and Vitaly Ginzburg)

# Discovery of the High $T_c$ Superconductivity (1986)



**J. Georg Bednorz (b. 1950)** **K. Alexander Müller (b. 1927)**

**Nobel Prize in Physics 1987**

*"for their important break-through in the discovery of superconductivity in ceramic materials"*

# Discovery of the High $T_c$ Superconductivity (1986)

**Karl Alexander Müller**
* 20. April 1927 in Basel

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

# Summary of Lecture No. 1

- information on contents and structure of the lectures on superconductivity and low temperature physics I & II

  related lectures and seminars

- general introduction into the field of low temperature physics

  important research fields, related Nobel prizes

  information on related research at WMI

- A brief history of superconductivity and low temperature physics

  important discoveries, key researchers, ....

Walther Meißner Institut

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Technische Universität München

# Superconductivity and Low Temperature Physics I

**Lecture No. 2**

**R. Gross**

# 1. Basic Properties of Superconductors

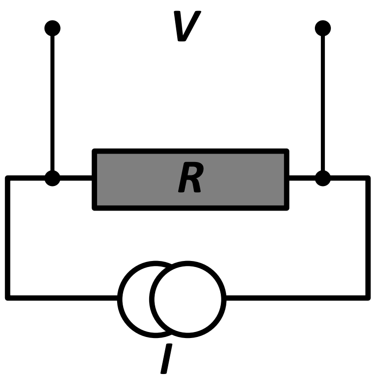
# 1.2 Perfect Conductivity



- **can we measure *R* = 0 ?**

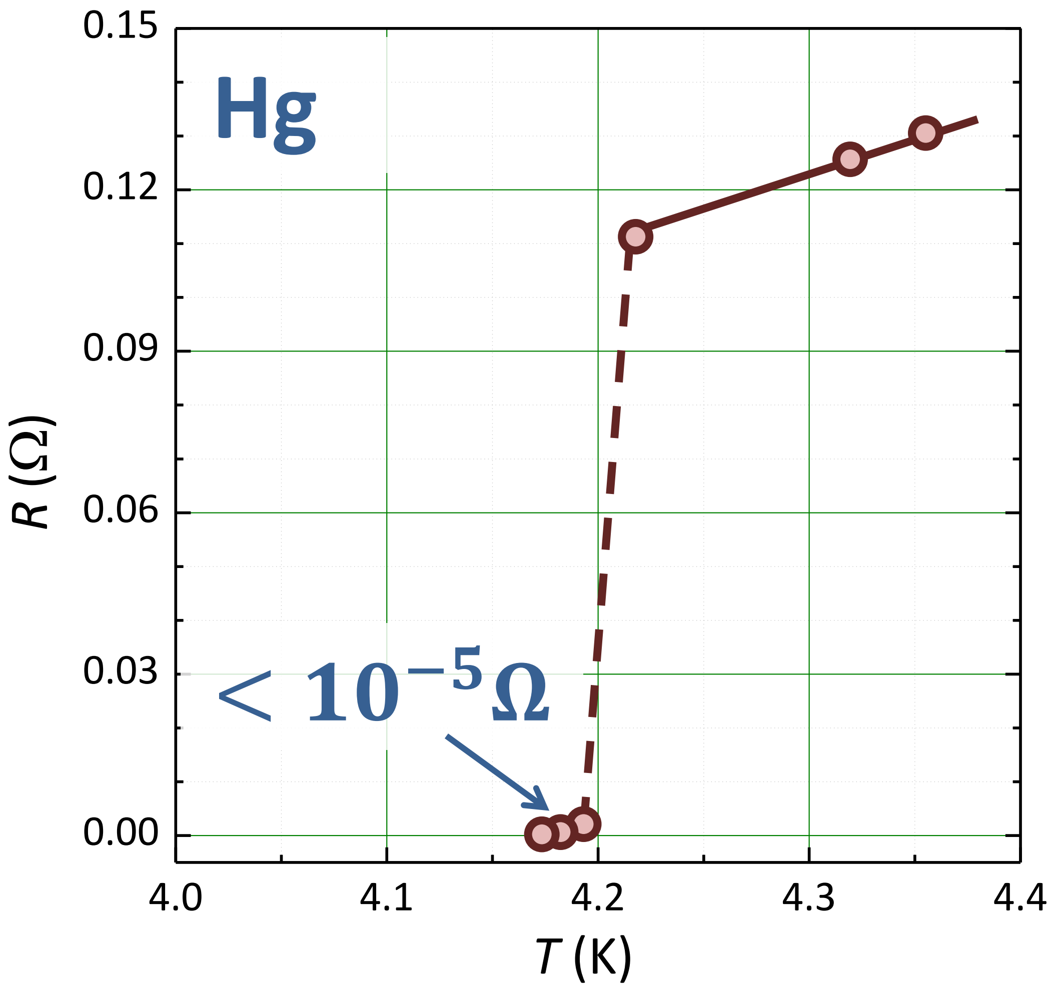
**no, only lower threshold can be obtained in experiment**

**limited resolution of voltage measurement**




$$\Delta R = \Delta V / I \approx 10^{-8}\ \Omega$$

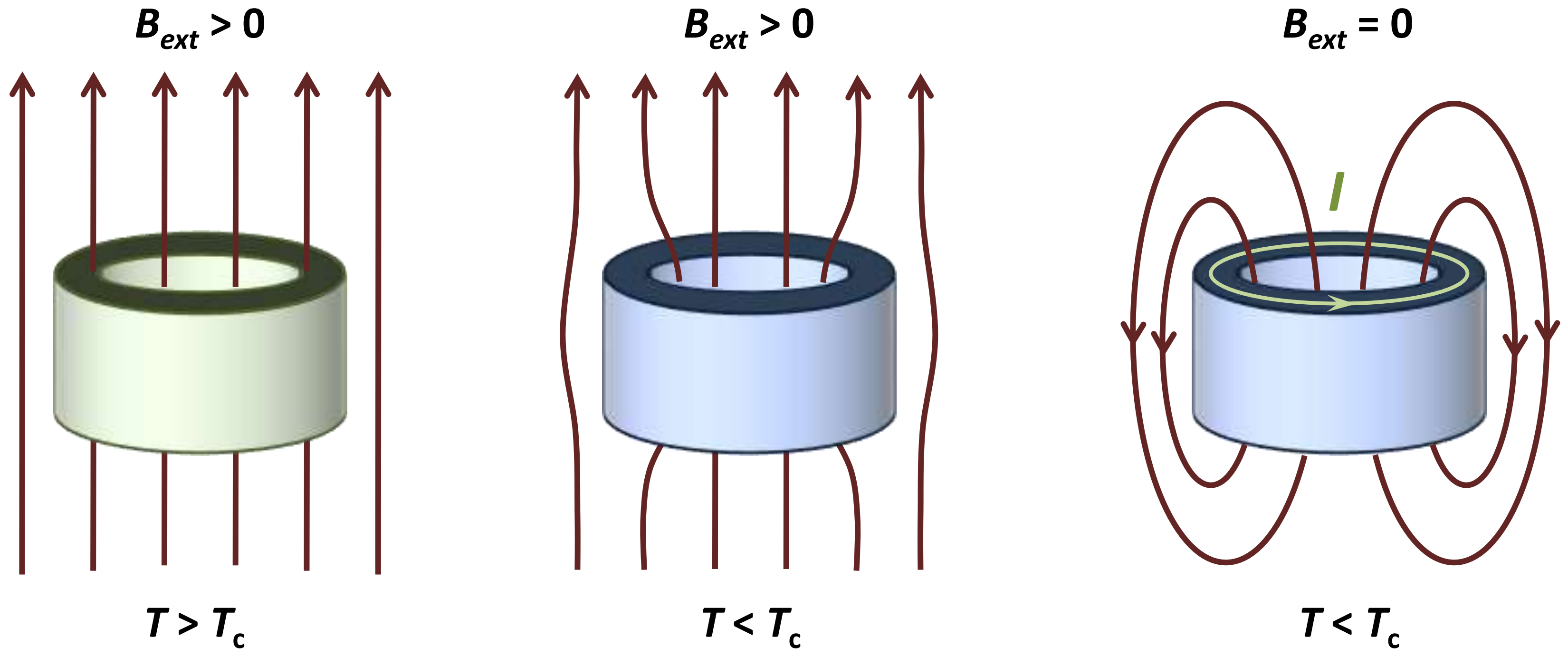
@ $\Delta V$ = 10 nV, $I$ = 1 A




**H. K. Onnes**: resistance drops by about 4 orders of magnitudes (later 14)

# 1.2 Perfect Conductivity

**improvement of resistance mesurement by study of decay of persistent current**



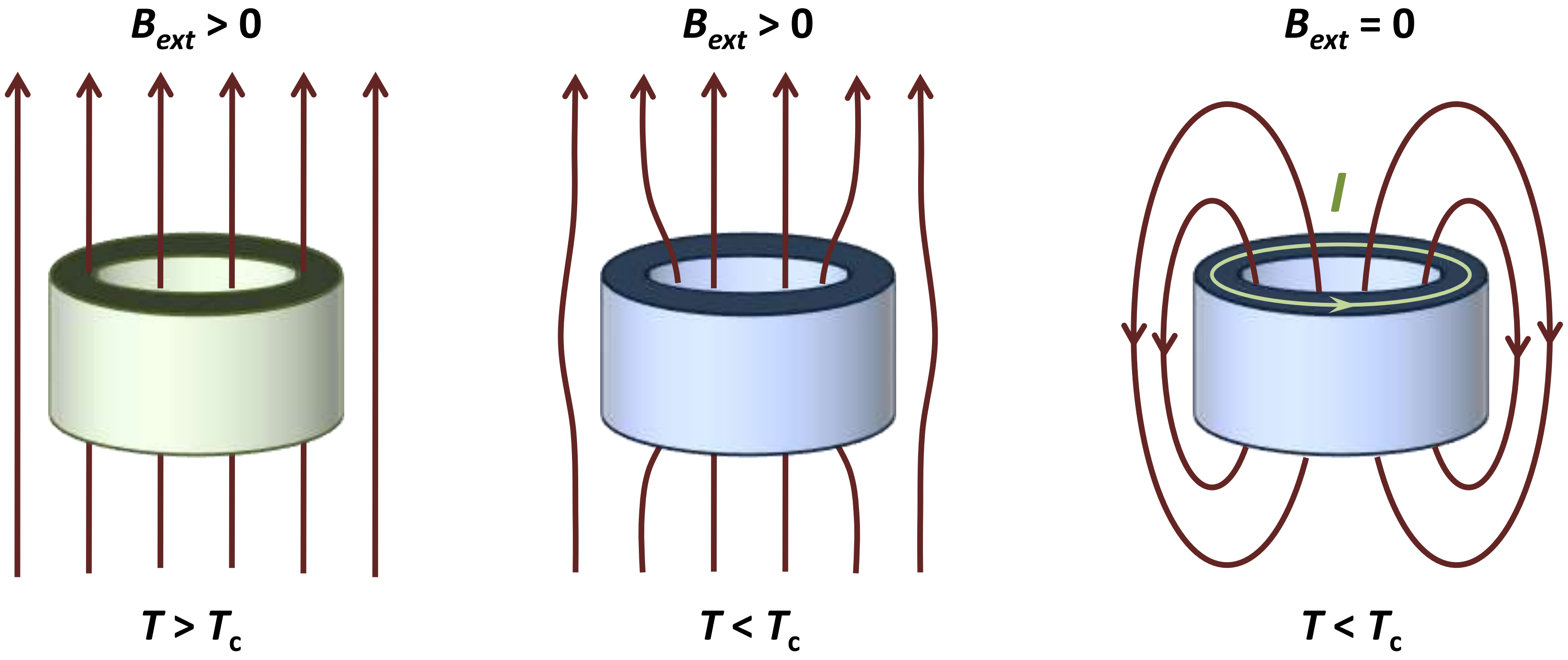

*flux trapping:* ***Faraday's law:*** $$-\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}$$

$$-\frac{\partial}{\partial t}\int_A \mathbf{B}\cdot\hat{\mathbf{n}}\; dS = -\frac{\partial}{\partial t}\Phi = \int_A (\nabla\times\mathbf{E})\cdot\hat{\mathbf{n}}\; dS = \oint_\Gamma \mathbf{E}\cdot d\ell = 0$$

***in superconductor (or any perfect conductor):*** $\boldsymbol{E} = \mathbf{0} \quad \Rightarrow \quad \dot{\boldsymbol{\Phi}} = \mathbf{0}$ or $\dot{\mathbf{B}} = \mathbf{0}$

# 1.2 Perfect Conductivity

**improvement of resistance mesurement by study of decay of persistent current**




→ ***measure decay of magnetic moment generated by frozen in persistent current***

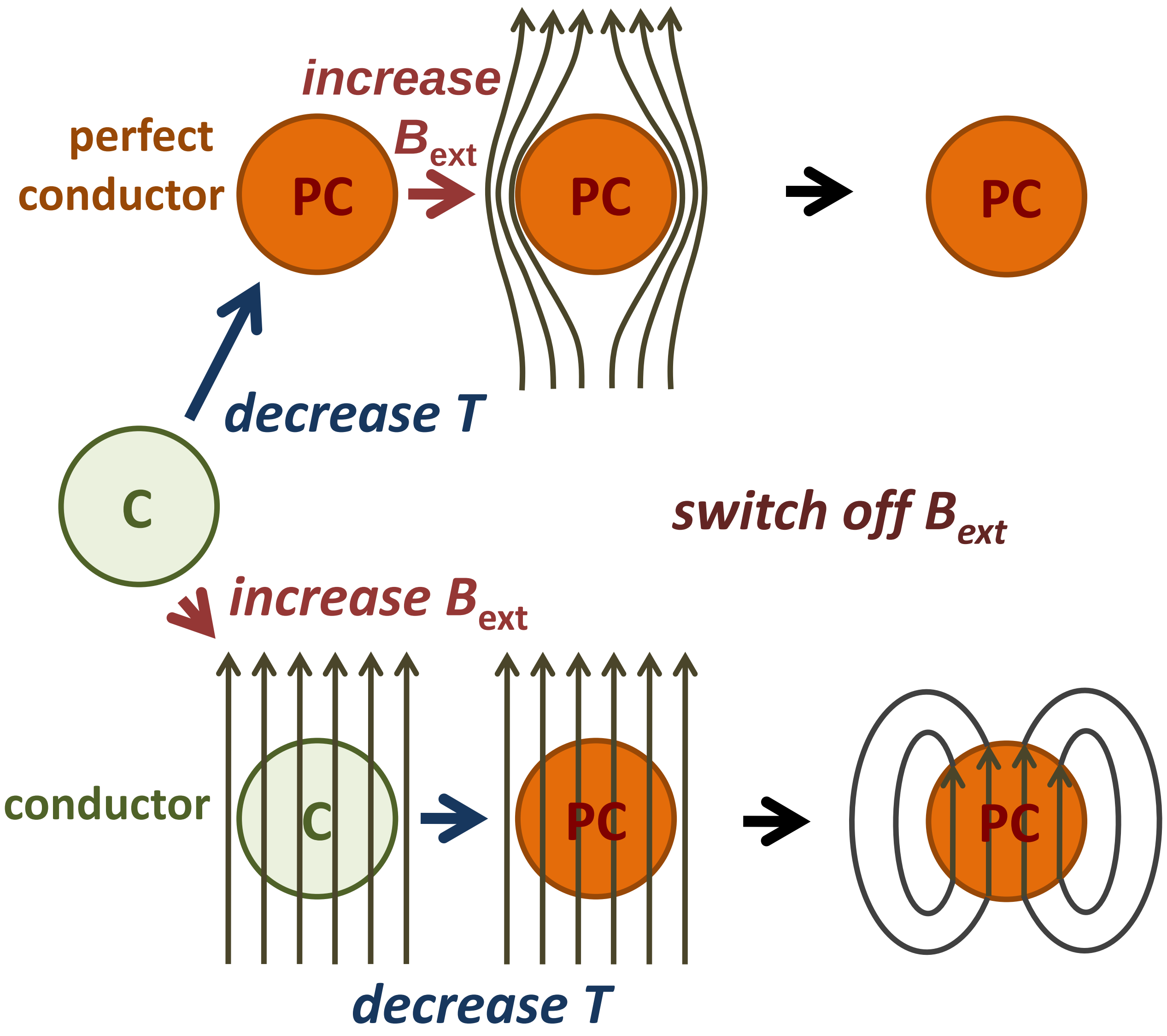
loop with inductance $L$ and resistance $R$:

$$RI + L\frac{dI}{dt} = 0 \quad \Rightarrow \boldsymbol{I(t) = I_0 \exp\left(-\frac{R}{L}t\right)}$$

example: 10% decay in 1 year observed
@ $L$ = 1 nH
➔ $\boldsymbol{R < 10^{-17}\Omega}$

# 1.3 Perfect Diamagnetism

## perfect conductor in magnetic field




**path dependent final state of the perfect conductor**

# 1.3 Perfect Diamagnetism

## variation of applied magnetic field for a perfect conductor

*Faraday's law:* $$-\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}$$

*Ohm's law:* $$\mathbf{J} = \sigma \mathbf{E} \quad \Rightarrow \quad \mathbf{E} = \frac{\mathbf{J}}{\sigma} = \rho \mathbf{J} = 0$$

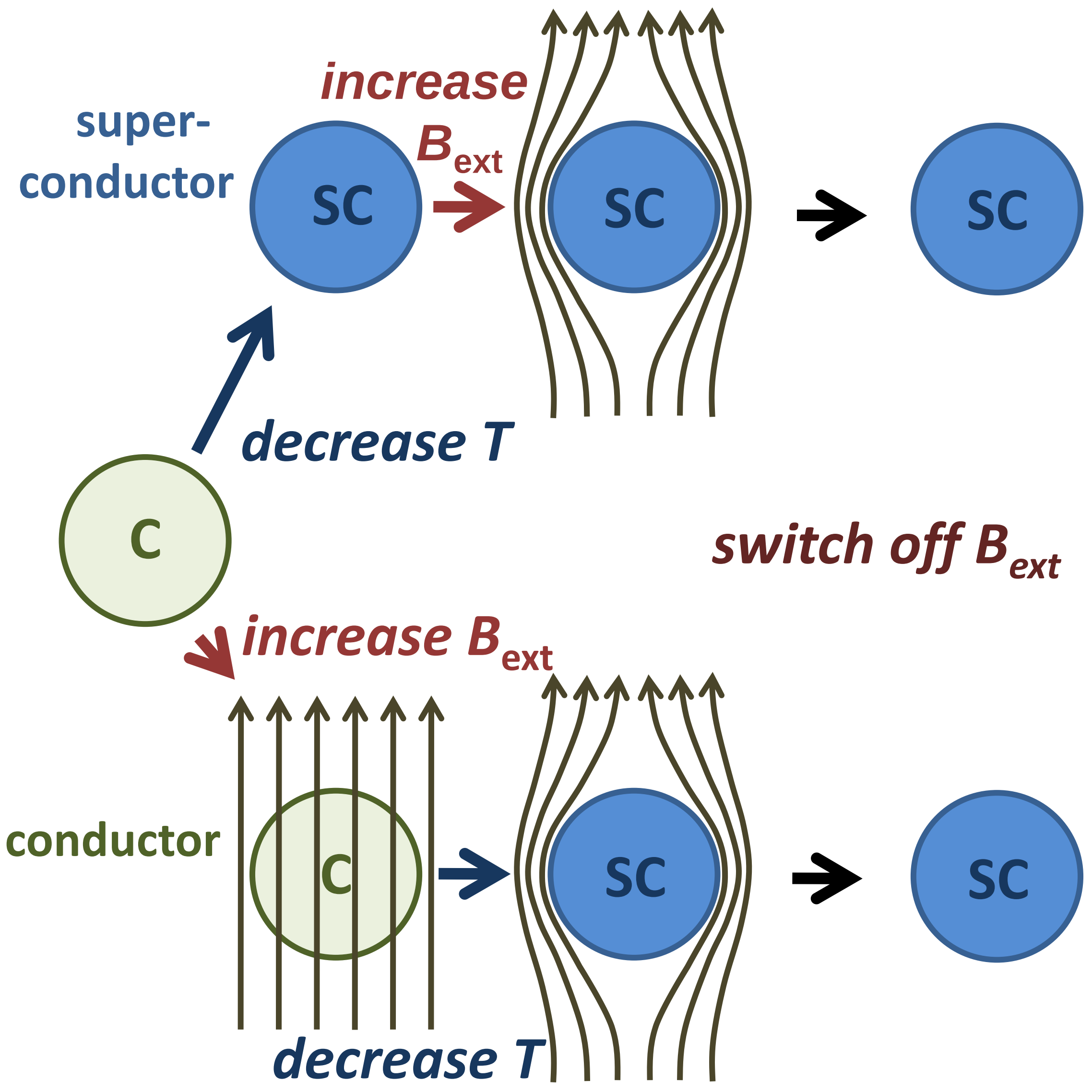
= 0  in superconductor

$$\Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = 0$$

➔ $B_i = const.$ *inside a perfect conductor*

- *field variation* → *screening currents* → *shielding of temporal variation of flux density*
- *screening current do not decay* ➔ $B_i = const.$ *forever*
- *e.g. flux trapping in ring when switching off external field*

## superconductor in magnetic field




path independent
final state of the
superconductor

superconducting state is a thermodynamic phase

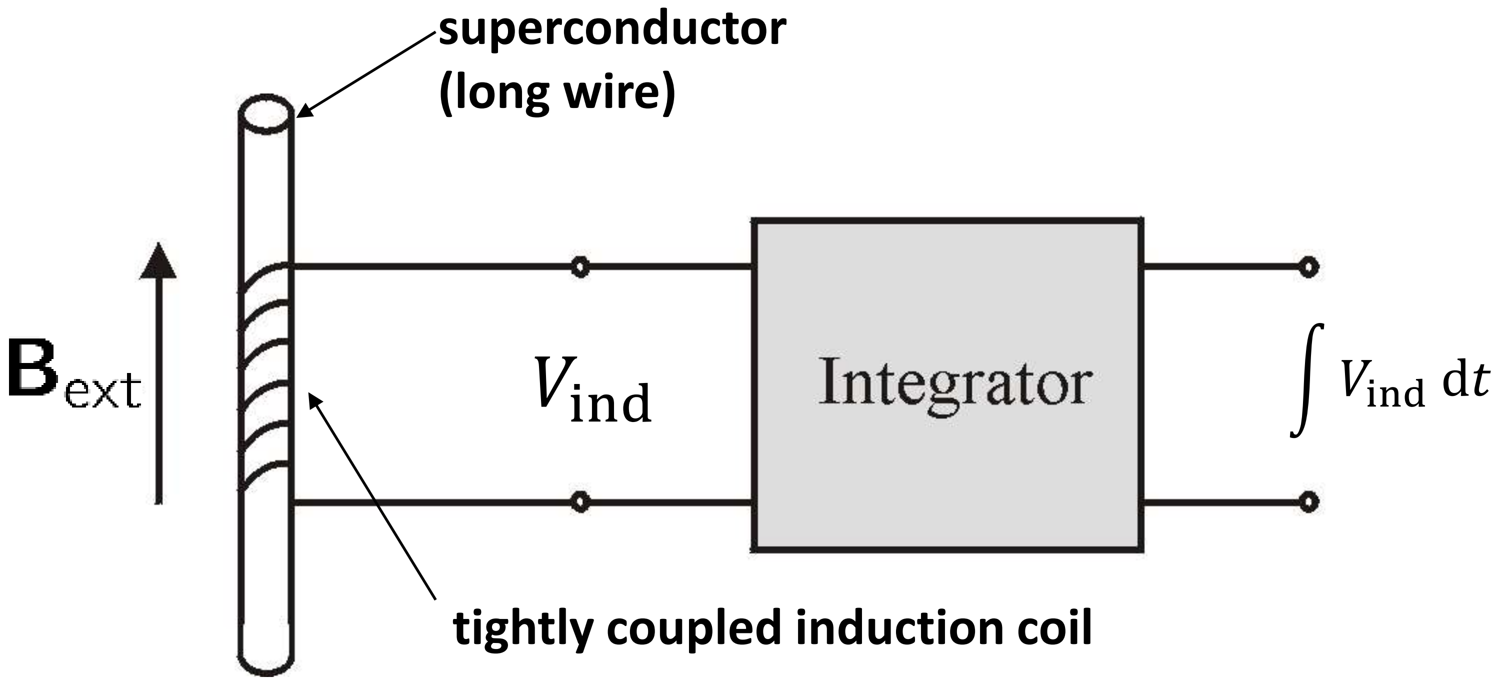
*Meißner-Ochsenfeld-Effect*

or

*perfect diamagnetism*

# 1.3 Perfect Diamagnetism

## simple experimental technique for determination of $B_i$:

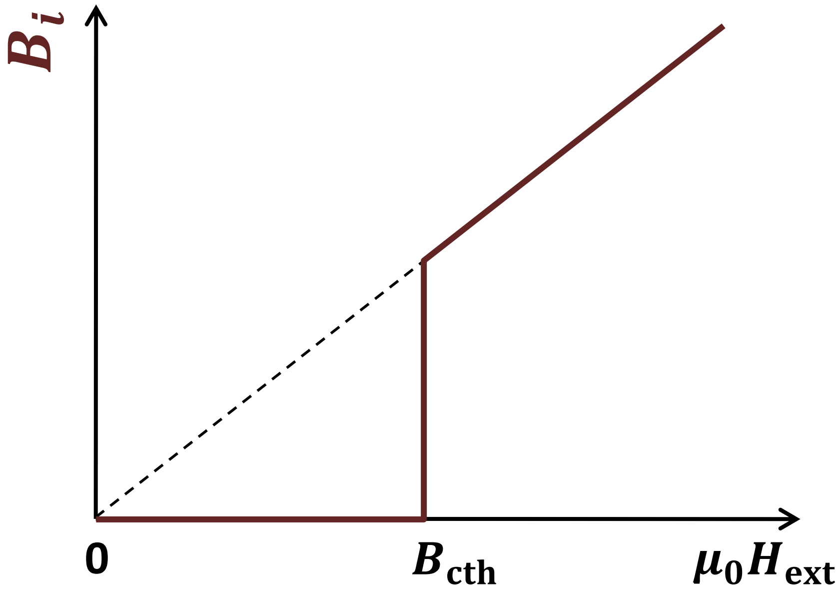


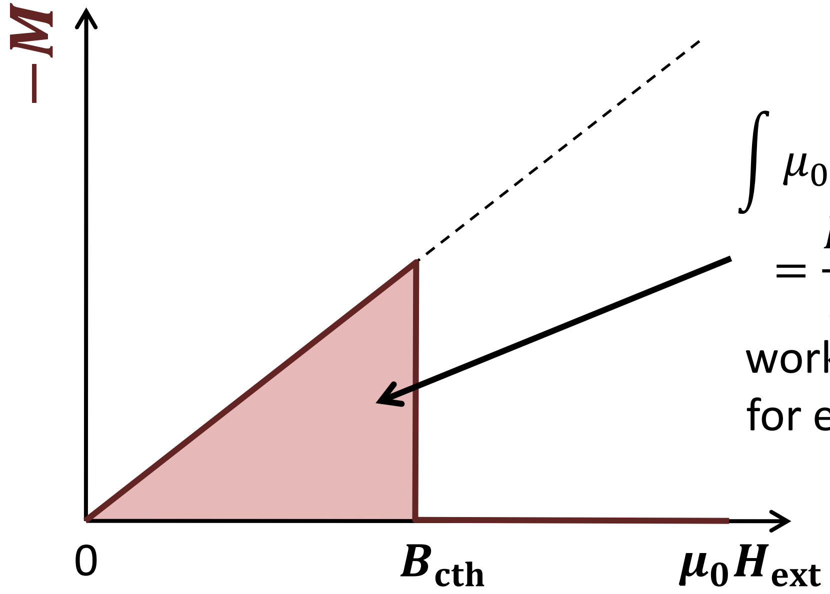

$$V_{ind} = -\frac{\partial \Phi}{\partial t} \propto -\frac{\partial B_i}{\partial t}$$

$$\Rightarrow \int V_{ind}\, dt \propto B_i$$

# 1.3 Perfect Diamagnetism

## inner magnetic field $B_i$ and magnetization $M$ of superconductors




$$\int \mu_0 \mathbf{M} \cdot \mathrm{d}\mathbf{H}_{\mathrm{ext}} = \frac{B_{\mathrm{cth}}^2}{2\mu_0}$$

work performed for expelling field

$$\mathbf{B}_i = \mu_0(\mathbf{H}_{\mathrm{ext}} + \mathbf{M})$$

$$\chi = -1$$

$$\mathbf{M} = \mathbf{B}_i/\mu_0 - \mathbf{H}_{\mathrm{ext}}$$

$$\mathbf{M} = \chi\, \mathbf{H}_{\mathrm{ext}}$$

## perfect diamagnetism survives only up to $T$-dependent critical field $B_{\mathrm{cth}}(T)$

→ *finite energy available for expelling magnetic field*
→ *condensation energy* (discussed later)

# 1.3 Perfect Diamagnetism

**observation: perfect diamagnetism survives only up to $T$ - dependent critical field $B_{\mathrm{cth}}(T)$**

***interpretation:***

superconductor has only finite amount of energy available for expelling field

$$\frac{B_{\mathrm{cth}}^2(T)}{2\mu_0} = g_n(T) - g_s(T)$$

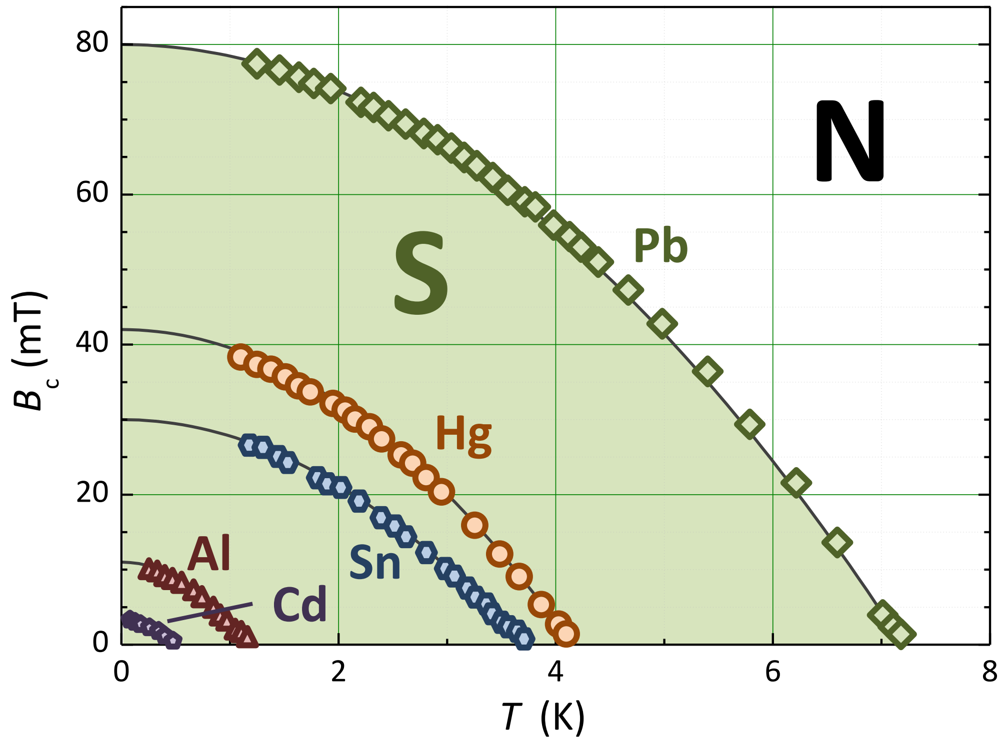
*condensation energy*

*free enthalpy difference of N and S state*

***temperature dependence of $B_{\mathrm{cth}}$:***

$$B_{\mathrm{cth}}(T) = B_{\mathrm{cth}}(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

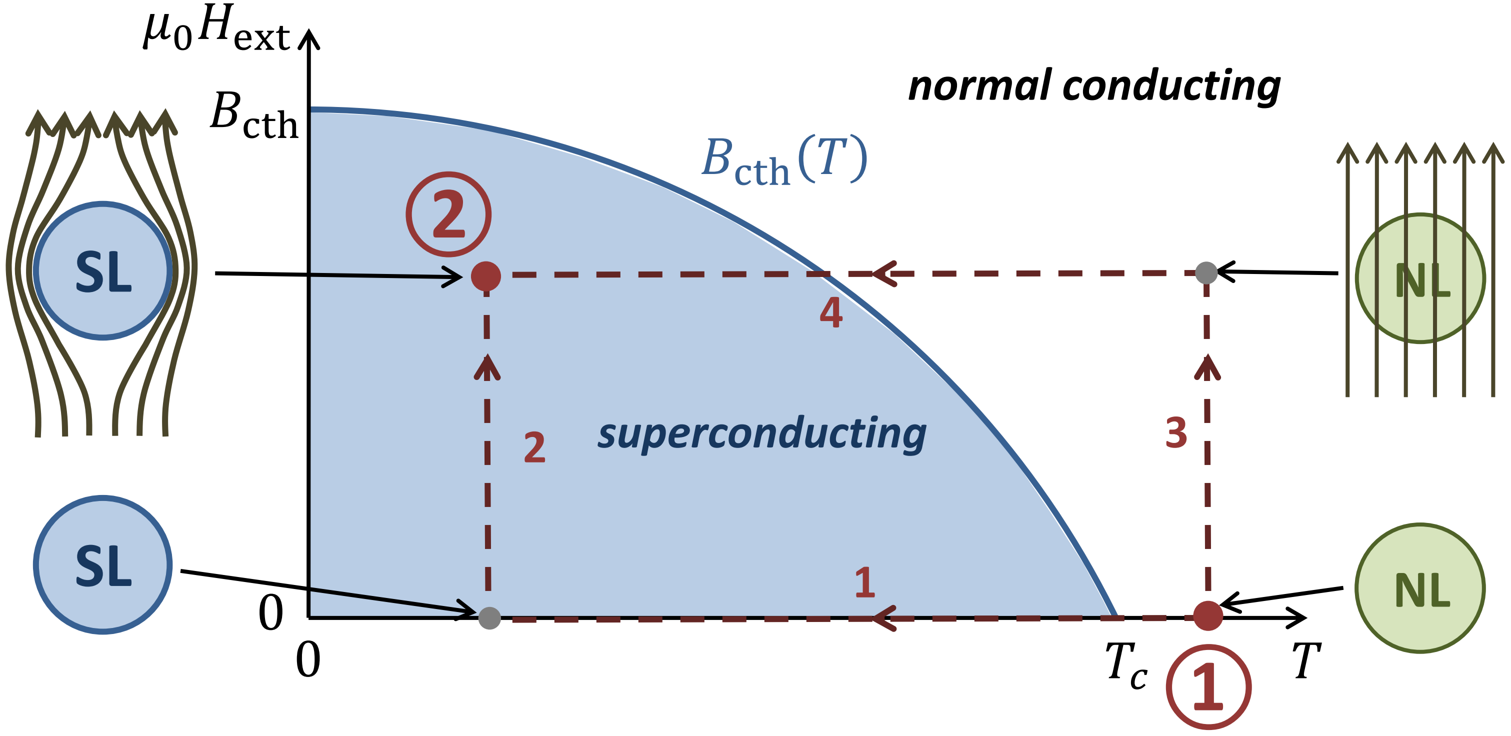
***phase diagram***




***empirical relation***,
good approximation to exact result of BCS theory

# 1.3 Perfect Diamagnetism

## superconductor: $B_i = 0$ independent of path to position ②




$$\mathbf{B}_i = \mu_0(\mathbf{H}_{\text{ext}} + \mathbf{M}) = \mu_0(\mathbf{H}_{\text{ext}} + \chi\mathbf{H}_{\text{ext}}) = \mu_0\mathbf{H}_{\text{ext}}(1+\chi) = 0$$

➔ **perfect diamagnetim:** $\chi = -1$

➔ **superconducting state is** ***thermodynamic phase***

# 1.3 Perfect Diamagnetism



**Meißner effect**:

***path-independent complete exclusion of magnetic flux from the interior of a bulk superconductor***

**important remaining questions**

- How does the magnetic induction $B$ change at the surface? Step-like change?
- How do the screening currents set-off if not according to Faraday's law?
- Can the magnetic flux penetrate partially to reduce the magnetic energy?
- What happens in a superconductor that is not simply connected (e.g. superconductor with hole such as a cylinder)?

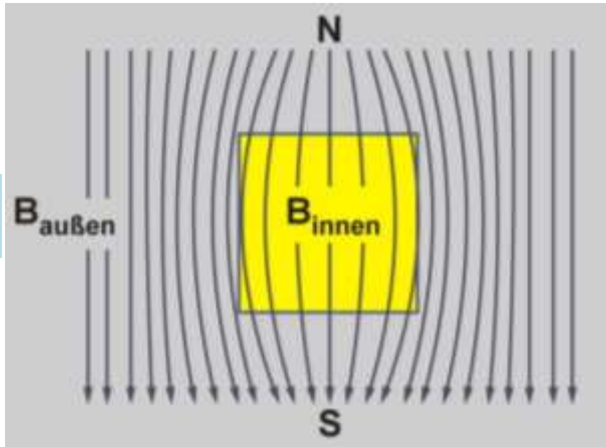
# 1.3 Perfect Diamagnetism

## levitation of diamagnetic materials

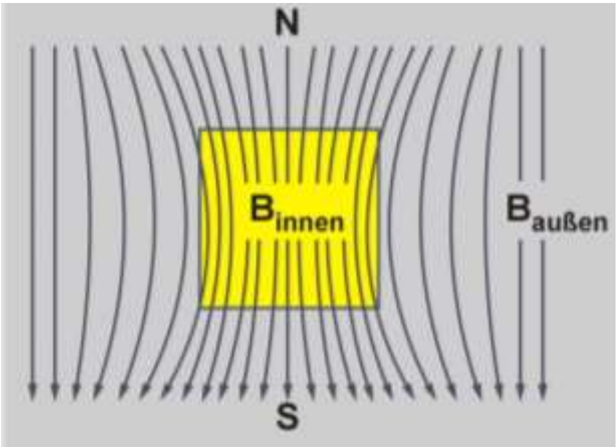
*diamagnetic materials*

*para- or ferromagnetiv materials*

$\chi < 0$

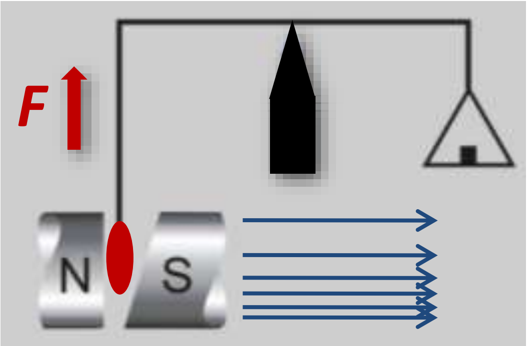



$\chi > 0$

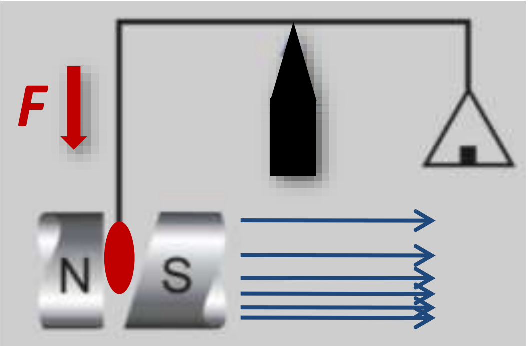



$$\mathbf{B}_i = (1+\chi)\,\mu_0 \mathbf{H}_{\text{ext}}$$

(χ = magnetic susceptibility)




***Faraday balance***




*material becomes „lighter“*

*material becomes „heavier“*

# 1.3 Perfect Diamagnetism

## levitation of diamagnetic materials

$$\mathbf{F}_{\text{buoyancy}} = \frac{\chi}{2\mu_0}\, \mathbf{B}\cdot\nabla\mathbf{B}$$

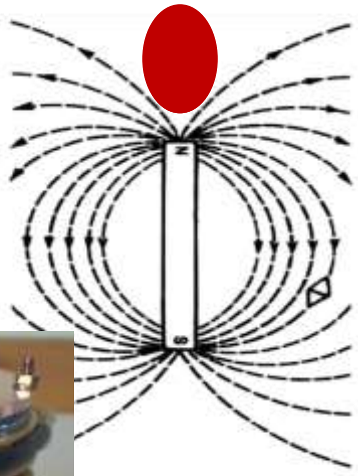
*magnetic field* *gradient of magnet field*

***buoyancy = gravity***

$$\mathbf{F}_{\text{gravity}} = \rho\ g$$

*mass density* *acceleration of gravity: 9.8 m/s²*

$$\mathbf{B}\cdot\nabla\mathbf{B}\left[\frac{\mathrm{T}^2}{\mathrm{m}}\right] \approx \mathbf{0.02}\cdot\frac{\boldsymbol{\rho}[\mathrm{g/cm^3}]}{\boldsymbol{\chi}}$$



- ***organic materials:***

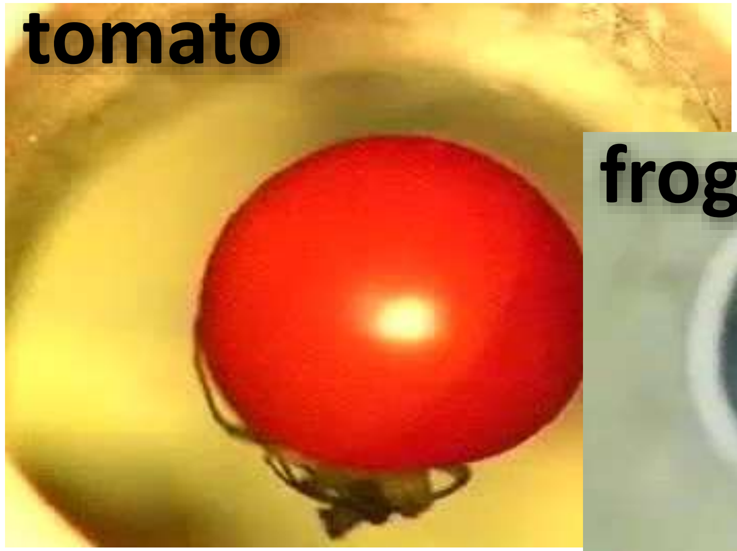
  $\rho \simeq 1$ ***g /cm³***, $\chi \simeq -1\cdot 10^{-5}$

  ⇨ $\mathbf{B}\cdot\nabla\mathbf{B} \simeq 1\,000\left[\frac{\mathrm{T}^2}{\mathrm{m}}\right]$

  *can be achieved with strong magnet:*
  *B = 20 Tesla, grad B = 100 T/m*

# Levitated tomatos, strawberries, ….

source: http://www.hfml.ru.nl/







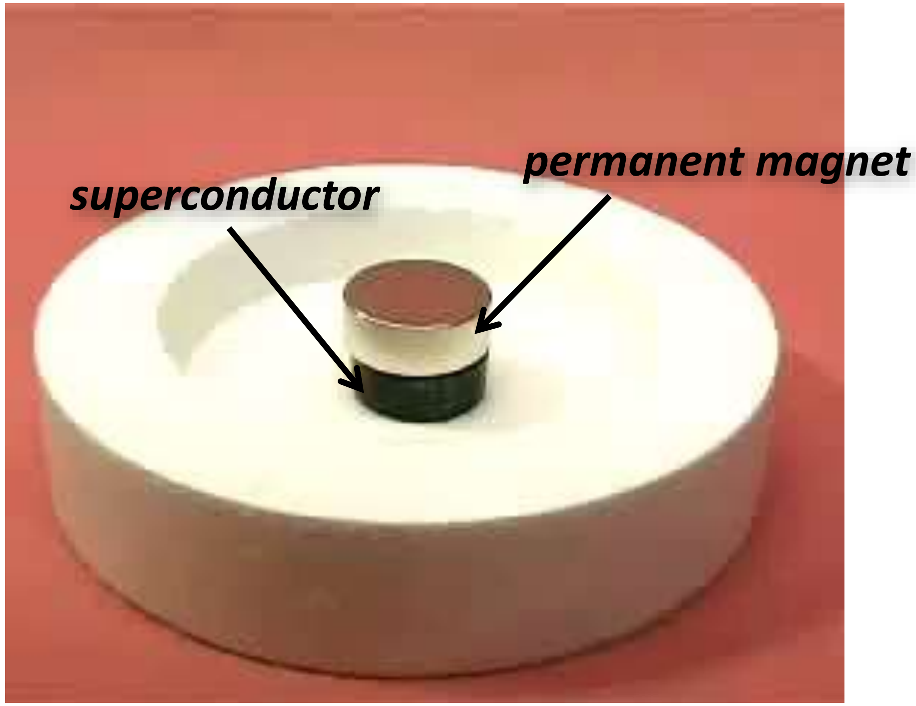
# 1.3 Perfect Diamagnetism

- *organic materials:* $\rho \simeq 1$ g/cm³, $\chi \simeq -1 \cdot 10^{-5}$

$$\Rightarrow \quad \mathbf{B} \cdot \nabla \mathbf{B} \simeq 1\,000 \left[\frac{\mathrm{T}^2}{\mathrm{m}}\right]$$

- *superconductors:* $\rho \simeq$ a few g/cm³, $\chi \simeq -1$

$$\Rightarrow \quad \mathbf{B} \cdot \nabla \mathbf{B} \simeq 0.01 \left[\frac{\mathrm{T}^2}{\mathrm{m}}\right]$$




**Superconductors:**

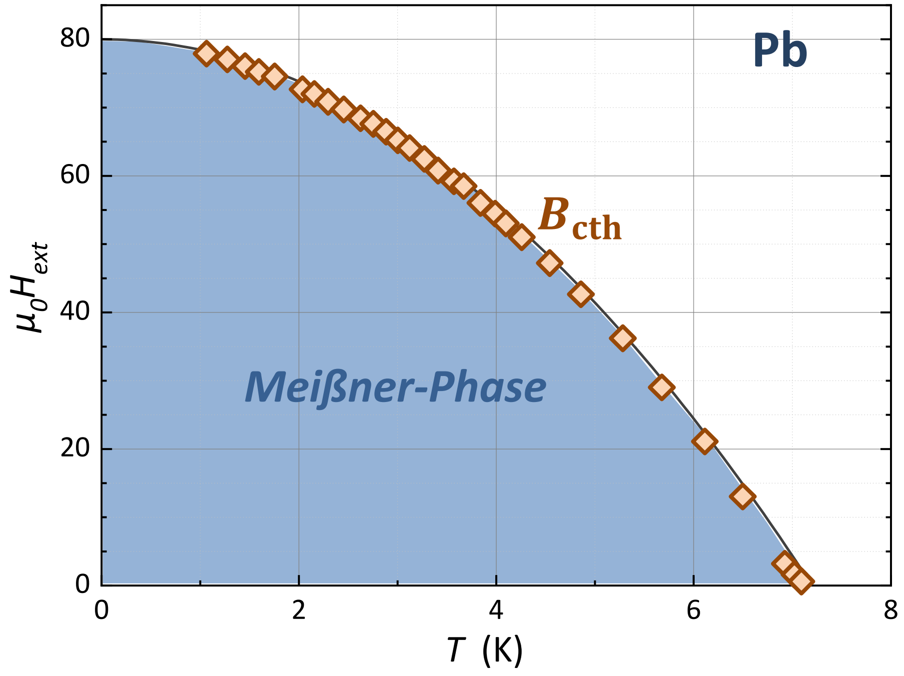
***ideal materials for magnetic levitation***

# 1. Basic Properties of Superconductors

# 1.4 Type-I and Type-II Superconductors

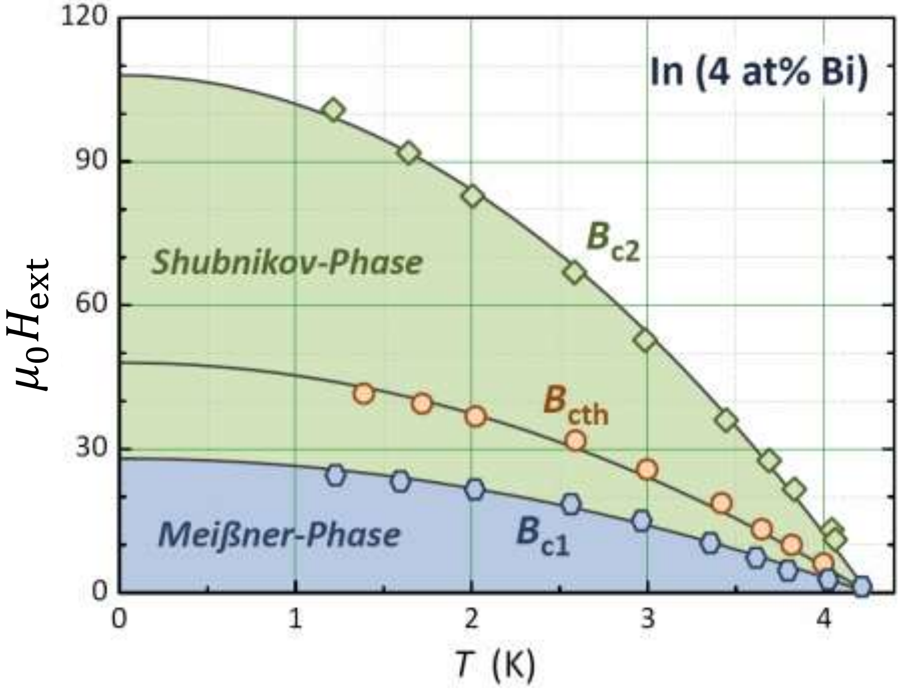


**Type-I Superconductor**




- Meißner-Phase for $B_{\mathrm{ext}} < B_{\mathrm{cth}}$
- no Shubnikov-Phase

**Type-II Superconductor**




- Meißner-Phase for $B_{\mathrm{ext}} < B_{c1}$
- Shubnikov-Phase for $B_{c1} < B_{\mathrm{ext}} < B_{c2}$

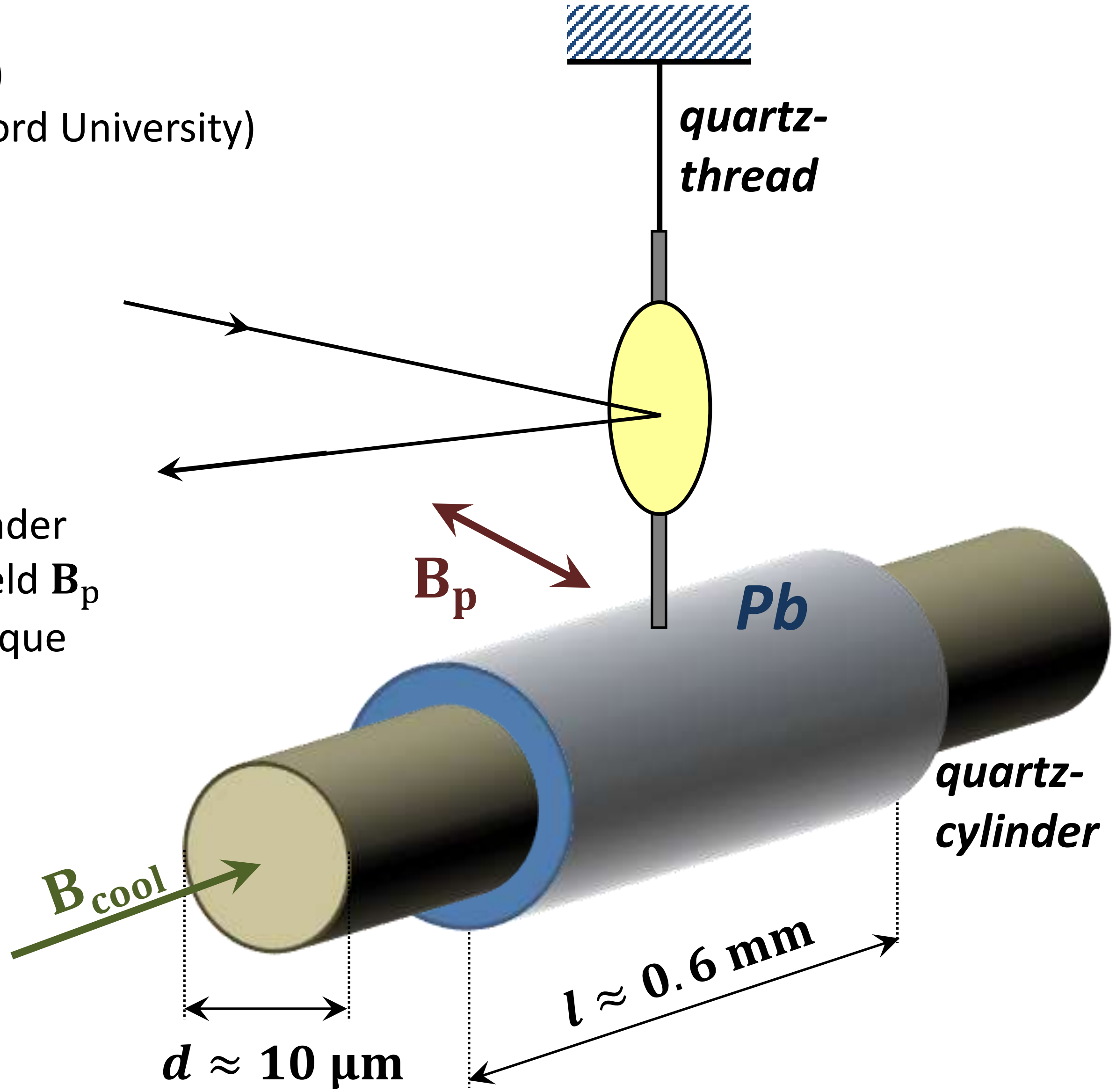
$$B_{c1} < B_{\mathrm{cth}} < B_{c2}$$

## 1. Basic Properties of Superconductors

# 1.4 Flux Quantization



- discoverd 1961 by
  - *Robert Doll* and *Martin Näbauer* (WMI)
  - *B.S. Deaver* and *W.M. Fairbanks* (Stanford University)




- *experiment by Doll and Näbauer (WMI)*

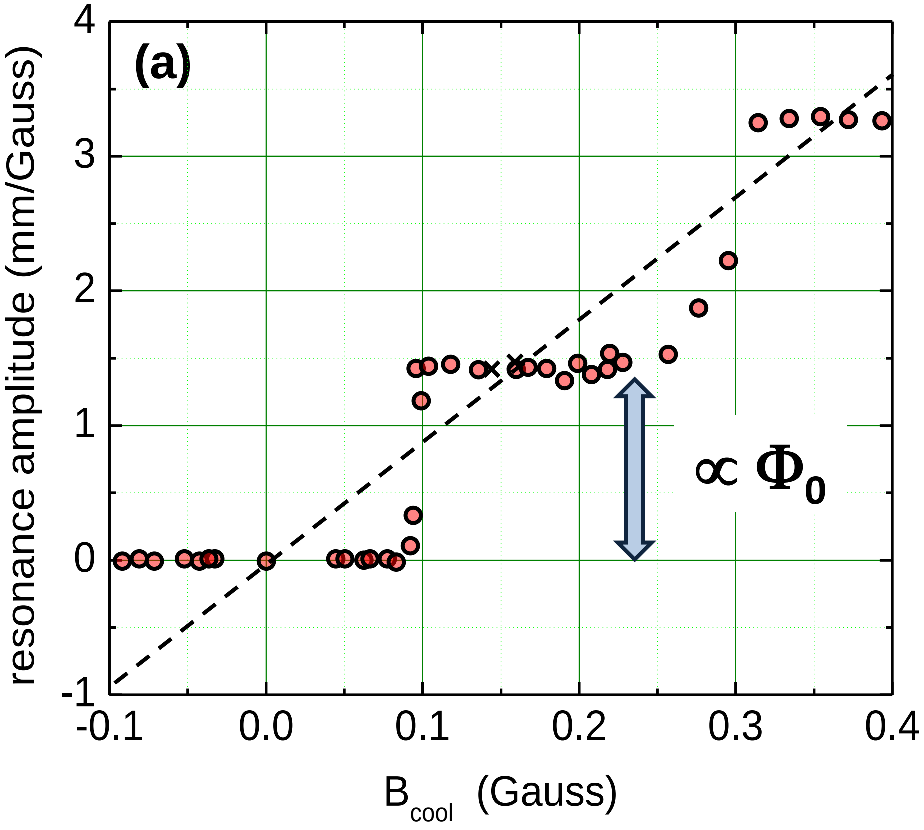
  - trapping of magnetic flux in hollow cylinder
  - apply torque $\mathbf{D} = \boldsymbol{\mu} \times \mathbf{B}_\mathrm{p}$ by probing field $\mathbf{B}_\mathrm{p}$
  - increase sensitivity by resonance technique

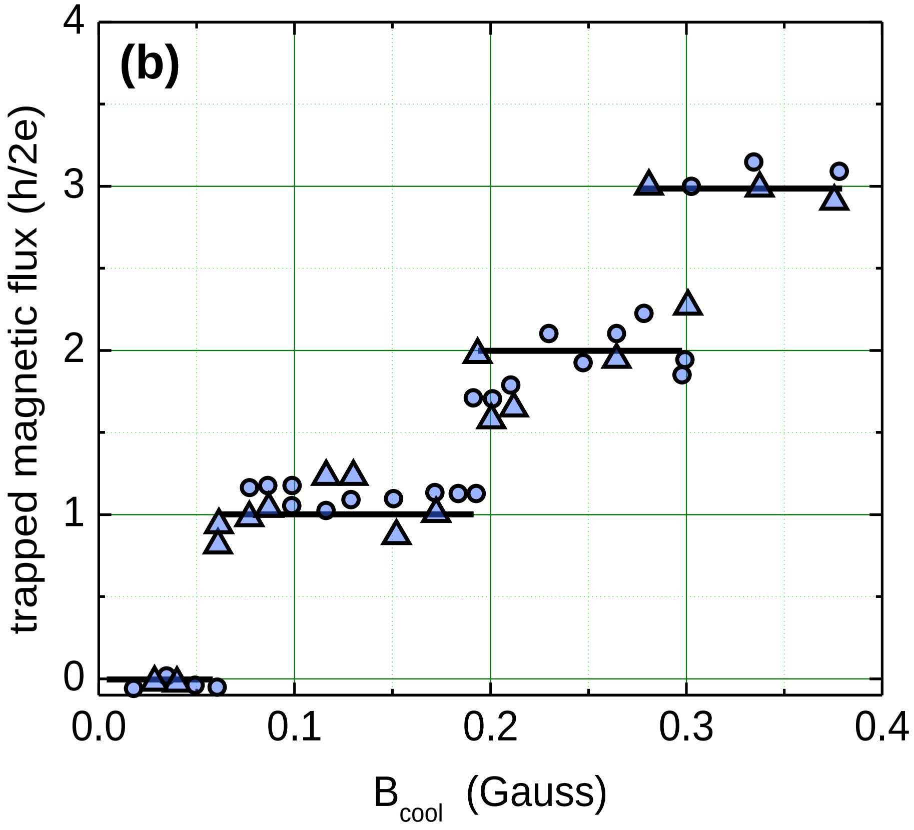
- number of trapped flux quanta:

$$N = B_\mathrm{cool}\, \pi (d/2)^2$$

$N \simeq 1$
@ $B_\mathrm{cool} = 10^{-5}\ \mathrm{T}, d = 10\ \mu\mathrm{m}$

# 1.4 Flux Quantization




***R. Doll, M. Näbauer***
Phys. Rev. Lett. **7**, 51 (1961)

***B.S. Deaver, W.M. Fairbank***
Phys. Rev. Lett. **7**, 43 (1961)

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

prediction by F. London: $h/e$
→ ***experimental proof for existence of Cooper pairs***

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

# 1. Basic Properties of Superconductors

# 1.6 Superconducting Materials

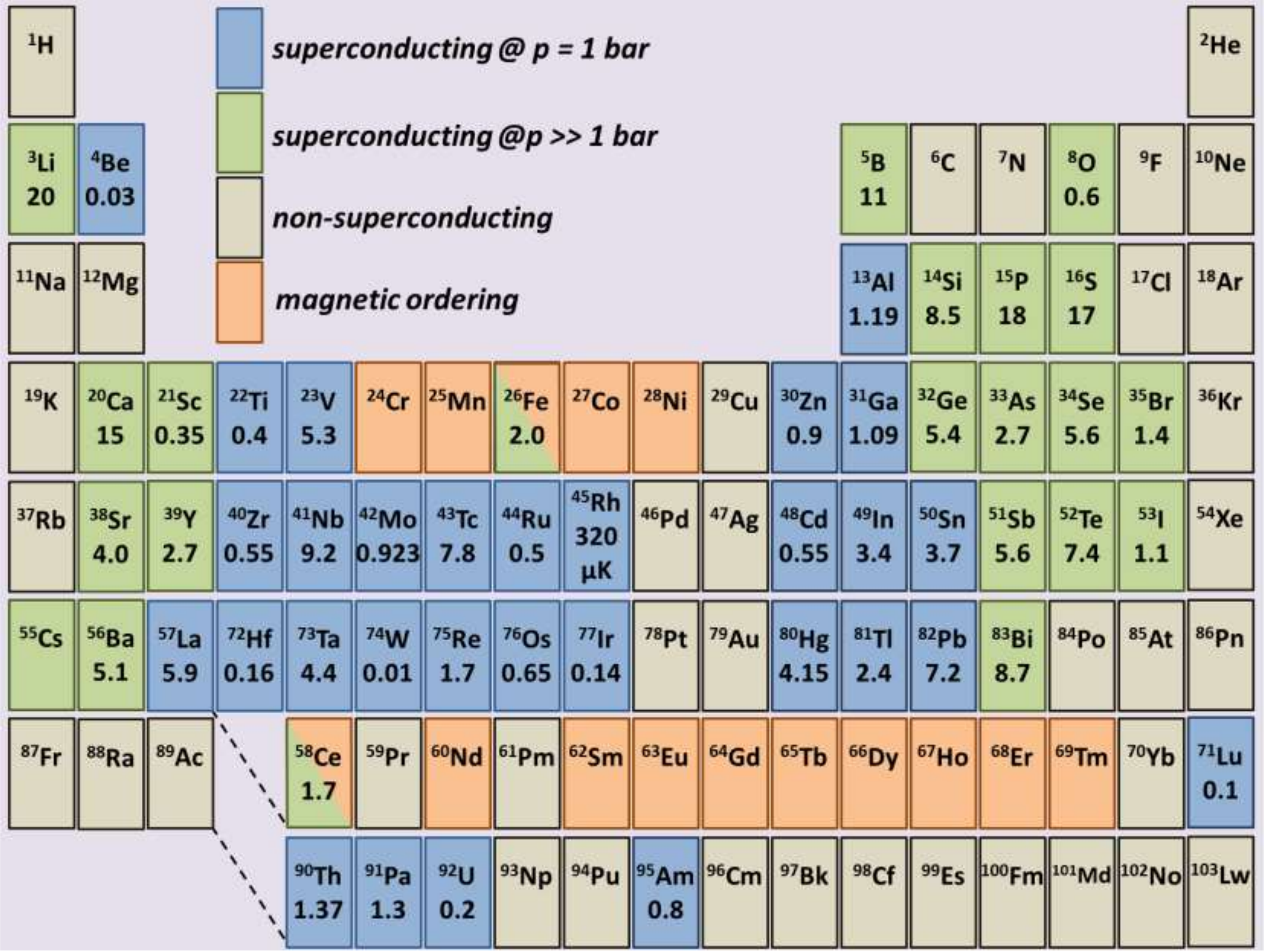
- discovery of superconductivity in chemical element Hg
- since then thousands of further superconducting compounds found
- classification into families:

1. elemental superconductors (Hg, 1911)
2. alloys and intermtellic compounds
3. heavy Fermion superconductors (1979)
4. organic superconductors (1981)
5. fullerides (1991)
6. oxides superconductors , cuprates (1986)
7. iron pnictides (2006)

$MgB_2$ (2001)

# 1.6 Superconducting Materials






**elemental superconductors**

# 1.6 Superconducting Materials

- *elemental superconductors*

  - highest $T_c$: Nb, 9.2 K

  - lowest $T_c$: Rh, 0.32 mK

  - many elements become superconducting under pressure
    e.g. Li: $T_c$ almost 20 K @ $p = 0.5$ Mbar
    non-magnetic high pressure Fe phase: $T_c = 2$ K

- *problem related to observation of superconductivity in materials with very low $T_c$ :*

$$k_\mathrm{B} T_c = 1.38 \cdot 10^{-26}\,\mathrm{J} \quad @ \quad T_c = 1\,\mathrm{mK}$$

requires small pair breaking rate → very pure materials

$$\tau^{-1} \leq \frac{k_\mathrm{B} T_c}{\hbar} = 1.38 \cdot 10^{-26} \frac{\mathrm{J}}{\hbar} @ \quad T_c = 1\,\mathrm{mK} \;\Rightarrow \tau \geq 10^{-8}\, s$$

# 1.6 Superconducting Materials

| material | $T_c$ |
|---|---|
| *@ 1 bar* | |
| Ru | 0.35 K |
| Al | 1.2 K |
| In | 3.4 K |
| Sn | 3.7 K |
| Hg, Ta | 4.2 K |
| Pb | 7.2 K |
| Nb | 9.2 K |
| *@ > 120 kbar* | |
| Si | 6.7 K |
| Ge | 5.4 K |
| S | 17 K |
| Li | 16 K |

| material | $T_c$ | |
|---|---|---|
| amorphous: | Pt | 0.6 .. 0.9 K |
| quenched condensed: | Ga | 8.0 K (orthorhombic phase: 1.09 K) |
| | Bi | 6.0 K (crystalline phase: semimetal, no SC) |

# 1.6 Superconducting Materials

- *alloys and intermetallic compounds*
  - more than 1000 systems found until today
  - some have high relevance for applications:

    e.g. A15 compounds (1953) with with β-tungsten structure
    $Nb_3Ge$: $T_c = 23.2$ K, $Nb_3Sn$: $T_c = 18$ K, $V_3Si$: $T_c = 17$ K

    e.g. NbTi: $T_c = 10 - 11$ K, NbN: $T_c = 13 - 16$ K

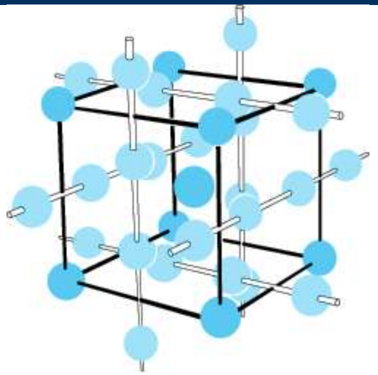
  - Chevrel phases: $M_xMo_6X_8$ — $M$ = Ca, Sr, Ba, Sn, Pb, Au, RE; $X$ = S, Se, Te (chalcogenides)

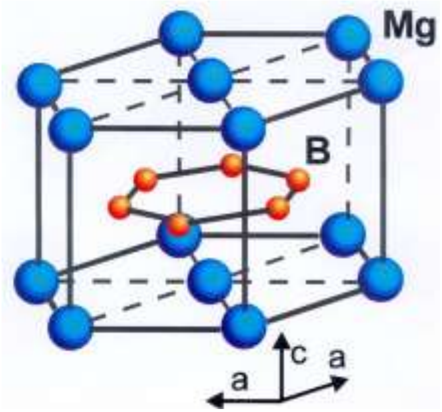
    e.g. $PbMo_6S_8$ : $T_c = 15$ K

  - boron carbides: $RM_2B_2C$ (1994) — $R$ = rare earth elem. (e.g. Tm, Er, Ho); $M$ = Ni, Pd

    e.g. $(Lu/Y)Ni_2B_2C$ : $T_c = 16$ K

  - $MgB_2$ (2001) — $T_c$ almost 40 K





- ***heavy Fermion superconductors***

  - found by ***Frank Steglich*** *et al*. in 1979

    - $CeCu_2Si_2$ $T_c = 0.5$ K
    - today many systems known

  - electrons in these compounds have very large effective mass
    → heavy Fermions: $m^\star \sim 100 - 1000\ m_\mathrm{e}$

  - mechanism of superconductivity still under debate

# 1.6 Superconducting Materials

- *organic superconductors*

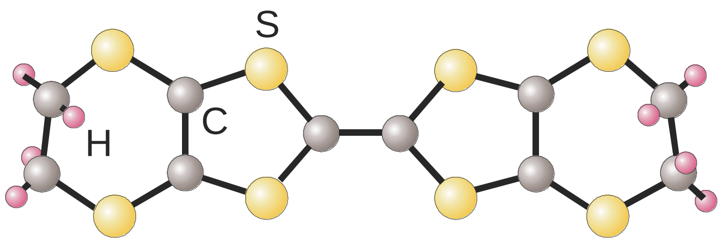
- found by ***Jerome*** et al. in 1980

- TMTSF (tetramethyl-tetraselenafulvalen) $T_c = 0.9$ K
- today many systems known with $T_c$ up to 12 K

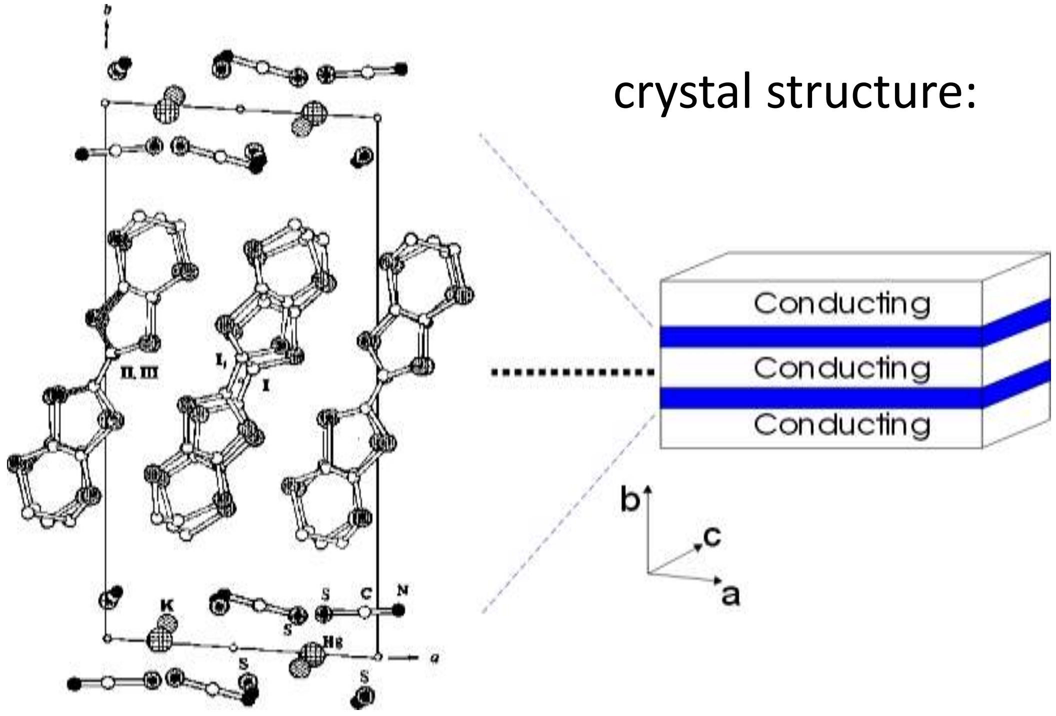
e.g. $(BEDT\text{-}TTF)_2Cu[N(CN)_2]Br$ $T_c = 11.2$ K

bis(ethylenedithio)-tetrathiafulfalene

BEDT-TTF-molecule:




crystal structure:




- most systems are highly anisotropic

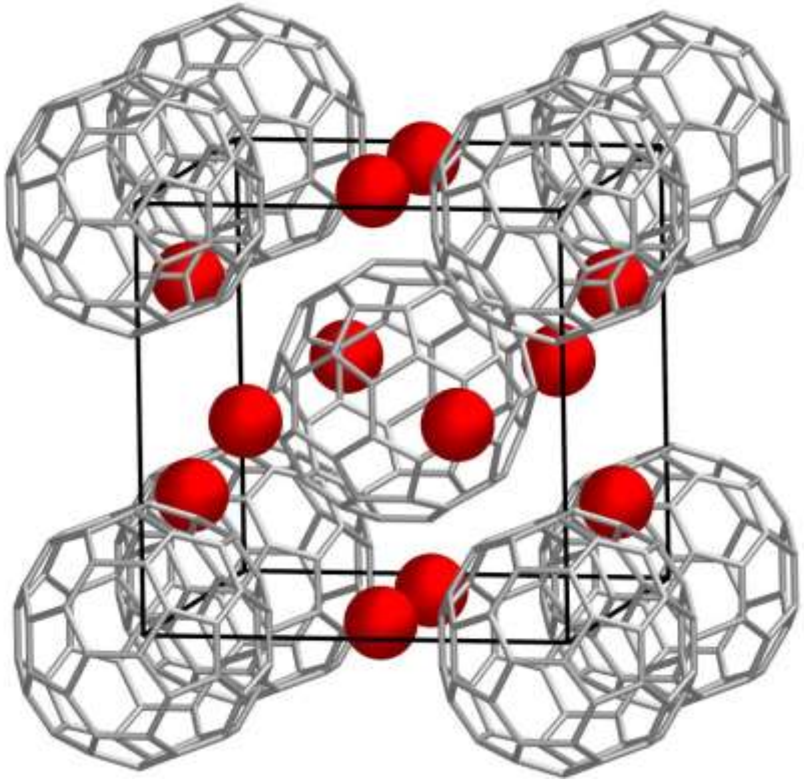
- *fullerides*

  - doping of $C_{60}$ molecules (fullerene), arrangement in regular structure → *fullerides*

  - superconductivity found in 1991 by ***Robert Haddon*** at Bell Labs
    $K_3C_{60}$ with $T_c = 18$ K

  - until today $T_c$ up to 40 K found

    $Cs_2RbC_{60}$ $T_c = 33$ K
    $Cs_3C_{60}$ $T_c = 40$ K @ $p = 15$ kbar



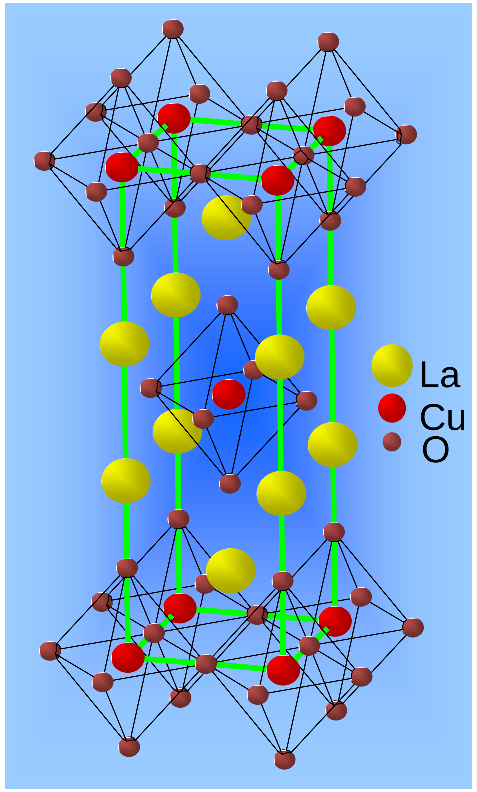
# 1.6 Superconducting Materials

- *oxide superconductors*

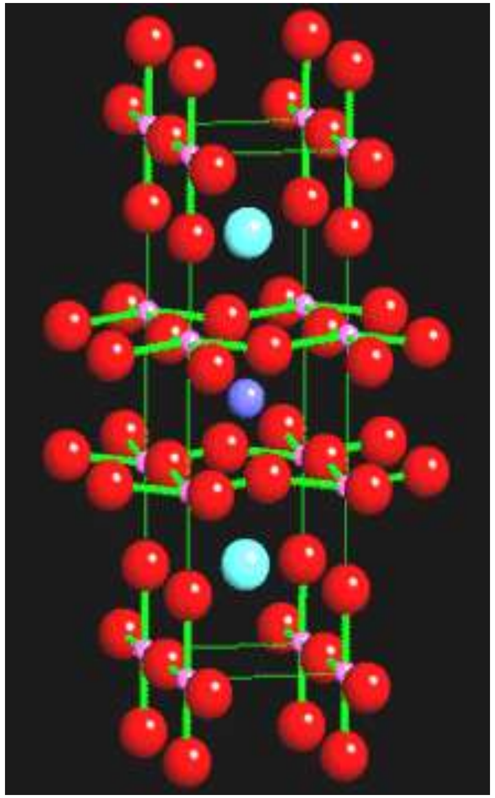
  - discovered by ***Georg Bednorz*** and ***Alex Müller*** in 1986 in $La_{2-x}Ba_xCuO_4$ (Zurich oxide)

  - until today several compounds found with $T_c$ up to 135 K (165 K under pressure)

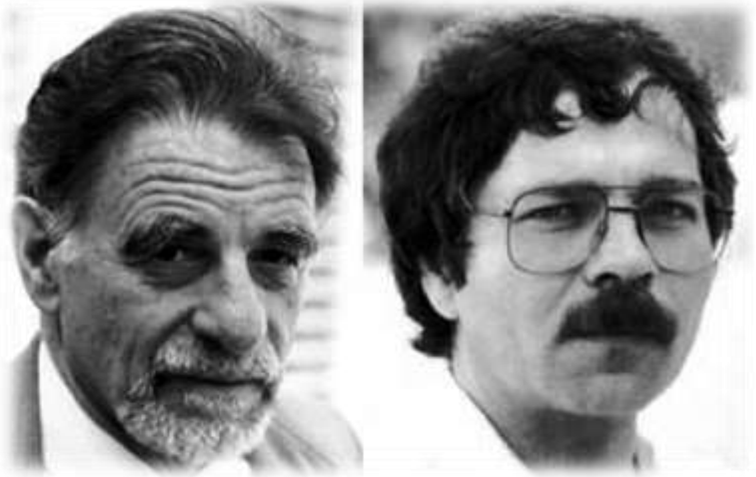
  - layered crystal structure formed by $CuO_2$ planes and charge reservoir layers




$La_{2-x}Sr_xCuO_4$



$YBa_2Cu_3O_7$



# 1.6 Superconducting Materials



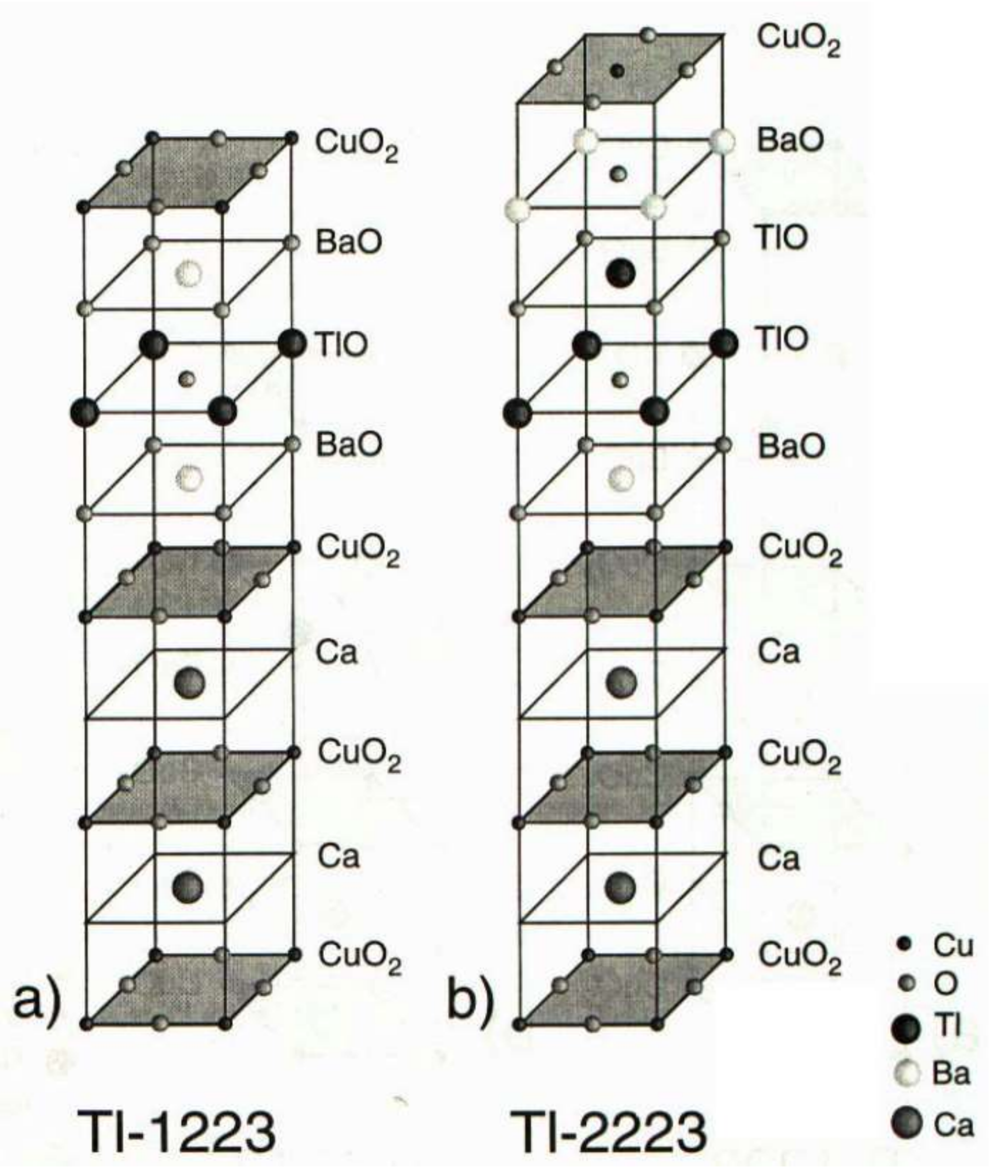
4 component systems

$A_m B_2 Ca_{n-1} Cu_n O_{2+m+2n}$

Bi, Tl, Hg    Ba, Sr = alcaline earth metals

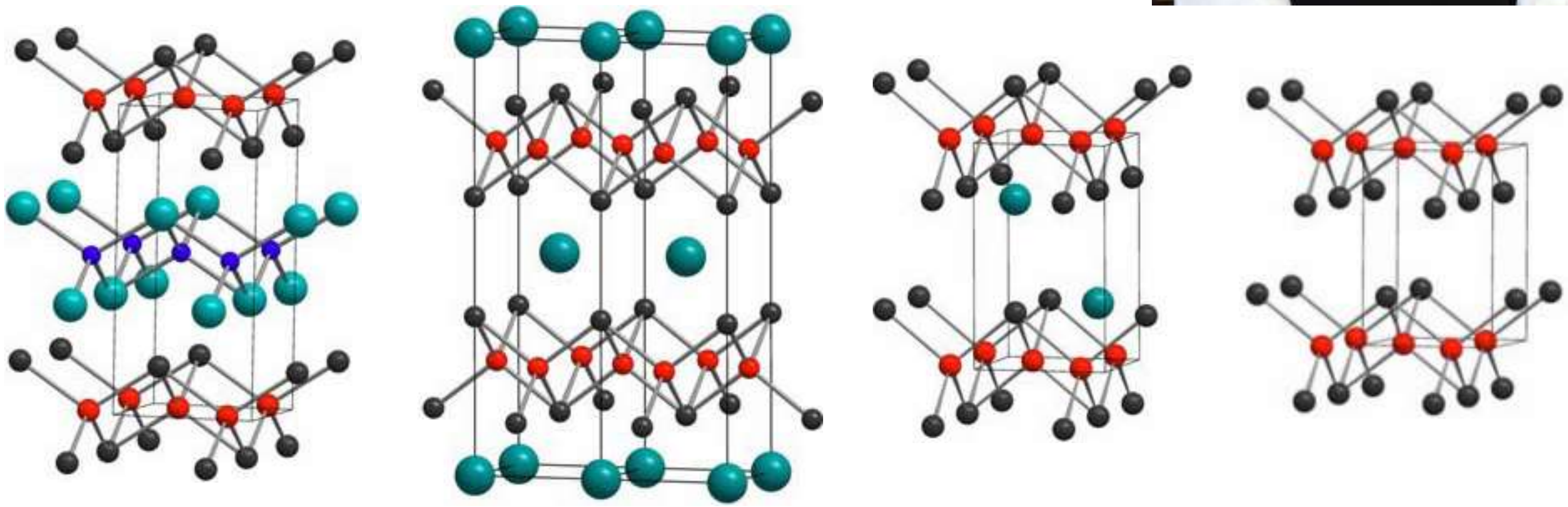
examples

$Bi_2Sr_2Ca_2Cu_3O_{10}$ = Bi-2223 (110 K)
$Tl_2Ba_2Ca_2Cu_3O_{10}$ = Tl-2223 (127 K)
$HgBa_2Ca_2Cu_3O_9$ = Hg-1223 (135 K)



# 1.6 Superconducting Materials

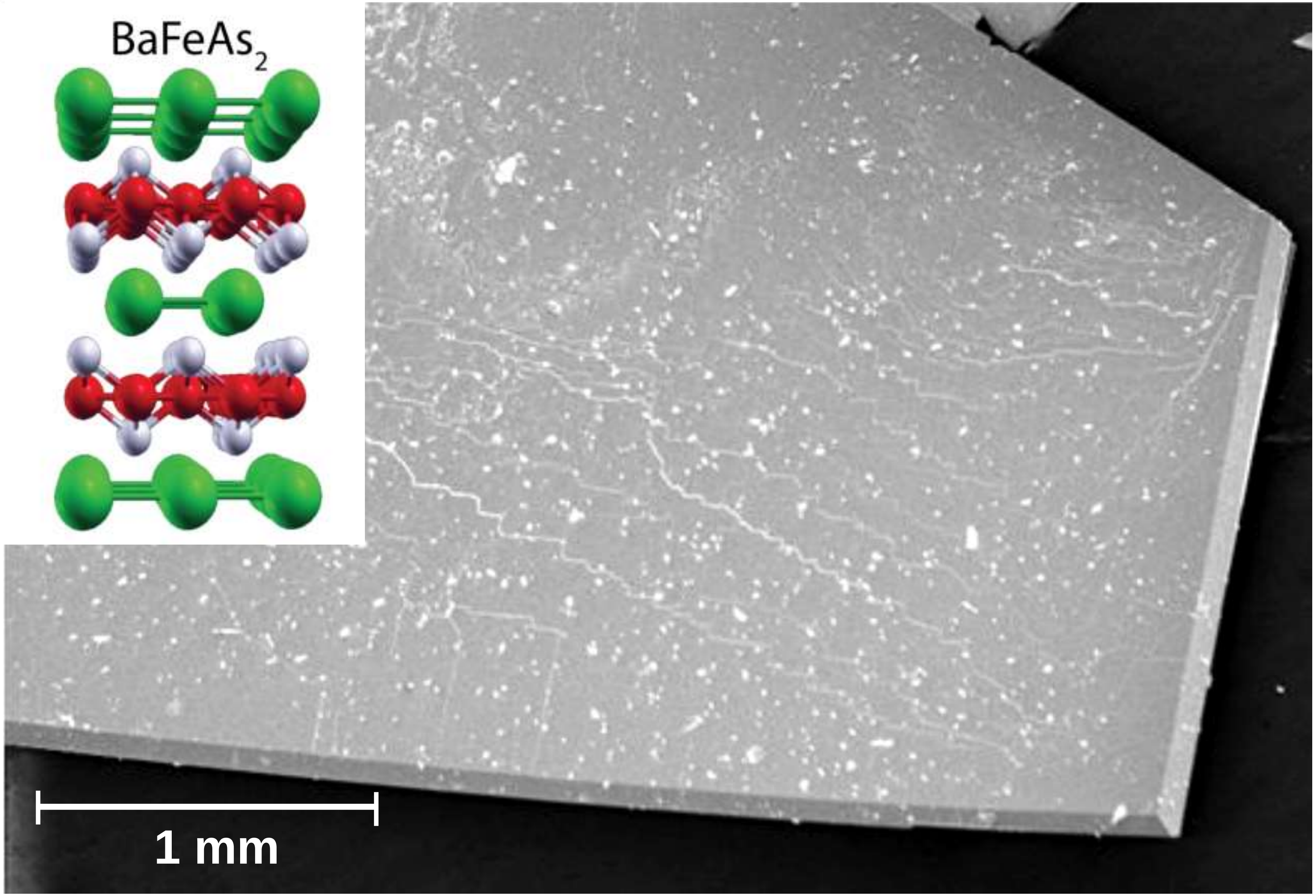
- *iron pnictide superconductors*
  - discovered in 2006 by ***Hideo Hosono*** et al. in $La[O_{1-x}F_x]FeAs$, $T_c = 26$ K
  - until today several compounds/families found with $T_c$ up to 55 K



LaFeAsO (1111) $BaFe_2As_2$ (122) LiFeAs (111) FeSe (11)

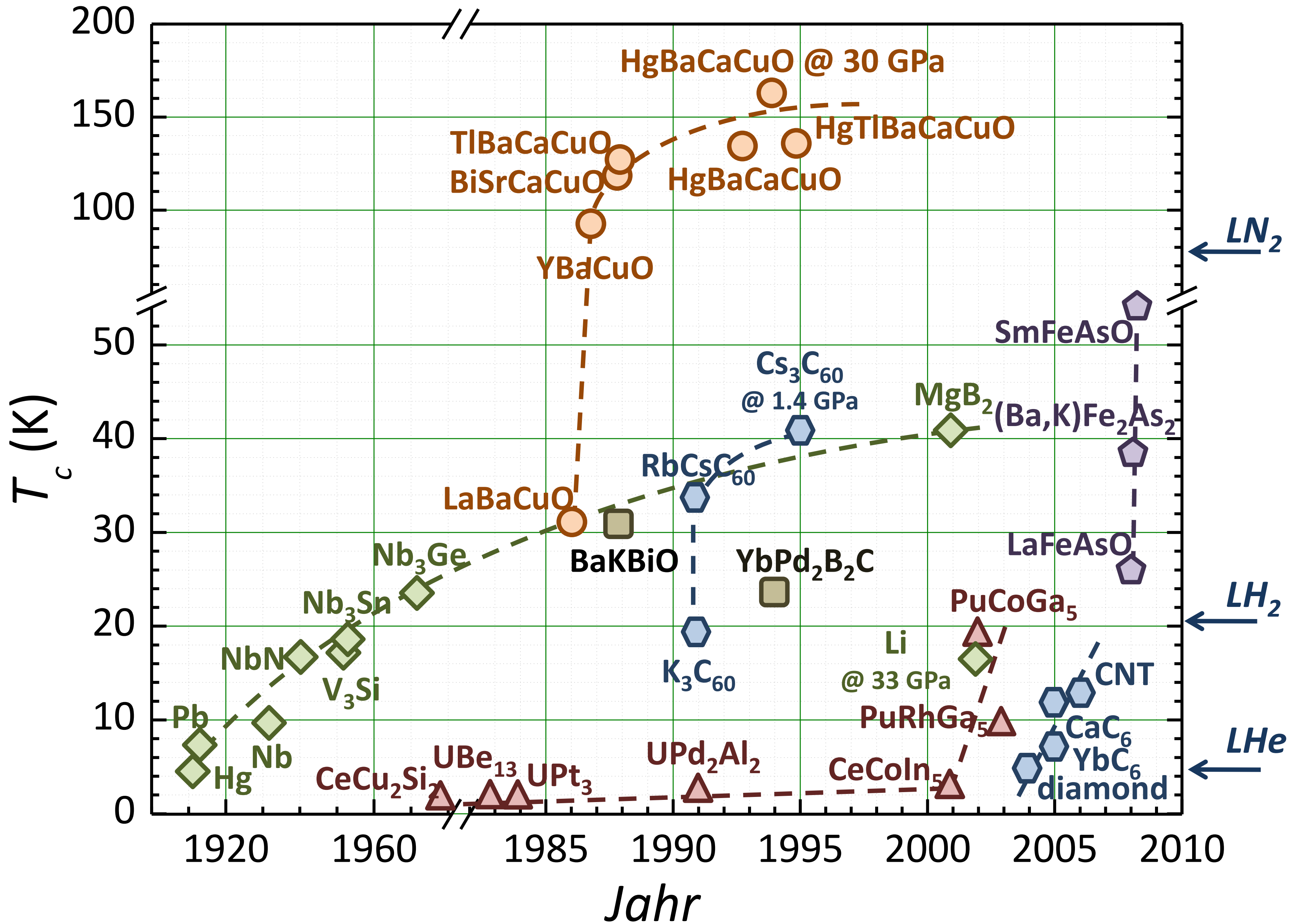
Yoichi Kamihara, Hidenori Hiramatsu, Masahiro Hirano, Ryuto Kawamura, Hiroshi Yanagi, Toshio Kamiya, and Hideo Hosono "Iron-Based Layered Superconductor: LaOFeP". *J. Am. Chem. Soc.* **128** (31): 10012–10013 (2006).

# 1.6 Superconducting Materials



# 1. Basic Properties of Superconductors

# 1.7 Transition Temperatures



# 1.7 Transition Temperatures

- **recently discoverd materials with very high transition temperatures**

  – **2015**:
  Eremets and co-workers report that $H_2S$ becomes a metallic conductors under high pressure (100–300 GPa) and shows a transition temperature of $T_c = -70°\text{C}$ (203 K).

LETTER

doi:10.1038/nature14964

**Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system**

A. P. Drozdov[1]*, M. I. Eremets[1]*, I. A. Troyan[1], V. Ksenofontov[2] & S. I. Shylin[2]

  – **2019**:
  Eremets *et al*. measured for $LaH_{10}$ under high pressure (170 GPa) a transition temperature of $T_c \simeq 250$ K (≈ −23 °C)

LETTER

https://doi.org/10.1038/s41586-019-1201-8

**Superconductivity at 250 K in lanthanum hydride under high pressures**

A. P. Drozdov[1,7], P. P. Kong[1,7], V. S. Minkov[1,7], S. P. Besedin[1,7], M. A. Kuzovnikov[1,6,7], S. Mozaffari[2], L. Balicas[2], F. F. Balakirev[3], D. E. Graf[2], V. B. Prakapenka[4], E. Greenberg[4], D. A. Knyazev[1], M. Tkacz[5] & M. I. Eremets[1]*

# 1.7 Transition Temperatures

- **recently discoverd materials with very high transition temperatures**

  - **2020**:
    Snider *et al*. measured for $CH_8S$ under high pressure (267 GPa) a transition temperature of $T_c \simeq 288$ K (≈ 15 °C), Nature 586, 373 - 377 (2020)

Article

**Room-temperature superconductivity in a carbonaceous sulfur hydride**

https://doi.org/10.1038/s41586-020-2801-z
Received: 21 July 2020
Accepted: 8 September 2020
Published online: 14 October 2020
Check for updates

Elliot Snider[1,6], Nathan Dasenbrock-Gammon[2,6], Raymond McBride[1,6], Mathew Debessai[3], Hiranya Vindana[3], Kevin Vencatasamy[3], Keith V. Lawler[4], Ashkan Salamat[5] & Ranga P. Dias[1,2]

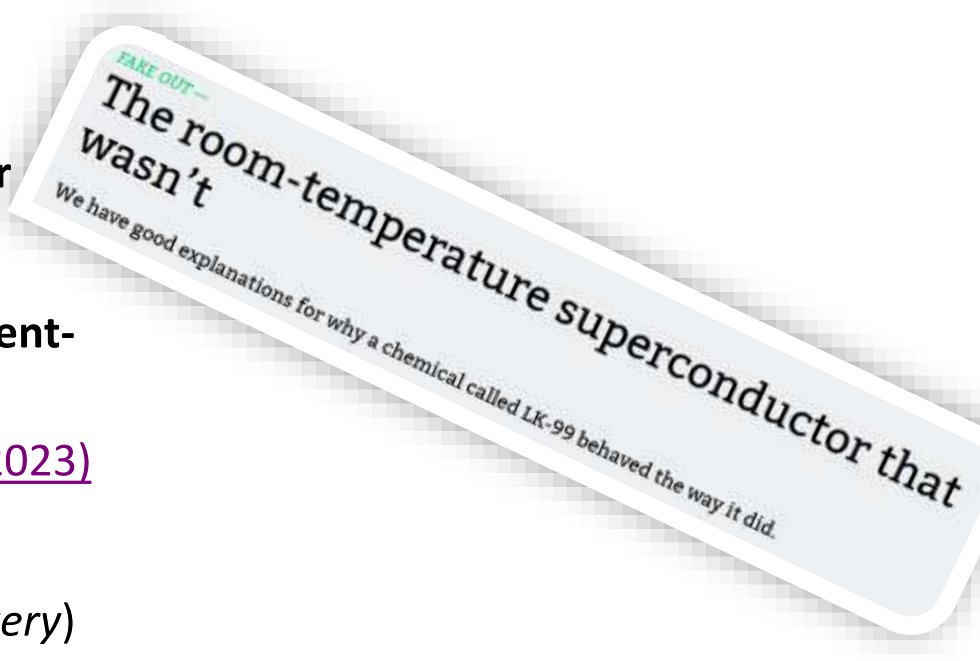
One of the long-standing challenges in experimental physics is the observation of room-temperature superconductivity[1,2]. Recently, high-temperature conventional superconductivity in hydrogen-rich materials has been reported in several systems under high pressure[3-5]. An important discovery leading to room-temperature superconductivity is the pressure-driven disproportionation of hydrogen sulfide

➔ **material with the so far highest transition temperature**

# 1.7 Transition Temperatures

- **recently reported but not confirmed room temperature superconductors**

**2023**:


FAKE OUT —
The room-temperature superconductor that wasn't
We have good explanations for why a chemical called LK-99 behaved the way it did.

– **The First Room-Temperature Ambient-Pressure Superconductor**
  Sukbae Lee, Ji-Hoon Kim, Young-Wan Kwon, arXiv:2307.12008

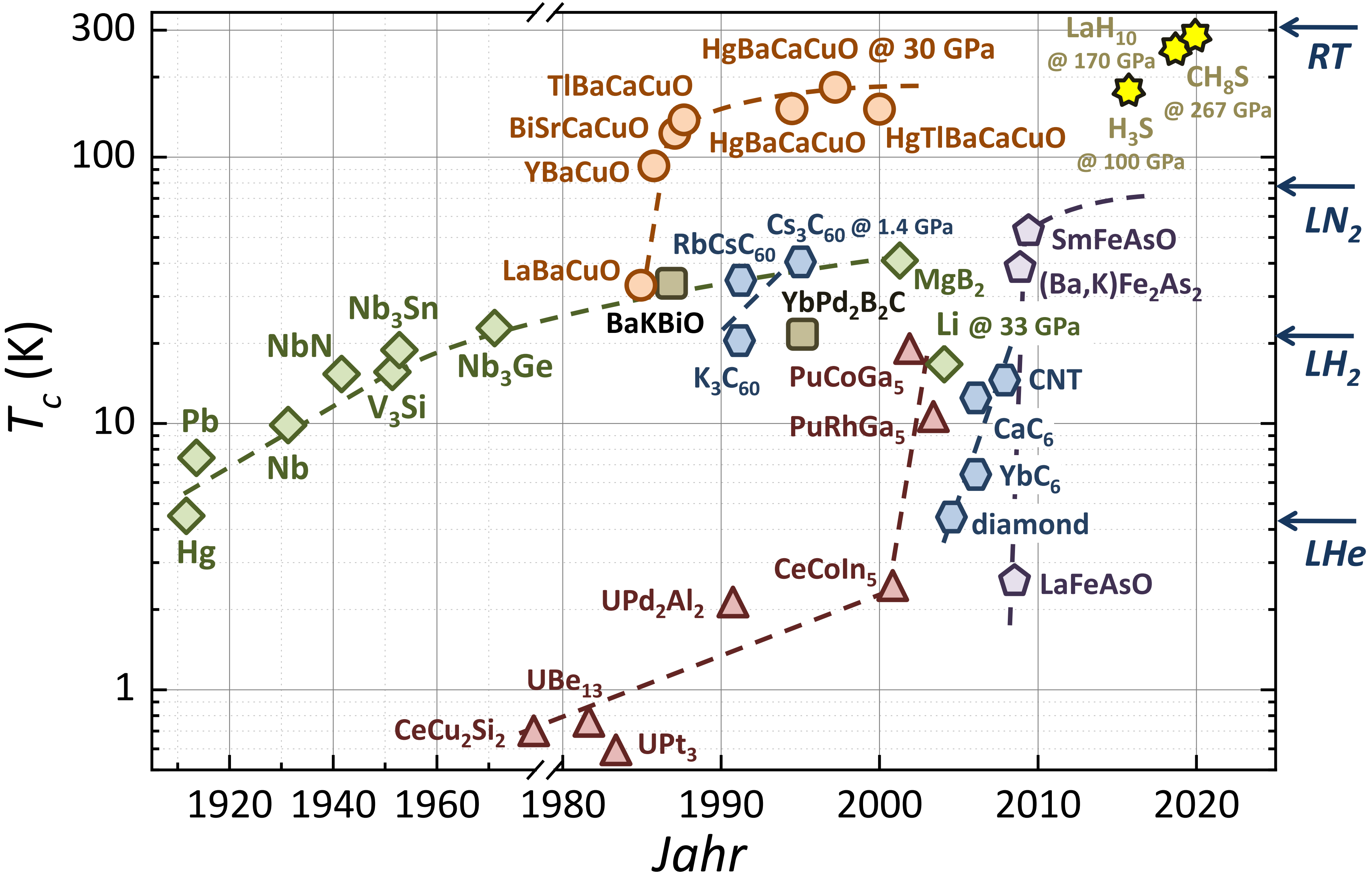
– **Consideration for the development of room-temperature ambient-pressure superconductor (LK-99)**
  J. Korean Crystal Growth and Crystal Technology 33 (2), 61–70 (2023)

– Material: **LK-99** (*named after Lee and Kim and the year of discovery*)
  LK-99 is decidedly weird for a putative high-temperature superconductor:

  – it's a greyish-black phosphate mineral called apatite containing copper and lead

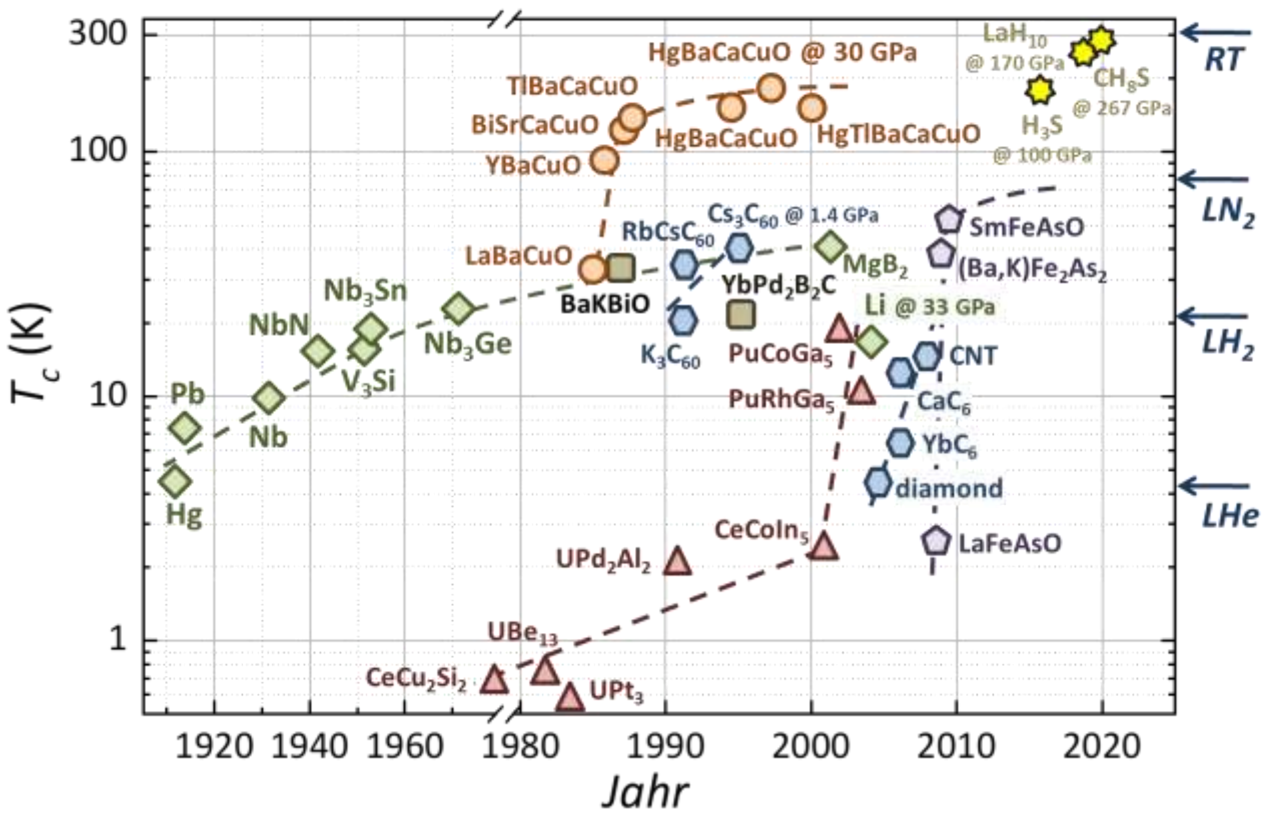
  – while most superconductors are pretty good normal electrical conductors before they turn superconducting, LK-99 is an insulator above its purported $T_c = 127°\mathrm{C}$

# 1.7 Transition Temperatures



# 1.7 Transition Temperatures






relevant material parameters for technical applications:

- high transition temperatures $T_c$
- high critical current densities $J_c$
- high critical magnetic fields $B_c$