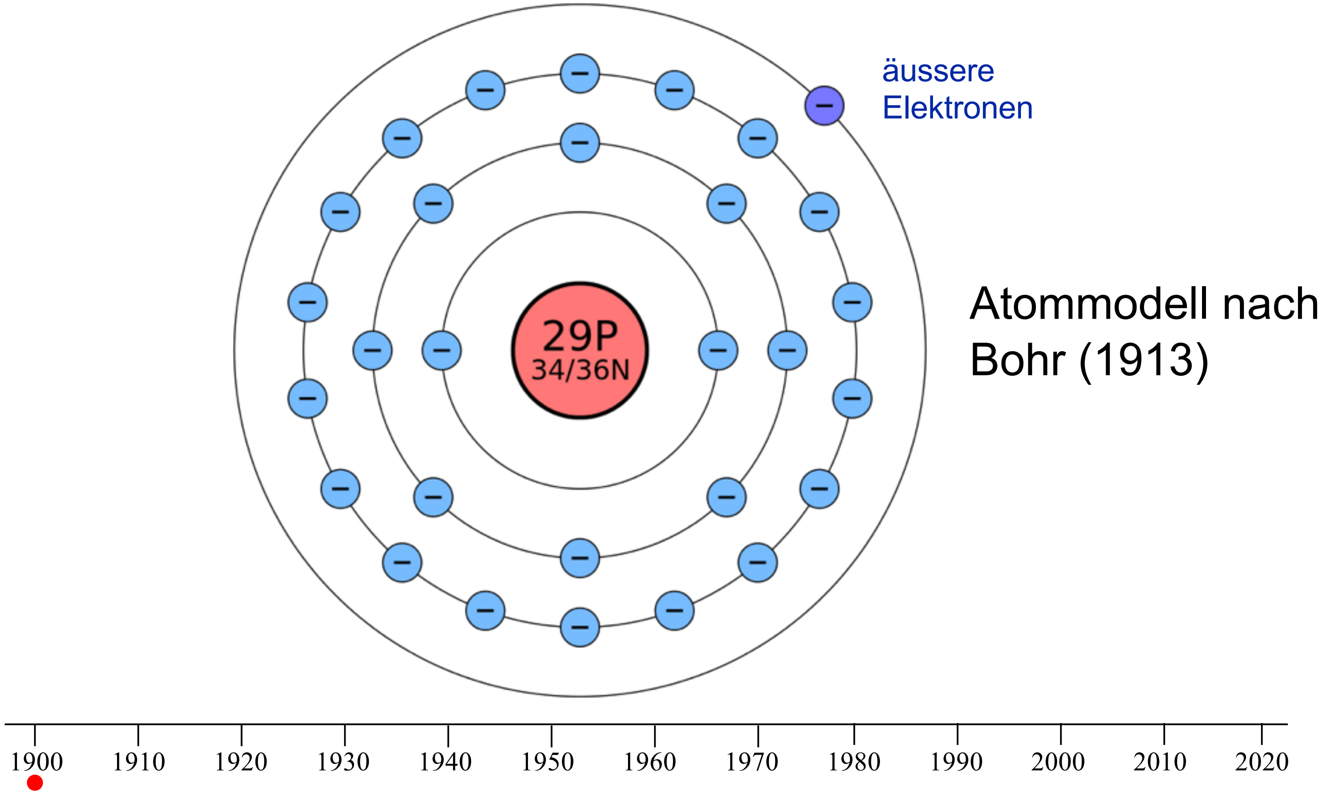
Supraleitung

Elektrischer Widerstand... Vorstellung um ca. 1900



Atommodell nach
Bohr (1913)

Elektrischer Widerstand... Vorstellung um ca. 1900

Stossprozesse:
Drude-Theorie (um 1900)

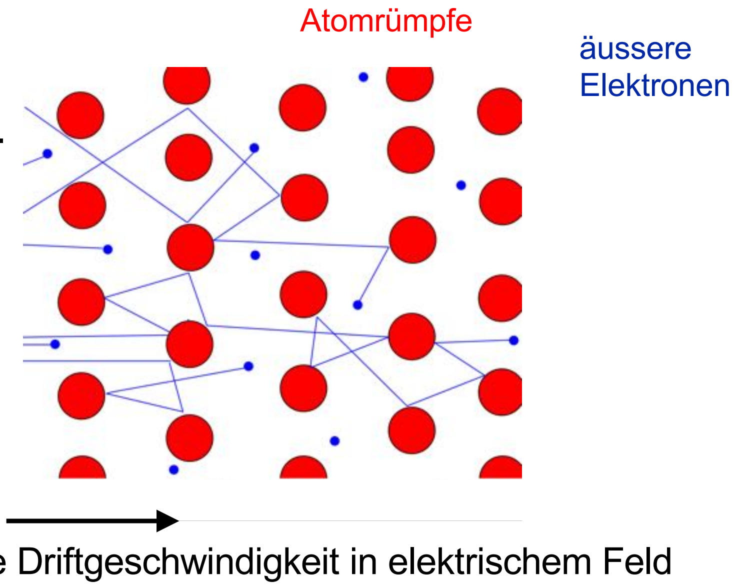
Metall

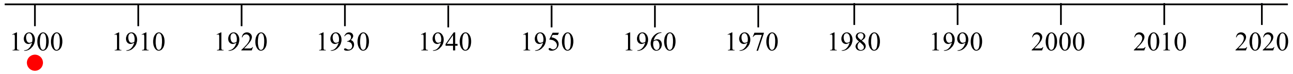
Äussere Elektronen sind beweglich und nicht an feste Plätze gebunden.

Durch Stossprozesse ergibt sich eine Art Reibung:

Die Elektronen können sich nur fortbewegen, wenn ständig eine Kraft auf sie wirkt.

=> Elektrischer Widerstand





Elektrischer Widerstand... Vorstellung um ca. 1900

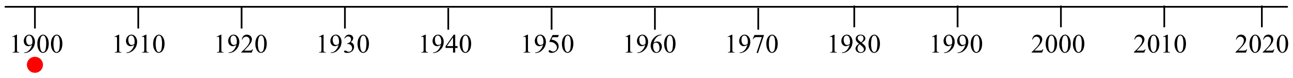
Metall

Verhalten „nahe“ dem Temperaturnullpunkt?

Dewar (1904): Widerstand geht stetig gegen null
Matthiesen (1884): Widerstand hat Grenzwert
Kelvin (1902): Widerstand nimmt wegen Lokalisierung der Elektronen stark zu

Verhalten beim absoluten Temperaturnullpunkt?

Walter Nernst 3. Hauptsatz (1906):
absoluter Stillstand: ***Isolator***
Max Planck „2. Quantentheorie“ (1911):
Nullpunktsbewegung ***Leitend***



Elektrischer Widerstand... Vorstellung um ca. 1900

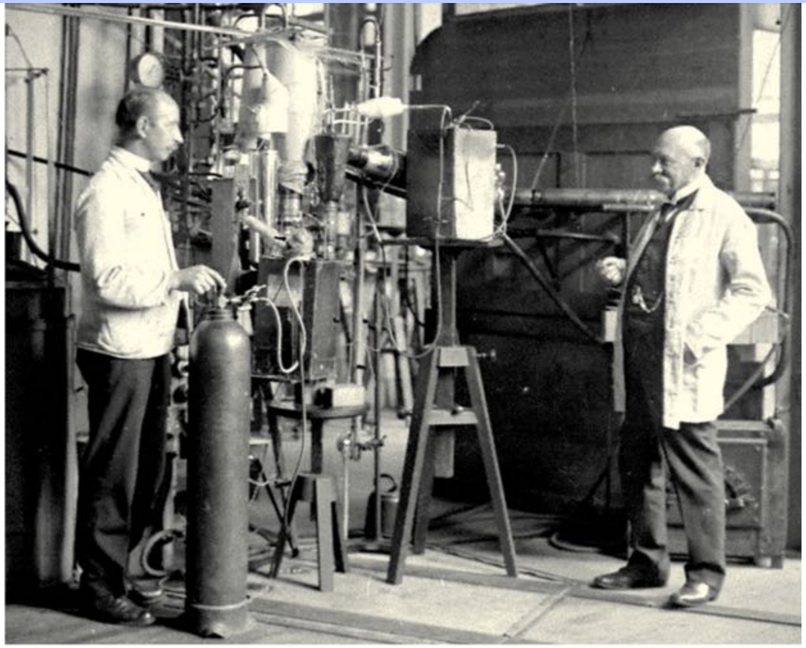
Metall


1913

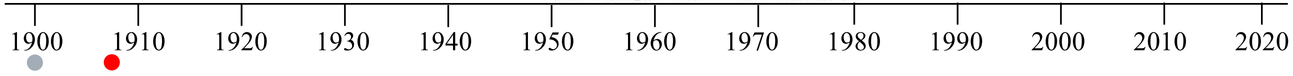
Verhalten „nahe“ dem Temperaturnullpunkt?

Joule Thomson Effekt nach Vorkühlung unter 40 K:

Verflüssigung von Helium durch Team von Heike Kammerlingh Onnes (1908)



Heike Kamerlingh Onnes (rechts) zusammen mit seinem Techniker Gerrit J. Flim neben dem zweiten in Leiden gebauten Heliumverflüssiger (Foto: Collection Kamerlingh Onnes Laboratorium).

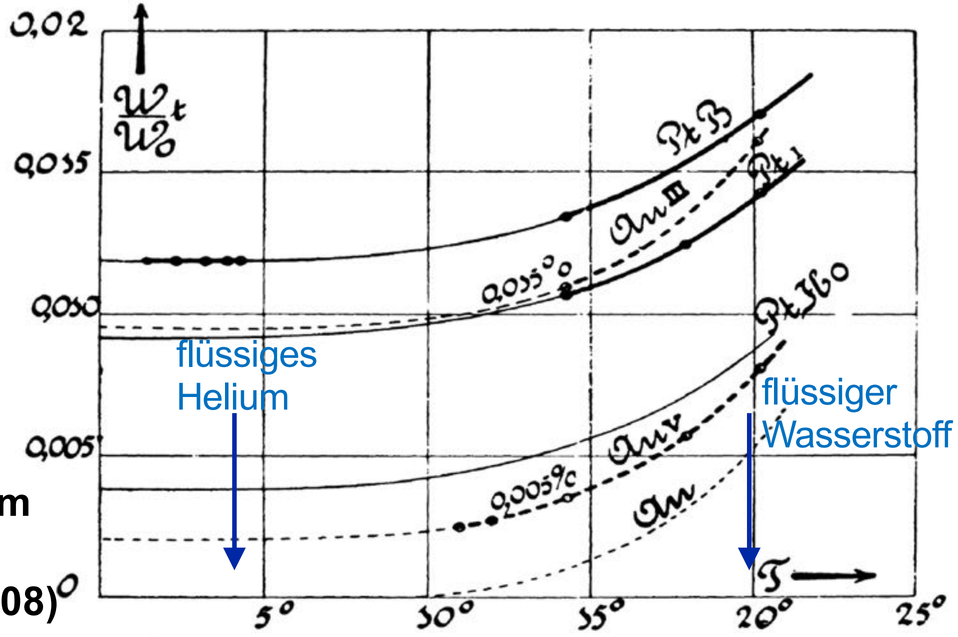


Elektrischer Widerstand... Vorstellung um ca. 1900

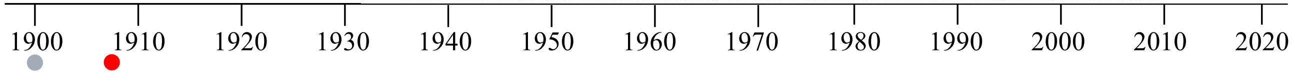
Metall

Verhalten „nahe“ dem Temperaturnullpunkt?

Verflüssigung von Helium durch Team von Heike Kammerlingh Onnes (1908)



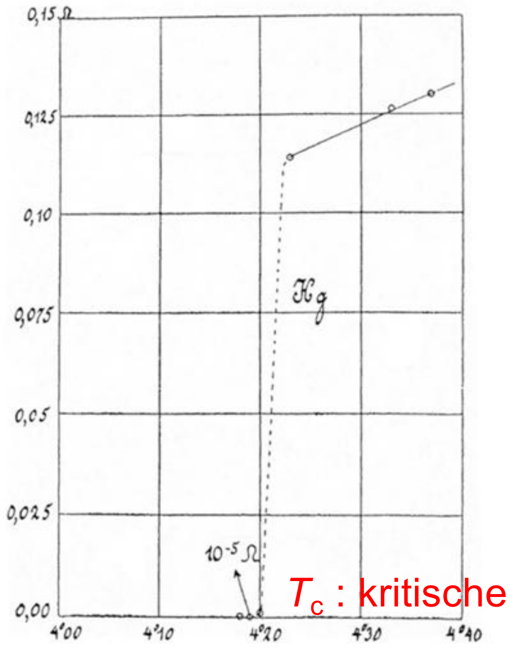
Messungen von Kamerling Onnes, Cornelis Dorsman & Gilles Holst an mehreren Proben von Platin (Pt) und Gold (Au) verschiedenen Reinheitsgrades ca.1910



Entdeckung der Supraleitung

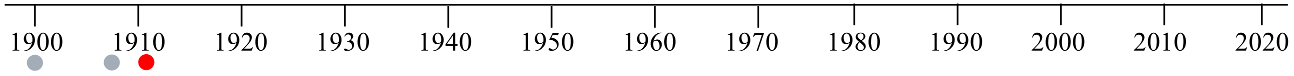
Entdeckung der Supraleitung in Quecksilber

Kammerlingh Onnes (1911)



T_c : kritische Temperatur

Abb. 1.1 Entdeckung der Supraleitung. Elektrischer Widerstand in Ohm einer Quecksilber-Probe, aufgetragen in Abhängigkeit von der Temperatur in Kelvin. (H. Kamerlingh Onnes)



Verhalten im Magnetfeld

Supraleitung wird durch hohe Magnetfelder zerstört (kritisches Feld B_c)

Kritische Stromdichte j_c

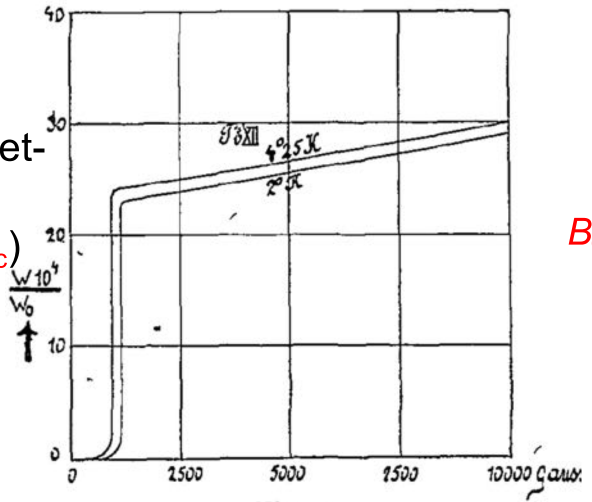
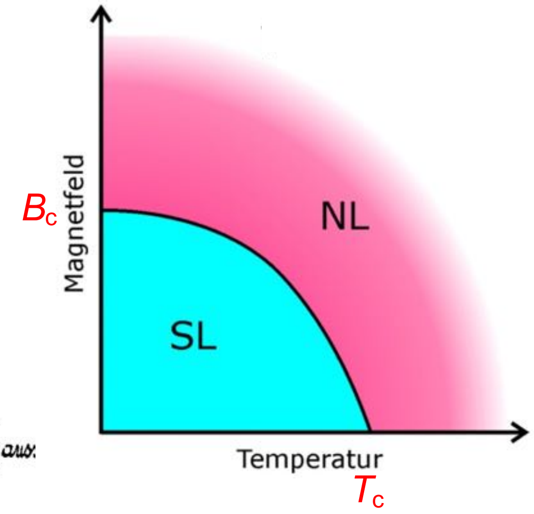
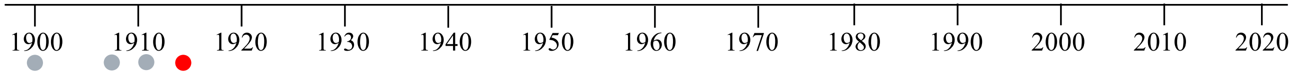


Fig. 1.

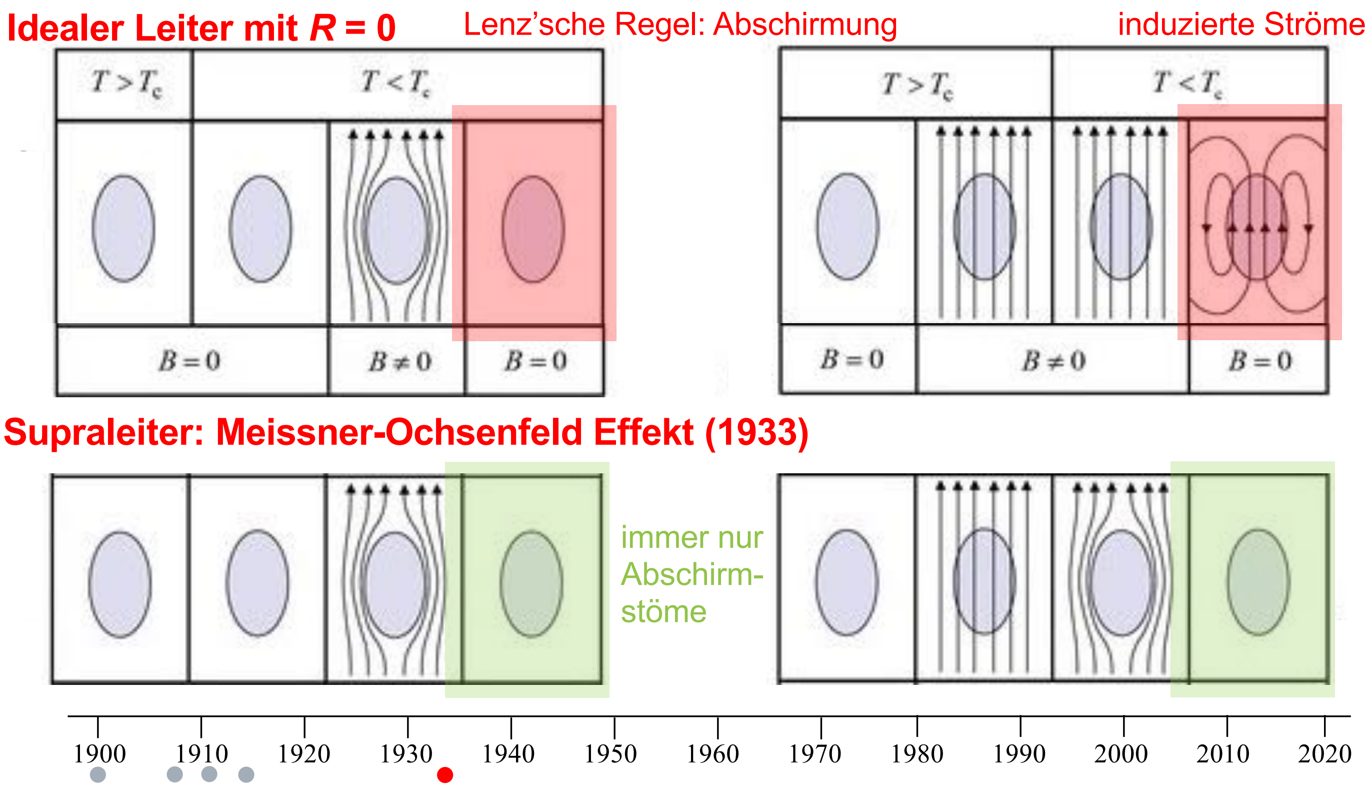


Kammerlingh Onnes (1914)

Faustregel: Je höher T_c, desto „robuster die Supraleitung“ (hohe Werte für B_c und j_c)



Verhalten im Magnetfeld: Meissner Ochsenfeld-Effekt (1933)



Idealer Leiter mit $R = 0$

Lenz'sche Regel: Abschirmung

induzierte Ströme

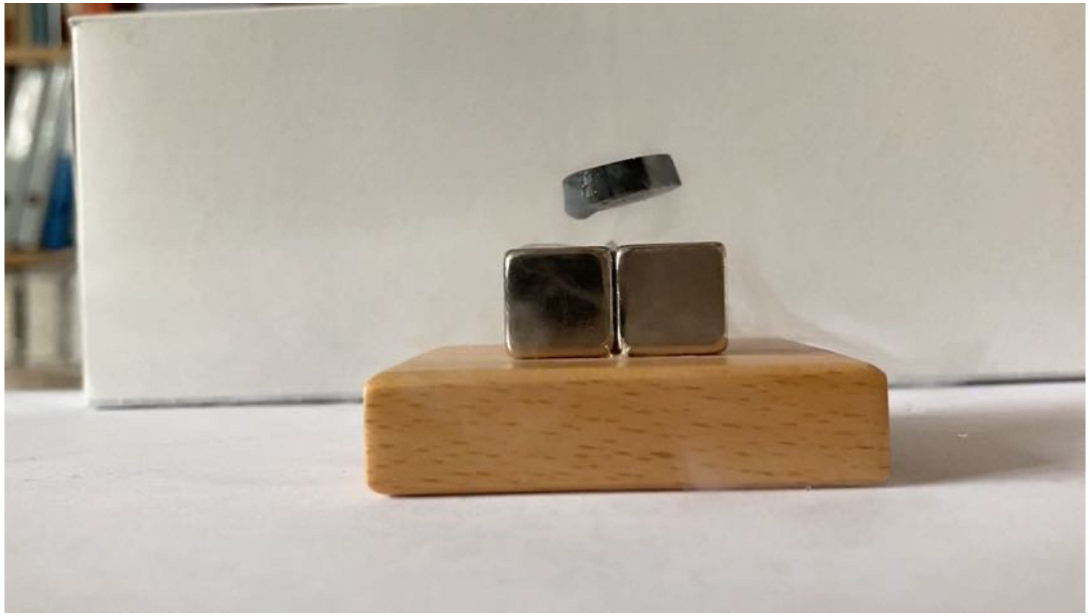
Supraleiter: Meissner-Ochsenfeld Effekt (1933)

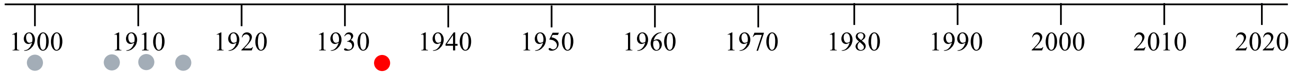
immer nur Abschirm-stöme

Verhalten im Magnetfeld: Meissner Ochsenfeld-Effekt (1933)

Supraleiter:

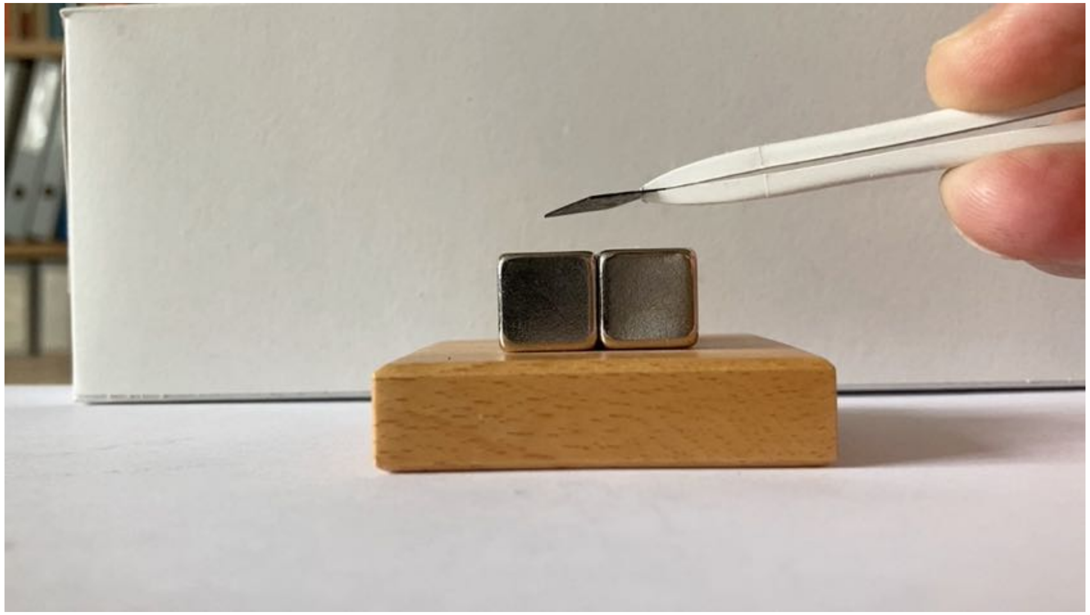
ideale Diamagneten

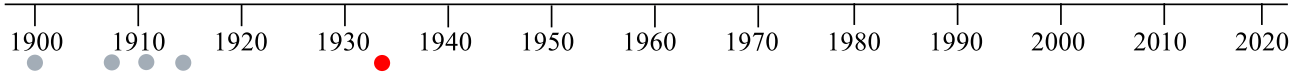




Nicht jeder Diamagnet ist ein Supraleiter.....

Pyrolytisches Graphit





Erklärung des Meissner Ochsenfeld-Effektes: London Gleichungen (1934)

Anstelle des Ohm'schen Gesetzes (*I* = *U*/*R*),

$$\vec{j} = \sigma \vec{E}$$

$$= -e\, n\, \vec{v}$$

E: Elektronenladung
n: Ladungsträgerdichte
v: Driftgeschwindigkeit

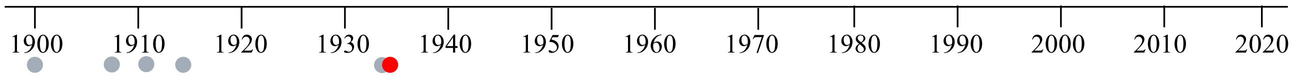
2. Newtonsches Gesetz: *F* = *ma* ohne Reibungseffekte:

$$\vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt} = -\frac{m}{e\,n}\frac{d\vec{j}}{dt}$$

$$-e\vec{E} \quad \text{(Coulombkraft)}$$

$$\boxed{\frac{d\vec{j}}{dt} = \frac{ne^2}{m}\vec{E}}$$

1. London Gleichung



Erklärung des Meissner Ochsenfeld-Effektes: London Gleichungen (1934)

$$(1\ dim:)\ \frac{d^2}{(dx)^2}B_z = \frac{\mu_0 n q^2 B_z}{m} = \frac{B_z}{\lambda_L^2}$$

2. London Gleichung

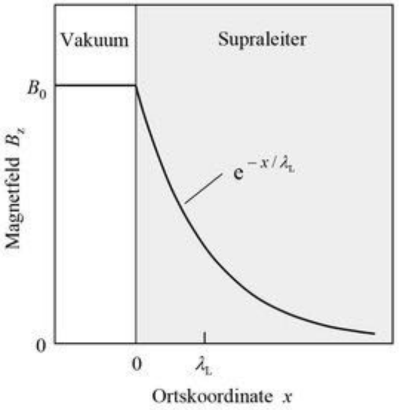
$$\lambda_L = \sqrt{\frac{m}{\mu_0 n q^2}}$$

London’sche Eindringtiefe

Maxwell-Gleichungen

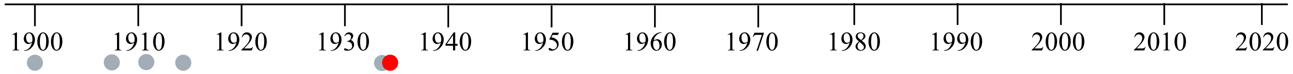
$$\frac{d\vec{j}}{dt} = \frac{ne^2}{m}\vec{E}$$

1. London Gleichung



$$B_z(x) = B_0 e^{-x/\lambda_L}$$

….unabhängig von der magnetischen Vorgeschichte



Supraleitung: «Zustand» im Sinne der Thermodynamik

Wärmekapazität zeigt eine Diskontinuität (2. Ordnungs-Phasenübergang)

Keesom and Kok (1932)

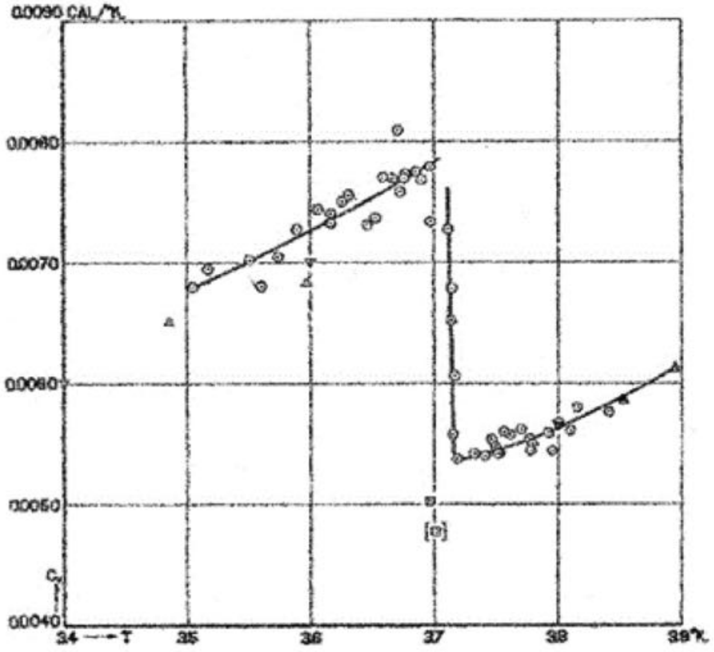
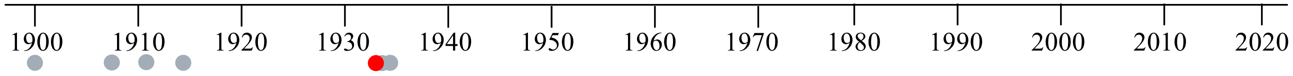
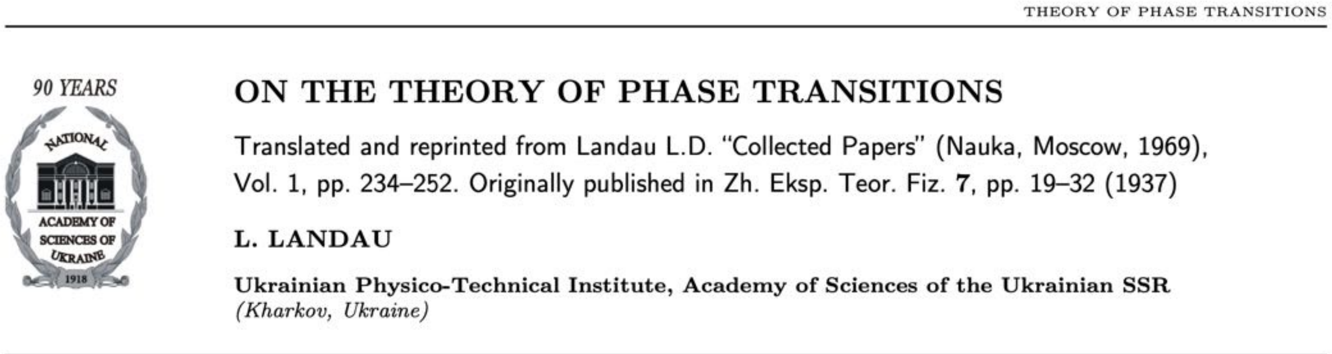


Fig. 3. A discontinuous change in specific heat at T_c for tin – Keesom and Kok [10].



Supraleitung: «Zustand» im Sinne der Thermodynamik

2. Ordnungs-Phasenübergang


THEORY OF PHASE TRANSITIONS

90 YEARS
NATIONAL ACADEMY OF SCIENCES OF UKRAINE
1918

ON THE THEORY OF PHASE TRANSITIONS

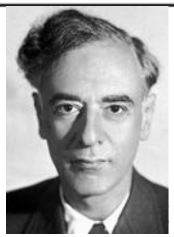
Translated and reprinted from Landau L.D. "Collected Papers" (Nauka, Moscow, 1969), Vol. 1, pp. 234–252. Originally published in Zh. Eksp. Teor. Fiz. **7**, pp. 19–32 (1937)

L. LANDAU

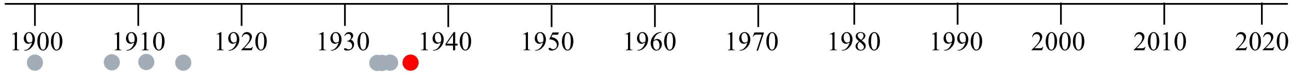
Ukrainian Physico-Technical Institute, Academy of Sciences of the Ukrainian SSR
(Kharkov, Ukraine)

Konzept des „Ordnungsparameters“

Lew Landau (1937)



1962



Ginzburg-Landau Theorie (1950)

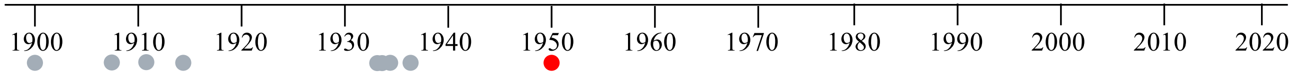
$$\alpha\psi + \beta|\psi|^2\psi + \frac{1}{2m^*}\left(-i\hbar\vec{\nabla} + 2e\vec{A}\right)^2\psi = 0 \text{ und}$$

$$\vec{j} = -\frac{2e}{m^*}\mathrm{Re}\left\{\psi^*\left(-i\hbar\vec{\nabla} + 2e\vec{A}\right)\psi\right\}.$$

„Ordnungsparameter“: Makroskopische Wellenfunktion im Sinne Schrödingers

Ginzburg-Landau Theorie der Supraleitung (1950)

Entwicklung um kritische Temperatur: $\propto(T) = \propto_0\,(T - T_c)/T_c$



Ginzburg-Landau Theorie (1950)

$$\alpha\psi + \beta|\psi|^2\psi$$

$$|\psi|^2 = -\alpha/\beta$$

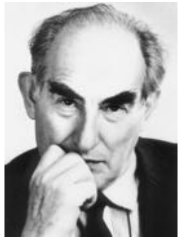
Dichte der supraleitenden Ladungsträger

Zwei Längenskalen:

$$\lambda = \sqrt{\frac{m\beta}{\mu_0 \alpha q^2}} = \lambda_L$$

$$\xi = \frac{\hbar}{\sqrt{2m|\alpha|}}$$

„Kohärenzlänge“



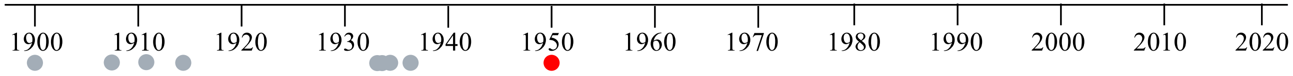
Valeri Ginzburg

2003

„Ordnungsparameter“: Makroskopische Wellenfunktion im Sinne Schrödingers

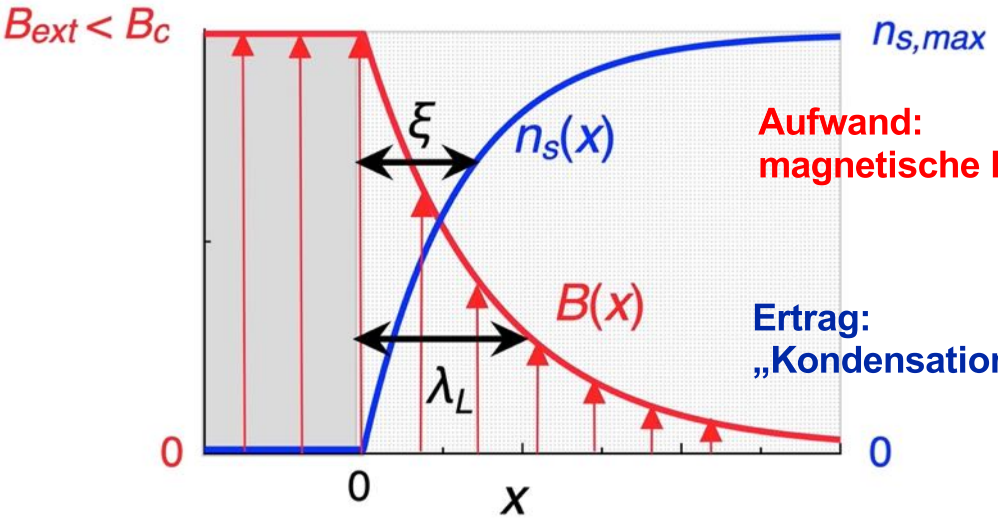
Ginzburg-Landau Theorie der Supraleitung (1950)

Entwicklung um kritische Temperatur: $\propto(T) = \propto_0 \, (T - T_c)/T_c$

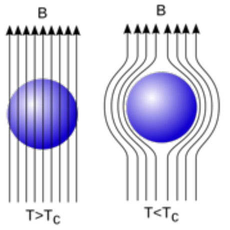


Ginzburg-Landau Theorie (1950)

Zwei Längenskalen:



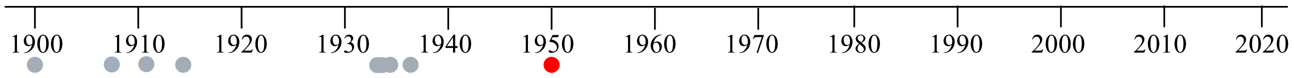
Aufwand:
magnetische Energie



λ_L

Ertrag:
„Kondensationsenergie“

ξ

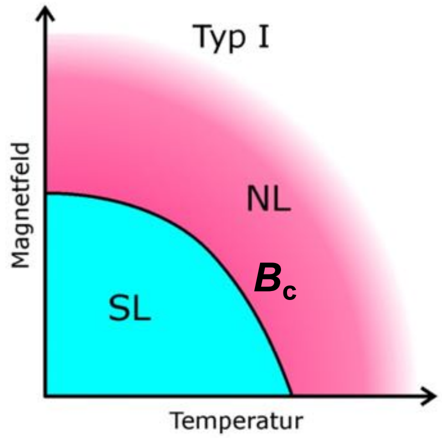


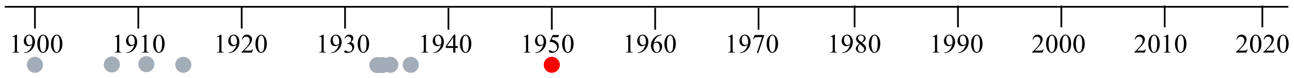
Ginzburg-Landau Theorie (1950)

Zwei Längenskalen:

$\xi \gtrsim \lambda_L$: Grenzfläche kostet viel Kondensationsenergie, gewinnt wenig Magnetfeldenergie: **Typ-I**

Magnetfeld wird für $B < B_c$ (ausser an der Oberfläche) vollständig verdrängt





Abrikosov: Vortexgitter (1957)

Zwei Längenskalen:

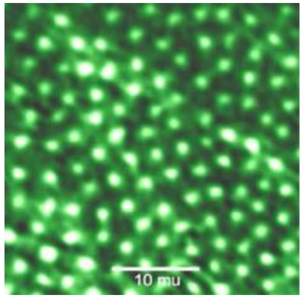
$\xi \lesssim \lambda_L$: Grenzfläche kostet wenig Kondensationsenergie, gewinnt viel Magnetfeldenergie: **Typ-II**

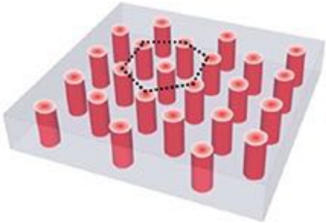
Vergösserung der Grenzfläche für $B_{c1} < B < B_c$ durch Bildung von "Flussschläuchen" (Vortices)

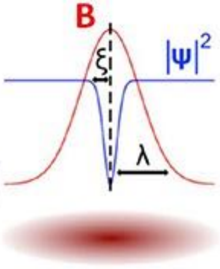
Magnetisches Flussquantum: $\Phi = h/2e = 2.068 \times 10^{-15}$ Wb

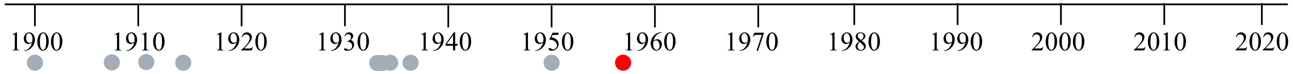
Alexei Abrikosov

2003







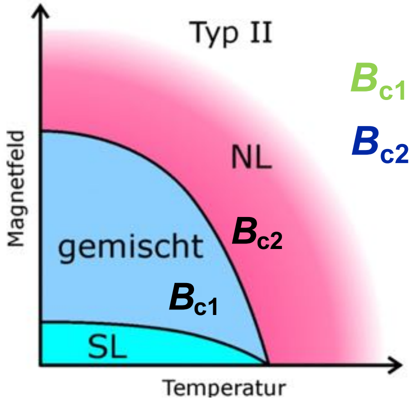


Abrikosov: Vortexgitter (1957)

Typ-II Supraleiter: Zwei “kritische Felder”, B_{c1} und B_{c2}

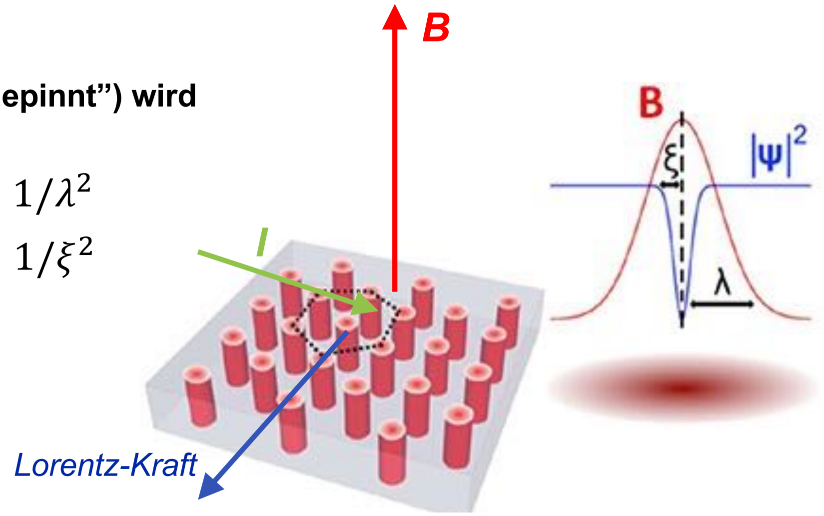
$B < B_{c1}$: Meissner Effekt
$B > B_{c2}$: normalleitend
$B_{c1} < B < B_{c2}$: gemischter Zustand mit Flussschläuchen

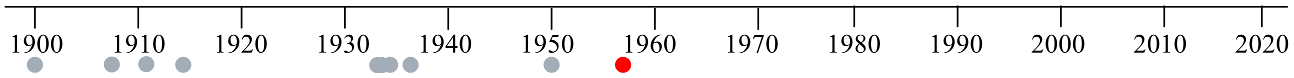
Dort: hohe technische Stromdichten
sobald das Vortexgitter festgehalten (“gepinnt”) wird



B_{c1} : prop. $1/\lambda^2$

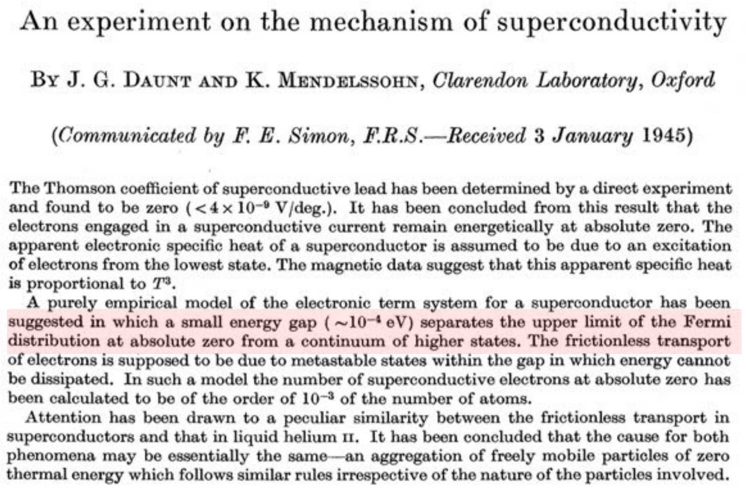
B_{c2} : prop. $1/\xi^2$





Thomson Koeffizient – Hinweis auf eine Energielücke (1945)

Supraleitender Strom transportiert keine Wärme:
«Thomson Koeffizient» = 0 im supraleitenden Zustand



An experiment on the mechanism of superconductivity

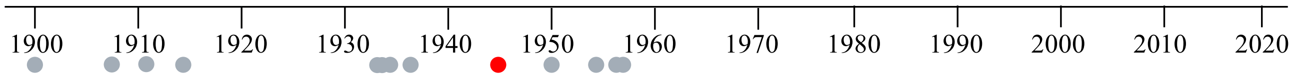
By J. G. Daunt and K. Mendelssohn, *Clarendon Laboratory, Oxford*

(*Communicated by F. E. Simon, F.R.S.—Received 3 January* 1945)

The Thomson coefficient of superconductive lead has been determined by a direct experiment and found to be zero ($<4\times10^{-9}$ V/deg.). It has been concluded from this result that the electrons engaged in a superconductive current remain energetically at absolute zero. The apparent electronic specific heat of a superconductor is assumed to be due to an excitation of electrons from the lowest state. The magnetic data suggest that this apparent specific heat is proportional to T^3.

A purely empirical model of the electronic term system for a superconductor has been suggested in which a small energy gap ($\sim10^{-4}$ eV) separates the upper limit of the Fermi distribution at absolute zero from a continuum of higher states. The frictionless transport of electrons is supposed to be due to metastable states within the gap in which energy cannot be dissipated. In such a model the number of superconductive electrons at absolute zero has been calculated to be of the order of 10^{-3} of the number of atoms.

Attention has been drawn to a peculiar similarity between the frictionless transport in superconductors and that in liquid helium II. It has been concluded that the cause for both phenomena may be essentially the same—an aggregation of freely mobile particles of zero thermal energy which follows similar rules irrespective of the nature of the particles involved.



Wärmekapazität – Hinweis auf eine Energielücke (1954)

Zweiflüssigkeitsmodell (Gorter, Casimir, 1934):

$$\frac{C_{el,s}(T)}{C_{el,n}(T_c)} = 3\left(\frac{T}{T_c}\right)^3$$

Corak et al, (1954):

$$\frac{C_{el,s}(T)}{C_{el,n}(T_c)} = ae^{-b(\frac{T_c}{T})}$$

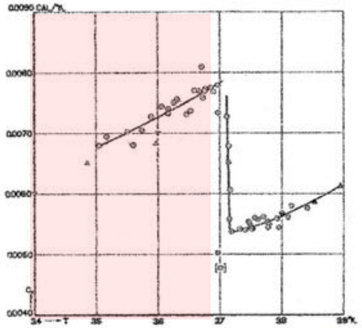


Fig. 3. A discontinuous change in specific heat at T_c for tin – Keesom and Kok [10].

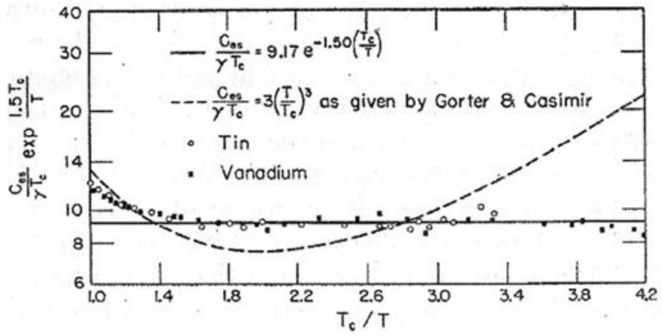
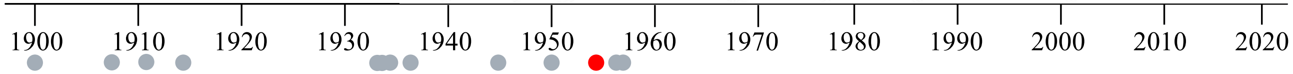
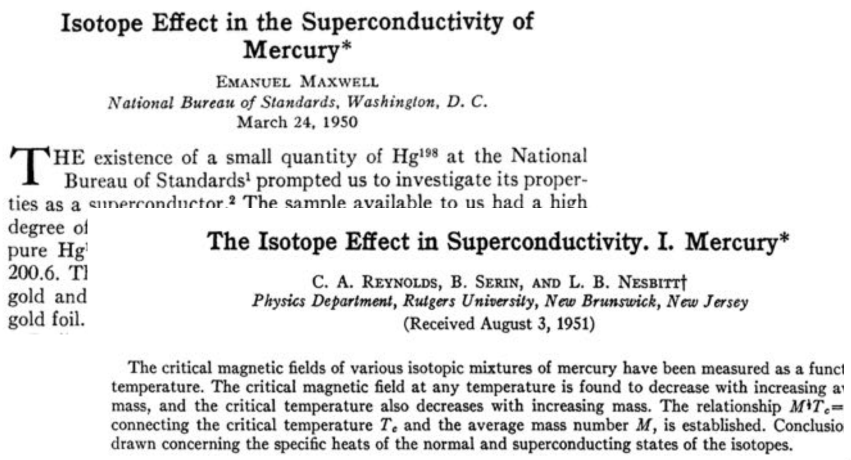


Fig. 7. Fittings to C_{es} of vanadium and tin supported an exponential temperature- over a T^3- dependence – Corak and Satterthwaite [17].



Isotopeneffekt (1950)

Die kritische Temperatur für das gleiche Element hängt von der Art des Isotops zusammen (E. Maxwell, B. Serin):



Isotope Effect in the Superconductivity of Mercury*

Emanuel Maxwell

National Bureau of Standards, Washington, D. C.

March 24, 1950

THE existence of a small quantity of Hg^{198} at the National Bureau of Standards[1] prompted us to investigate its properties as a superconductor.[2] The sample available to us had a high
degree o
pure Hg
200.6. T
gold and
gold foil.

The Isotope Effect in Superconductivity. I. Mercury*

C. A. Reynolds, B. Serin, and L. B. Nesbitt†

Physics Department, Rutgers University, New Brunswick, New Jersey

(Received August 3, 1951)

The critical magnetic fields of various isotopic mixtures of mercury have been measured as a funct
temperature. The critical magnetic field at any temperature is found to decrease with increasing a
mass, and the critical temperature also decreases with increasing mass. The relationship $M^{\frac{1}{2}}T_c=$
connecting the critical temperature T_c and the average mass number M, is established. Conclusio
drawn concerning the specific heats of the normal and superconducting states of the isotopes.

$$T_c \propto \frac{1}{\sqrt{m}}$$

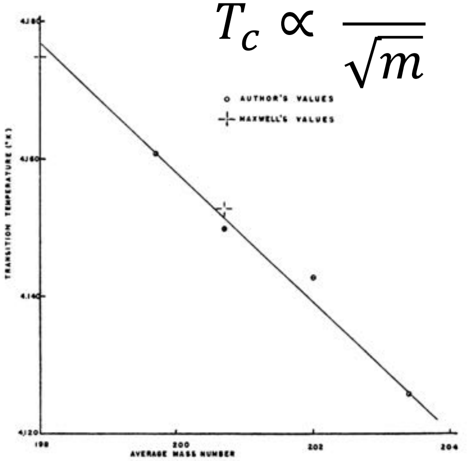
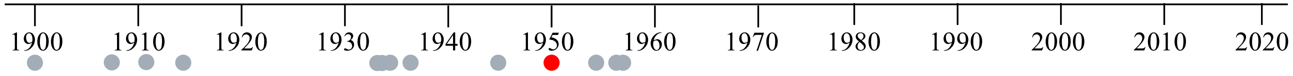
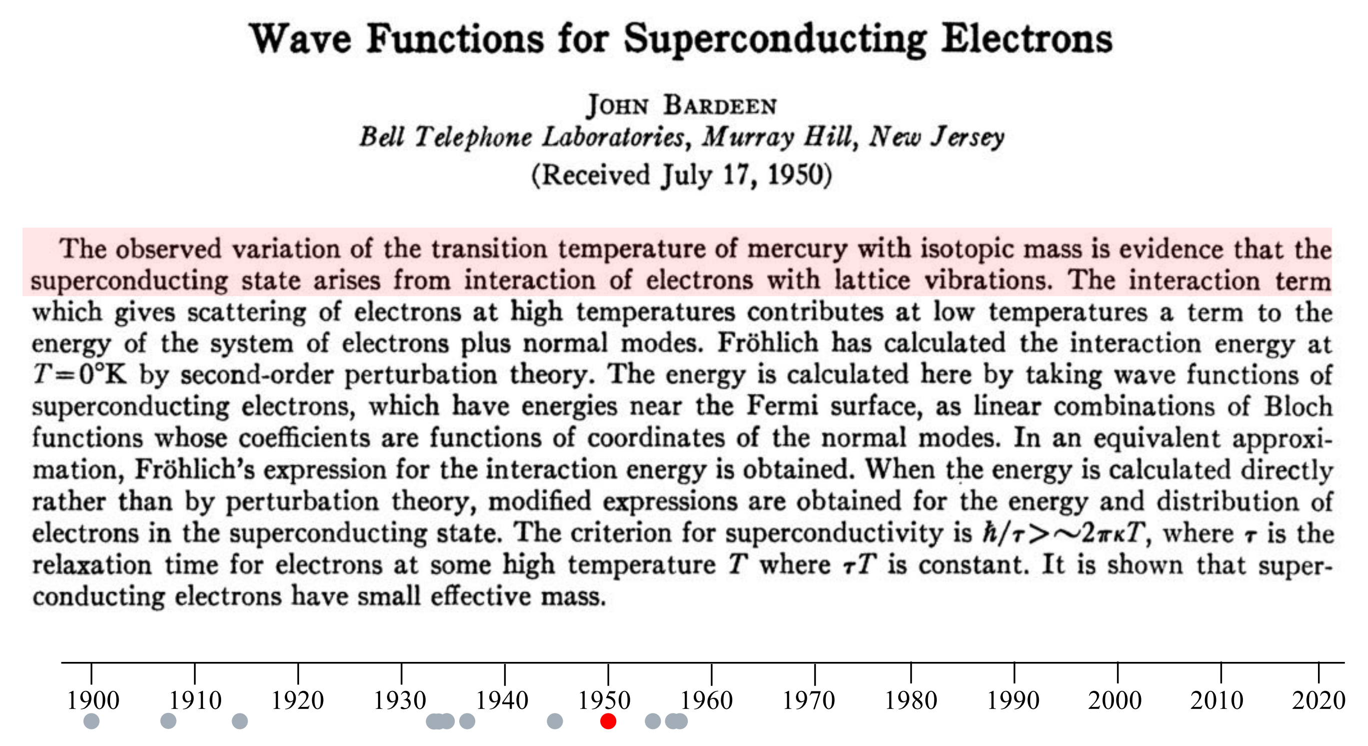


Fig. 2. The transition temperature *vs.* the average mass numbers of the isotopic mixtures.



Isotopeneffekt (1950): Elektronen wechselwirken mit Gitterschwingungen



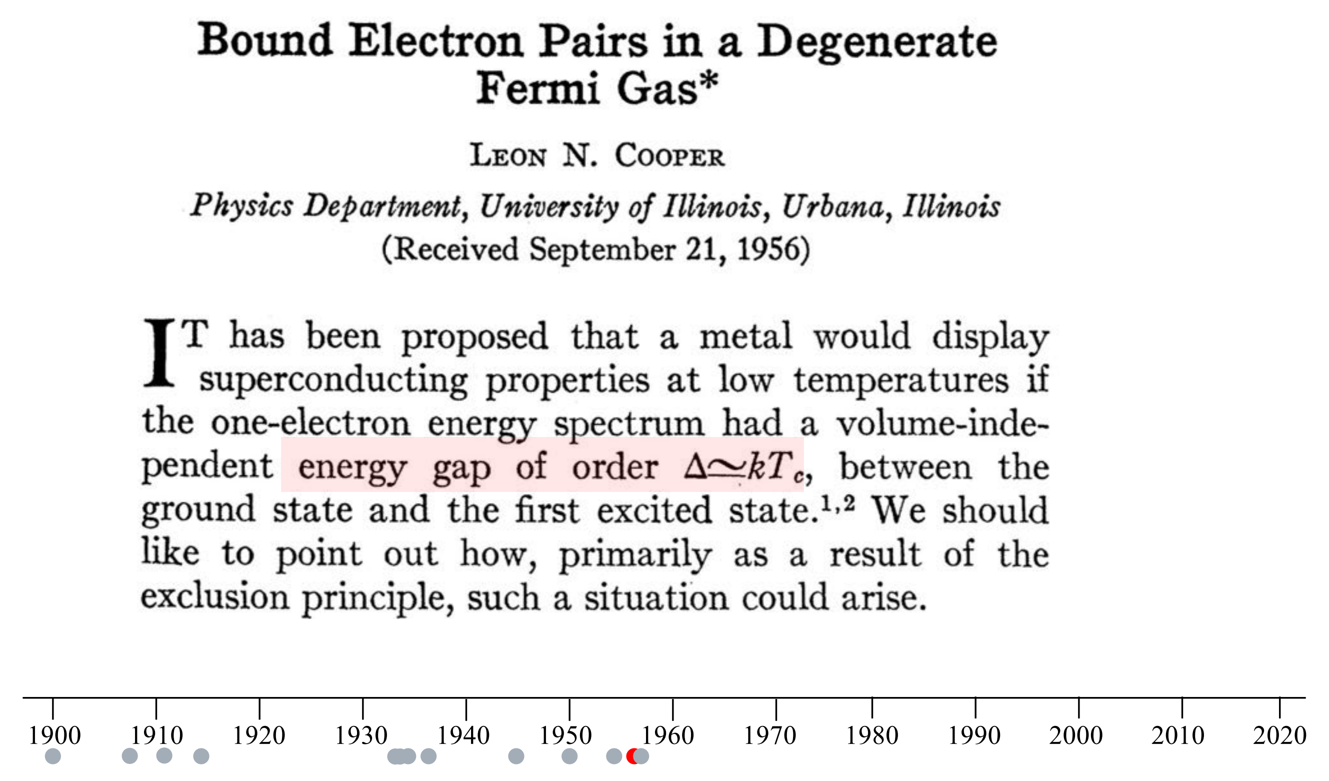
Wave Functions for Superconducting Electrons

JOHN BARDEEN
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received July 17, 1950)

The observed variation of the transition temperature of mercury with isotopic mass is evidence that the superconducting state arises from interaction of electrons with lattice vibrations. The interaction term which gives scattering of electrons at high temperatures contributes at low temperatures a term to the energy of the system of electrons plus normal modes. Fröhlich has calculated the interaction energy at $T=0°\mathrm{K}$ by second-order perturbation theory. The energy is calculated here by taking wave functions of superconducting electrons, which have energies near the Fermi surface, as linear combinations of Bloch functions whose coefficients are functions of coordinates of the normal modes. In an equivalent approximation, Fröhlich's expression for the interaction energy is obtained. When the energy is calculated directly rather than by perturbation theory, modified expressions are obtained for the energy and distribution of electrons in the superconducting state. The criterion for superconductivity is $\hbar/\tau > \sim 2\pi\kappa T$, where τ is the relaxation time for electrons at some high temperature T where τT is constant. It is shown that superconducting electrons have small effective mass.

Paarbildung (1956) durch anziehende Wechselwirkung



Bound Electron Pairs in a Degenerate Fermi Gas*

Leon N. Cooper

Physics Department, University of Illinois, Urbana, Illinois

(Received September 21, 1956)

It has been proposed that a metal would display superconducting properties at low temperatures if the one-electron energy spectrum had a volume-independent energy gap of order $\Delta \simeq kT_c$, between the ground state and the first excited state.[1,2] We should like to point out how, primarily as a result of the exclusion principle, such a situation could arise.

BCS Theorie (1957): Detaillierte mikroskopische Theorie

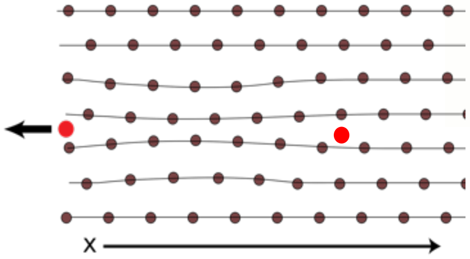
Jede anziehende Wechselwirkung («V_0») zwischen Elektronen Führt zur Bildung von sog. Cooper-Paaren

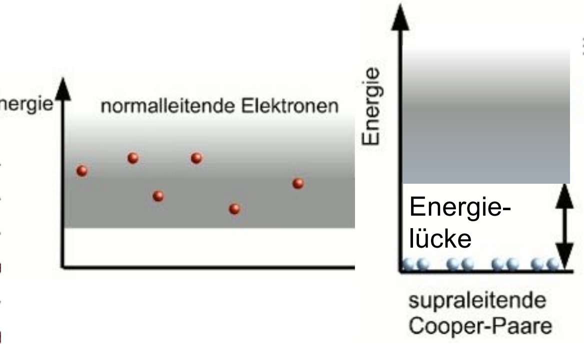
Diese Anziehung erfolgt in konventionellen Supraleitern via Schwingungen des Kristallgitters («Phononen»)

Erklärung von Energielücke, Isotopeneffekt und Grösse der kritischen Temperatur

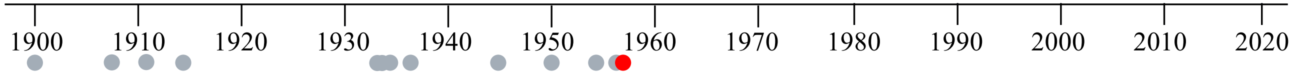
John Bardeen, Leon Cooper und Robert Schrieffer

1972

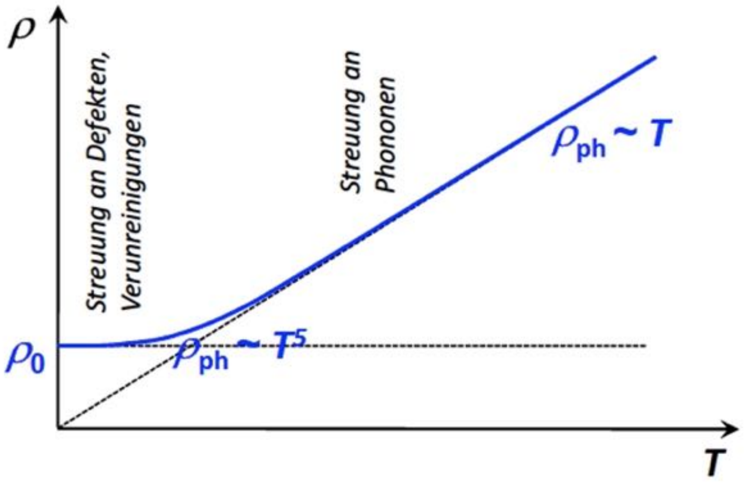




$$T_c = 1.14\,\Theta_D \exp\left(\frac{-1}{D(E_F)V_0}\right)$$



BCS Theorie (1957): Detaillierte mikroskopische Theorie

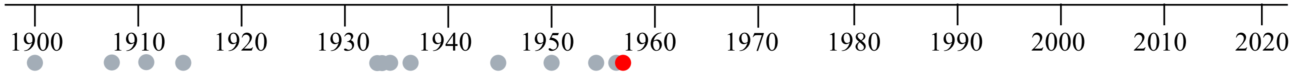


$$\rho(T) = \rho_0 + \lambda \frac{\pi k_B \Theta_D m_e}{8 e^2 \hbar n_e} \left(\frac{T}{\Theta_D}\right)^5 \int_0^{\Theta_D/T} \frac{x^5}{(e^x - 1)(1 - e^{-x})} dx \quad \text{(Bloch – Grüneisen)}$$

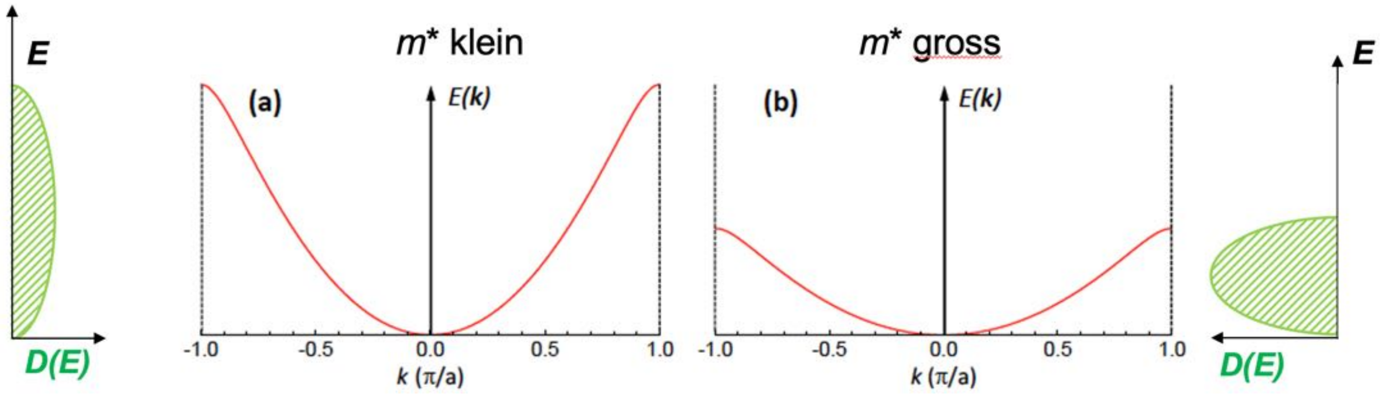
λ ...... Mass für die Stärke der Elektron – Phonon Wechselwirkung

$\lambda \approx D(E_F)V_0$

$$T_c = 1.14\ \Theta_D \exp\left(\frac{-1}{D(E_F)V_0}\right)$$



Flache Energiebänder, hohe elektronische Zustandsdichte bei E_F....



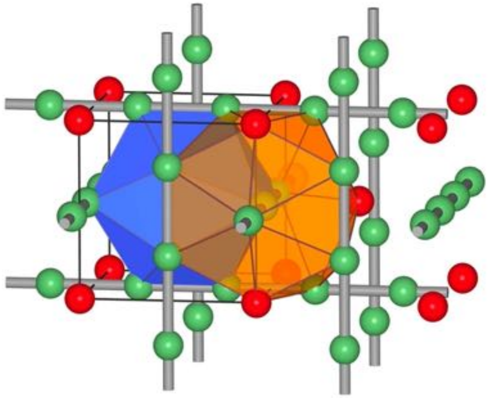
$$\lambda \approx D(E_F)V_0$$

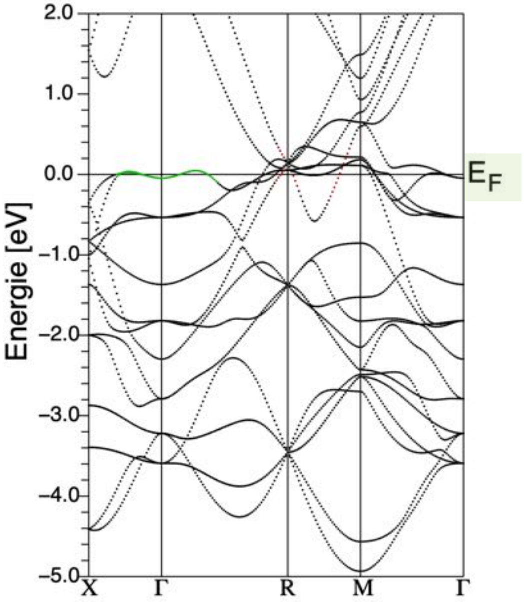
$$T_c = 1.14\,\Theta_D \exp\left(\frac{-1}{D(E_F)V_0}\right)$$

Flache Energiebänder, hohe elektronische Zustandsdichte bei E_F....

Nb_3Sn

$T_c \approx 18.3$ K





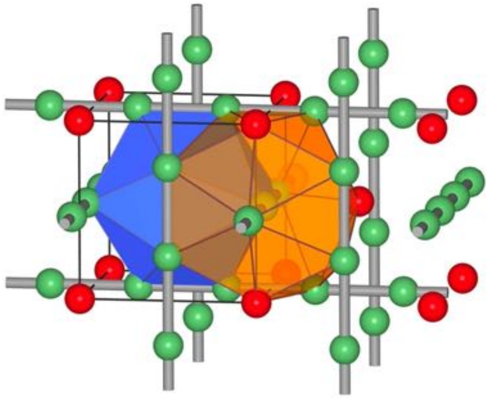
$$\lambda \approx D(E_F)V_0$$

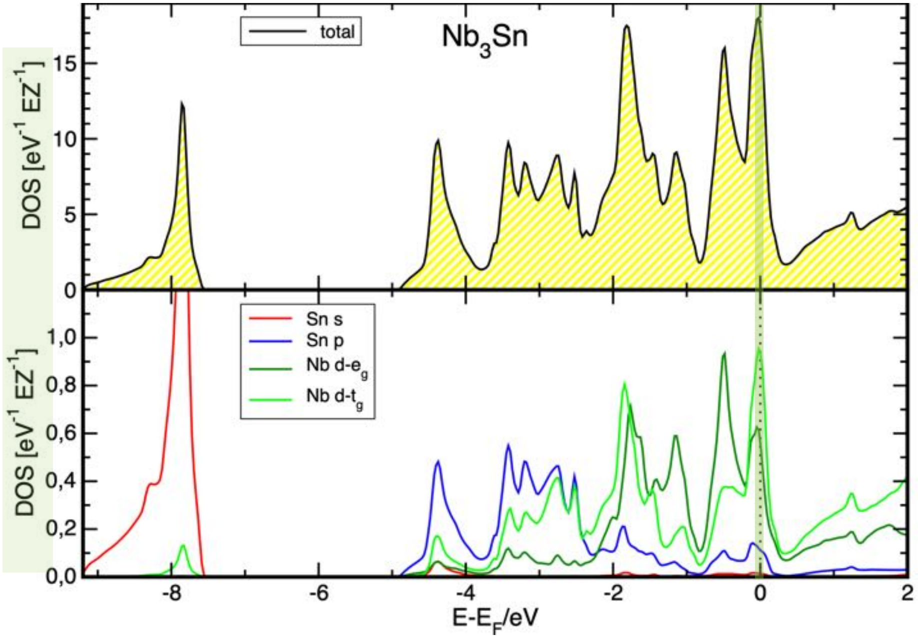
$$T_c = 1.14\,\Theta_D \exp\left(\frac{-1}{D(E_F)V_0}\right)$$

Flache Energiebänder, hohe elektronische Zustandsdichte bei E_F....

Nb_3Sn

$T_c \approx 18.3$ K

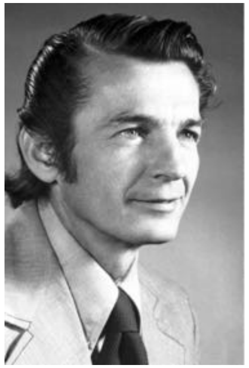




$$\lambda \approx D(E_F)V_0$$

$$T_c = 1.14\,\Theta_D \exp\left(\frac{-1}{D(E_F)V_0}\right)$$

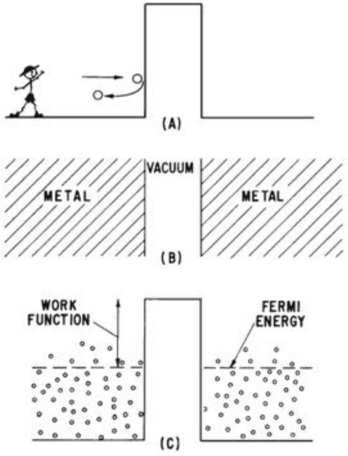
Tunneleffekte (1960)

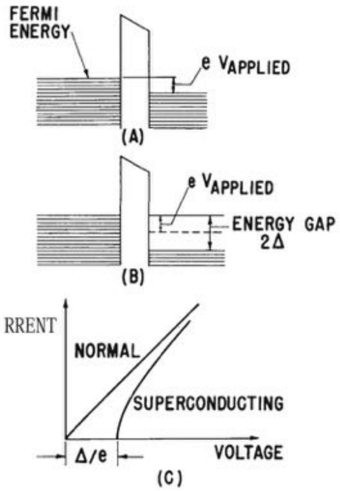


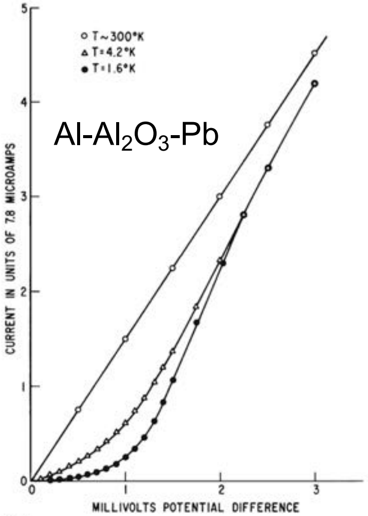
Ivar Giaever

1973

Tunneleffekte in Supraleiter-Isolator-Supraleiter Übergängen - Bestimmung der Energielücke

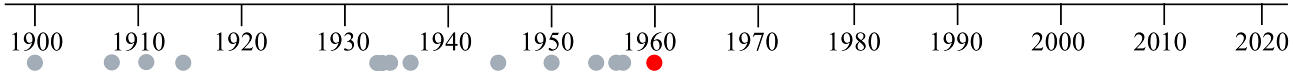






Al-Al_2O_3-Pb

Fig. 7.
The current-voltage characteristic of an aluminum-aluminum oxide-lead sample. As soon as the lead becomes superconducting the current ceases to be proportional to the voltage. The large change between 4.2° K and 1.6° K is due to the change in the energy gap with temperature. Some current also flows at voltages less than Δ/e because of thermally excited electrons in the conductors.



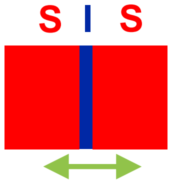
Josephsoneffekte (1962)

Brian Josephson

1973

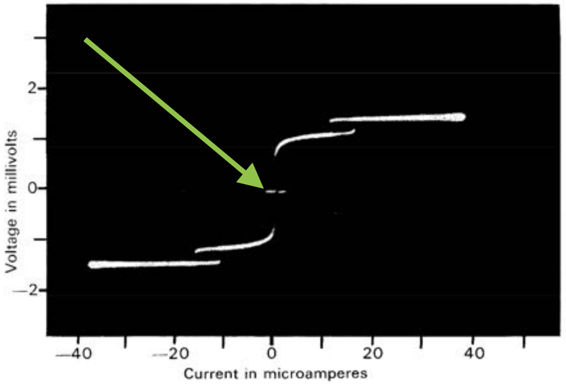
«d.c.» Josephson Effekt:

Supraleitender Tunnelgleichstrom
ohne angelegte Spannung
durch isolierende Barriere



«a.c.» Josephson Effekt:

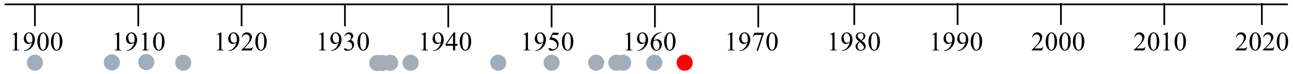
Supraleitender
Tunnelwechselstrom
bei angelegter Spannung *V*



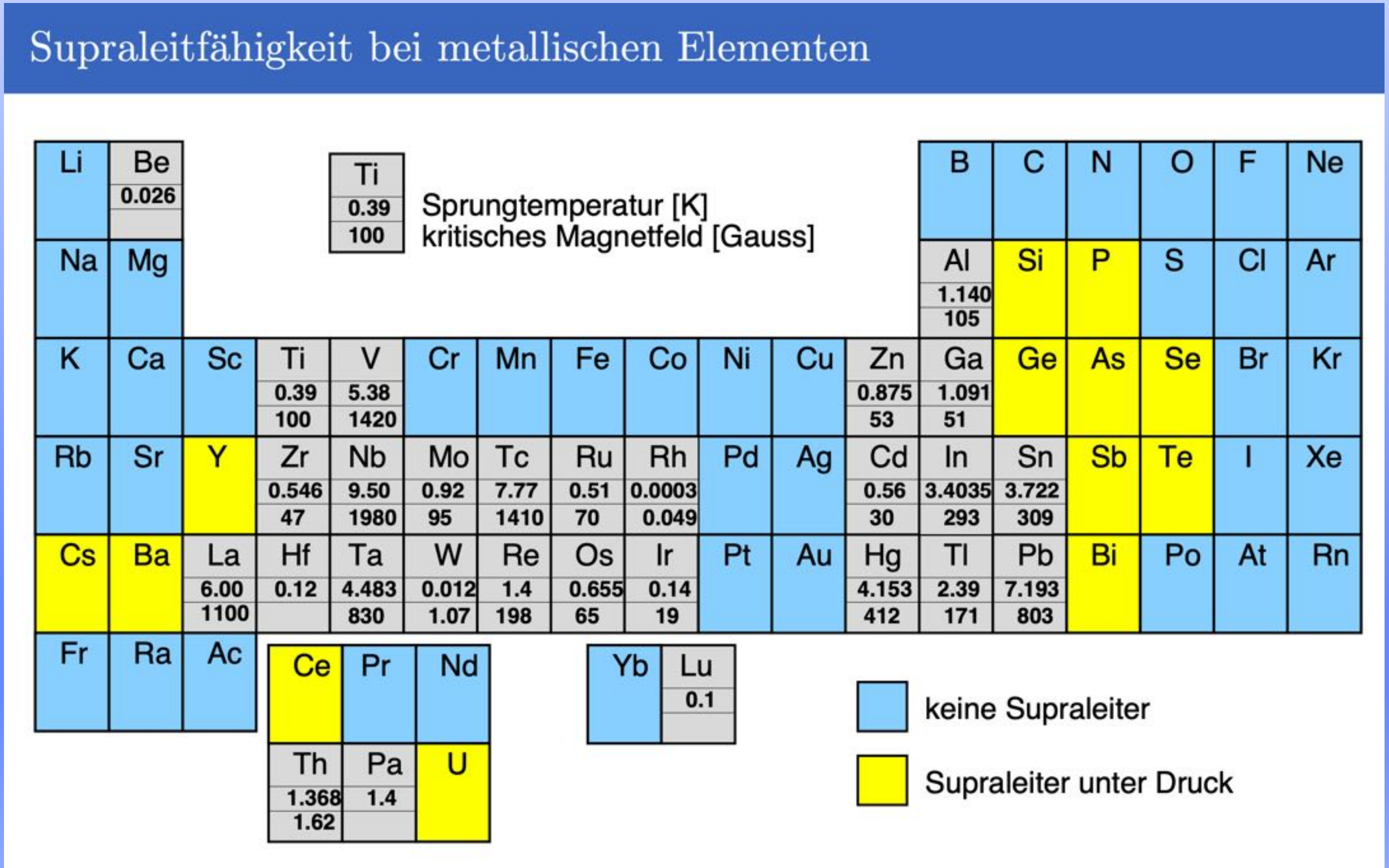
Frequenz: $f = 2eV/h$

Josephson-Volt-standard

Grundlage von supraleitenden Detektoren (SQUID's)



Kritische Temperatur der Elemente



Supraleitfähigkeit bei metallischen Elementen

Ti
0.39 Sprungtemperatur [K]
100 kritisches Magnetfeld [Gauss]

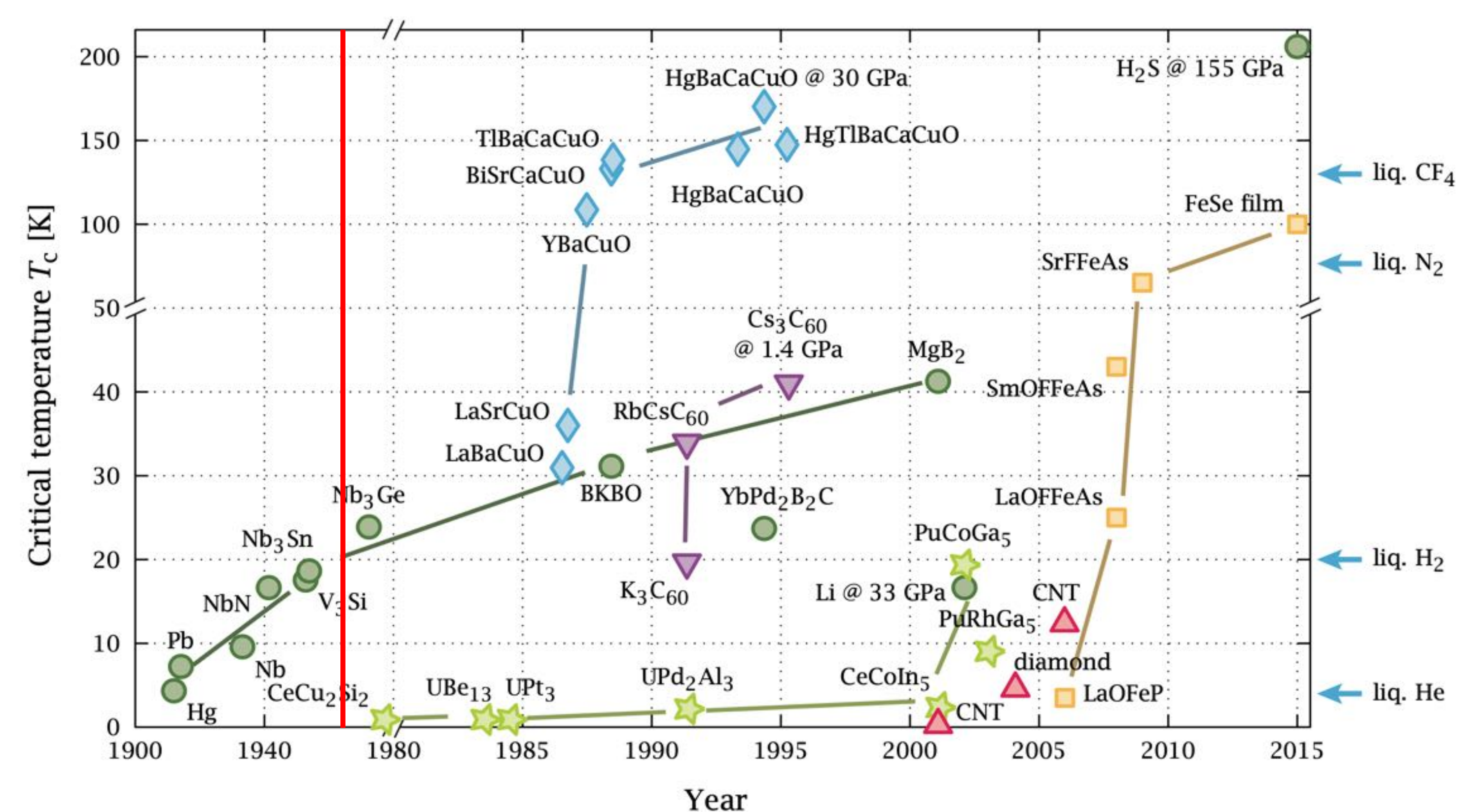
Li	Be 0.026											B	C	N	O	F	Ne
Na	Mg											Al 1.140 105	Si	P	S	Cl	Ar
K	Ca	Sc	Ti 0.39 100	V 5.38 1420	Cr	Mn	Fe	Co	Ni	Cu	Zn 0.875 53	Ga 1.091 51	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr 0.546 47	Nb 9.50 1980	Mo 0.92 95	Tc 7.77 1410	Ru 0.51 70	Rh 0.0003 0.049	Pd	Ag	Cd 0.56 30	In 3.4035 293	Sn 3.722 309	Sb	Te	I	Xe
Cs	Ba	La 6.00 1100	Hf 0.12	Ta 4.483 830	W 0.012 1.07	Re 1.4 198	Os 0.655 65	Ir 0.14 19	Pt	Au	Hg 4.153 412	Tl 2.39 171	Pb 7.193 803	Bi	Po	At	Rn
Fr	Ra	Ac															

Ce	Pr	Nd	Yb	Lu 0.1
Th 1.368 1.62	Pa 1.4	U		

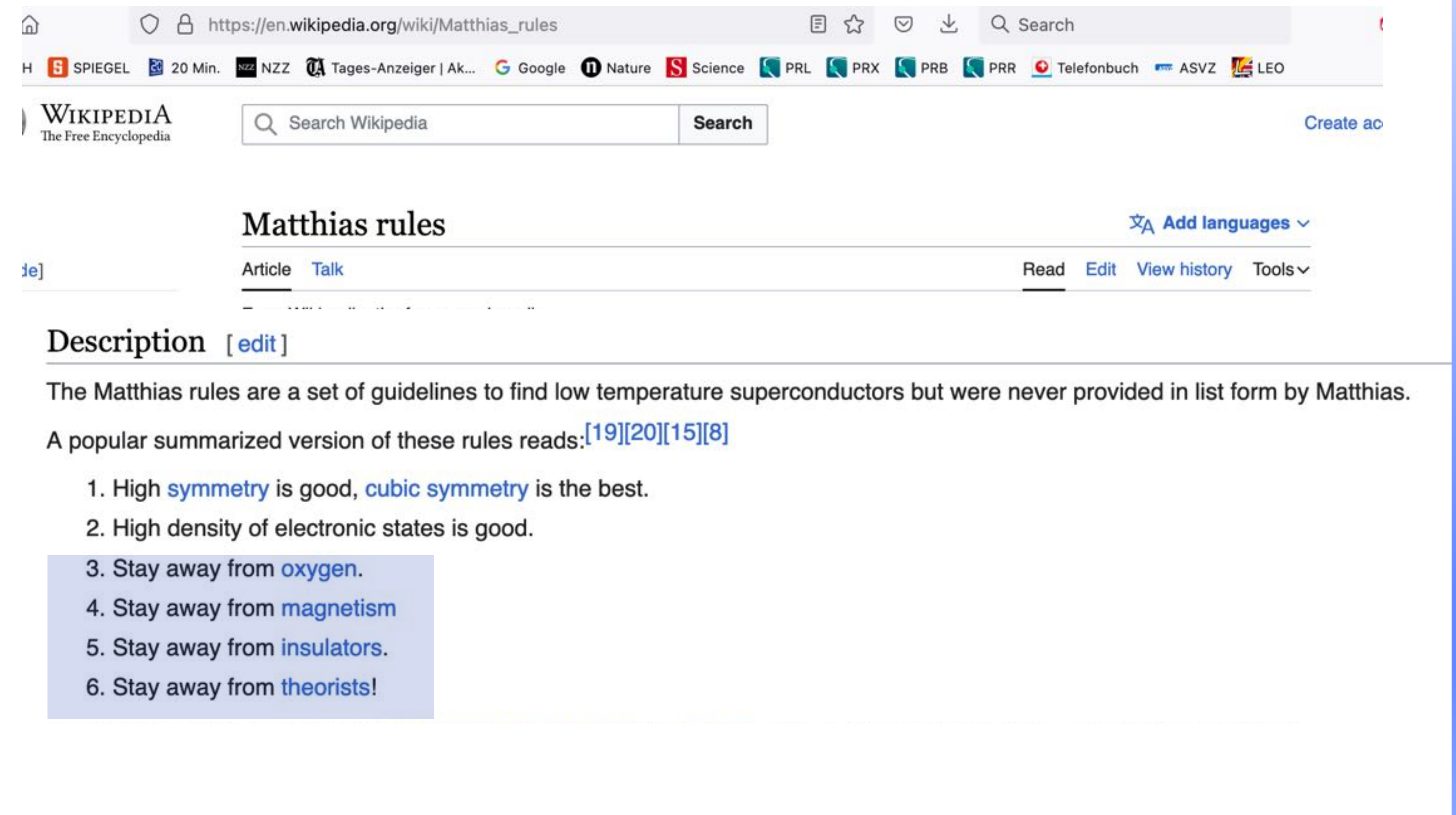
🟦 keine Supraleiter

🟨 Supraleiter unter Druck

Kritische Temperatur vs. Zeit (bis 2015)



Wie neue Supraleiter finden? Matthias Regeln....



Matthias rules

Description [edit]

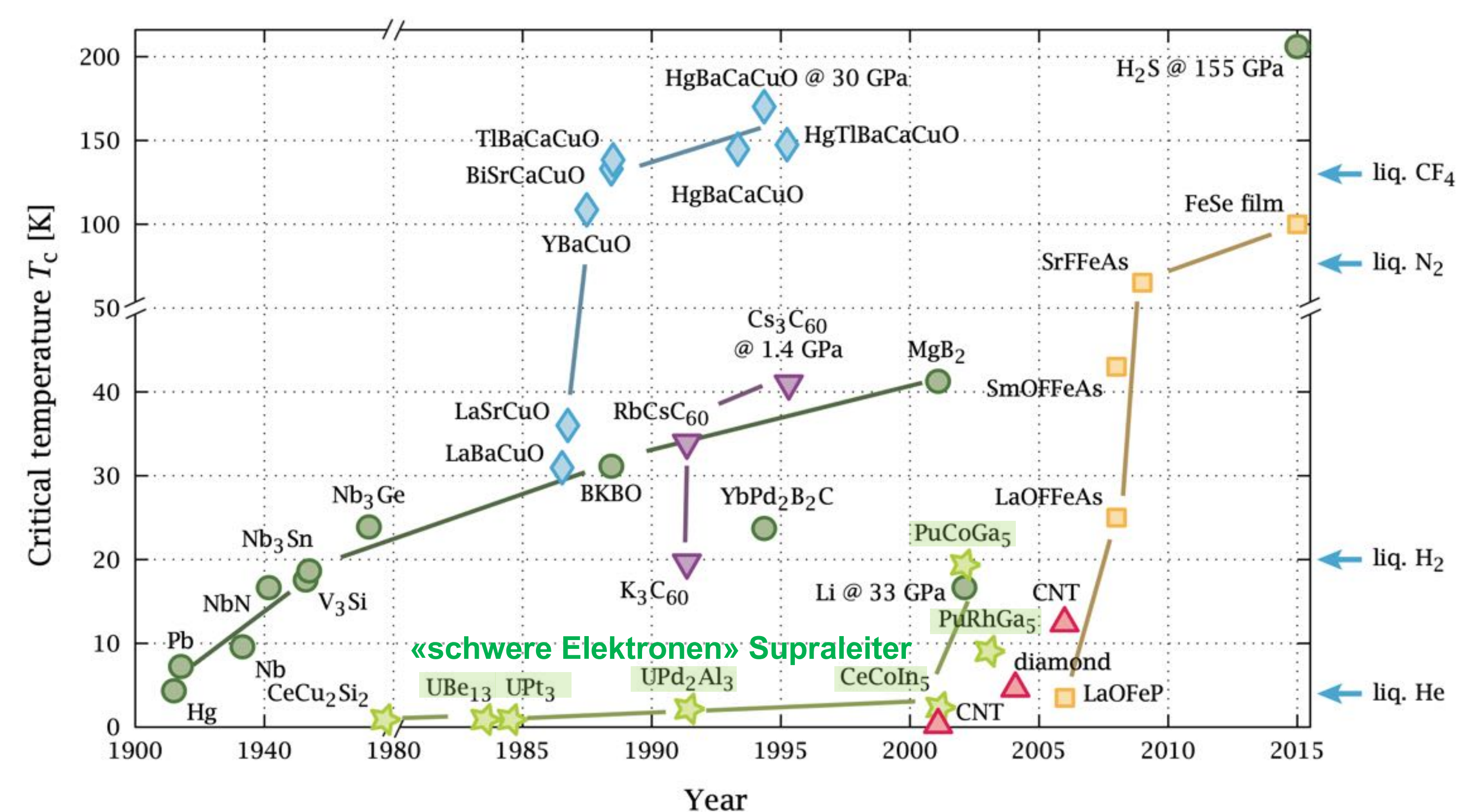
The Matthias rules are a set of guidelines to find low temperature superconductors but were never provided in list form by Matthias.

A popular summarized version of these rules reads:[19][20][15][8]

1. High symmetry is good, cubic symmetry is the best.
2. High density of electronic states is good.
3. Stay away from oxygen.
4. Stay away from magnetism
5. Stay away from insulators.
6. Stay away from theorists!

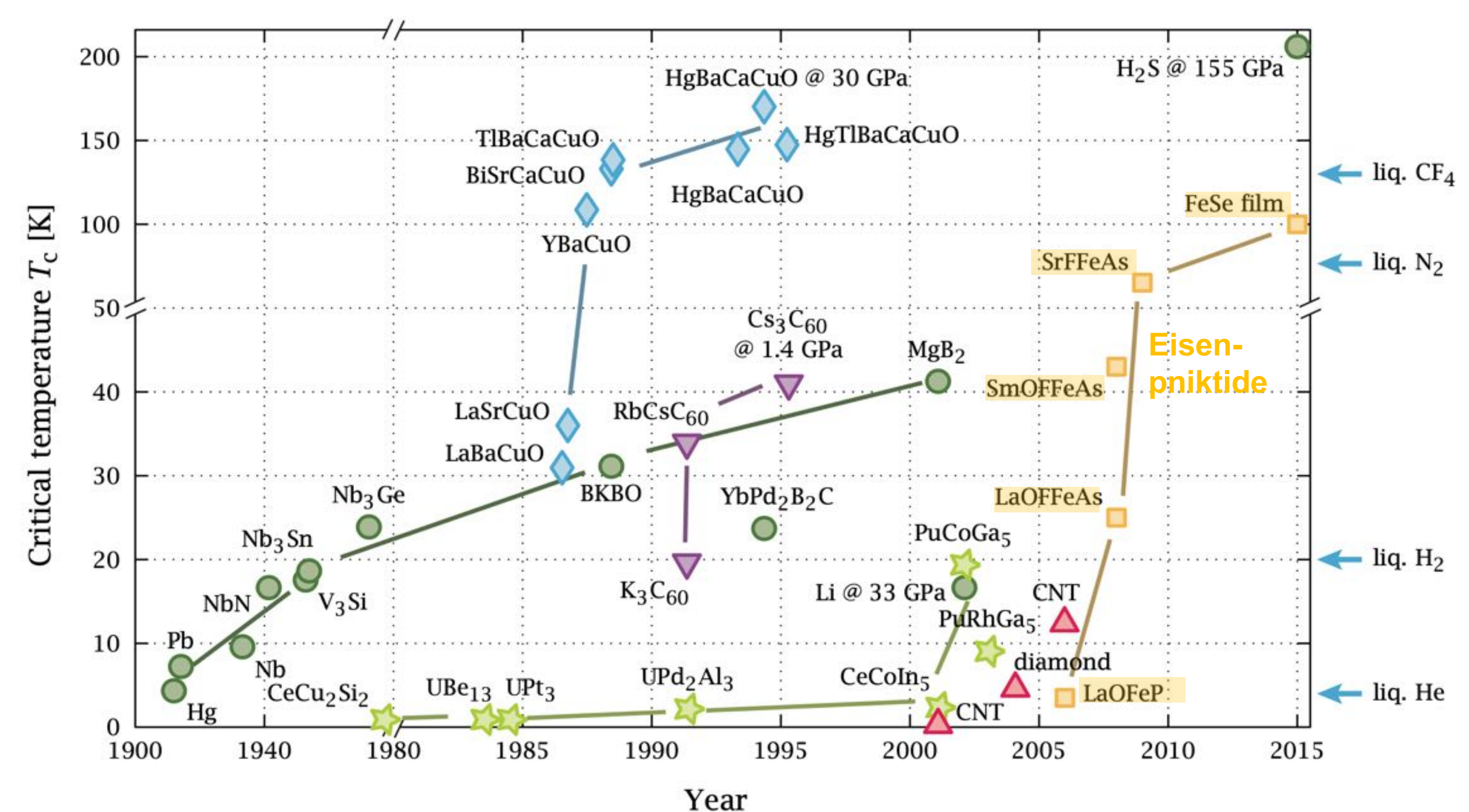
«schwere Elektronen» Supraleiter

- Intermetallische Verbindungen mit Cer, Uran oder Plutonium
- Fast delokalisierte ”*f*-Elektronen», **hohe effektive Masse *m****
- magnetische Wechselwirkung mit den Leitungselektronen

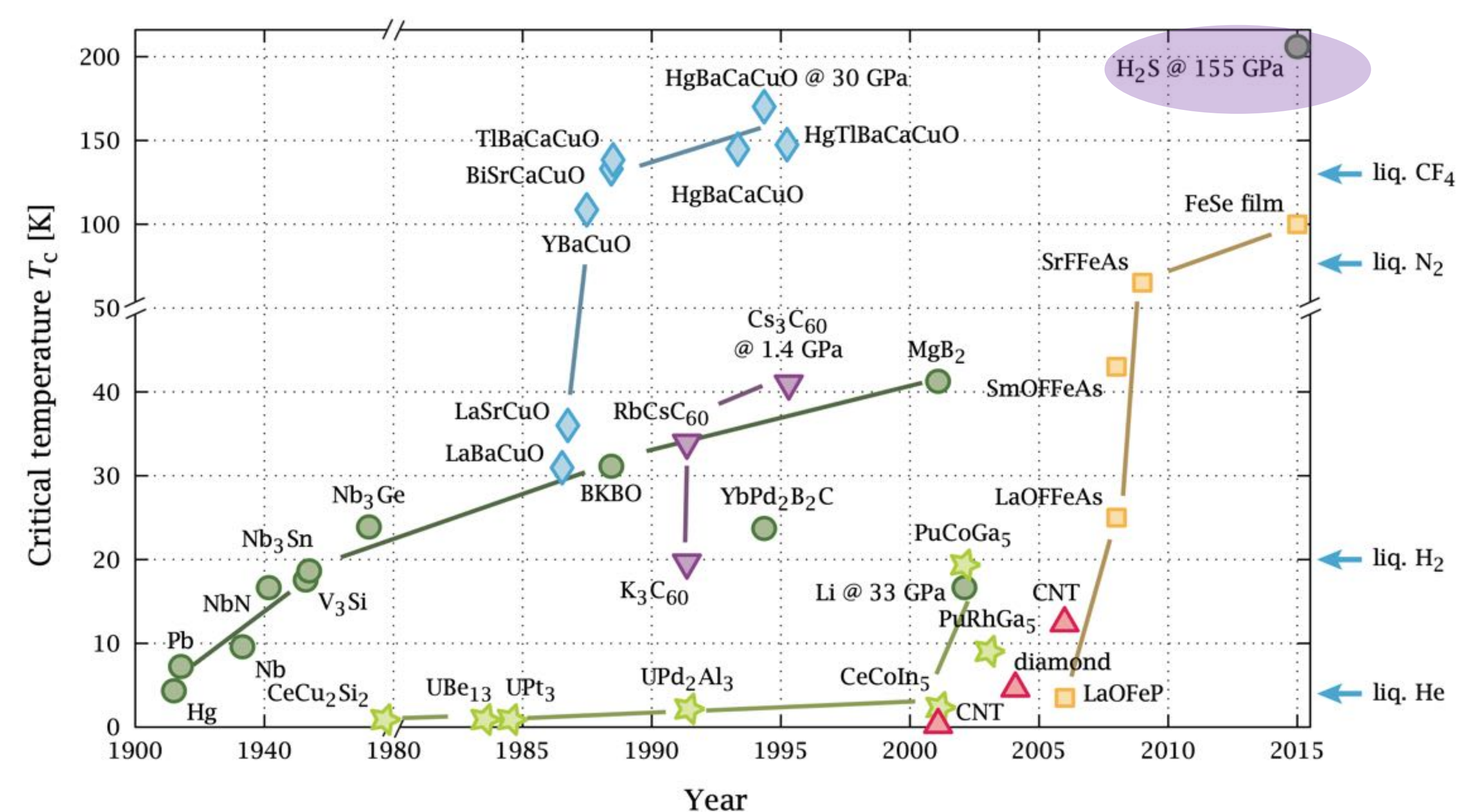


Eisenpniktide

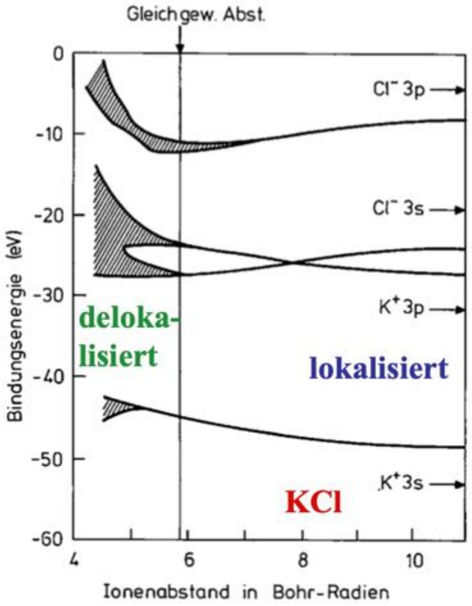
- Meist geschichtete Eisen-Arsen oder Phosphor-Verbindungen
- Mechanismus: *??*

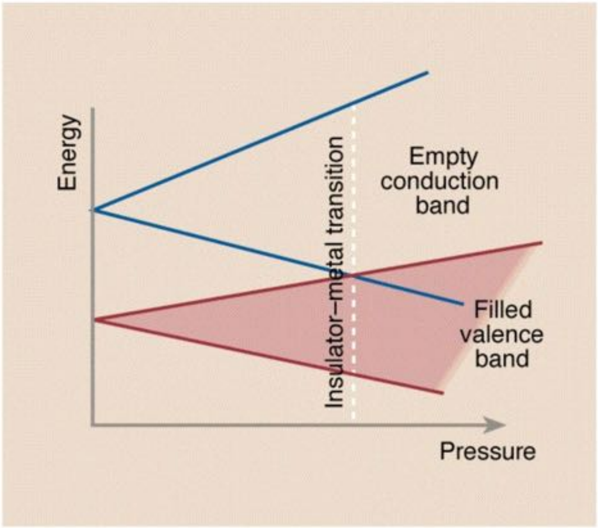


Wasserstoffverbindungen unter extremem Druck



Wasserstoffverbindungen unter extremem Druck





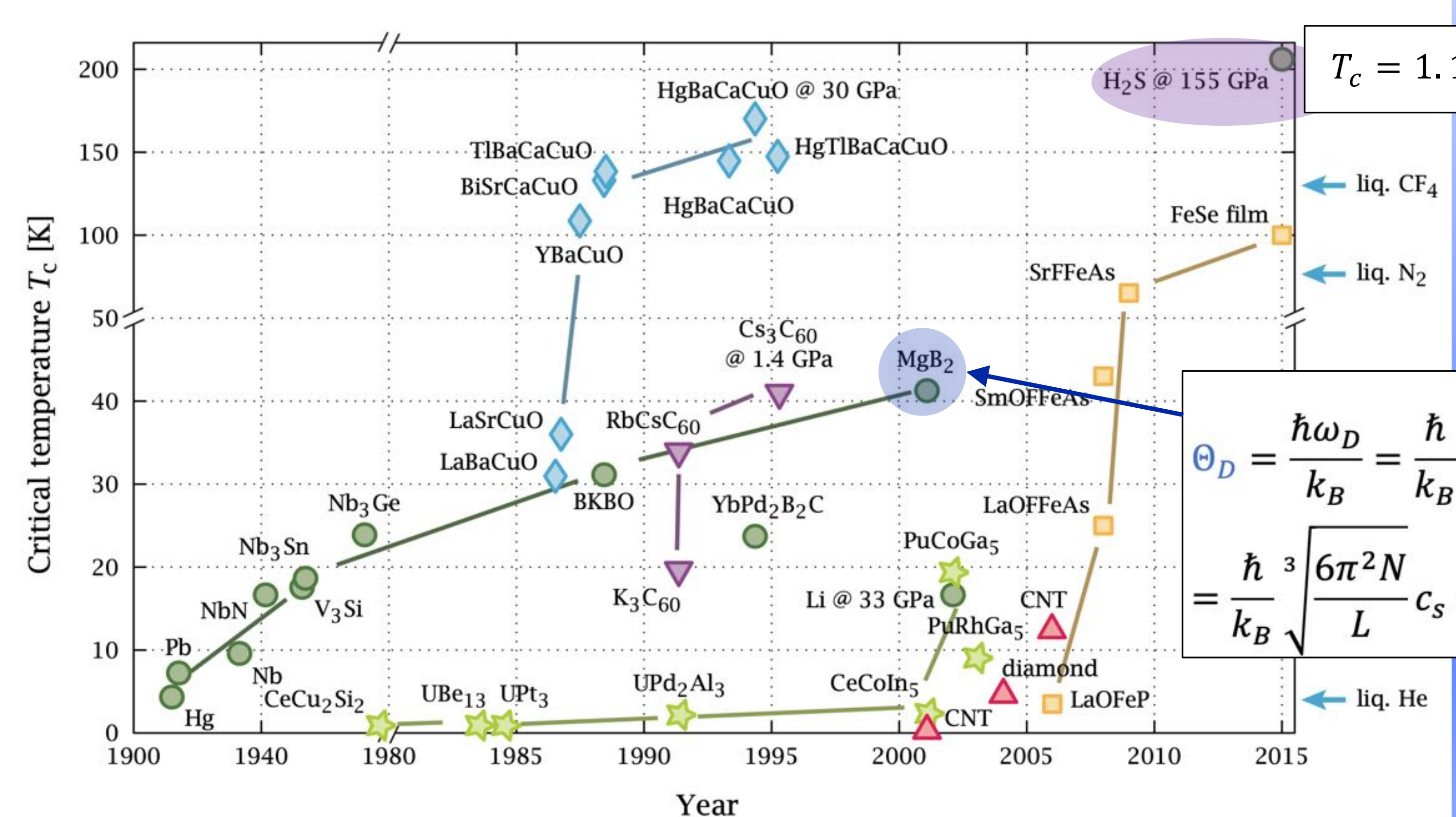
Metalle:

Wasserstoff-"Metall":

Übergang vom Isolator zum Metall erwartet, sobald Gitterkonstante $a \le 4.5 r_{Bohr}$ **,**

= Mott'scher Metall-Isolator Übergang.

... harte Materialien mit leichten Elementen

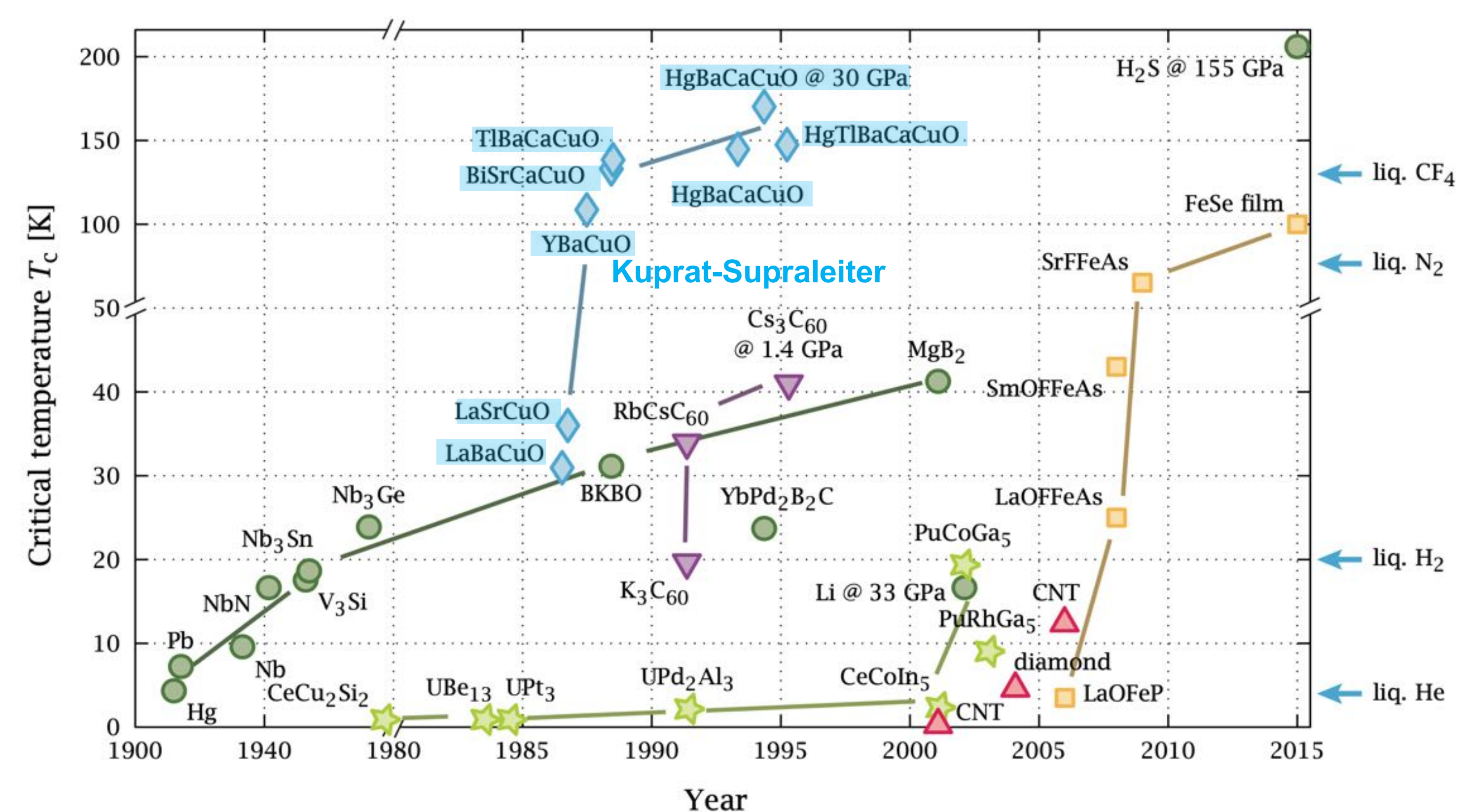


$$T_c = 1.14\,\Theta_D \exp\left(\frac{-1}{D(E_F)V_0}\right)$$

$$\Theta_D = \frac{\hbar\omega_D}{k_B} = \frac{\hbar}{k_B}\sqrt[3]{\frac{6\pi^2 N}{L}}\,c_s$$

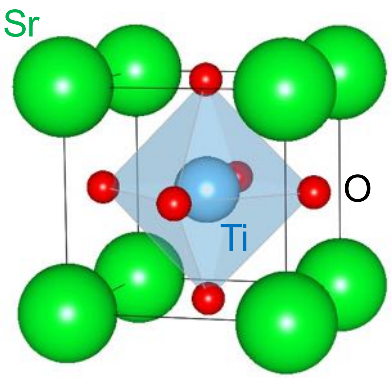
$$= \frac{\hbar}{k_B}\sqrt[3]{\frac{6\pi^2 N}{L}}\,c_s = \frac{\hbar}{k_B}\sqrt[3]{\frac{6\pi^2 N}{L}}\sqrt{E/\rho}$$

Kuprat-Supraleiter



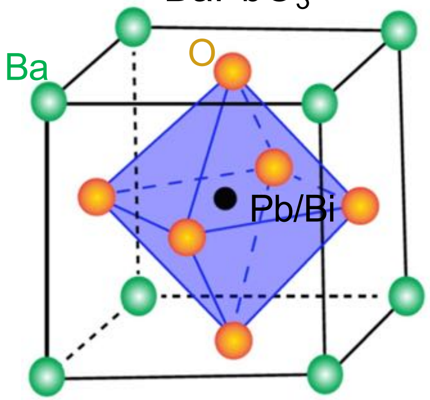
Keramische Oxid-Supraleiter

«Perovskite» $SrTiO_3$



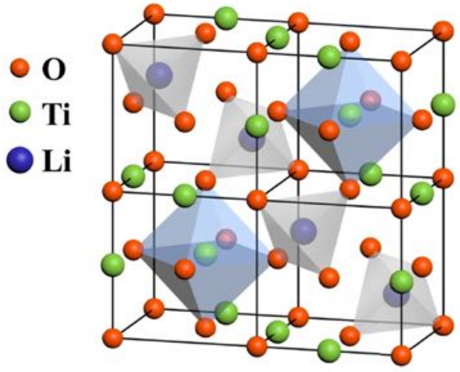
(1964)

$BaPbO_3$



(1975)

«Spinel» $LiTi_2O_4$



(1973)

Metallische Leitfähigkeit erst durch «Dotierung» → gemischte Valenzen

.....z.B. mit Nb

$BaPb_{1-x}Bi_xO_3$

$T_c \approx 0.5$ K

$T_c \approx 10$ K

$T_c \approx 12$ K

Ladungsträgerkonzentration

$\approx 10^{26} / m^3$ ($6x10^{-3}$ pro Ti Atom!)

$\approx 2x10^{27} / m^3$

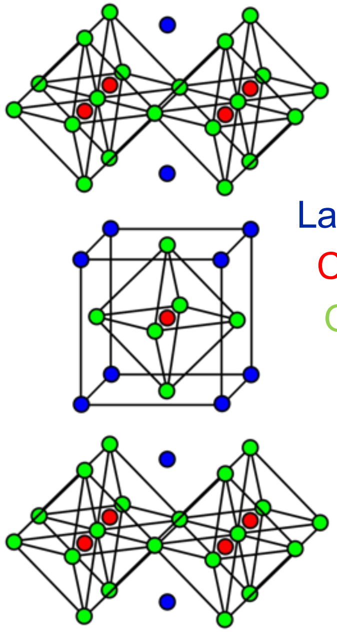
$\approx 2x10^{27} / m^3$

Zum Vergleich: Kupfer $8x10^{28} / m^3$, Blei $1.3x10^{29} / m^3$

Kuprate: Hochtemperatur-Supraleiter

Isolator-Metall Übergang durch Dotierung in Übergangs-Metall-basierten Perovskiten

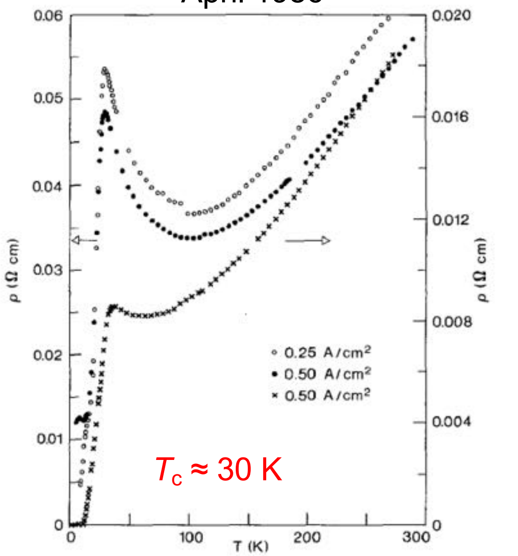
$La_{2-x}Ba_xCuO_4$



La/Ba
Cu
O

J.G. Bednorz and K.A. Müller: Ba – La – Cu – O System

April 1986

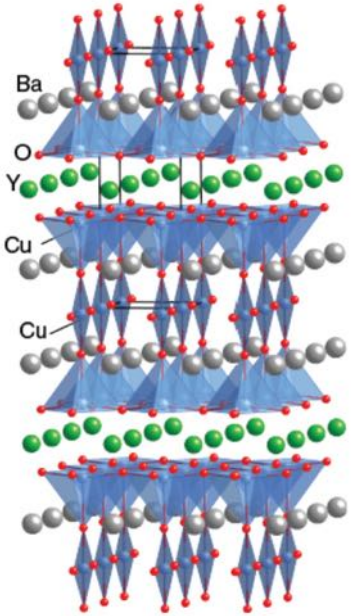


$T_c \approx 30$ K

Fig. 1. Temperature dependence of resistivity in $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ for samples with x(Ba) = 1 (upper curves, left scale) and x(Ba) = 0.75 (lower curve, right scale). The first two cases also show the influence of current density

Z. Phys. B: Cond. Matter 64 (1986) 189

$YBa_2Cu_3O_7$ März 1987

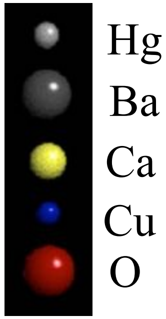


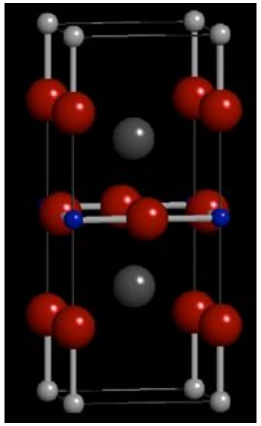
$T_c \approx 93$ K

Wu et al., Phys. Rev. Lett. 58 (1987) 908

Kuprate: Hochtemperatur-Supraleiter

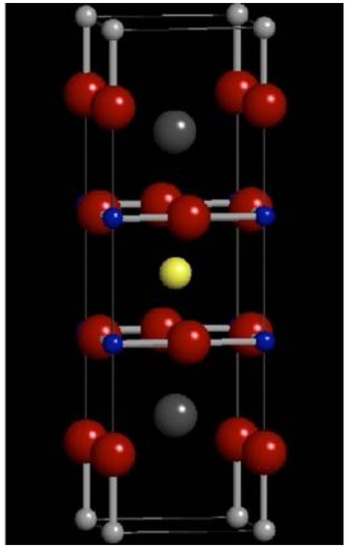
$HgBa_2Ca_{n-1}Cu_nO_{2n+2}$





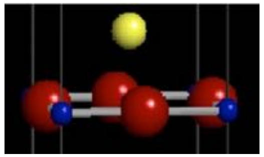
$n = 1$, $T_c = 96$ K

S.N. Putilin et al.,
Nature 362 (1993) 226

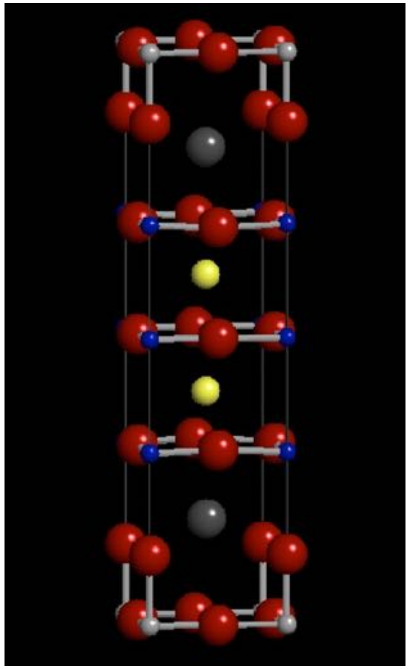


$n = 2$, $T_c = 127$ K

+



+ “ $CaCuO_2$ “



$n = 3$, $T_c = 134$ K

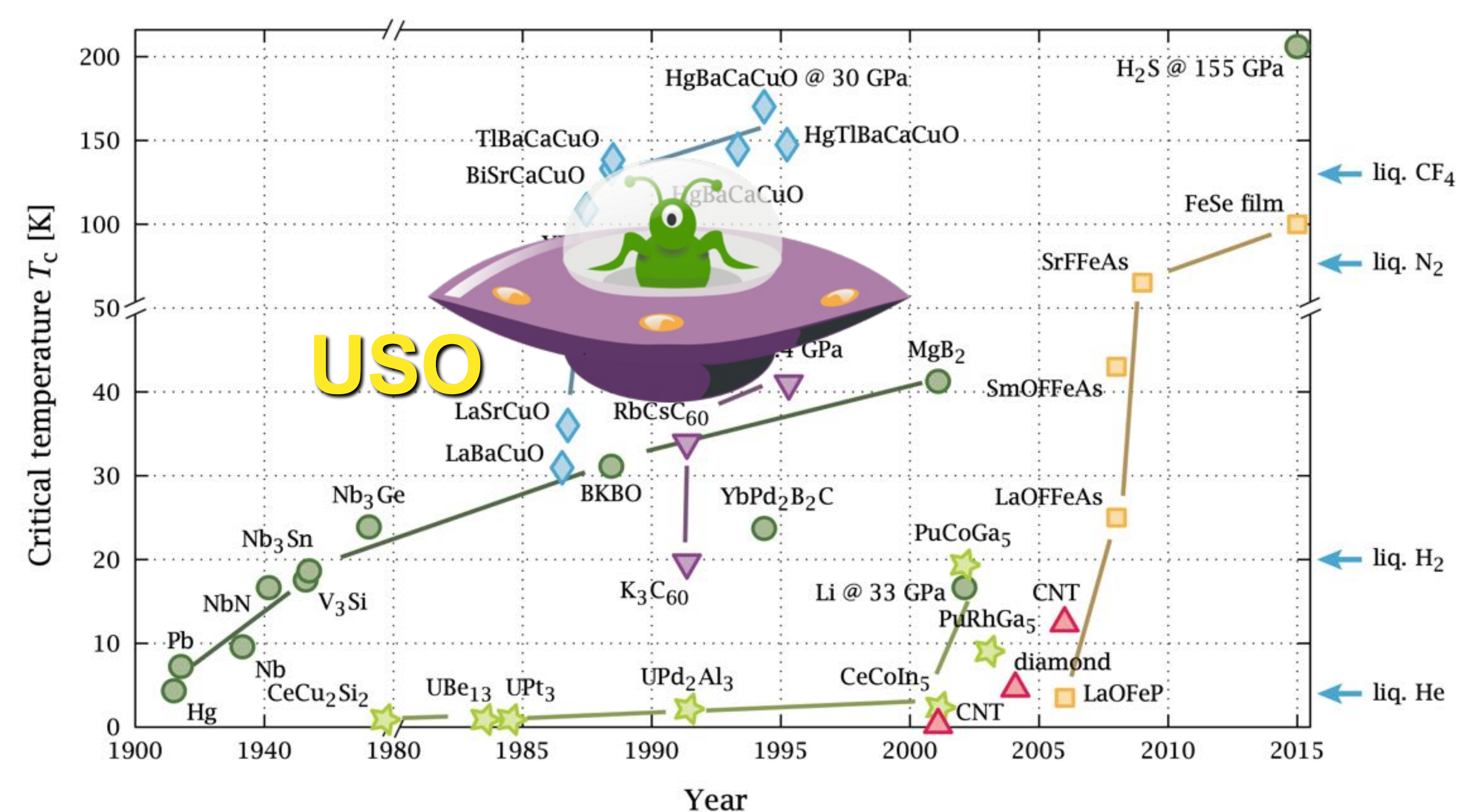
A. Schilling et al.,
Nature 363 (1993) 56

Kuprate: Hochtemperatur-Supraleiter

Speziell bei Kuprat-Supraleitern:

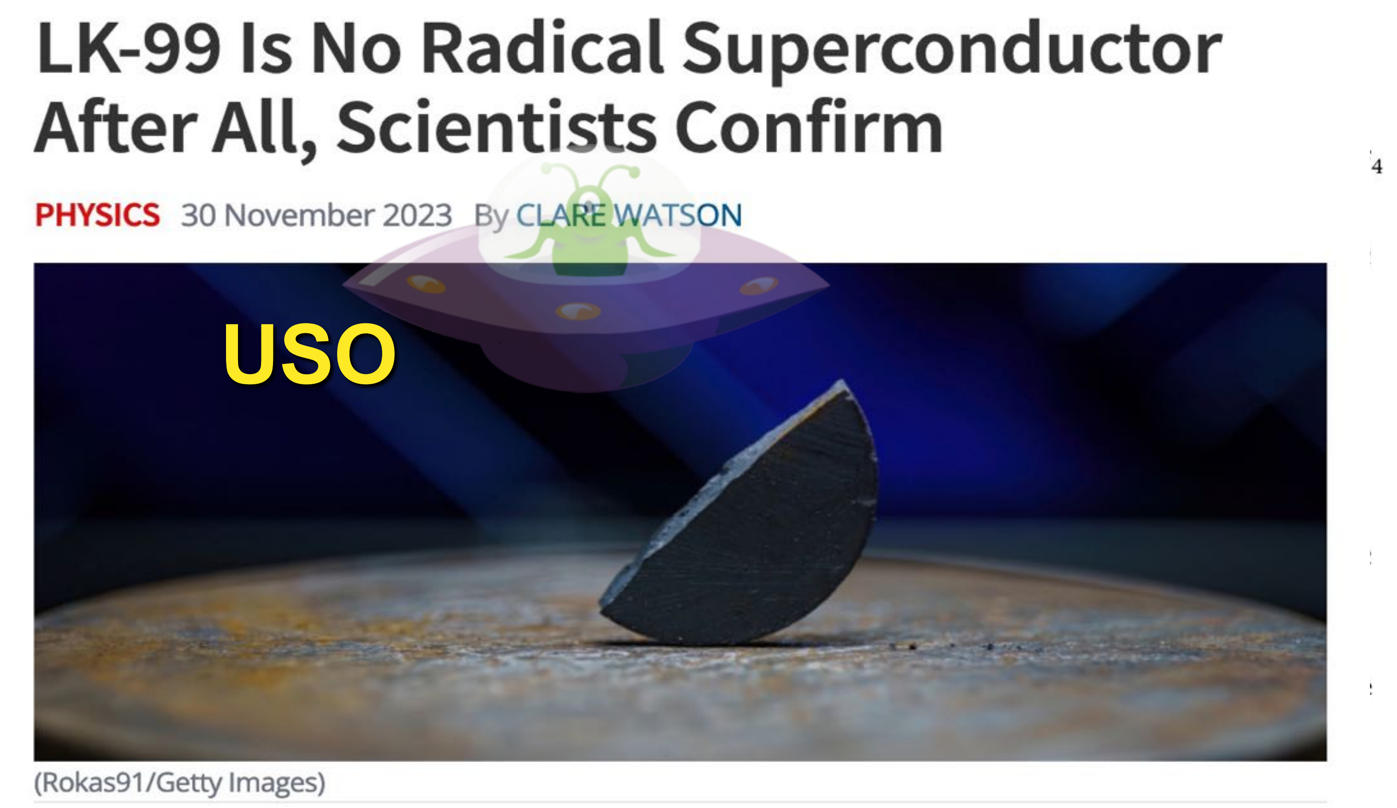
- Kritische Temperatur bei Normaldruck oberhalb 77 K (-196 ºC) 😀
- Extrem Typ-II: Deshalb sehr hohe kritische Magnetfelder B_{c2} möglich (> 100 Tesla) 😀
- Sehr hohe kritische Stromdichten bei tiefen Temperaturen (≈ 10^7 A/cm^2) 😀
- Sehr anisotrop auf Grund der Schichtstruktur: «Vortex-Pinning» geht nahe T_c verloren 🙄
- Spröde (Oxid-Keramik): schwierige Metallurgie (Drähte, Spulen etc.) 😠

Supraleitung



USO

Kritische Temperatur vs. Zeit (bis 2015)

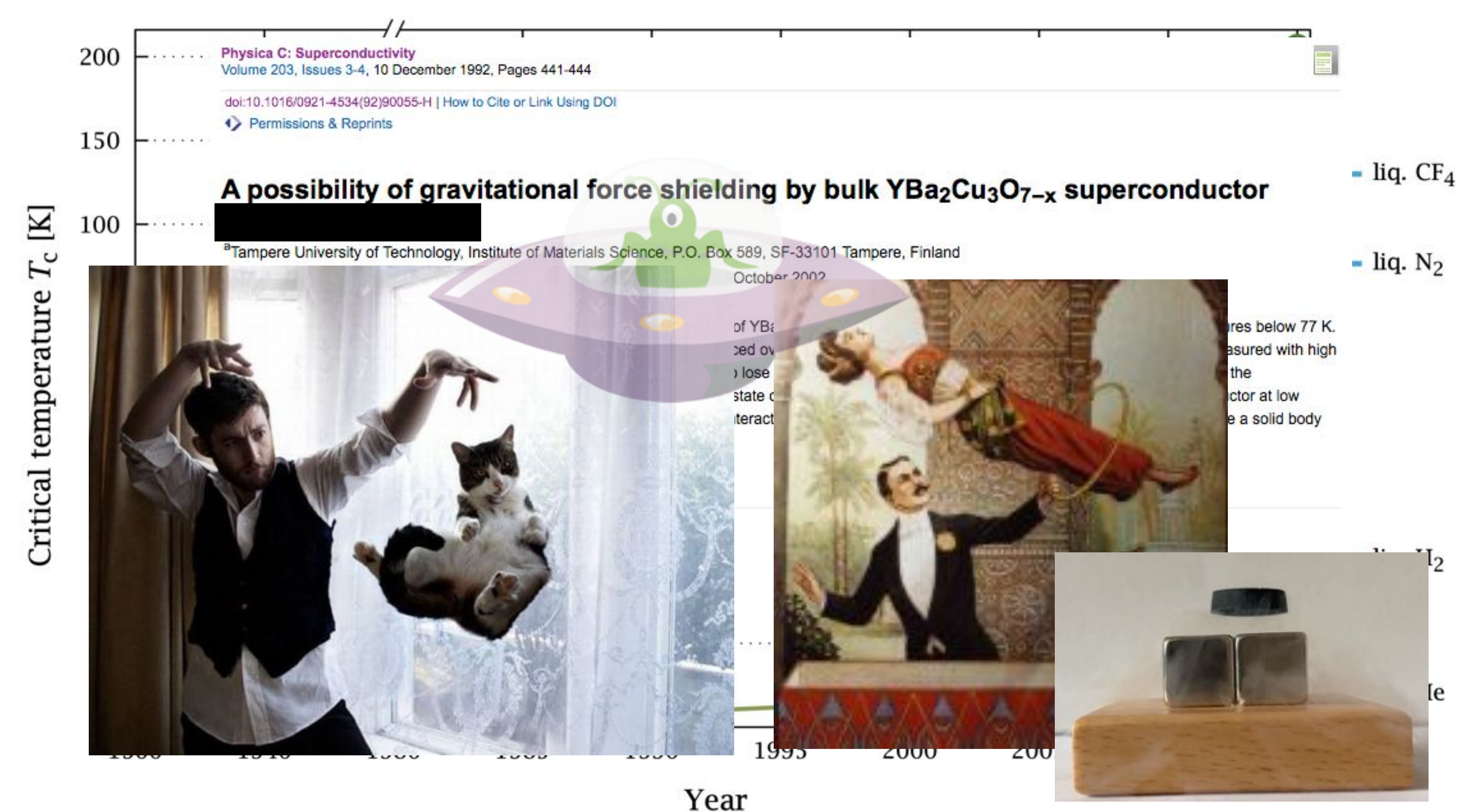


LK-99 Is No Radical Superconductor After All, Scientists Confirm

PHYSICS 30 November 2023 By CLARE WATSON

(Rokas91/Getty Images)

Supraleitung



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A possibility of gravitational force shielding by bulk $YBa_2Cu_3O_{7-x}$ superconductor

[redacted]

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October 2002

of YBa … res below 77 K.
ced ov … asured with high
lose … the
state … ctor at low
teract … e a solid body