# Optical properties of superconductors

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## Part I.
## A little of history

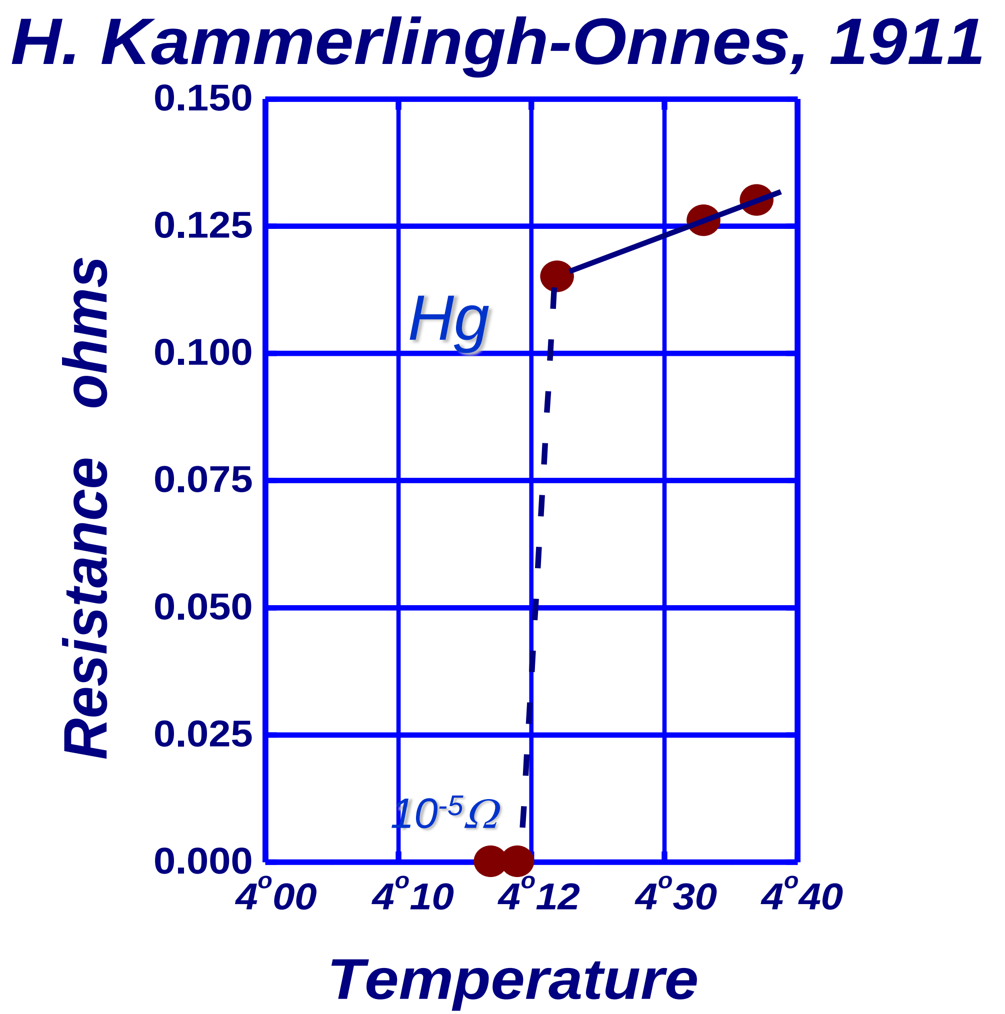
## Part II.
## Optical properties of superconductors

# Part I.
# A little of history

# Discovery of superconductivity

Kamerlingh Onnes

Nobel Prize 1913




$T_c$=4.15 K

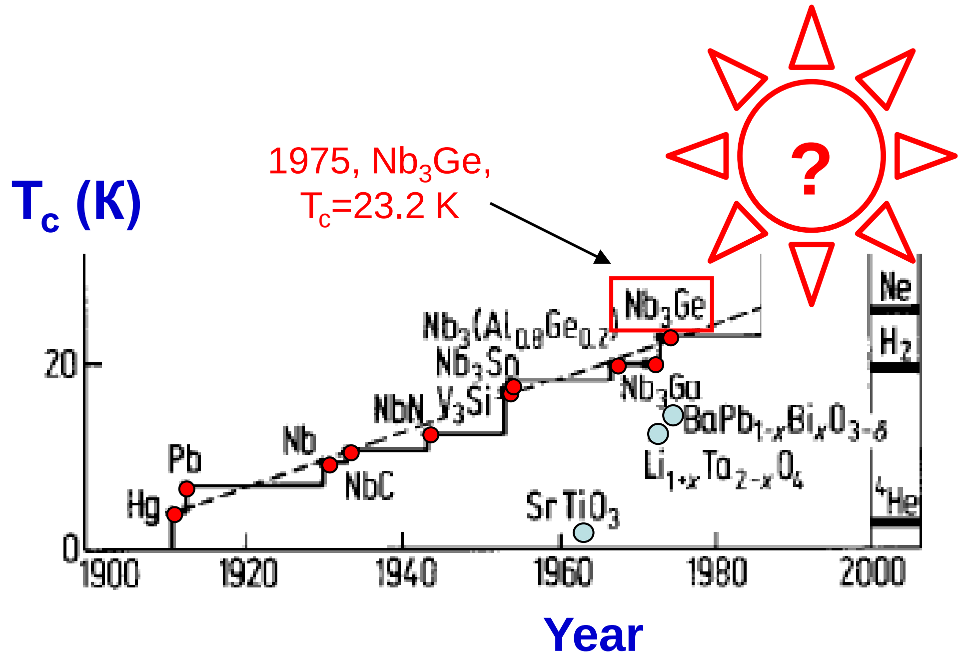
# Mechanism of superconductivity Bardeen-Cooper-Schrieffer (BCS)

Year 1957

**Nobel Prize 1972**



# «Conventional» (BCS) superconductors




# One-dimensional conductors/superconductors

### *1964, Excitonic superconductors*

***$T_C \sim 1000$ K!***

SCIENTIFIC AMERICAN

Established 1845 — February 1965 — Volume 212 — Number 2

## Superconductivity at Room Temperature

*It has not yet been achieved, but theoretical studies suggest that it is possible to synthesize organic materials that, like certain metals at low temperatures, conduct electricity without resistance*

by W. A. Little

***W.A.Little**. Possibility of synthesizing an organic superconductor. Phys. Rev. **134**, A1416 (1964).*

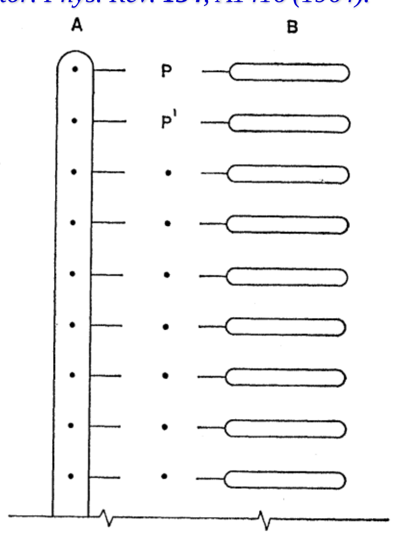
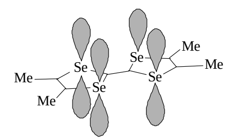
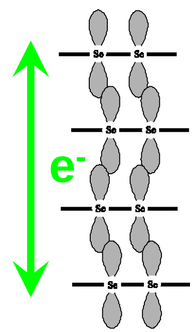
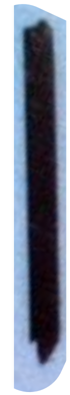



FIG. 1. Proposed model of a superconducting organic molecule. The molecule A is a long unsaturated polyene chain called the "spine." The molecules B are side chains attached to the spine at points P, P′, · · ·.

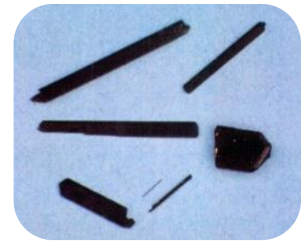
**TMTSF molecule**



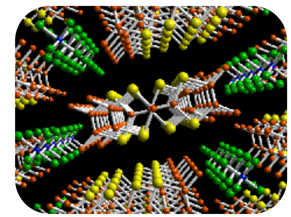



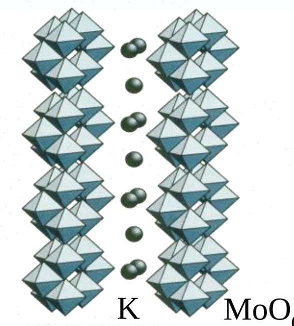



**$(TMTSF)_2PF_6$**

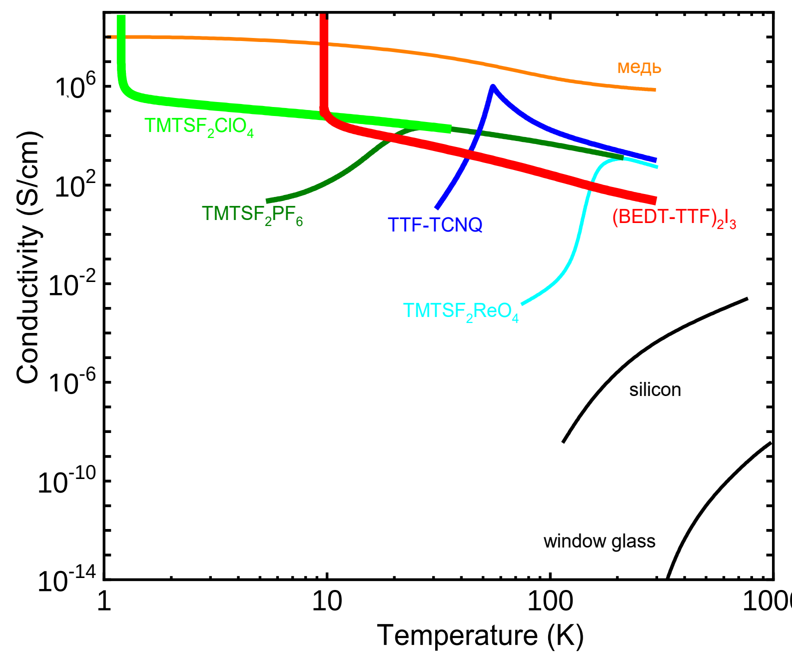


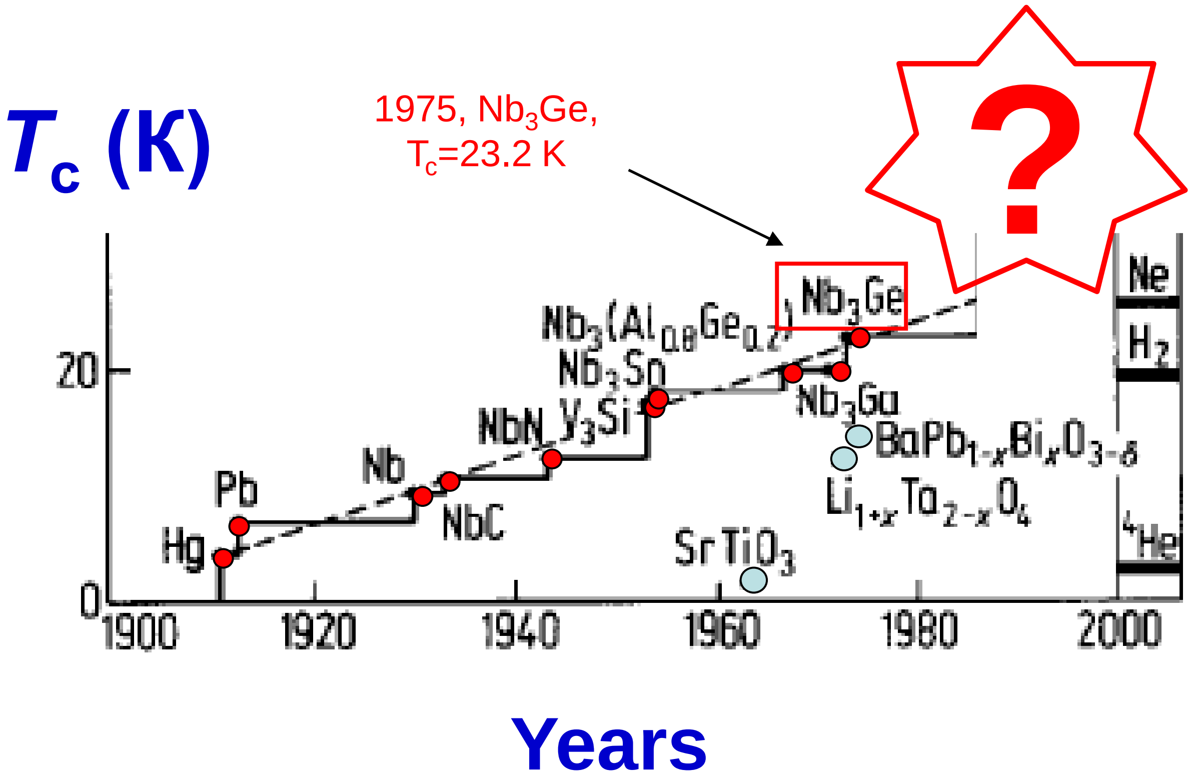
**$K_{0.3}MoO_3$**





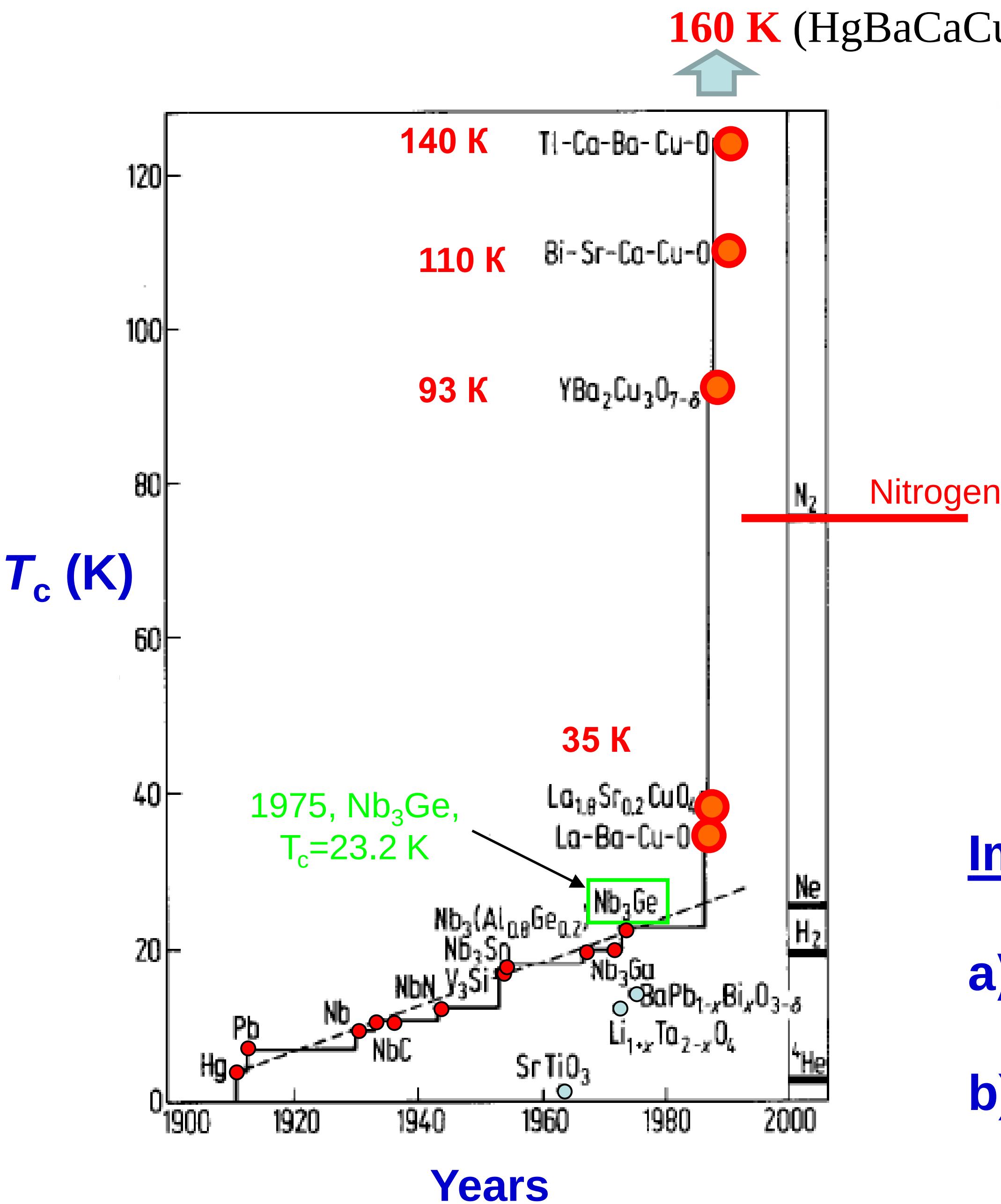

$T_c^{max} \approx 10$ K





Tc (K)
1975, Nb3Ge,
Tc=23.2 K
?
Nb3Ge
Nb3(Al0.8Ge0.2)
Nb3Sn
V3Si
NbN
Nb
NbC
Pb
Hg
Nb3Ga
BaPb1-xBixO3-δ
Li1+xTa2-xO4
SrTiO3
Ne
H2
4He
20
0
1900
1920
1940
1960
1980
2000
Years

# 1986: high-temperature superconductors (HTSC) - *cuprates*




K.Muller J.Bednorz

**Nobel Prize 1972**

## Important:

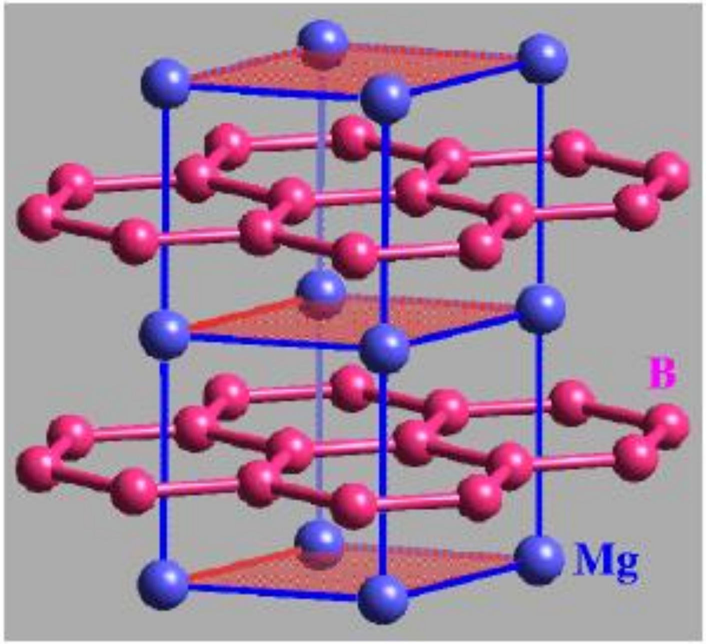
a) $T_c$>77 K;

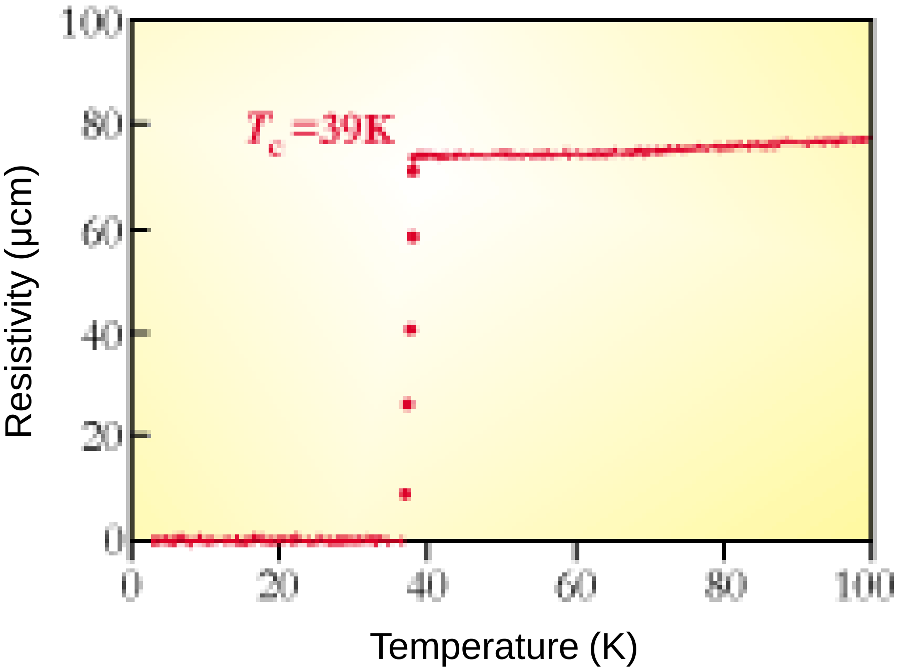
b) "restrictions" on $T_c$ removed ($T_c$<30-50 K)

# Exotic superconductors

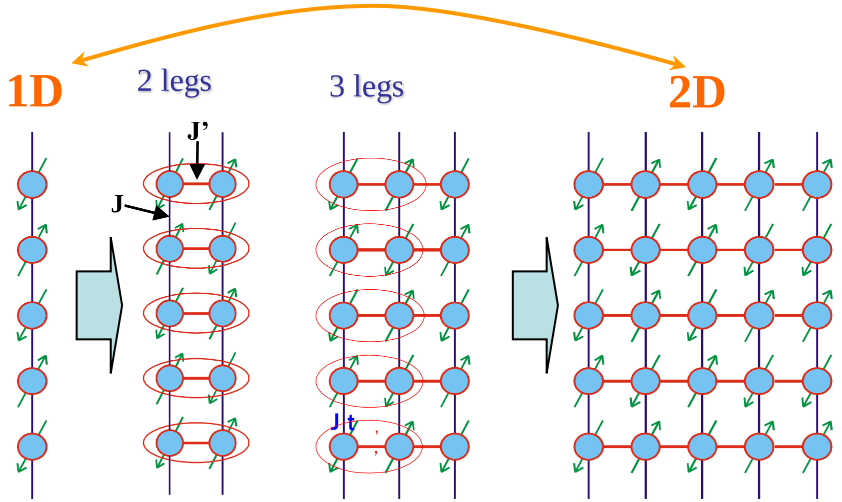
*Exotic superconductors*


## January 2001: $MgB_2$, $T_c$=40 K.



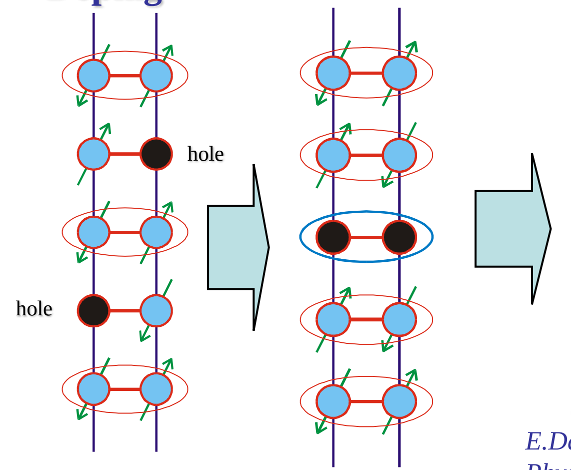



# Spin ladders – "intermediate" dimensionality




Ladders:
Intermediate dimensionality

**Doping**




**Superconductivity**

***Predicted***

*E.Dagotto, J.Rieira, D.Scalapino. Phys. Rev. B., **45**, 5744 (**1992**).*

***discovered***

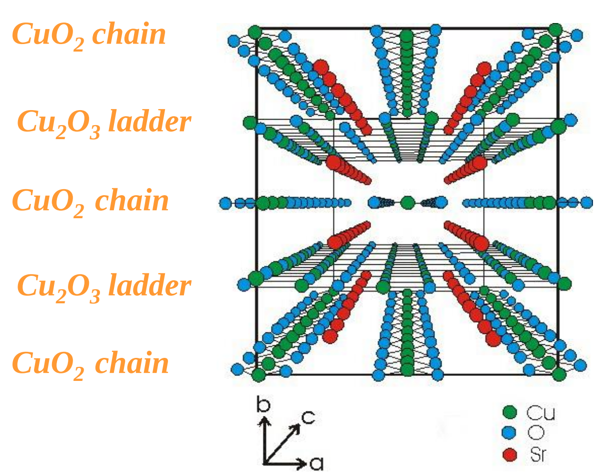
*T.Nagata, et al. Phys. Rev. Lett., **81**, 1090 (**1998**).*

$Sr_{14-x}Ca_xCu_{24}O_{41}$

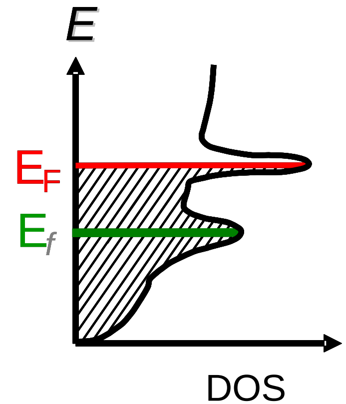
**$T_c$=12 K under P=3 GPa**

$Sr_{14-x}Ca_xCu_{24}O_{41}$

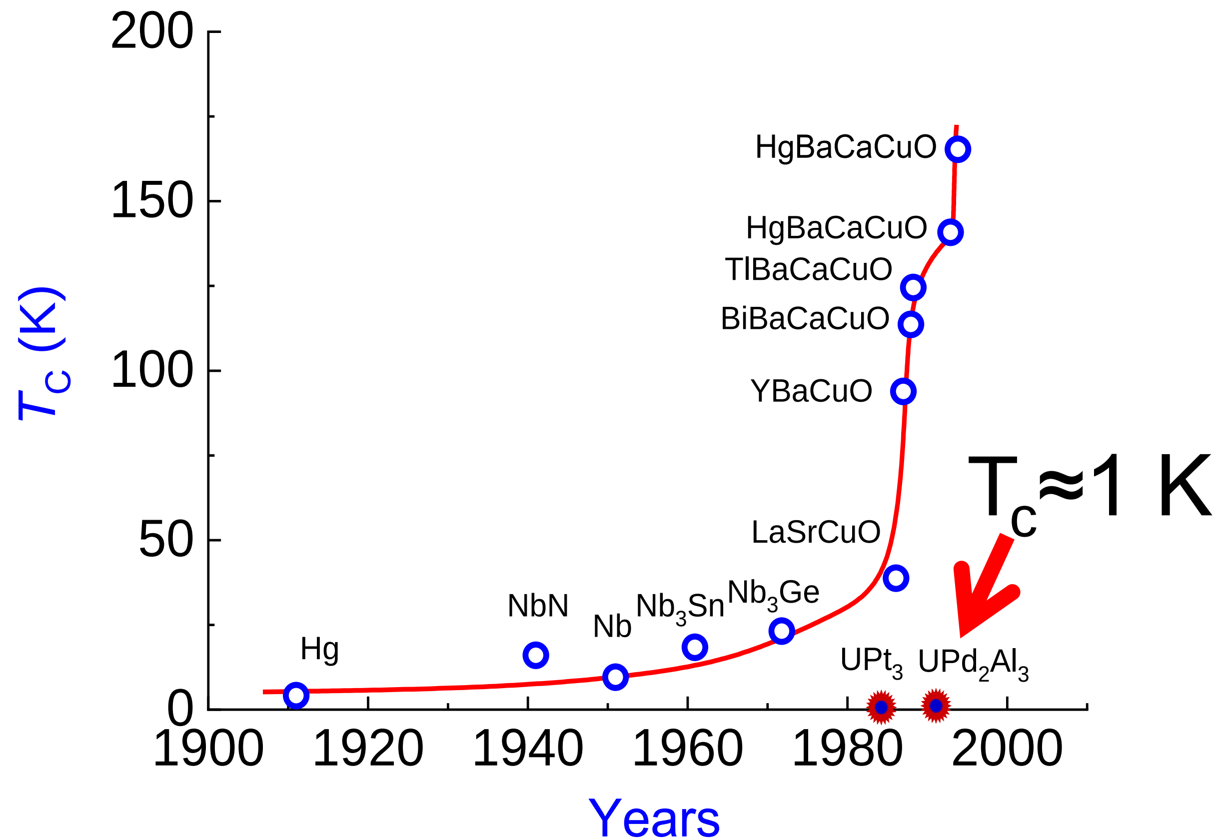
"Telephone number"



# ***Heavy fermion*** **superconductors**



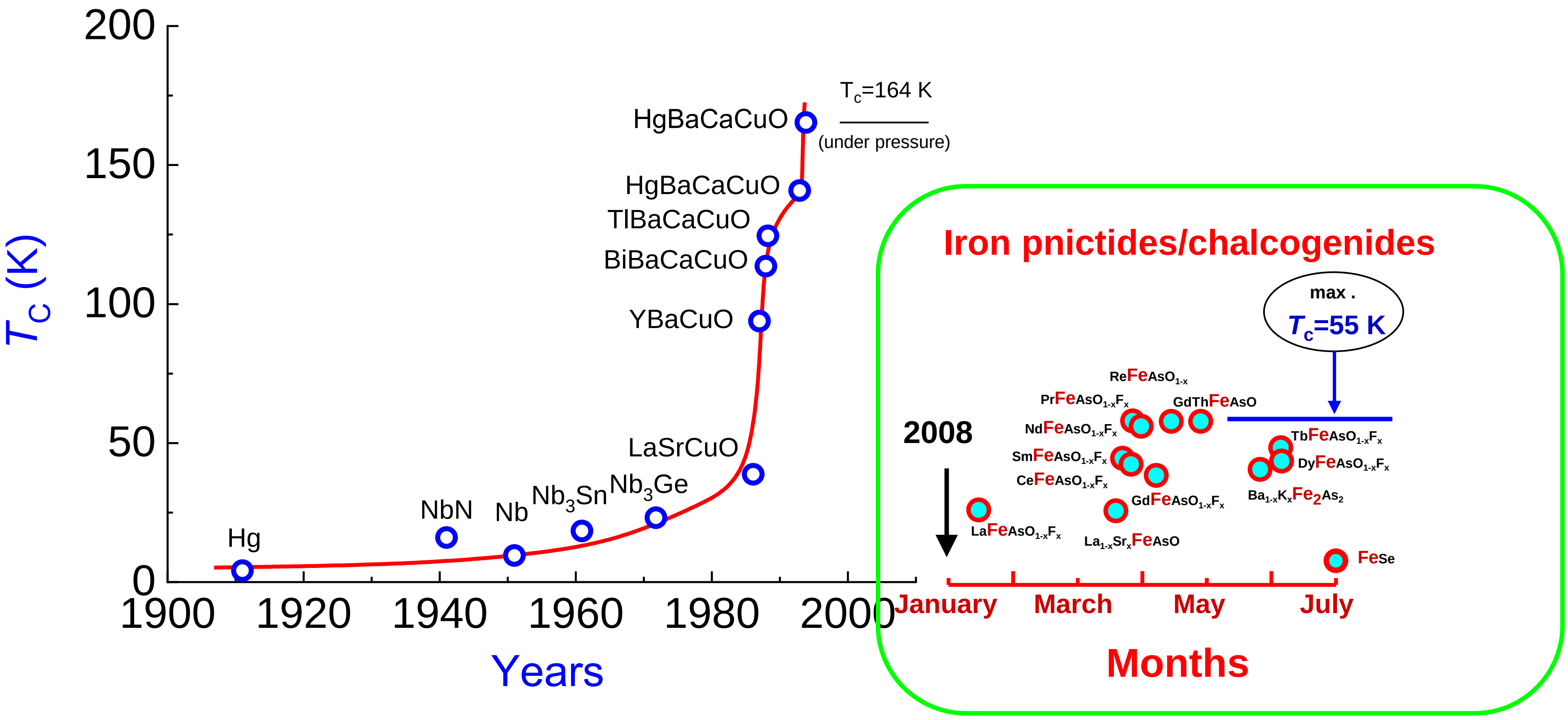

Hybridization of localized *f*- and delocalized Electrons, $m^* \approx 1000\ m_0$




| Material | $T_C$(K) |
|---|---|
| $CeCu_2Si_2$ | 0,7 |
| $CeCoIn_5$ | 2.3 |
| $CePt_3Si$ | 0,75 |
| $CeIn_3$ | 0,2 |
| $UBe_{13}$ | 0,85 |
| $UPt_3$ | 0,48 |
| $URu_2Si_2$ | 1,3 |
| $UPd_2Al_3$ | 2,0 |
| $UNi_2Al_3$ | 1,1 |

# Year 2008: *Iron-based superconductors*
# end of «cuprates monopoly» on HTSC

Kamihara et al. *J. Am. Chem. Soc*. **128** (31): 10012;
**130** (11): 3296



# Fakes

Fakes

2016

# 373 K Superconductors

arXiv:1603.01482v1

Ivan Zahariev Kostadinov
*373K-SUPERCONDUCTORS, Private Research Institute*

(Dated: March 7, 2016)

Experimental evidence of superconductors with critical temperatures above $373\,K$ is presented. In a family of different compounds we demonstrate the superconductor state, the transition to normal state above $387\,K$, an intermediate $242\,K$ superconductor, susceptibility up to $350\,K$, $I-V$ curves at $4.2\,K$ in magnetic field of $12\,T$ and current up to $60\,A$, $300\,K$ Josephson Junctions and Shapiro steps with radiation of $5\,GHz$ to $21\,THz$, $300\,K$ tapes tests with high currents up to $3000\,A$ and many $THz$ images of coins and washers. Due to a pending patent[1], the exact chemical characterization and technological processes for these materials are temporarily withheld and will be presented elsewhere.

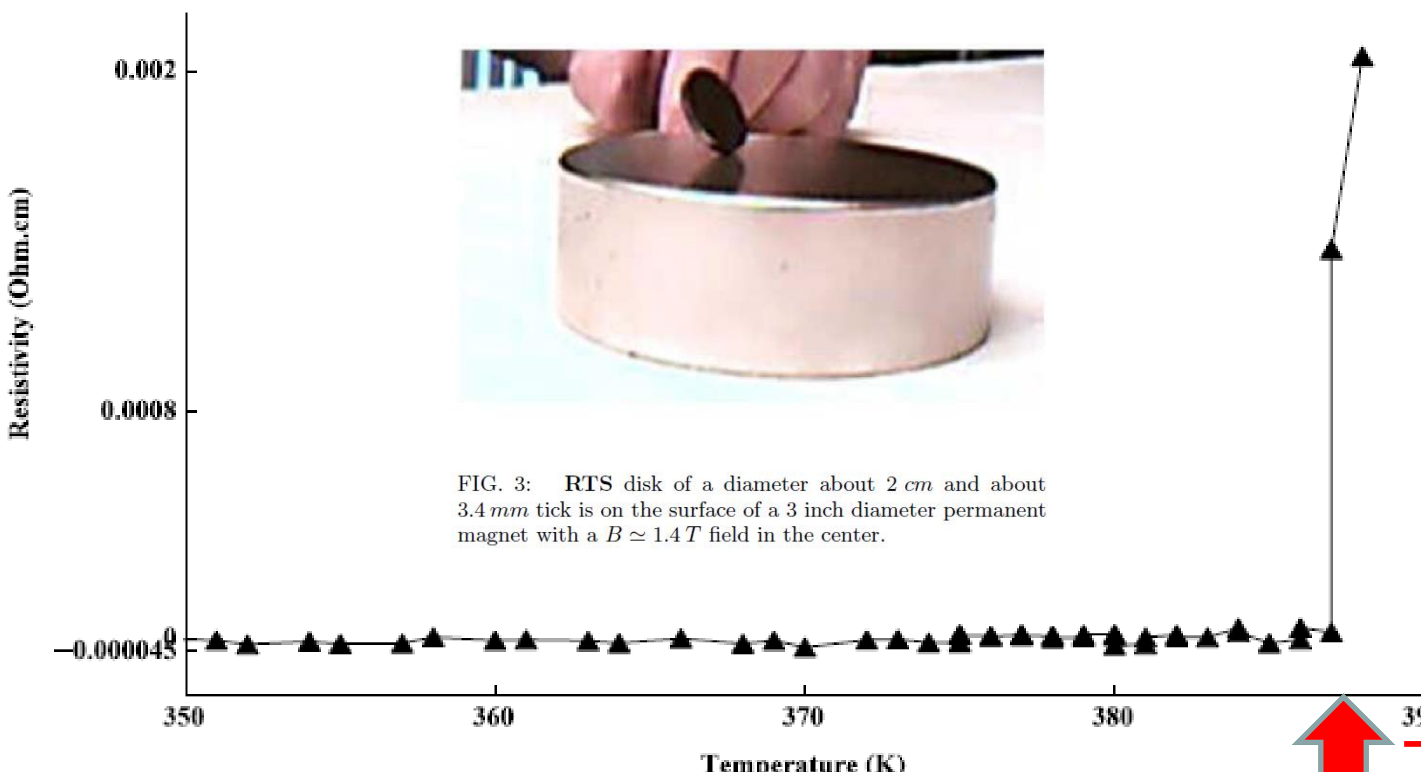



FIG. 3: RTS disk of a diameter about 2 $cm$ and about 3.4 $mm$ tick is on the surface of a 3 inch diameter permanent magnet with a $B \simeq 1.4\,T$ field in the center.

$T_c$=100 °C

# Superconductor $Pb_{10-x}Cu_x(PO_4)_6O$ showing levitation at room temperature and atmospheric pressure and mechanism

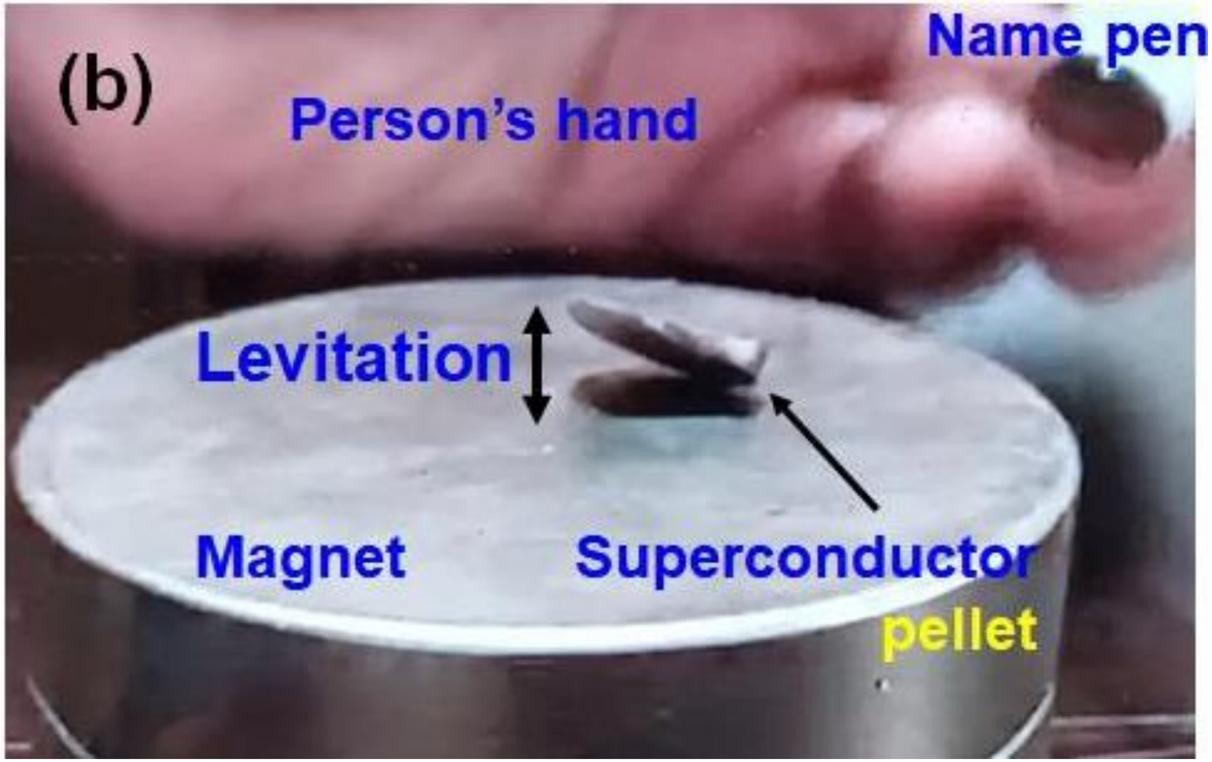
Sukbae Lee,[1,a)] Jihoon Kim,[1] Hyun-Tak Kim,[2,3,b)] Sungyeon Im,[1] SooMin An,[1] and Keun Ho Auh[1,4]

[1]Quantum Energy Research Centre, Inc., Seoul 05822, South Korea
[2]ICT Basic Research Lab. ETRI, Daejeon 34129, South Korea
[3]Department of Physics, College of William & Mary, Williamsburg, VA 23185, USA
[4]Hanyang University, Seoul 04763, South Korea

**August 2023**

arHiv:2307.12037

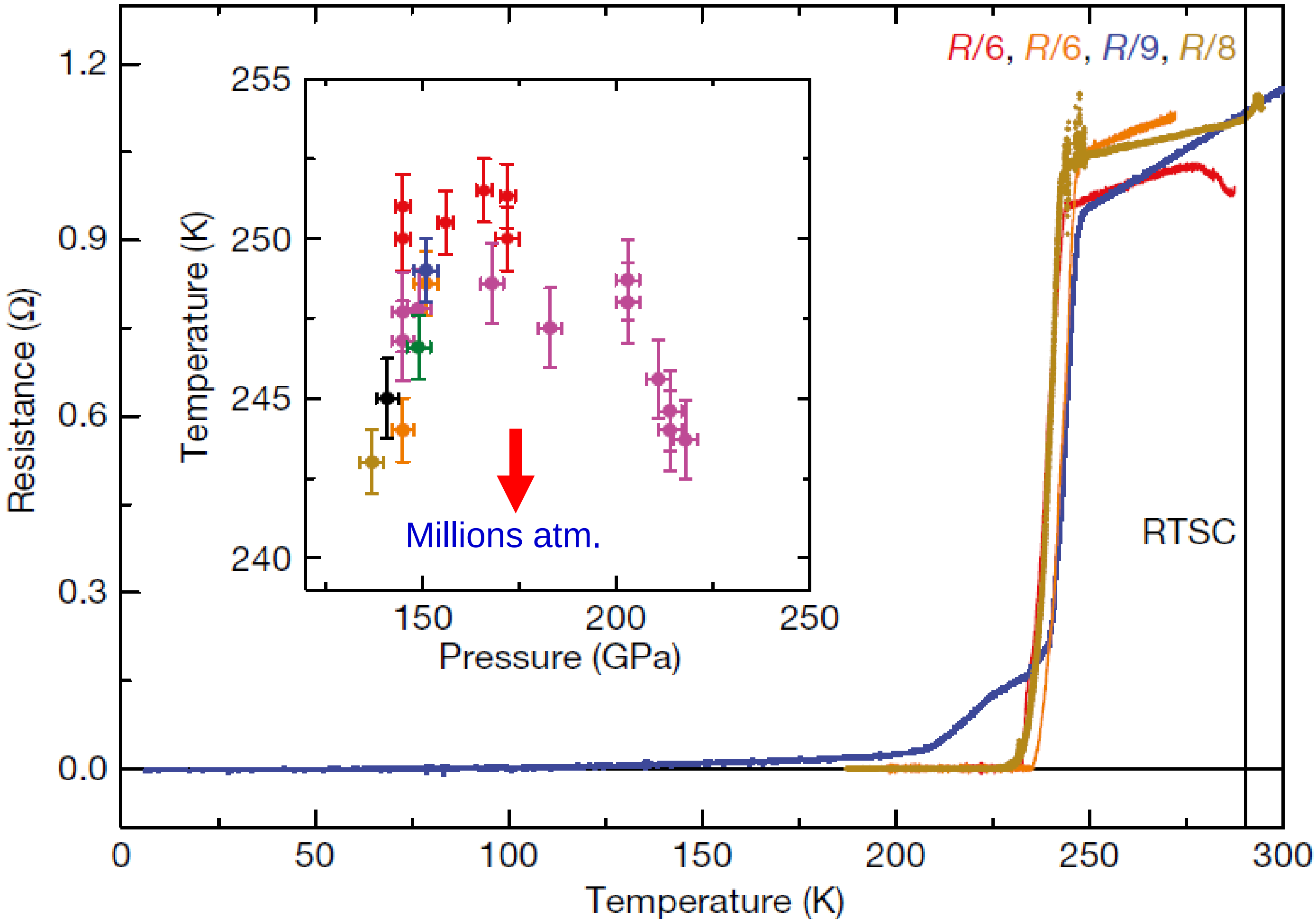
$T_c$=125 °C




**$Pb_{10-x}Cu_x(PO_4)_6O$ (0.9<x<1.1)**

# Real research

**Hydrides:** $BaH_{12}$, $LaH_{10}$, $ThH_9$, $YH_6$, $FeH_5$, $RuH_4$, …




Drozdov et al. Nature 569 528 (2019)

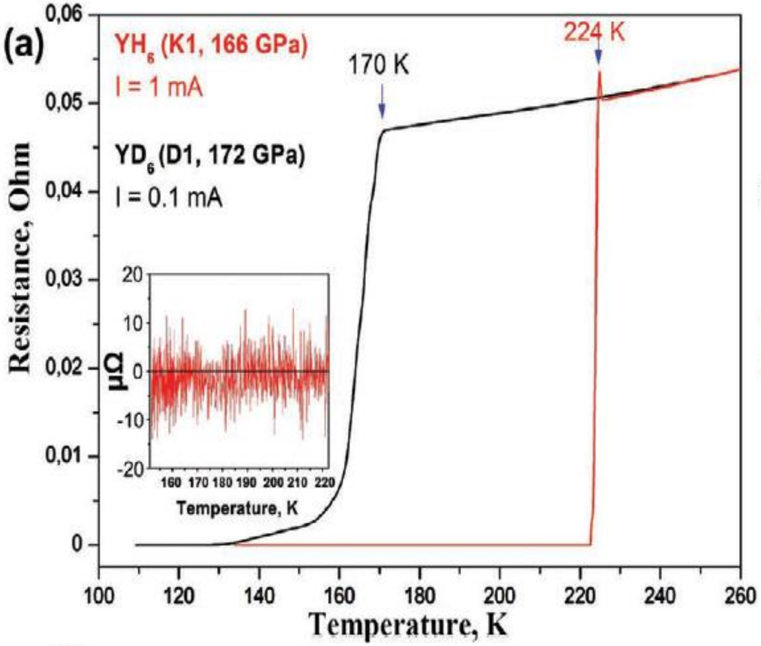
$LaH_{10}$
$T_c$=250 K

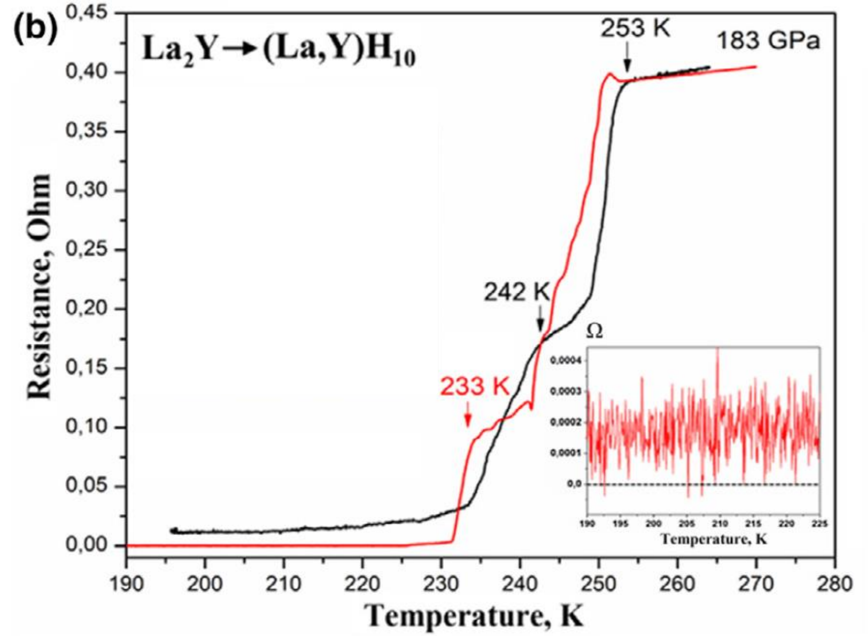
# Real research

## Hydrides

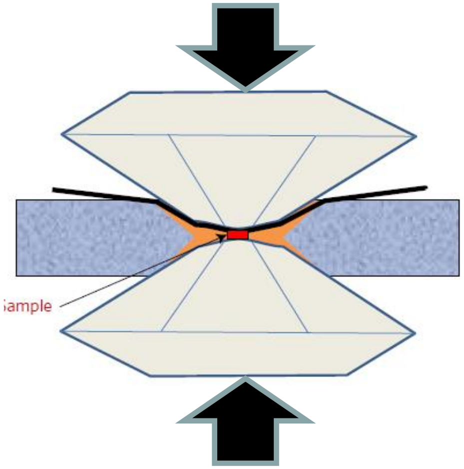
$YH_6$, $T_c$=224 K, 166 GPa
*Troyan et al. Adv. Mater.* 2021, *33*, 2006832

170–196 GPa $T_C$=253 K
*Semenok et al. Materials Today, **48**, 18 (2021)*

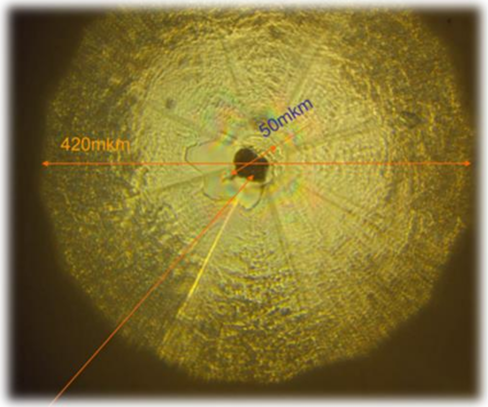


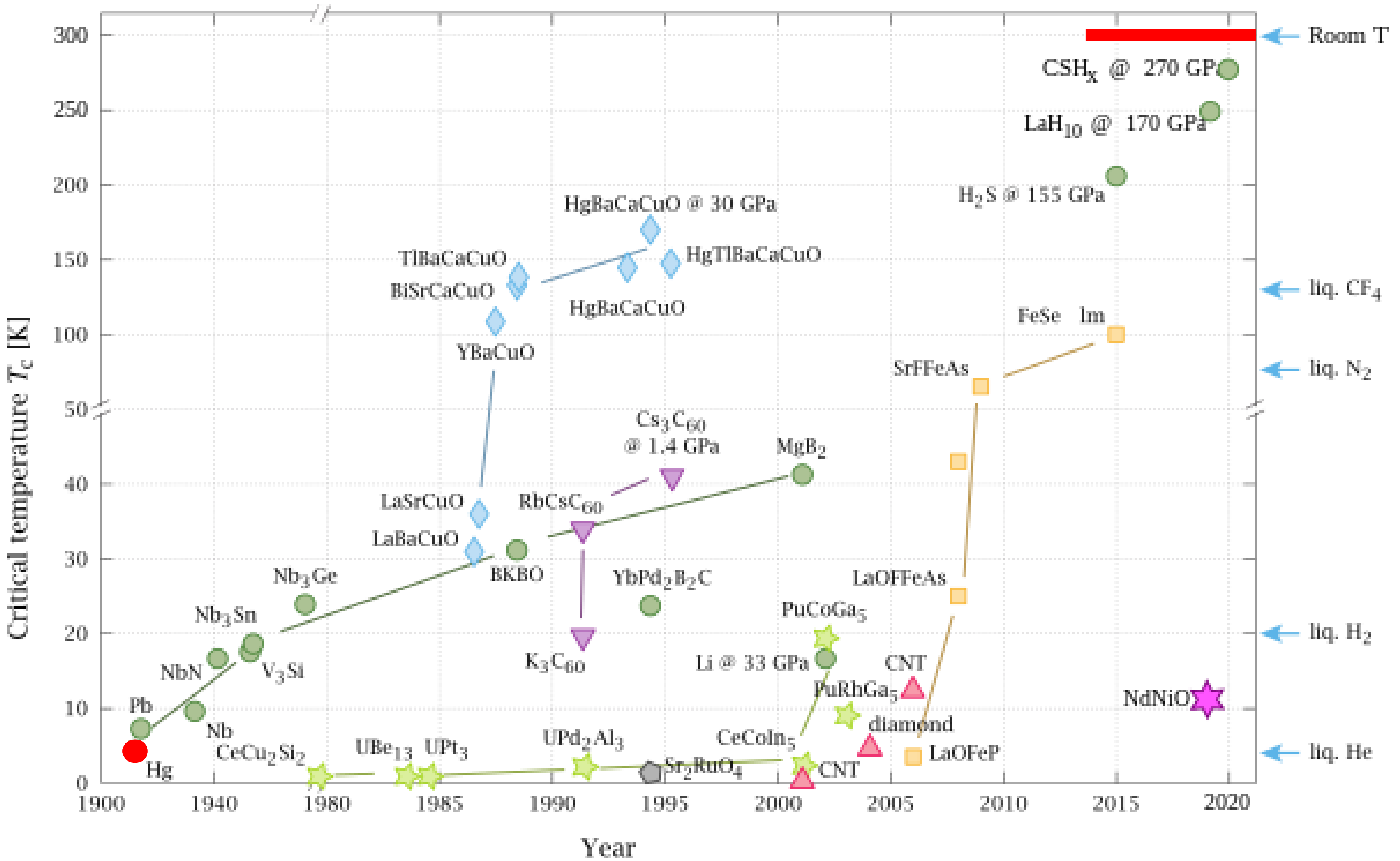
# Superconductivity under pressure




Troyan et al. Uspekhi 192, 2022



# Nowadays



Critical temperature $T_c$ [K]
Year
Room T
liq. $CF_4$
liq. $N_2$
liq. $H_2$
liq. He
$CSH_x$ @ 270 GPa
$LaH_{10}$ @ 170 GPa
$H_2S$ @ 155 GPa
HgBaCaCuO @ 30 GPa
HgTlBaCaCuO
TlBaCaCuO
BiSrCaCuO
HgBaCaCuO
YBaCuO
FeSe lm
SrFFeAs
$Cs_3C_{60}$ @ 1.4 GPa
$MgB_2$
LaSrCuO
$RbCsC_{60}$
LaBaCuO
BKBO
$Nb_3Ge$
$YbPd_2B_2C$
LaOFFeAs
$Nb_3Sn$
PuCoGa$_5$
NbN
$V_3Si$
$K_3C_{60}$
Li @ 33 GPa
CNT
PuRhGa$_5$
NdNiO
Pb
Nb
diamond
$CeCu_2Si_2$
$UBe_{13}$
$UPt_3$
$UPd_2Al_3$
CeCoIn$_5$
$Sr_2RuO_4$
LaOFeP
Hg
CNT

# Part II.
# Optical (electrodynamic) properties of superconductors

# Optical characteristics of materials

- **dielectrics**
- **conductors**
- **semiconductors**
- **superconductors**

*Dielectric function*

$$\varepsilon^* = \varepsilon' + i\varepsilon''$$

*Refractive index*

$$n^* = n + ik$$

*Optical conductivity*

$$\sigma^* = \sigma_1 + i\sigma_2$$

# Optics of superconducting state:

## 1) delta-function

**Superconductivity:**

$\rho_{dc}=\rho(\omega=0)=\mathbf{0}$

⇩

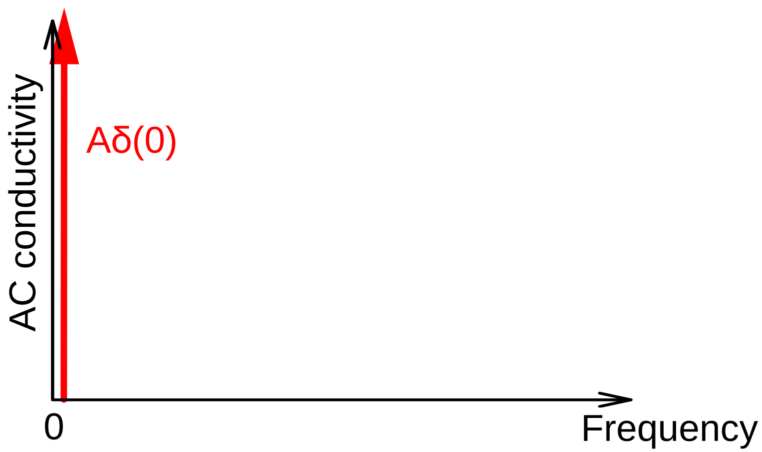
$\sigma_{dc}=1/\ \rho_{dc}\rightarrow\ \infty$

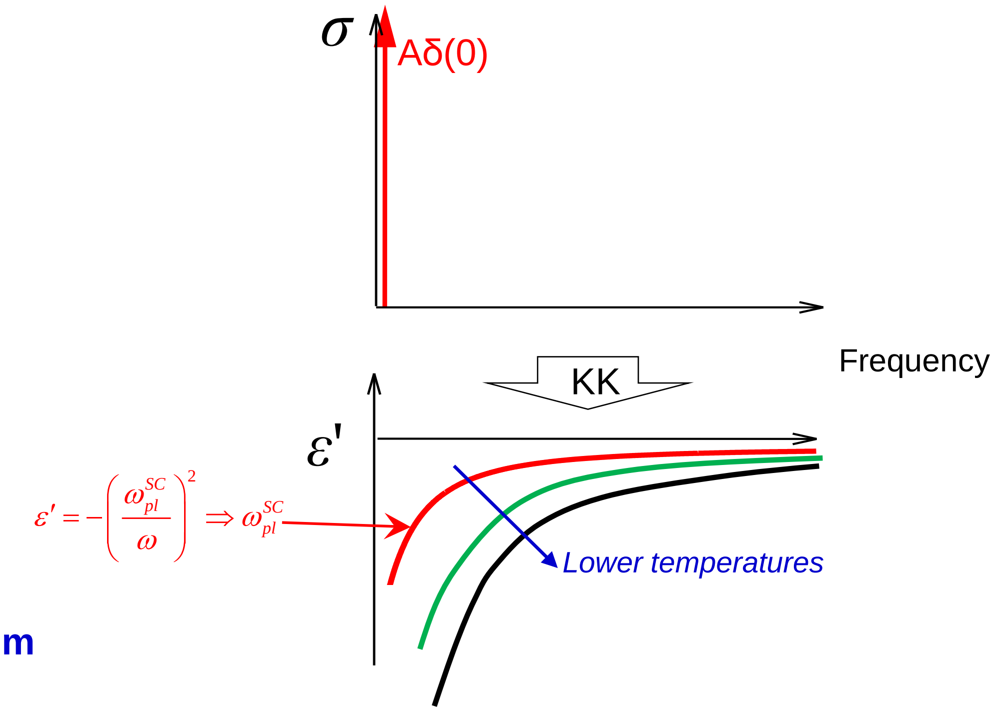
**Kramers-Kronig relations (causality principle):**

**connection of AC conductivity σ with permittivity ε′**

**Kramers-Kronig «image» of δ - function :**

$$\varepsilon' = -\frac{4}{\omega}P\int_0^\infty \frac{\sigma_1(\omega')}{\omega'-\omega}d\omega' = -\frac{4}{\omega}P\int_0^\infty \frac{A\delta(\omega')}{\omega'-\omega}d\omega' = -\frac{4A}{\omega^2} = -\left(\frac{\omega_{pl}^{SC}}{\omega}\right)^2$$



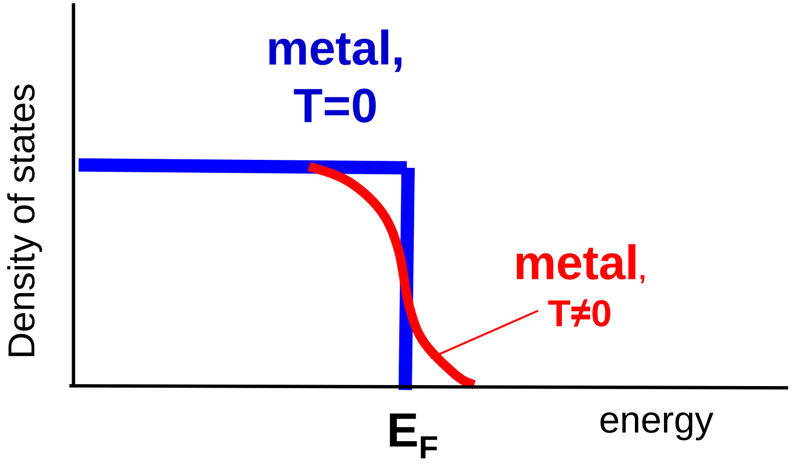

**Superconductivity – delta-function at zero frequency in AC conductivity spectrum**

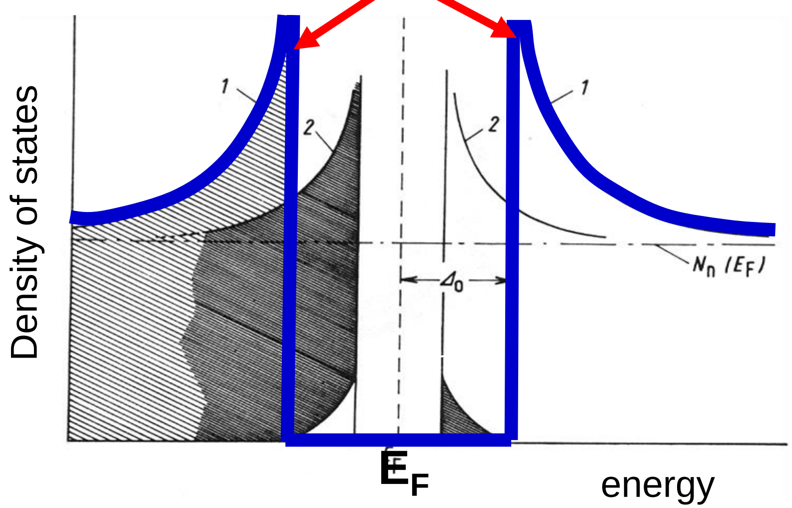
**at a frequency $\nu$= 0**

1. Density of SC condensate $\rho_{SC}$.
2. Penetration depth $\lambda_L = c/\omega_{pl}^{SC}$.

# Optics of superconducting state:

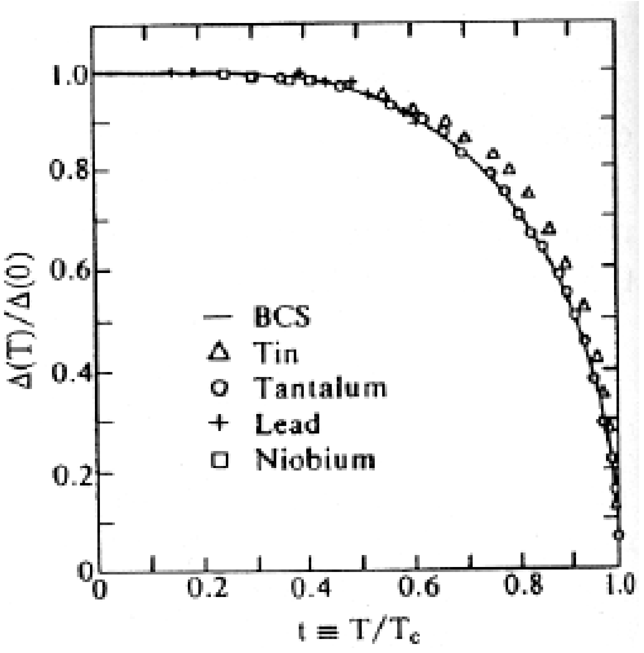
## 2) Gap in the density of states



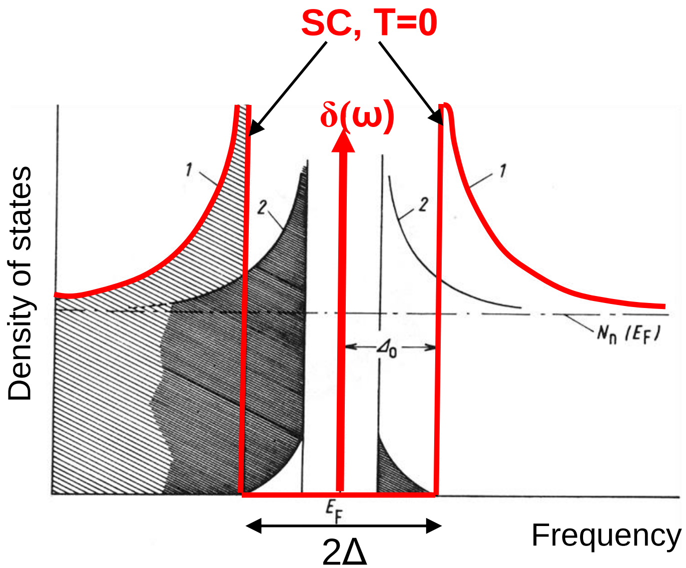



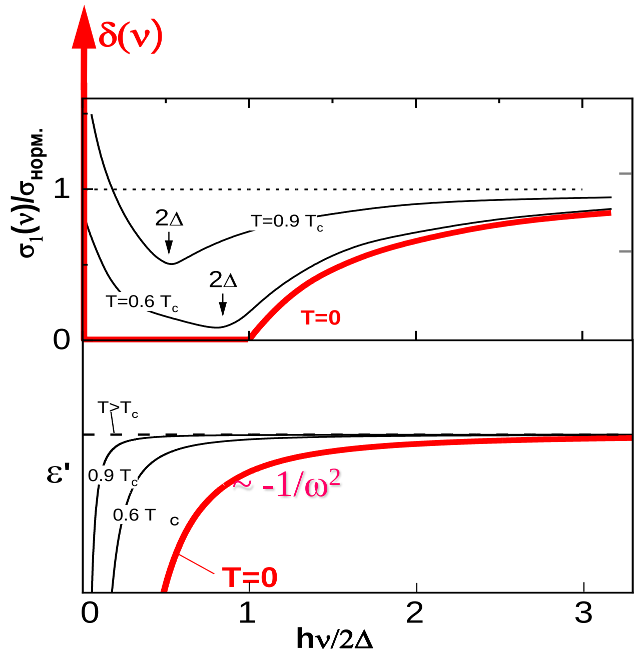

BSC (weak coupling):

$$\frac{2\Delta(T=0)}{k_B T_c} = 3.5$$



# Optics of BCS superconductor



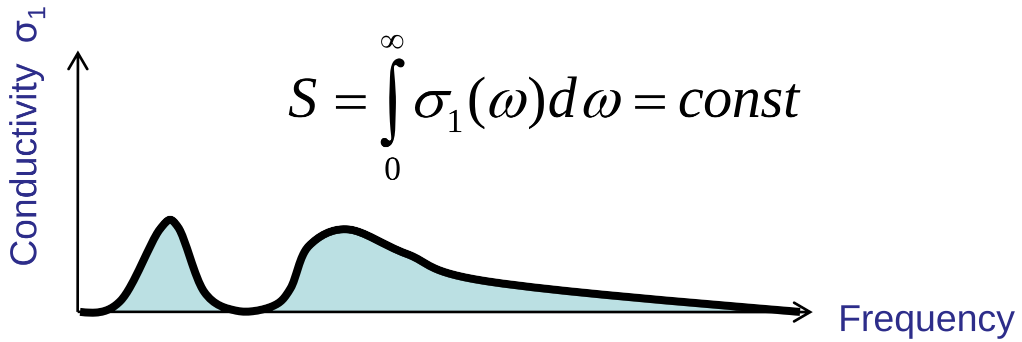

Mattis, Bardeen:

$$\frac{\sigma_1(\omega,T)}{\sigma_n}=\frac{2}{\hbar\omega}\int_{\Delta}^{\infty}\frac{\left[f(E)-f(E+\hbar\omega)\right](E^2+\Delta^2+\hbar\omega E)}{\sqrt{E^2-\Delta^2}\sqrt{(E+\hbar\omega)^2-\Delta^2}}\mathrm{d}E+\int_{\Delta-\hbar\omega}^{-\Delta}\frac{\left[1-2f(E+\hbar\omega)\right](E^2+\Delta^2+\hbar\omega E)}{\sqrt{E^2-\Delta^2}\sqrt{(E+\hbar\omega)^2-\Delta^2}}\mathrm{d}E$$

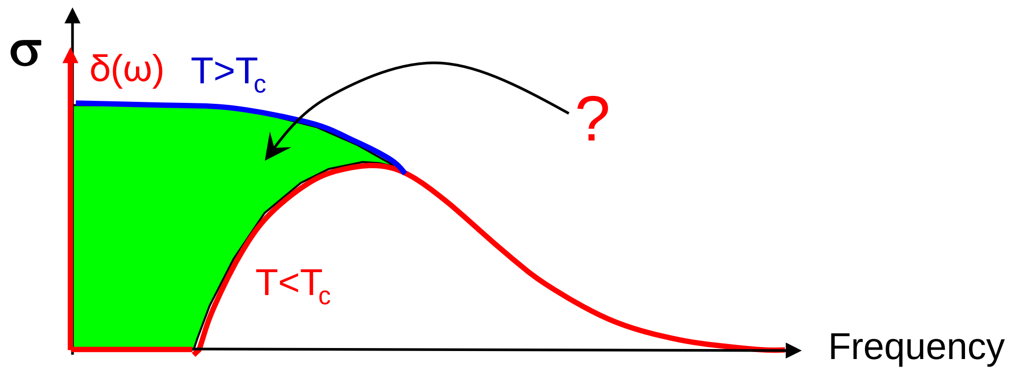
$$\frac{\sigma_2(\omega,T)}{\sigma_n}=\frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega,-\Delta}^{\Delta}\frac{\left[1-2f(E+\hbar\omega)\right](E^2+\Delta^2+\hbar\omega E)}{\sqrt{E^2-\Delta^2}\sqrt{(E+\hbar\omega)^2-\Delta^2}}\mathrm{d}E$$

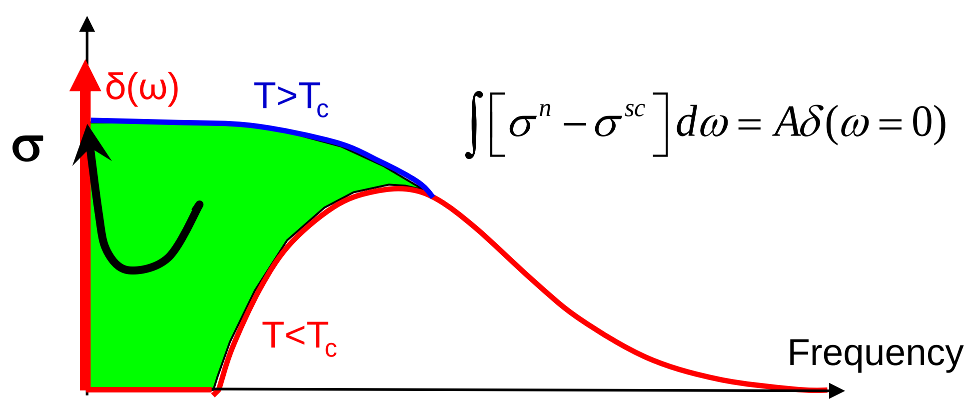
**$\sigma^*(\omega,T) = \sigma_1(\omega,T) + i\sigma_2(\omega,T)$**

# Optical Sum Rule




$$S = \int_0^\infty \sigma_1(\omega)d\omega = const$$

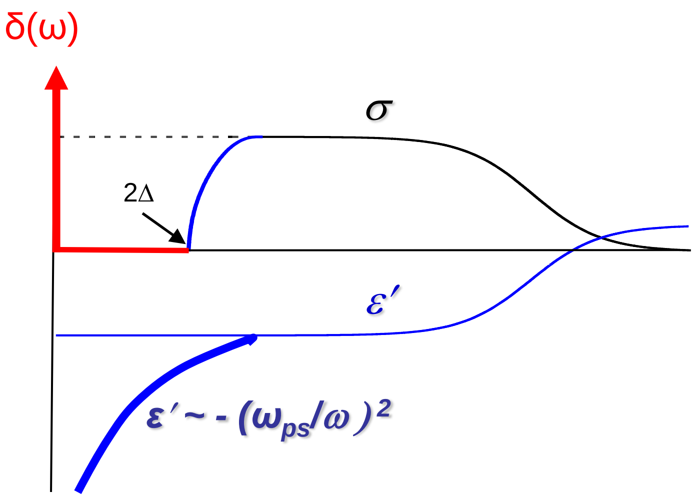



$$\int \left[ \sigma^n - \sigma^{sc} \right] d\omega = A\delta(\omega = 0)$$

Ferrel-Glover-Tinkham Sum Rule
for a superconductor

# Optics of a superconductor




## Optical spectroscopy:

- SC energy gap (pseudo-gap at $T>T_c$), temperature dependence.
- Concentration of SC electrons (hoes), $n_s(T)$.
- *Absolute value of* $\lambda_L$, temperature dependence
- SC order parameter type [*via* $n_s(T)$].
- Change of kinetic energy after SC PT (*via* Sum Rule).
- Collective excitations, …

# **Problem** of optical spectroscopy of superconductors

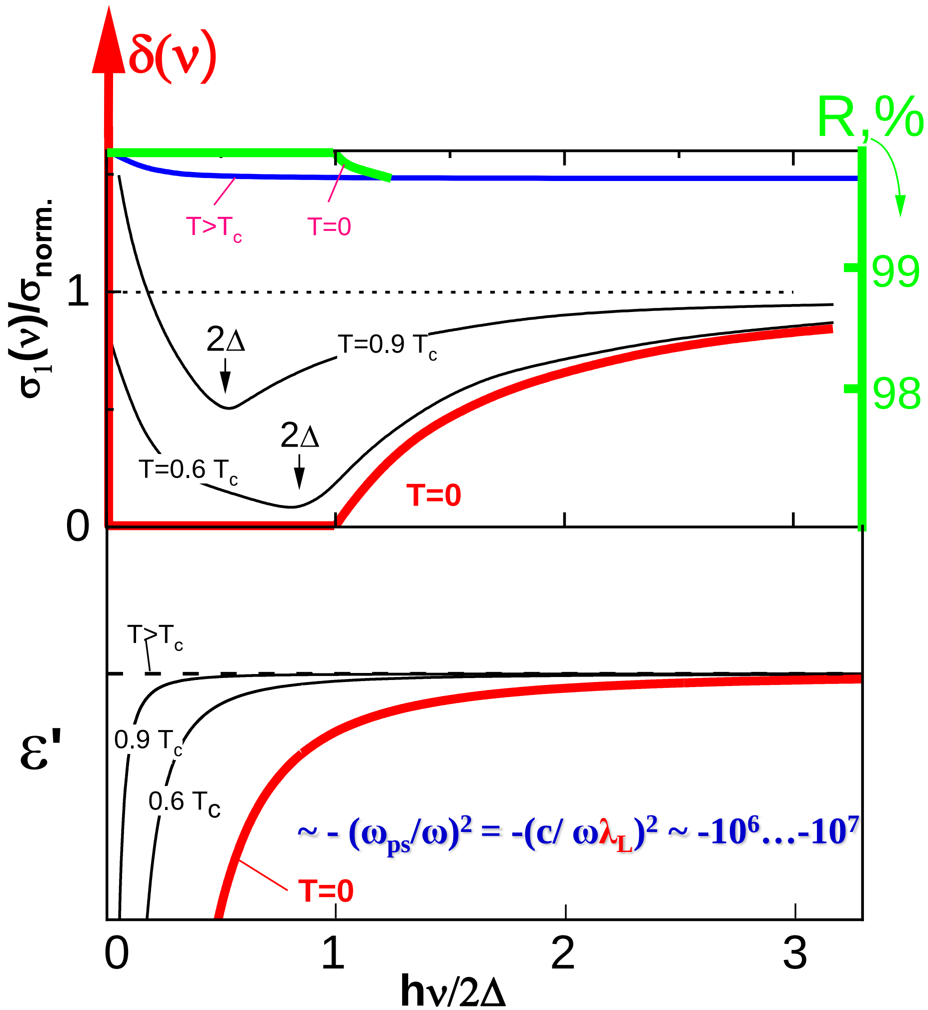
Fourier-spectroscopy

Reflectivity $R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$ $n^* = n + ik$

$k \gg 1$; $|\varepsilon'| \gg 1$

$R \rightarrow 100\%$

**!!!**



# *Problem* of reflection Fourier-spectroscopy of superconductors

- Kramers-Kronig analysis of reflectivity spectra R(ω).
- Need to accurately determine the **absolute** value of reflection coefficient R(ω) at the level of 99%.

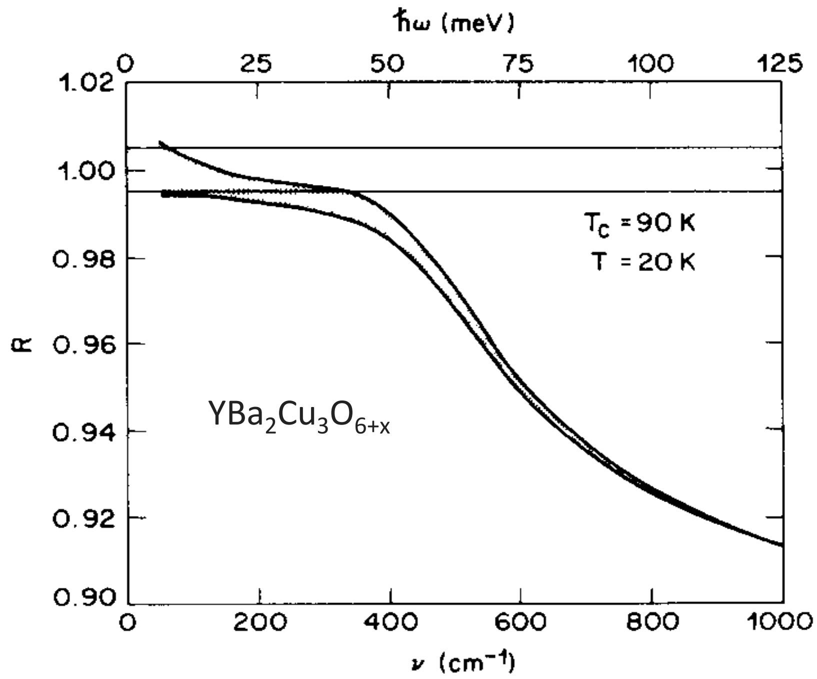



FIG. 13. Reflectivity as a function of frequency for a sample with $T_c = 90$ K at $T = 20$ K. The uncertainty associated with oscillations or noise in the data which have been taken out by smoothing is indicated by the shaded region. The uncertainty associated with the absolute magnitude of $R$ is indicated by the two solid lines located 0.005 above and below $R = 1$.

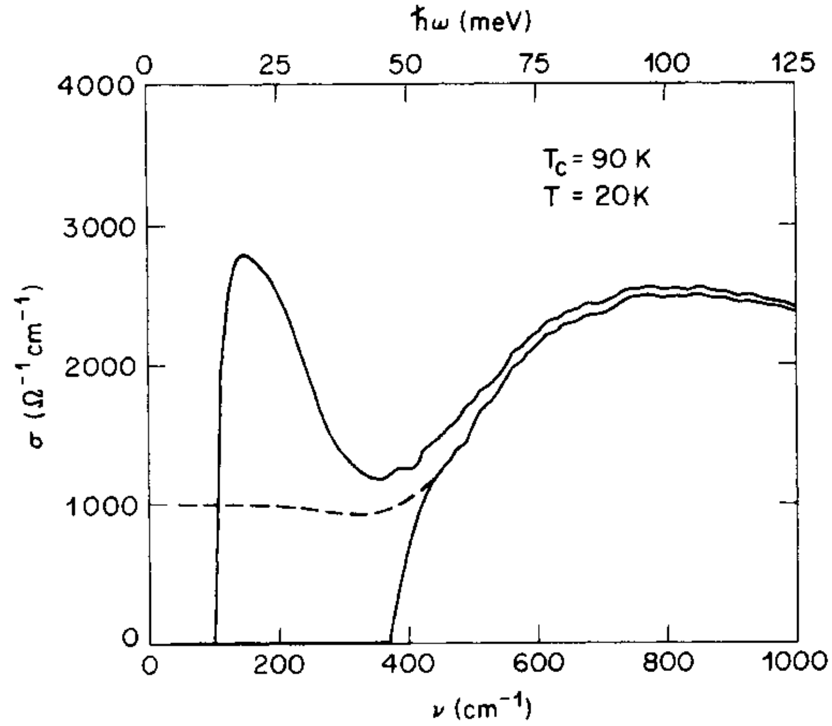
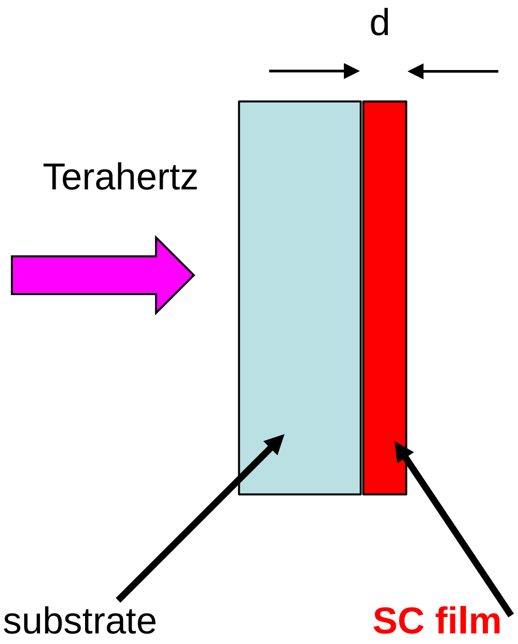
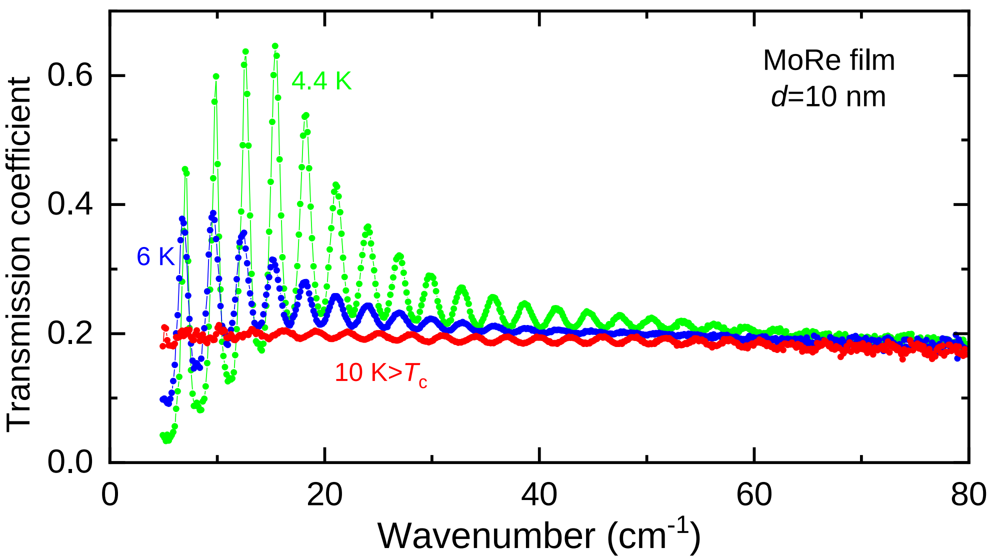



FIG. 14. Conductivity as a function of frequency calculated from the data of Fig. 13. To illustrate the substantial uncertainty in values of $\sigma$ derived from $R$ where $R$ is near 1, we have shown three behaviors that are possible for this data set when we take into account the uncertainties illustrated in Fig. 13.

J.Orenstein et al. Phys. Rev. B42, 6342 (1990):

# Solution: Spectroscopy of SC films on substrates



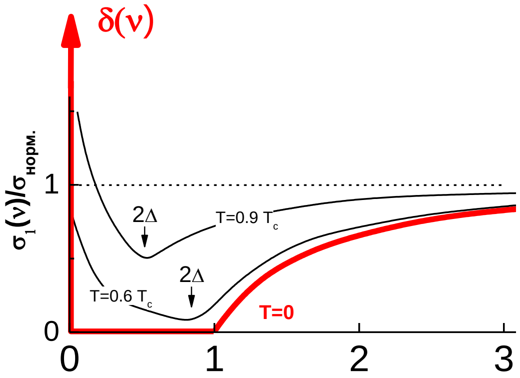




Zhukova et al. Submitted to J Mesosc. & Nanotechn.

# As long ago as in the last century:

R.E.Glover, **M.Tinkham**. Phys. Rev., vol.108. N15, p.243-256, 1957.
L.H.Palmer, **M.Tinkham**. Phys. Rev., vol.165, N2, p.588-595, 1968.
D.M.Ginsberg, **M.Tinkham**. Phys. Rev. Vol.118, N4, p.990-1000, 1960.
P.L.Richards, **M.Tinkham**. Phys. Rev., vol.119, N2, p.575-590, 1960.

Lead films



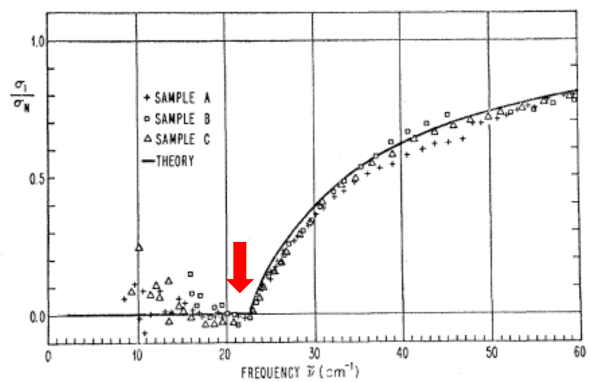




FIG. 3. Results of measurements of the real part of the normalized conductivity of three thin lead films at 2°K, compared with Mattis-Bardeen theory with gap frequency fitted to 22.5 cm⁻¹. To reduce the clutter in the figure, only about one fourth as many points are shown as were taken and recorded in Ref. 7. The points shown are selected typical points above the gap and local averages below the gap.

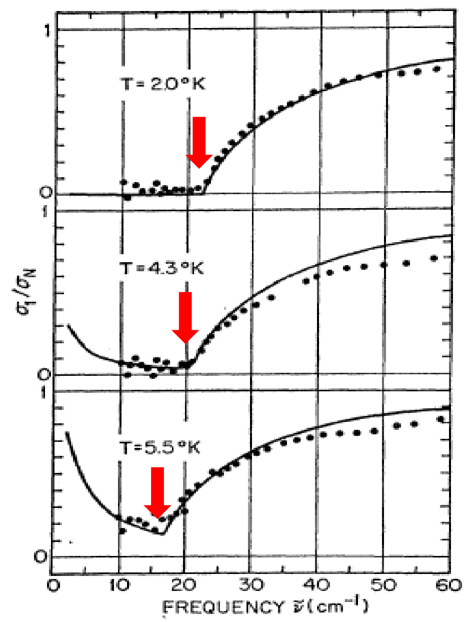



FIG. 4. Temperature and frequency dependence of normalized conductivity $\sigma_1/\sigma_N$ in a thin superconducting lead film (sample C), compared with predictions of Mattis-Bardeen theory (calculated with the assistance of a program supplied by Harris), shown as solid curve. The gap frequency was fitted only for the low-temperature limit. The number of data points shown has been reduced as in Fig. 3.

# Laboratory of terahertz spectroscopy at MIPT

**RF Zurich Instruments MFIA**

**1 Hz – 1 MHz**

**Frequencies 1 Hz – 30 THz**
**Temperatures   0.3 K – 300 K**

**IR Fourier-transform spectrometer**

**5 cm$^{-1}$ – 25 000 cm$^{-1}$**

**THz time-domain spectrometers**

**0.3 THz – 4 THz**

TeraView


Menlo Systems

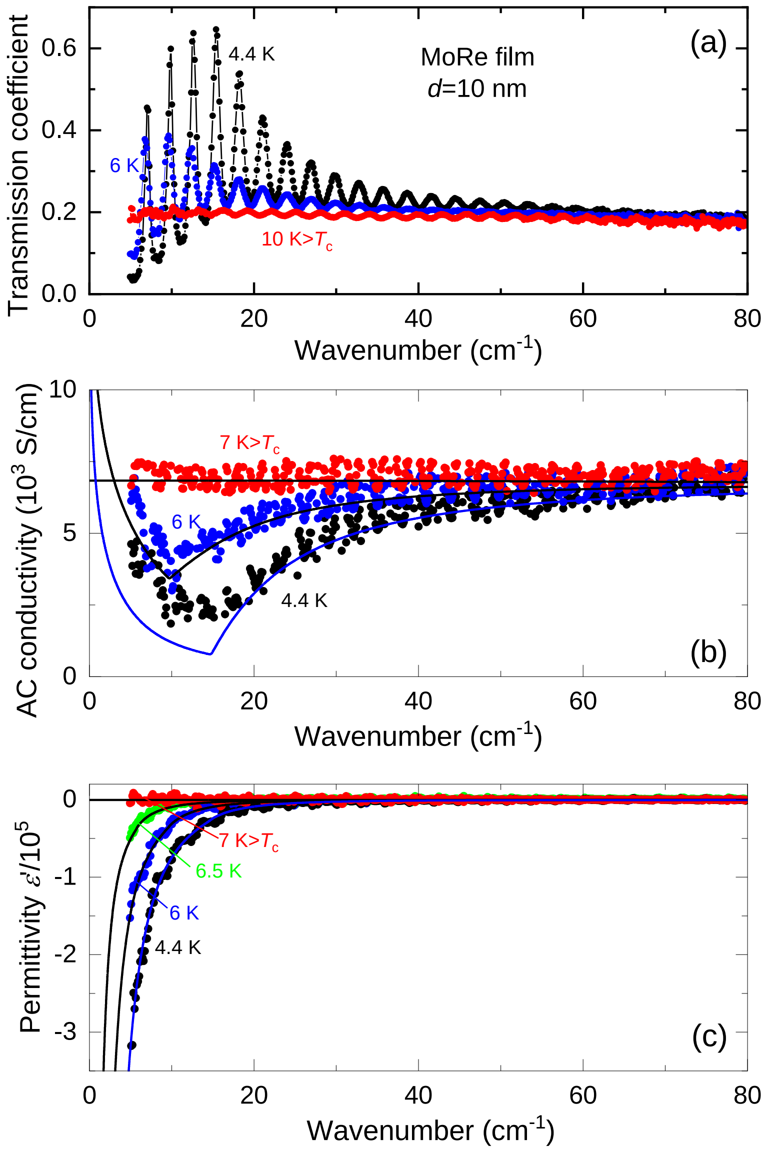
**subTHz coherent-source BWO-spectrometer**

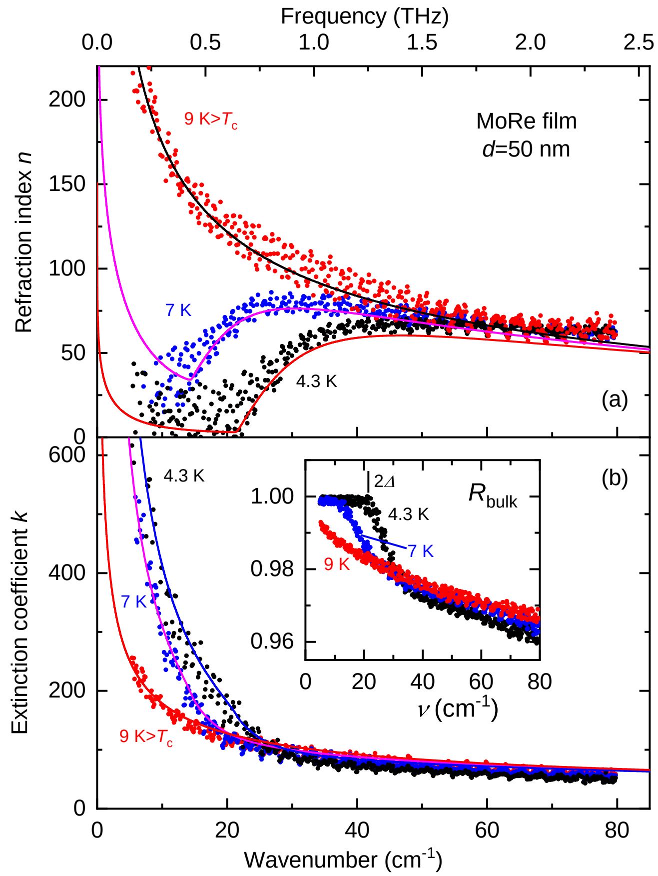
**0.03 THz – 1.5 THz**

# Few examples
# of optical spectroscopy of superconductors

# Superconductivity of thin MoRe films

## $Mo_{0.6}Re_{0.4}$



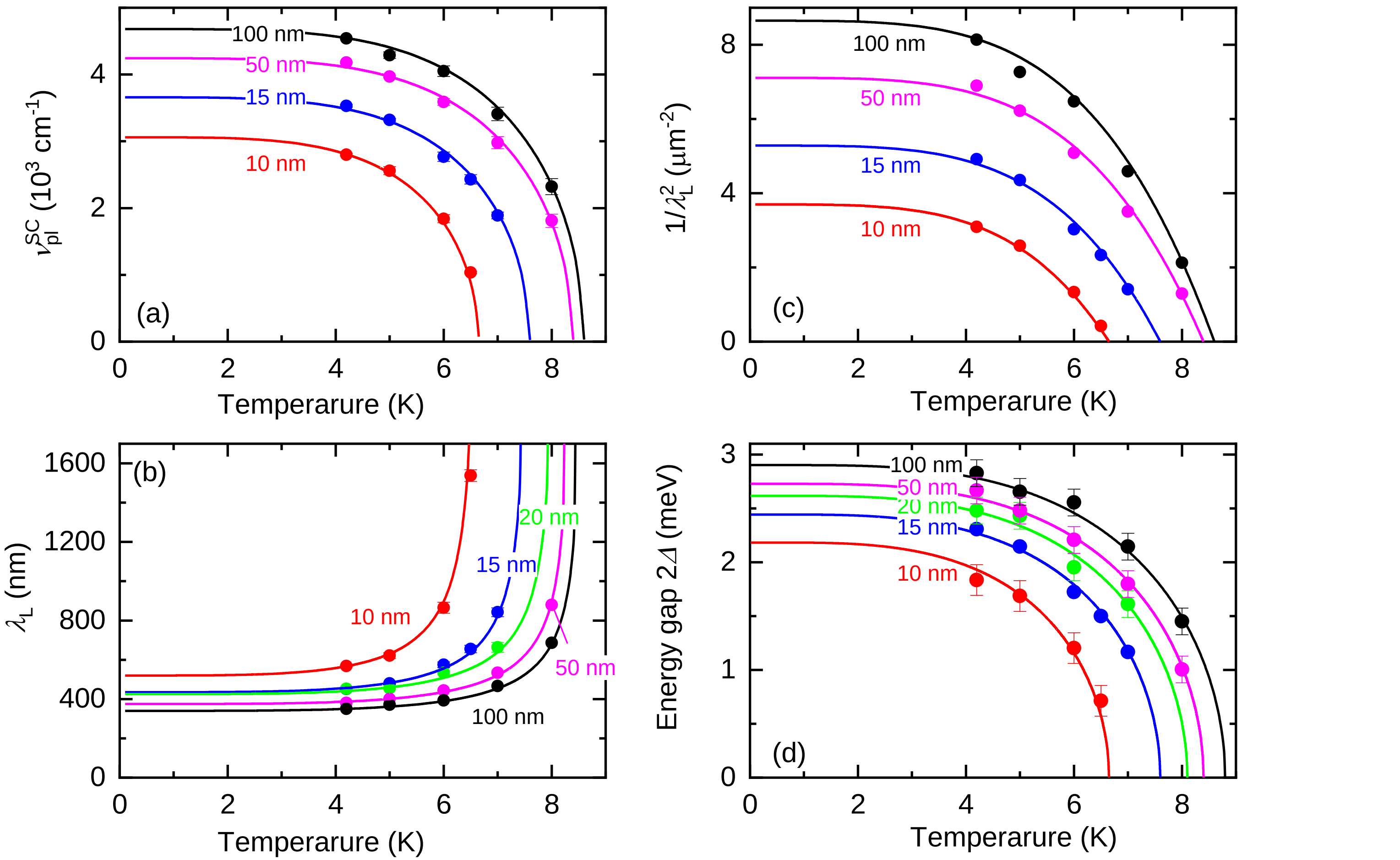

Zhukova et al. Submitted to J Mesosc. & Nanotechn.

Nekrasov et al. Poster at this School

# Superconductivity of thin MoRe films

## $Mo_{0.6}Re_{0.4}$

MoRe films

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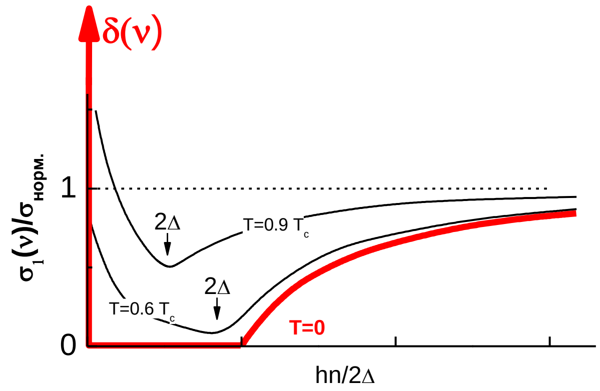
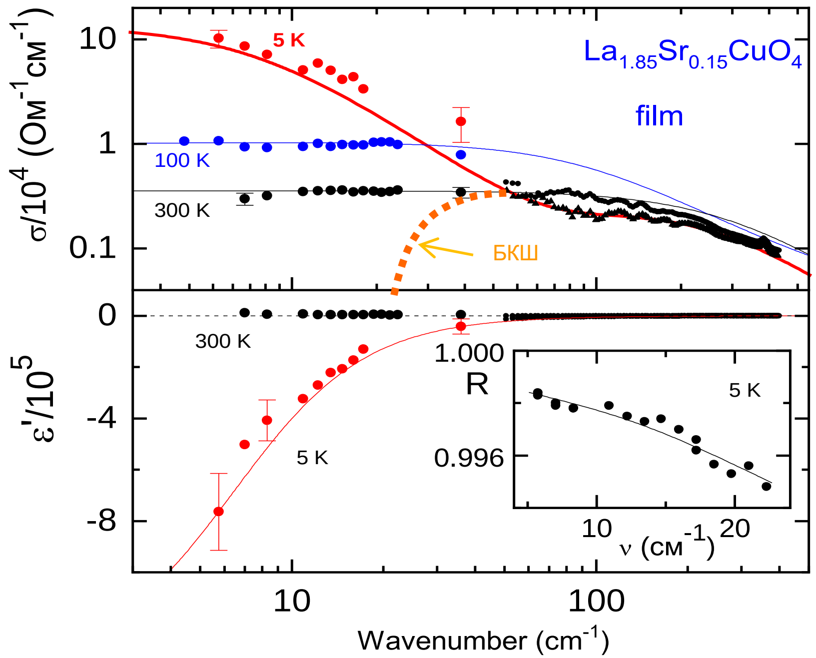
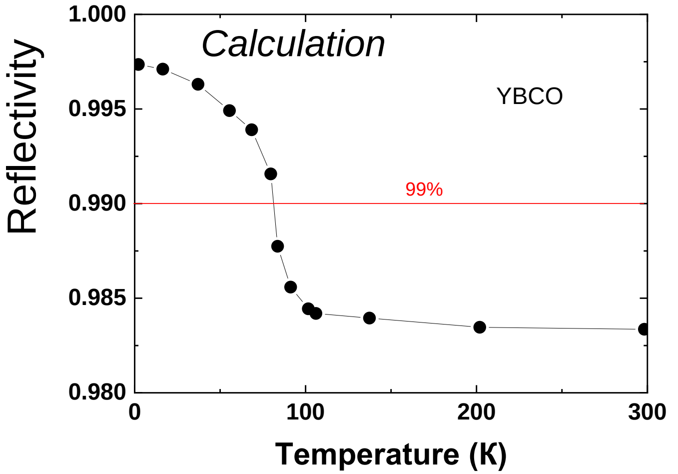
# «Anomalous» absorption In HTSC cuprates



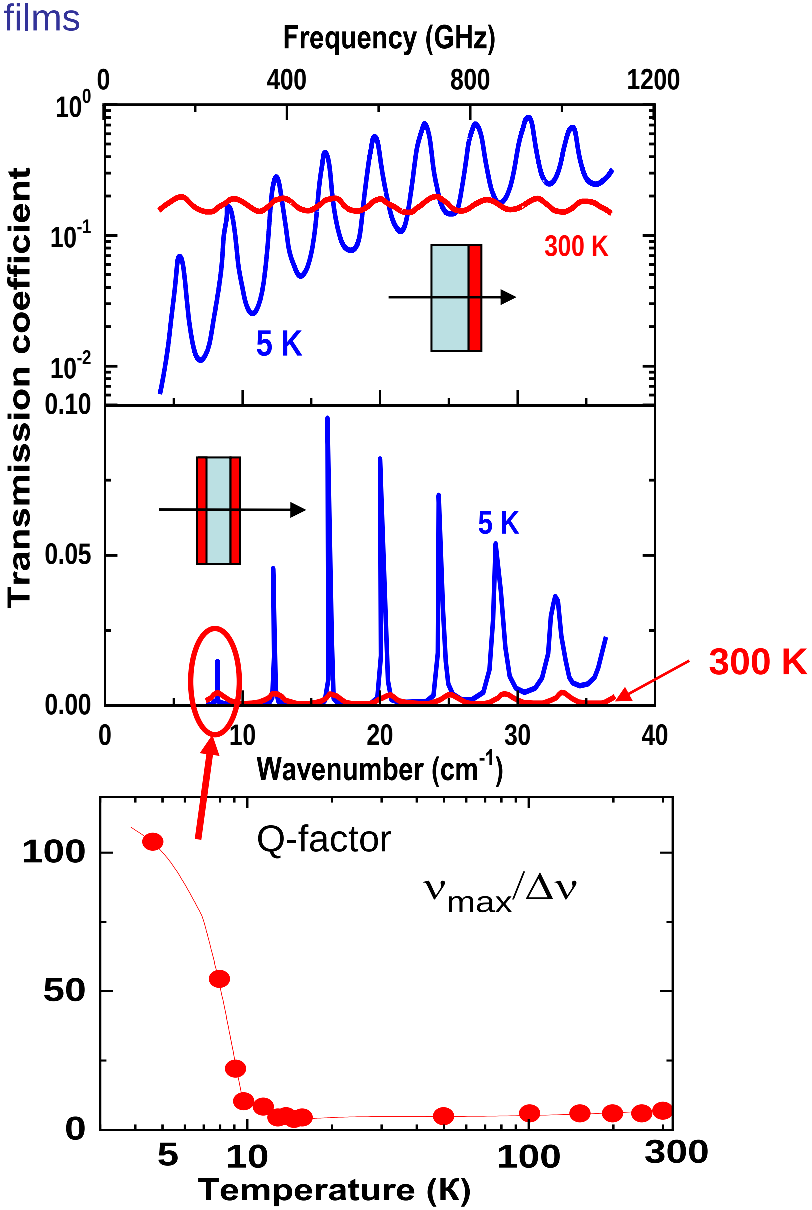




*B.P.Gorshunov et al.. Physica C, **153-155**, 667 (1988)*

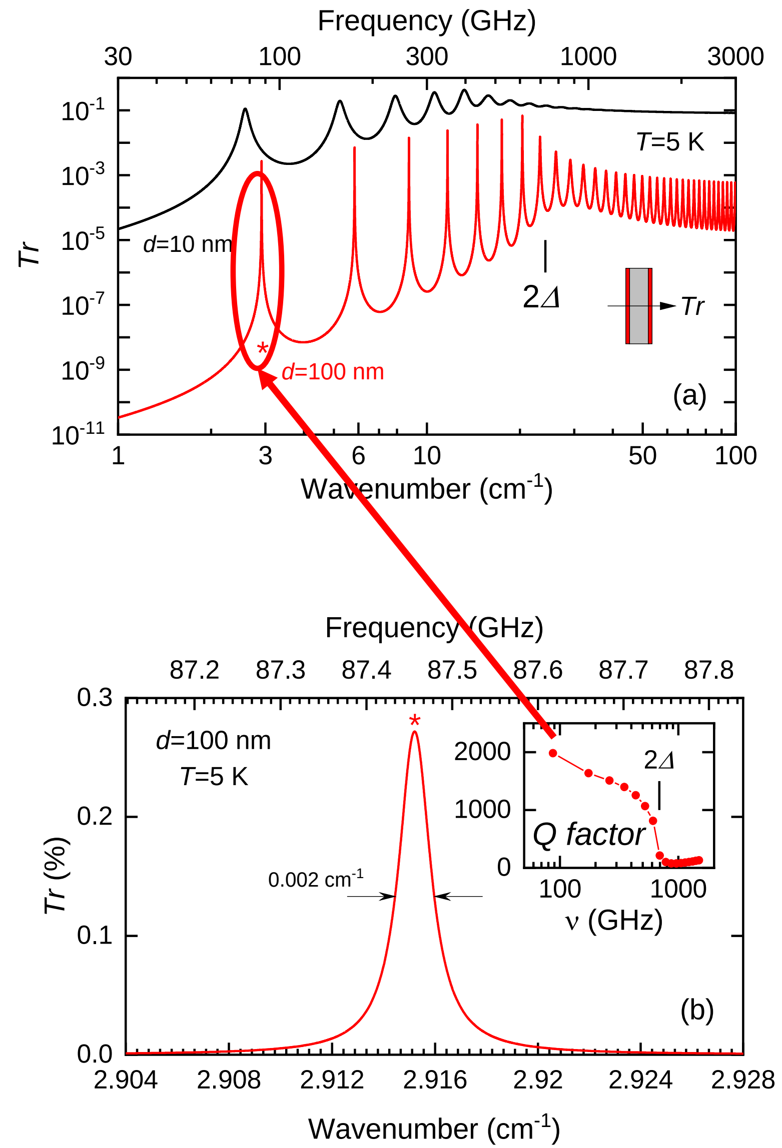


# High-Q resonators for μW and THz spectra domains

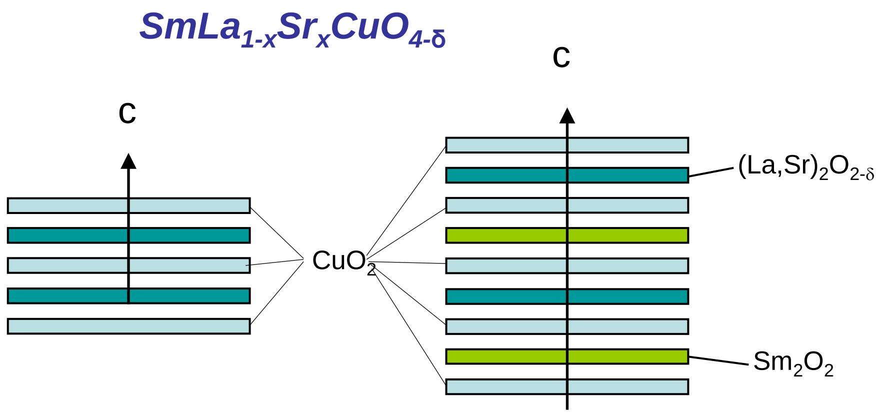
Nb films




MoRe films

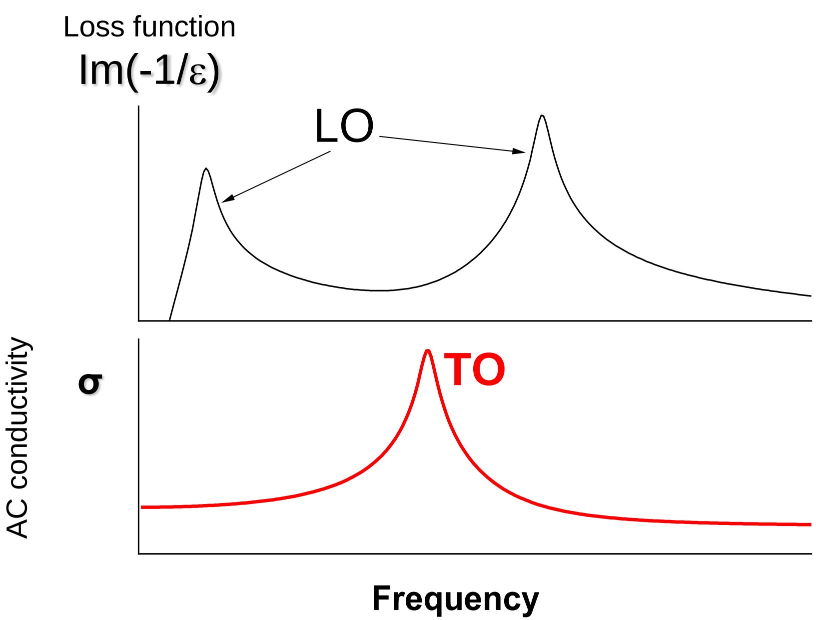


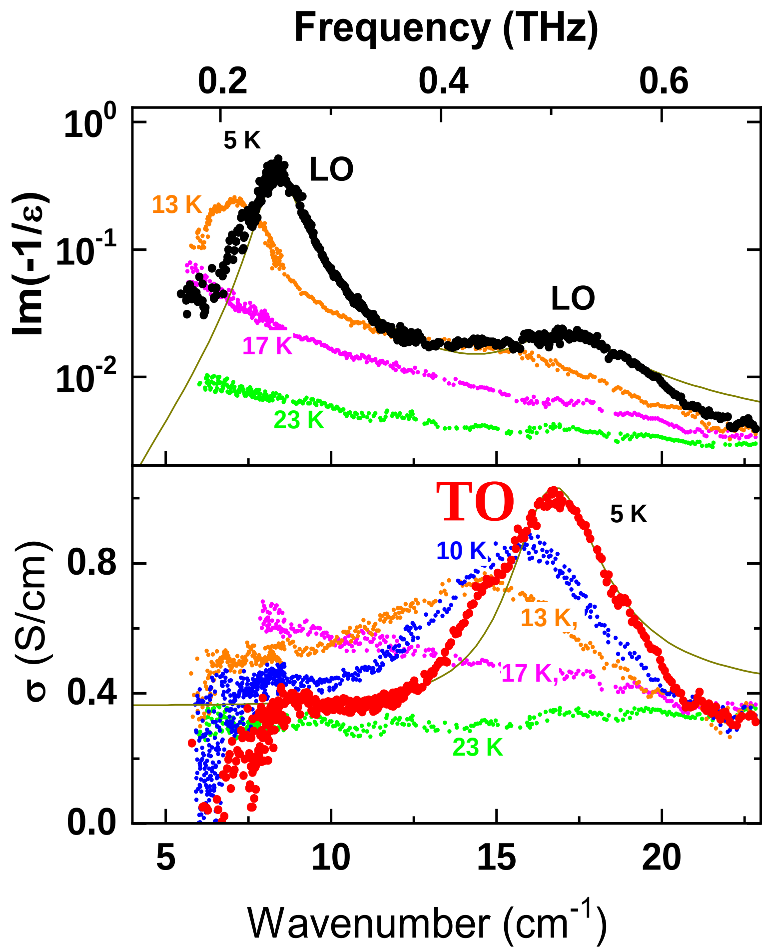
# Transverse plasmon in layered SC




Theoreticians predicted:
**transverse plasmons**!

*D. Van der Marel, A.Tsvetkov. Czech. J. Phys., **46**, 3165 (1996);*



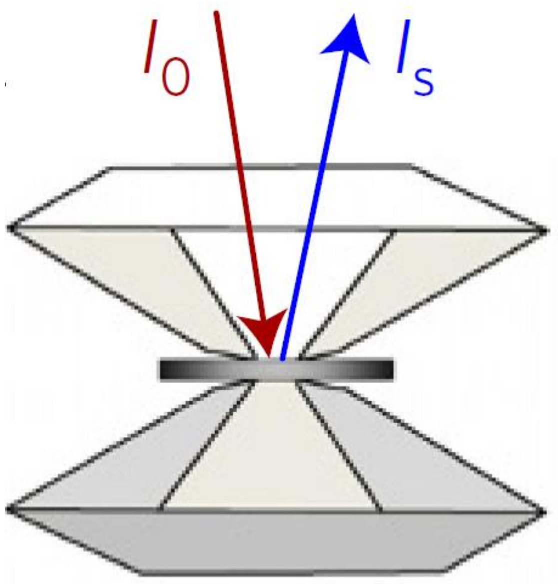

*B.Gorshunov et al. PRL vol.86, 4140, 2001*

# Summarizing…

# Spectroscopy of superconductivity in hydrades

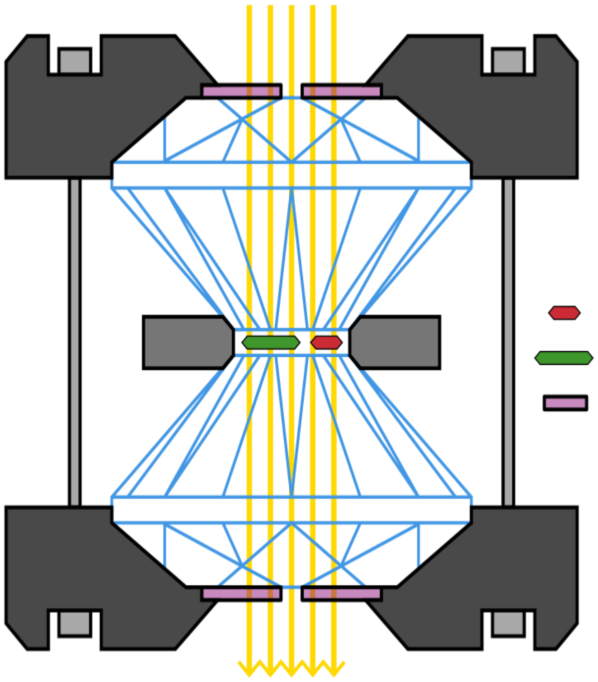
$BaH_{12}$, $LaH_{10}$, $ThH_9$, YH6, $FeH_5$, $RuH_4$, …

**Reflection** INFRARED spectroscopy




$$R_s = I_s / I_0$$

**Transmission** INFRARED spectroscopy



**Transmission**

# Hydrides spectroscopy at MIPT

# Laboratory of terahertz spectroscopy at MIPT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**https://mipt.ru/thz**


Thank you for your attention