Superconductivity on the localization threshold

from quantum corrections

to magnetic-field-tuned superconductor-insulator quantum phase transition

International Argonne Fall Workshop on Nanophysics V:
Nanoscale Superconductivity and Magnetism

15 November 2005

Tatyana Baturina

Concrete address

- ✓ Disordered

$$\boxed{T\tau = 1}$$

- ✓ Superconducting
- ✓ Two-dimensional systems

quasi-2D → electronic spectrum is 3D

$$\boxed{l,\ \lambda_F < d < \xi,\ l_T}$$

Evolution

weak disorder ↔ strong disorder

metal

Drude conductivity
+
quantum corrections

insulator

activated conductivity

+

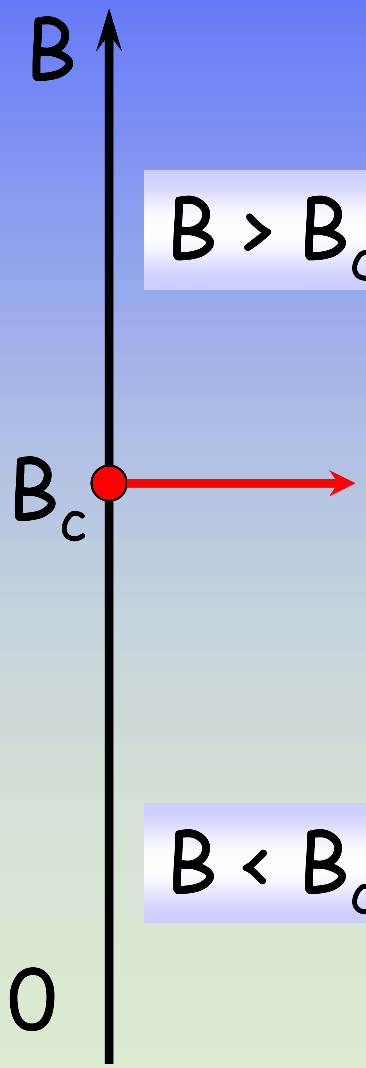
superconductivity
Cooper pairing
attractive interaction

Suppression of Superconductivity by **Magnetic Field**

$T = 0$

Field-induced

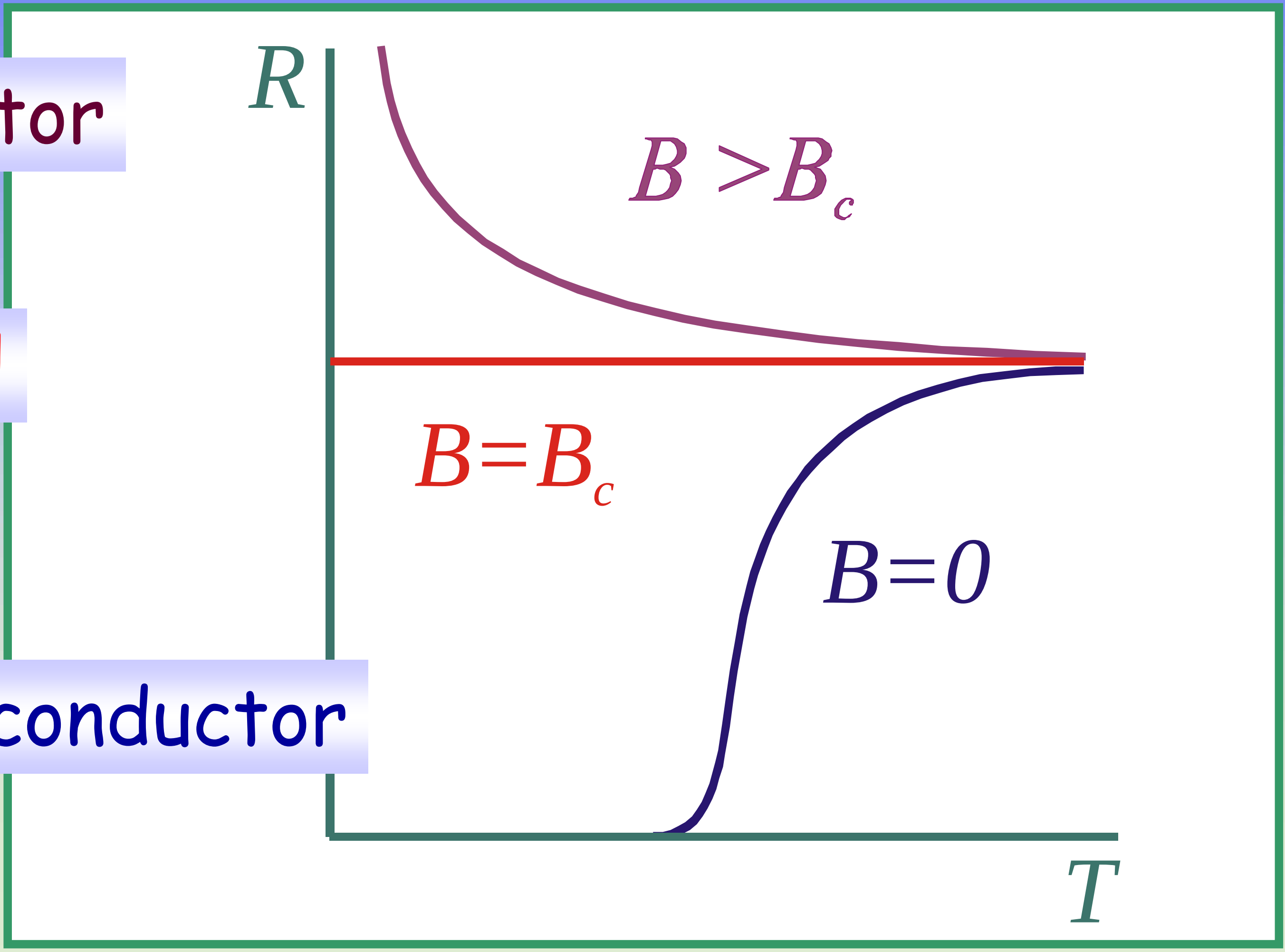
superconductor - insulator transition



$B > B_c$ Insulator

Metal

$B < B_c$ Superconductor



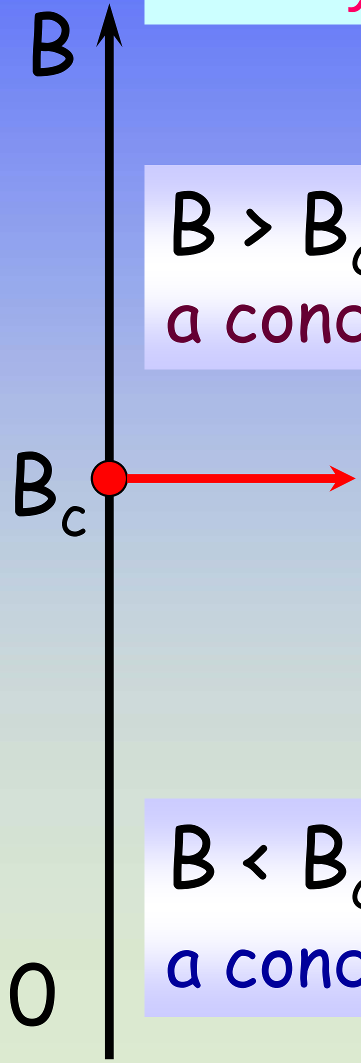
Field-induced superconductor – insulator transition

$T = 0$

*** Quantum phase transition ***

Duality between the dynamics of Cooper pairs and vortices

Matthew P.A. Fisher, PRL **65**, 923 (1990)



$B > B_c$ **Insulator:**

a condensate of vortices; Cooper pairs are localized

Metal:

The resistance has a finite, nonzero value at $T = 0$.

This value is *universal* – $R_c = h/(2e)^2$

$B < B_c$ **Superconductor:**

a condensate of Cooper pairs; vortices are localized

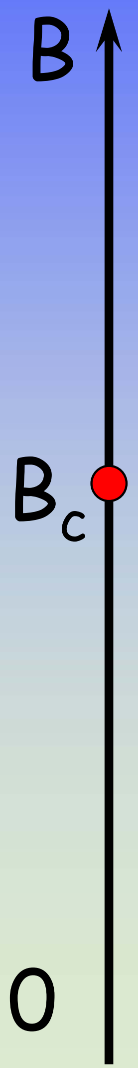
Field-induced superconductor – insulator transition

$T = 0$

*** Quantum phase transition ***

Continuos zero-temperature phase transition

Matthew P.A. Fisher, PRL **65**, 923 (1990)



$B > B_c$ quantum disordered phase

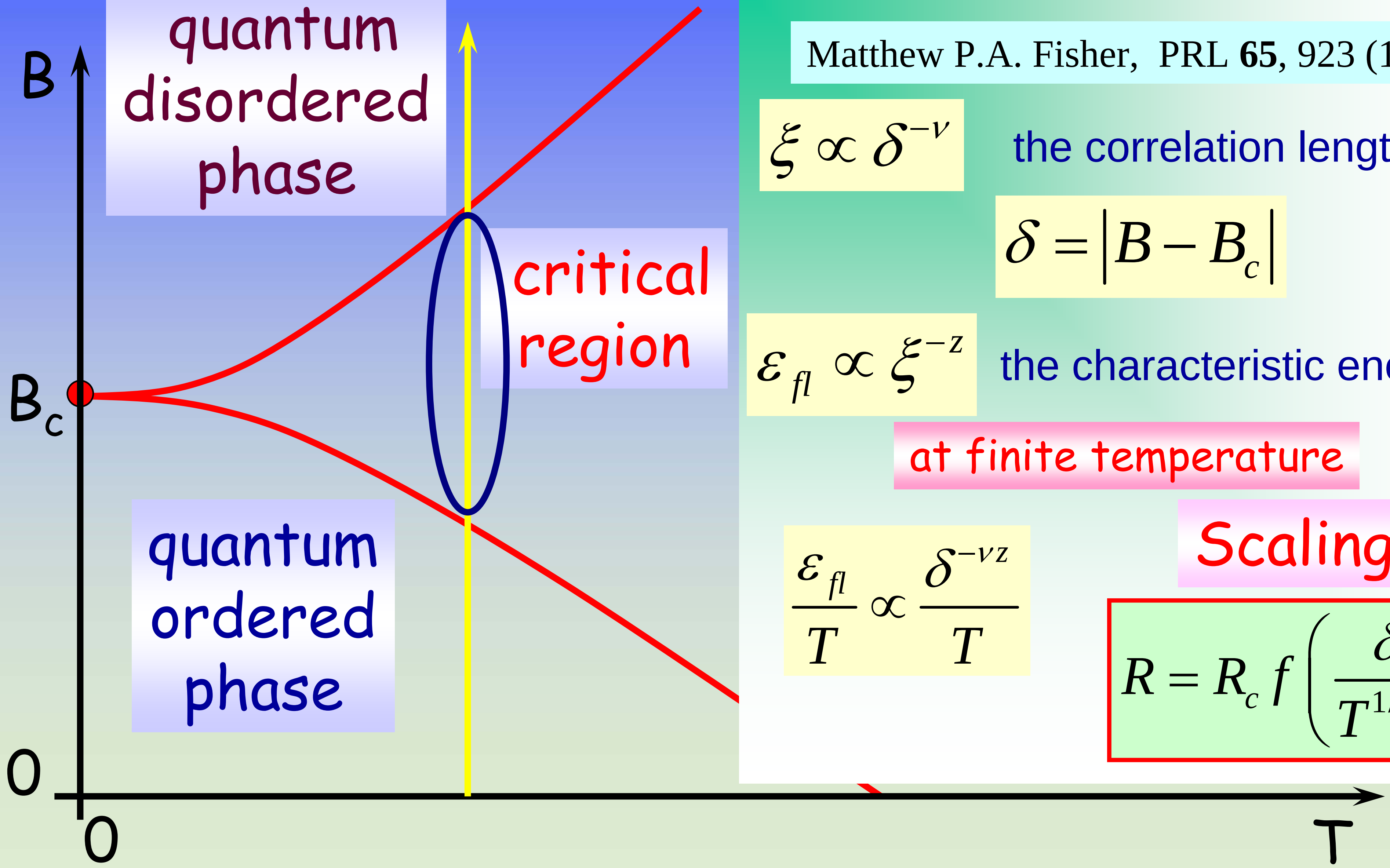
$B = B_c$ quantum critical point

$B < B_c$ quantum ordered phase

Field-induced superconductor – insulator transition

$T > 0$

***** Quantum phase transition *****



quantum disordered phase

critical region

quantum ordered phase

Matthew P.A. Fisher, PRL **65**, 923 (1990)

$$\xi \propto \delta^{-\nu}$$ the correlation length

$$\delta = \left| B - B_c \right|$$

$$\varepsilon_{fl} \propto \xi^{-z}$$ the characteristic energy

at finite temperature

$$\frac{\varepsilon_{fl}}{T} \propto \frac{\delta^{-\nu z}}{T}$$

Scaling

$$\boxed{R = R_c\, f\left(\frac{\delta}{T^{1/\nu z}} \right)}$$

Field-induced superconductor – insulator transition

*** Quantum phase transition ***

EXPERIMENT

✓ Fan-shaped curves

$dR/dB > 0$ at $B < B_c$

$dR/dB < 0$ at $B > B_c$

✓ Scaling

$$R = R_c f(|B - B_c|/T^{1/\nu z})$$

✓ Negative magnetoresistance at high magnetic fields

(as result of the break up of the localized Cooper pairs)

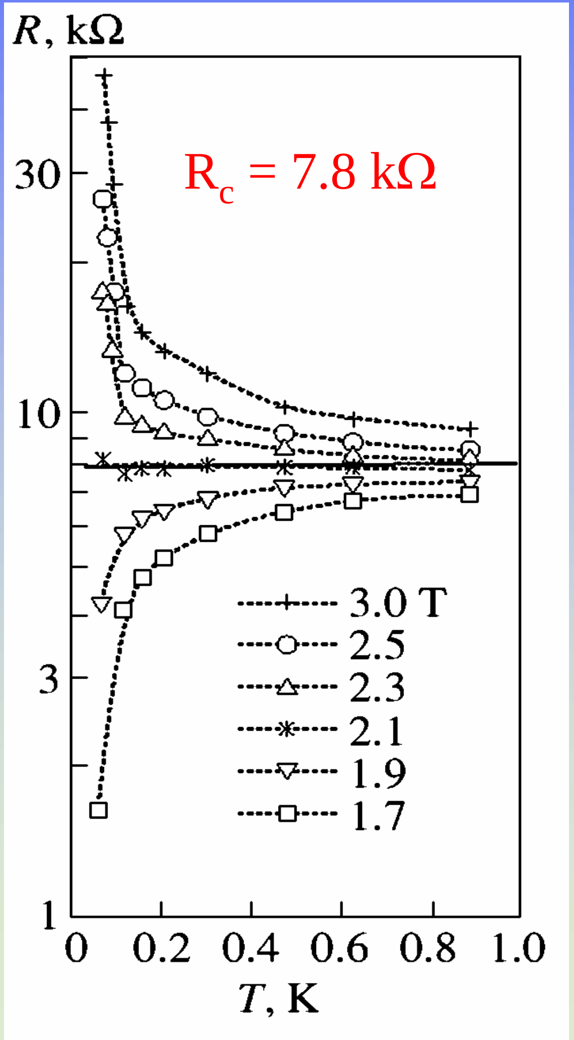
V.F. Gantmakher, et. al. JETP Lett. 68, 363 (1998)

Field-induced superconductor – insulator transition

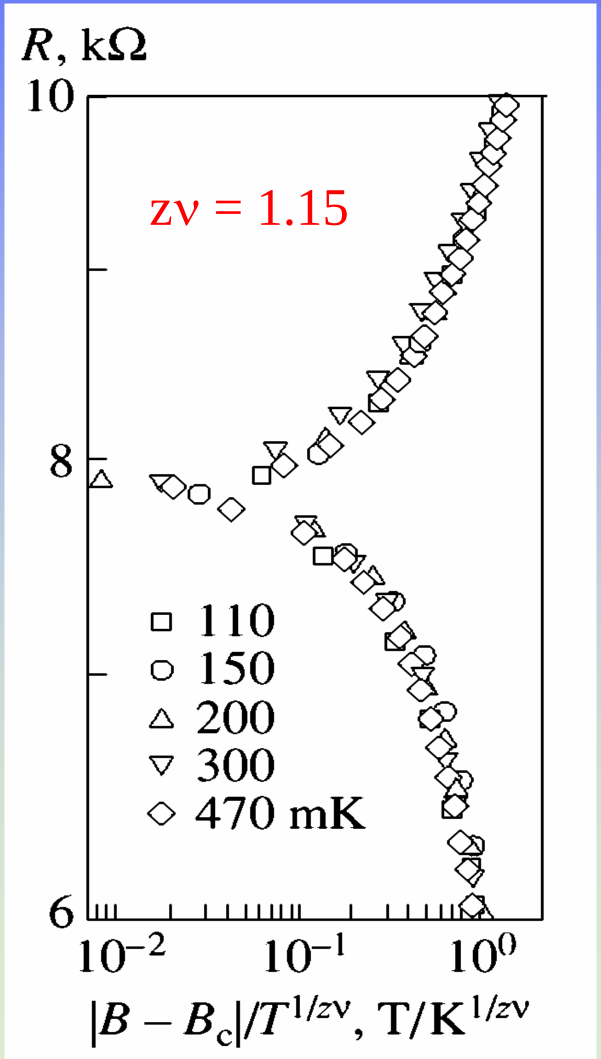
V. F. Gantmakher, M. V. Golubkov, V. T. Dolgopolov, A. A. Shashkin, G. E. Tsydynzhapov,
JETP Lett. **71**, 160 (2000); **71**, 473 (2000)

a-InO$_x$

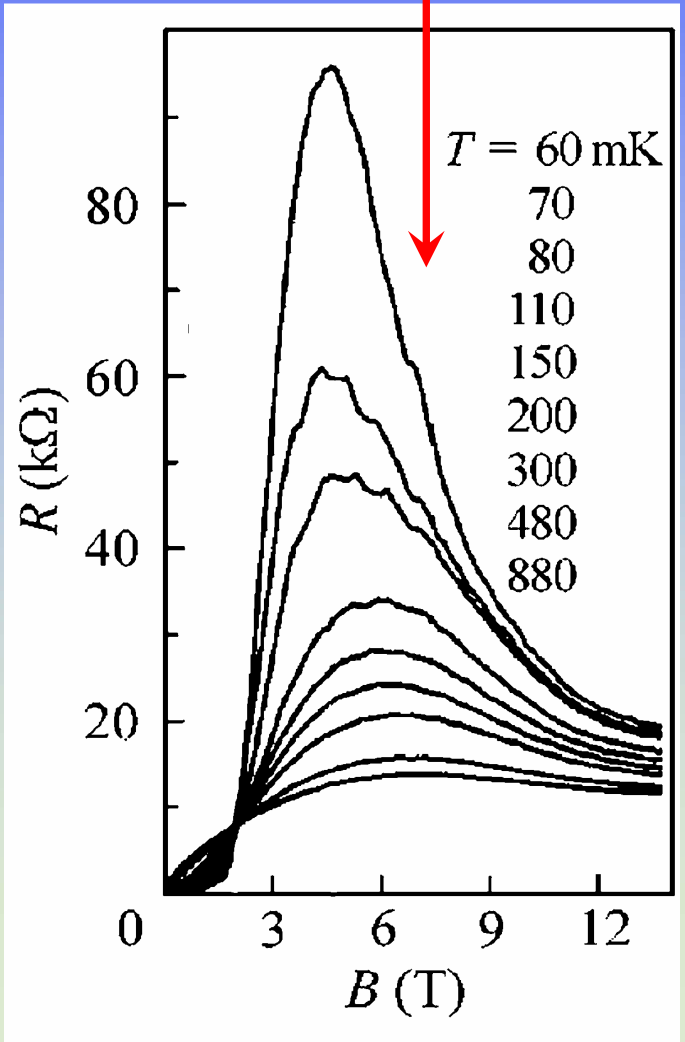
Fan-shaped curves



Scaling



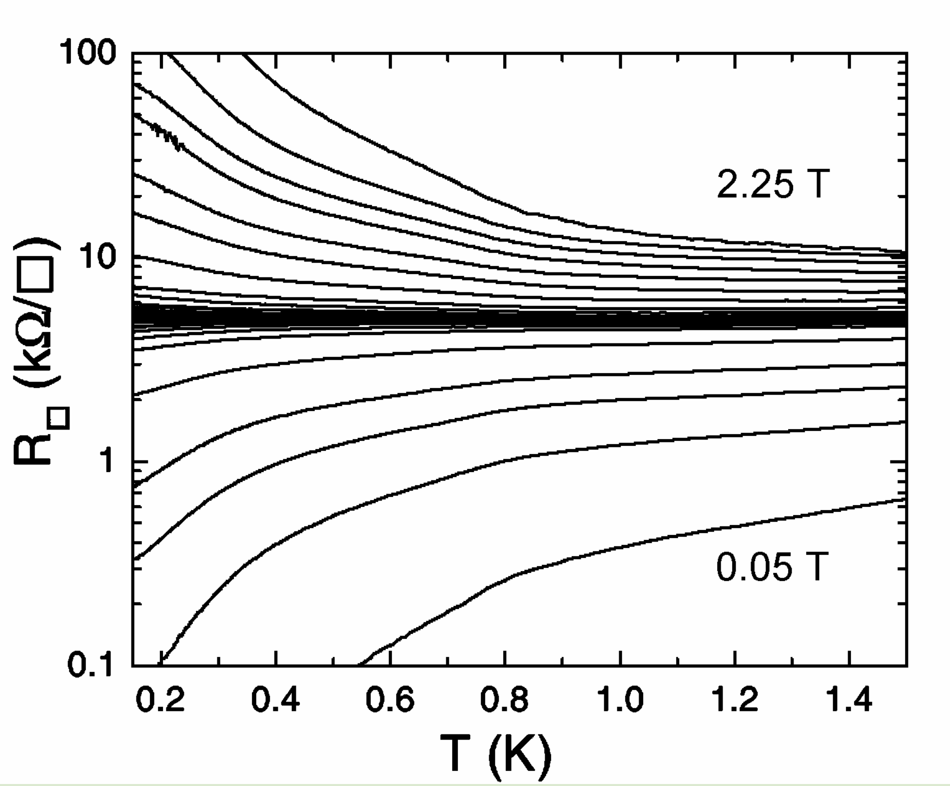
Negative magnetoresistance



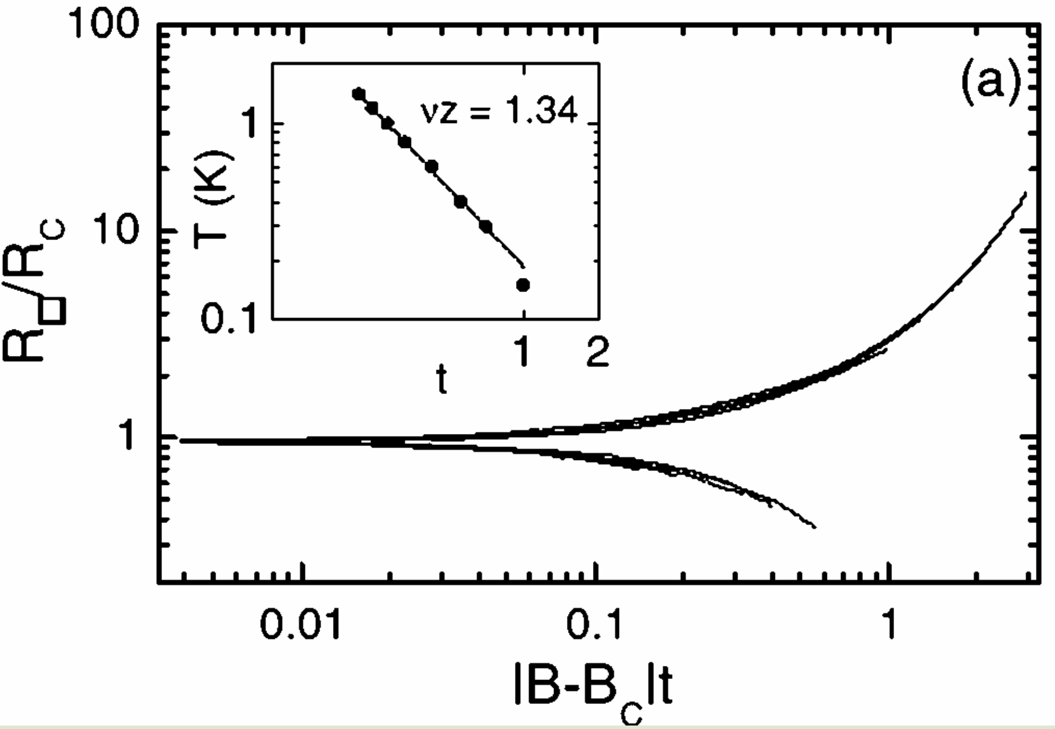
Field-induced superconductor – insulator transition

E. Bielejec and Wenhao Wu, PRL **88**, 206802 (2002) Be films

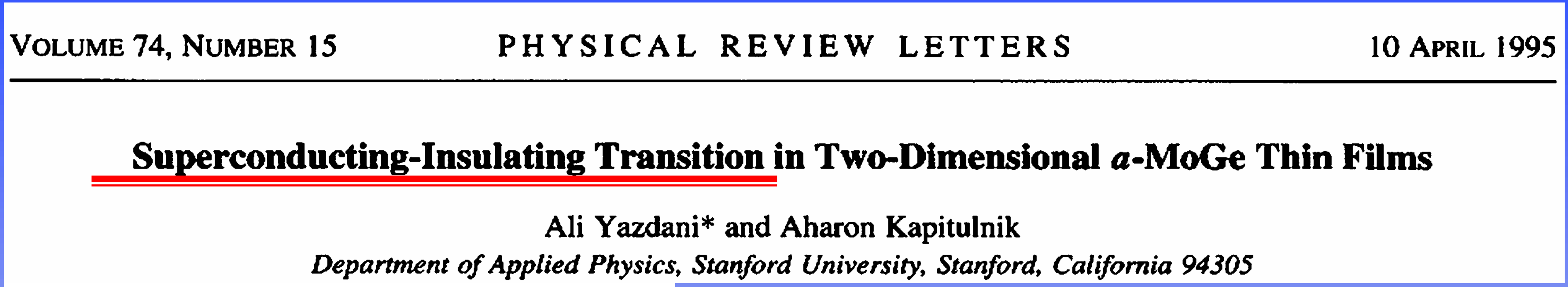
Fan-shaped curves



Scaling



Field-induced superconductor – insulator transition



VOLUME 74, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 1995

Superconducting-Insulating Transition in Two-Dimensional *a*-MoGe Thin Films

Ali Yazdani* and Aharon Kapitulnik

Department of Applied Physics, Stanford University, Stanford, California 94305

$Mo_{21}Ge_{79}$, d = 8 nm, $R_c = 1750\ \Omega$

Fan-shaped curves

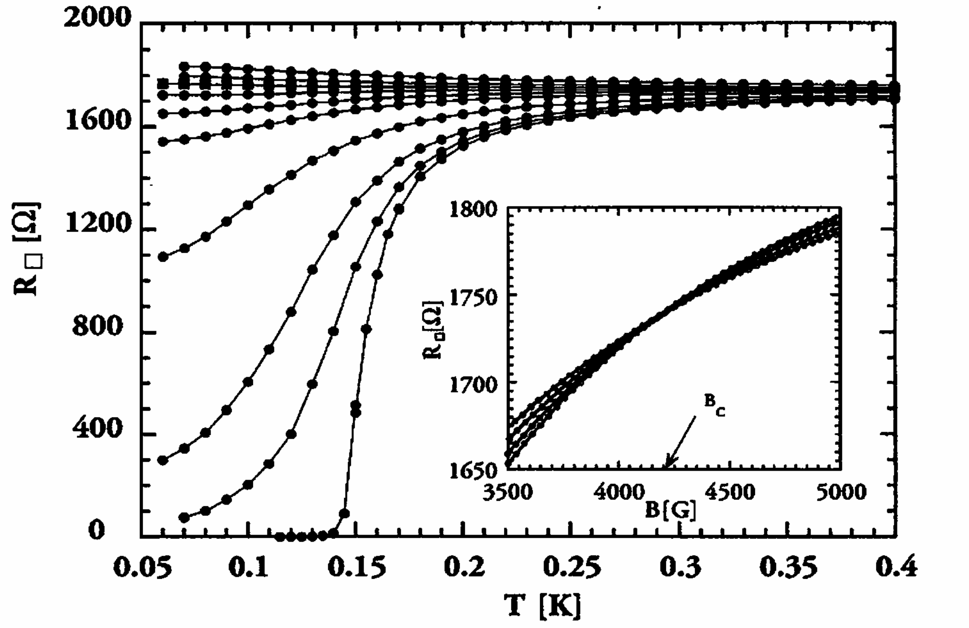


FIG. 1. Zero bias resistance of sample 2 plotted versus temperature at $B = 0, 0.5, 1.0, 2.0, 3.0, 4.0, 4.4, 4.5, 5.5, 6$ kG. In the inset, $R_\square(B,T,E=0)$ for the same sample measured versus field, at $T = 80, 90, 100, 110$ mK.

Scaling

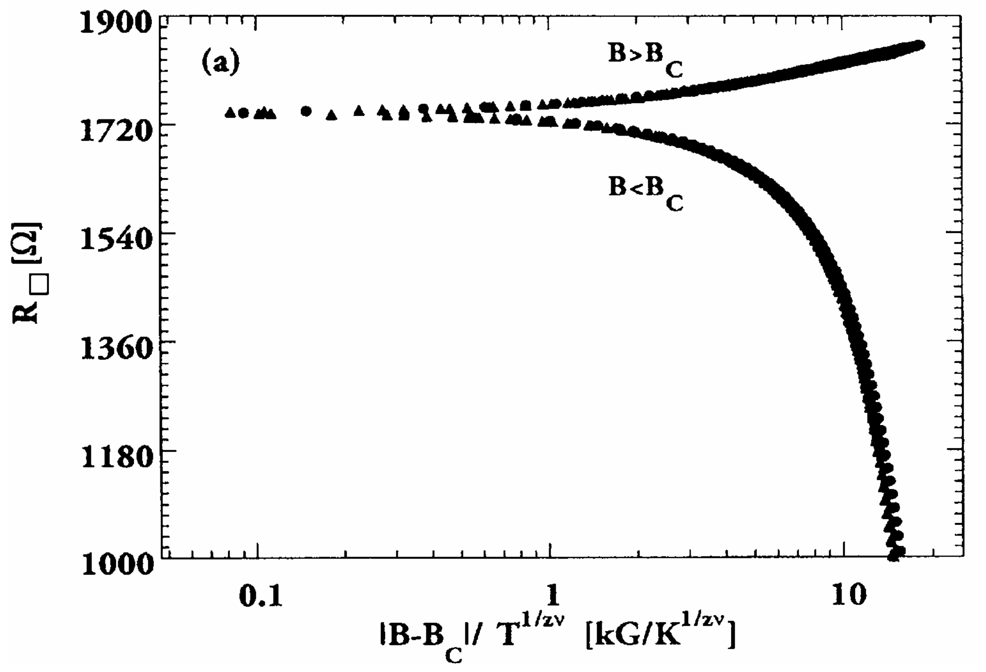
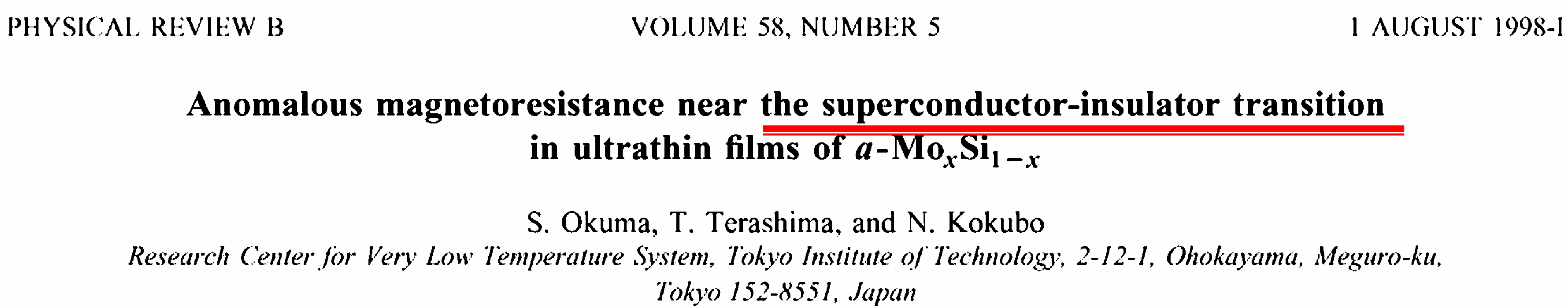


FIG. 3. Top: Scaling of $R_\square(B,T,E=0)$ for sample 2 measured at $T = 80, 90, 100, 110$ mK ($B_c = 4.19$ kG, $\nu z = 1.36$).

Field-induced superconductor – insulator transition



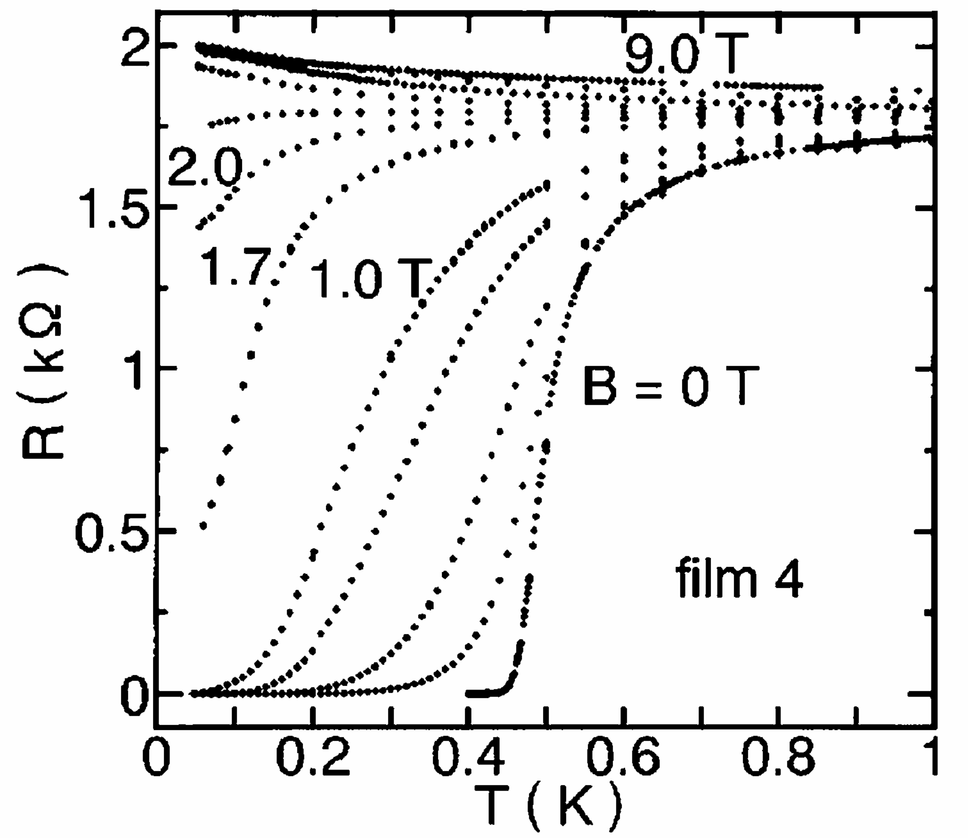
PHYSICAL REVIEW B VOLUME 58, NUMBER 5 1 AUGUST 1998-I

Anomalous magnetoresistance near the superconductor-insulator transition in ultrathin films of a-Mo$_x$Si$_{1-x}$

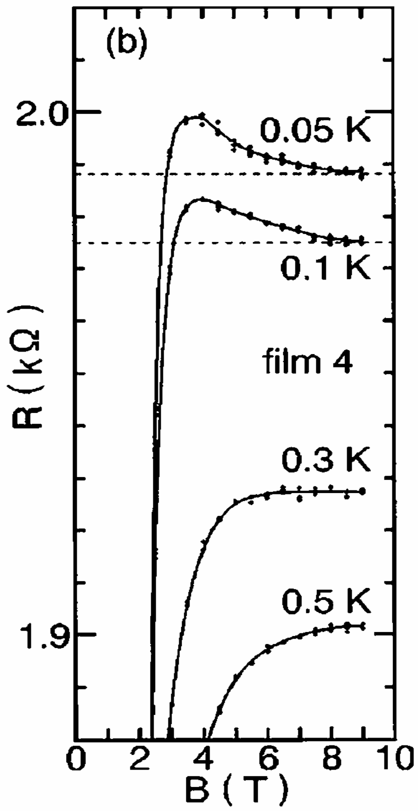
S. Okuma, T. Terashima, and N. Kokubo

Research Center for Very Low Temperature System, Tokyo Institute of Technology, 2-12-1, Ohokayama, Meguro-ku, Tokyo 152-8551, Japan

Fan-shaped curves



Negative magnetoresistance

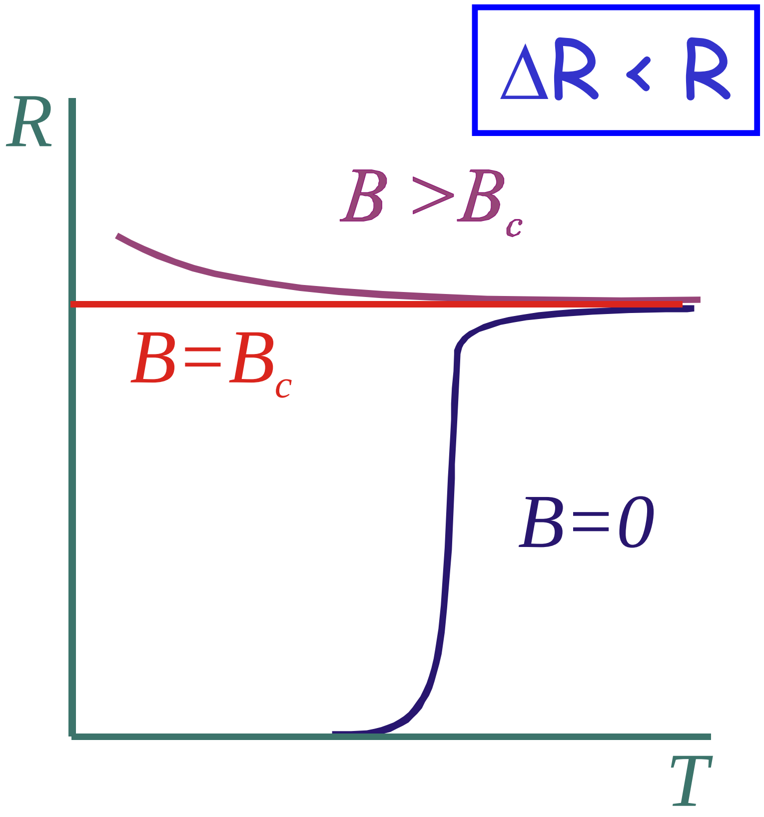


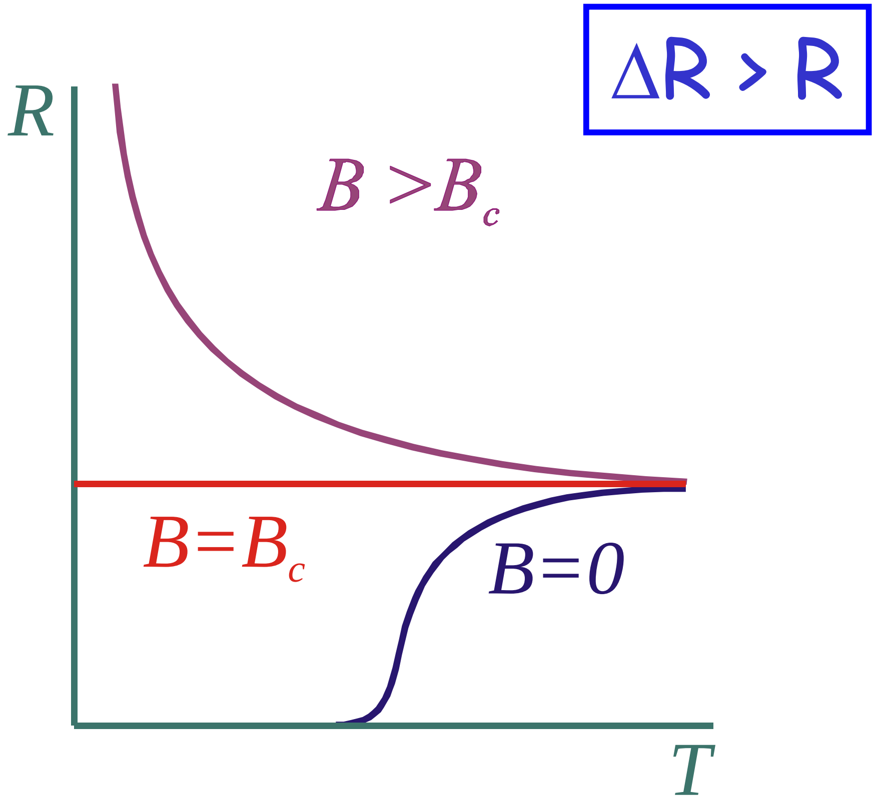
Suppression of Superconductivity by **Magnetic Field**

Field-induced...

?

superconductor – insulator transition

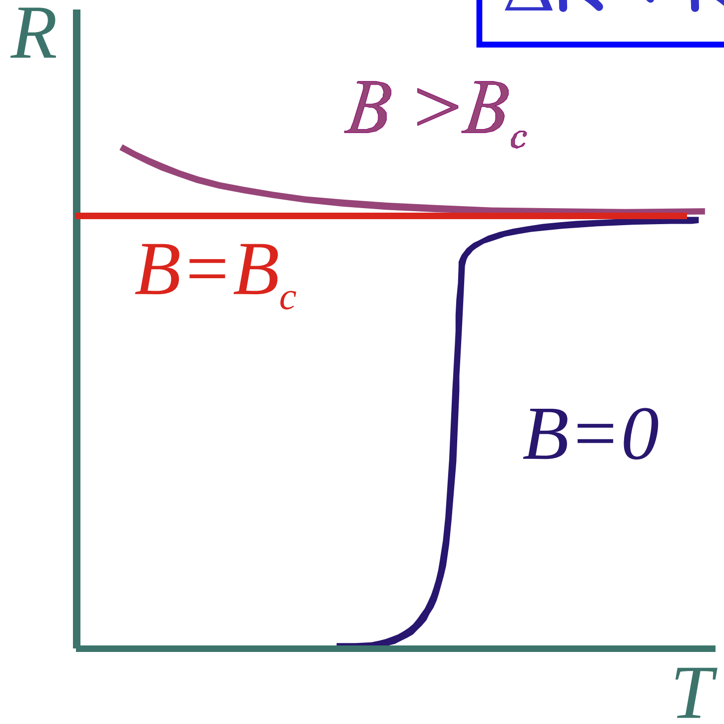




Suppression of Superconductivity by **Magnetic Field**

Field-induced...

$\Delta R < R$



This reminds us of the behavior of a disordered metal with quantum corrections to the conductivity rather than that of an insulator.

Quantum corrections to conductivity

one-particle interference

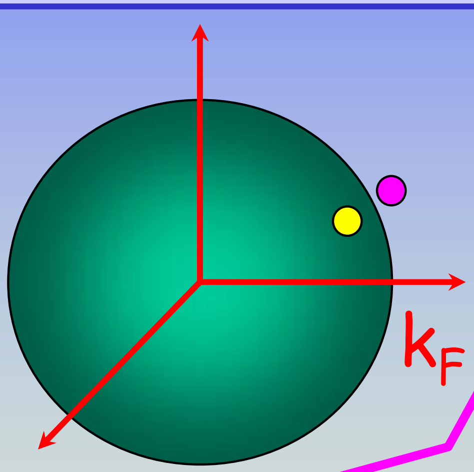
~~Weak Localization~~

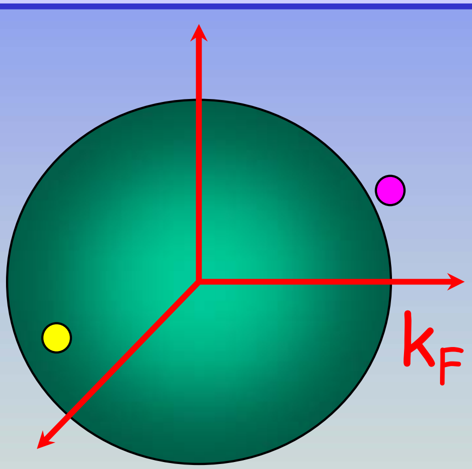
two-particle interference

(e-e interaction)

Diffusion Channel

Cooper Channel





Aronov - Altshuler

Aslamasov - Larkin

Density–Of-States

Maki - Thompson

Superconducting fluctuations

Quantum corrections to conductivity

Aronov - Altshuler

$\delta_{AA}\sigma(T)$

$\propto \ln(T)$

Aslamasov - Larkin

Density–Of-States

Maki - Thompson

Superconducting fluctuations

at $T \ll T_{c0}$ in magnetic field ???

V.M. Galitski and A.I. Larkin, PRB **63**, 174506 (2001)

An analytical expression for the fluctuation conductivity in the region close to the transition line at low temperatures

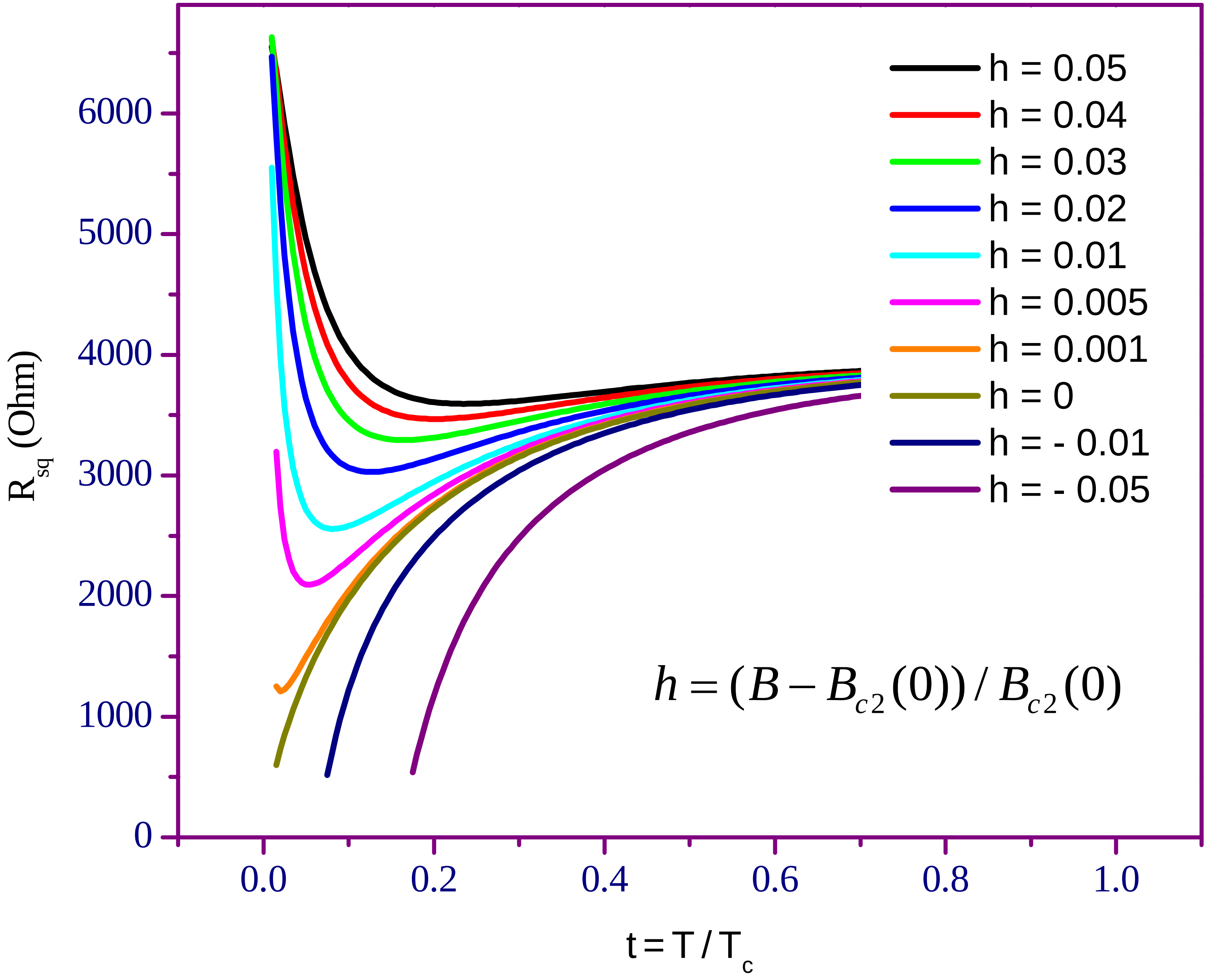
$T_{c0}\tau \ll 1,$

$$d\sigma = \frac{2e^2}{3\pi^2\hbar}\left[\ln\frac{r}{h} - \frac{3}{2r} + \psi(r) + 4[r\psi'(r) - 1]\right]$$

$t = T/T_{c0} \ll 1,$ $\quad h = (B - B_{c2}(T))/B_{c2}(0) \ll 1$ $\quad r = (1/2\gamma)h/t$

$\gamma = 1.781$

Superconducting fluctuations at low temperature



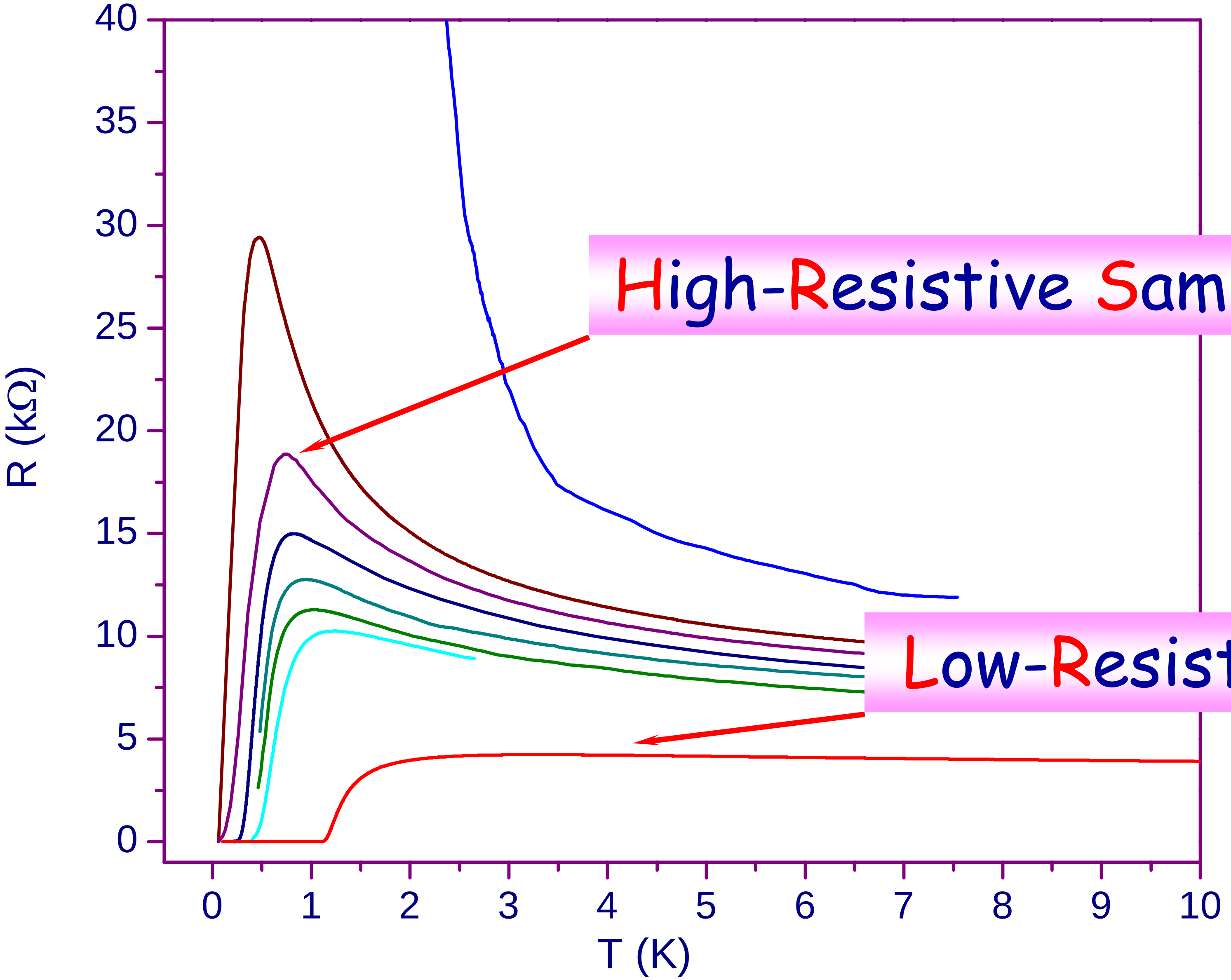
Experiment

TiN films

- ✓ TiN films were formed by atomic layer chemical vapor deposition onto a Si/SiO_2 substrate.
- ✓ The films consist of a dense packing of the crystallities.
- ✓ The average size of the crystallities is ~ 30 nm.

Experiment

Temperature dependence



High-Resistive Sample

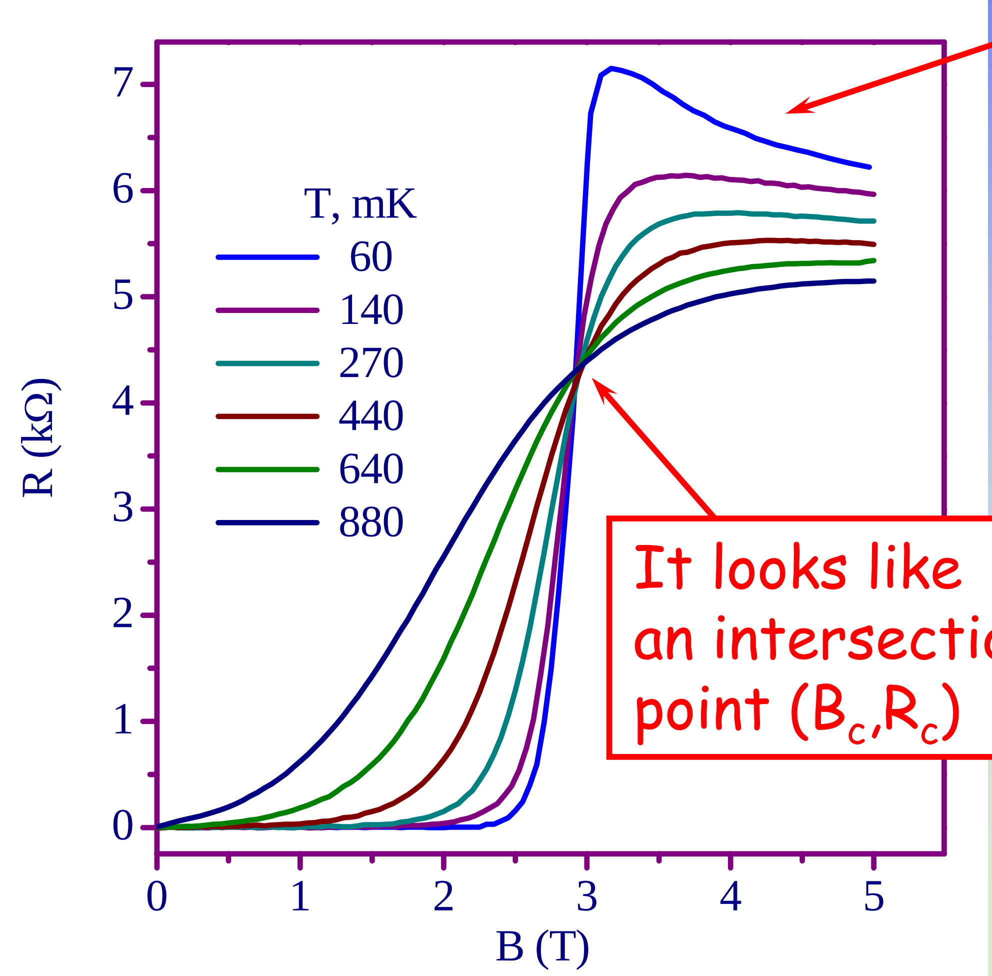
Low-Resistive Sample

Experiment

TiN films

Magnetic-field dependence

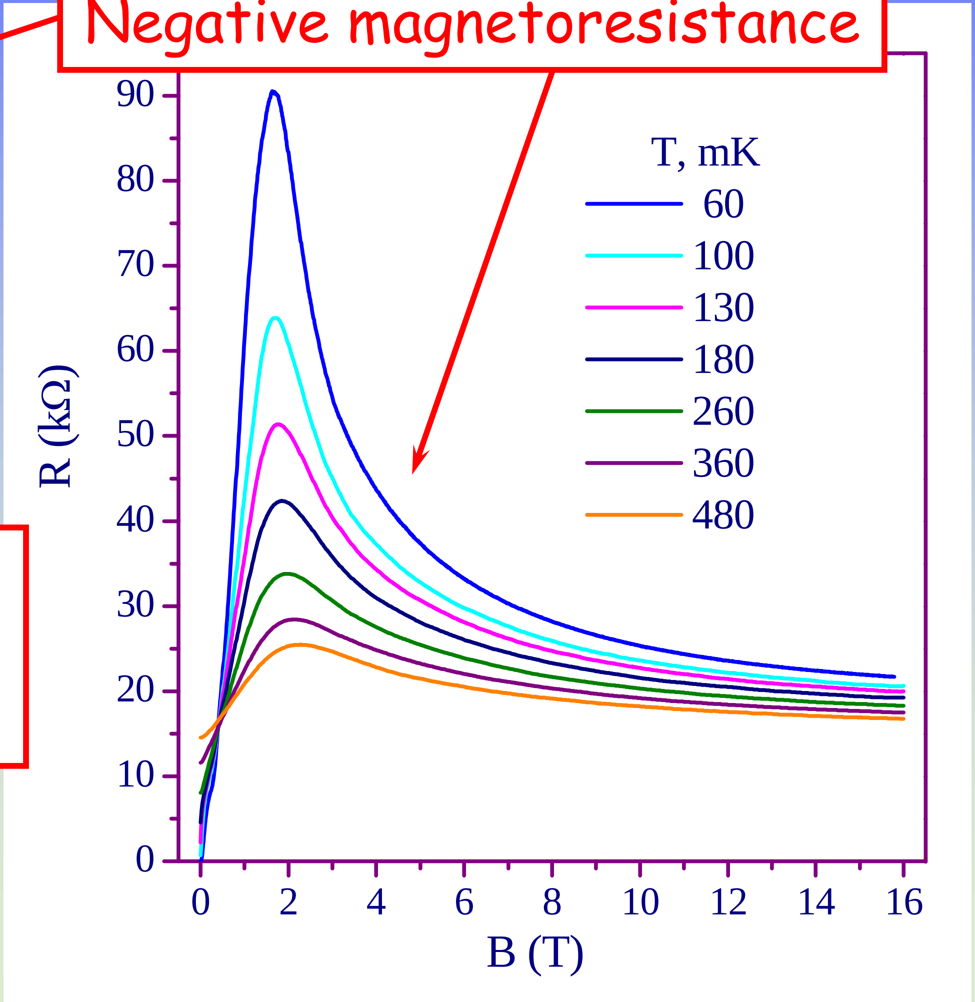
Low-Resistive Sample



It looks like an intersection point (B_c,R_c)

High-Resistive Sample

Negative magnetoresistance

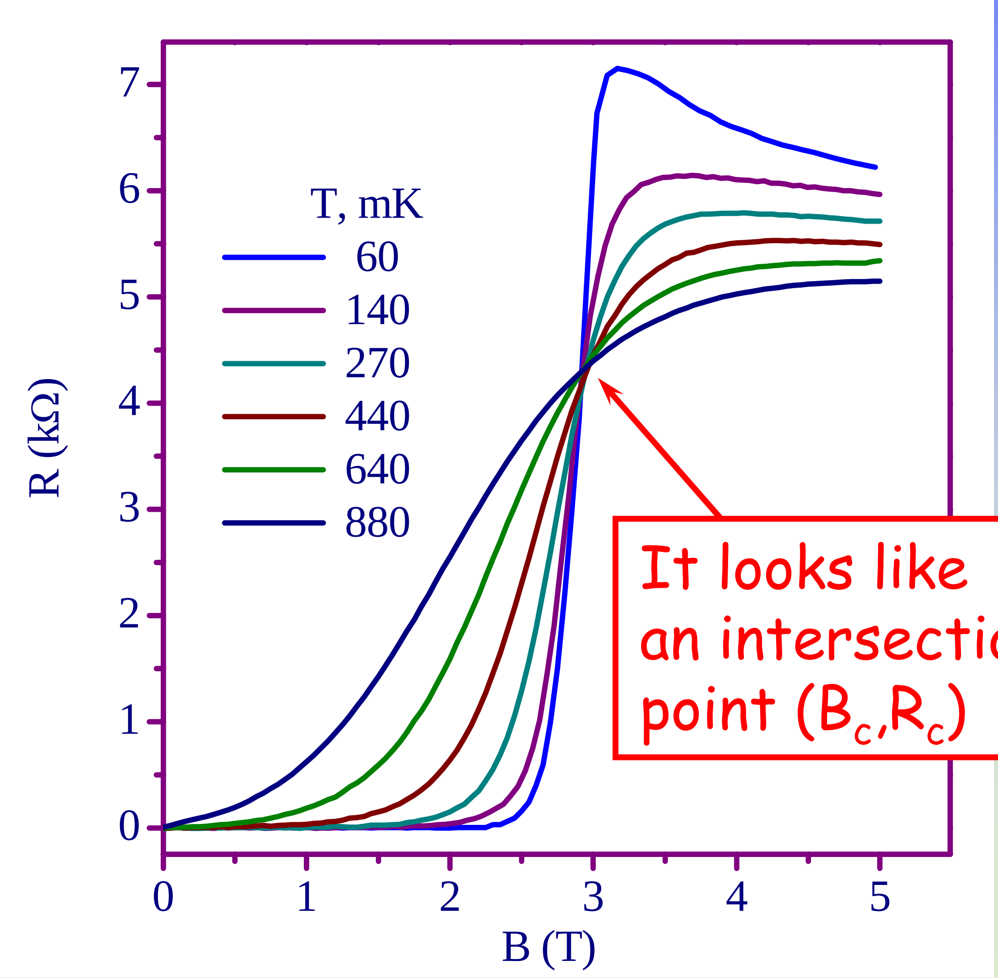


Experiment

TiN films

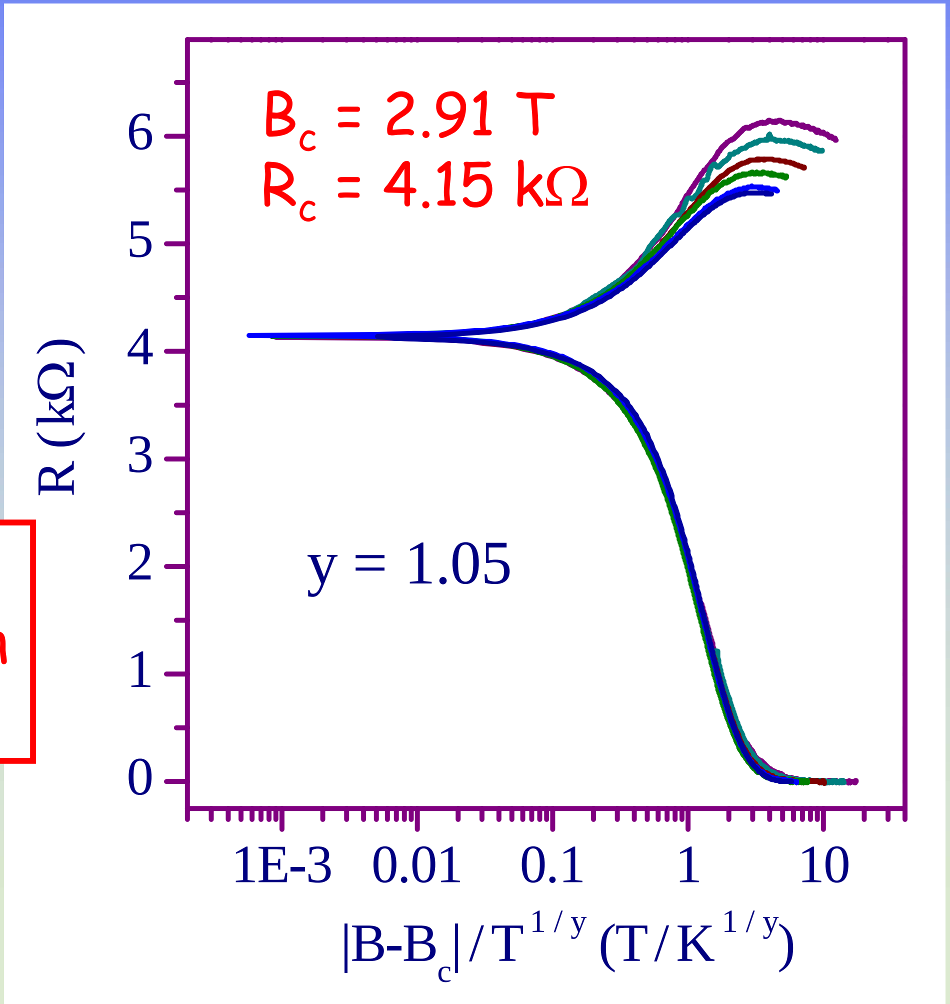
Magnetic-field dependence

Low-Resistive Sample



It looks like an intersection point (B_c,R_c)

Scaling



B_c = 2.91 T
R_c = 4.15 kΩ

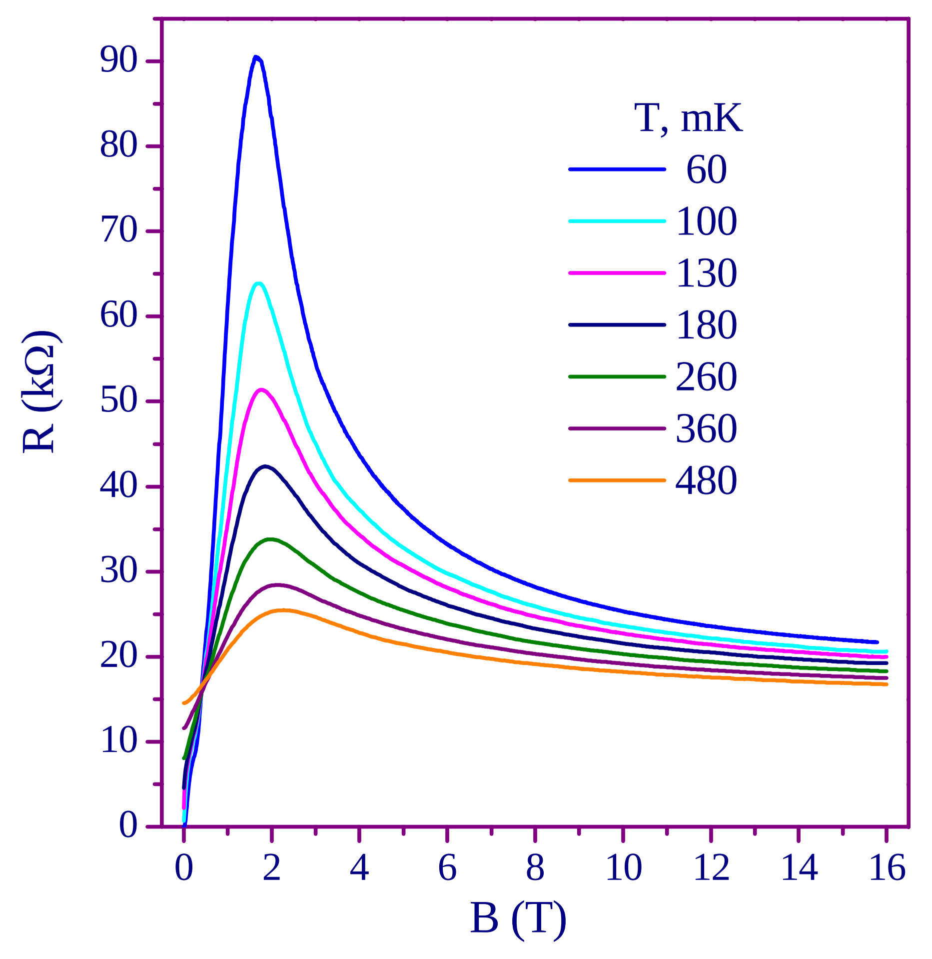
y = 1.05

Experiment

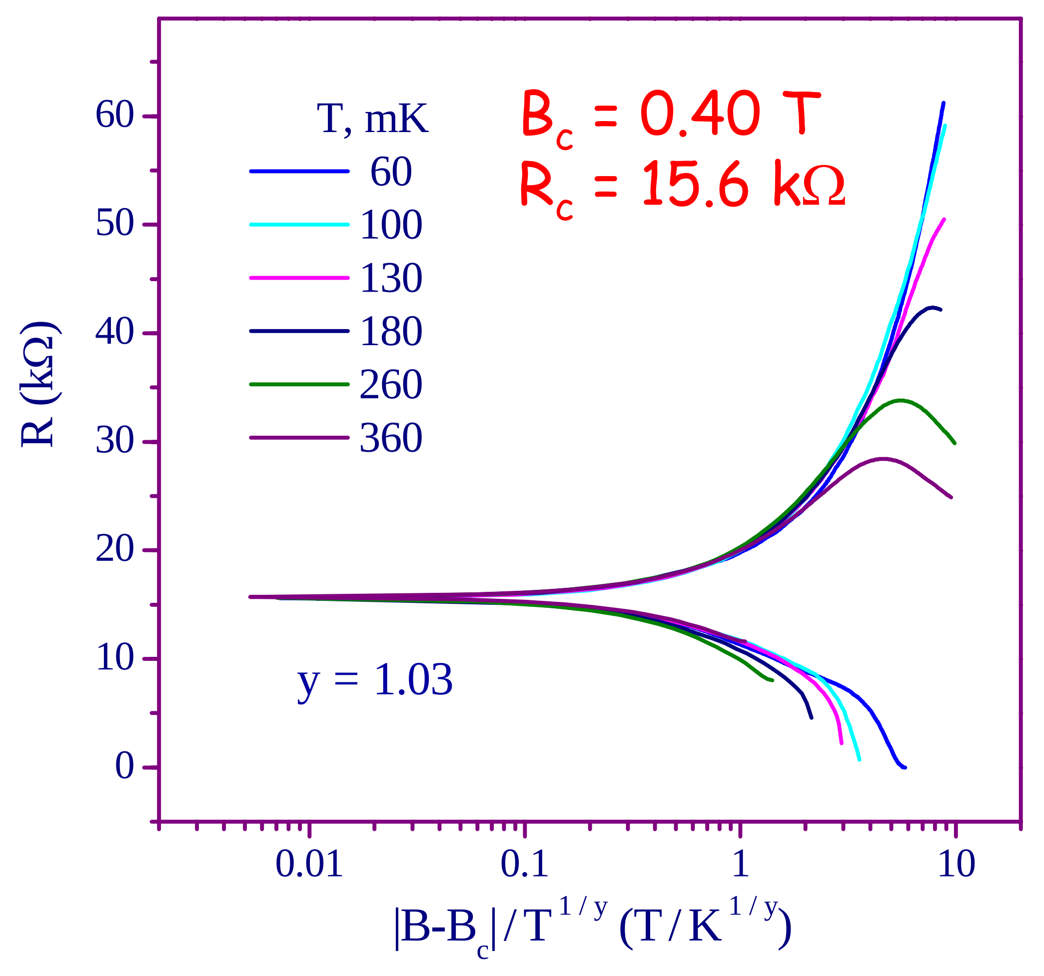
TiN films

Magnetic-field dependence

High-Resistive Sample



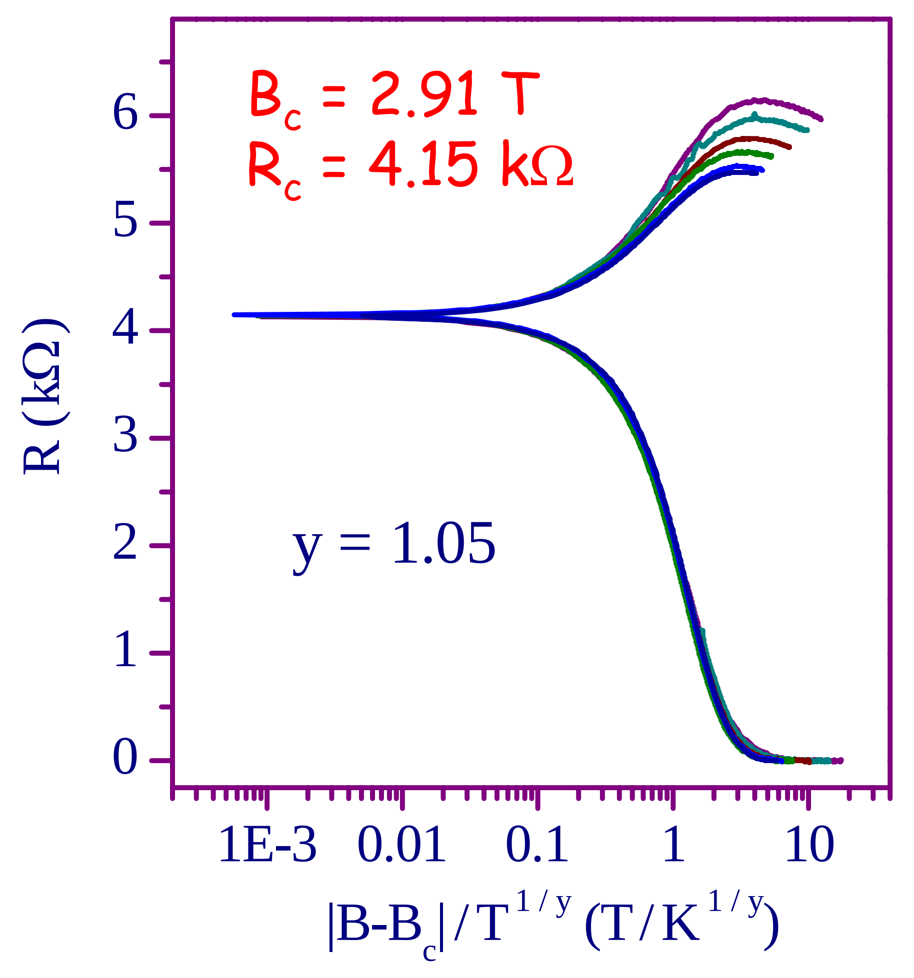
Scaling



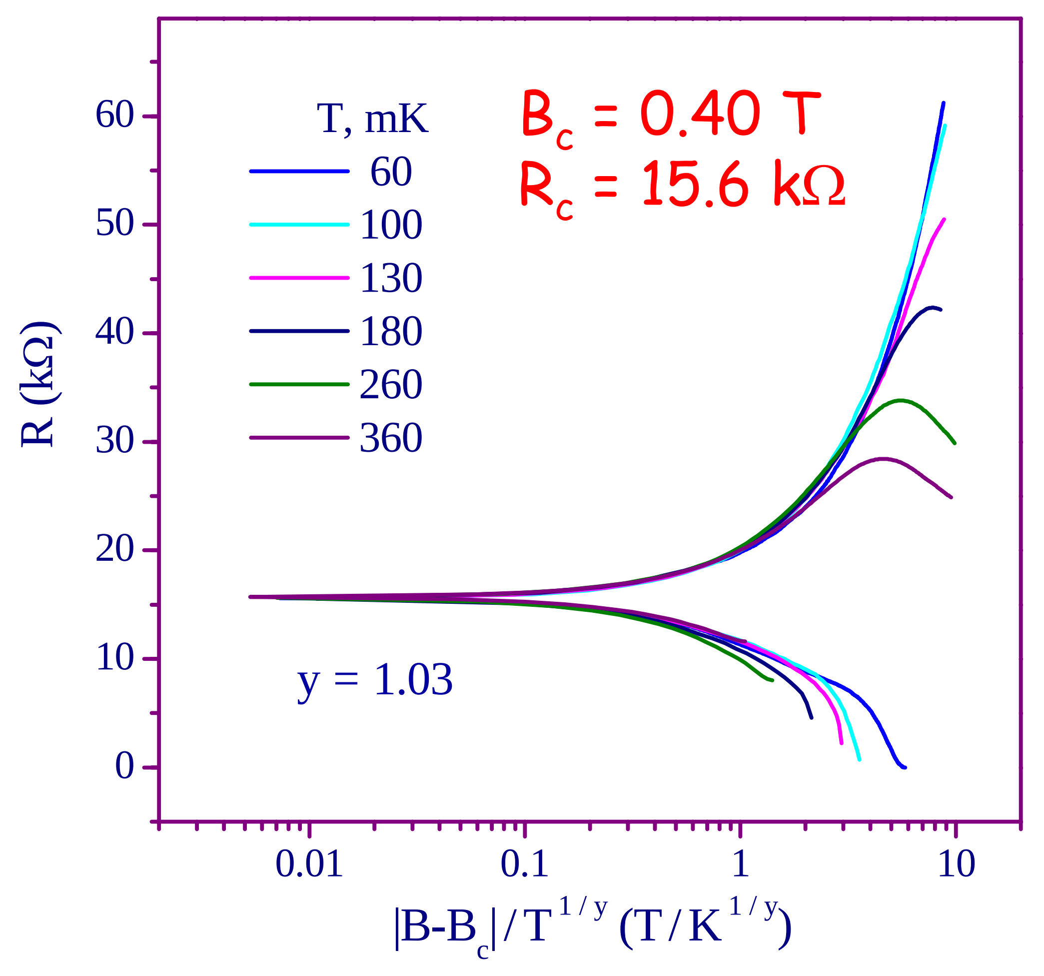
Scaling

Magnetic-field dependence

Low-Resistive Sample



High-Resistive Sample



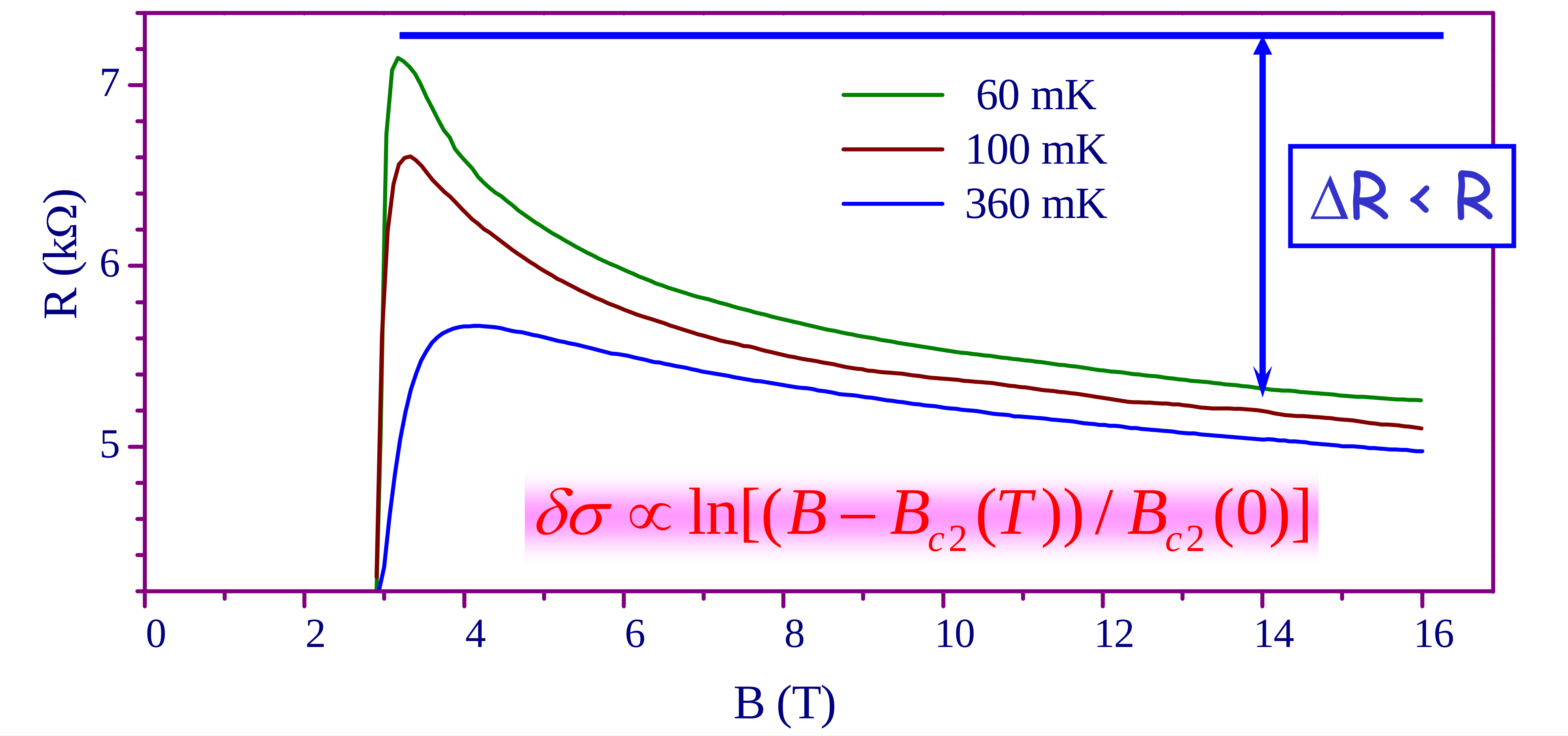
$y\ (=\nu z) \approx 1$ for both samples !

Magnetic-field dependence

Low-Resistive Sample

Negative magnetoresistance

comparison with Galitski – Larkin calculations of the quantum corrections



ΔR < R

$$\delta\sigma \propto \ln[(B - B_{c2}(T)) / B_{c2}(0)]$$

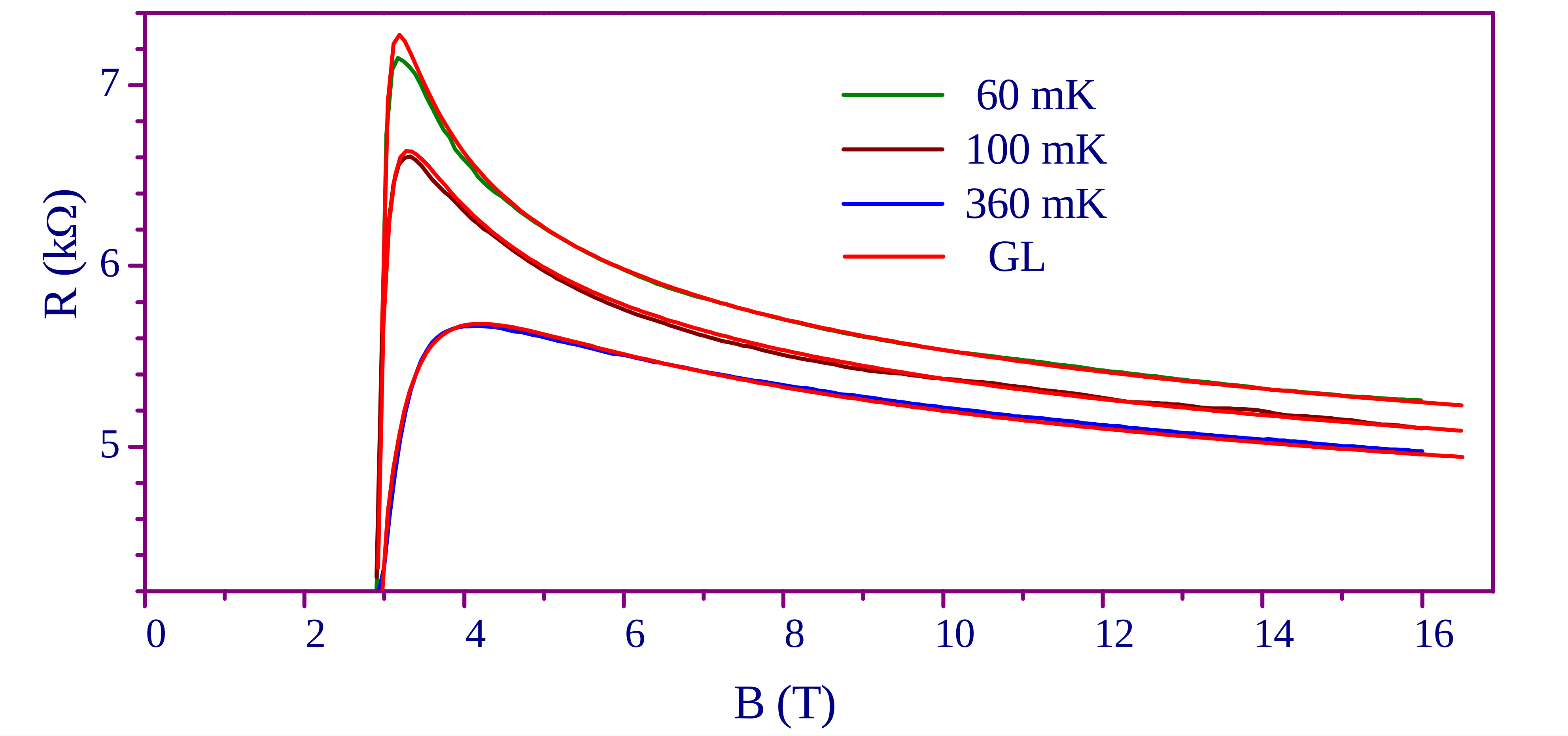
LRS

Negative magnetoresistance

comparison with Galitski - Larkin calculations of the quantum corrections

$T_c = 2$ K, $B_{c2}(0) = 2.8$ T

$$\delta\sigma = \frac{2e^2}{3\pi^2\hbar}\left[\ln\frac{r}{h} - \frac{3}{2r} + \psi(r) + 4[r\psi'(r) - 1]\right]$$



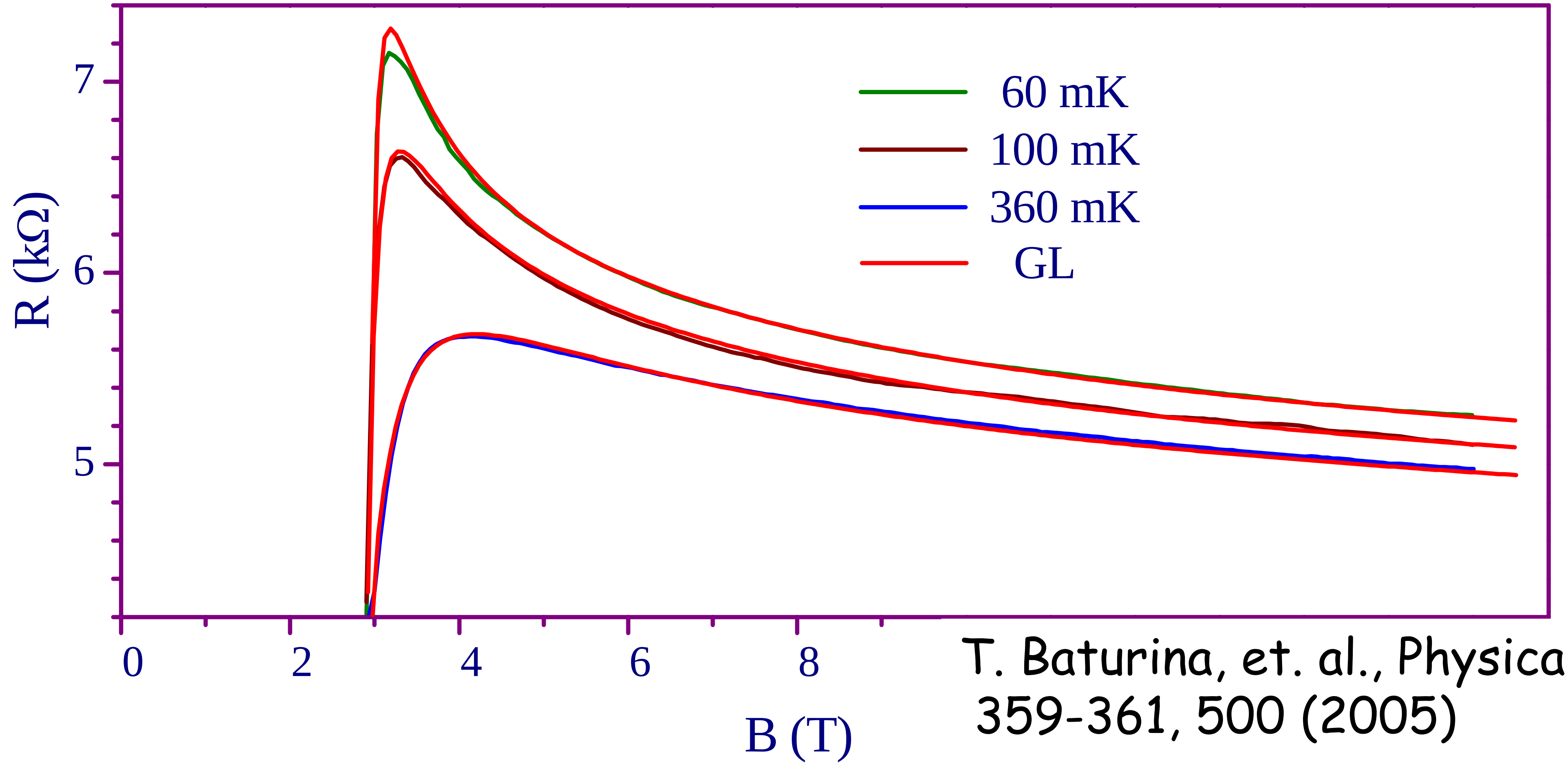
LRS

Negative magnetoresistance

comparison with Galitski - Larkin calculations of the quantum corrections

T_c = 2 K, $B_{c2}(0)$ = 2.8 T

$$ds = \frac{2e^2}{3p^2\text{h}} \left[\ln\frac{r}{h} - \frac{3}{2r} + y(r) + 4[ry'(r) - 1] \right]$$

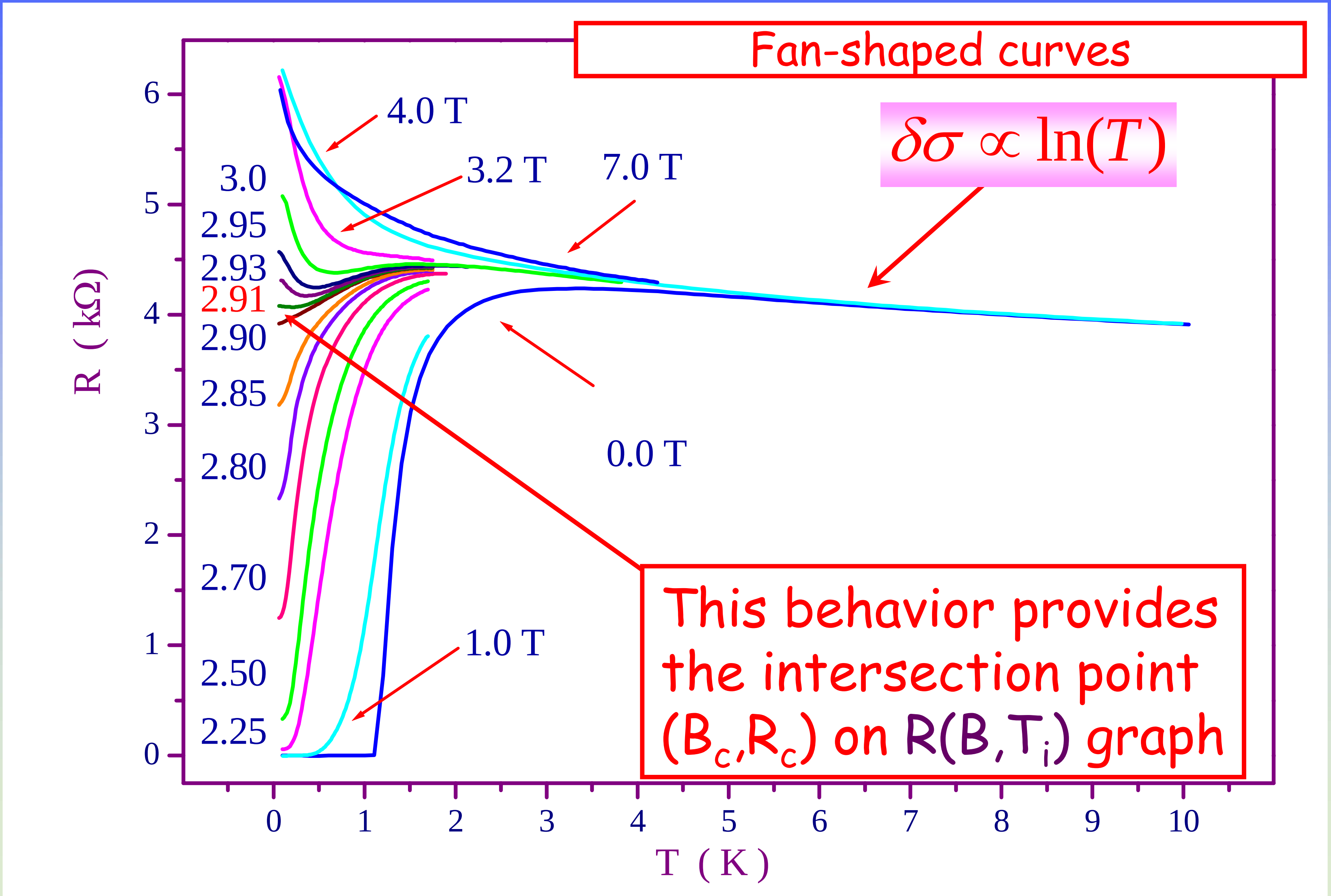


T. Baturina, et. al., Physica B 359-361, 500 (2005)

Temperature dependence

Low-Resistive Sample

$R(T,B_i)$



Fan-shaped curves

$\delta\sigma \propto \ln(T)$

This behavior provides the intersection point (B_c,R_c) on $R(B,T_i)$ graph

LRS

Temperature dependence

comparison with Galitski – Larkin calculations of the quantum corrections

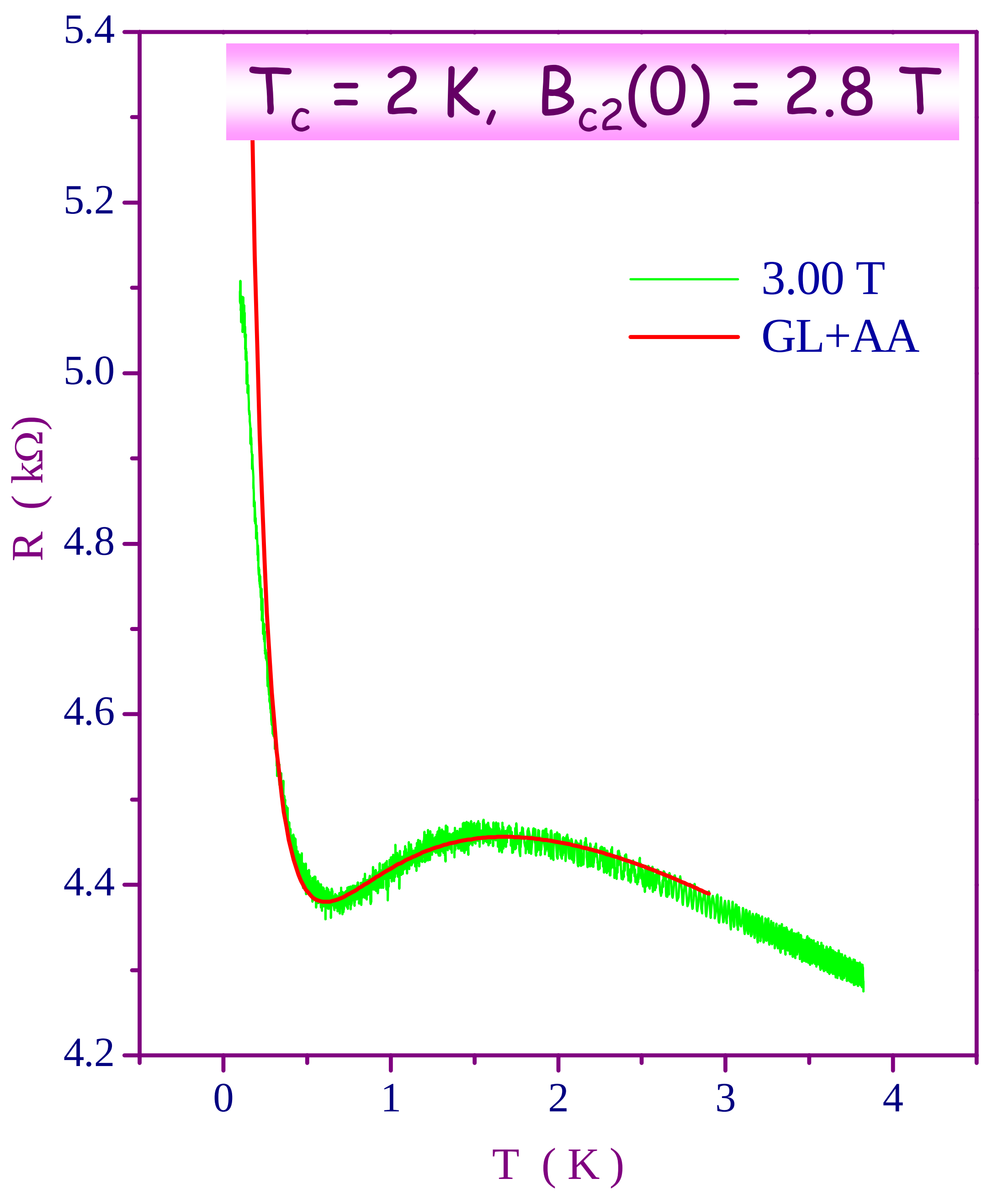
Cooper Channel

+

Aronov - Altshuler

$\delta\sigma_{AA} \propto \ln(T)$

Diffusion Channel



$T_c = 2$ K, $B_{c2}(0) = 2.8$ T

LRS

Temperature dependence

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Cooper Channel

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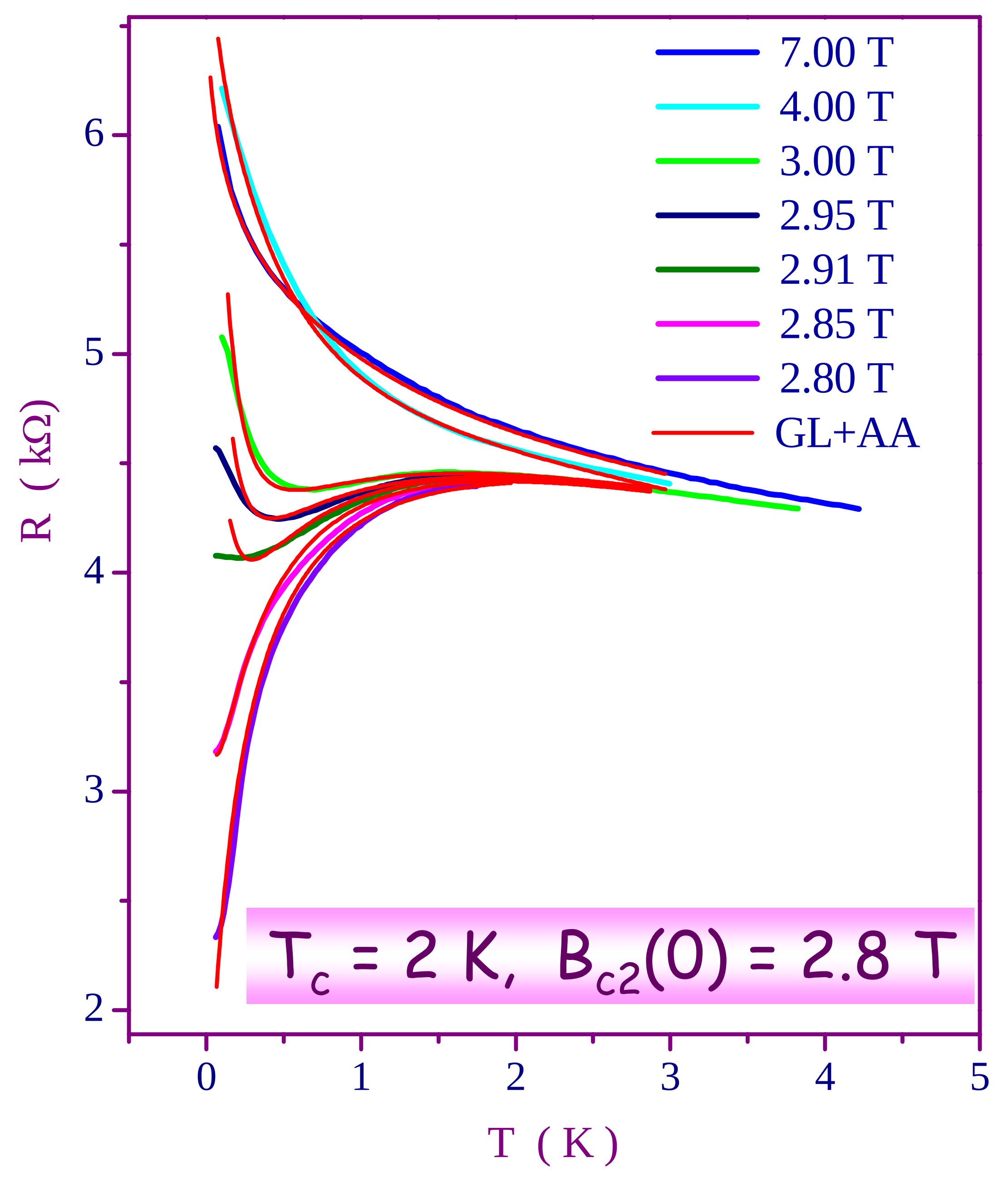
Diffusion Channel

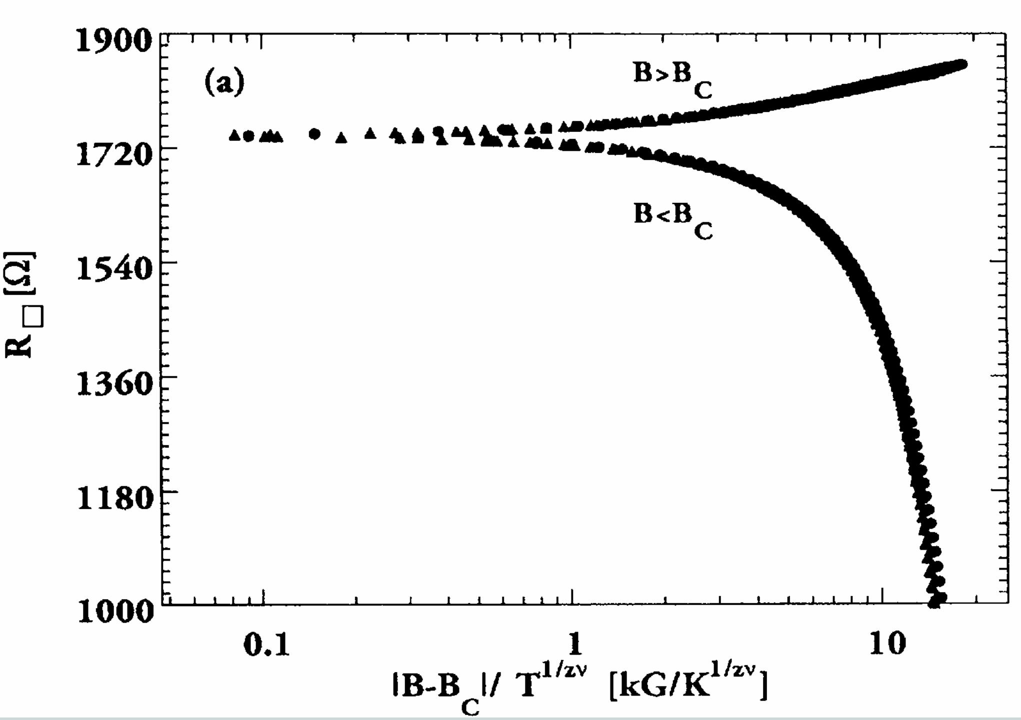


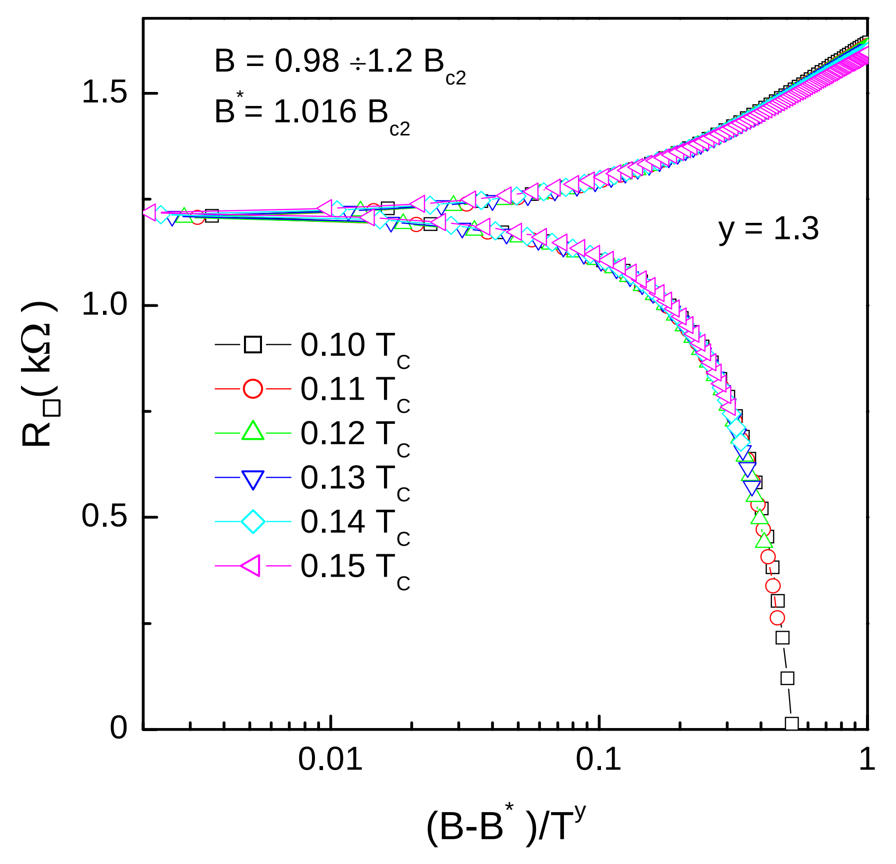
T_c = 2 K, $B_{c2}(0)$ = 2.8 T

Superconducting fluctuations at low temperature

Scaling

A.Yazdani and A.Kapitulnik (1995)





$T_C = 0.15$ K $\quad B_C = 4.19$kG

$T = 0.08 \div 0.11$ K $\quad B - B_C < 1$ kG

$z\nu = 1.36$

Theoretical expression does not contain scaling properties, but in restricted region of values T and B scaling presentation can be done

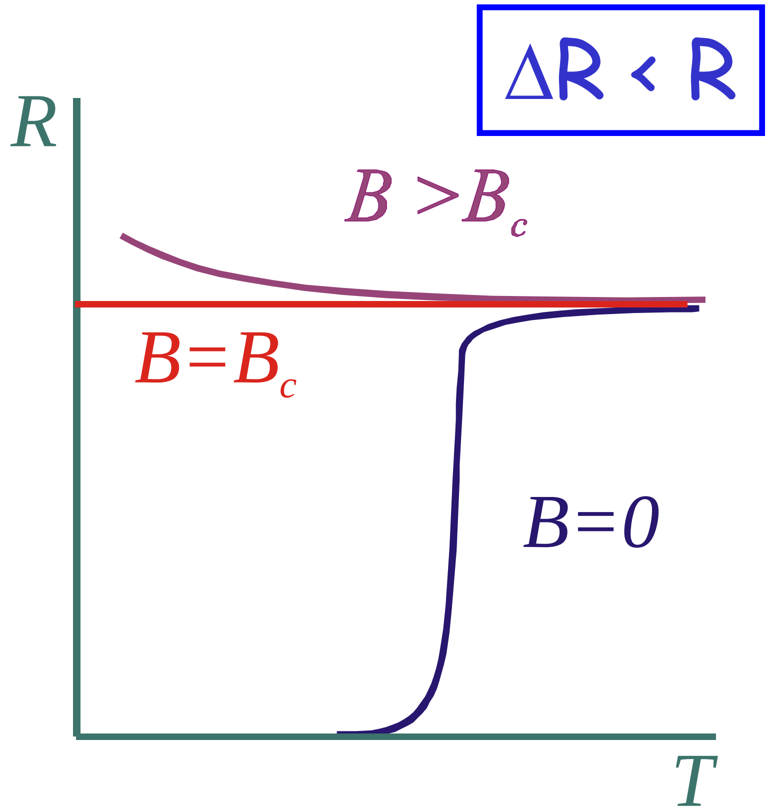
[V.F. Gantmakher, S.N. Ermolov, G.E. Tsydynzhapov, A.F. Zhukov, T.I. Baturina, JETP Lett. 77, 424 (2003)]

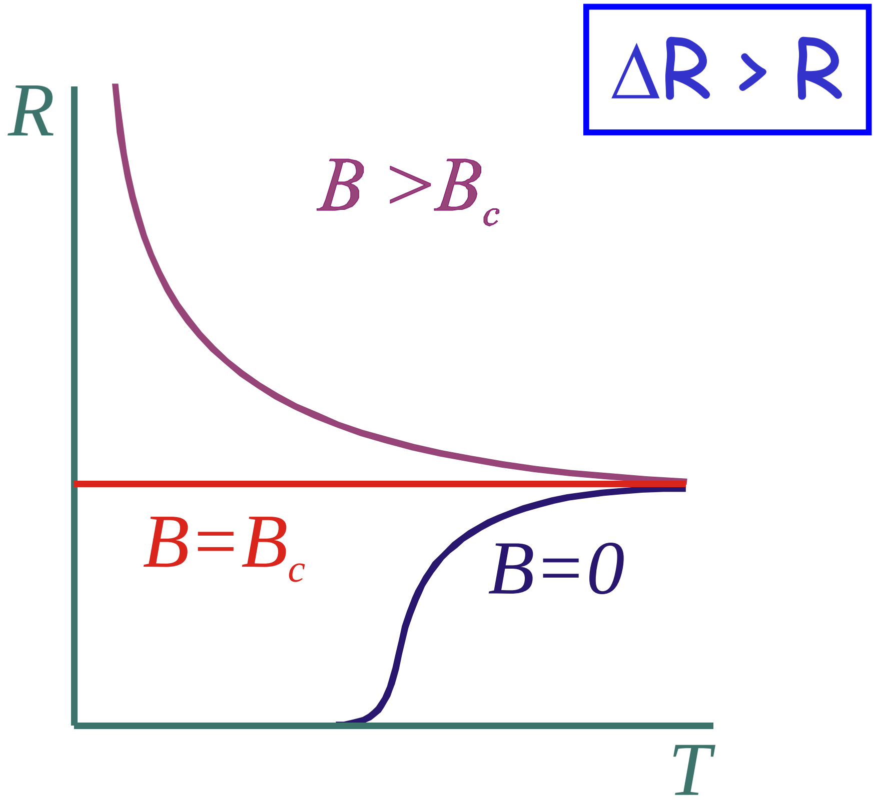
Suppression of Superconductivity by **Magnetic Field**

Field-induced...

superconductor – metal transition

superconductor – insulator transition


$\Delta R < R$


$\Delta R > R$

Suppression of Superconductivity by **Magnetic Field**

Conclusion (first step)

superconductor – metal transition

V.M. Galitski and A.I. Larkin,
PRB **63**, 174506 (2001)

superconductor – insulator transition

Matthew P.A. Fisher,
PRL **65**, 923 (1990)

Common features

- ✓ Fan-shaped structure of $R(T,B_i)$ curves
- ✓ Negative magnetoresistance in high fields
- ✓ Scaling

All main features can be explained in the frames of the theory of the quantum corrections to the conductivity in disordered metals !

Let’s take a close look

(second step)

LRS

Temperature dependence

comparison with Galitski – Larkin calculations of the quantum corrections

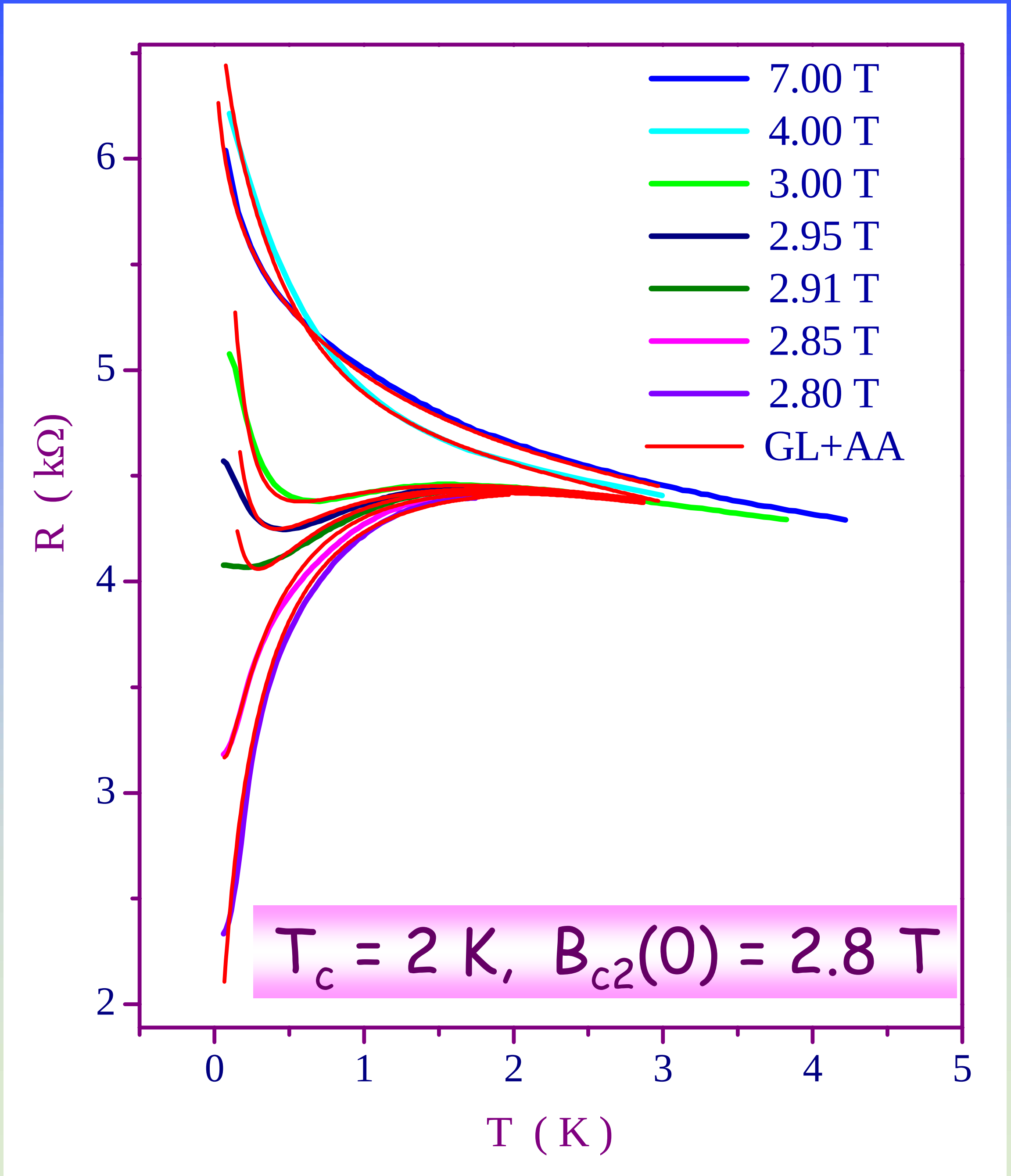
Cooper Channel

+

Aronov - Altshuler

$\delta\sigma_{AA} \propto \ln(T)$

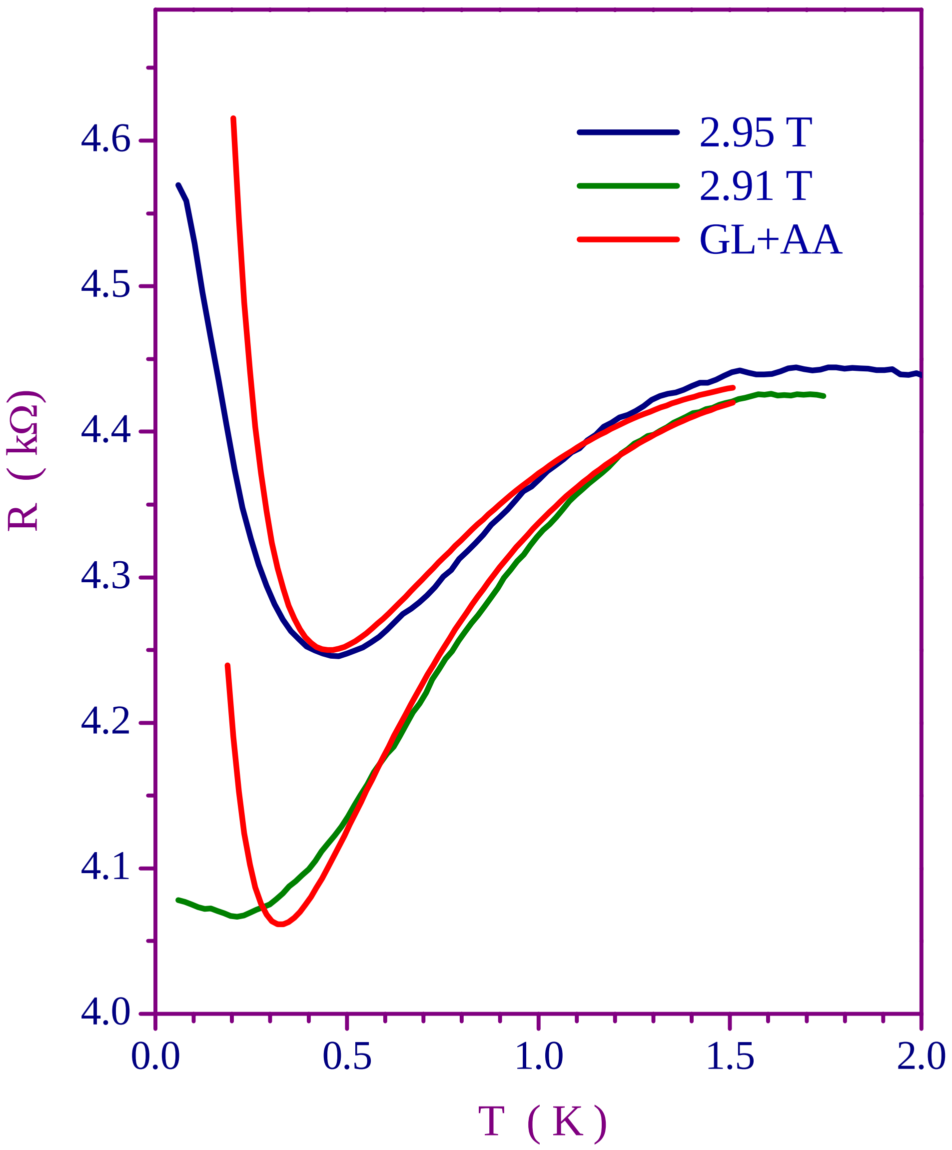
Diffusion Channel

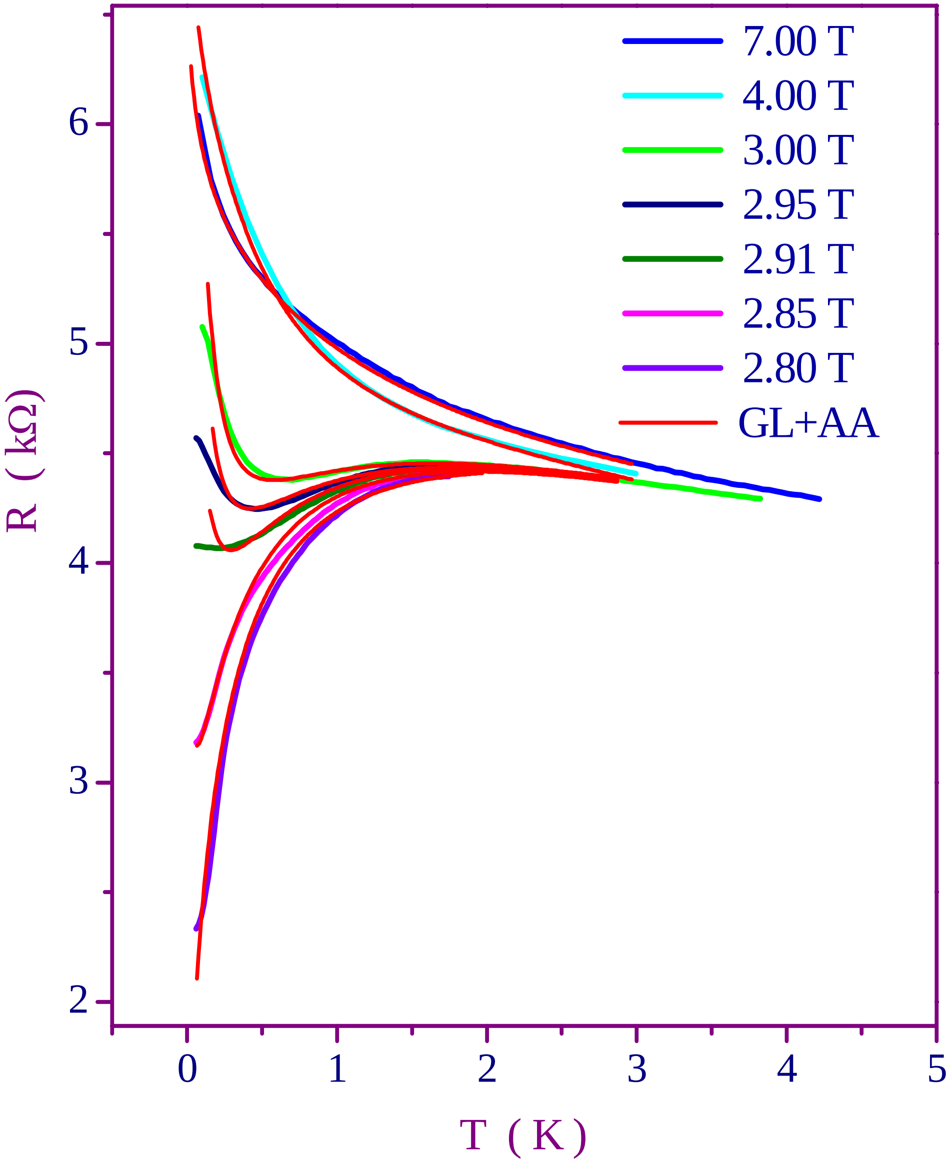


$T_c = 2$ K, $B_{c2}(0) = 2.8$ T

LRS

Temperature dependence





N. Hadacek, M. Sanquer, and J.-C. Villeger,
Double reentrant superconductor-insulator transition in TiN films,
PRB 69, 024505 (2004)

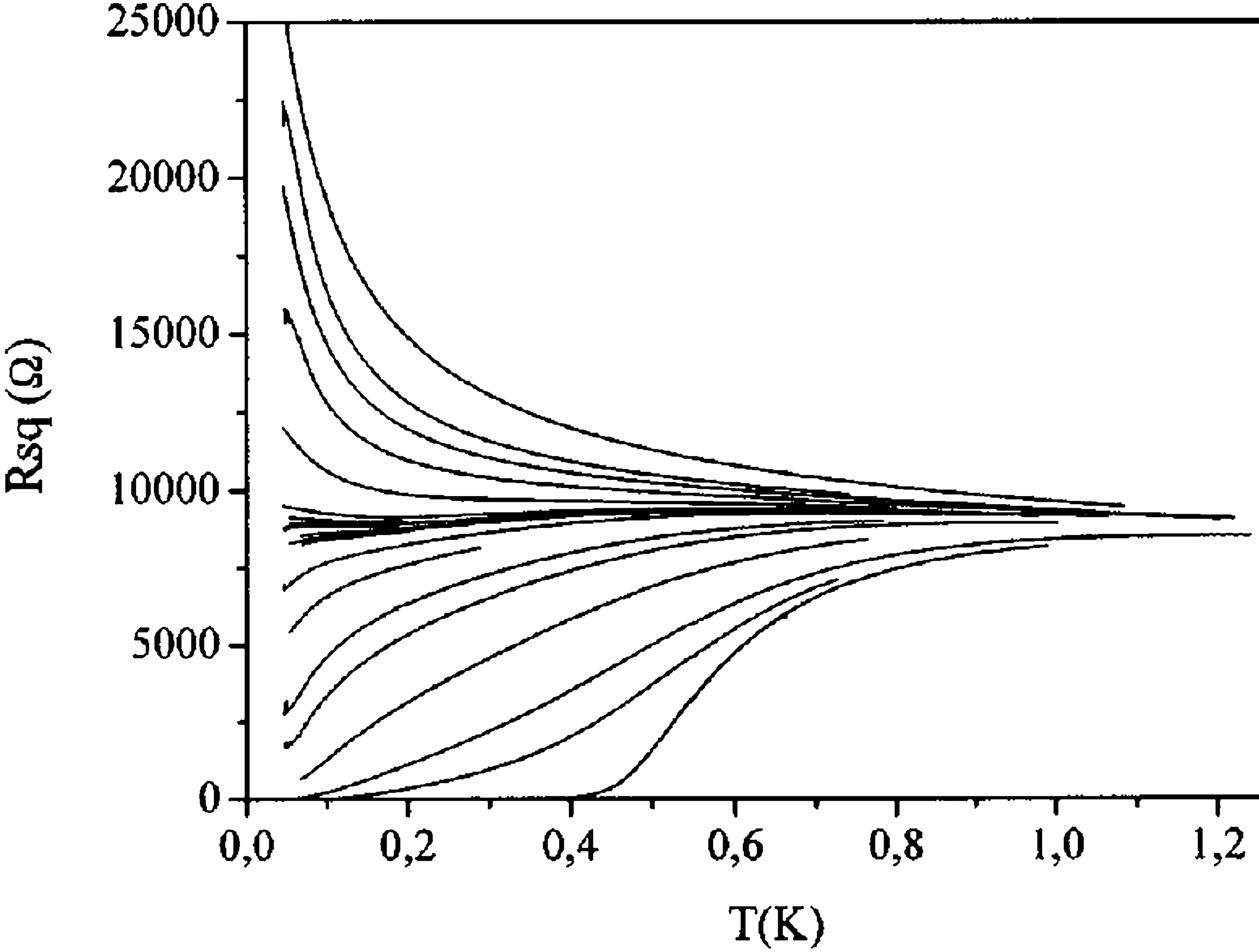
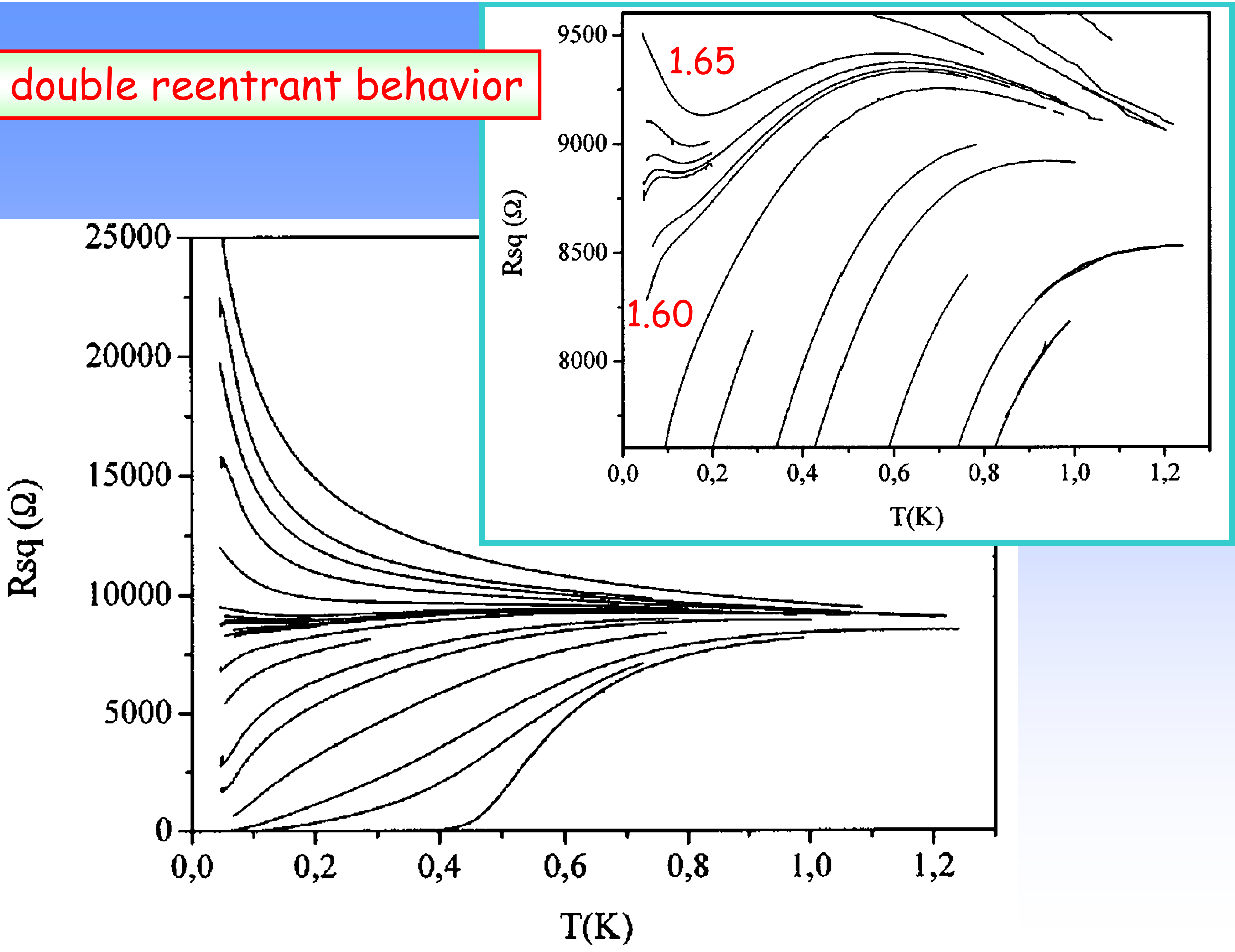
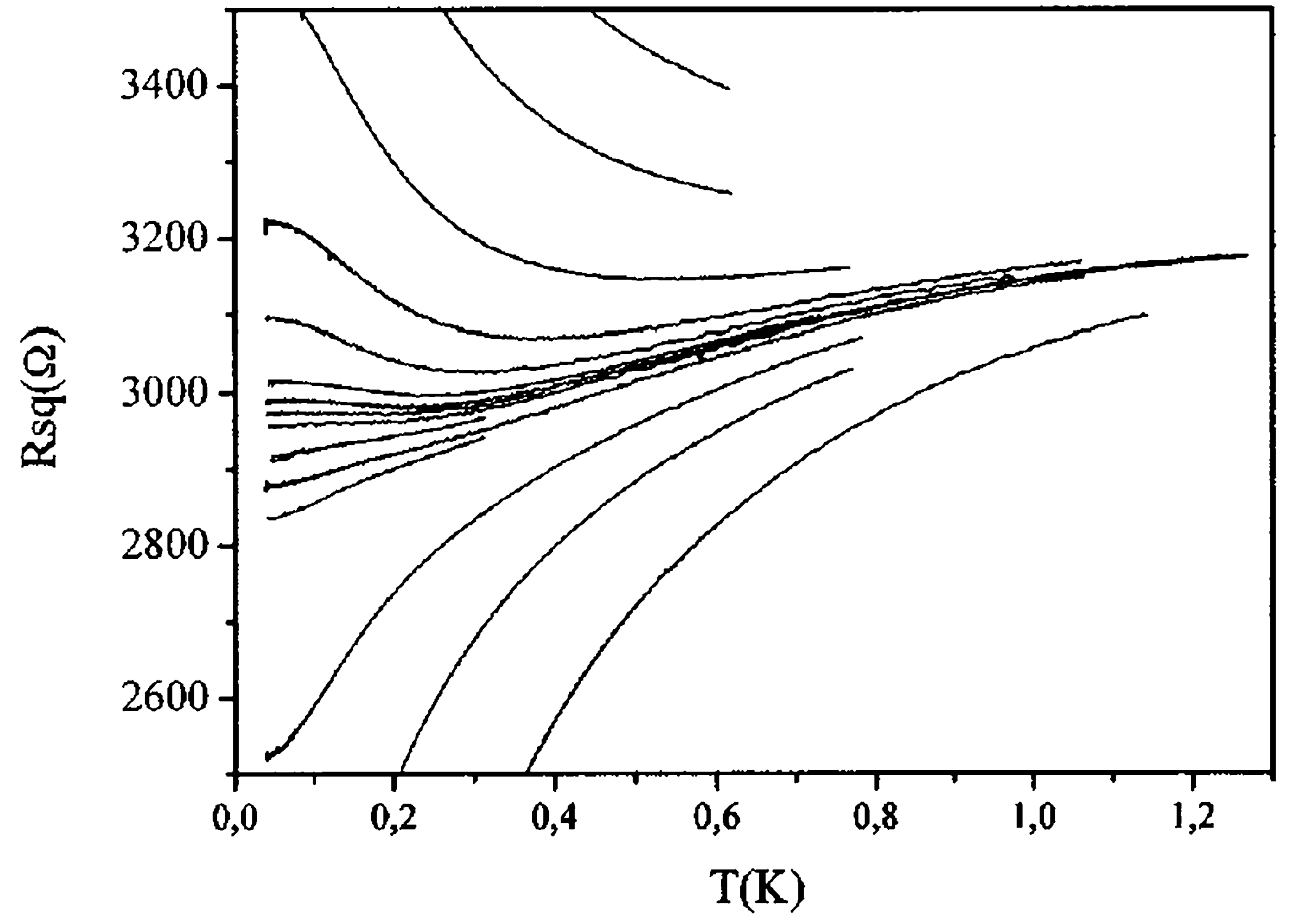


FIG. 4. Resistance per square versus temperature for various perpendicular magnetic fields. Top: TiN NH63 sample. From bottom to top the magnetic field is 0, 0.3, 0.6, 1.0, 1.3, 1.4, 1.5, 1.57, 1.60, 1.615, 1.625, 1.635, 1.64, 1.645, 1.65, 1.7, 1.8, 1.9, 2.0, 2.4 T.

double reentrant behavior

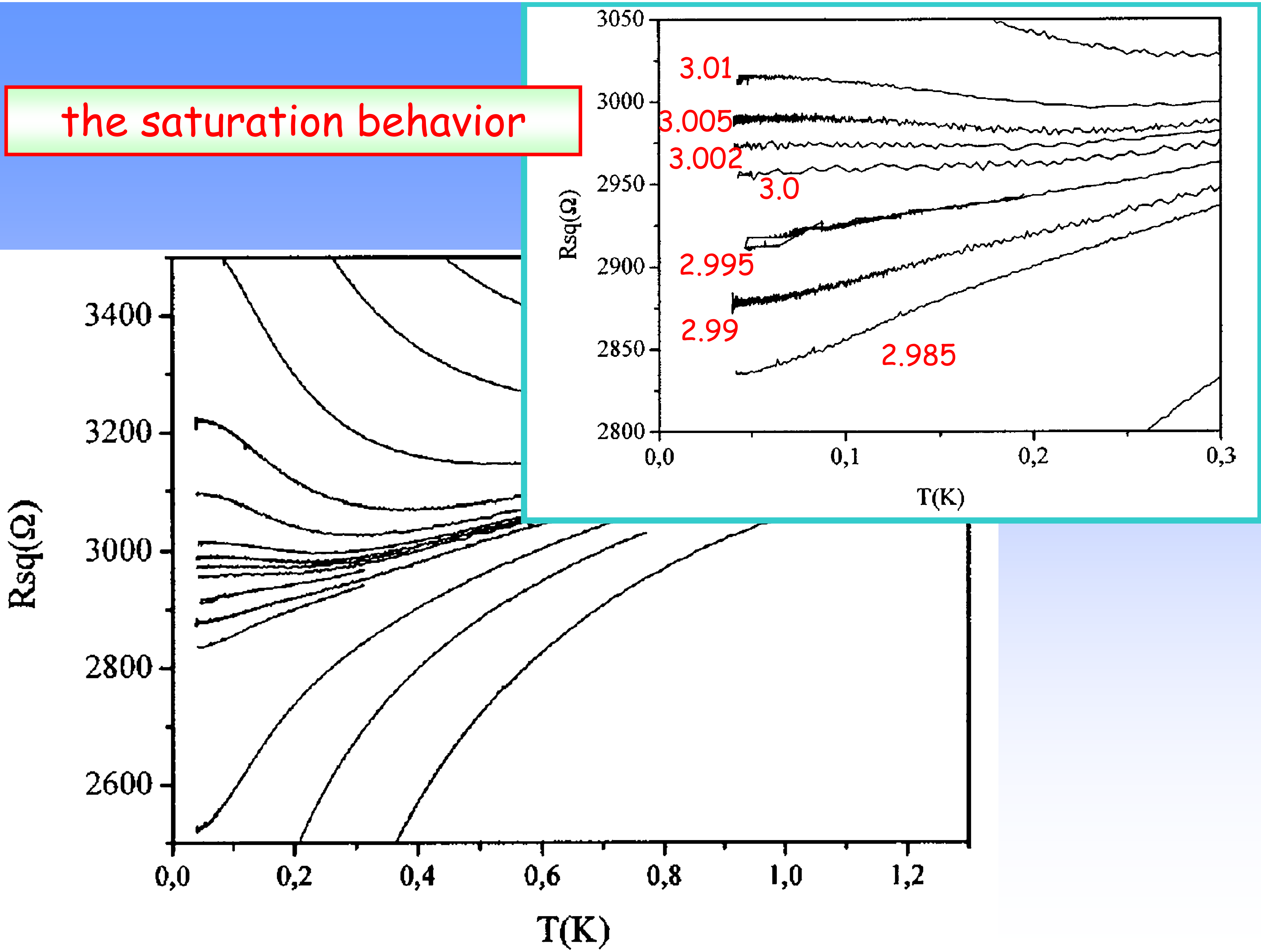


N. Hadacek, M. Sanquer, and J.-C. Villeger,
Double reentrant superconductor-insulator transition in TiN films,
PRB 69, 024505 (2004)



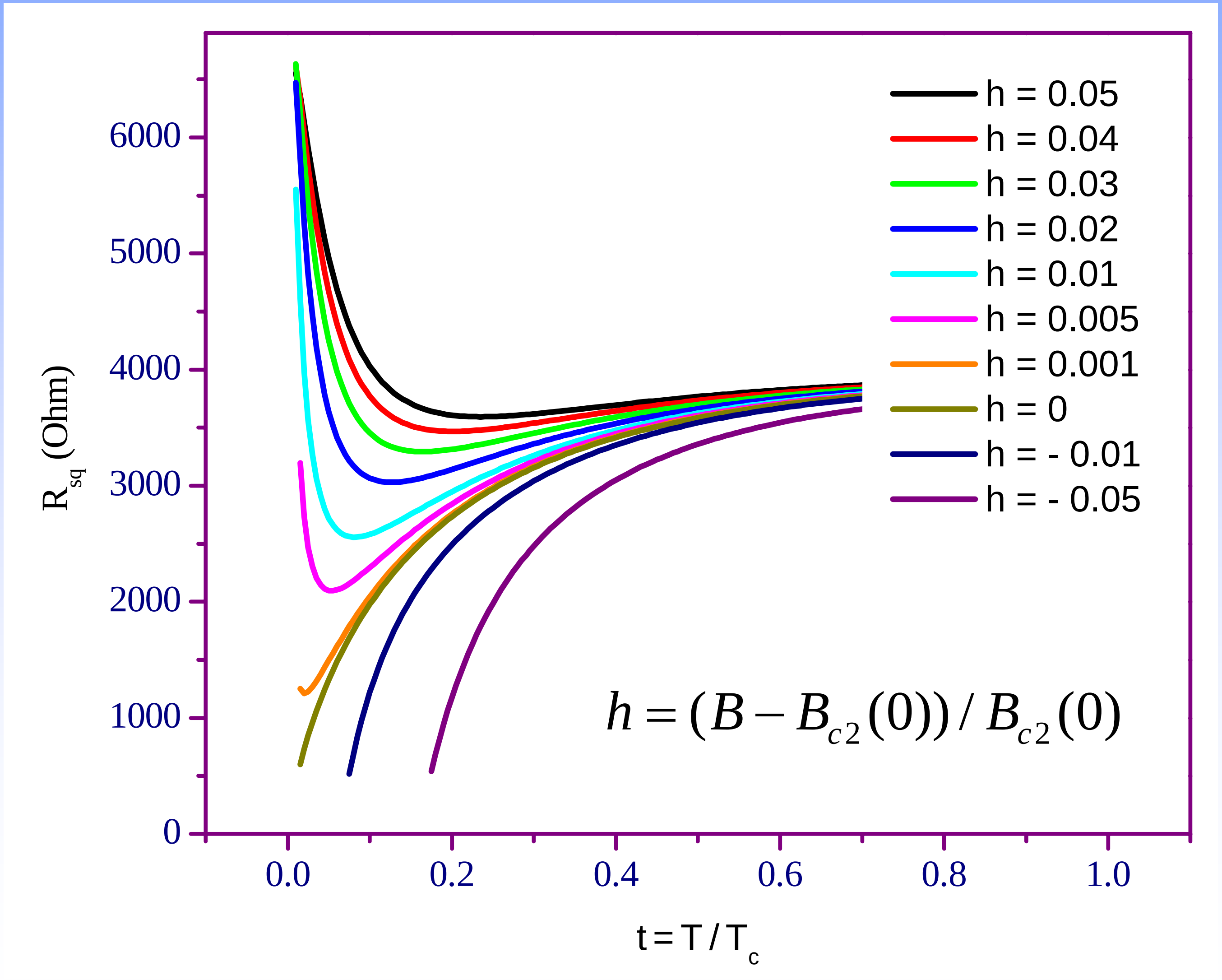
Bottom: TiN NH57 sample. From bottom to top the magnetic field is 2.8, 2.9, 2.95, 2.985, 2.99, 2.995, 3.0, 3.002, 3.005, 3.01, 3.02, 3.1, 3.25, 3.5 T.

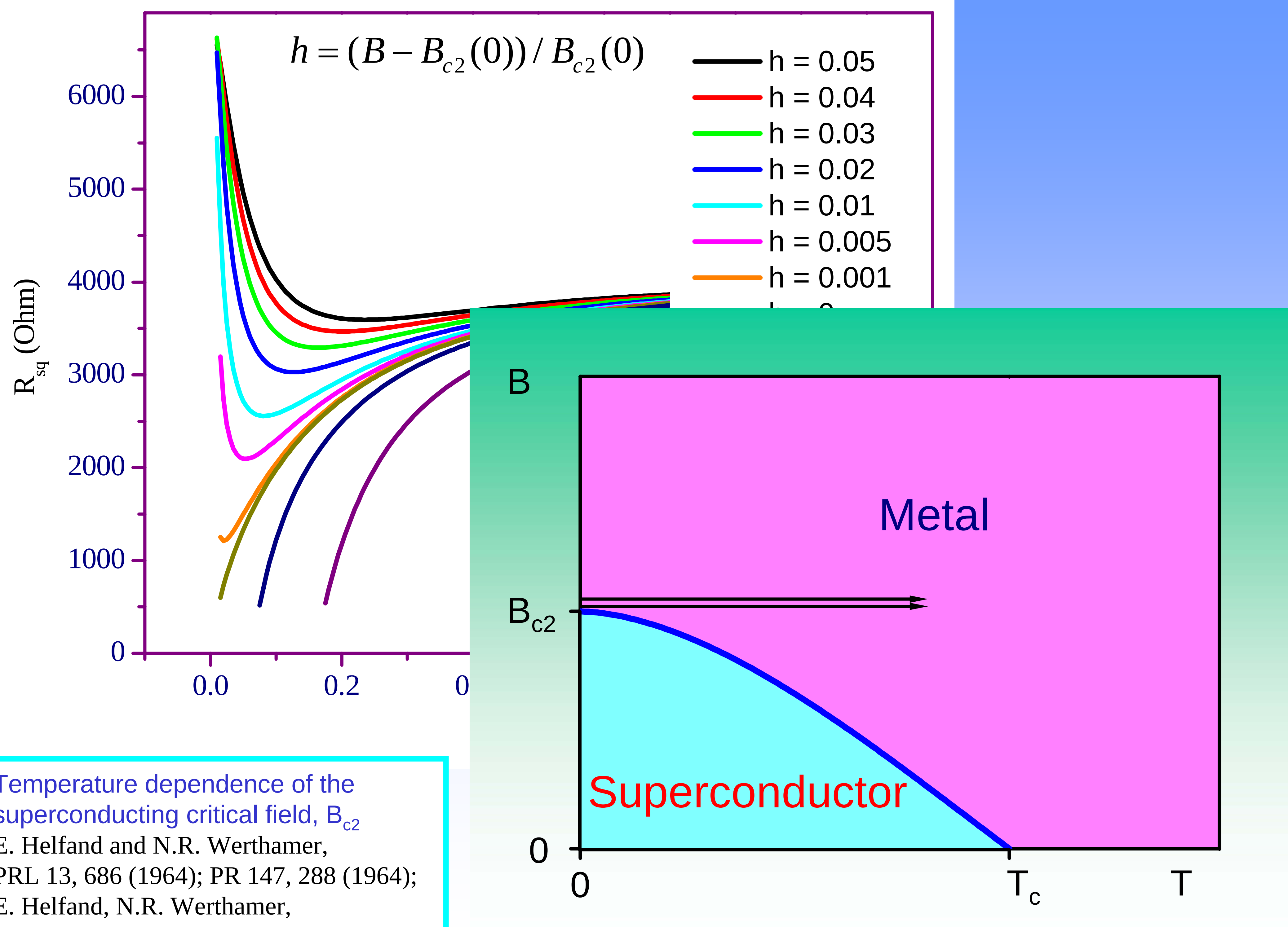
the saturation behavior



Superconducting fluctuations at low temperature

small change of B leads to a drastic change of the shape of R(T) curves





Temperature dependence of the superconducting critical field, B_{c2}

E. Helfand and N.R. Werthamer,
PRL 13, 686 (1964); PR 147, 288 (1964);
E. Helfand, N.R. Werthamer,
and C. Hohenberg, PR 147, 295 (1964)

Superconducting fluctuations at low temperature

What about the saturation and double reentrant behavior?..

Practically, always there is

inevitable dispersion of $B_{c2}(0)$ along the film…

fragmentation on two phases:
in the very region of the magnetic fields close to $B_{c2}(0)$ the film most likely constitutes the superconducting islands embedded in the normal metal

The more resistive film, the larger fluctuations in T_c and $B_{c2}(0)$

How we can include this effect in our calculations?

First way

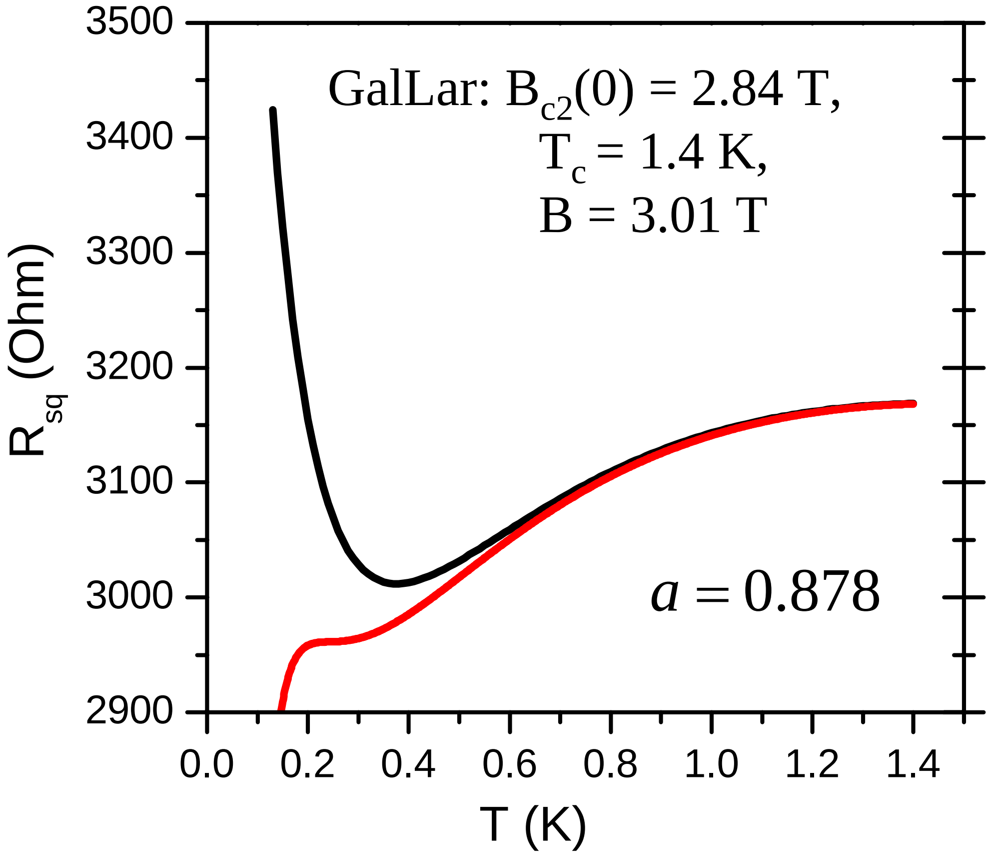
fragmentation on two phases:

$$\Delta G = a \cdot \Delta G_1 + (1 - a) \cdot \Delta G_2$$

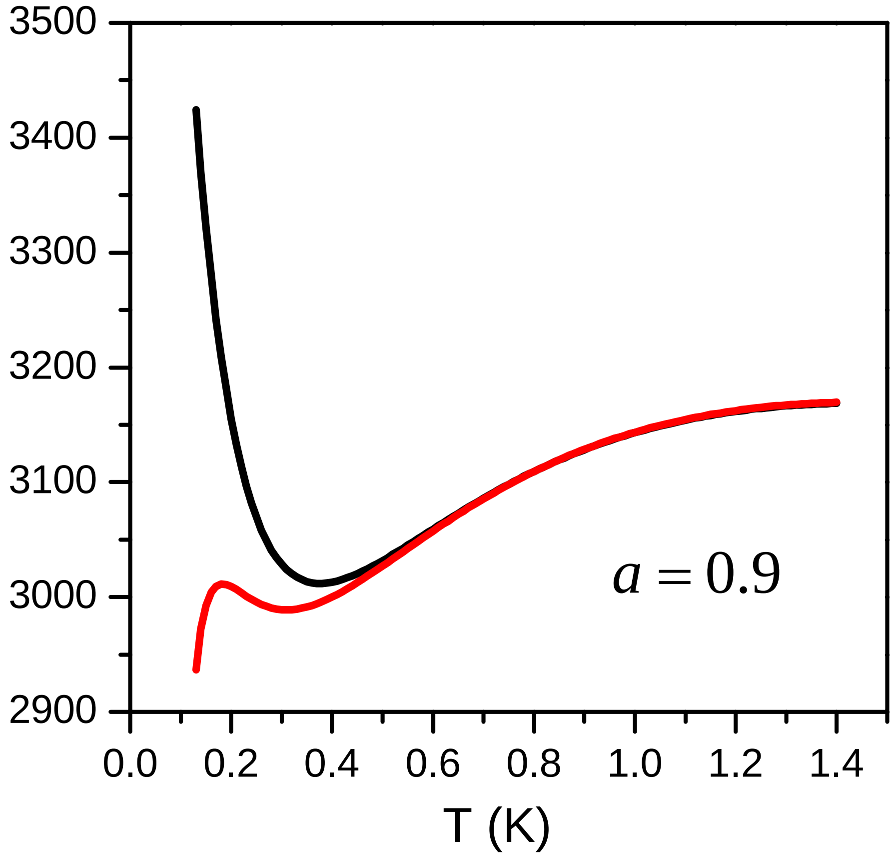
$$\Delta G_1 : B_{c2}(0) = 2.81\ \mathrm{T},\ T_c = 1.4\ \mathrm{K}$$

$$\Delta G_2 : B_{c2}(0) = 3.03\ \mathrm{T},\ T_c = 1.5\ \mathrm{K}$$

the saturation behavior



double reentrant behavior

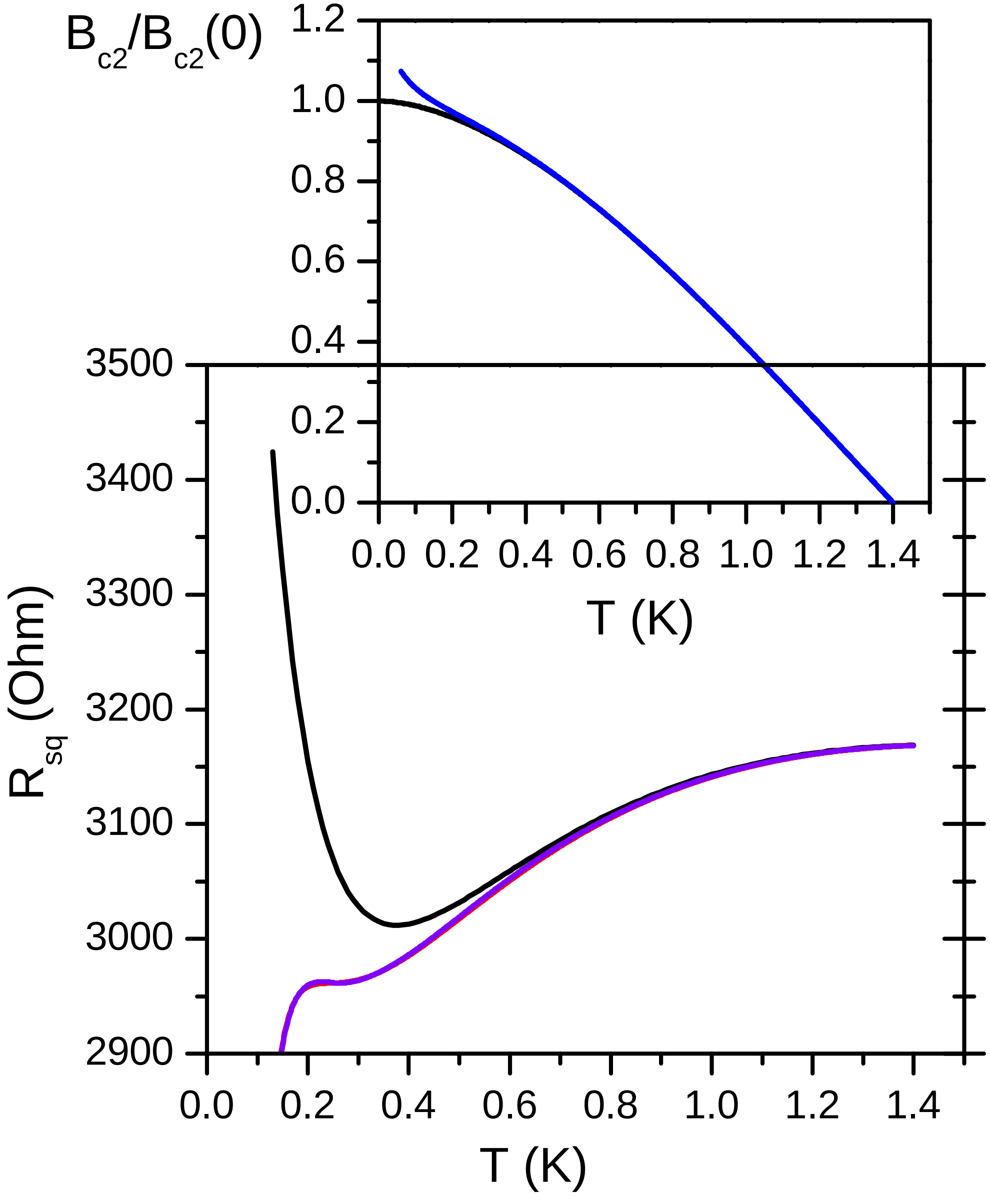


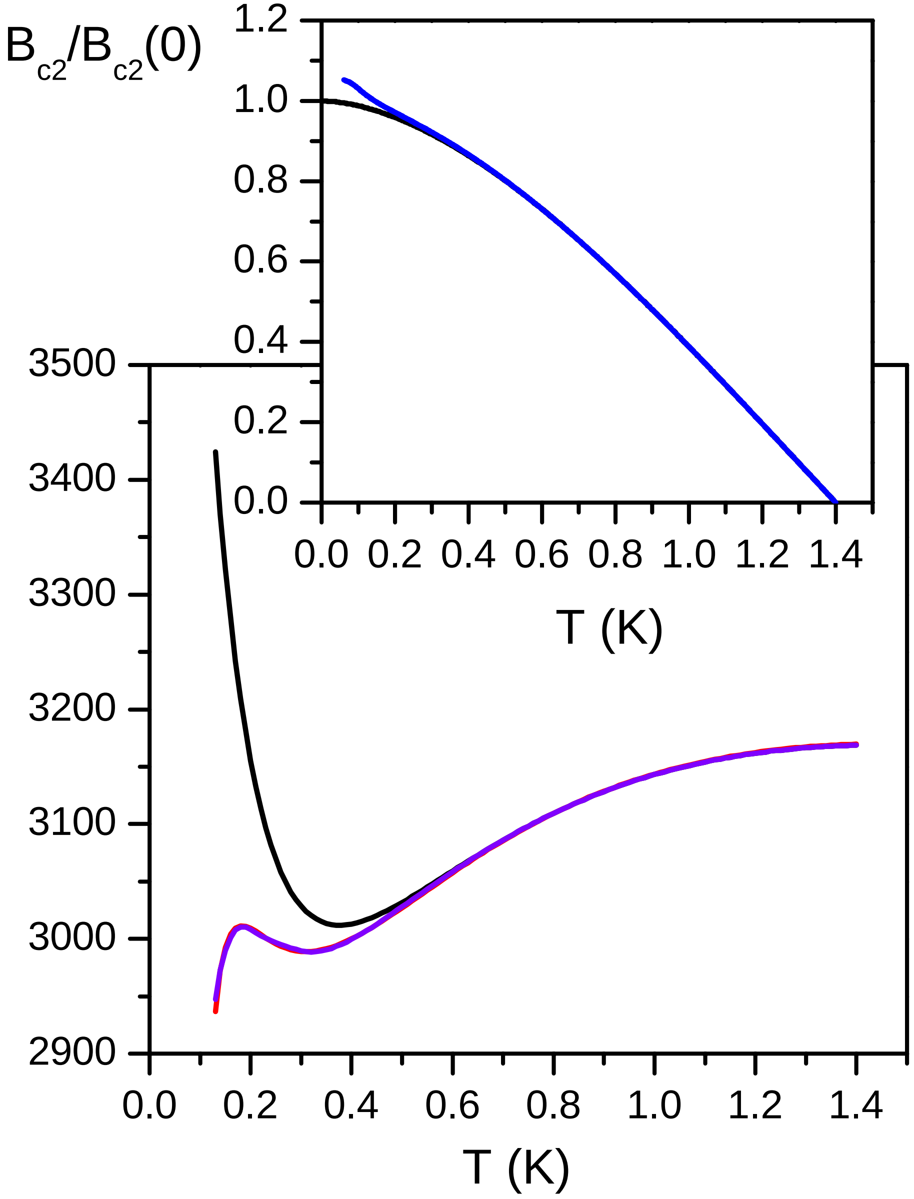
Second way

modificated $B_{c2}(T)$

the saturation behavior

double reentrant behavior





Mesoscopic effects in Disordered Superconductors near H_{c2}

B. Spivak and Fei Zhou, PRL 74, 2800 (1995)

In the case of bulk samples at $T = 0$, due to the existence of the mesoscopic fluctuations, superconducting solutions of mean field theory exist in arbitrary H (see Fig. 2). This means that although $T_c(H)$ decreases with H it is never zero in the framework of mean field theory.

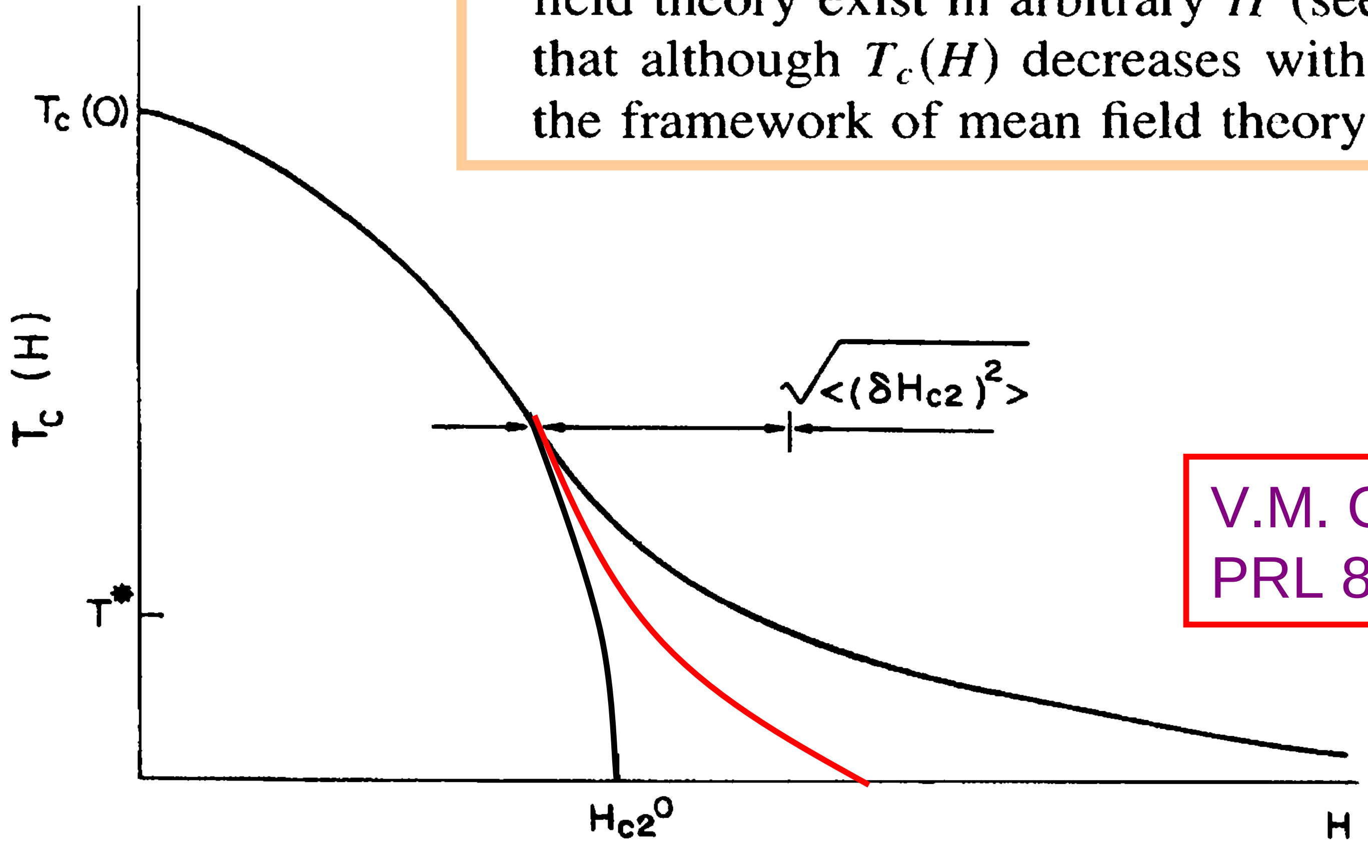
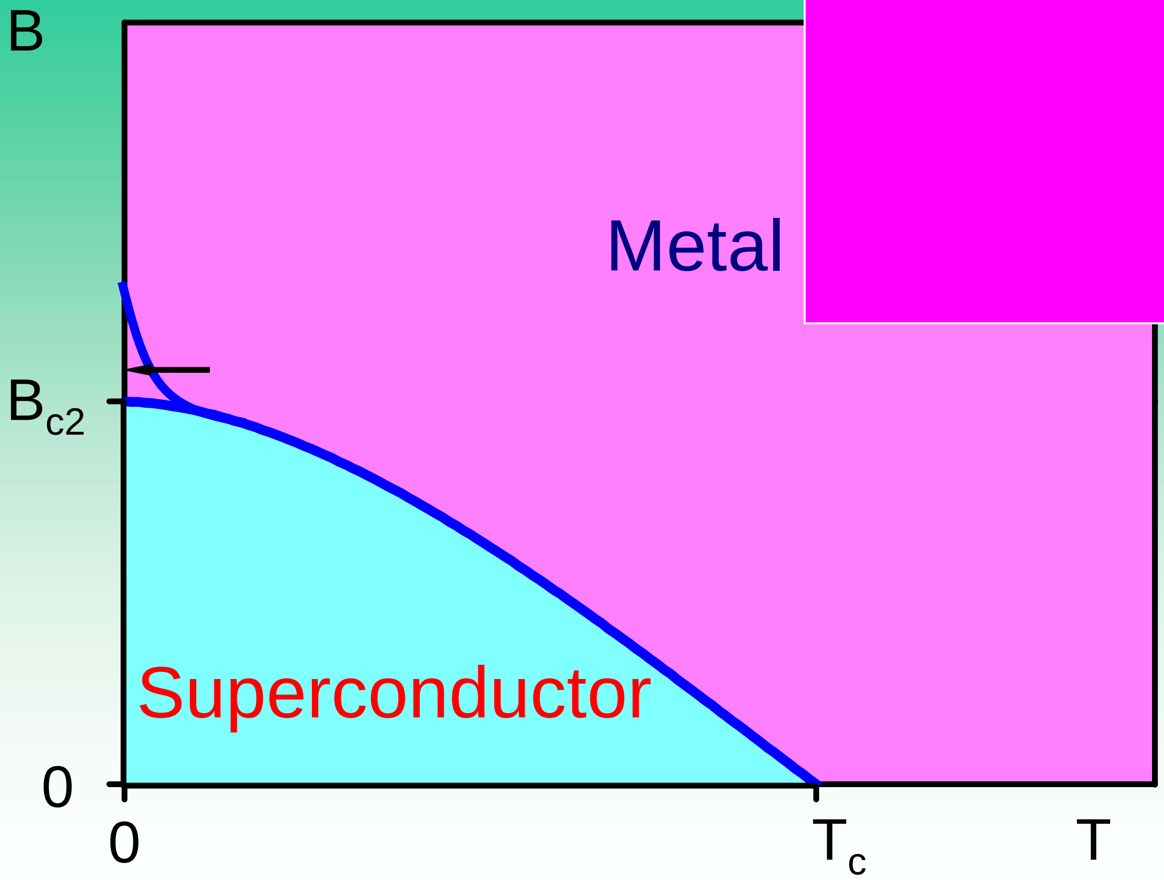


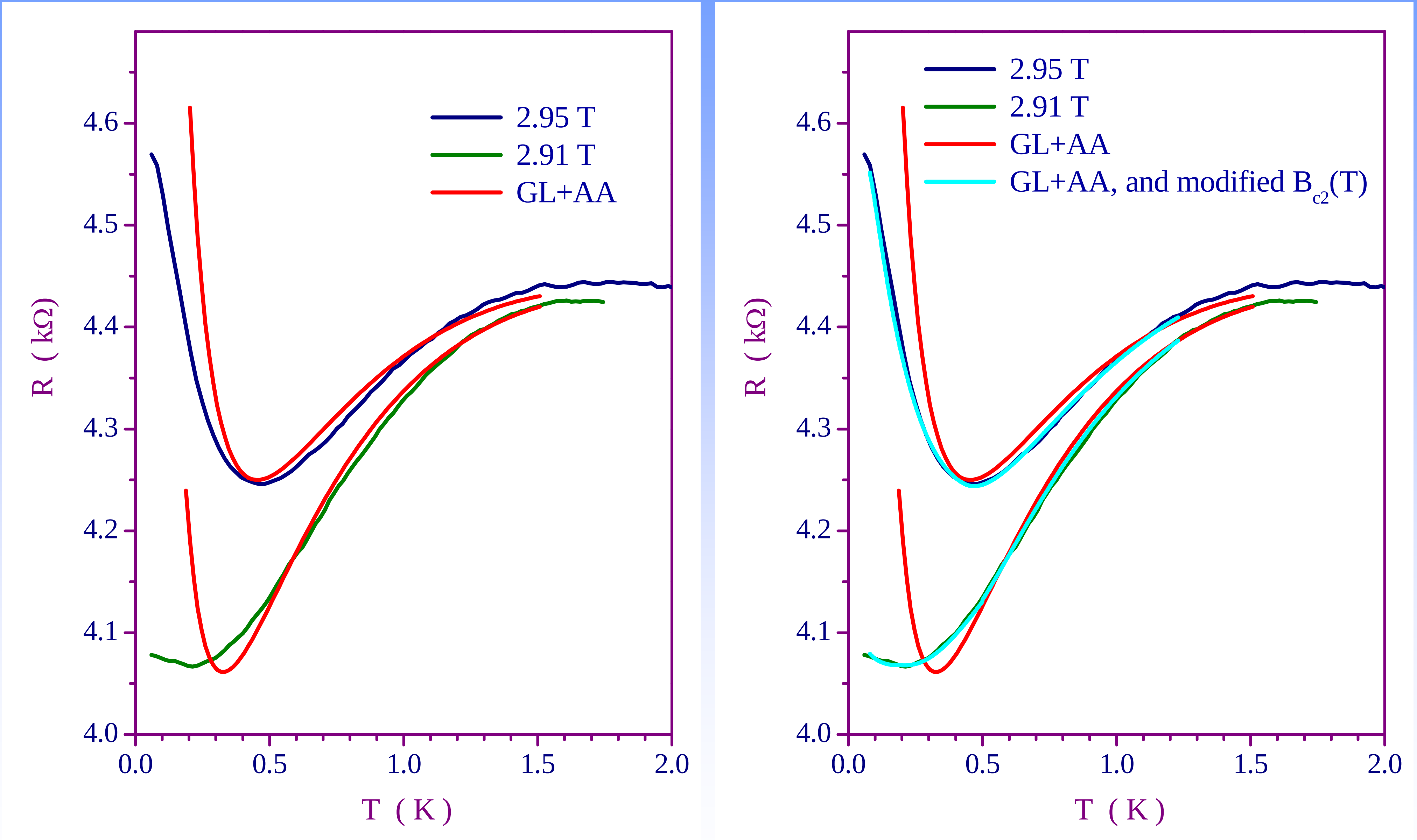
FIG. 2. Qualitative picture of $T_c(H)$ in bulk samples.

V.M. Galitski and A.I. Larkin, PRL 87, 087001 (2001)


B
Metal
B_c2
Superconductor
0
0
T_c
T

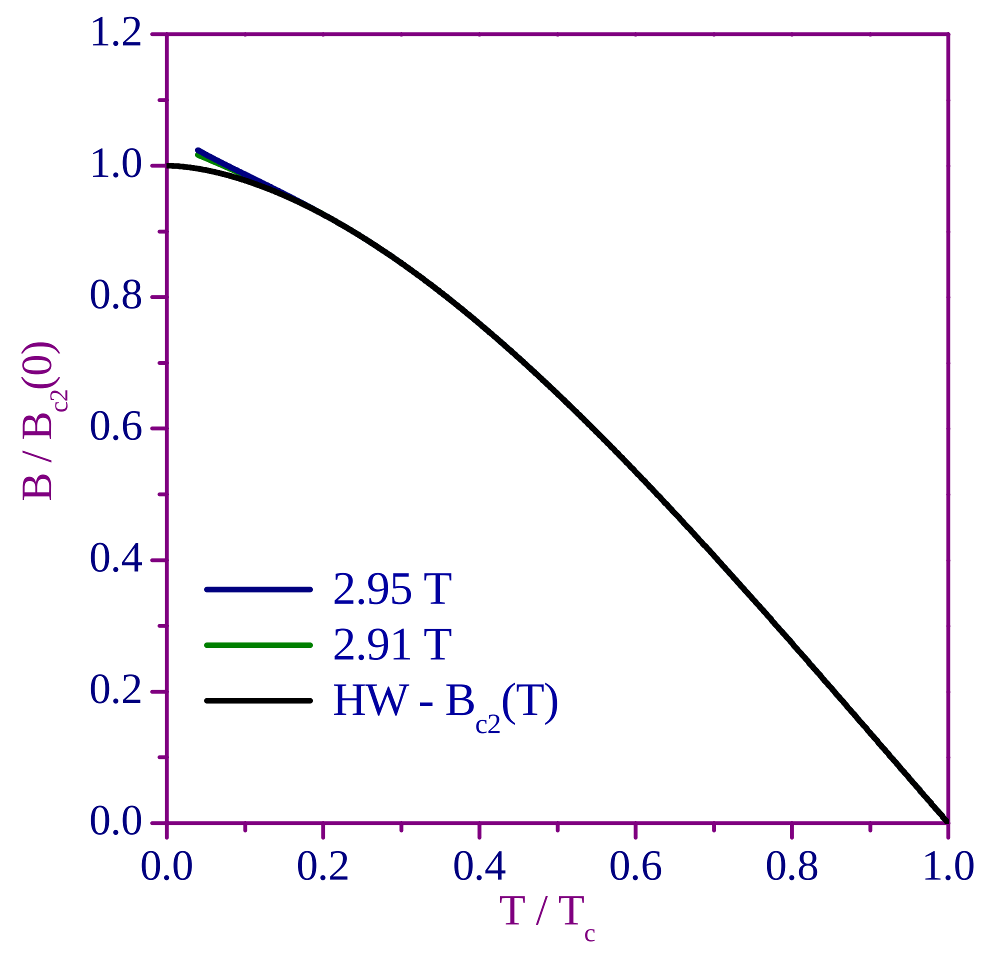
LRS

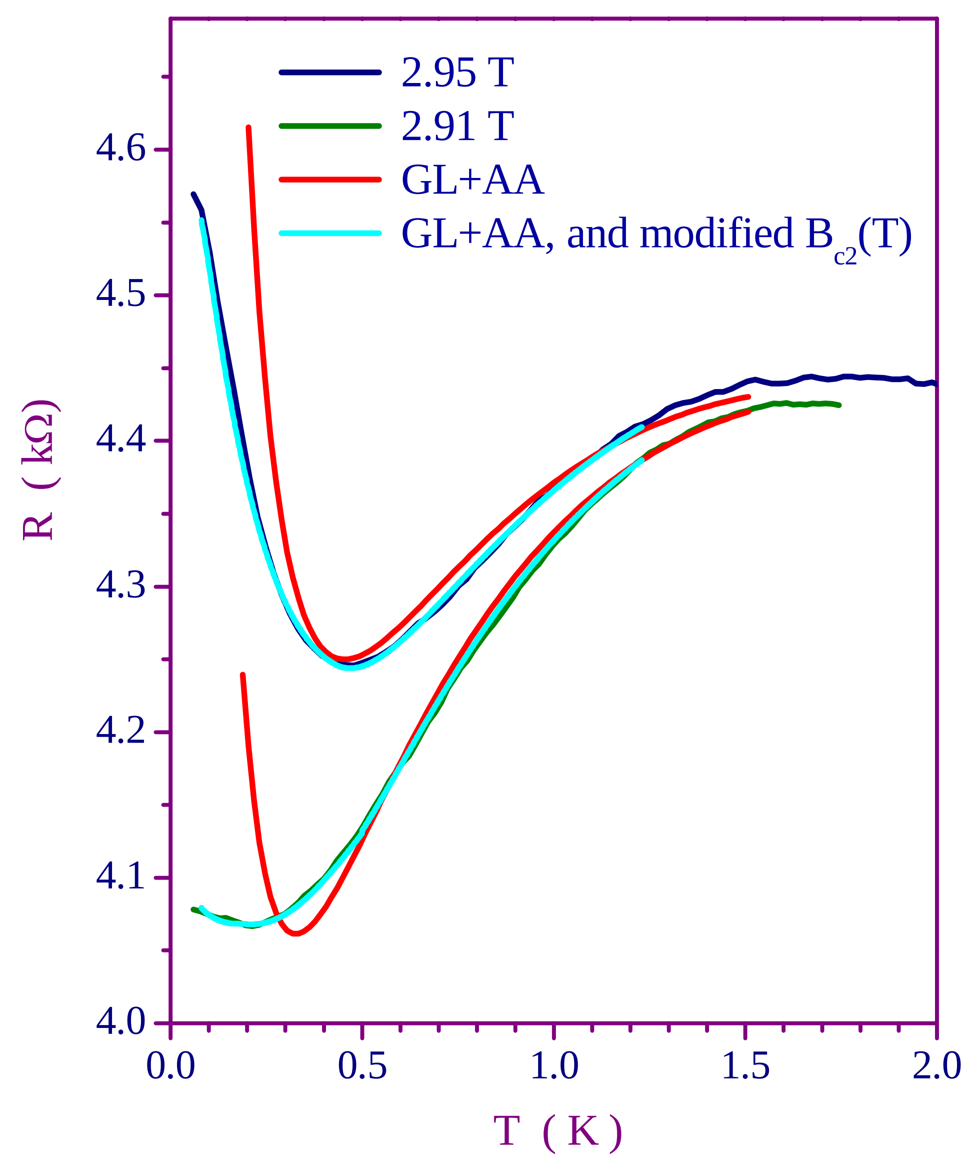
Temperature dependence



LRS

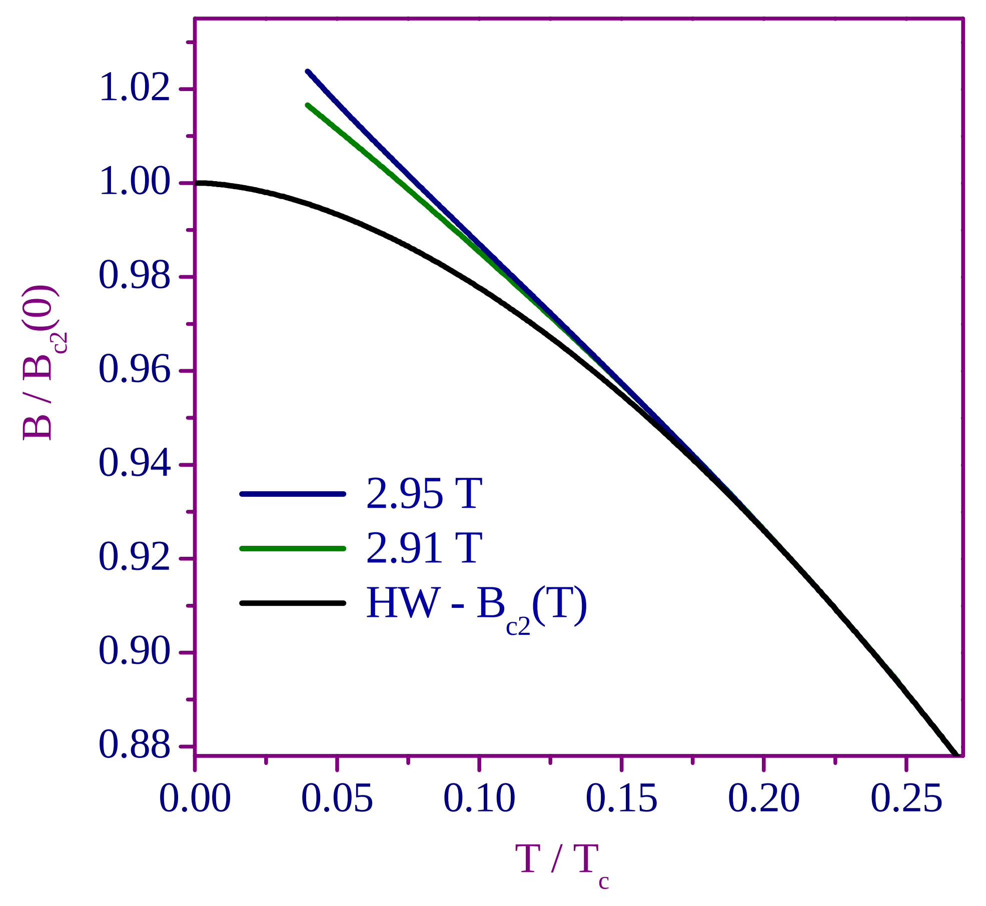
Temperature dependence

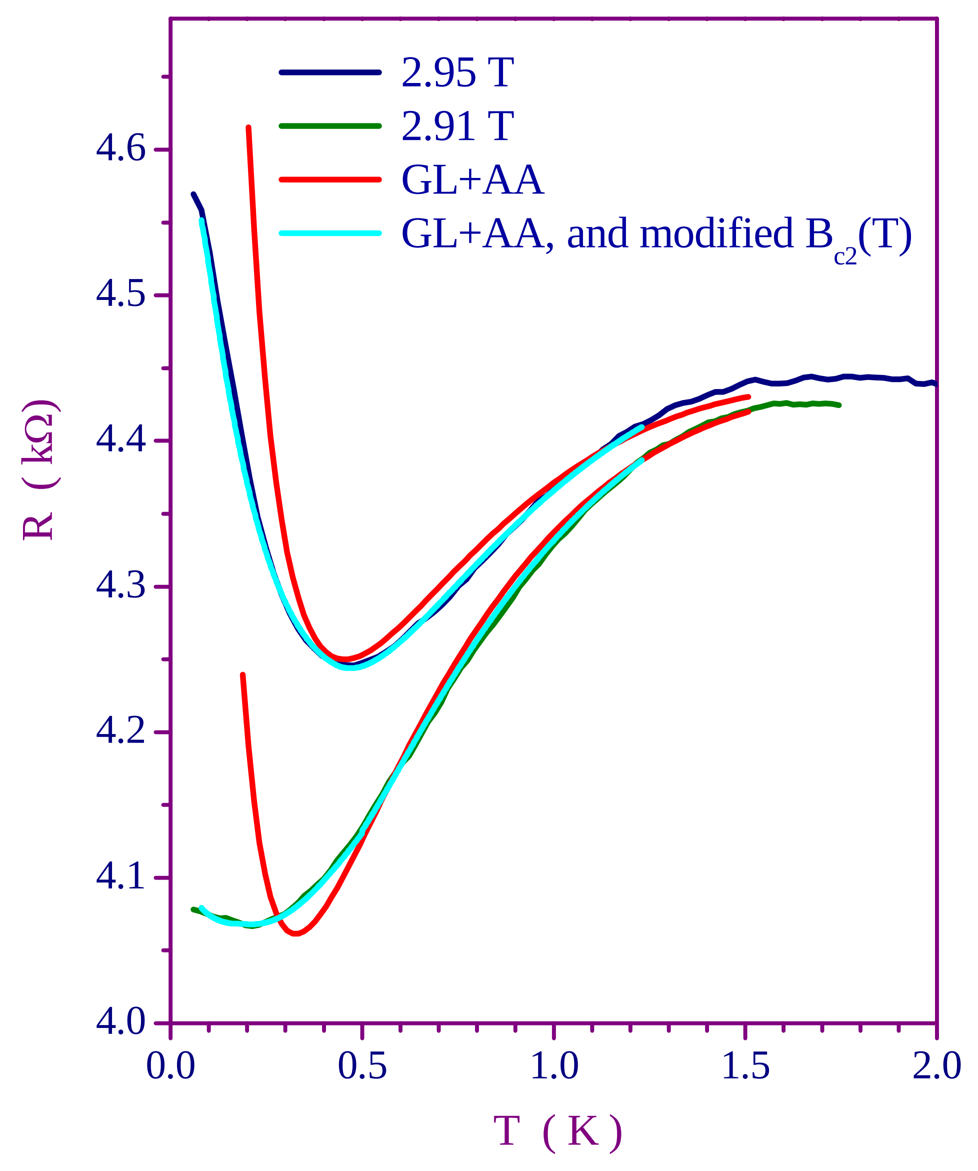




LRS

Temperature dependence





Suppression of Superconductivity by **Magnetic Field**

Conclusion

superconductor – metal transition → ***superconductor – insulator transition***

Strong quantum or mesoscopic fluctuations cause the fragmentation of uniformly disordered film on two phases, namely, the formation of local superconducting islands surrounded by a normal metal.

A uniformly disordered film may appear as a granular one in terms of its superconducting properties