The Superconductor-Insulator Transition Far From Equilibrium

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KITP, 2015

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Tal Levinson

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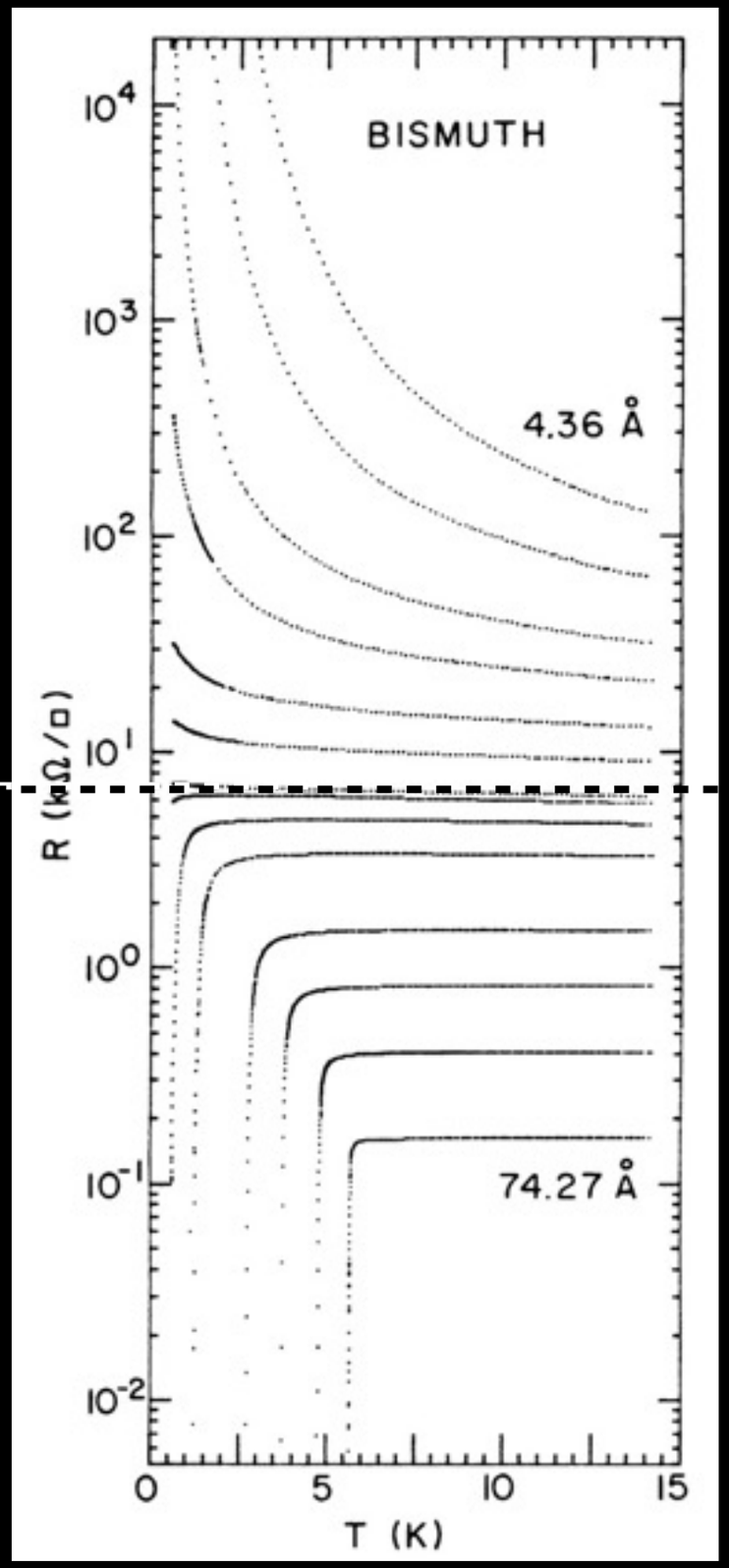
The Superconductor-Insulator Transition

M. Strongin, et. al., Phys. Rev. B1, 1078 (1970).

Haviland, Liu and Goldman, Phys. Rev. Lett. 62, 2180 (1989)...



Thickness

Reviews: Finkl'stein ('94)
Markovic and Goldman ('98)
Gantmakher and Dolgopolov ('10)

ARTICLES
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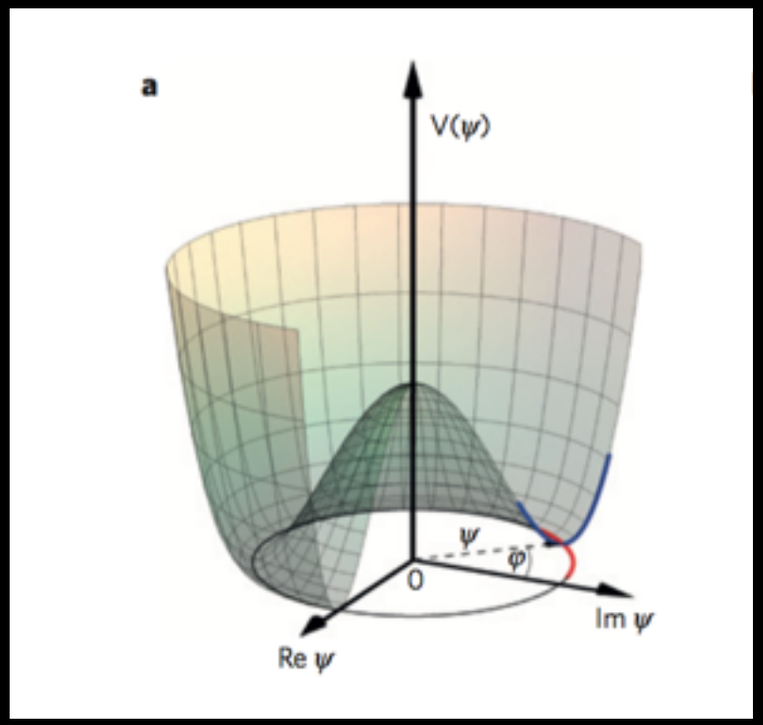
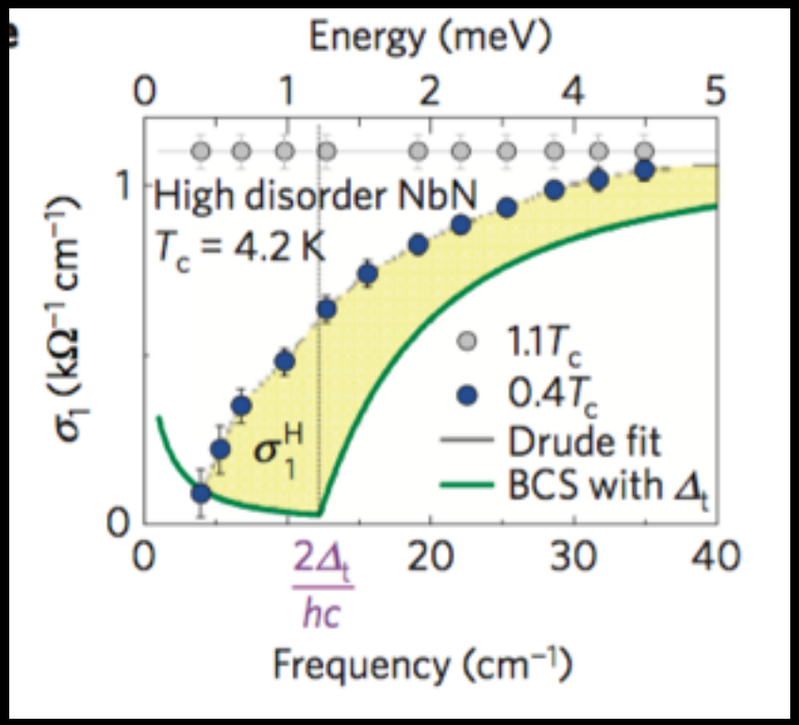
nature physics

The Higgs mode in disordered superconductors close to a quantum phase transition

Daniel Sherman[1,2†], Uwe S. Pracht[2], Boris Gorshunov[2,3,4], Shachaf Poran[1], John Jesudasan[5], Madhavi Chand[5], Pratap Raychaudhuri[5], Mason Swanson[6], Nandini Trivedi[6], Assa Auerbach[7], Marc Scheffler[2], Aviad Frydman[1*] and Martin Dressel[2]





A quantum phase transition

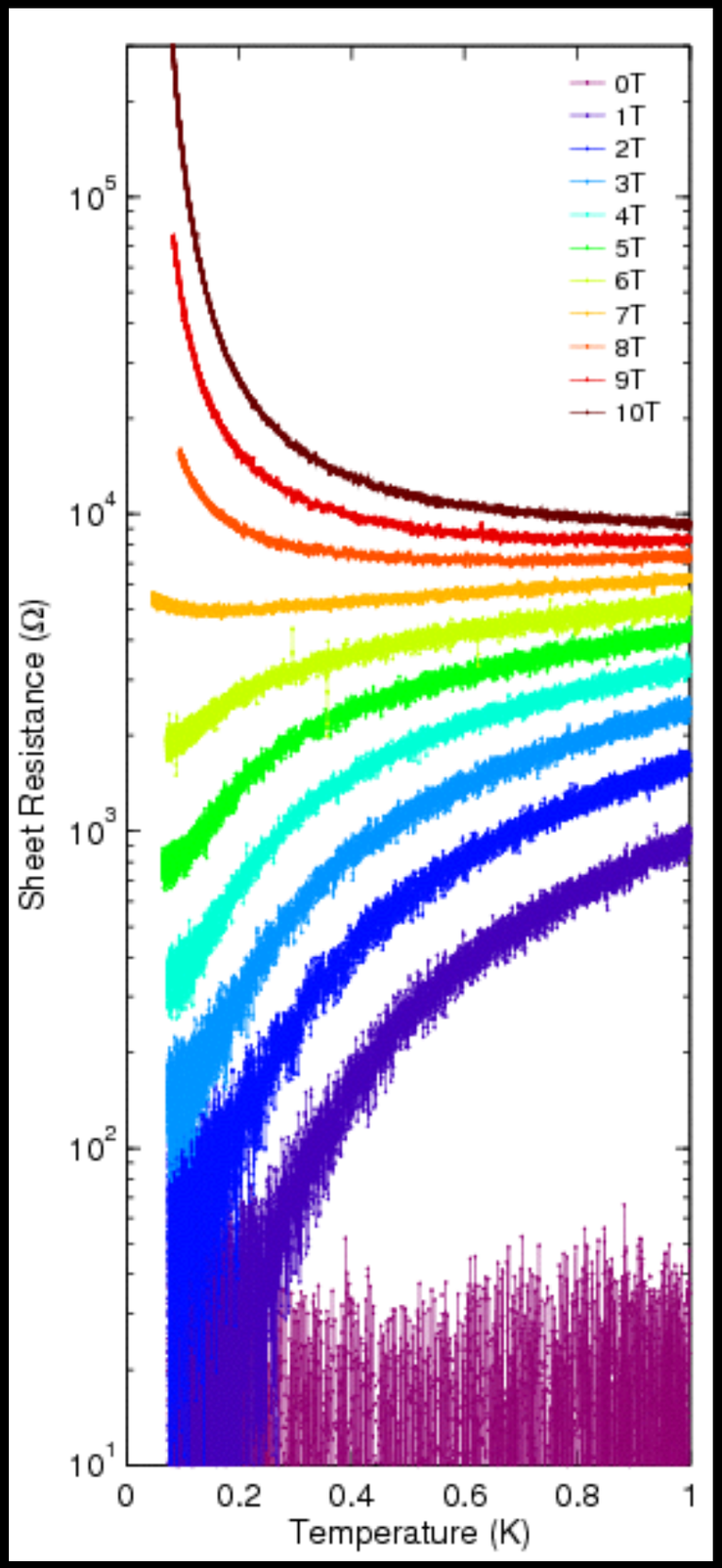
Strictly T=0.

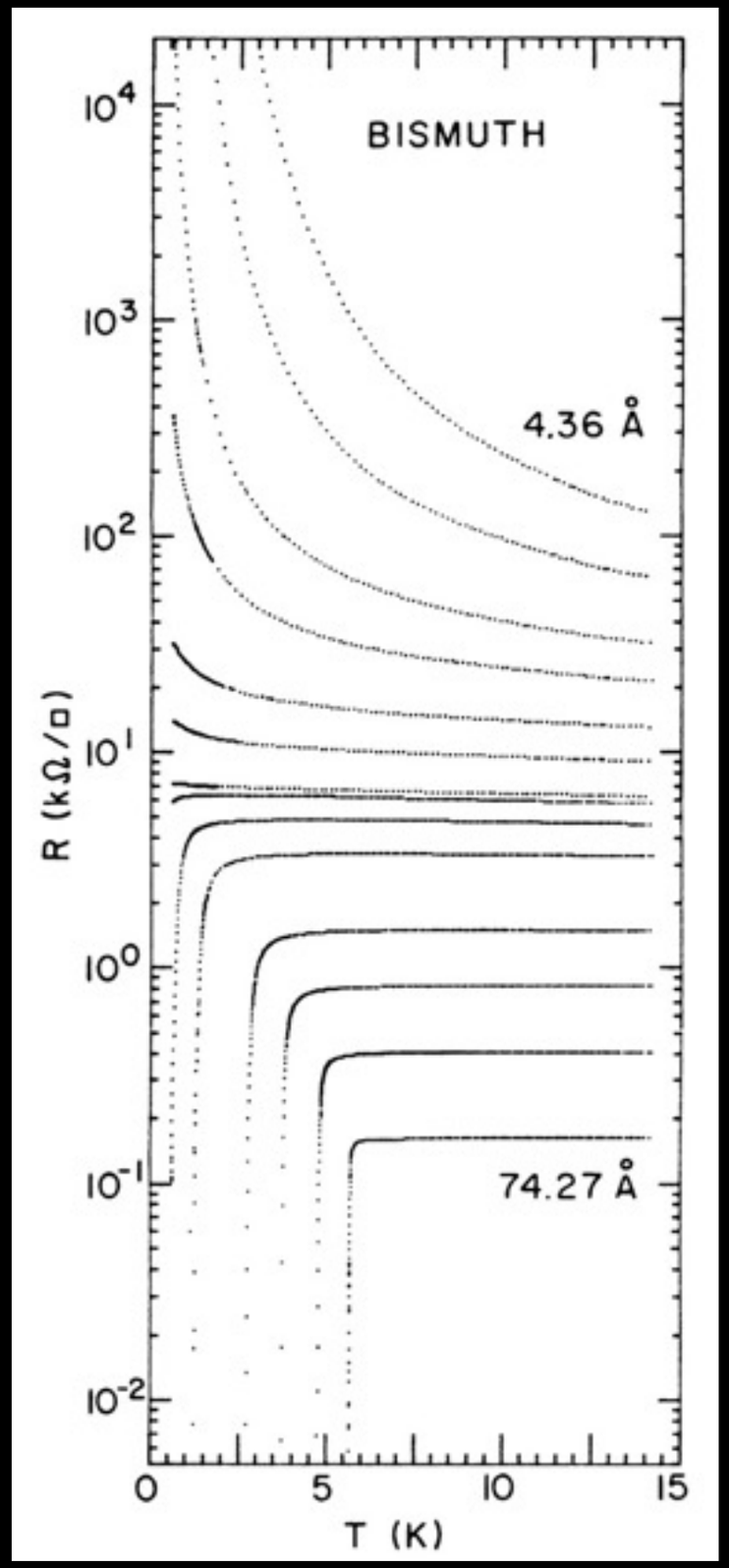
driven by:

Thickness
Magnetic field
Disorder
Carrier density
Pressure
Chemical composition
Structural composition
…

Magnetic-field dependence

Magnetic-field dependence





A quantum phase transition

How do we know?

zv = 1.26-1.31

Hebard and Paalanen 1990

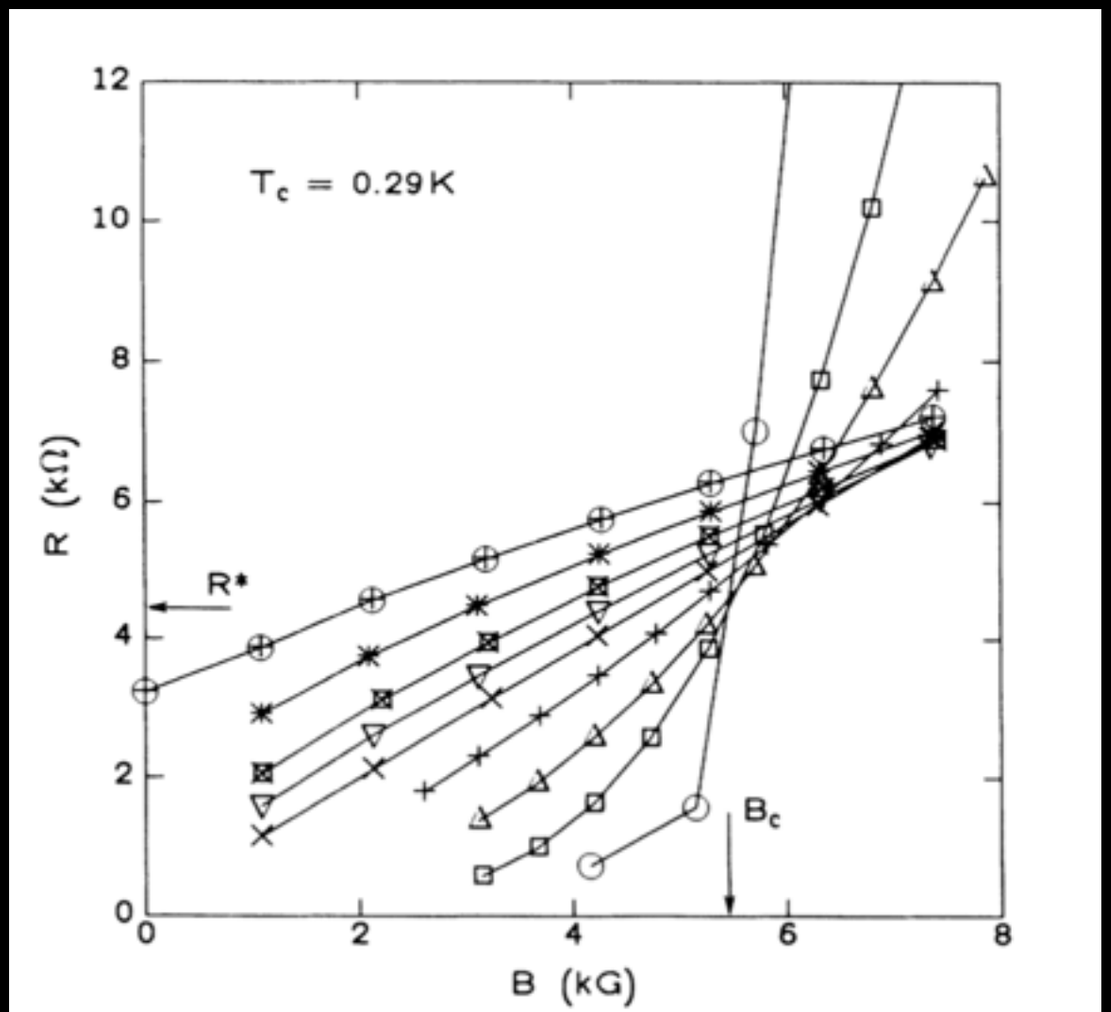
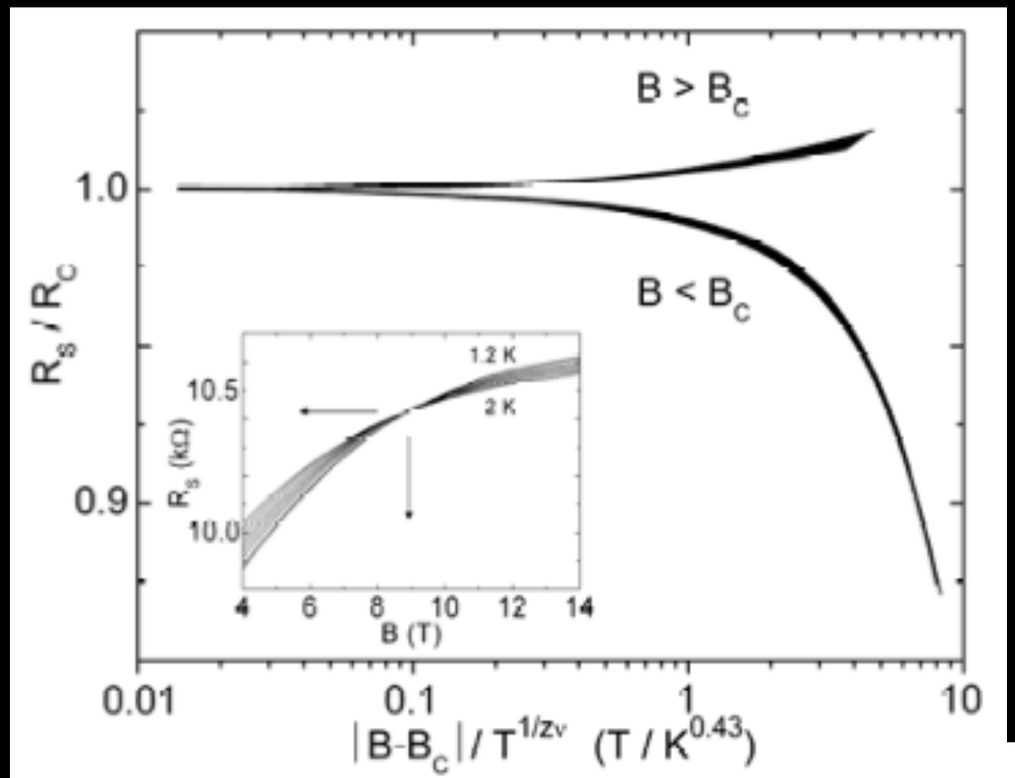
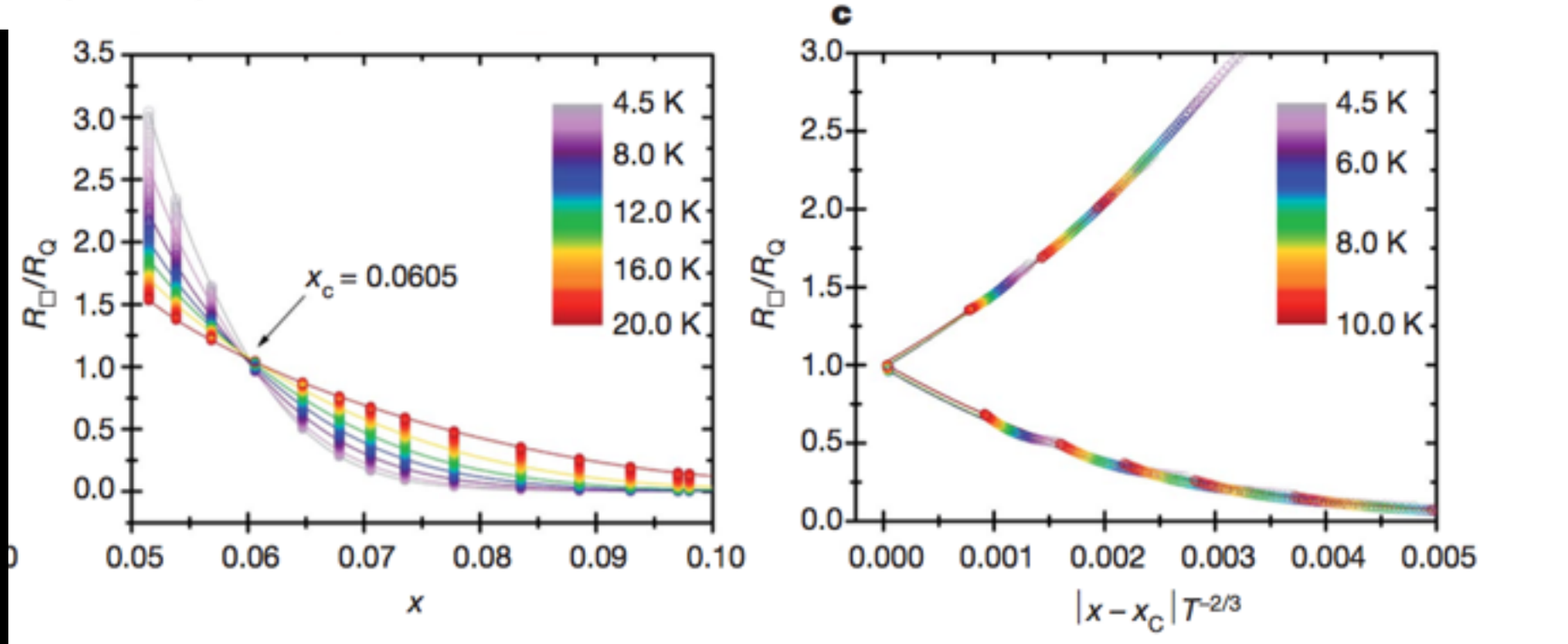


FIG. 2. Magnetic-field dependence of the resistance isotherms for the same film shown in Fig. 1. The temperatures and corresponding symbols are 0.015 K (○), 0.060 K (□), 0.114 K (△), 0.200 K (+), 0.308 K (×), 0.379 K (▽), 0.434 K (□), 0.528 K (*), and 0.599 K (⊕). The horizontal and vertical arrows identify R^* and B_c, respectively.

Scaling analisys

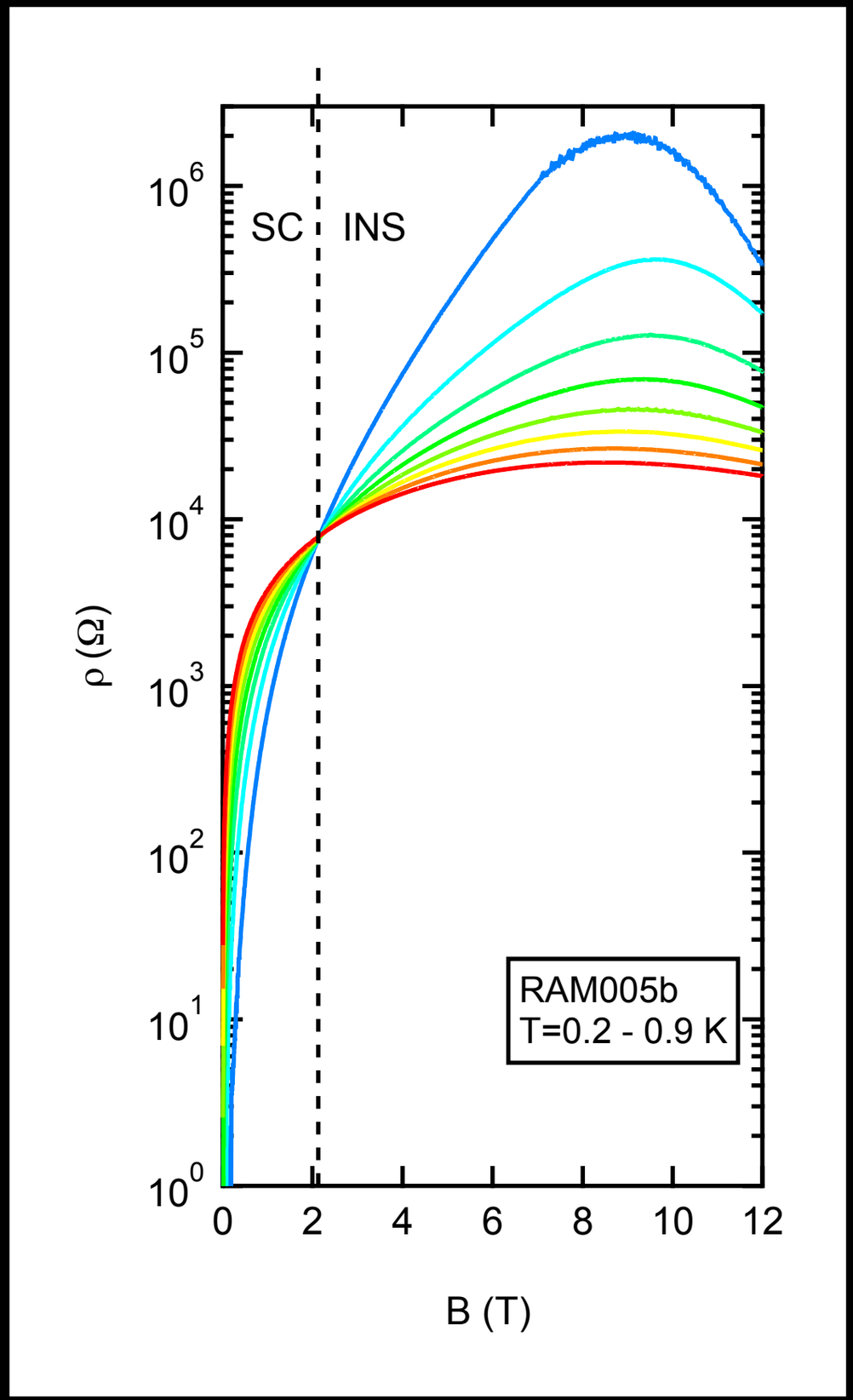


Hebard and Paalanen 1990
Yazdany and Kapitulnik 1995
…
Bollinger et al, Nature 2011
Schneider et al,
Phys. Rev. Lett. 108, 257003 (2012)
…



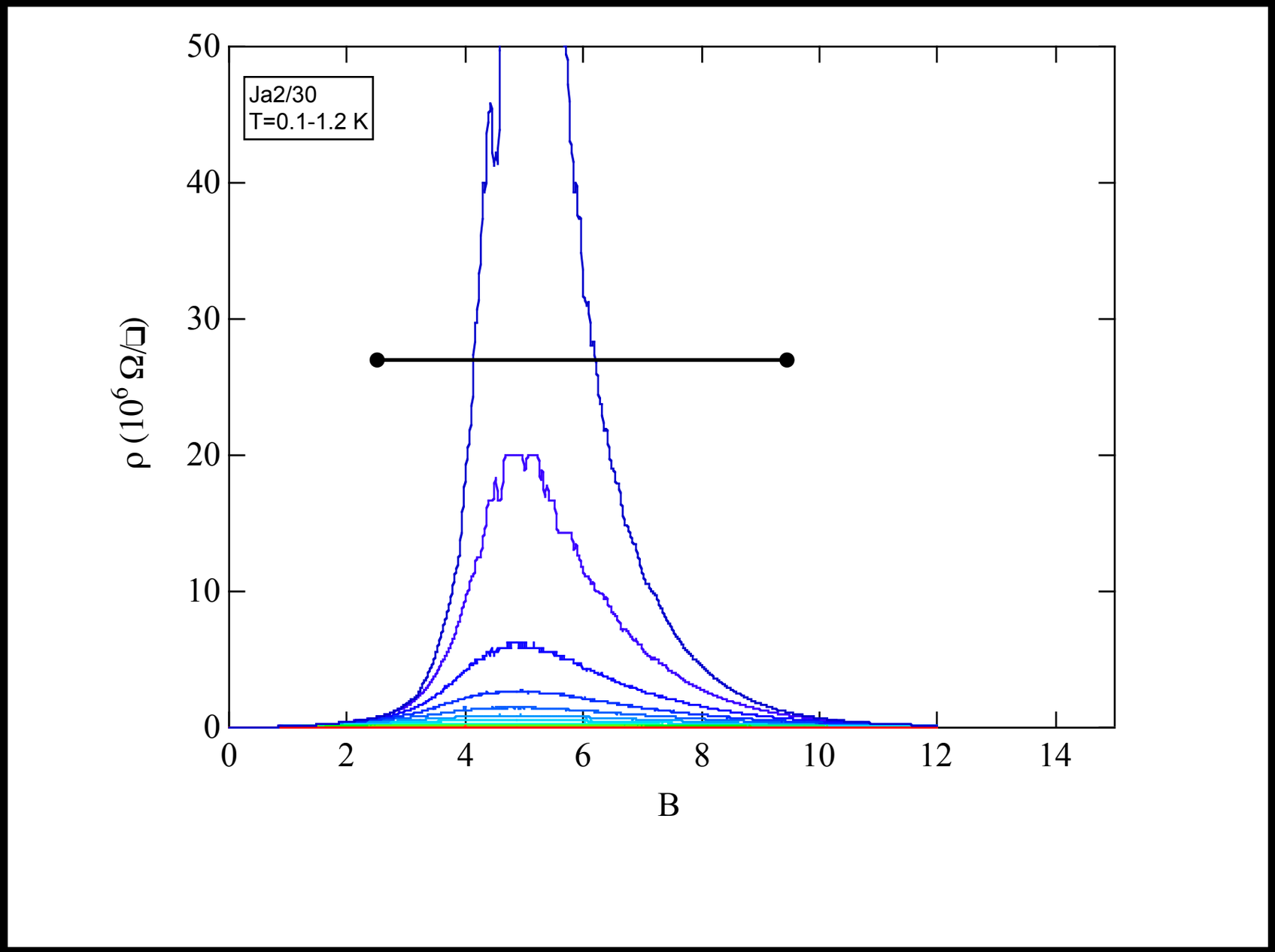
Magnetic-field dependence

a:InO

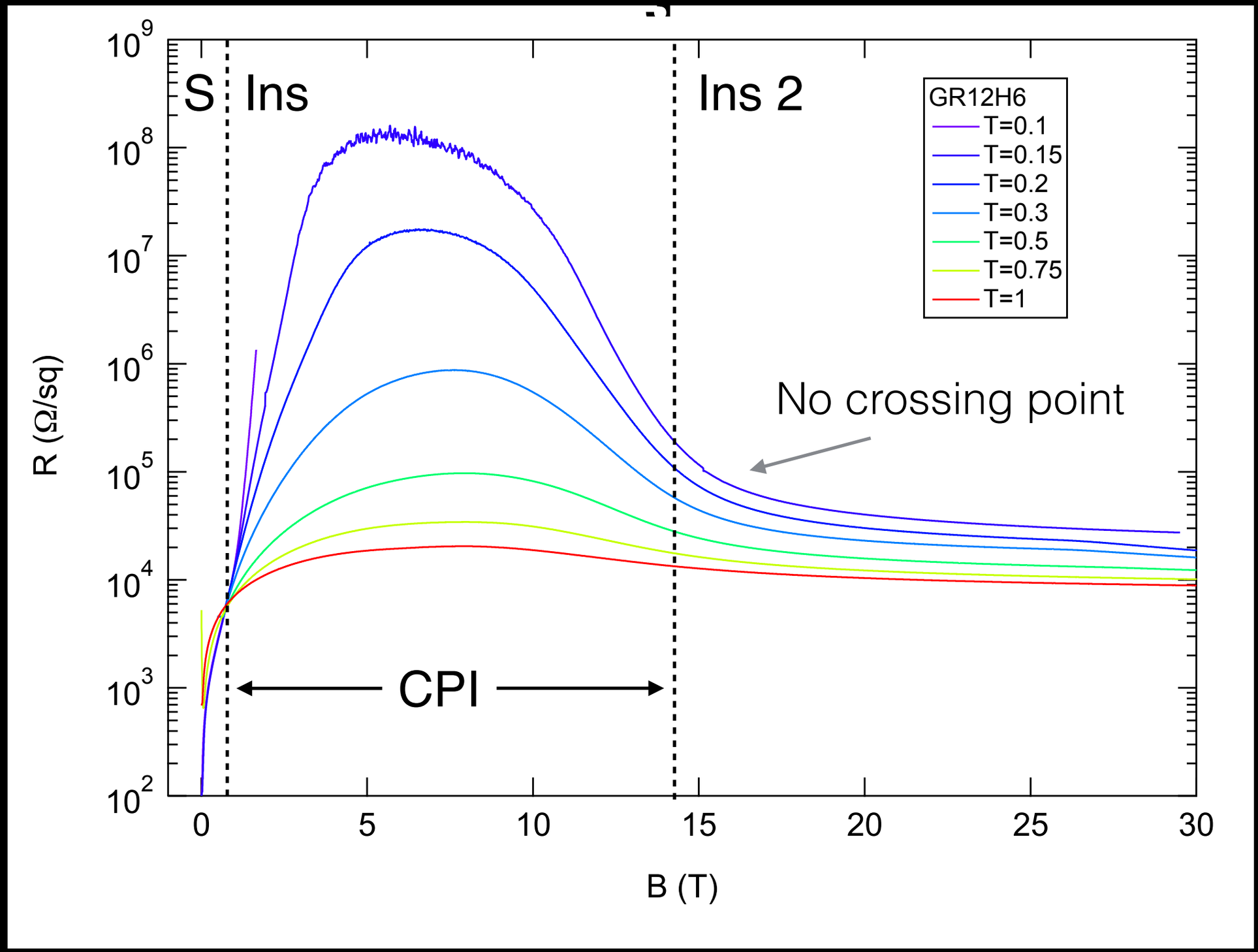


Narrow range in B

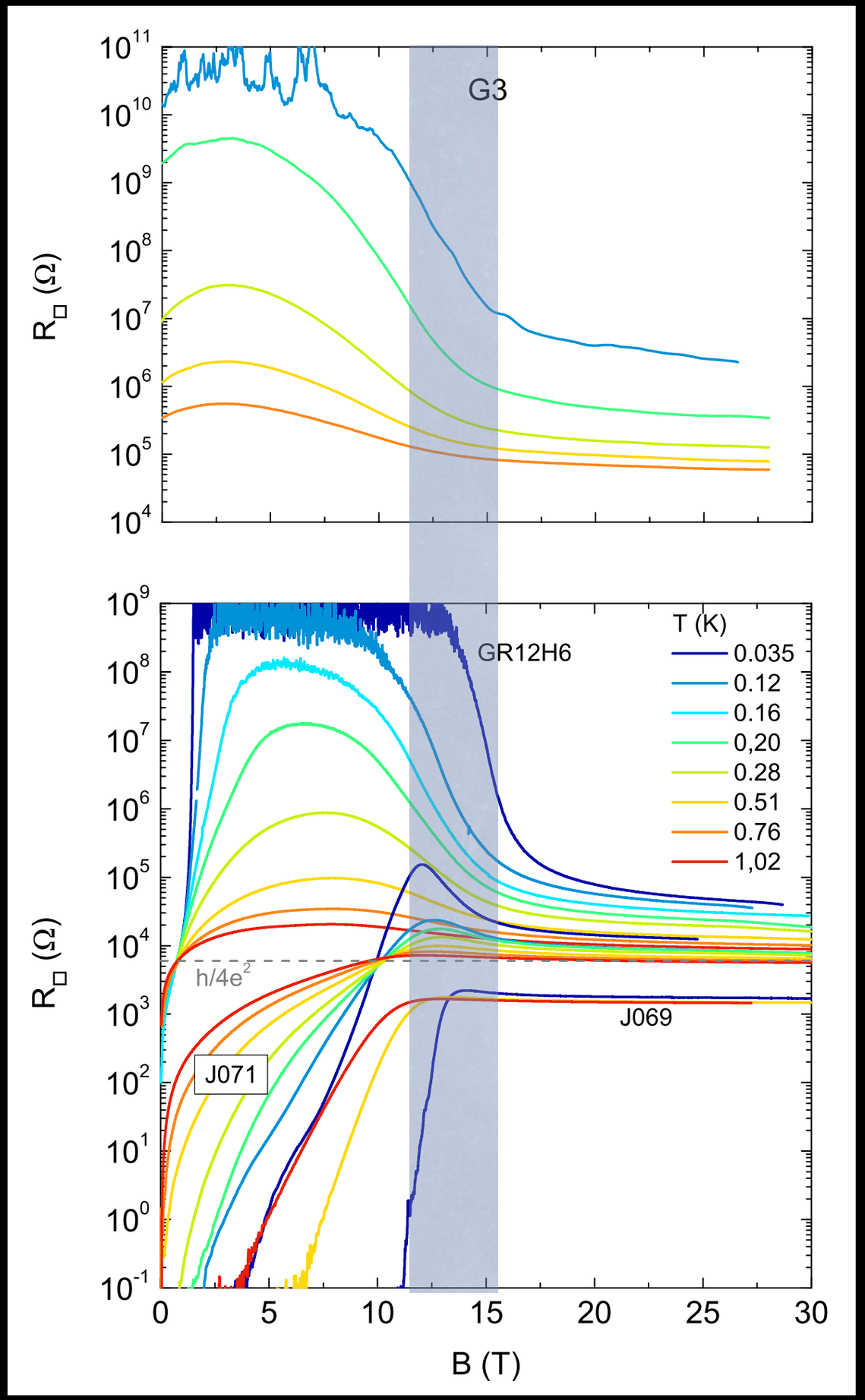
The insulating peak



The insulating peak



a:InO disorder range

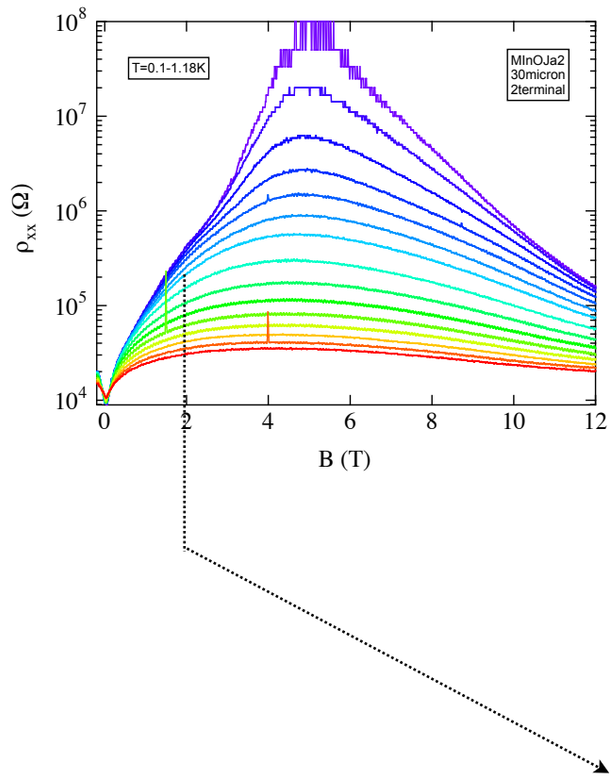


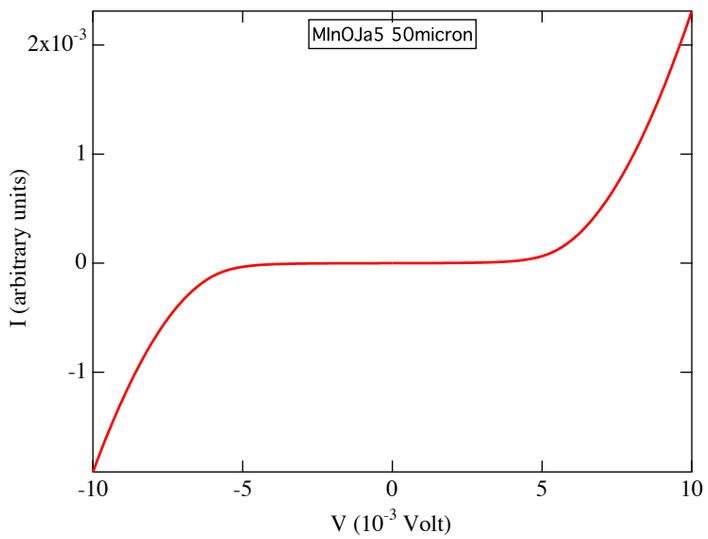
B. Sacépé et al,
Phys. Rev. B 91, 220508(R)

The Insulator at T<0.2 K:

Current-voltage characteristics

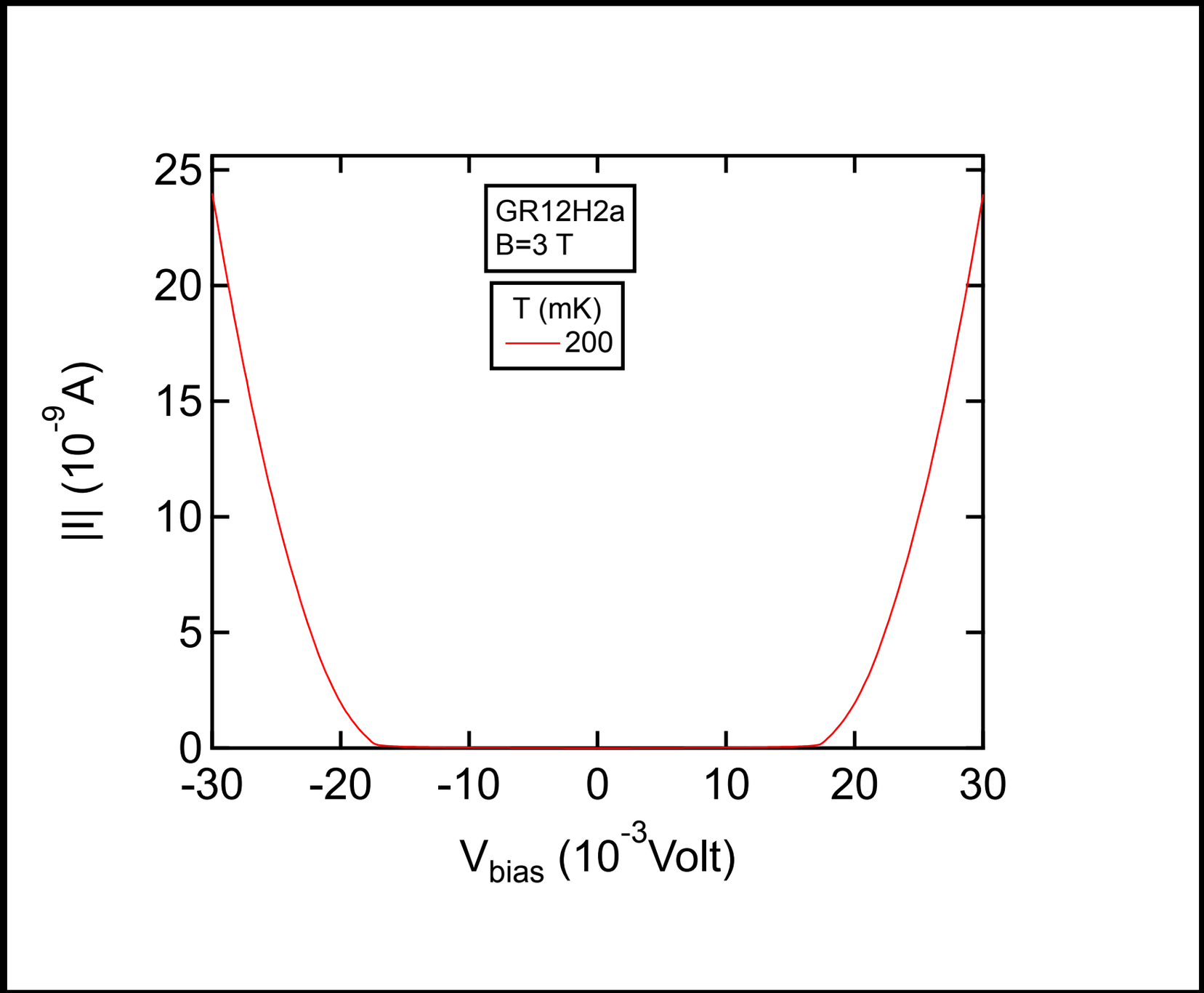
Current-voltage characteristics



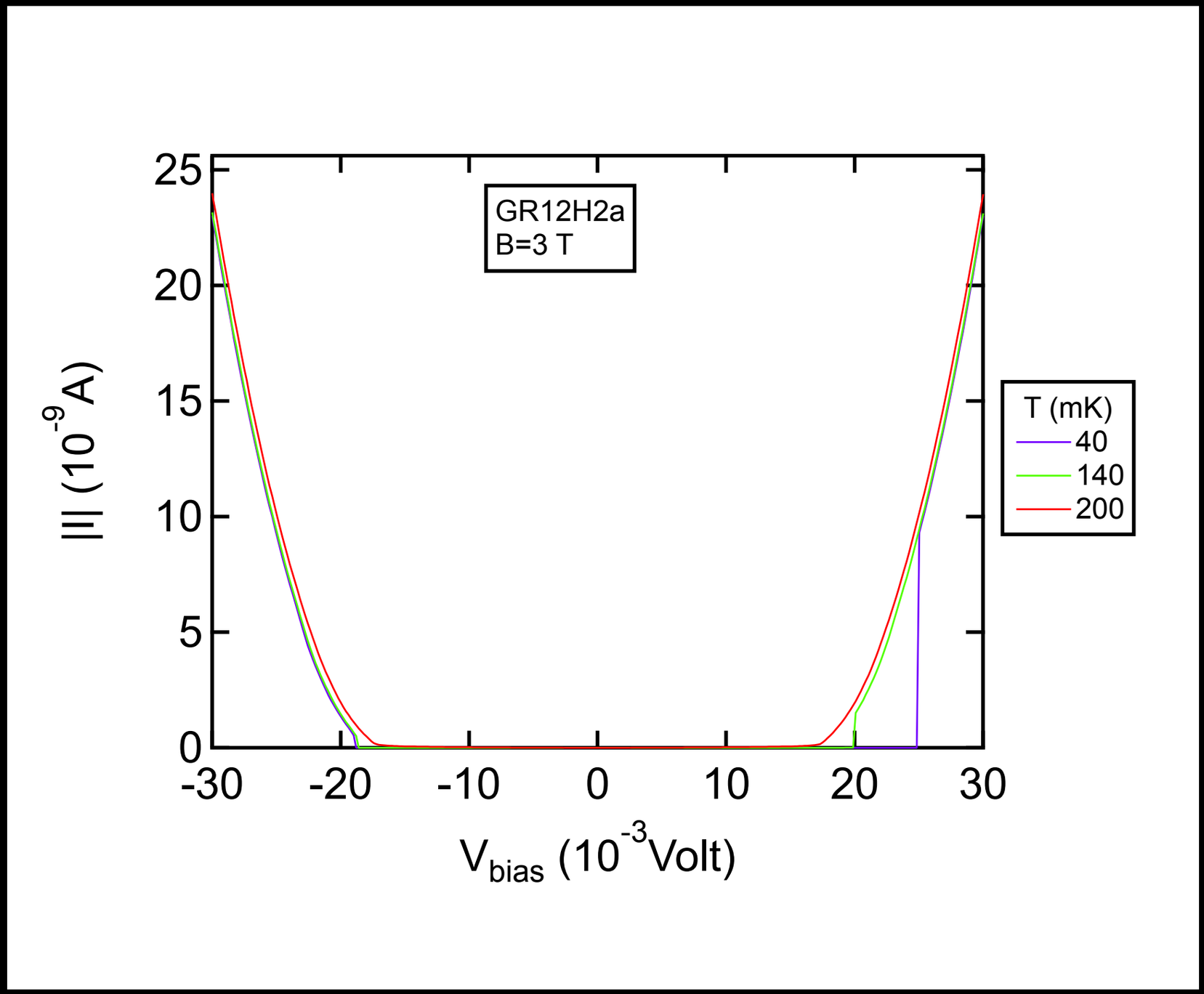


Sambandamurthy et. al,
PRL **94**, 017003 (2005).

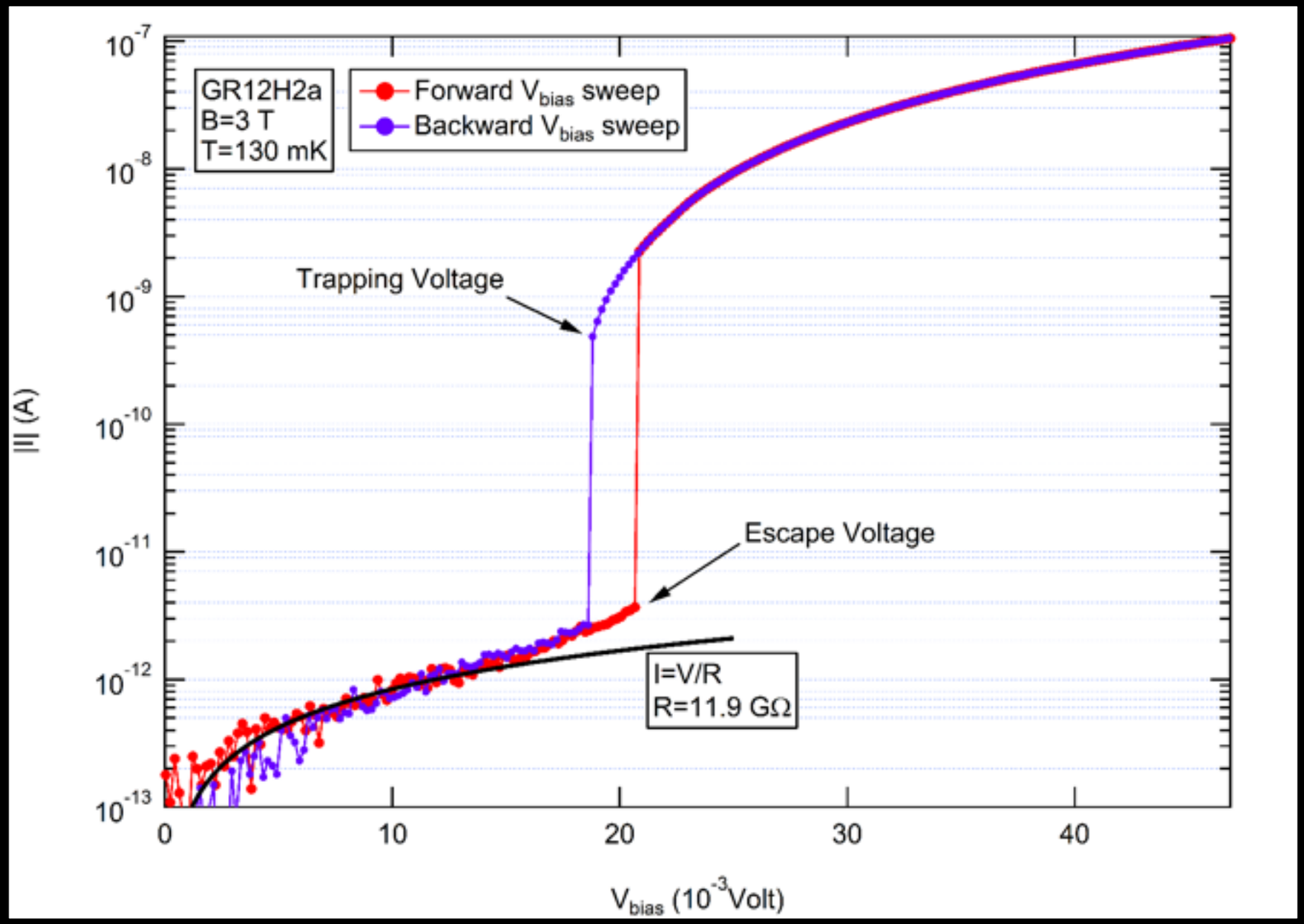
Highly non-linear



Transition to abrupt I-V



Hysteresis


GR12H2a
B=3 T
T=130 mK
Forward V_{bias} sweep
Backward V_{bias} sweep
Trapping Voltage
Escape Voltage
I=V/R
R=11.9 GΩ
|I| (A)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0
10
20
30
40
V_{bias} (10^{-3}Volt)

PRL **94,** 017003 (2005) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2005

Experimental Evidence for a Collective Insulating State in Two-Dimensional Superconductors

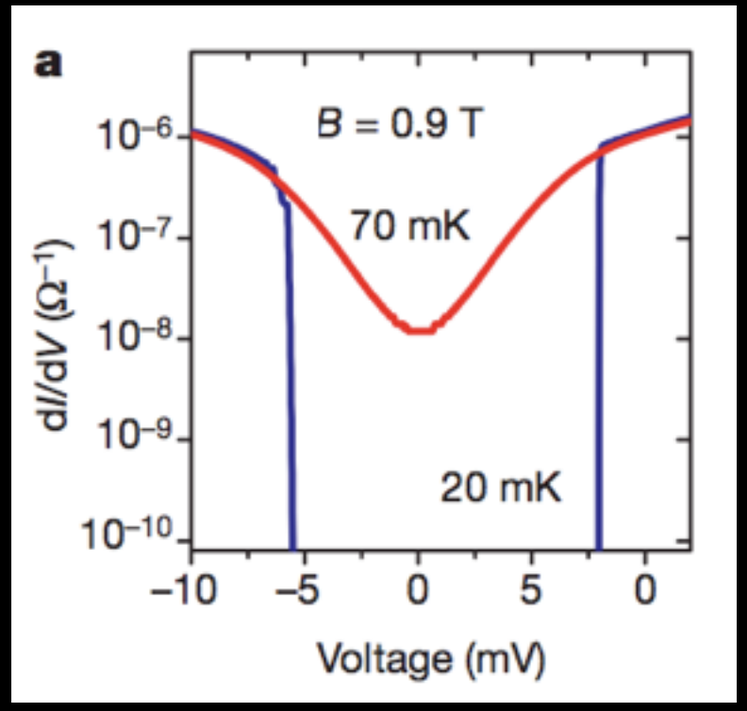
G. Sambandamurthy,[1] L. W. Engel,[2] A. Johansson,[1] E. Peled,[1] and D. Shahar[1]

[1]*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel,*
[2]*National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32306, USA*

(Received 18 March 2004; published 12 January 2005)

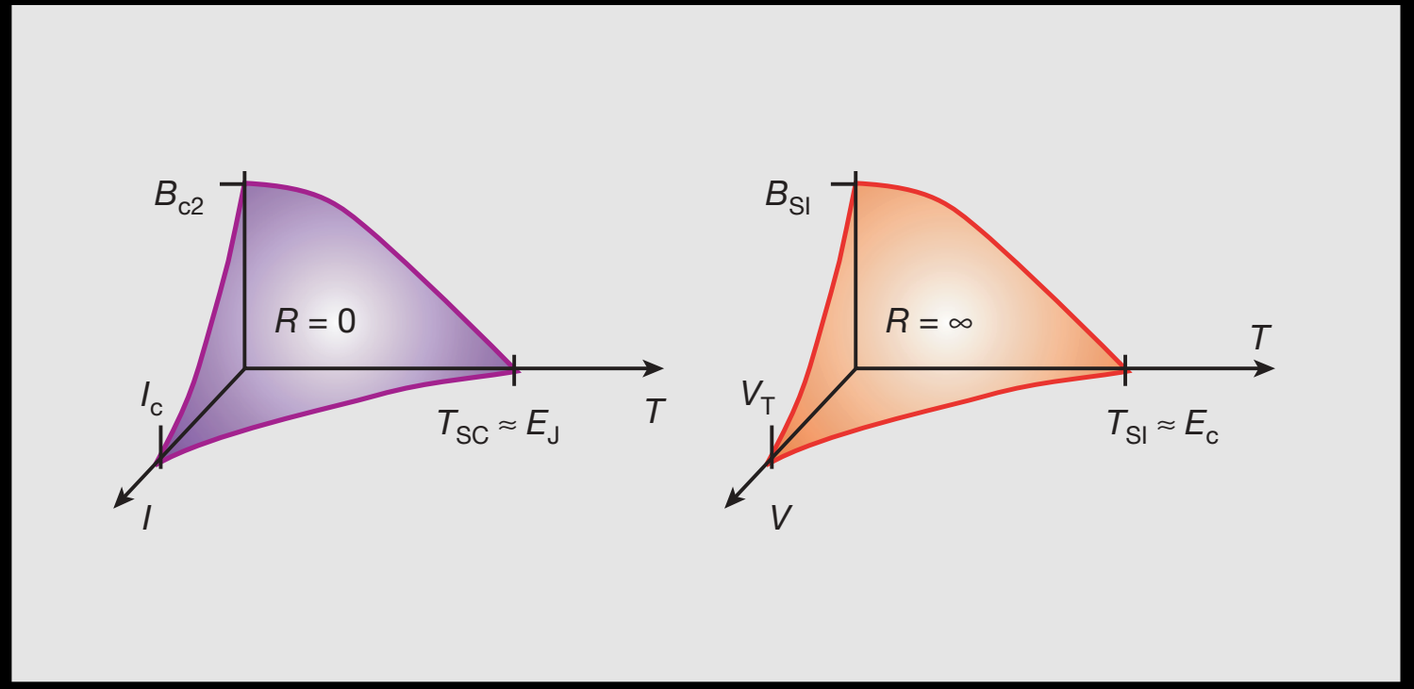
TiN

Baturina et al, 2007



Superinsulator and quantum synchronization

Vinokur et al., NATURE | Vol 452 | 3 April 2008



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ANNALS of PHYSICS
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Metal–insulator transition in a weakly interacting many-electron system with localized single-particle states

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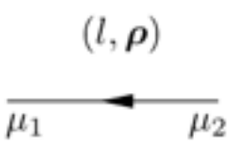
[b] *Physics Department, Columbia University, New York, NY 10027, USA*
[c] *NEC-Laboratories America, 4 Independence Way, Princeton, NJ 085540, USA*

Received 14 August 2005; accepted 30 November 2005
Available online 23 January 2006

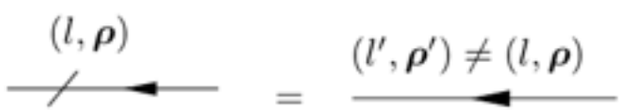
$$\hat{\mathcal{G}} = \begin{bmatrix} \mathcal{G}_l^R(\boldsymbol{\rho}) & \mathcal{G}_l^K(\boldsymbol{\rho}) \\ 0 & \mathcal{G}_l^A(\boldsymbol{\rho}) \end{bmatrix}_K; \quad \hat{\boldsymbol{\Sigma}} = \begin{bmatrix} \boldsymbol{\Sigma}_l^R(\boldsymbol{\rho}) & \boldsymbol{\Sigma}_l^K(\boldsymbol{\rho}) \\ 0 & \boldsymbol{\Sigma}_l^A(\boldsymbol{\rho}) \end{bmatrix}_K; \tag{54}$$

$$\hat{\tau}^0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}_K; \quad \hat{\tau}^2 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}_K.$$

A



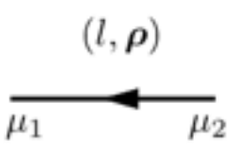
$$= i\left[\hat{G}_l(\boldsymbol{\rho})\right]_{\mu_1\mu_2} = i\begin{bmatrix} G_l^R(\boldsymbol{\rho}) & G_l^K(\boldsymbol{\rho}) \\ 0 & G_l^A(\boldsymbol{\rho}) \end{bmatrix}_{\mu_1\mu_2}$$



$$G_l^R(\boldsymbol{\rho}) = \left[G_l^A(\boldsymbol{\rho})\right]^* = \frac{1}{\epsilon - \xi_l(\boldsymbol{\rho}) + i0^+}$$

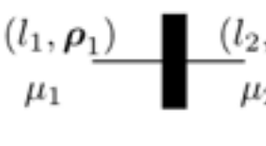
$$G_l^K(\boldsymbol{\rho}) = -2\pi i n_l(\boldsymbol{\rho}, \epsilon)\delta\left[\epsilon - \xi_l(\boldsymbol{\rho})\right]$$

B



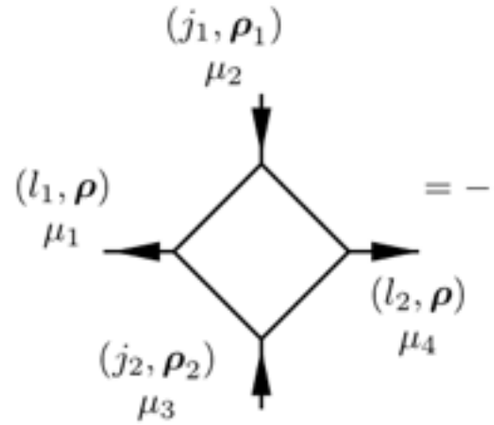
$$= i\left[\hat{\mathcal{G}}_l(\boldsymbol{\rho})\right]_{\mu_1\mu_2};$$

C



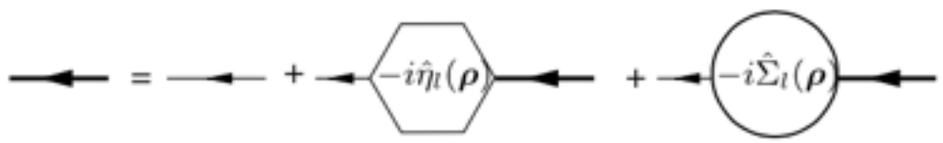
$$= -iI\delta_\xi \left[\hat{\tau}^0\right]_{\mu_1\mu_2} (\boldsymbol{\rho}_1, \boldsymbol{\rho}_2)_{nn};$$

D



$$= -\frac{i}{2} V_{l_1 l_2}^{j_1 j_2}(\boldsymbol{\rho}) \left(\left[\hat{\tau}^2\right]_{\mu_1\mu_2} \left[\hat{\tau}^0\right]_{\mu_3\mu_4} + \left[\hat{\tau}^2\right]_{\mu_1\mu_2} \left[\hat{\tau}^0\right]_{\mu_3\mu_4} \right)$$

E

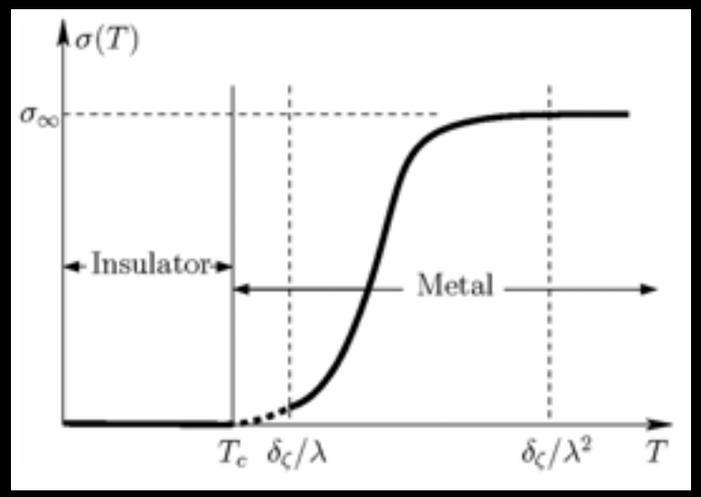


PHYSICAL REVIEW B **76**, 052203 (2007)

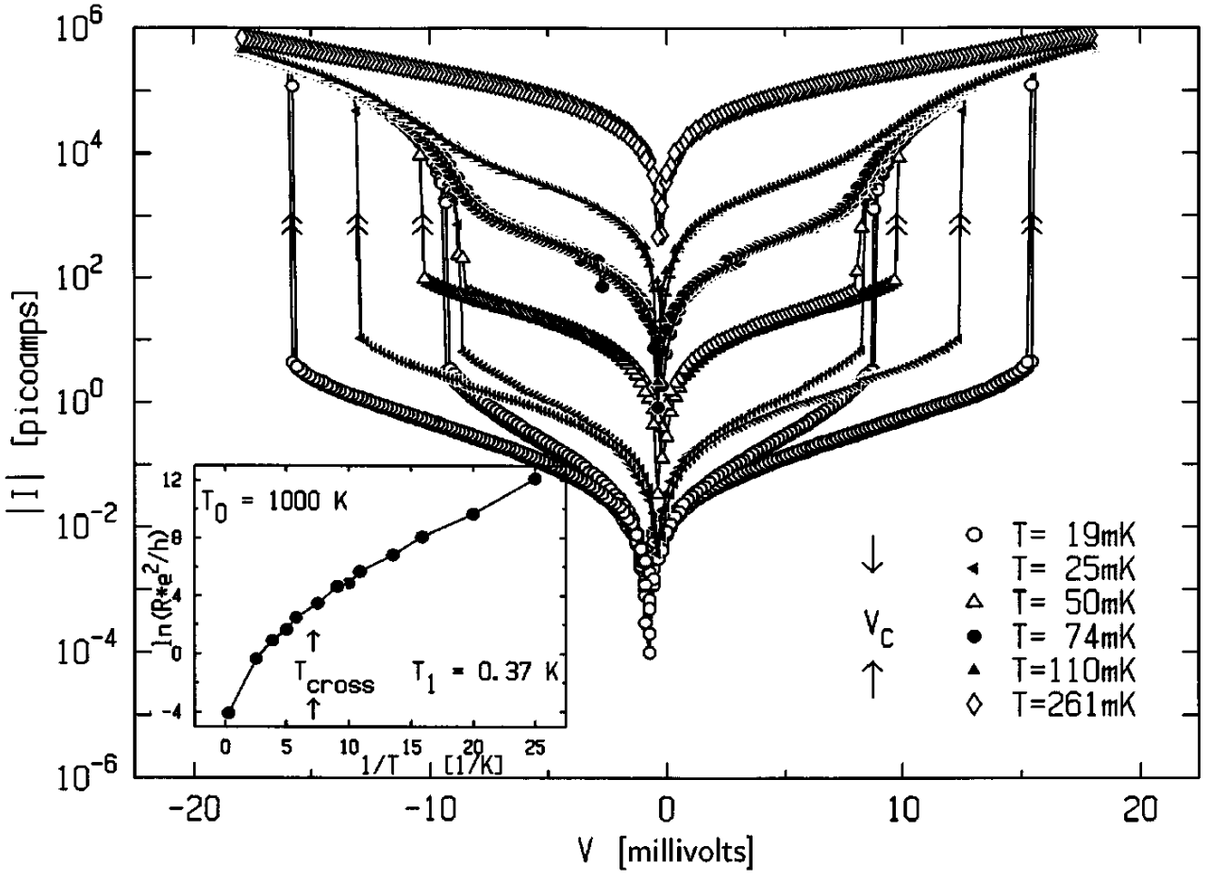
Possible experimental manifestations of the many-body localization

D. M. Basko,[1,*] I. L. Aleiner,[1] and B. L. Altshuler[1,2]
[1]*Physics Department, Columbia University, New York, New York 10027, USA*
[2]*NEC-Laboratories America, Inc., 4 Independence Way, Princeton, New Jersey 08540, USA*
(Received 24 July 2007; published 23 August 2007; publisher error corrected 14 September 2007)

Recently, it was predicted that if all one-electron states in a noninteracting disordered system are localized, the interaction between electrons in the absence of coupling to phonons leads to a finite-temperature metal-insulator transition. Here, we show that even in the presence of a weak coupling to phonons the transition manifests itself (i) in the nonlinear conduction, leading to a bistable I–V curve, and (ii) by a dramatic enhancement of the nonequilibrium current noise near the transition.



No Superconductivity.



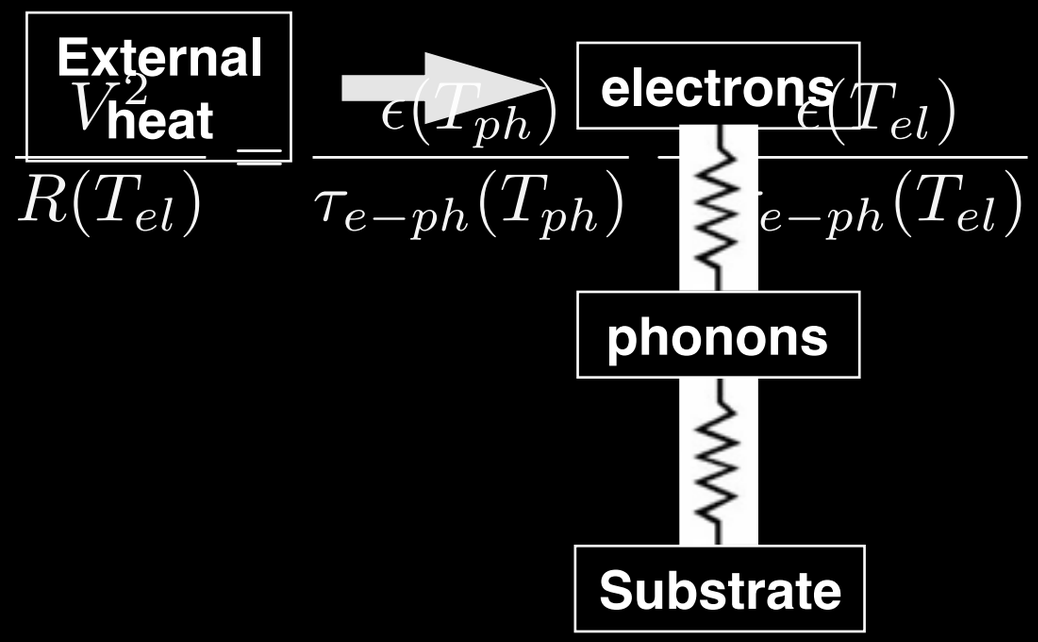
Ladieu, Sanquer, and Bouchaud, 1996

a:Y_xSi_{1-x}

Jumps in current-voltage characteristics in disordered films

B. L. Altshuler, V. E. Kravtsov, I. V. Lerner, and I. L. Aleiner,
Phys. Rev. Lett. 102, 176803 (2009)

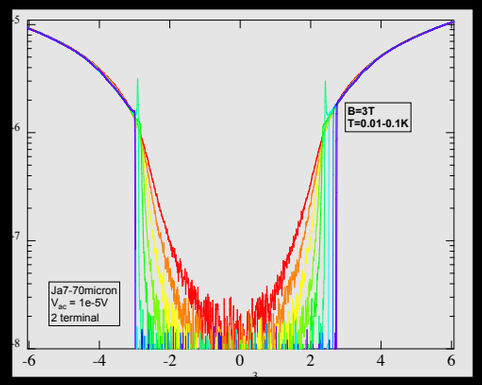
Heat balance equation:



Jumps in current-voltage characteristics in disordered films

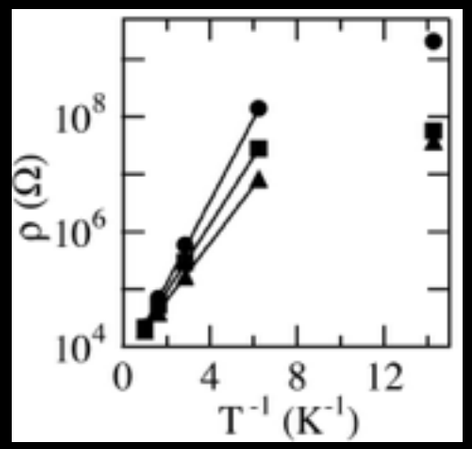
1. Electrons and phonons are decoupled
2. Electrons are strongly interacting
   (electrons can have $T_{el} \neq T_{ph}$)

3. I-V is linear
   (Apparent non-linearity from electron heating)



4. R(T) is a fast function

$$\rho(T) = \rho_0 e^{T_I/T}$$

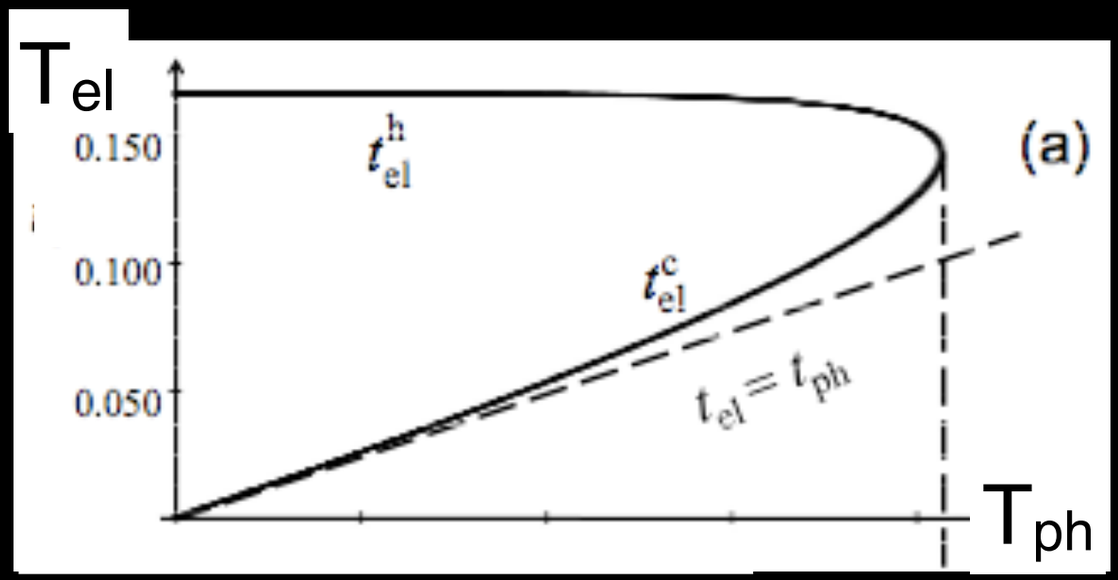


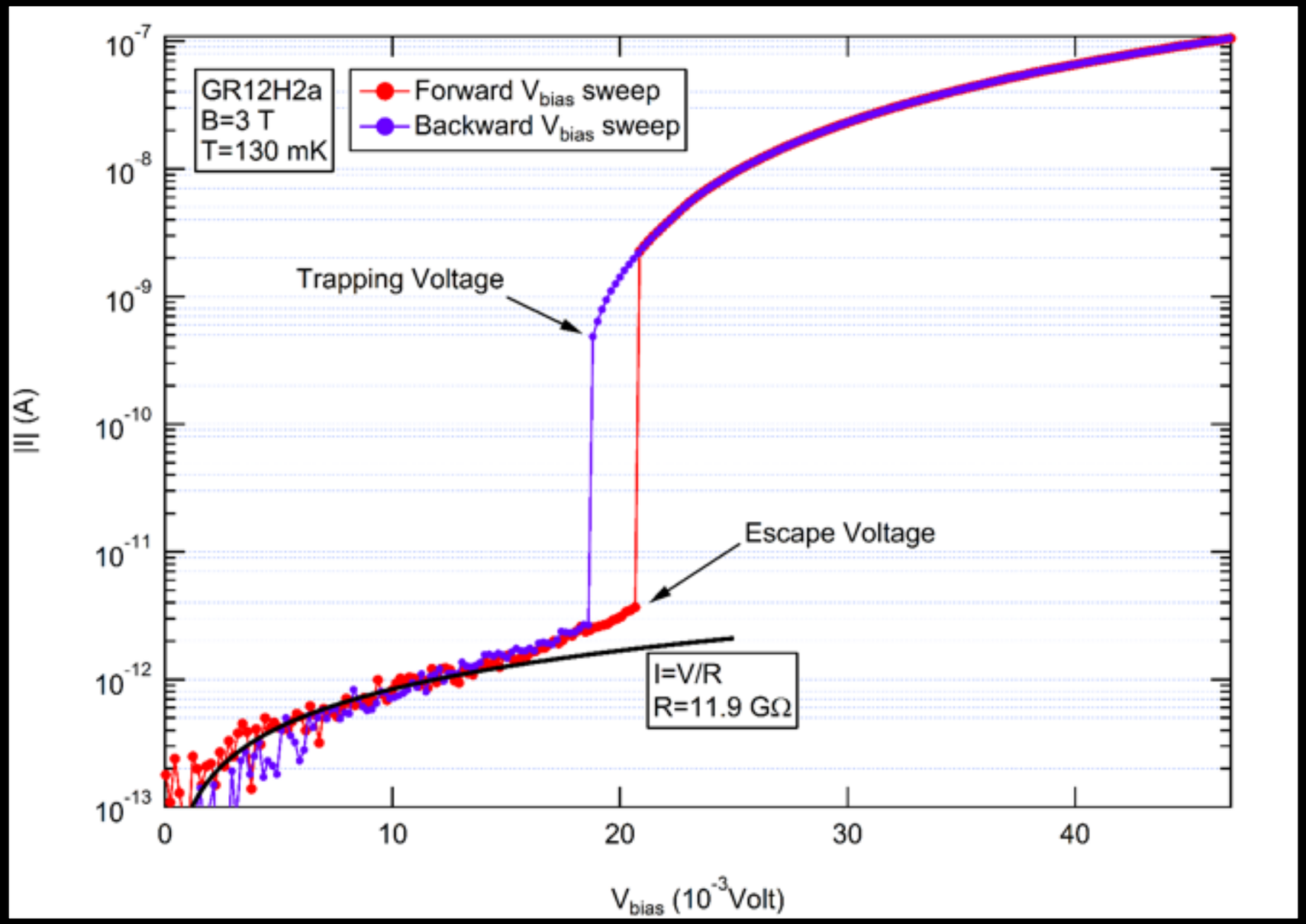
Jumps in current-voltage characteristics in disordered films

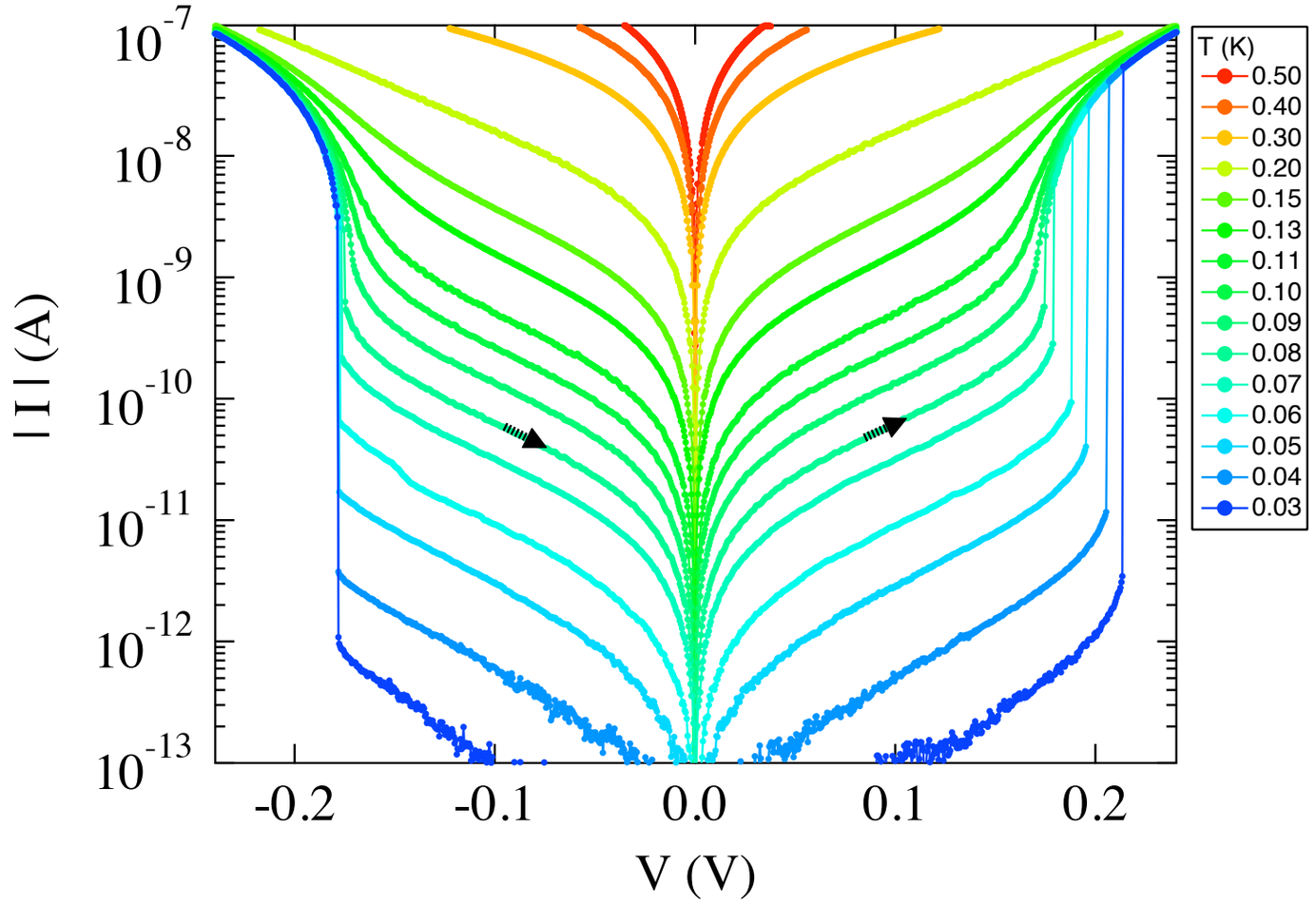
B. L. Altshuler, V. E. Kravtsov, I. V. Lerner, and I. L. Aleiner,
Phys. Rev. Lett. 102, 176803 (2009)

Heat balance equation:

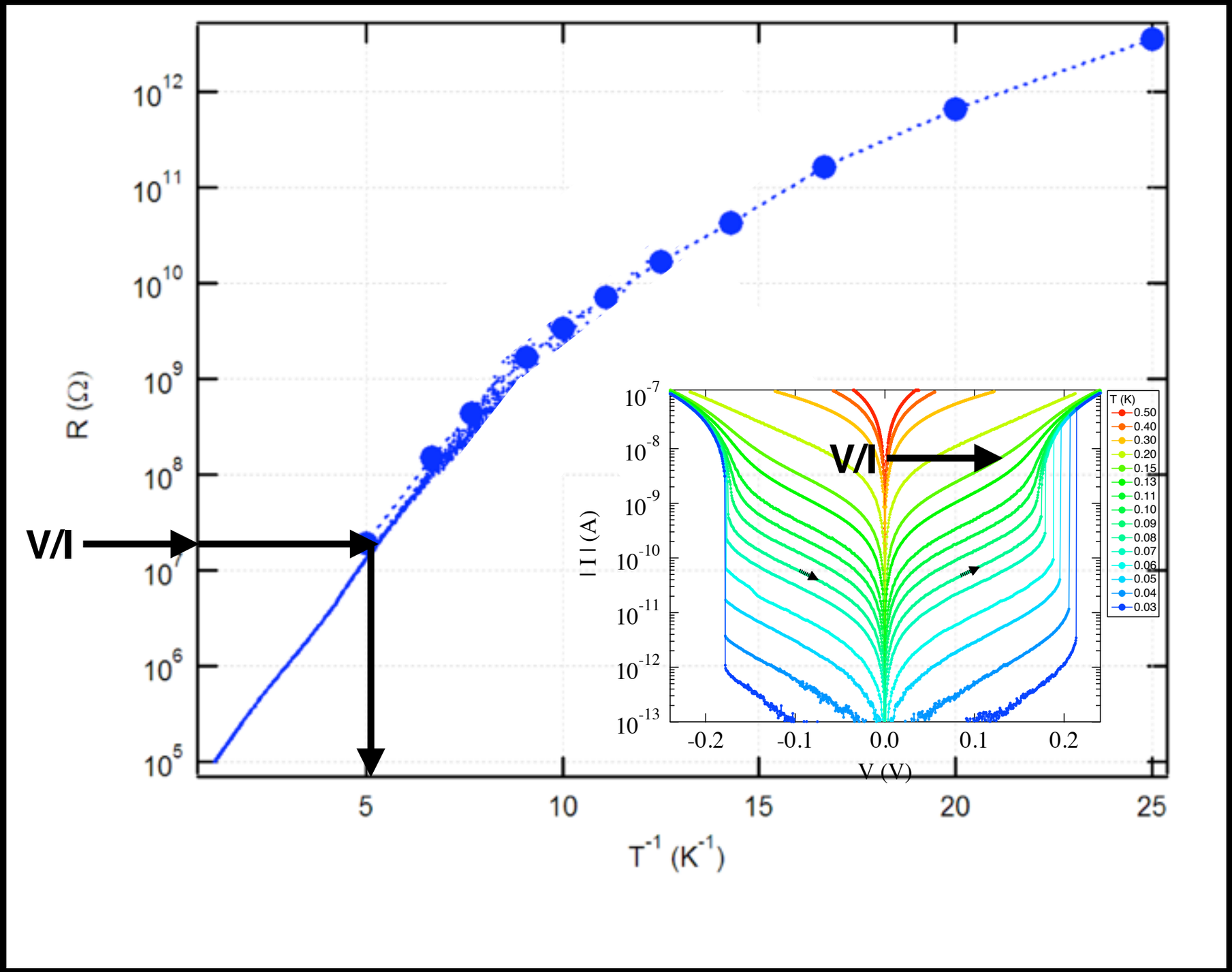
$$\frac{V^2}{R(T_{el})} = AT_{el}^6 - BT_{ph}^6$$



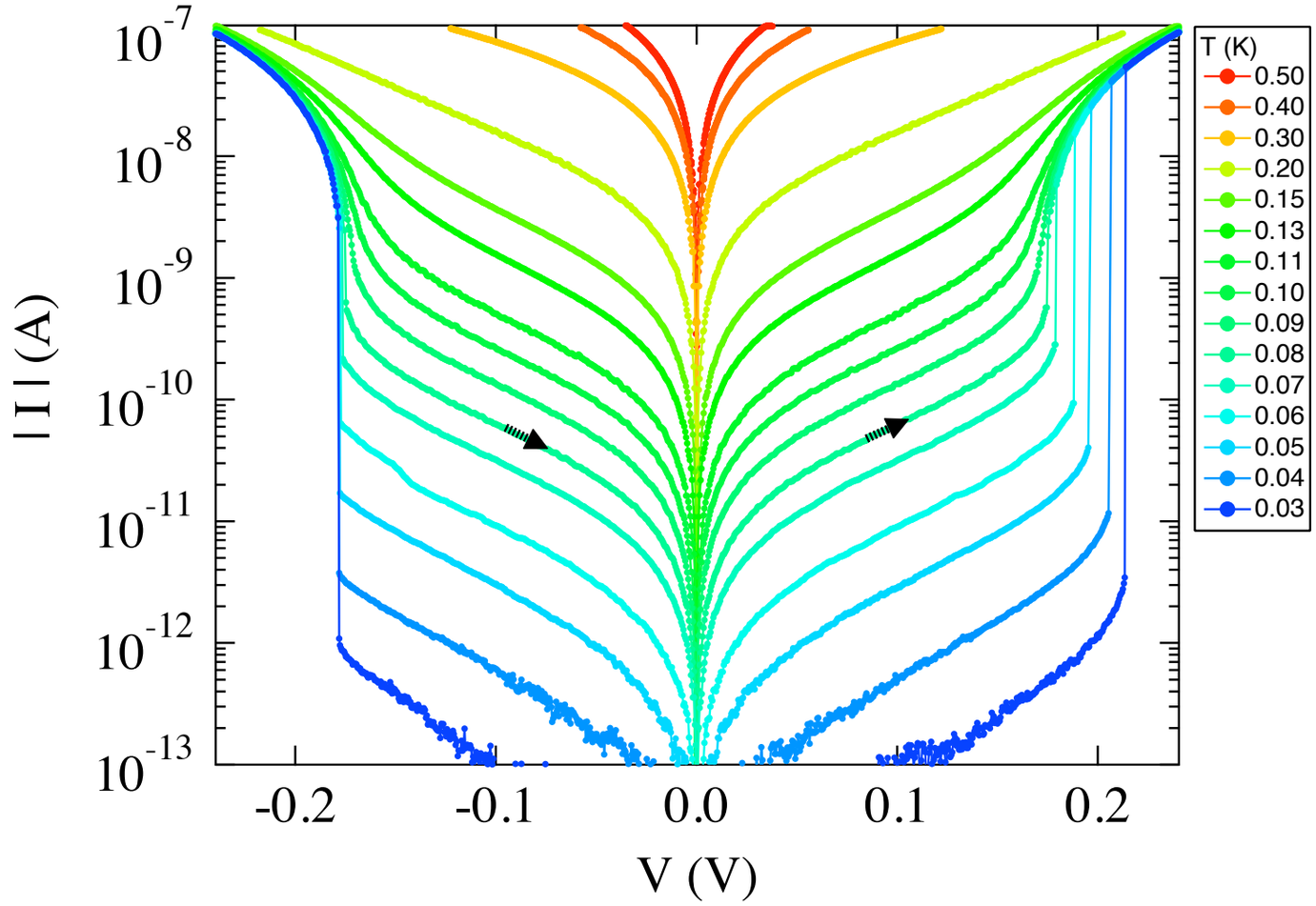

GR12H2a
B=3 T
T=130 mK
Forward V_bias sweep
Backward V_bias sweep
Trapping Voltage
Escape Voltage
I=V/R
R=11.9 GΩ
|I| (A)
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
0
10
20
30
40
V_bias (10^-3 Volt)

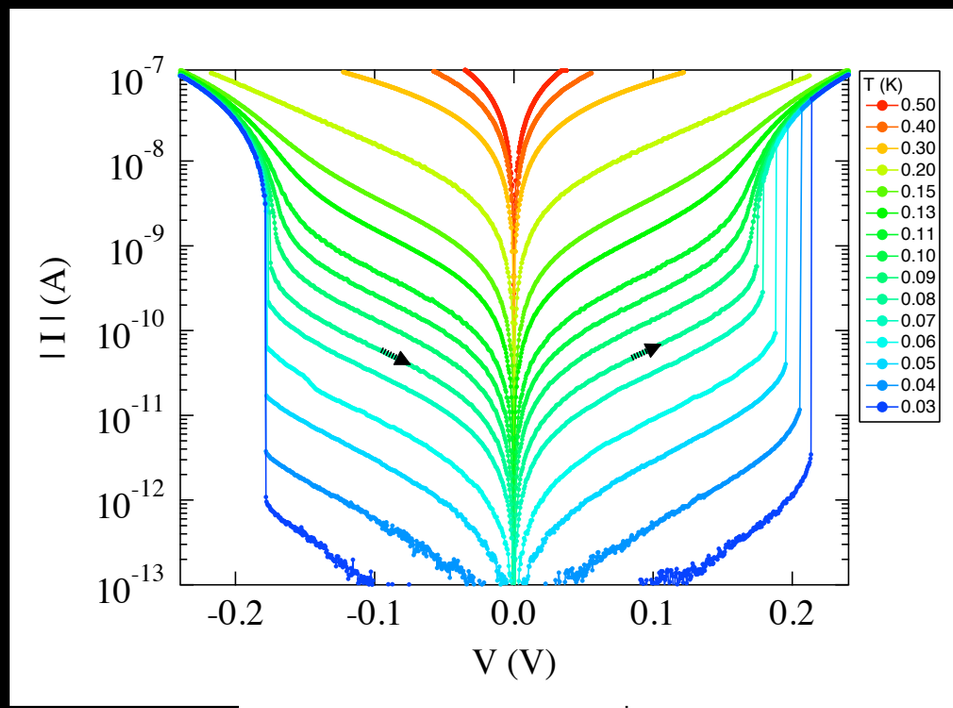

|I| (A)
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
-0.2
-0.1
0.0
0.1
0.2
V (V)
T (K)
0.50
0.40
0.30
0.20
0.15
0.13
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03

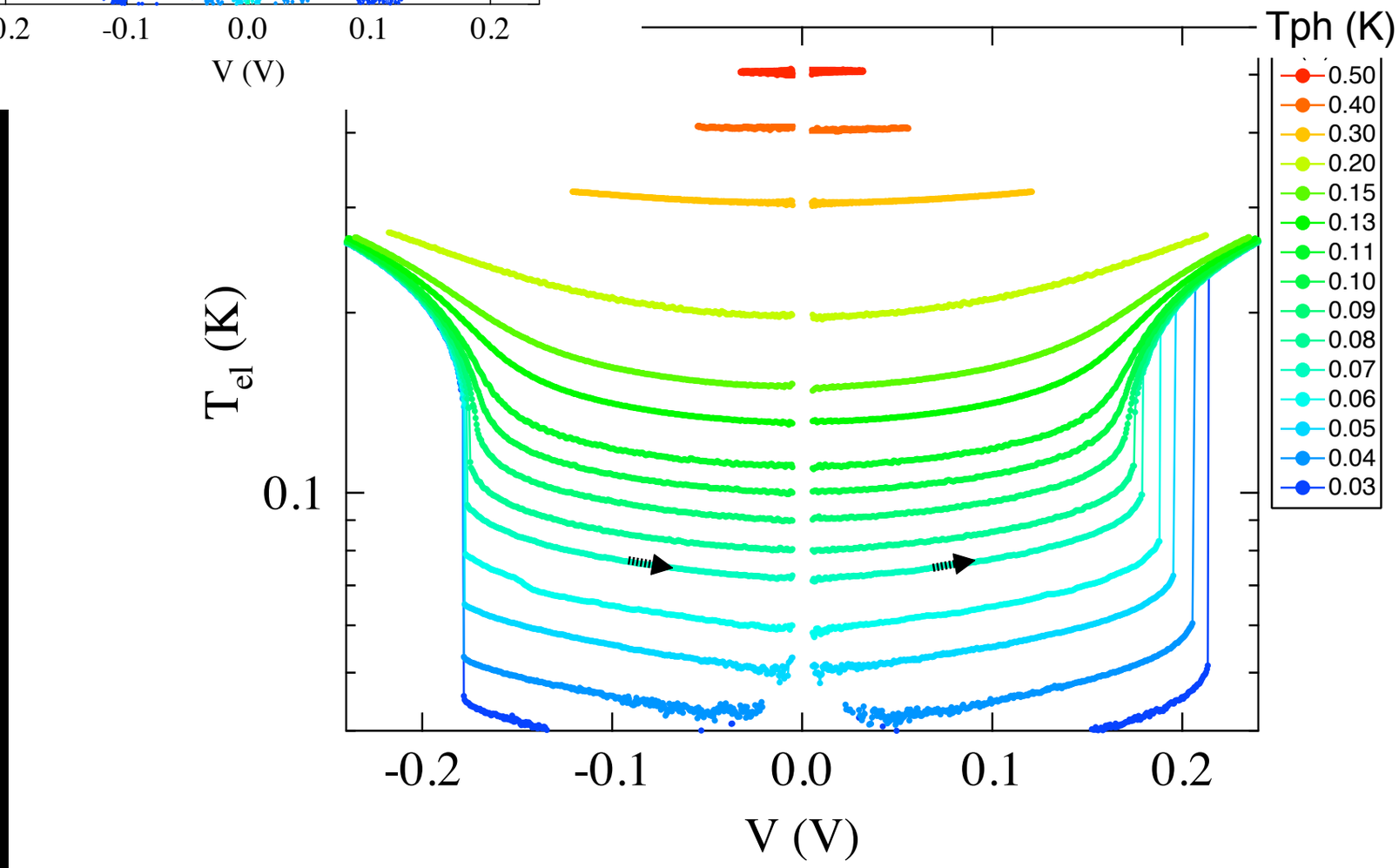
Determine T_{el}



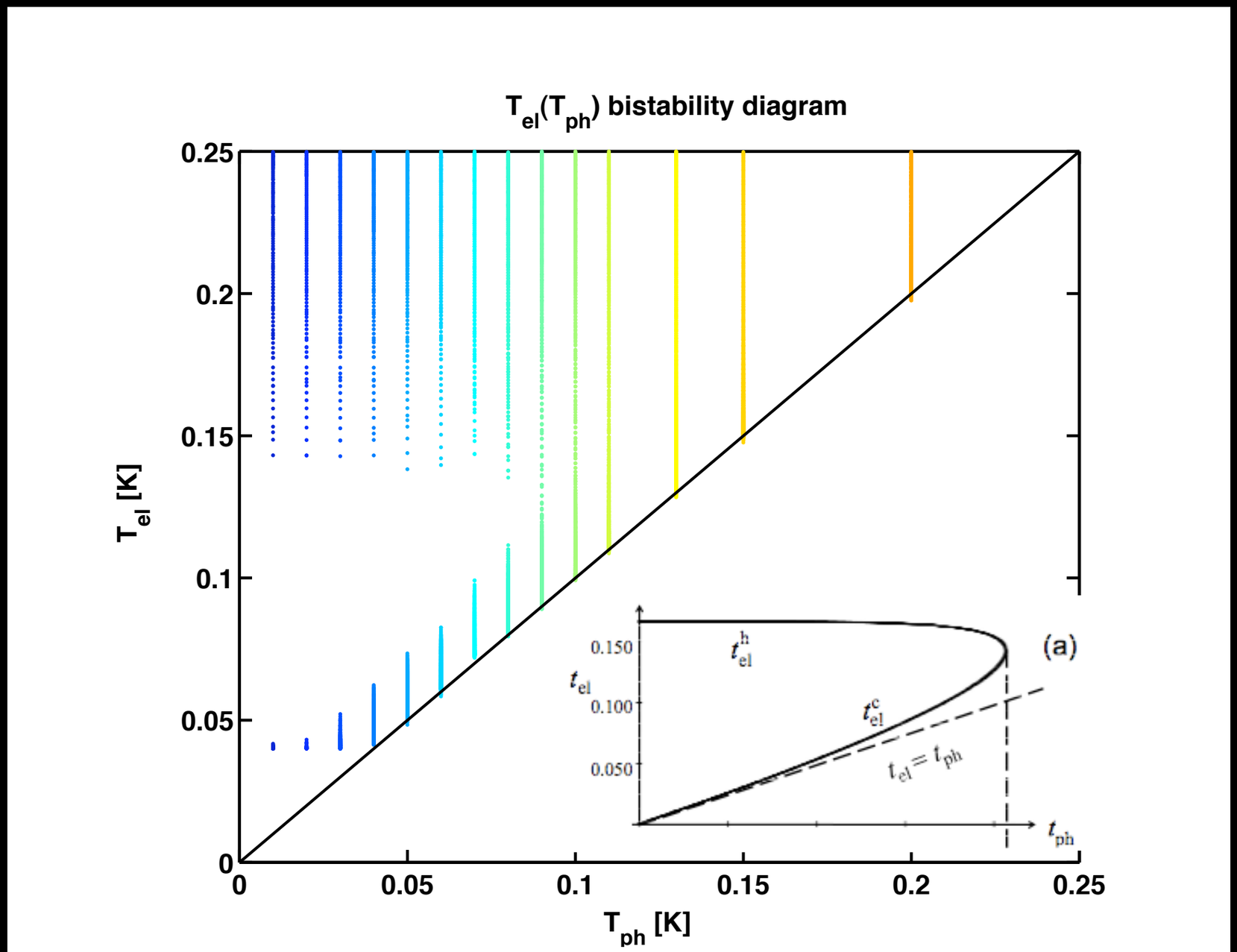
Applying to I-V

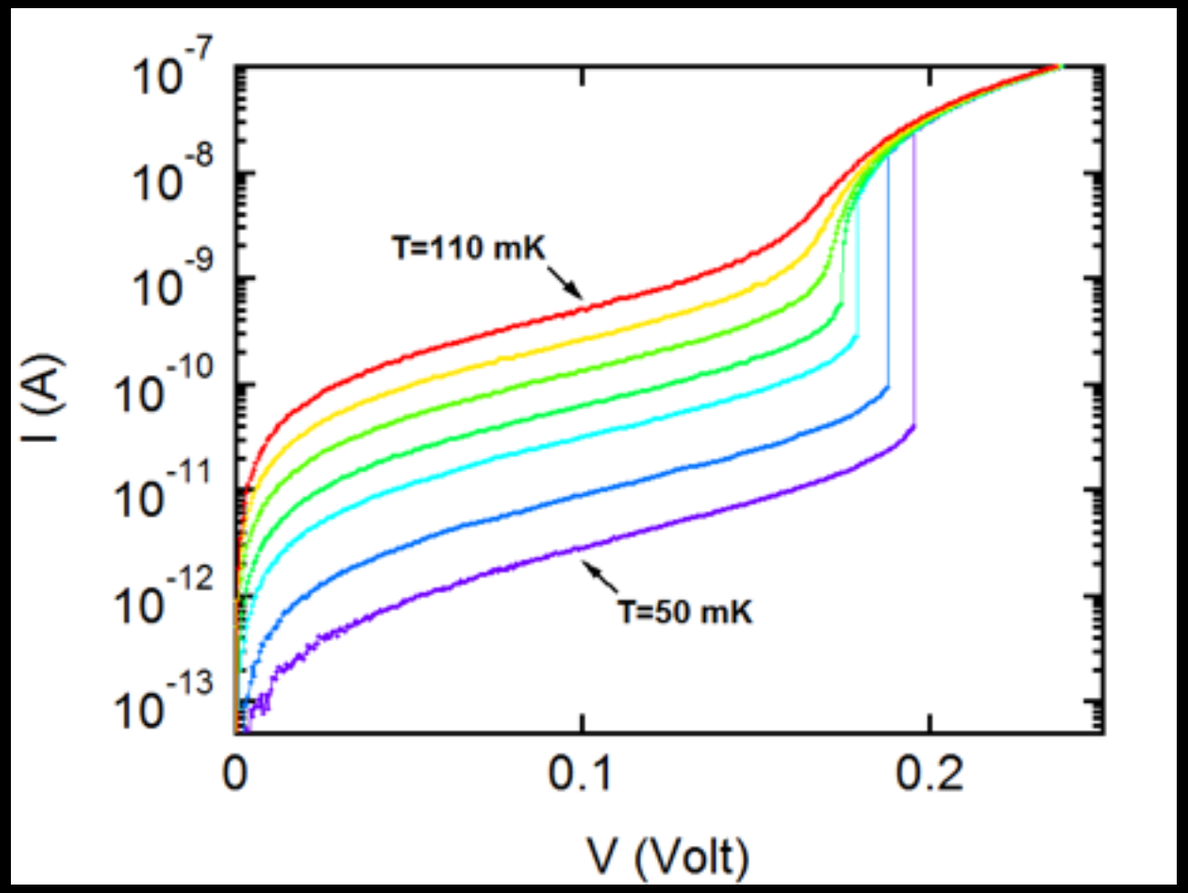



10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
| I | (A)
-0.2
-0.1
0.0
0.1
0.2
V (V)
T (K)
0.50
0.40
0.30
0.20
0.15
0.13
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03

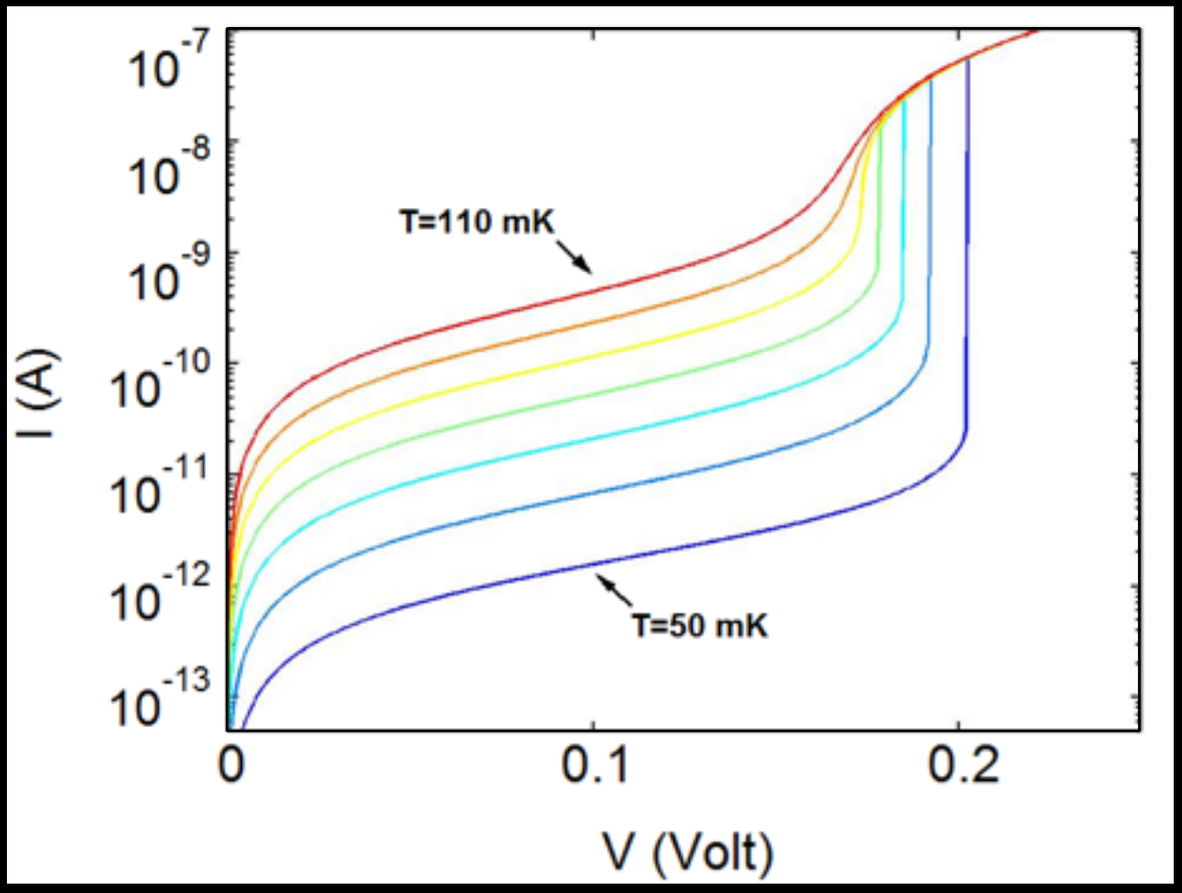

Tph (K)
T_{el} (K)
0.1
-0.2
-0.1
0.0
0.1
0.2
V (V)
0.50
0.40
0.30
0.20
0.15
0.13
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03

Excluded Region

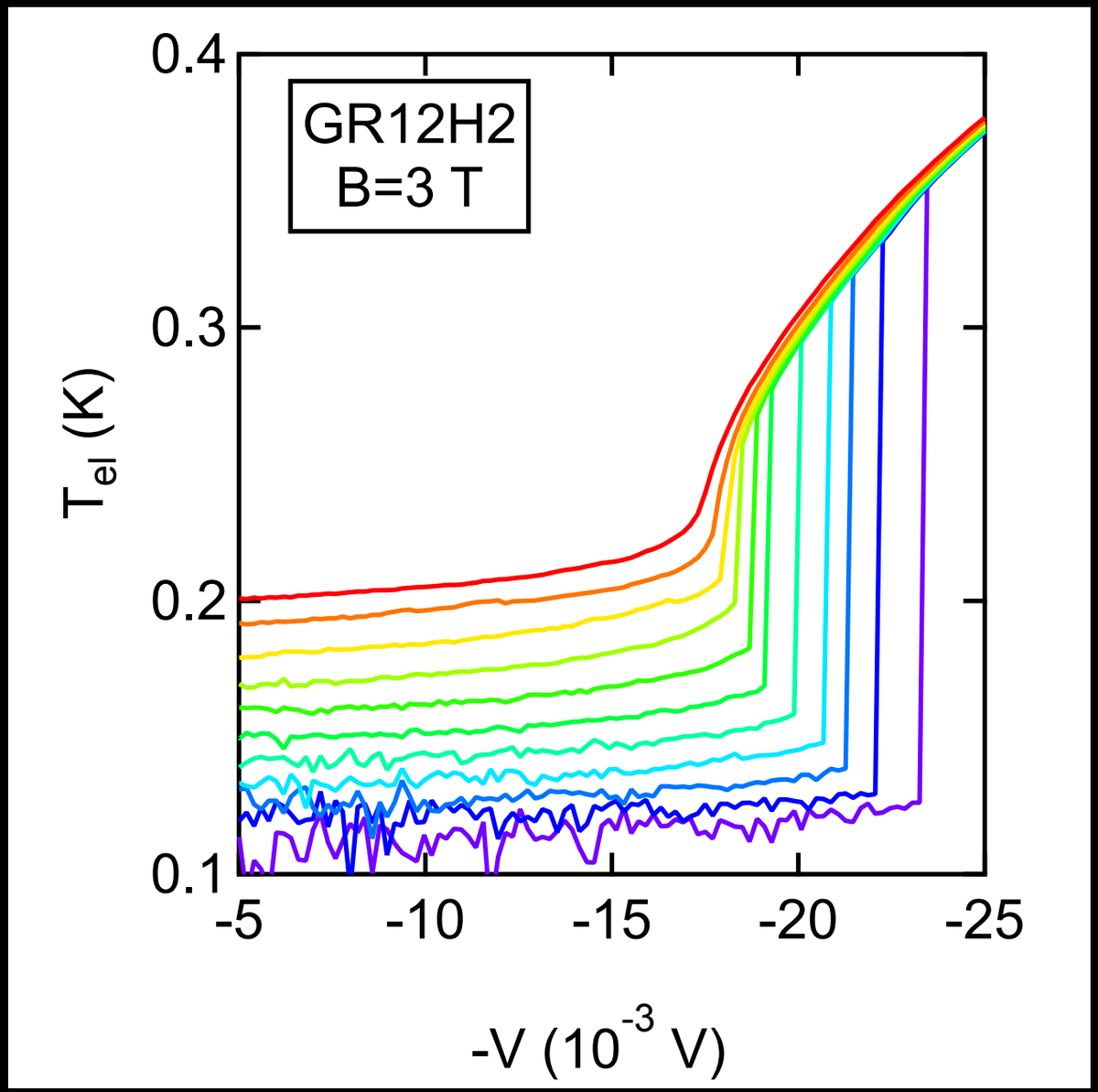


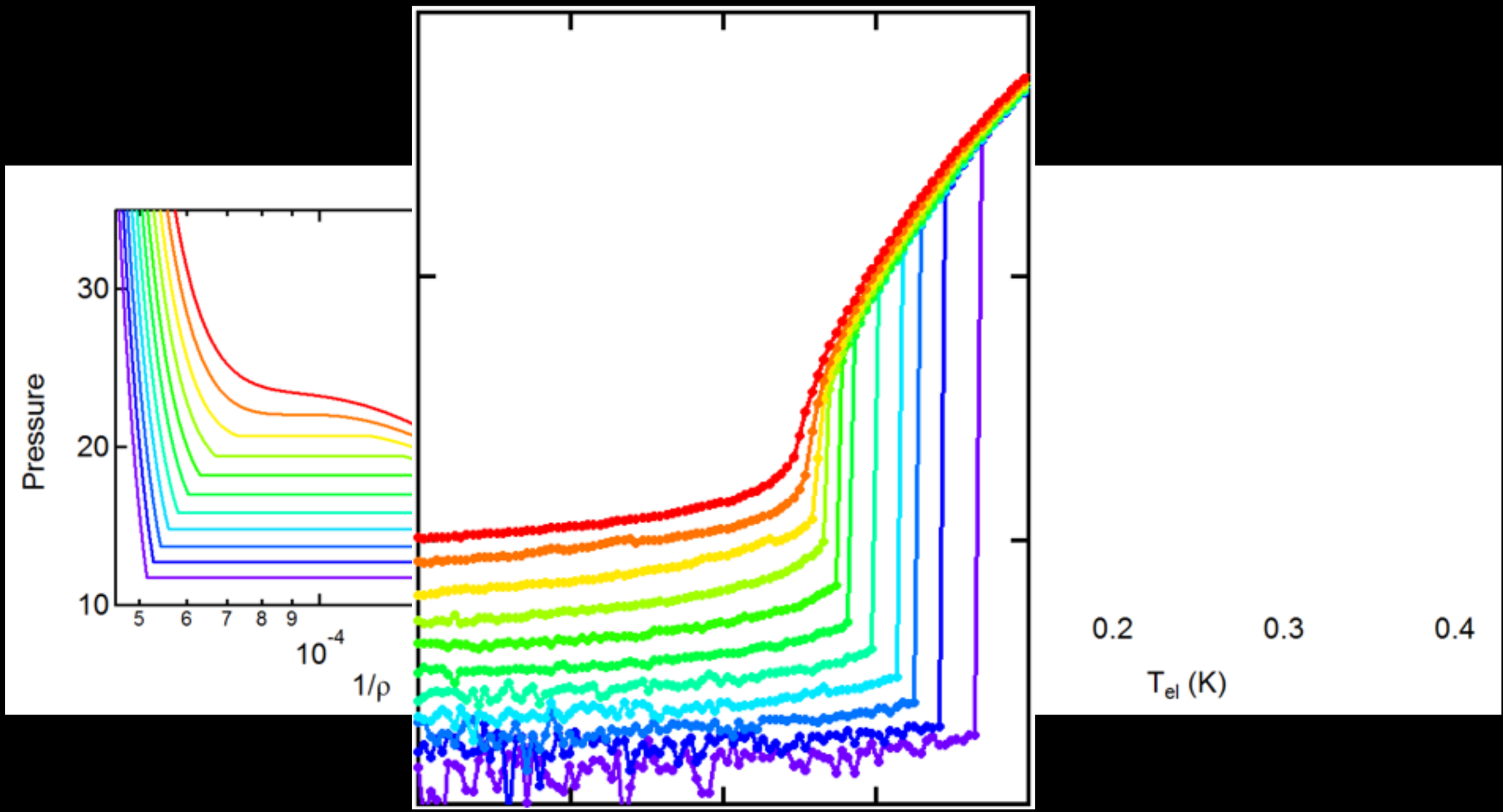


M. Ovadia, B. Sacepe, and D. Shahar, Phys. Rev. Lett. 102, 176802 (2009)



B. L. Altshuler, V. E. Kravtsov, I. V. Lerner, and I. L. Aleiner, Phys. Rev. Lett. 102, 176803 (2009)


GR12H2
B=3 T
0.4
0.3
0.2
0.1
T_{el} (K)
-5
-10
-15
-20
-25
-V (10^{-3} V)

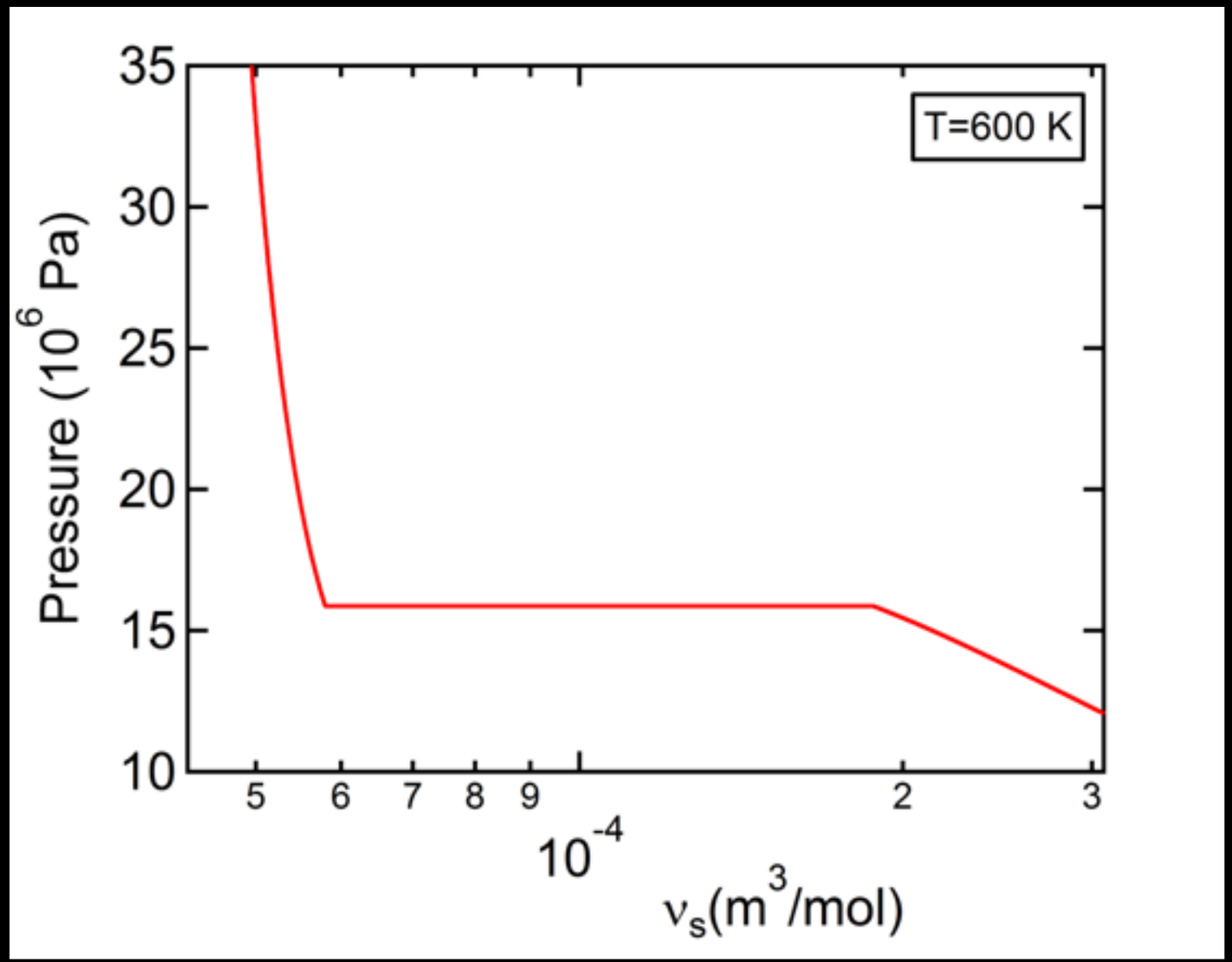

30
20
10
Pressure
5
6
7
8
9
10^-4
1/ρ
0.2
0.3
0.4
T_el (K)

The Van der Waals equation

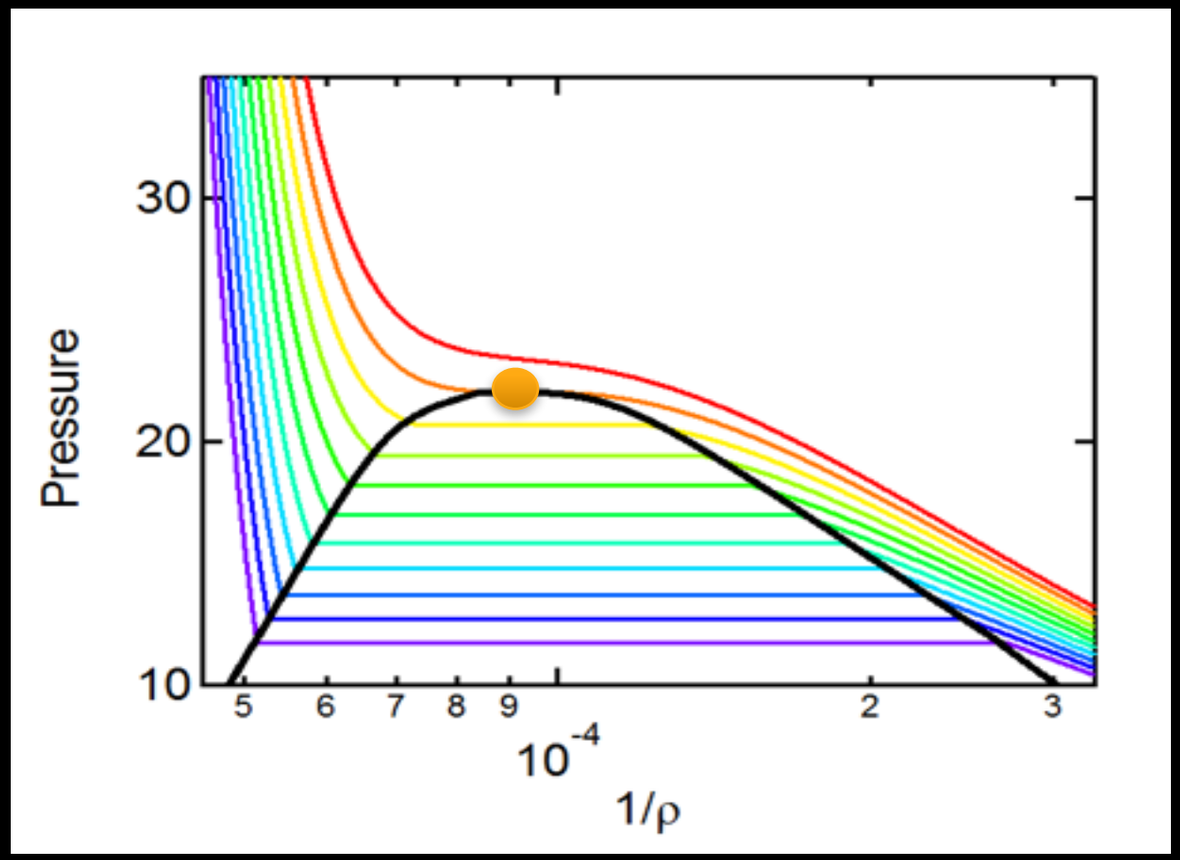
- First correction to the pressure equation of state

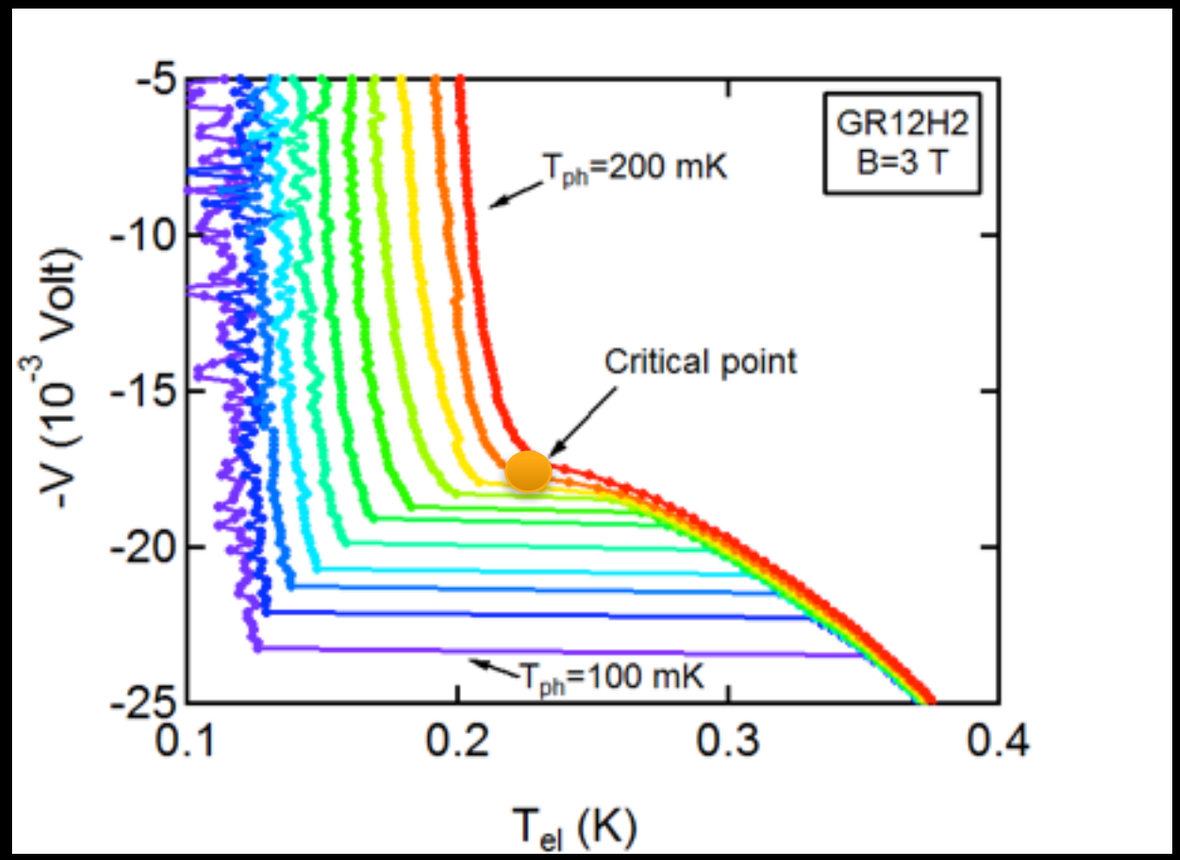
$$P = \frac{Nk_BT}{V-b} - \frac{N^2a}{V^2}$$

- Maxwell construction

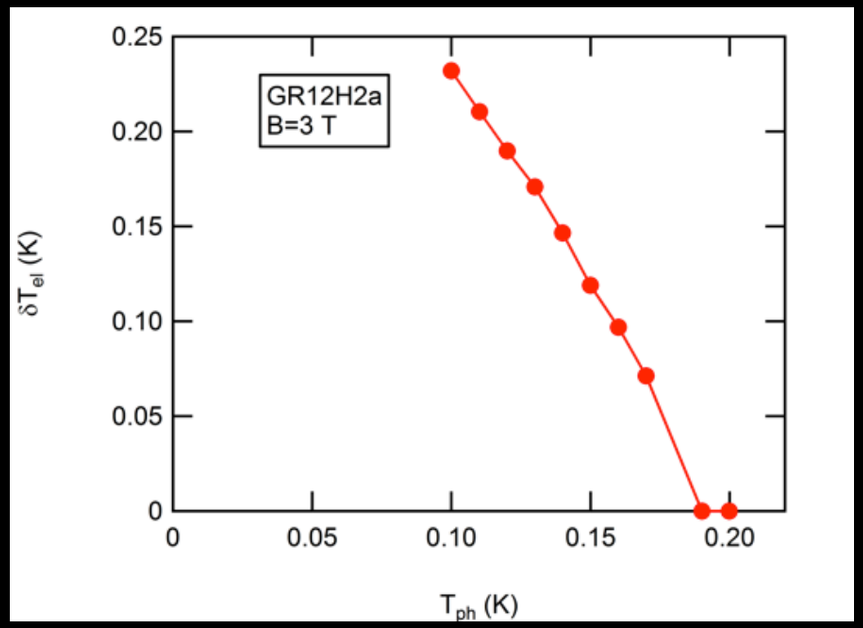


An Analogy

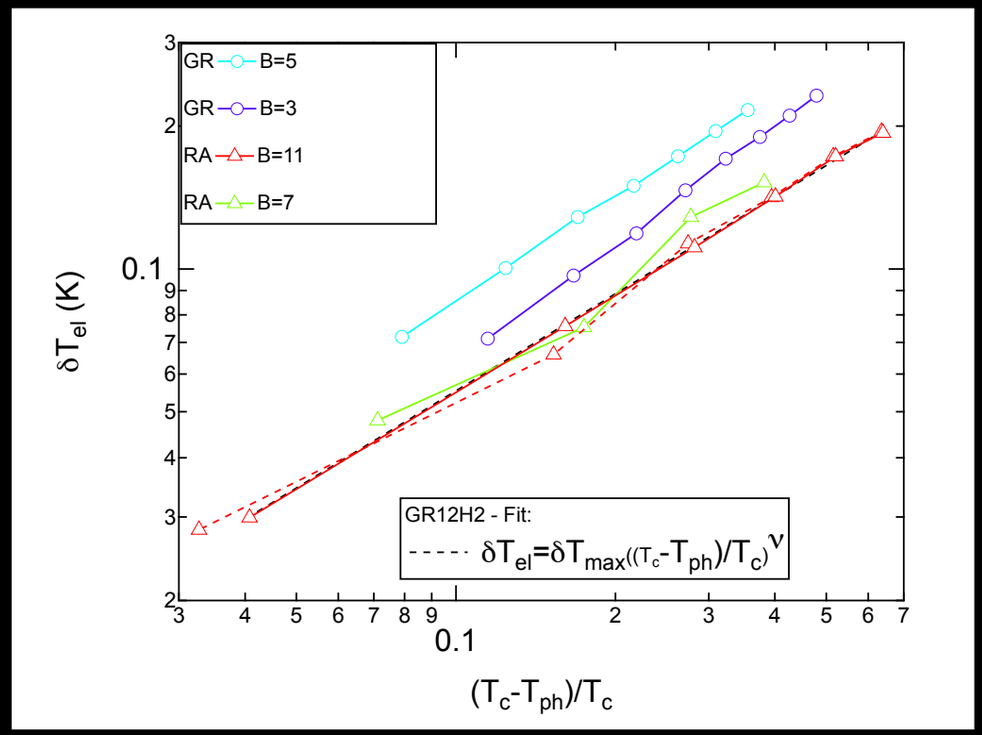

Pressure
30
20
10
5
6
7
8
9
2
3
10^{-4}
1/ρ


GR12H2
B=3 T
T_{ph}=200 mK
Critical point
T_{ph}=100 mK
-V (10^{-3} Volt)
-5
-10
-15
-20
-25
0.1
0.2
0.3
0.4
T_{el} (K)

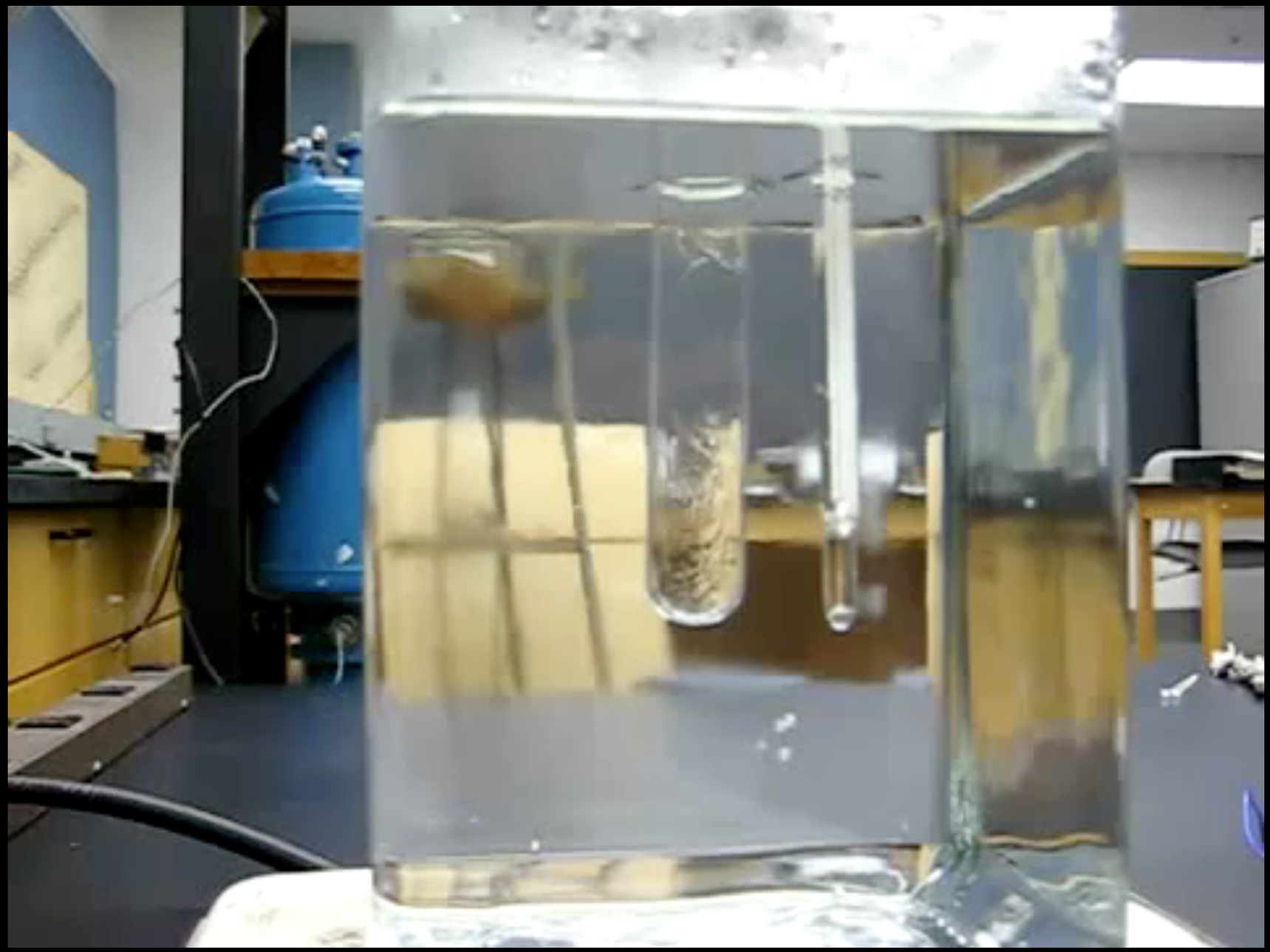
Order parameter



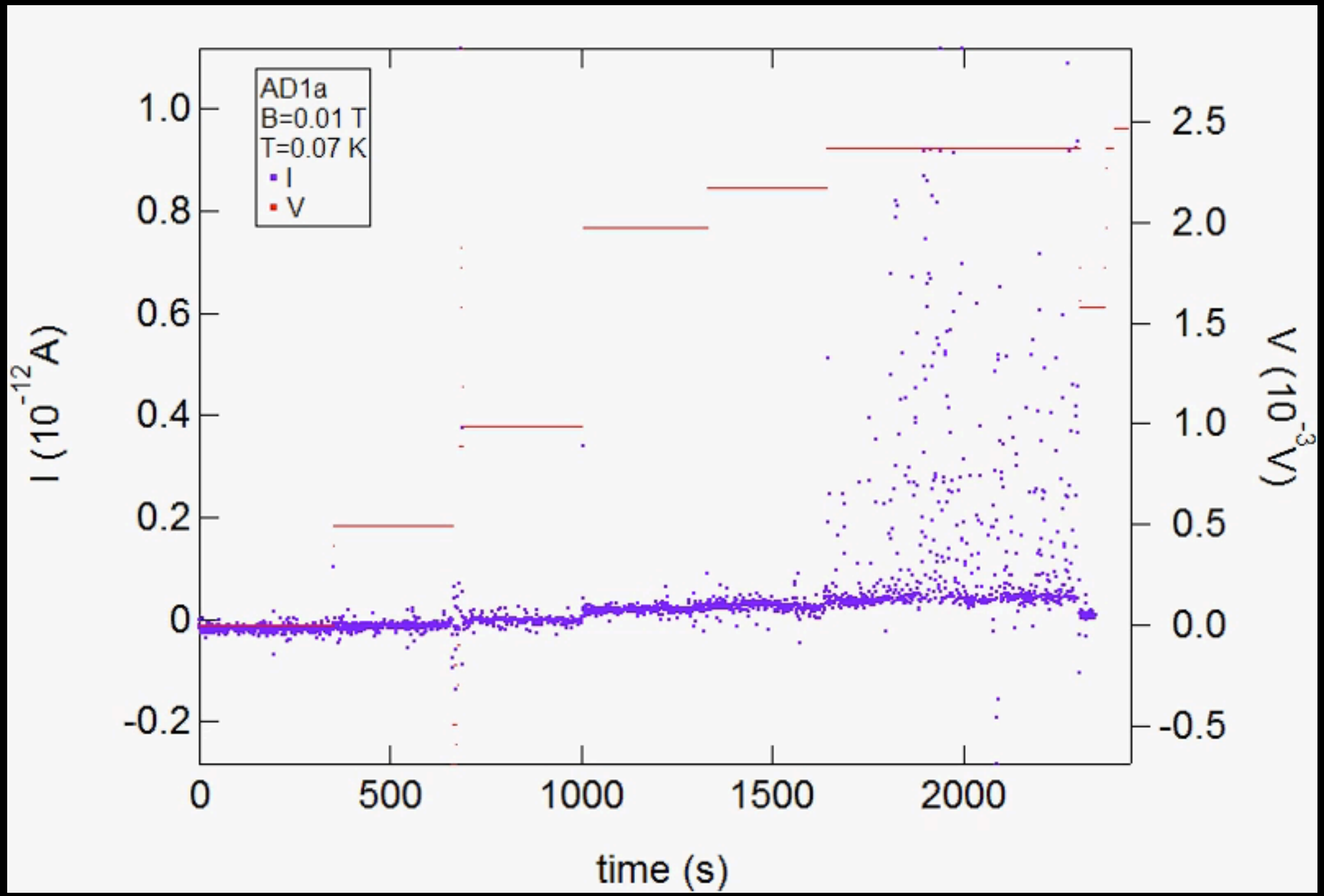
Critical exponents



Critical Opalescence



Time dependence


AD1a
B=0.01 T
T=0.07 K
I
V
1.0
0.8
0.6
0.4
0.2
0
-0.2
I (10^-12 A)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
V (10^-3 V)
0
500
1000
1500
2000
time (s)

The Insulator at T<0.2 K:

Ohmic transport

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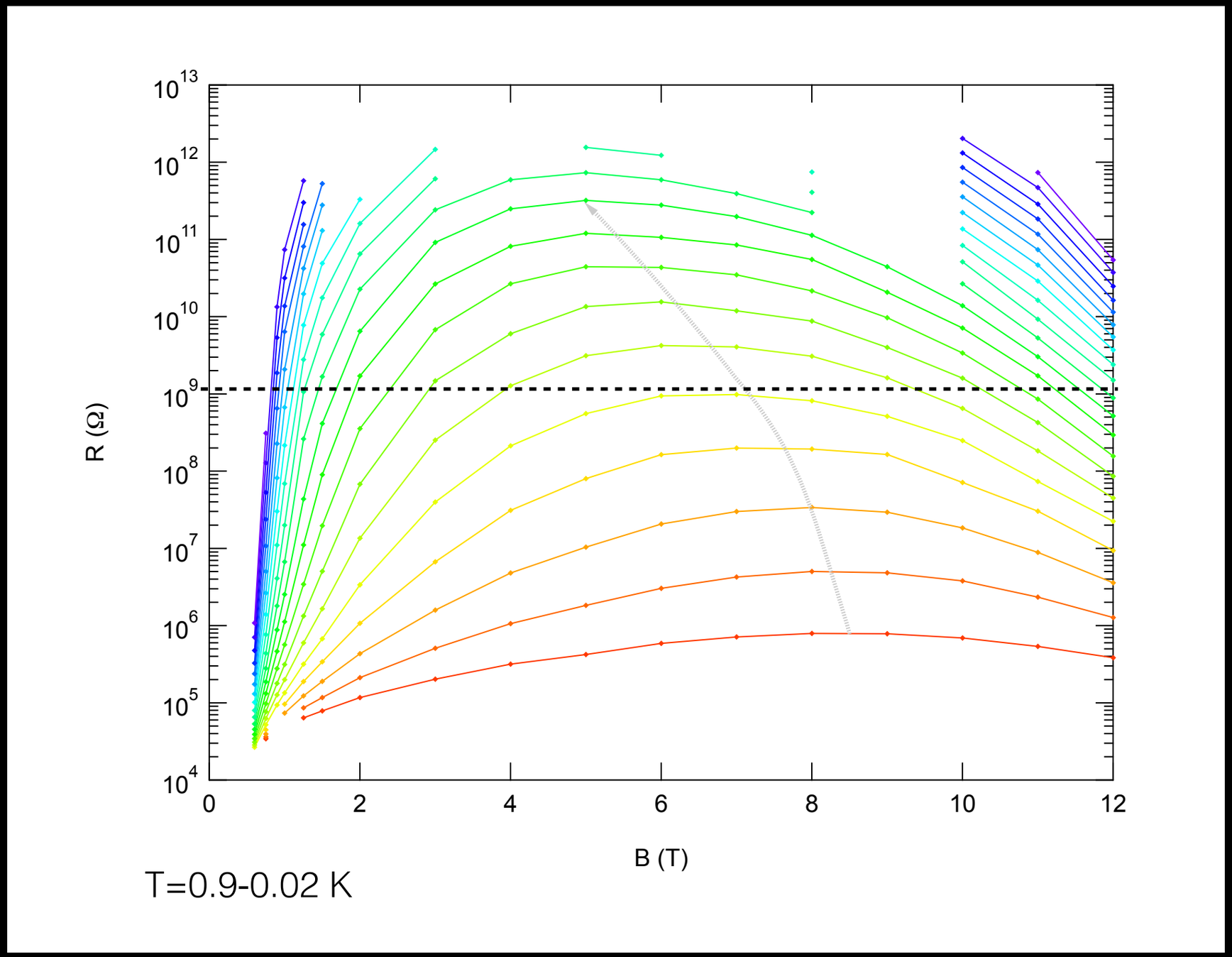
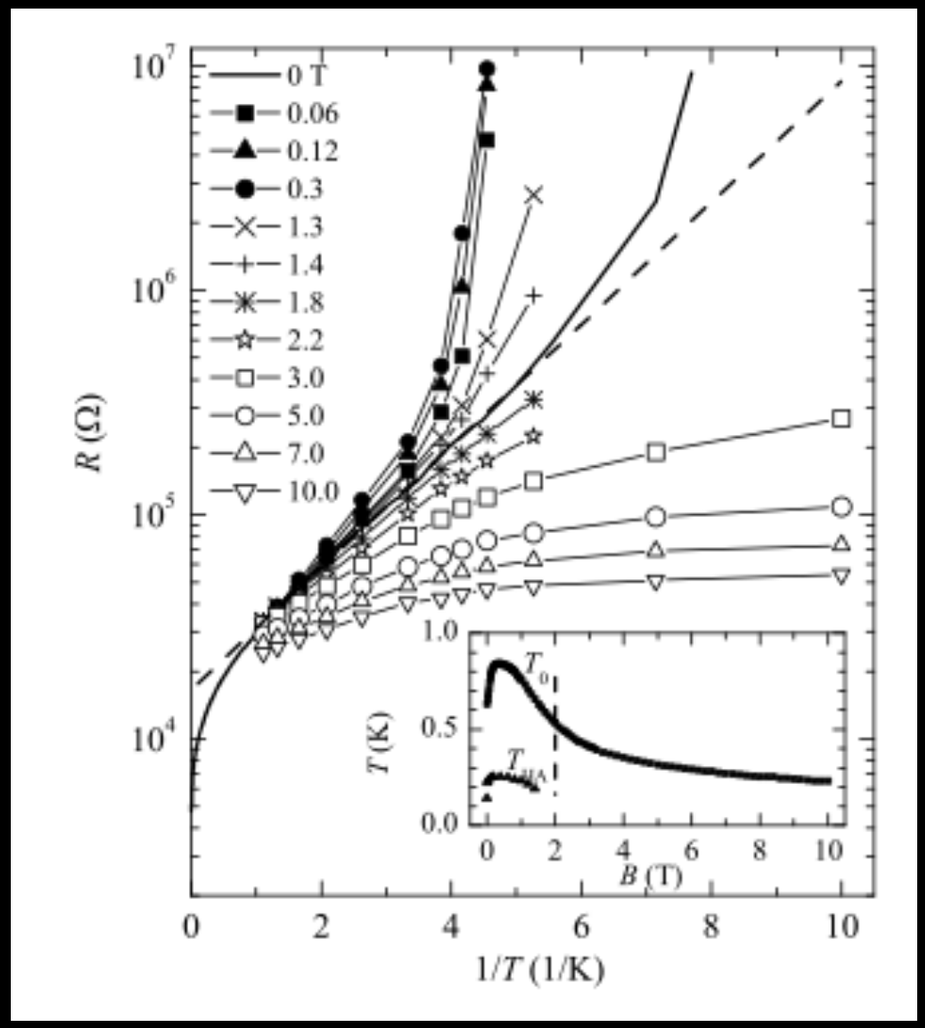
Ohmic transport



ISSN 0021-3640, JETP Letters, 2008, Vol. 88, No. 11, pp. 752–757. © Pleiades Publishing, Ltd., 2008.

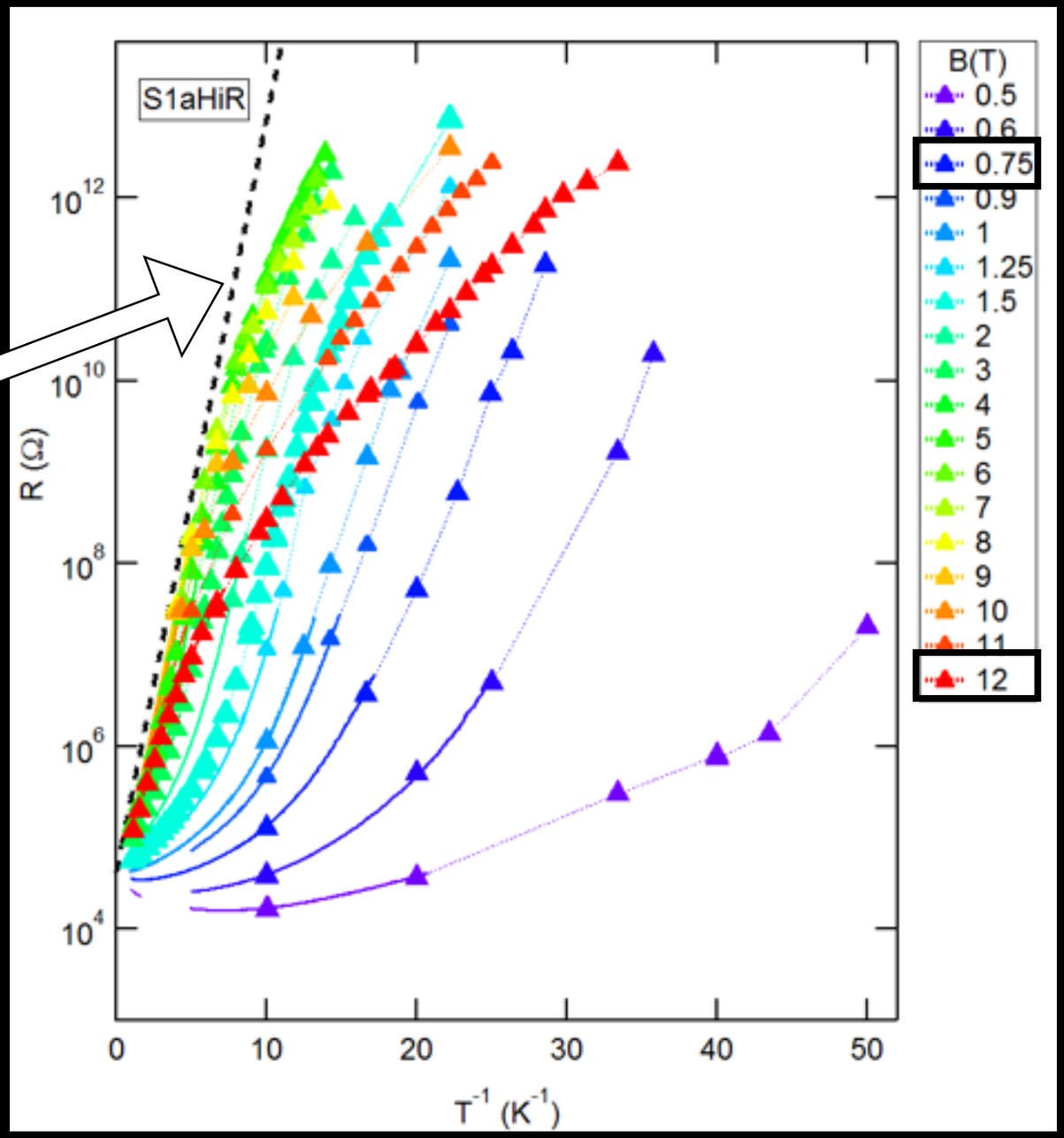
Hyperactivated Resistance in TiN Films on the Insulating Side of the Disorder-Driven Superconductor-Insulator Transition¶

T. I. Baturina[a], A. Yu. Mironov[a], V. M. Vinokur[b], M. R. Baklanov[c], and C. Strunk[d]

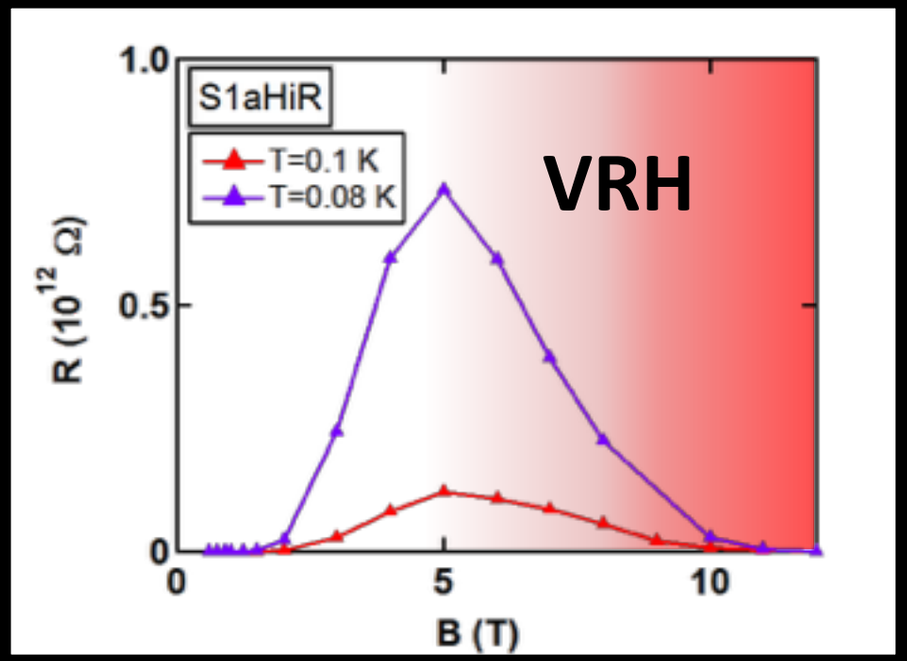


Arrhenius plot

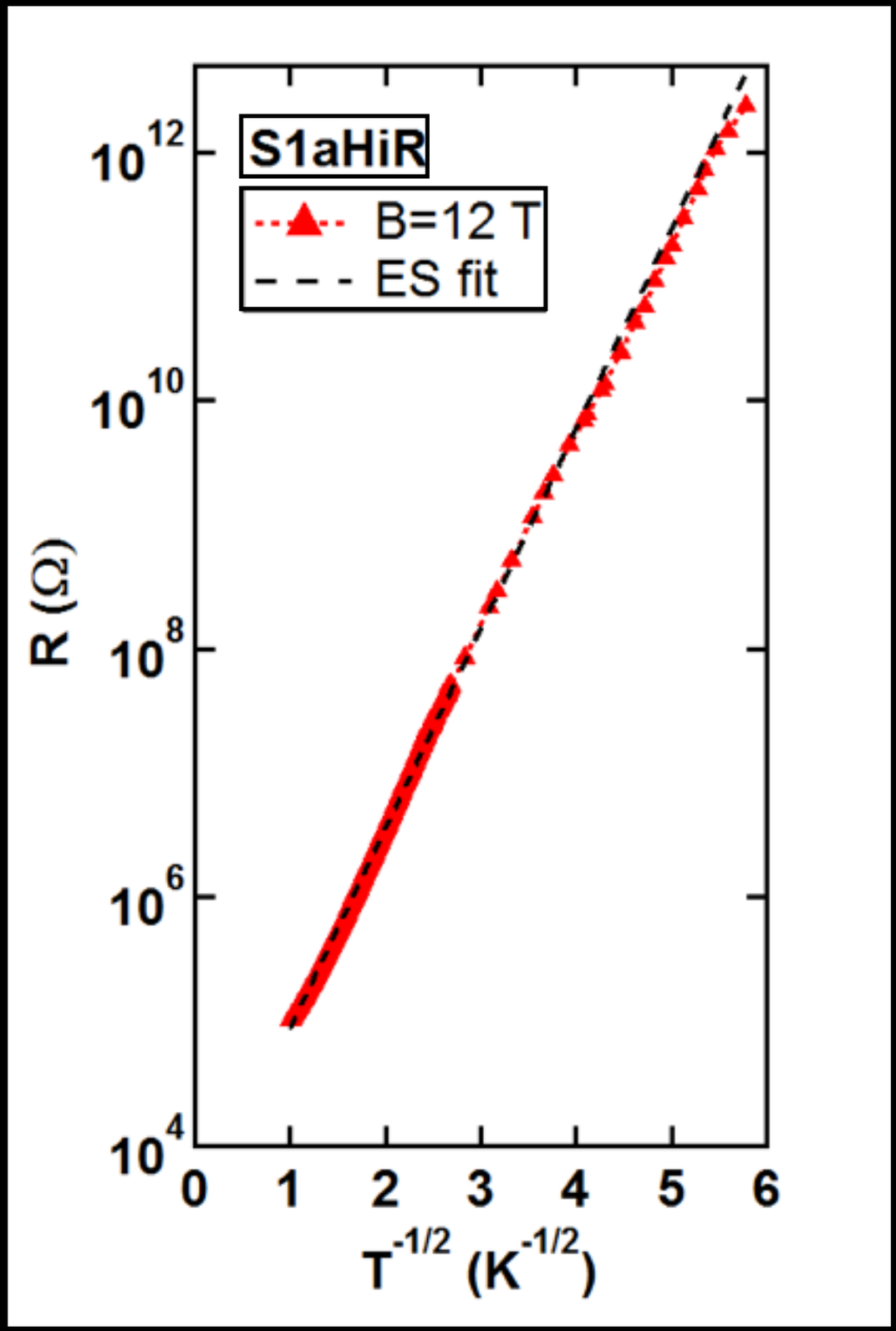
Activation



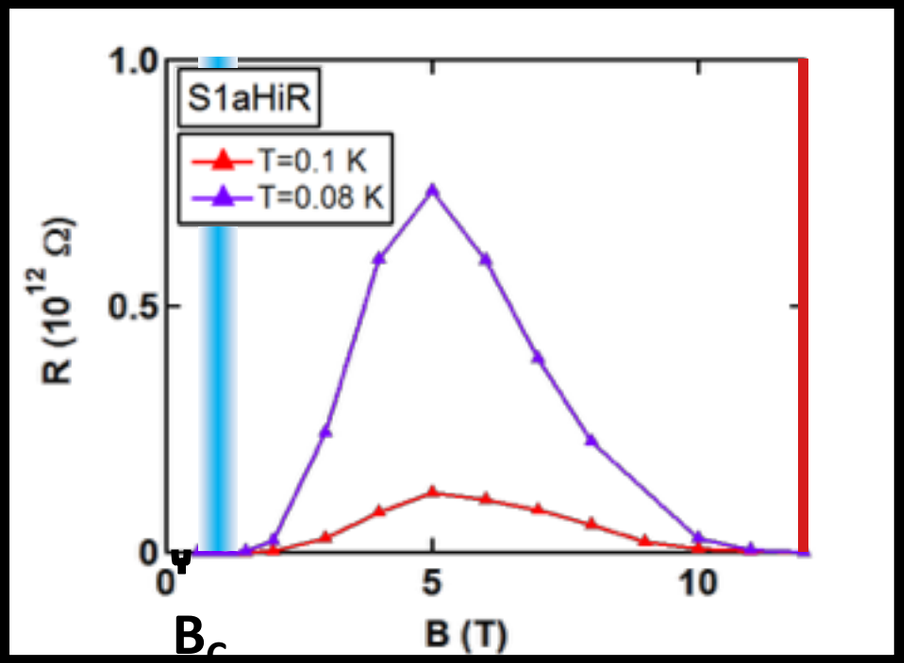
Efros-Shklovskii Hopping at High B

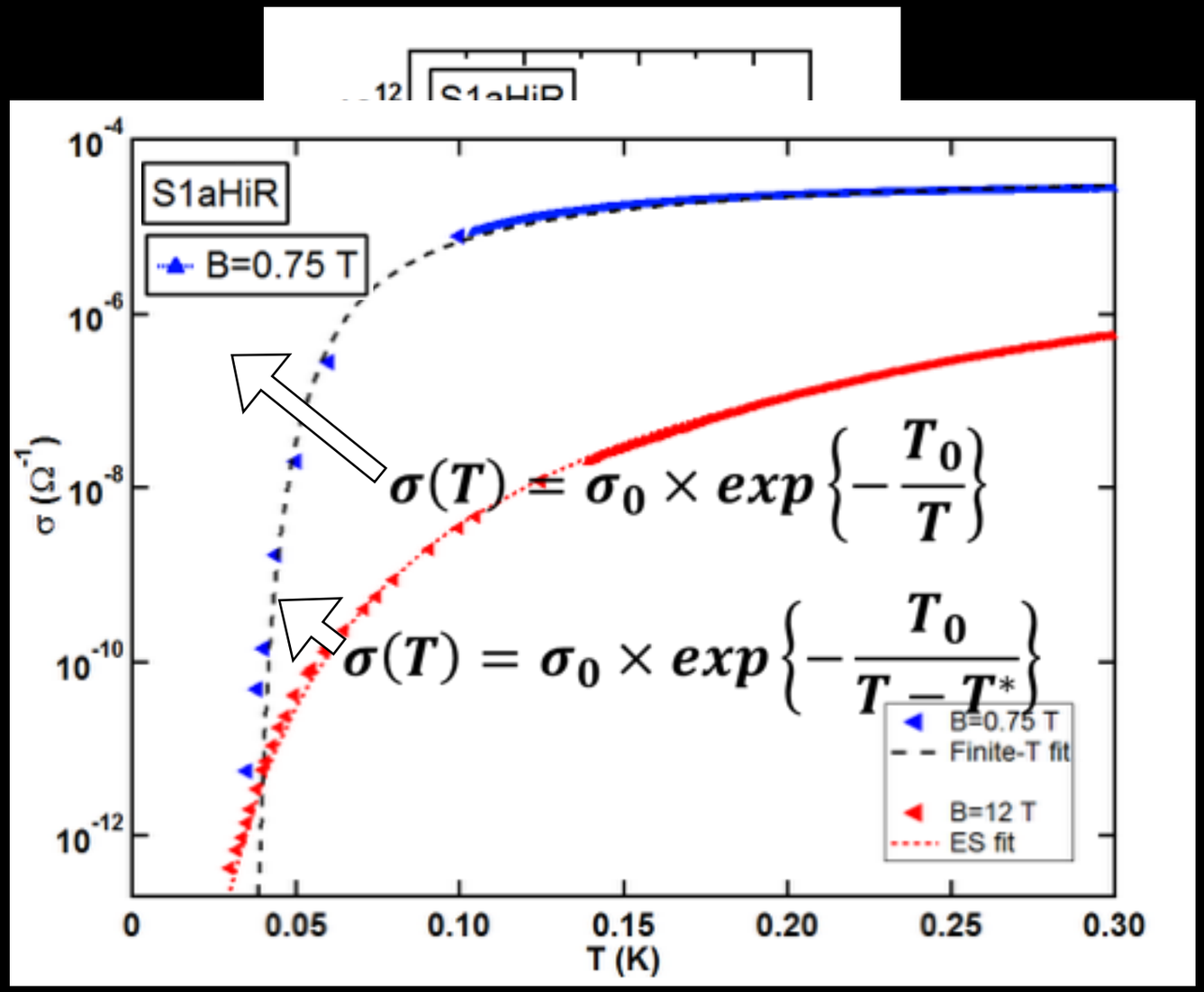


$$R(T) = R_{ES} \times exp\left\{\left(\frac{T_{ES}}{T}\right)^{1/2}\right\}$$

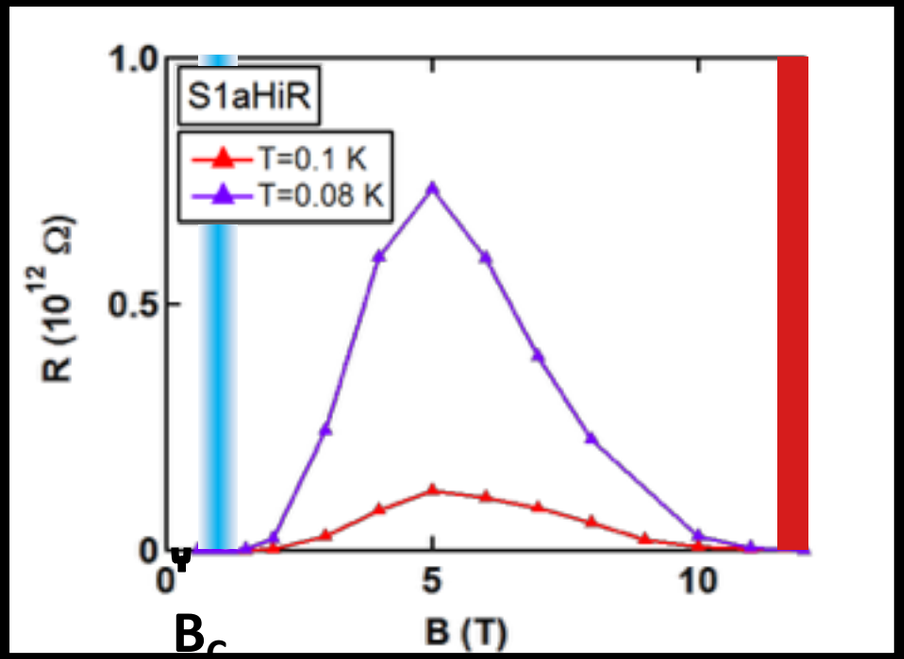


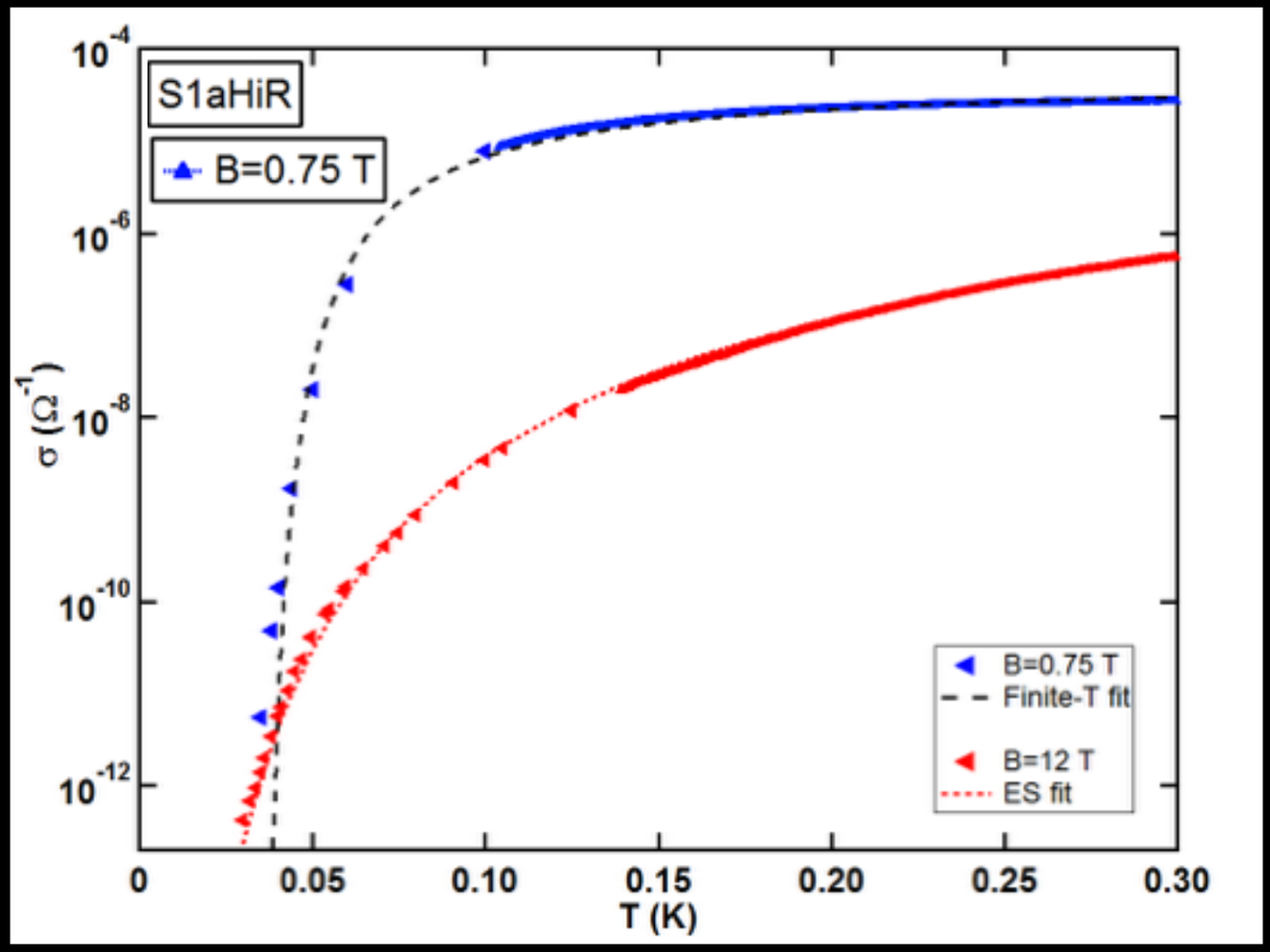
Resistivity Near B_c



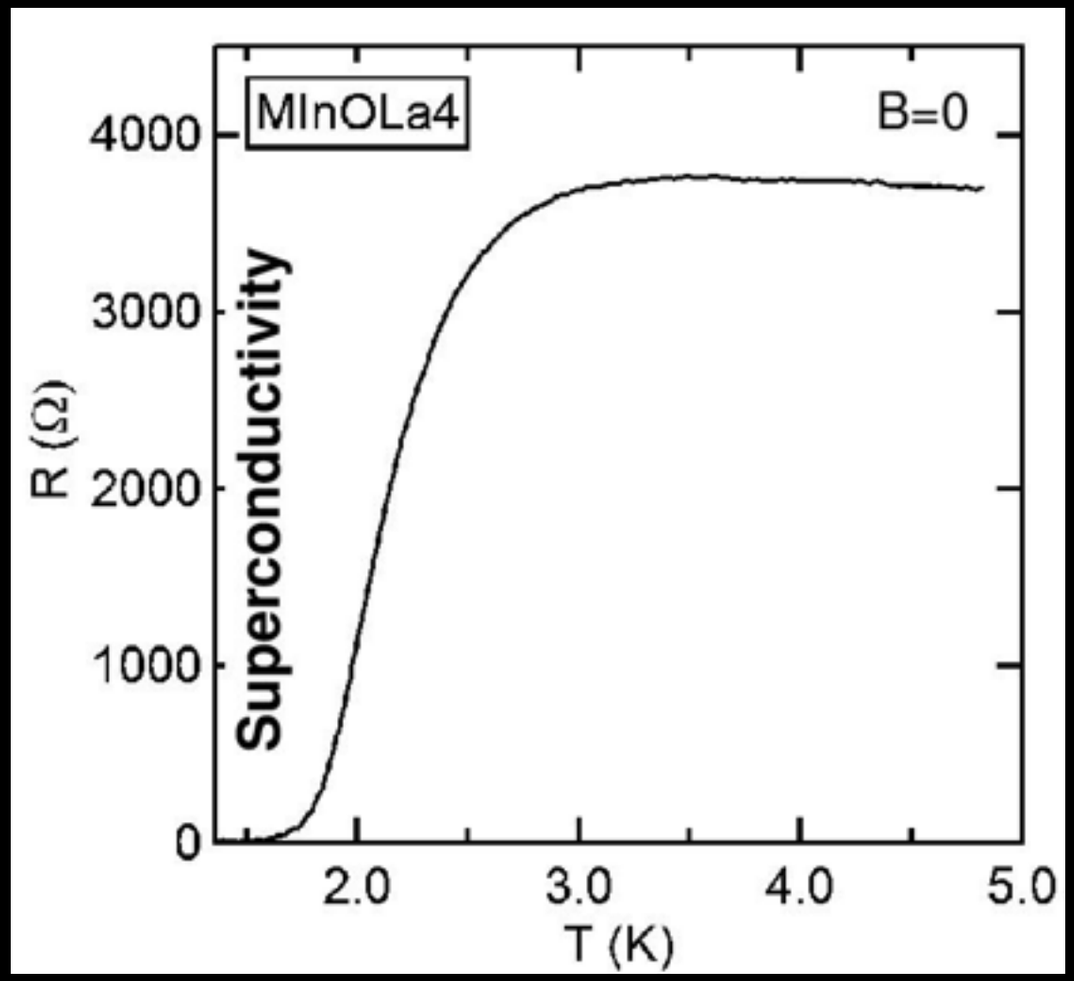


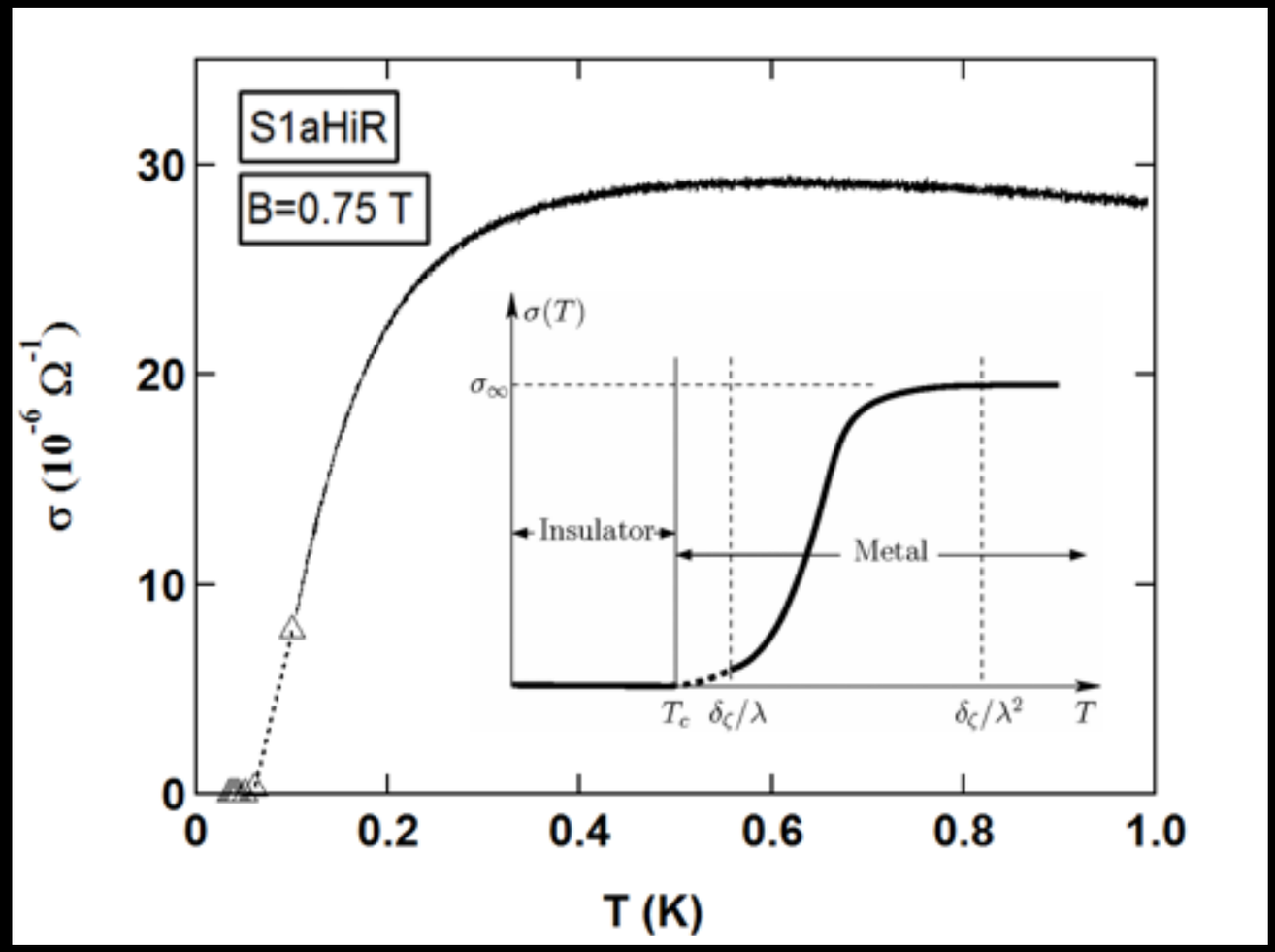
Conductivity





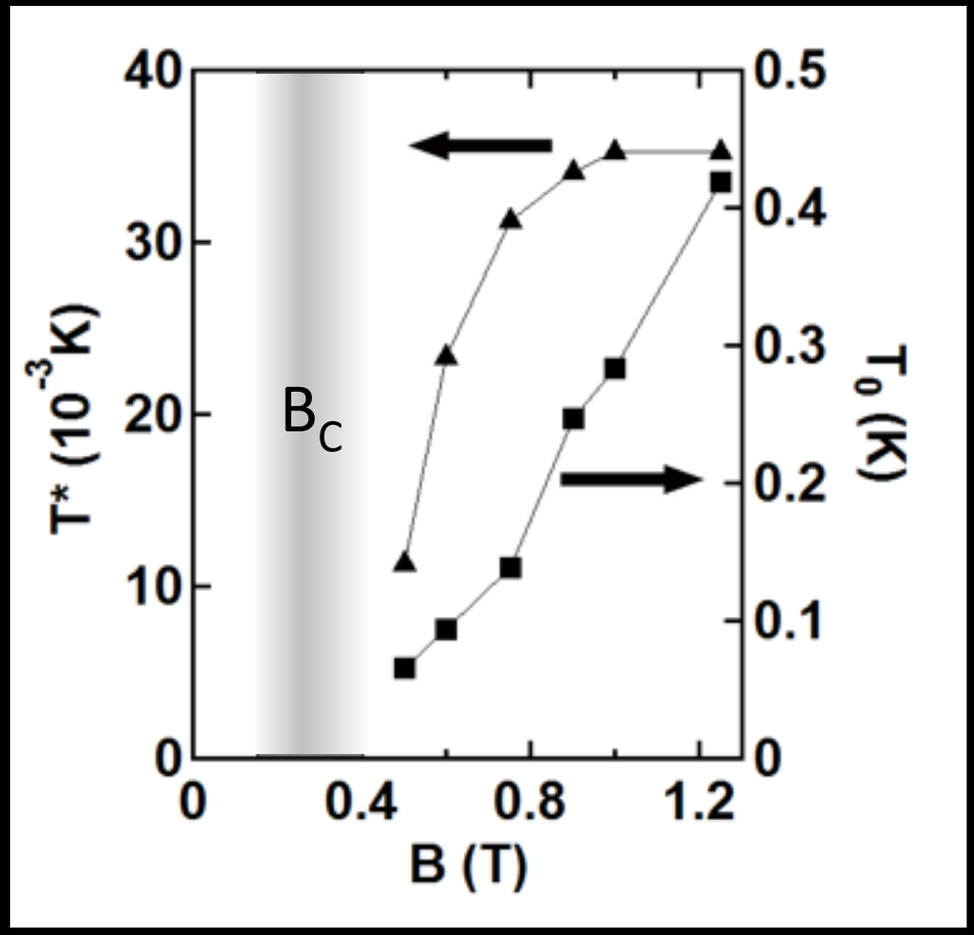
Many-body localization?





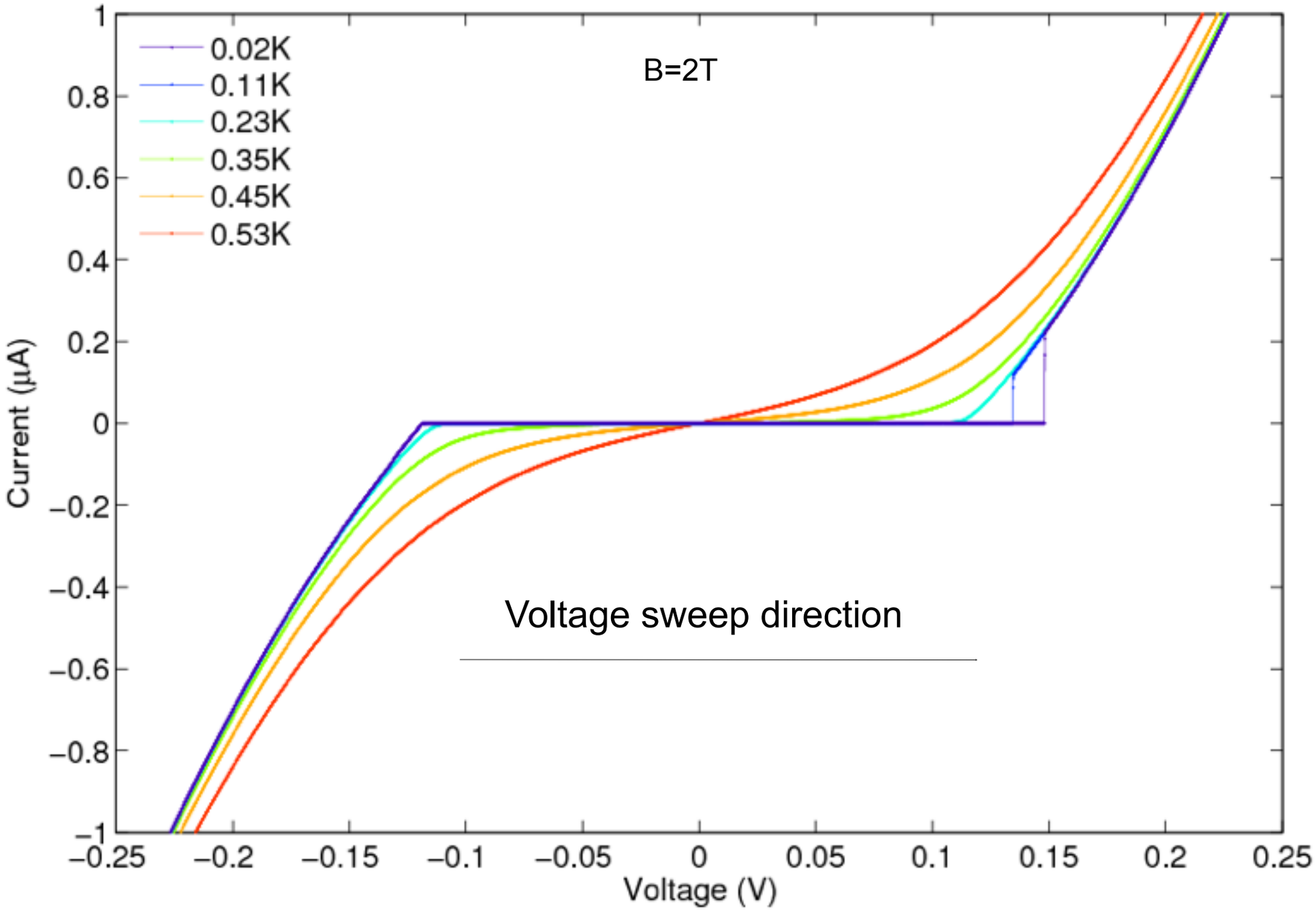
Thank you.

Fit Parameters

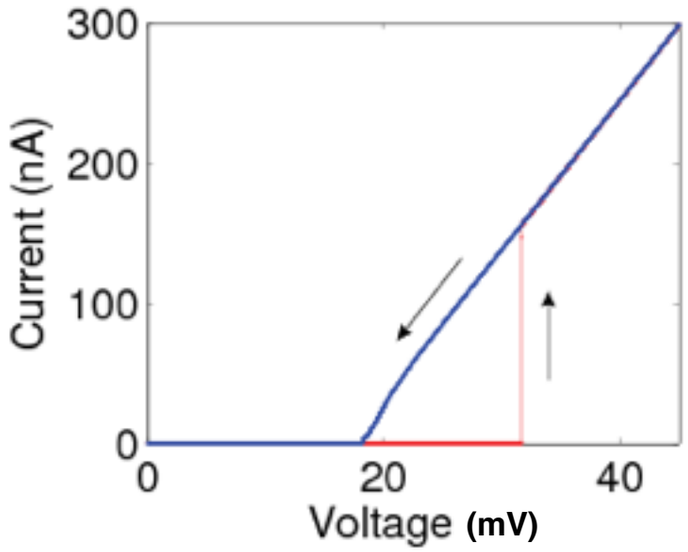


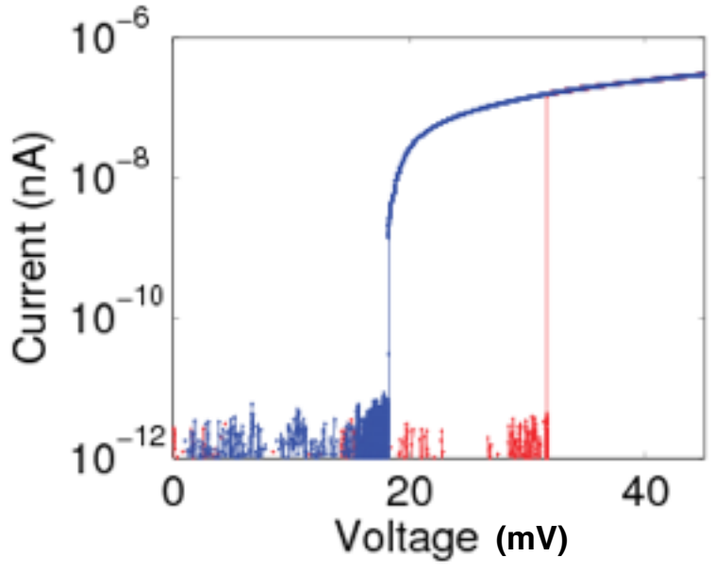
$$\sigma(T) = \sigma_0 \times exp\left\{-\frac{T_0}{T - T^*}\right\}$$

In the strongly insulating regime the I-V curves exhibit a voltage threshold

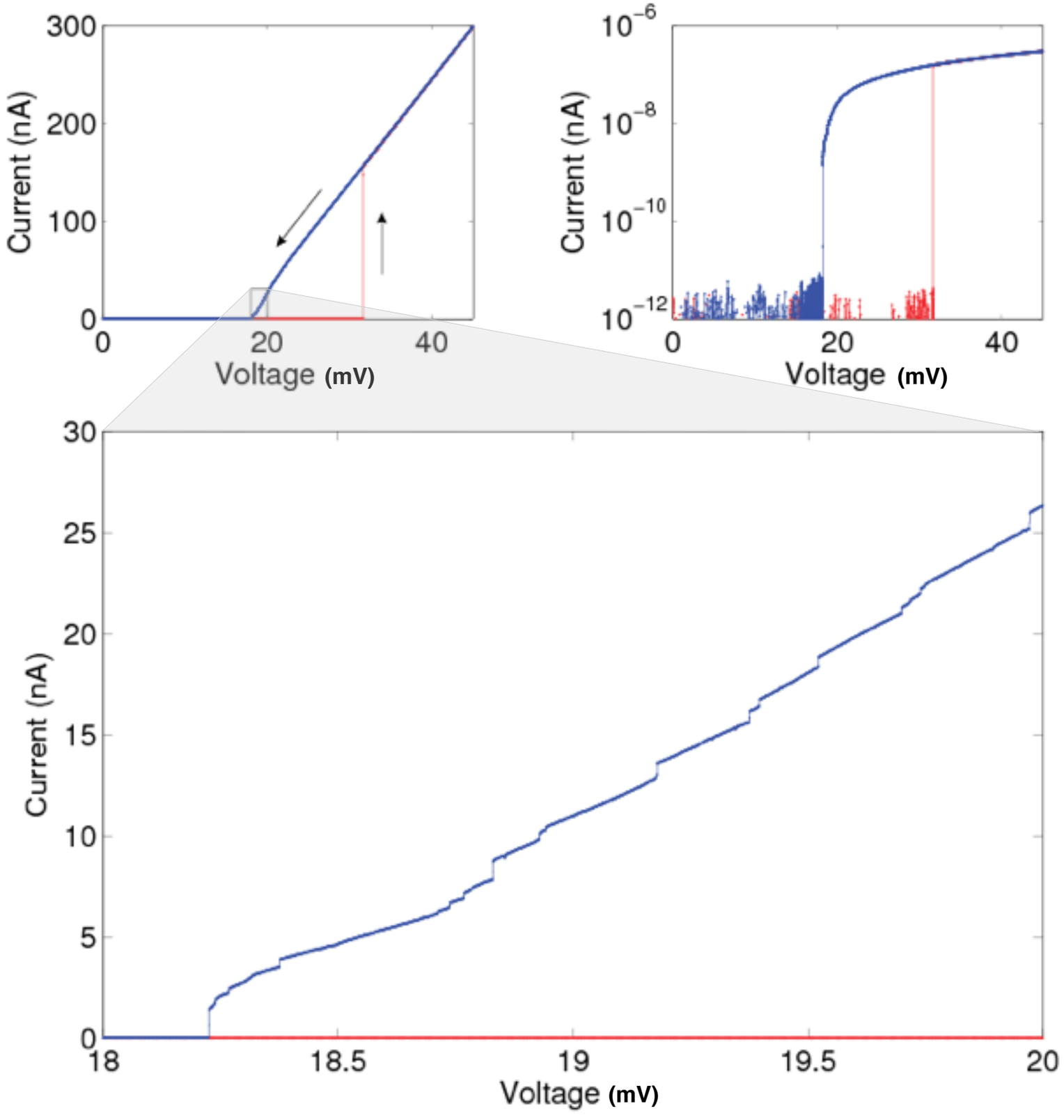


At low temperatures (T<0.2 K), the threshold is accompanied by switching and hysteresis

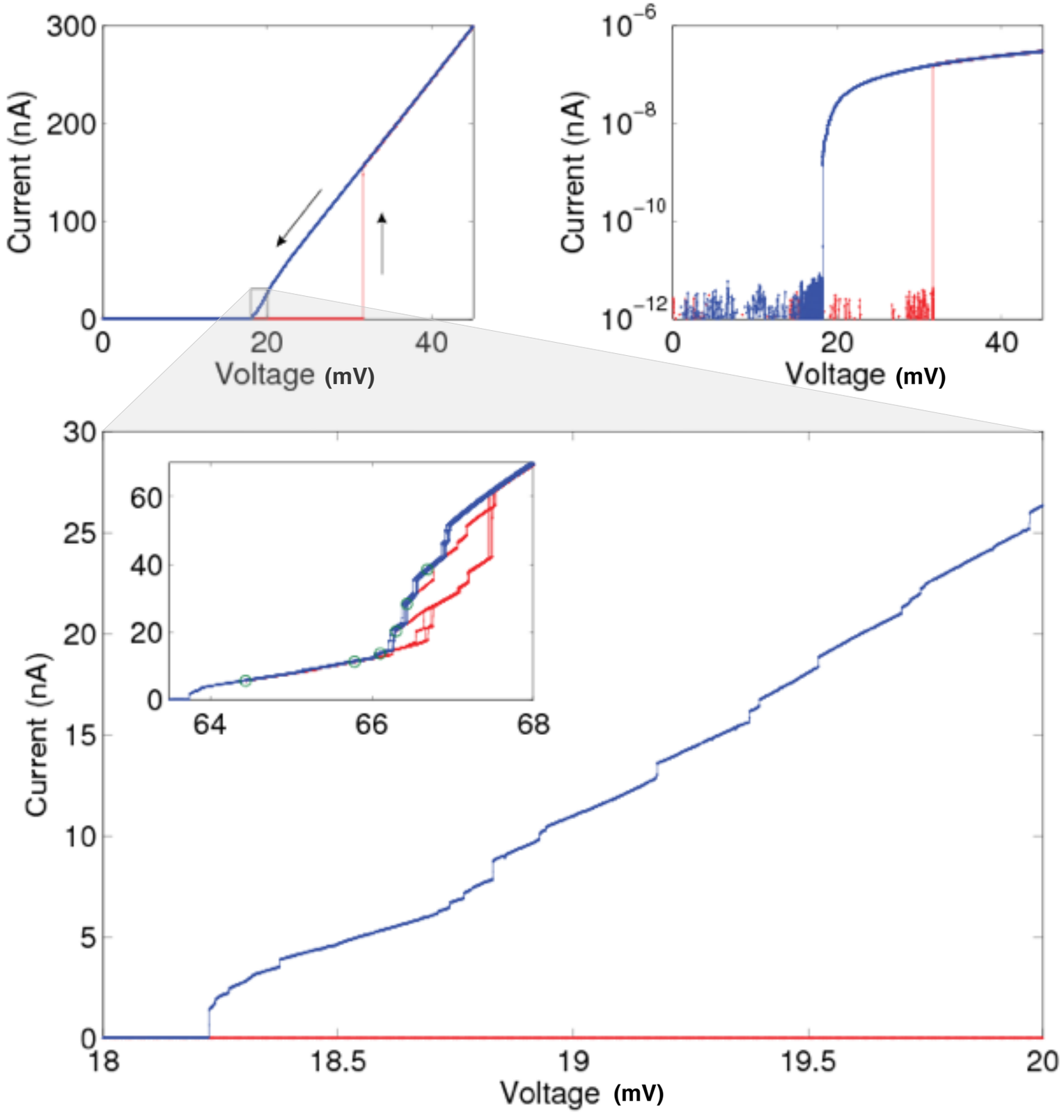




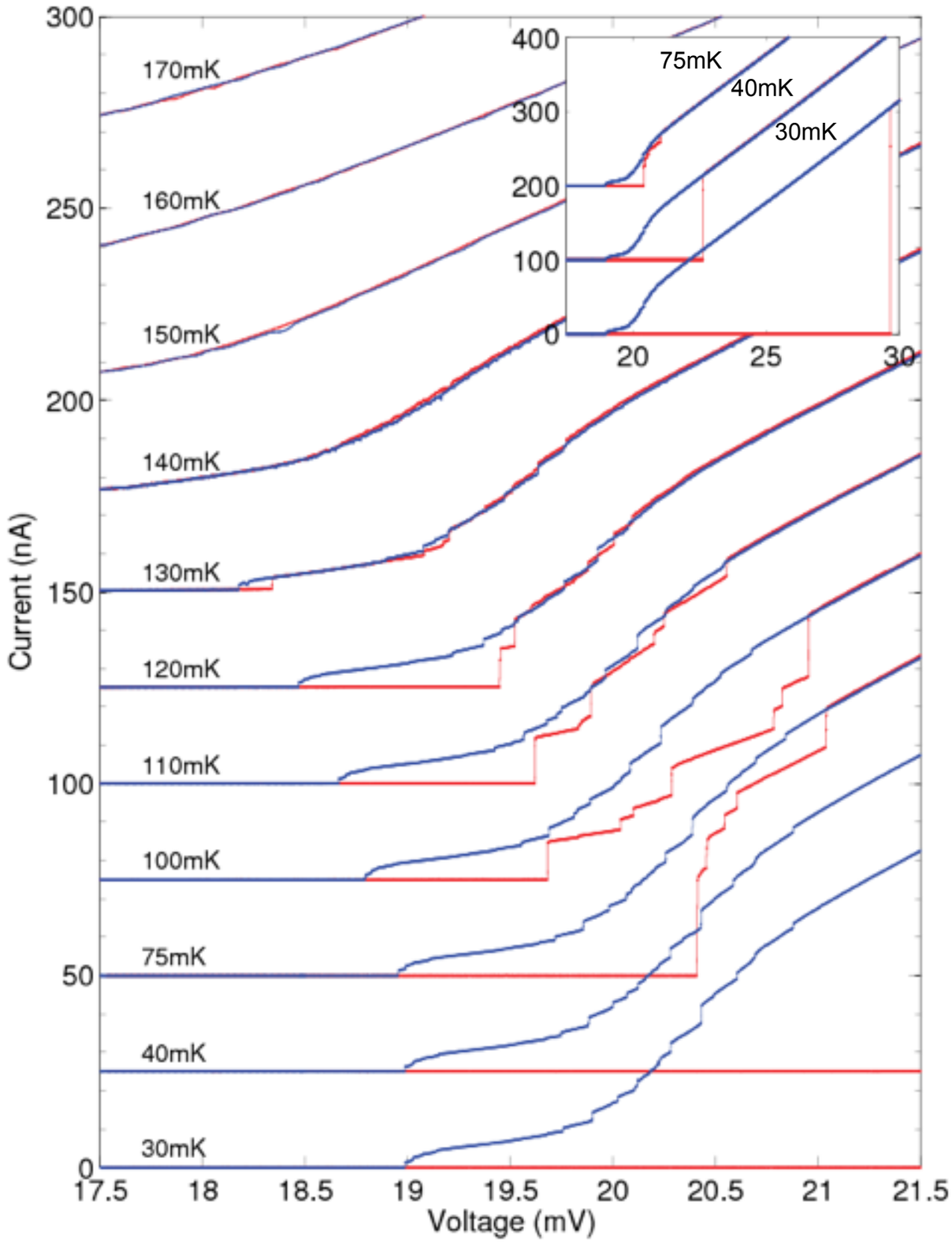
A series of discontinuous steps in current is revealed in the negative sweep direction



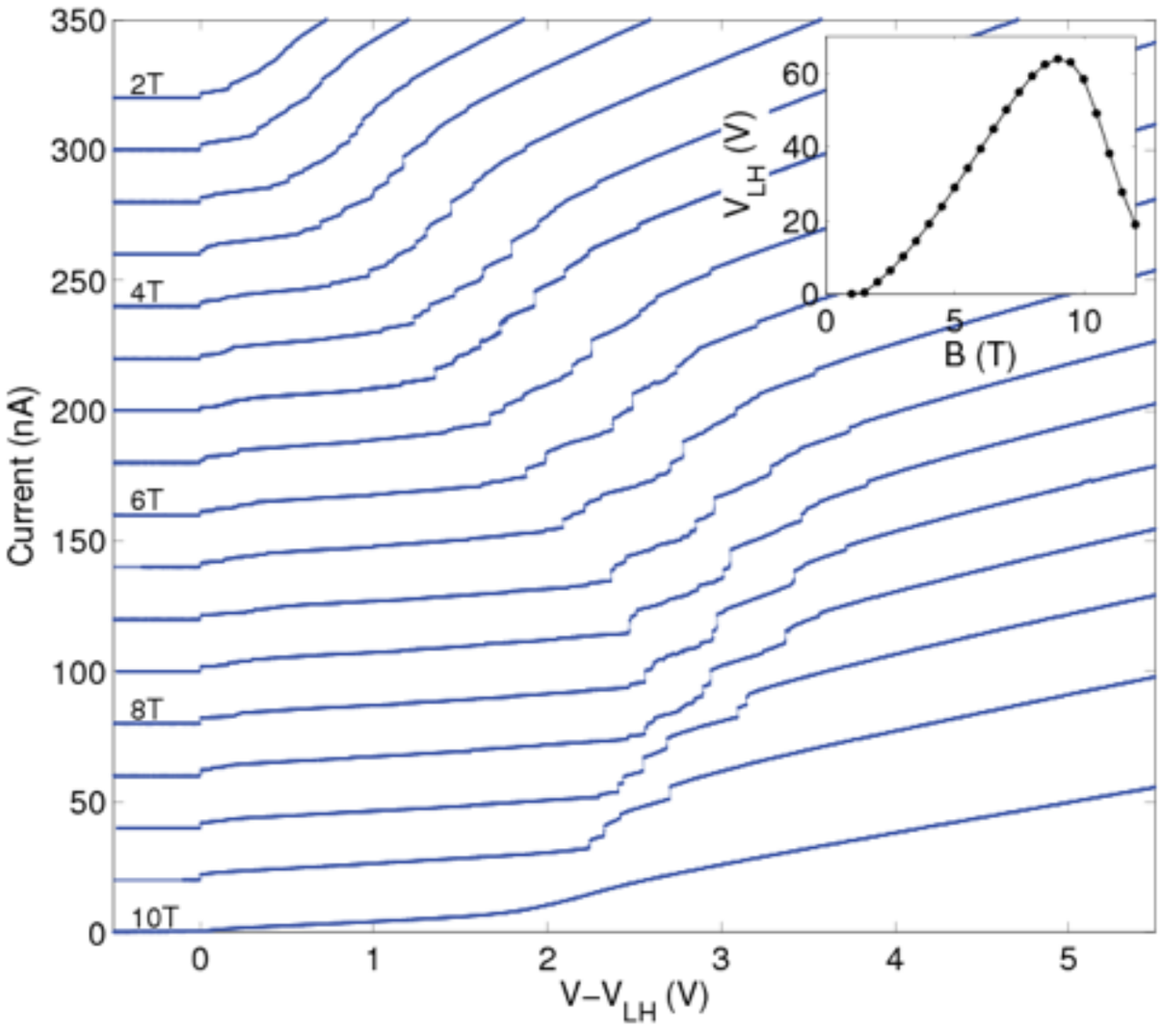
The current steps are accompanied by a complex hysteresis phenomenon



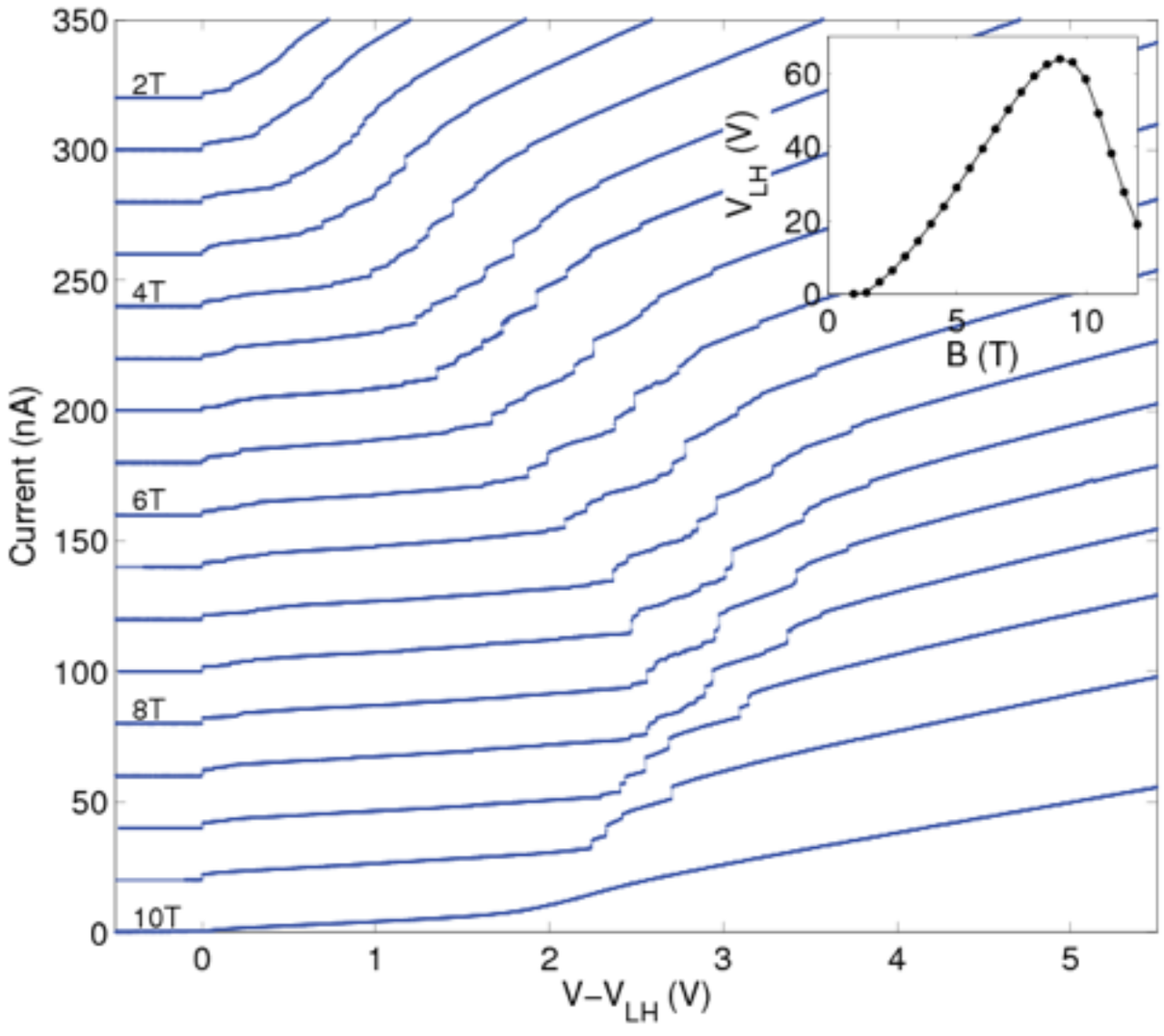
As T increases, the steps pattern deforms gradually

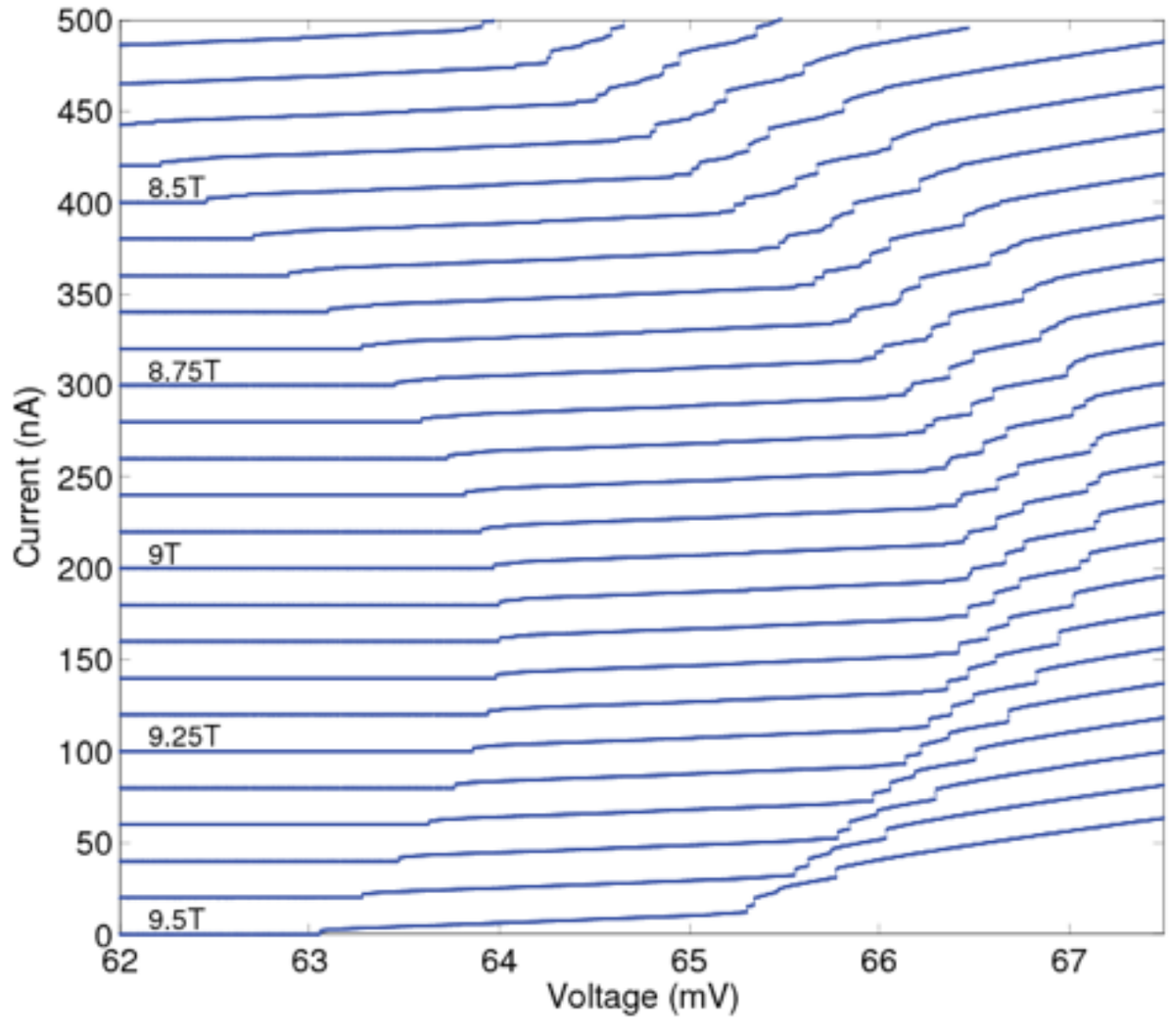


The magnetic field is seen to have only a moderate influence on the hierarchy of the steps pattern

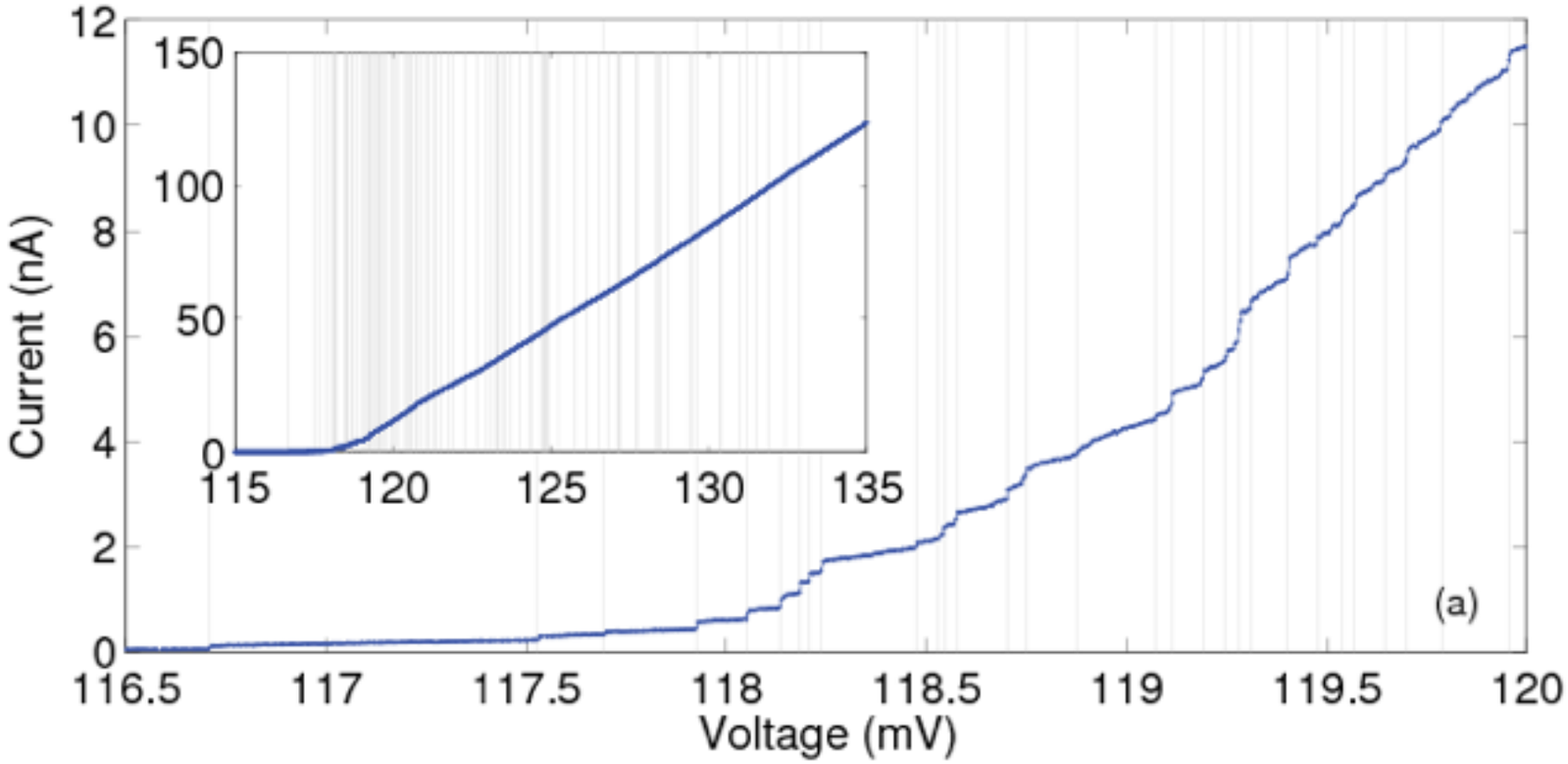


The magnetic field is seen to have only a moderate influence on the hierarchy of the steps pattern

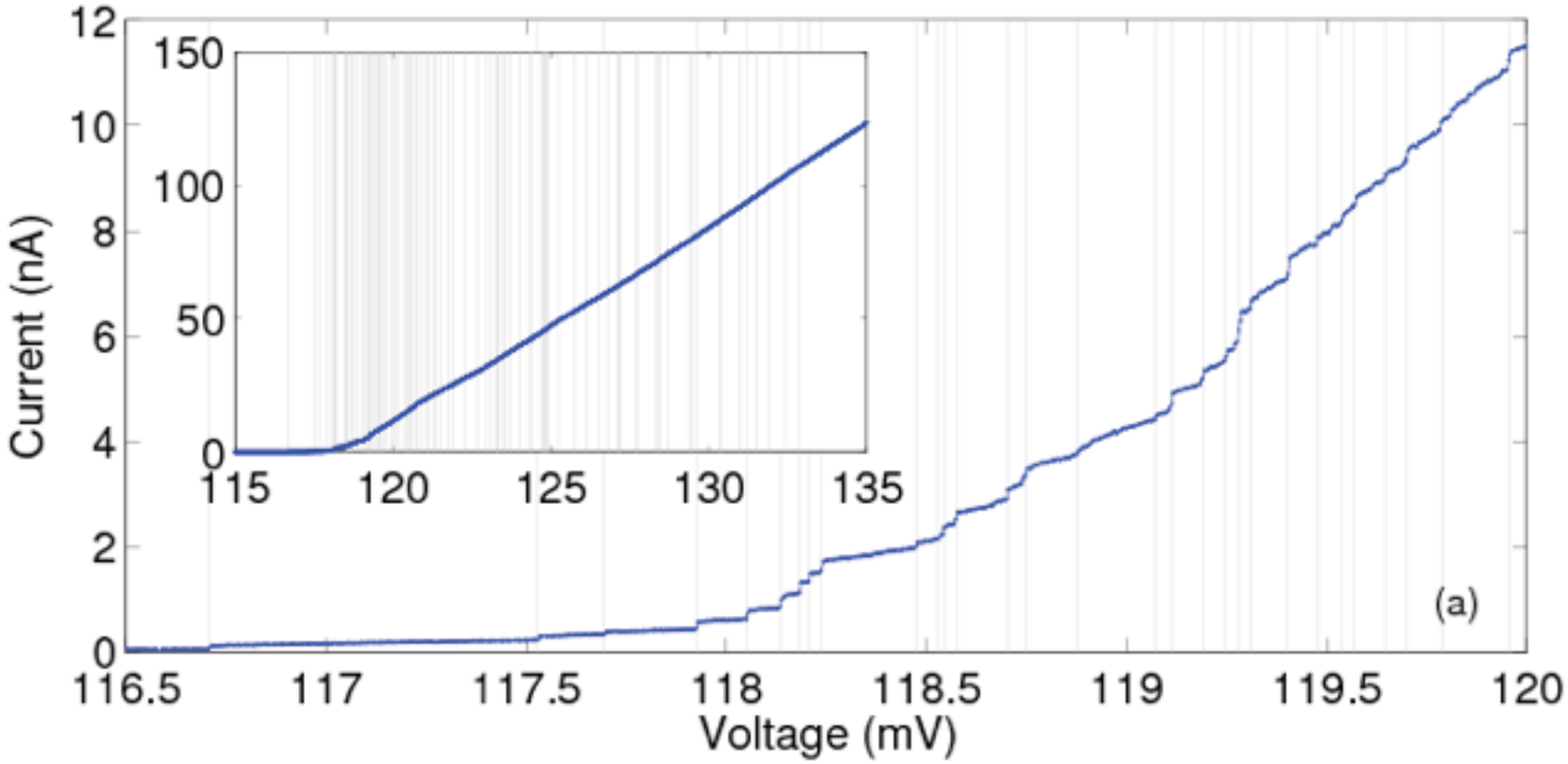


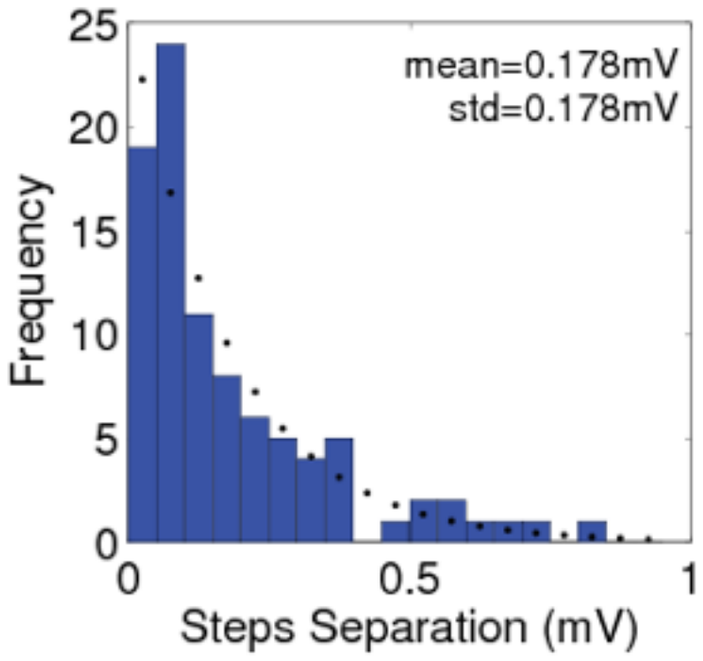


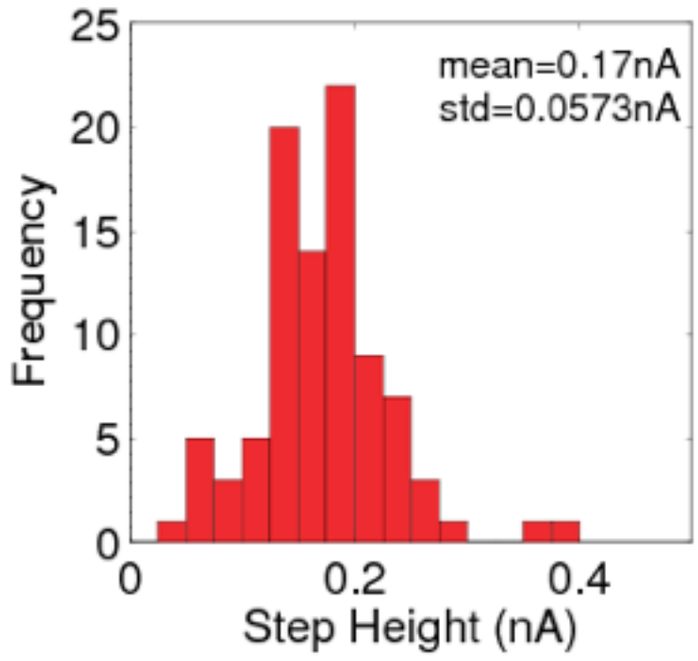
Films with higher degree of disorder show larger number of steps



Films with higher degree of disorder show larger number of steps

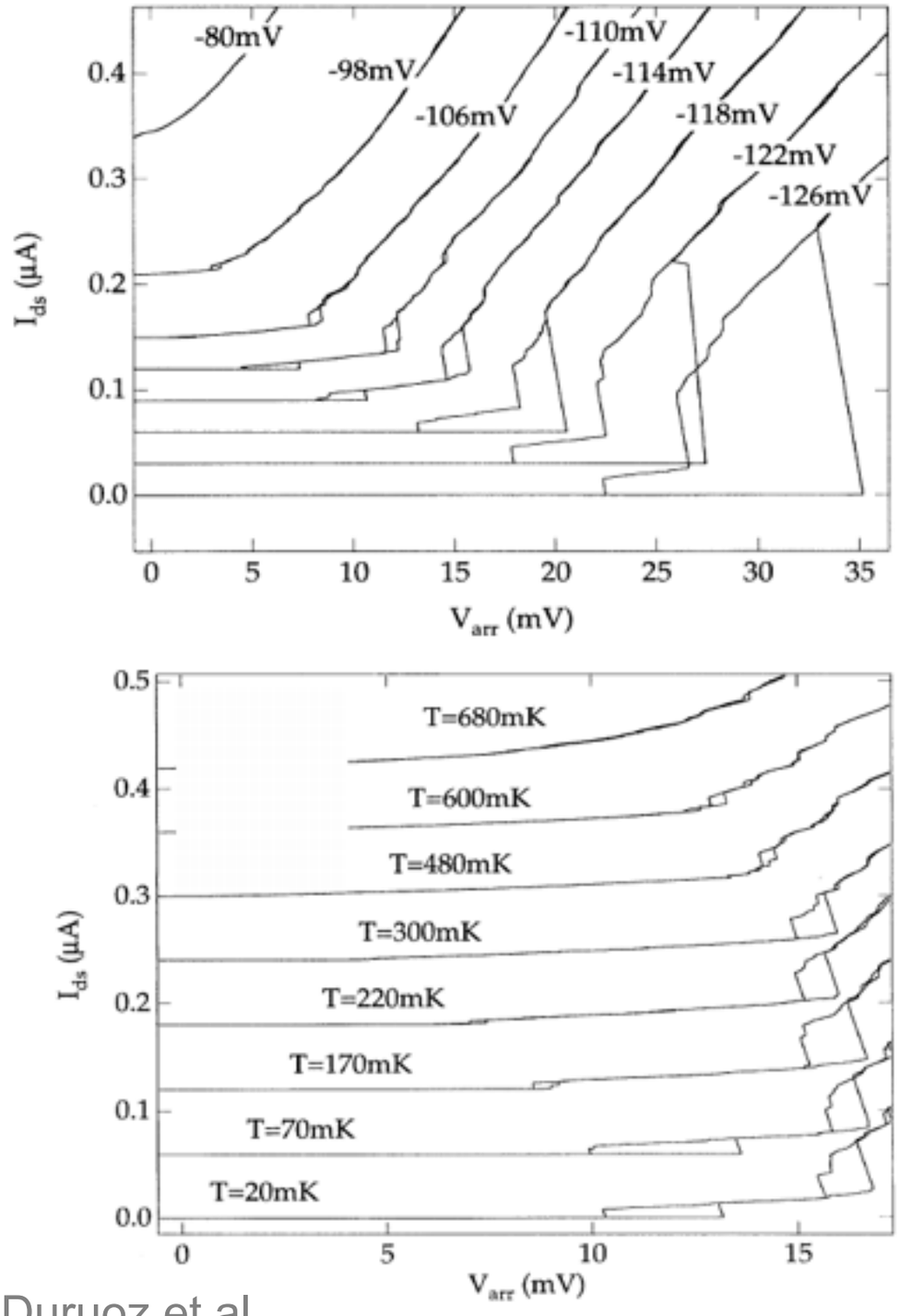






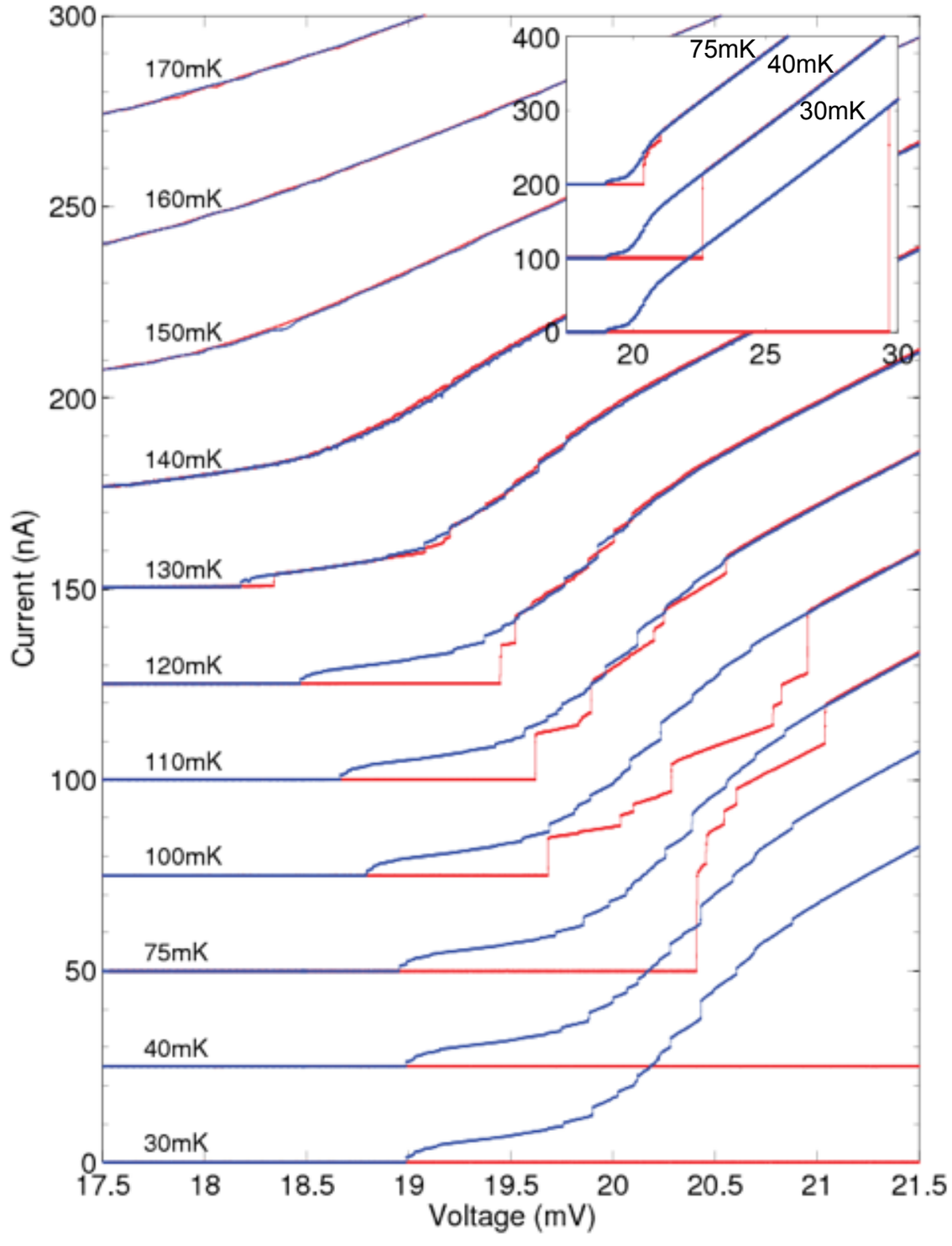
Experiment: QD array vs Thin Film

2D QD array

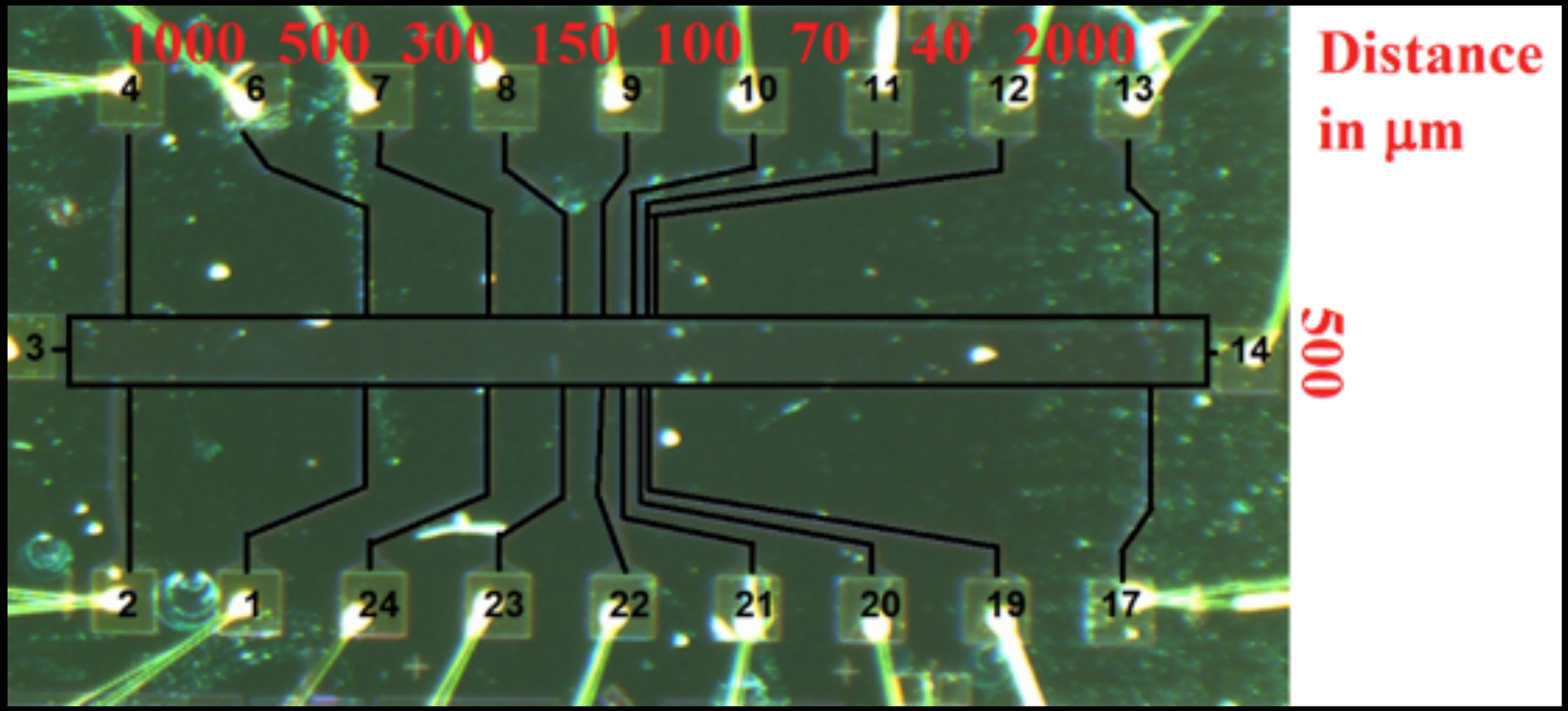


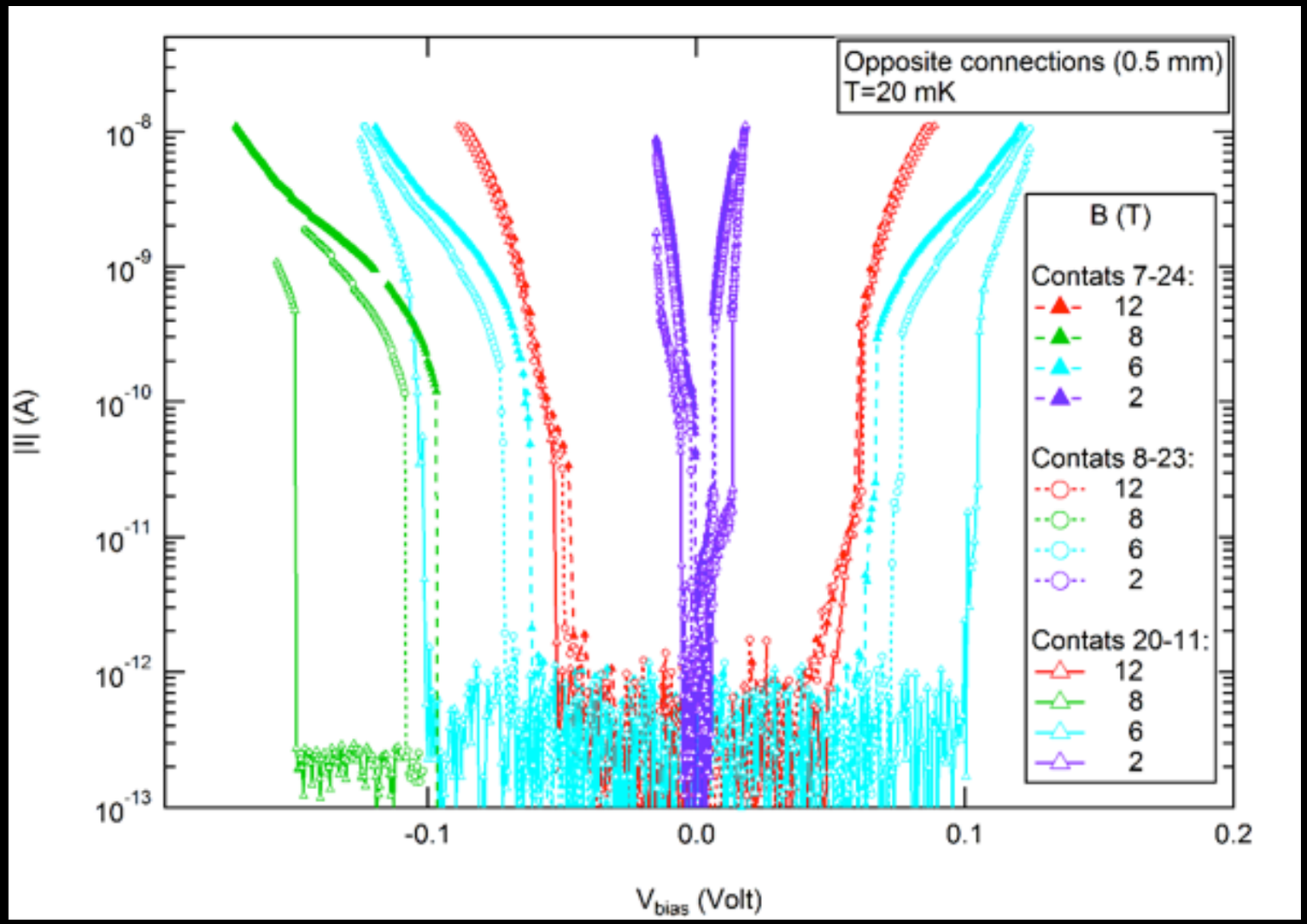
C. I. Duruoz et al.,
PRL 74, 3237 (1995)

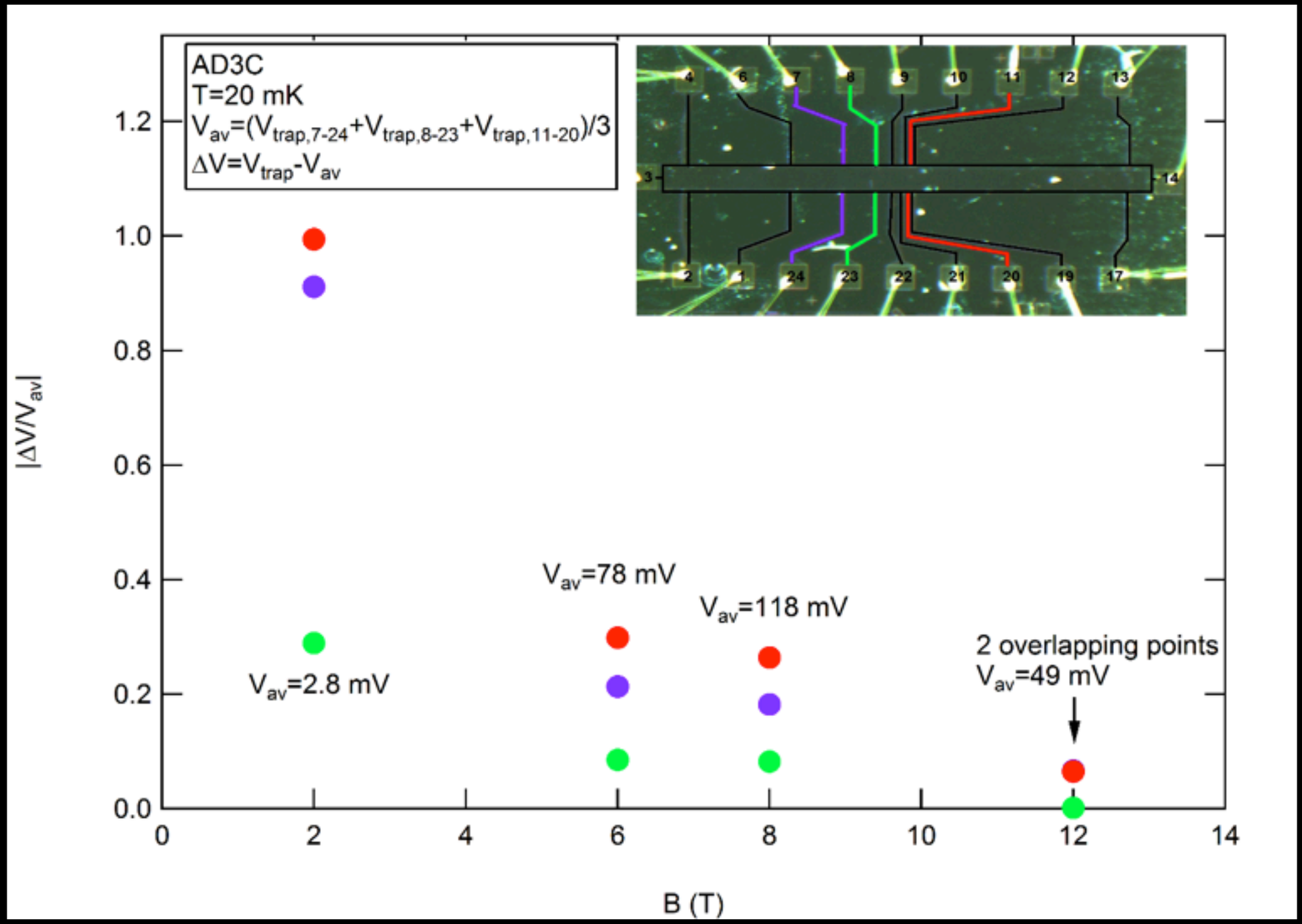
InO Thin Film



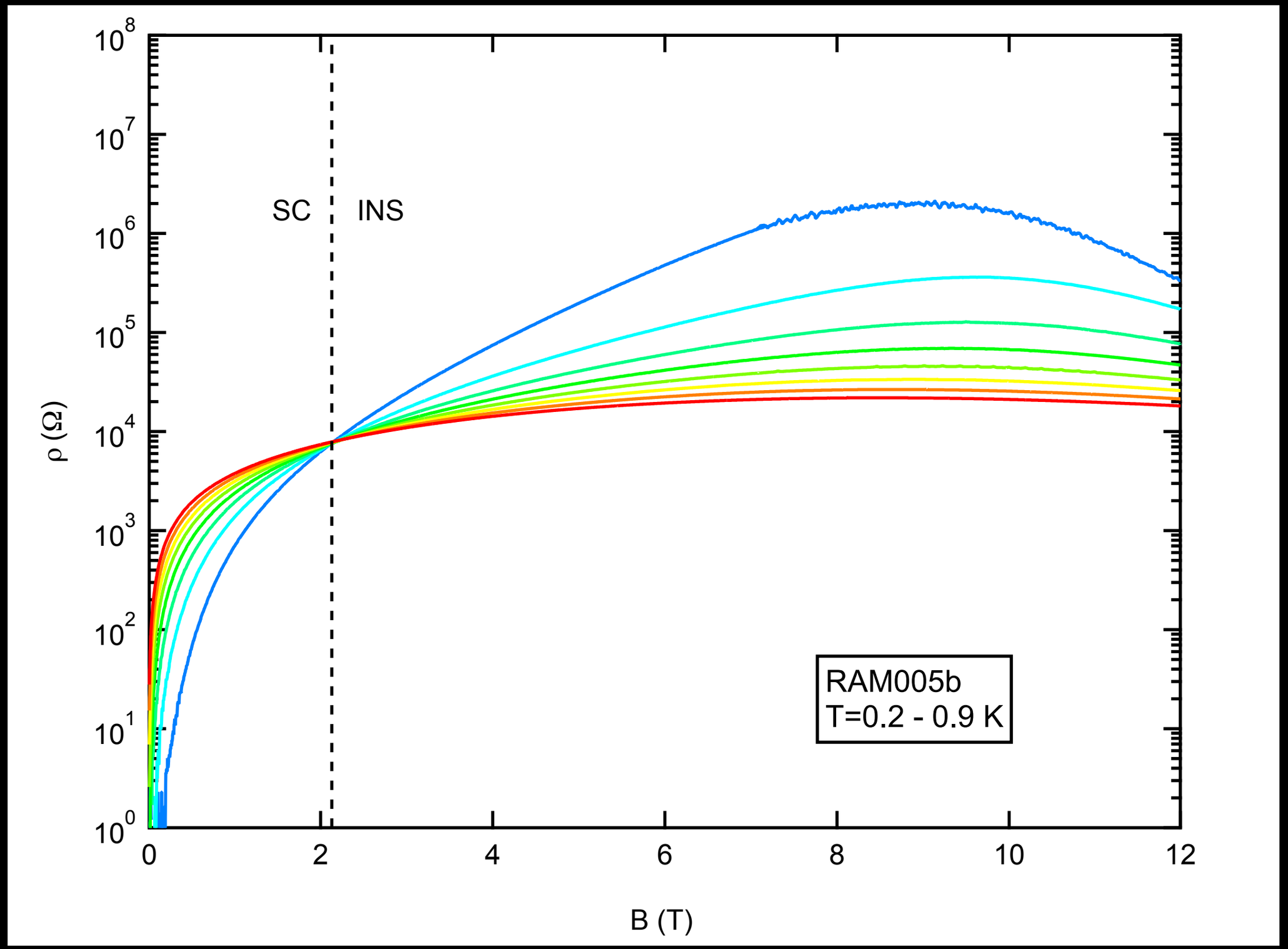
Inhomogeneity

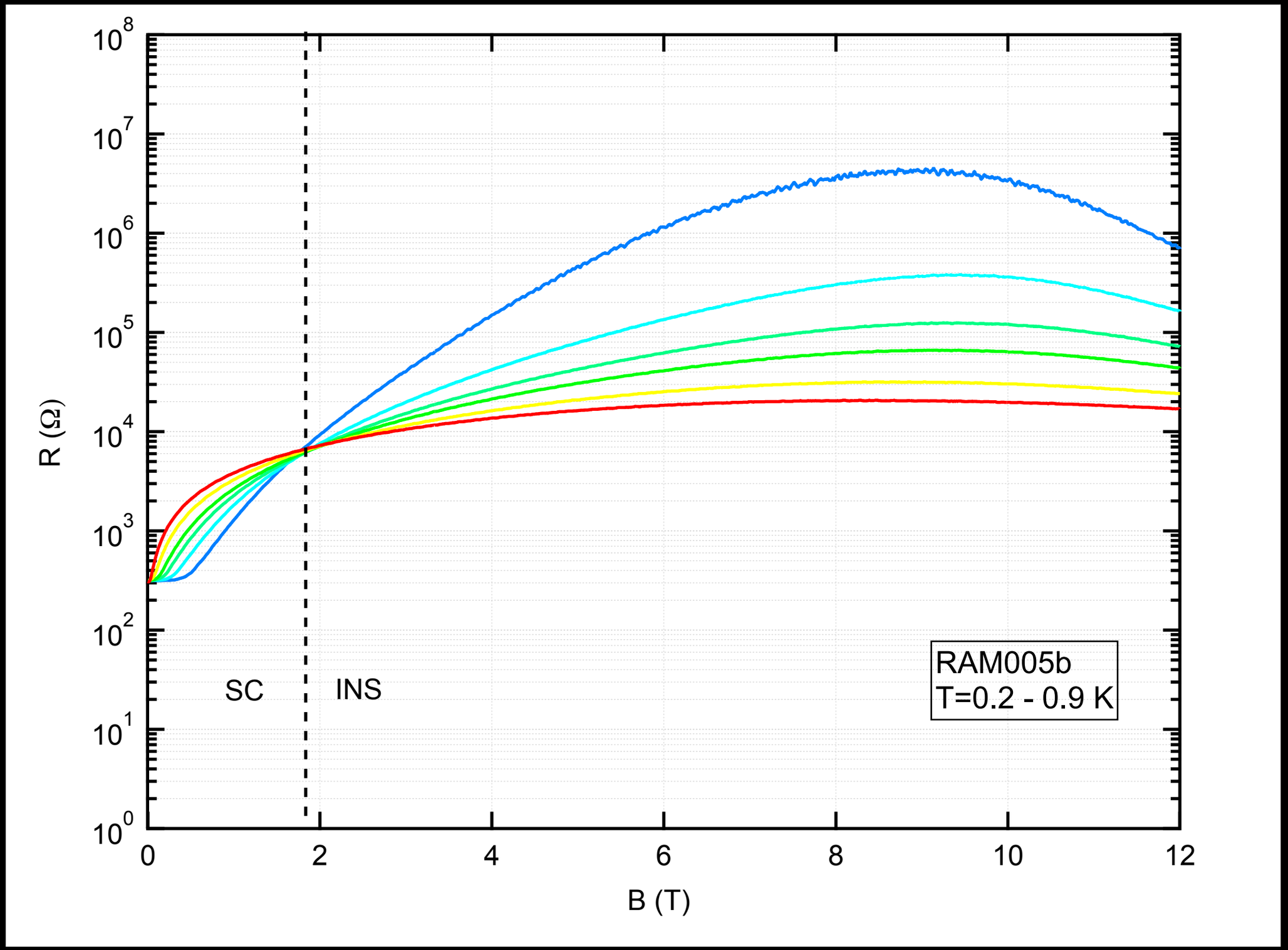


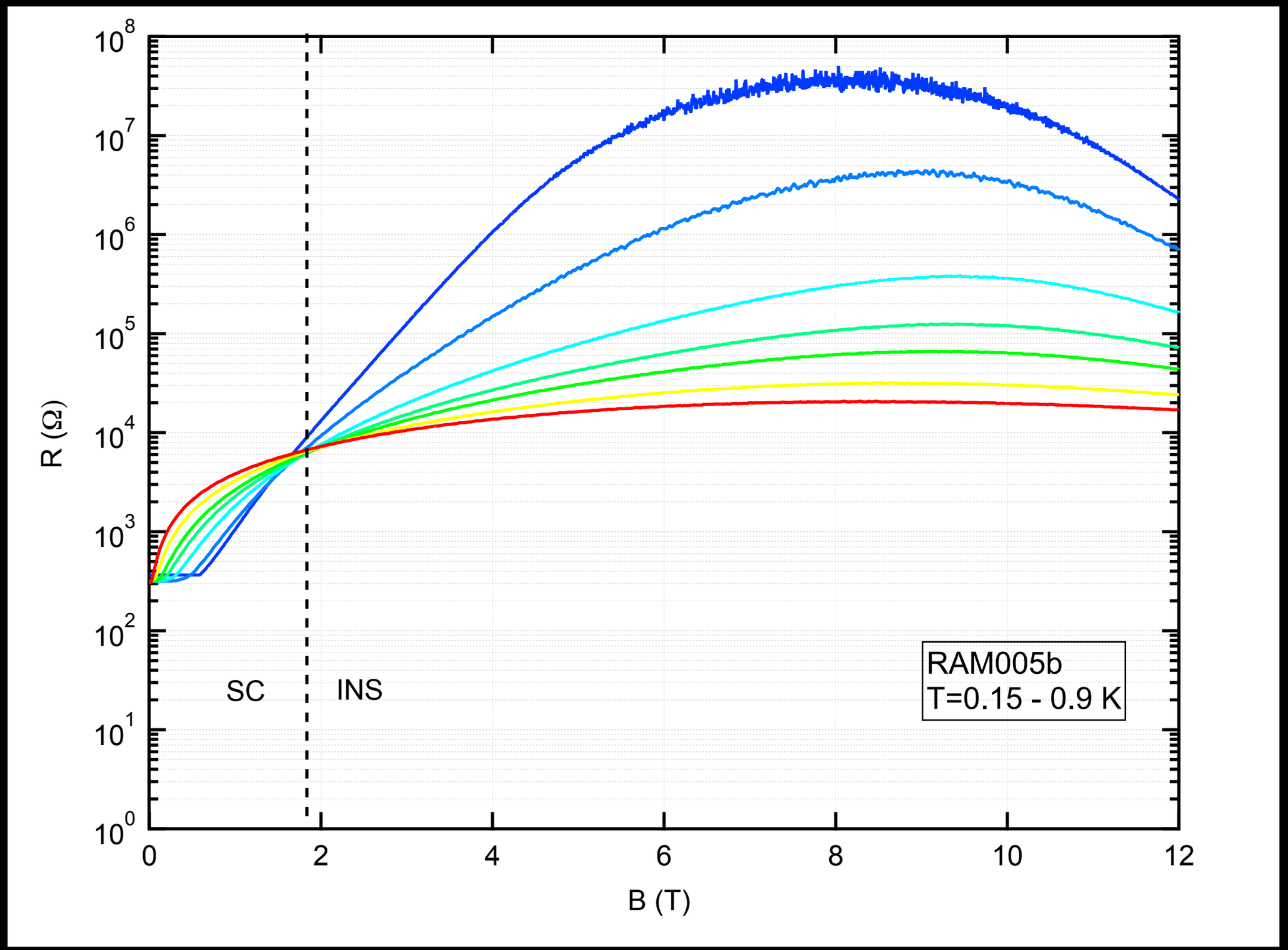

Opposite connections (0.5 mm)
T=20 mK
B (T)
Contats 7-24:
12
8
6
2
Contats 8-23:
12
8
6
2
Contats 20-11:
12
8
6
2
|I| (A)
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
-0.1
0.0
0.1
0.2
V_bias (Volt)

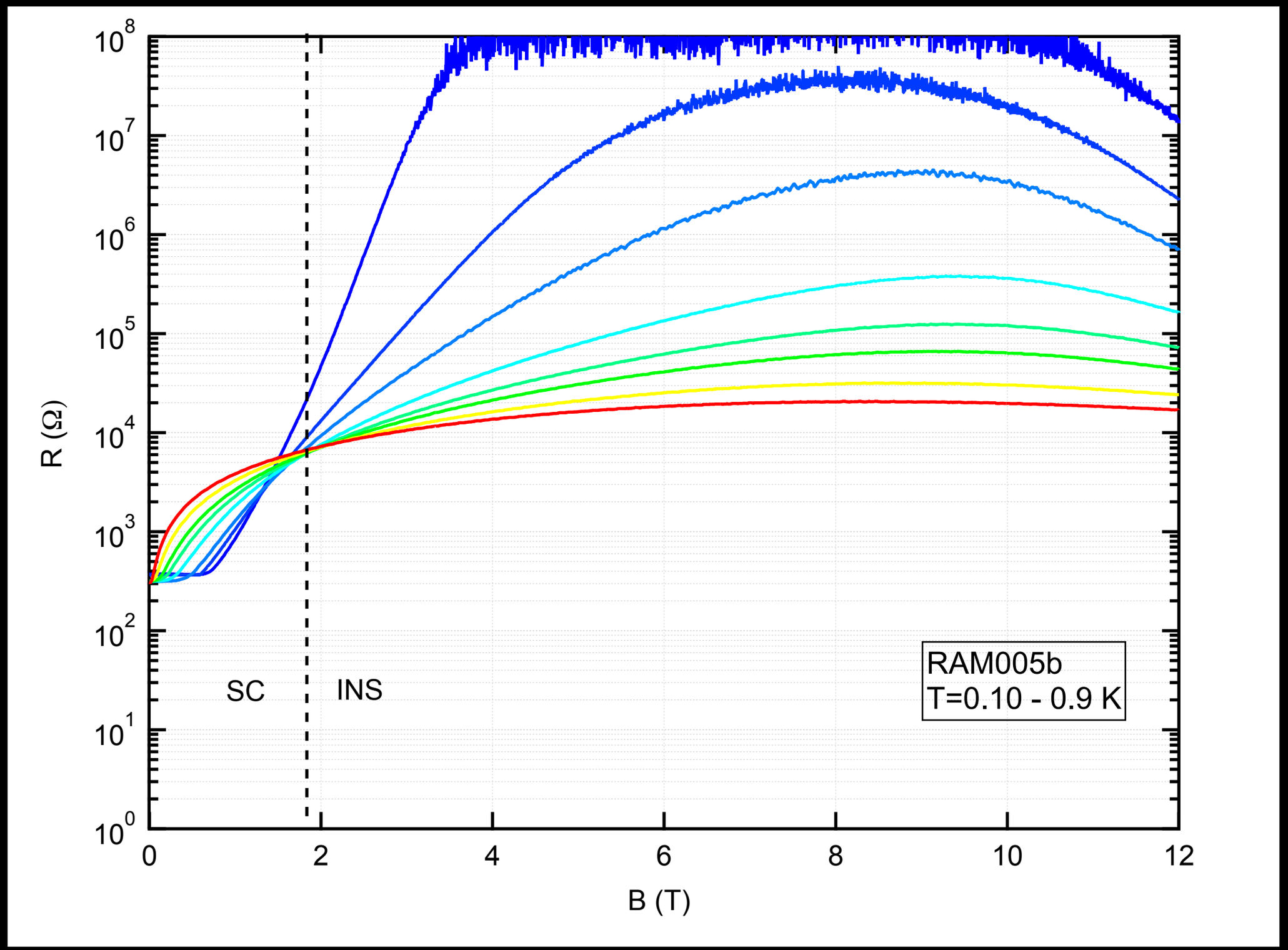

AD3C
T=20 mK
$V_{av}=(V_{trap,7-24}+V_{trap,8-23}+V_{trap,11-20})/3$
$\Delta V=V_{trap}-V_{av}$
4
6
7
8
9
10
11
12
13
3
14
2
1
24
23
22
21
20
19
17
$|\Delta V/V_{av}|$
1.2
1.0
0.8
0.6
0.4
0.2
0.0
V_{av}=2.8 mV
V_{av}=78 mV
V_{av}=118 mV
2 overlapping points
V_{av}=49 mV
0
2
4
6
8
10
12
14
B (T)

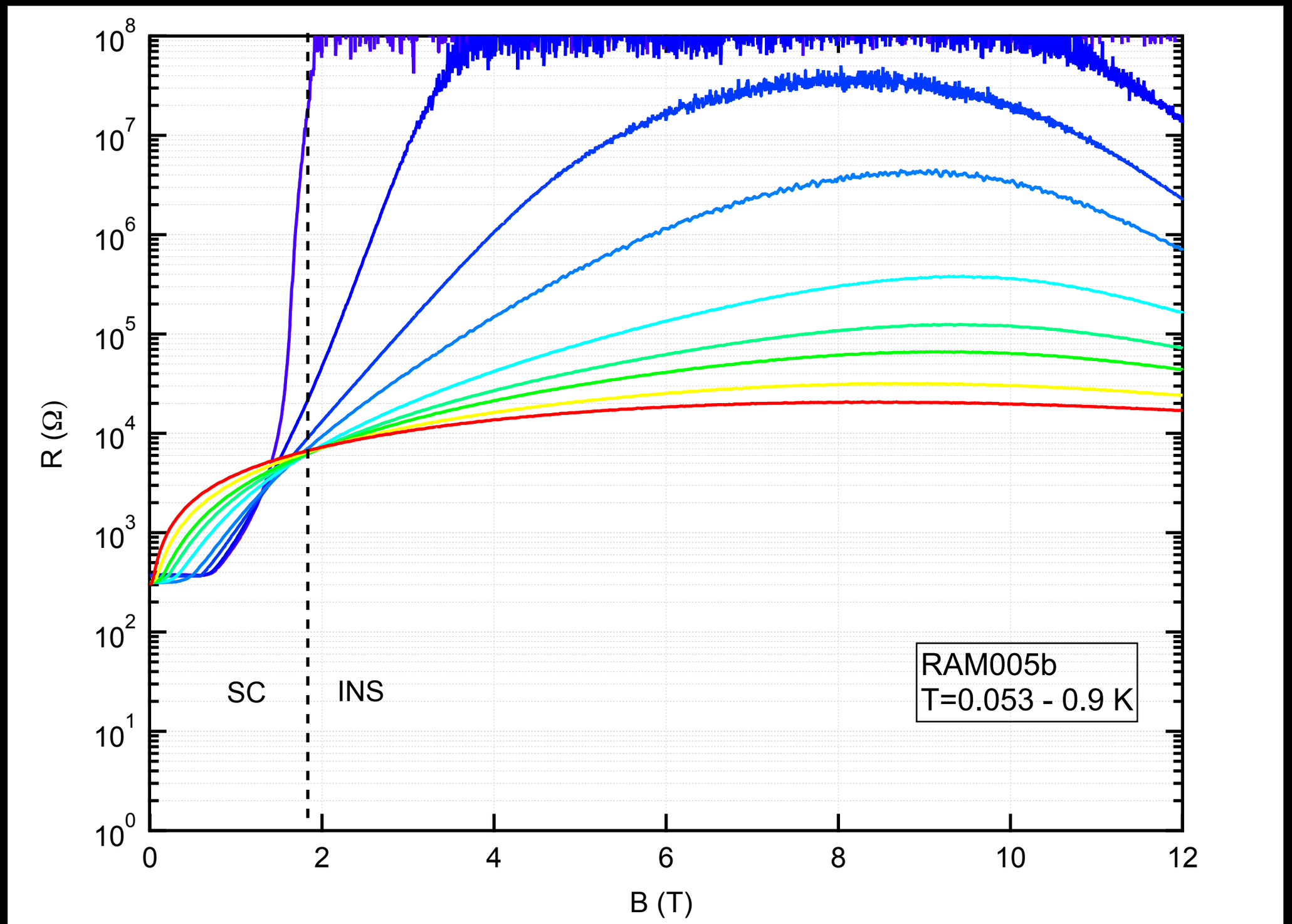
The SIT below T=0.2 K:

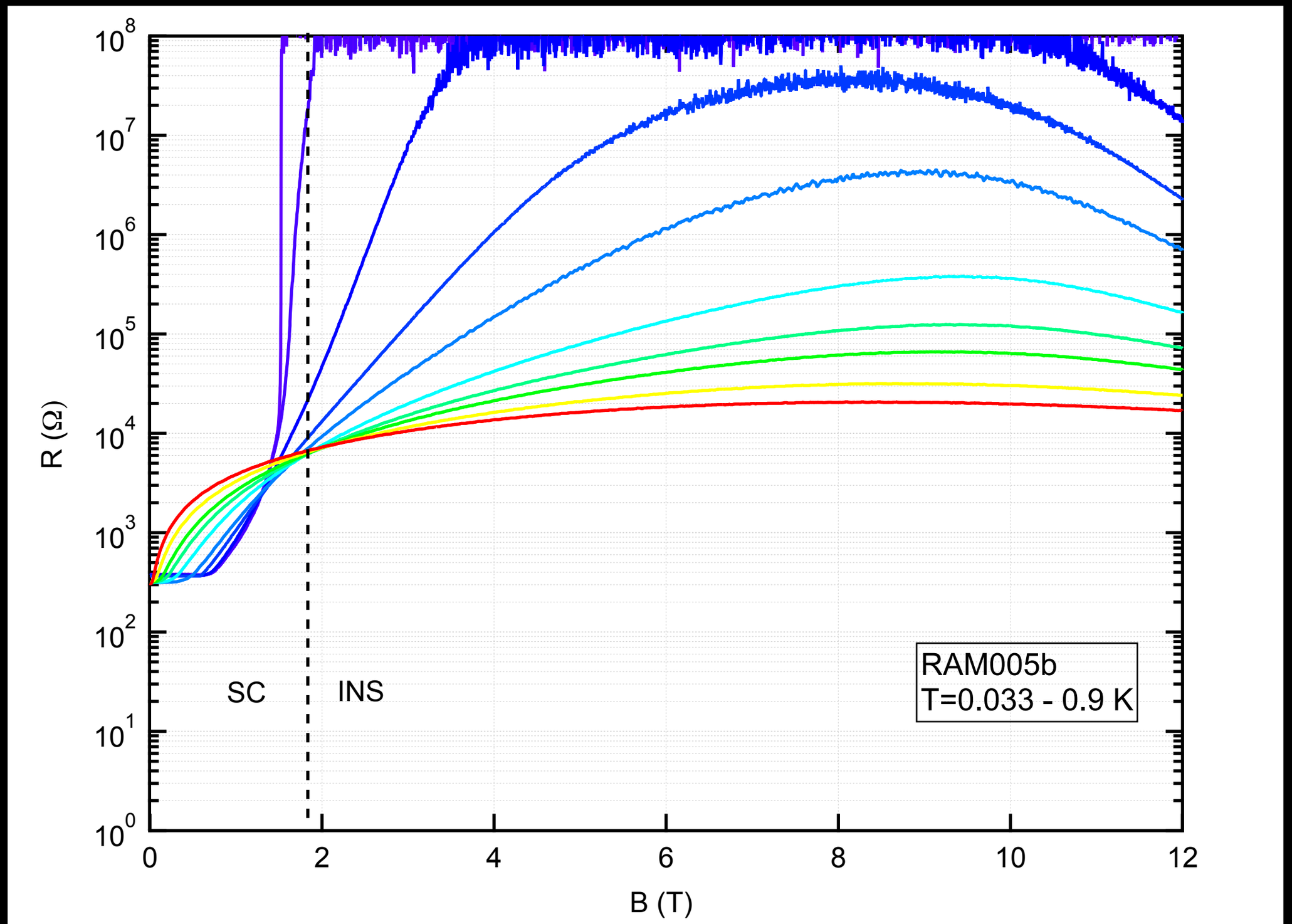

SC
INS
RAM005b
T=0.2 - 0.9 K
ρ (Ω)
B (T)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
0
2
4
6
8
10
12

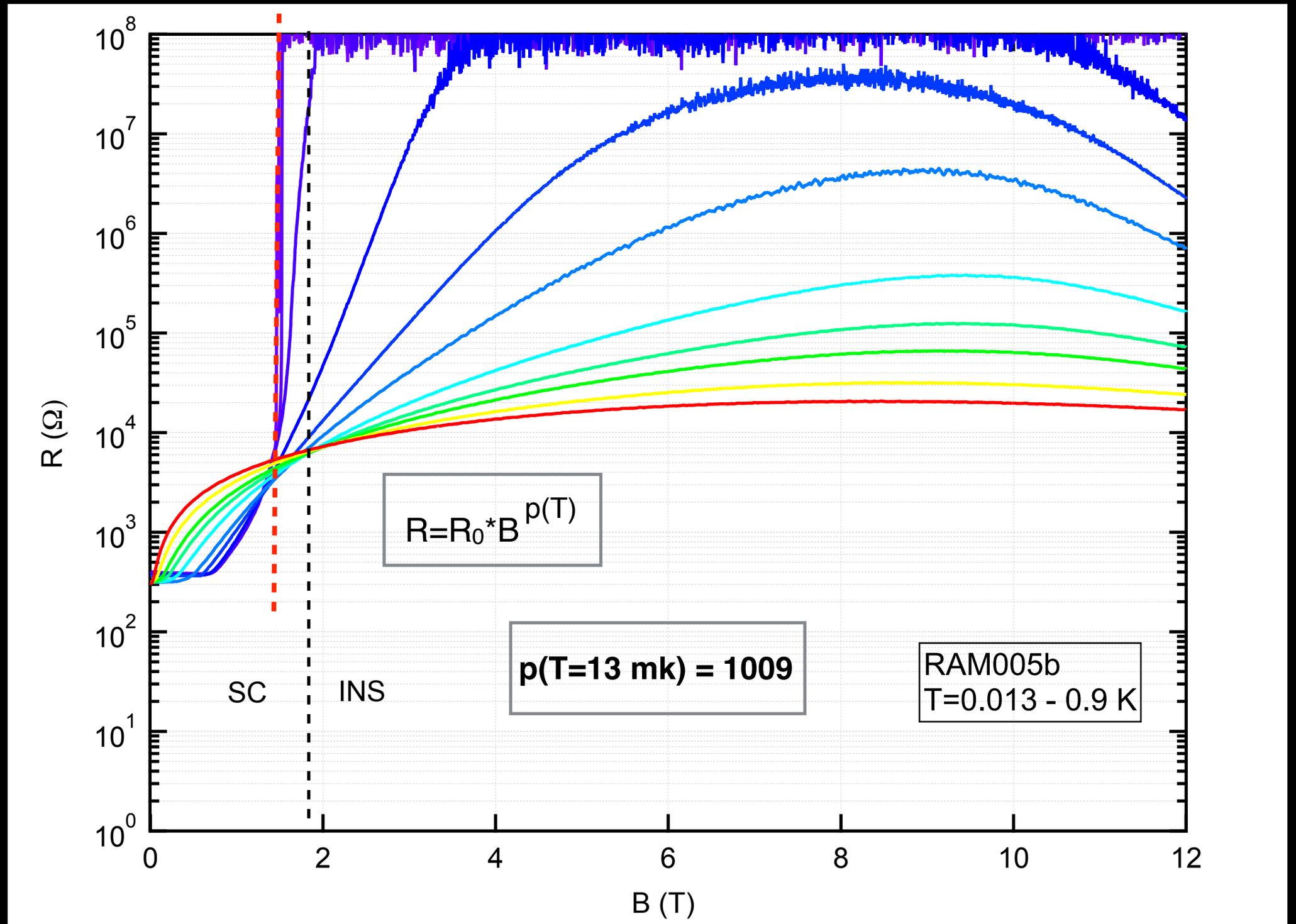

R (Ω)
B (T)
SC
INS
RAM005b
T=0.2 - 0.9 K


R (Ω)
B (T)
SC
INS
RAM005b
T=0.15 - 0.9 K


R (Ω)
B (T)
SC
INS
RAM005b
T=0.10 - 0.9 K

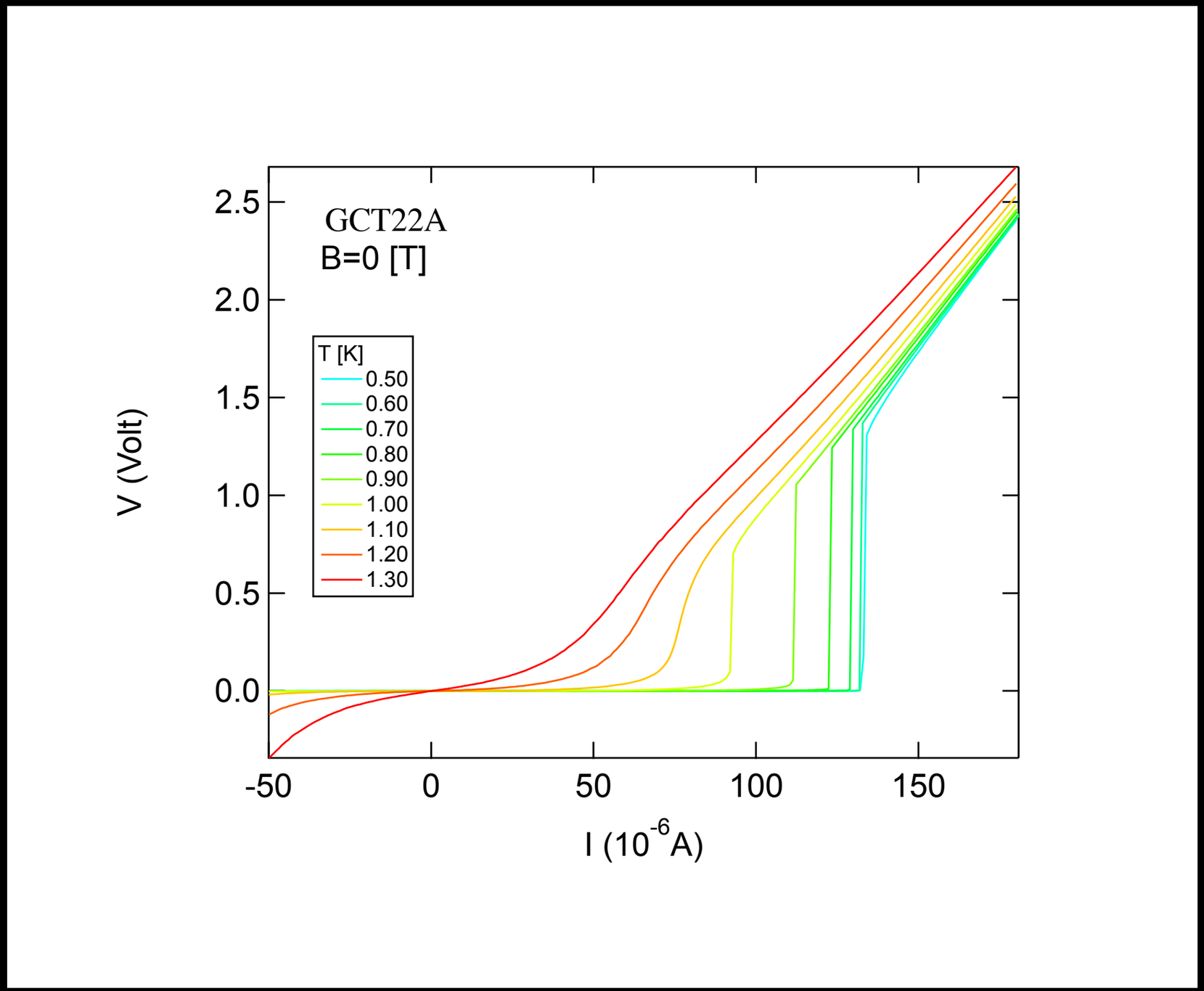

R (Ω)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
SC
INS
RAM005b
T=0.053 - 0.9 K
0
2
4
6
8
10
12
B (T)

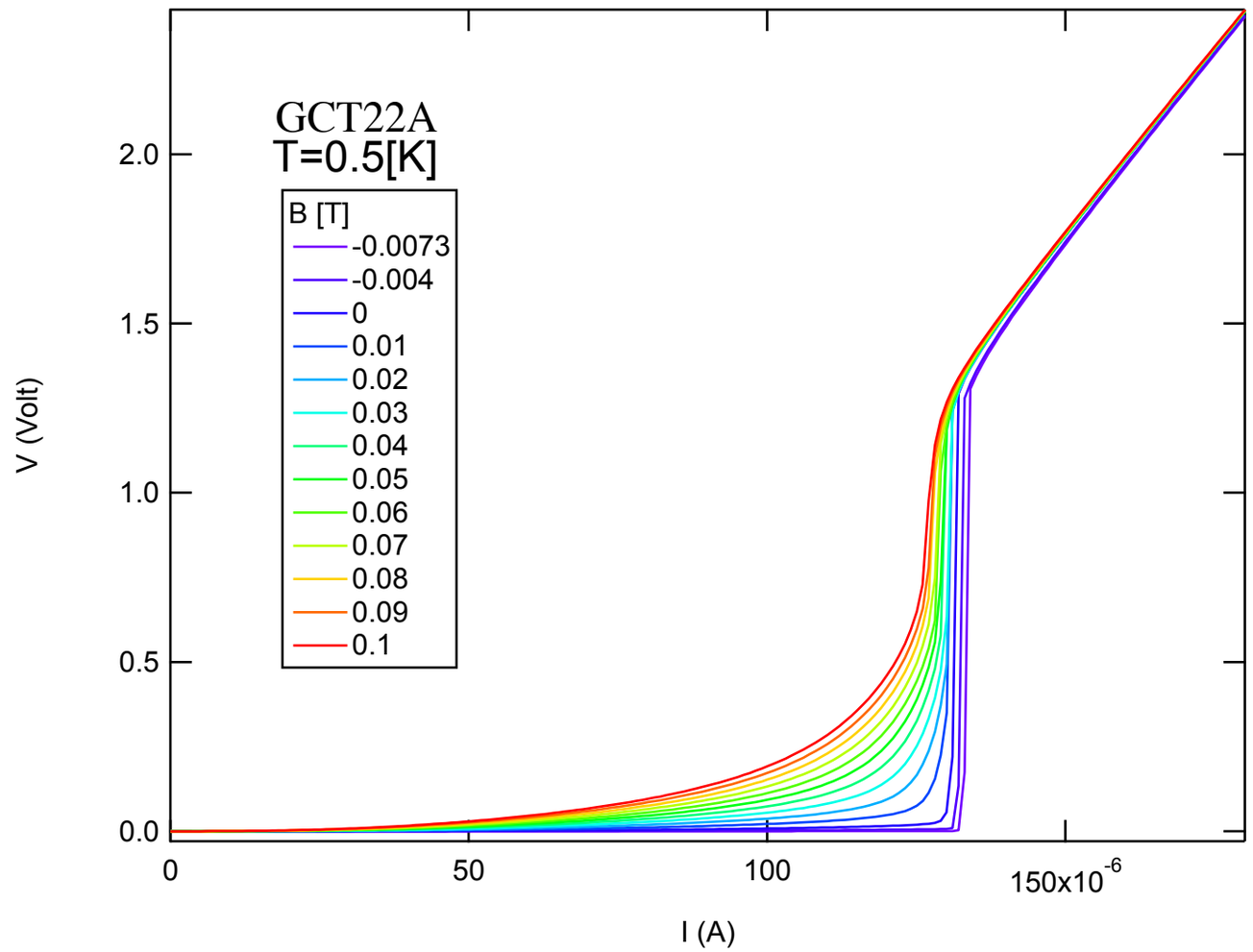

R (Ω)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
SC
INS
RAM005b
T=0.033 - 0.9 K
0
2
4
6
8
10
12
B (T)


R (Ω)
B (T)
SC
INS
R=R0*B p(T)
p(T=13 mk) = 1009
RAM005b
T=0.013 - 0.9 K

The superconductor

The superconductor




GCT22A
T=0.5[K]
B [T]
-0.0073
-0.004
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
V (Volt)
I (A)
0.0
0.5
1.0
1.5
2.0
0
50
100
150x10-6