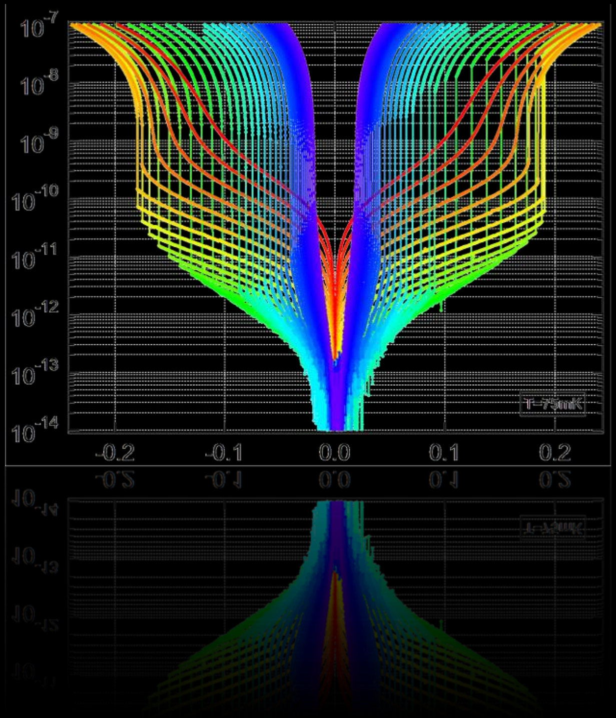
The magnetic field induced insulating state in amorphous superconductors

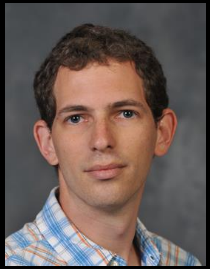
Benjamin Sacépé

Néel Institute, CNRS & Univ. Grenoble Alpes



Strongly disordered and inhomogeneous superconductivity

Grenoble, Nov. 2016



Idan Tamir

Maoz Ovadia
(Harvard)

Dan Shahar

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Johanna Seidemann

Benjamin Piot

Christoph Strunk

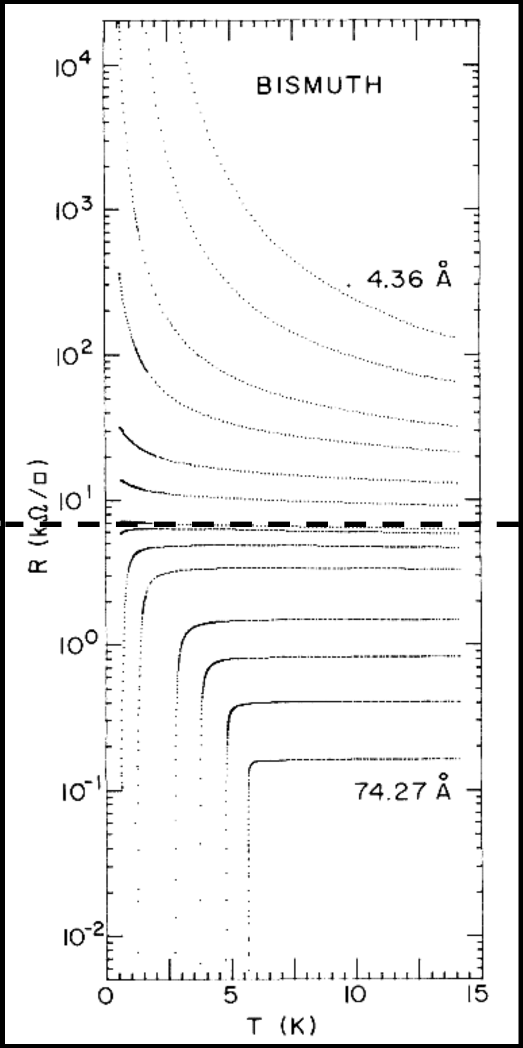
cnrs
advancing the frontiers

UR
Universität Regensburg

The Superconductor-Insulator Transition

Strongin et al.
Phys. Rev. B 1, 1078 (1970)

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



Thickness

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

Prototypical quantum phase transition

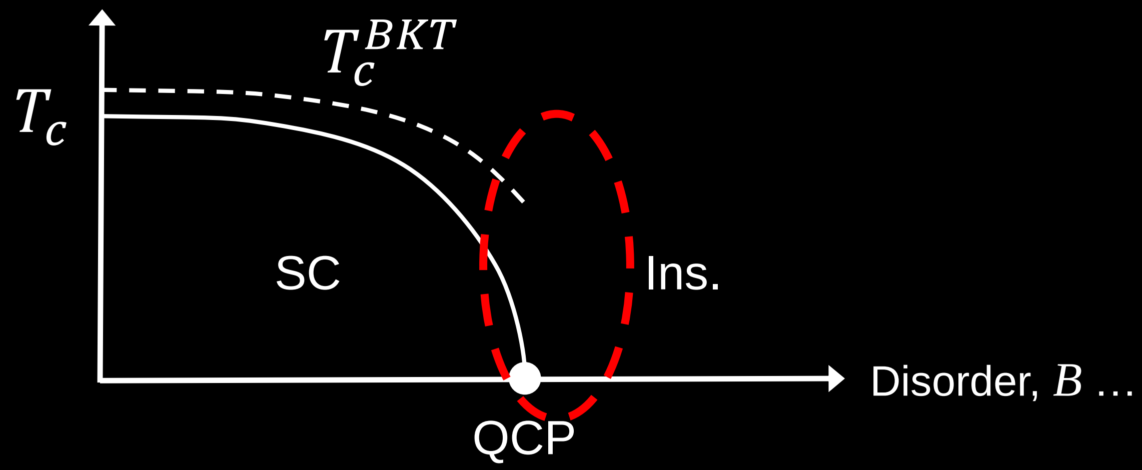
Strictly T=0.

Driven by:

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

Suppression of superconductivity

M.P.A. Fisher ('90)

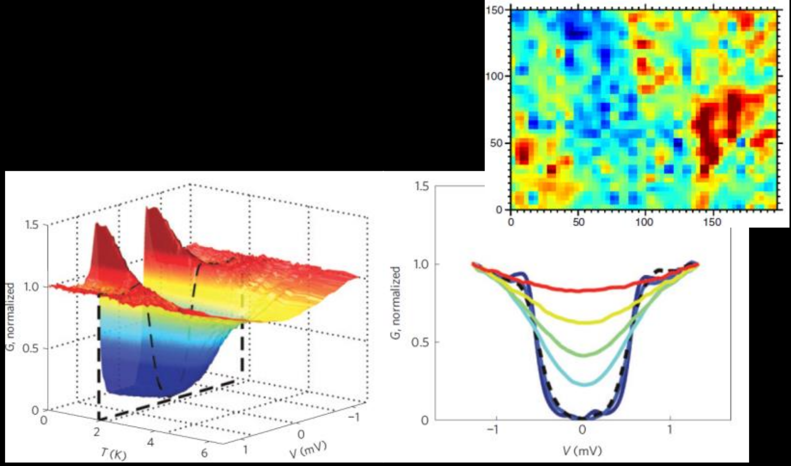


Insulator with localized Cooper-pairs ?

nature physics
ARTICLES
PUBLISHED ONLINE: 30 JANUARY 2011 | DOI: 10.1038/NPHYS1892

Localization of preformed Cooper pairs in disordered superconductors

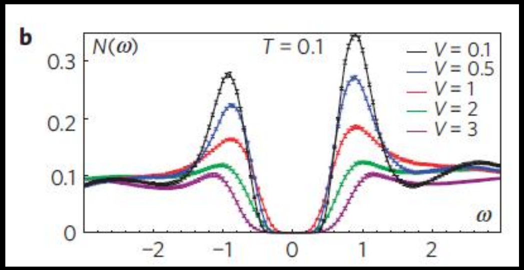
Benjamin Sacépé[1,2★†‡], Thomas Dubouchet[1†], Claude Chapelier[1], Marc Sanquer[1], Maoz Ovadia[2], Dan Shahar[2], Mikhail Feigel'man[3] and Lev Ioffe[4]



Annals of Physics 325 (2010) 1390–1478
Contents lists available at ScienceDirect
Annals of Physics
journal homepage: www.elsevier.com/locate/aop
ELSEVIER

Fractal superconductivity near localization threshold

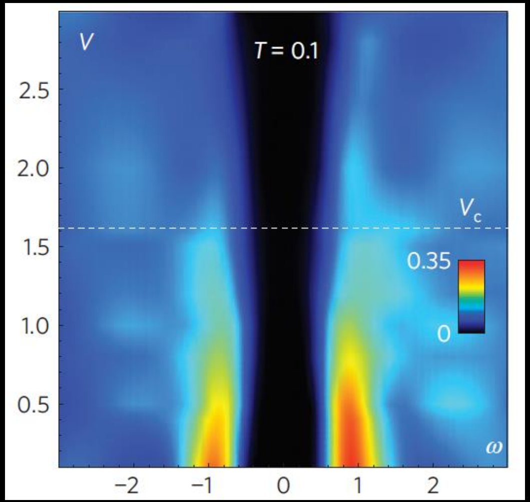
M.V. Feigel'man [a,b], L.B. Ioffe [a,c,d,*], V.E. Kravtsov [a,e], E. Cuevas [f]



ARTICLES
PUBLISHED ONLINE: 31 JULY 2011 | DOI: 10.1038/NPHYS2037
nature physics

Single- and two-particle energy gaps across the disorder-driven superconductor–insulator transition

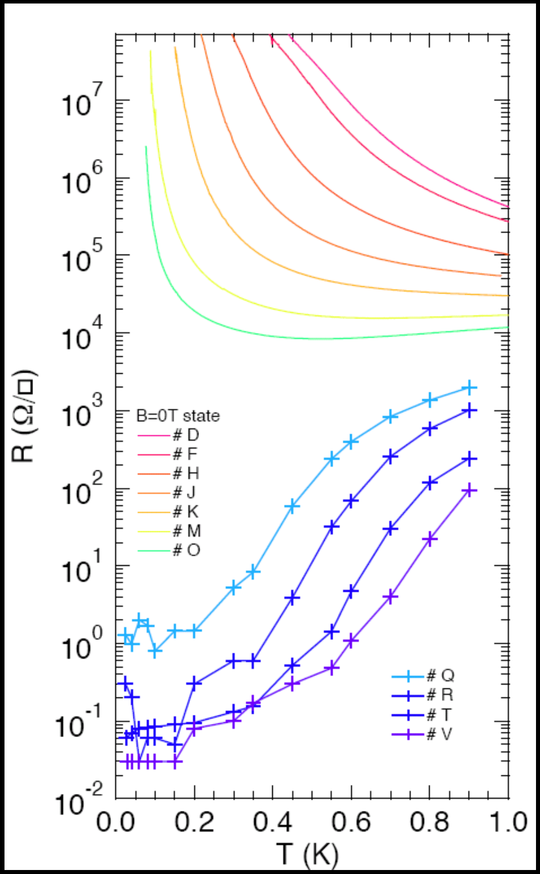
Karim Bouadim, Yen Lee Loh, Mohit Randeria and Nandini Trivedi*



Direct superconductor-insulator transition

Amorphous indium oxide films

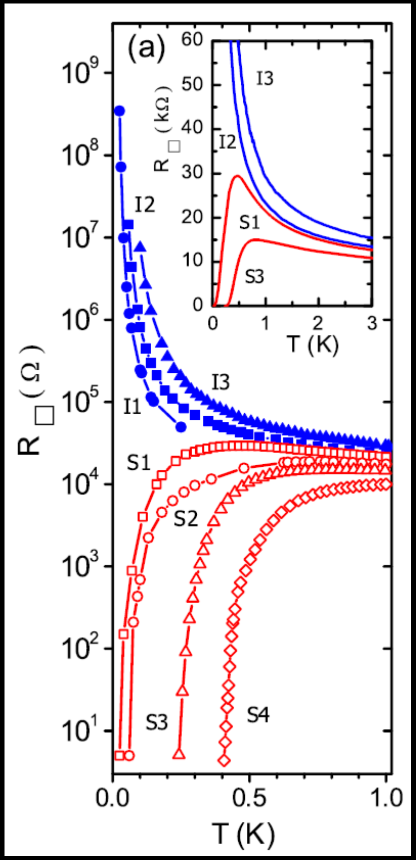
D. Shahar's group



$n \lesssim 10^{21} cm^{-3}$

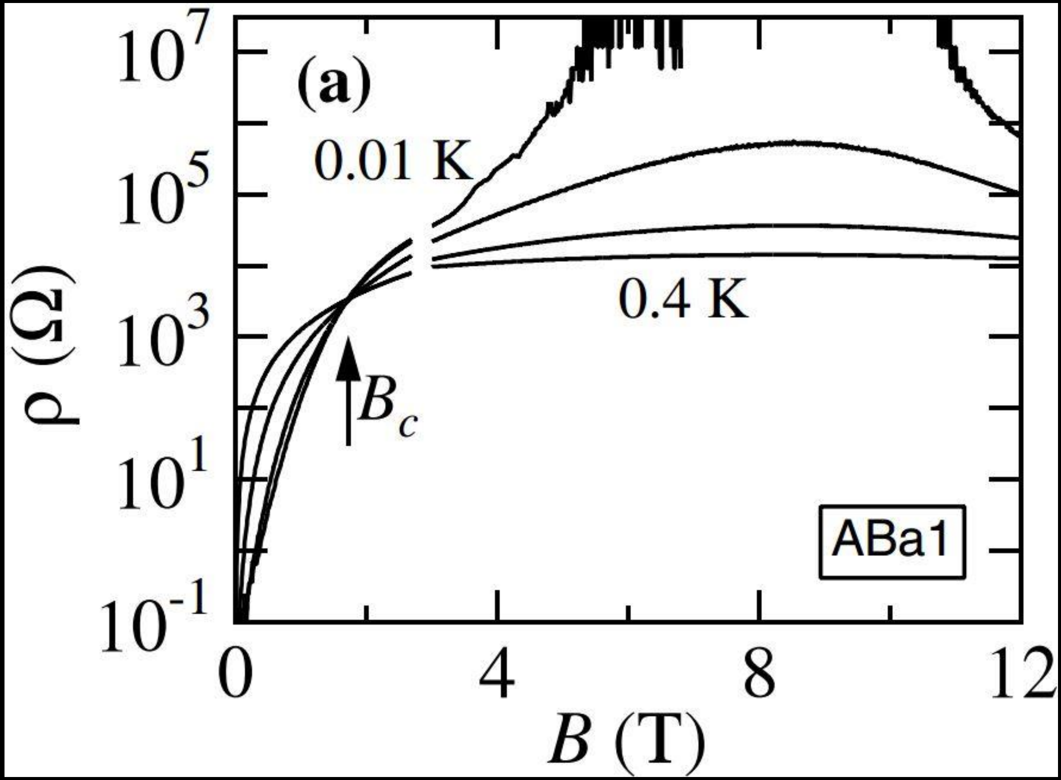
Titanium nitride

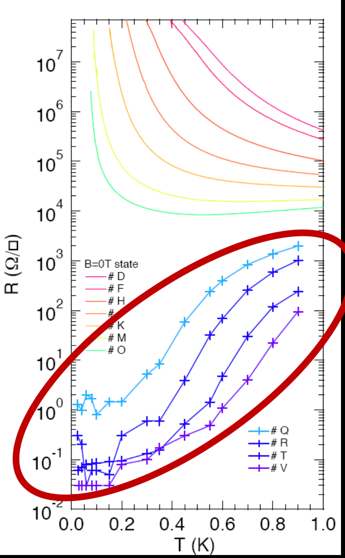
T. Baturina PRLs ('07)



$n \lesssim 10^{22} cm^{-3}$

Giant magnetoresistance peak

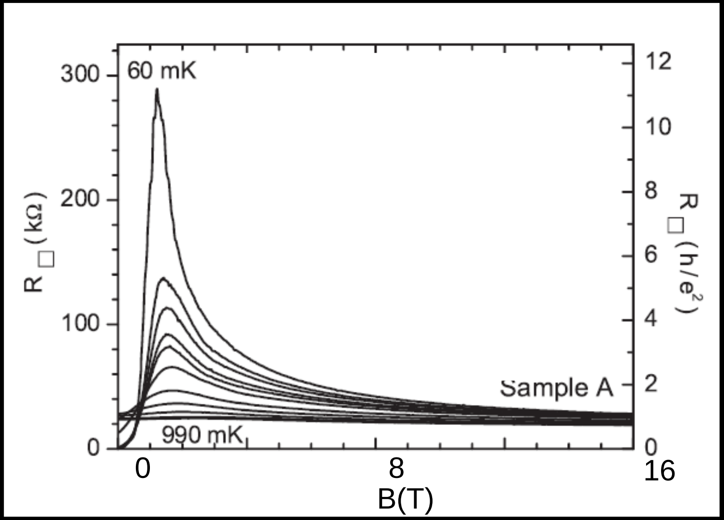




Sambandamurthy et. al. *PRL* (‘05)

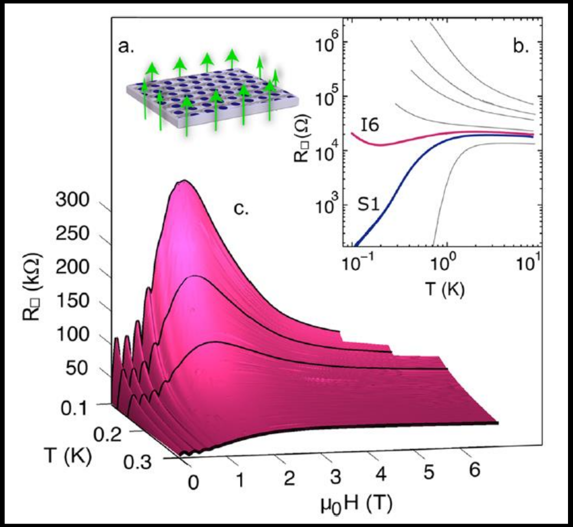
Giant magnetoresistance peaks

Titanium nitride



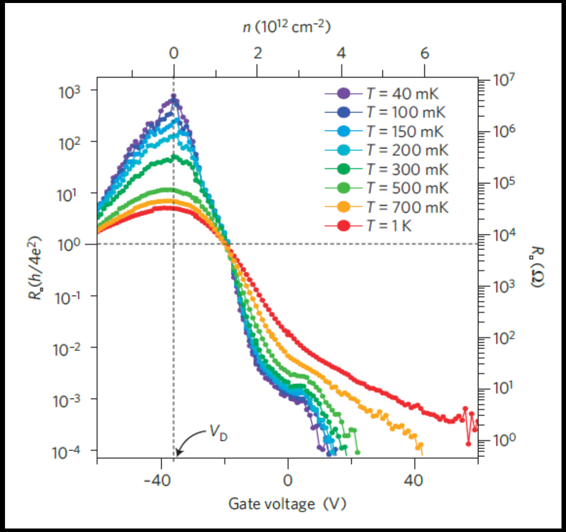
Baturina et al. *PRLs* ('07)

Quenched Bi



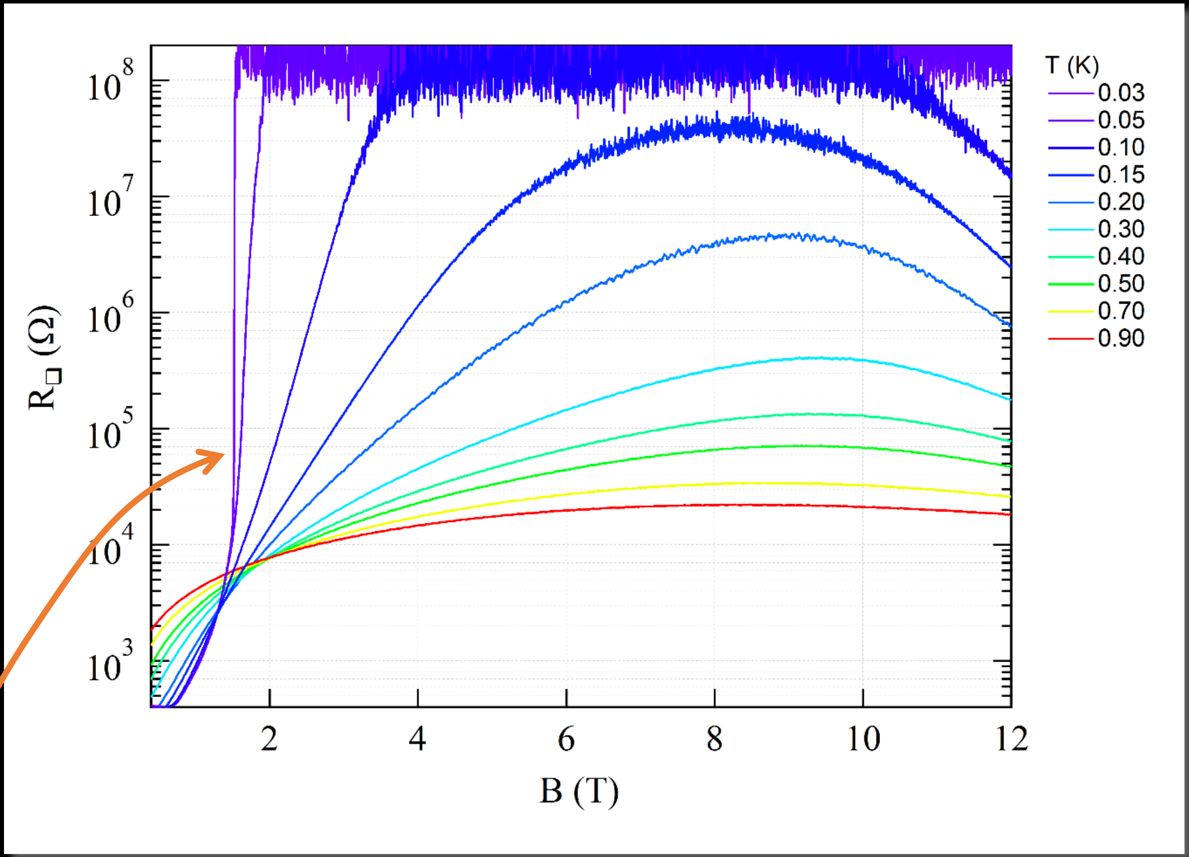
J. Valles group, *Science* ('07), *PRL* ('09)

Tin decorated insulating graphene



Allain et al. *Nature Mat*. ('12)

Insulating peak in a:InO



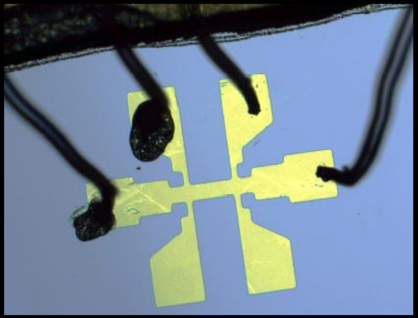
R raises by 1 decade per 0.01 tesla

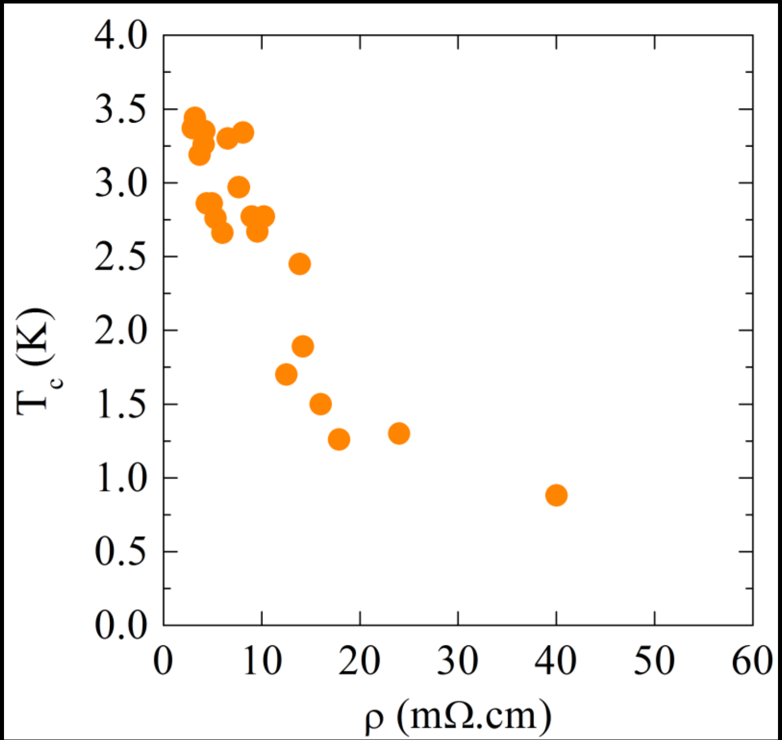
Paalanen, Hebard, Ruel PRL (‘90)
Sambandamurthy et al. PRL (‘04)
Steiner, Kapitulnik et al. PRL (‘05)

Disorder-dependence of the insulating peak

Amorphous indium oxide (a:InO)

- E-gun evaporation of In_2O_3 on SiO_2 under O_2 pressure
- 30-60 nm thick
- *e*-density : $n \sim 10^{20} - 10^{21}\ cm^{-3}$
- Disorder : $k_F l_e \sim 0.3 - 0.4$

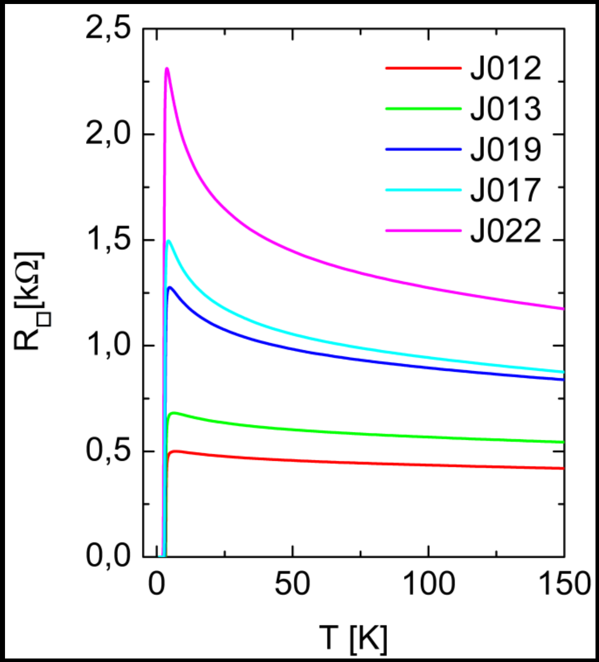


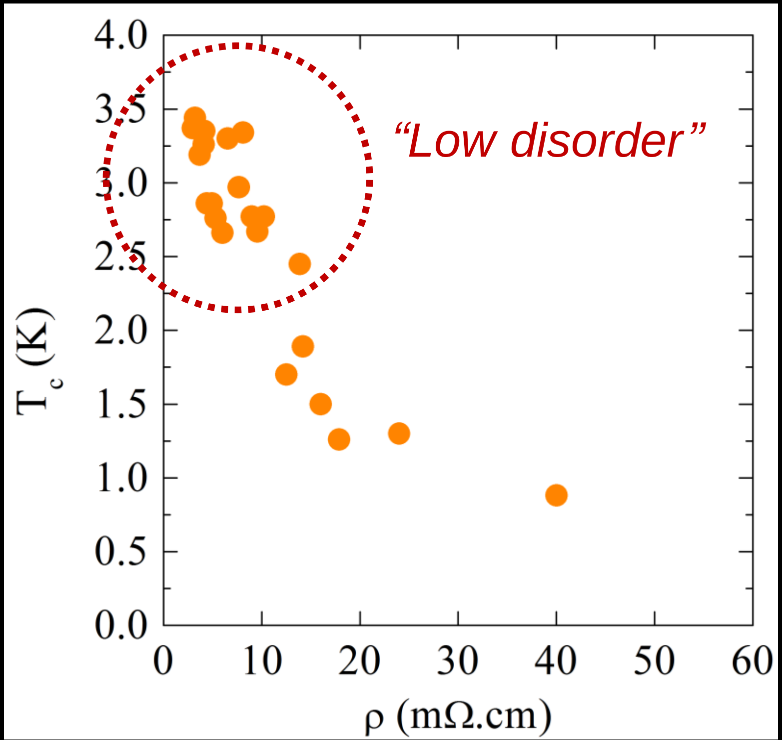


Disorder tuned by annealing, thickness or O2 pressure

Amorphous indium oxide (a:InO)

- E-gun evaporation of In_2O_3 on SiO_2 under O_2 pressure
- 30-60 nm thick
- *e*-density : $n \sim 10^{20} - 10^{21}\ cm^{-3}$
- Disorder : $k_F l_e \sim 0.3 - 0.4$





Amorphous indium oxide (a:InO)

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- *e*-density : $n \sim 10^{20} - 10^{21}\ cm^{-3}$
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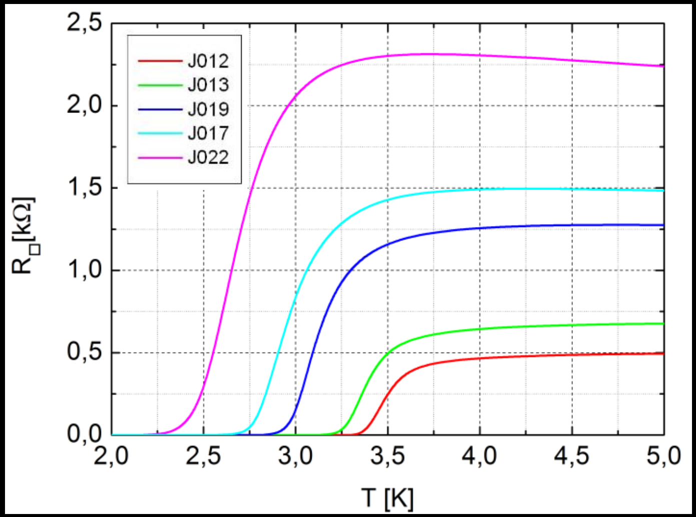
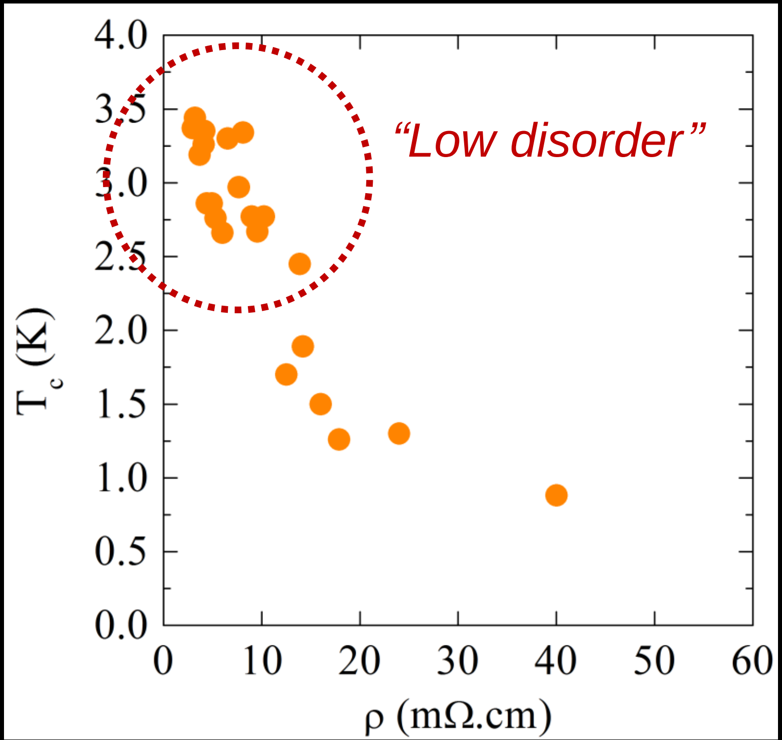
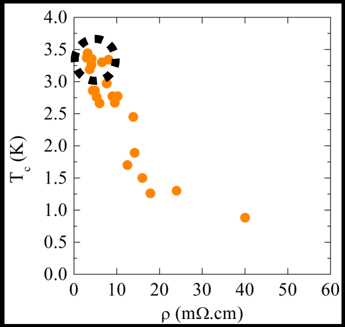
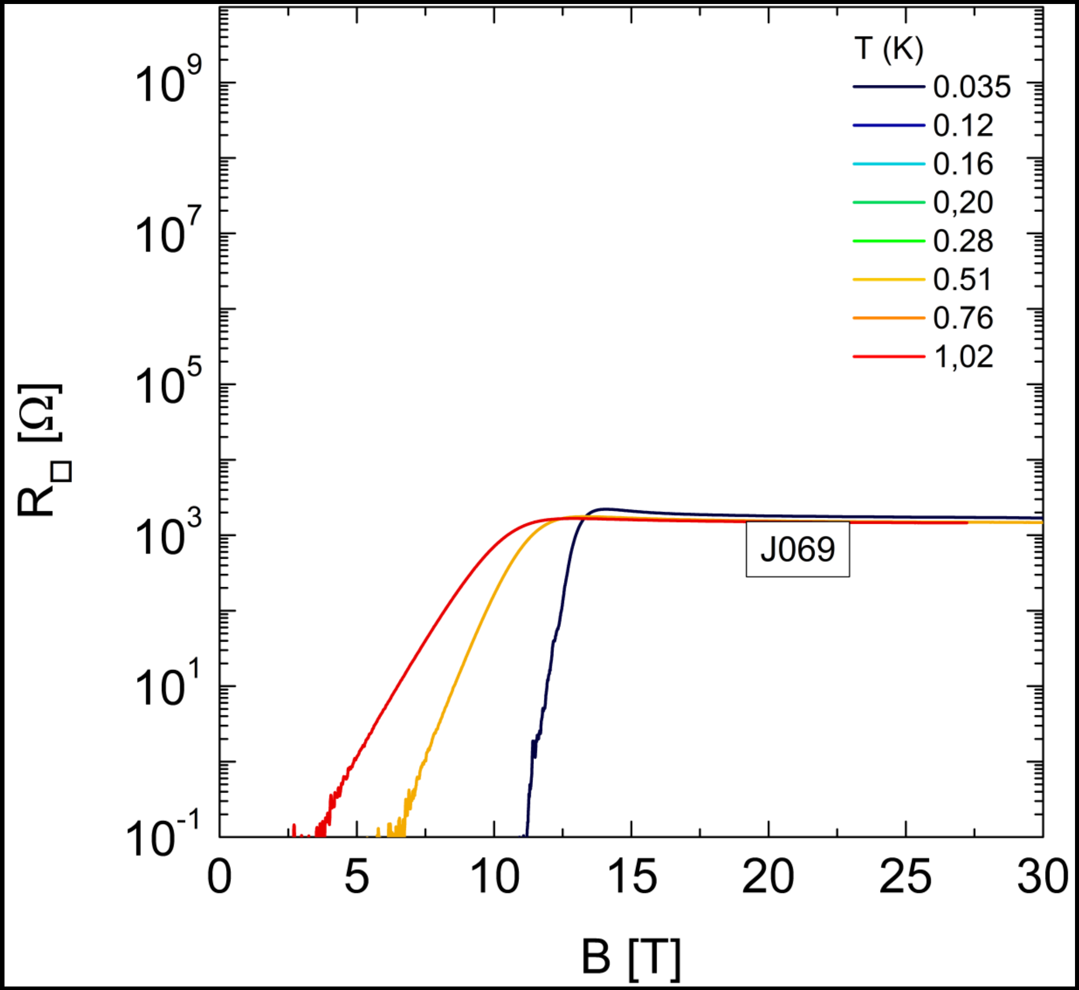


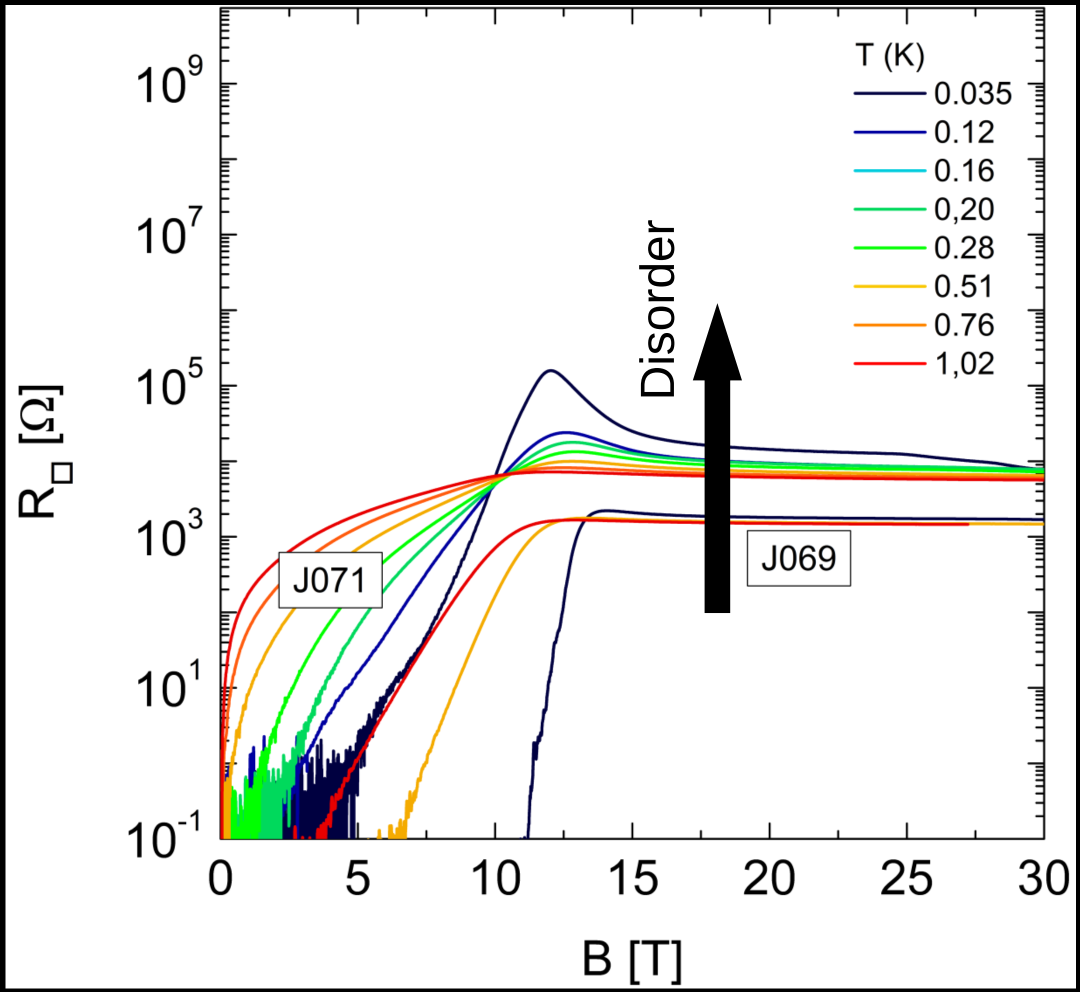


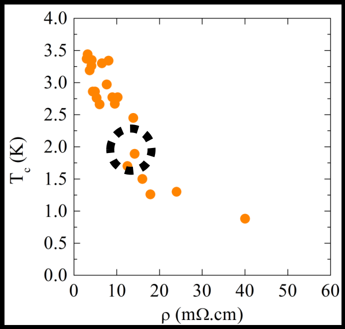
Low disorder



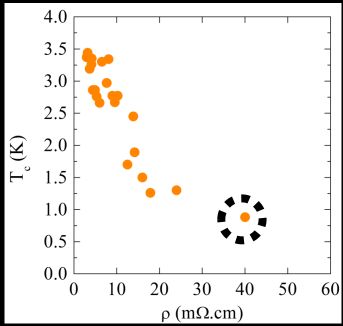


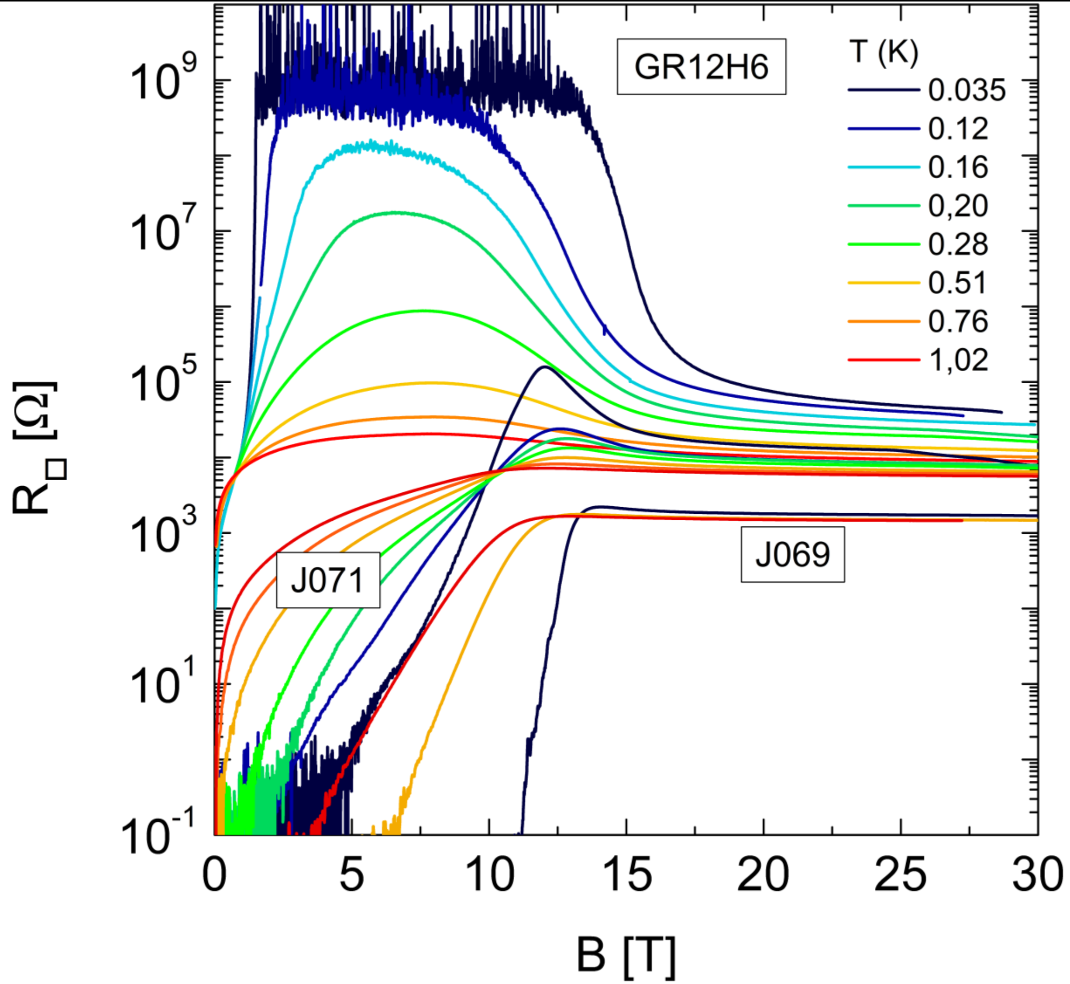
Medium disorder



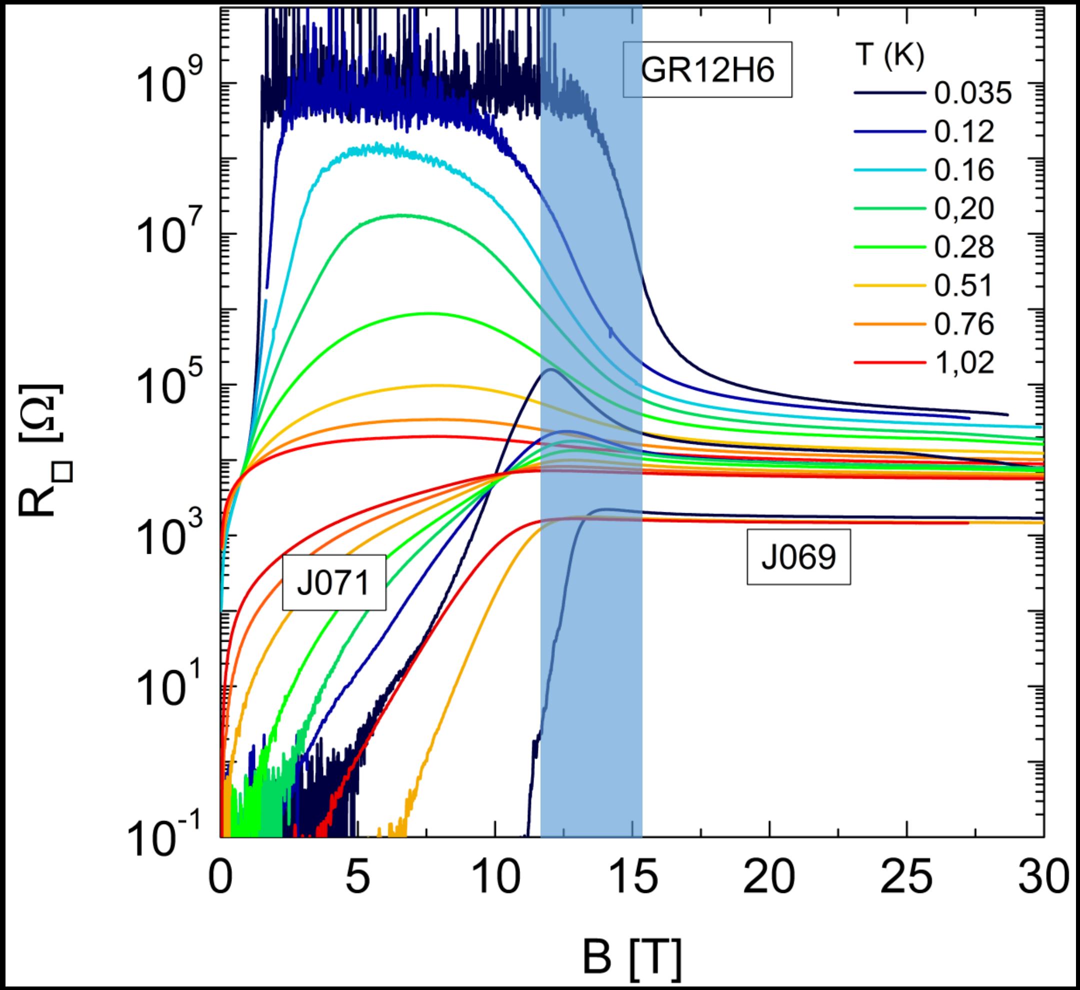


High disorder: Insulating peak

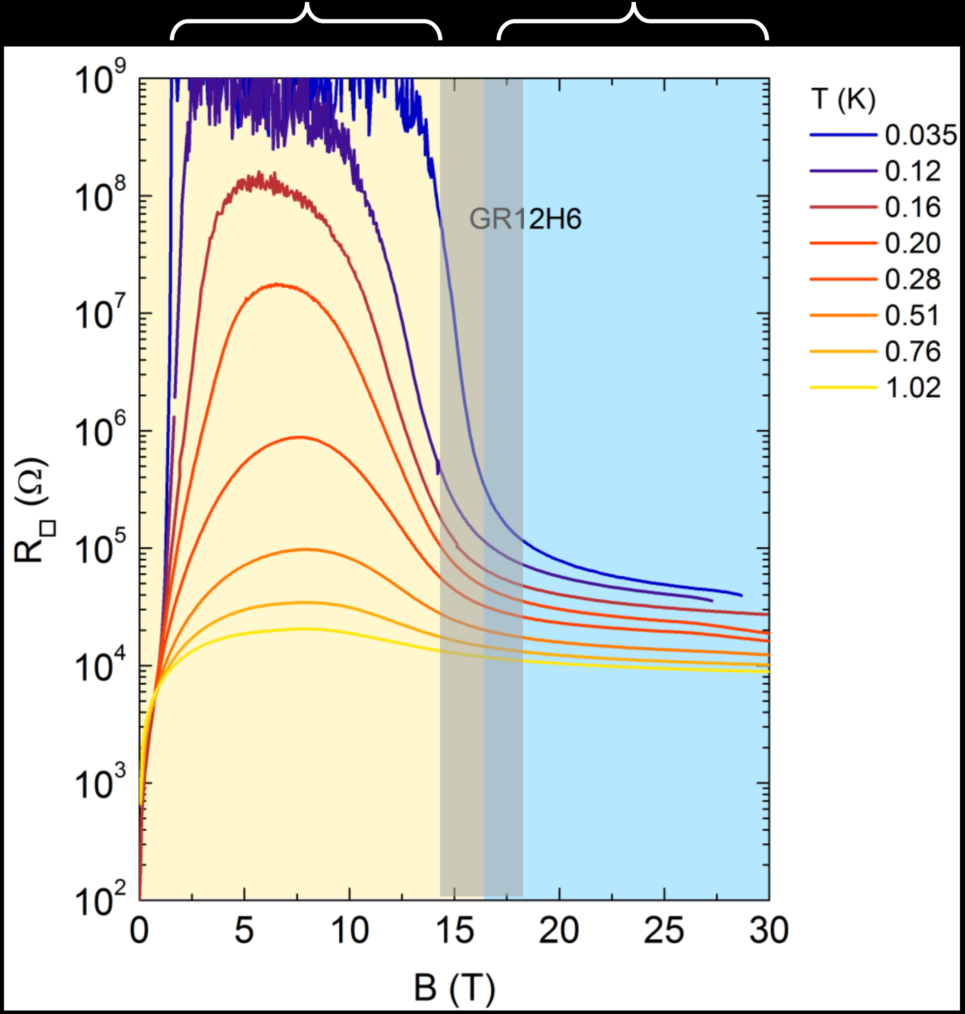




End of Cooper-pairing



Cooper-pair insulator | Fermionic insulator

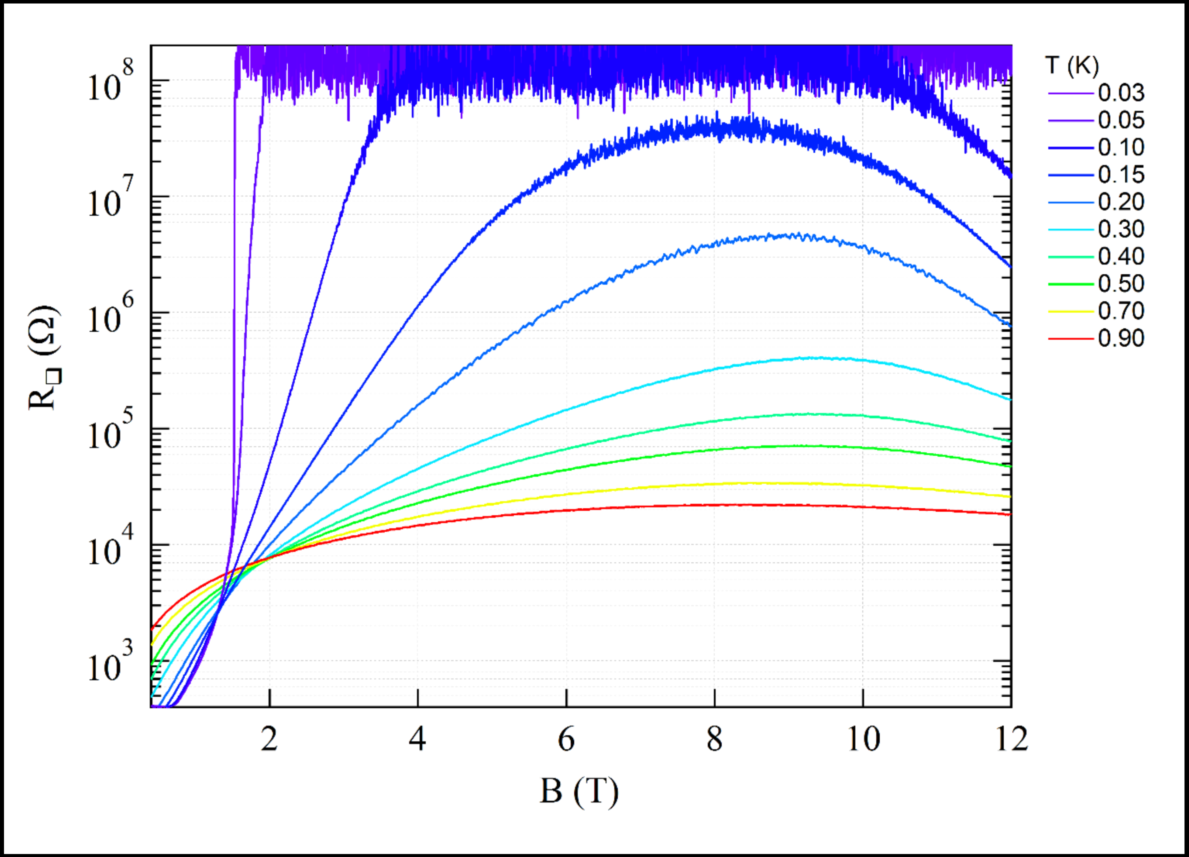


B.S. et al. *PRB* 91, 220508(R) (2015)

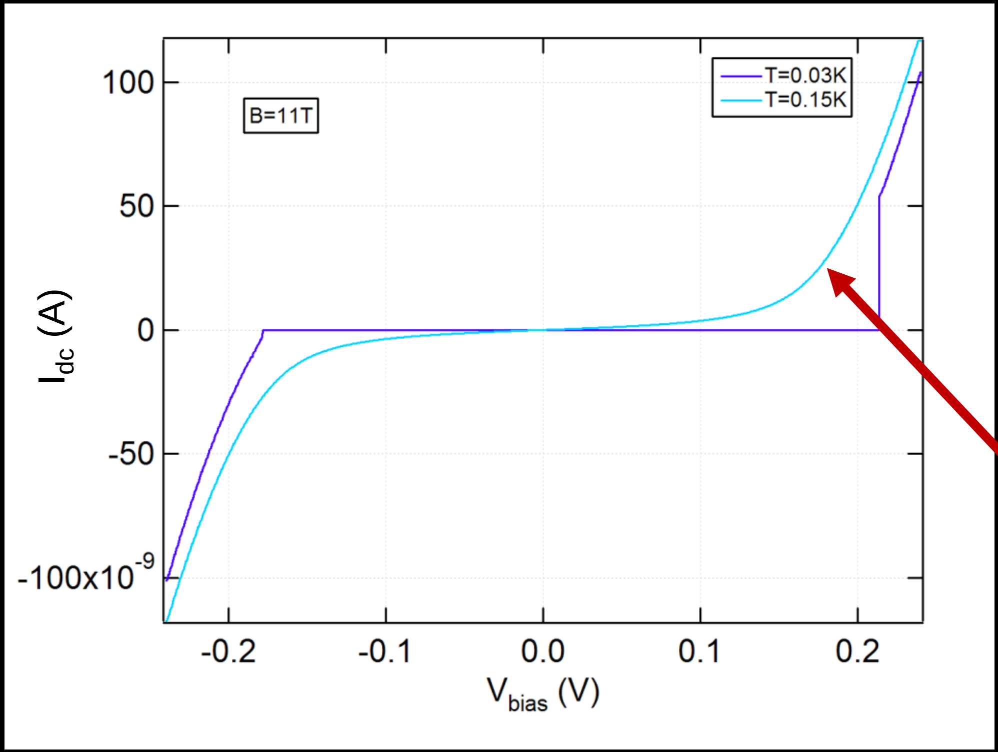
The insulator at $T<0.2$ K

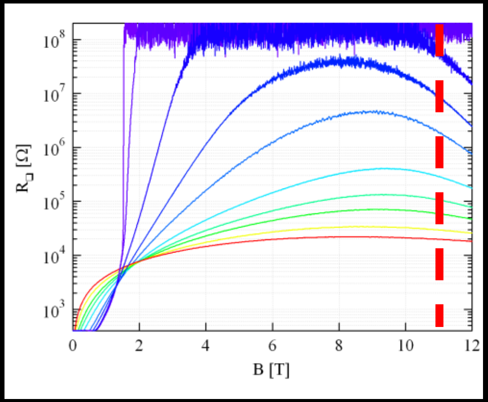
Current–voltage characteristics

Insulating peak



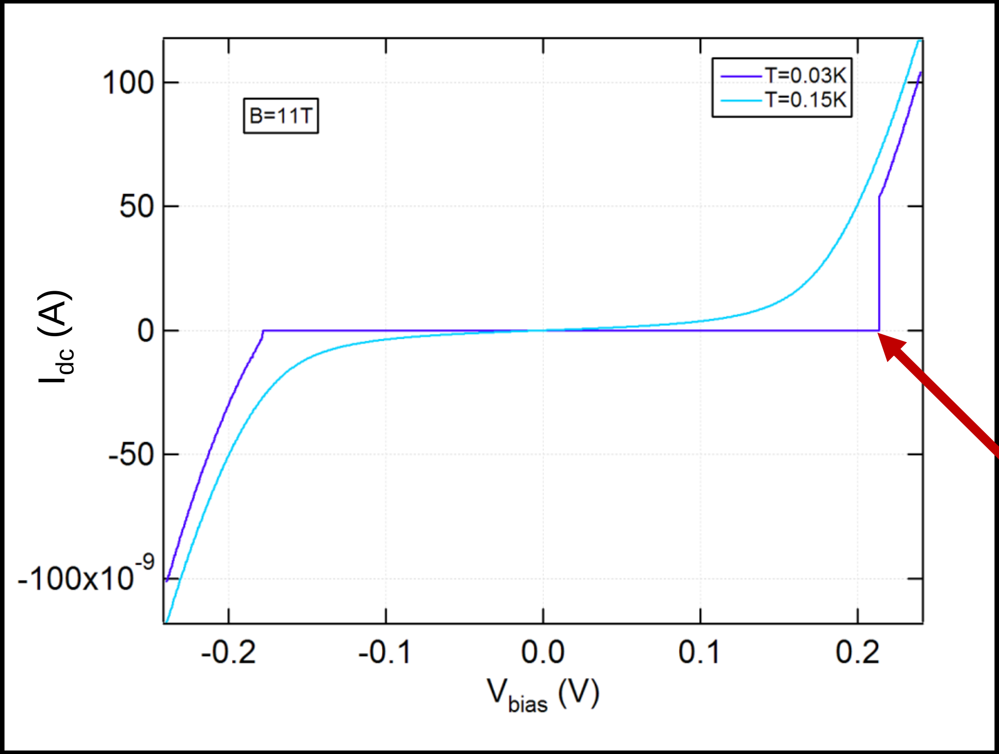
Non-linear IVs and voltage threshold

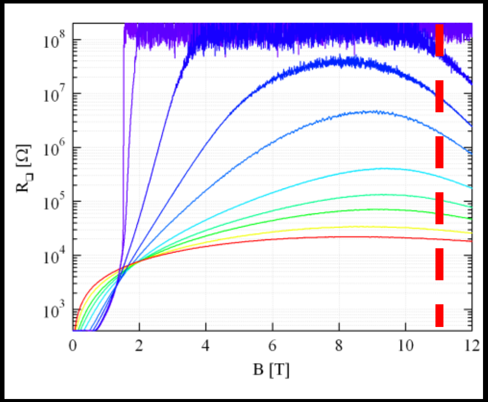




Non linear IV

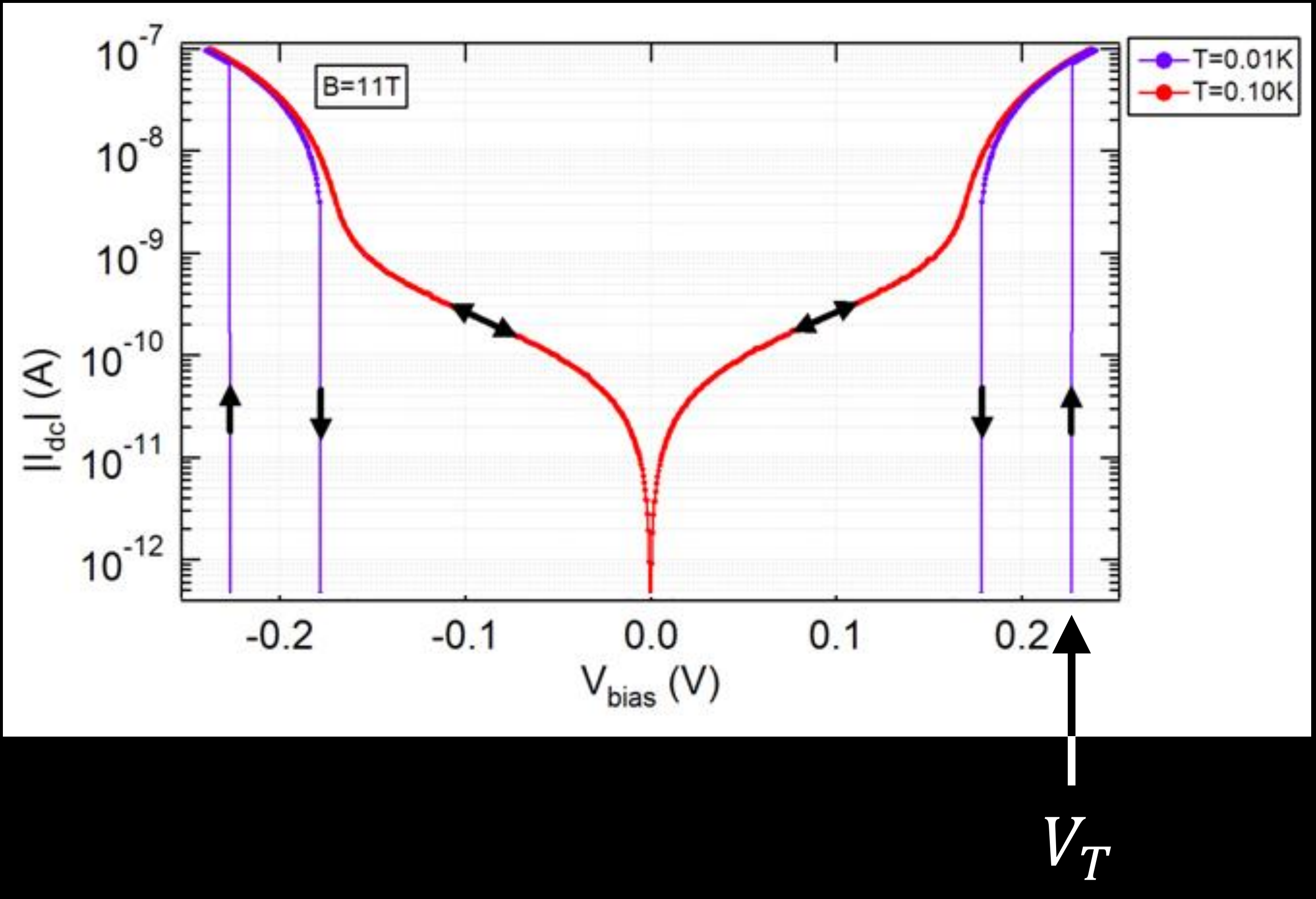
Non-linear IVs and voltage threshold



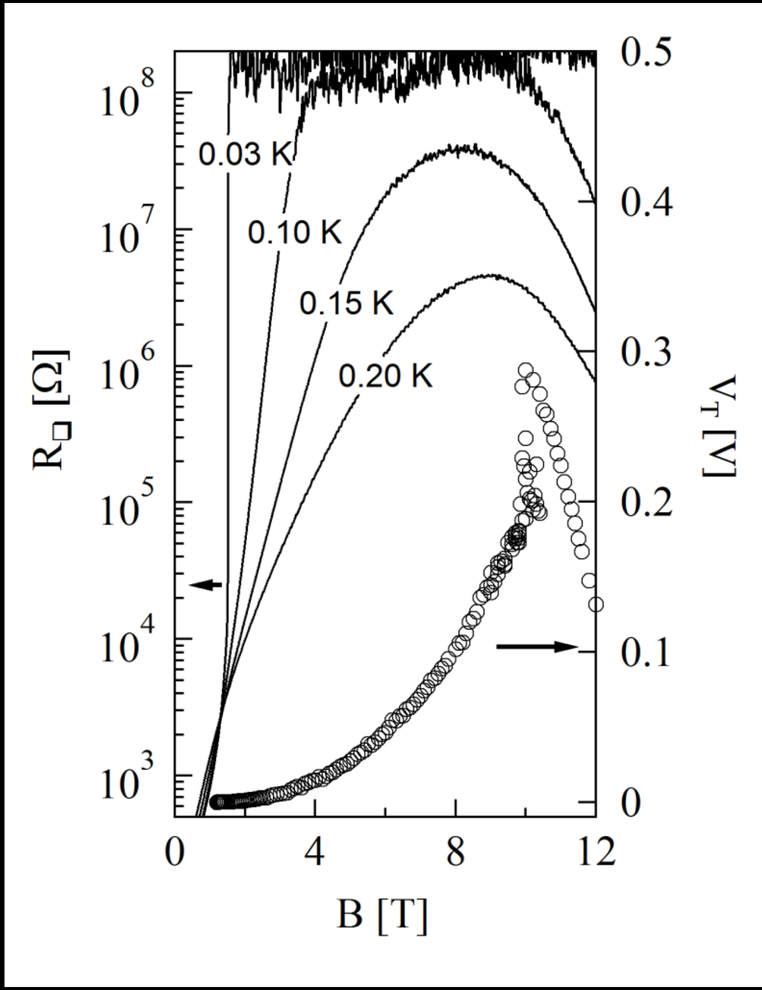


Voltage threshold

Transition to abrupt IV



Voltage threshold

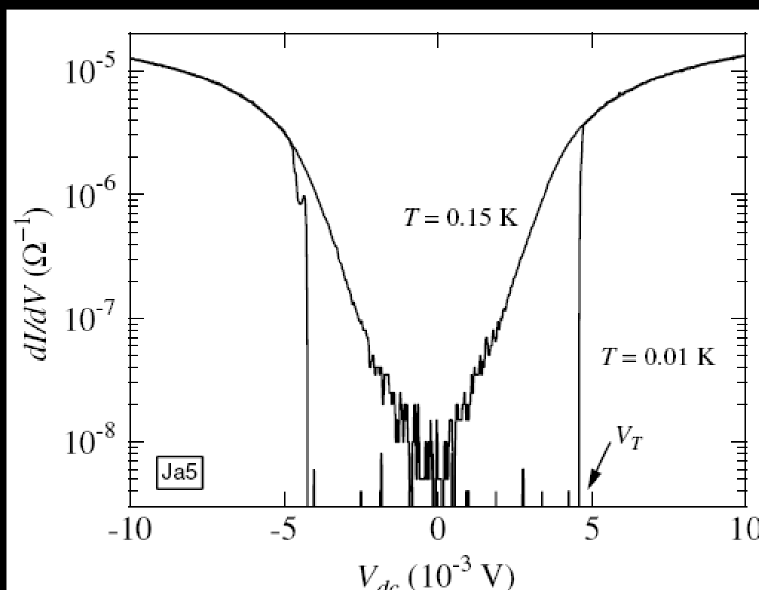


PRL **94,** 017003 (2005) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2005

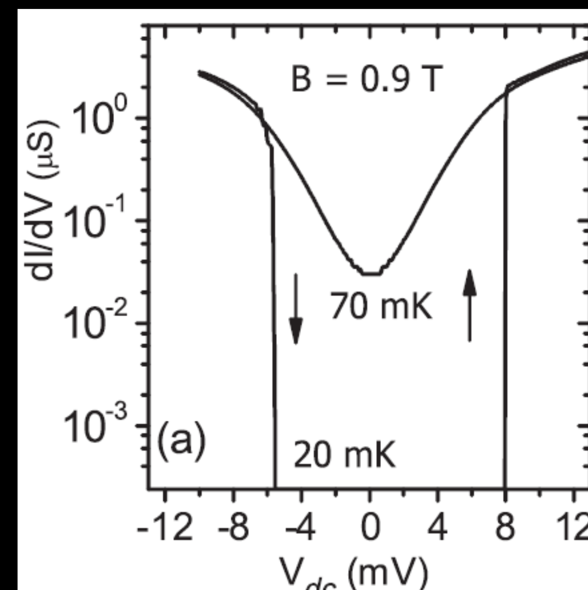
Experimental Evidence for a Collective Insulating State in Two-Dimensional Superconductors

G. Sambandamurthy,[1] J. 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)

a:InO_x



TiN



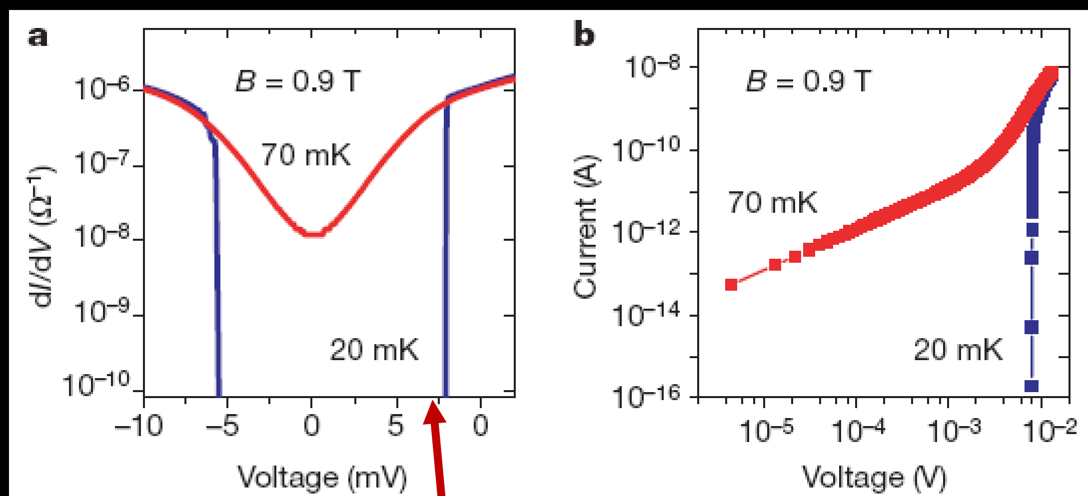
Baturina et al. *PRL* ***99***, 257003 (2007)

Dramatic transition occurs around T* ~ 0.1K

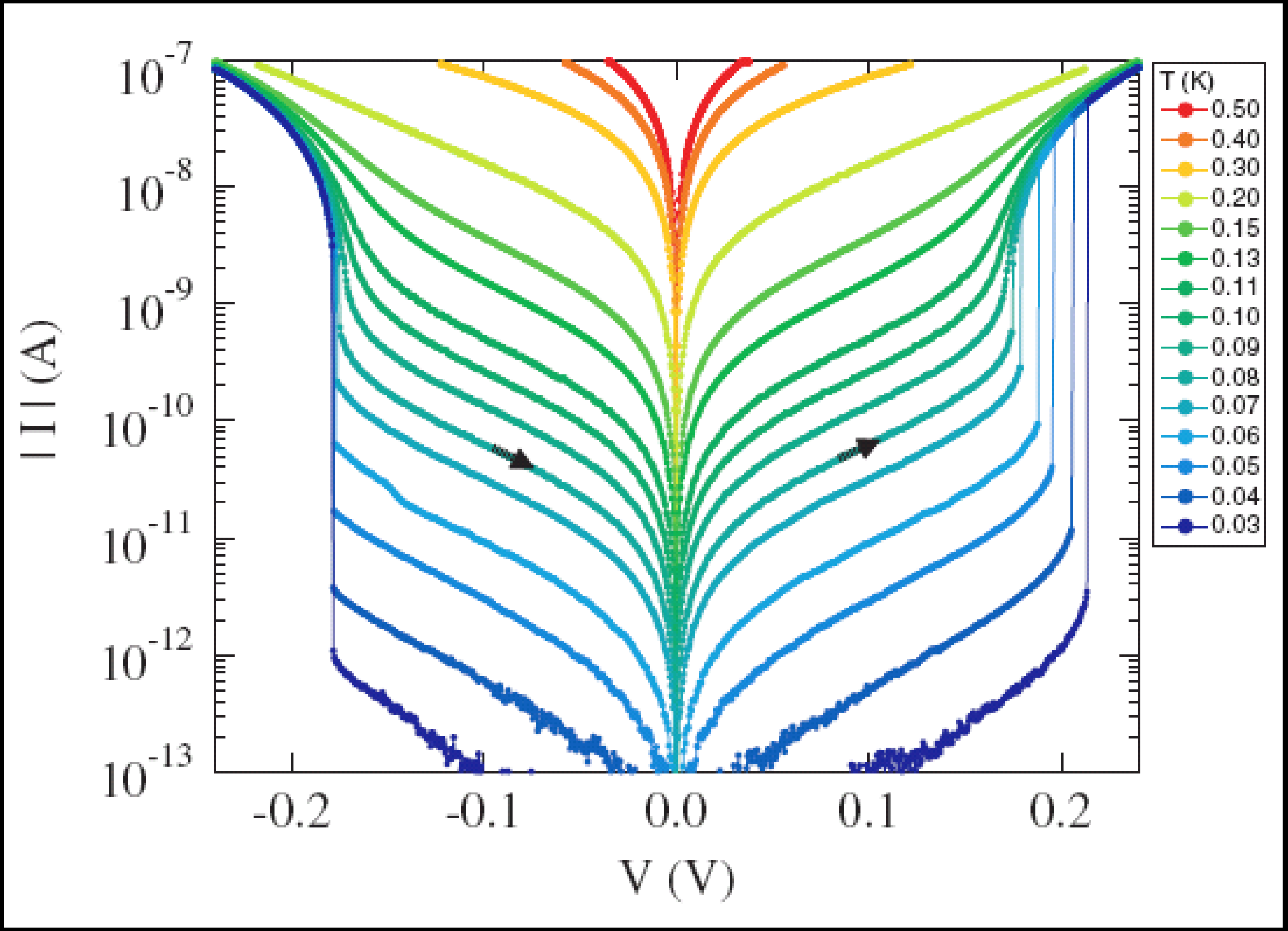
Superinsulator and quantum synchronization

Valerii M. Vinokur[1], Tatyana I. Baturina[1,2,3], Mikhail V. Fistul[4], Aleksey Yu. Mironov[2,3], Mikhail R. Baklanov[5] & Christoph Strunk[3]

NATURE 452, 613 (2008)



G=0 below V_T !?



Ovadia, Sacépé, Shahar PRL ‘09

PRL 102, 176803 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Jumps in Current-Voltage Characteristics in Disordered Films

Boris L. Altshuler,[1,2] Vladimir E. Kravtsov,[3] Igor V. Lerner,[4] and Igor L. Aleiner[1]

Hysteresis → electron overheating

PRL 102, 176803 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Jumps in Current-Voltage Characteristics in Disordered Films

Boris L. Altshuler,[1,2] Vladimir E. Kravtsov,[3] Igor V. Lerner,[4] and Igor L. Aleiner[1]

1. **Electrons and phonons are decoupled**

2. **Electrons are strongly interacting (can have $T_{el} \neq T_{ph}$)**

3. **Intrinsic I-V is linear: heating is the only source of non-linearity**

4. **R is a fast function of *electron temperature***

$$R(T_{el}) = R_0 e^{(T_0/T_{el})^{\gamma}}, with\, \gamma \leq 1$$

PRL 102, 176803 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

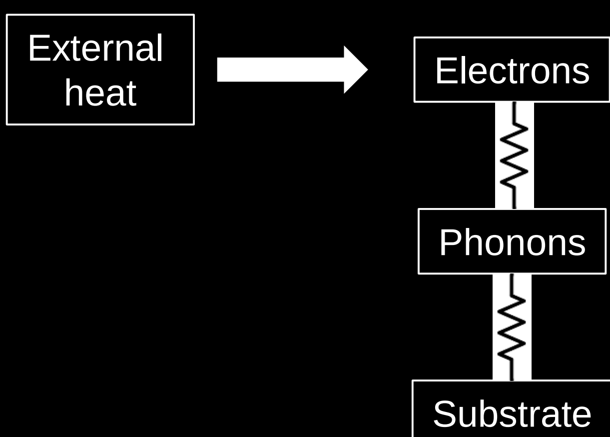
Jumps in Current-Voltage Characteristics in Disordered Films

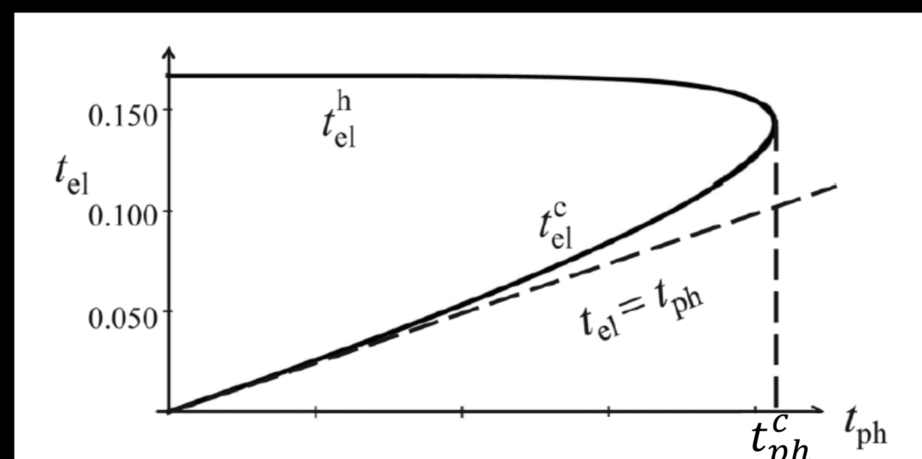
Boris L. Altshuler,[1,2] Vladimir E. Kravtsov,[3] Igor V. Lerner,[4] and Igor L. Aleiner[1]

Heat balance equation :

$$\frac{V^2}{R(T_{el})} = \Gamma\Omega\left(T_{el}^6 - T_{ph}^6\right)$$

$$R(T_{el}) = R_0 e^{(T_0/T_{el})^\gamma}$$

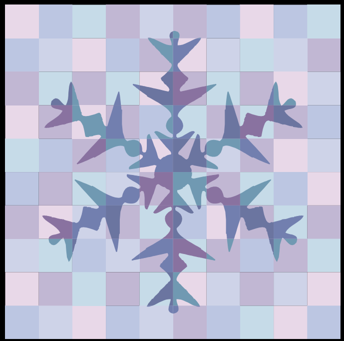


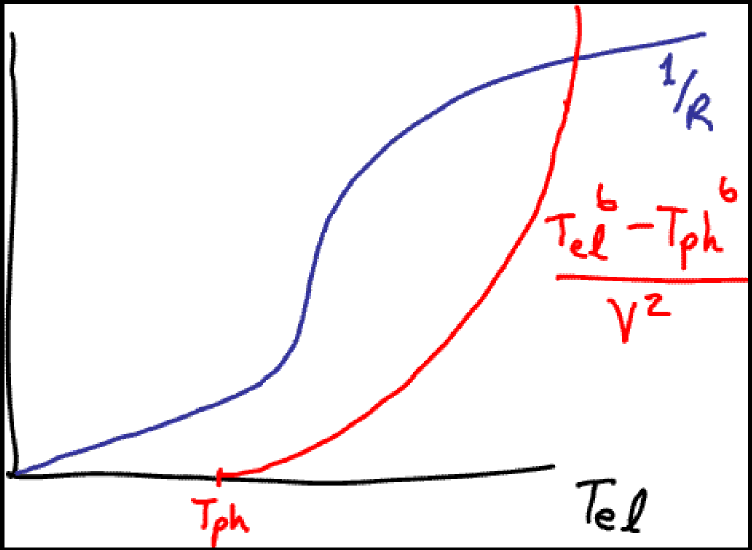


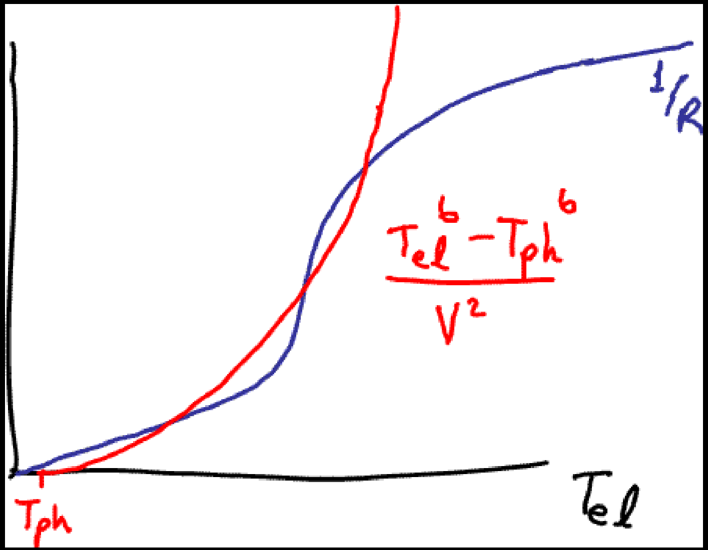
Lowering T_{phonon}

$$\frac{1}{R(T_{el})} = \frac{\Gamma\Omega\left(T_{el}^6 - T_{ph}^6\right)}{V^2}$$

$$R(T_{el}) = R_0 e^{\Delta/T}$$



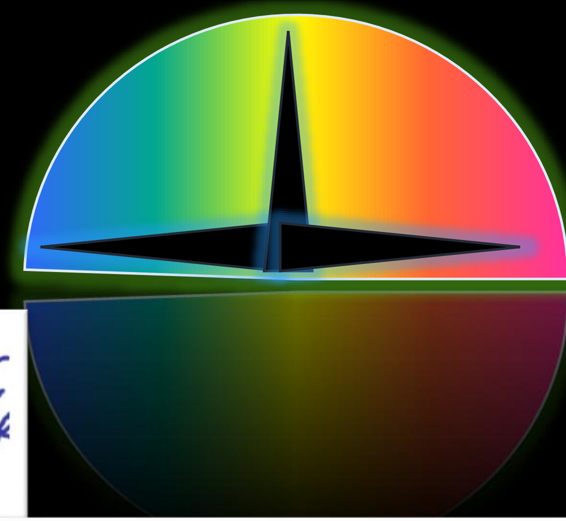


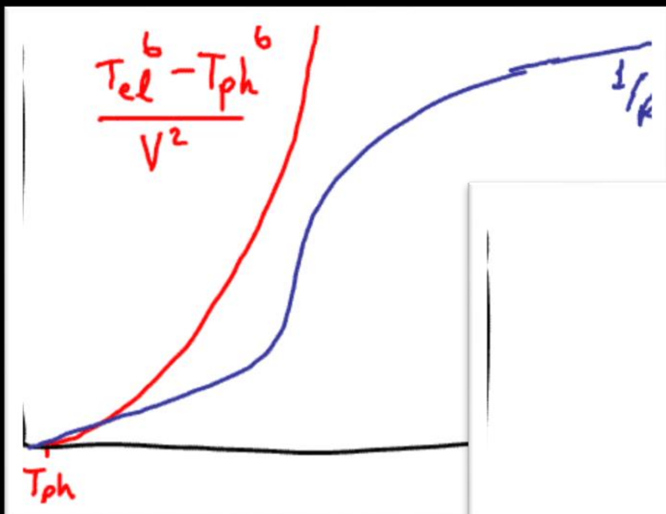


One solution at $T_{el} > T_{ph}$

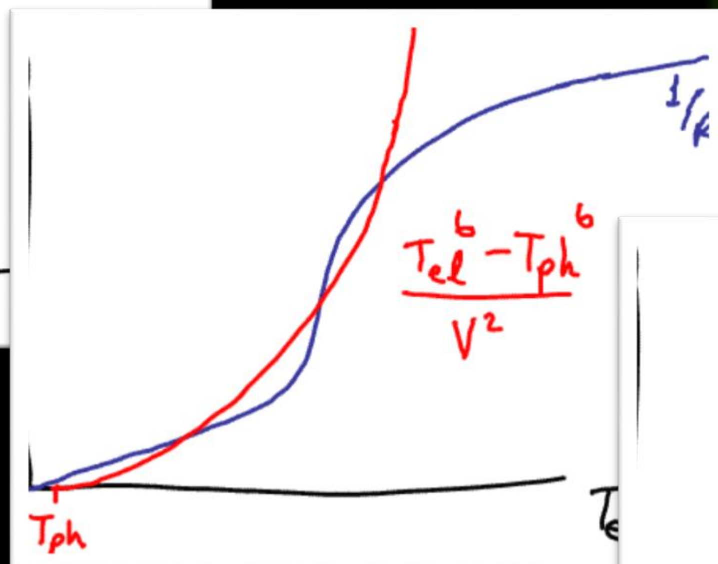
Multiple solutions for T_{el}

Changing voltage…

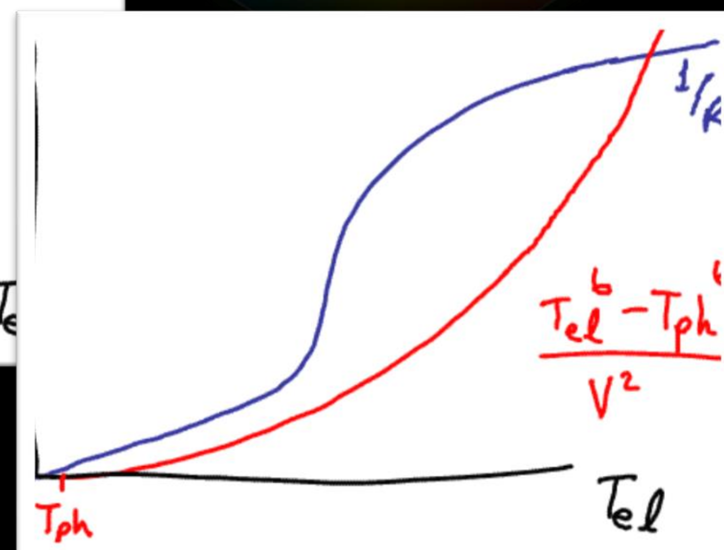




Single solution
at $T_{el} \sim T_{ph}$

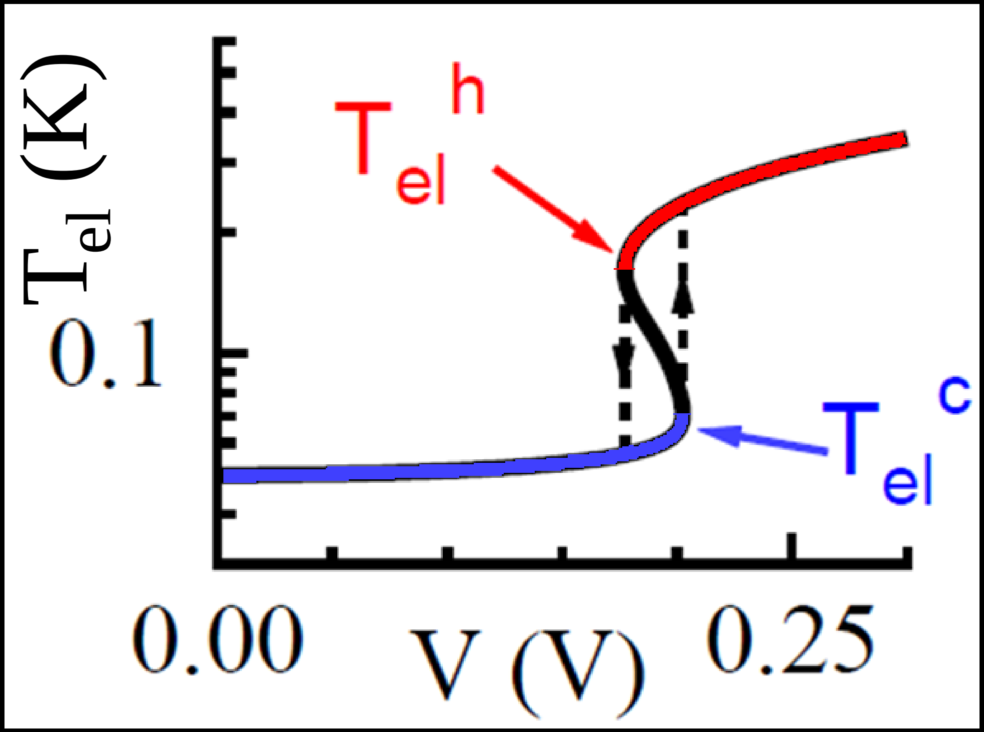


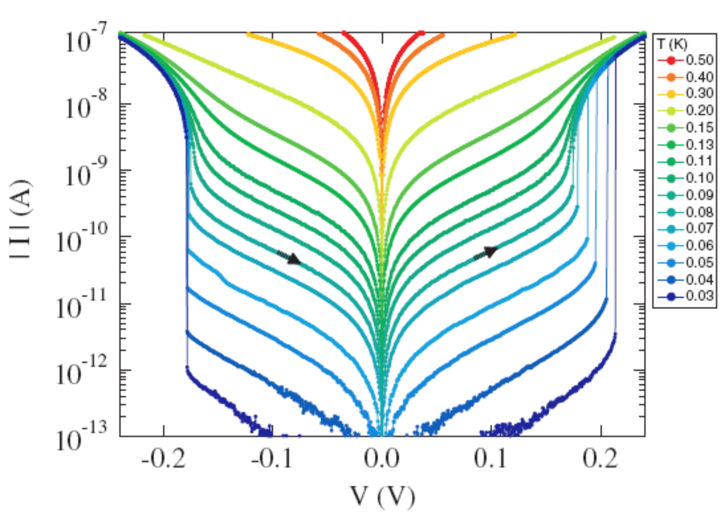
Multiple solutions



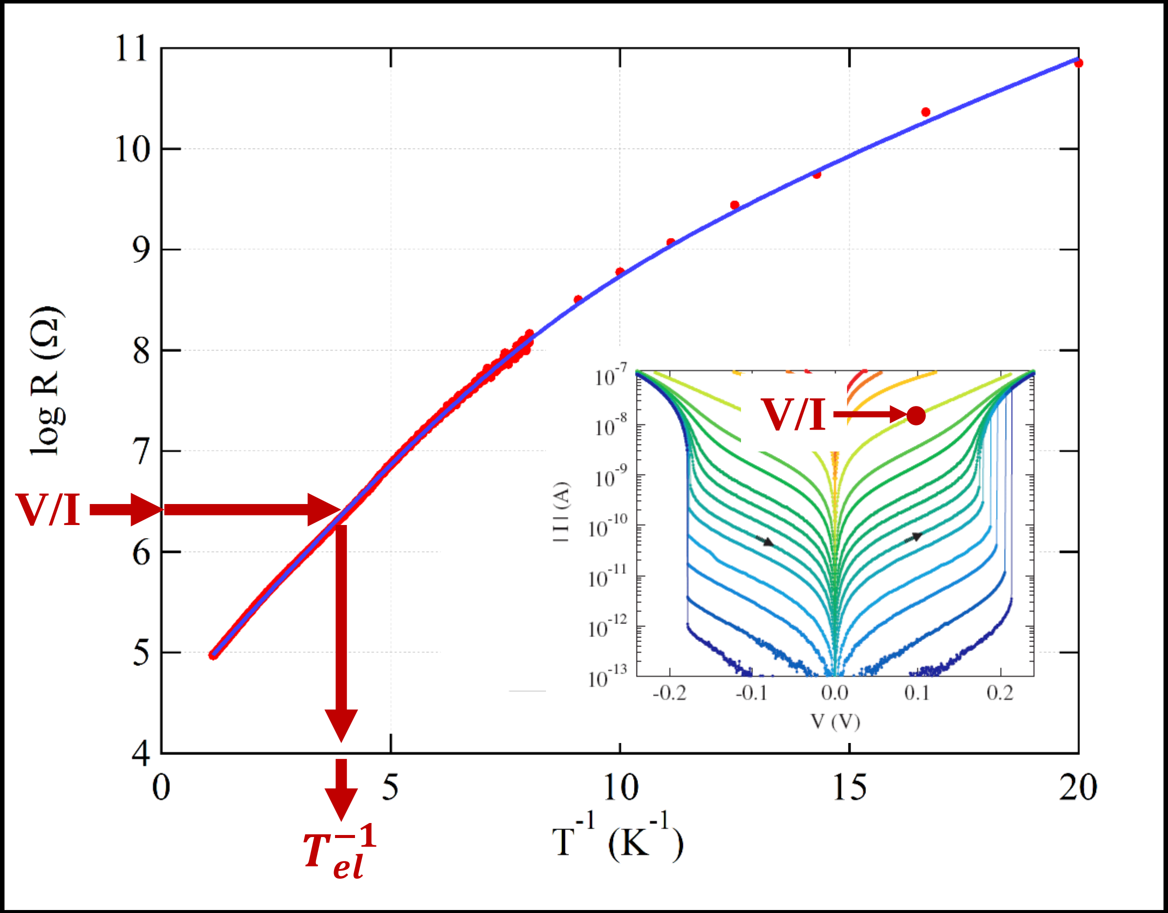
Single solution
at $T_{el} > T_{ph}$

Thermal bi-stability

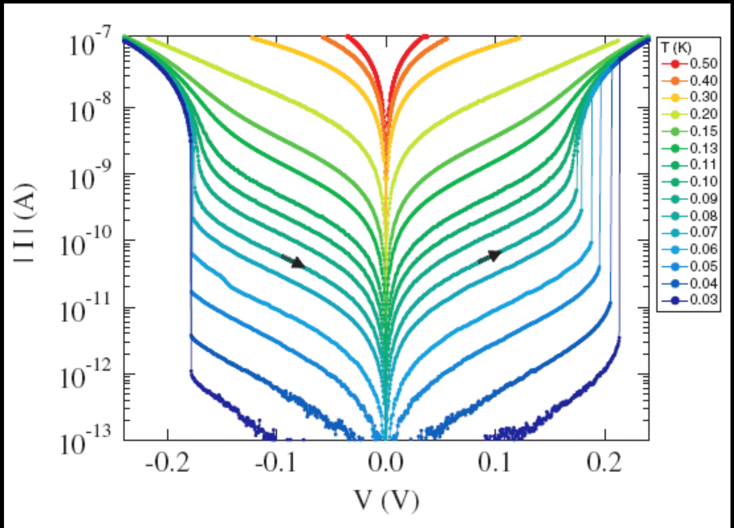


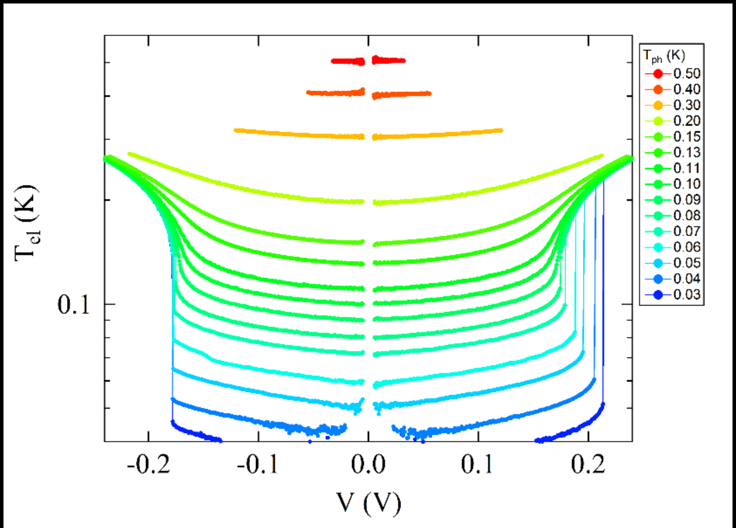


Determine T_{el}

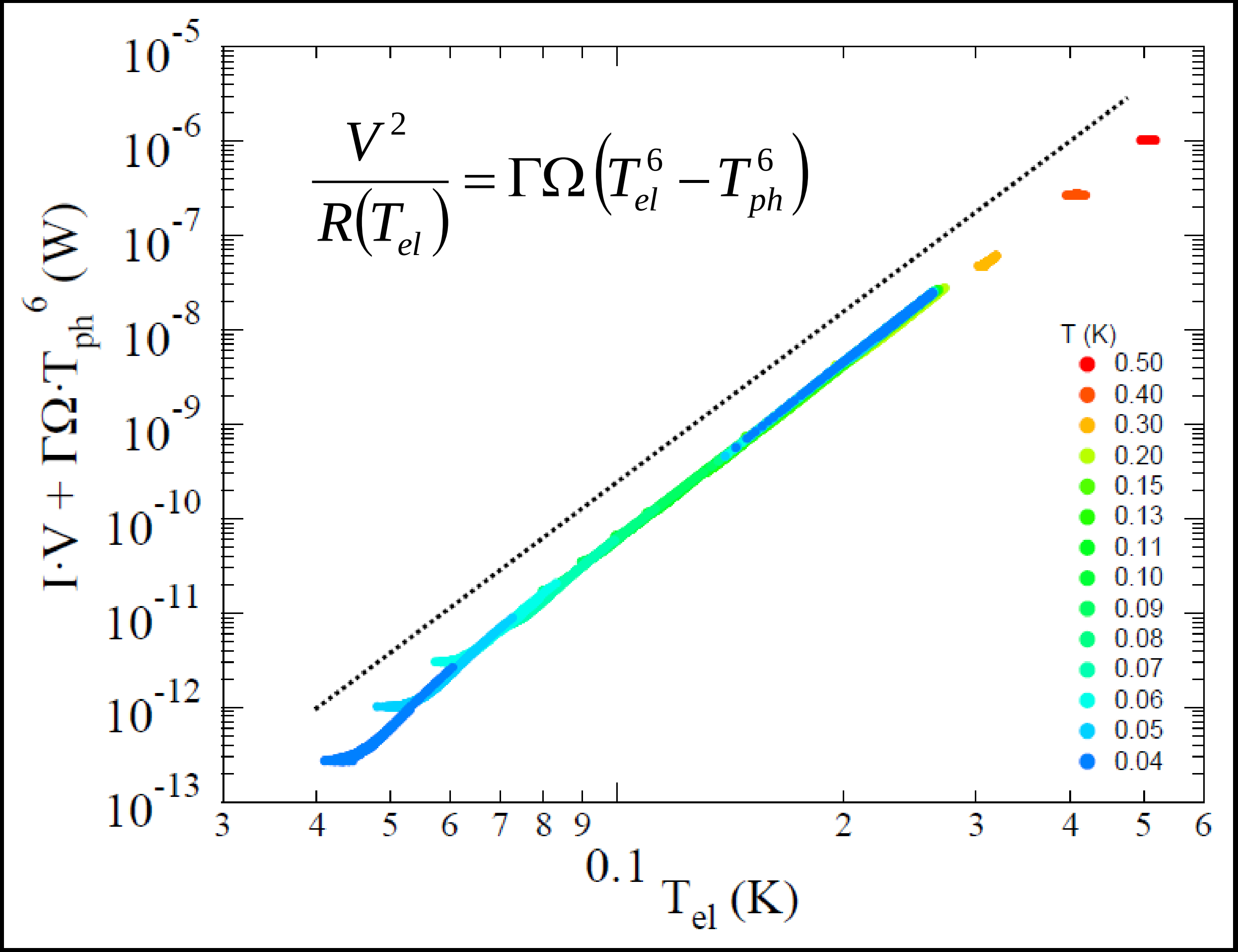


Determine T_{el}



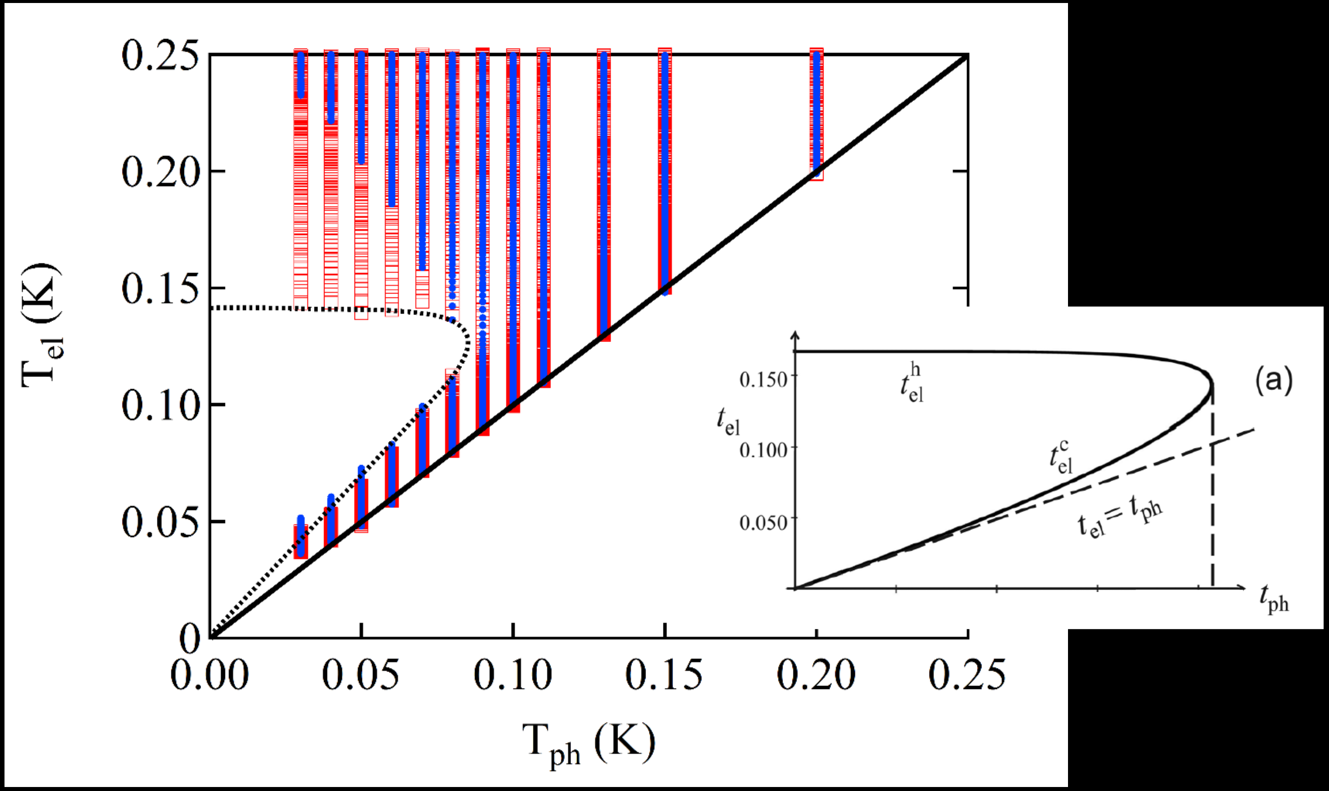


Electron overheating

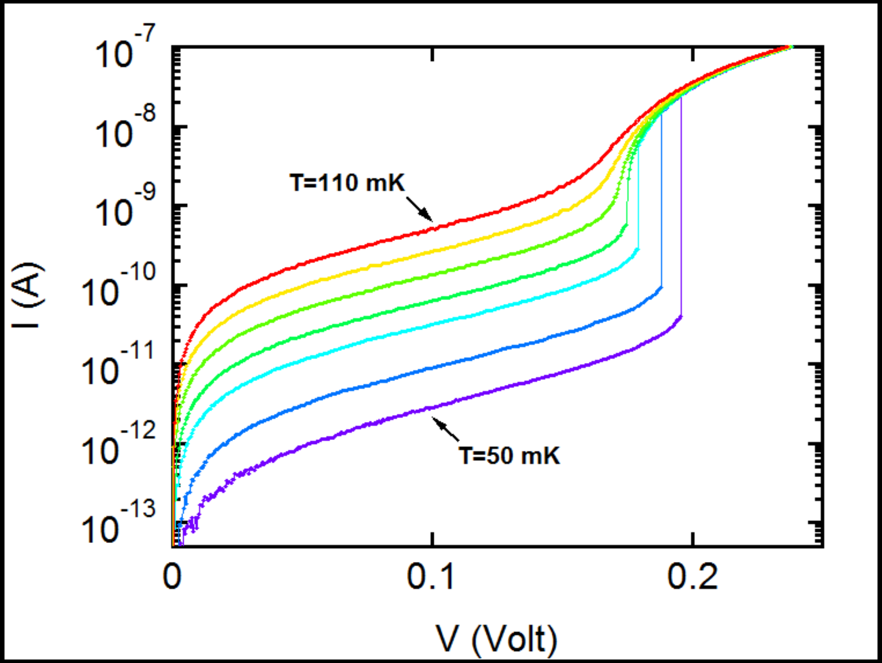


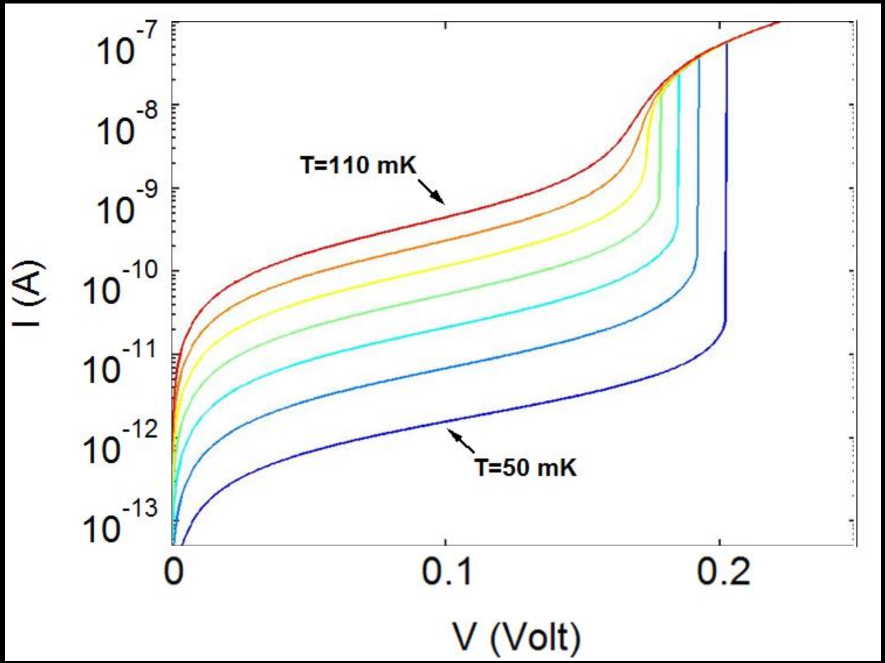
Assume hot-electron scenario ⇒ recover heat balance equation !

Excluded region



IV's computed with $R(T)$ curve and heat balance eqation

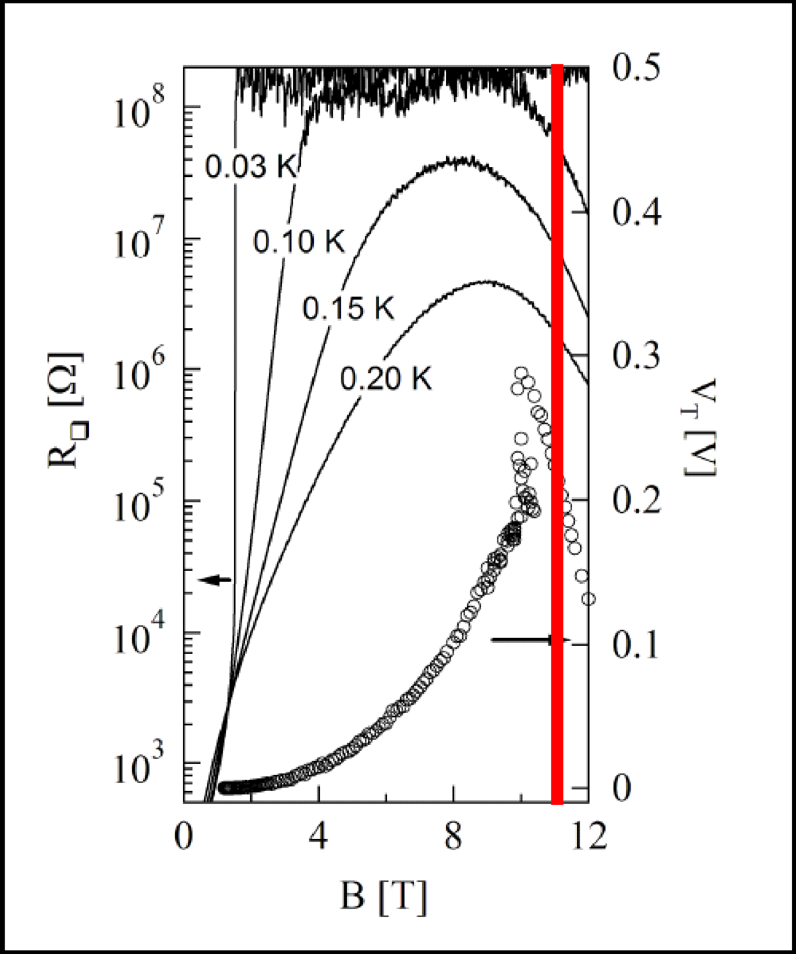


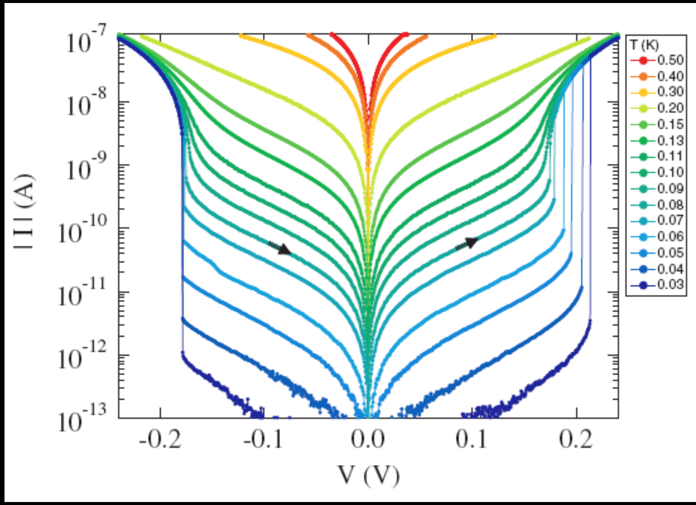


M. Ovadia, B. Sacépé, and D. Shahar
Phys. Rev. Lett. 102, 176802 (2009)

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

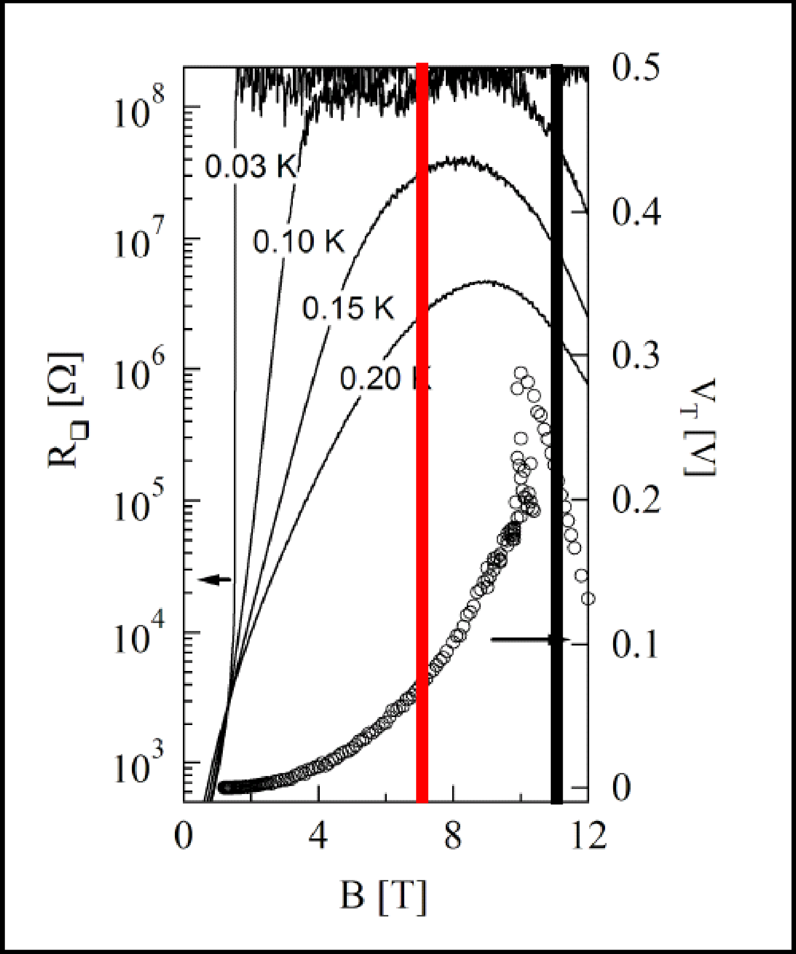
Heating at B = 11 T

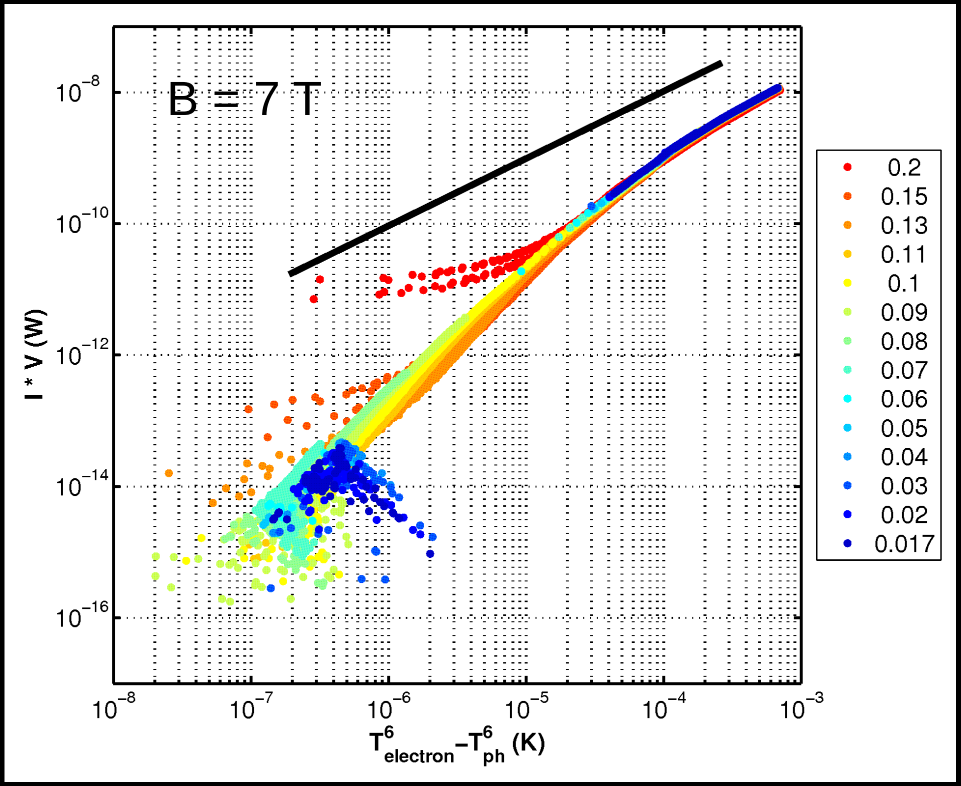




$$\frac{V^2}{R(T_{el})} = \Gamma\Omega\left(T_{el}^6 - T_{ph}^6\right)$$

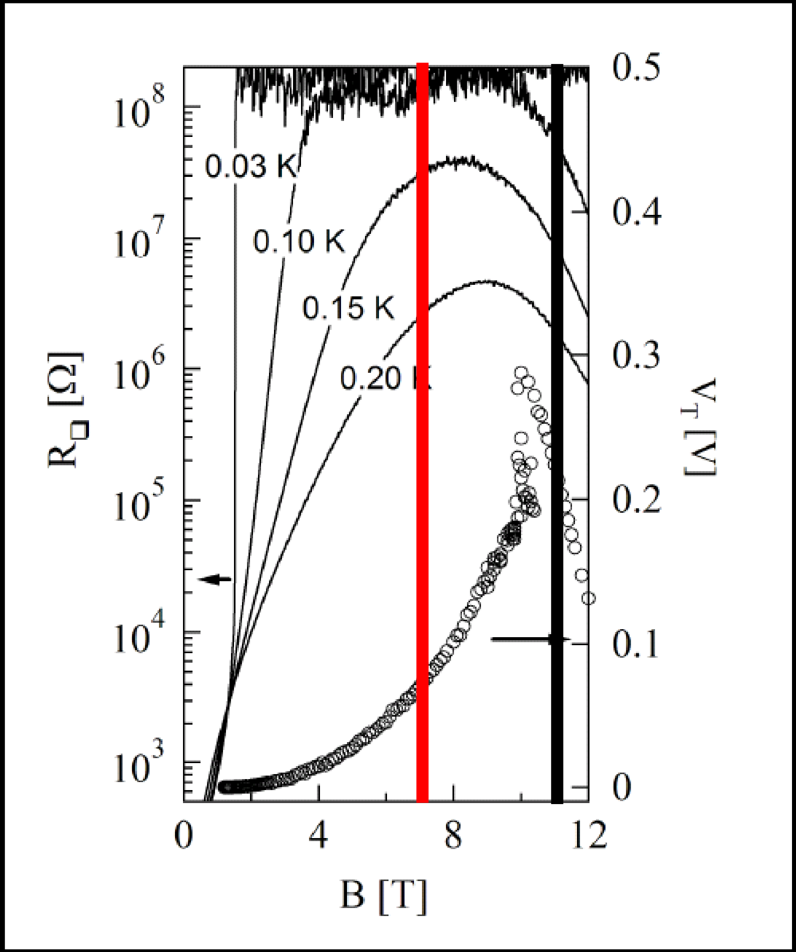
Heating at lower field

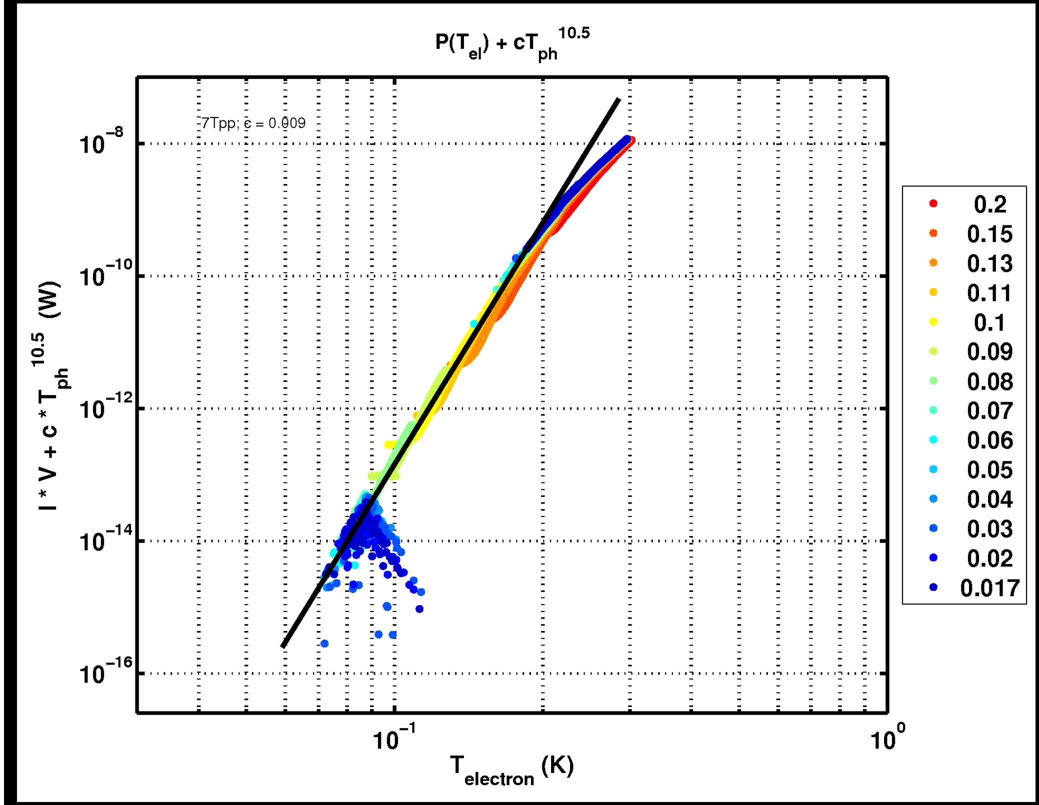




$$\frac{V^2}{R(T_{el})} = \Gamma\Omega\left(T_{el}^6 - T_{ph}^6\right)$$

Heating at lower field



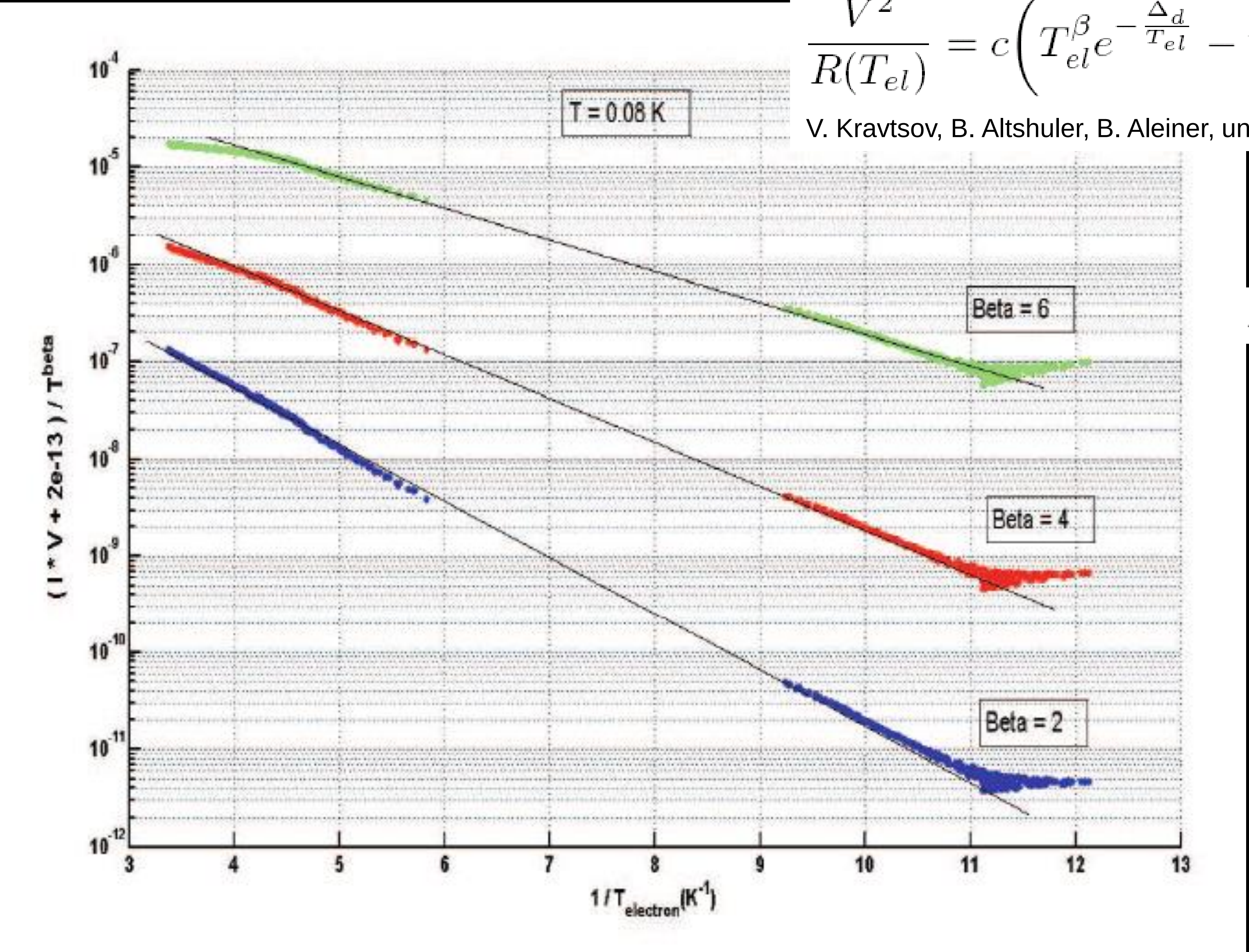


$$\frac{V^2}{R(T_{el})} = \Gamma\Omega\left(T_{el}^{\alpha} - T_{ph}^{\alpha}\right), \quad \alpha > 10 \text{ ???}$$

Exponentially suppressed cooling rate at B=7T

$$\frac{V^2}{R(T_{el})} = c\left(T_{el}^{\beta} e^{-\frac{\Delta_d}{T_{el}}} - T_{ph}^{\beta} e^{-\frac{\Delta_d}{T_{ph}}}\right),$$

V. Kravtsov, B. Altshuler, B. Aleiner, unpublished



For beta=4

$\Delta_d = 0.97\,K$

Conclusion on non-linear transport

☑ Charge carriers are interacting and **form a bath at T_{el}**

☑ Charge carriers and phonons are **weakly coupled**

☑ IV non-linearities due to **electron overheating**

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

D.M. Basko [a,b,*], I.L. Aleiner [b], B.L. Altshuler [a,b,c]

[a] Department of Physics, Princeton University, Princeton, NJ 08544, USA
[b] Physics Department, Columbia University, New York, NY 10027, USA
[c] NEC-Laboratories America, 4 Independence Way, Princeton, NJ 085540, USA

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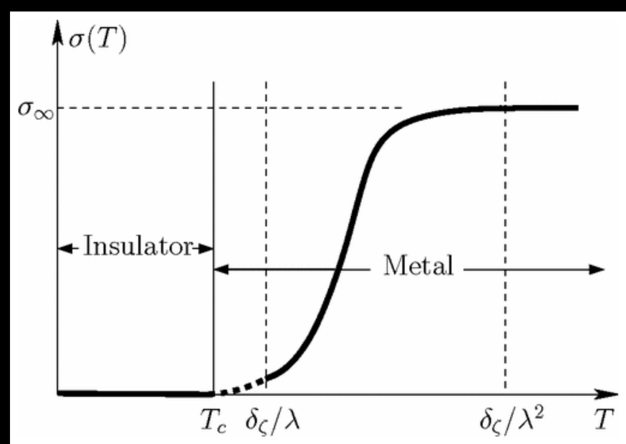
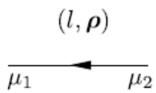
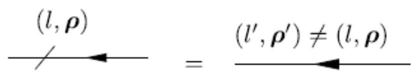


$$
\begin{aligned}
&[\mathrm{i}\partial_{t_1} - \xi_l(\boldsymbol{\rho})]\hat{\mathcal{G}}_l(\boldsymbol{\rho}) = \hat{\tau}_0\delta(t_1 - t_2) + \hat{\boldsymbol{\Sigma}}_l(\boldsymbol{\rho}) \circ \hat{\mathcal{G}}_l(\boldsymbol{\rho});\\
&[-\mathrm{i}\partial_{t_2} - \xi_l(\boldsymbol{\rho})]\hat{\mathcal{G}}_l(\boldsymbol{\rho}) = \hat{\tau}_0\delta(t_1 - t_2) + \hat{\mathcal{G}}_l(\boldsymbol{\rho}) \circ \hat{\boldsymbol{\Sigma}}_l(\boldsymbol{\rho});\\
&\hat{\mathcal{G}} = \begin{bmatrix} \mathcal{G}_l^R(\boldsymbol{\rho}) & \mathcal{G}_l^K(\boldsymbol{\rho}) \\ 0 & \mathcal{G}_l^A(\boldsymbol{\rho}) \end{bmatrix}_K; \quad \hat{\boldsymbol{\Sigma}} = \begin{bmatrix} \boldsymbol{\Sigma}_l^R(\boldsymbol{\rho}) & \boldsymbol{\Sigma}_l^K(\boldsymbol{\rho}) \\ 0 & \boldsymbol{\Sigma}_l^A(\boldsymbol{\rho}) \end{bmatrix}_K;\\
&\hat{\tau}^0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}_K; \quad \hat{\tau}^2 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}_K.
\end{aligned}
$$

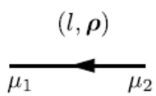


$$= i\left[\hat{G}_l(\boldsymbol{\rho})\right]_{\mu_1\mu_2} = i\begin{bmatrix} G_l^R(\boldsymbol{\rho}) & G_l^K(\boldsymbol{\rho}) \\ 0 & G_l^A(\boldsymbol{\rho}) \end{bmatrix}_{\mu_1\mu_2}$$



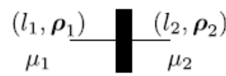
$$
\begin{aligned}
G_l^R(\boldsymbol{\rho}) &= \left[G_l^A(\boldsymbol{\rho})\right]^* = \frac{1}{\epsilon - \xi_l(\boldsymbol{\rho}) + i0^+}\\
G_l^K(\boldsymbol{\rho}) &= -2\pi i n_l(\boldsymbol{\rho}, \epsilon)\delta\left[\epsilon - \xi_l(\boldsymbol{\rho})\right]
\end{aligned}
$$

B



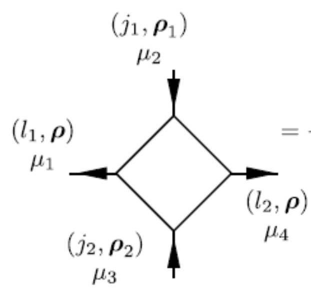
$$= i\left[\hat{\mathcal{G}}_l(\boldsymbol{\rho})\right]_{\mu_1\mu_2};$$

C



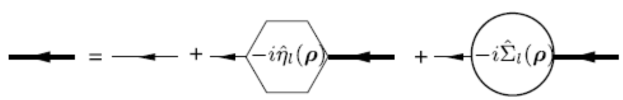
$$= -iI\delta_\xi\left[\hat{\tau}^0\right]_{\mu_1\mu_2}(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2)_{nn};$$

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



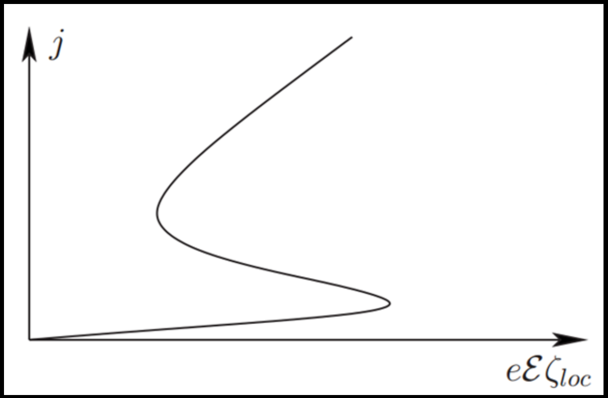
$=$ Fig. 4 $+$ Fig. 5 $+ \ldots$

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)

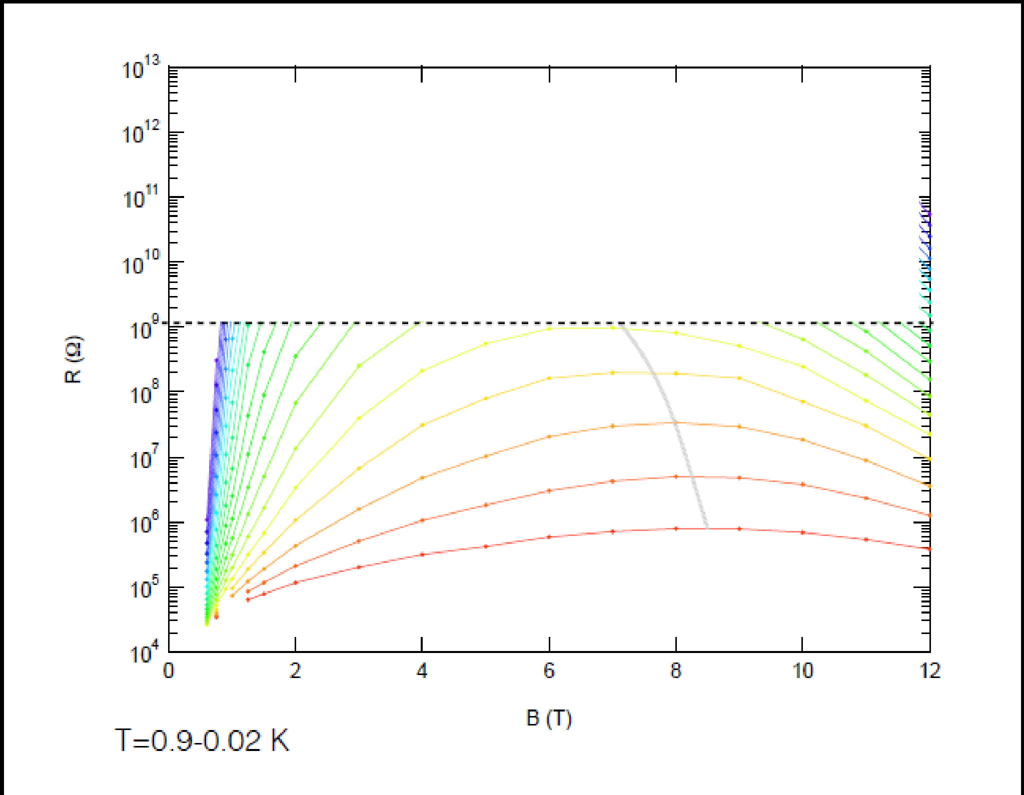
Recently, it was predicted that if all one-electron states in a noninteracting disordered system are localized, the interaction between electrons in the absence of coupling to phonons leads to a finite-temperature metal-insulator transition. Here, we show that even in the presence of a weak coupling 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.

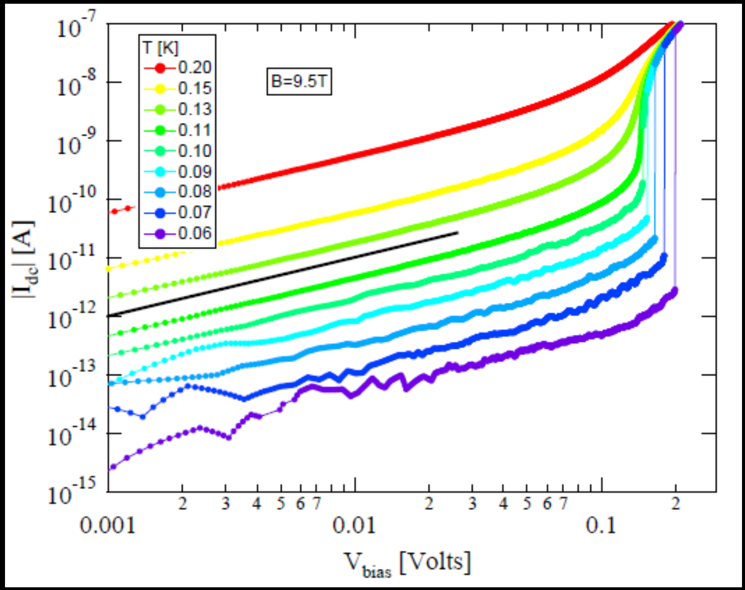


The insulator at $T < 0.2$ K

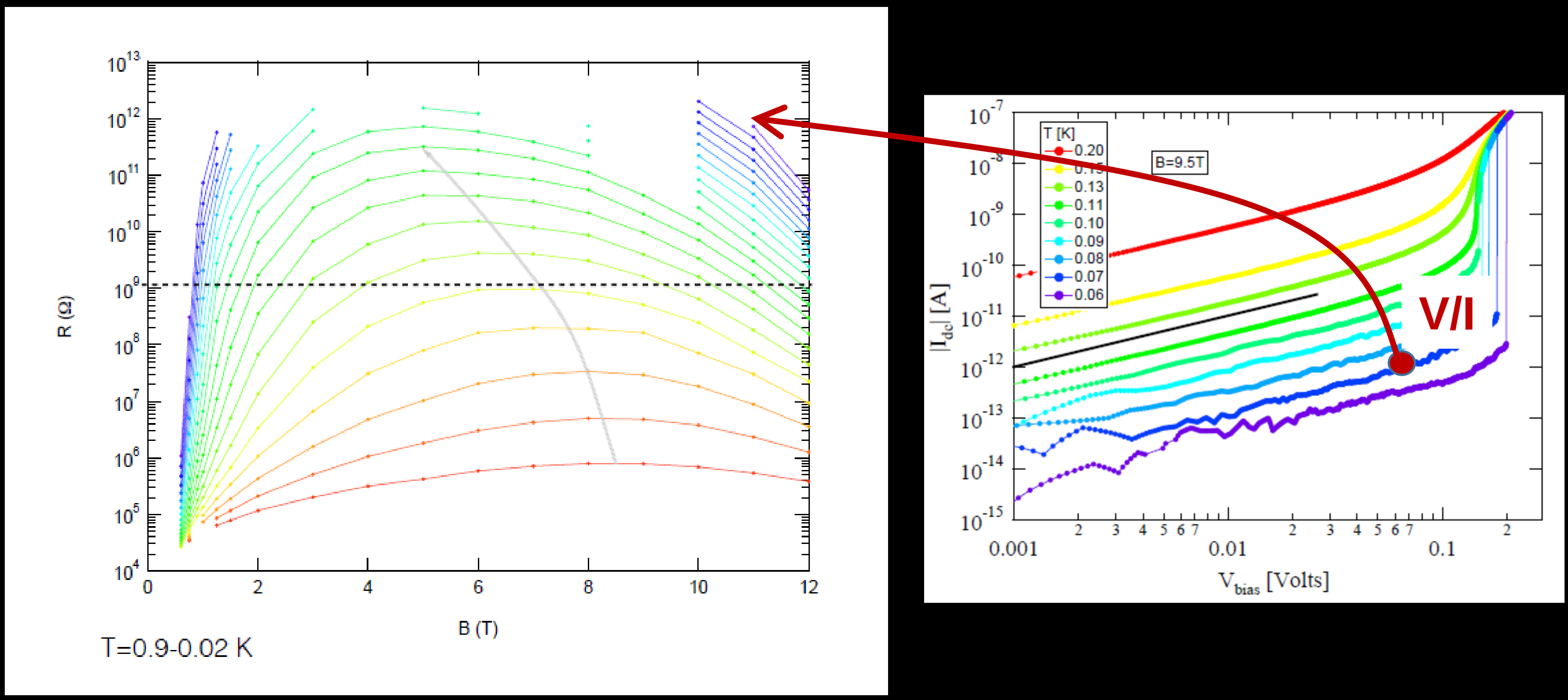
Ohmic transport

Ohmic transport

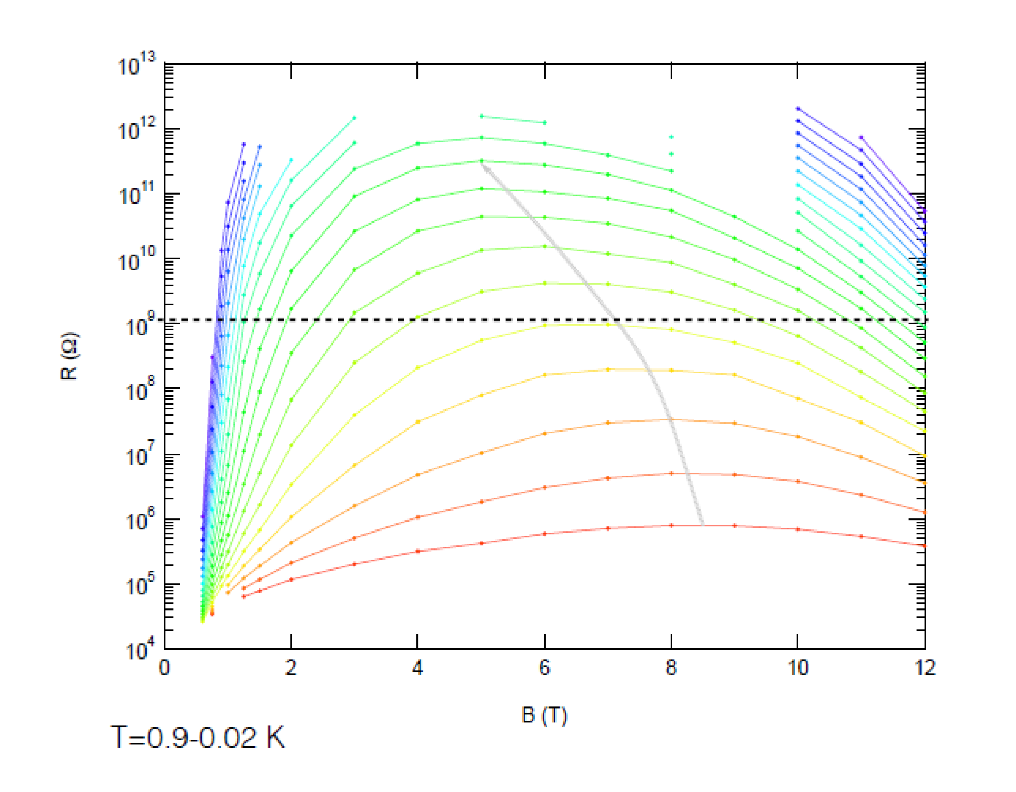


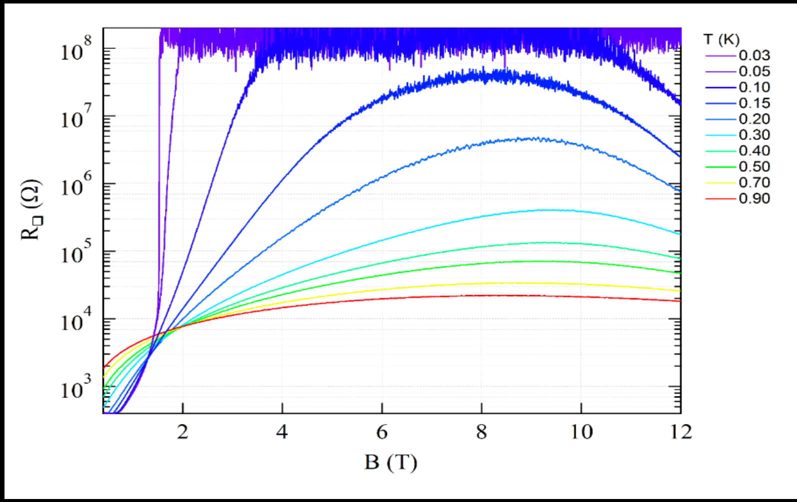


Ohmic transport

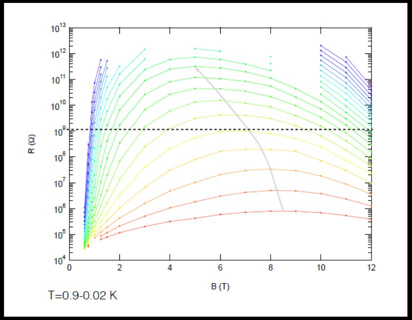


Ohmic transport

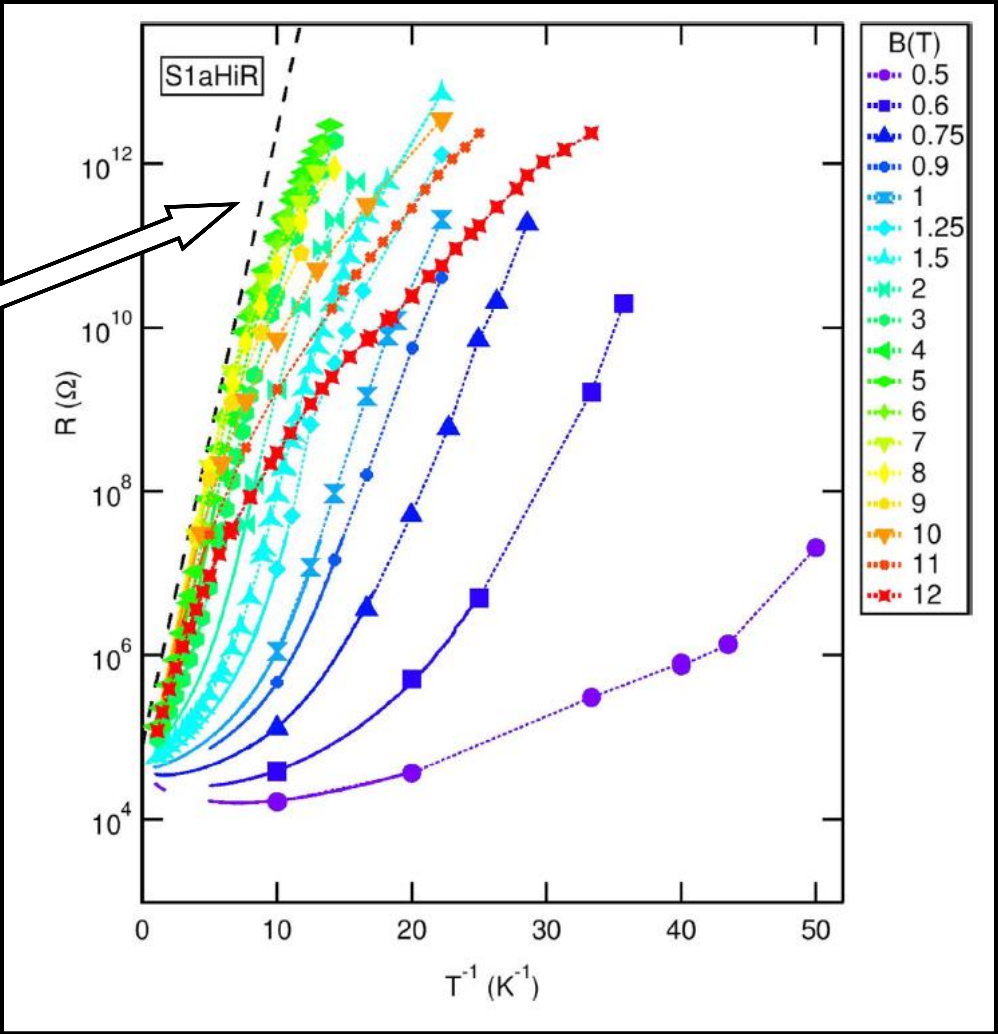




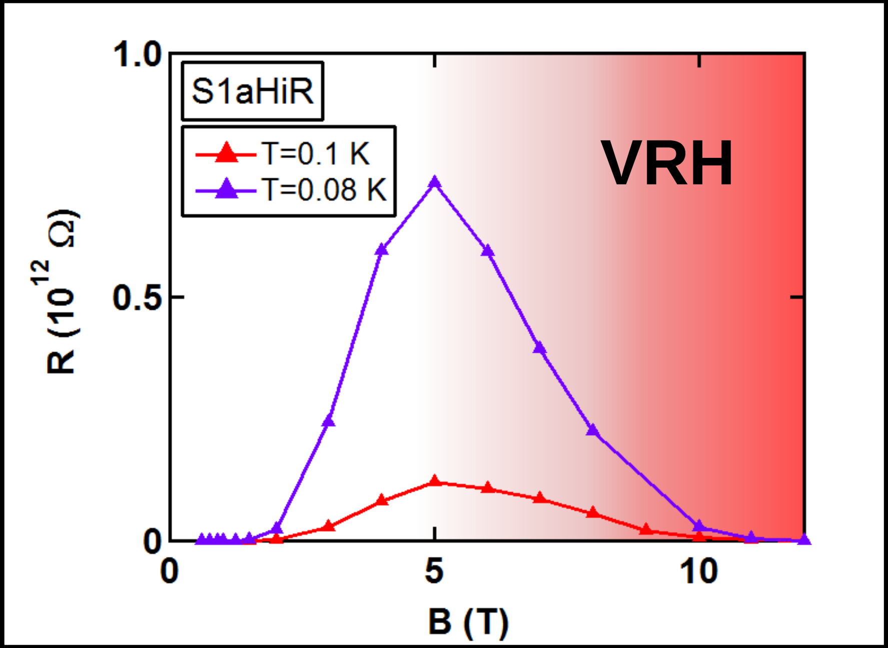
Arrhenius plot

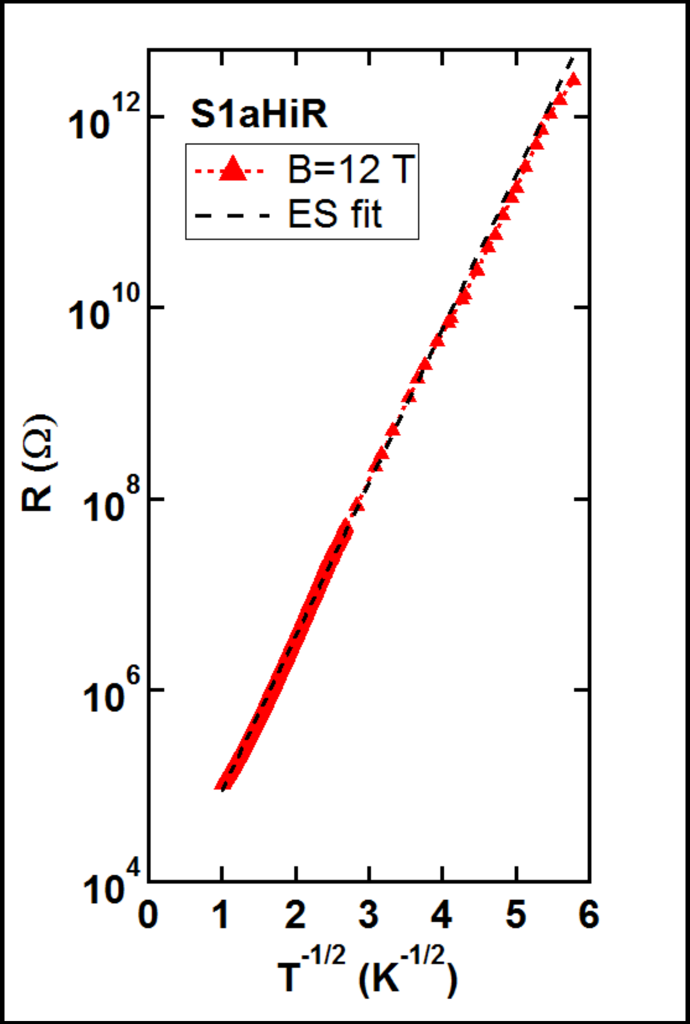


Activation



Efros-Shklovskii Hopping at high B

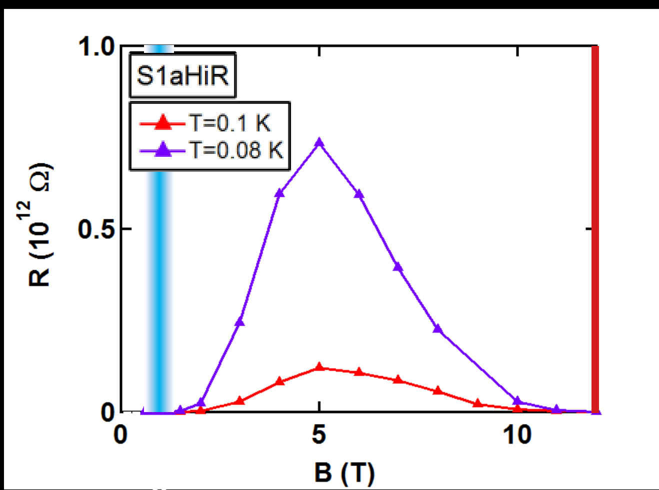


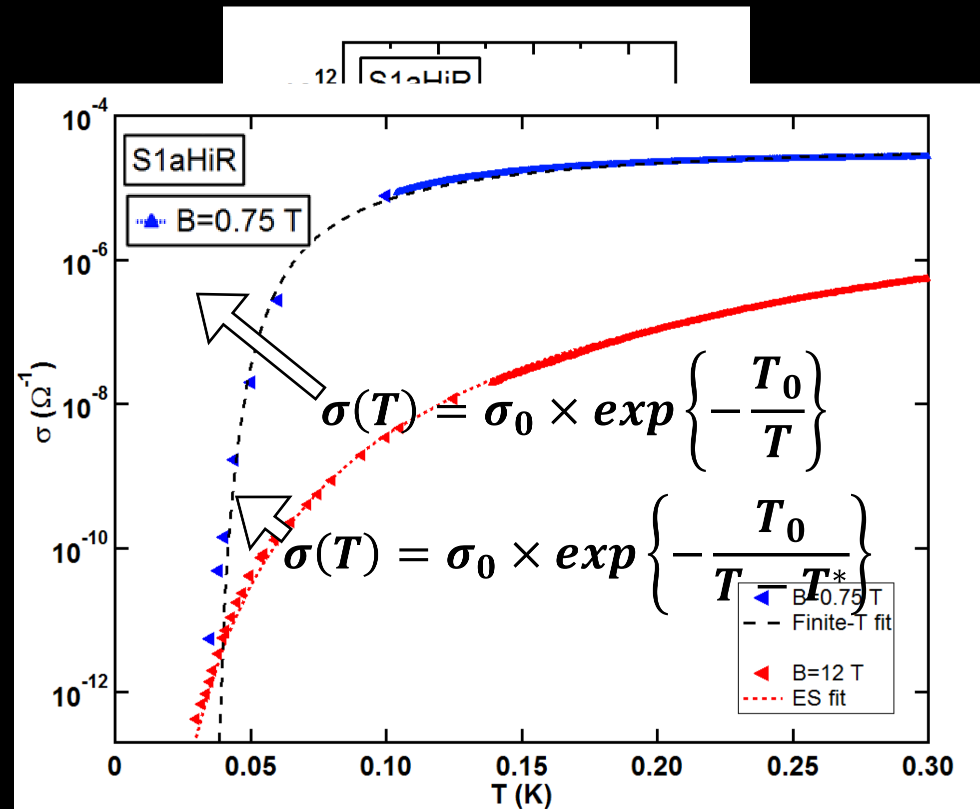


$$R(T) = R_{ES} \times exp\left\{\left(\frac{T_{ES}}{T}\right)^{1/2}\right\}$$

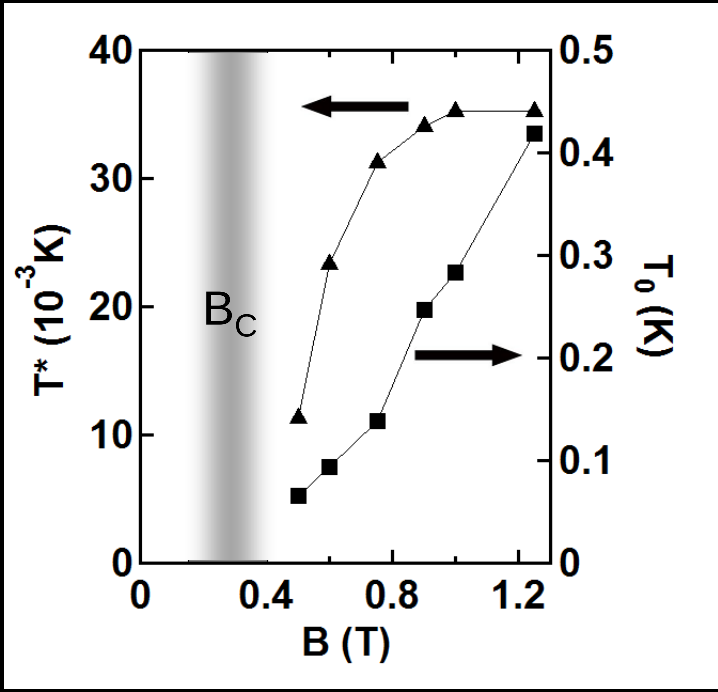
Resistivity Near B_c

Conductivity (ρ^{-1}) B_c



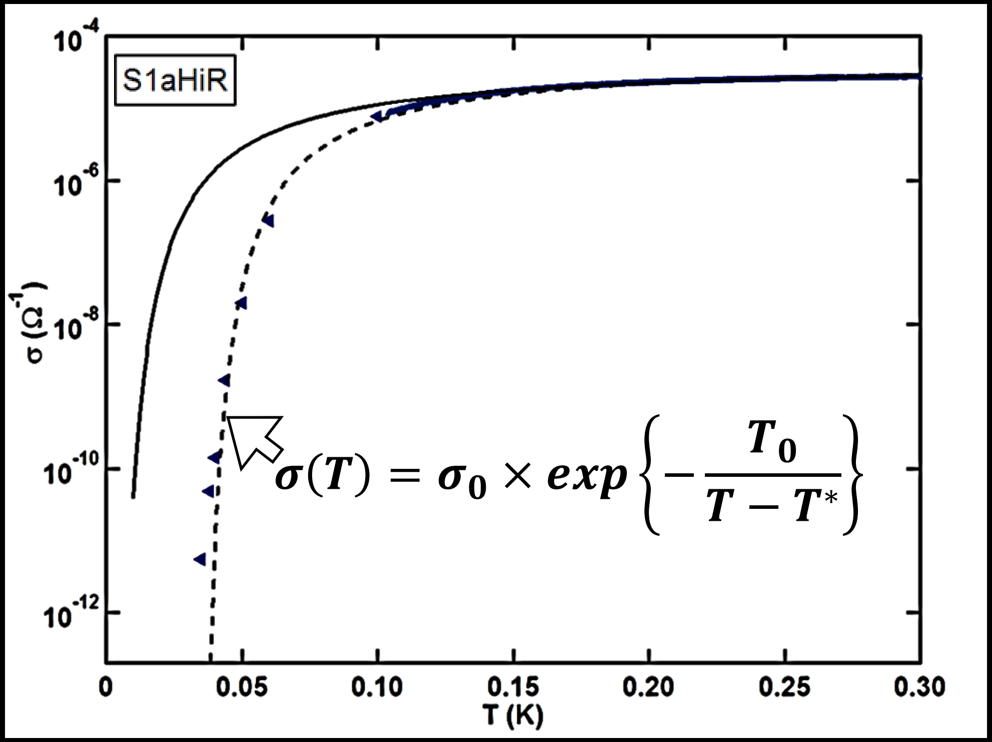


Fit Parameters



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

Many-body localization ?



M. Ovadia *et al. Scientific Reports* **5**, 13503 (2015)

Thank you.