ÉCOLE DE PHYSIQUE
des HOUCHES

FEATURES OF THE INSULATOR CLOSE TO THE SUPERCONDUCTOR-INSULATOR TRANSITION

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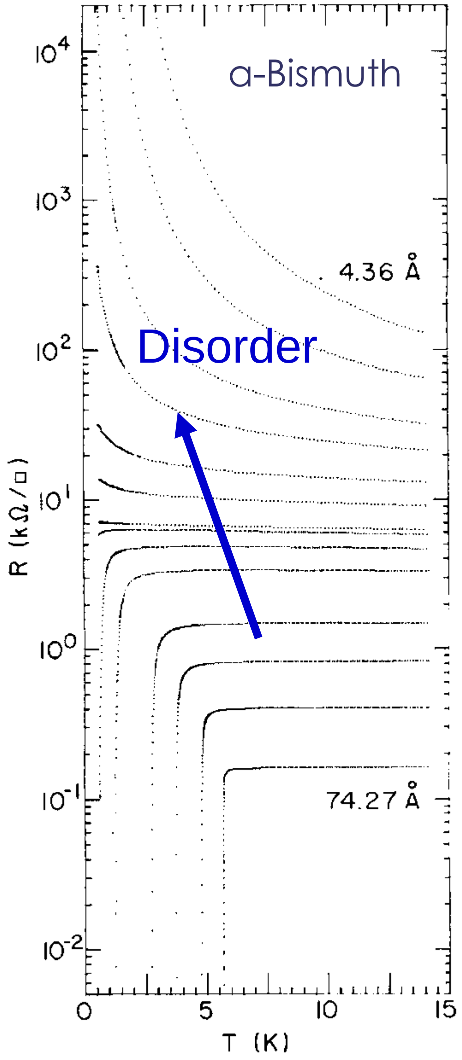
Motivation

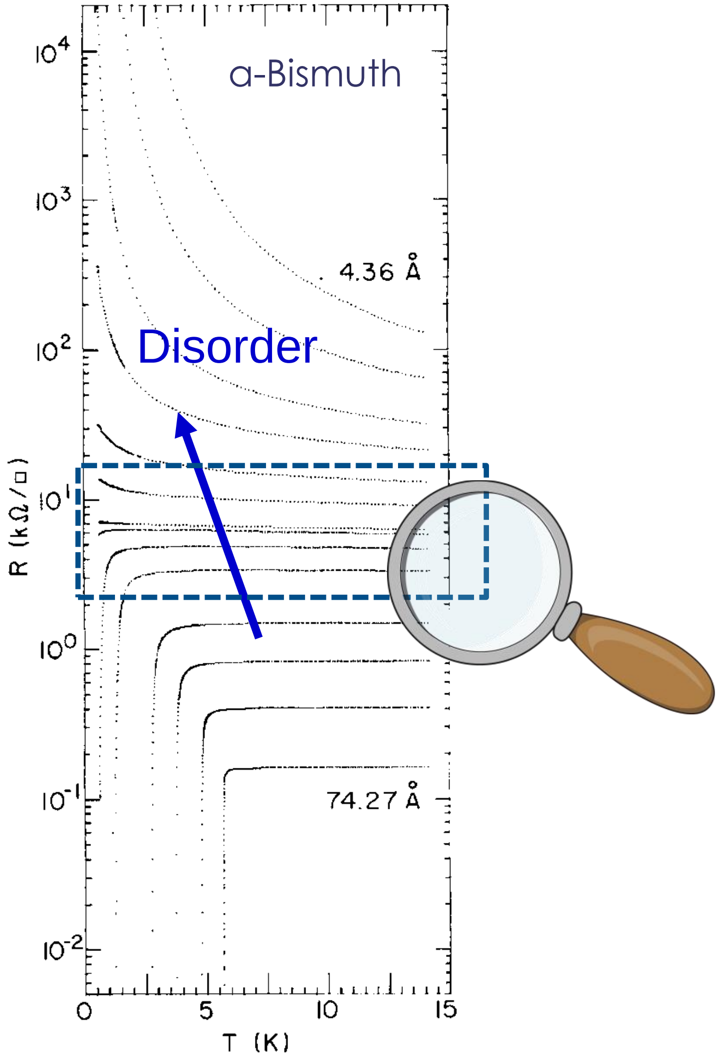
Haviland et al, PRL 62 18 1989



Superconductor-Insulator Transitions

Disorder-induced transition

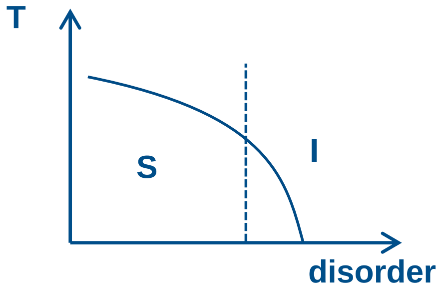
Haviland et al, PRL 62 18 1989



Disorder-induced SIT in 2D systems

Bosonic scenarii

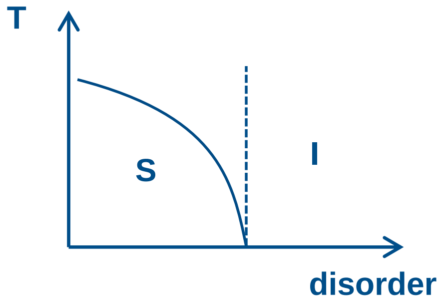
Cooper pairs
in the insulator



Fisher, *Phys. Rev. Lett.*, **65** 7 1990

Fermionic scenarii

NO Cooper pairs
in the insulator

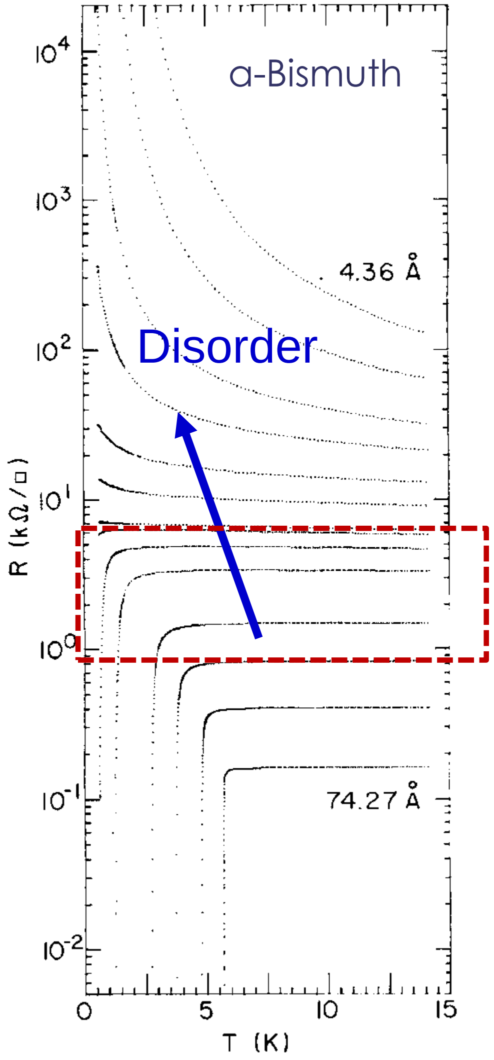


Finkel'stein, *JETP Letters*, **45** 46 (1987)

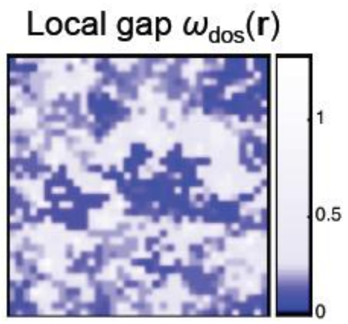
Superconductor-Insulator Transitions

Electronic inhomogeneities

Haviland et al, PRL 62 18 1989

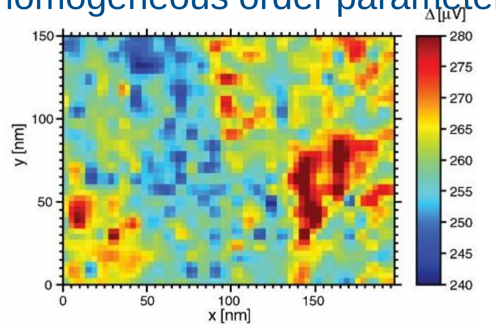


Superconducting side

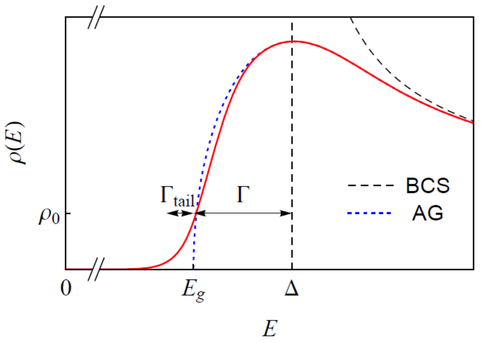


Bouadim et al., *Nat. Phys.*, **7** 884 2011

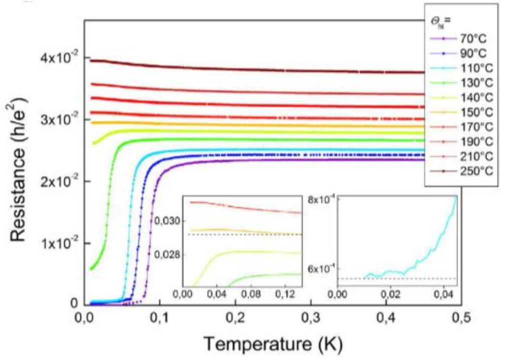
Inhomogeneous order parameter



Sacépé et al., *PRL*, **101** 157006 2008



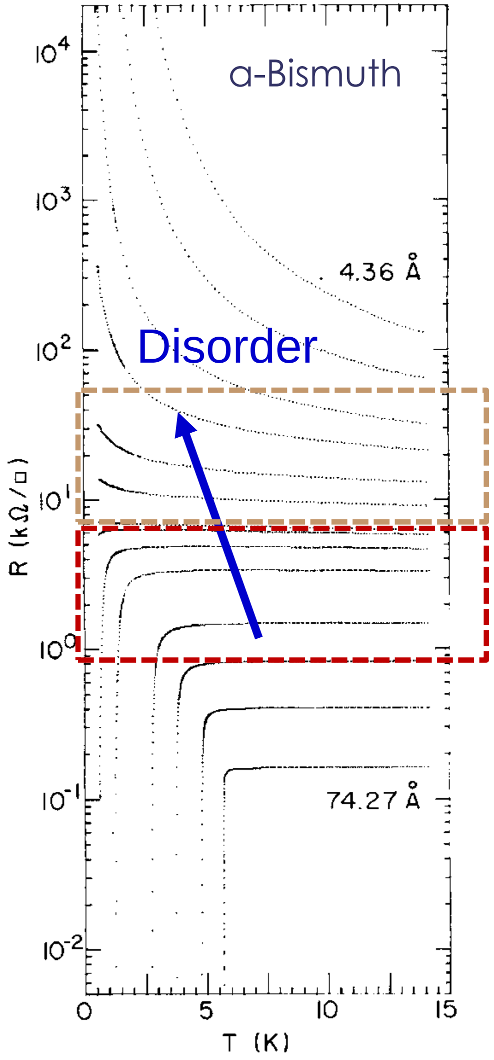
Skvortsov & Feigel’man, *JETP*, **117**, 487 2013



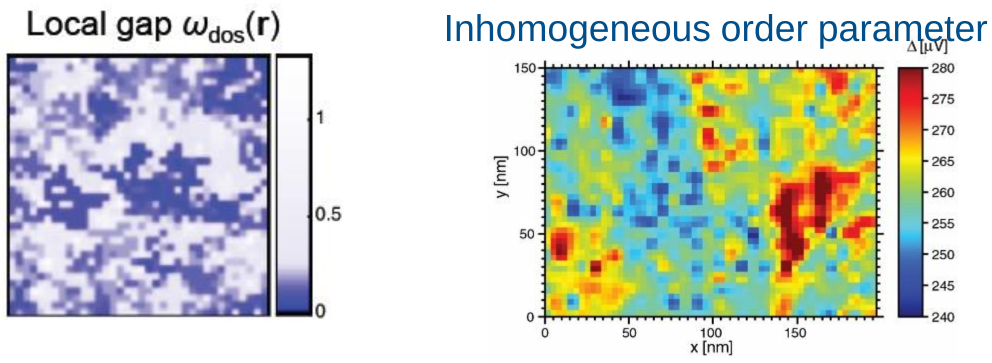
Couëdo et al., *Sci. Rep.*, **6** 35824 2016

Superconductor-Insulator Transitions

Haviland et al, PRL 62 18 1989



Superconducting side



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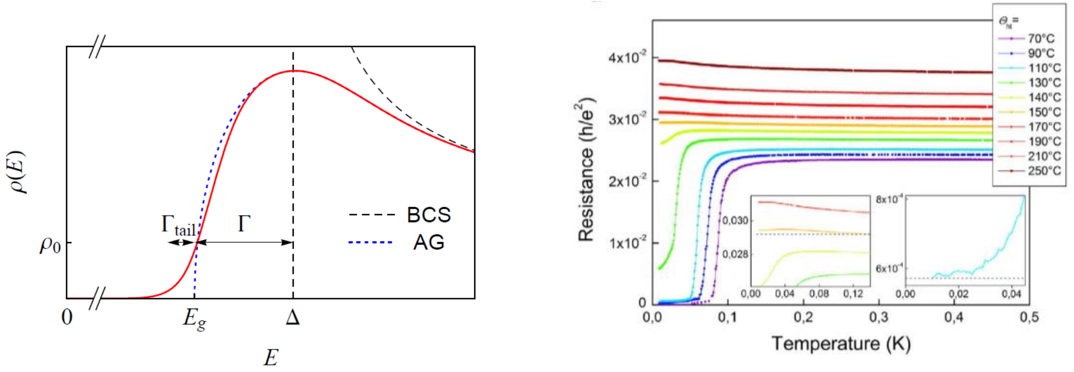

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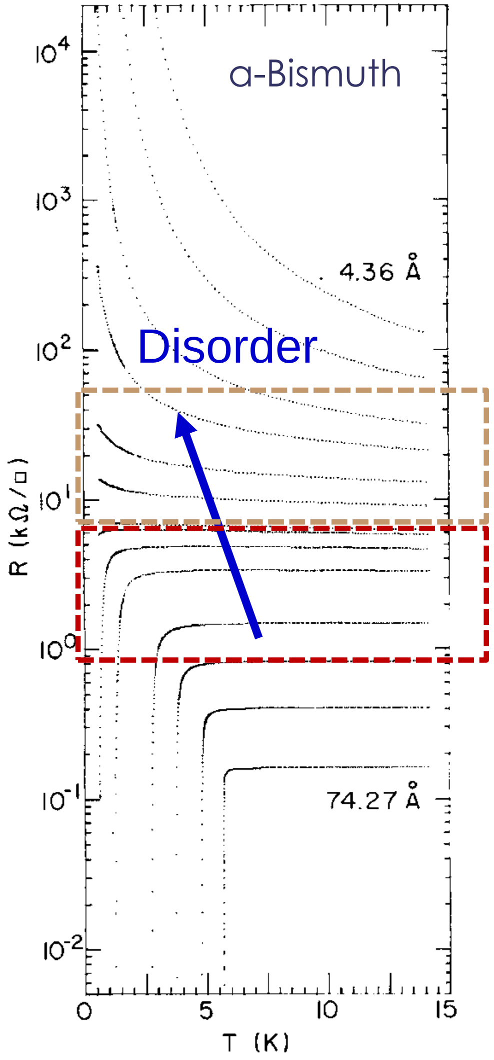
Insulating side

- ✓ Homogeneous phase ?
- ✓ Superconducting grains ?
- ✓ Influence on electronic transport ?

Superconductor-Insulator Transitions

Electronic inhomogeneities

Haviland et al, PRL 62 18 1989



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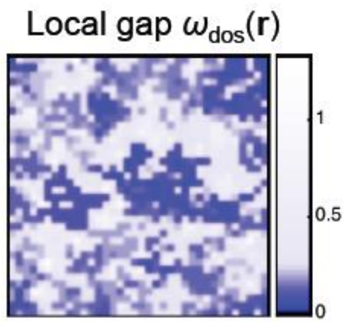

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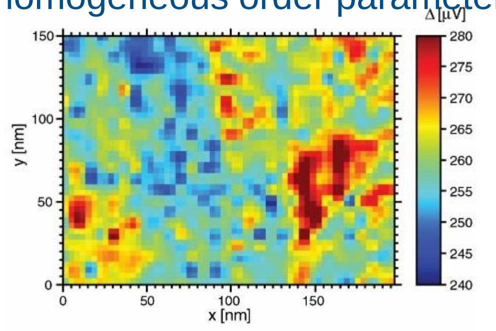

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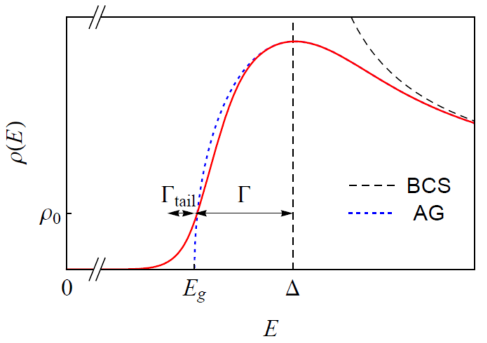

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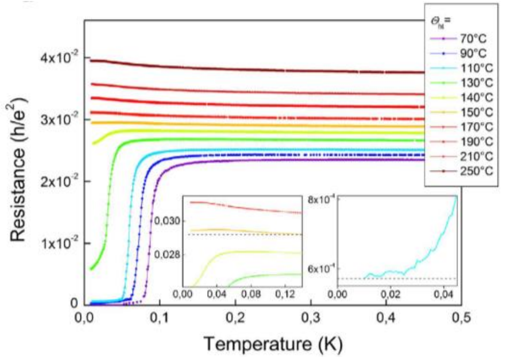

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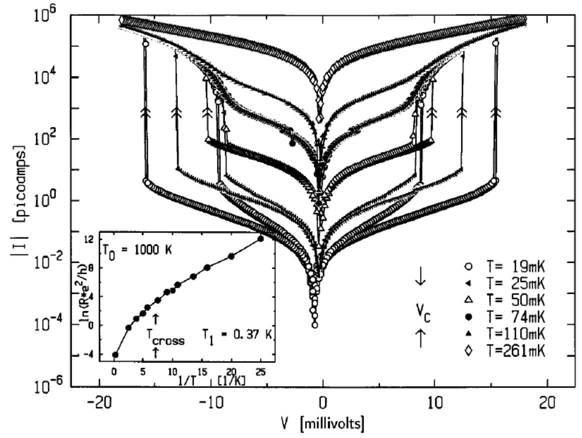


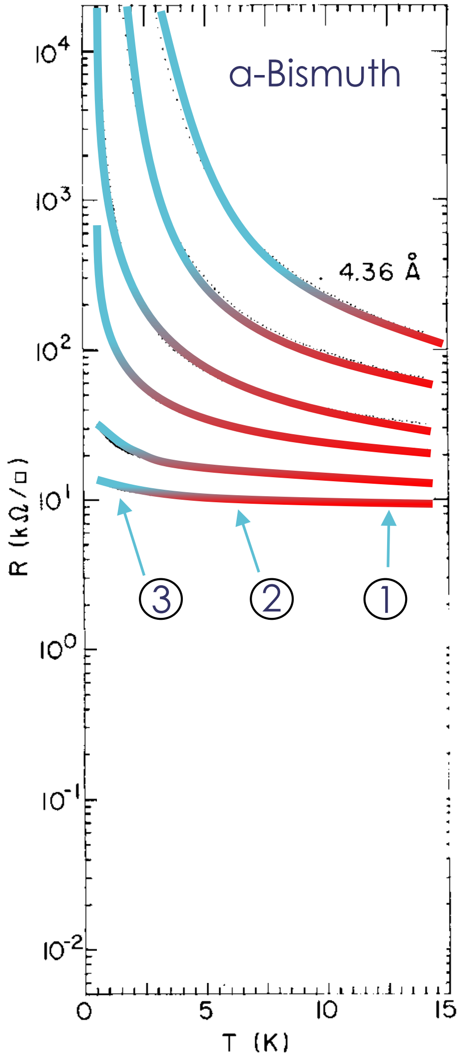
Ladieu et al., *PRB*, 53 973 1996
Sambandamurthy et al., PRL 94, 017003 (2005)
Fistul et al., PRL 100, 086805 (2008)
Vinokur et al., Nature 452, 613 (2008)
Ovadia et al., PRL 102, 176802 (2009)

ACTIVATED ELECTRONIC TRANSPORT

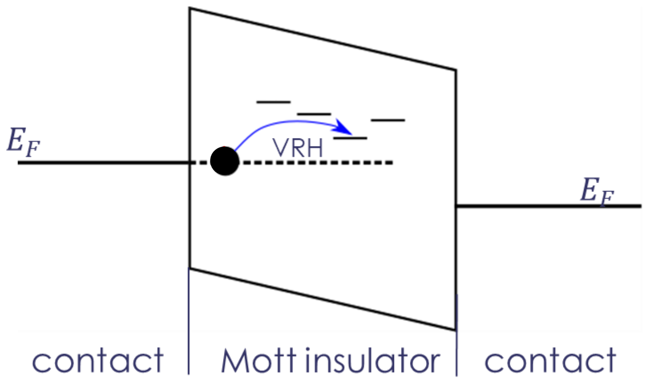
Electronic transport in disordered insulators

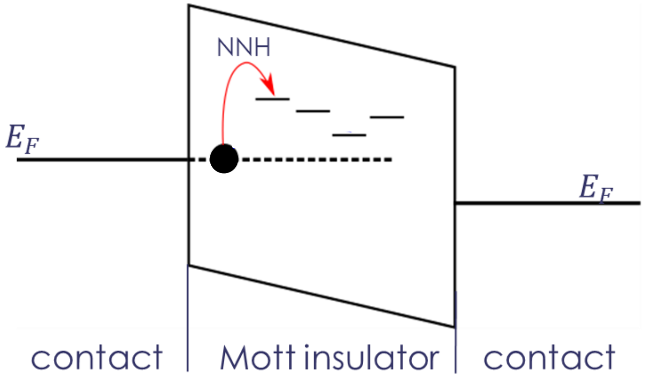
Expected behaviors

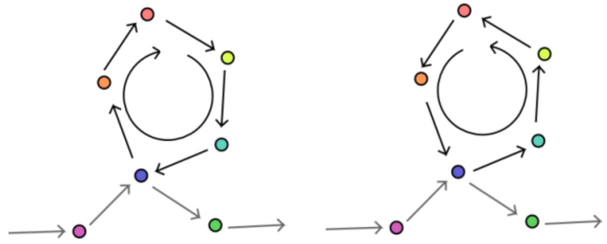
Haviland et al, PRL 62 18 1989



Temperature







③ **Variable Range Hopping (VRH)**

$$R \propto e^{\left(\frac{T_0}{T}\right)^n}$$

$$n = \frac{1}{4}, \frac{1}{3}, \frac{1}{2}$$

② **Nearest Neighbor Hopping (NNH)**

$$R \propto e^{\frac{T_0}{T}}$$

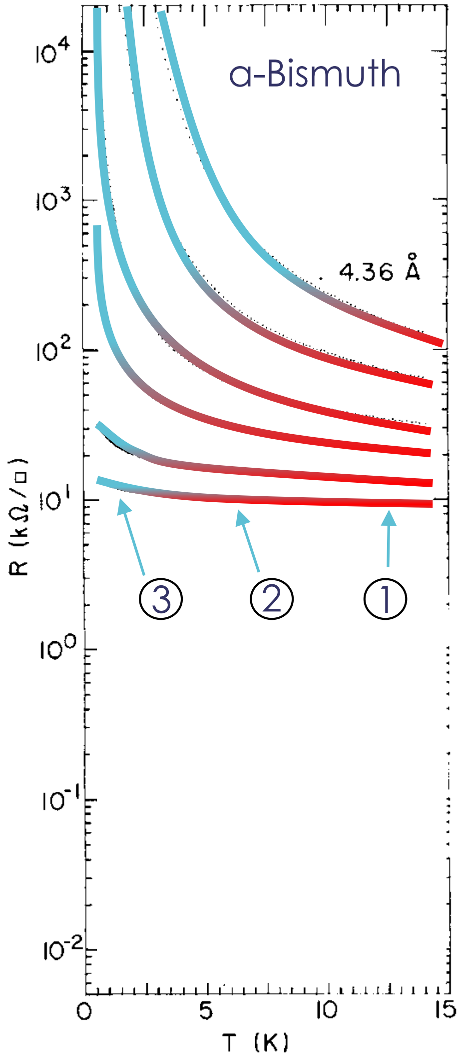
① **Weak Localization**

$$R \propto \ln \frac{T}{T_0}$$

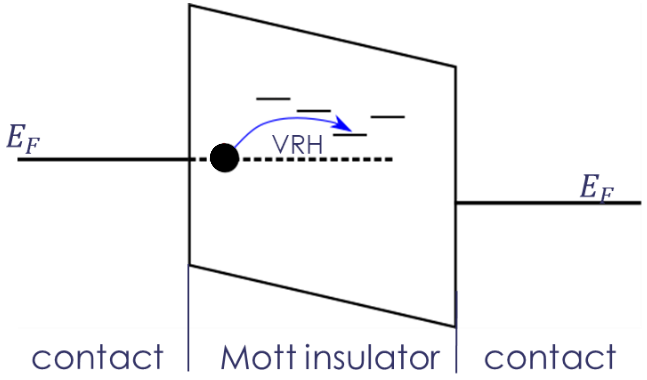
Electronic transport in disordered insulators

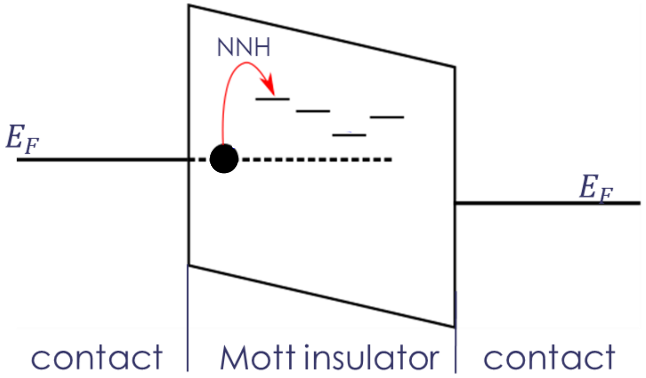
Expected behaviors

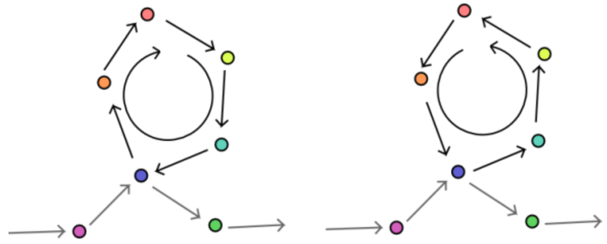
Haviland et al, PRL 62 18 1989



Temperature







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① Weak Localization

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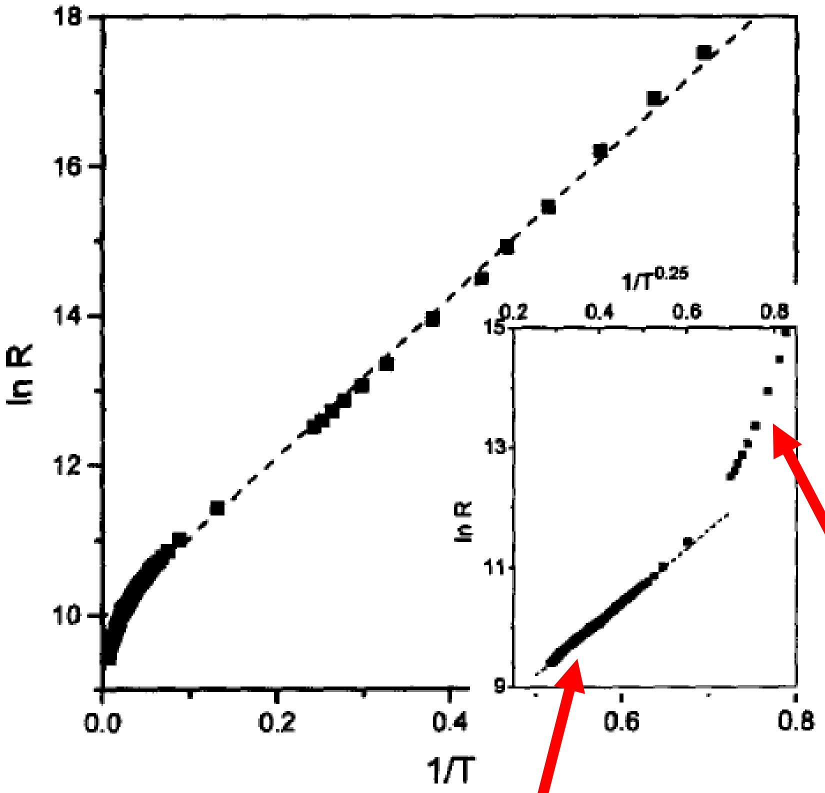
Electronic transport in disordered insulators

Unexpected behaviors

Shahar JETP Lett 88 752 2008



Mott VRH

$R \propto e^{(T_0/T)^{1/4}}$

Stronger than VRH

Systems with $R \propto e^{\frac{T_0}{T}}$ at the lowest temperatures

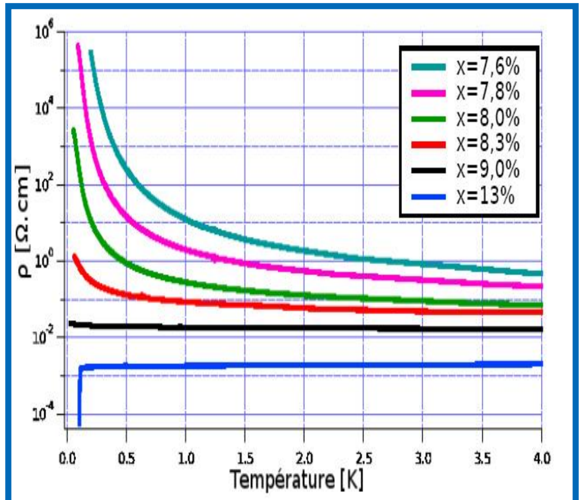
- ✓ Thin films of Al, Ga, Bi, Pb, Sn, In
  - Dynes *PRL* **40** 479 1978
  - Goldman PRB 40 1 1989
  - Desing PRB 50 3959 1994
- ✓ InOx
  - Gandmakher
  - Shahar *JETP Lett* **88** 752 2008
  - Kowal *Sol. St. Comm.* **90** 783 1994
- ✓ Josephson Junctions Arrays
  - Desing *PRB* **50** 3959 1994
- ✓ Organics
  - Adkins J Phys. C **13** 3427 1980
  - Tajima *EPL* **83** 27008 2008
- ✓ etc…

Nb_xSi_{1-x} thin films

Tuning the disorder

Usual disorder parameter in 2D : $R_\square = \frac{\rho}{d_\perp} \propto \frac{1}{k_F l}$

Disordered superconductor
2D $(d \ll \xi_{SC})$

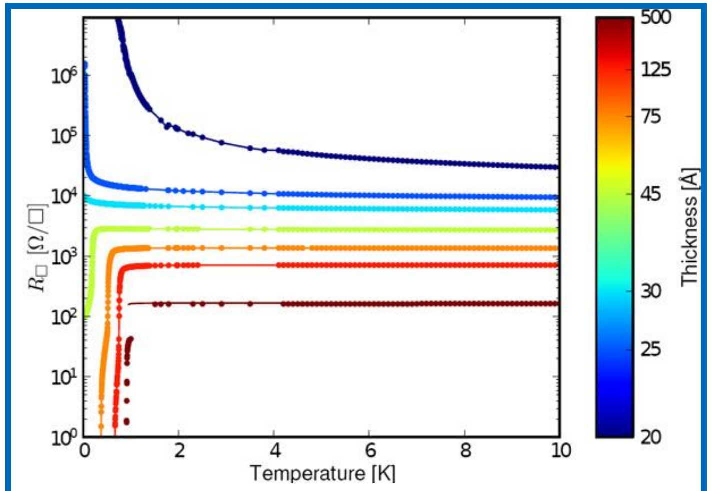


x induced

Composition

- 3D : d > 100 nm

$$R_\square = \frac{1}{k_F l}$$

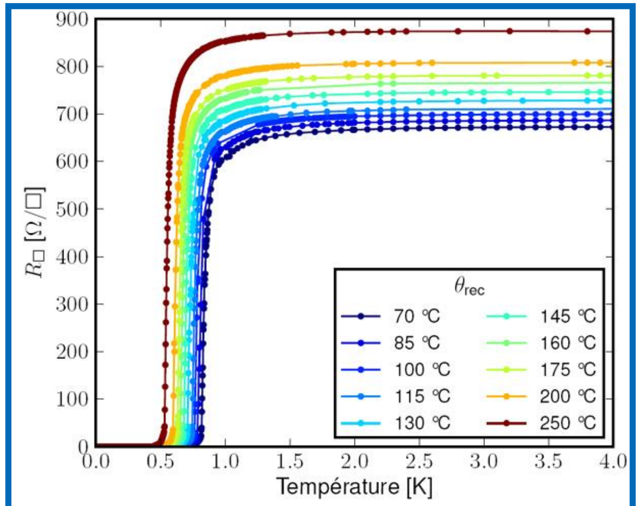


$d_\perp$ induced

Thickness

- 2D, 18%
- ξ ~ 50 nm

$$R_\square = \frac{\rho}{d}$$



θ_{anneal} induced

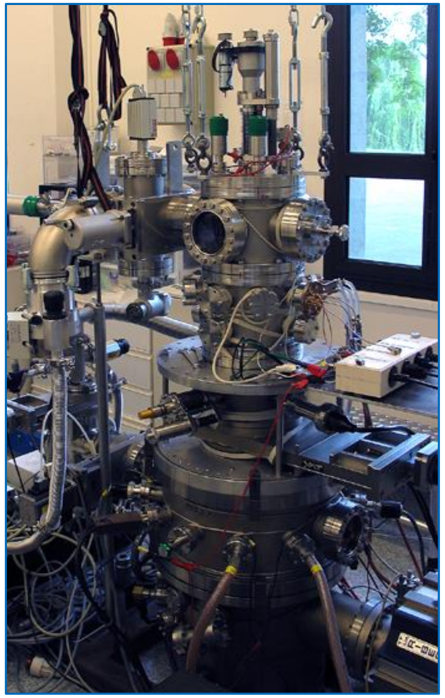
Heat treatment

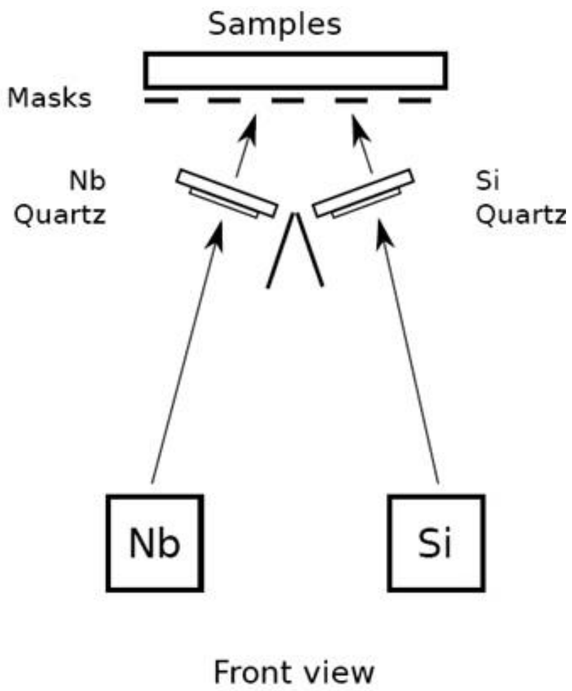
- d=12.5 nm, 18%

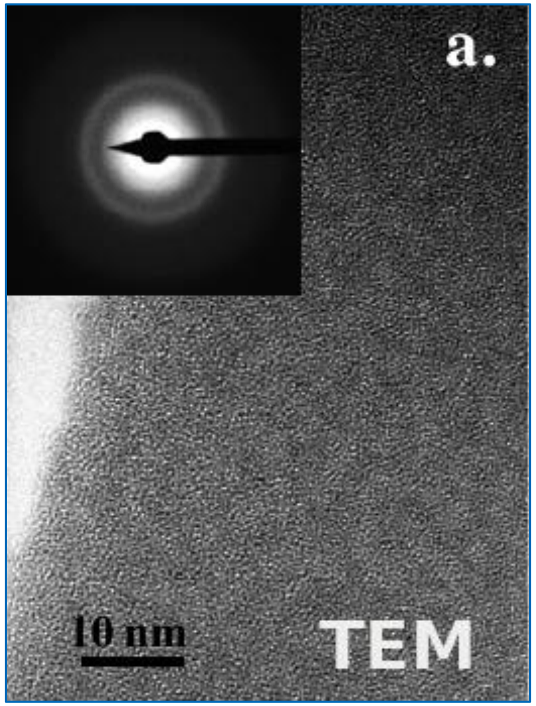
$$R_\square = \frac{1}{k_F l}$$

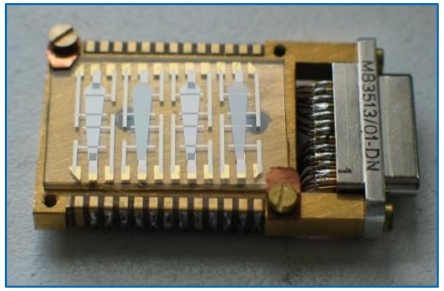
Crauste et al. *PRB* **87** 144514 2013

Nb_xSi_{1-x} thin films









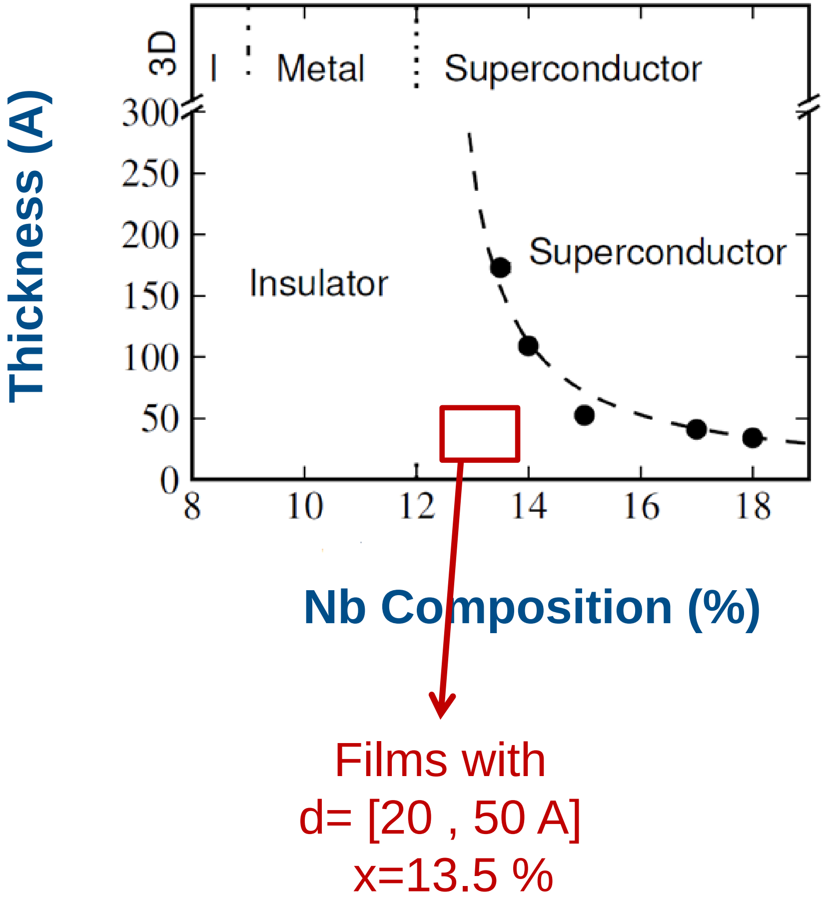
- ✓ **Morphology :**
  - ✓ Continuous down to 2.5 nm (at least)
  - ✓ Amorphous
- ✓ **Mean free path** $l = 2.6\,\text{Å} \text{ to } 5\,\text{Å}$

- ✓ **Electronic density n ~** a few 10^{27} m^{-3}
- ✓ **Heat treatment :**
  - ✓ No modification of n
  - ✓ No modification of the composition x

Theoretical model

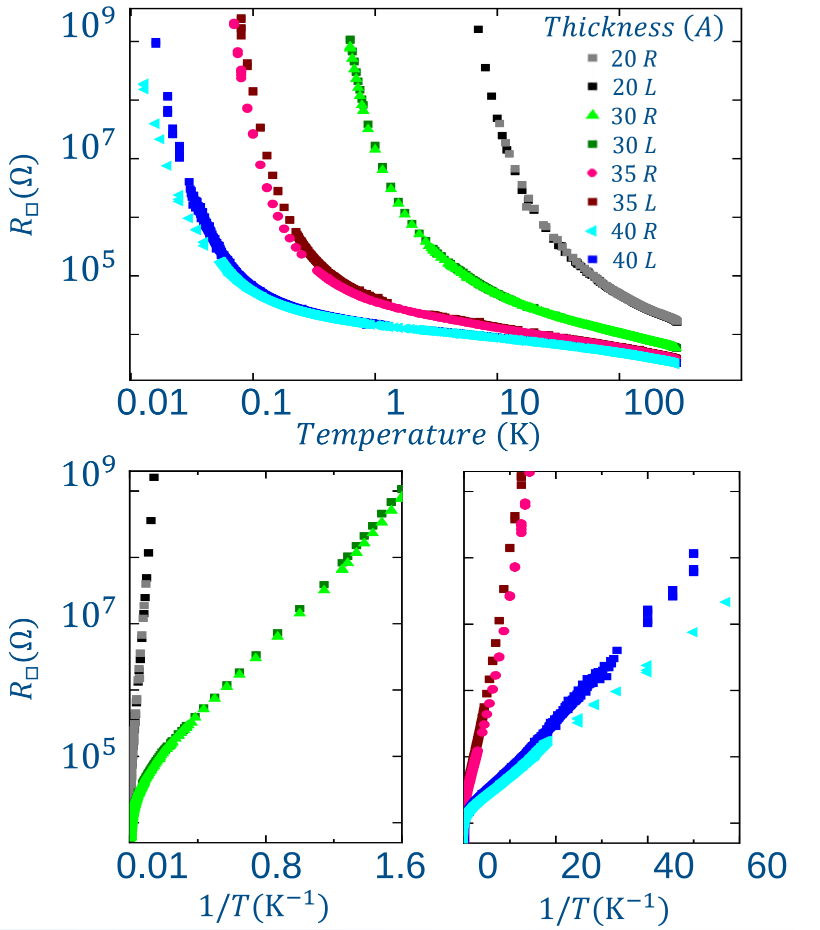
Activated law at low temperature

Crauste PRB 90 060203 2014



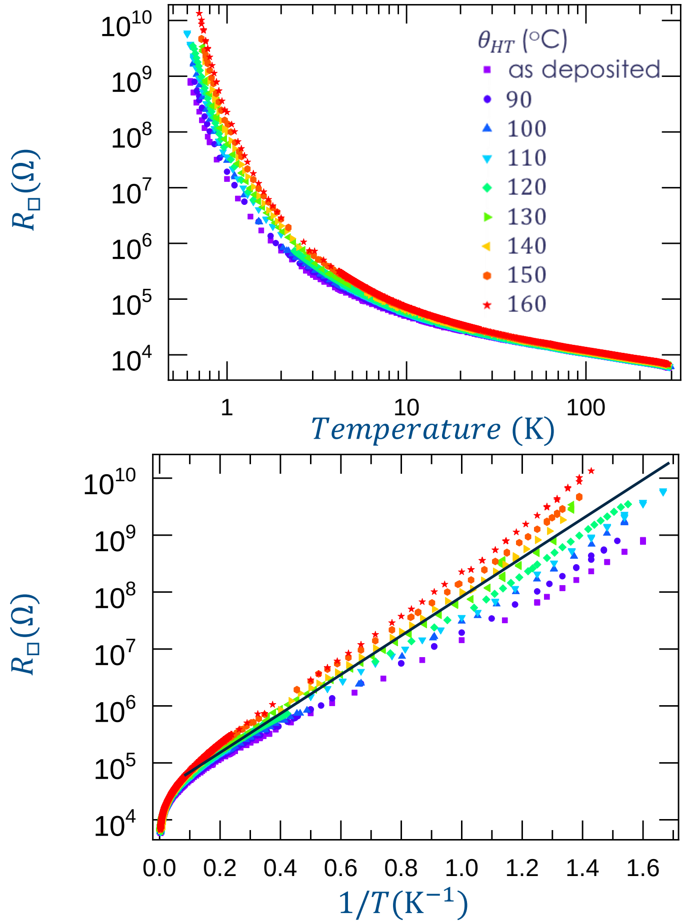
Thickness

As deposited, $x = 13.5\%$



Heat treatment

30 A, $x = 13.5\%$

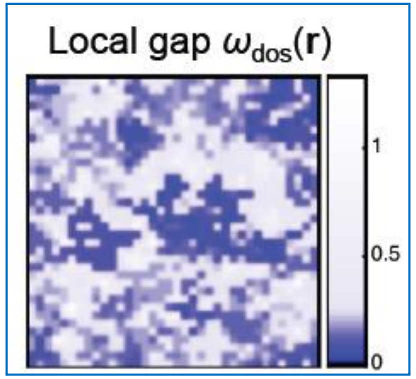


Humbert *Nature Comm.* **12** 6733 2021

Theoretical model

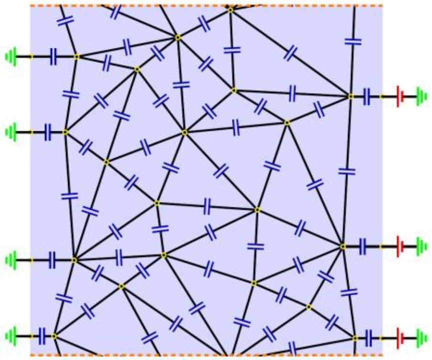
Mechanisms for $R \propto e^{\frac{T_0}{T}}$ at low T

Charging energies (inhomogeneous systems)



Bouadim et al., Nat. Phys., 7 884 2011

→



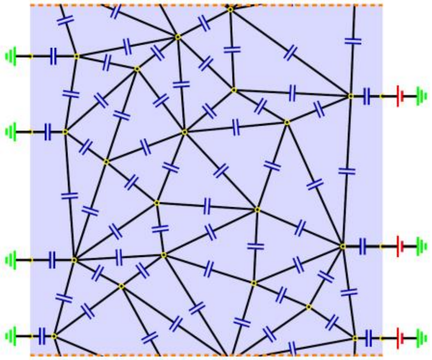
Divergent localization length ξ_{loc} close the transition

→ Divergent κ → **logarithmic Coulomb interactions**
→ charging energy

$$V(r) \sim \frac{e^2}{2\,\pi\epsilon_0\kappa d}\ln\frac{\kappa d}{r}$$

With $\kappa = \kappa_0 + 4\,\pi\beta_2\frac{e^2}{a}N(E_F)\xi_{loc}^2$

→



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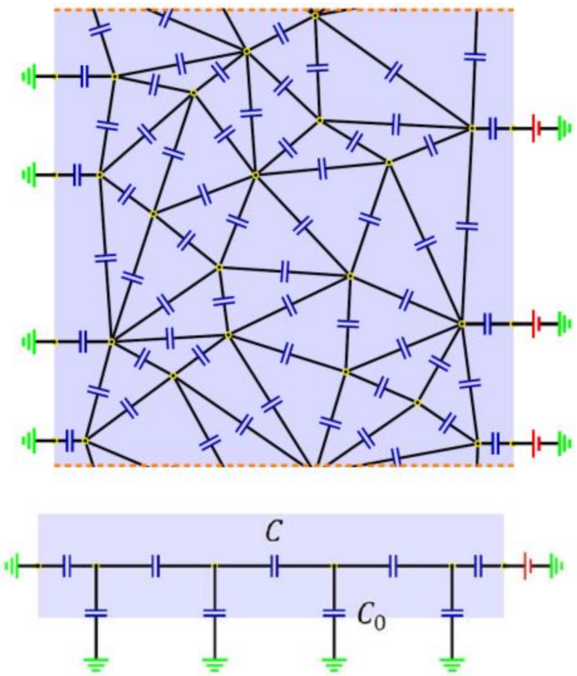
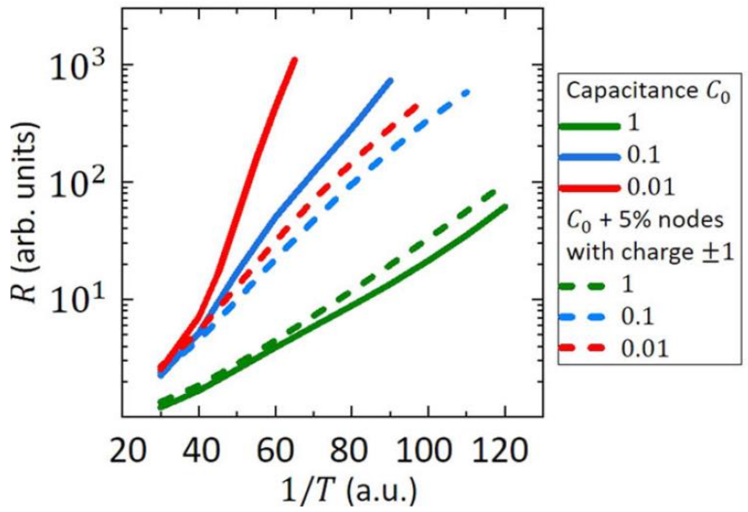
Theoretical model

Activated law at low temperature

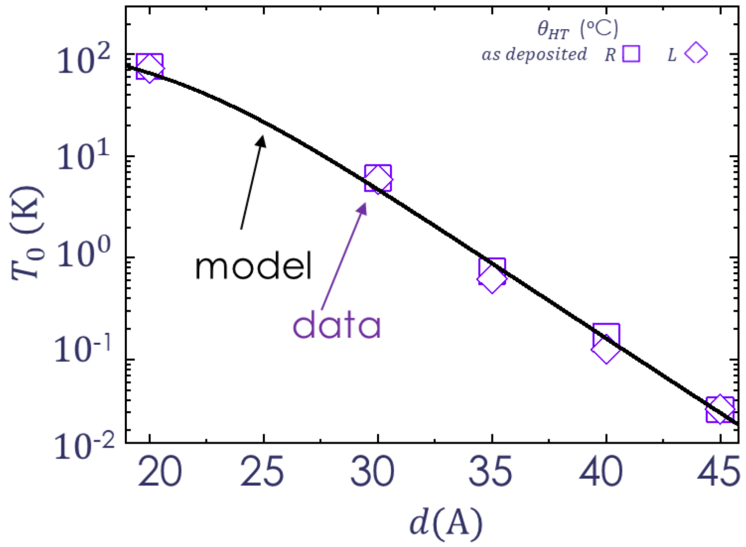


Random distribution of capacitances
- ✓ Fixed boundary conditions
- ✓ Fluctuating charges



$$R \propto e^{\frac{T_0}{T}}$$

$$k_B T_0 \sim \frac{e^2}{4\,\pi\epsilon_0 \kappa\, d} \ln\left(\frac{\kappa\, d}{a}\right)$$



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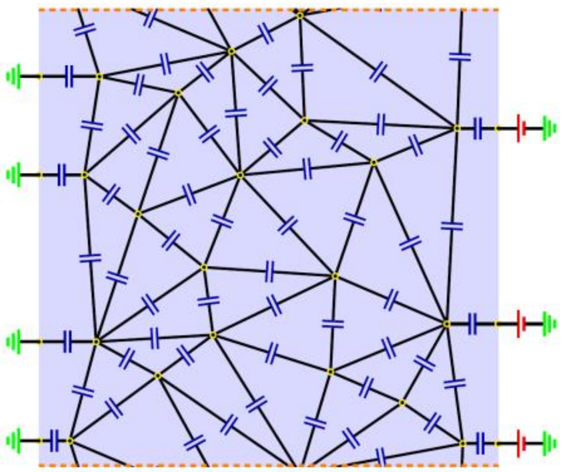
Theoretical model

Activated law at low temperature



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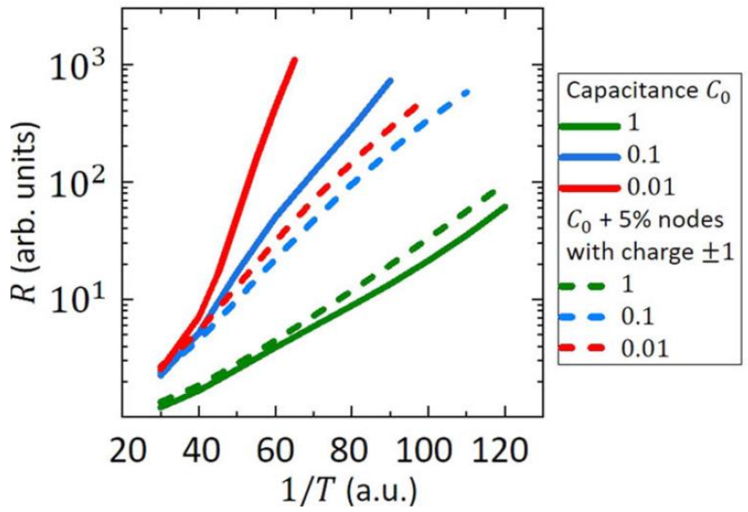

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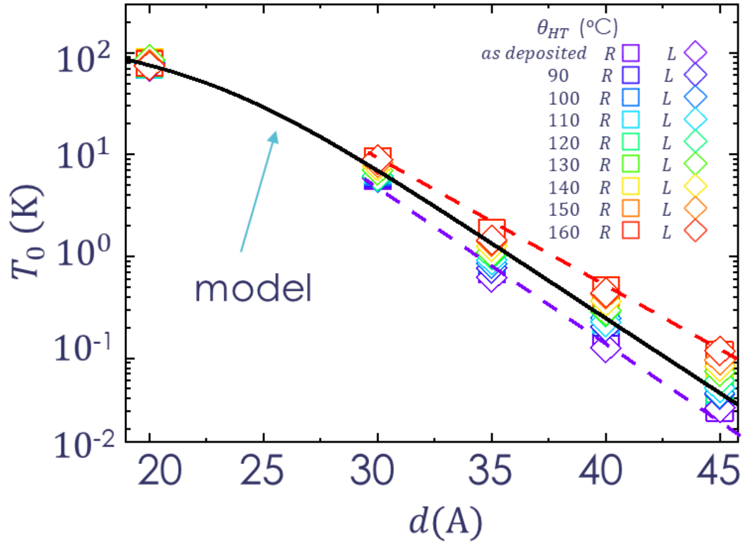

$$\kappa = \kappa_0 + 4\,\pi\beta_2 \frac{e^2}{a} N(E_F)\xi_{loc}^2$$

θ_{HT} modifies microscopic disorder
→ Modifies κ

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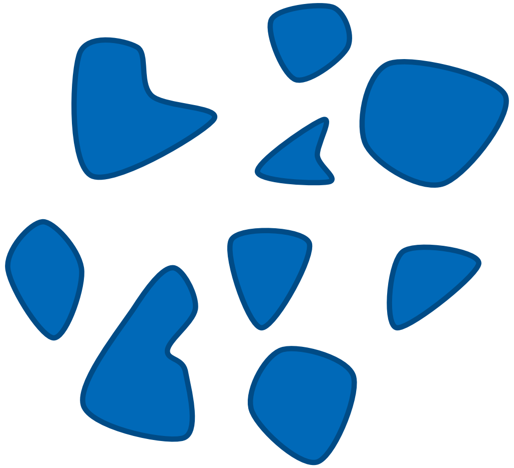
Theoretical model

Activated law at low temperature



- ✓ Electronic granularity due to:
  - ✓ Inhomogeneities
  - ✓ High dielectric constant κ

$$k_B T_0 \sim \frac{e^2}{4\,\pi\epsilon_0\kappa\, d}\ln\left(\frac{\kappa\, d}{a}\right)$$

with $\kappa = \kappa_0 + 4\,\pi\beta_2 \frac{e^2}{a} N(E_F)\xi_{loc}^2$

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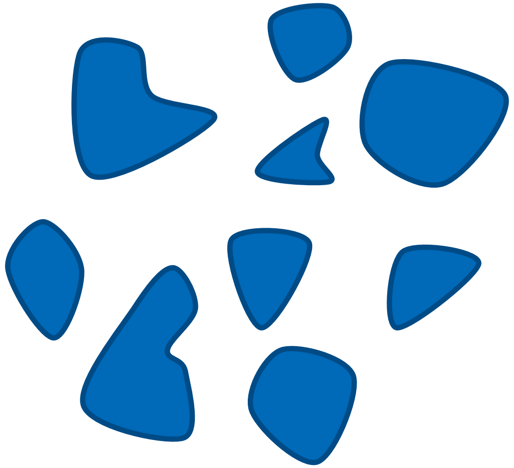
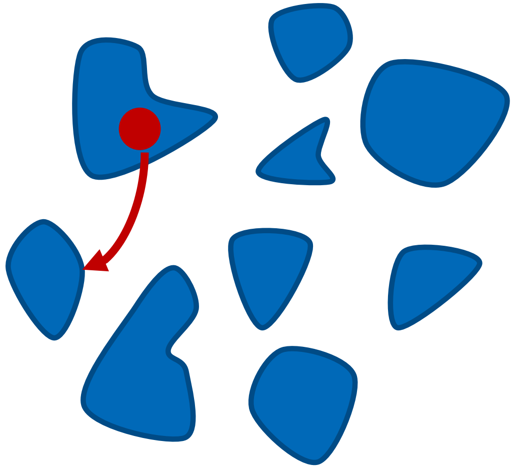
Theoretical model





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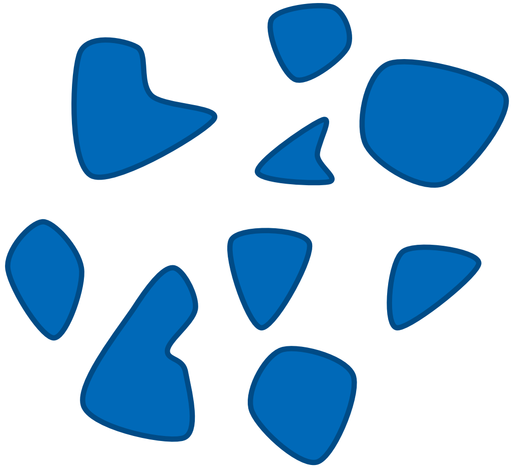
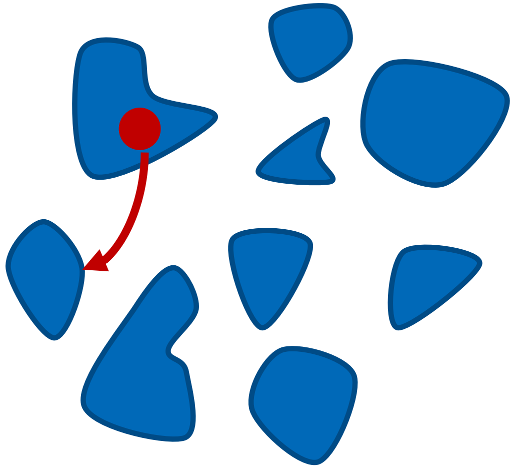
✓ Electrons hopping between grains

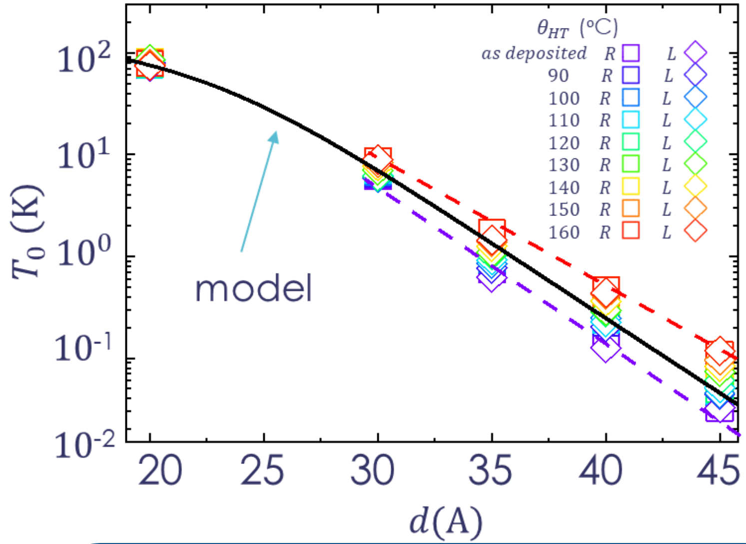
Humbert *Nature Comm.* **12** 6733 2021

Theoretical model

Activated law at low temperature







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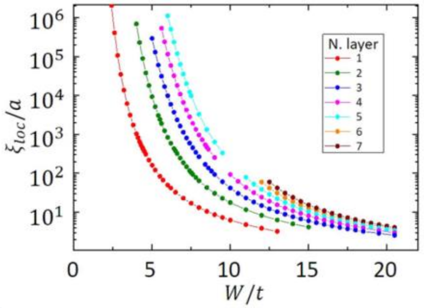
- ✓ Electrons hopping between grains

W = disorder level
t = kinetic energy



- ✓ Experimentally: $T_0 \propto e^{-\zeta d}$
- ✓ Theoretically: $T_0 \propto \frac{1}{\kappa d} \simeq \frac{1}{\xi_{loc}^2 d}$
- ✓ This implies:

$$\xi_{loc} \simeq A\, e^{\frac{\eta d}{W^2}}$$

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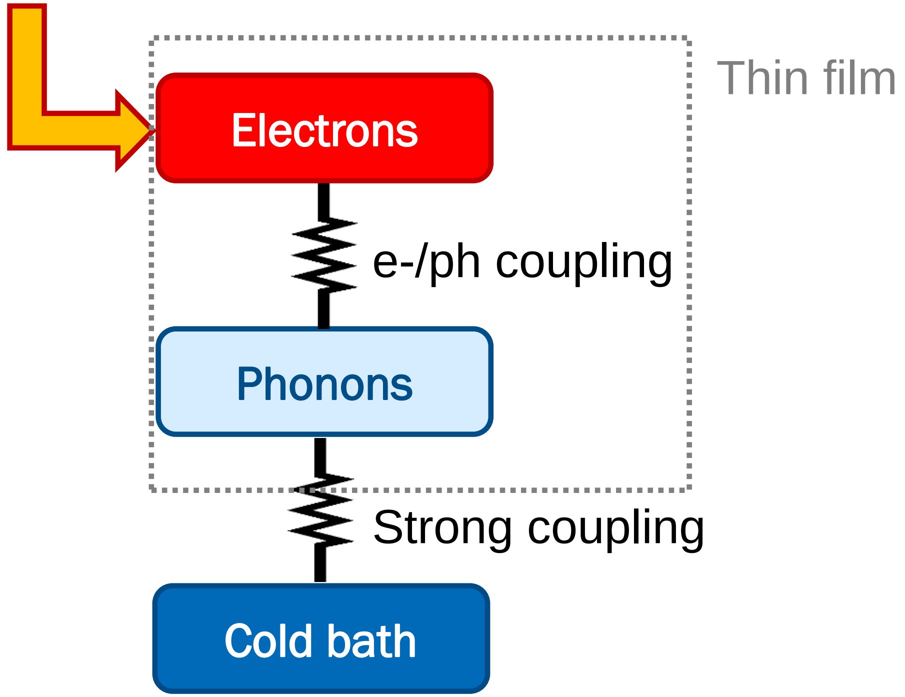
ELECTRON-PHONON DECOUPLING IN THE INSULATOR

E-Phonon coupling

Electrical measurement



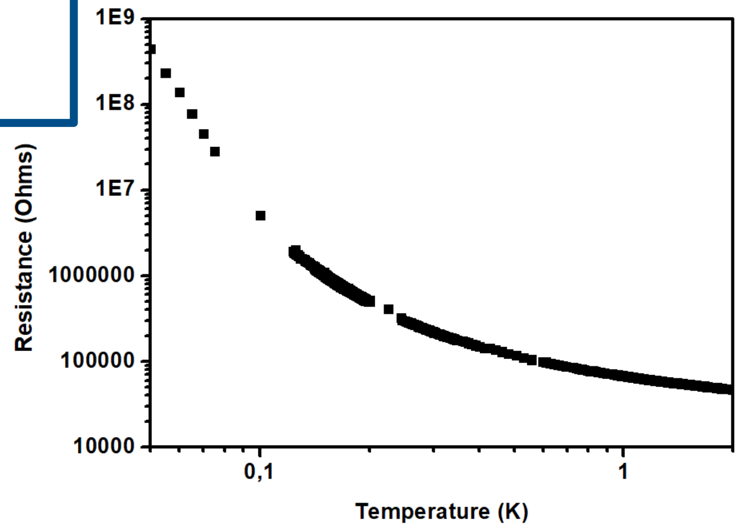
✓ **Heat balance equation**

Exact value not really known

$$P = VI = g_{e-ph}\left(T_e^{\beta} - T_{ph}^{\beta}\right)$$

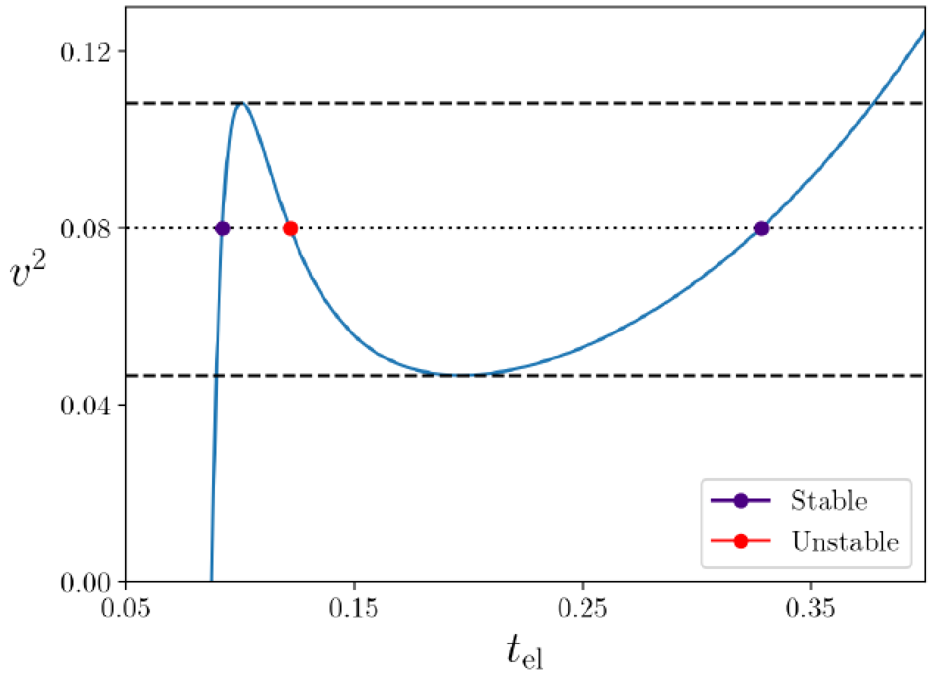
Expression valid for metals
- Assumes all power go to phonons

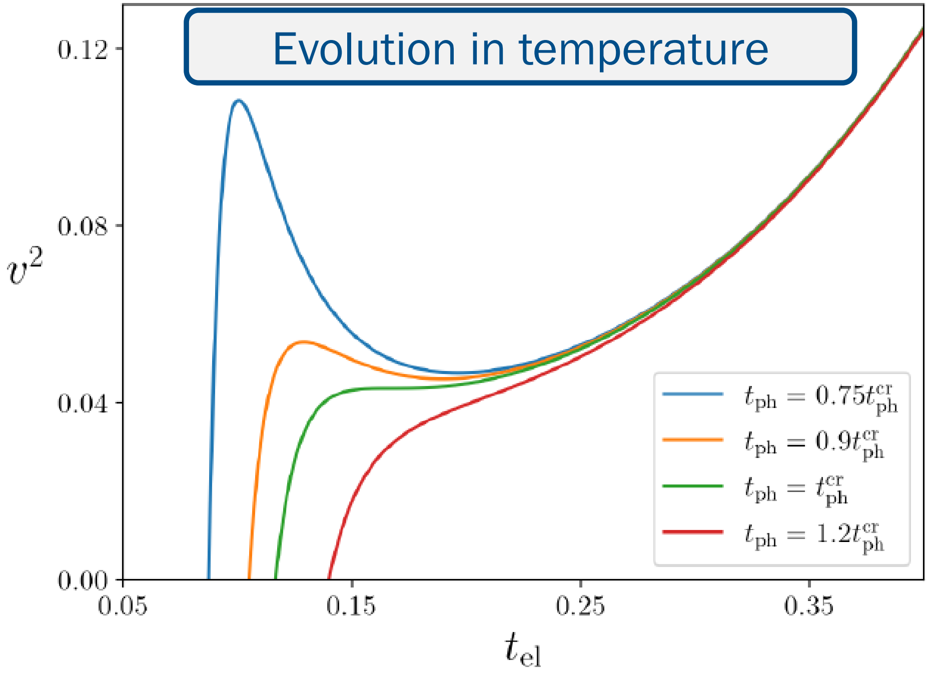
Determined by R(T) curve:
- Assumes resistance is only fct of T_e.



E-Phonon coupling

McArdle and Lerner Scientific Reports 11 24293 2021

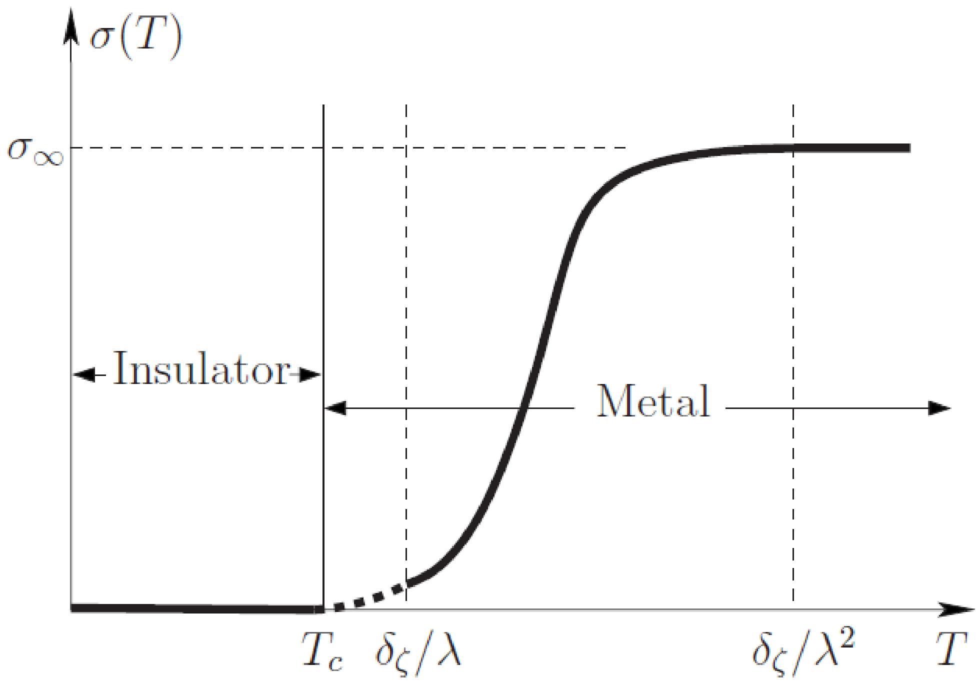




$$P = \frac{V^2}{R} = g_{e-ph}\left(T_e^{\beta} - T_{ph}^{\beta}\right)$$

- ✓ At low enough T, there is *always* a bistability
- ✓ The max T at which bistability observed does not evolve with g_{e-ph} (assuming constant R(T)).

E-Phonon coupling



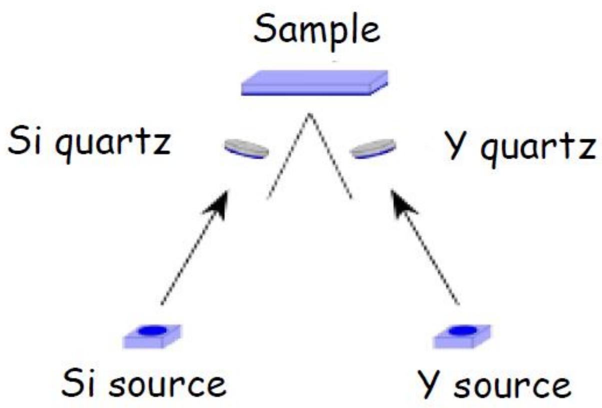
- ✓ Disordered superconductors as a possible platform for MBL
- ✓ Weak e-/phonon coupling
- ✓ Zero conductivity below T_c

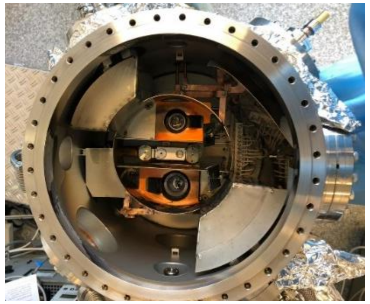
Basko, Aleiner, Altshuler PRB 76, 052203 2007

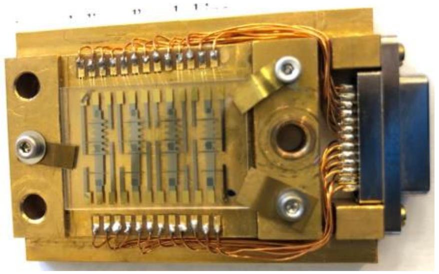
Altshuler, Kravtsov, Lerner, Aleiner PRL 102, 176803 2009

Y_xSi_{1-x} thin films

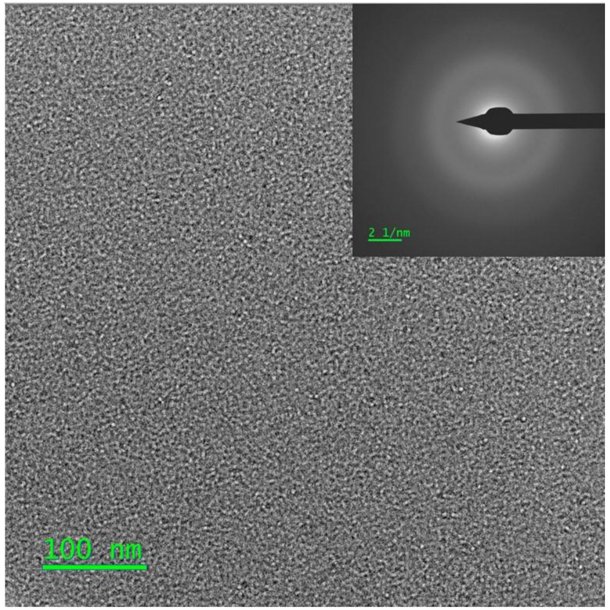
E-beam co-deposition







TEM

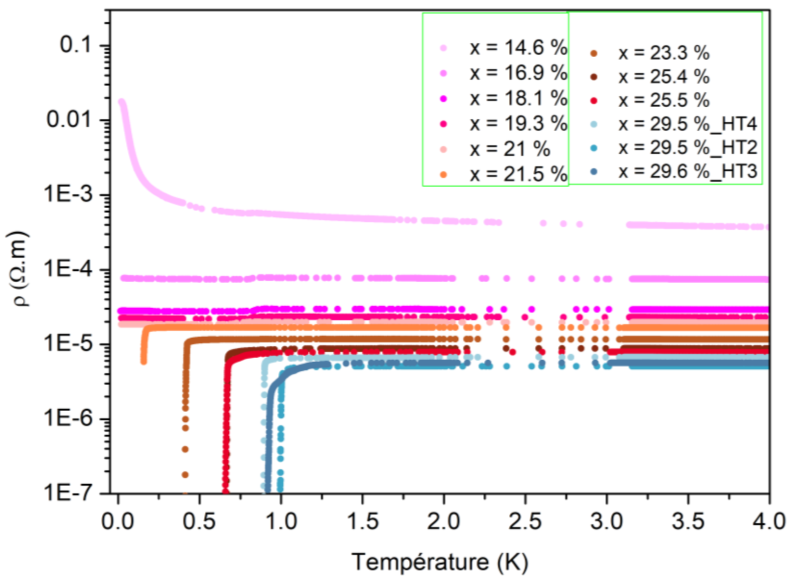


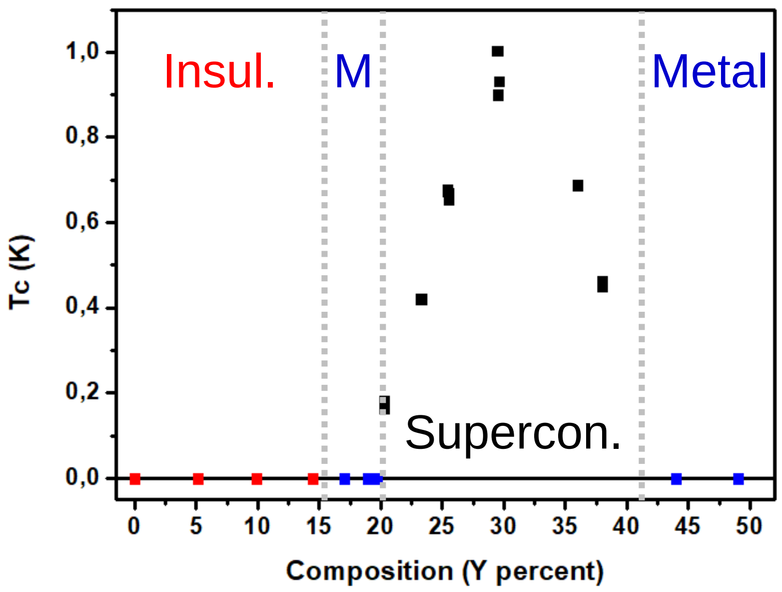
- ✓ **Amorphous**
- ✓ **Mean free path** $l \sim 2 - 5$ Å
- ✓ **Electronic density n ~** a few 10^{27} m^{-3}
- ✓ **Heat treatment until 500°C:**
  - ✓ No modification of the composition x

Y_xSi_{1-x} thin films

Composition

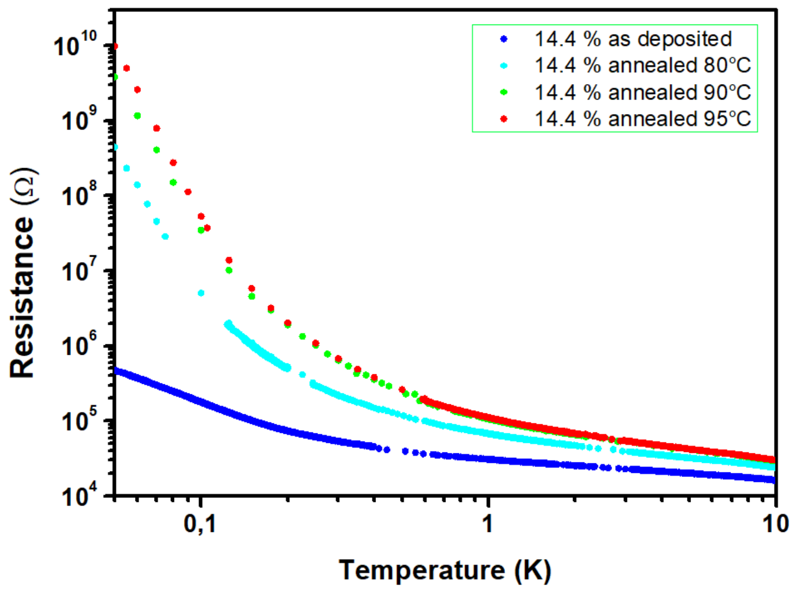
As deposited, $d \in [30,60]$ nm





Heat treatment

14,4%, $d = 30$ nm

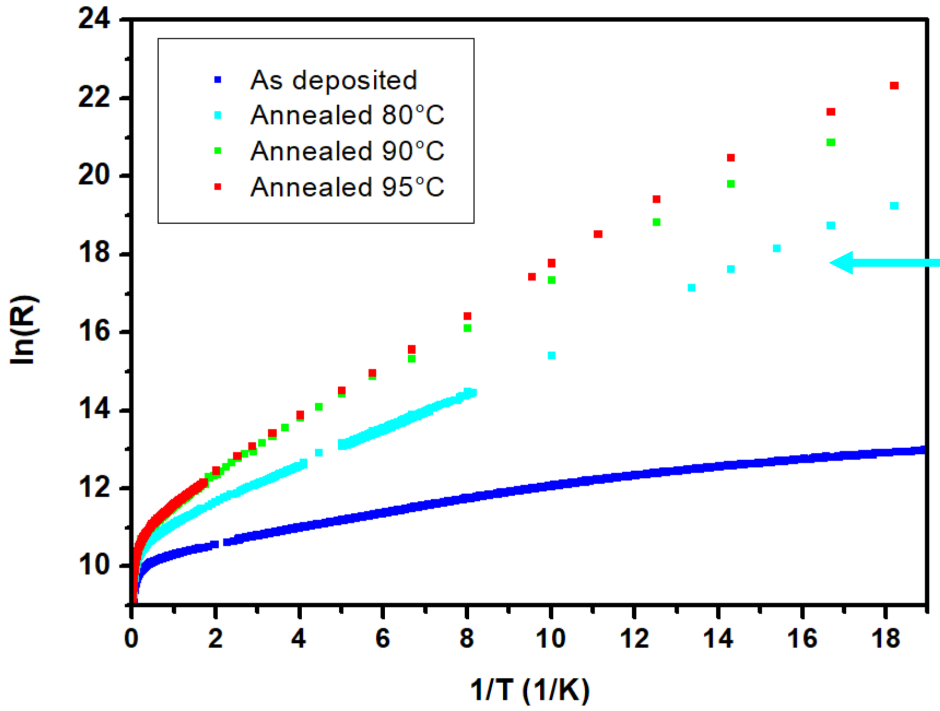


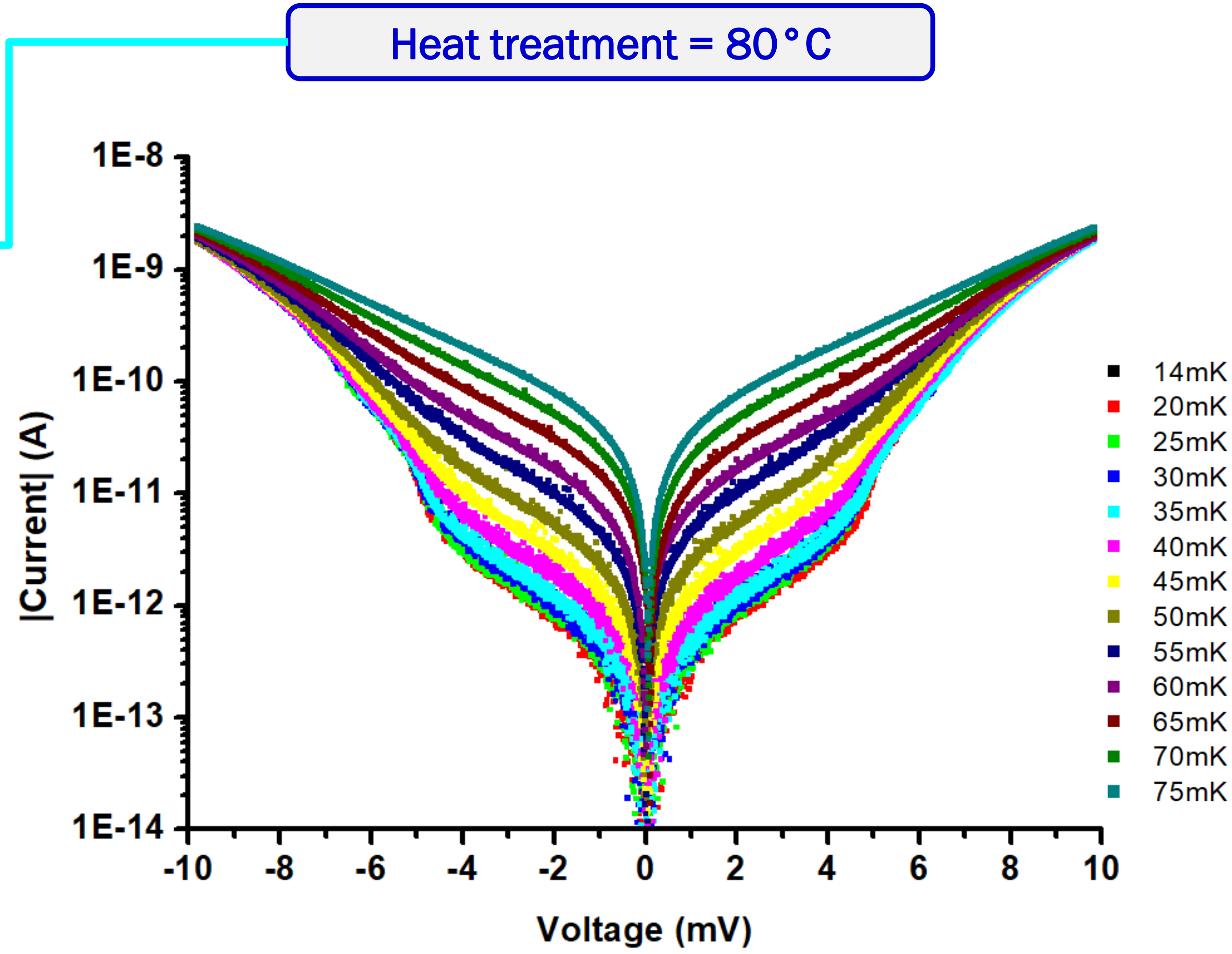
- ✓ Metal-to-Insulator transition: $x \sim 16\%$
- ✓ Superconducting for $20\% < x < 40\%$

- ✓ Heat treatment renders film more insulating

I(V) curves

Low disorder

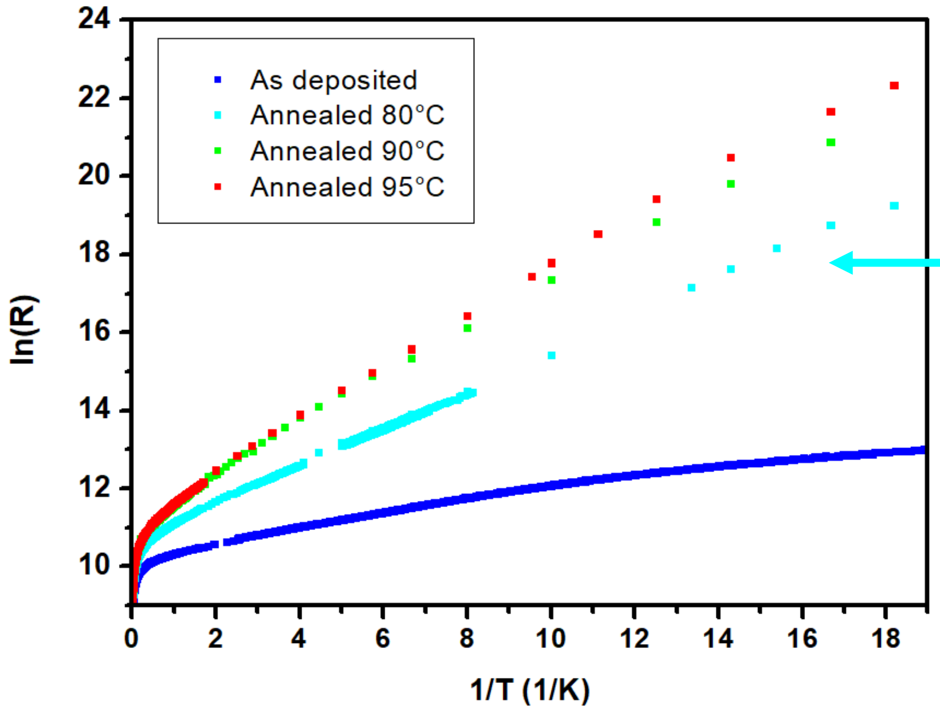




- ✓ Activated behavior at low temperature

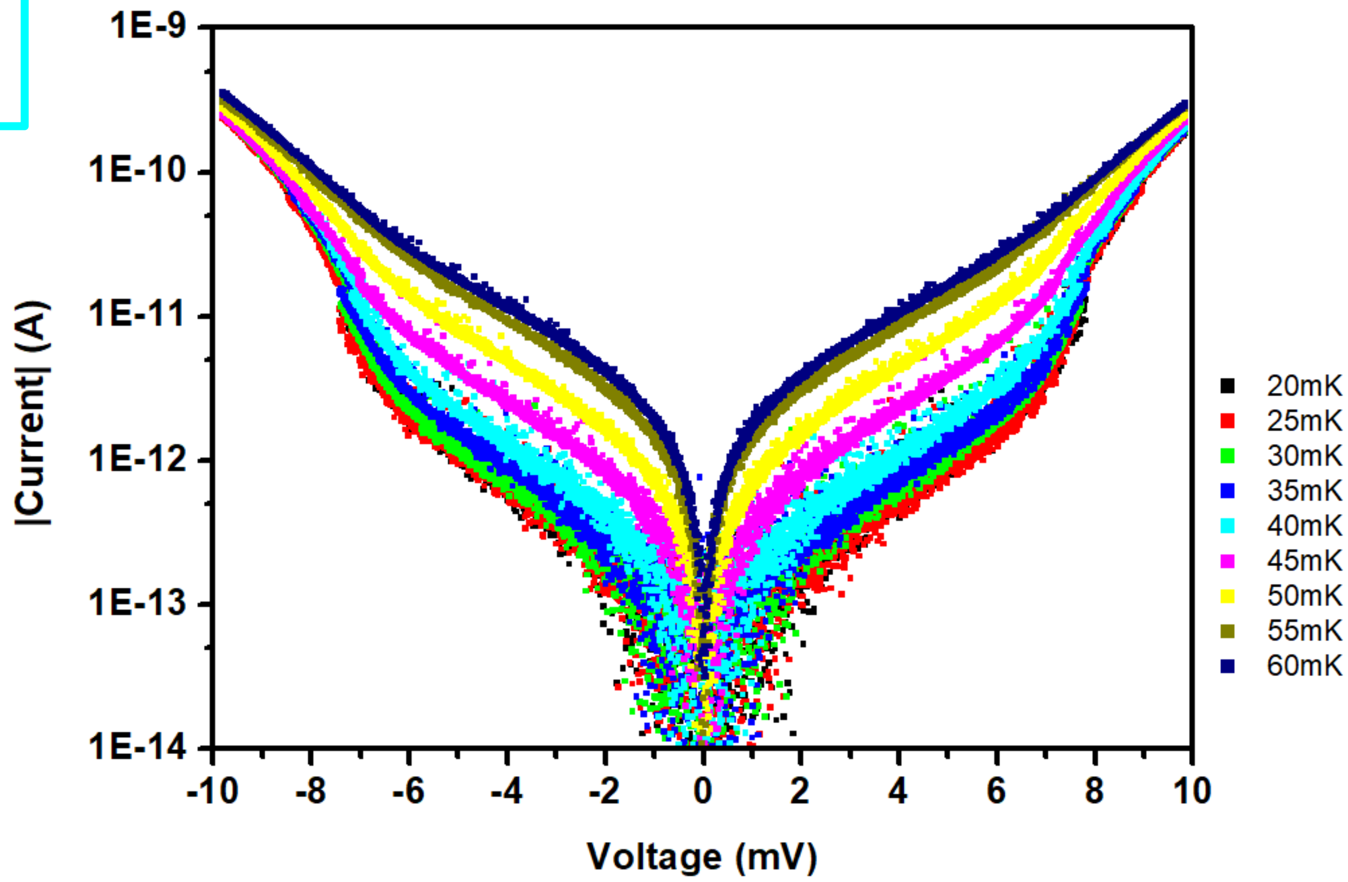
I(V) curves

Low disorder



Heat treatment = 80 °C

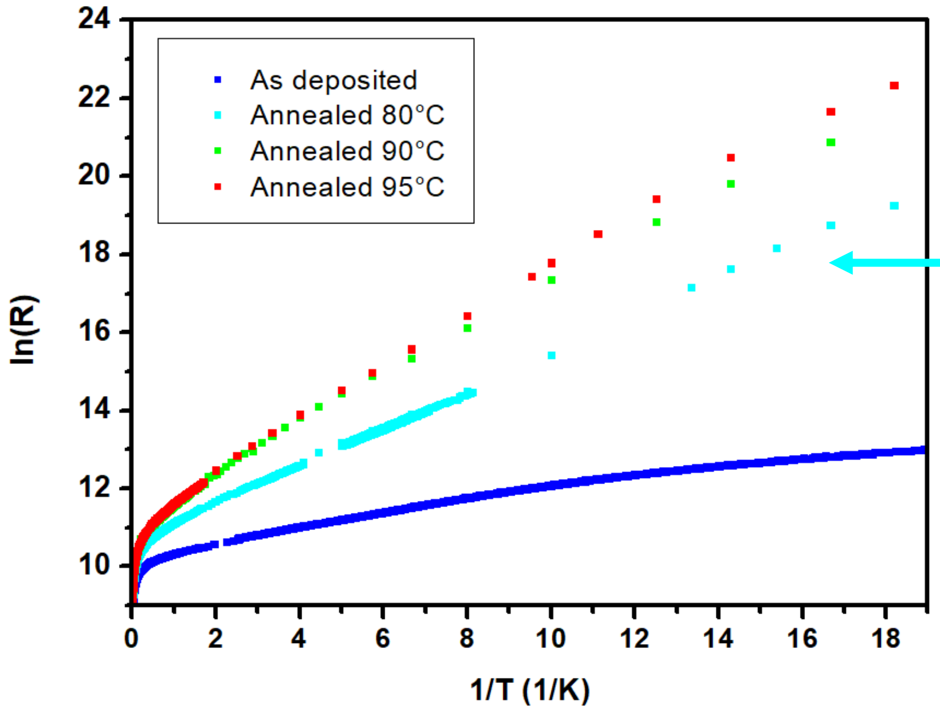
Another sample

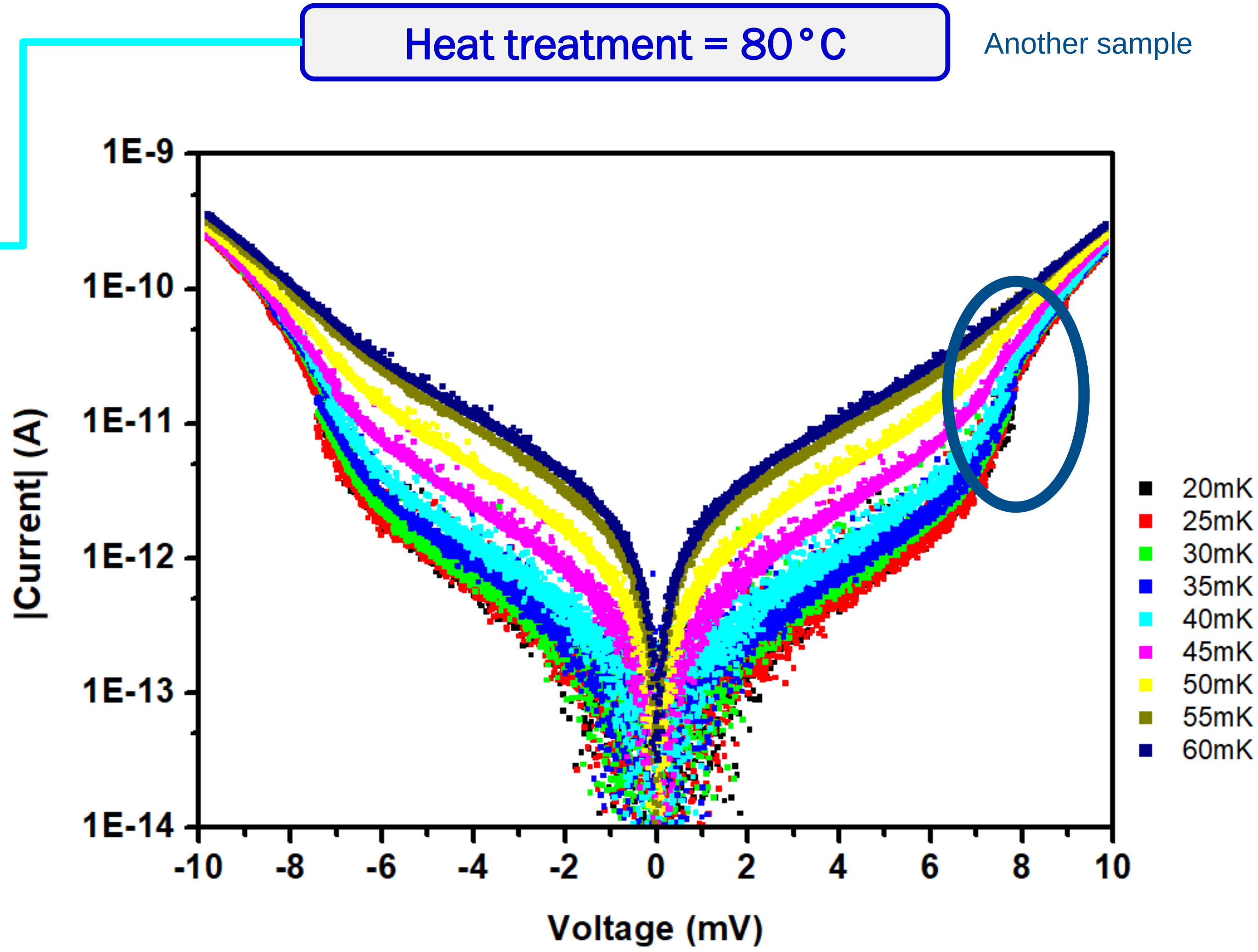


- ✓ Activated behavior at low temperature

I(V) curves

Low disorder

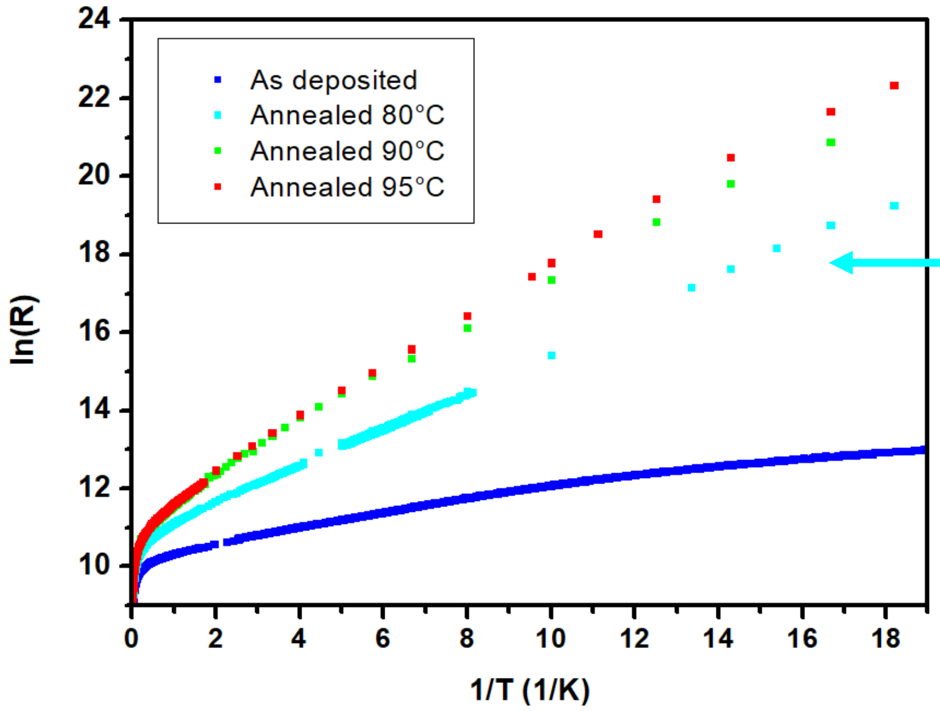




- ✓ Activated behavior at low temperature

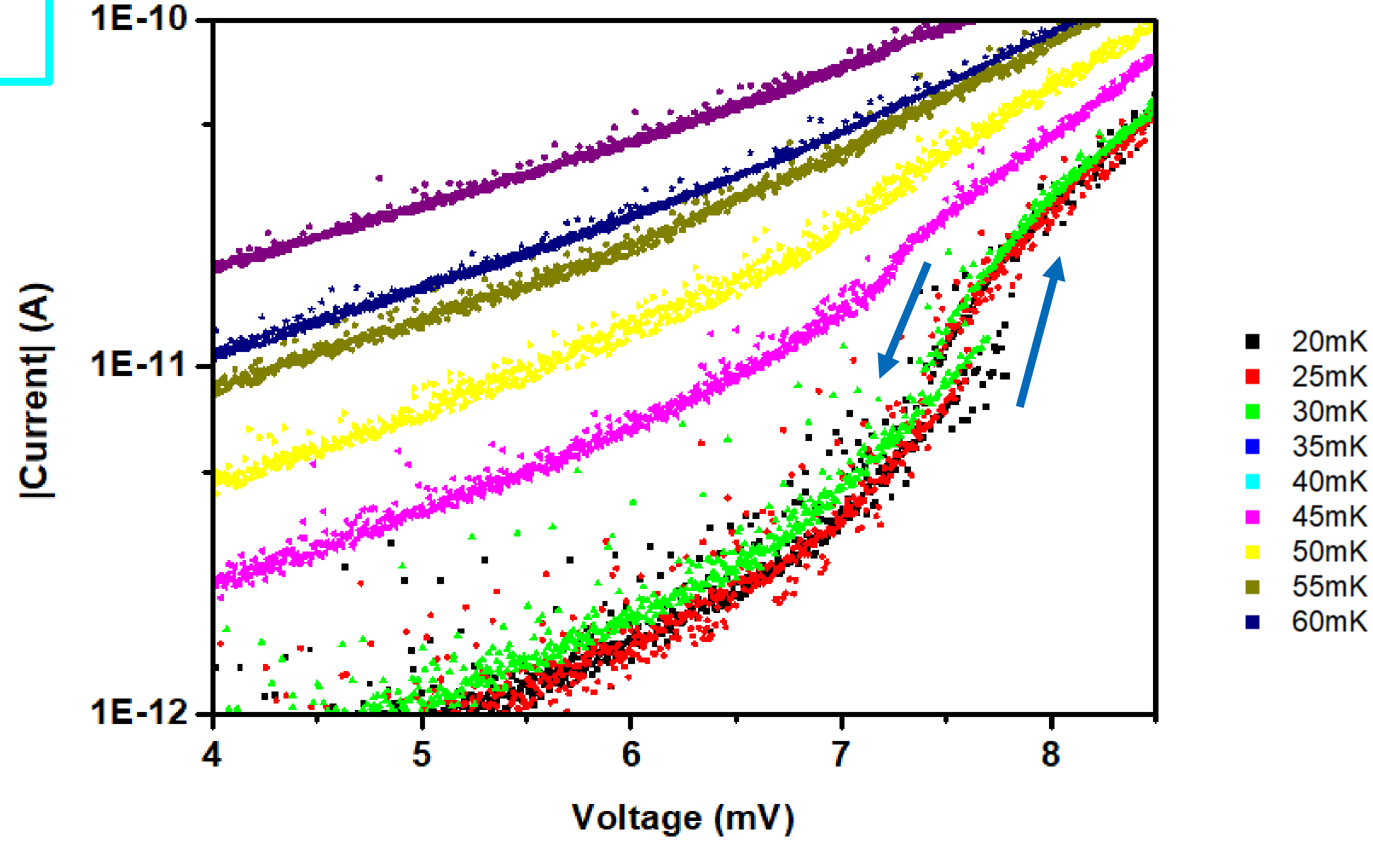
I(V) curves

Low disorder



Heat treatment = 80 °C

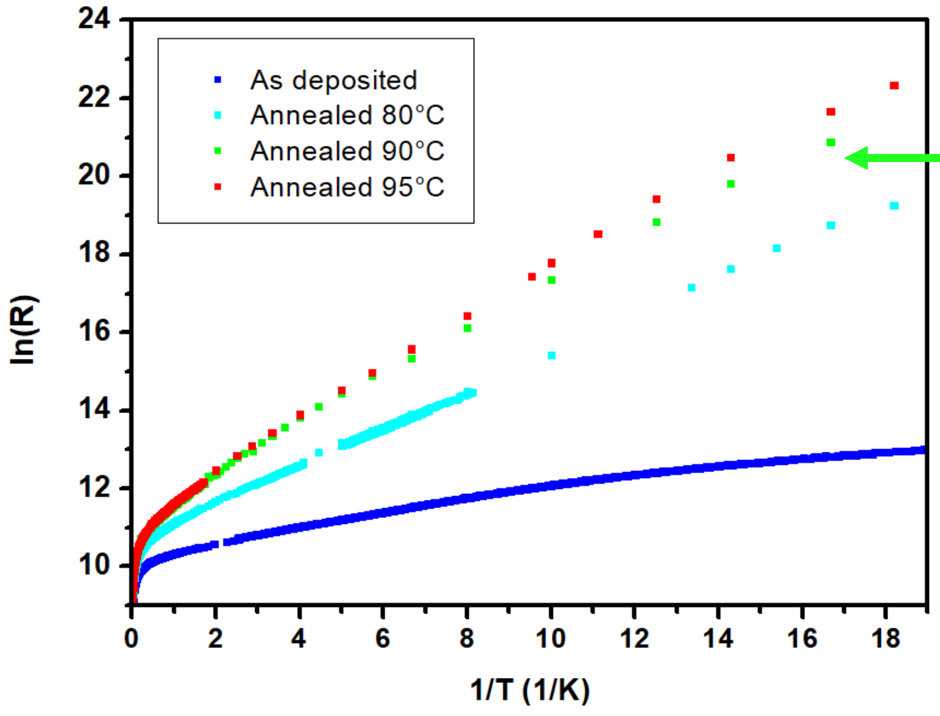
Another sample

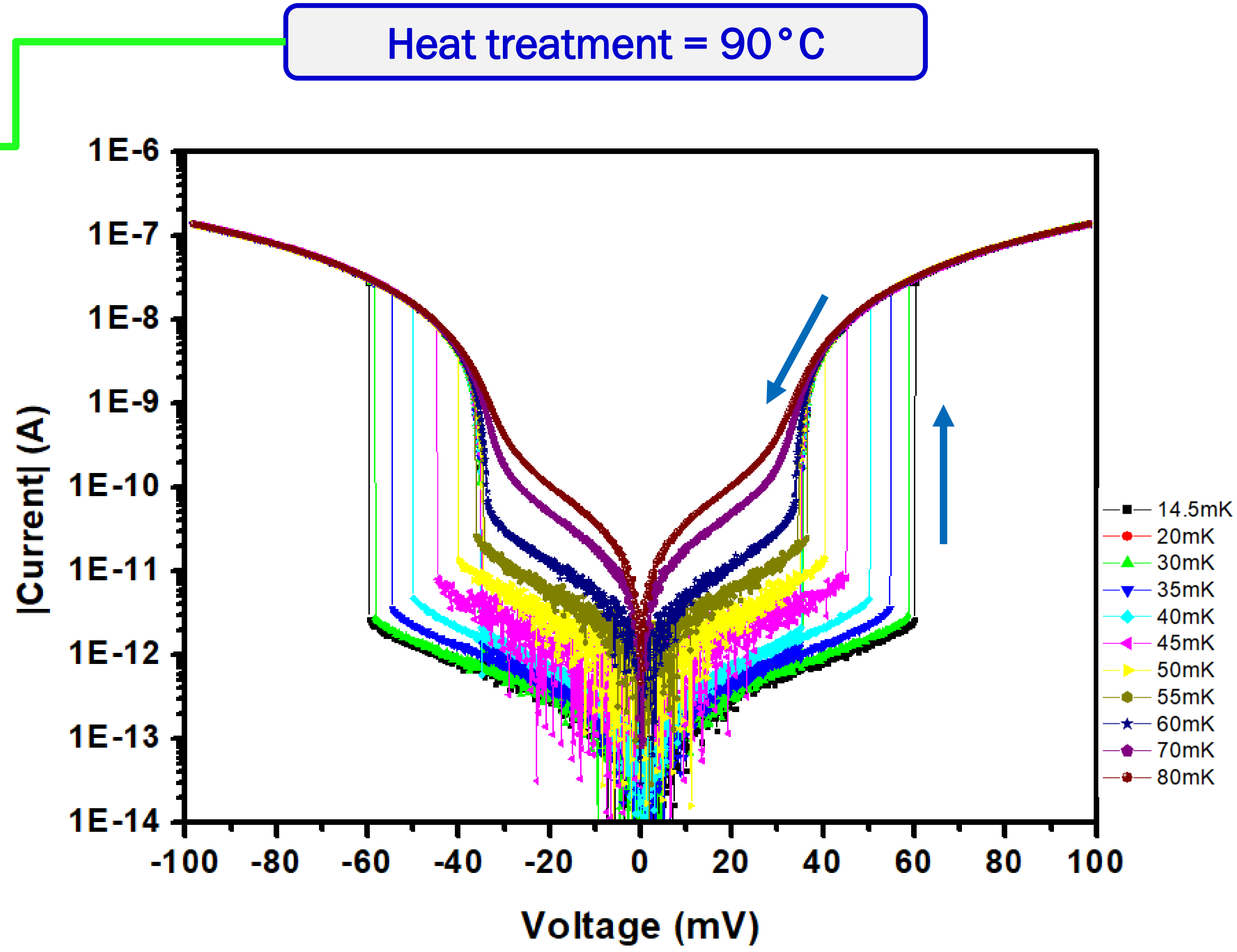


✓ Activated behavior at low temperature

I(V) curves

Higher disorder

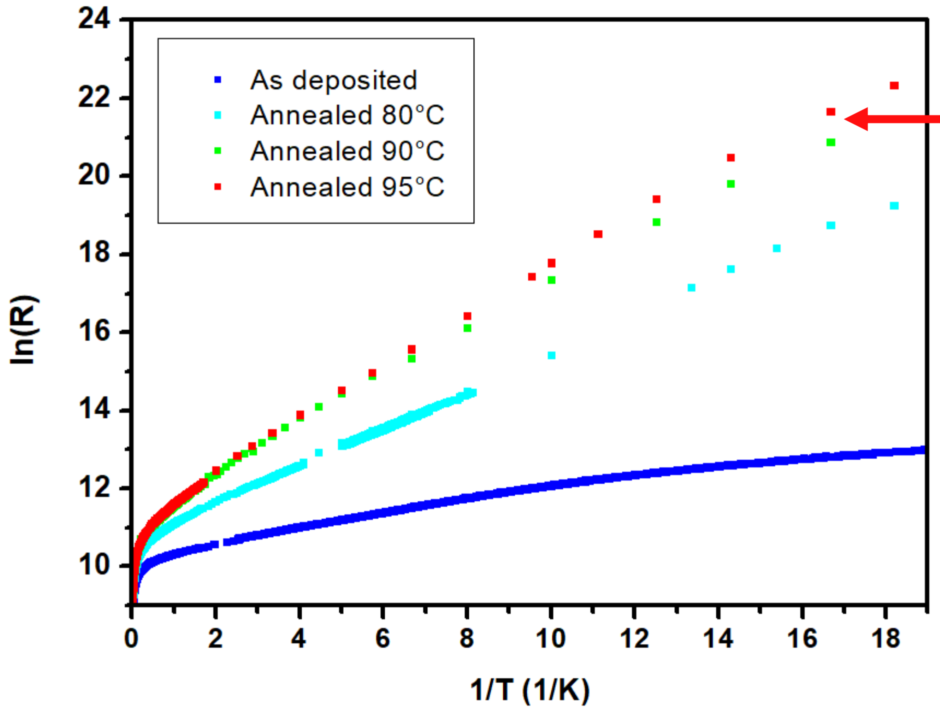




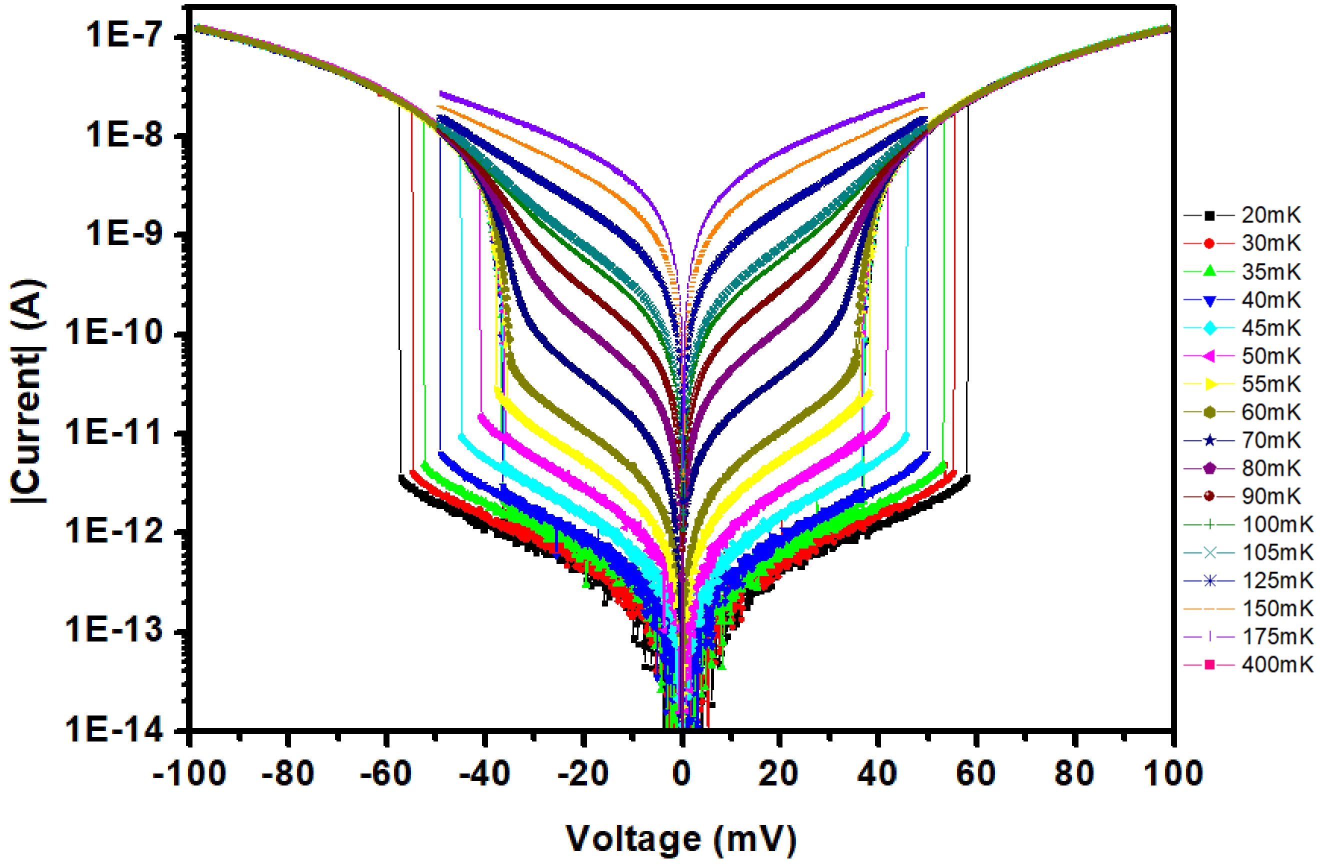
✓ Activated behavior at low temperature

I(V) curves

Even larger disorder



Heat treatment = 95 °C



✓ Activated behavior at low temperature

I(V) curves

Comparison with heat balance equation

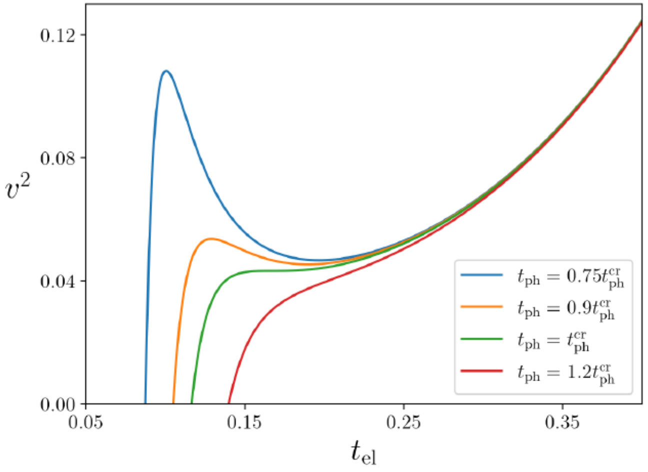
- ✓ **Heat balance equation**

$$P = g_{e-ph}\left(T_e^{\beta} - T_{ph}^{\beta}\right)$$

- ✓ **Activated transport**

$$R = R_0\, e^{T_0/T_e}$$

McArdle and Lerner Scientific Reports 11 24293 2021



- ✓ **Maximum T_{ph} for bistability**

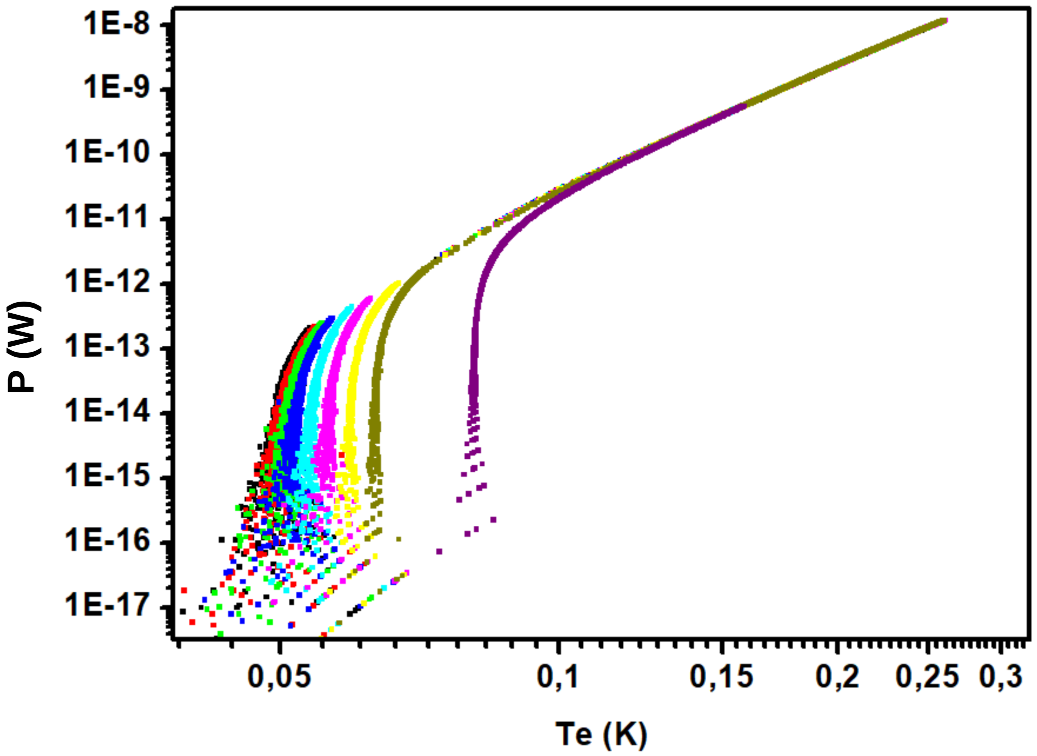
$$T_c = (\beta+1)^{\frac{\beta+1}{\beta}}\, T_0$$

- ✓ **Voltage at which the current jumps**

$$V_c^2 = \frac{g_{e-ph} R_0\, \beta\, T_0^{\beta}\, e^{\beta+1}}{(\beta+1)^{\beta+1}}$$

See also V. Kravtsov's talk (expmtl value of g_{e-ph} larger than predicted)

Heat treatment 95°C



I(V) curves

Comparison with heat balance equation

- ✓ **Heat balance equation**

$$P = g_{e-ph}\left(T_e^{\beta} - T_{ph}^{\beta}\right)$$

- ✓ **Activated transport**

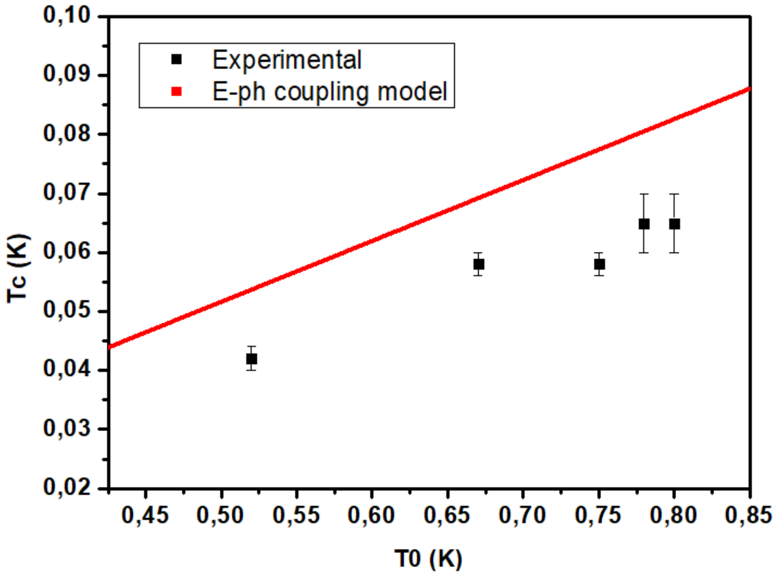
$$R = R_0\, e^{T_0/T_e}$$

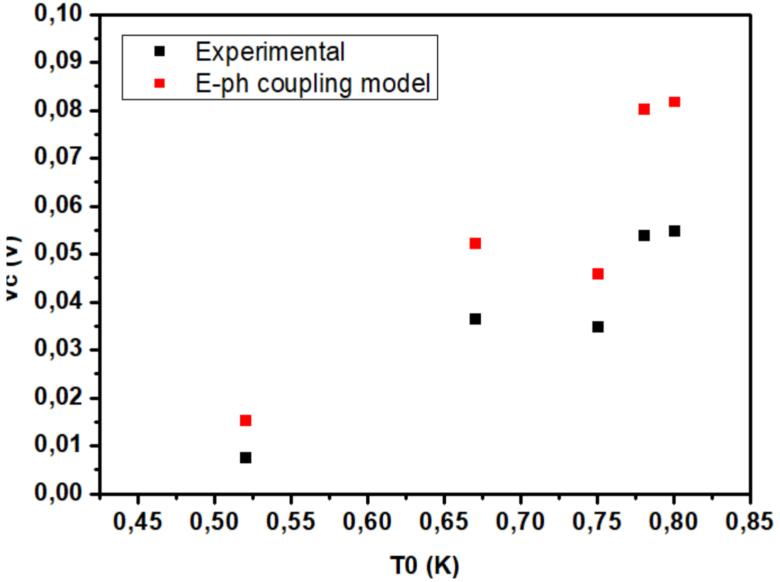
- ✓ **Maximum T_{ph} for bistability**

$$T_c = (\beta+1)^{\frac{\beta+1}{\beta}} T_0$$

- ✓ **Voltage at which the current jumps**

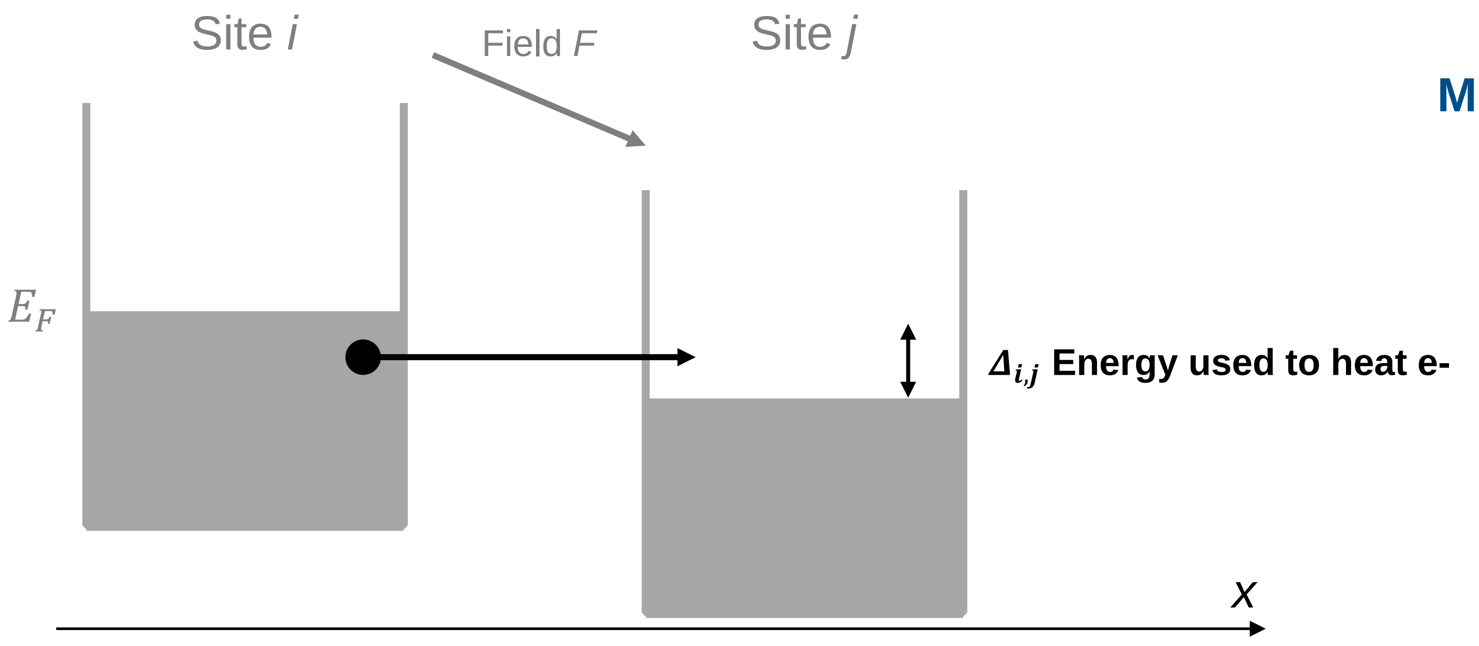
$$V_c^2 = \frac{g_{e-ph} R_0\, \beta\, T_0^{\beta}\, e^{\beta+1}}{(\beta+1)^{\beta+1}}$$





- ✓ Qualitatively explains the features
- ✓ Needs to explain the disappearance of current jumps

Simulations



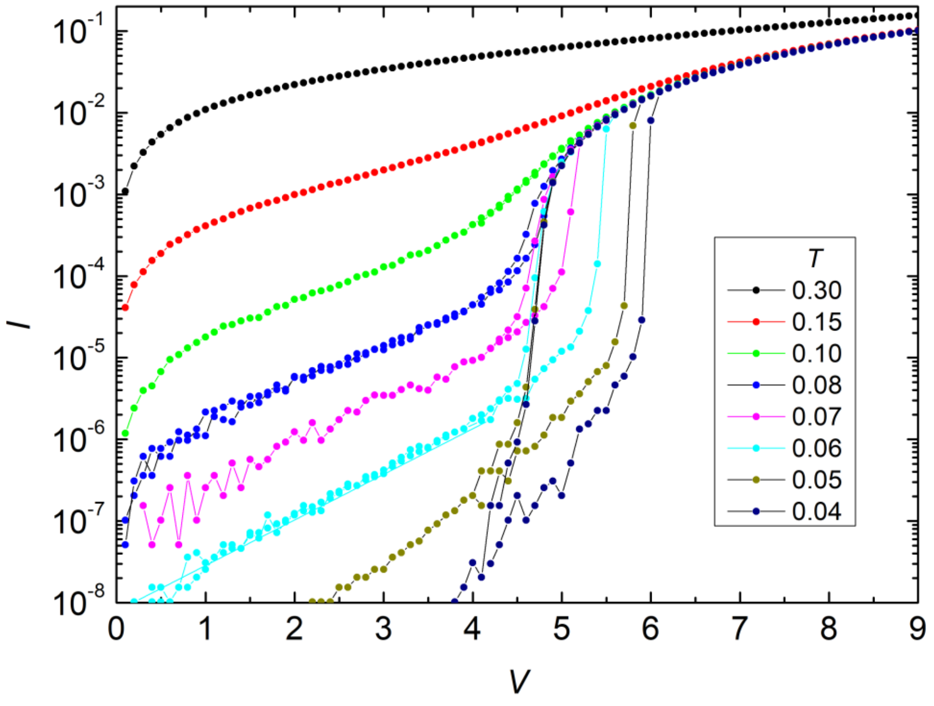
$$\Delta_{i,j} = \epsilon_j - \epsilon_i + 2E_c - (x_j - x_i)F$$

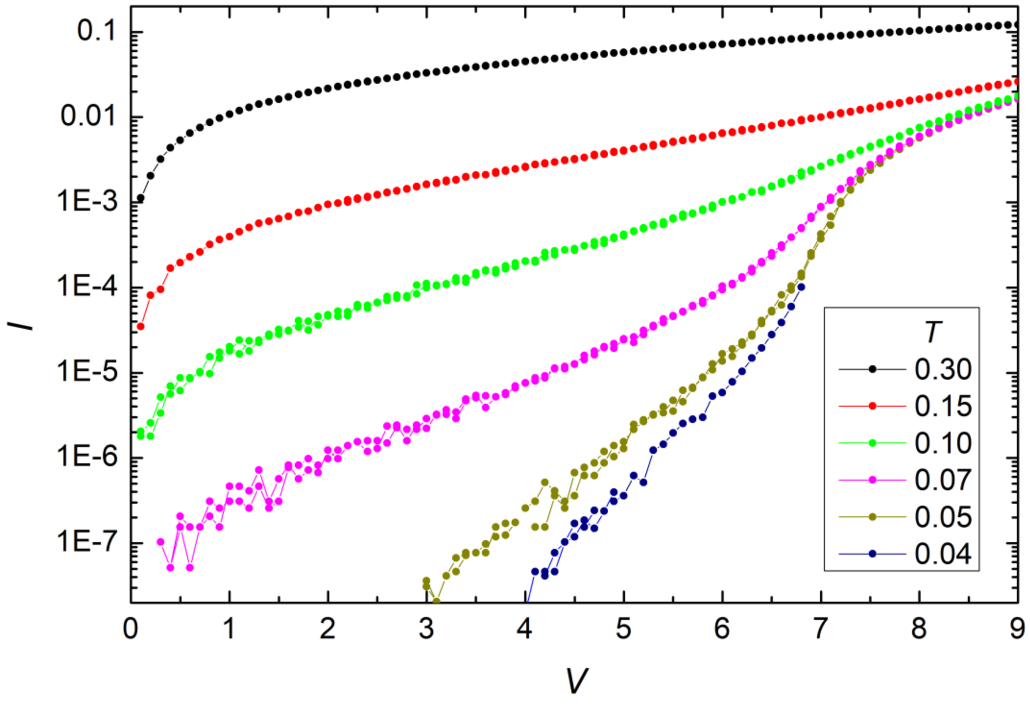
Transition rate: $$\Gamma_{i,j} = \frac{\Delta_{i,j}}{e^{\frac{\Delta_{i,j}}{kT}} - 1}$$

Monte Carlo simulations

- ✓ Metallic grains
- ✓ No interaction between grains
- ✓ Coulomb interactions effect:
  - ✓ Coulomb blockade (activated transport)
  - ✓ Ensures common T_e for all grains
- ✓ Phononless transport
- ✓ Phonons involved in dissipation only

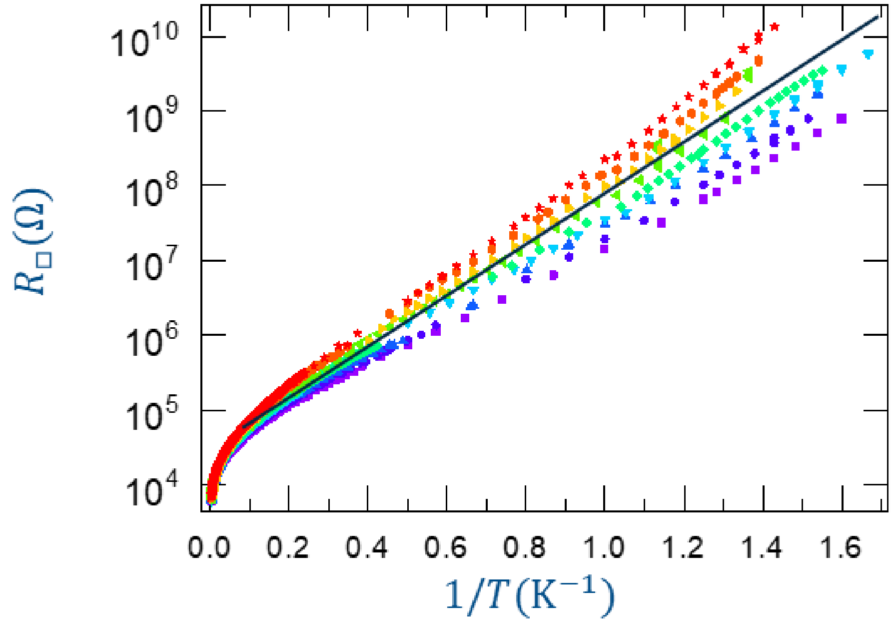
Simulations





$g_{e-ph} \times 5$

Conclusion



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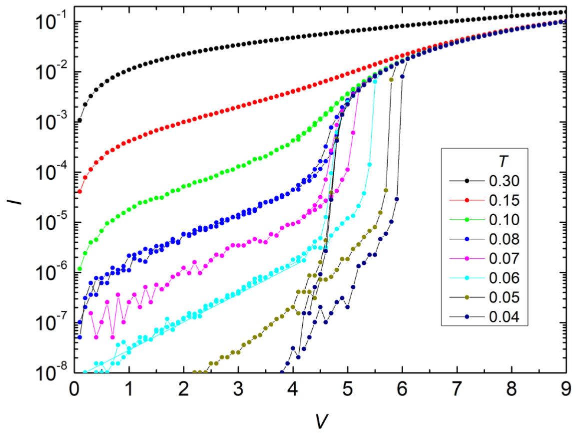
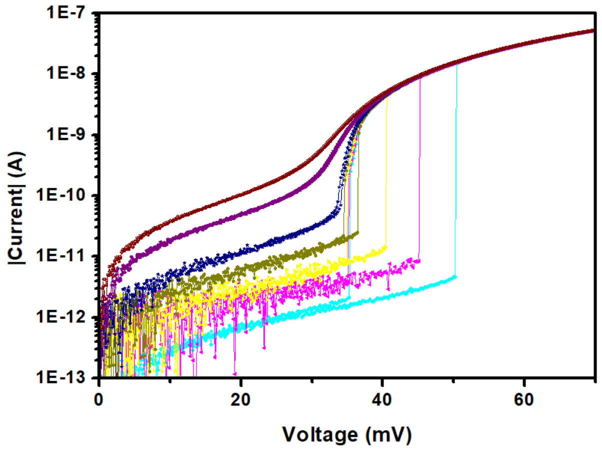
Simulations



Experiments



Heat treatment 90°C

1. Activated behavior due to:
   - ✓ Hopping e-
   - ✓ High dielectric constant κ

2. Revisiting e-/ph coupling model
   - ✓ Want to compare quantitatively expmt/simulations

Thank you for your attention !

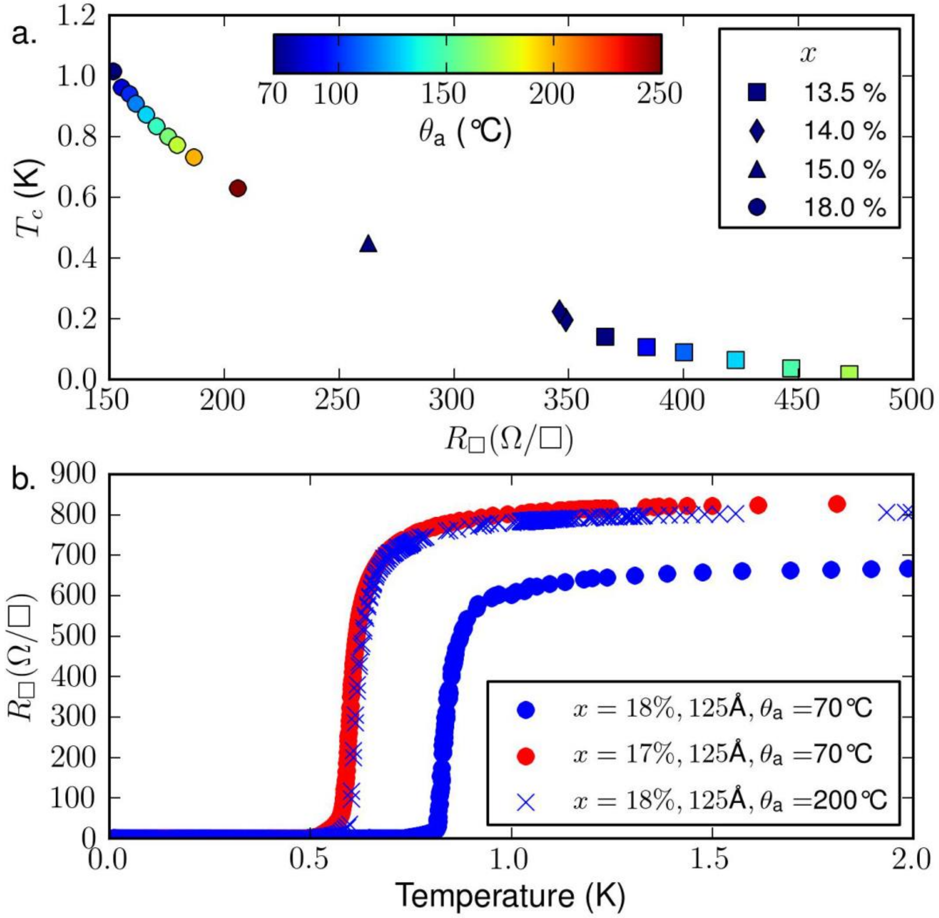
Thank you for your attention !

Outline

1. **Motivation**
   - Superconductor-Insulator transition (SIT)
2. **Activated electronic transport at the onset of the insulating regime**
   - a-NbSi
   - 3 ways of tuning the disorder
   - a-NbSi : an activated insulator
3. **Electron-phonon decoupling in a-YSi films**
   - a-NbSi : an activated insulator
   - Toward an over-activated regime close to the SIT
   - Application of our model on other system

QUALIFICATION DU DÉSORDRE

Désordre



50 nm samples
- 1 color = 1 annealing temp.
- 1 shape = 1 composition

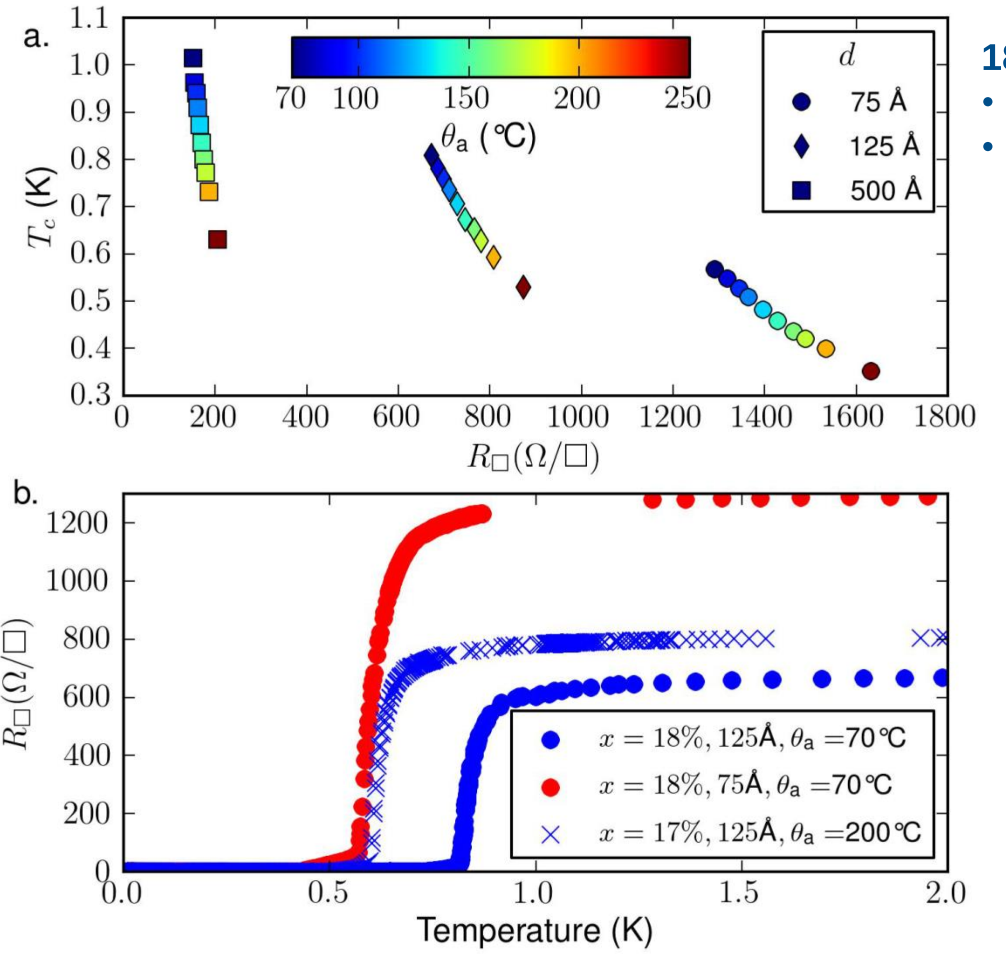
- **Same T_c evolution with the composition and the annealing**
- **Both affect :**

$$R_\square \propto \frac{1}{k_F l}$$

Crauste et al. PRB 87 144514 2013

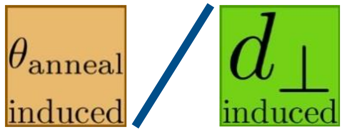
Désordre

Qualification du désordre

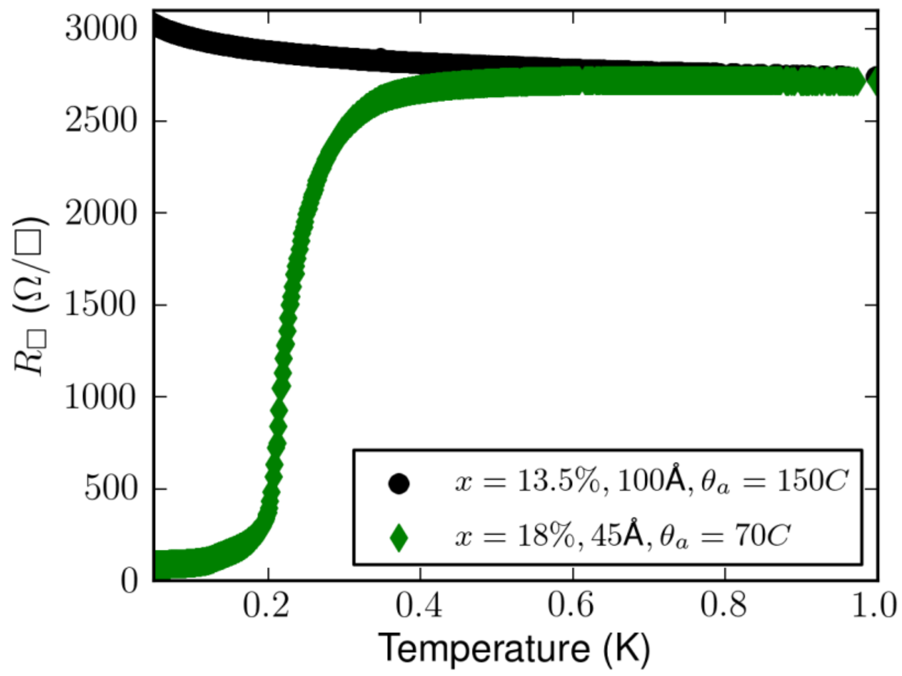


18% samples

- **1 color = 1 annealing temp.**
- **1 shape = 1 thickness**



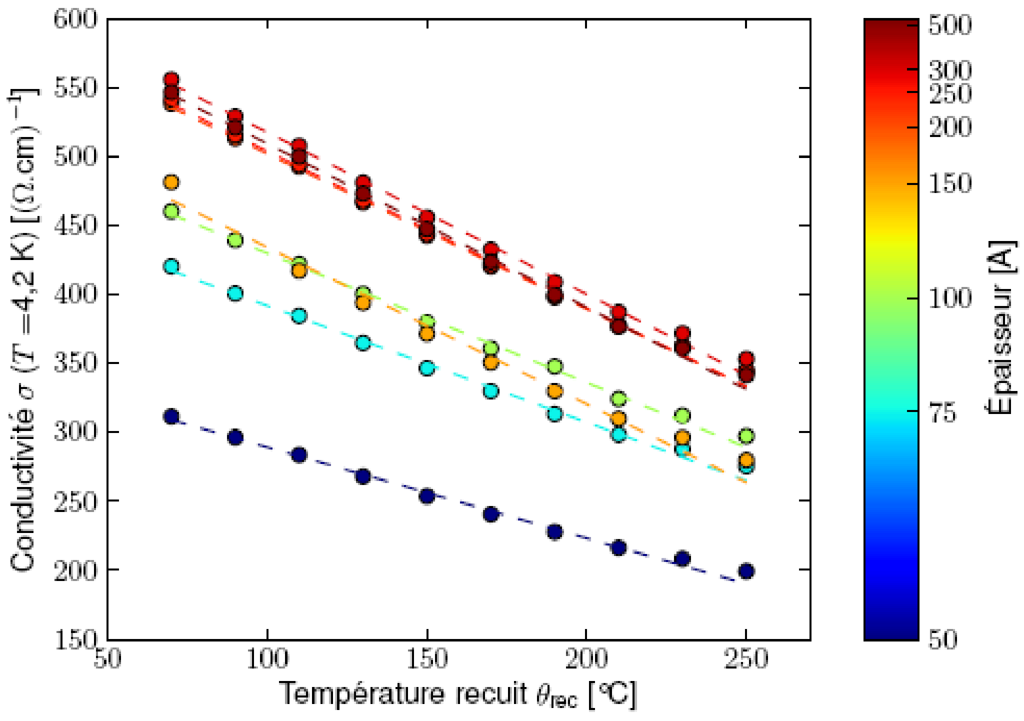
- **Different T_c evolution between the thickness and the annealing**



Crauste et al. PRB 87 144514 2013

Désordre

Recuit – un parameter de contrôle du désordre



(a) *pour* $x = 13{,}5\%$ *(OC5).*

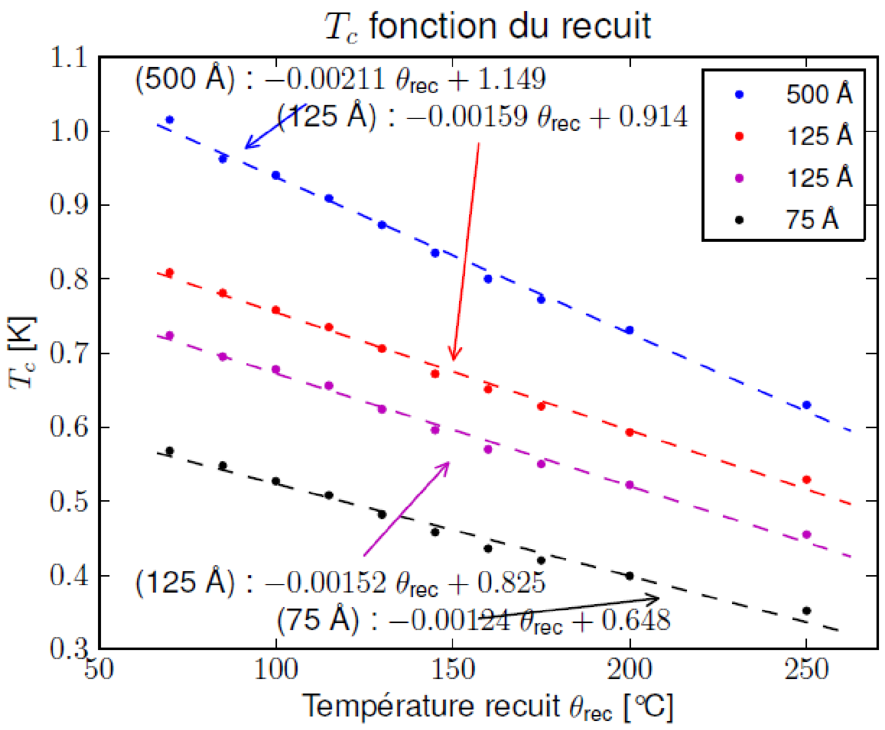
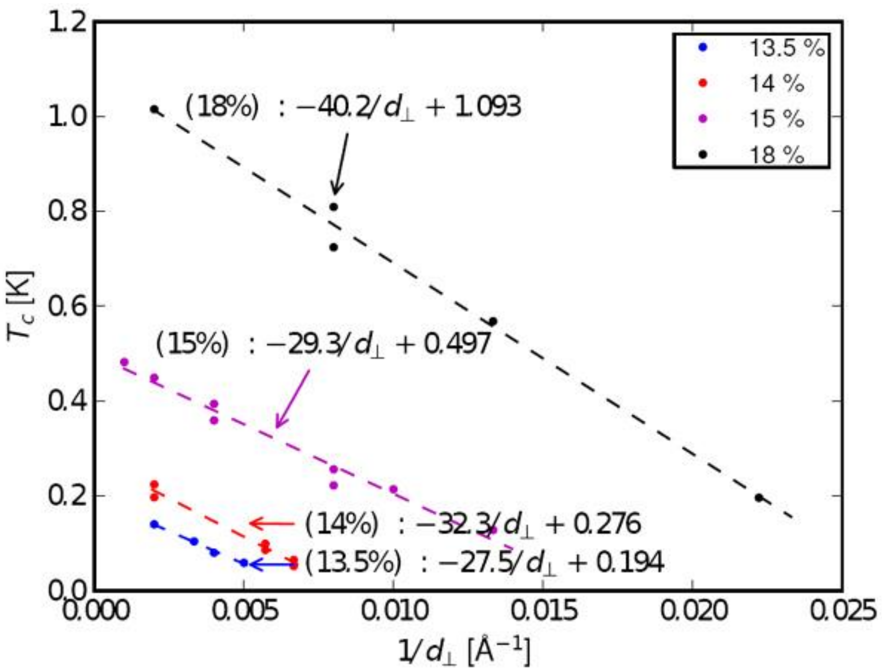
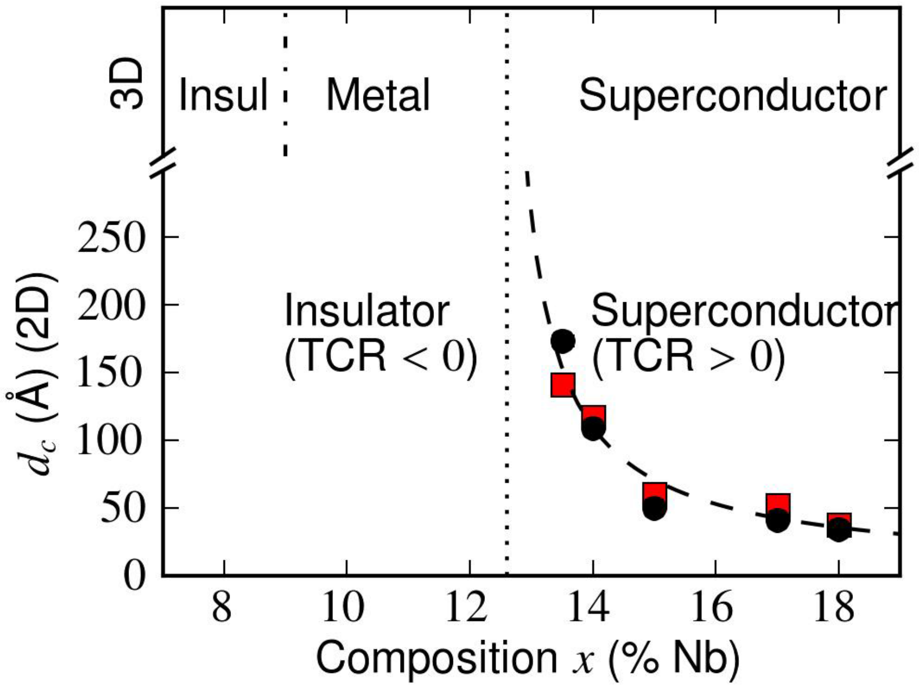


FIGURE 4.28 – *Évolution des* T_c *en fonction du recuit. Les courbes en pointillées correspondent aux régressions linéaires, dont les valeurs sont indiquées dans la figure.*

Crauste et al. PRB 87 144514 2013

Désordre





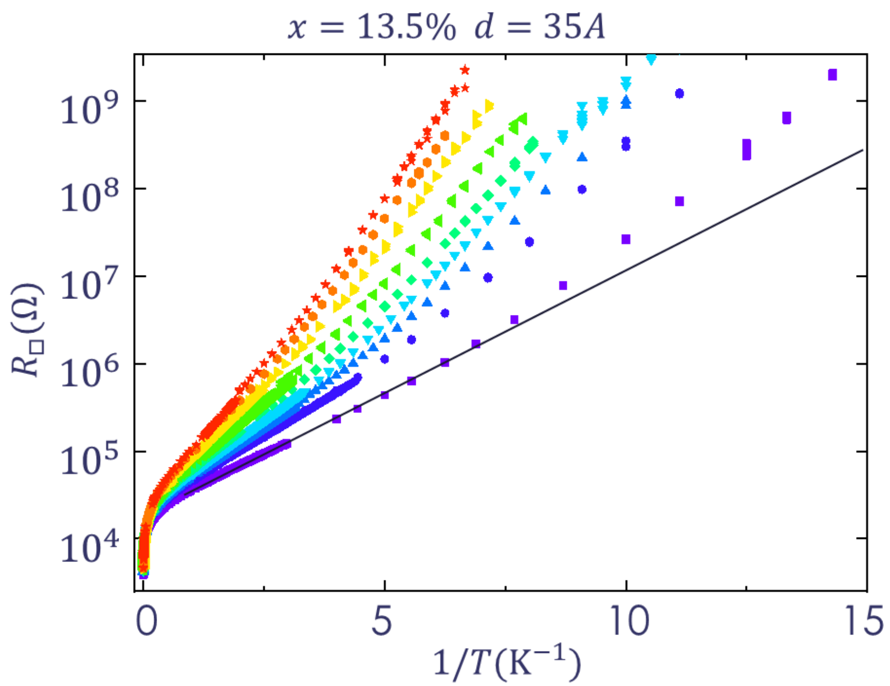
- **The 2D SIT connects with the 3D MIT**
- **Divergence of d_c**

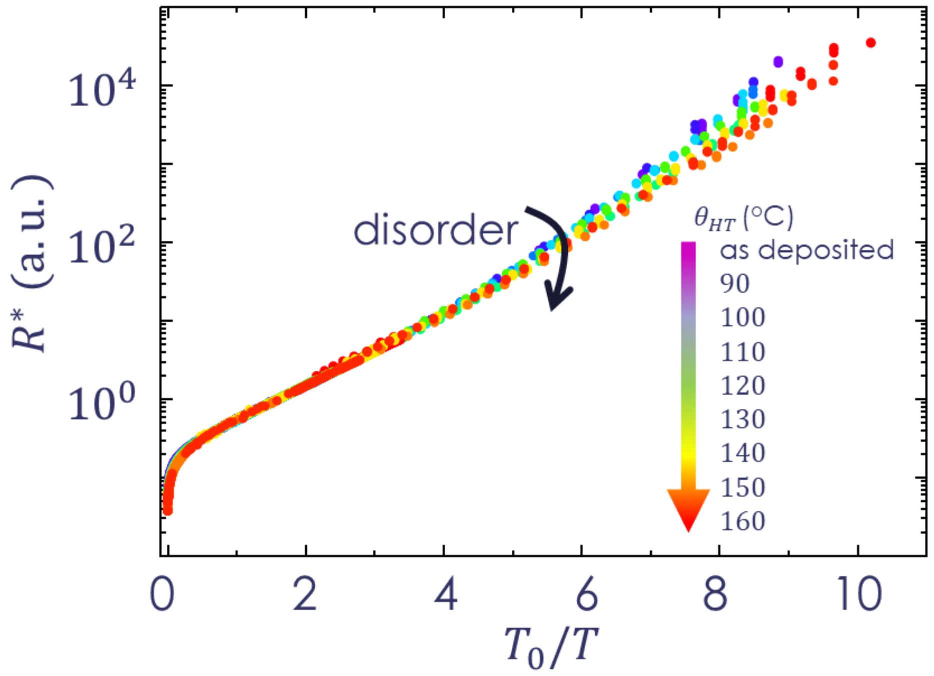
Crauste et al. PRB 90 060203 2014

OVERACTIVATED REGIME

Towards a stronger insulator

Over-activated law at low temperature





Scaling of the resistance does not work at low temperature

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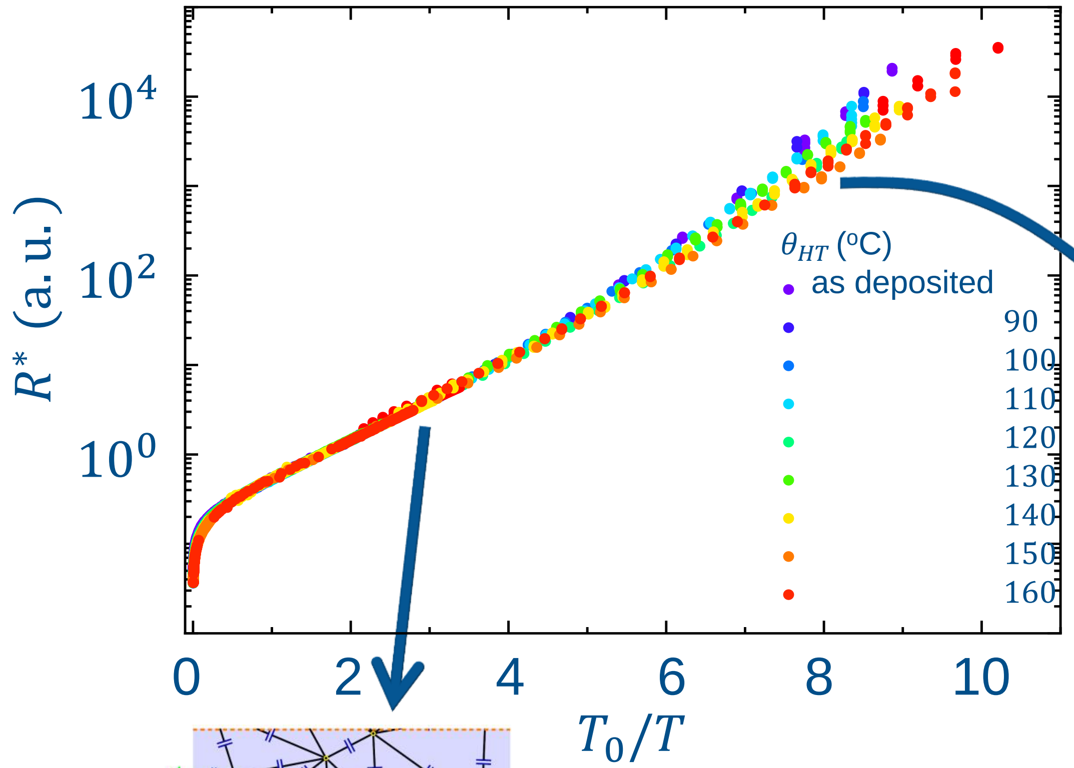
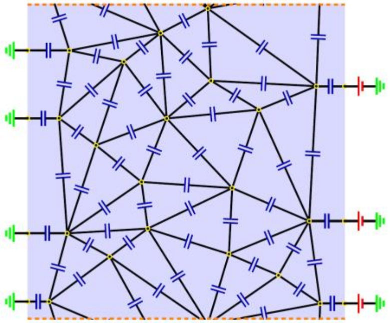
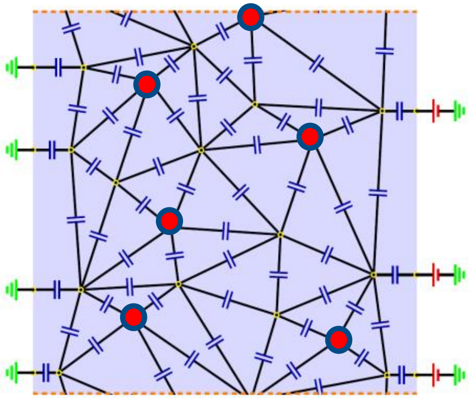
Over-activated regime

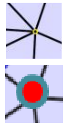
Influence of local superconductivity?





Crossing temperature ~ T_c of the grains





Non superconducting material

Superconductor

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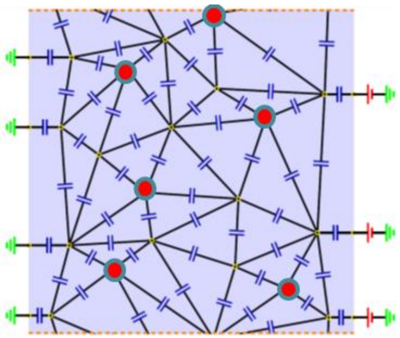
Over-activated regime



p = proportion of superconducting grains

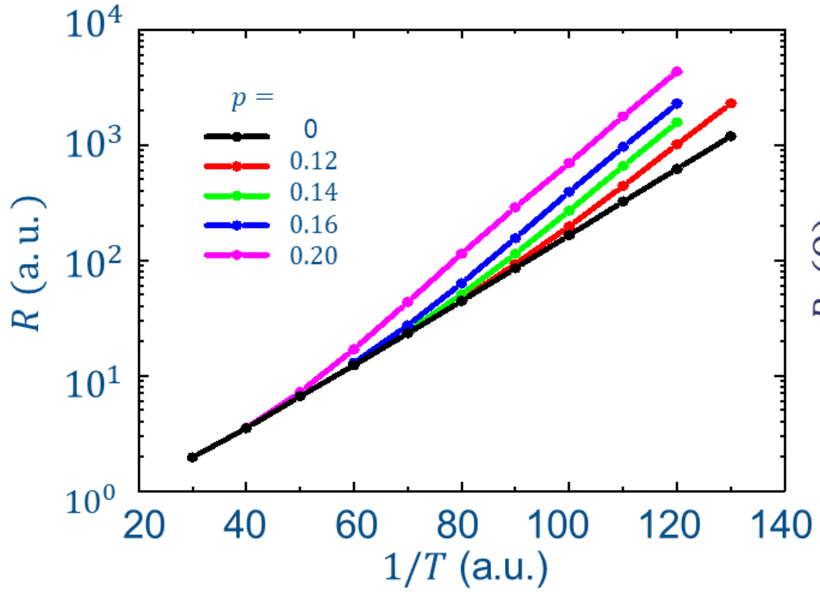
$$T_{cross} = p\, T_0$$

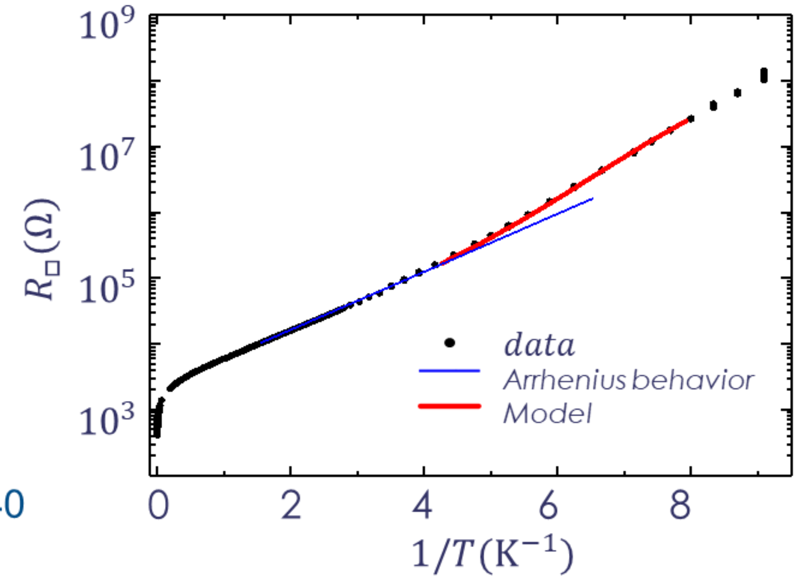
Disorder increases (move further from SIT)

→ Less superconducting puddles

→ Less deviations from simple $R \sim e^{T_0/T}$

→ crossover temperature decreases





Excellent agreement with expmts!

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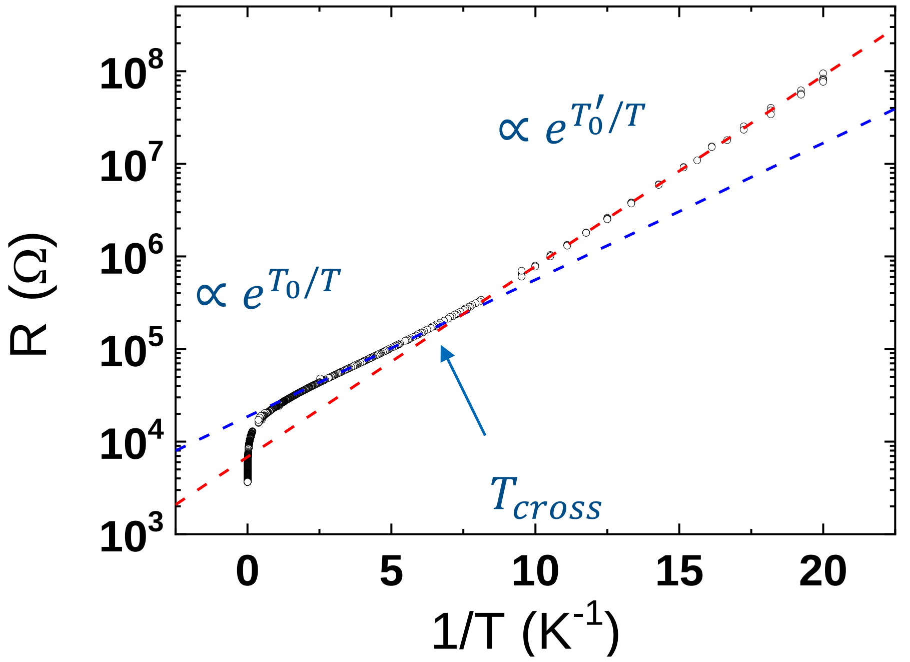
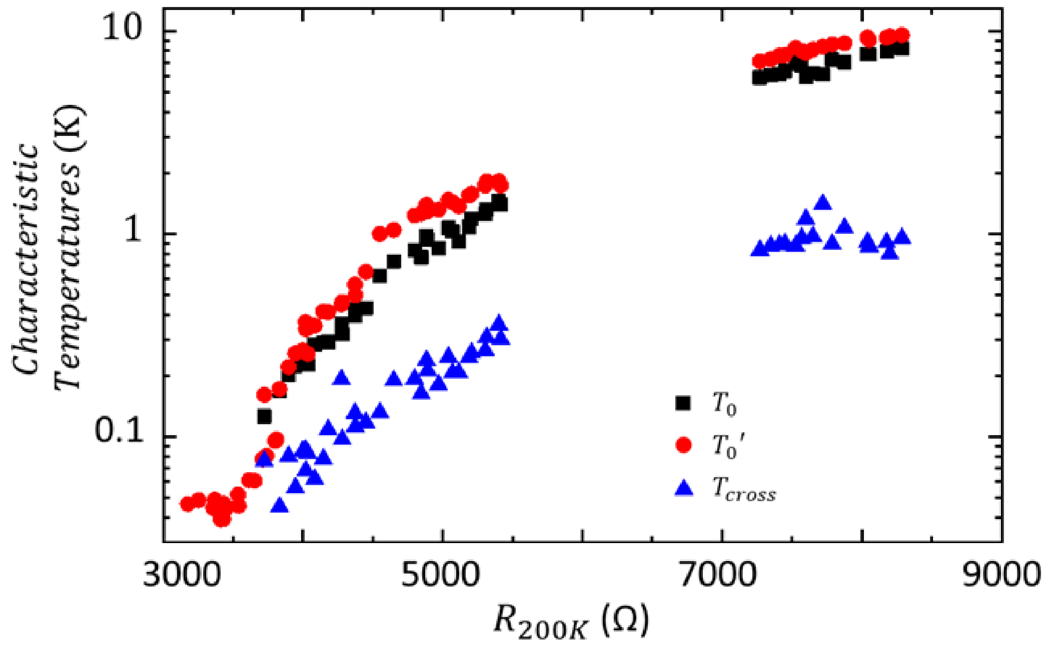
Over-activated regime

Numerical simulations





Electron hopping between grains

T_0 activation energy at moderate temperatures

T_0' activation energy at the lowest temperatures

T_{cross} crossover temperature

$$E_0' = E_0 + \mathrm{c}\,\Delta(T)$$
$$E_0'(T=0) = E_0 + \mathrm{c}\,\Delta_0$$
$$\sim E_0 + 2\,c\,k_B T_c$$

$$T_0'(T{=}0) = T_0 + \gamma\, T_{cross}$$

Monte-Carlo simulation
$$T_0'(T{=}0) = T_0 + 1.8\, T_{cross}$$

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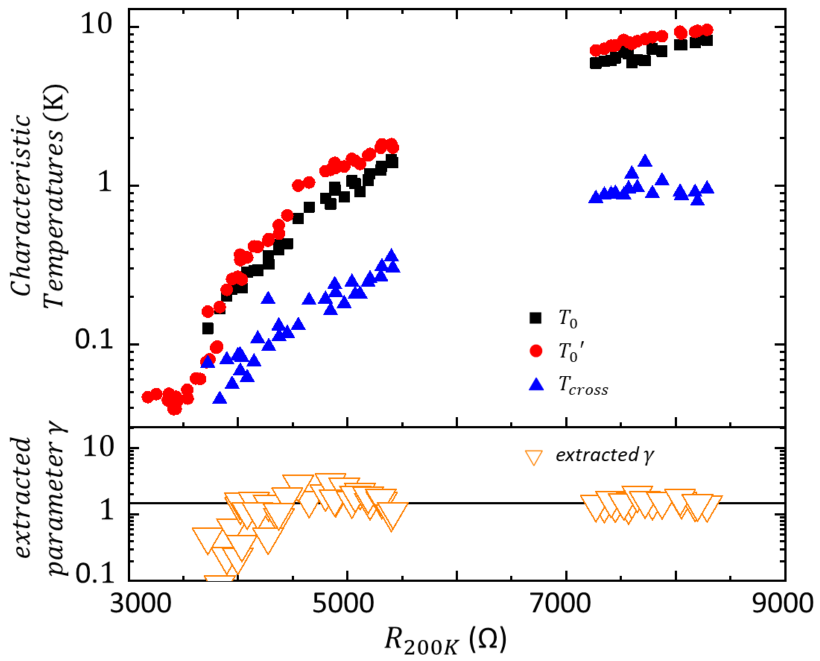
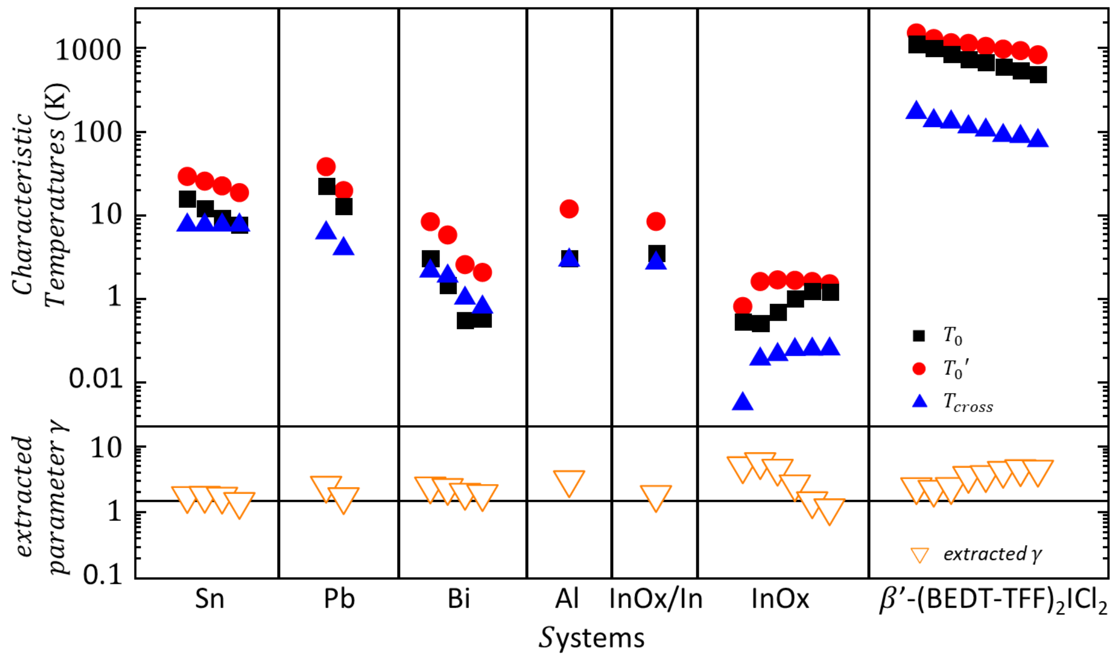
Over-activated regime

Numerical simulations





$T_0' = T_0 + \gamma\, T_{cross}$ with $\gamma \sim \Delta_0 / k_B T_c$

Monte-Carlo simulation
$\gamma = 1.8$

Sources

Sn, Pb : Dynes *PRL* **40** 479 (1978)
Bi, Al : Parendo PRB 100508 (2007)
InO_x/In : Kim **PRB 46**(**18**) **11709** (**1992**)
InO_x :Dan Shahar (shared data)
β'-(BEDT-TFF)$_2$ICl$_2$: Tajima *EPL* **83** 27008 (2008)

Humbert *Nature Comm.* **12** 6733 2021

E-PH COUPLING

I(V) curves

Even larger disorder

- ✓ **Heat balance equation**

$$P = g_{e-ph}\left(T_e^{\beta} - T_{ph}^{\beta}\right)$$

- ✓ **Activated transport**

$$R = R_0\, e^{T_0/T_e}$$

- ✓ **Maximum T_{ph} for bistability**

$$T_c = (\beta+1)^{\frac{\beta+1}{\beta}} T_0$$

- ✓ **Voltage at which the current jumps**

$$V_c^2 = \frac{g_{e-ph} R_0\, \beta\, T_0^{\beta}\, e^{\beta+1}}{(\beta+1)^{\beta+1}}$$