Characteristics of the Superconductor-Metal-Insulator transitions in thin Nb_xSi_{1-x} films

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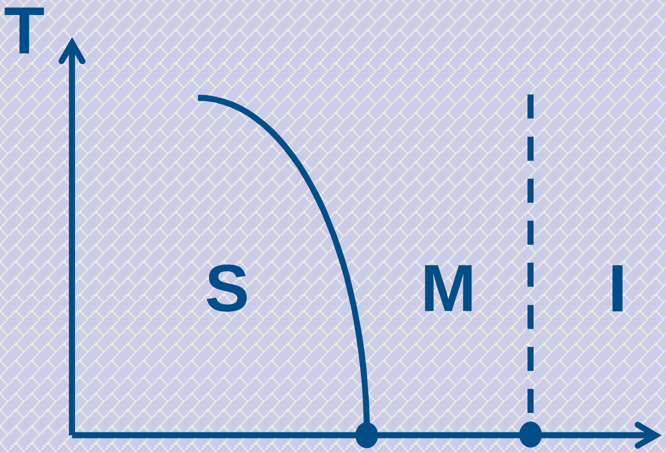
OUTLINE OF THE TALK

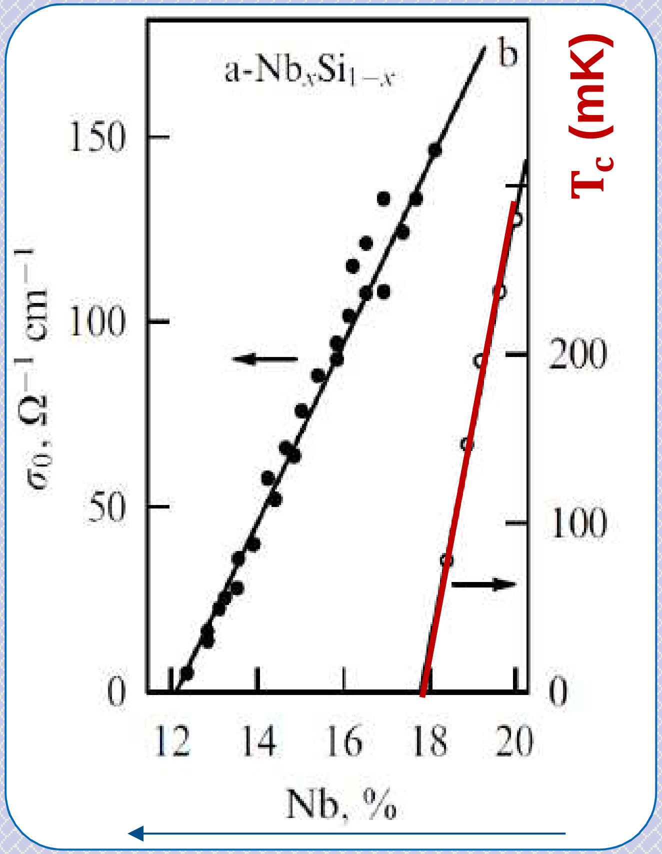
1. Motivation
2. NbSi thin films
   + System characterization
   + 3 ways of tuning the disorder
3. Destruction of superconductivity in NbSi films
   + 2 intermediate metallic phases
4. Onset of the insulating regime

MOTIVATION

i. Superconductor – Metal – Insulator



Possible in 2D ?

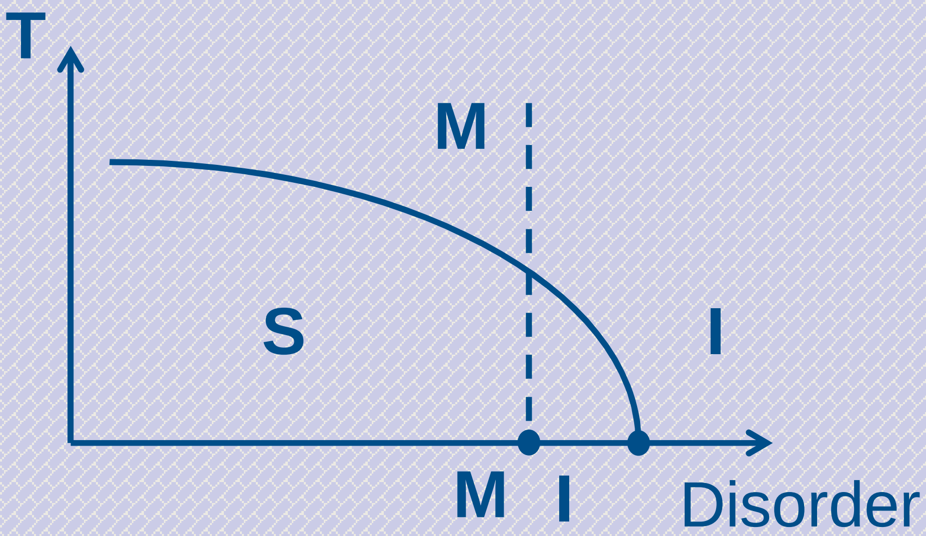


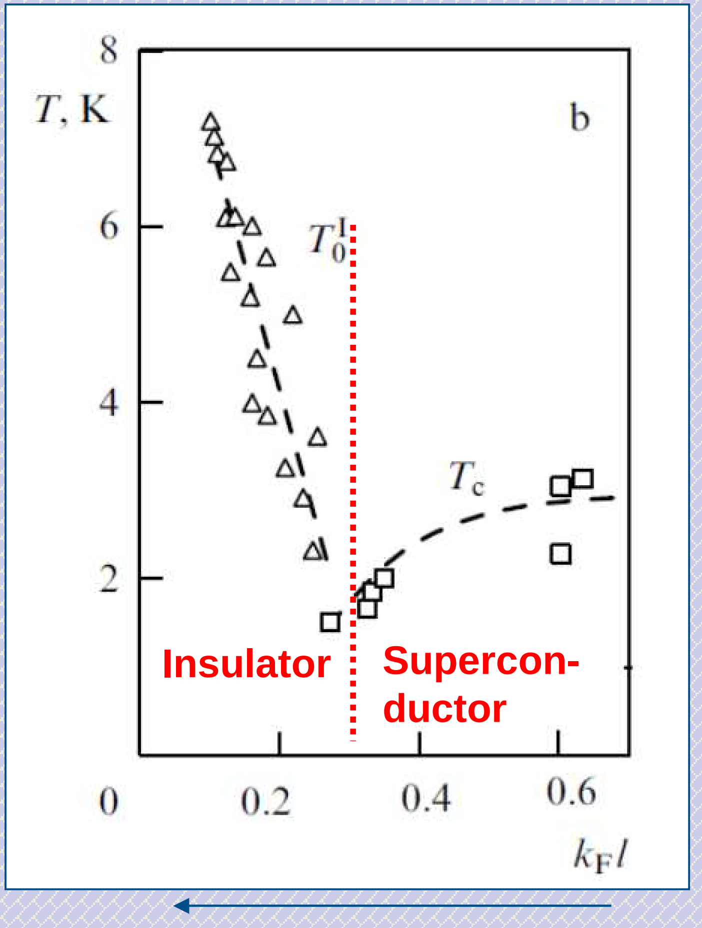
Increasing disorder

Bishop et al., *Sol. St. Elec.*, **28** 73 1985

MOTIVATION

ii. Superconductor – Insulator



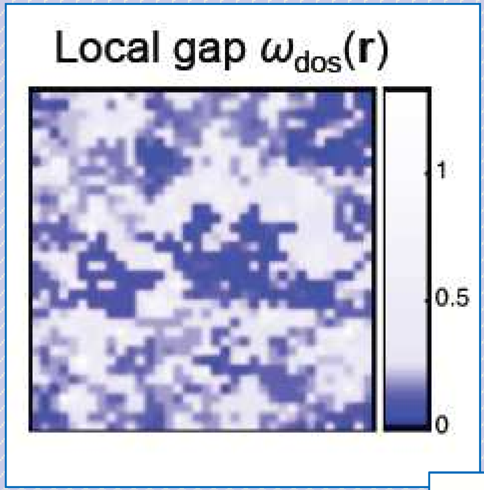


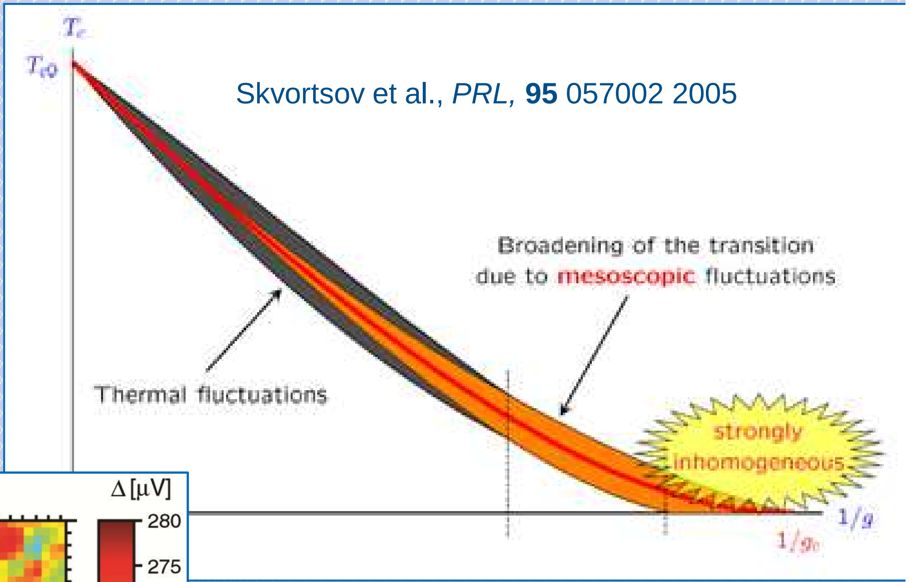
Shahar & Ovadyahu, *Phys. Rev. B*, **46** 10917 1992

MOTIVATION

iii. Electronic inhomogeneities

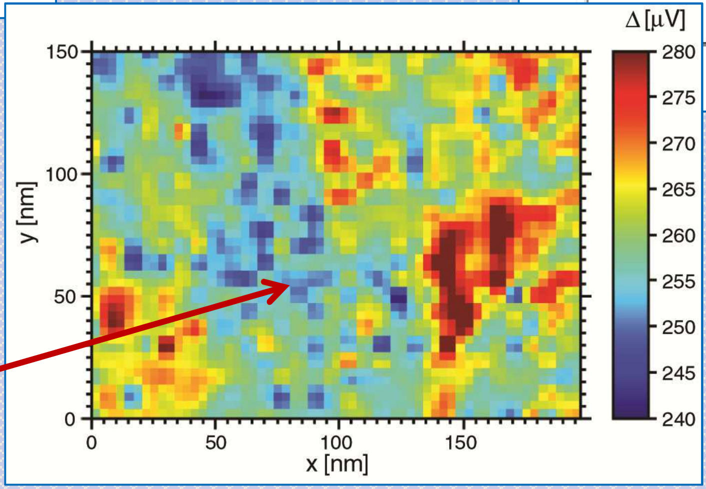
Bouadim et al., *Nat. Phys.*, **7** 884 2011





Skvortsov et al., *PRL,* **95** 057002 2005

Inhomogeneous order parameter



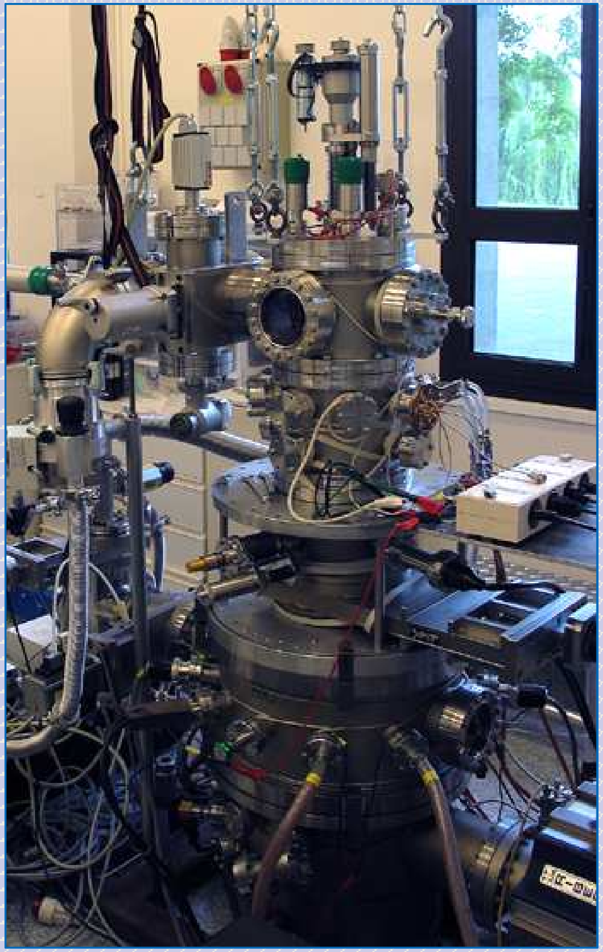
Sacépé et al., *PRL,* **101** 157006 2008

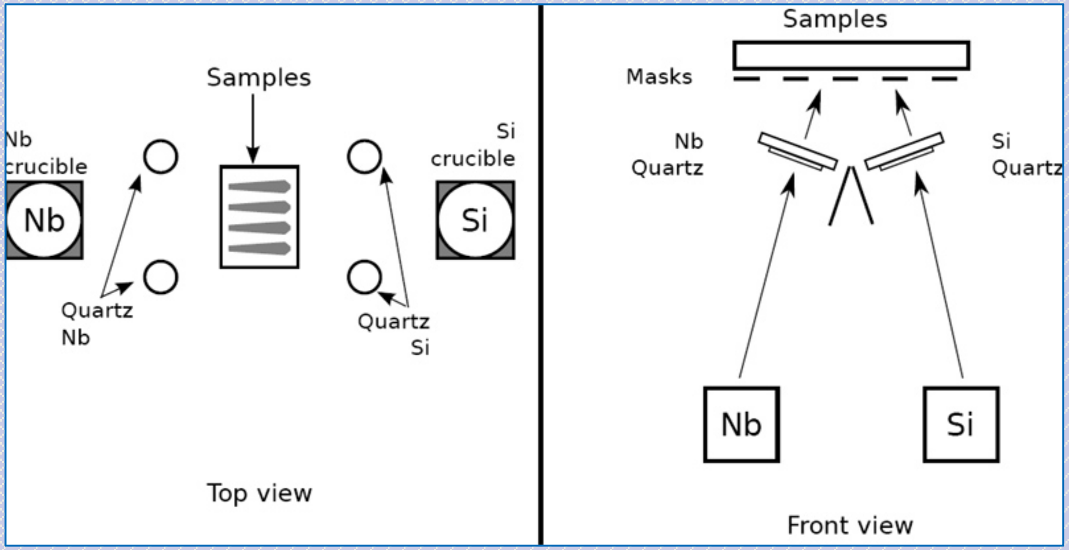
A-NBSI THIN FILMS

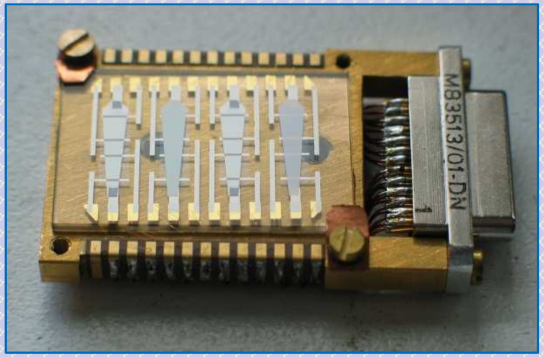
- System characterization
- 3 ways of tuning the disorder

NBSI THIN FILMS

Synthesis



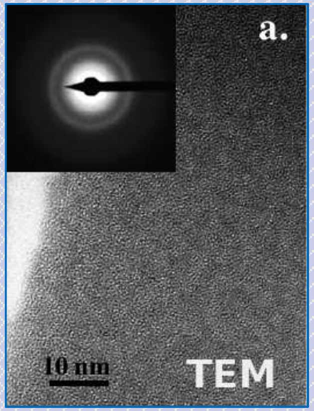


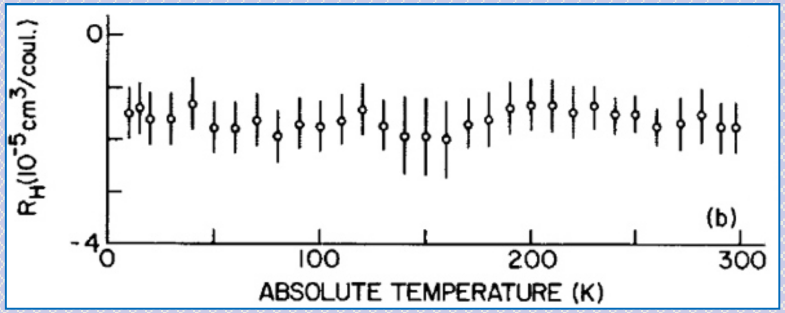


NBSI THIN FILMS

General characteristics

- **Morphology :**
  - Continuous down to 2.5 nm (at least)
  - Amorphous
- **Mean free path** $l = 2.6\,\text{Å}$ to $5\,\text{Å}$
- **Electronic density n ~** a few 10^{27} m^{-3}
- **Superconducting coherence length**
  ξ ~ 50 nm for T_c=1K
- **Heat treatment :**
  - No modification of n
  - No modification of the composition x





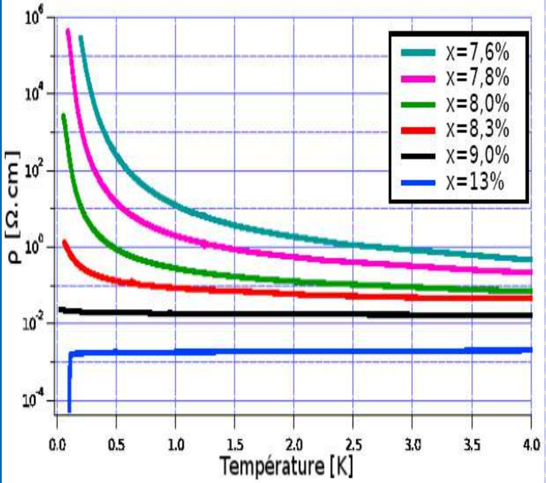
Nava et al., *J. Mat. Res.*, **1** 327 1986

NBSI THIN FILMS

3 different disorder-induced SITs

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

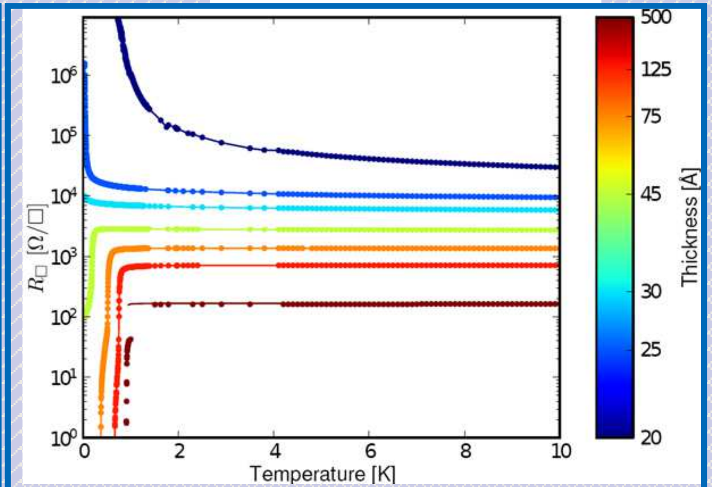
Crauste et al. *PRB* **87** 144514 2013



x induced — **Composition**

- 3D : d > 100 nm

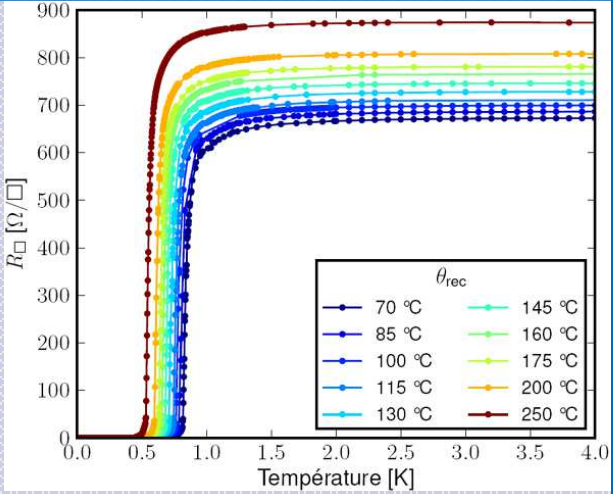
$$R_\square = \frac{1}{k_F l}$$



$d_\perp$ induced — **Thickness**

- 2D, 18%
- ξ ~ 50 nm

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



θ_{anneal} induced — **Heat treatment**

- d=12.5 nm, 18%

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

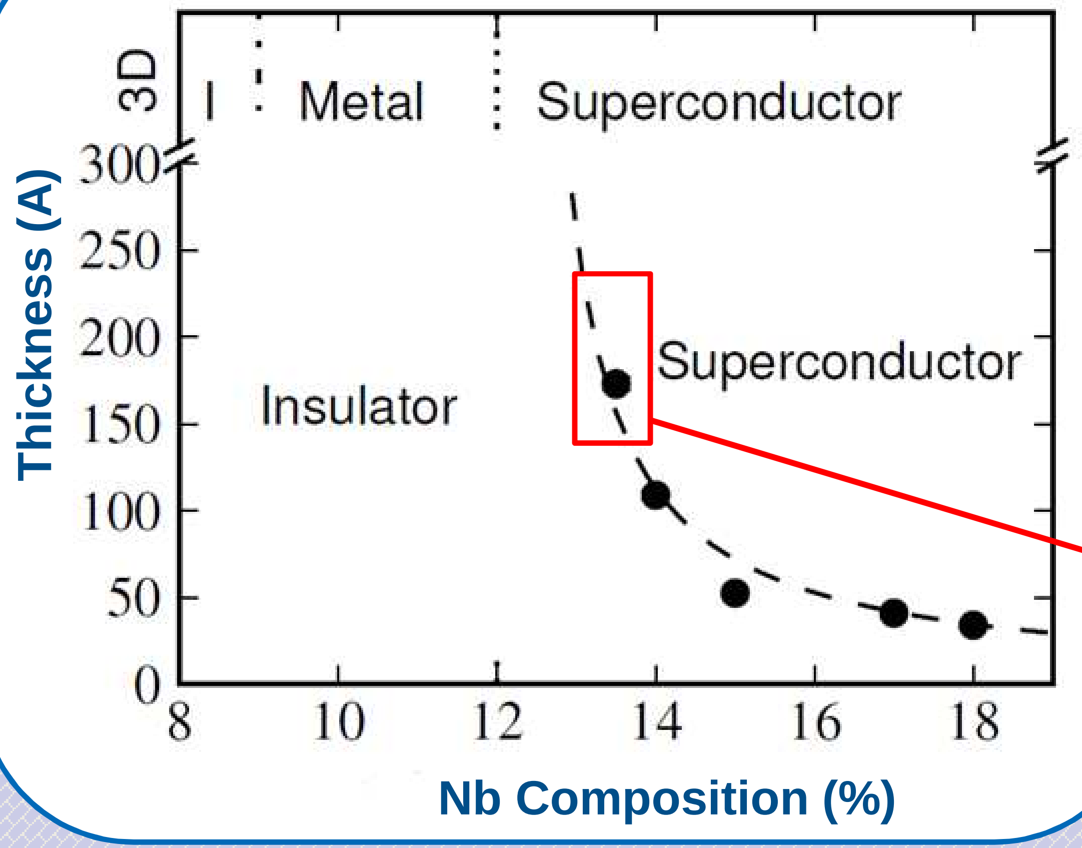
DESTRUCTION OF SUPERCONDUCTIVITY IN NBSI FILMS

- 2 dissipative phases

SAMPLES

Near the SIT

Crauste *PRB* **90** 060203 2014

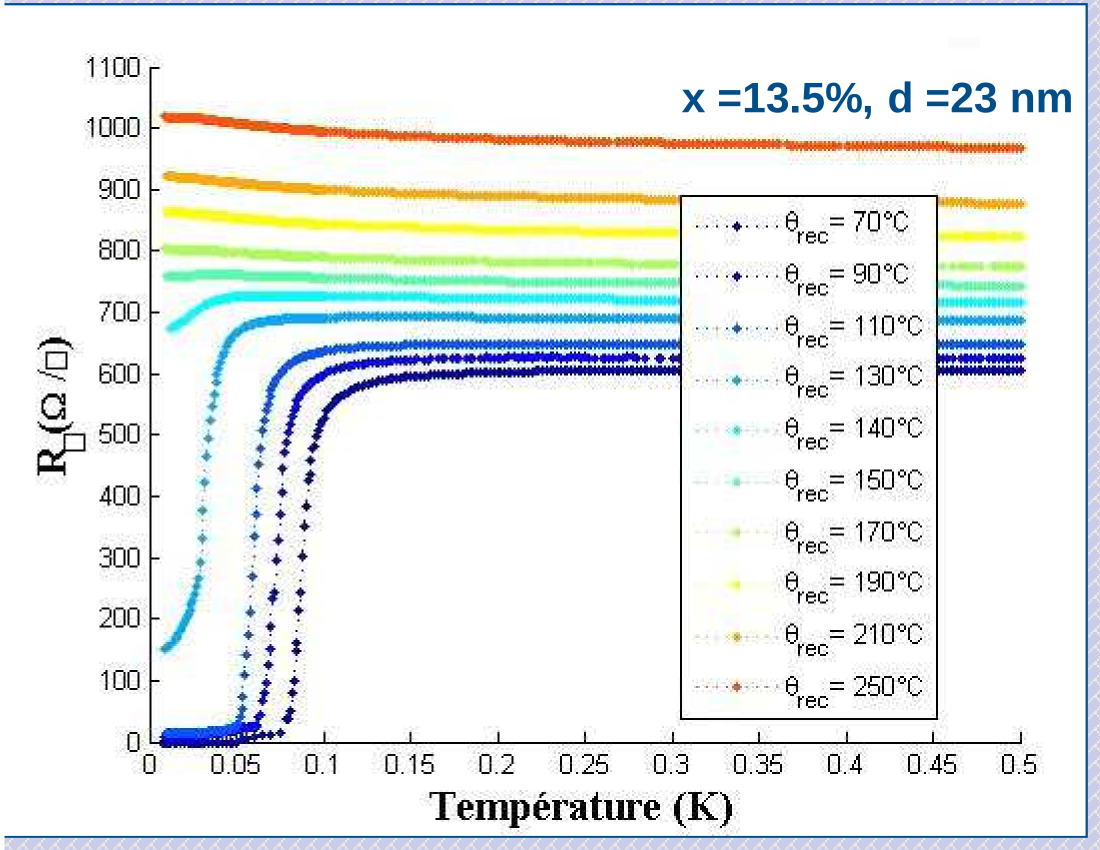


x= 13.5 %, $d_c \approx$ 18 nm

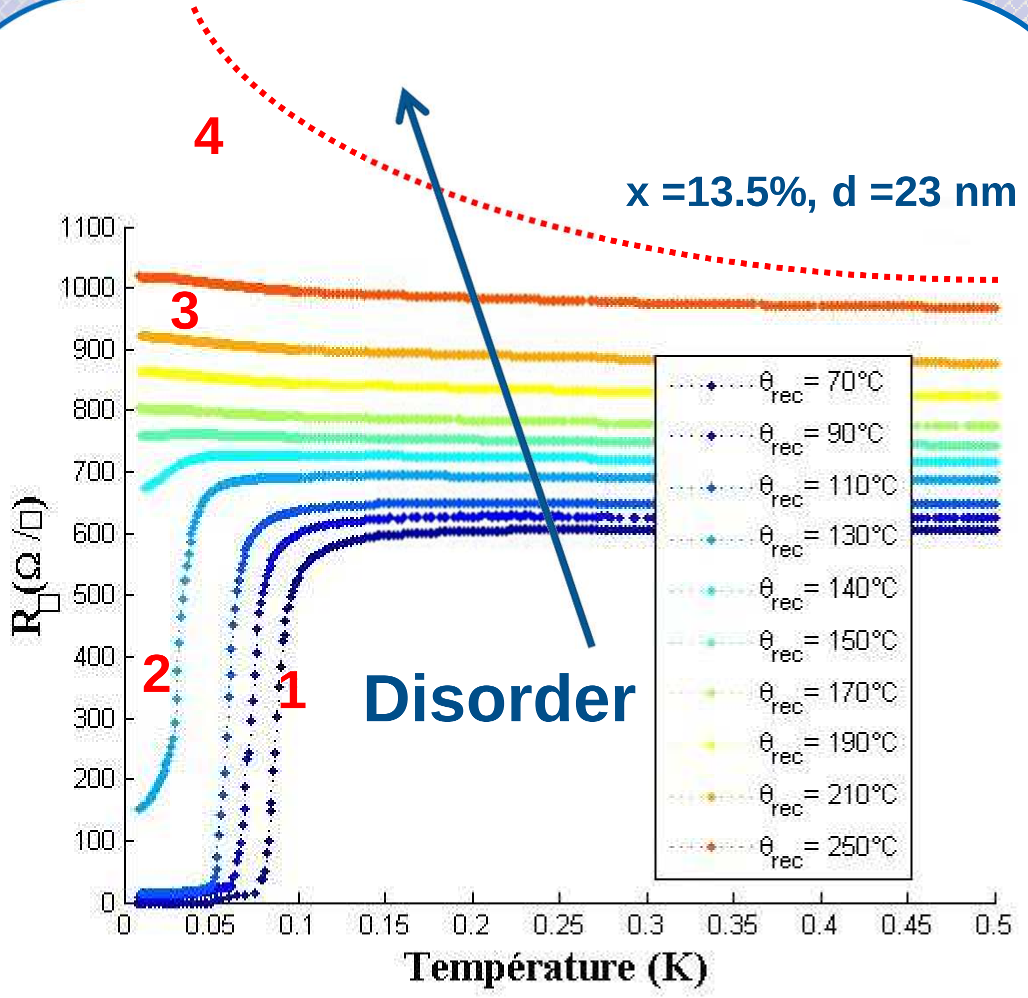
4 Films
with d= [14, 23 nm]

SAMPLES

Fine-tuning the disorder



4 DISTINCT REGIMES



At $T \to 0$

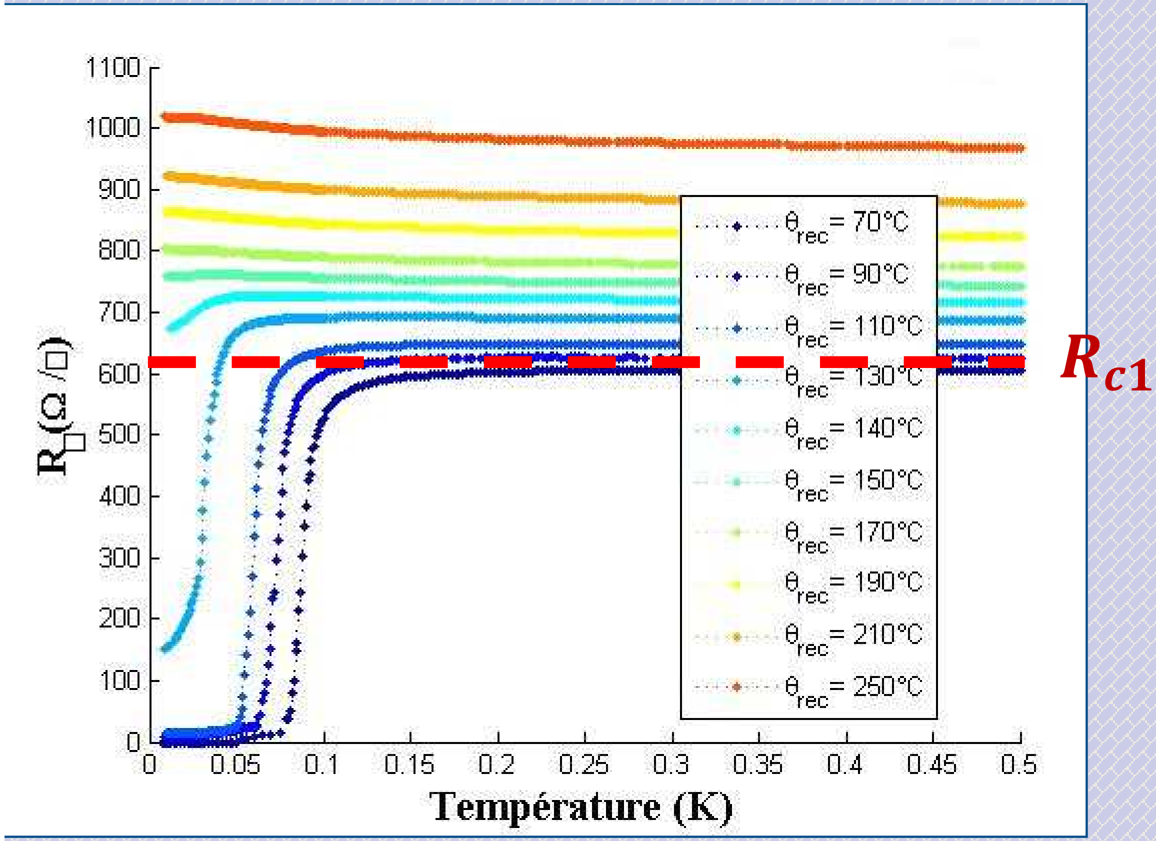
1 – Superconductor (R=0)
2 – Finite R & TCR > 0
3 – Finite R & TCR < 0
4 – Insulator

Disorder measured by :

$$R_{\square,N} = R_{\square}(500\ \text{mK})$$

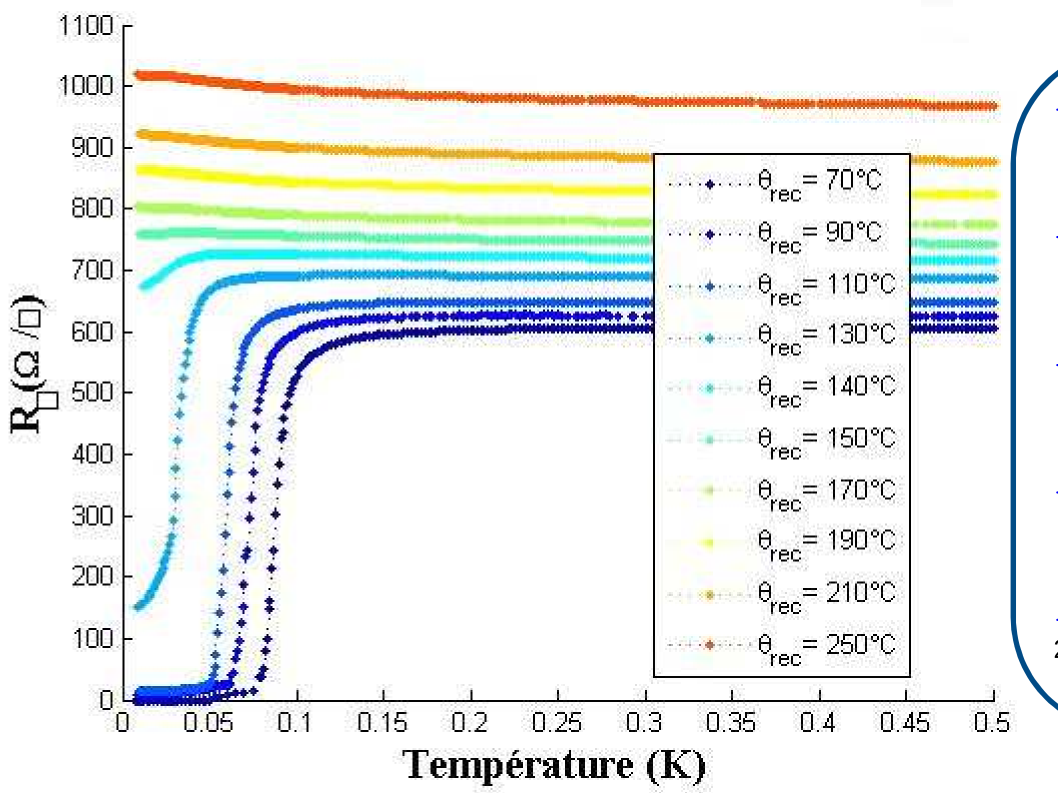
« METAL 1 » PHASE

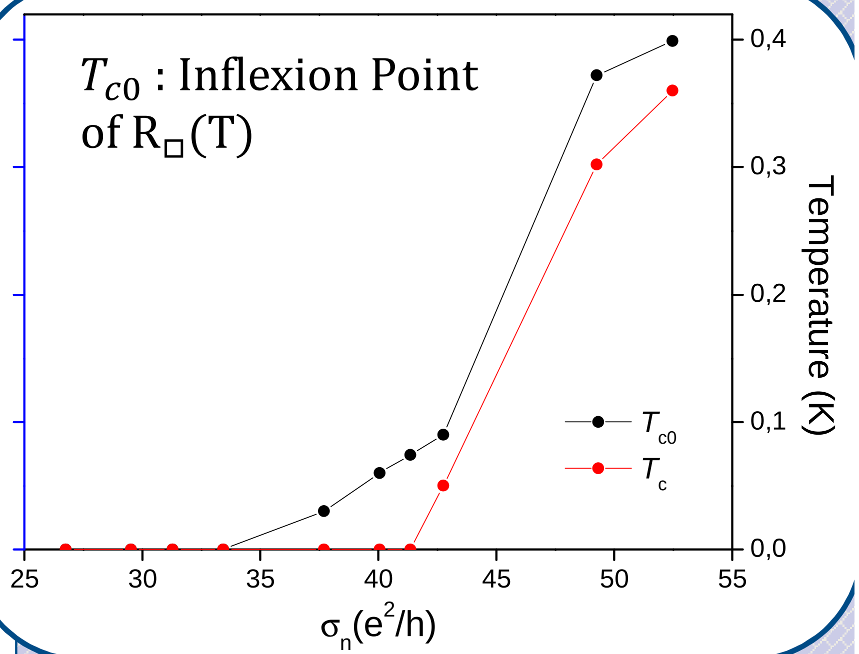
Superconductor – Metal 1 Transition



« METAL 1 » PHASE

Energy scale T_{c0}





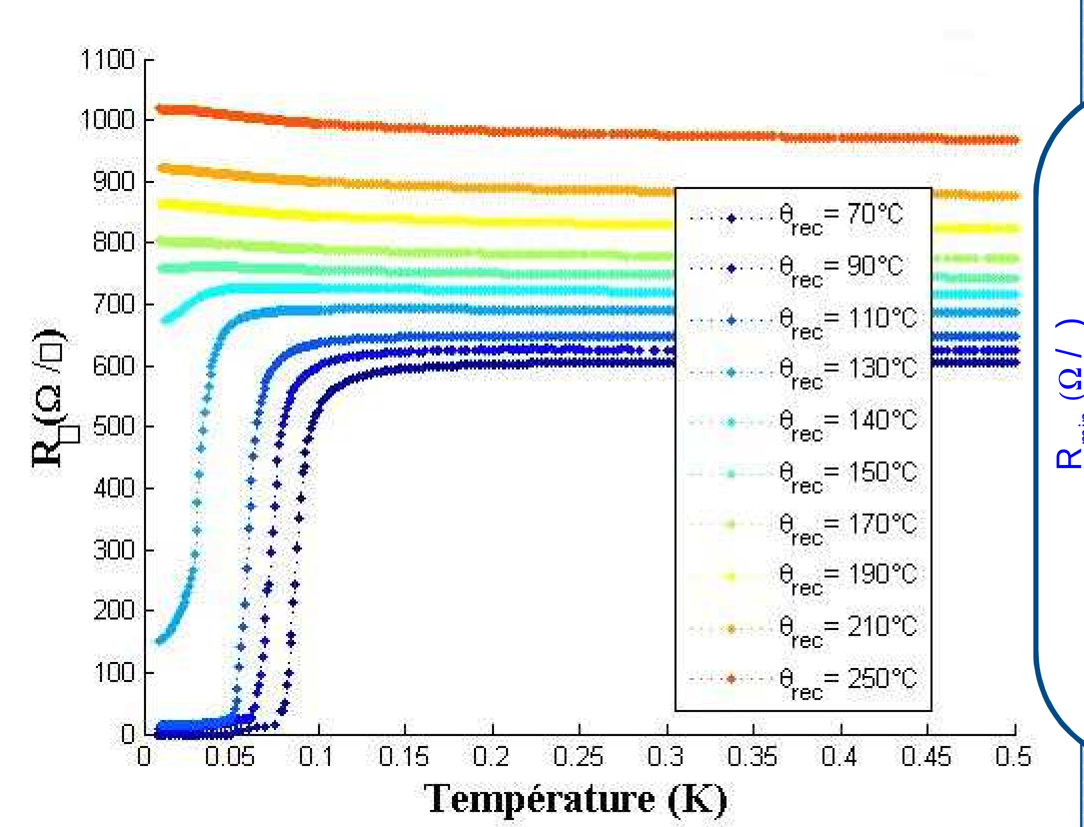
Increasing disorder

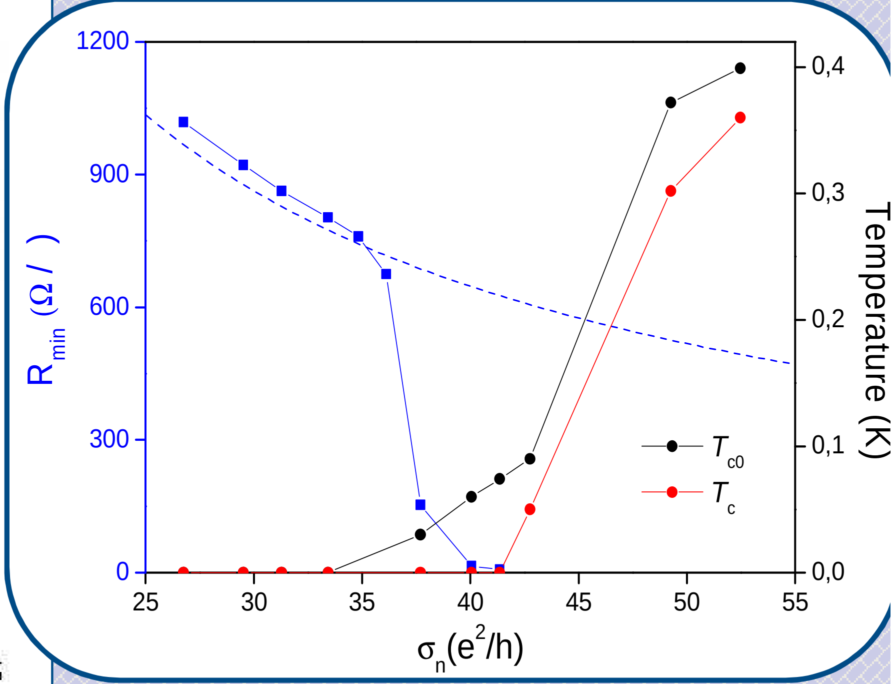
« METAL 1 » PHASE

Minimum resistance

$R_{min} = R_{\square}(10\ mK)$

T_{c0} : Inflexion Point of $R_{\square}(T)$





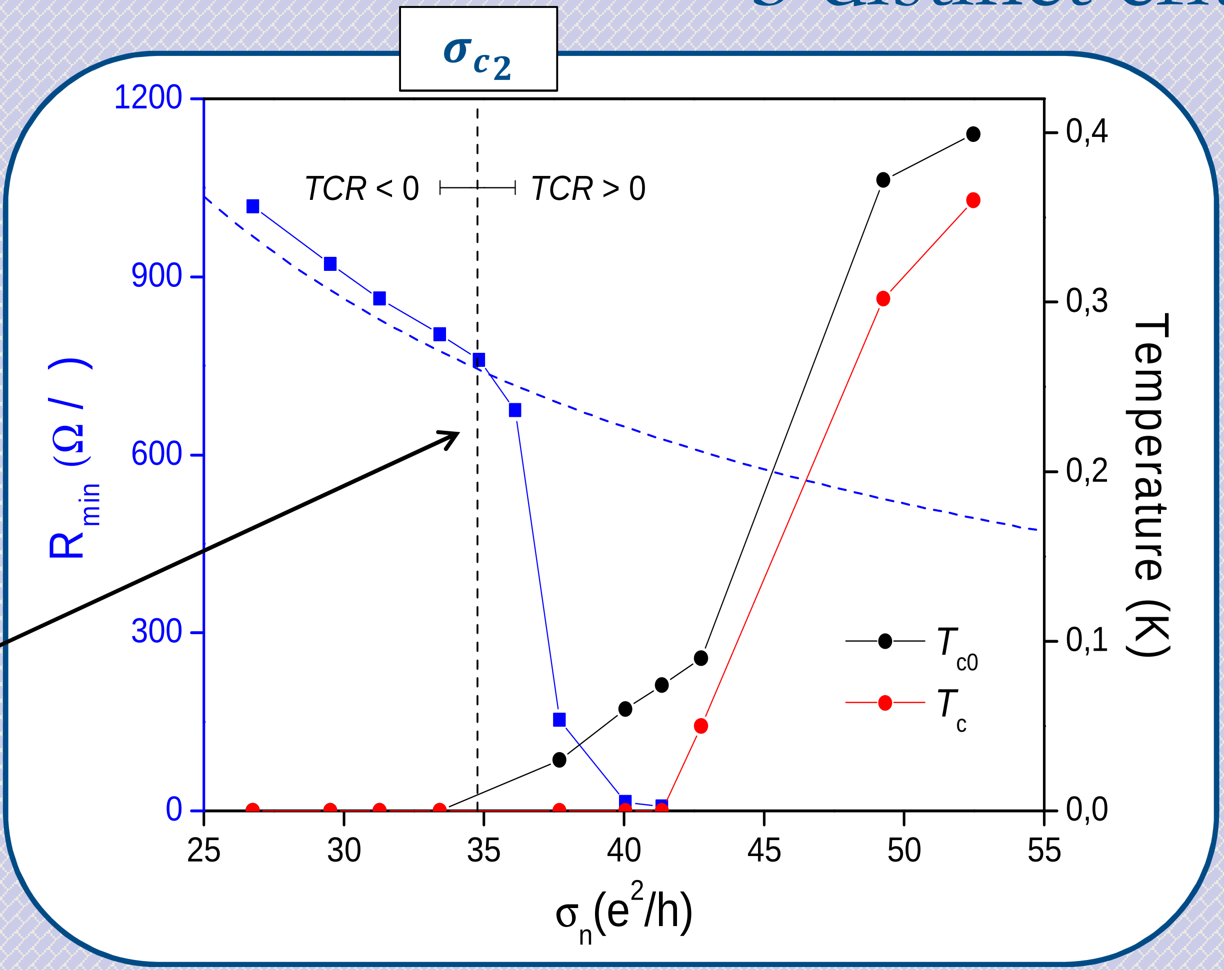
Increasing disorder

« METAL 1 » - « METAL 2 » TRANSITION

3 distinct criteria

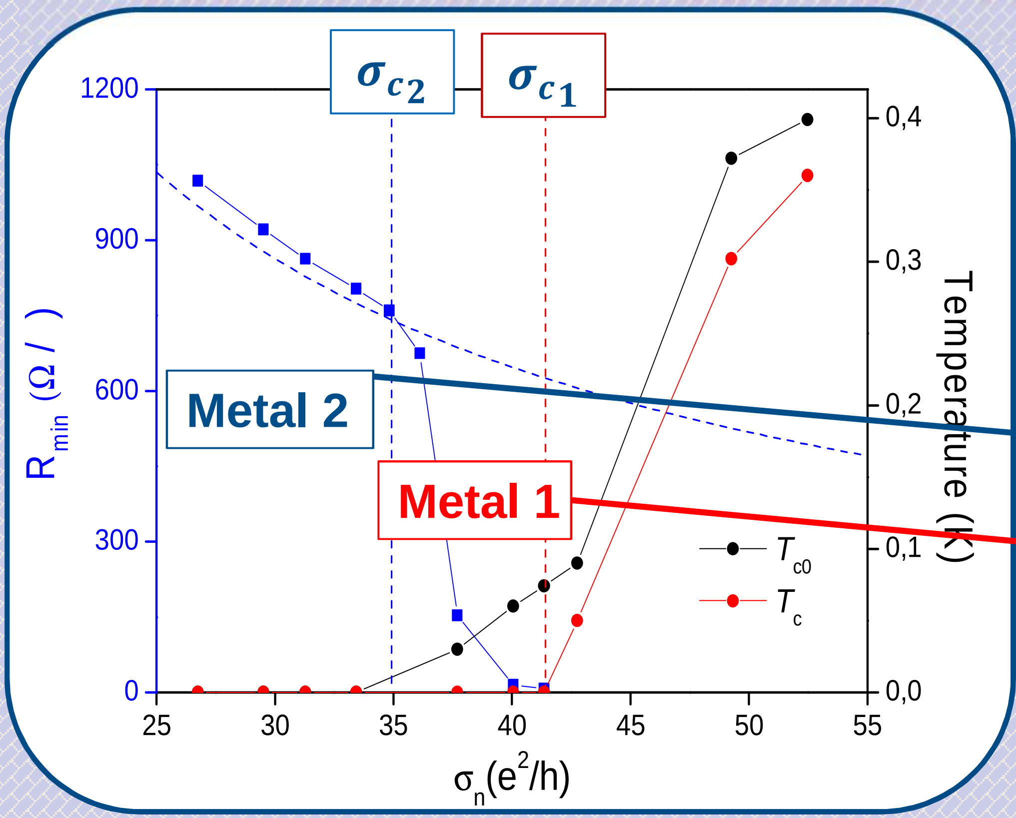
$R_{min} = R_{\square}(10\ mK)$

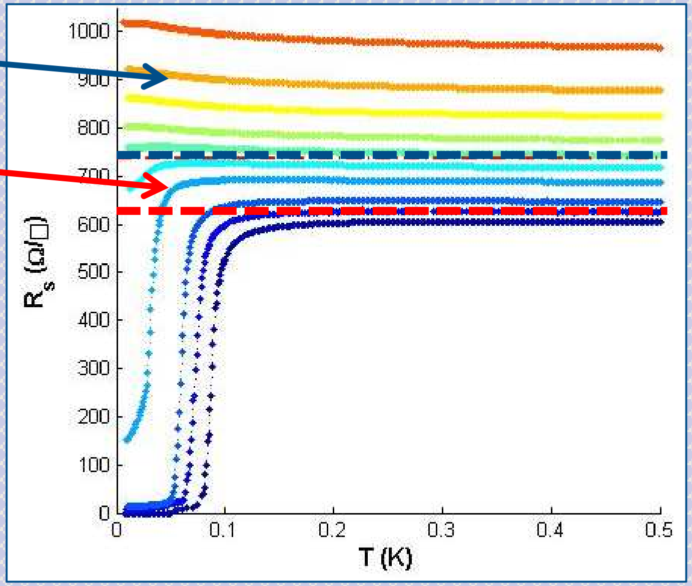
T_{c0} : Inflexion Point



Change of sign of the TCR $= \frac{dR}{dT}$

« METAL 1 » - « METAL 2 » TRANSITION

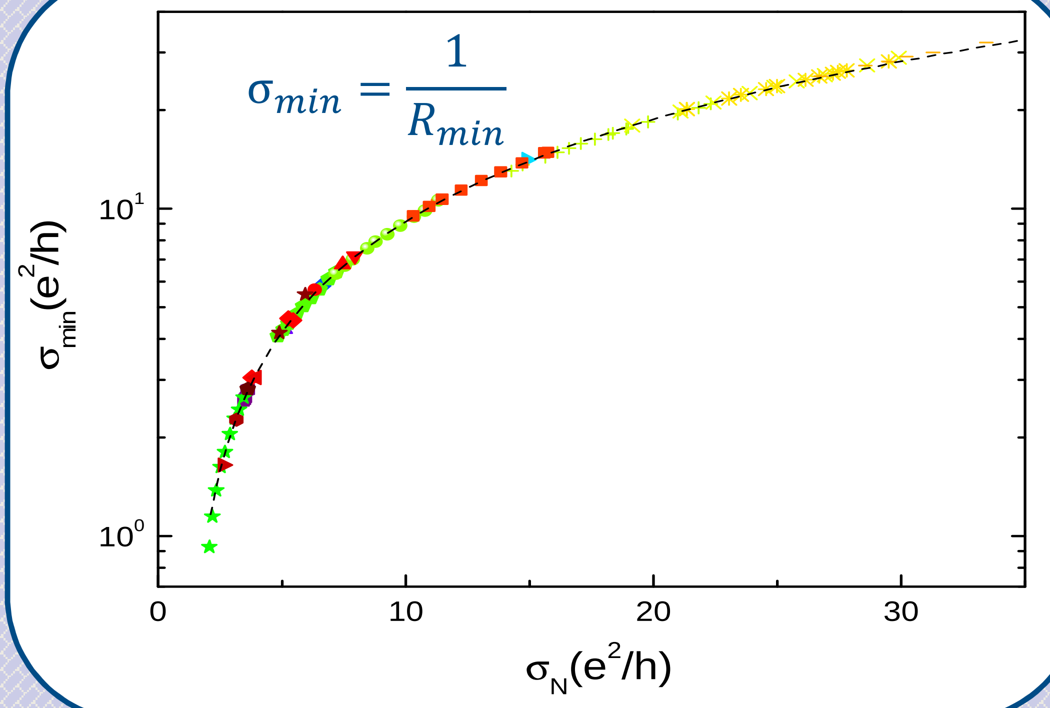




2 dissipative regimes separating the Superconducting and Insulating ground states

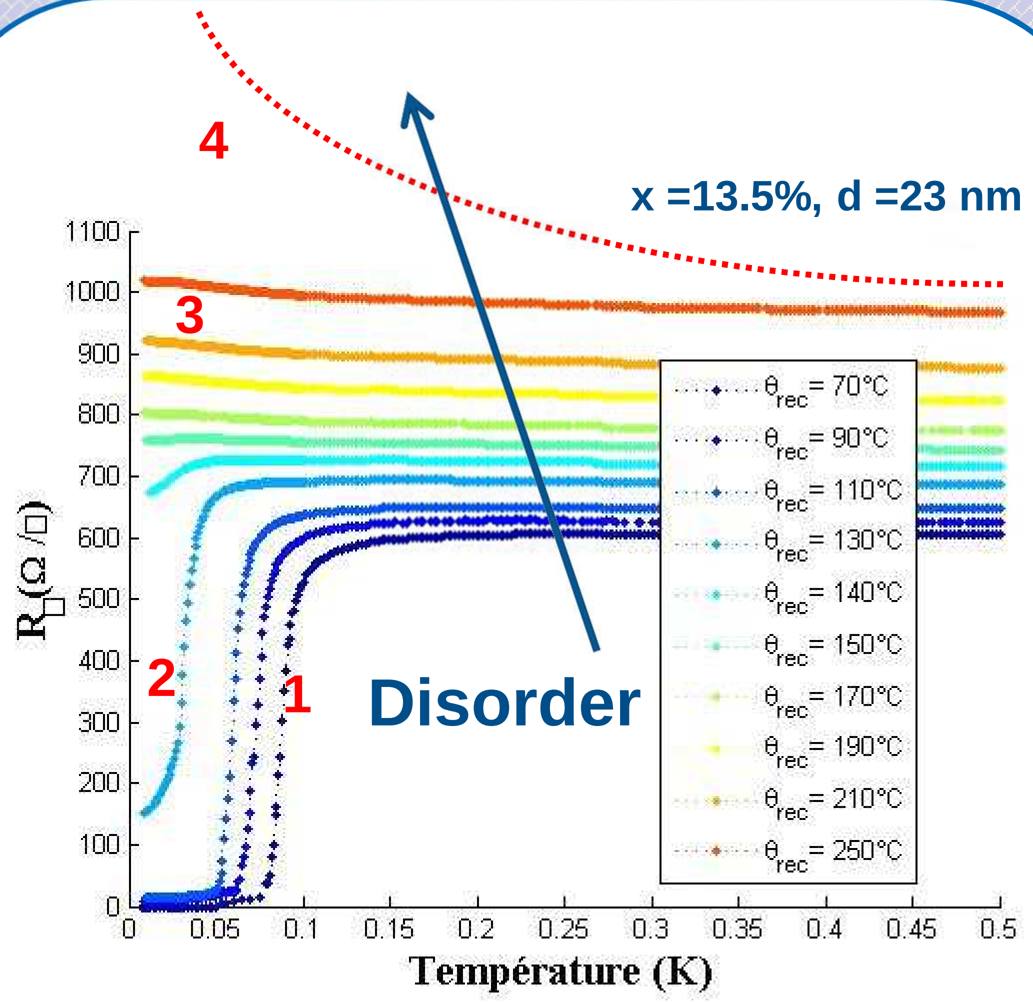
« METAL 2 » PHASE

Universal behavior of R_{min}



- **Universal** behavior (x, d, Θ)
- Vanishing of σ_0 at the Ioffe-Regel limit $\mathbf{k_F l} \approx 1$

4 DISTINCT REGIMES



At $T \to 0$

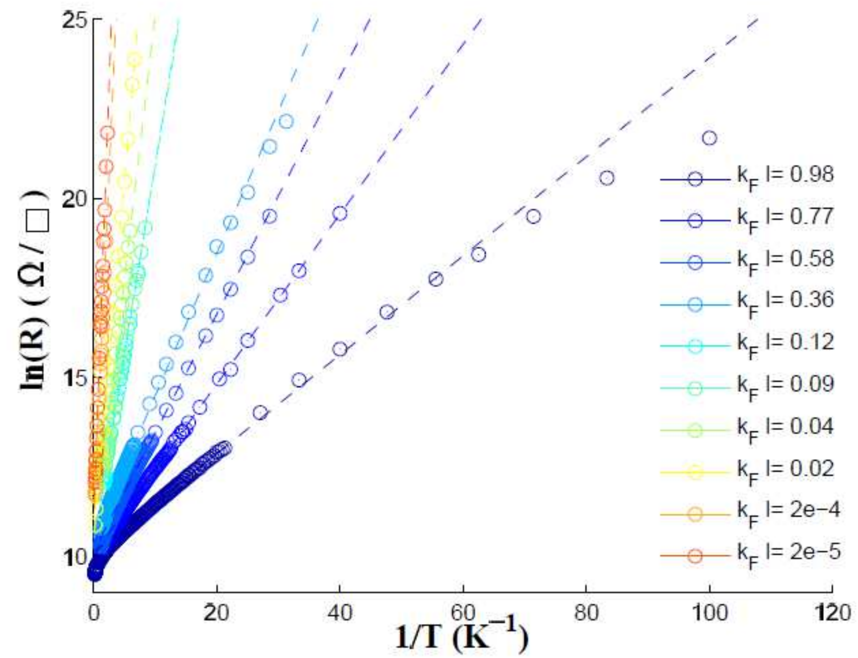
1 – Superconductor (R=0)
2 – Finite R & TCR > 0
3 – Finite R & TCR < 0
4 – Insulator

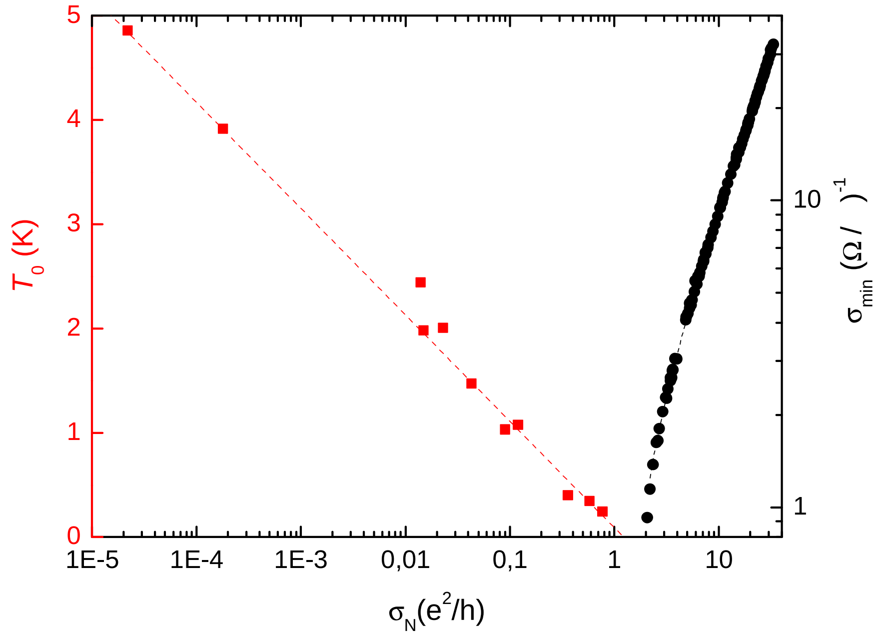
Disorder measured by :

$$R_{\square,N} = R_\square(500\ \text{mK})$$

« METAL 2 » - INSULATOR TRANSITION

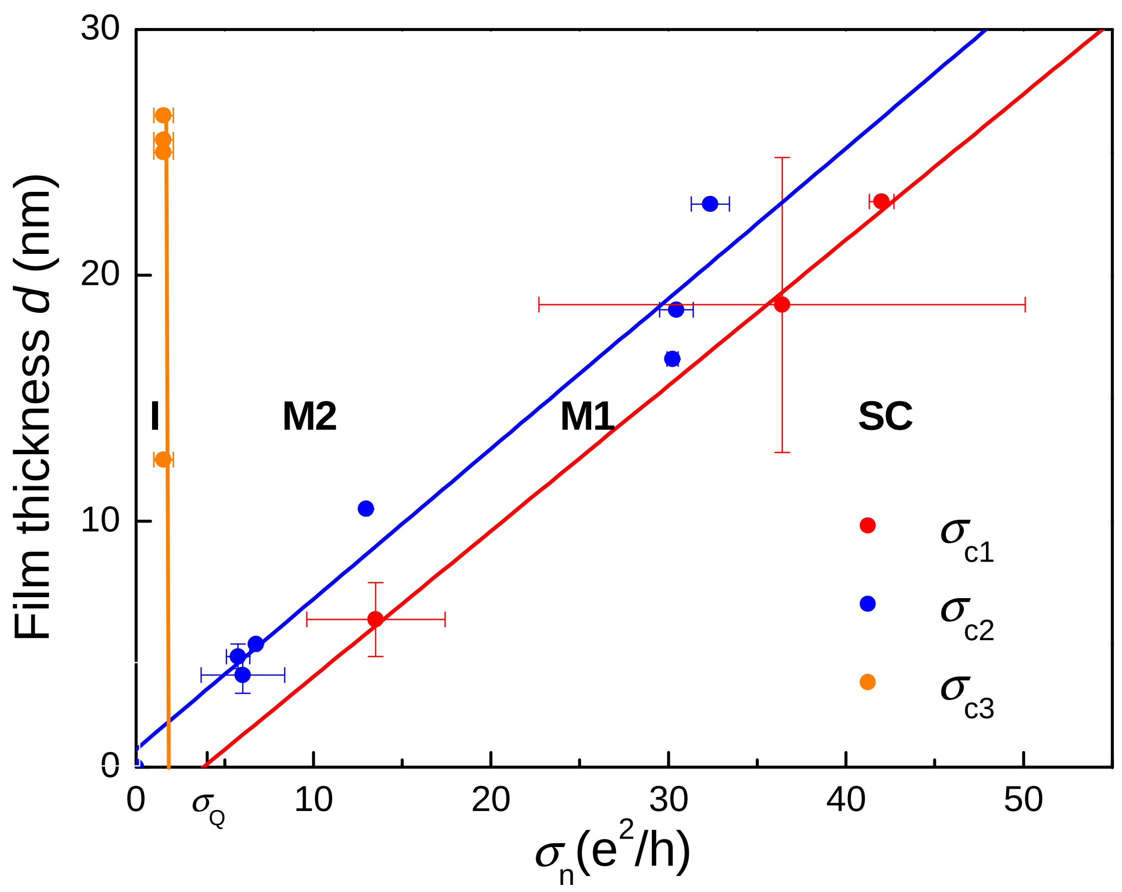
Energy scale T_0



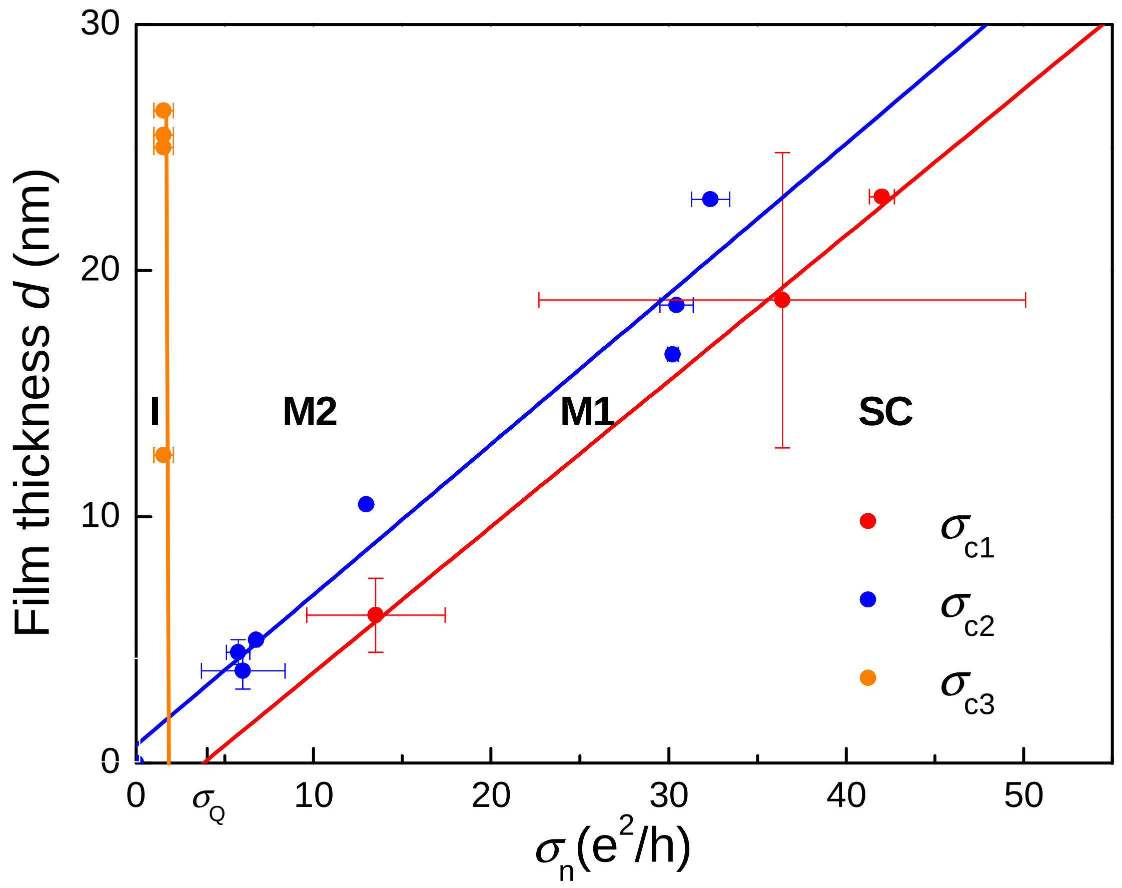


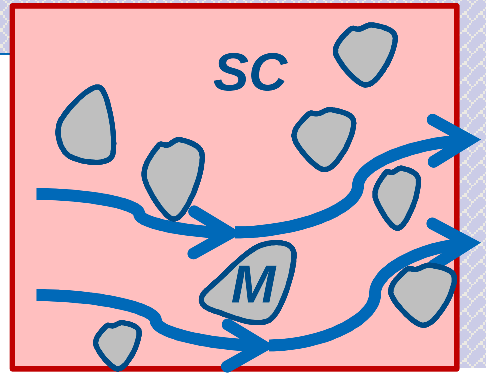
Vanishing of the T_0 and σ_{min} at $(\mathbf{k_F l})_3 \approx 1$

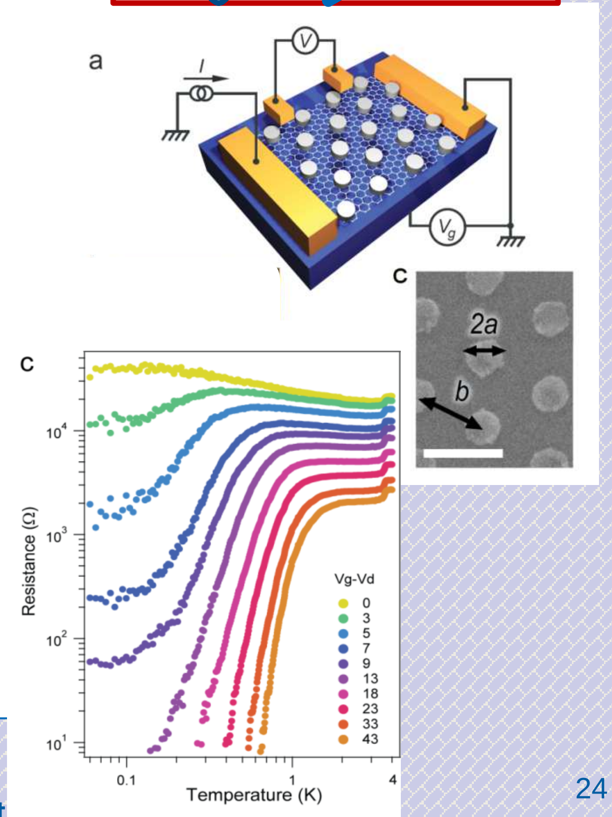
PHASE DIAGRAM



PHASE DIAGRAM



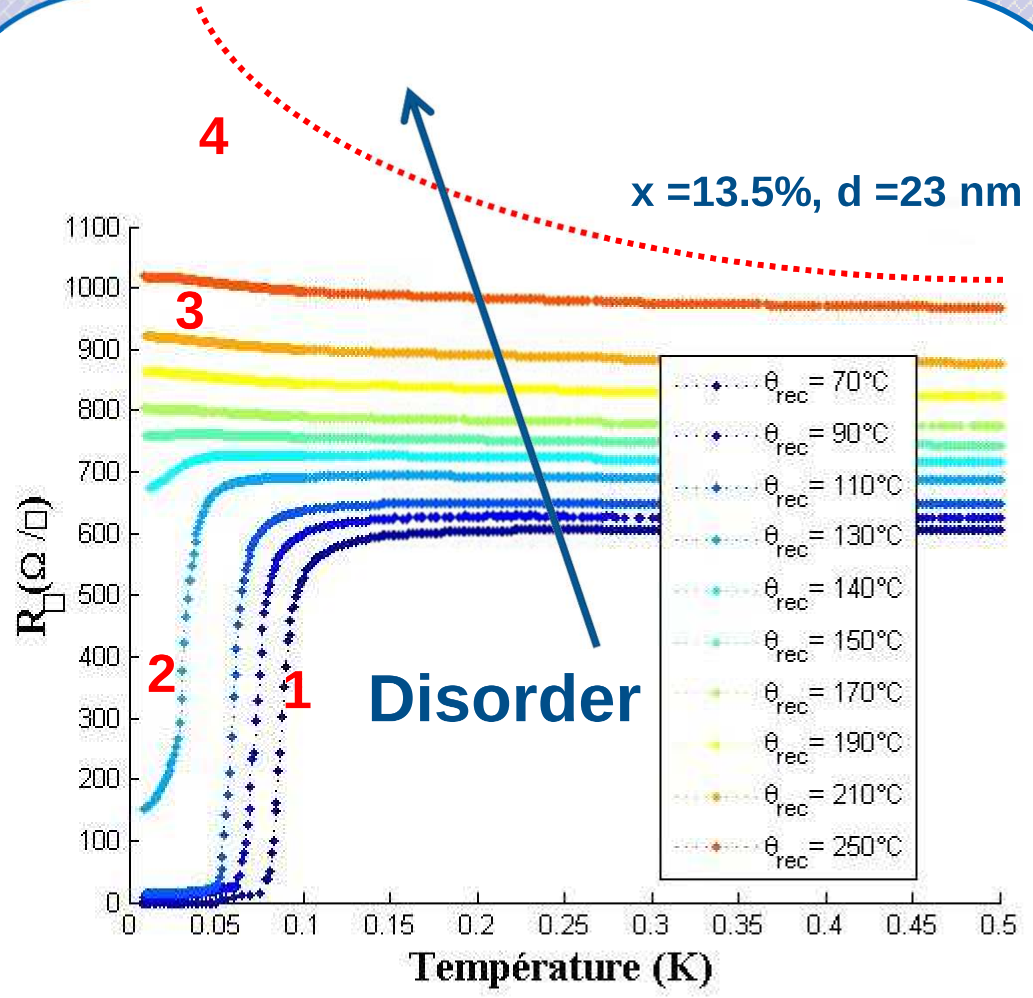




Han et al. *Nat. Phys.* **10** 380 2014

ONSET OF THE INSULATING REGIME

4 DISTINCT REGIMES



At $T \longrightarrow 0$

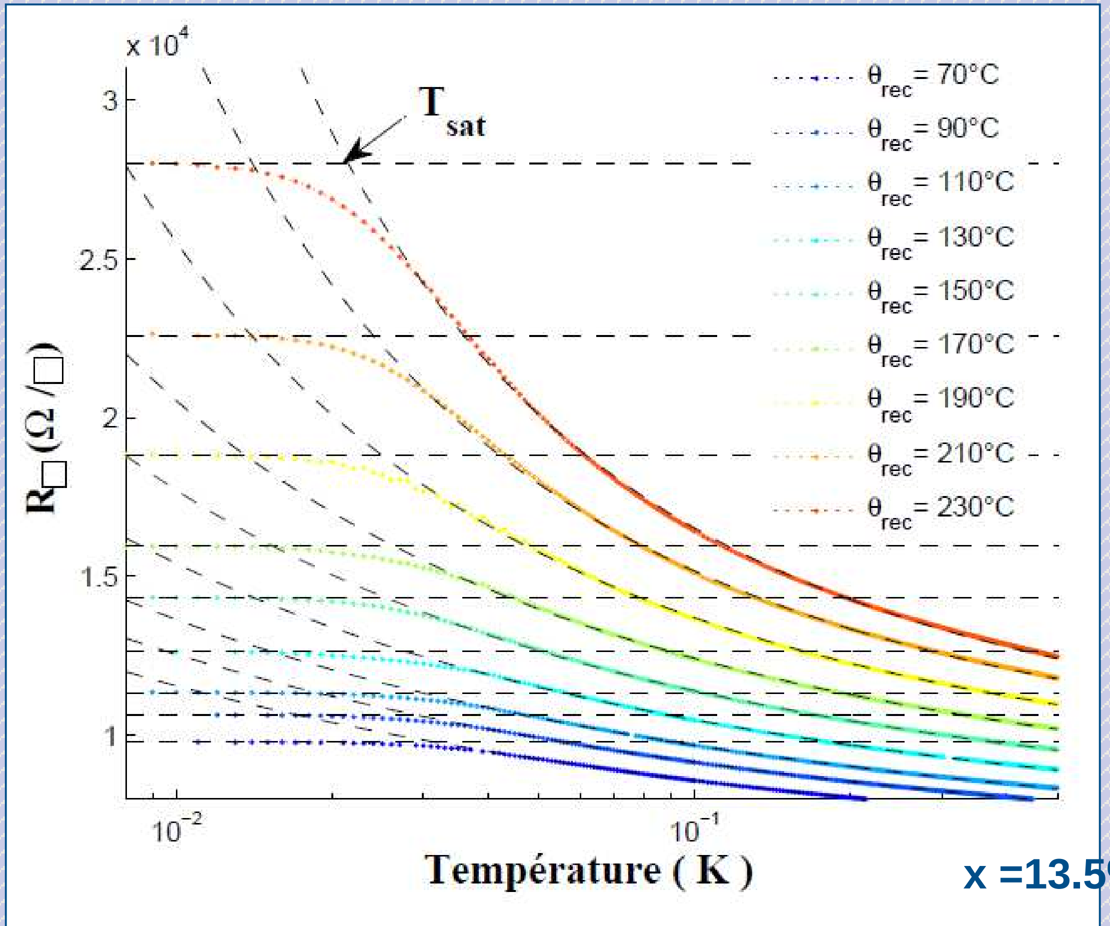
1 – Superconductor (R=0)
2 – Finite R & TCR > 0
3 – Finite R & TCR < 0
4 – Insulator

Disorder measured by :

$$R_{\square,N} = R_{\square}(500\ \mathrm{mK})$$

ONSET OF THE INSULATING REGIME

From the Metal 2 phase

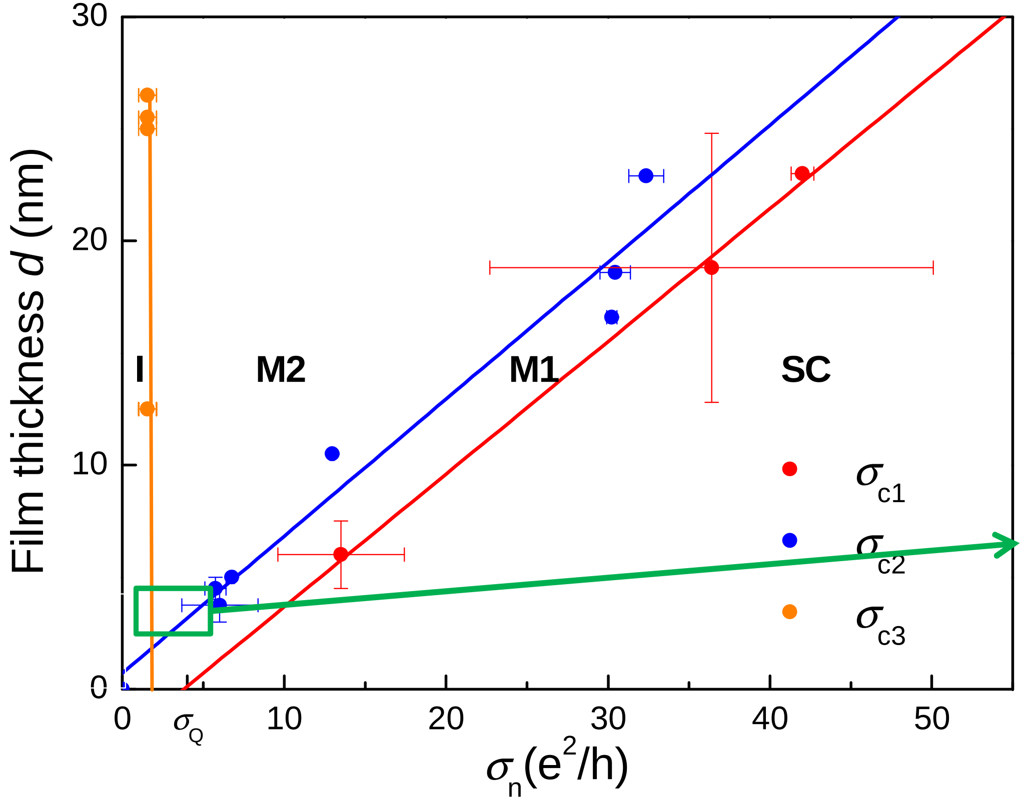


x =13.5%, d = 5 nm

- **How does the « Metal 2 » phase evolve towards an insulating regime ?**
- **Are there any signature of localization in the « Metal 2 » regime ?**

SAMPLES

Near the « Metal 2 » - Insulator transition



x= 13.5 %

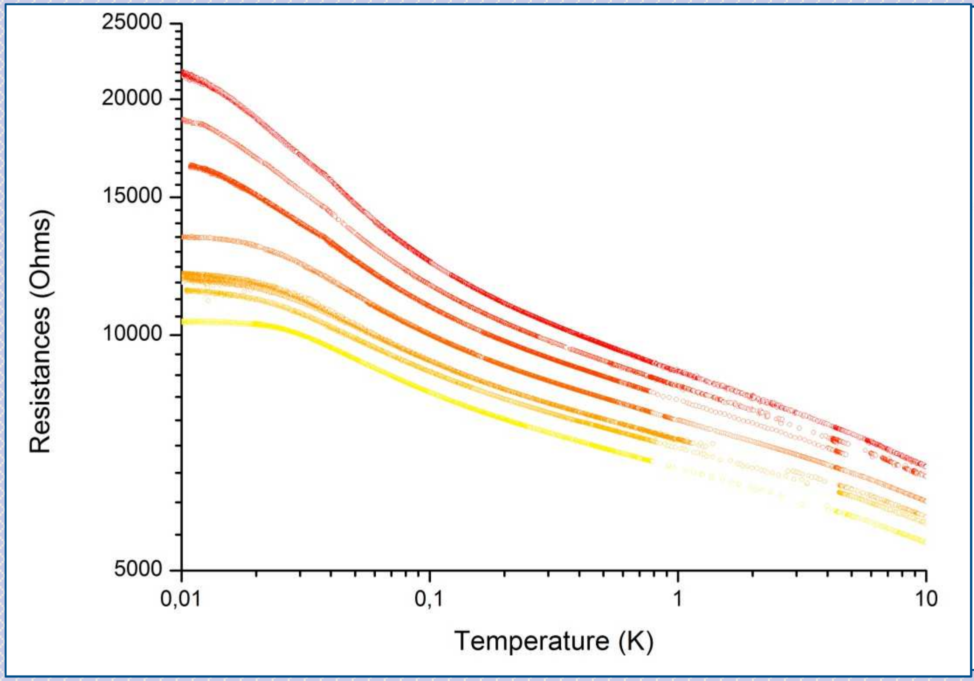
6 Films with d= [2, 5 nm]

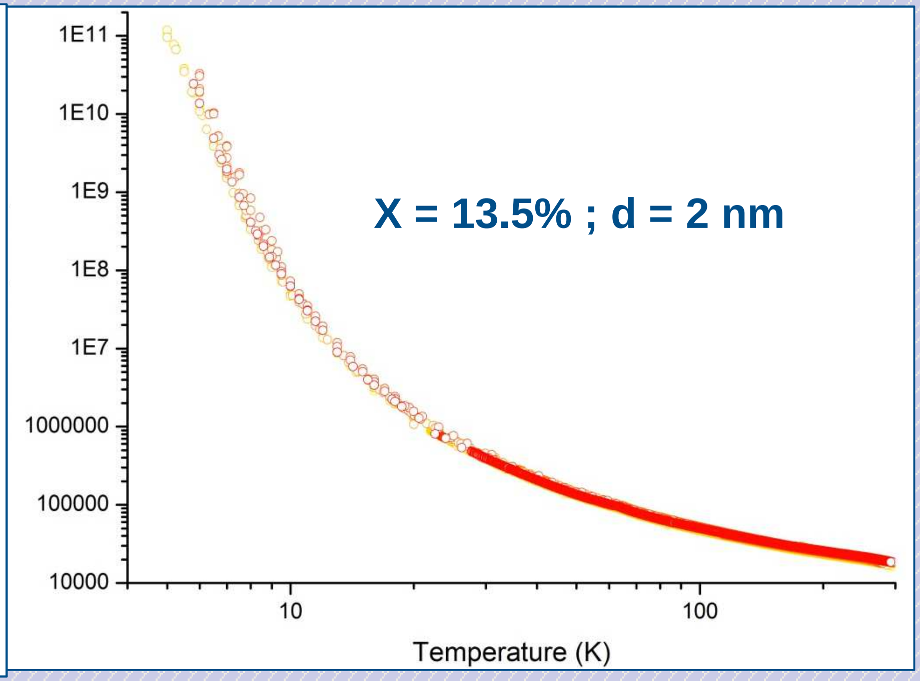
EVOLUTION WITH ANNEALING

Annealing Θ = 70°C – 150°C

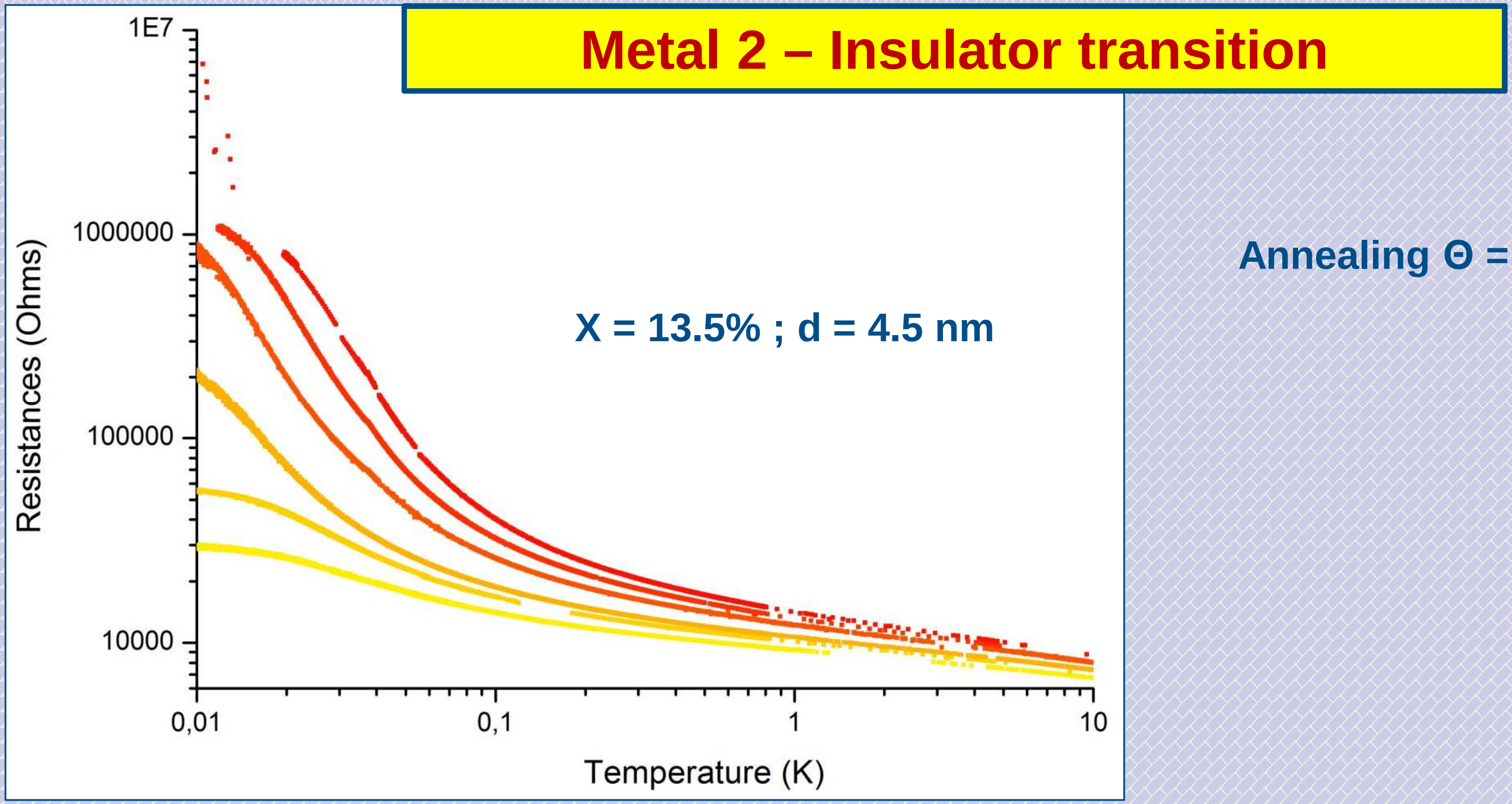
Metal 2

Insulator





EVOLUTION WITH ANNEALING

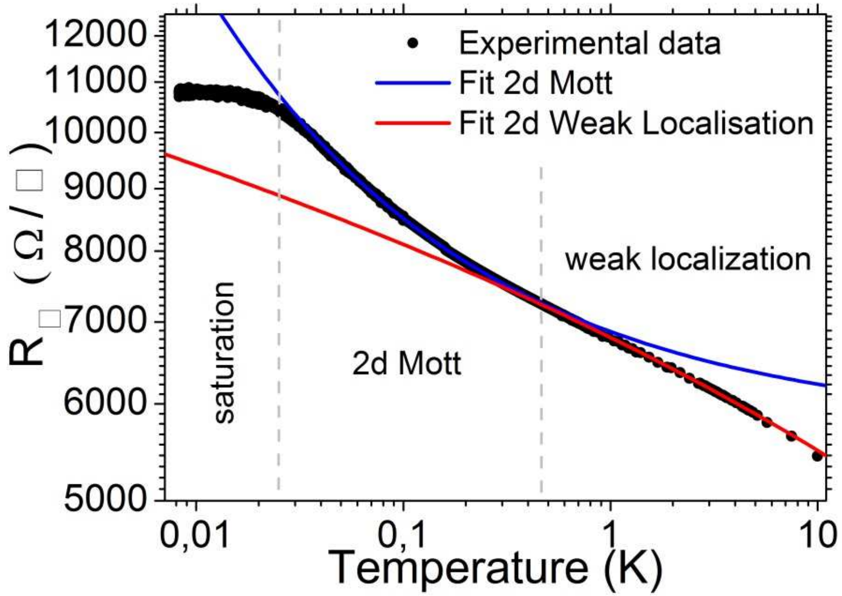


Annealing Θ = 70°C – 150°C

R(T) EVOLUTION

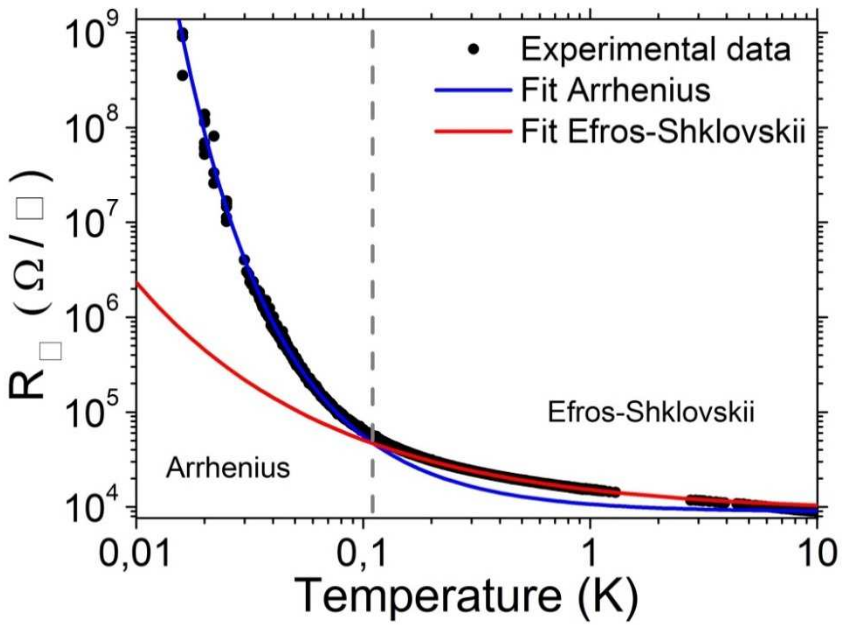
$$R = R_0 e^{-\left(\frac{T}{T_0}\right)^n}$$

Metal 2



Resistance saturating at low temperature

Insulator

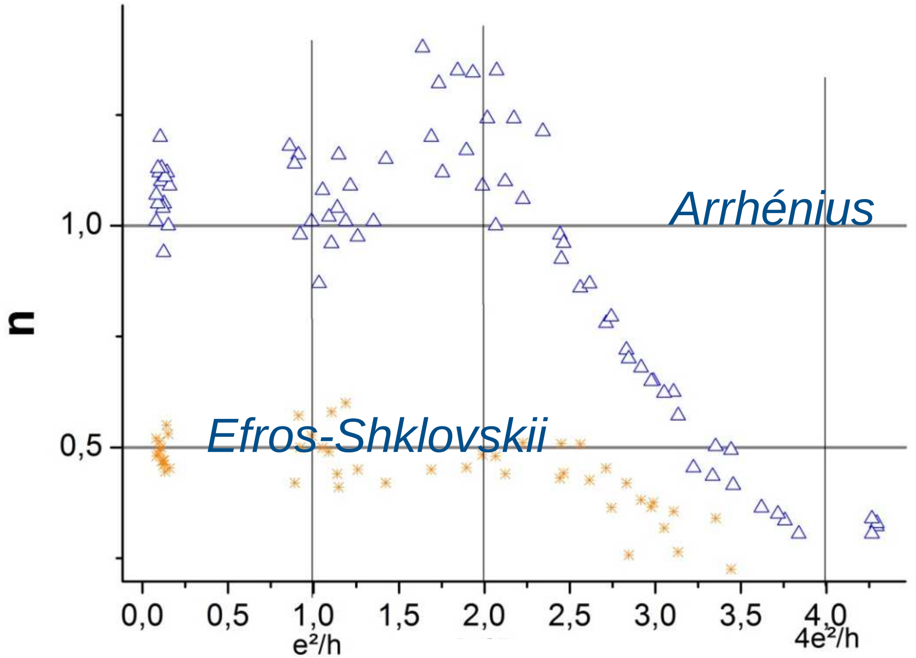


Insulating even at the lowest temperatures

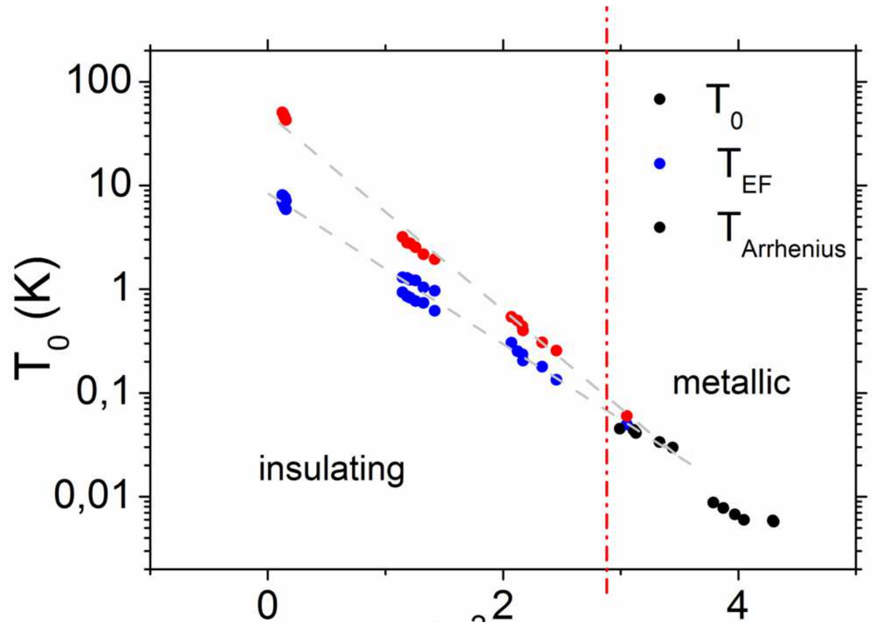
	Weak loc	Strong loc
2d	$\alpha \ln(T)$	Exp[(-T/T0)^n]

R(T) EVOLUTION

$$R = R_0 e^{-\left(\frac{T}{T_0}\right)^n}$$

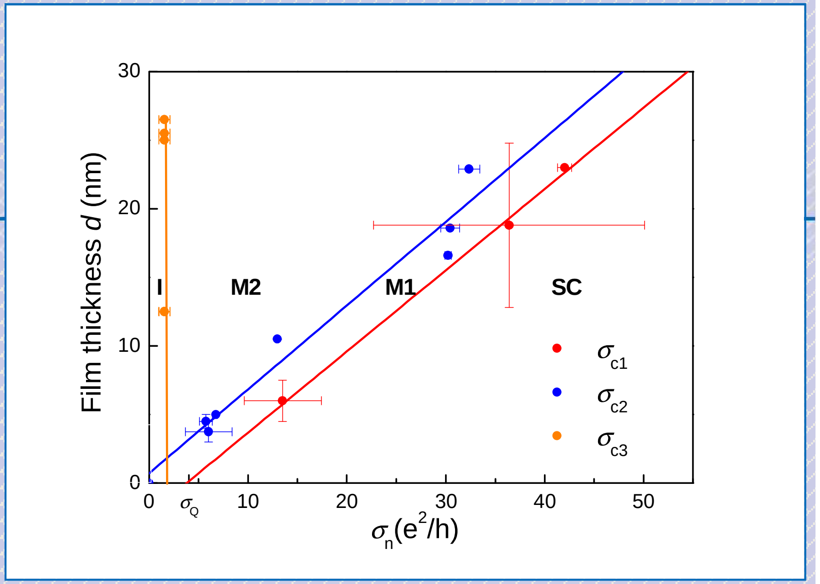


$\sigma_{4K}\ (\frac{e^2}{h})$



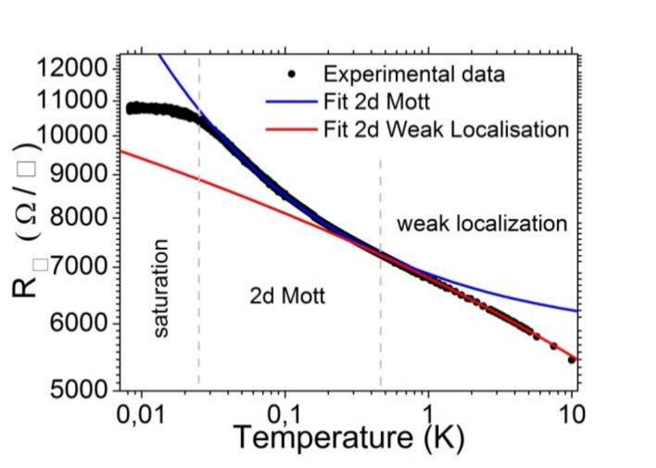
$\sigma_{4K}\ (\frac{e^2}{h})$

SUMMARY



- 2 dissipative phases observed, possibly linked to inhomogeneous electronic phases

- Gradual evolution from metallic to insulating phase



THANK YOU FOR YOUR ATTENTION !