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International Centre for Theoretical Physics*



**2035-4**

**Conference on Superconductor-Insulator Transitions**

*18 - 23 May 2009*

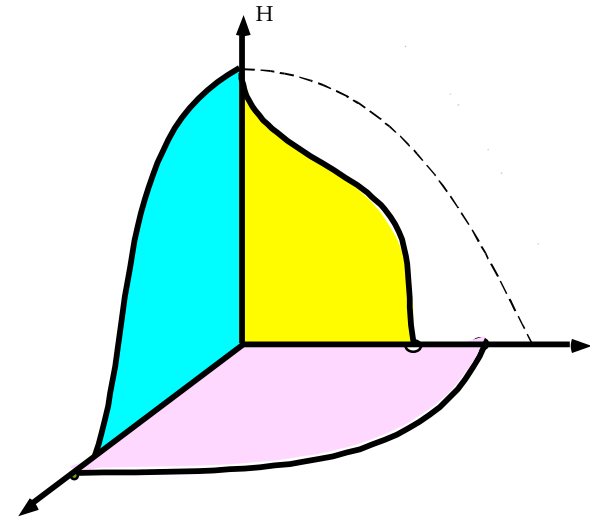
**Critical behavior near the superconductor-insulator transitions in two-dimensions**

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Stanford University  
USA*

# *Some Aspects of the Superconductor-Insulator Transition*



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## **Collaborators:**

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Myles Steiner

Nicholas Breznay

Mac Beasley

Steve Kivelson

Efrat Shimshoni

Assa Auerbach

Sudip Chakravarty

# Importance of phase fluctuations for two-dimensional superconductors:

The superconducting order parameter:  $\Psi(\vec{r}) = |\Psi(\vec{r})|e^{i\phi(\vec{r})}$

For BCS - Eliashberg theory  $\phi$  is not important to determine the transition -  $T_{c0}$ .

When are phase fluctuations important?

- \* Introduce the temperature  $T_\phi$  that gives the scale of “phase stiffness”

- \*The Hamiltonian  $\mathcal{H}$  governing the effects of long wavelength phase fluctuations is the kinetic energy of the superfluid

$$\mathcal{H} = \frac{1}{2}m^*|\Psi|^2a \int d\vec{r} v_s^2(\vec{r})$$

There is also a short distance cutoff -  $a$

with:  $v_s = \frac{\hbar}{2m^*} \nabla \phi$

$T_\phi$  is given by:

$$k_B T_\phi \approx \frac{\hbar^2}{4m} |\Psi|^2 a = \frac{(\hbar c)^2 a}{16\pi e^2 \lambda^2}$$

If  $T_\phi/T_{c0} \gg 1$  phase fluctuations are not important

If  $T_\phi/T_{c0} \ll 1$  phase fluctuations **are** important

Examples:

- ◆ Pb -  $T_\phi/T_{c0} \sim 10^5$
- ◆ High-Tc -  $T_\phi/T_{c0} \sim 10 - 100$

- ◆ 2-D superconductors -  $T_\phi/T_{c0} \sim 1$

**phase fluctuations are important in 2-D**

What about quantum phase fluctuations?  
These are associated with the uncertainty:

$$\Delta n_s \Delta \phi \geq 1$$



**Phase coherence implies large coulomb energies** (unless screening)

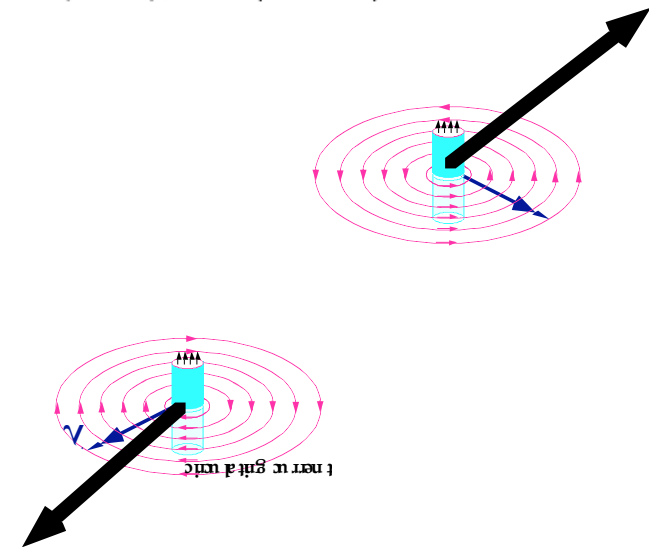
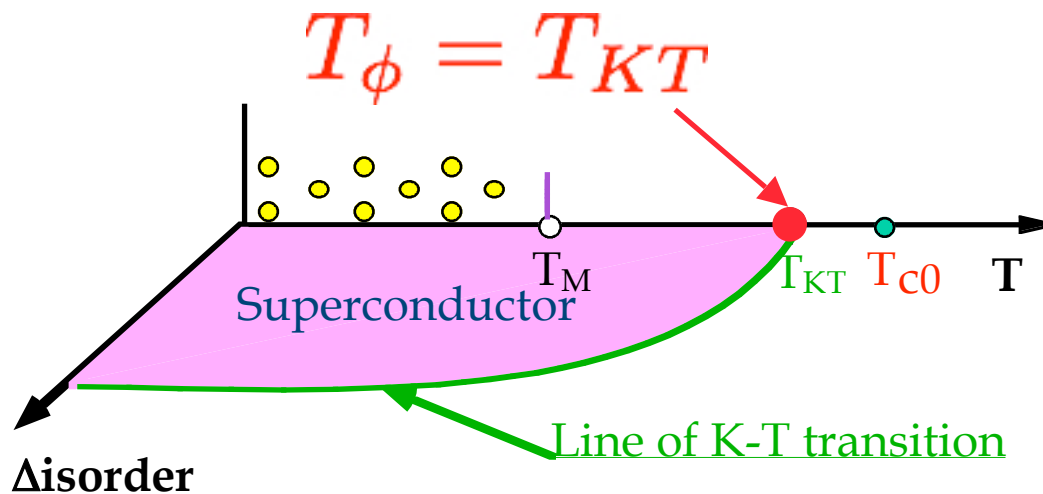
# Zero Magnetic-Field

Superconductivity is established below the **Kosterlitz-Thouless transition**

$$k_B T_\phi \approx \frac{\hbar^2}{4m} |\Psi|^2 a = \frac{(\hbar c)^2 a}{16\pi e^2 \lambda^2}$$

Setting  $a = d$  (film thickness):

$$T_{KT} = k_B^{-1} \left( \frac{\hbar c}{2e} \right)^2 \frac{2d}{(4\pi\lambda)^2}$$



J. M. Kosterlitz & D. J. Thouless,, Journal of Physics C: Solid State Physics 6, 1181-1203 (1973).

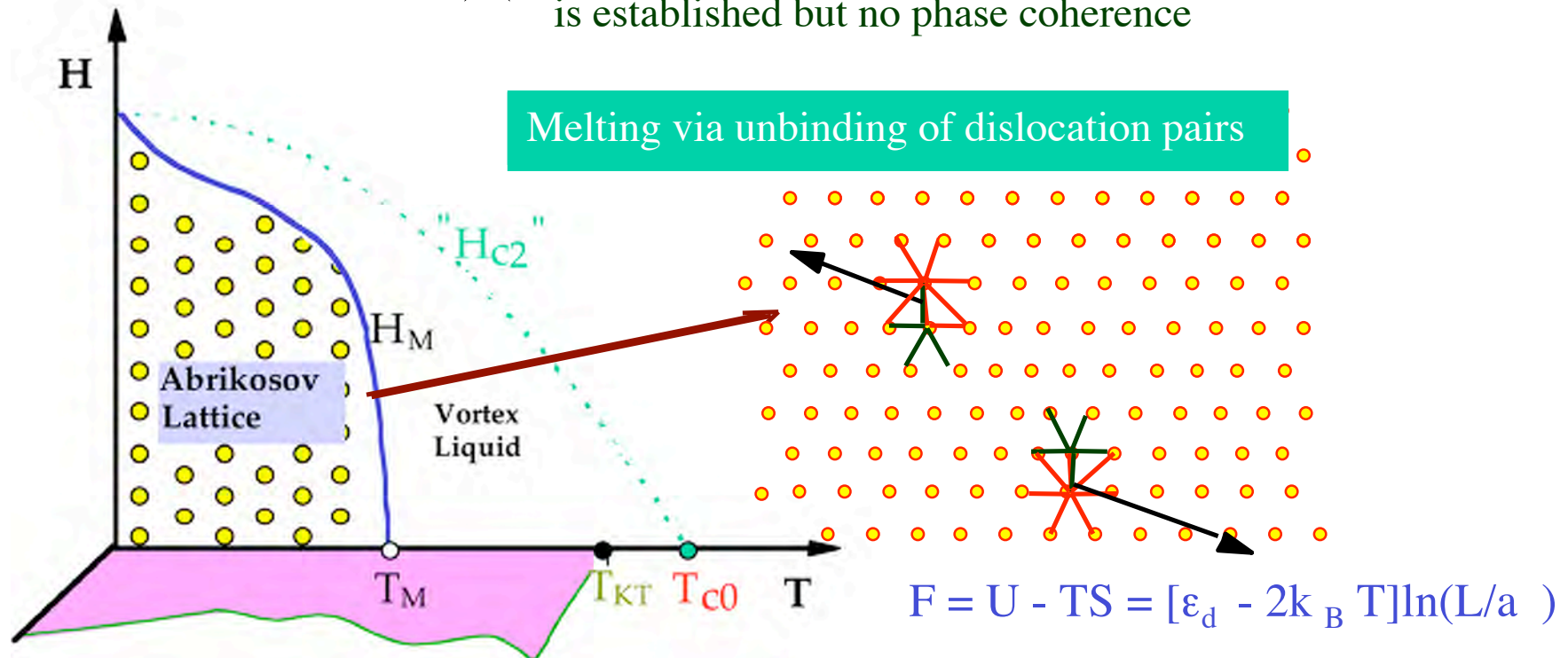
S. Doniach and B.A. Huberman, Phys. Rev. Lett. 42, 1169 (1979).

# Finite Magnetic Field

(no disorder)

Superconductivity is established below the melting transition:  
again a **Kosterlitz-Thouless Transition**\*

★  $H_{c2}$  is only a crossover field below which pair amplitude is established but no phase coherence



B.A. Huberman and S. Doniach, Phys. Rev. Lett. 43, 950 (1979).

D. S. Fisher, Phys. Rev. B 22, 1190 (1980).

\* Experimentally this was shown by: A. Yazdani, W.R. White, M.R. Hahn, M. Gabay, M.R. Beasley, and A. Kapitulnik, Phys. Rev. Lett. 70 (1993), 505.

## Effect of disorder:

- \* **Larkin, 1970; Larkin & Ovchinnikov, 1979**

With disorder (pinning), positional long range order is lost:  
New length scale that describes by how much the disorder perturbs the positional order  $R_c$

At  $R_c$  the cumulative displacement is  $\sim \xi$

- \* **Feigelman et al., 1991**

For dislocations in 2-D the relevant length scale is:

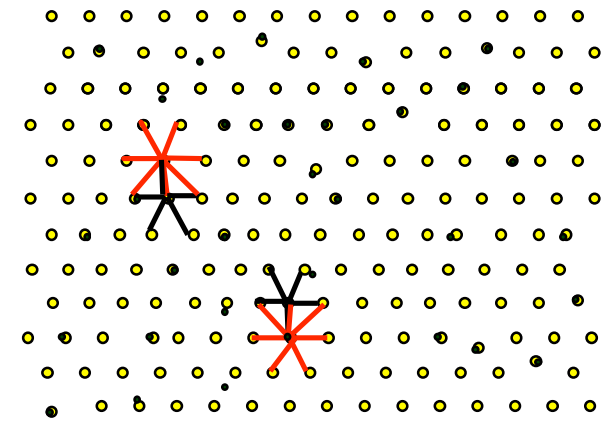
$$R_d \sim R_c \left( \frac{a_0}{\xi} \right) \gg R_c$$

At  $R_d$  the cumulative displacement is  $\sim a_0$

- \* **Tonner, 1992**

Orientational order is also lost with disorder

In the presence of disorder: for  $H > 0$  and finite  $T$  there is no true superconducting phase

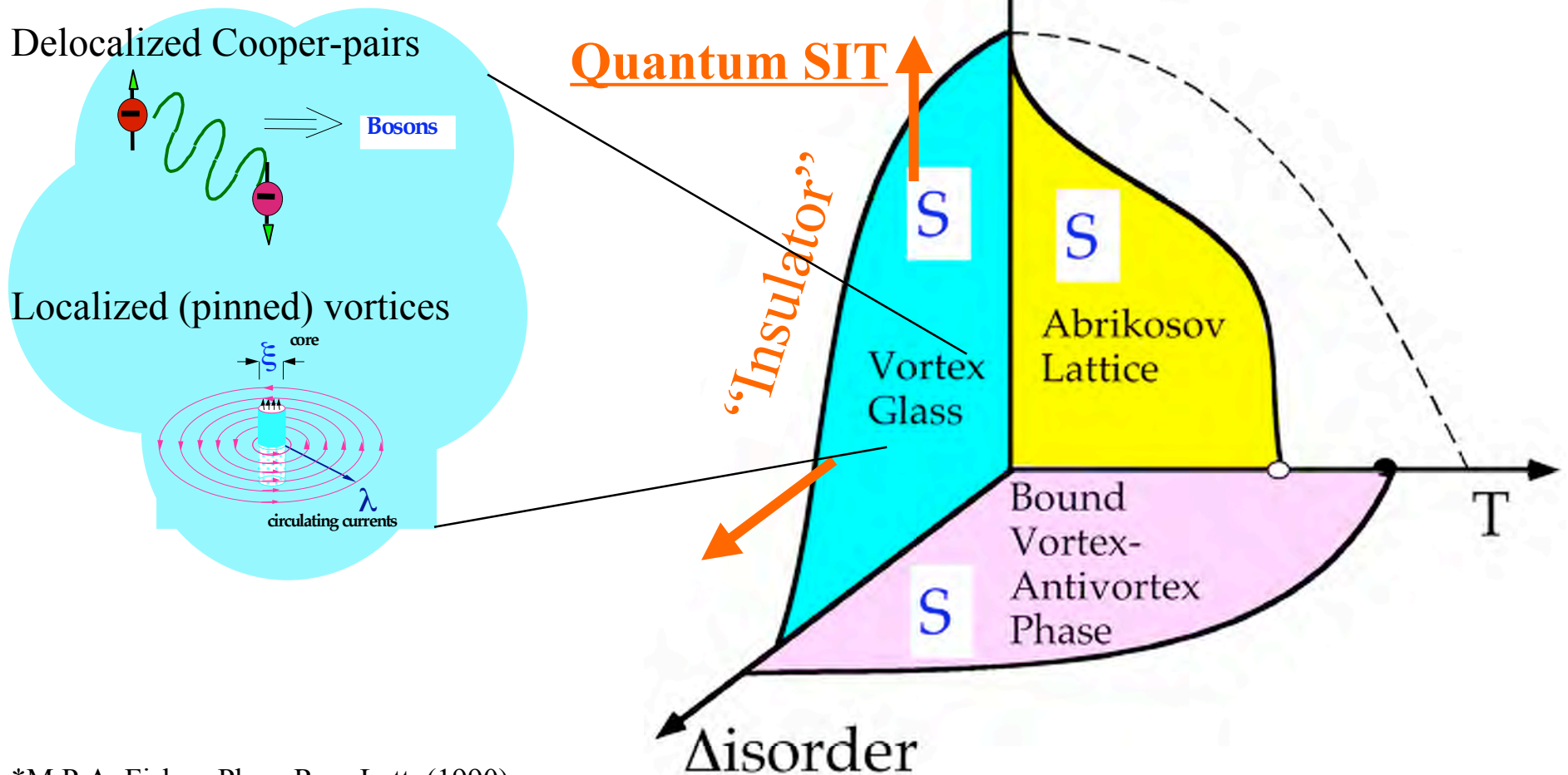


Vortex lattice gets distorted due to pinning - dislocation pairs are induced

# Summary Phase Diagram:

Superconducting phases exist only on the planes ( $H$ - $T$ ,  $\Delta$ - $T$ ,  $H$ - $\Delta$ )

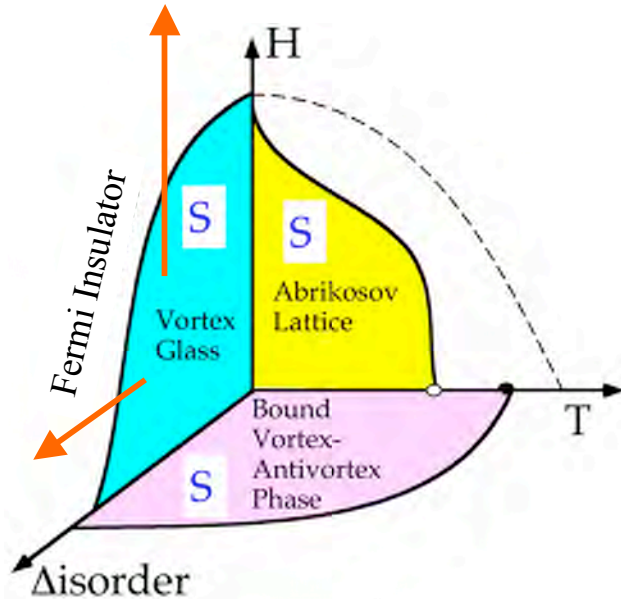
## Vortex Glass:



\*M.P.A. Fisher, Phys. Rev. Lett. (1990)

# Two possible Superconductor-“Insulator” Transition at $T=0$ :

## Superconductor $\rightarrow$ Fermi-Insulator

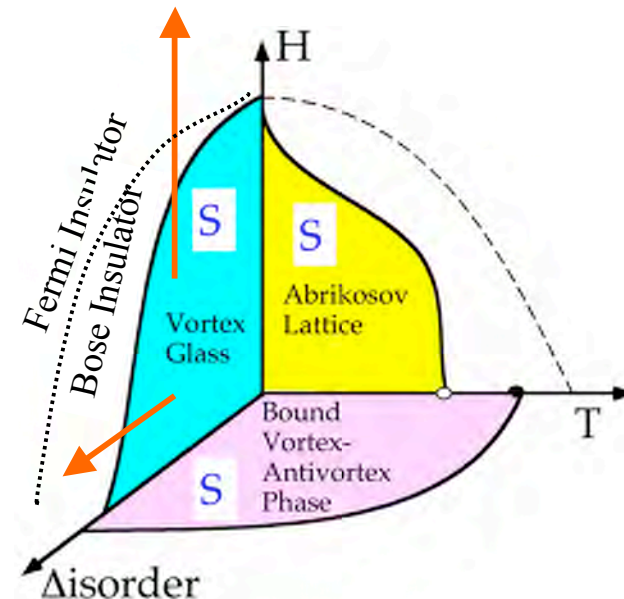


1) Superconductivity is destroyed by disappearance of Cooper pairs altogether. Cooper attraction is reduced due to Large Coulomb interaction. \*

\* A.M. Finkelstein, JETP Lett. 45, 46 (1987).

This model however neglects quantum fluctuations of the Bosonic field! **Free electrons exist!**

## Superconductor $\rightarrow$ Bose-Insulator



2) Bosons in a random potential. Pairs can become localized due to coulomb repulsion.

**Equivalent to array of Josephson-Junctions ( $E_J$  vs.  $E_C$ ).** \*

\* M.P.A. Fisher, Phys. Rev. Lett. (1990).

**No free electrons exist!**

We will argue below that in disordered thin films the transition will always be phase-dominated.  
(analyze data in terms of Superconductor to Bose-Insulator Transition)

We will argue below that in disordered thin films the transition will always be phase-dominated. (analyze data in terms of Superconductor to Bose-Insulator Transition)

## A note about the disorder axis:

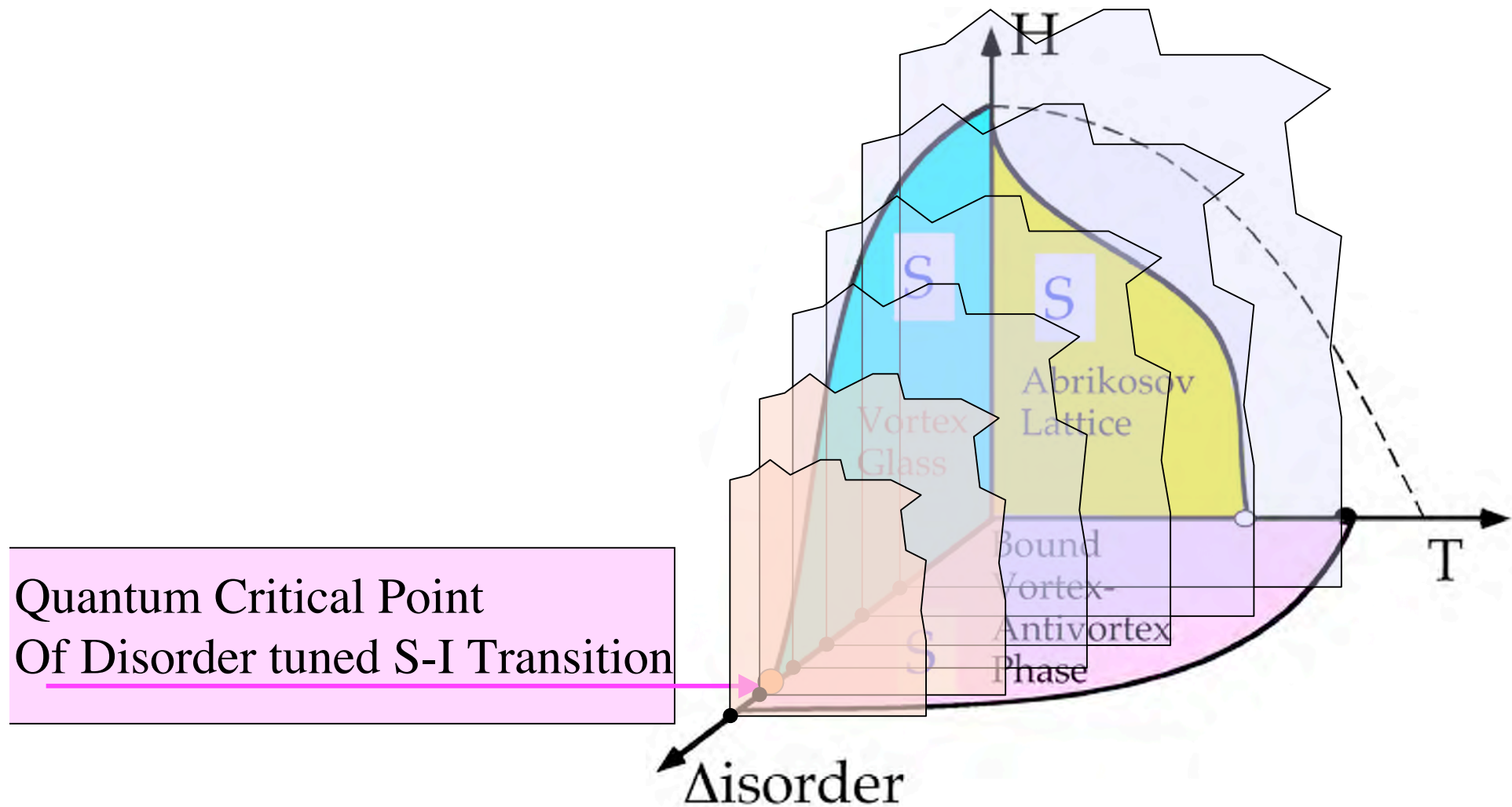
While in general the disorder axis is taken as proportional to  $R_{\text{square}}$ , we note that since vortices are involved, this **may not** be an accurate measure of the disorder.

\*for example, a very homogeneous, large- $R_{\text{square}}$  film will pin vortices very poorly and may therefore overestimate the disorder. Similarly, lower- $R_{\text{square}}$  films that are granular in nature may underestimate the disorder because of their ability for strong pinning.

With this observation, we will argue that all films, whether granular or uniform (and become granular due to phase separation and puddle formation), are in the same universality class with respect to the SIT and the behavior near it.

# Disorder tuned S-I Transition

In experiment one fabricate films where the disorder is fixed



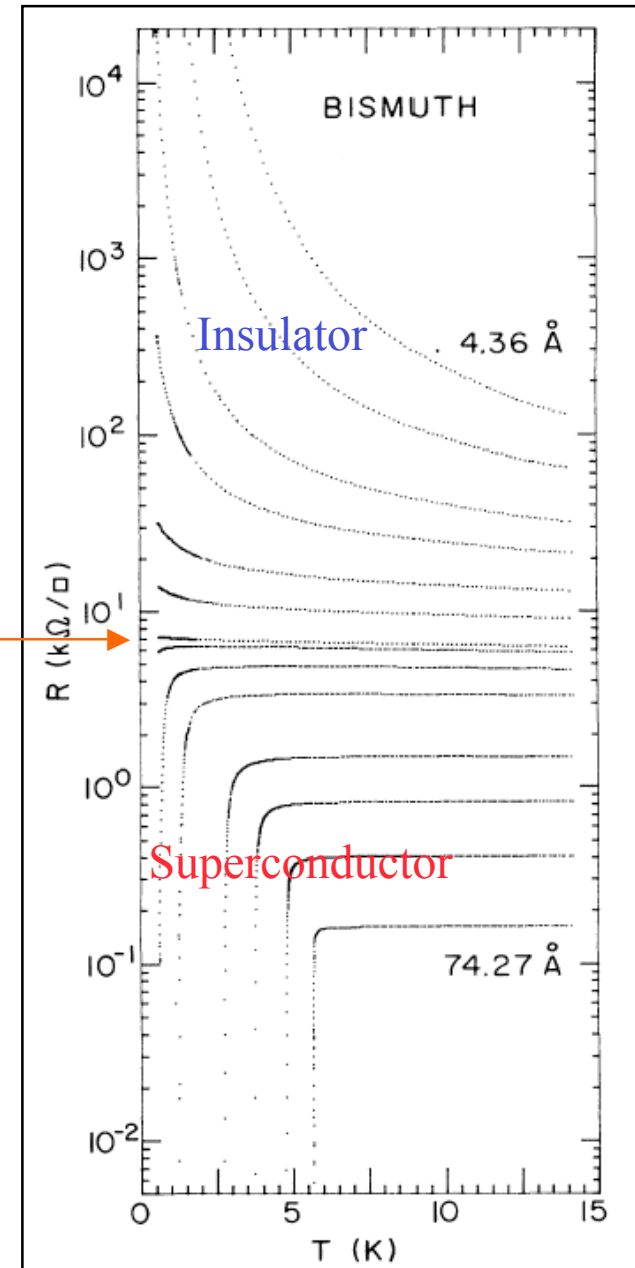
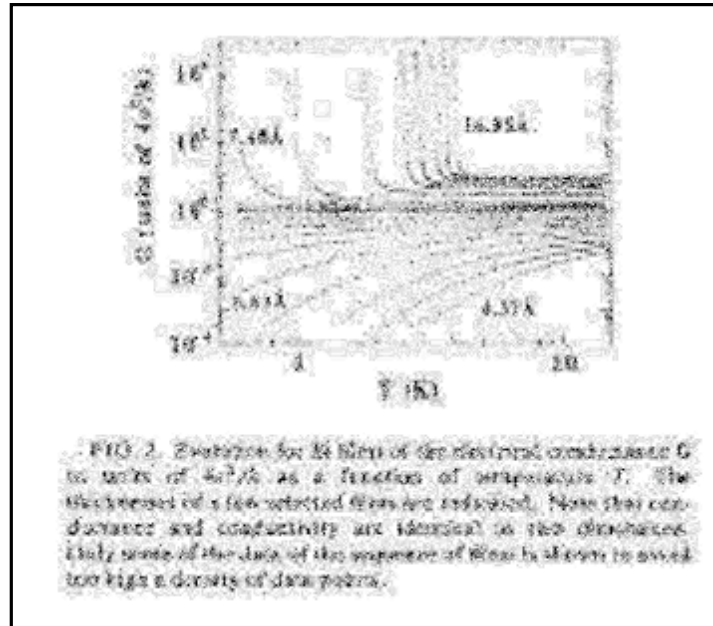
# Onset of Superconductivity in the Two-Dimensional Limit

D. B. Haviland, Y. Liu, and A. M. Goldman

Experiments on Bi layer grown on amorphous Ge

Disorder is varied by  
changing film thickness

$R_c$



**Threshold for superconductivity in ultrathin amorphous gallium films**

H. M. Jaeger, D. B. Haviland, and A. M. Goldman

*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455*

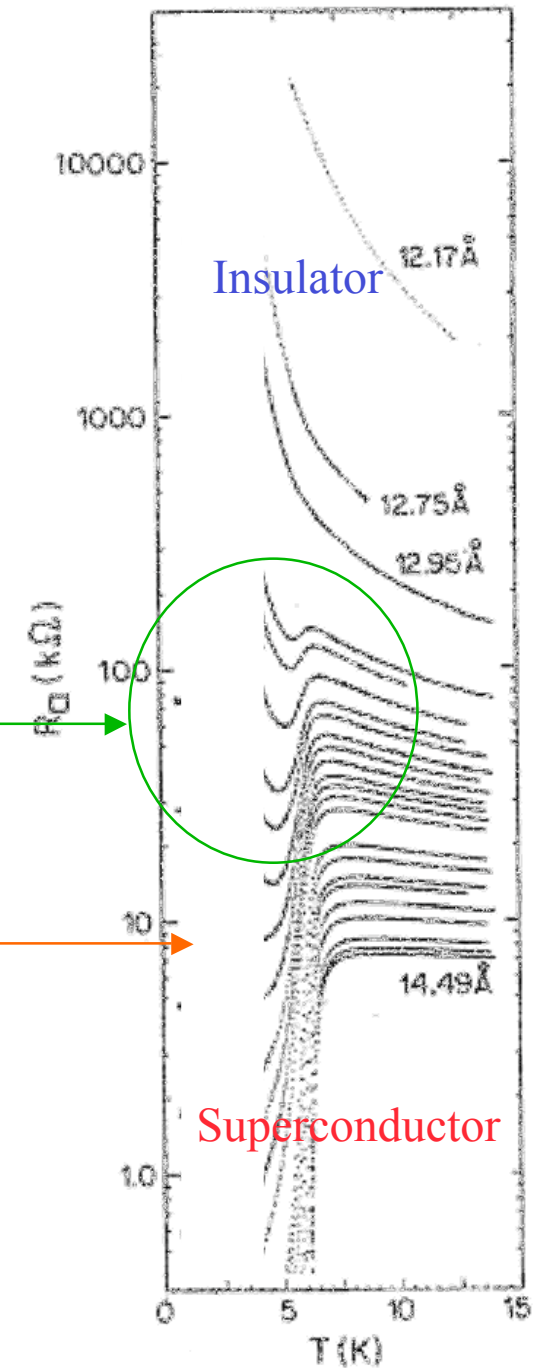
B. G. Orr

*IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598*

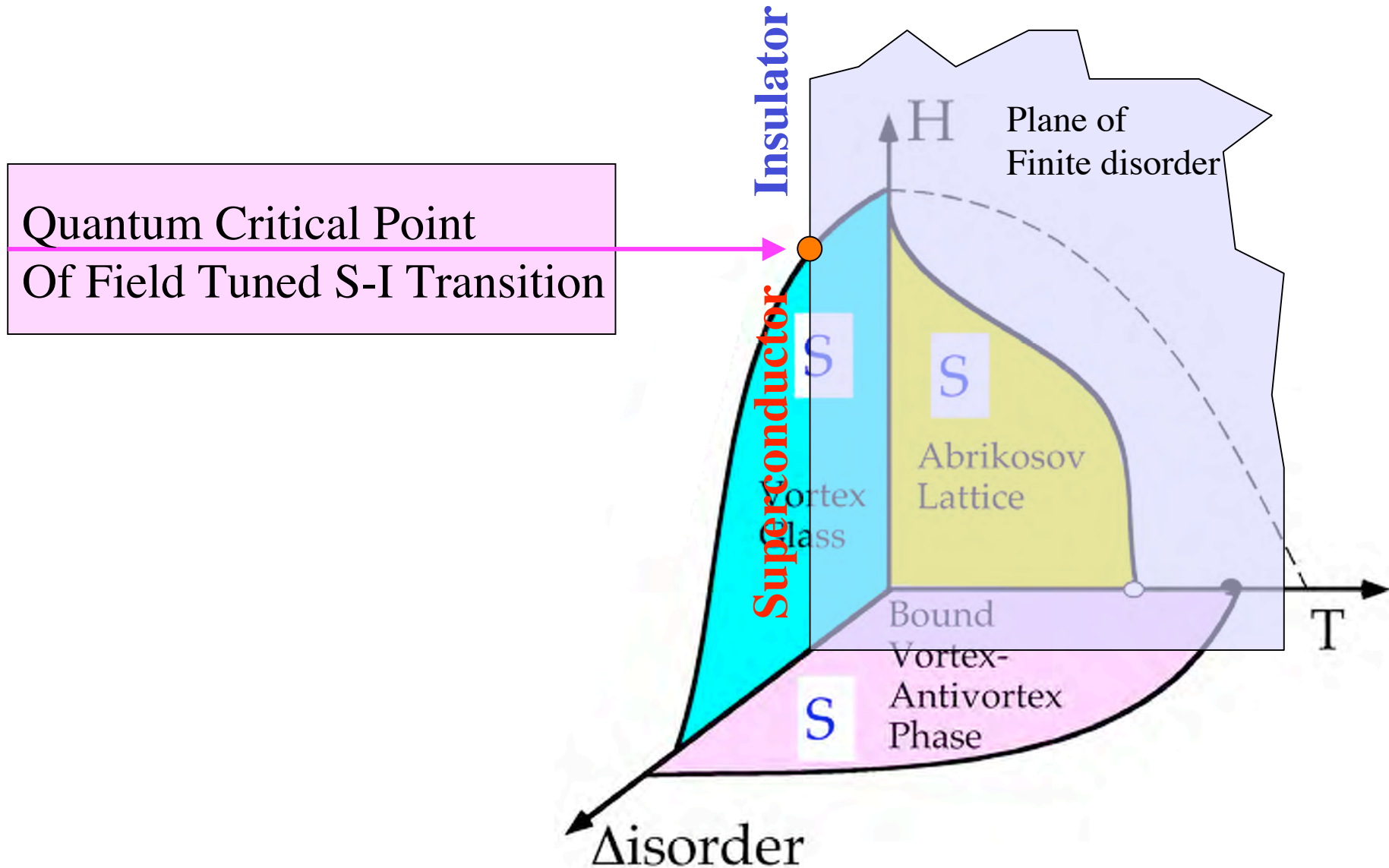
Experiments on Ga layer grown on amorphous Ge

Granular (Local) effects

$R_c$



# Field tuned S-I Transition



# Magnetic-Field-Tuned Superconductor-Insulator Transition in Two-Dimensional Films

A. F. Hebard and M. A. Paalanen

*AT&T Bell Laboratories, Murray Hill, New Jersey 07974*

(Received 26 February 1990)

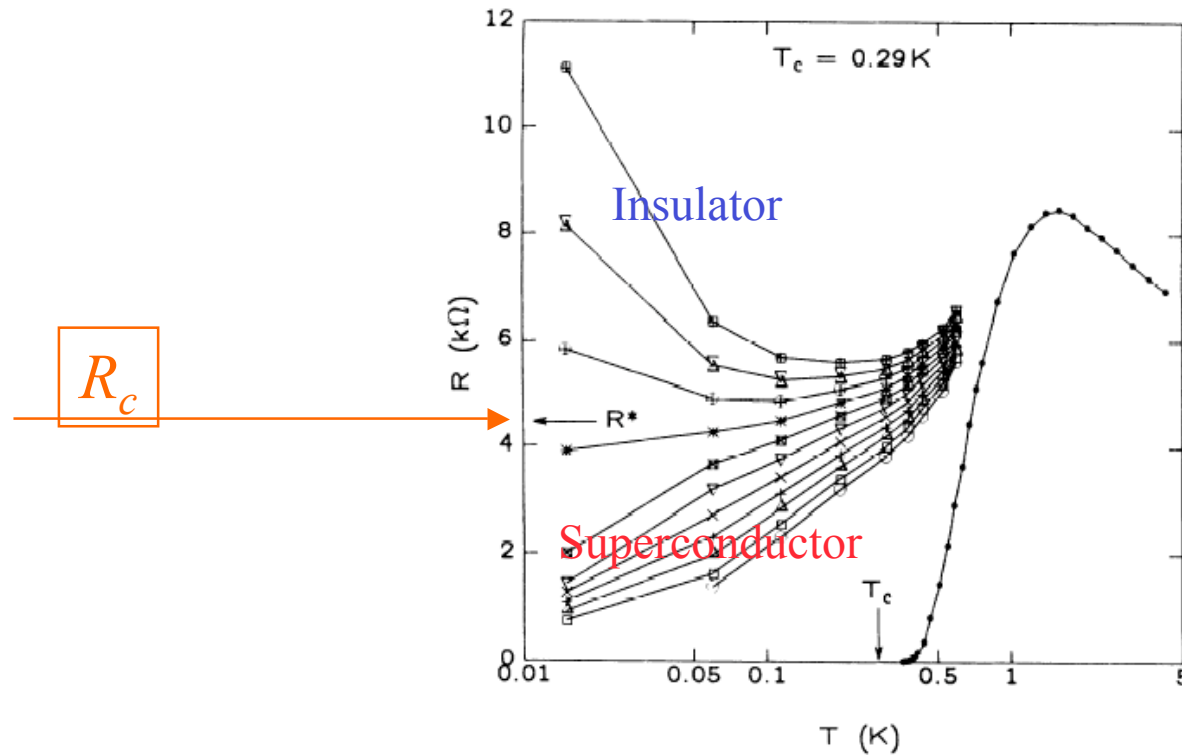
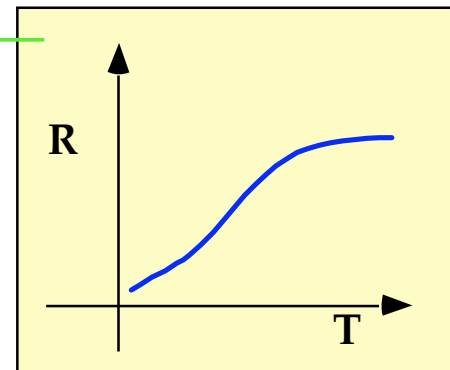
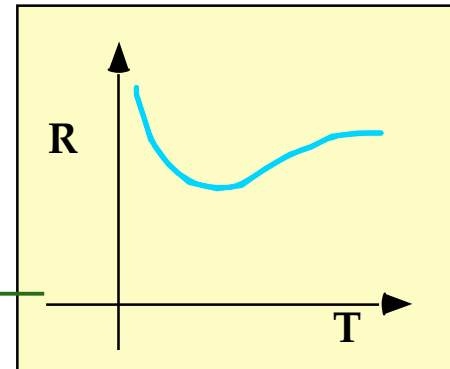
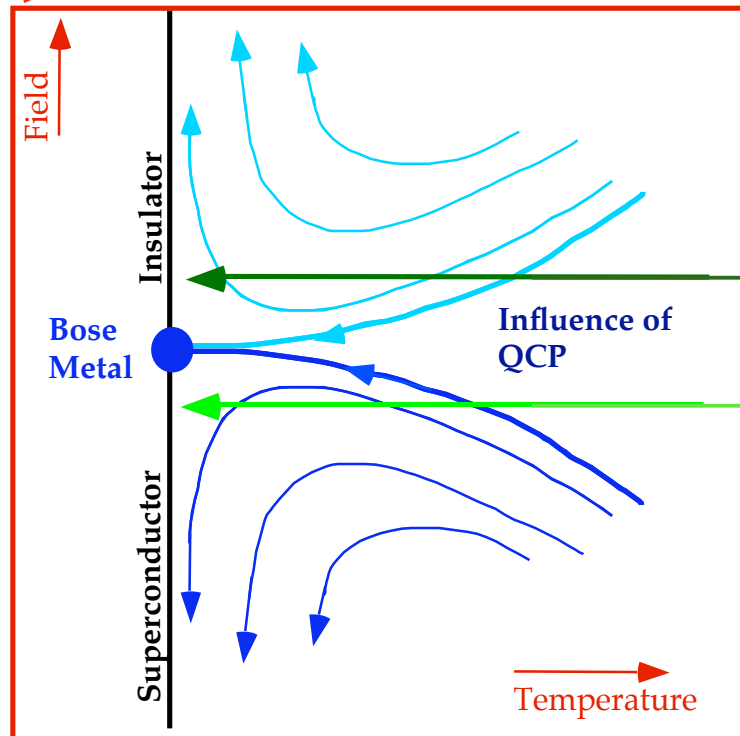
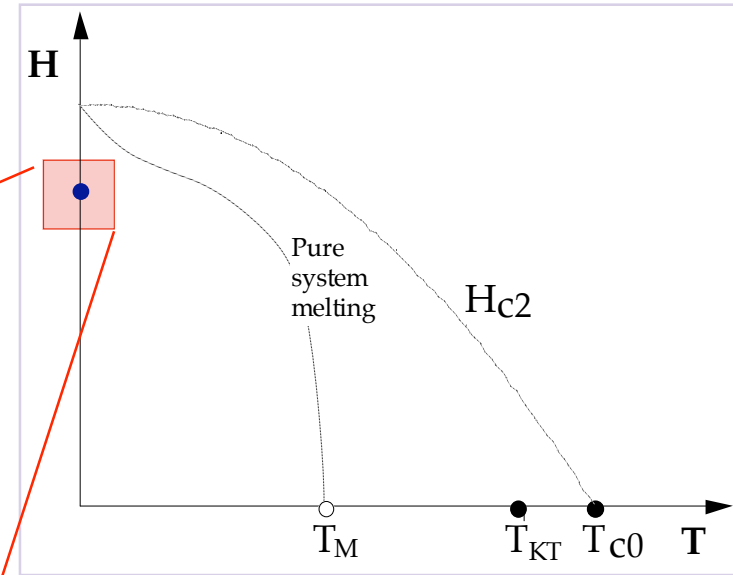


FIG. 1. Logarithmic plots of the resistance transitions in zero field ( $\bullet$ ) and nonzero field (open symbols) for a film with  $T_c = 0.29$  K. The isomagnetic lines range from  $B = 4$  kG ( $\circ$ ) to  $B = 6$  kG ( $\square$ ) in  $0.2$ -kG steps. The horizontal and vertical arrows identify  $R^*$  and  $T_c$ , respectively.

# Field-tuned transition: Approach to the critical point:

For a plane of finite disorder:



# Inhomogeneous nature of the transition

## I. Granular films are inherently inhomogeneous

Equivalent to phase fluctuations and strong disorder

## II. Homogeneous films: Amplitude fluctuations + Disorder

Island formation due to strong fluctuations of  $\Delta$

B. Spivak and F. Zhou, Phys. Rev. Lett. 74, 2800 (1995);

F. Zhou and B. Spivak, Phys. Rev. Lett. 80, 5647 (1998).

→ Island formation at the **mean-field level**

V. M. Galitski and A. I. Larkin, Phys. Rev. Lett. 87, 087001 (2001).

→ Adding **quantum fluctuations** result in a phase transition

M. A. Skvortsov, M. V. Feigel'man, Phys. Rev. Lett. 95, 057002 (2005).

→ Mesoscopic fluctuations in **large dimensionless conductance**

A. Ghosal, M. Randeria and N. Trivedi, Phys. Rev. Lett. 81, 3940 (1998);

Phys. Rev. B 65, 14501 (2001).

→ Solving B-dG in the presence of disorder- show island formation

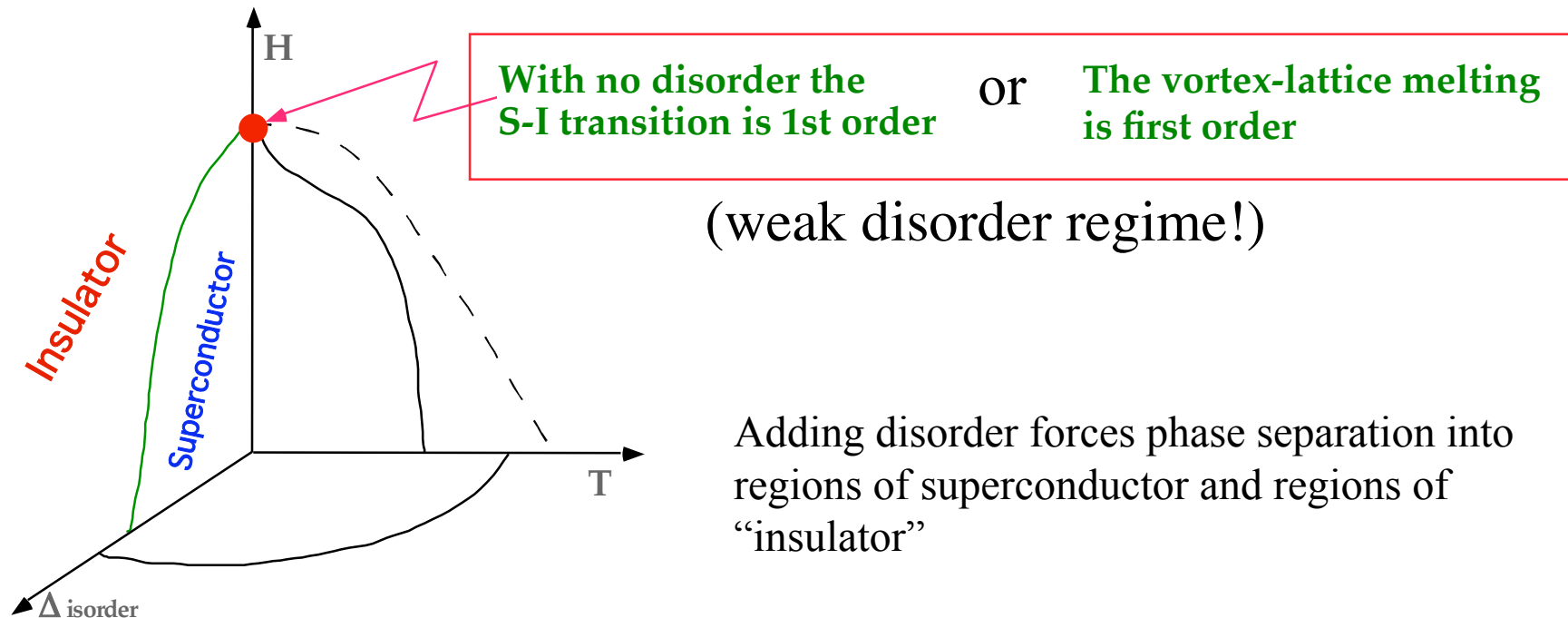
Yonatan Dubi, Yigal Meir, and Yshai Avishai, Phys. Rev. B 78, 024502 (2008).

→ Using a locally self-consistent numerical solution of the B-dG equations, show **island formation** and evolution with magnetic field.

### III. Homogeneous films: Phase fluctuations + weak disorder

#### Island formation due to proximity to quantum melting + disorder (Imry & Ma mechanism)

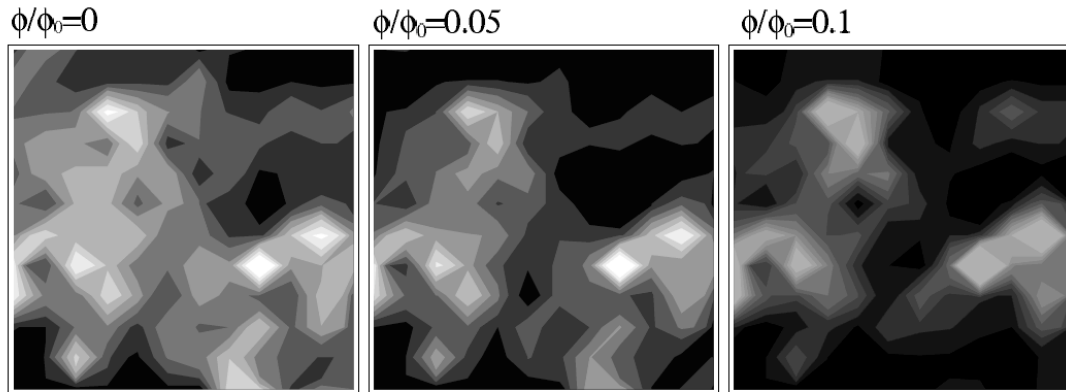
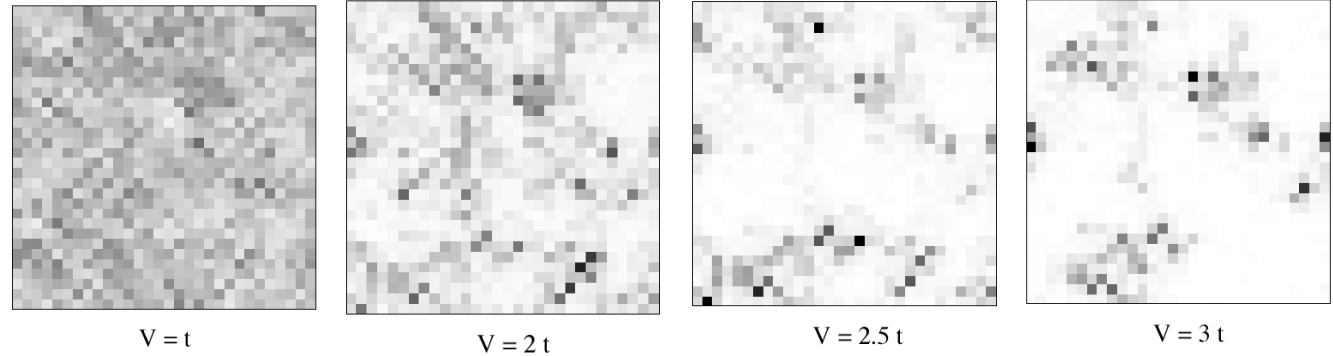
- E. Shimshoni, A. Auerbach and A. Kapitulnik, Phys. Rev. Lett. 80 (1998), 3352.



## Numerical examples:

A. Ghosal, M. Randeria and N. Trivedi, Phys. Rev. Lett. 81, 3940 (1998); Phys. Rev. B 65, 14501 (2001).

### Zero-magnetic-field



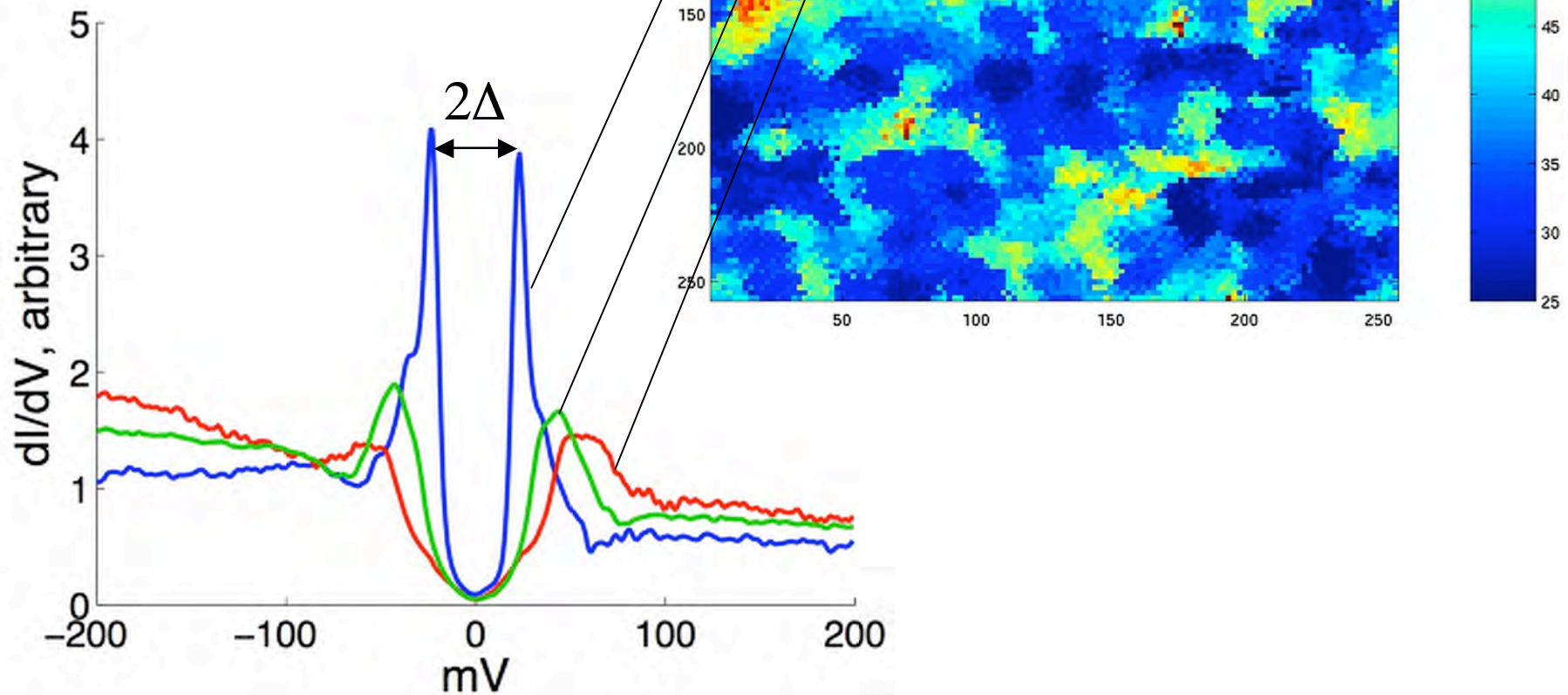
Yonatan Dubi, Yigal Meir, and Yshai Avishai, arXiv:0712.4398: cond-mat

FIG. 1: Spatial distribution of the order parameter amplitude  $|\Delta|$  for different values of the orbital magnetic field,  $\phi/\phi_0 = 0, 0.05, 0.1$ . Bright regions, corresponding to large values of  $|\Delta|$ , constitute "superconducting islands", separated by regions of small  $|\Delta|$  (dark regions). Increasing magnetic field leads to attenuation of the SC order parameter and even to the vanishing of SC order in some areas of the sample. Calculation is performed on a  $12 \times 12$  size lattice with electron density  $\langle n \rangle = 0.875$ , disorder strength  $W = 1$  and interaction strength  $U = 2$  (this value for  $U$  is maintained throughout).

### Finite-magnetic-field

**Experimental example:**

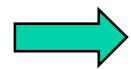
Gap inhomogeneities on  
the surface of  
 $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$   
(quasi-2D system)



C. Howald, P. Fournier, and A. Kapitulnik, Phys. Rev. B 64 (2001), 100504.

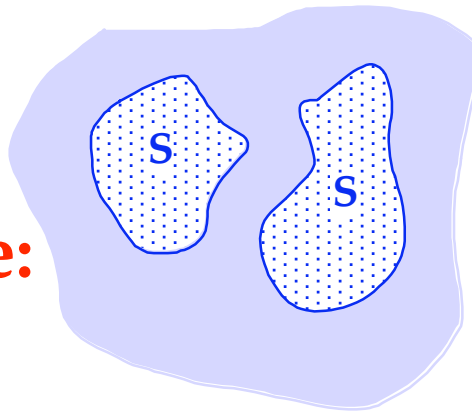
A. C. Fang, L. Capriotti, D.J. Scalapino, S.A. Kivelson, and A. Kapitulnik, Phys. Rev. Lett. 96 (2006), 017007.

Modeling the inhomogeneous nature of superconductivity near the transition to the superconducting state:

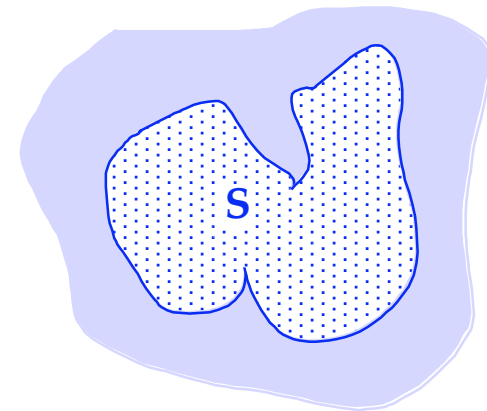


Transition is

**Percolation - like:**

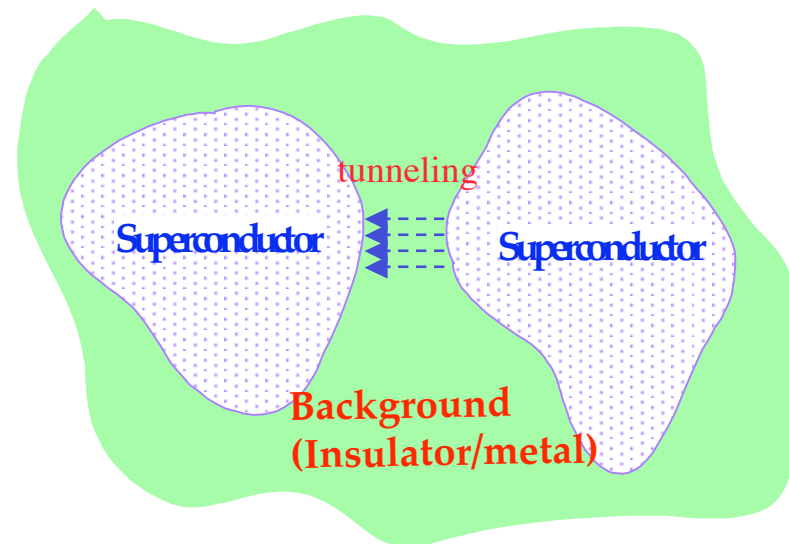


$H > H_c$

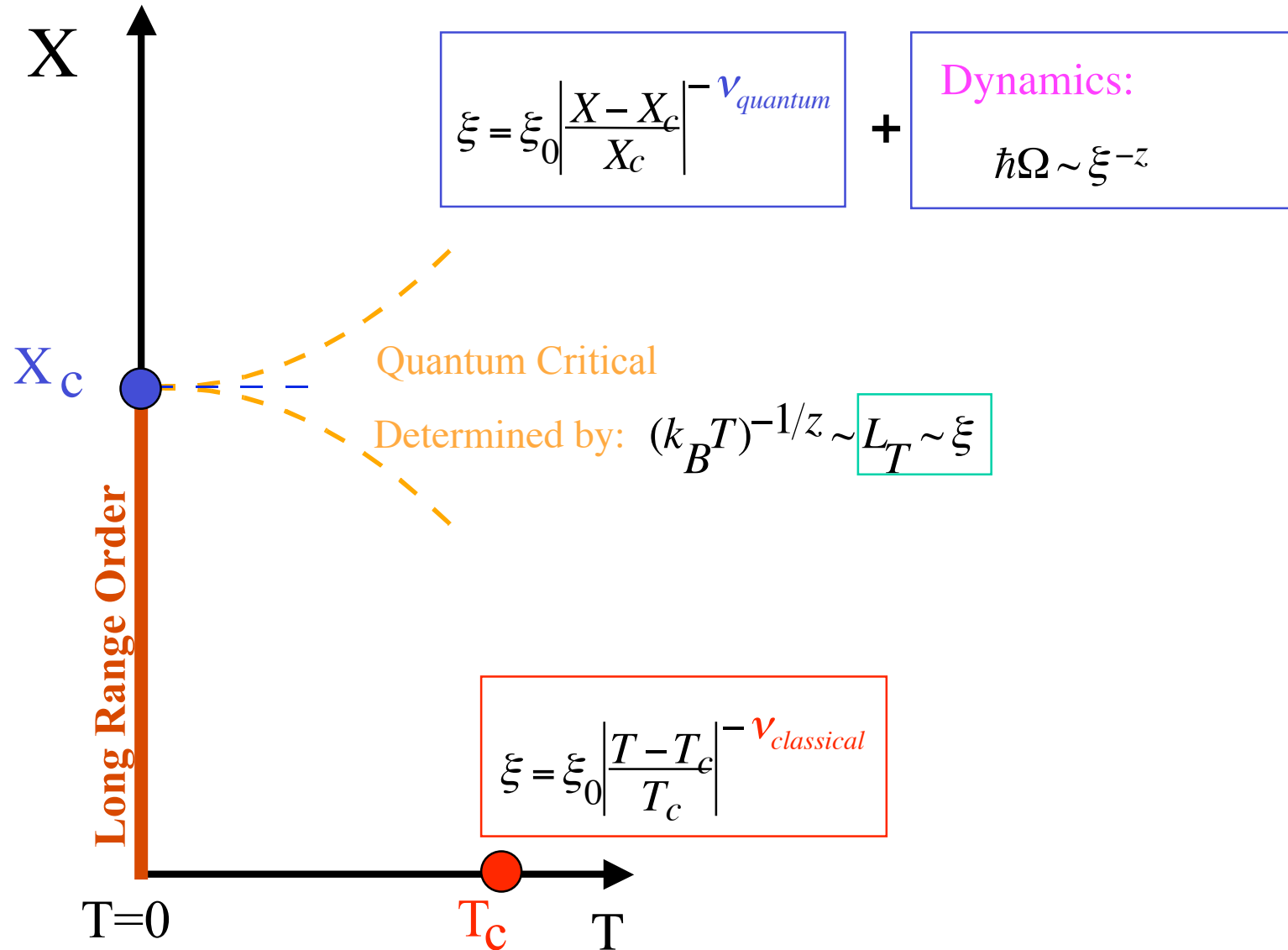


$H < H_c$

But, with quantum effects  
(**Quantum Percolation**)

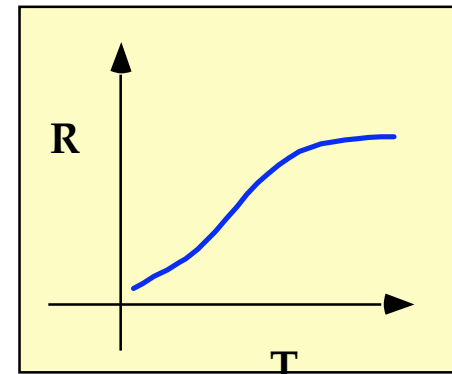
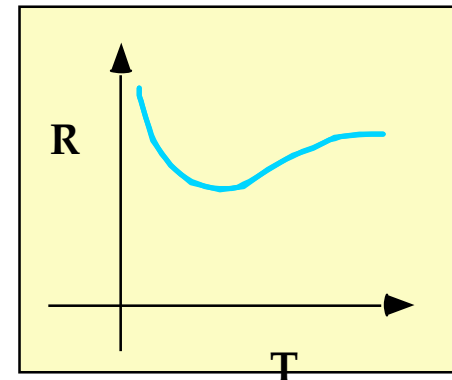
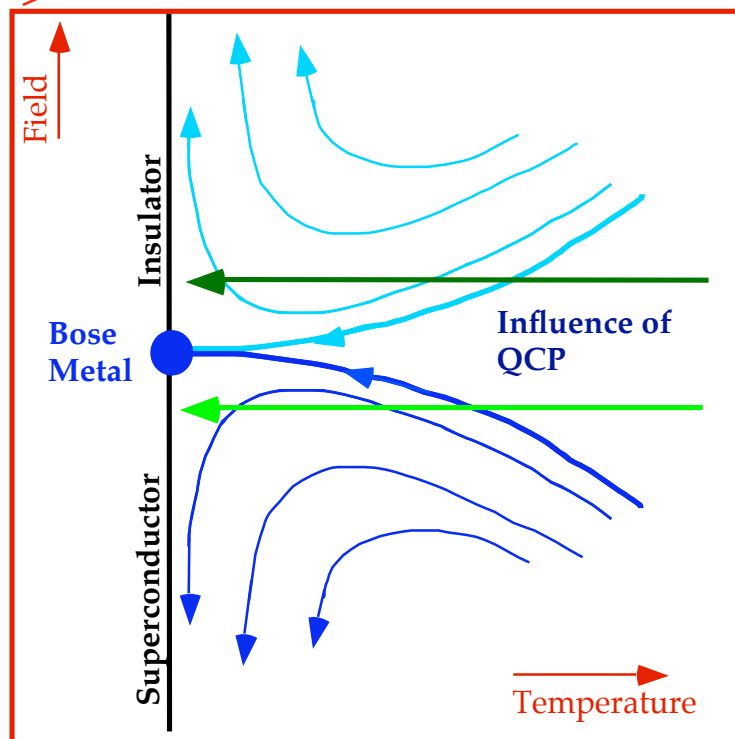
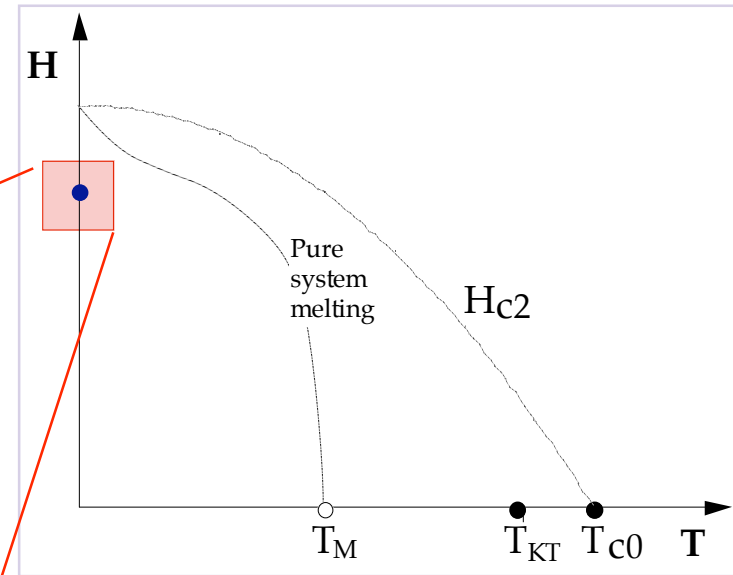


# Quantum Critical Point



# Approach to the critical point:

For a plane of finite disorder:



# Field-tuned SIT at T=0: Scaling Theory

\* M.P.A. Fisher, Phys. Rev. Lett. (1990).

Assume a continuous quantum transition at the critical field  $H_c$ . The correlation length near the transition is:

$$\xi \sim \left| \frac{H - H_c}{H_c} \right|^{-\nu}$$

The dynamics of the transition is described by the vanishing frequency as the transition is approached:

$$\Omega \sim \xi^{-z}$$

$$(\xi \sim \Omega^{-1/z})$$

From vortex displacement argument the current density must enter the scaling relation with the combination:

$$\frac{(\hbar/2e)J\xi}{\hbar\Omega}$$

From Cooper pair displacement argument the electric field  $E$  will appear in the scaling function with the combination:

$$\frac{2eE\xi}{\hbar\Omega}$$

Thus, the J-E relation near the Superconductor-Insulator transition should be:

$$E = \frac{\hbar\Omega}{2e\xi} \mathcal{E}_{\pm} \left( \frac{J\xi}{2e\Omega} \right)$$

## Finite temperature and electric field:

At finite temperature,  $k_B T$  will determine the frequency scale:  $L_T \sim (k_B T)^{-1/z}$

Similarly, for the electrostatic energy:  $L_E \sim E^{-1/(z+1)}$

General scaling function:  $R(H, T, E) = R_c \mathcal{F} \left( \frac{C_a |H - H_c|}{T^{1/z\nu}}, \frac{C_b |H - H_c|}{E^{1/(z+1)\nu}} \right)$

The resistance near the transition in the Ohmic regime is given by:

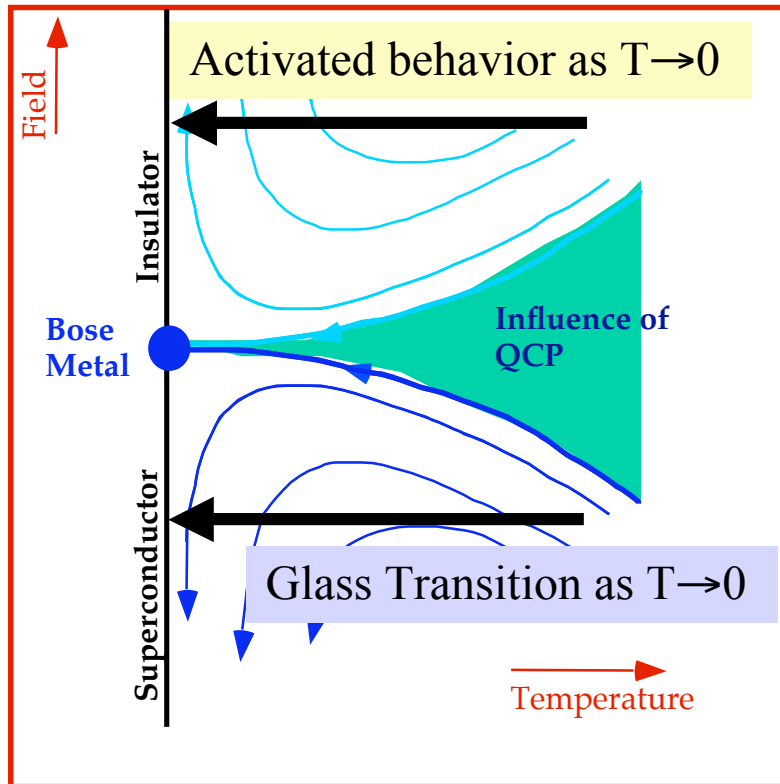
$$R = R_c \mathcal{F}_T \left( \frac{c_T |H - H_c|}{T^{1/z\nu}} \right) \quad c_T \text{ is a constant}$$

And the non-linear resistance at **fixed temperature**\*:

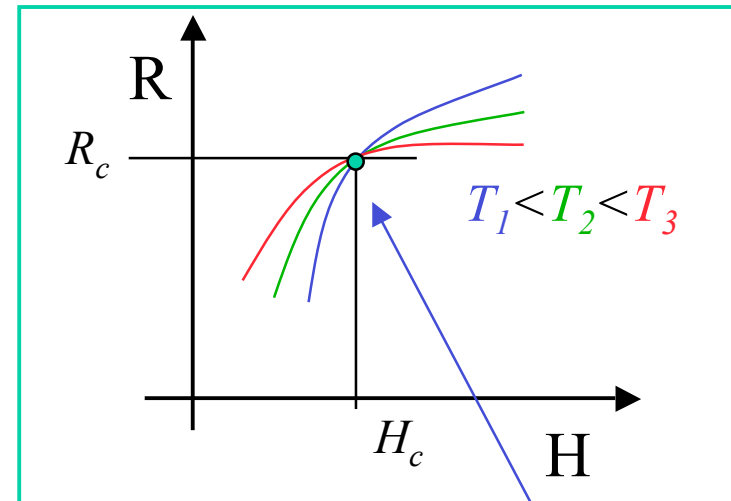
$$R = R_c \mathcal{F}_E \left( \frac{c_E |H - H_c|}{E^{1/(z+1)\nu}} \right) \quad c_E \text{ is a constant}$$

\* Provided that heating is not present ( $T > T_\phi$ ) A. Yazdani and A. Kapitulnik, Phys. Rev. Lett. 74, 3037 (1995).

# Hallmarks of the SIT



Isotherms show a crossing point!



$$R_c = \frac{h}{(2e)^2} \approx 6.5 \text{ k}\Omega/\square$$

$$R = R_c \mathcal{F}_T \left( \frac{c_T |H - H_c|}{T^{1/z\nu}} \right)$$

With the above arguments:

Critical behavior is expected to be in the same universality class as quantum percolation:  $\nu \approx 2.3$  ( $\approx 7/3$ )

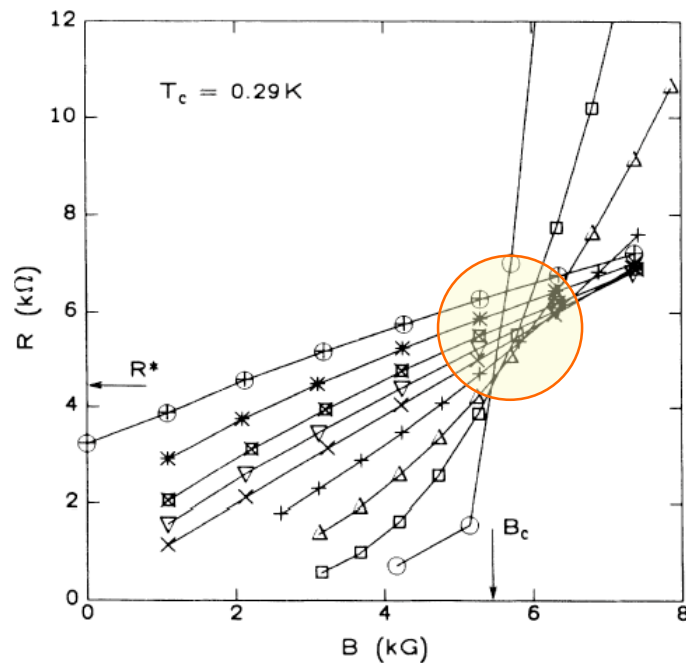
# Early work: Scaling - InOx

A. F. Hebard and M. A. Paalanen, Phys. Rev. Lett. 65, 927 (1990).

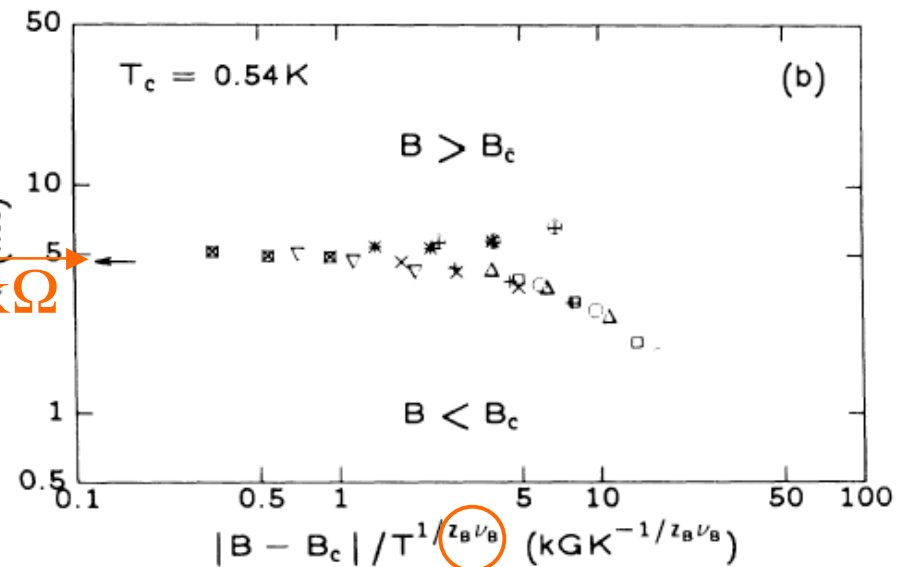
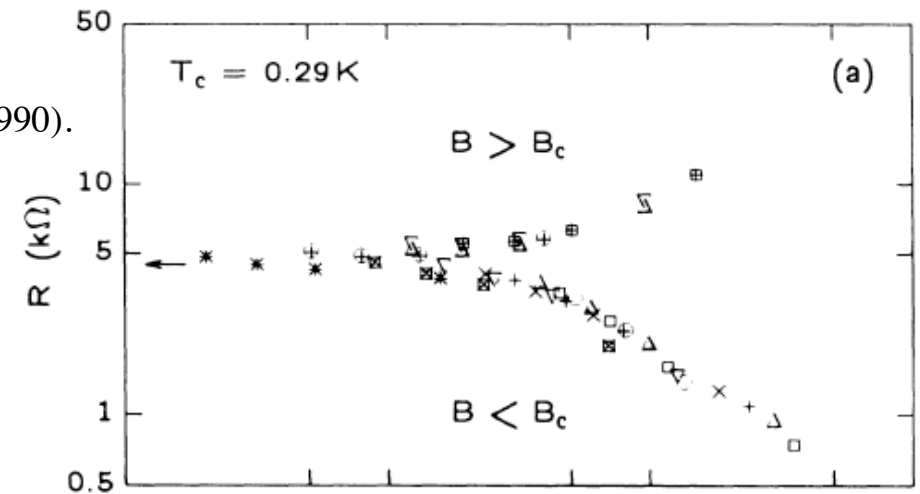
$$R = R_c \mathcal{F}_T \left( \frac{c_T |H - H_c|}{T^{1/z\nu}} \right)$$

Which implies:

$$R(H = H_c) = R_c \mathcal{F}_T(0) \equiv R_c$$

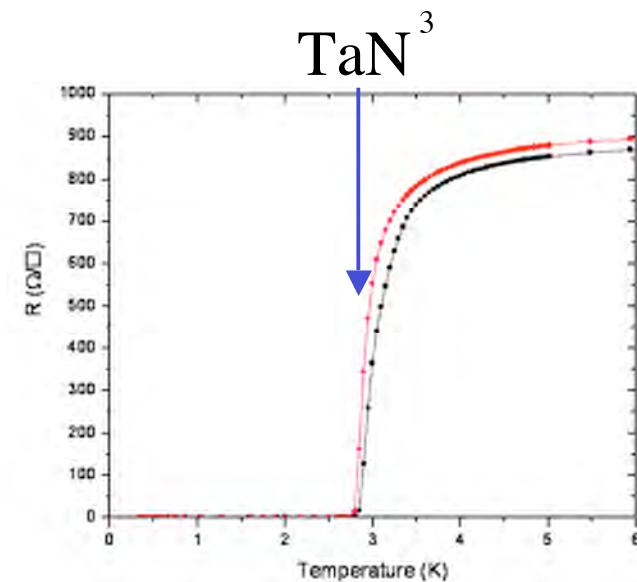
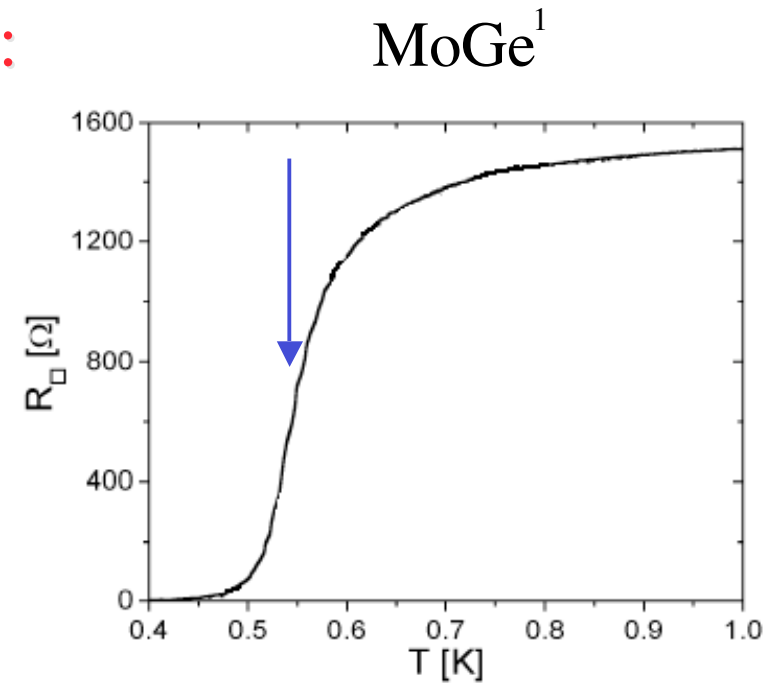
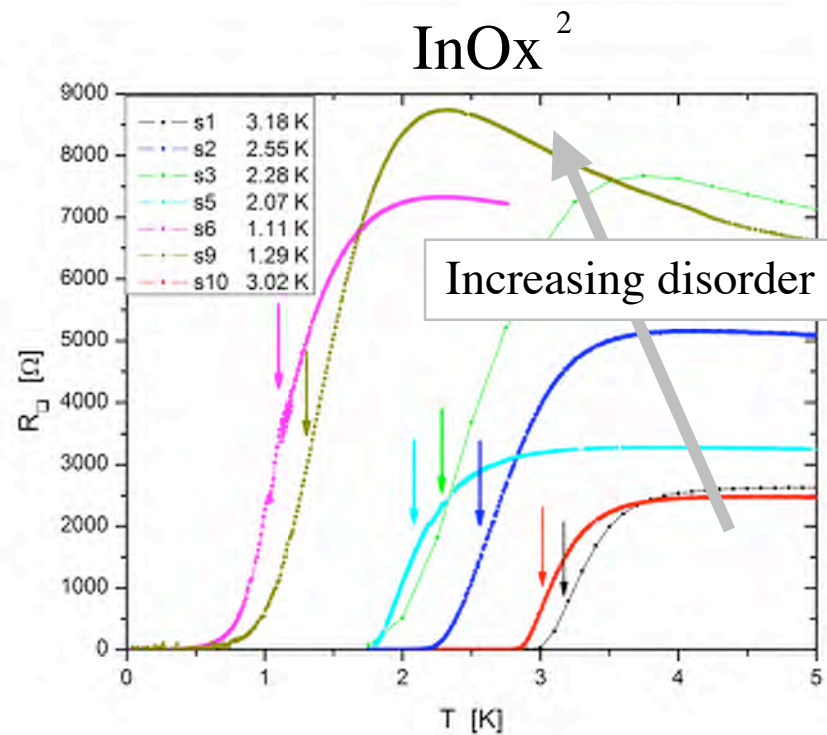


$R_c \approx 4.9 \text{ k}\Omega$



$z\nu \approx 1.3$

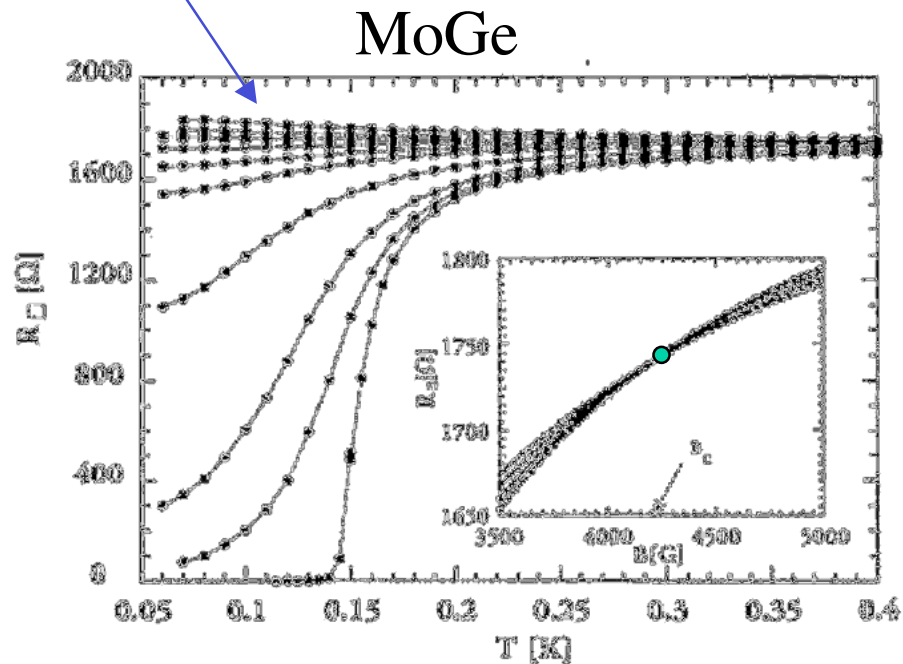
# More recent results: Superconducting Transitions ( $H=0$ ):



1. A. Yazdani and A. Kapitulnik, Phys. Rev. Lett. 74, 3037 (1995).
2. M. Steiner and A. Kapitulnik, Physica C 422, 16 (2005)
3. N. Brezney and A. Kapitulnik, (2008)

# Weak disorder behavior

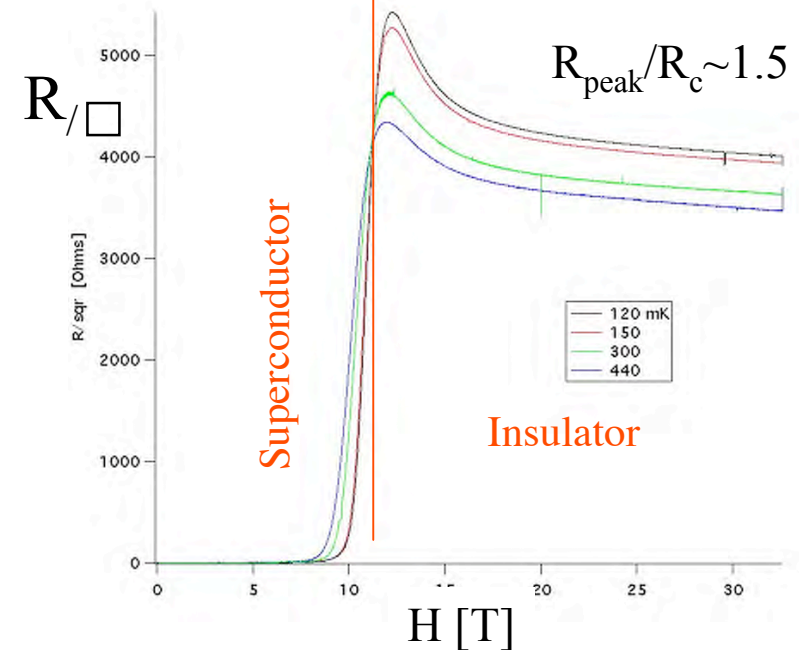
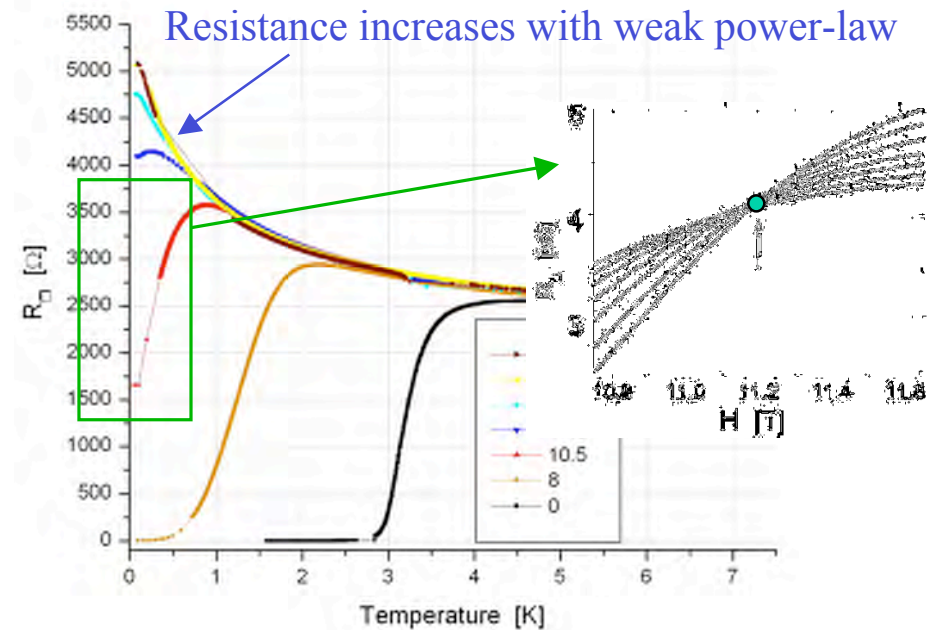
Resistance increases according to weak-localization



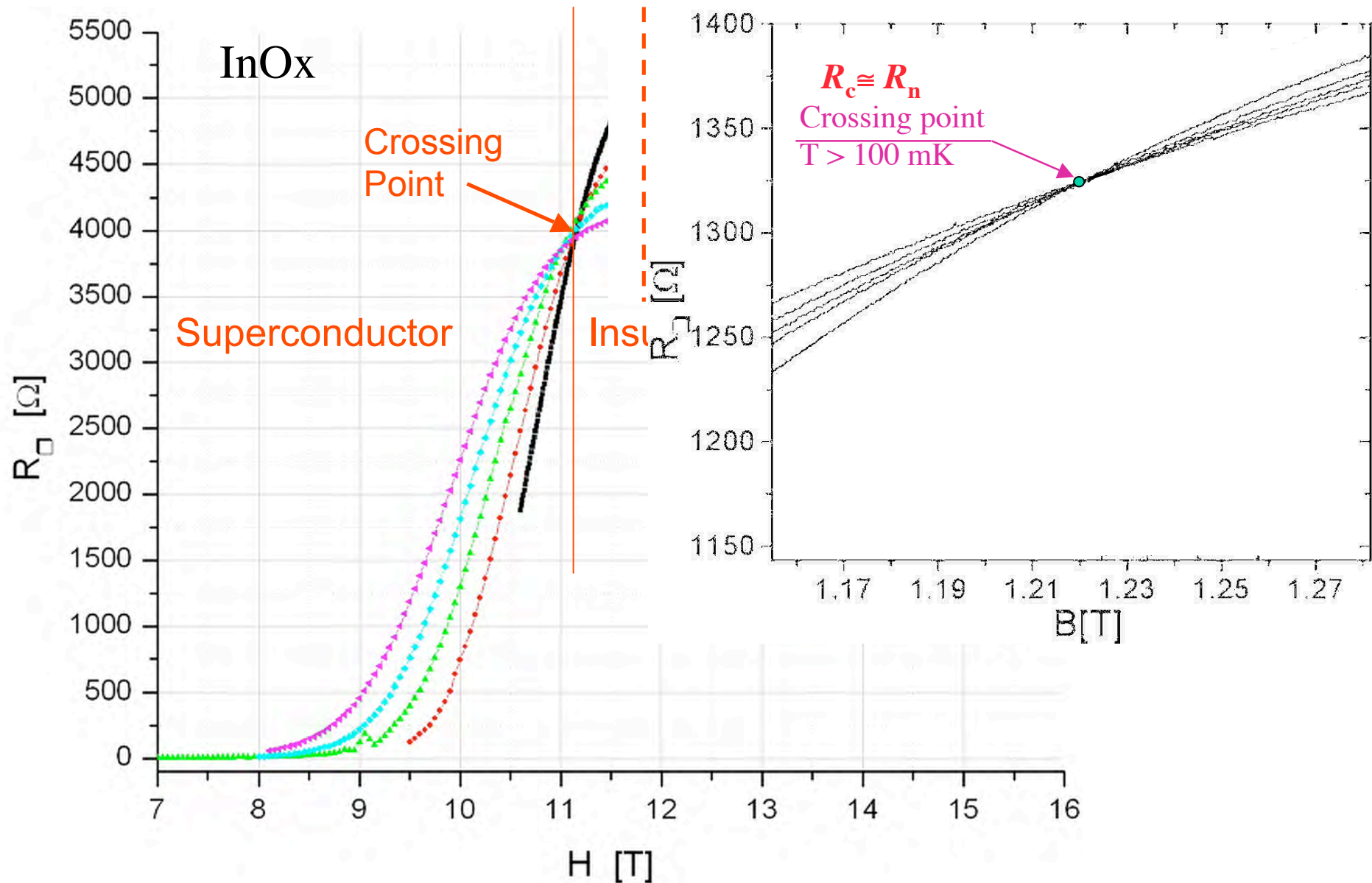
A. Yazdani and A. Kapitulnik, Phys. Rev. Lett. 74, 3037 (1995).

M. Steiner and A. Kapitulnik, Physica C 422, 16 (2005)

## InOx

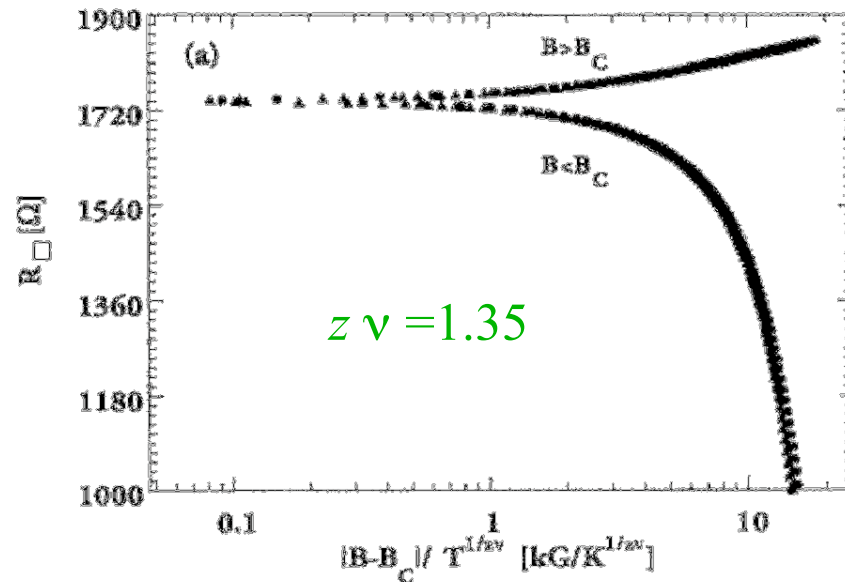


# Crossing points:

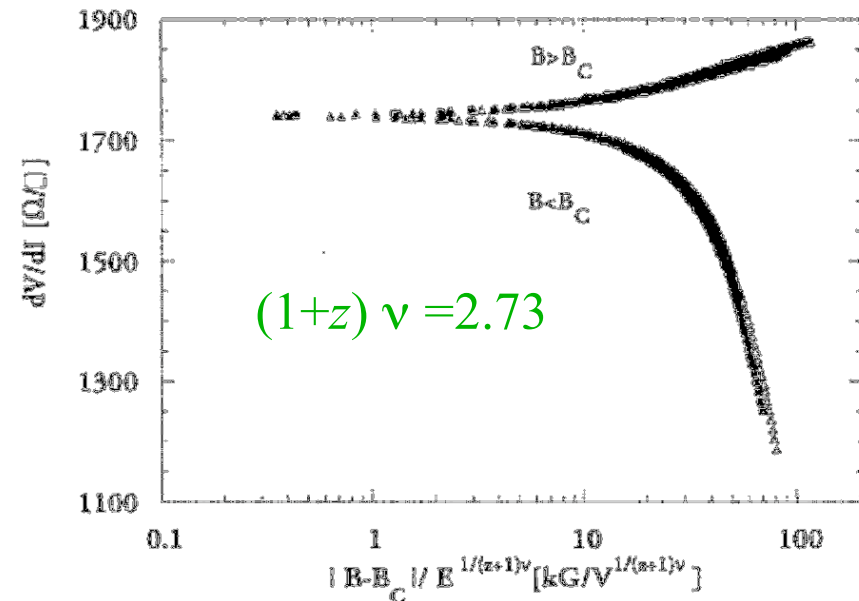


# Scaling (MoGe)

R vs. T at different field



R vs. E at different field



Solve for  $z$  and  $\nu$ :

$$\nu \approx 1.35 ; \quad z \approx 1.00$$

Note:  $\nu \approx 1.35$  represents a classical percolation exponent  
indeed - a metallic phase intervenes!

# Properties of the Superconducting phase

- Zero-resistance

Resistance will approach zero in an activated fashion

- Vortices are localized with disorder: **VORTEX GLASS**

For Vortex Glass phase:  $\xi_g \sim T^{-\nu_g}$

I-V will have non-linear component that sets in at

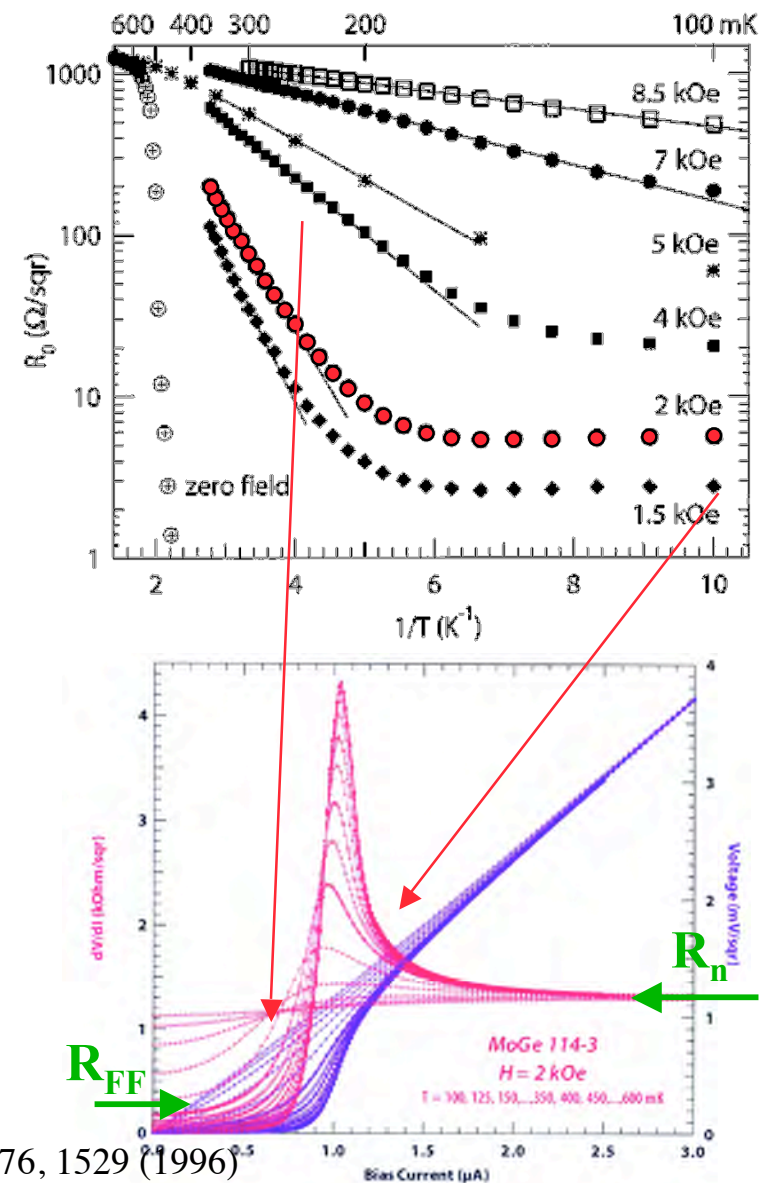
$$I_{nl}(T) \sim T / \xi_g \sim T^{1+\nu_g}$$

(at T=0 no linear resistance as R=0)

# A “Metallic State” emerges at low-T

## For MoGe Films:

- A new metallic phase with resistance 2-3 orders of magnitude lower than the “Fermi” resistance:
- The metallic phase is almost a superconductor. Internal Josephson couplings dominate:

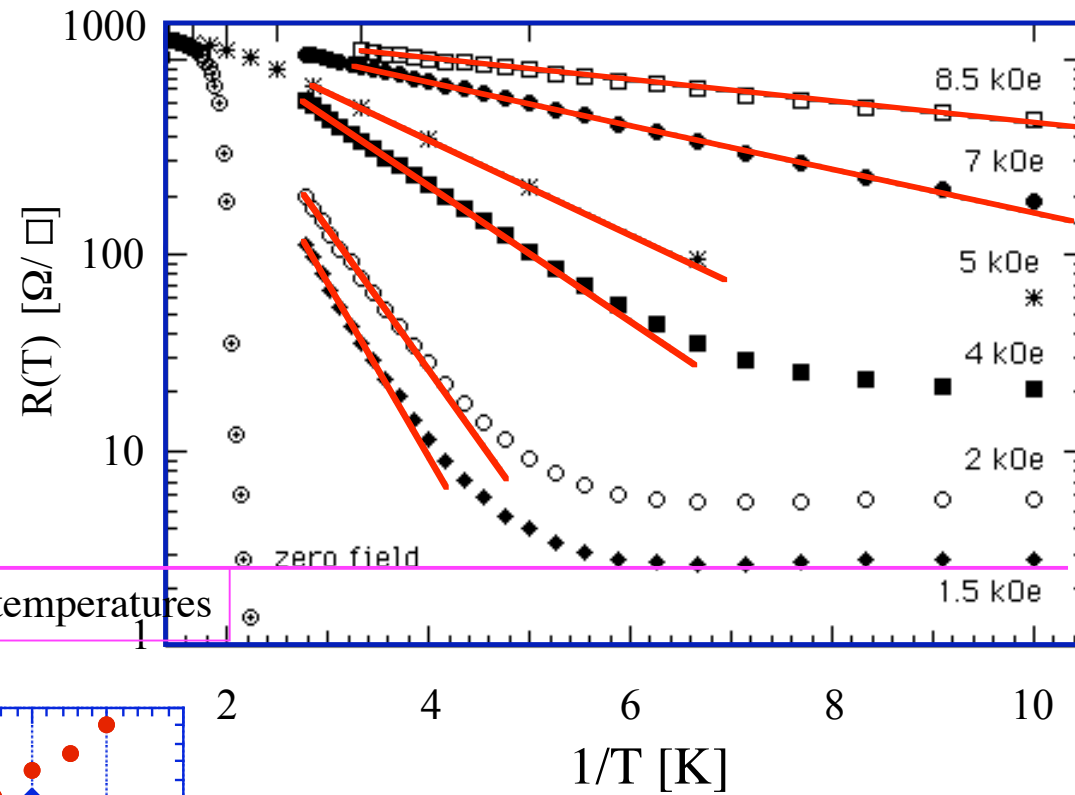


D. Ephron, A. Yazdani, A. Kapitulnik, and M. R. Beasley, Phys. Rev. Lett. 76, 1529 (1996)

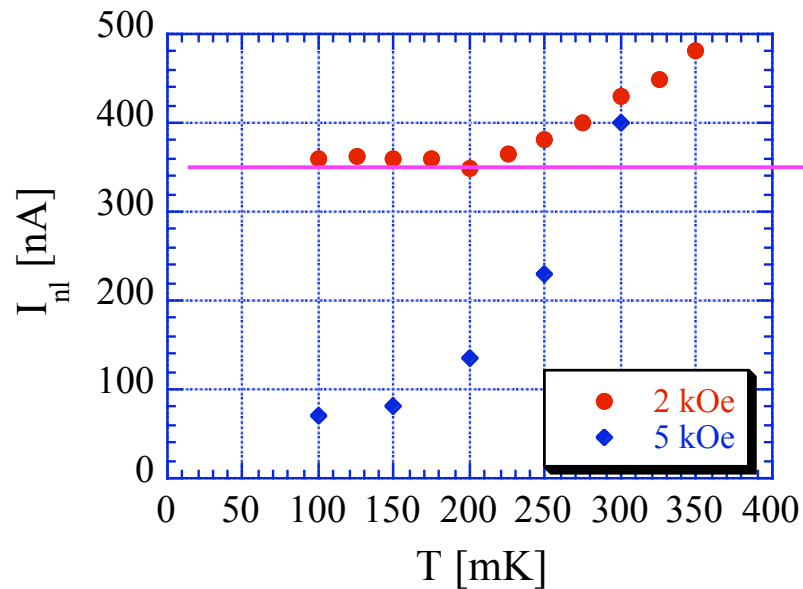
N. Mason and A. Kapitulnik, Phys. Rev. Lett. 82, 5341 (1999).

Example:

$H_c \sim 9.1 \text{ kOe}$



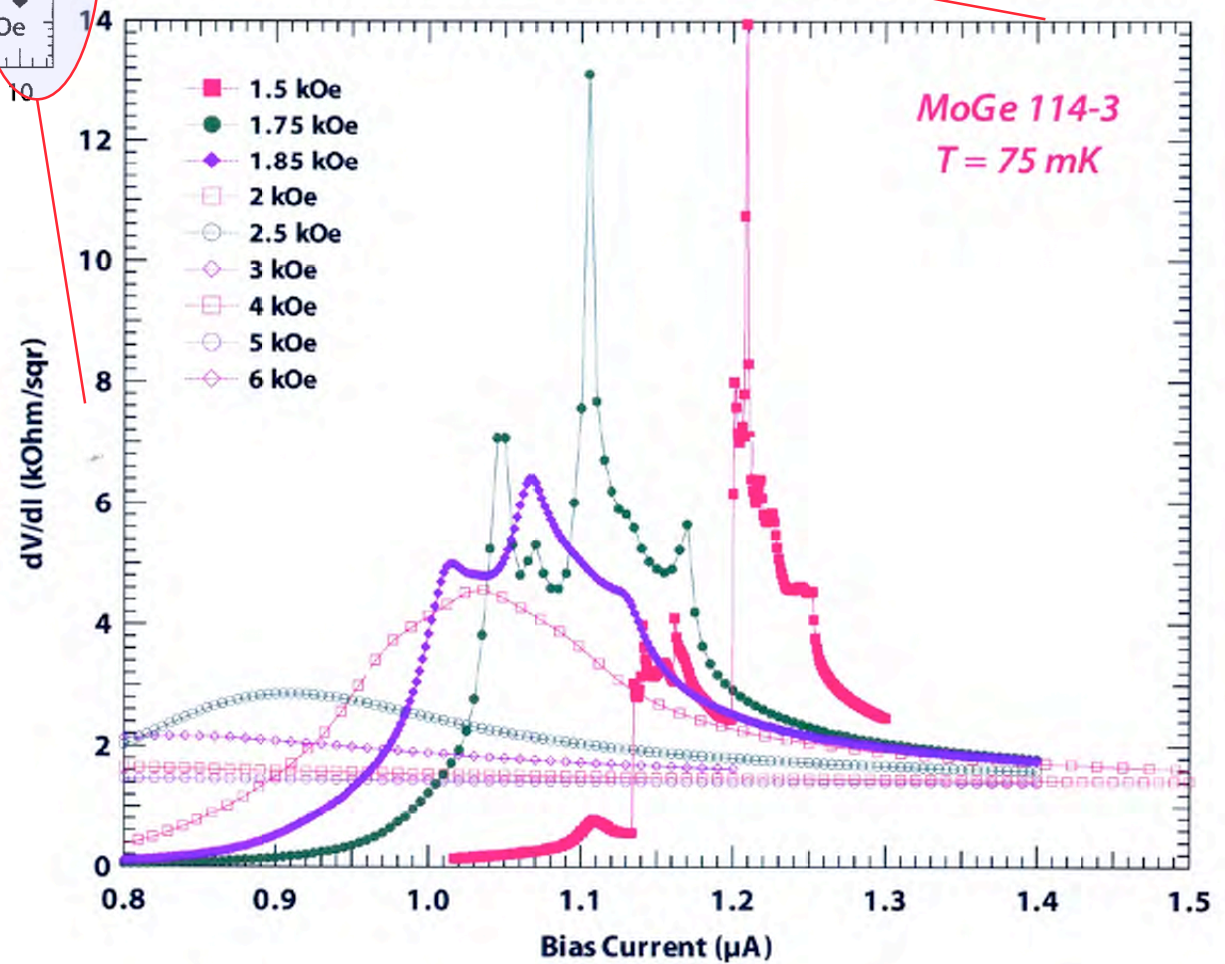
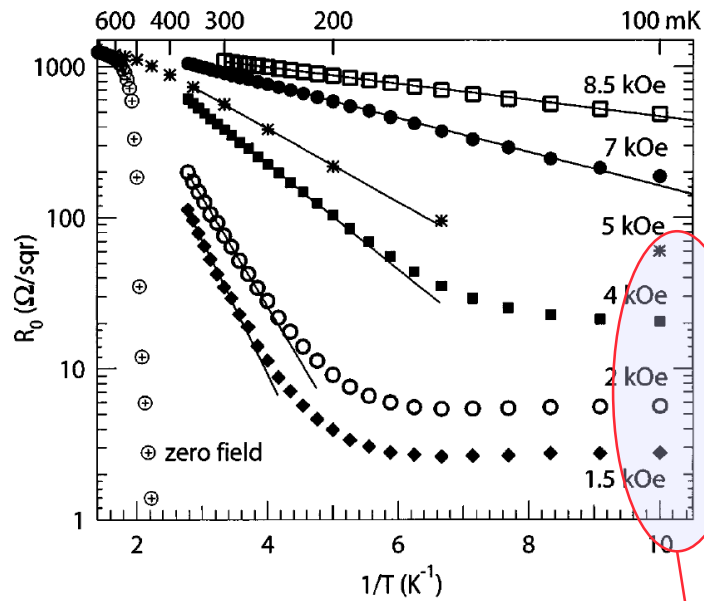
Saturation of resistance at low temperatures



Ohmic resistance all the way to  $T=0$

**No True Superconducting  
Phase at Low-T**

## Instabilities in the “Metallic State” (Vortex Physics?)



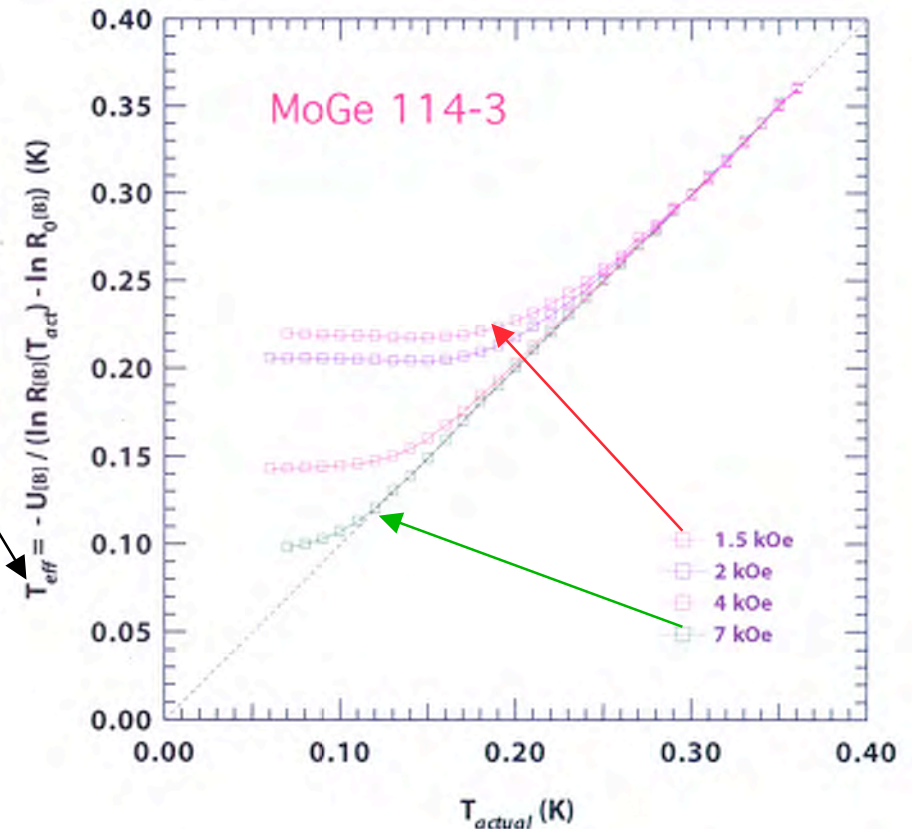
# It is not heating!

1. Similar Sample (with no superconductivity, same  $n$ ,  $R_{\square}$ ) shows Weak Localization -  $\log(T)$  down to 50 mK
2. Compare effective activation temperature to actual temperature:  
(similar treatment to that used in MQT by J. Clarke et al.)

In the activated regime:

$$R(T) = R_0 e^{-\frac{T_{act}}{T}}$$

$T_{eff}$



**Threshold for superconductivity in ultrathin amorphous gallium films**

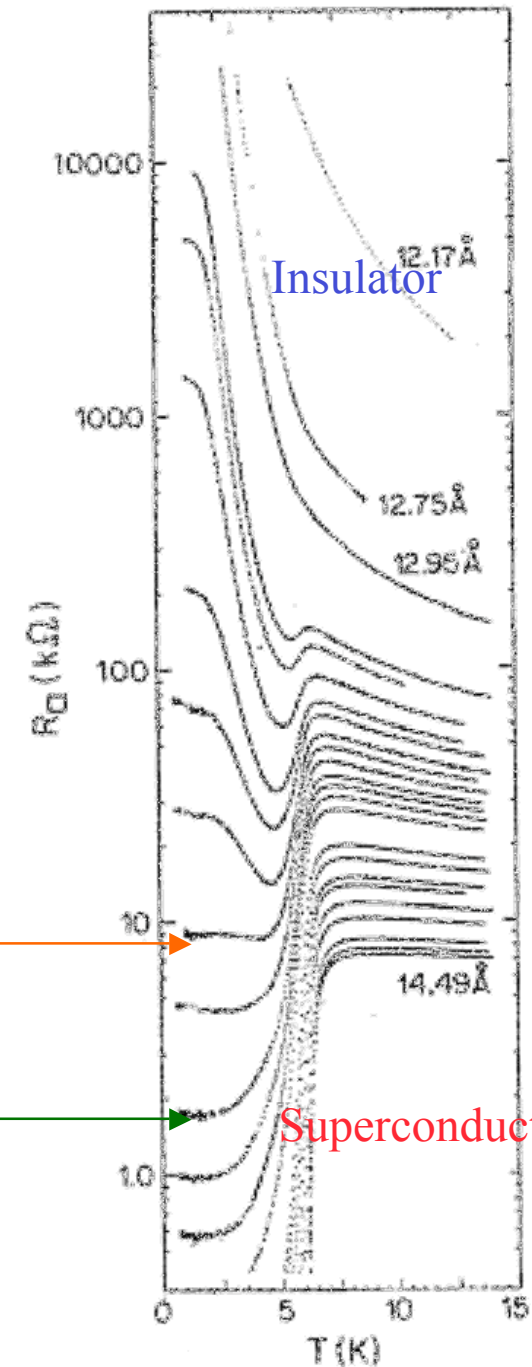
H. M. Jaeger, D. B. Haviland, and A. M. Goldman

*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455*

B. G. Orr

*IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598*

Experiments on Ga layer grown on amorphous Ge



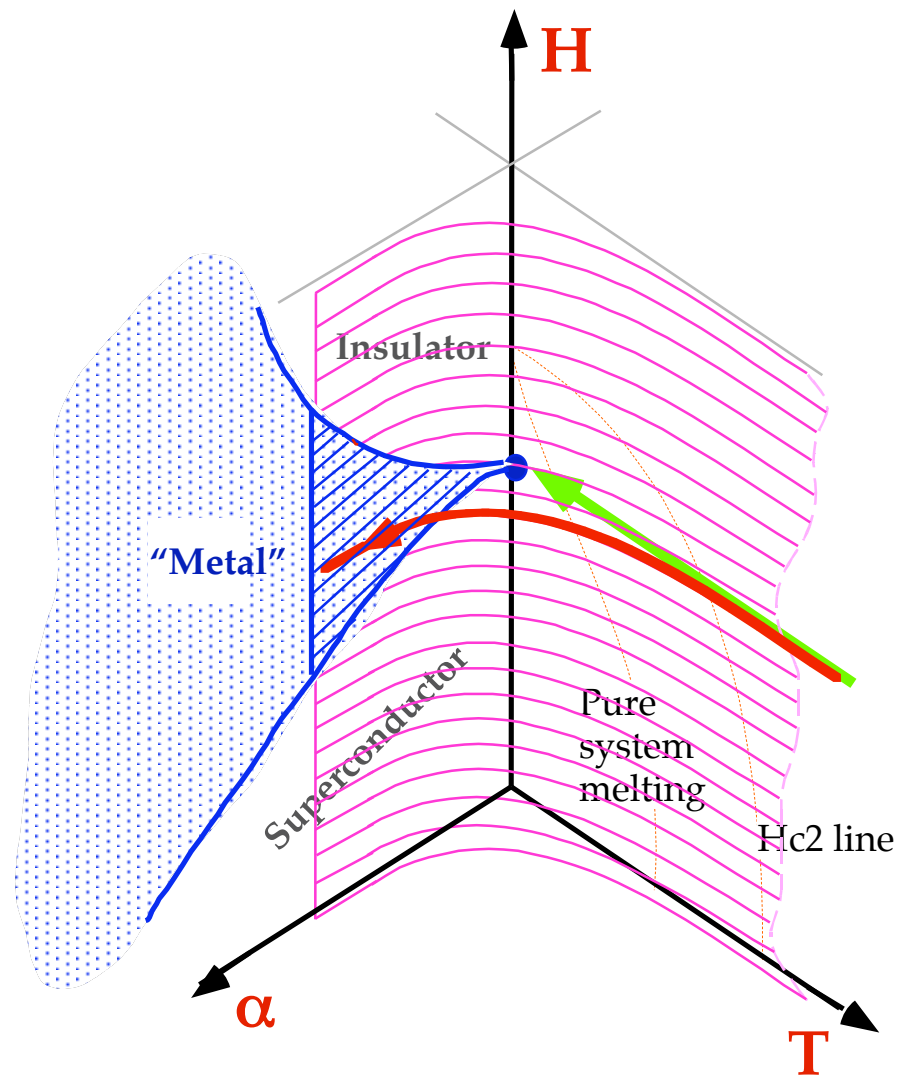
Insulator

 $R_c$ *Bose metal*

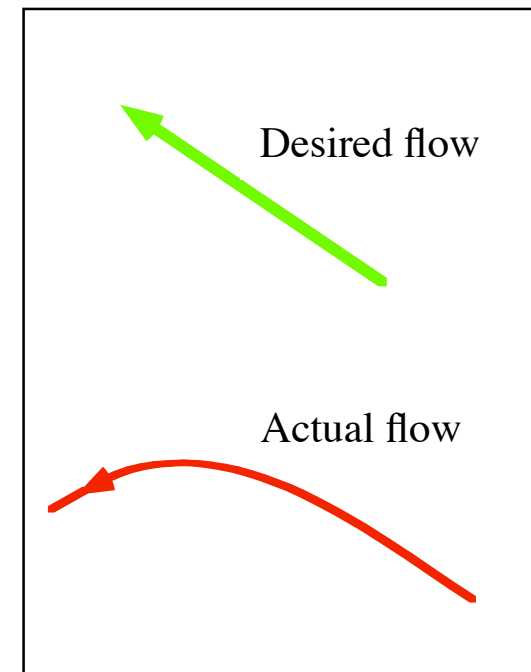
Metallic state?

Superconductor

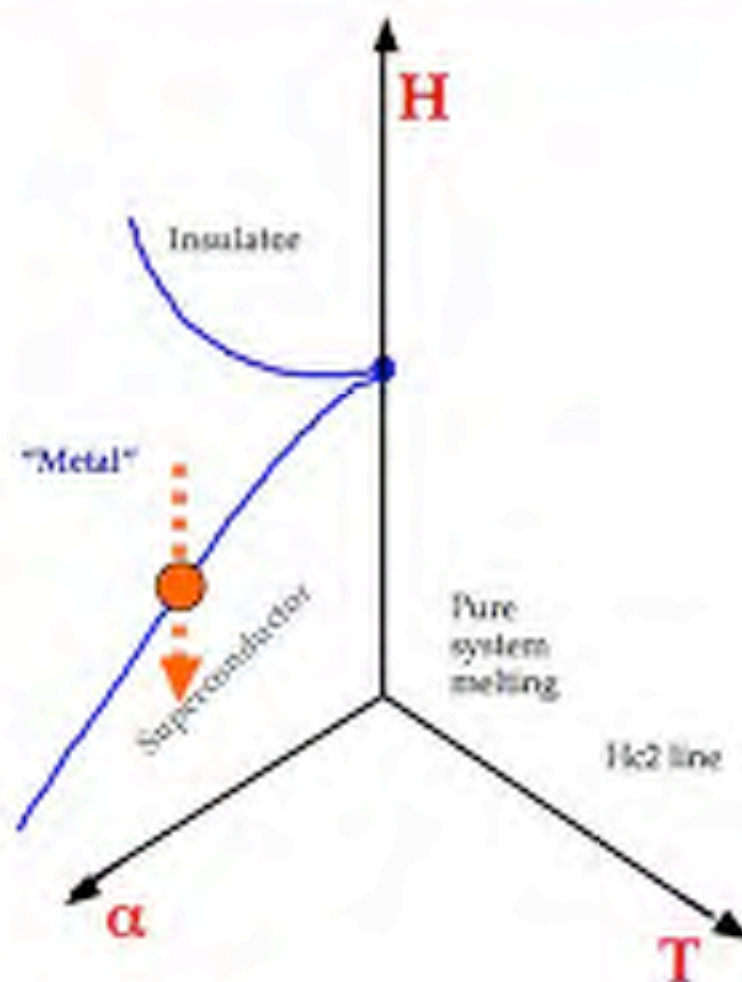
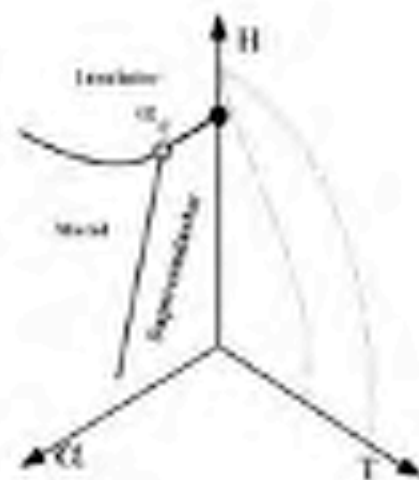
# Proposed flow in phase space during experiment:



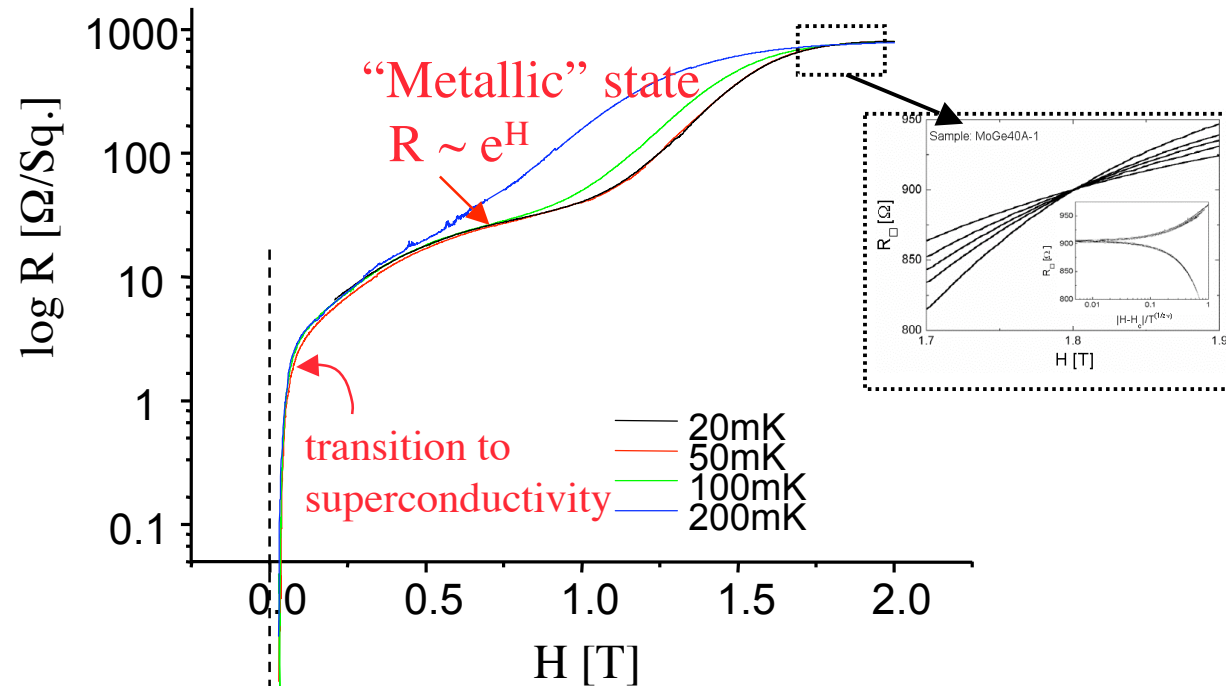
$\alpha$  can be e.g. dissipation



# Is there “True Superconductivity”?

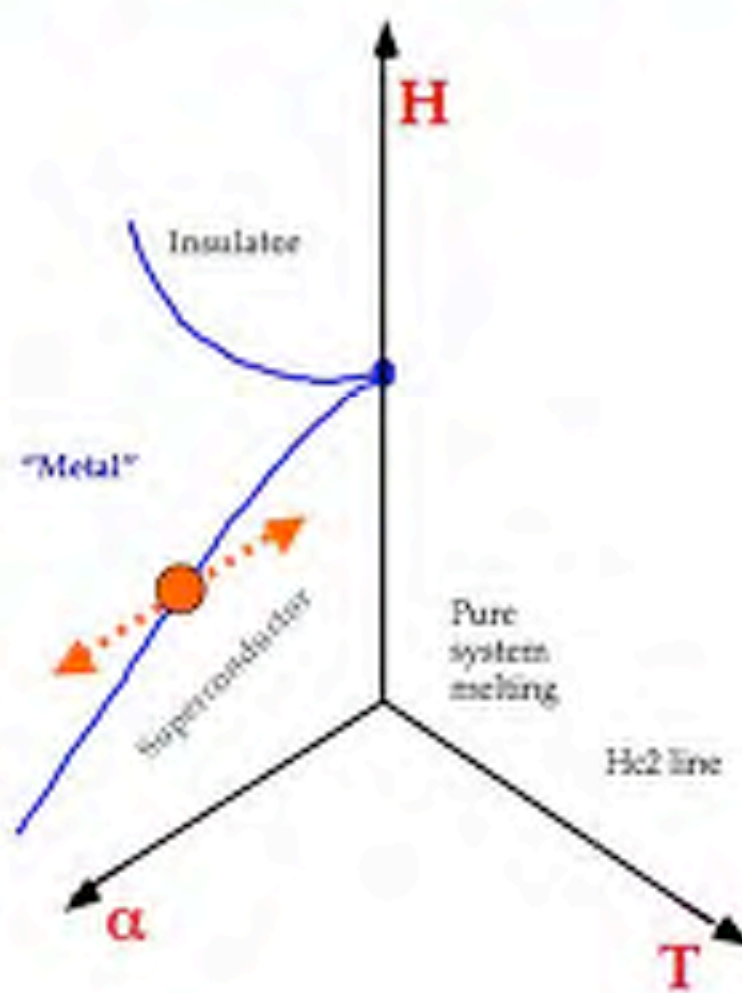
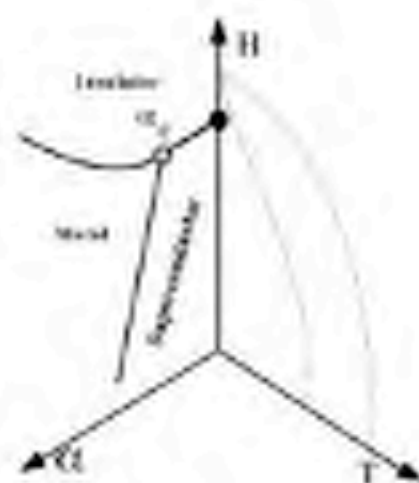


- At low fields the metallic phase undergoes a transition to a true superconductor.



- There is an underlying Superconductor-Insulator transition that is Bose-dominated that the metallic phase “knows” about.
- The almost superconductor-insulator transition is percolation like With classical-percolation exponent.

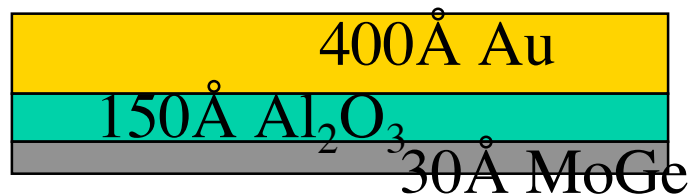
## Introducing a Ground Plane



*Modify properties of transition with metallic plane near sample ...*

★ Change dynamical scaling exponent  $\Omega \sim \xi^{-z}$  ?

- $z=1$  for charged bosons w/ long-range Coulomb repulsion
- $z=2$  for neutral (or screened) bosons



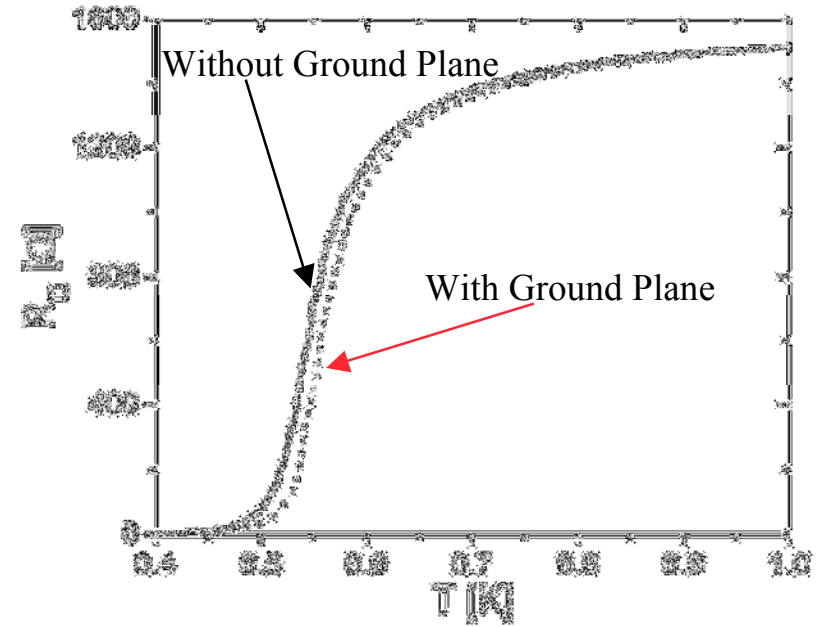
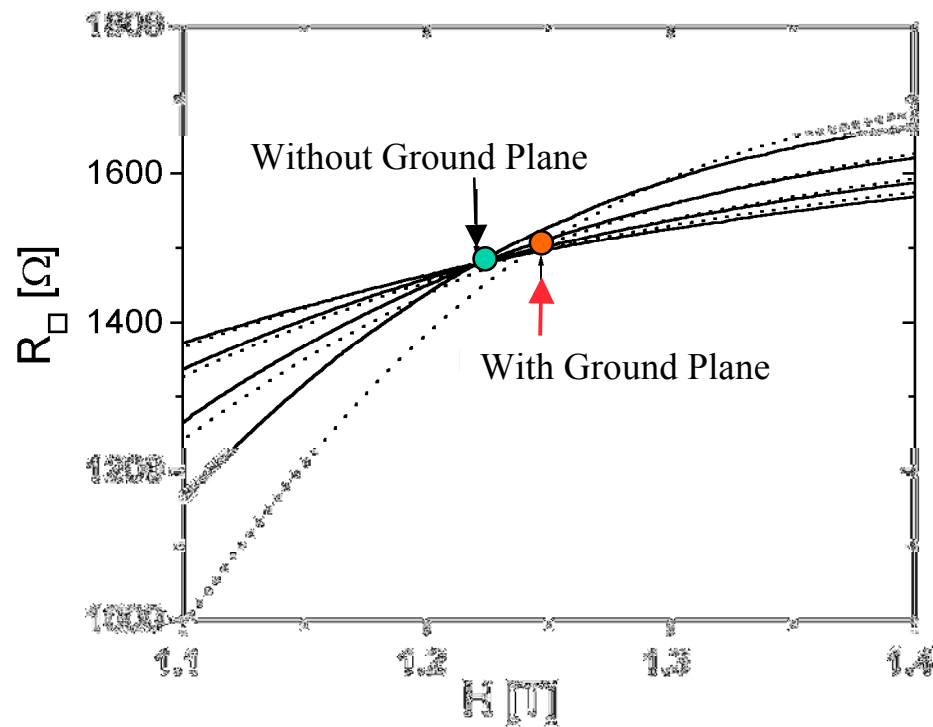
In pure boson picture, screening length  
should be  $< \xi \sim \xi_{GL} |H-H_c|/H_c$   
 $\xi_{min} \sim 150\text{\AA}$

★ Metallic plane could change dissipative environment

$$\text{diss.} \sim 1/R$$

# Effects on $T_c$ and $H_c$

$$\frac{H_C^{GP} - H_C}{H_C} = 2\%$$

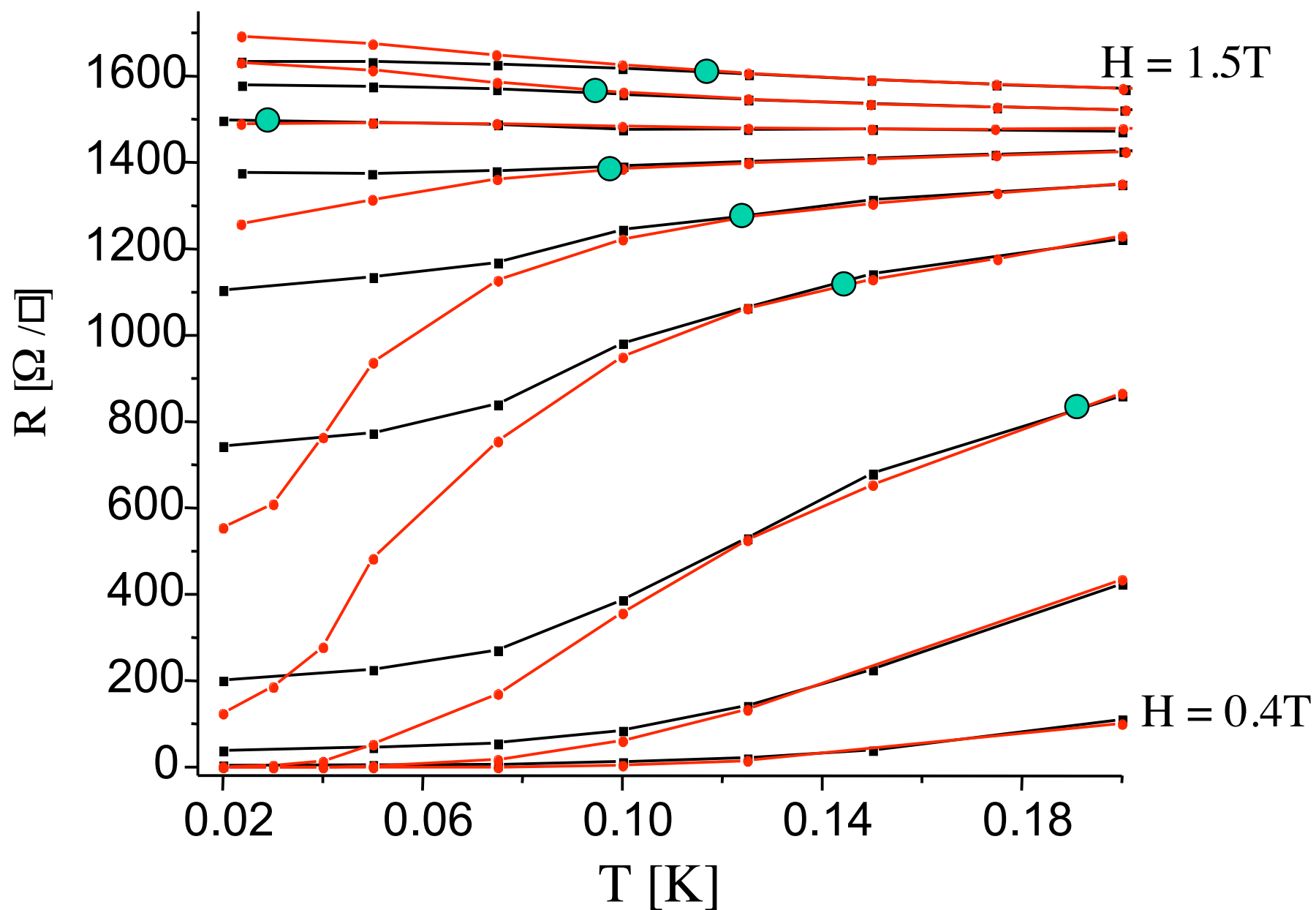


$$\frac{T_C^{GP} - T_C}{T_C} = 2\%$$

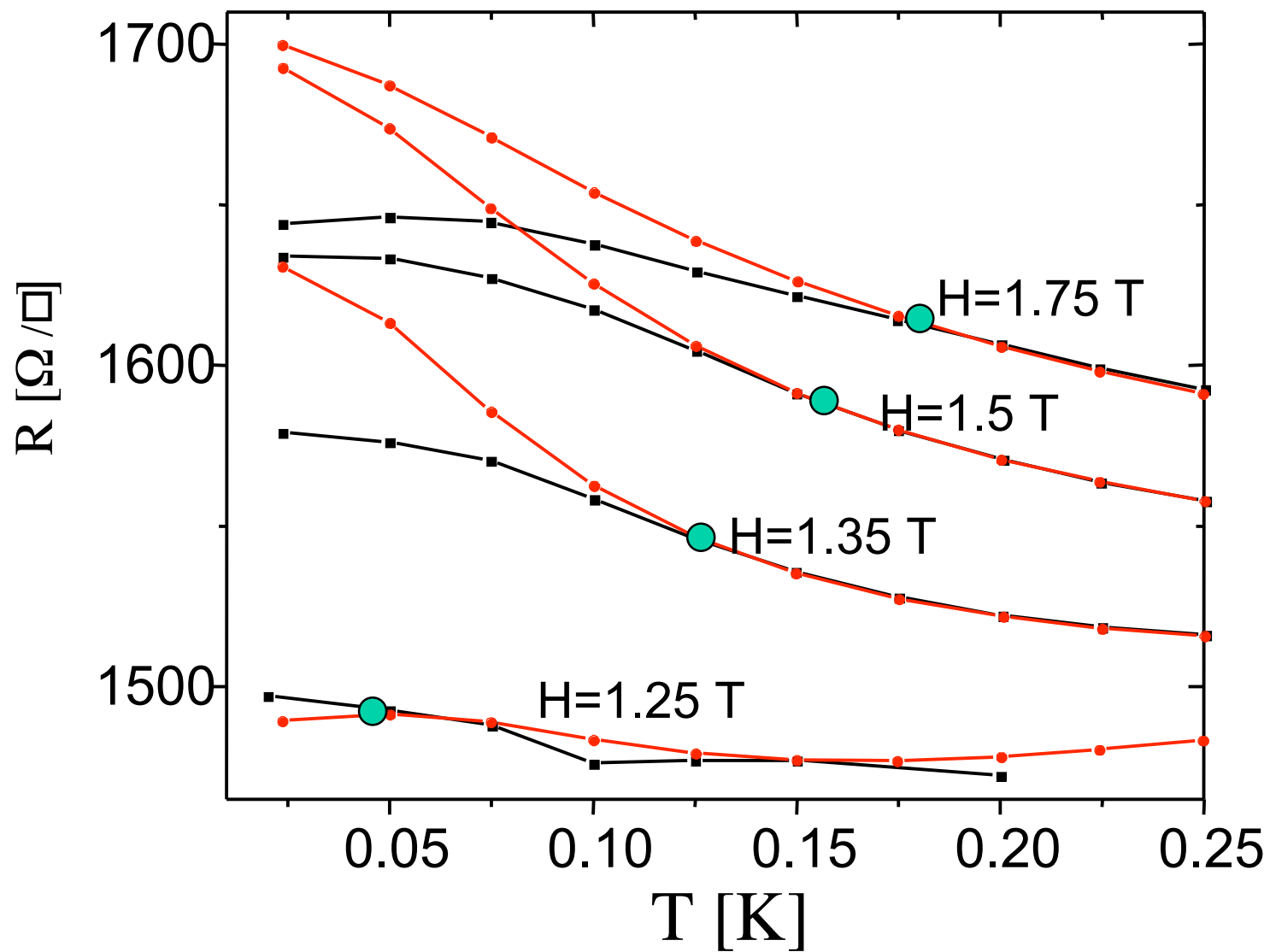
30Å MoGe

On the “Superconducting” side

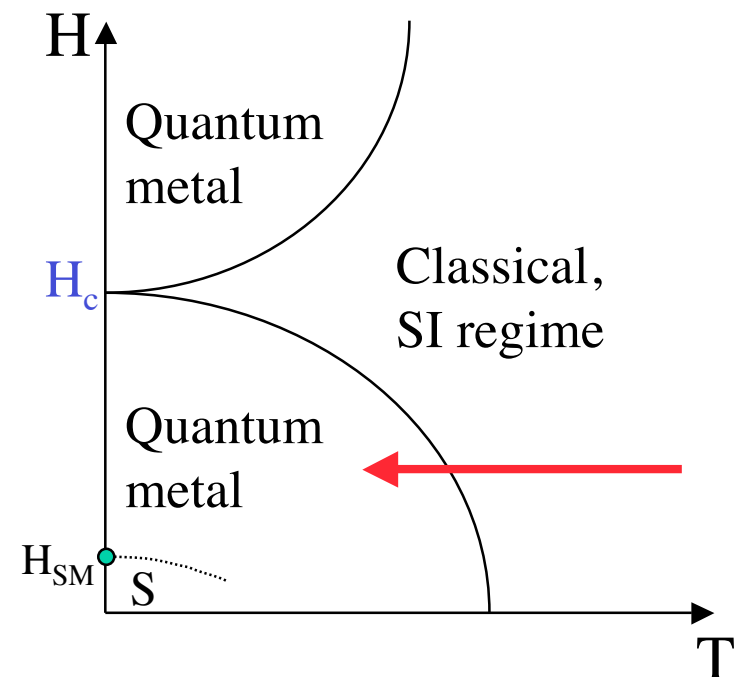
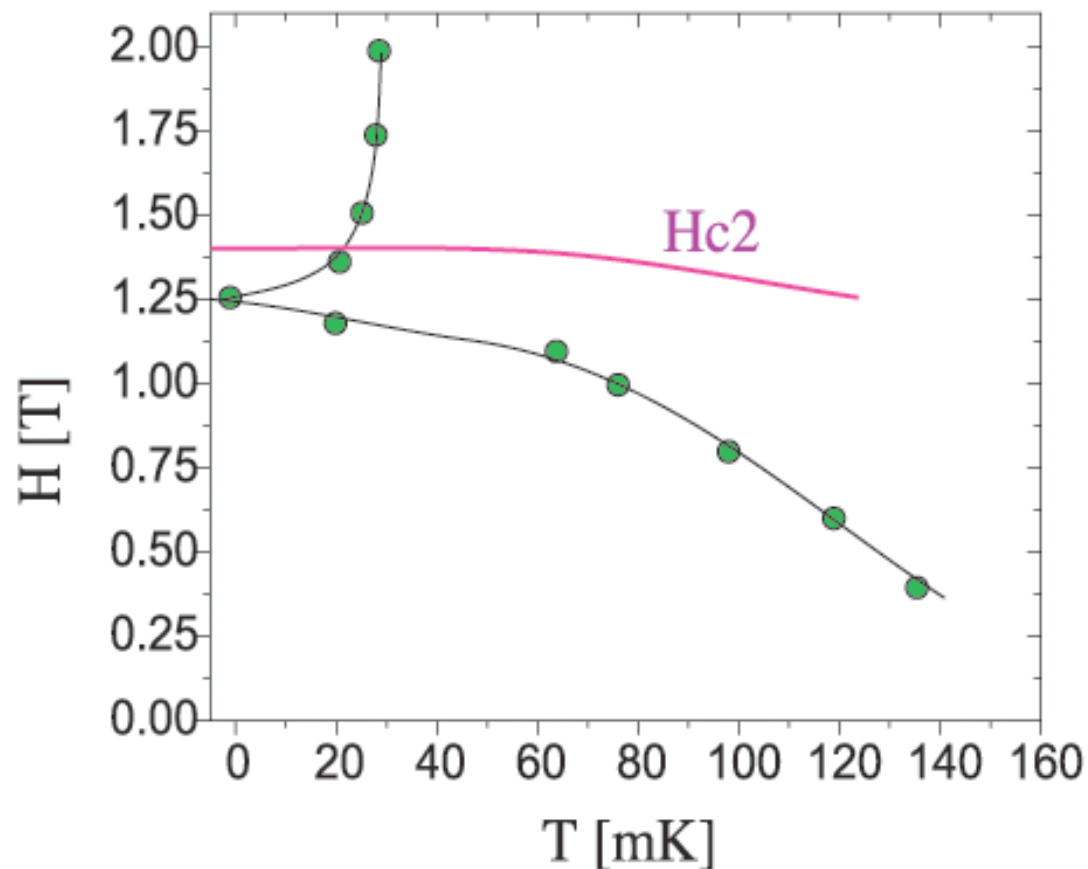
— metallic plane  
— bare



## On the “Insulating” side

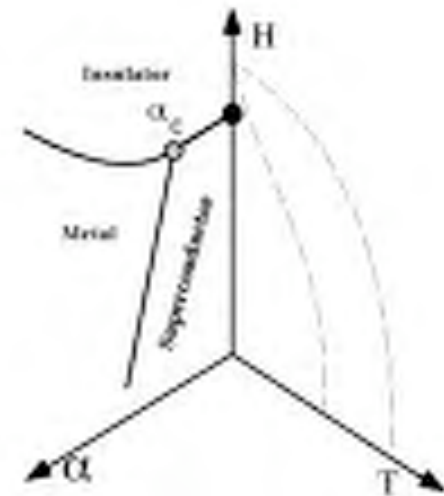


Ground plane starts to have an effect when system crosses over into quantum metal phase :

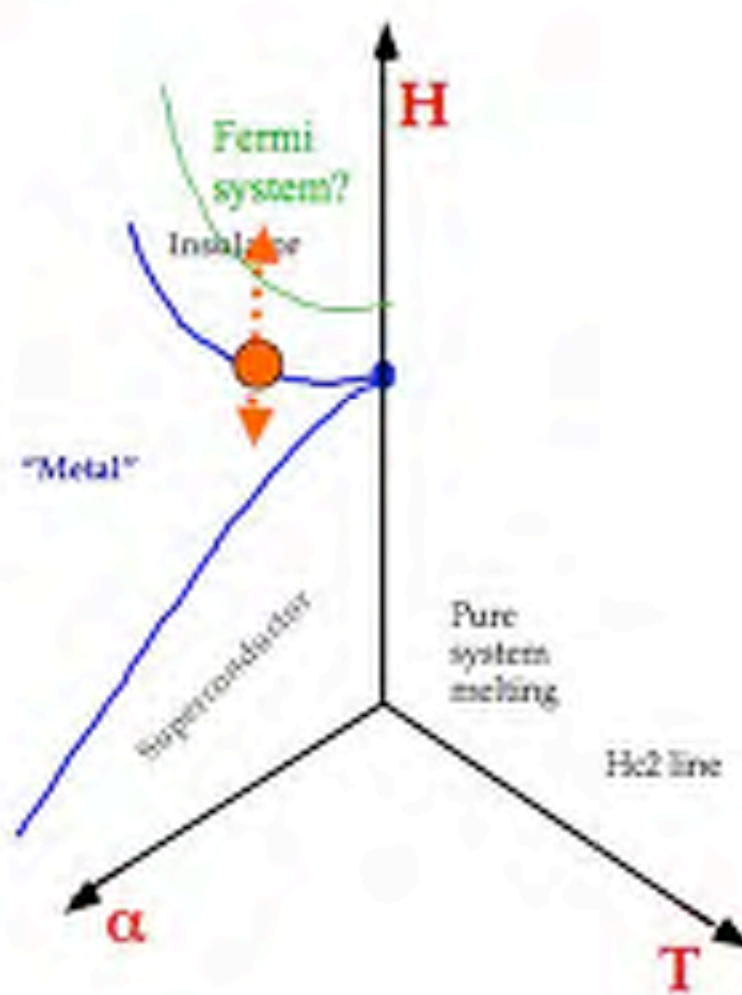


## Conclusions for weak insulators:

- A new metallic phase with resistance 2-3 orders of magnitude lower than the “Fermi” resistance
- The metallic phase is almost a superconductor. Internal Josephson couplings.
- At low fields the metallic phase undergoes a transition to a true superconductor
- There is an underlying Superconductor-Insulator transition that is Bose-dominated that the metallic phase “knows” about.
- The almost superconductor-insulator transition is percolation like With classical-percolation exponent.



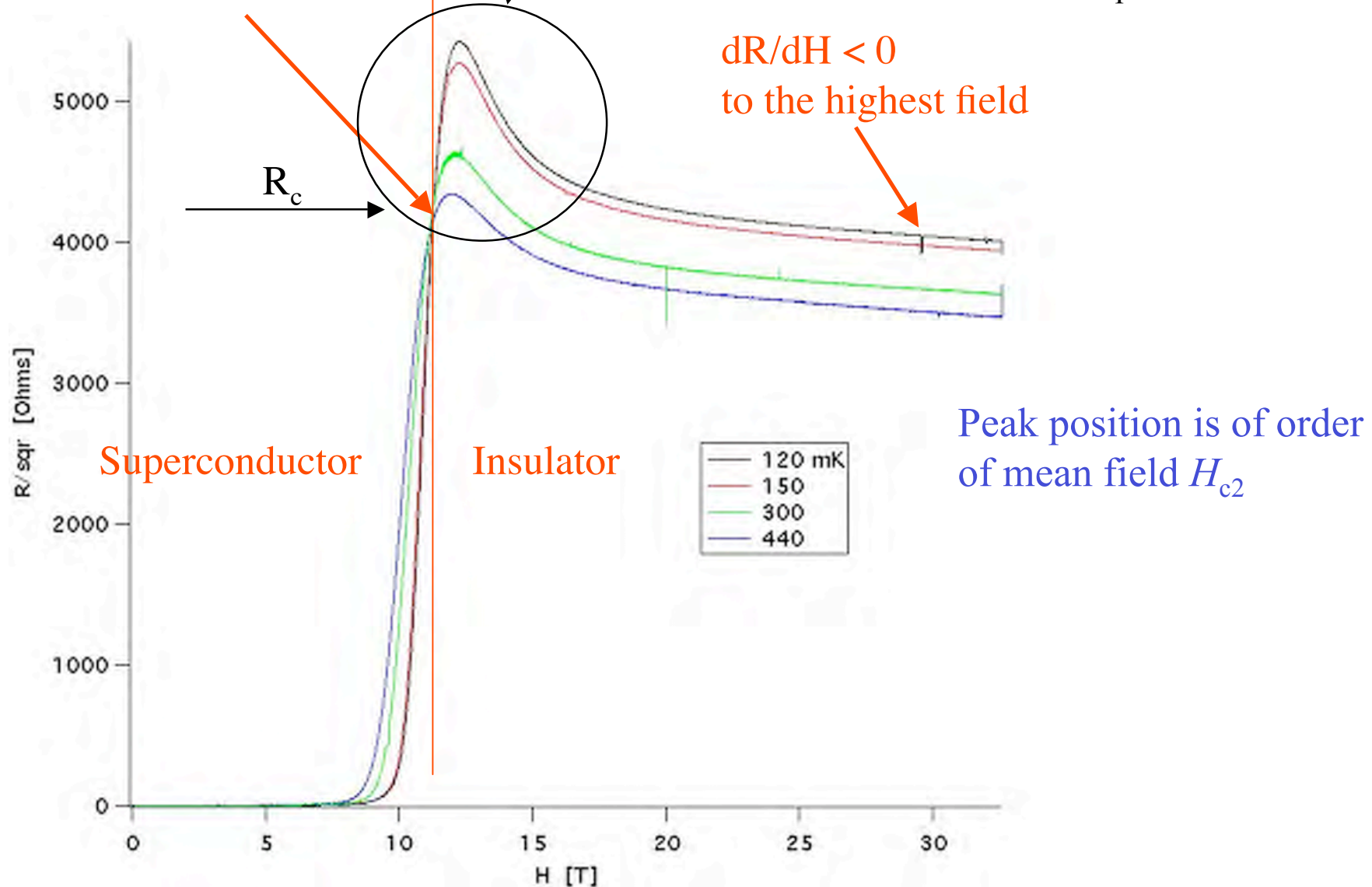
How good is the insulator?



For weak disorder Insulating behavior is “weak”

Crossing Point:  $H_c \sim 11.2$  T

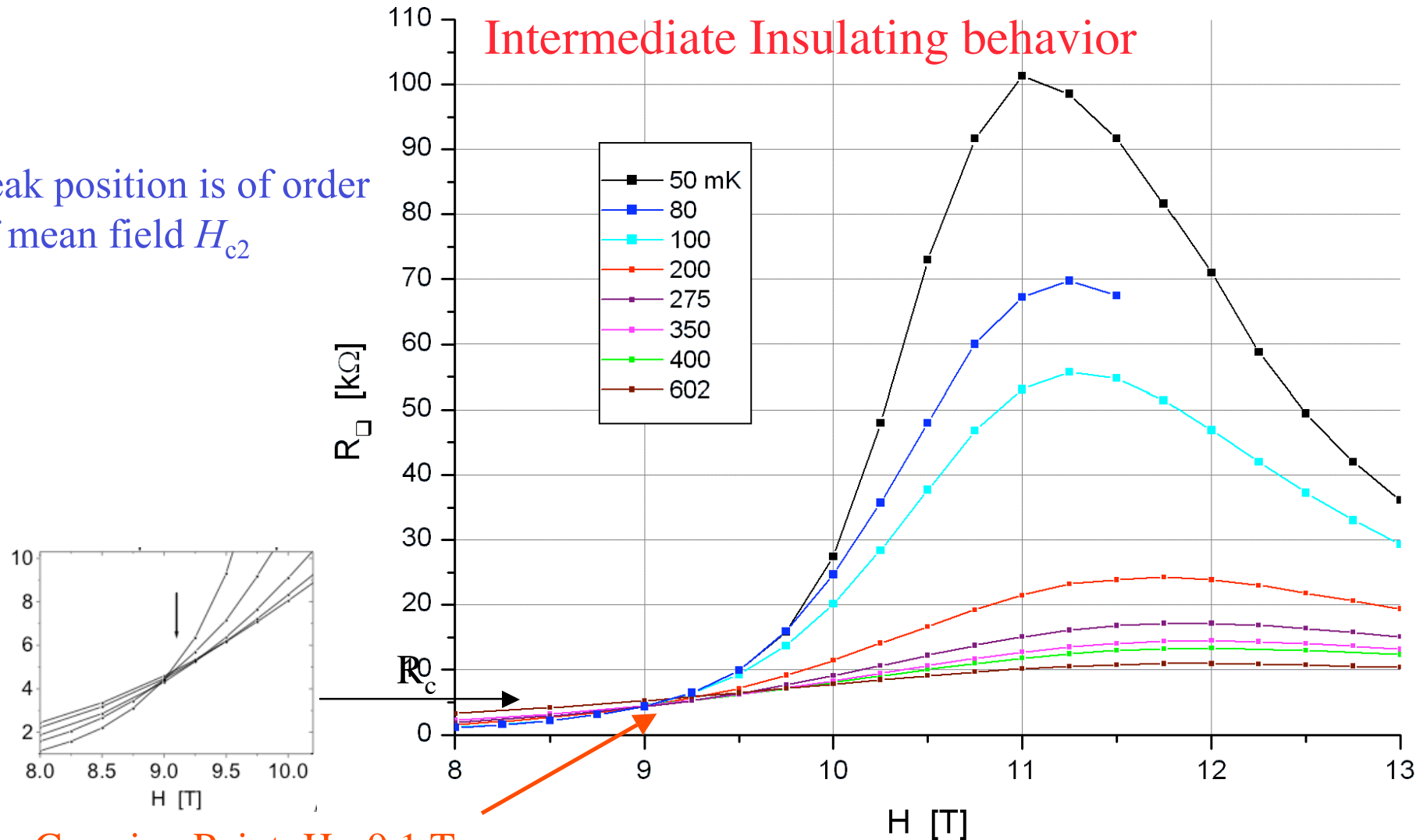
$$R_{\text{peak}}/R_c \sim 1.4$$



# Intermediate disorder

$$R_{\text{peak}}/R_c \sim 20$$

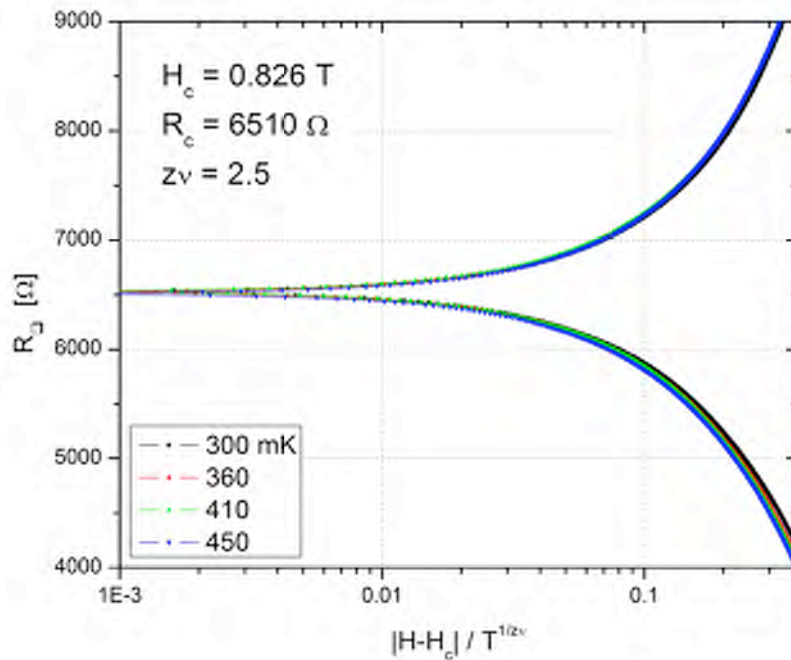
Peak position is of order  
of mean field  $H_{c2}$



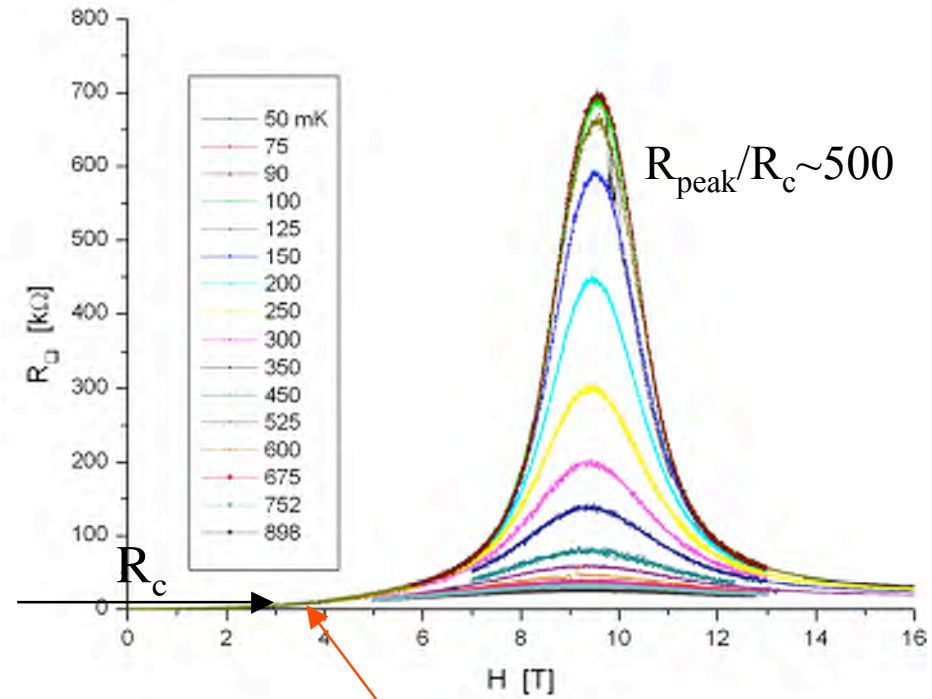
Crossing Point:  $H_c \sim 9.1$  T

# Strong disorder behavior ( $\text{InO}_x$ )

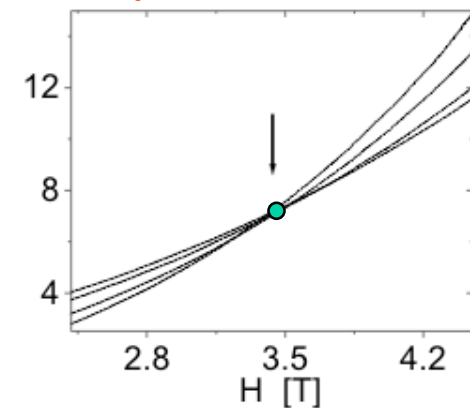
Scaling with temperature



Observed  $\nu$  is consistent with quantum percolation:  $z\nu=2.5$

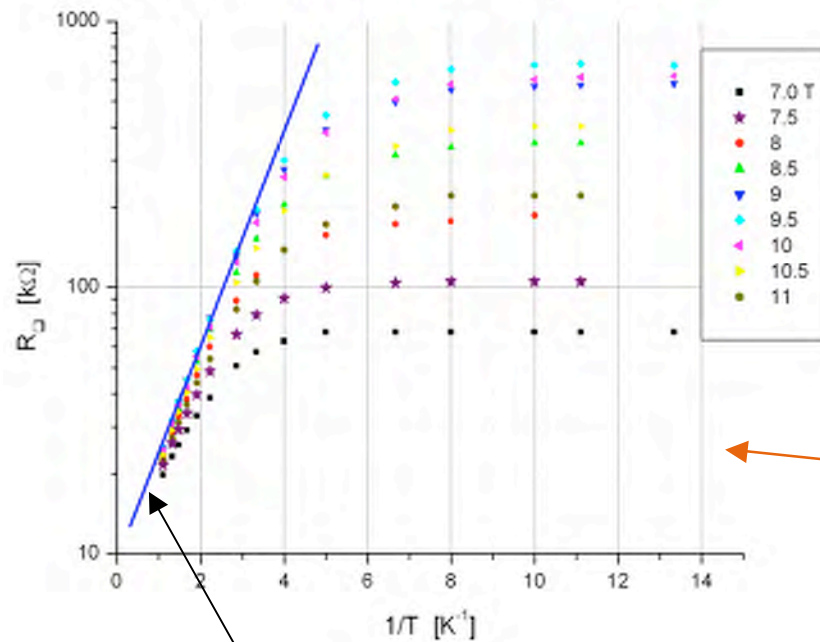


Crossing point:  $H_c \sim 3.6 \text{ T}$

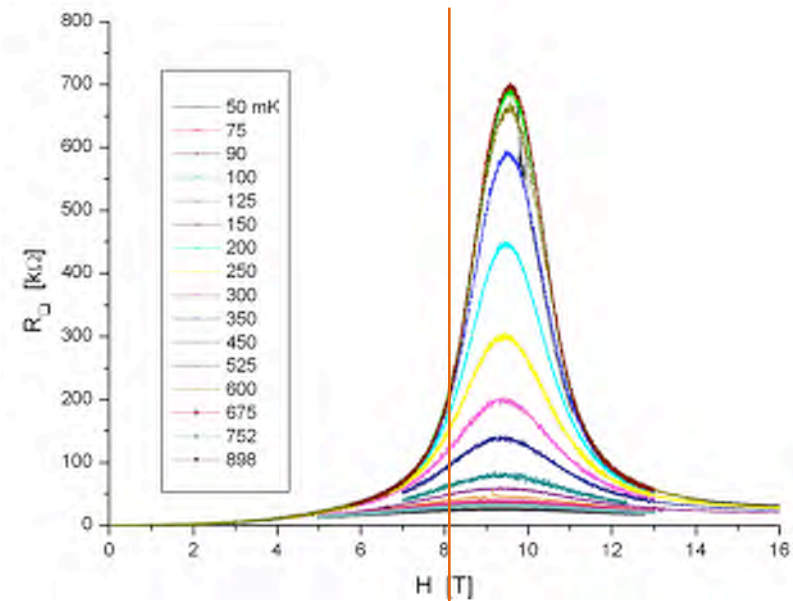


# Activated behavior of the strong insulator

Replotting of the isotherms following an Arrhenius model



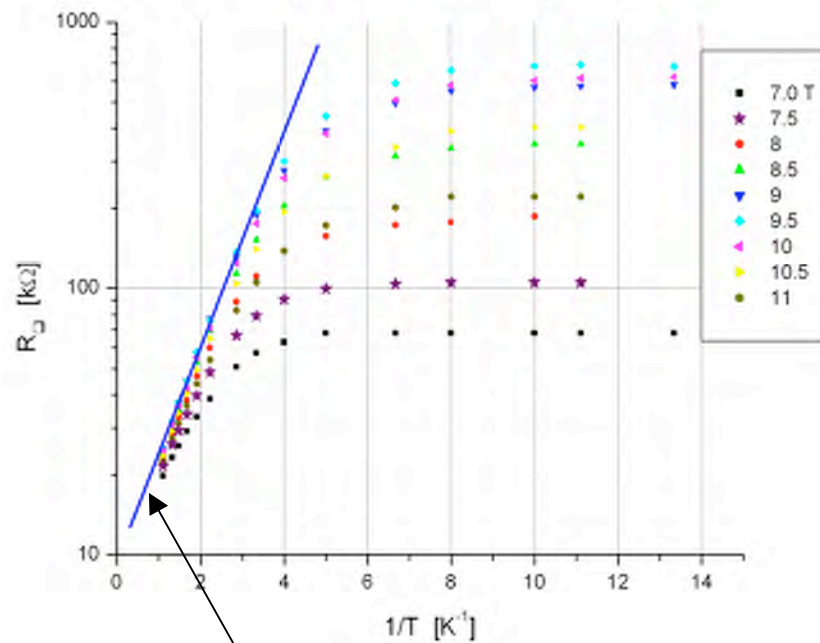
$$R_{\square} \sim e^{T_a/T}$$



Plot  $R$  vs.  $1/T$  for const.  $H$

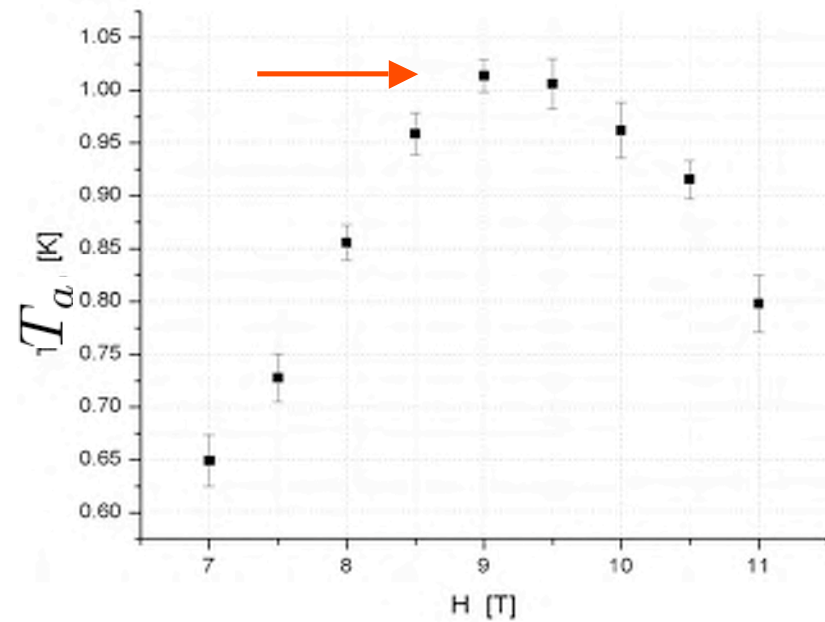
Repeat for each field:

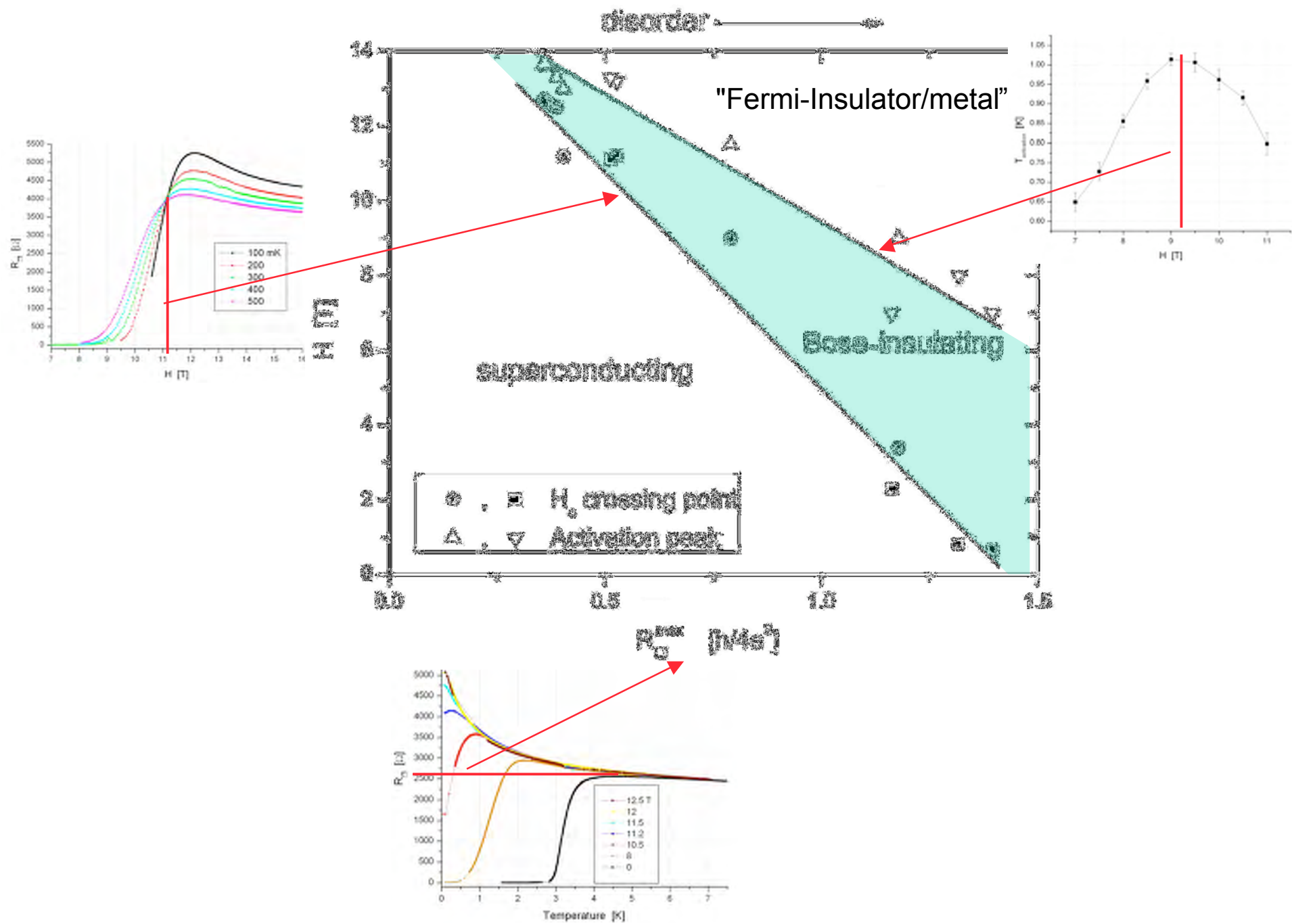
Replotting of the isotherms following an Arrhenius model



$$R_0 \sim e^{T_a/T}$$

Activation temperature at high magnetic fields





## Construction of Summary phase diagram:

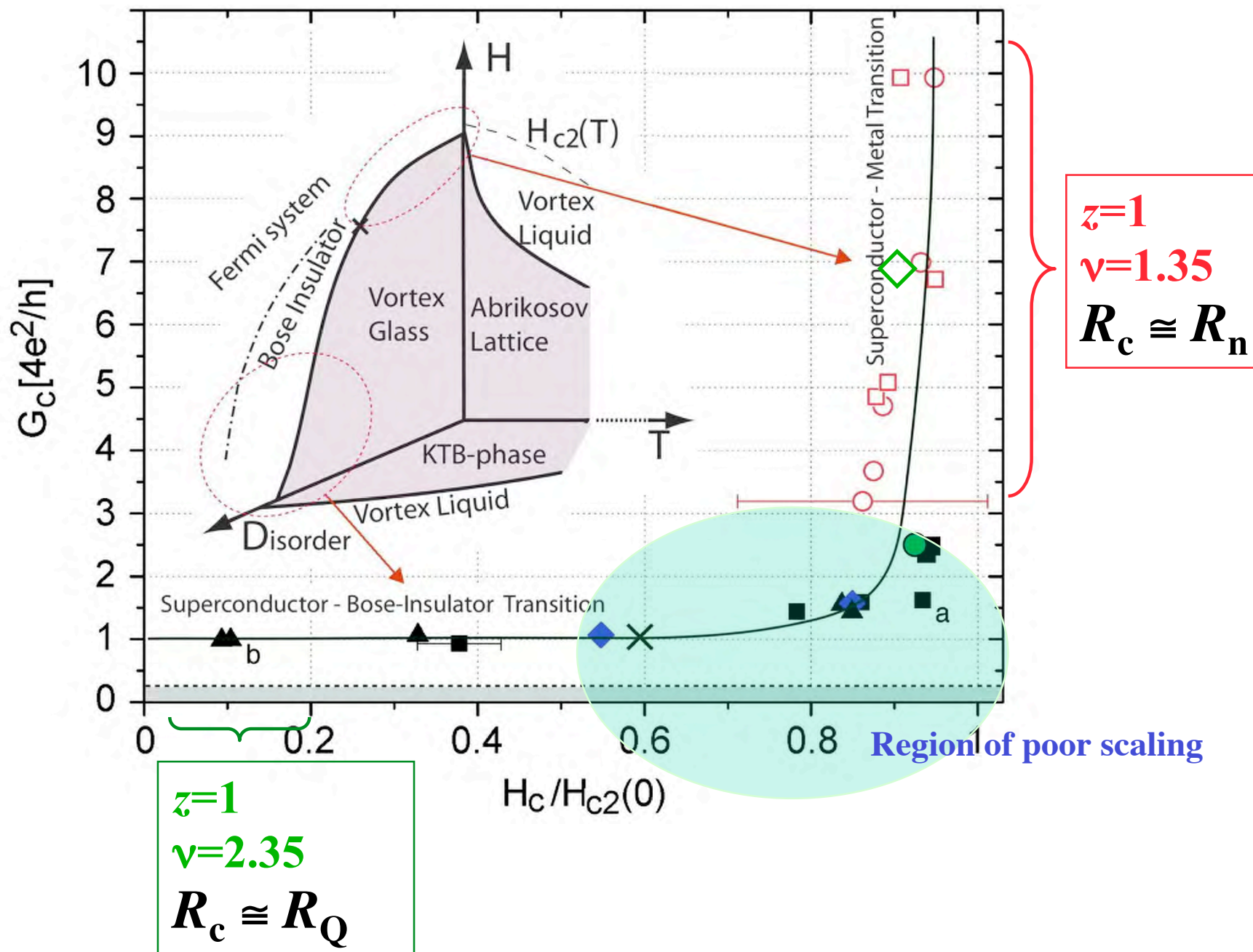
Scale the conductance and field to produce a global phase diagram:

➔ Scale the critical conductance by the quantum conductance of pairs:

$$G_Q = \frac{4e^2}{h} \approx [6.5 \text{ k}\Omega]^{-1}$$

➔ Scale the critical field by the (mean field) upper critical field -  $H_{c2}(0)$ .

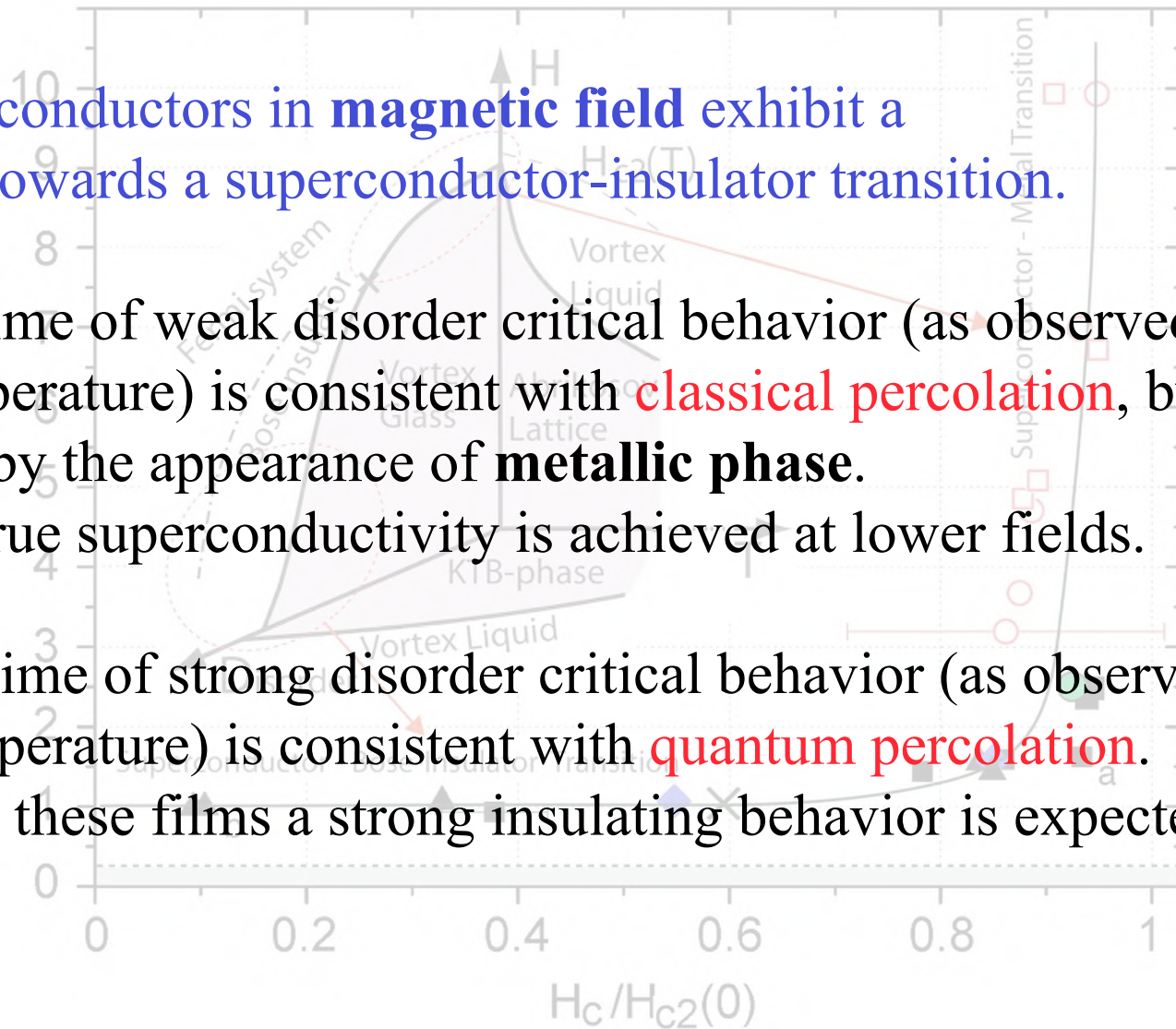
\* The upper critical field is found from the low field slope and from the **peak of the magnetoresistance** (which is found to be close to  $H_{c2}(0)$ ).



(Samples used: amph-InO<sub>x</sub>, poly-InO<sub>x</sub>, TaN, Ta, amph-MoGe)

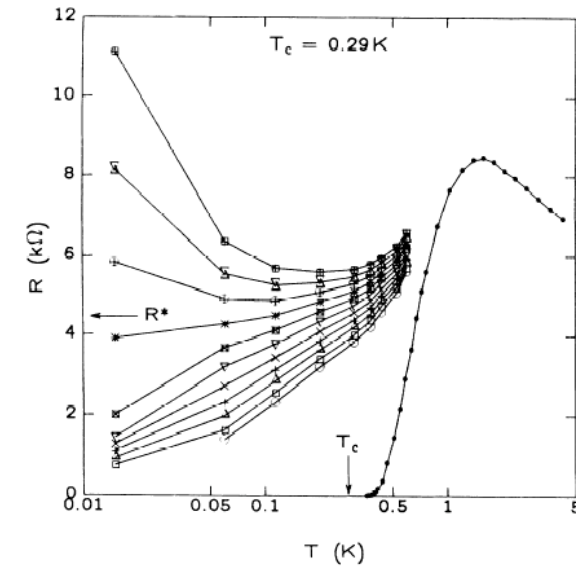
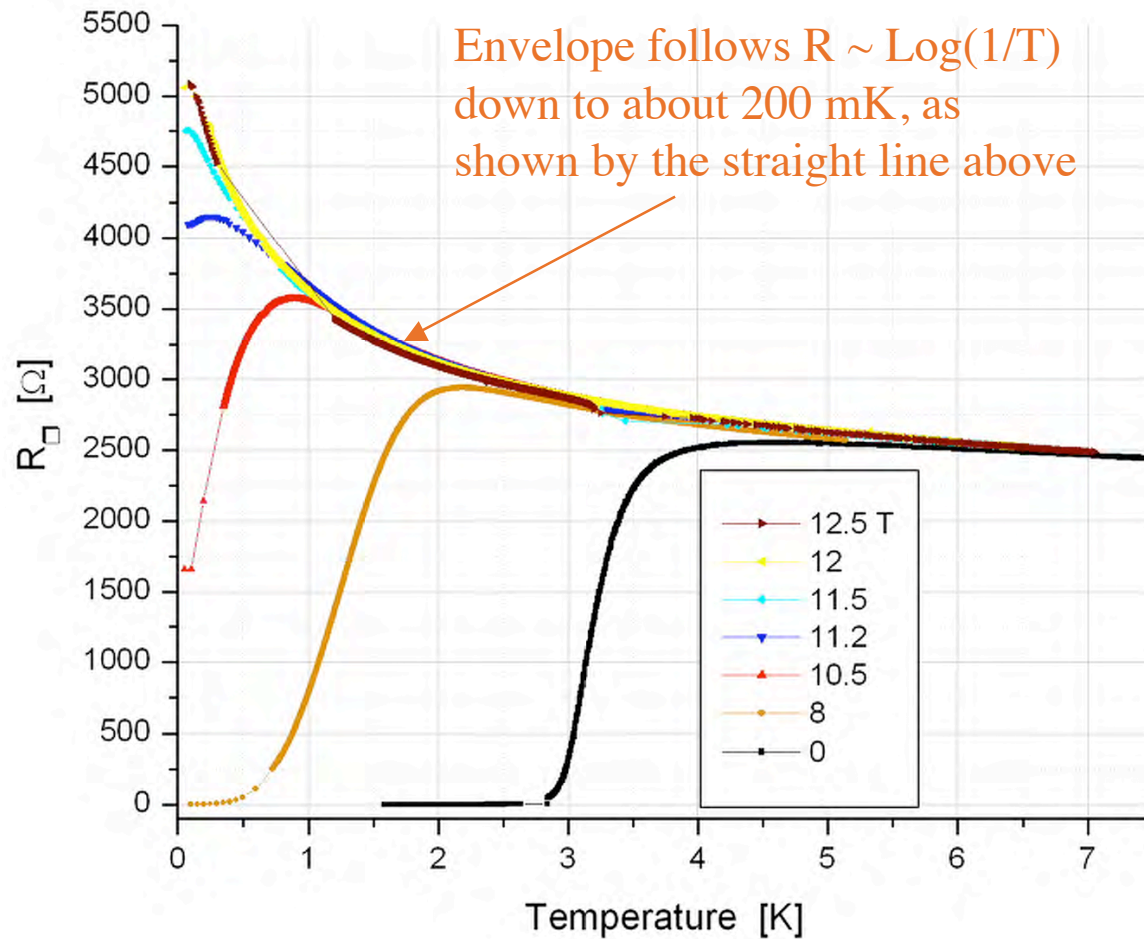
## Conclusions:

- 2-D superconductors in **magnetic field** exhibit a tendency towards a superconductor-insulator transition.
- In the regime of weak disorder critical behavior (as observed from finite temperature) is consistent with **classical percolation**, but is disrupted by the appearance of **metallic phase**.
  - ➔ True superconductivity is achieved at lower fields.
- In the regime of strong disorder critical behavior (as observed from finite temperature) is consistent with **quantum percolation**.
  - ➔ In these films a strong insulating behavior is expected at low T.



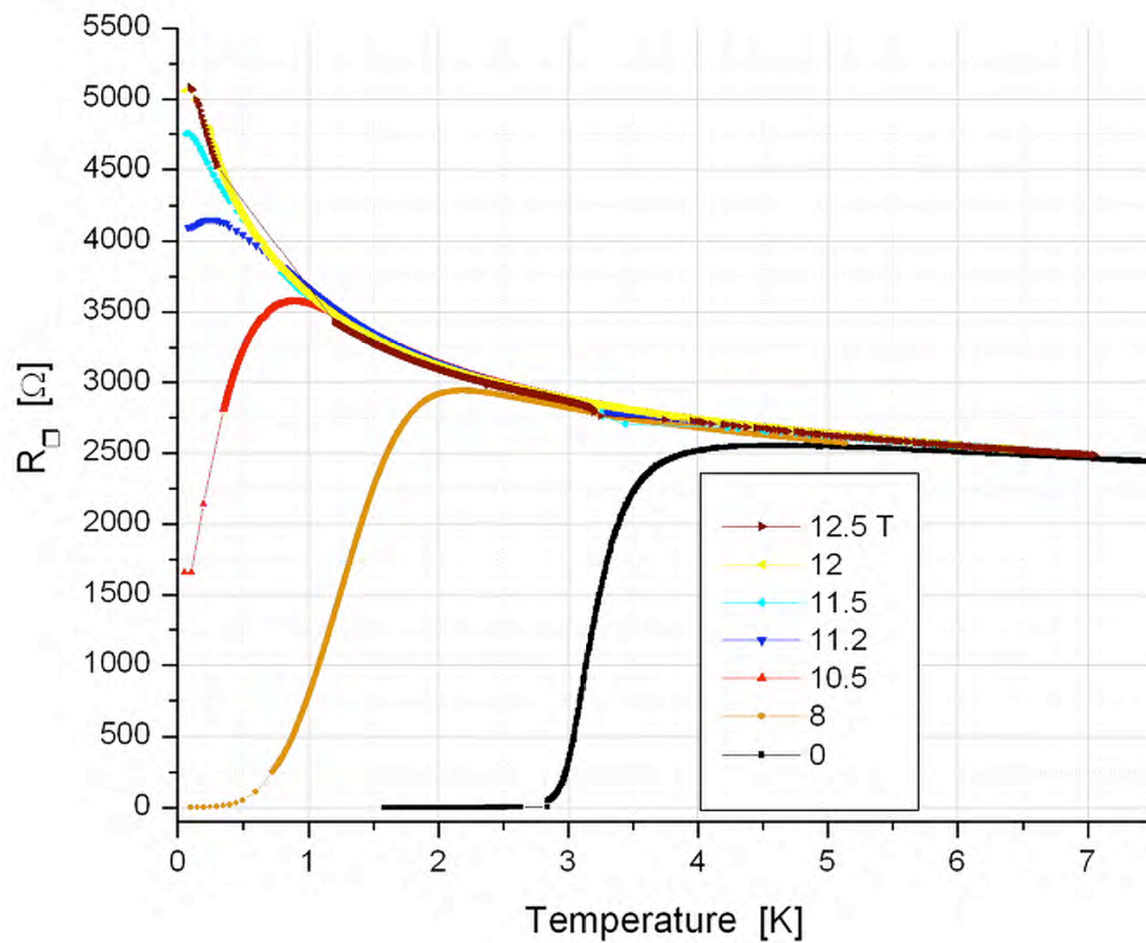
# Observations Relevant to High-T<sub>c</sub>

# Resistive Transitions in a Field



M.A. Steiner, G. Boebinger and A. Kapitulnik, Phys. Rev. Lett. 94, 107008 (2005)..

Back to the envelope behavior:  $R \sim \log T$



# Logarithmic Divergence of both In-Plane and Out-of-Plane Normal-State Resistivities of Superconducting $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ in the Zero-Temperature Limit

Yoichi Ando,\* G. S. Boebinger, and A. Passner

*AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974*

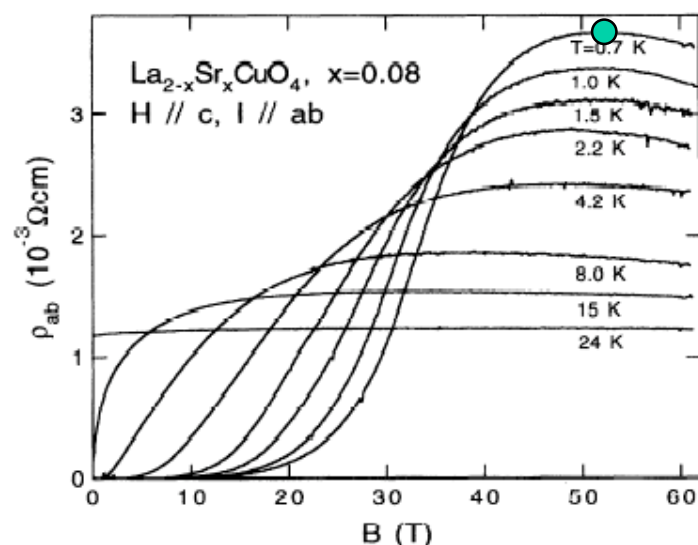


FIG. 1. In-plane resistivity  $\rho_{ab}$  versus magnetic field for the  $x = 0.08$   $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$  single crystal at various temperatures.

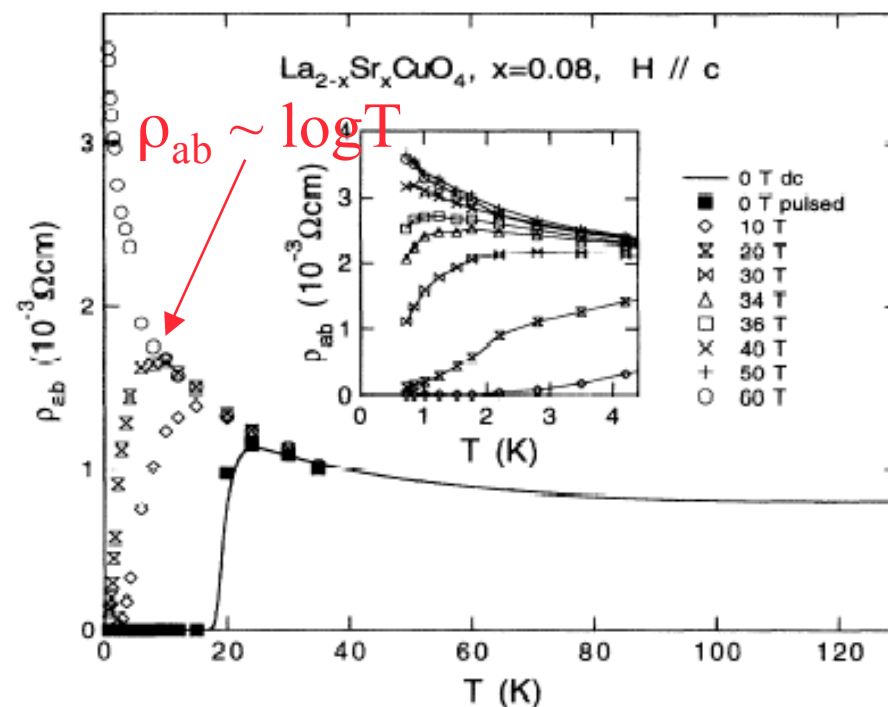
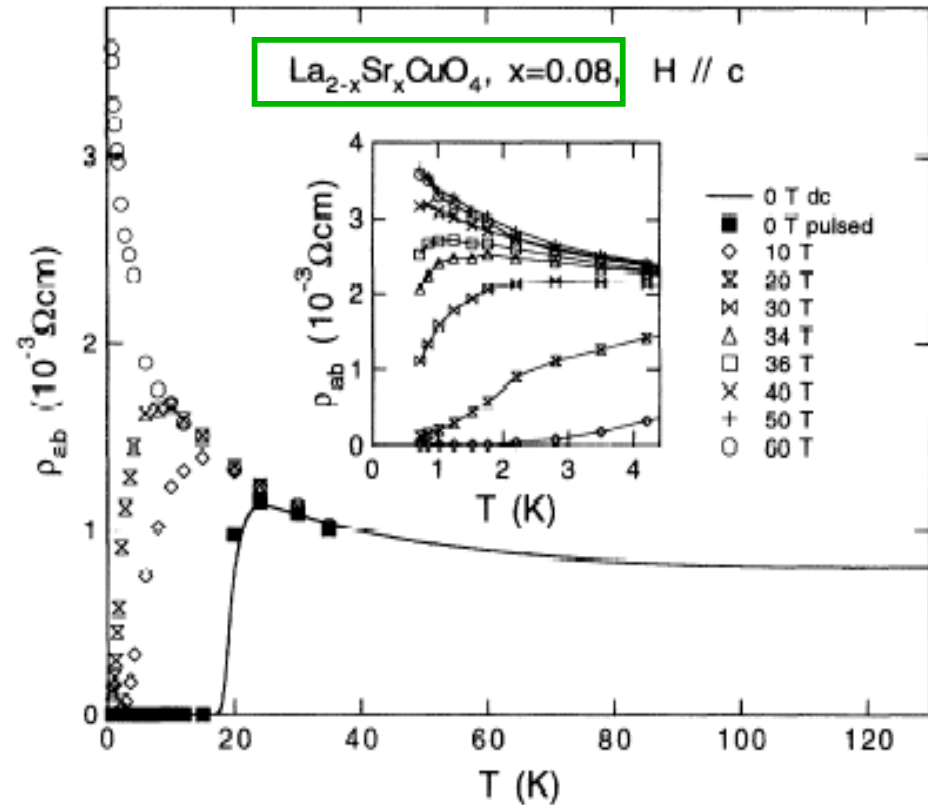
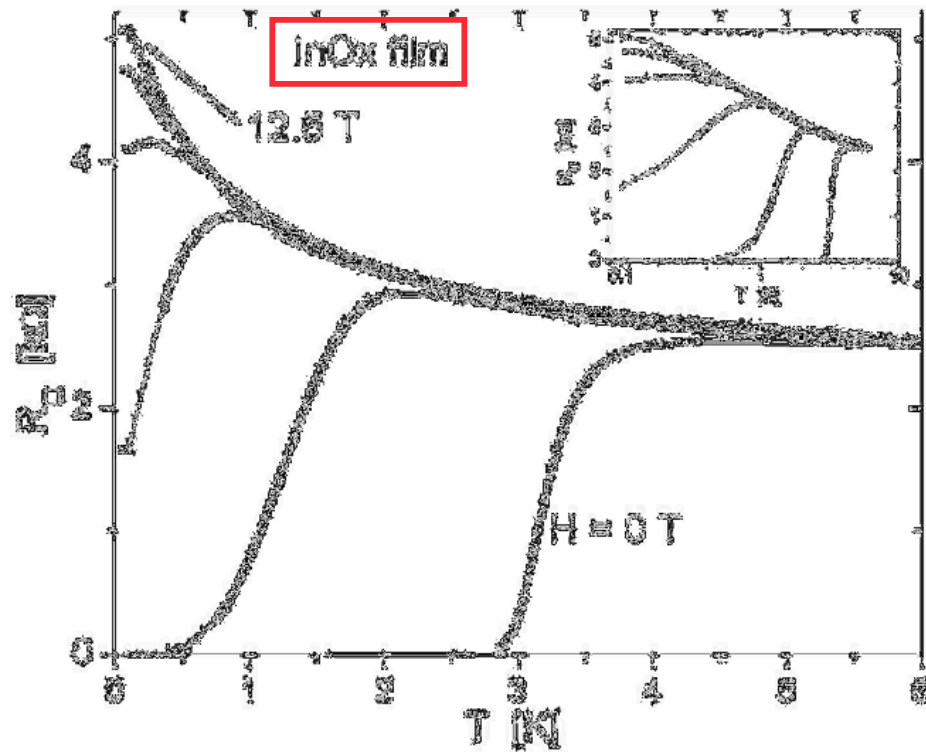


FIG. 2. Temperature dependence of  $\rho_{ab}$  in 0, 10, 20, and 60 T, obtained from the pulsed magnetic field data. The solid line shows the zero-field resistive transition. The inset contains the low-temperature data.

# Comparison of Envelopes



In-plane resistivity measured with a perpendicular magnetic field

- Amorphous, type II BCS film
- Field rolls over at  $\sim 12.5$  T

- High- $T_c$ , layered structure
- Field saturates at  $\sim 50$  T

The “logT” phase in high-Tc **IS NOT** the “normal state”

There are still a large number of pairs in this phase.

High-Tc in a field could be close to a field-tuned SIT where pairs persist much above the mean field  $H_{c2}$ .

Results support the Nernst effect measurements\* which find “vortices” at fields much above where the “normal state” is achieved.

\* Z. A. Xu, N. P. Ong, Y. Wang, T. Kakeshita, and S. Uchida, Nature 406, 486 (2000).

Yayu Wang, N. P. Ong,<sup>1</sup> Z. A. Xu, T. Kakeshita, S. Uchida, D. A. Bonn, R. Liang, and W. N. Hardy, Phys. Rev. Lett. 88, 257003 (2002).

C. Capan, K. Behnia, J. Hinderer, A. G. M. Jansen, W. Lang, C. Marcenat, C. Marin, and J. Flouquet, Phys. Rev. Lett. 88, 056601 (2002).