Disordered superconductors: From 1D to 2D

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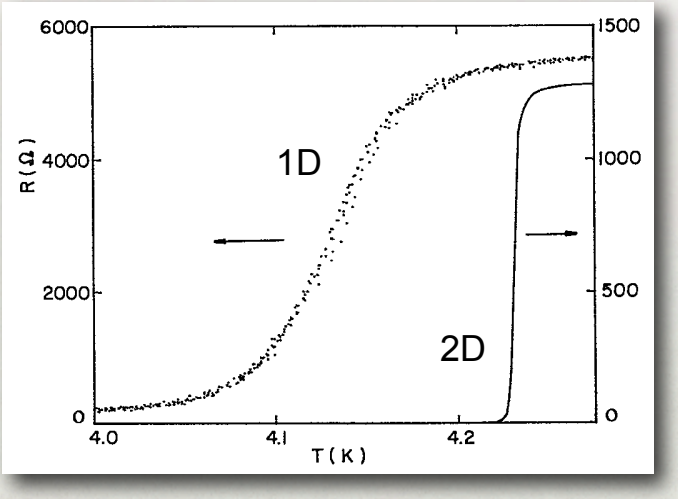
The Weizmann Institute of Science

Argonne, Nov. 2010

1D SUPERCONDUCTORS

Dimensionality of a superconductor

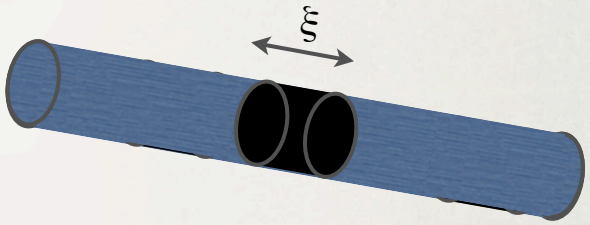
- Superconducting correlation length ξ.



Giordano ('91).

Why?

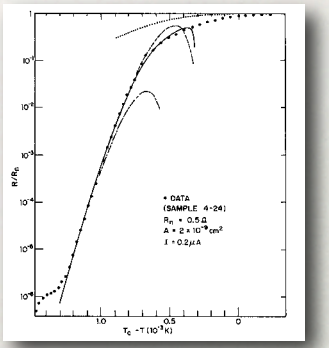
Phase slips



Thermal: Langer & Ambegaokar (‘67),
McCumber & Halperin (‘70)

$$R_{\mathrm{LAMH}} = \frac{\pi\hbar^2\Omega}{2e^2kT}\, e^{-\Delta F/kT}$$

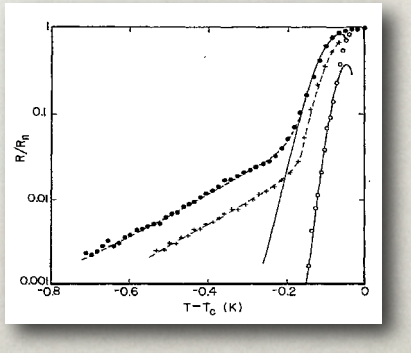
Newbower et al, (‘72)



Quantum: Giordano (‘88)

$$R_{\mathrm{MQT}} = B\,\frac{\pi\hbar^2\Omega_{\mathrm{MQT}}}{2e^2(\hbar/\tau_{\mathrm{GL}})}\, e^{-a\Delta F\tau_{\mathrm{GL}}/\hbar}$$

Giordano (‘88)

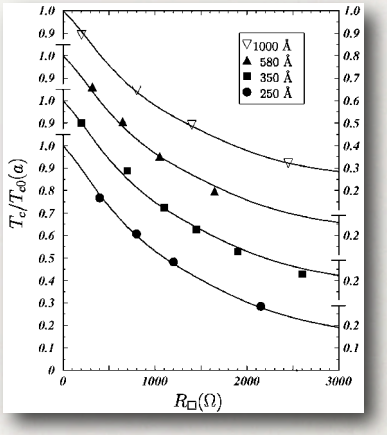


Zaikin et. al., PRL (‘97)

Why?

- **Tc suppression in wires**

  Oreg & Finkl'stein ('99)



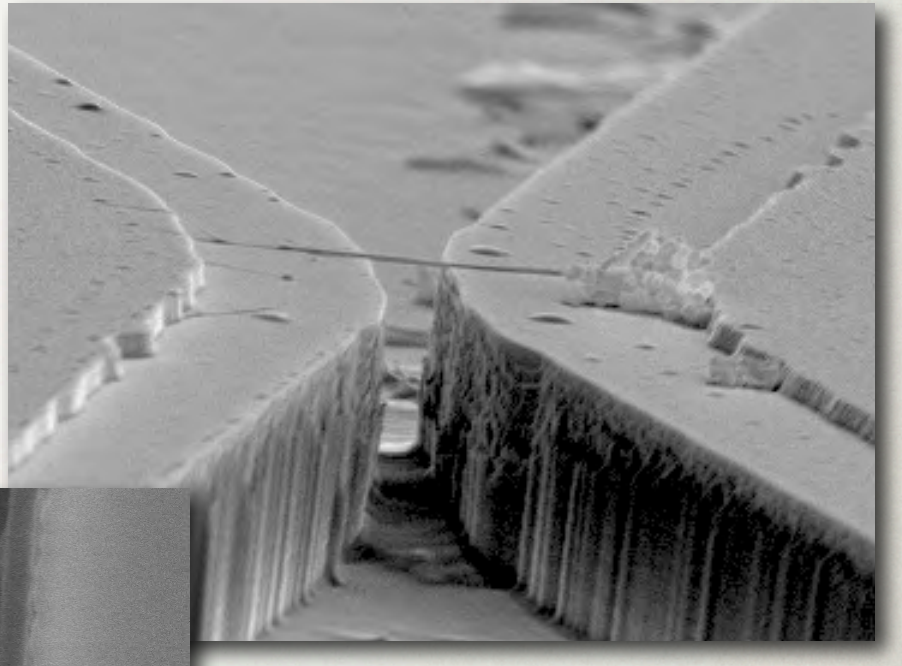
Xiong et al, ('97)

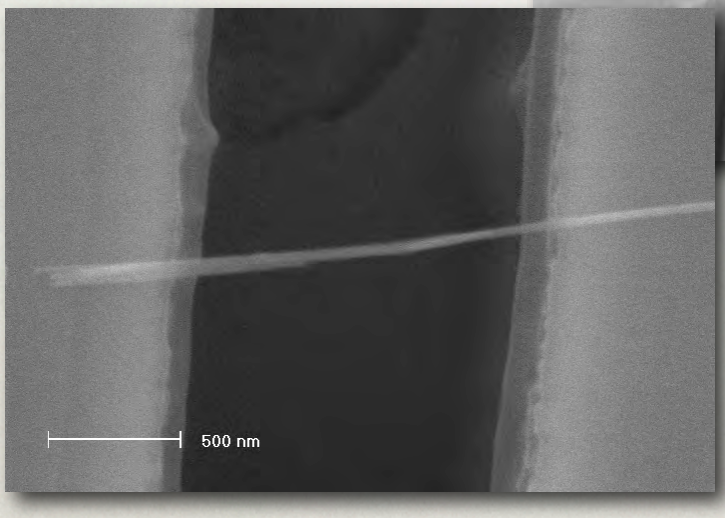
- **R_N >h/e^2, superconductor-insulator transition?**
- **Minimum size of a superconducting wire**
- **Is there true superconductivity in 1D?**

How?

The new whiskers

Bezryadin et al. nature **404**, 971 (2000).

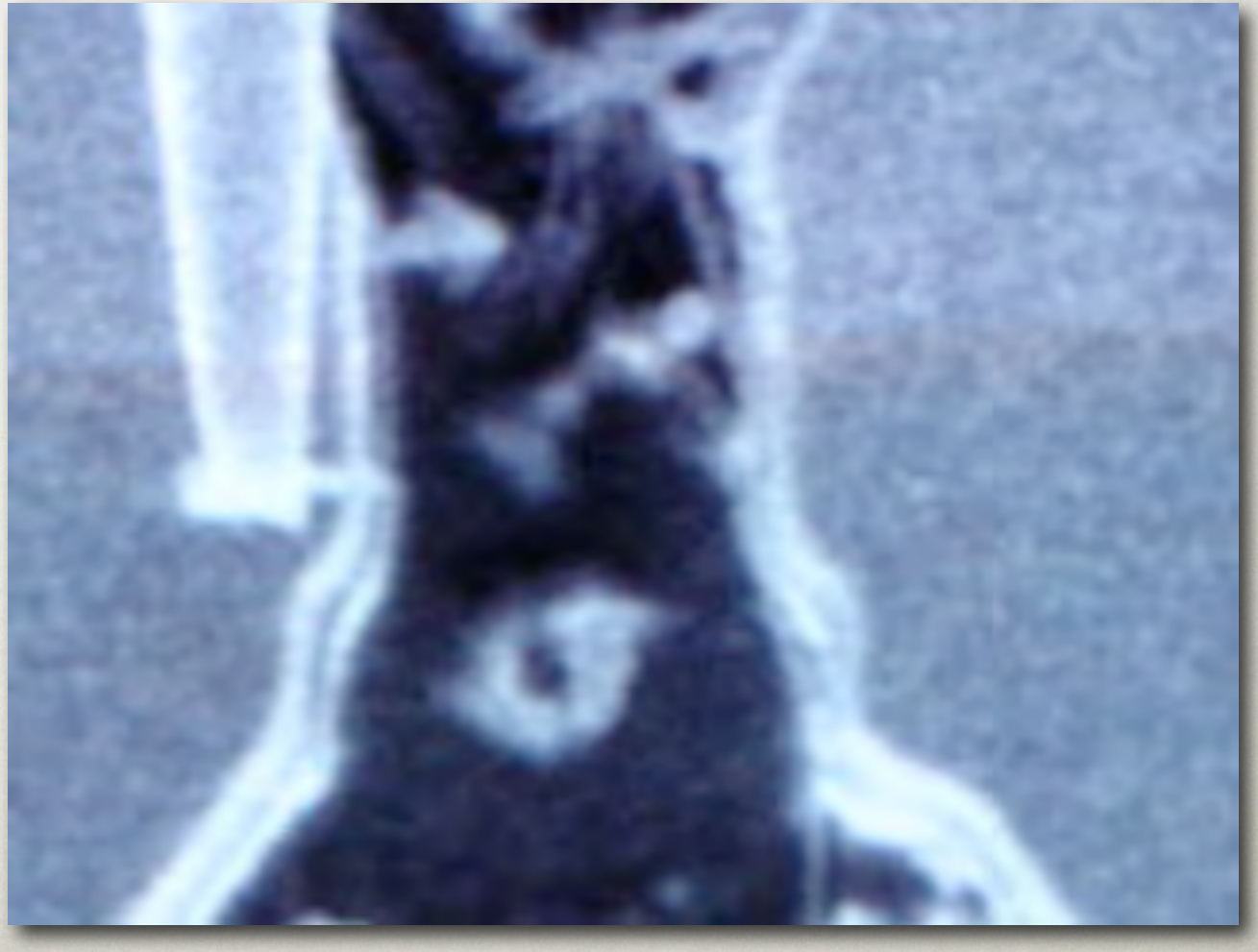




WS_2 nanotubes

How?

Nanotube manipulation



Our wires

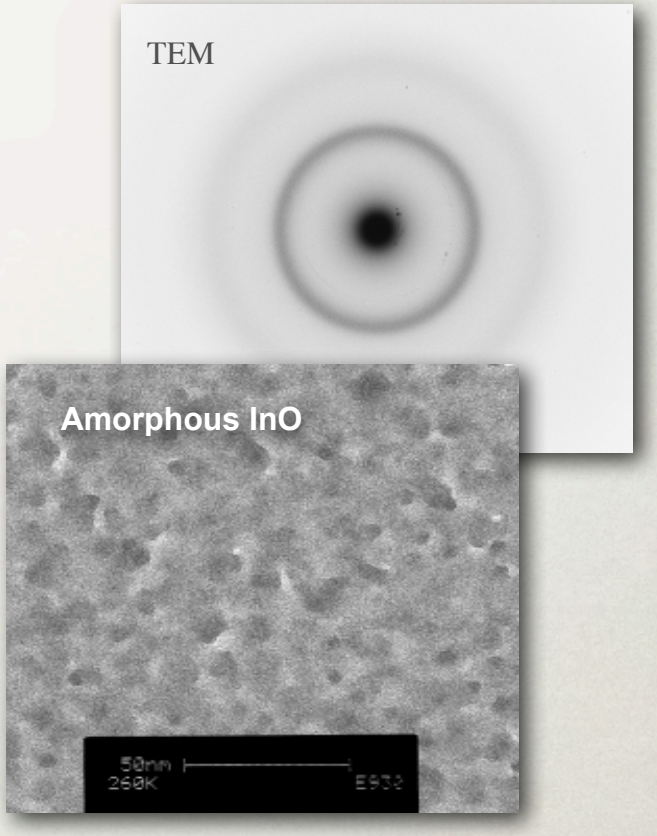
1. WS_2 nanotubes - insulating.

2. The superconductor: Amorphous InO

   Width: 40-100 nm

   Thickness: 20-30 nm

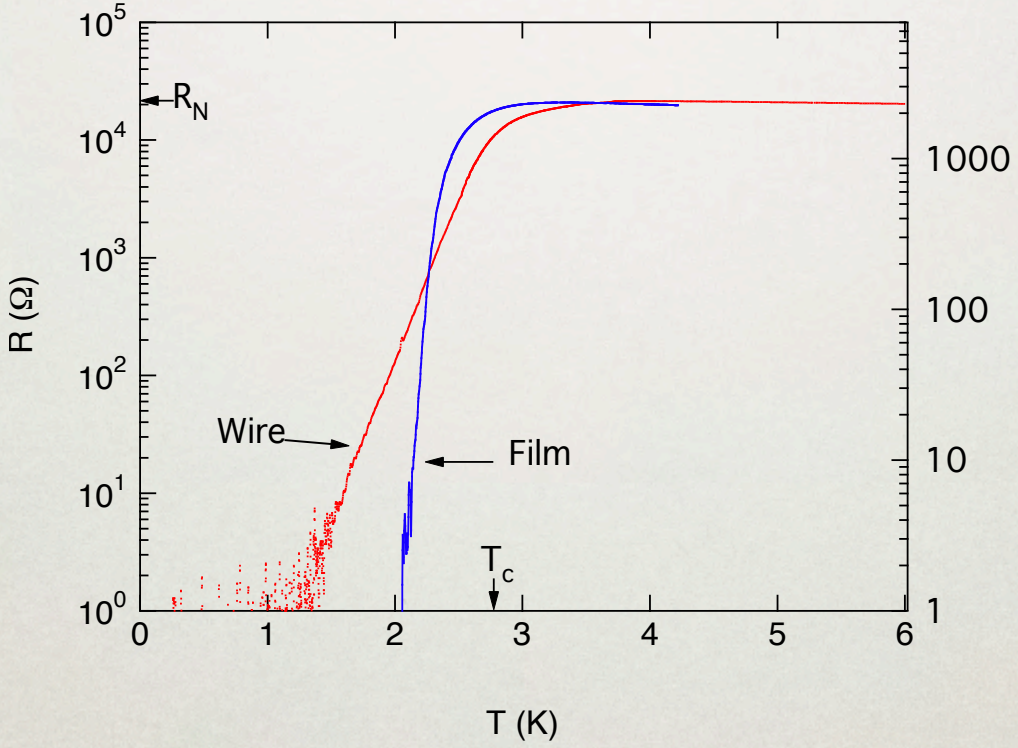
   ξ: 10-30 nm ⟶ Near 1D limit.



a:InO wires are superconducting

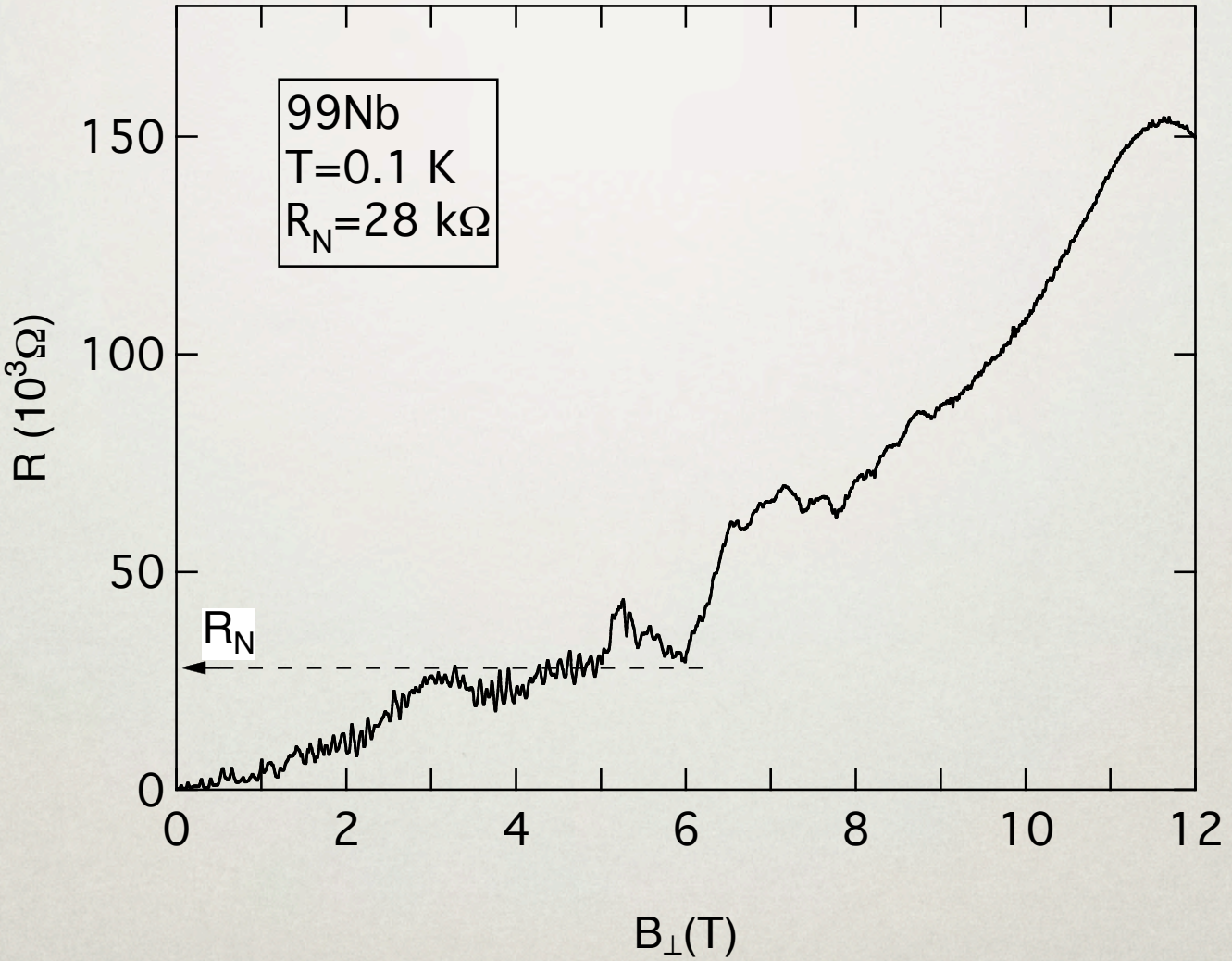
Magnetic field dependence

Comparing film and wire



Magnetic field

Magnetic Field



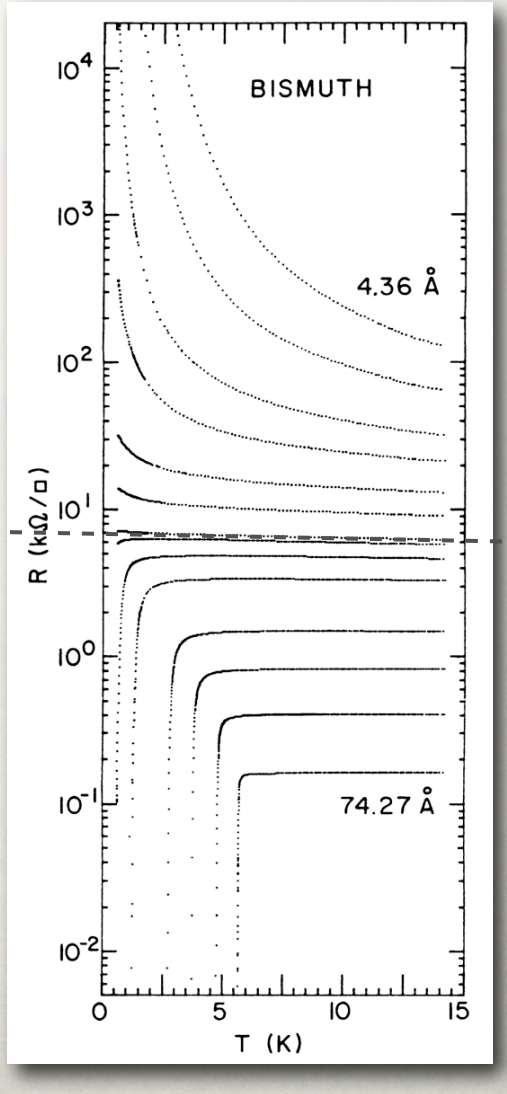
Disordered superconductors

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

D. B. Haviland, Y. Liu, and A. M. Goldman, Phys. Rev. Lett. 62, 2180 (1989)...

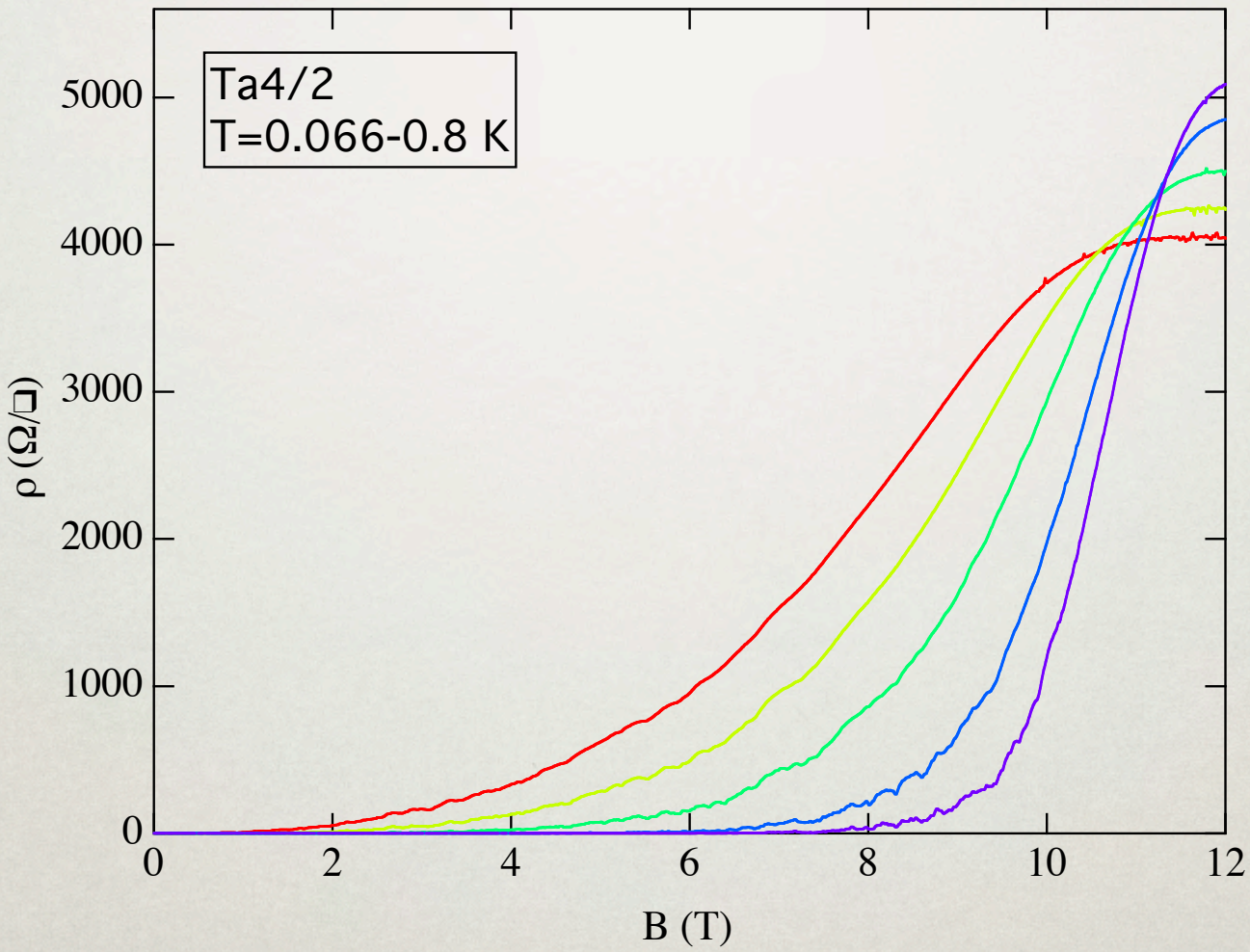
2D

T = 0 transition

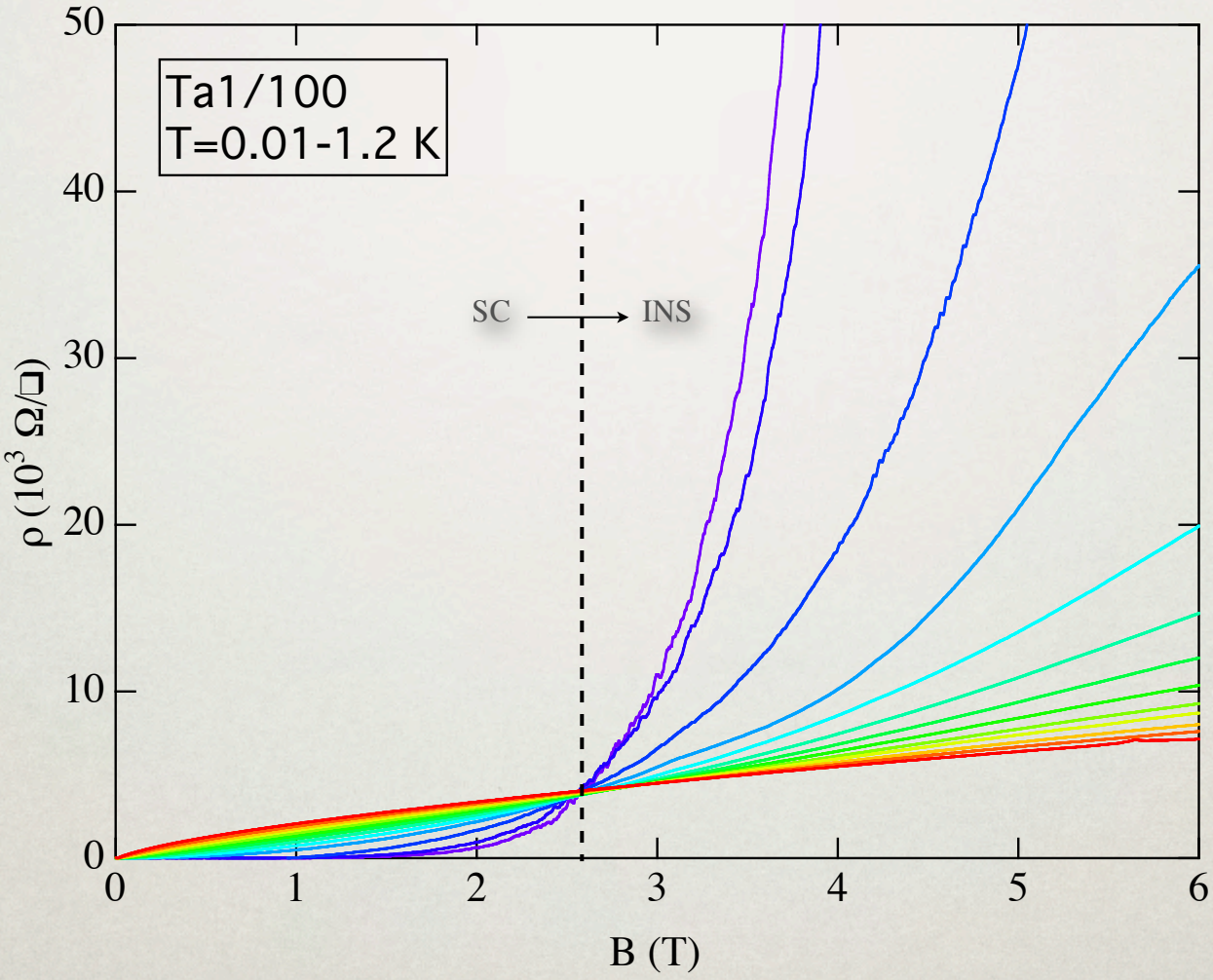


Review: Finkl'stein ('94),
Markovic and Goldman ('98).

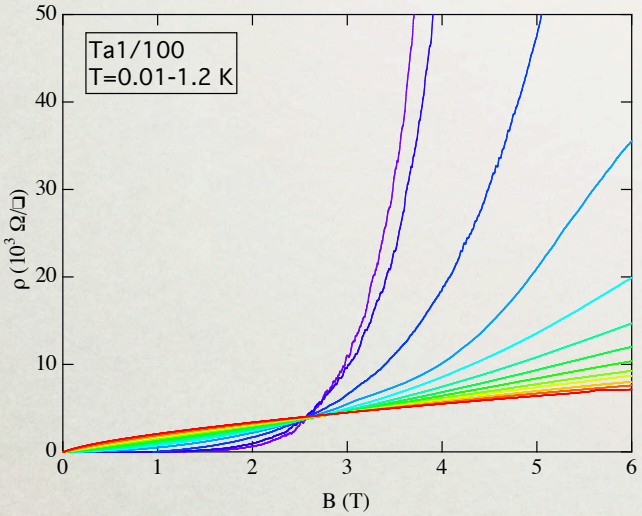
‘Good’ superconductor

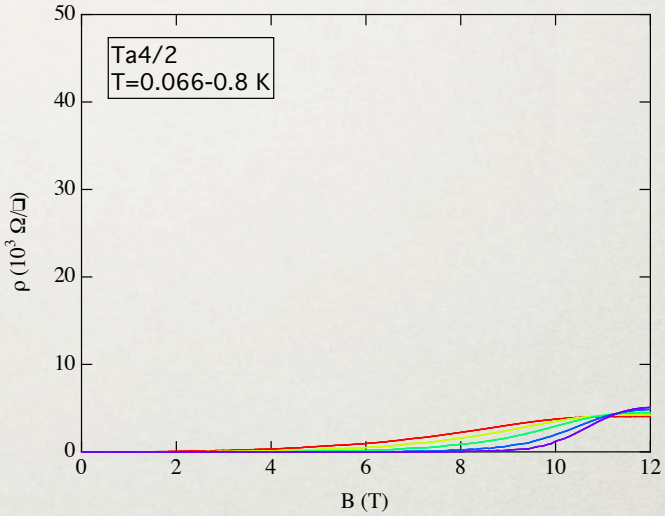


‘Bad’ superconductor



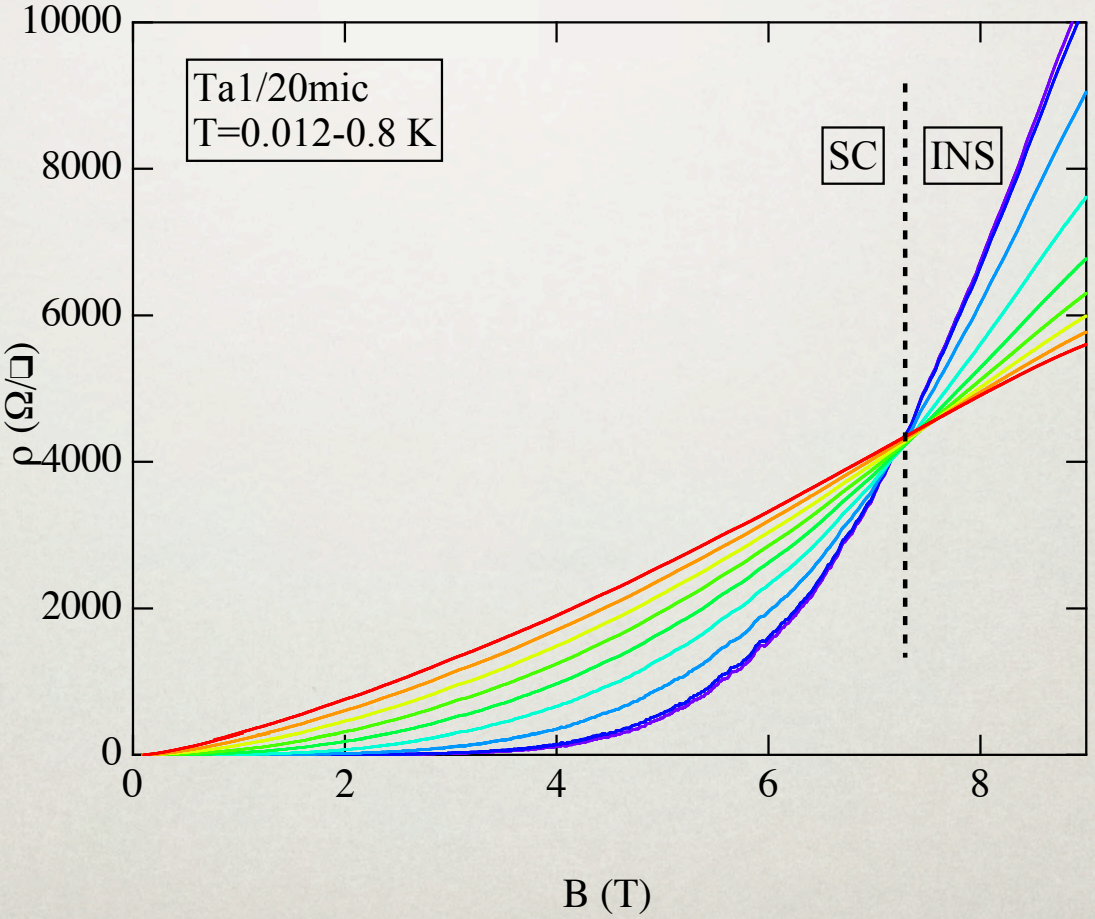
The good, bad and ...



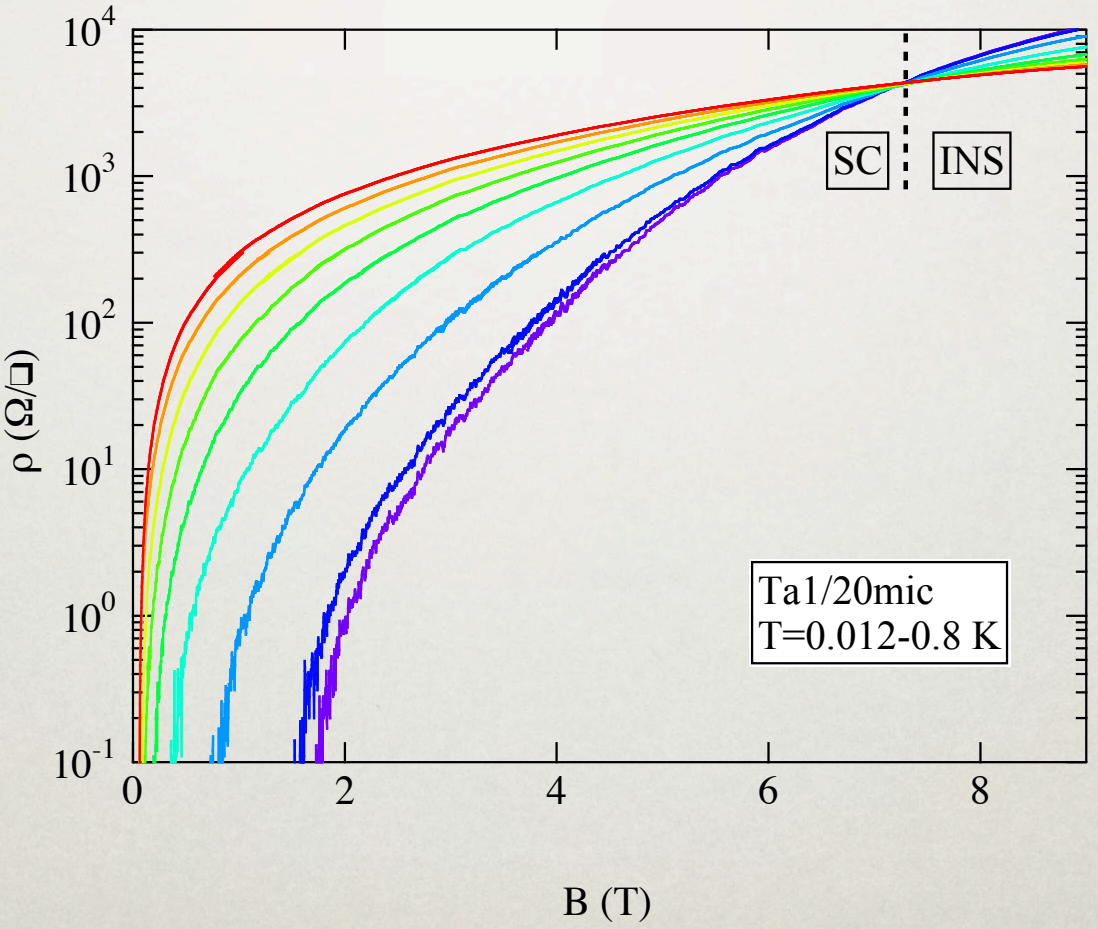


Hebard and Paalanen, ('90).
Yazdani and Kapitulnik ('95).

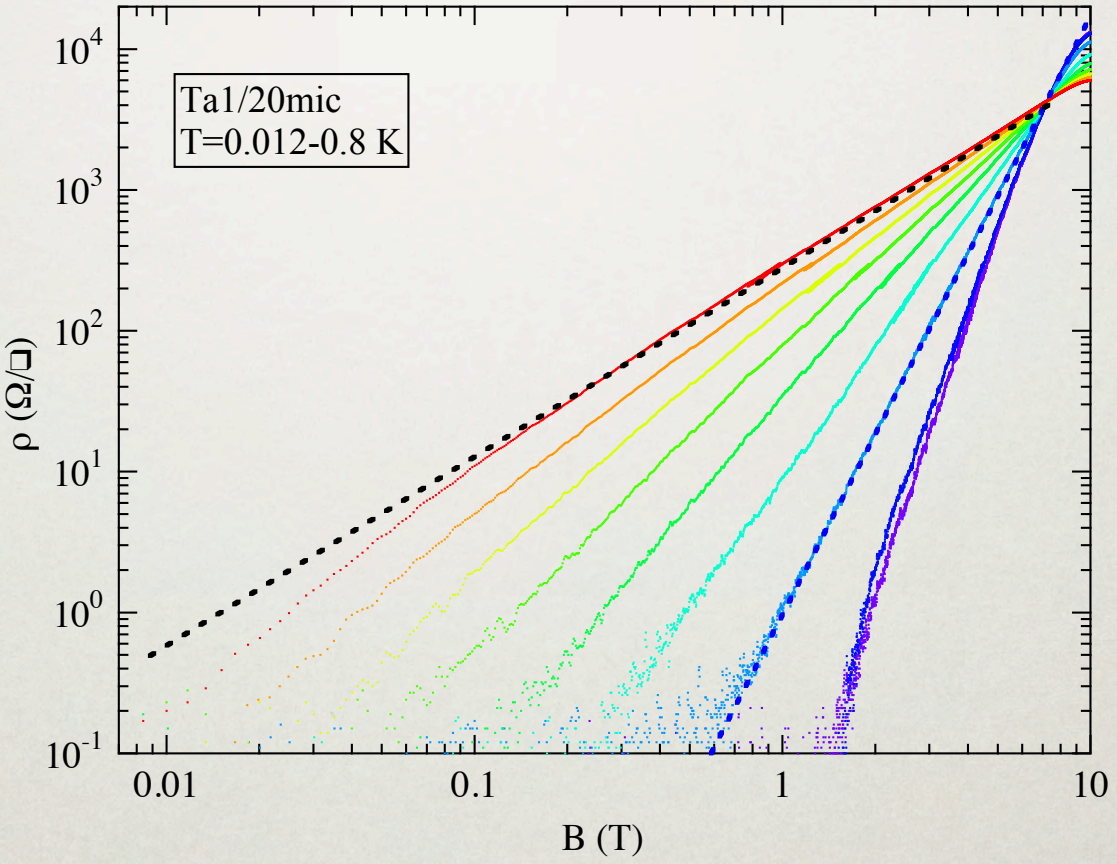
Linear scale



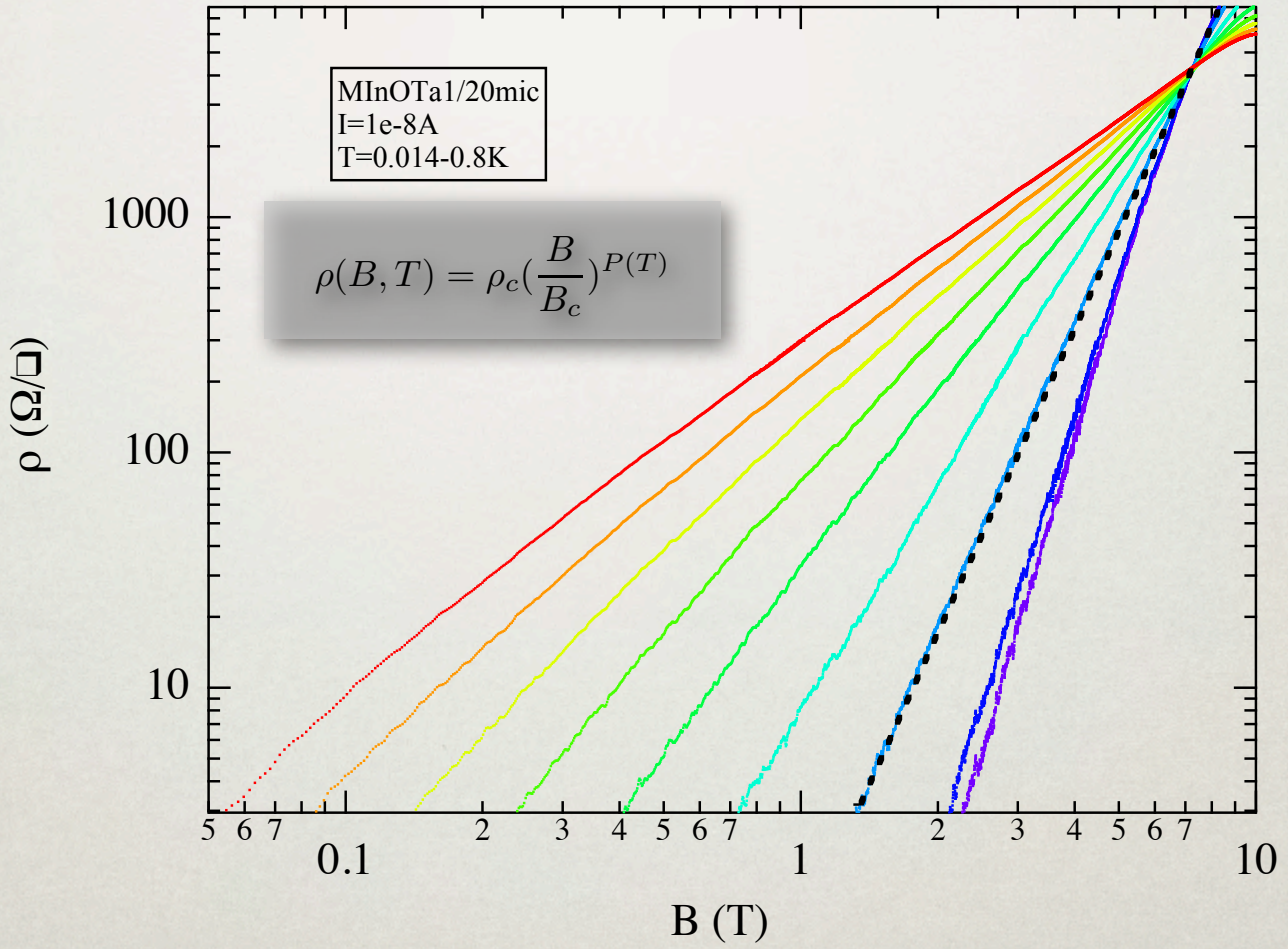
Log scale



Power-law



Power-law


MInOTa1/20mic
I=1e-8A
T=0.014-0.8K
$\rho(B,T) = \rho_c(\frac{B}{B_c})^{P(T)}$
ρ (Ω/□)
1000
100
10
5 6 7
0.1
2 3 4 5 6 7
1
2 3 4 5 6 7
10
B (T)

Power-law

$$\rho(B,T) = \rho_c(\frac{B}{B_c})^{T_0/2T}$$ (3 parameters)

Sambandamurthy et. al,
Europhysics Letters 75, 611 (2006).

$T_0/2$ is close to Tc (0.9-2K)

if:

$$U_0 = k_B T_0 ln(B/B_c)^{-\frac{1}{2}}$$

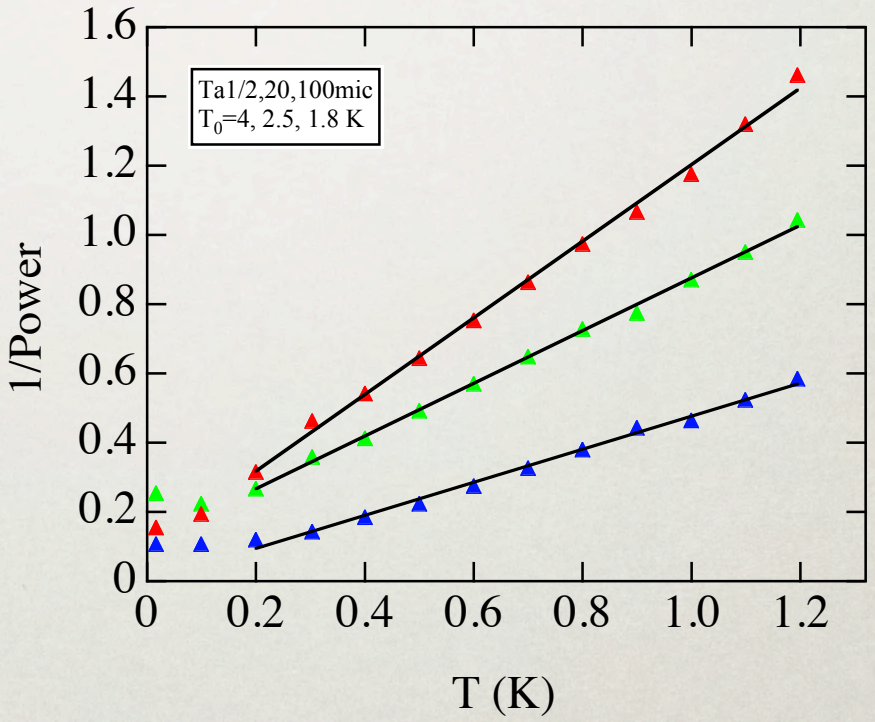
Than

$$\rho(B,T) = \rho_c e^{-U_0/k_B T}$$

= Activation.

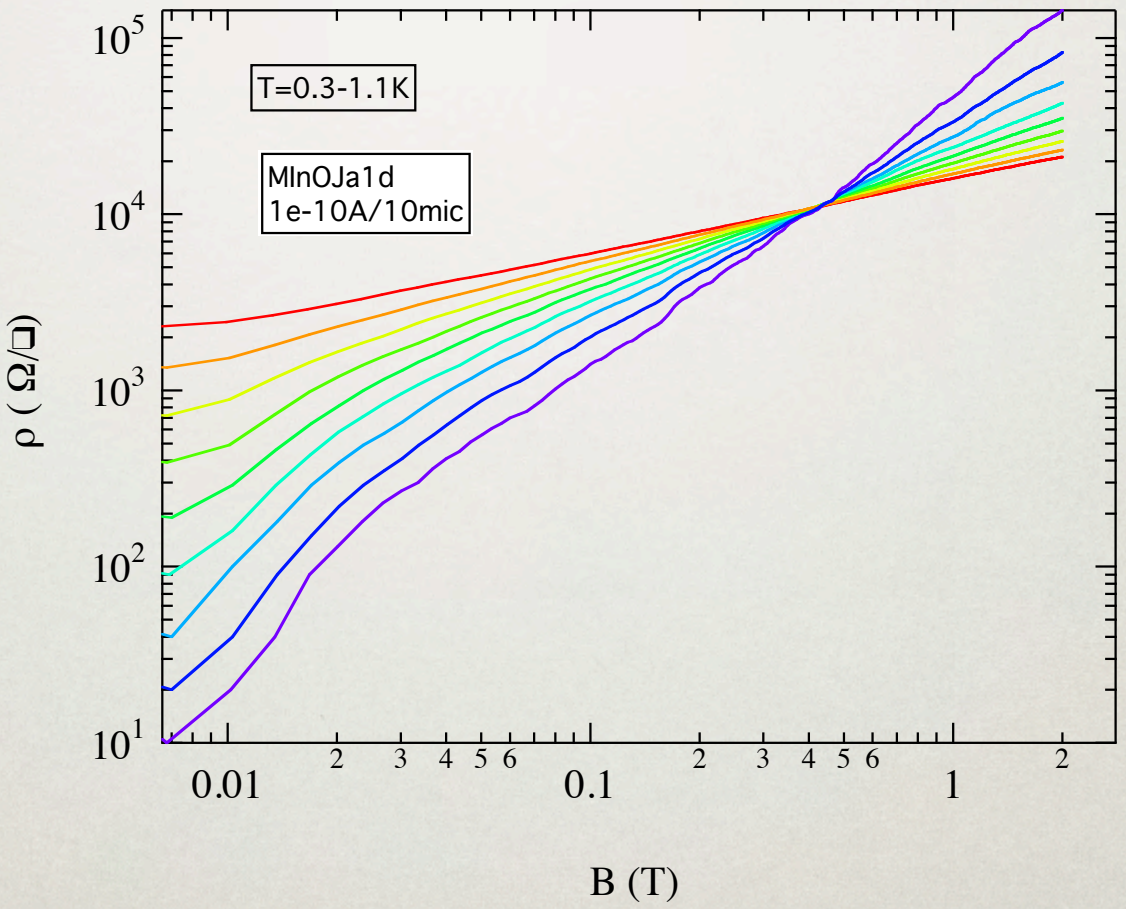
Vortices?

Blatter et al., Rev. Mod. Phys. 66, 1125 (1994).

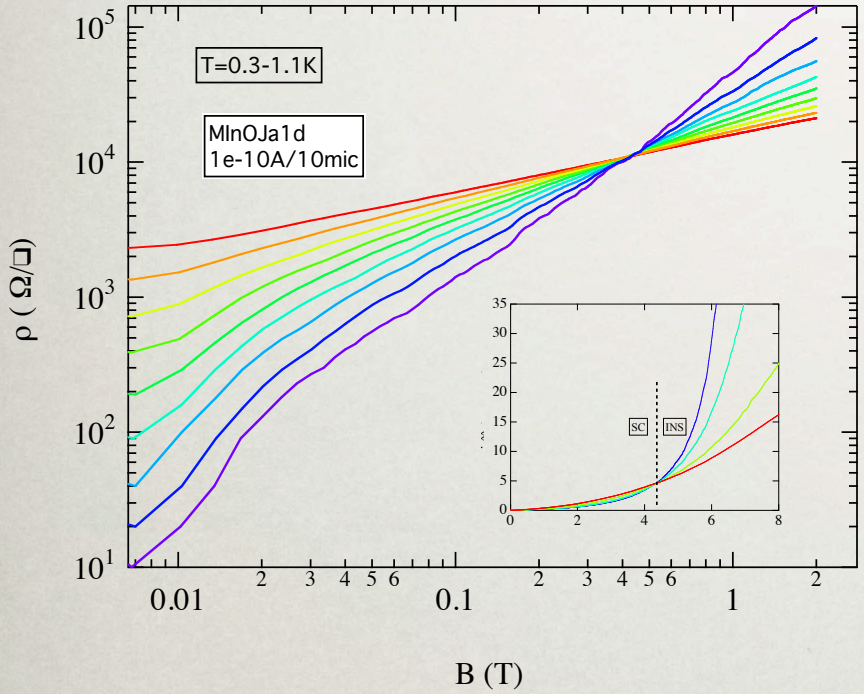


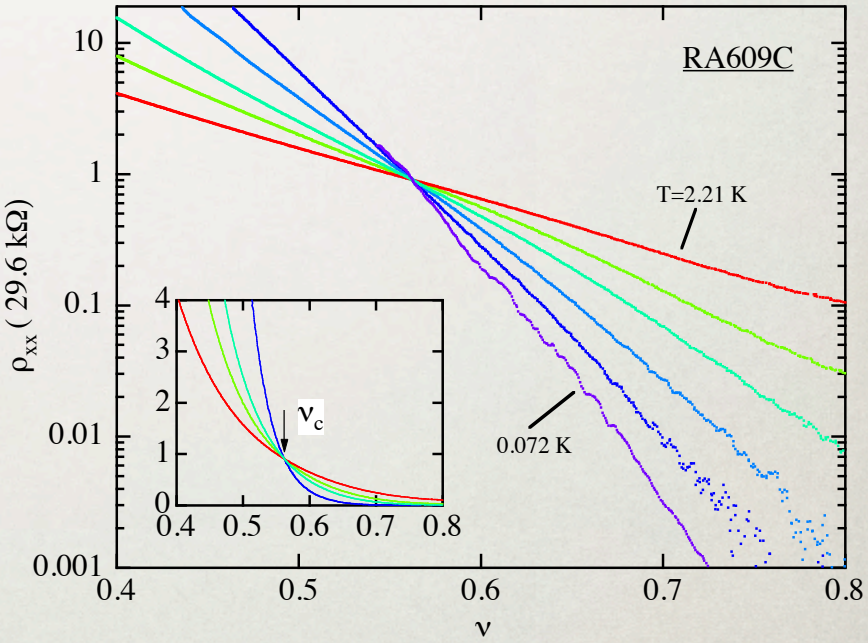
Power-law

- Well-beyond the 'critical' point



Quantum-Hall effect...

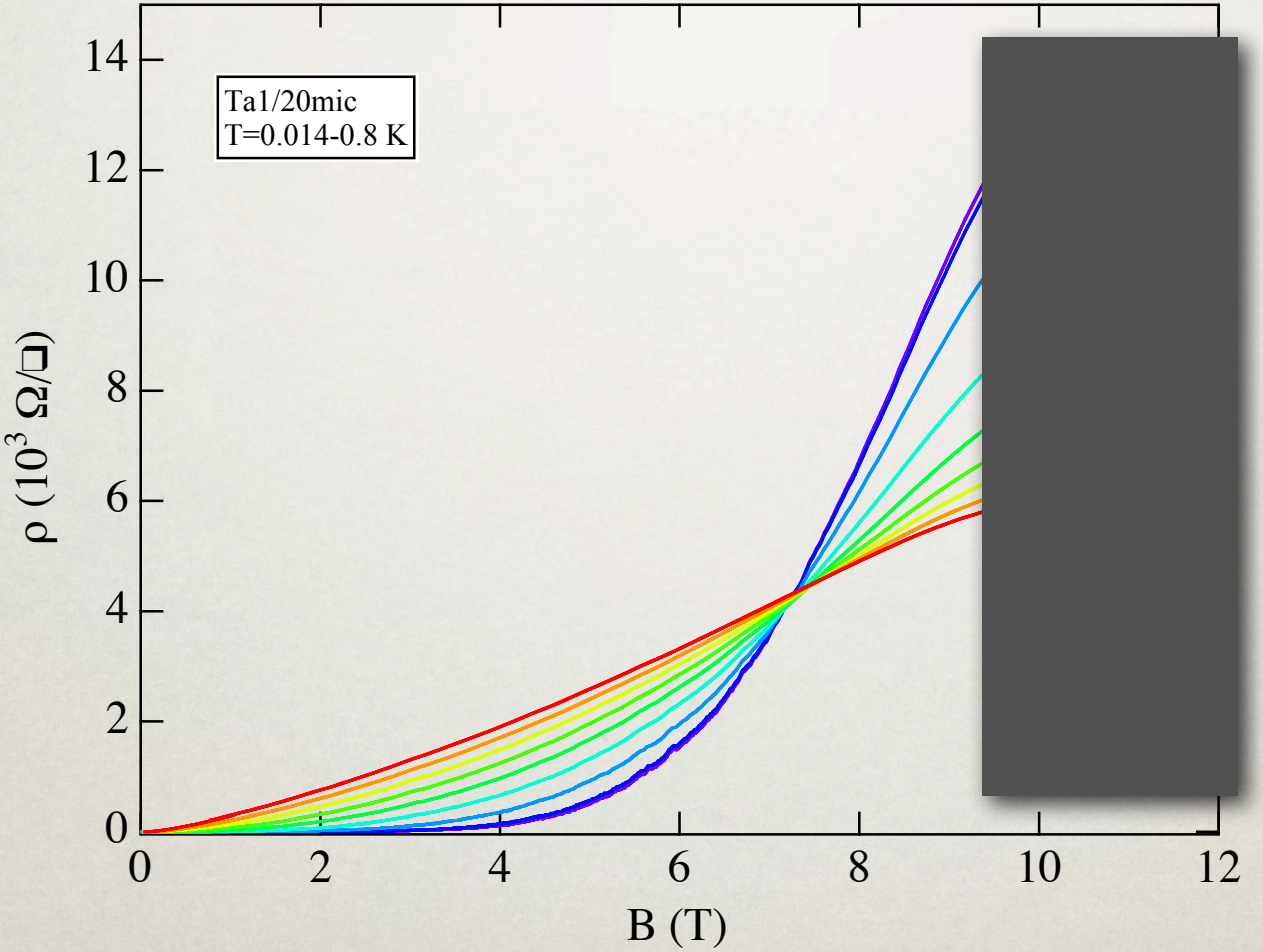




Lee and Fisher, Phys. Rev. Lett. **63**, 1442 (1989)
Dubi, Meir and Avishai,
Phys. Rev. Lett. **94**, 156406 (2005).

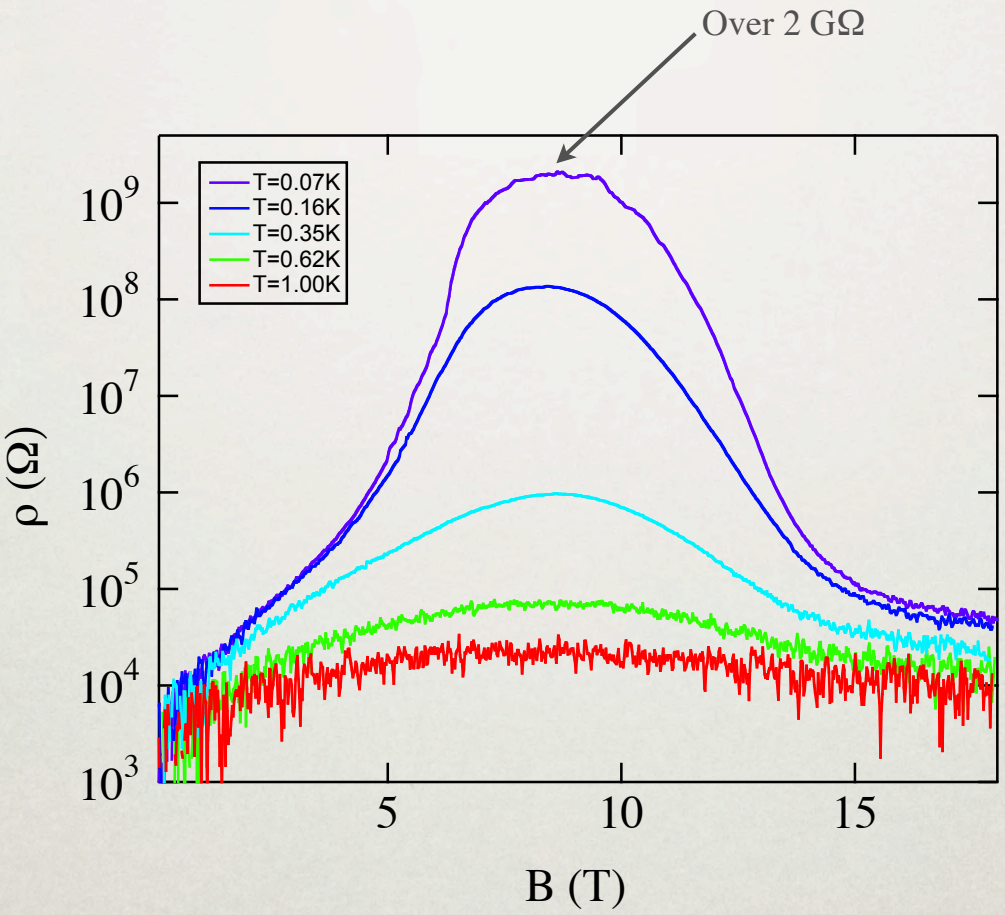
Insulator

Sambandamurthy et. al,
PRL **92**, 107005 (2004).

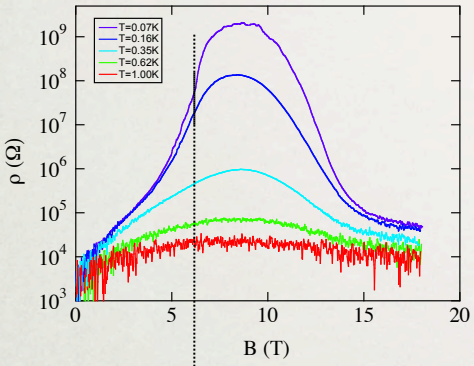


Insulating peak

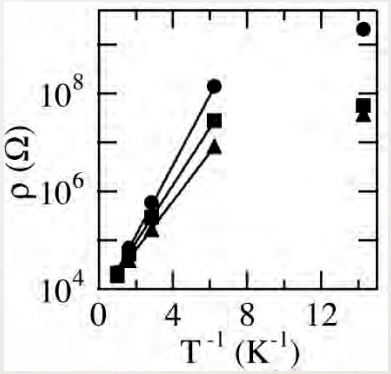
2200 squares
(Log scale)



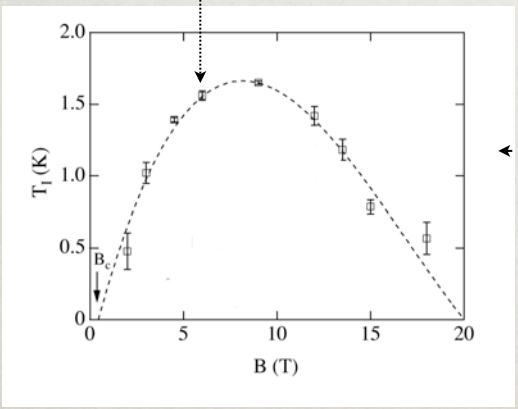
Properties of the insulator



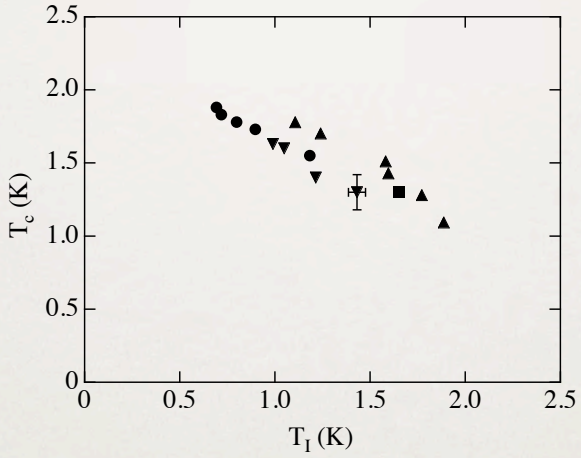
Fixed B



$$\rho(T) = \rho_0 e^{T_1/T}$$



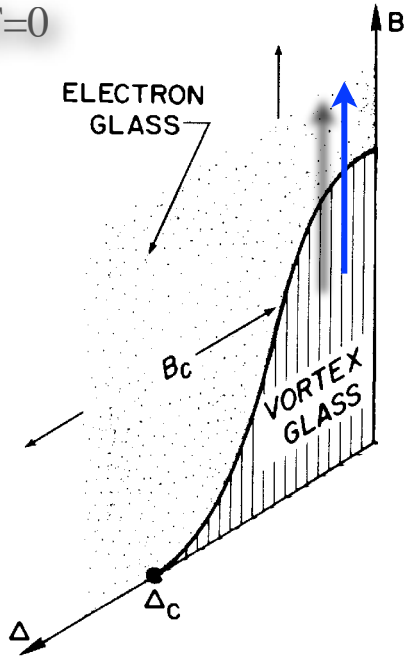
Typical energies



$T_I \sim T_C$

Dirty-boson model

Vortices are bosons



B-driven SIT

M. P. A. Fisher, Phys. Rev. Lett. **65**, 923 (1990)

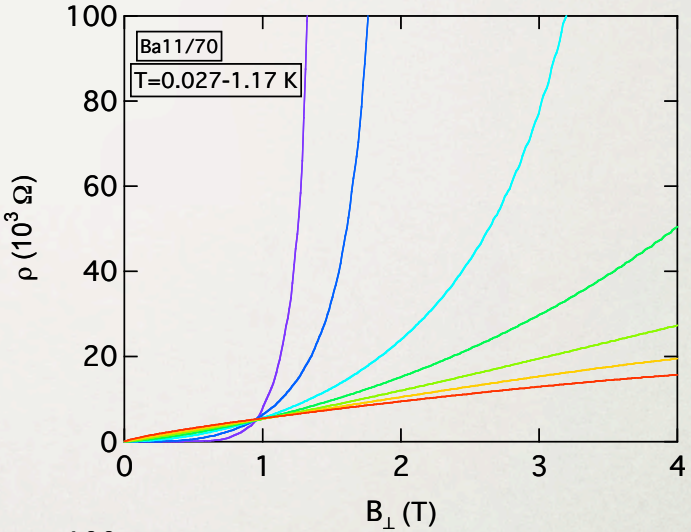
Vortices condense =
Cooper-pairs localize

⇩

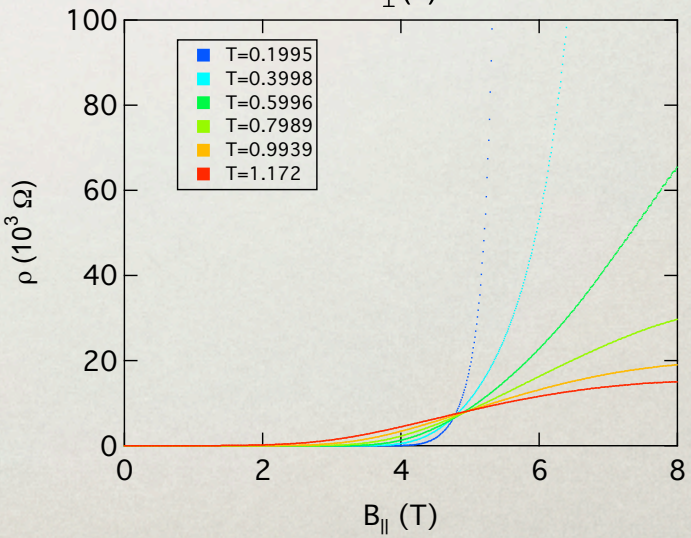
SIT

B_c ORIENTATION DEPENDENCE

Perpendicular B:

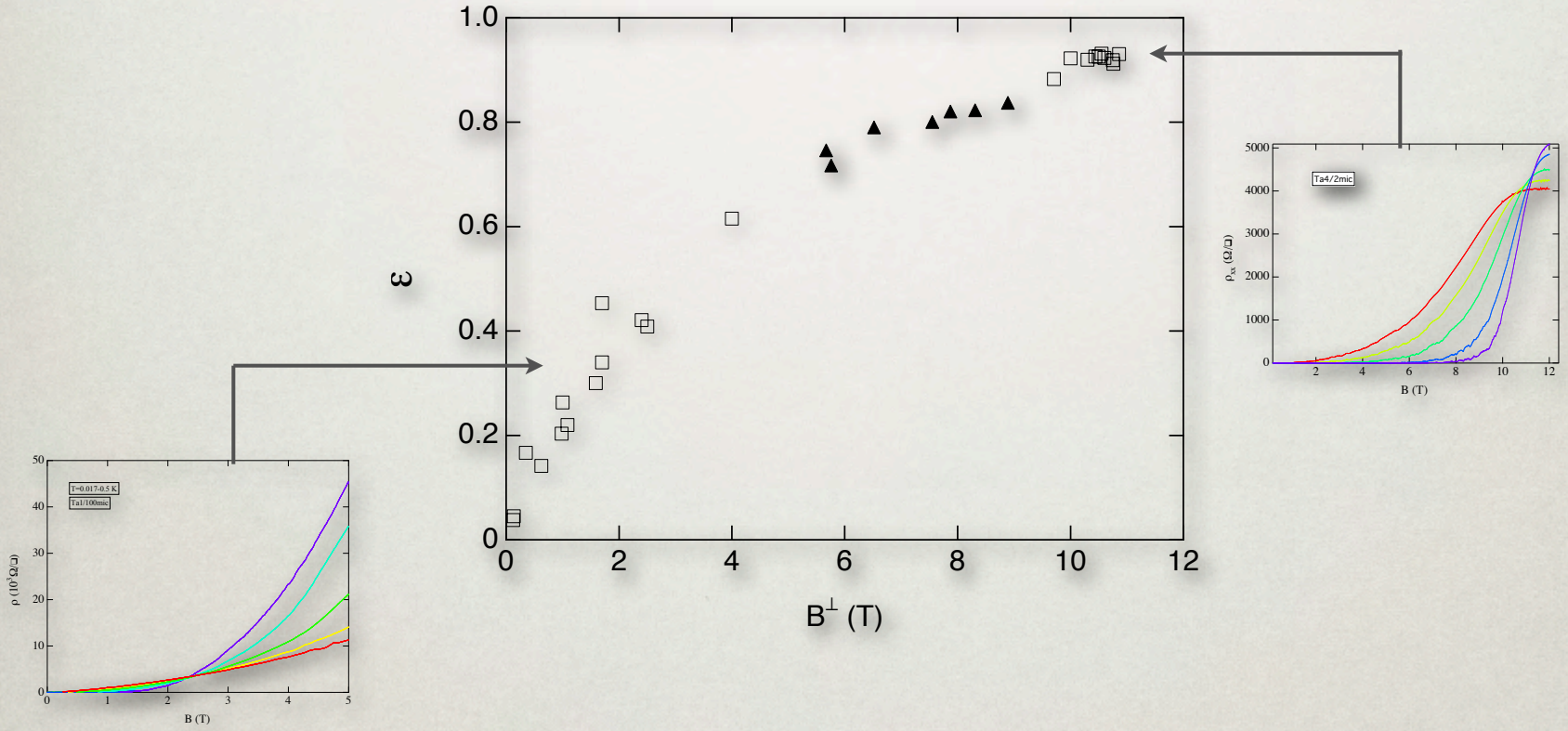


Parallel B:

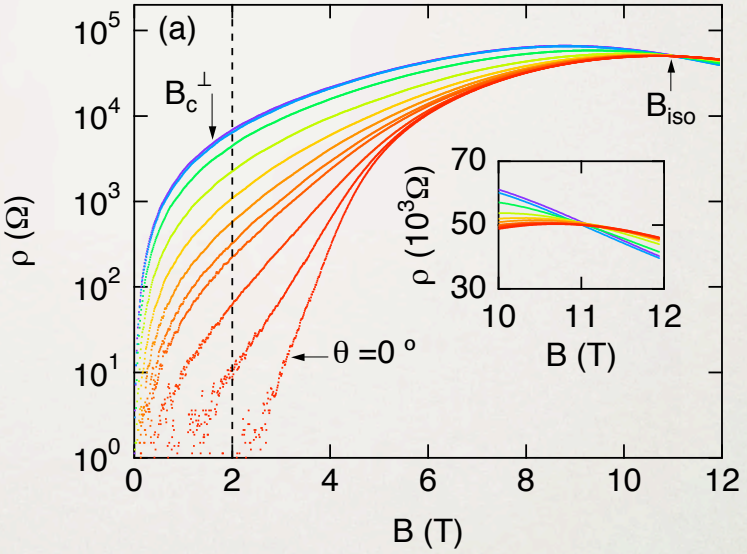


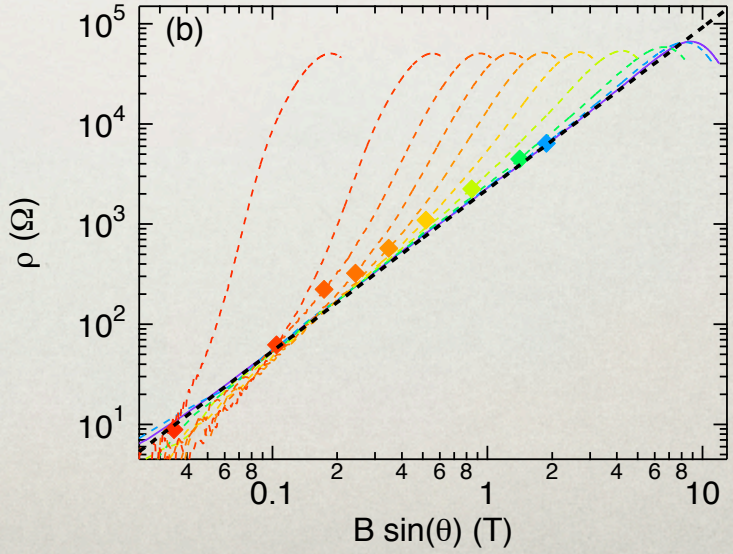
Anisotropy

$$\varepsilon = B_c^{\perp} / B_c^{||}$$

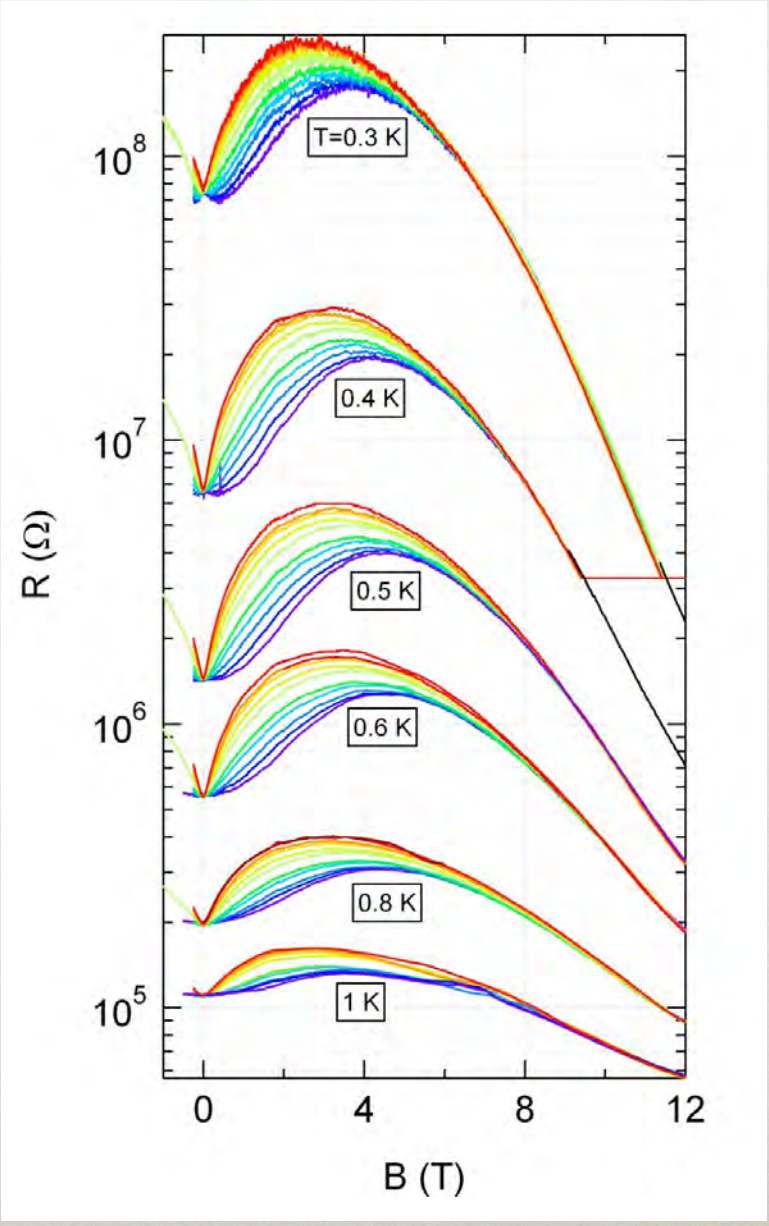


Angular dependece



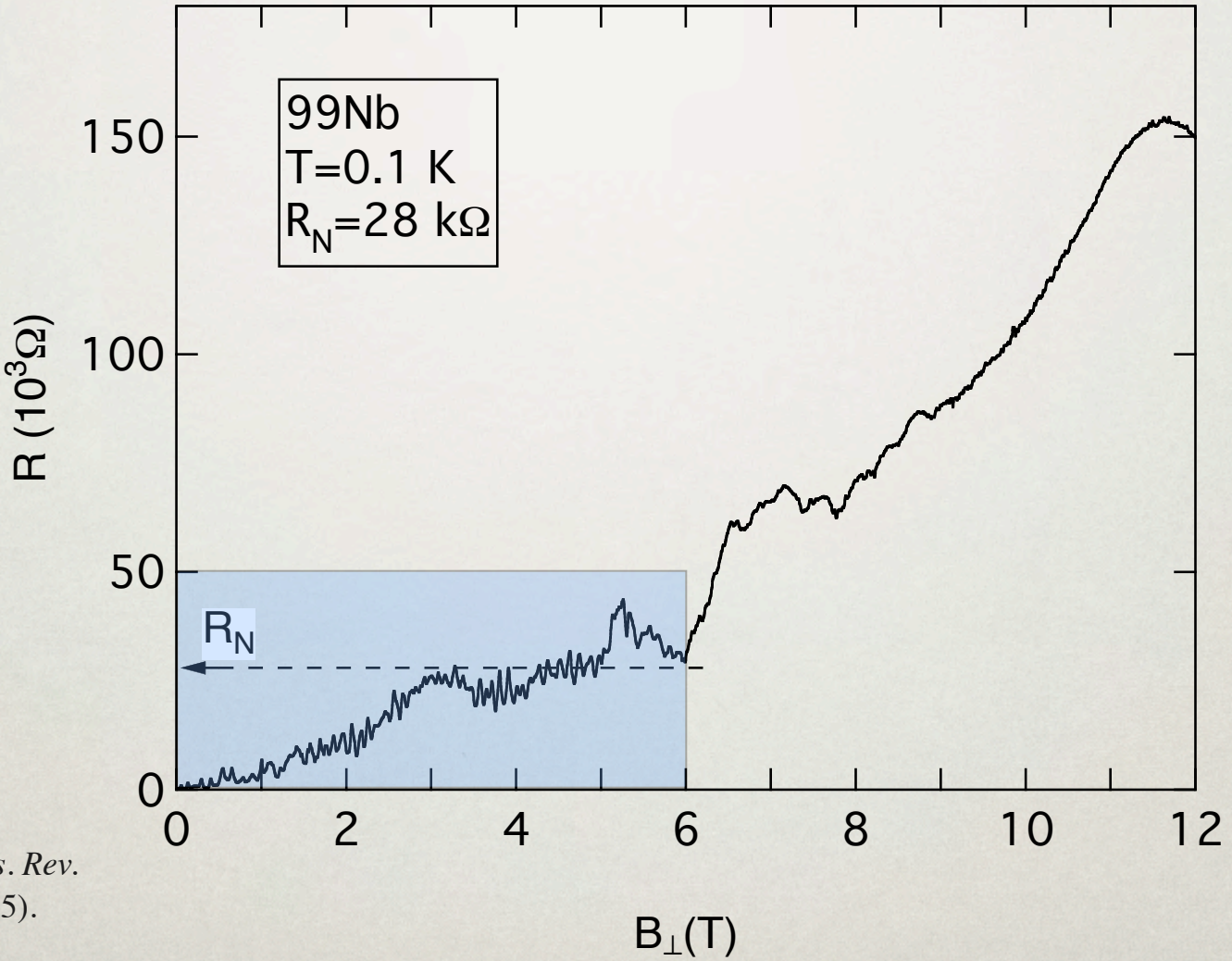


Insulating samples



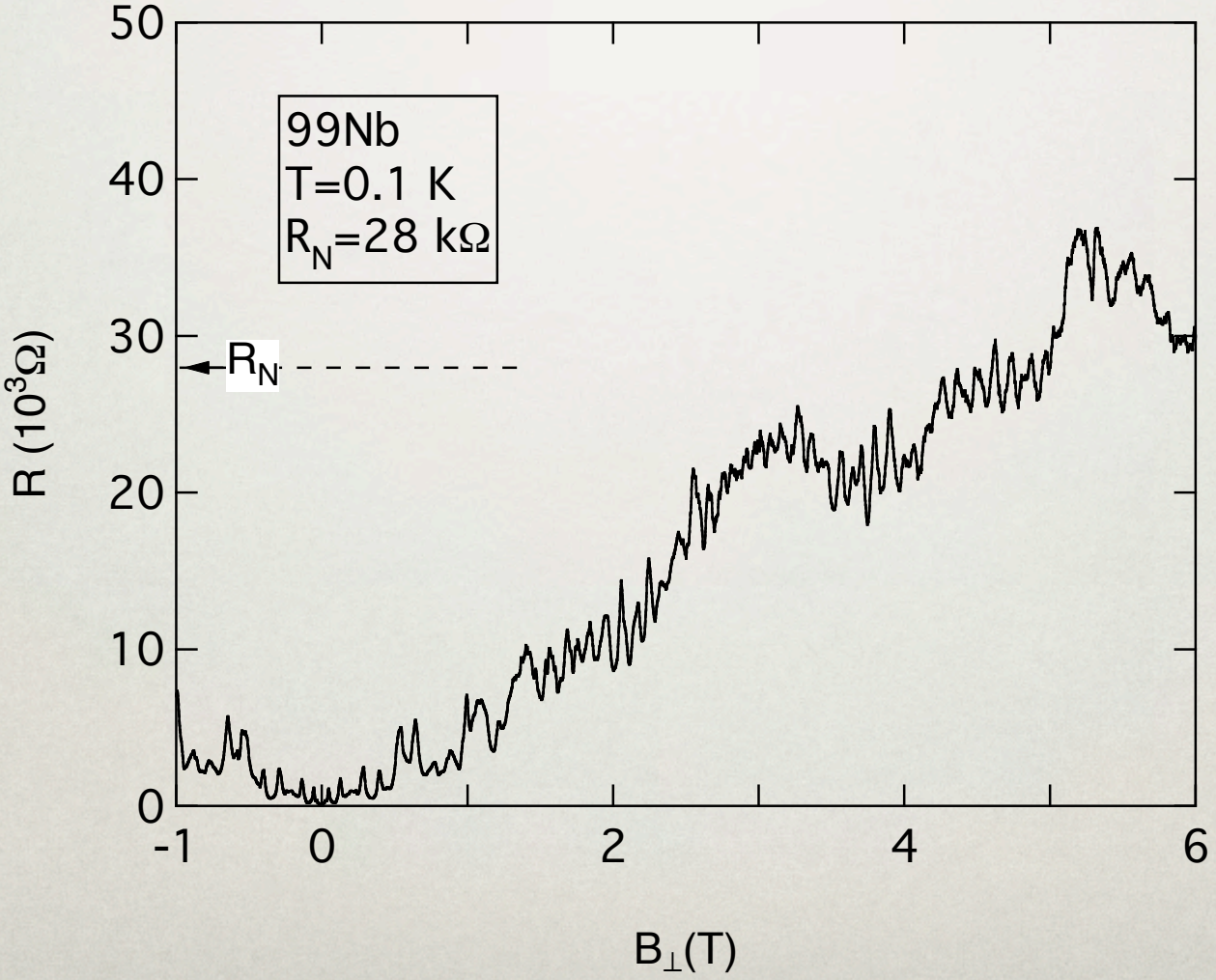
Baturina ('08)

Magnetic Field

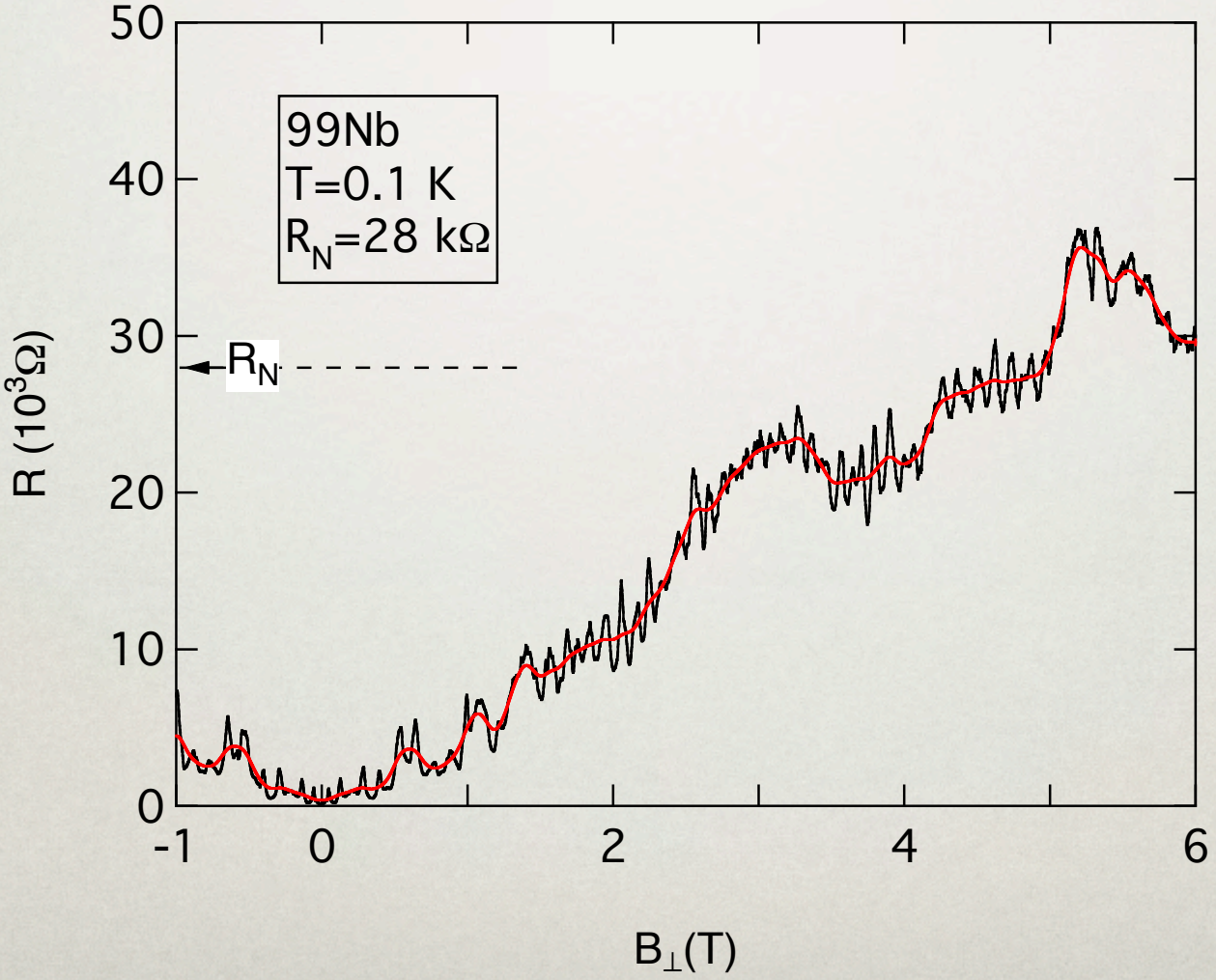


Johansson et. al, *Phys. Rev. Lett.* **95**, 116805 (2005).

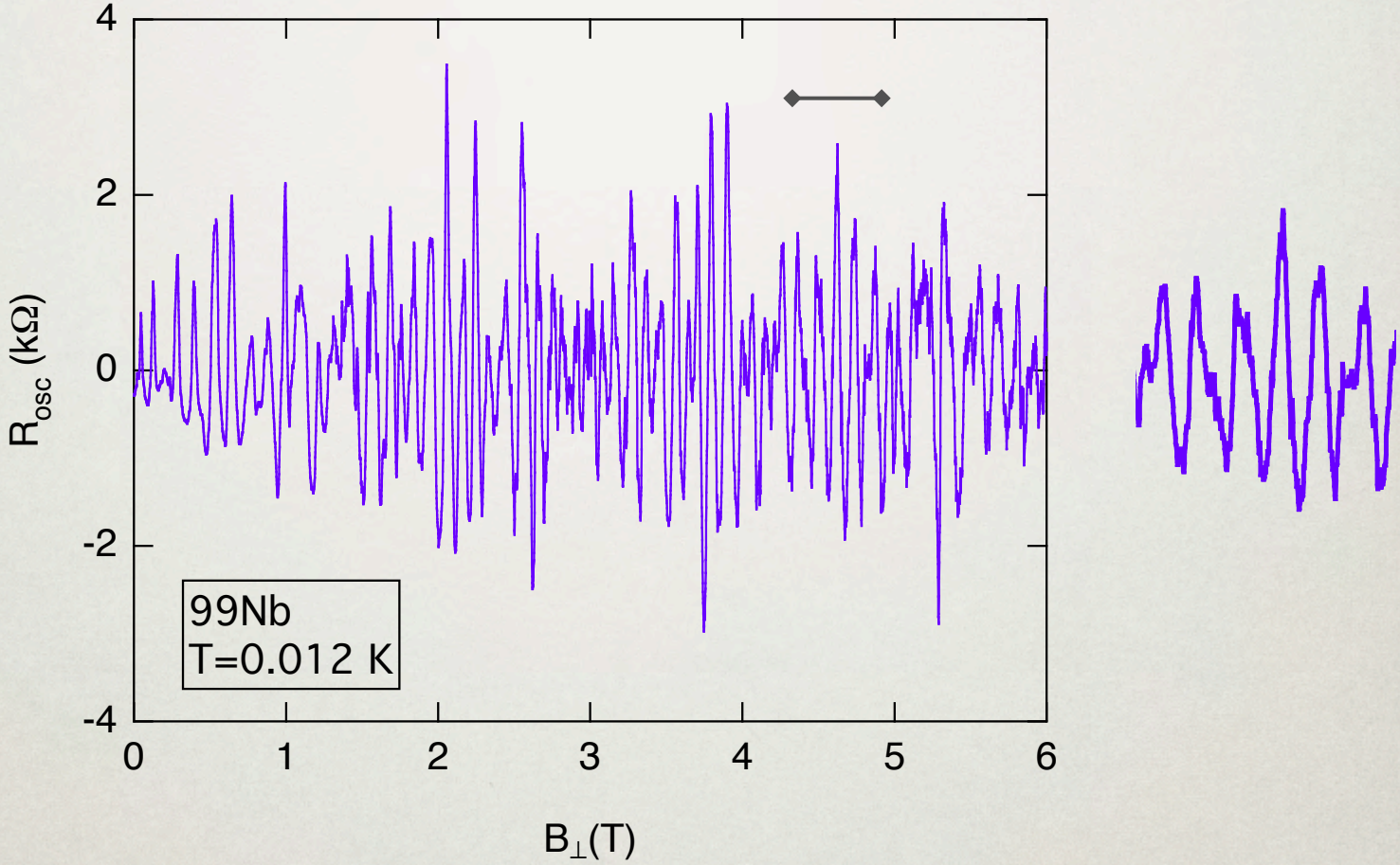
Oscillations!



Subtracting background...



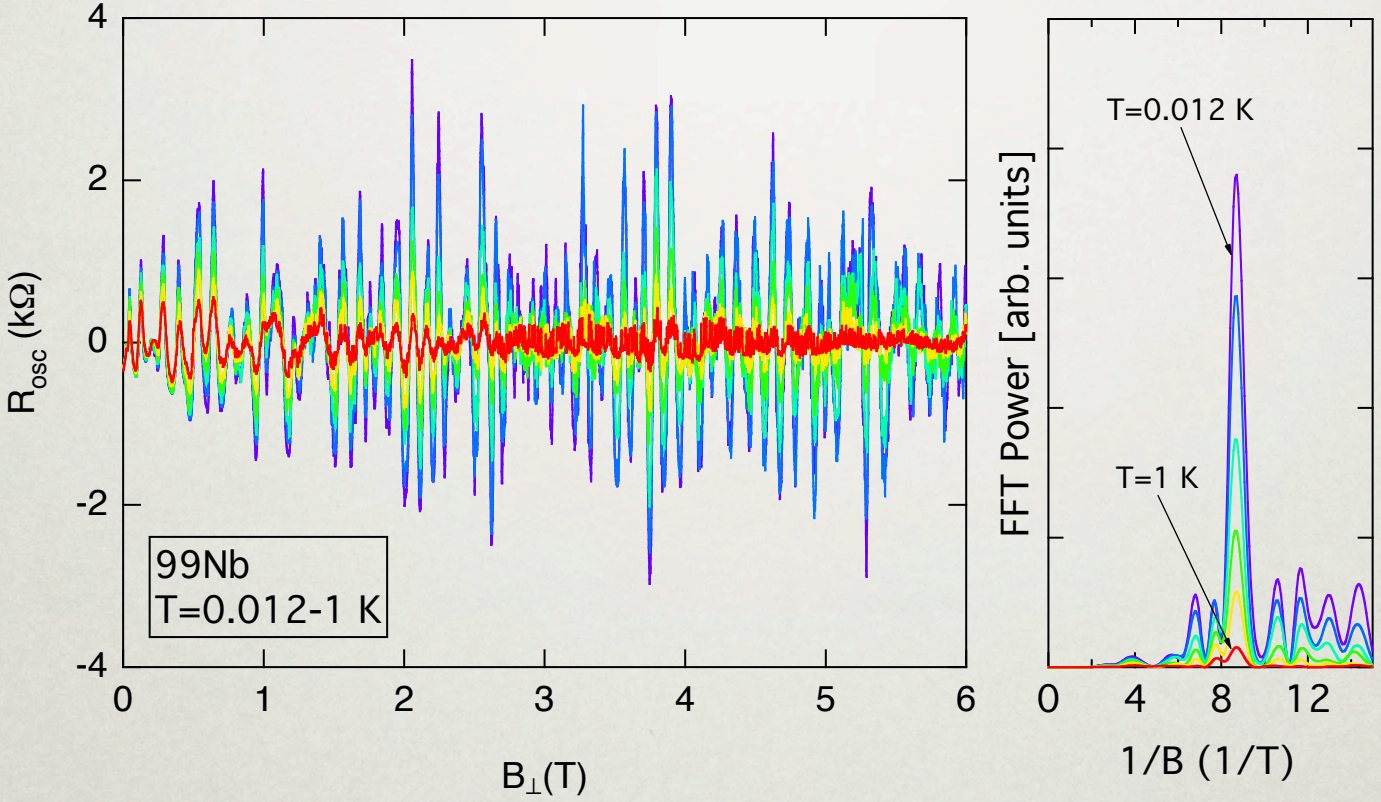
Background subtracted



A SQUID.

T DEPENDENCE OF OSCILLATIONS

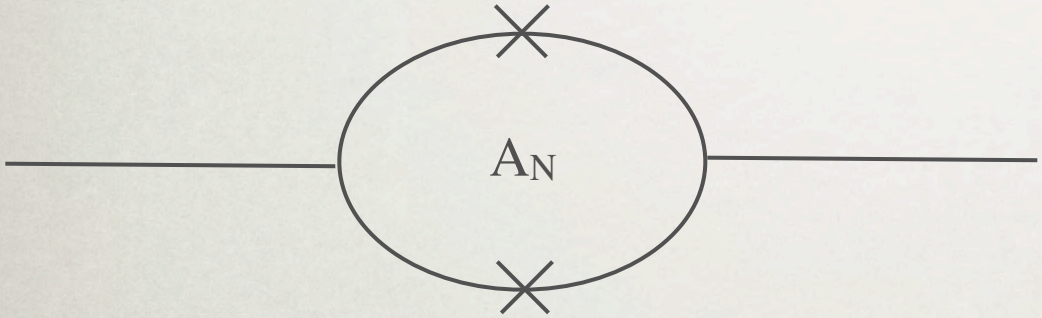
Oscillation amplitude suppressed by T = 1 K...



...but the periodicity doesn't change!

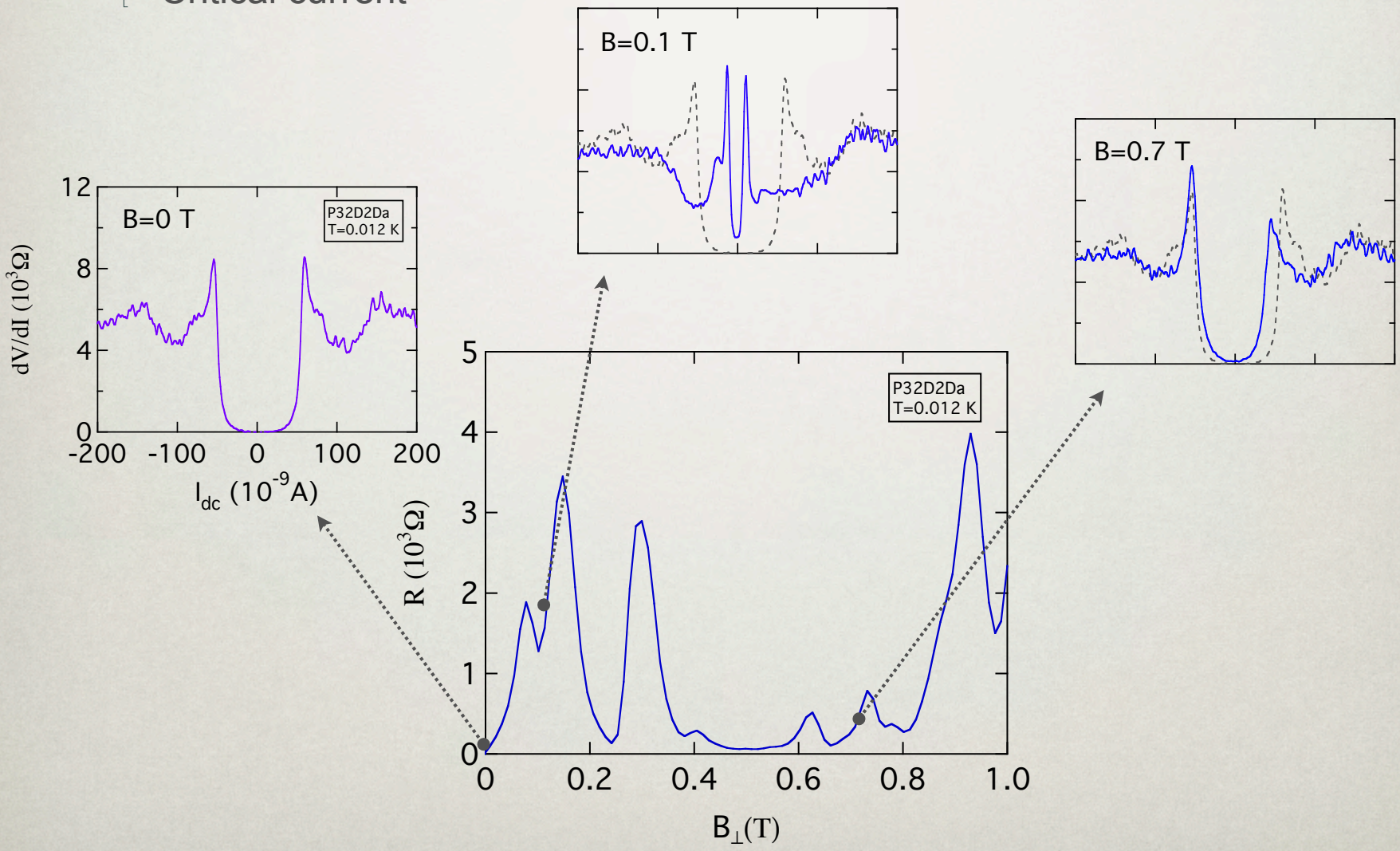
A SQUID

$$B_{period} = \Phi_0 / A_N$$

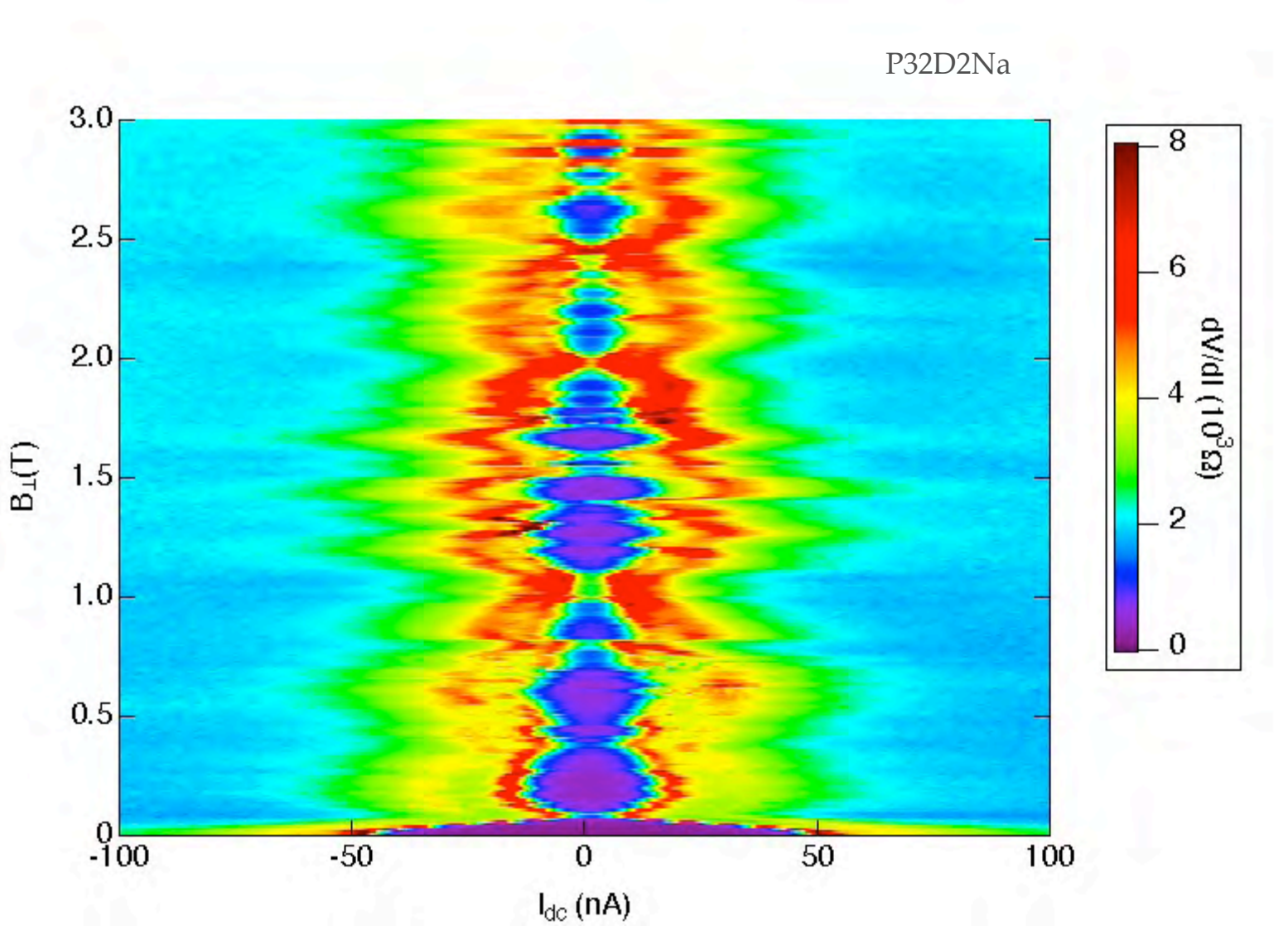


Non-linear I-V

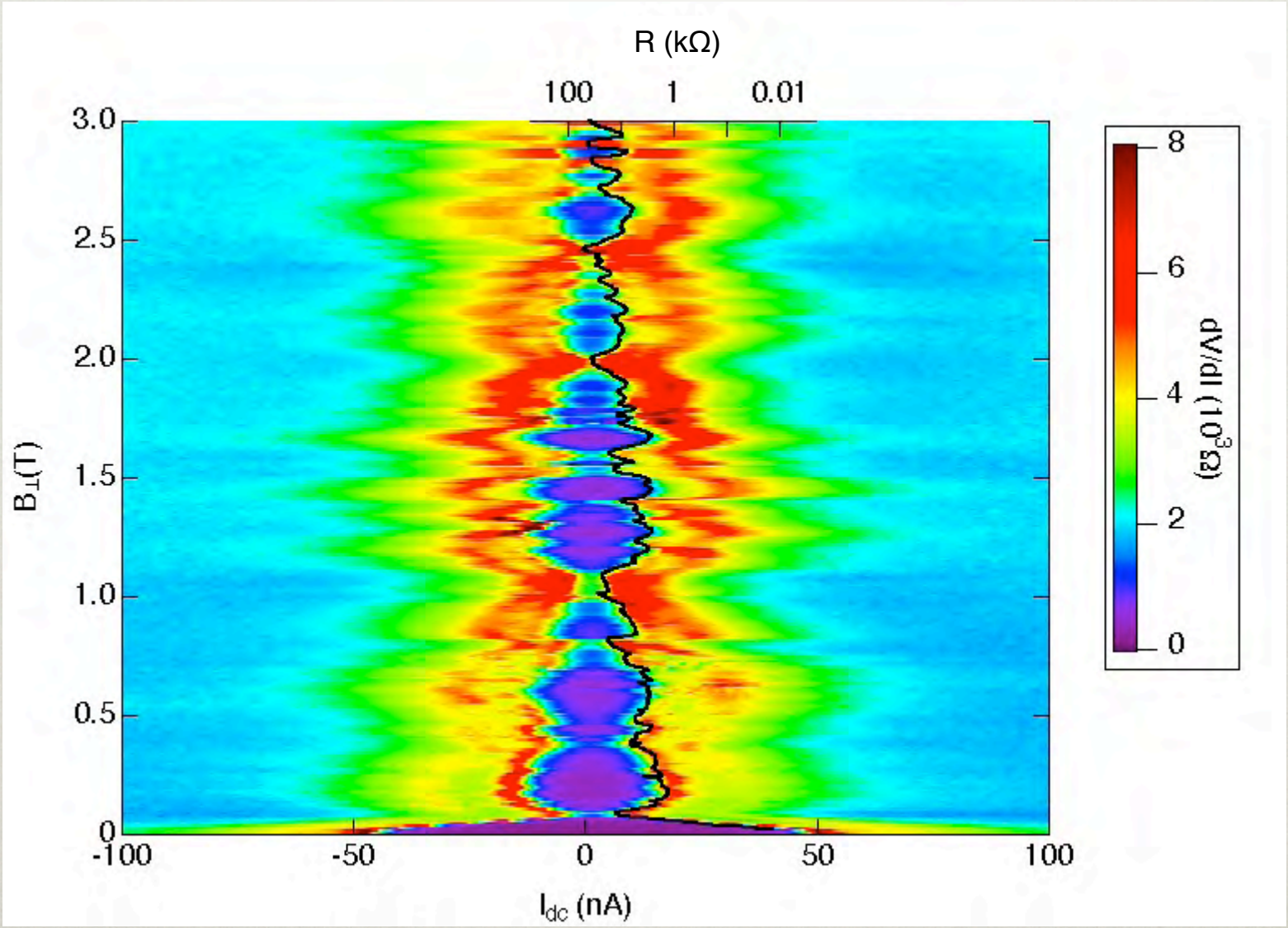
- Critical current

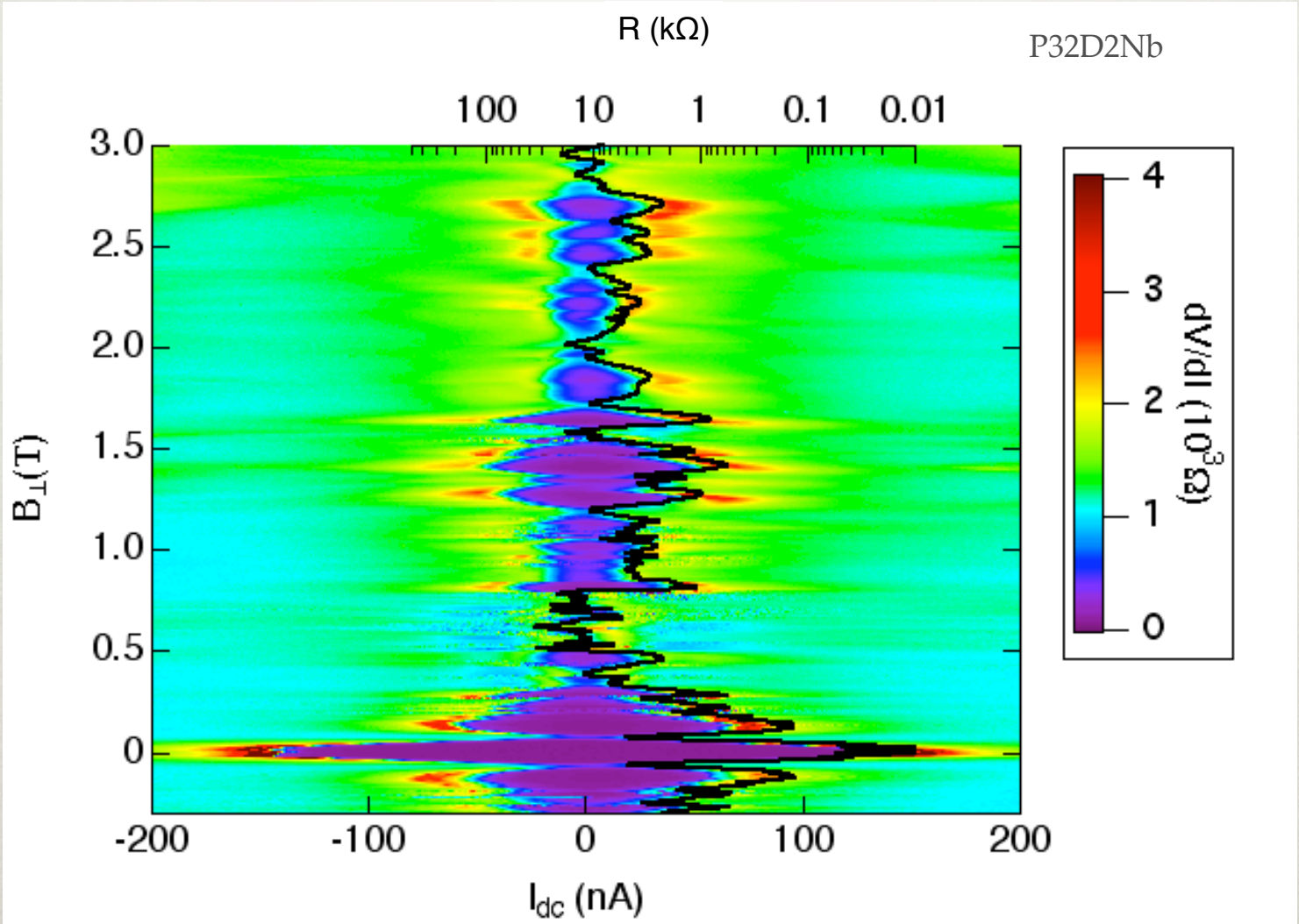


I-V and R correspondence

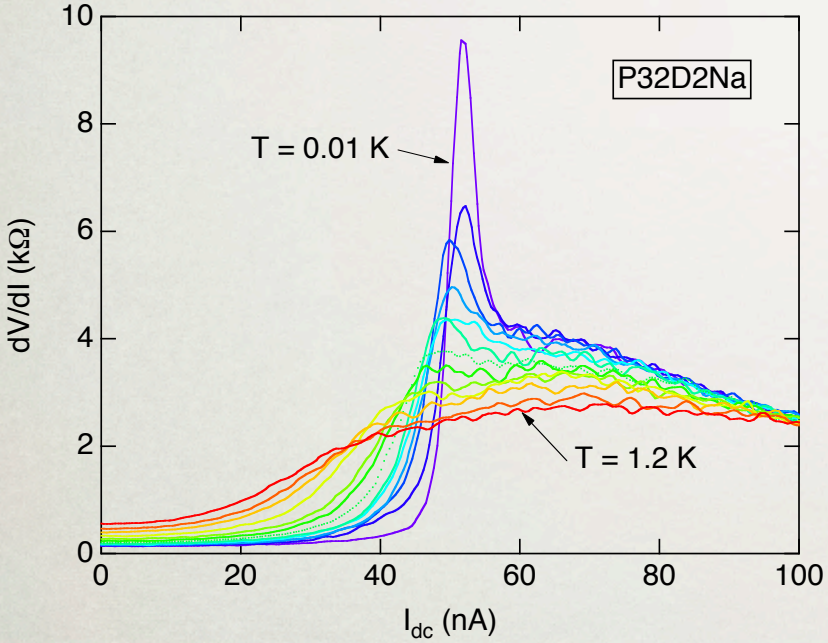


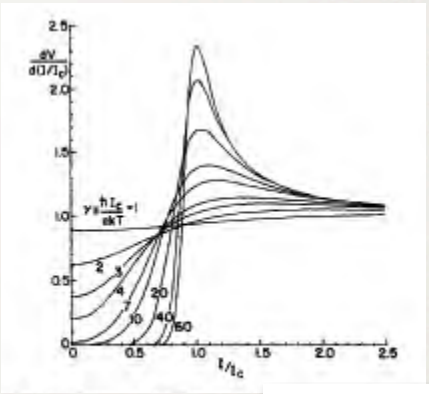
I-V and R correspondence



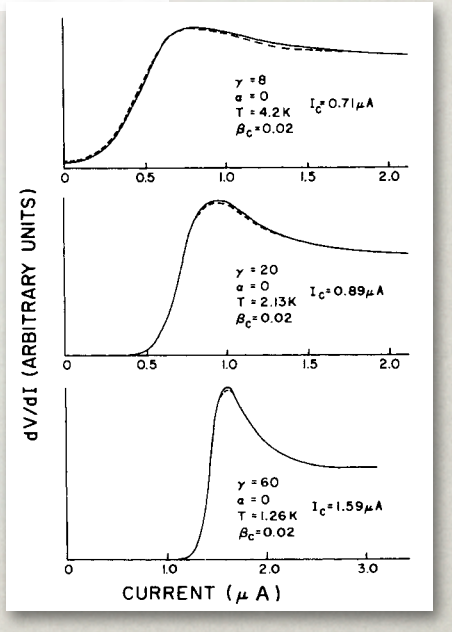

R (kΩ)
P32D2Nb
100
10
1
0.1
0.01
3.0
2.5
2.0
1.5
1.0
0.5
0
$B_\perp$(T)
-200
-100
0
100
200
I_{dc} (nA)
4
3
2
1
0
dV/dI ($10^3\Omega$)

Isotherms of dV/dI



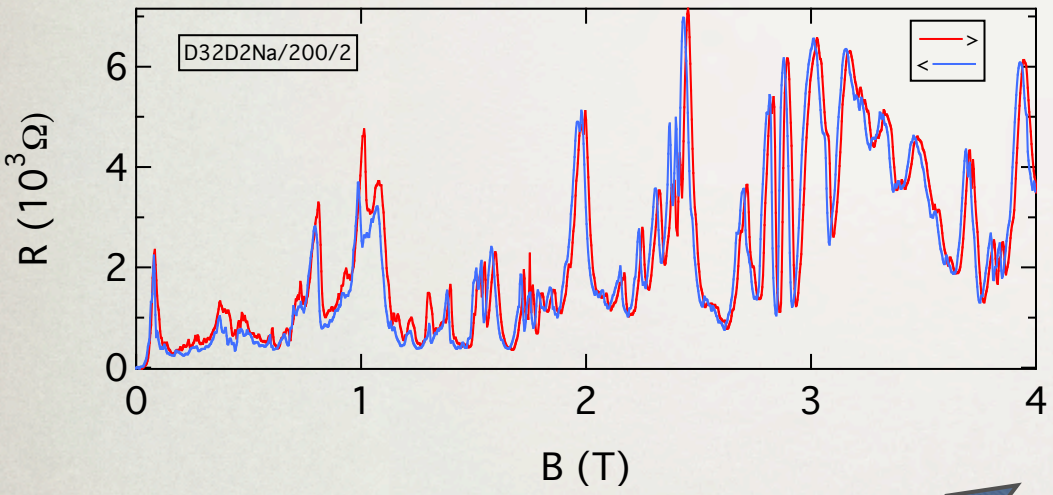


Falco *et al.*, ('74)



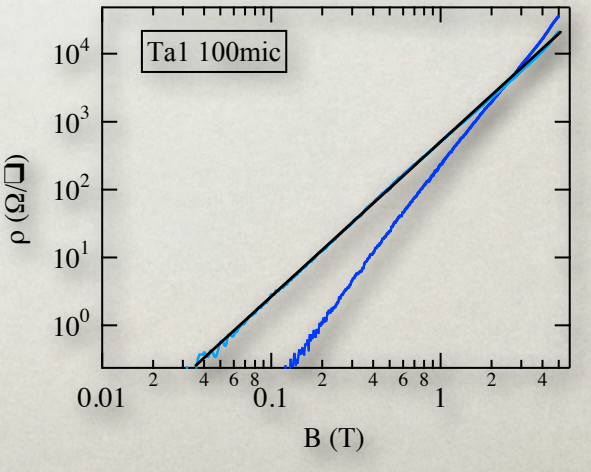
Josephson Junction?

From small to large



Goal:

Identify the microscopic mechanism of resistance.



Superconductor-Insulator Magneto-Oscillations in Superconducting Strips

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Vortex Blockade theory of Magneto Resistance oscillations in SC strips

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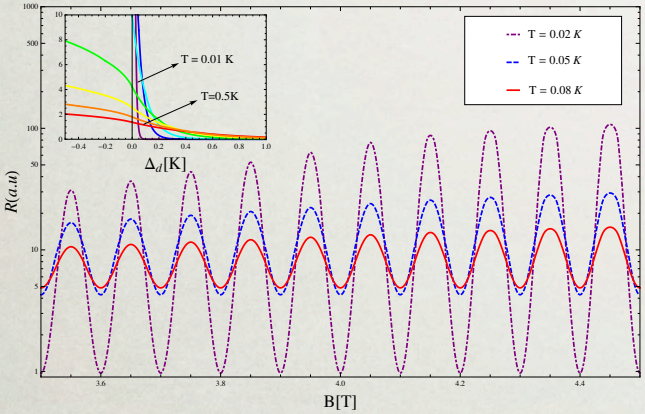
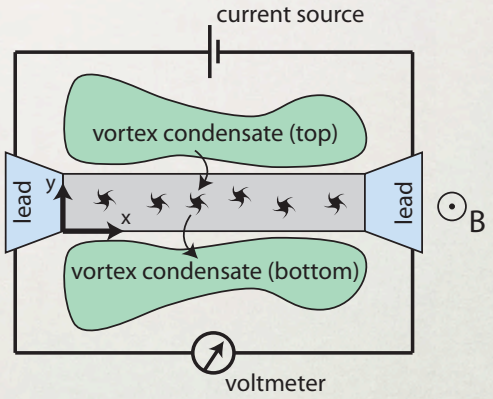
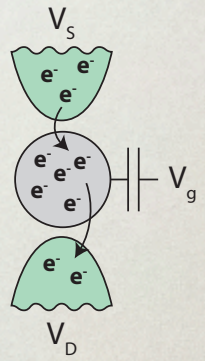
Multiple SIT theory



Vortex Blockade theory

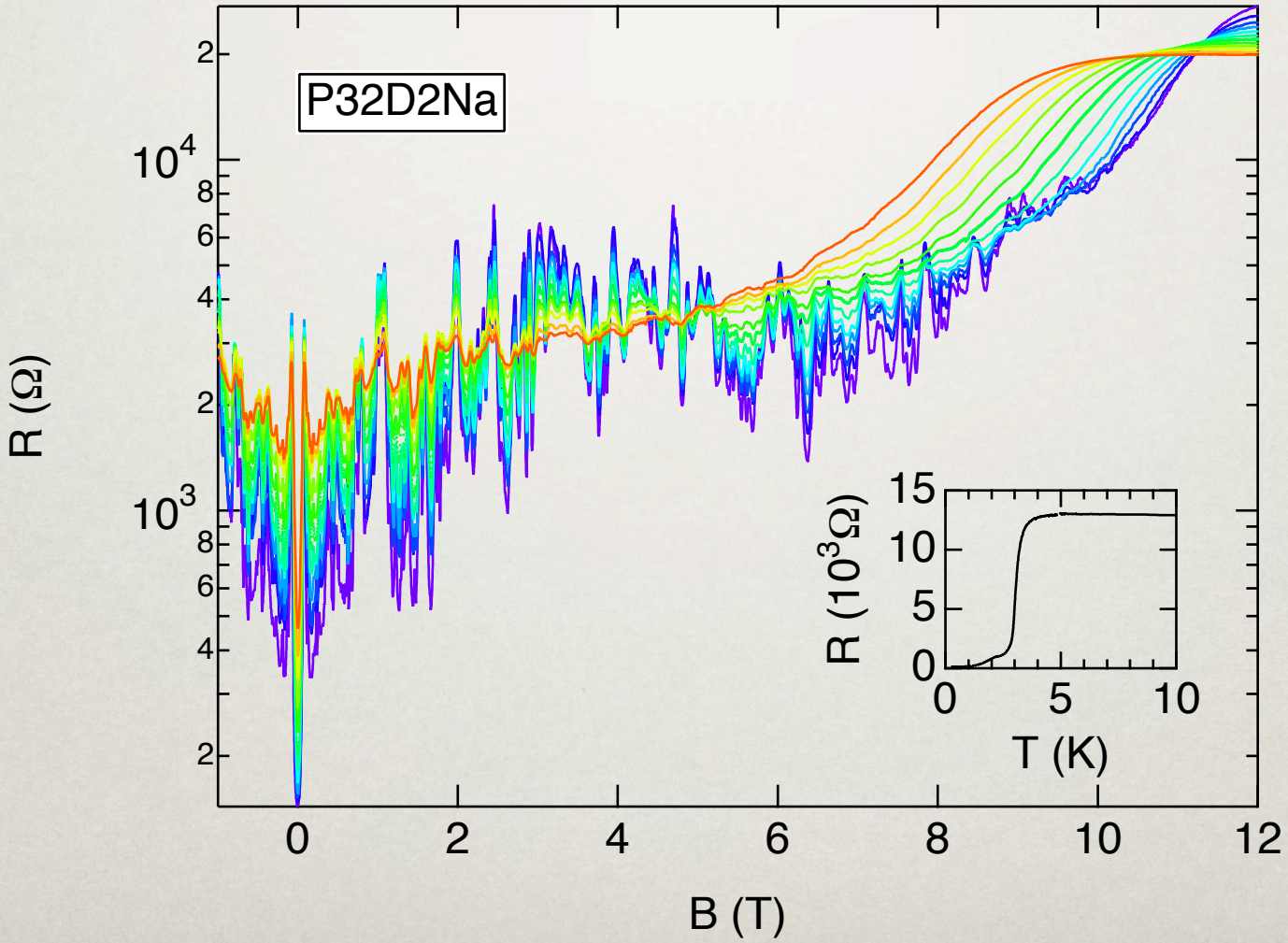


a. Superconducting Strip



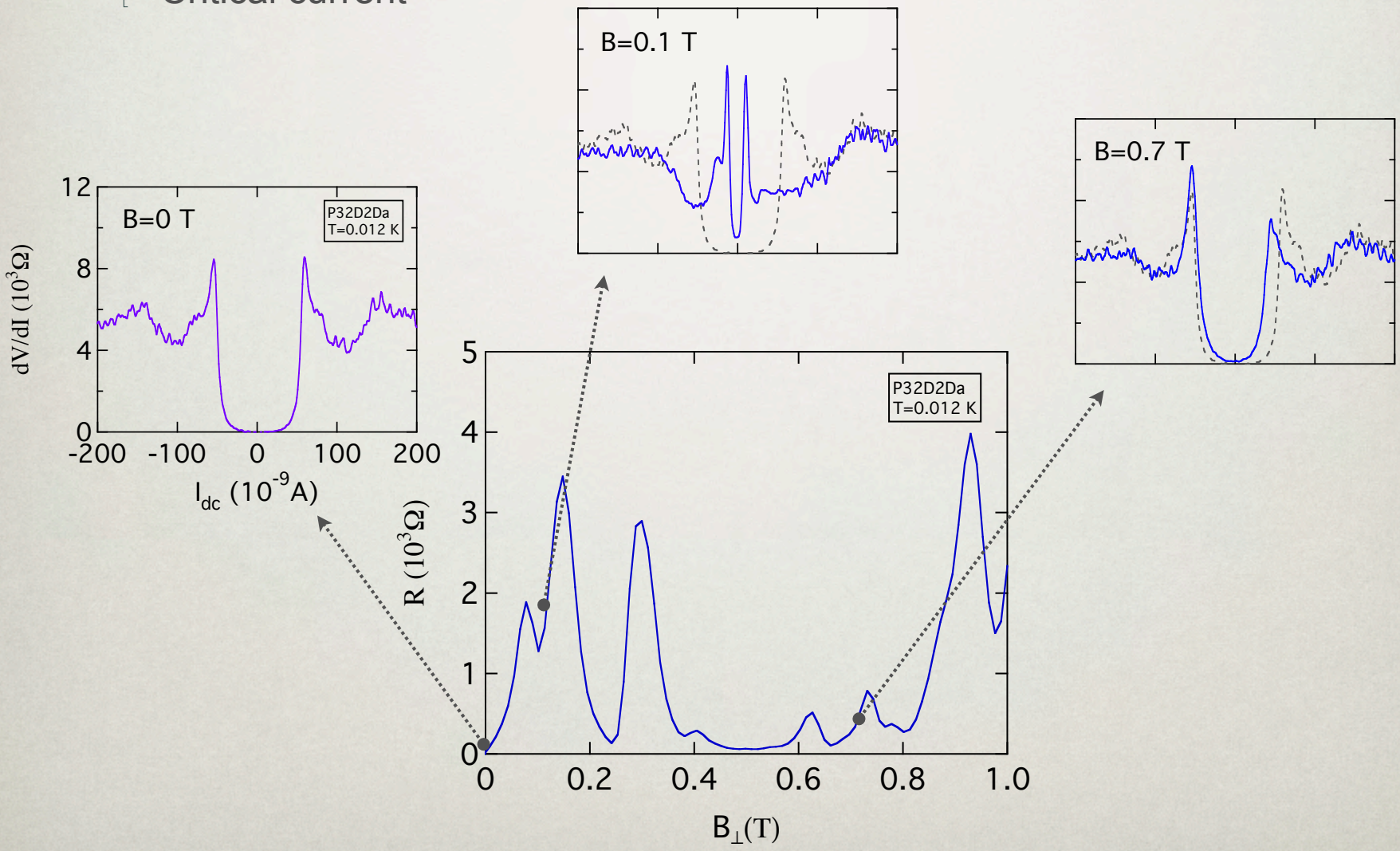
b. Quantum Dot Analogue

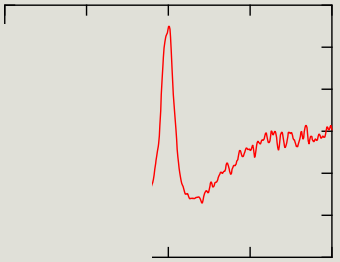
Multiple SIT theory

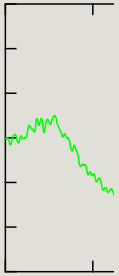


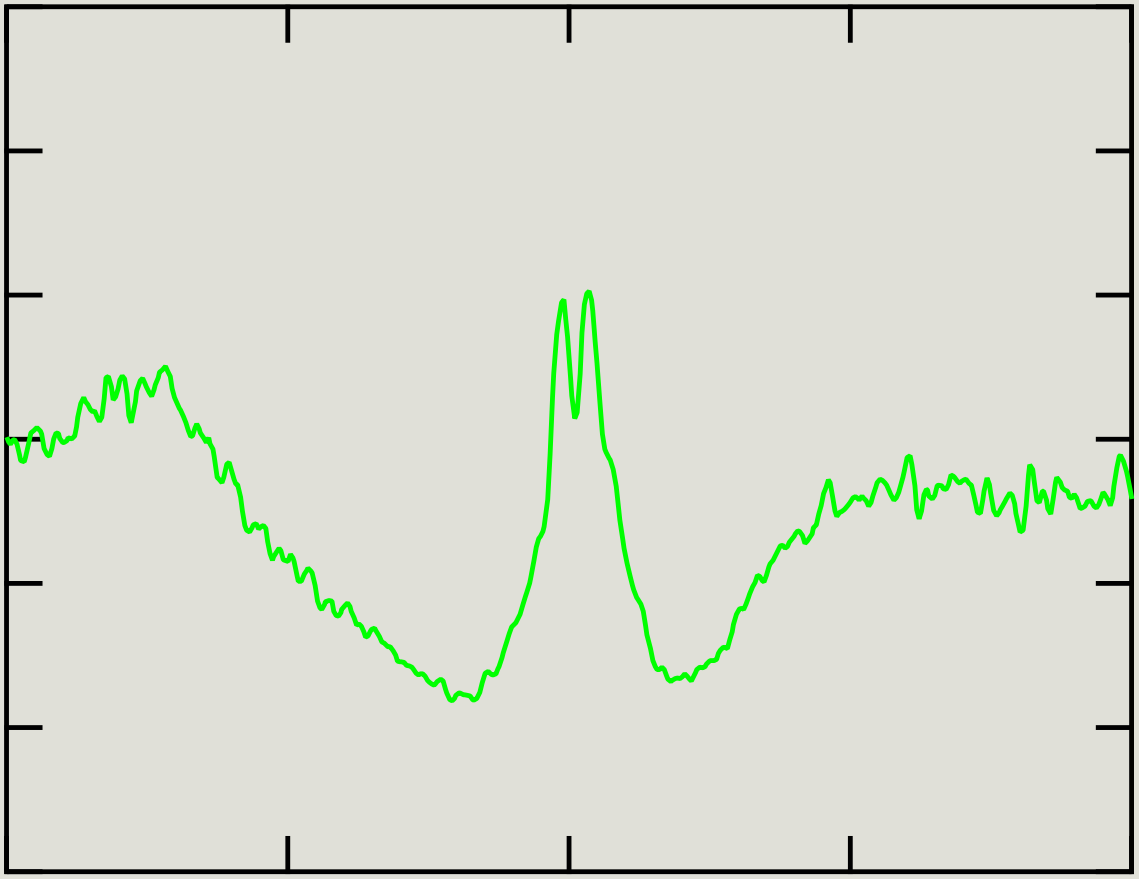
Non-linear I-V

- Critical current

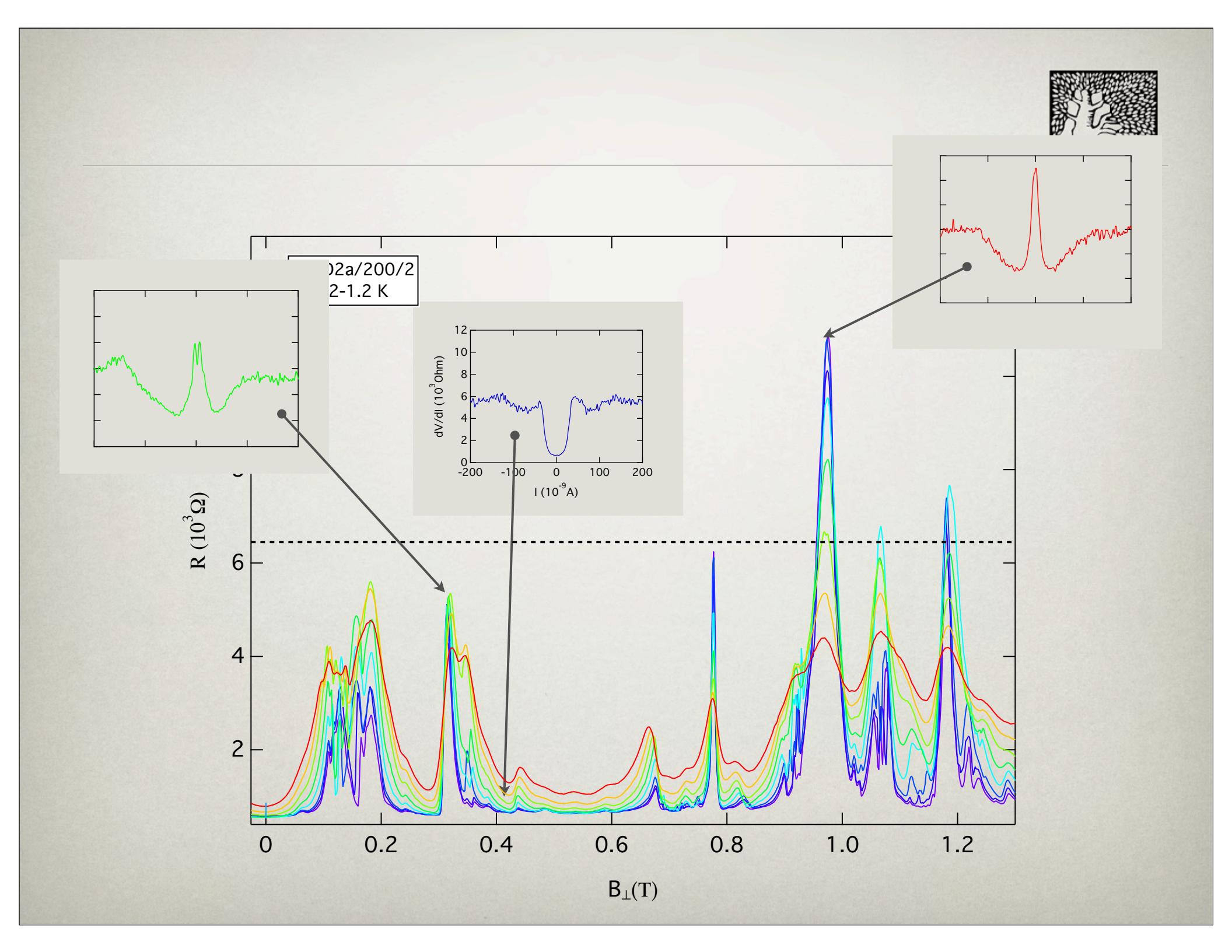




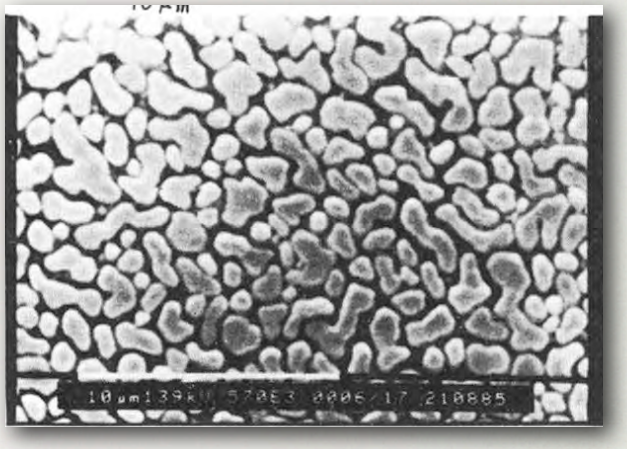


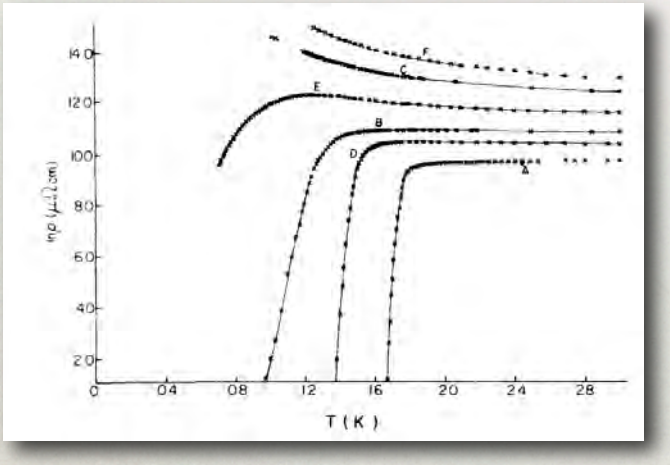


$B_{\perp}(T)$


02a/200/2
2-1.2 K
dV/dI (10^3 Ohm)
I (10^-9 A)
R (10^3 Ω)
B⊥(T)
0
0.2
0.4
0.6
0.8
1.0
1.2
2
4
6

Material

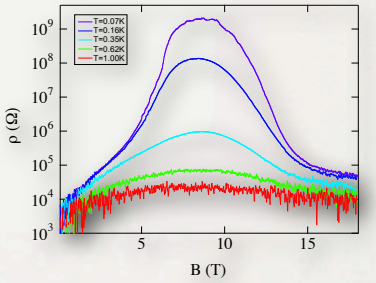




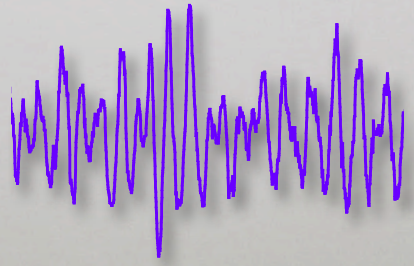
Shapira and Deutscher, PRB ‘83

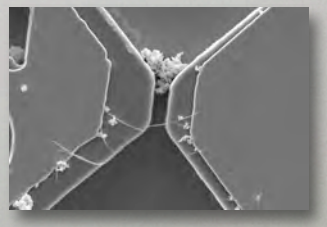
Summary

- B-driven, reentrant insulator

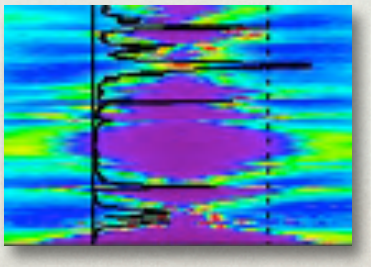


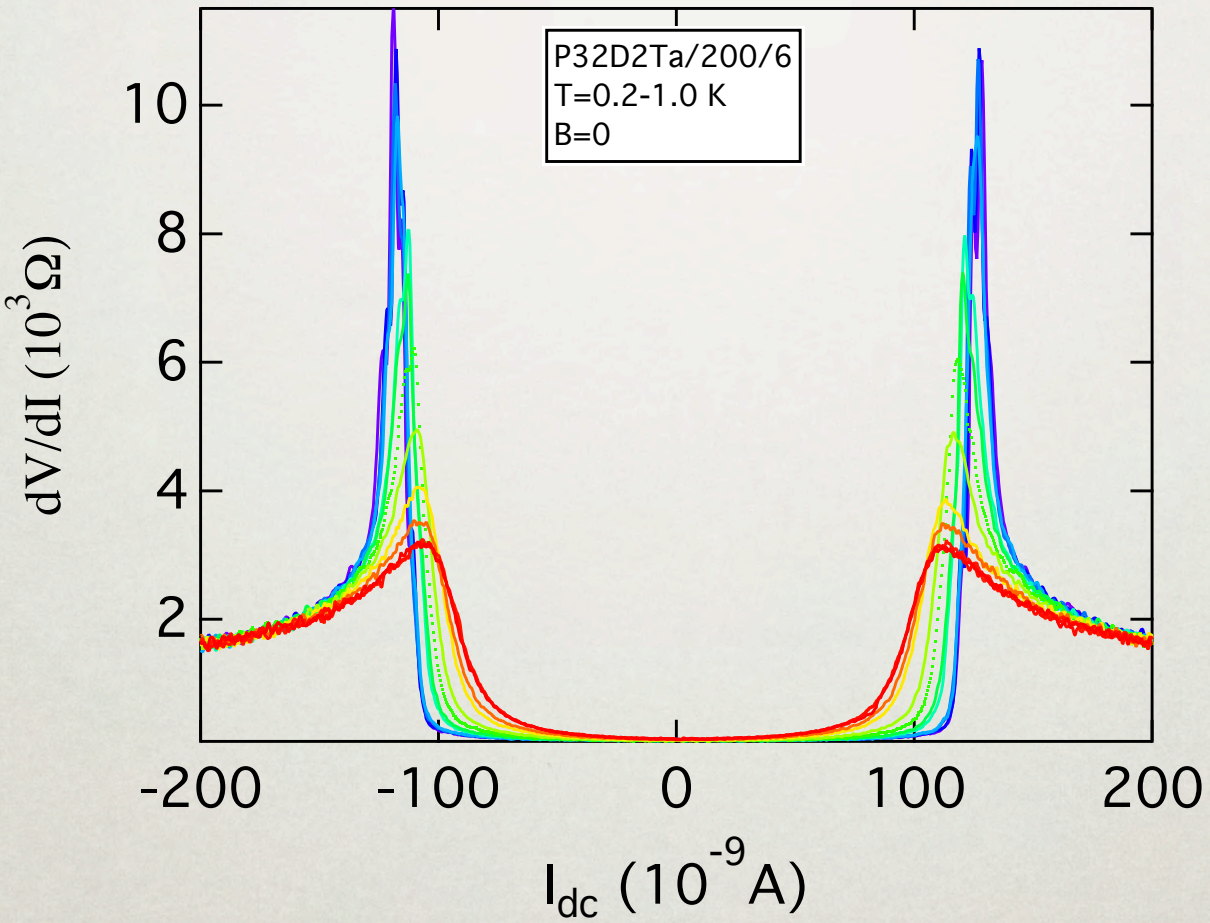
- SQUID-like oscillations in wires





- Oscillating I_c




P32D2Ta/200/6
T=0.2-1.0 K
B=0
dV/dI (10^3Ω)
10
8
6
4
2
-200
-100
0
100
200
I_dc (10^-9 A)