The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2144-3

Workshop on Localization Phenomena in Novel Phases of Condensed Matter

17 - 23 May 2010

Asymmetric Metal-Insulator Transition in Ferromagnetic Films

Khandker A. MUTTALIB

University of Florida, Dept.of Physics
P.O. Box 118440, 32611-8440 FL Gainesville
U.S.A.

Asymmetric metal-insulator transition in ferromagnetic films

KAM

UF UNIVERSITY of FLORIDA

Collaborators:

Rajiv Misra: Penn State
Art Hebard: UF
Peter Wölfle: KIT

Why ferromagnets?

- What happens to itinerant spins when charges localize?
- Is there a separation of spin and charge degrees of freedom that changes the nature of the metal-insulator transition?

Is M-I transition any different in itinerant magnetic systems ?

Why films?

- Gd films show weak localization effects as well as quantum corrections due to scattering off spin waves. Both disorder and spin important.

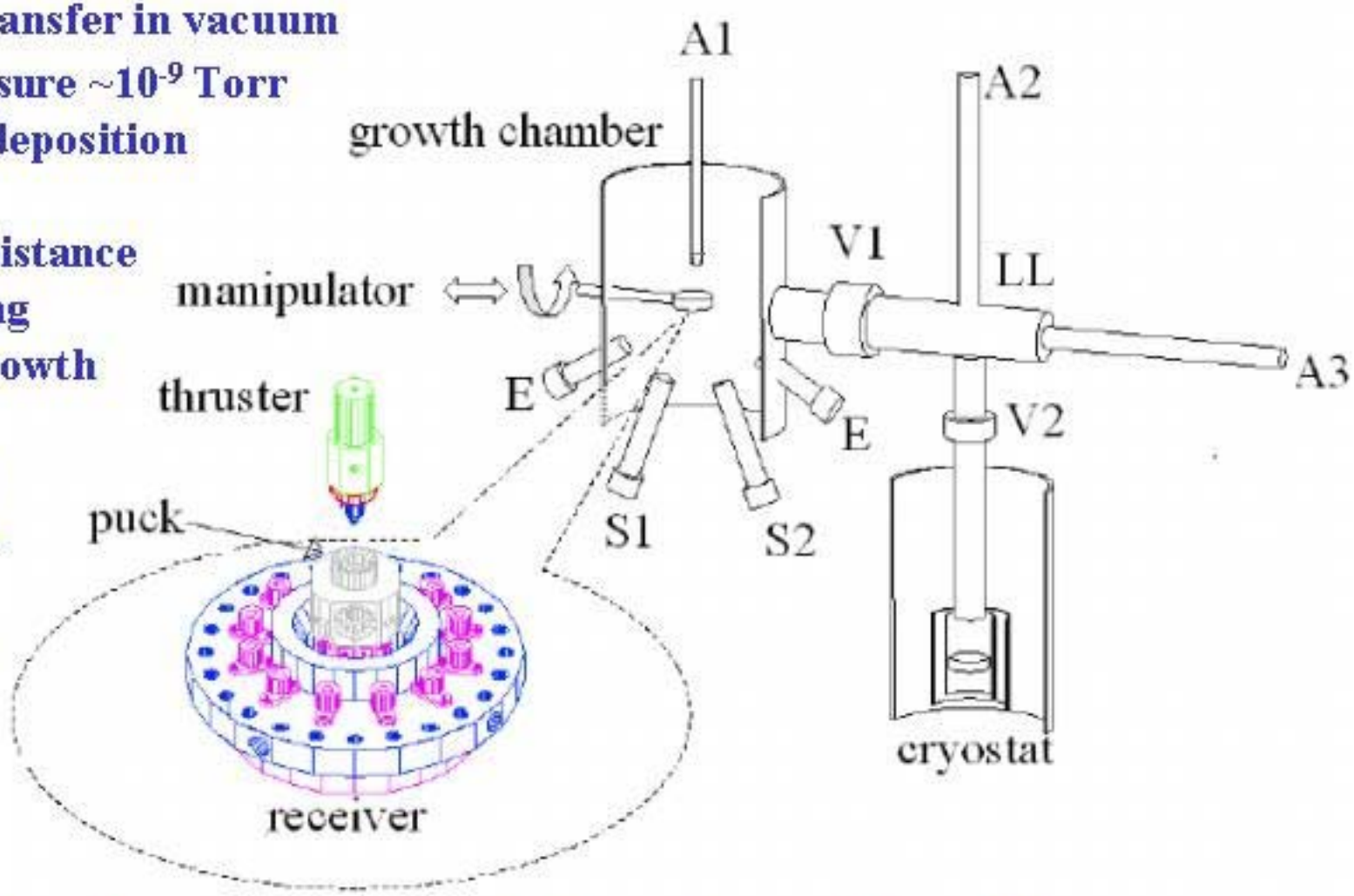
- Film geometry allows one to change disorder in small steps, over a wide range across M-I transition, by varying deposition parameters.

- Highly reproducible T-dependent conductivity.

Problem: ferromagnetic films oxidize easily.
Need *in situ* measurements in high vacuum.

"SHIVA": SAMPLE HANDLING IN VACUUM

- Sample transfer in vacuum
- Base pressure ~10^{-9} Torr
- Multiple deposition sources
- *In situ* resistance monitoring during growth
- *In situ* magneto transport up to 7T, 4.5K



In situ measurements for air sensitive films

Experimental constraints and limitations

- SHIVA limited to $T \geq 5$ K . Can not extrapolate to T=0.
- High disorder requires thin films: ~ 20 – 30 A.
- Thickness of such films can not be measured very accurately.

Resolution of experimental limitations

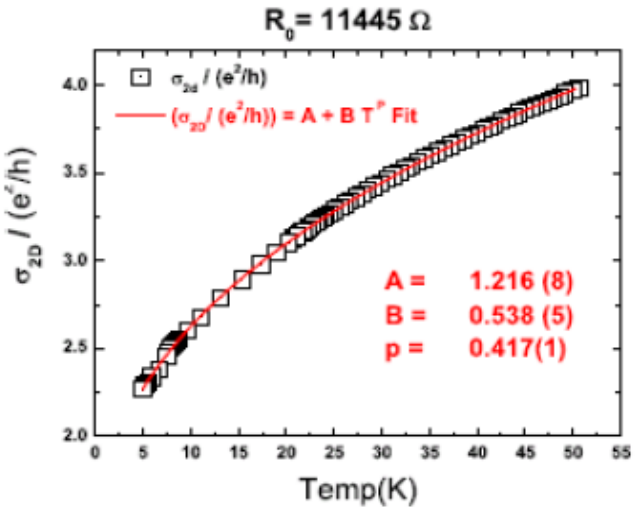
- Use finite temperature scaling to analyze data. No need to extrapolate to T=0.

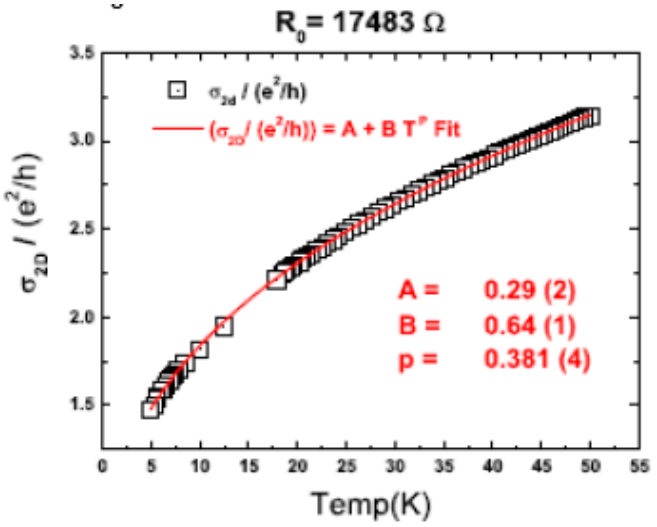
- Use sheet resistance R_0 as measure of disorder. No need to know the thickness accurately.

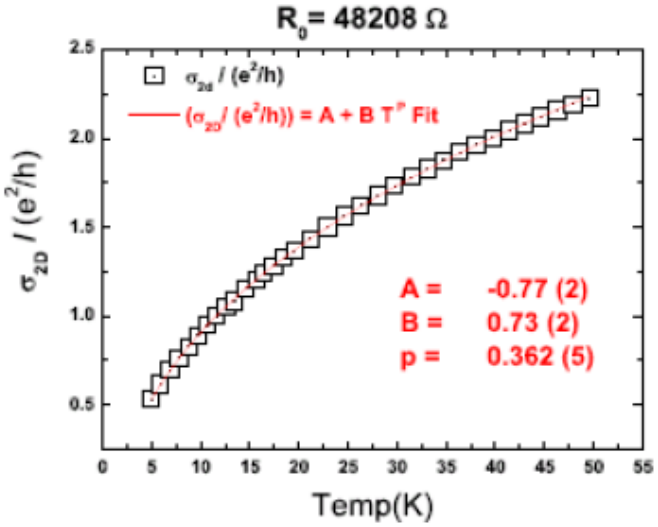
- Same thickness for annealed samples. Check reproducibility when grown separately.

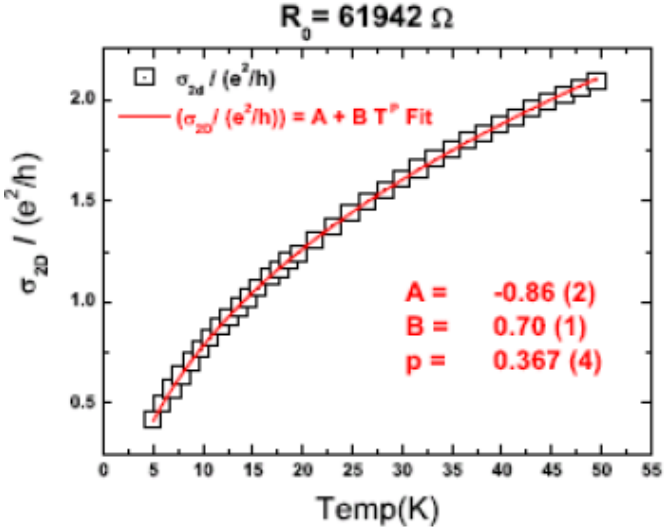
Critical region is well-defined If scaling collapses all T and R_0 dependent data onto a single curve.

Data: T dependent conductivity









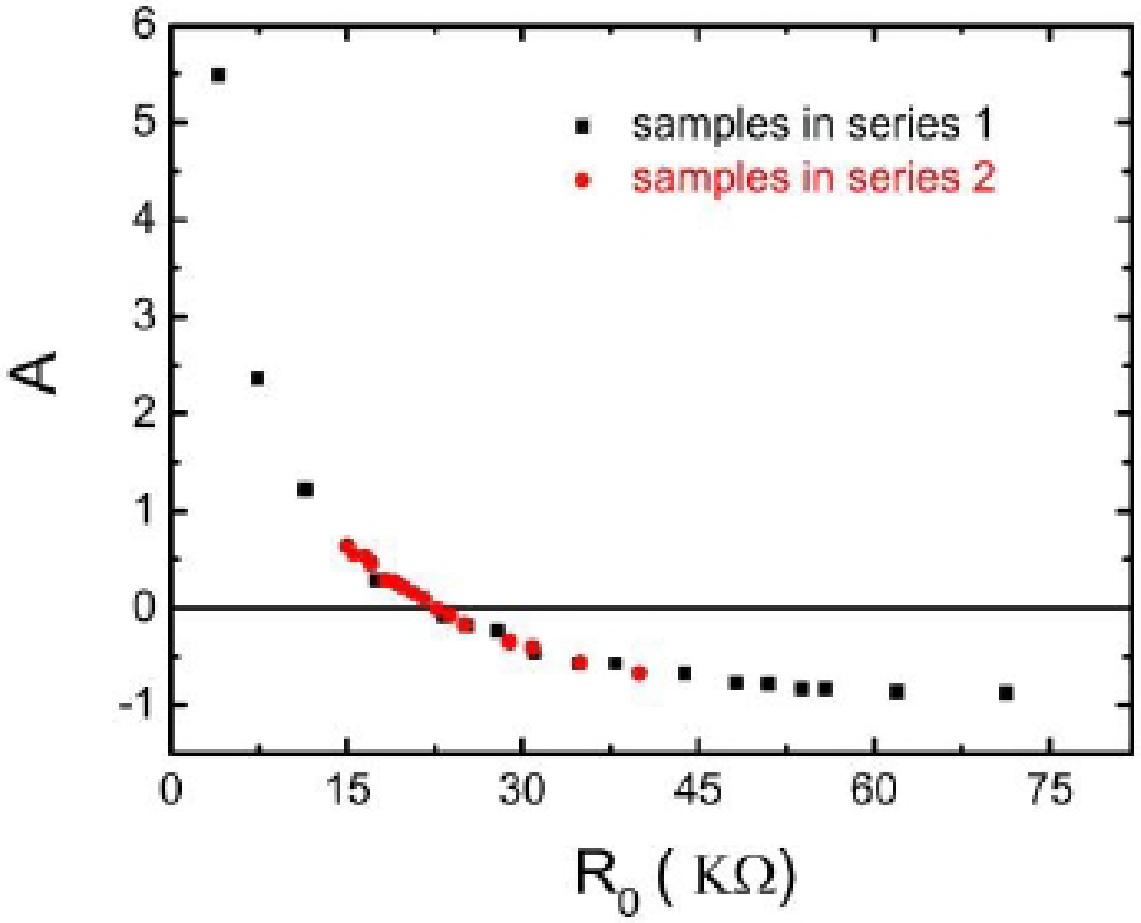
power law fit:

$\sigma(T;R_0)/L_0 = A + B\,T^p$

where $L_0 = e^2/h$;

A, B, p vary with disorder

A as a function of disorder

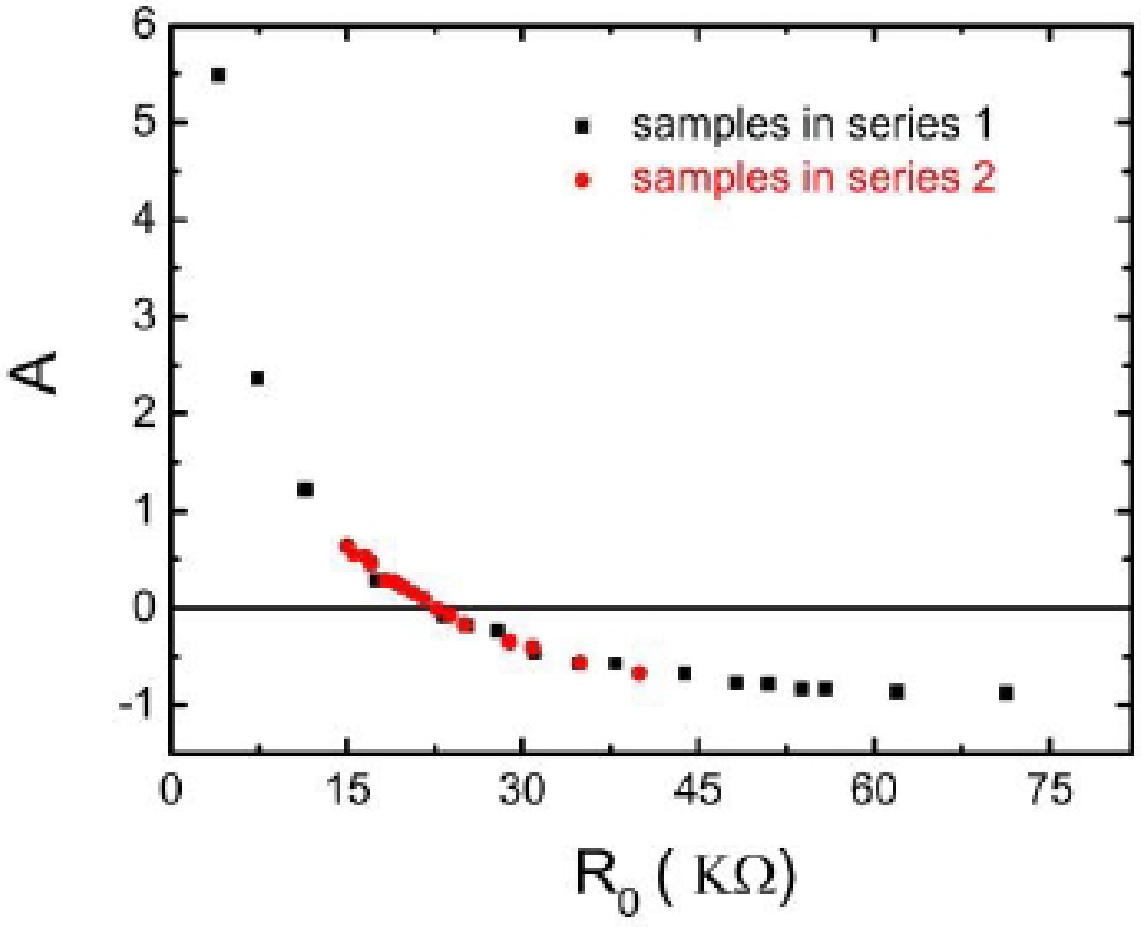


$\sigma(T;R_0)/L_0 = A + B\,T^p$

A, B, p allowed to vary with disorder

A changes sign !

A as a function of disorder



Series 1:
5 separate depositions;
2 annealed
12 times;
Total 17 data

Series 2:
single sample;
annealed
15 times;
Total 16 data

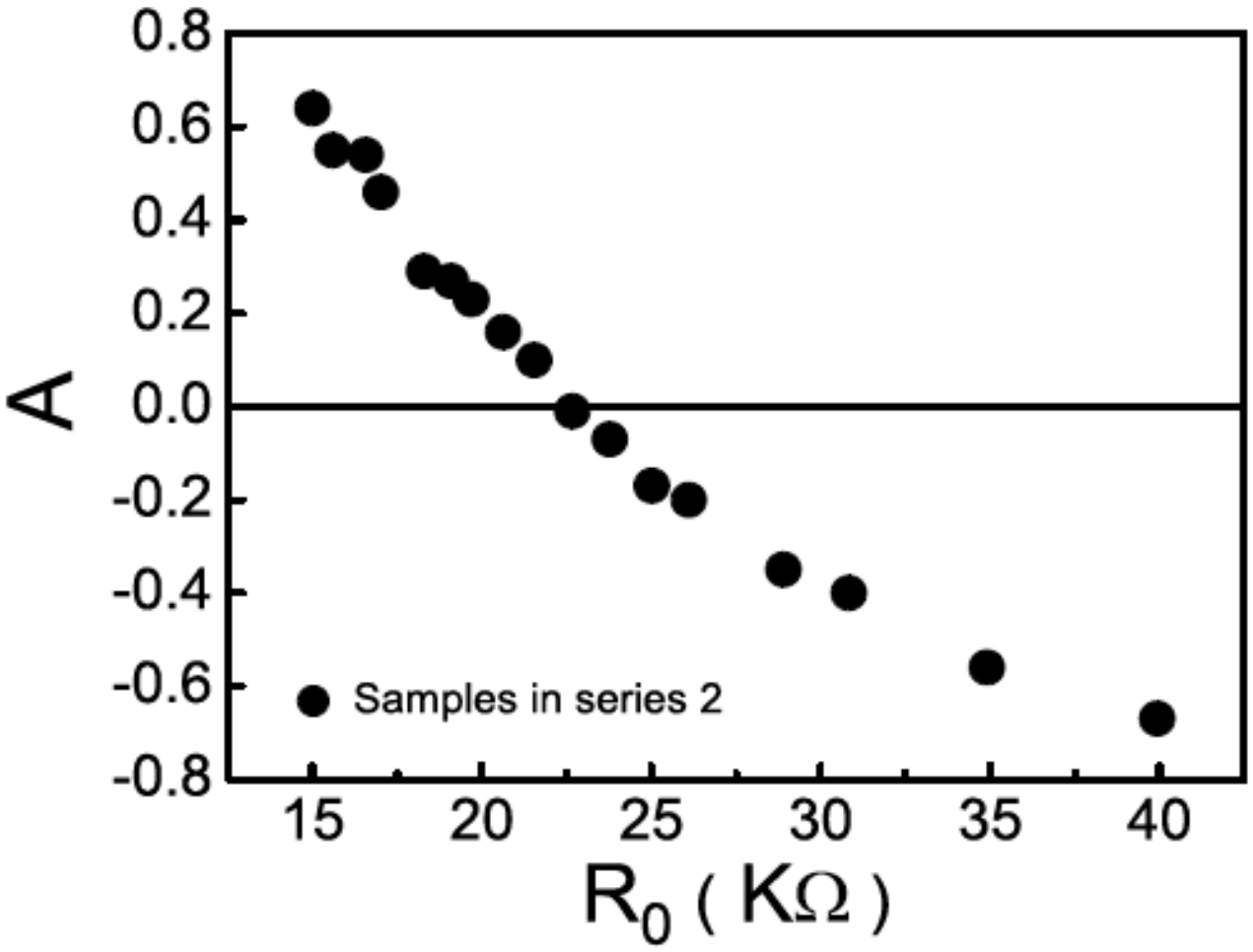
Highly reproducible

What does negative A mean?

- Conductivity can not be negative. Negative A means the extrapolation to T=0 must include opposite curvature, sign of an insulator.
- Exactly at the critical point, conductivity should follow a pure power law.

A=0 must be the critical point.

Critical point: A=0

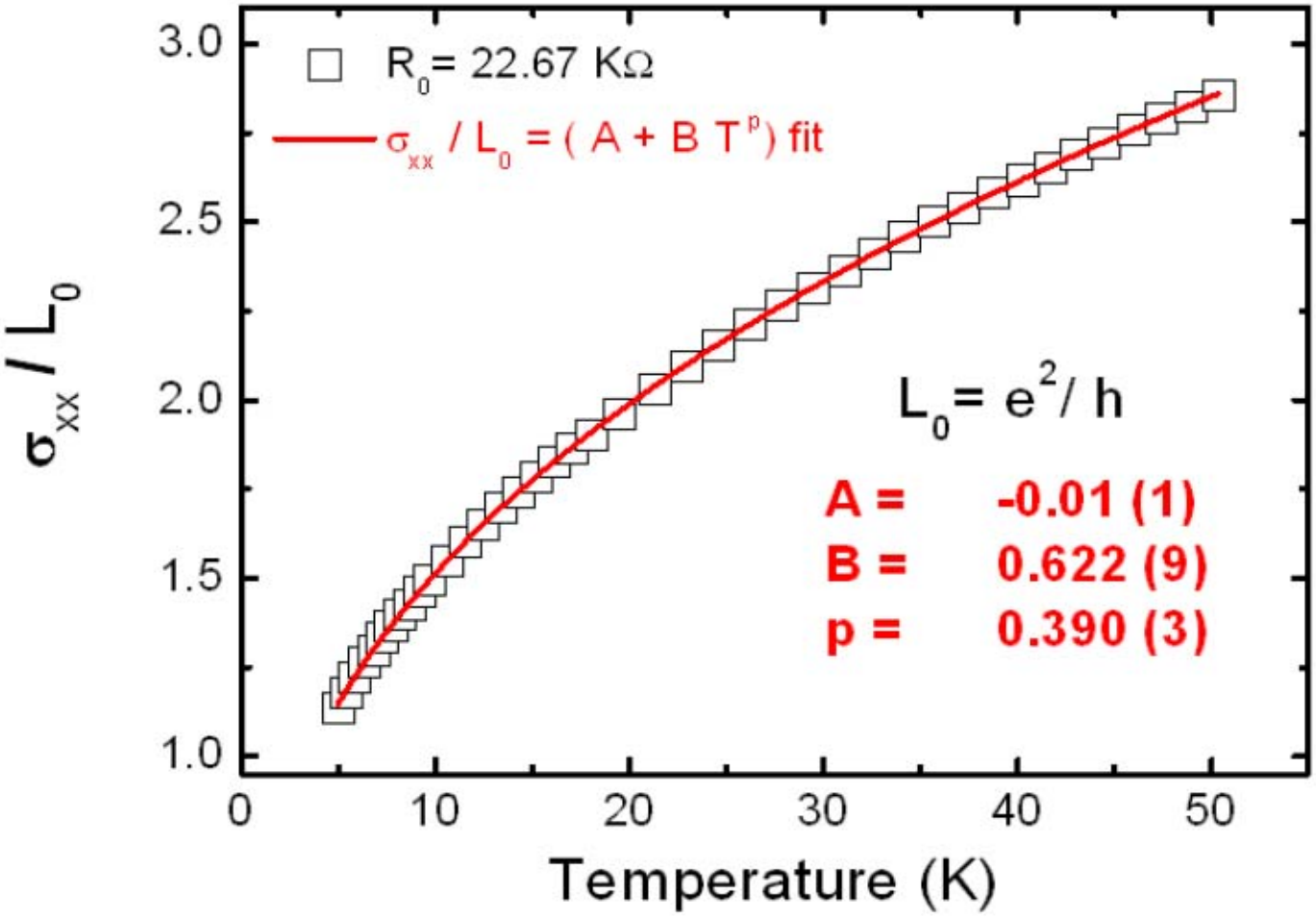


One data point with $A \approx 0$ at $R_0 \approx 22.67$ kΩ

Precise determination of the critical point.

No extrapolation needed

Critical point: pure power law



$R_c \approx 22.67\ k\Omega;\ p \approx 0.39$

Critical exponents: definitions

$\sigma(R_0) \sim |R_c - R_0|^{s}$, s: conductivity exponent

$\sigma(\omega, R_c) \sim \omega^{1/z}$, z: dynamical exponent

$\xi \sim |R_c - R_0|^{-\nu'}$; $R_0 < R_c$, ν': correlation length exponent

$\xi \sim |R_c - R_0|^{-\nu}$; $R_0 > R_c$, ν: localization length exponent

ν and ν' can be different

Exponents: theoretical expectations

Non Linear Sigma Model (epsilon expansion):

$s = \nu' = 1;\ z = 3$ in 3d Wegner

Numerical simulations (Anderson model):

$s = 1.6$ Slevin and Ohtsuki

Interacting systems: No reliable theoretical way

No statement on asymmetric exponents

Exponents: experiments on non-magnetic systems

s = 0.5, Si:P (uniaxial stress) Paanalen et al '82

s = 1, Ge:Sb (doping) Field et al '85, Hirsch et al '88
Thomas et al '82, Zabrodskii et al '84

$\nu' = \nu = 1.6$ and z = 2, Si:B (uniaxial stress)

Bogdanovich et al '99

$\nu' = \nu = 1$ and z = 2.94, Si:P (uniaxial stress)

Waffenschmidt et al '99

$s = \nu' = \nu$: same exponent on both sides

Note: expts at 3 – 700 mK, emphasizing $T \rightarrow 0$

Finite T: scaling relation

For $\omega > \omega_\xi \sim (\xi/\ell)^{-z}/$:

$$\sigma(R_0;\omega) = \xi^{-1} G(\xi^{1/\nu} |R_c - R_0|; \xi^z \omega)$$
$$= \xi^{-1} G(\pm 1; \xi \omega^{1/z})$$

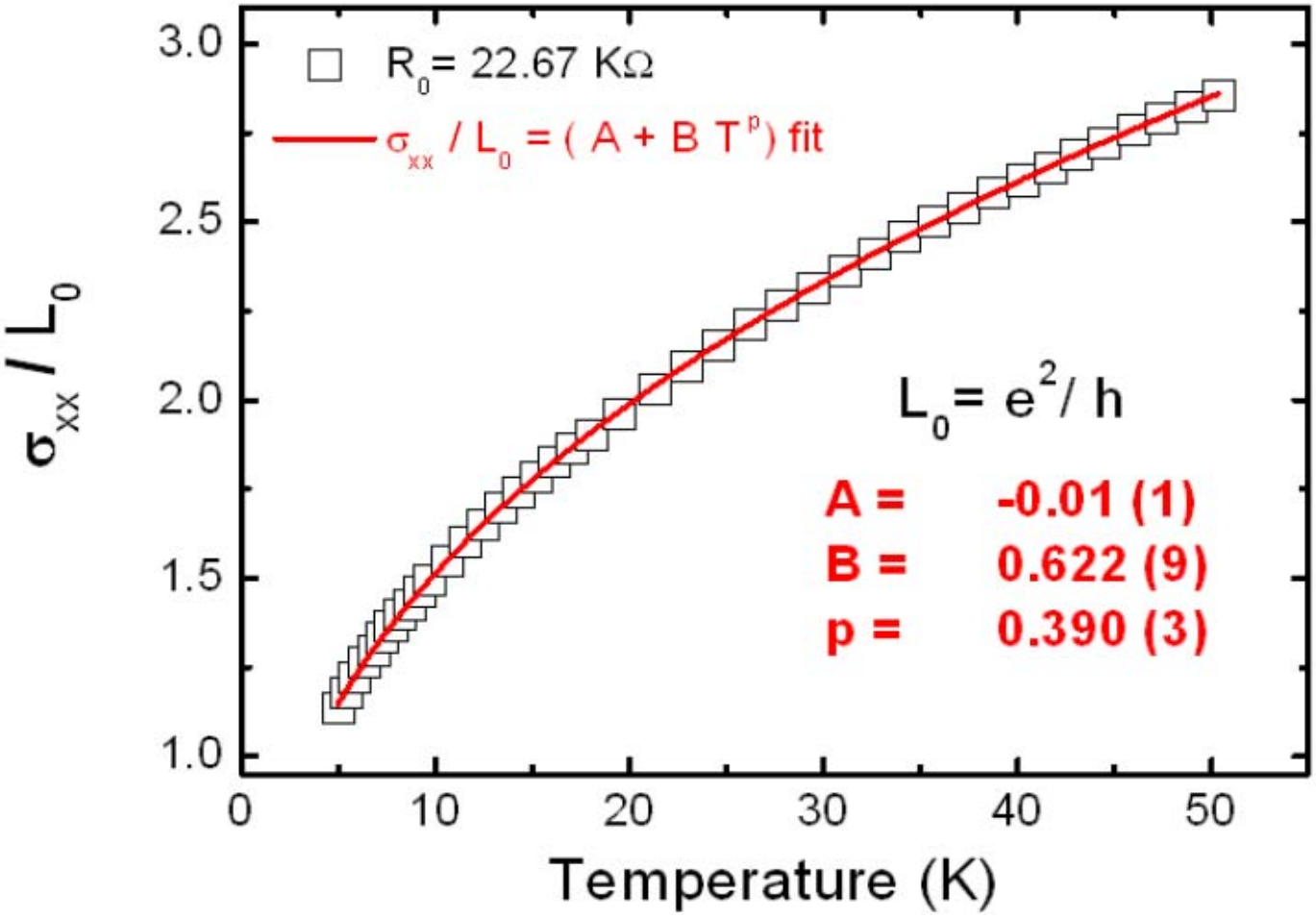
At critical point: $G(\pm 1; \xi\omega^{1/z}) \sim \xi\omega^{1/z}$

For $\xi \sim |R_c - R_0|^{-\nu}$ and $\omega \to T$
conductivity should obey the scaling at $T > T_\xi$:

$$|R_c - R_0|^{-\nu} \sigma(T;R_0) = G(+/-1; |R_c - R_0|^{-\nu} T^{1/z})$$

Compare: expts at 3 – 700 mK, emphasizing $T \to 0$

Critical point: dynamical exponent



$\sigma(T,R_c) \sim T^{1/z}$ □ $p = 0.39 = 1/z$

Scaling function G

Scaling regime:

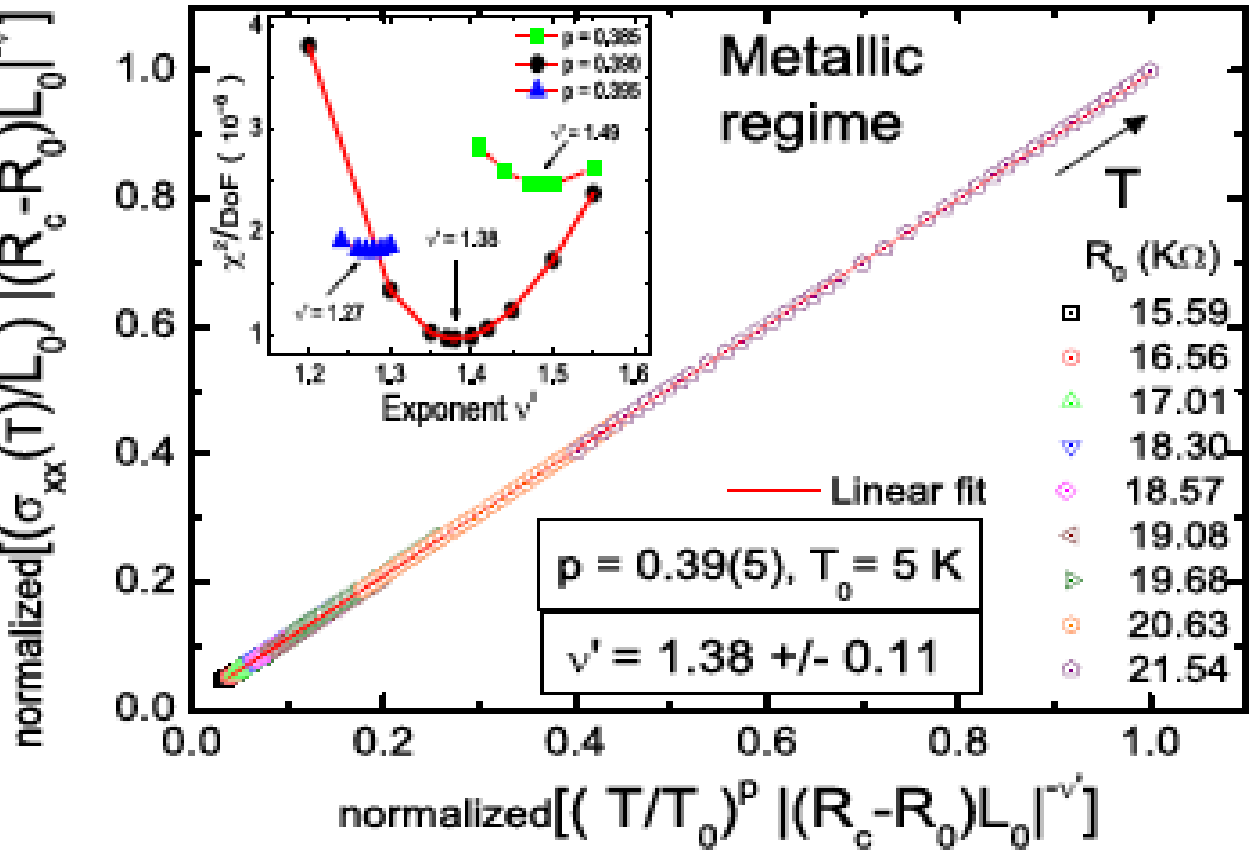
$$|R_0-R_c|^{-\nu}\sigma(T;R_0) = G(+/-1;\ |R_0-R_c|^{-\nu}T^{1/z})$$

Use $1/z = p = 0.39$

Plot $|R_0-R_c|^{-\nu}\sigma(T;R_0)$ as a function of $|R_0-R_c|^{-\nu}T^{1/z}$

All data should collapse on a single scaling function G for one particular value of

Scaling of the data: metallic side

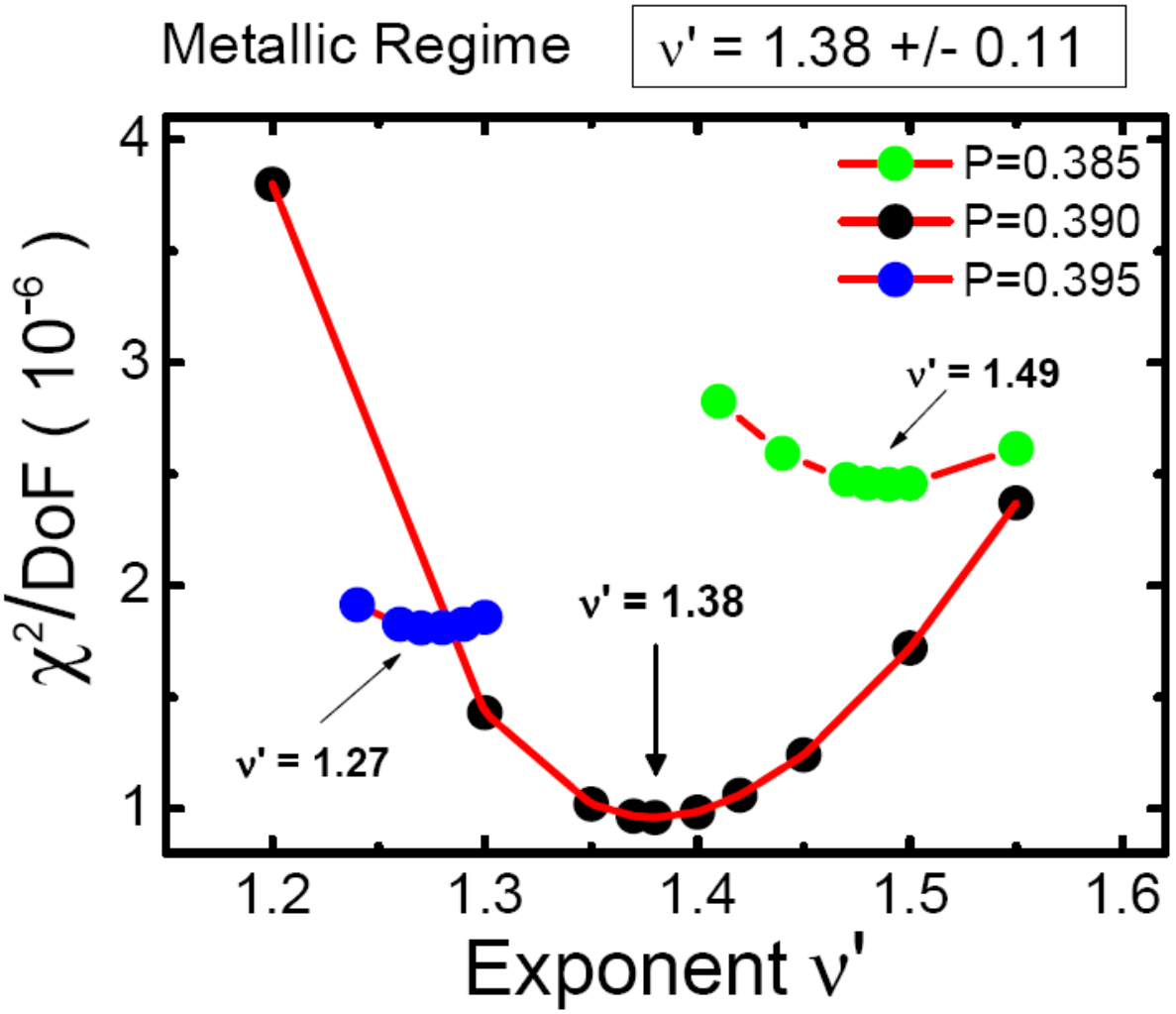


scaling points include
41 values of T
for each of the
9 values of R_0

Total 369 data points

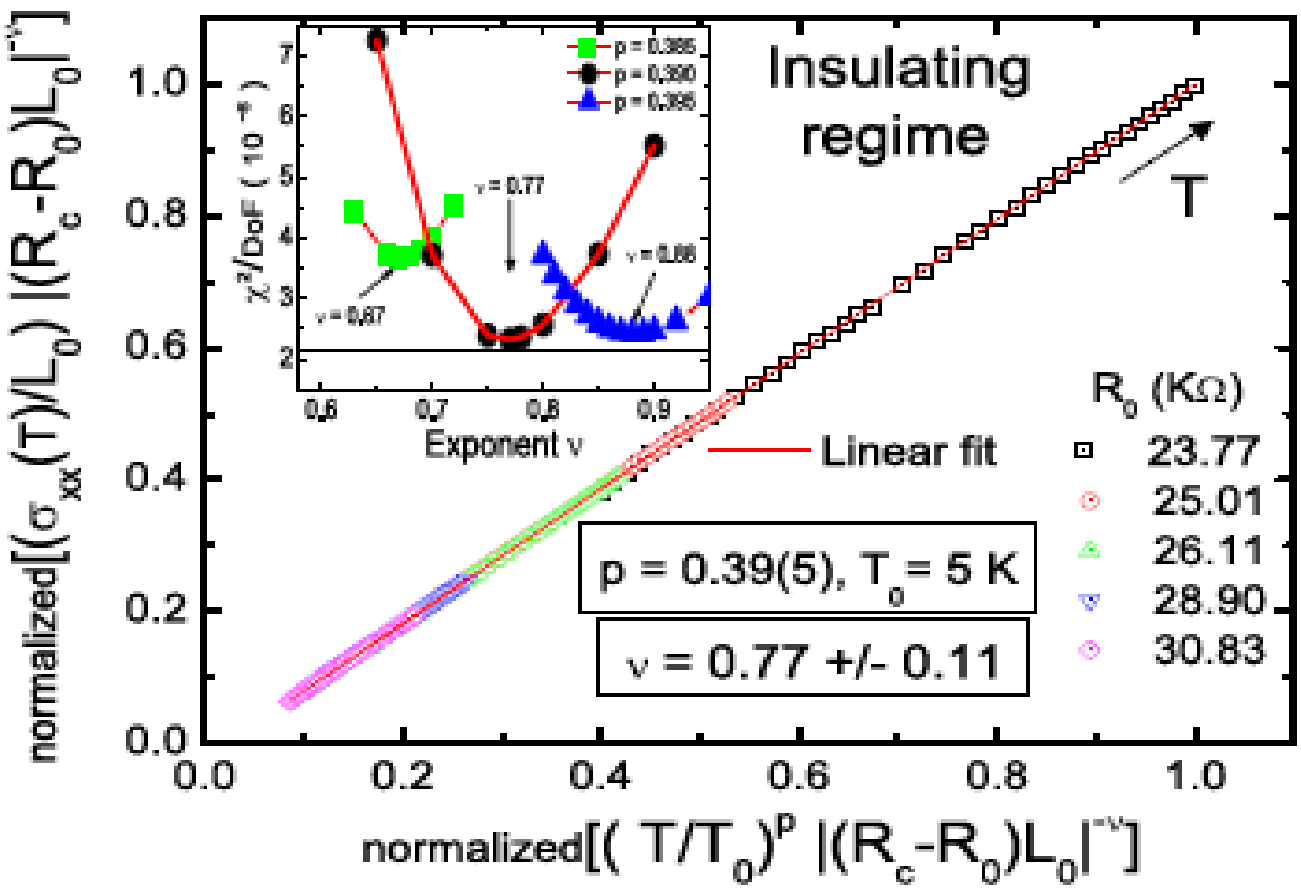
Correlation length exponent $\nu' \approx 1.38$

χ^2 fit allowing uncertainty in p



Observed p = 0.39 gives the best fit

Scaling of the data: insulating side

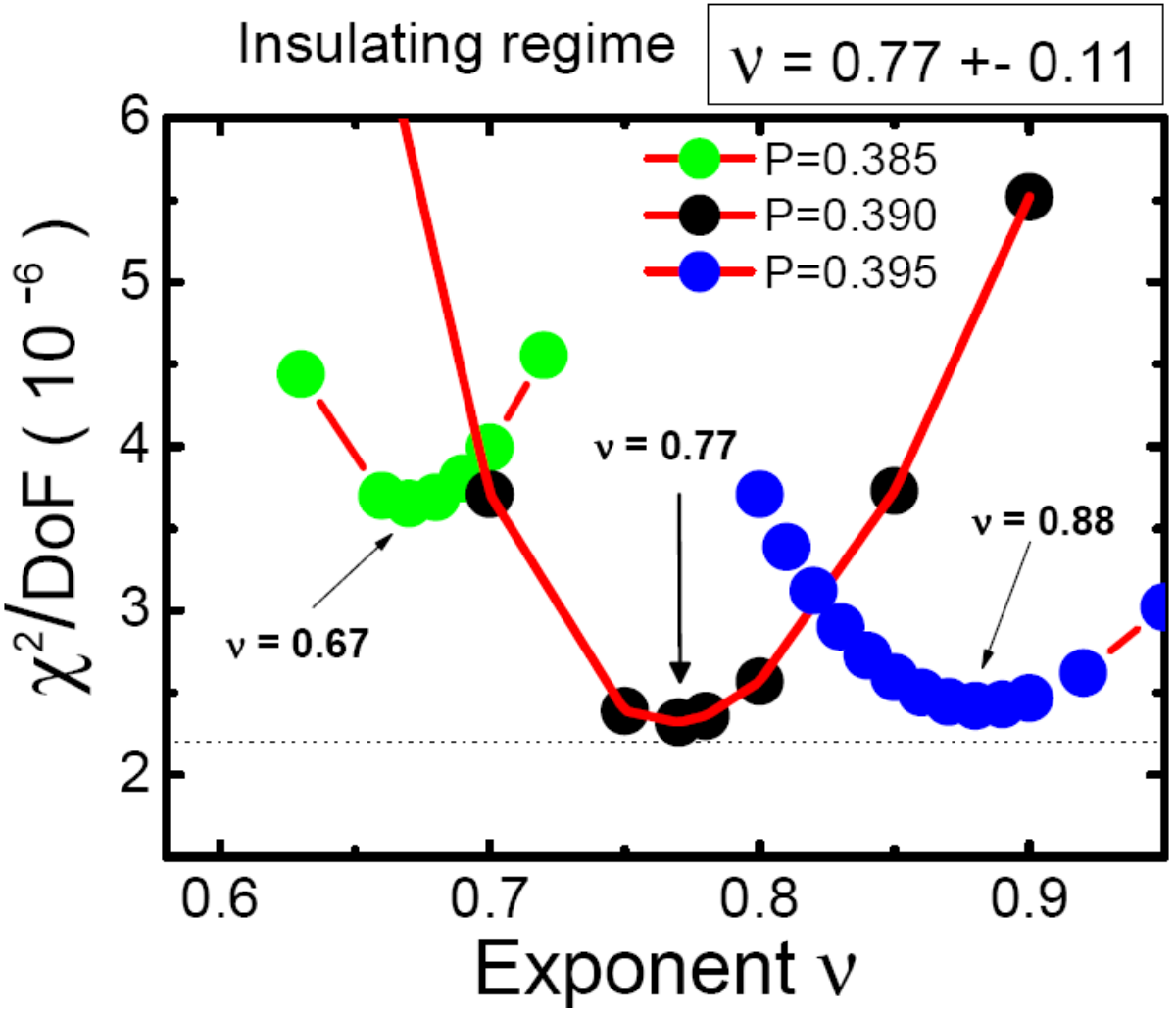


scaling points include 41 values of T for each of the 5 values of R_0

Total 205 data points

localization length exponent $\nu \approx 0.77$

χ^2 fit allowing uncertainty in p



Observed p = 0.39 gives the best fit

Critical region

Experimentally: Minimum in χ^2 fit for data restricted to 15 – 31 kΩ

Theoretical estimate:

$T_\xi \sim (\xi/\ell)^{-z}/\tau \sim (|R_0-R_c|/R_c)^{\nu z}/\tau$;

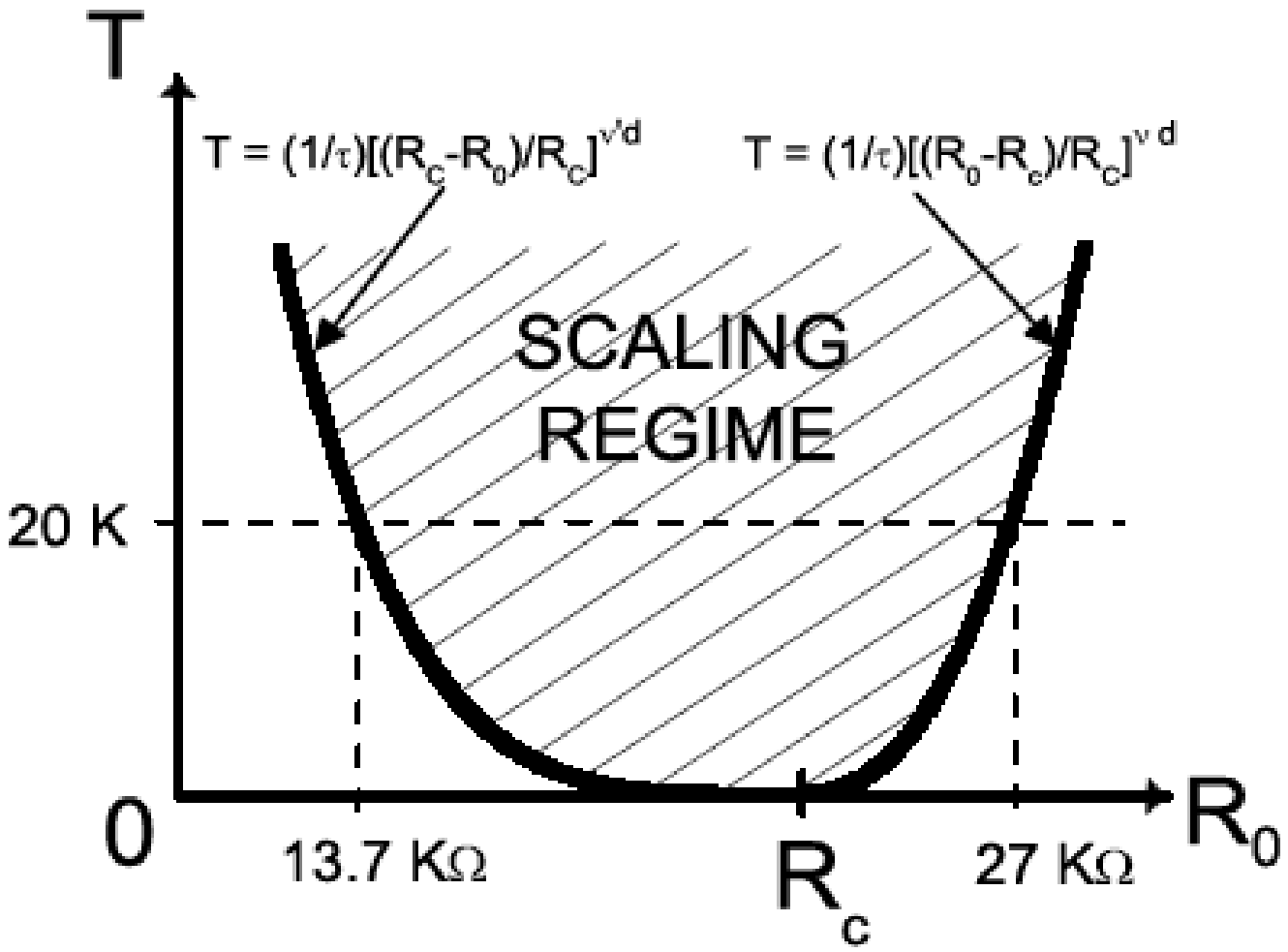
$1/\tau \sim 10^3$ K ; $T = T_\xi = 20$ K

→ $|R_0-R_c|/R_c \sim 0.4$: metallic side and

$|R_0-R_c|/R_c \sim 0.2$: insulating side.

Critical region extends from ~ 15 – 30 kΩ at 20K

Estimate of critical region



Large T better!

3d vs 2d

Film thickness: 20 – 35 Å

Effectively 3d if T-dependent correlation length

$$L_\varphi(T) \equiv \sqrt{\sigma\ \tau_\varphi/N_0} < \text{film thickness}$$

Phase relaxation rate in ferromagnetic films dominated by scattering off spin waves:

$$\tau_\varphi^{-1} \sim T$$ Wölfle and KAM '10

Inequality satisfied if T ~ 1K or larger

Summary

- Distinctly different exponents for correlation lengths on two sides of the M-I transition in ferromagnetic Gd films.
- Unambiguous Identification of critical point and wide critical regime results in excellent scaling.
- Magnetism seems important. Thin film geometry might also be relevant.
- Scaling function G seems linear.

No theoretical model available