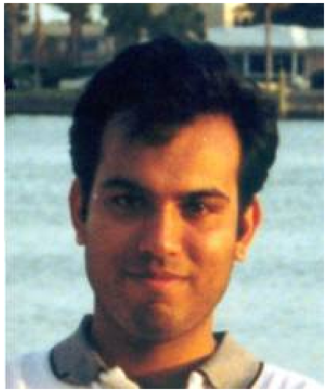
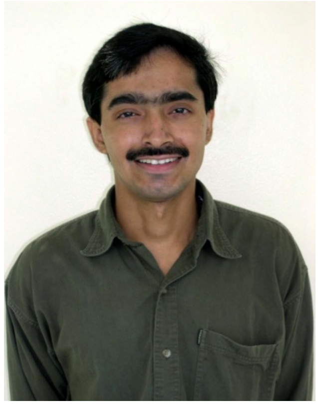
Disorder tuned approach to critical behavior in thin-film ferromagnets

A. F. Hebard (University of Florida, Gainesville, FL)





P. Mitra R. Misra

K. Muttalib (UF) & P. Wölfle (Karlsruhe)

Research supported by NSF

FM in 2D: Motivating Questions.

1. Band ferromagnetism relies on itinerant electrons. When itinerancy is compromised by disorder, what happens?

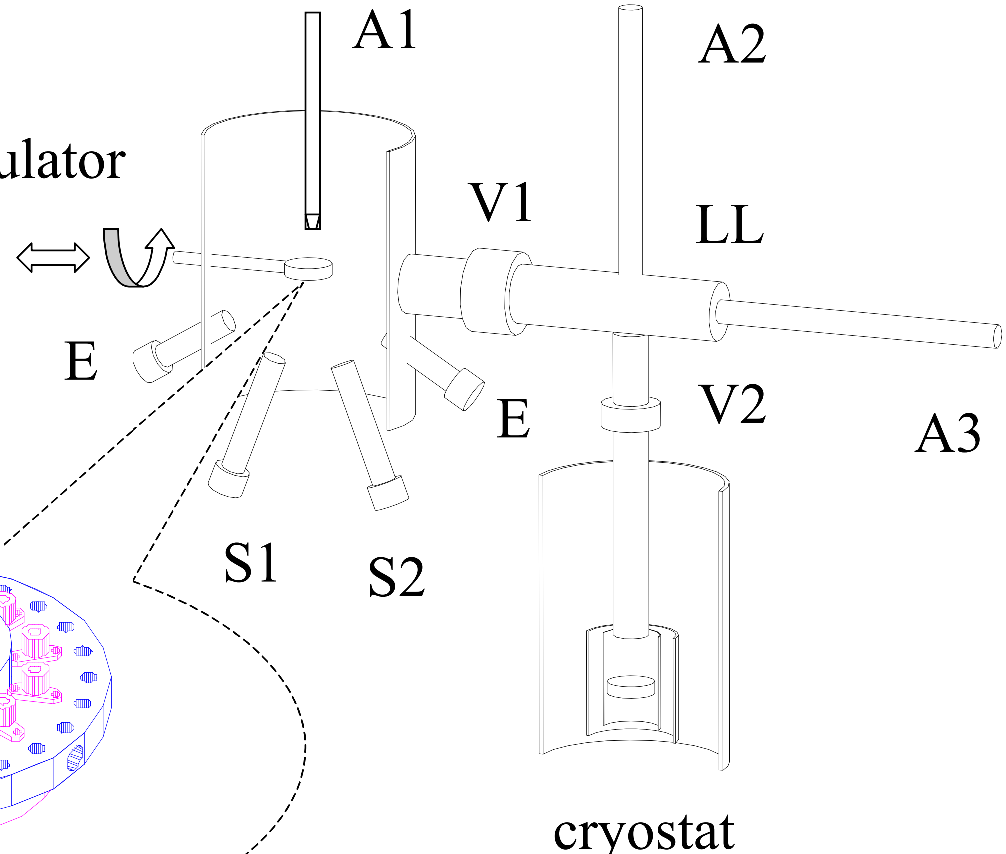
2. Any signatures at $\hbar/e^2 = 4100\ \Omega$?

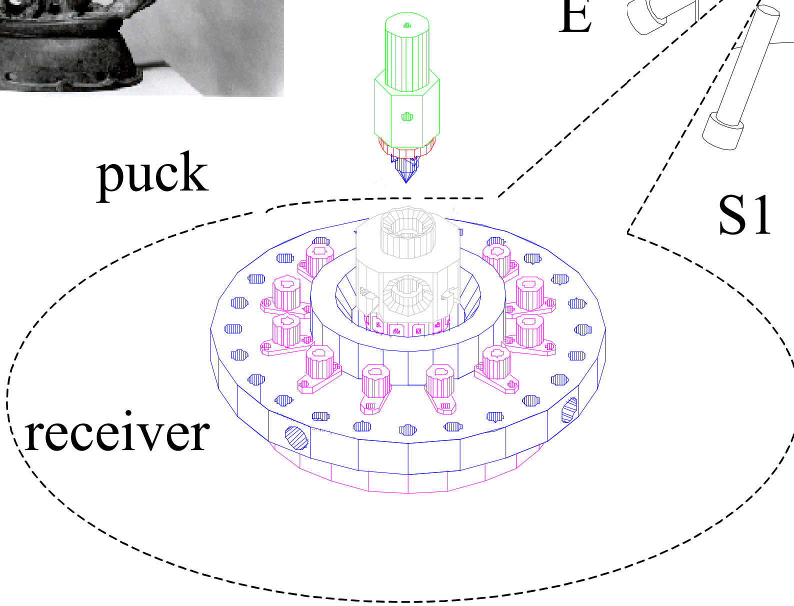
3. Is there a ferromagnetic metal-insulator transition?

4. Ferromagnetic behavior and film morphology?

Presentation (answers?) in multiple Acts !

SHIVA- Sample Handling In VAcuum





ACT (I)

Evidence for a disorder-dependent localization correction to the anomalous Hall (AH) conductance of Fe thin films

P. Mitra, et al, PRL **99**, 046804 (2007)

Prelude (some background)

At low temperatures,

$$\sigma_{2D} = \sigma_{Drude} + \Delta\sigma_{WL} + \Delta\sigma_{e-e}$$

Disorder:-

Lattice imperfections, grain boundaries, etc

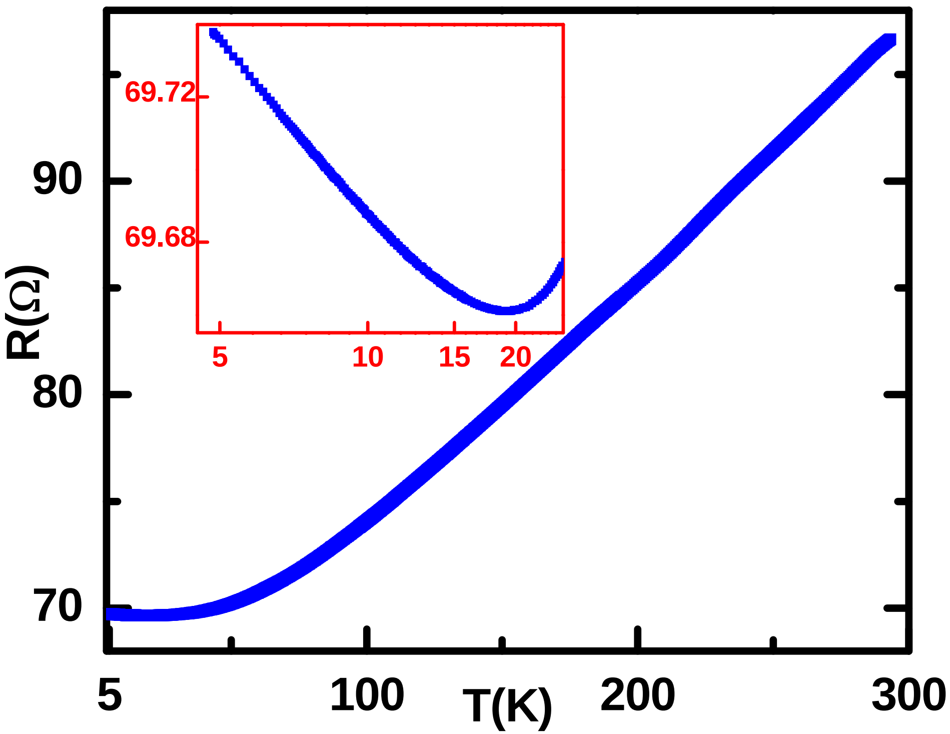
Which of the processes (WL or e-e interaction) is dominant at different disorder strength?

Quantum corrections are affected by spin alignment (ferromagnetic order).

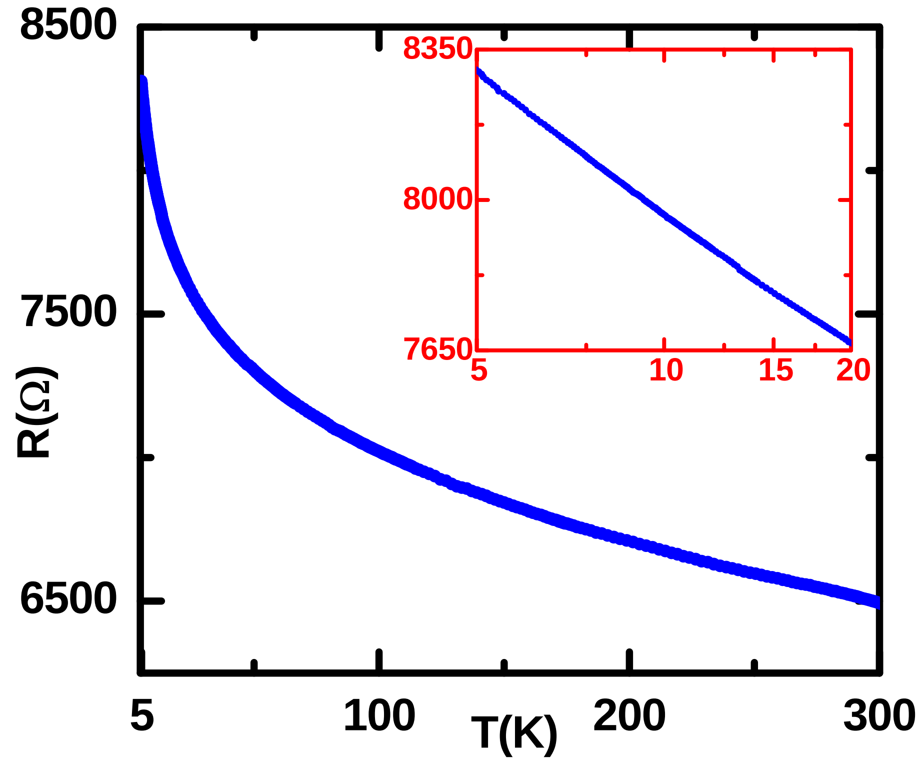
Weak disorder: Fe on glass substrates

Magnetron sputtering at room T

d=100Å, R_0=70Ω



d=20Å, R_0=8300Ω



Inset: Log(T) dependence of Rsq at low temperature

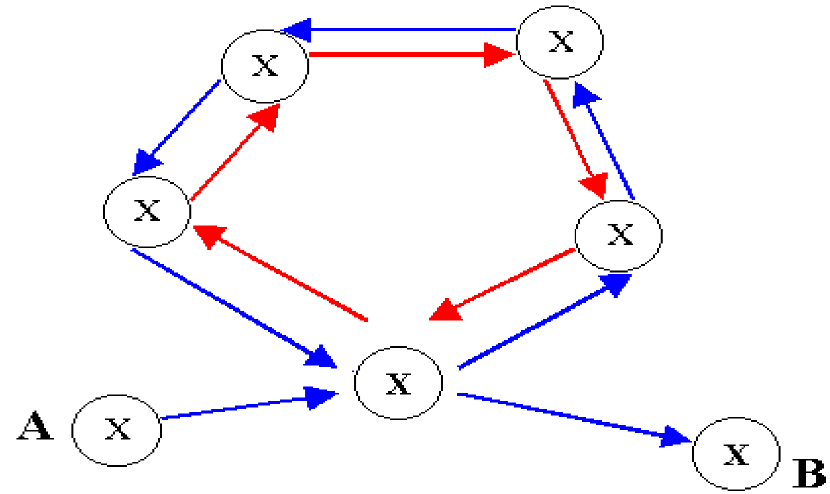
Weak localization

Magnetic Field

$$\vec{p} \rightarrow \vec{p} - \frac{e}{c}\vec{A}$$

$$\Delta\varphi_H = \frac{2e}{c\hbar}\oint \vec{A}\cdot d\vec{l} = 2\pi\frac{\Phi}{\Phi_0}$$

$$\sigma(H) - \sigma(0) \sim \frac{e^2}{\hbar}\ln\left(\frac{eHD\tau_\varphi}{\hbar c}\right)$$



Negative magnetoresistance

Magnetic field suppresses coherent backscattering

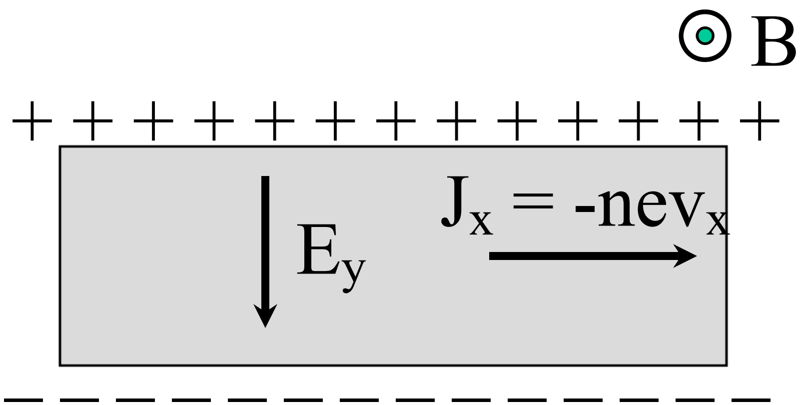
A necessary condition for localization,

$$\max\{\tau_s^{-1}, \tau_{so}^{-1}, \omega_c\} << \tau_\varphi^{-1} << \tau_{tr}^{-1}$$

$\tau_\varphi^{-1} \sim T$ in FM films due to spin conserving inelastic scattering off of spin wave excitations!

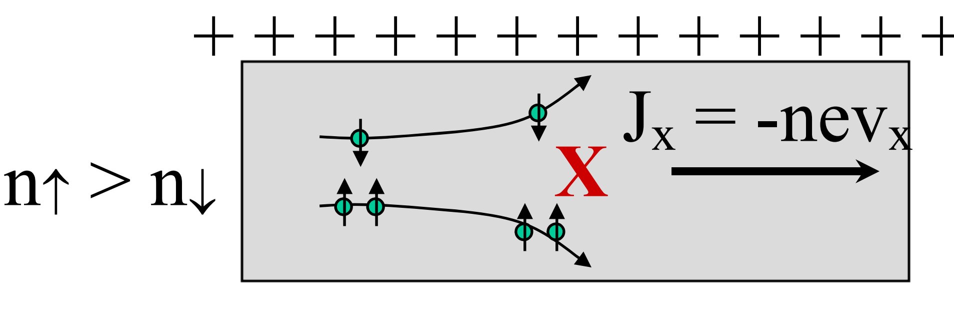
Hall effect(s)

Normal Hall Effect



$$R_{xy} = V_y/I_x = B/Ne$$

Itinerant ferromagnetism and the Anomalous Hall Effect (AHE)



X ≡ spin-orbit scattering

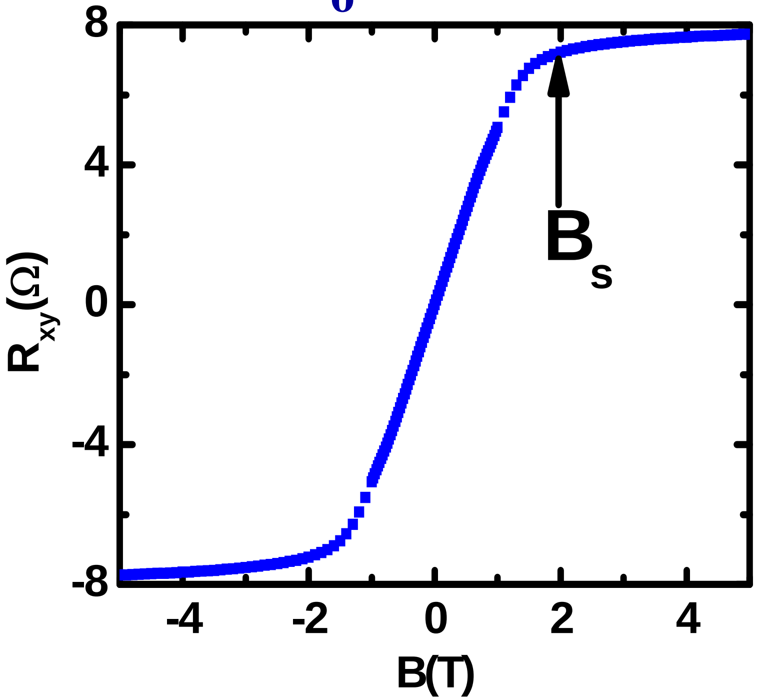
$$R_{xy} = V_y/I_x = \mu_0 R_s M$$

Anomalous Hall effect in iron

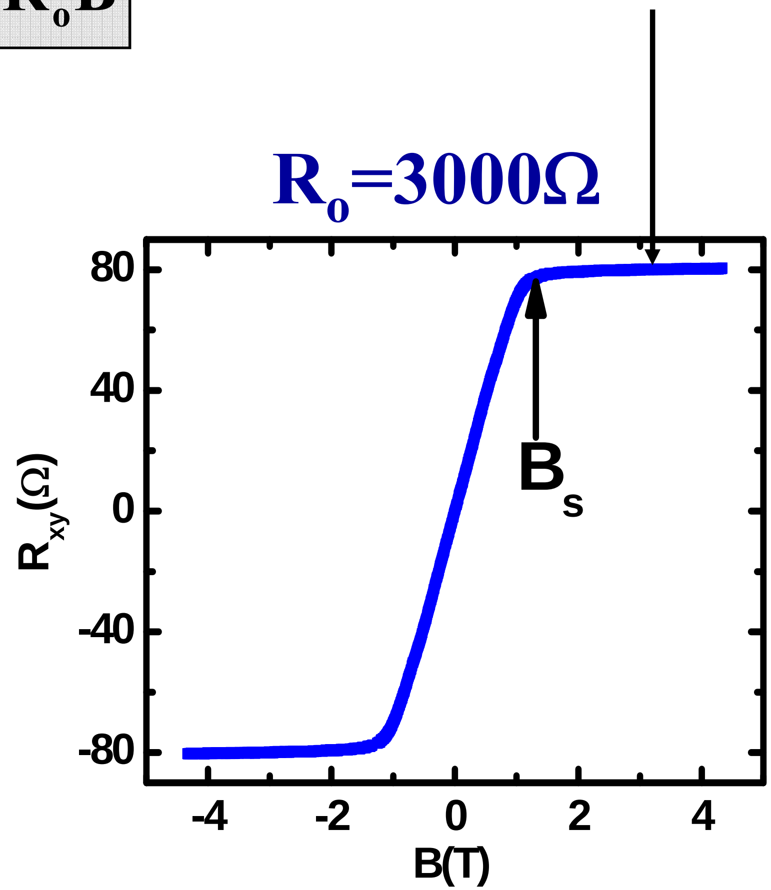
$$R_{xy} = \mu_o R_s M + R_o B$$

Remember this value

R_o=300Ω



R_o=3000Ω



Note: decrease in B_s and increase in R_{xy} with R_o

Relative resistance/conductance changes

Experimentally, $R_{xx}^{AH} >> R_{xy}^{AH}$

$$\sigma_{xy}^{AH} \approx \frac{R_{xy}^{AH}}{(R_{xx}^{AH})^2} \quad \Rightarrow \quad \frac{\delta\sigma_{xy}^{AH}}{\sigma_{xy}^{AH}} = \frac{\delta R_{xy}^{AH}}{R_{xy}^{AH}} - 2\frac{\delta R_{xx}^{AH}}{R_{xx}^{AH}}$$

Theorists

Experimentalists

Quantum corrections to AH conductivity- Previous work

Effect of electron interactions on σ_{xy}^{AH} (skew scattering regime)

$$\frac{\delta\sigma_{xy}^{AH}}{\sigma_{xy}^{AH}} = 0 \Rightarrow \frac{\delta R_{xy}^{AH}}{R_{xy}^{AH}} = 2\frac{\delta R_{xx}}{R_{xx}}$$

Langenfeld et. al. PRL(67)739,1991

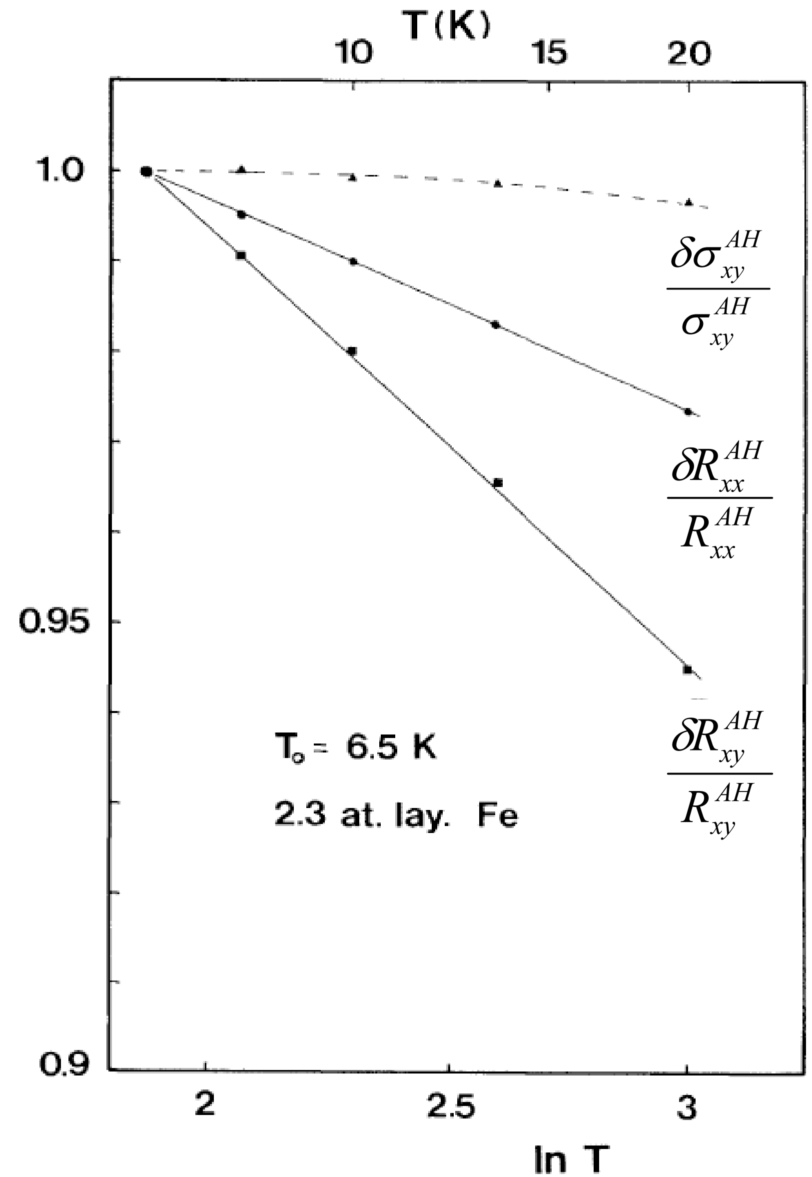
Amorphous Iron films on Sb grown at T< 20K

Bergmann et.al. PRL(67)735,1991

Bergmann-Ye (BY) Scaling

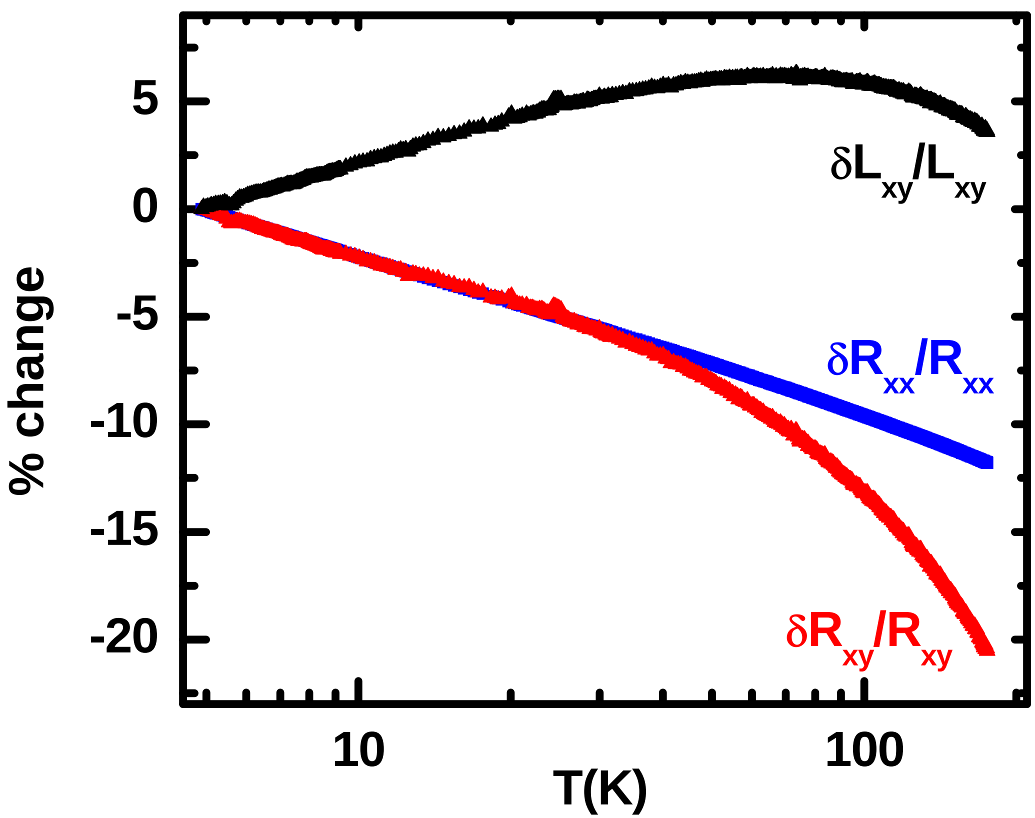
Weak localization corrections to AH conductivity due to side jump mechanism are negligible in a 2D ferromagnet.

Dugaev et. al. PRB 104411 (2001)



Ultra thin Fe on glass: $\delta L_{xy} \neq 0$!

$R_0 = 2730\Omega \quad T_0 = 5K$



$$\frac{\delta\sigma_{xy}^{AH}}{\sigma_{xy}^{AH}} = \frac{\delta R_{xy}^{AH}}{R_{xy}^{AH}} - 2\frac{\delta R_{xx}^{AH}}{R_{xx}^{AH}}$$

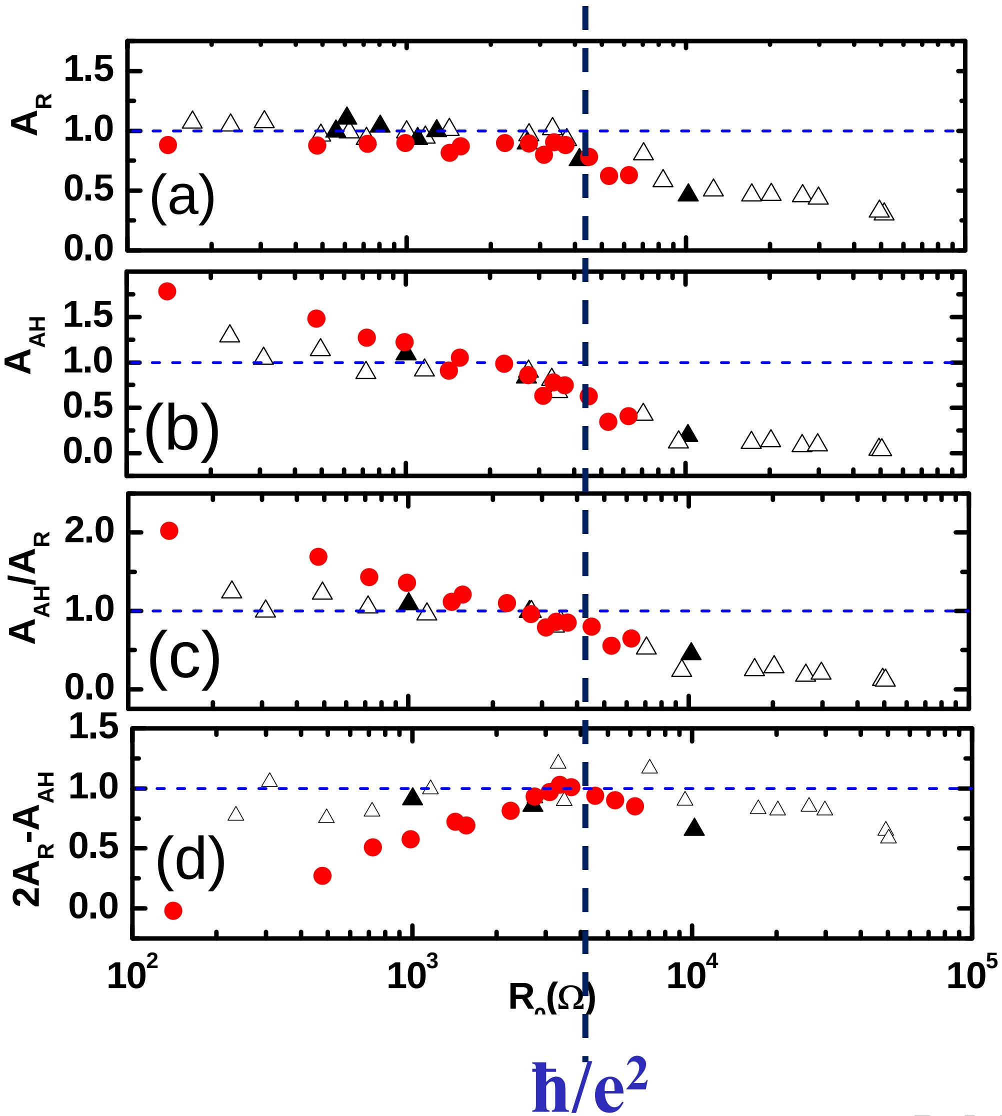
Our Result(T<20K)

$$\frac{\delta R_{xx}}{R_{xx}} = \frac{\delta R_{xy}}{R_{xy}} = -\frac{\delta L_{xy}}{L_{xy}}$$

Note the deviation at high T

Log(T): Relative resistance(RR) scaling !

A_R and A_{AH} for Fe films on glass (triangles) and sapphire (circles) substrates



$$\Delta^N \sigma_{xx}^{WL} = \ln(T/T_0)$$

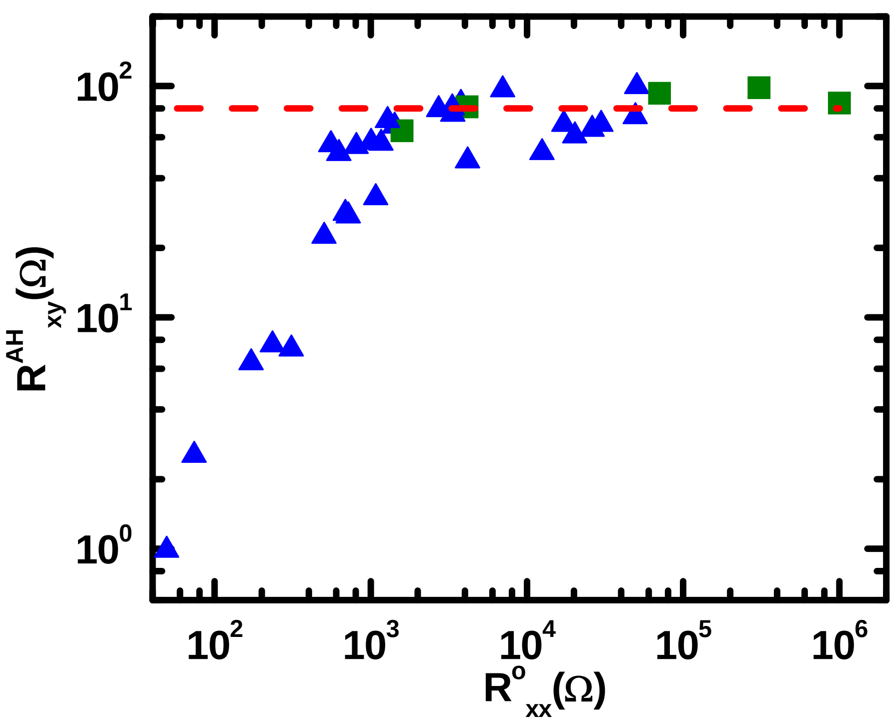
$$\Delta^N \sigma_{xy}^{WL} = \frac{\sigma_{xy}^{SSM} \ln(T/T_0)}{(\sigma_{xy}^{SSM} + \sigma_{xy}^{SJM})}$$

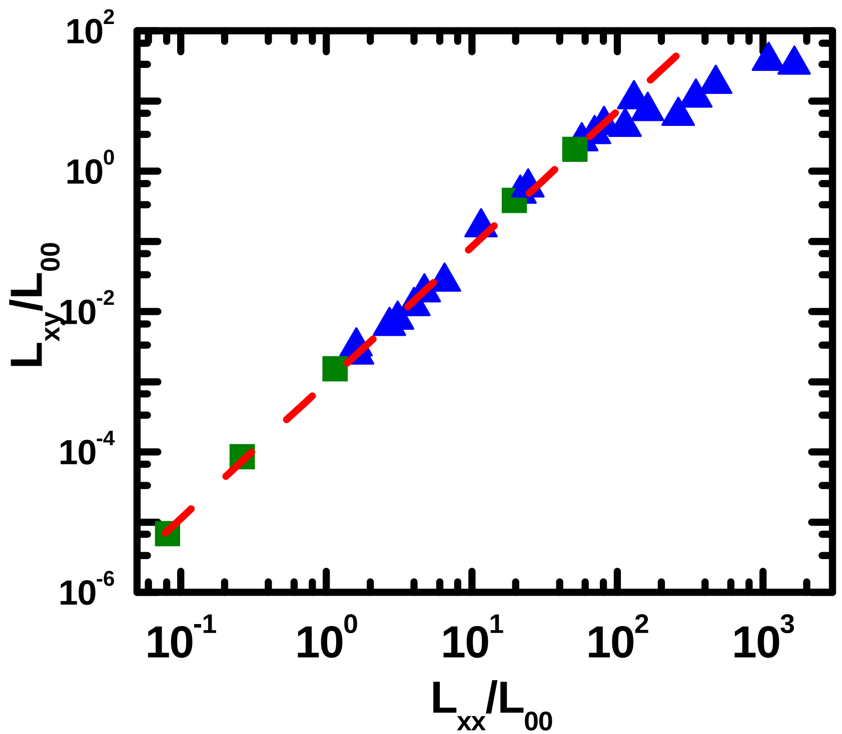
A weak localization correction within the skew scattering model is present in Fe films !

P. Mitra et al, PRL **99**, 046804 (2007)

The Anomalous Hall Insulator (AHI)

Anomalous Hall Insulator





$$L_{xx} \to 0, L_{xy} \to 0$$

$$L_{xy} \propto L_{xx}^2$$

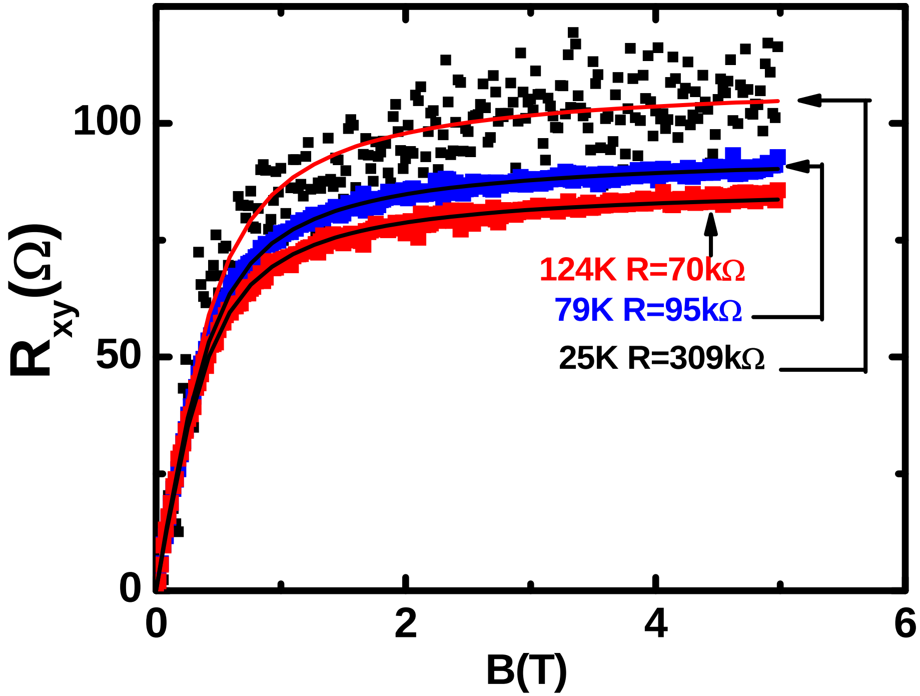
$$R_{xy} = \frac{L_{xy}}{L_{xx}^2} \approx 70\Omega$$

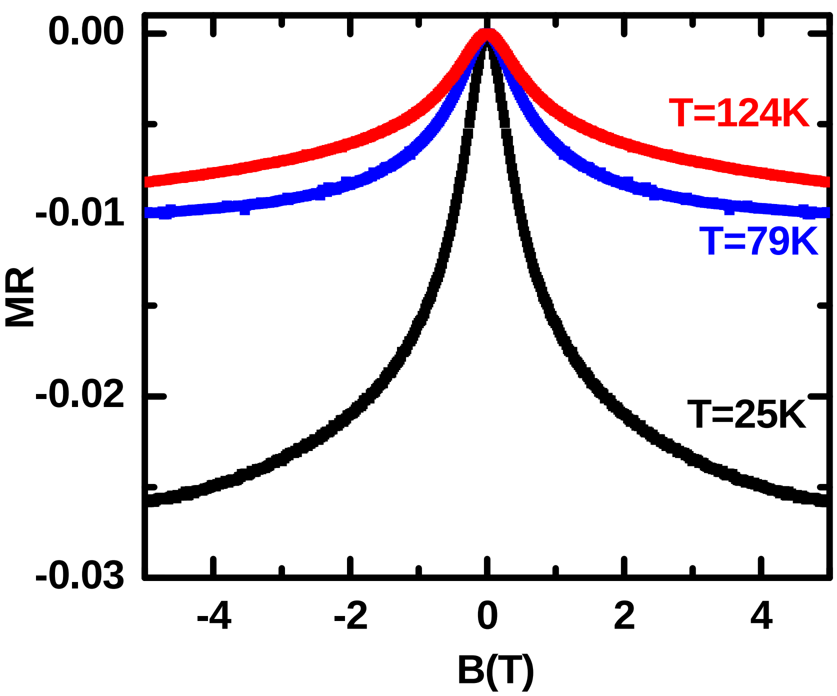
Blue points iron

Green points Fe/C_{60} samples

AH effect in Fe/C_{60}

$$R_{xy}^{AH}(T,B) = R_s(T)M(T,B) = R_{xy}^0(T)(\coth(P_1(T)B) - \frac{1}{P_1(T)B})$$

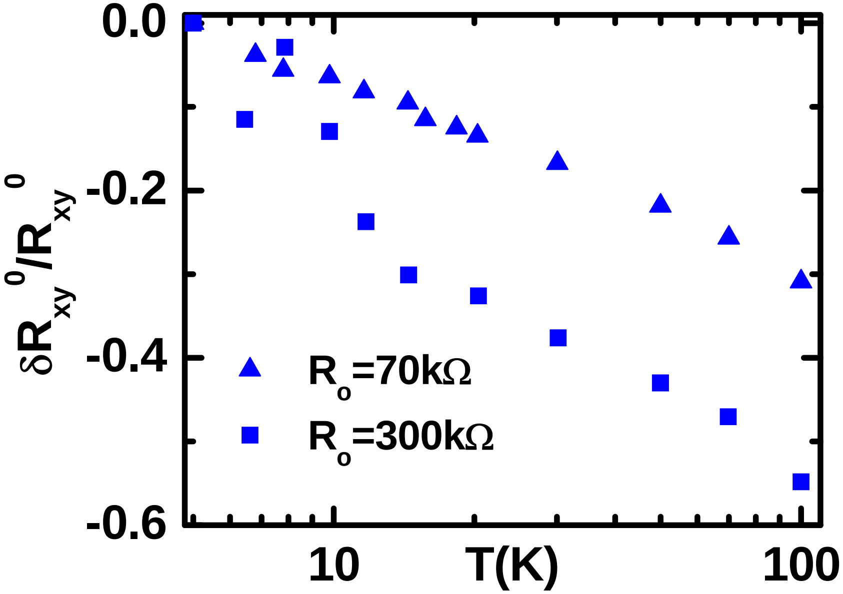




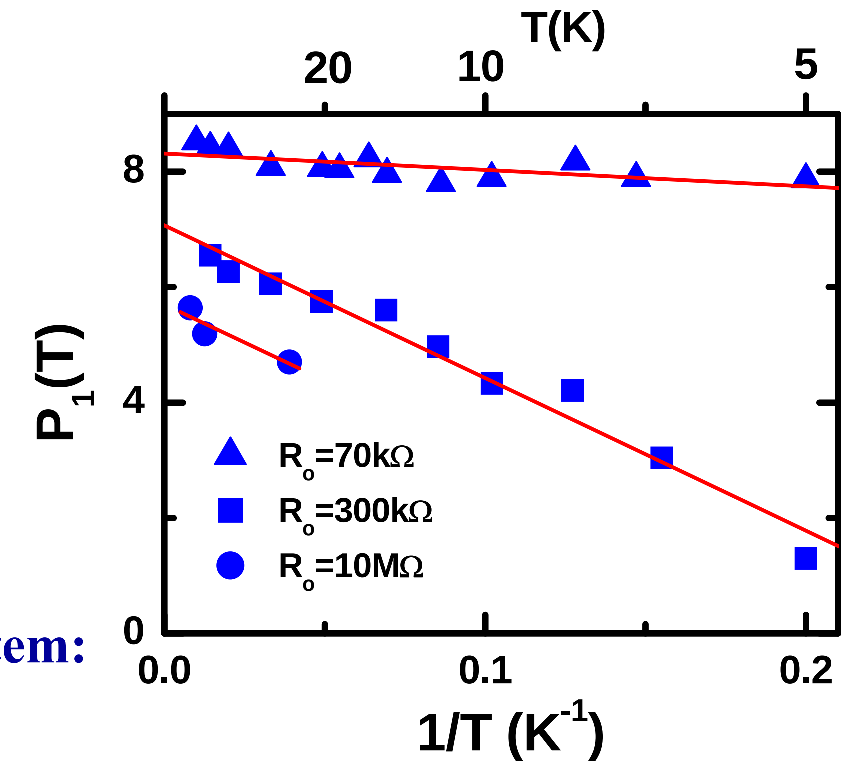
Indication of weakly coupled moments

Results of fits to Langevin function!

R_{xy} still logarithmic



$$R_{xy}^{AH}(T,B) = R_{xy}^{0}(T)(\coth(P_1(T)B) - \frac{1}{P_1(T)B})$$



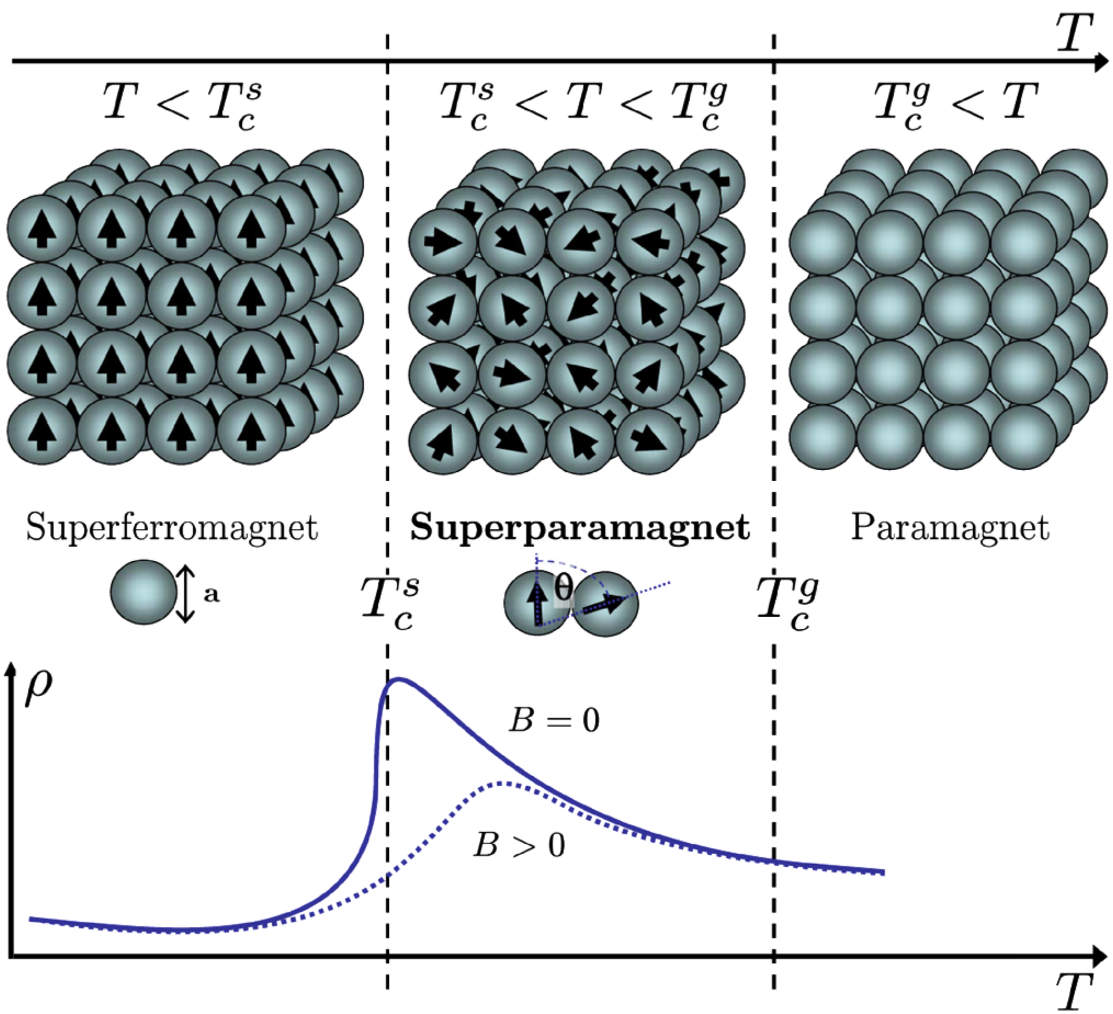
Magnetization in superparamagnetic system:

$M=M_S[\coth(\mu B/k_BT)-k_BT/\mu B]$

$P_1(T) = \mu/k_BT$

“Electron Transport in Nanogranular FMs”

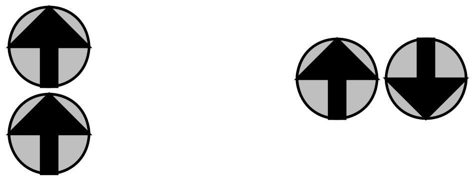
I. S. Beloborodov et al., PRL 99, 066602 (2007)



T_c^s = macroscopic Curie temperature

T_c^g = single grain Curie temperature

SFM state from dipole interactions

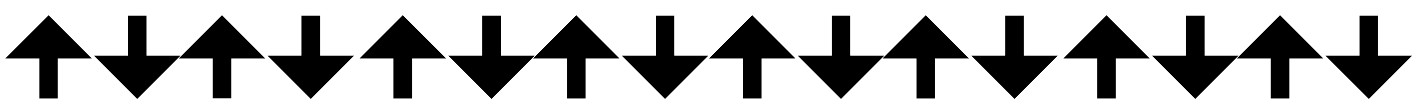


SAFM state in 2D?

Two particle dipole-dipole interaction*

$$T_g = \frac{\mu_0 M^2}{4\pi k_B d^3} \text{, where } M = M_s V$$

$$= 12 \text{ K for } d = 10 \text{ Angstrom}$$



*T. Jonsson et al., Phys. Rev Lett. 75, 4138 (1995)

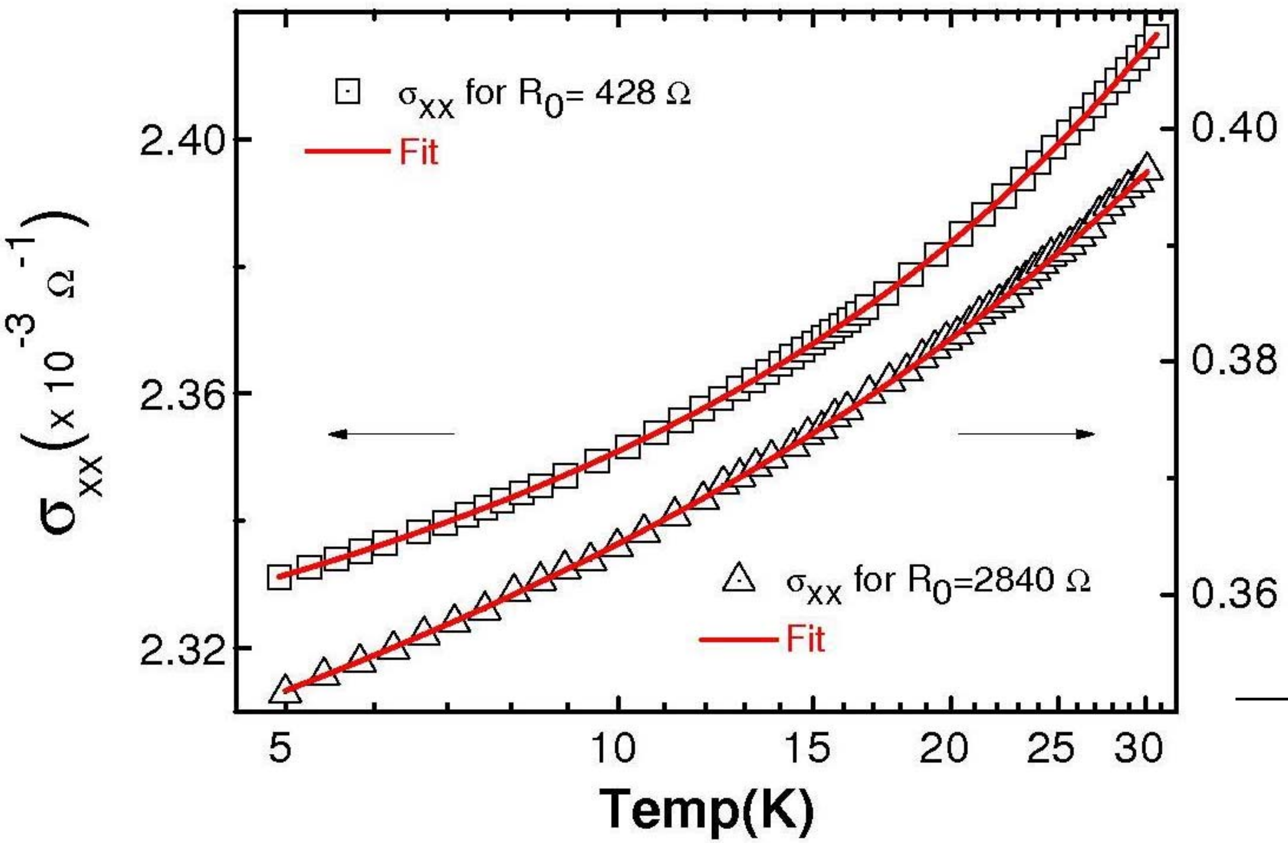
ACT (III)

Spin-wave mediated quantum corrections to the conductivity in thin ferromagnetic gadolinium films

Given the importance of spin waves in Fe films, one might expect to observe even larger effects in FM films such as Gd (a local moment system)which has larger and more strongly coupled magnetic moments.

Quantum corrections to Conductivity

Misra et al., Phys. Rev. B79, 140408(R) 2009

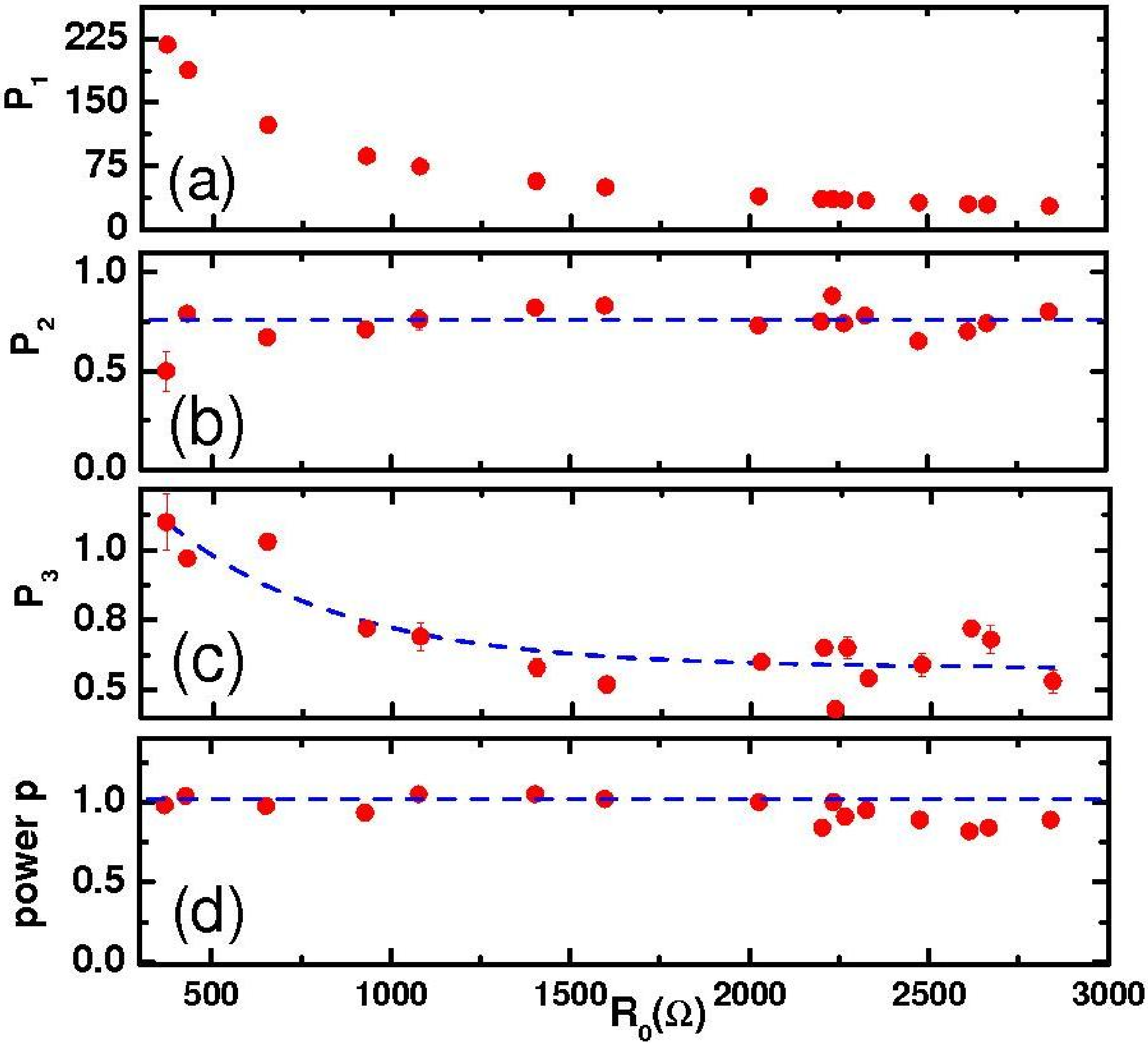


Note logarithmic and Linear Corrections to the conductivity!

Fitting function:

$$\frac{\sigma_{xx}}{L_{00}} = P_1 + P_2 \ln\left(\frac{T}{T_0}\right) + P_3\left(\frac{T}{T_0}\right)^P$$

Dependence of fitting parameters on disorder parameter R_0 of Gd films



16 films

Fitting Equation :

$$\frac{\sigma_{xx}}{L_{00}} = P_1 + P_2 \ln\left(\frac{T}{T_0}\right) + P_3\left(\frac{T}{T_0}\right)^P$$

A linear-in-T localizing quantum correction to the conductivity !

Spin wave mediated Altshuler-Aronov corrections to conductivity-

Effective spin wave mediated interaction:

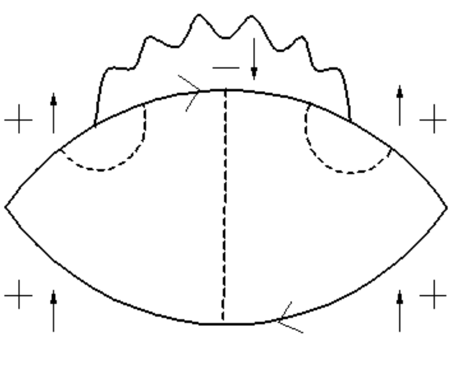
$$V_{SW}(q,\omega) = nJ^2 2\omega_q / (\omega^2 + \gamma\omega\omega_q + \omega_q^2); \qquad \omega_q = \Delta + Aq^2$$

n : 2D density of states J : spin exchange interaction

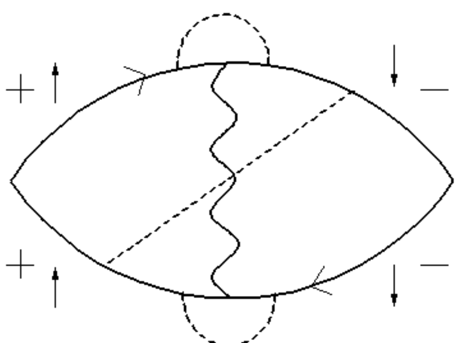
Δ : spin wave gap A : spin stiffness

γ : spin wave damping B : Exchange splitting

Spin wave mediated Altshuler-Aronov correction to conductivity:



(a)



(b)

$$\delta\sigma_{xx} \propto T$$

$$\text{for} \quad T << B$$

K. A. Muttalib & P. Wölfle

wavy line: sw interaction dashed line: diffusons

Spin wave mediated Altshuler-Aronov corrections to conductivity

The total spin wave contribution

$$\frac{\delta\sigma_{xx}}{L_{00}} \approx \left(\frac{Jk_F^2}{2\pi B}\right)^2 (\varepsilon_{\mathrm{F}}\tau)\frac{T}{Ak_F^2}$$

- The disorder dependence of the linear T contribution is given by $P_3 \propto \varepsilon_F \tau$, which decreases with increasing disorder.
- Experimentally, P_3 does indeed decrease with disorder up to $R_0 \approx 2000\Omega$ and then saturates.
- A localizing linear-in-T quantum correction to the conductivity.

*** Misra et al. Phys. Rev. B79, 140408(R) 2009**

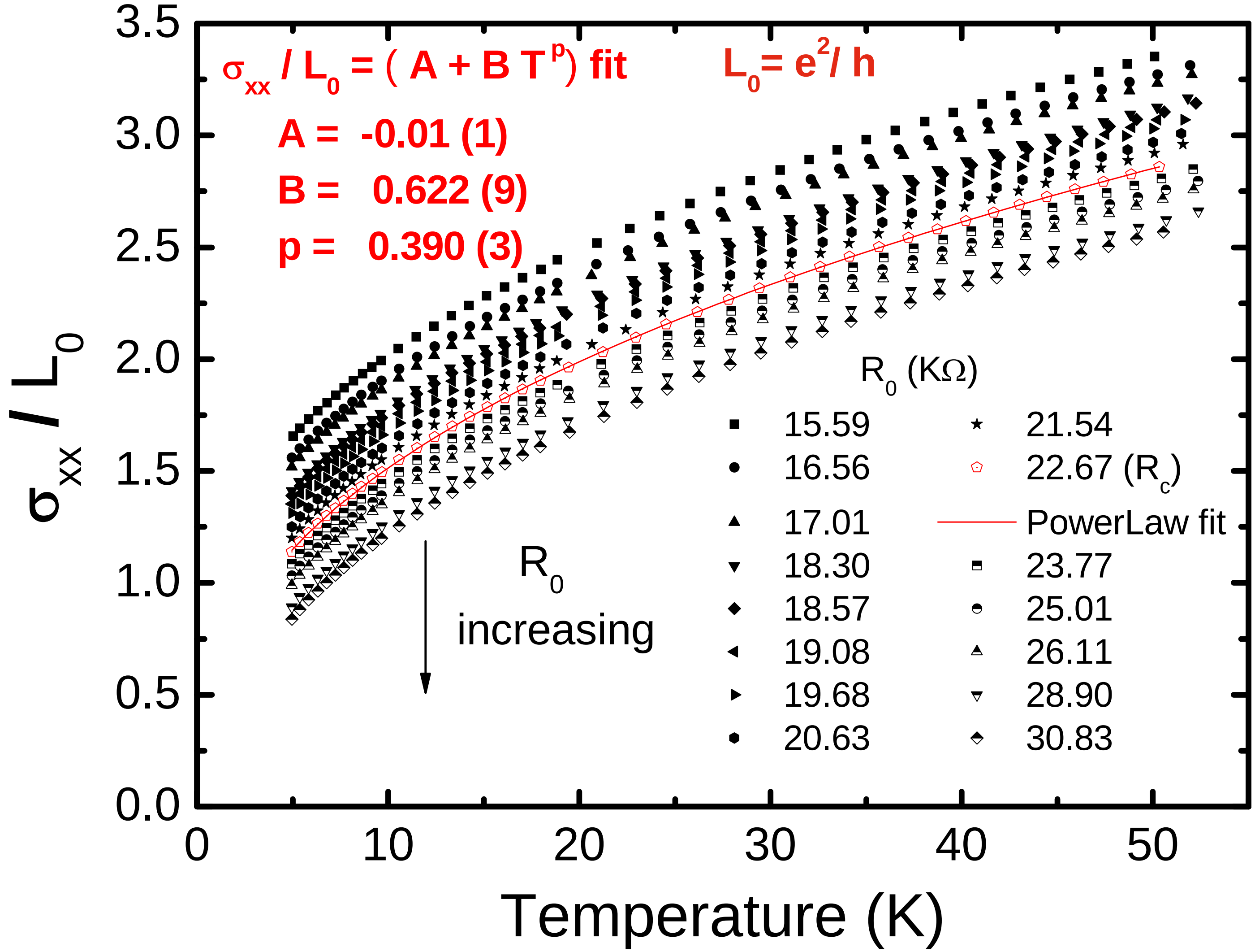
ACT (IV)

Finite temperature critical behavior near the Anderson quantum phase transition

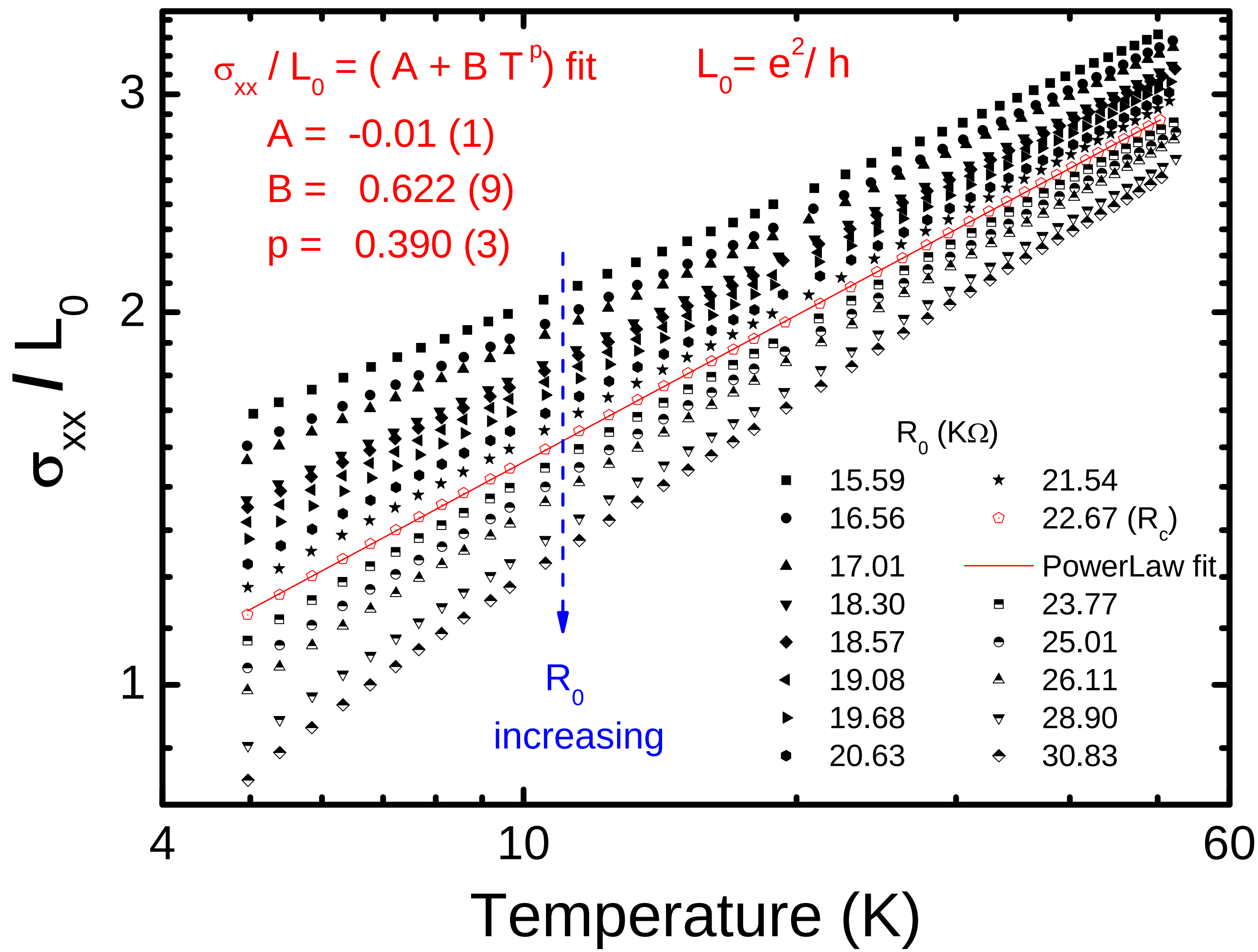
An oxymoron???

Beyond the region of quantum corrections

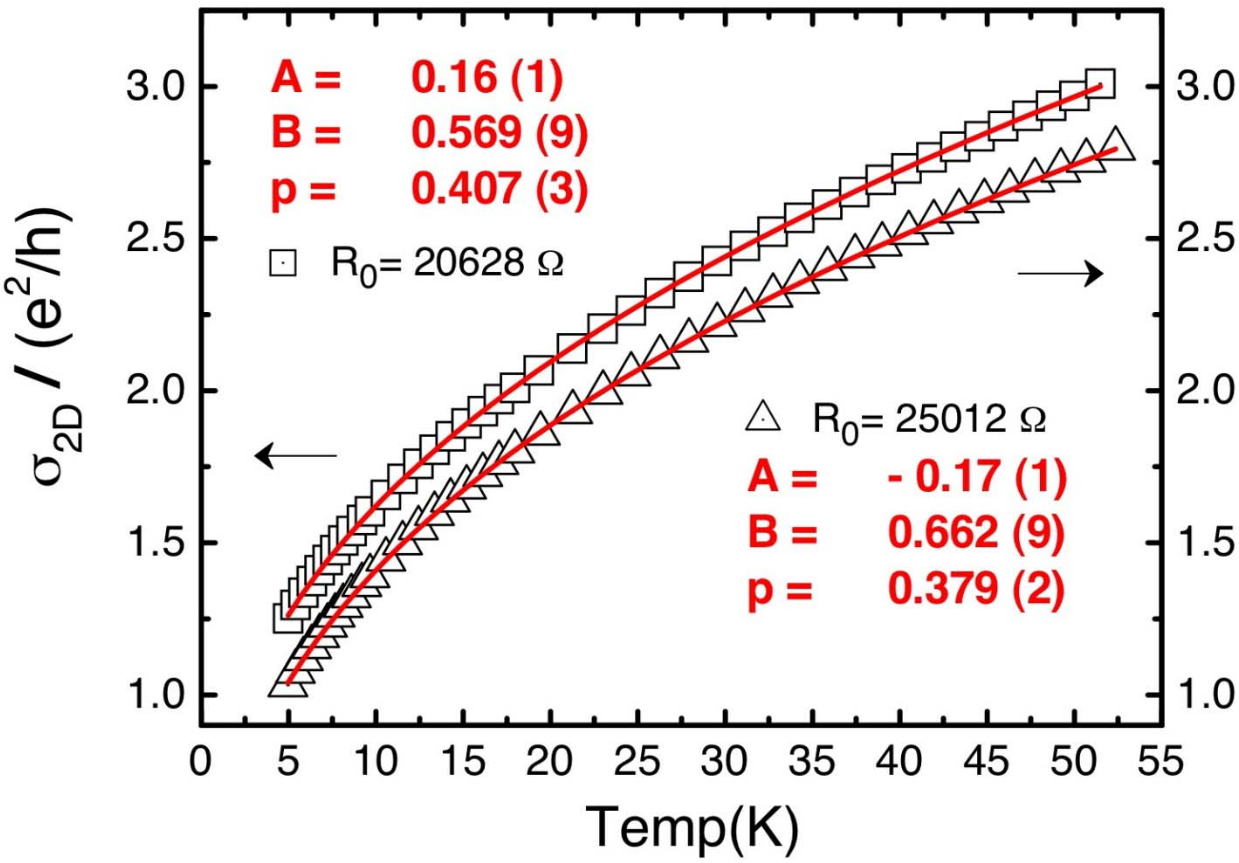
Single film annealed: 16 stages



Single film annealed: 16 stages



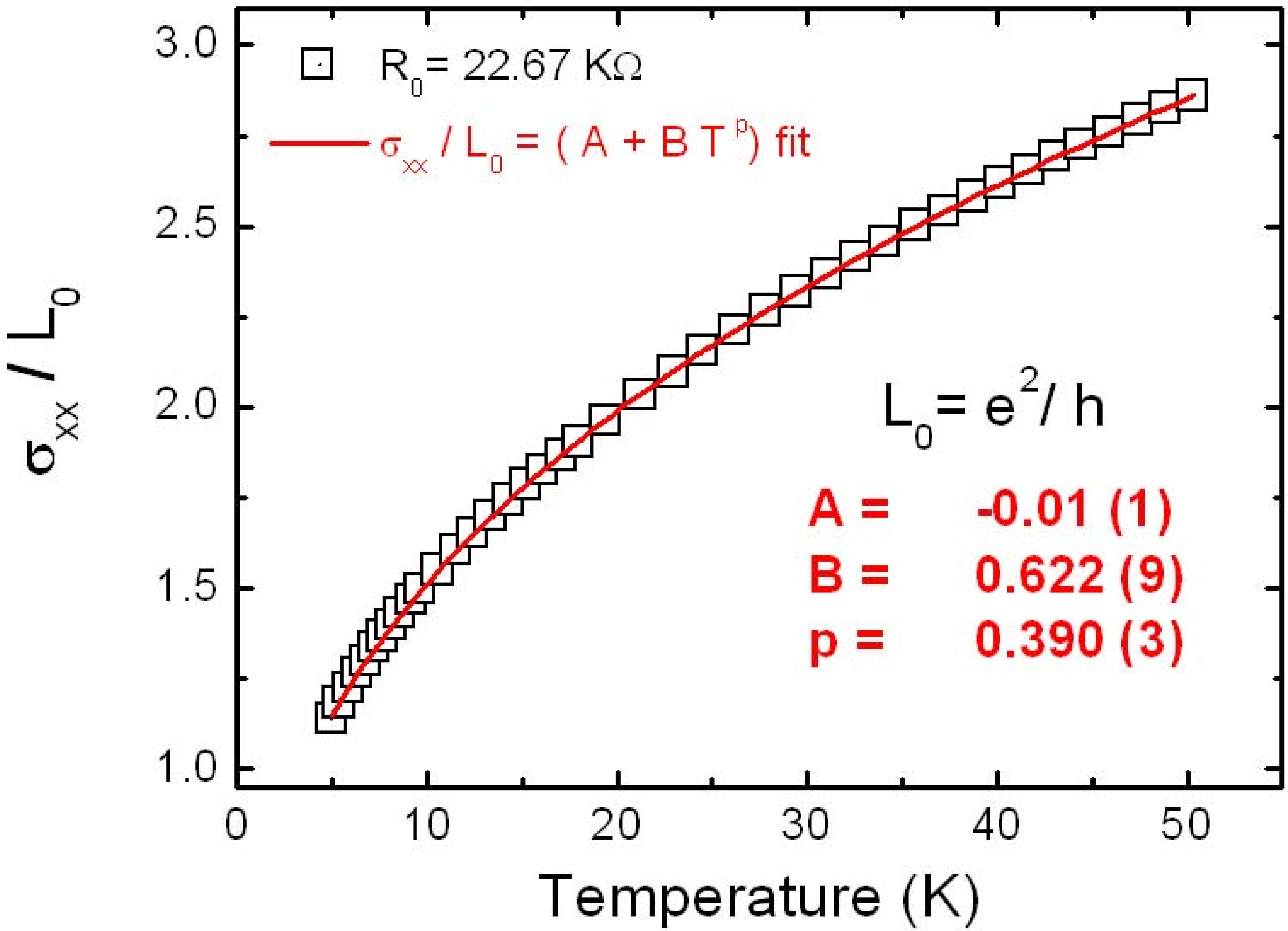
Two samples straddling critical disorder



Conductivity is not a quantum correction & can be modeled as:

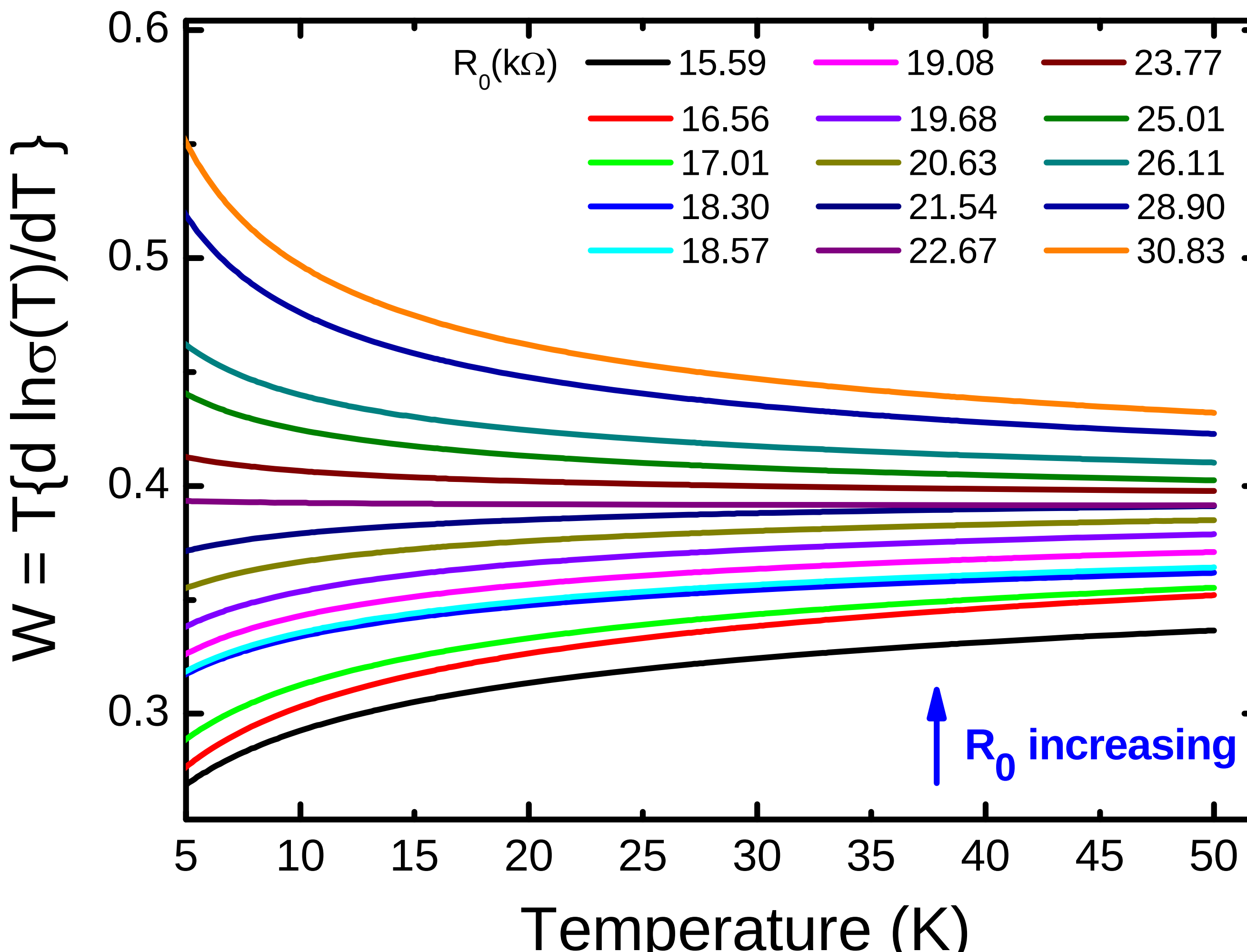
$$\frac{\sigma_{2D}}{(e^2/h)} = A + BT^p$$

Single sample closest to critical disorder (A = 0)



Remember p = 0.390 and $R_0 = R_c$ = 22.67 kΩ !

Single film annealed: 16 stages



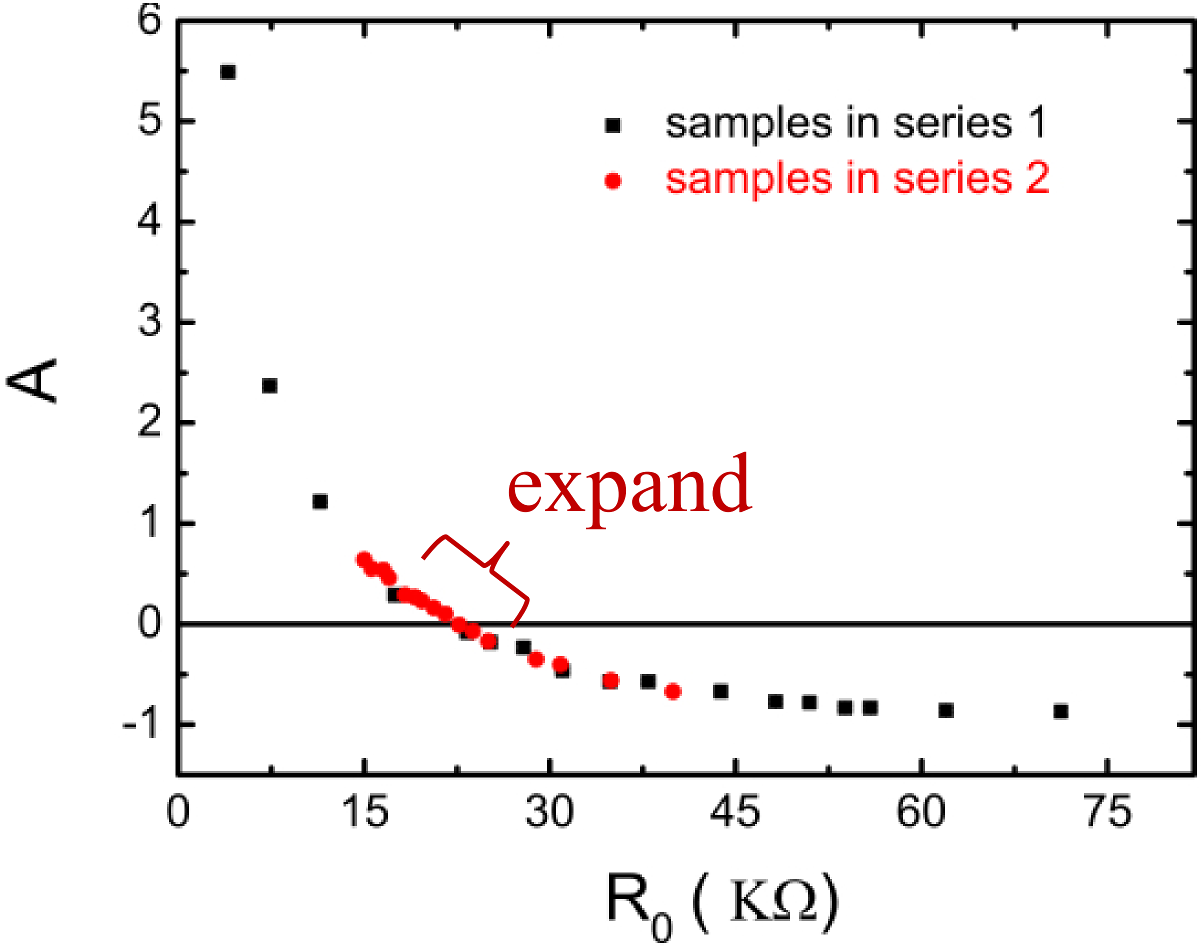
$w(T)$ plots

$$= \frac{d\ln(\sigma(T))}{d\ln(T)}$$

$$= \frac{d\ln(A + BT^p)}{d\ln T}$$

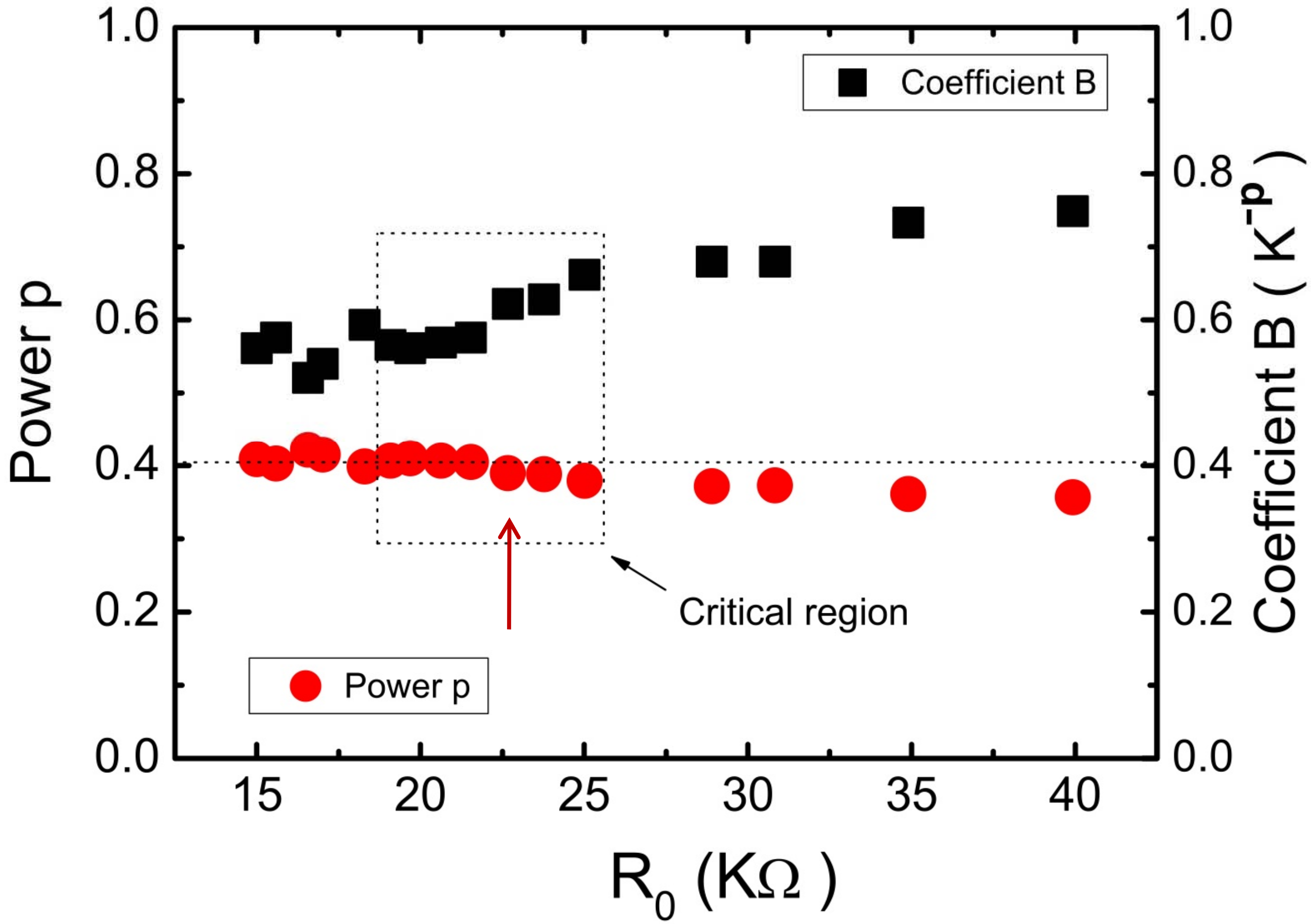
$$= \frac{pBT^p}{A + BT^p}$$

Parameter *A* as function of disorder



Series 1: 5 separate depositions with 2 samples undergoing 12 successive anneals.
Series 2: 1 sample undergoing 15 successive anneals.

Dependence of *p* & *B* on disorder



With $R_0\uparrow$**,** $p\downarrow$ **and** $B\uparrow$

$$\frac{\sigma_{2D}}{(e^2/h)} = A + BT^p$$

Primer on exponents: Finite T scaling of the Anderson QPT

$\sigma \sim (1-\lambda/\lambda_c)^s$ dc conductivity, σ(0), with exponent s

$\sigma(\omega;\lambda_c) \sim \omega^{1/z}$ dynamical conductivity, σ(ω), with exponent z

Replace frequency by $T \propto 1/\tau_\varphi$, the phase relaxation rate

$\xi' \sim |1-\lambda/\lambda_c|^{-\nu'}$ Correlation length (metal, $\lambda < \lambda_c$, $R_0 < R_c$)

$\xi \sim |1-\lambda/\lambda_c|^{-\nu}$ Localization length (insulator, $\lambda > \lambda_c$, $R_0 > R_c$)

Exponents ν and ν′ are not necessarily equal to each other !!!

In 3D, $\sigma \sim 1/\xi'$ & $s = \nu'$ (=1.6 by numerical calculations*) and $z = 3$

* K. Slevin and T. Ohtsuki, PRL 82, 382 (1999)

Finite temperature scaling description of the transition

σ near the transition given by the scaling form

$$\sigma(\omega;\lambda) = \xi^{-1} G(\pm 1, \xi\omega^{1/z}), \qquad t > 0, t < 0$$

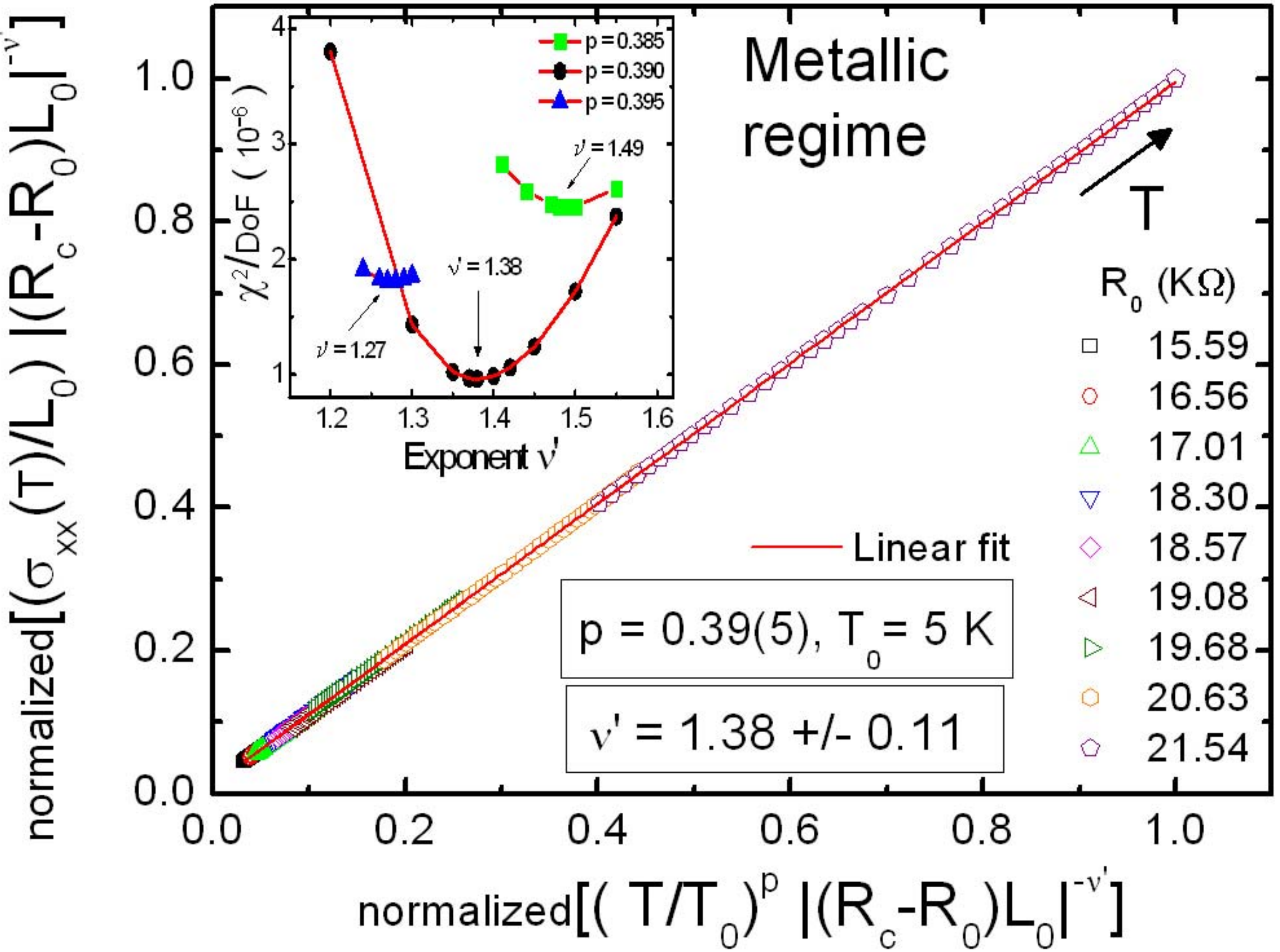
$$\sigma(\omega) \propto \omega^{1/z} \propto T^{1/z} \text{ at critical point}$$

where $\xi \propto |R_0 - R_c|^{-\nu'} \to \infty$

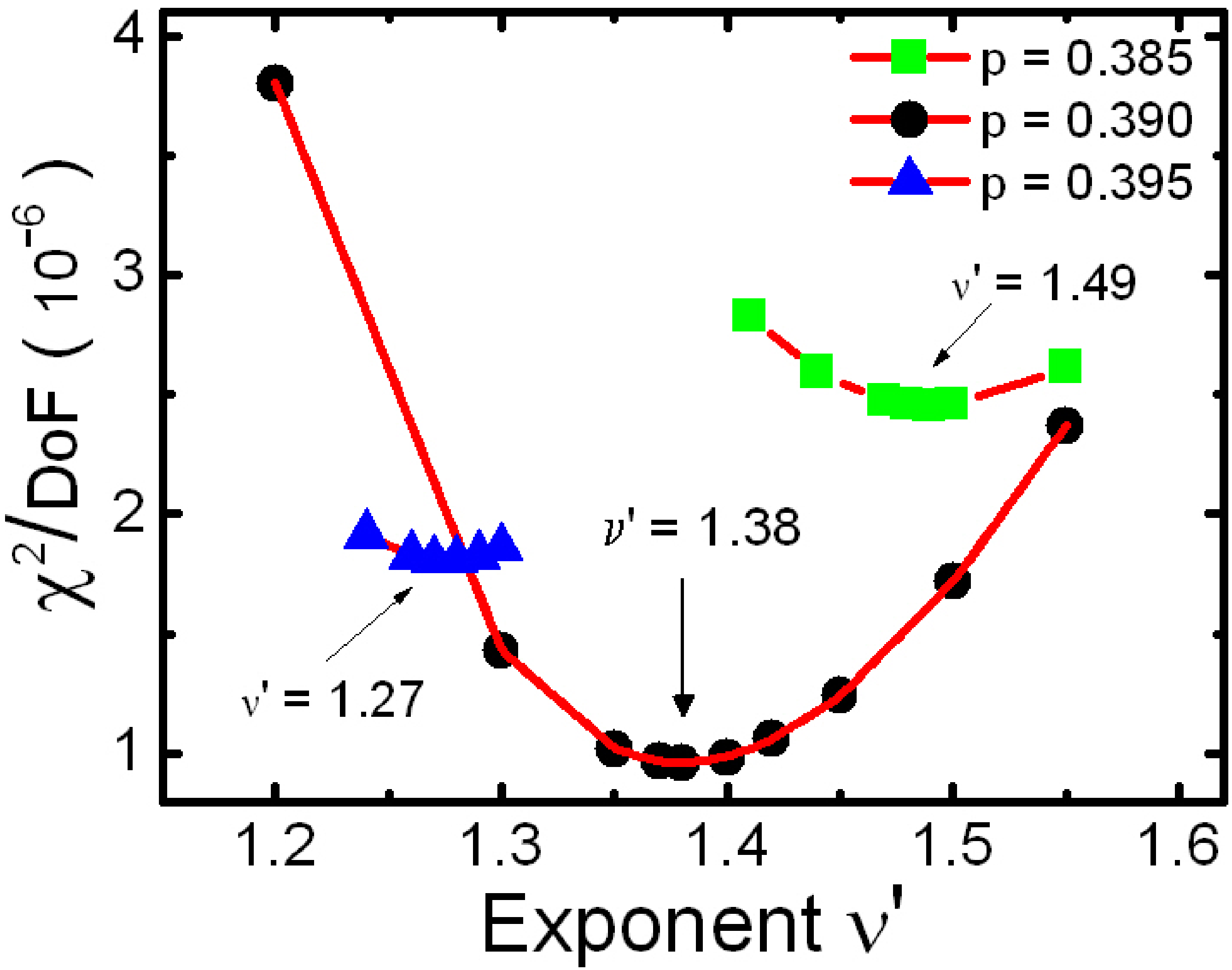
⇓

$$|R_0 - R_c|^{-\nu'} \sigma(T;R_0) = G(\pm 1, |R_0 - R_c|^{-\nu'} T^{1/z})$$

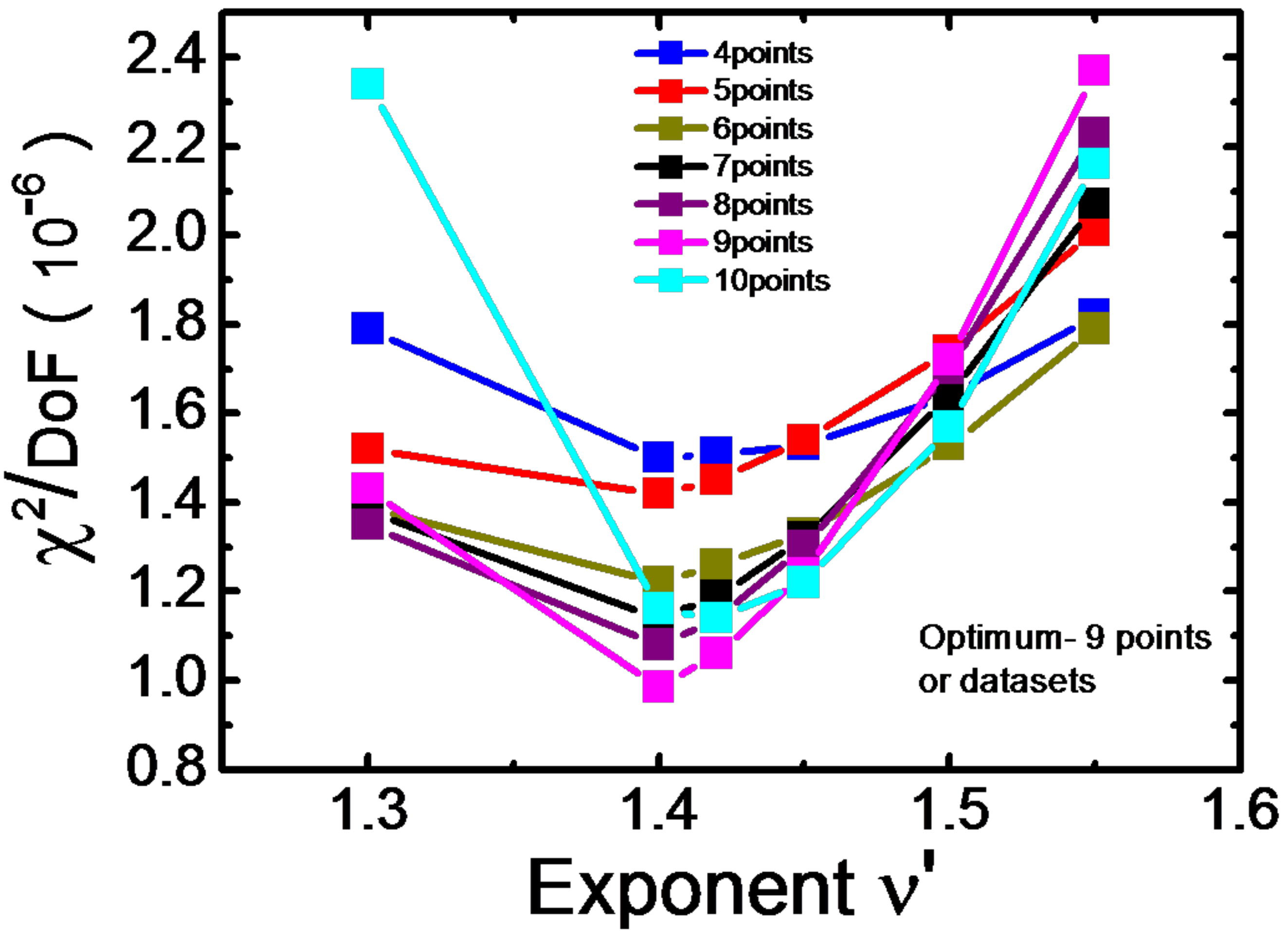
Scaling collapse for indicated values of R_0 (metallic side, recall R_c=22.67 kΩ)



Sensitivity of ν' to power *p* at criticality (metal)

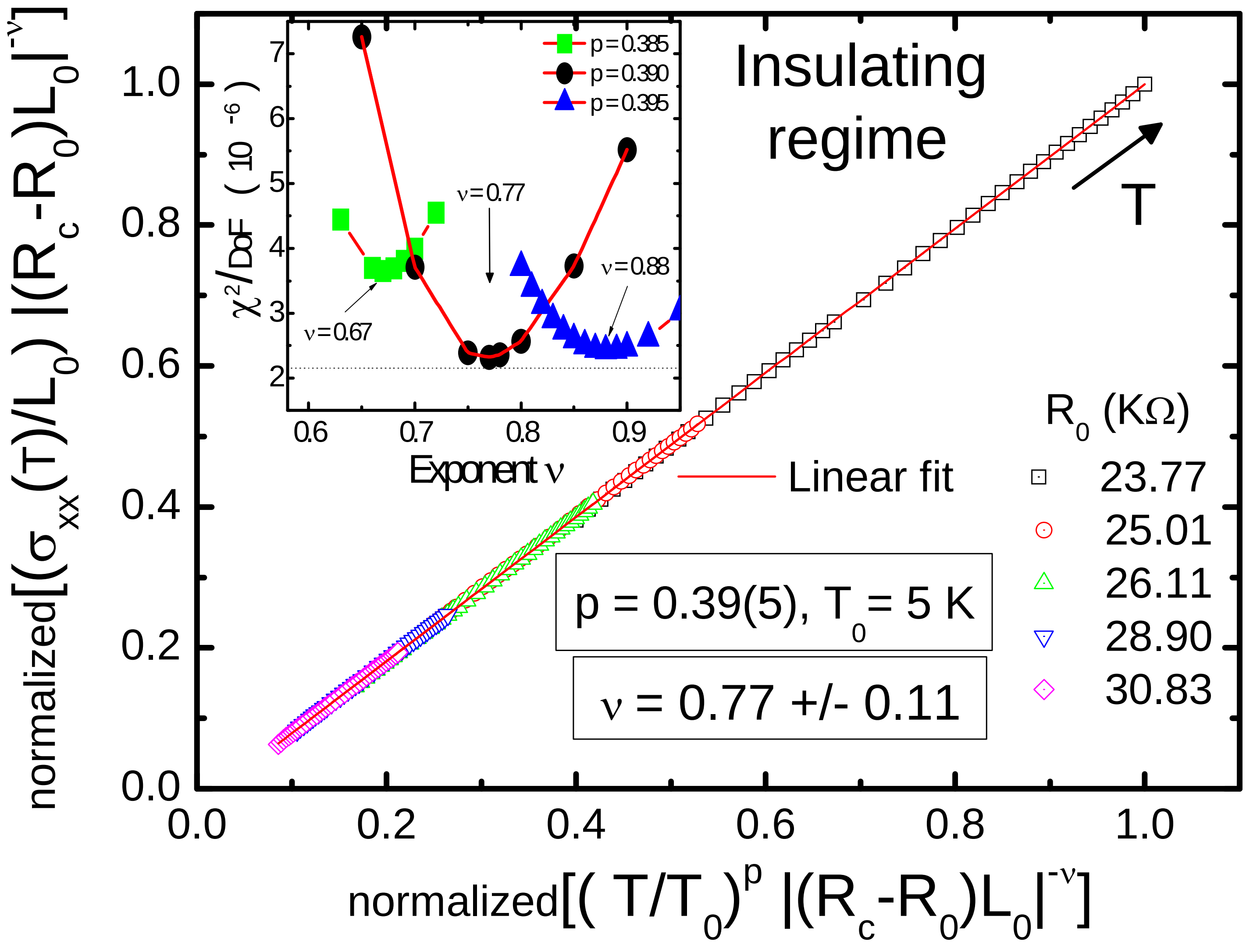


Dependence of χ2 minima on # data sets (metallic side)

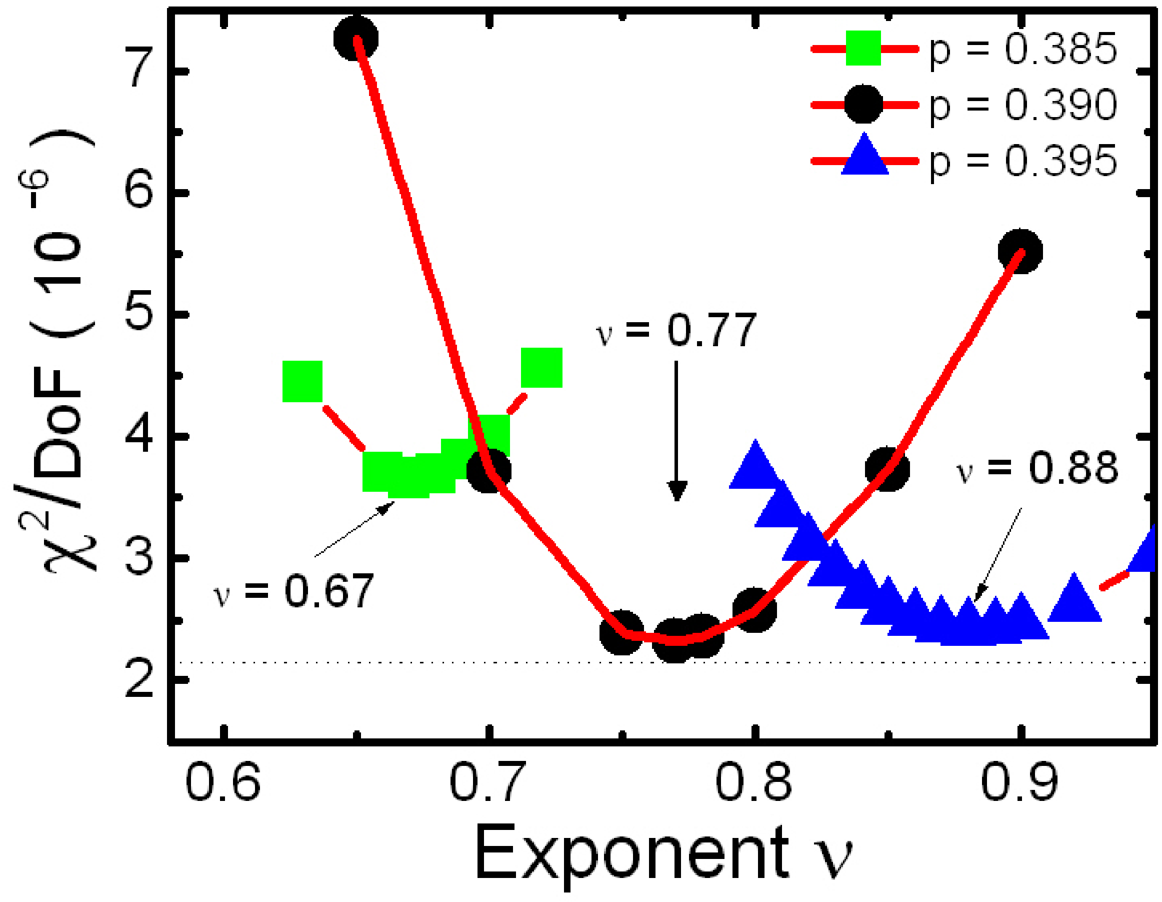


Optimum: include nine data sets on metallic side !

Scaling collapse for indicated values of R_0 (insulating side, recall R_c=22.67 kΩ)

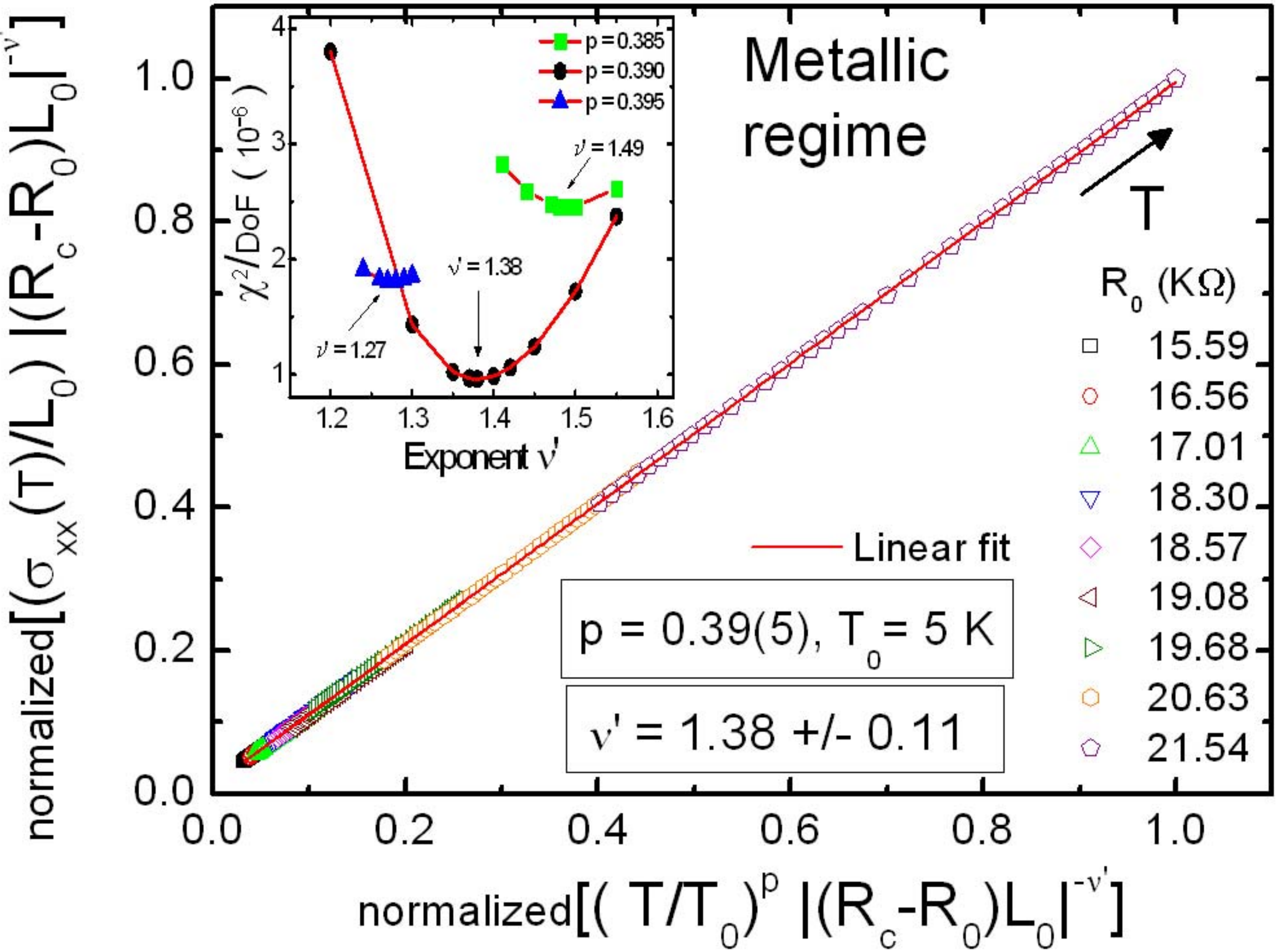


Sensitivity of ν to power p at criticality (insulator)

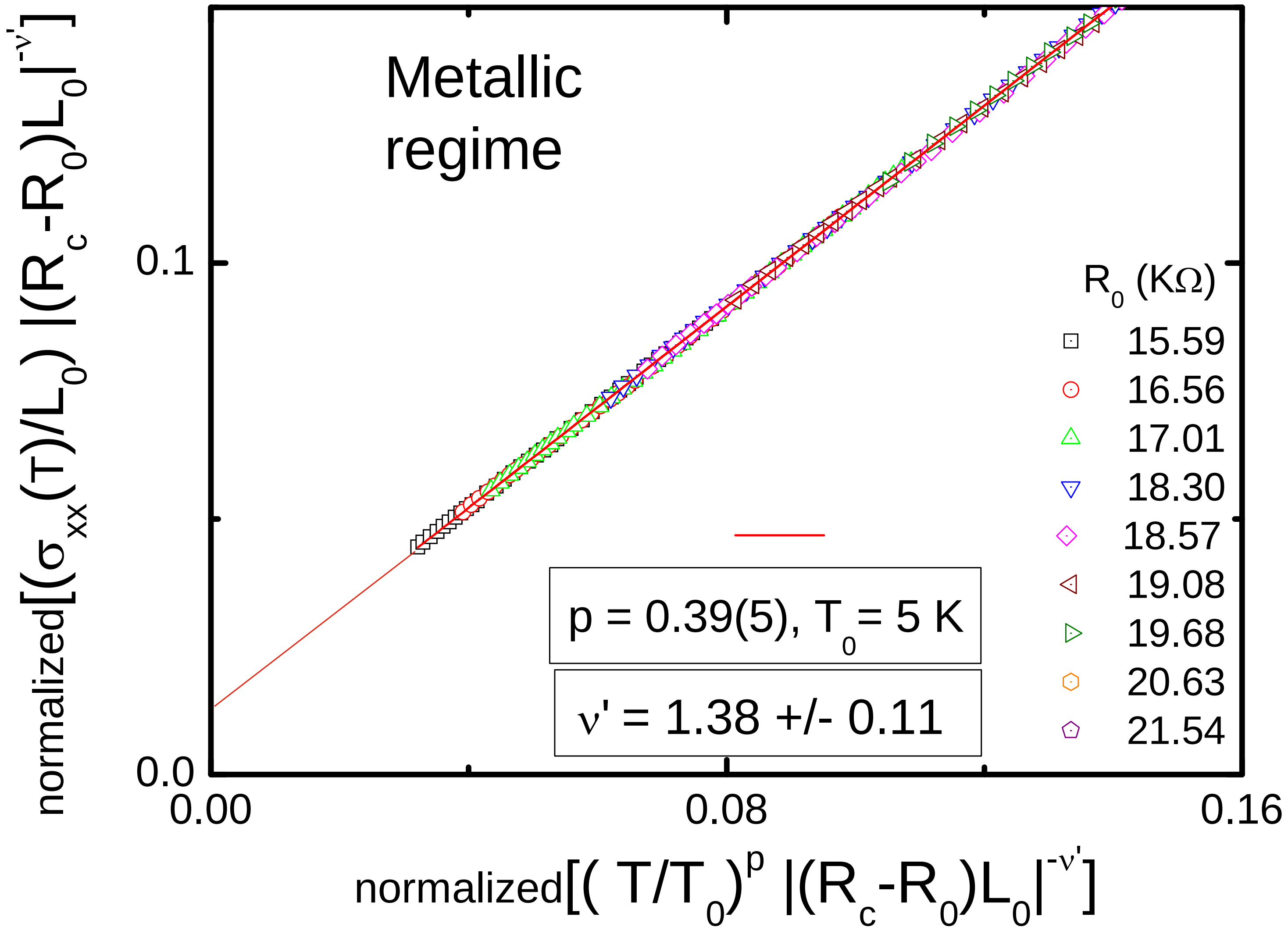


Substitute $\nu = \nu' = 1.38$ and χ^2 increases by 10×!

Scaling collapse for indicated values of R_0 (metallic side, recall R_c=22.67 kΩ)



Extrapolation to a non-zero intercept



Reconciliation with w(T) plots

Recall our "first impression" with varying parameters

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

Linear scaling collapse tells us however that for the fixed coefficients B and $p = 1/z$ at criticality

$$\sigma(T;R_0)/L_0 = BT^{1/z} + a\left|R_0 - R_c\right|^{\nu'}$$

where a is the intercept of the collapsed data plot

dc conductivity exponent: $s = \nu' = 1.38$

Experiment is interpreted using finite *T* theory; *T*=0 extrapolations not needed!

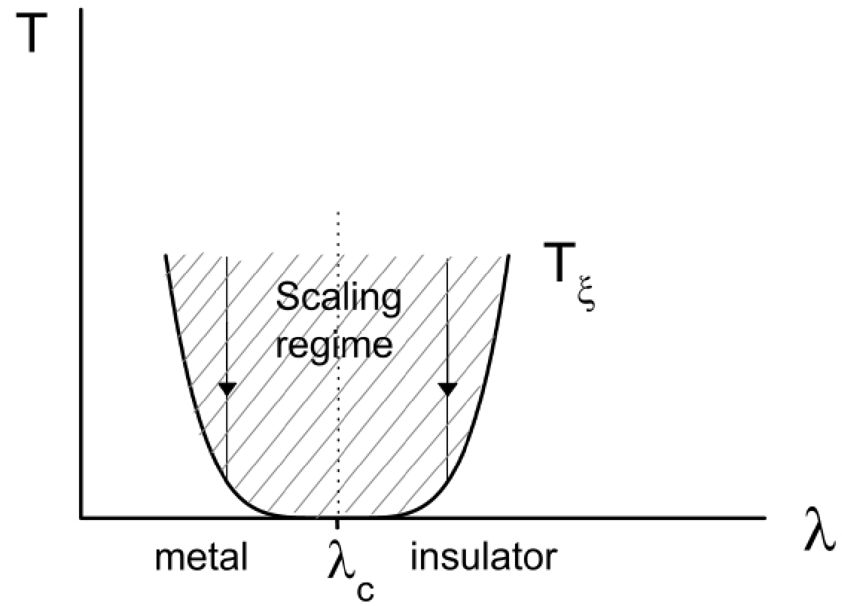
At finite T in the scaling regime,

$$\omega > \omega_\xi = \frac{1}{\tau}\left(\xi / \ell\right)^{-3} \quad \text{or} \quad T > T_\xi$$

the d.c. conductivity is obtained from the dynamical conductivity, with leading dynamical scaling behavior

$$\sigma(\omega) \propto \omega^{1/3}$$

by replacing frequency by the phase relaxation rate $1/\tau_\varphi$



The effective dimension is THREE, provided the temperature dependent correlation length

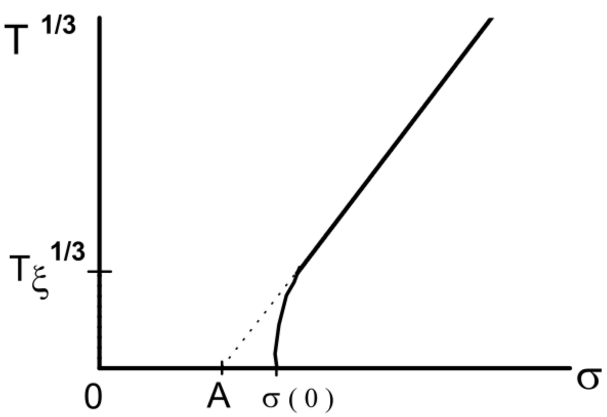
$L_\varphi < b$, (b is the thickness of the film)

Understanding the meaning of parameter *A*

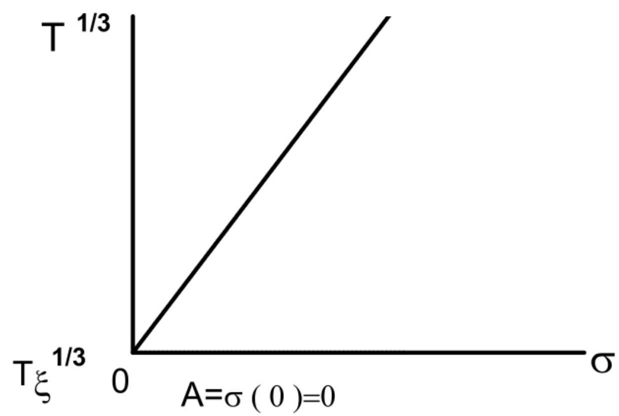
The inequality $L_\varphi < b$ is satisfied for temperatures

$$T > T_x = \left[B(bk_F)^{-3}(\varepsilon_F \tau_\varphi)/\hbar \right]^{\frac{1}{1-p}}. \qquad T_x \approx 1.2\ K$$

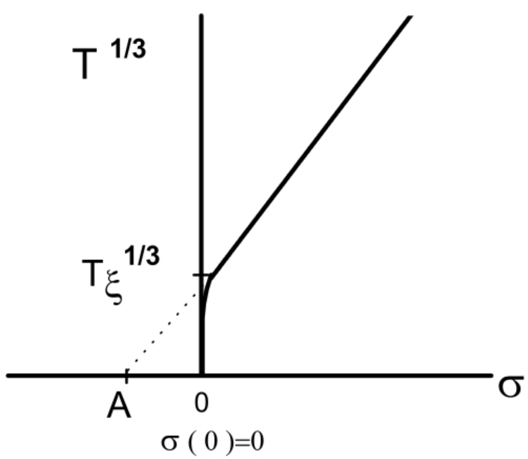
Frequency is cut off by phase relaxation rate: $\omega \to \frac{1}{\tau_\varphi} \propto T$



Metal

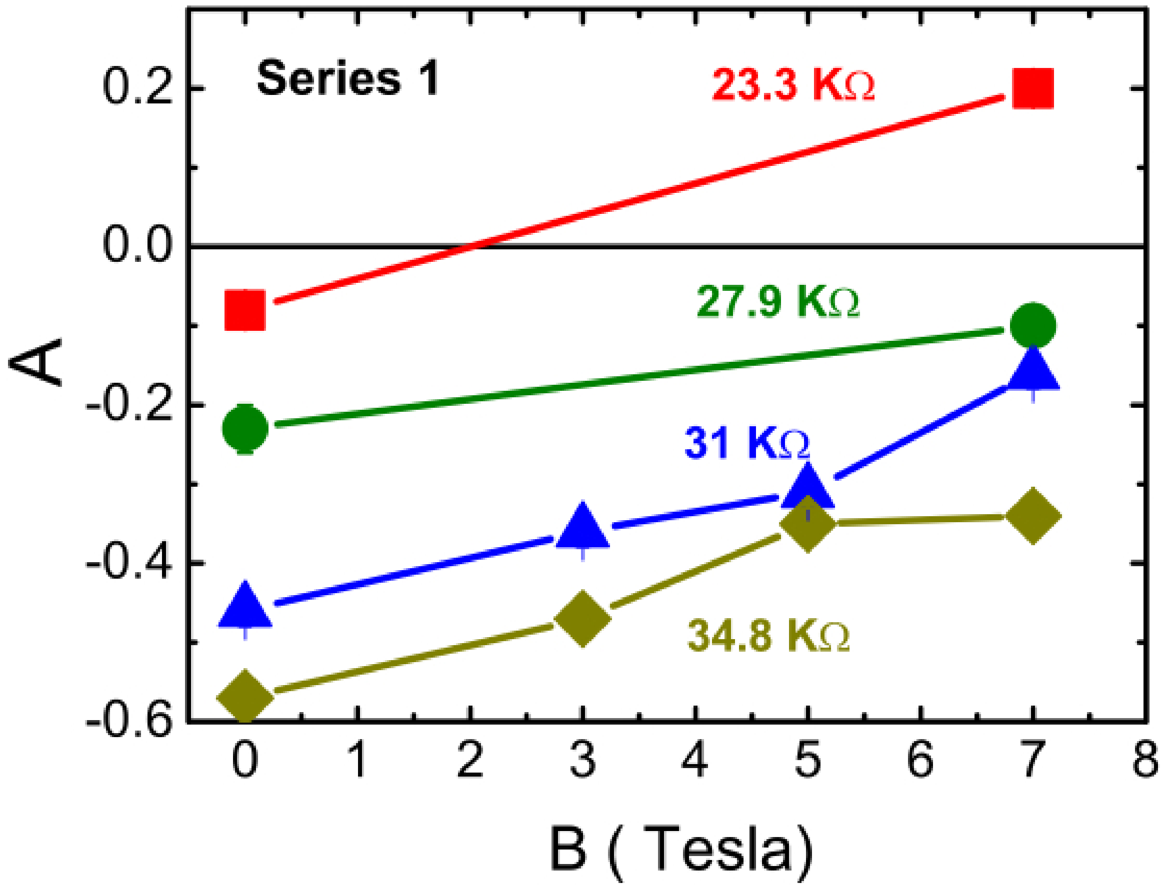


Critical point



Insulator

Field tuned insulator-to-metal transition



$$\frac{\sigma_{2D}}{(e^2/h)} = A + BT^p$$

Magnetic fields tend to destroy the constructive interferences of backscattered electrons that are responsible for localization!

Motivating Questions/(Answers)

1. Band ferromagnetism (FM) relies on itinerant electrons. When itinerancy is compromised by disorder, what happens? (FM is quite robust!)
2. Any signatures at $\hbar/e^2 = 4100\ \Omega$? (See only gradual crossovers.)
3. Is there a ferromagnetic-insulator transition? (Yes, asymmetric exponents, charge becomes localized but spin waves exist on both sides.)
4. Ferromagnetic behavior and film morphology? ($\sigma_{xy}^{SJM}/\sigma_{xy}^{SSM}$ is small (large) on glass (sapphire) substrates; granularity important for AHI.)

Closing Comments

"If you look around, you can see a lot"

Y. Berra

"No experimental result should be accepted until confirmed by theory"

Eddington