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SMR 1232 - 40

XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

17 - 28 July 2000

TRANSPORT IN THE 2D PEROVSKITES

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Transport in the 2D Perovskites

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Theme: C-axis magnetotransport as a spectroscopy of in-plane physics

- Open questions
- What new experiments could be done soon

Collaborators

J.R. Cooper, (J.M. Wheatley)
A.J. Millis, K.G. Sandeman

Outline

- Perovskites: testing and refining theory
- C-axis magnetotransport
- Ruthenates and the linear MR
- Other avenues

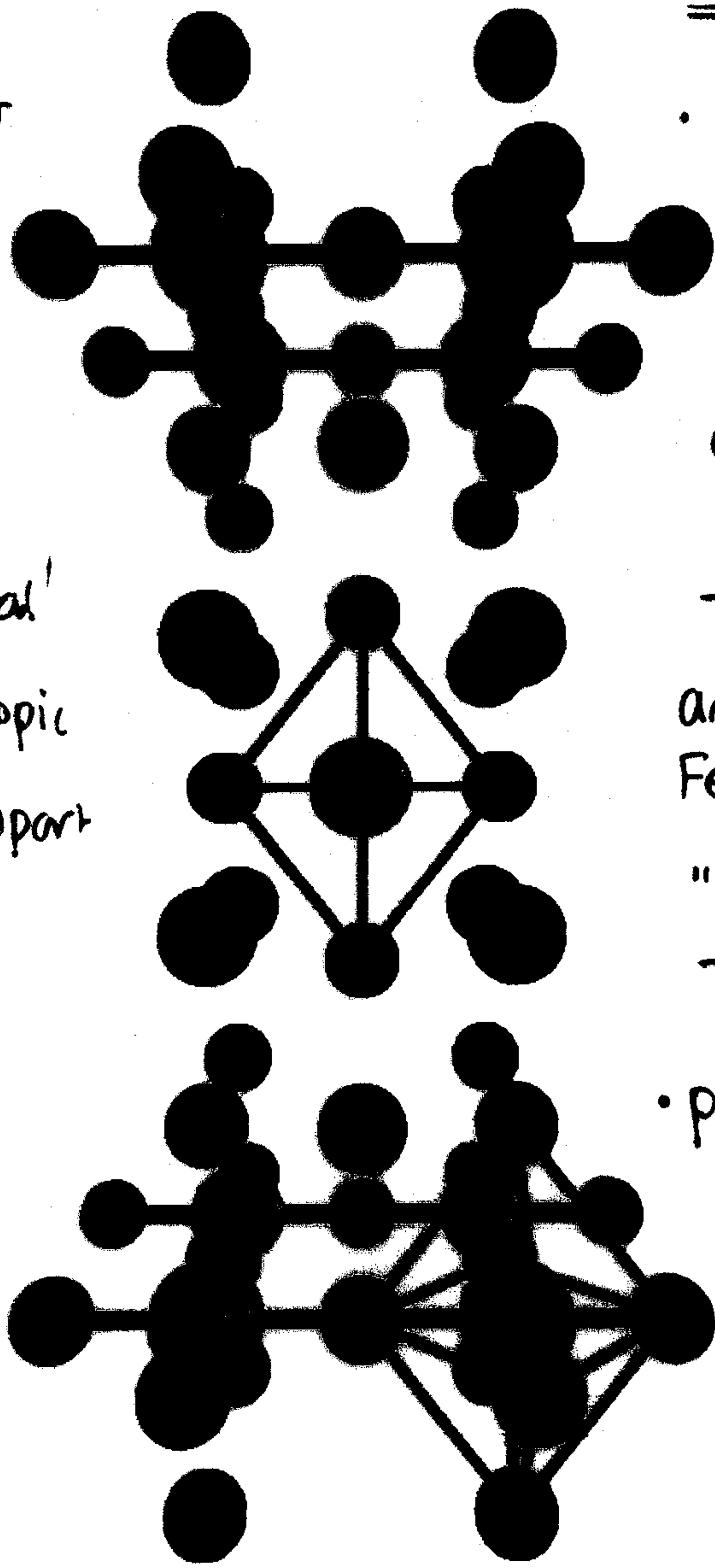
La_2CuO_4

- AFM insulator
- Dope
  $La^{2+} \rightarrow Sr^{3+}$

$\Rightarrow$ 'strange metal'

- highly anisotropic
- in-plane transport properties unusual
- d-wave s/c

?



Sr_2RuO_4

- metal
- no doping required

T < 10 K
anisotropic Fermi liquid

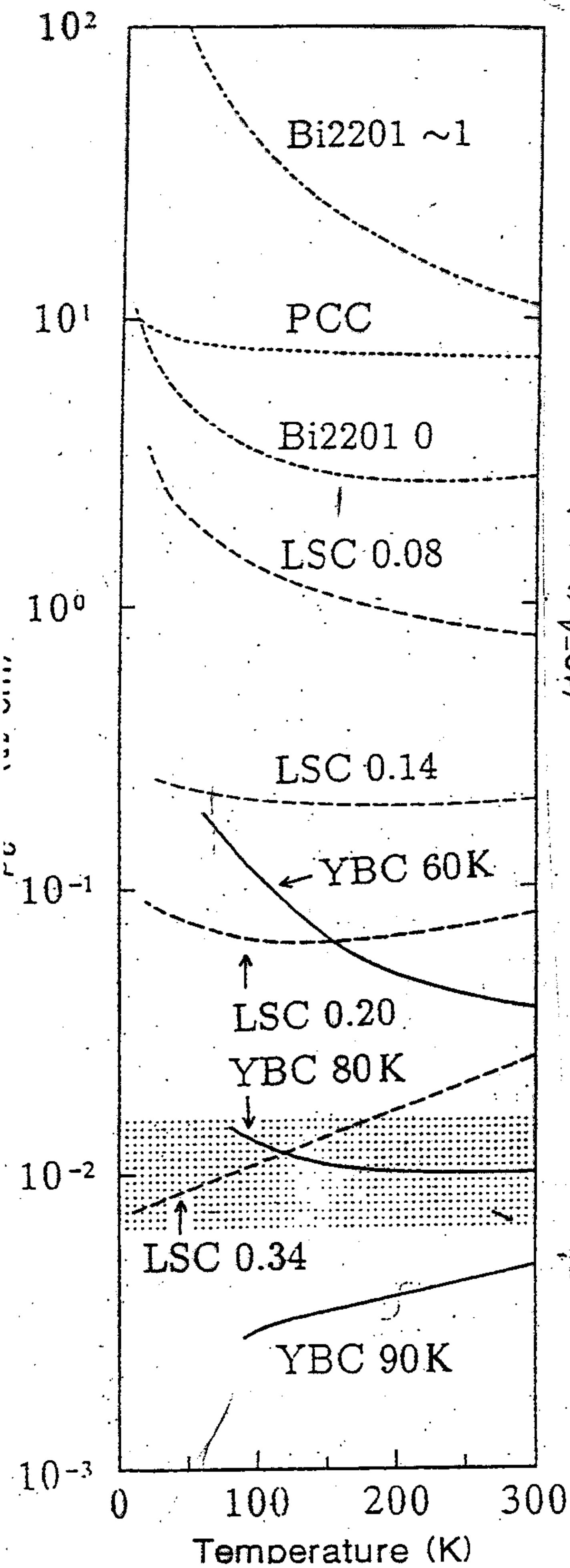
"bad metal"
T > 400 K

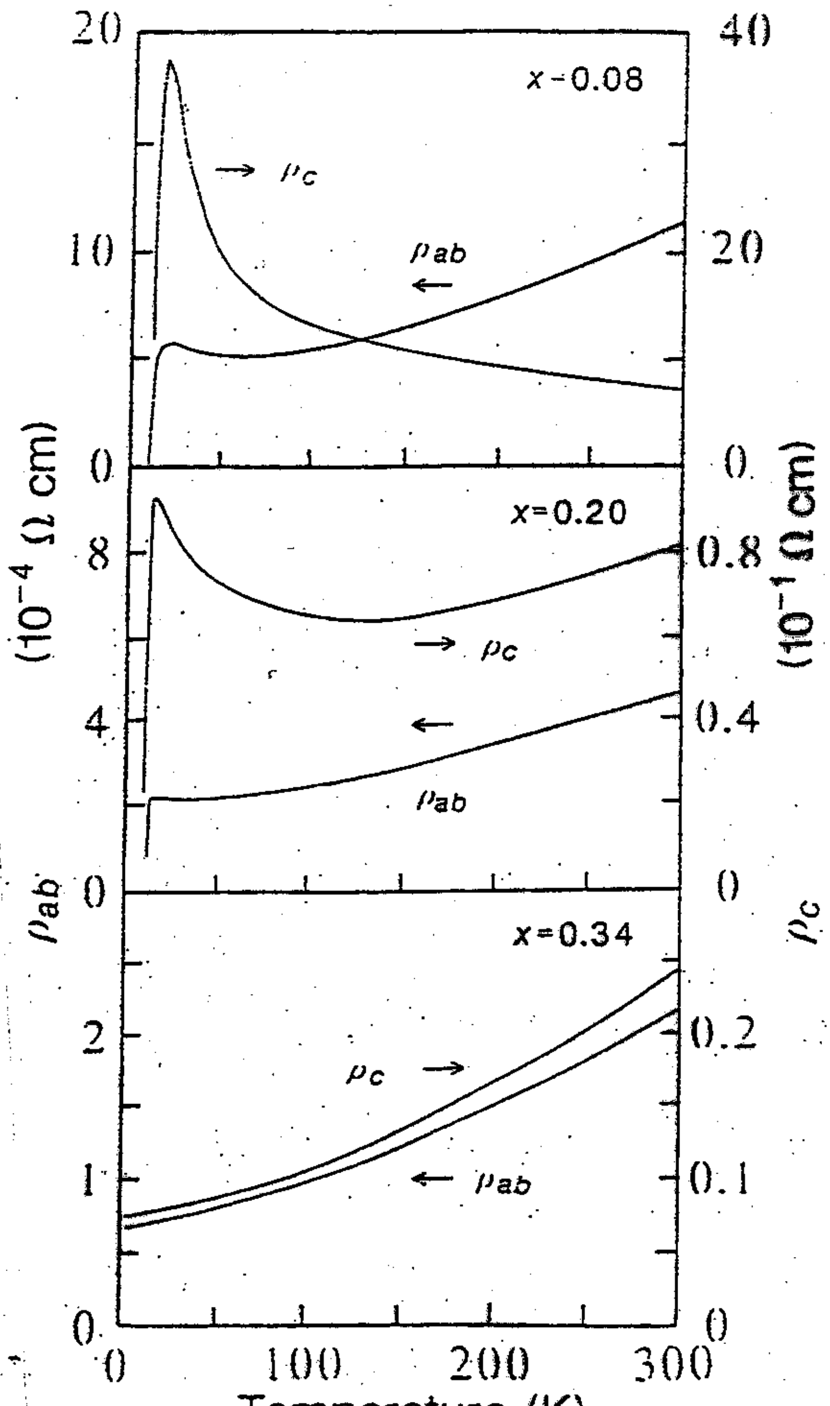
- p-wave s/c

Can we use other perovskites to test/refine our understanding of HiTc cuprates ?

• There are a growing number of highly anisotropic materials

e.g. HiTc cuprates

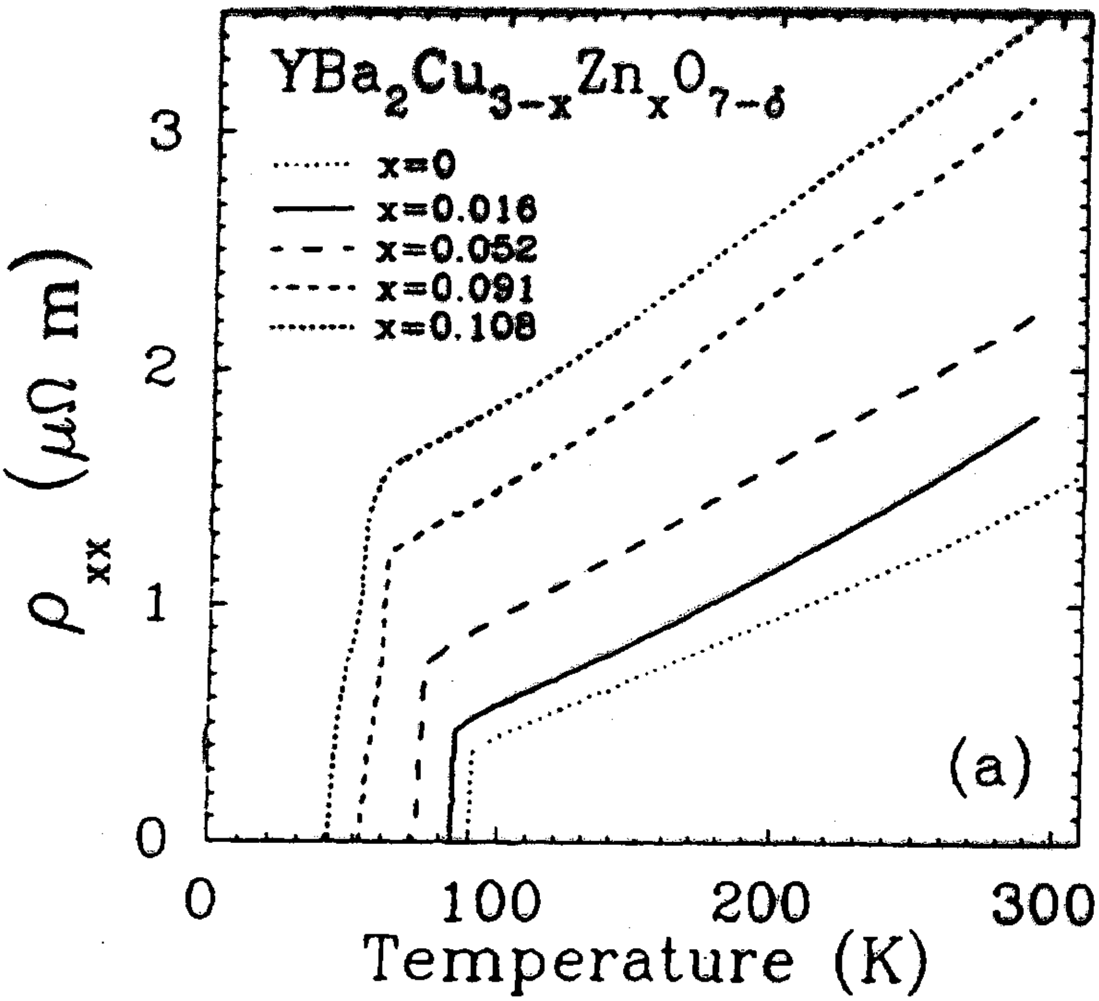


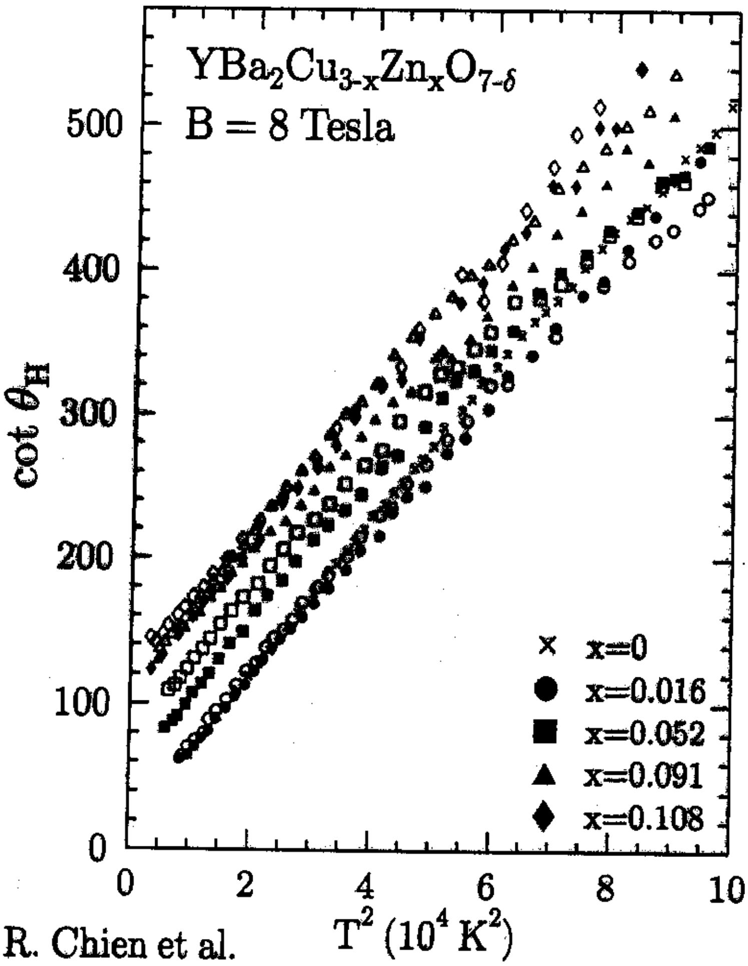


Ito et. al. Nature '91

$\rho_c \gg \rho_{ab}$

$\rho_c \not\propto \rho_{ab}$

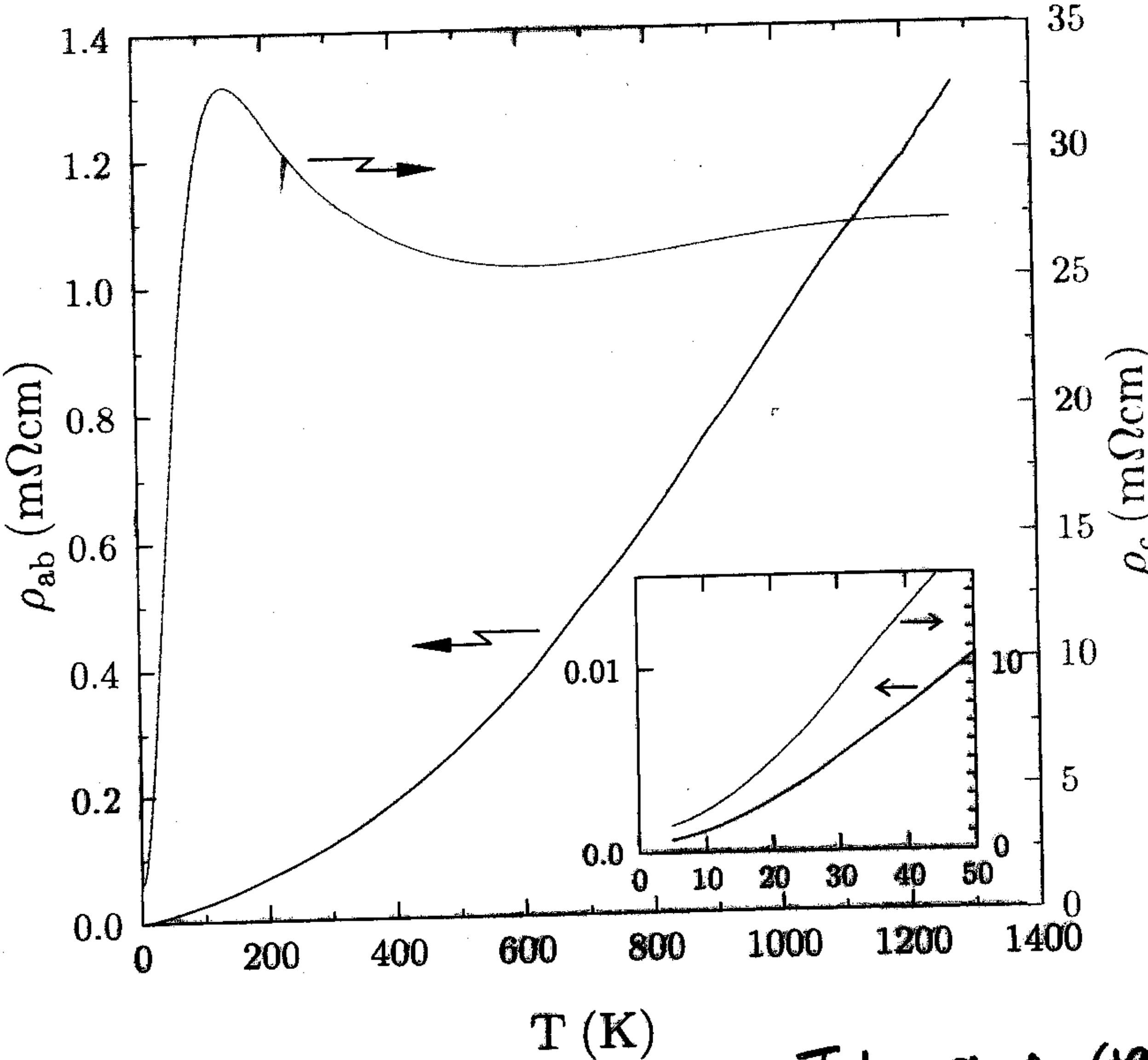




T. R. Chien et al.

- Also materials which look like
  (i) Fermi liquids at low T
  (ii) Something else at high T

$Sr_2 Ru O_4$



Tyler et al (1998)
PRB

The puzzles: $La_{2-x}Sr_xCuO_4$, Sr_2RuO_4, BEDTTF $(TMTTF)_2PF_6$ .....

- many of these show unusual behaviour
  eg. non-Fermi liquid
  bad metallic

- yet few solvable models to help
  - are these models appropriate

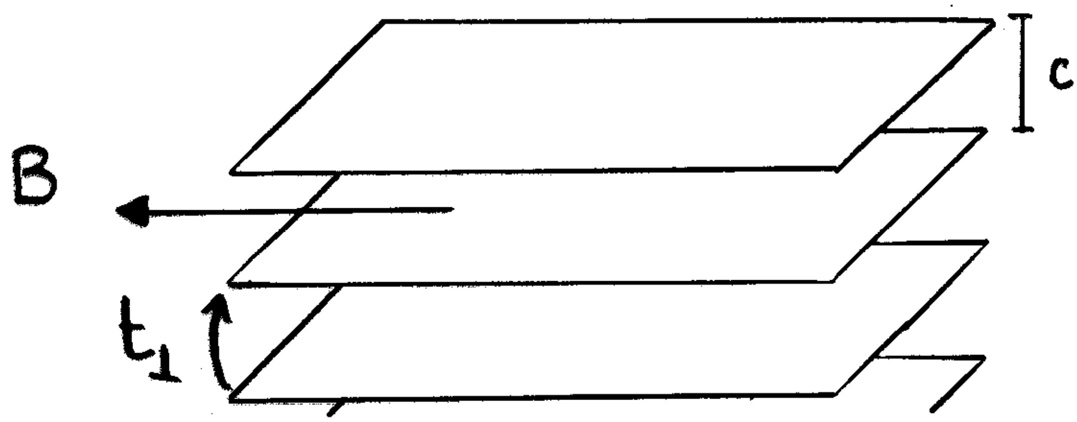
An approach:

Use experiment to tell you the form of the theory ... phenomenology

But

Easy experiment	$\longleftrightarrow$	complicated theoretical interpretation
resistivity (T)		2 particle Green's f^{n}.
"Easy" theory	$\longleftrightarrow$	hard to see in experiment
1 particle spectral function		(ARPES).

C-axis transport in quasi-2D materials



$(\bar{c}.\bar{B}=0)$
in-plane fie

- Assume planes <u>only</u> coupled by single electron hopping.

$$\hat{H} = \sum_n \hat{H}_{\parallel} + \sum_{n,\vec{k}_\parallel} t_\perp(\vec{k}_\parallel)\, \hat{C}^{\dagger}_{n+1,\vec{k}_\parallel+\frac{\vec{q}_B}{2}}\, \hat{C}_{n,\vec{k}_\parallel-\frac{\vec{q}_B}{2}} + H.$$

$$\vec{q}_B = \frac{e}{\hbar}\bar{c}\times\bar{B}$$ a change in momentum due to Lorentz force

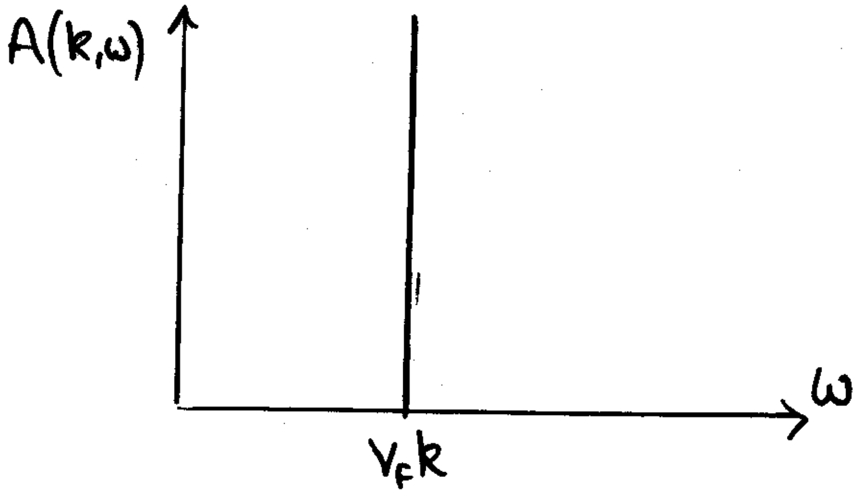
- <u>Basic idea</u>: use $\frac{t_\perp}{\epsilon_F} \ll 1$ as a small parameter to probe $\hat{H}_\parallel$.

- <u>Related work</u>
  - Anderson, Hsu & Wheatley, Kumar
  - Clark, Strong & Anderson,
  - Ioffe & Millis
  - McKenzie & Moses.

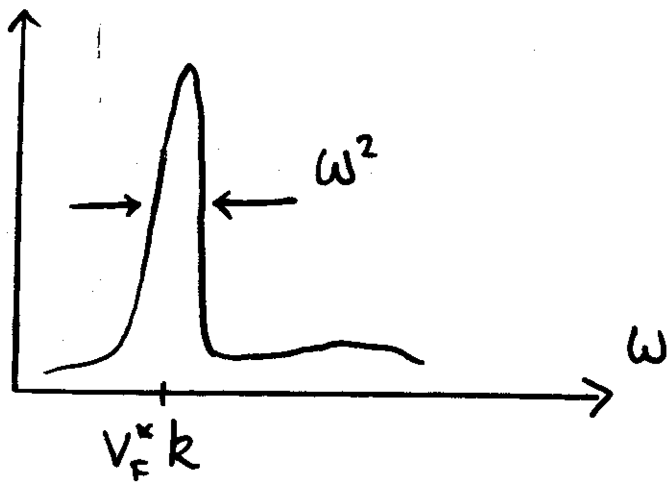
The spectral function

Probability of finding an electron with a specific momentum

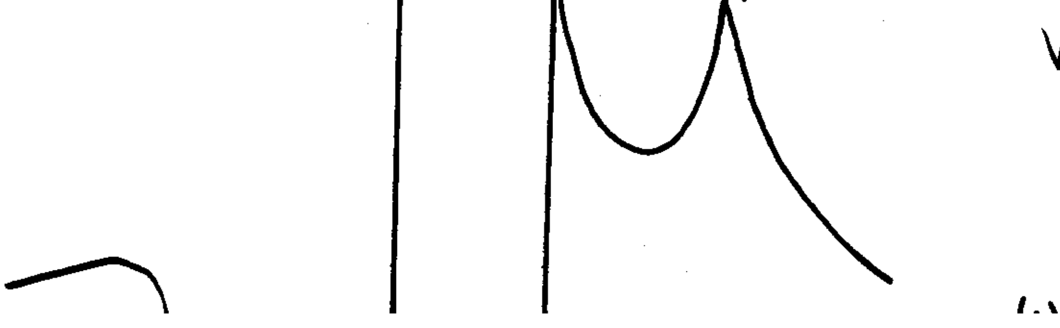
Non-interacting electrons



Fermi liquid



Luttinger Liquid - a non-Fermi liquid



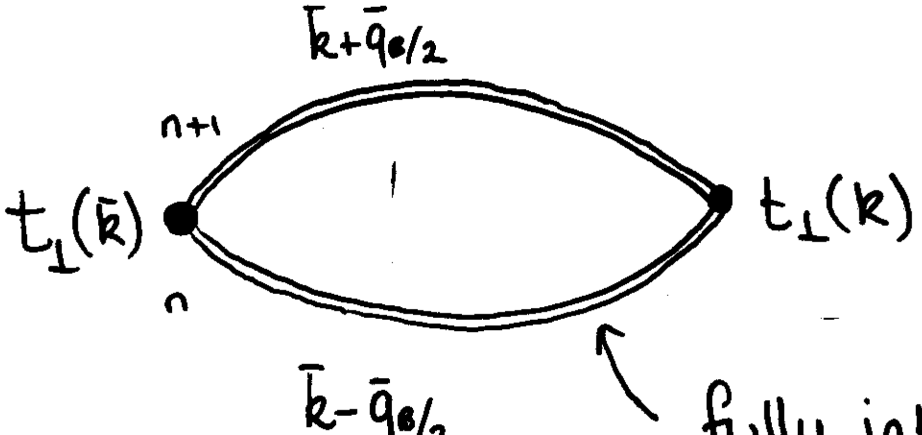
Voit, Dias ...

Consequence

- c-axis conductivity is like tunnelling

$$j_c \sim \frac{ie}{\hbar} \sum_{n, k_\parallel} t_\perp \, c^\dagger_{n+1} c_n - \text{H.c.}$$

- so $\quad \sigma_c \sim \frac{1}{i\omega} \langle j_c j_c \rangle$



$+ \; O(t_\perp^4)$

fully interacting in-plane Green's function

<u>But</u> no vertex corrections

$$\boxed{\sigma_c = \frac{e^2 c}{\hbar \pi} \int \frac{d^2 \bar{k}}{(2\pi)^2} \int d\omega \; A\left(\bar{k} + \frac{q_B}{2}, \omega\right) A\left(\bar{k} - \frac{q_B}{2}, \omega\right) t_\perp^2(k) \left(-\frac{\partial f}{\partial \omega}\right)}$$

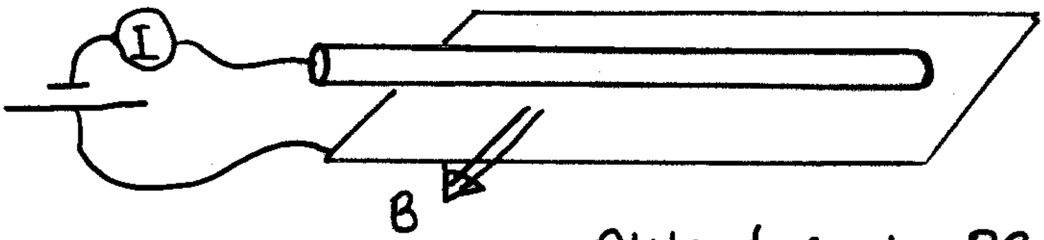
$\sigma_c(B)$: a spectroscopy of in-plane physics

e.g. $\quad l_c < c \quad$ is irrelevant

a single electron probe: spectral function

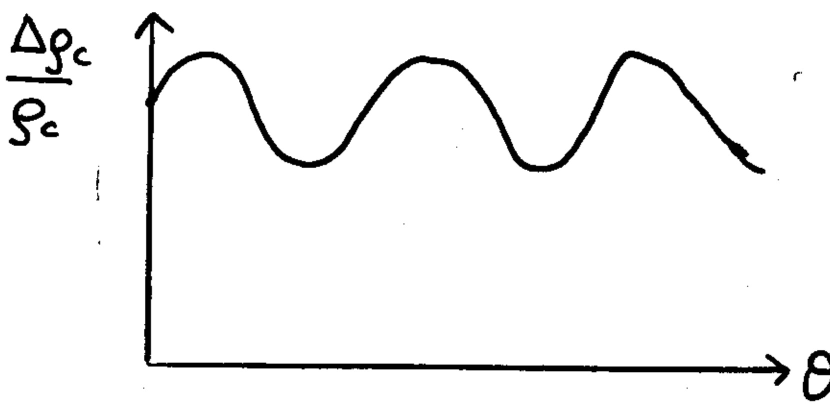
Many applications of this idea

- Seeing spin-charge separation



Altland et al. PRL 83, 1203 (1999)
Barnes, Hekking, Schofield.

- Measuring anisotropic lifetimes in cuprates



Sandeman + AJS cond-mat/0007299

- Application to ruthenates

- Quasi 1D metals: $(TMTSF)_2PF_6$

  2D – 1D crossovers

Application: A linear in B magneto-resistance for quasi-2D 'metals'

"metal" = spectral weight ~~within~~ for $|\omega| < k_B T$ is centred around k_F

Simple example:

Fermi liquid with quasiparticle damping
eg. impurities at $T=0$

$$A(k,\omega) = \frac{\hbar/\tau}{(\varepsilon_k - \omega - \varepsilon_F)^2 + (\hbar/2\tau)^2}$$

Can do the integrals...

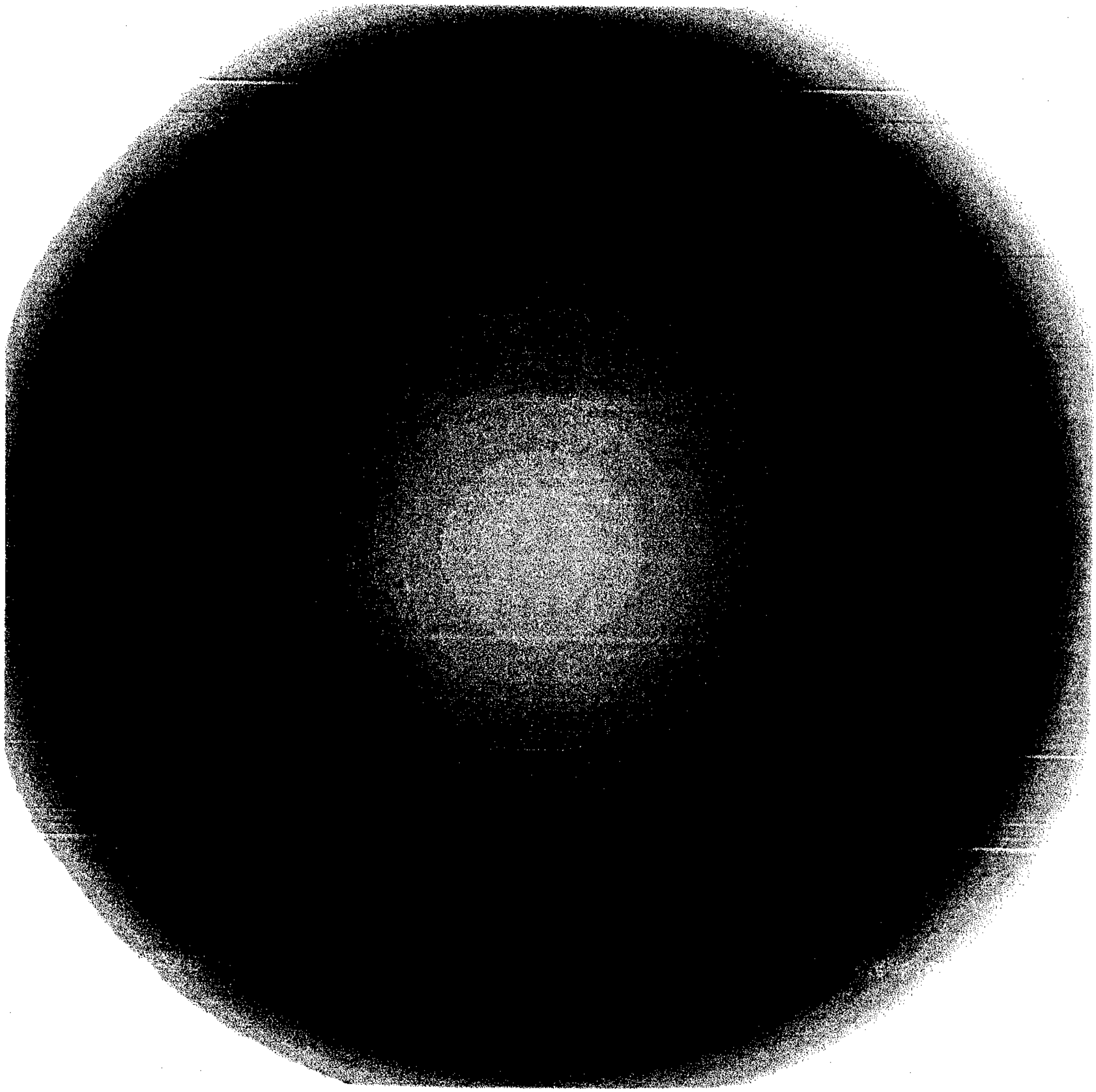
$$\sigma_{zz} = \frac{2e^2 c k_F t_\perp^2 \tau}{\pi v_F \hbar^3} \frac{1}{\sqrt{1 + (\Omega_c \tau)^2}}$$

$$\Omega_c = \frac{e v_F B c}{\hbar}$$

$$\Rightarrow \frac{\Delta \rho_c}{\rho_c} = \sqrt{1 + (\Omega_c \tau)^2} - 1$$

$$\sim B^2 \qquad \Omega_c \tau \ll 1$$

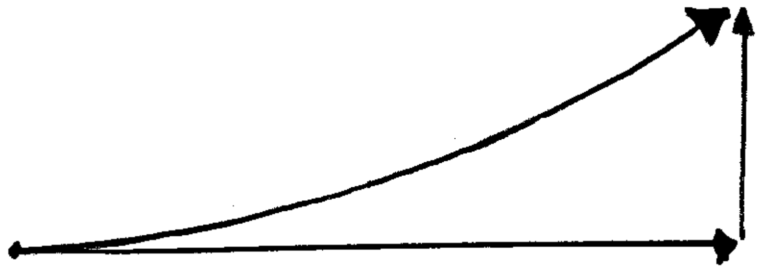
$$\sim |B| \qquad \Omega_c \tau \gg 1$$



Orbital Magneto-resistance

- traditional view (ie Boltzmann)

  eg Ziman's book, Abrikosov's book ...



$$j_y = \frac{j_0 \theta_H}{1+\theta_H^2} \quad \otimes B$$

$\longrightarrow$ E

$$j_x = \frac{j_0}{1+\theta_H^2}$$

- Current deflected by the Hall angle: $\Omega_c \tau = \theta_H$

$$\sigma_{xx}(B) \approx \sum_{\text{all orbits}} \frac{1}{1 + \theta_H^2(\text{orbit})}$$

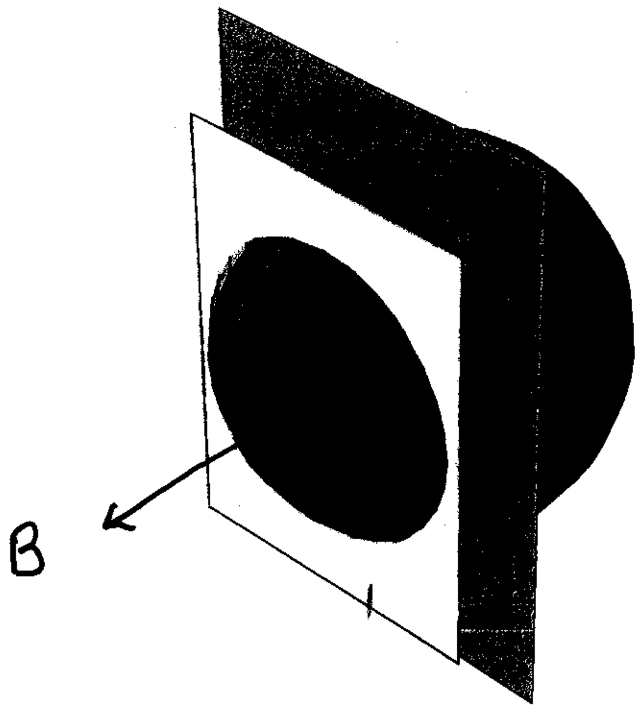
- Isotropic metal: only one θ_H in the metal

  $\Rightarrow$ Hall voltage cancels the deflection

  $$\Rightarrow \frac{\Delta\rho}{\rho} = 0$$

- Magneto resistance requires anisotropy.

Isotropic Case



$$\dot{p} = e\bar{v}\times\bar{B}$$

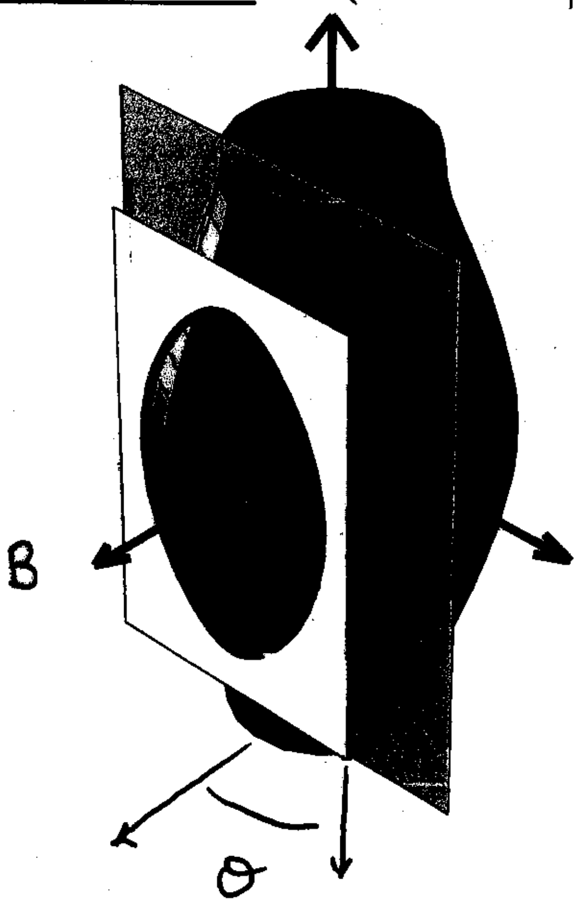
$\Rightarrow$ v.B is constant
ε is constant

all orbits have $\theta_H = \Omega_c\tau$

$$\Rightarrow \sigma \sim \frac{\sigma_0}{1+(\Omega_c\tau)^2}$$

Open orbits

(see Schofield, Cooper, Wheatley: condmat/97)



define $\Omega_c = \frac{e v_F c B}{\hbar}$

$\theta_H(\text{orbit}) \simeq \Omega_c\tau \sin\theta$

$$\sigma \sim t_\perp^2 \int_0^{2\pi} d\theta \, \frac{\tau}{1+(\Omega_c\tau\sin\theta)^2}$$

$$\sim \frac{t_\perp^2\tau}{\sqrt{1+(\Omega_c\tau)^2}}$$

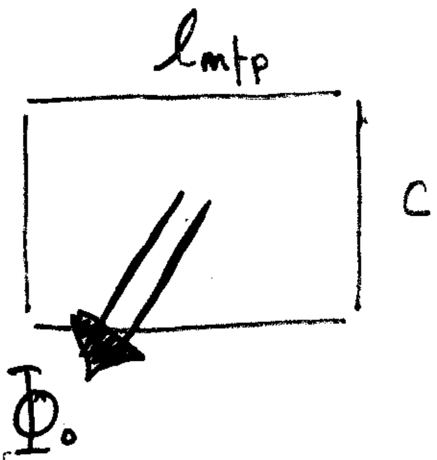
Also: Hall voltage v. small $\left(\frac{t_\perp^*}{E_F}\right)$ $\Rightarrow$ no cancelling

Points to note

(i) Does not rely in a quasi particle picture

(ii) $\Omega_c \tau = \dfrac{l_{mfp}\, c}{l_B^2}$

$\Rightarrow$ Cross-over when one flux quantum through



eg. Perovskites: $c \sim 12\,\text{Å}$

$\Rightarrow \quad l_{mfp} \sim 500\,\text{Å} \quad$ at $B = 10\,T$

(iii) $\dfrac{\Delta\rho_c}{\rho_c}$ is large

(iv) Can ~~solve~~ derive this using the Boltzmann Equation:

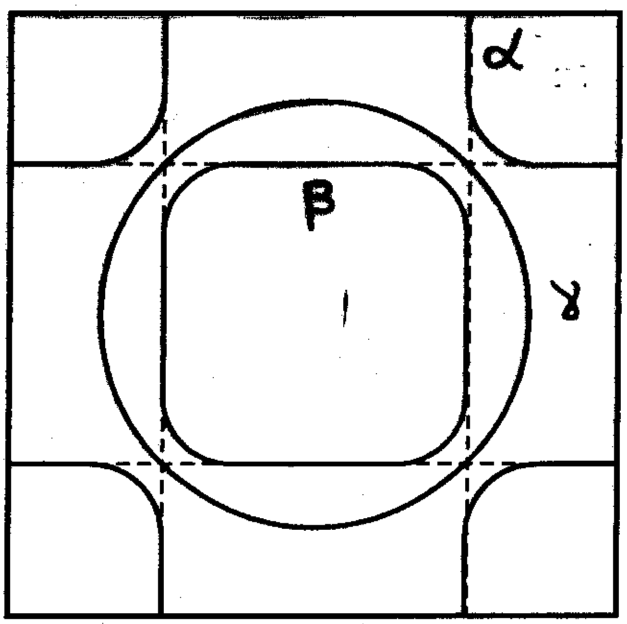
$$\frac{\Delta\rho_c}{\rho_c} \sim B^2 \quad \text{for} \quad (\Omega_c\tau)^2 \gg \left(\frac{E_f}{t_\perp}\right)$$

Electronic Structure of Sr_2RuO_4

Ru^{4+} : $4e^-$ in t_{2g} d_{xy} hybrid with O 2p — 2D

d_{yz} — 1D

d_{xz} — 1D



p-wave $(k_x + ik_y)$?
on γ sheet?
Agterberg + Rice, Sigrist
Baskaran

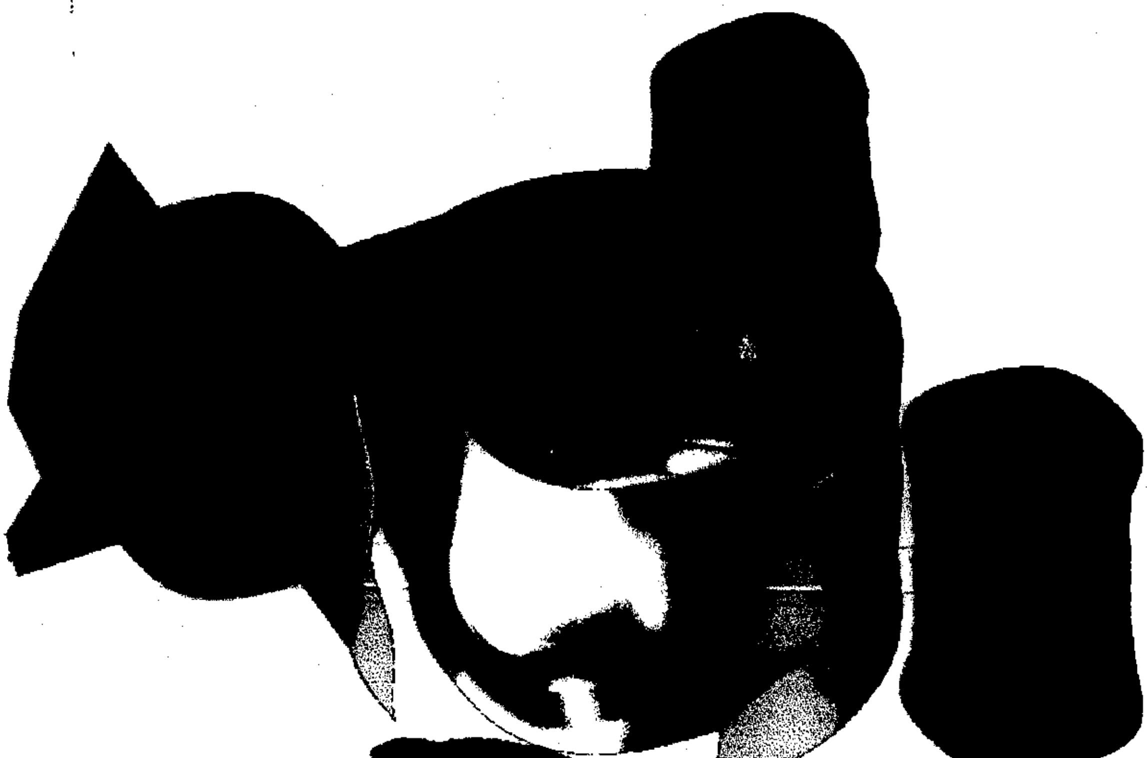
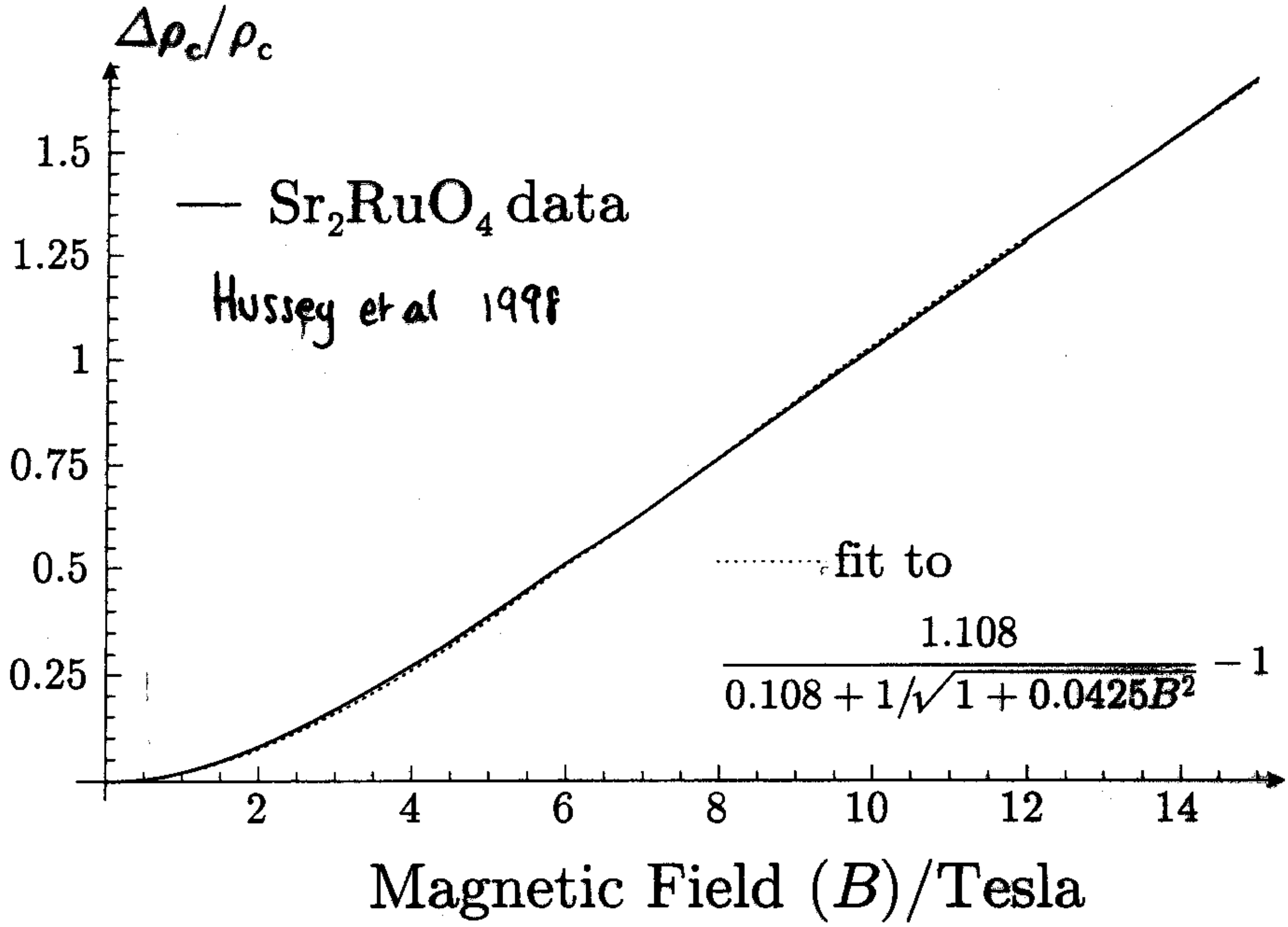


figure due to
C. Bergemann

dHvA: Mackenzie et al '9
Bergemann et al '00

Fit to data

T=3K

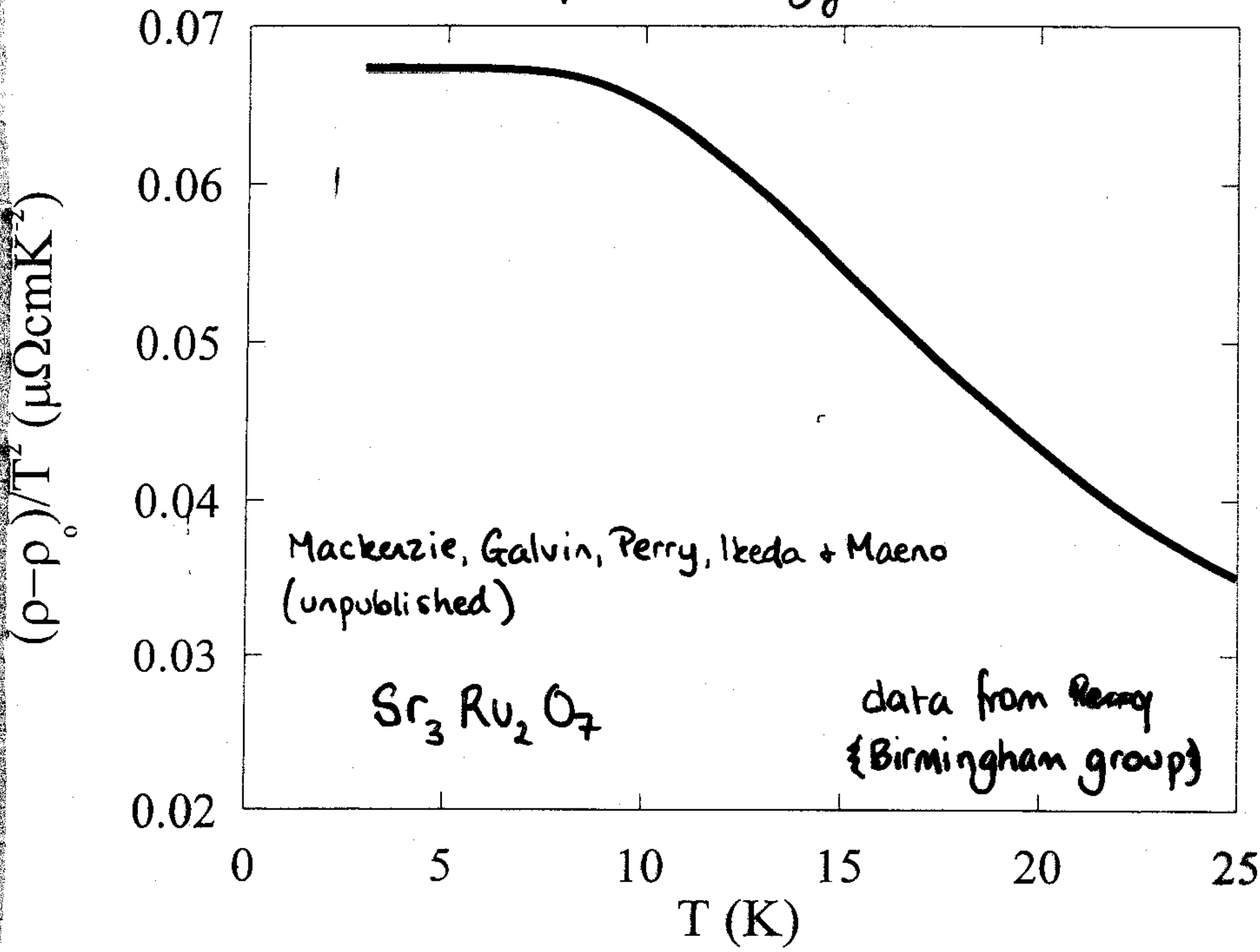


- assumed one sheet with v. small mean free path.
- data consistent with γ sheet with v. small l.
  - also fits with $R_H(T)$

$\Rightarrow$ is pairing really happening first on γ ?

Is Sr_2RuO_4 so straight forward

T^2 scattering switches on/off abruptly – a new energy scale.



Does anything happen in MR at this scale.

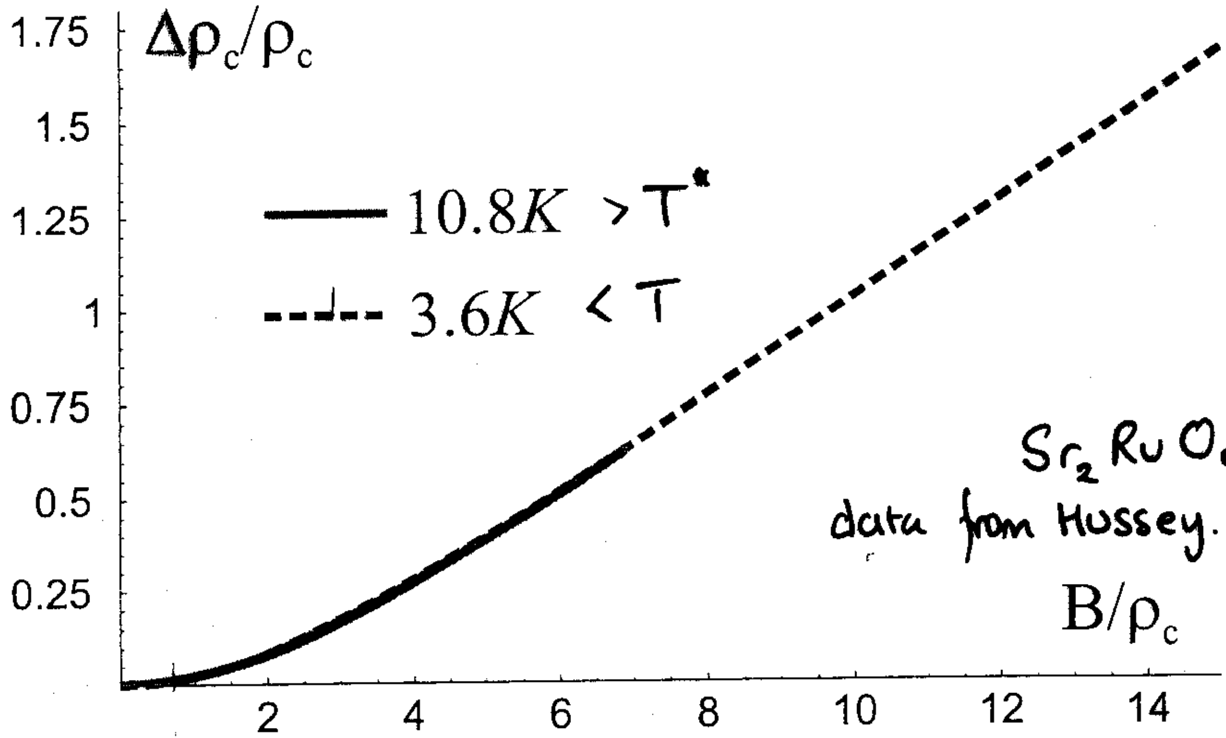
- Sr_2RuO_4 : $T^* \simeq$ ~~4K~~ 5K
- $Sr_3Ru_2O_7$: $T^* \simeq$ 8K

In a Fermi liquid : for $\ell \gg \lambda_e$

there is only one scale : Γ

$\Rightarrow$ scale B by Γ and expect MR to scale.

Kohler plot.



$\Rightarrow$ System remains Fermi liquid like above T^*

only the scattering mechanism changes

Conclusions

- What could one learn from a 100 T + magnet ?

- C-axis magneto transport as a spectroscopy

- Tested this in single layer ruthenates

$$2D \Rightarrow \frac{\Delta\rho}{\rho} \sim |B|$$

- Future work
  - cross-overs in the quasi 1D organics
  - cuprates : testing 'hot-spot/cold-spot'
    see cond-mat/0007299

  ....

Which mean-free-path controls c-axis MR in the cuprates

see cond-mat/0007299

- MR depends on angle of field in the plane

Hussey et al. 1996 (PRL)

$$\frac{\Delta\rho}{\rho} = \Gamma_1 B^2 \left[1 + c\Gamma_1 B^2 (1 + A\cos 4\theta) + \cdots\right.$$

	Γ_1	c	A
Ioffe + Millis model	$\frac{\sqrt{l_{tr} l_H}}{l_B}$	$-\left(\frac{l_H}{l_{tr}}\right)^3$	$+\frac{1}{3}$ const.
Isotropic scattering $t_\perp \sim t\cos^2 2\theta$	$\frac{l_0}{l_B}$	$-1/2$	$-2/3$
Expt:	ranges from $(l_{0tr} l_H)^{1/2}$ to l_0	-0.6	~ 0 but weakly T dependent.

$$\sigma_c \sim \int \frac{d\theta}{2\pi} \cdot \frac{t_\perp^2(\theta)}{\Gamma(\theta)\left[1 + \left(\frac{\hbar q_B v_F}{\Gamma(\theta)}\sin\theta\right)^2\right]}$$

Prediction: Maxima in c-axis MR should rotate by $\pi/4$ in going