Luttinger liquid behavior in the spectral and transport properties of $Li_{0.9}Mo_6O_{17}$

Feng Wang S.-K. Mo[1] J. W. Allen *University of Michigan*
[1]Stanford

G.-H. Gweon *UCSC*

H. Höchst *Synchrotron Radiation Center*
University of Wisconsin

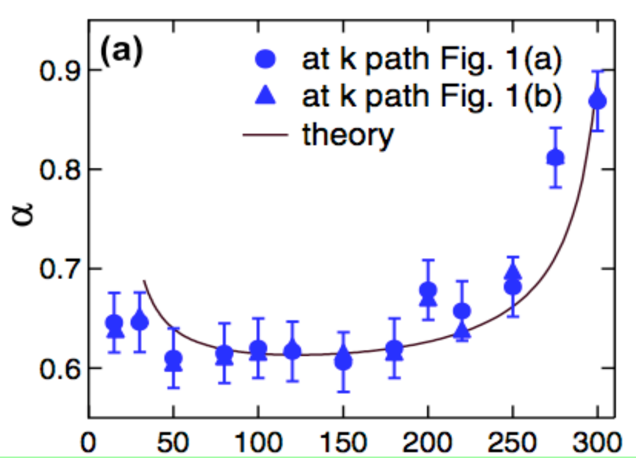
J. He, R. Jin, D. Mandrus[2] *Oak Ridge National Laboratory*
[2] *also: University of Tennessee*

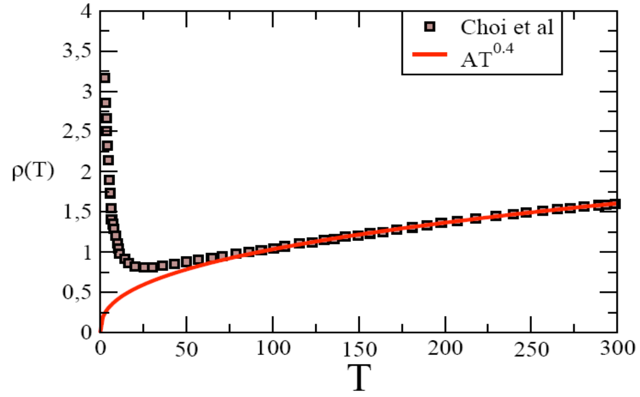
Jose V. Alvarez.
Universidad Autonoma de Madrid

Supported at UAM by MEC

Outline

- Review of the TLM and extensions.
- Lithium Purple Bronze as quasi-1D material.
- Temperature dependence of the DOS exponent.
- Upturn in the resistivity at 24K.
- Conclusions.





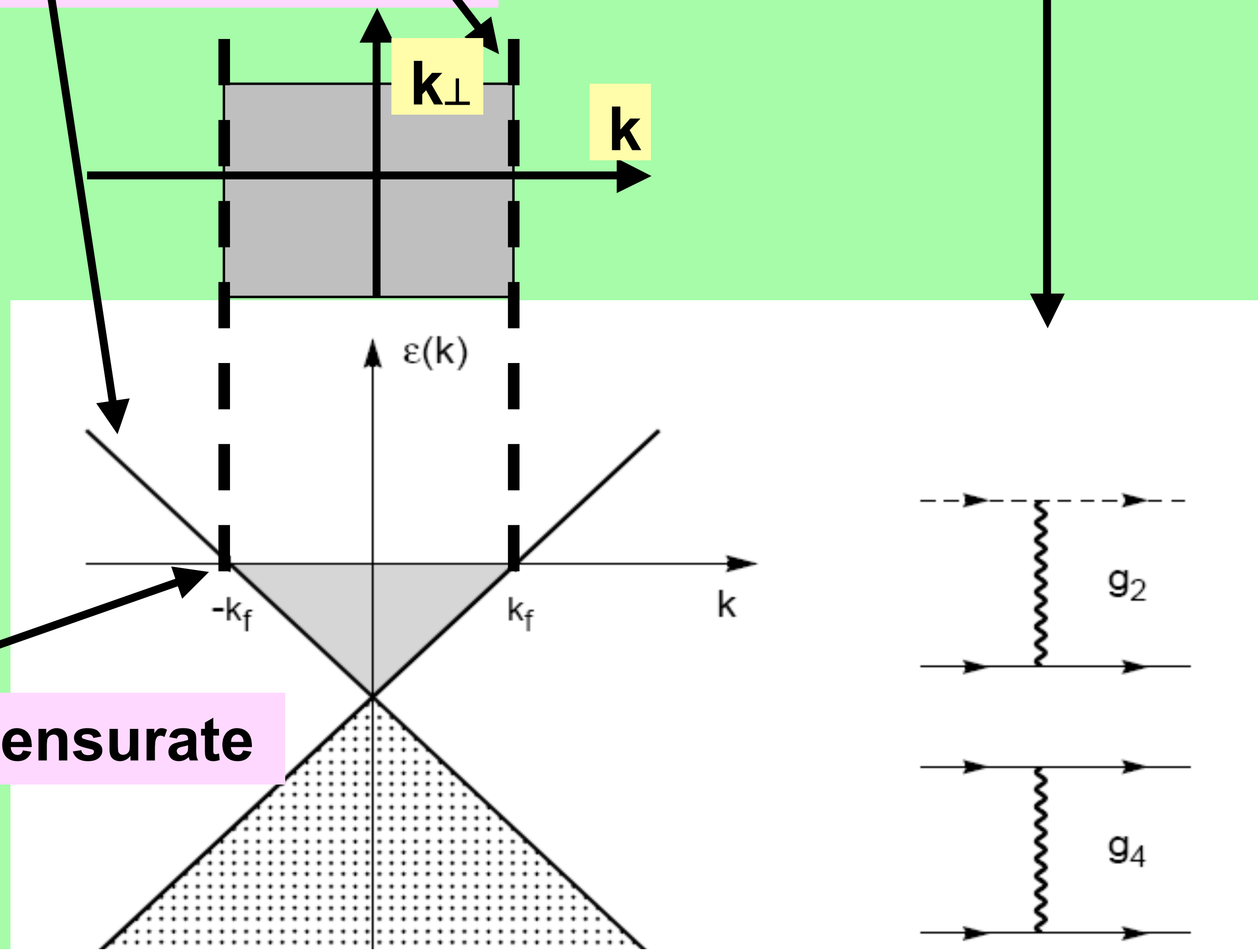
The Basic Luttinger Assumptions = TLM Model

Kinetic Energy

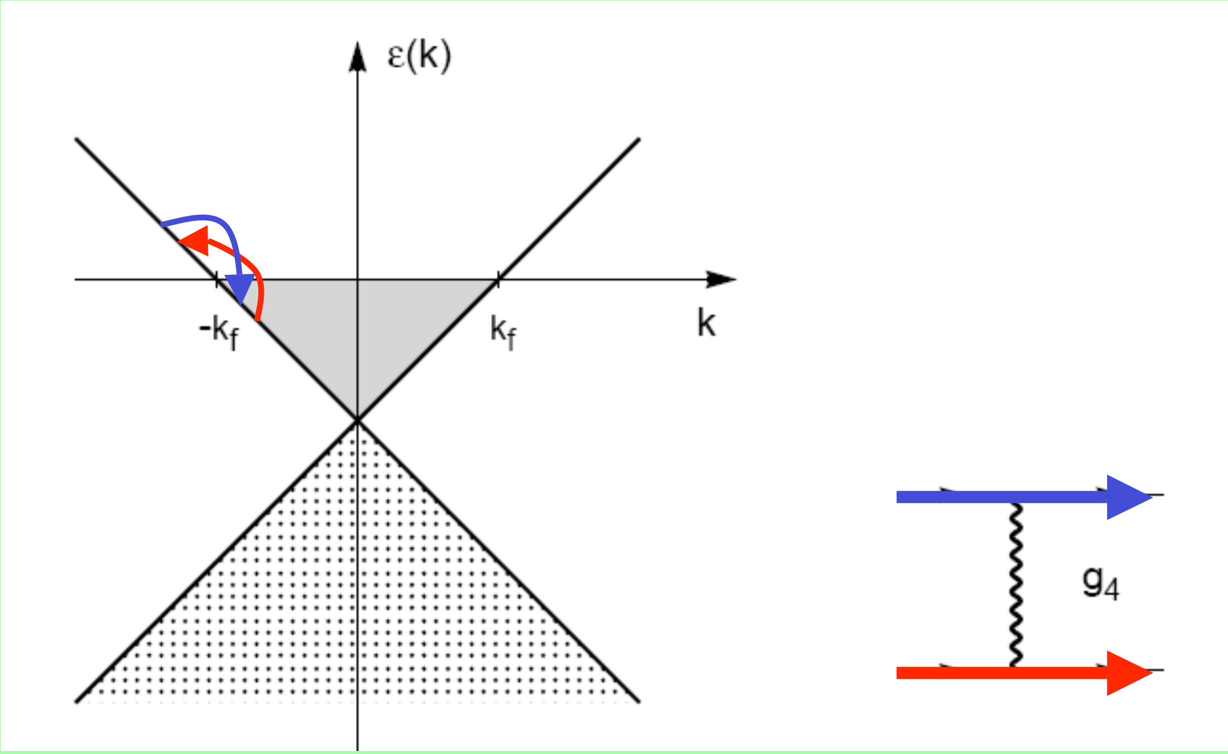
- Strictly 1D (flat FS)
- Perfectly Linear

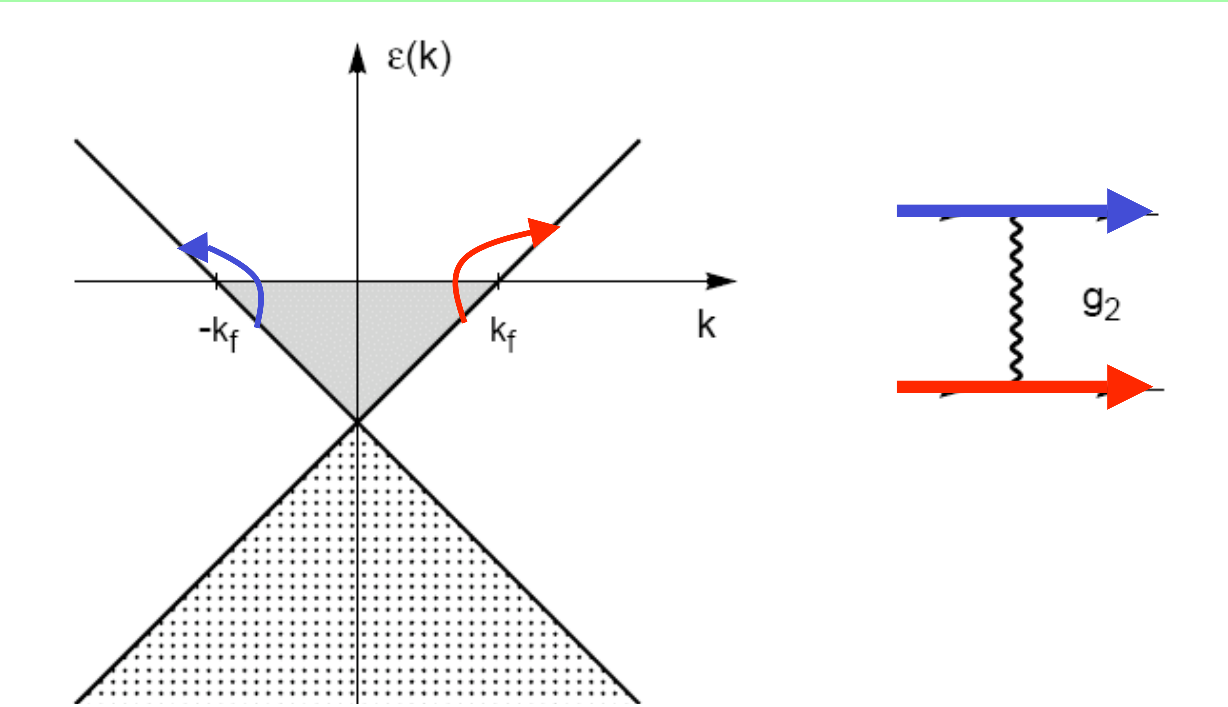
Interaction Energy

- Only small momentum-transfer in-chain interactions.



K_F Incommensurate


ε(k)
-kf
kf
k
g4


ε(k)
-kf
kf
k
g2

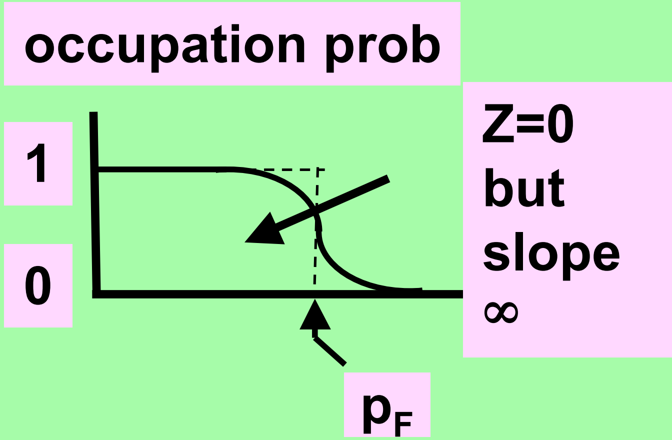
Physical Properties of the TLM

Excitations:

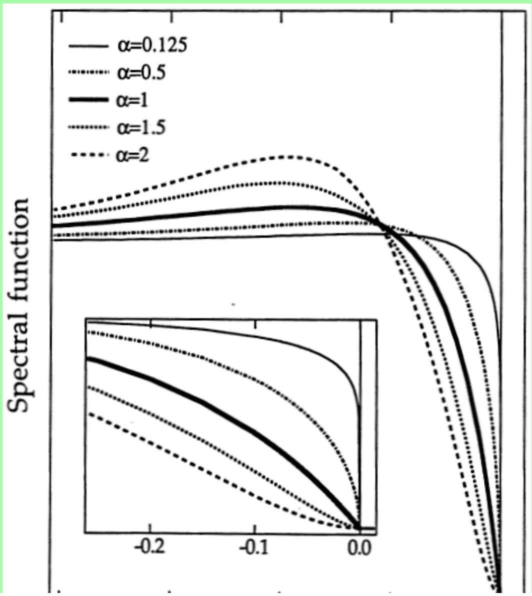
- No poles in GF : no quasi-particles
- Excitations are density fluctuations of charge & spin

with different velocities v_ρ and v_σ

- Static and dynamic correlation functions display power-law behavior
- Exact form factors are known



Example:
Anomalous exponent
α for DOS at E_F.



Bosonic Representation

$$\mathcal{H}_\rho = \int dx \frac{v_\rho}{2}\left[K_\rho \Pi_\rho^2 + \frac{1}{K_\rho}(\partial_x \phi_\rho)^2\right]$$

$$\mathcal{H}_\sigma = \int dx \frac{v_\sigma}{2}\left[K_\sigma \Pi_\sigma^2 + \frac{1}{K_\sigma}(\partial_x \phi_\sigma)^2\right]$$

v_ρ
K_ρ

v_σ
K_σ

$$K_\rho = \sqrt{\frac{2\pi v_f - g_\rho}{2\pi v_f + g_\rho}}$$

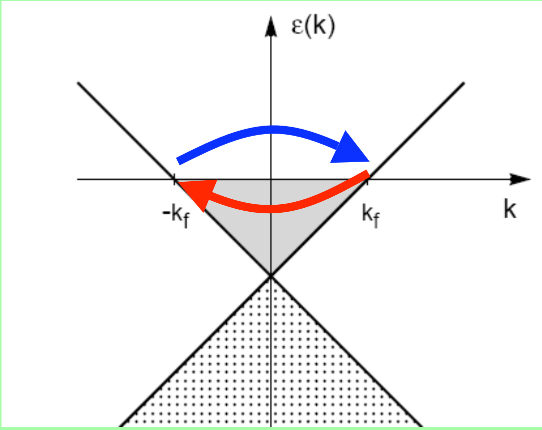
K_ρ>1 attaractive interactions
K_ρ=1 non-interacting fermions
K_ρ<1 repulsive interactions

K_σ=1 if spin rotationally invariant

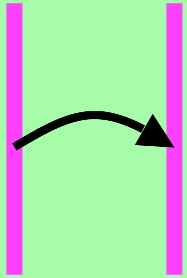
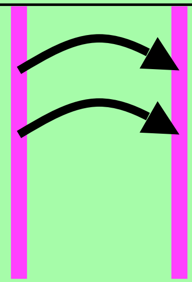
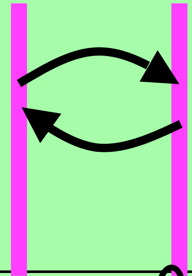
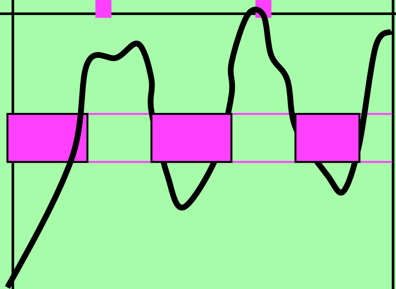
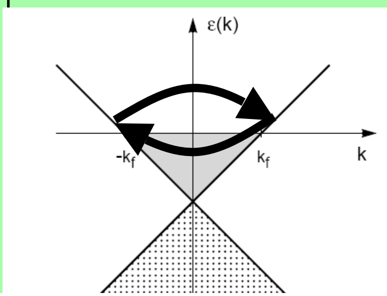
Relaxing the TLM assumptions: The Luttinger Liquid

- **Consider curvature on the bands: but negligible within a cut-off energy: T*.**
- **Include backward scattering repulsive interaction g_1.**

g_1



- **g_1 is irrelevant and TLM is the fixed point in the RG sense.**
- **Physical properties remain asymptotically valid below the cut-off energy T*.**

Single particle hopping ($\perp$) $t_\perp$		Orbitals overlap and/or bridges	FL	"enough" spectral weight at the Fermi Level
Pair hopping ($\perp$) $J_\perp$		2nd order	SC	Attractive interacions in the chains
Particle-hole hopping ($\perp$) $V_\perp$		2nd order	CDW	Strong repulsion in the chains
Disorder (Collective) D		Random Potential. Impurities Defect	Localization	Critical value of the repulsion in the chains
Attractive Backward scattering y		Momentum transfer in chain interactions	Spin Gap (Luther-Emery Liquid) Charge stays	Attractive spin backscattering

Coupling LL's: the Sliding LL

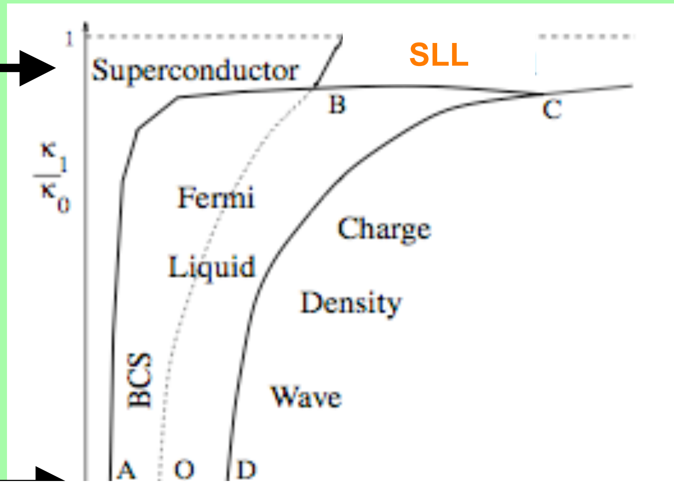
Emery,Kivelson,Fradkin and Lubensky (00)

$$S_\theta = \int \frac{d^3Q}{(2\pi)^3} \frac{1}{2} \kappa(q_\perp) \left\{ \frac{1}{v(q_\perp)} \omega^2 + v(\vec{q}_\perp) q_\parallel^2 \right\} |\phi(\mathbf{Q})|^2$$

$$\mathbf{Q} = (\omega, q_\parallel, q_\perp)$$

- **Couple the LL with interchain interactions that keep TLM structure.**
- **Such set of couplings include the density-density interactions.**
- **System decouples in as many independent modes as chains are coupled "TLM modes".**
- **Electronic motion is still 1D.**

coupled chains →



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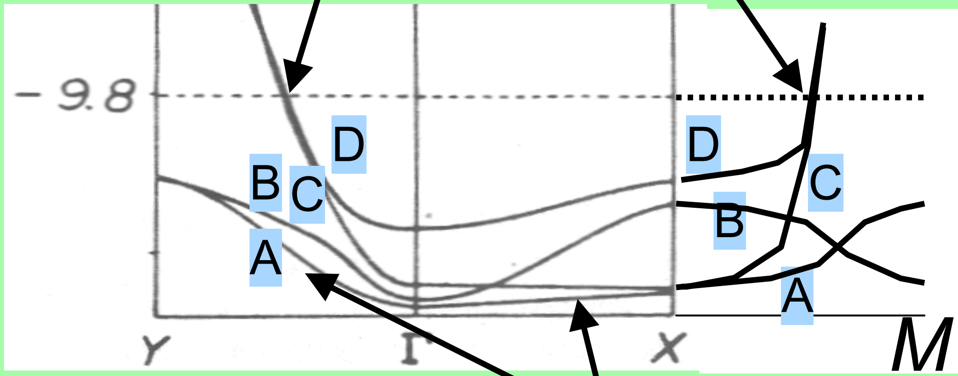
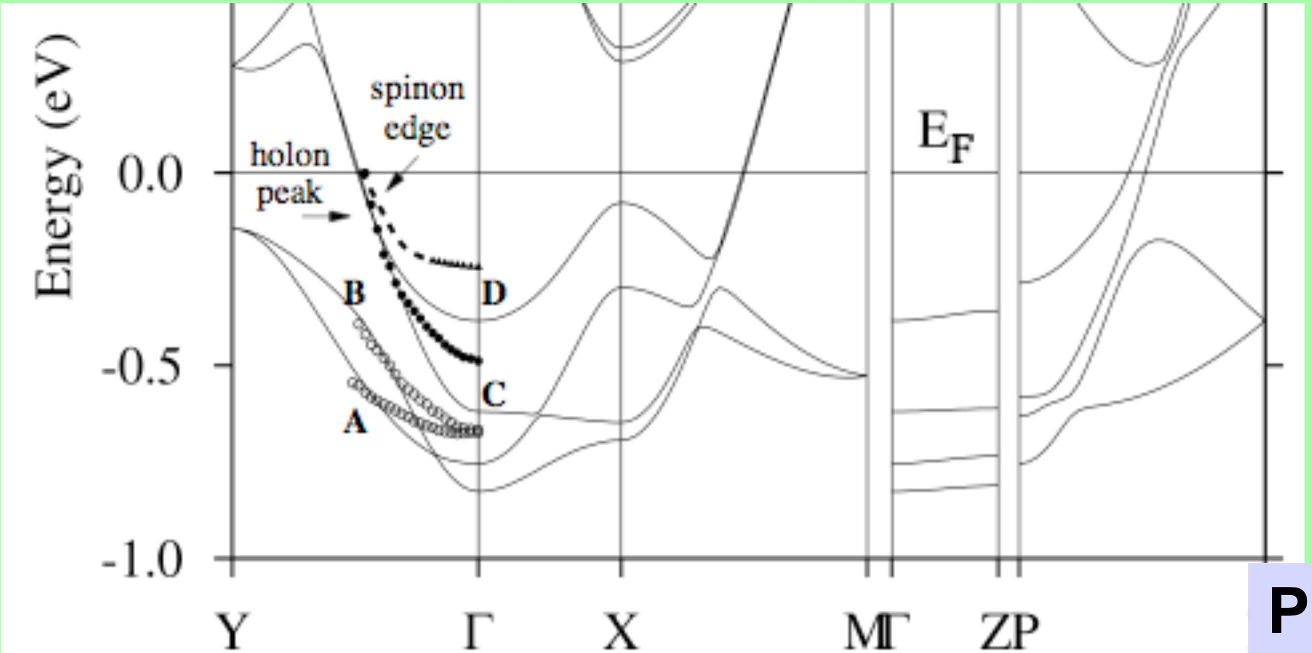
Band structure calculations.

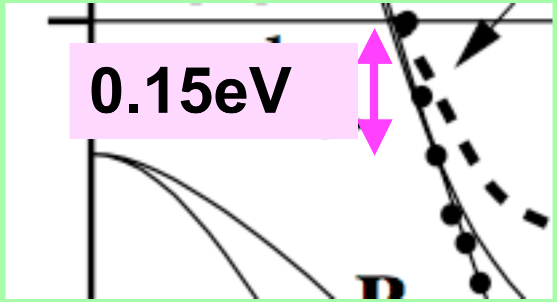
1D Fermi surface due to bands C and D
k_F incommensurate and linear dispersion

Whangbo & Canadell 88'



Bands A and B don't cross E_F

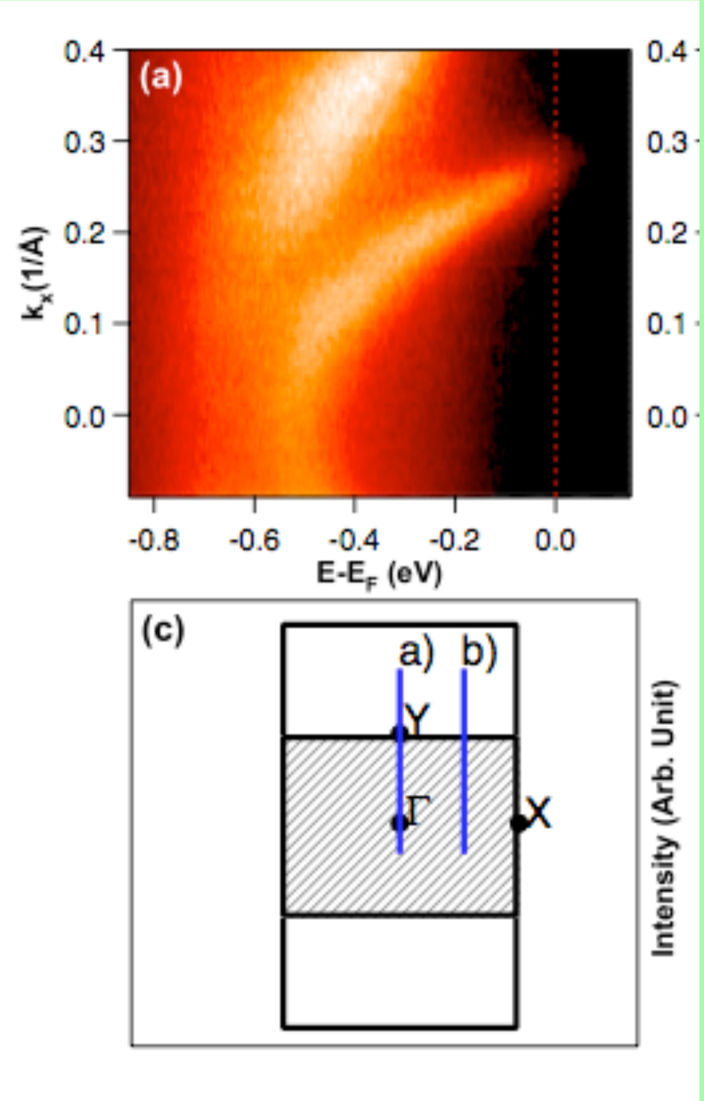


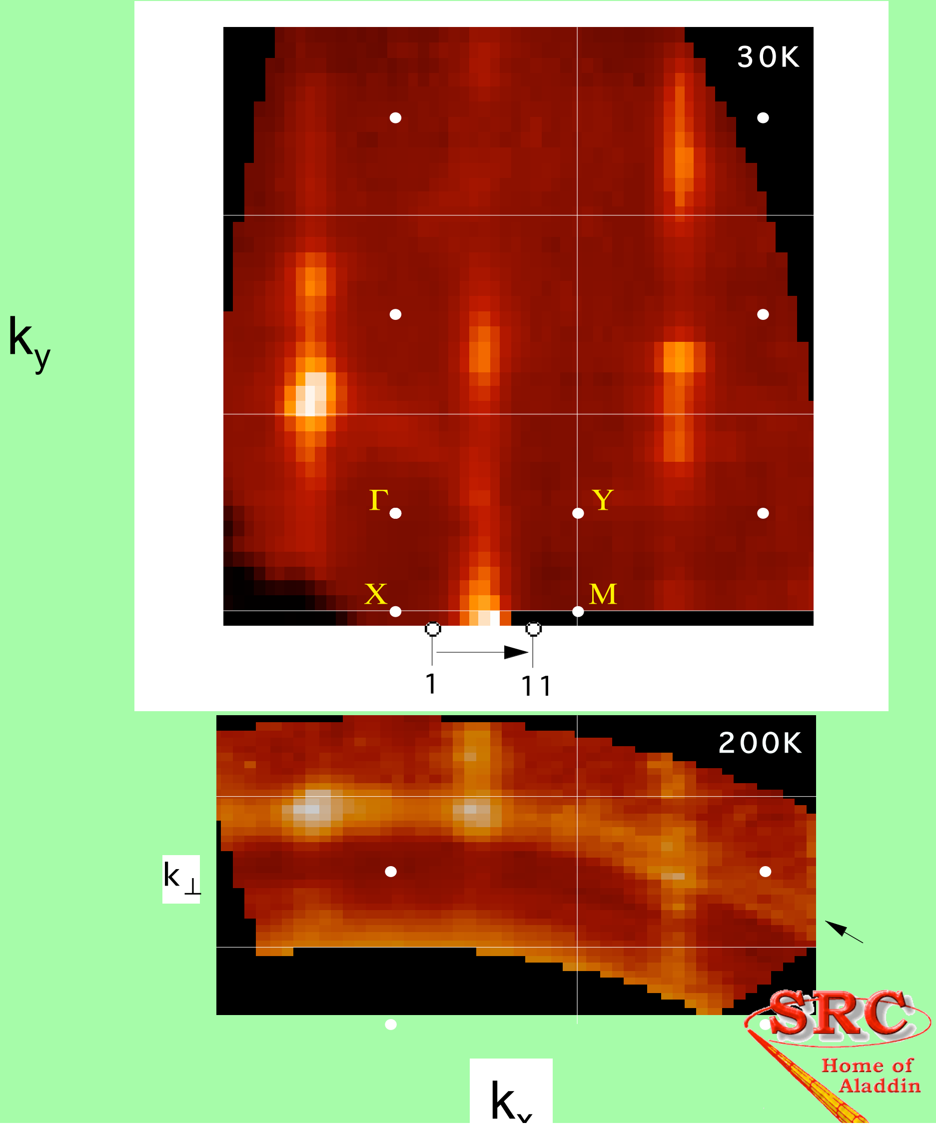


Popovic & Satpathy 06'

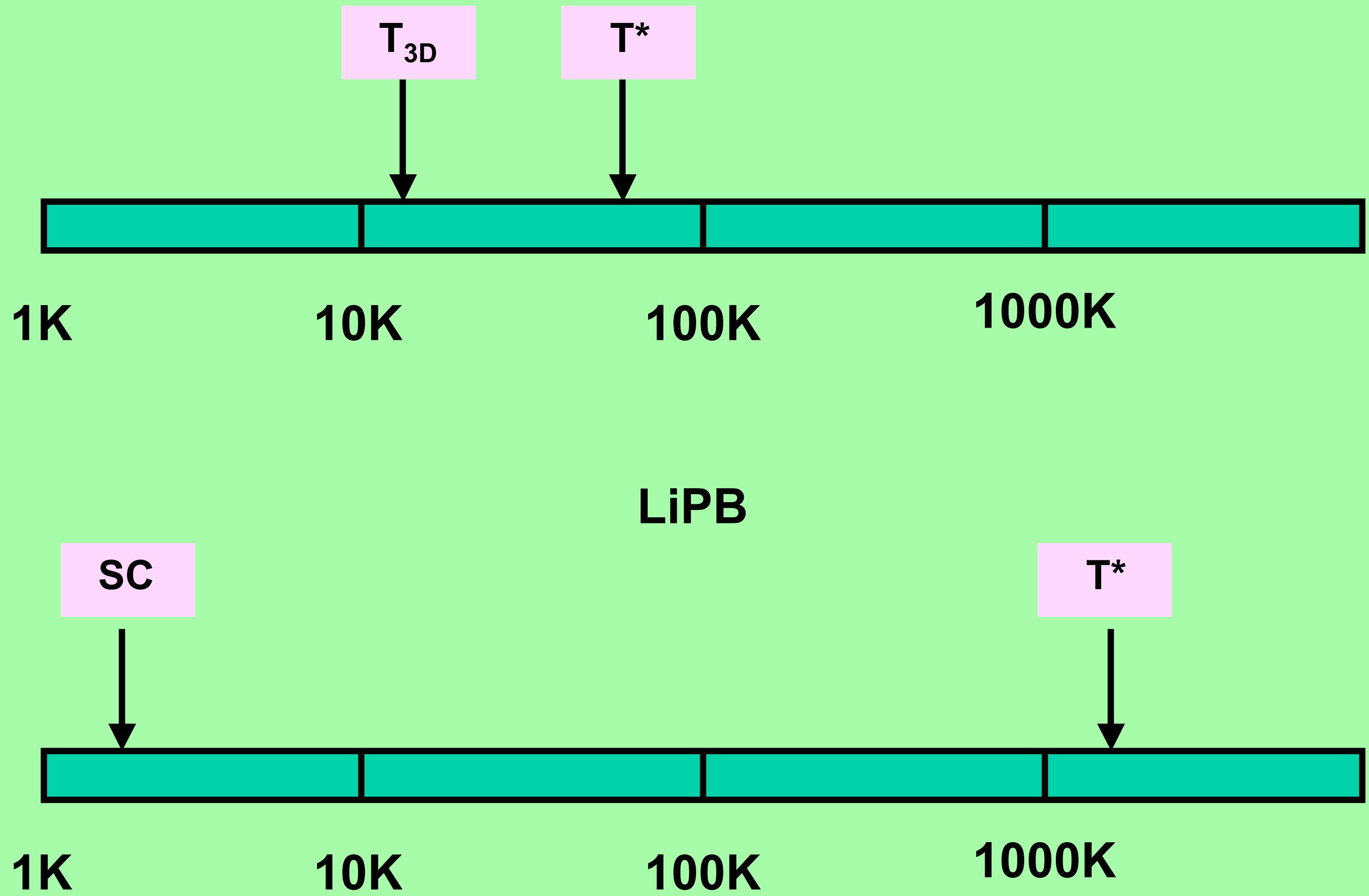
ARPES band structure and Fermi surface map.

Quasi-1D nature, incommensurability and linearity actually observed in ARPES





In which T range can we observe LL physics.



Outline

- **Review of the TLM and extensions.**
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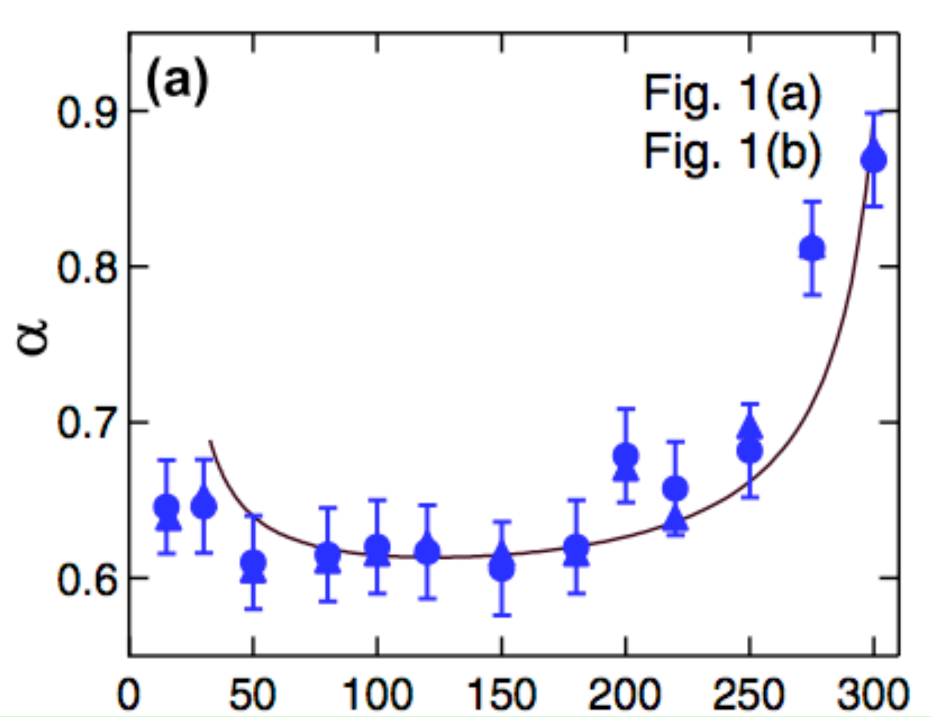
- **Temperature dependence of the DOS exponent.**
- **Upturn in the resistivity at 24K.**
- **Beyond the LL**
- **Conclusions.**

Temperature dependence of the DOS exponent

- LiPB QCS, LL lineshapes .
- $\alpha(T) \Rightarrow$ scale dependence.
- Marginality. Common in 1D.

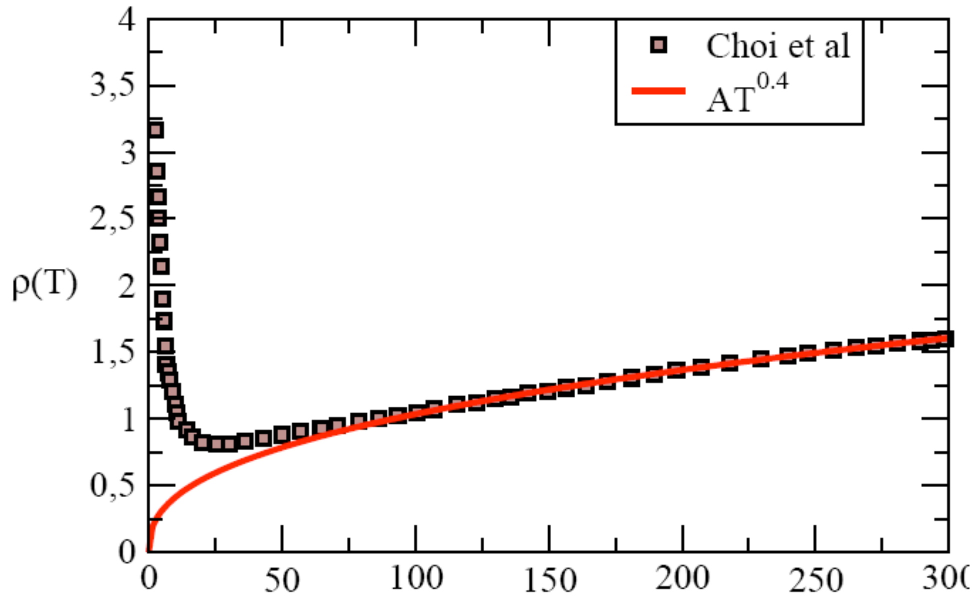


$$\alpha = \frac{1}{4}(K_\rho + K_\rho^{-1} + K_\sigma + K_\sigma^{-1} - 4)$$

SU(2) $K_\sigma=1$

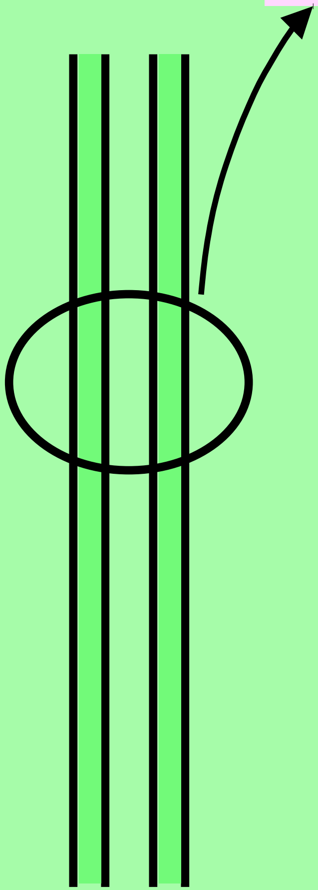
$$\rho_{||}(T) \sim T^\delta$$

$$\delta = K_\rho - \beta$$



Experimentally: lack of scaling relation between exponents.
Are there neutral modes?

Two-band Model



2 chains
2 bands

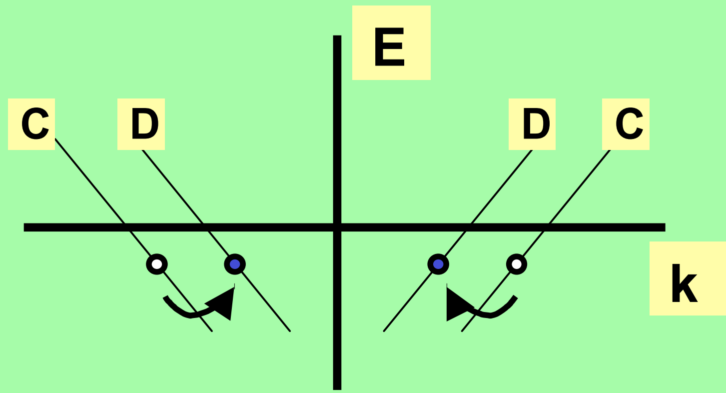
$\rho^+ = \rho_C + \rho_D$
$\rho^- = \rho_C - \rho_D$
$\sigma^+ = \sigma_C + \sigma_D$
$\sigma^- = \sigma_C - \sigma_D$

} **Neutral Modes**

$$\mathcal{H}_{\rho,\pm} = \int dx \frac{v_{\rho,\pm}}{2} \left[K_{\rho,\pm} \Pi^2_{\rho,\pm} + \frac{1}{K_{\rho,\pm}} (\partial_x \phi_{\rho,\pm})^2 \right]$$

$$\mathcal{H}_{\sigma\pm} = \int dx \frac{v_{\sigma,\pm}}{2} \left[K_{\sigma,\pm} \Pi^2_{\sigma,\pm} + \frac{1}{K_{\sigma,\pm}} (\partial_x \phi_{\sigma,\pm})^2 \right]$$

\+ intra & interband back-scattering terms
\+ Pair tunneling J's



RG equations.

$$\alpha = \frac{1}{8}(K_{\rho+} + K_{\rho+}^{-1} + K_{\rho-} + K_{\rho-}^{-1} - 4)$$

$K_{\rho-}$ renormalizes and changes α

$$\begin{aligned}
(K_{\rho-})' &= \frac{1}{4}\left\{3(J_2)^2 + J_1^2\right\} \;, \\
(J_1)' &= \{d + g_{\sigma+}\} J_1 + g_{\sigma-} J_2 \;, \\
(J_2)' &= g_{\sigma-} J_1 + \{d - g_{\sigma+}\} J_2 \;, \\
(g_{\sigma+})' &= -\left\{g_{\sigma-}^2 + g_{\sigma+}^2\right\} - \frac{1}{2}(J_2)^2 \;, \\
(g_{\sigma-})' &= -2\left\{g_{\sigma-} g_{\sigma+}\right\} + \frac{1}{2} J_2 J_1
\end{aligned}$$

RG equations to treat couplings:

- **SU(2) ⇒ $K_{\sigma+}$, $K_{\sigma-}$ absent**
- **k_F incommensurate. No Umklapp ⇒ $K_{\rho+}$ constant**

$$d = 1 - \frac{1}{K} - g_{\sigma+}$$

Understanding the RG flow

$J_2 = 0\ ,\ \ g_{\sigma-} = 0$:

$\rho-$ decouples from spin sector

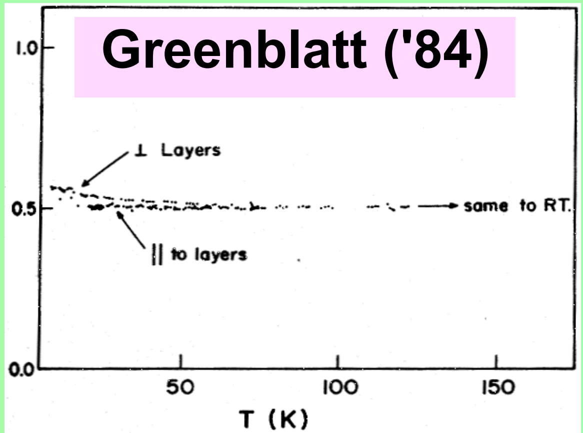
Kosterlitz-Thouless flow

$$
\begin{aligned}
(K_{\rho-})' &= \frac{1}{4} J_1^2 \\
(J_1)' &= (d + g_{\sigma+}) J_1 \\
(g_{\sigma+})' &= -g_{\sigma+}^2
\end{aligned}
$$

Irrelevance of repulsive back-scattering → $(g_{\sigma+})' = -g_{\sigma+}^2$

$$d = 1 - \frac{1}{K_{\rho-}} - g_{\sigma+}$$

- Change in $K_{\rho-}$ change α
- Gapless σ^+: $\chi(T) \propto$ const



magnetic susceptibility

Chain physics: α (T)

$$
\begin{aligned}
(K_{\rho-})' &= \frac{1}{4}\left\{3(J_2)^2 + J_1^2\right\} \ , \\
(J_1)' &= \{d + g_{\sigma+}\} J_1 + g_{\sigma-} J_2 \ , \\
(J_2)' &= g_{\sigma-} J_1 + \{d - g_{\sigma+}\} J_2 \ , \\
(g_{\sigma+})' &= -\left\{g_{\sigma-}^2 + g_{\sigma+}^2\right\} - \frac{1}{2}(J_2)^2 \ , \\
(g_{\sigma-})' &= -2\{g_{\sigma-} g_{\sigma+}\} + \frac{1}{2} J_2 J_1
\end{aligned}
$$

Repulsive back-scattering

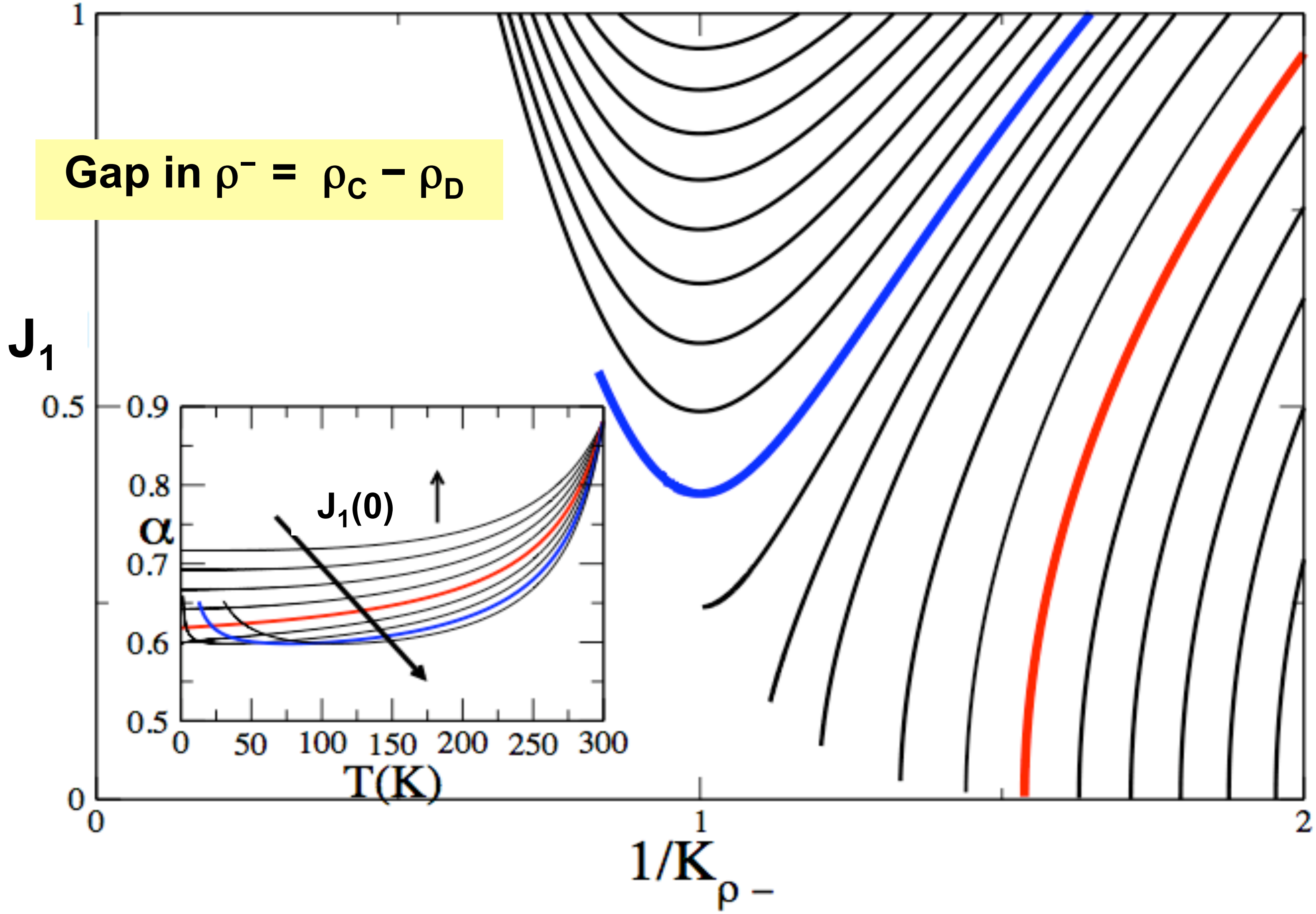
Those interesting flows are stable

$$0 < g_{\sigma-}(0) < g_{\sigma+}(0)$$

$$\lambda = d + \sqrt{g_{\sigma+}^2 + g_{\sigma-}^2} <$$

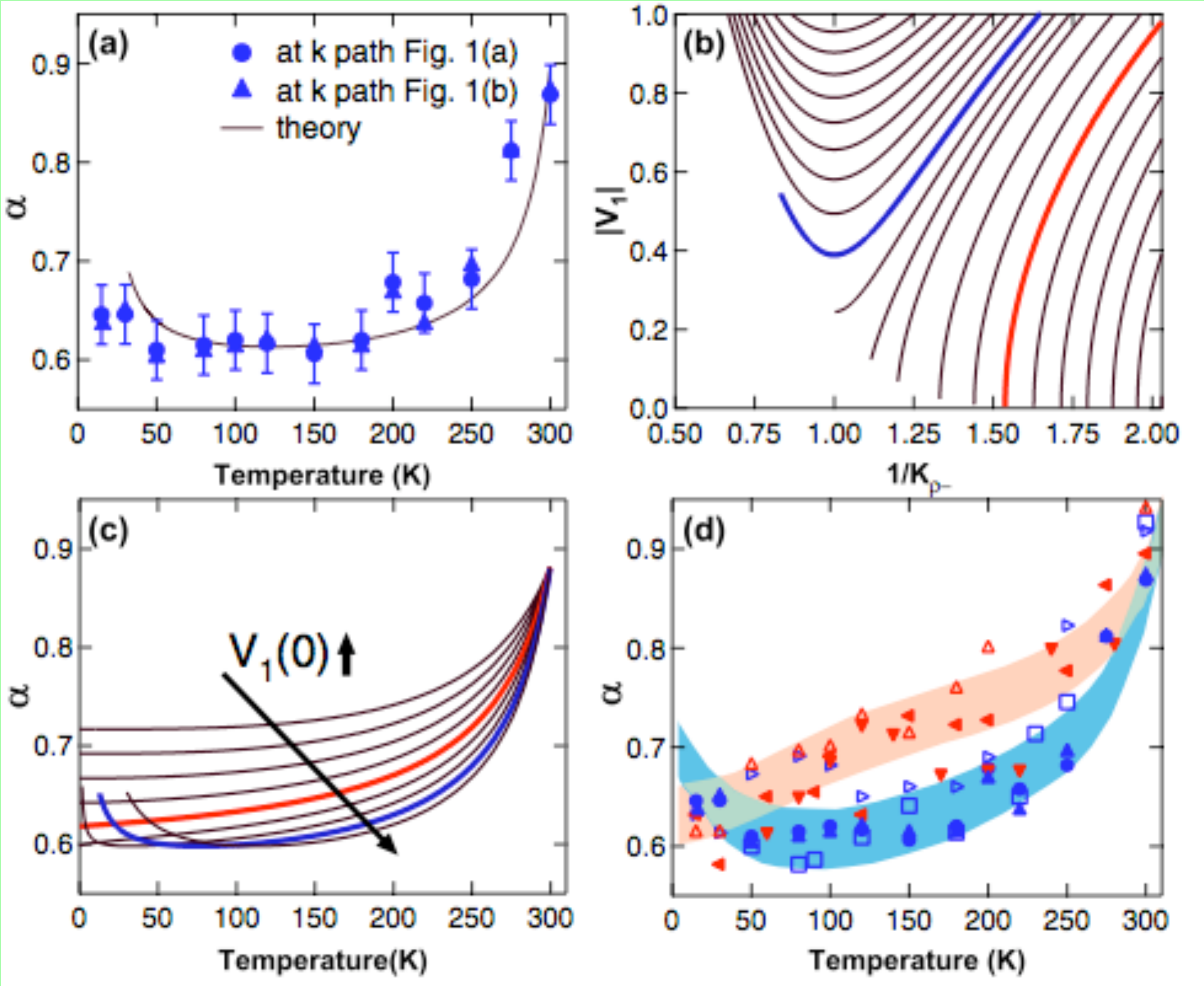
$$d = 1 - \frac{1}{K_{\rho-}} - g_{\sigma+}$$

α (T)



Gap in ρ⁻ = ρC − ρD
J1
1
0.5
0
0
1
2
1/Kρ −
0.9
0.8
0.7
0.6
0.5
α
J1(0)
0
50
100
150
200
250
300
T(K)

T dependence of DOS exponent



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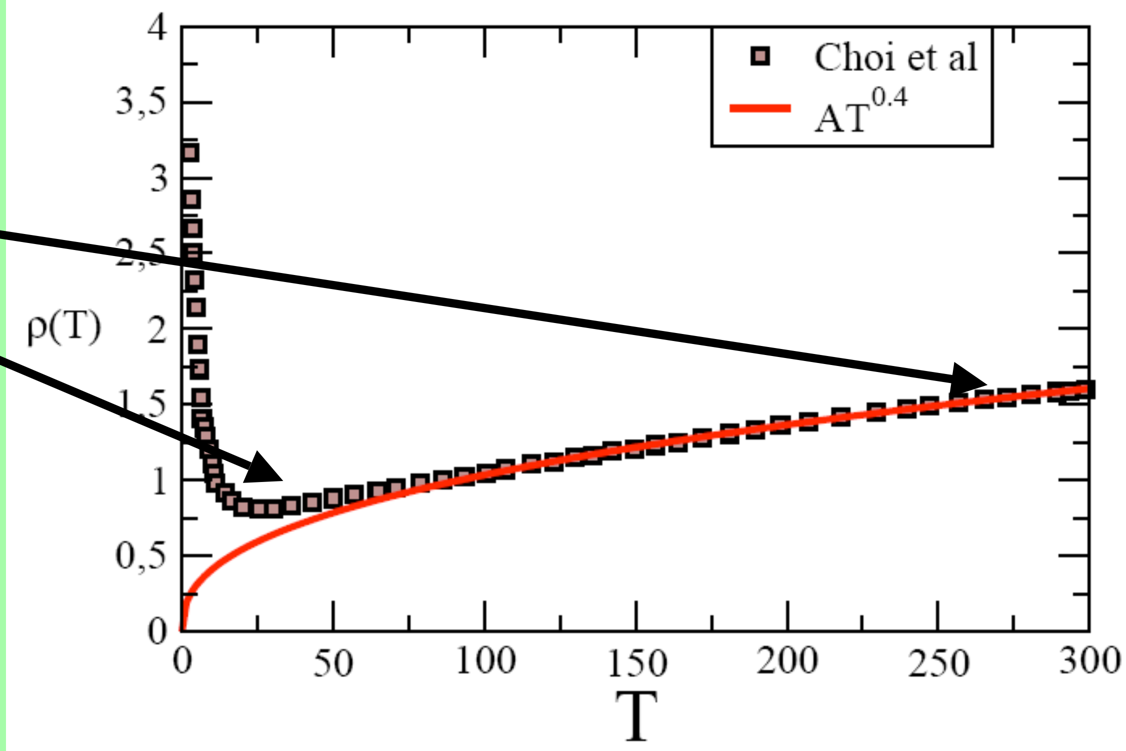
Parallel Transport :Power laws & resistivity rise

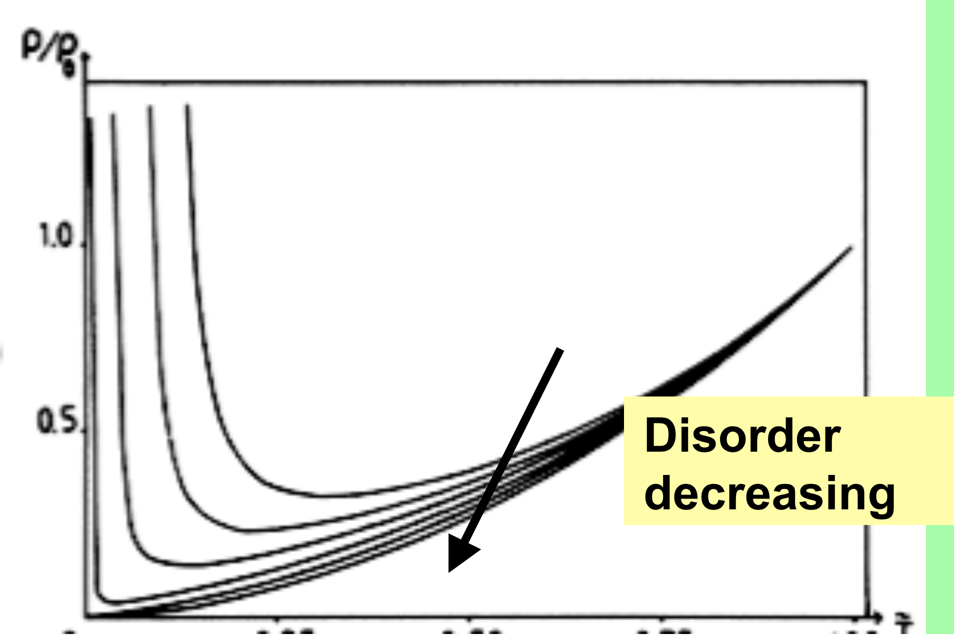
“High-T” power law?
Low T crossover T_{min}?



- **Not a transition to a CDW. No q**
- **No optical gap.**
- **Lineshapes very similar above and below the transition.**

Giamarchi & Schulz 88’:
Include disorder as a small pert. in the LL and treat it with RG.

Result: The scattering increases at low-T BUT the system characterized by eff. LL. It undergoes Anderson Localization below T_{min}



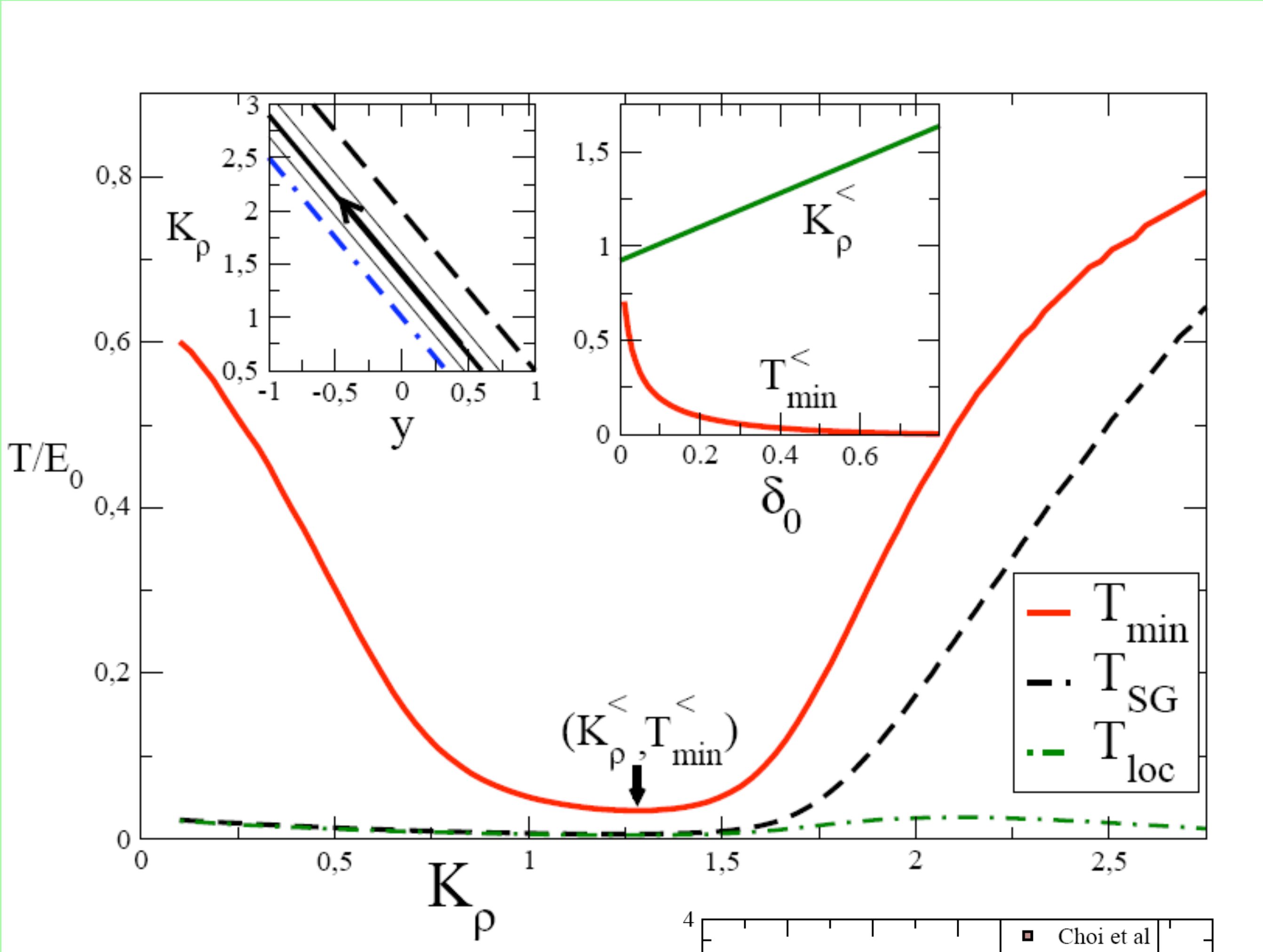
Parallel Transport :Power laws & resistivity rise

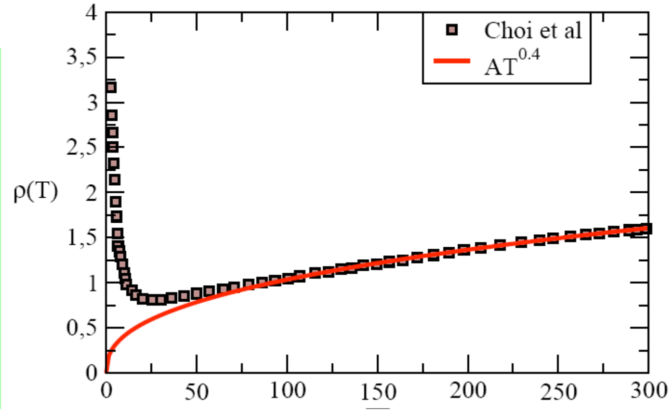
RG equations:
GS: (88)

$$(K_\rho)' = -\frac{K_\rho^2 u_\rho}{2u_\sigma}\mathcal{D}$$

$$y' = \{2 - 2K_\sigma\} y - \mathcal{D}$$

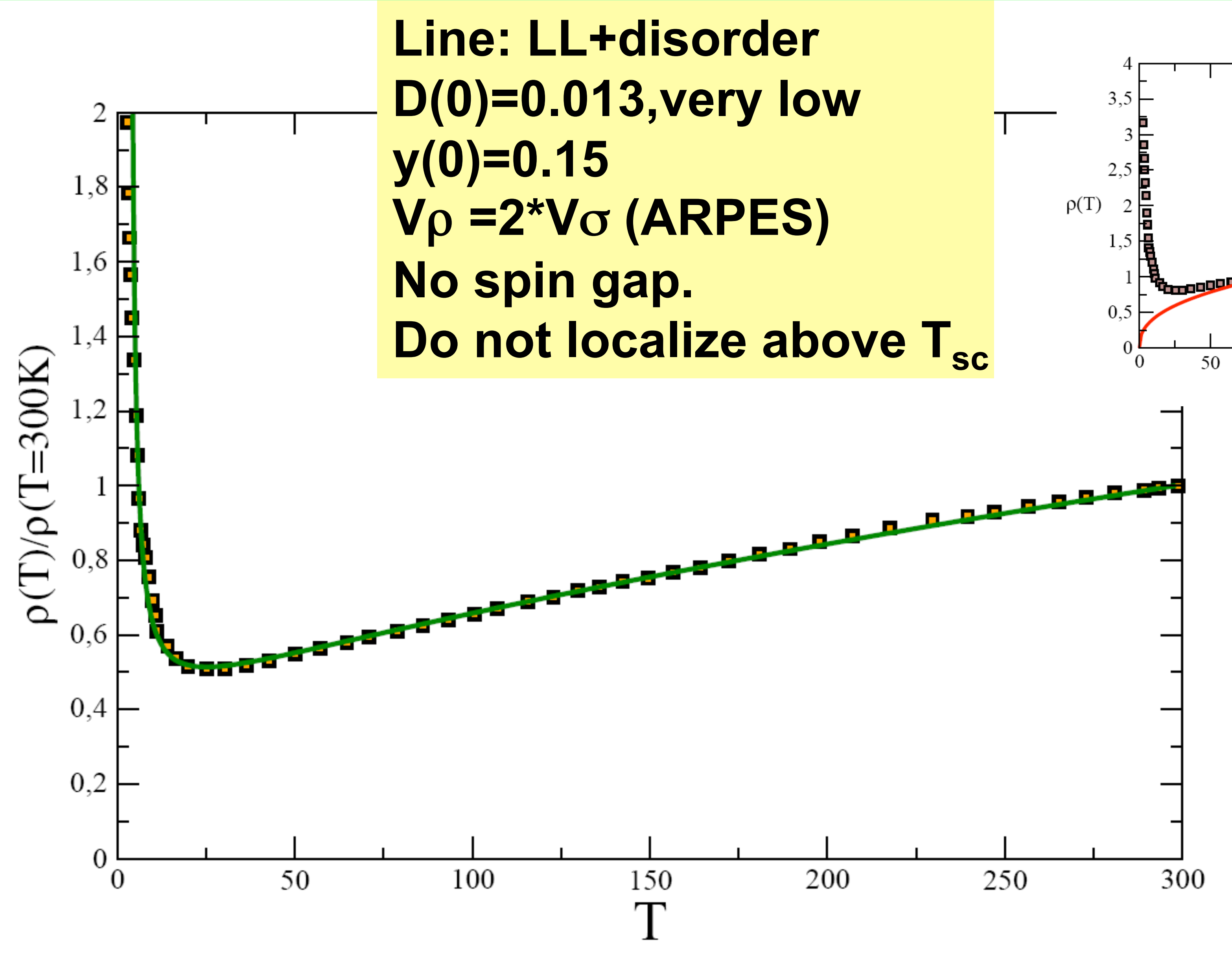
$$\mathcal{D}' = \{3 - K_\sigma - y - K_\rho\} \mathcal{D}$$



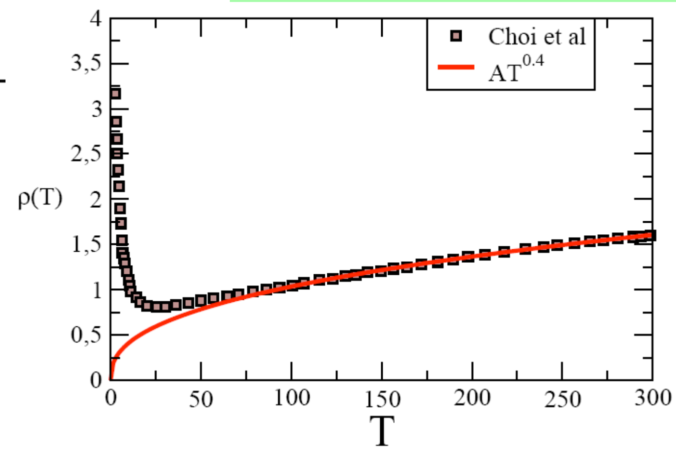


Compute resistivity using Kubo formula and Born approximation.

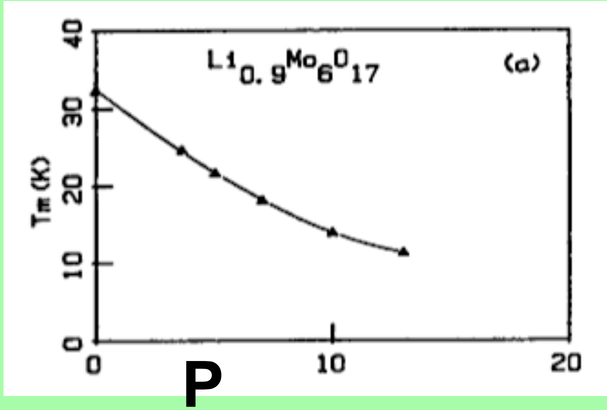
Experiment & Theory



Line: LL+disorder
D(0)=0.013,very low
y(0)=0.15
$V\rho = 2*V\sigma$ (ARPES)
No spin gap.
Do not localize above T_{sc}

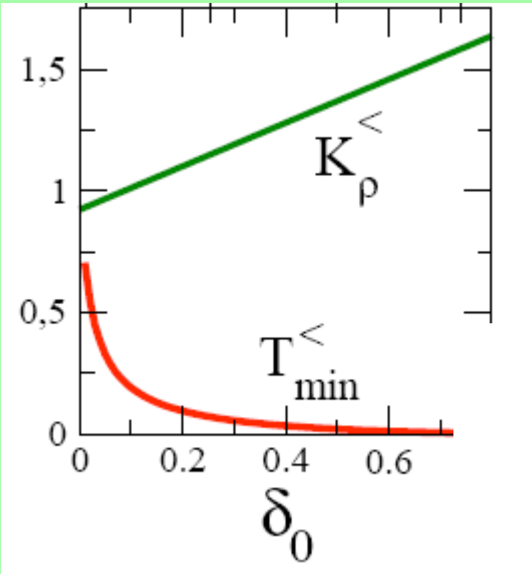


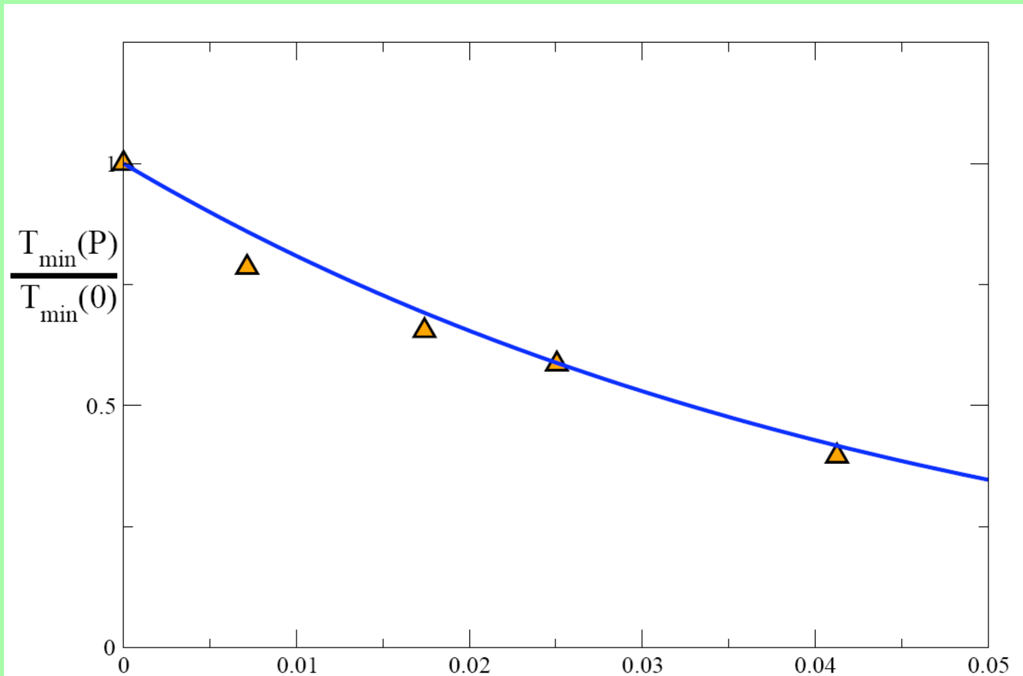
Parallel Transport : pressure dependence



Theoretical Relation:
asipmtotic δ and Tmin
Pressure changes both.
Same D(0) and y

Dots:Exp. Schlenker ('89)

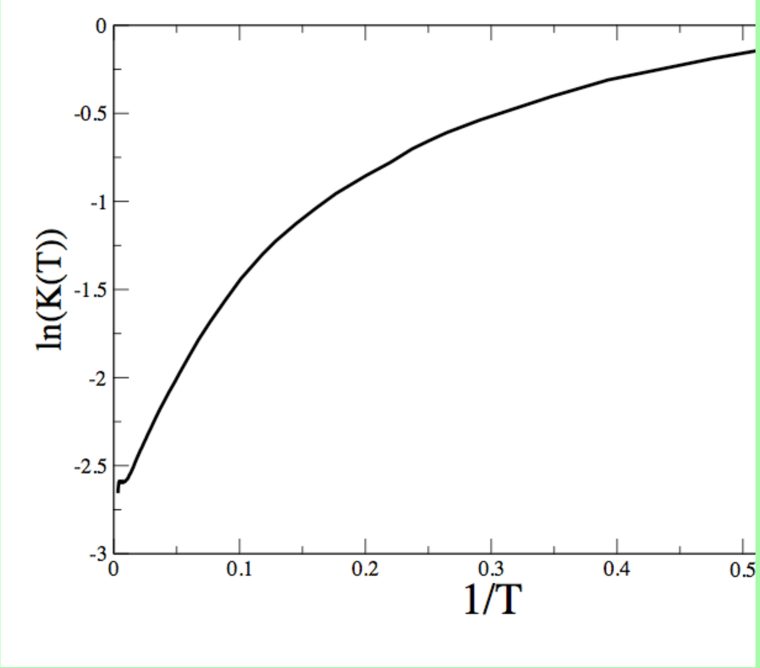


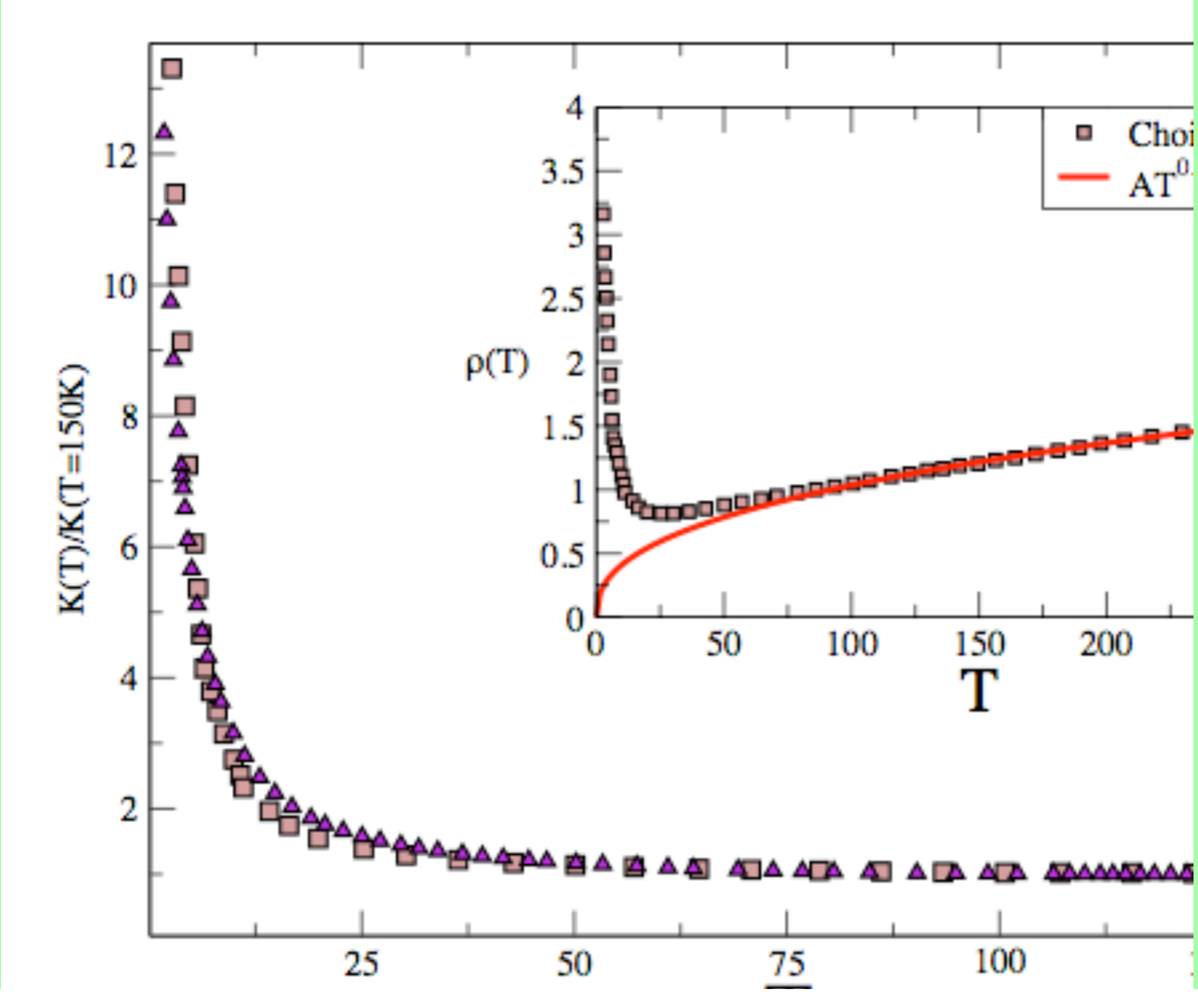


Parallel resistivity analysis.

- K(T): Substract the
  power-law part.
- Low-T:
- Different measurements:
  Schlenker (89) & Choi (04)
  very similar

Upturn does not fit
to an exponential
gapped behavior at low T





Summary

- $Li_{0.9}Mo_6O_{17}$ linear dispersion at E_F, large T*, small T_{3D}
  k_F incommensurate.

- Charge neutral critical modes contribute to the spectral density but not to transport; Interaction between these modes renormalize α (decreases with decreasing T).

- LL+Disorder can account for the upturn in the resistivity.
  Power laws shows up in the intermediate temperature regime.

- Sliding LL model and T=0 phase diagram
  position from resistivity exponents.