Confinement and Bechgaard salts

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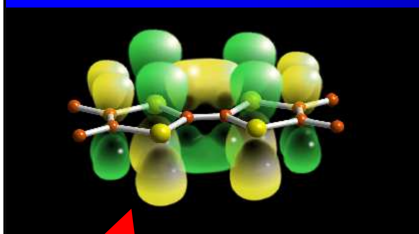
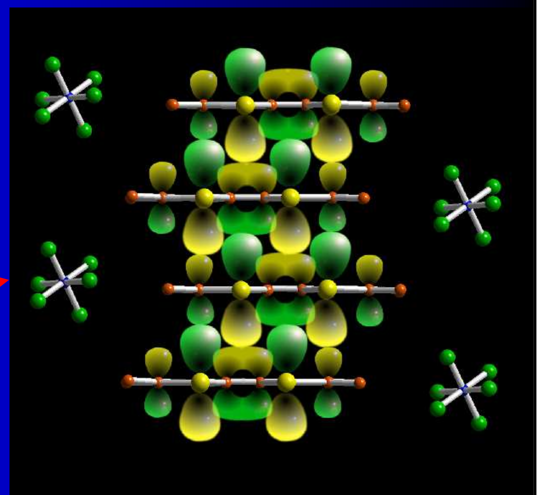
- Organic Superconductors: quasi-one dimensional systems (Bechgaard salts)
- TMTTF and TMTSF molecules
- Remarquable properties :
  - Non Fermi liquid behavior
  - Quantum Hall effect
  - Superconductivity and Frohlich conductivity

Organic (super-) conductors

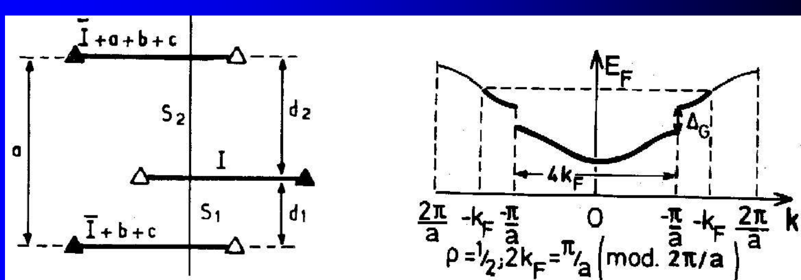




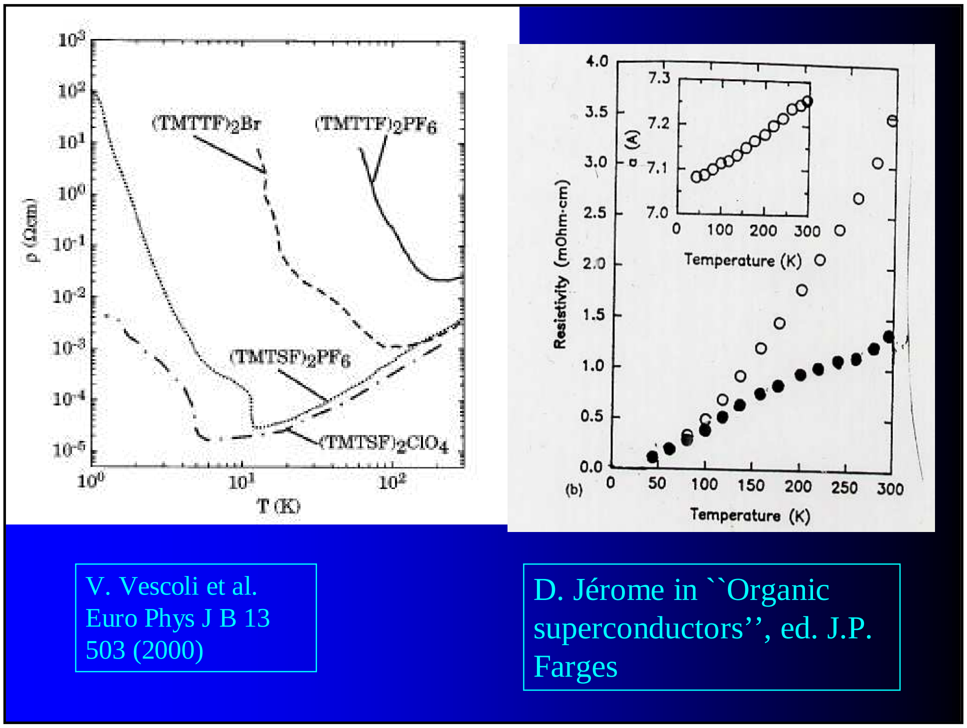
$TMTSF_2(X)$

• Propagation of electrons along the chains

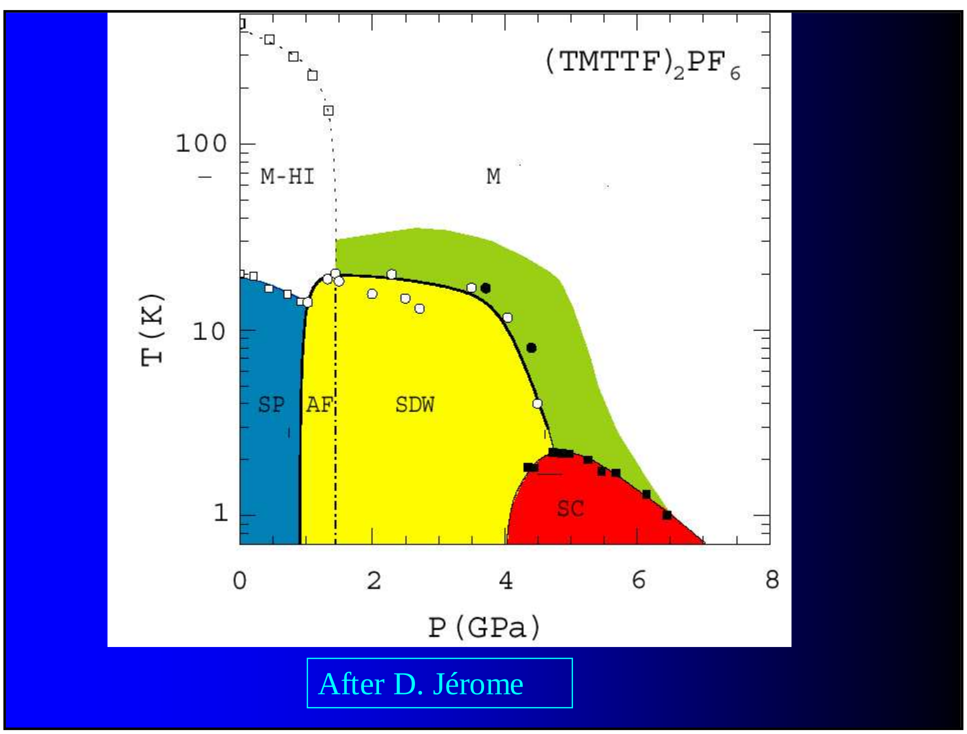
• Chemistry : quarter filled
• Small dimerization: half filled
• Mott insulator
• Is dimerization important ?



	TMTTF			TMTSF		
	PF6	ClO4	Br	PF6	ClO4	NO3
$\Delta = d_1 - d_2$	0.1.	0.04	0.03	0.03	0.01	0.01



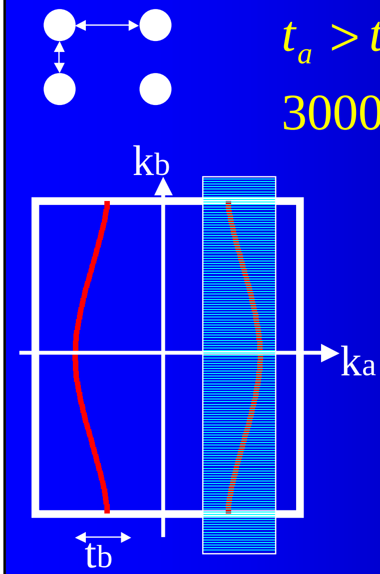
ρ (Ωcm)
T (K)
(TMTTF)2Br
(TMTTF)2PF6
(TMTSF)2PF6
(TMTSF)2ClO4
Resistivity (mOhm-cm)
Temperature (K)
a (Å)
(b)
V. Vescoli et al. Euro Phys J B 13 503 (2000)
D. Jérome in ``Organic superconductors'', ed. J.P. Farges



(TMTTF)2PF6
T (K)
P (GPa)
M-HI
M
SP
AF
SDW
SC
After D. Jérome

$t_a > t_b > t_c$

$3000K, 300K, 20K$



- High Energy (T,ω): 1D
- Low Energy (T,ω) : 2D,3D

Dimensional crossover

How is it modified by interactions ? T* ?

Questions

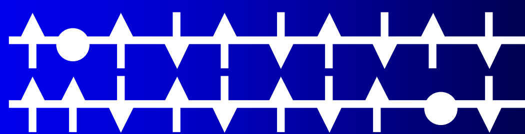
- Is the high temperature phase a Luttinger liquid/Mott insulator ?
- What is the strength of interactions ?
- How to describe the dimensional crossover ? (scale ?)
- What is the resulting ‘Fermi liquid’

Luttinger liquid

- Spin charge separation

Fermion

Spinon

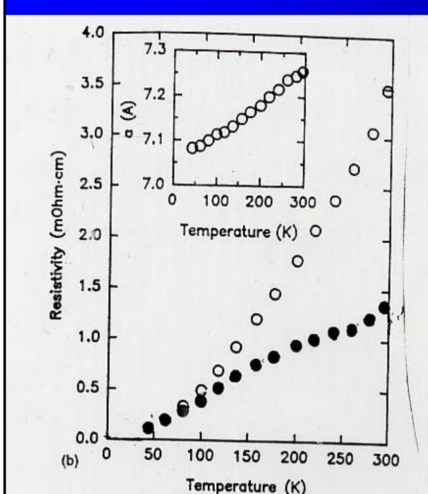


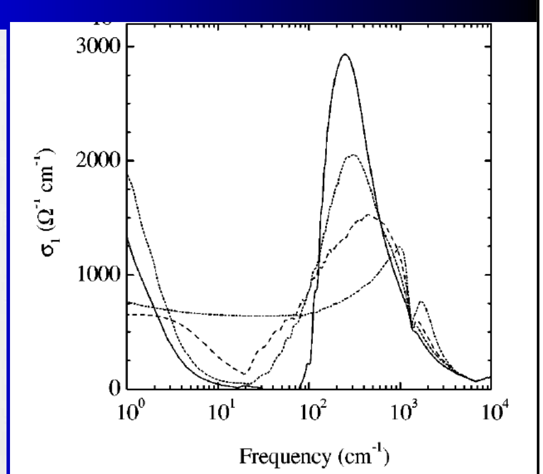
Holon

- No fermionic quasiparticles
- Power law decay of correlation functions

$$\langle S(x)S(0)\rangle = \frac{1}{x^2} + \cos(2k_F x)\left(\frac{1}{x}\right)^{1+K_\rho} + \ldots$$

Kρ contains all information about interactions

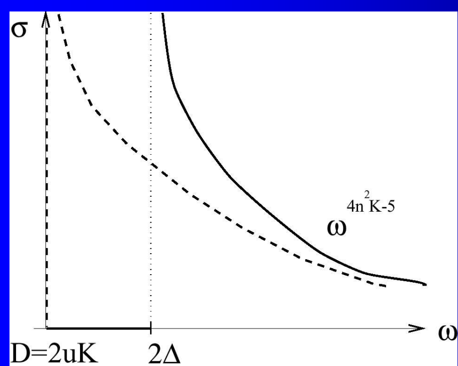




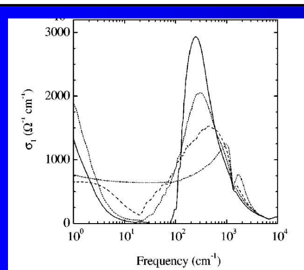
A. Schwartz et al. PRB 58 1261 (1998)

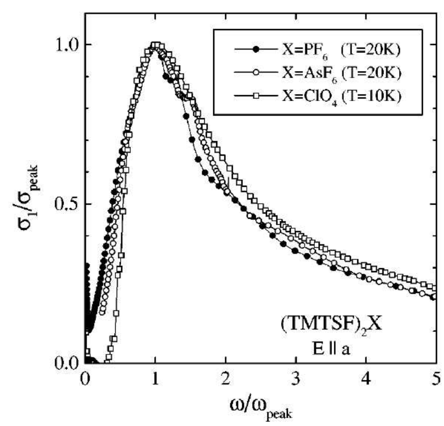
Transport in a LL

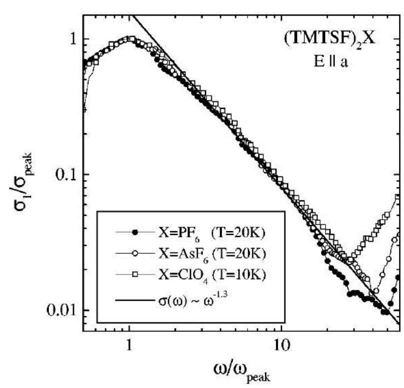
(TG PRB 44 2905 (91); Physica B 230 975 (97))



- Mott insulator for ¼ filling also !
- Power law in σ(ω) determines Kρ
- Deviations from 1D law gives Ec







A. Schwartz et al. PRB 58 1261 (1998)

Consequences

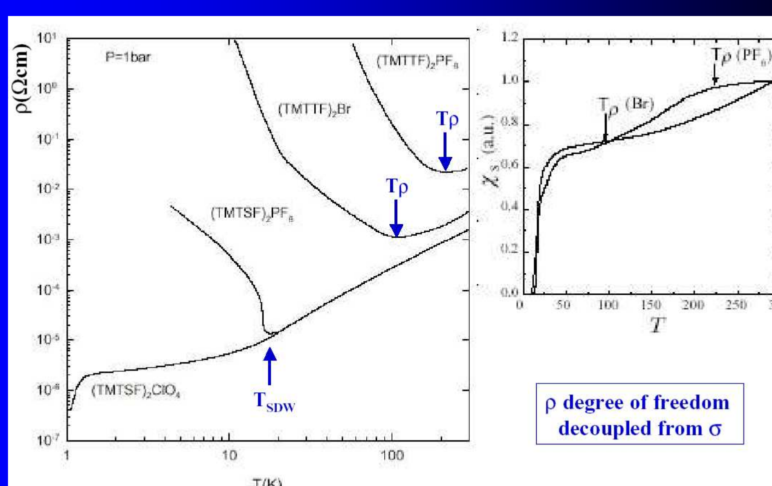
- Luttinger Liquid !
- $K\rho$ = 0.23 very strong interactions

• Dimerization not important (1/4 filled Mott insulator) [confirmed in new non-dimerized compound]

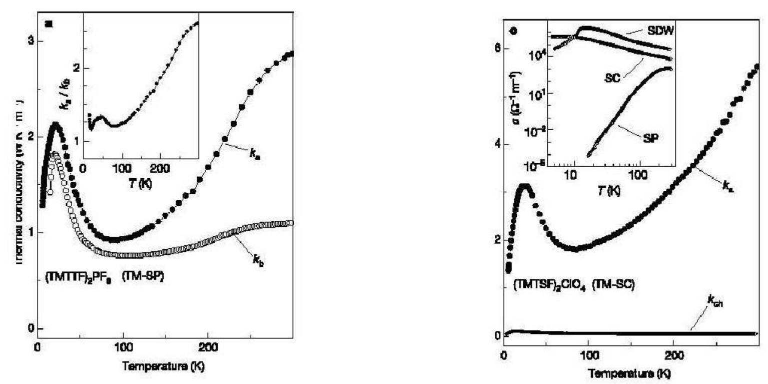
• TF vs SF likely to be due to change of interactions (quantum critical point)

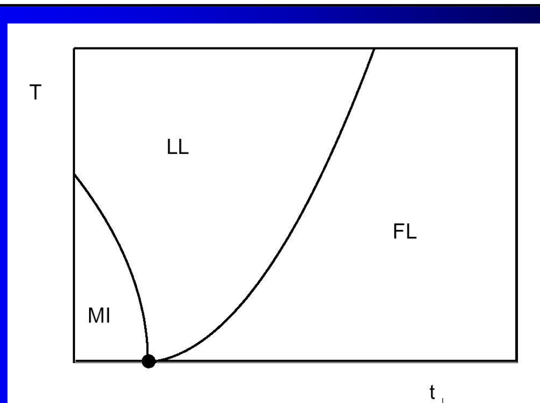
•Dimensional crossover at E=100K !

Charge spin separation ?



Lorenz et-al, Nature 418, 614, 2002





- Deconfinement : How to study ?
- Difficult (RG, RPA, etc.)

(S. Biermann, A. Georges, TG, A. Lichtenstein, cond-mat 0201542)

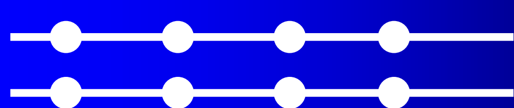
- Renormalization arguments
  (Bourbonnais, Brazovskii+Yakovenko, Schulz)

$$E^* \sim t_\perp (t_\perp / t)^{\alpha/(1-\alpha)}$$

$$\alpha = \frac{1}{4}(K_\rho + 1/K_\rho) - \frac{1}{2}$$

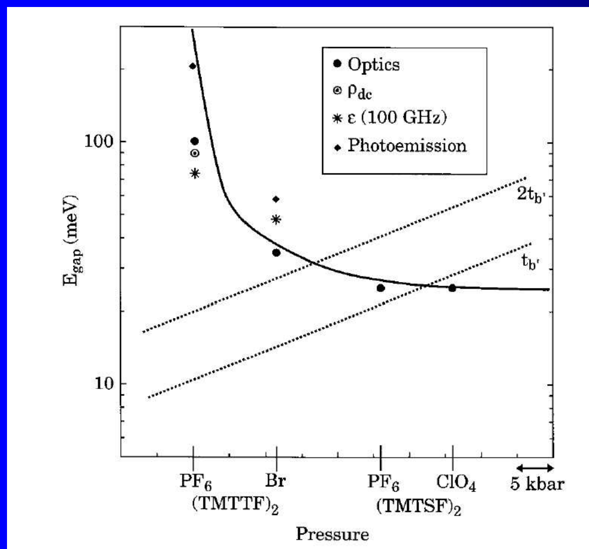
Strong reduction of crossover temperature. But hopping still relevant !

Mott insulators: confinement



- 1 chain : Mott insulator U >0
- 3d : Mott insulator U > Uc

Competition Mott insulator/Interchain hopping

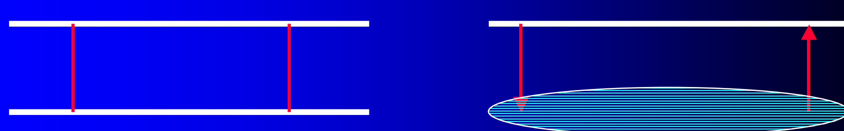


V. Vescoli et al.
Euro Phys J B 13
503 (2000)

Dimensional Crossover

(A. Georges, TG, N. Sandlers PRB 61 16393 (00))

(also E. Arrigoni 1999; 2000)



- $d = \infty + 1$ (chDMFT)
- Effective one dimensional theory

$$S_{\text{eff}} = -\int\int_0^\beta d\tau d\tau' \sum_{ij,\sigma} c^+_{i\sigma}(\tau)\mathcal{G}_0^{-1}(i-j,\tau-\tau')c_{j\sigma}(\tau') + \int_0^\beta d\tau H^{\text{int}}_{1\text{D}}[\{c_{i\sigma}, c^+_{i\sigma}\}], \quad (4)$$

$$G(k,i\omega_n) = \int d\epsilon_\perp \frac{D(\epsilon_\perp)}{i\omega_n + \mu - \epsilon_k - \Sigma(i\omega_n,k) - \epsilon_\perp}.$$

$$\text{Re}\,\sigma_\perp(\omega,T) \propto t_\perp^2 \int d\epsilon_\perp D(\epsilon_\perp) \int \frac{dk}{2\pi} \int d\omega' A(\epsilon_\perp,k,\omega') \times A(\epsilon_\perp,k,\omega+\omega') \frac{f(\omega') - f(\omega'+\omega)}{\omega}.$$

- Self consistent theory for Σ
- Feedback of $t_\perp$ in Σ (a priori important for deconfinement)
- Different from RPA

$$G(k,k_\perp,i\omega_n) = \frac{1}{i\omega_n - \varepsilon_k - \varepsilon_\perp(k_\perp) - \Sigma_{1D}(k,i\omega_n)}$$

- Difficult to solve the equations analytically

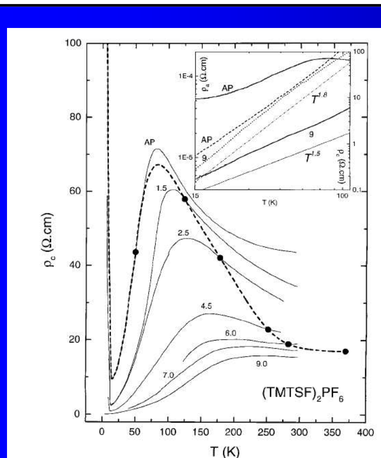
Transverse transport

$$\sigma(\omega,T) \propto (\omega,T)^{2\alpha-1}$$

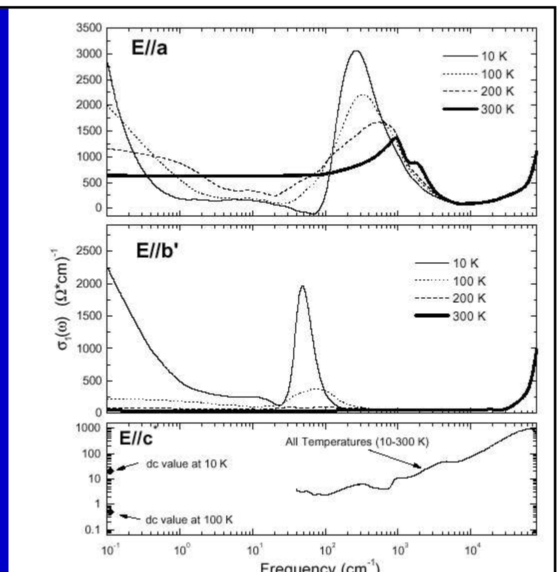
$$\alpha = \tfrac{1}{4}(K + K^{-1}) - \tfrac{1}{2}$$

$$\alpha \approx 0.6$$

$$\omega_{D\perp}^2/\omega_{P\perp}^2 \propto (t_\perp/t)^{2\alpha/(1-\alpha)} = Z^2$$



J. Moser et al. Euro Phys. J. B 1 39 (1998)



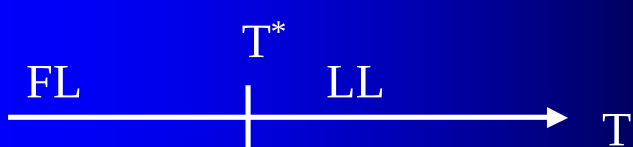
V. Vescoli et al. Euro Phys J B 11 365 (1999)

Numerical Solution

(S. Biermann, A. Georges, A. Lichtenstein, TG, PRL 87 276405 (2001))

- Hubbard Model
- QMC (16 – 32 sites)
- 32 time slices (T/W = 1/50)

Incommensurate case



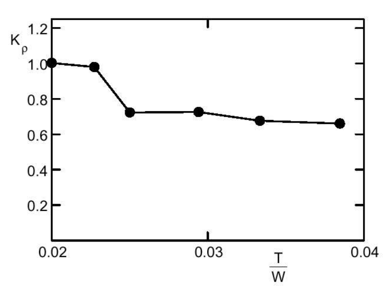


FIG. 2: Effective K_ρ *vs.* temperature in the doped case (filling $n \simeq 0.8$) for $U/W = 1.0$, $t_\perp/W = 0.14$.

$$T^* \approx \frac{t_\perp}{\pi}\left(\frac{t_\perp}{t}\right)^{\frac{\theta}{1-\theta}}$$

$$T^* \approx 0.5\frac{t_\perp}{\pi}$$

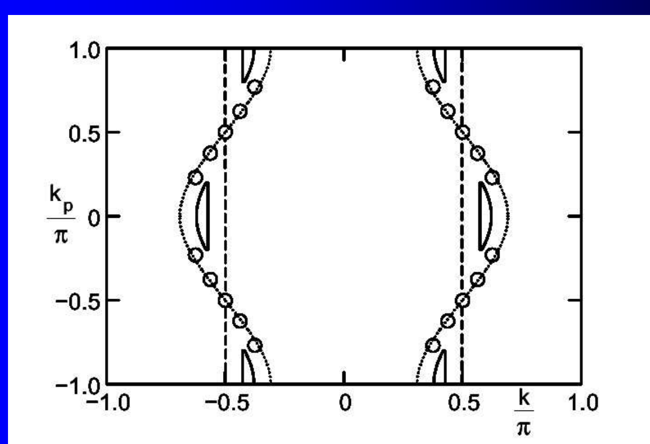
Commensurate case

TABLE II: Effective K_ρ at half-filling, as a function of $t_\perp/W$ for $U/W = 0.65$ and $T/W = 1/40$.

$t_\perp/W$	0.00	0.04	0.07	0.11	0.14	0.16	0.18
K_ρ	0.00	0.02	1.01	1.09	1.07	1.06	1.04

$$t_\perp^* \approx \Delta_{1D}$$

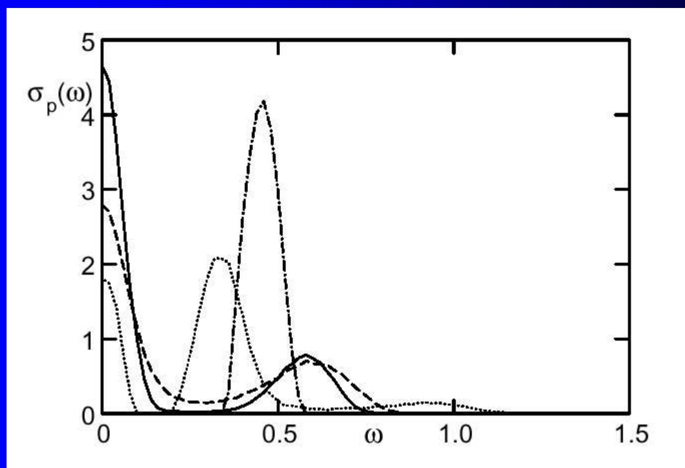
Fermi Surface

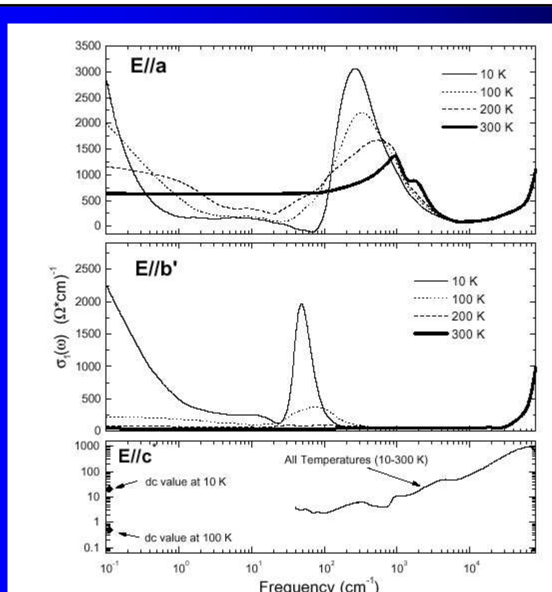


Z

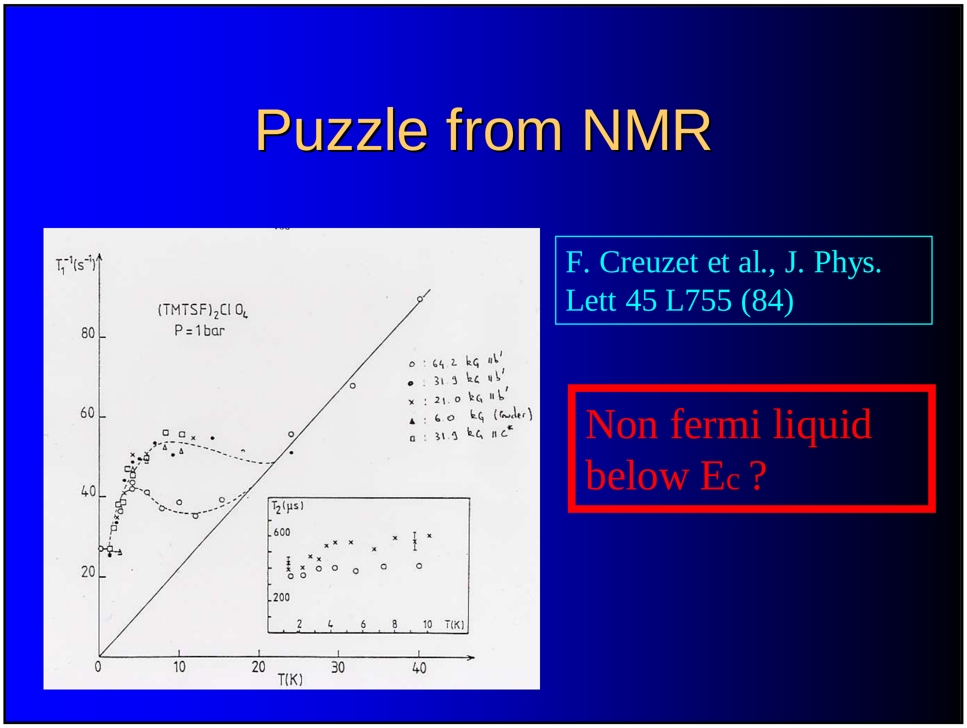
$k_\perp/\pi$	0.23	0.38	0.50	0.62	0.77
$Z(k_\perp)$	0.78	0.77	0.76	0.77	0.79

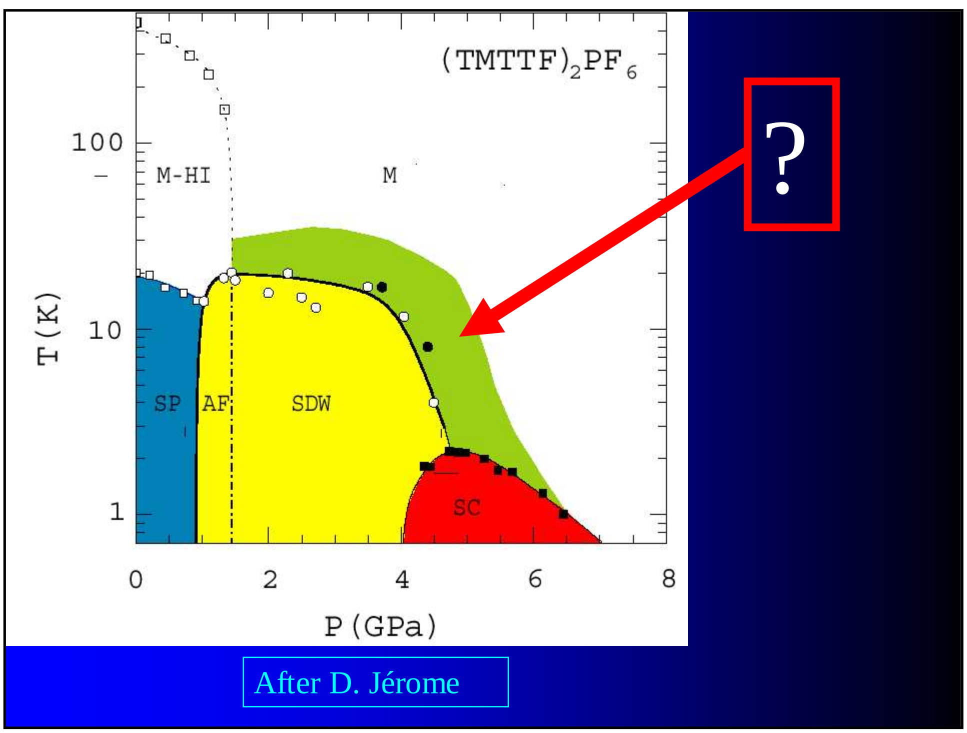
Transverse conductivity

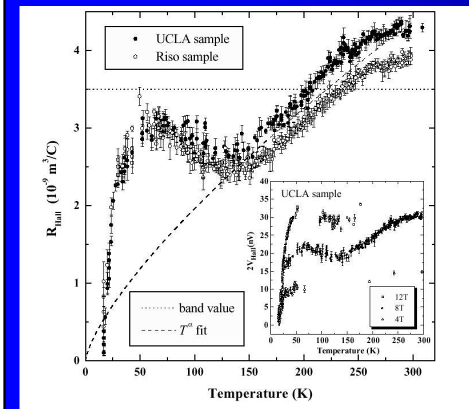




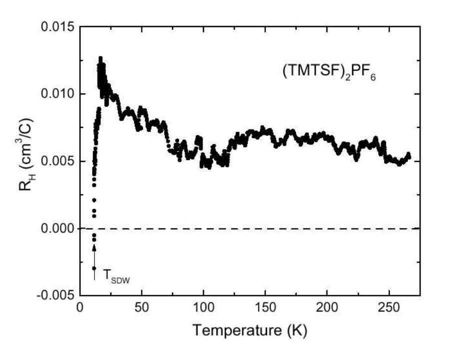
V. Vescoli et al. Euro Phys J B 11 365 (1999)


Puzzle from NMR
F. Creuzet et al., J. Phys. Lett 45 L755 (84)
Non fermi liquid below Ec ?
(TMTSF)2ClO4
P = 1 bar
T(K)
T2(µs)


(TMTTF)2PF6
M-HI
M
SP
AF
SDW
SC
T (K)
P (GPa)
?
After D. Jérome



J. Moser et al., PRL 84 2674 (00)



G. Mihaly et al., PRL 84 2670 (00)

Hall Effect

(A. Lopatin, A. Georges, TG PRB 62 (00))

If no momentum relaxation (no umklapp) along the chains:

$$\rho_{yx} = \frac{H}{nec}\frac{2\alpha k_F}{v_F}.$$

With umklapp : scaling expression for Hall

$$R_H(T) = R_H^0\left(1 + a_1\frac{g_3}{T^{1/x}} + a_2\frac{g_3^2}{T^{2/x}} + \cdots\right)$$

$$2x = 1/(1 - n^2 K_\rho)$$

Plot of R_h vs ρ_{xx}/T

Conclusions

- Transport proves LL nature of high enery phase
  - K=0.23, ¼ filled Mott insulators
  - Ec = 100K much higher than expected
- Good method to tackle the dimensional crossover

- ¼ Filling with chDMFT
- Other physical quantities : Hall effect
- Nature of the 2D phase ? 2D non Fermi liquid ?
- Ordered phases (superconductivity)