

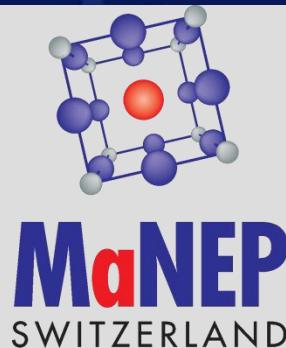
Transport and magnetism in 1D and quasi-1D systems



UNIVERSITÉ
DE GENÈVE

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SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION



One and quasi-one systems

- Peculiar physics: Tomonaga-Luttinger liquid
- Collective excitations with powerlaw decay
$$\langle S(x)S(0) \rangle = \frac{1}{x^2} + \cos(2k_F x) \left(\frac{1}{x}\right)^{K_\sigma + K_\rho}$$
- Fractionalization of excitations

Questions

- Consequences for magnetism and transport
- Coupled 1D chains: 1D or 3D behavior ?
Dimensional crossover
- Hall effect

More details:

TG, Quantum physics in one dimension, Oxford (2004)

TG, Chemical reviews 104, 5037 (2004)

TG, C. R. Physique 17, 322 (2016)

Magnetism



Magnetic insulators

- Interesting problem in itself (spin liquid,...)
- Many materials; dimensions, interactions,....
- Microscopic interactions **short range** and thus well controlled
- Can be used as quantum simulators

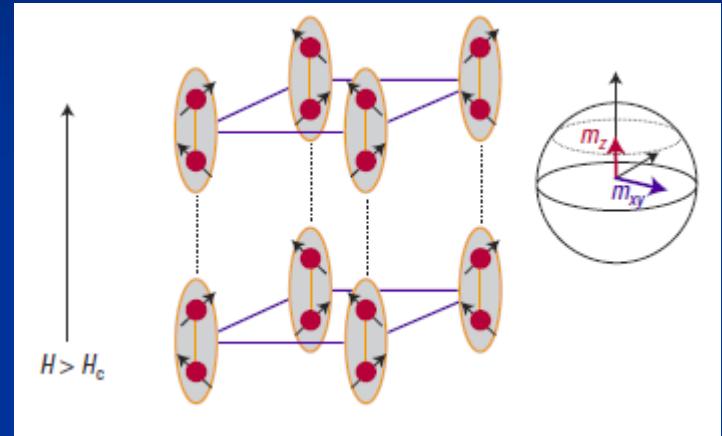
S. Ward et al, J. of Physics 25, 014004 (2013)

Magnets and molecular materials

- Use molecular compounds to get small exchange $J \sim 10 \text{ K}$ magnets
- Possibility to manipulate with magnetic field
- $T, E, \text{etc.} \sim J$: field theory alone is not enough
- Need to develop essentially exact solutions

Examples of possible use of QS

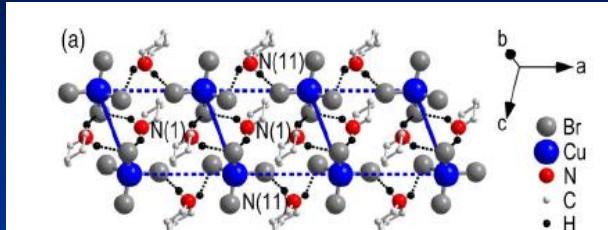
- Bose Einstein condensation
(d=3,d=2....)



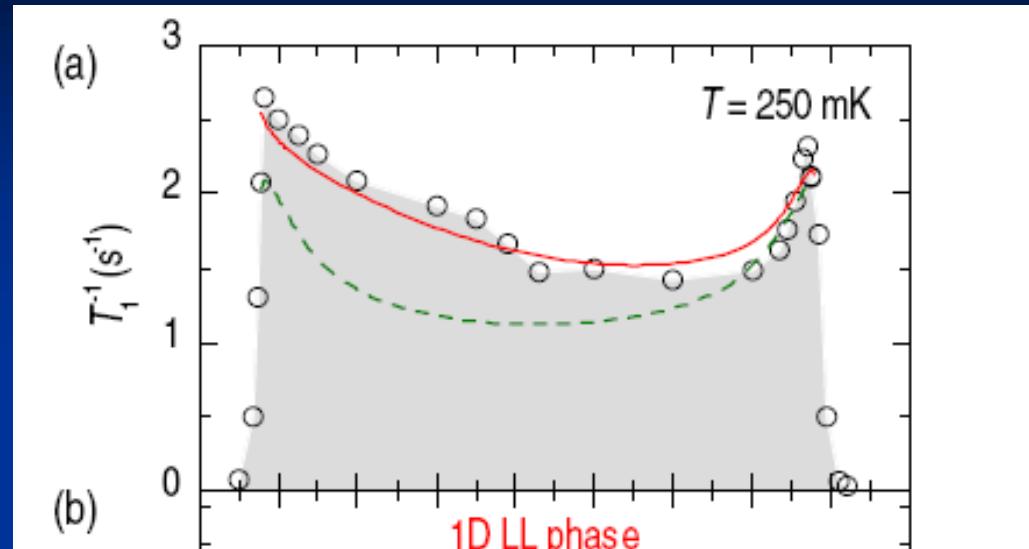
TG and A. M. Tsvelik PRB 59 11398 (1999)

TG, Ch. Rüegg, O. Tchernyshyov, Nat. Phys. 4 198 (08)
V. Zapf, M. Jaime, C. Batista, Rev Mod Phys 86 563;
86 1453 (2014)

Quantitative test of Tomonaga-Luttinger liquids

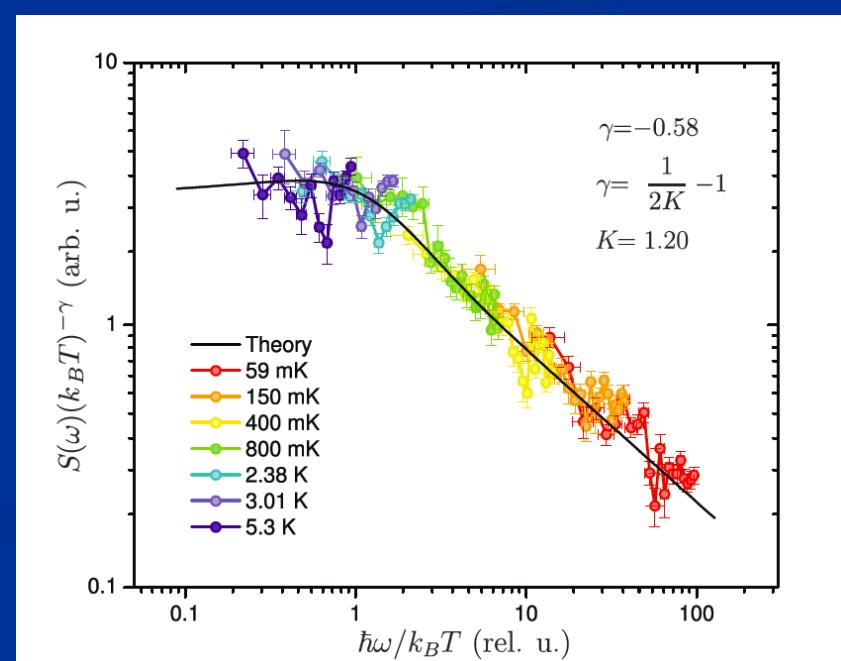


M. Klanjsek et al., PRL
101 137207 (2008)



D. Schmidiger et al. PRL 108
167201 (12):
K. Yu et al. arxiv/1406.6876
(14)

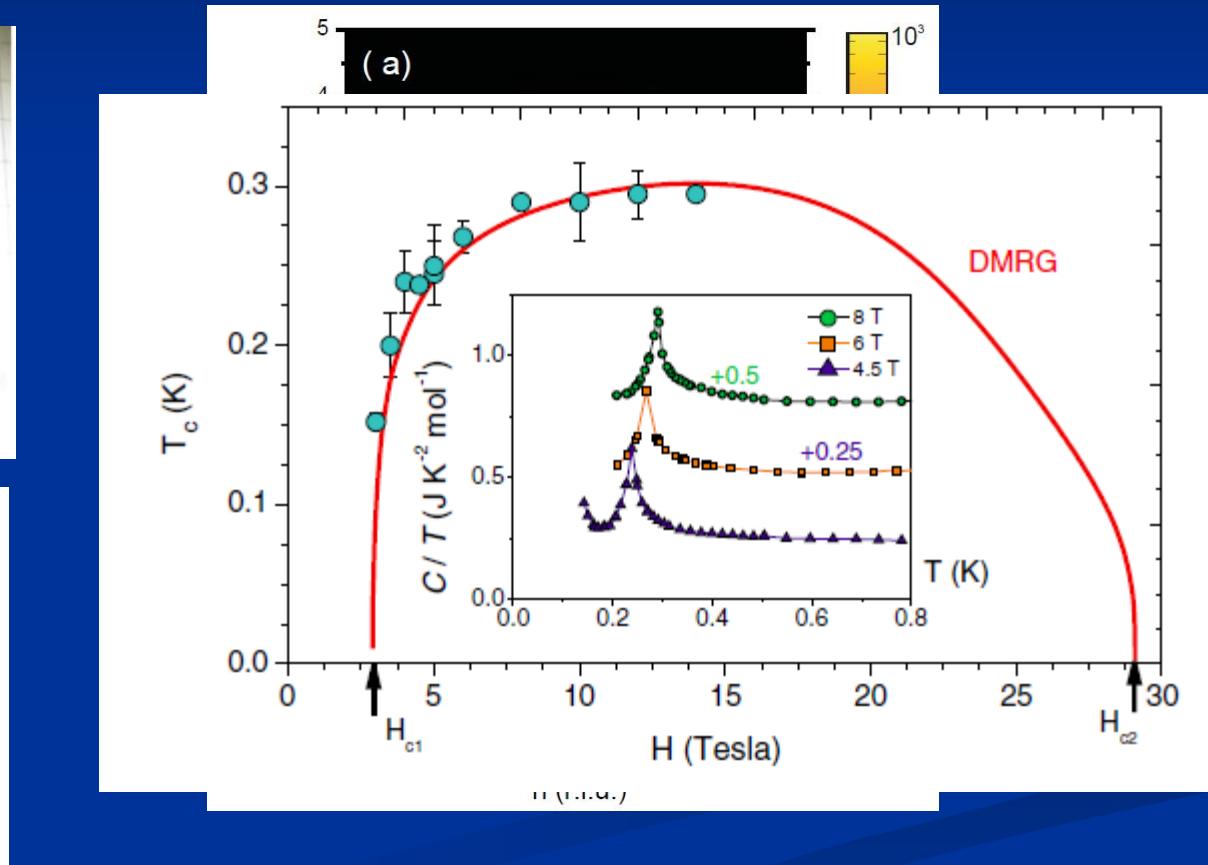
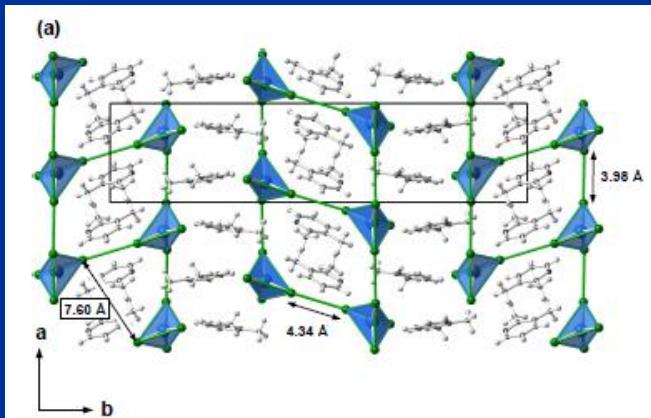
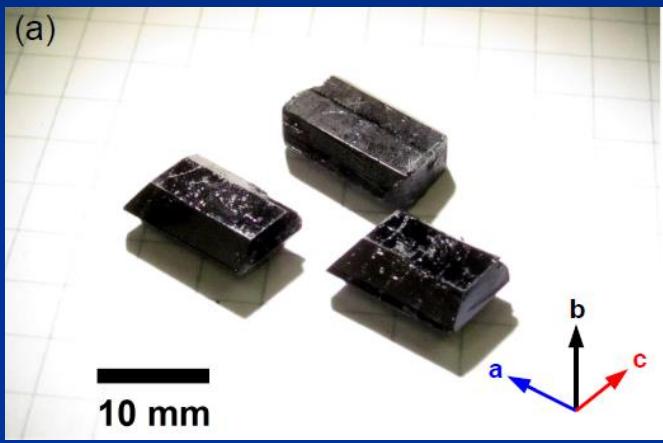
$$\langle S^- S^+ \rangle_{q,\omega} = \langle \psi \psi^\dagger \rangle_{q,\omega}$$



Hamiltonian reconstruction



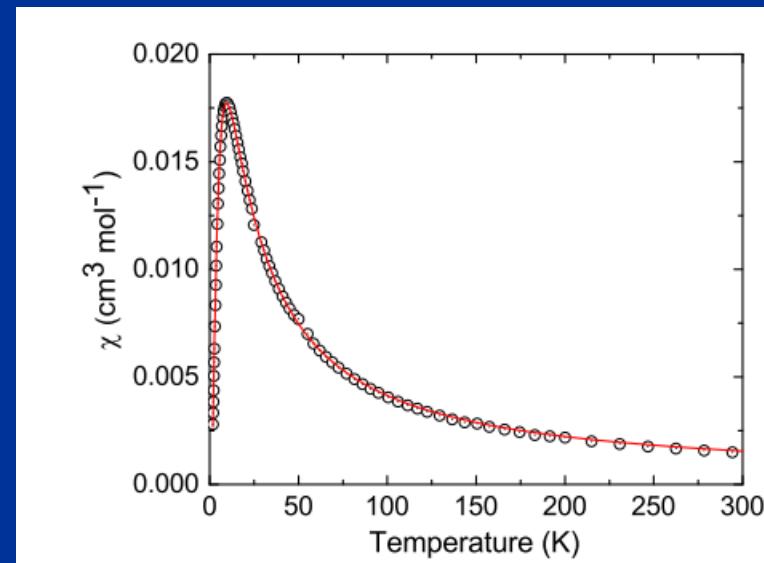
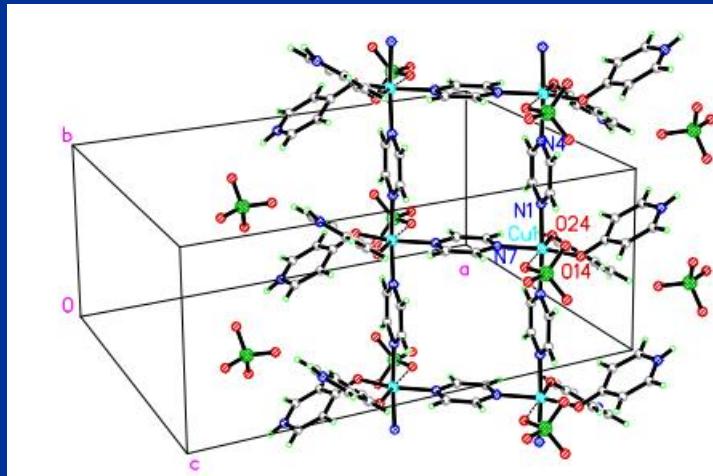
D. Schmidiger et al. PRL 108 167201 (2012)



$$\mathcal{H} = J_{\text{leg}} \sum_{l,j} S_{l,j} \cdot S_{l+1,j} + J_{\text{rung}} \sum_l S_{l,1} \cdot S_{l,2} - g\mu_B H \sum_{l,j} S_{l,j}^z.$$

Magnetic properties of a quantum spin ladder in proximity to the isotropic limit

S. A. Zvyagin^{1,*}, A. N. Ponomaryov^{1,†}, M. Ozerov^{1,‡}, E. Schulze,^{1,2} Y. Skourski,¹ R. Beyer,¹ T. Reimann^{1,§}, L. I. Zviagina,¹ E. L. Green^{1,‡}, J. Wosnitza,^{1,2} I. Sheikin,³ P. Bouillot,⁴ T. Giamarchi⁴, J. L. Wikara,⁵ M. M. Turnbull^{1,6}, and C. P. Landee^{1,7,§}



J= 10-12K

We need new molecular quantum
spin systems !!

Transport



Thanks to ...

H. J. Schulz

C. Berthod

C. Bourbonnais

S. Biermann

A. Georges

G. Leon

A. Lichtenstein

A. Lopatin

A. J Millis

J. Voit

P. Auban

P. Batail

L. DeGiorgi

M. Dressel

G. Gruner

D. Jerome

V. Vescoli

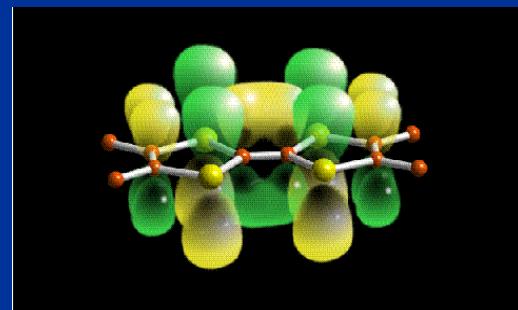
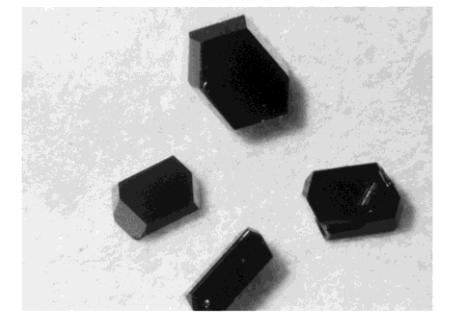
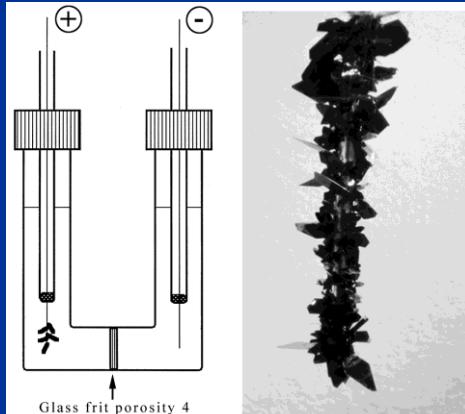
A. Schwarz

.....

.....

Bechgaard salts

1979: K. Bechgaard

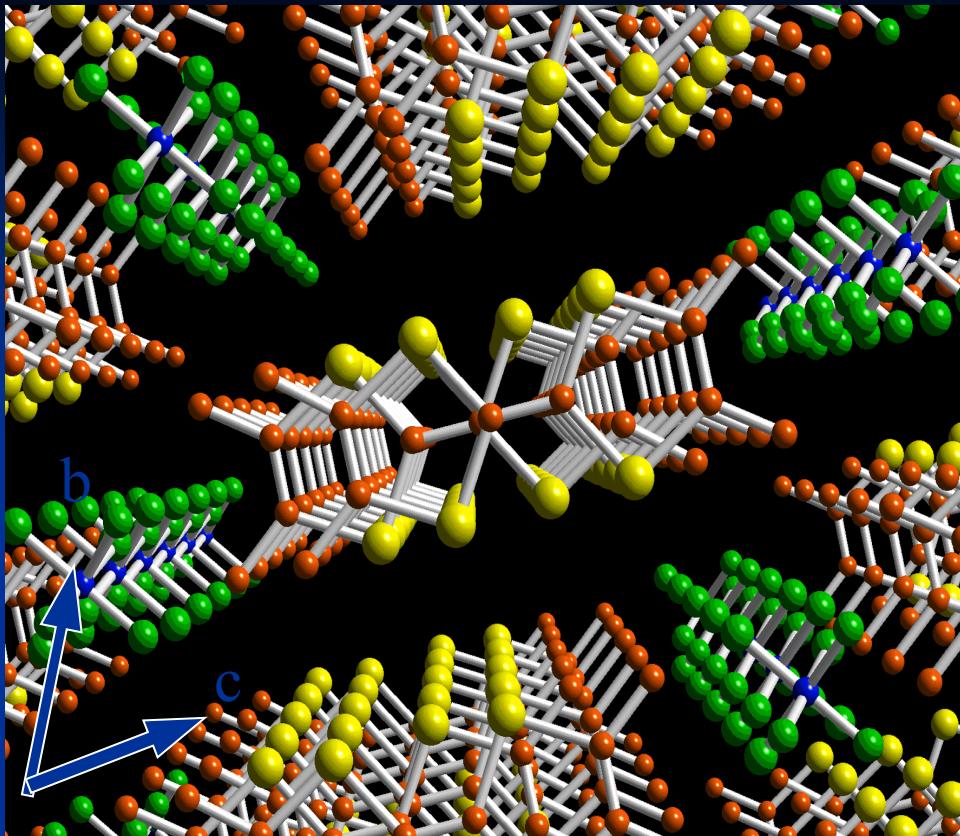


TMTSF

$(TMTSF)_2X$, $X=PF_6^-$, ..., ClO_4^- , ..

TMTTF : atoms S (Fabre)

TMTSF : atoms Se (Bechgaard)

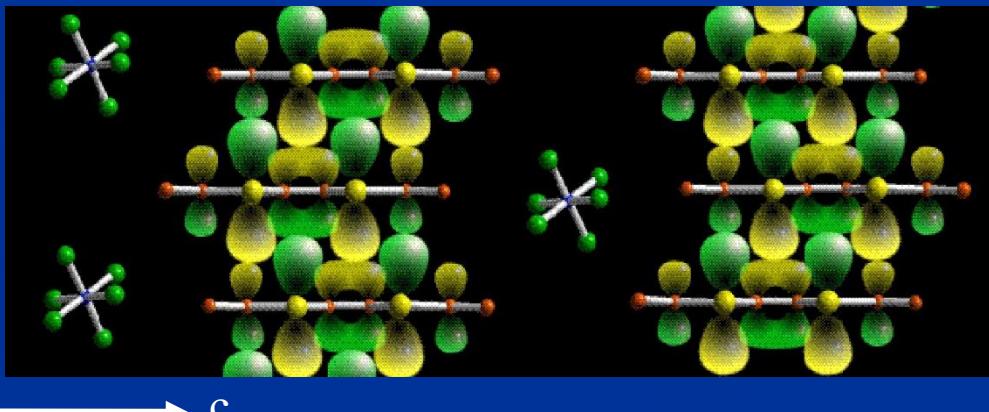


- Salt
- Quarter filled band

$$t_a \sim 3000\text{K}$$

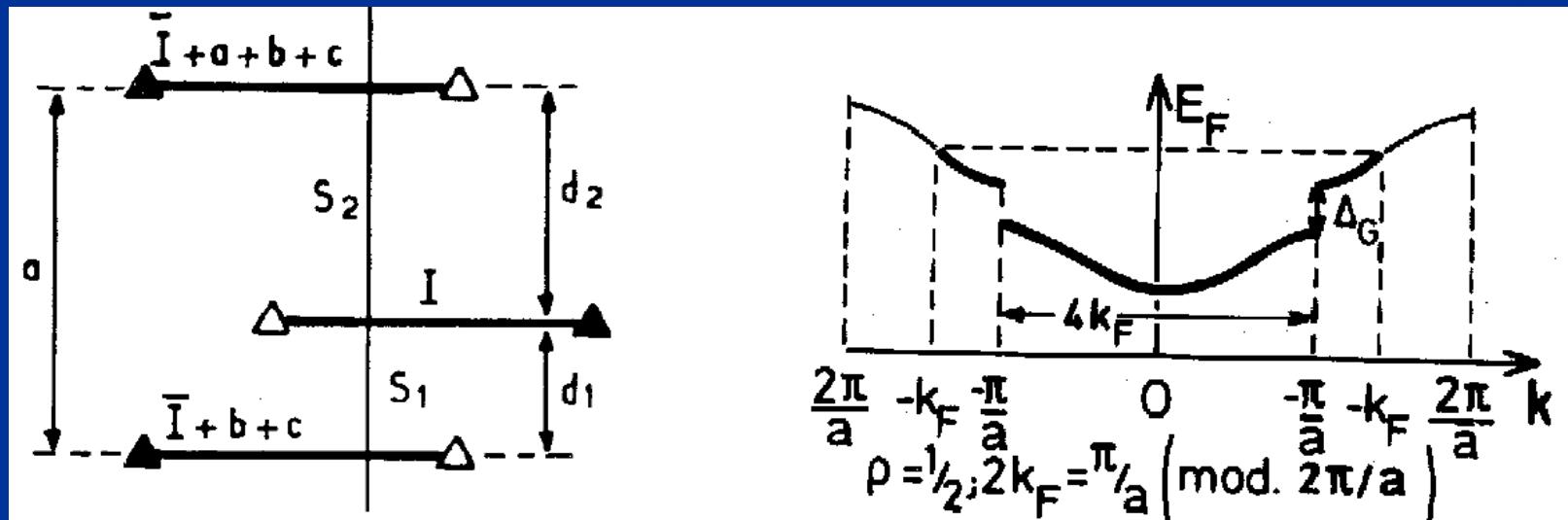
$$t_b \sim 300\text{K}$$

$$t_c \sim 30\text{K}$$



Quasi 1D

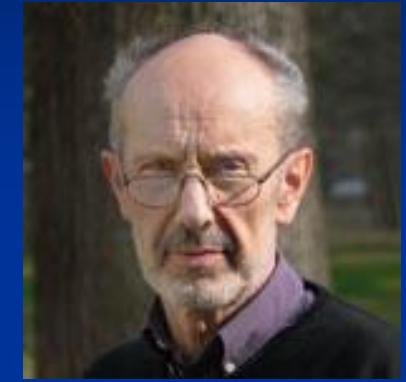
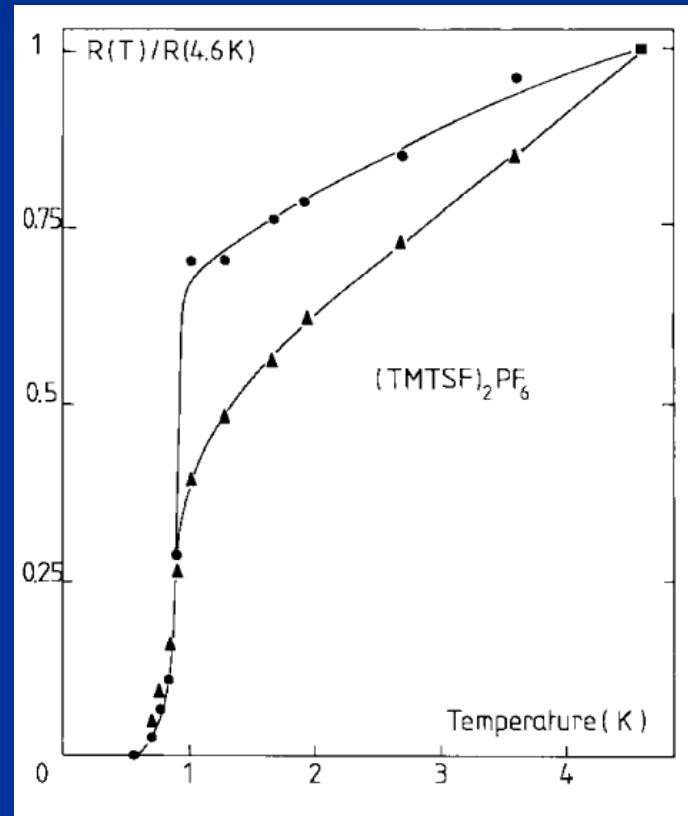
- Chemistry : quarter filled
- Small dimerization: half filled
- Mott insulator [Emery,Barisic]
- Is dimerization important ?



	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

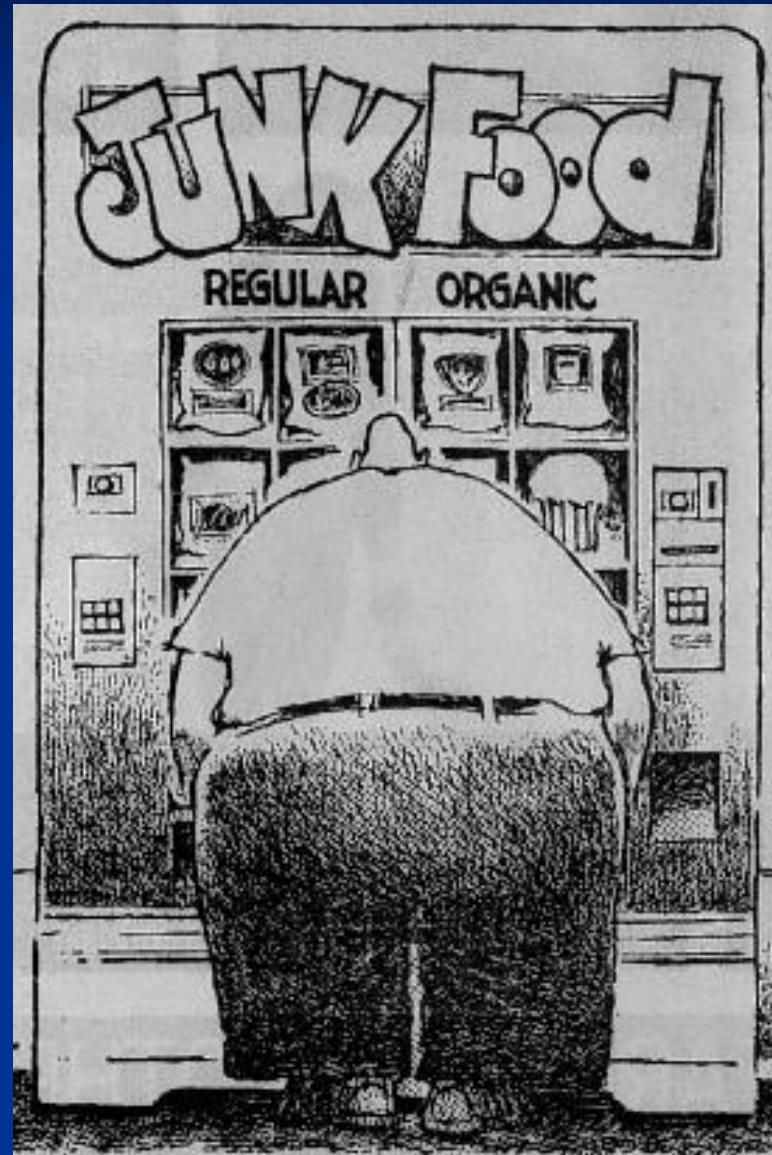
Superconductivity !

1981: D. Jerome

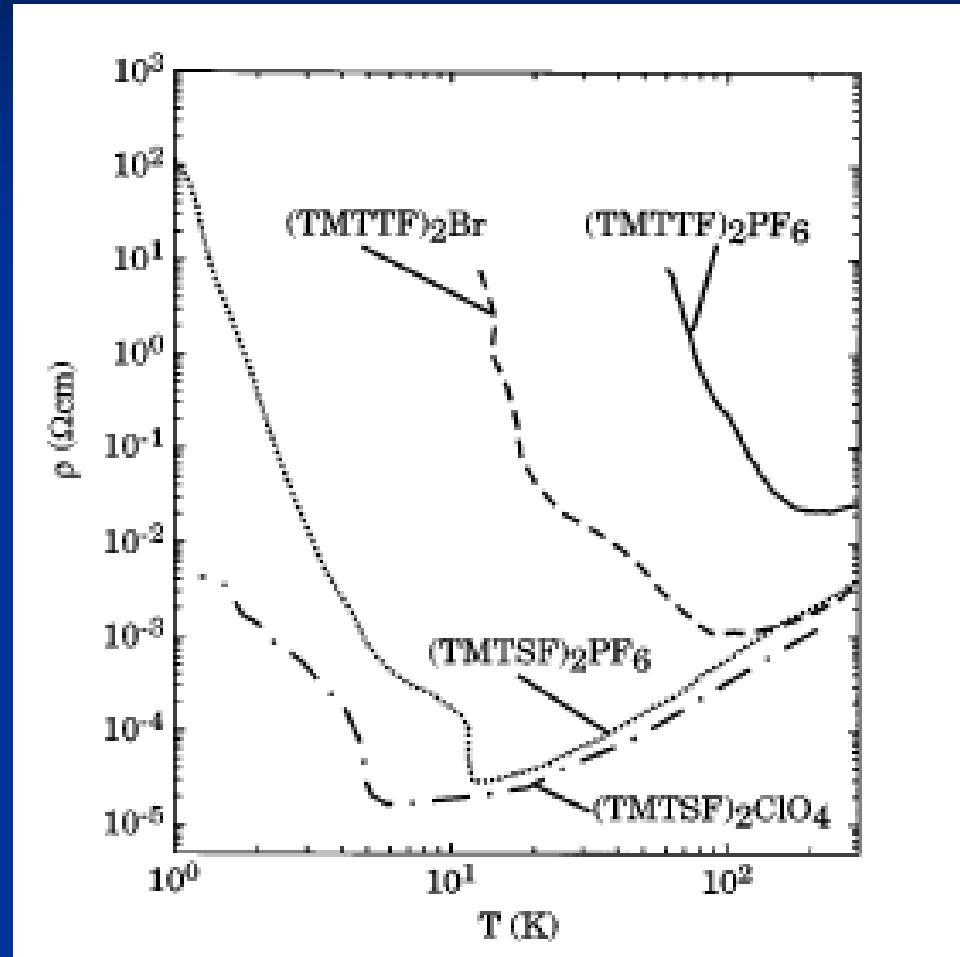
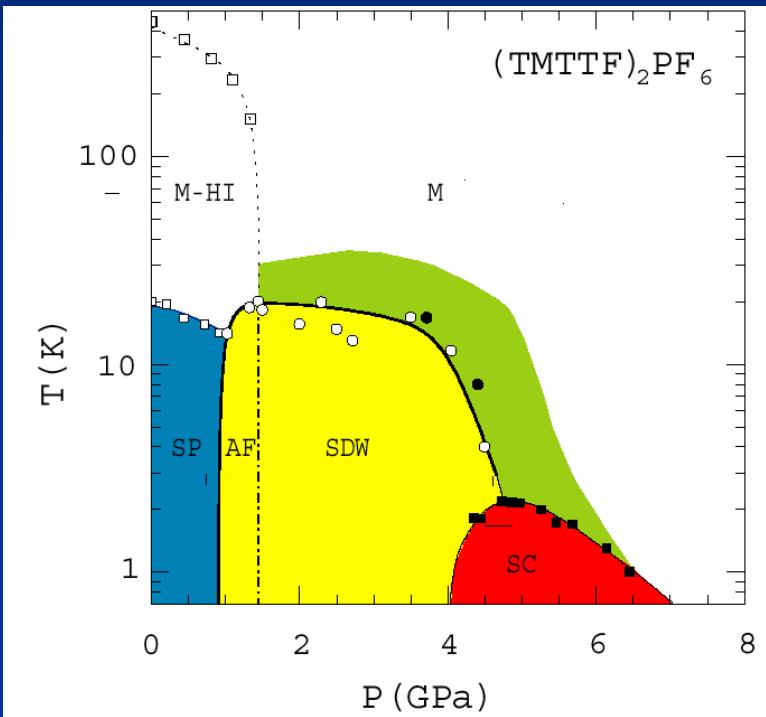


D. Jerome, M.Ribault,J.Mazaud and K.Bechgaard (1980)

Should we still care ?

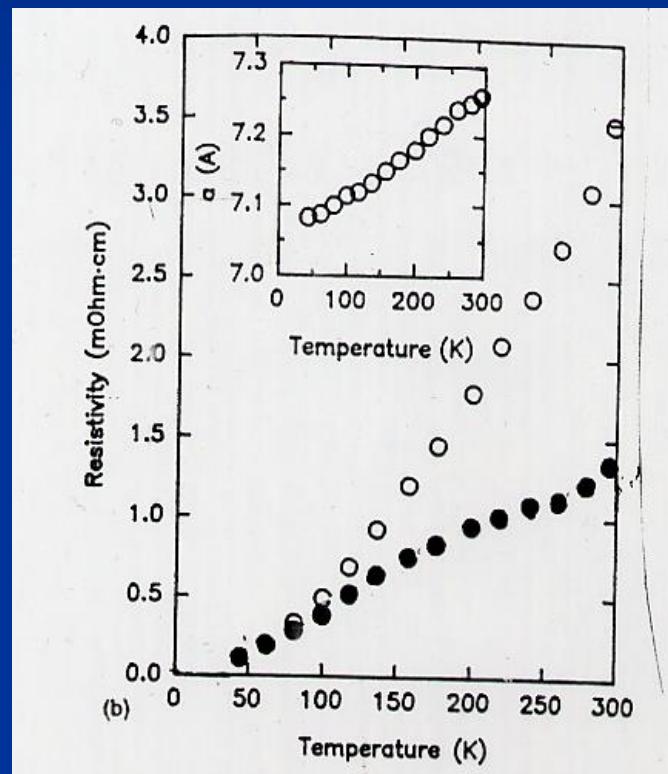
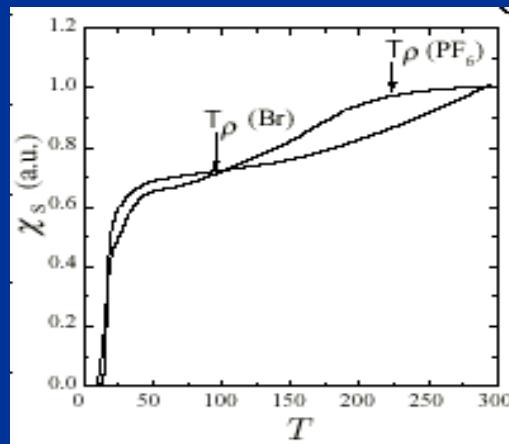
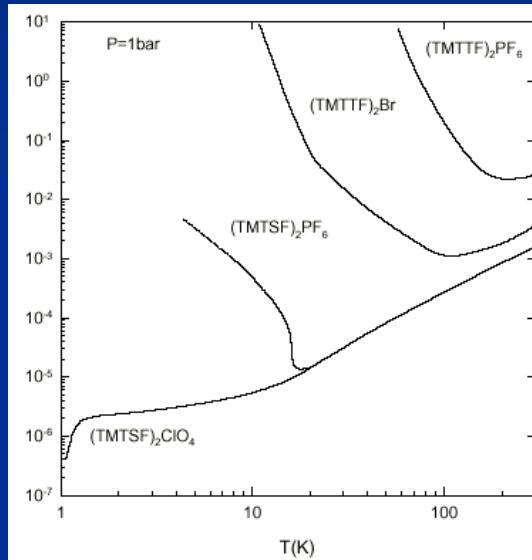


Strongly correlated; 1D physics



Mott insulators

Are organics TLLs ?

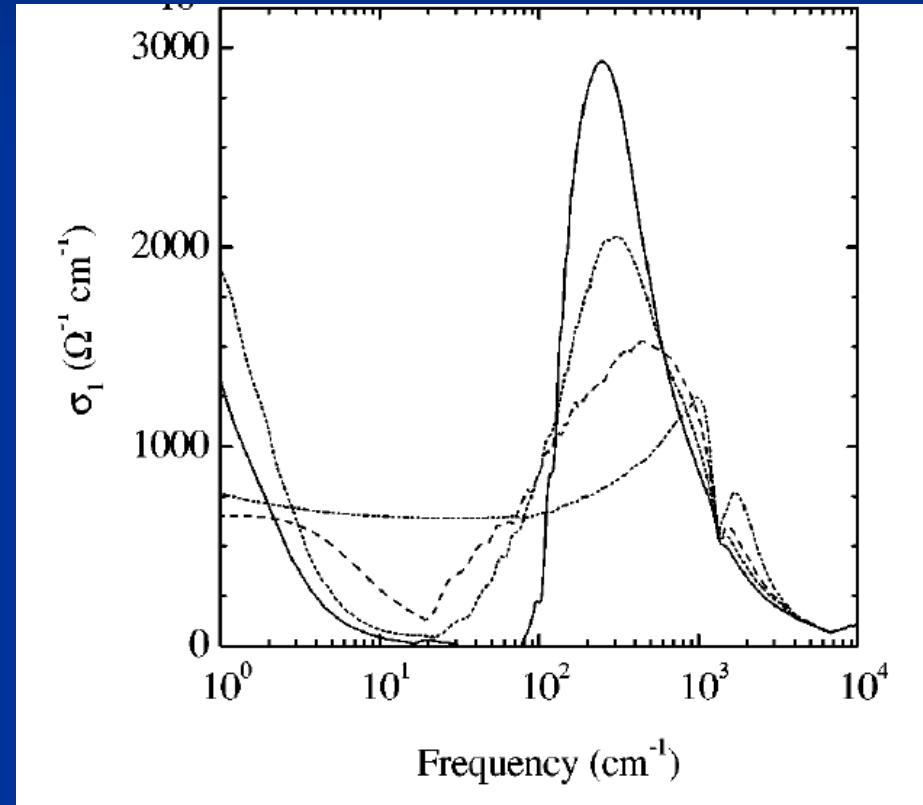


T^2 : why not FL ?

Optical conductivity



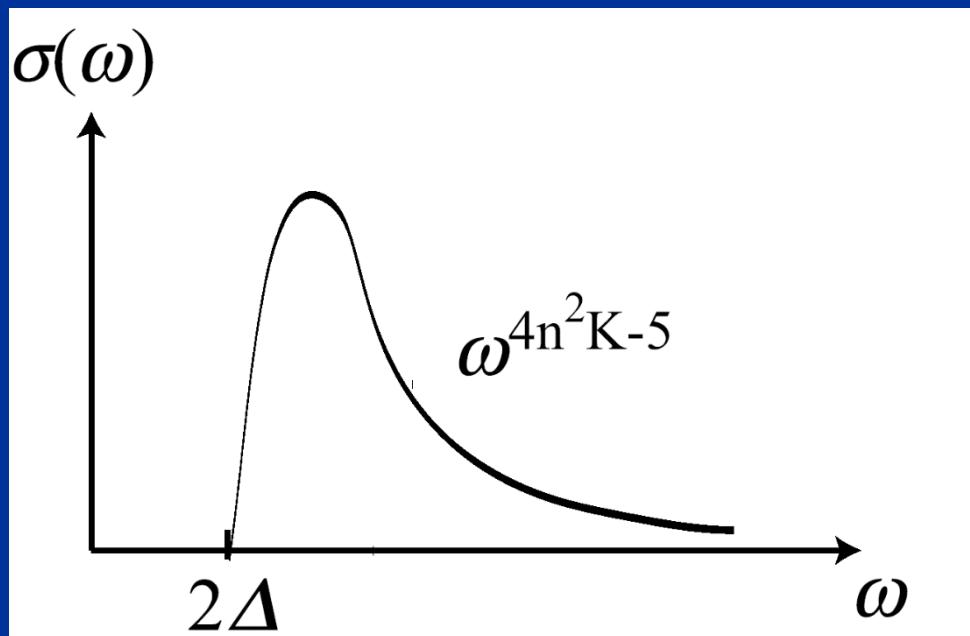
G. Gruner, L. DeGiorgi, M. Dressel



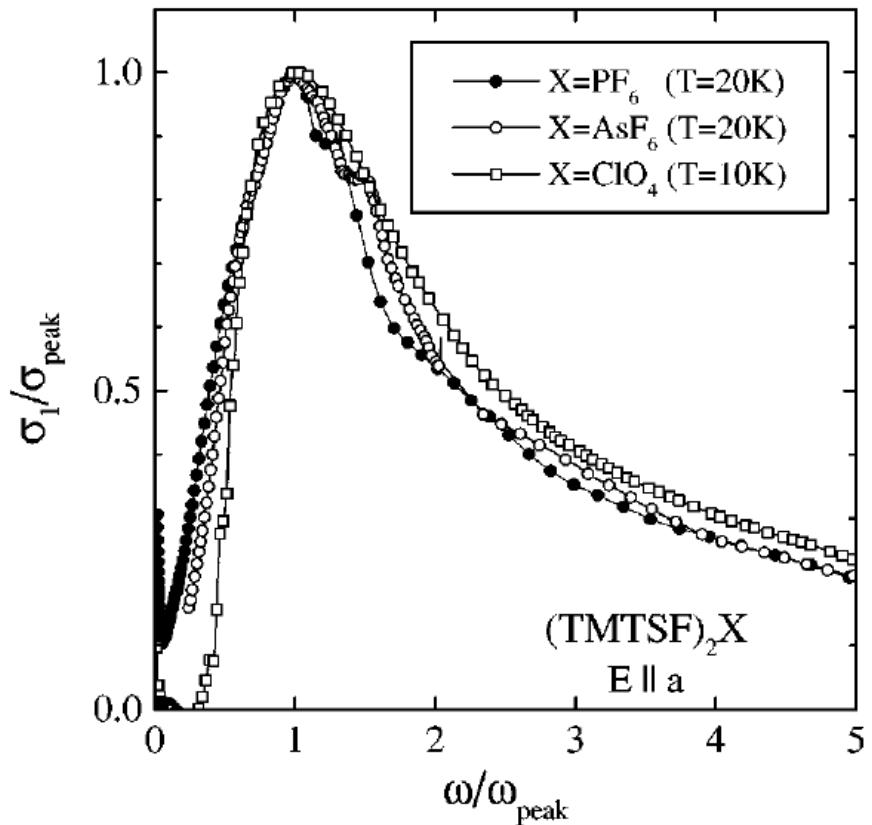
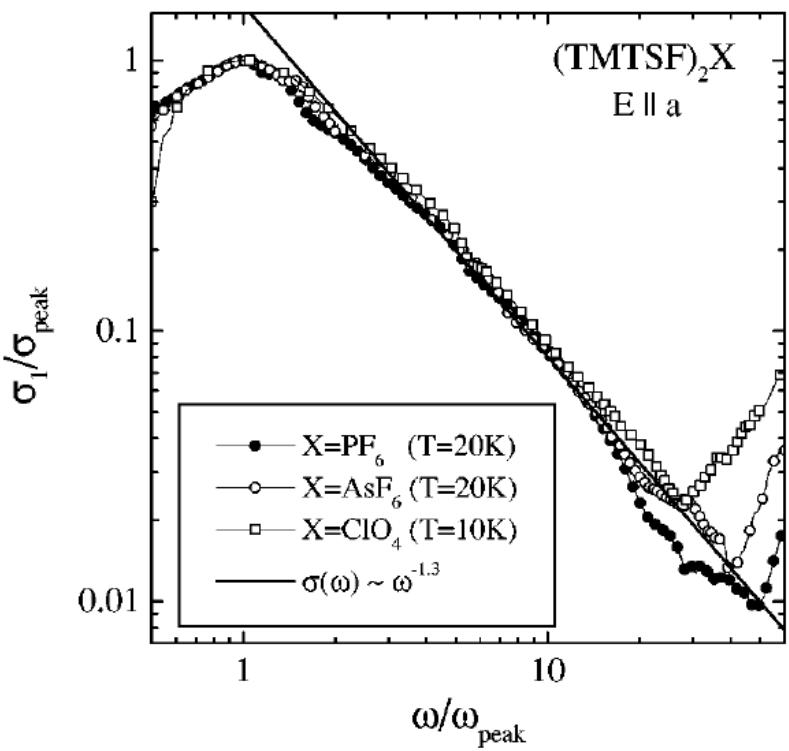
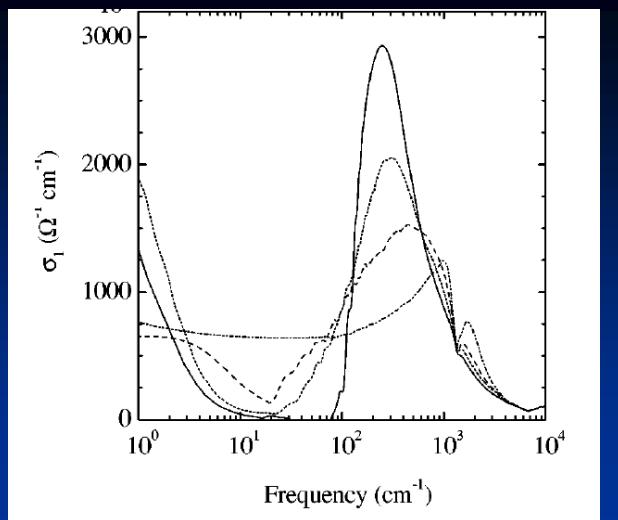
A. Schwartz et al. PRB 58 1261 (1998)

Transport in a LL

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

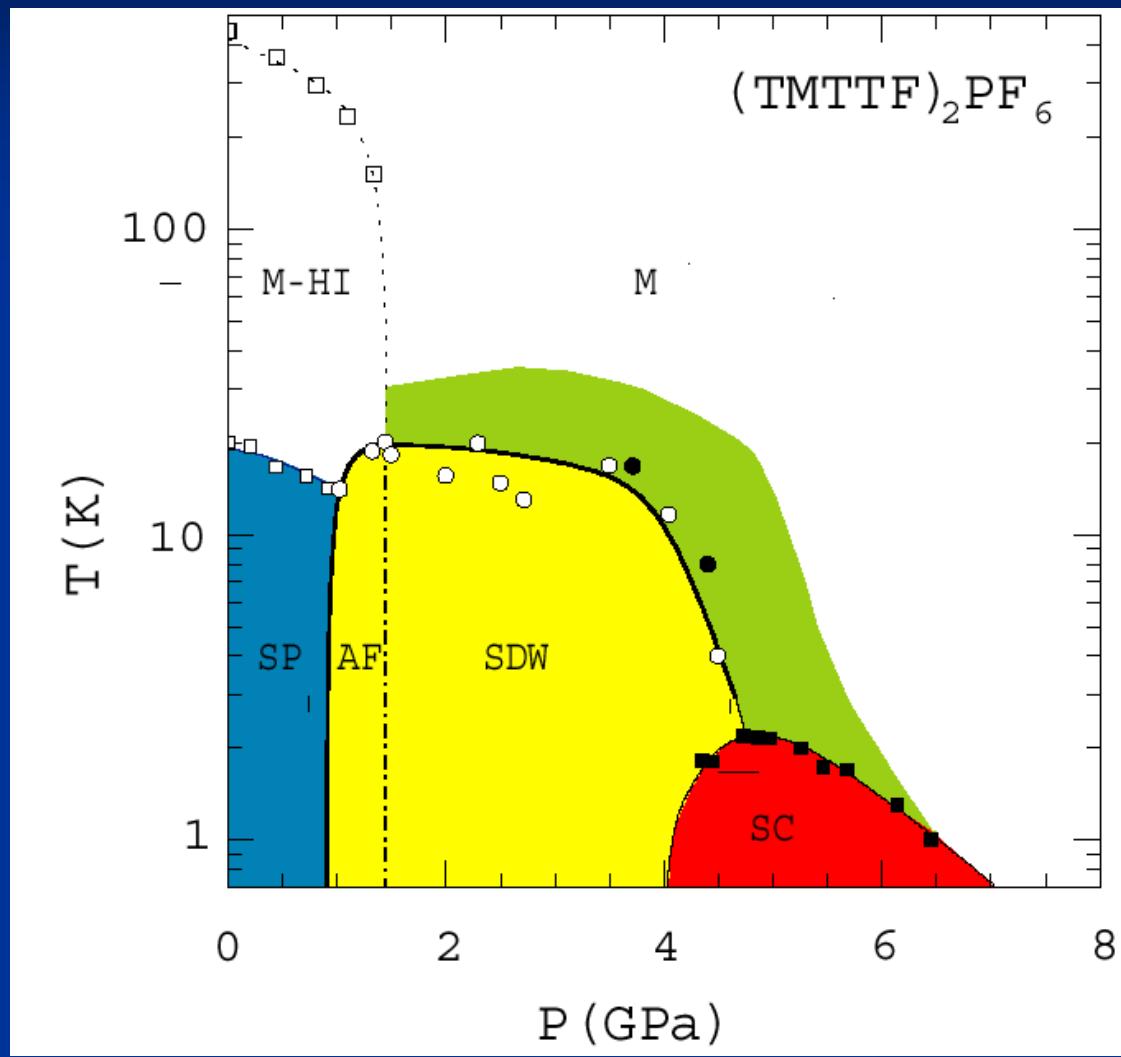


- Mott insulator for $1/4$ filling also !
- Power law in $\sigma(\omega)$ determines $K\rho$
- Deviations from 1D law gives E_c



A. Schwartz et al. PRB 58
1261 (1998)
First observation of LL !!
 $\frac{1}{4}$ filled; $K = 0.23$
Strong interactions (non local)

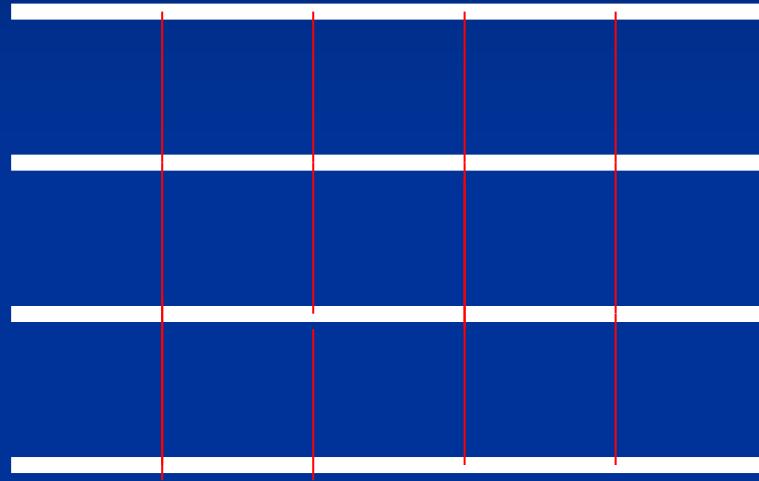
« Normal » phase = TLL



Dimensional crossover



- Interaction effects vary enormously with dimension



Dimensional
Crossover



2D,3D

1D

E, T

- Renormalization arguments

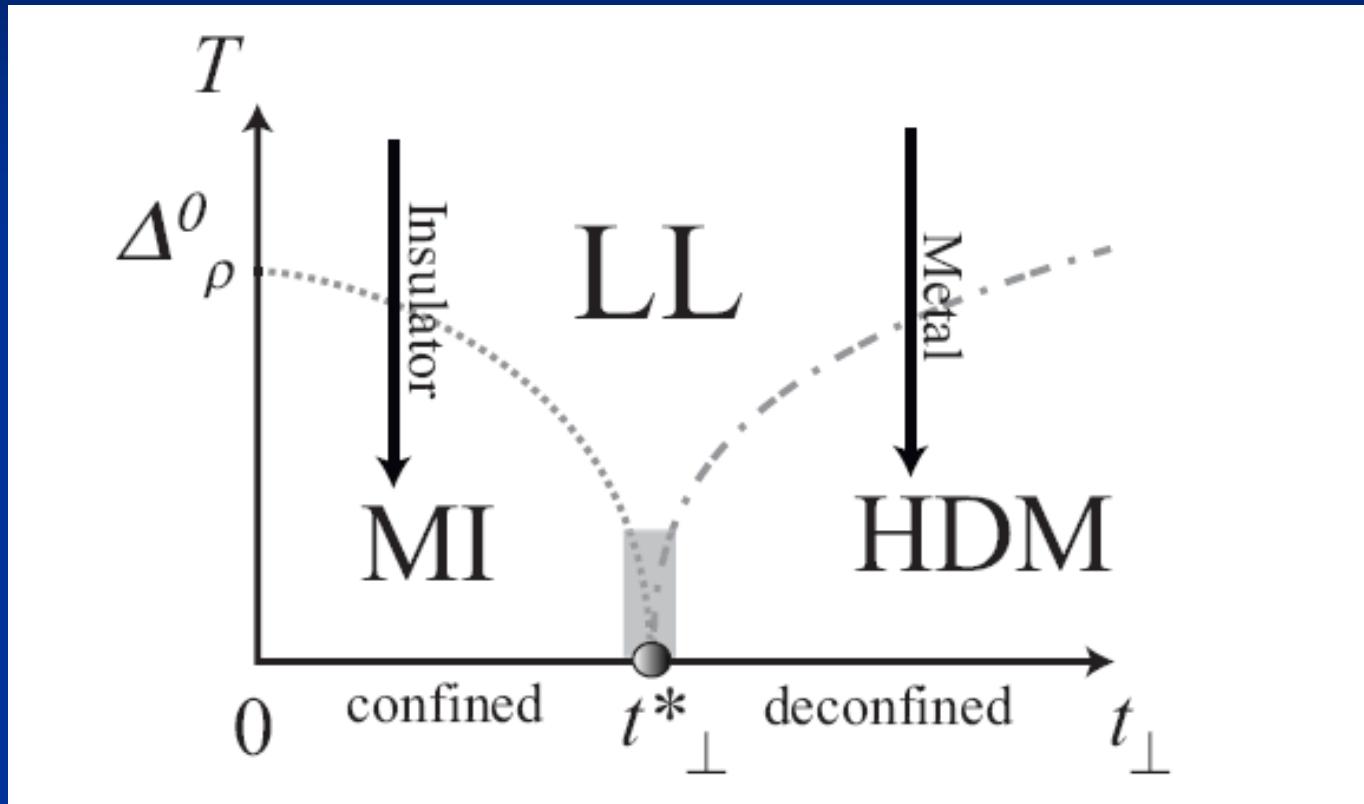
(Bourbonnais, Brazovskii+Yakovenko, Schulz)

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

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

Strong reduction of crossover temperature. But hopping still relevant !

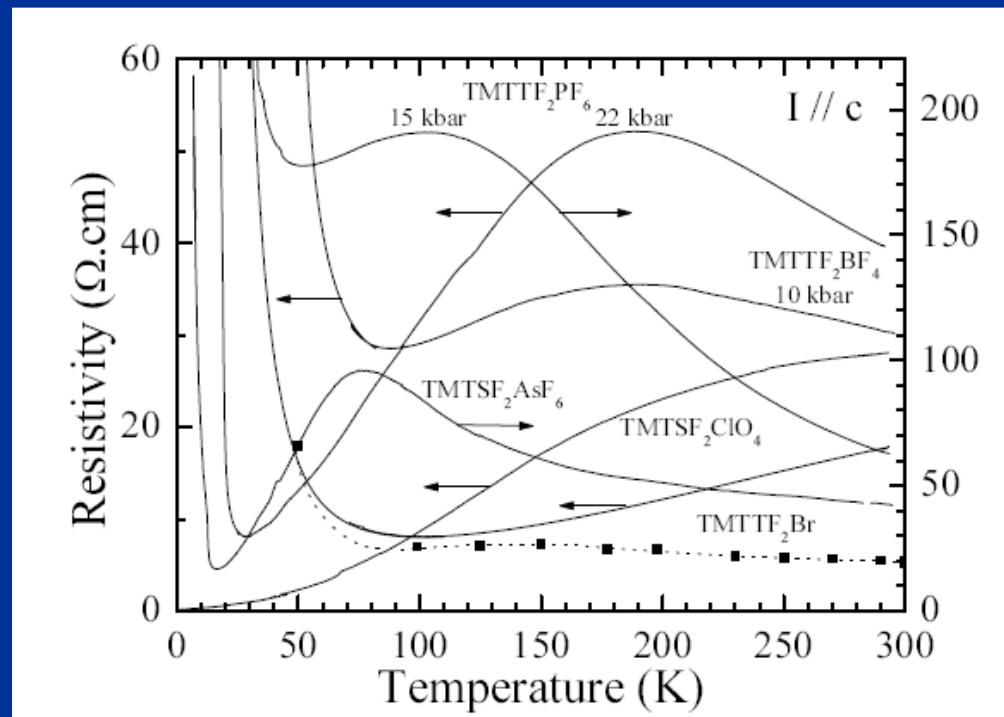
Lower phase gapped



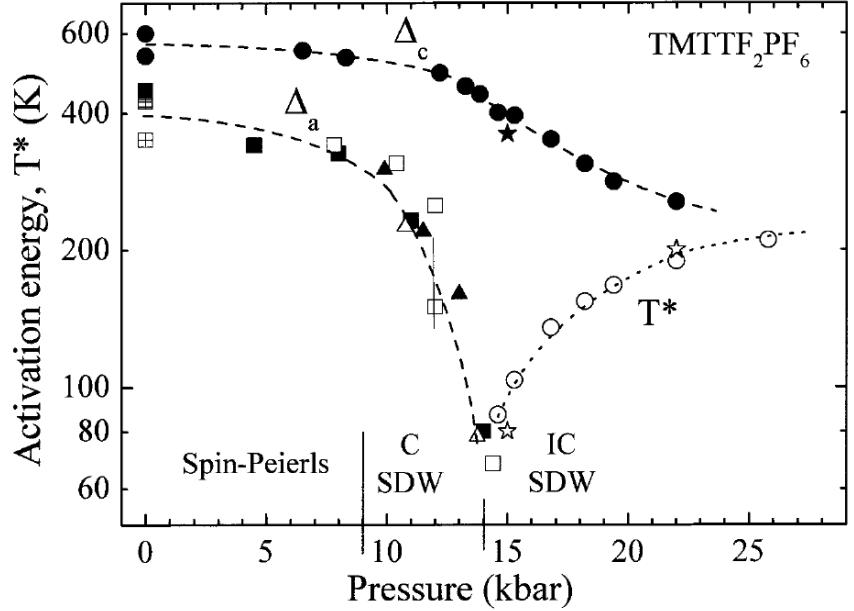
TG Physica B 230 975 (97); Chem Rev 104 5037 (2004)

Transverse transport

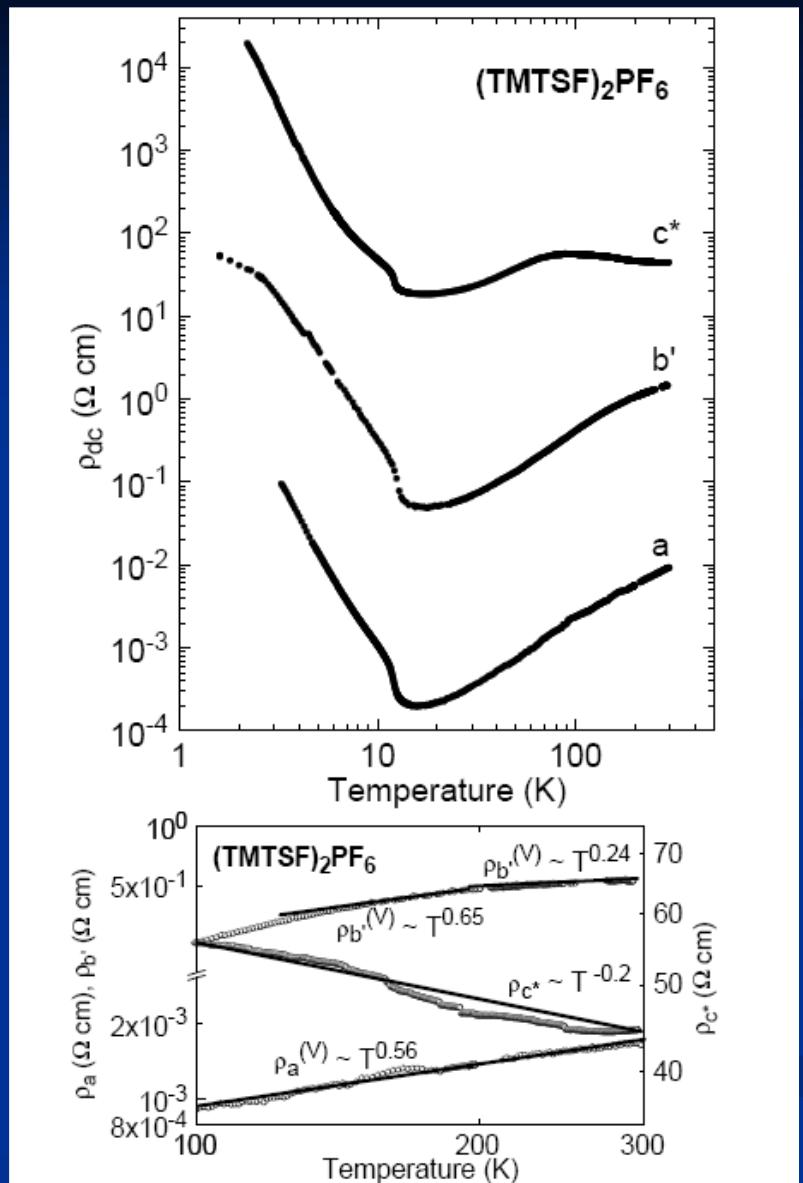
- $t_c \sim 20 \text{ K} < T$
- Tunnelling experiment !



J. Moser et al (98)



V. Vescoli et al.
 P. Auban-Senzier et al.
 Science 284, 191 (2004)
 J. Phys IV, 114 (2004)
 Euro Phys. J. B 13, 503 (2000)



M. Dressel et al., Phys. Rev. B 71, 075104 (2005).

Transverse transport

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

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

$$\alpha \approx 0.6$$

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

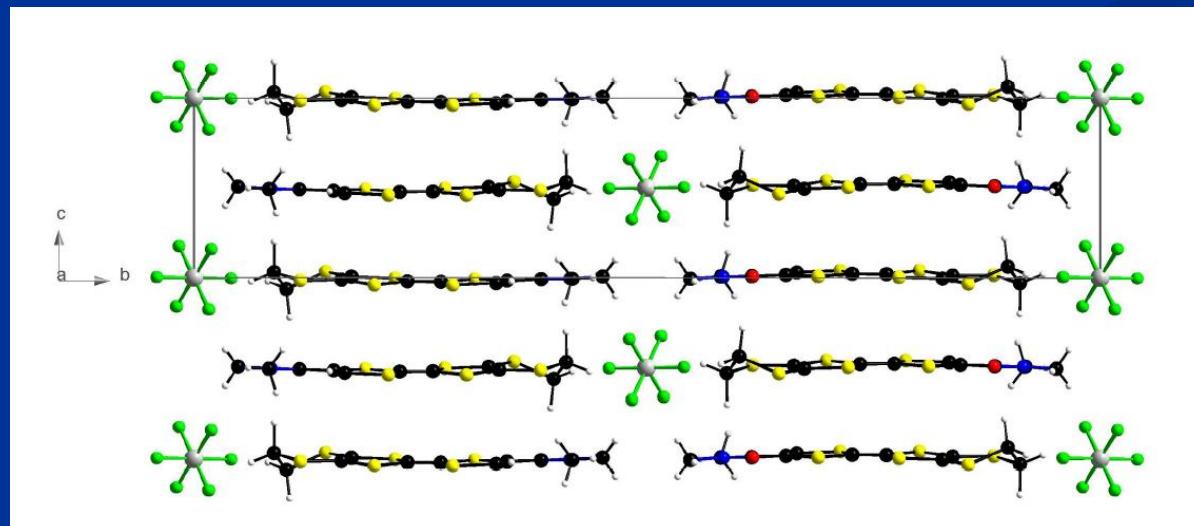
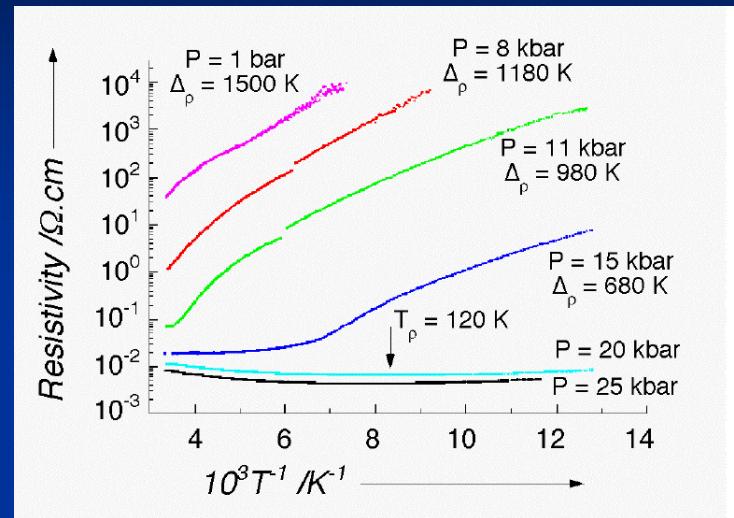
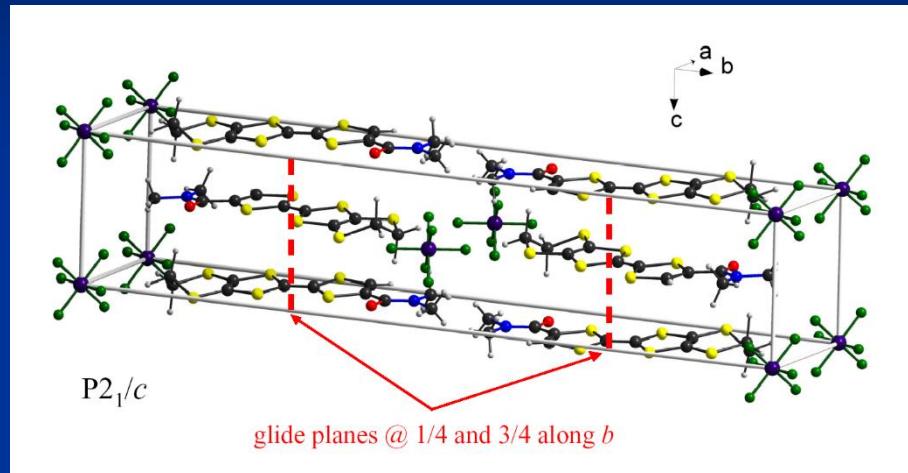
Conclusions from transport

- Tomonaga Luttinger Liquid !
- $K\rho = 0.23$ very strong interactions
 - Dimerization not important (1/4 filled Mott insulator)
TF vs SF likely to be due to change of interactions (quantum critical point)
 - Dimensional crossover at $E=100K$!

Several puzzles !

Dimerization free compound

$(\text{EDT-TTF-CONMe}_2)_2\text{AsF}_6$:



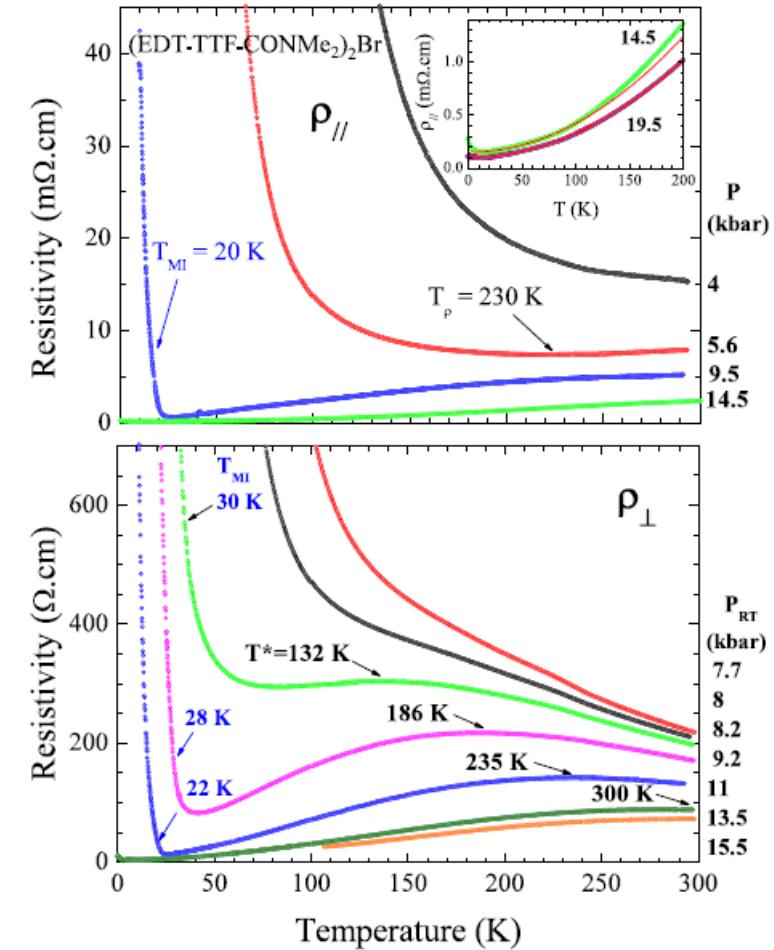
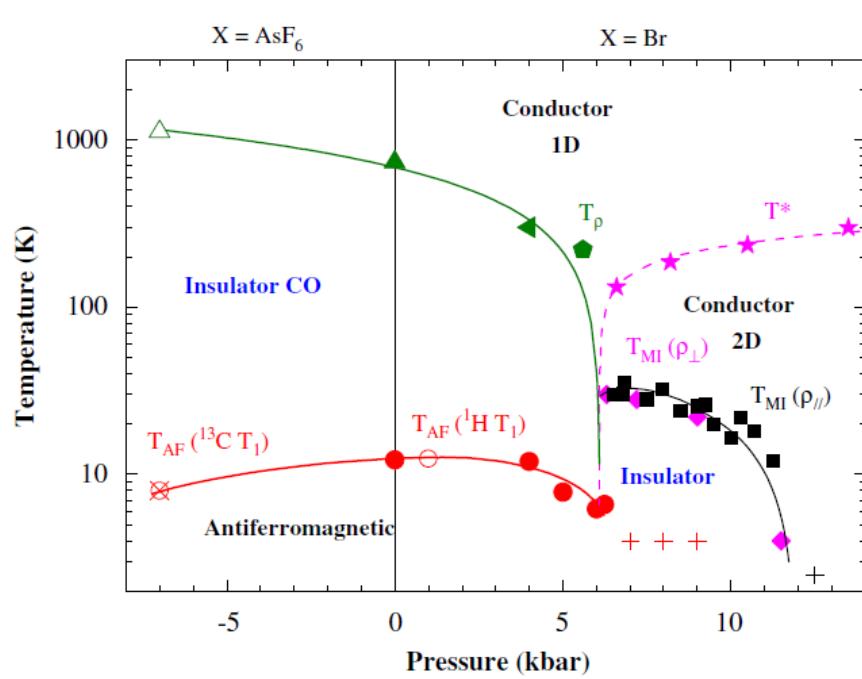
K. Heuze et al, Adv.
Materials **15** 1251 (2003)

Properties ?

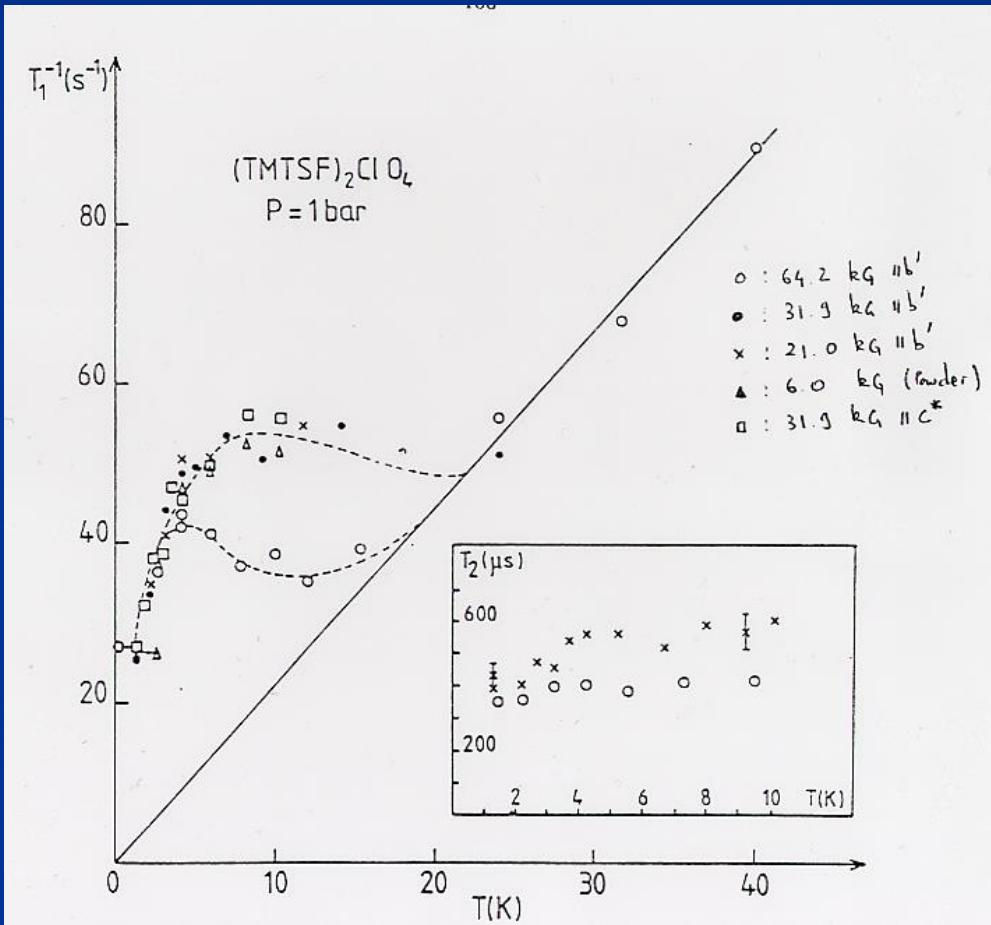
Phase diagram of quarter-filled band organic salts, $[\text{EDT-TTF-CONMe}_2]_2\text{X}$, $\text{X} = \text{AsF}_6$ and Br

P. Auban-Senzier^{a,*}, C.R. Pasquier^a, D. Jérôme^a, S. Suh^b, S.E. Brown^b, C. Mézière^c, P. Batail^c

Physica B 405 (2010) S82–S85

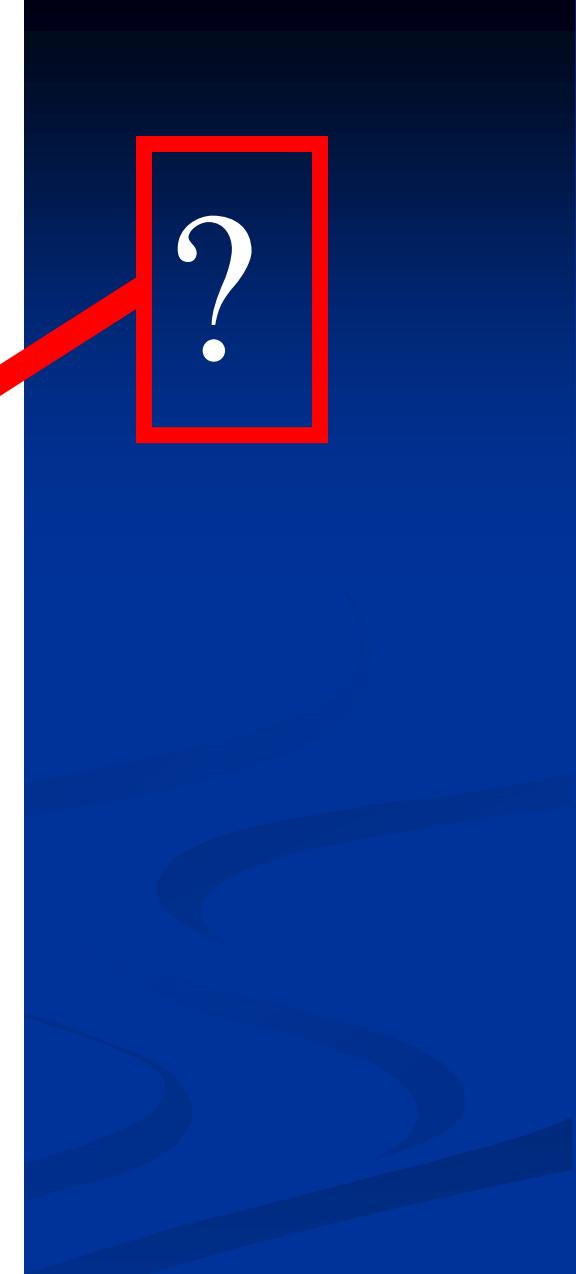
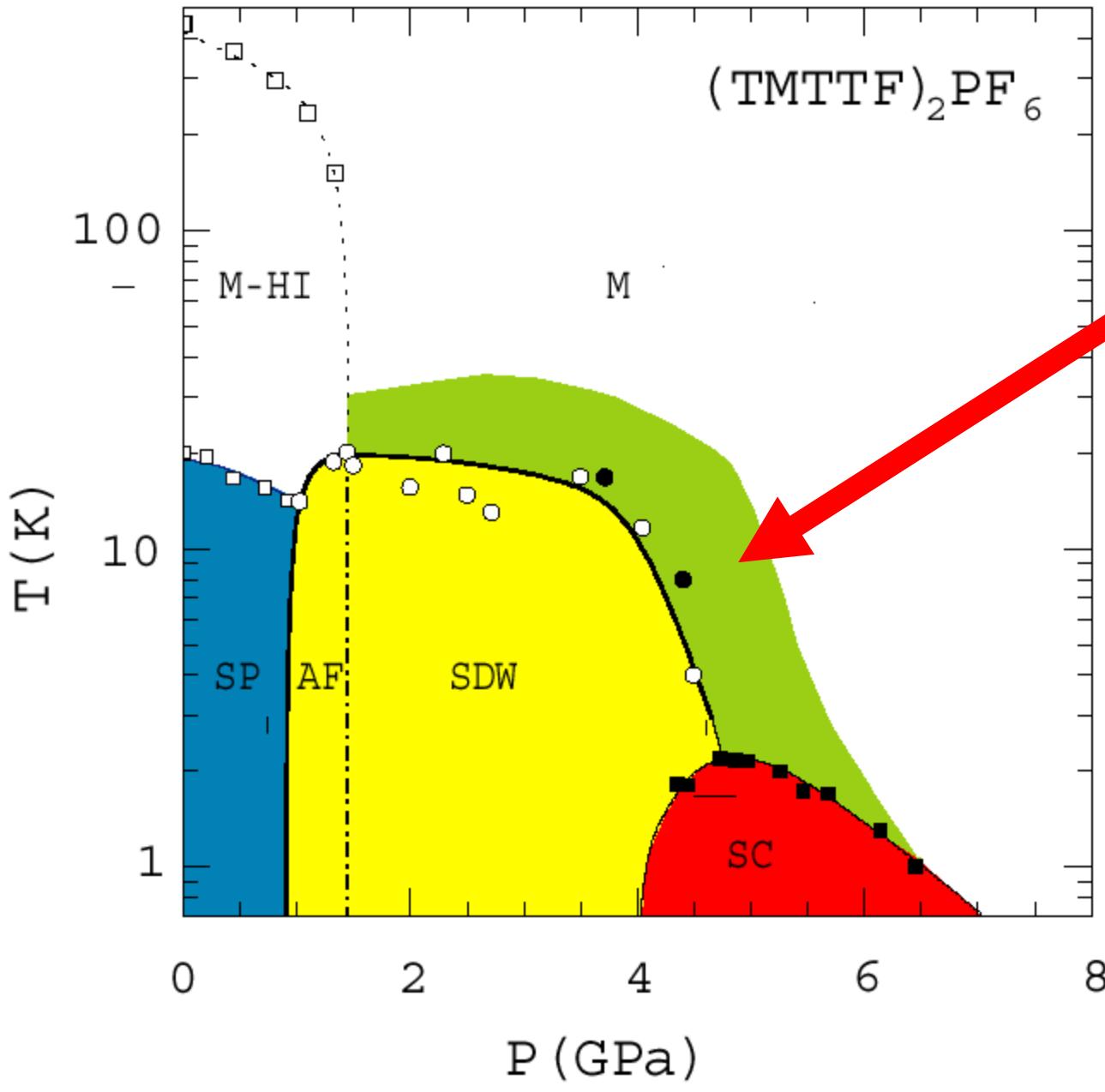


Puzzle from NMR



F. Creuzet et al., J. Phys.
Lett 45 L755 (84)

Non fermi liquid
below E_c ?



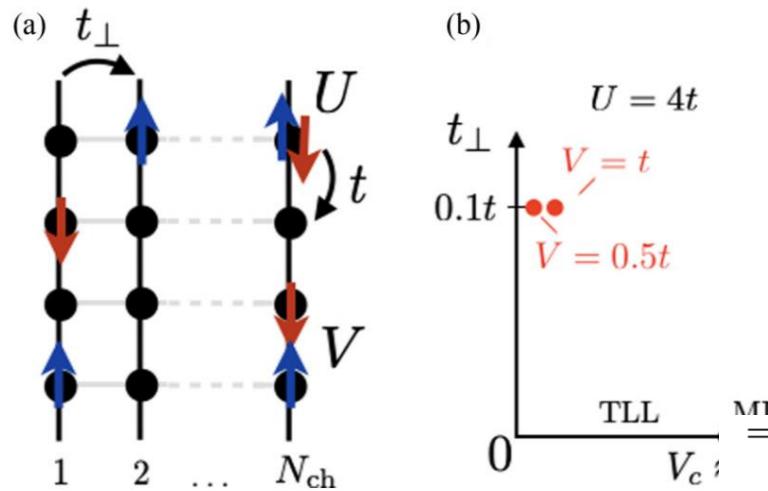
Coupled 1D chains



PHYSICAL REVIEW B **100**, 075138 (2019)

Understanding repulsively mediated superconductivity of correlated electrons via massively parallel density matrix renormalization group

A. Kantian¹, M. Dolfi,^{2,3,*} M. Troyer,² and T. Giamarchi⁴

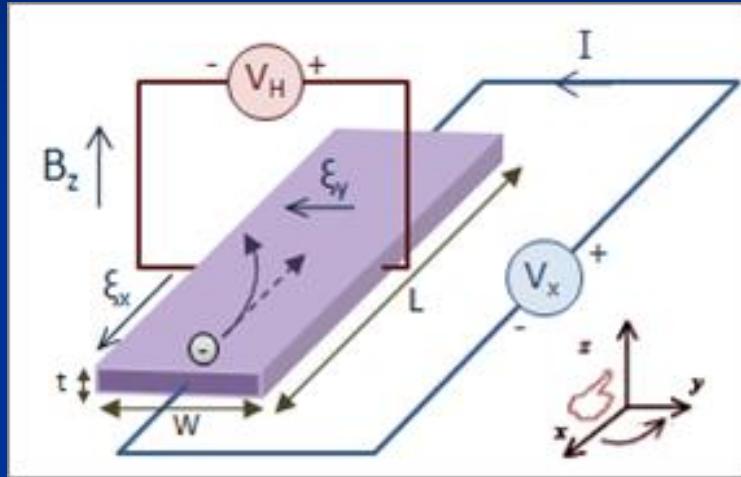


N_{ch}	$\overline{\Delta_s}[N_{\text{ch}}] [t \times 10^{-3}]$			
	Straight extrapolation		Extr. + estimates	
	$V/t = 0.5$	$V/t = 1$	$V/t = 0.5$	$V/t = 1$
2	5.59	7.59	5.36	7.31
4	9.68	10.2	10.77(10) ^a	10.268(11)
6	9.37	11.4	4.3(1.4) ^b	11.20(97)
8	9.45		7.6(1.3) ^c	

Hall effect



Non interacting systems



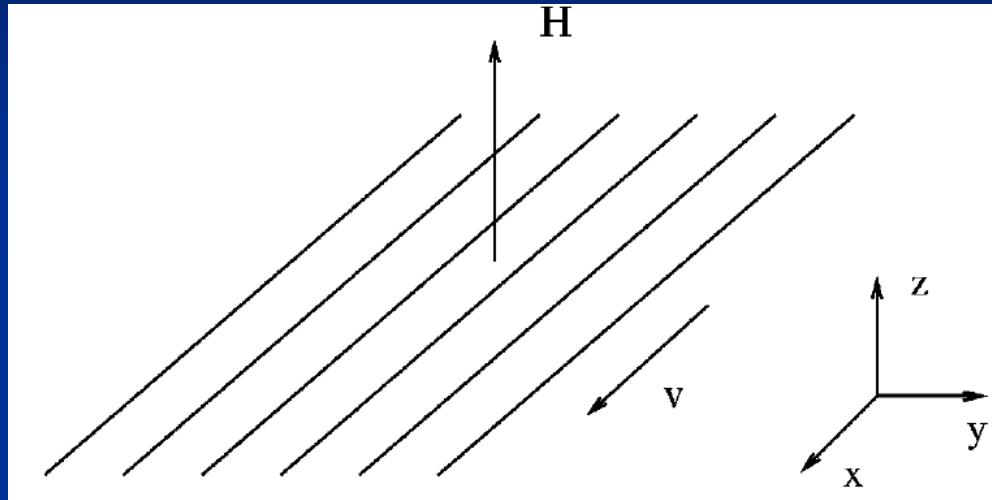
Non interacting ``simple''

$$R_h = \frac{V_{\perp}}{I_{\parallel} B} \propto \frac{1}{n}$$

No interactions: curvature of fermi surface
- topological formula (Thouless-Kohmoto)

With interactions: open question

Semi-classical calculation



$$F = qV \wedge B = qJB / n$$

$$F = qE$$

$$E / (BJ) = 1 / n$$

“Real” calculation

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

$$H = \int dx \left[\sum_i v_F \hat{\psi}_i^\dagger \tau_3 (-i \partial_x) \hat{\psi}_i - \alpha \sum_i \hat{\psi}_i^\dagger \partial_x^2 \hat{\psi}_i + g \sum_i \hat{\psi}_{i+}^\dagger \hat{\psi}_{i+} \hat{\psi}_{i-}^\dagger \hat{\psi}_{i-} - t_\perp \sum_{\langle i,j \rangle} \hat{\psi}_i^\dagger \hat{\psi}_j e^{-i \frac{e}{c} A_{i,j}} \right],$$

$$\epsilon_{\pm} = \pm v_F (p \mp p_F) + \alpha (p \mp p_F)^2.$$

Needs band curvature !

$\alpha = 0$: usual TLL description of 1D systems

Kubo formula (linear response)

$$\begin{bmatrix} j_x \\ j_y \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix}.$$

$$\rho_{xy} = \frac{-\sigma_{xy}}{\sigma_{xx}\sigma_{yy} + \sigma_{xy}^2}.$$

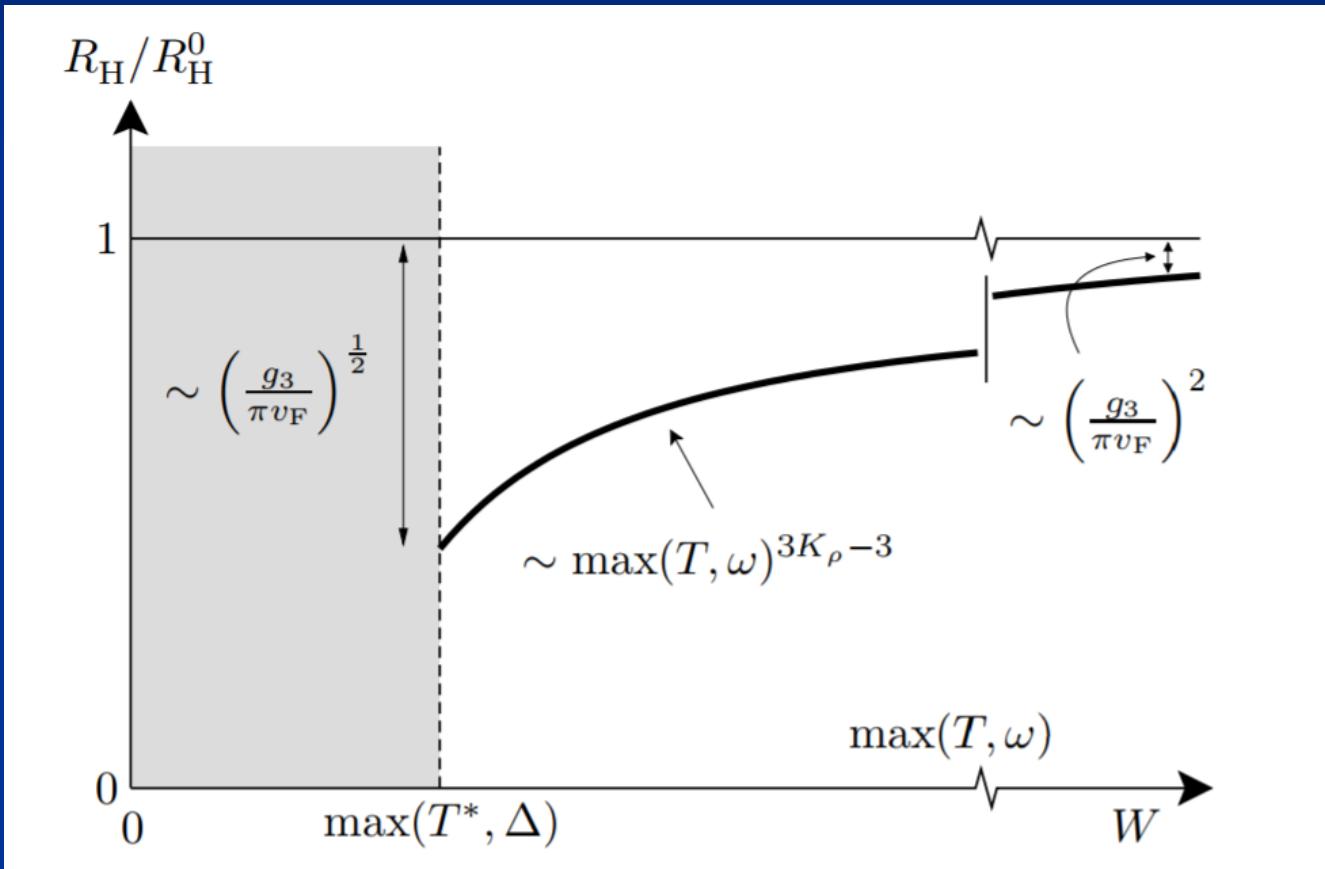
$\alpha = 0$: Particle hole symmetry; Hall = 0

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

Expansion in scattering, t, B, α

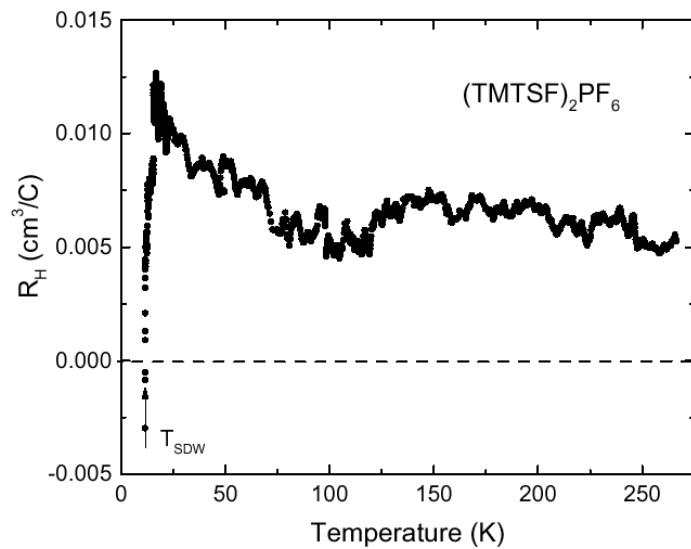
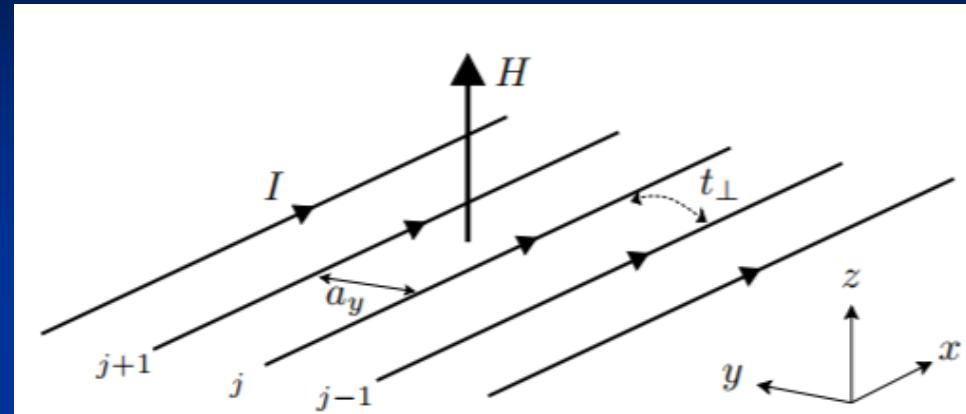
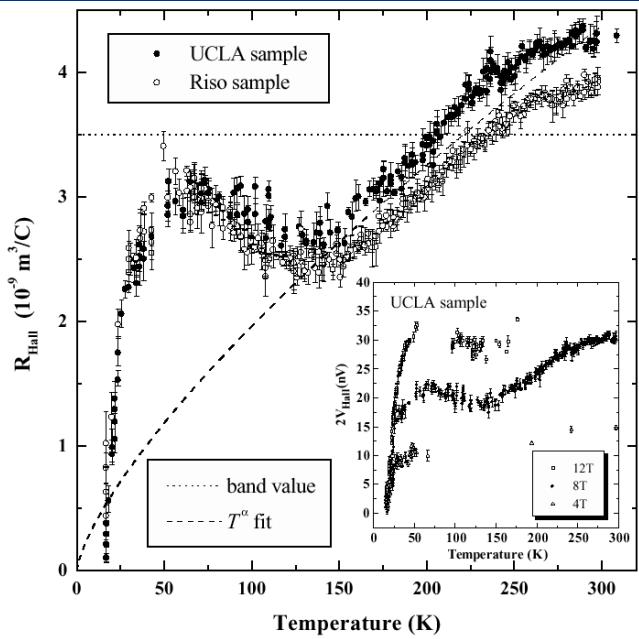
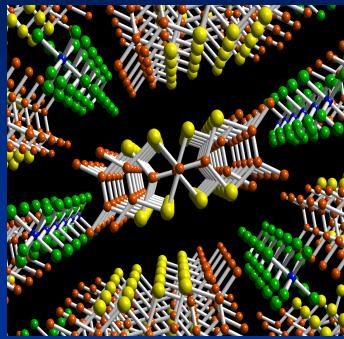


High temperature regime



G. Leon, C. Berthod, TG PRB 75, 195123 (2007)

Experiments ?



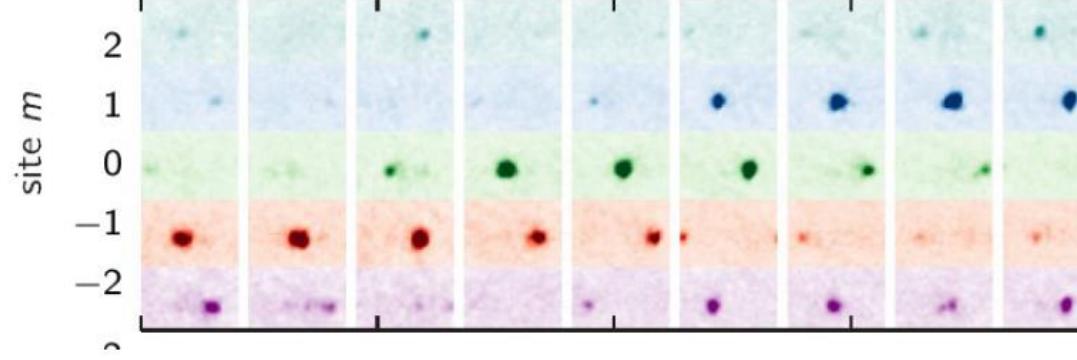
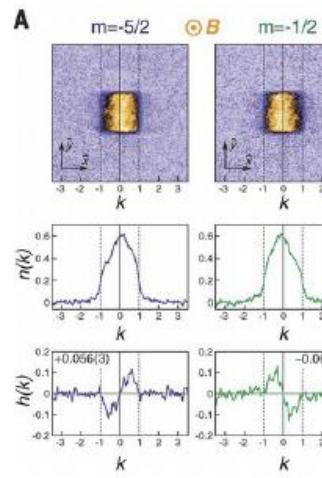
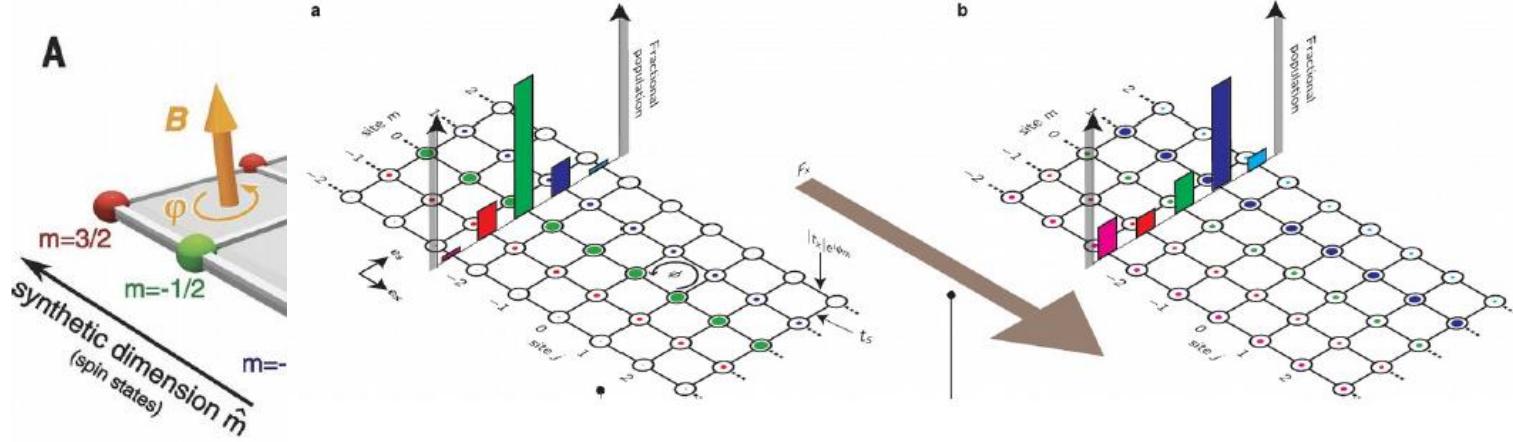
J. Moser et al., PRL 84
2674 (00)

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

Artificial gauge fields



Hall effect: measurements



Effect of interactions ??

EXPERIMENTAL TEAM

Daniele Tusi

Lorenzo Franchi

Jacopo Parravicini

Leonardo Fallani



Jacopo Catani

Giacomo Cappellini

Lorenzo Livi

Tianwei Zhou



UNIVERSITÀ
DEGLI STUDI
FIRENZE

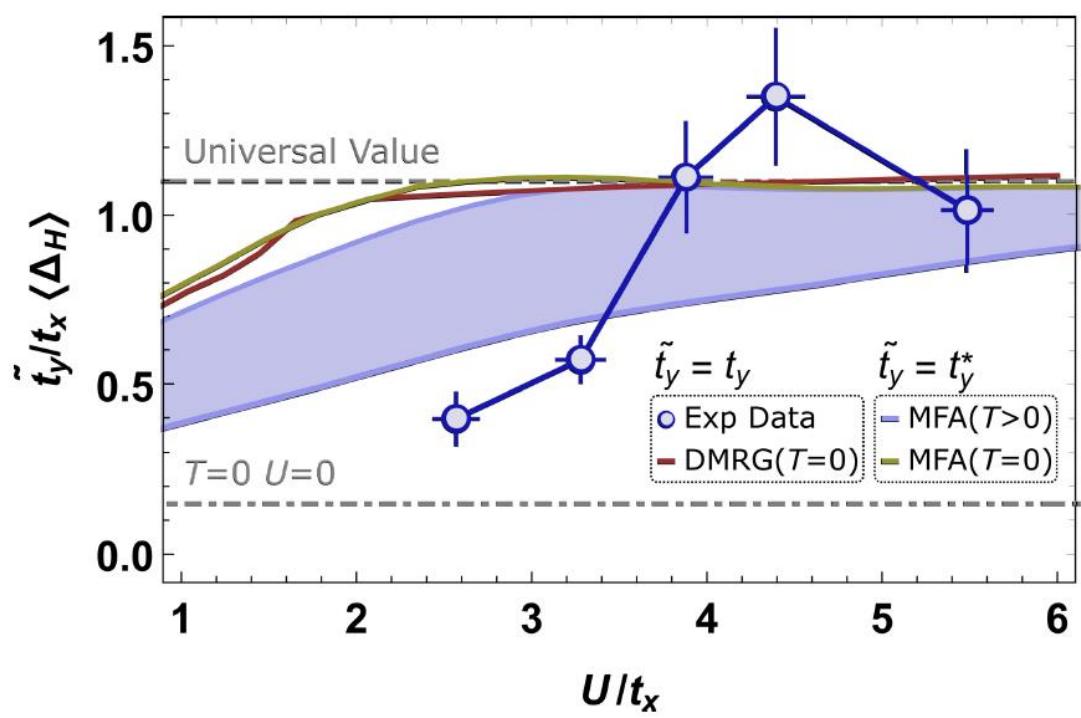
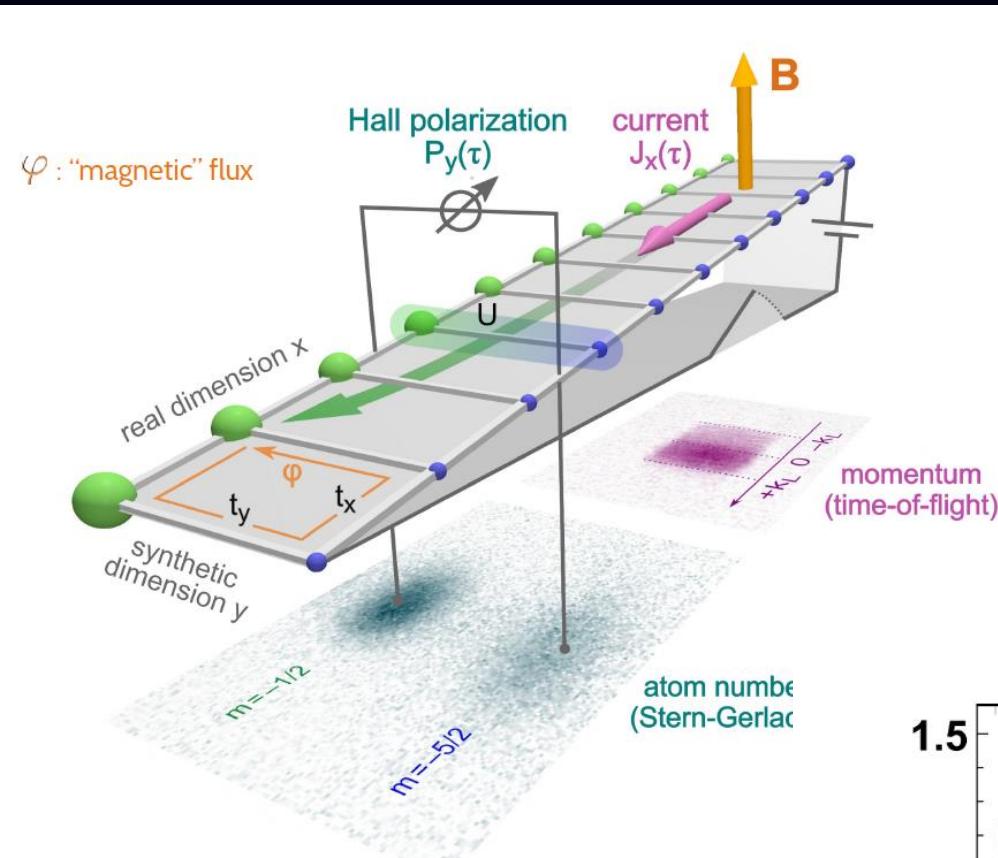


Cécile
Repellin



Sebastian
Greschner

M. Filippone, CEA



Conclusions

- Organic have the incredibly rich physics of coupled one-dimensional chains
- At intermediate T: Luttinger liquid physics
- Deconfinement
- At low T: « fermi liquid » that remembers strong correlations

Future

- Many open questions for quasi-1D:
Needs other compounds, other probes !
- Other correlations (Hall effect etc.)
- Properties of the « FL » phase;
How to go from 1D to 2D
- Superconductivity