Introduction to the physics of organic conductors and superconductors

Part II

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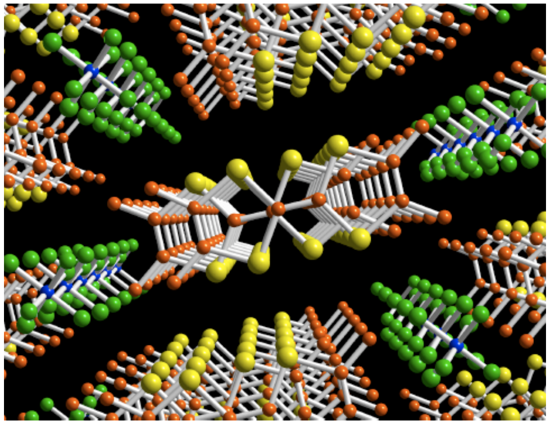
Summer school Boulder July 2008

UNIVERSITÉ DE SHERBROOKE

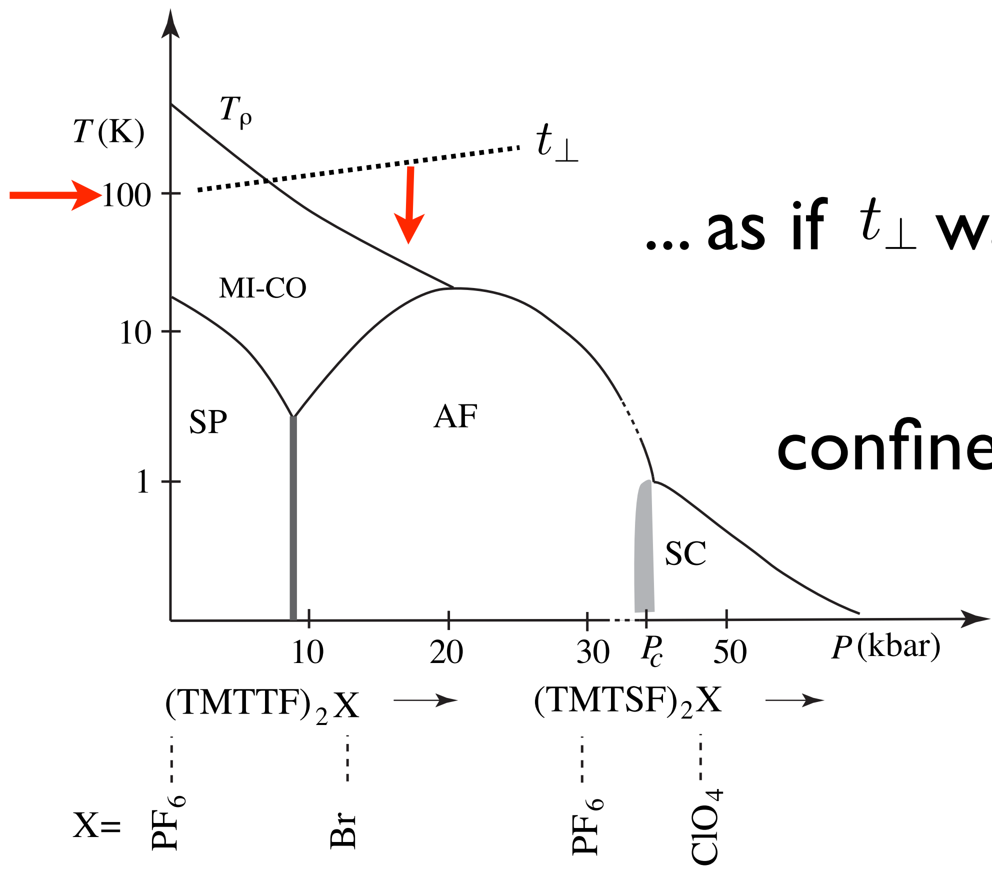
Outline

II-Quasi-1D materials: electronic confinement, ordered phase, superconductivity and antiferromagnetism

$(TMTSF)_2$ X-$(TMTSF)_2$ X



Why higher dimensional physics does not show up as $T_\rho \downarrow \; (< t_\perp \sim 100\mathrm{K})$

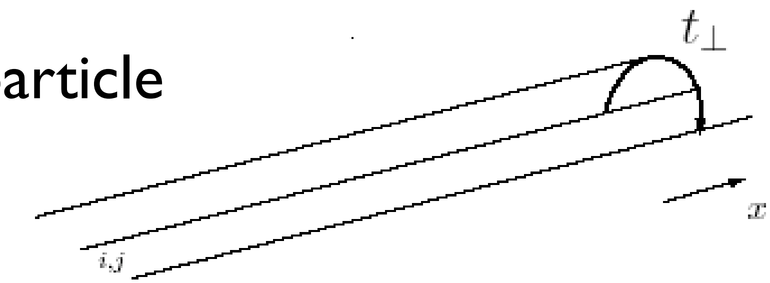


... as if $t_\perp$ was effectively smaller (! ?)

confinement of electronic motion by correlations

Electronic confinement ...

$t_\perp$ is an interchain transfer of a quasi-particle

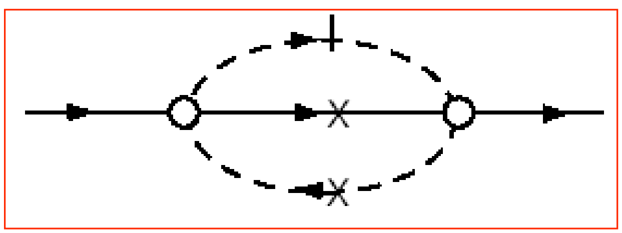


Density of quasi-particle states N(E) on each chain ?

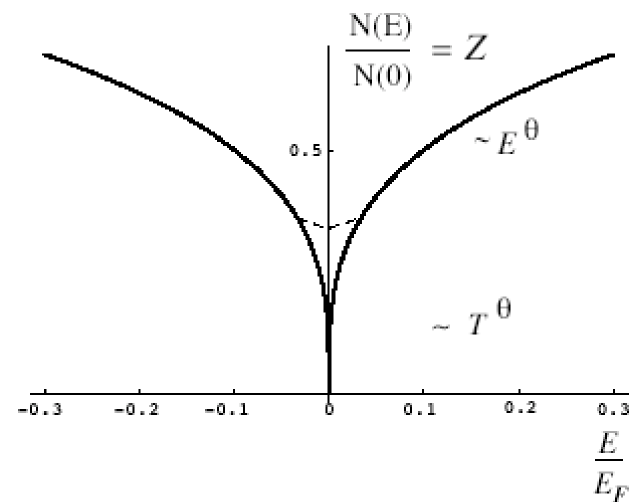
1D RG : beyond one-loop

$$\mu_S(\ell) = \left.(G_p^0, g_1(\ell), g_2(\ell), g_3(\ell))\right|_{1\ \text{loop}}$$

$$\mu_S(\ell) = \left.(z(\ell)G_p^0, g_1(\ell), g_2(\ell), g_3(\ell))\right|_{2\ \text{loops}}$$



a 2-loop diagram



$$z(T) \sim \left(\frac{T}{E_F}\right)^{\theta}$$

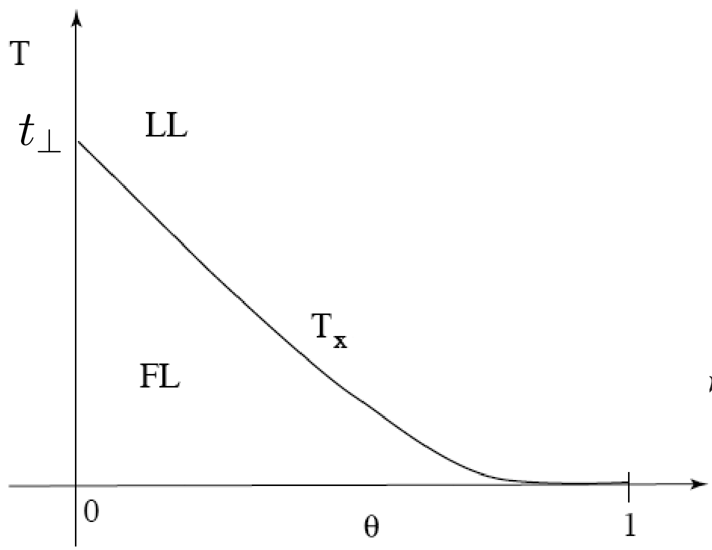
Suppression of qp (LL and LE)

Confinement ...

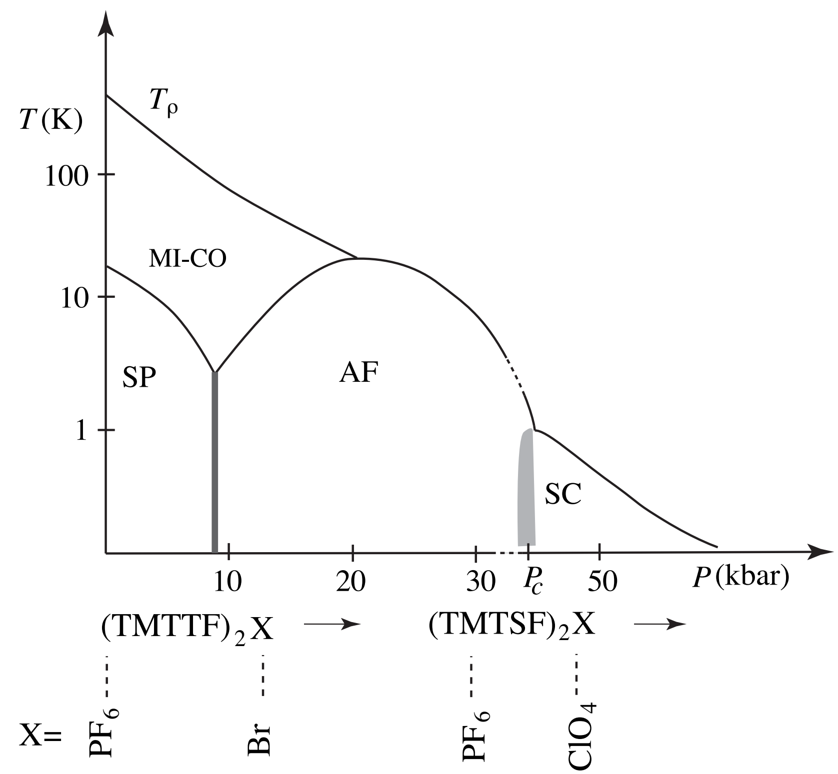
Renormalization (downward) of $t_\perp$: $\quad t_\perp \to z(T)t_\perp$

$$T_x \sim z(T_x)t_\perp \quad \longrightarrow \quad T_x \sim t_\perp\Big(\frac{t_\perp}{E_F}\Big)^{\frac{\theta}{1-\theta}} \qquad \theta = \mathcal{O}(g^2)$$

Reduction of the scale for the electronic deconfinement

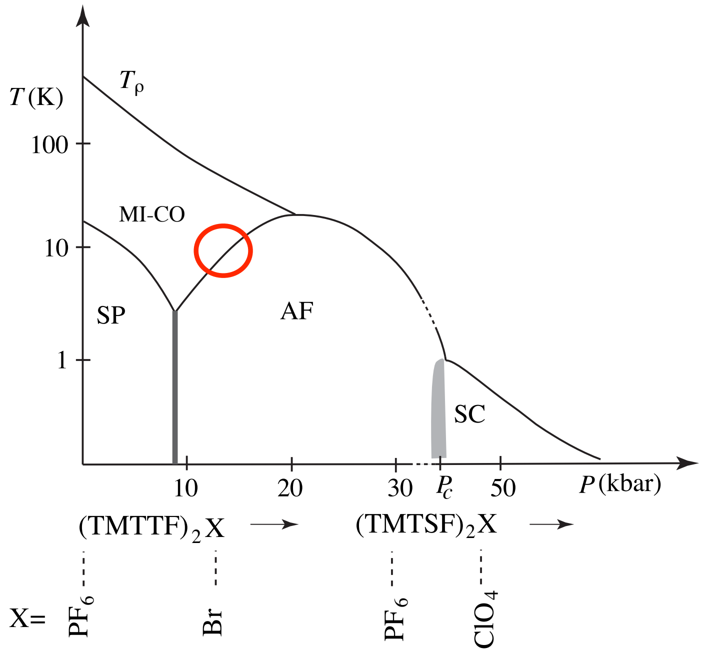


Boies et al., PRL **74**, 968 (1995)



- 'Normal' phase of $(TMTTF)_2X$ at low pressure : confined (1D)

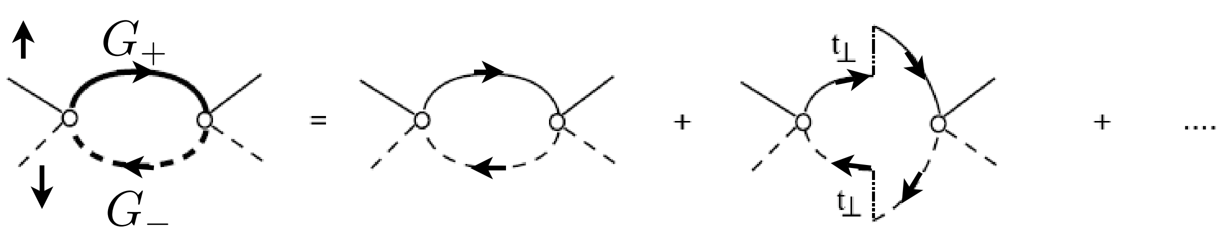
Mechanism of long-range AF order in the presence of confinement



What can be learnt from RG ?

$$G_p(k,k_\perp,\omega) \rightarrow \frac{z(\ell)}{i\omega_n - \epsilon_p(k) + 2z(\ell)t_\perp \cos k_\perp}$$

(effect. one-ptle propagator at step ℓ



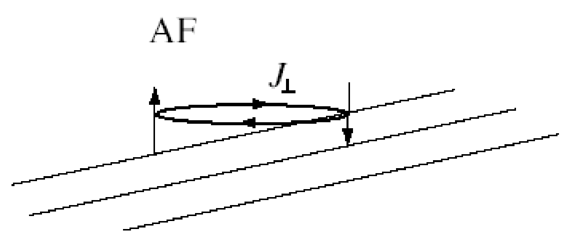
Generation of interchain density-wave propagation

RG generation of pair hopping terms:

$$\mu_S = (G_p^0, t_\perp, g_1, g_2, g_3) \qquad \ell = 0$$

$$\mathcal{R}_\ell \mu_S = \big(z(\ell)G_p^0, z(\ell)t_\perp, g_1(\ell), g_2(\ell), g_3(\ell), \underline{J_\perp(\ell)}, \dots\big) \qquad \ell$$

$$\delta S_{\perp,1} \sim \int dz \sum_{\langle i,j\rangle} J_\perp \boldsymbol{S}_i^*(z)\boldsymbol{S}_j(z)$$



Interchain AF exchange: $J_\perp \propto t_\perp^2$

$$\mathcal{R}_\ell \mu_S \;=\; \big(z(\ell)G_p^0, z(\ell)t_\perp, g_1(\ell), g_2(\ell), g_3(\ell), \underline{J_\perp(\ell)}, \dots\big) \quad @ \quad E_0\, e^{-\ell}$$

Distinct RG flow for $J_\perp$: a relevant coupling

$$\frac{dJ_\perp}{d\ell} = f(\ell) + J_\perp \frac{d\ln\bar{\chi}_{AF}}{d\ell} + \frac{1}{2}J_\perp^2$$

Solution for $E_0\, e^{-\ell} \sim T$ in the presence of Δ_ρ

$$J_\perp(q_0, T) \sim \frac{J_\perp^0(\Delta_\rho)}{1 - J_\perp^0(\Delta_\rho)\chi^*_{AF}(T)}\,;\; J_\perp^0(\Delta_\rho) \approx \pi v_F \frac{t_\perp^{*2}}{\Delta_\rho^2} \qquad \chi^*_{AF}(T) \approx (\pi v_F)^{-1}\frac{\Delta_\rho}{T}$$

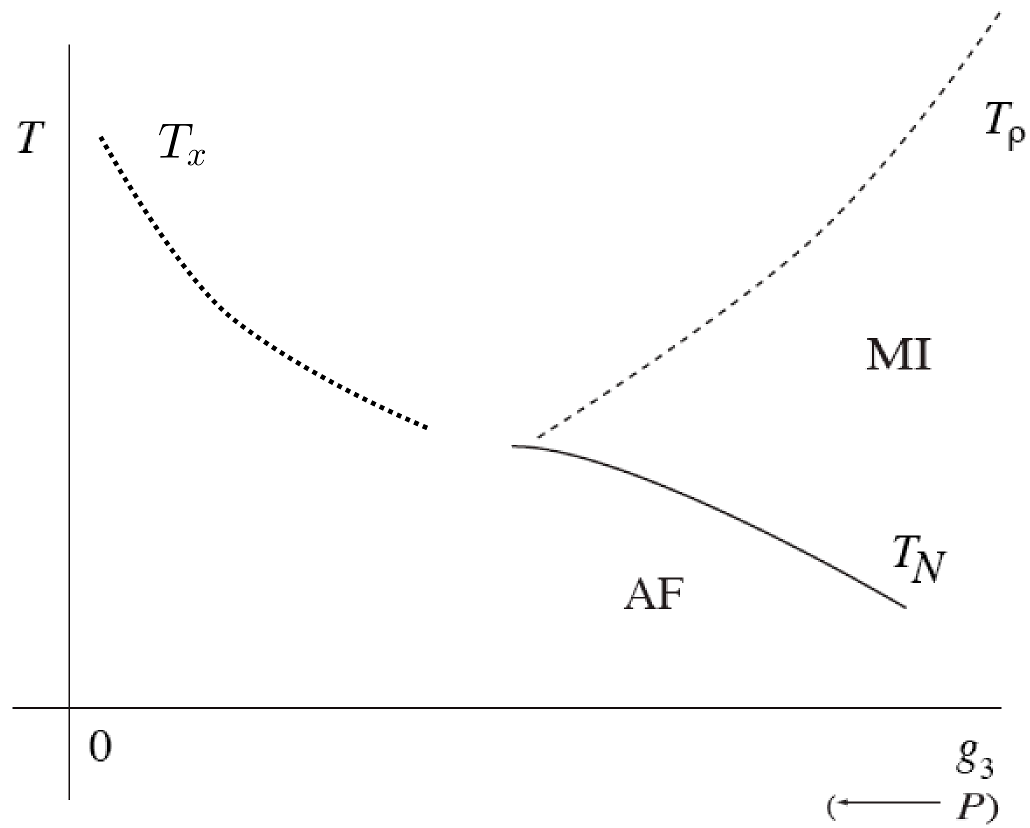
$$T_N \sim \frac{t_\perp^{*2}}{\Delta_\rho}$$ *T*emp. scale for AF long-range order

$T_N \uparrow$ when $\Delta_\rho \downarrow$

In the absence of Mott gap (weak coupling)

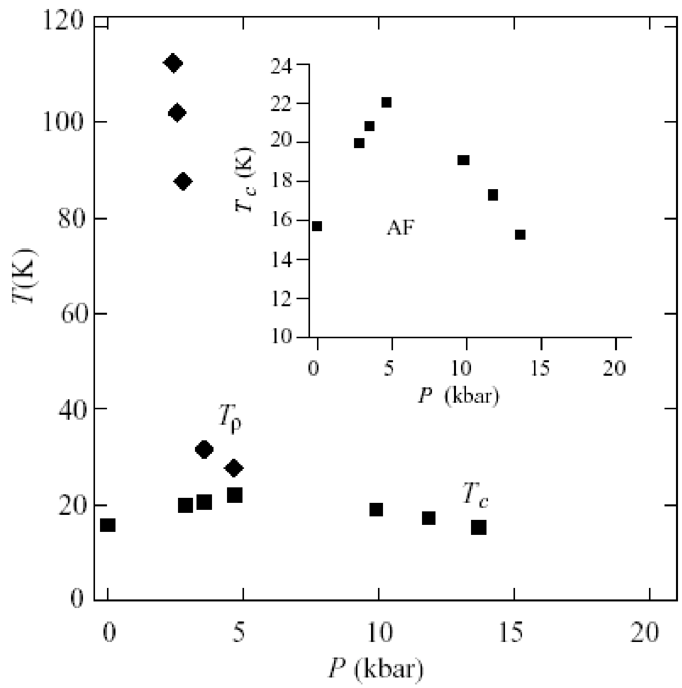
RG: $T_c \approx (g_2^* + g_3^*)t_\perp^*$ $\downarrow$ as interactions decrease

Strong to weak coupling : a maximum of T_c

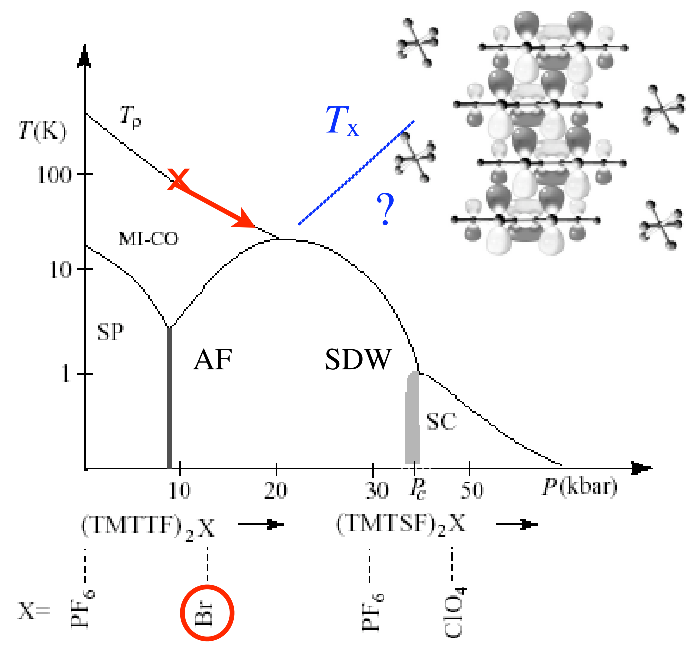


Strong to weak coupling :   the AF dome

$(TMTTF)_2Br$



Klemme *et al.*, PRL**75,** 2408 (95)

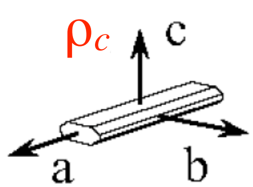


Signs of deconfinement ?

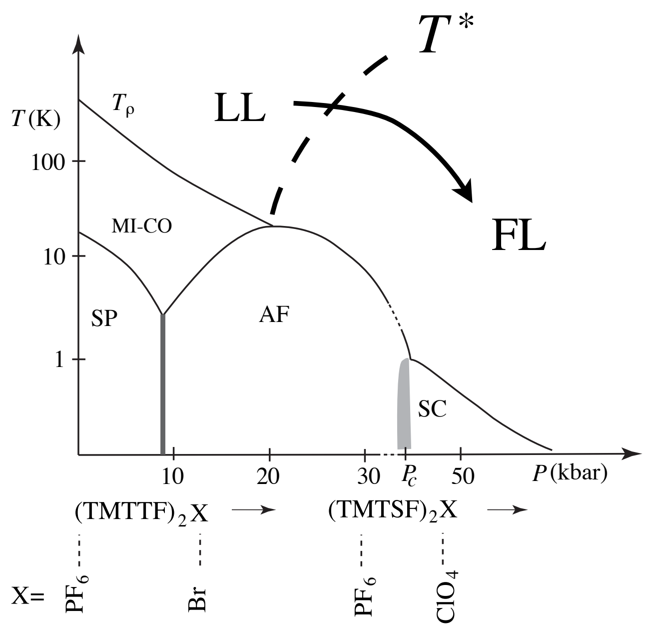
SDW ⟶ SC

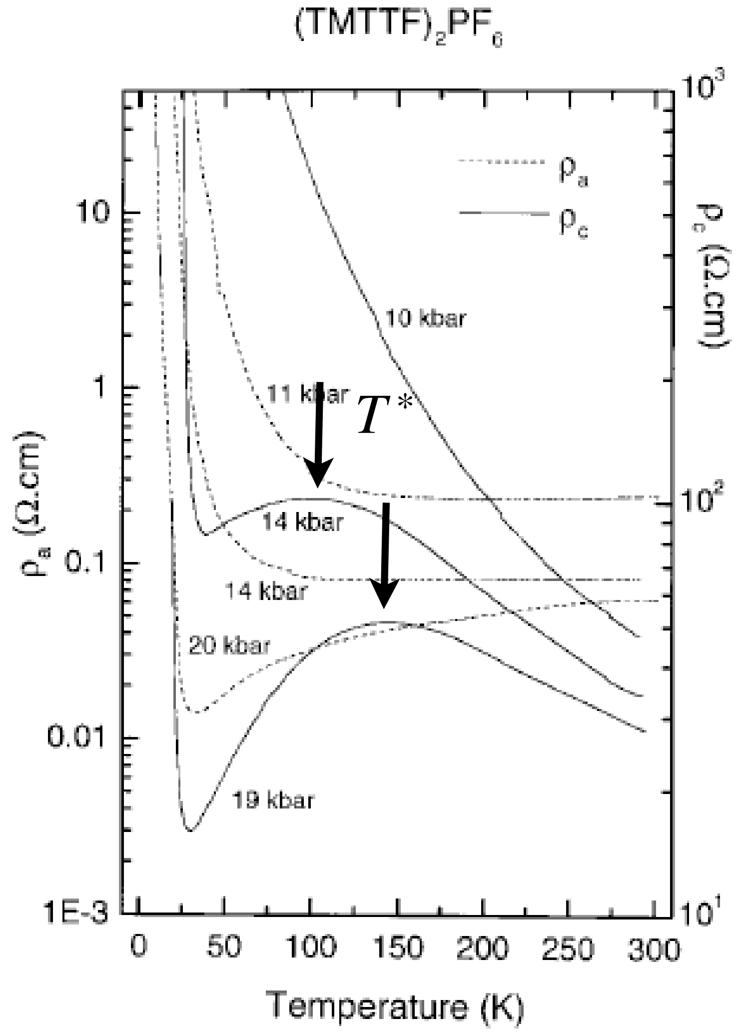
Electronic deconfinement : $(TMTTF)_2\ PF_6$ ....

Transverse resistivity as a probe of single particle coherence in the *ab* plane



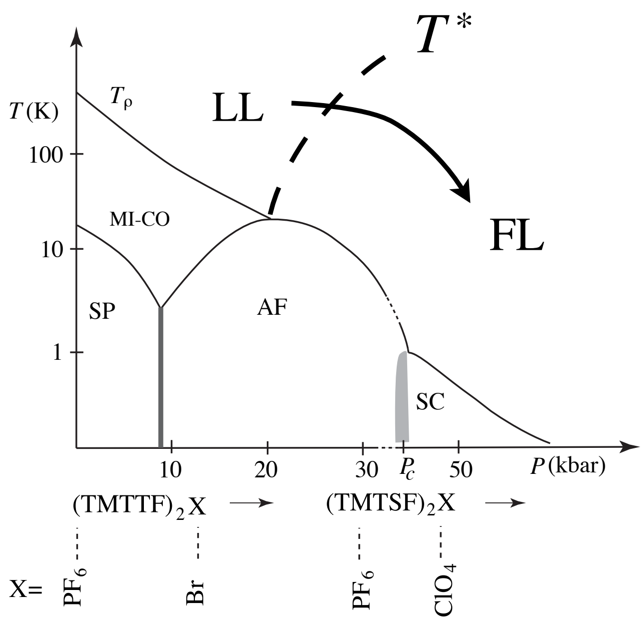
Coherence peak at T^*

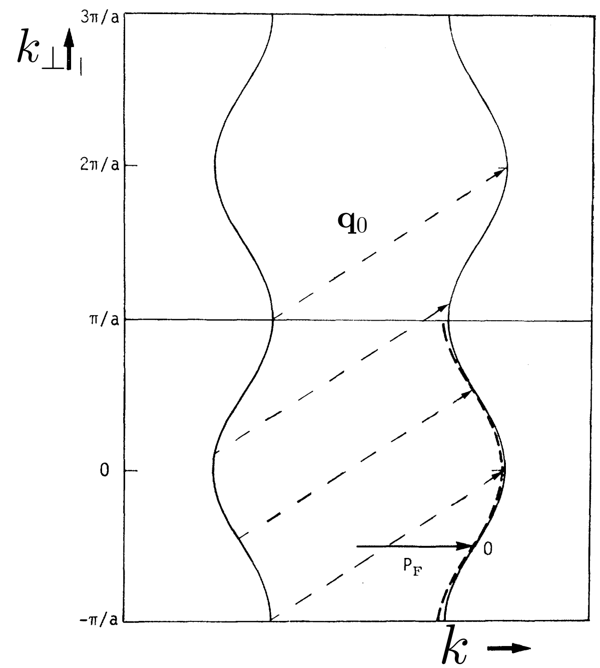




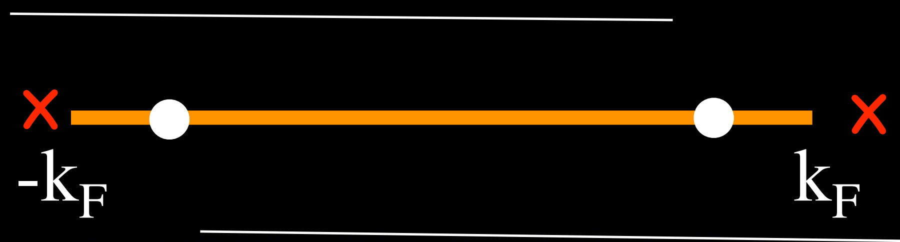
Moser et al., Eur. Phys. J. B 1, 39 (1998)

Electronically deconfined region : from SDW state to superconductivity





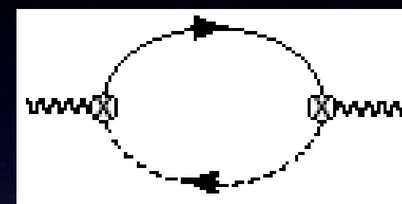
In the deconfined FL region, the warping of the Fermi surface is coherent : sensitivity to nesting deviations

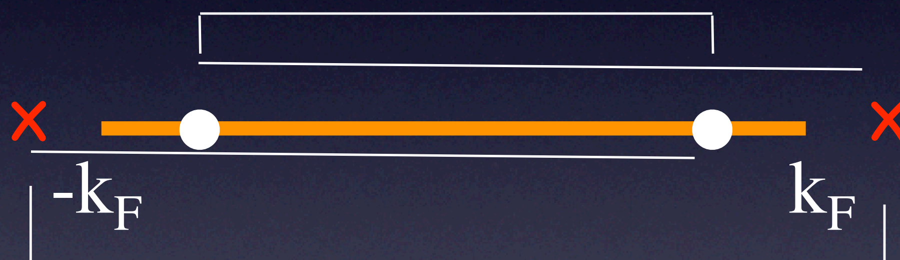


$E(k - 2k_F) = -E$

Nesting $\rightarrow \chi_{OD}(2k_F, T) \sim \ln(E_F/T)$

CDW, SDW

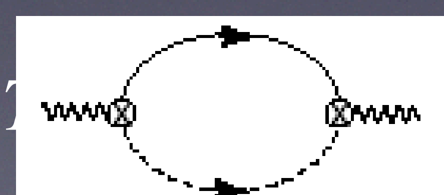




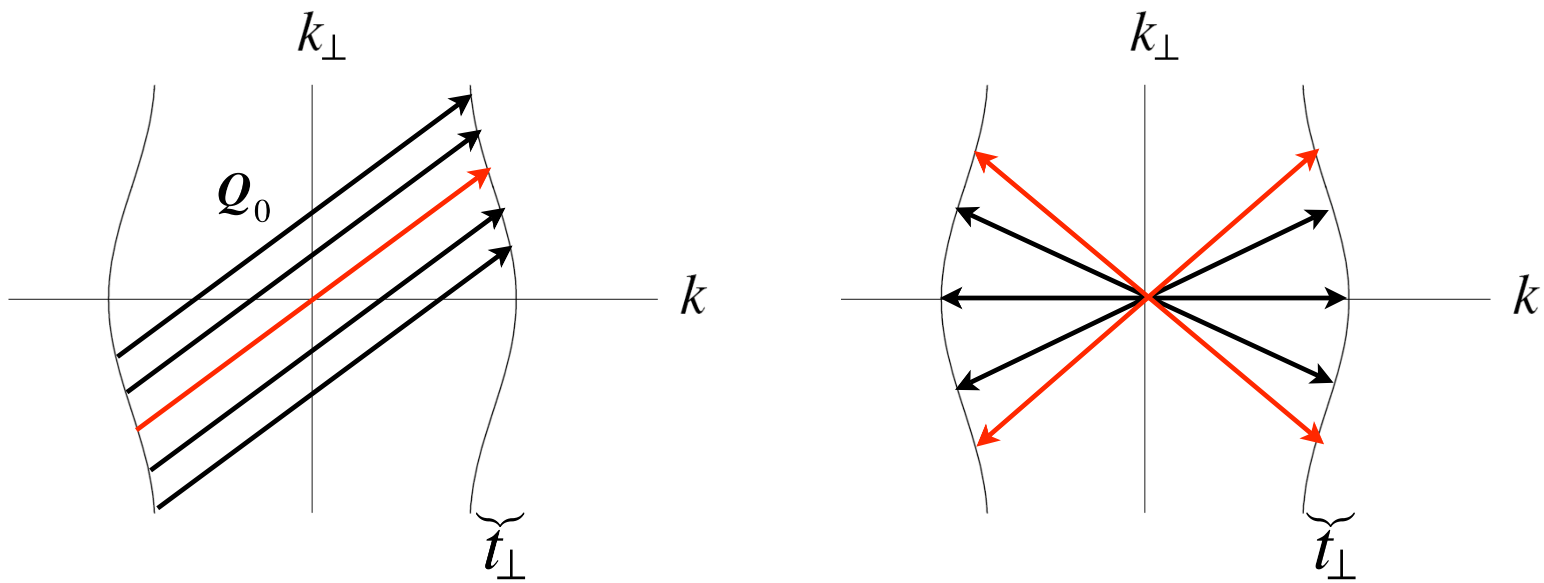
Interference

$E(k) = E(-k)$

inversion $\rightarrow \chi_{SC}($



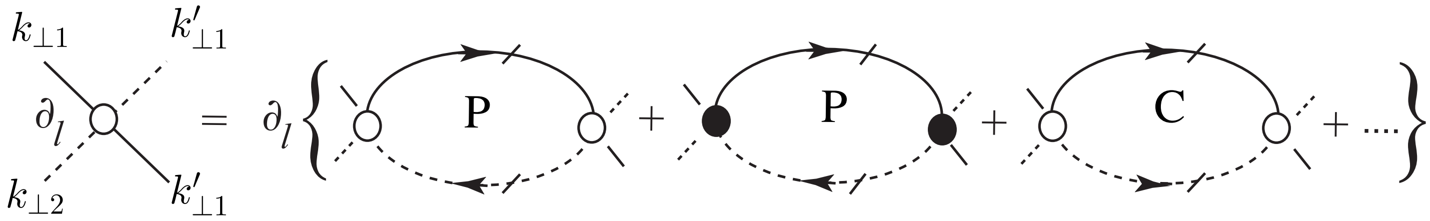
Cooper-Peierls interference near a quasi-1D Fermi surface

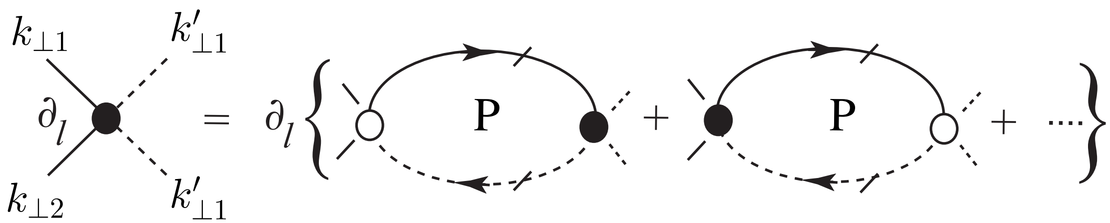


- Interference is incomplete
- Not uniform in momentum space ($k_\perp$-dependent)
- Scattering events not uniform

$$g_{1,2,3} \;\longrightarrow\; g_{1,2,3}(k_{\perp_1}, k_{\perp 2}; k'_{\perp 1}, k'_{\perp 2})$$

One-loop 3 variables RG :





$$\partial_\ell g_{1,2}\big(\{k_\perp, k'_\perp\}\big) \;=\; \sum_{\bar{k}_\perp} g_{1,2}\big(\{k_\perp, \bar{k}_\perp\}\big)\;\mathcal{L}_P\; g_{1,2}\big(\{\bar{k}_\perp, k'_\perp\}\big) \;+\; g_{1,2}\big(\{k_\perp, \bar{k}_\perp\}\big)\;\mathcal{L}_C\; g_{1,2}\big(\{\bar{k}_\perp, k'_\perp\}\big)$$

$$+\; g_3\big(\{k_\perp, \bar{k}_\perp\}\big)\;\mathcal{L}_P\; g_3\big(\{\bar{k}_\perp, k'_\perp\}\big)$$

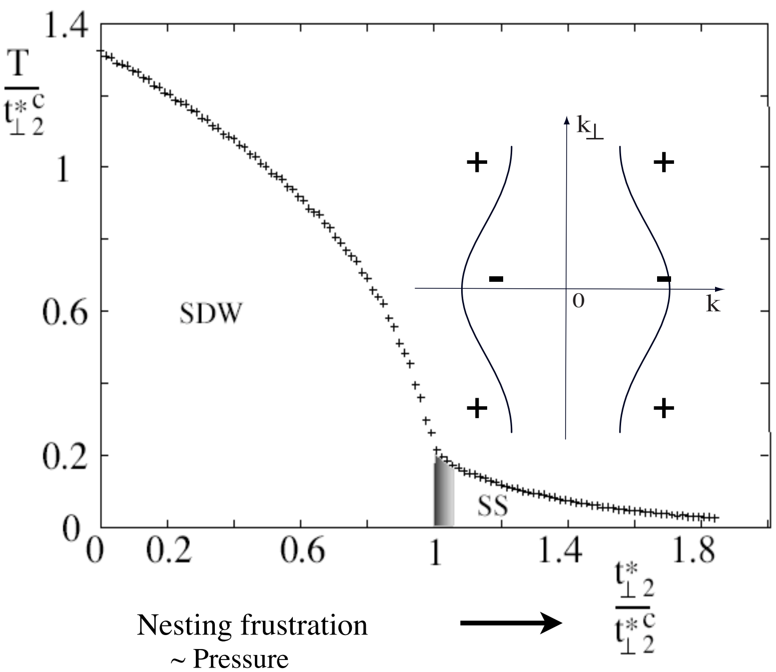
$$\partial_\ell g_3\big(\{k_\perp, k'_\perp\}\big) \;=\; \sum_{\bar{k}_\perp} g_{1,2}\big(\{k_\perp, \bar{k}_\perp\}\big)\;\mathcal{L}_P\; g_3\big(\{\bar{k}_\perp, k'_\perp\}\big)$$

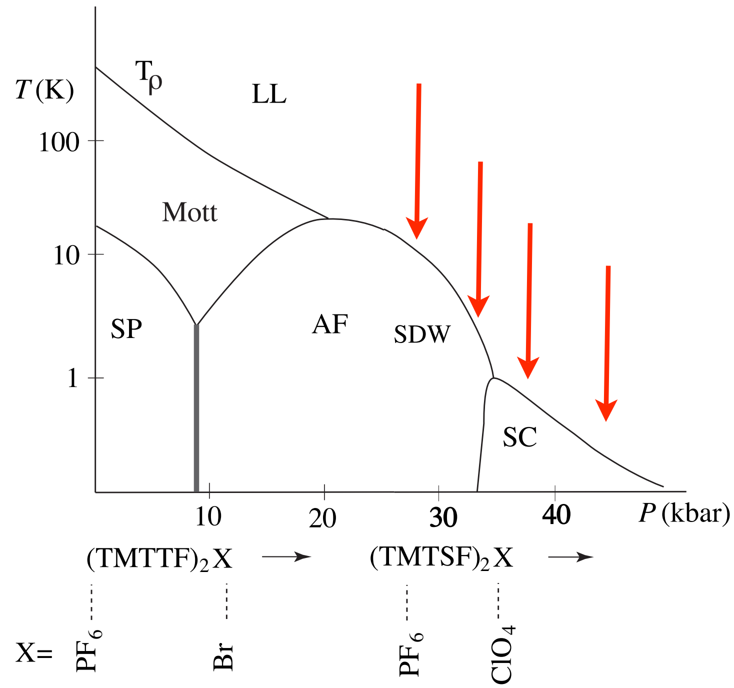
Eur. Phys. J. B **21**, 219–228 (2001)

THE EUROPEAN PHYSICAL JOURNAL B
EDP Sciences

Interplay between spin-density-wave and superconducting states in quasi-one-dimensional conductors

R. Duprat and C. Bourbonnais[a]





On the origin of pairing : an historical disgression

VOLUME 15, NUMBER 12 PHYSICAL REVIEW LETTERS 20 SEPTEMBER 1965

NEW MECHANISM FOR SUPERCONDUCTIVITY*

W. Kohn

University of California, San Diego, La Jolla, California

and

J. M. Luttinger

Columbia University, New York, New York

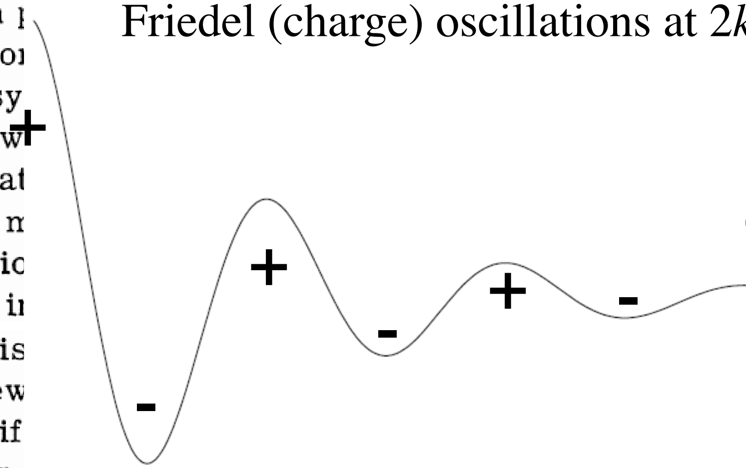
(Received 16 August 1965)

It is the purpose of th
new mechanism which
against Cooper-pair for
a weakly interacting sy
not remain normal dow
of temperature, no mat
the interaction. This m
to do with the conventic
attractive interaction in

To understand what is
an over-simplified view
long been known[1] that if
a metal, the screening is such that there re-
mains a long-range oscillatory potential of
the form cos(2$k_F r$) ... the Fermi mo
mentum). This leads to a long-range interac-
tion between charges. Formally, the source
of this long-range force is the singularity of

...nt as a function of the mo-
...when $q = 2k_F$.[1] This sin-
...r transform of the inter-
... long-ranged oscillatory
...ce. All that is necessary
... Fermi surface; a
... surface due to (say)
... impurities will give rise
...h drops off exponential-
...nces.
...ppose that, similarly,
...on between the fermions
... long-range oscillatory
...of the attractive
... form thus giving

Friedel (charge) oscillations at $2k_F$



Minimum as source of attraction
(exchange of charge fluctuations)

$$1-|\lambda_\ell| \ln \epsilon_F/T_c = 0$$

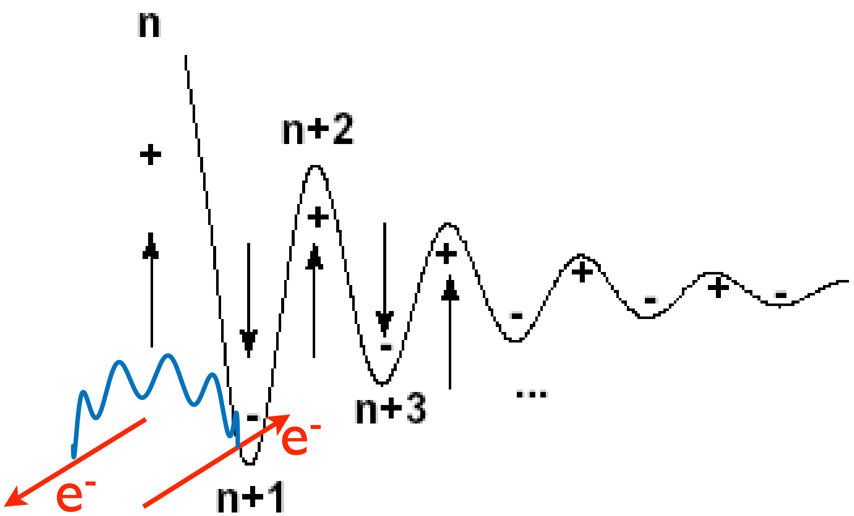
Cooper first.

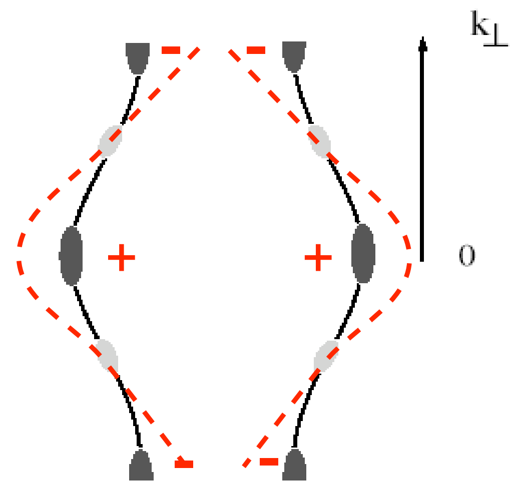
$$(kT_c/\epsilon_0) \sim \exp[-(2l)^4].$$

$\sim 10^{-7}$ (l=1, p-wave) ....

Pairing mechanism for `d-wave' like superconductivity

AF fluctuations as an oscillating potential

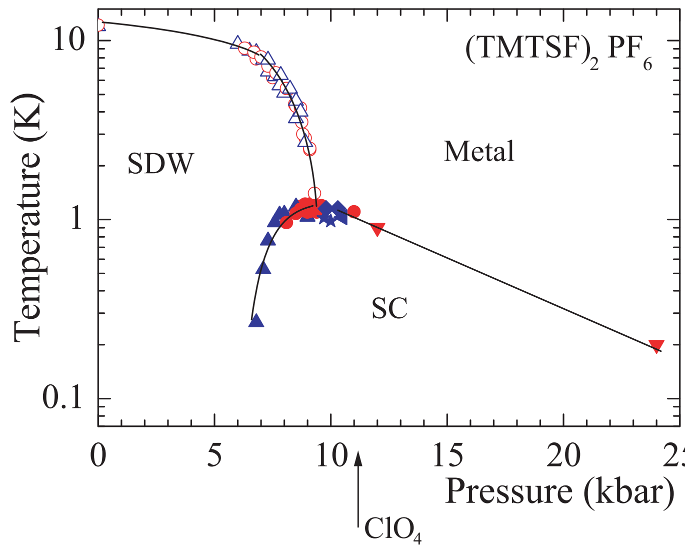




$$\boxed{\Delta(k_\perp) = |\Delta| \cos k_\perp}$$

Interchain attraction
Gap with nodes

Superconductivity: Experimental status for the Bechgaard salts

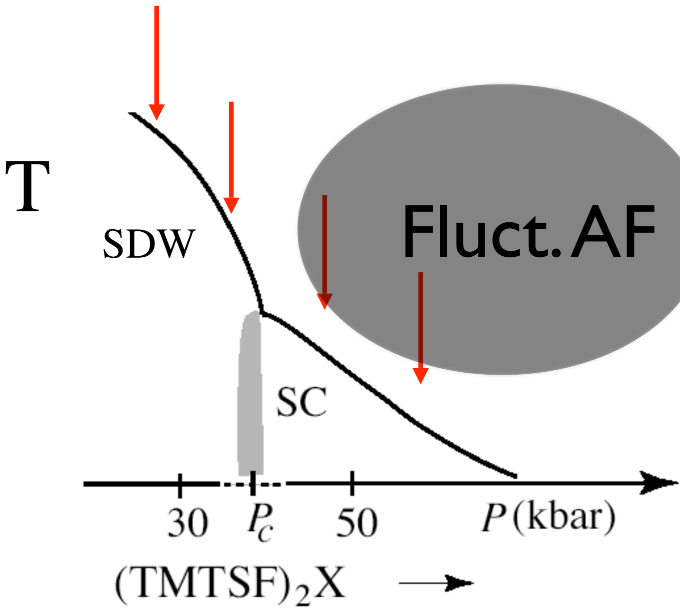


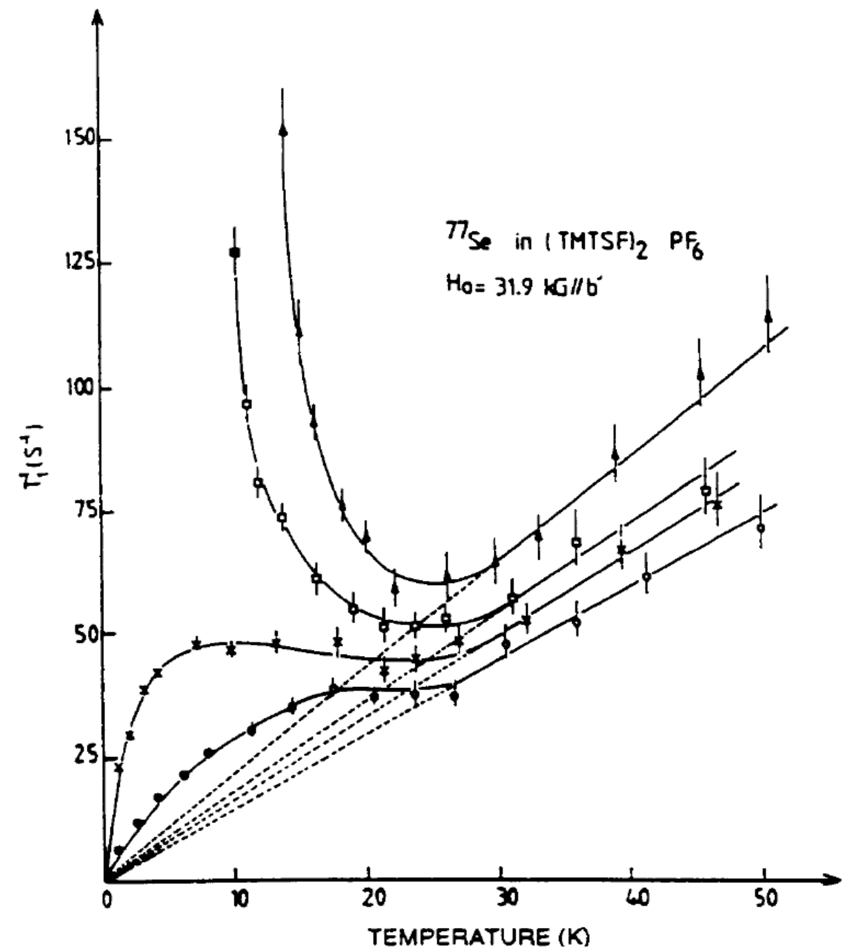
T_c is max. when $T_{SDW} \longrightarrow 0$

Rapid suppression under pressure

Metallic state dominated by spin fluctuations

Antiferromagnetic fluctuations in the normal state seen by NMR

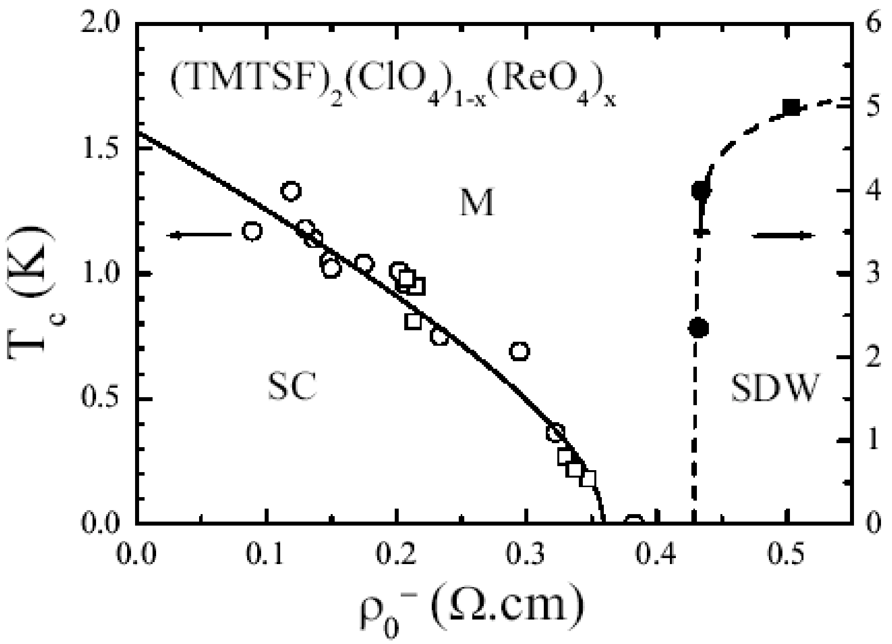


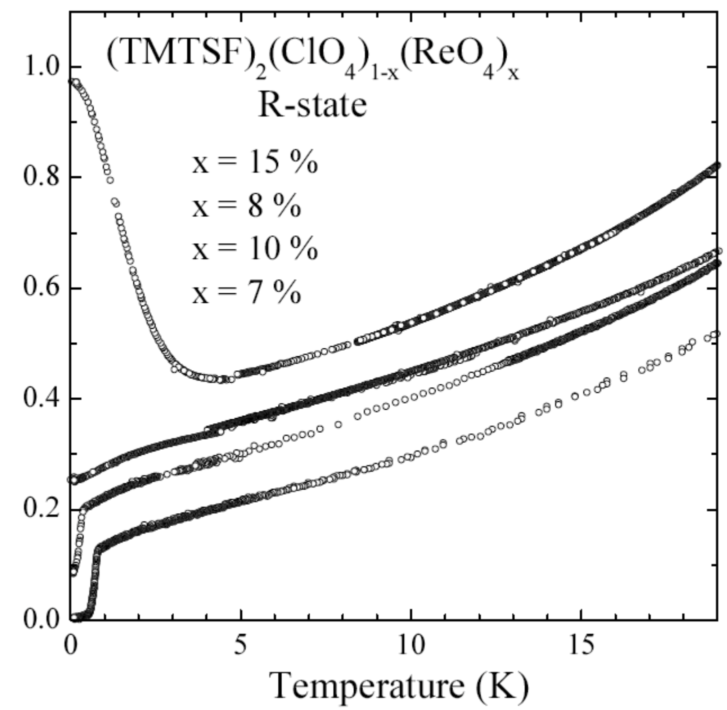


- Strong AF fluctuations in the metallic state ($T \sim 25\ T_C$)
- Pressure dependence

F. Creuzet et al., Synthetic Metals 1987

The critical temperature and non magnetic defects





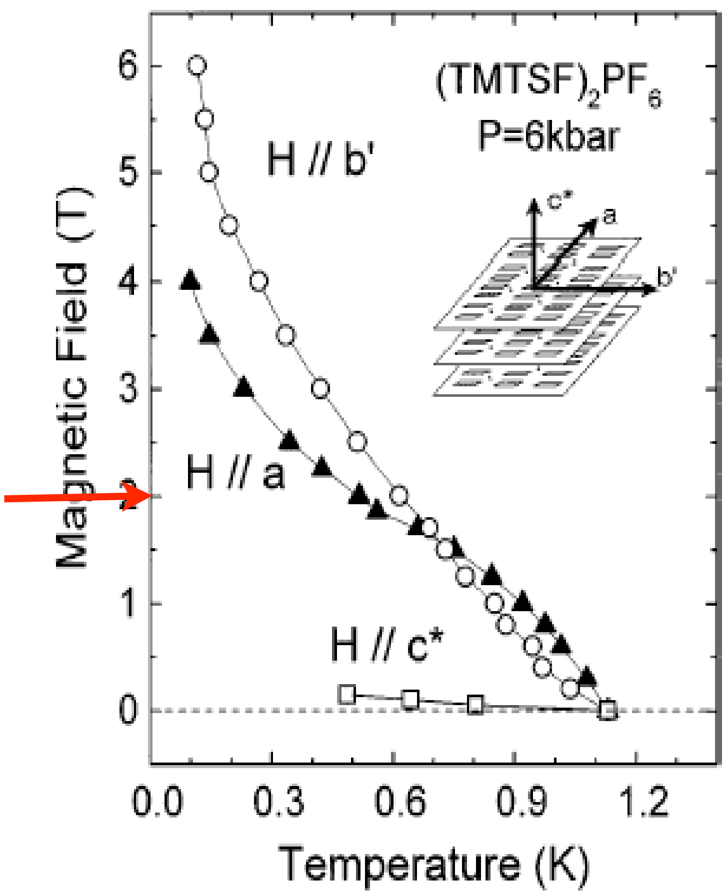
Joo et al., EPL 72, 645 (05); EPJB (2004).

T_c quickly decreases with % of non magnetic defects

Gap changes sign on the Fermi surface

SC triplet (p, f, ...) or singulet (d, g ...) $\langle\, \Delta(\boldsymbol{k})\, \rangle_{\mathrm{Imp.}} = 0$

Critical fields



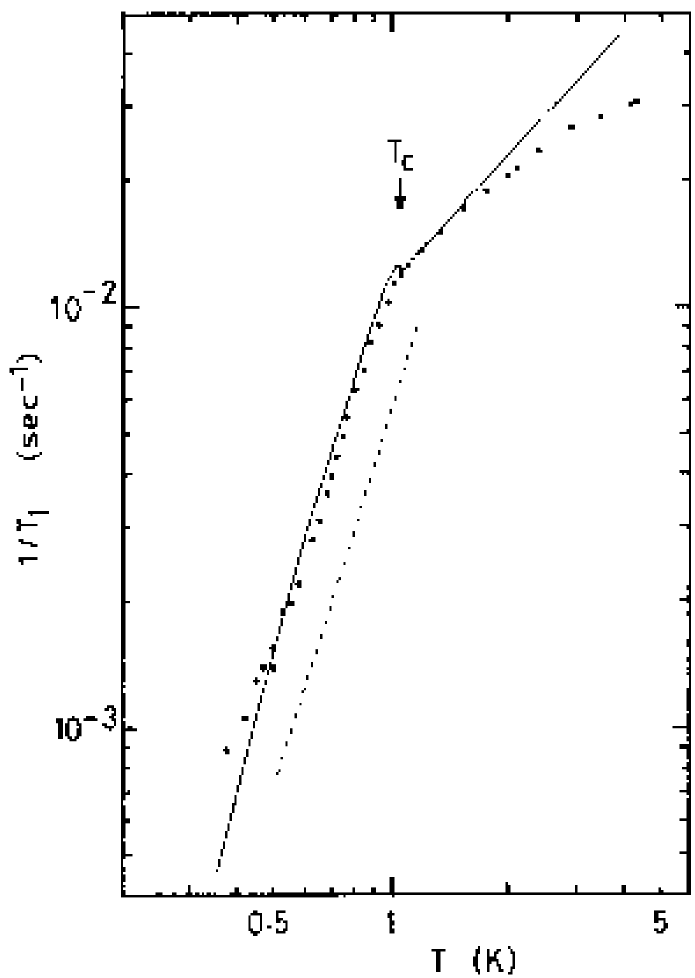
Lee *et al.*, PRL **78,** 3555, (1997).

- Violation of Pauli 2 dir.

$$\boxed{H_{\mathrm{Pauli}} = 1.84\, T_c}$$

- Triplet superconductivity ?
  (p, f ...)

Nature of SC: Nuclear relaxation rate *vs T*



- Absence of Hebel-Slichter anomaly
- Power law $1/T_1 \sim T^3$
- Gap with nodes

Takigawa *et al.*, JPSJn **56,** 873 (1987).