Review of typical behaviours observed in strongly correlated systems

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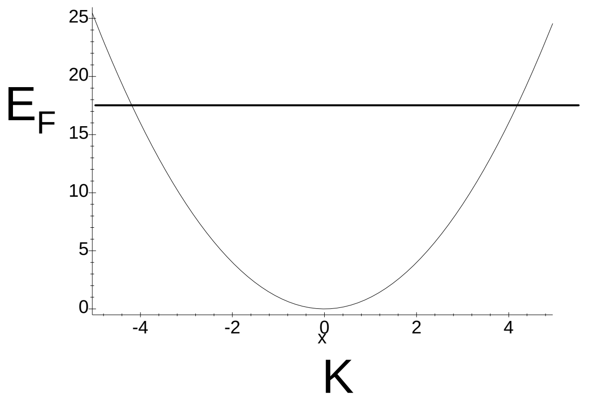
“Models in magnetism: from basics aspects to practical use”
Timisoara september 2009

Some examples of strongly correlated electrons

- Superconductivity
- Magnetism
- Low dimensionnality
- Heavy fermions
- Mott insulators

Free electrons



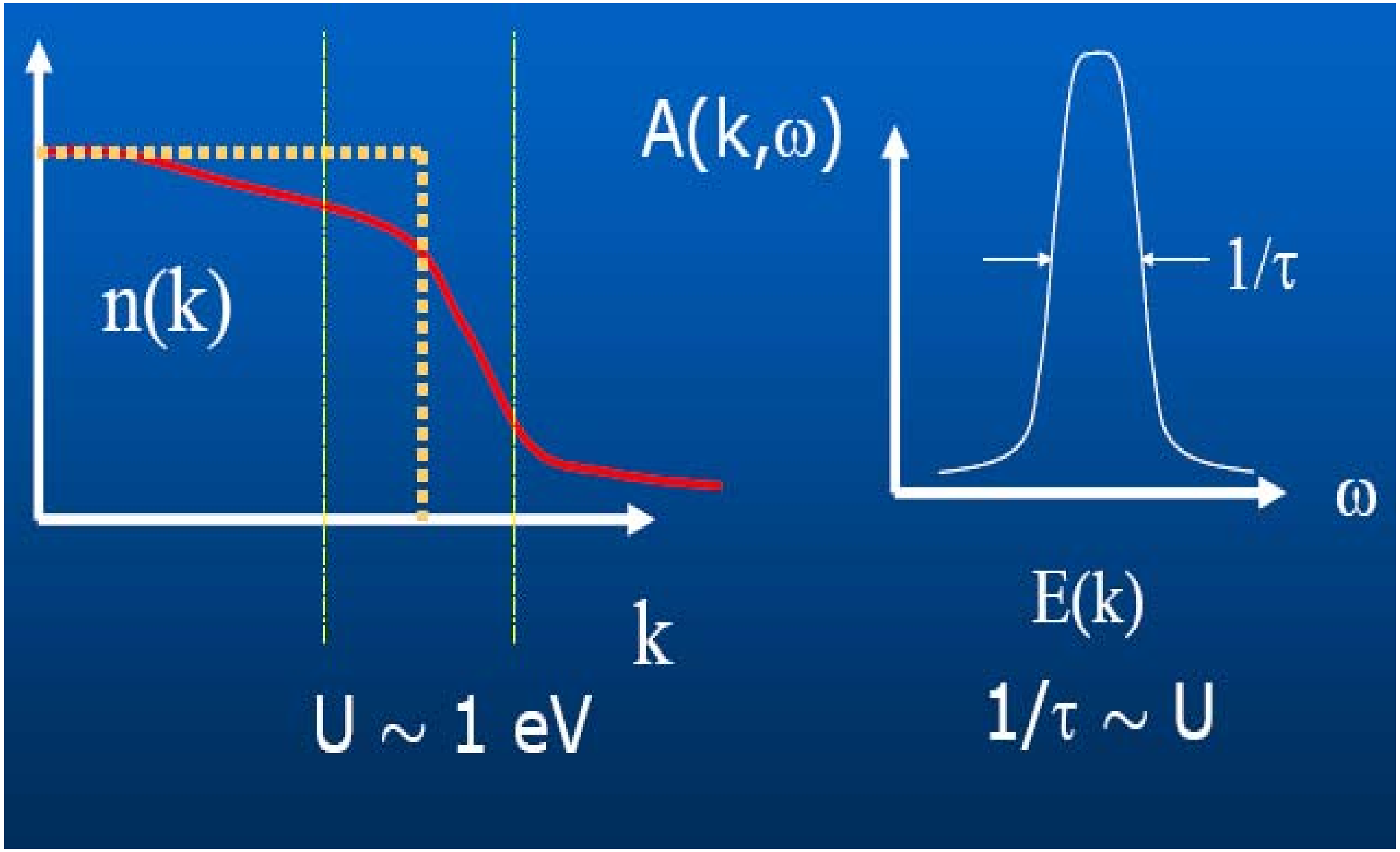
$$\frac{h^2 k_F^2}{2m}$$

Temperature effects (E_F=1eV = 30 000K)

Band structure (tight binding calculations)

Effect of electron electron repulsion U

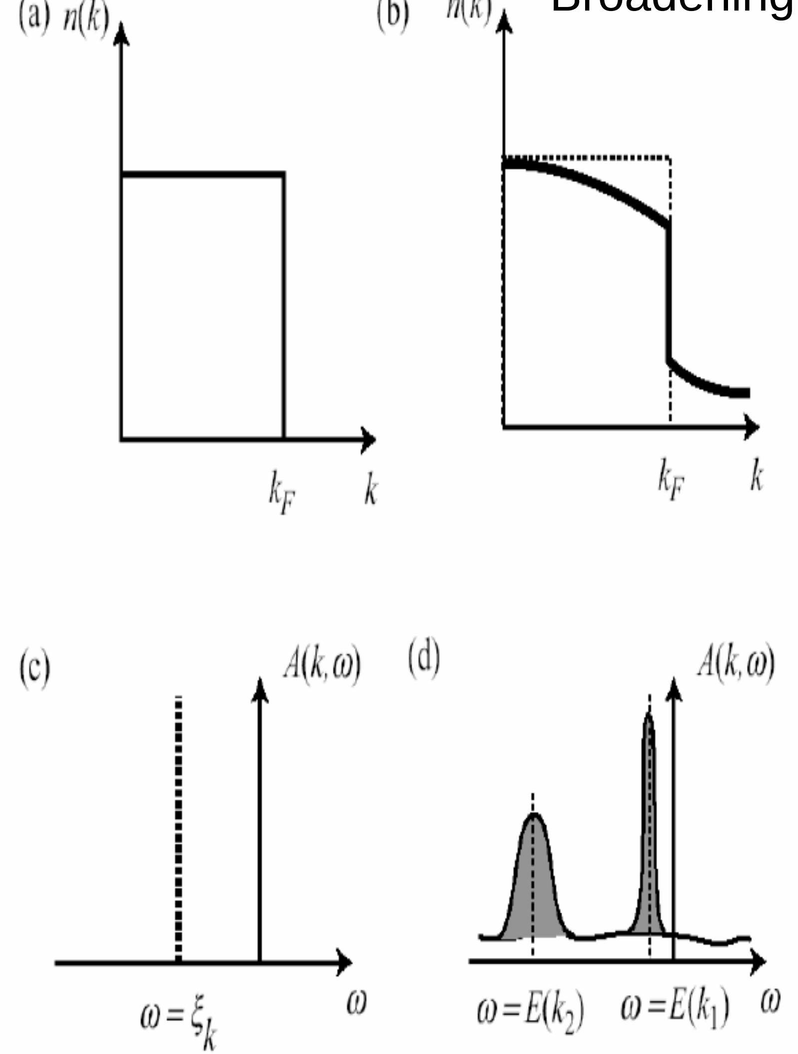
From T. Giamarchi



Not so strong

Effect of correlations

Broadening



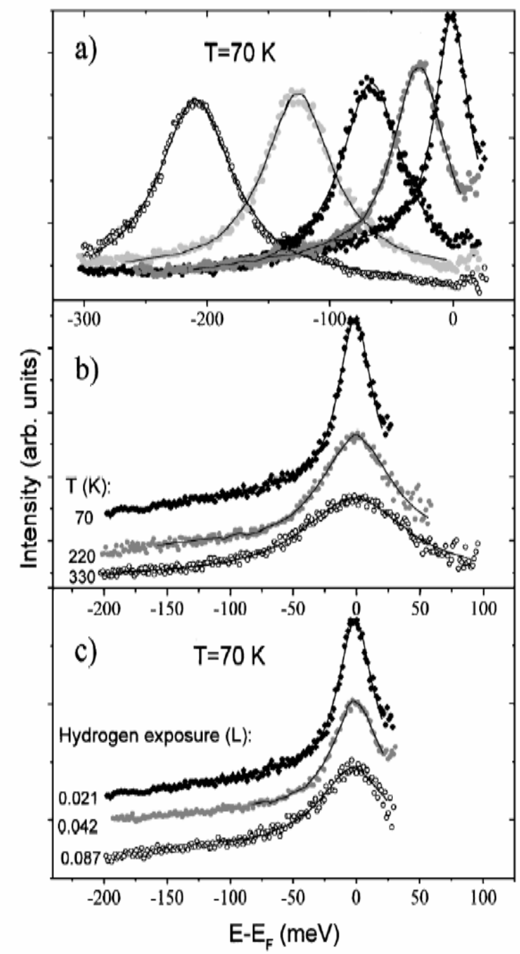
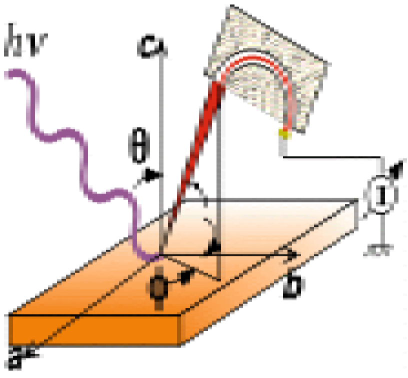
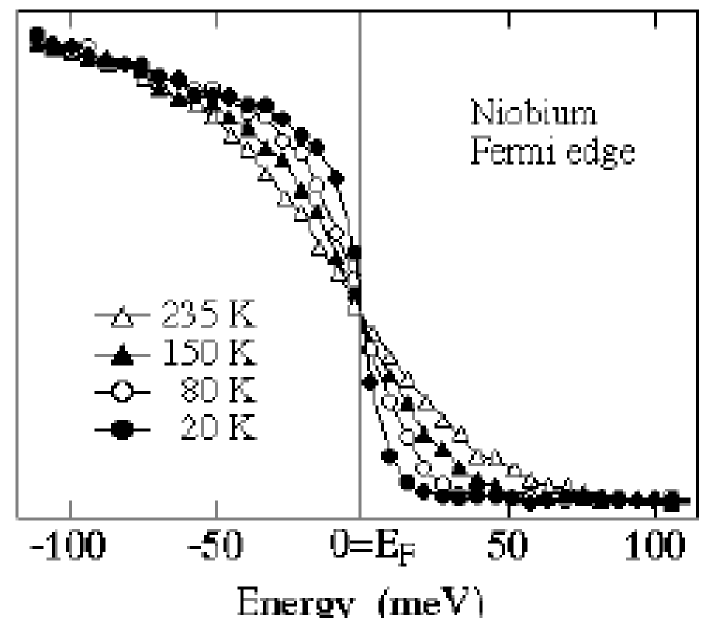


FIG. 2. Spectral intensity as a function of binding energy for constant emission angle, normalized to the experimentally determined Fermi cutoff. Data are symbols, while lines are fits to the Lorentzian peaks with a linear background. The dependence on the (a) binding energy, (b) temperature, and (c) hydrogen exposure is shown.

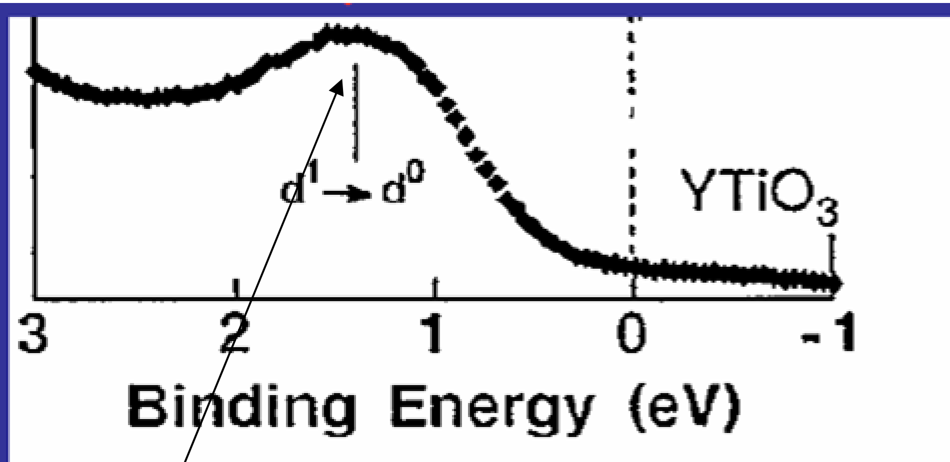
Photoemission



$$k_{//} = \sqrt{\frac{2mE_{kin}}{\hbar}}\sin\theta$$

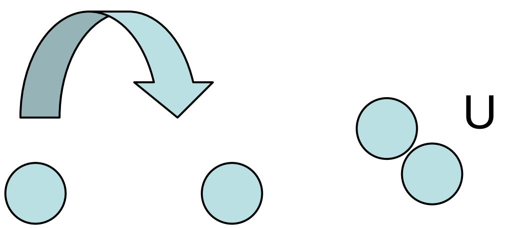


Photoemission in insulators



Photoemission: Fujimori et al., PRL 1992

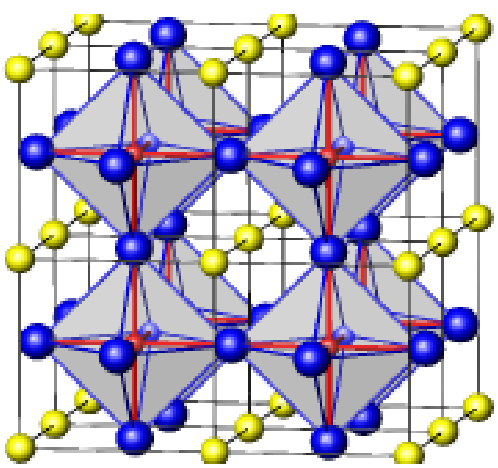
Hubbard satellite

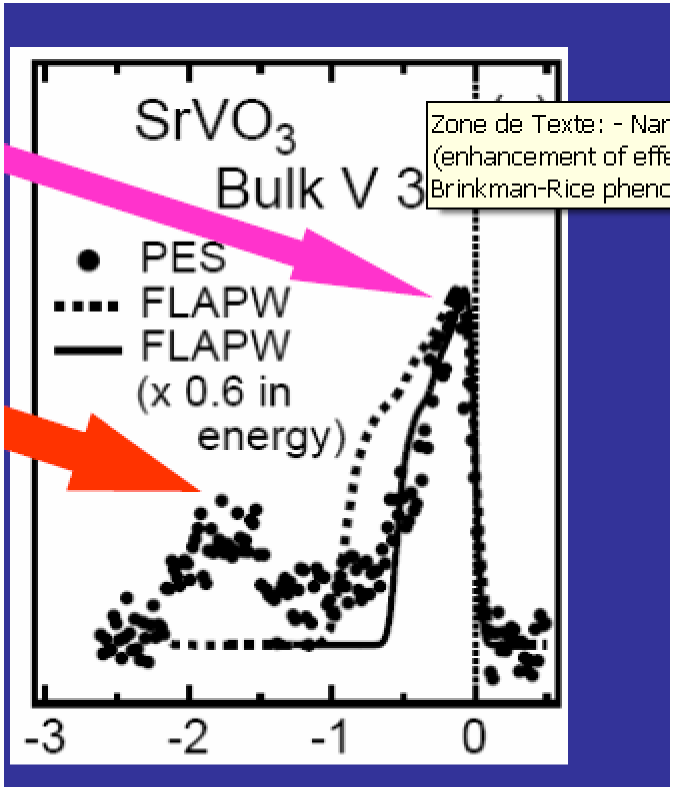


Strongly correlated metal

Peak of quasi particules

Hubbard peak





Sekiyama et al., PRL 2004

Transport properties

- Specific heat Cp:
  - Sommerfeld expansion:

$$
\begin{aligned}
C_p &= dU/dT \\
&= d/dT\left(\int (f(E) - f(E,T=0))n(E)dE + \int (f(E,T=0))n(E)dE\right) \\
&= d/dT\left(\int (f(E) - f(E,T=0))n(E)dE\right) \\
&= n(E_F)\left(\int d/dT(f(E) - f(E,T=0))dE\right) \\
&= k_B^2 T\, n(E_F)\frac{\pi^2}{3} \\
&= k_B\,\frac{\pi^2}{2}\frac{T}{T_F} = \gamma T \\
k_B T_F &= \frac{\hbar^2 k_F^2}{2m}
\end{aligned}
$$

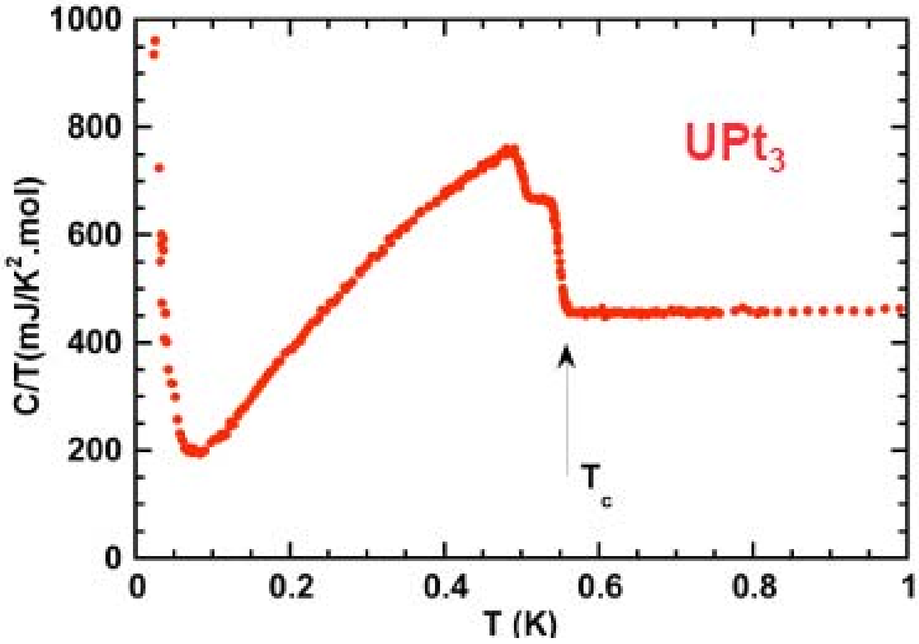
Heavy fermions

- Macroscopic manifestations:

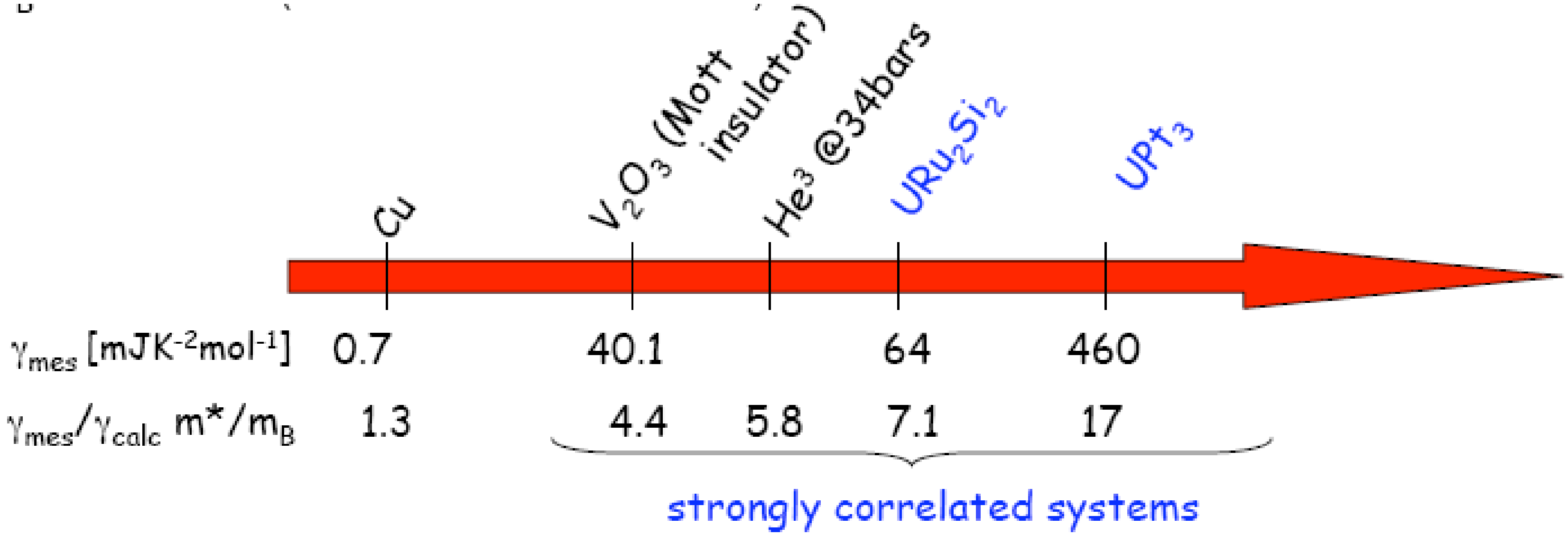
  large Sommerfeld coefficient
  (Cu : $\gamma \sim 0.5 mJ/K^2.mol$)

$$C_v \approx nk_B \frac{k_B T}{E_F} \Rightarrow \gamma \approx nk_B^2 \frac{m^*}{(\hbar k_F)^2}$$

γ-UPt_3 ~1000 γ-Cu (/mol)



Band mass and effective mass



De Haas Van Alphen effect

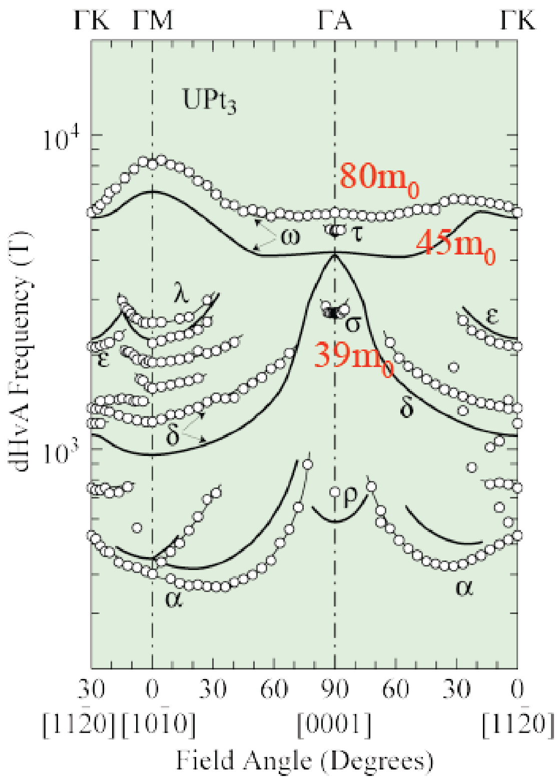
- In presence of magnetic field, it appears oscillations periodic in 1/H related to the extremum area of the Fermi surface.
- In addition, there is a magnetic field dependence of the amplitude related to effective mass. (high mass, high field).

Heavy masses

- Microscopic manifestations:

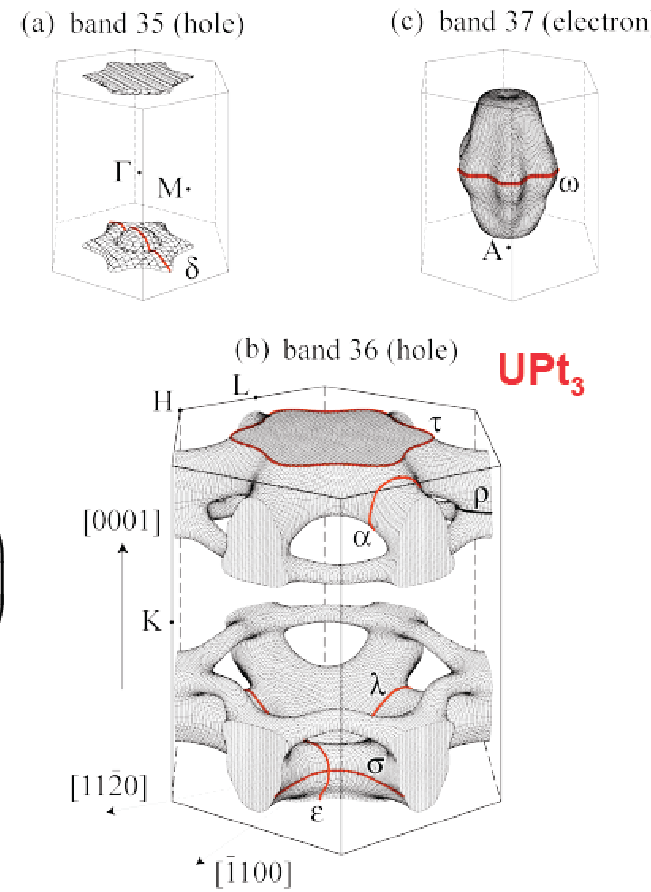
  Fermi surface and large m* observed with dHvA oscillations !

  Heaviest mass: 160 m_0…



$$A \propto \exp\left(-\frac{k_B(T+T_D)}{\hbar\omega_c}\right)$$

$$\omega_c = \frac{eB}{m^*}$$



From JP Brison

Resistivity in T^2

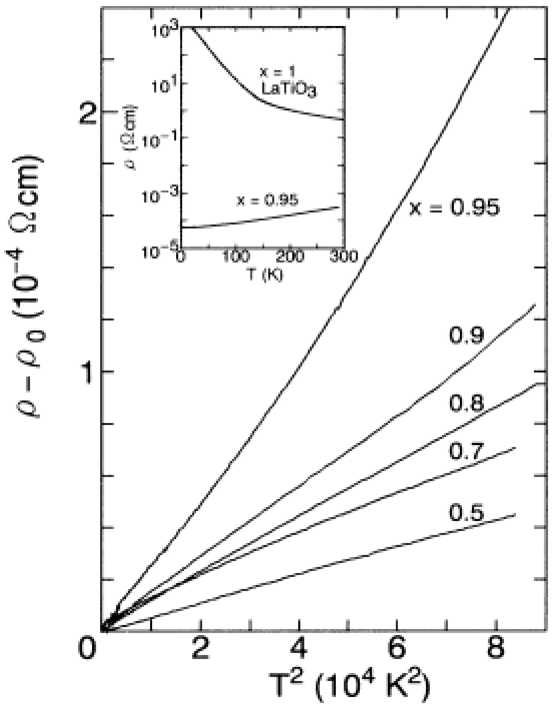
The prefactor A scales with γ^2

condcutivity=$ne^2\tau/m$

Also magnetic susceptibility is Cte

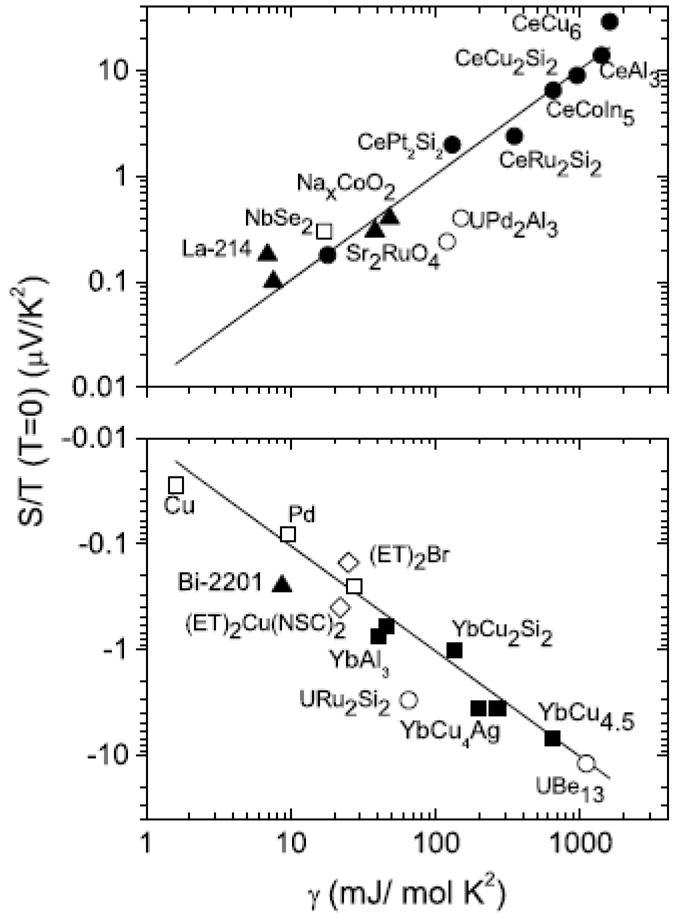
From R. Fresard

$La_xSr_{1-x}TiO_3$



- Signature d'un liquide de Fermi.
- $LaTiO_3$: isolant de Mott.

Thermoelectric power S



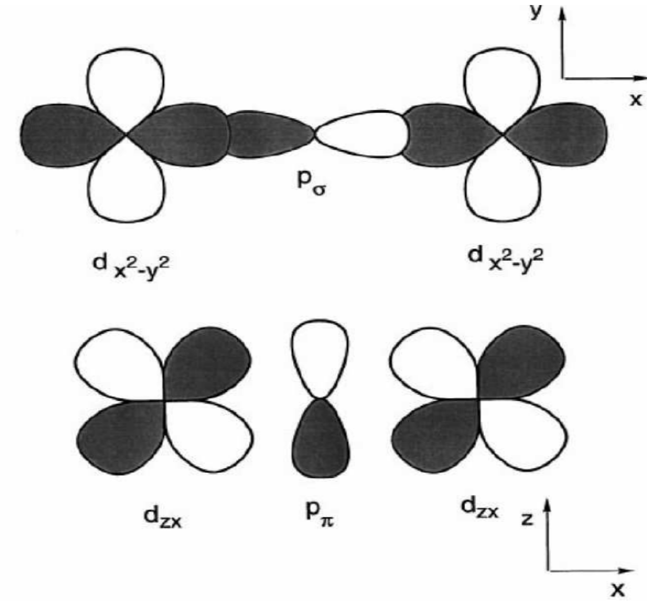
$S = k/e \; \pi^2/2 \quad T/T_F \; (1 + 2/3 \; z)$

From Behnia et al.

Narrow 3d, 4f orbitals → strong electronic correlations

Why oxides ?

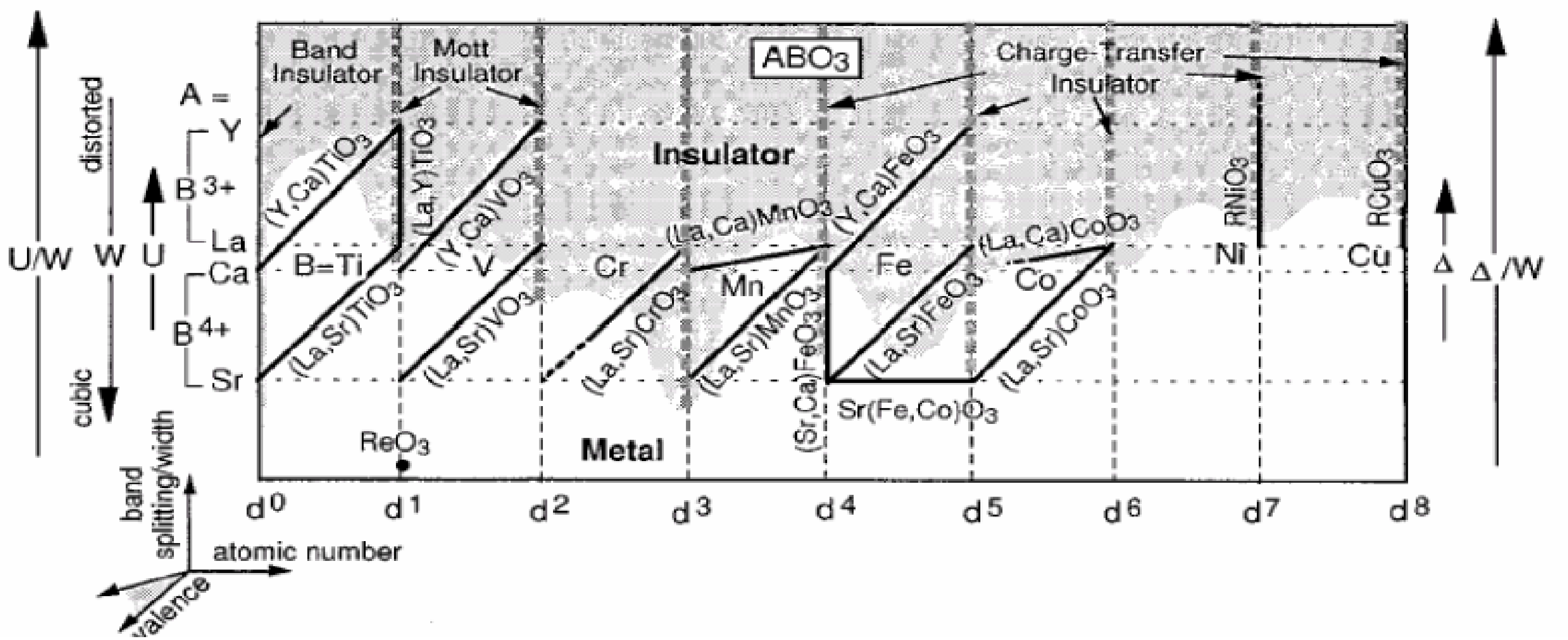
- Metal U/t small, no correlations, screening of interactions by excitations electron-hole
- Oxides



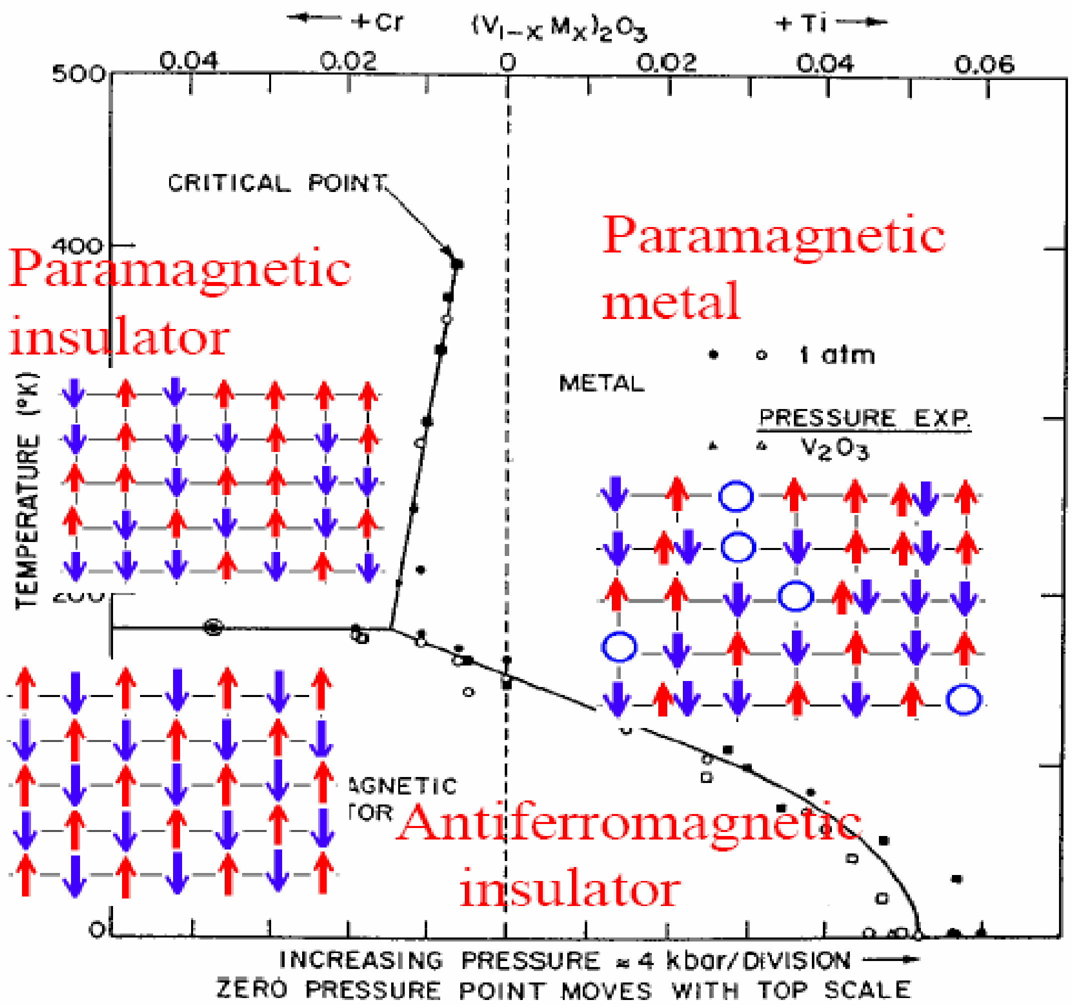
Effective t can be small
U/t large

Oxides are interesting

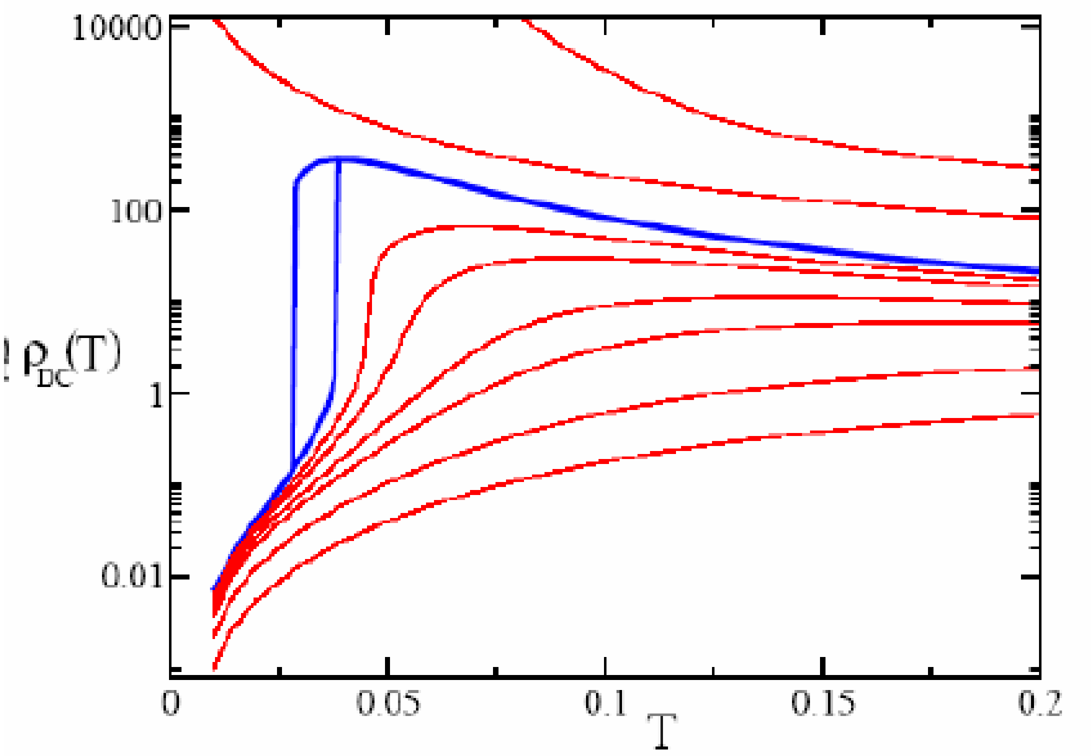
Fujimori's map of perovskite 3d TMOs (ABO_3)



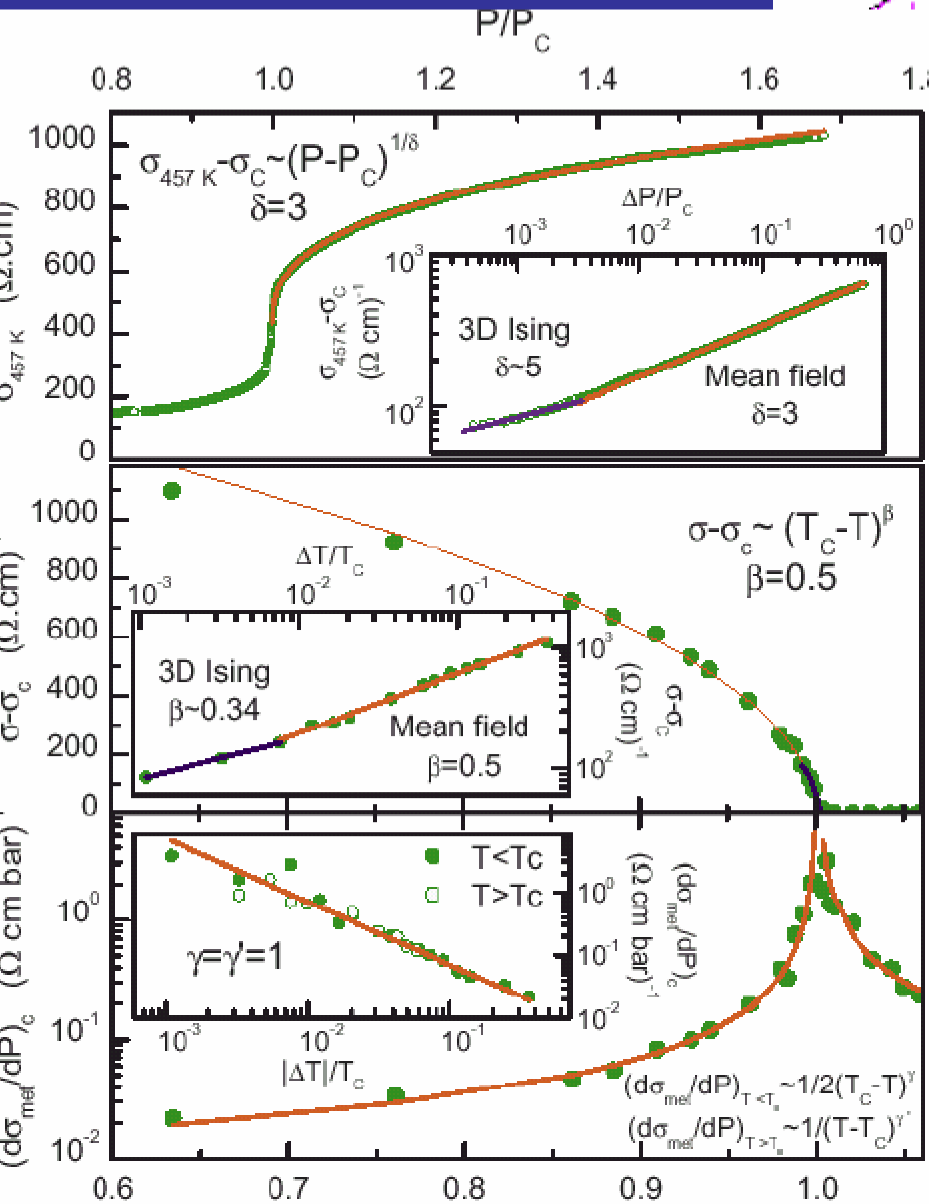
Mott insulators V_2O_3

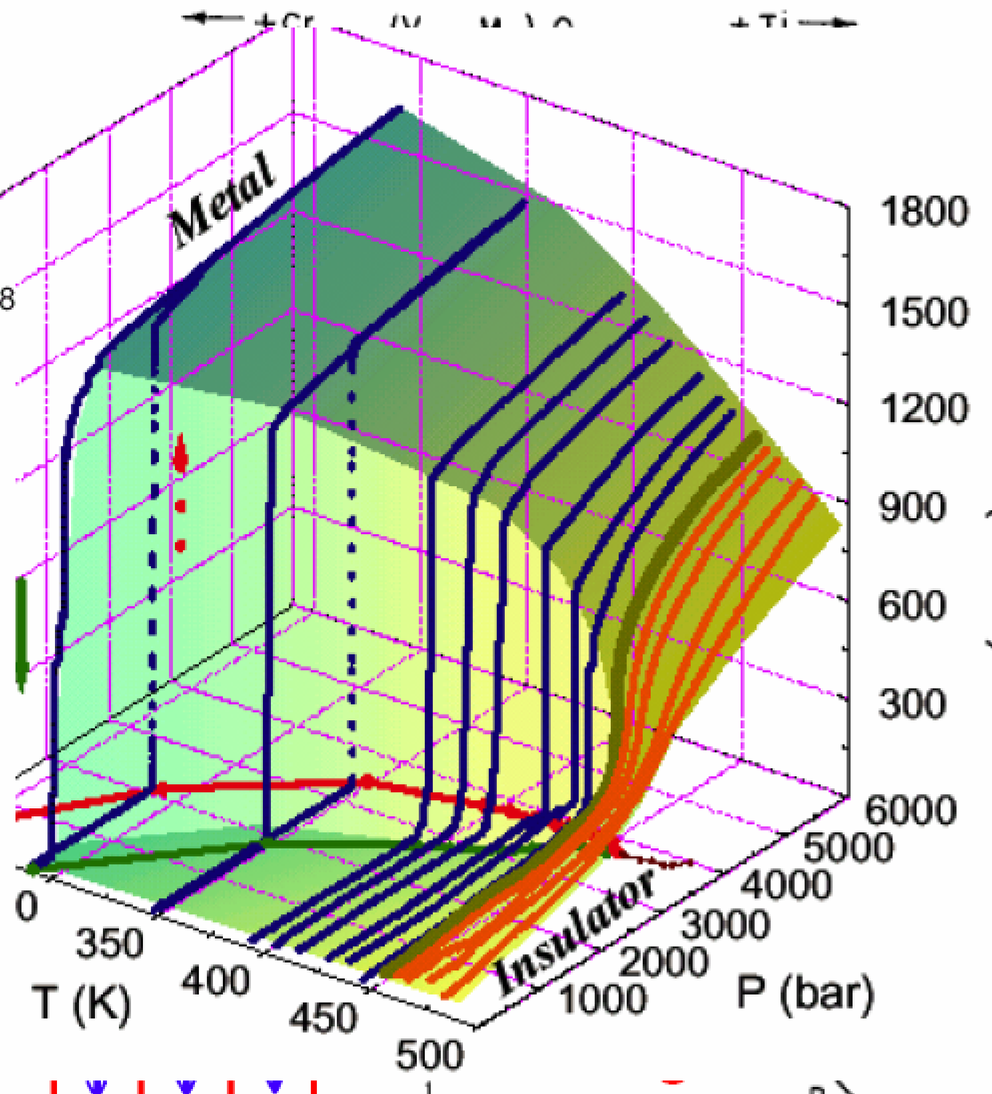


Mott insulators V_2O_3



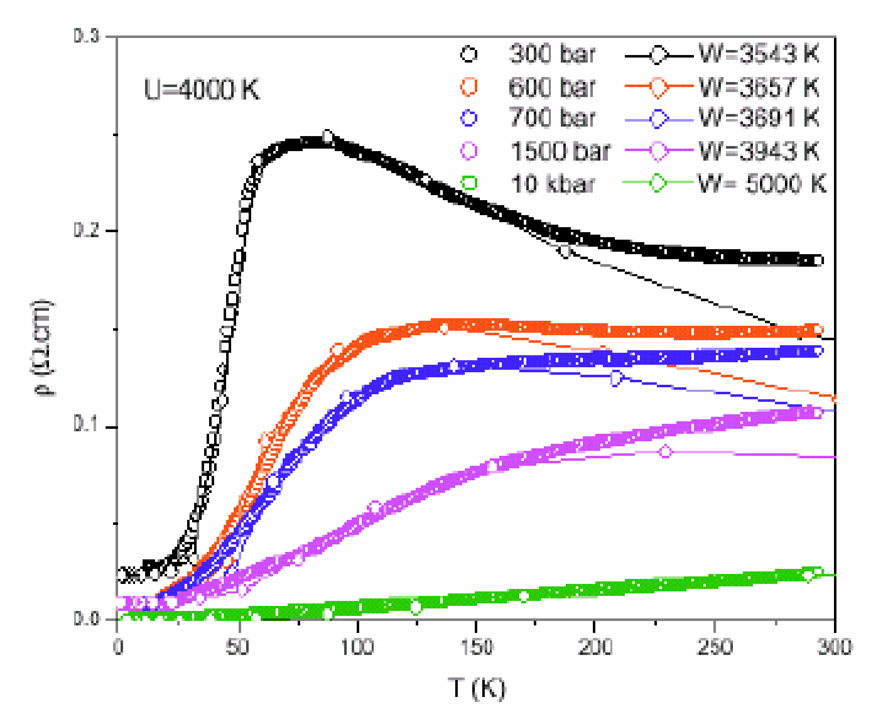
Liquid-gas critical endpoint

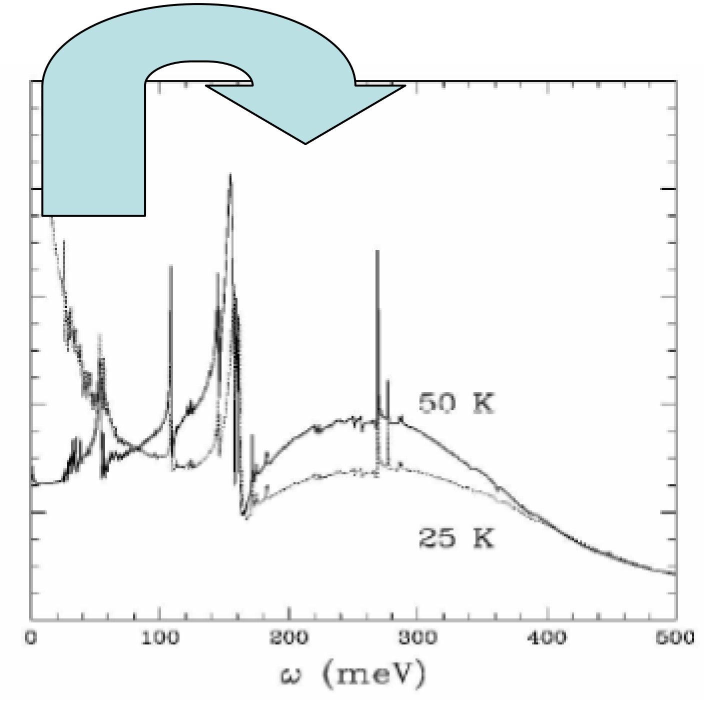




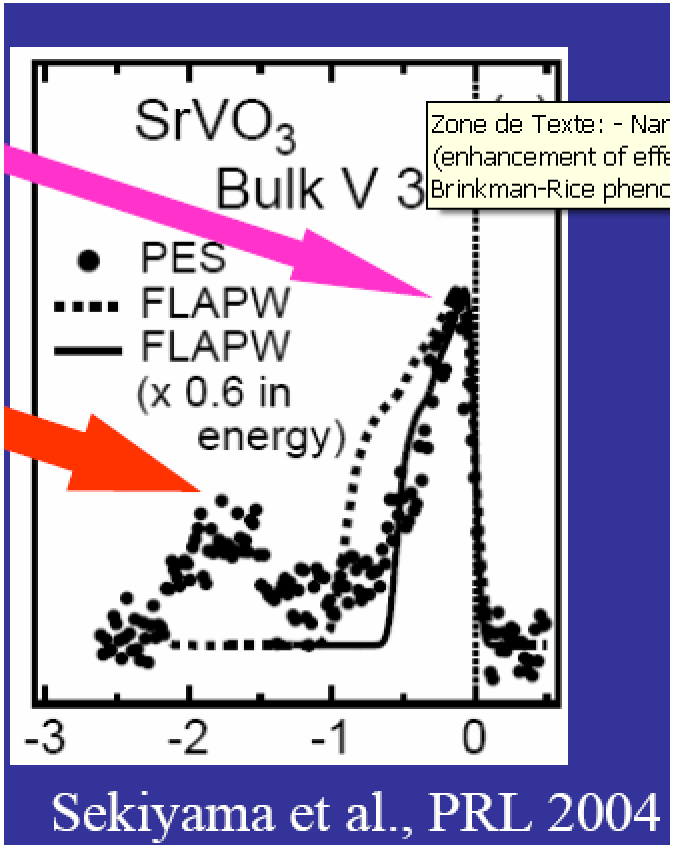
Limelette et al, Science 2003: conductivity under variable pressure

Organic conductor from Limelette et al.

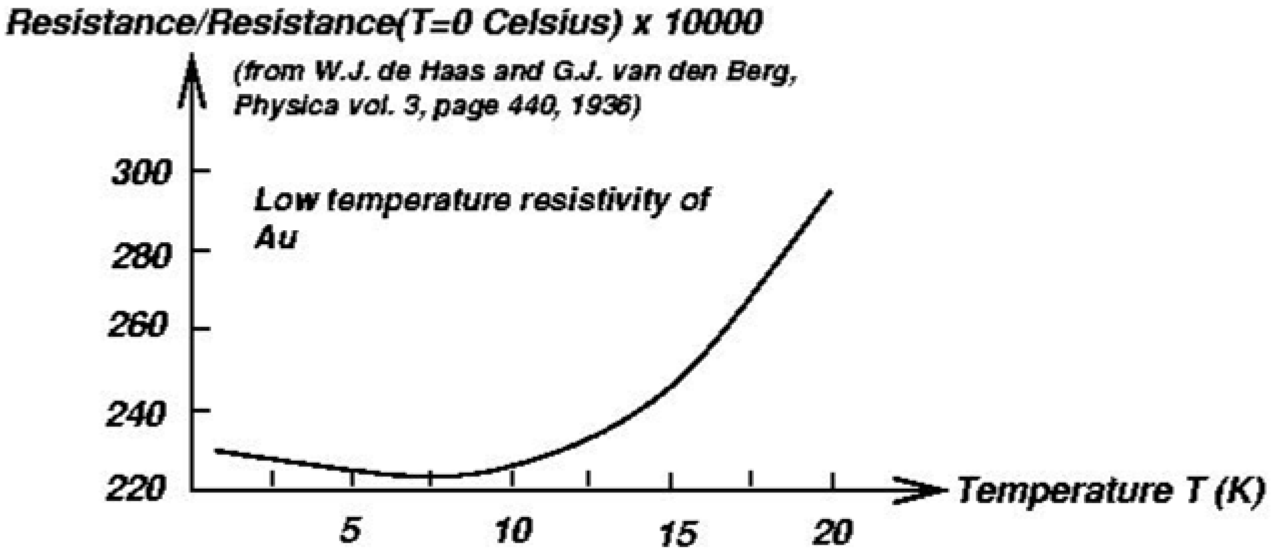


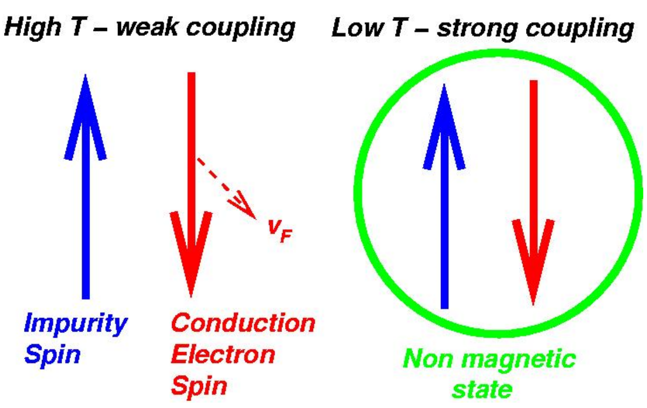


Transfer of the spectral weight


SrVO$_3$
Bulk V 3
PES
FLAPW
FLAPW
(x 0.6 in
energy)
-3
-2
-1
0
Zone de Texte: - Nar
(enhancement of effe
Brinkman-Rice pheno
Sekiyama et al., PRL 2004

Kondo effect

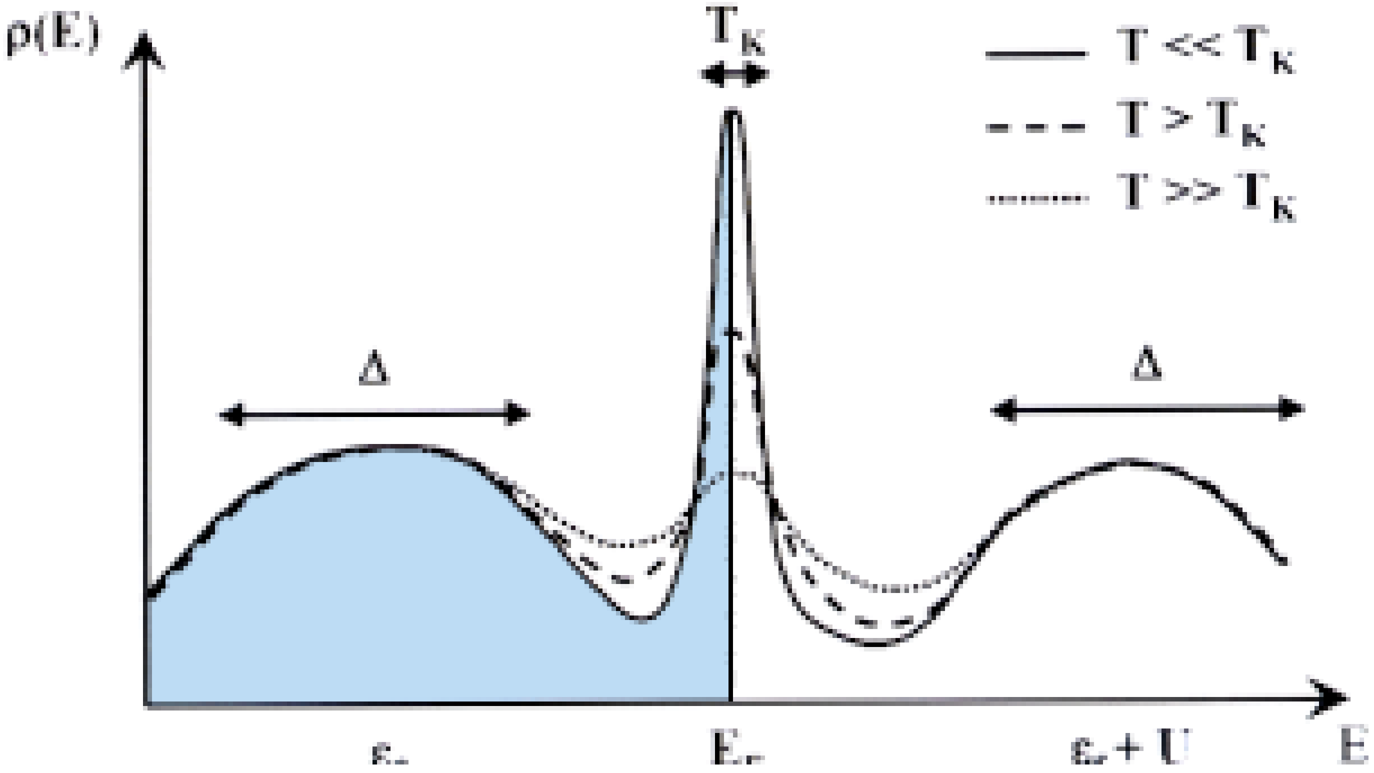




$$\rho(T) = \rho_0 + aT^2 + c_m \ln\frac{\mu}{T} + bT^5$$

Kondo effect

Magnetic impurities



DMFT

- Dynamical mean field theory
- To put together quasiparticules and Hubbard states
- Limit: no Q dependence, cluster DMFT…

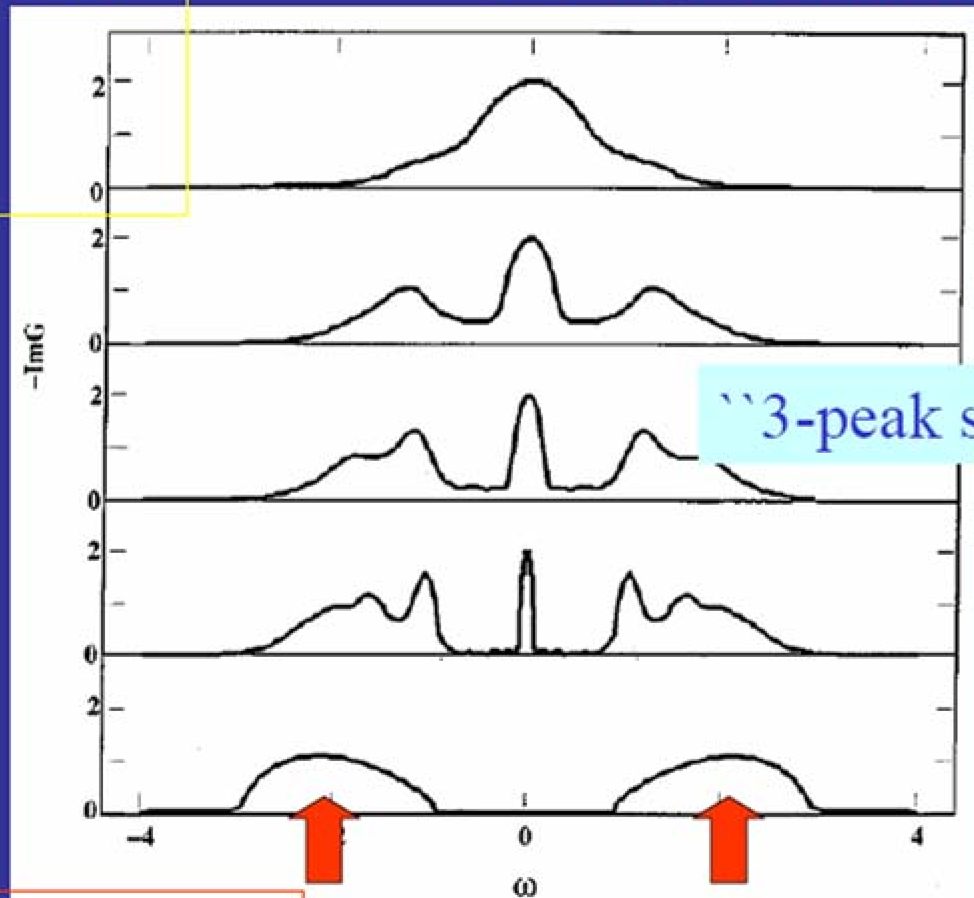
k-integrated spectral Function: early DMFT results

(AG&G.Kotliar 1992, AG&W.Krauth, M.Rozenberg et al. 1992-94)

Quasiparticle peak

⟷ QP bandwidth ε_F^*

Increasing U



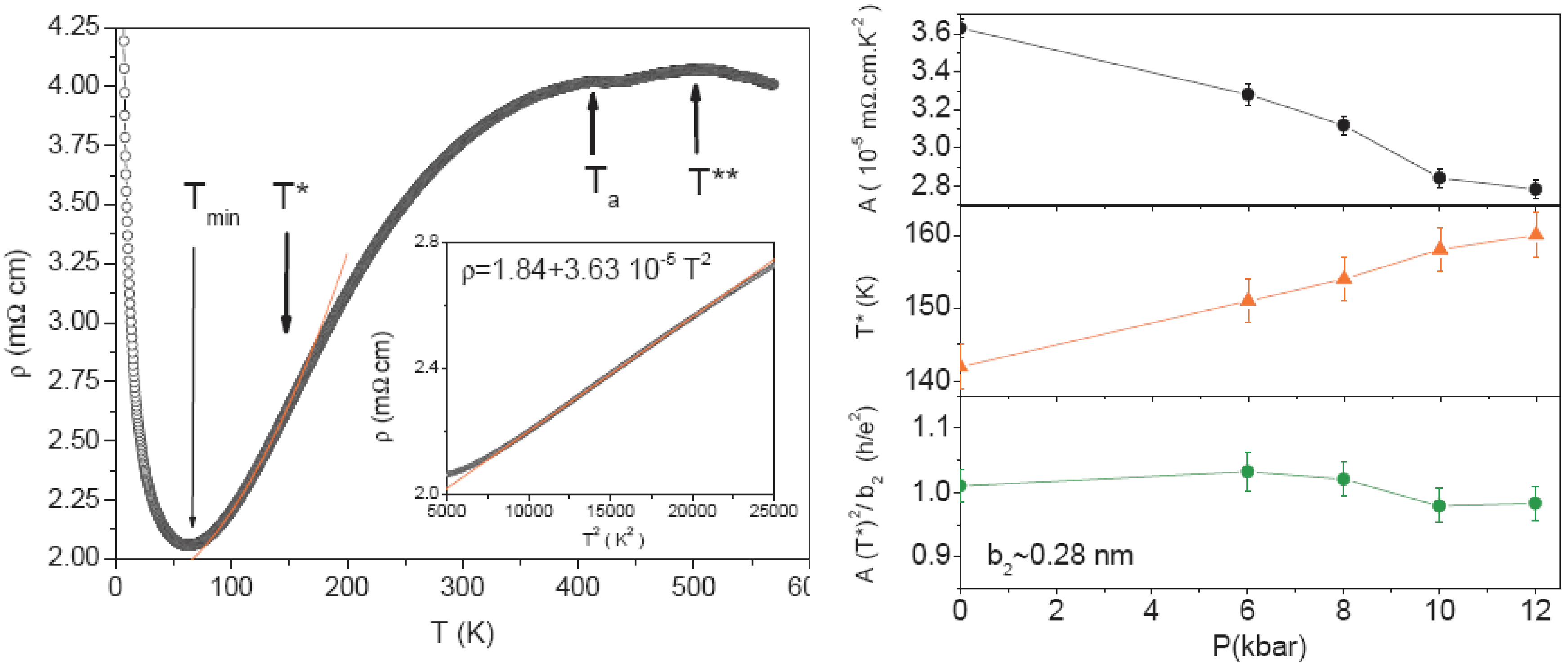
``3-peak structure''

Hubbard bands

> GAP <

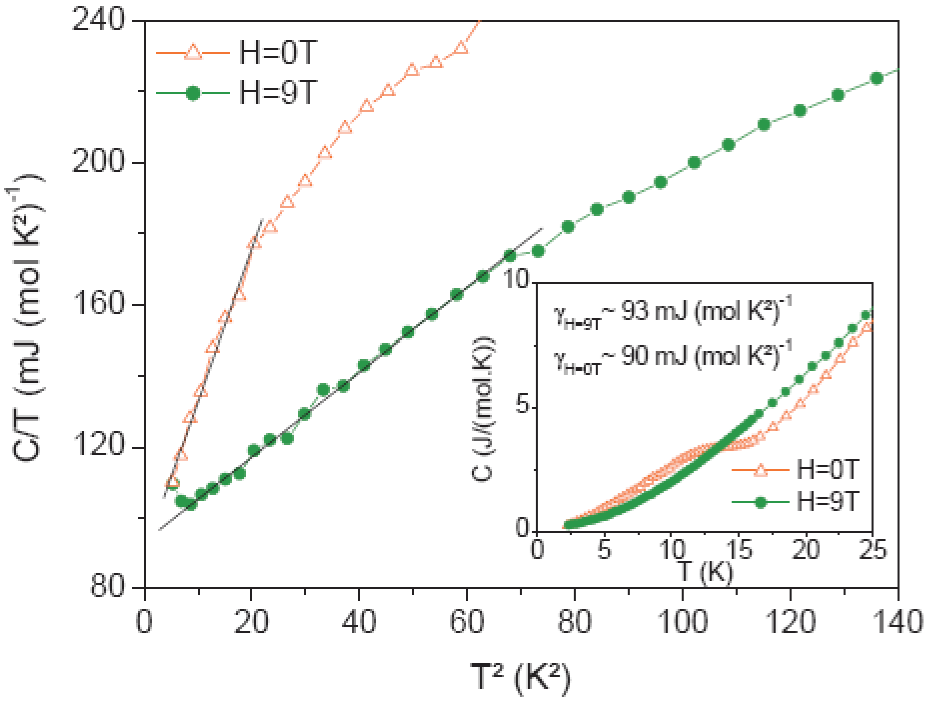
From A. Georges

Cobaltates $Ca_3Co_4O_9$

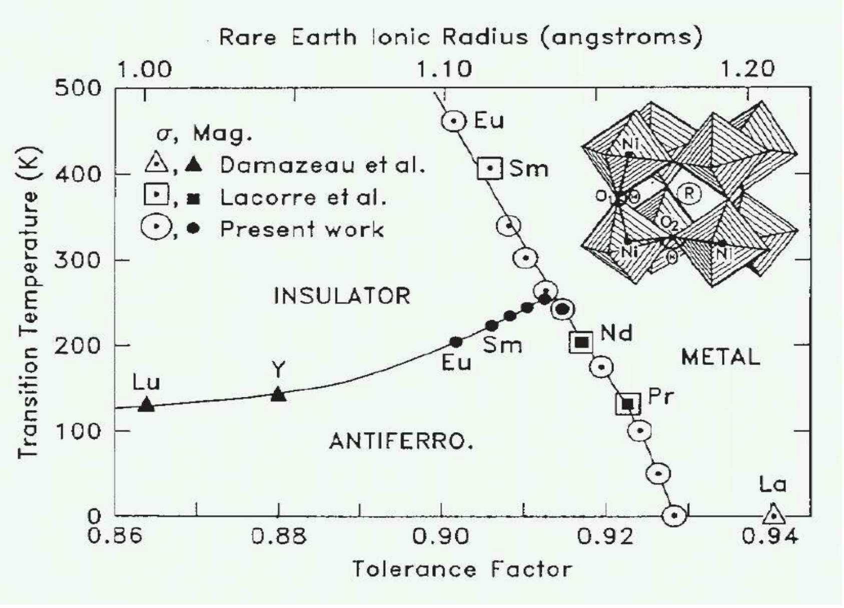


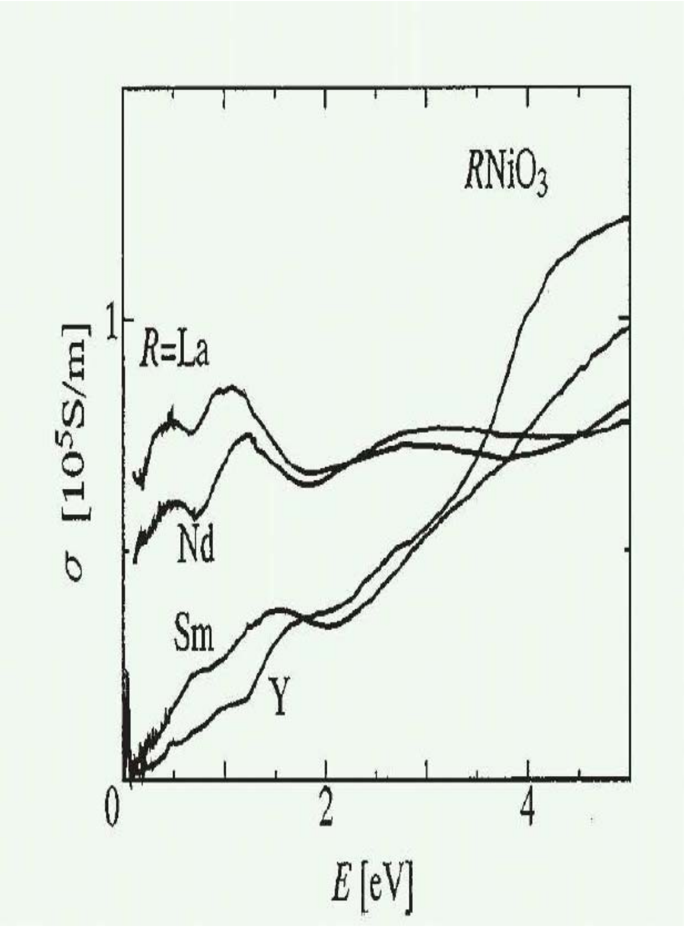
From Limelette

Specific heat



Nickelates $RNiO_3$

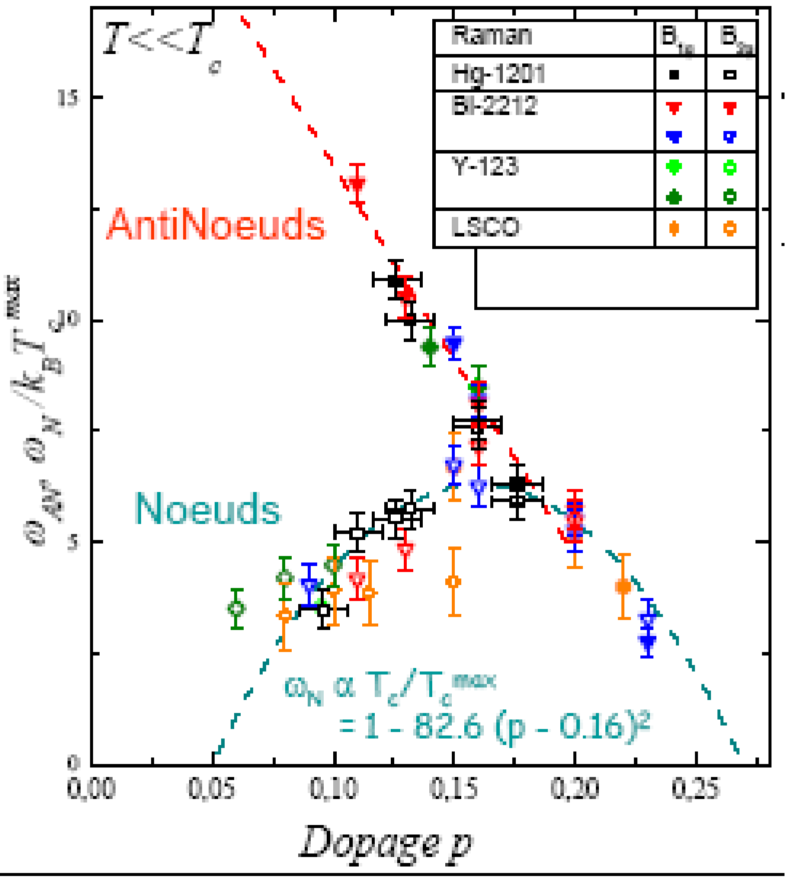




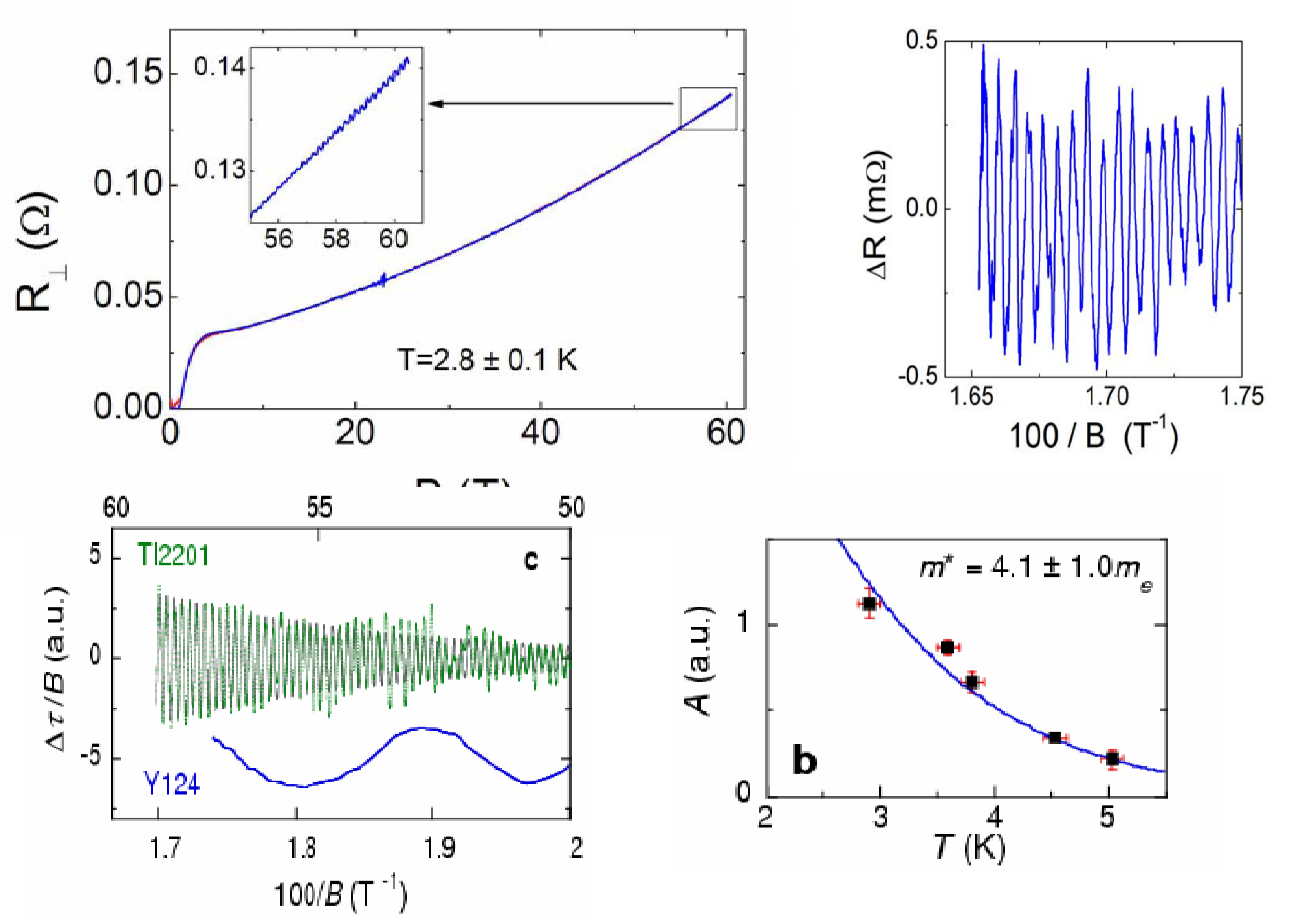
Cuprates

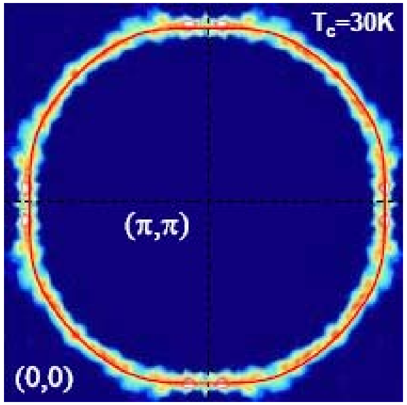
- They are high Tc superconducting materials

Two different scales of energies



Overdoped cuprate: normal Fermi liquid





From B. Vignolle

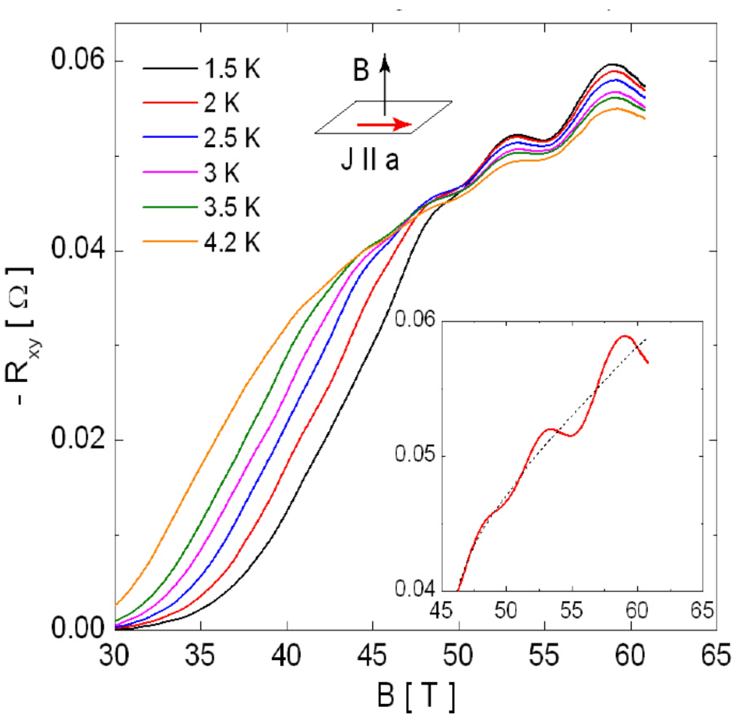
Théorème de Luttinger : $n = \frac{2A_k}{(2\pi)^2} = \frac{F}{\phi_0}$

$\Rightarrow$ Densité de porteurs : n=1.3 porteur / atome de Cu (n=1+p avec p=0.3)

- $m^* = 4.1 \pm 1\ m_e > m_{bande} = 1.2\ m_e$
- Chaleur spécifique électronique : $\gamma_{el} = \frac{\pi N_A k_B^2 a^2}{3\hbar^2} m^* \Rightarrow \gamma_{el} = 6 \pm 1\,\mathrm{mJ/mol.K^2}$

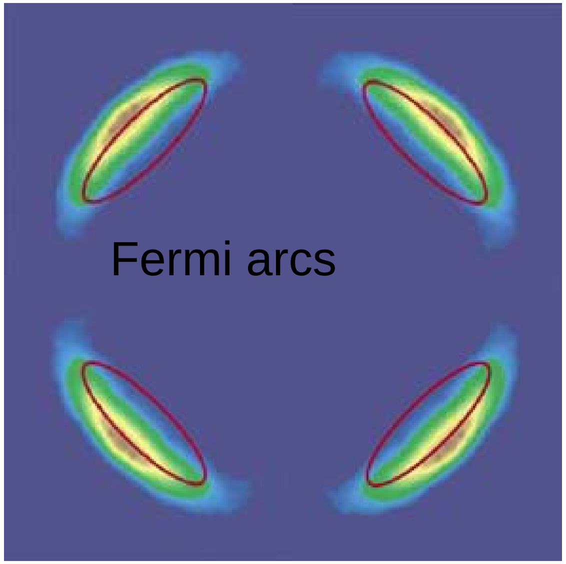
Pour Tl2201 polycristallin surdopé: $\gamma_{el} = 7 \pm 2\,\mathrm{mJ/mol.K^2}$

YBaCuO underdoped



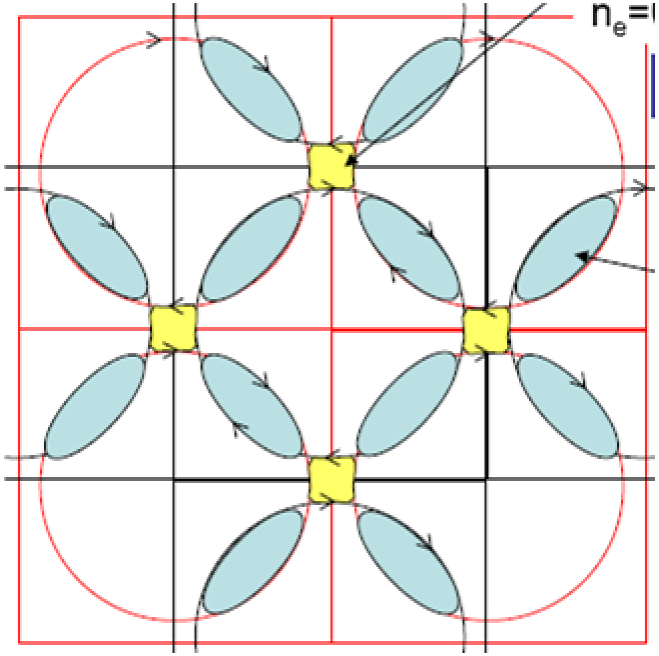
$YBa_2Cu_3O_{6.5}$(p = 0.1)

A= 5.1 nm^{-2}= 1.9 % of the carriers



Abnormal photoemission

Fermi surface reconstruction: small pockets

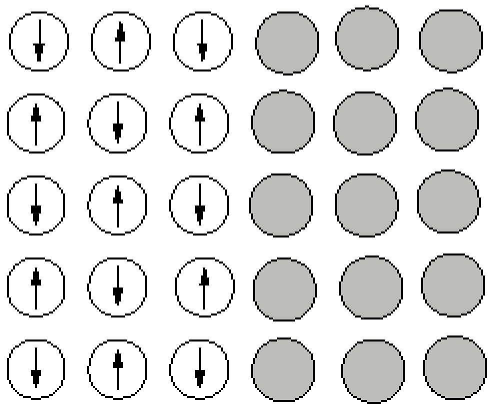


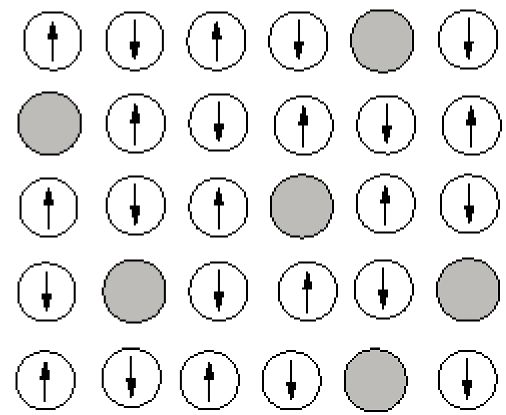
Emery et Kivelson, 1990-2000

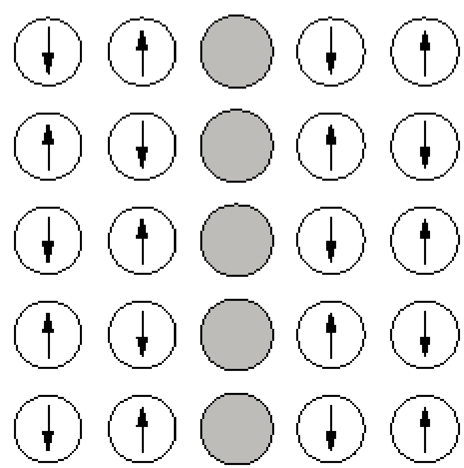
Short-range attractive force

X

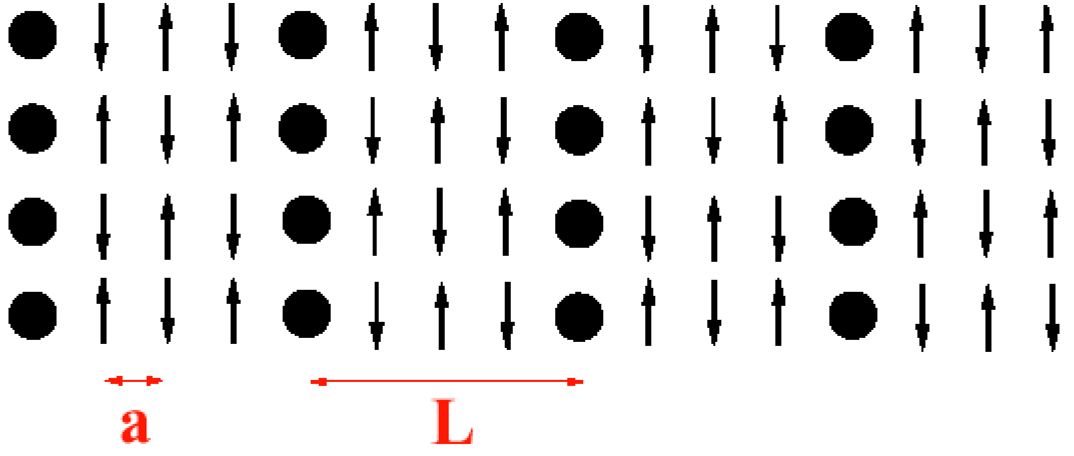
Long-range repulsive Coulomb interaction



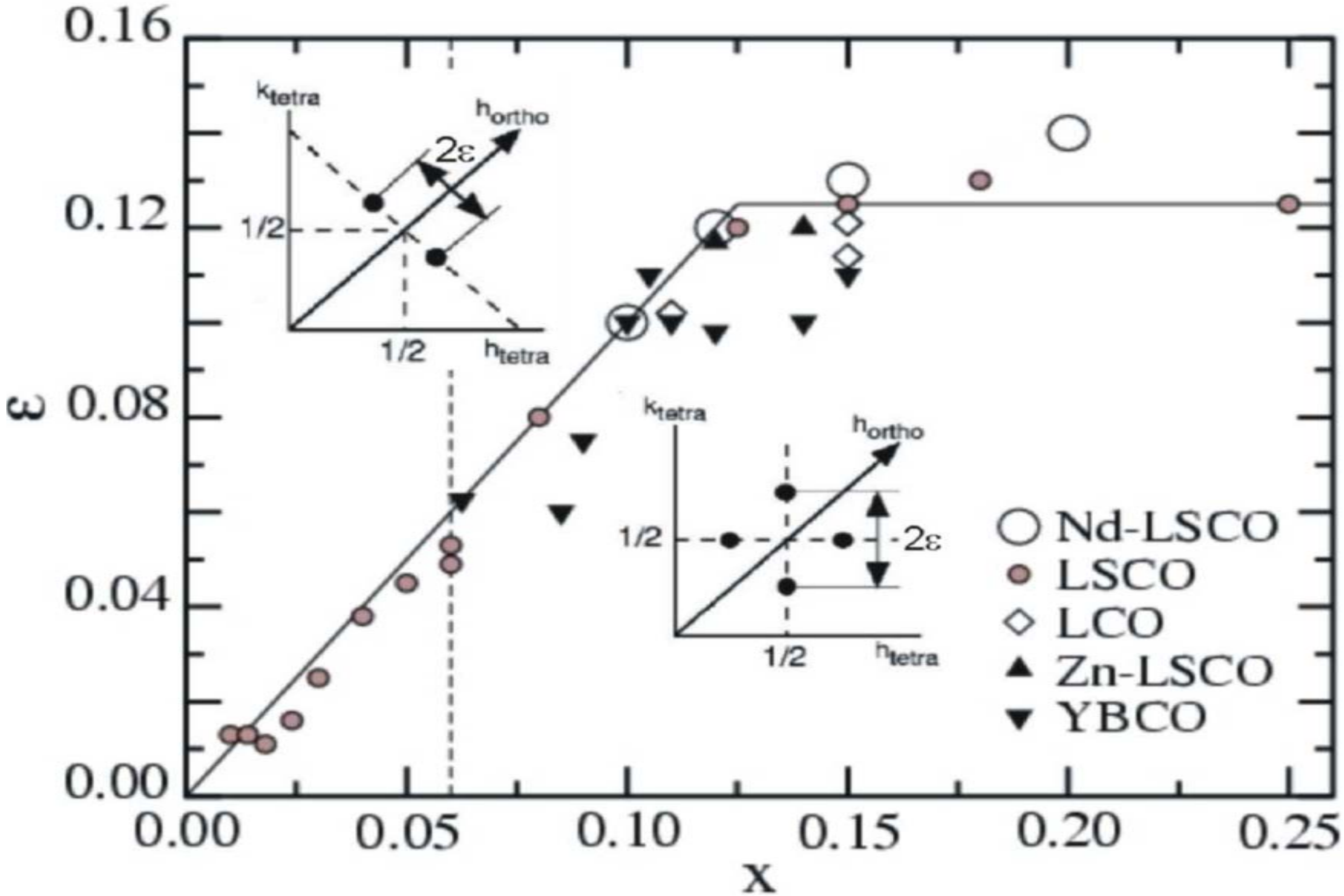




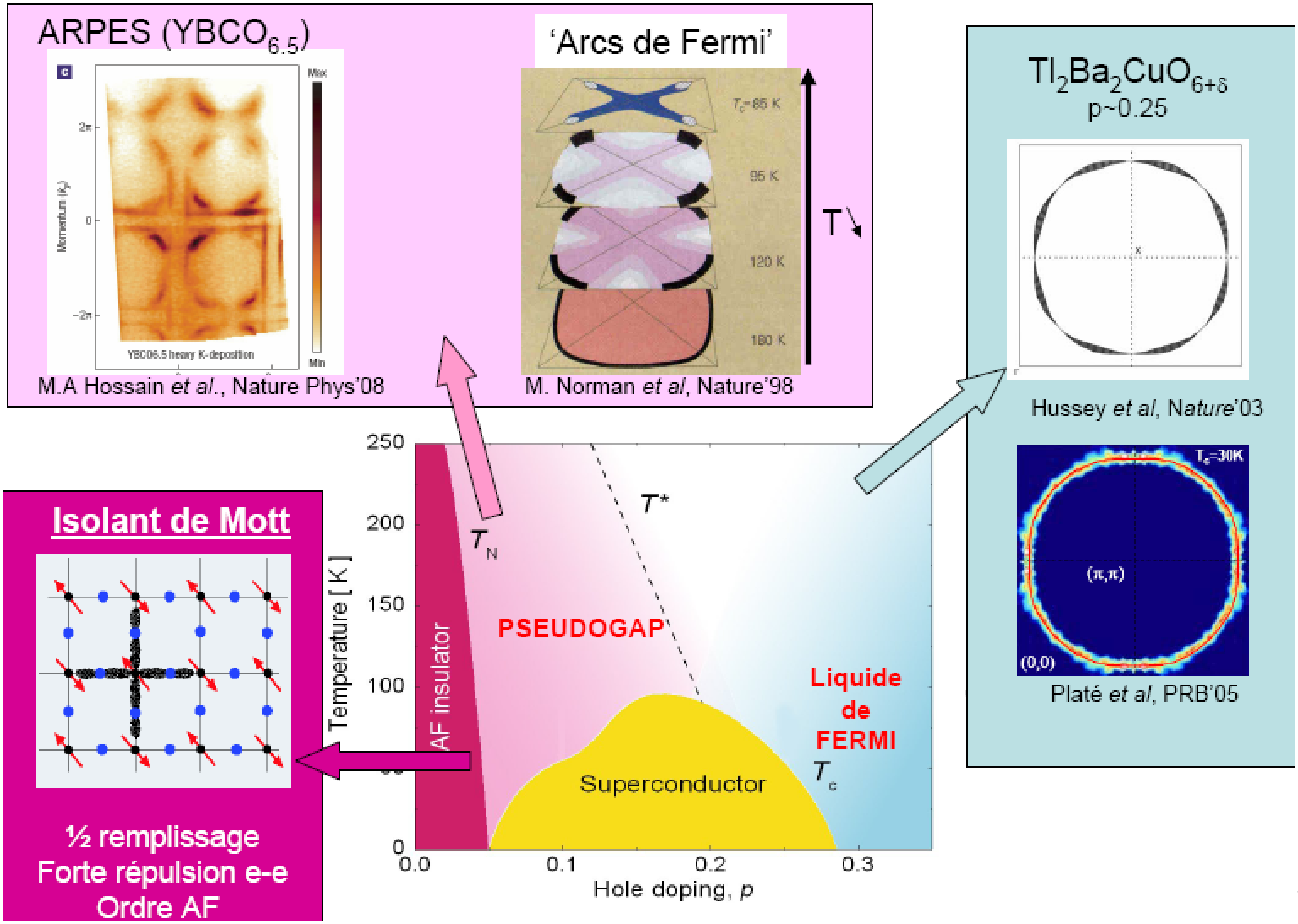
$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$



Other interpretation: stripes

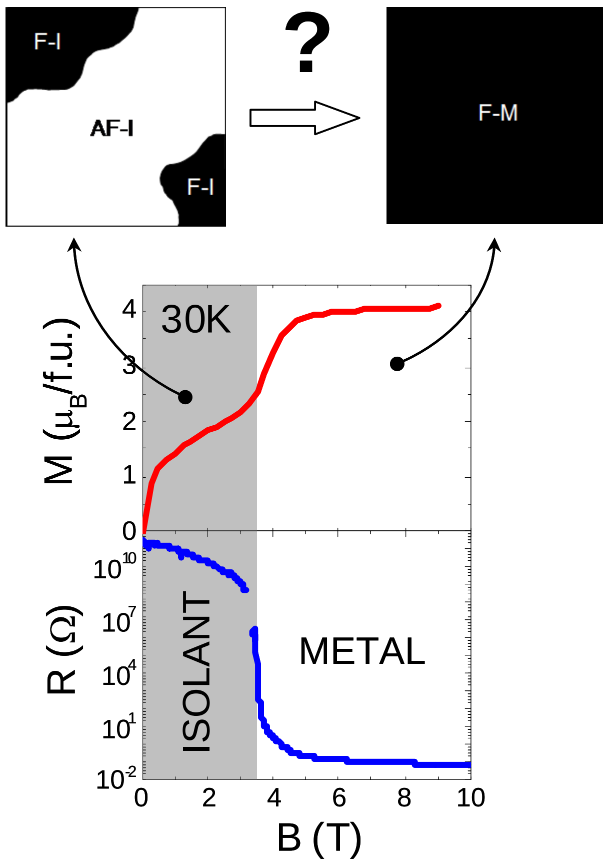


Cuprates

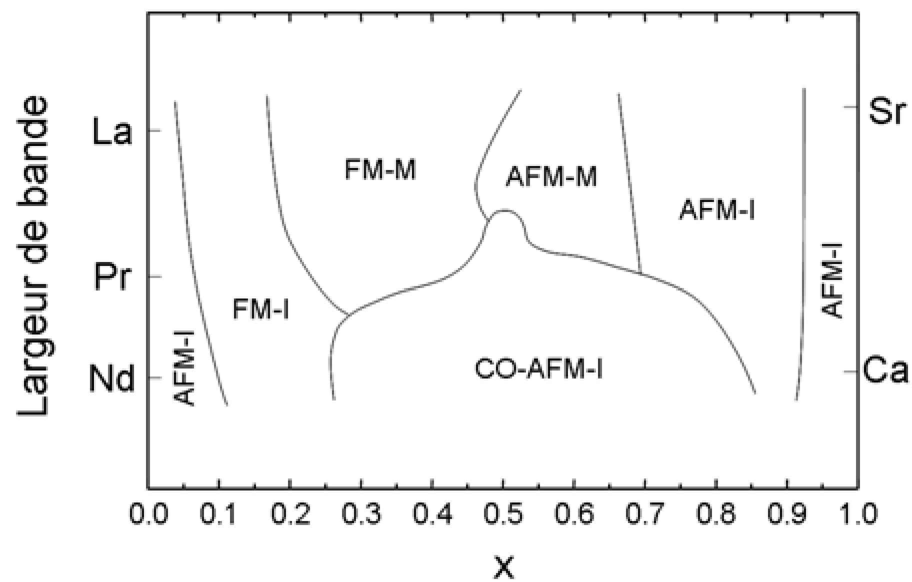


ARPES ($YBCO_{6.5}$)
M.A Hossain *et al.*, Nature Phys'08
'Arcs de Fermi'
M. Norman *et al*, Nature'98
T
$Tl_2Ba_2CuO_{6+\delta}$
p~0.25
Hussey *et al*, *Nature*'03
Platé *et al*, PRB'05
Isolant de Mott
½ remplissage
Forte répulsion e-e
Ordre AF
Temperature [K]
Hole doping, *p*
AF insulator
PSEUDOGAP
Superconductor
Liquide de FERMI
T_N
T^*
T_c

Manganites $Pr_{0.7}Ca_{0.3}MnO_3$

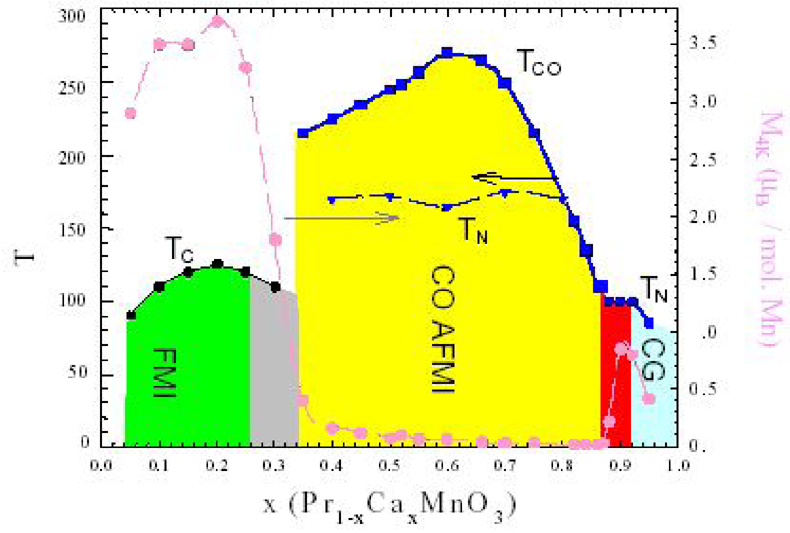


Electronic phase separation

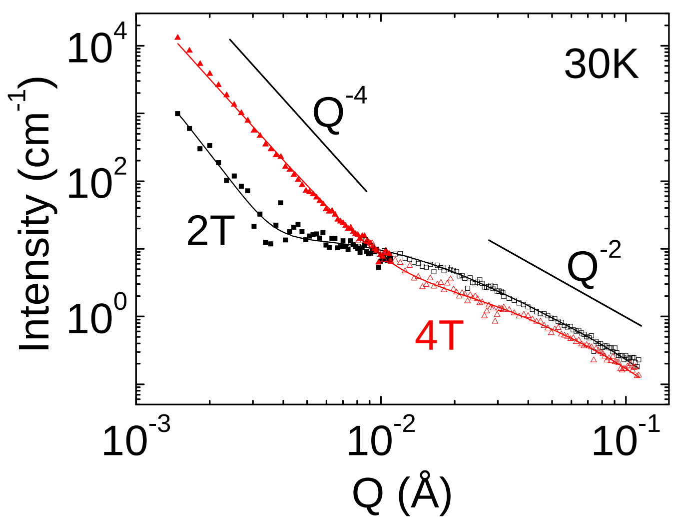


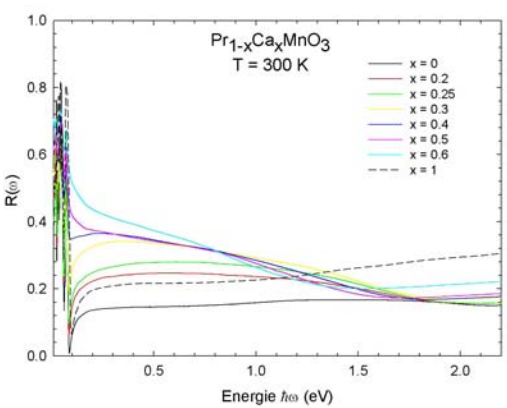
Jahn Teller effect = orbital ordering
Colossal magnetoresistance

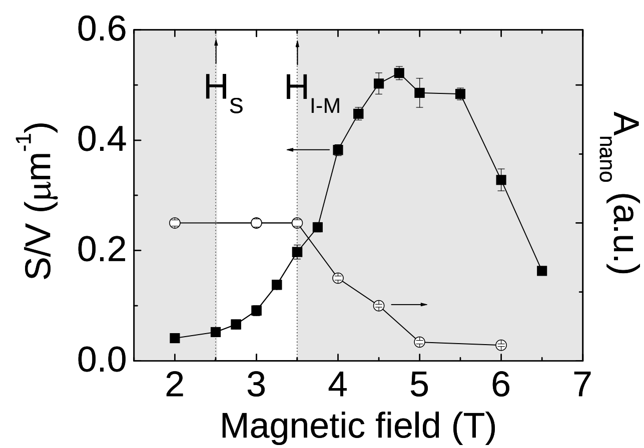
From C. Martin



From D. Saurel







From R. Sopracase

Conclusions

- Effects of correlations: Fermi surface, effective mass, …
  - Specific heat, conductivity, magnetic susceptibility, photoemission and dHvA effects
- Mott transition, Kondo effects
  - Phase separation, transfer of spectral weight
- Effects of low dimensions