united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

ICTP 40th Anniversary

SMR/1567 - 8

WORKSHOP ON

QUANTUM SYSTEMS OUT OF EQUILIBRIUM

(14 – 25 June 2004)

" Kondo effect and RKKY interactions in mesoscopic quantum wires"

presented by:

C. Bäuerle

Centre de Recherches sur le Très Basses Temperatures - C.N.R.S., Grenoble
France

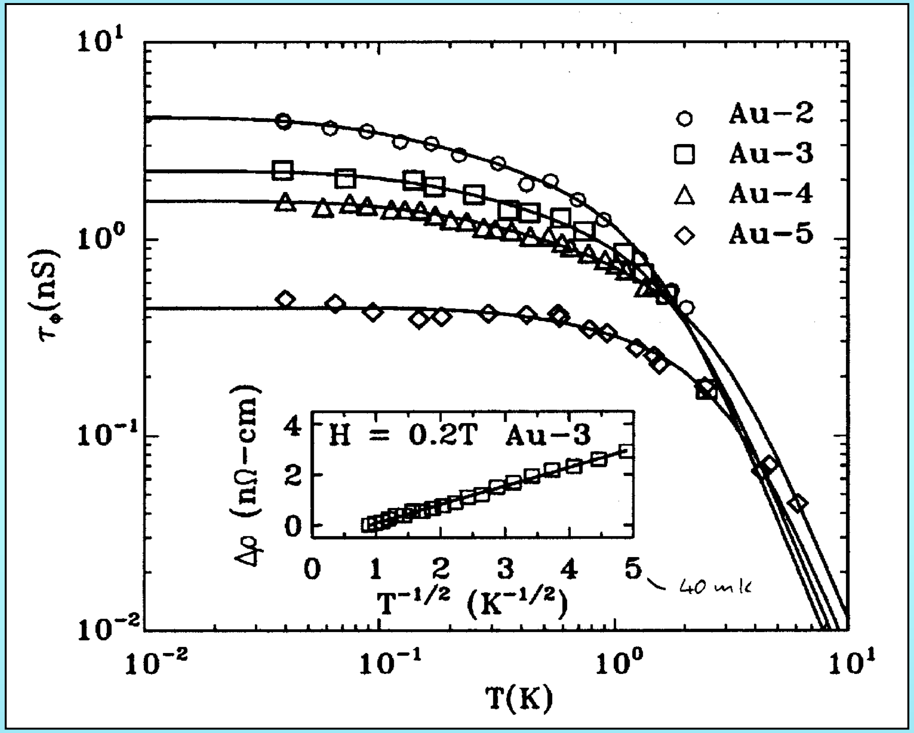
Kondo effect and RKKY interactions in mesoscopic quantum wires

Felicien Schopfer
Wilfried Rabaud
François Mallet
Stephan Bonifacie

Laurent Saminadayar
C.B.

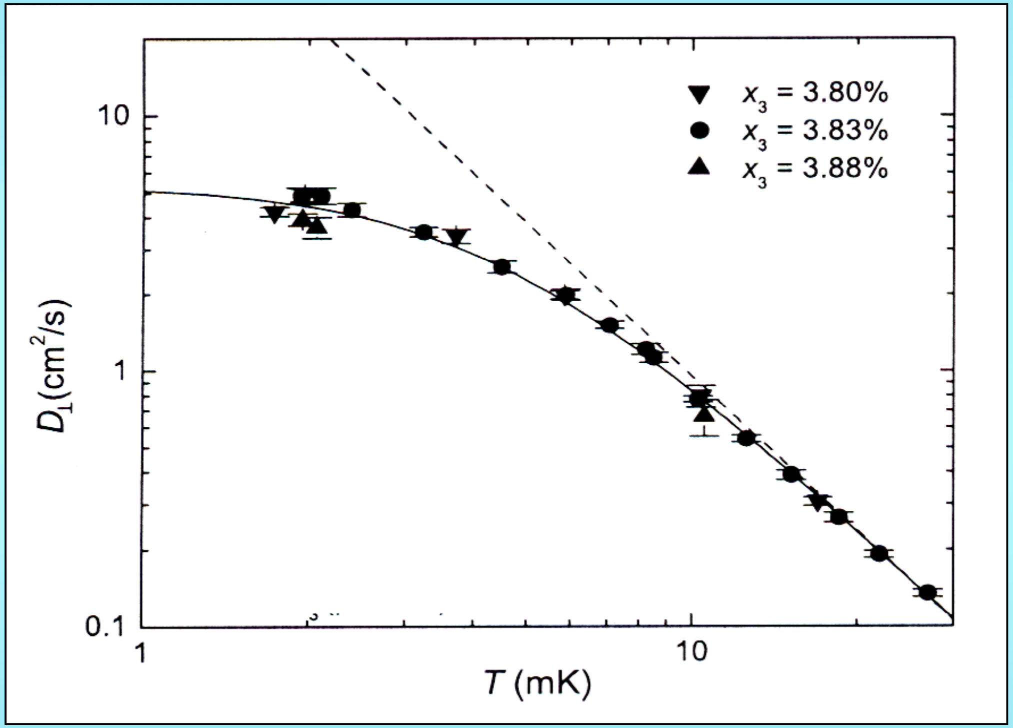
The τ_ϕ - problem

mesoscopic systems



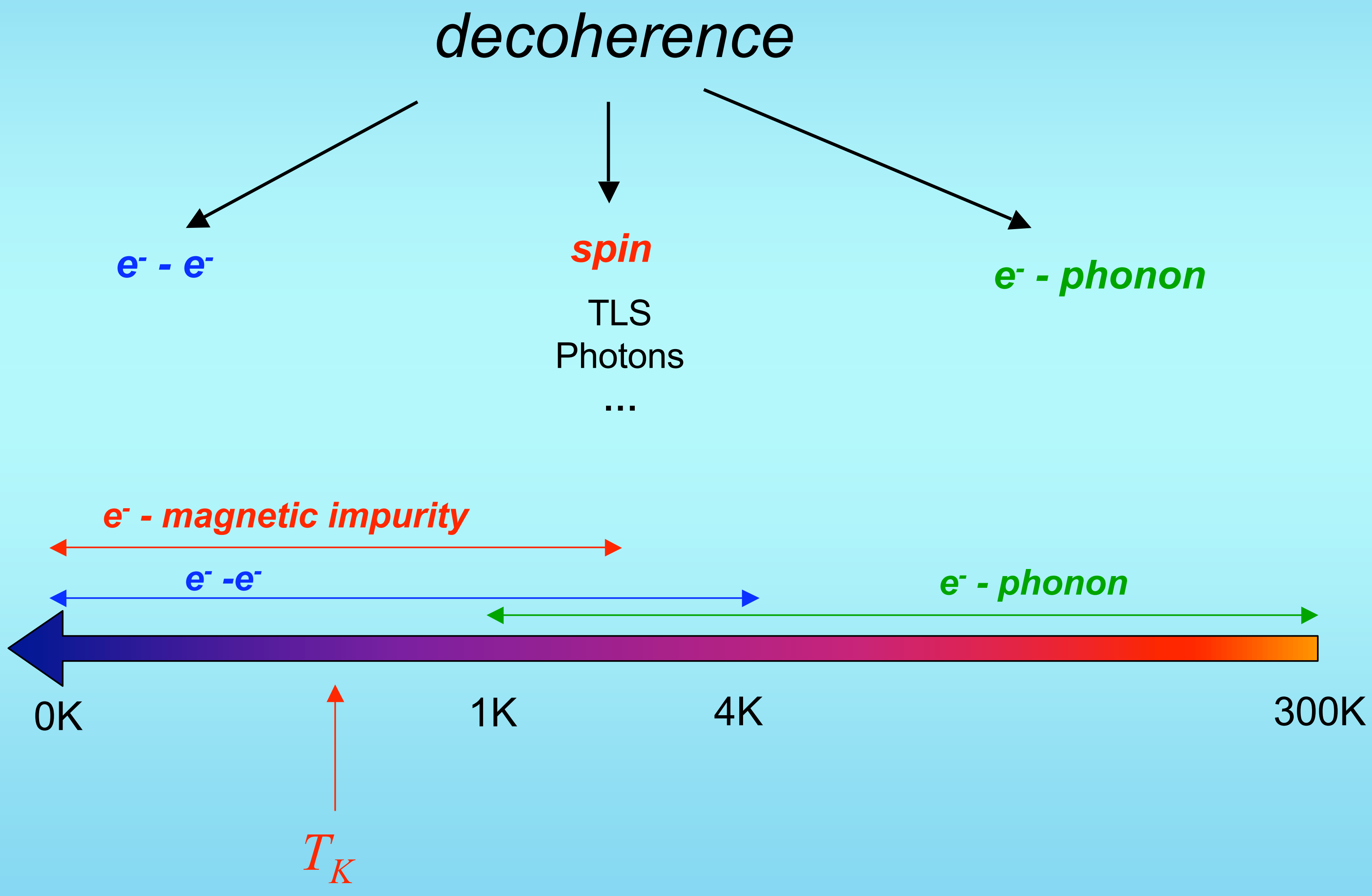
Mohanthy & Webb PRL 1997

spin polarized ^{3}He



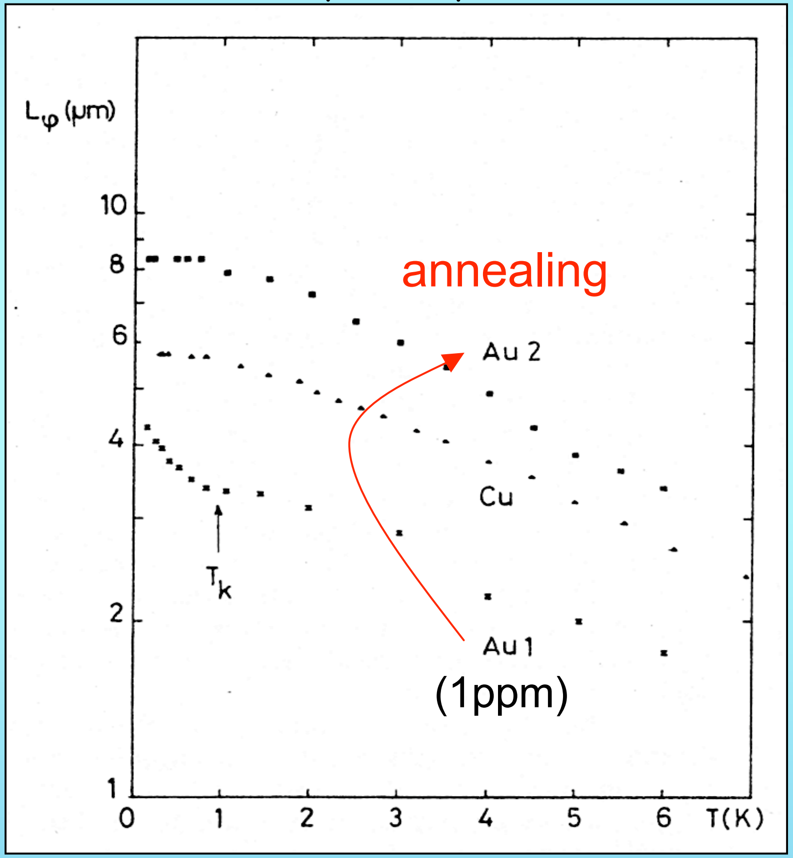
Akimoto et al. PRL 2003

Scattering mechanisms

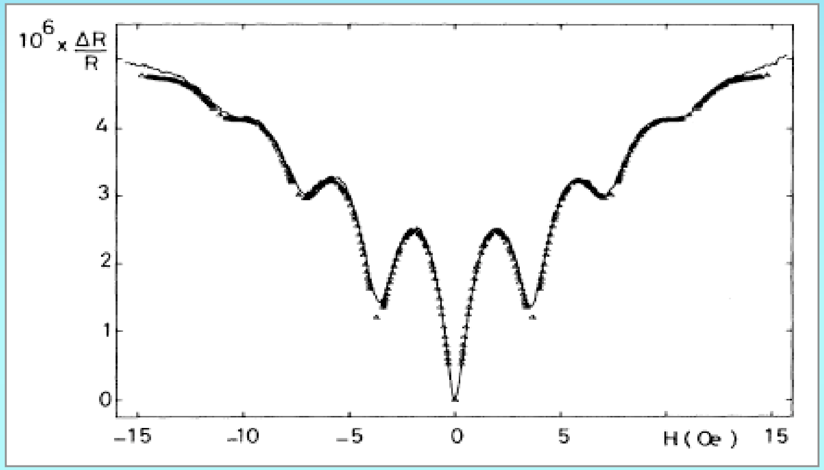


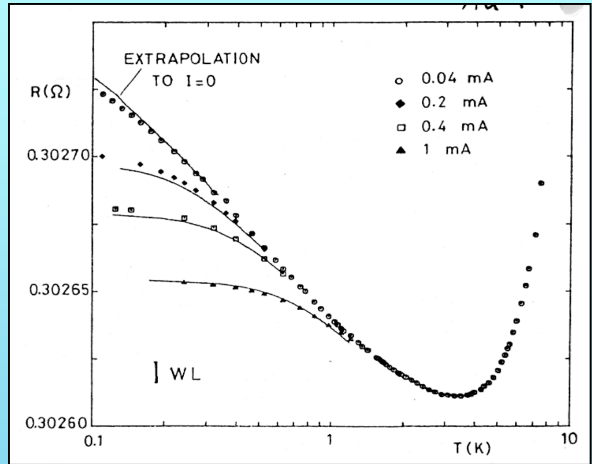
Earlier experiments: AAS oscillations in 2D networks

Pannetier et al. Phys. Scripta 86



Pannetier et al. PRL 84





Earlier experiments: AB effect

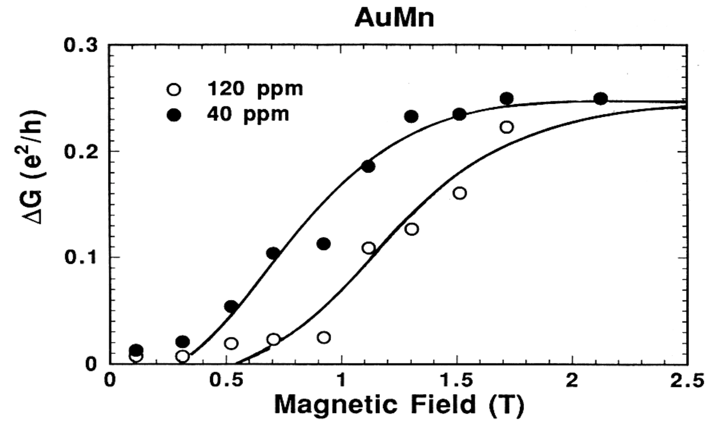
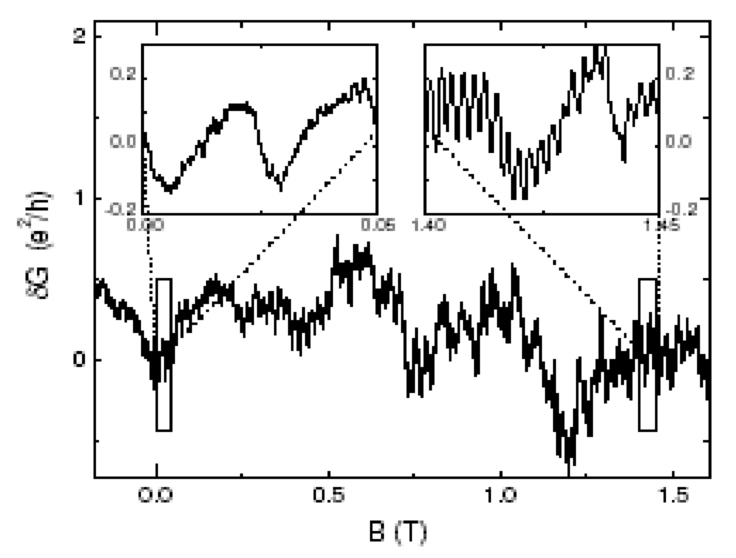
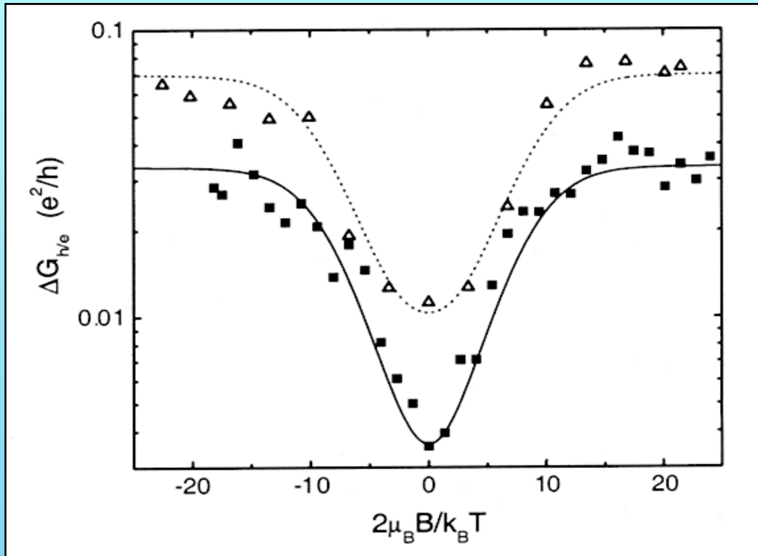


Figure 2: Amplitude of AB oscillations vsersus magnetic field for 40ppm (open circles) and 120 ppm (full circles) AuMn alloys

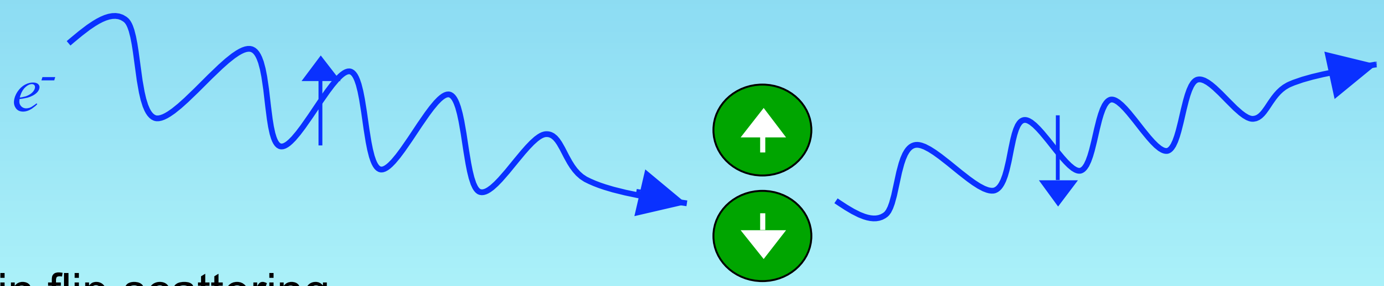
Benoit et al. 88'

Pierre and Birge, PRL 02'





Kondo effect



- spin flip scattering

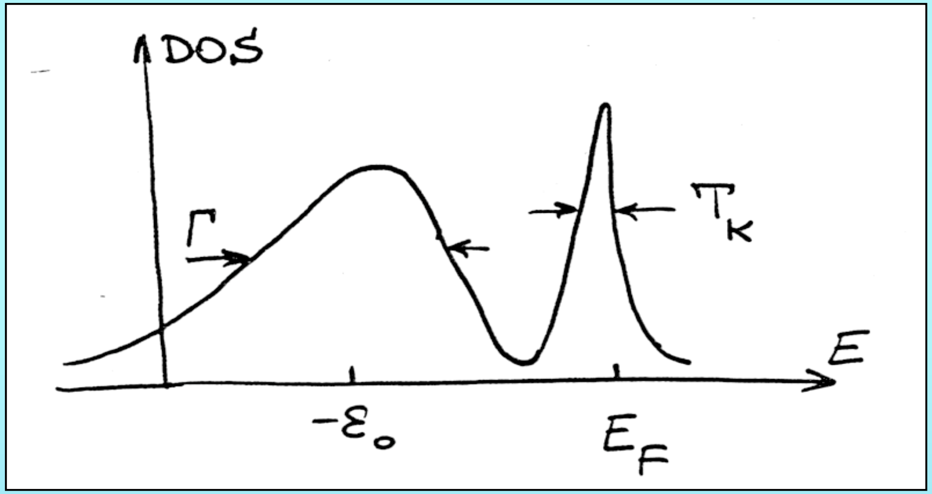
  purely elastic !!

- single impurity model (q, S)

- energy scale

$$T_K \sim \sqrt{|\varepsilon_0|\Gamma}\, \exp\left\{-\frac{\pi|\varepsilon_0|}{\Gamma}\right\}$$

Haldane 78'

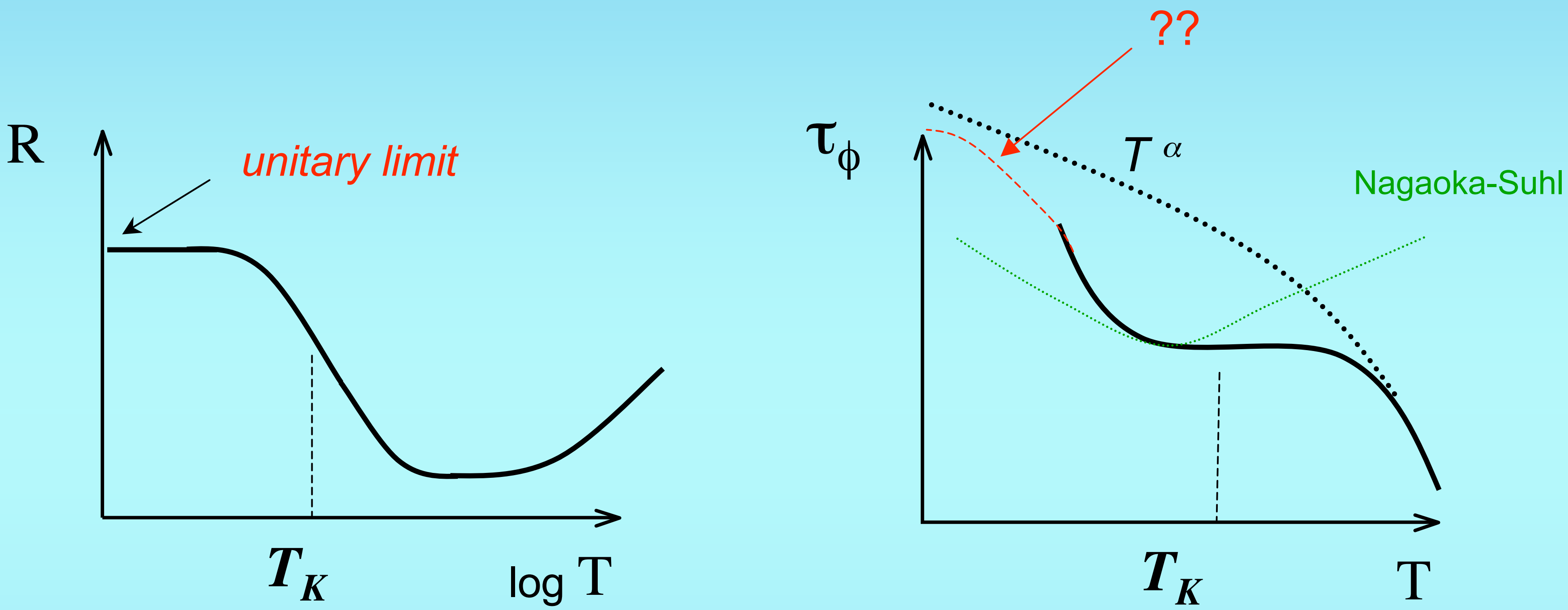


T < T_K : *screening of magnetic impurity spin*

T= 0: *complete screening - formation of a **spin singlet** ground state*

« unitary limit »

Kondo effect



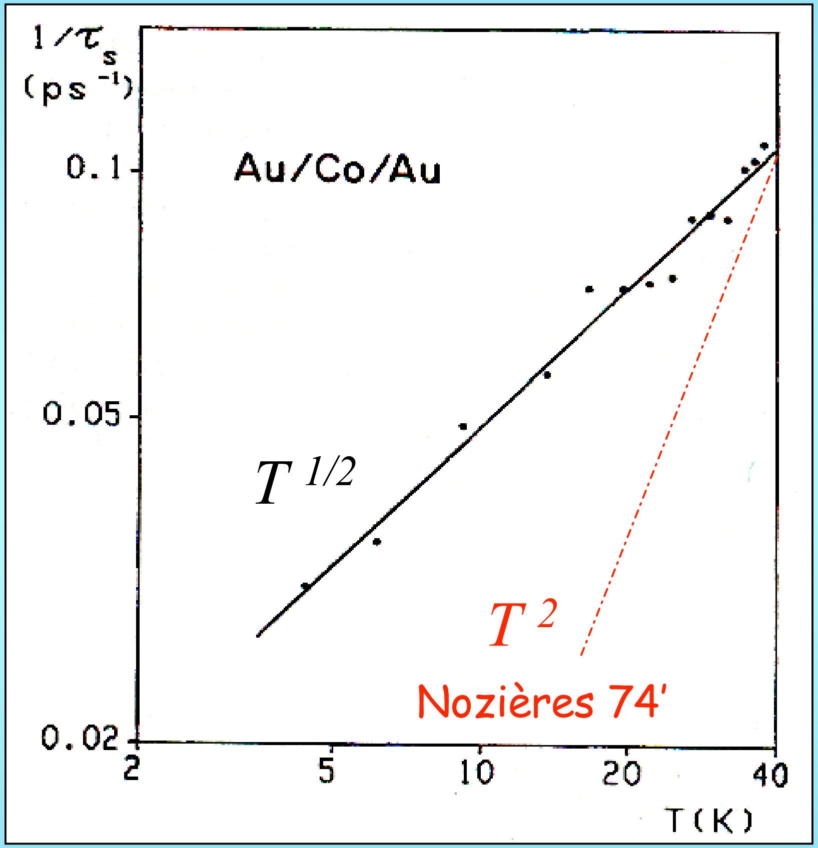
For $T \ll T_K$ Fermi liquid theory should be valid again (s=1/2)

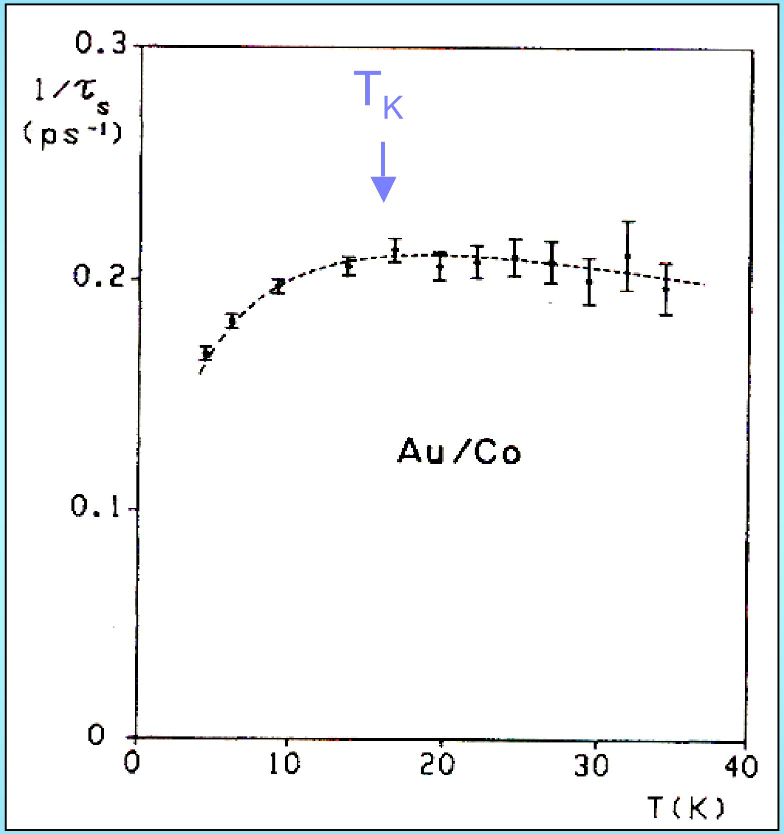
Nozières 1974

unitary limit: very hard to achieve experimentally in metals !

Ground state of Kondo system

2D films





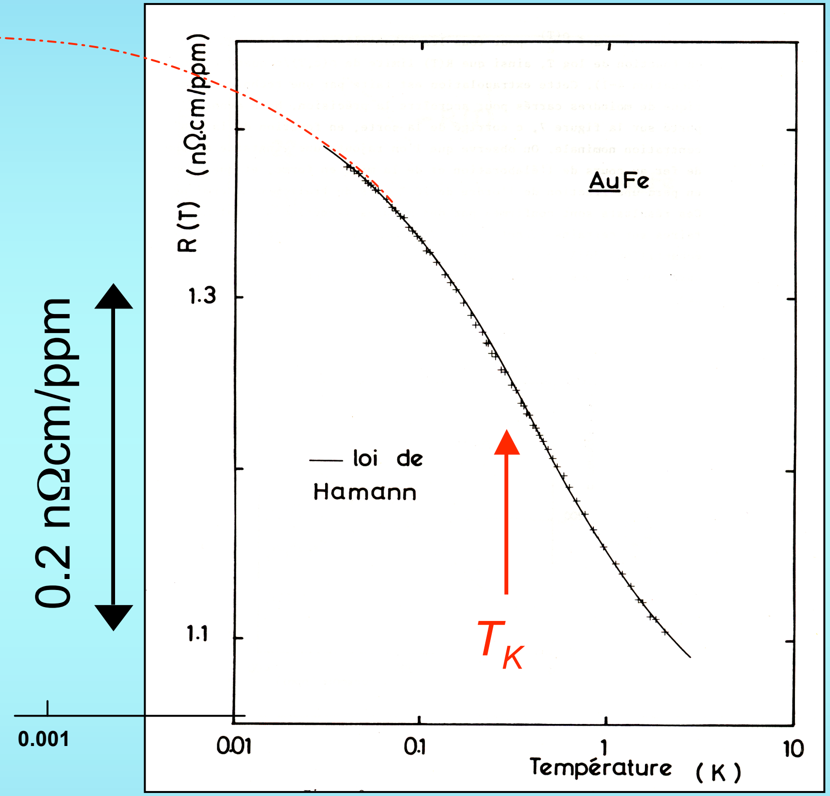
Bergmann et al. PRL87, PRB 89
also: v. Haesendonk et al. PRL87

low temperature behaviour is NOT described by Fermi liquid theory

Kondo system Au/Fe

Laborde 71'

unitary limit



- *well known Kondo system*
- *easy to use for nanolithography*
- *no surface oxidation*

$T_{measure} < T_K < phonon$

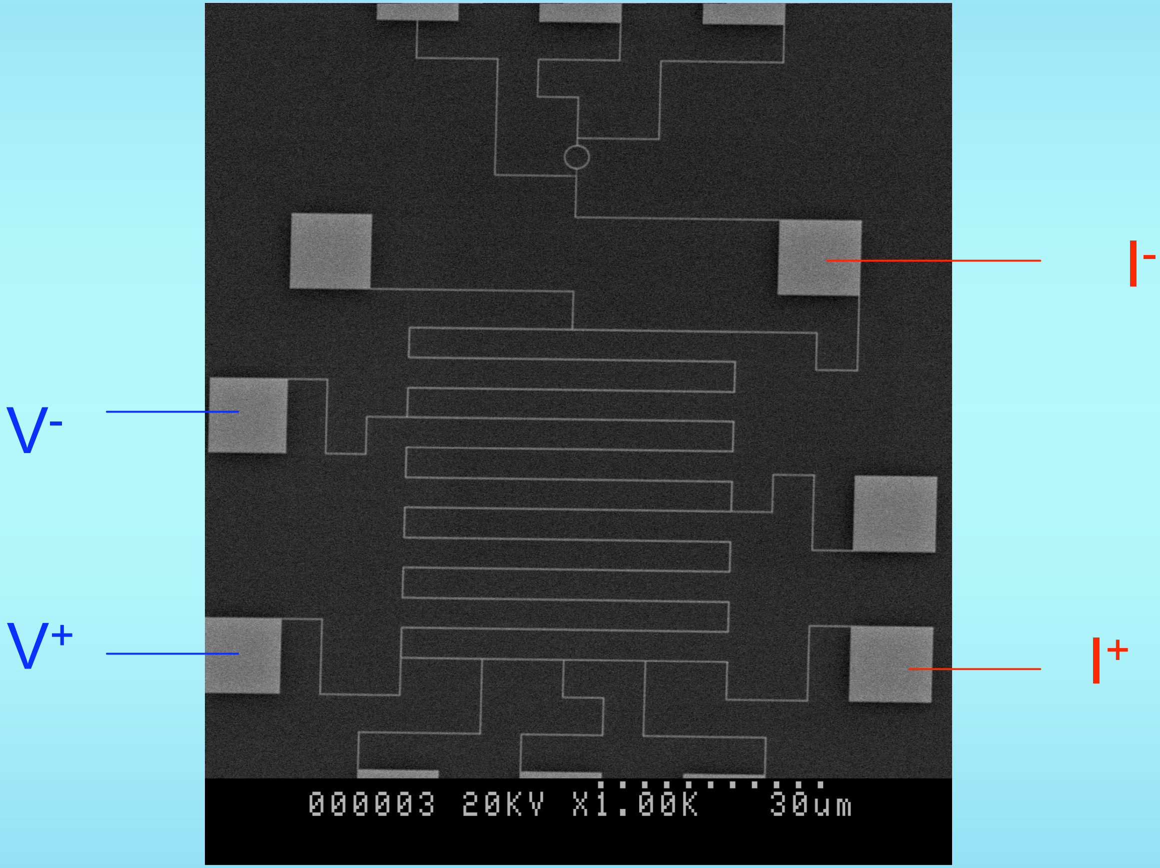
Sample

Au wire (4N) containing **Fe** impurities

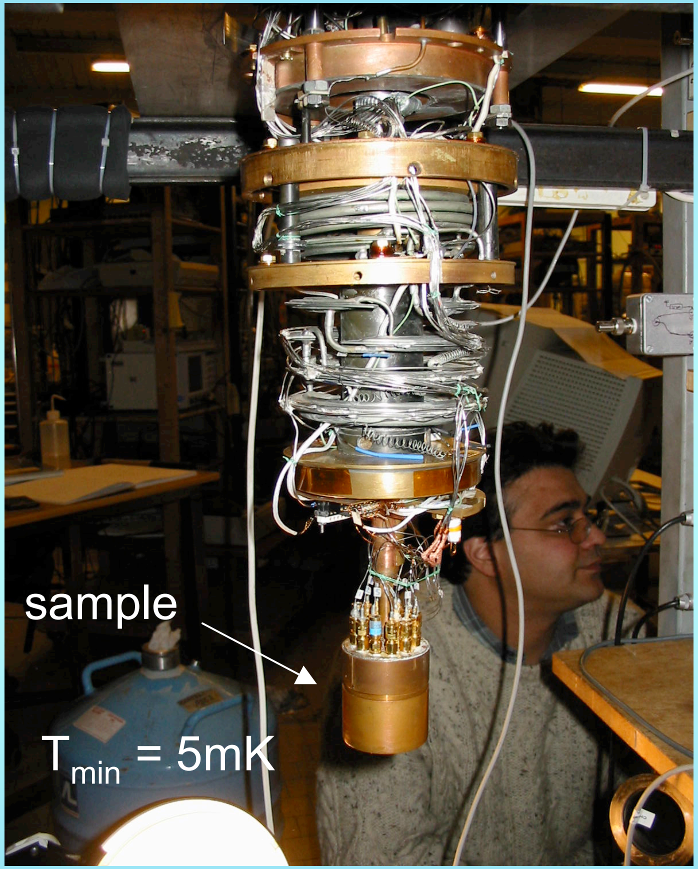
quasi 1D wire

Length $l = 450\ \mu m$
Width $w = 150\ nm$
Thickness $t = 50\ nm$

$\Big\} < l_\phi$

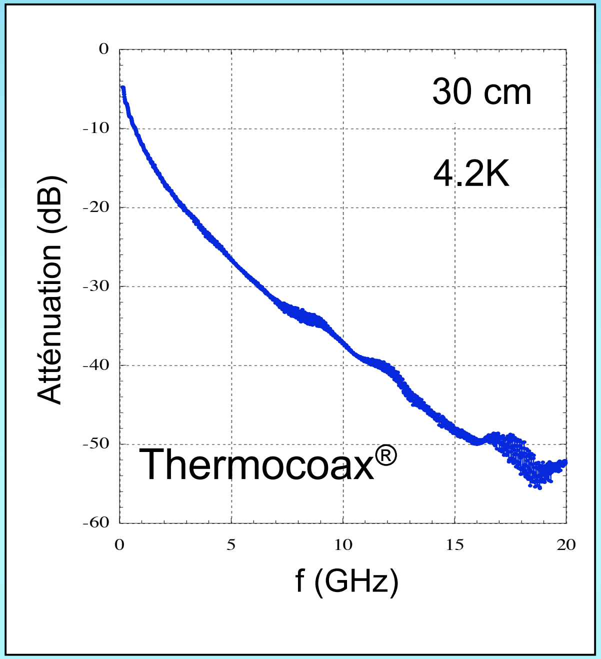


Experimental set-up



RF filtering

-420 dB at 20 GHz



$eV < k_B T$

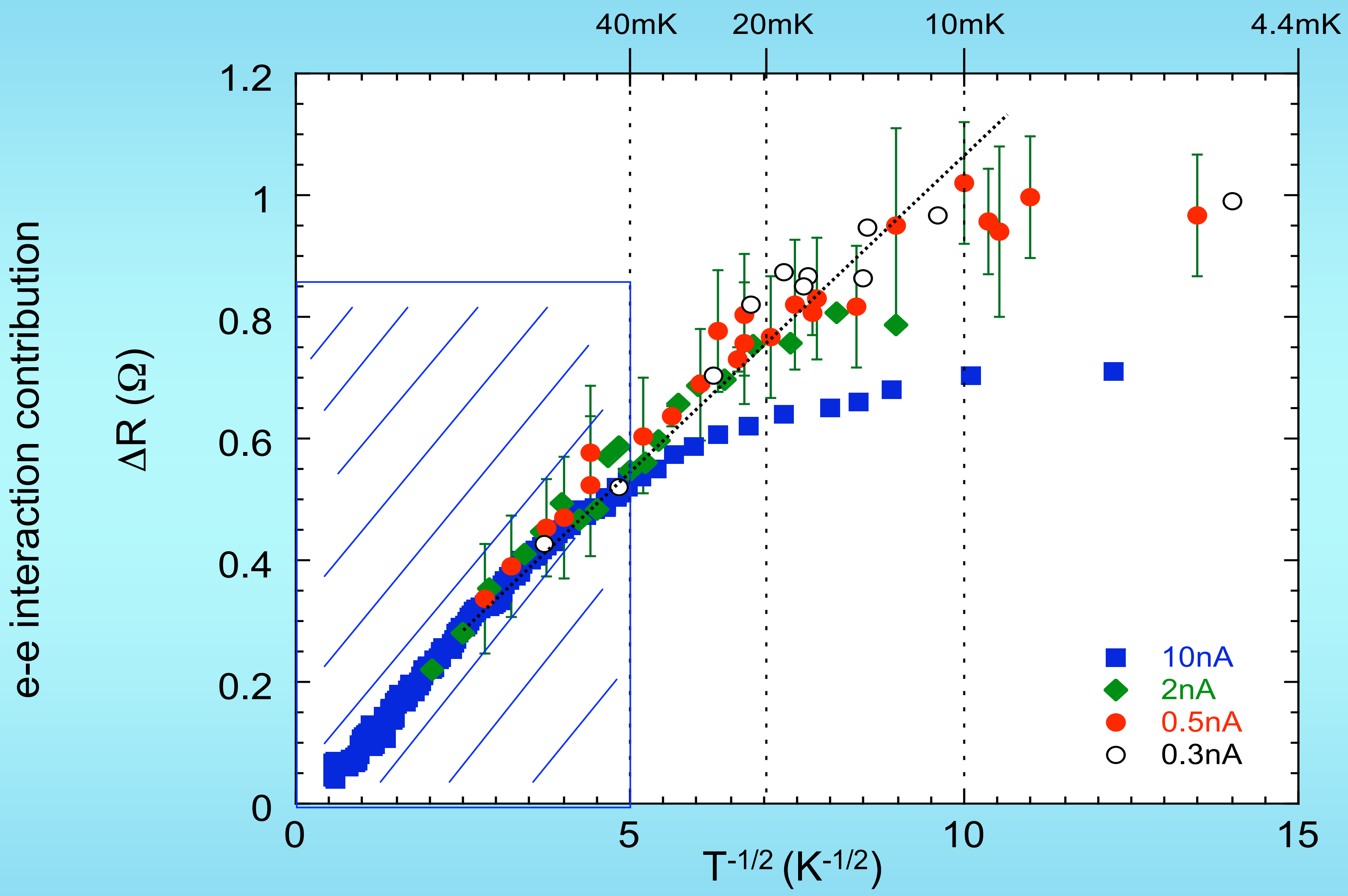
↓

I_{inj} = 2 nA

↓

Weak localisation signal: $\Delta V \sim 10^{-4}\ \mu V$

Extremely clean gold wire



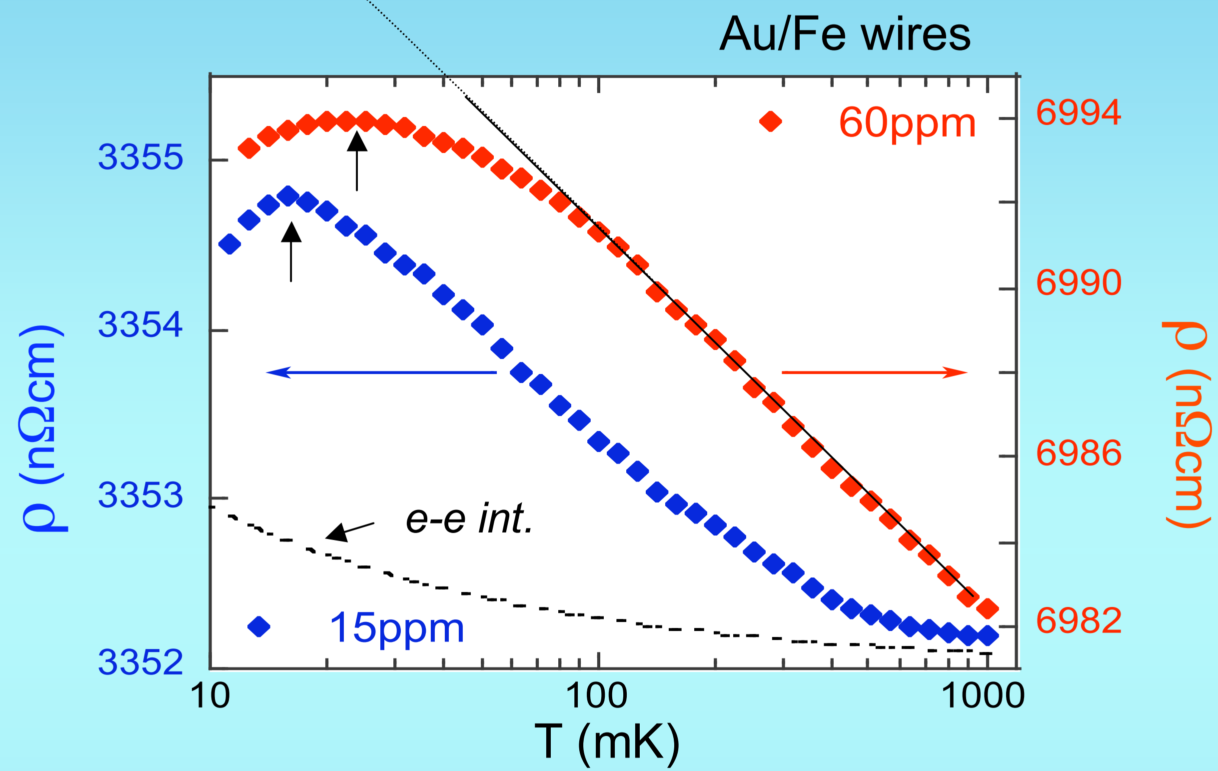
l_ϕ = 22μm

l_{wire}= 450μm

Electrons are cooled to 10 mK !!

Electrical resistivity

B=0T



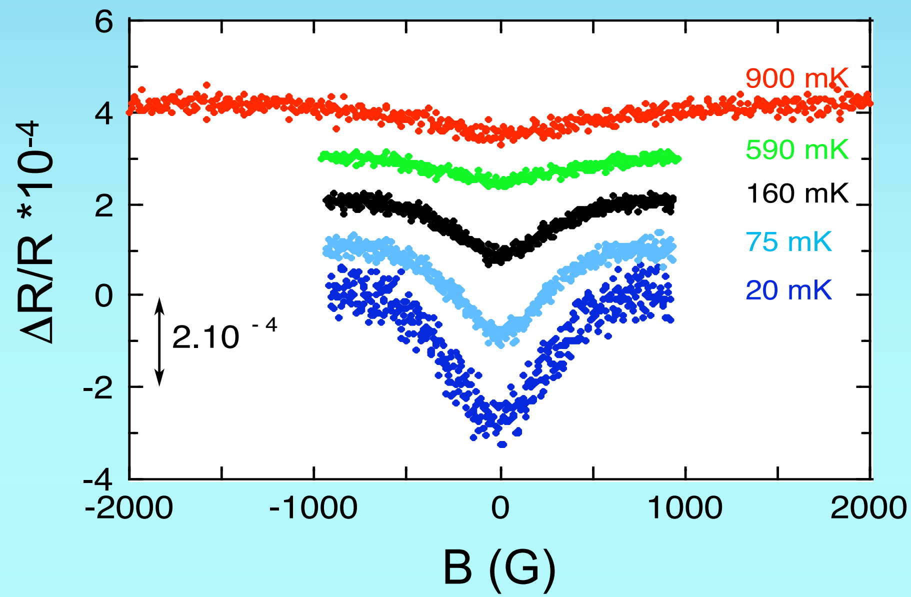
determination of impurity concentration via resistivity

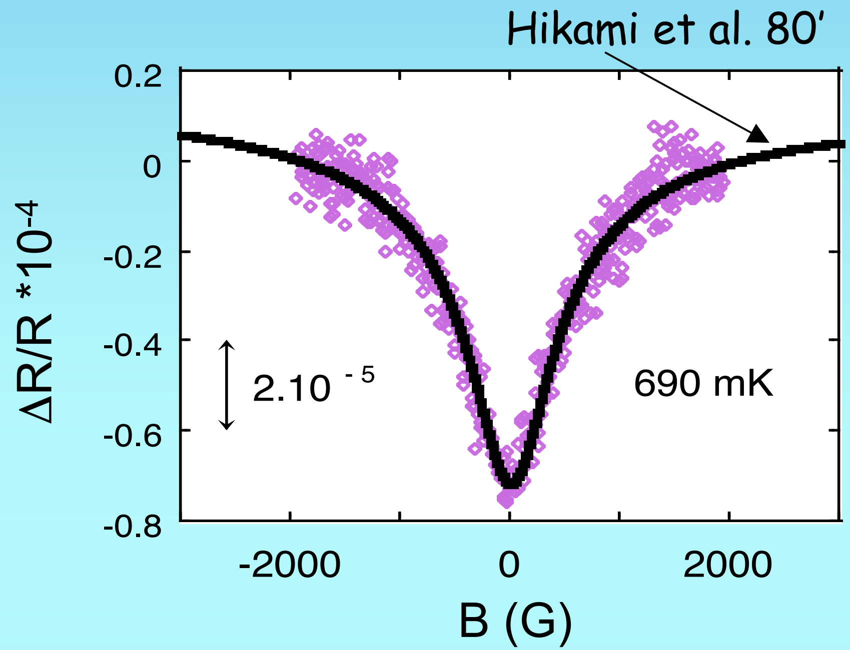
3 contributions: weak loc + e-e interaction + magnetic impurities

$\alpha\ 1/\sqrt{T}$ $\qquad \ln(T/T_K)$

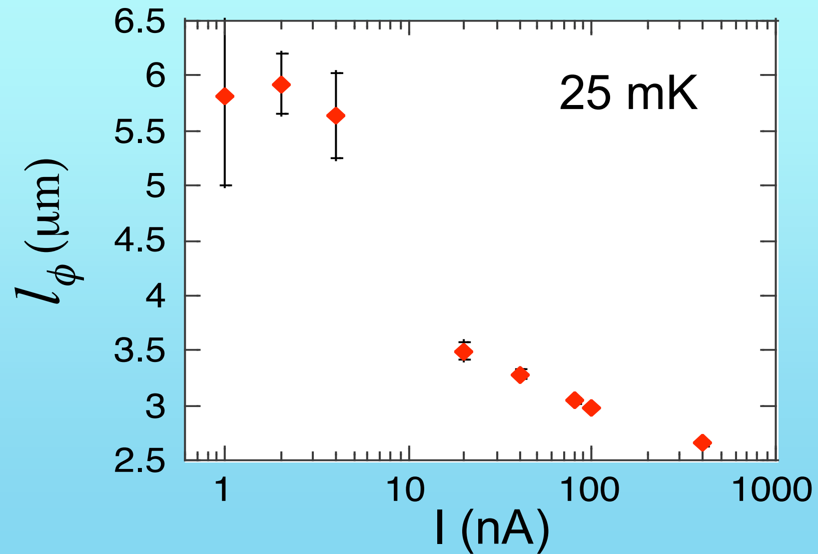
maximum is due to magnetic impurities

Weak localisation

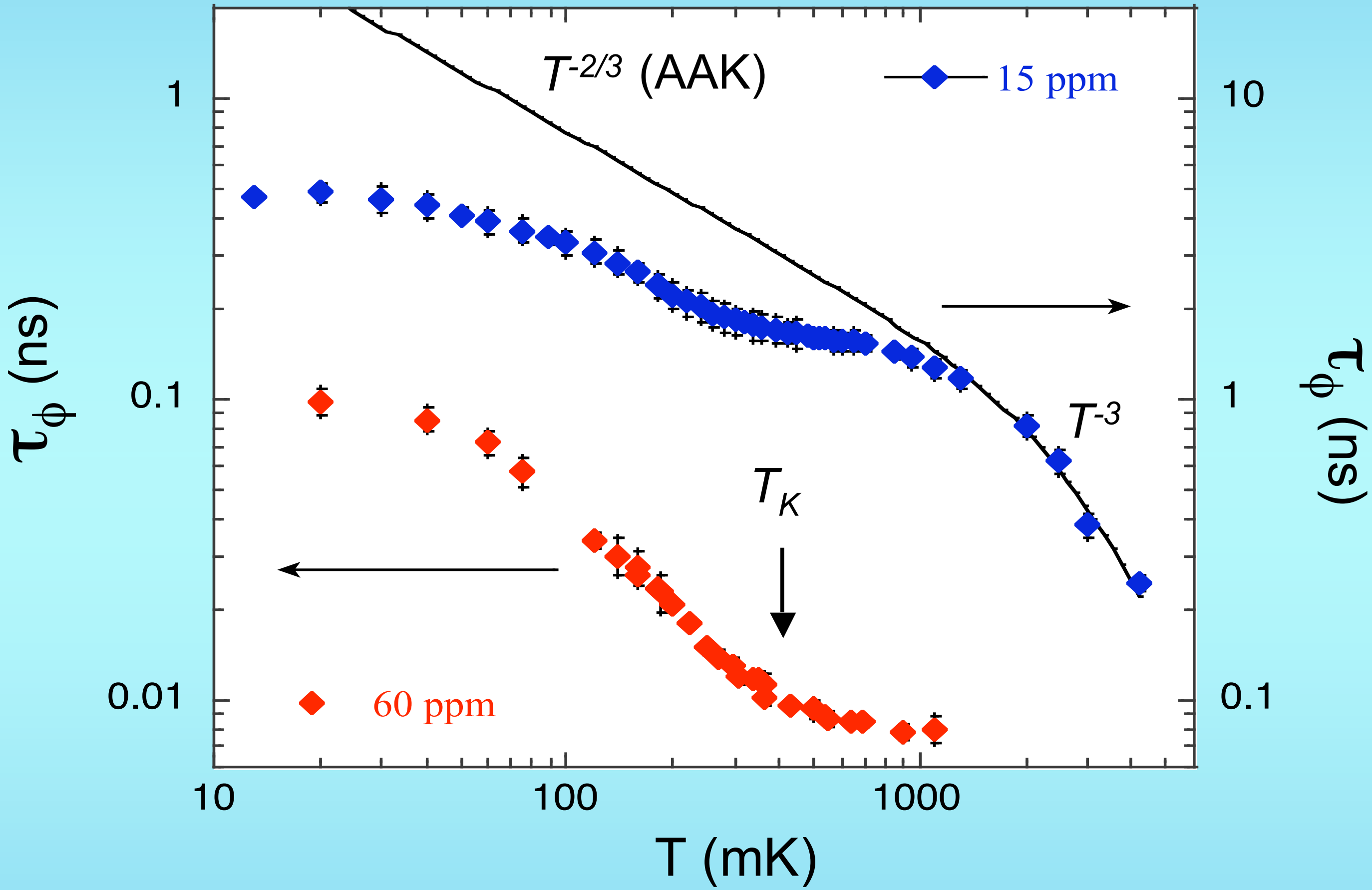




l_ϕ

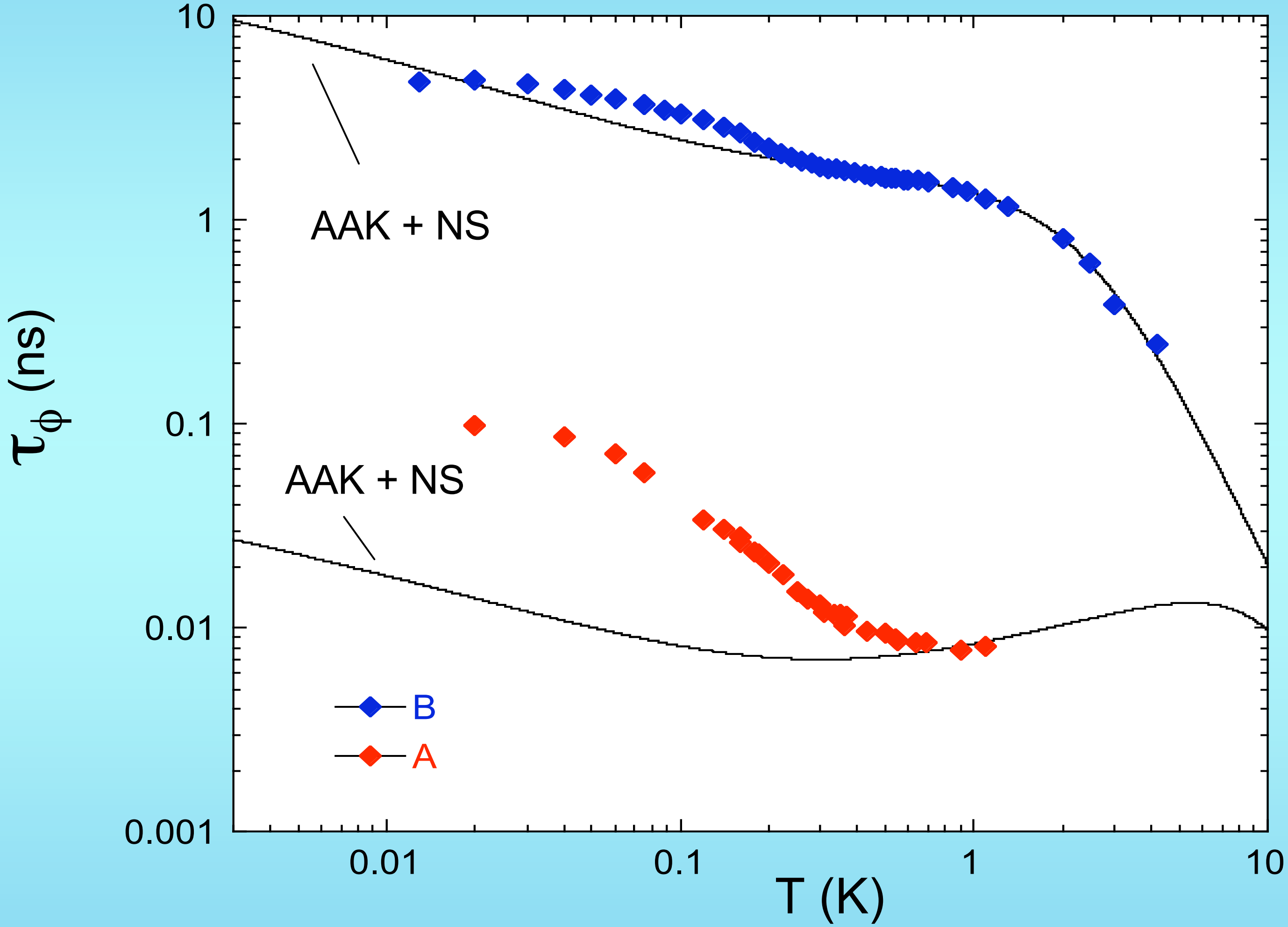


phase coherence time τ_ϕ



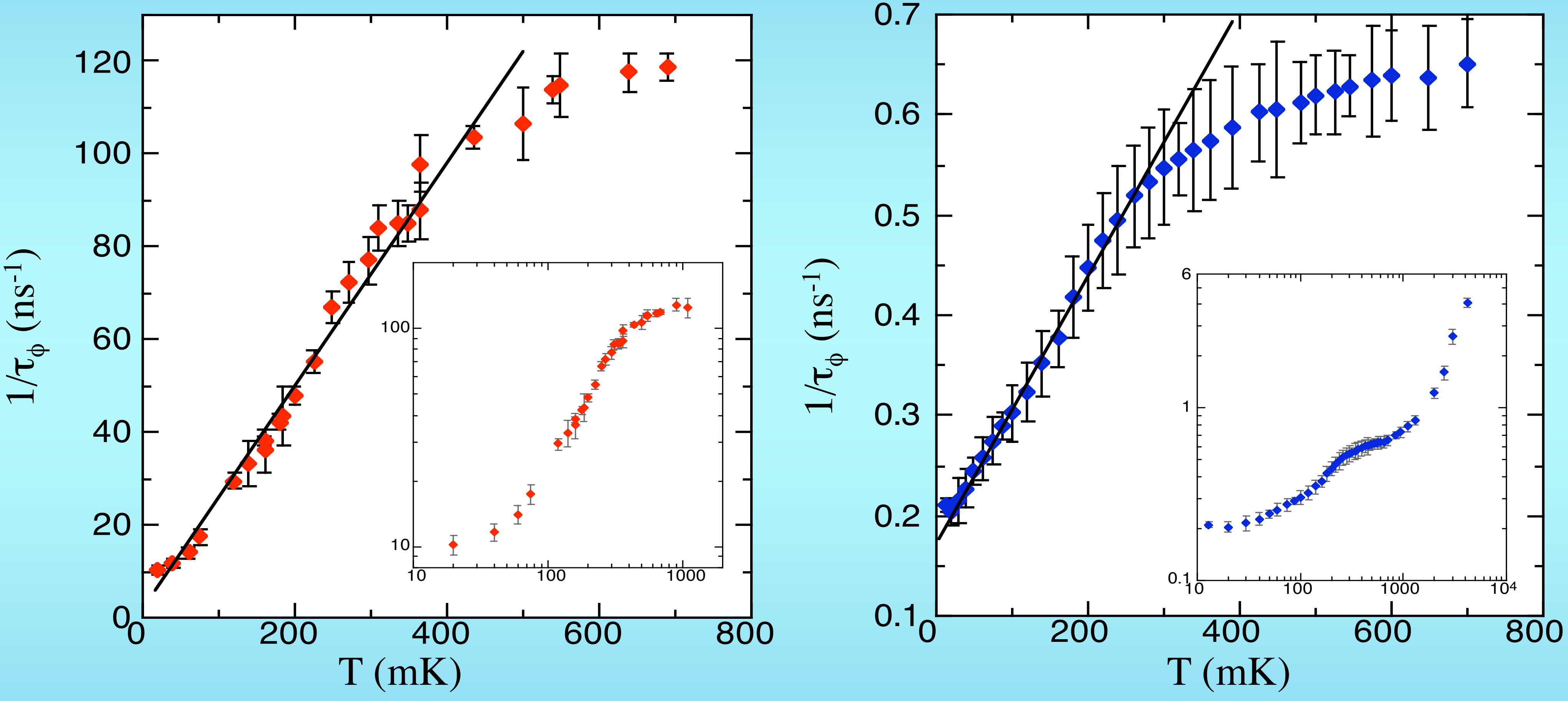
Three distinct temperature regimes

Nagaoka-Suhl approximation



also: Vavilov & Glazman PRB 03'

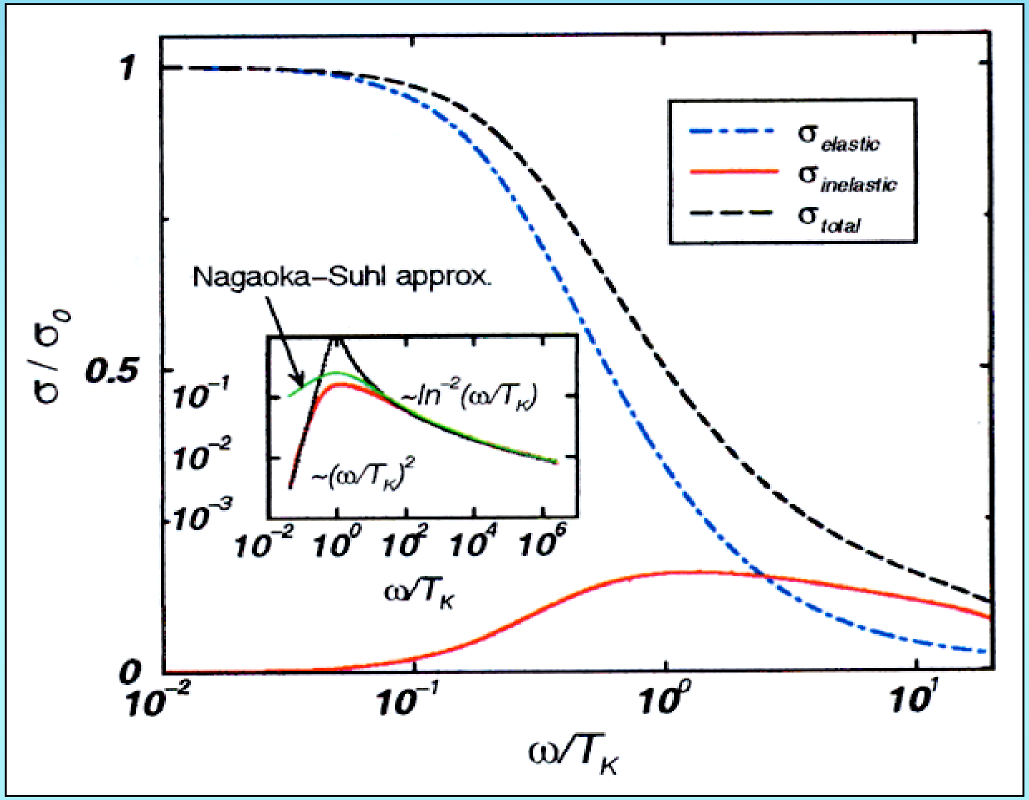
$1/\tau_\phi$ versus T



Linear variation of $1/\tau_\phi$ with T is an experimental fact !

NRG calculation of $\tau_{inelastic}$

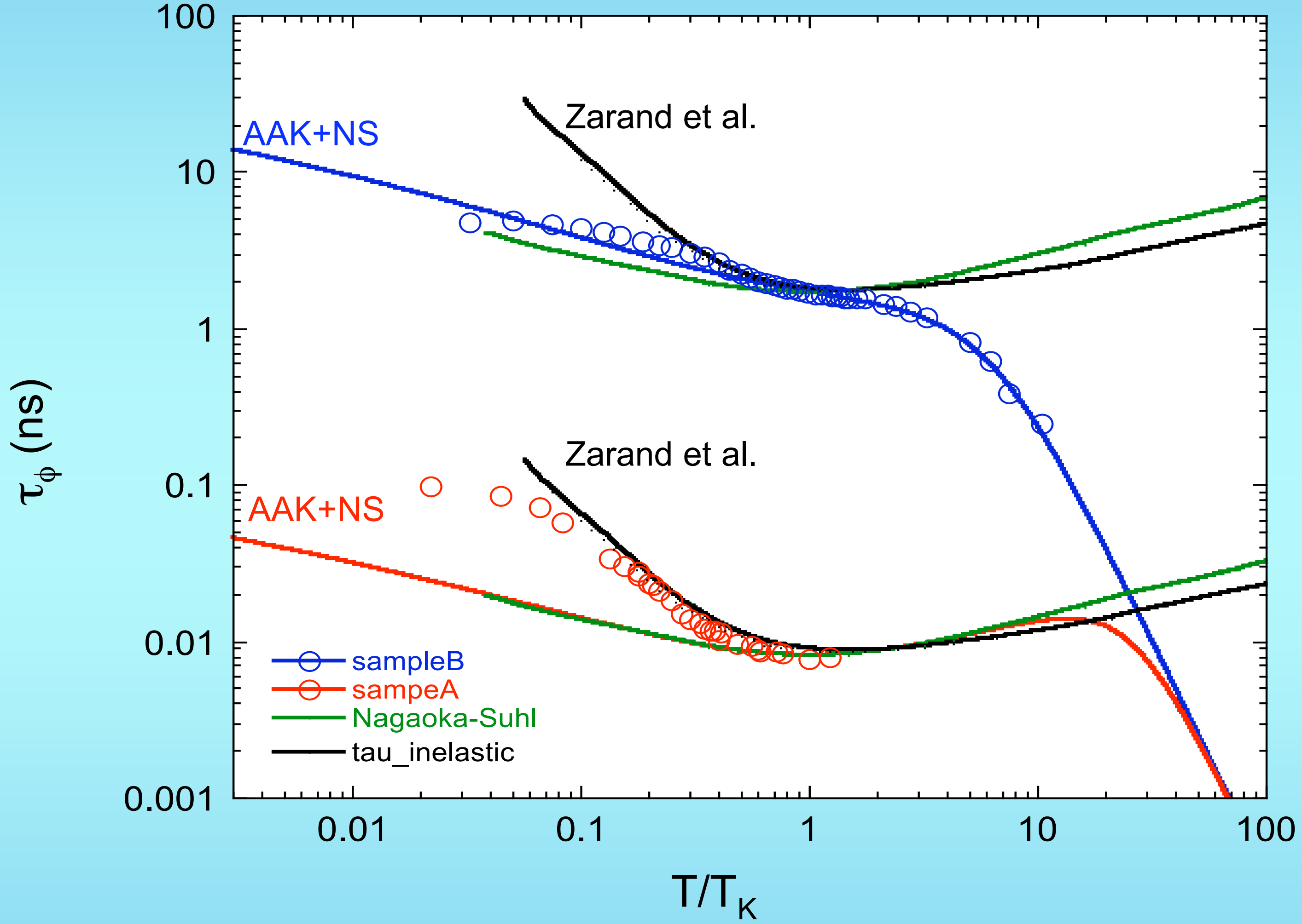
scattering cross section



Zarand et al. Cond-mat 0403696

$T > 10T_K$	Nagaoka-Suhl approximation
$0.1T_K < T < T_K$	*Linear T* dependence
$T < 0.01T_K$	T^2-depencence (Nozières)

Comparison with NRG calculation



- Kondo picture decribes well data around T_K, but not in the *T=0* limit
- deviations approximately at the *same T* as R(T)

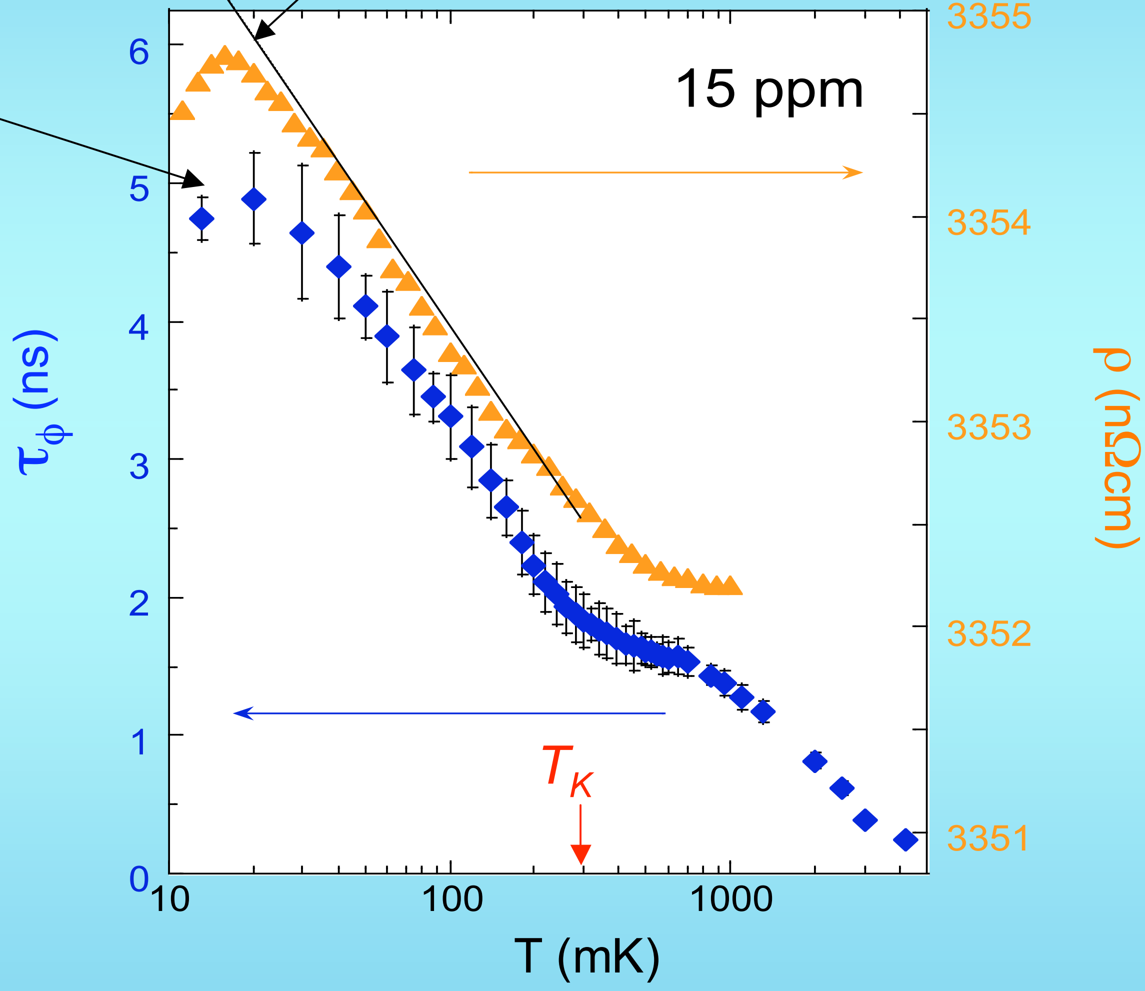
τ_ϕ versus $\rho(T)$

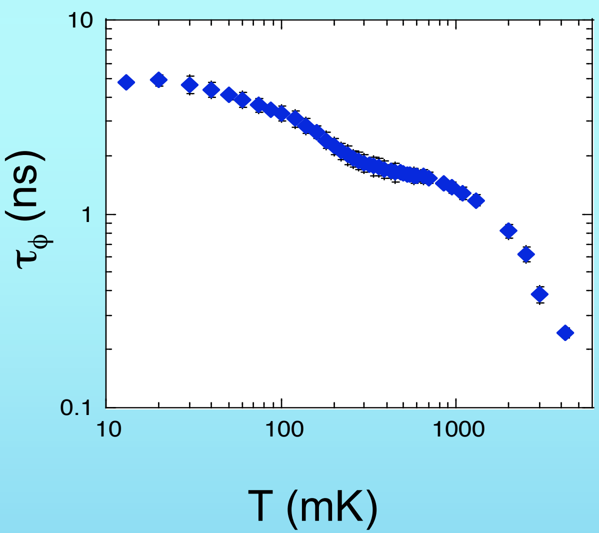
unitary limit

maximum in ρ(T)

saturation at LT

new regime

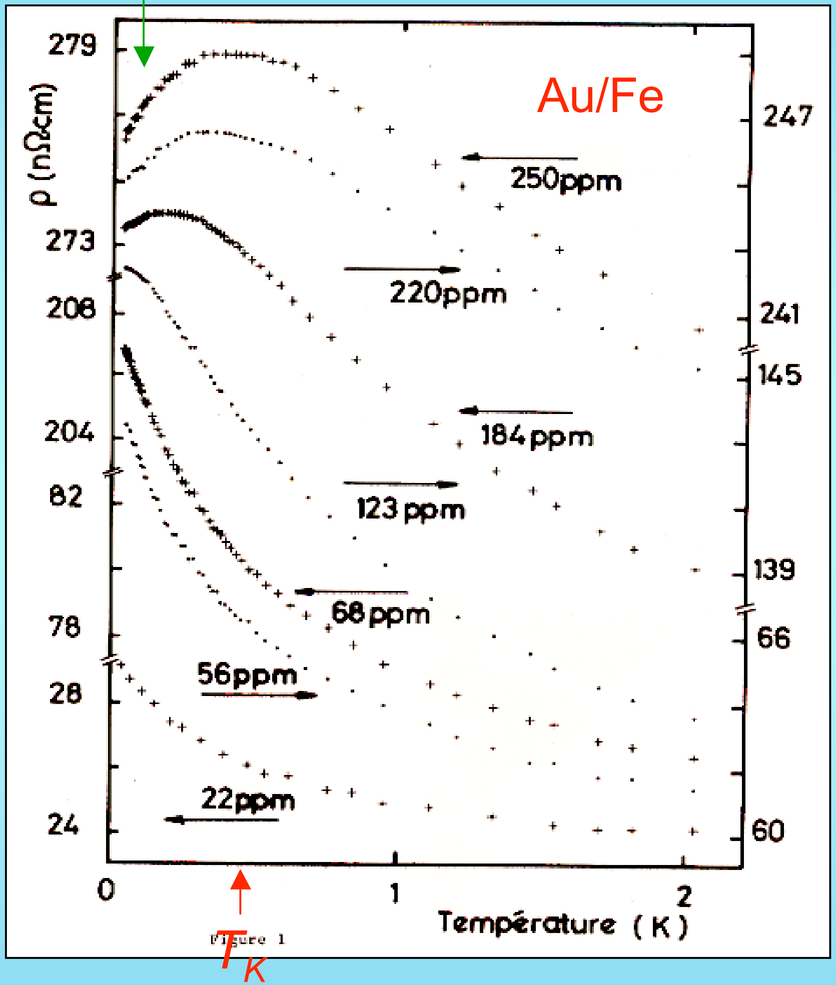


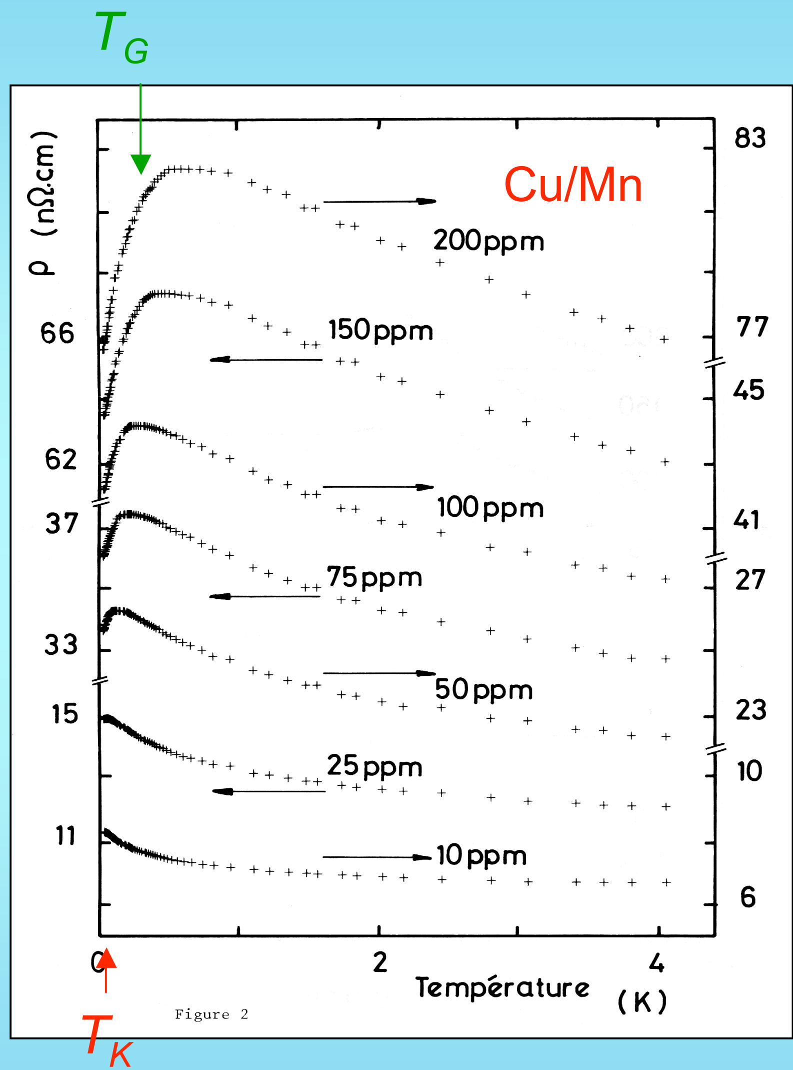


T-variation of $\rho(T)$ and $\tau_\phi(T)$ are correlated

Resistance Maximum

Laborde et al 71'; Ford et al 70'





Laborde 71'

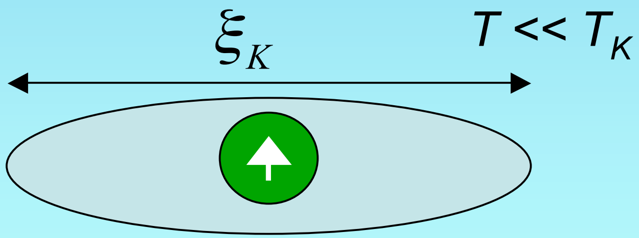
maximum in R(T) is an indication of ***spin glass*** *formation*

SG transition, however, is well below the resistance maximum

Kondo versus RKKY

Kondo effect :

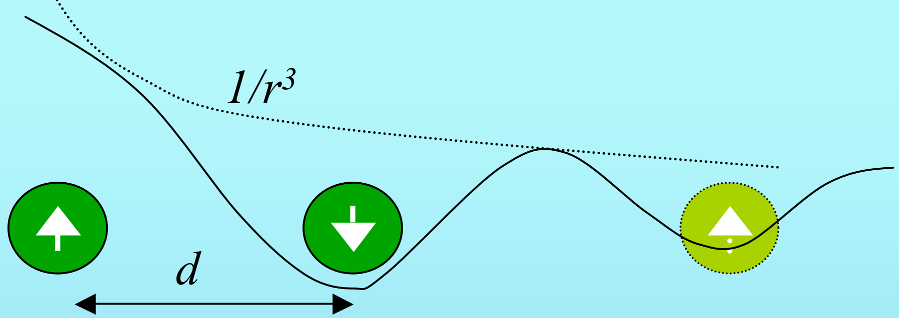
screening of impurity spin via the conduction electrons



- energy scale: T_K
- length scale: $\xi_K = \dfrac{v_F}{T_K}$

*complete screening of the magnetic impurity spin **only if** the distance between magnetic impurities > ξ_K*

RKKY interactions :



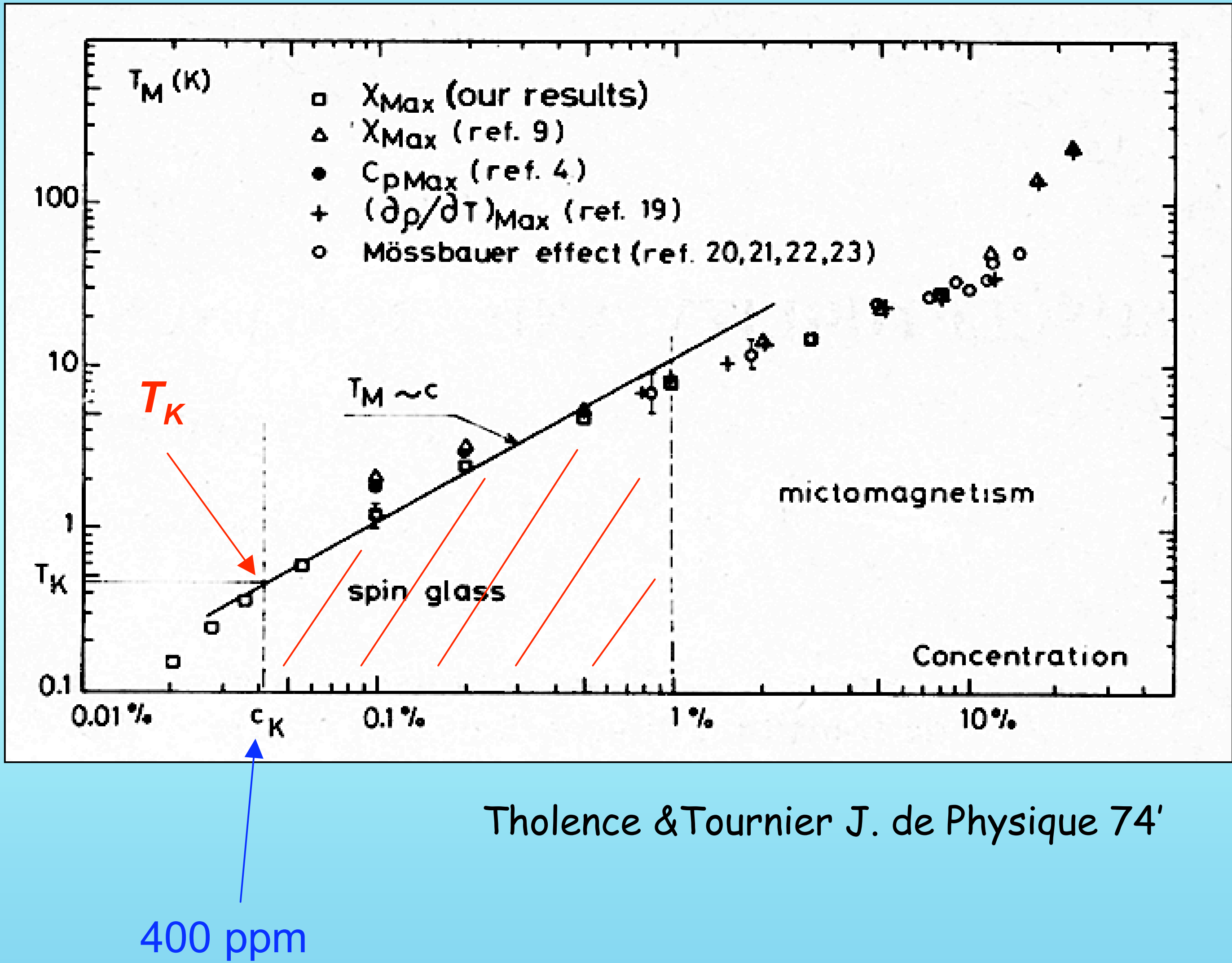
- energy scale: T_{SG}
- length scale: d

leads to magnetic ordering at T_{SG} into a random spin configuration which destroys phase coherence

Competition between screening of magnetic impurities and spin glass formation

T_{SG} versus concentration

Au/Fe

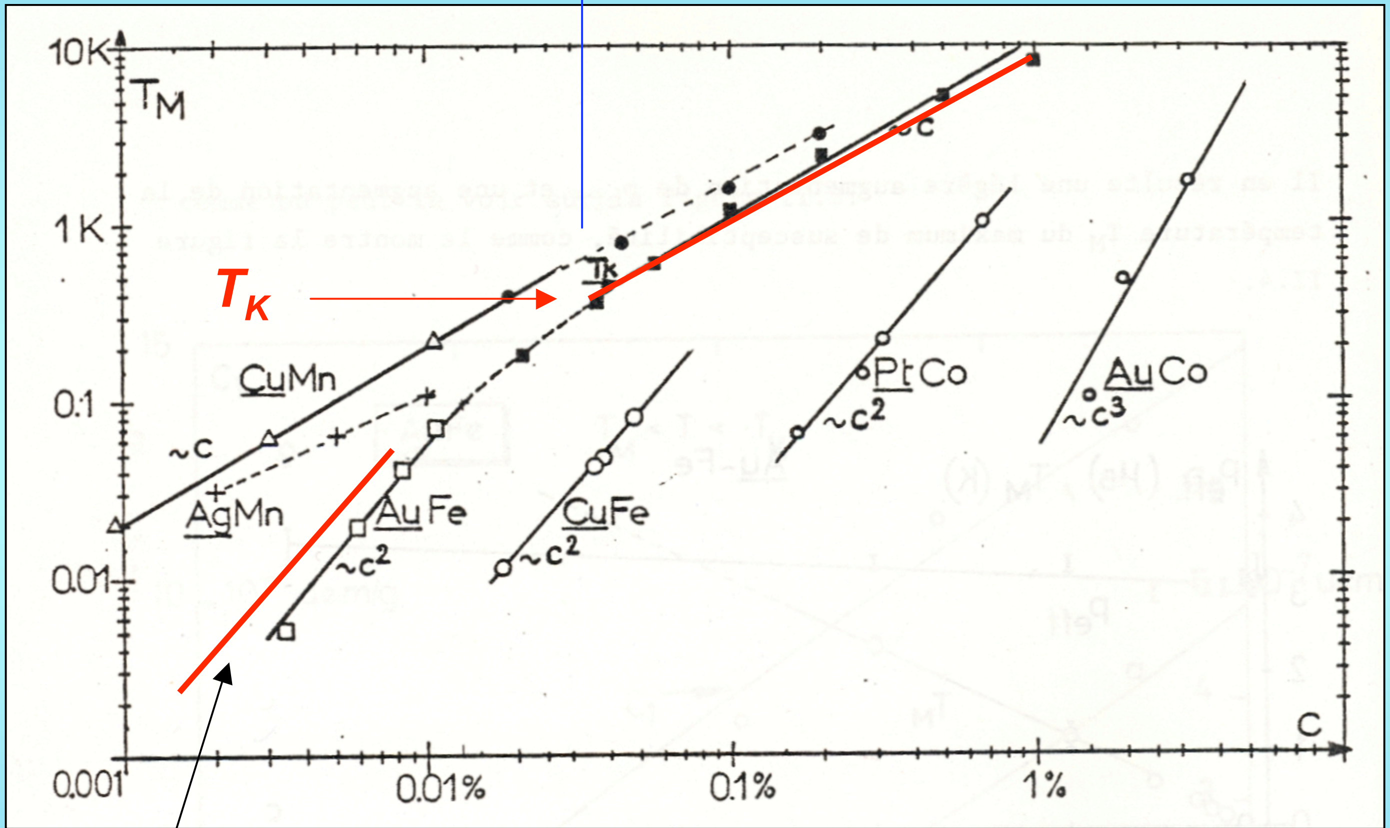


Tholence &Tournier J. de Physique 74'

T_{SG} versus concentration

400ppm

T_K



G. Frossati et al, Physica B 76'

magnetism of pair of spins

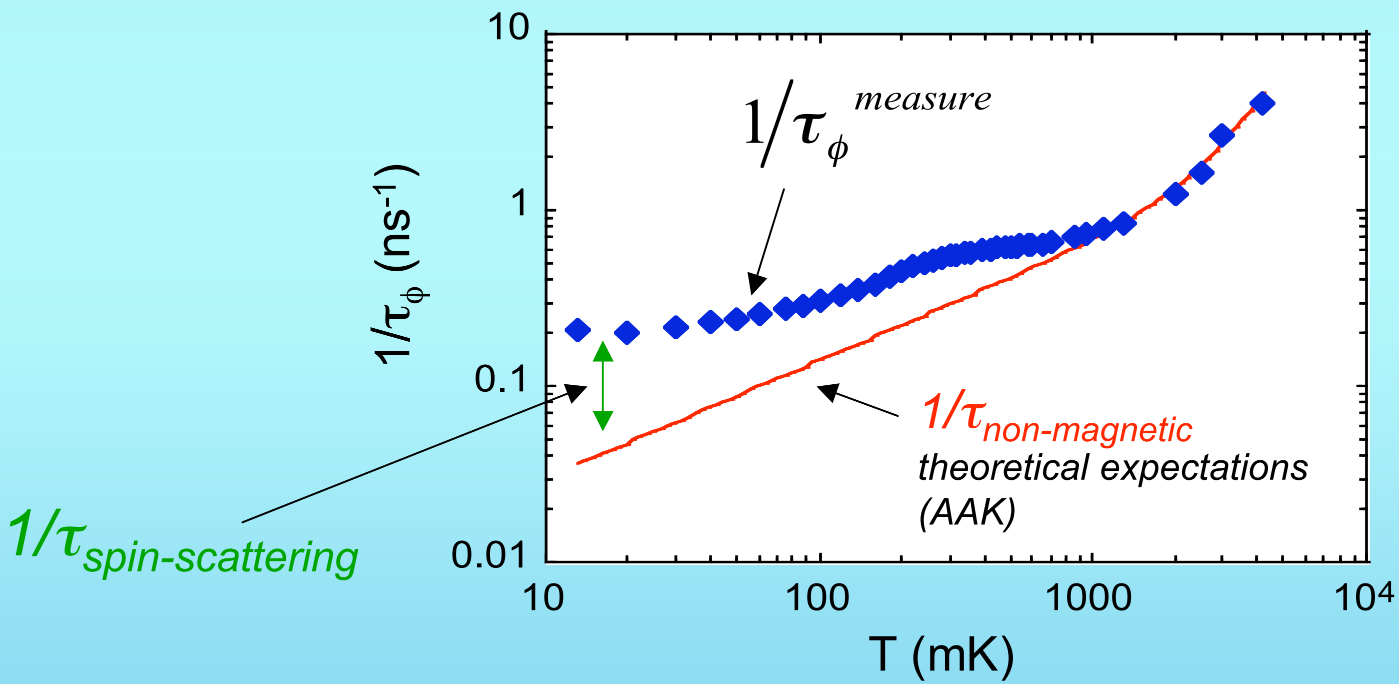
Kondo effect of pair of spins with: $T_K' << T_K$

$T_{SG} \sim c^2$

Spin scattering time τ_s

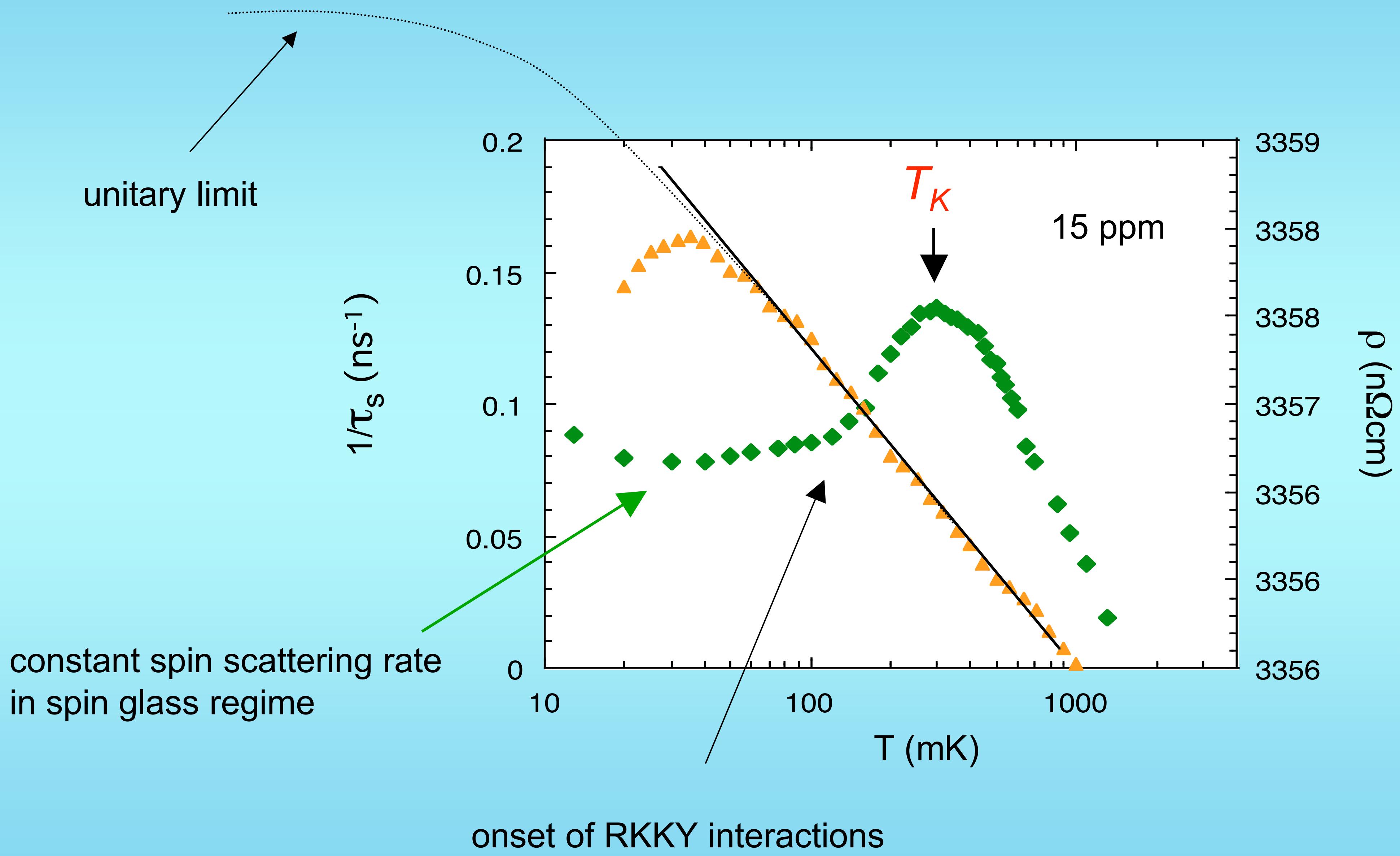
depends on τ_{sf} / τ_K

$$\frac{1}{\tau_\phi^{measure}} = \frac{1}{\tau_{spin-scattering}} + \frac{1}{\tau_{non-magnetic}}$$



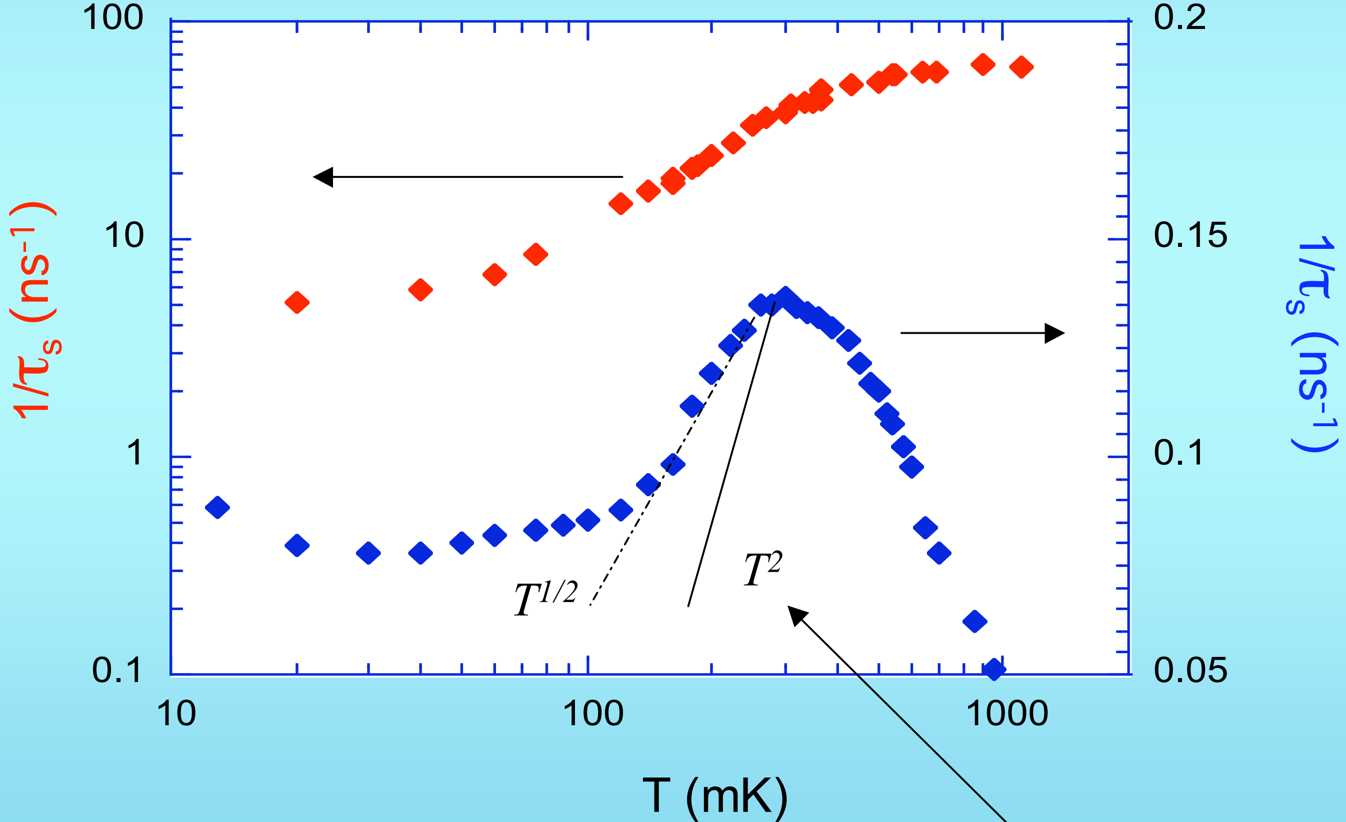
allows to extract spin scattering rate

Spin scattering time τ_s

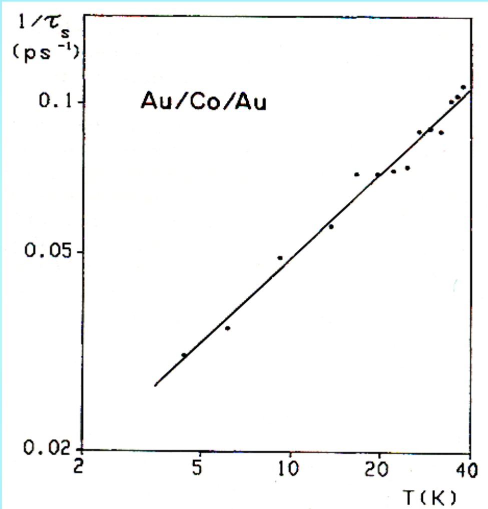


Spin scattering time τ_s

Schopfer et al., PRL 03



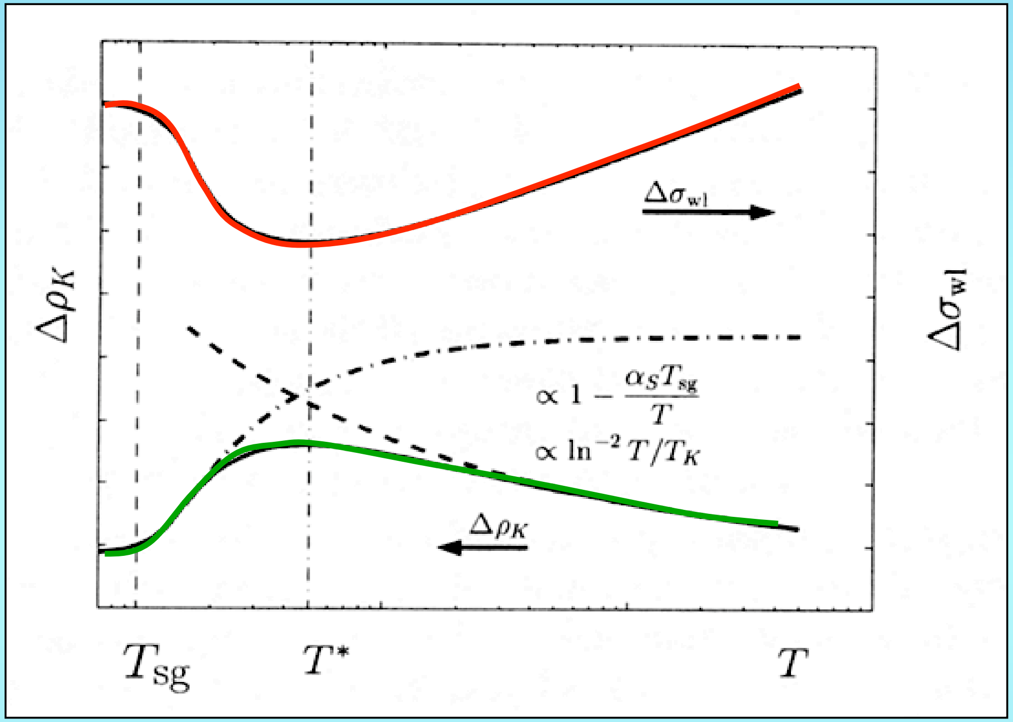
Nozières



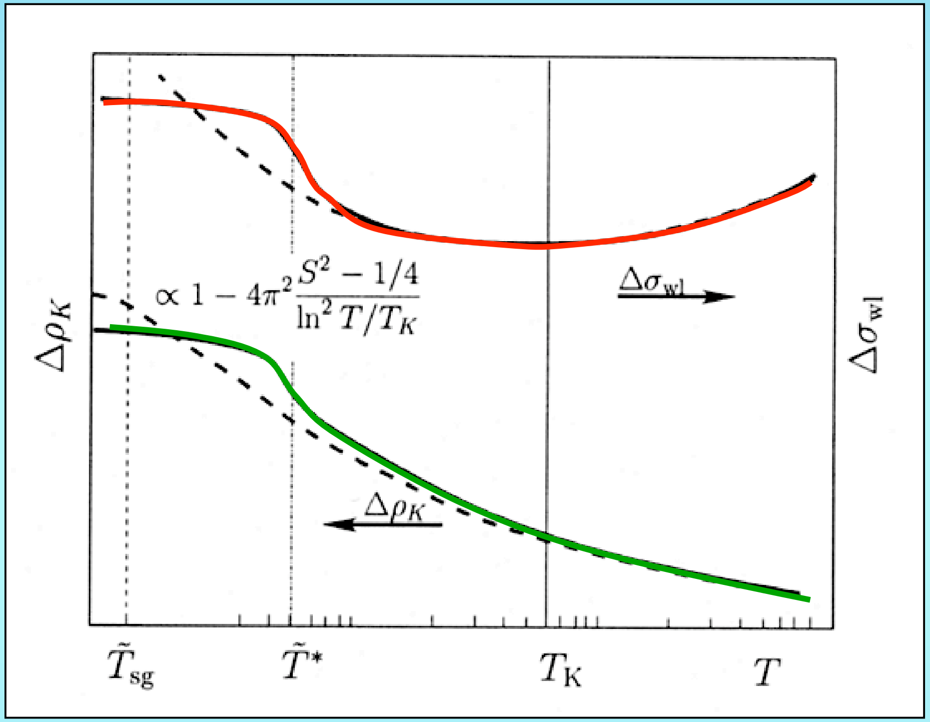
Bergman et al 88'

Comparison theory- experiment

$T_{SG} >> T_K$



$T_{SG} << T_K$



Vavilov, Glazman, Larkin PRB 03'

τ_ϕ in good qualitativ agreement with theory

however:

Resistance maximum ?? ⇒ R(T) measurements of bulk samples at very low temperatures (T~ 1mK)

Conclusions

- even in the presence of very dilute magnetic impurities, RKKY interactions are important

- when working with metals which *almost always* contain magnetic impurities, one has to worry about 2 energy scales :

T_K and T_{SG}

leads to saturation of τ_ϕ

open questions:

Resistance maximum for $T_{SG} < T_K$

What kind of spin glass is formed ?

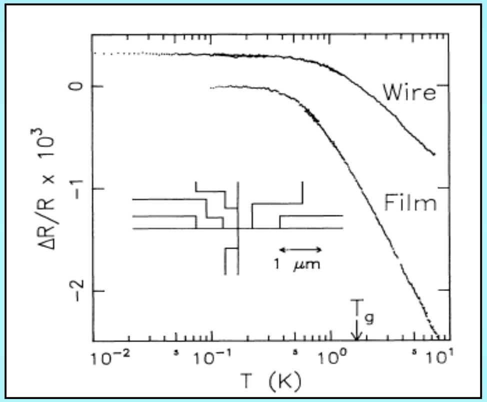
Finite size effects ?

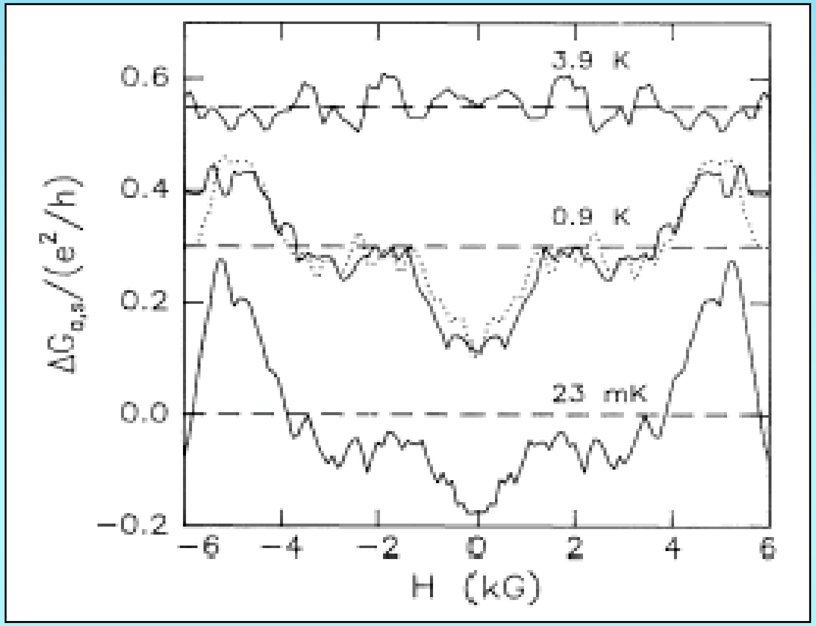
τ_{sf} in Fermi liquid ground state ?

Other phase coherent measurements in spin-glasses

a) De Vegvar, Levy, Fulton PRL 91

CuMn (1000ppm)





b) Alers, Weissman, Israeloff PRB 92
Israeloff & Weissman PRL89

CuMn

⟶ Not at all understood