Quantum transport in spin-glasses

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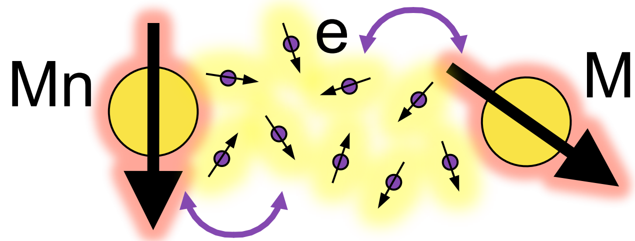
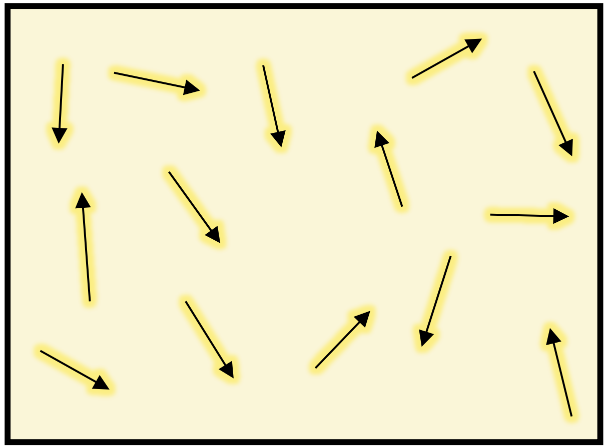
Spin Glass

Examples:
Cu:*Mn*, Ag:*Mn*



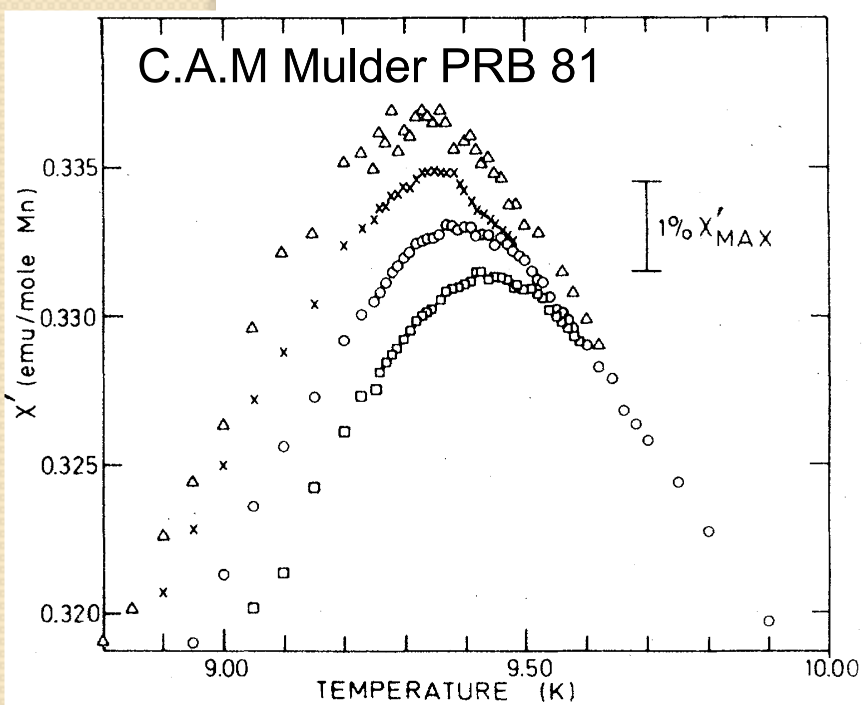
$T>T_g$: free spins

$T<T_g$:spin frozen

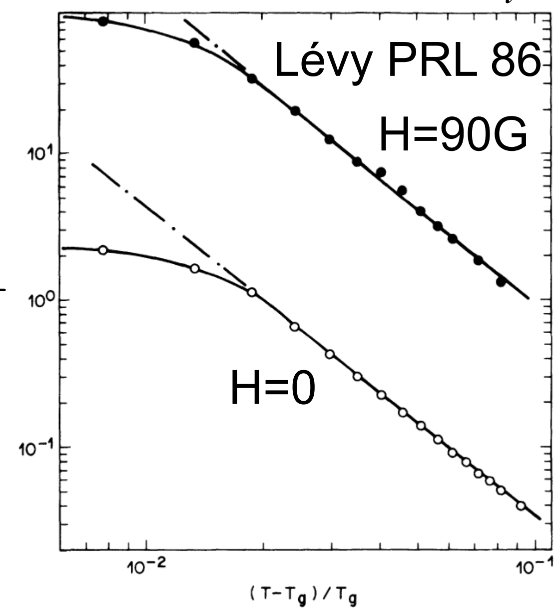


RKKY interaction between *Mn* random position ⇒ random ferro/antiferro couplings

$T<T_g$, order parameter $q_{EA} = \sum_i \left\langle \vec{S}_i \right\rangle^2$



$$\chi_3 \propto \frac{\partial q_{EA}}{\partial H}$$



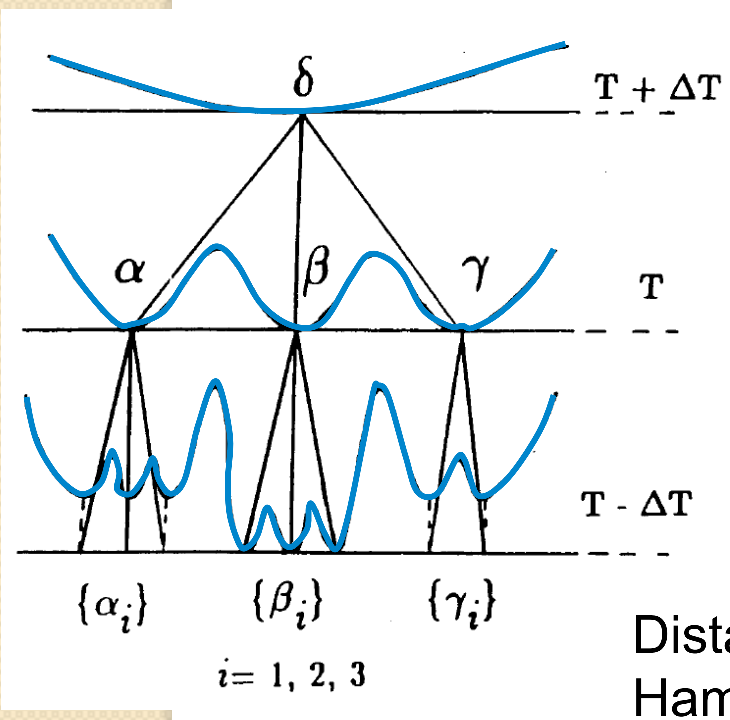
Low temperature SG phase

Many experiments: aging, rejuvenation, dynamics, irreversibility lines

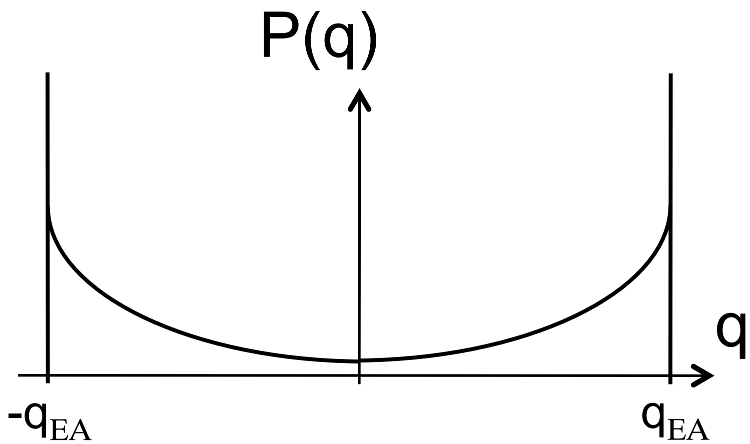
→ this workshop

competing theoretical views: mean field (inf. range SK model) *vs* droplets (short range)

mean-field: Parisi 83 solution



Many LE states



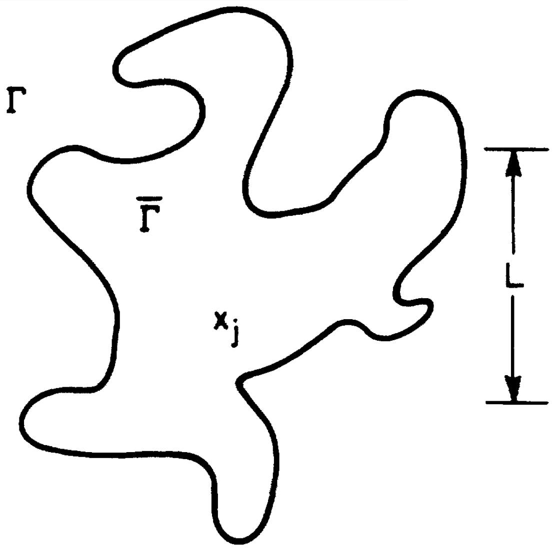
no spatial structure
"Ultrametric" tree

Distance ? overlap between states $q_{\alpha\gamma} = \frac{1}{N}\sum_i \left\langle S_i^\alpha . S_i^\gamma \right\rangle$
Hamming distance: common ancestor
$d_H(\alpha\gamma)=3$

exp. analysis requires bifurcation rules & dynamics
within the ultrametric space

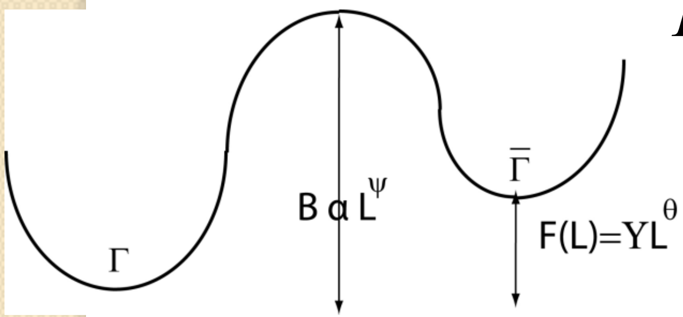
Droplets picture

Local excitations



$\bar{\Gamma}$ excited droplet

Fisher and Huse 1988

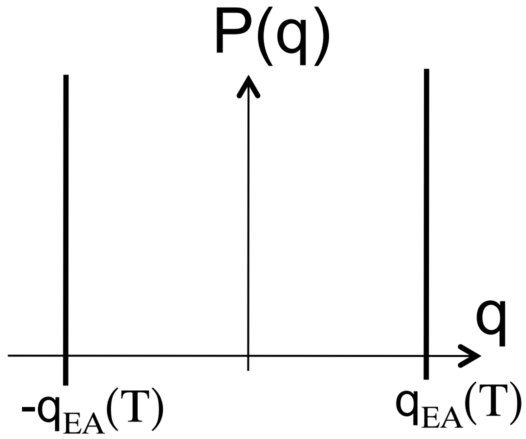


$$F_{\bar{\Gamma}}(L) = \mathrm{Y}L^{\theta}$$

$$\theta \approx 0.2$$

Collections of broadly distributed two level systems

Single ground state Γ



Arrhenius barriers dynamics

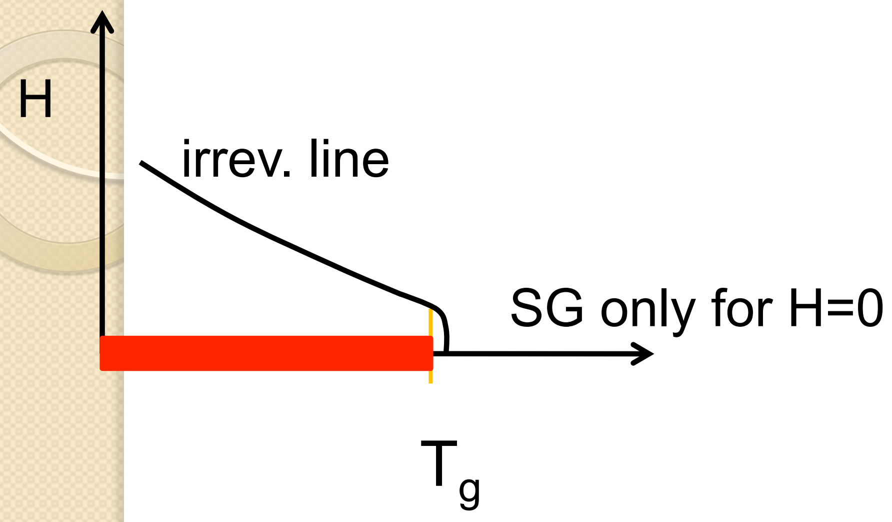
$$\tau_L = \tau_0 e^{\frac{B_L}{k_B T}} = \tau_0 e^{\frac{\Delta L^{\psi}}{k_B T}}, \ln\frac{\tau_L}{\tau_0} = \frac{\Delta L^{\psi}}{k_B T}$$

slow relaxation

$$\chi''(\omega) = \frac{\pi}{2}\frac{\theta}{\psi}\frac{K}{\mathrm{Y}}\left(\frac{\Delta}{kT\ln\omega}\right)^{1+\theta/\psi}$$

$$q_{EA}(T) = 1 - c\frac{kT}{\mathrm{Y}L^{\theta}}$$

Droplets picture in a field



$$\chi \propto H^{d/(d-2\theta)}$$

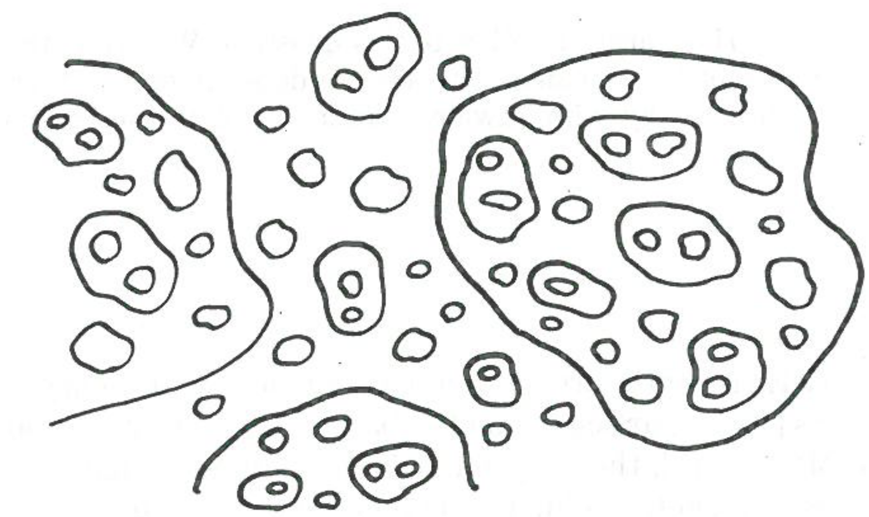
$$\chi_3 \propto H^{-2\frac{d-3\theta}{d-2\theta}}$$

Other view (J. Villain EPL 1986)

Argument:

$$\left(\mu L^{d/2}\right) H > \Upsilon L^{\theta}$$

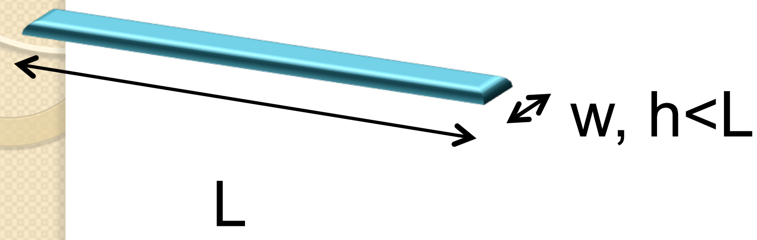
Proliferation of
large (L) droplets
→SG phase unstable



Finite Tg(H) possible

A quantum coherence primer

Sample: a wire



Quasi 1D diffusion for electrons

$$\tau_L = \frac{L^2}{D}$$ diffusion time

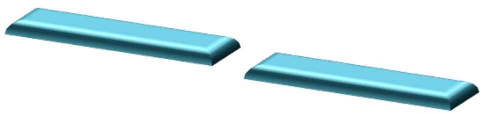
$$E_c(L) = \frac{\hbar}{\tau_L} = \frac{\hbar D}{L^2}$$ Thouless energy

small energies $k_B T, \hbar\omega < E_c$

UNIVERSAL MESOSCOPIC REGIME

wavepackets diffuse over the whole sample and "feel" ALL impurities, i.e. *the whole sample*

larger energies $k_B T, \hbar\omega > E_c(L)$ Cut sample in smaller pieces L'



such $E_c(L') = \frac{\hbar D}{L'^2} = kT, \hbar\omega$

Each piece behave as an *independent sample*

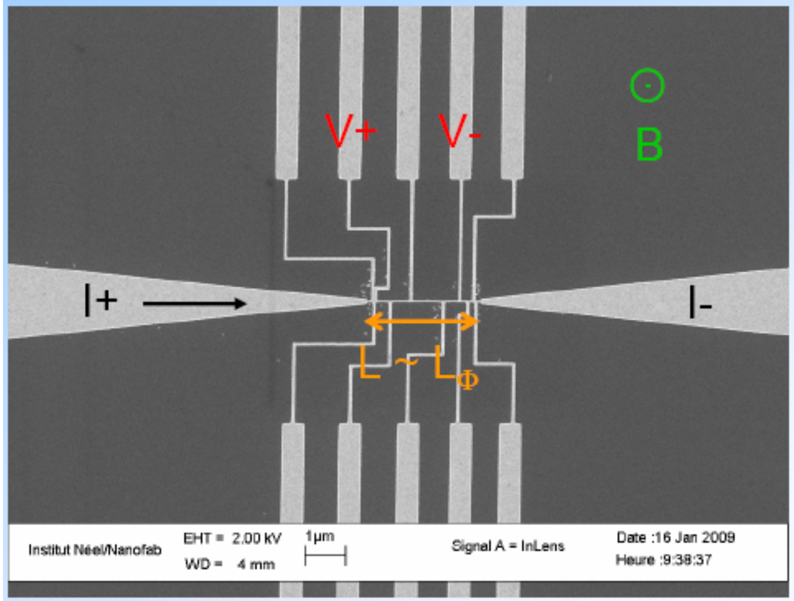
Wanted: one spin glass sample, not several indep. SG samples

Somme numbers

T_g=0.7 K

$$L_{Tg} = 0.58\mu m$$

$$L_{0.05Tg} = 2.8\mu m$$



T_g=28 K

$$L_{Tg} = 70nm$$

$$L_{0.5Tg} = 96nm$$

too small

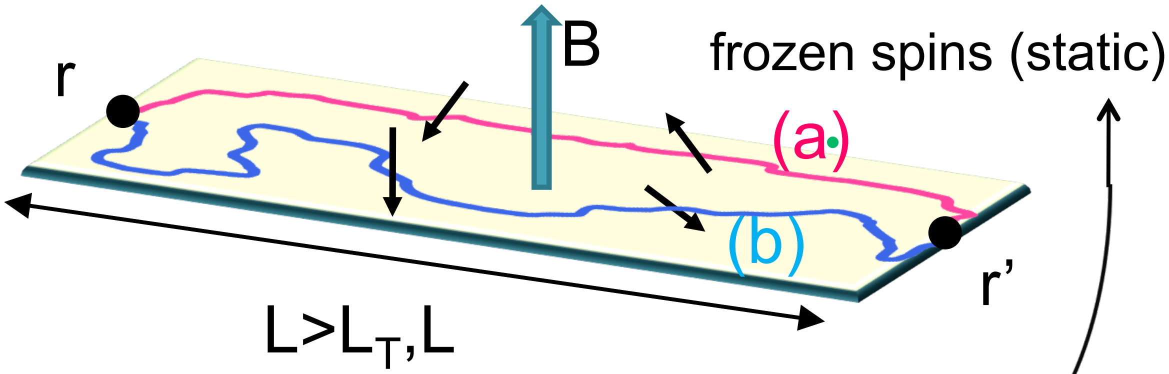
Other issues: phase coherence length $L_\varphi \geq L$

$T_K << T$ → Ag:*Mn* , Cu:*Mn* 500-1000ppm

dilution temperatures

Universal Conductance Fluctuations in Spin Glasses

Universal regime
all paths interfere



Interferences depend on
path length ($k_F L$), impurities phase shifts (incl. spins), $\frac{e}{\hbar}\int \vec{A} \bullet d\vec{l}$

"new sample" when

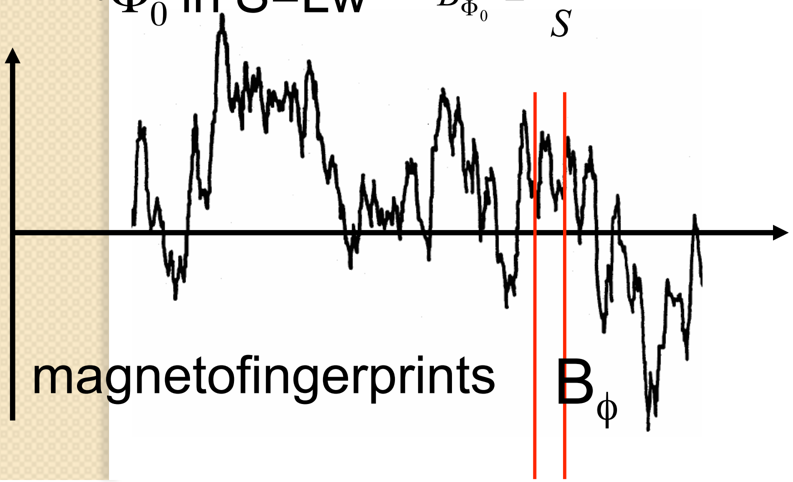
- move $n_0 \approx \frac{n_{\text{imp}}}{d}\left(\frac{l_e}{L}\right)^2$ impurities (more for spins)
-
- Φ_0 in S=Lw $B_{\Phi_0} = \frac{\Phi_0}{S}$

Access spin-glass configurations

$$\left\langle \delta g\{S_{(1)}\}\delta g\{S_{(2)}\}\right\rangle_V = \frac{E_c}{\gamma_m(1-Q_{12})}$$

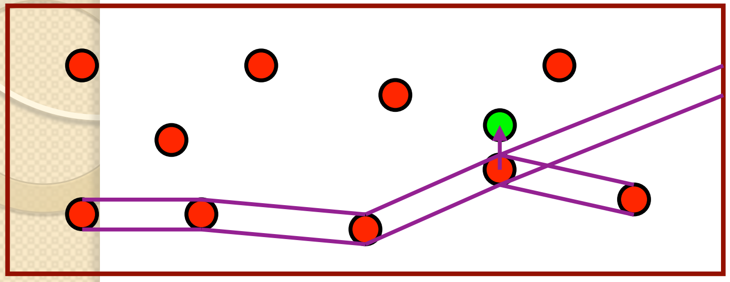
$$Q_{12} = \frac{1}{N_{imp}}\sum_i \left\langle S_i^{(1)} \cdot S_i^{(2)} \right\rangle$$

Holy grail



Altshuler and Spivak, JETP Lett. (1986)
Feng et al. PRB (1987)
Carpentier and Orignac PRL (2008)

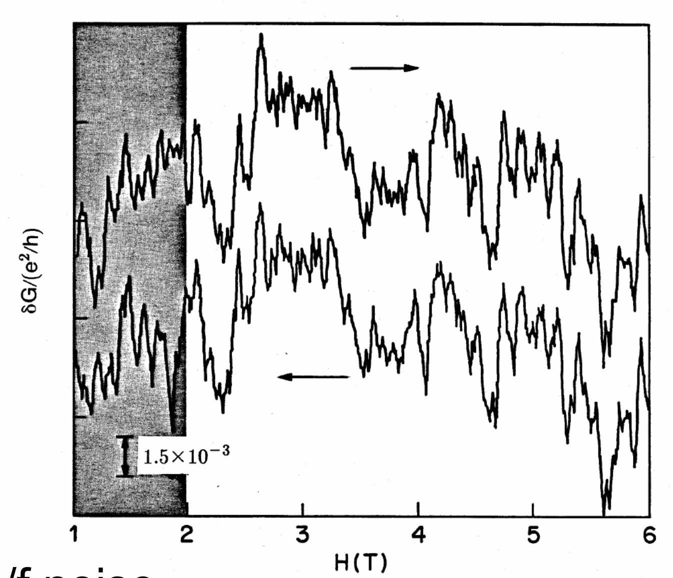
Noise and UCF two limits of the same physics



Few differences: size of coherent blocks (L_ϕ^3, L_T^3), other noises

Feature: *cannot distinguish between local and global rearrangements*

Only thing probed # of spins involved



1/f noise | UCF regime

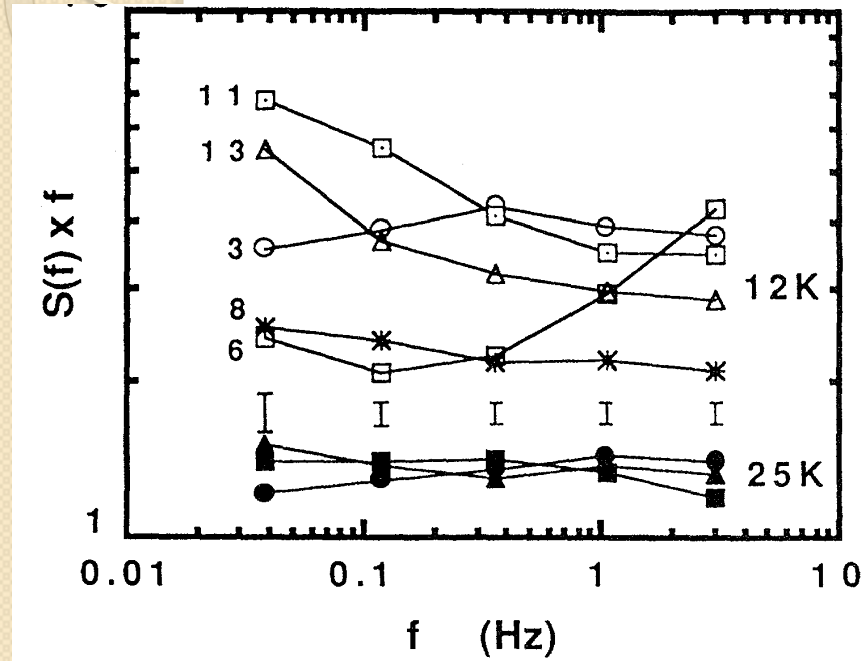
Slow rearrangement | Frozen impurities

Weissman group Studies (Israeloff PRL 89,91, Weissman RMP 88,93)

deVegvar, Lévy PRL 91,92
Jaroszynski et al PRL 97
Capron et al

SG noise studies

Sample T_g=30K 50x50x150-500 nm (constriction)   5-50 L_T^3 blocks, 10^8 spins

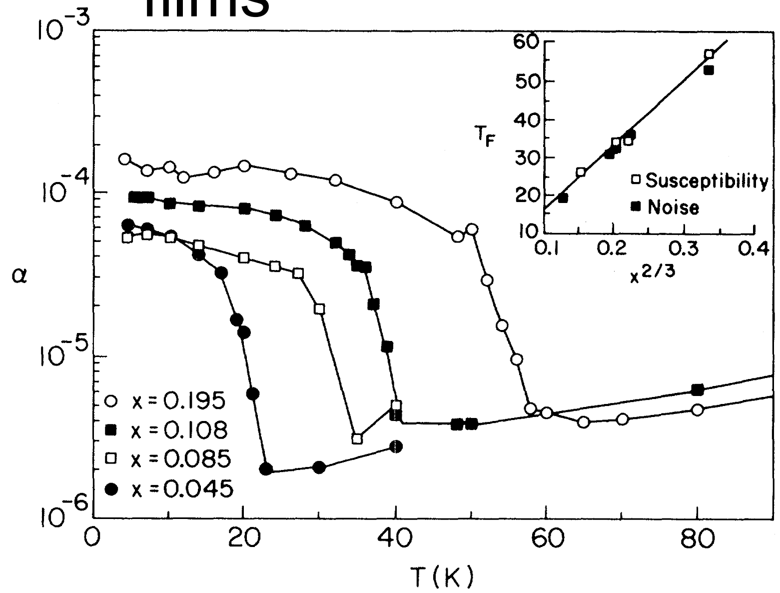


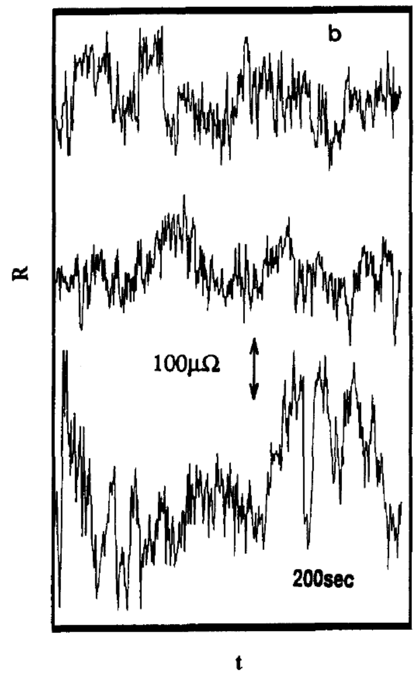
3,..,13: sequence of noise measurements

Noise is NONSTATIONNARY

→ inconsistent with droplets (TLS)
Analysis in term of second spectra and dynamics in Parisi model

films





Discrete jumps blocks of 10^4 spins

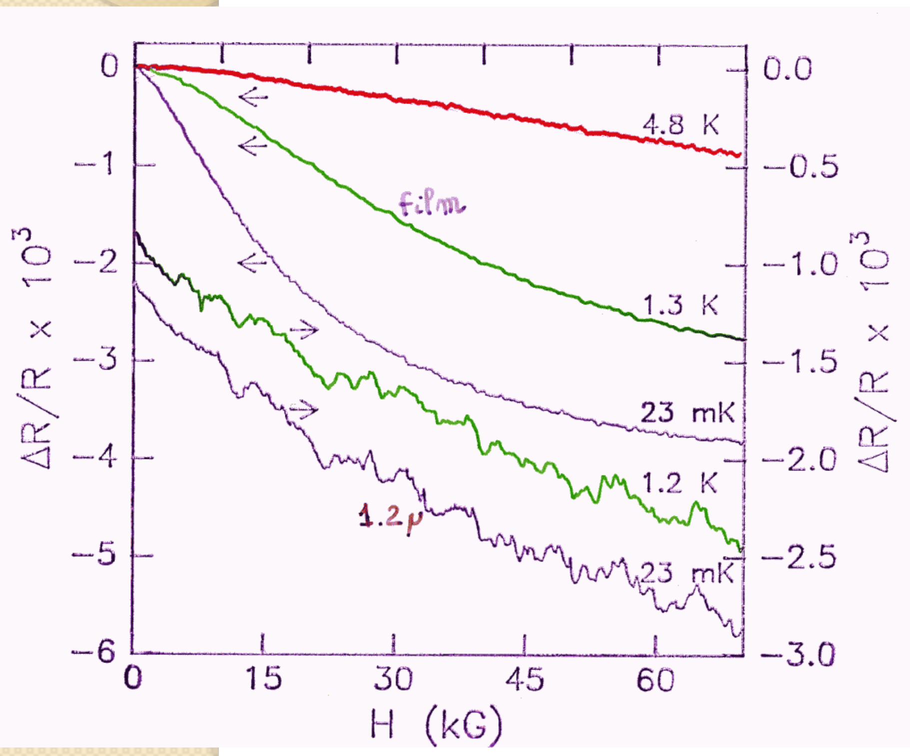
SG UCF studies

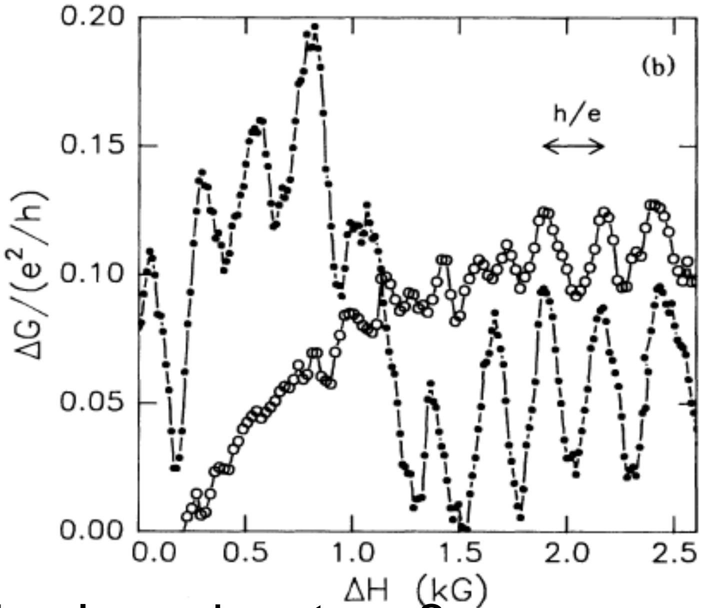
deVegvar-Levy PRL 91

Observable UCF in Cu*Mn*
1000ppm wire 200nmX1.2μm
10^6 spins

(sputtered using Cu*Mn* target)

Comparison between field intevals

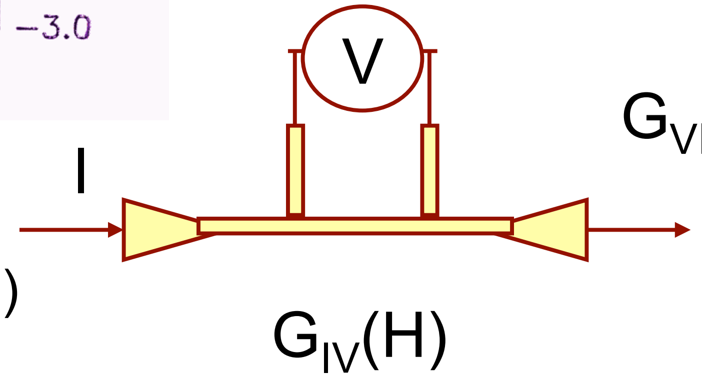


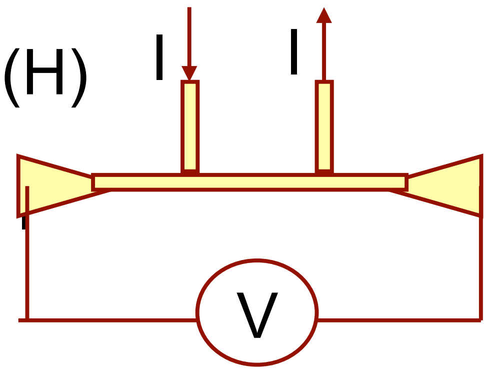


Spin glass signature ?

T symmetry $t_{\alpha\beta}(H)=t_{\beta\alpha}^*(-H)$

Onsager relation $G_{IV}(H)= G_{VI}(-H)$





SG freezing: appearance of UCF

$T > T_g$

Build antisymmetric combinaison sensing t↔ -t

$$G_{odd}(H) = G_{IV}(H) - G_{VI}(-H)$$
$$G_{as}(H) = G_{odd}(H) + G_{odd}(-H)$$

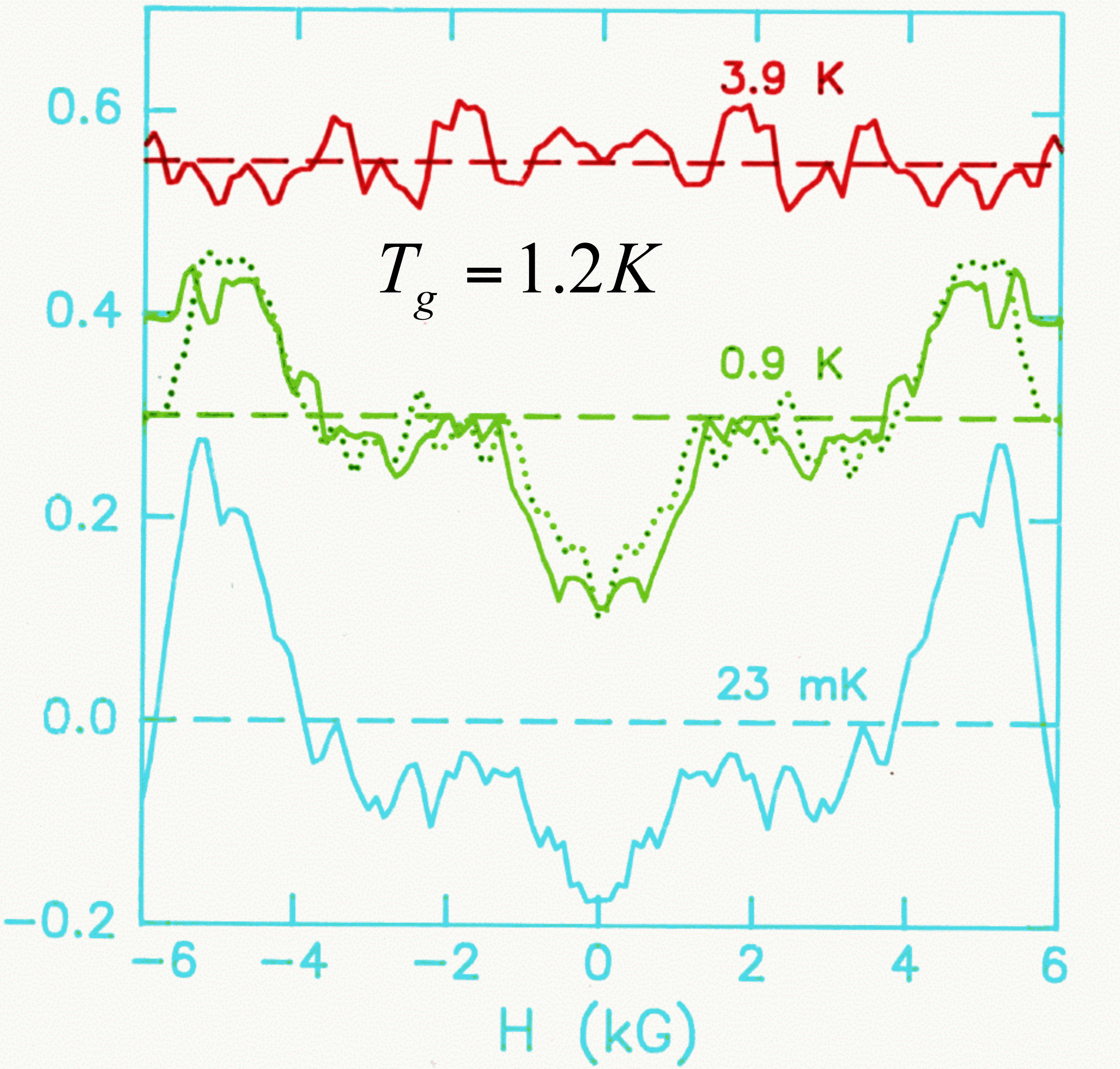
large δg correlation

$T < T_g$

$$\left\langle \delta g^1(H, 0.8T_g)\delta g^2(H, 0.05T_g)\right\rangle$$

$$\left\langle \delta g^1(H, 0.05T_g)\delta g^2(H, 0.05T_g)\right\rangle$$

1:ZFC   2:after cycling to 10T

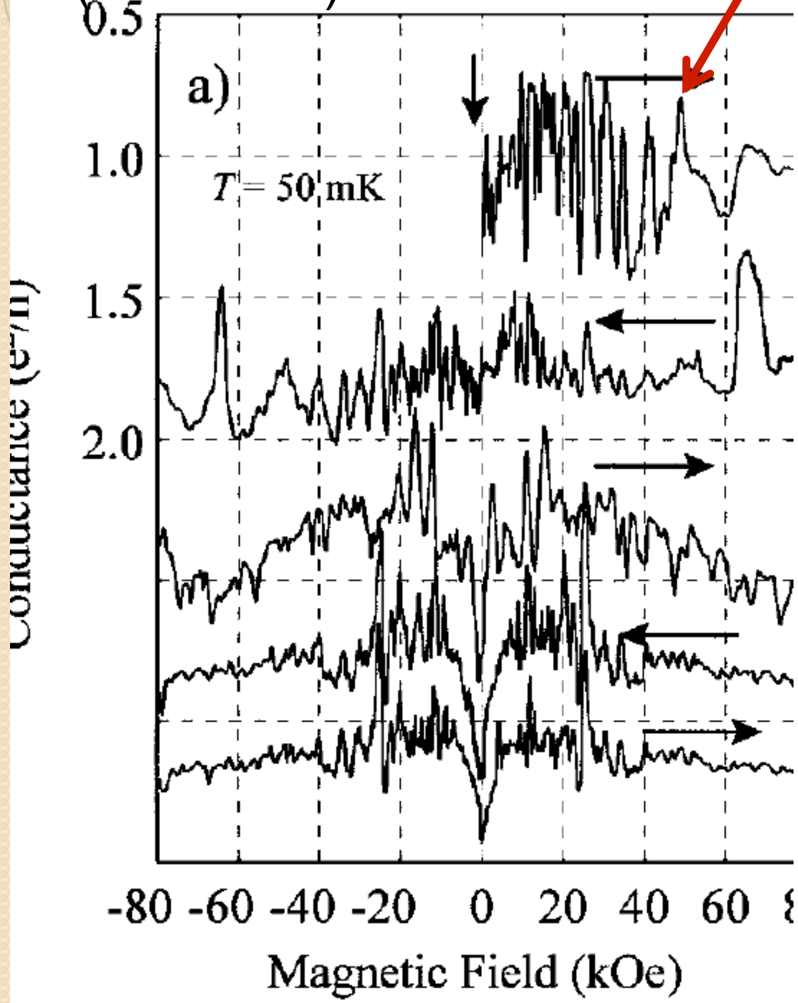


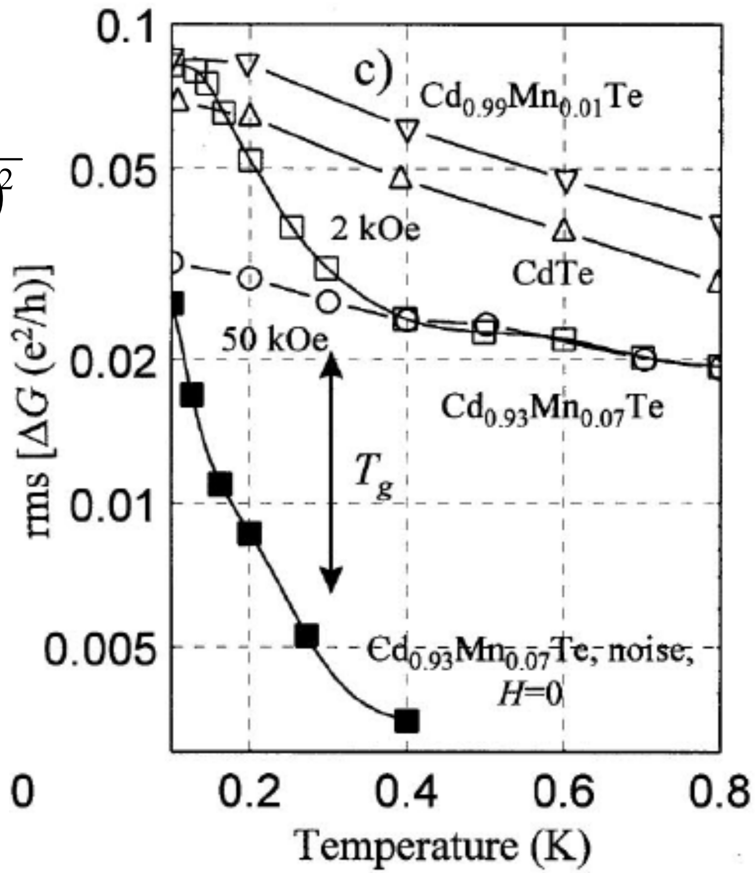
CdMnTe SG UCF

Magnetic semiconductor
Super-exchange coupling
(not RKKY)

$$D \Rightarrow \frac{D}{1+(\omega\tau)^2}$$

S. Xiong
A.D. Stone
PRL 92





$$\left\langle \delta g^1(H,0.05T_g)\delta g^2(H,0.05T_g)\right\rangle$$ large

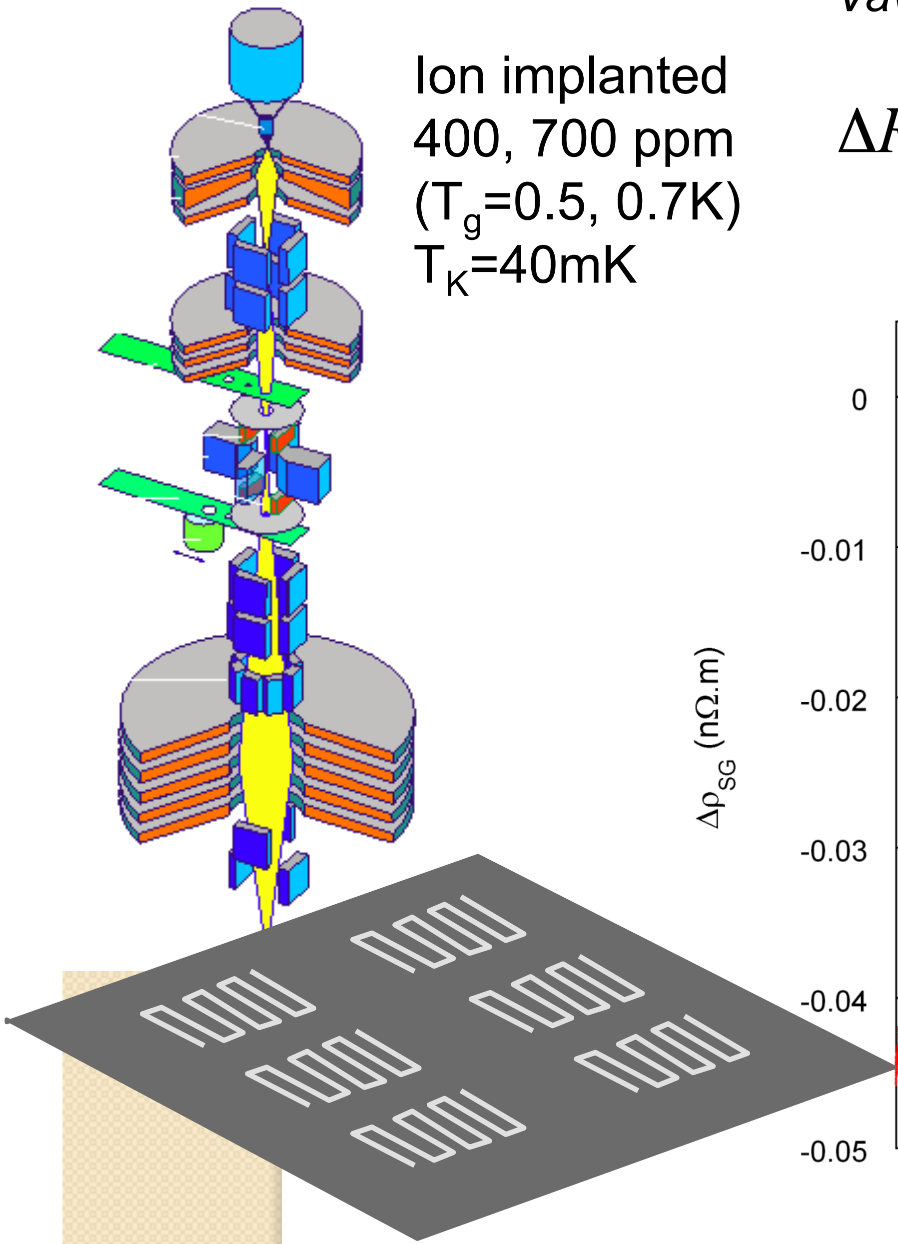
1:ZFC 2:after cycling to 10T

$$\left\langle \delta g^1(H,0.05T_g)\delta g^2(H,0.05T_g)\right\rangle$$ small

1:ZFC1 ZFC2

Jaroszynski et al PRL 97

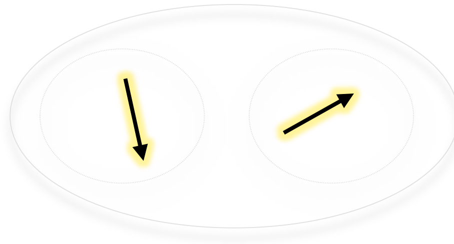
AgMn studies



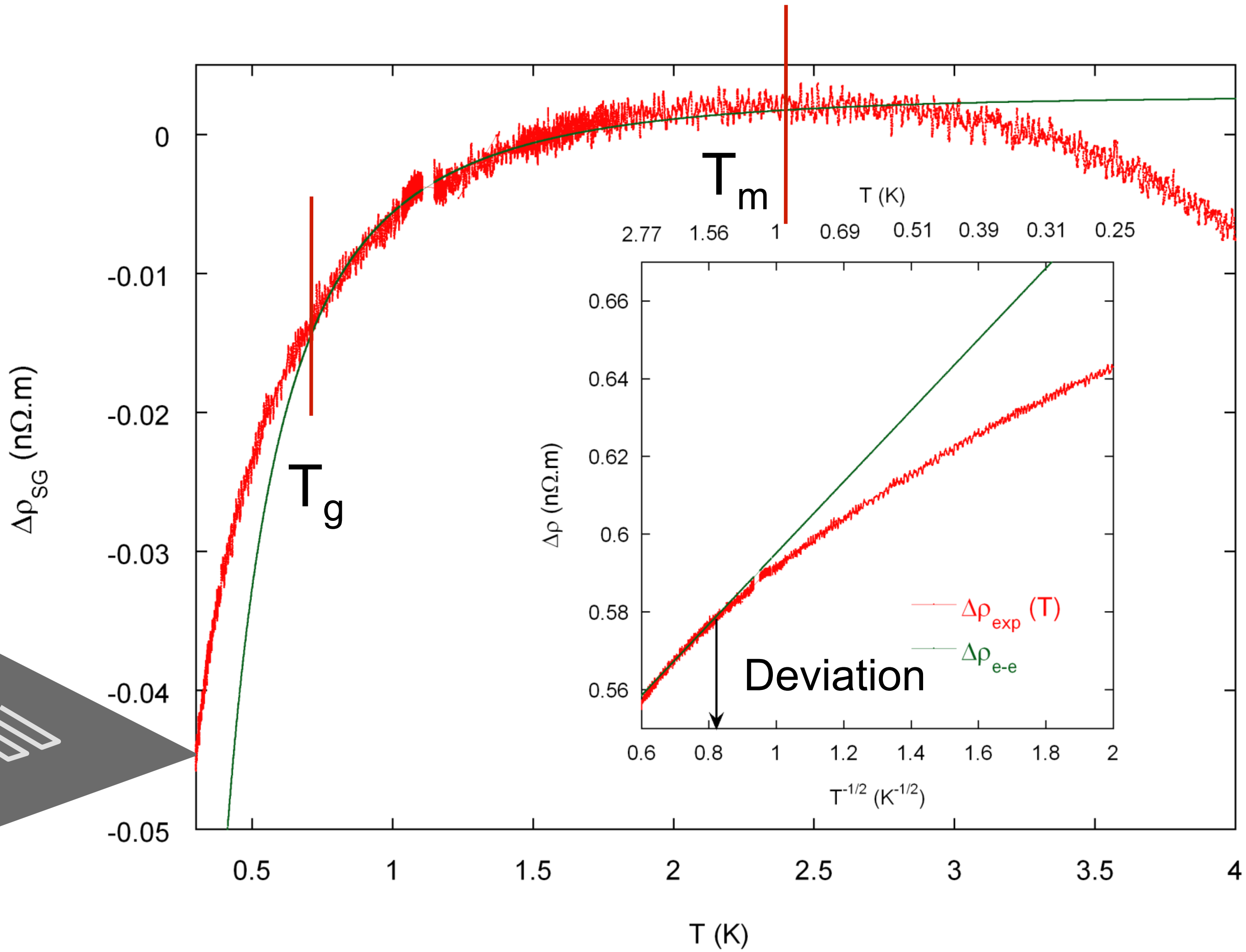
Ion implanted
400, 700 ppm
(T_g=0.5, 0.7K)
T_K=40mK

$T>T_g$ Kondo pairs

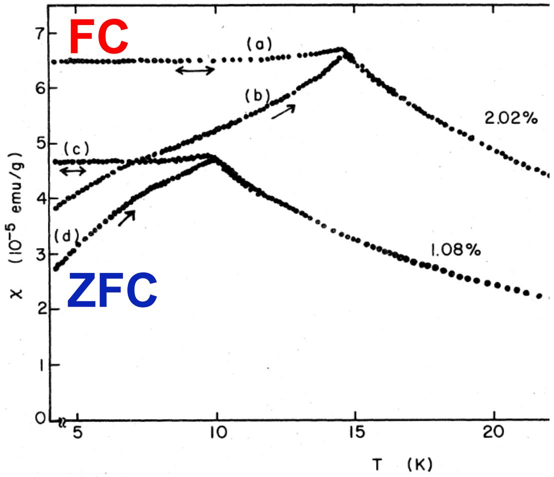
Vavilov Glazman PRB 2003



$$\Delta R_{SG}(T) = \frac{A}{\ln^2(T/T_K)}\left(1-\alpha_S\frac{T_g}{T}\right)$$



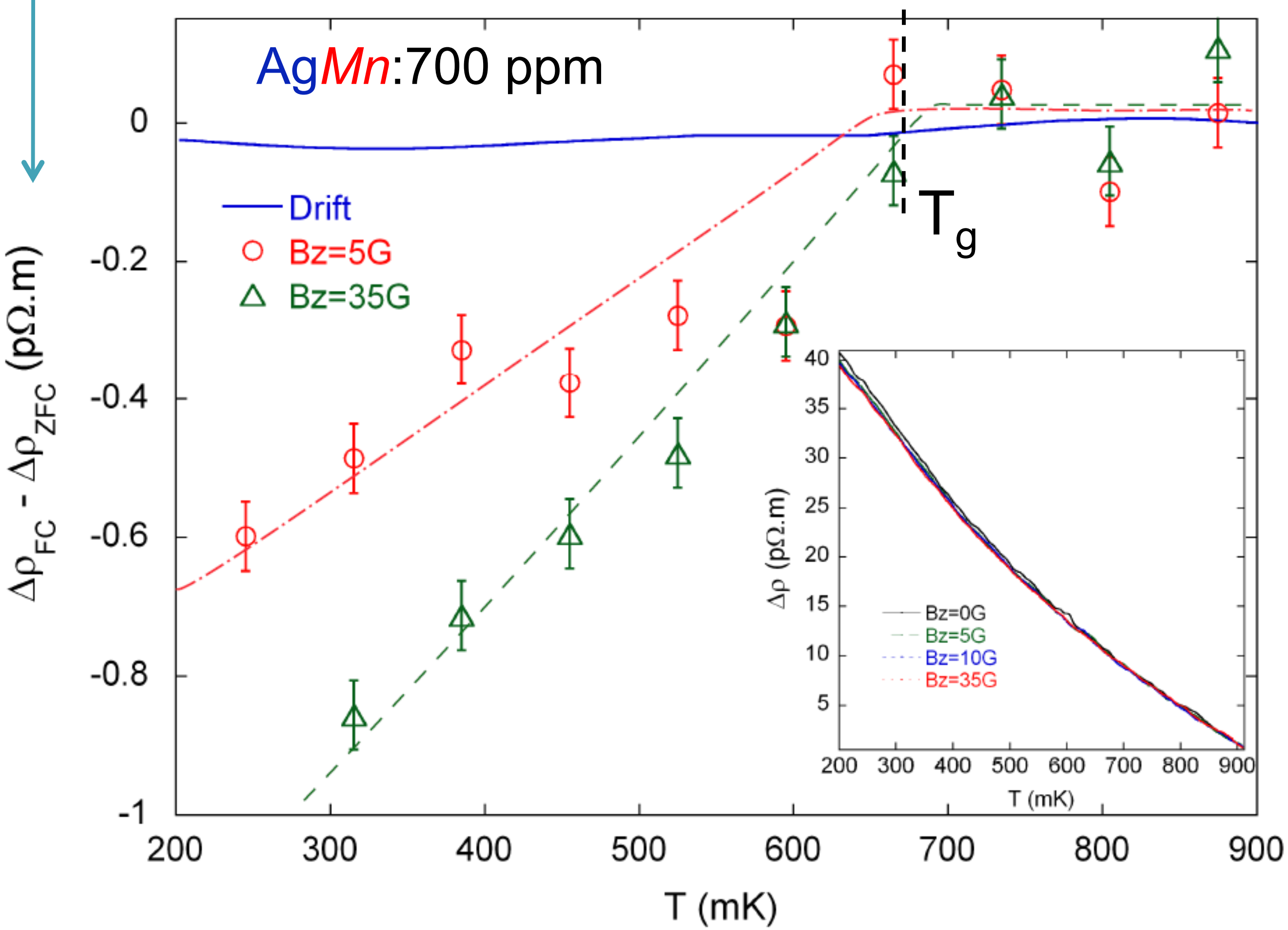
Where is Tg ?



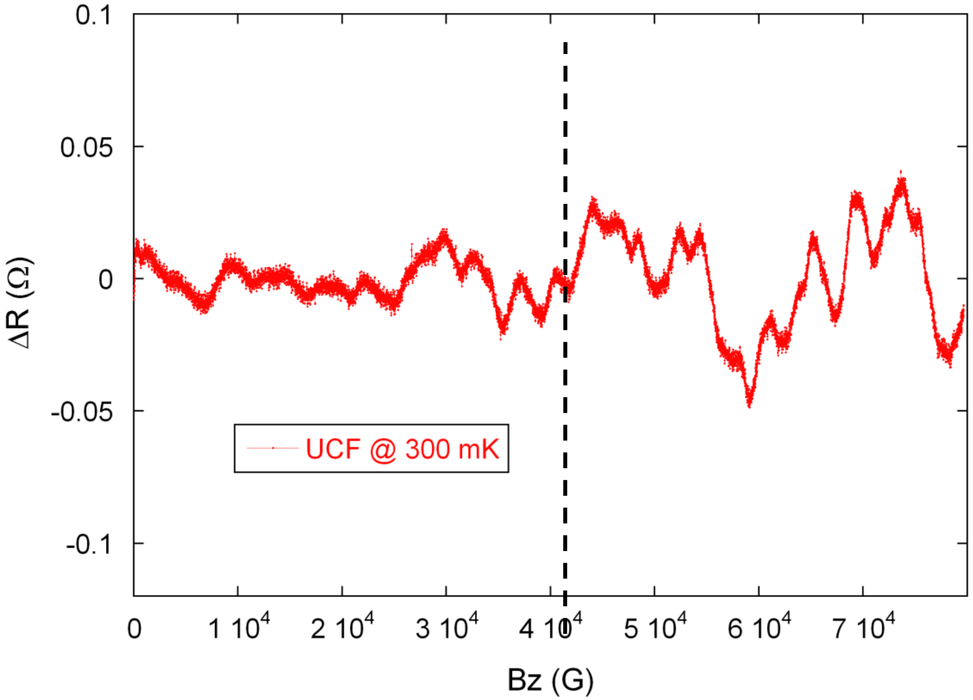
Nagata et al.1979

Noise (small R)

Small but observable remanence



UCF in the SG phase

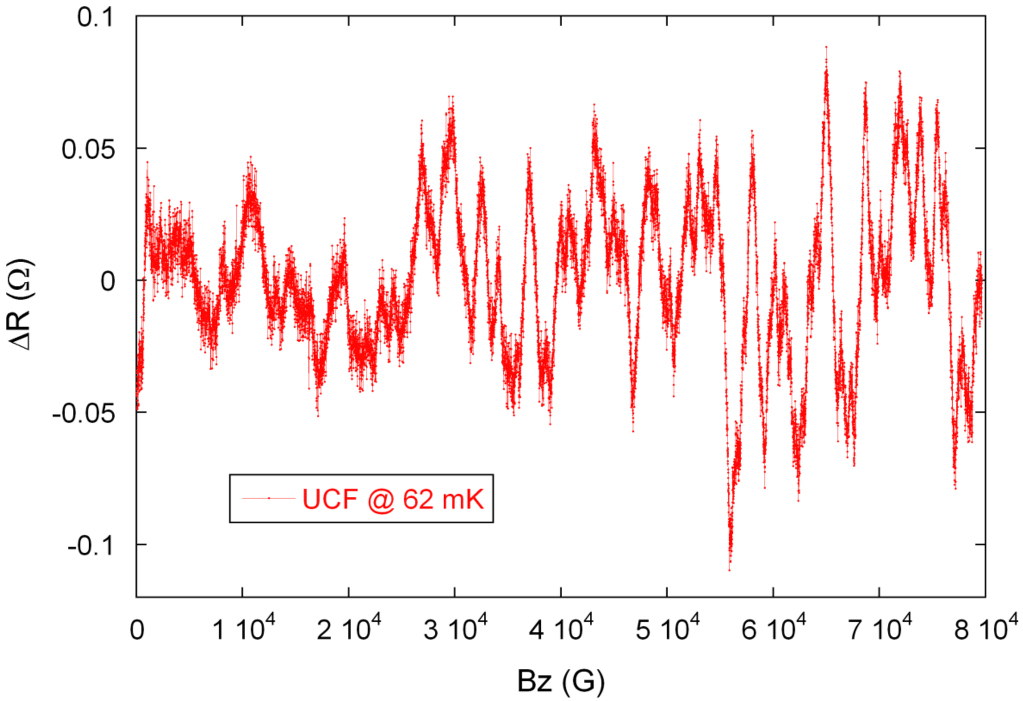


AgMn:700 ppm
(Tg≈700 mK)

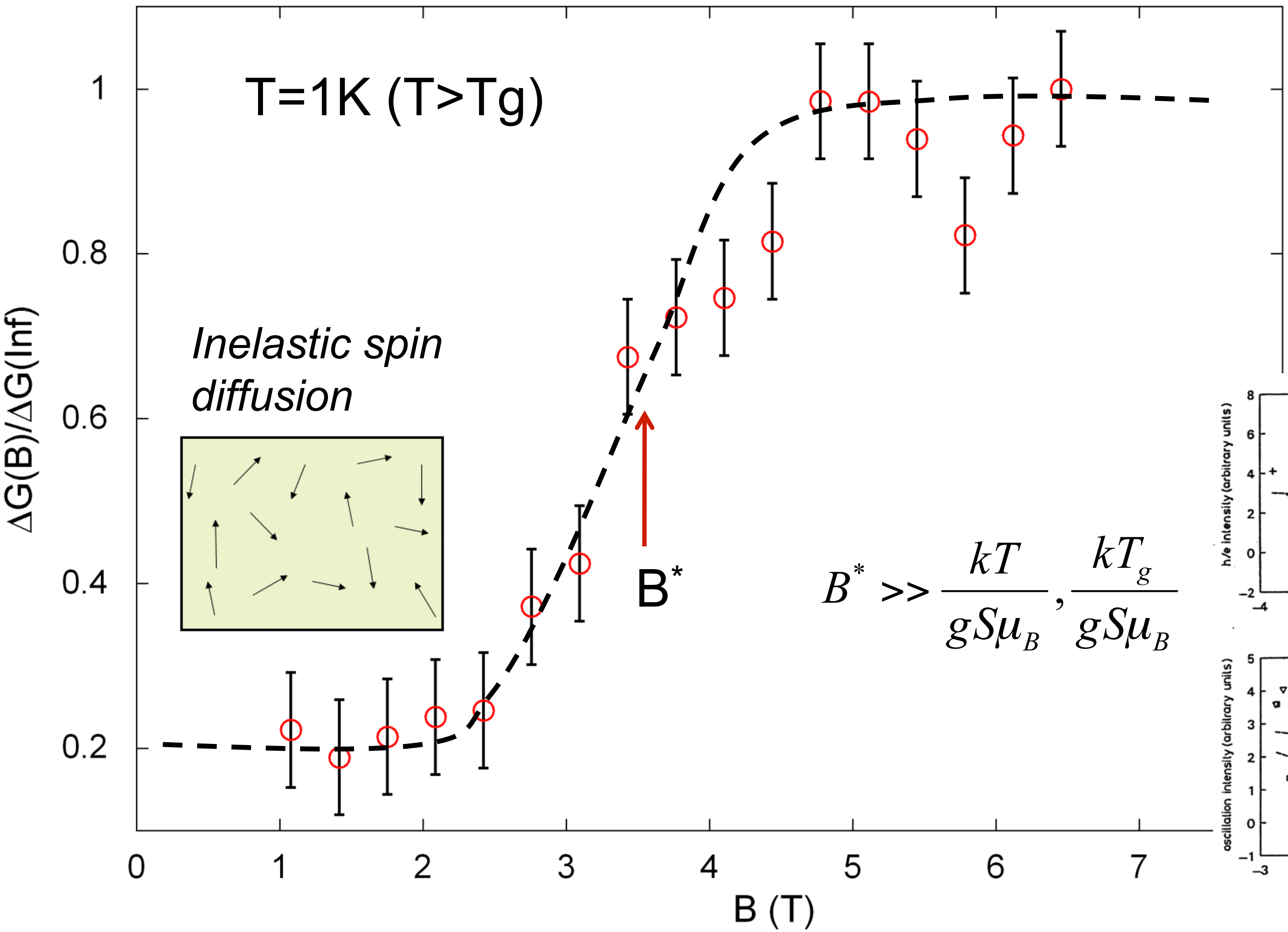
Amplitude increase with H

→ L_ϕ increases with H

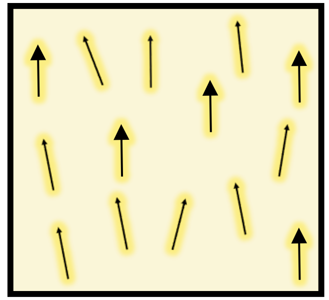
Two regimes :
0 – 4 T ; 4 – 8 T



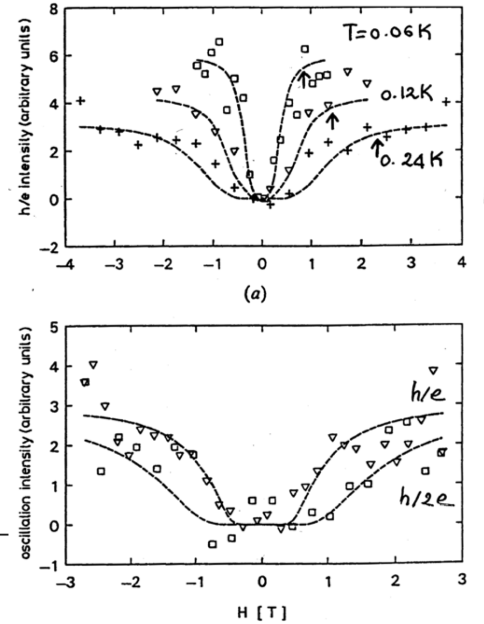
Spin polarization seen in UCF



$$B^* >> \frac{kT}{gS\mu_B}, \frac{kT_g}{gS\mu_B}$$



No spin flips

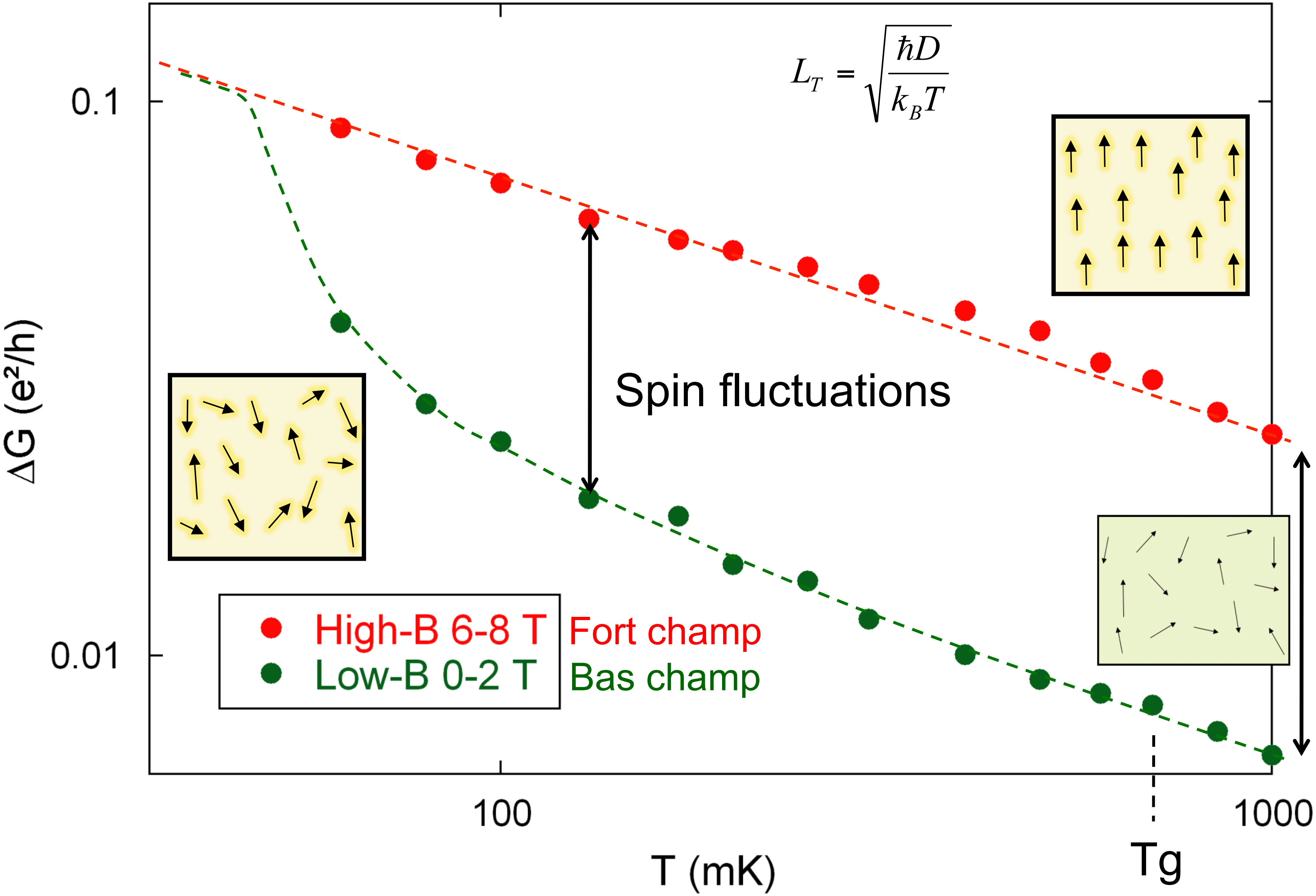


Benoît et al. 1992

L_Φ **increased** when Mn spins are polarized

Spin freezing in SG phase

$$\left\langle \delta g^2 \right\rangle_{\Delta B} = \frac{4\pi}{9} \frac{L_T^2 L_\varphi(T)}{L^3} \qquad L_T \le L_\varphi \le L$$



L_Φ in the SG phase

Low field
(validity?→later)

$$\delta g \approx \frac{4\pi}{9}\left(\frac{L_\Phi}{L}\right)^3, L_\varphi < L_T < L$$

$$\delta g \approx \frac{4\pi}{9}\frac{L_T^2 L_\Phi}{L}, L_T < L_\varphi < L$$

$$\frac{1}{L_\Phi^{\ 2}} = \frac{1}{L_{sf}^{\ 2}} + \frac{1}{L_{e-e}^{\ 2}}$$

AAK

Altshuler
Aronov
Khemelnitskii
1982

$L_{e-e} \approx 4\mu m$

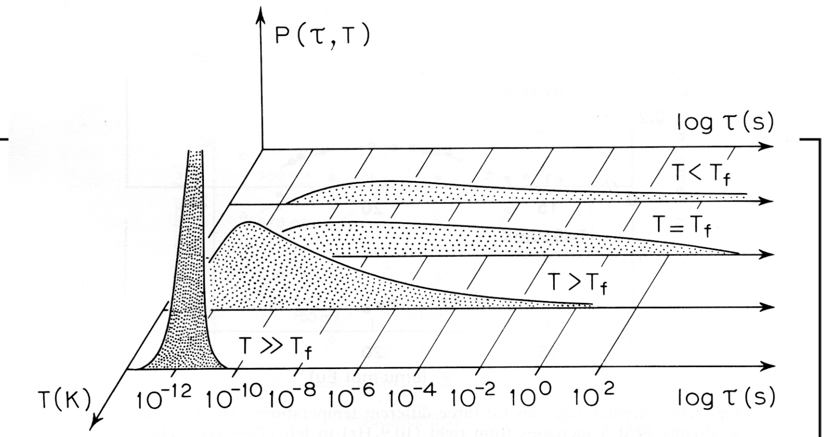
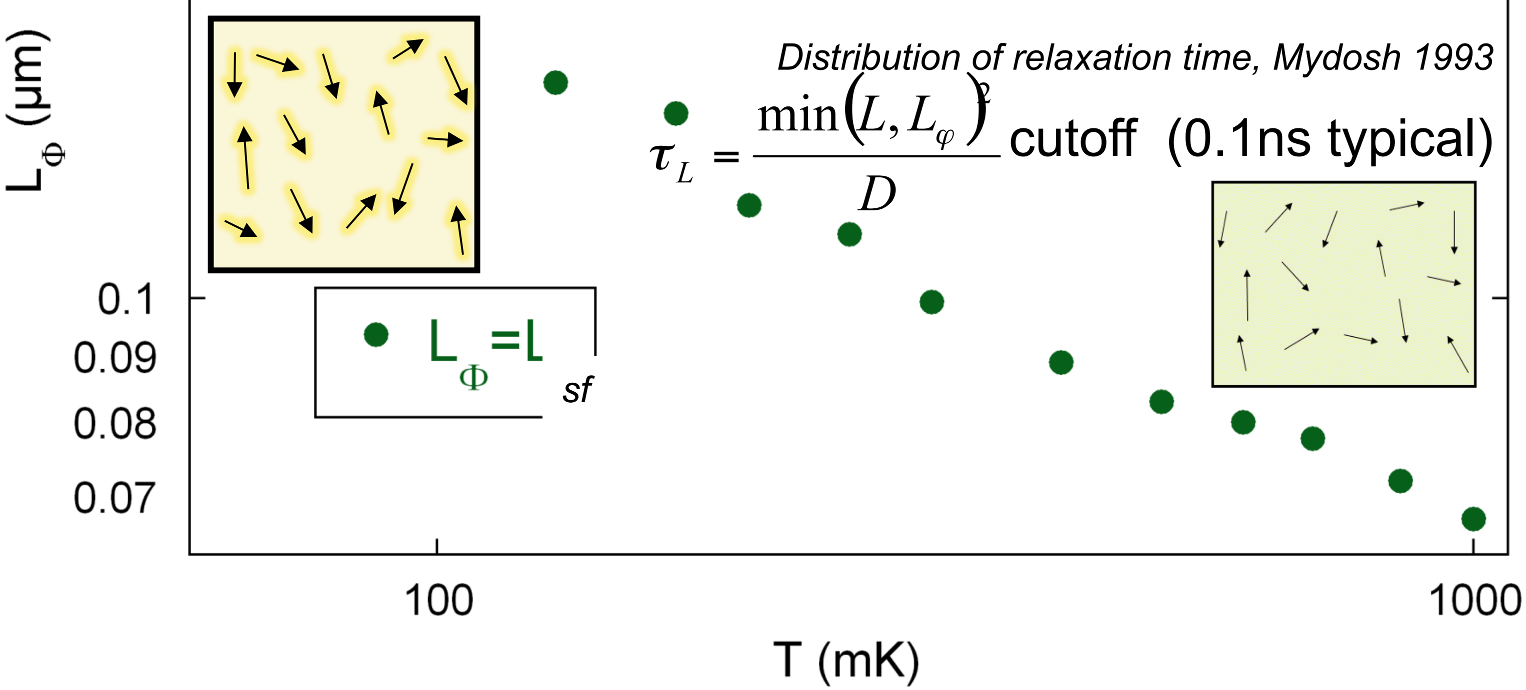


Fig. 3.19 Schematic representation of the probability distribution for spin relaxation times with its evolution as a function of temperature.

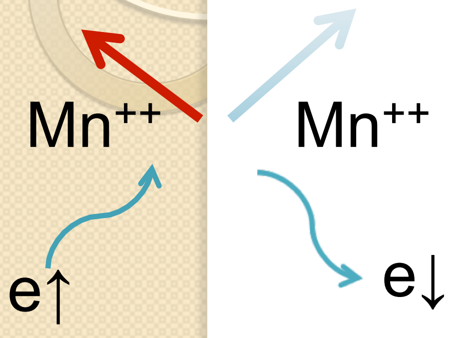
Distribution of relaxation time, Mydosh 1993

$$\tau_L = \frac{\min\left(L, L_\varphi\right)^2}{D}$$ cutoff (0.1ns typical)



From spin flips to « free » spins

Assumption: single spin-flip decoherence → Nagaoka-Suhl Kondo spin-flip (PR 138 1965)



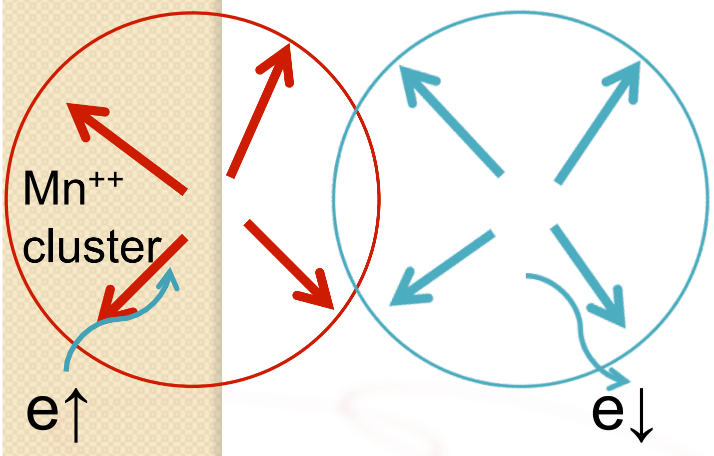
imp. conc.

B=0 $$\frac{\hbar}{\tau_{sf}} = \pi \frac{c_{Mn}}{\nu} \frac{S(S+1)}{\pi^2 S(S+1) + \left(2 \ln\left(\frac{T}{T_K}\right)\right)^2}$$

Other possibilities not considered

B≠0 $$\frac{1}{\tau_{sf}(B)} = f\left(\frac{B}{T}\right)\frac{1}{\tau_{sf}}$$

Vavilov Glazman PRB 2003



$$c_{Mn}(T) = c_{Mn}\int f\left(\frac{B_{loc}}{T}\right)P(B_{loc})d^d B_{loc}$$

analysis→ later

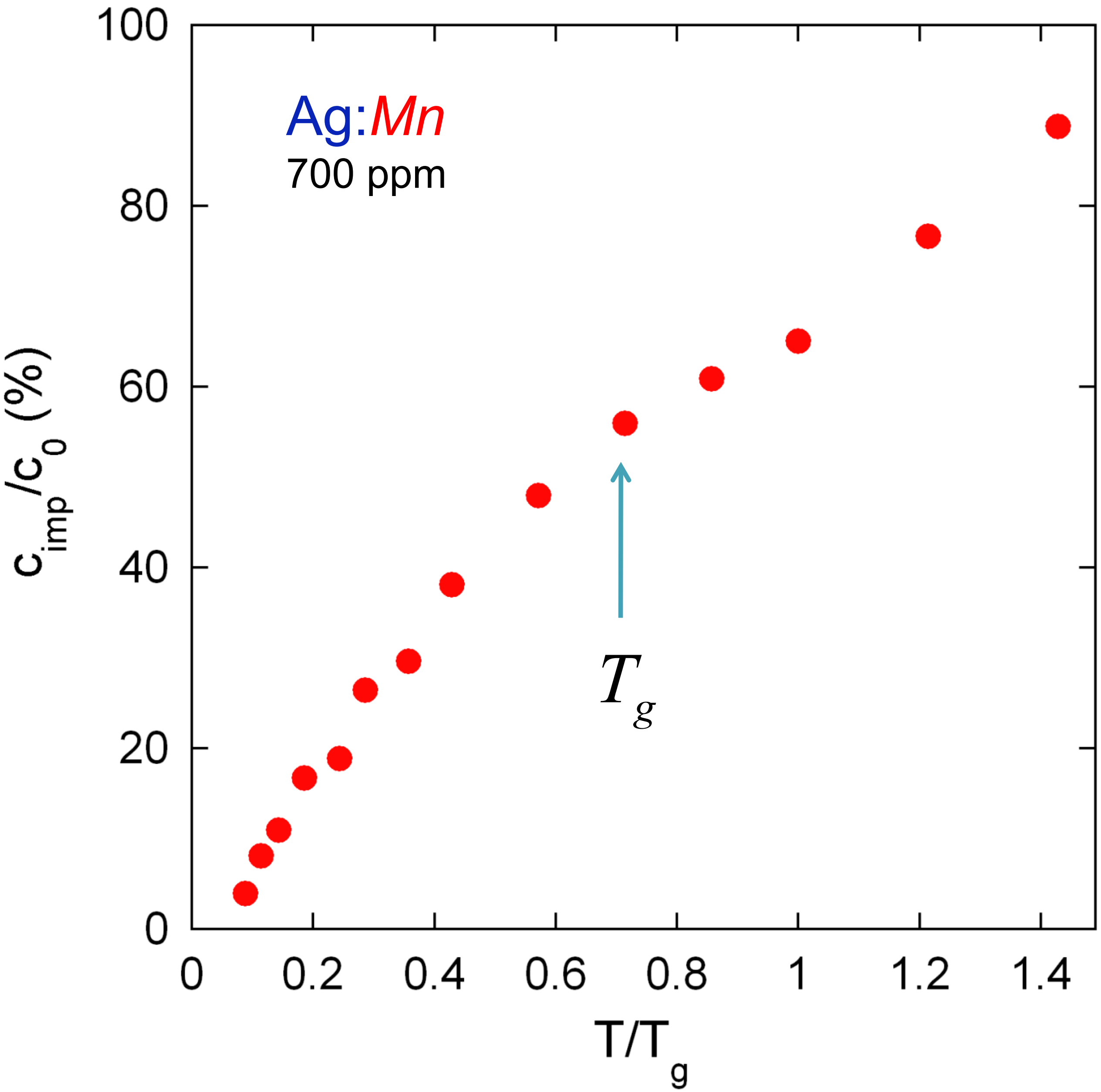
or larger objects (magnons)

Spins contributing to L_ϕ

T^{Ag}_K=40 mK

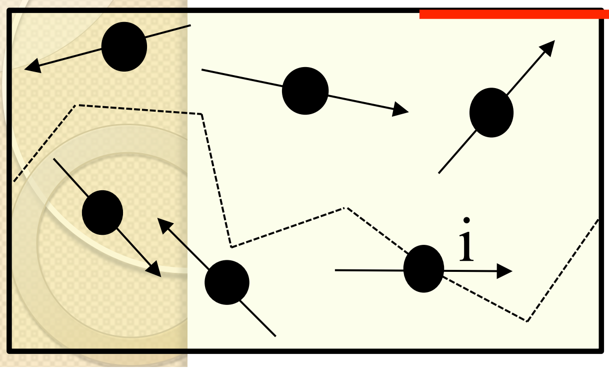
$$\langle \delta g^2 \rangle \to L_\varphi \approx \sqrt{D\tau_{sf}} \to c_{Mn}(T)$$

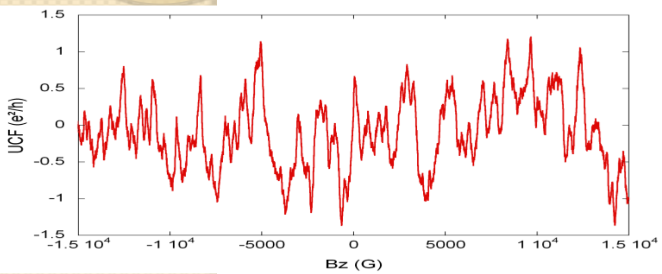
"slow" freezing



Measuring correlations

Configuration 1





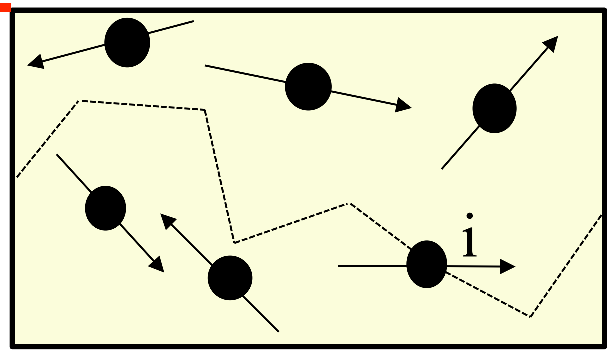
Frozen configuration

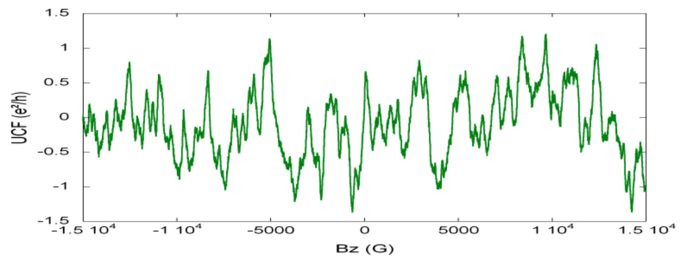
$$C_{(1,2)} = \left\langle \delta g^{(1)}(B) . \delta g^{(2)}(B) \right\rangle$$

C = 1

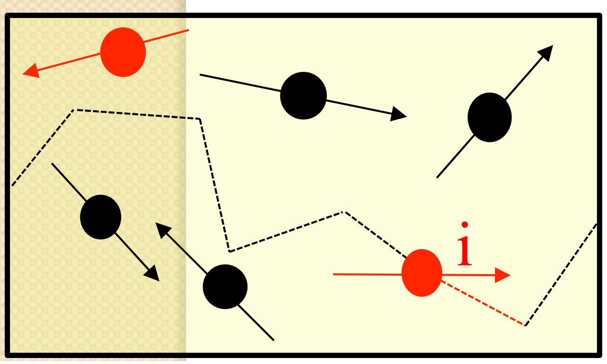
Correlation coefficient

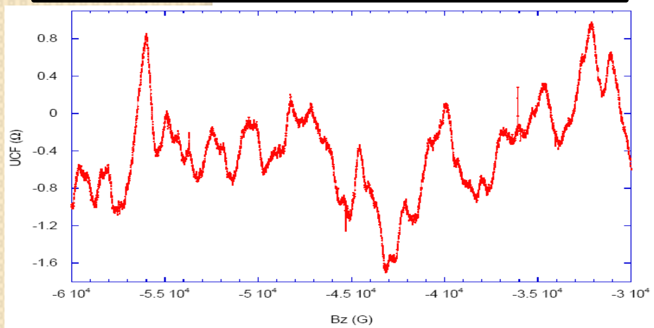
Configuration 2





Configuration 1





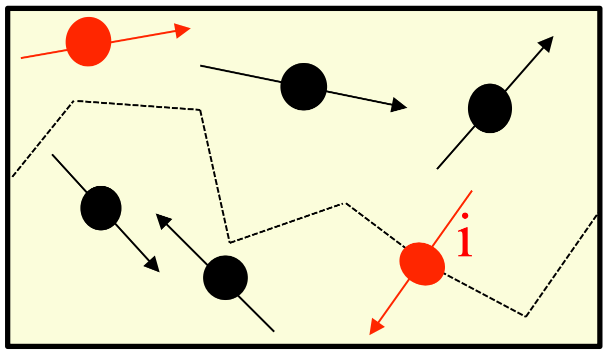
configuration change (T, B,…)

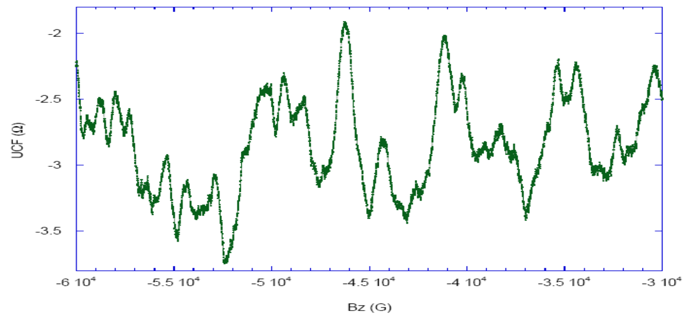
$$q_{12} = \frac{1}{N} \sum_{i=1}^{N} \vec{S}_i^{(1)} . \vec{S}_i^{(2)}$$

Spin configuration overlap

0 < C < 1

Configuration 2



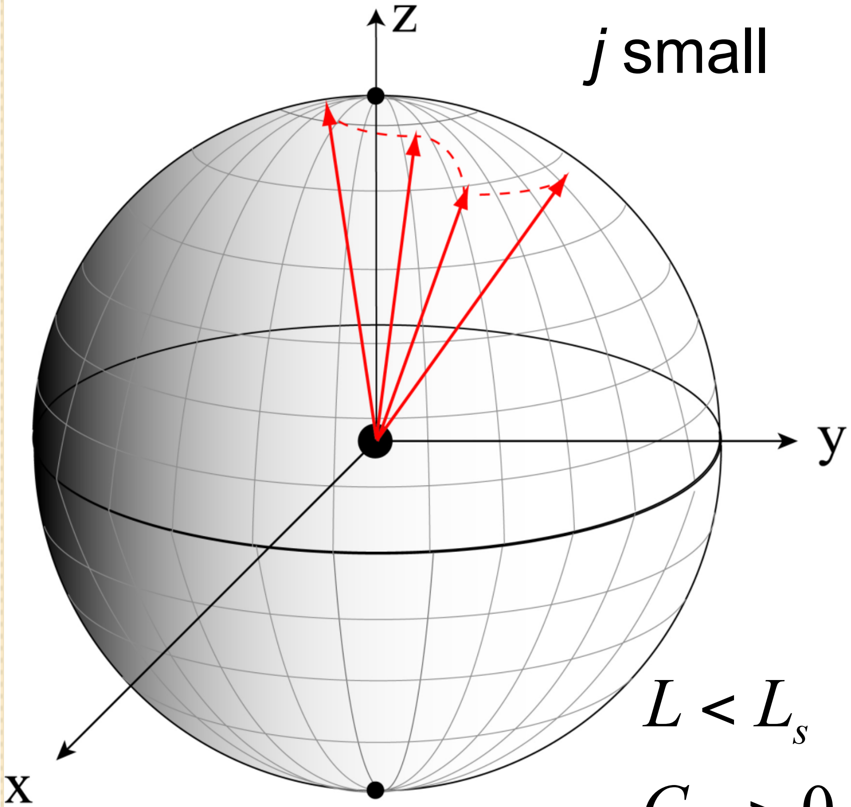


The spin diffusion length

$$q_{12} = \frac{1}{N}\sum_{i=1}^{N}\vec{S}_i^{(1)}.\vec{S}_i^{(2)} = 0$$

$$H_{e-Mn} = -j\vec{\sigma}\bullet\vec{S}$$

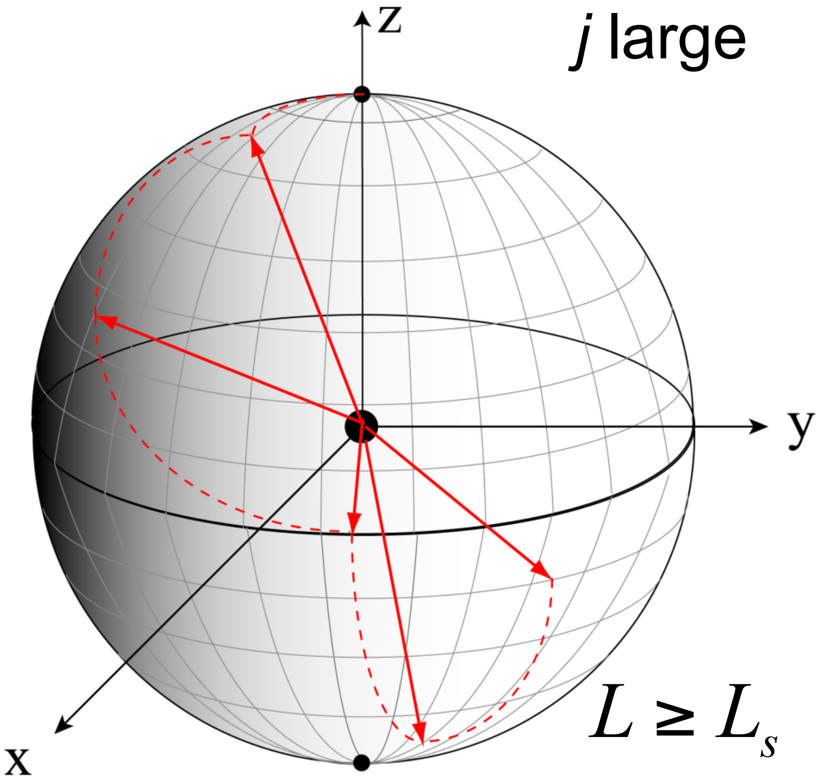
$$\xrightarrow{NOT} C_{(1,2)} = \left\langle \delta g^{(1)}(B)\delta g^{(2)}(B)\right\rangle = 0$$



$L < L_s$

$C_{12} > 0$

$\forall q_{12}$

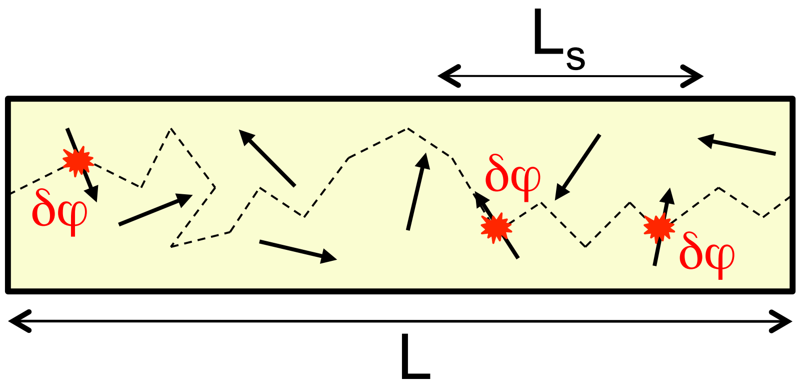


$L \geq L_s$

$C_{12} \propto q_{12}$

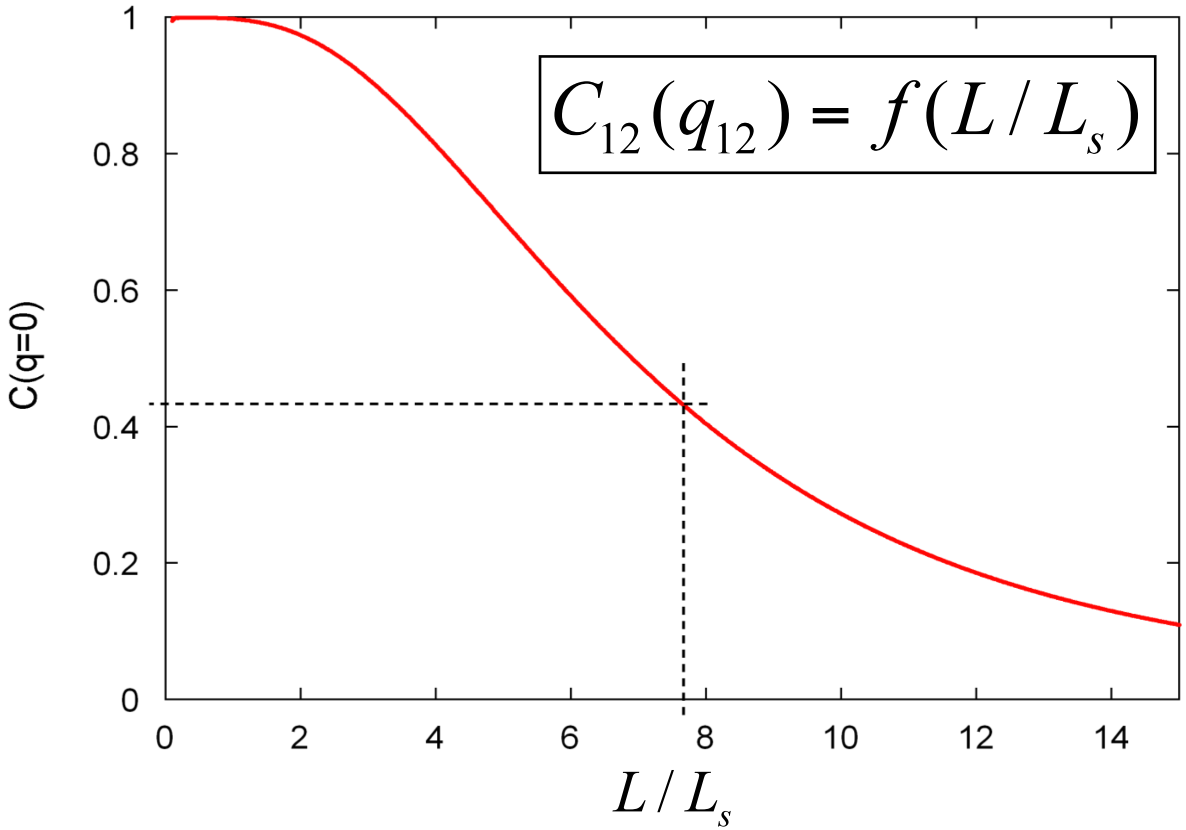
Use C_{12} to measure q

$$q_{12} = \frac{1}{N}\sum_{i=1}^{N} \vec{S}_i^{(1)}.\vec{S}_i^{(2)}$$



- q=1 : Frozen disorder
- q=0: diff. configurations

Required: wires longer than L_s



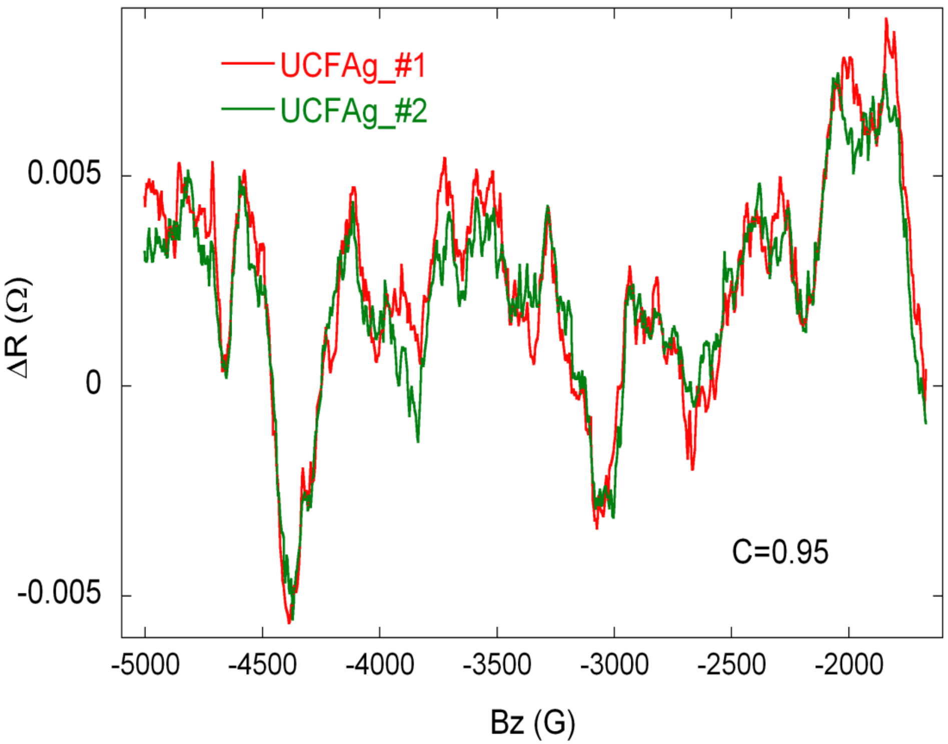
D. Carpentier et E. Orignac PRL 2008

Sensitivity to q_{12}

Temperature cycling

Ag 0 ppm

T=15K 15h

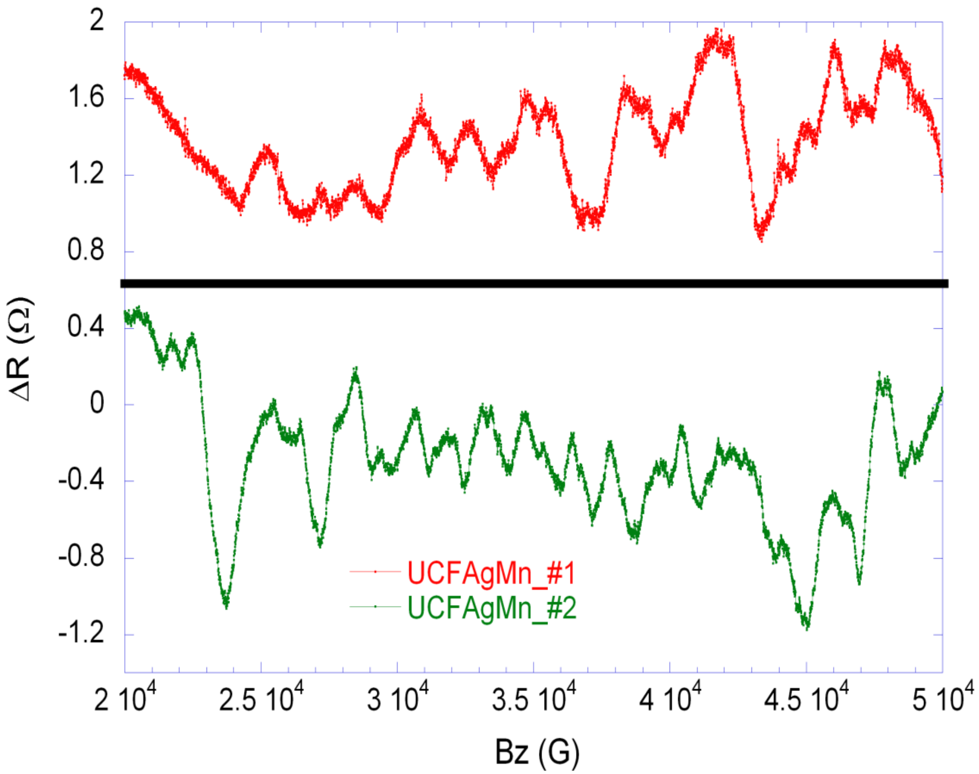


$C_{12} = 0.95$

Ag*Mn:400 ppm*

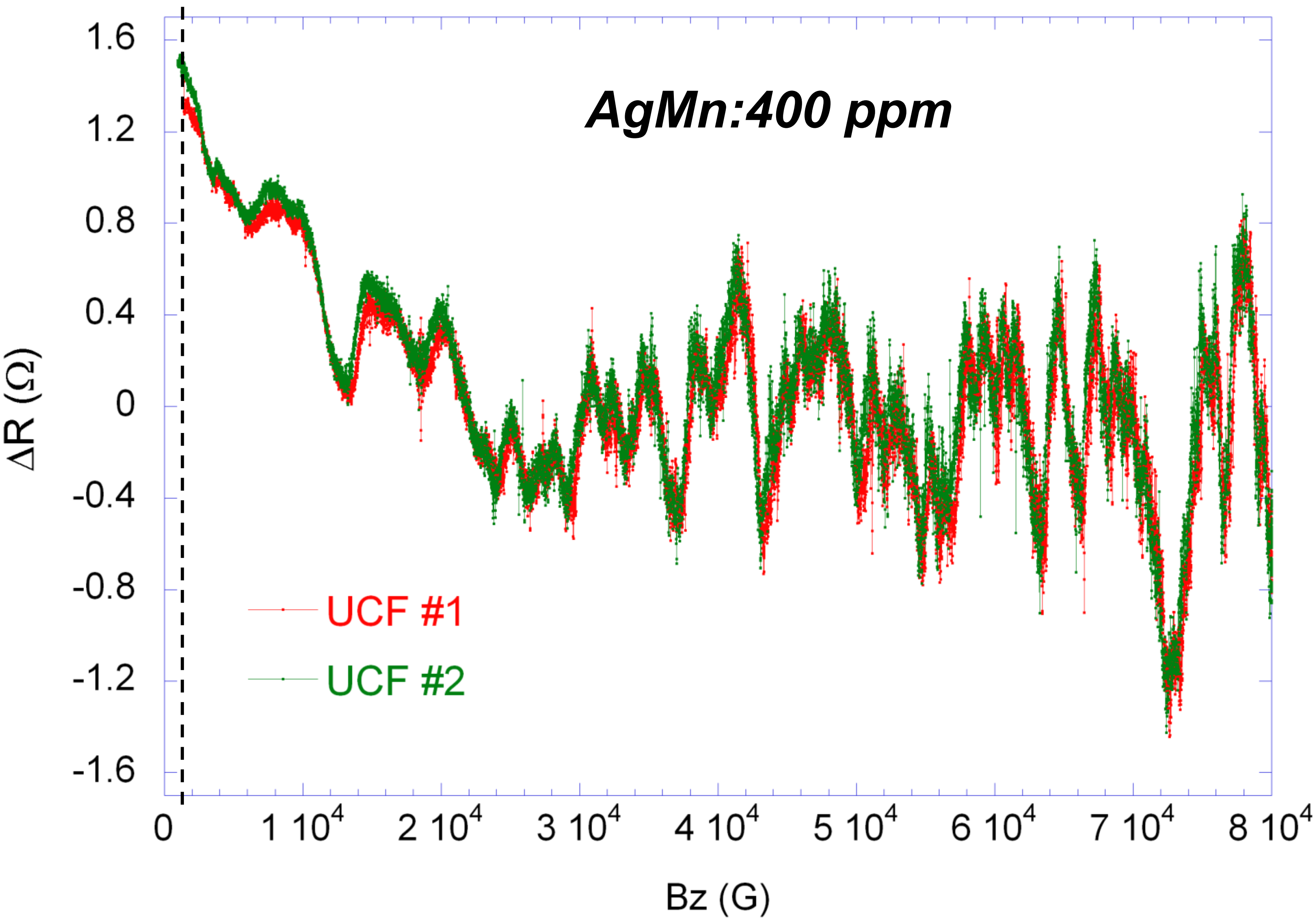
($T_g \approx 400$mK)

T=15K



$C_{12} \approx 0.2$

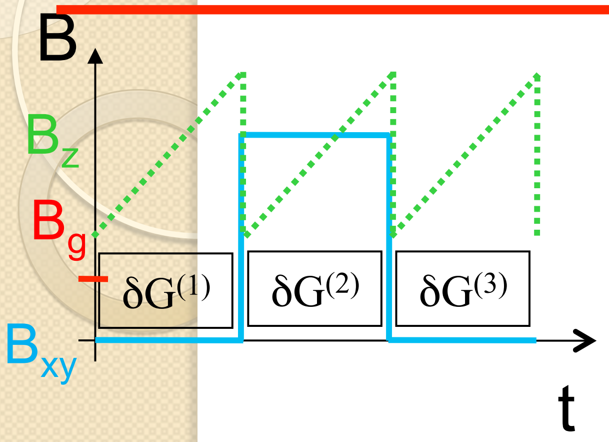
Adiabatic deformation of q with field (I)



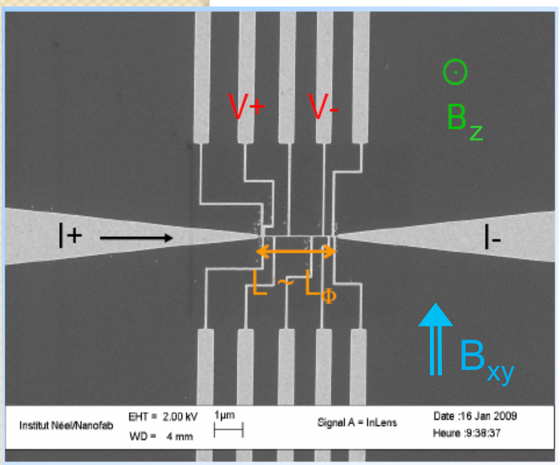
$T<T_g$

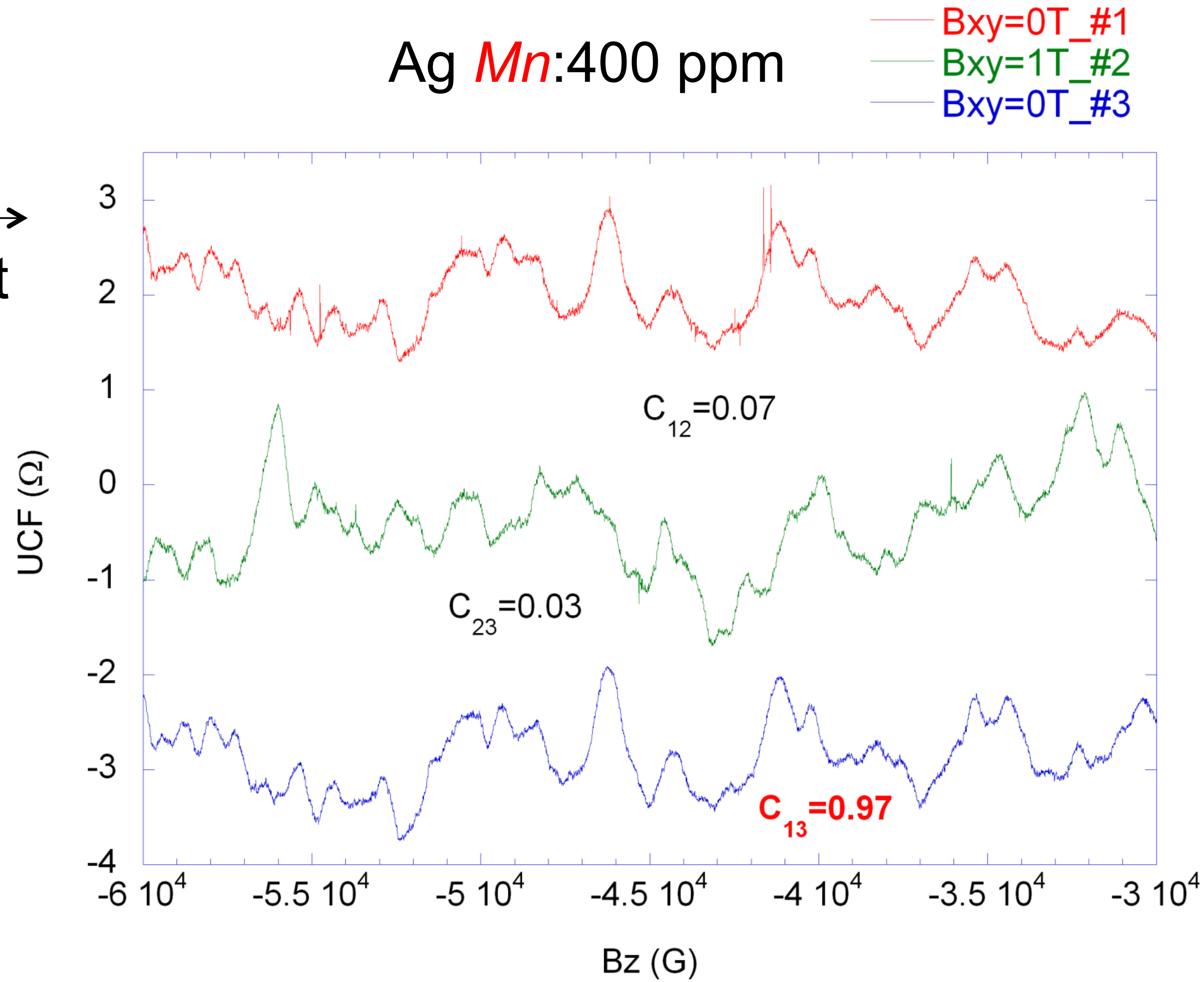
Little to no change in magnetic configuration

Elastic deformation of q with ⊥ field (2)

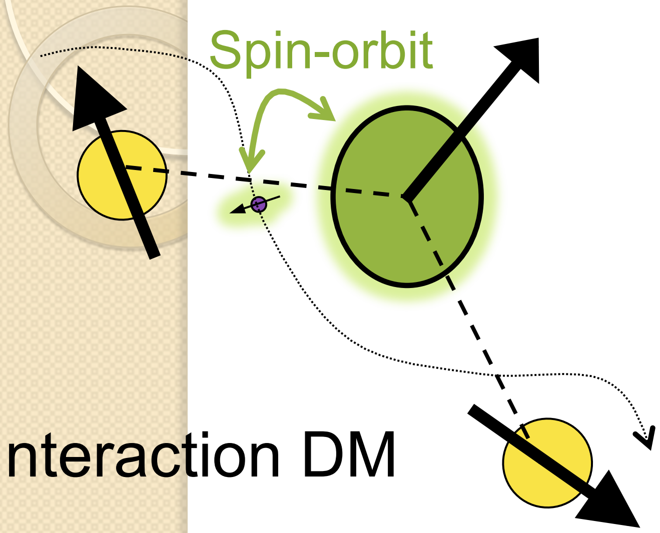


$B_g \approx 0.1$T





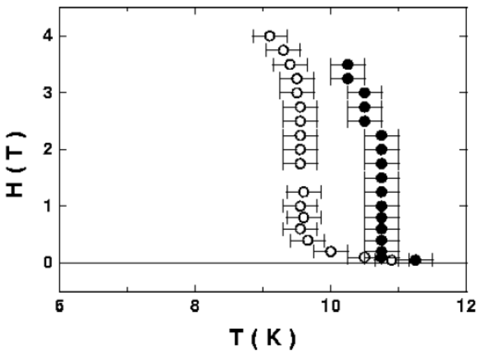
Role of anisotropy ?

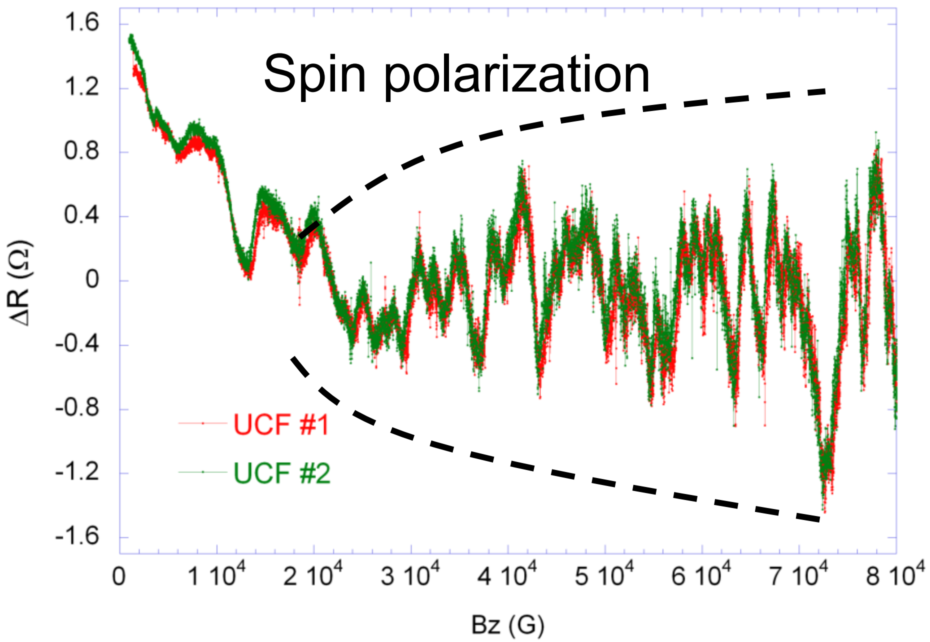


Interaction DM

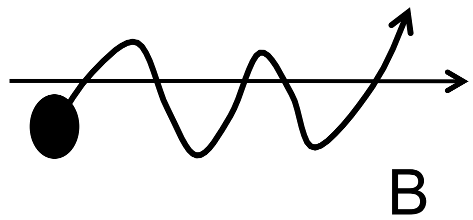
Random anisotropy

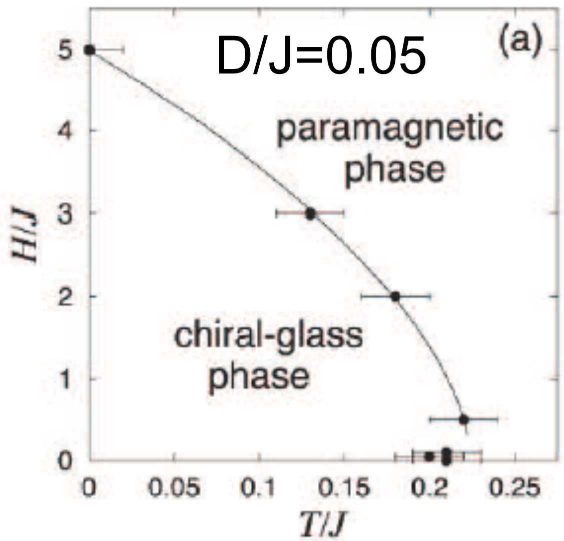
Petit-Campbell





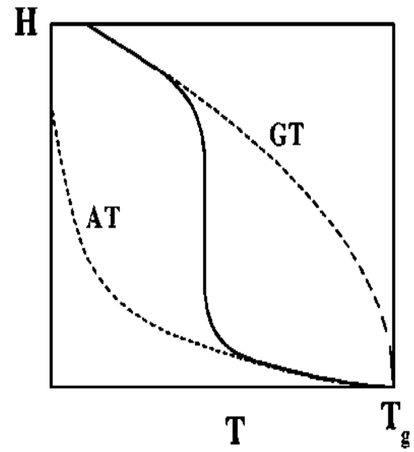
System does not leave the SG phase



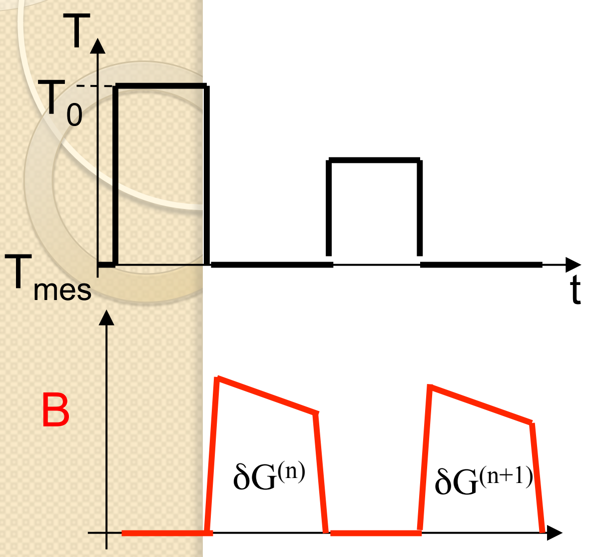


H. Kawamura, (PRL 1998,2001,2004), PRB 2004.

Kotliar and Sompolinsky 1984

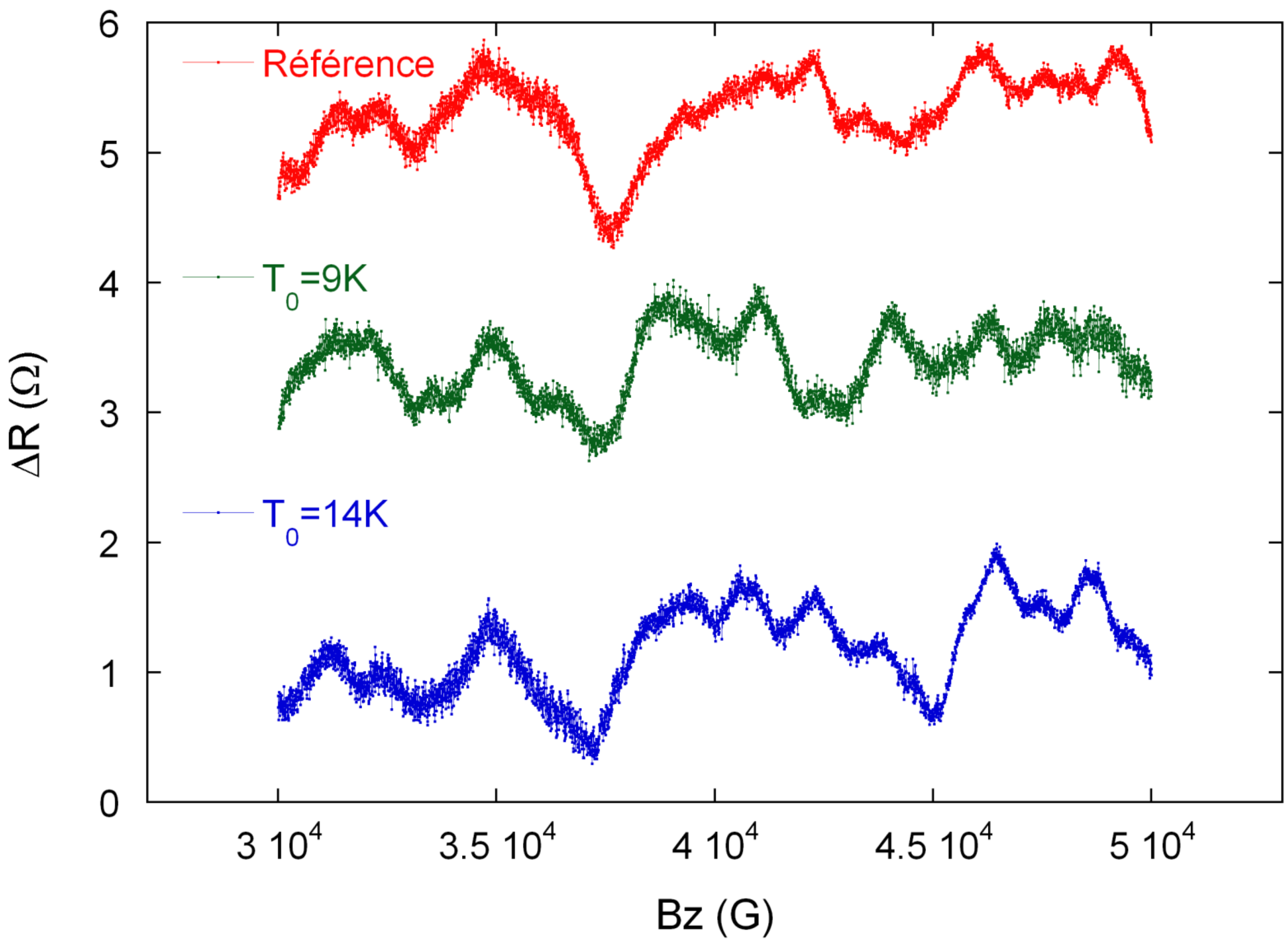


Decorrelations above Tg



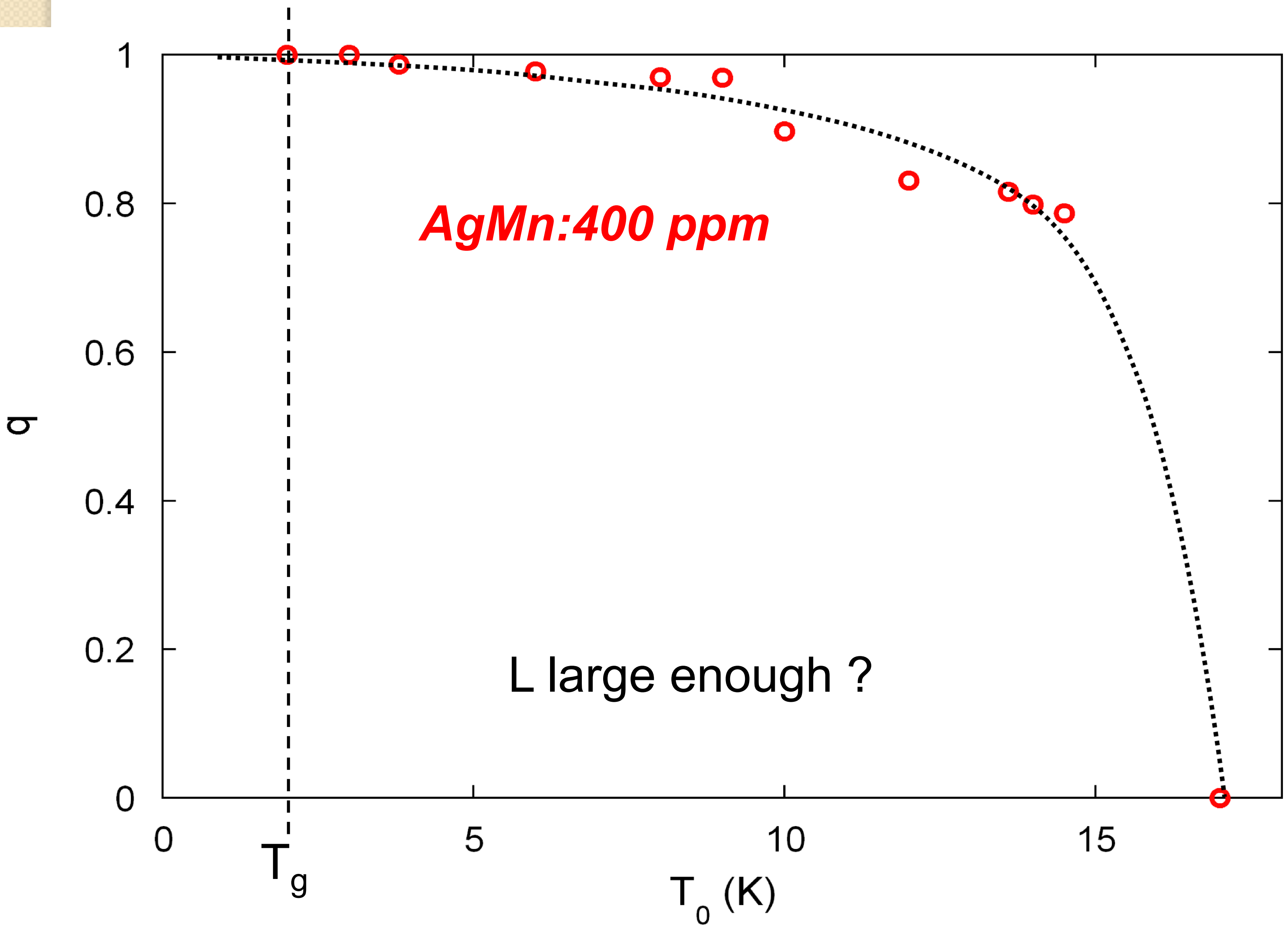
$C_{(n,n+1)}$ measured

AgMn:400 ppm



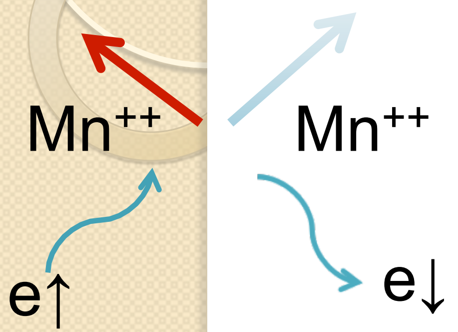
decorrelations

Experimental measurements for q



Discussion: from $L_\Phi(T)$ to width of P(h)

Single spin flip



$$H \to h_{ex} + h_a + H$$

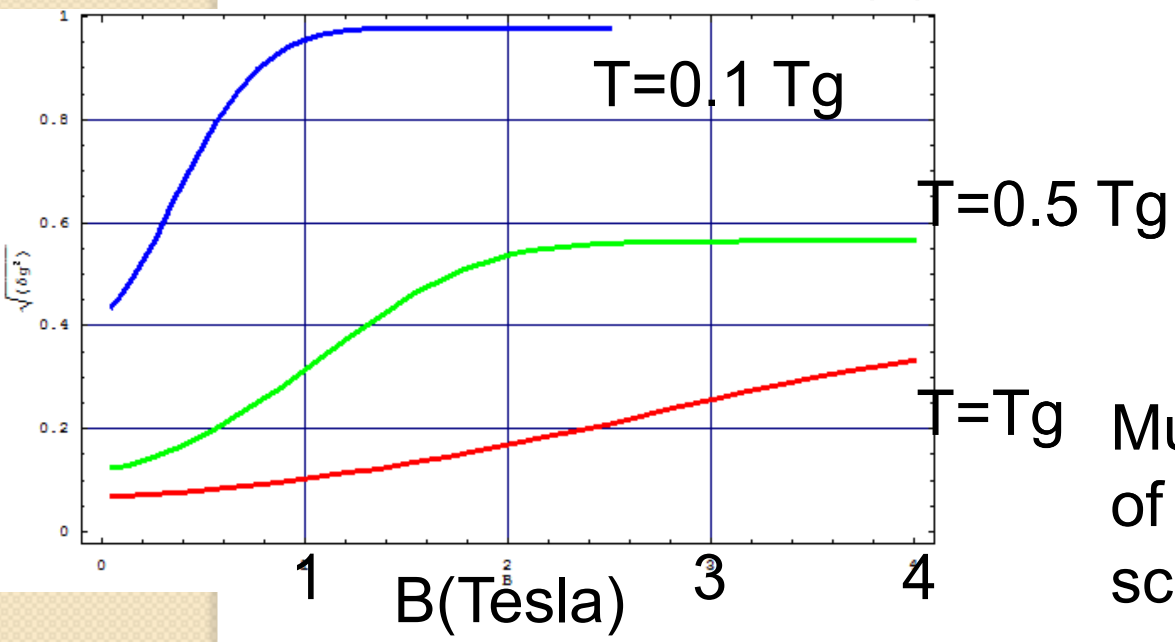
Vavilov Glazman PRB 2003

Fluctuating Kondo impurities in a field

$$\frac{\hbar}{\tau_{sf}} \to \Gamma\left(u = \frac{\varepsilon}{k_B T}, v = \frac{gS\mu_B H}{k_B T}\right) = \left(1 - \frac{\langle S_Z^2\rangle_v + \langle S_Z\rangle \tan(u + v/S)}{S(S+1)}\right)\frac{\hbar}{\tau_{sf}}$$

$$\langle \delta g^2 \rangle = \pi \frac{L_T^2}{L^3}\int \frac{d\varepsilon}{\cosh^4\left(\frac{\varepsilon}{k_B T}\right)} \frac{1}{\sqrt{\frac{1}{L_{sf}^2\left(\frac{\varepsilon}{kT}, \frac{gS\mu_B H}{kT}\right)} + \frac{1}{L_\varphi^2}}}$$

Play with different model for P(h)



Need to multiply
Field scale by 5-6

Much broader distribution of local fields compared to Tg scale

Conclusions on UCF in SG

- Observable (CuMn, AgMn, CdMnTe)
- Sensitive to SG configuration
- reveal surprising robustness to applied fields
- Spin diffusion length key parameter for C(q) measurements
- All data consistent with very broad distribution of local fields on scales >> Tg (GT line never reached)

Open issues

- How many spins need to flip to drive C(q) to zero ?
- Pin L_s better
- reconciliation with macroscopic measurements (χ, C)

→ films