Complementary aspects of MuSR and other experimental methods

Tomo Uemura, Columbia University

Spin Glasses AuFe and CuMn

$La_2CuO_{4.12}$, $(La,Nd,Sr)_2CuO_4$

$Sr_4V_2O_6Fe_2As_2$, $Sr_4Sc_2O_6Fe_2As_2$

MnSi under applied pressure

Muon-spin relaxation in *Au*Fe and *Cu*Mn spin glasses

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(Received 22 June 1984)

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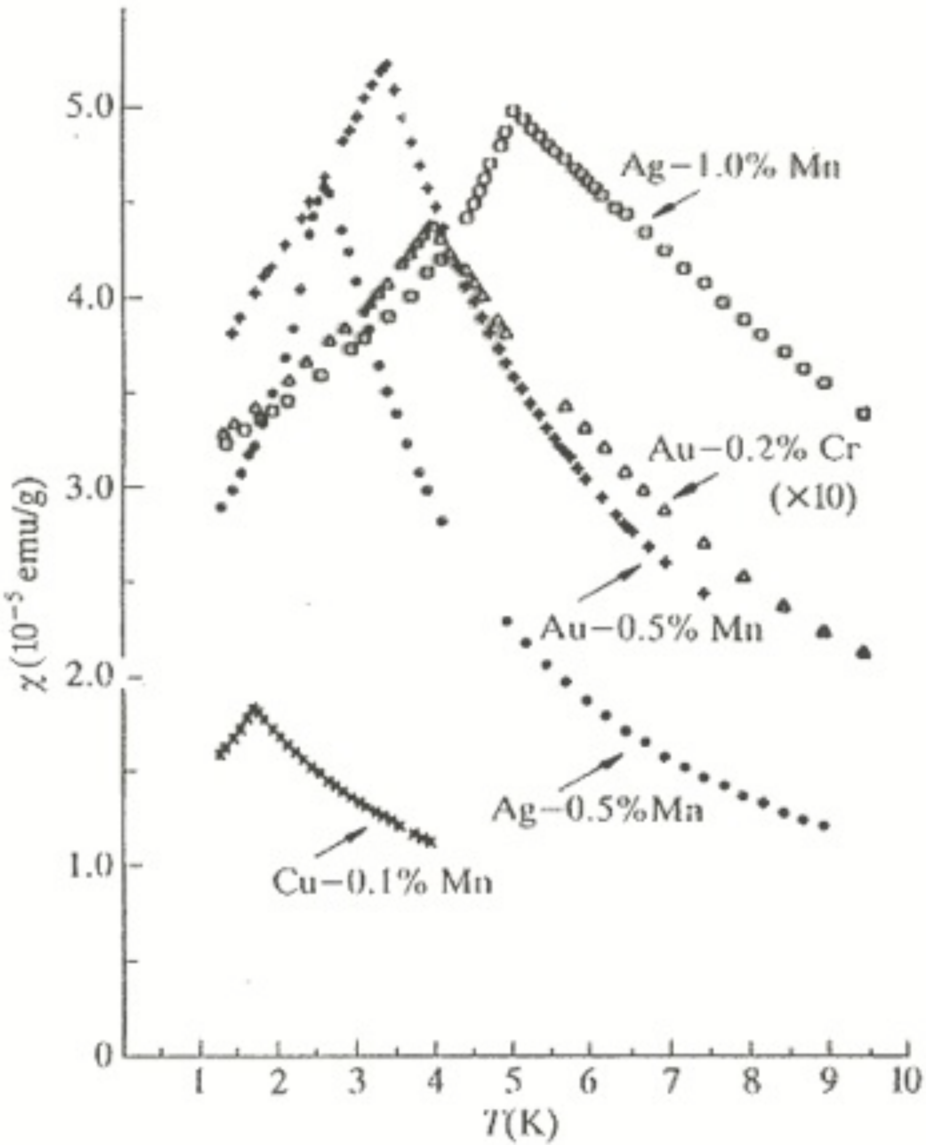
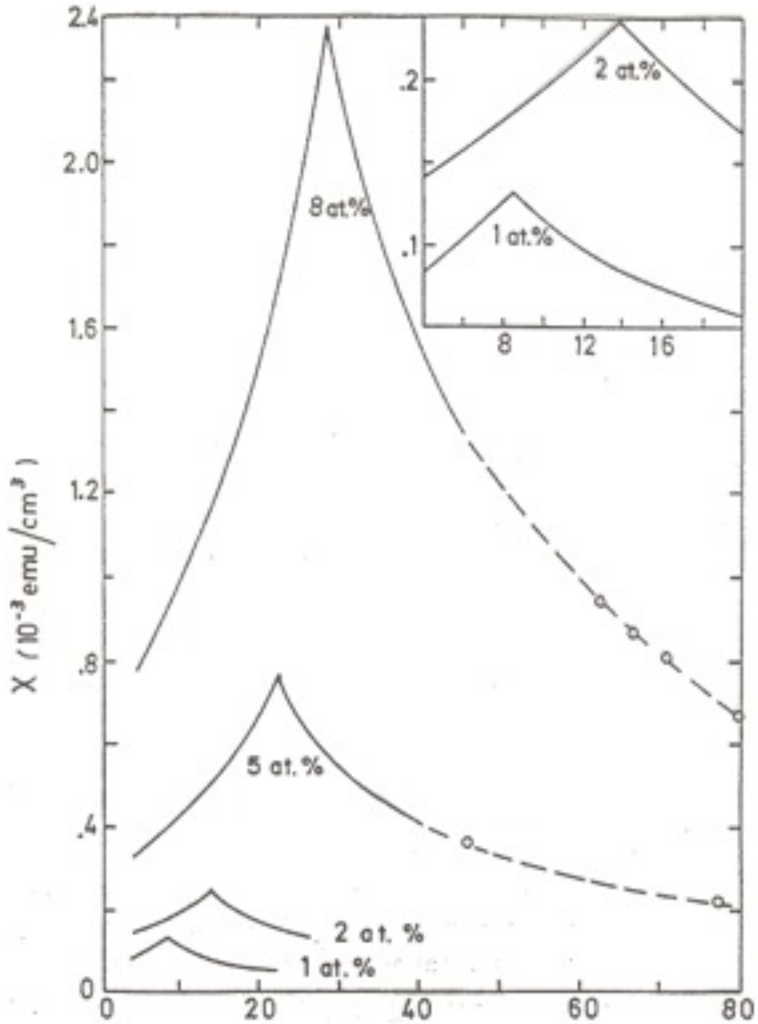
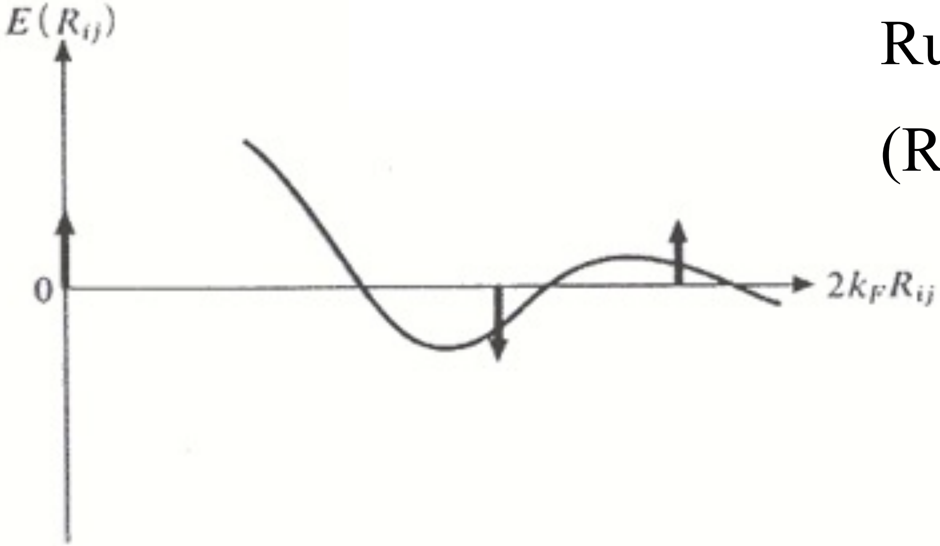

5.0
4.0
3.0
2.0
1.0
0
1
2
3
4
5
6
7
8
9
10
T(K)
χ (10⁻⁵ emu/g)
Ag−1.0% Mn
Au−0.2% Cr
(×10)
Au−0.5% Mn
Ag−0.5%Mn
Cu−0.1% Mn

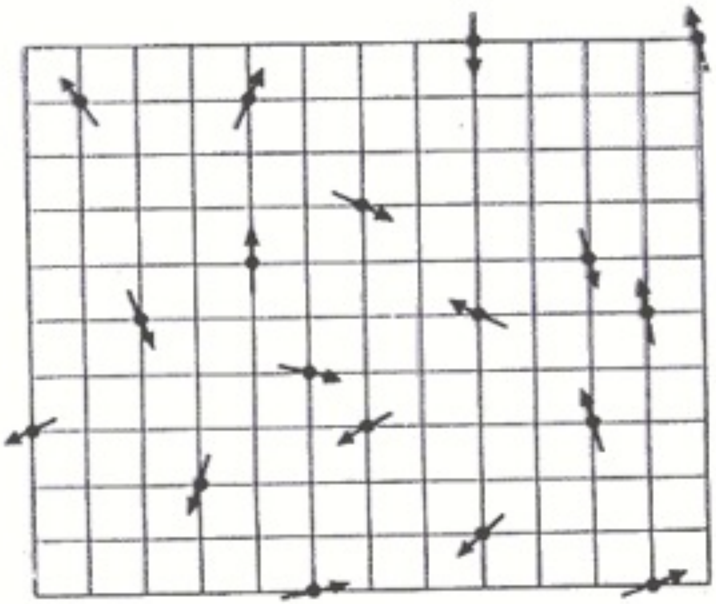

2.4
2.0
1.6
1.2
.8
.4
0
0
20
40
60
80
χ (10⁻³ emu/cm³)
8 at.%
5 at.%
2 at. %
1 at.%
.2
.1
8
12
16
2 at.%
1 at.%

T (K)

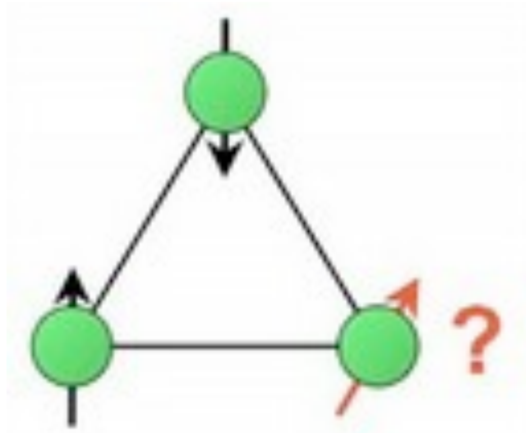


Ruderman-Kittel-Kasuya-Yoshida

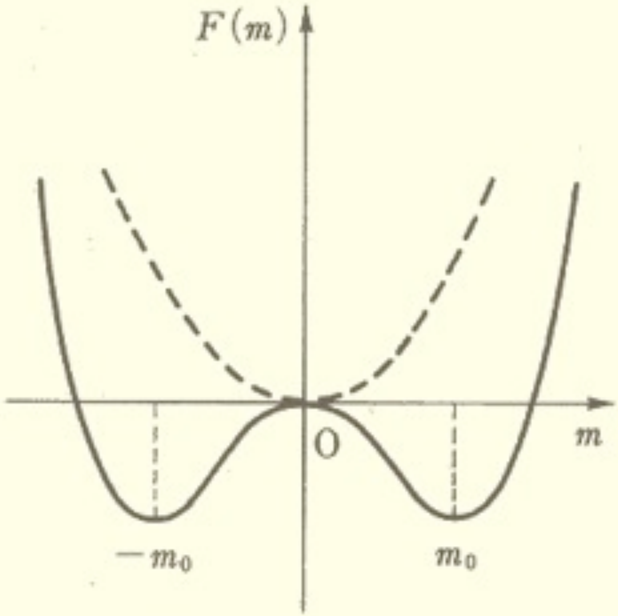
(RKKY) interaction



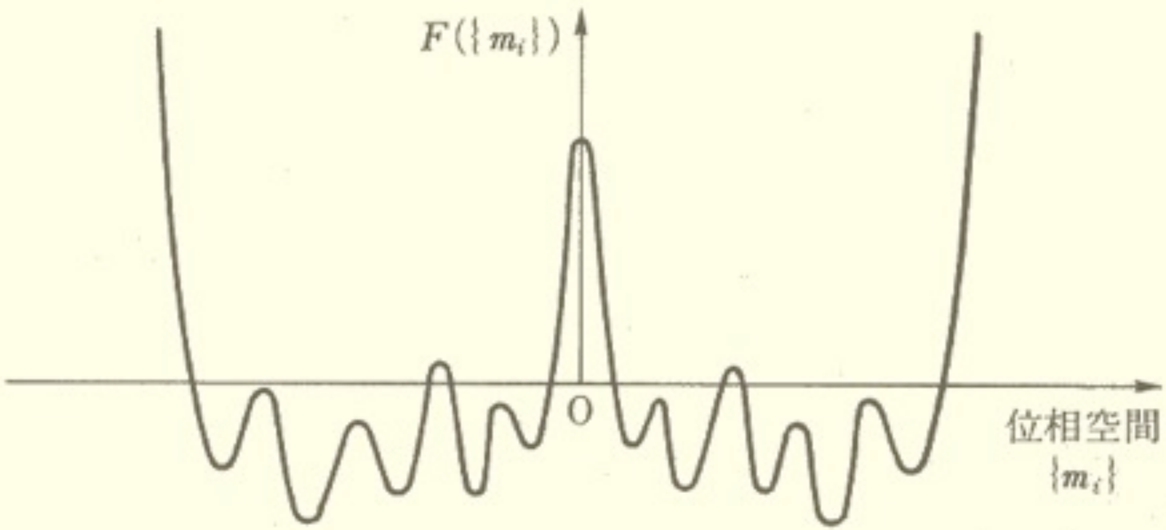
randomness in geometry



frustration



$F(m)$
O
m
$-m_0$
m_0



$F(\{m_i\})$
O
位相空間
$\{m_i\}$

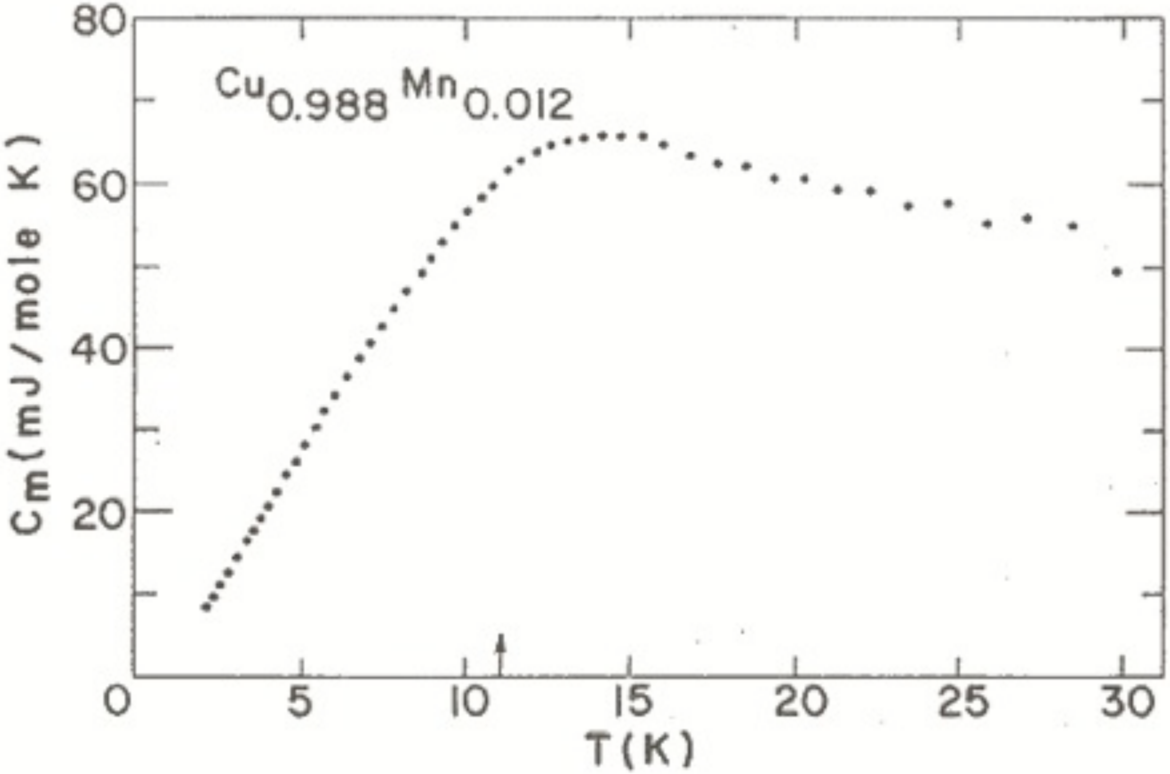
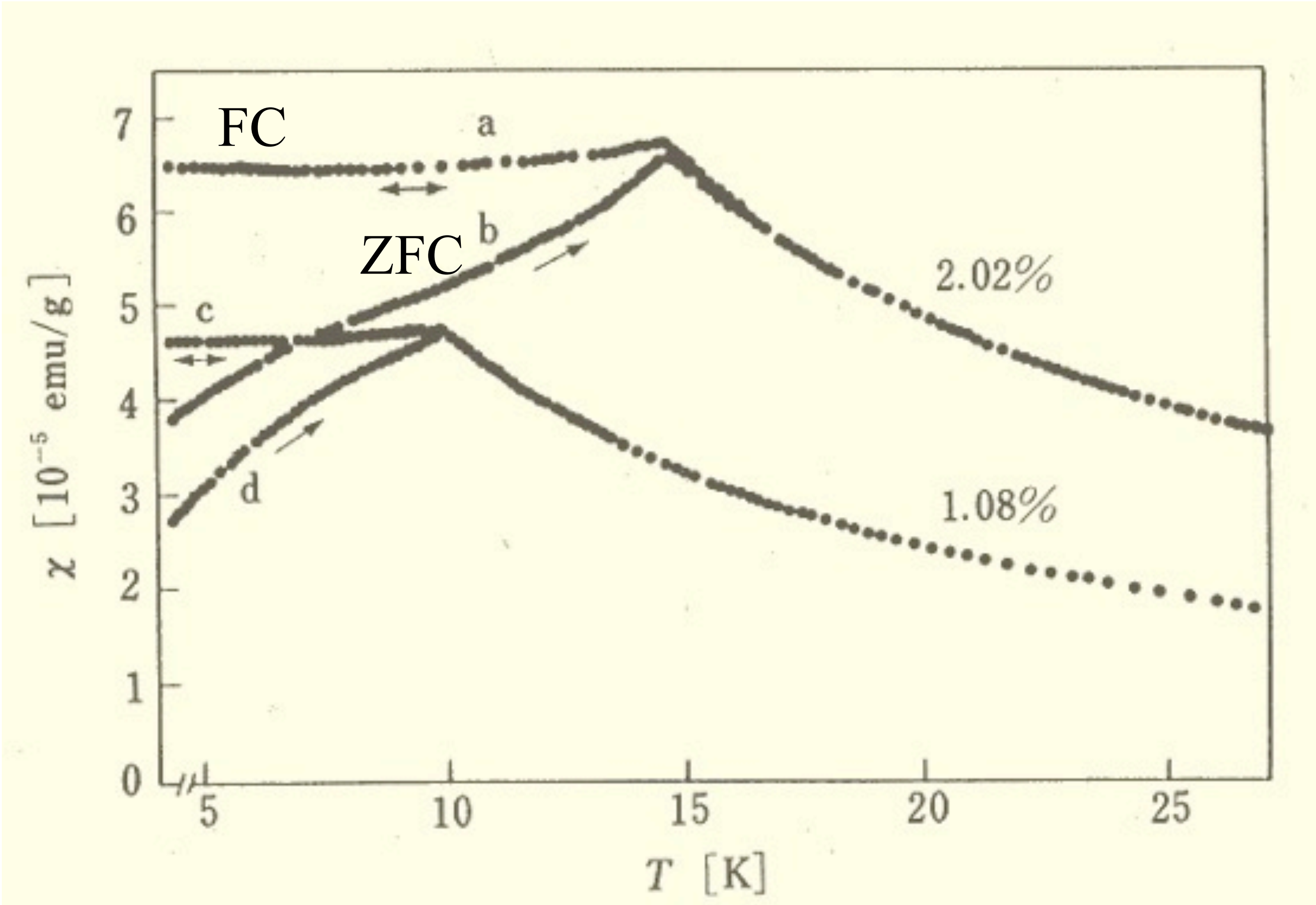


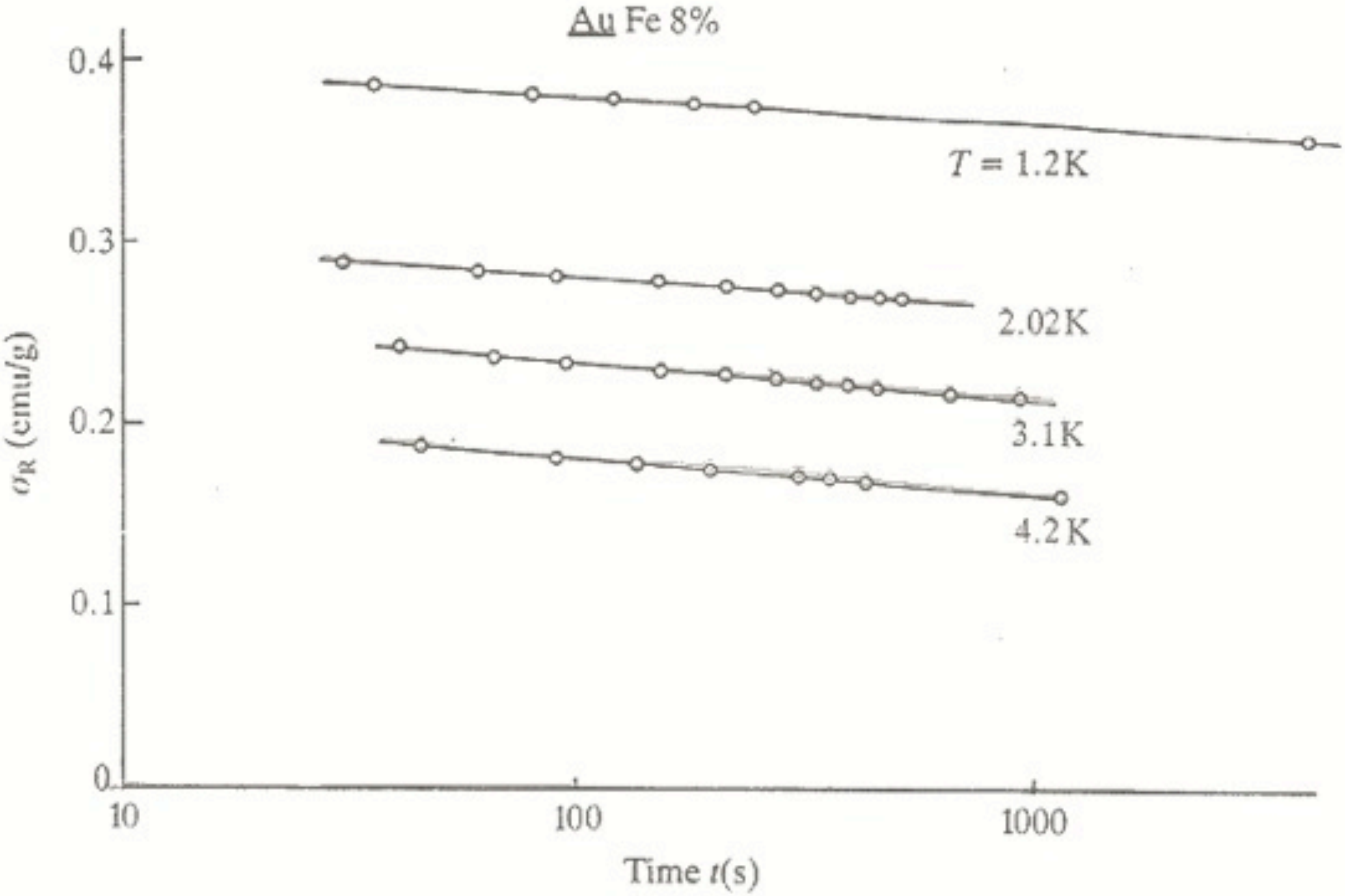
FIG. 3. Magnetic specific heat of $Cu_{0.988}Mn_{0.012}$ in the temperature range 2–30 K. The arrow indicates the ordering temperature T_0.

no sharp feature in the specific heat

dc susceptibility of CuMn



Field-Cooling (FC) vs Zero-Field-Cooling (ZFC)



Time-dependent isothermal remanent magnetization

ac susceptibility depending on measuring frequency

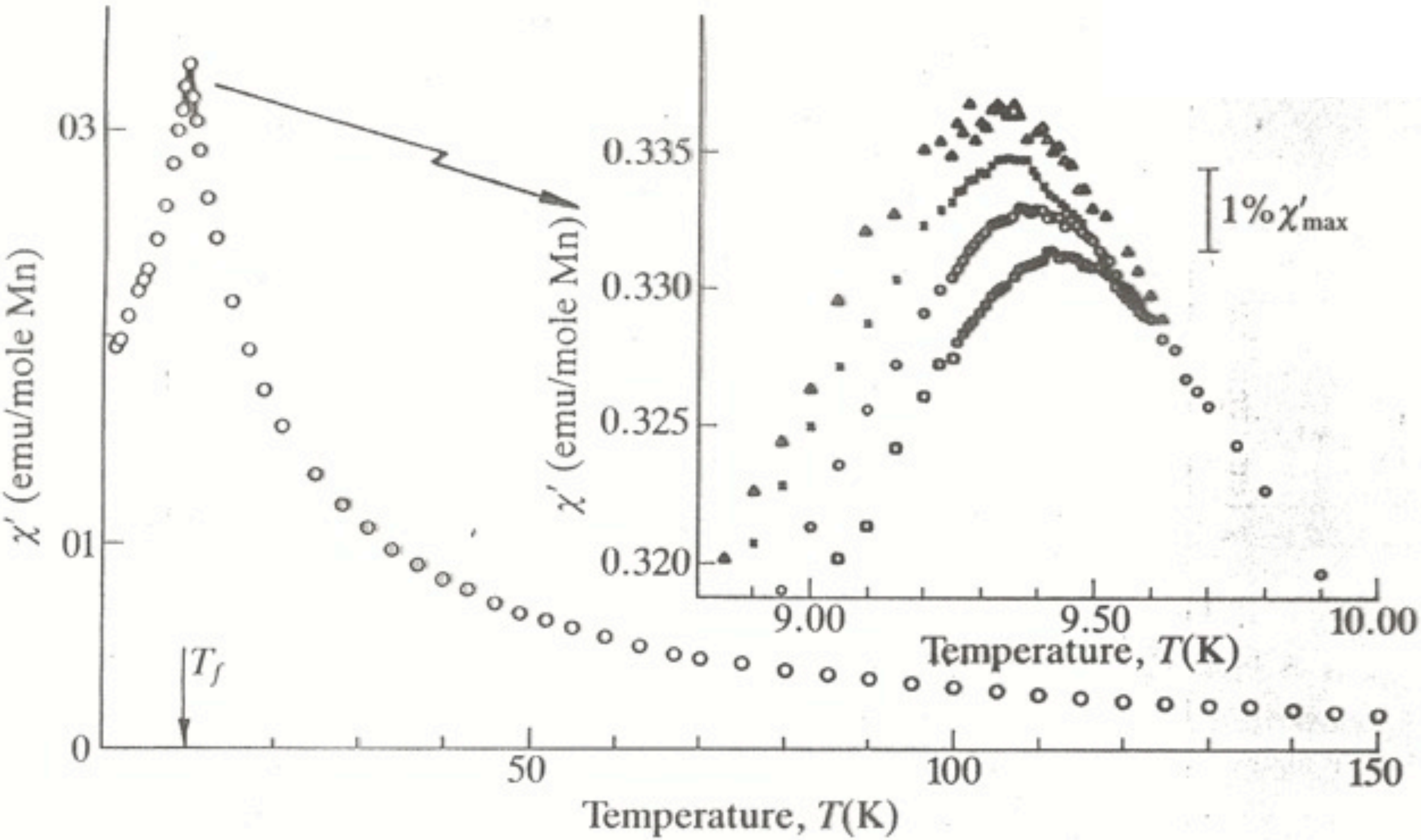
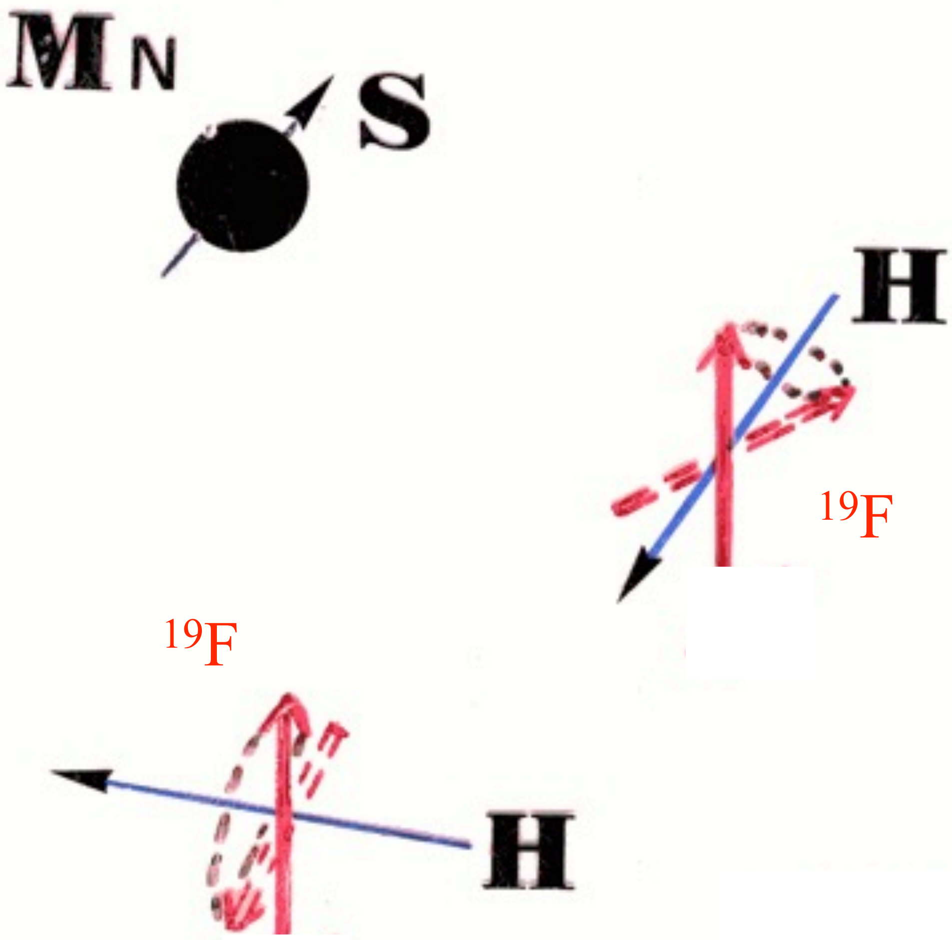
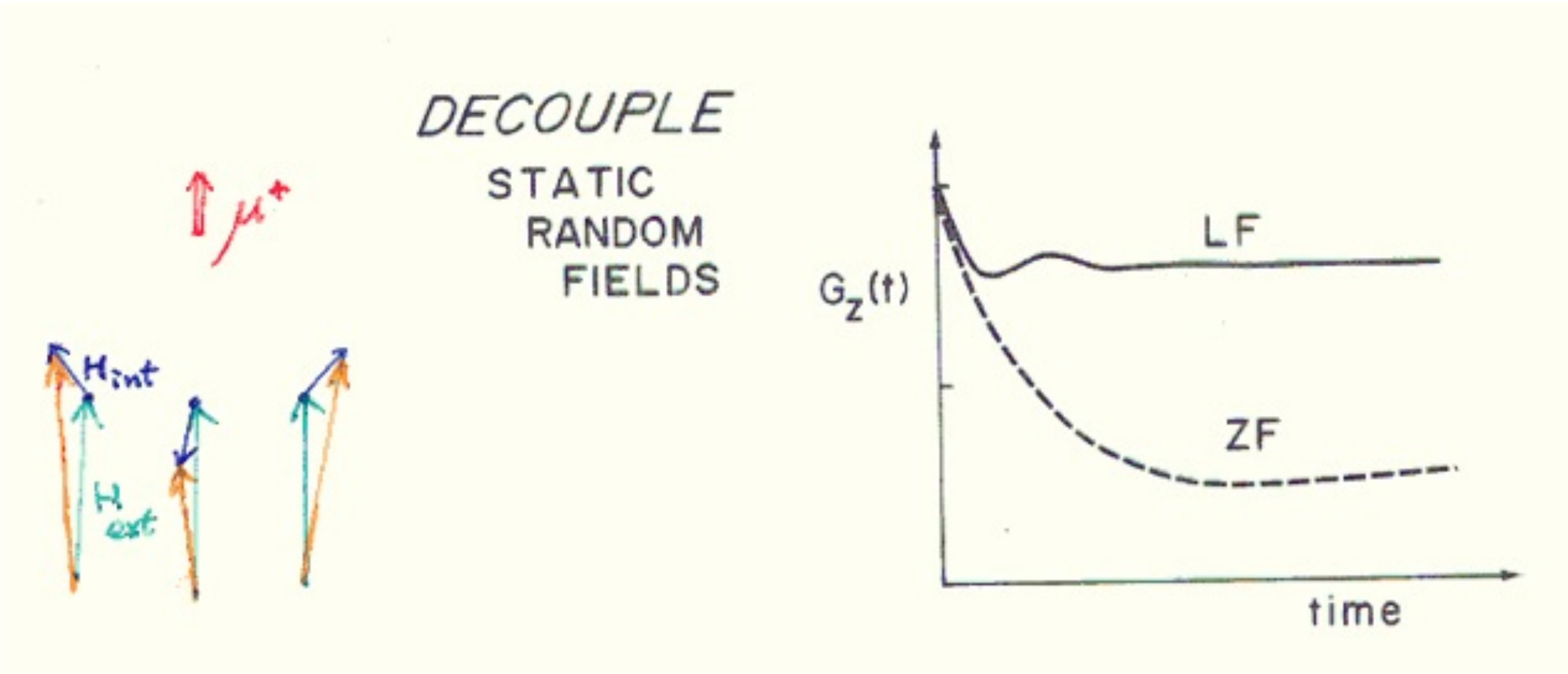


Figure 1.2: The ac susceptibility as a function of temperature for Cu-0.9% Mn for the frequencies 1.33 kHz (□), 234 Hz (○), 10.4 Hz (x), and 2.6 Hz (△) (from Mulder et al, 1981, 1982).

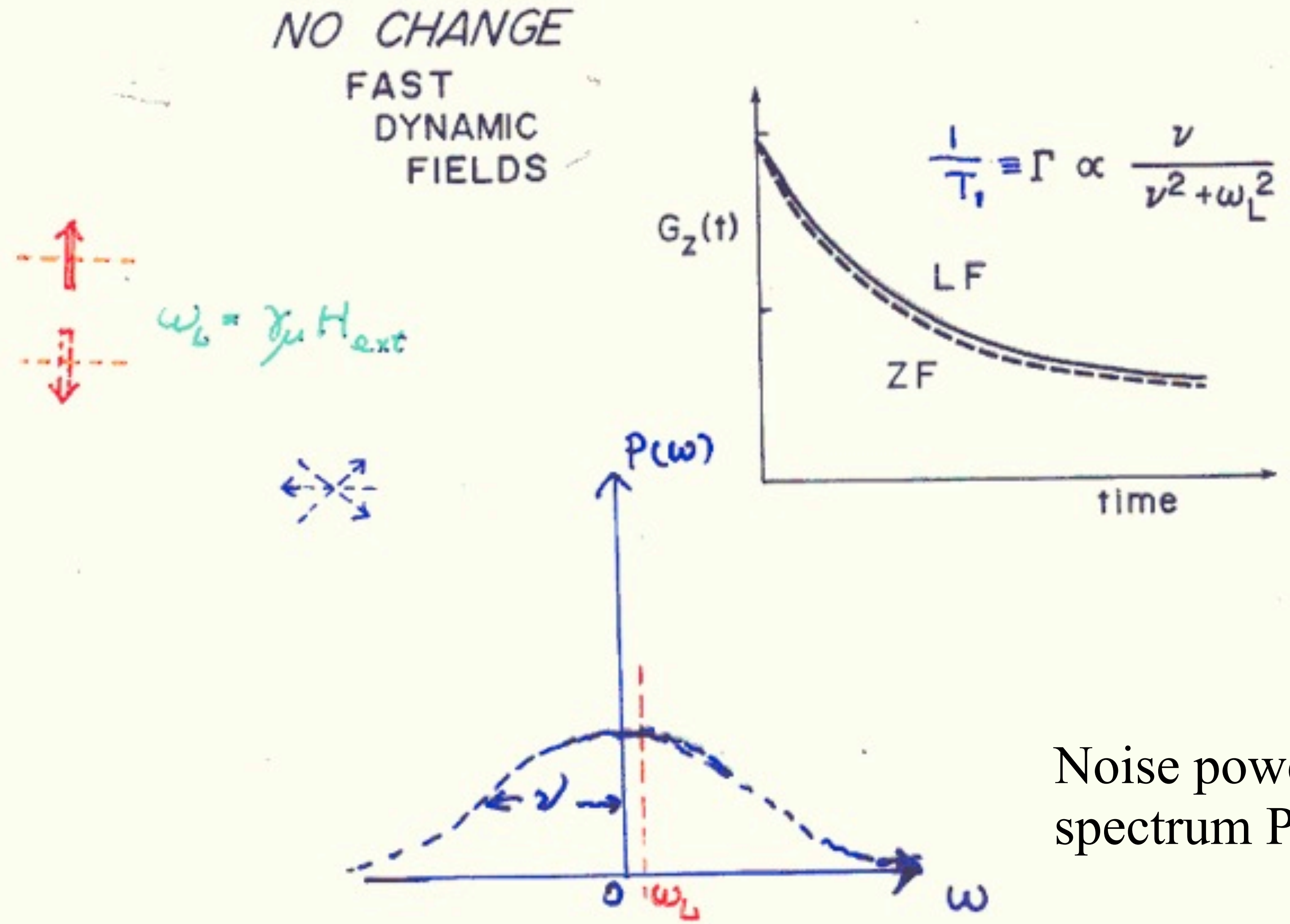
RANDOM LOCAL FIELD H



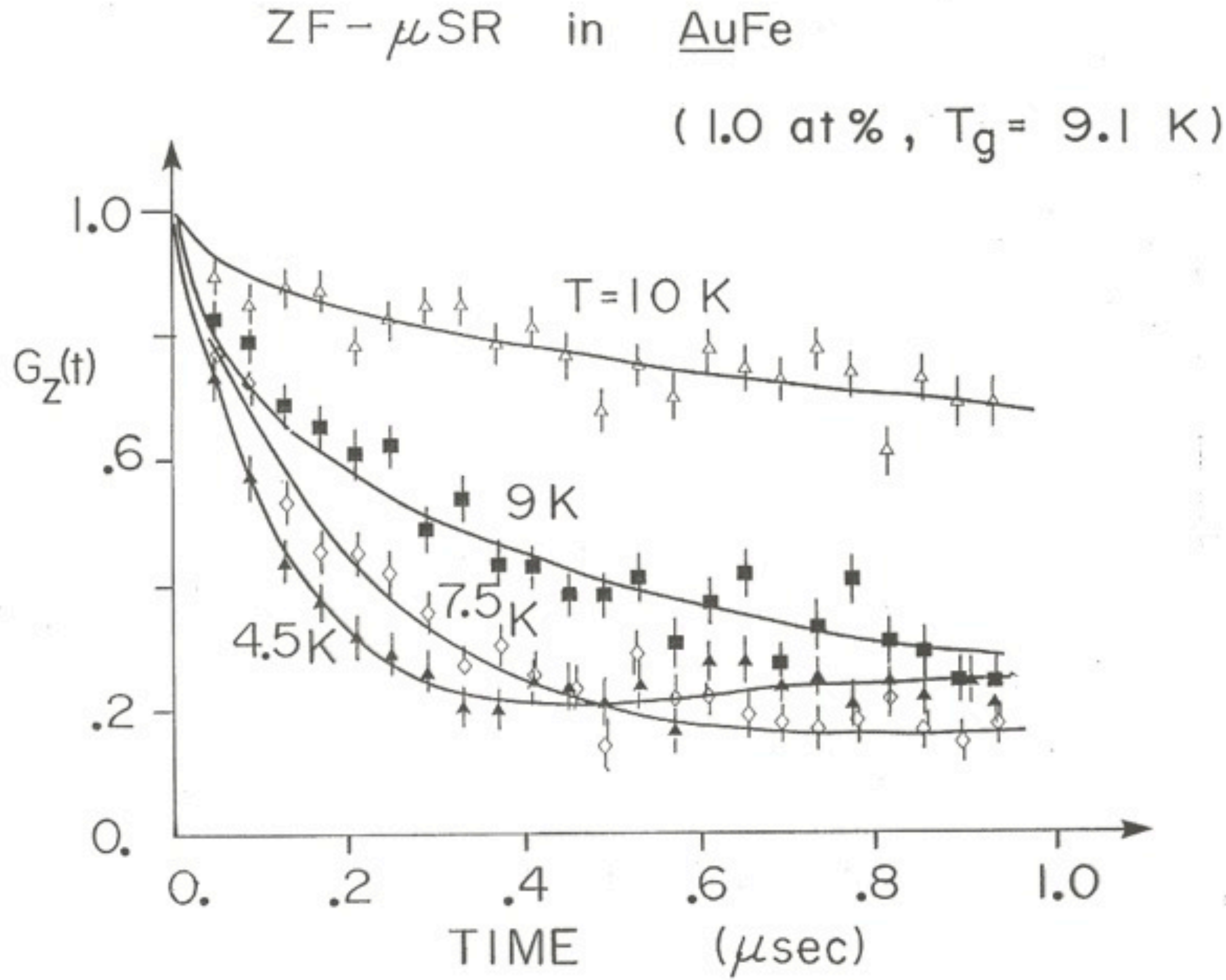
Distinguishing static versus dynamic effects



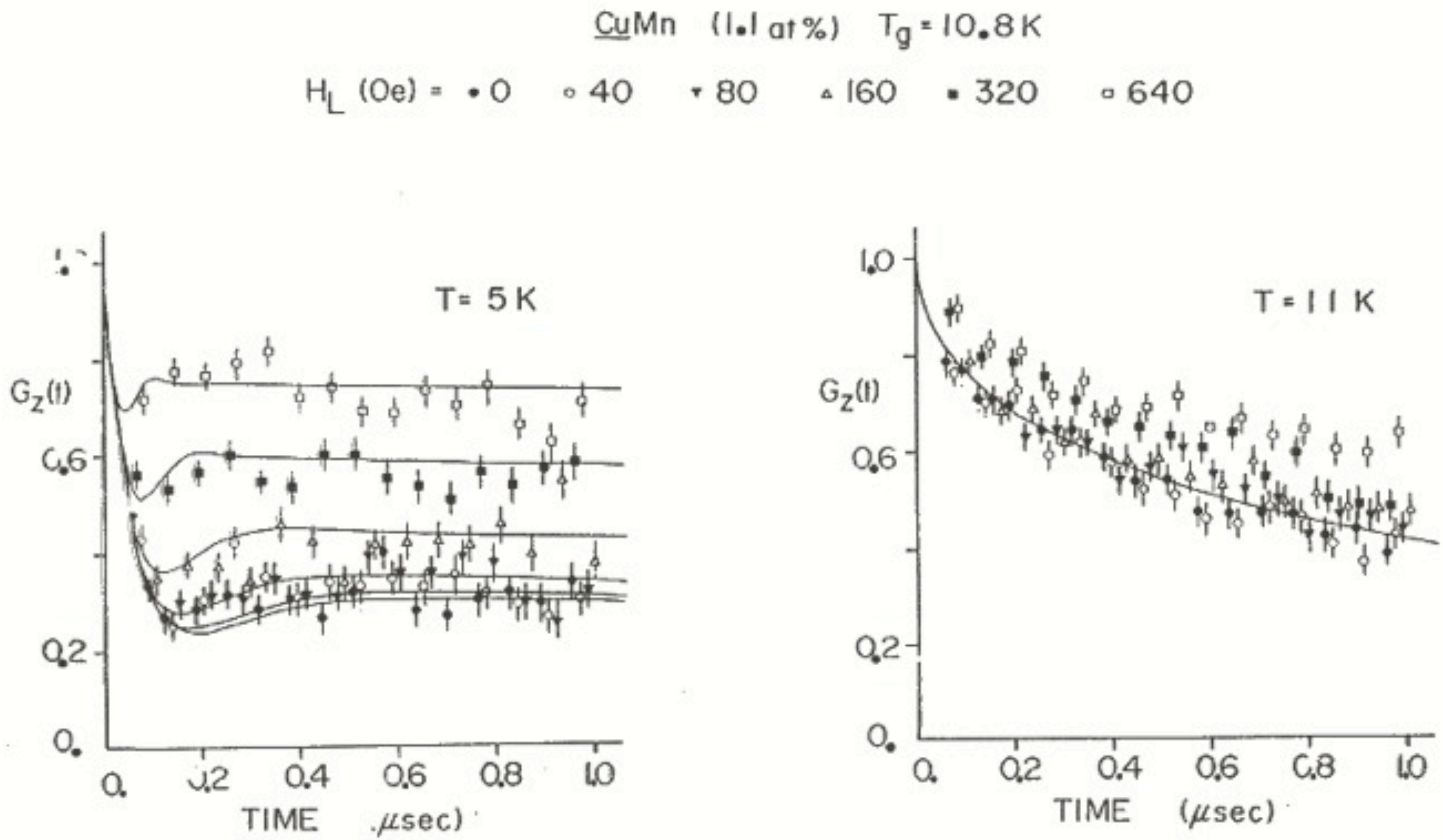
fluctuation rate ν

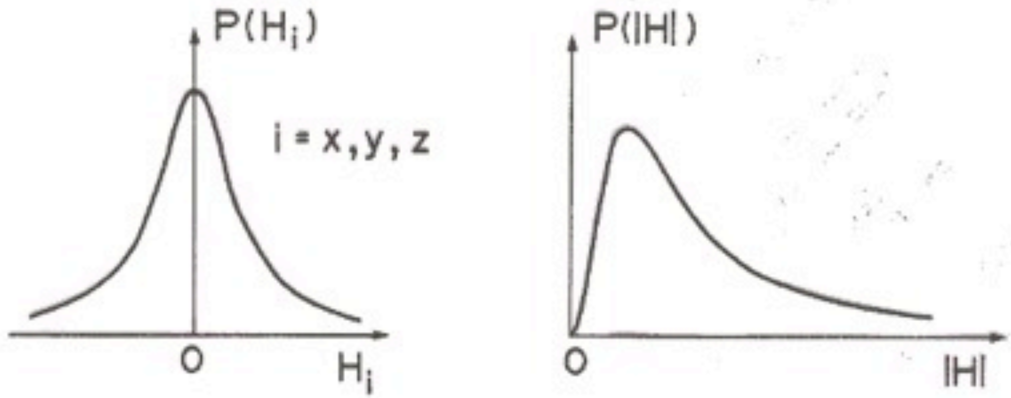


Noise power
spectrum P(ω)



ZF - μSR in AuFe
(1.0 at % , Tg= 9.1 K)
1.0
.6
.2
0.
Gz(t)
T=10 K
9 K
7.5 K
4.5 K
0.
.2
.4
.6
.8
1.0
TIME (μsec)

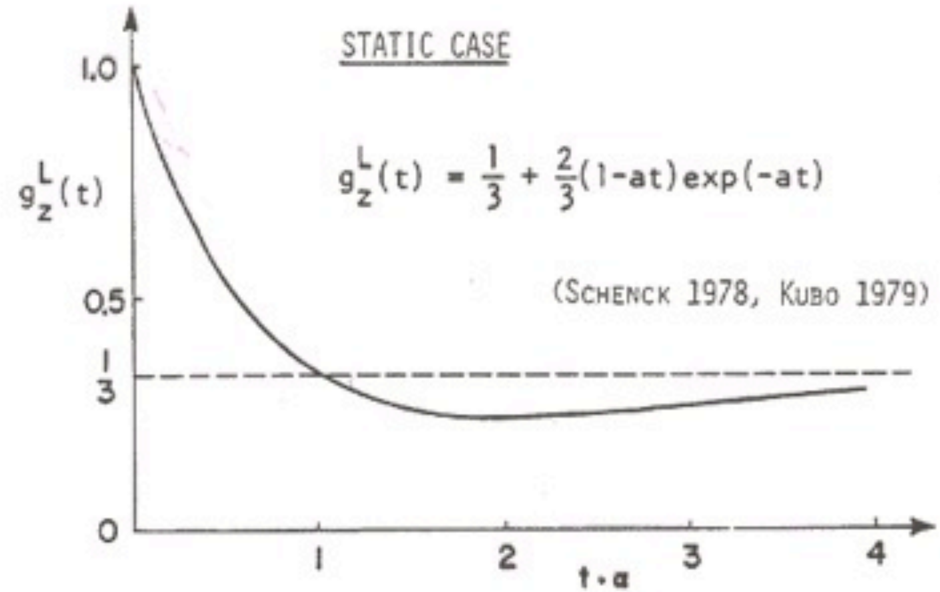

CuMn (1.1 at%) Tg = 10.8 K
HL (Oe) = • 0 ○ 40 ▾ 80 ▵ 160 ▪ 320 ▫ 640
T= 5 K
Gz(t)
0.6
0.2
0.
0.
0.2
0.4
0.6
0.8
1.0
TIME (μsec)
T = 11 K
1.0
Gz(t)
0.6
0.2
0.
0.
0.2
0.4
0.6
0.8
1.0
TIME (μsec)

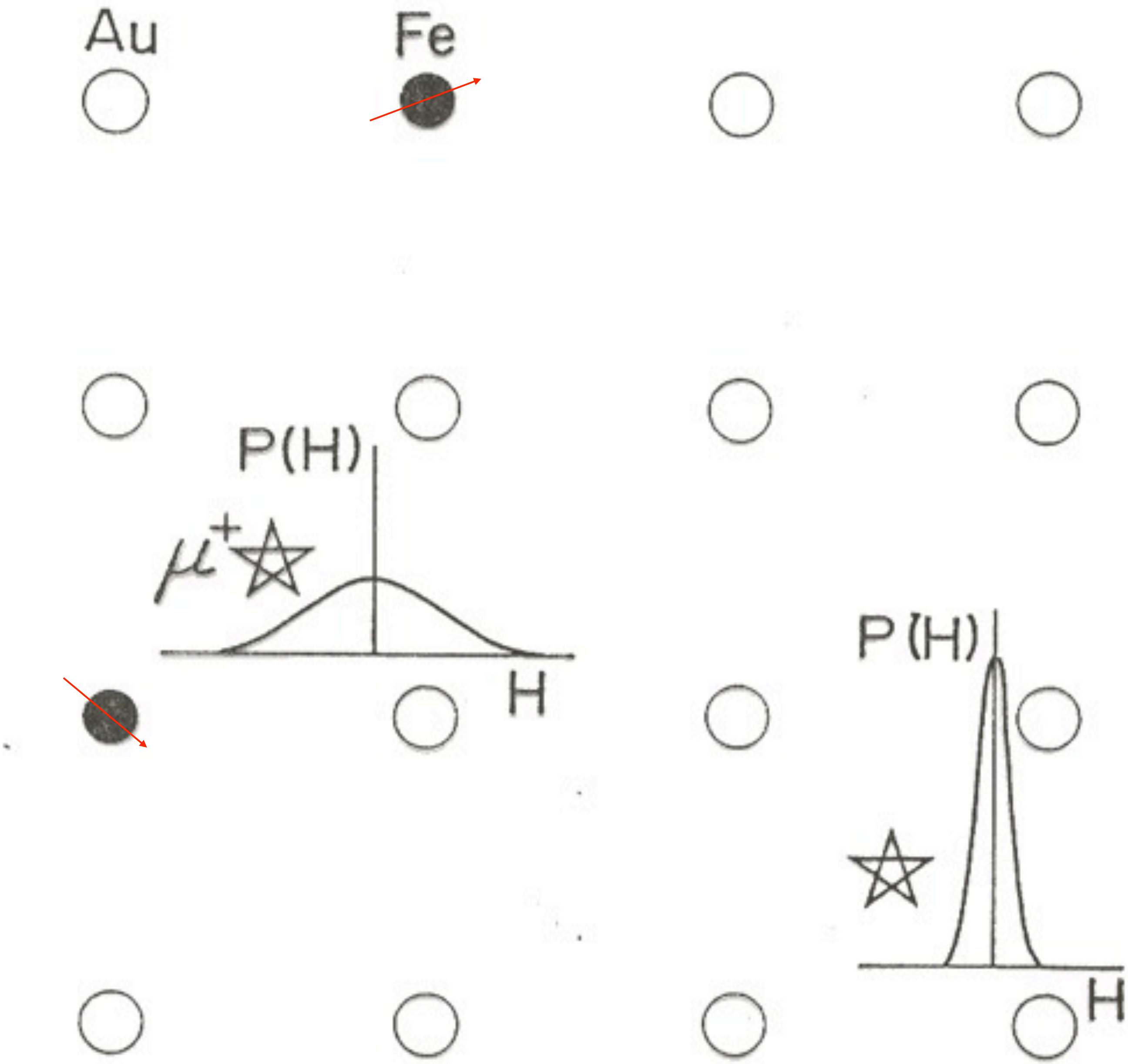


Lorentzian

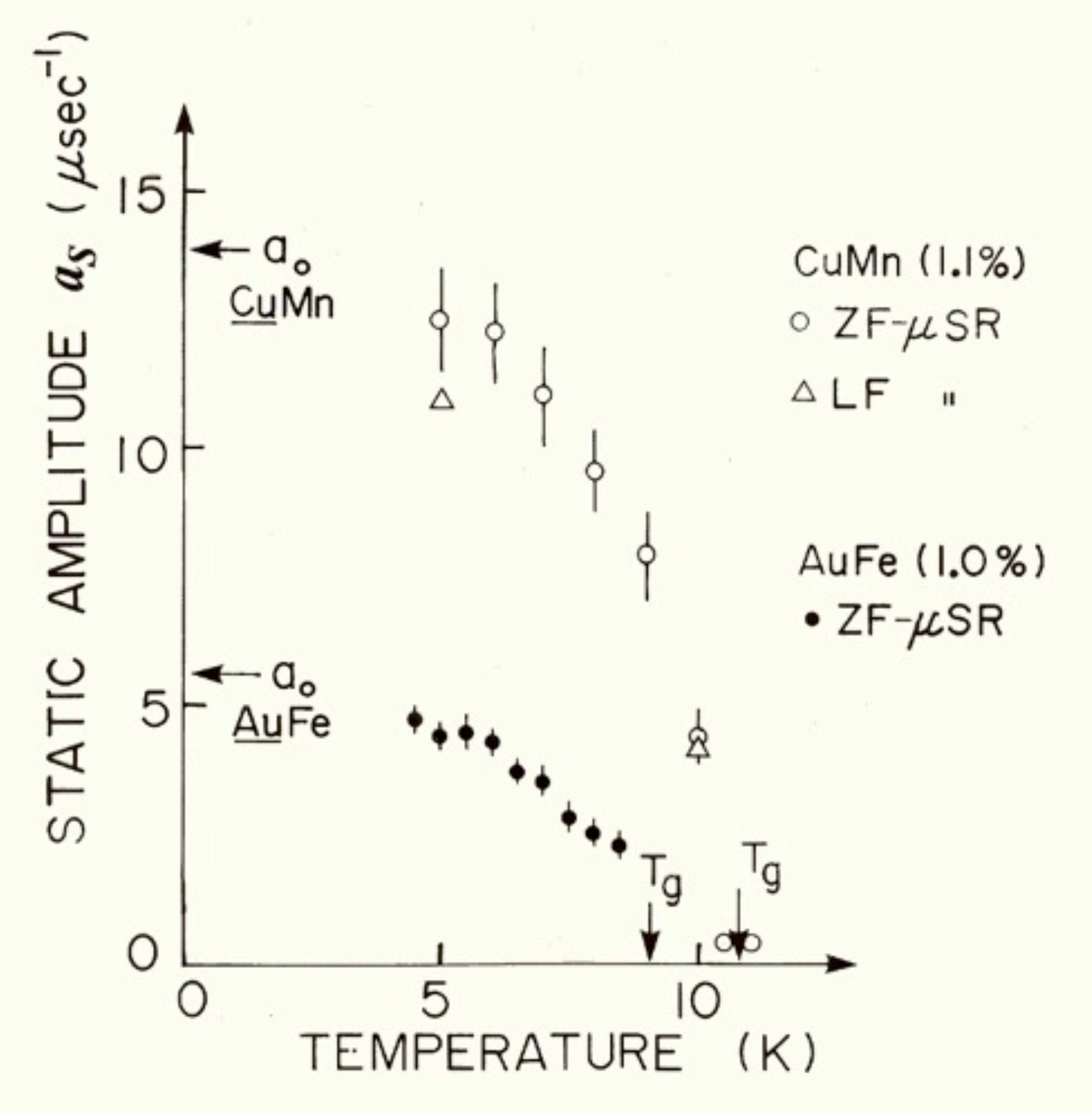
$$P^L(H_i) = \frac{\gamma_\mu}{\pi} \cdot \frac{a}{(a^2+\gamma_\mu{}^2 H_i{}^2)}$$

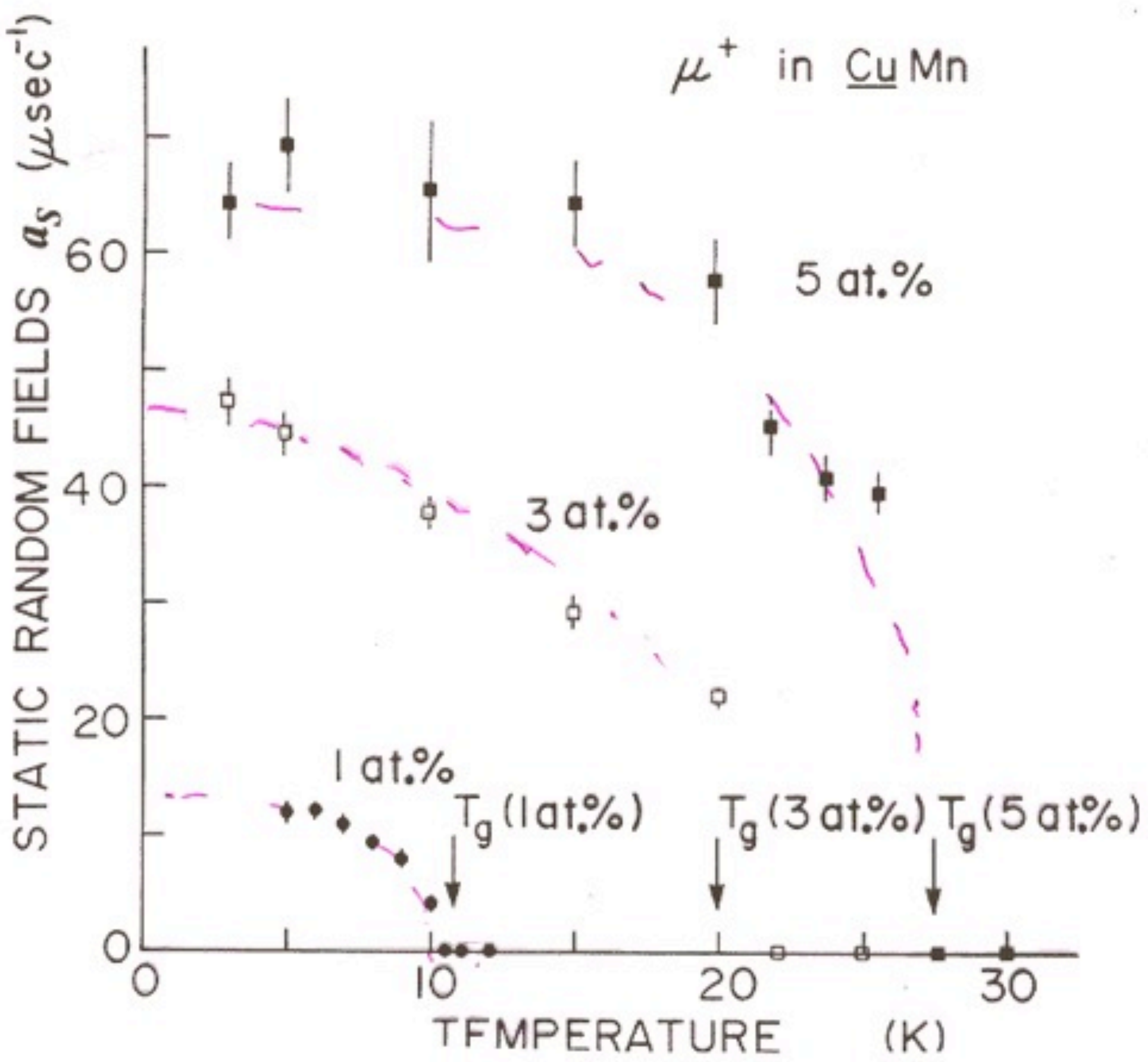
(Walstedt & Walker, 1974)



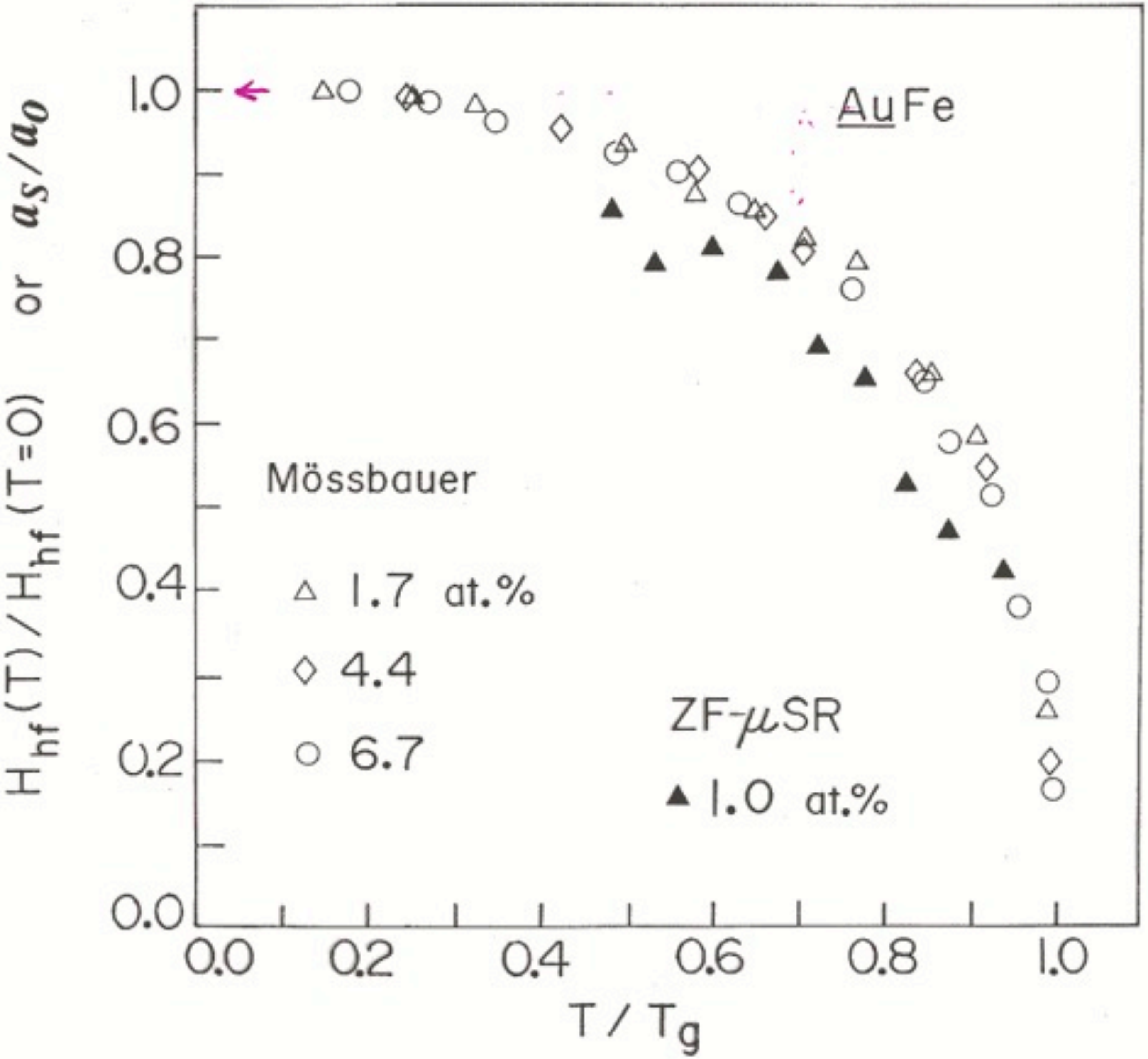


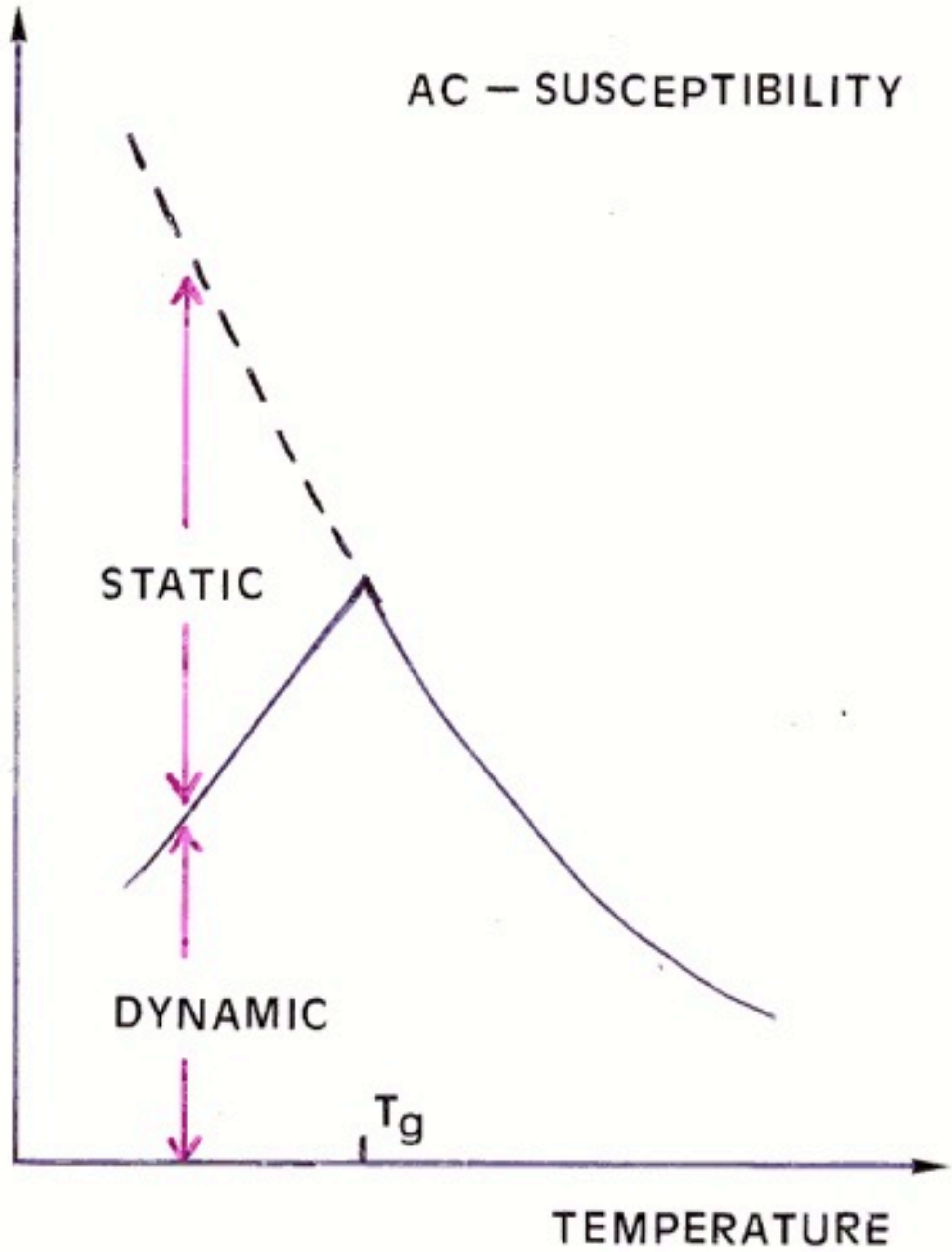
Au
Fe
P(H)
μ+
H
P(H)
H

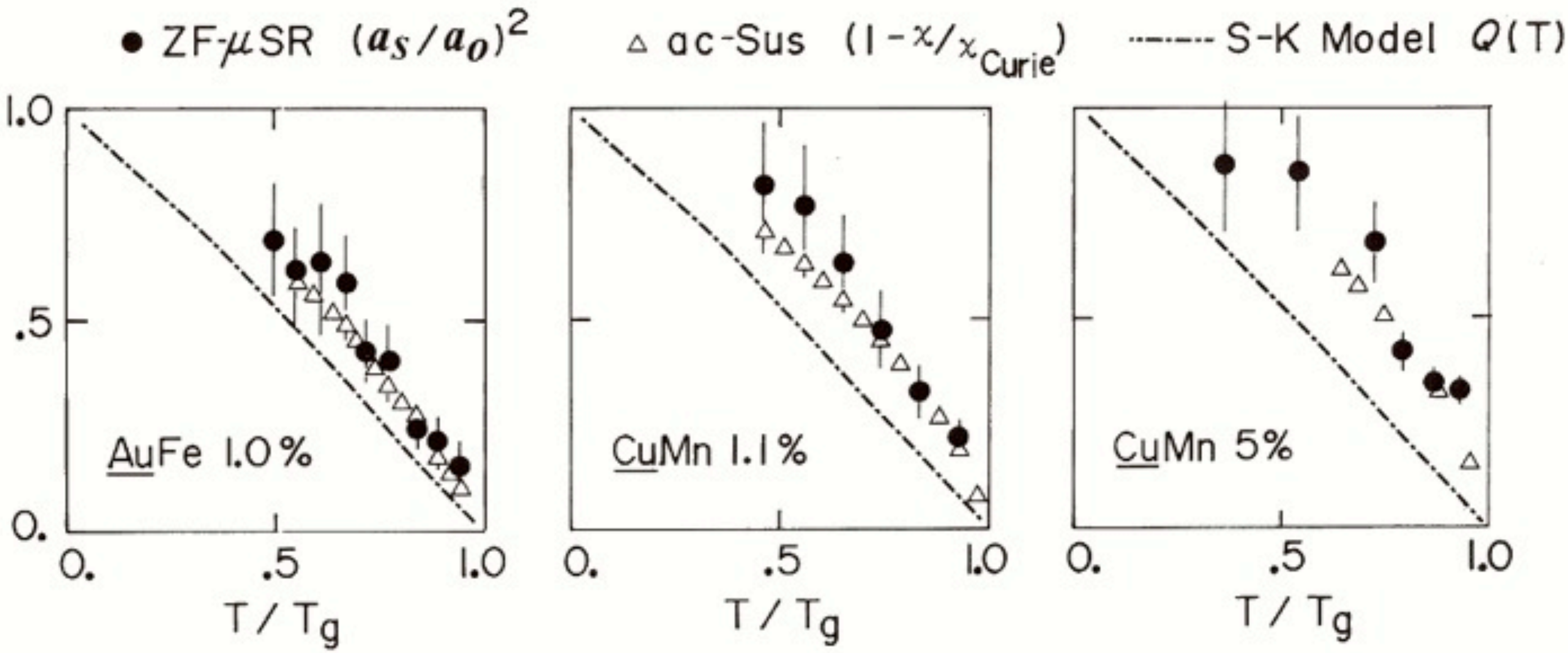

STATIC AMPLITUDE a_S (μsec^{-1})
15
10
5
0
← a_o
CuMn
← a_o
AuFe
CuMn (1.1%)
○ ZF-μSR
△ LF "
AuFe (1.0%)
• ZF-μSR
T_g
T_g
0
5
10
TEMPERATURE (K)



μ^+ in CuMn
STATIC RANDOM FIELDS a_S (μsec^{-1})
60
40
20
0
5 at.%
3 at.%
1 at.%
T_g(1at.%)
T_g(3 at.%)
T_g(5 at.%)
0
10
20
30
TEMPERATURE (K)


AuFe
$H_{hf}(T)/H_{hf}(T=0)$ or a_S/a_0
Mössbauer
1.7 at.%
4.4
6.7
ZF-μSR
1.0 at.%
T / Tg
0.0
0.2
0.4
0.6
0.8
1.0

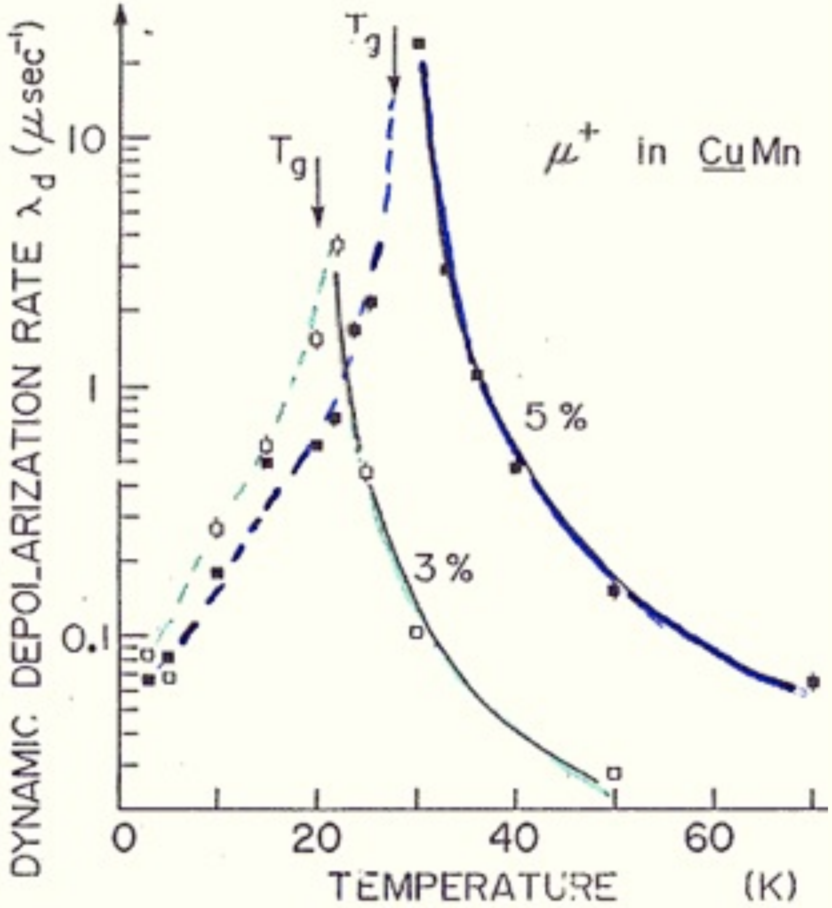

AC – SUSCEPTIBILITY
STATIC
DYNAMIC
Tg
TEMPERATURE

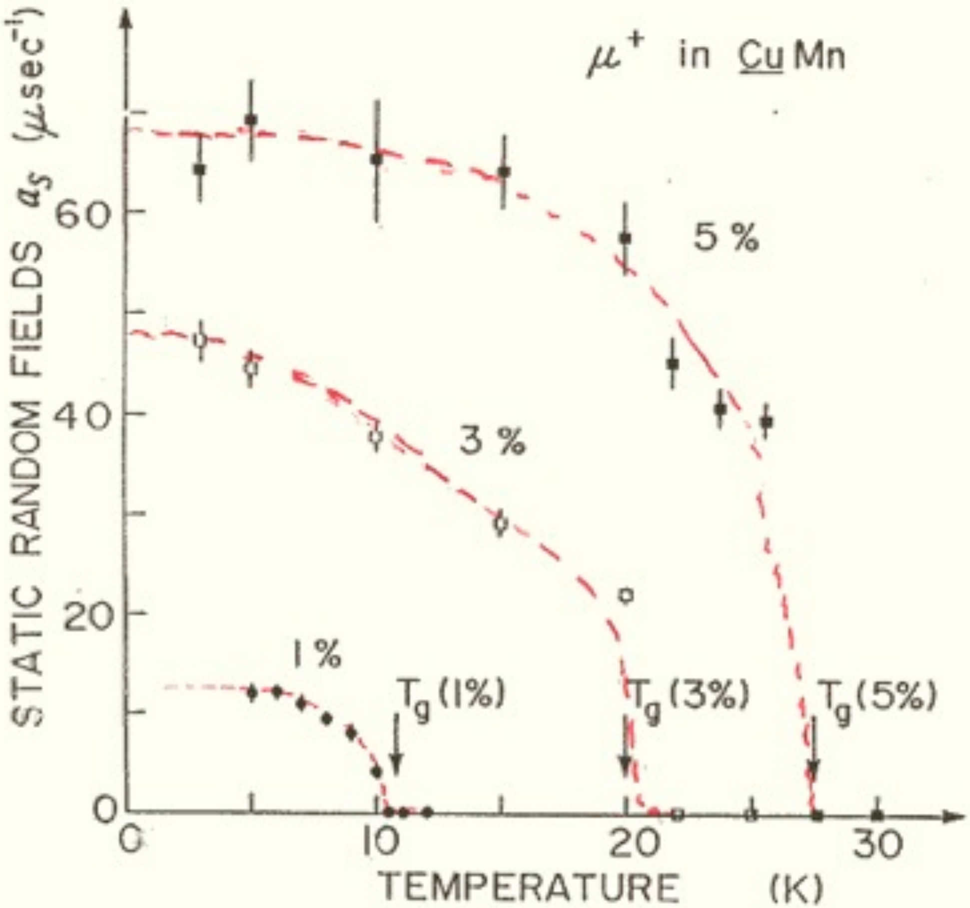


● ZF-μSR $(a_S/a_0)^2$
△ ac-Sus $(1-\chi/\chi_{Curie})$
S-K Model $Q(T)$
AuFe 1.0%
CuMn 1.1%
CuMn 5%
T / Tg
1.0
.5
0.

$\propto \frac{1}{T_1}$

$\propto \sqrt{Q_{EA}}$

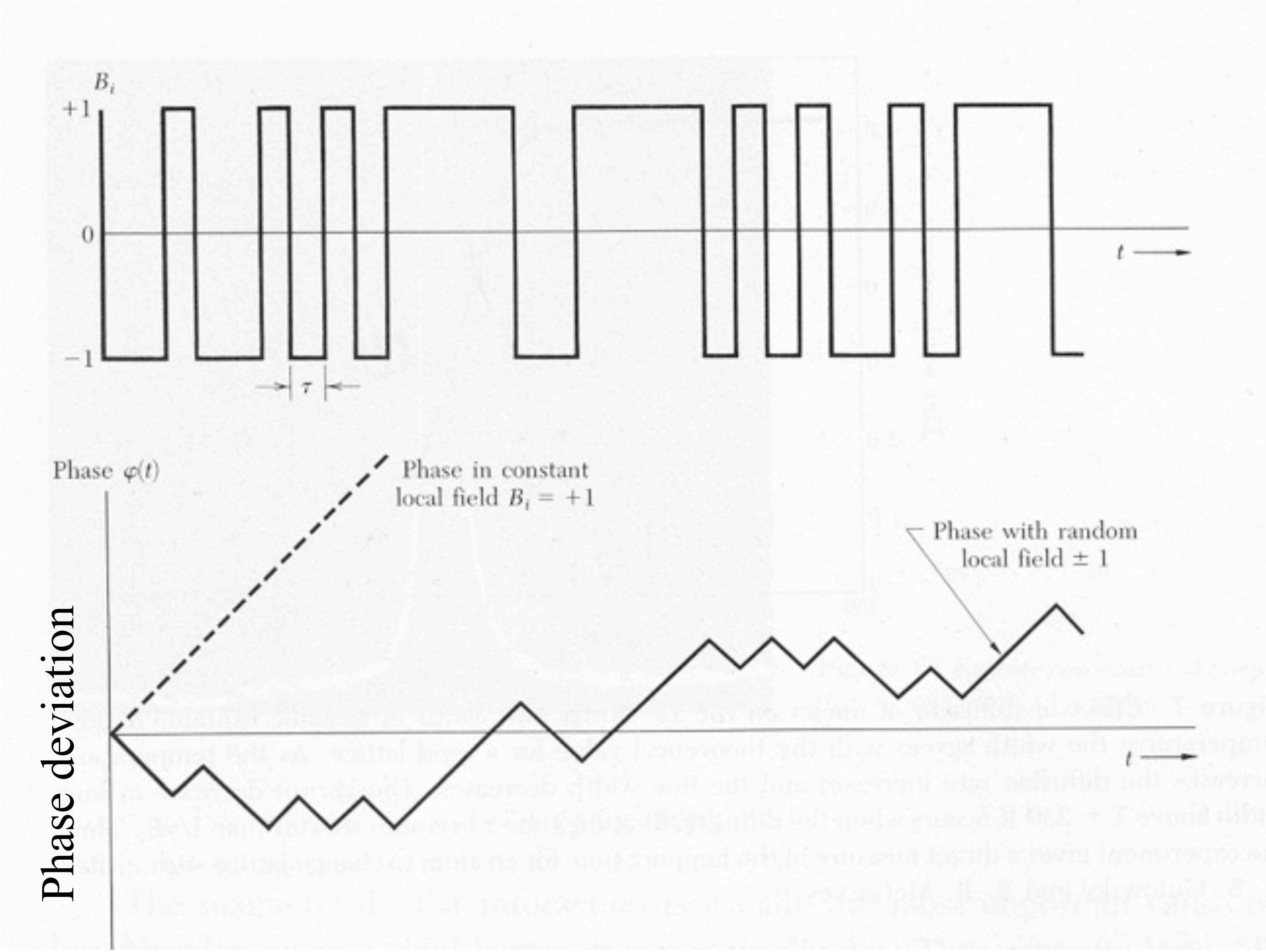




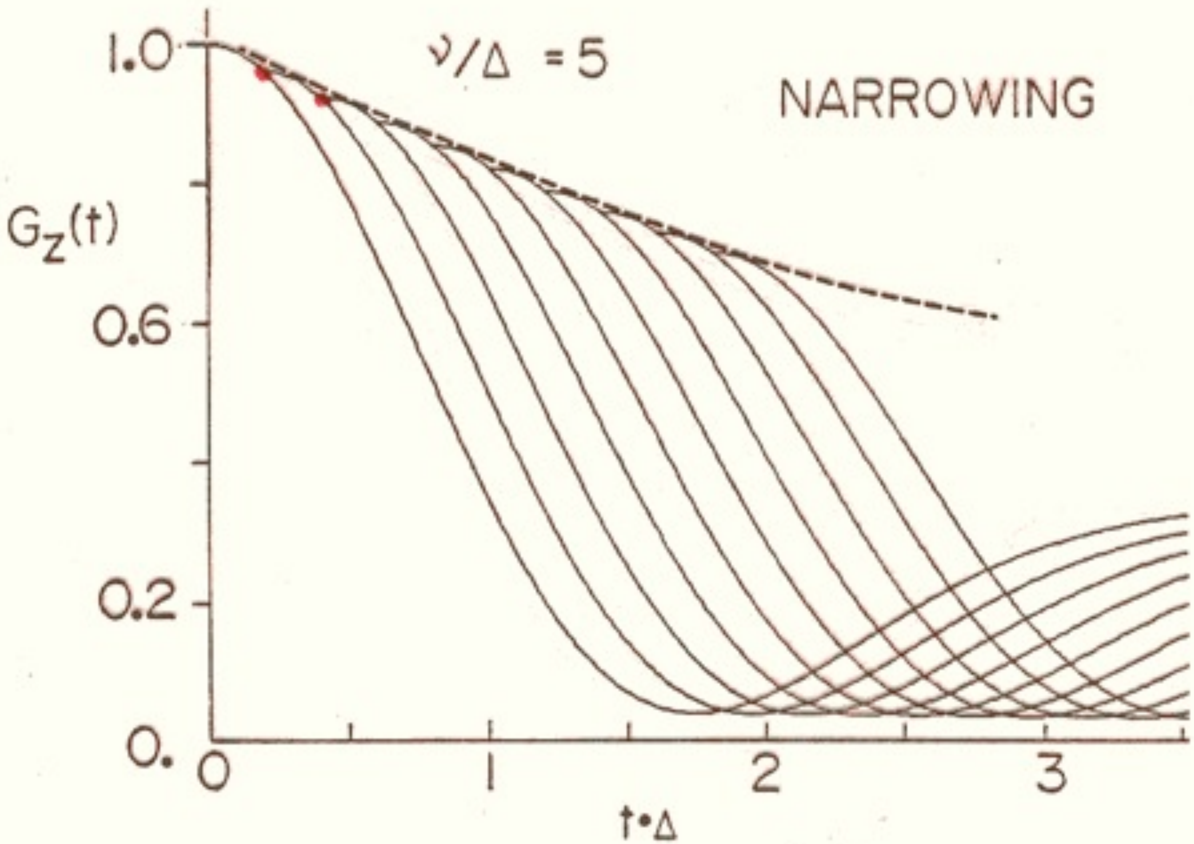
$1/T_1 \sim a_s^2 / \nu$

Thursday, August 18, 2011

Mn spin fluctuations ➔ Brownian motion of nuclear spin precession



STRONG COLLISION MODEL



Static Gaussian Field

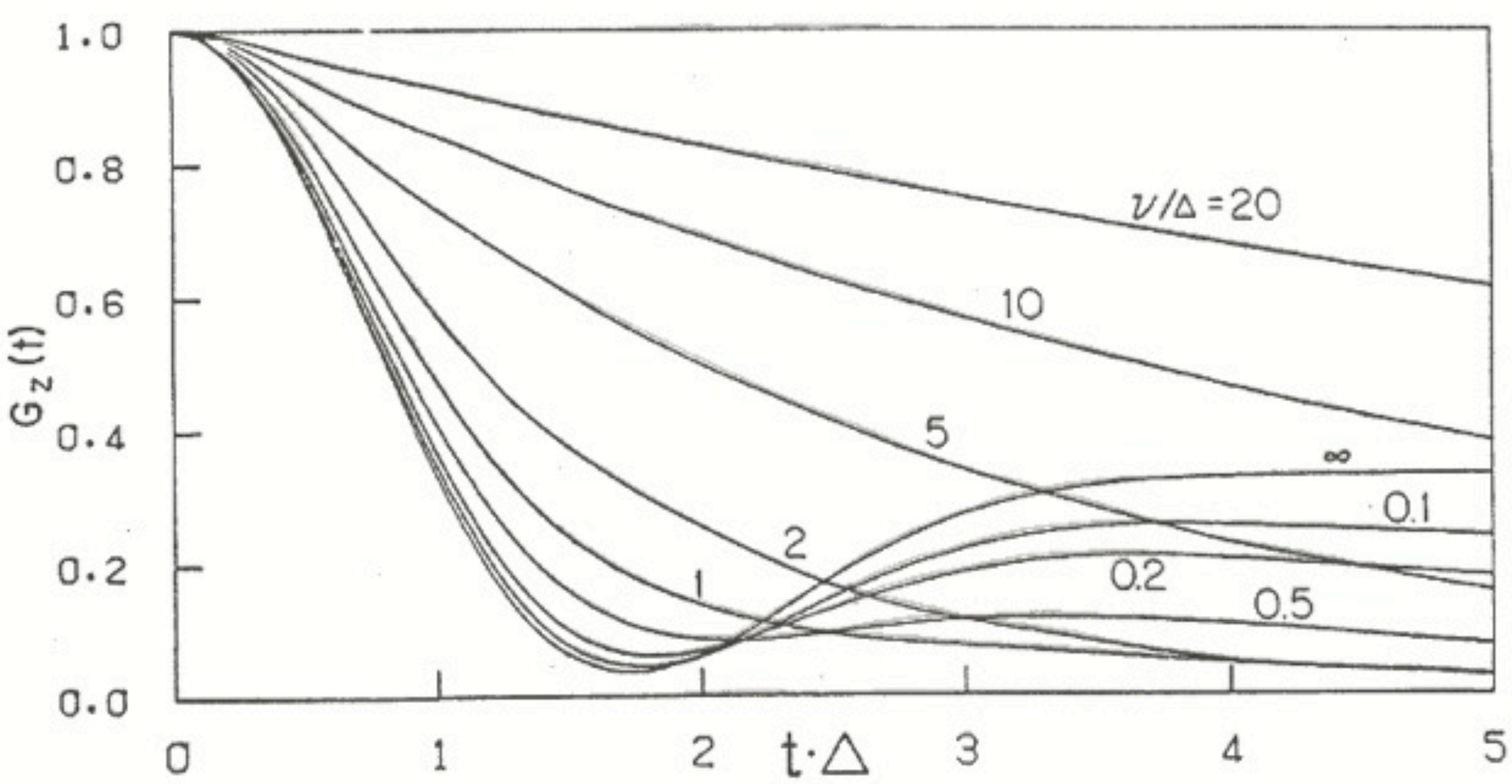
➔ $G_z(t) \sim \exp(-\Delta^2 t^2)$

near t ~ 0

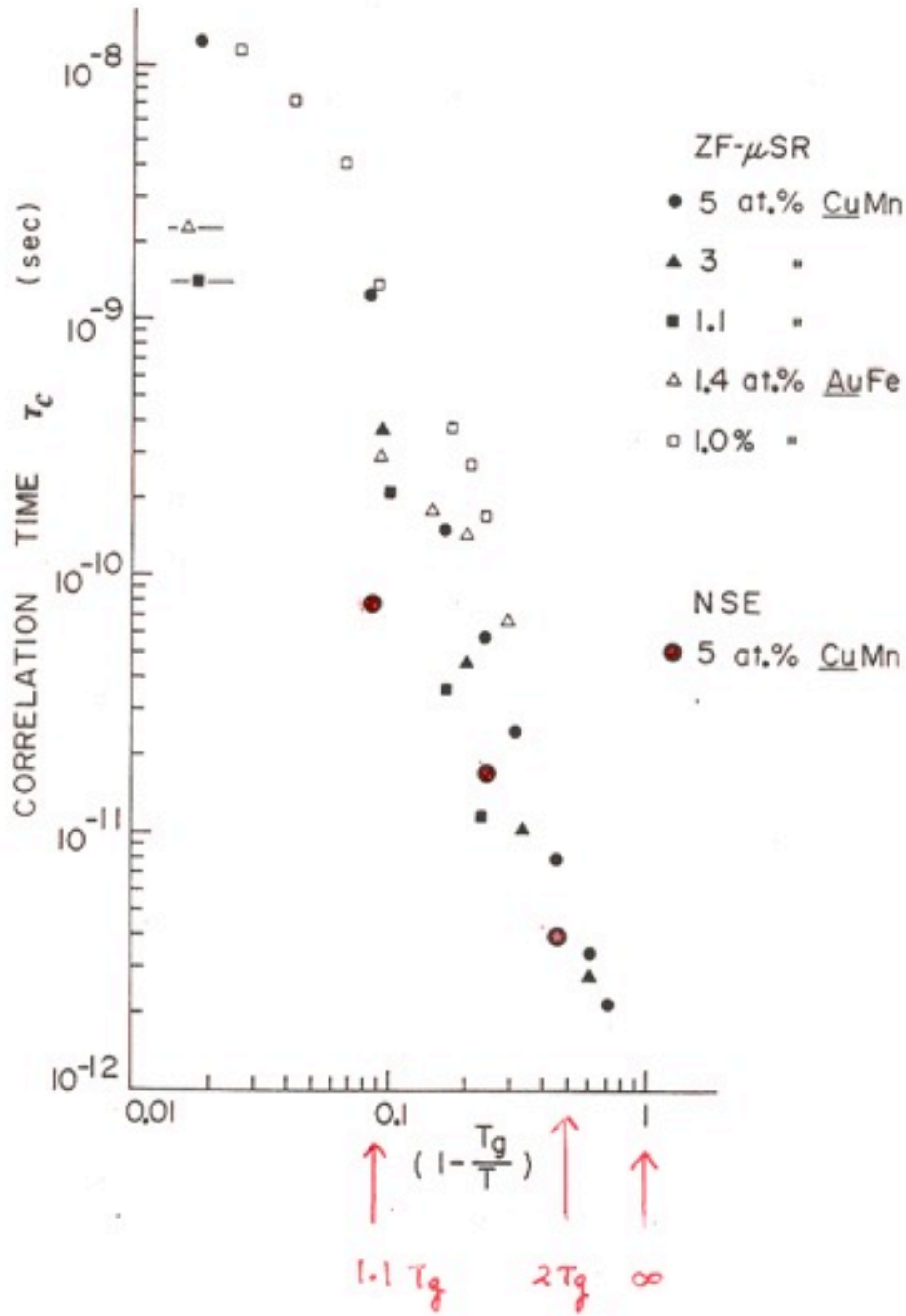
Dynamic field makes it into

$G_z(t) \sim \exp(-t/T_1)$

$$G_z(t,\nu) = \exp(-\nu t)\,\{\, g_z(t) + \nu \int_0^t g_z(t_1) g_z(t-t_1)\, dt_1 + \nu^2 \cdot \int_0^t \int_0^{t_2} g_z(t_1) g_z(t_2-t_1) g_z(t-t_2)\, dt_1 dt_2 + \ldots \,\} \; .$$

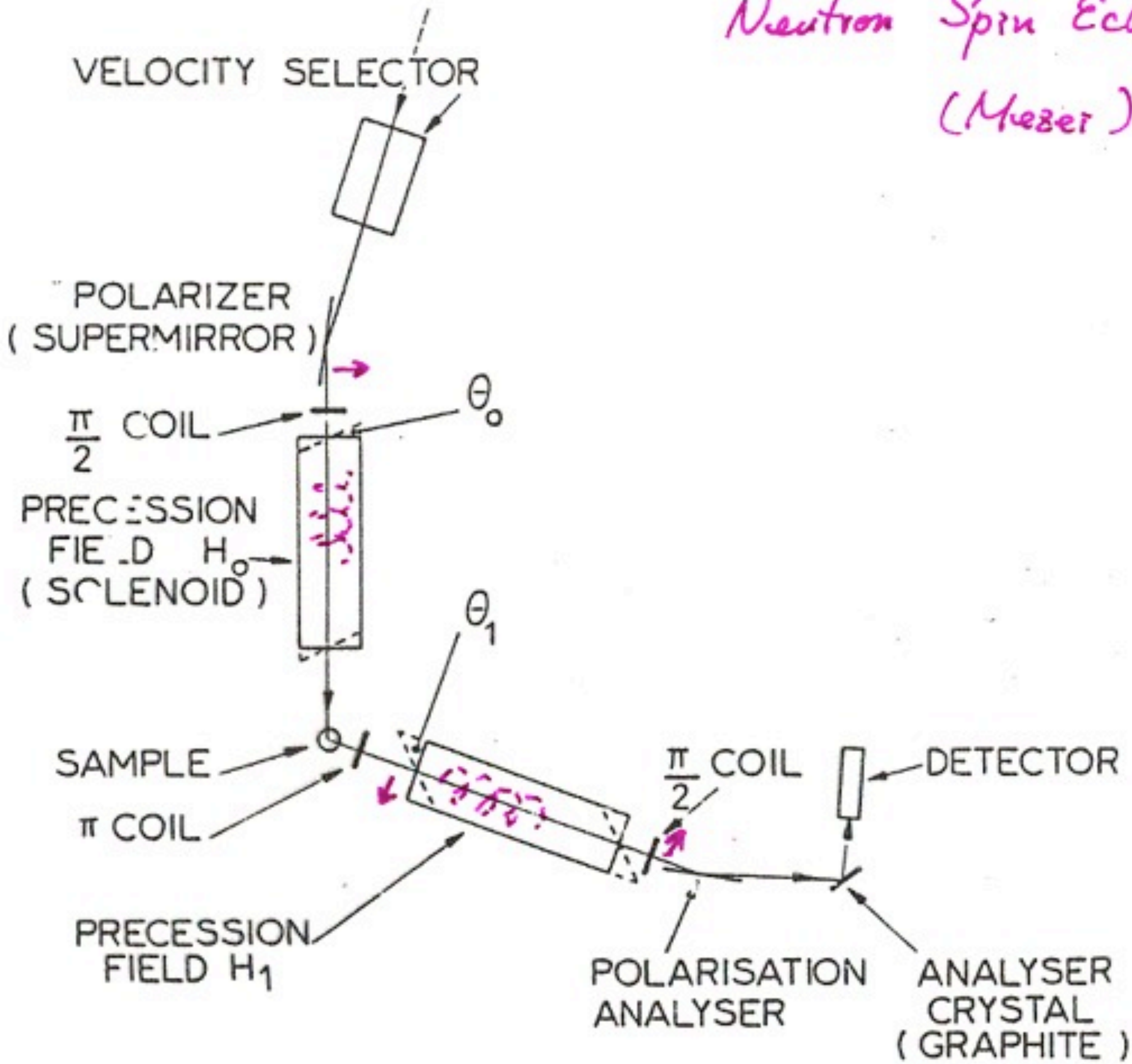


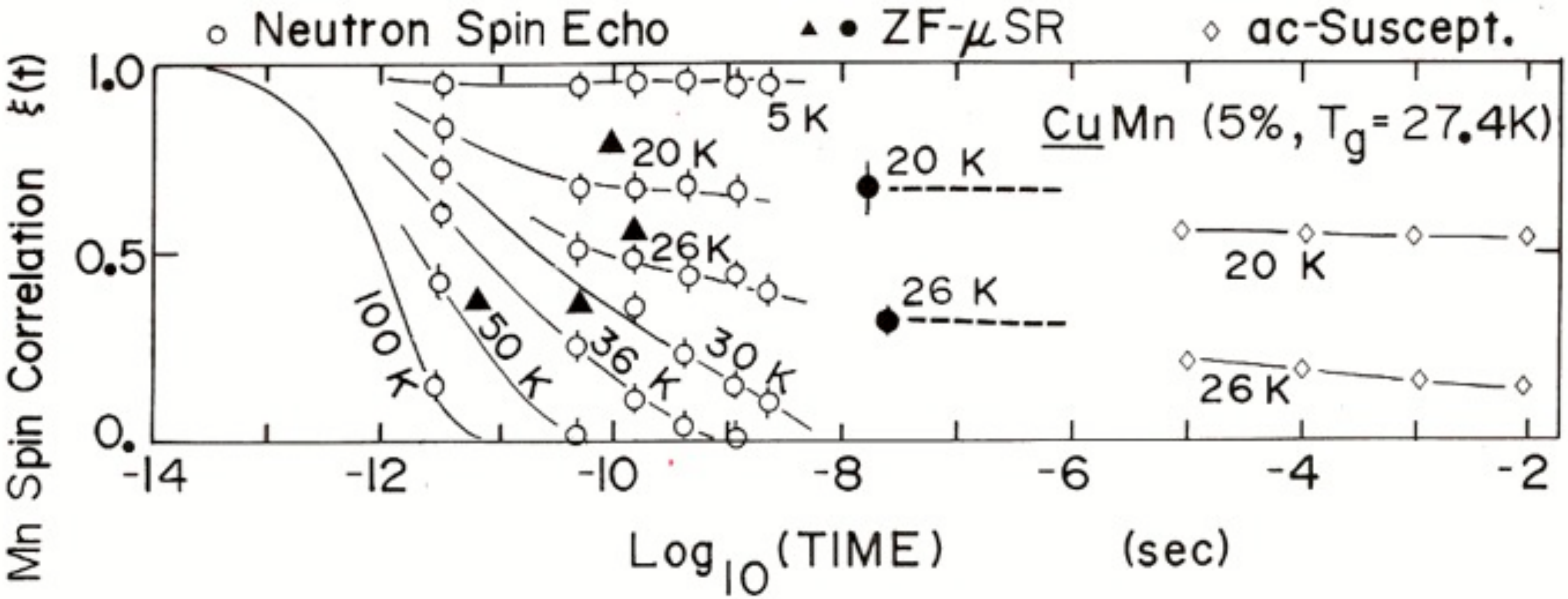
1.0
0.8
0.6
0.4
0.2
0.0
$G_z(t)$
0
1
2
3
4
5
$t \cdot \Delta$
$\nu/\Delta = 20$
10
5
2
1
∞
0.1
0.2
0.5



ZF-μSR
5 at.% CuMn
3 "
1.1 "
1.4 at.% AuFe
1.0% "
NSE
5 at.% CuMn
CORRELATION TIME τc (sec)
10^-8
10^-9
10^-10
10^-11
10^-12
0.01
0.1
1
(1- Tg/T)
1.1 Tg
2 Tg
∞

Neutron Spin Echo
(Mezei)




○ Neutron Spin Echo
▲ ● ZF-μSR
◇ ac-Suscept.
CuMn (5%, Tg= 27.4K)
Mn Spin Correlation ξ(t)
1.0
0.5
0.
5 K
20 K
26 K
30 K
36 K
50 K
100 K
20 K
26 K
20 K
26 K
-14
-12
-10
-8
-6
-4
-2
Log10(TIME) (sec)

PHYSICAL REVIEW B **66**, 014524 (2002)

Muon spin relaxation studies of incommensurate magnetism and superconductivity in stage-4 $La_2CuO_{4.11}$ and $La_{1.88}Sr_{0.12}CuO_4$

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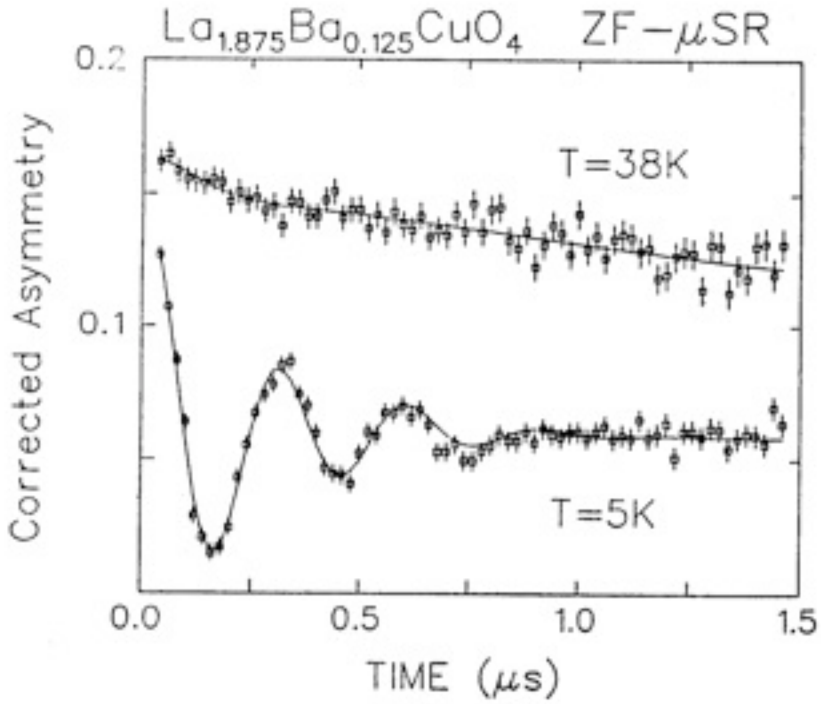
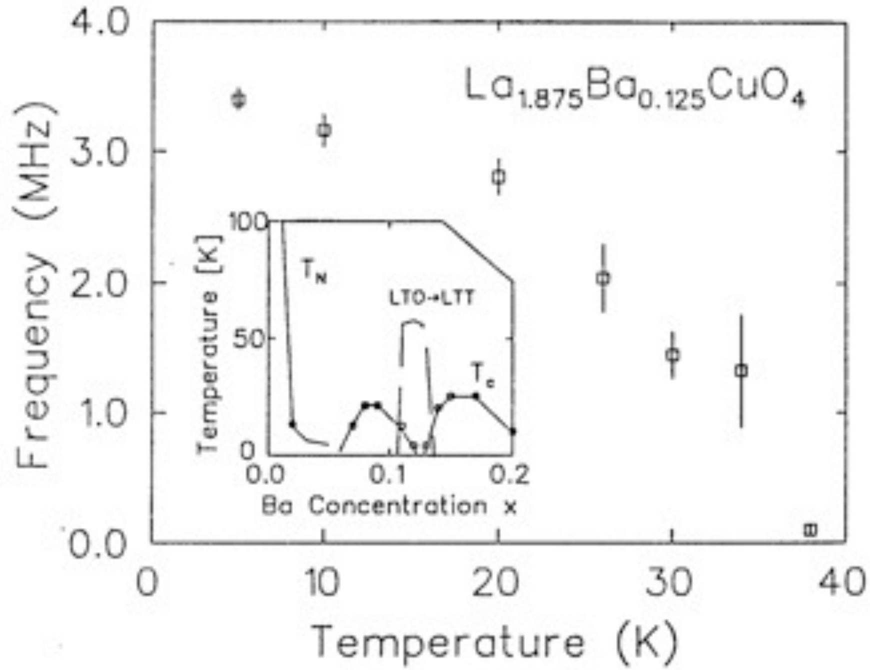
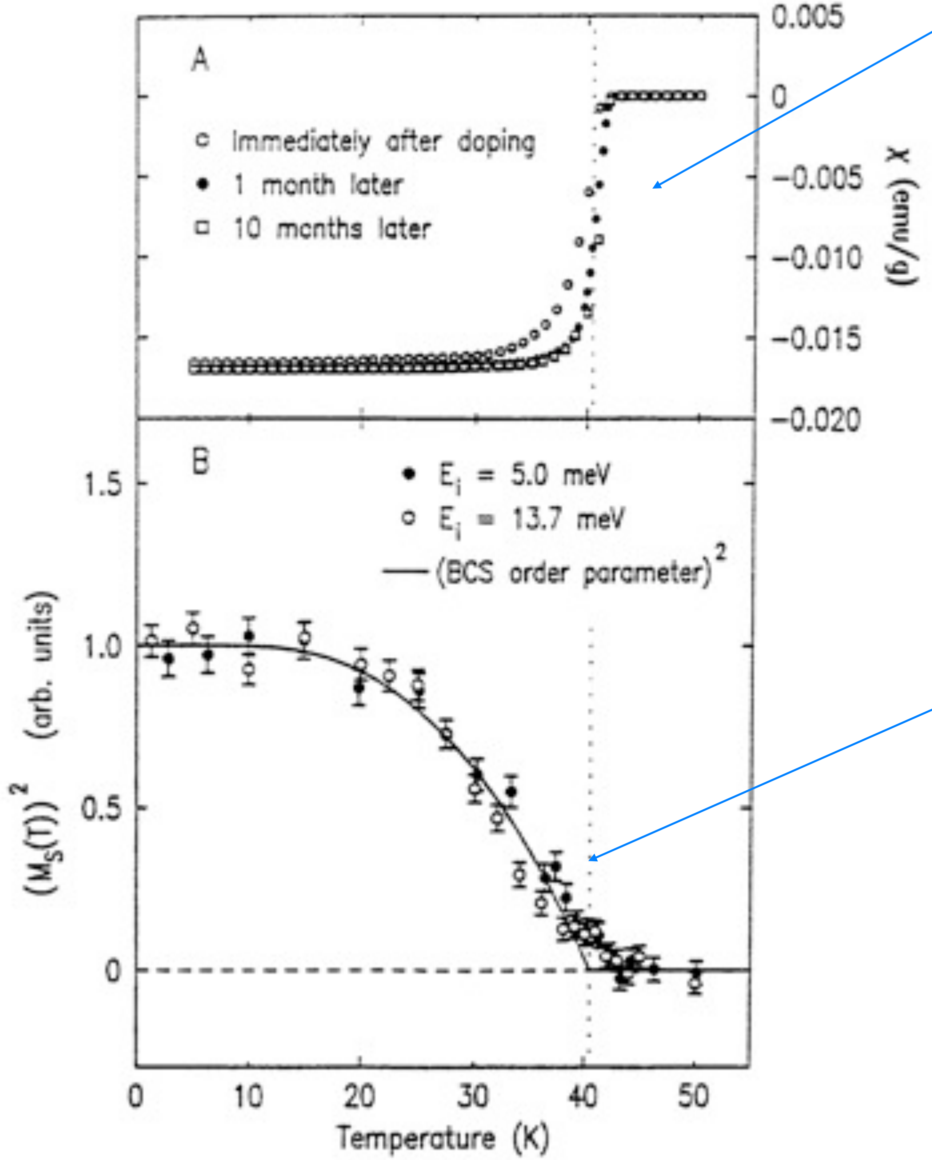
(Received 1 February 2002; published 16 July 2002)

static magnetism in the stripe : 1/8 systems ZF-μSR





Luke et al., 1991



$T_C = 42$ K

Stage-4 $La_2CuO_{4.11}$

from MIT

$T_N = 42$ K

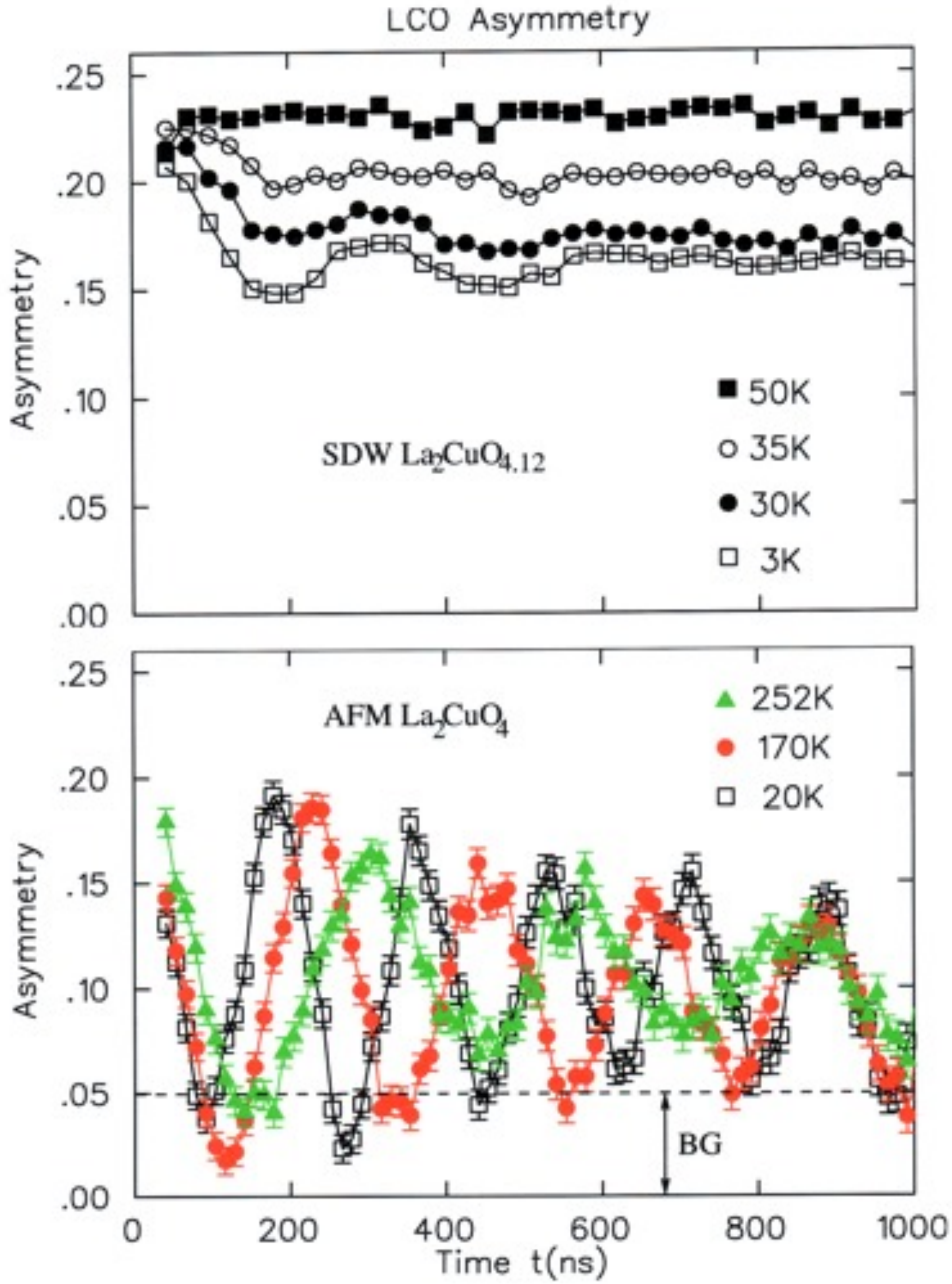
sharp satellite Bragg peak

long range spin correlations

ZF-μSR

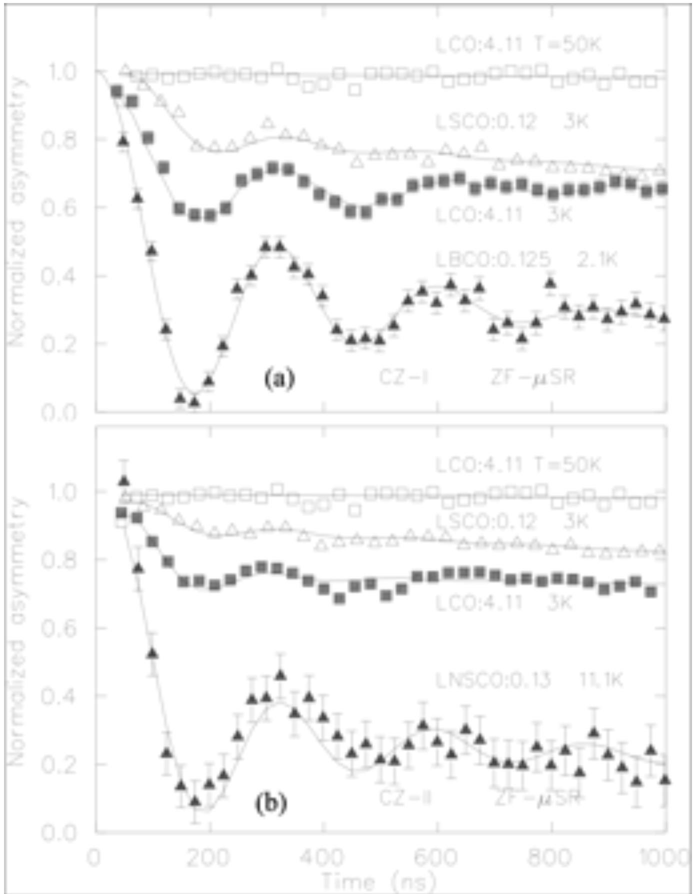
Finite Volume Fraction

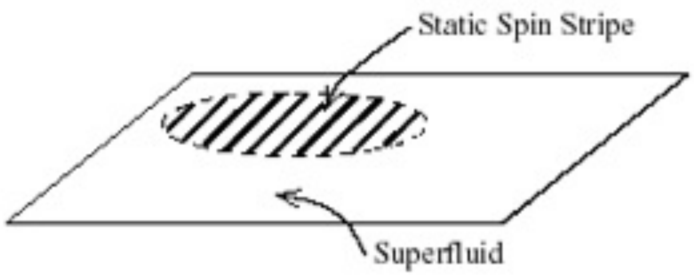
Full Volume Fraction



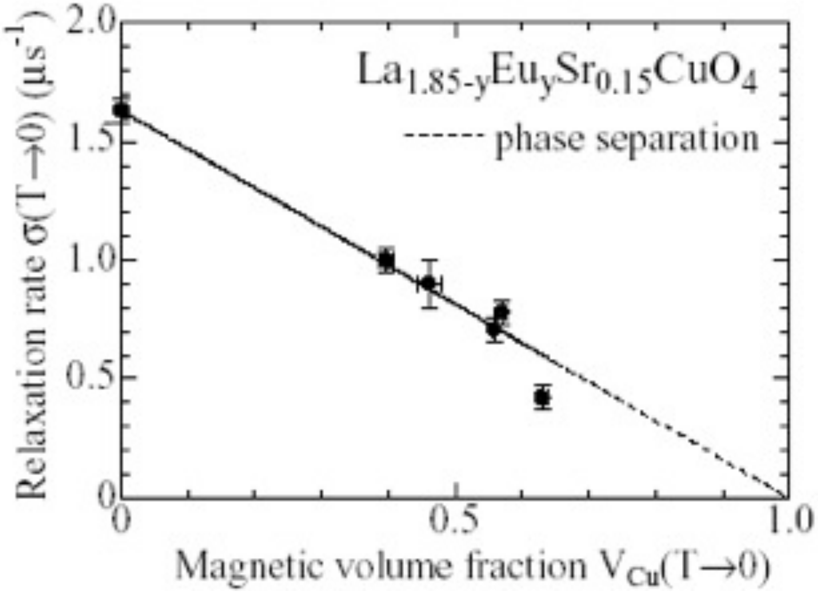
Stripe systems: ZF-μSR

in LCO:4.11, LSCO:0.12





Trade-off between magnetic volume and superfluid

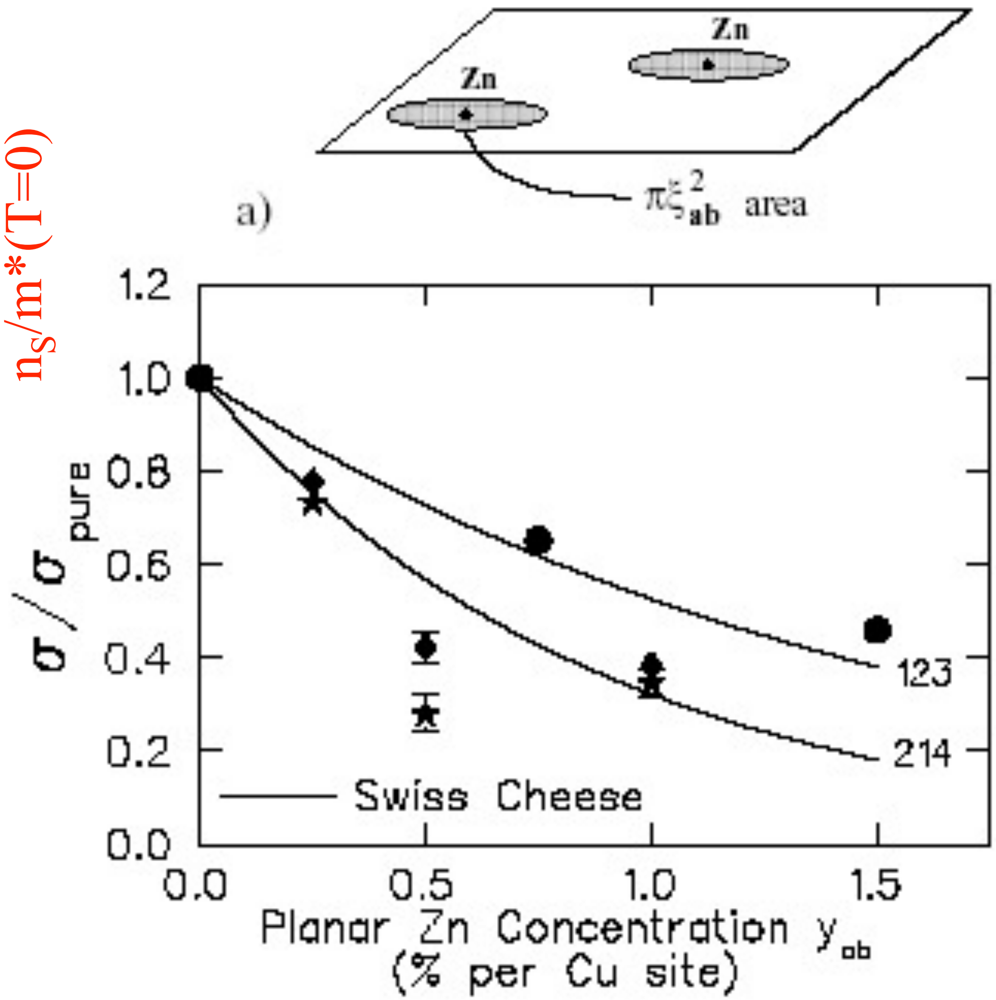


No superfluid on SDW island

with K.M. Kojima, S,Uchida

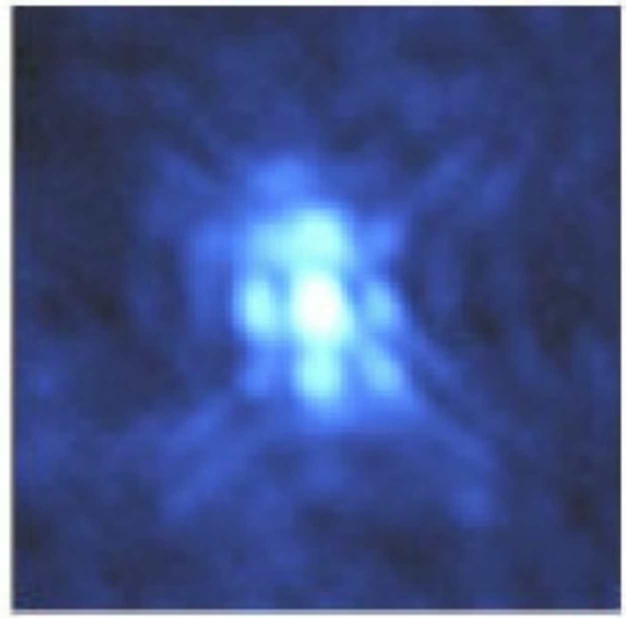
Zn-doped cuprates

TF-μSR: Superfluid density



PRL 1996

STM (Davis)



PHYSICAL REVIEW B **84**, 024527 (2011)

Static magnetic order of $Sr_4A_2O_6Fe_2As_2$ (A = Sc and V) revealed by Mössbauer and muon spin relaxation spectroscopies

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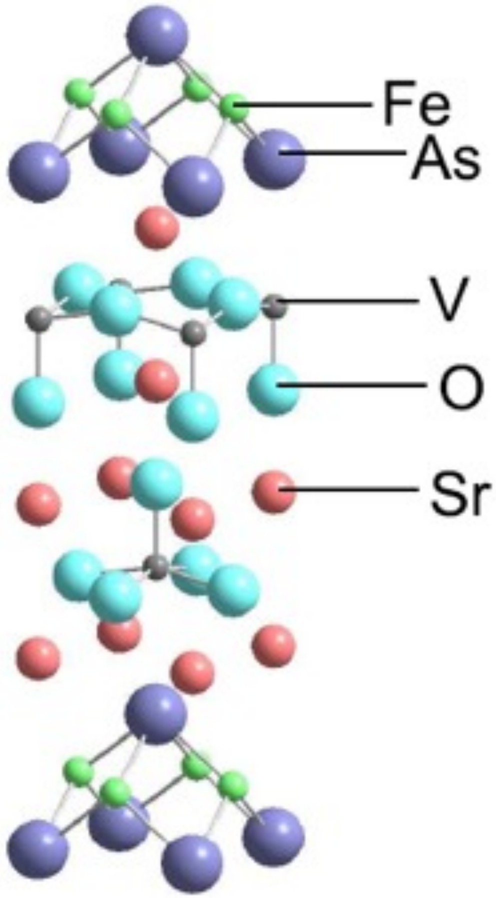
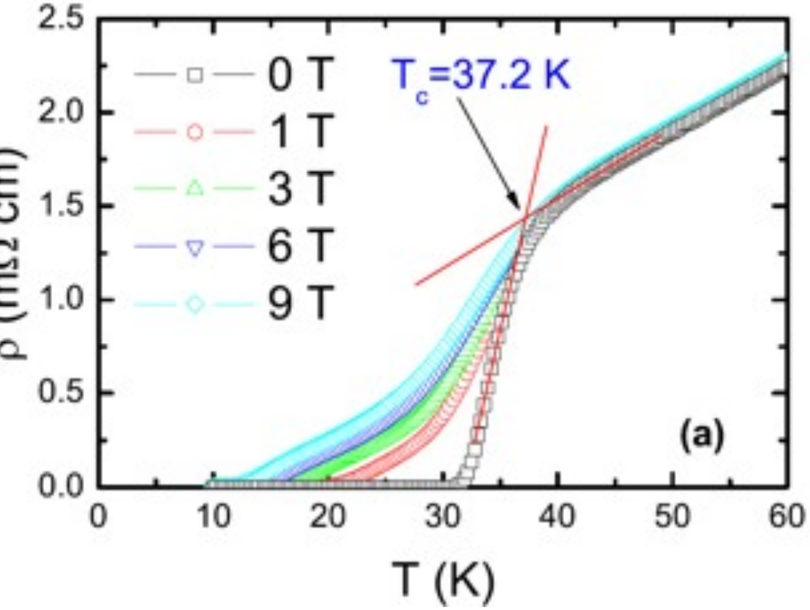
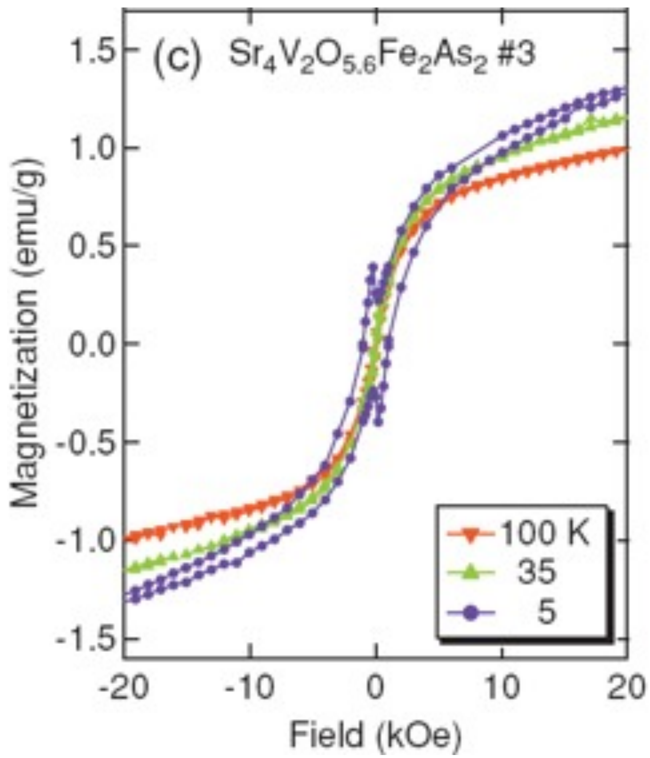
(Received 8 November 2010; revised manuscript received 30 March 2011; published 22 July 2011)



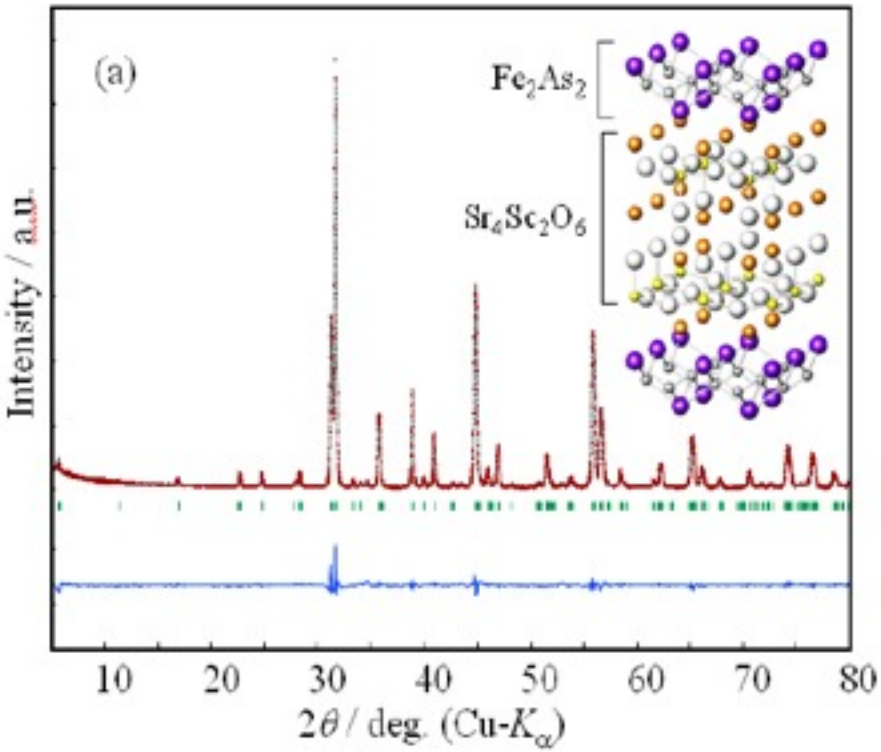
$Sr_4V_2O_6Fe_2As_2$

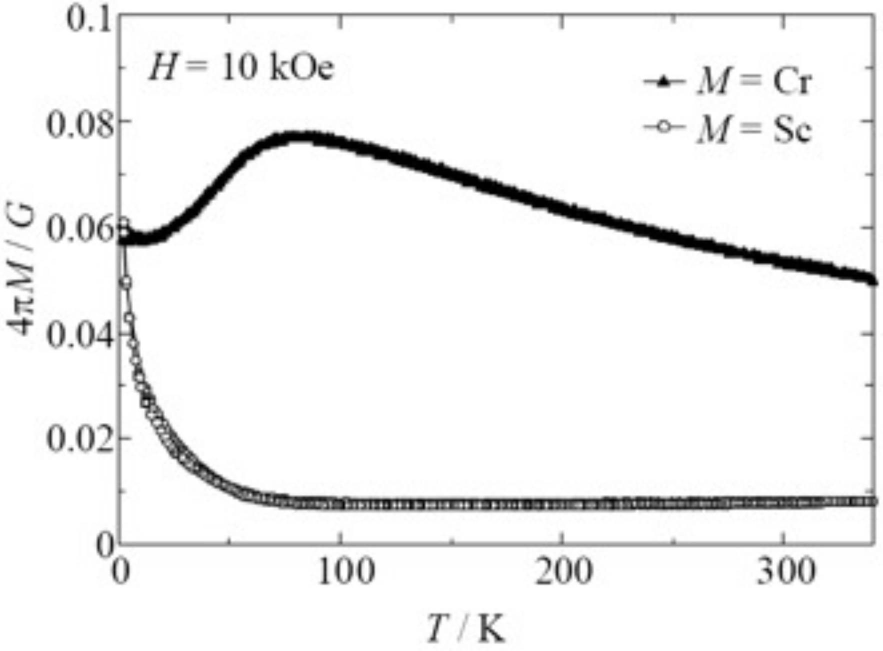


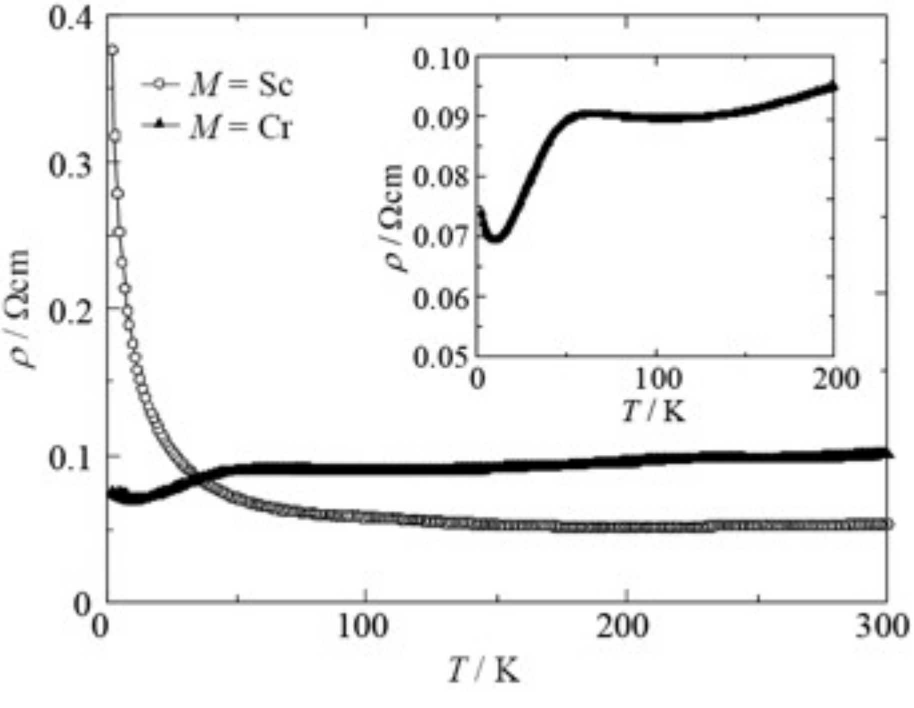


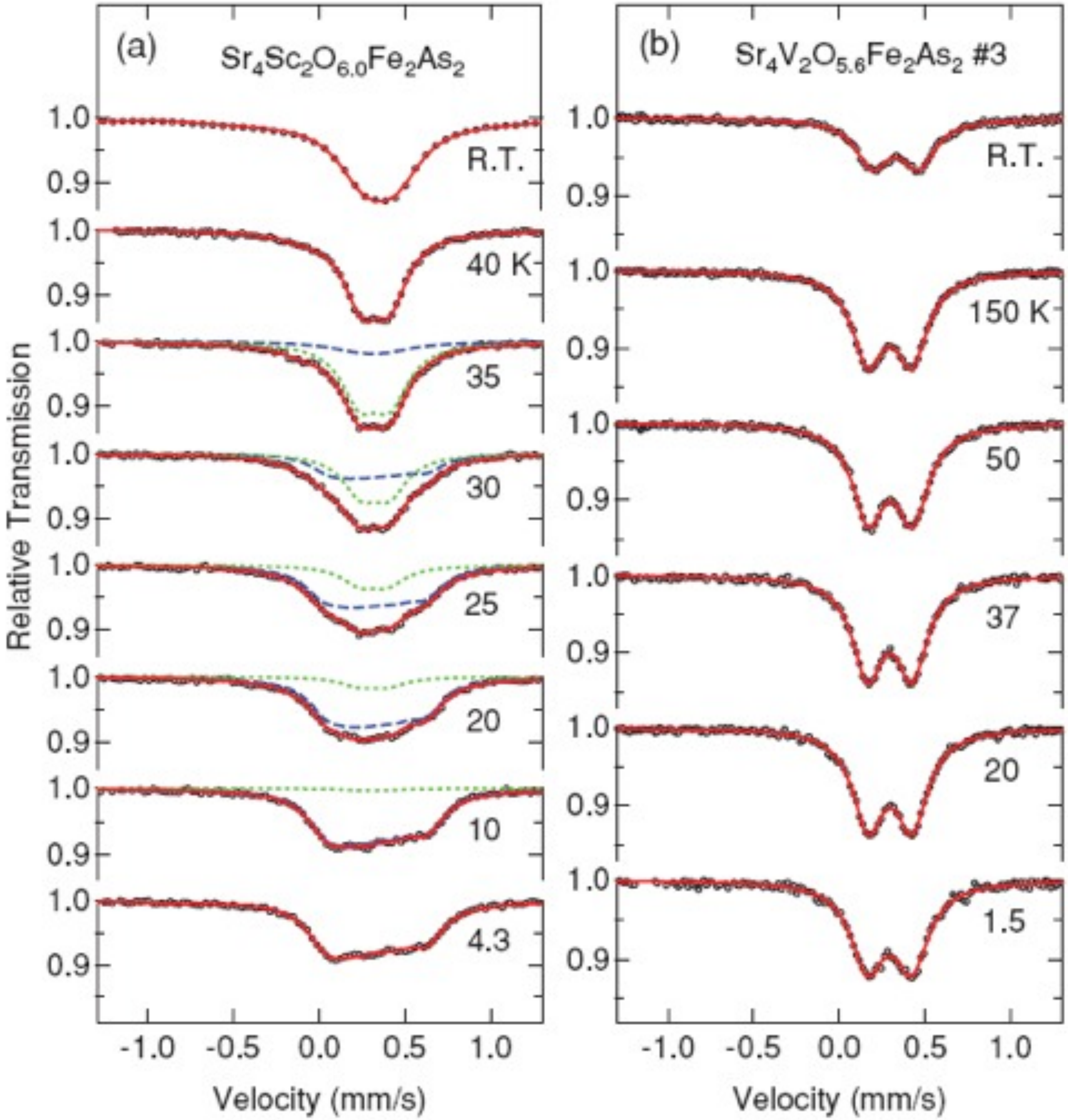
$(Fe_2As_2)(Sr_4M_2O_6)$

M = Sc

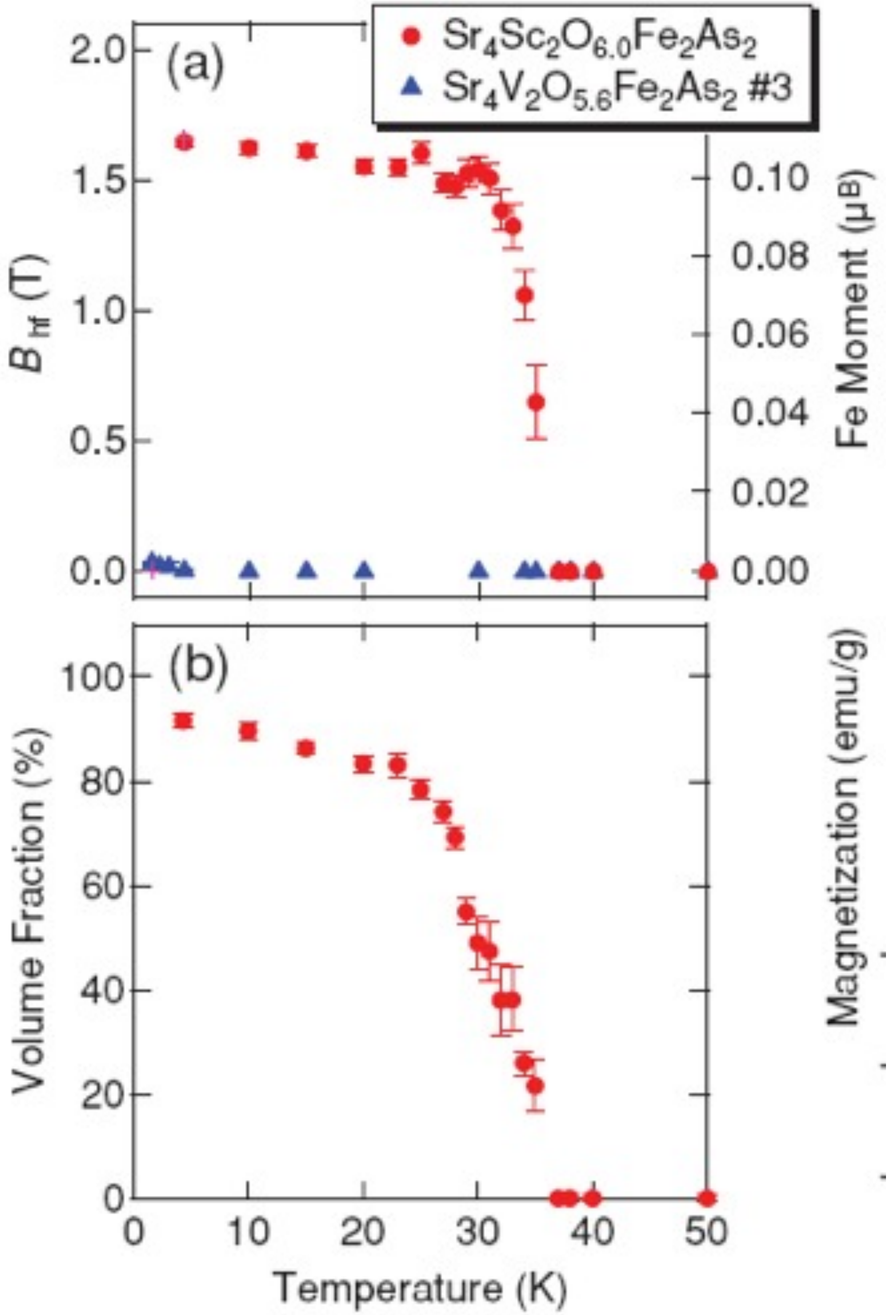




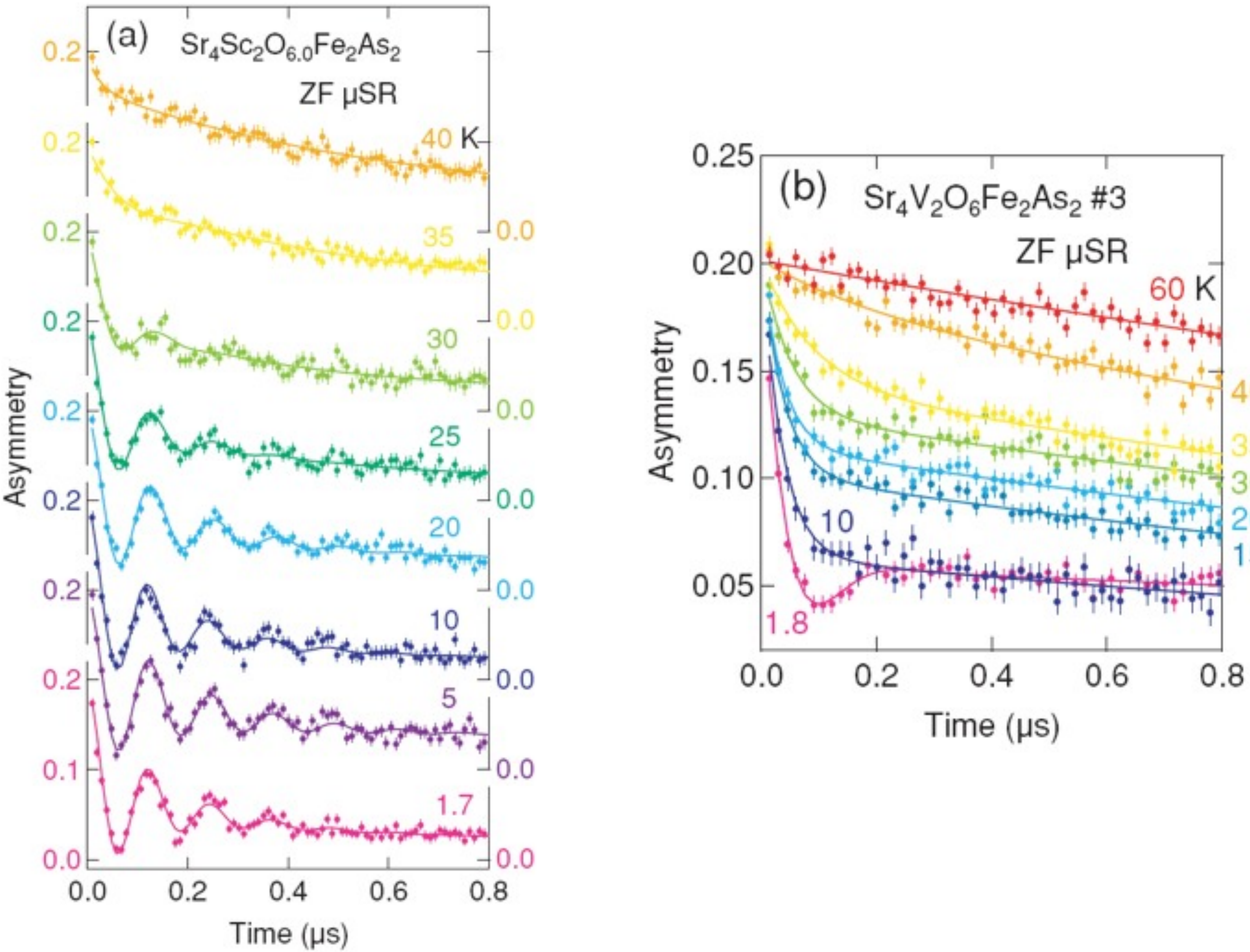




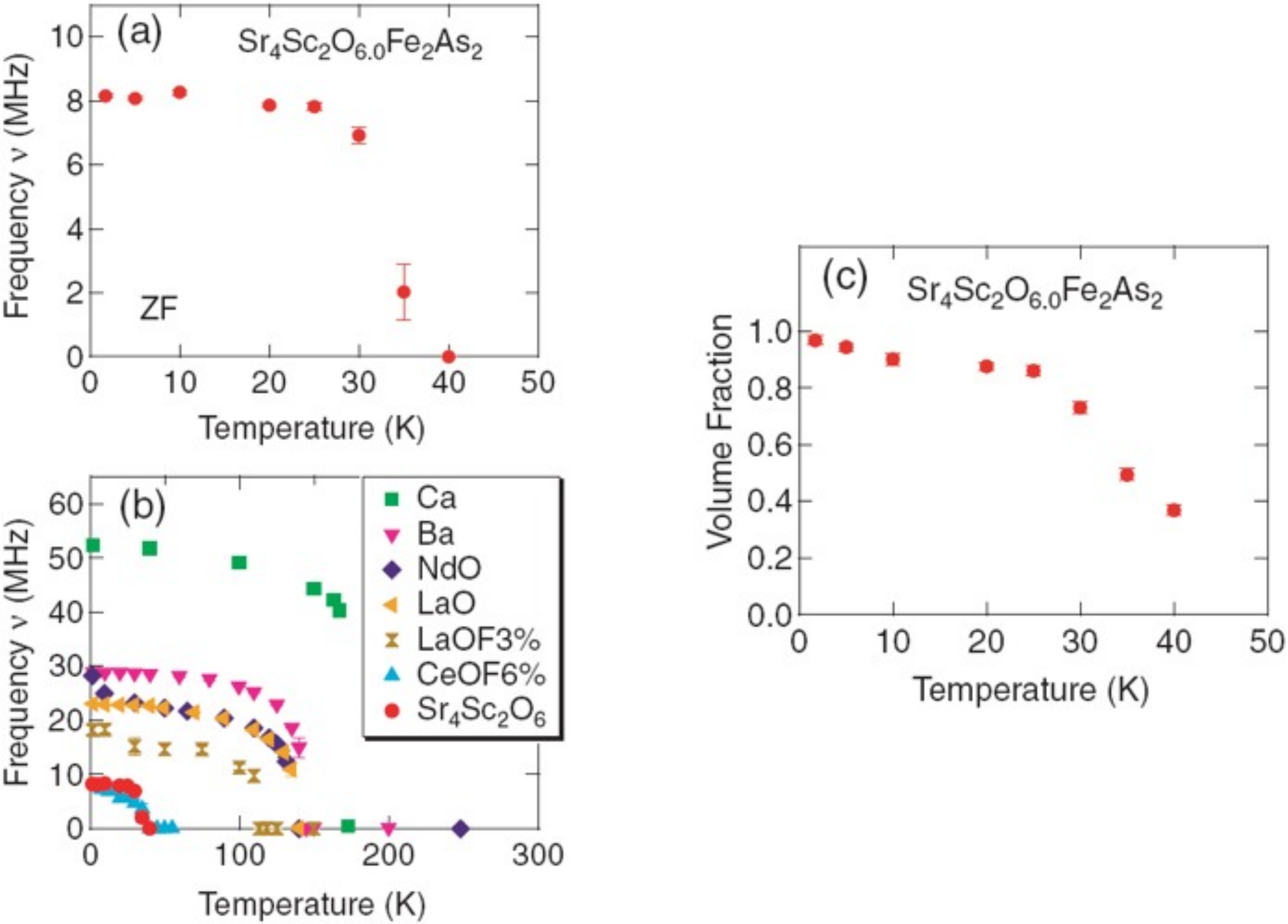
(a)
$Sr_4Sc_2O_{6.0}Fe_2As_2$
R.T.
40 K
35
30
25
20
10
4.3
Relative Transmission
Velocity (mm/s)
(b)
$Sr_4V_2O_{5.6}Fe_2As_2$ #3
R.T.
150 K
50
37
20
1.5
Velocity (mm/s)

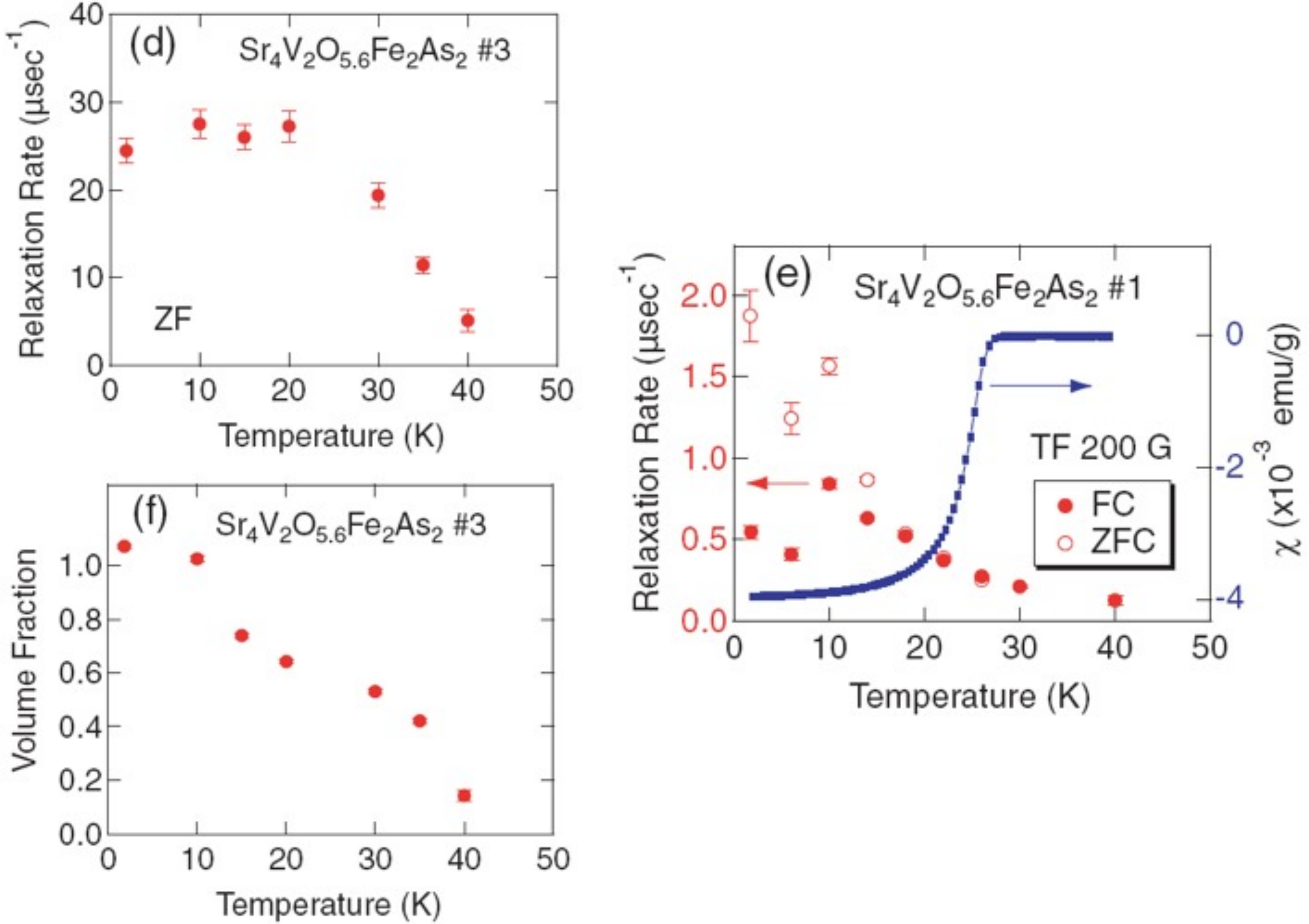


(a)
Sr4Sc2O6.0Fe2As2
Sr4V2O5.6Fe2As2 #3
B hf (T)
Fe Moment (μB)
2.0
1.5
1.0
0.5
0.0
0.10
0.08
0.06
0.04
0.02
0.00
(b)
Volume Fraction (%)
Magnetization (emu/g)
100
80
60
40
20
0
0
10
20
30
40
50
Temperature (K)



Thursday, August 18, 2011


(a)
$Sr_4Sc_2O_{6.0}Fe_2As_2$
ZF
Frequency ν (MHz)
Temperature (K)
0
2
4
6
8
10
0
10
20
30
40
50
(b)
Ca
Ba
NdO
LaO
LaOF3%
CeOF6%
$Sr_4Sc_2O_6$
Frequency ν (MHz)
Temperature (K)
0
10
20
30
40
50
60
0
100
200
300
(c)
$Sr_4Sc_2O_{6.0}Fe_2As_2$
Volume Fraction
Temperature (K)
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50



(d)
$Sr_4V_2O_{5.6}Fe_2As_2$ #3
ZF
Relaxation Rate (μsec^{-1})
Temperature (K)
(f)
$Sr_4V_2O_{5.6}Fe_2As_2$ #3
Volume Fraction
Temperature (K)
(e)
$Sr_4V_2O_{5.6}Fe_2As_2$ #1
TF 200 G
FC
ZFC
Relaxation Rate (μsec^{-1})
χ (x10^{-3} emu/g)
Temperature (K)

Static magnetic order of quasi-two-dimensional FeAs compounds $Sr_4A_2O_{6-x}Fe_2As_2$, with $A =$ Sc and V, has been detected by ^{57}Fe Mössbauer and muon spin relaxation (μSR) spectroscopies. The nonsuperconducting stoichiometric ($x = 0$) $A =$ Sc system exhibits a static internal/hyperfine magnetic field both at the ^{57}Fe and μ^+ sites, indicating antiferromagnetic order of Fe moments below $T_N = 35$ K with ~0.1 bohr magneton per Fe at $T = 2$ K. The superconducting and oxygen deficient ($x = 0.4$) $A =$ V system exhibits a static internal field only at the μ^+ site below $T_N \sim 40$ K, indicating static magnetic order of V moments coexisting with superconductivity without freezing of Fe moments. These results suggest that the 42622 FeAs systems belong to the same paradigm with the 1111 and 122 FeAs systems with respect to magnetic behavior of Fe moments.

Phase separation and suppression of critical dynamics at quantum phase transitions of MnSi and $(Sr_{1-x}Ca_x)RuO_3$

Y. J. UEMURA[1]*, T. GOKO[1,2], I. M. GAT-MALUREANU[1,3], J. P. CARLO[1], P. L. RUSSO[1], A. T. SAVICI[1], A. ACZEL[4], G. J. MacDOUGALL[4], J. A. RODRIGUEZ[4], G. M. LUKE[4], S. R. DUNSIGER[4], A. McCOLLAM[5], J. ARAI[2], CH. PFLEIDERER[6], P. BÖNI[6], K. YOSHIMURA[7], E. BAGGIO-SAITOVITCH[8], M. B. FONTES[8], J. LARREA[8], Y. V. SUSHKO[9] AND J. SERENI[10]

Nature Physics 3 (2007) 29 - 35

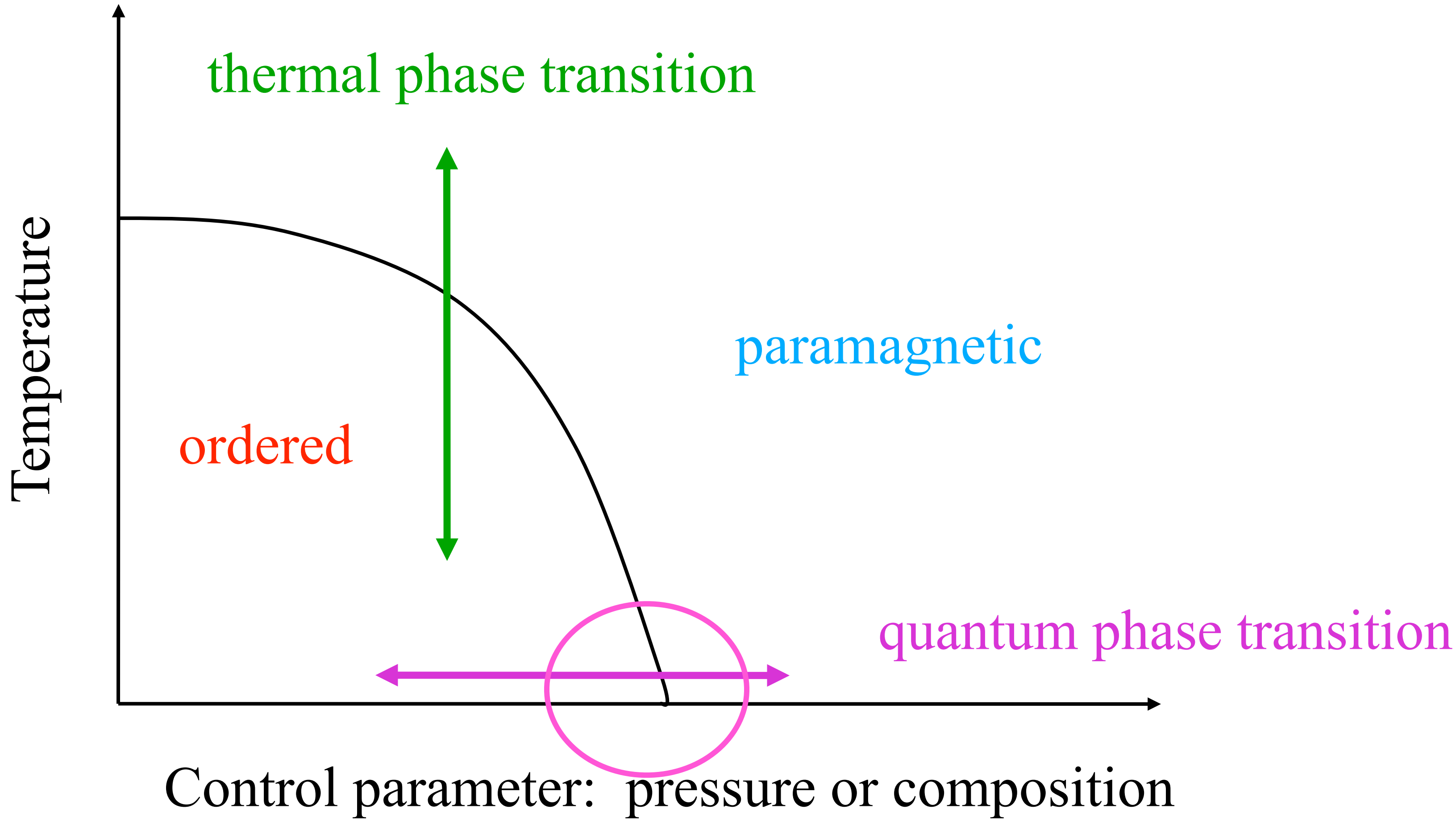
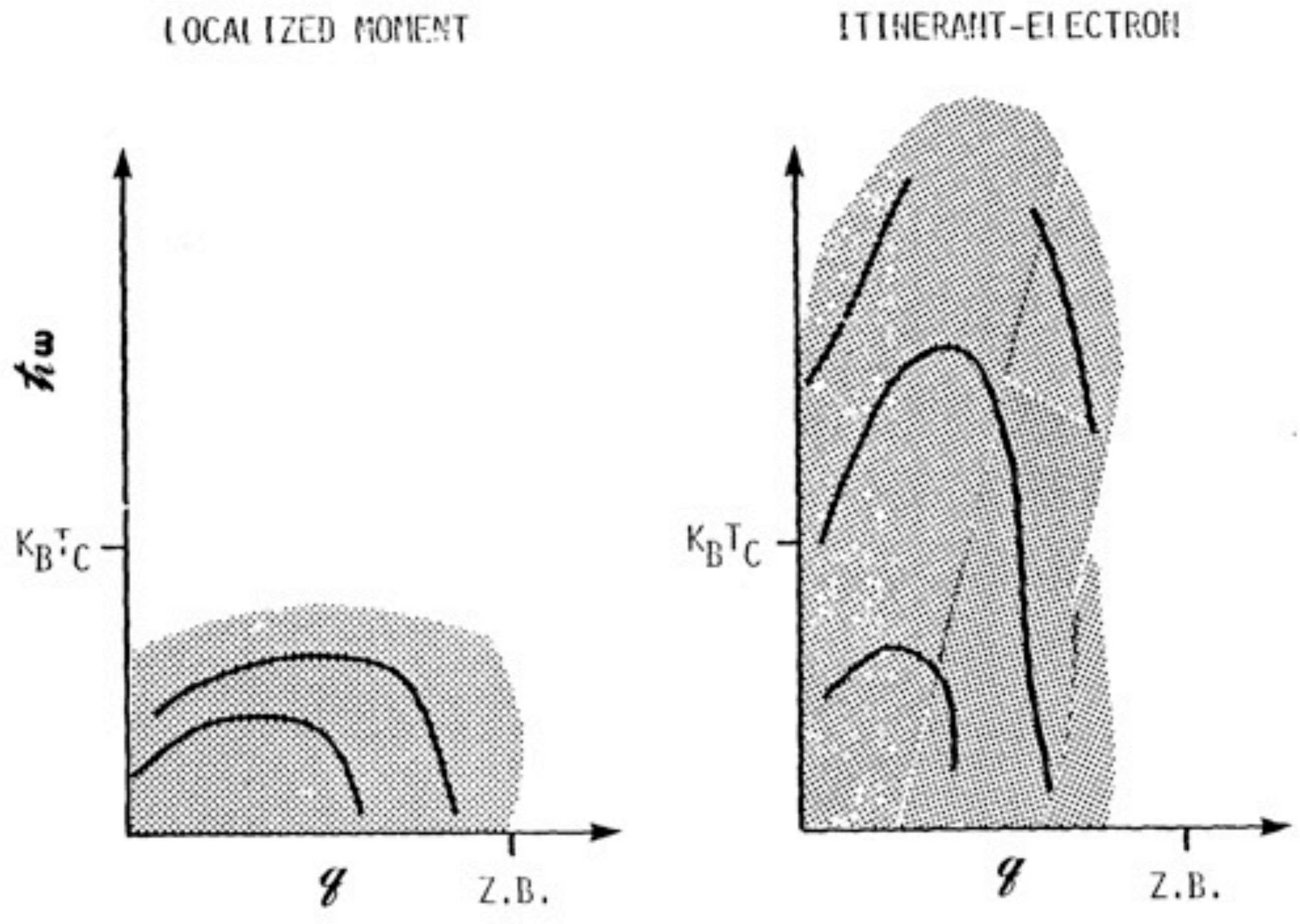

thermal phase transition
paramagnetic
Temperature
ordered
quantum phase transition
Control parameter: pressure or composition

Table 1. T_c versus Spin-wave Stiffness in Ferromagnets

	MnSi	Ni	Fe	Pd_2MnSn	EuO
T_c [K]	29	630	1020	193	69
Spin-wave Stiffness D [meV Å^2]	50	400	320	110	13.5
$E_{sw}{}^{zb}$ at zone boundary [meV]	37	496	373	42	7.9
$E_{sw}{}^{zb}/kT_c$ (measured)	15	9.1	4.2	2.5	1.3
$E_{sw}{}^{zb}/kT_c$ (NN Heisenberg)	5	4.6	2.9	2.0	1.3
Ordered Moment $S(T \to 0)$	0.18	0.3	1.1	2.0	3.5
P_{para}/P_{ord} *	4.1	1.5	1.05	1.0	1.0

* Rhodes-Wohlfarth Ratio

← **itinerant** **localized** →



In both cases,

$$\chi \propto \frac{1}{T - T_C}$$

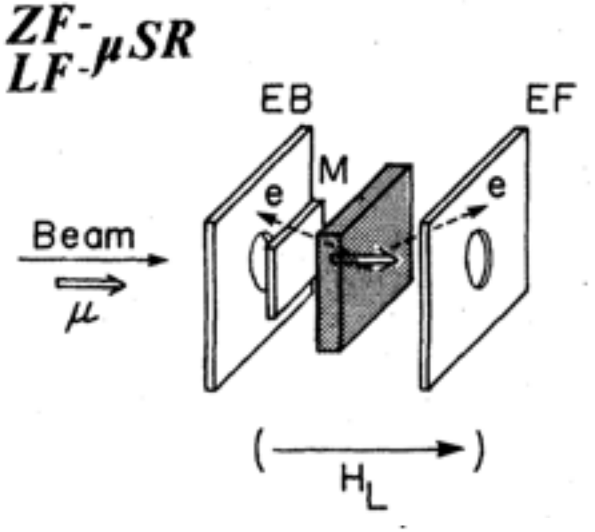
Heisenberg

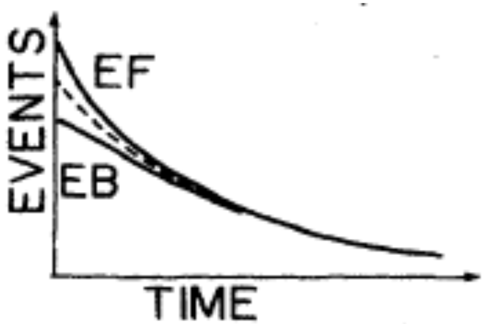
Slater

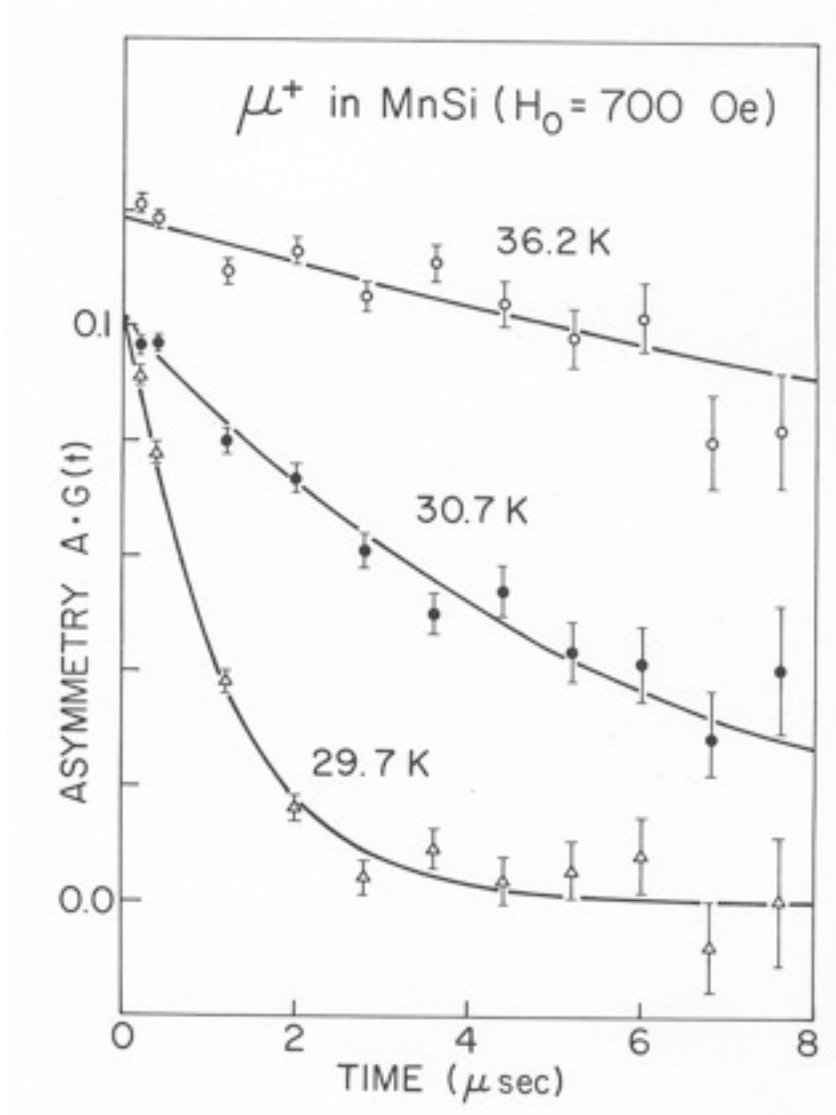
Stoner

Doniach

Moriya


ZF-
LF-μSR
EB
EF
M
e
e
Beam
μ
H_L

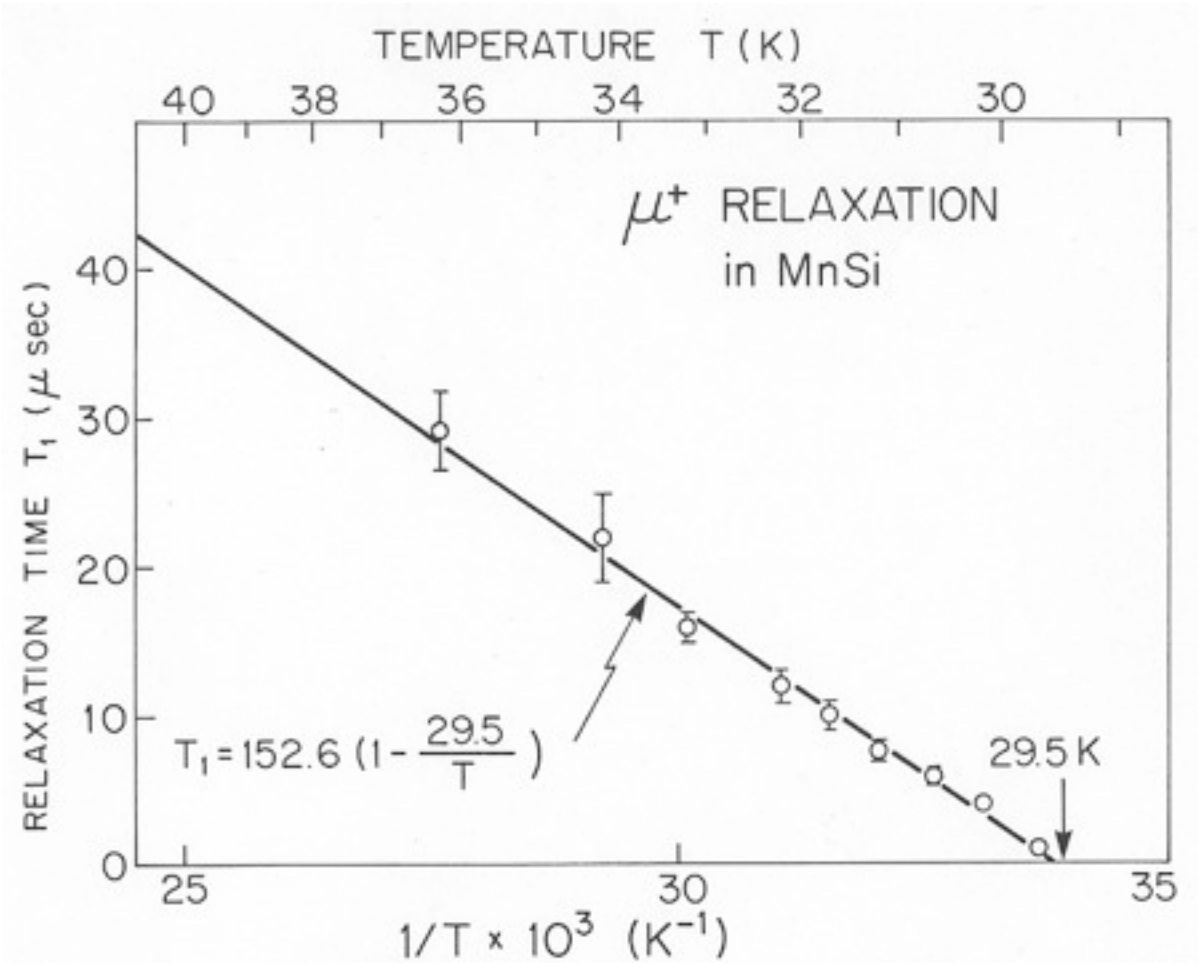

EVENTS
EF
EB
TIME

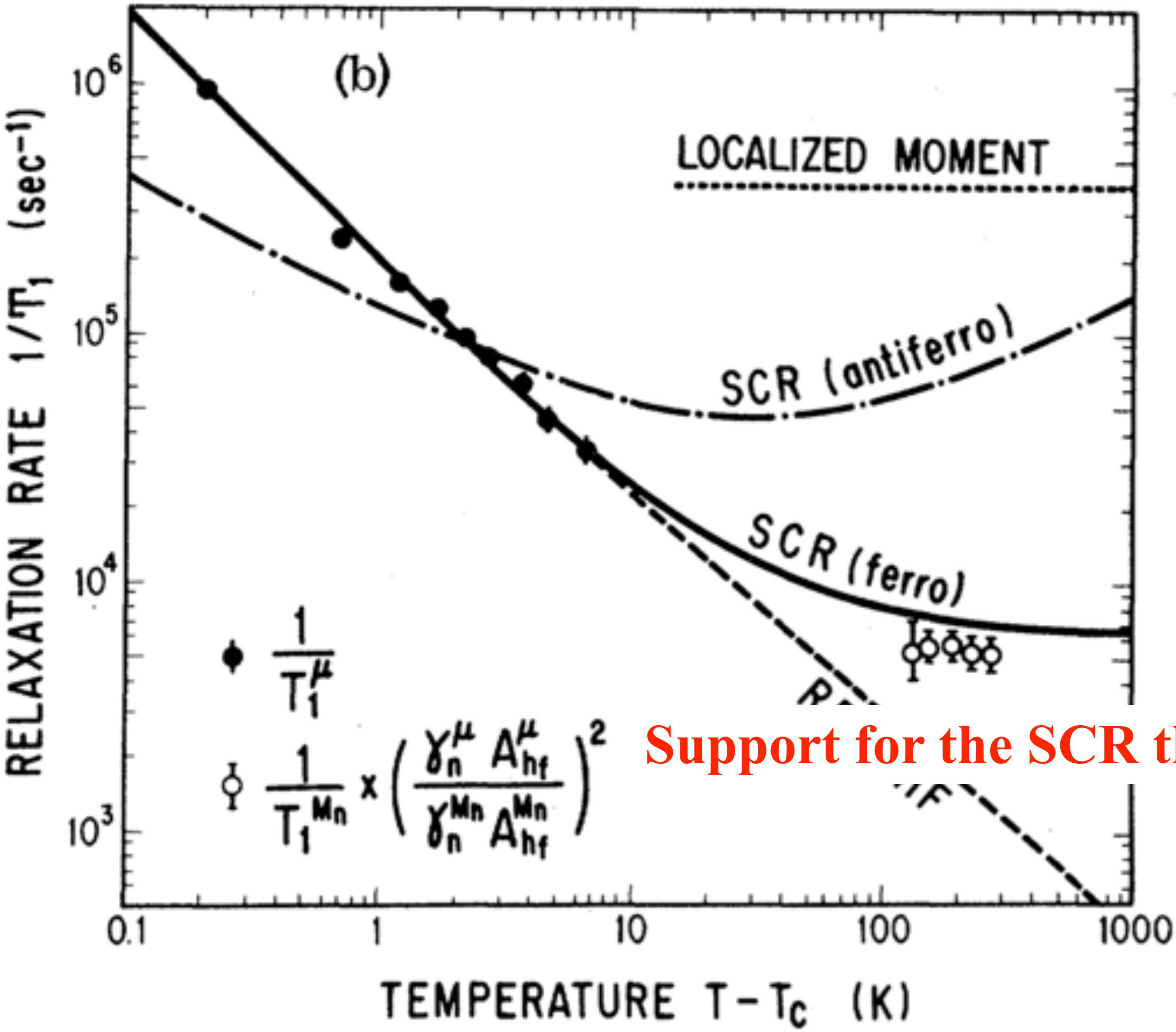

μ+ in MnSi (H_0 = 700 Oe)
36.2 K
30.7 K
29.7 K
0.1
0.0
ASYMMETRY A·G(t)
0
2
4
6
8
TIME (μsec)

1979 PRL

μSR in MnSi: PRL 1978

$H_{LF} = 700$ G



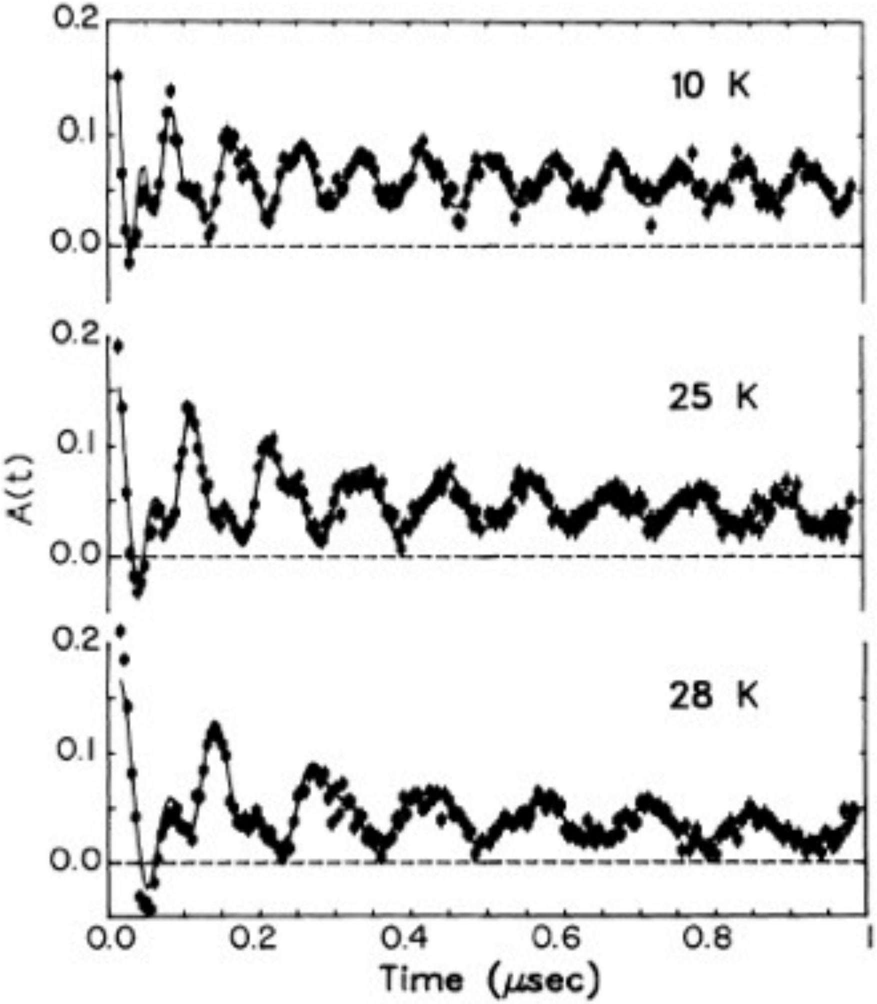


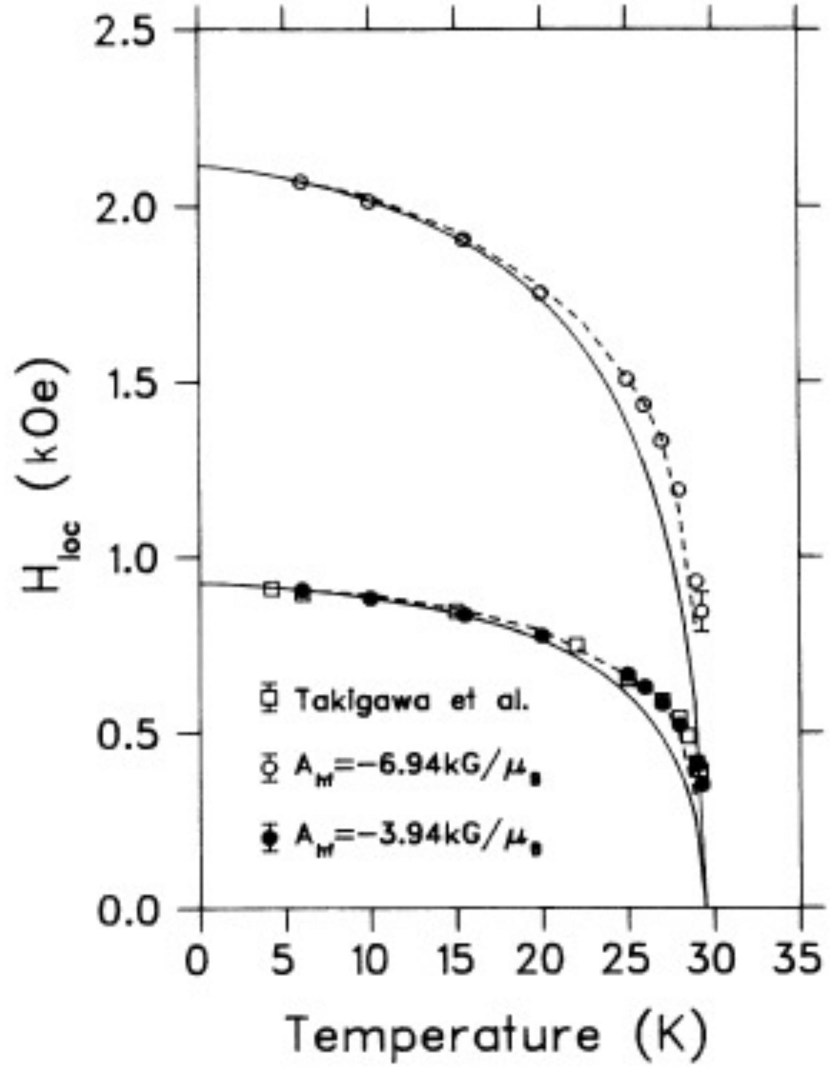
Support for the SCR theory of Moriya

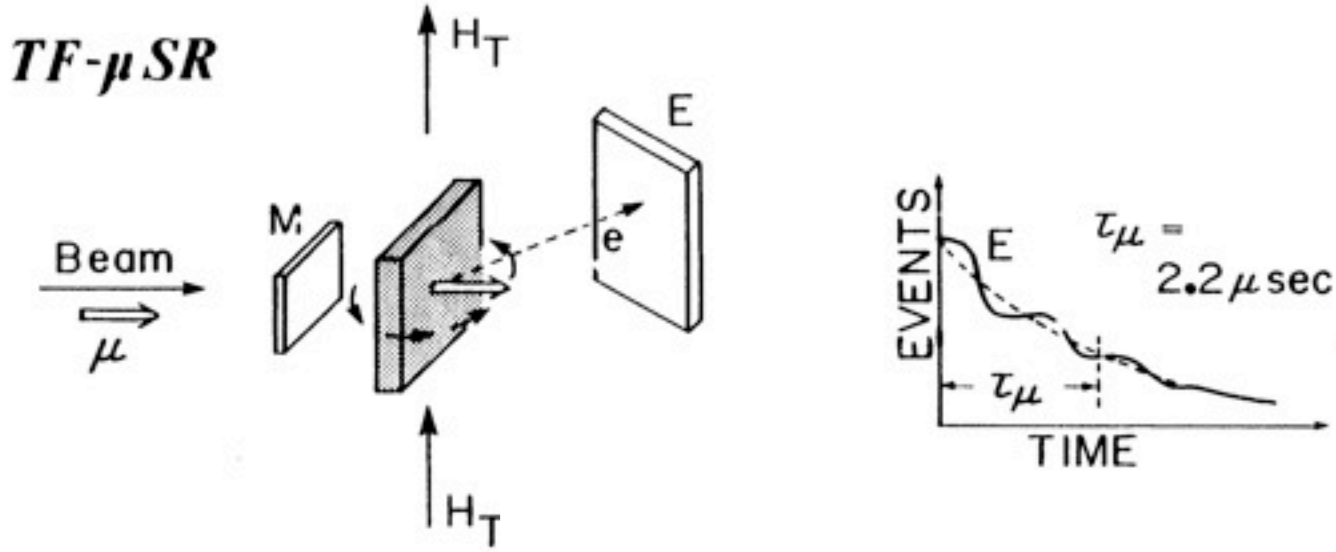
μSR covers wide temperature region, complementary to NMR

ZF precession in ordered state:

frequency scales with ordered moment

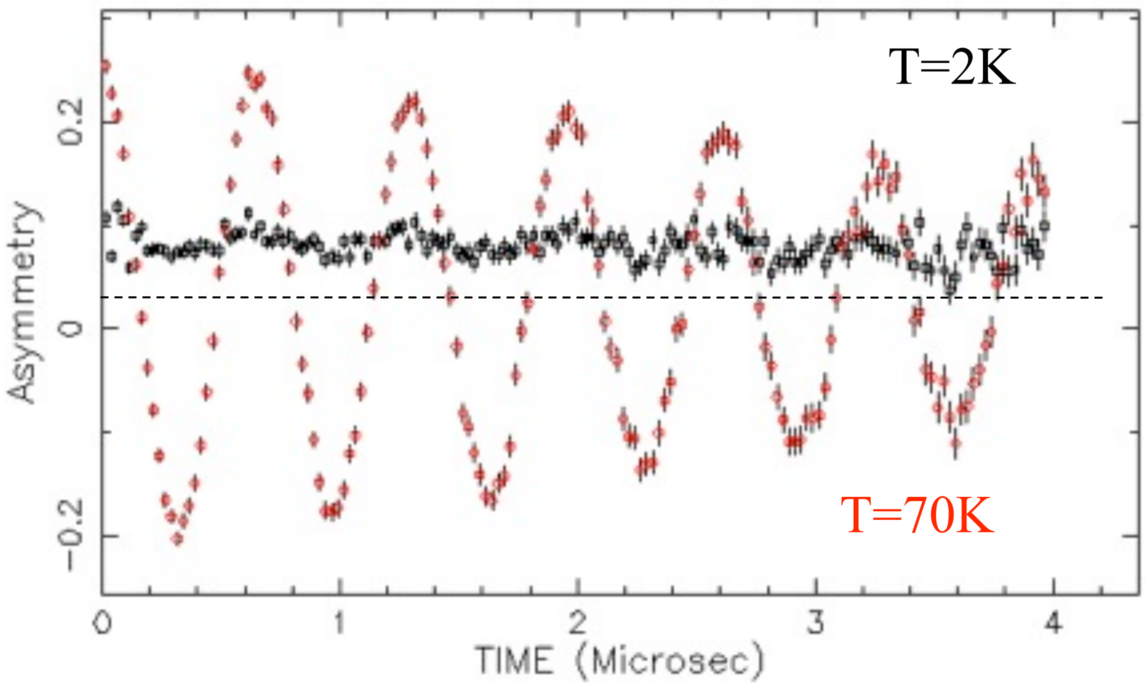




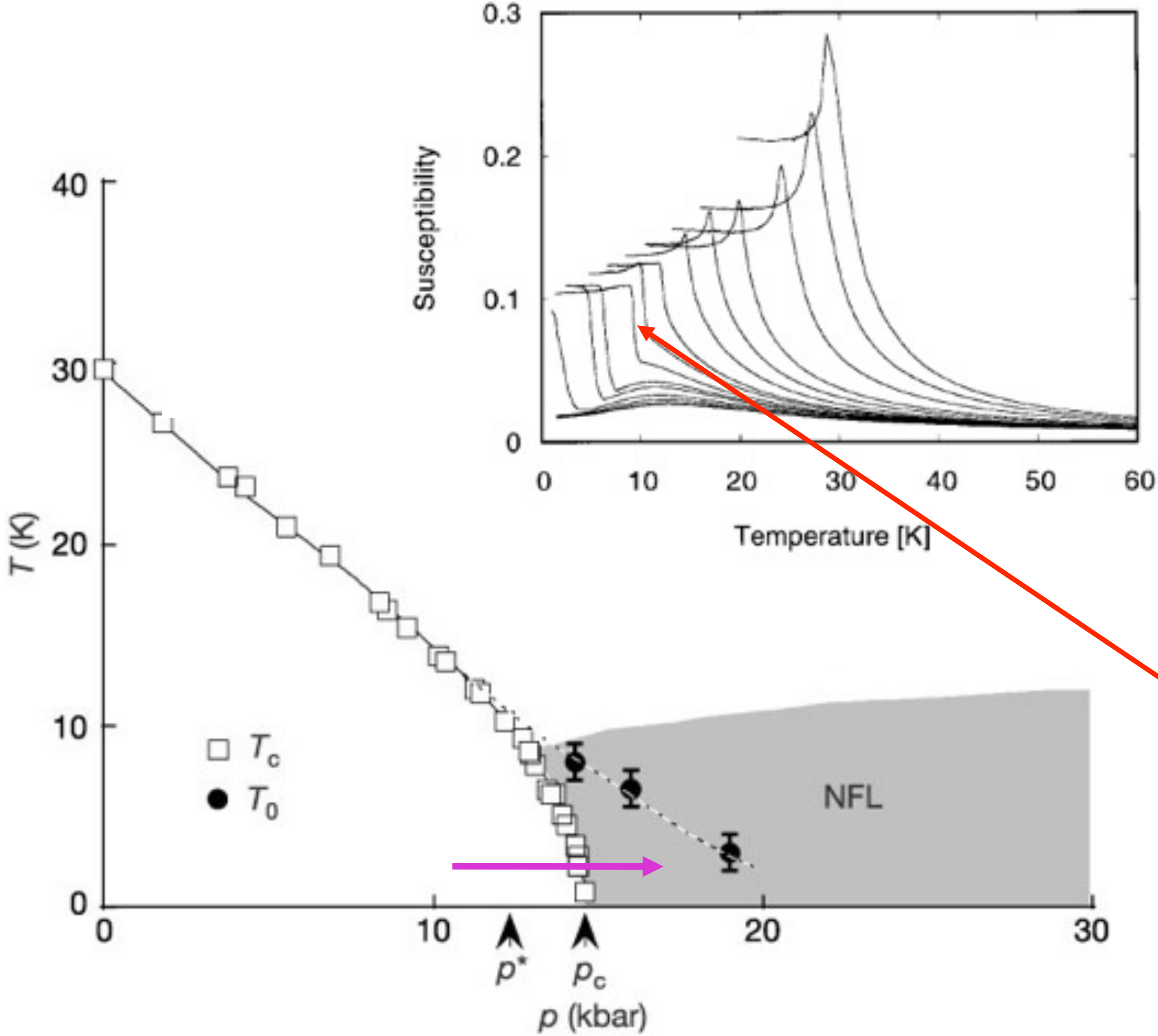


Weak TF 100 G

Precession amplitude represents para- / non-magnetic volume



Pfleiderer et al., PRB1997; Nature2004



ɔn scatt.

nomalous short-
ınge correlations
p* > p

Transport /
suscepti.
weakly
first order
transition
above
p*~12 kbar

1998 - MuSR in MnSi under applied pressure

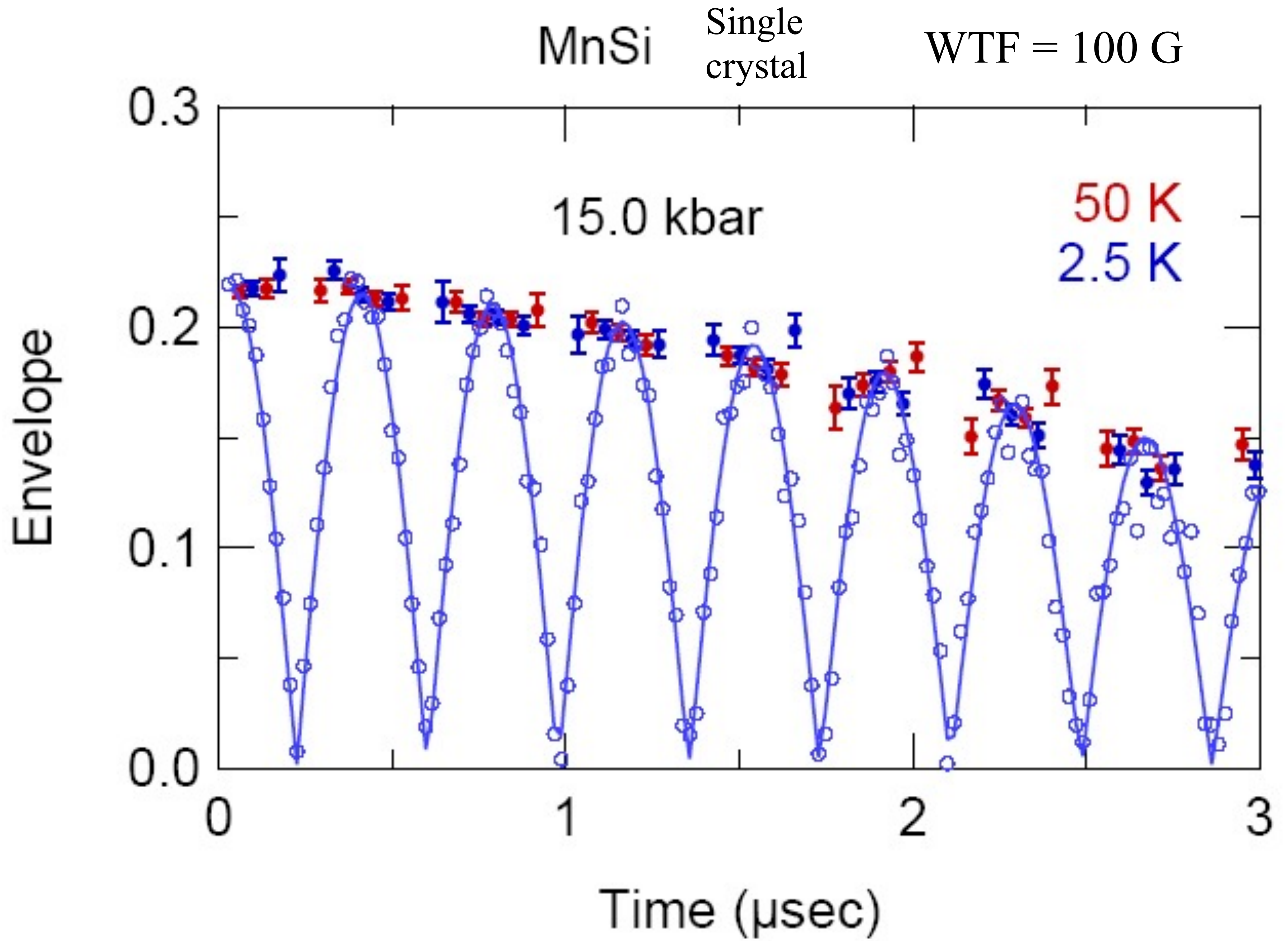
---- difficulty in large background from cell

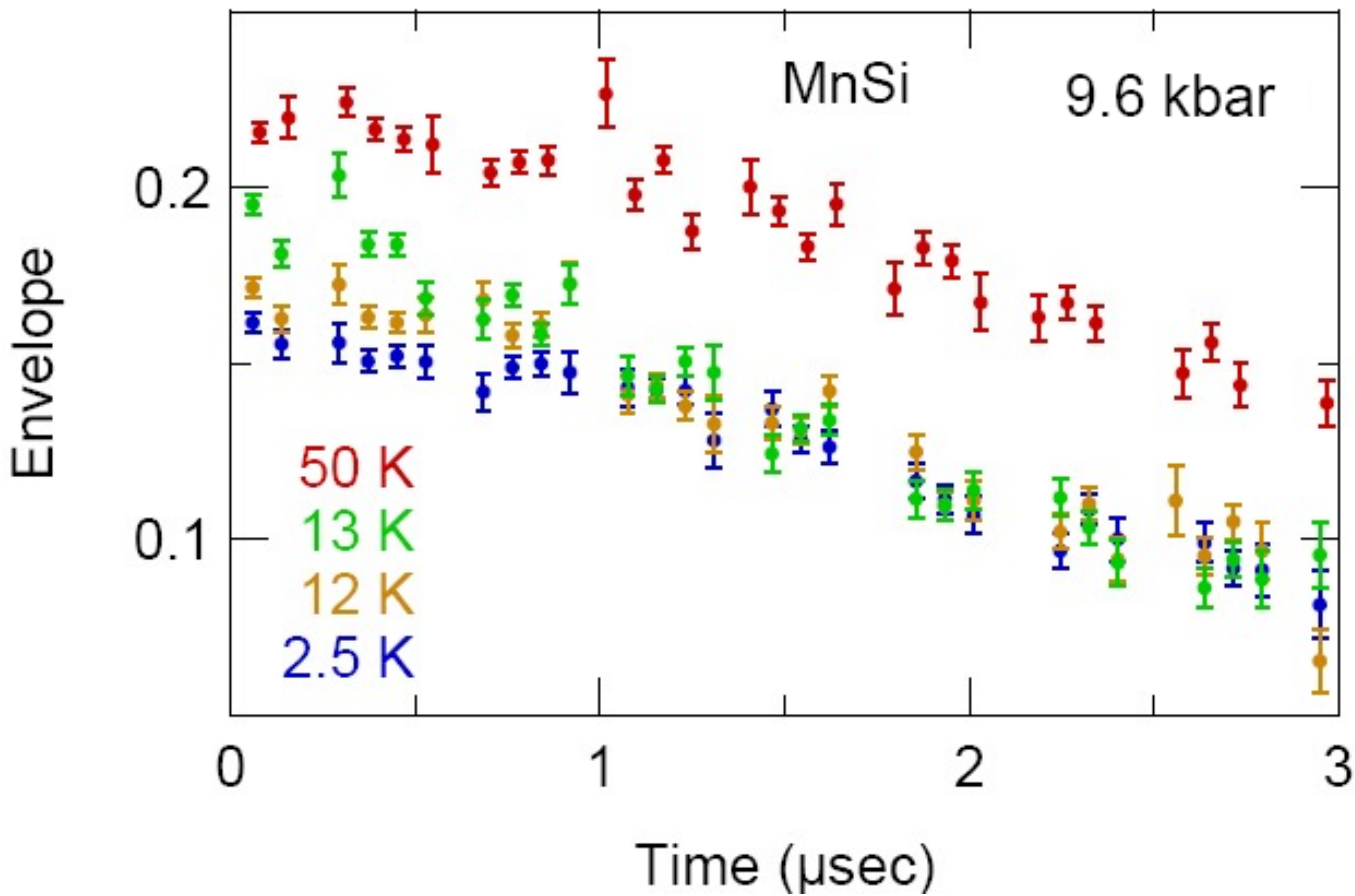
and limited accessible pressure

2004 Summer and November: major progress with T. Goko

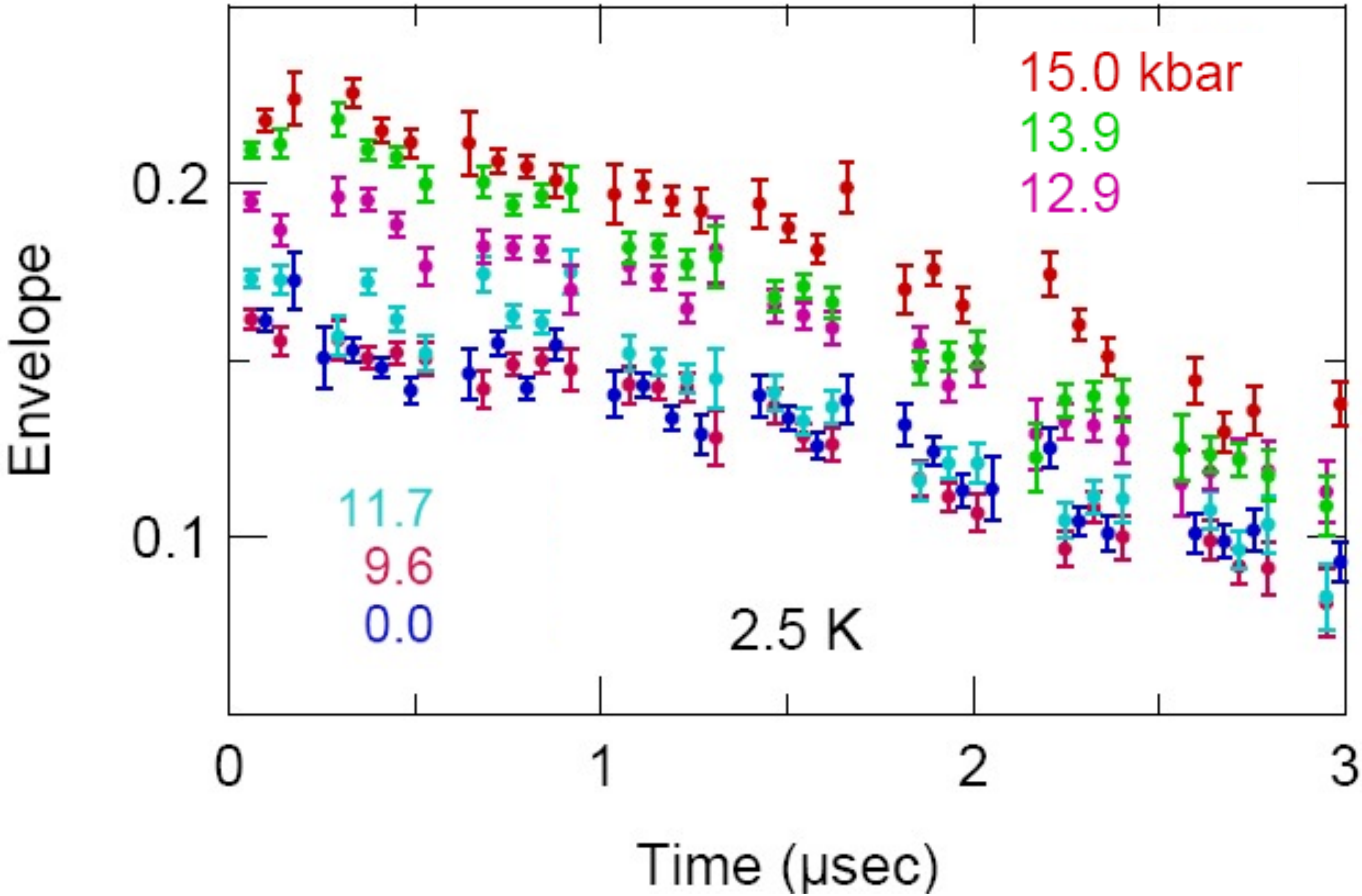
MuSR in Transeverse Field of 100 G.

Single crystal specimen from Pfleiderer (TU Munich)

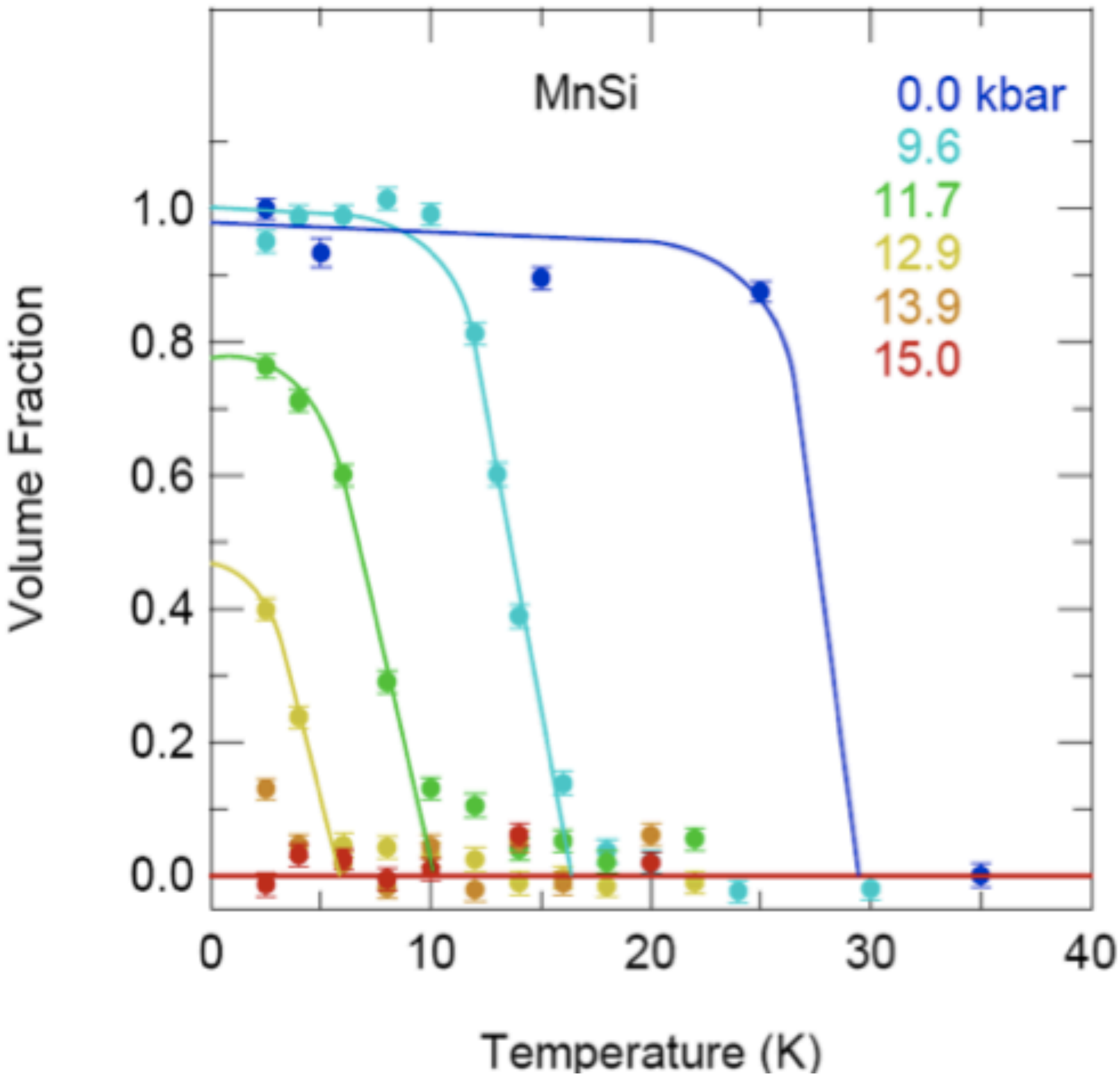

MnSi
Single crystal
WTF = 100 G
15.0 kbar
50 K
2.5 K
Envelope
Time (μsec)
0.0
0.1
0.2
0.3
0
1
2
3

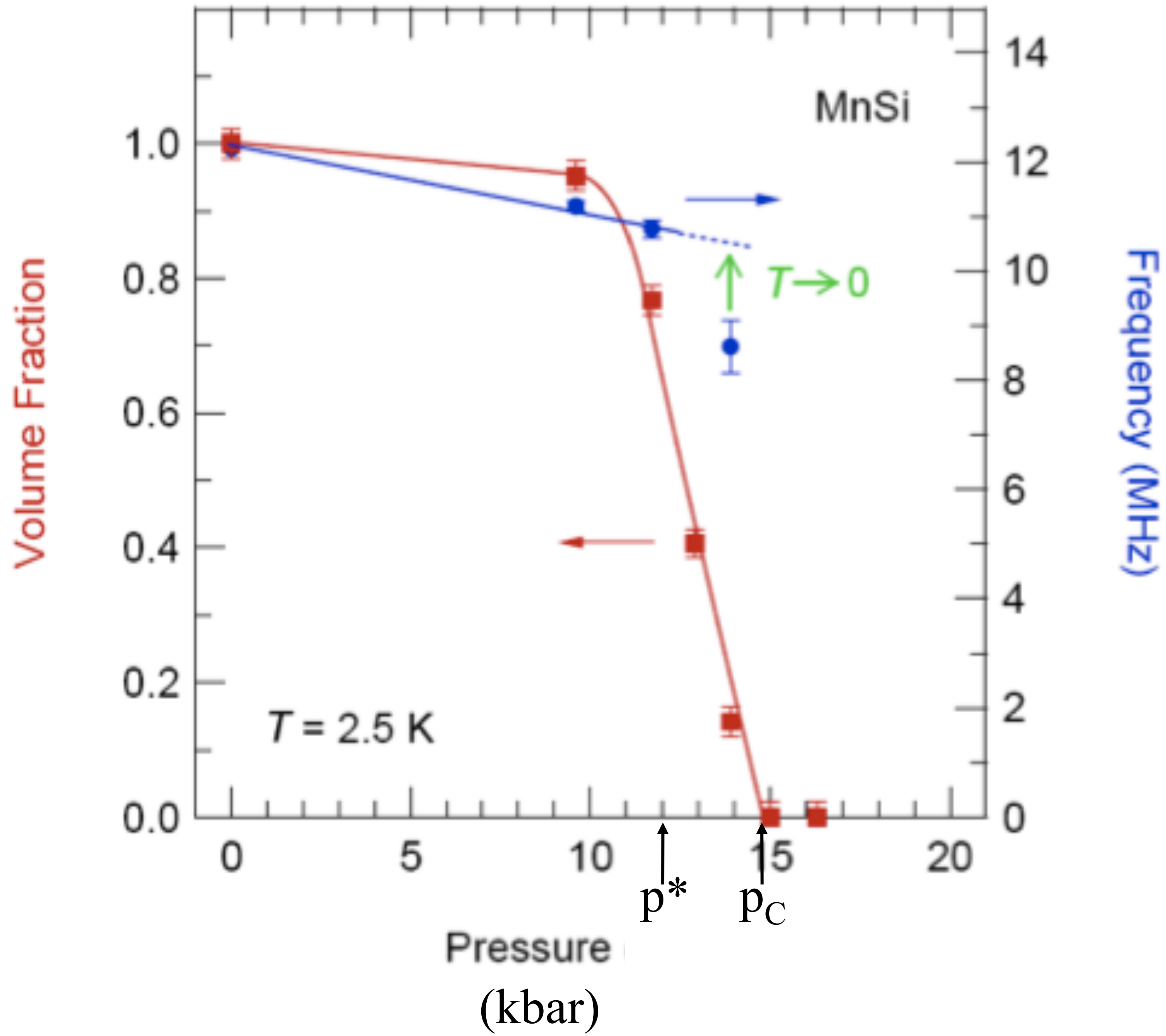


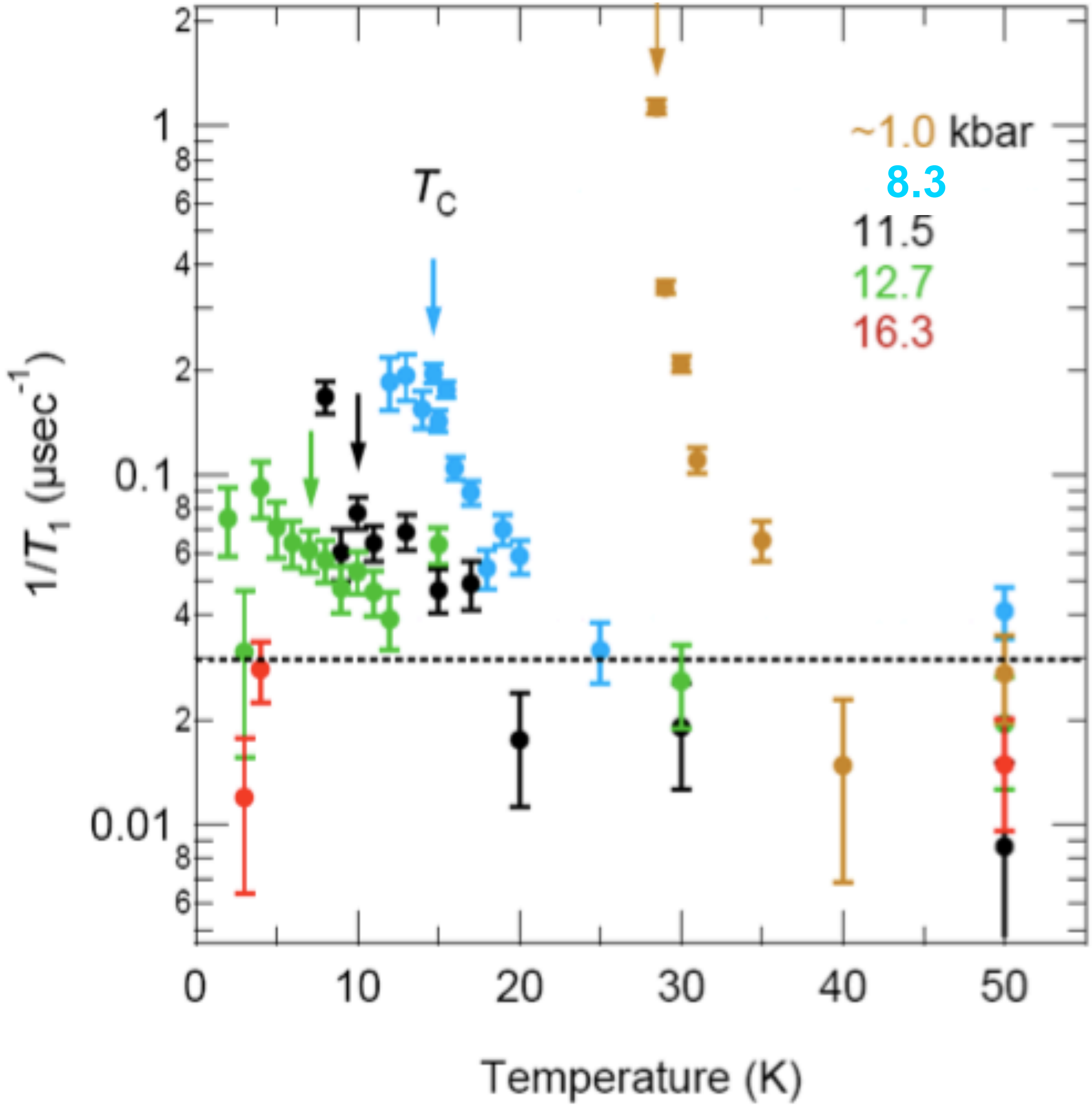
MnSi
9.6 kbar
Envelope
0.2
0.1
50 K
13 K
12 K
2.5 K
0
1
2
3
Time (µsec)



15.0 kbar
13.9
12.9
11.7
9.6
0.0
2.5 K
Envelope
Time (μsec)
0.2
0.1
0
1
2
3


MnSi
0.0 kbar
9.6
11.7
12.9
13.9
15.0
Volume Fraction
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
Temperature (K)


MnSi
Volume Fraction
Frequency (MHz)
T → 0
T = 2.5 K
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10
12
14
0
5
10
15
20
p*
p_C
Pressure
(kbar)



~1.0 kbar
8.3
11.5
12.7
16.3
T_C
$1/T_1$ (μsec^{-1})
Temperature (K)

New Information from MuSR

p^* → 12, p_C → 15

1. Finite Static Volume Fraction between 12– 15 kbar

----- **Spontaneous Phase Separation**

2. No static component above 15 kbar

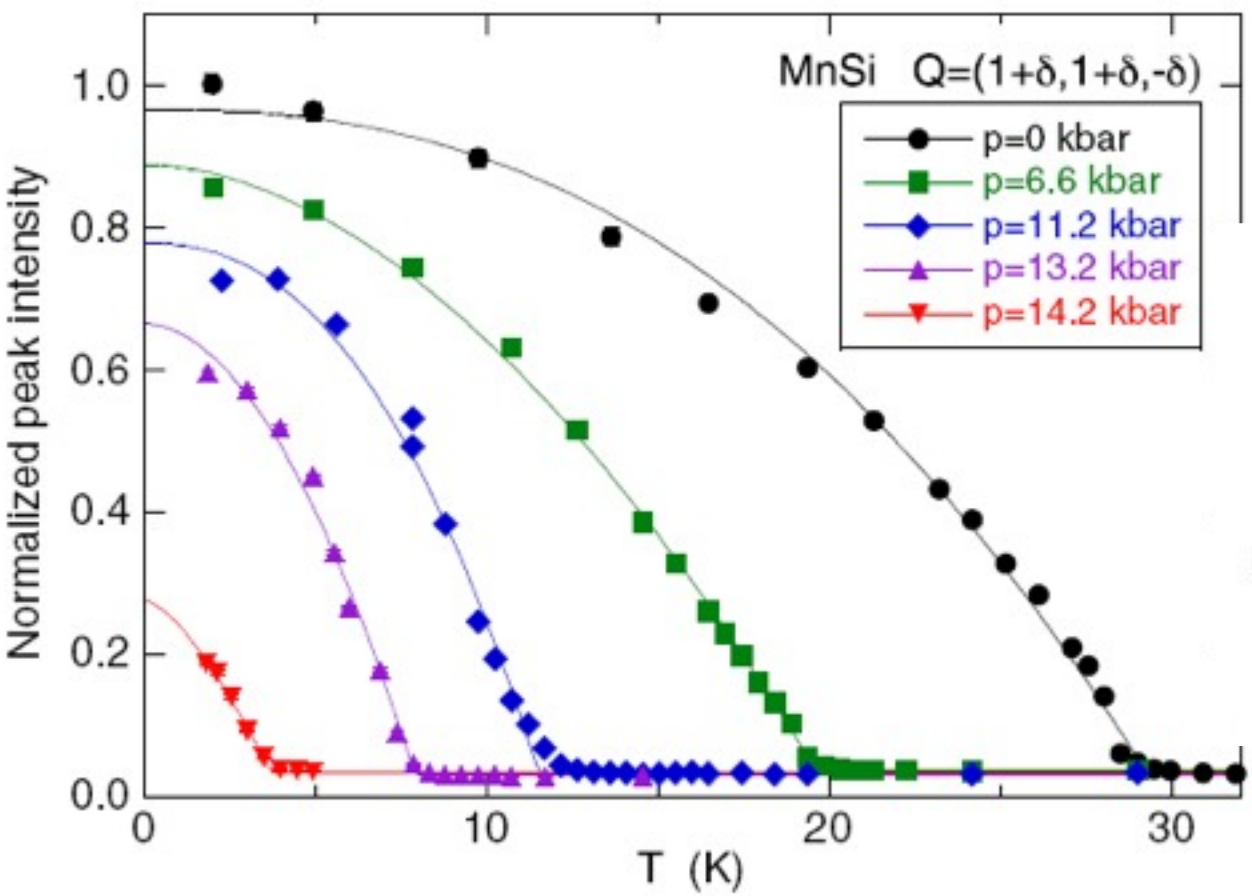
3. No dynamic critical behavior above p*

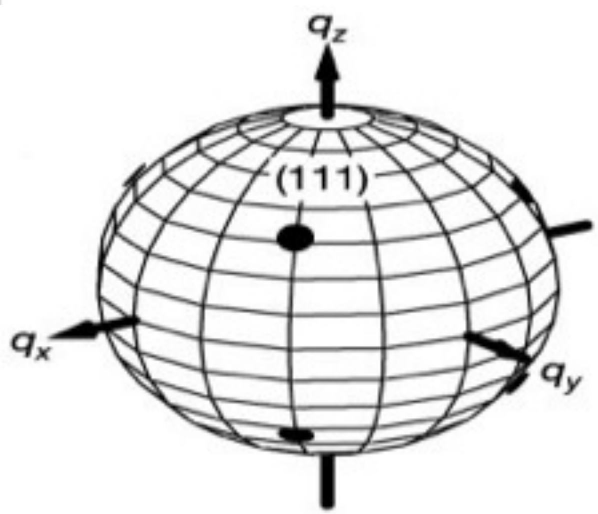
Also: Little temperature dependence of ordered moment size (ZF-μSR frequency) --- confirming NMR ---

➔ **First-order QPT**

Pressure dependence of the magnetic structure of the itinerant electron magnet MnSi

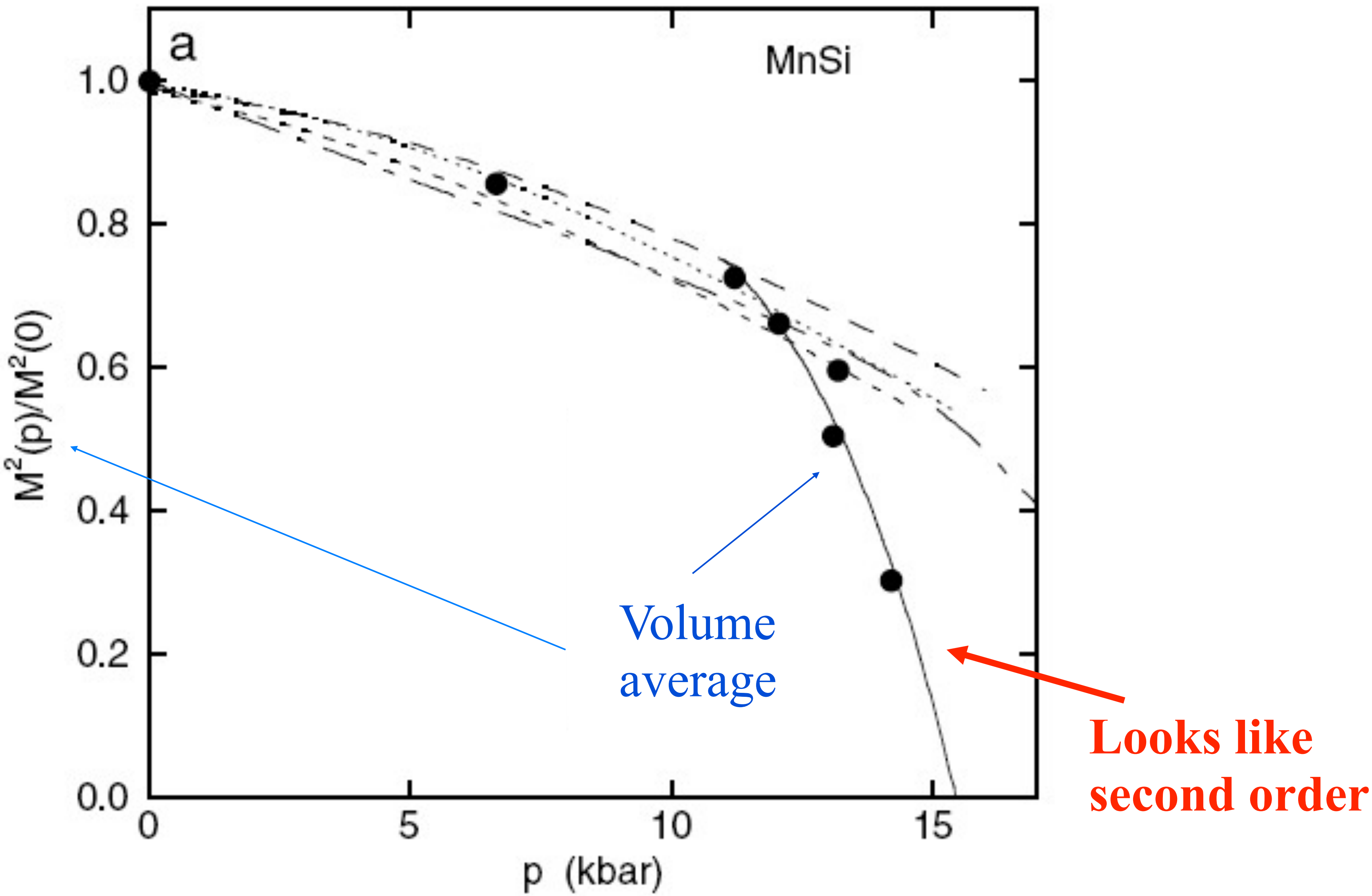
B Fåk[1], R A Sadykov[2], J Flouquet[1] and G Lapertot[1]



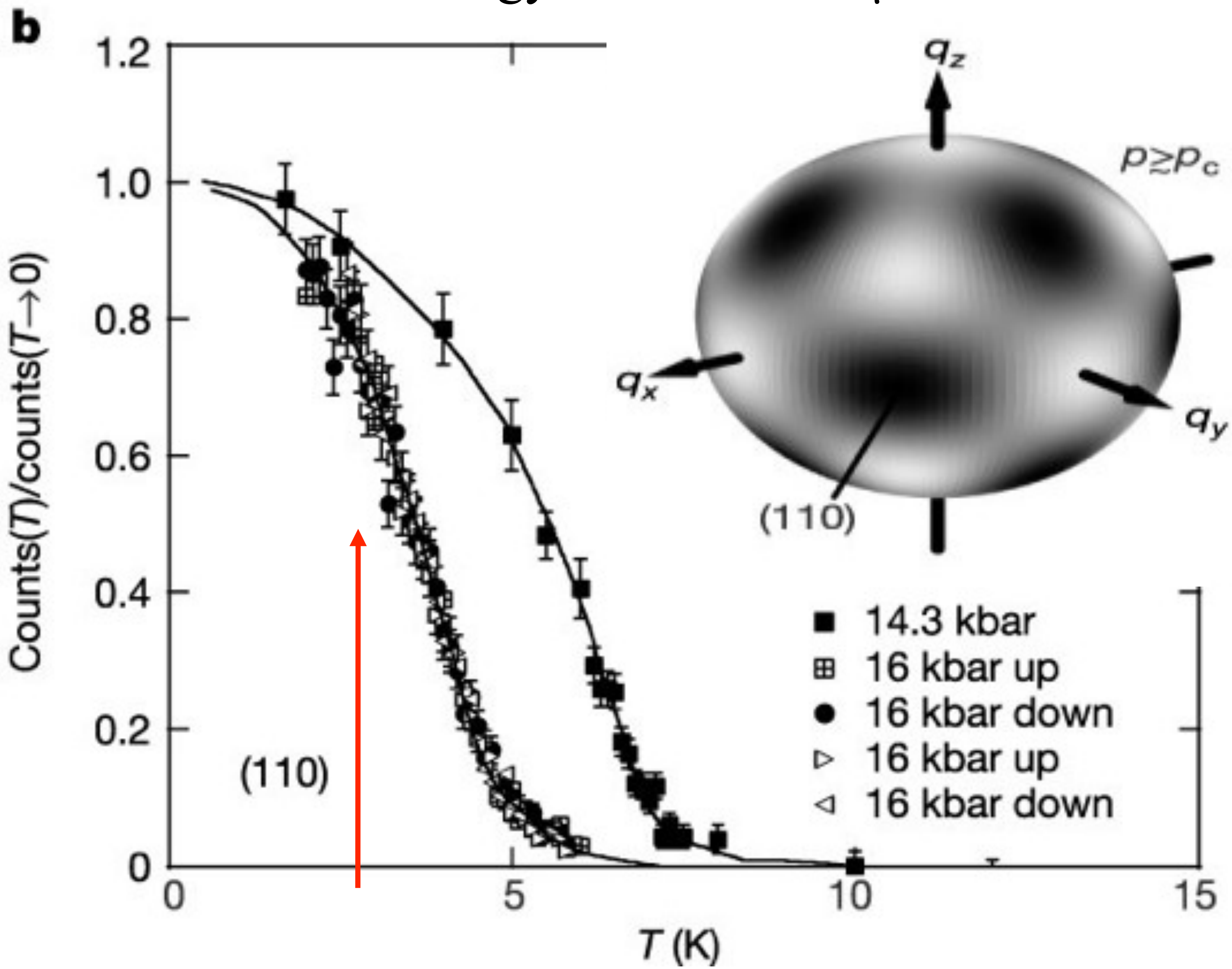


Neutron scattering

Neutron intensity: S^2 times Volume fraction



Neutron energy resolution 50 μ eV



Mn spin fluctuation rate ν < 10^{11} /s at 16 kbar

Mn spin fluctuation rate ν at 16 kbar ($p_C < p$) at $T = 2.5$ K

MuSR: $\nu > 10^{10}$ /s, if instantaneous moment size ~ 0.2 μ_B

Neutron: $\nu < 10^{11}$ /s

$10^{10} < \nu < 10^{11}$ /s

➔Very slow but definitely dynamic fluctutions of the diffusive spin correlations

➔ In para/non mag state, very slow soft mode towards competing magnetic state

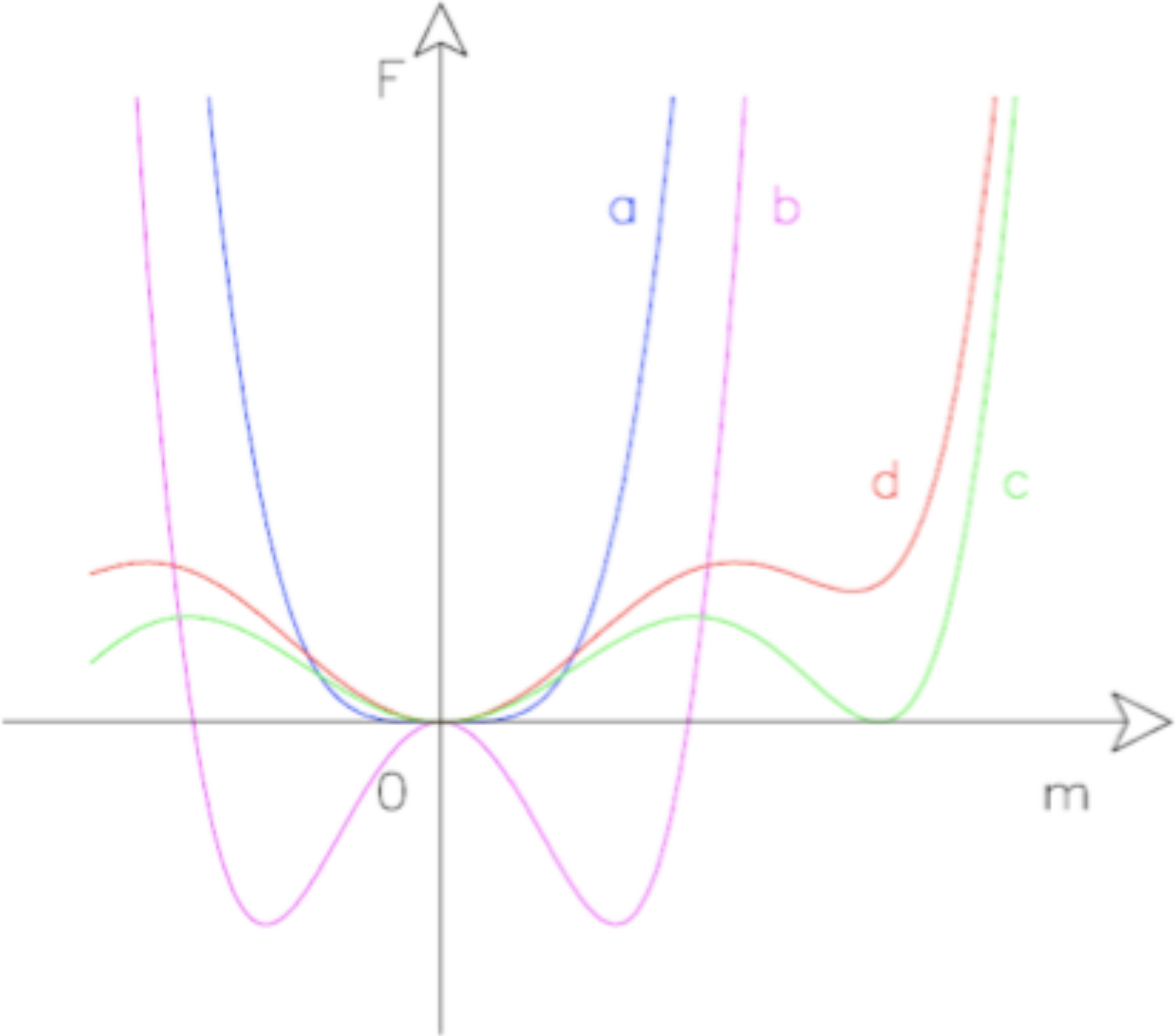

F
a
b
d
c
0
m

Table 1 Phase separation (PS)/first-order transition (FOT)/partial-volume (PVF) features detected at QPT.

System	Crossover	Parameter (p in kbar)	FOT/PS/PVF	Method
Itinerant electron magnets				
UGe_2	FM1–para	$p_c = 16$	FOT	Magnetization
			PS	Ge NQR
$ZrZn_2$	FM–para	$p_c = 16.5$	FOT	Magnetization
MnSi	Helical–para	$12 = p^* < p < p_c = 14.6$	FOT	Susceptibility
		$p < p_c$	FOT	Si NMR
		$p < 18$	PVF	Si NMR
		$p^* < p < p_c$	PS	μSR
			FOT	
$(Sr_{1-x}Ca_x)RuO_3$	FM–para	$0.7 < Ca(x) < 0.65$	PS	μSR
			FOT	
Heavy-fermion systems				
$CeCu_{2.2}Si_2$	AF(a)–SC	Temp.	PS	μSR
URu_2Si_2	AF–hidden	$3 < p < 10$	PVF	Si NMR
		$0 < p < 10$	PVF/FOT	μSR
$CeIn_3$	AF–SC	$p_c = 24.3$	FOT	In NQR
High-T_c systems				
$(La, Sr)_2(Cu_{1-x}Zn_x)O_4$	SC–normal	$Zn(x)$	PS	μSR
$Bi_2Sr_2Ca(Cu_{2-x}Zn_x)O_8$	SC–fnormal	$Zn(x)$	PS	STM
$(La_{1.85-y}Sr_{0.15}Eu_y)CuO_4$	Stripe–SC	$Eu(y)$	PS	μSR
O-doped $(La_{2-x}Sr_x)CuO_{4+y}$	Stripe–SC	Temp., $Sr(x)$	PVF/PS	μSR
$Tl_2Ba_2CuO_{6+\delta}$	SC–metal	Overdope $O(\delta)$	PS	μSR
$Bi_2Sr_2CaCu_2O_{8+\delta}$	SC–metal	Overdope $O(\delta)$	PS	STM