SPIN DYNAMICS IN NANOSCALE MAGNETISM BEYOND THE STATIC MEAN FIELD MODEL

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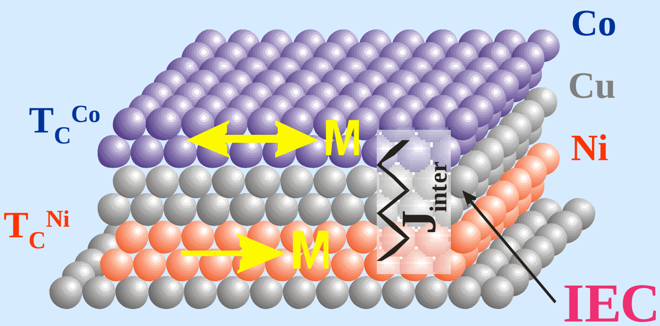
Arnimallee 14 D-14195 Berlin-Dahlem Germany

1. Element specific magnetizations and T_C's in trilayers.
2. Interlayer exchange coupling and its T-dependence.
3. Gilbert damping versus magnon-magnon scattering.



ICNM 2007, Istanbul: *physica status solidi* b <u>245</u>, 174 ff (2008)
***Handbook of Magnetism Adv. Magn. Mater.* (Wiley & Sons 2007)**
D. L. Mills, p. 247ff and K. Baberschke p.1618ff

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Lab. experiments: K. Lenz, J. Lindner, E. Kosubek, S. Kalarickal, X. Xu

Theory: H. Ebert, LMU; J.J. Rehr, UW; O. Eriksson UU; P. Weinberger, TU Vienna; R. Wu, D.L. Mills, UCI; P. Jensen + K.H. Bennemann, FUB; W. Nolting, HUB

www.physik.fu-berlin.de/~bab

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A whole variety of experiments on nanoscale magnets are available nowadays. Unfortunately many of the data are analyzed using theoretical *static mean field (MF) model*, e. g. by assuming only magnetostatic interactions of multilayers, static exchange interaction, or static interlayer exchange coupling (IEC), etc. We will show that such a mean field ansatz is insufficient for nanoscale magnetism, 3 cases will be discussed to demonstrate the importance of *higher order spin-spin correlations* in low dimensional magnets.

Spin-Spin correlation function $\frac{\partial}{\partial t}\langle\langle S_i^+ S_j^- \rangle\rangle \rightarrow$

$$S_i^z S_j^+ \approx \langle S_i^z \rangle S_j^+ - \langle S_i^- S_i^+ \rangle S_j^+ - \langle S_i^- S_j^+ \rangle S_i^+ + \cdots$$

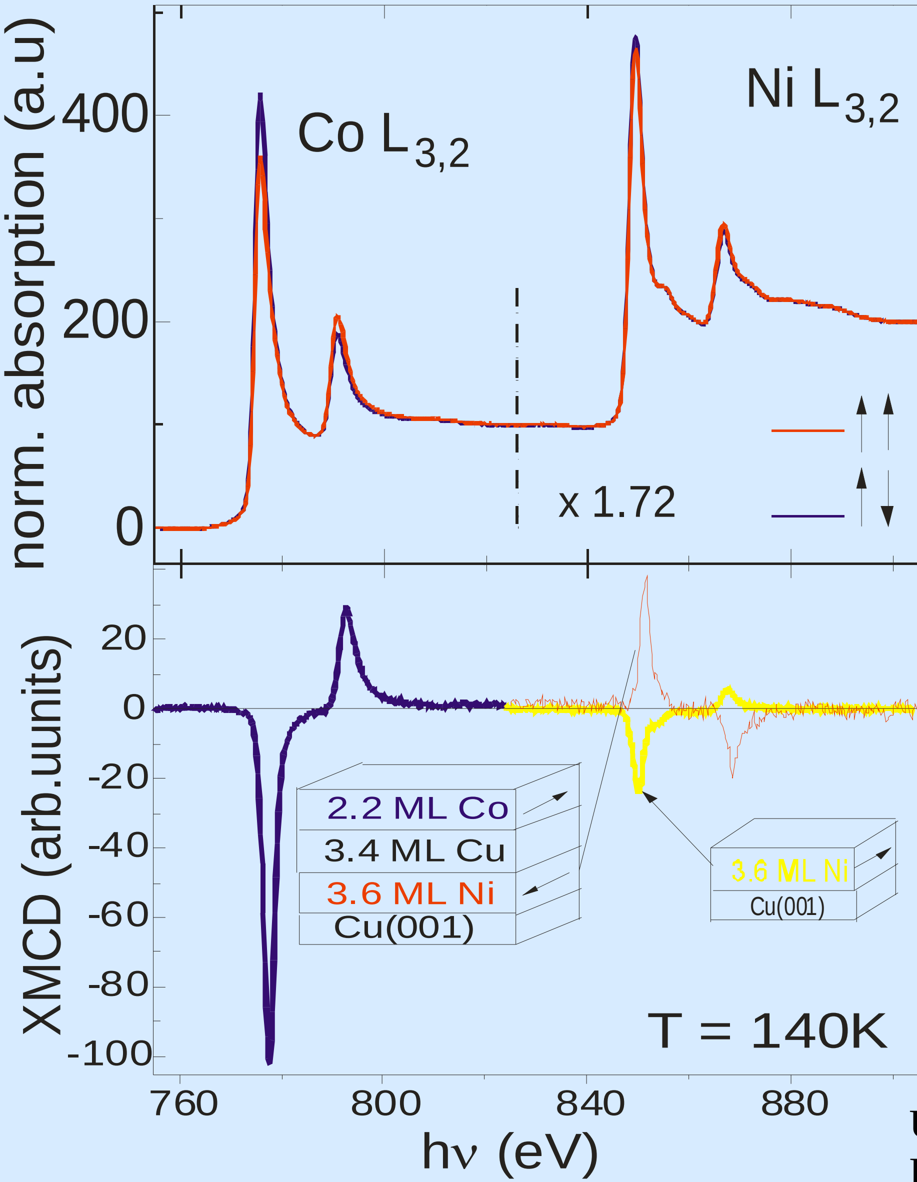
← RPA →

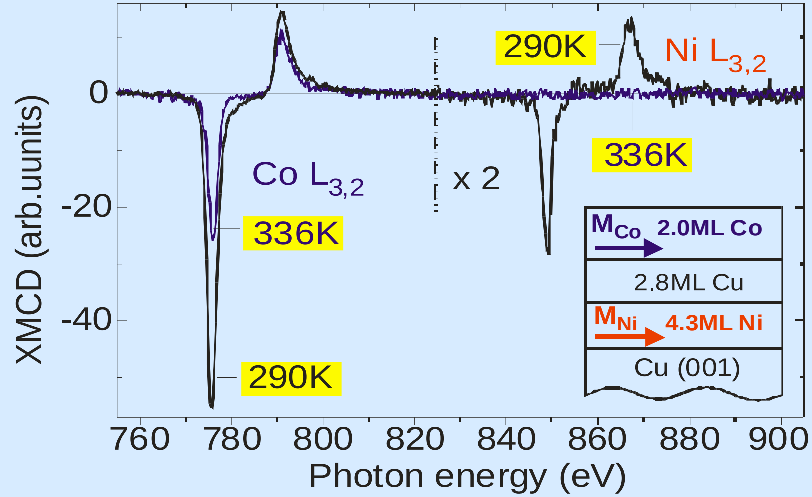
The damping of spin motions in ultrathin films: Is the Landau–Lifschitz–Gilbert phenomenology applicable?☆

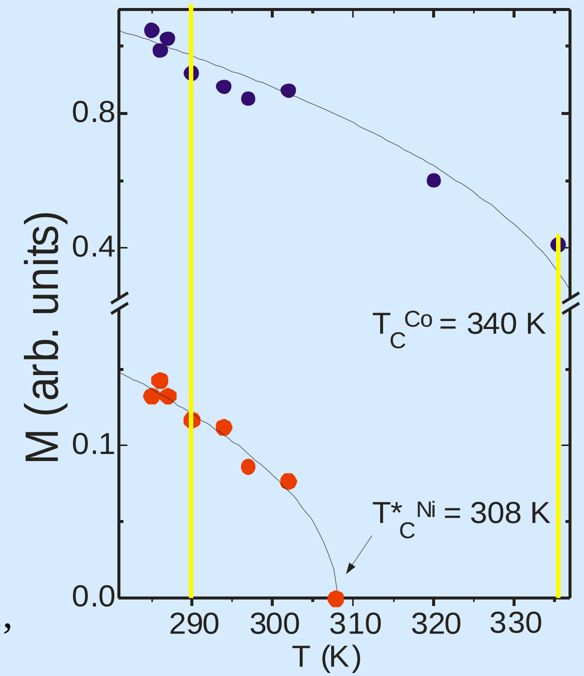
D.L. Mills[a,*], Rodrigo Arias[b]

Physica B **384**, 147 (2006)

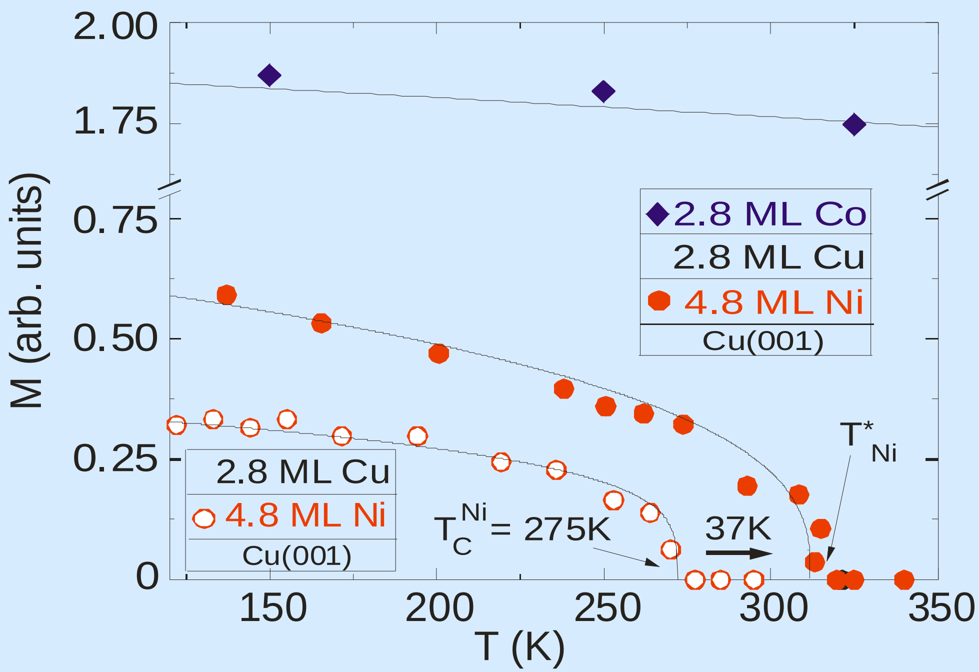
1. Element specific magnetizations and T_C's in trilayers.



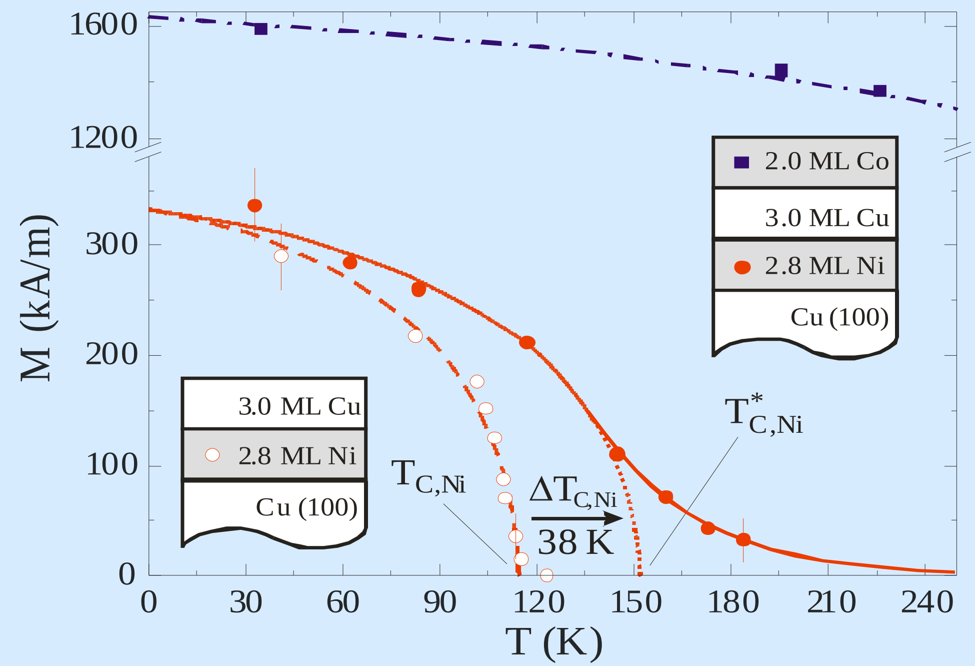




U. Bovensiepen et al.,
PRL **81**, 2368 (1998)



P. Poulopoulos, K. B., Lecture Notes in Physics **580**, 283 (2001)

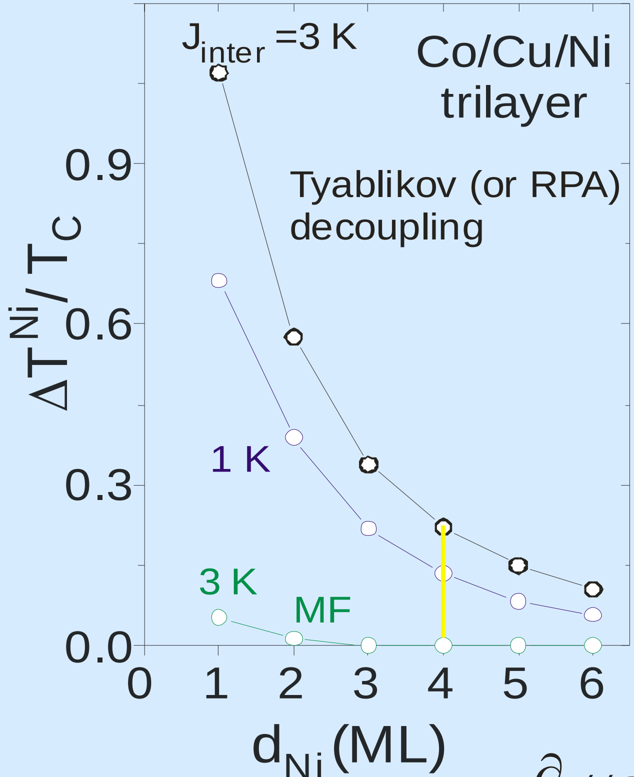


A. Scherz et al. PRB **65**, 24411 (2005)

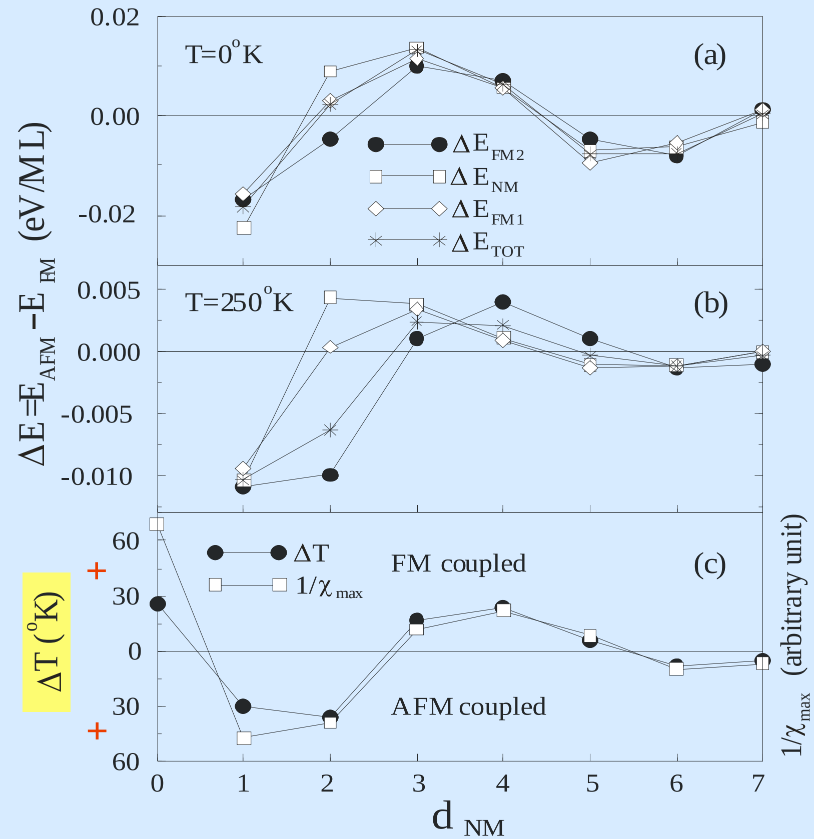
The large shift of T_C^{Ni} can **NOT** be explained by the static exchange field of Co.

Enhanced spin fluctuations in 2D (theory)

P. Jensen et al. PRB **60**, R14994 (1999)



J.H. Wu et al. J. Phys.: Condens. Matter **12** (2000) 2847



Spin-Spin correlation function $\frac{\partial}{\partial t}\langle\langle S_i^+ S_j^- \rangle\rangle \rightarrow$

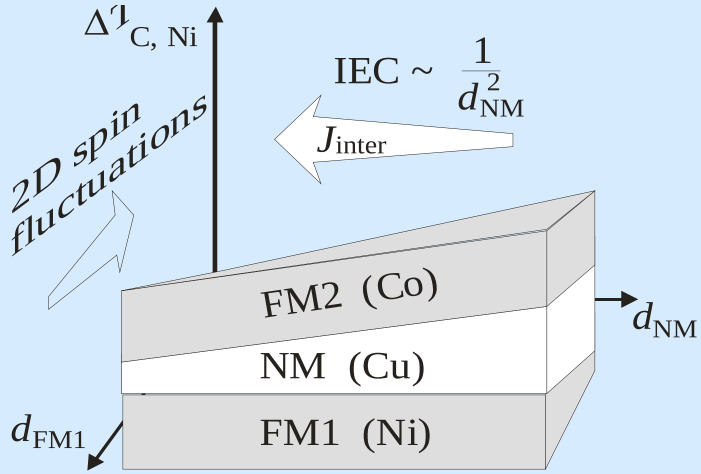
$$S_i^z S_j^+ \approx \langle S_i^z \rangle S_j^+ - \langle S_i^- S_i^+ \rangle S_j^+ - \langle S_i^- S_j^+ \rangle S_i^+ + \cdots$$

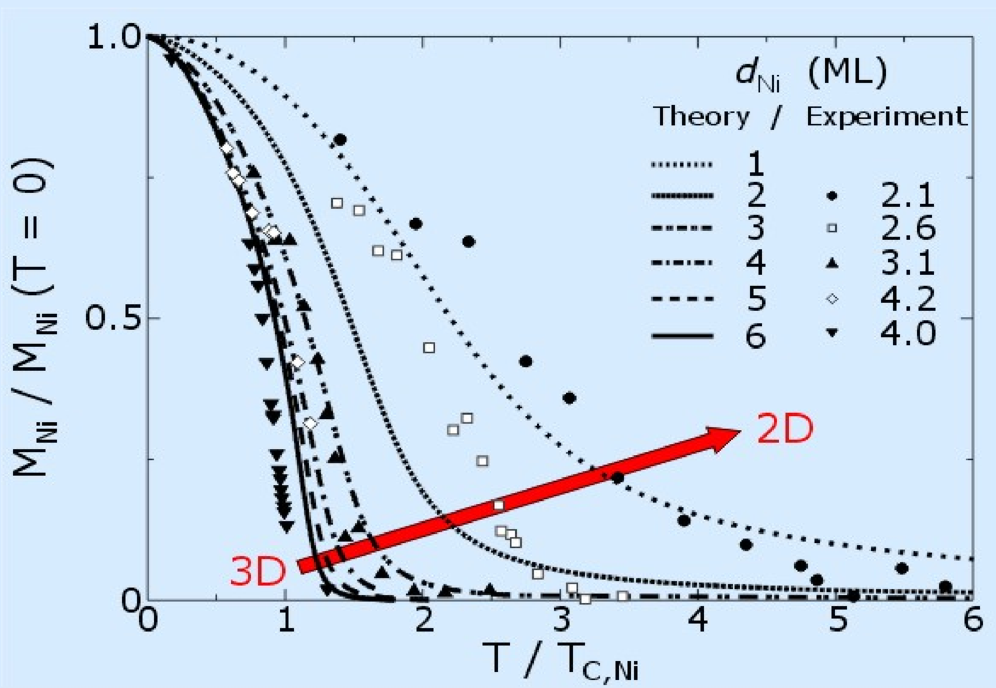
← RPA →

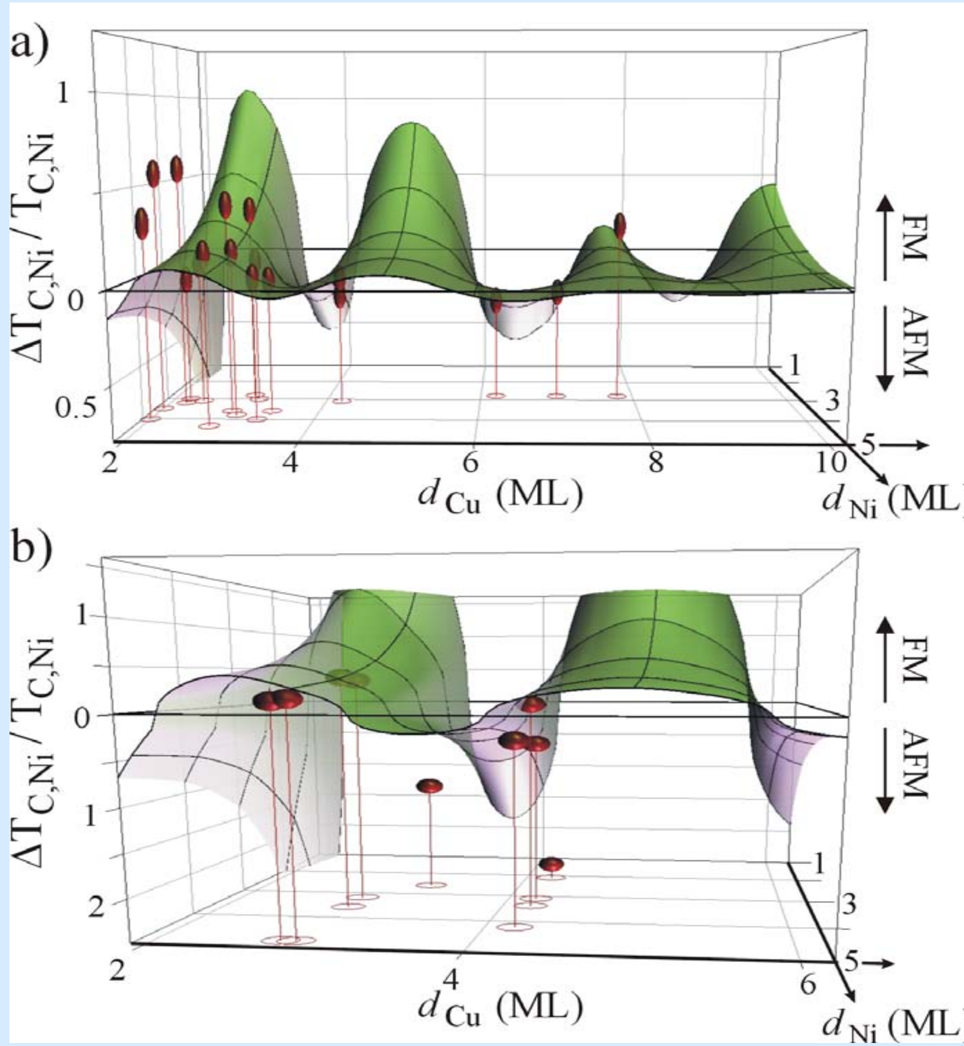
$\langle S_i^z \rangle S_j^+$, mean field ansatz (Stoner model) is insufficient to describe spin dynamics at interfaces of nanostructures

Single band Hubbard model:
Simple Hartree-Fock (Stoner) ansatz is insufficient
Higher order correlations are needed to explain T_C-shift

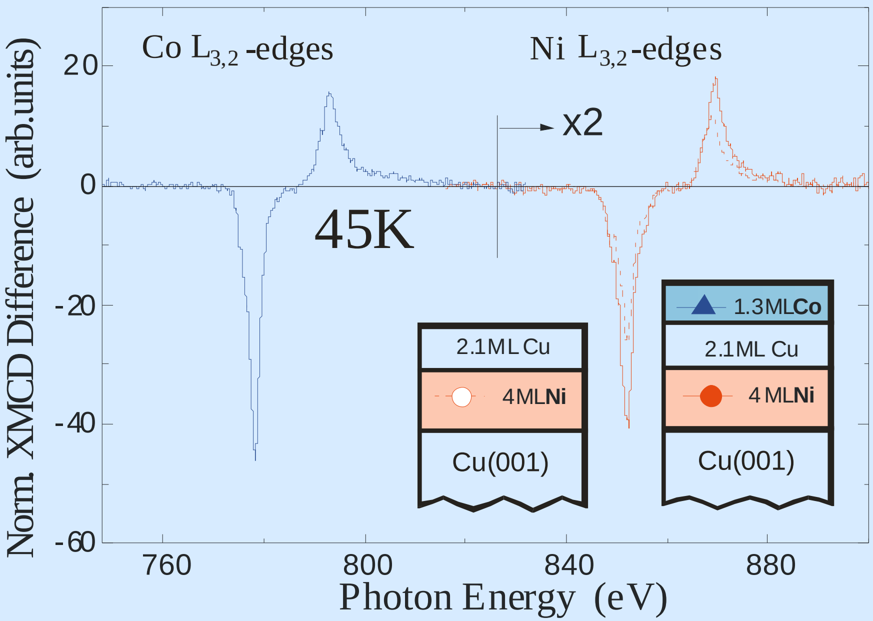
Evidence for giant spin fluctuations (A. Scherz, C. Sorg et al. PRB **72**, 54447 (2005))

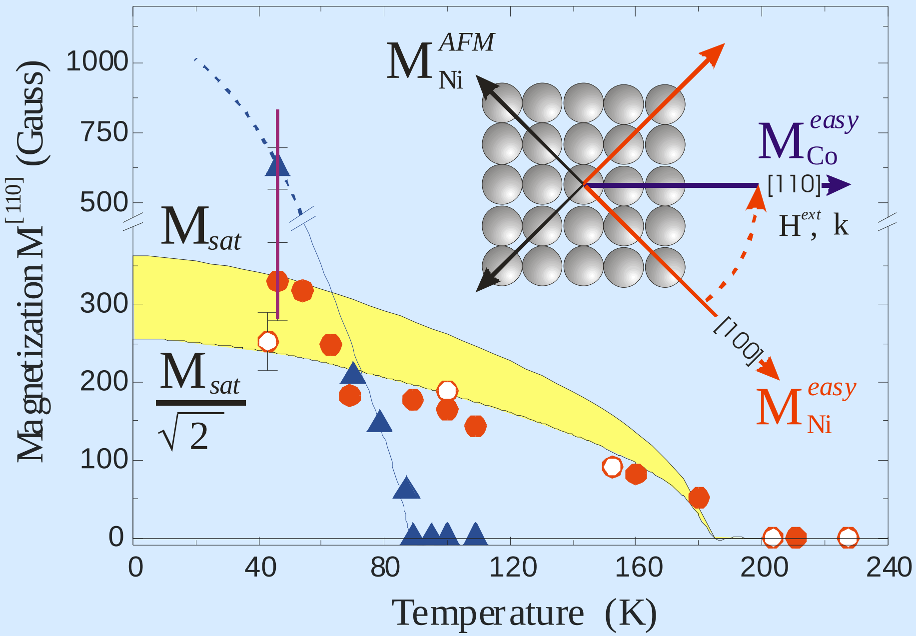






Crossover of $M_{Co}(T)$ and $M_{Ni}(T)$





Two order parameter of T_C^{Ni} and T_C^{Co}

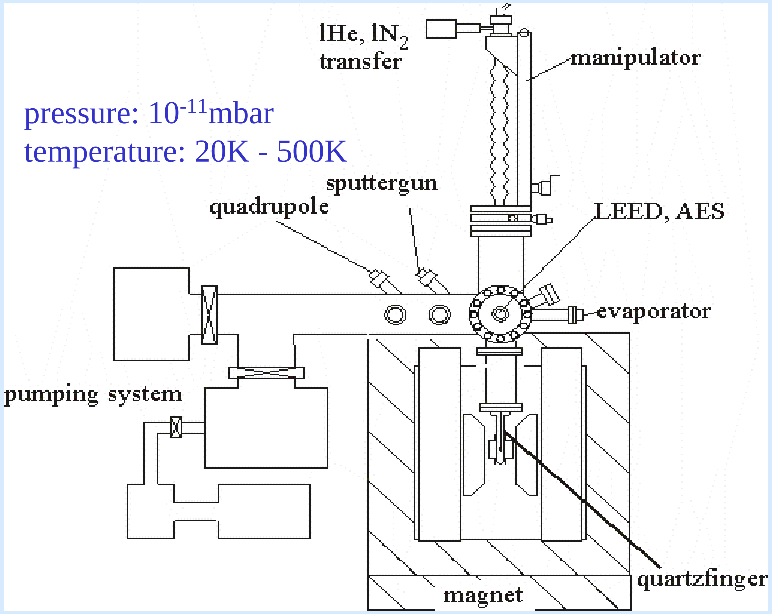
A further reduction in symmetry happens at T_c^{low}

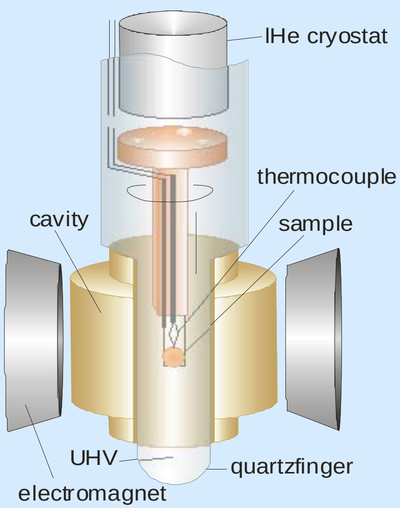
A. Scherz et al. J. Synchrotron Rad. **8**, 472 (2001)

L. Bergqvist, O. Eriksson J. Phys. Conds. Matter **18** ,1 (2006)

2. IEC in coupled films measured withUHV-FMR

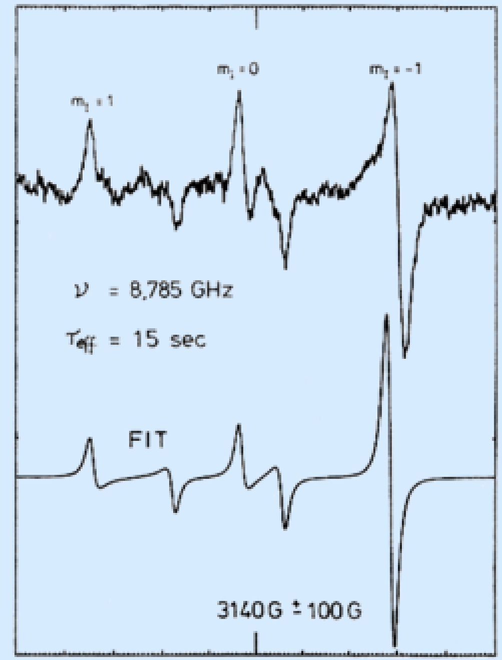
In situ UHV-ESR/FMR set up 1, 4, 9 GHz





ESR of
0.01L NO_2/10L Kr/Ag(110);
T=20K
1/100 ML ~ 10^{12} particles

M. Zomak et al.,
Surf. Sci. **178**, 618 (1986)



M. Farle, K.B. PRL **58**, 511 (1987)

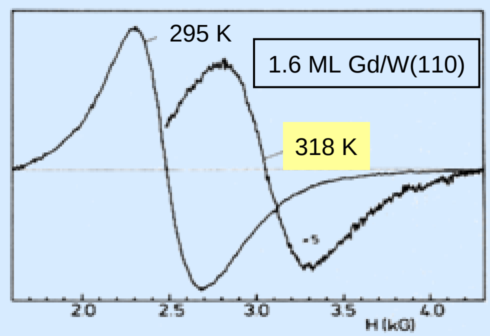


Fig. 4. ESR spectra for the new 1.6 ML sample (not cited in [2, 3]). Note the significant change in intensity and resonance field from 16 to 39 K above T_c

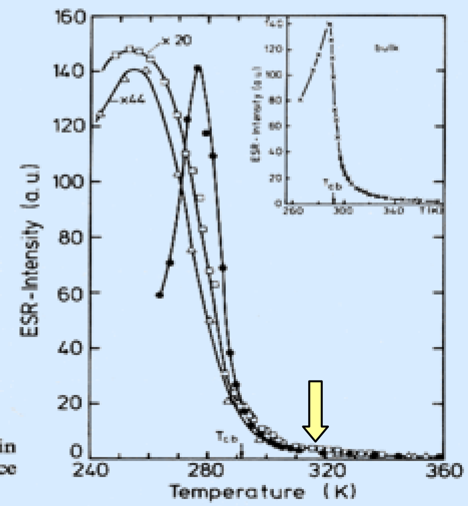
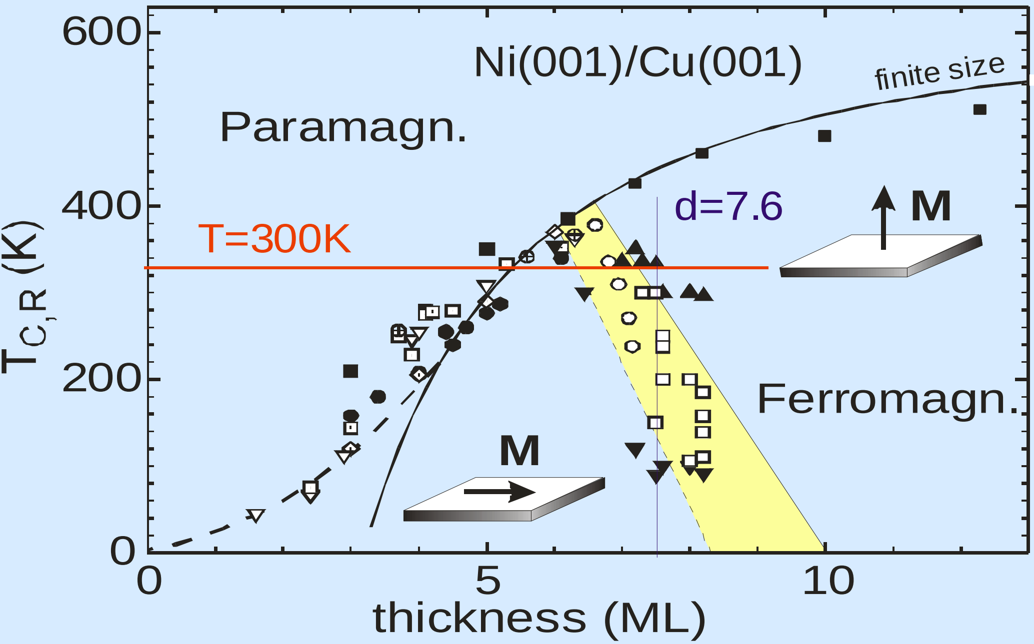
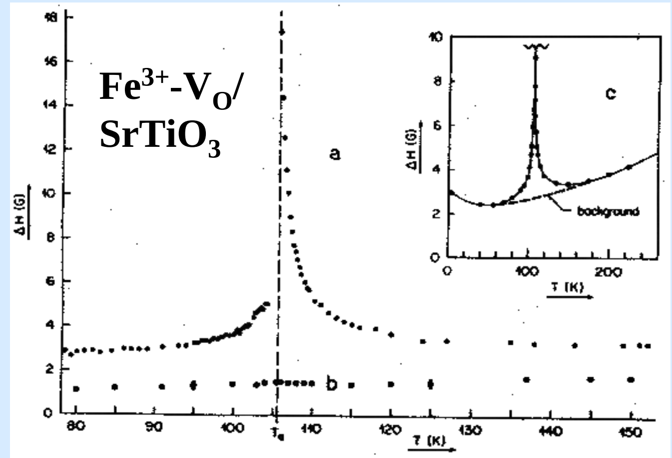


Fig. 5. Area of the ESR signal as a function of temperature for 80 Å (●), the new 1.6 ML (□), and the 0.8 ML (△). The insert shows the same data for a 18 μm thick Gd foil (bulk). Solid lines are guides to the eye. The 1.6 and 0.8 ML have a vertical gain factor of 20 and 44 with respect to 80 Å. The insert is not to scale

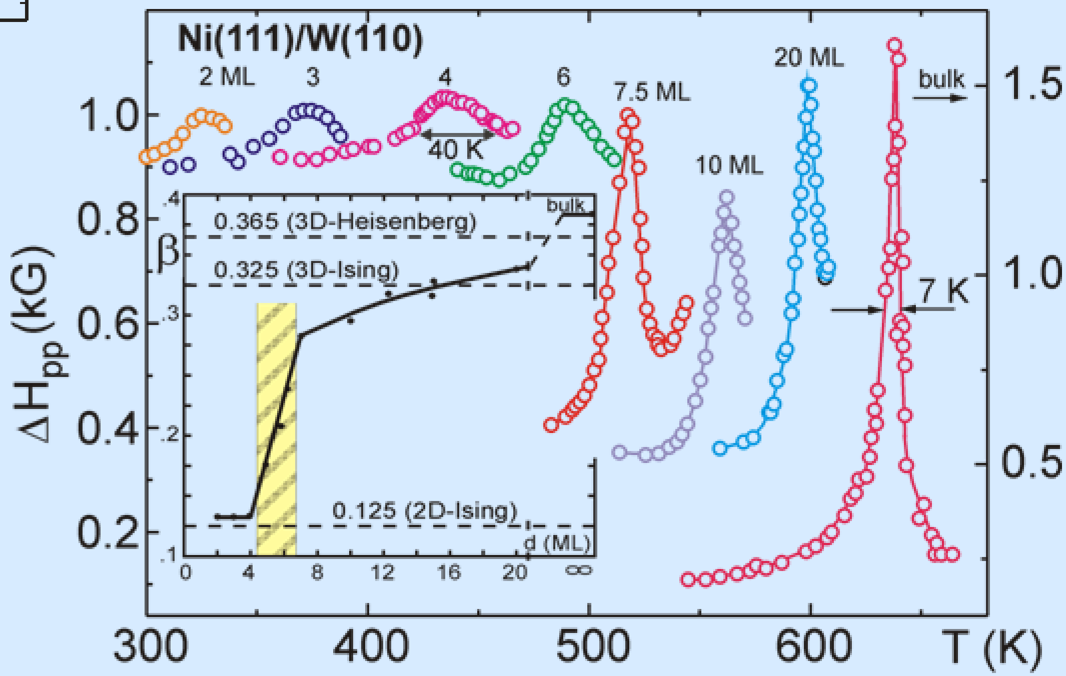
For thin films the Curie temperature can be manipulated





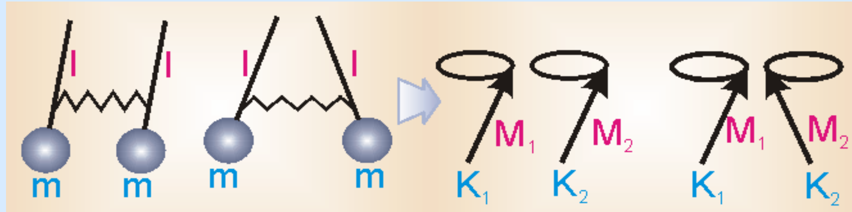
Th.v. Waldkirch, K.A. Müller, W. Berlinger, PRB (1973)

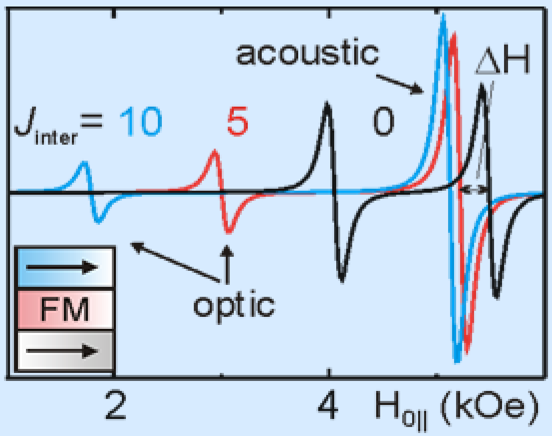
P. Poulopoulos and K. B.
J. Phys.: Condens. Matter **11**, 9495 (1999)



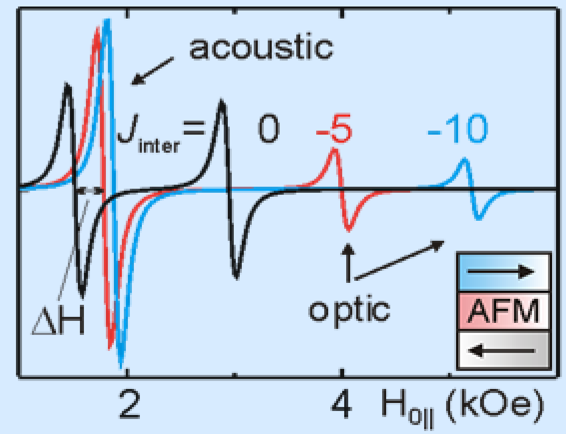
Yi Li, K. B., PRL **68**, 1208 (1992)

in-situ FMR in coupled films

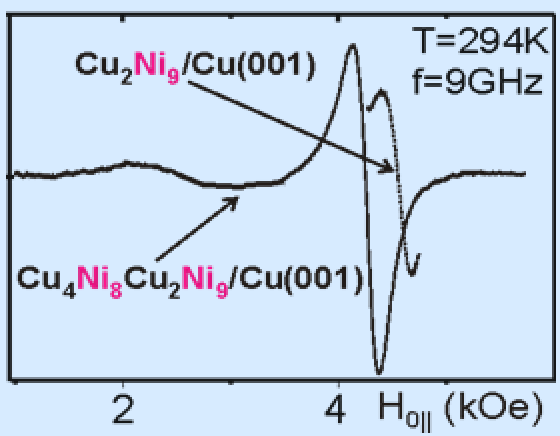




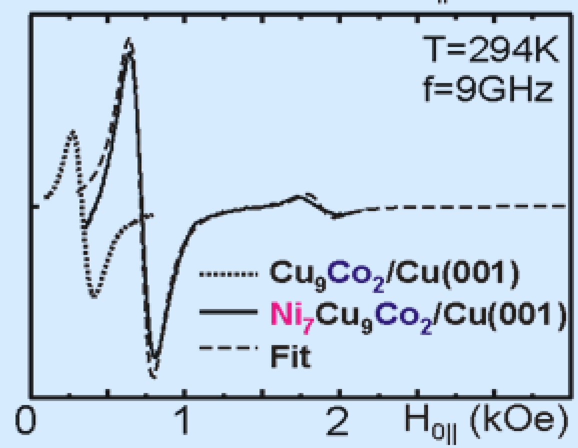
theory



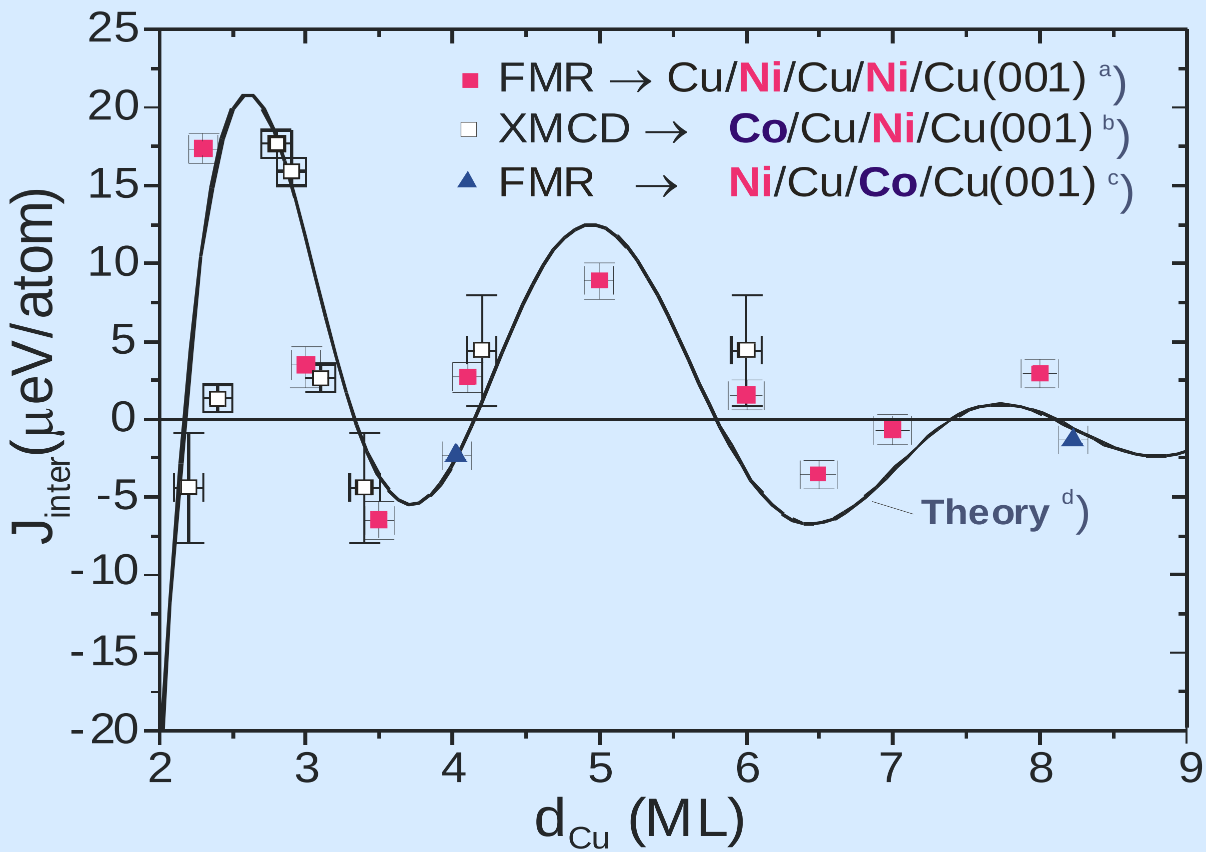
FMR



in-situ
UHV-experiment



J. Lindner, K. B. Topical Rev., J. Phys. Condens. Matter **15**, R193-R232 (2003)



a) J. Lindner, K. B., J. Phys. Condens. Matter **15**, S465 (2003)

b) A. Ney et al., Phys. Rev. B **59**, R3938 (1999)

c) J. Lindner et al., Phys. Rev. B **63**, 094413 (2001)

d) P. Bruno, Phys. Rev. B **52**, 441 (1995)

Interlayer exchange coupling and its T-dependence.

P. Bruno, PRB **52**, 411 (1995); V. Drchal et al. PRB **60** , 9588 (1999)

$$J_{inter} = J_{inter,0} \left[\frac{T/T_0}{\sinh(T/T_0)} \right] \quad T_0 = \hbar v_F / 2\pi k_B d$$

N.S. Almeida et al. PRL **75**, 733 (1995)

$$J_{inter} = J_{inter,0} \left[1-(T/T_C)^{3/2}\right]$$

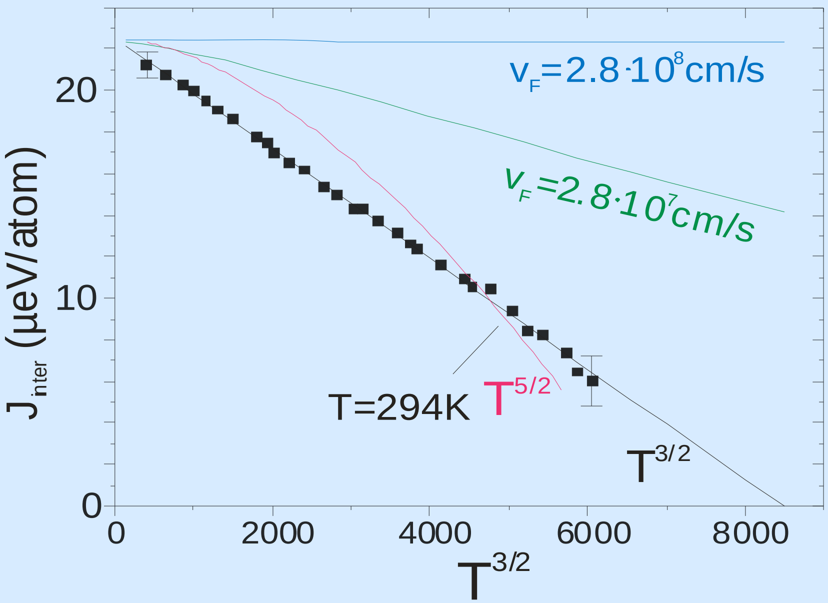
$Ni_7Cu_9Co_2$/Cu(001)

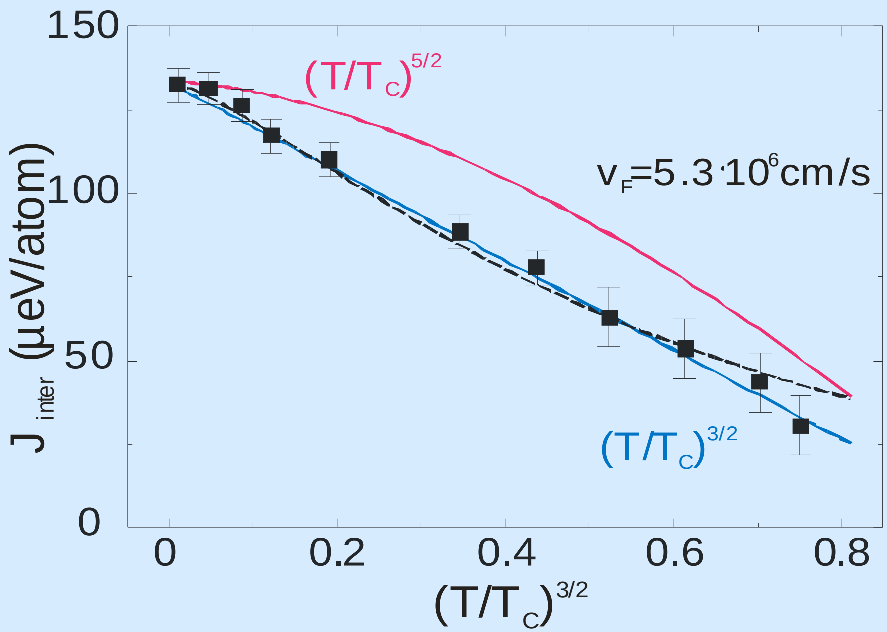
T=55K - 332K

J. Lindner et al.
PRL **88**, 167206 (2002)

$(Fe_2V_5)_{50}$

T=15K - 252K, T_C=305K





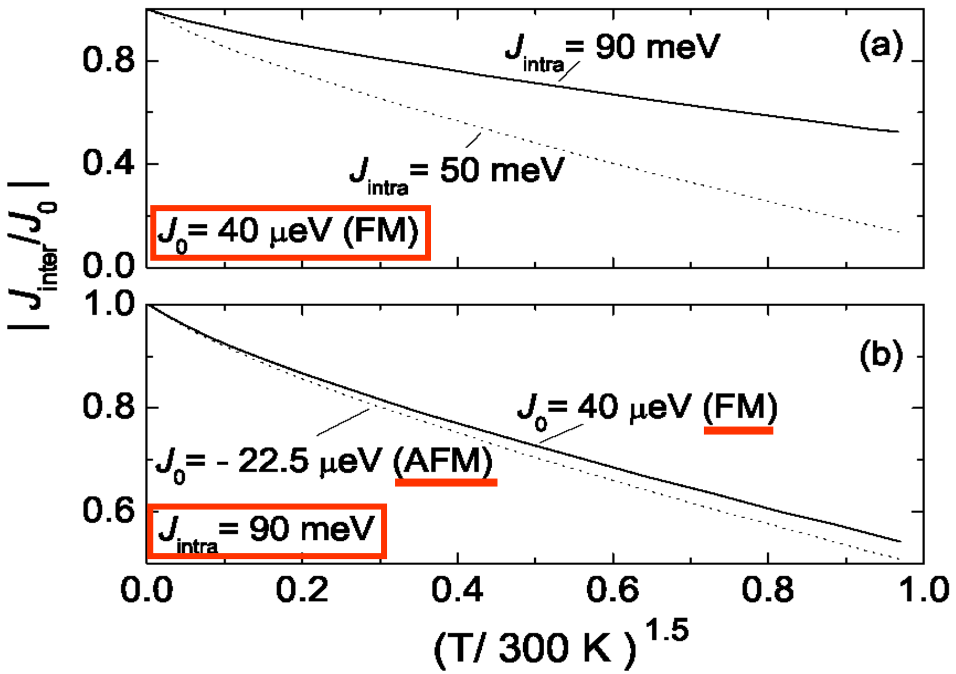
S. Schwieger, W. Nolting, PRB **69**, 224413 (2004)

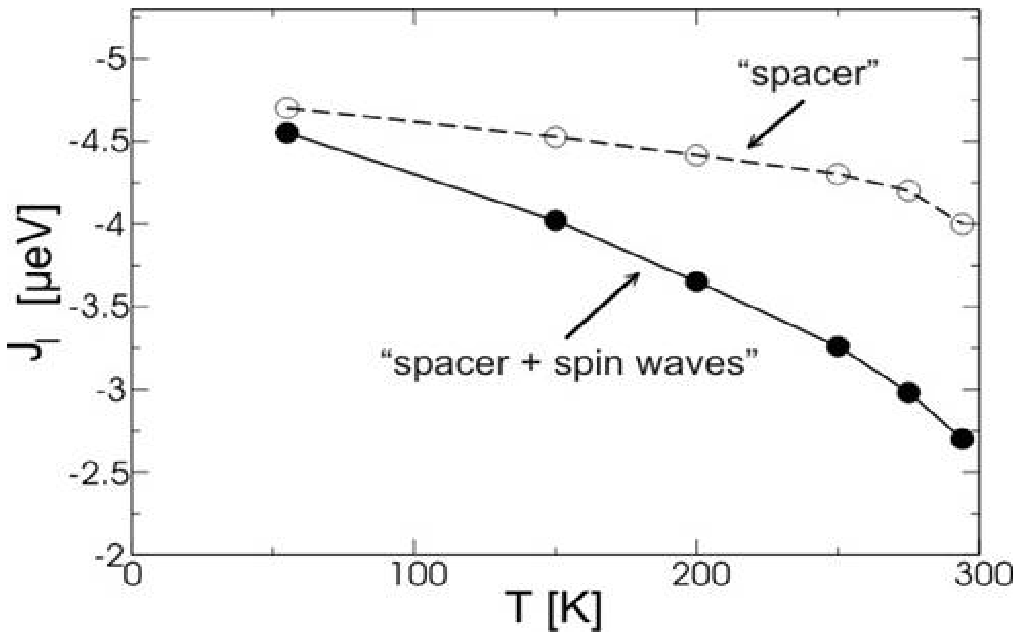
T dependence of IEC

All contributions due to the spacer, interface and magnetic layers, nevertheless give an effective power law dependence on the temperature:

$$J(T) \approx 1 - AT^n, \quad n \approx 1.5 \qquad (1)$$

S. Schwieger et al., PRL **98**, 57205 (2007)

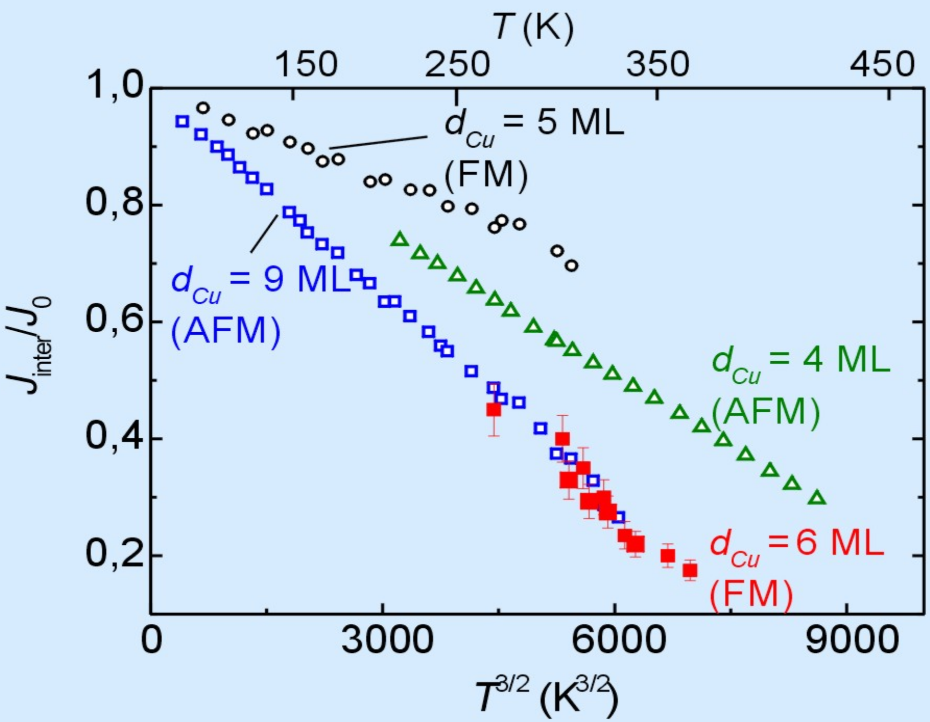




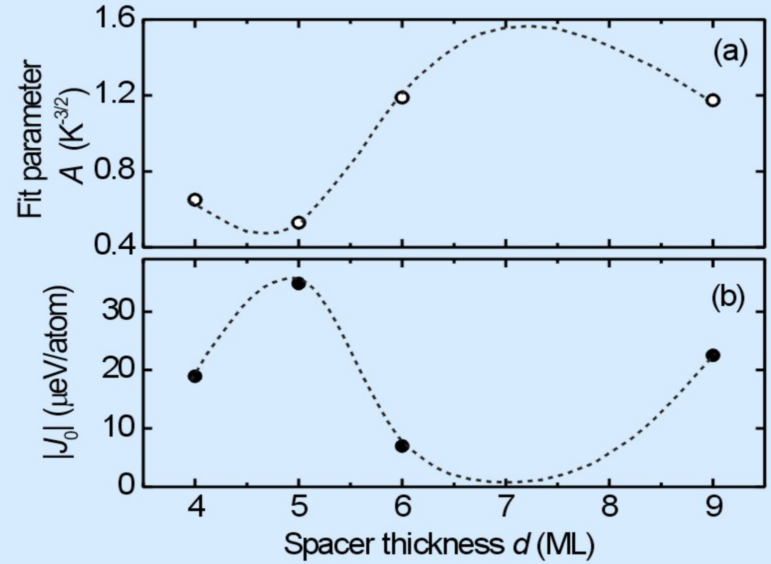
The dominant role of thermal magnon excitation in the temperature dependence of the interlayer exchange coupling: experimental verification

S. S. Kalarickal,* X. Y. Xu,† K. Lenz, W. Kuch, and K. Baberschke‡
Institut für Experimentalphysik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany
(Dated: March 20, 2007)

PRB **75**, 224429 (2007)



$J(T) \approx 1 - A(d)T^n$, with $n \approx 1.5$



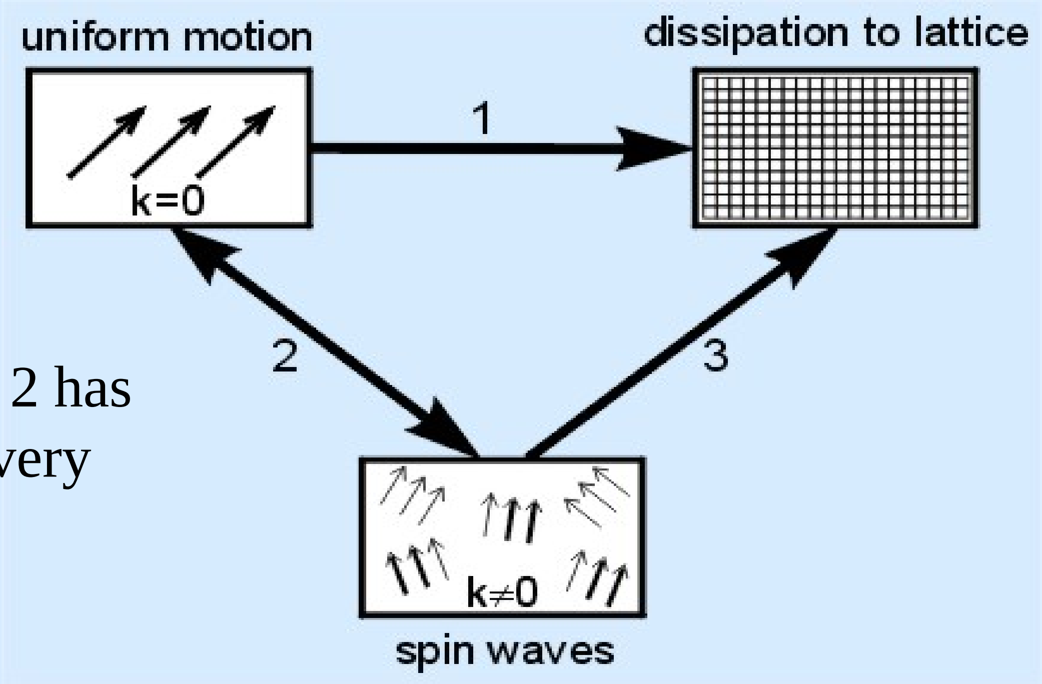
$A(d) \neq$ const.	(interface)
$A(d) \neq$ linear function	(electronic bandstructure)
$A(d) \approx$ osc. function	(spin wave excitation)

3. Gilbert damping versus magnon-magnon scattering.

1834 IEEE TRANSACTIONS ON MAGNETICS, VOL. 34, NO. 4, JULY 1998

THEORY OF THE MAGNETIC DAMPING CONSTANT

Harry Suhl
Department of Physics, and Center for Magnetic Recording Research, Mail Code 0319,
University of California-San Diego, La Jolla, CA 92093-0319.



Mostly an effective damping (path 1) was modeled/fitted.

In nanoscale magnetism path 2 has been discussed very very little.

Landau-Lifshitz-Gilbert equation(1935)

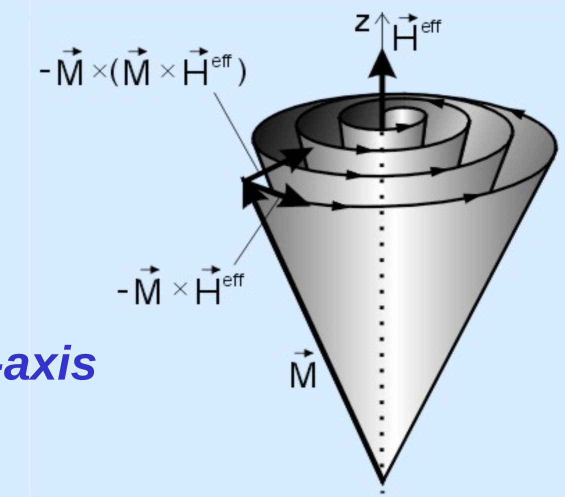
$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = -\gamma\, \mathbf{m} \times \mathbf{H}_{\mathrm{eff}} \quad + \alpha\, \mathbf{m} \times \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t}$$

Gilbert damping

|M|=const.

M spirals on

a sphere into z-axis



Bloch-Bloembergen Equation (1956)

$$\frac{\mathrm{d}m_z}{\mathrm{d}t} = -\gamma(\, \mathbf{m} \times \mathbf{H}_{\mathrm{eff}}\,)_z - \frac{m_z - M_S}{T_1}$$

spin-lattice relaxation

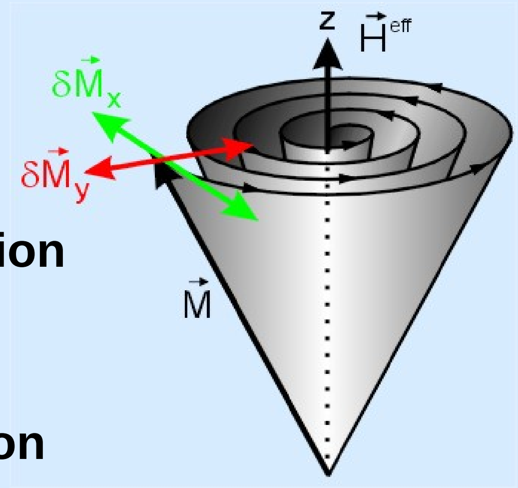
(longitudinal)

$$\frac{\mathrm{d}m_{x,y}}{\mathrm{d}t} = -\gamma(\, \mathbf{m} \times \mathbf{H}_{\mathrm{eff}}\,)_{x,y} - \frac{m_{x,y}}{T_2}$$

spin-spin relaxation

(transverse)

M_z=const.



FMR Linewidth - Damping

Landau-Lifshitz-Gilbert-Equation

$$\frac{1}{\gamma}\frac{\partial \mathbf{M}}{\partial t} = -(\mathbf{M}\times\mathbf{H}_{eff}) + \frac{G}{\gamma M_S^2}\left(\mathbf{M}\times\frac{\partial \mathbf{M}}{\partial t}\right)$$

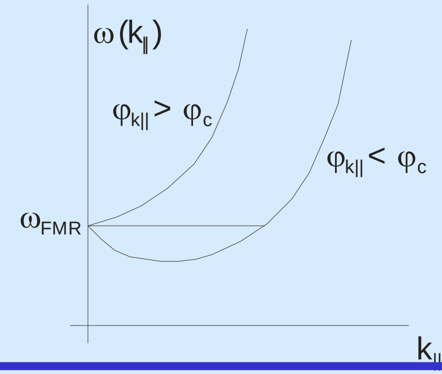
viscous damping,
energy dissipation

Gilbert-damping ~ω

$$\Delta H^{Gil}(\omega) = \frac{G}{\gamma^2 M_S}\,\omega$$

2-magnon-scattering

R. Arias, and D.L. Mills, *Phys. Rev. B* **60**, 7395 (1999);
D.L. Mills and S.M. Rezende in
'Spin Dynamics in Confined Magnetic Structures',
edt. by B. Hillebrands and K. Ounadjela, Springer Verlag



$$\Delta H^{2Mag}(\omega) = \Gamma \arcsin\sqrt{\frac{[\omega^2+(\omega_0/2)^2]^{1/2} - \omega_0/2}{[\omega^2+(\omega_0/2)^2]^{1/2} + \omega_0/2}}$$

$\omega_0 = \gamma(2K_{2\perp} - 4\pi M_S)$, $\gamma = (\mu_B/h)g$
$K_{2\perp}$ - uniaxial anisotropy constant
M_S - saturation magnetization

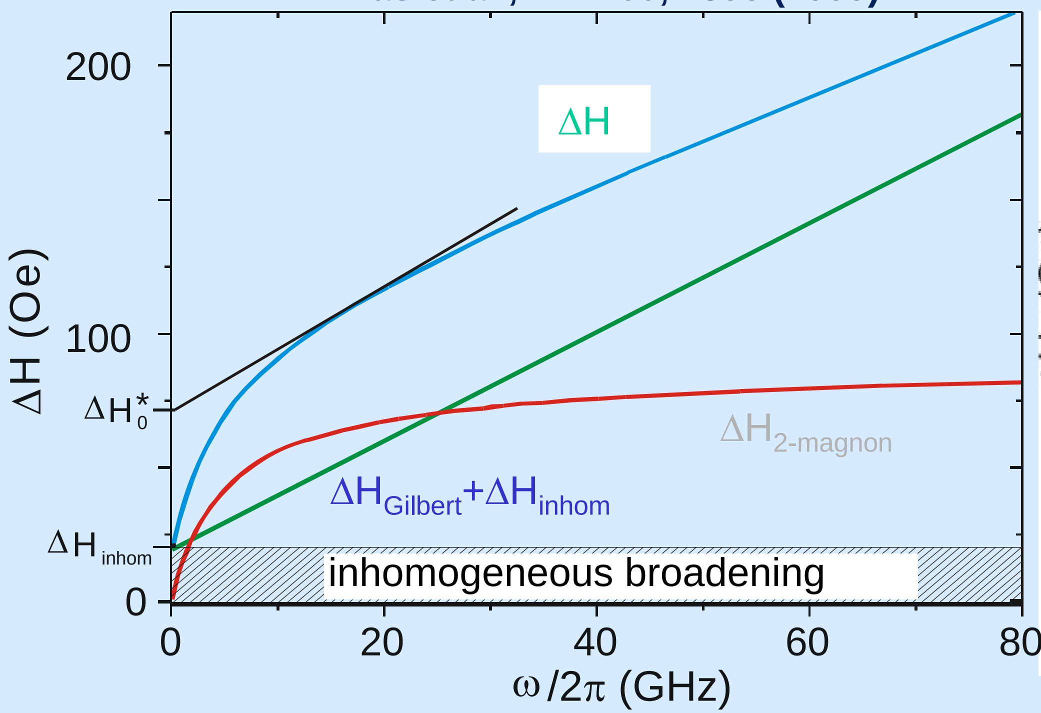
Which (FMR)-publication has checked (disproved) quantitatively this analytical function?

- Gilbert damping contribution:
- linear in frequency
- two-magnon excitations (thin films):
  non-linear frequency dependence

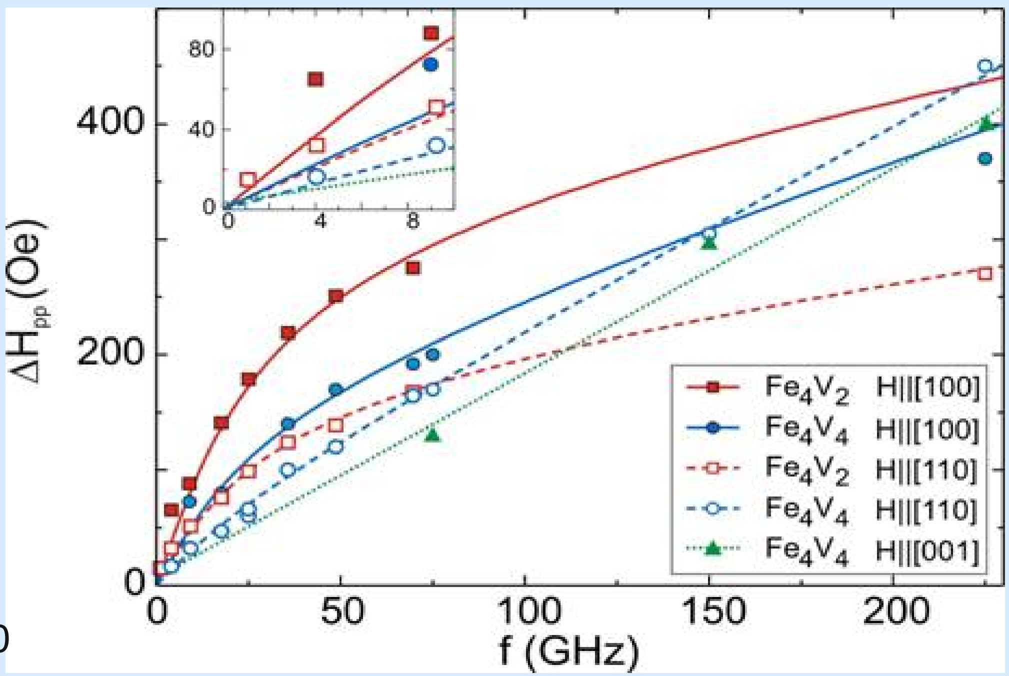
$$\Delta H_{2-\text{magnon}}(\omega) = \Gamma \arcsin \sqrt{\frac{\sqrt{\omega^2 + (\omega_0/2)^2} - \omega_0/2}{\sqrt{\omega^2 + (\omega_0/2)^2} + \omega_0/2}}$$

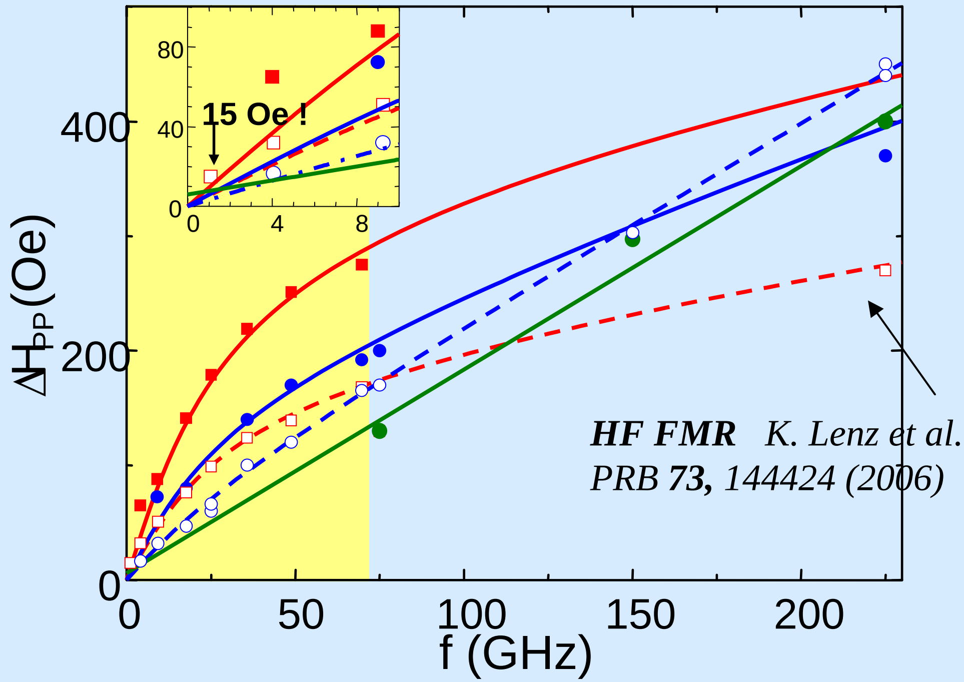
with $\omega_0 = \gamma M_{eff}$

R. Arias et al., PRB 60, 7395 (1999)



K. Lenz et al., PRB 73, 144424 (2006)





- **two-magnon scattering observed in Fe/V superlattices –**

- *J. Lindner et al., PRB* ***68****, 060102(R) (2003)*

real relaxation – no inhomogeneous broadening

two-magnon damping dominates Gilbert damping by two orders of magnitude:

$1/T_2 \sim 10^9\ s^{-1}$ vs. $1/T_1 \sim 10^7\ s^{-1}$

	Γ (kOe)	γ·Γ ($10^8\ s^{-1}$)	G ($10^8\ s^{-1}$)	α (10^{-3})	ΔH_0 (Oe)
■ Fe_4V_2 ; H||[100]	0.270	50.0	0.26	1.26	0
● Fe_4V_4 ; H||[100]	0.139	26.1	0.45	2.59	0
□ Fe_4V_2 ; H||[110]	0.150	27.9	0.22	1.06	0
○ Fe_4V_4 ; H||[110]	0.045	8.4	0.77	4.44	0
● Fe_4V_4 ; H||[001]	0	0	0.76	4.38	5.8

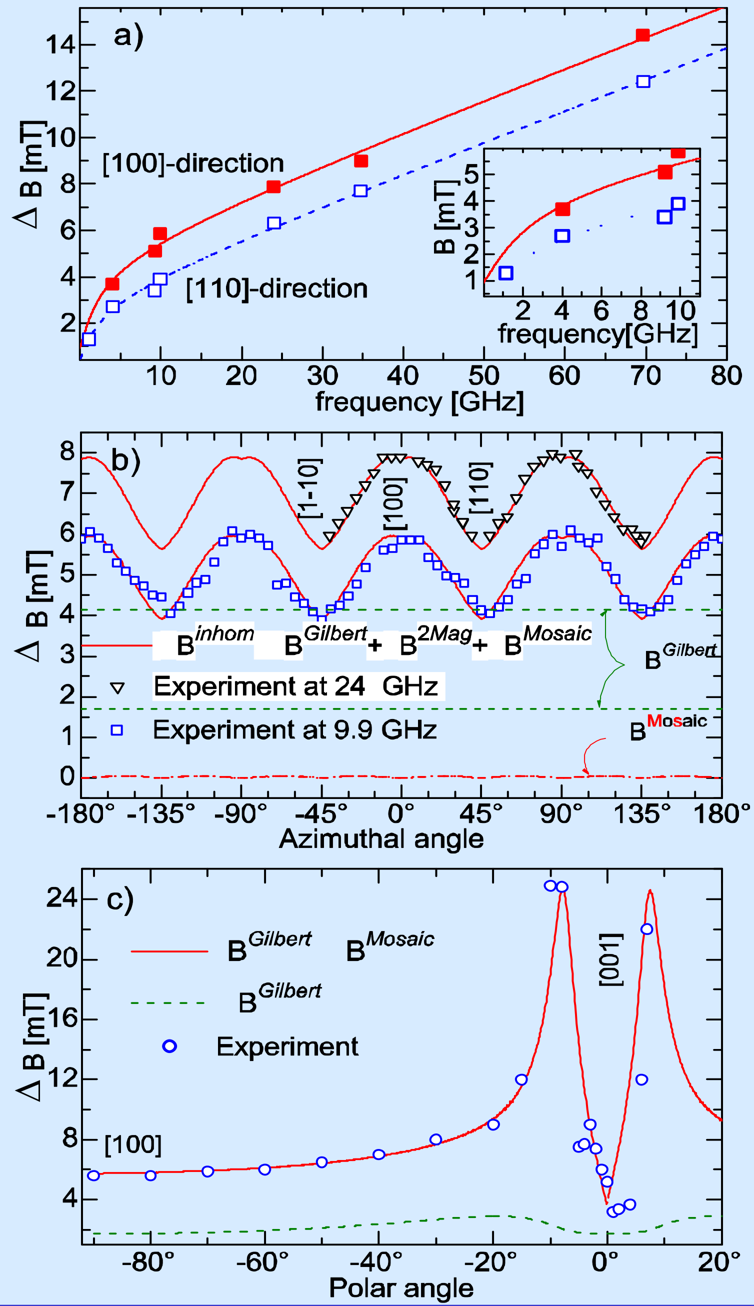
- **recent publications with similar results:**
  - Pd/Fe on GaAs(001) – network of misfit dislocations
    G. Woltersdorf et al. PRB ***69****, 184417 (2004)*
  - NiMnSb films on InGaAs/InP
    B. Heinrich et al. JAP ***95****, 7462 (2004)*

Angular- and frequency-dependent FMR
on
Fe_3Si binary Heusler structures epitaxially grown on MgO(001)
d = 40nm
Kh. Zakeri et al.
PRB 76,104416 (2007)

Angular dependence at 9 and 24 GHz

$\gamma\Gamma \approx (26 – 53) \cdot 10^7\ \mathrm{sec}^{-1}$, anisotropic

$G \approx 5 \cdot 10^7\ \mathrm{sec}^{-1}$, isotropic



Conclusion

Higher order spin-spin correlations are important to explain the magnetism of nanostructures.

In most cases a *mean field model* is insufficient.

A phenomenological effective *Gilbert damping parameter* gives very little insight into the microscopic relaxation mechanism. It seems to be more instructive to separate scattering mechanisms within the magnetic subsystem from the dissipative damping into the thermal bath;

Todays advanced experiments and analysis result in:

G ≈ isotropic dissipation

and

Γ ≈ anisotropic spin wave scattering