International Workshop on Spin Dynamics in Nanomagnets: "Dissipative versus Non-Dissipative Processes"

SFB 445

Organization Committee:

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Monday 18.10. (12:00) – Wednesday 20.10.2010 (13:00)
Venue: Wolfsburg, Falkenweg 6, 45478 Mulheim, Germany
(near Campus Duisburg, Universitat Duisburg-Essen)

Spin dynamics measured in various experiments: A review

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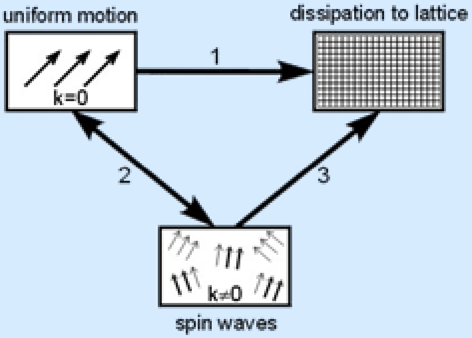

It is common practise to interprect experiments in dynamics of magnetism in terms of the Landau-Lifshitz-Gilbert (LLG) equation, be it with micro- or femtosecond (µs, fs) time resolution, with a damping constant α. This is analogue to a friction constant in mechanics, good for engineering, but of little insight what happens on a microscopic scale. On the other hand, long time ago Harry Suhl and others have discussed the "spin dynamics" like in the cartoon.
In path 1 the uniform motion or switching of M relaxes to the thermal bath with energy dissipa-tion – an irreversible process like in LLG.
In path 2 the energy stays in the magnetic subsys-tem and scatters between spin wave modes, transverse and longitudinal components of M are involved. The transverse scattering rates, also called dephasing, are usually faster by orders of magnitude, than the longitudinal rates /1-4/.
Two- and four-magnon scattering are examples for path 2. Path 3, the magnon-phonon scattering is again irreversible. It has been investigated by Raman spectroscopy and laser pump-probe experiments.
Another distinction in spin dynamics is: Does one measure the thermodynamic ground state?
Or does one see a hot electron-spin gas system for example after a laser pulse or a core hole excitation.
We also may find that the spin dynamic depends on the wave number k of the spin waves with k ≠ 0.
Magnons with short wave length may relax faster than those with k→0.
Different experiments will be discussed like magnetic resonance, X-ray magnetic circular dichroism,
spin dependent photo emission, laser spectroscopy, etc.

/1/ K. Baberschke in *Handbook of magnetism and advanced magnetic materials* vol. **3**, p.1617 ff
John Wiley & Sons 2007
/2/ A. G. Gurevich, G. A. Melkov *Magnetization Oscillations and Waves,* CRC Press (1996)
/3/K. Lenz, H. Wende, W. Kuch, K. Baberschke, K. Nagy, A. Jánossy Phys. Rev. B **73**, 144424 (2006)
/4/ K. Baberschke physica status solidi (b) **245,** 174 (2008)

Spin dynamics measured in various experiments: A review

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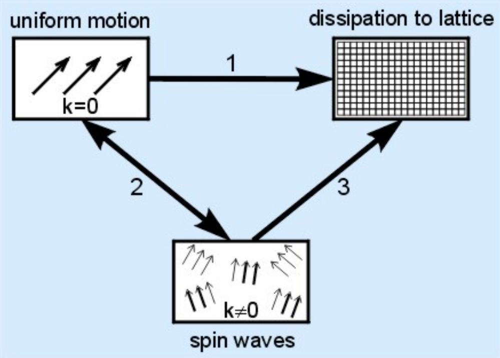
1. Introduction
2. 2-magnon scattering, FMR linewidth
3. (3-) 4-magnon scattering, BLS, XDMR
4. magnon-phonon scattering,
   laser pump-probe experiments
5. XMCD, X-ray FEL, LCLS

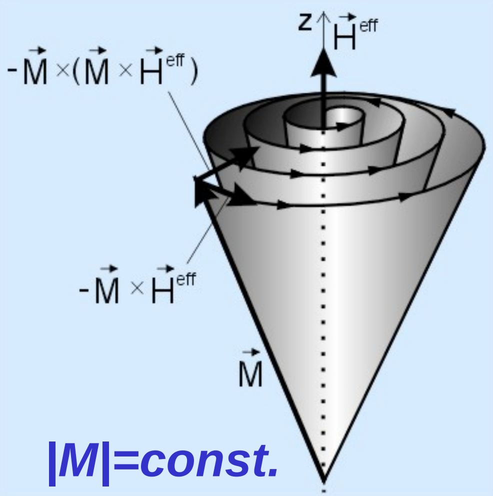


Spin Dynamics: Damping and Scattering

Landau-Lifshitz-Gilbert equation(1935)

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

Gilbert damping



|M|=const.

M spirals on a sphere into z-axis

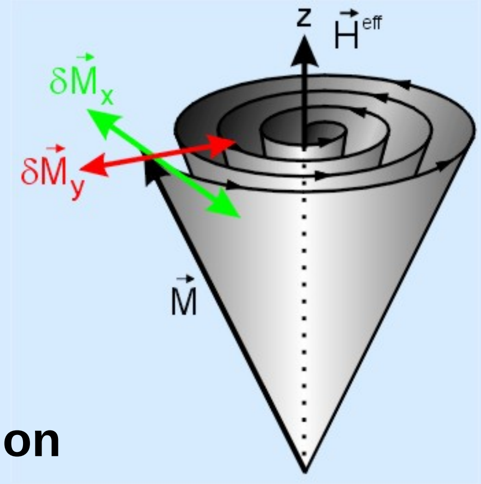
Bloch-Bloembergen Equation (1956)

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

spin-lattice relaxation *(longitudinal)*

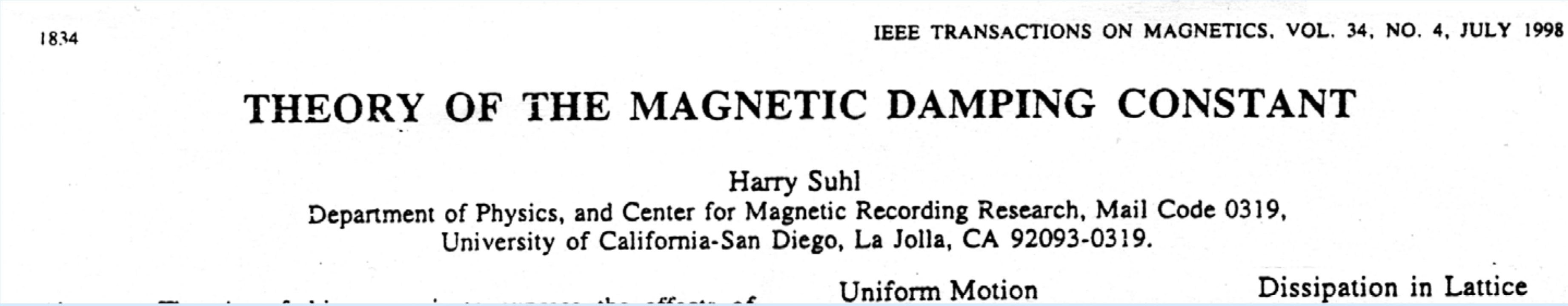
$$\frac{\mathrm{d}m_{x,y}}{\mathrm{d}t} = -\gamma(\,\mathbf{m}\times\mathbf{H}_{\mathrm{eff}}\,)_{x,y} - \frac{m_{x,y}}{T_2}$$

spin-spin relaxation *(transverse)*



M_z=const.

Gilbert damping versus magnon-magnon scattering.



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

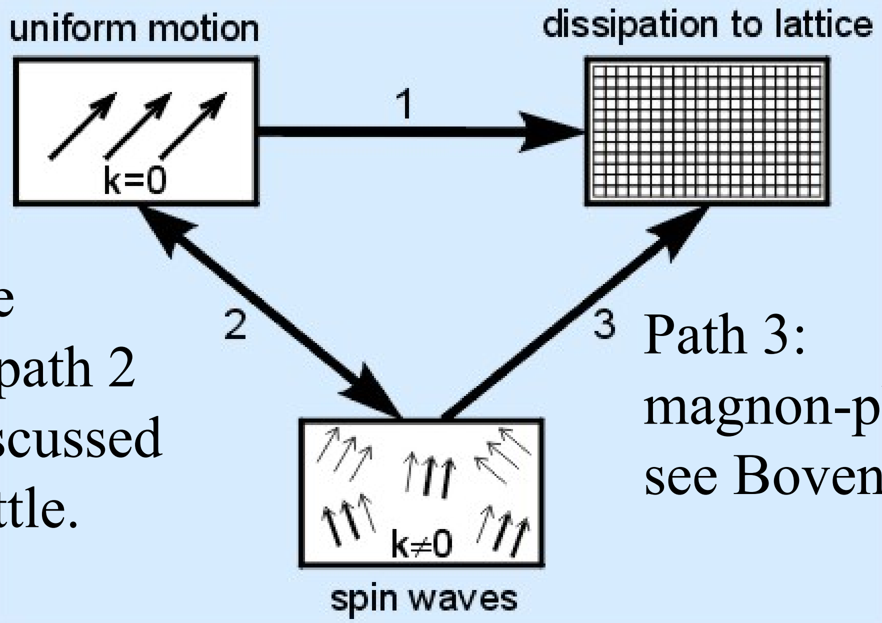
THEORY OF THE MAGNETIC DAMPING CONSTANT

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

Uniform Motion

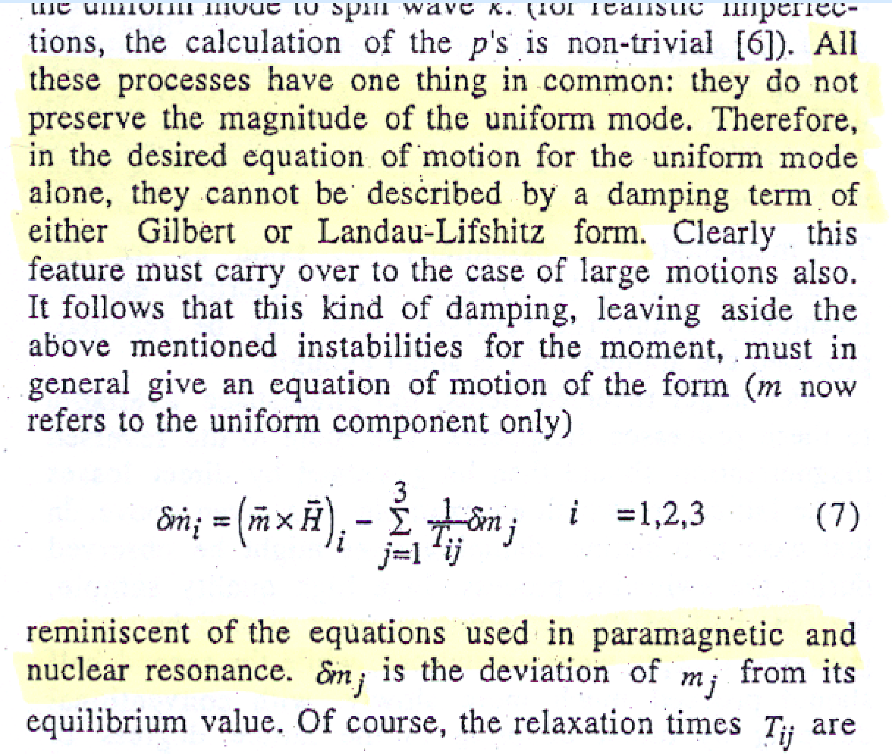
Dissipation in Lattice

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



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

Path 3:
magnon-phonon scattering,
see Bovensiepen PRL 2008



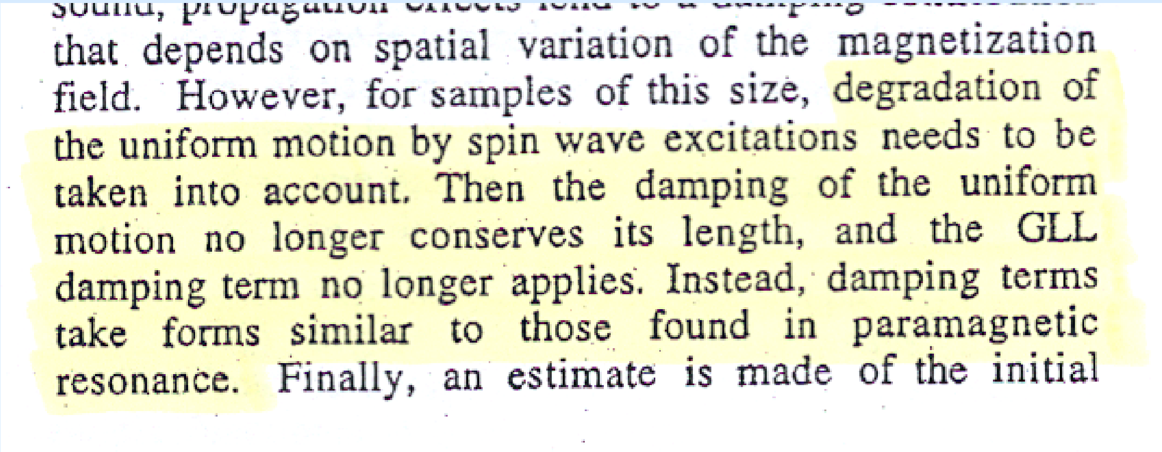
the uniform mode to spin wave k. (for realistic imperfections, the calculation of the p's is non-trivial [6]). All these processes have one thing in common: they do not preserve the magnitude of the uniform mode. Therefore, in the desired equation of motion for the uniform mode alone, they cannot be described by a damping term of either Gilbert or Landau-Lifshitz form. Clearly this feature must carry over to the case of large motions also. It follows that this kind of damping, leaving aside the above mentioned instabilities for the moment, must in general give an equation of motion of the form (m now refers to the uniform component only)

$$\delta\dot{m}_i = \left(\vec{m}\times\vec{H}\right)_i - \sum_{j=1}^{3}\frac{1}{T_{ij}}\delta m_j \qquad i \;=1,2,3 \qquad (7)$$

reminiscent of the equations used in paramagnetic and nuclear resonance. δm_j is the deviation of m_j from its equilibrium value. Of course, the relaxation times T_{ij} are

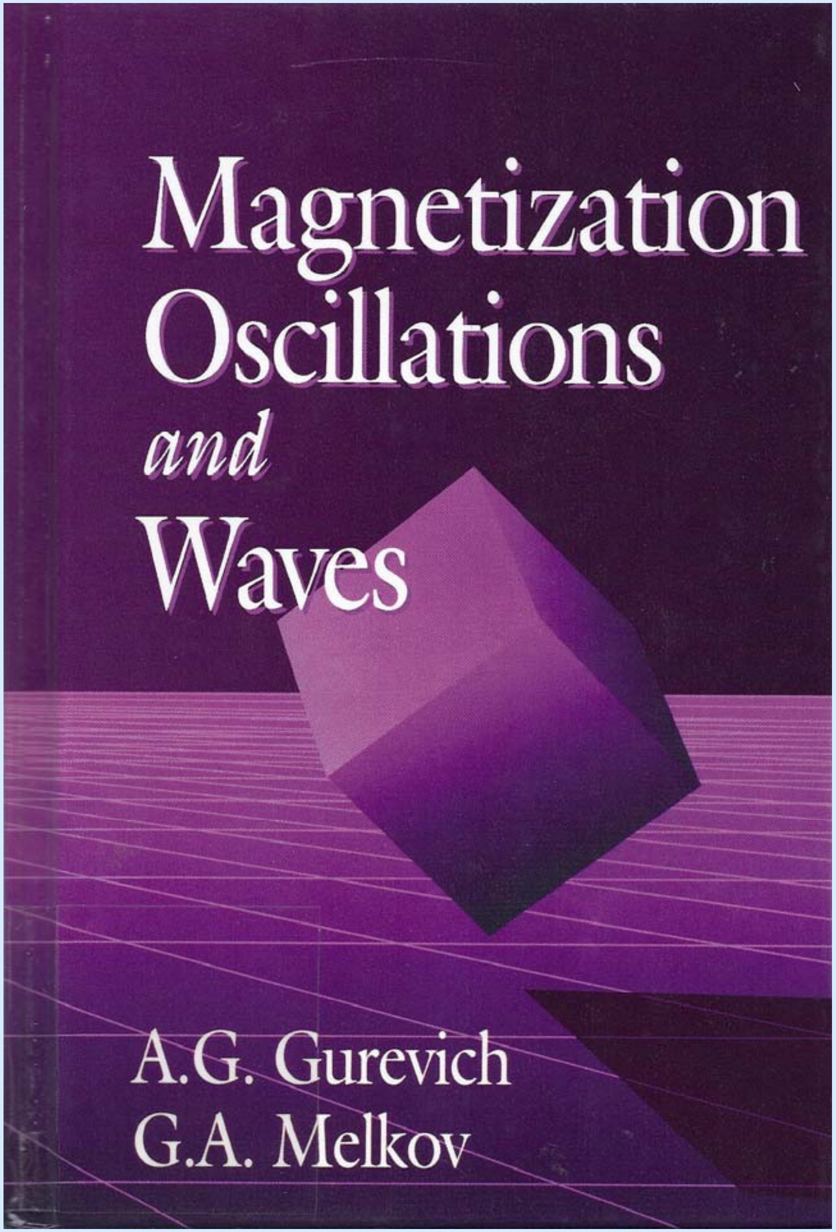
All these processes…do not preserve the magnitude of the uniform mode…

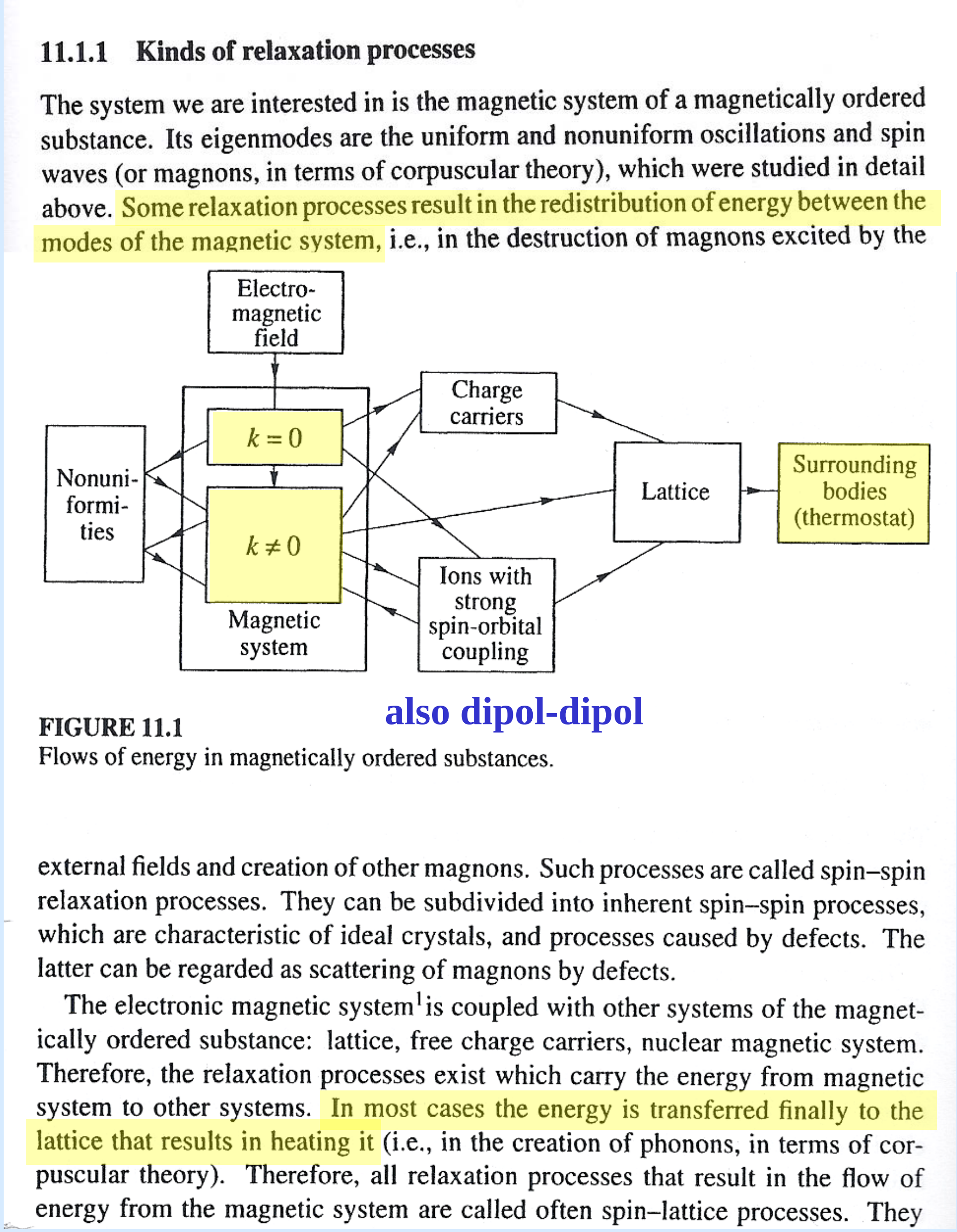
Longitudinal T_1 and transvers T_2 - scattering



sound, propagation effects lead to a damping contribution that depends on spatial variation of the magnetization field. However, for samples of this size, degradation of the uniform motion by spin wave excitations needs to be taken into account. Then the damping of the uniform motion no longer conserves its length, and the GLL damping term no longer applies. Instead, damping terms take forms similar to those found in paramagnetic resonance. Finally, an estimate is made of the initial

…the GLL damping term no longer applies…





11.1.1 Kinds of relaxation processes

The system we are interested in is the magnetic system of a magnetically ordered substance. Its eigenmodes are the uniform and nonuniform oscillations and spin waves (or magnons, in terms of corpuscular theory), which were studied in detail above. Some relaxation processes result in the redistribution of energy between the modes of the magnetic system, i.e., in the destruction of magnons excited by the external fields and creation of other magnons. Such processes are called spin–spin relaxation processes. They can be subdivided into inherent spin–spin processes, which are characteristic of ideal crystals, and processes caused by defects. The latter can be regarded as scattering of magnons by defects.

FIGURE 11.1
Flows of energy in magnetically ordered substances.

also dipol-dipol

The electronic magnetic system^1 is coupled with other systems of the magnetically ordered substance: lattice, free charge carriers, nuclear magnetic system. Therefore, the relaxation processes exist which carry the energy from magnetic system to other systems. In most cases the energy is transferred finally to the lattice that results in heating it (i.e., in the creation of phonons, in terms of corpuscular theory). Therefore, all relaxation processes that result in the flow of energy from the magnetic system are called often spin–lattice processes. They

2. FMR Linewidth - Damping

Landau-Lifshitz-Gilbert-Equation

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

viscous damping,
energy dissipation

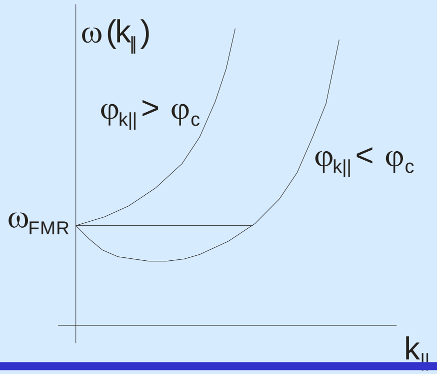
Gilbert-damping ~ω

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

in conventional FMR

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



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

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

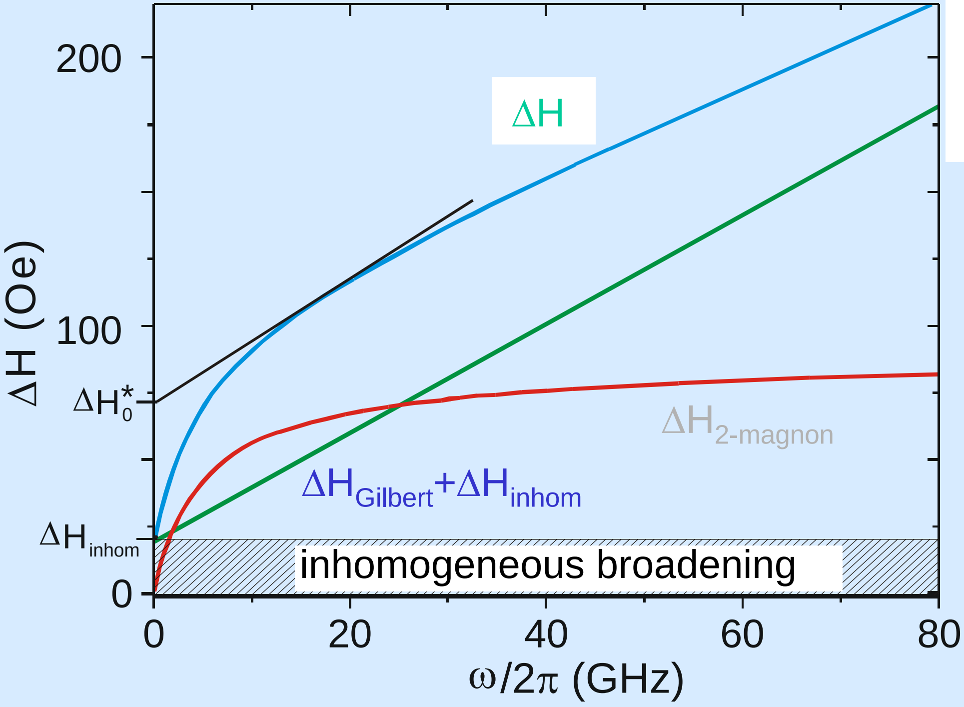
Which (FMR)-publication has checked (disproved) quantitatively this analytical function?

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

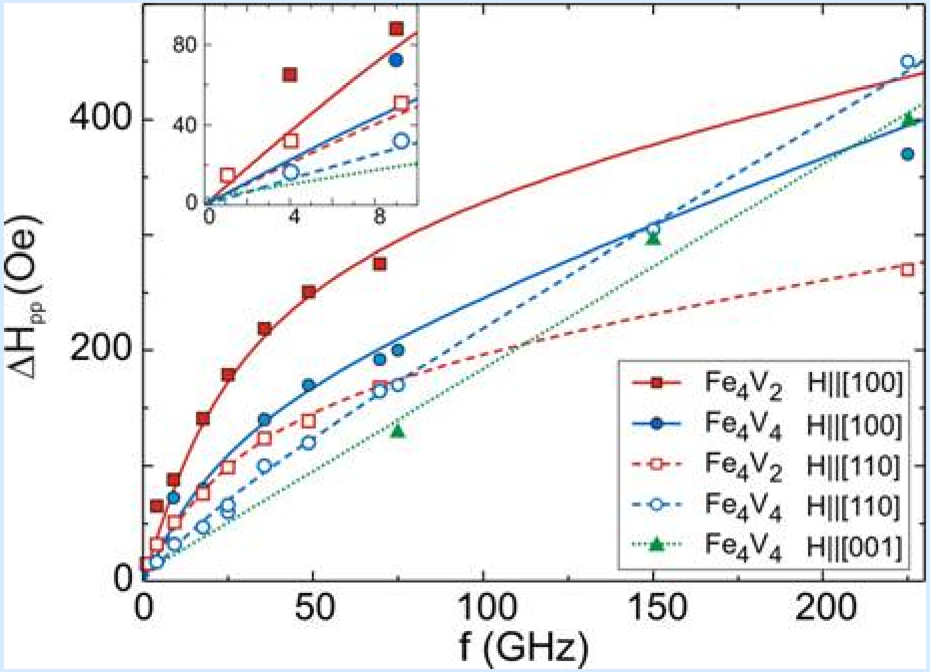
$$\Delta H_{2-\mathrm{magnon}}(\omega) = \Gamma \arcsin\sqrt{\frac{\sqrt{\omega^2 + (\omega_0/2)^2} - \omega_0/2}{\sqrt{\omega^2 + (\omega_0/2)^2} + \omega_0/2}}$$

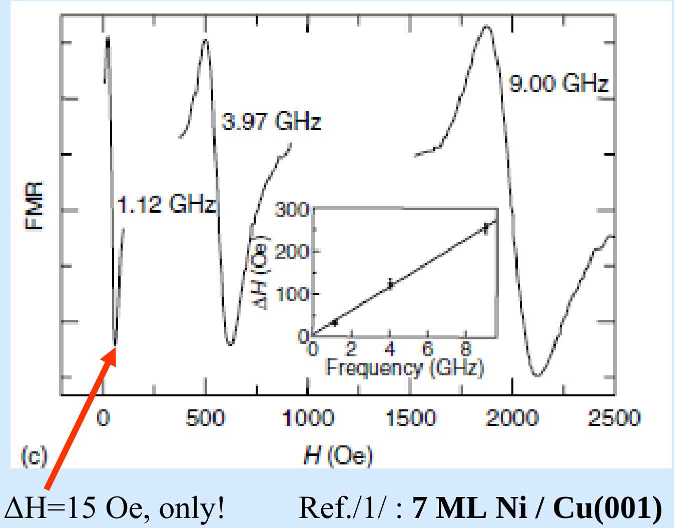
with $\omega_0 = \gamma M_{\mathrm{eff}}$

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

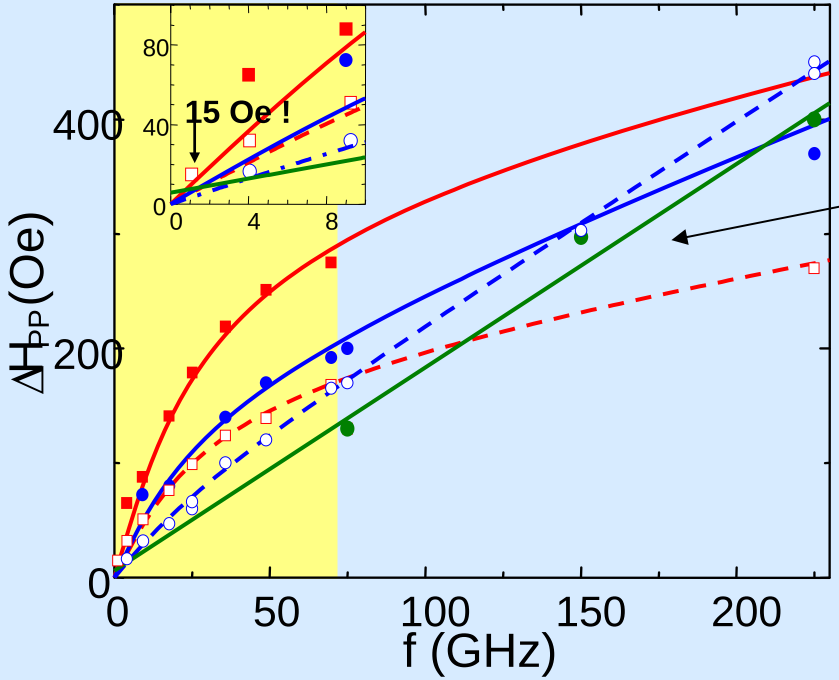


K. Lenz et al., PRB 73, 144424 (2006)





ΔH=15 Oe, only!   Ref./1/ : **7 ML Ni / Cu(001)**



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

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

two-magnon scattering dominates Gilbert damping

by two orders of magnitude:

T_2~ 0.2 n s vs. T_1~ 40 n s

	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

Γ ≈ anisotropic spin wave scattering
G ≈ isotropic dissipation
no anisotropic conductivity is need

PHYSICAL REVIEW B **69**, 184417 (2004)

Two-magnon scattering in a self-assembled nanoscale network of misfit dislocations

G. Woltersdorf and B. Heinrich
Simon Fraser University, 8888 University Drive, Burnaby, British Columbia, Canada V5A 1S6

TABLE II: Fit parameters for the $Pd_{200}Fe_{30}/GaAs(001)$ sample from Ref. [21]. The values given in italics correspond to the solid line fit in Fig. 5 omitting the datapoint at 73 GHz.

orientation	Γ (Oe)	$\gamma\Gamma$ ($10^8\ s^{-1}$)	G ($10^8\ s^{-1}$)	α (10^{-3})	ΔH_0 (Oe)
$\vec{H}\ \Vert [100]$	260	46	0.35	1.23	70
$\vec{H}\ \Vert [100]$	*215*	*38*	*(1.31)*	*4.6*	*55*
$\vec{H}\ \Vert [110]$	0	0	1.31	4.6	48
$\vec{H}\ \Vert [001]$	0	0	1.36	4.8	5

Reanalyzed in K. Lenz et al. PRB 2006

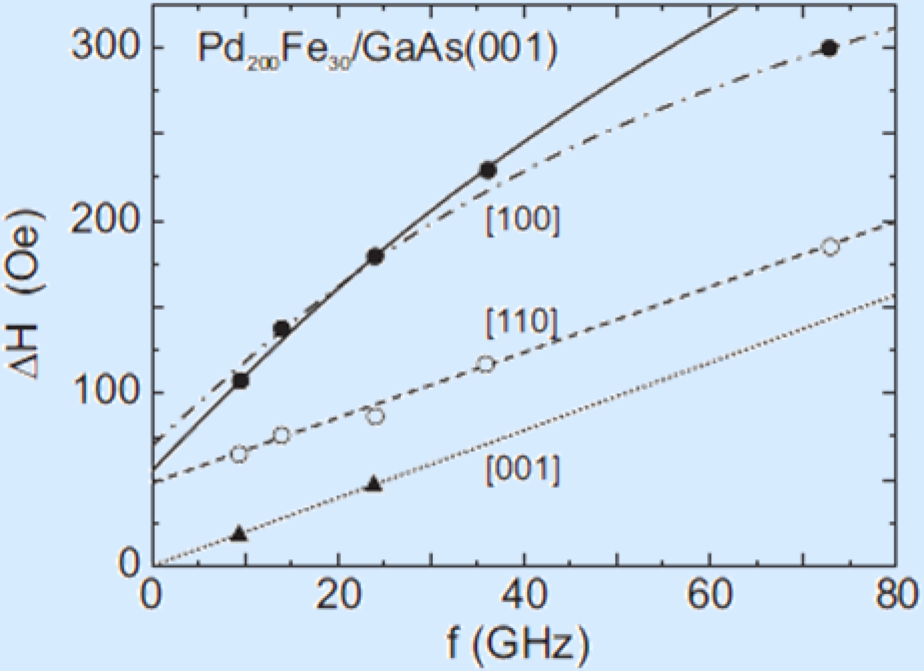
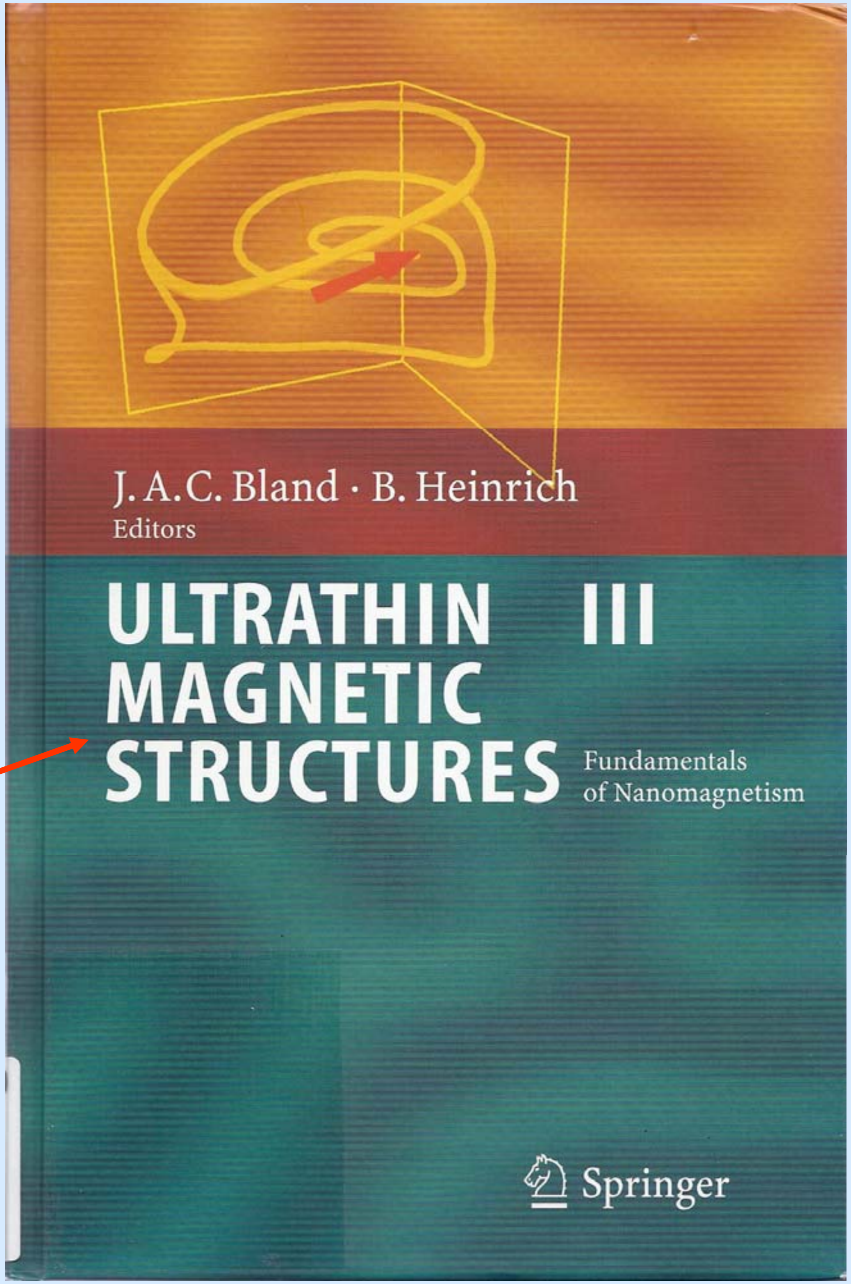


FIG. 5: Frequency dependence of the resonance linewidth of $Pd_{200}Fe_{30}/GaAs(001)$ taken from Ref. [21].

Anonymous referee report on an invited conference paper in 2008 /4/:

… Bloch Bloembergen damping in eq. (7) is absolutely incorrect. It violates thermodynamics. This was shown already by Onsager, Landau, Ginzburg, and Mori. This point is addressed on pages 146-148 in (1).

…I am not able to accept the paper…



J. A. C. Bland · B. Heinrich
Editors

ULTRATHIN III
MAGNETIC
STRUCTURES

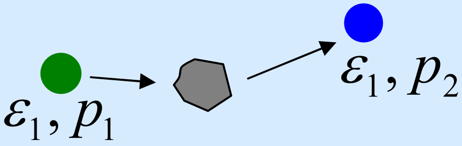
Fundamentals
of Nanomagnetism

Springer

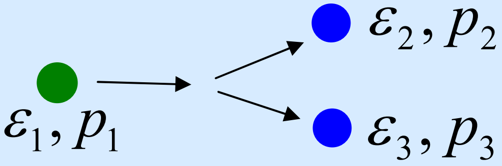
3. Magnon scattering

By courtesy of B. Hillebrands

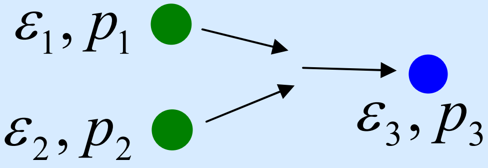
TWO-MAGNON SCATTERING



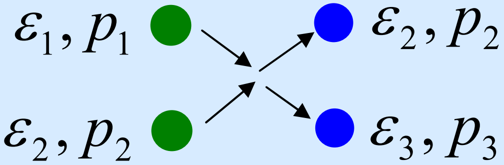
THREE-MAGNON SPLITTING



THREE-MAGNON CONFLUENCE



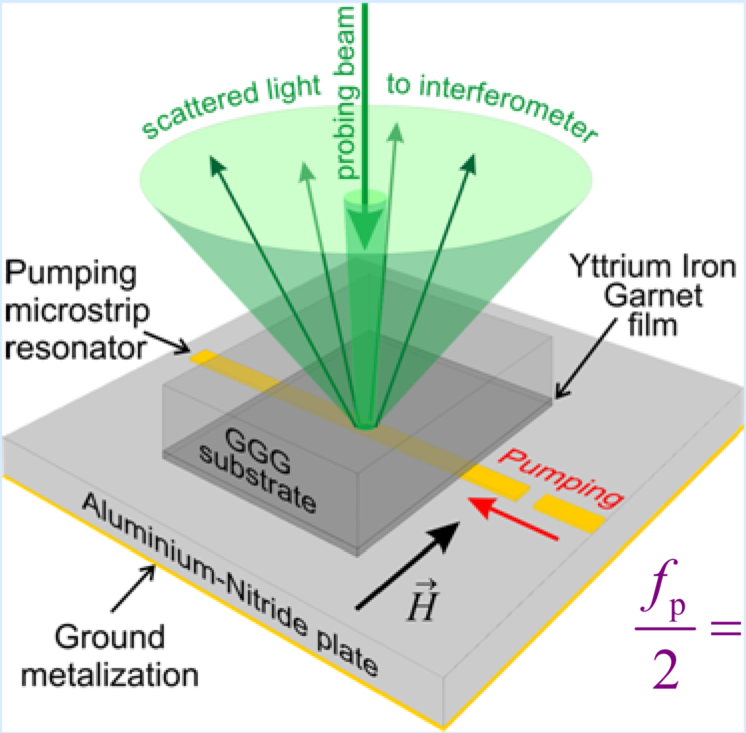
FOUR-MAGNON SCATTERING



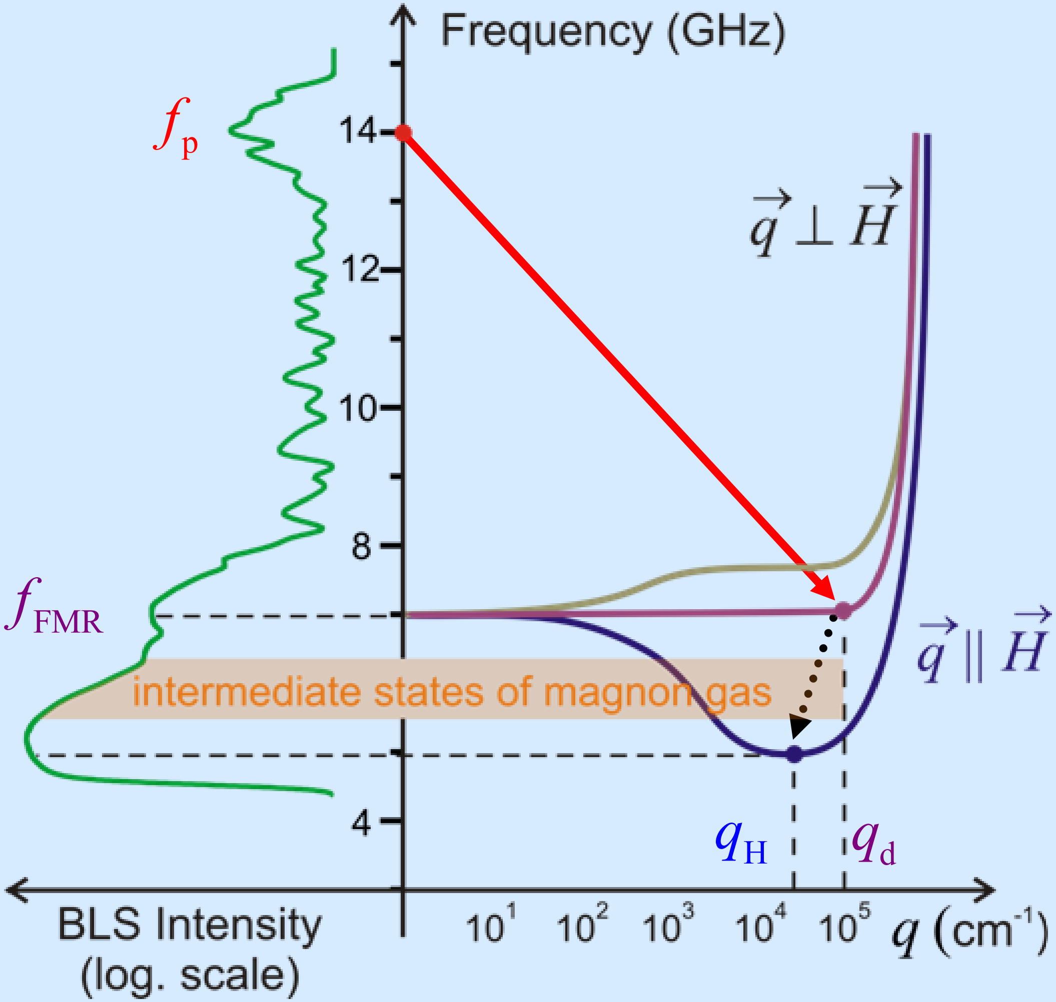
BLS spectrum of magnon gas

By courtesy of B. Hillebrands

Microwave photons split into pairs of phase-correlated magnons - creating a condensate of magnon



BLS spectrum of magnon excitations around the pumping resonator

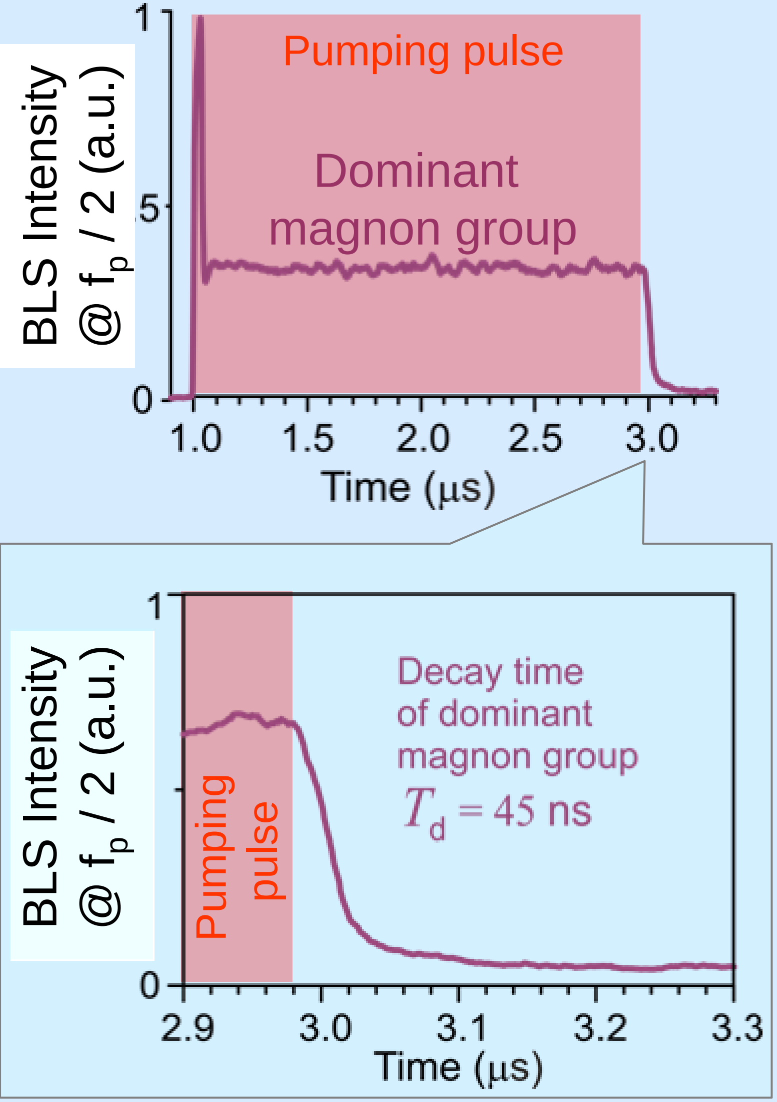


Bose-Einstein condensate of magnons → f_H

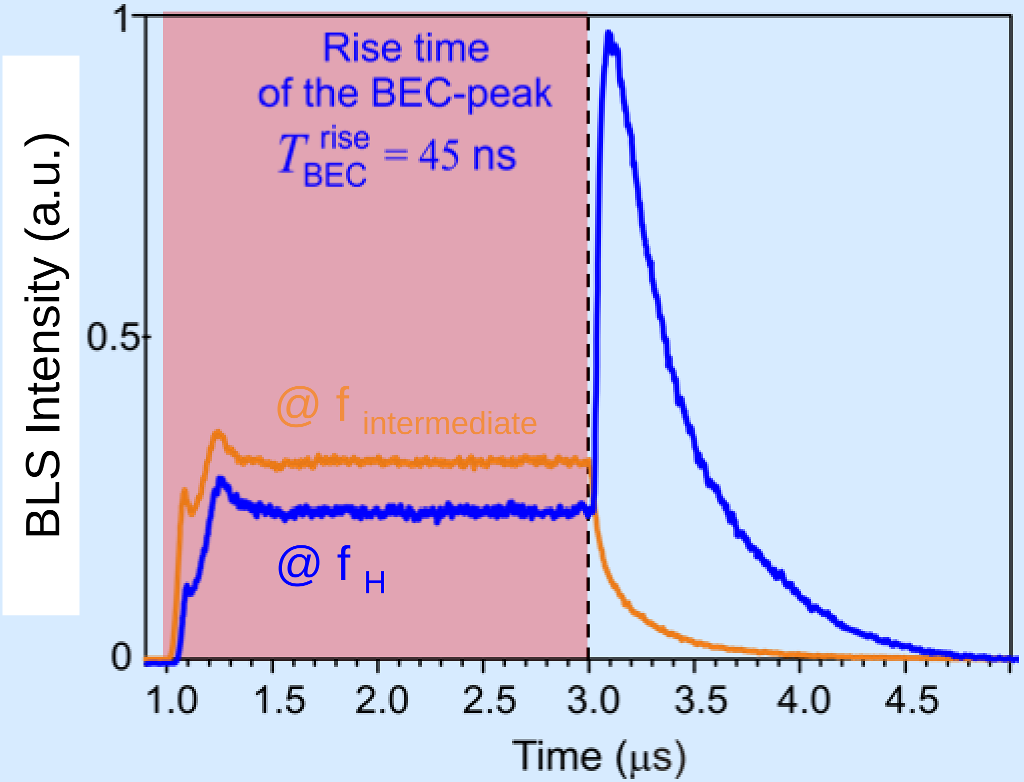
S.O. Demokritov et al., Nature **443**, 430 (2006)

By courtesy of B. Hillebrands

Pump-free evolution of Bose-Einstein condensate of magnons



Temporal dynamics of BEC of magnons and intermediate states of maqnon gas:



Decay and rise time is in the order of 40 ns.

Variable damping and coherence in a high-density magnon gas

S. Schäfer,[1] V. Kegel,[1] A.A. Serga,[1] and B. Hillebrands[1]
[1] *Fachbereich Physik and Forschungszentrum OPTIMAS,*
Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
(Dated: July 13, 2010)

New paper
online July 2010

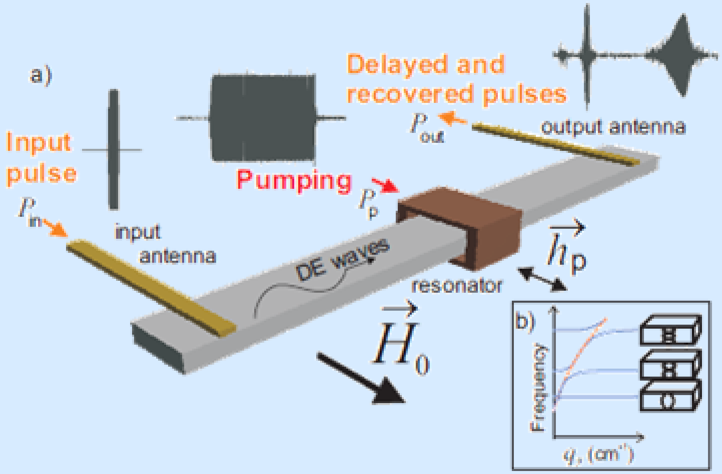


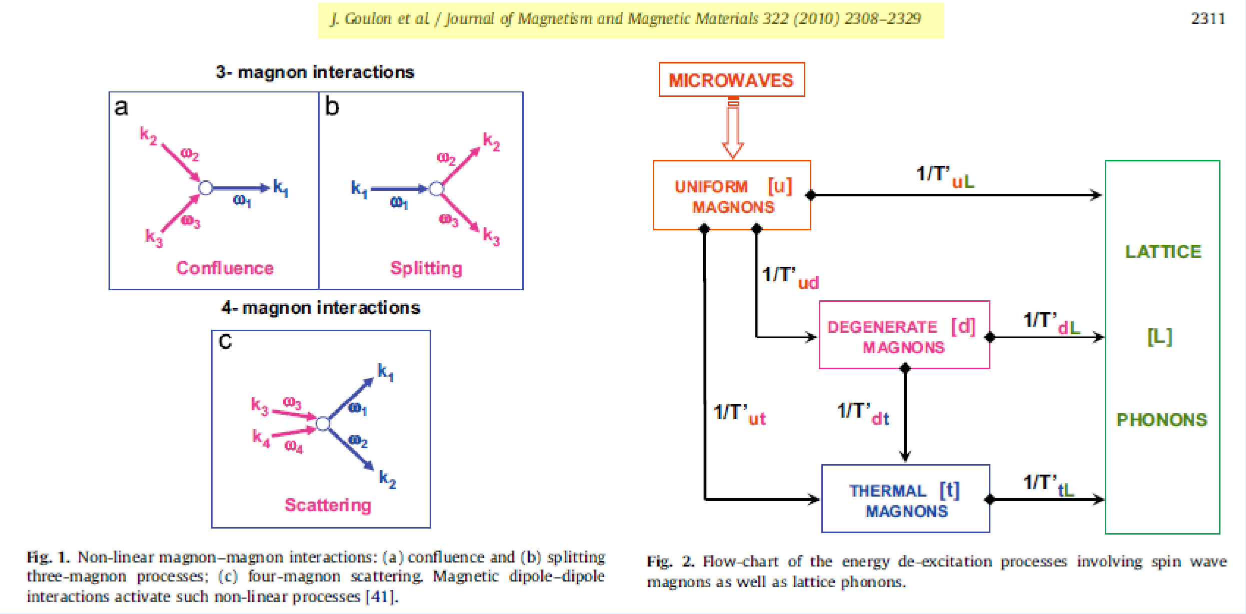
FIG. 1: (Color online) a) Experimental setup, consisting of a single-crystal YIG waveguide, input and output antennas and a dielectric resonator for the application of the pumping microwave field. The waveforms indicate the form of the input, pumping and restored pulses as seen on the oscilloscope. b) Section of the spin-wave dispersion spectrum for a thin magnetic waveguide schematically showing the hybridization of Damon-Eshbach (dashed line) wave with perpendicular standing spin wave modes.

In conclusion, we investigated the relaxation of a free evolving gas of previously parametrically pumped magnons. The experimental results show a clear deviation from the phenomenological Gilbert model of spin-wave damping. They also exceed the observations on non-linear four-magnon scattering caused damping described so far [6]. The model we

field. We interpret this as the microwave field causing a suppression of scattering for parametrically excited magnons, a mechanism which will be further focused upon in future

X-ray detected magnetic resonance of YIG thin films in the nonlinear regime of spin waves

J. Goulon [a,*], A. Rogalev [a], F. Wilhelm [a], G. Goujon [a], Ch. Brouder [b], A. Yaresko [c],
J. Ben Youssef [d], M.V. Indenbom [d]

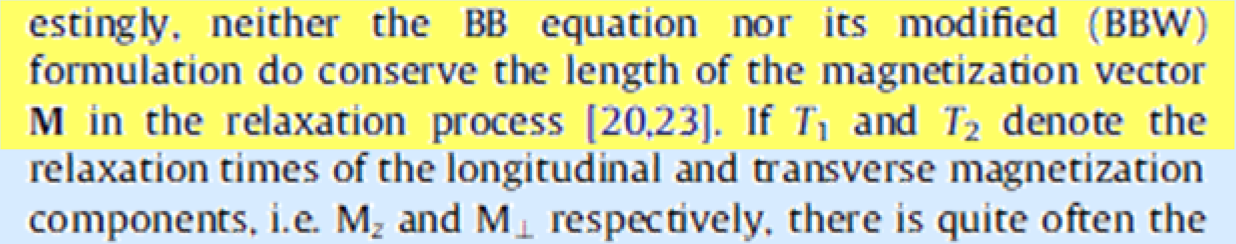


J. Goulon et al / Journal of Magnetism and Magnetic Materials 322 (2010) 2308–2329

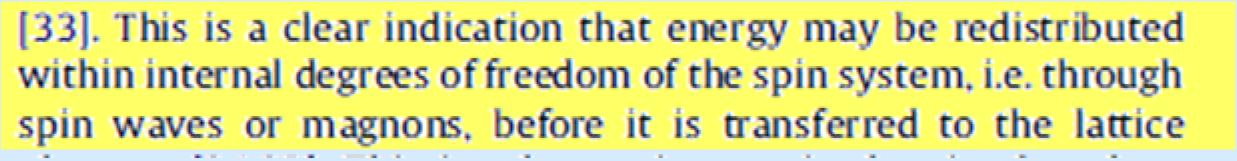
2311

Fig. 1. Non-linear magnon–magnon interactions: (a) confluence and (b) splitting three-magnon processes; (c) four-magnon scattering. Magnetic dipole–dipole interactions activate such non-linear processes [41].

Fig. 2. Flow-chart of the energy de-excitation processes involving spin wave magnons as well as lattice phonons.



estingly, neither the BB equation nor its modified (BBW) formulation do conserve the length of the magnetization vector **M** in the relaxation process [20,23]. If T_1 and T_2 denote the relaxation times of the longitudinal and transverse magnetization components, i.e. M_z and $M_\perp$ respectively, there is quite often the



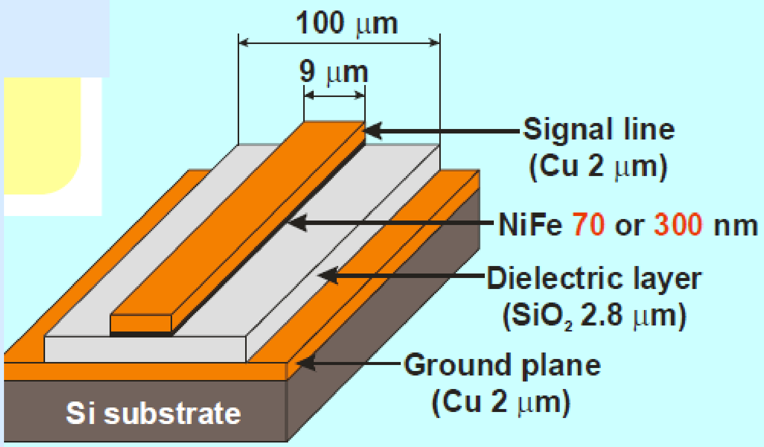
[33]. This is a clear indication that energy may be redistributed within internal degrees of freedom of the spin system, i.e. through spin waves or magnons, before it is transferred to the lattice

Nonlinear Ferromagnetic Dynamics

By courtesy of Bob Camley, Tim Fal, Jeff Marsh, Yuri Khivintsev, Zbigniew Celinski

Nonlinear mixing of 2 signals
with increasing power

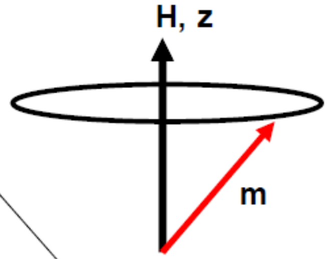
Geometry:



Microstrip waveguide length = 6.58 mm

We need to look for a <u>cubic</u> term in our equation of motion

$$\frac{d}{dt}\begin{pmatrix}m_x\\ m_y\\ m_z\end{pmatrix} = -|\gamma|\begin{vmatrix}\hat{i} & \hat{j} & \hat{k}\\ m_x & m_y & \boxed{m_z}\\ \boxed{H_x} & \boxed{H_y} & H_z\end{vmatrix}$$



Simple Case – The H terms involve

Applied Field - H

Demagnetizing field

$(H_d)_x = -N_x m_x$

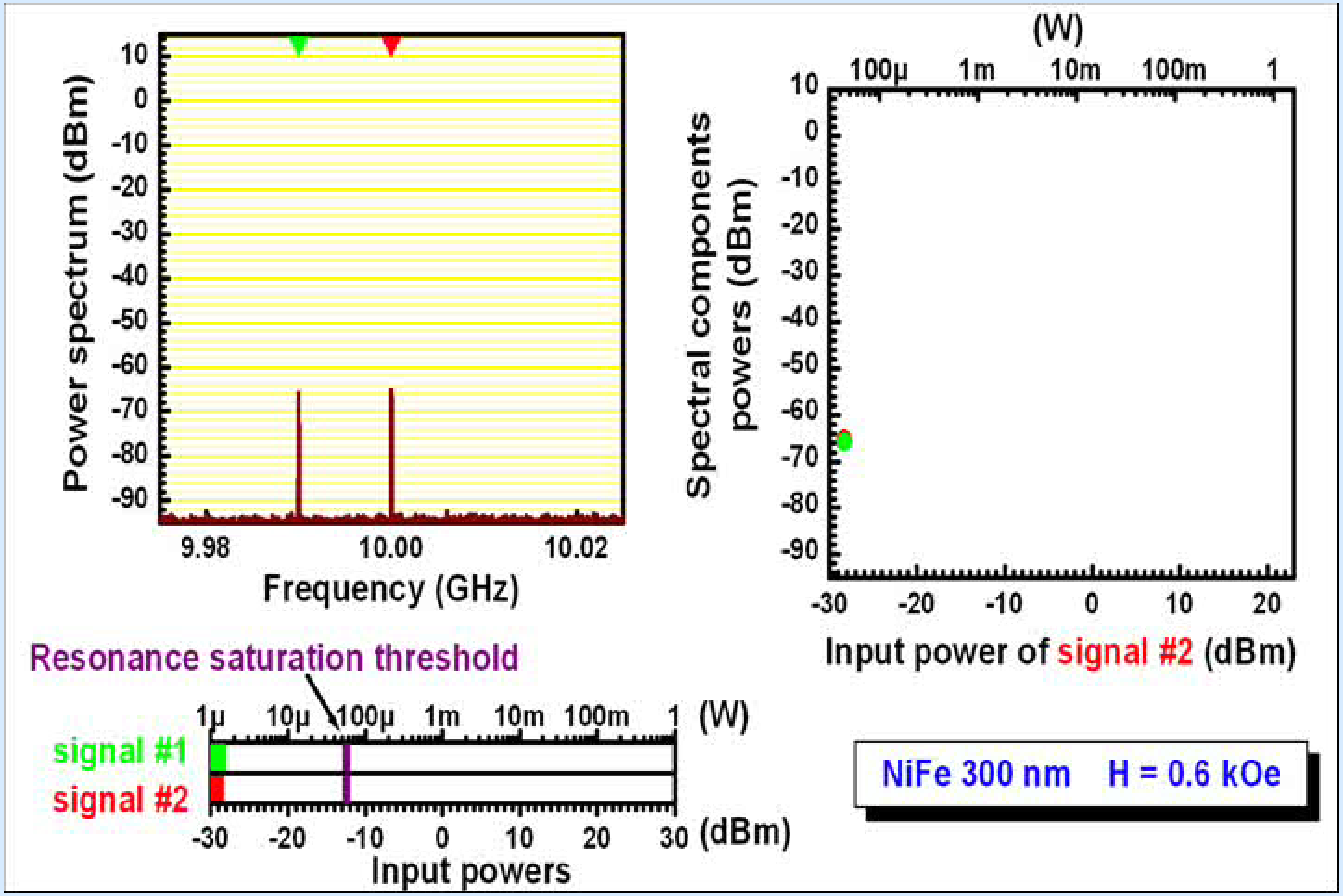
$(H_d)_y = -N_y m_y$

Oscillating h field in FMR

terms quadratic in m_x and m_y

terms linear in m_x , m_y and h_y

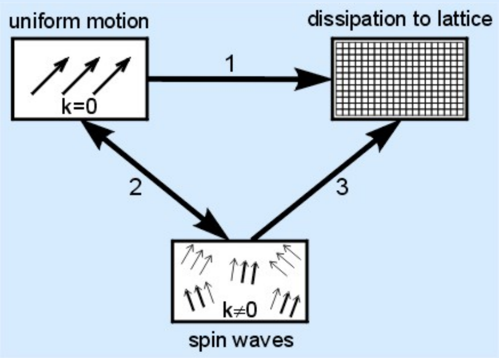
The product gives us the cubic terms



New frequencies come from sum or difference terms

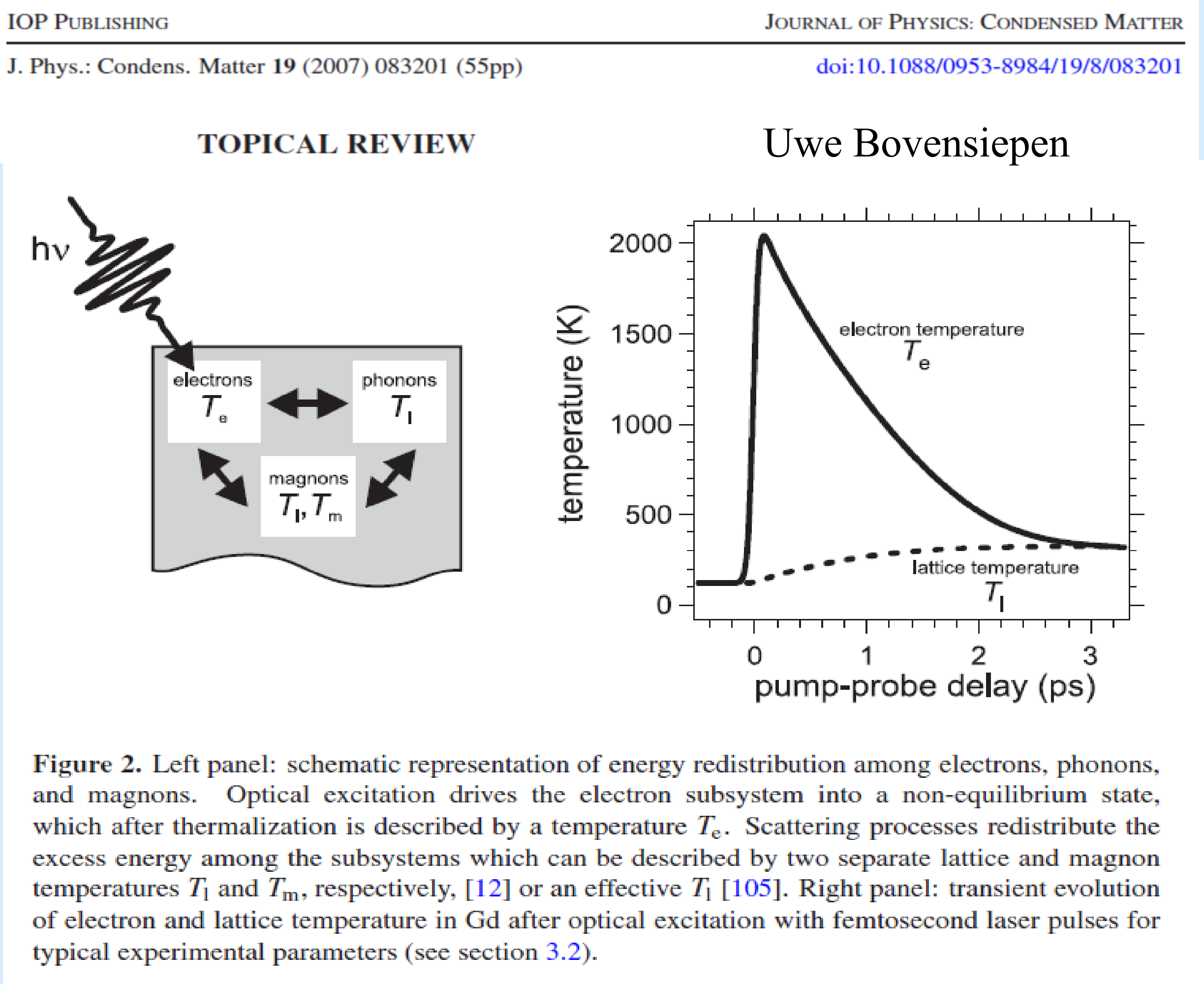
see PRB **81**, 054436 (2010)

1. Introduction
2. 2-magnon scattering, FMR linewidth
3. (3-) 4-magnon scattering, BLS, XDMR
4. magnon-phonon scattering,
   pump-probe experiments
5. X-FEL, LCLS



1. Introduction
2. 2-magnon scattering, FMR linewidth
3. (3-) 4-magnon scattering, BLS, XDMR
4. magnon-phonon scattering,
   pump-probe experiments
5. X-FEL, LCLS

4. Laser irradiation creates a hot electron gas.



IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **19** (2007) 083201 (55pp) doi:10.1088/0953-8984/19/8/083201

TOPICAL REVIEW

Uwe Bovensiepen

Figure 2. Left panel: schematic representation of energy redistribution among electrons, phonons, and magnons. Optical excitation drives the electron subsystem into a non-equilibrium state, which after thermalization is described by a temperature T_e. Scattering processes redistribute the excess energy among the subsystems which can be described by two separate lattice and magnon temperatures T_l and T_m, respectively, [12] or an effective T_l [105]. Right panel: transient evolution of electron and lattice temperature in Gd after optical excitation with femtosecond laser pulses for typical experimental parameters (see section 3.2).

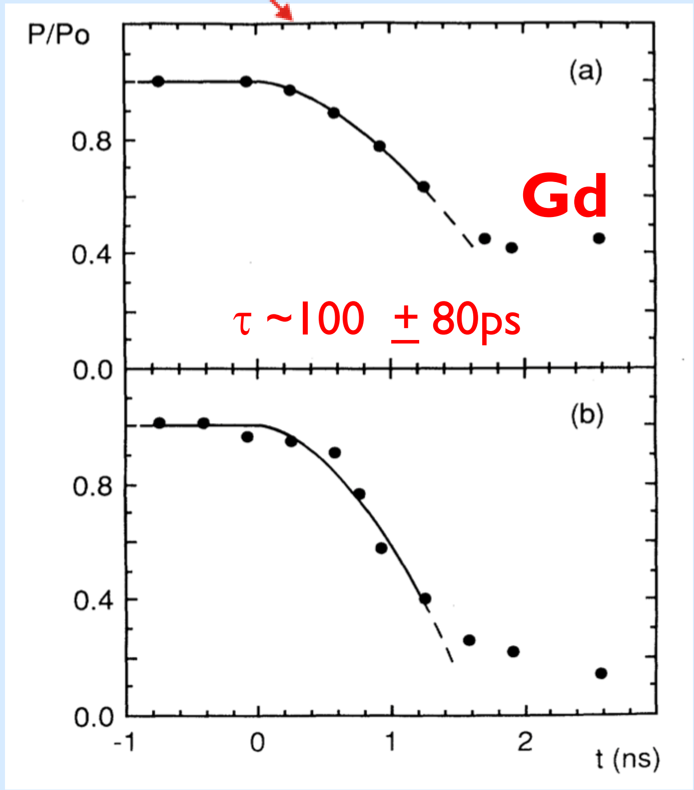
T_e may be larger than T_C
as consequence M = 0

Rise time for T_e ≈ 100 fs

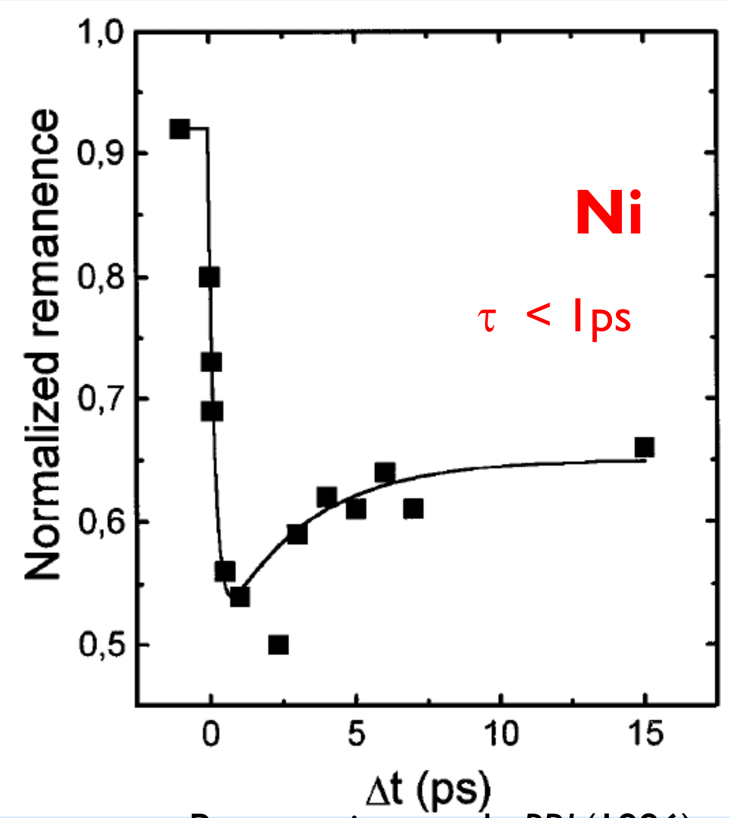
Electron gas cools down,

T_l increases in ≈ 1-3 ps

Ultrafast Laser-induced Demagnetization

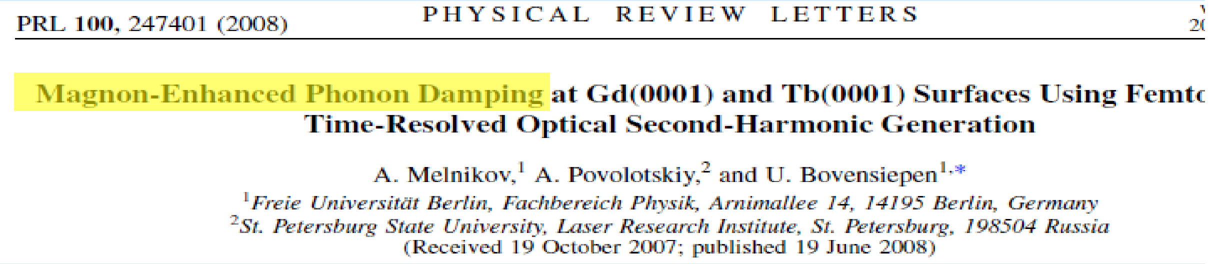


Vaterlaus, et al., *PRL*(1991)



Beaurepaire, et al., *PRL*(1996)

$\tau_M \approx 1 - 100$ ps, slow for Gd because of small SOC



PRL **100**, 247401 (2008) PHYSICAL REVIEW LETTERS

Magnon-Enhanced Phonon Damping at Gd(0001) and Tb(0001) Surfaces Using Femt Time-Resolved Optical Second-Harmonic Generation

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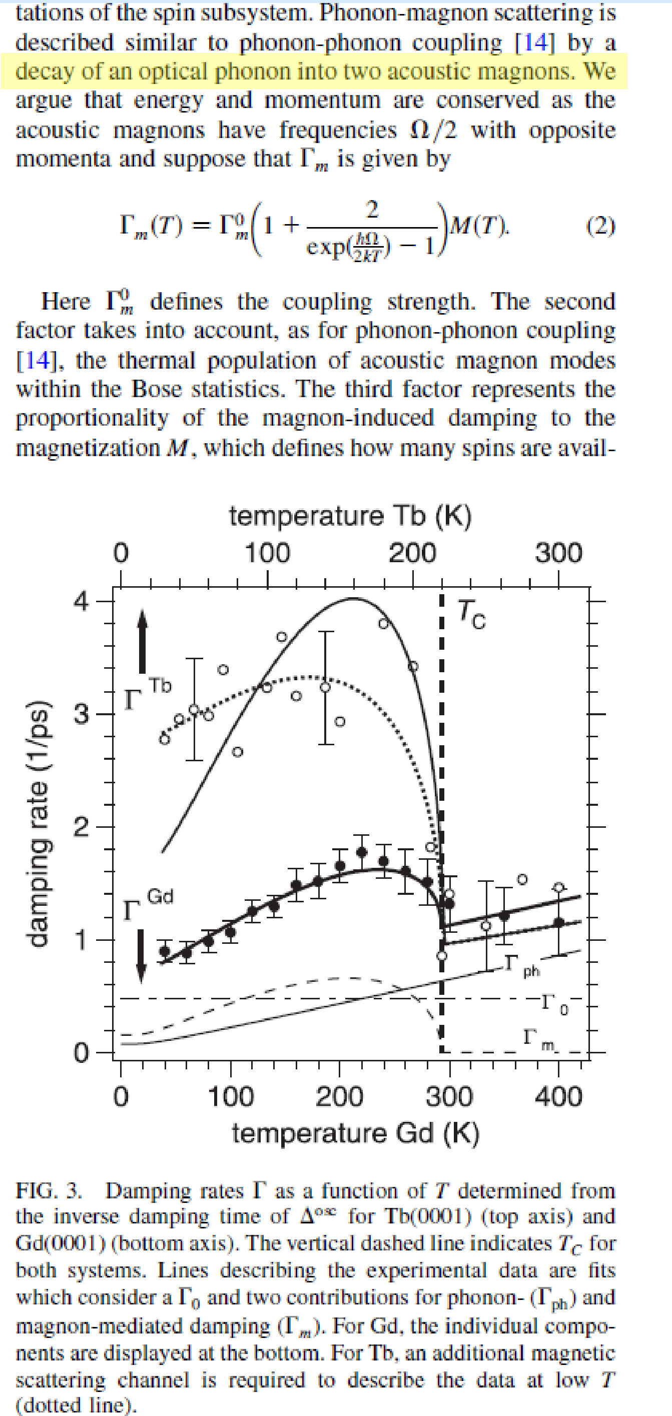
(Received 19 October 2007; published 19 June 2008)

close to T_C the phonon damping rate is strongly reduced

optical phonons decay into acoustic magnons

phonon-magnon scattering dominates the damping of optical phonons…



tations of the spin subsystem. Phonon-magnon scattering is described similar to phonon-phonon coupling [14] by a decay of an optical phonon into two acoustic magnons. We argue that energy and momentum are conserved as the acoustic magnons have frequencies $\Omega/2$ with opposite momenta and suppose that Γ_m is given by

$$\Gamma_m(T) = \Gamma_m^0\left(1+\frac{2}{\exp(\frac{\hbar\Omega}{2kT})-1}\right)M(T). \qquad (2)$$

Here Γ_m^0 defines the coupling strength. The second factor takes into account, as for phonon-phonon coupling [14], the thermal population of acoustic magnon modes within the Bose statistics. The third factor represents the proportionality of the magnon-induced damping to the magnetization M, which defines how many spins are avail-

FIG. 3. Damping rates Γ as a function of T determined from the inverse damping time of Δ^{osc} for Tb(0001) (top axis) and Gd(0001) (bottom axis). The vertical dashed line indicates T_C for both systems. Lines describing the experimental data are fits which consider a Γ_0 and two contributions for phonon- (Γ_{ph}) and magnon-mediated damping (Γ_m). For Gd, the individual components are displayed at the bottom. For Tb, an additional magnetic scattering channel is required to describe the data at low T (dotted line).

Hot electrons may change the electron configuration of Co or Fe ions and that in turn will change the magnetization and MAE as well as SRT, and the spin wave spectra.

PHYSICAL REVIEW B 81, 214440 (2010)

Large ultrafast photoinduced magnetic anisotropy in a cobalt-substituted yttrium iron garnet

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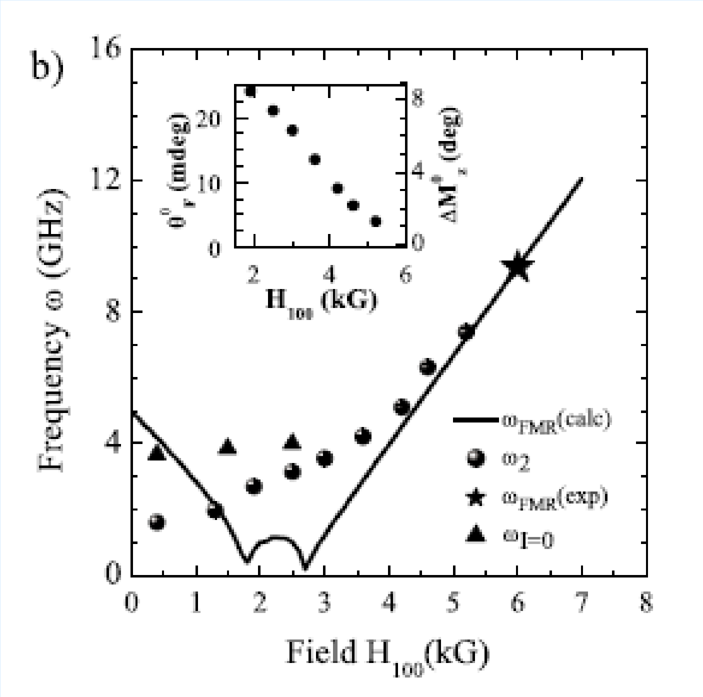
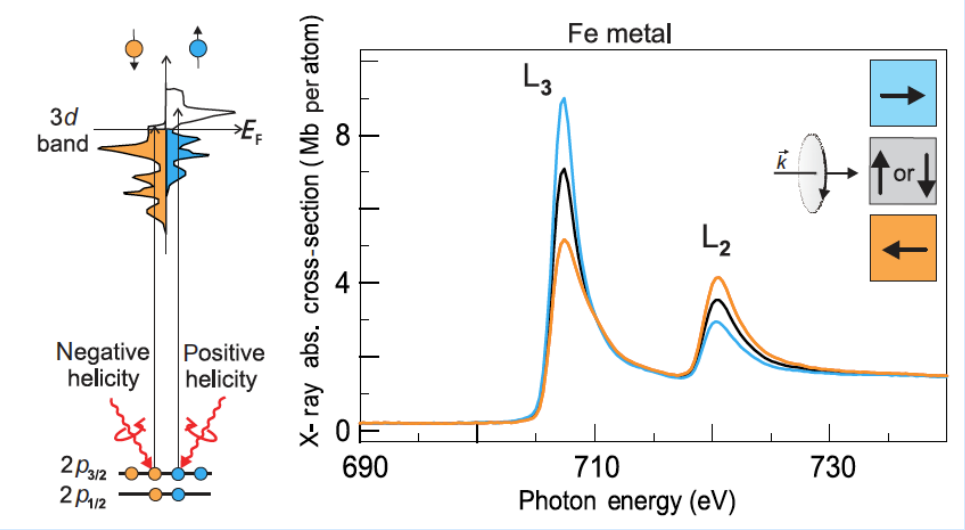
“ Right after the laser pulse the magnetic moments start to precess around the new effective field … which decays to its equilibrium value with a characteristic time of $\tau = 20$ ps.”

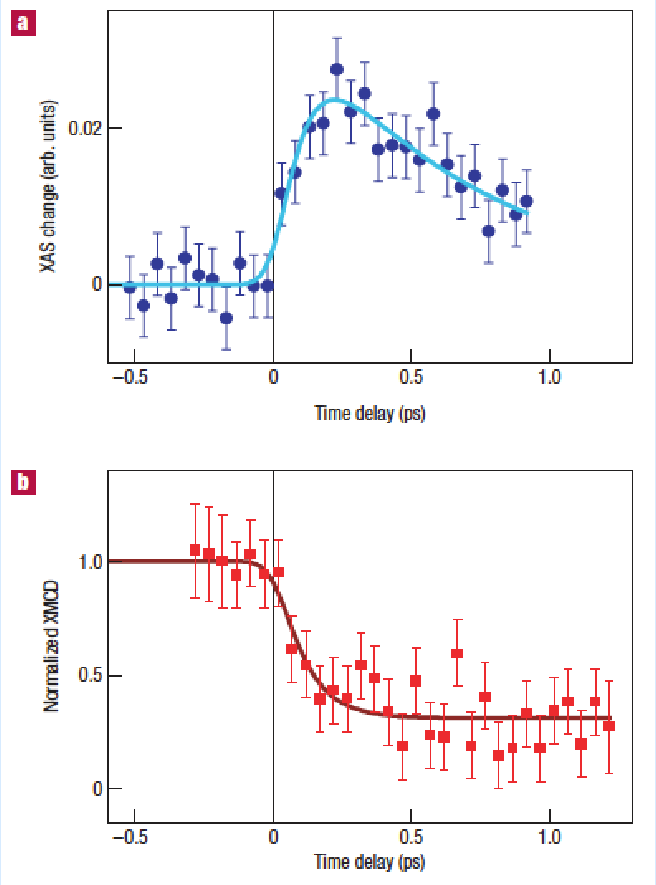


By courtesy of Andreas Scherz, SSRL

Time-resolved XMCD at femto-slicing source



X-ray Magnetic Circular Dichroism



fs evolution Ni electronic and magnetic structure

C. Stamm, et al., Nat. Mater. 6, 740 (2007)

Distinguishing the ultrafast dynamics of spin and orbital moments in solids

C. Boeglin[1], E. Beaurepaire[1], V. Halté[1], V. López-Flores[1], C. Stamm[2], N. Pontius[2], H. A. Dürr[2]† & J.-Y. Bigot[1]

New experiments at BESSY   nature LETTERS, May 2010

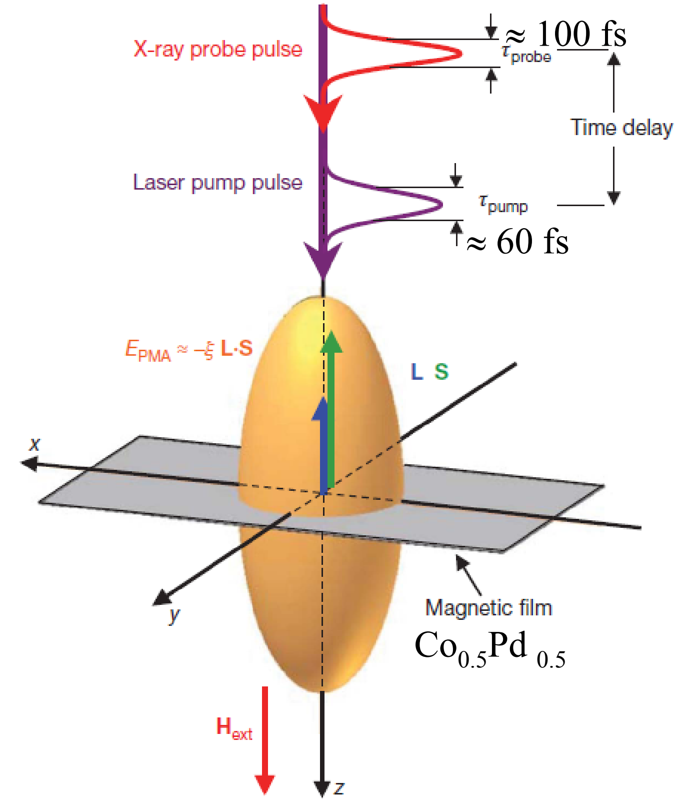


Figure 1 | Geometry of the pump–probe experiment. Sketch of the geometry of the pump–probe experiment at the femtoslicing synchrotron beam line at BESSY. Time-resolved XMCD allows measurement of the ultrafast dynamics of spin and orbital momenta along the quantification axis *z* parallel to the applied

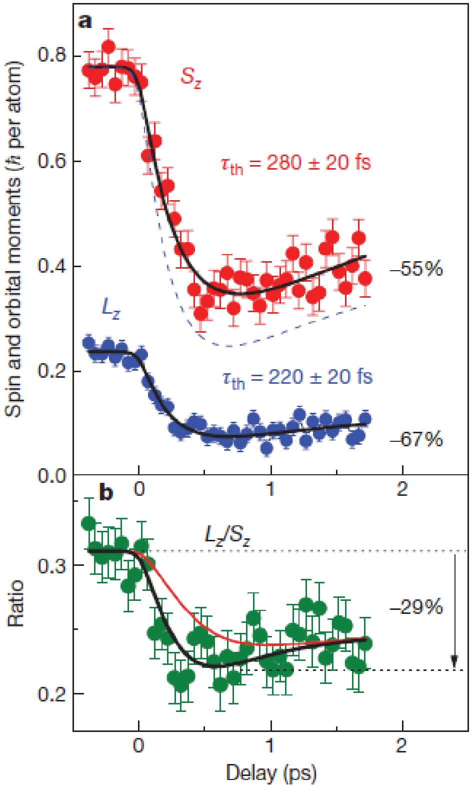
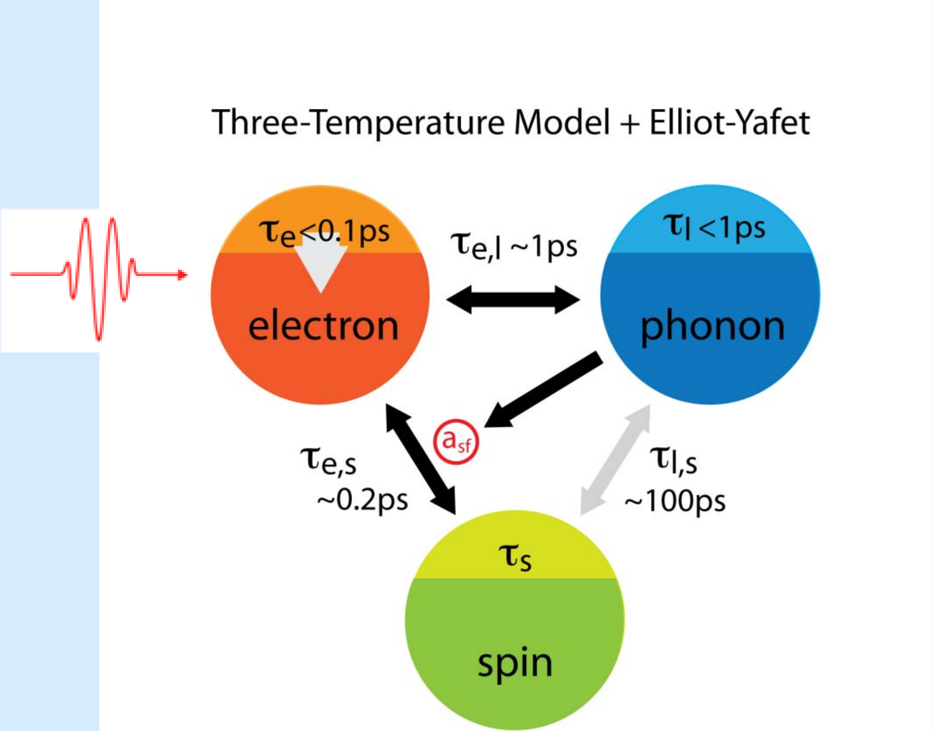


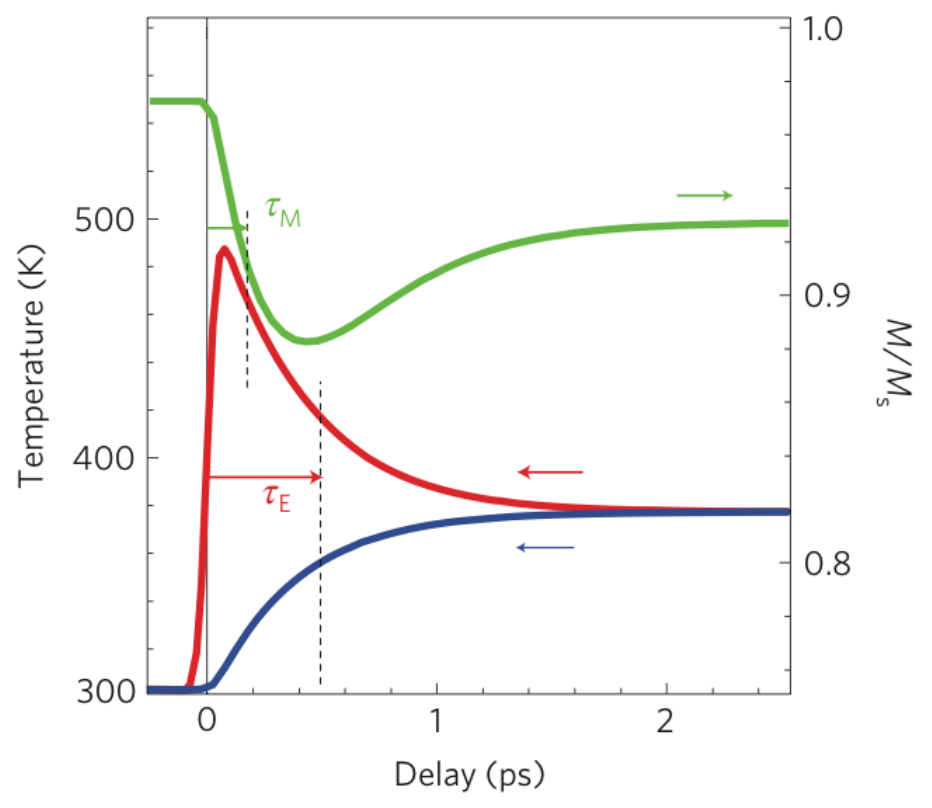
Figure 4 | Femtosecond evolution of the magnetic spin and orbital moments. **a,** Sum rule extracted effective spin and orbital magnetic moments $S_z(t)$ and $L_z(t)$ as a function of the delay time between the laser pump and the X-ray

Three-Temperature Model

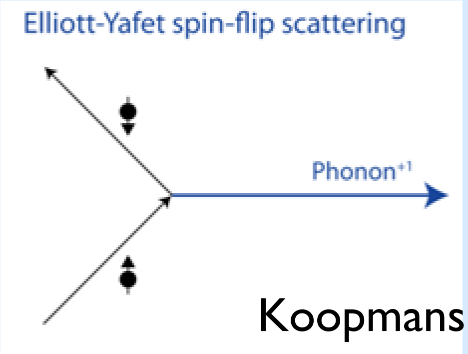
By courtesy of Andreas Scherz



Microscopic channels for ultrafast transfer of angular momentum?



Koopmans, et al., Nature mat. (2009)

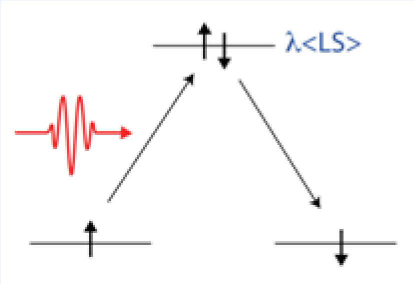


Incoherent Process

Koopmans et al., PRL (2005)

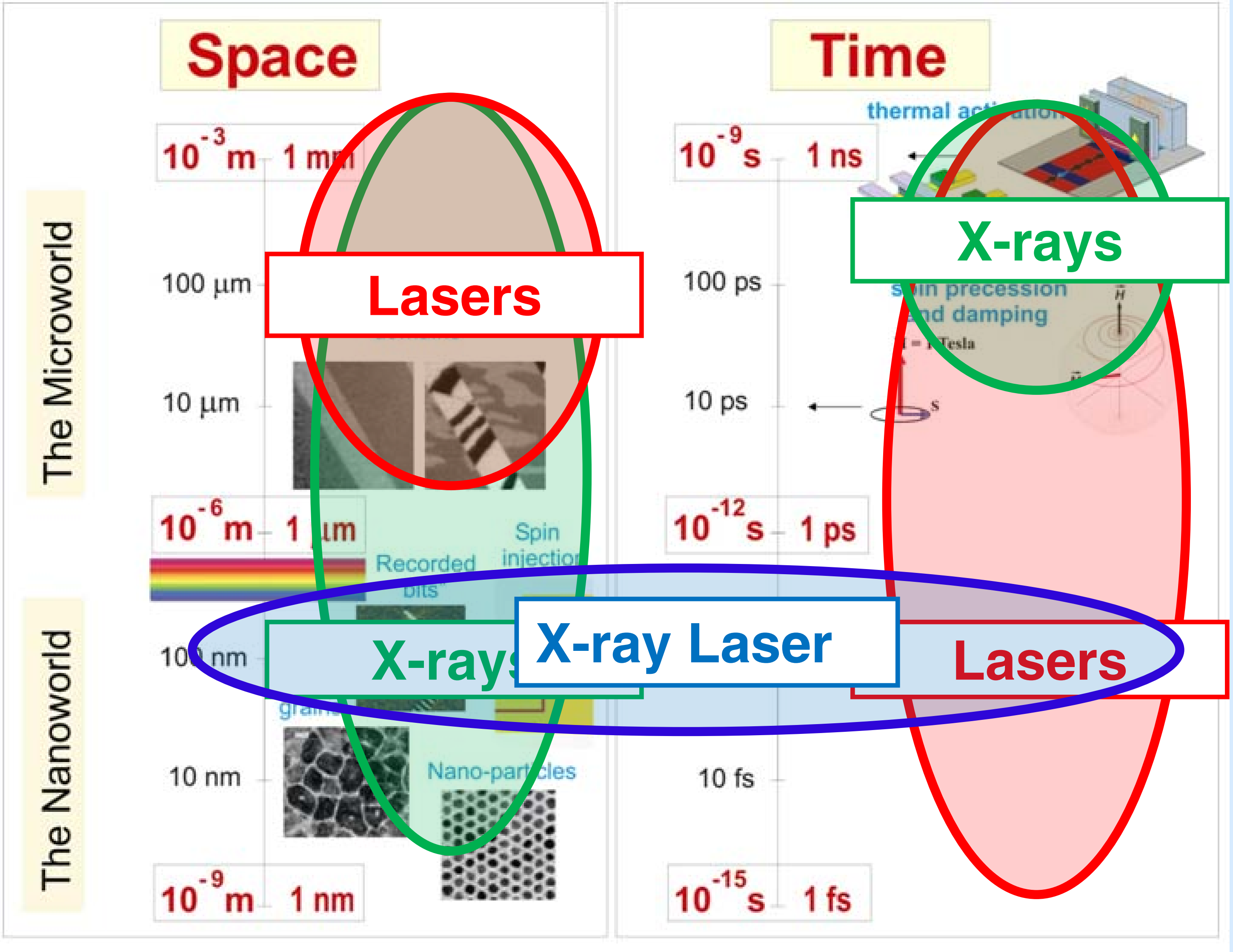
Coherent Process

Zhang, Hübner, PRL (2000)
Bigot et al.,
Nature phys. (2009).



Combining high temporal and spatial resolution

By courtesy of Andreas Scherz, SSRL



X-ray laser at LCLS is running these days

Performance is excellent, undulator at LINAC works better than expected

Time resolution may be better than 10 fs !!

Summary:

Thermodynamic ground state

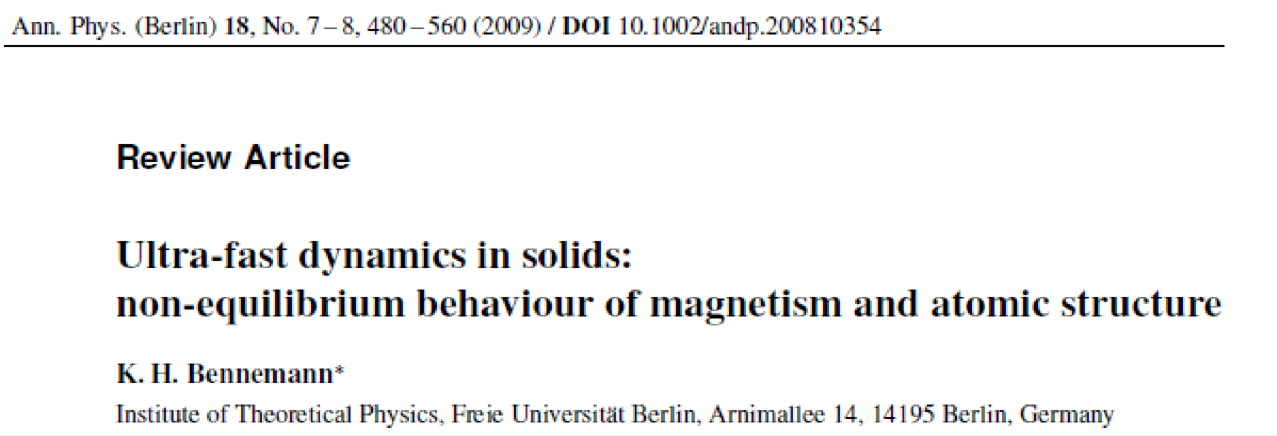
- Todays analysis of spin-wave dynamics should not assume |M| = const, i. e. T=0 assumption.
- Long wavelength spin-waves relax slowly with G ~ ns
  2-magnon scattering with T ~ 10-100 ps
- All spin wave excitations need a second scattering –dephasing- constant. Not only a damping constant for energy dissipation.

Thank you

Hot electron gas, non-equilibrium

- For a spin flip the shortest wave length is λ ≈ a, very fast.
- Hot electrons may change the magnetization within 100 fs.

For this part see:



Ann. Phys. (Berlin) 18, No. 7 – 8, 480 – 560 (2009) / **DOI** 10.1002/andp.200810354

Review Article

Ultra-fast dynamics in solids:
non-equilibrium behaviour of magnetism and atomic structure

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