Ultrafast magnetization dynamics: the role of angular momentum

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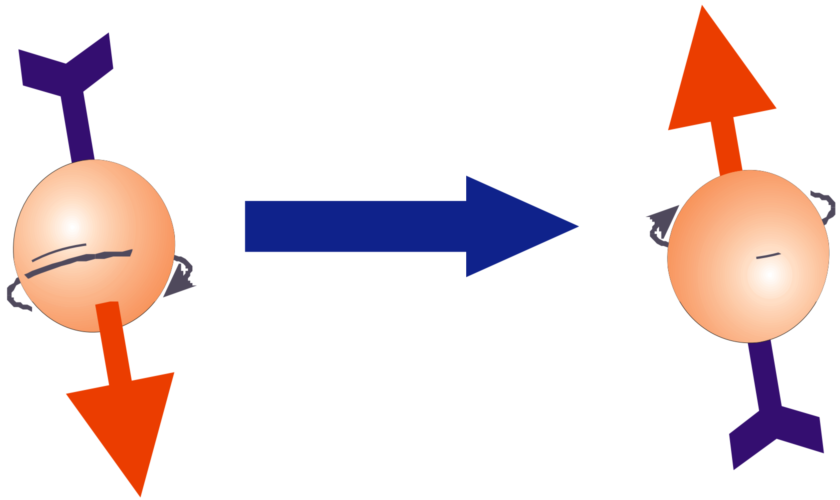
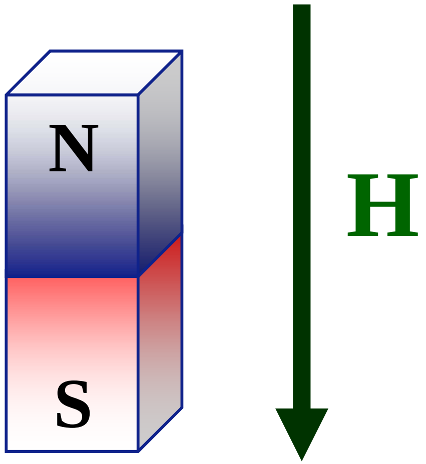


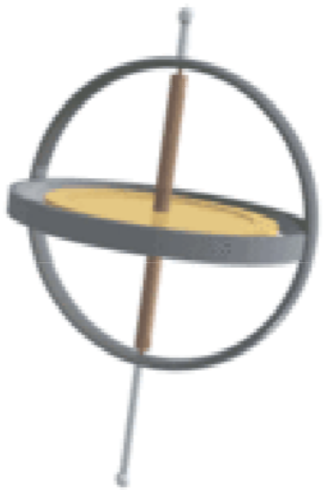
Magnetization dynamics and switching



energy gain: $E = -\vec{M} \cdot \vec{H}$

torque: $\dfrac{d\vec{L}}{dt} = \vec{T}$

$\vec{M} = \gamma \vec{L}$ $\qquad \vec{T} = \left[\vec{M} \times \vec{H}\right]$



$$\frac{d\vec{M}}{dt} = \gamma \cdot \left[\vec{M} \times \vec{H}\right]$$

Landau & Lifshitz, 1935

$$\gamma = g \cdot \frac{e}{2mc} \quad = 28 \text{ GHz/T}$$

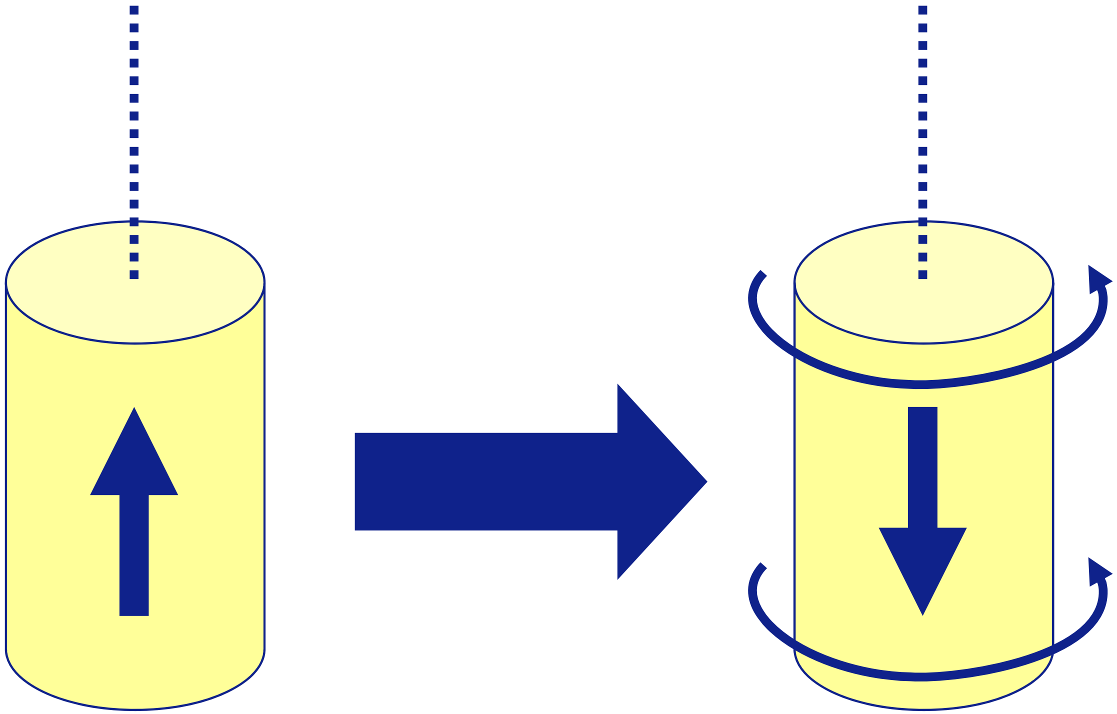
with damping: $$\frac{dM}{dt} = -|\gamma|\left(M \times H^{eff}\right) + \frac{\alpha}{M}\left(M \times \frac{dM}{dt}\right)$$

Consequence 1: Inertia-free motion

$$\frac{d\vec{M}}{dt} = \gamma \cdot \left[\vec{M} \times \vec{H} \right]$$

The motion happens only as long as the field is there

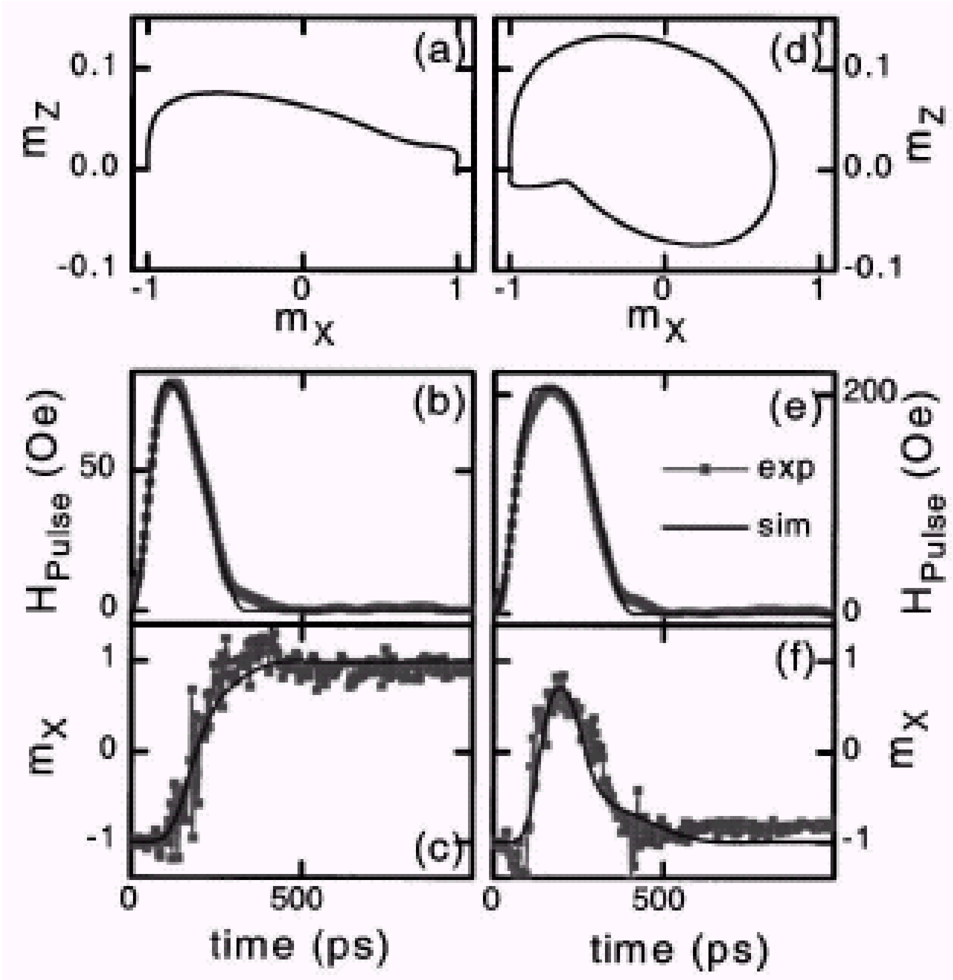
Consequence 2: conservation of angular momentum



Einstein – de Haas effect

A. Einstein & W.J. de Haas, *Experimenteller Nachweis der Amperèschen Molekülströme*, Verhandl. Deut. Phys. Ges. **17**, 152–170 (1915).
S. J. Barnett, *Magnetization by Rotation*, Physical Review **6,** 239–270 (1915).

Consequence 3: Precessional magnetization reversal



Kaka et al, APL **80**, 2958 (2002);

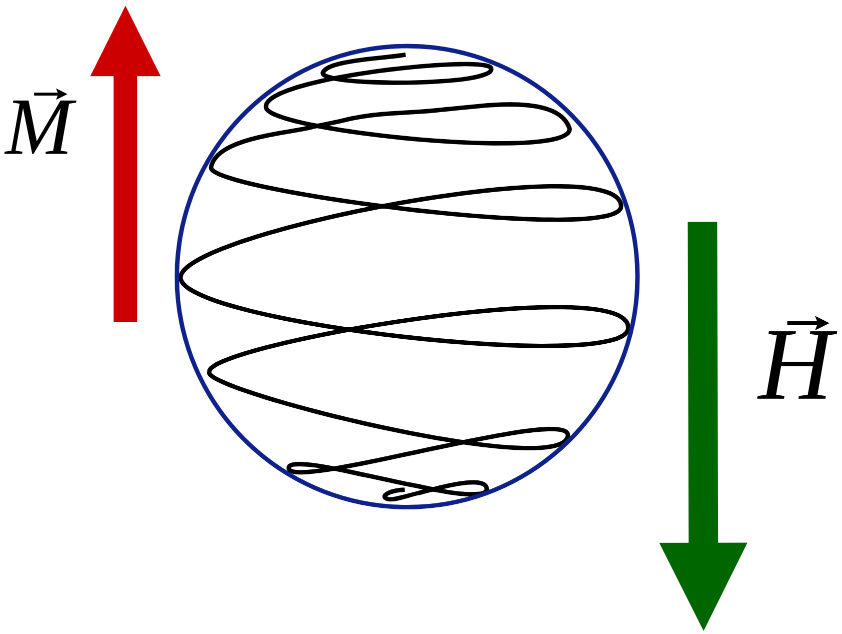
Gerrits et al, Nature **418**, 509 (2002);

Schumaher et al, PRL **90**, 017201 (2003).

The fastest way to reverse the magnetization is via precession

Angular momentum transfer and two ways of reversal

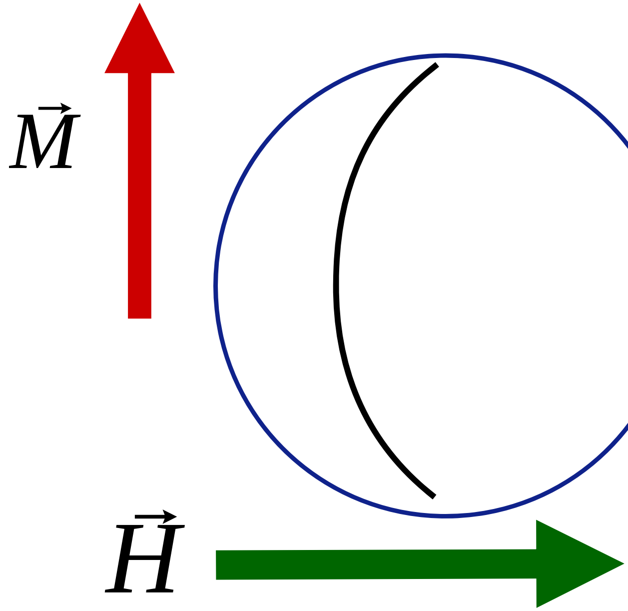
usual (practical)



$$\frac{dM}{dt} = -|\gamma|\left(M \times H^{eff}\right) + \underline{\frac{\alpha}{M}\left(M \times \frac{dM}{dt}\right)}$$

from spins to lattice

precessional (fast)



$$\frac{dM}{dt} = \underline{-|\gamma|\left(M \times H^{eff}\right)} + \frac{\alpha}{M}\left(M \times \frac{dM}{dt}\right)$$

from spins to field

Outline of the lecture

- **Angular momentum gone, inertia recovered: antiferromagnets**
- **Tuning angular momentum in ferrimagnets: faster precession / switching**
- **Angular momentum conservation vs exchange interaction**

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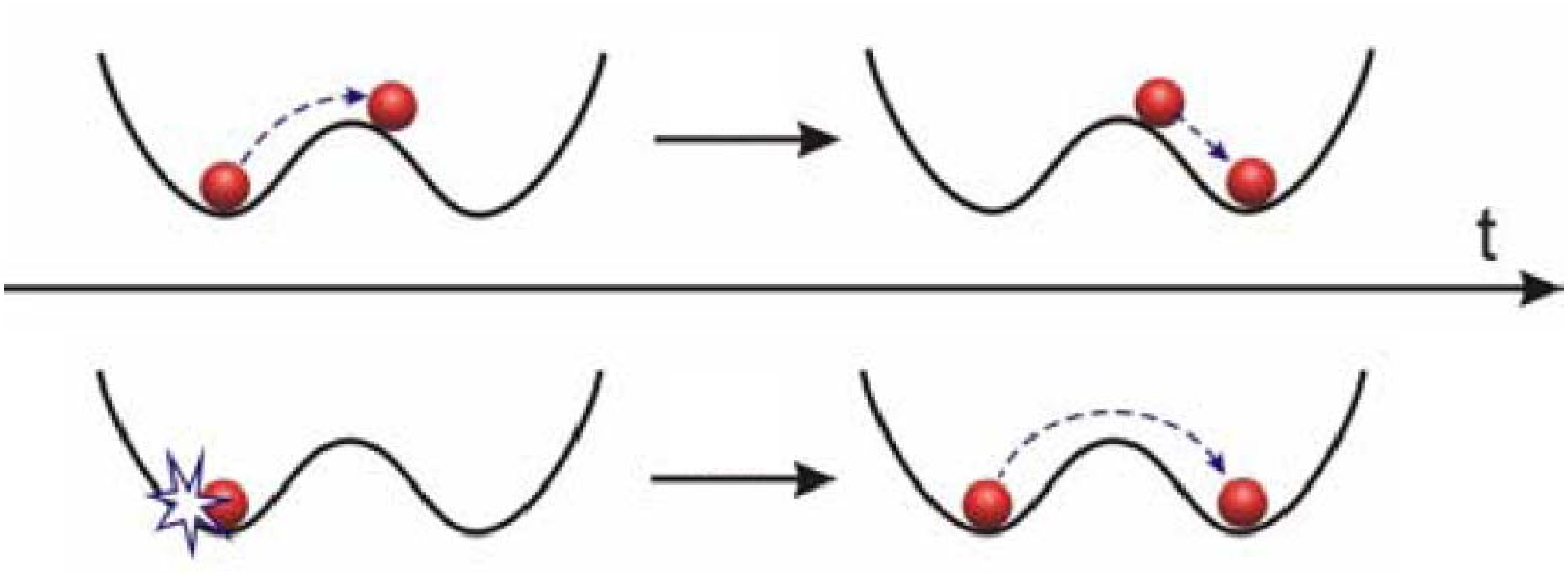
Ballistic (inertial) magnetic dynamics?



Consequence of the LL equation: Inertia-free motion

$$\frac{d\vec{M}}{dt} = \gamma \cdot \left[\vec{M} \times \vec{H} \right]$$

The motion happens only as long as the field is there

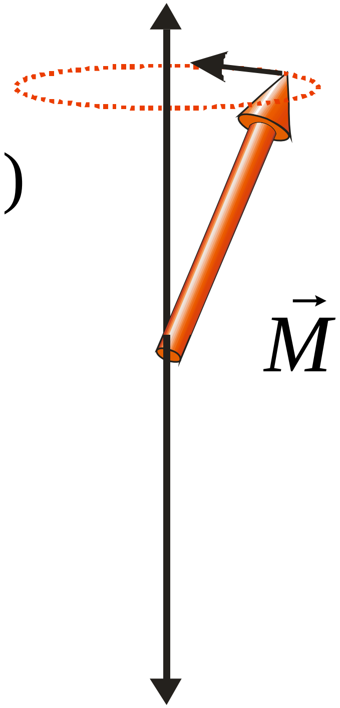
Inertia may appear when the angular momentum is gone!

Ferromagnet and antiferromagnet

$$\omega_{FM} \sim \gamma(H_A + H)$$

1-10 GHz

no inertia



$$\omega_{AFM} \sim \gamma\sqrt{H_A H_{ex}}$$

100-1000 GHz

$$\vec{m} = \vec{M}_1 + \vec{M}_2 \approx 0$$

$$\vec{l} = \vec{M}_1 - \vec{M}_2$$

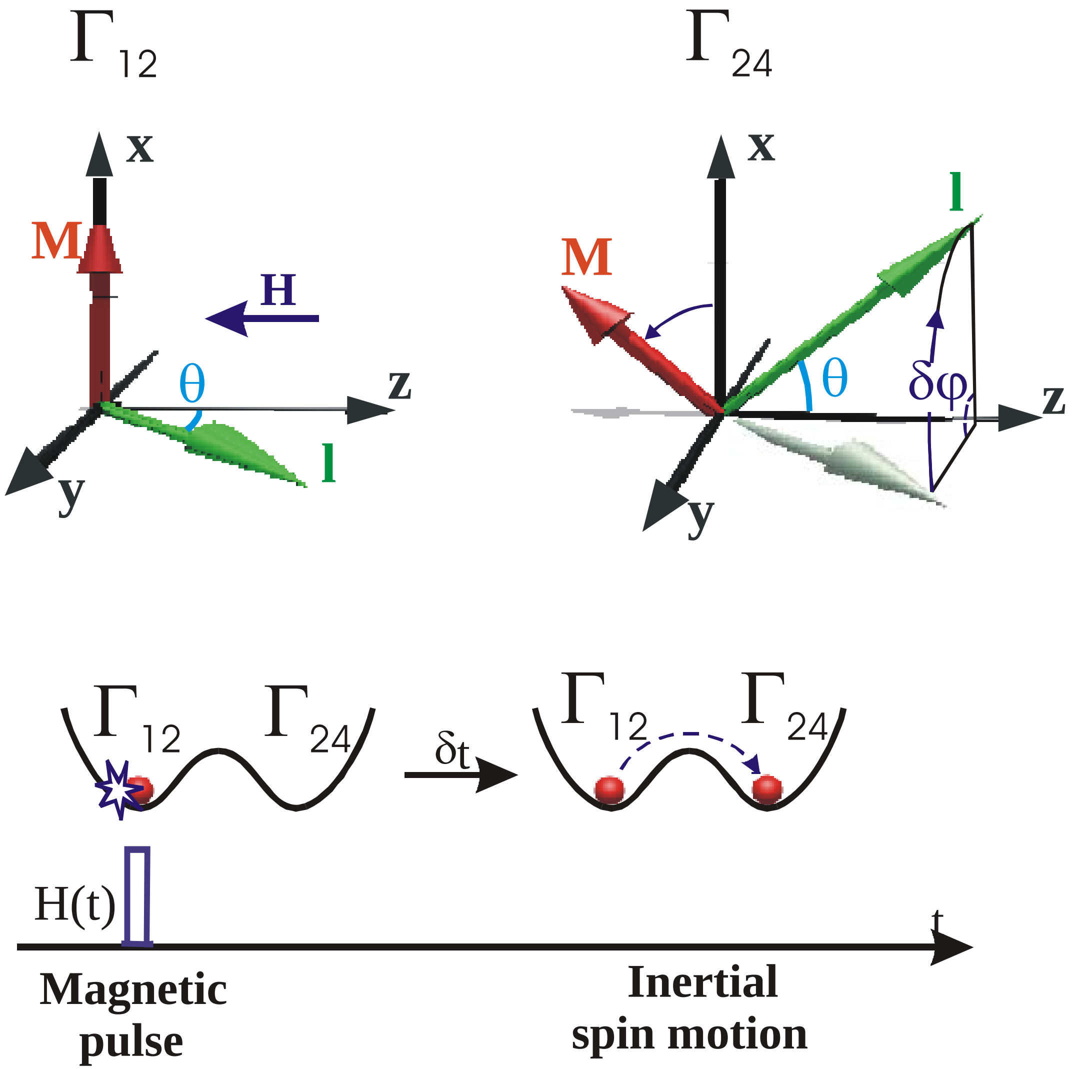
inertia!

Lagrangian $$L = \frac{\hbar}{\gamma H_e}\left[\frac{1}{2}\left(\frac{\partial \mathbf{l}}{\partial t}\right)^2 - \gamma\left(\mathbf{H}\left(\mathbf{l} \times \frac{\partial \mathbf{l}}{\partial t}\right)\right)\right] - W(\mathbf{l})$$

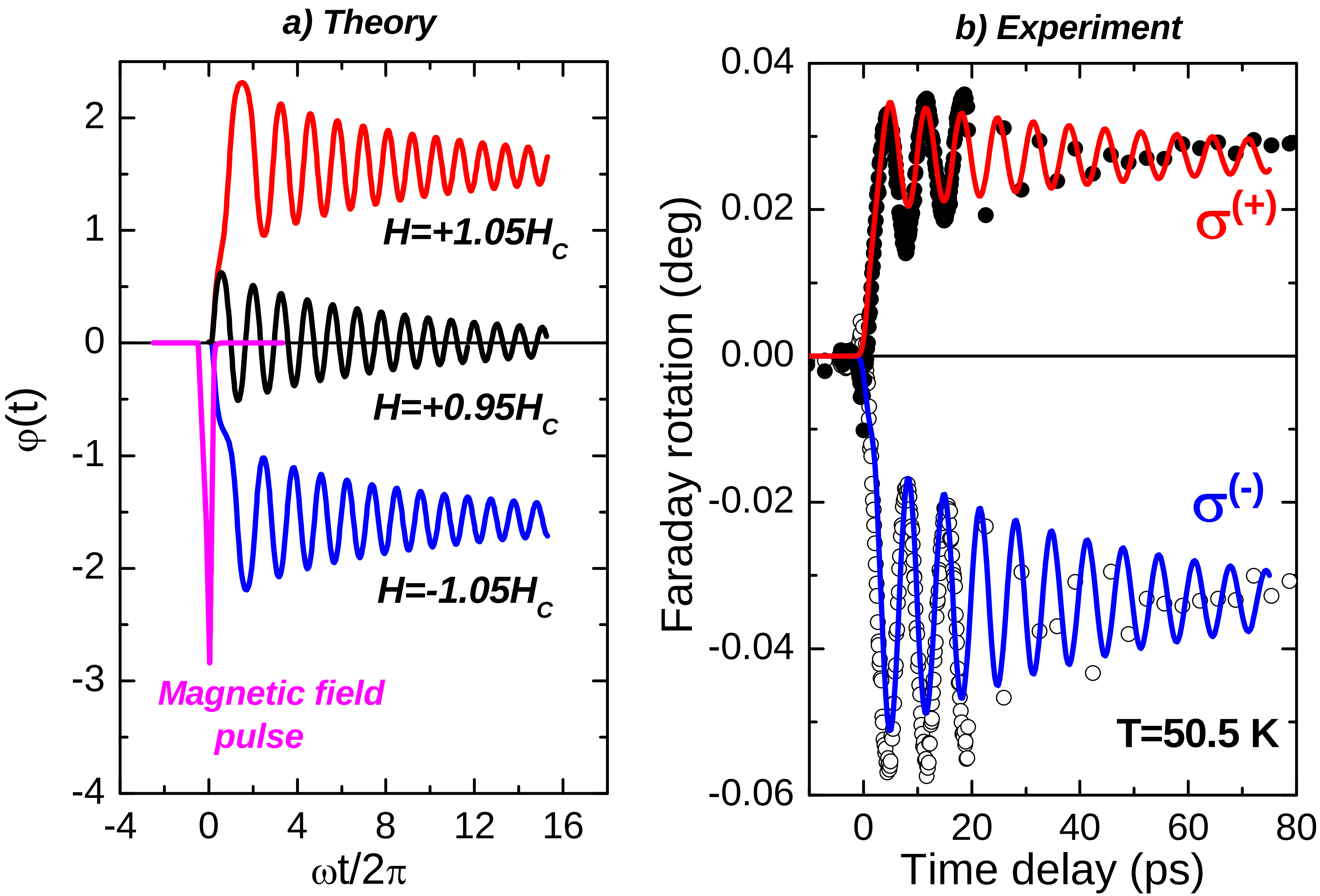
Equation of motion $$\frac{d^2\varphi}{dt^2} + 2\Gamma\frac{d\varphi}{dt} + \omega_0^2\frac{dw(\varphi)}{d\varphi} + \gamma\Omega_D H(t)\cos\varphi - \gamma\frac{dH}{dt} = 0$$

Andreev and Marchenko, Sov. Phys. Usp. **23**, 21 (1980)

Magnetic phases in $HoFeO_3$

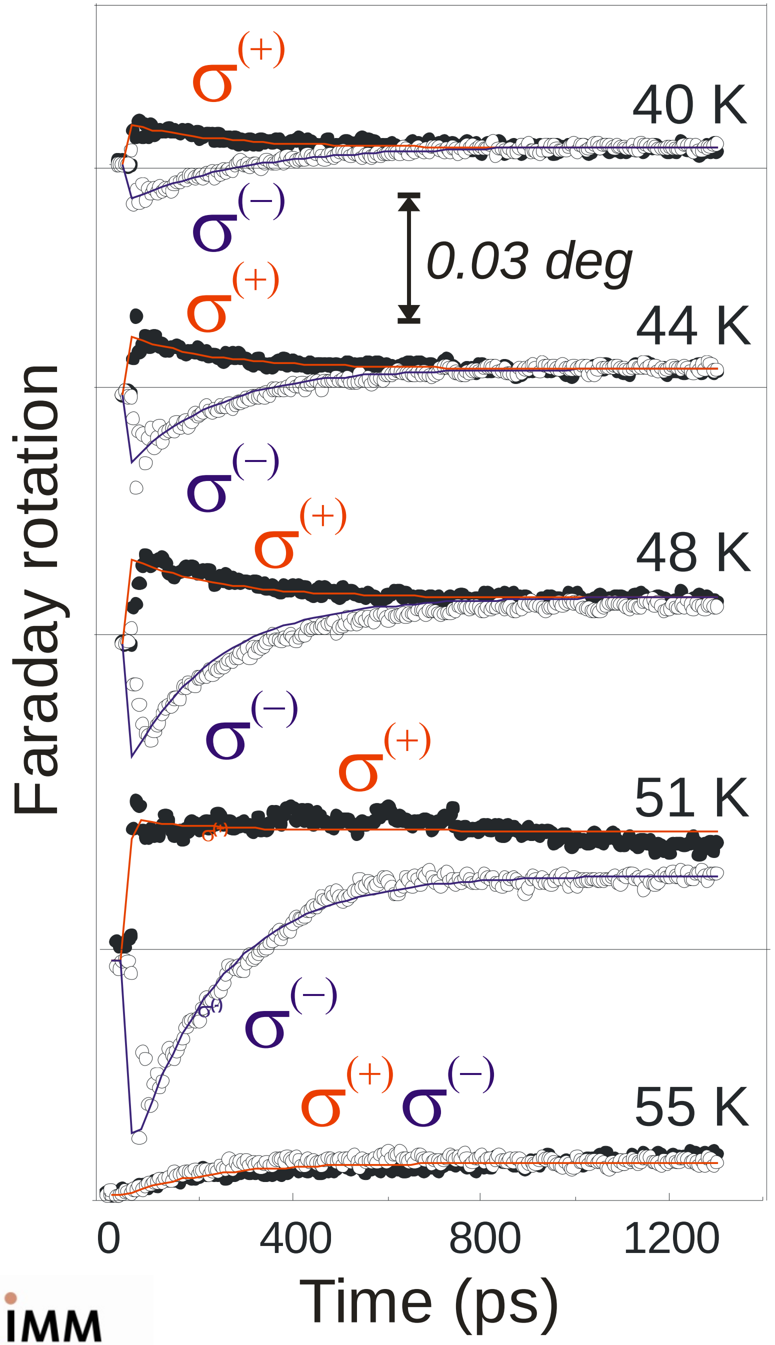


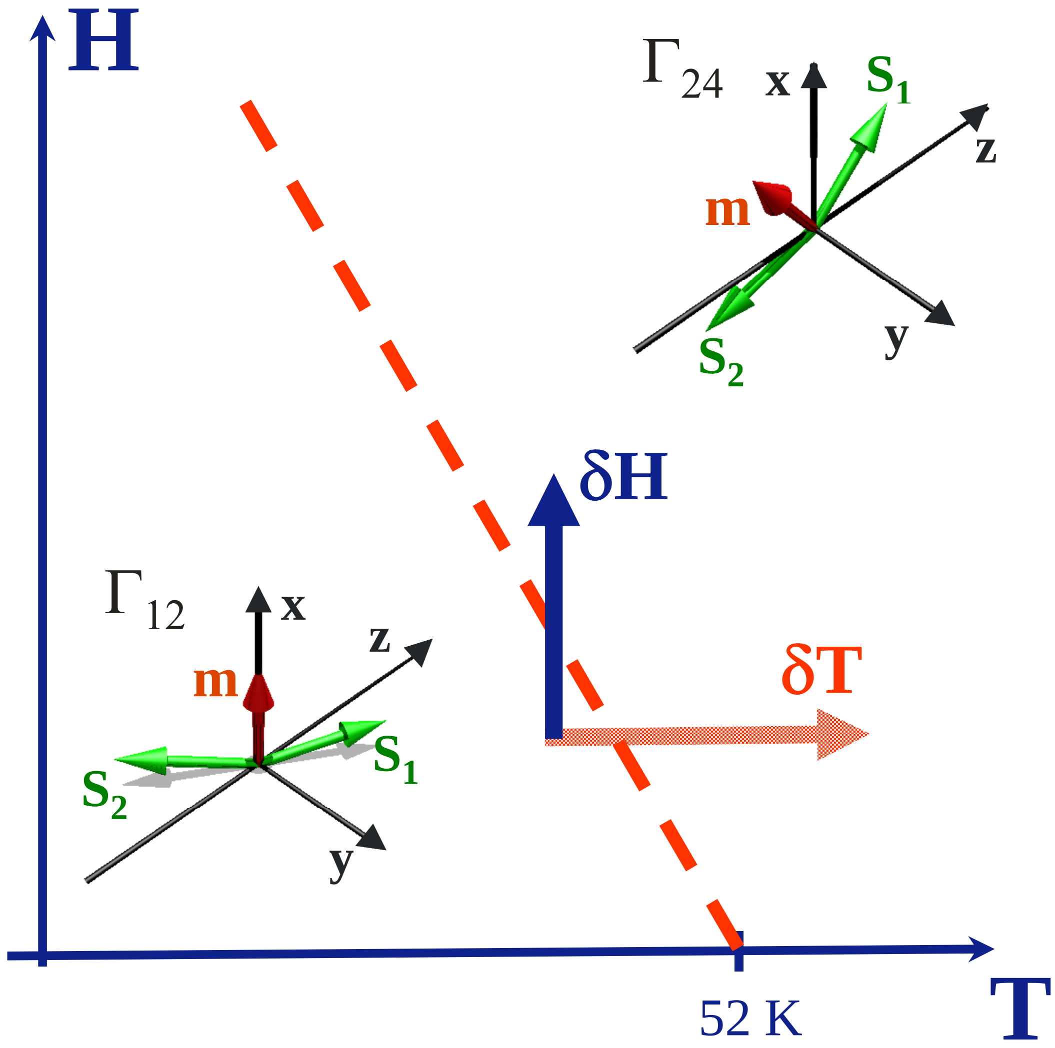
Inertia-driven spin reorientation in $HoFeO_3$



Kimel et al., Nature Physics **5**, 727 (2009)

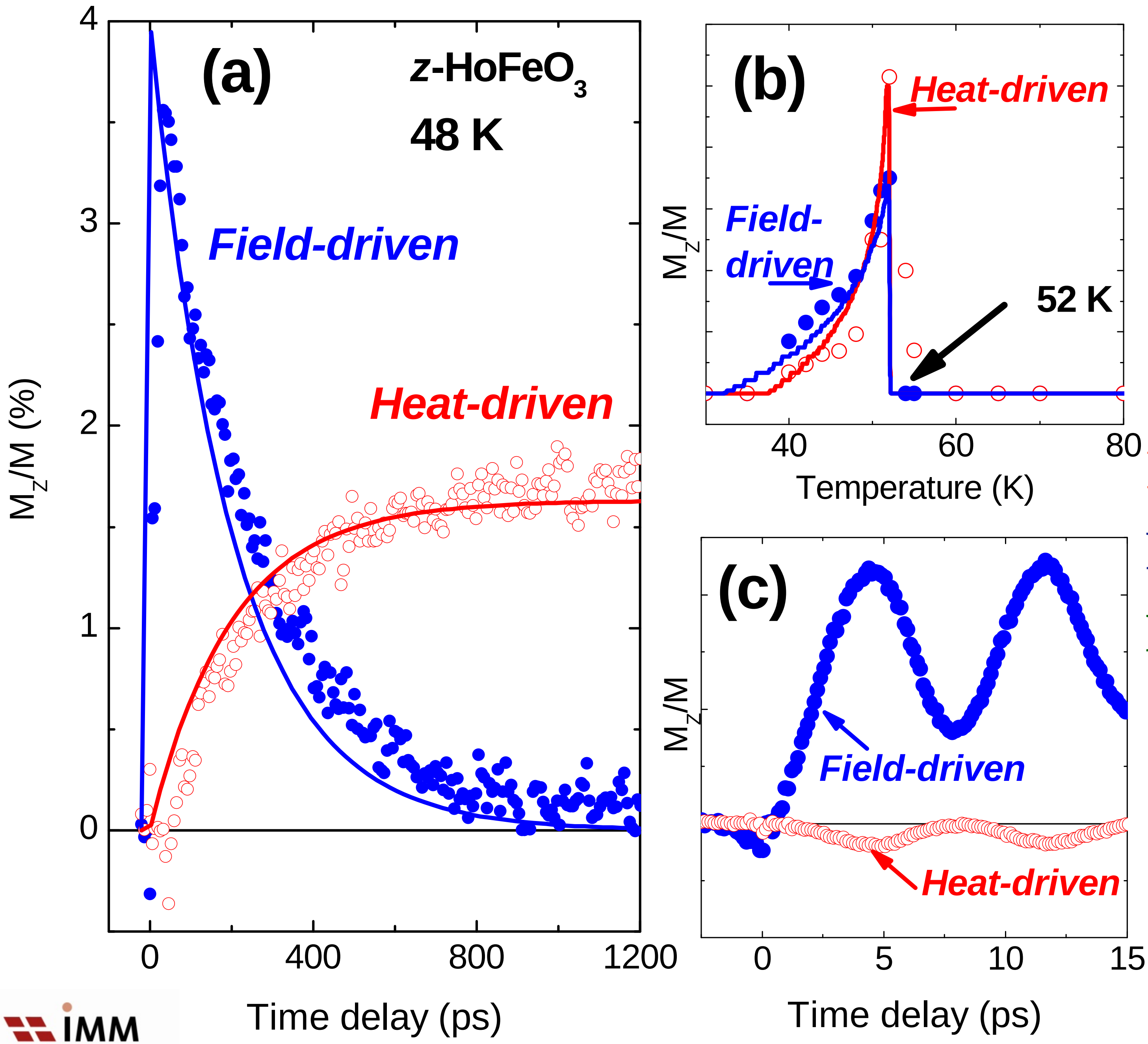
Ultrafast reorientation in $HoFeO_3$





What route is faster?

Heat driven vs field-driven dynamics



Heat-driven ~ 400 ps

Field-driven ~ 3 ps

Laser pulse ~ 0.1 ps

Outline of the lecture

- Angular momentum gone, inertia recovered: antiferromagnets
- **Tuning angular momentum in ferrimagnets: faster precession / switching**
- Angular momentum conservation vs exchange interaction

To reverse the magnetization fast(er):

- **apply stronger torque**

$$\frac{d\vec{M}}{dt} = \gamma \cdot \left[\vec{M} \times \vec{H}\right]$$

or

- **reduce associated angular momentum**

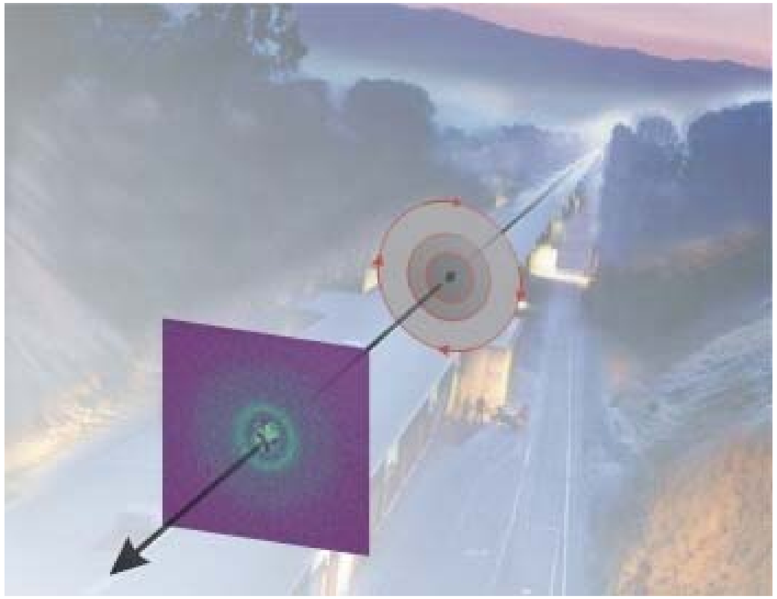
Solution: make the field stronger?

letters to nature

The ultimate speed of magnetic switching in granular recording media

I. Tudosa[1], C. Stamm[1], A. B. Kashuba[2], F. King[3], H. C. Siegmann[1], J. Stöhr[1], G. Ju[4], B. Lu[4] & D. Weller[4]

We therefore believe that our experiment reveals 'fracture of the magnetization' under the load of the fast and high field pulses, putting an end to deterministic switching as we know it today. □



Applied physics

Speed limit ahead

C. H. Back and D. Pescia

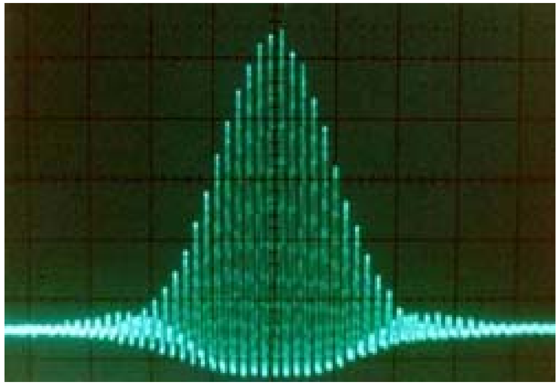
Are there any limits to what science and technology can achieve? When it comes to recording data in magnetic media, the answer is yes: there is a natural limit to the speed at which data can be encoded.

2 ps, several Teslas

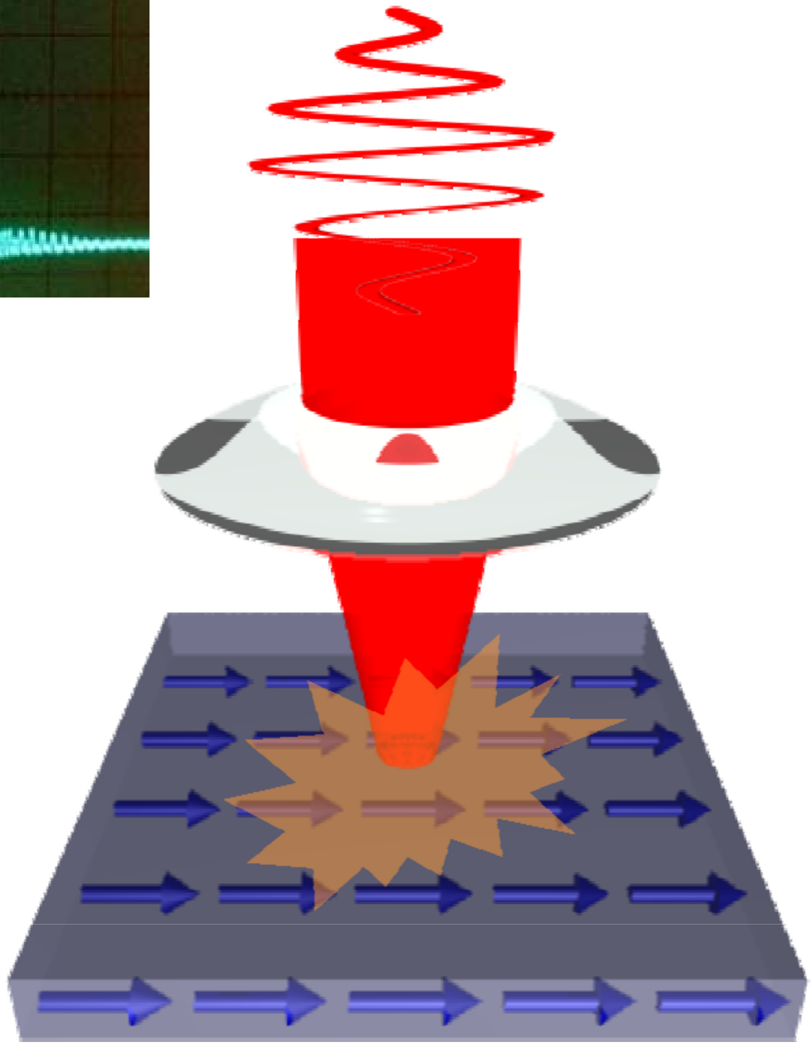
end of ultrafast magnetism?

Any way around?

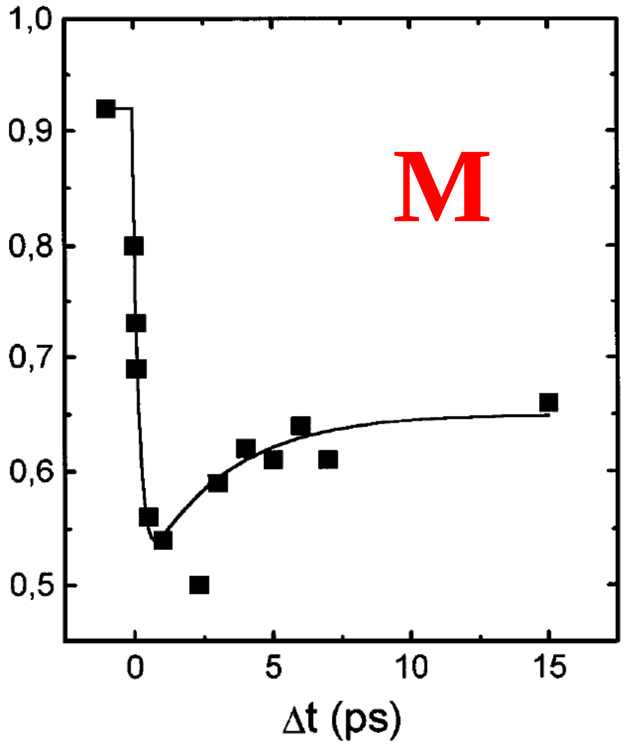
Ultrafast laser-induced demagnetization



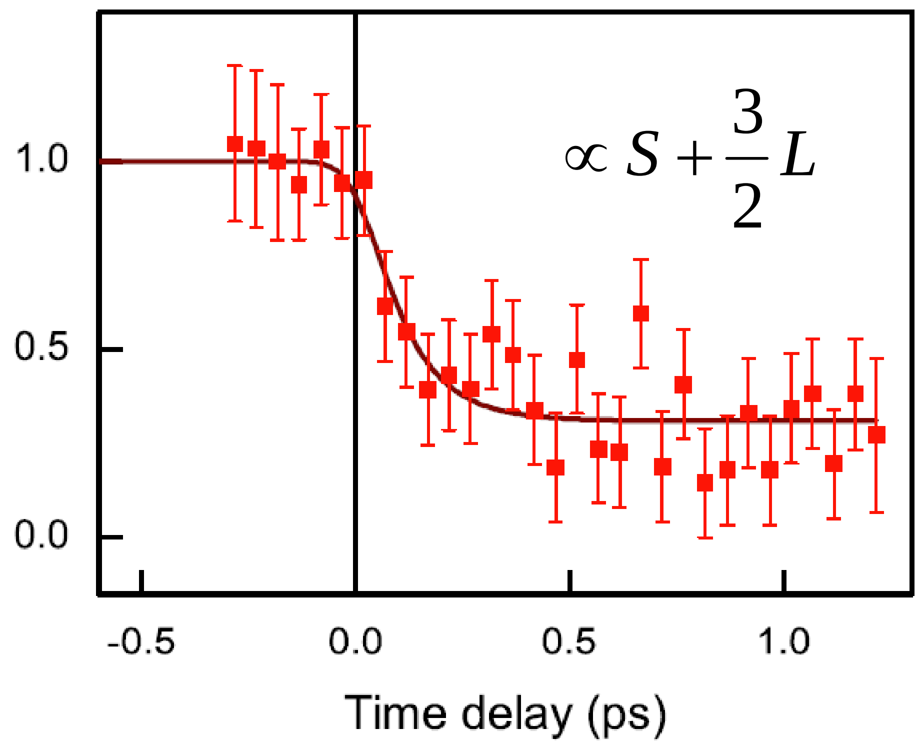
thin Ni film



Ultrafast laser-induced demagnetization (Ni film)



Beaurepaire et al. (1996)

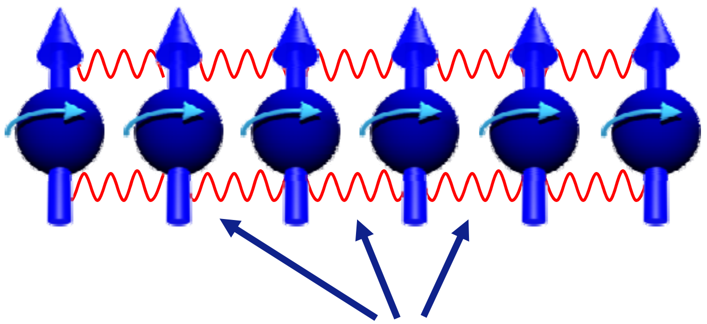


Stamm et al. (2007)

see any difference??

Simple model to describe the process

localized atomistic spin model with a Heisenberg exchange



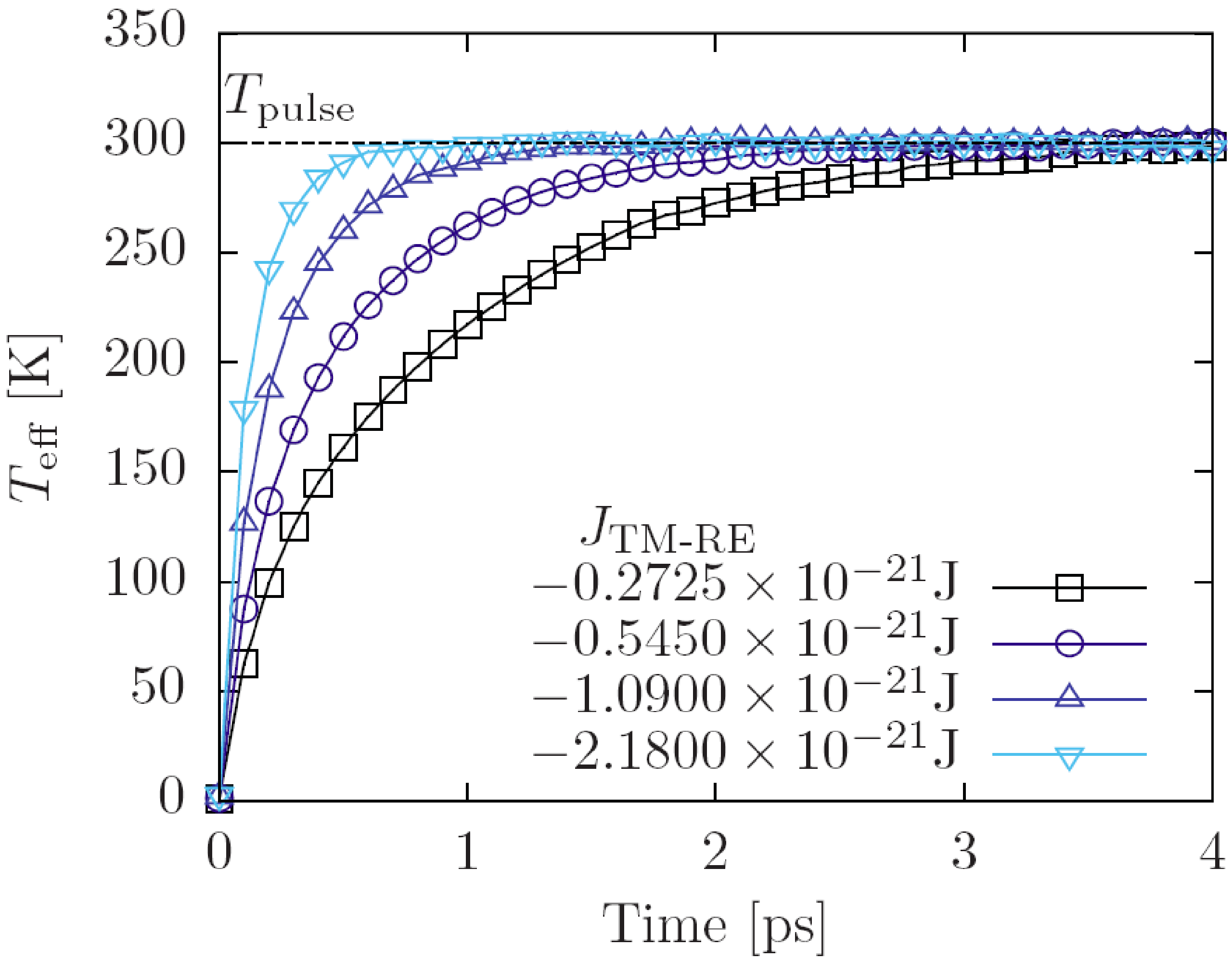
exchange interaction

electron temperature is introduced via stochastic field term

$$\frac{d\mathbf{s}}{dt} = \gamma[\mathbf{s} \times (\mathbf{H} + \zeta)] - \gamma\lambda[\mathbf{s} \times [\mathbf{s} \times \mathbf{H}]]$$

$$\langle \zeta_\alpha(t)\zeta_\beta(t')\rangle = \frac{2\lambda T}{\gamma\mu_0}\delta_{\alpha\beta}\delta(t-t')$$

Example: thermalization of Gd spins in GdFe alloy



temperature is applied as a step at t=0

T.A. Ostler et al., PRB (2011)

Landau-Lifshitz-Bloch equation

$$\frac{d\mathbf{m}}{dt} = \gamma[\mathbf{m} \times \mathbf{H}^{\mathrm{eff}}] - \gamma\lambda_{\parallel}\frac{(\mathbf{m}\cdot\mathbf{H}^{\mathrm{eff}})\mathbf{m}}{m^2} + \gamma\lambda_{\perp}\frac{[\mathbf{m} \times [\mathbf{m} \times \mathbf{H}^{\mathrm{eff}}]]}{m^2}$$

longitudinal relaxation

transverse relaxation

Assuming that the heat bath (phonons or electrons) acts much faster than the spins, the bath degrees of freedom can be averaged out.

The ensemble-averaged spin polarization gives the magnetization m

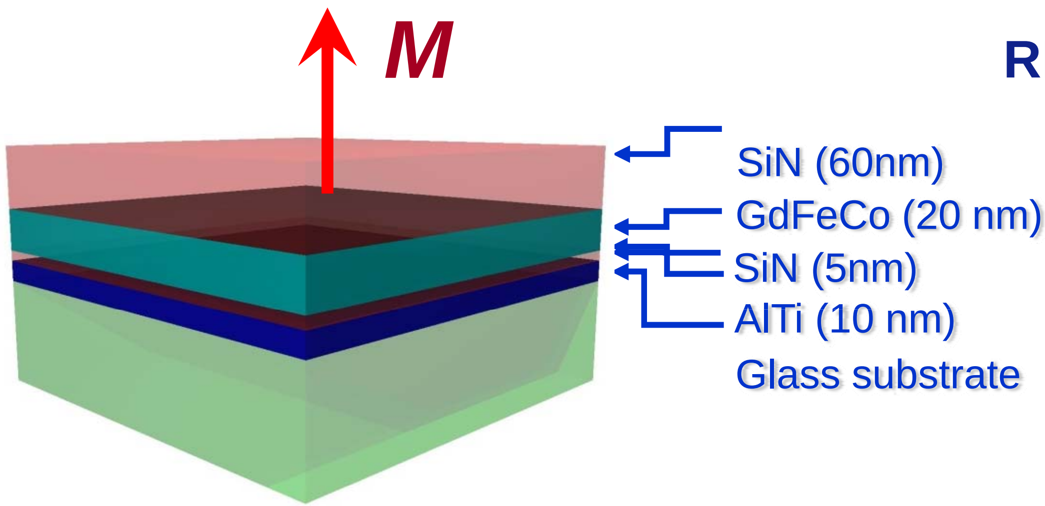
Garanin, Phys. Rev. B **55**, 3050 (1997).

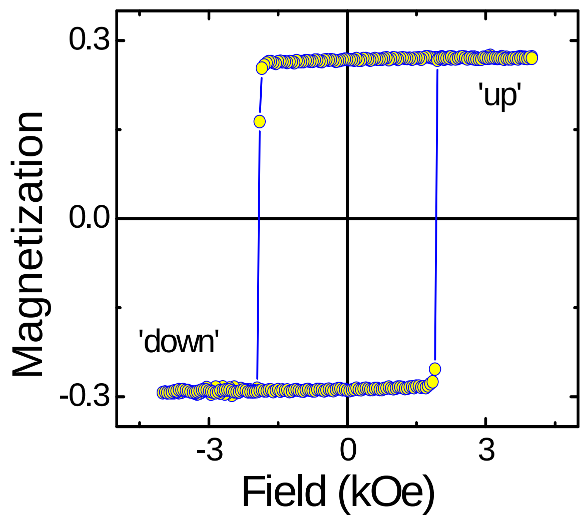
to summarize here:

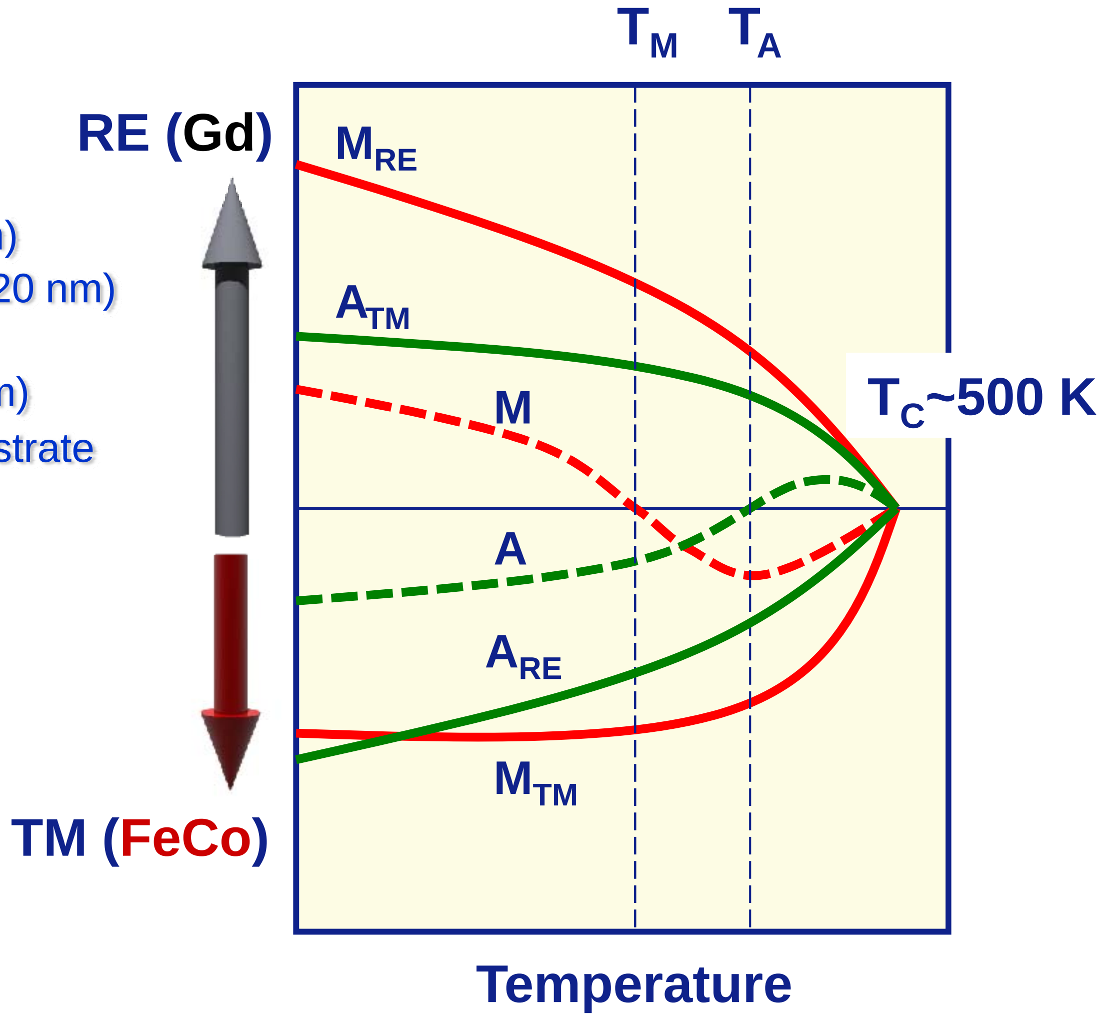
- laser does change M (and L) very fast
- but only to disorder the system
- can we still do something useful with it?

Ferrimagnet with a compensation point(s)

samples in our experiments: $Gd_{20\text{-}30\%}Fe_{65\text{-}75\%}Co_{5\%}$



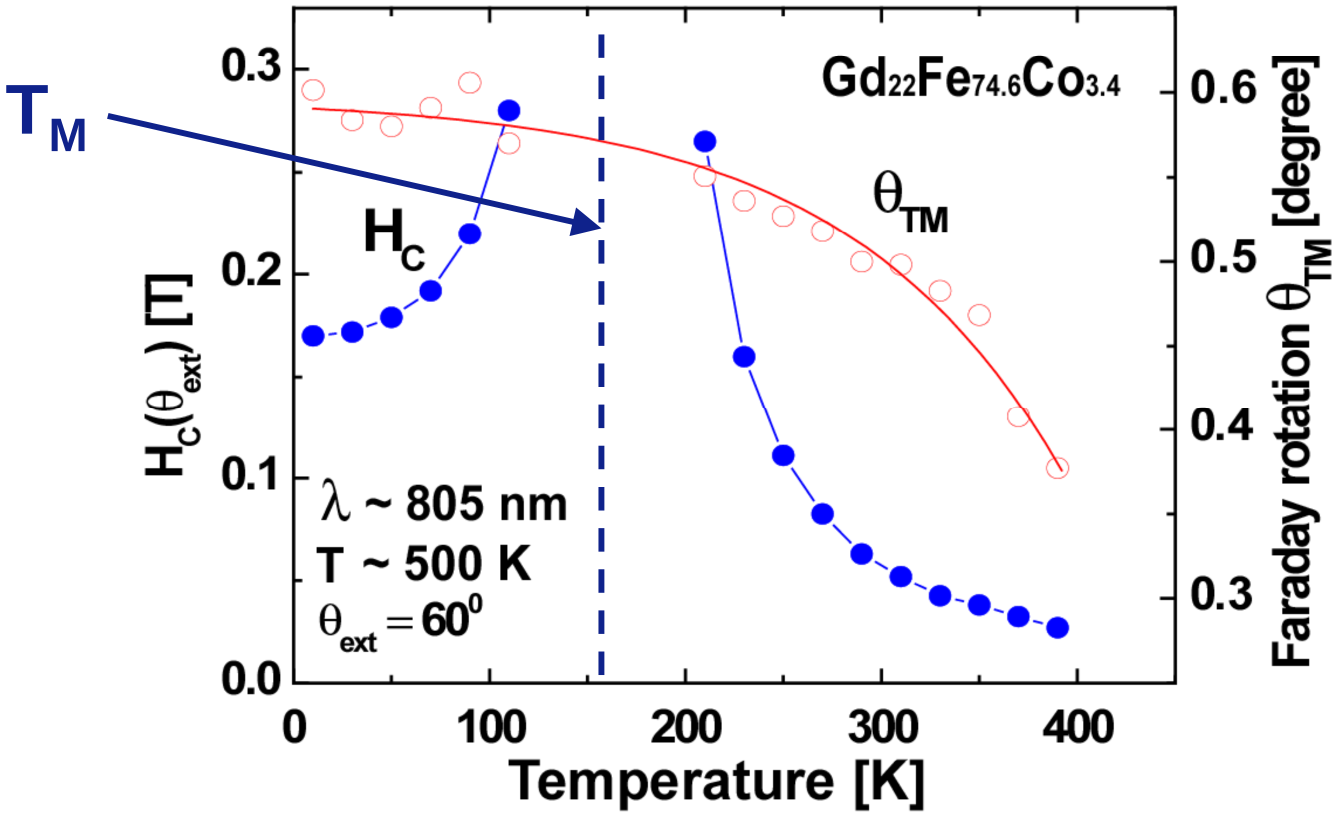




$g_{Gd} < g_{FeCo}$

GdFeCo – static measurements

The vanishing of the total magnetic moment (T_M) is accompanied by the divergence of coercive field (H_c).



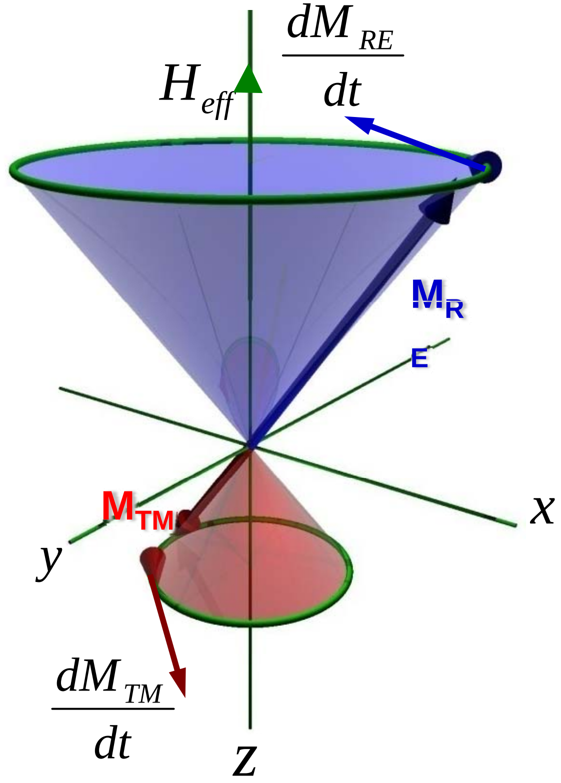
samples by A. Tsukamoto and A. Itoh

Ferrimagnetic resonance

Landau – Lifshitz – Gilbert equation
for two sublattices:

$$\frac{d\vec{M}_{TM}}{dt} = \gamma\left[\vec{M}_{TM} \times \left(\vec{H}^{eff}_{TM} - \lambda\vec{M}_{RE}\right)\right]$$

$$\frac{d\vec{M}_{RE}}{dt} = \gamma\left[\vec{M}_{RE} \times \left(\vec{H}^{eff}_{RE} - \lambda\vec{M}_{TM}\right)\right]$$

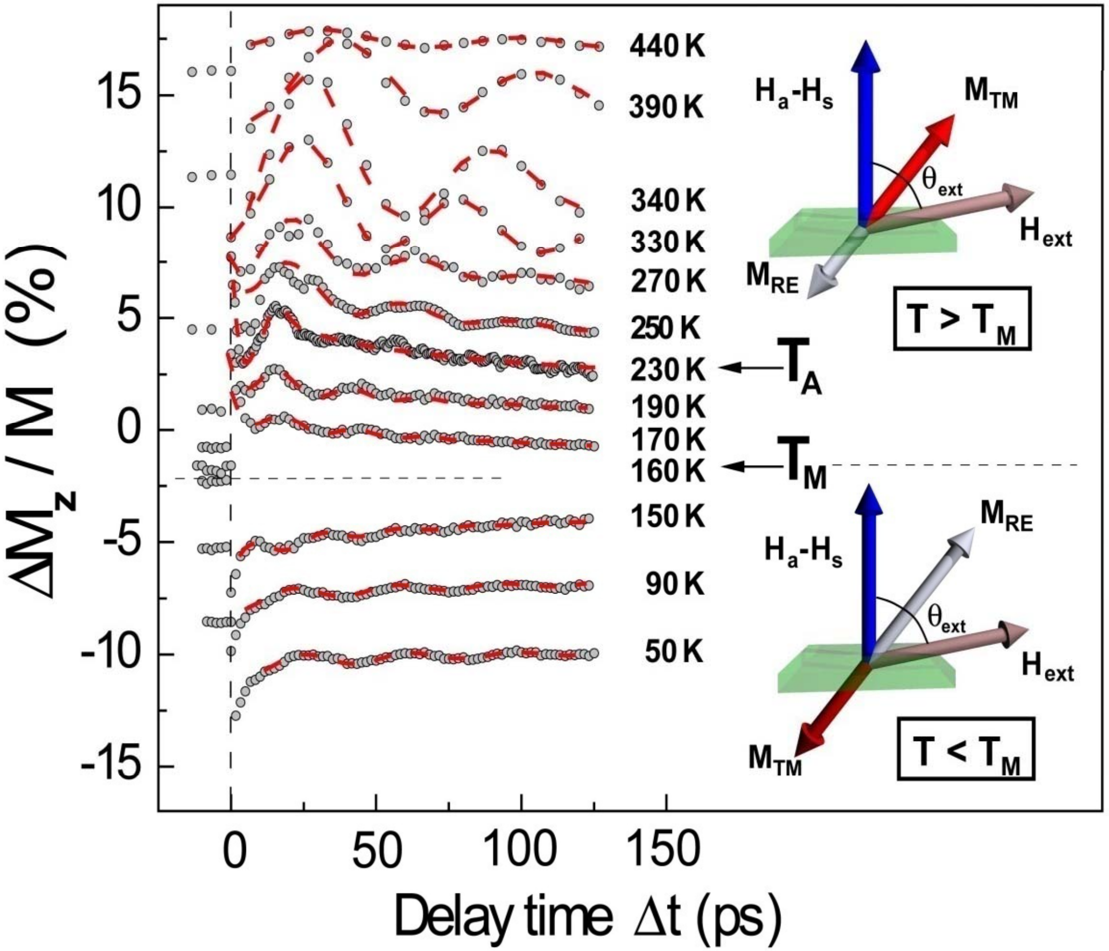


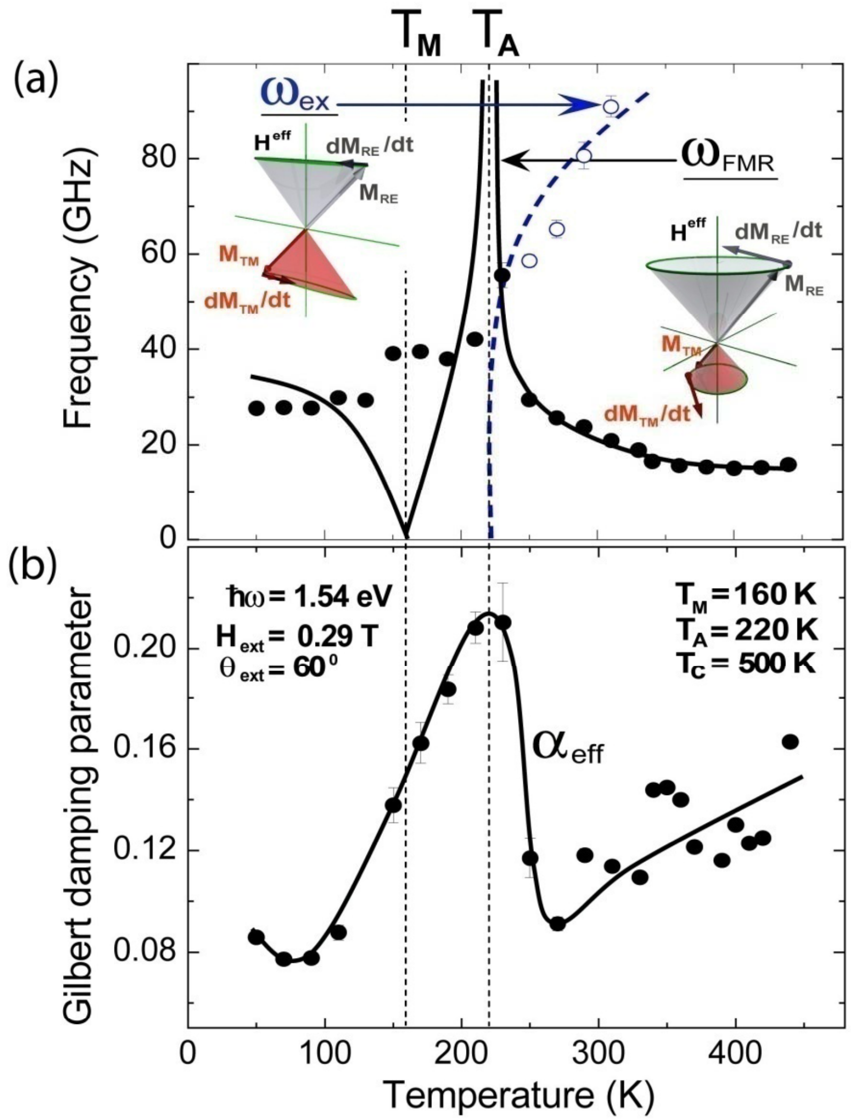
$$\gamma_{eff}(T) = \frac{M_{RE}(T) - M_{TM}(T)}{\frac{M_{RE}(T)}{|\gamma_{RE}|} - \frac{M_{TM}(T)}{|\gamma_{TM}|}} = \frac{M(T)}{A(T)}$$

$$\omega_{FMR} = \gamma_{eff} H^{eff} \rightarrow \infty \quad \text{if} \quad T = T_A$$

also $\alpha_{eff} \rightarrow \infty$

Dynamics of magnetization in GdFeCo.

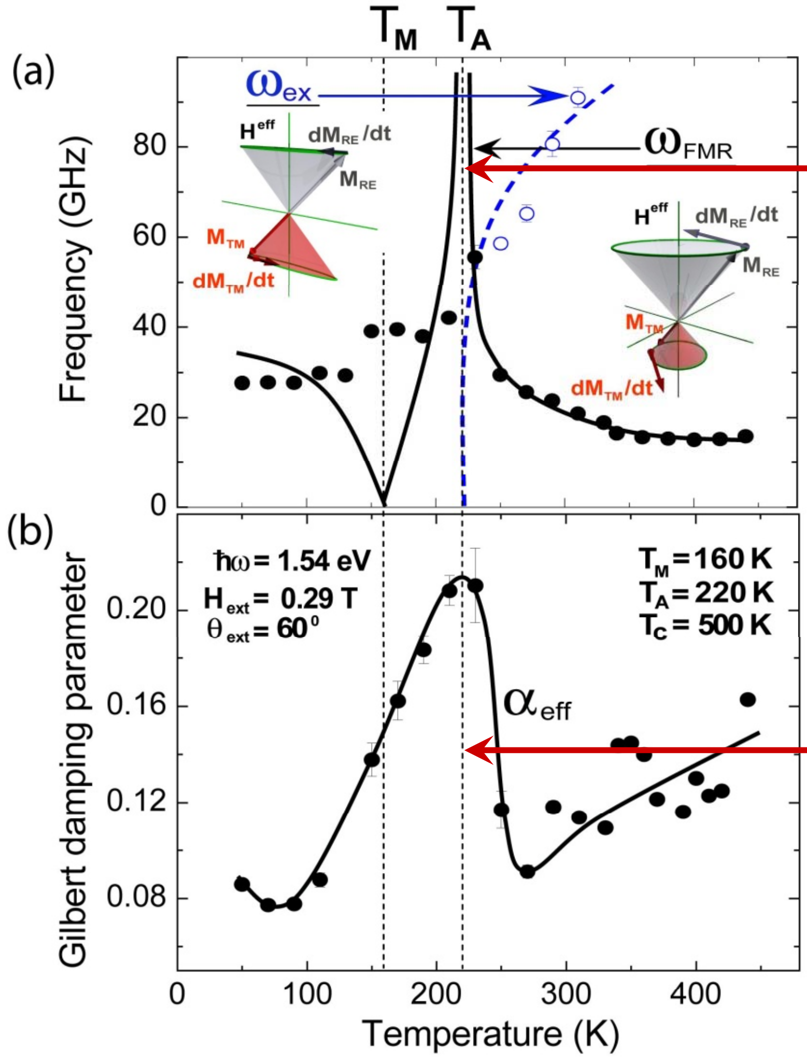


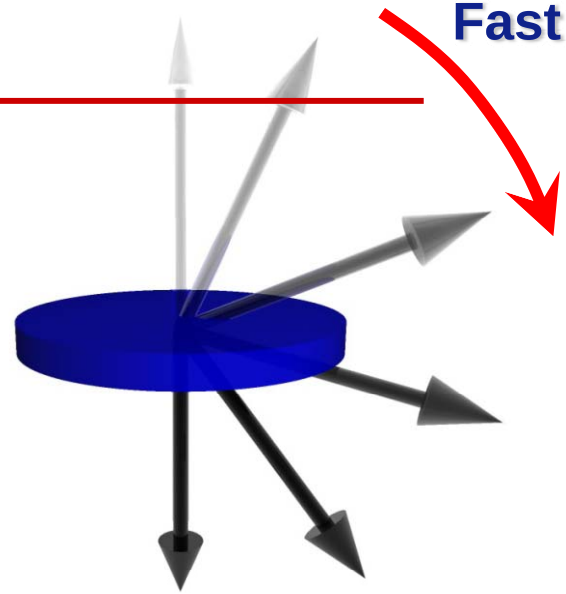


$H_{ext} = 0.29$ T

Phys. Rev. B **73**, 220402 (2006)

High frequency + high damping near T_A

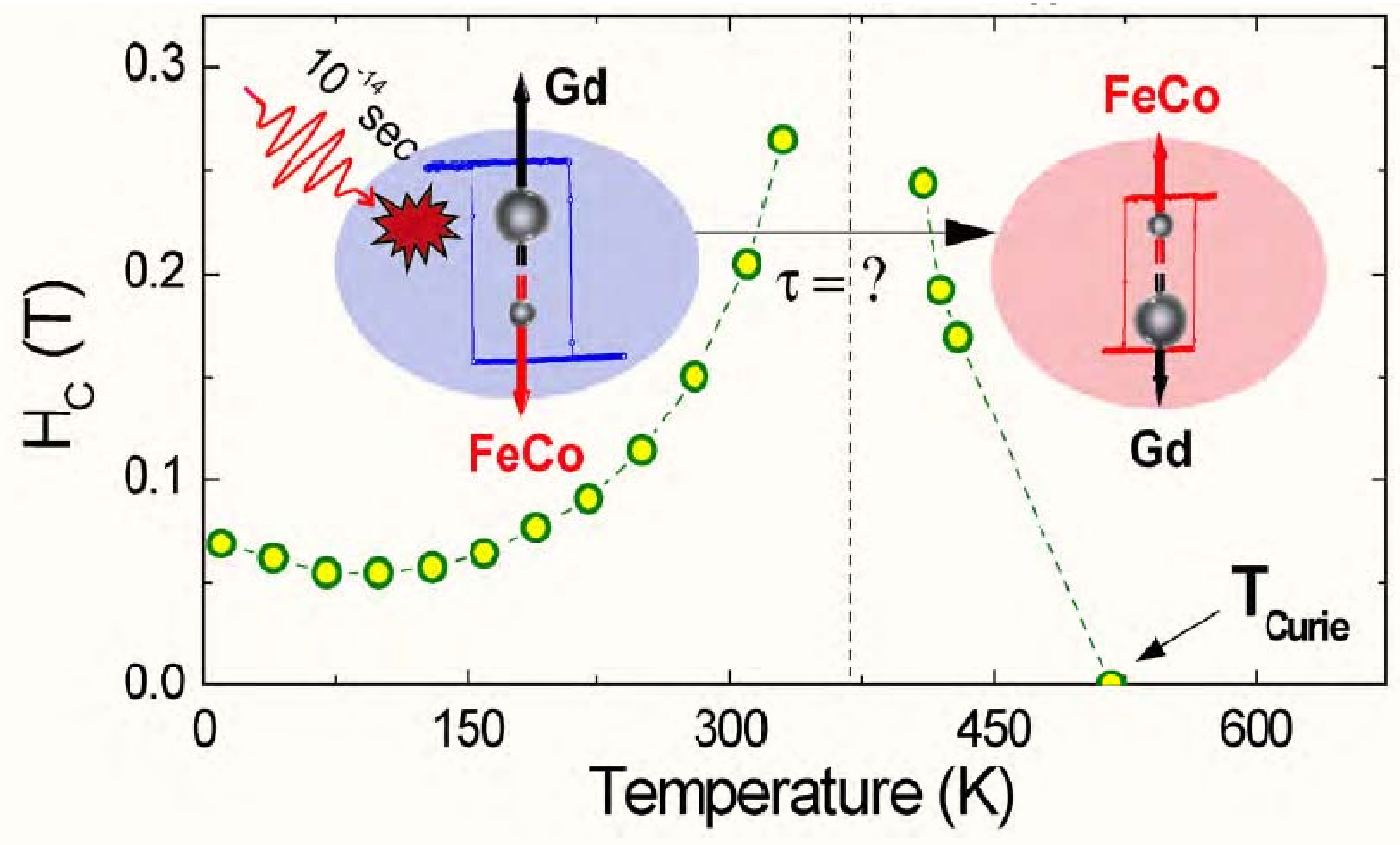




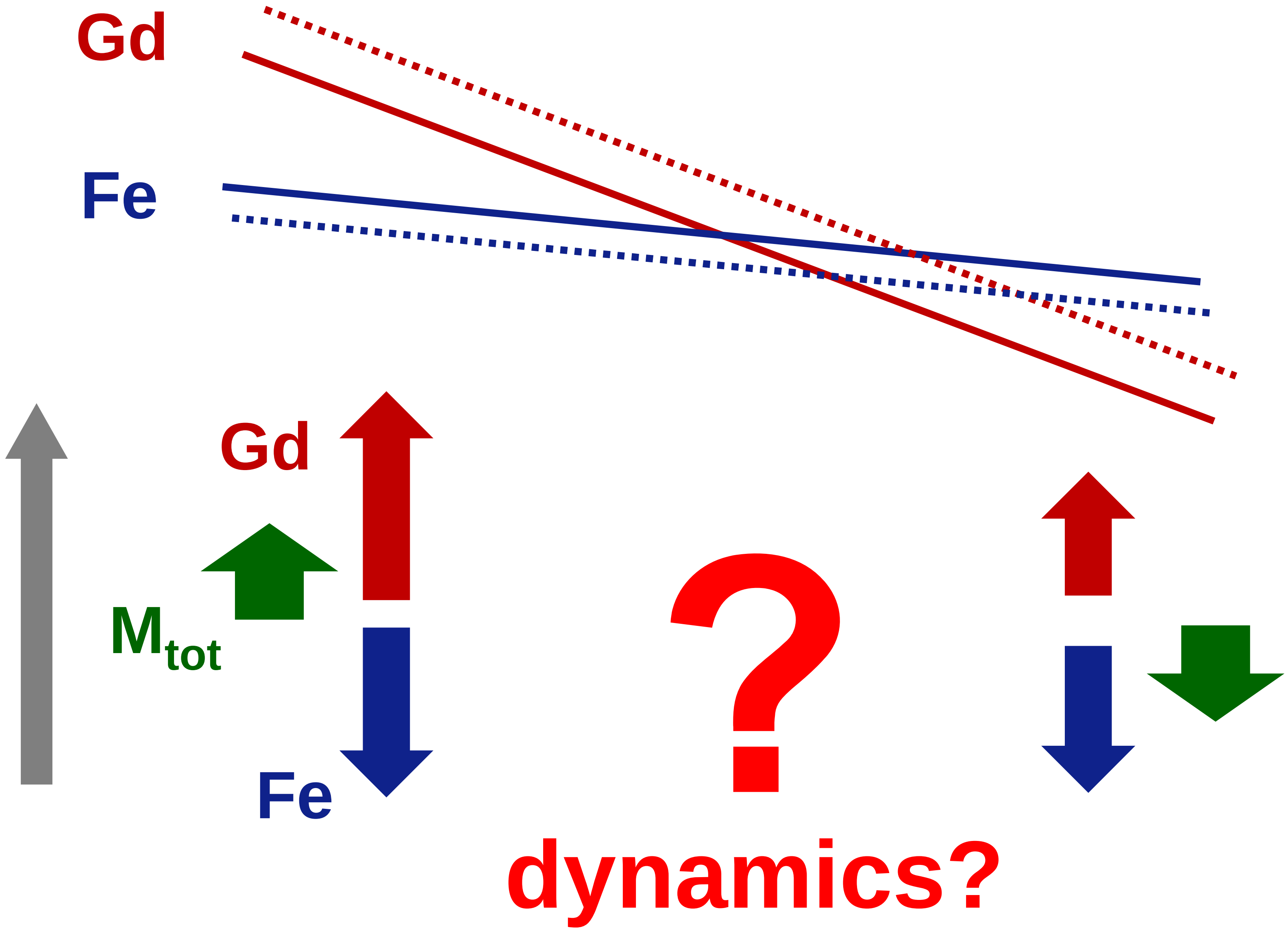
Angular momentum compensation is the key to increase the reversal speed

Phys. Rev. B **73**, 220402 (2006)

Can this be realized in practice?

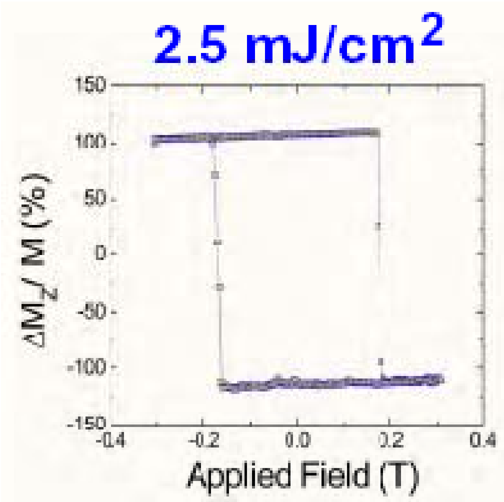


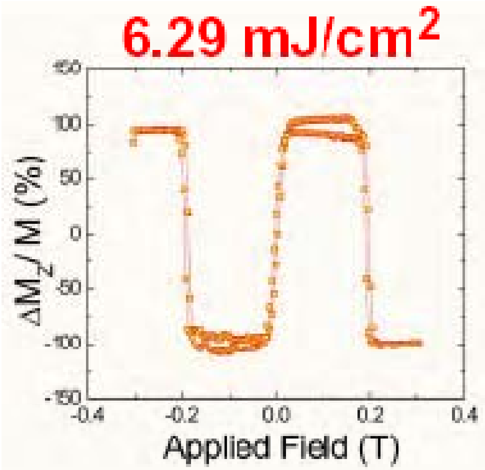
Temperature increase over T_{comp}

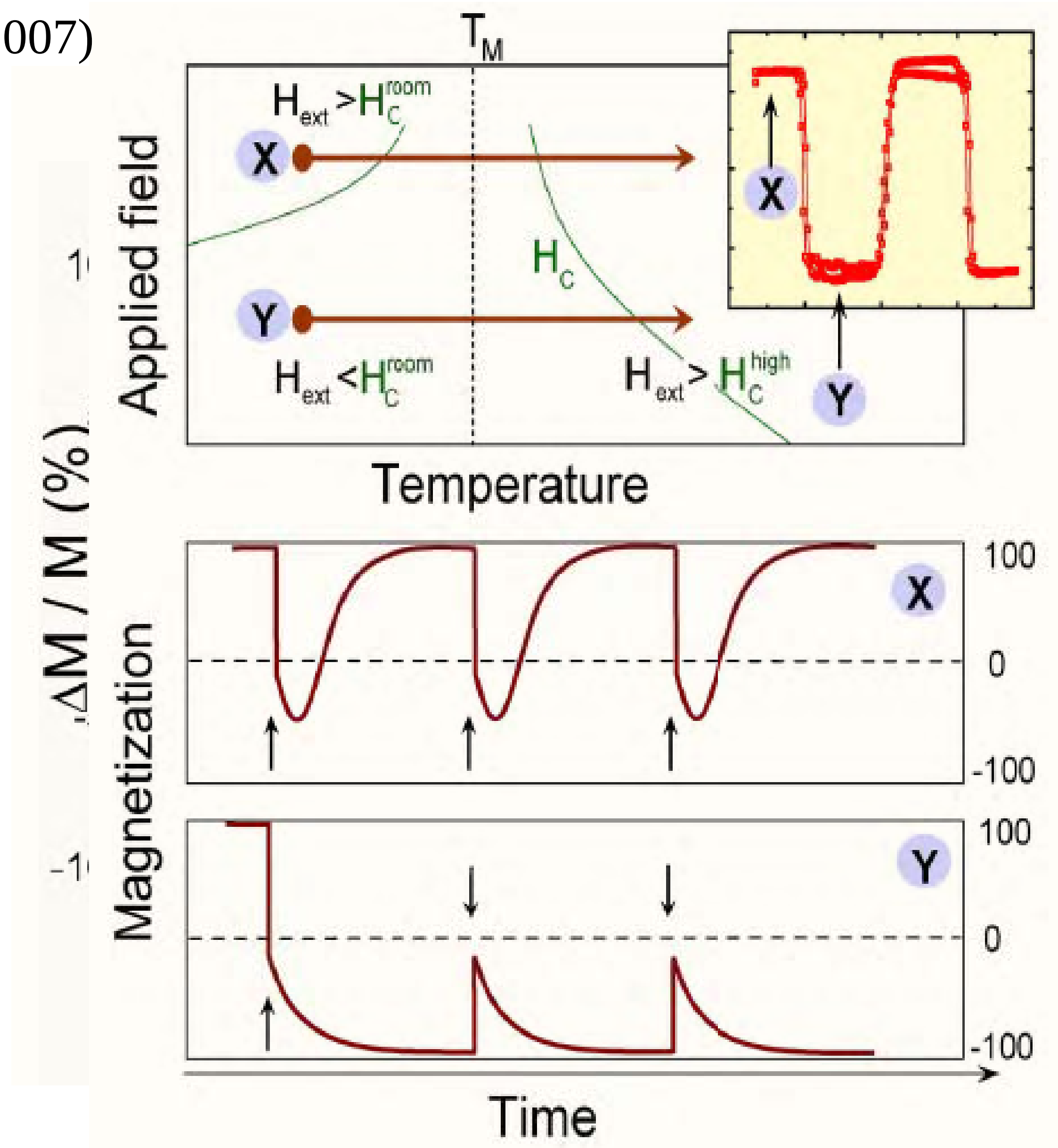


Hysteresis loops with pump laser on

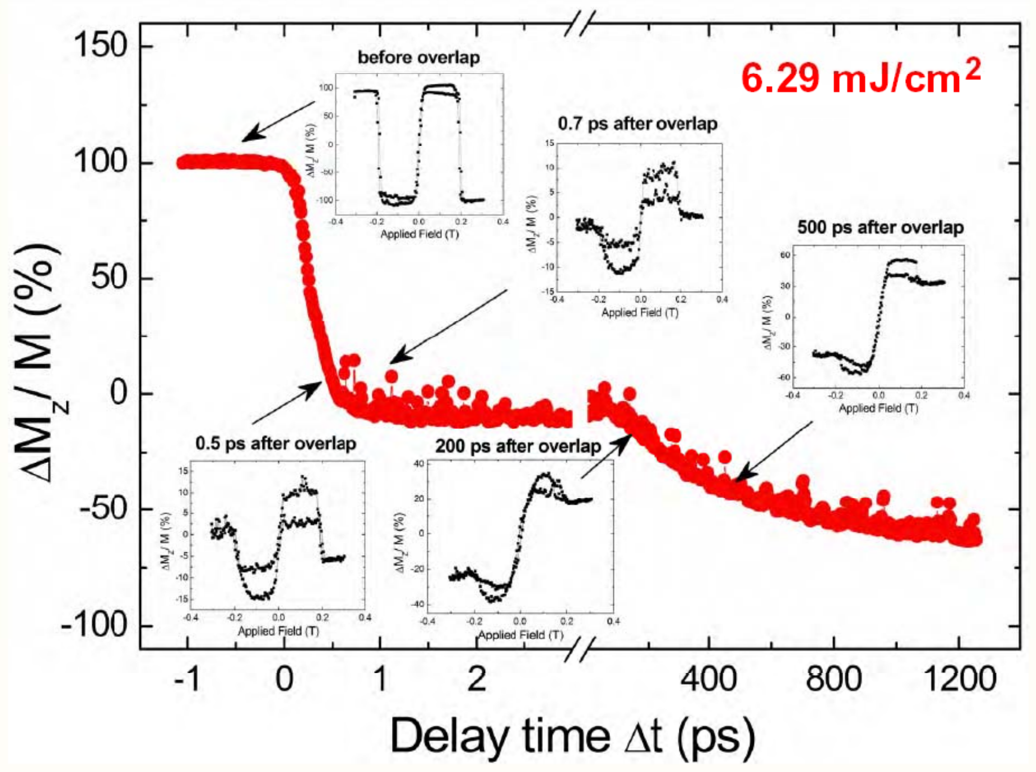
Phys. Rev. Lett. **99**, 217204 (2007)







Laser-induced magnetization reversal



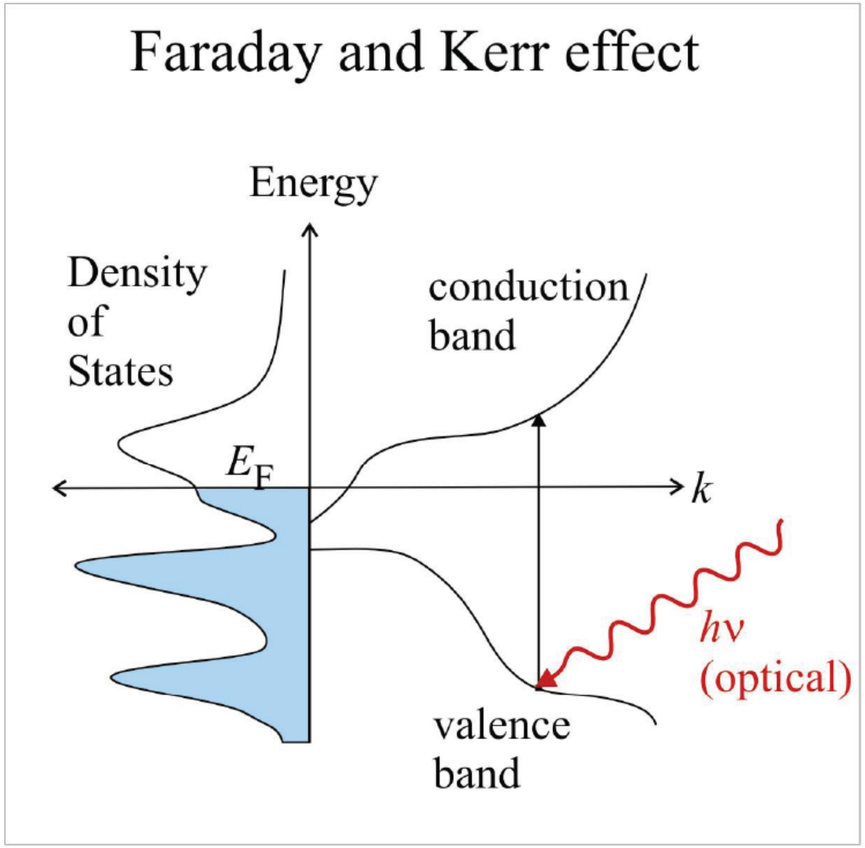
- ➢Contrast reverses in 0.7 ps
- ➢Also M_{Gd} is affected by the laser pulse on a sub-ps time scale (?)
- ➢Decrease of the angular momentum does work!

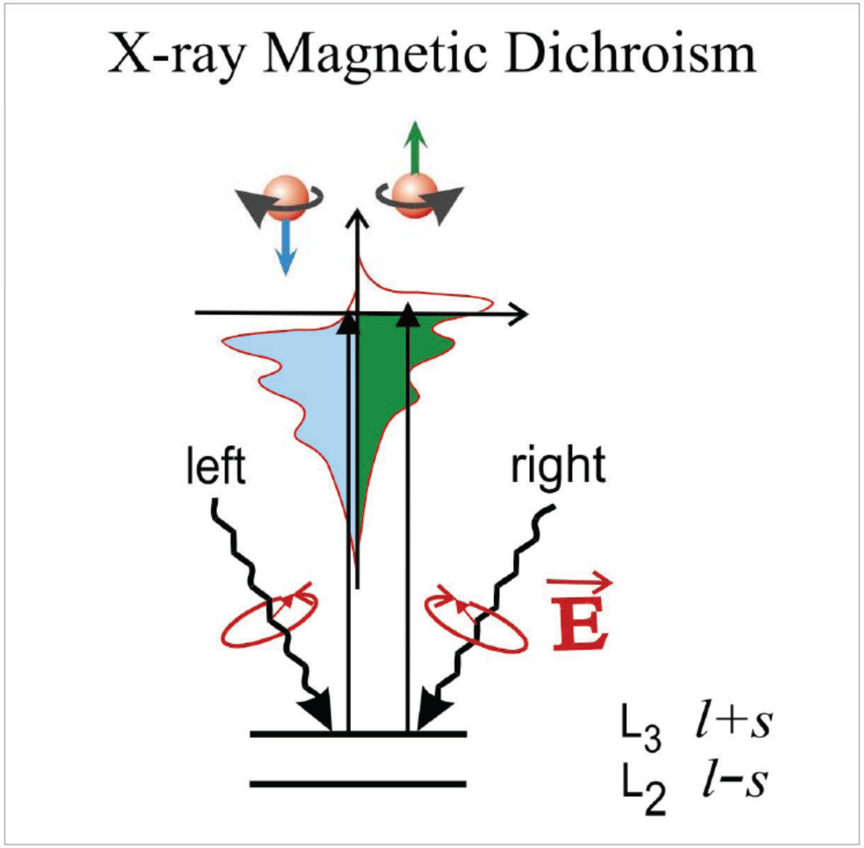
Stanciu et al, Phys. Rev. Lett. **99**, 217204 (2007)

Outline of the lecture

- Angular momentum gone, inertia recovered: antiferromagnets
- Tuning angular momentum in ferrimagnets: faster precession / switching
- **Angular momentum conservation vs exchange interaction**

To distinguish the two sublatices

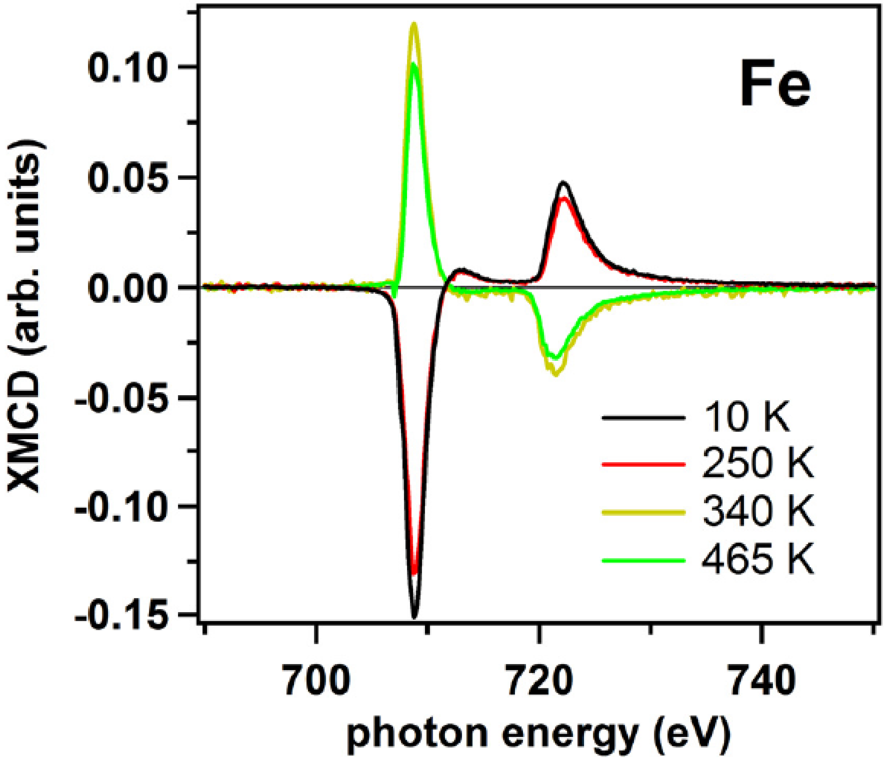


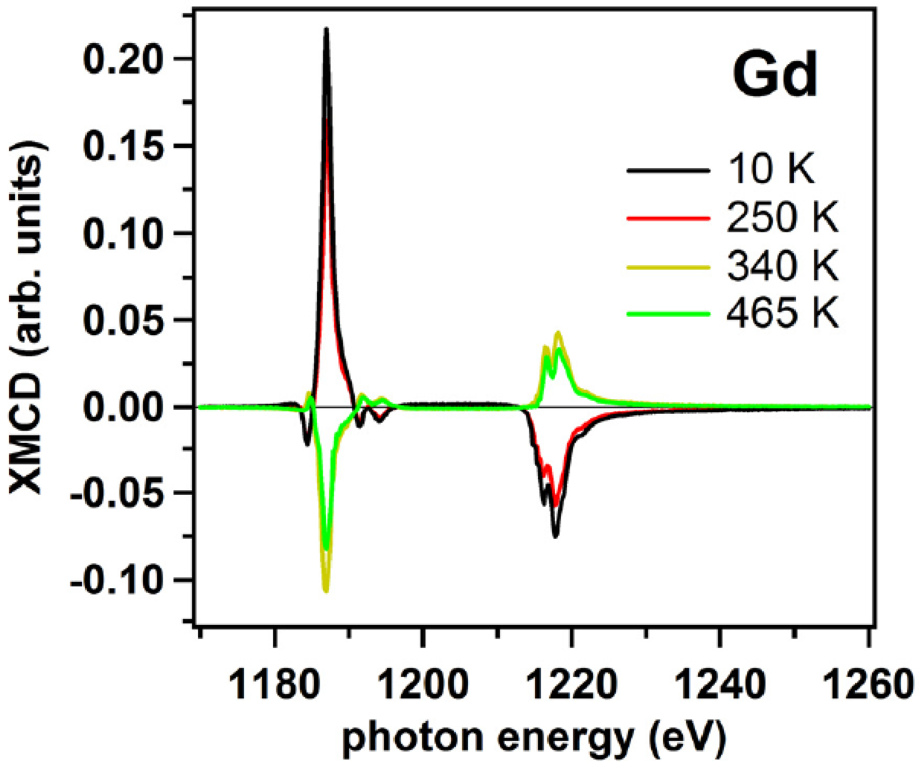


Magneto-optical response:
weak, k-dependent

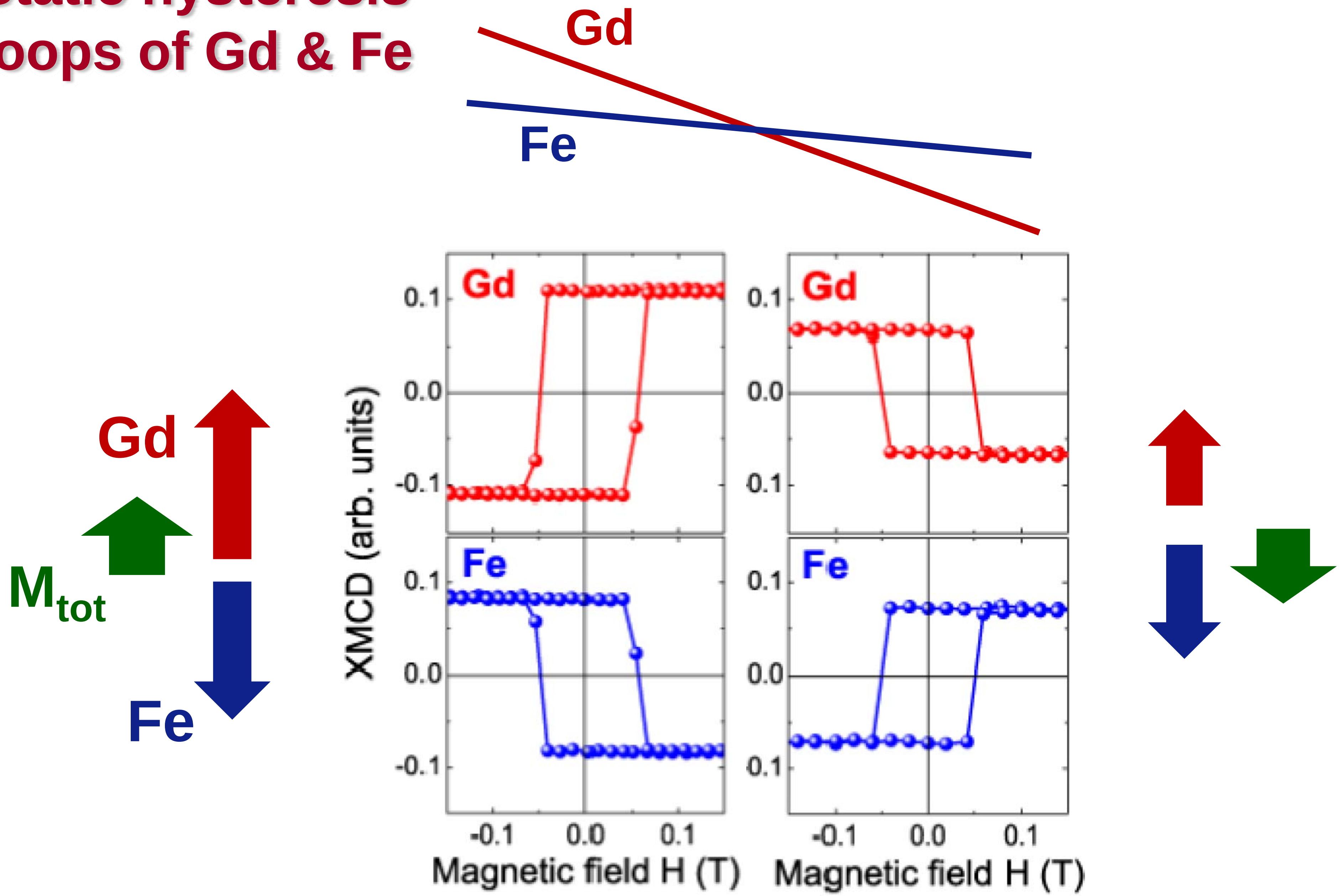
X-ray response:
strong, k-integrated quantities
number of holes, spin monent, orbital moment

XMCD contrast

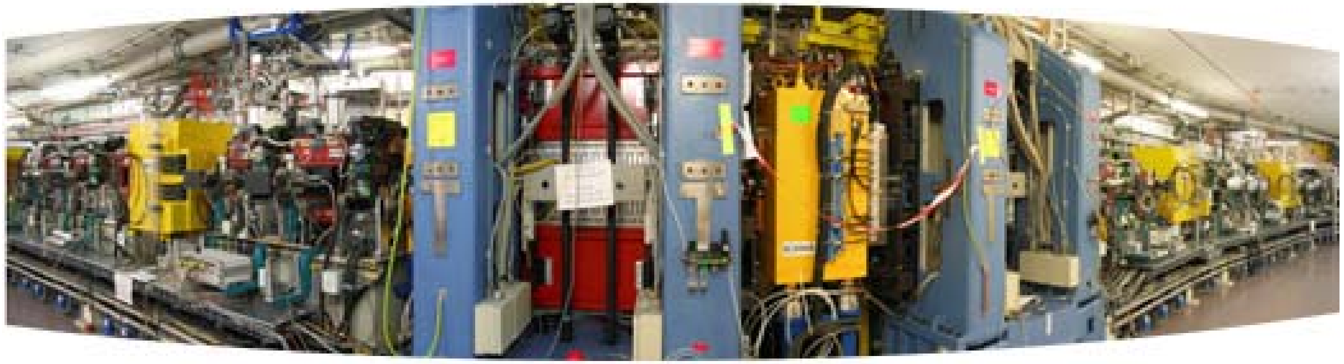


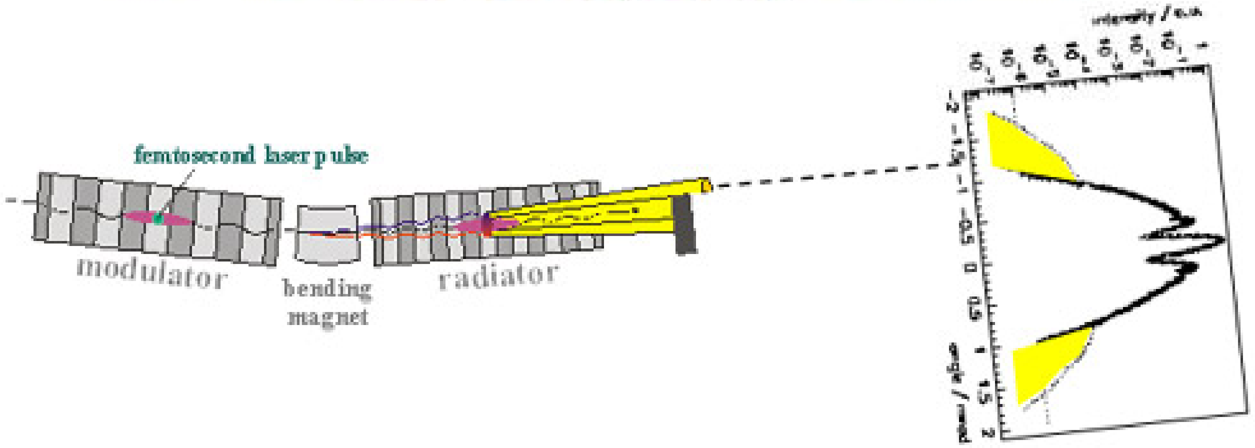


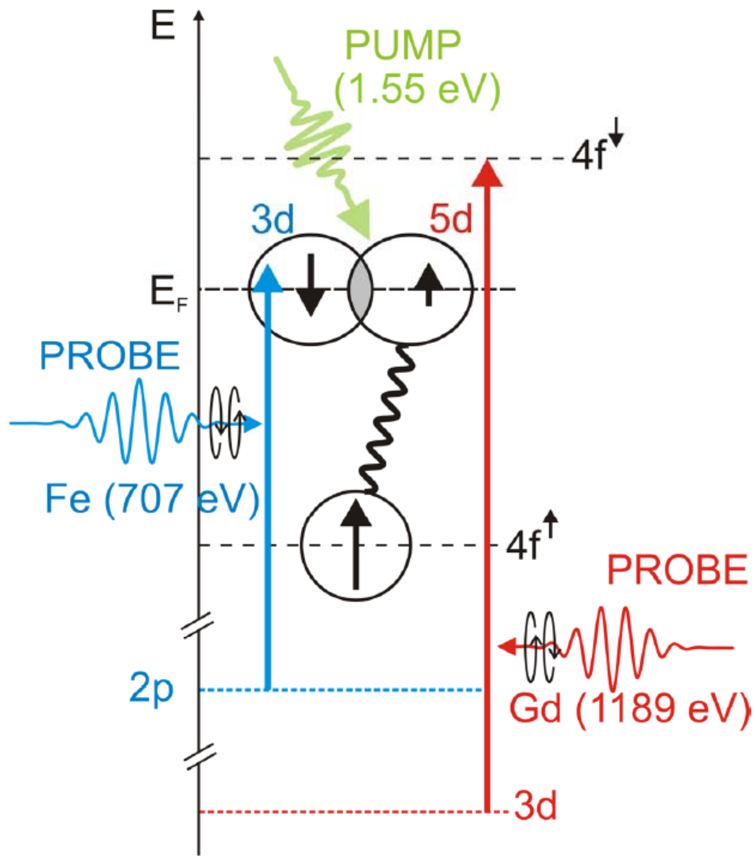
Static hysteresis loops of Gd & Fe



Femto slicing (BESSY)

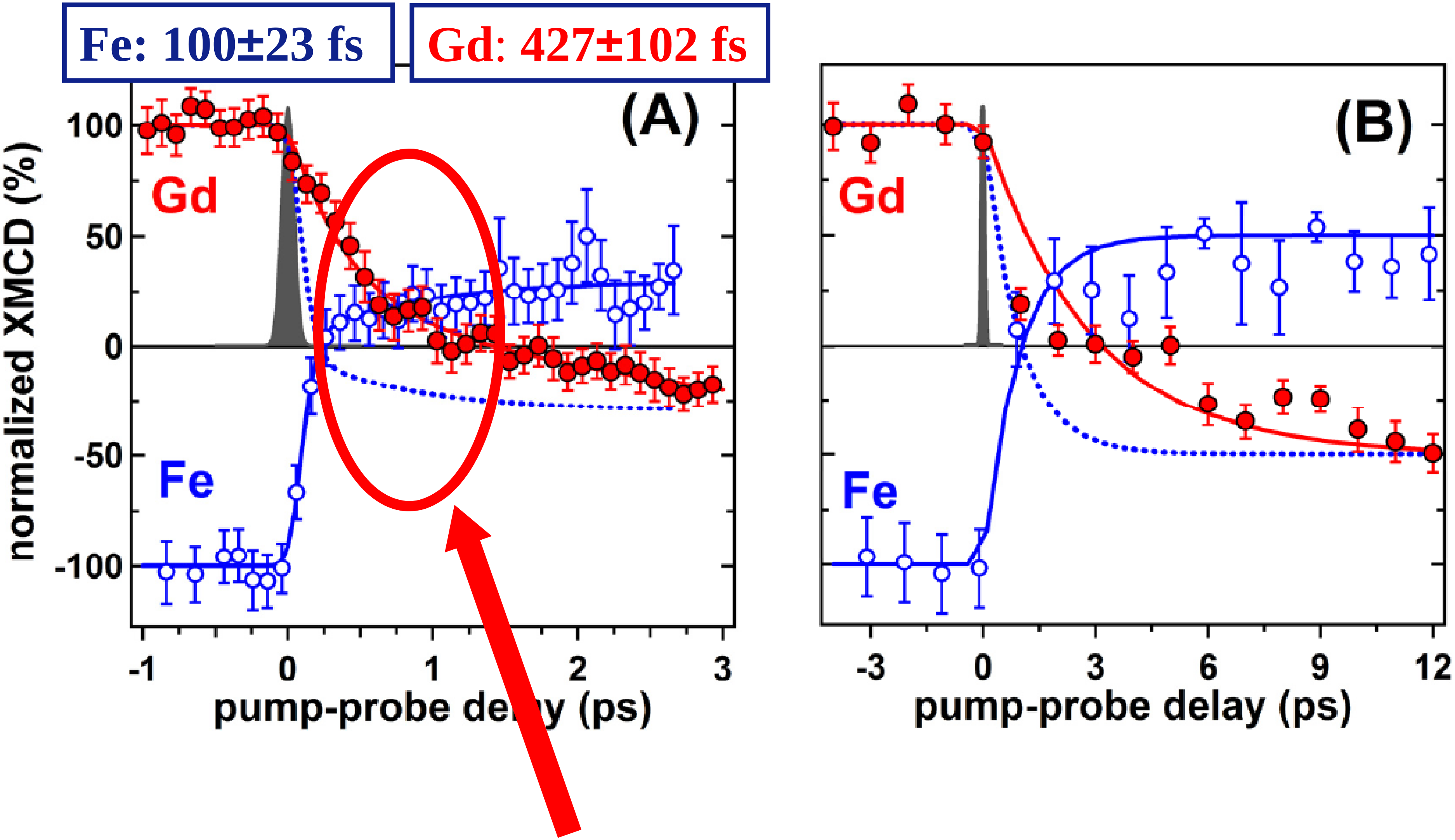






optical pump – X-ray probe fs time-resolved measurements

Ultrafast dynamics of sublattices



ferromagnetic GdFeCo!

Atomistic simulations

- localized atomistic spin model with a Heisenberg exchange
- exchange parameters (Fe-Fe, Gd-Gd, and Fe-Gd) obtained by fitting static $M_{Fe,Gd}(T)$ dependencies.
- stochastic term added to the effective field

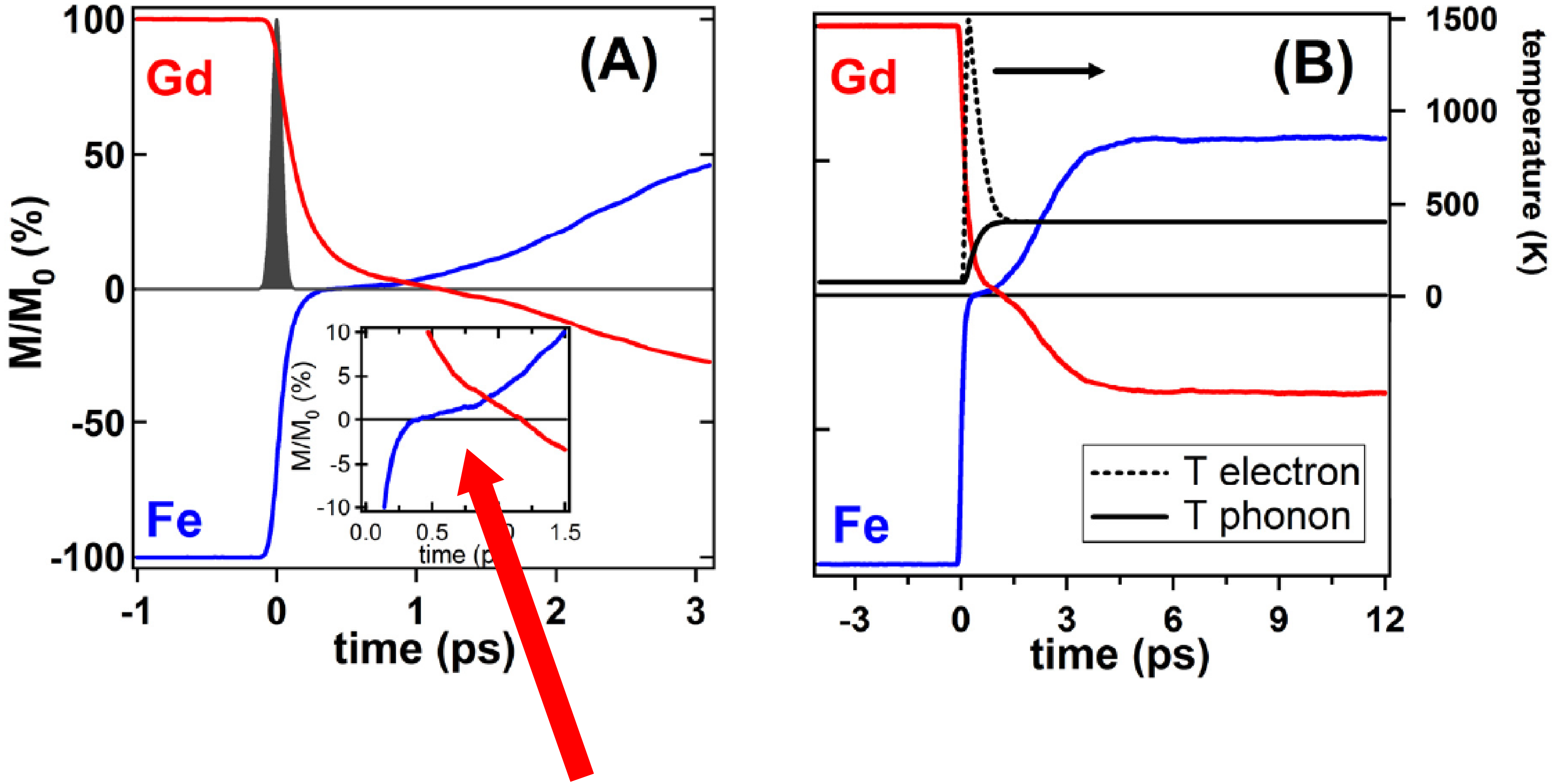
$$\frac{d\mathbf{s}}{dt} = \gamma[\mathbf{s} \times (\mathbf{H} + \zeta)] - \gamma\lambda[\mathbf{s} \times [\mathbf{s} \times \mathbf{H}]]$$

$$\langle \zeta_\alpha(t) \zeta_\beta(t') \rangle = \frac{2\lambda T}{\gamma\mu_0} \delta_{\alpha\beta} \delta(t - t')$$

- reversing field is present during the process

simulations by the group of R.W. Chantrell

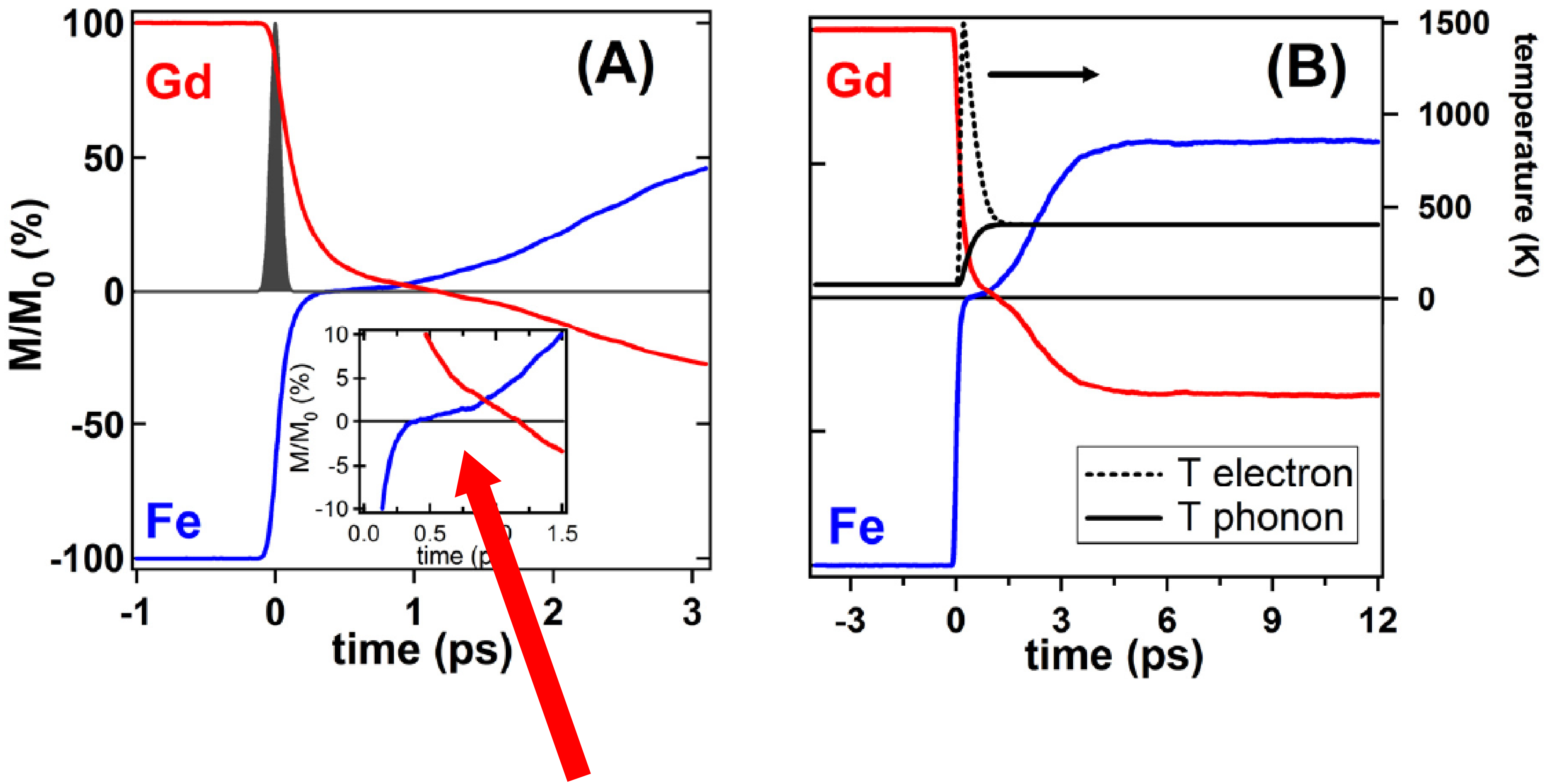
Simulation results



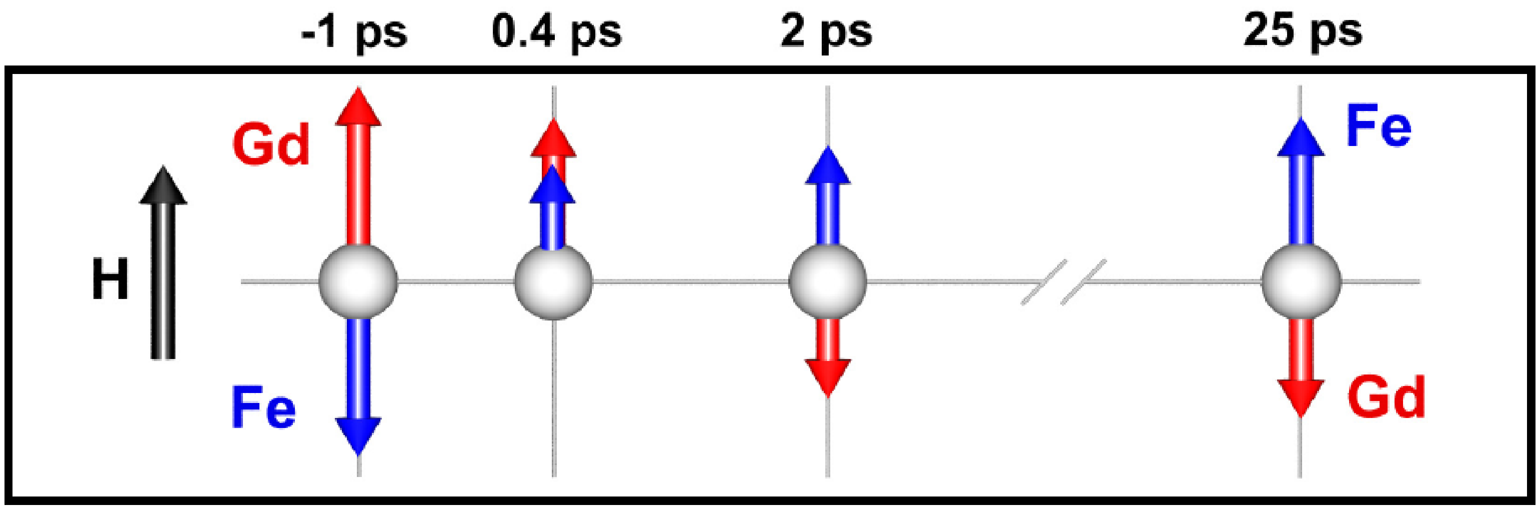
ferromagnetic state reproduced!

why??

Simulation results

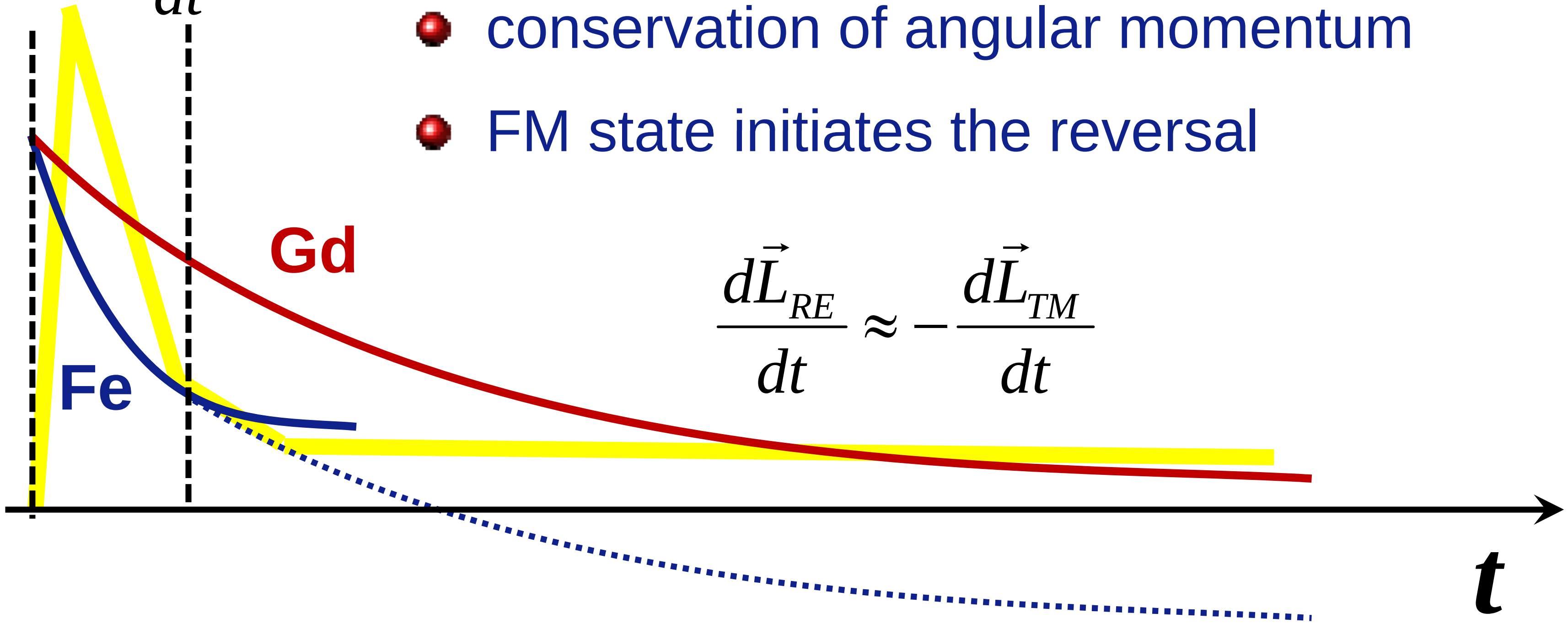


ferromagnetic state reproduced!



$$\frac{d\vec{L}_{RE}}{dt} \neq -\frac{d\vec{L}_{TM}}{dt}$$

- different demagnetization times of Fe and Gd
- conservation of angular momentum
- FM state initiates the reversal



$$\frac{d\vec{L}_{RE}}{dt} \approx -\frac{d\vec{L}_{TM}}{dt}$$

Therefore:

- angular momentum controls the switching
- different demagnetization times of the sublattices
- exact compensation is not required