Controlling magnetism with light

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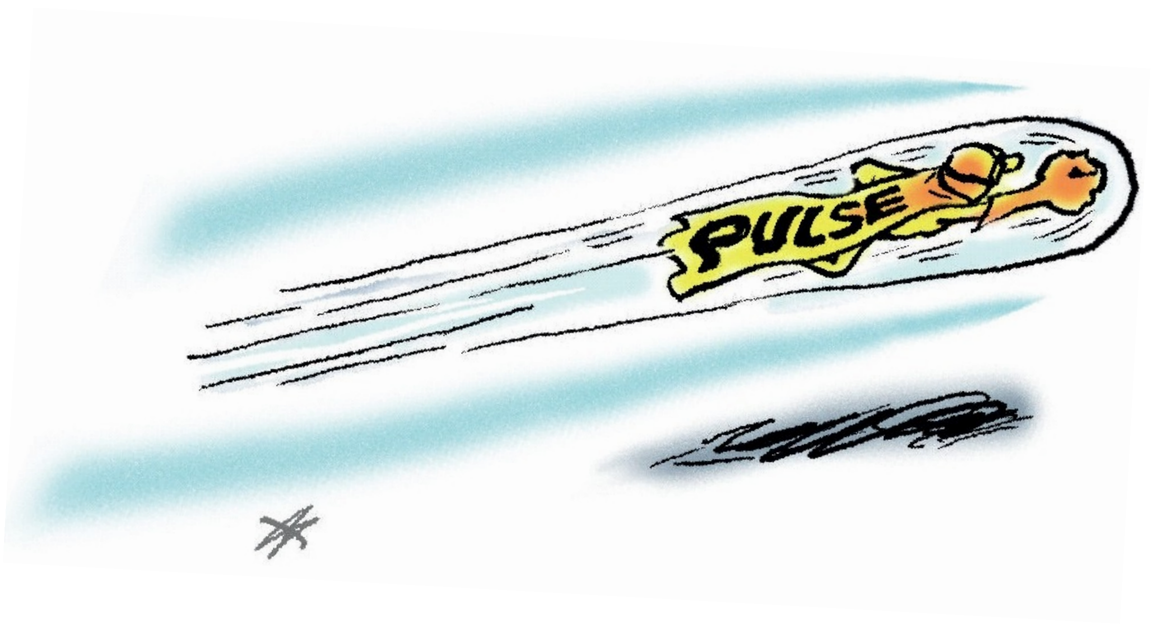


Ultrafast Magnetism Conference
UMC 2015
Nijmegen, the Netherlands
October 19-23 2015

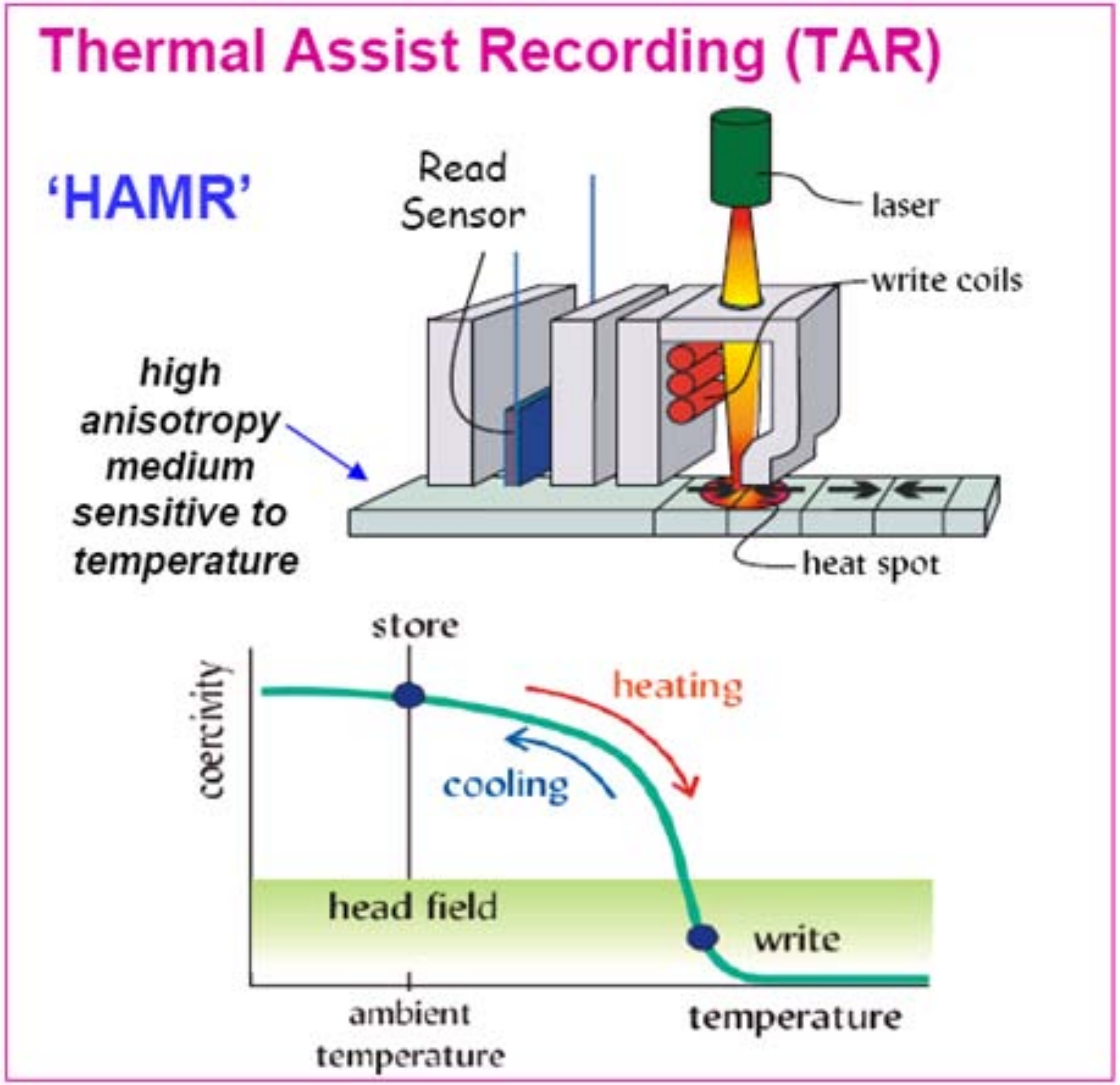
The submission of abstracts is extended until July 1

The selected papers will be published by Springer in the series "Springer Proceedings in Physics"

The instructions for abstract submission and key dates can be found online

http://www.ru.nl/ssi/umc-october-2015/

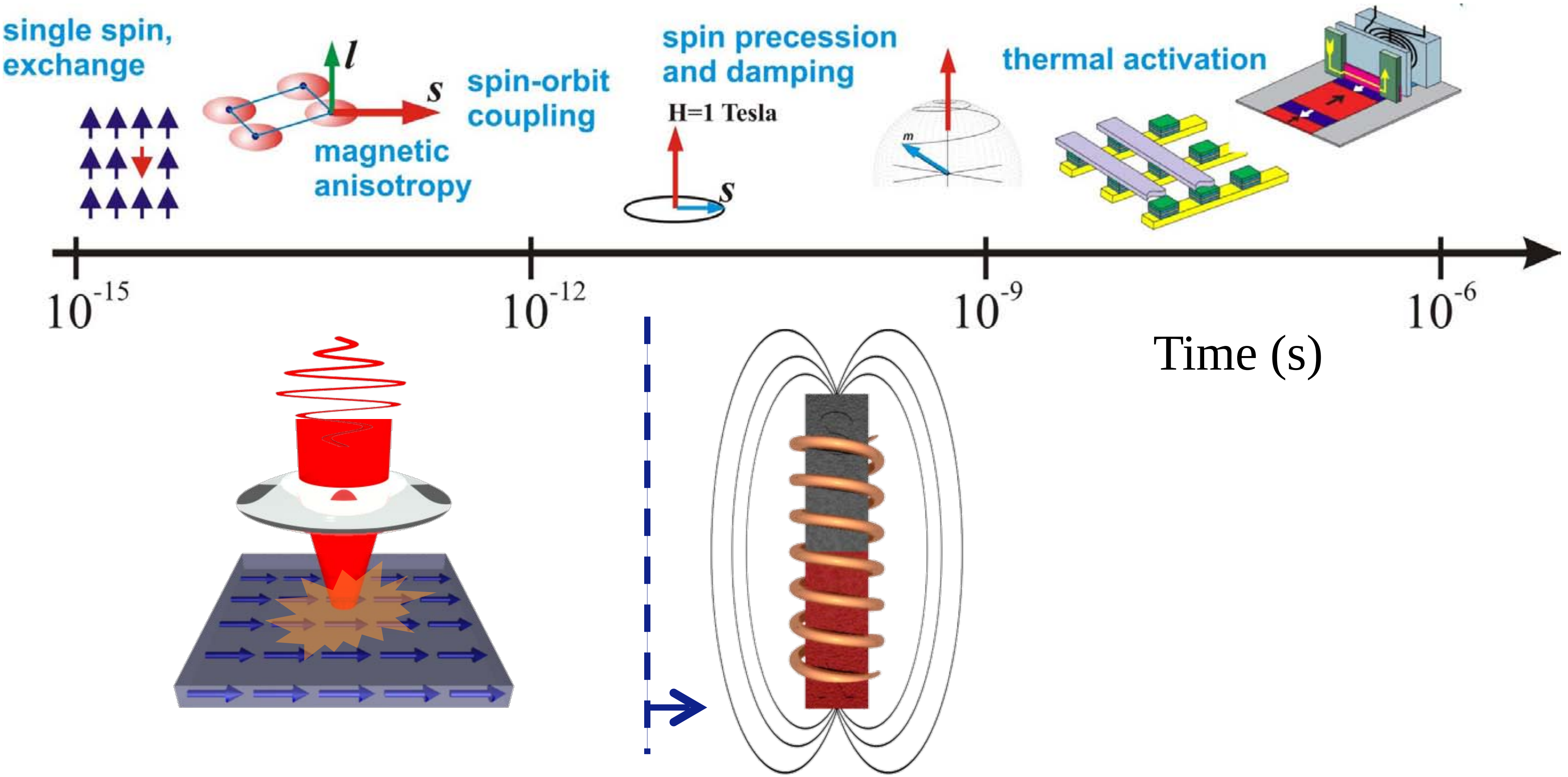
Magnetic recording – searching for options



Other options:

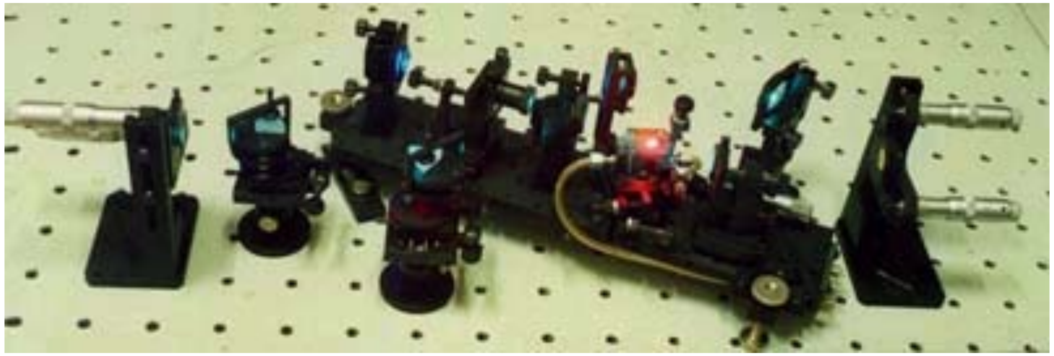
- **Bit Patterned Media**
- **Microwave-Assist**
- **Two-Dimensional**
- **.....**

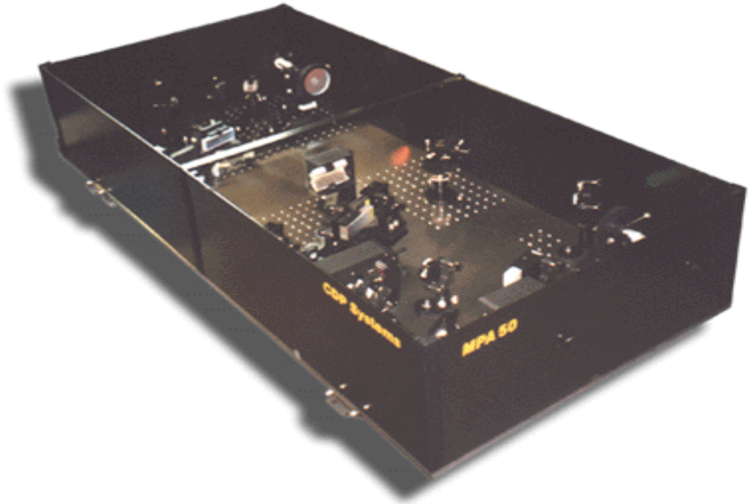
Time-scales and stimuli in magnetism



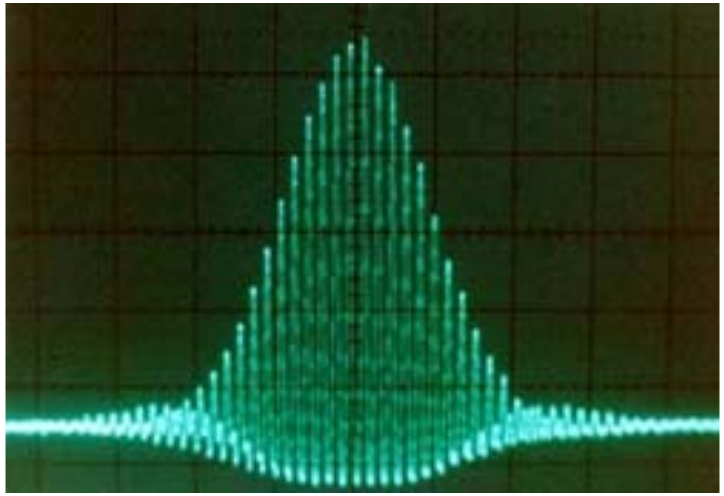
Experimental know-how:
time-resolved pump-probe setup

What you need: a femtosecond laser





	Model TISSA20	Model TISSA50	Model TISSA100
Pump Power[1)]	3-5 W	3-7 W	5-10 W
Output Power at 800 nm	150 - 250 mW	150-500 mW	>10% efficiency
Pulse Duration[2)]	<20 fs [3)]	< 50 fs	<100 fs
Tuning Range	800 ± 20 nm	740 - 950 nm[4)]	720 - 980 nm[4)]
Repetition Rate	70 - 140 MHz		

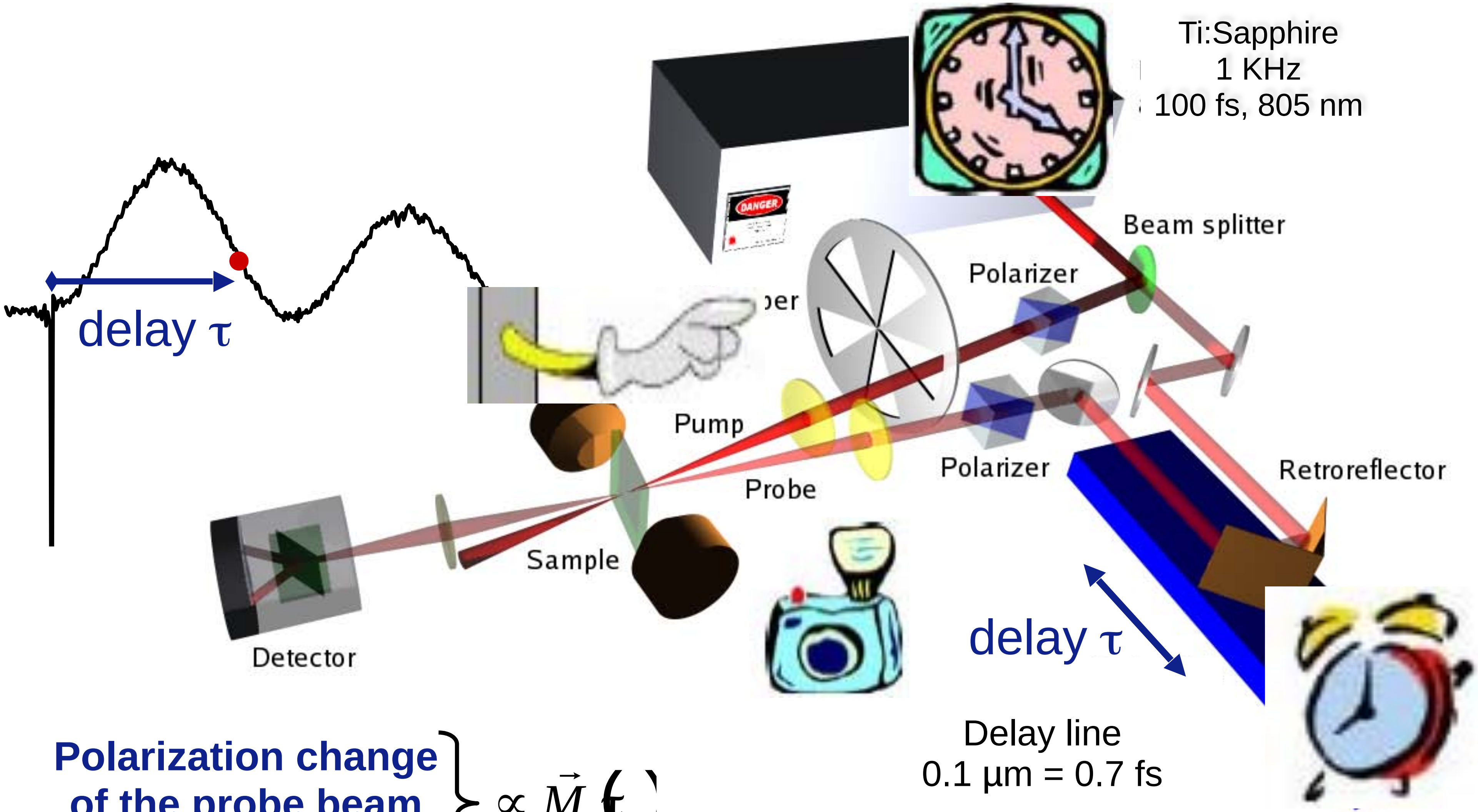


Interferometric autocorrelation function of 16 fs pulse obtained with external group velocity dispersion compensation

lots of choice!

pump & probe technique

Stroboscopic magneto-optical pump-probe setup



Polarization change of the probe beam is detected $\Bigg\} \propto \vec{M}(t)$

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Part 1: classification of laser-induced effects

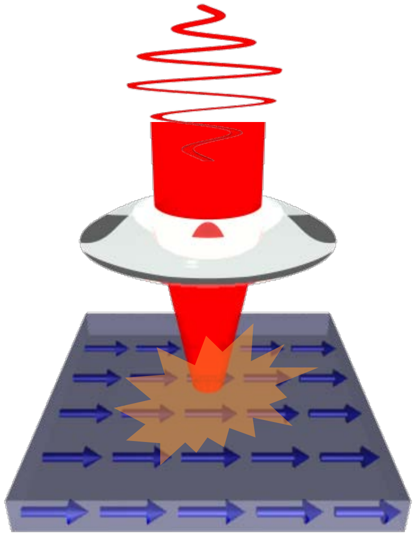
Part 2: the story of one experiment

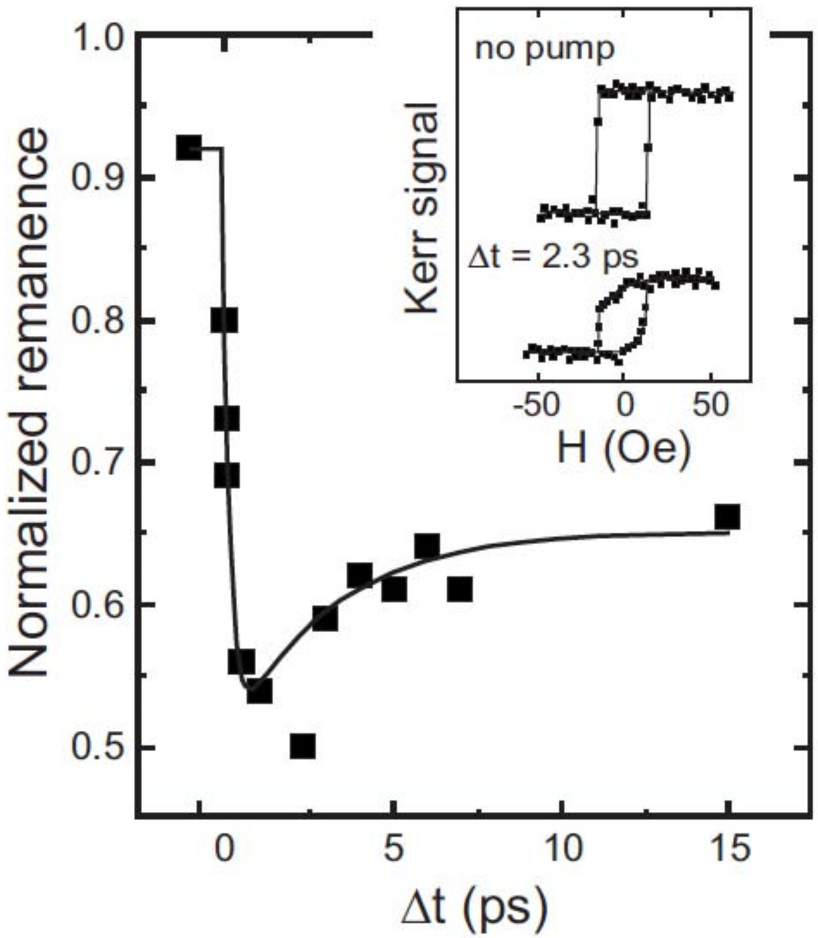
Effects of the laser pulse: classification

I. Thermal effects:

change of M is a result of change of T

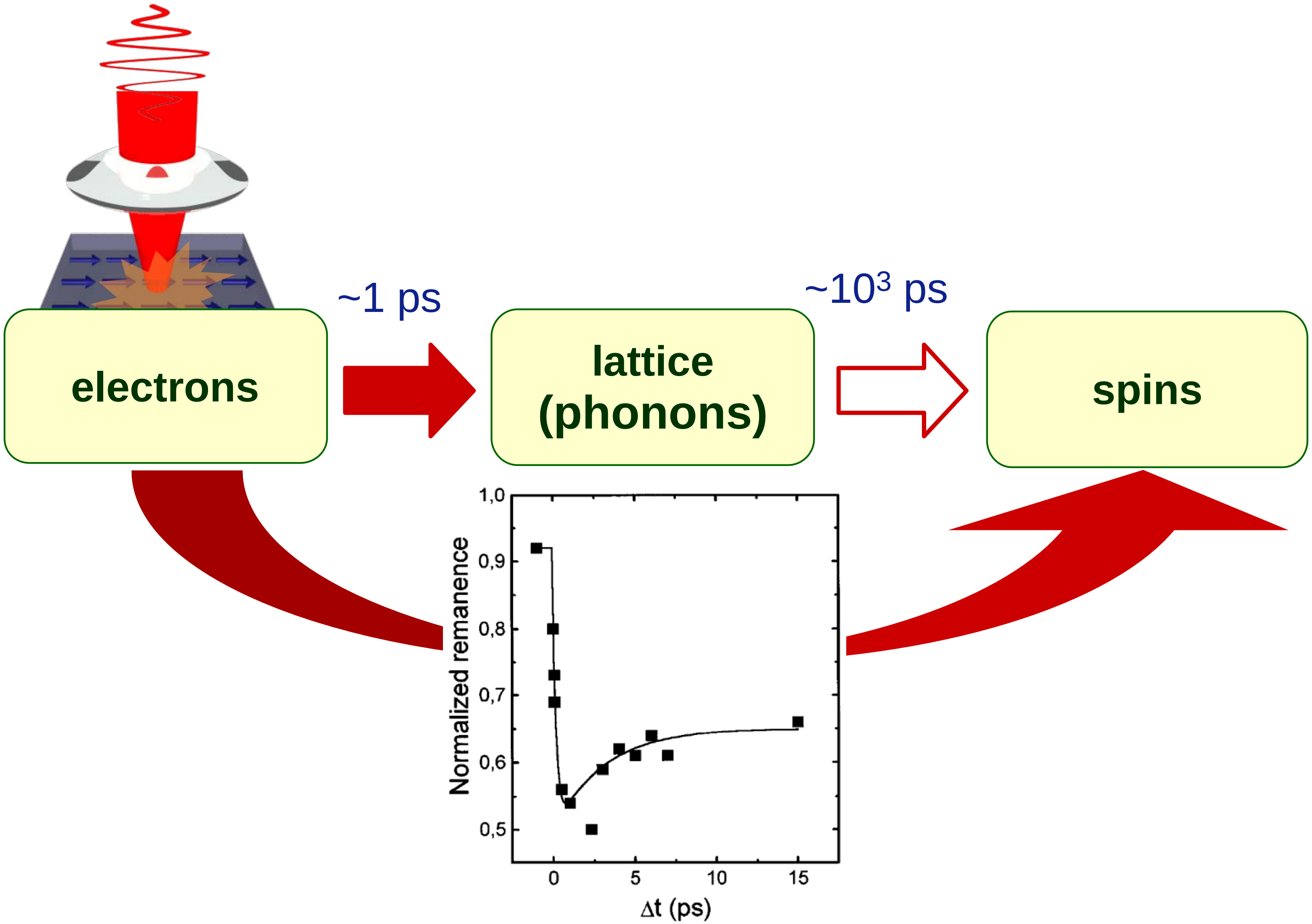
Laser-induced collapse of magnetization



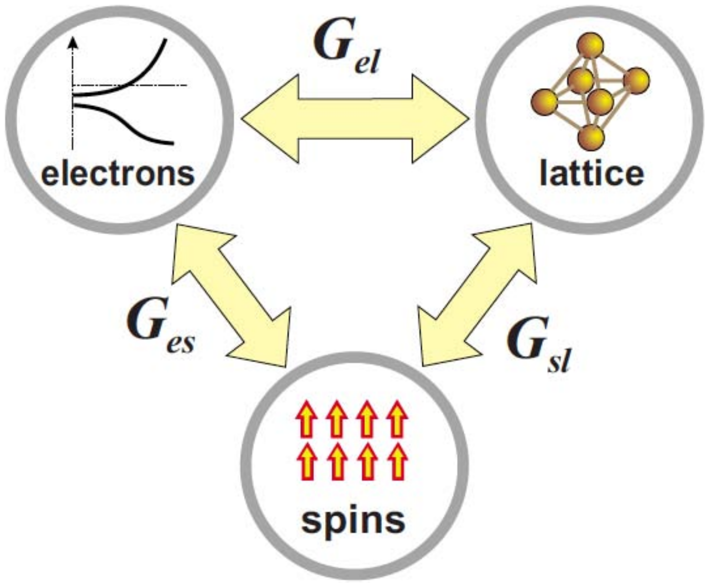


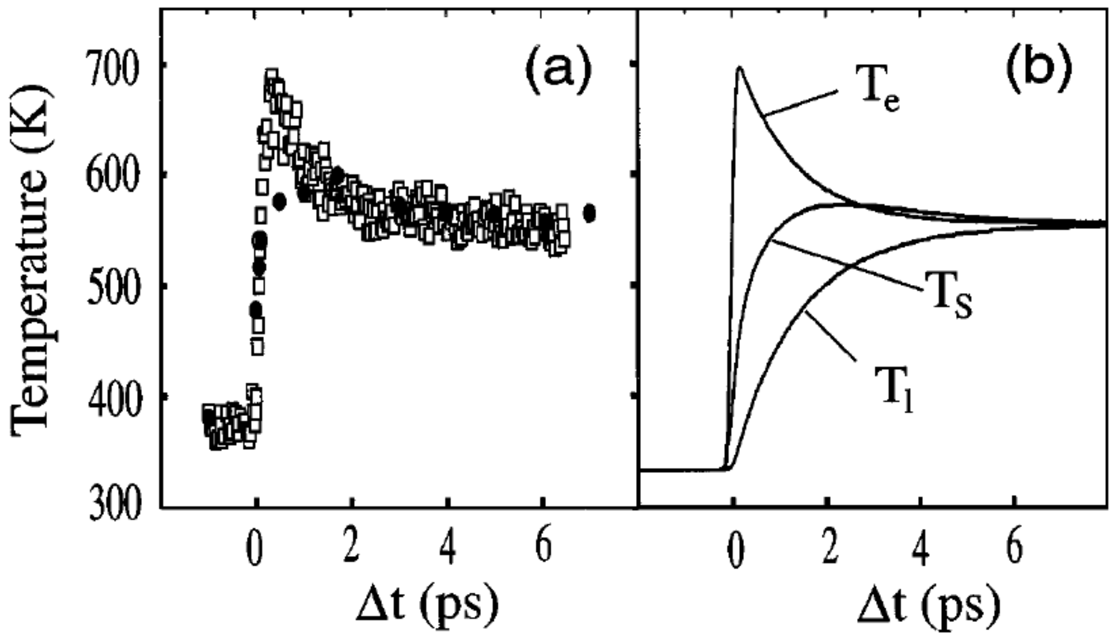
Beaurepaire et al, PRL **76**, 4250 (1996)

Energy transfer: time scales



3T model and derivatives



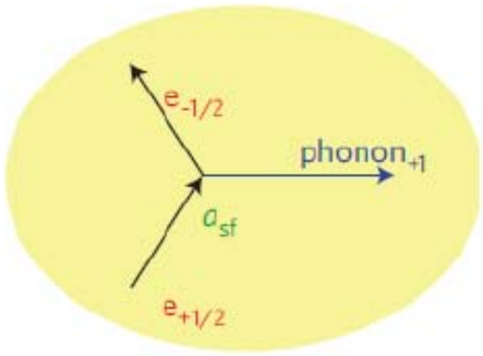


$$C_e d(T_e)/dt = -G_{el}(T_e - T_l) - G_{es}(T_e - T_s) + P(t)$$

$$C_s d(T_s)/dt = -G_{es}(T_s - T_e) - G_{sl}(T_s - T_l),$$

$$C_l d(T_l)/dt = -G_{el}(T_l - T_e) - G_{sl}(T_l - T_s),$$

microscopic 3-temperature model



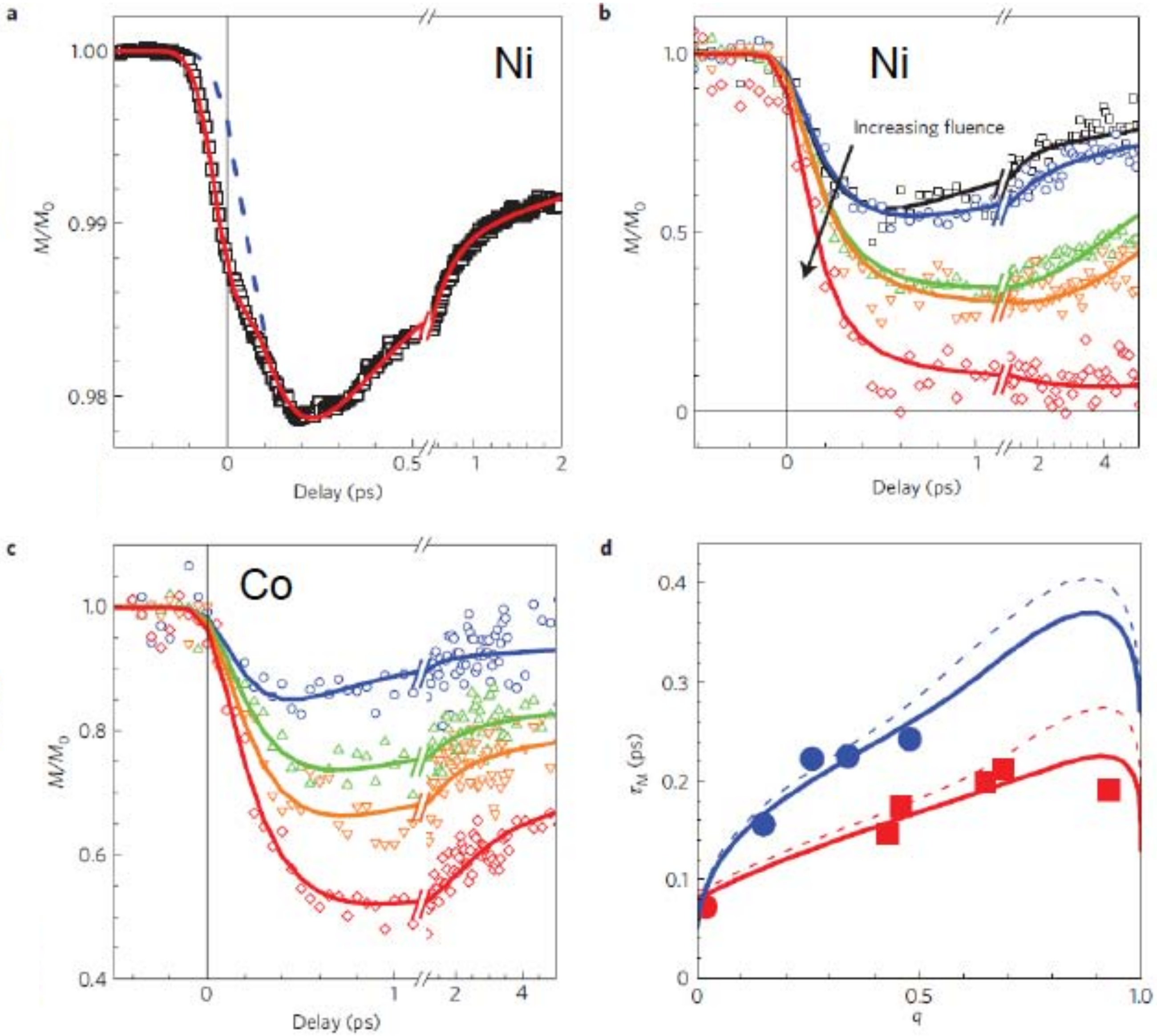
$$c_e \frac{dT_e}{dt} = -g_{ep}(T_e - T_p) + P(z,t)$$

$$c_p \frac{dT_p}{dt} = g_{ep}(T_e - T_p)$$

$$\frac{dm}{dt} = Rm\frac{T_p}{T_C}\left(1 - m\coth\left(\frac{mT_C}{T_e}\right)\right)$$

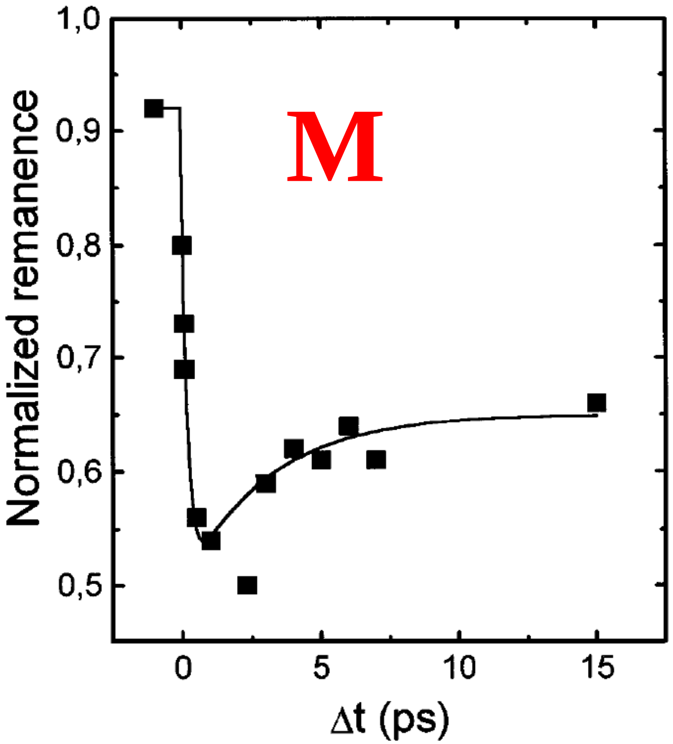
$$R = a_{sf}\frac{8 g_{ep} k T_C^2}{E_D^2 \mu_{at}}$$

$$\boxed{a_{sf}\frac{T_C}{\mu_{at}}}$$

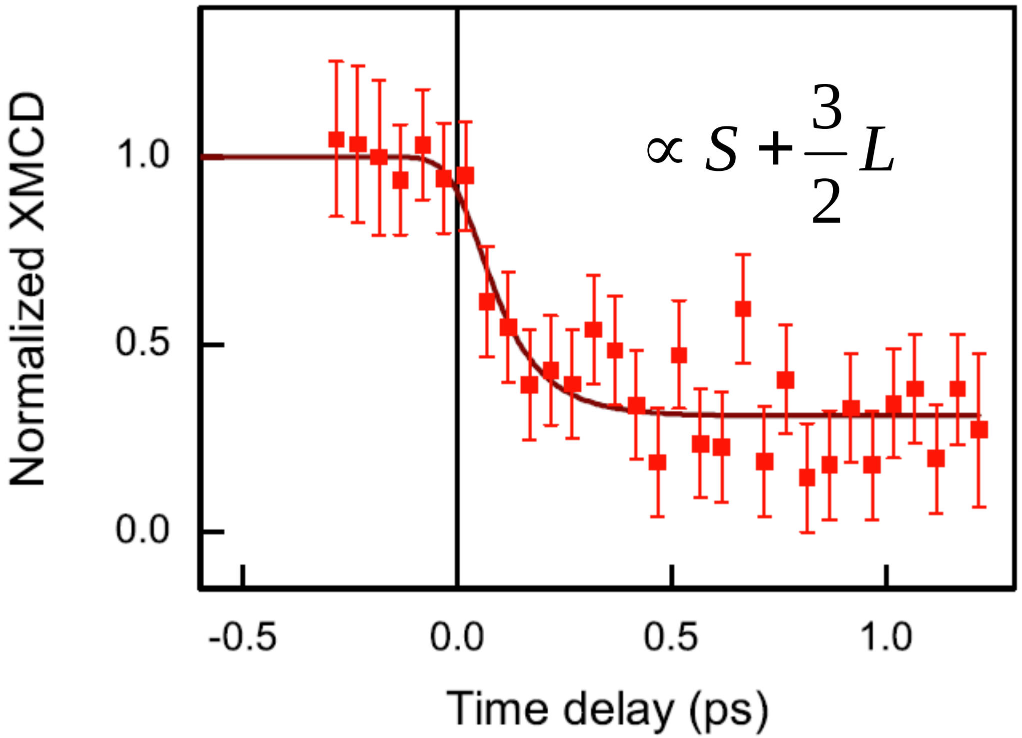


Koopmans et al., Nat. Mater. **9**, 259 (2010)

Ultrafast laser-induced demagnetization - once again

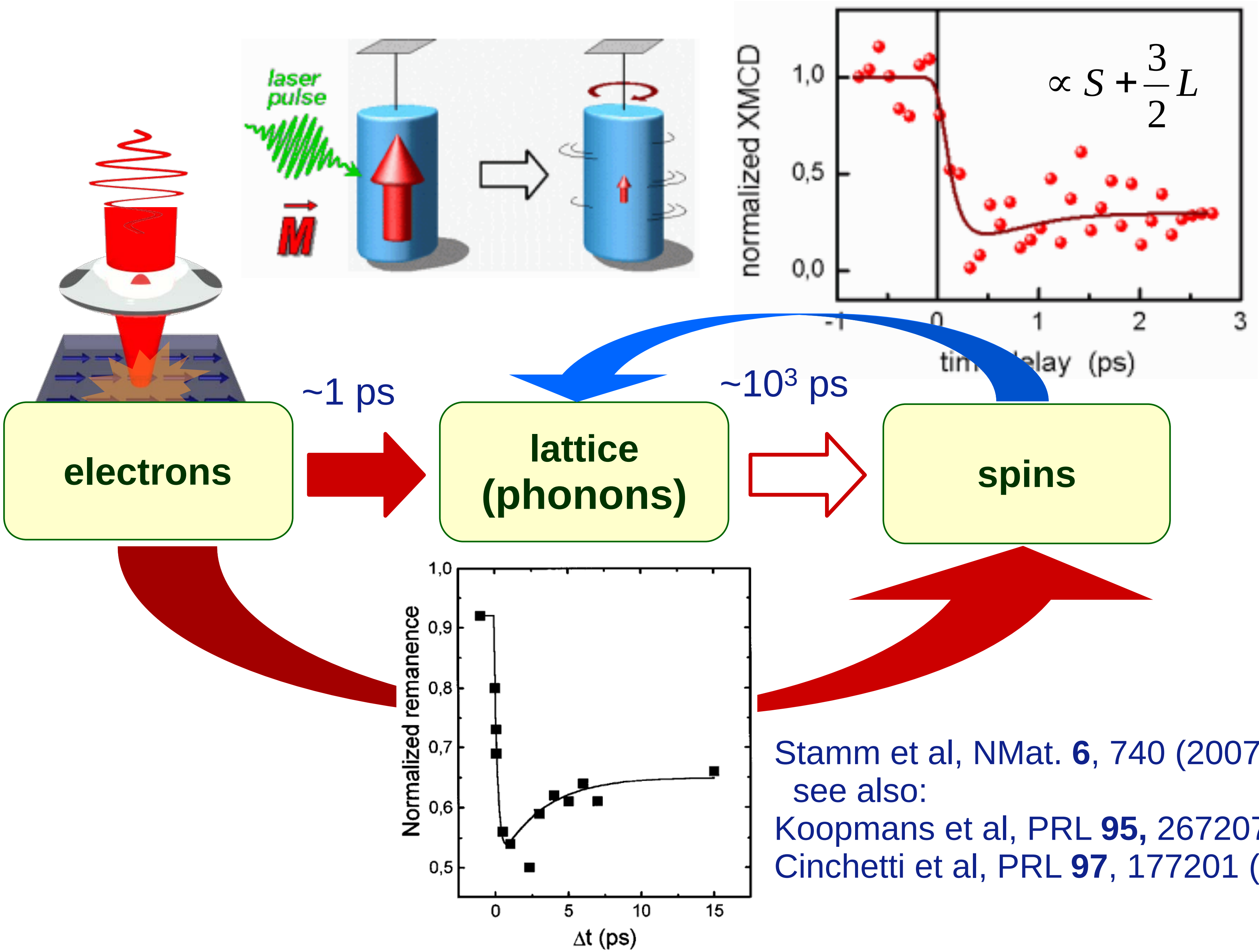


Beaurepaire et al. PRL **76**, 4250 (1996)



Stamm et al. Nature Mat. **6**, 740 (2007)

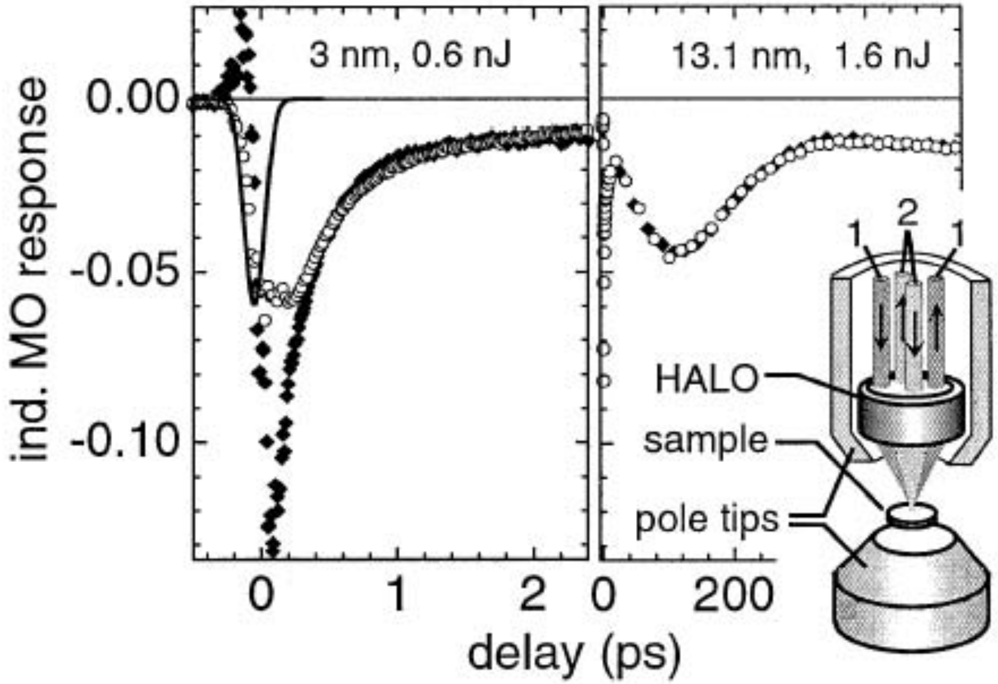
Energy- and angular momentum transfer



Stamm et al, NMat. **6**, 740 (2007);
see also:
Koopmans et al, PRL **95,** 267207 (2005);
Cinchetti et al, PRL **97**, 177201 (2006).

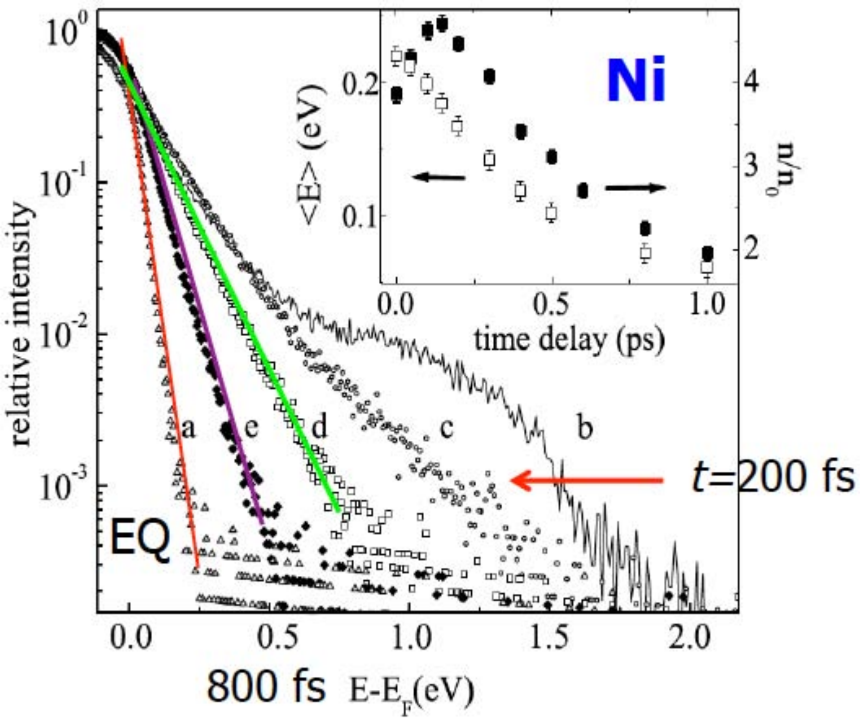
Magneto-optics??

Effect of “bleaching” or “state blocking”

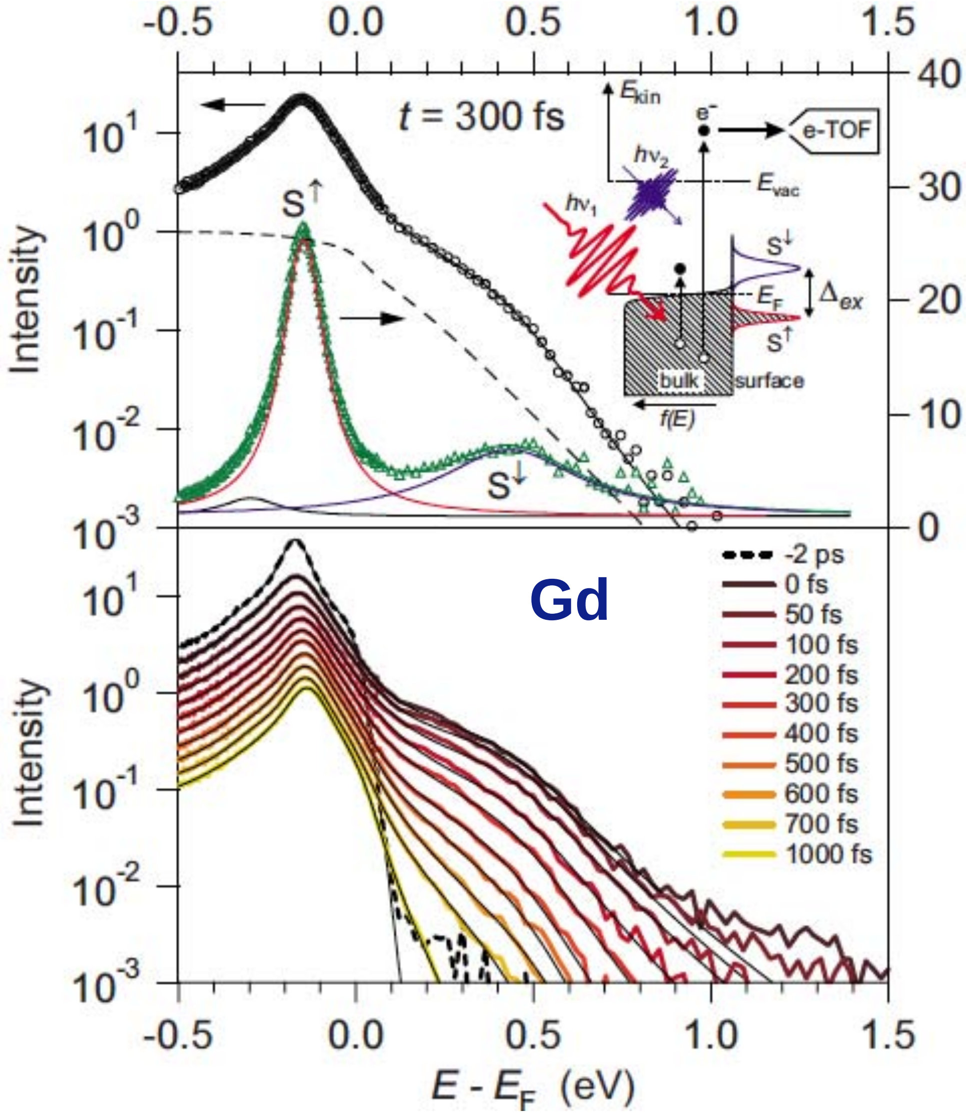


Koopmans et al, PRL 85 (2000) 844

Non-equilibrium electron population



Rhie et al., PRL **90** (2003)



Lisowski et al, Phys. Rev. Lett. **95**, 137402 (2005).

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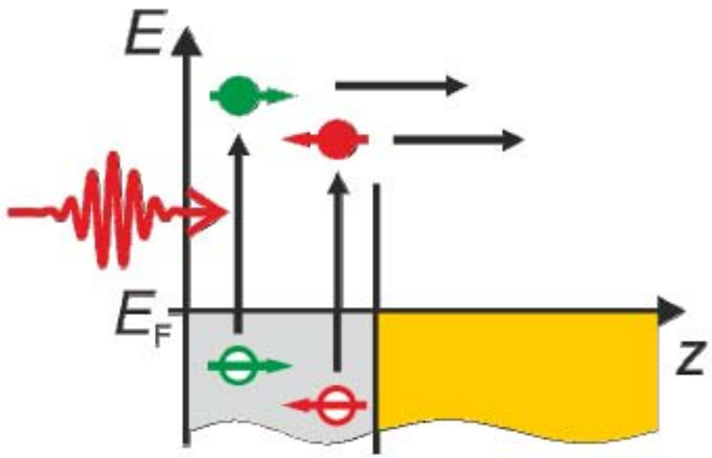
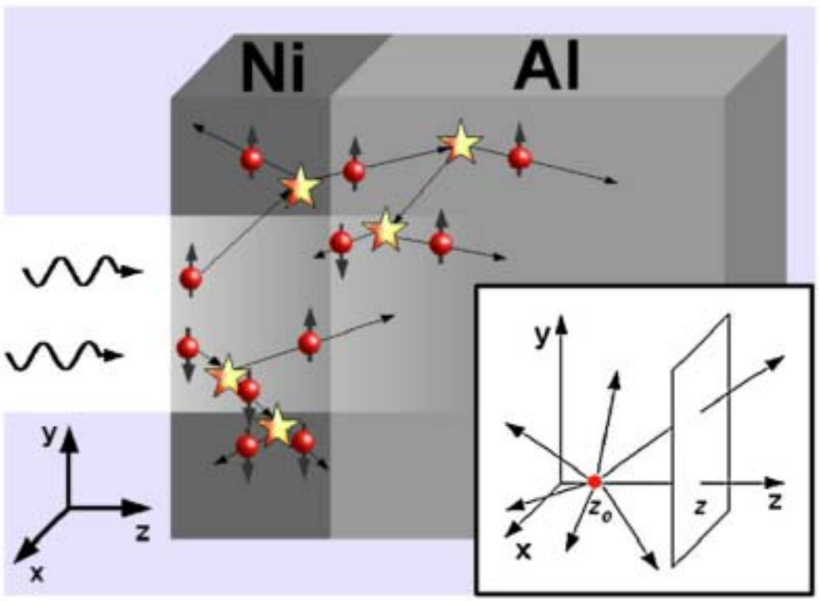
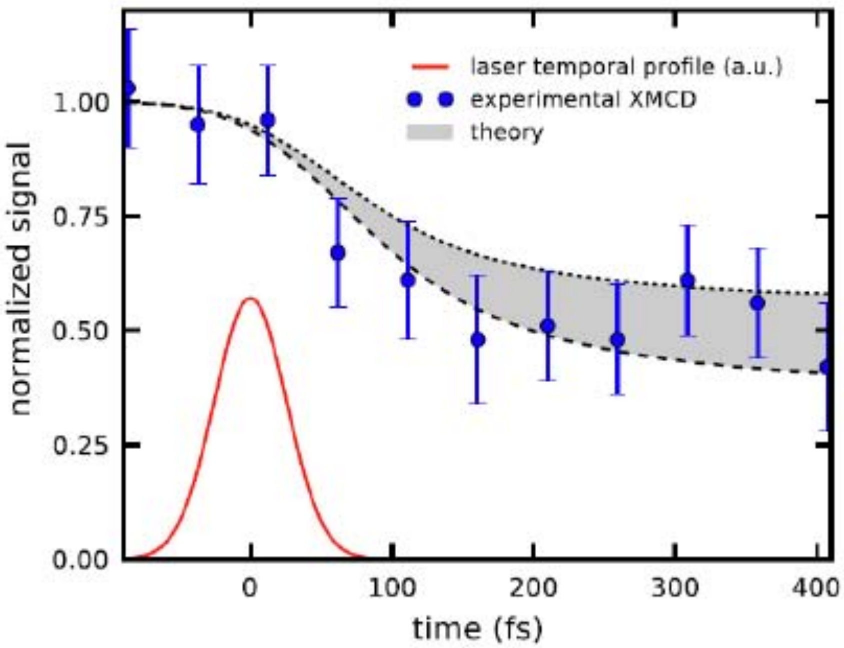
Superdiffusive spin transport



Battiato et al., Phys. Rev. Lett. **105**, 027203 (2010)





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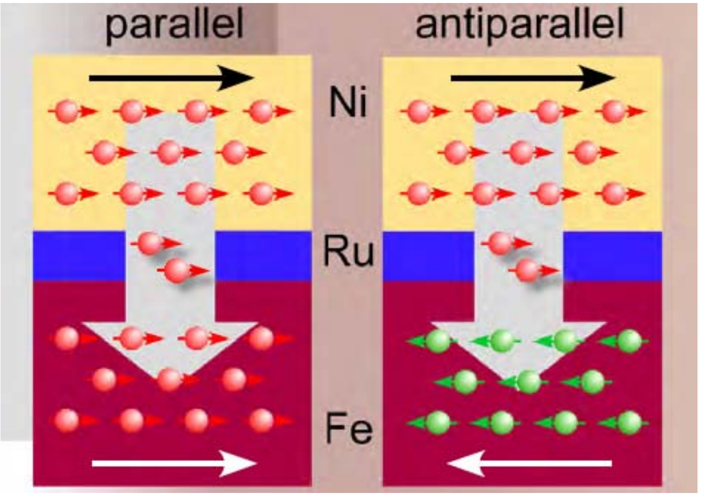
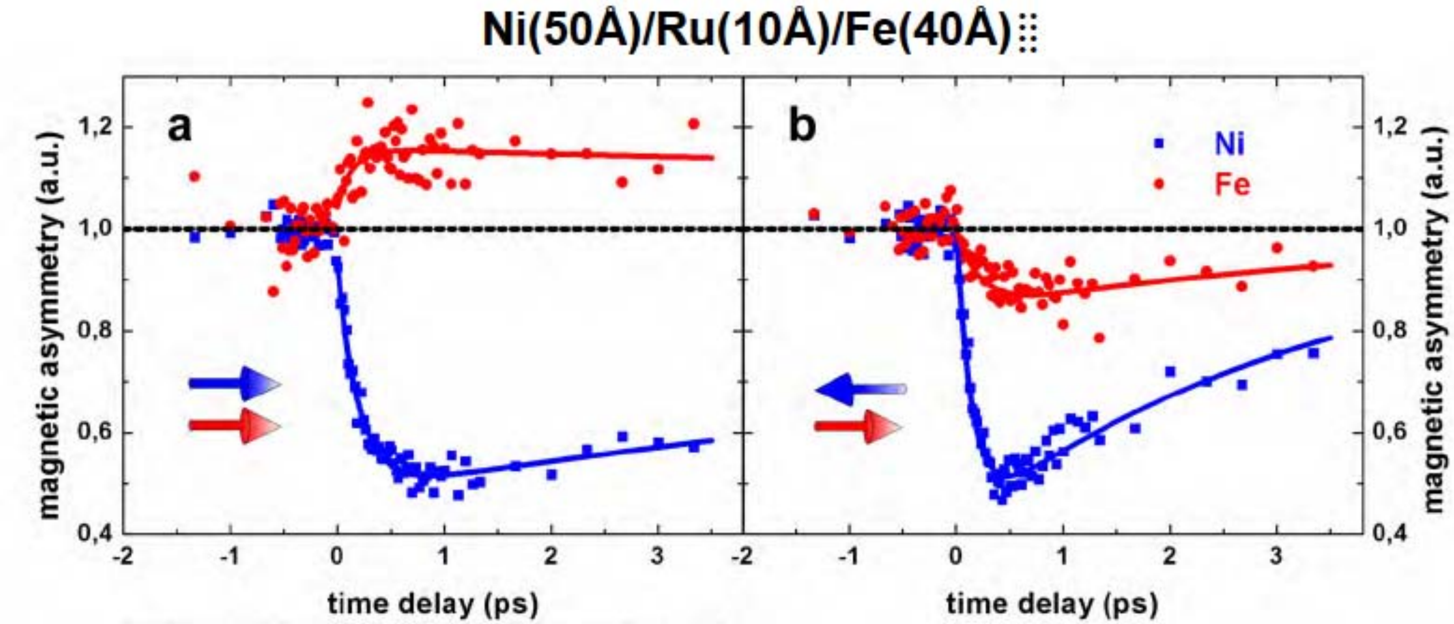
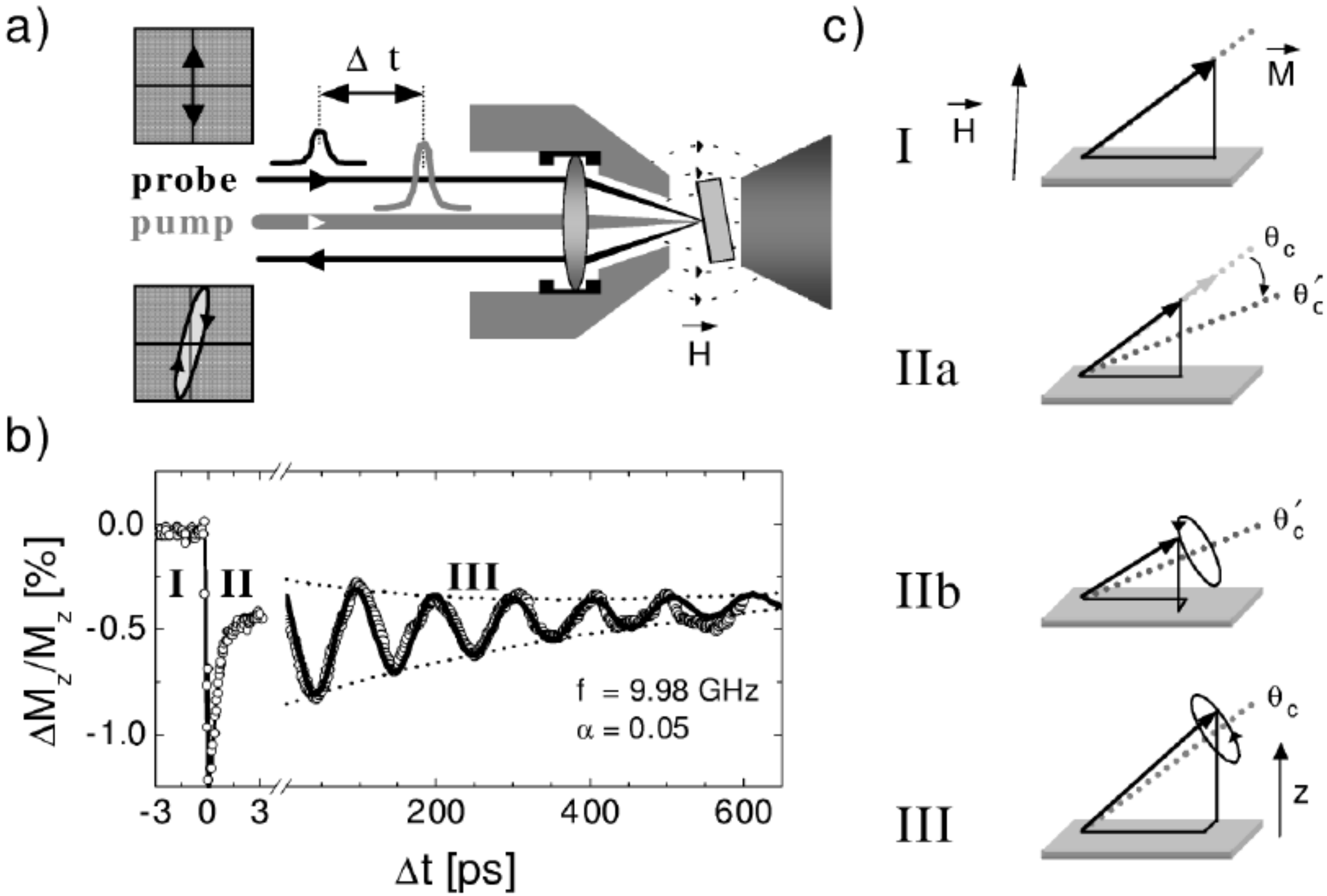
Local dynamics vs spin transport



D. Rudolf et al., Nat. Comm. (2013)



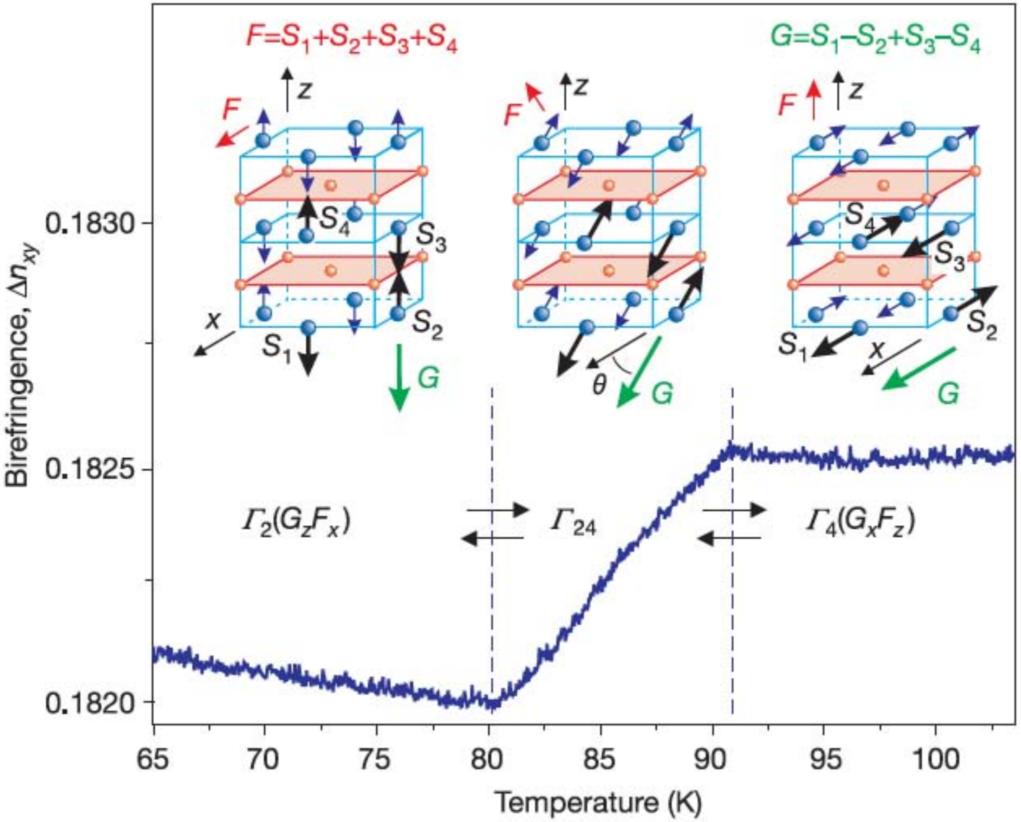
Laser effects 2: excitation of precession

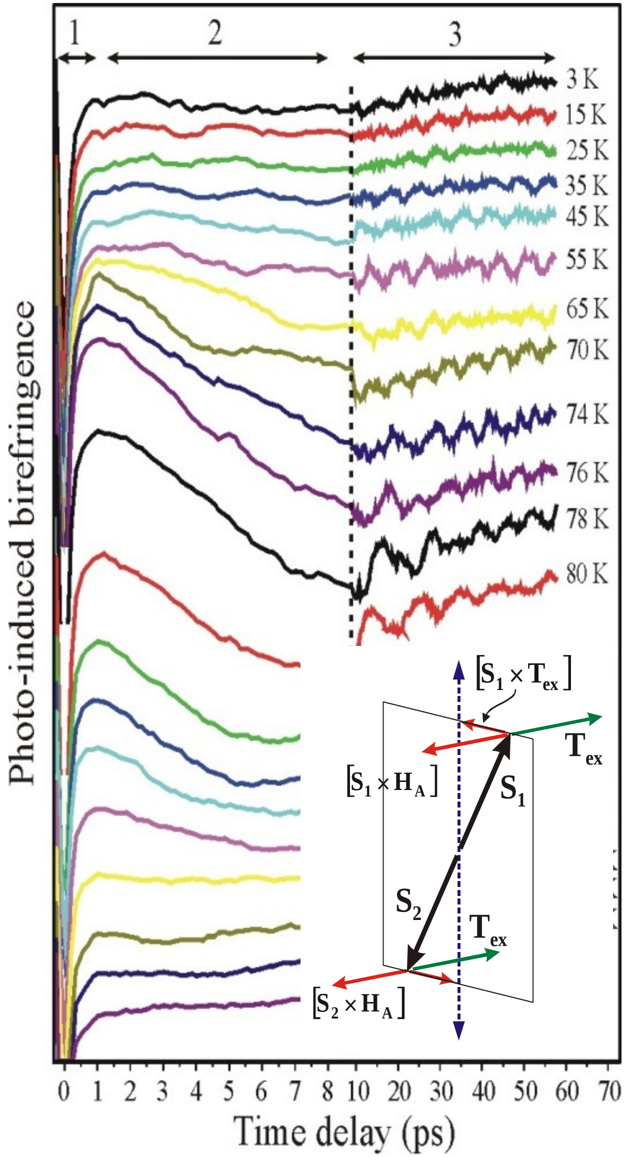


Ju et al., PRL **82**, 3705 (1999)
van Kampen et al, PRL **88**, 227201 (2002)

Laser effects 3: phase transitions

TmFeO$_3$





Kimel et al., Nature **429**, 850 (2004)

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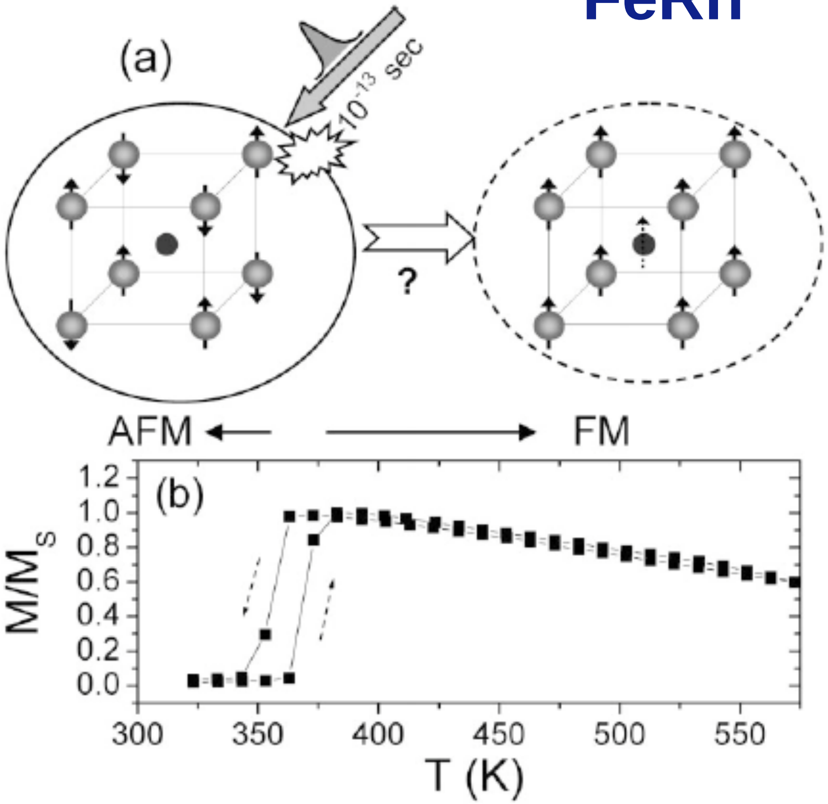
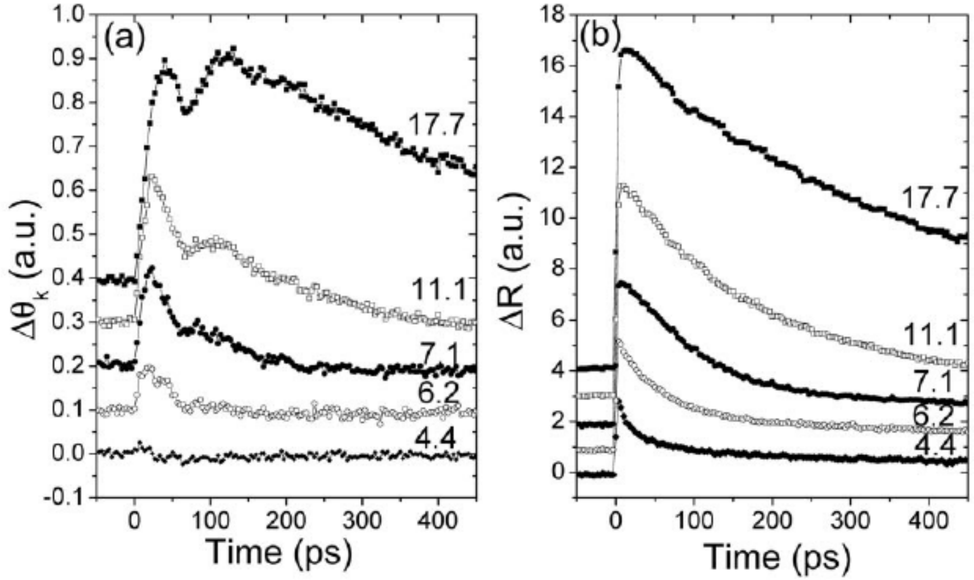
Laser effects 3: phase transitions

FeRh





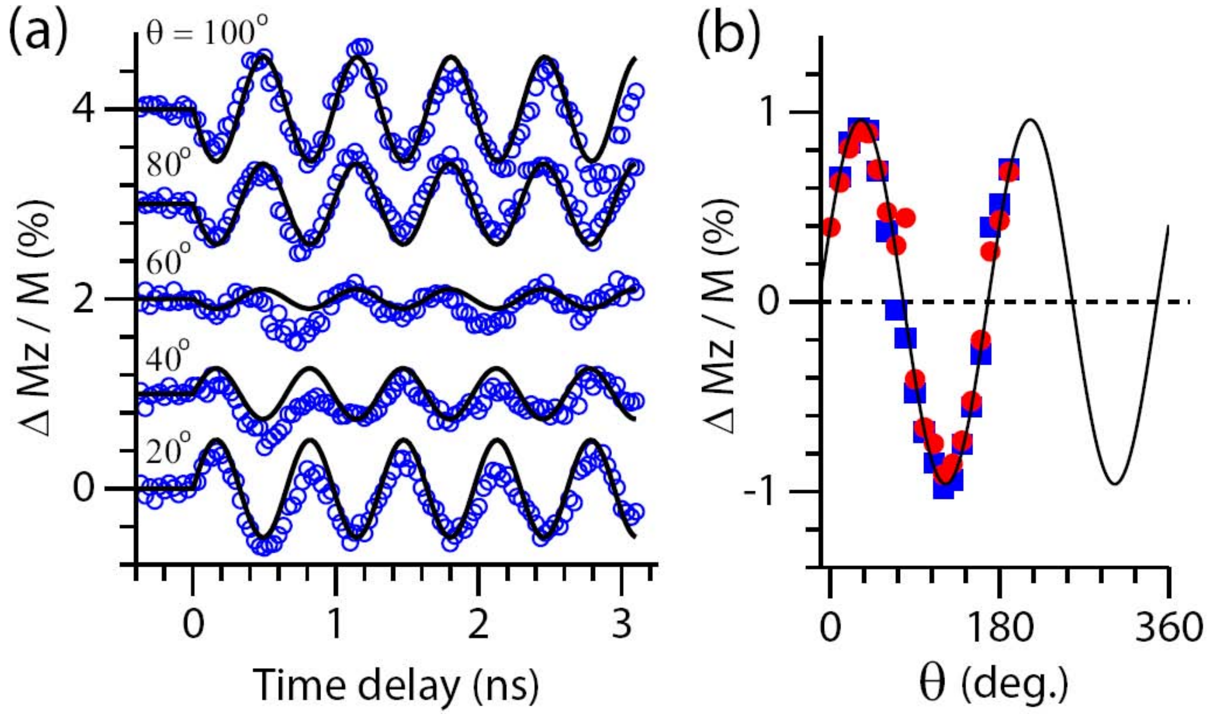
Ju et al, PRL **93**, 197403 (2004)
Thiele et al, APL **85**, 2857 (2004)

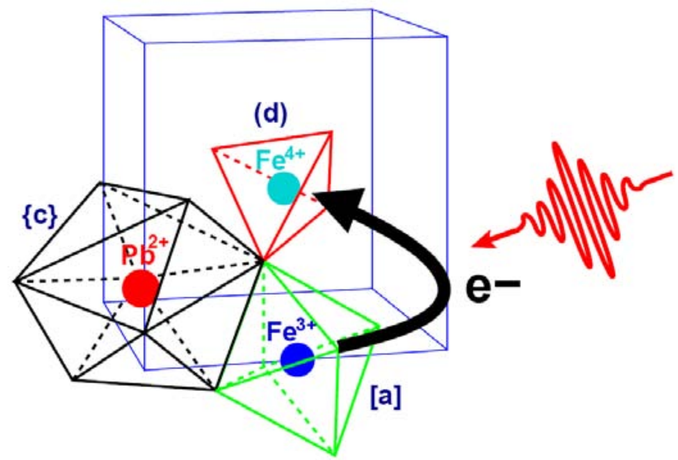
Effects of the laser pulse: classification

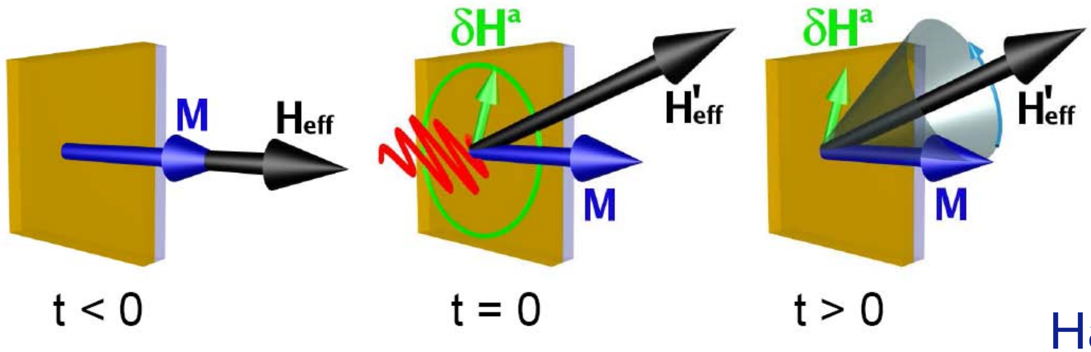
I. **Thermal effects:**
change of M is a result of change of T

II. **Nonthermal photo-magnetic effects:**
based on photon absorption

Photo-magnetic effects in magnetic garnets







Hansteen *et al.*, PRL **95**, 047402 (2005);
Phys. Rev. B **73**, 014421 (2006).

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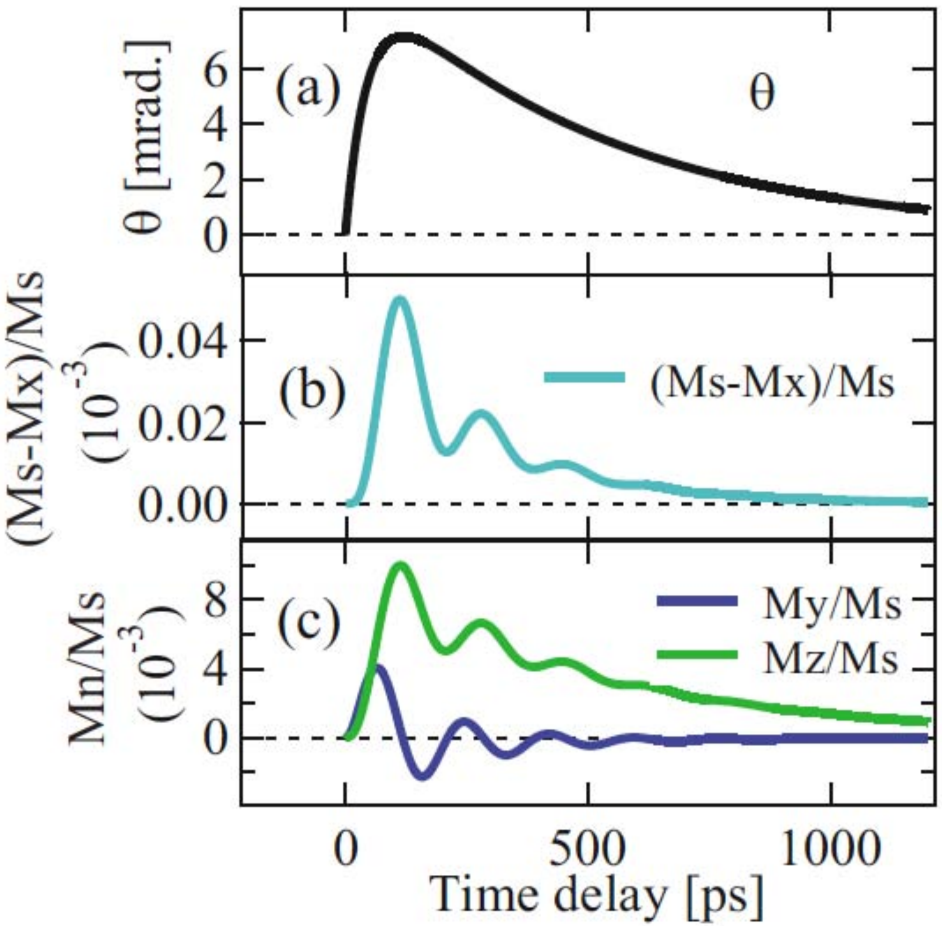
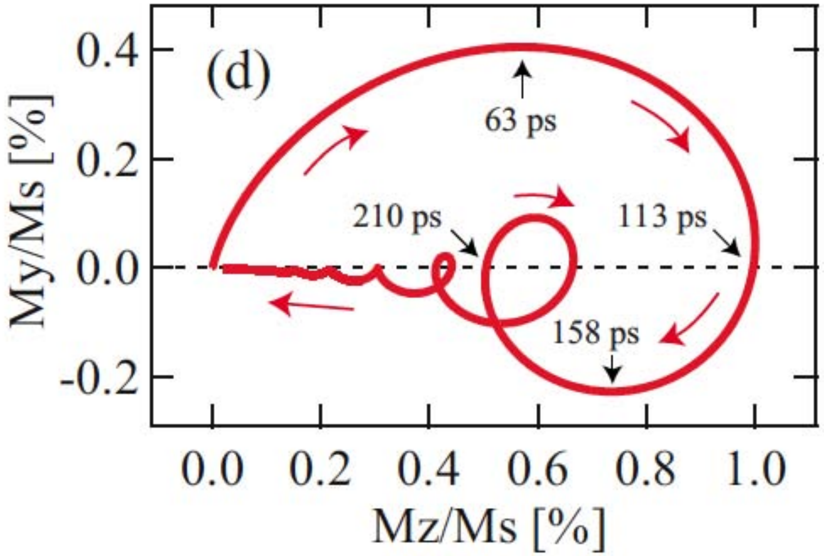
Photomagnetic excitation of precession in GaMnAs





photoinduced anisotropy due to a change in the number of holes near the Fermi level

Hashimoto et al, Phys. Rev. Lett. **100**, 067202 (2008)

Effects of the laser pulse: classification

I. **Thermal effects:**
change of M is a result of change of T

II. **Nonthermal photo-magnetic effects:**
based on photon absorption

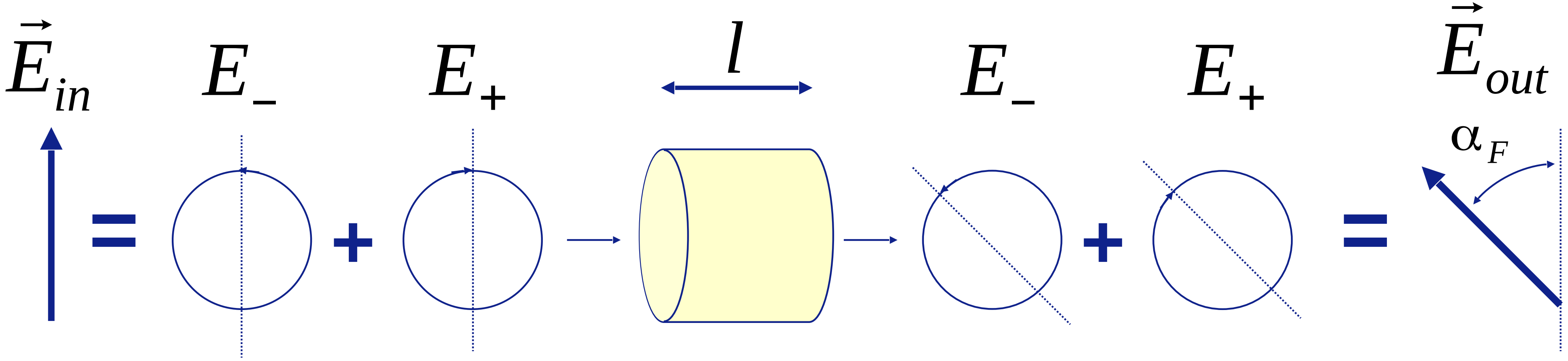
III. **Nonthermal opto-magnetic effects:**
do not require absorption

Faraday effect – reminder

Two circularly polarized waves with different refractive indices:

$$E_x = \pm i E_y$$

$$n_\pm \cong \sqrt{\varepsilon_0} \pm \frac{1}{2}\frac{\varepsilon_{xy}}{\varepsilon_0}$$



$$\boxed{\text{Faraday rotation: } \alpha_F = \frac{2\pi l}{\lambda}\frac{\varepsilon_{xy}}{\varepsilon_0}}$$

M. Faraday, *On the magnetization of light and the illumination of magnetic lines of force*, Phil. Trans. R. Soc. Lond. **136**, 104 (1846).

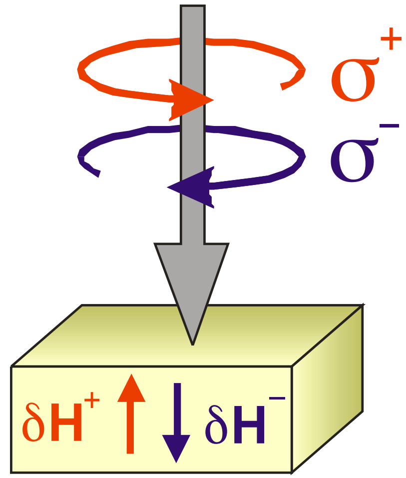
Inverse Faraday effect

$$\Phi = \varepsilon\varepsilon_0 E(\omega) E^*(\omega)$$

$$H(0) = -\frac{1}{\mu_0}\frac{\partial\Phi}{\partial M(0)} = -\frac{\varepsilon_0}{\mu_0} E(\omega) E^*(\omega) \frac{\partial\varepsilon}{\partial M}$$

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & -i\alpha M & 0 \\ +i\alpha M & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} + O(M^2) \end{pmatrix}$$

$$\boxed{\vec{H}(0) = \frac{\varepsilon_0}{\mu_0}\alpha\left[\vec{E}(\omega) \times \vec{E}^*(\omega)\right]}$$



Inverse Faraday effect

Pitaevskii, *Sov. Phys. JETP* **12**, 1008 (1961).
van der Ziel *Phys. Rev. Lett.* **15**, 190 (1965).

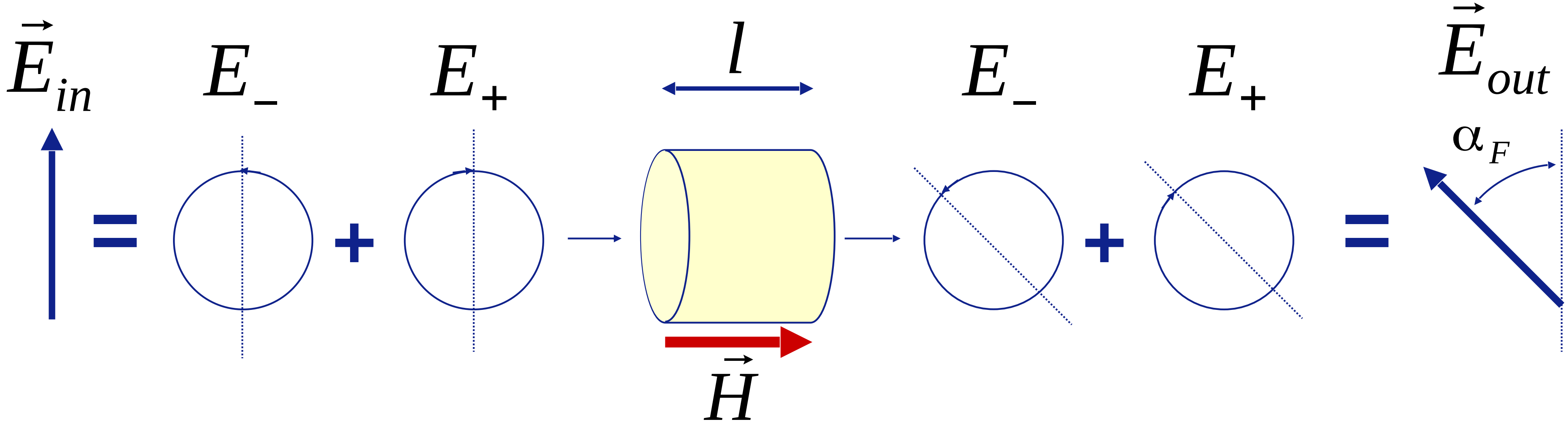
Inverse Faraday effect

Faraday rotation: $\theta_F = \frac{2\pi l}{\lambda}\frac{\alpha M}{\varepsilon_0}$

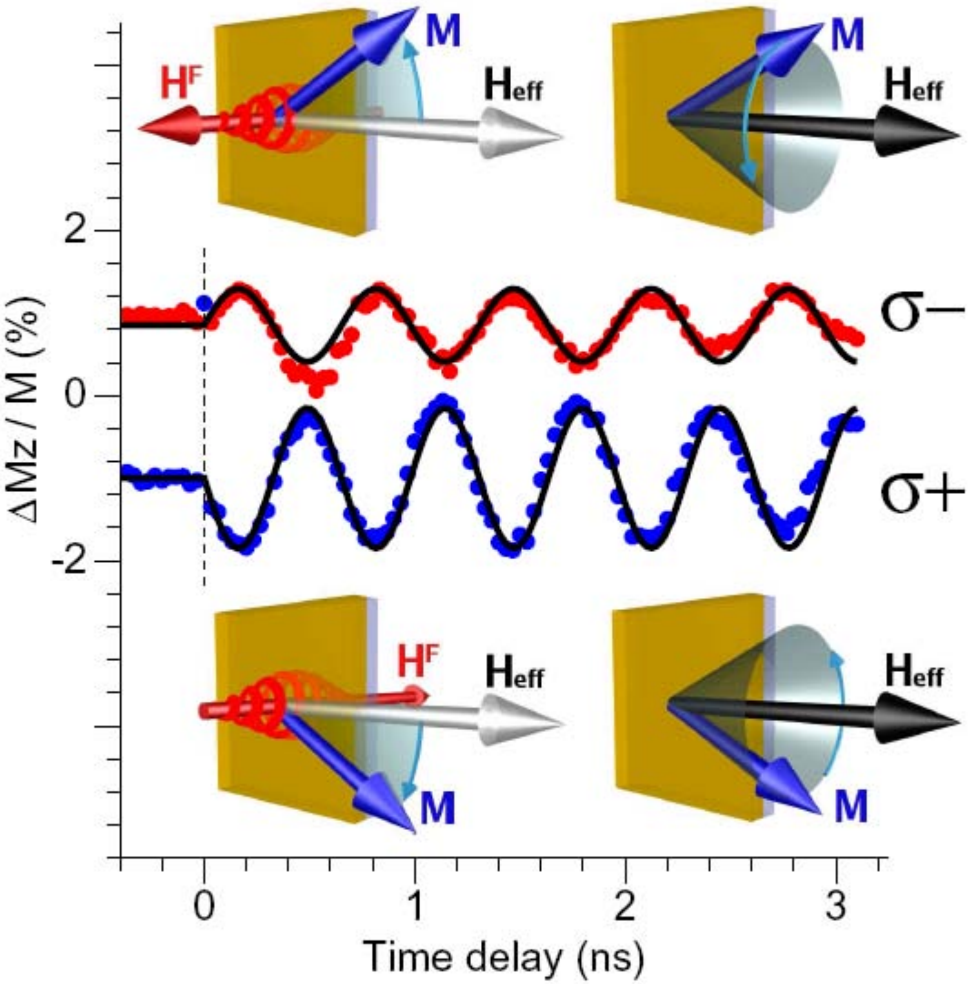
$$\vec{H}(0) = \frac{\varepsilon_0}{\mu_0}\alpha\left[\vec{E}(\omega)\times\vec{E}^*(\omega)\right]$$

⇨ **no absorption required!**

⇨ **no angular momentum transfer**



Effect for opposite pulse helicities



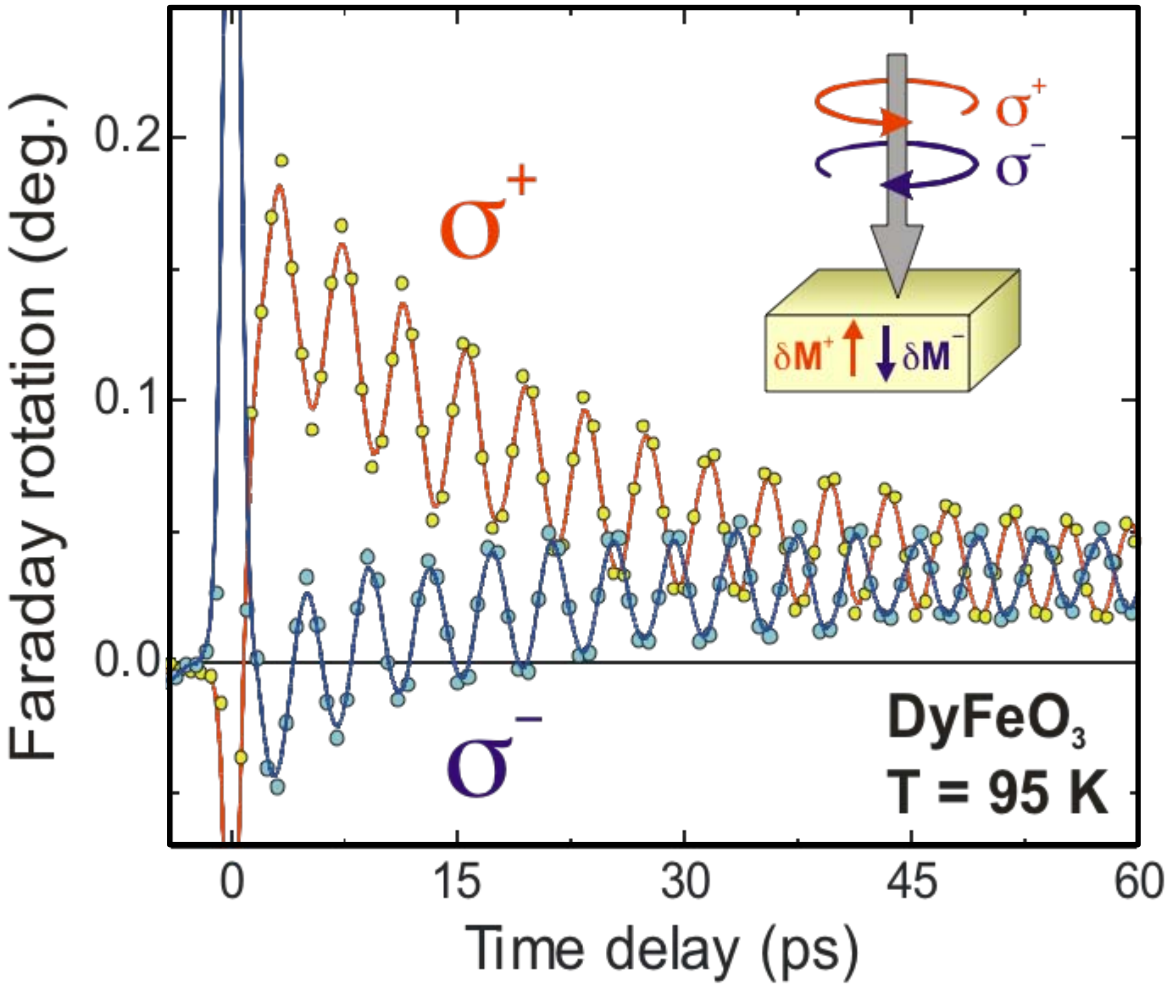
equivalent to a 100 fs magnetic field pulse of some 0.5–1 Tesla!

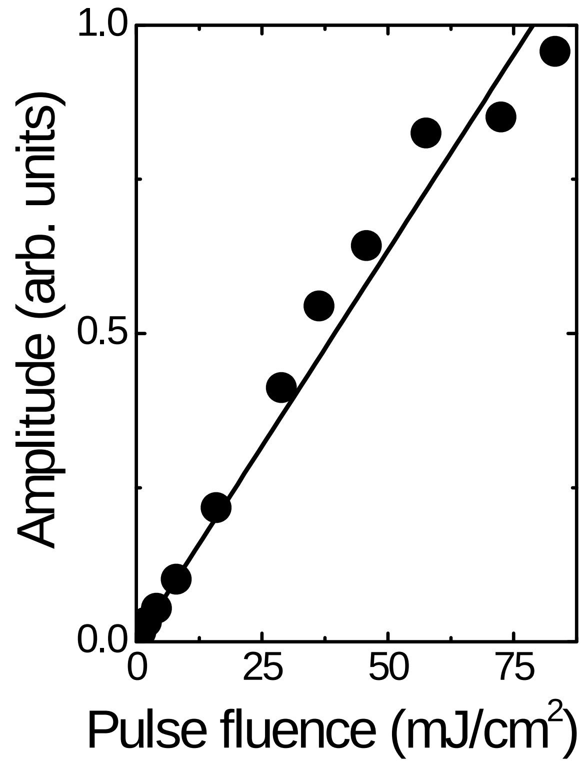
$$\vec{H}(0) = \frac{\varepsilon_0}{\mu_0}\alpha\left[\vec{E}(\omega)\times\vec{E}^*(\omega)\right]$$

$$\boxed{H_{IFE} \sim 0.1 - 100 \text{ Tesla}}$$

Hansteen *et al*., PRL **95**, 047402 (2005); Phys. Rev. B **73**, 014421 (2006).

Works everywhere! (almost)





$$\vec{H}(0) = \frac{\varepsilon_0}{\mu_0}\alpha\left[\vec{E}(\omega)\times\vec{E}^*(\omega)\right]$$

Kimel *et al*., Nature **435**, 655 (2005)

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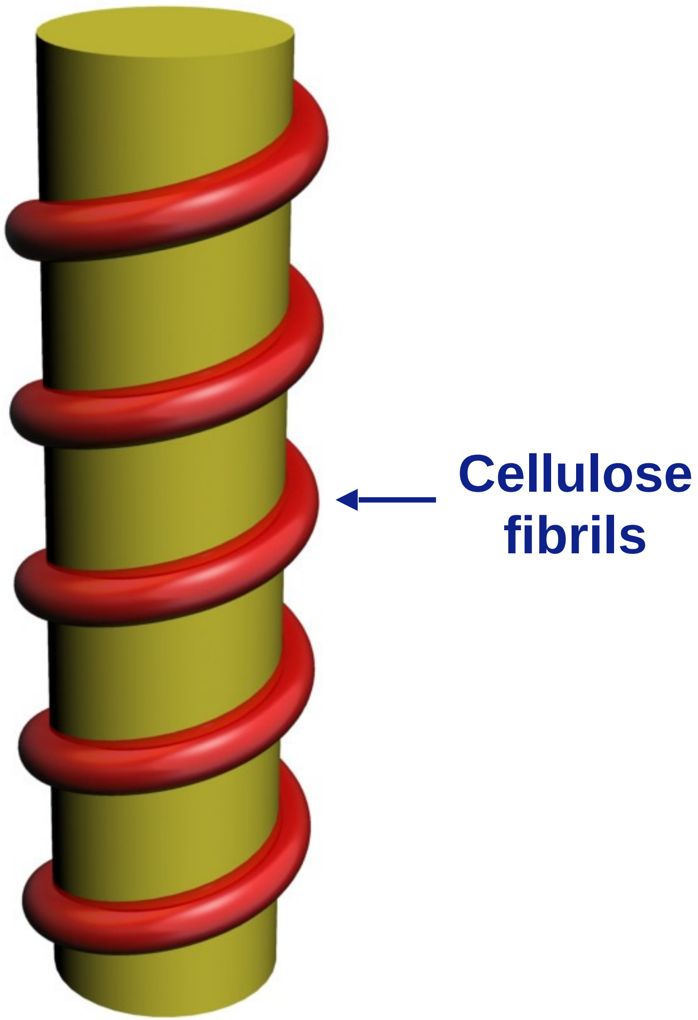
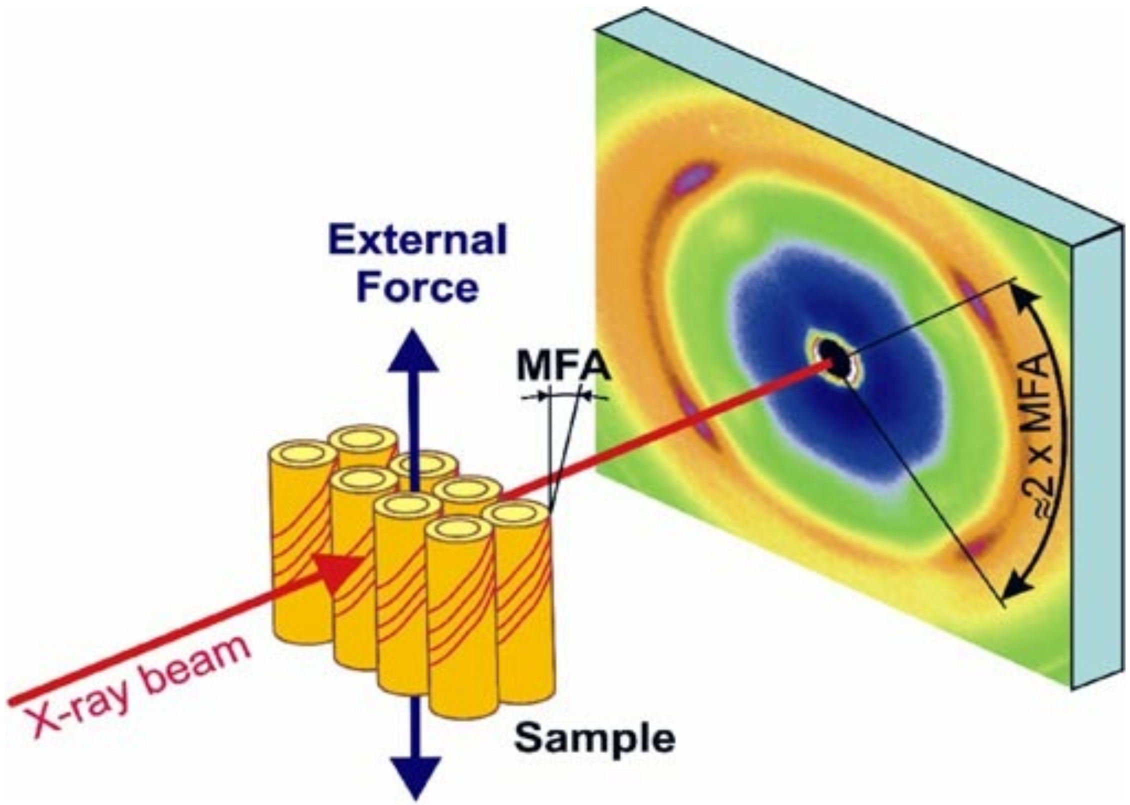
The tilt angle of the cellulose fibrils versus cell axis predetermines the mechanical behavior and strength of the tissue



Wood cell



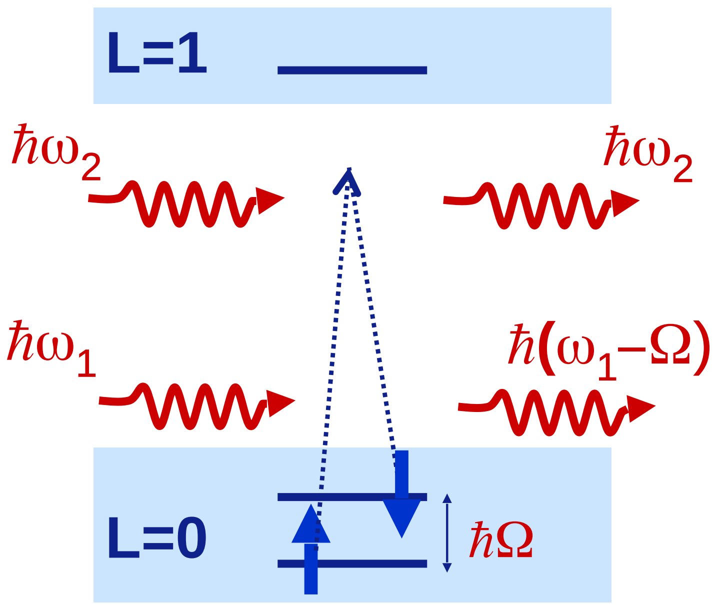
In situ wide-angle X-ray scattering (WAXS) on individual wood cells

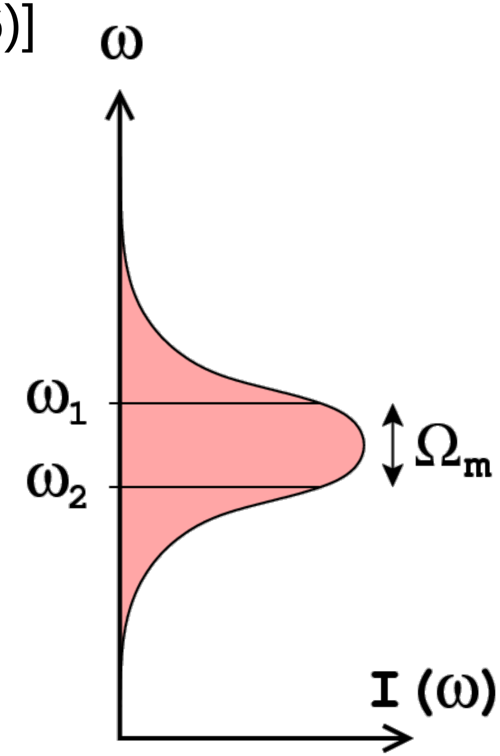
J. Keckes et al., Nature Materials **2**, 811 (2003).

Microscopic mechanism of the inverse Faraday effect

- Stimulated Raman scattering on magnons (2-photon process)

[Shen et al, Phys. Rev. (1966)]



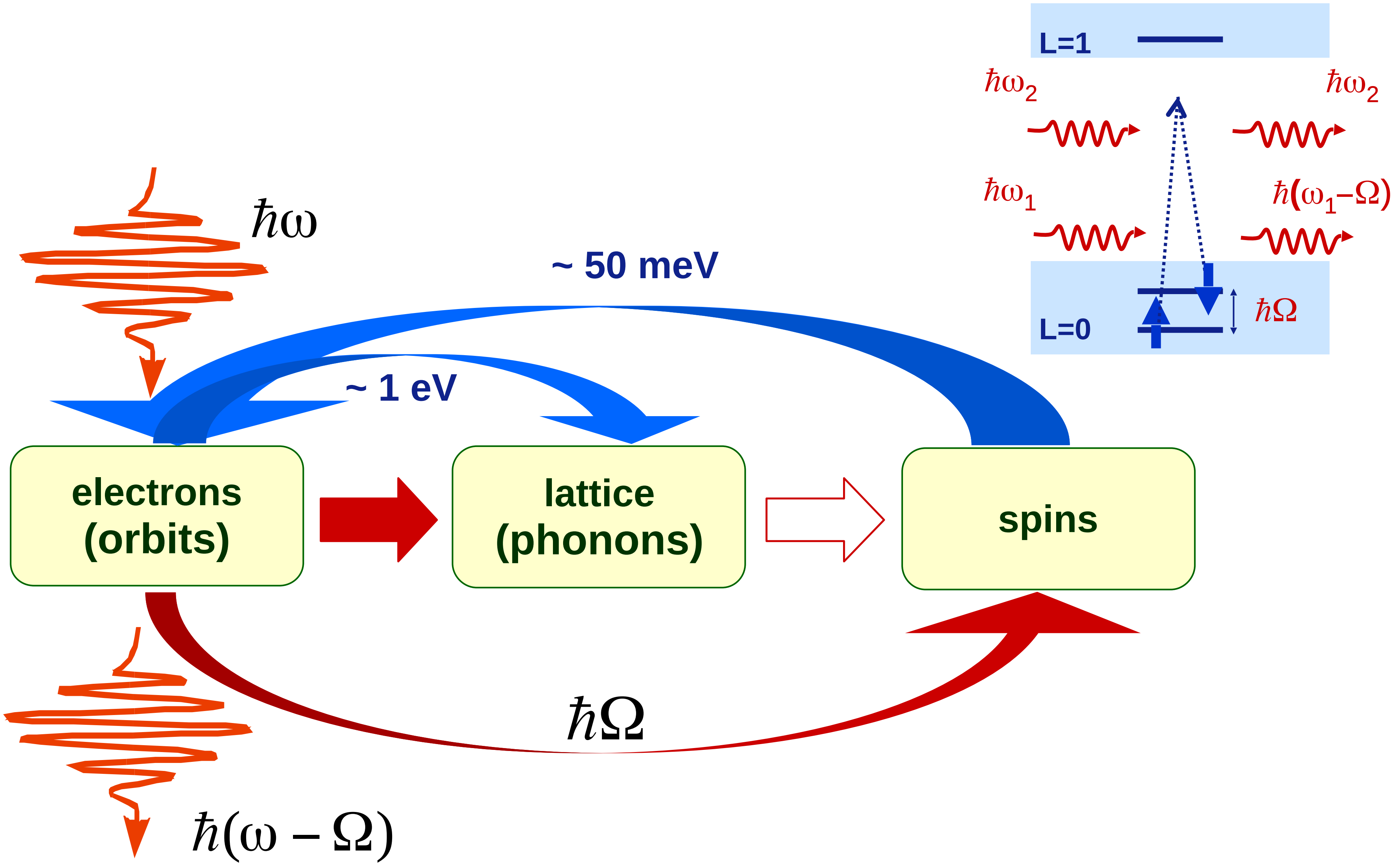


Number of photons is conserved

Process can be fast
$\tau \sim 1 / \omega \sim 1$ fs

light helicity (= angular momentum) is also conserved!

Energy- and angular momentum transfer II



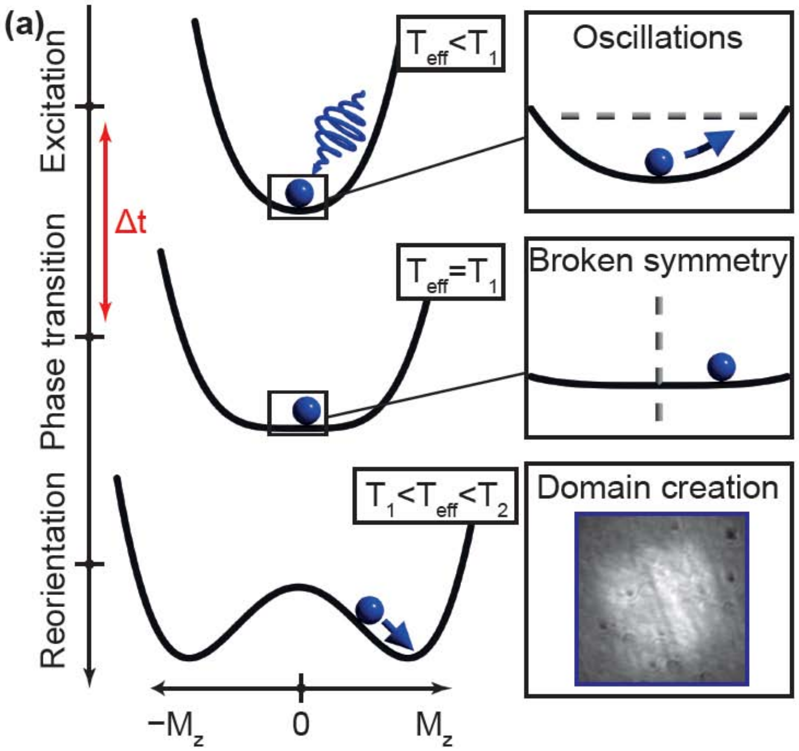
Effects of the laser pulse: summary

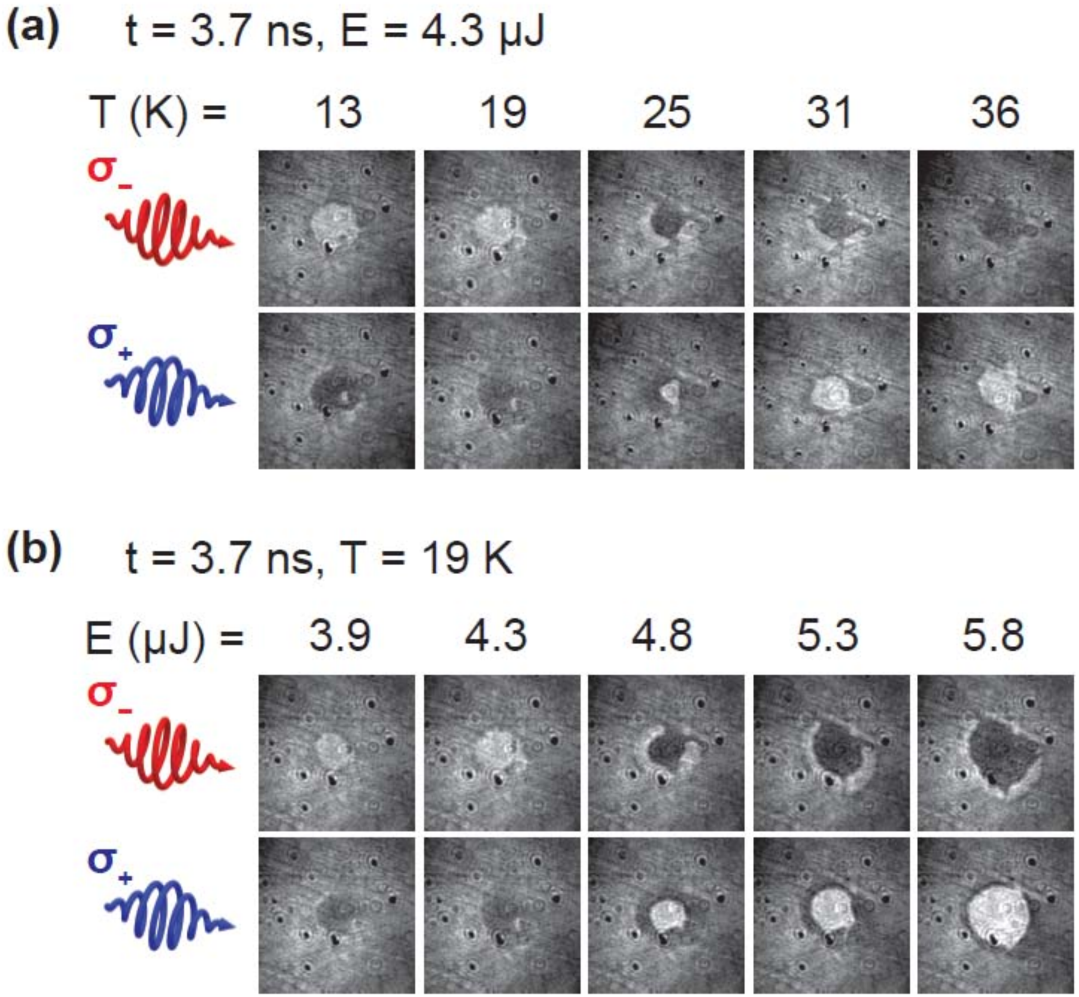
I. **Thermal effects:**
change of M is a result of change of T

II. **Nonthermal photo-magnetic effects:**
based on photon absorption

III. **Nonthermal opto-magnetic effects:**
do not require absorption

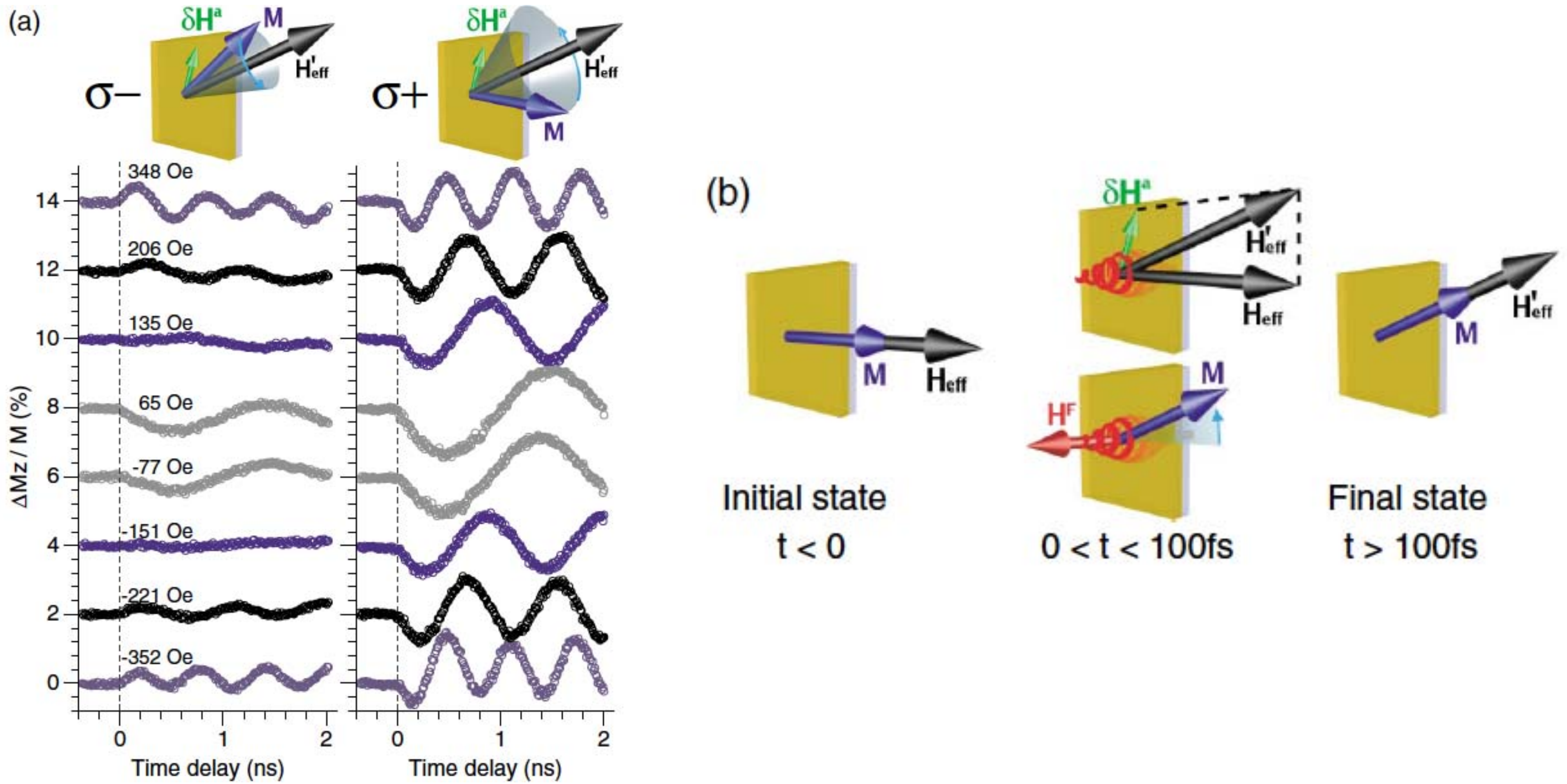
I + III = Controlling the route of the phase transition





de Jong et *al*, *Phys. Rev. Lett*, **108**, 157601 (2012). + Viewpoint in *Physics*.

II + III = sub-picosecond switching

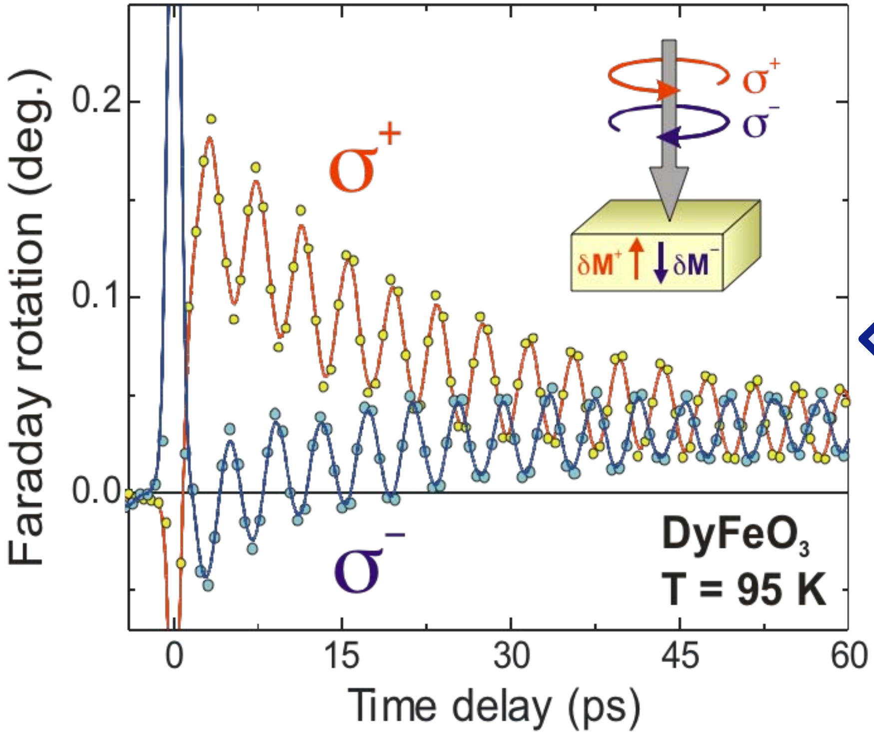


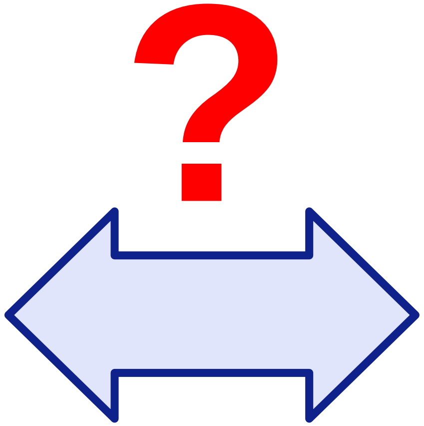
Hansteen *et al*., PRL **95**, 047402 (2005).

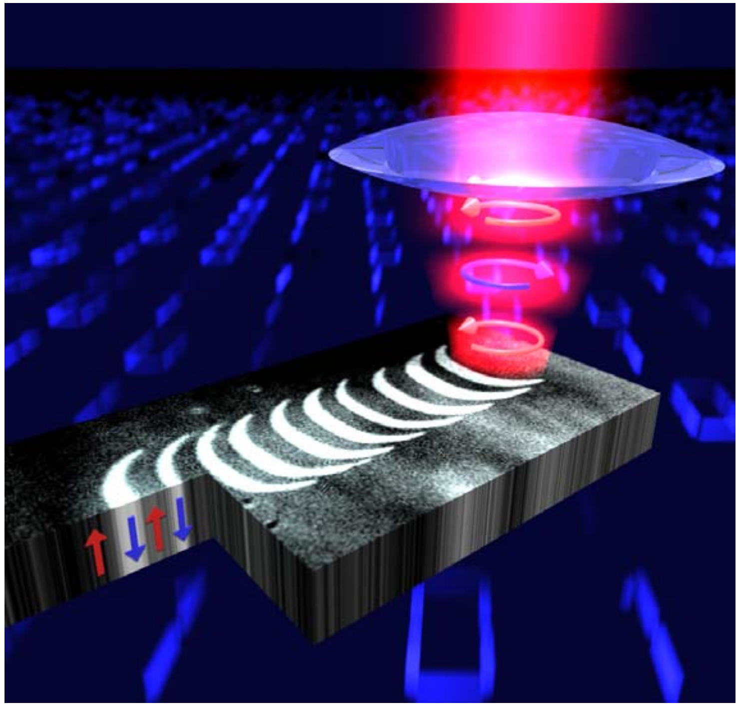
Part 1: classification of laser-induced effects

Part 2: the story of one experiment

Story of one experiment



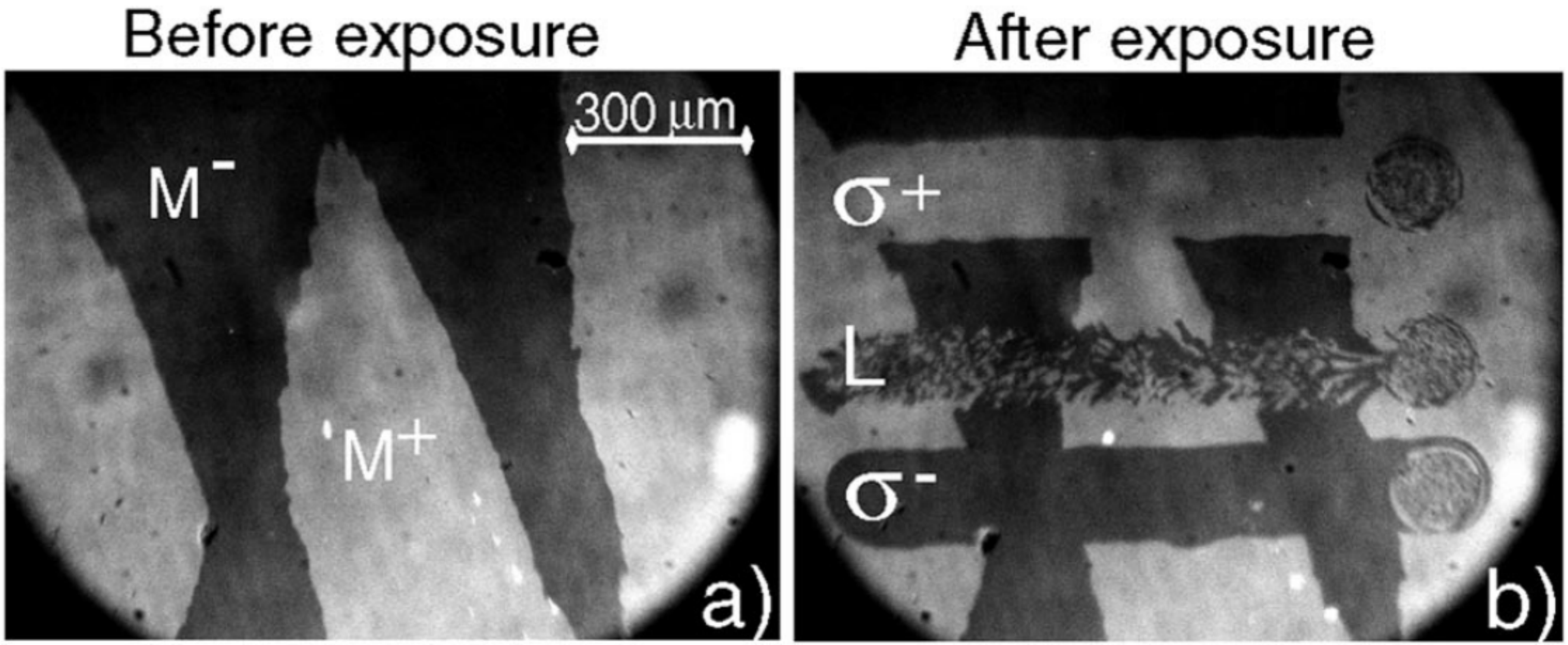




Kimel *et al*, Nature **435**, 655 (2005)

Stanciu *et al*, PRL **99**, 047601 (2007)

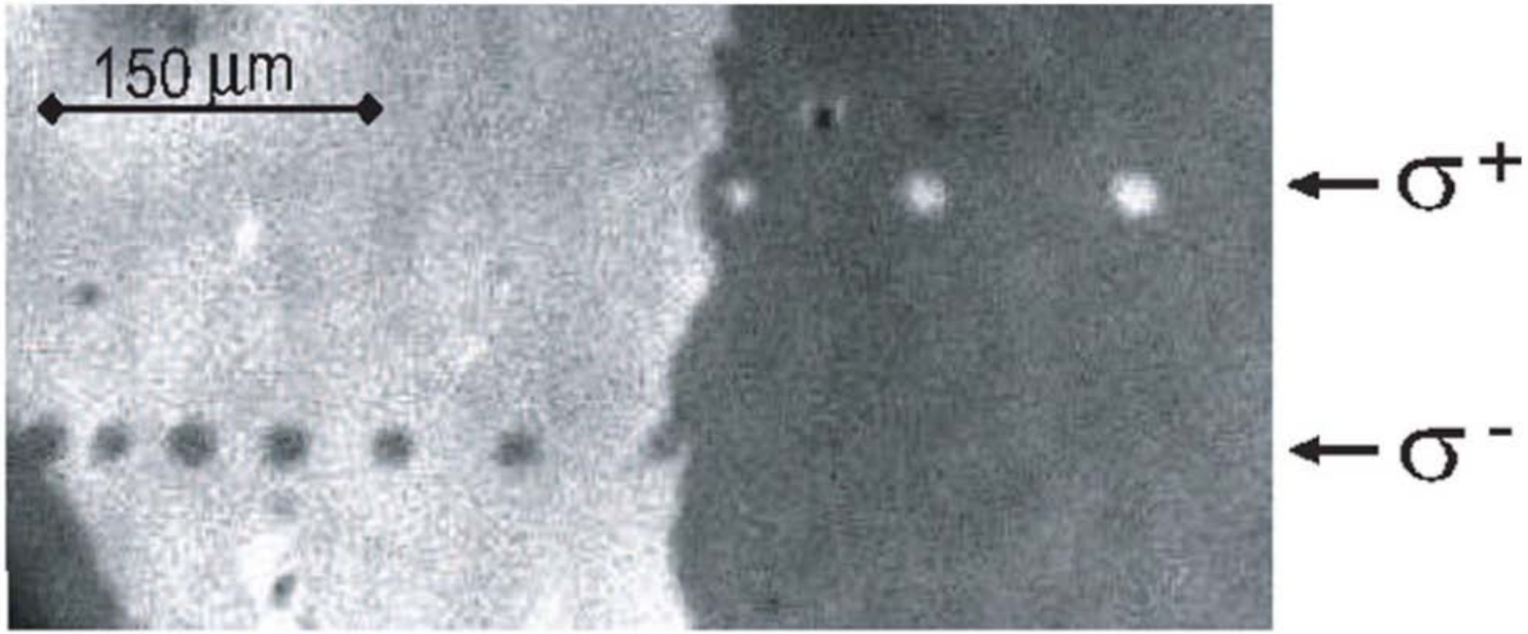
Starting point: scanning across the sample (GdFeCo)



Stanciu et al, Phys. Rev. Lett. **99**, 047601 (2007);

see also:
Mangin et al, Nature Materials **13**, 286 (2014);
Lambert et al, Science **345**, 1337 (2015)

Cumulative or single shot??

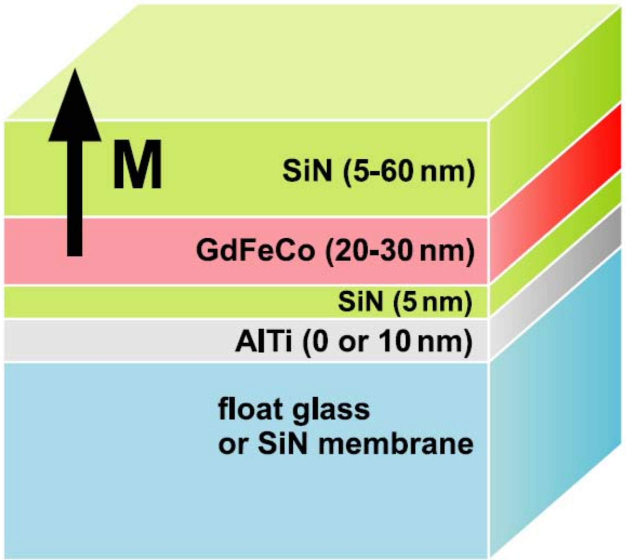


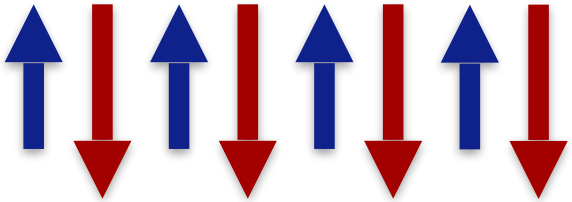
Stanciu et al, Phys. Rev. Lett. **99**, 047601 (2007)

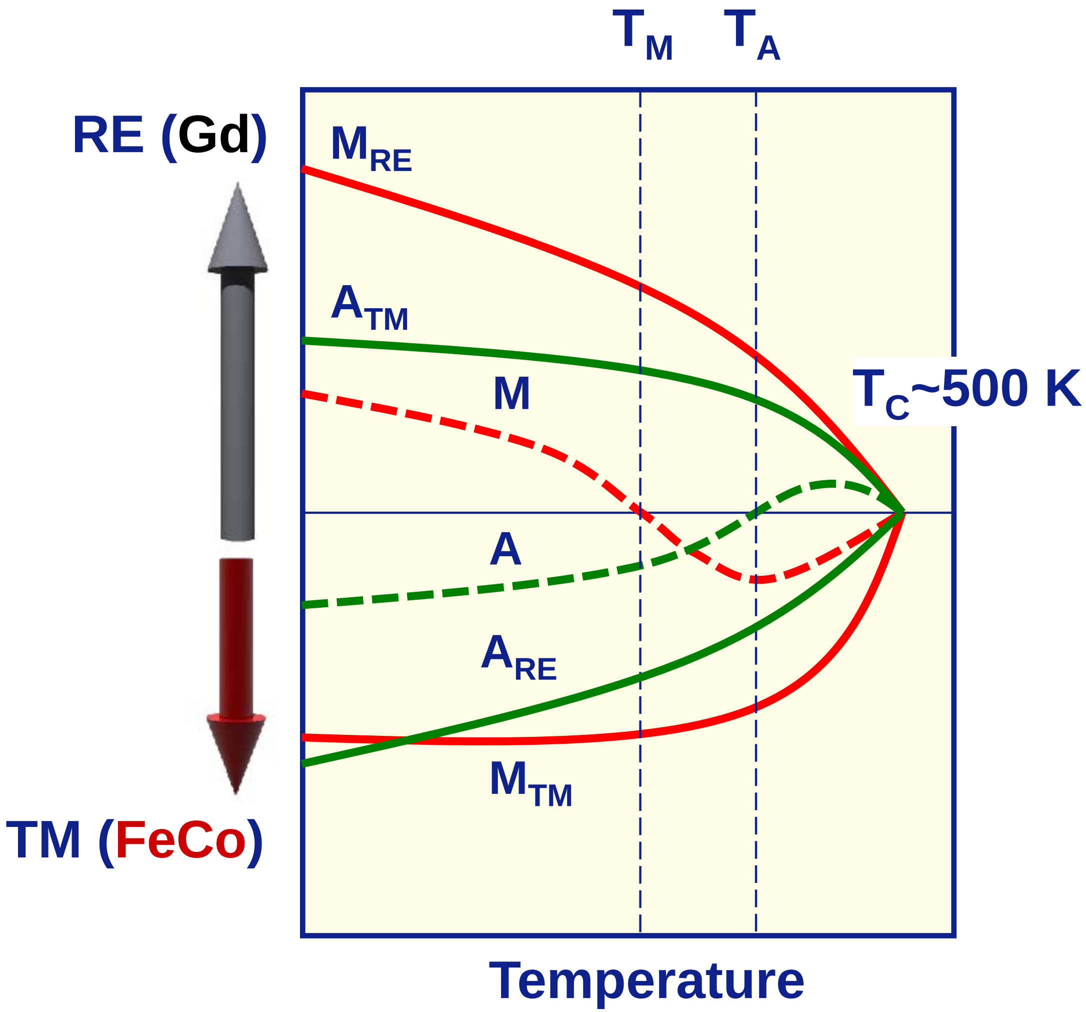
Questions:

- intensity dependence?
- time scale of the reversal?? fs, ps, ns, ms???
- what happens spatially?
- the role of the sublattices??

Samples 1: ferrimagnetic alloys GdFeCo and similar







$$g_{Gd} < g_{FeCo}$$

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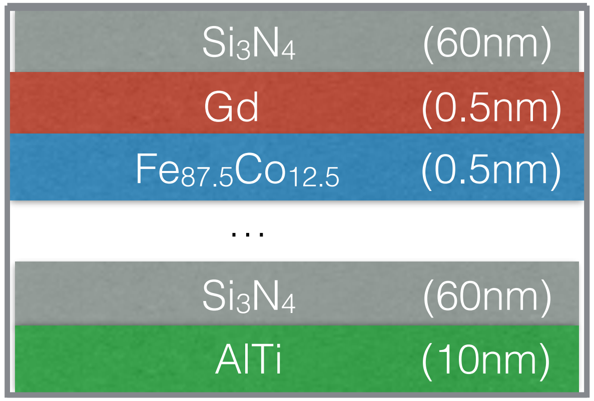
Samples 2: Gd/FeCo multilayers

For example:

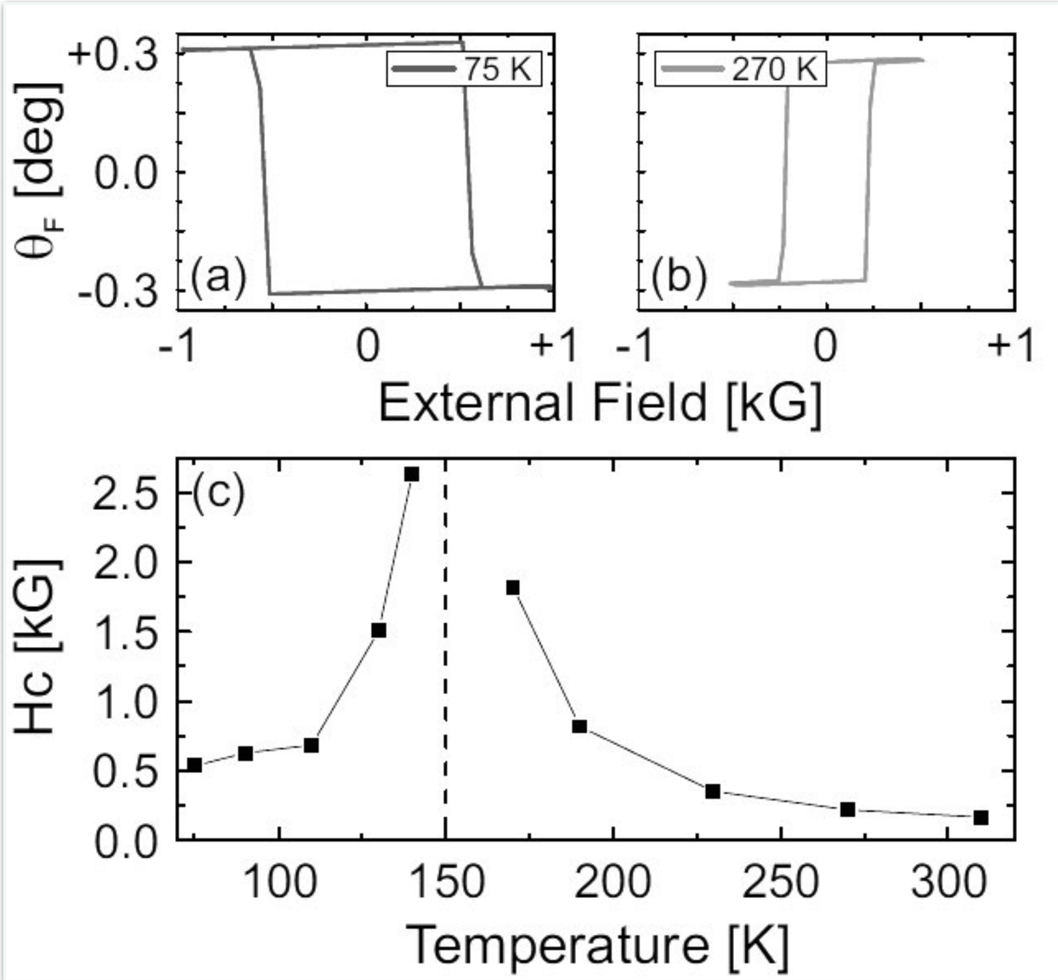


x20

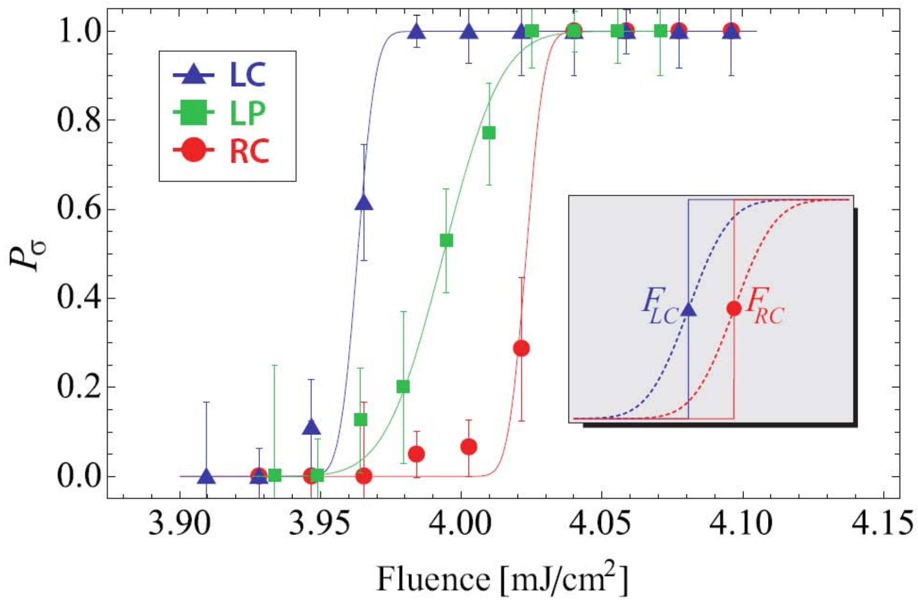
Features of the sample:

✓ not an amorphous alloy
✓ 39 magnetic interfaces
✓ out-of-plane magnetic anisotropy
✓ existence of a magnetization compensation temperature T_M around 150K

Static magneto-optical characterisation

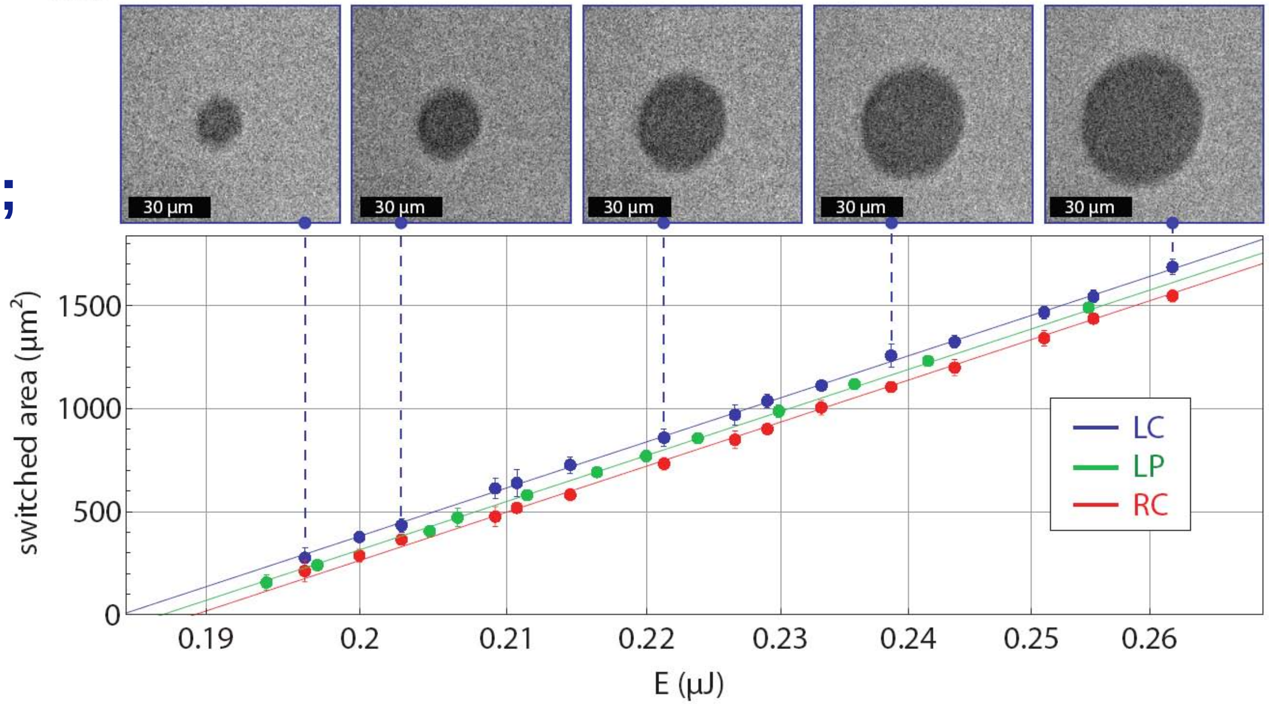


Intensity threshold for helicity-dependent switching



Khorsand et al,
Phys. Rev. Lett. **108**, 127205 (2012)

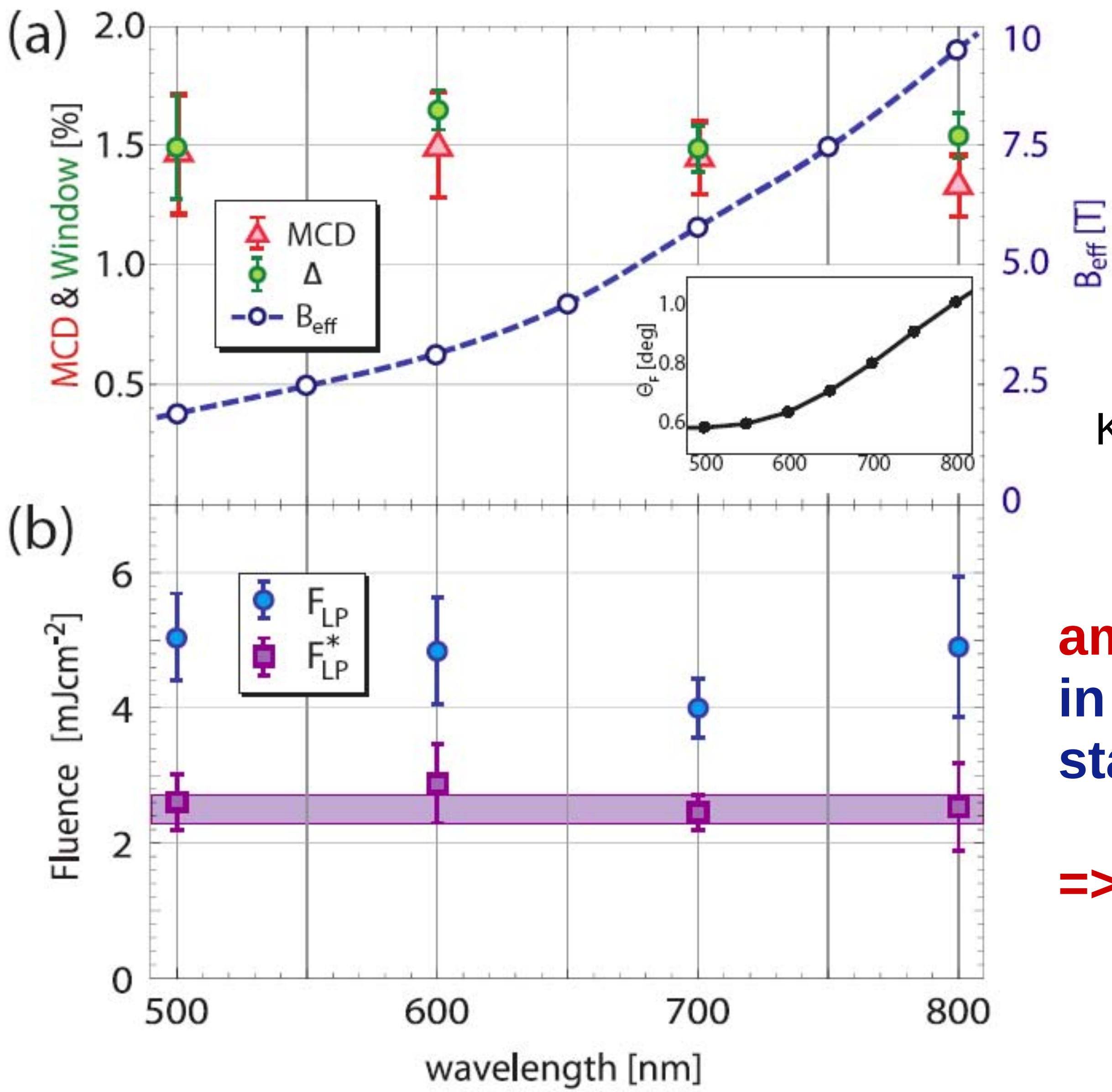
beam-size determination,
see Liu, Optics Letters **7**, 196 (1982)



measured optical constants;

calculated real absorption

MCD vs Faraday effect



effective field from inverse Faraday effect

$$\mathbf{B}_{\mathrm{eff}} = \frac{\varepsilon_0}{\mu_0}\alpha\left[\mathbf{E}(\omega) \times \mathbf{E}^*(\omega)\right]$$

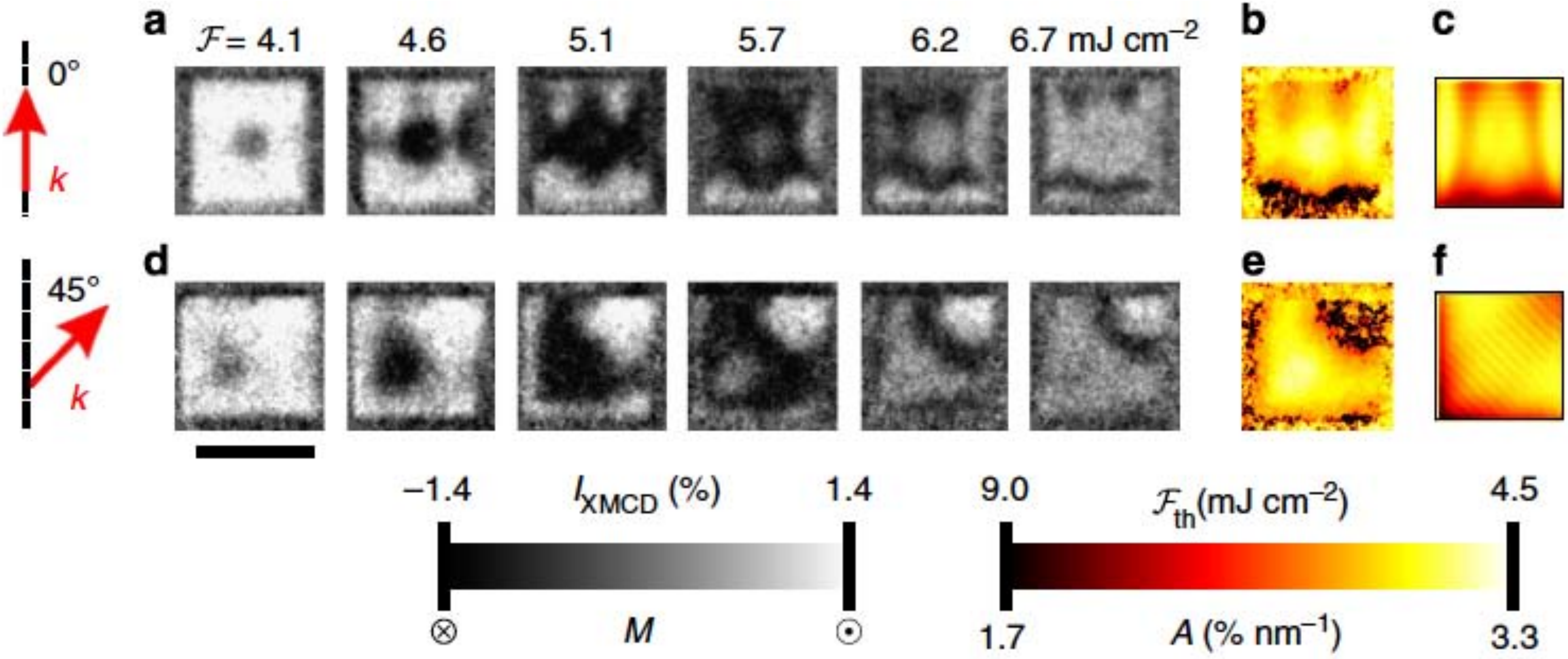
Kimel et al, Nature **435**, 655 (2005)

amount of energy absorbed in the sample per pulse stays constant

=> no inverse Faraday effect!

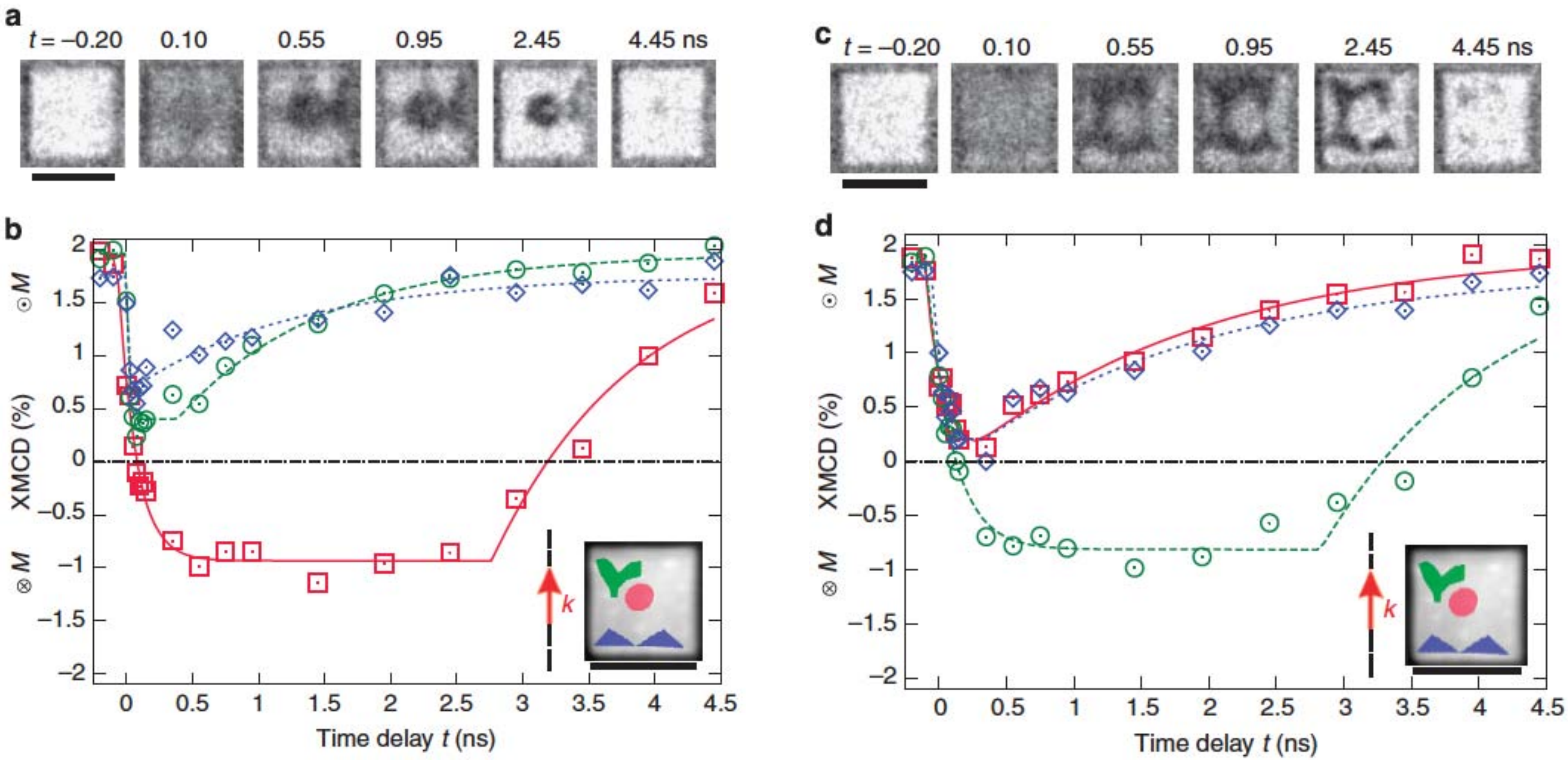
Khorsand et al, PRL **108**, 127205 (2012)

Another proof of the intensity dependence



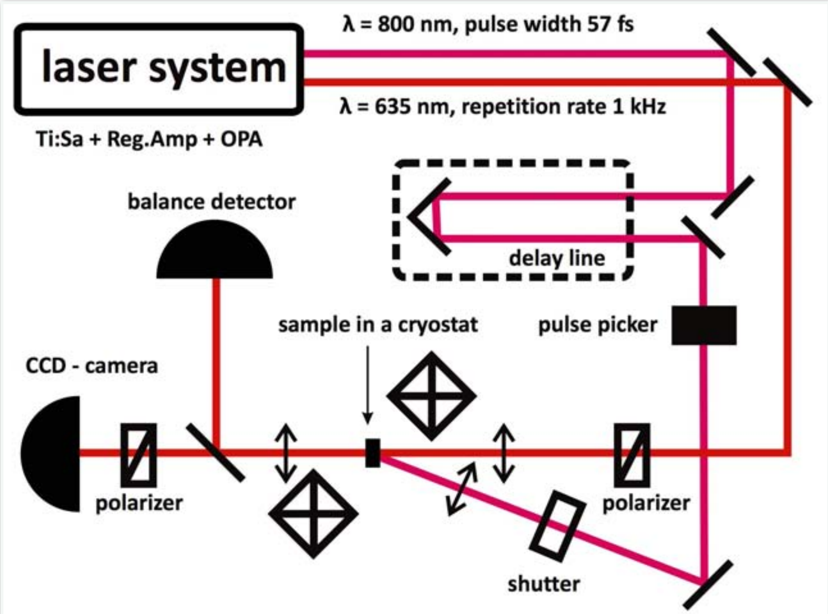
Le Guyader et al., Nature Comm. **6**, 5839 (2015)

Time dependence is also different

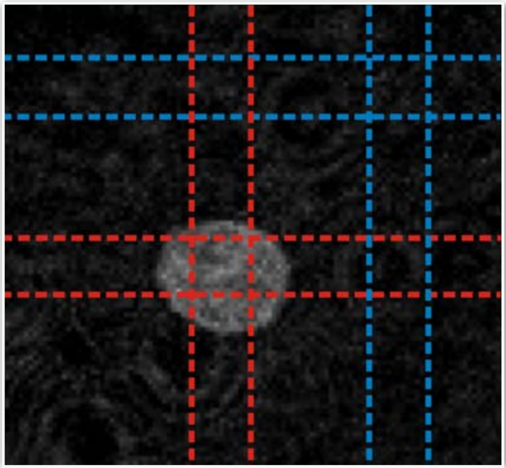


Setup for time resolved study of the switching

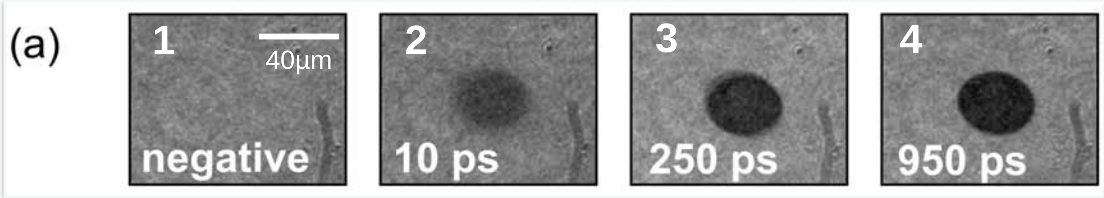
Single shot magnetic imaging



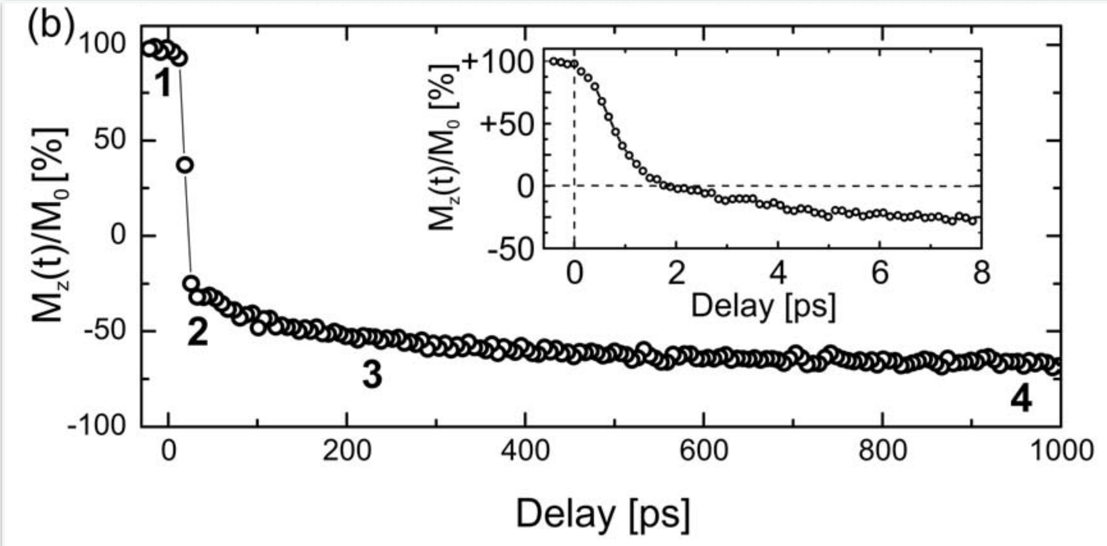
Intensity data:



Typical experimental data



Magnetization dynamics, $T<T_M$, $H_{ext}=0$



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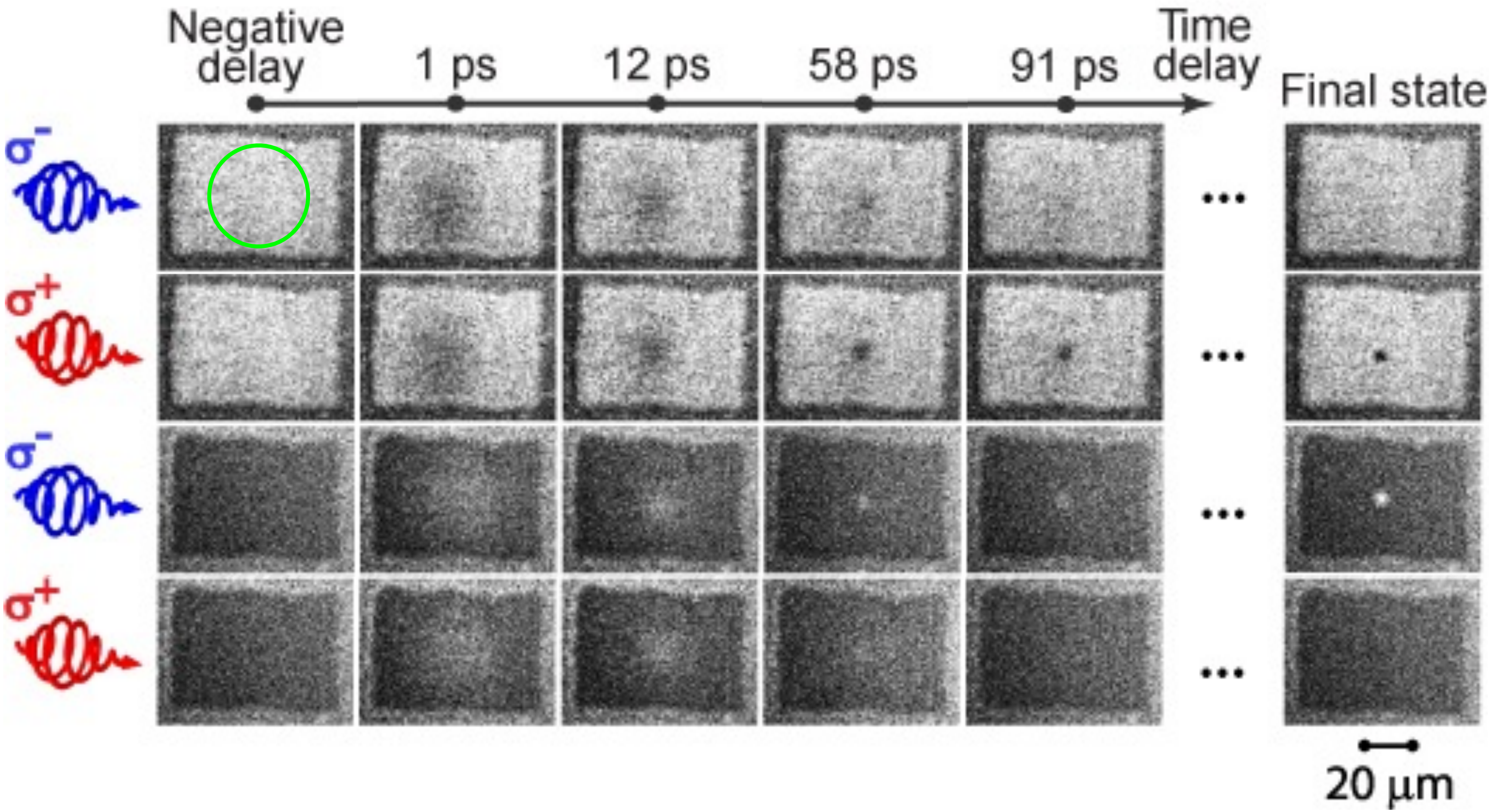
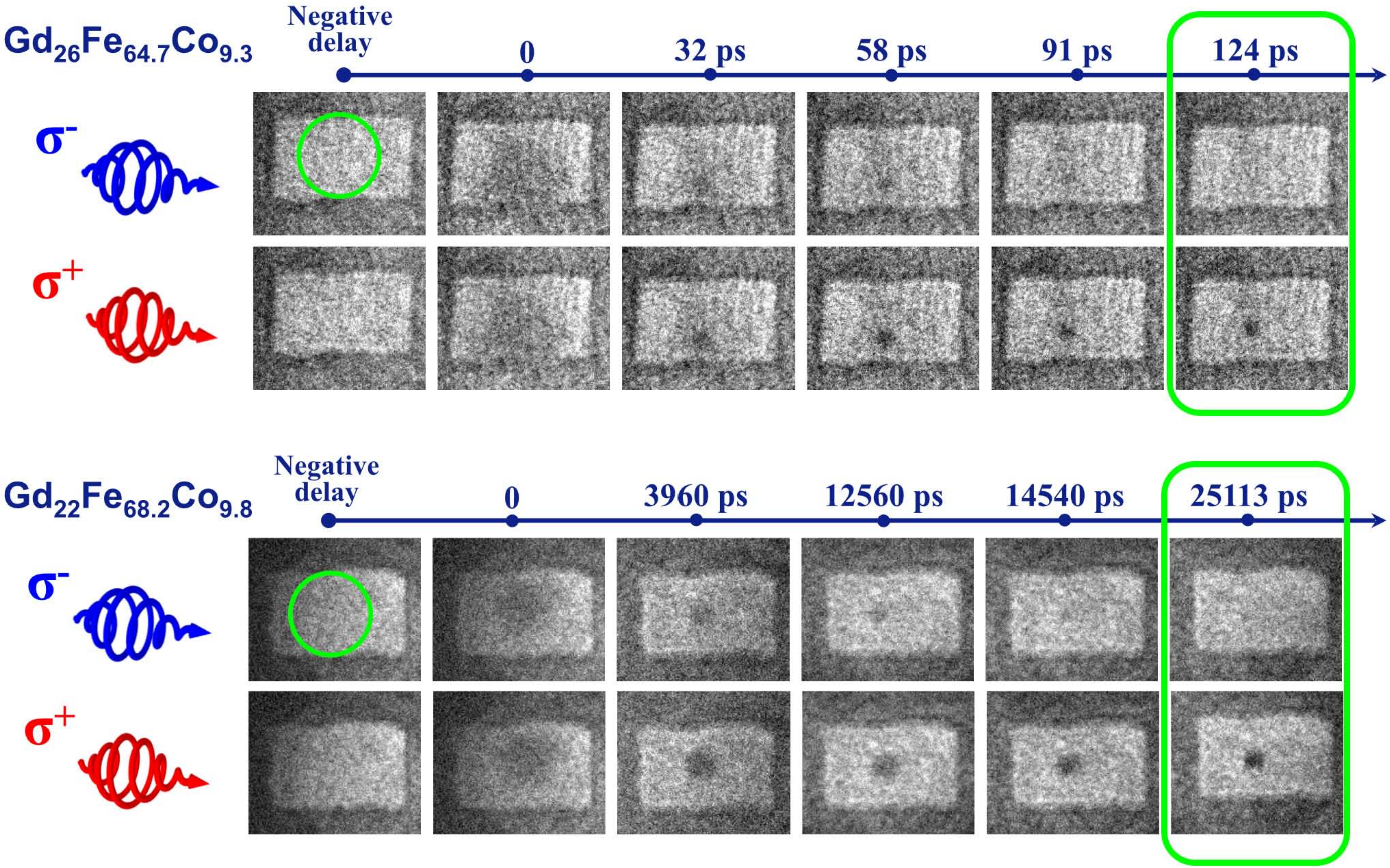
Reversal via a non-equilibrium state

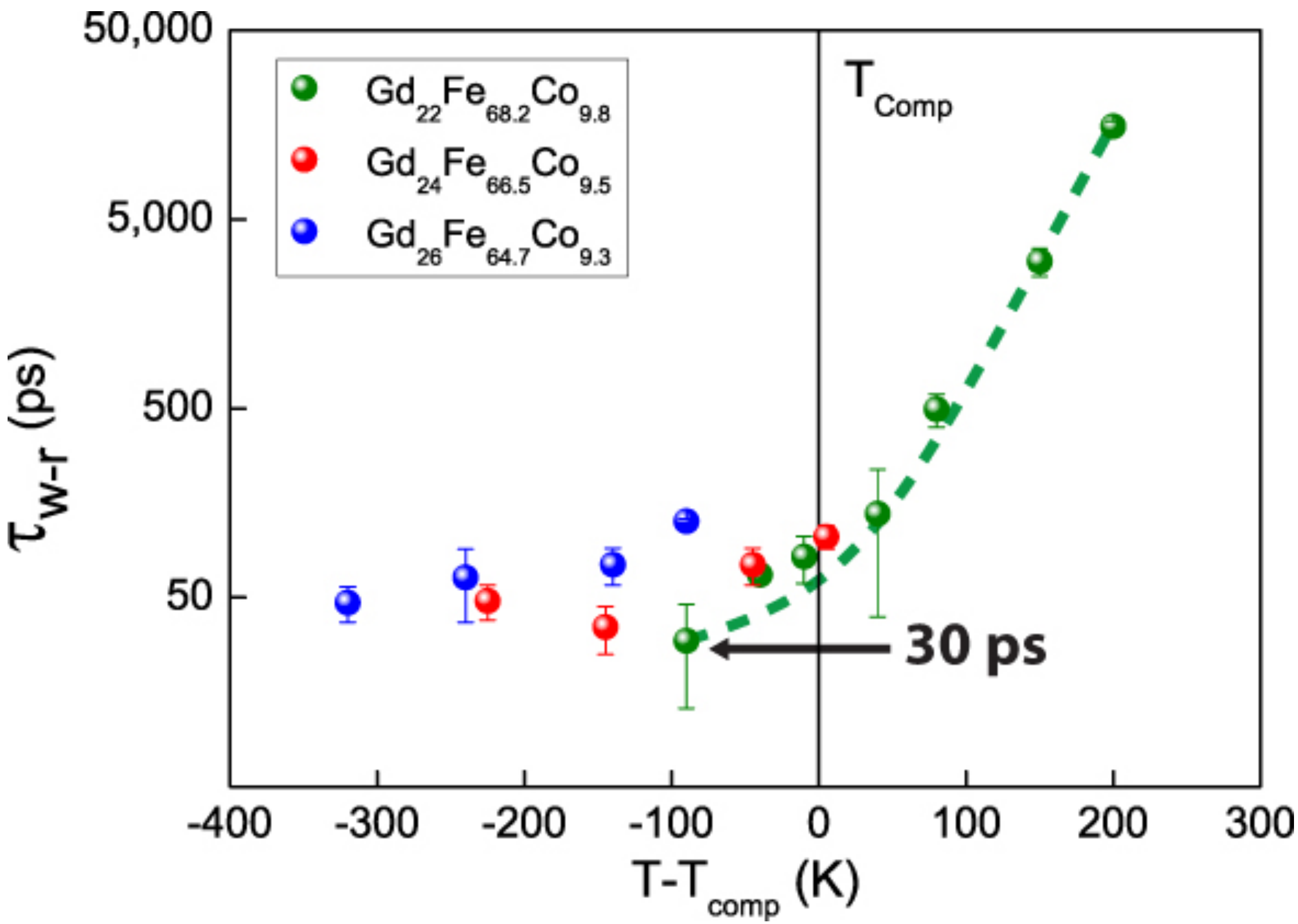


Vahaplar et al., Phys. Rev. Lett. **103**, 117201 (2009)

Time of the reversal



Switching time vs T: the role of compensation



cf: laser pulse 50-100 fs

Vahaplar et al., Phys. Rev. Lett. **103**, 117201 (2009)

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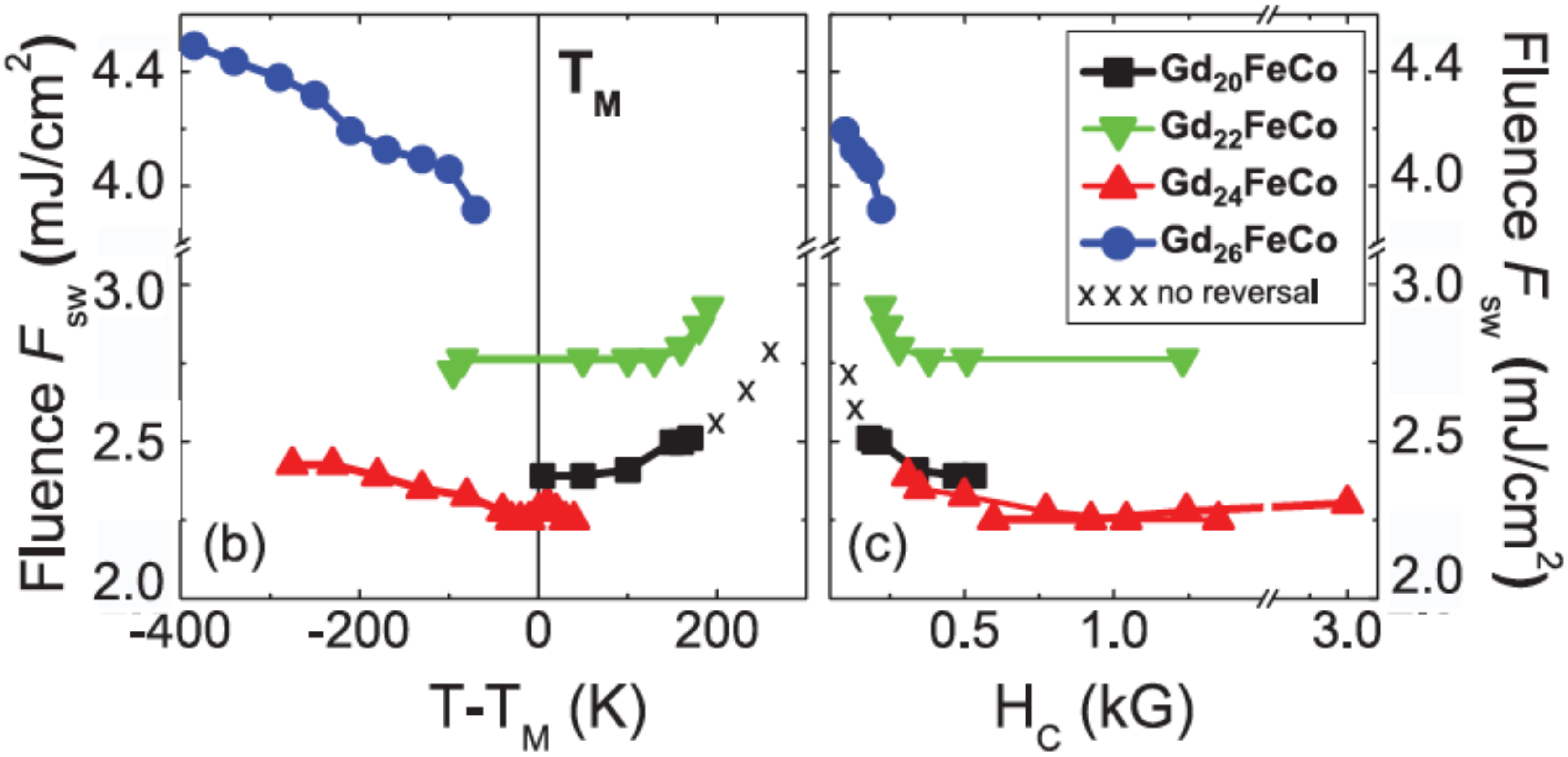
The role of the compensation point - 2



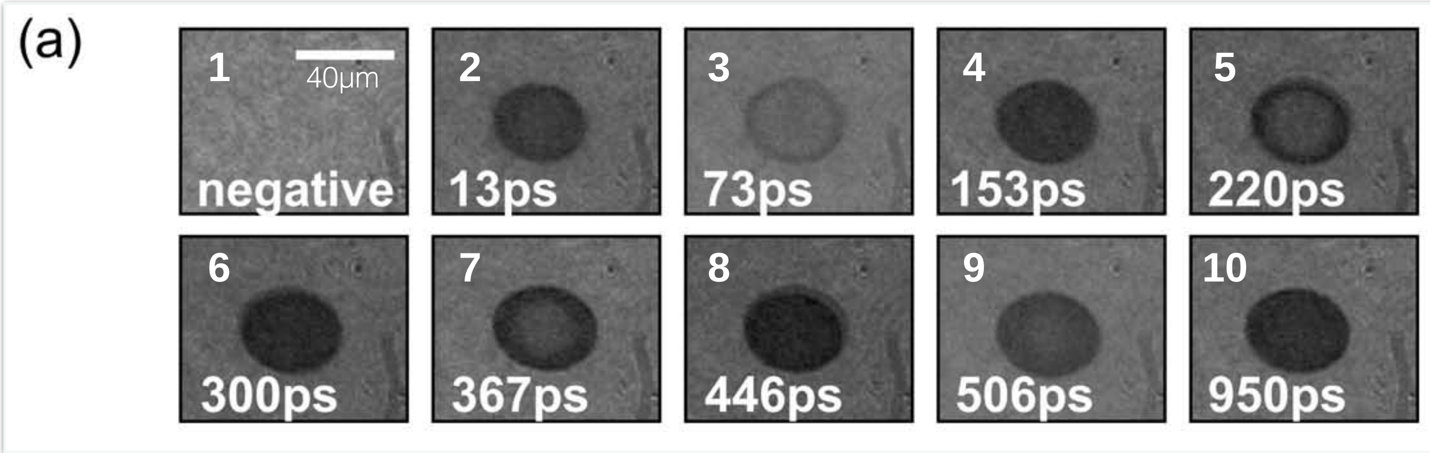
Vahaplar et al, PRB **85**, 104402 (2012)

It works in the broad vicinity of the compensation temperature

see also:
Mangin et al, Nature Materials **13**, 286 (2014)

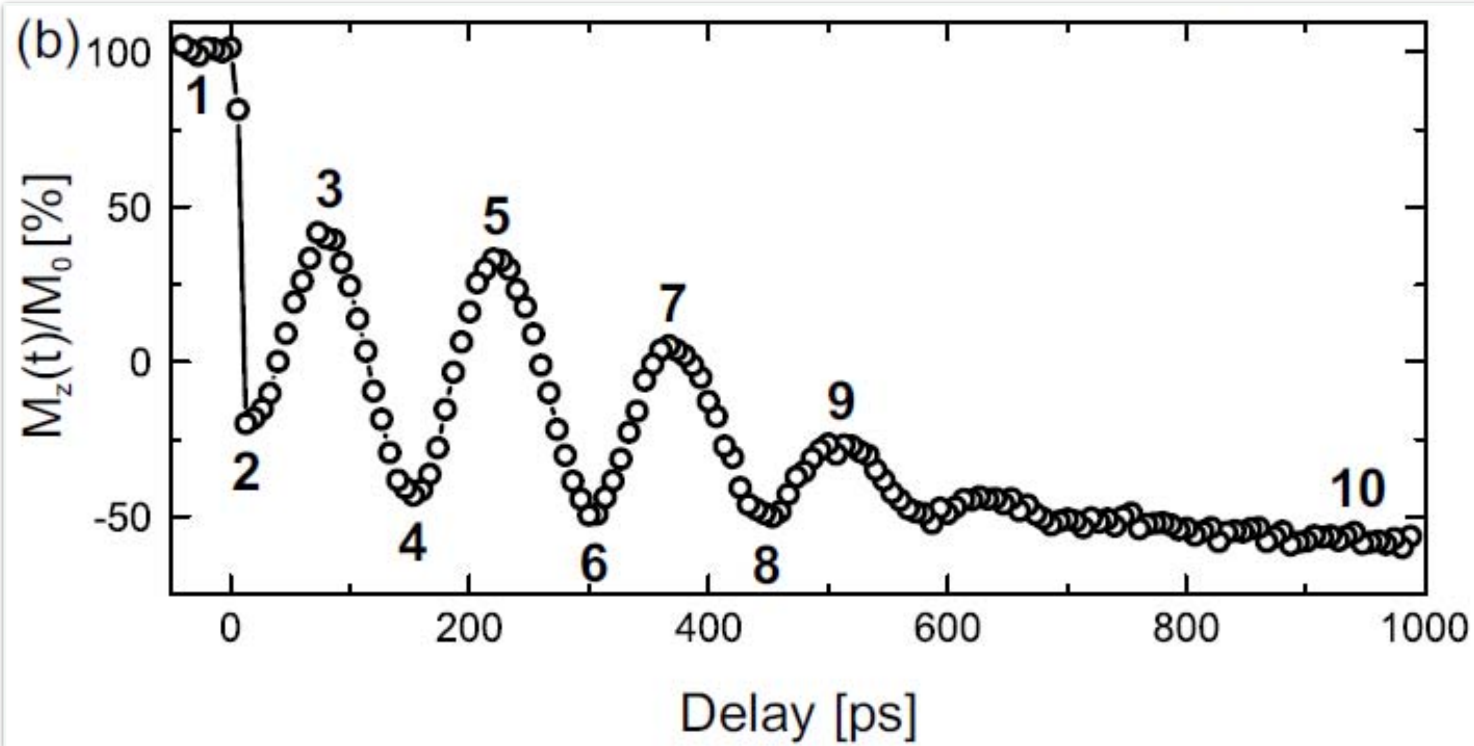
How will the dynamics change in an external field?

Experimental conditions:
$T<T_M$, $H_{ext} = 3kG$
multilayer

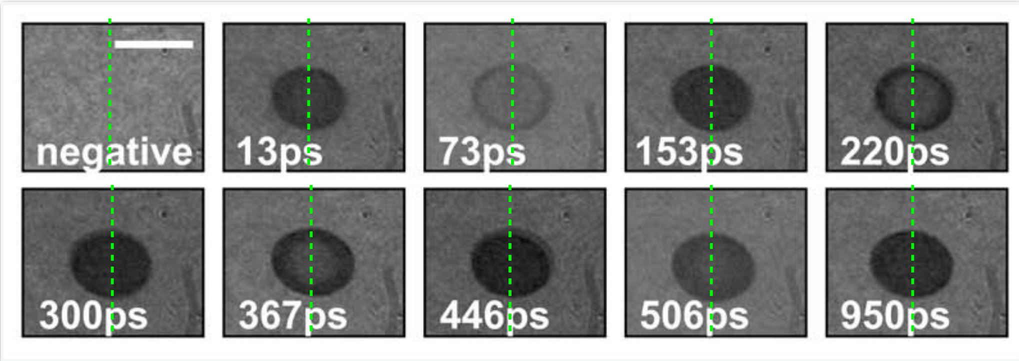


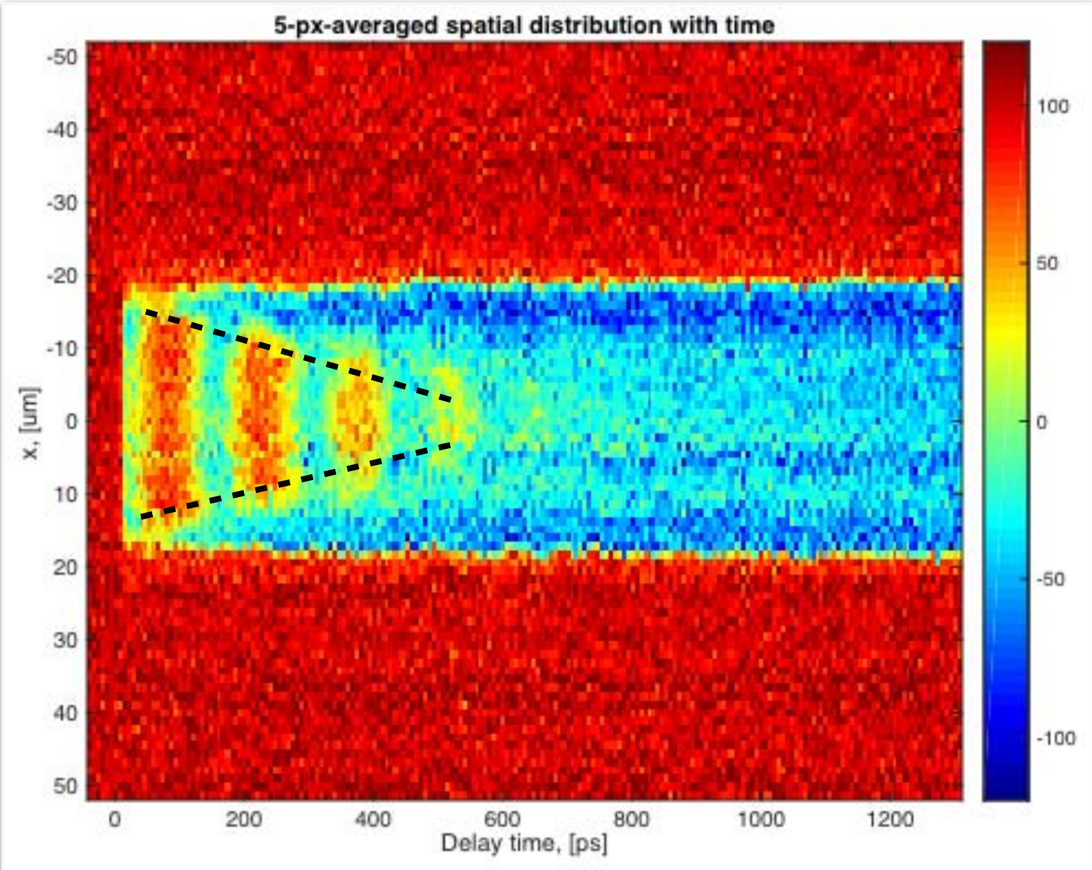
Magnetization dynamics:

reversal
+
precession



Spatially resolved magnetization dynamics





Strongly inhomogeneous magnetization dynamics

✓ precession with high amplitude

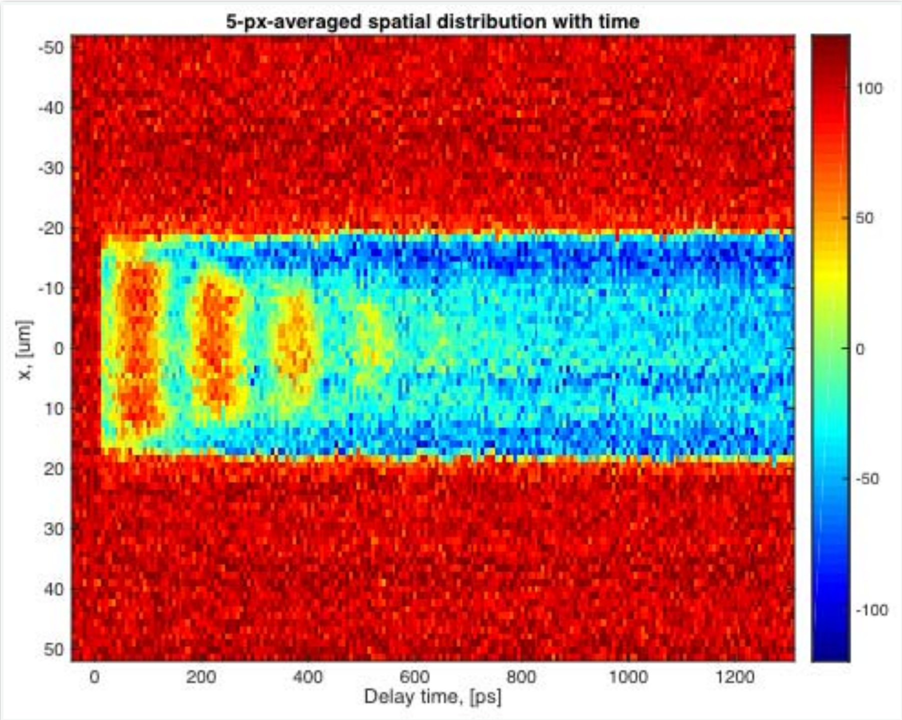
✓ oscillating part shrinks with time

✓ linear velocity of the shrinking is 30km/s

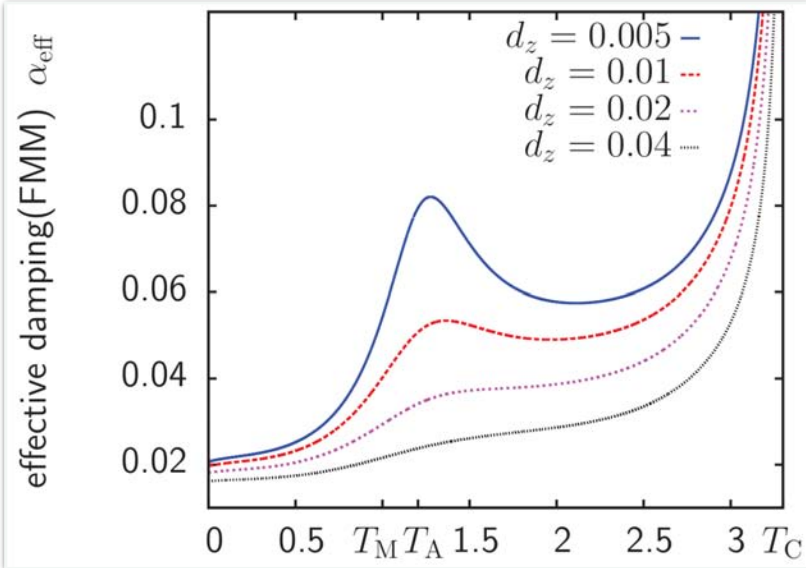
Magnetization is not destroyed!

Yu. Tsema, M. Savoini et al, to be published

Shrinking of the oscillating part



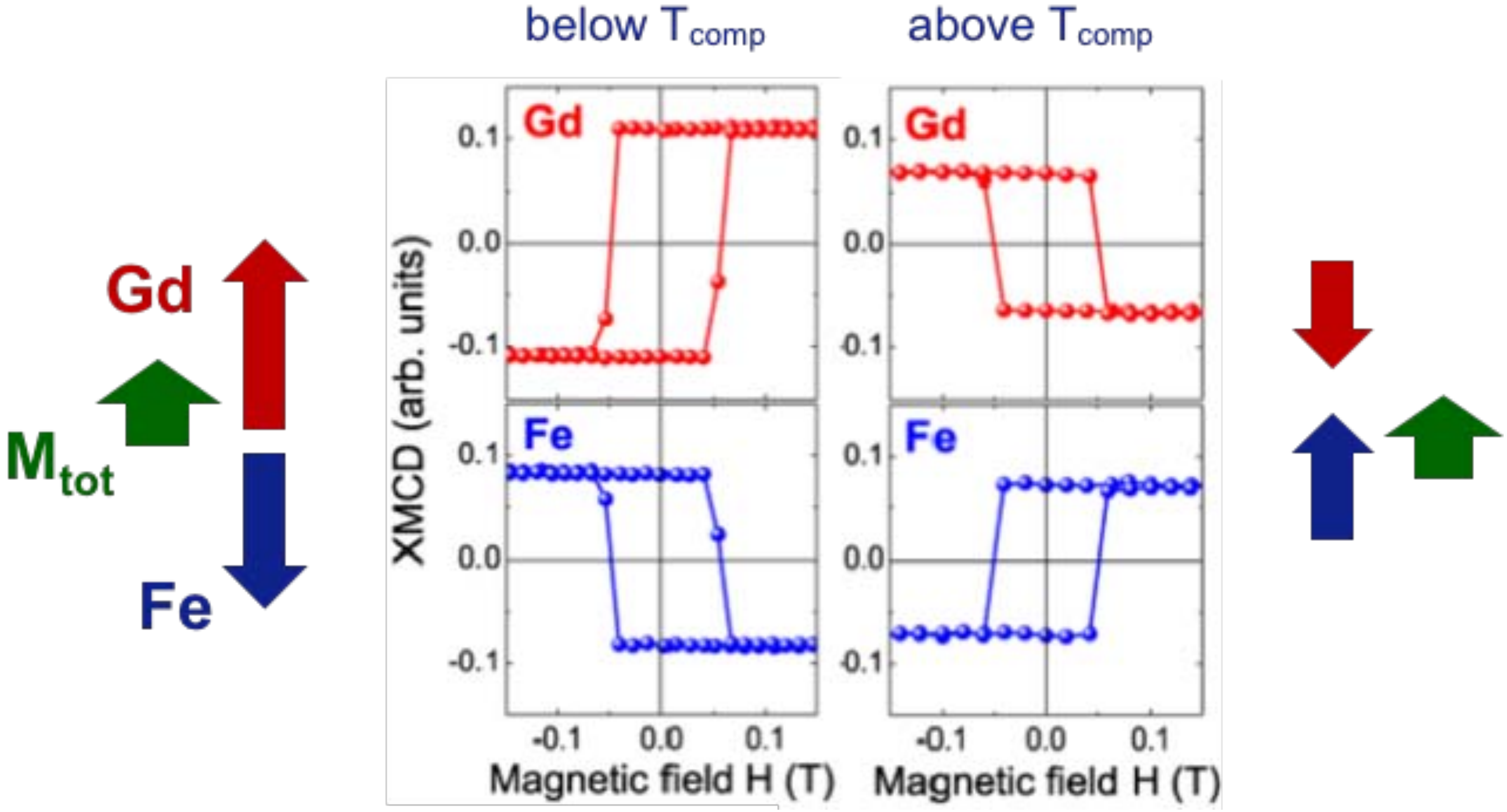
Calculations of the effective damping for a ferrimagnet



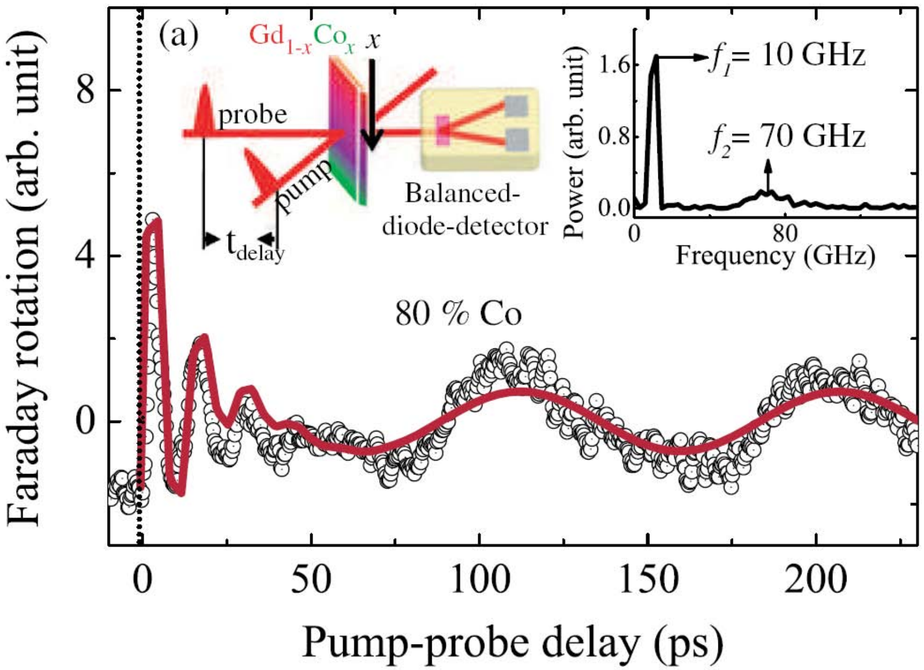
F. Schlickeiser et al., PRB **86**, 214416 (2012)

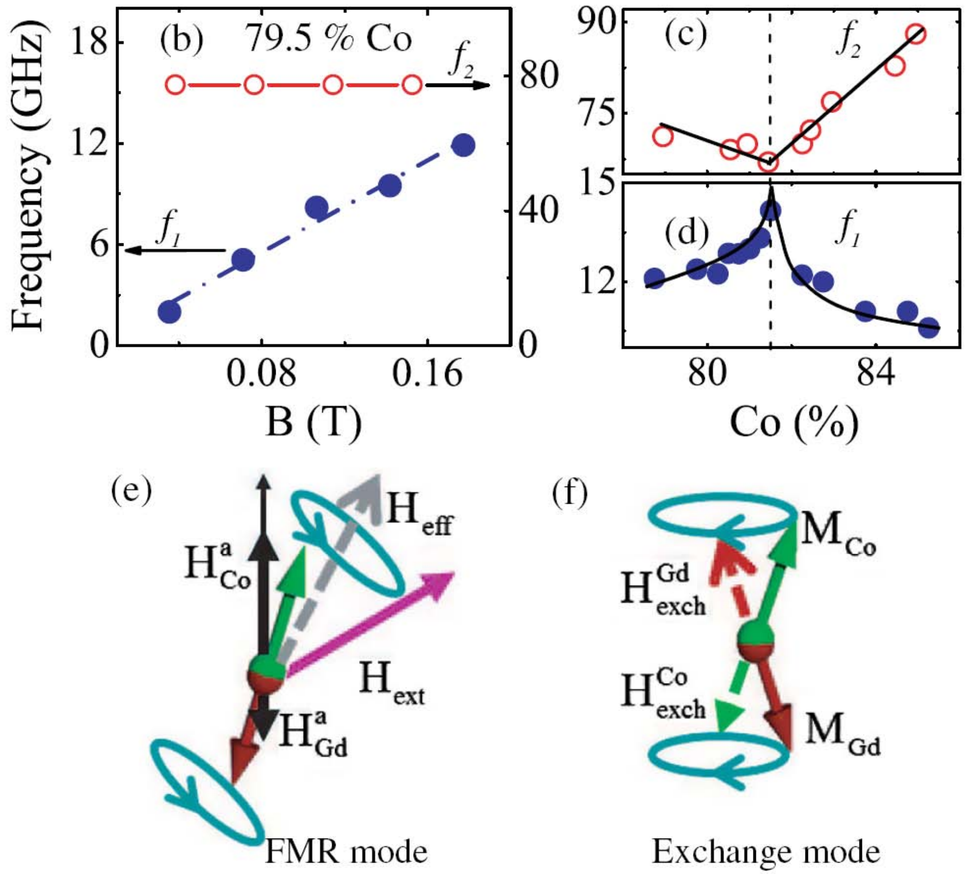
Yu. Tsema, M. Savoini et al, to be published

Sublattices: different behavior??



Thermal excitation of the exchange mode



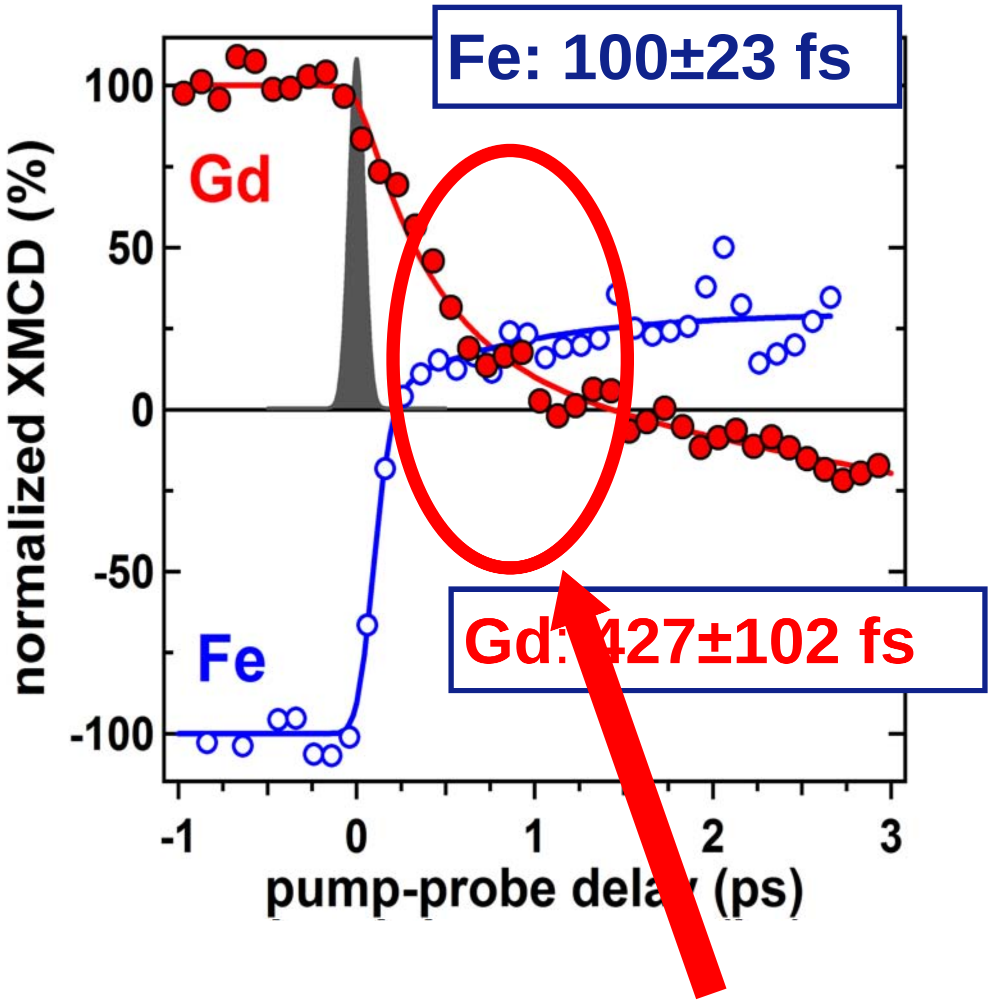


Mekonnen et al, PRL **107**, 117202 (2011)

heating leads to a decoupling of the substrates??

Dynamics of sublattices

Radu et al., Nature **472**, 205 (2011)



ferri-magnet turns ferro!

Atomistic simulations

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

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

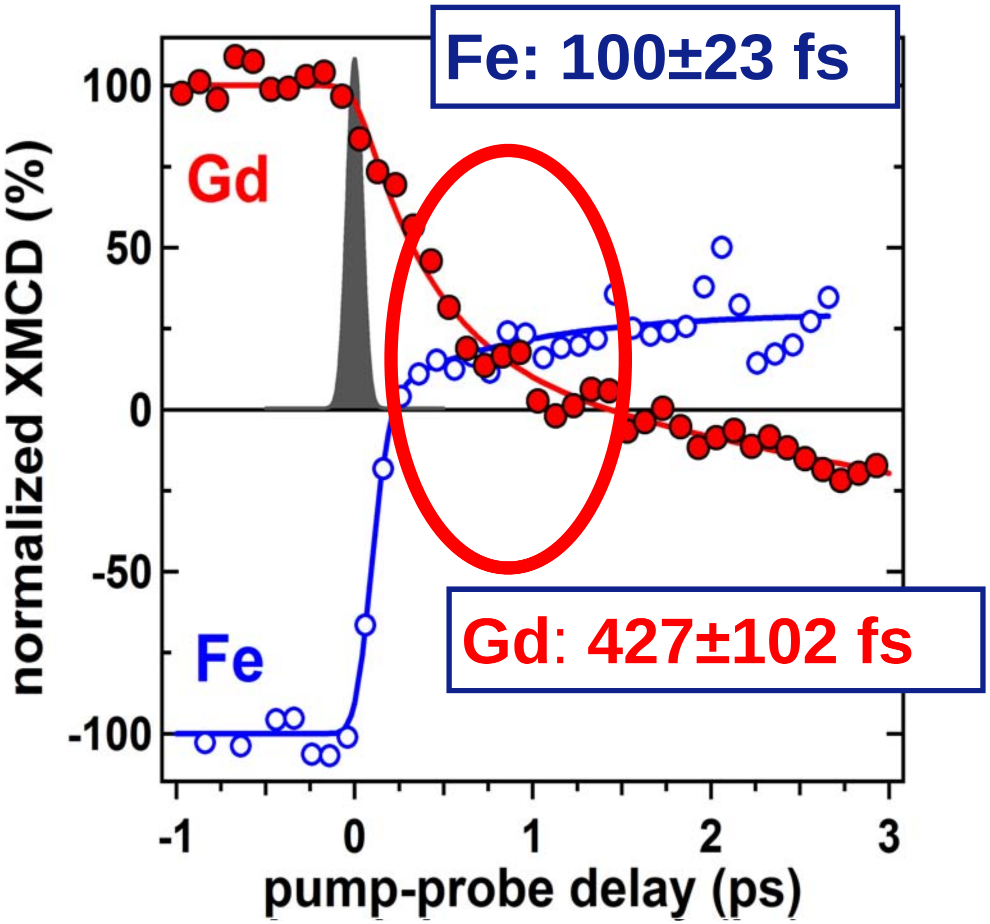
$$\langle \zeta_\alpha(t)\zeta_\beta(t')\rangle = \frac{2\lambda T}{\gamma\mu_0}\delta_{\alpha\beta}\delta(t-t')$$

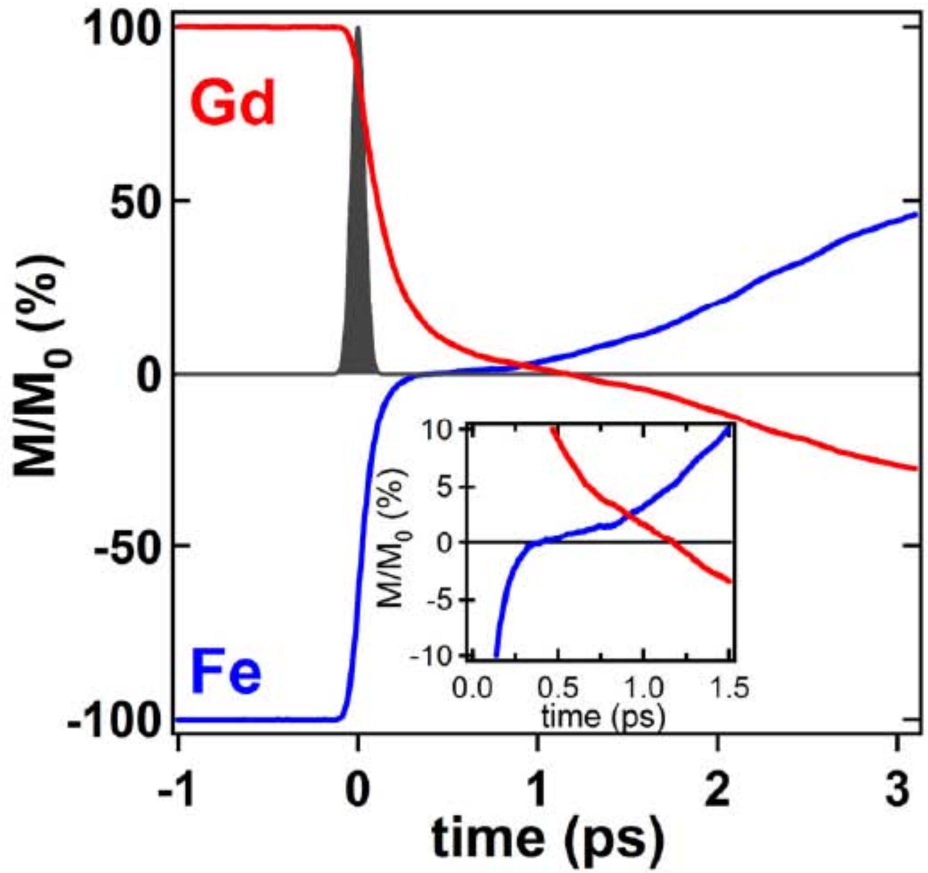
- magnetic field can be present during the process

Scubic et al, JPCM **20,** 315203 (2008);
Ostler et al, PRB **84**, 024407 (2011)

Dynamics of sublattices

Radu et al., Nature **472**, 205 (2011)





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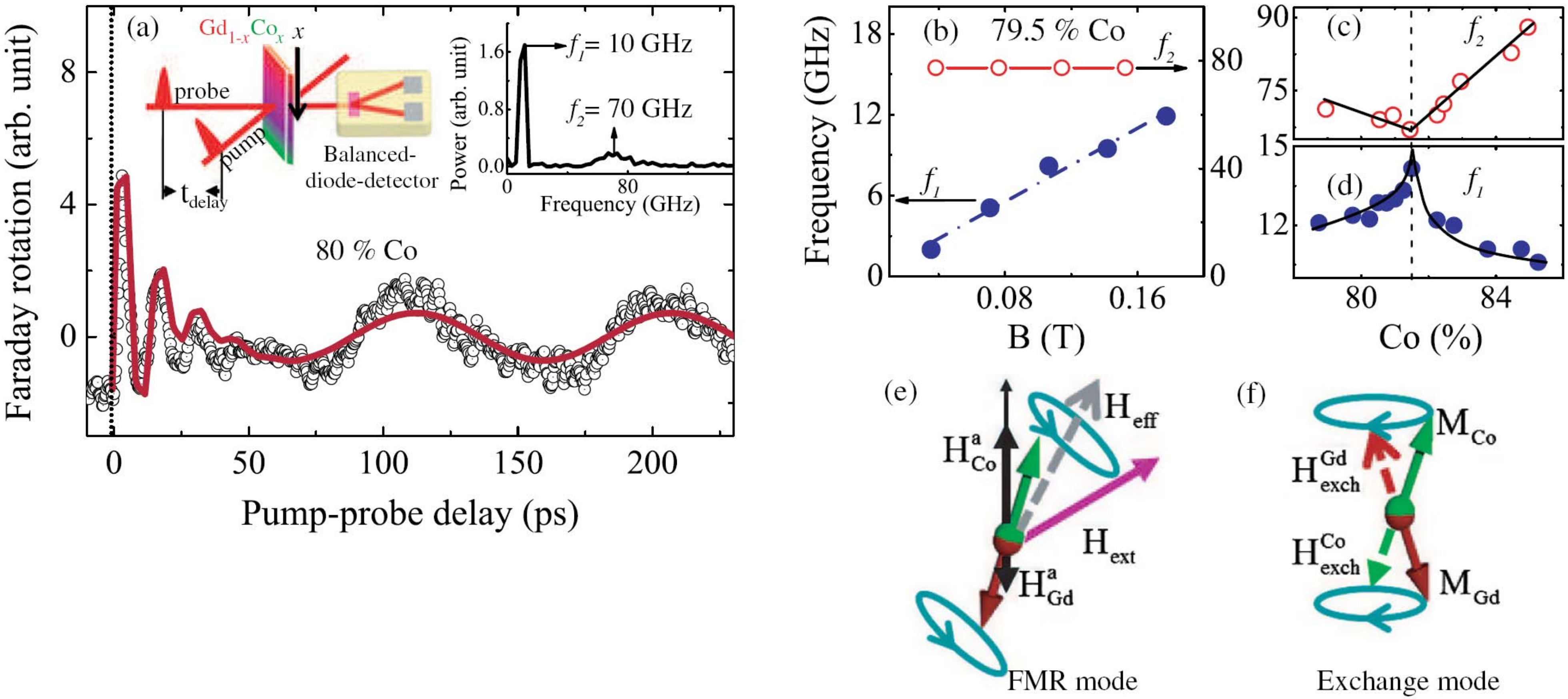
Thermal excitation of the exchange mode



Mekonnen et al, PRL **107**, 117202 (2011)

heating leads to a decoupling of the substrates??

Longitudinal relaxation in multi-sublattice magnets

see Mentink et al., Phys. Rev. Lett. **108**, 057202 (2012);
Kirilyuk et al, Rep. Prog. Phys. **76**, 026501 (2013)

$$dS_1/dt = \lambda_e (H_1 - H_2) + \lambda_1 H_1$$

$$dS_2/dt = -\underbrace{\lambda_e (H_1 - H_2)}_{\text{exchange}} + \underbrace{\lambda_2 H_2}_{\text{relativistic (usual damping)}}$$

where $S_i = M_i/\gamma_i$

and $H_i = -\delta W/\delta S_i$

$$\lambda_e(T) = \lambda_e(J_{12}(T)) \qquad \lambda_i(T) \sim T/T_C$$

conservation S_{tot} | Bloch relaxation

$$dS_1/dt = -dS_2/dt$$

$$dS_i/dt = -S_i/\tau_i$$

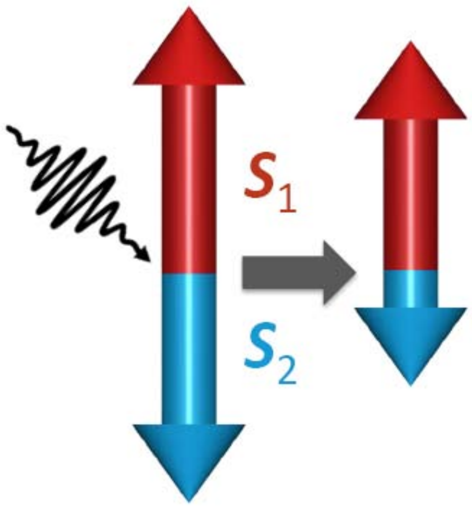
$$\tau_i = \chi_i/\lambda_i$$

$$\lambda_i \propto \frac{2\alpha_i \gamma k_B T}{\mu_i}$$

Temperature-dominated regime $\lambda_i >> \lambda_e$

interaction with the environment

$$dS_1/dt = \cancel{\lambda_e (H_1 - H_2)} + \lambda_1 H_1$$
$$dS_2/dt = \cancel{-\lambda_e (H_1 - H_2)} + \lambda_2 H_2$$



$$\lambda_i \propto \frac{2\alpha_i \gamma k_B T}{\mu_i}$$

Bloch relaxation

$$dS_i/dt = -S_i/\tau_i$$

$$\tau_i = \chi_i/\lambda_i$$
$$\tau_i = \mu_i/(2\alpha_i \gamma k_B T)$$

Dynamics scales with magnetic moment

$$\mu_2 < \mu_1 \Rightarrow \tau_2 < \tau_1$$

Brown 1963, Kubo 1970

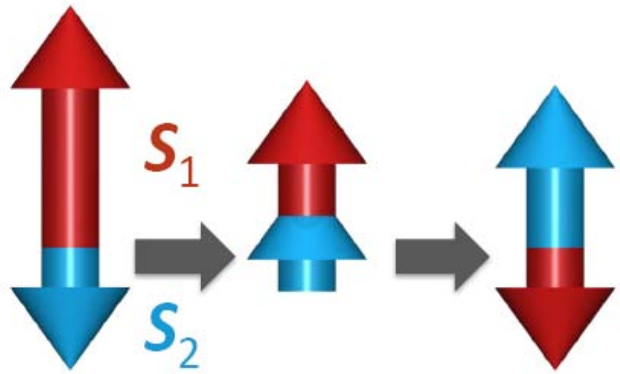
small magnetic moments change faster
$\rightarrow$ less angular momentum to be transferred

Exchange-dominated regime $\lambda_i << \lambda_e$

interactions between the sublattices

$$\frac{dS_1}{dt} = \lambda_e (H_1 - H_2) \cancel{+ \lambda_1 H_1}$$

$$\frac{dS_2}{dt} = -\lambda_e (H_1 - H_2) \cancel{+ \lambda_2 H_2}$$



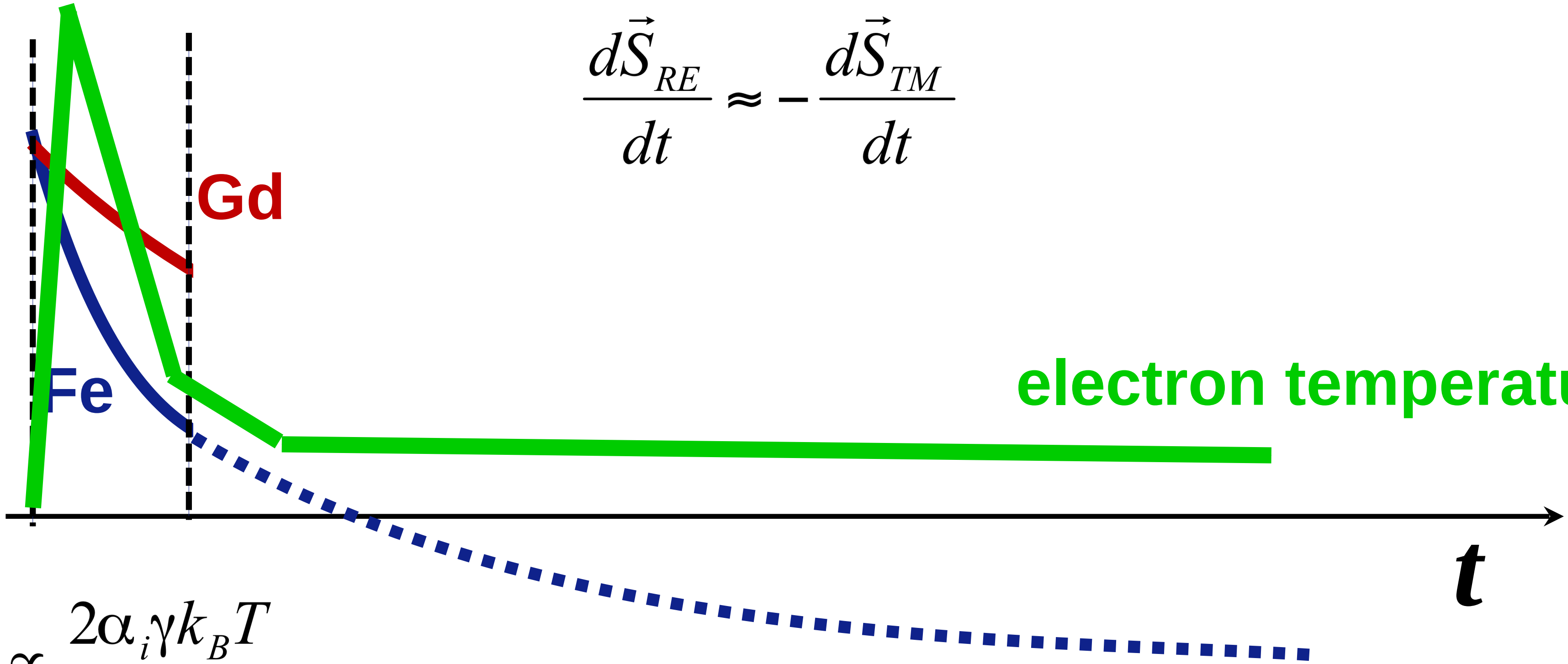
$$\Rightarrow \frac{dS_1}{dt} = -\frac{dS_2}{dt}$$

In this approximation, the total angular momentum is conserved

Crossover from temperature- to exchange-dominated

$\vec{S}_{RE}, \vec{S}_{TM}$ independent

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



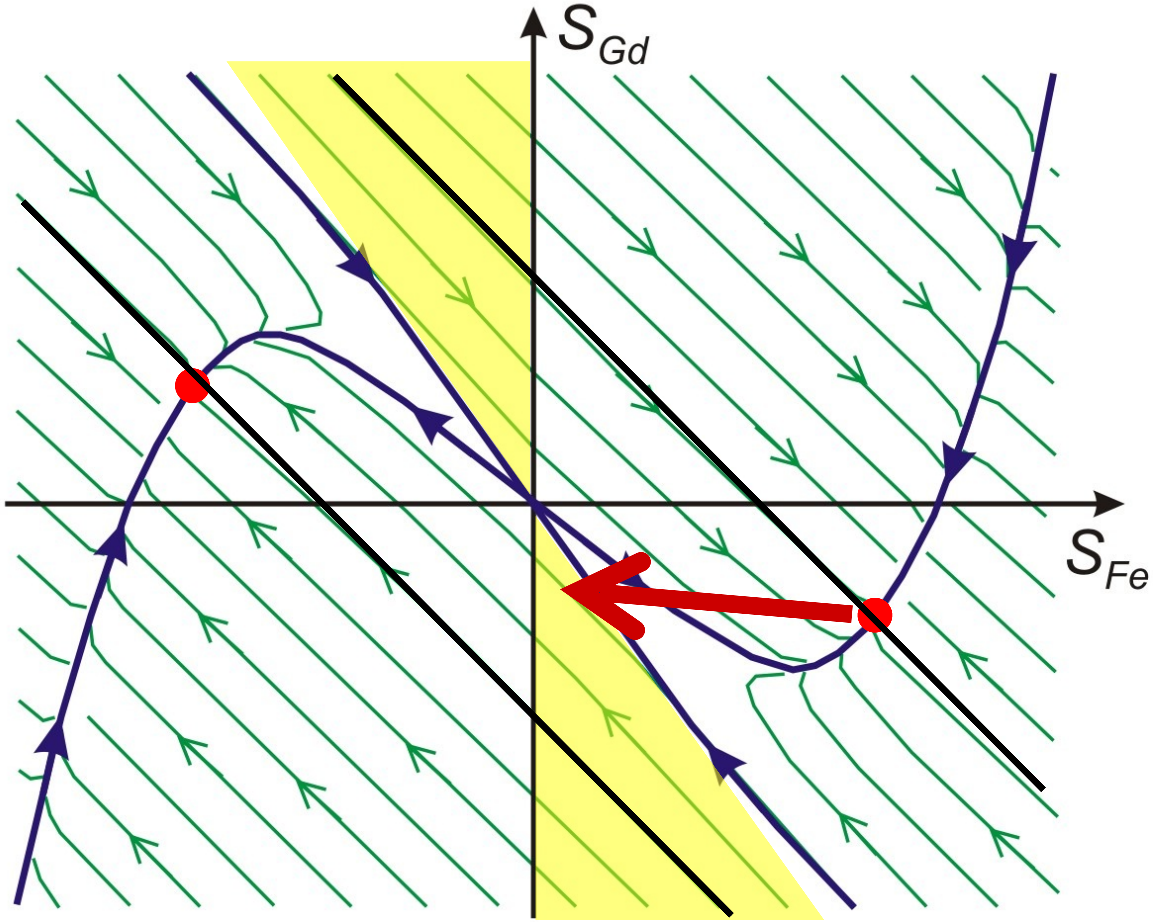
$$\lambda_i \propto \frac{2\alpha_i \gamma k_B T}{\mu_i}$$

derived in Mentink et al., PRL **108**, 057202 (2012);

see Rep. Prog. Phys. 76, 026501 (2013) for all details

Complete picture – phase diagram

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



see Mentink et al., PRL **108**, 057202 (2012)
for all details

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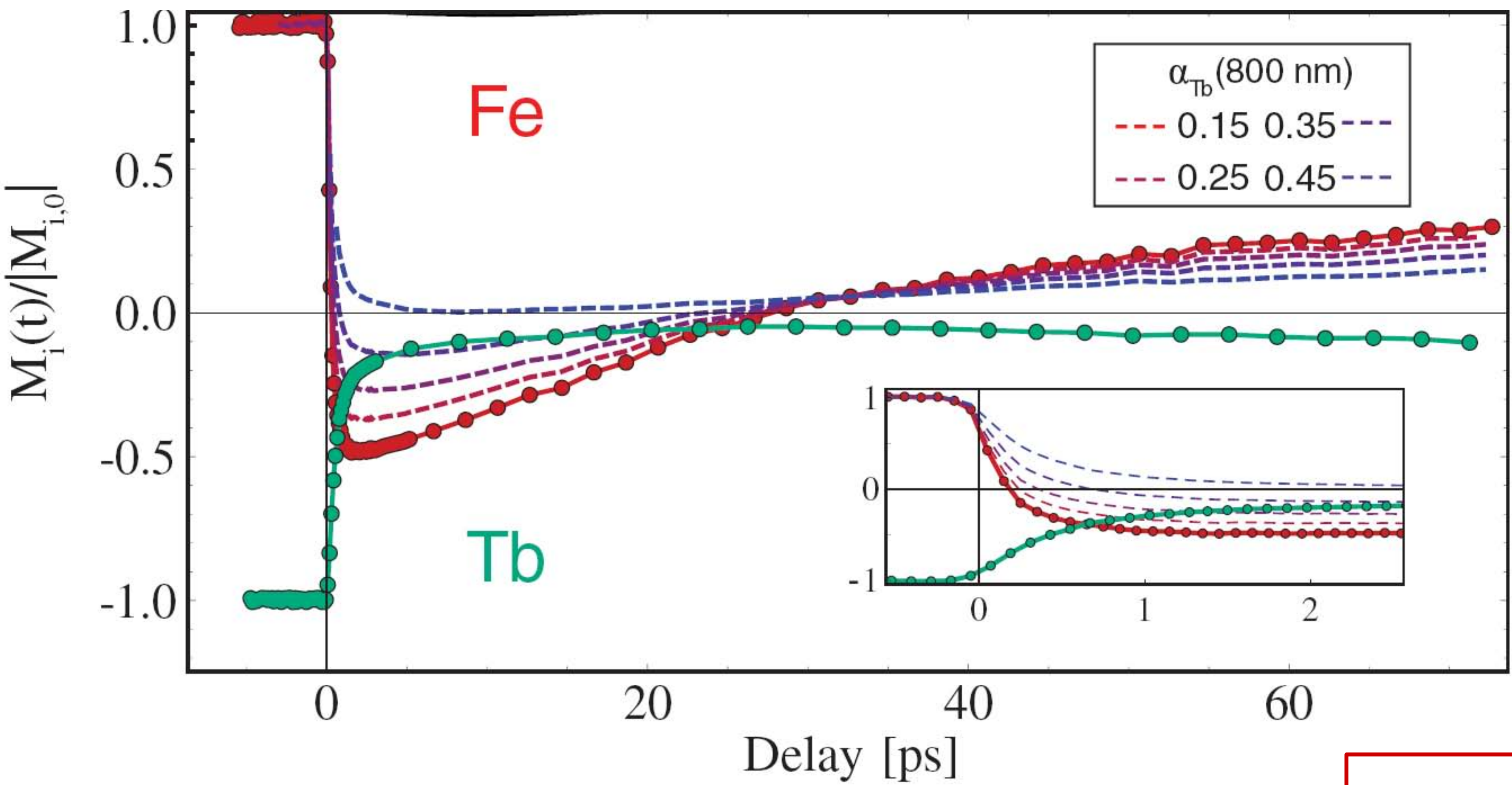
Is this switching universal?

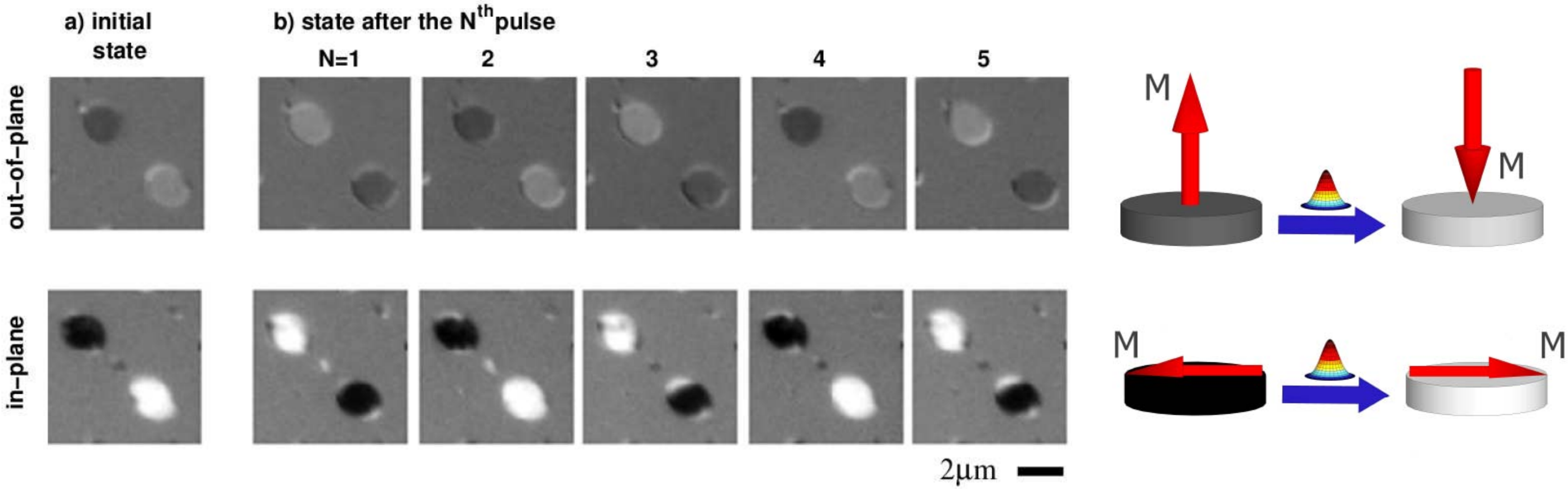


Khorsand et al., PRL **110**, 107205 (2013)

$$g_{\text{Tb}} = \frac{3}{2}$$

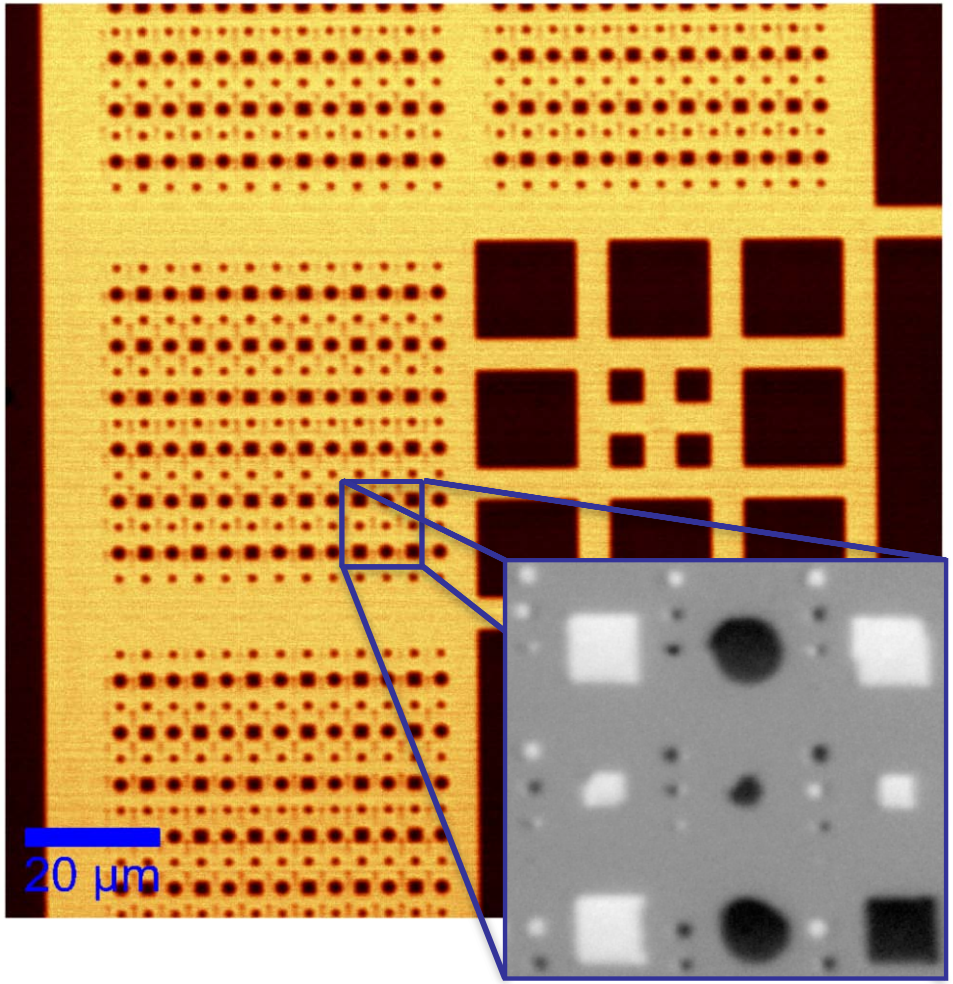
$$M_{\text{Tb}} = g_{\text{Tb}} L$$

Field-free switching: out-of-plane and in-plane



Ostler et al., Nature Commun. **3**, 666 (2012)

Towards applications 1: nanostructure the sample



Various sizes:
50 micron down to 200 nm

Savoini et al, Phys. Rev. B **86**, 140404 (2012)

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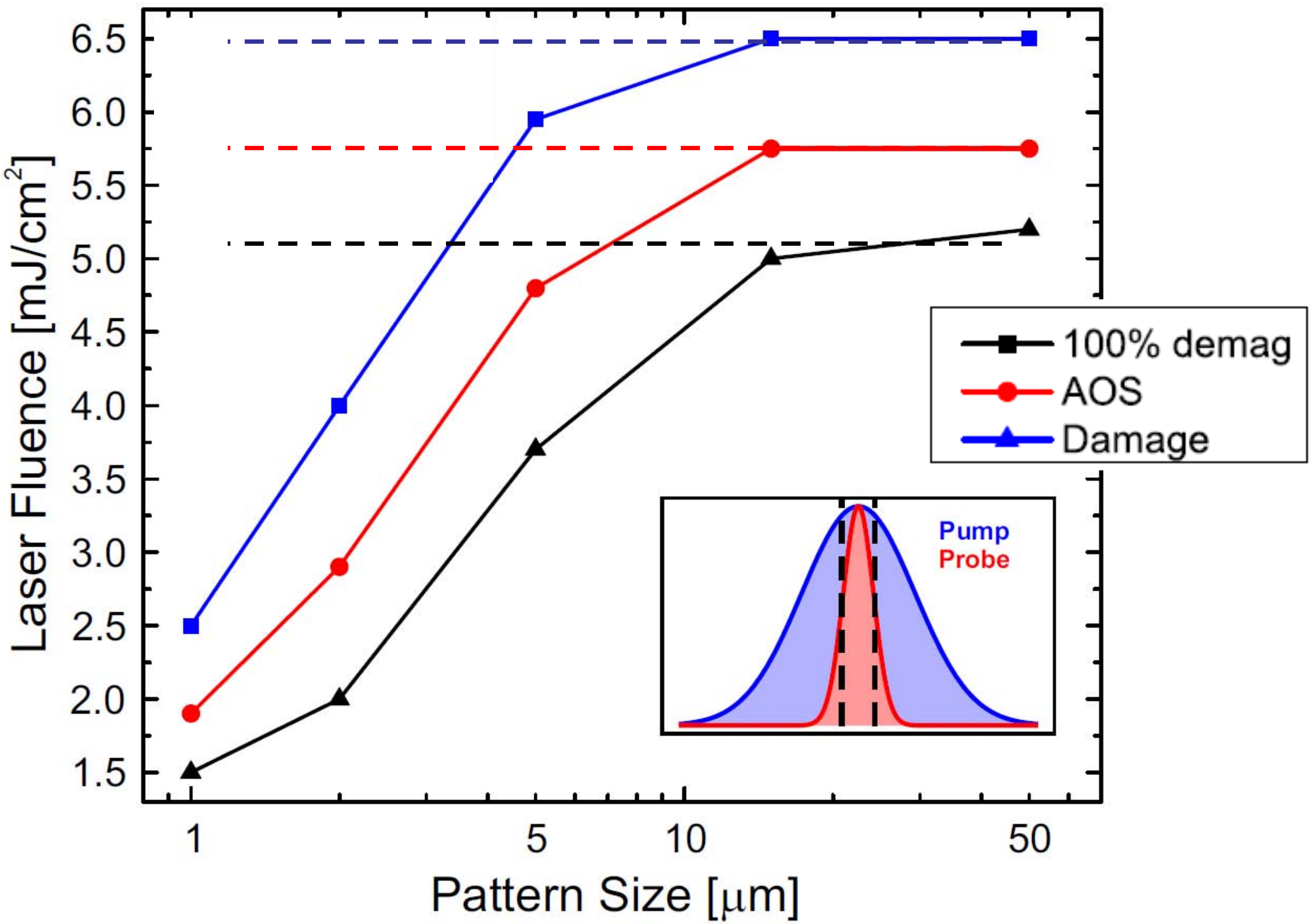
More energy-efficient at small sizes



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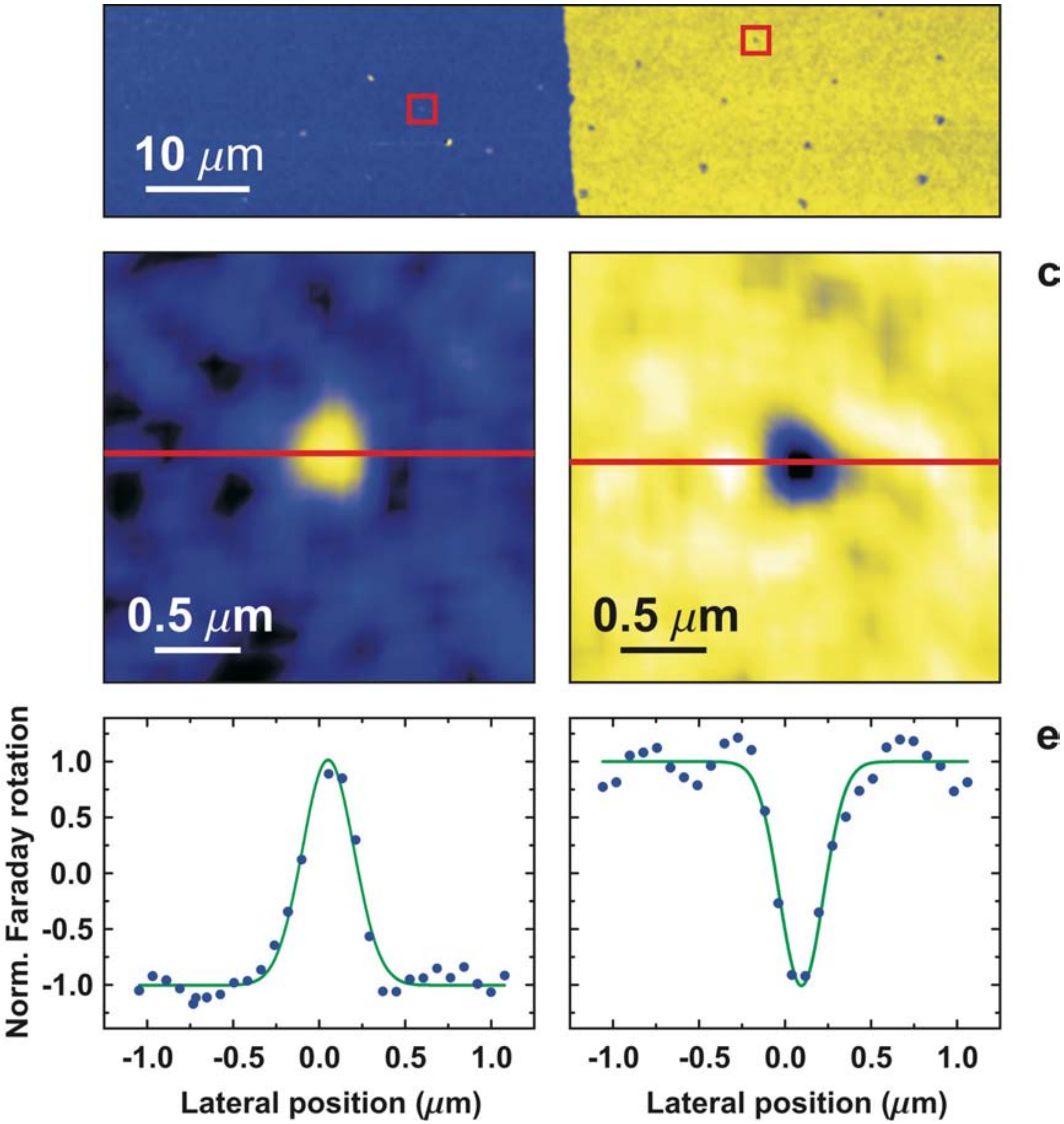
Towards applications 2: focus hard



Fit: $\sigma(r) = 1 - 2e^{-\frac{r^2}{R_1^2}}$

$R_1 \approx 200$ nm

Imaged with SNOM

Finazzi et al,
Phys. Rev. Lett. **110**, 177205 (2013)

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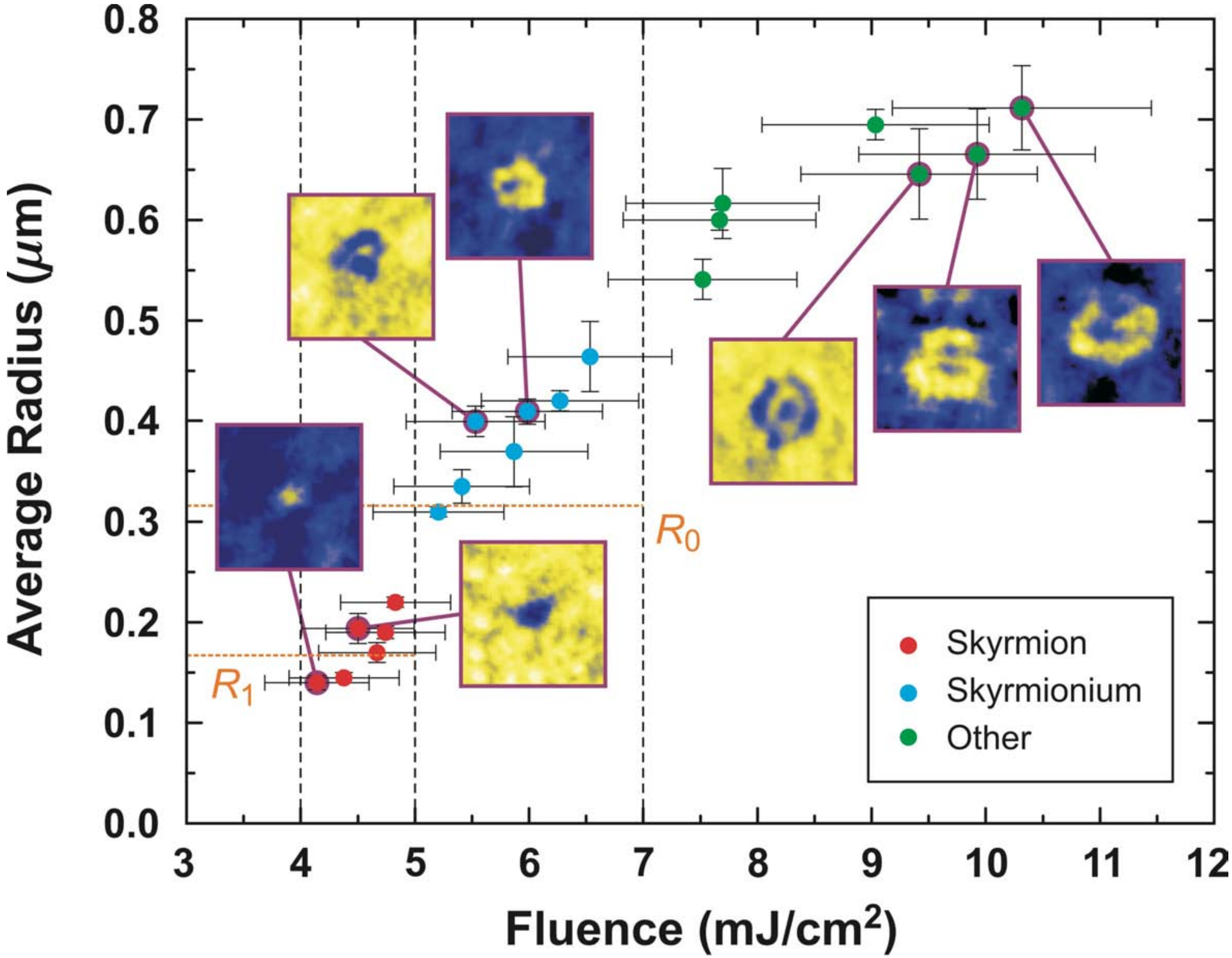
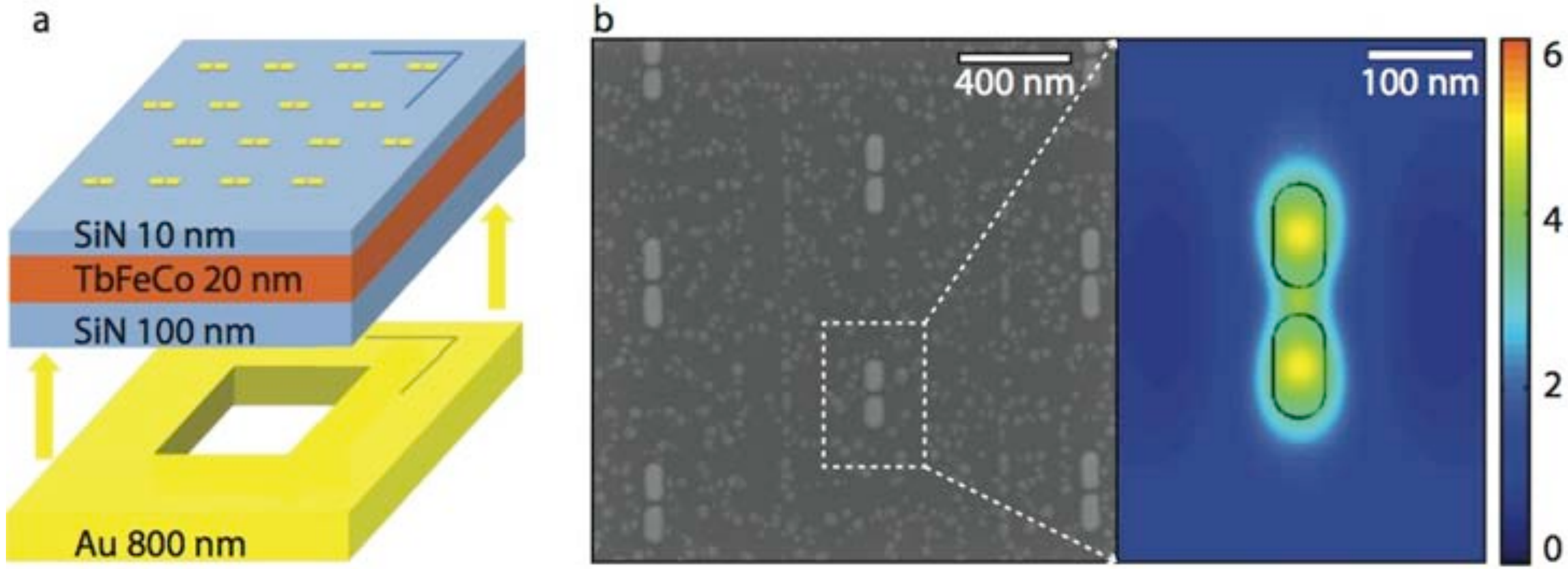
Various topologies of the written domain

Finazzi et al, Phys. Rev. Lett. **110**, 177205 (2013)

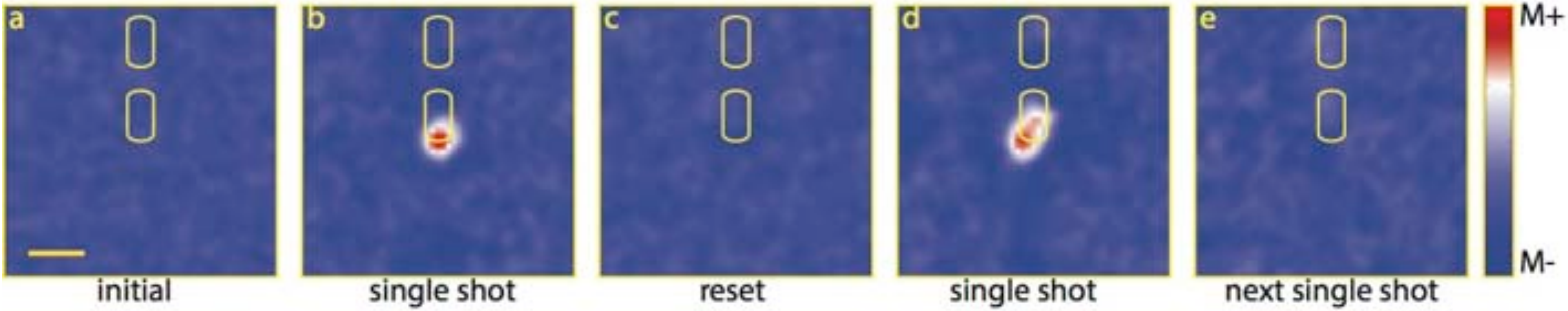


Towards applications 3: focus even harder



T.M. Liu et al, accepted in NanoLetters

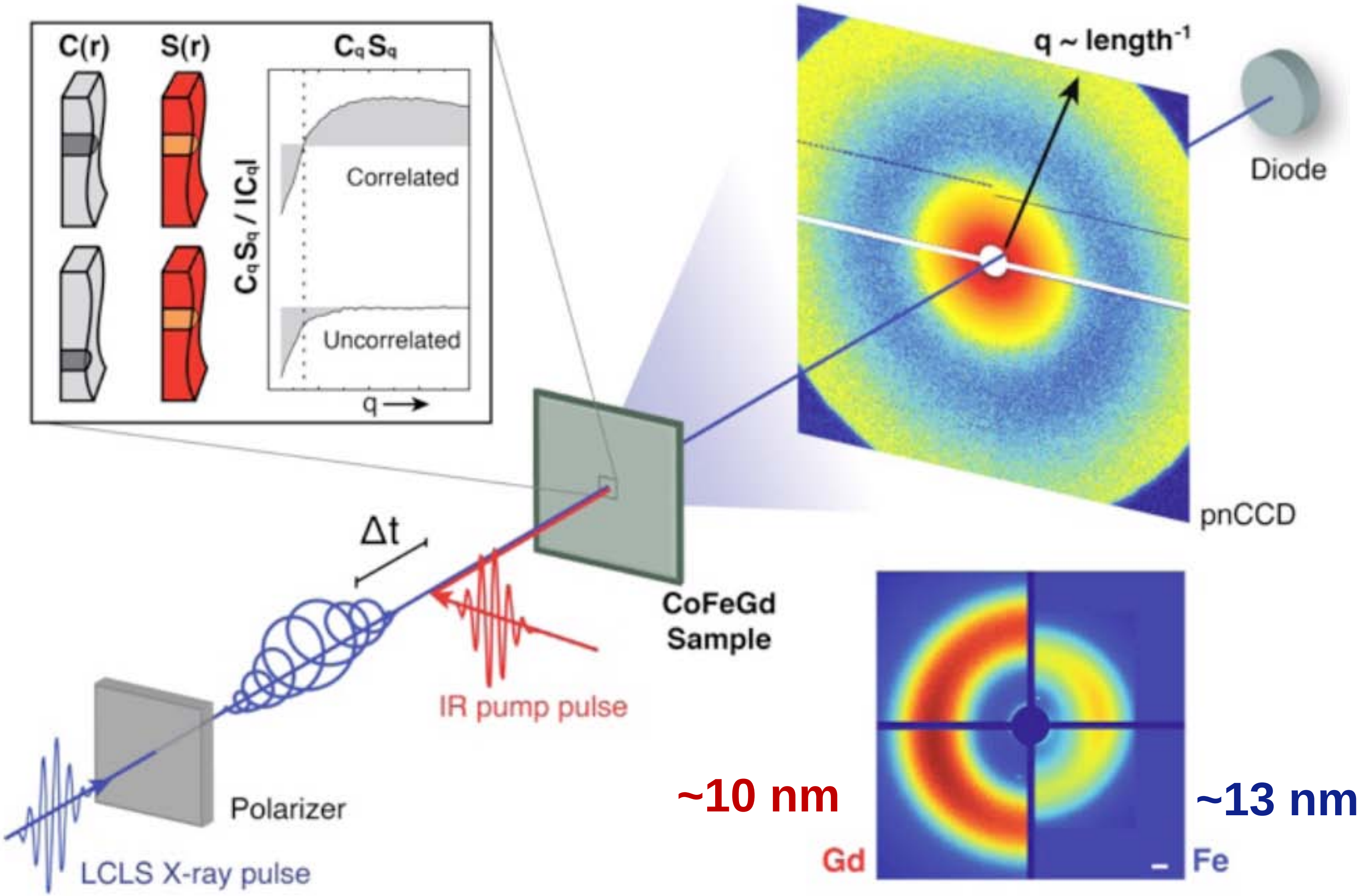
Reproducible switching of 40 nm bit!



with field **with light pulse**

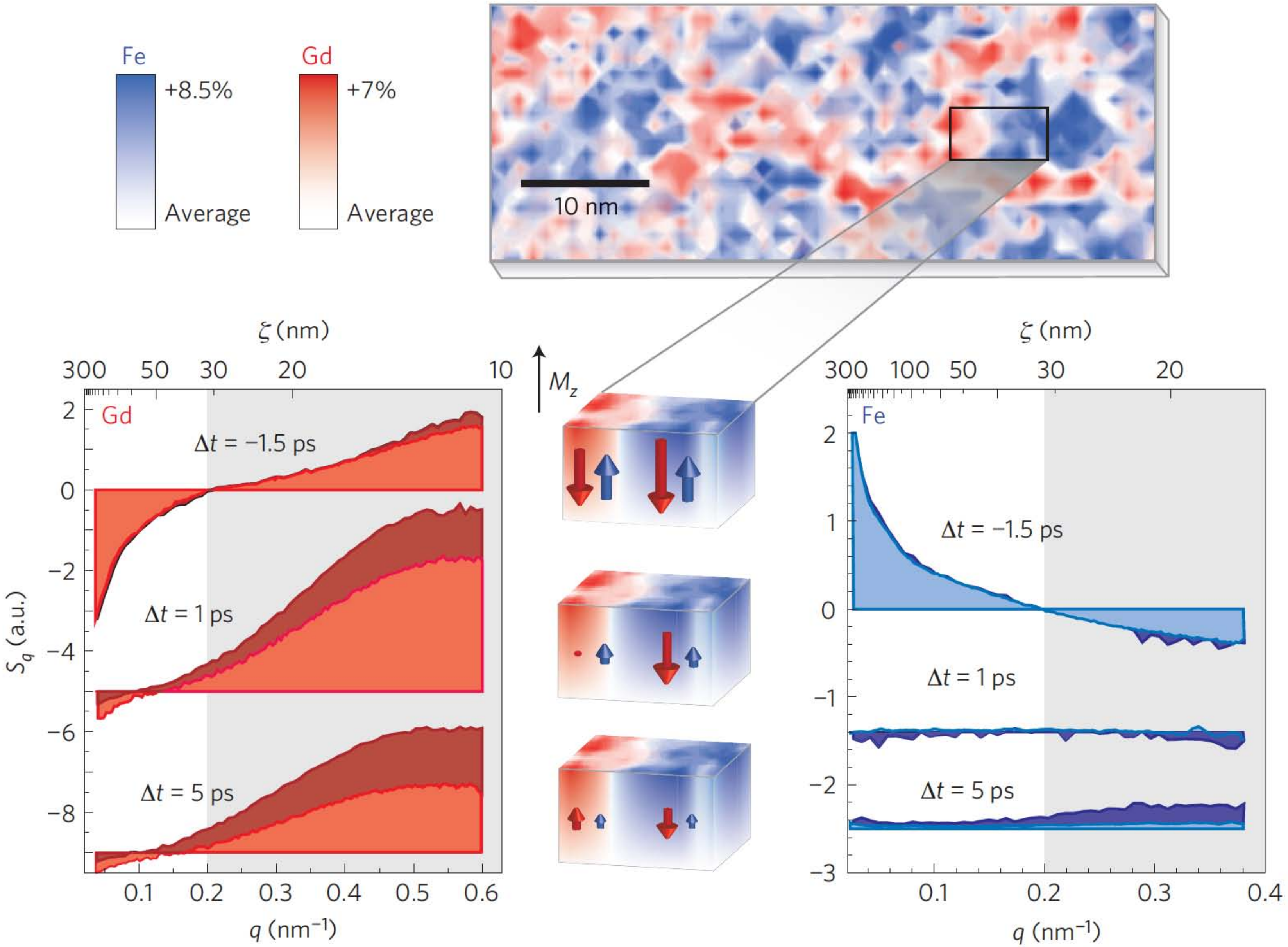
T.M. Liu et al, accepted in NanoLetters

Resonant soft X-ray diffraction at LCLS, Stanford



Graves et al, Nature Mat. **12**, 293 (2013)

Different temporal and spatial behavior of Gd and Fe



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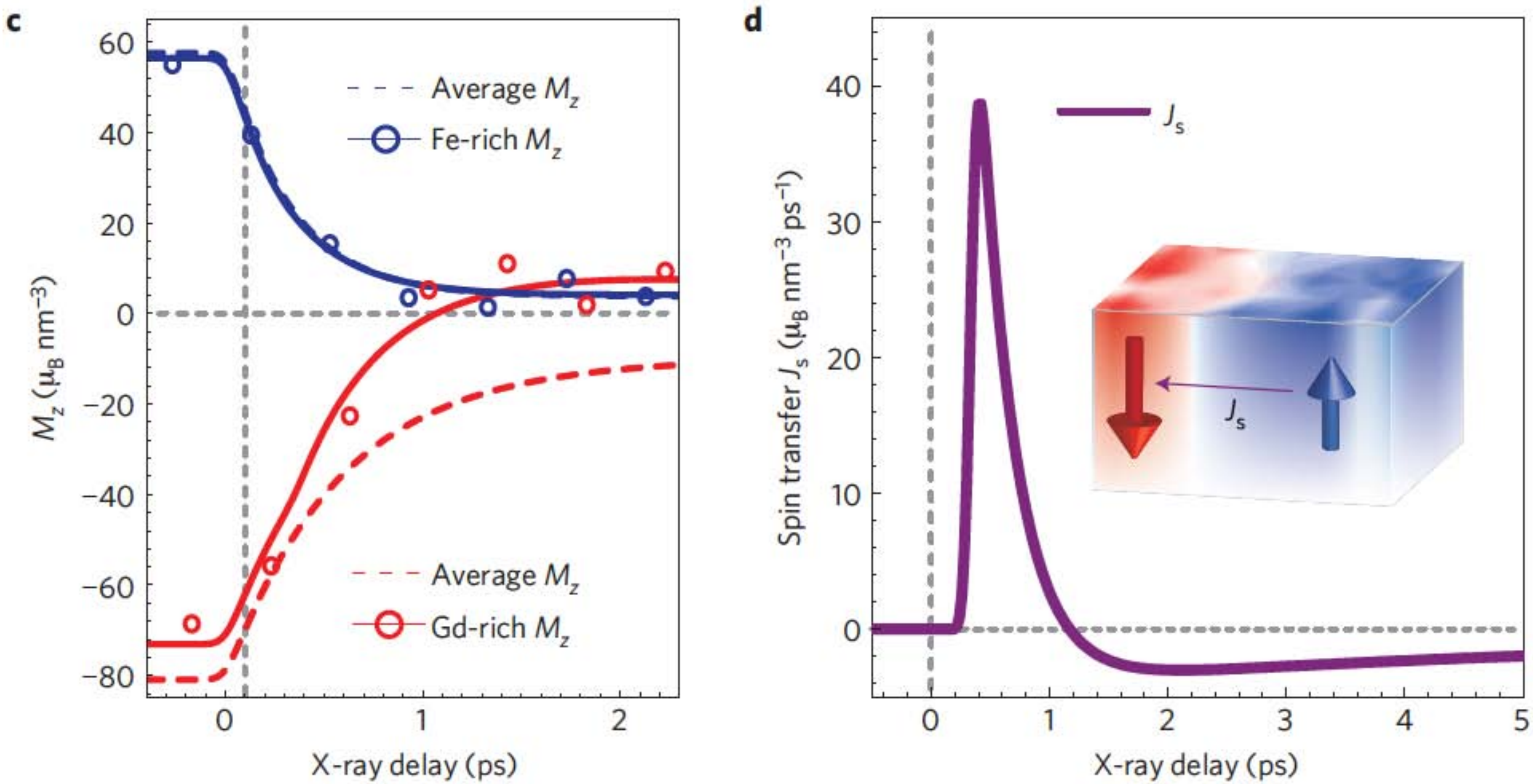
Spin transfer currents at ~10 nm distances



Graves et al, Nature Mat. **12**, 293 (2013)

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Answers

- intensity dependence?
- time scale of the reversal?? fs, ps, ns, ms???
- what happens spatially?
- the role of the sublattices??

Summary:

- temperature can switch the exchange ‘on’ and ‘off’
- heat-induced reversal is driven by the exchange-mediated conservation of angular momentum
- on nanoscale, the process is very complicated and needs further study
- no magnetic field is required at any stage – reversal by each pulse

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