The zoo of all-optical magnetic switching

mechanisms & time-scales

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VOLUME 76, NUMBER 22 PHYSICAL REVIEW LETTERS 27 MAY 1996

Ultrafast Spin Dynamics in Ferromagnetic Nickel

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(Received 17 October 1995)

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28.10.1959 – 24.04.2018

Jean-Yves Bigot
29.02.1956 – 02.05.2018

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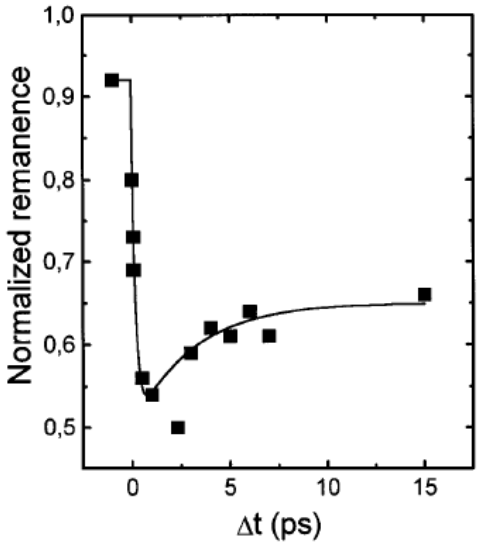

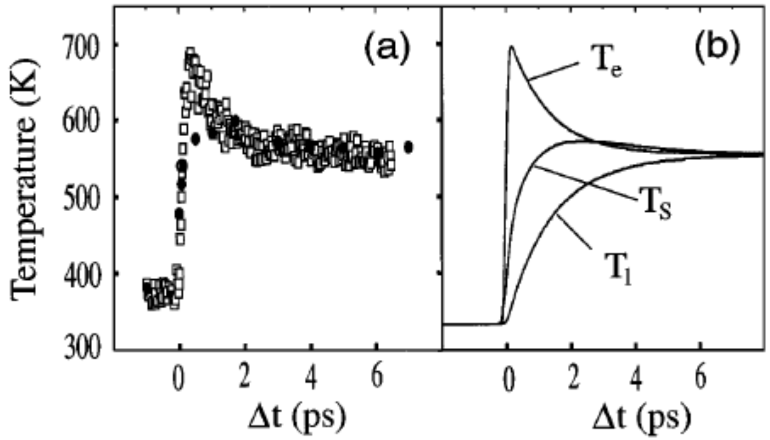

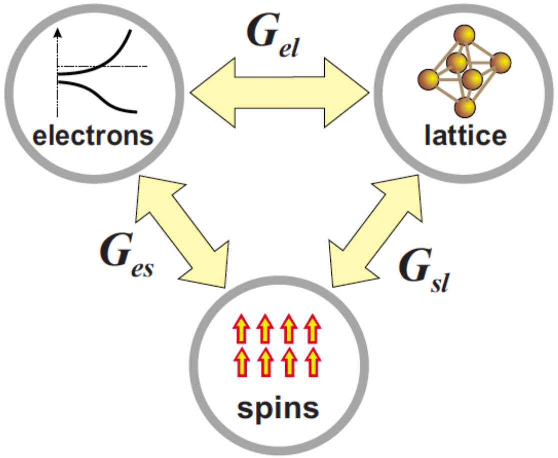

$$C_e d(T_e)/dt = -G_{el}(T_e - T_l) - G_{es}(T_e - T_s) + P(t)$$

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

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

Coherent terahertz emission from ferromagnetic films excited by femtosecond laser pulses

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C. A. Schmuttenmaer[a)]
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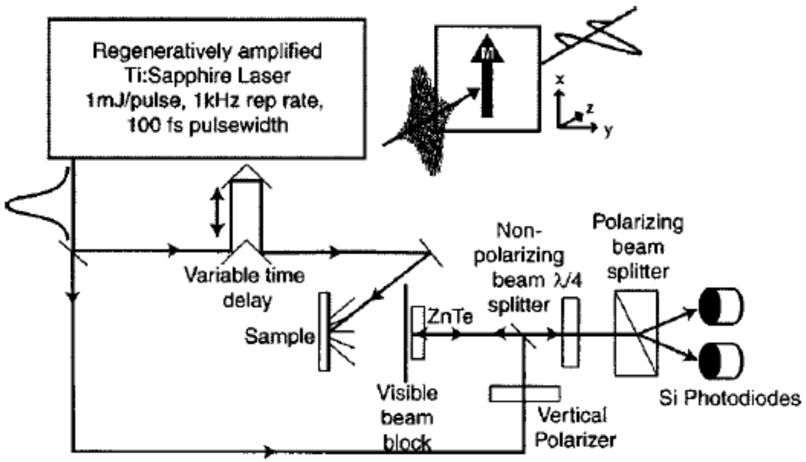
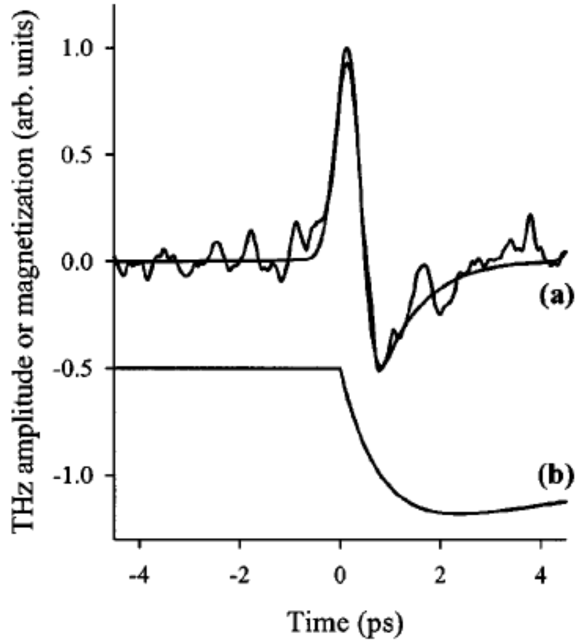


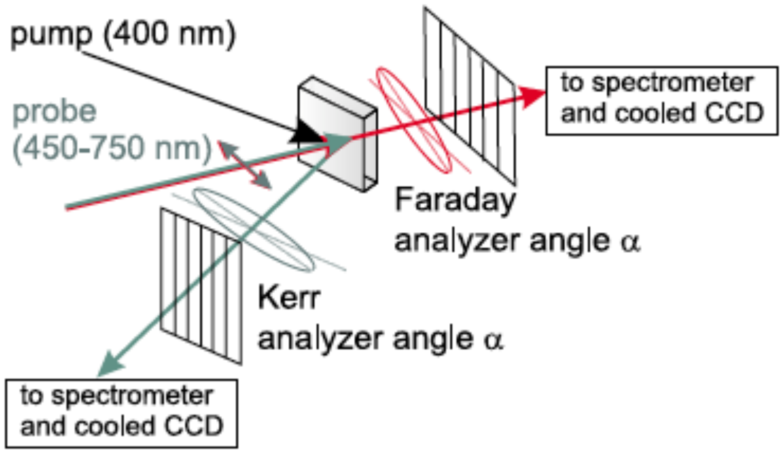


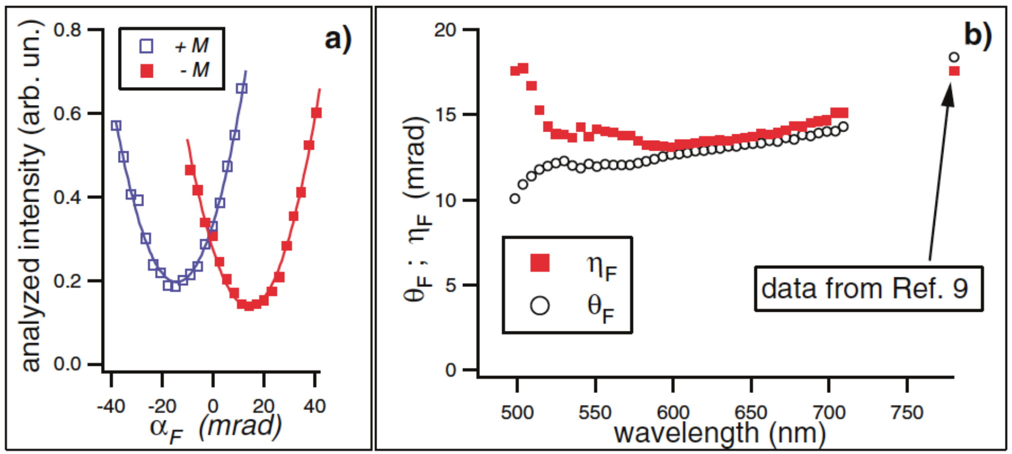
VOLUME 93, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 13 AUGUST 2004

Femtosecond Spectrotemporal Magneto-optics

J.-Y. Bigot,* L. Guidoni, E. Beaurepaire, and P. N. Saeta†
Institut de Physique et Chimie des Matériaux de Strasbourg, Unité Mixte CNRS-ULP-ECPM, 23 rue du Loess, B.P. 43, 67034 Strasbourg Cedex, France
(Received 31 October 2003; published 13 August 2004)

A new method to measure and analyze the time and spectrally resolved polarimetric response of magnetic materials is presented. It allows us to study the ultrafast magnetization dynamics of a $CoPt_3$ ferromagnetic film. The analysis of the pump-induced rotation and ellipticity detected by a broad spectrum probe beam shows that magneto-optical signals predominantly reflect the spin dynamics in ferromagnets.





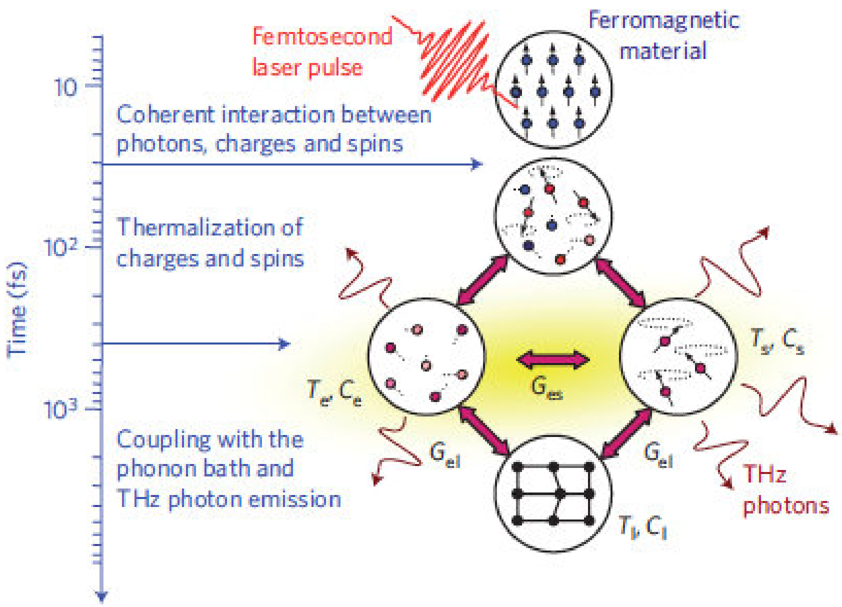
nature physics

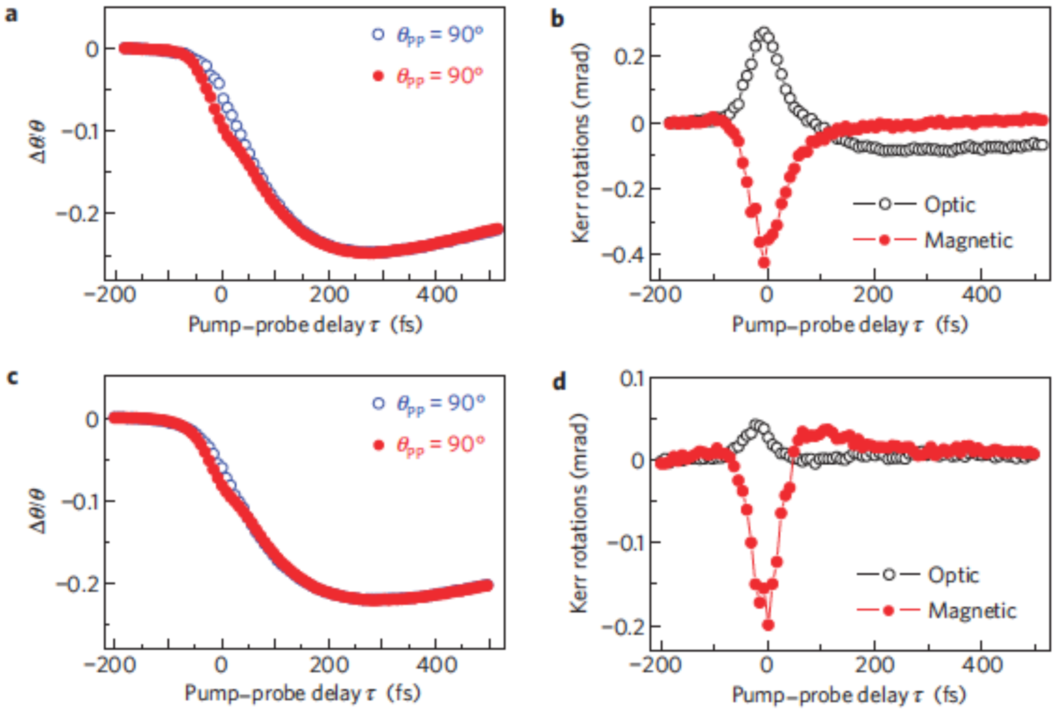
ARTICLES

PUBLISHED ONLINE: 31 MAY 2009 | DOI:10.1038/NPHYS1285

Coherent ultrafast magnetism induced by femtosecond laser pulses

Jean-Yves Bigot*, Mircea Vomir and Eric Beaurepaire



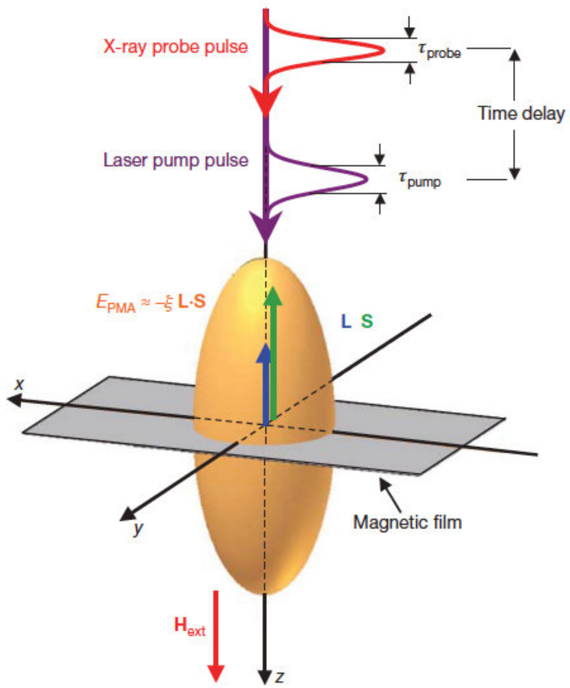


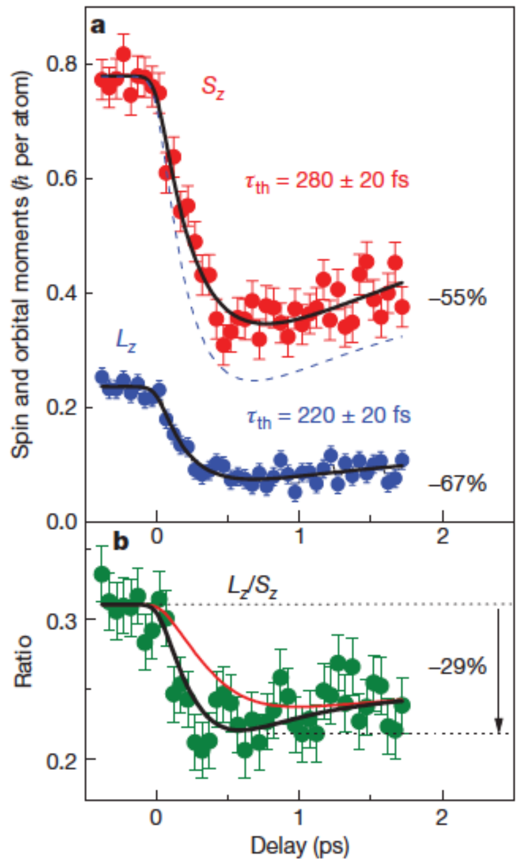
nature Vol 465 | 27 May 2010 | doi:10.1038/nature09070

LETTERS

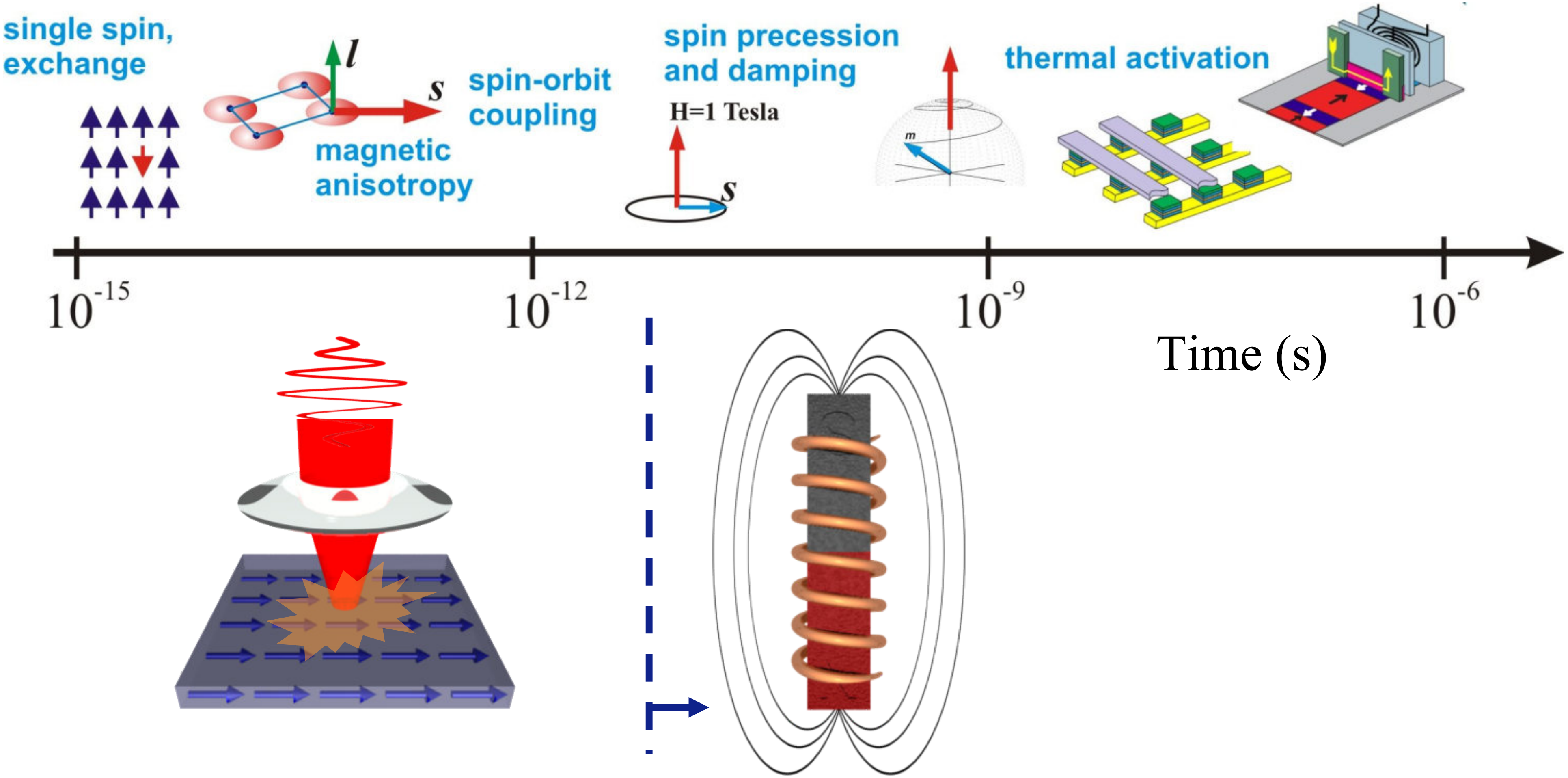
Distinguishing the ultrafast dynamics of spin and orbital moments in solids

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]





Only laser pulses can be fast enough!

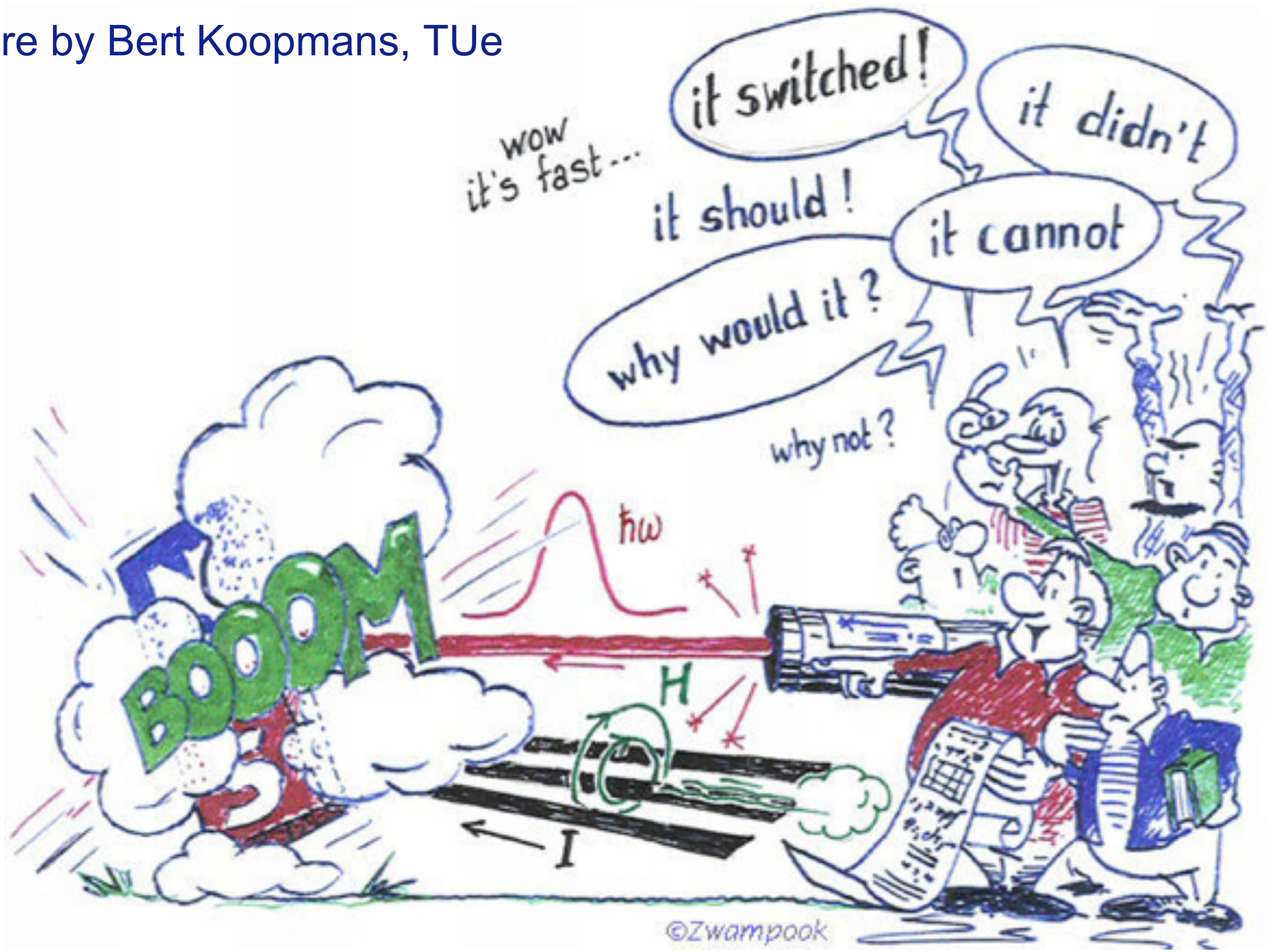


Benchmark: 180° (or 90°) switching

reverse in $<10^{-10}$ s, keep stable for 10^{8} s

Did it switch? Interpretation of the data...

picture by Bert Koopmans, TUe



Part 1: classification of laser-induced effects

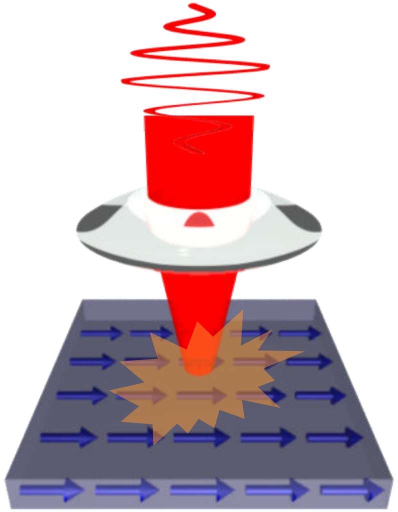
Part 2: the switching as such

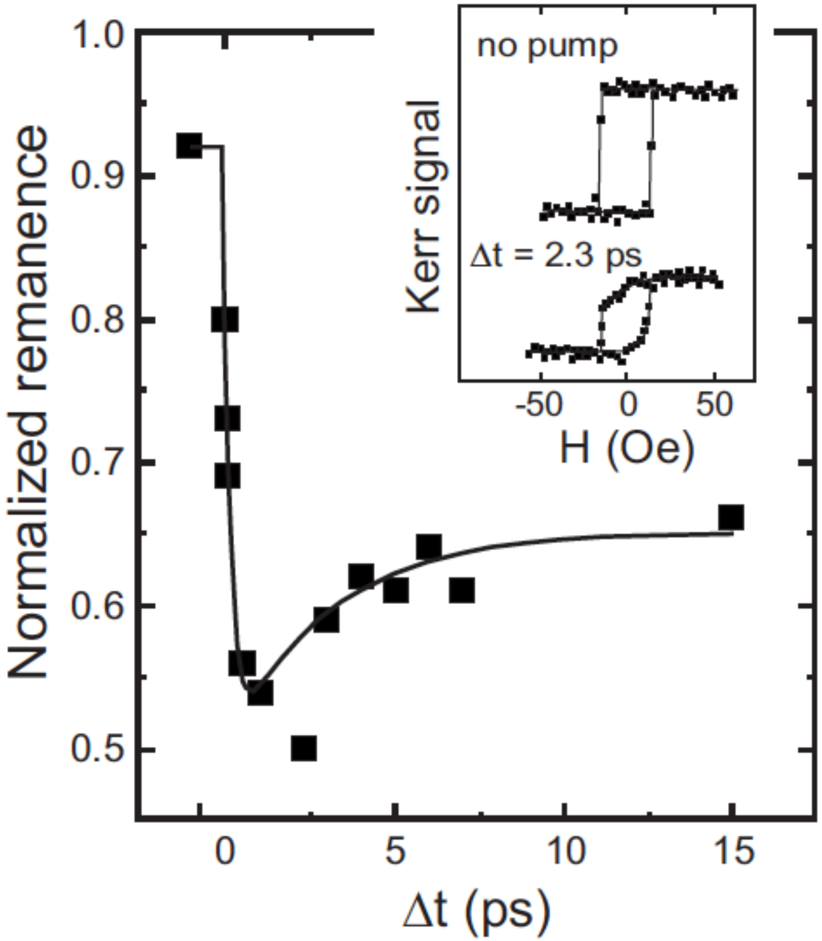
Effects of the laser pulse: classification

I. Thermal effects:

change of M is a result of change of T

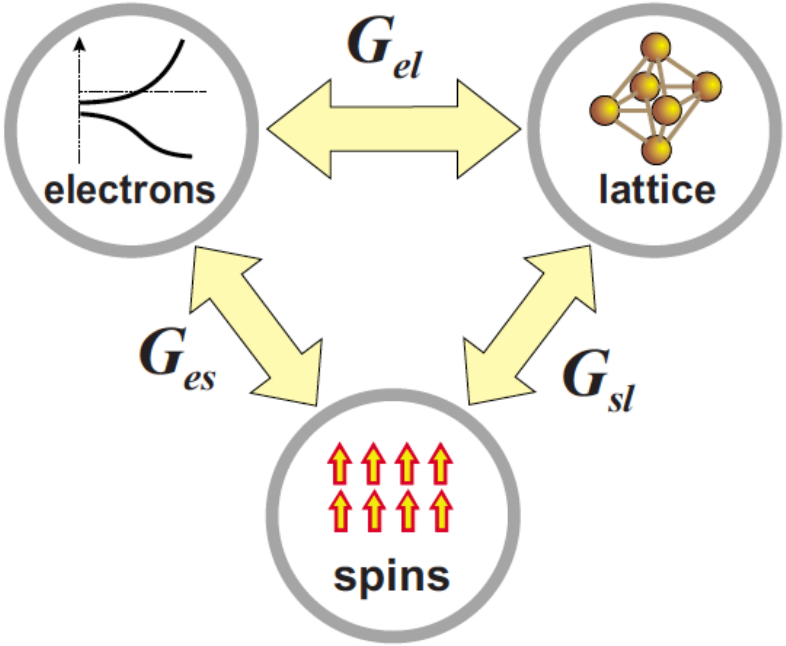
Laser-induced collapse of magnetization

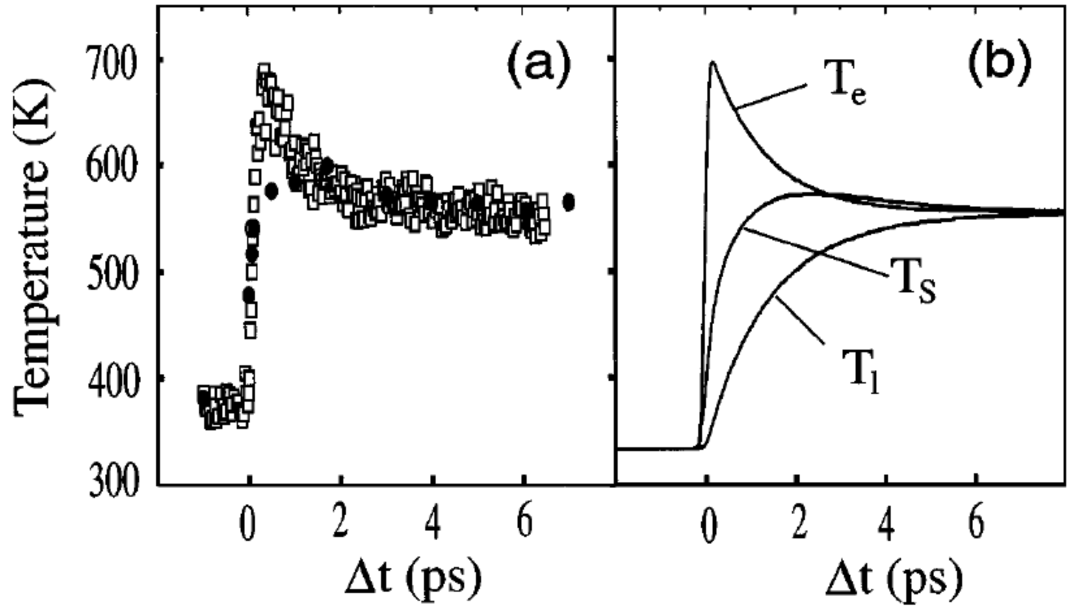




Beaurepaire et al, PRL **76**, 4250 (1996)

3T model and derivatives





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

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

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

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

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

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

M3TM

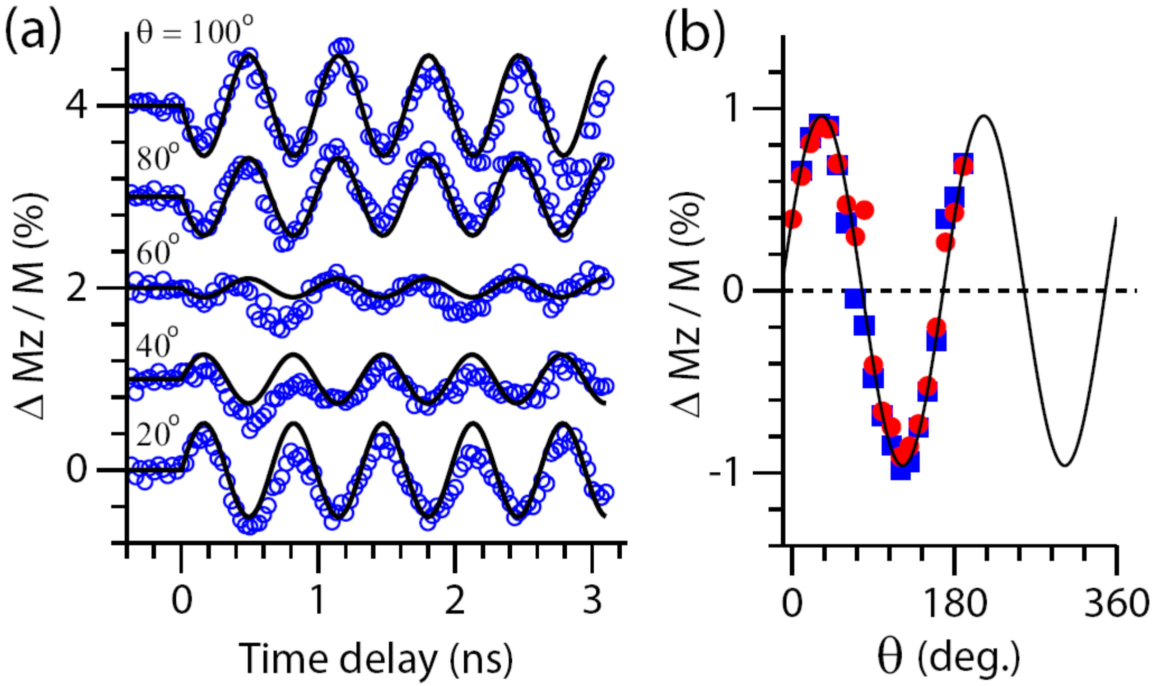
Koopmans et al, Nature Mater. **9**, 259 (2010)

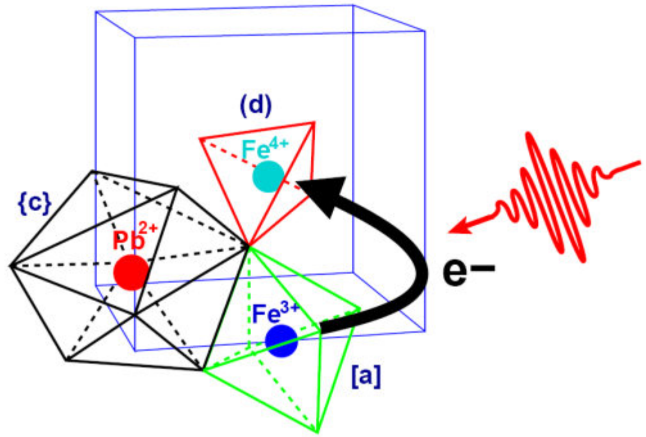
Radboud University

Effects of the laser pulse: classification

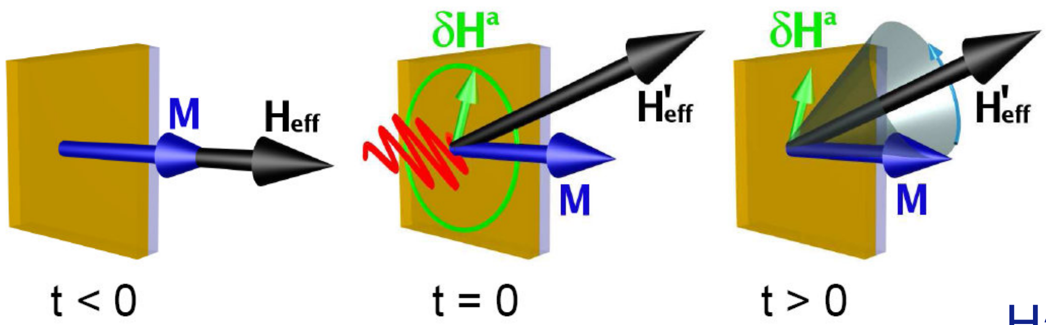
II. Nonthermal photo-magnetic effects:
based on photon absorption

Photo-magnetic anisotropy in garnets





pump polarization dependence!



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

Effects of the laser pulse: classification

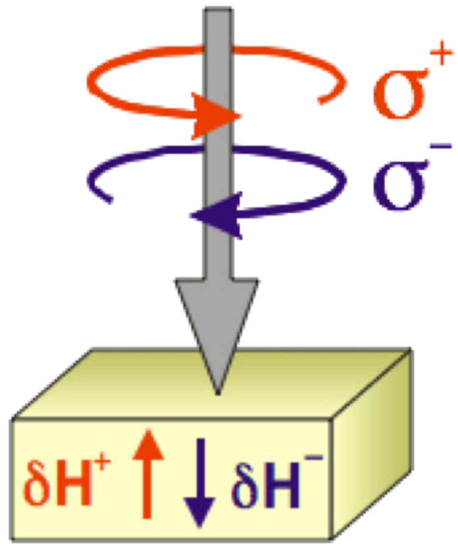
III. Nonthermal opto-magnetic effects:
do not require absorption

Inverse Faraday effect

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

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

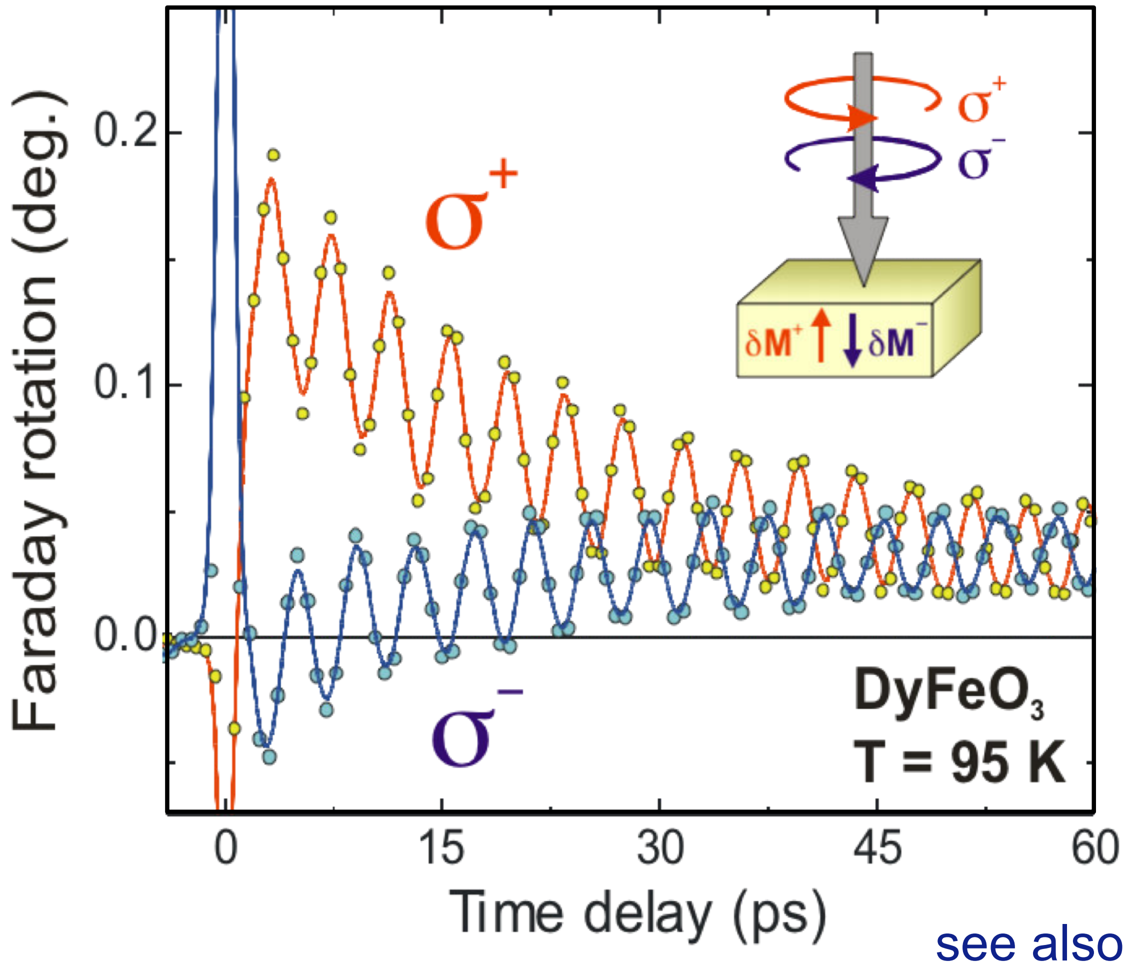
$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & -i\alpha M & 0 \\ +i\alpha M & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} + O(M^2) \end{pmatrix}$$



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

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

Inverse Faraday effect to excite spin dynamics



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

again, the dependence on pump polarization!

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

see also:
Hansteen et al., PRB **73**, 014421 (2006);
Kalashnikova et al, PRL **99**, 167205 (2007)

Effects of the laser pulse: summary

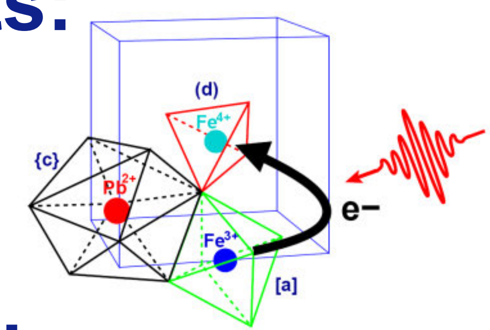
I. Thermal effects:

change of M is a result of change of T

II. Nonthermal photo-magnetic effects:

based on photon absorption

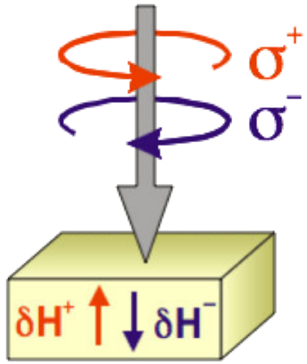
displacive effect



III. Nonthermal opto-magnetic effects:

do not require absorption

impulsive effect

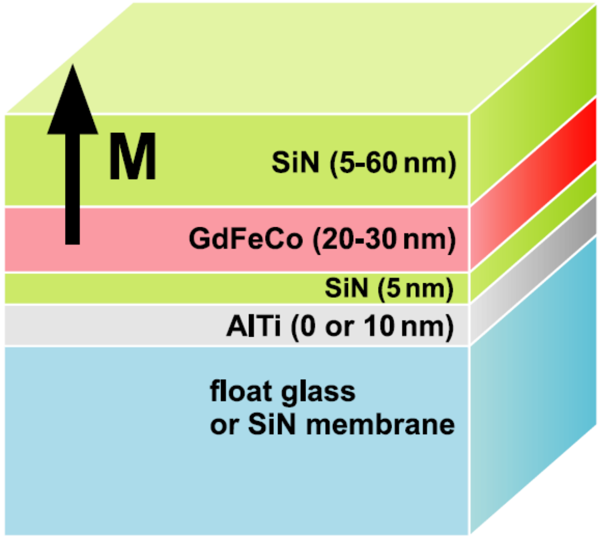


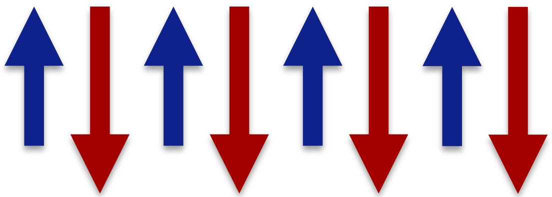
Part 1: classification of laser-induced effects

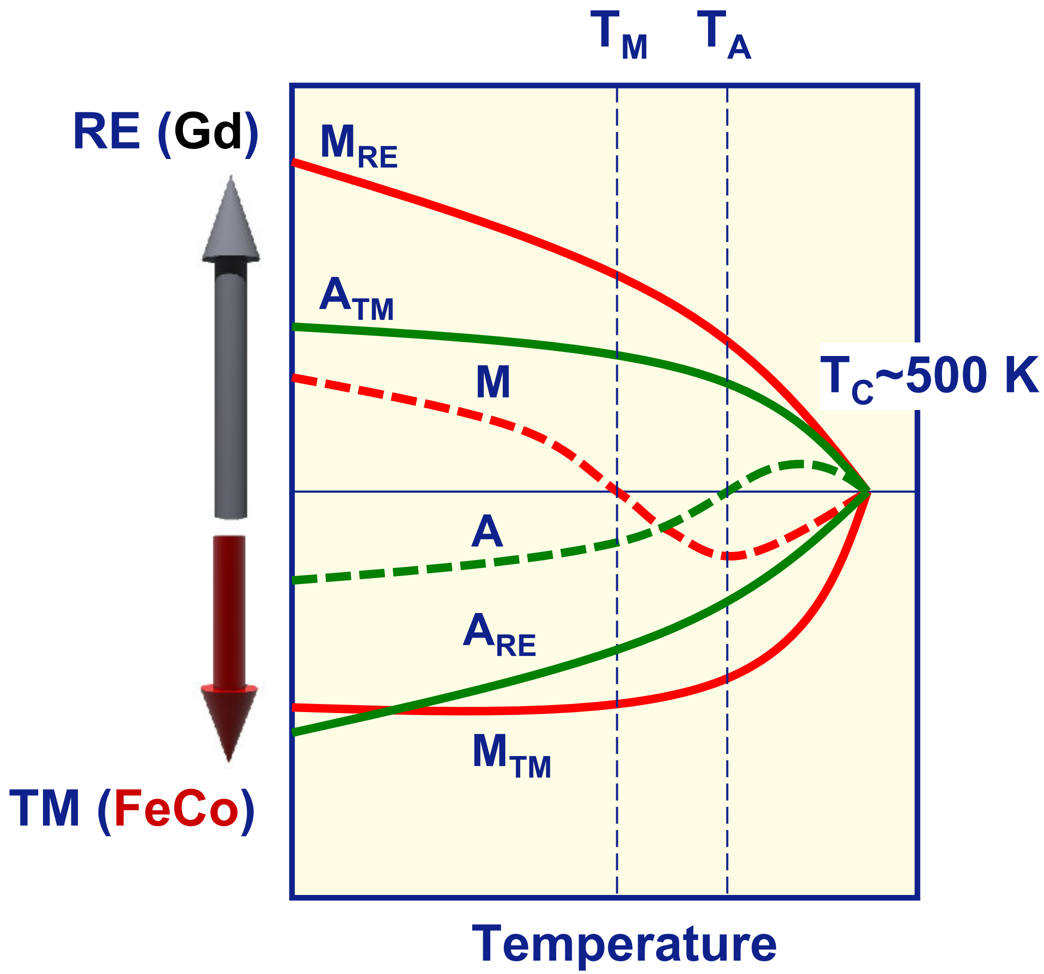
Part 2: the switching as such

1. Switching based on thermal effects

Ferrimagnetic RE-TM alloys & multilayers (e.g. GdFeCo)



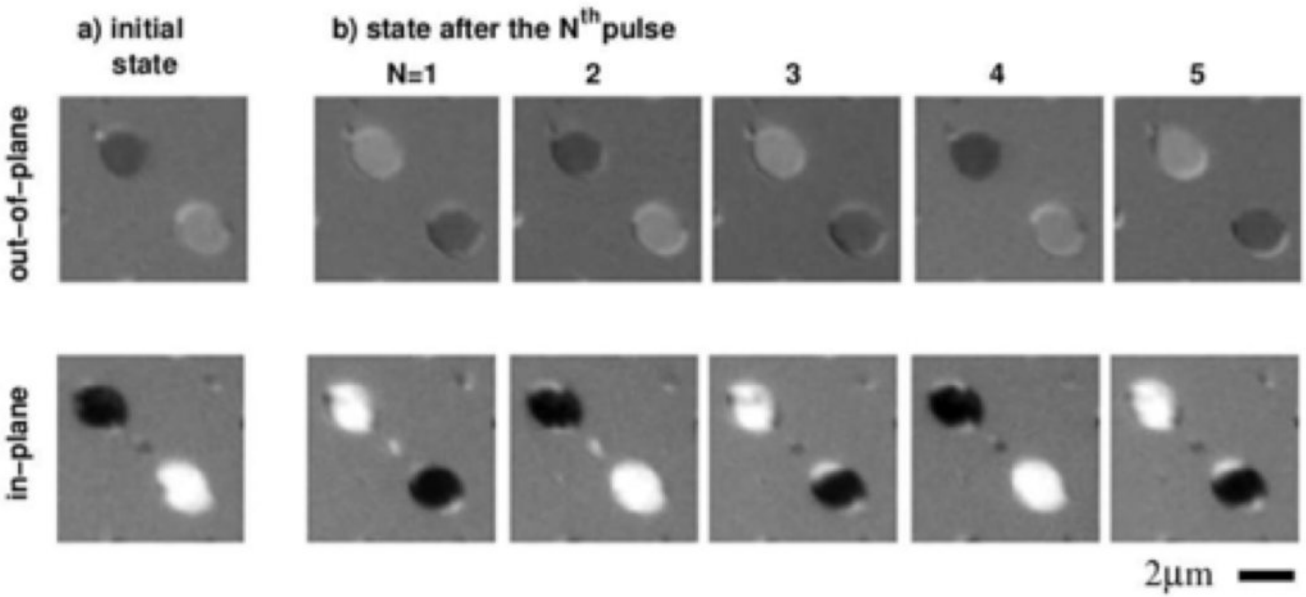


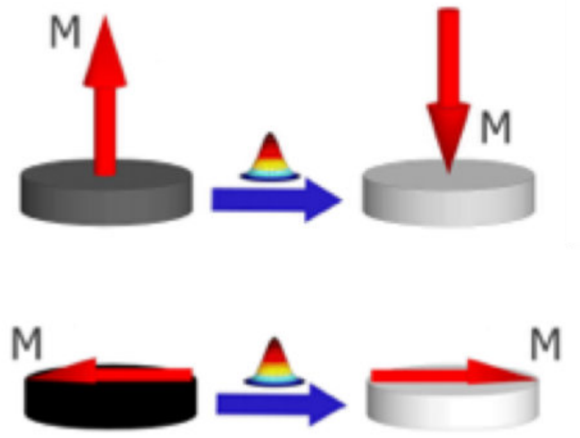


$$g_{Gd} < g_{FeCo}$$

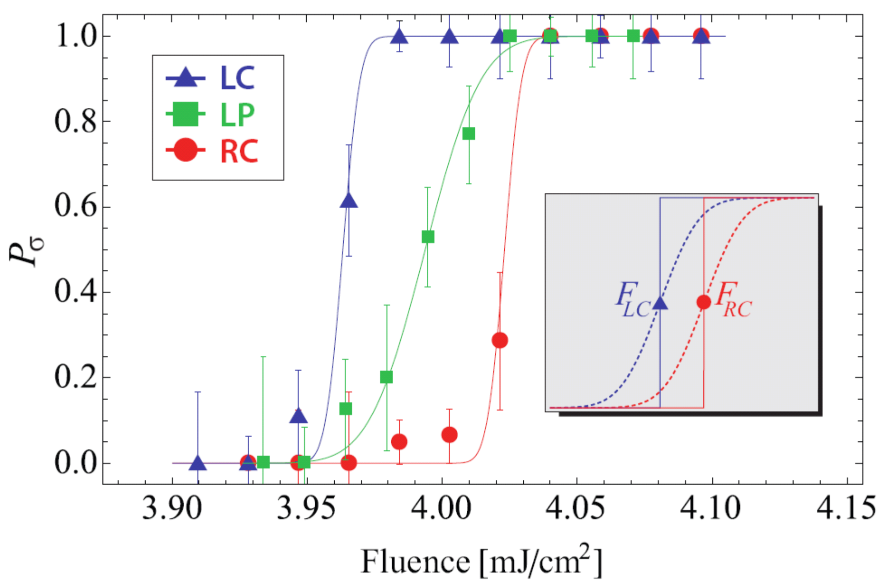
Toggle switching in GdFeCo

Each next image - a single unpolarized laser pulse





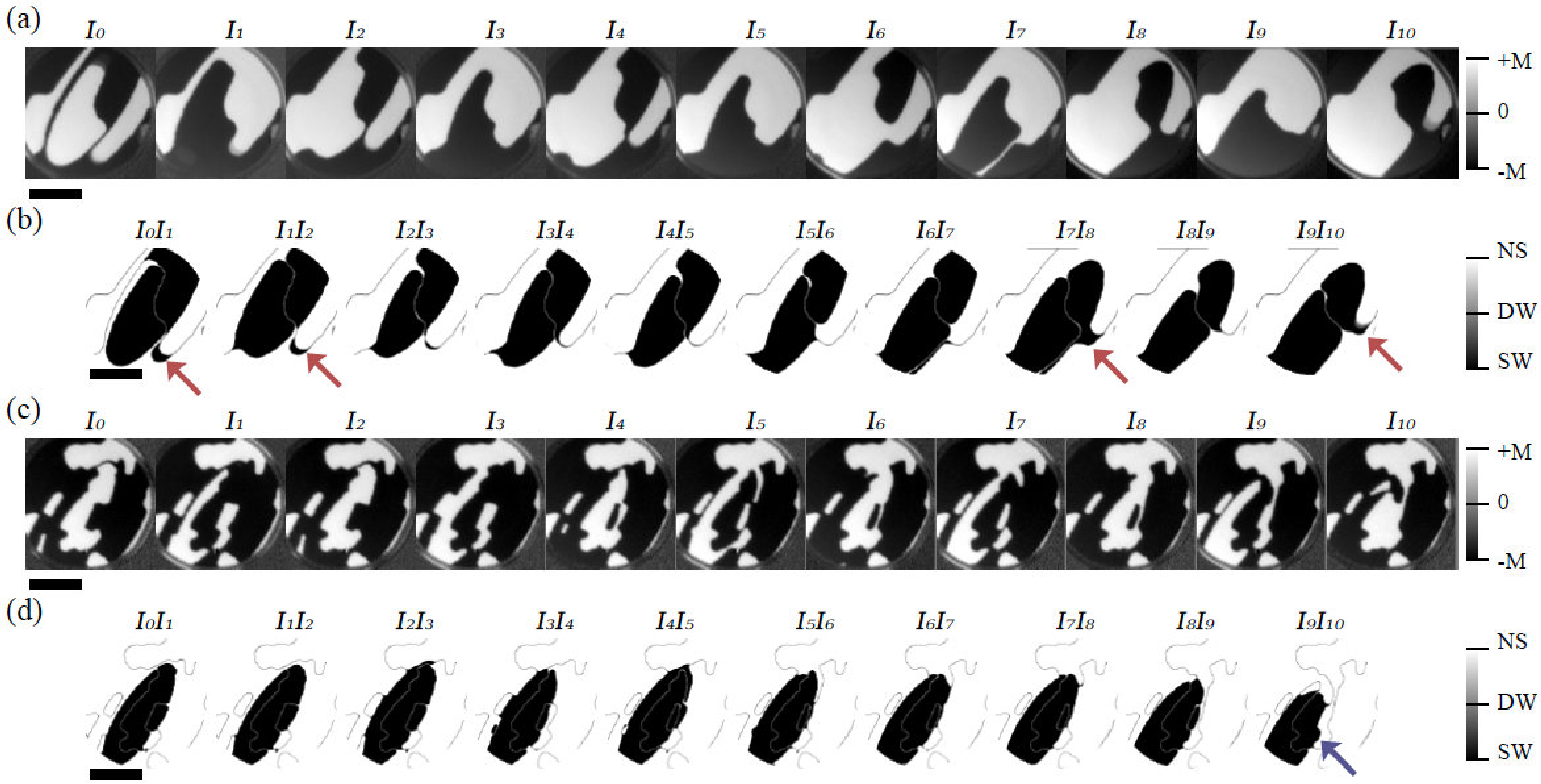
Ostler et al., Nature Commun. **3**, 666 (2012)



amount of energy absorbed in the sample per pulse stays constant

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

Switching of a multi-domains structure: reproducibility

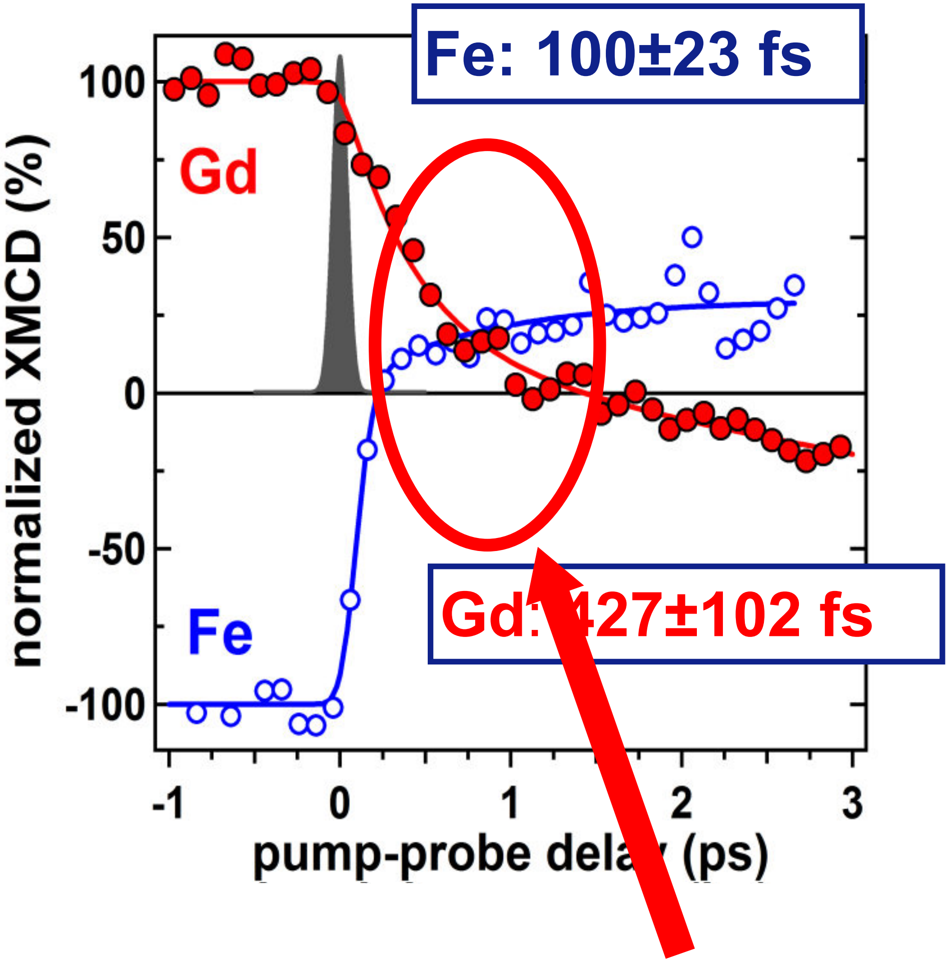


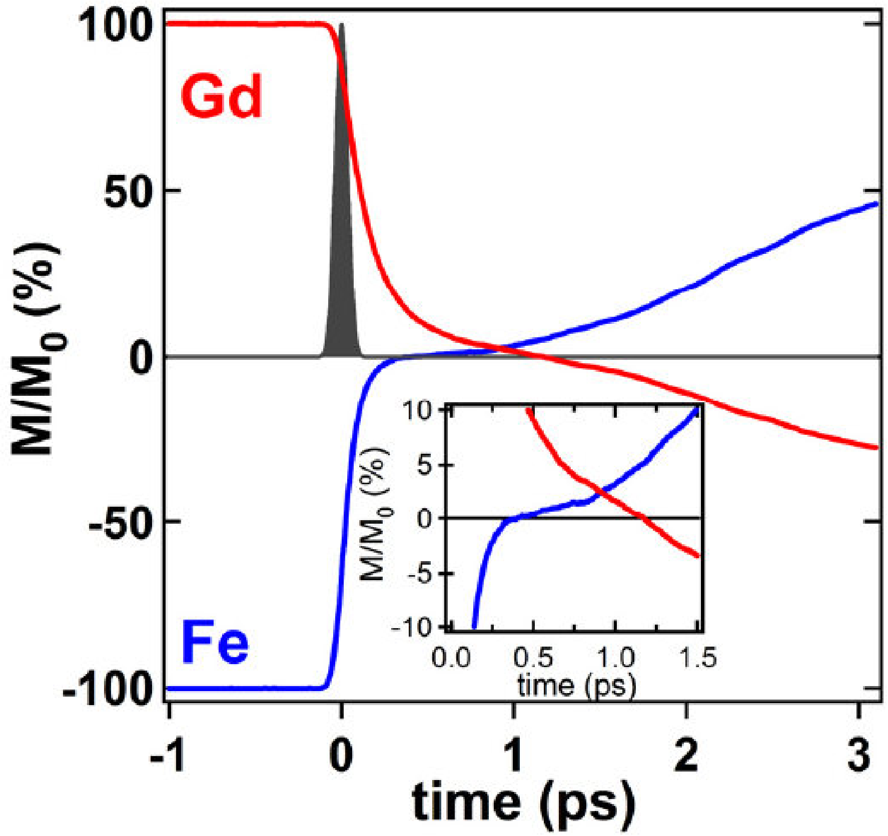
no domain wall motion, just reversal of the whole pattern

Le Guyader et al., Phys. Rev. B **93**, 134402 (2016)

Dynamics of sublattices

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





ferri-magnet turns ferro!

Longitudinal relaxation in multi-sublattice magnets

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

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

$$dS_2/dt = -\lambda_e(H_1 - H_2) + \lambda_2 H_2$$

where $S_i = M_i/\gamma_i$

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

exchange — relativistic (usual damping)

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

conservation S_{tot}

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

Bloch relaxation

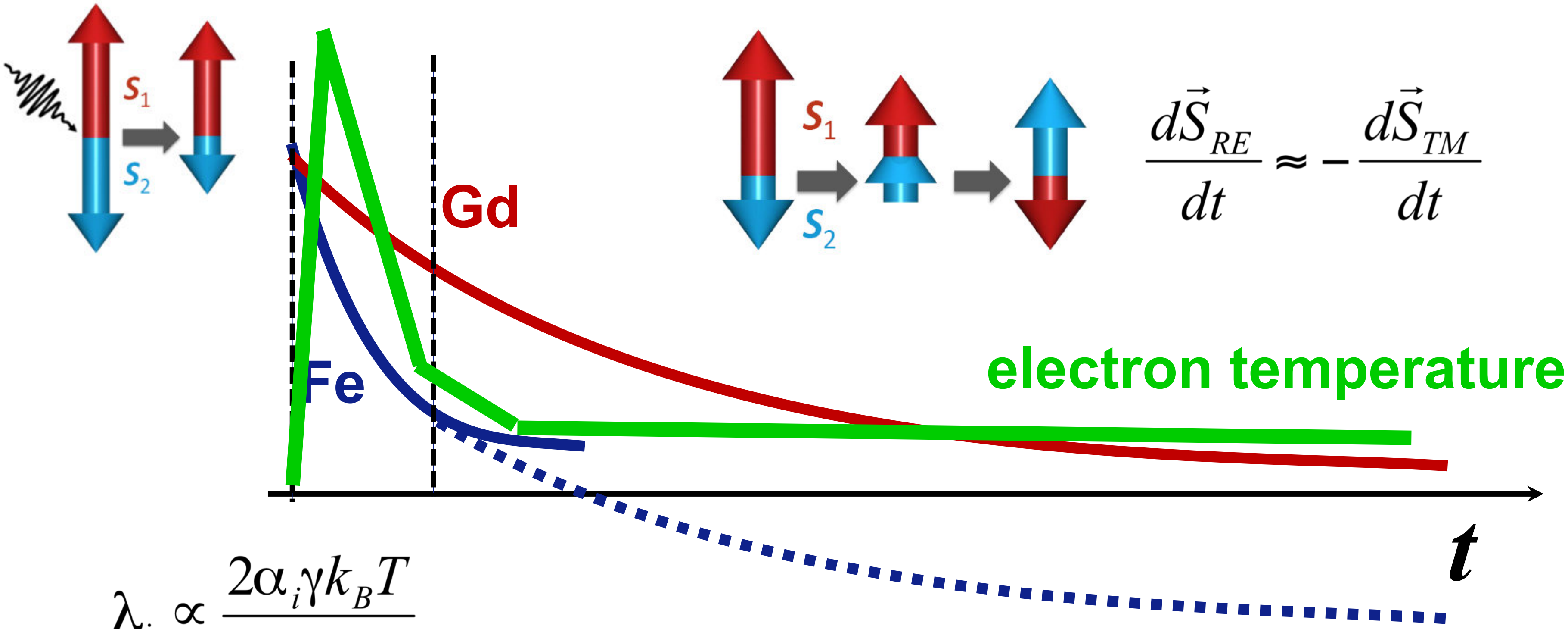
$$dS_i/dt = -S_i/\tau_i$$

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

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

Crossover from temperature- to exchange-dominated

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



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

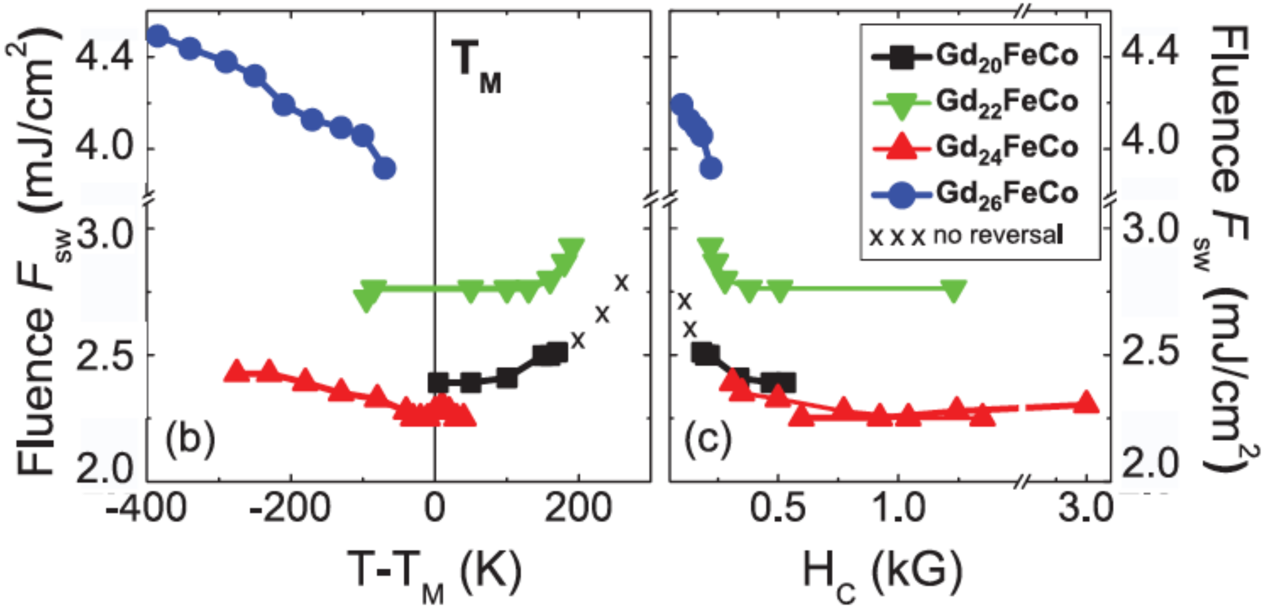
$$\lambda_i \propto \frac{2\alpha_i \gamma k_B T}{\mu_i}$$

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

see Kirilyuk et al., Rep. Prog. Phys. 76, 026501 (2013) for summary

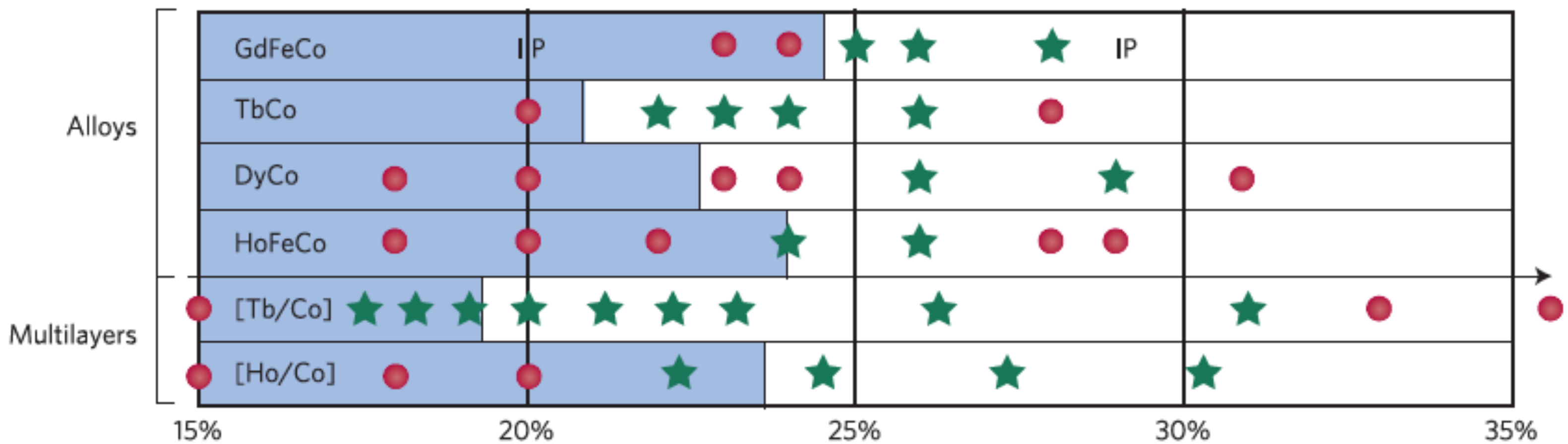
The range of switching

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



It works in
the broad vicinity
of the compensation
temperature

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



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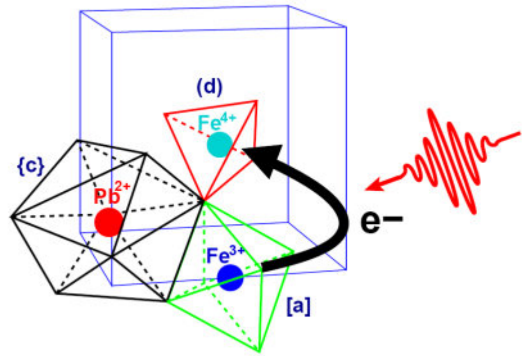
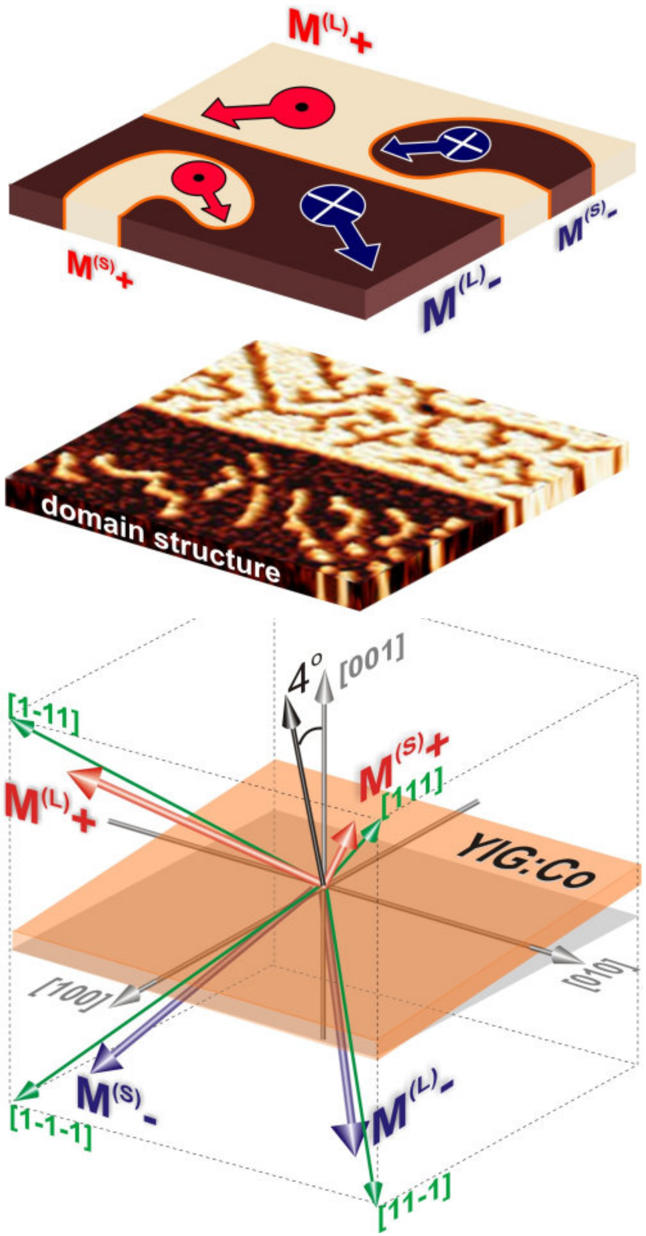
Mechanism: **thermal, fast sublattice-selective demagnetization + exchange-driven reversal**

Time-scale: **~1 ps reversal, 30-1000 ps recovery**

2. Photo-magnetic switching in dielectrics



Co-substituted YIG film



$Y_2CaFe_{3.9}Co_{0.1}GeO_{12}$ on GGG (001)

thickness d=7.5 μm (grown by LPE)

magnetic anisotropy:

K_1= -10^4 erg/cm^3

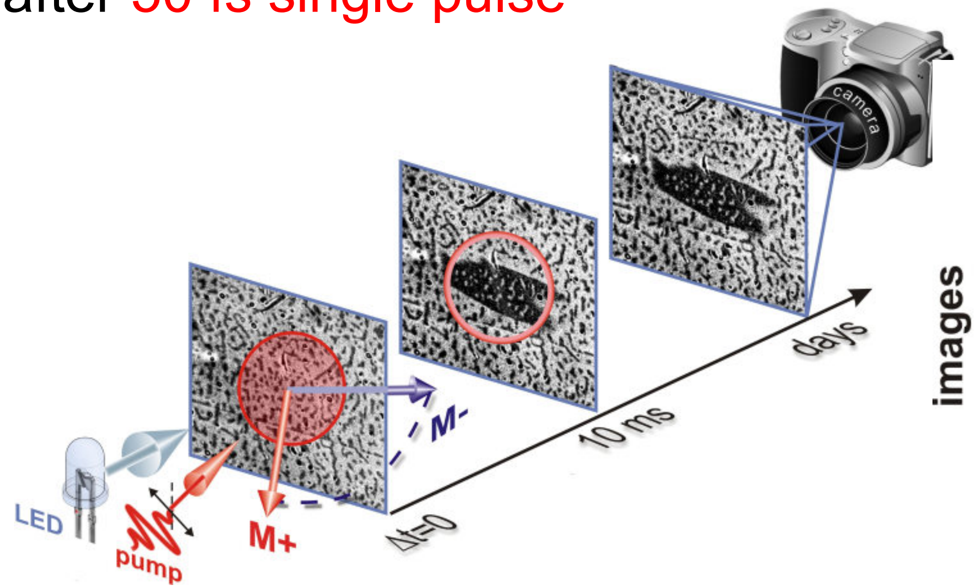
K_U= 10^3 erg/cm^3

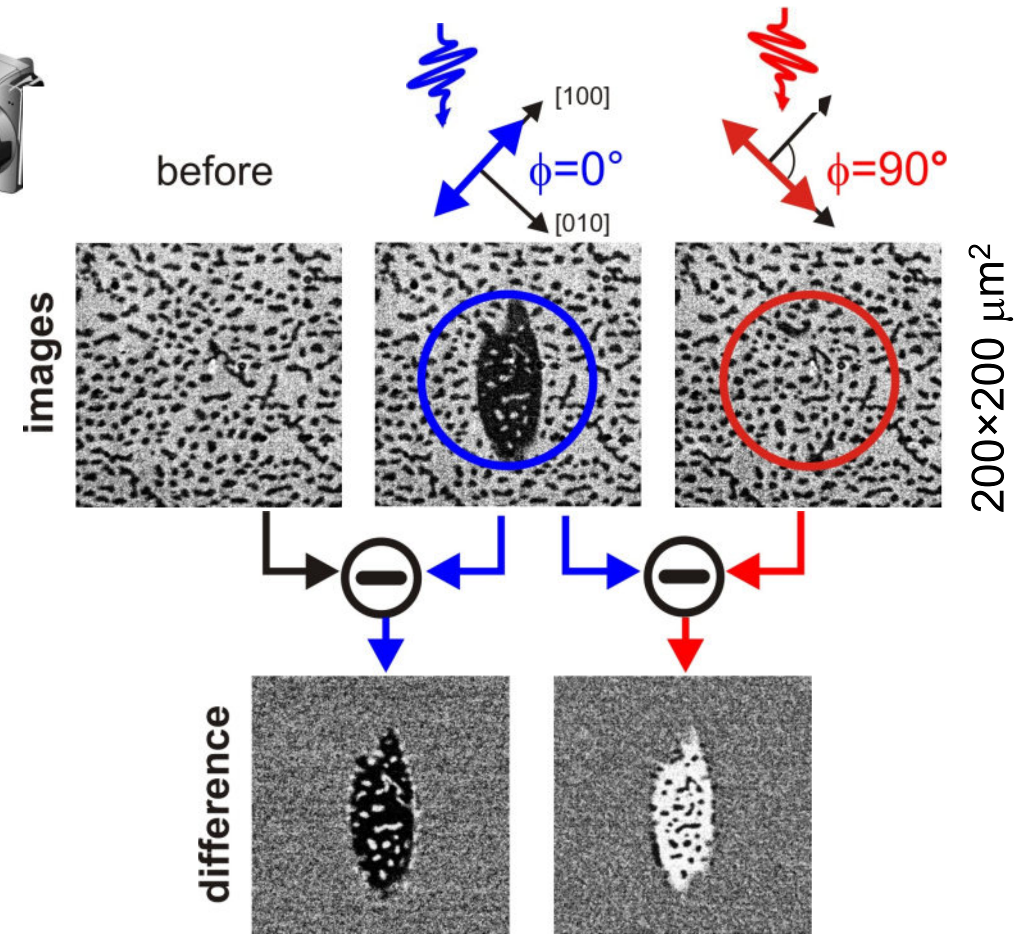
domain structure: metastable states

Single-pulse switching

A. Stupakiewicz et al., Nature **542**, 71 (2017)

Image of the final state >10 ms after 50 fs single pulse





- repeatable
- zero applied field
- room temperature
- tiny absorbed energy (<1 K)

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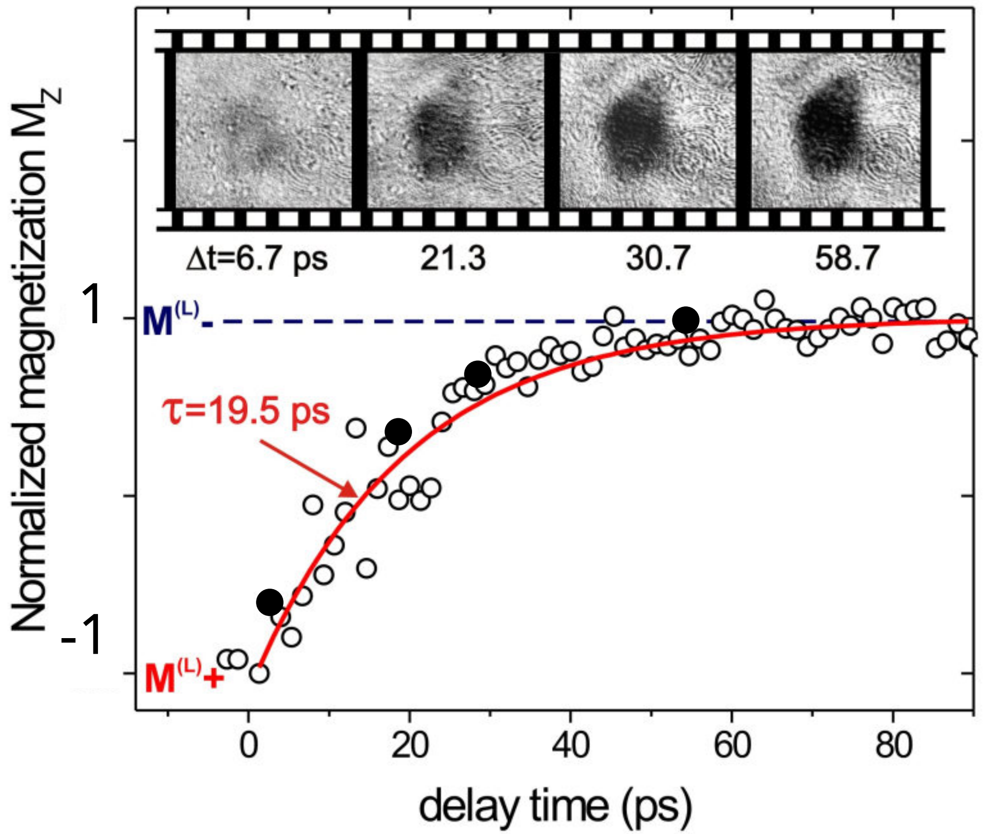
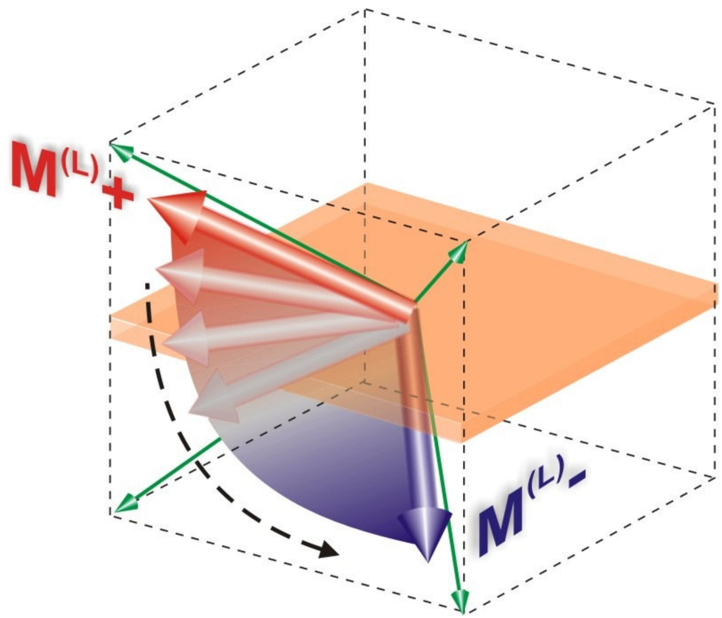
Time resolved observation of switching

switched after first quarter-period

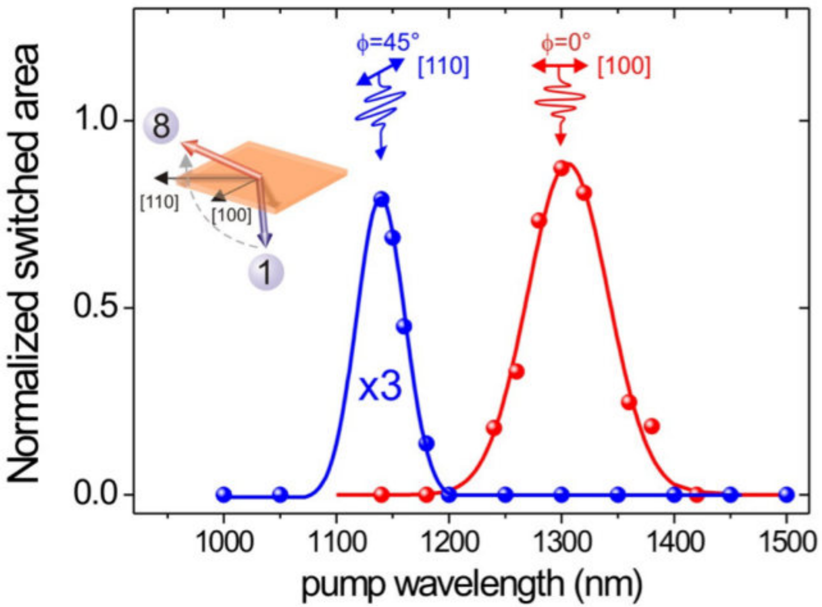


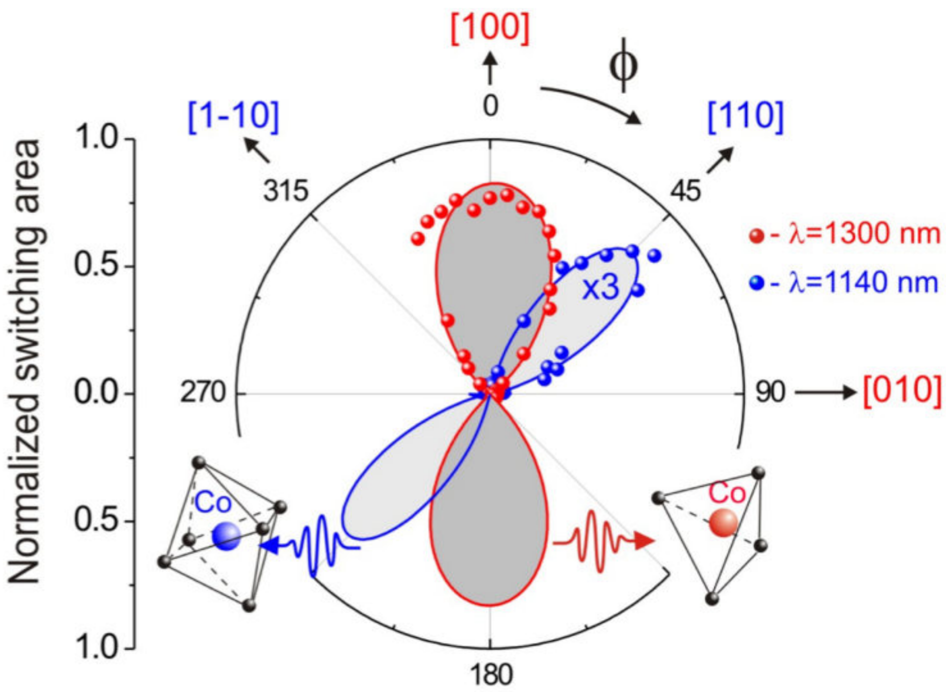


precessional switching!

A. Stupakiewicz et al., Nature **542**, 71 (2017)

Precise atomic-scale control of anisotropy?



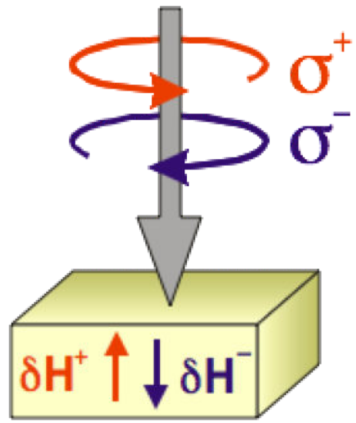


A. Stupakiewicz et al., to be published

Mechanism: photo-magnetic anisotropy driving the precessional reversal (nonthermal !)

Time-scale: precessional motion in the anisotropy field: 20-60 ps

3. Opto-magnetic effect (but not only...)



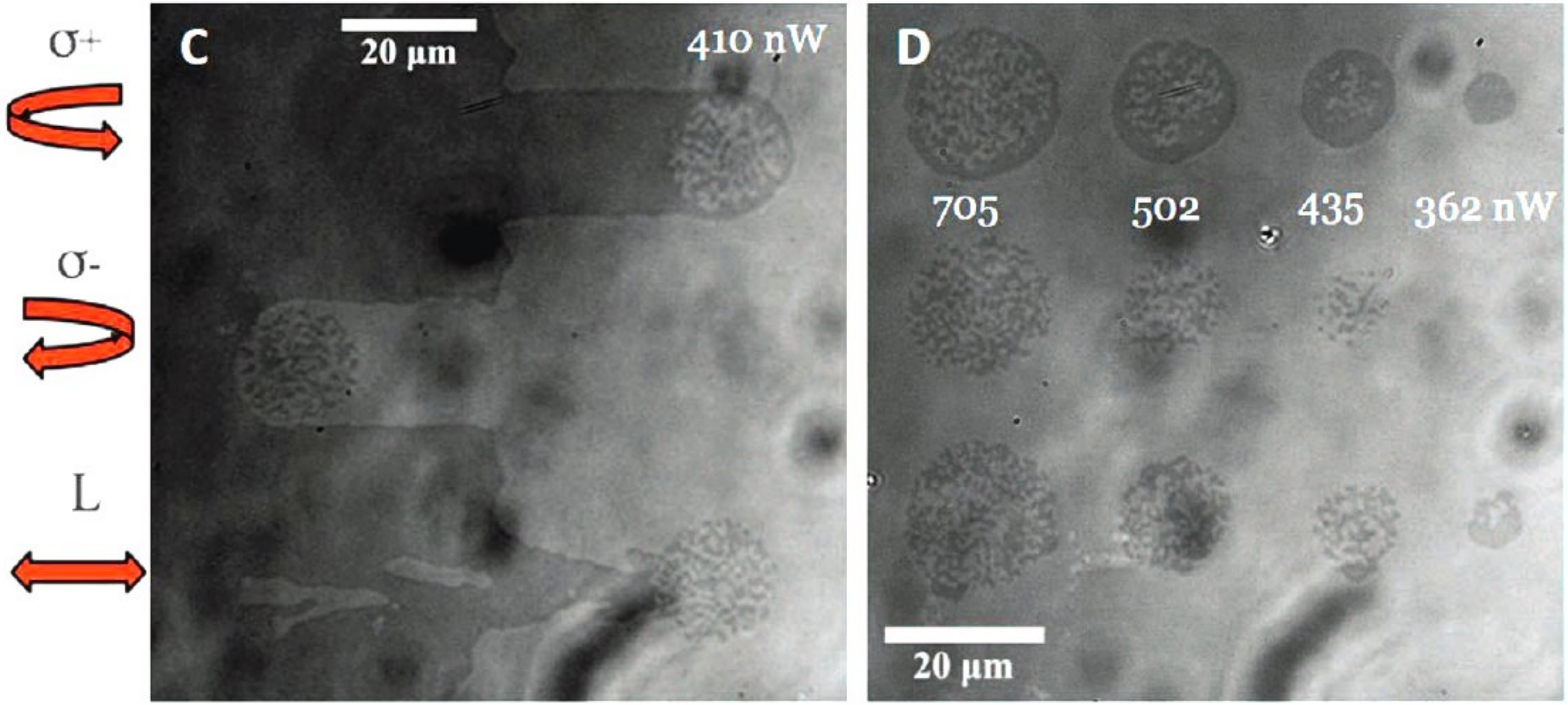
More universal?

All-optical control of ferromagnetic thin films and nanostructures

Co/Pt, FePt

C-H. Lambert,[1,2] S. Mangin,[1,2*] B. S. D. Ch. S. Varaprasad,[3] Y. K. Takahashi,[3] M. Hehn,[2] M. Cinchetti,[4] G. Malinowski,[2] K. Hono,[3] Y. Fainman,[5] M. Aeschlimann,[4] E. E. Fullerton[1,5*]

Science **345**, 1337 (2014)



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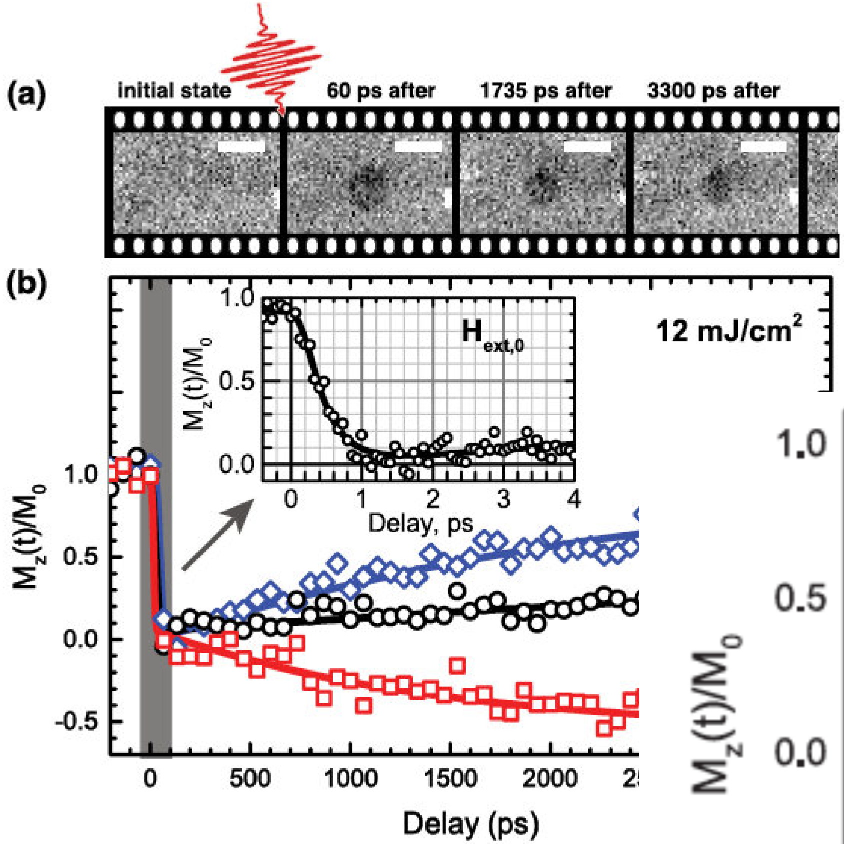
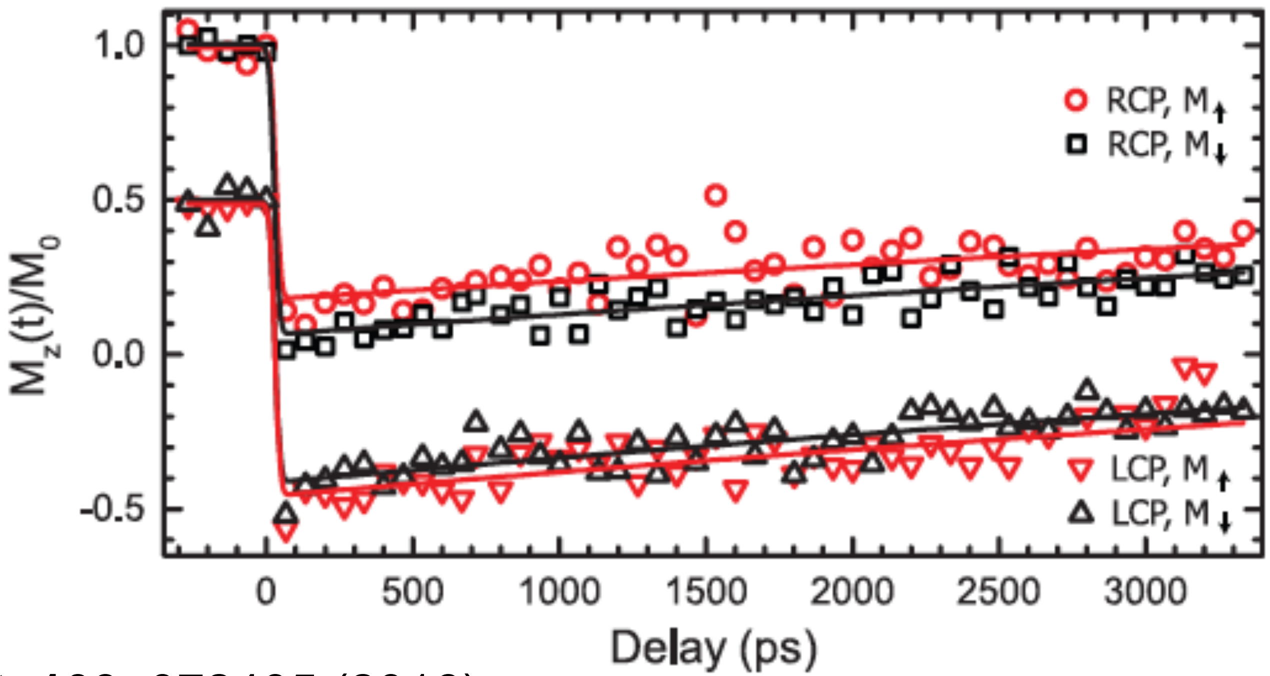
Helicity-effect in the ultrafast demagnetization



[Co(0.4 nm)/Pt(0.7 nm)]$_3$ multilayers

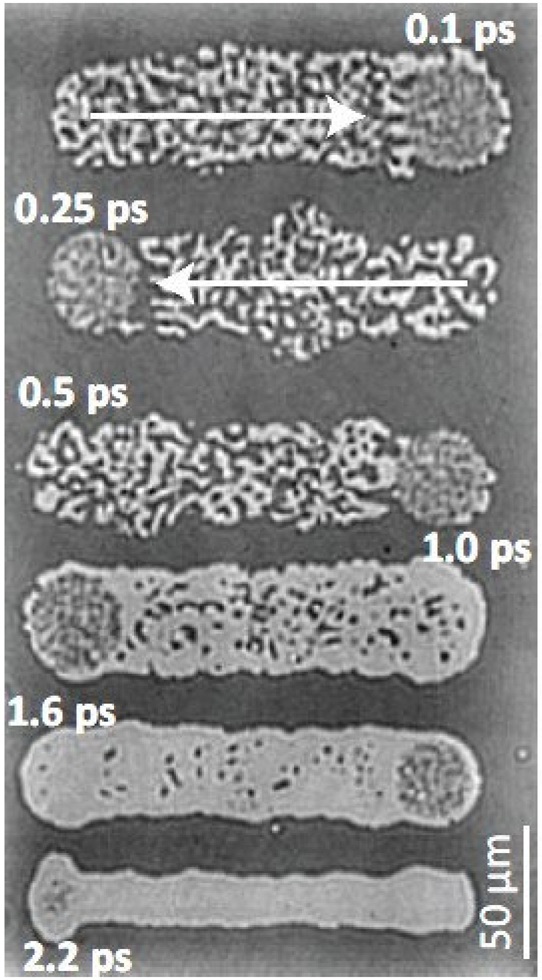
magnetic circular dichroism?

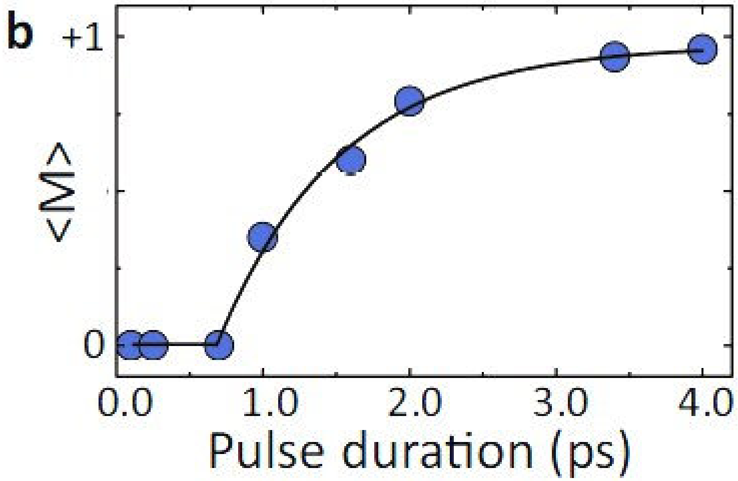


Tsema et al, Appl. Phys. Lett. **109**, 072405 (2016)

Pulse width dependence

R. Medapalli et al, PRB **96**, 224421 (2017)

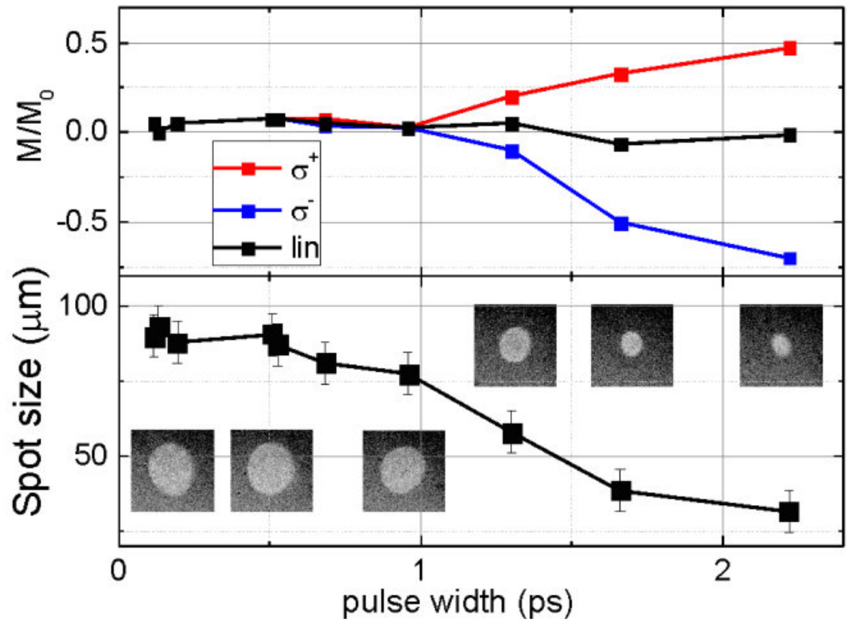




Co/Pt

Co/Pd

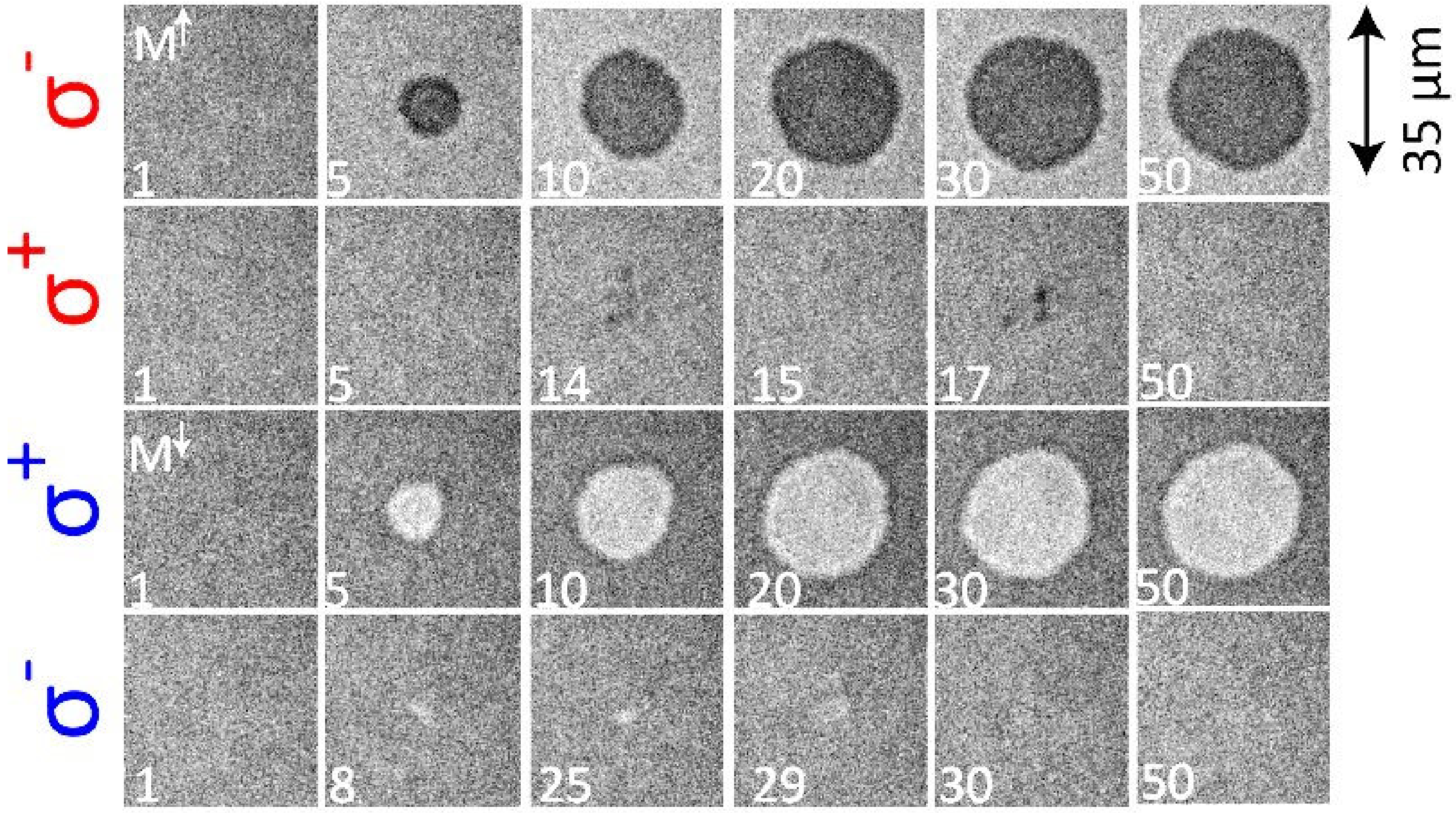
in collaboration with O. Hellwig, HGST



in collaboration with
R. Medapalli and E. Fullerton

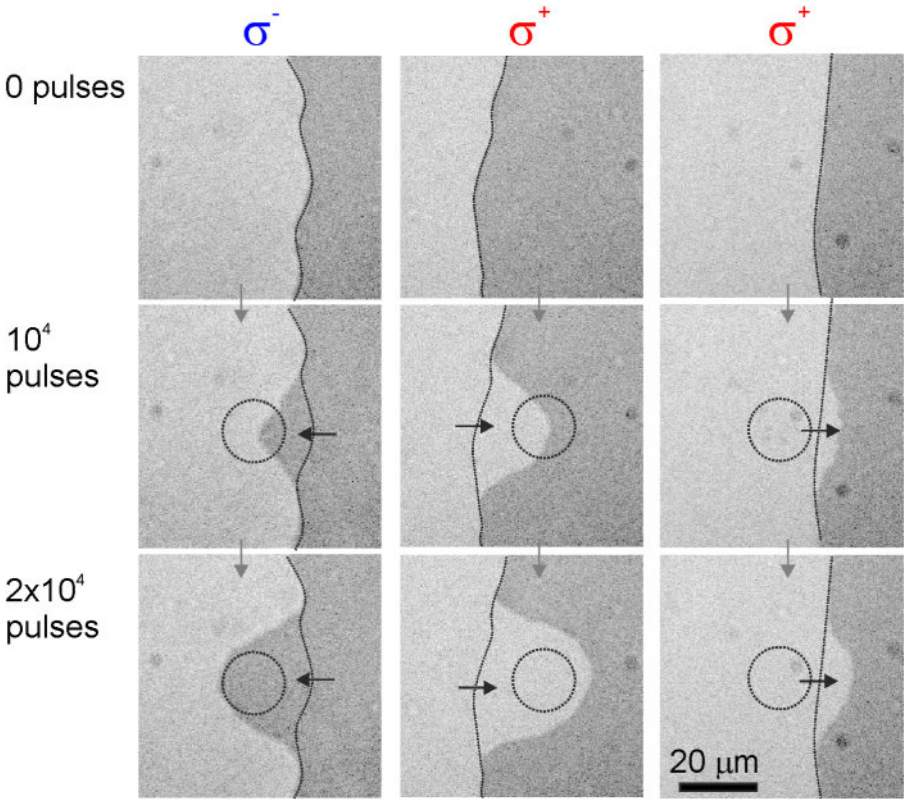
Radboud University

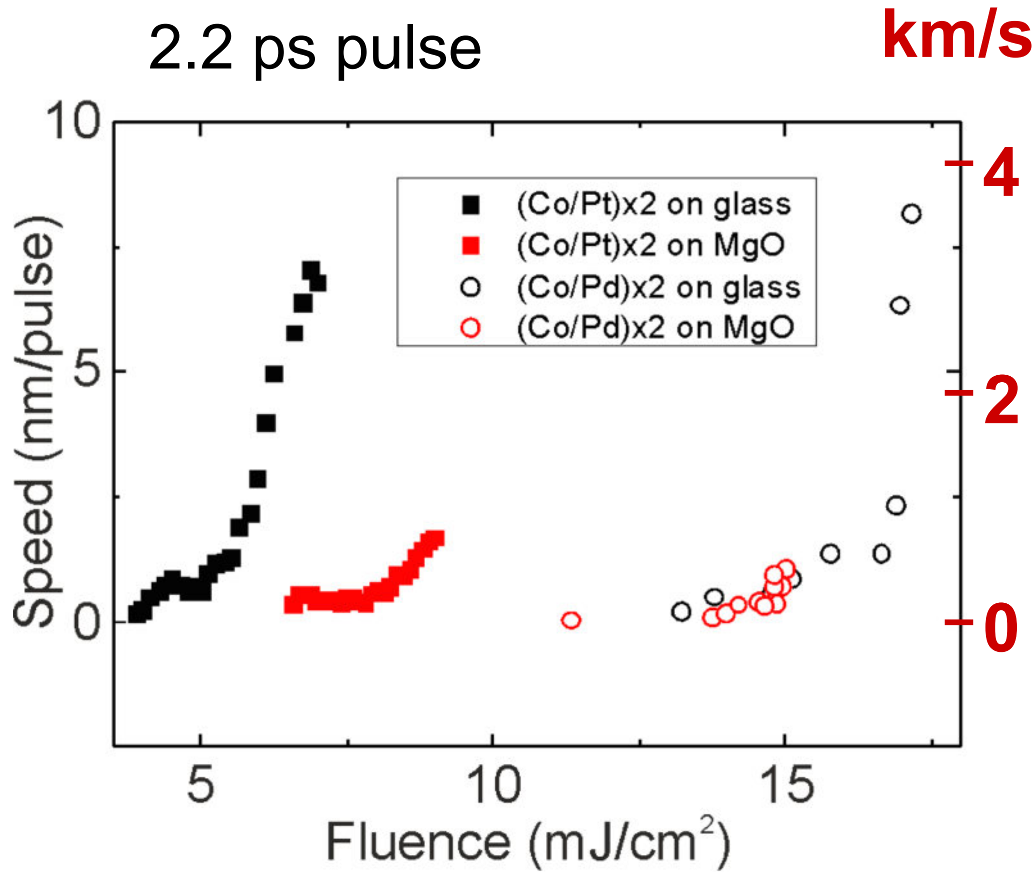
Number-of-pulses dependence in Co/Pt, Co/Pd



The initial nucleation is due to randomized demagnetization, and is followed by helicity-dependent growth

Domain wall motion (CoPd sample from HGST)





The (too) high speed probably implies after-pulse motion

thermal (MCD) *or* **opto-magnetic?**

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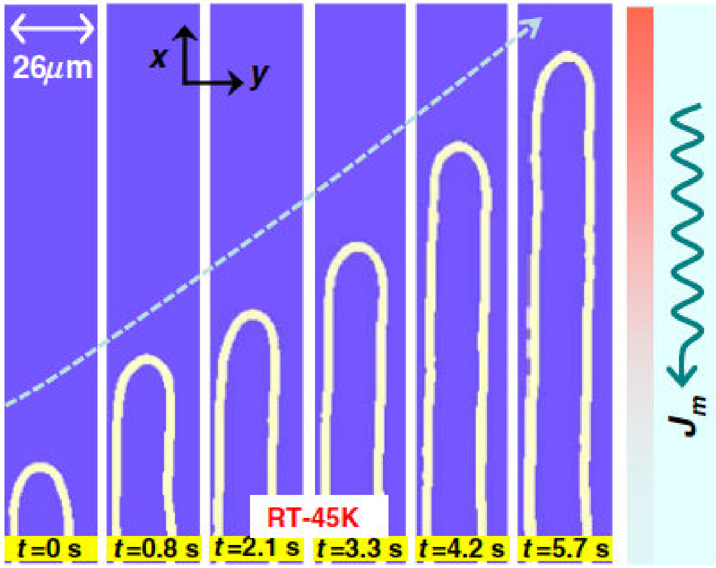
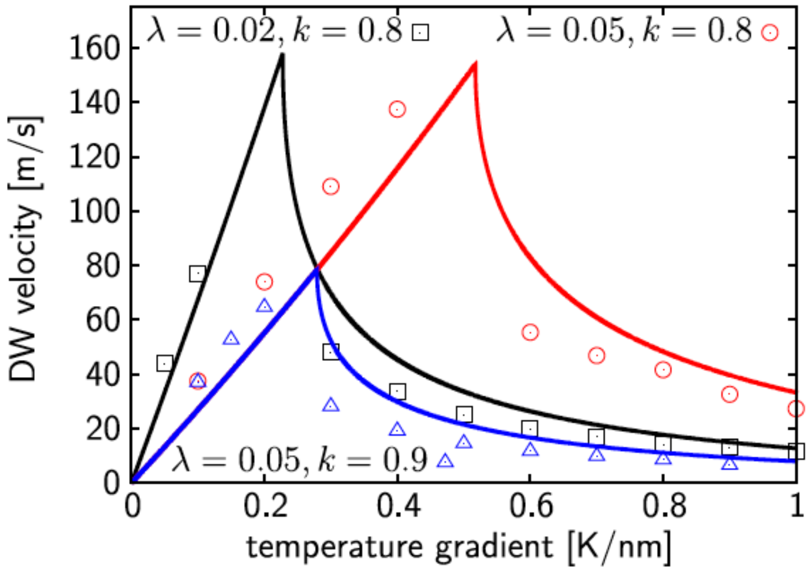
Entropy, thermal magnons?

Magnon flow

W.Jiang et al, PRL **110**, 177202 (2013)





Role of entropy

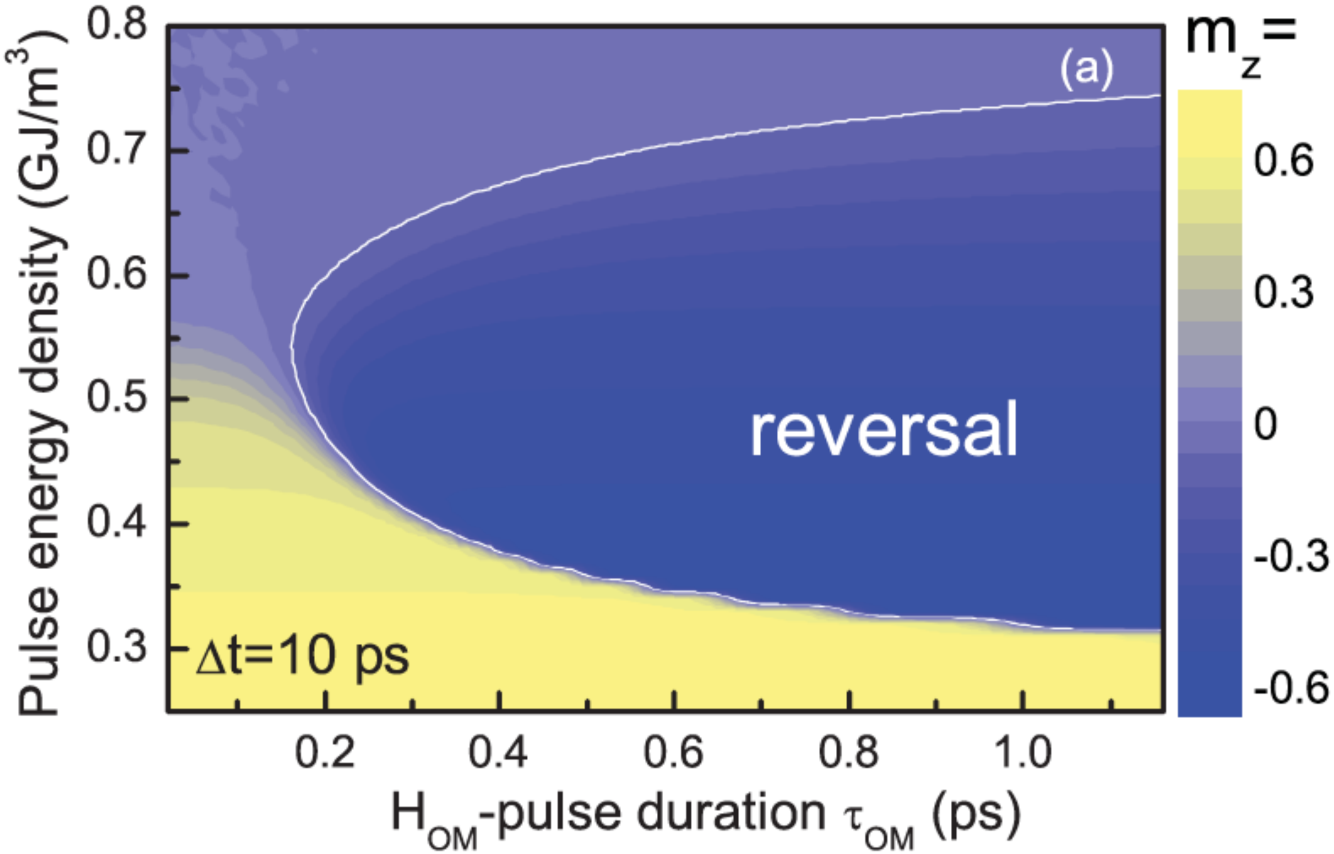
F. Schlickeiser et al, PRL **113**, 097201 (2014)

Both thermal, based on MCD

why would they be so sensitive to the pulse width??

inverse Faraday effect

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



Combination of thermal + opto-magnetic, better with longer pulses

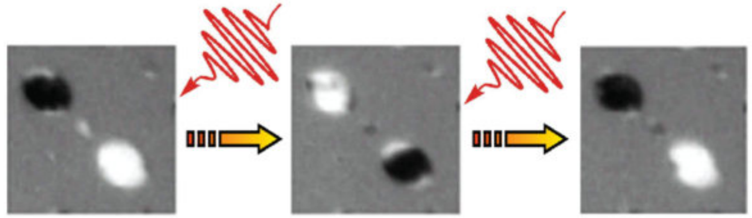
difficult to estimate the effective field!

Mechanism: demagnetization-driven nucleation followed by domain-wall motion (magnons, entropy, iFE?) - i.e. thermal + nonthermal II

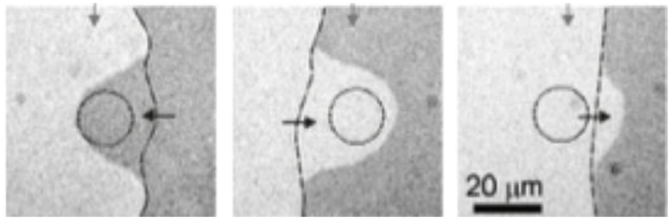
Time-scale: DW motion of few nm/pulse

Summary:

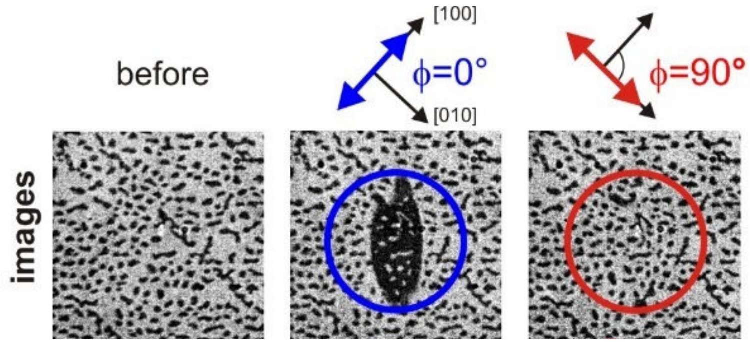
- **Metallic ferrimagnets:** thermally-induced, exchange driven toggle switching



- **Multilayers with strong spin-orbit:** domain wall motion by inverse Faraday effect



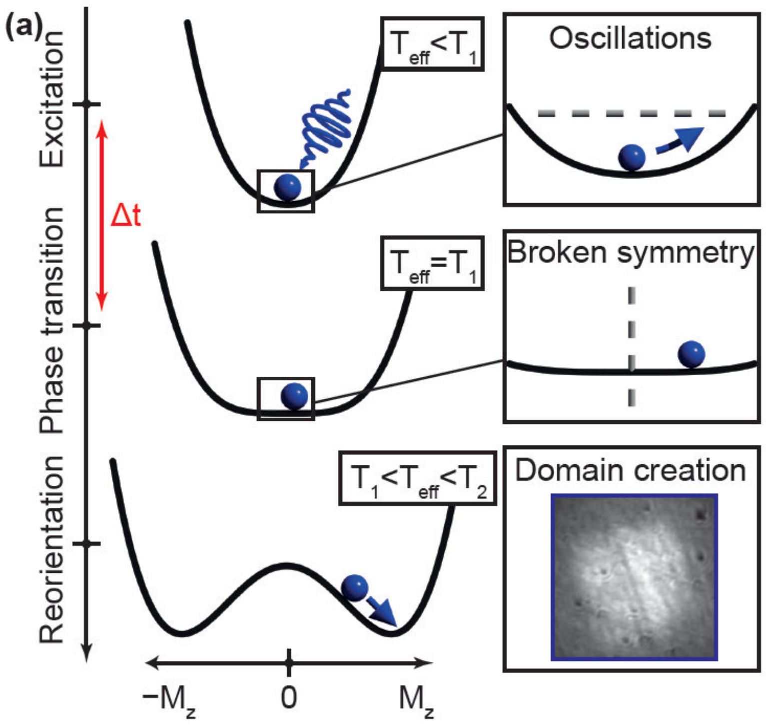
- **Dielectrics:** non-thermal, change of anisotropy by photo-magnetic effects



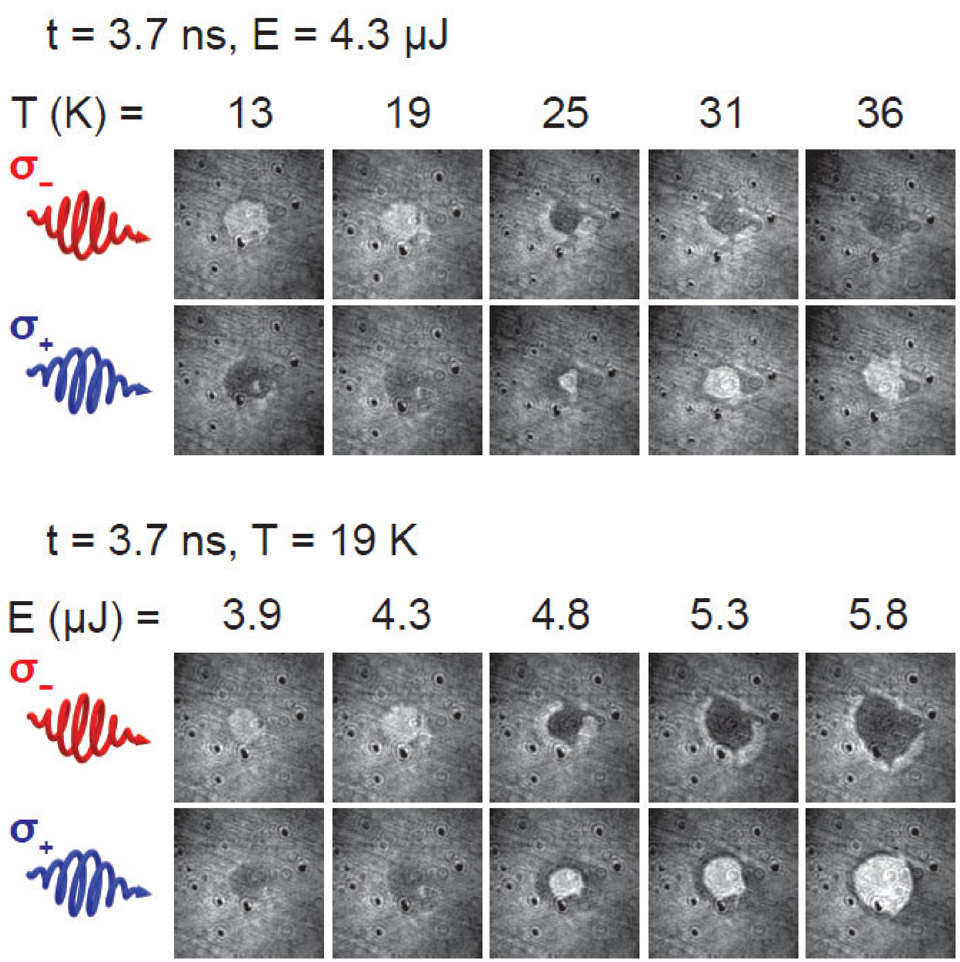
Spare slides

Controlling the route of the phase transition

90° reorientation phase transition



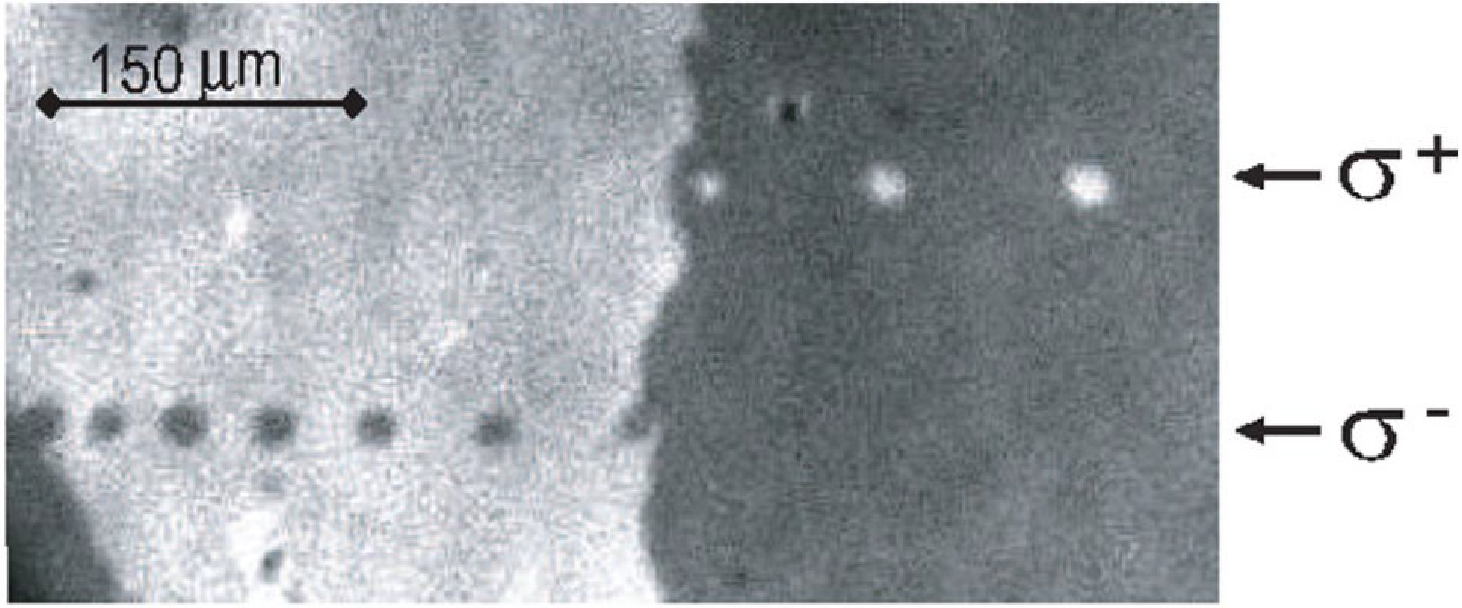
$(SmPr)FeO_3$



de Jong et al, PRL **108**, 157601 (2012)

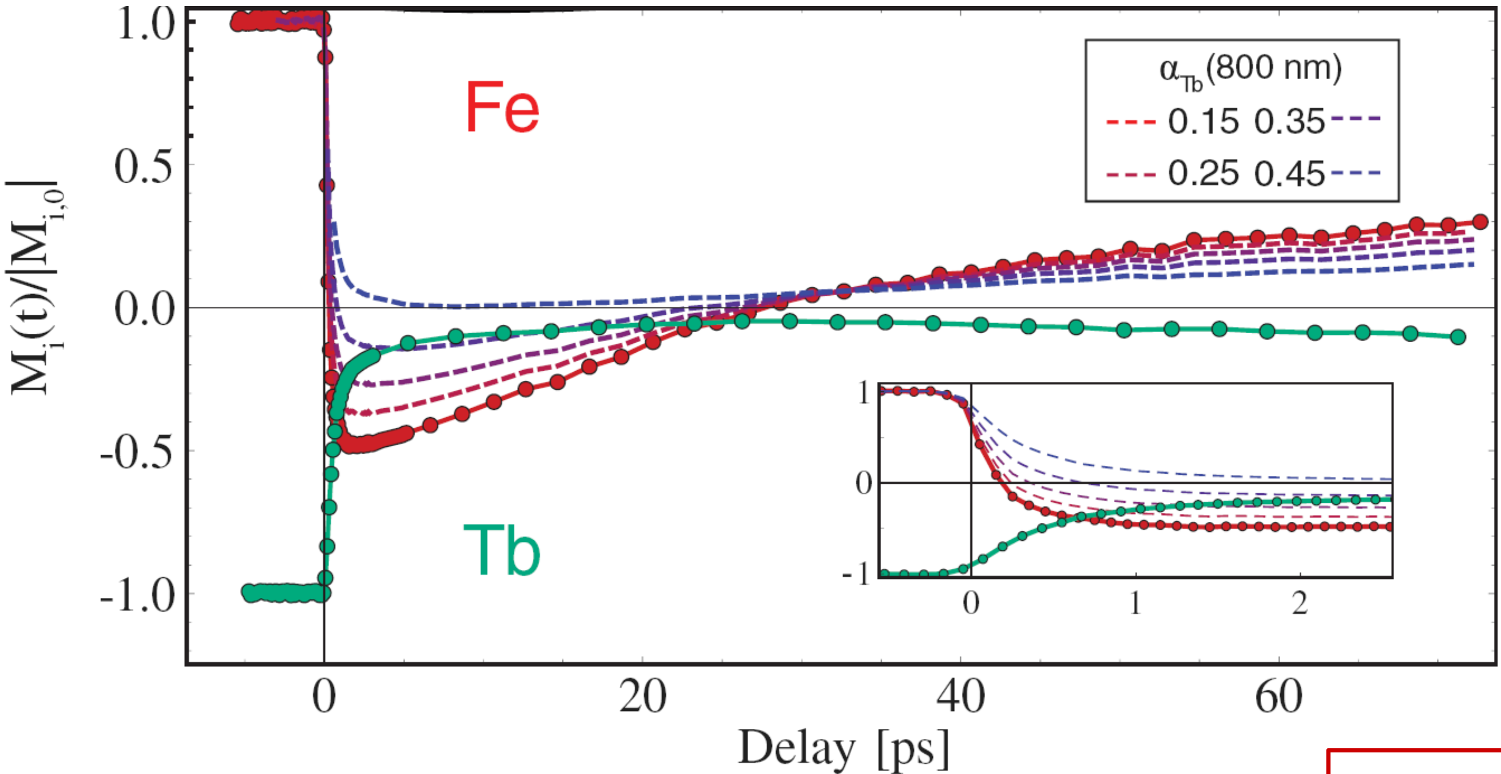
thermal + opto-magnetic

Polarization dependent…



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

Different ferrimagnets: TbFeCo



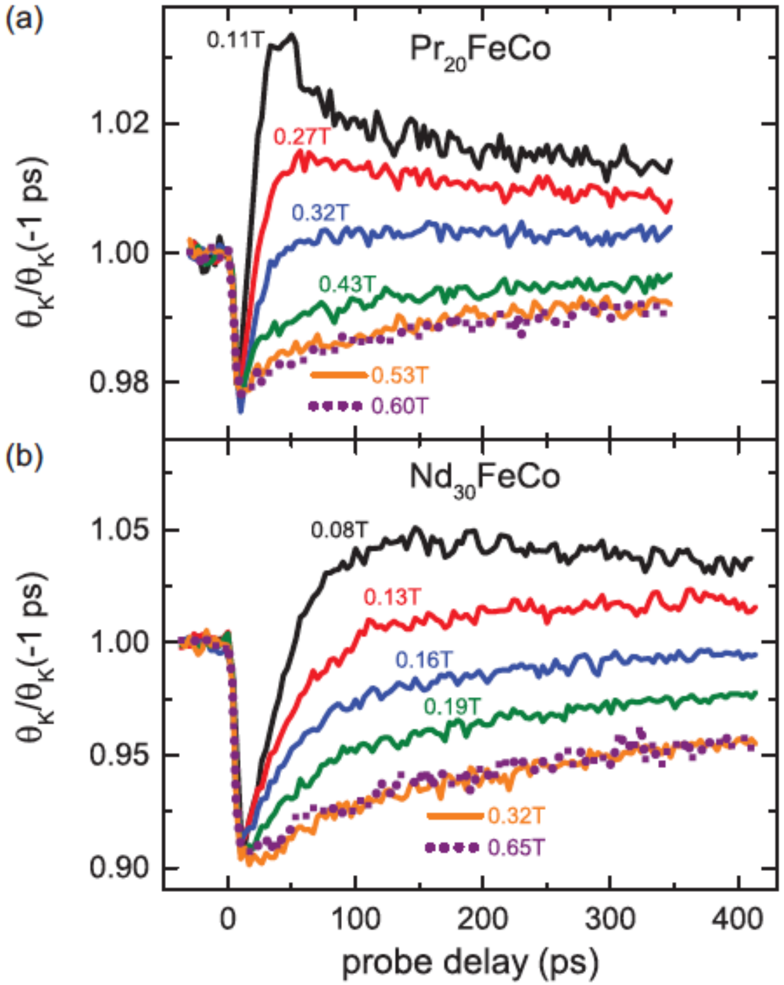
Khorsand et al., Phys. Rev. Lett. **110**, 107205 (2013)

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

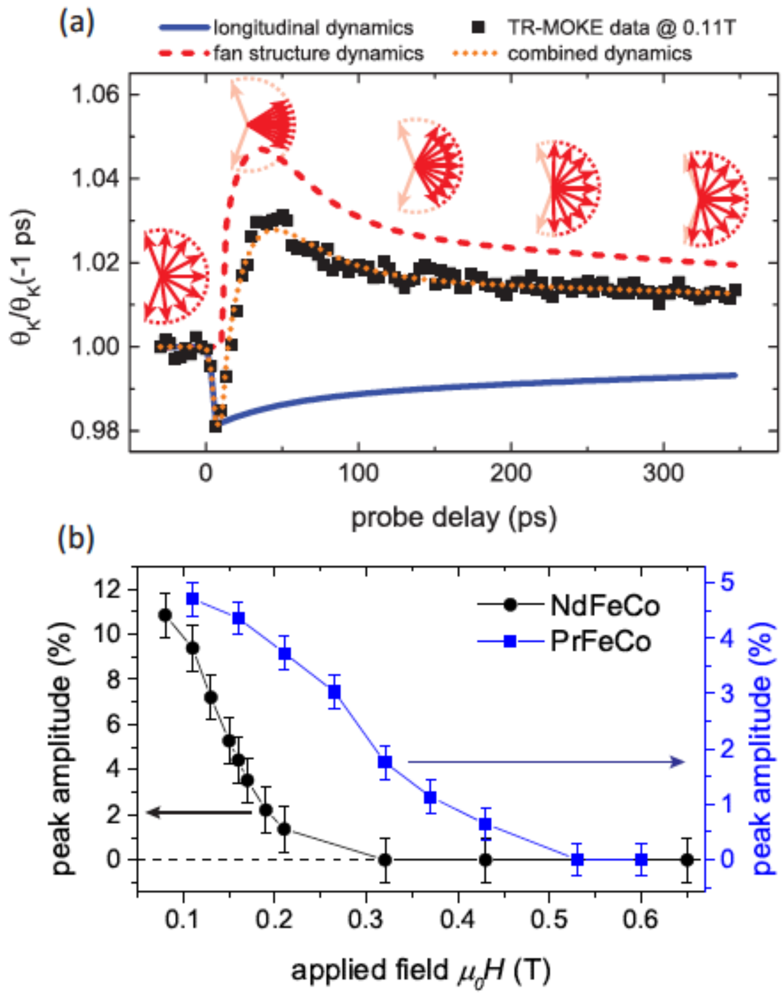
$$M_{\mathrm{Tb}} = g_{\mathrm{Tb}} L$$

Different ferrimagnets: NdFeCo and PrFeCo

demagnetization with an 'overshot'



sperimagnetic arrangement

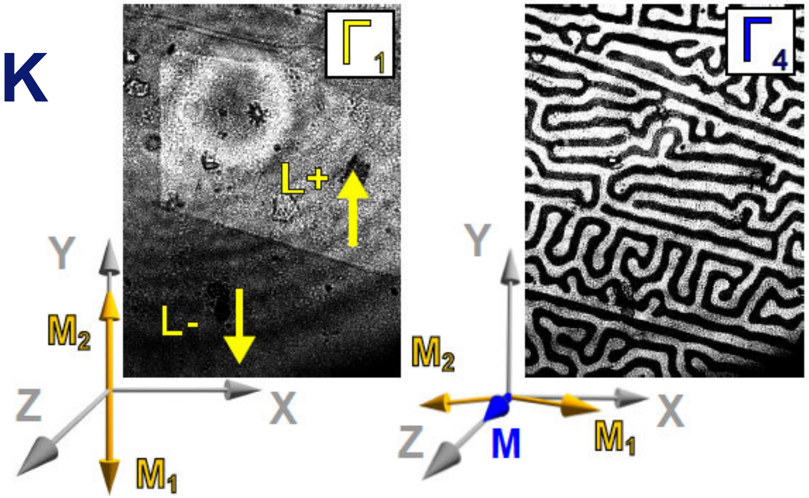


J. Becker et al, Phys. Rev. B **92**, 180407(R) (2015)

Morin 1st order phase transition in $DyFeO_3$

$T < T_M = 39$ K

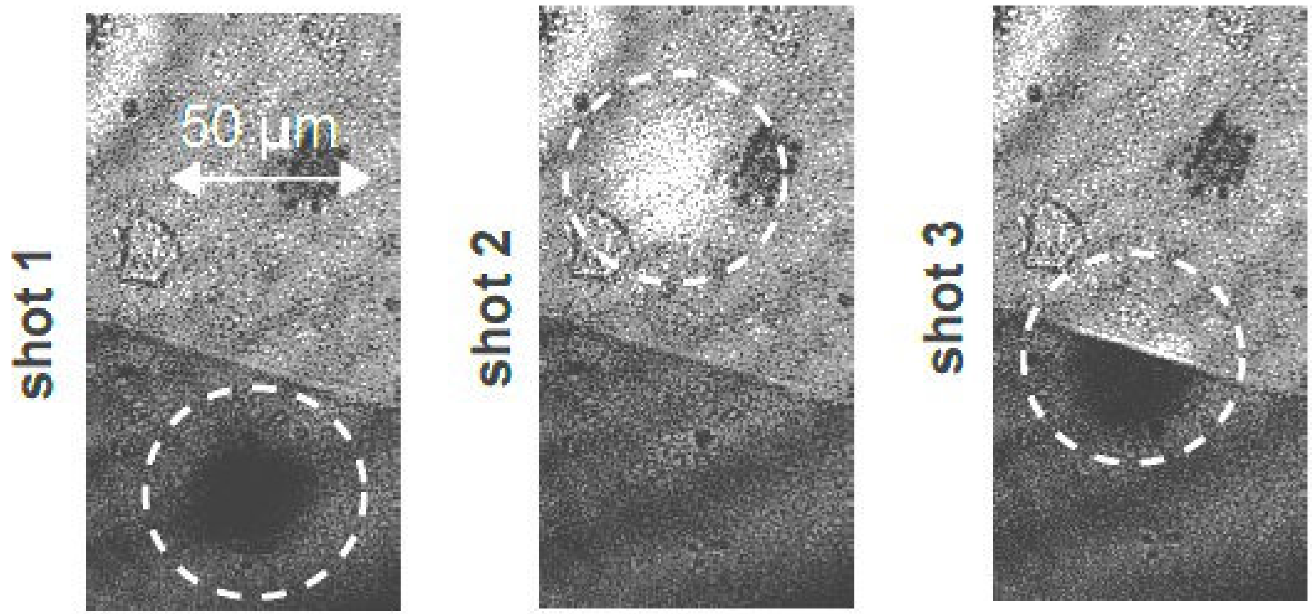
AFM



$T > T_M = 39$ K

weak FM

D. Afanasiev et al,
PRL **116**, 097401 (2016)



same linear polarization

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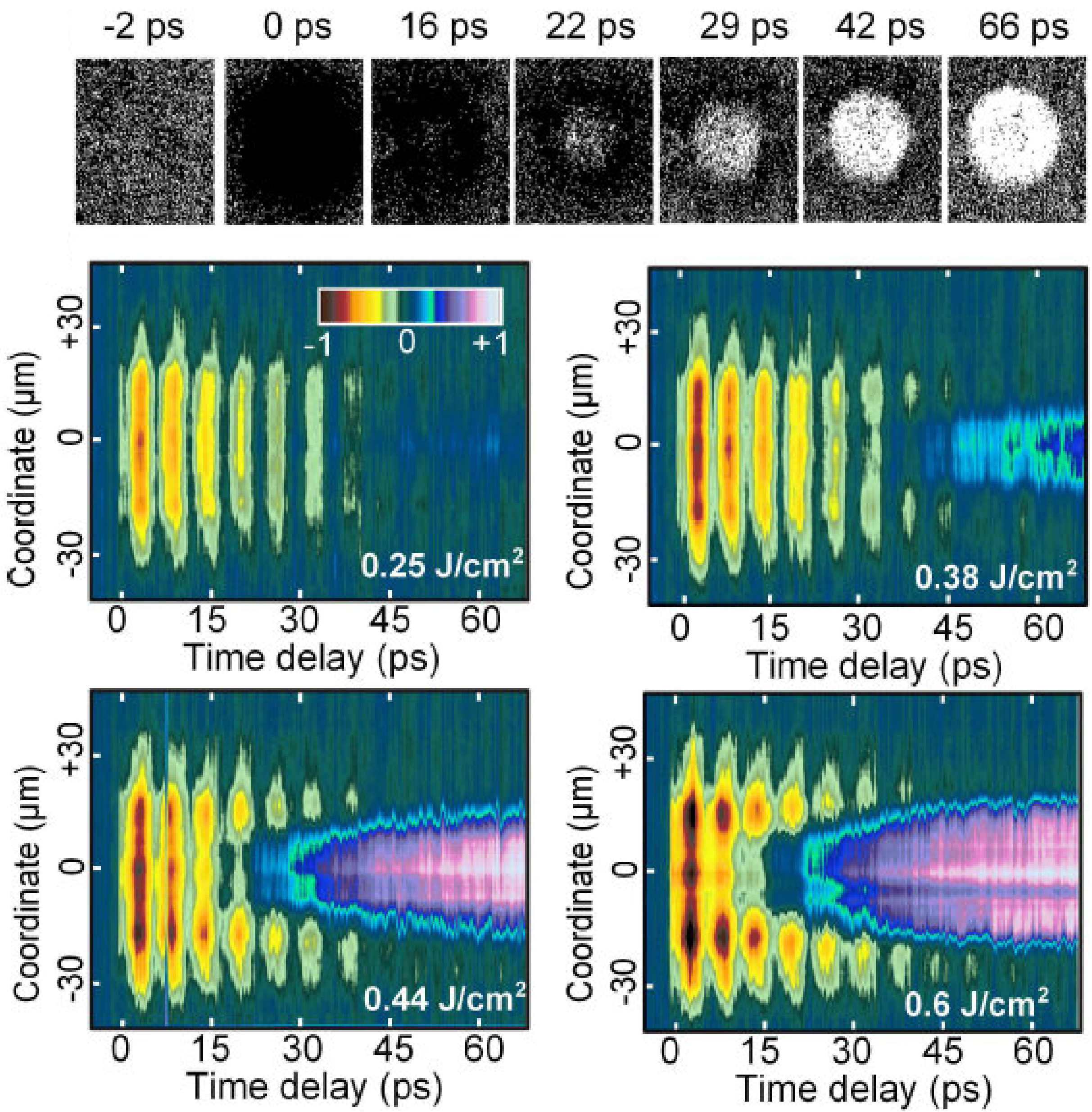
Dynamics: from precession to the new phase



difference with 2nd order

D. Afanasiev et al,
PRL **116**, 097401 (2016)

thermal + opto-magnetic