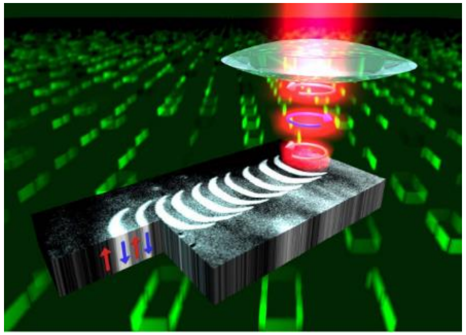
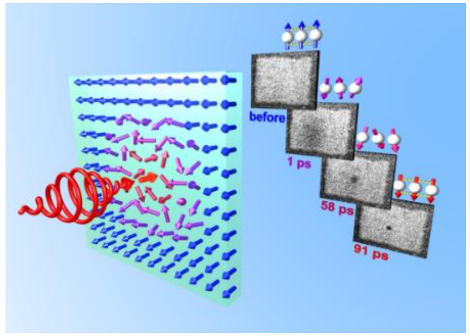
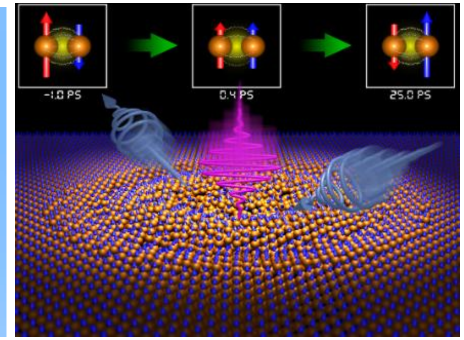
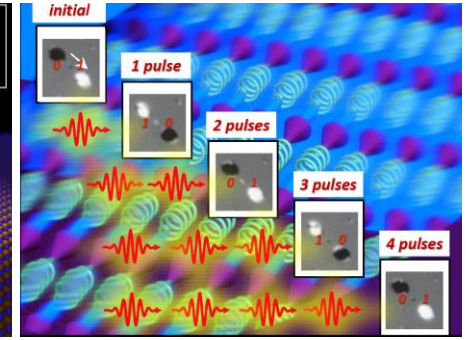








Femtosecond magnetism:
the role of the exchange spin-spin interaction

Alexey V. Kimel

Radboud University Nijmegen,
Institute for Molecules and Materials,
Nijmegen, The Netherlands

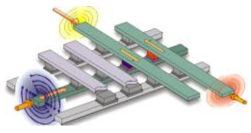
Radboud University Nijmegen

Ultrafast magnetism:

terra incognita of modern science

Technology

MRAM



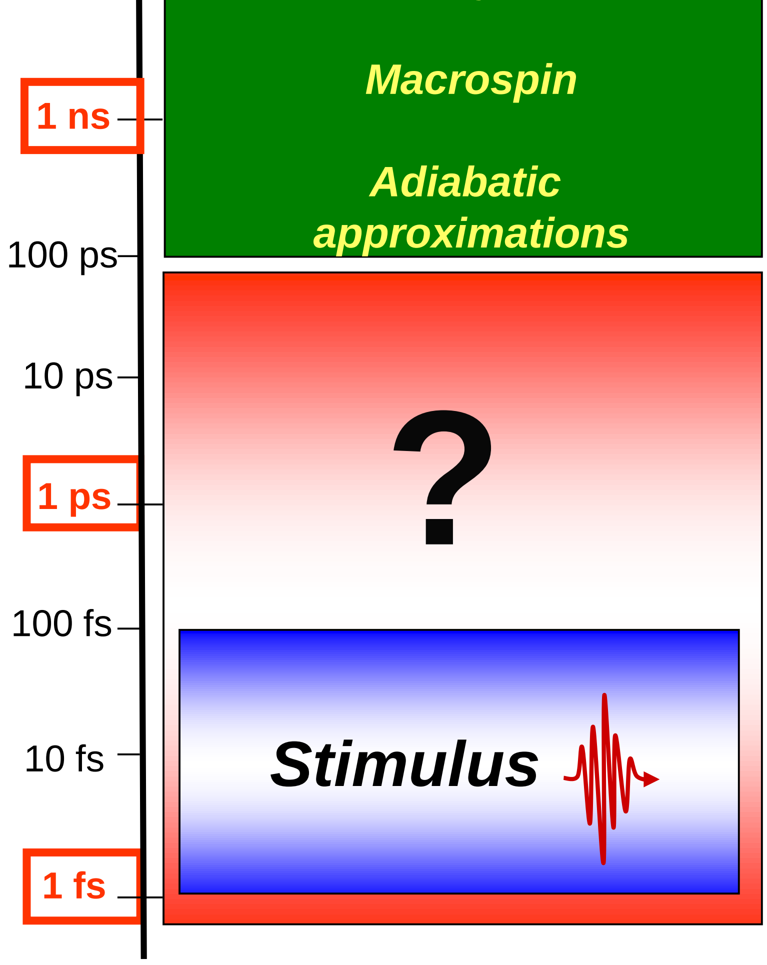
Hard Drive

Computing time per bit

Recording time per bit

Challenge:
To control magnetic state of a medium with the best possible temporal resolutions

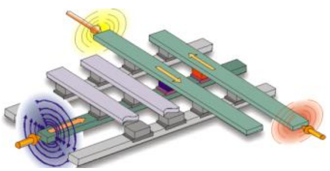
Science



Magnetism in Technology and Science

Technology

MRAM



Hard Drive

Computing time per bit

Recording time per bit

1 ns

100 ps

10 ps

1 ps

100 fs

10 fs

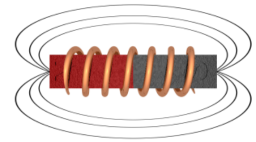
1 fs

Challenge:

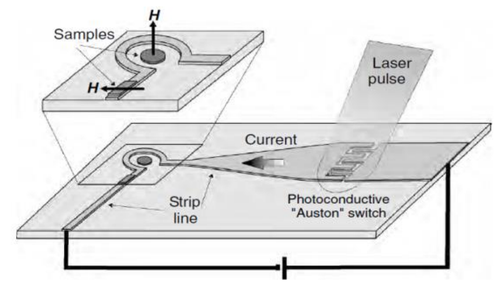
To control magnetic state
of a medium with the best possible
temporal and spatial resolutions

Stimuli

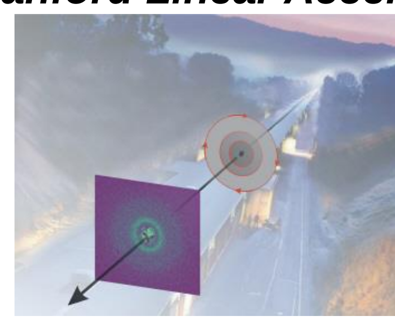
Electromagnets



Photoswitch



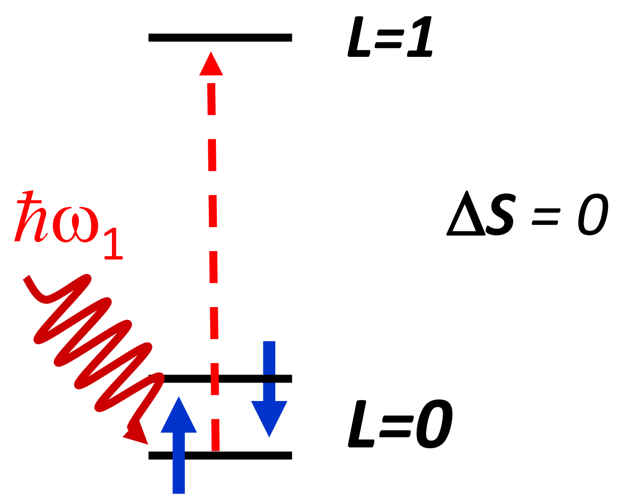
Stanford Linear Accelerator

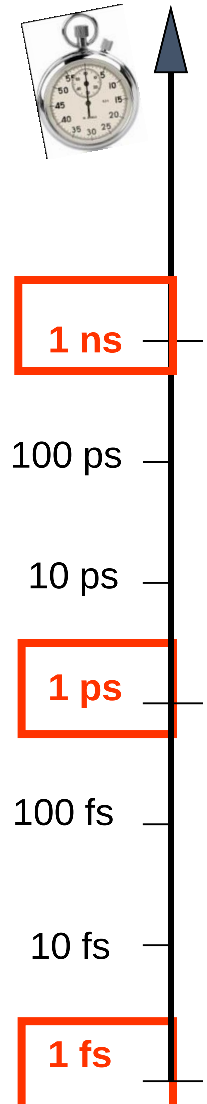


Laser Pulse

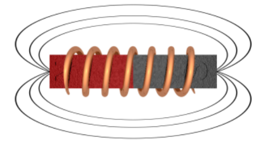
Magnetism in Technology and Science

Can light act as a magnetic field?

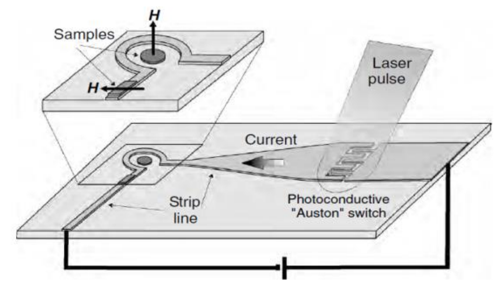




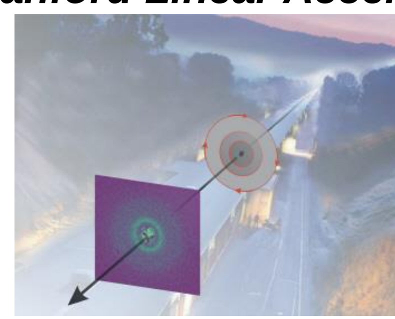
Electromagnets



Photoswitch



Stanford Linear Accelerator



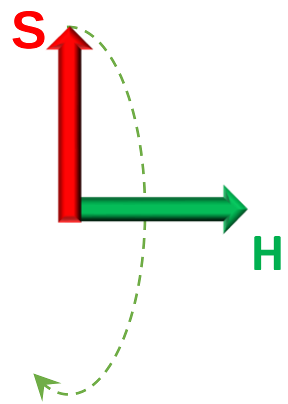
Laser Pulse

Challenge:

To control magnetic state of a medium with the best possible temporal and spatial resolutions

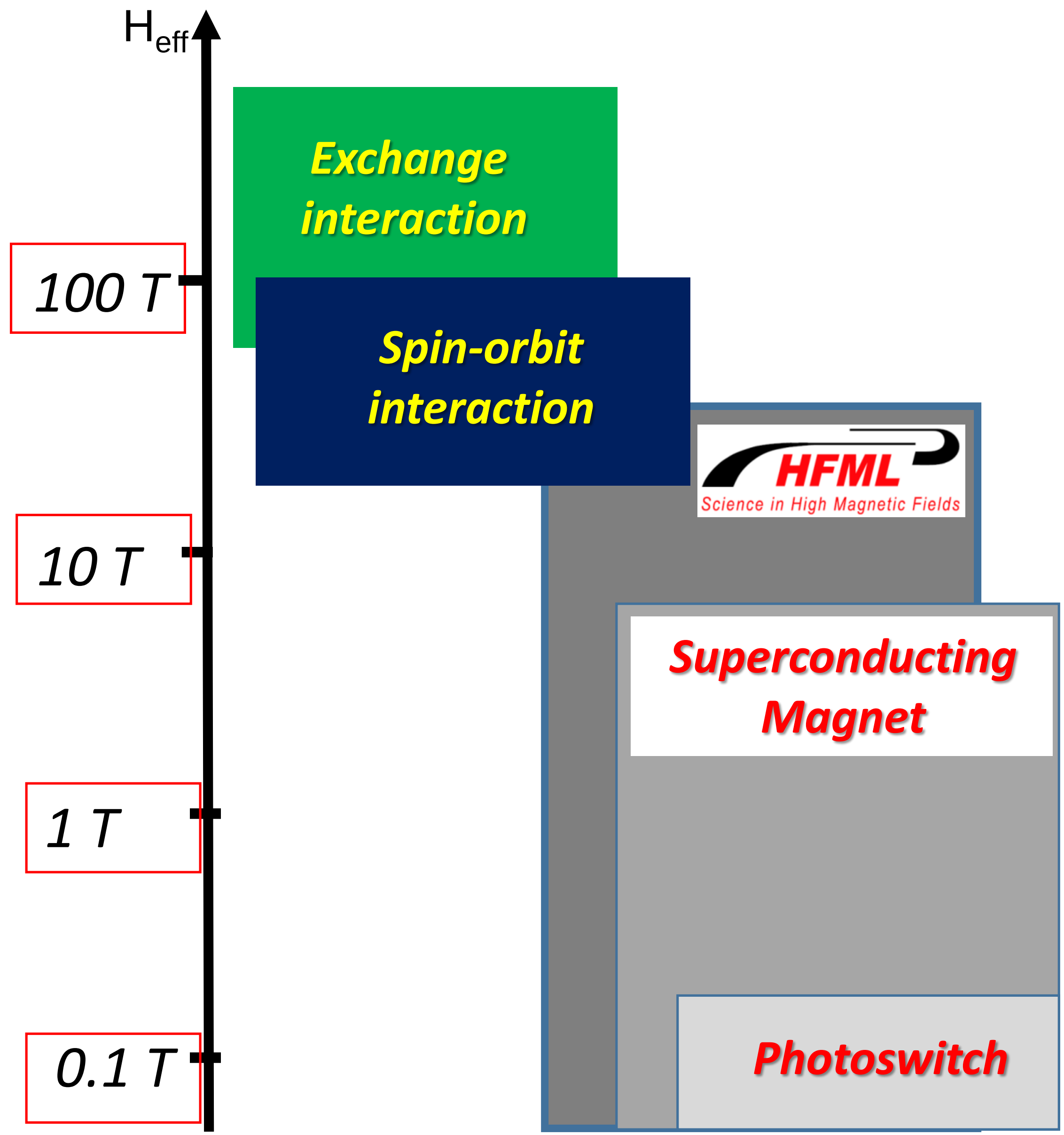
What can spins "feel"?

$\mathcal{H}_i = \mathbf{H}\mathbf{S}_i + \alpha \boldsymbol{L}_i \boldsymbol{S}_i + J_{ij} \boldsymbol{S}_j \mathbf{S}_i$



$$\frac{\partial \boldsymbol{S}_i}{dt} = -\gamma \boldsymbol{S}_i \times \mathbf{H}_{\mathbf{eff}}$$

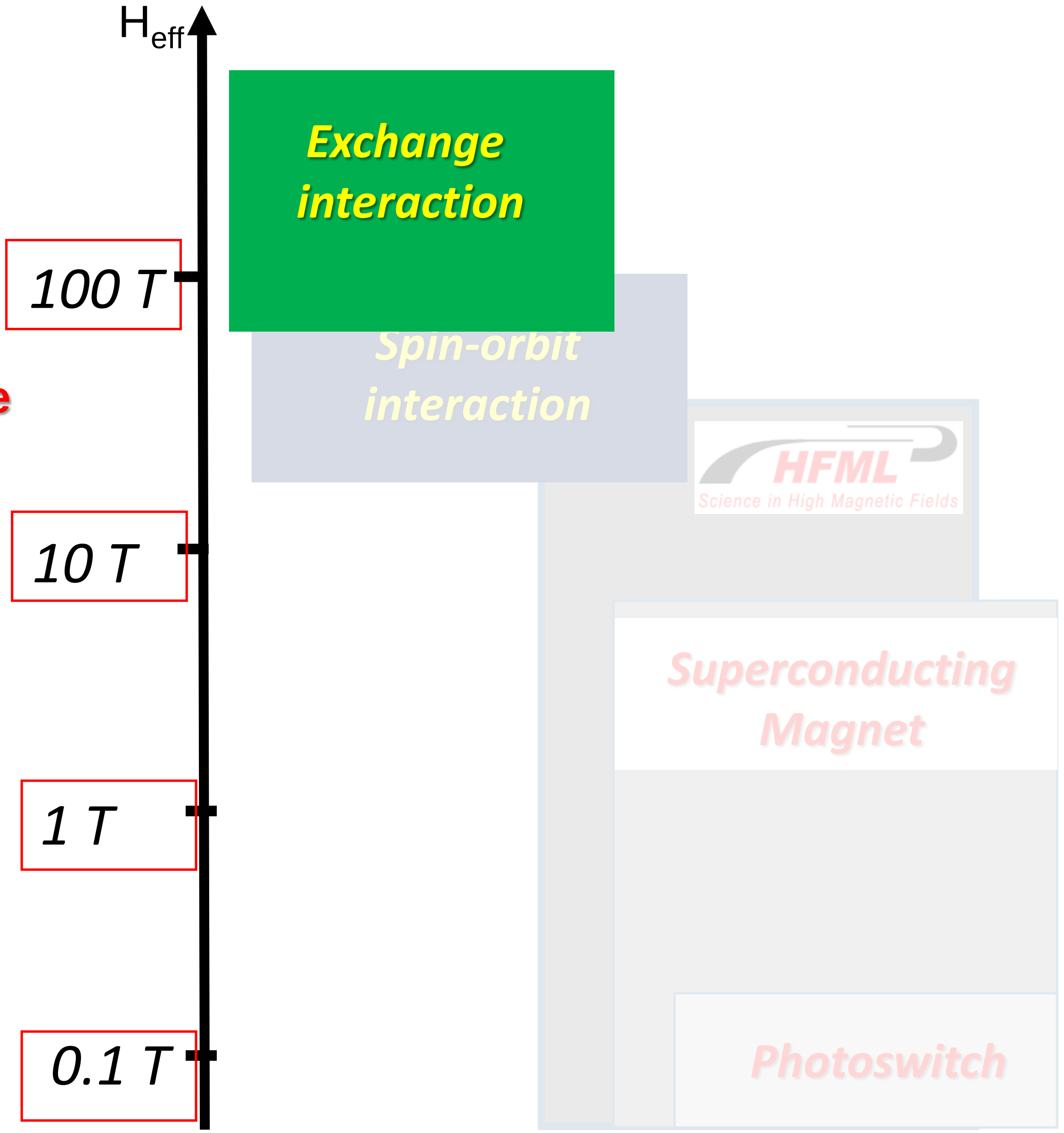
$$\mathbf{H}_{\mathrm{eff}} = \frac{\partial \mathcal{H}_i}{\partial \boldsymbol{S}_i} = \mathbf{H} + \alpha \boldsymbol{L}_i + Jij \boldsymbol{S}_j$$



Questions

Can we harness the exchange interaction for optical control of spins?

Can light control the exchange interaction?



Questions

Can we harness the exchange interaction for optical control of spins?

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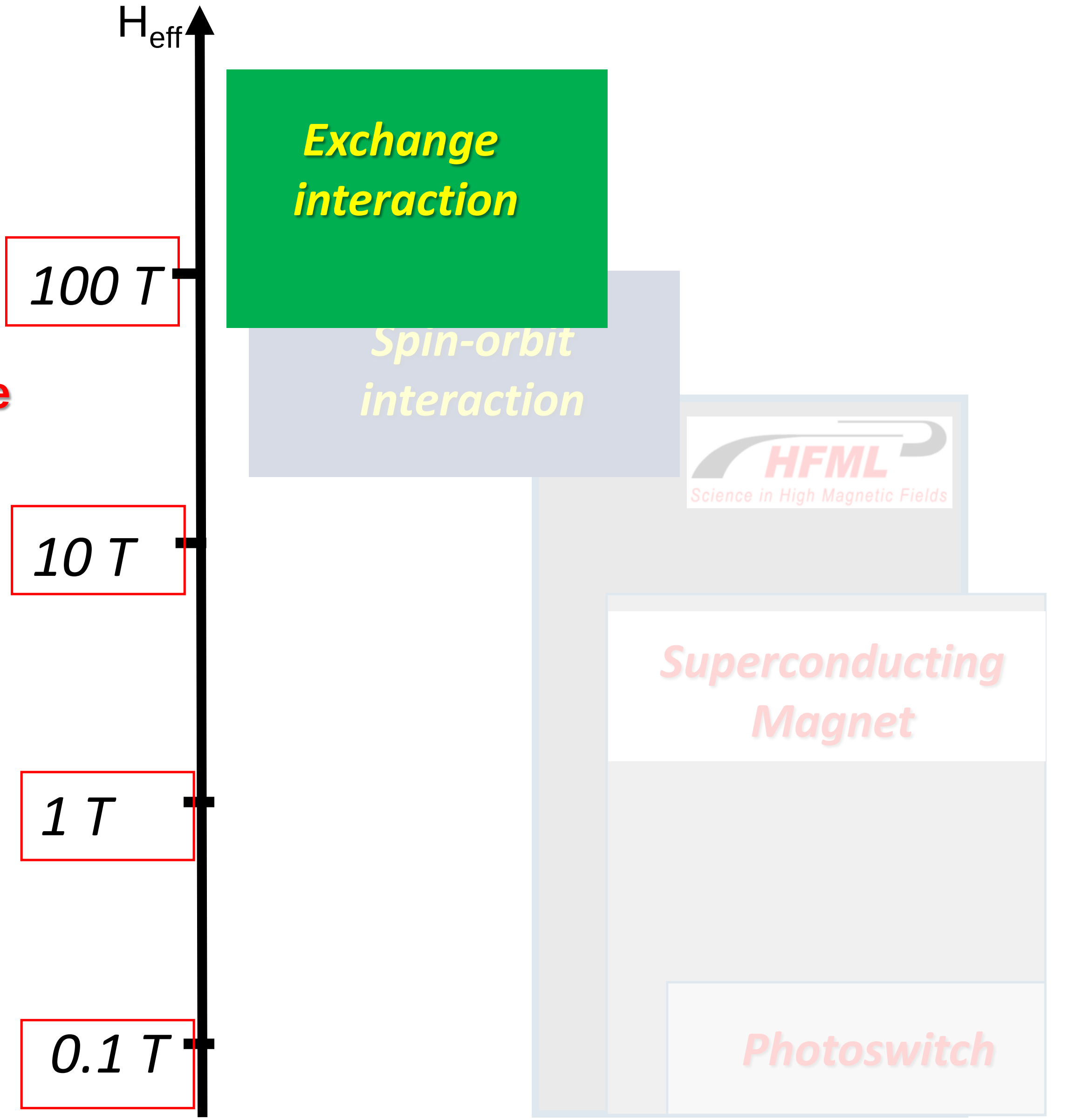
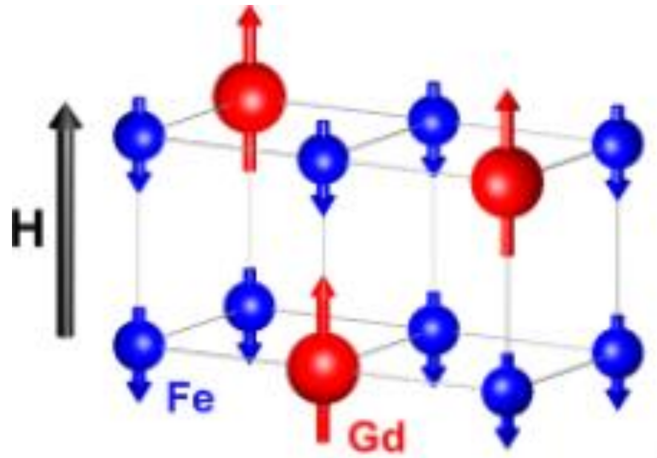


How do spins respond to a stimulus faster than the exchange interaction?

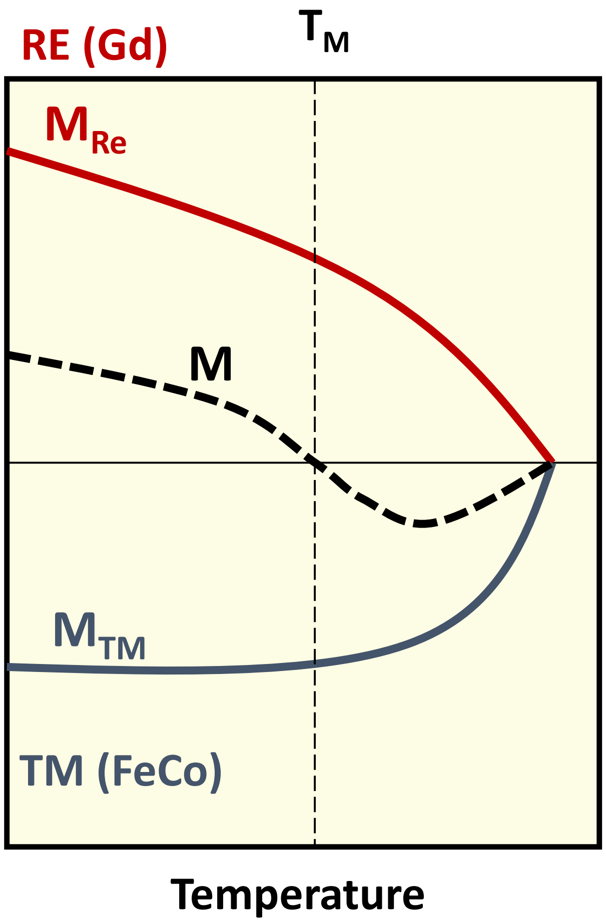
RE-TM ferrimagnetic alloy as a model system



$J_{Fe\text{-}Fe}$= 1.96x10^{-20} J ~ 35 fs

$J_{Fe\text{-}Gd}$=4.77x10^{-21} J ~ 140 fs

$J_{Gd\text{-}Gd}$=8.72x10^{-22} J ~ 750 fs



How do spins respond to a stimulus faster than the exchange interaction?

RE-TM ferrimagnetic alloy as a model system

1 ps

Gd-Gd exchange

$J_{Gd\text{-}Gd}=8.72\times10^{-22}$ J ~ 750 fs

100 fs

Fe-Gd exchange

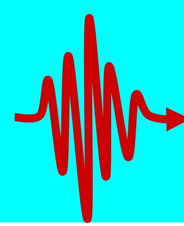
$J_{Fe\text{-}Gd}=4.77\times10^{-21}$ J ~ 140 fs

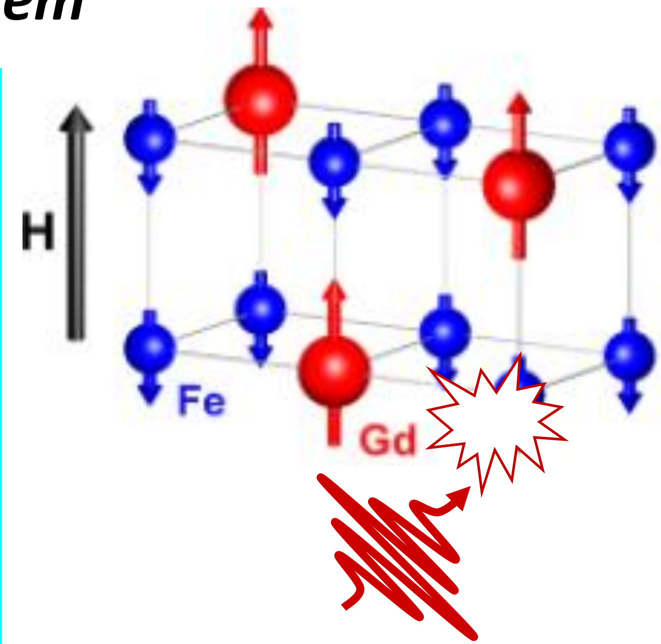
Fe-Fe exchange

$J_{Fe\text{-}Fe}= 1.96\times10^{-20}$ J ~ 35 fs

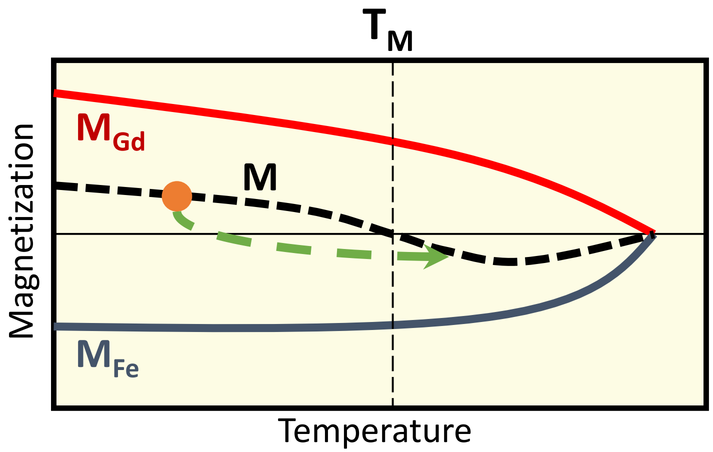
1 fs

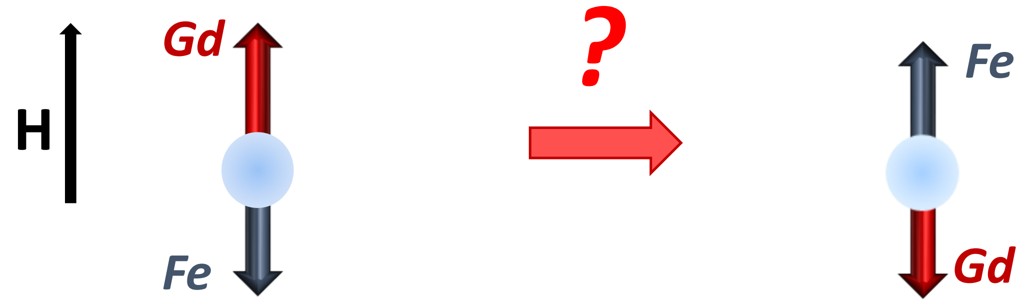
Laser





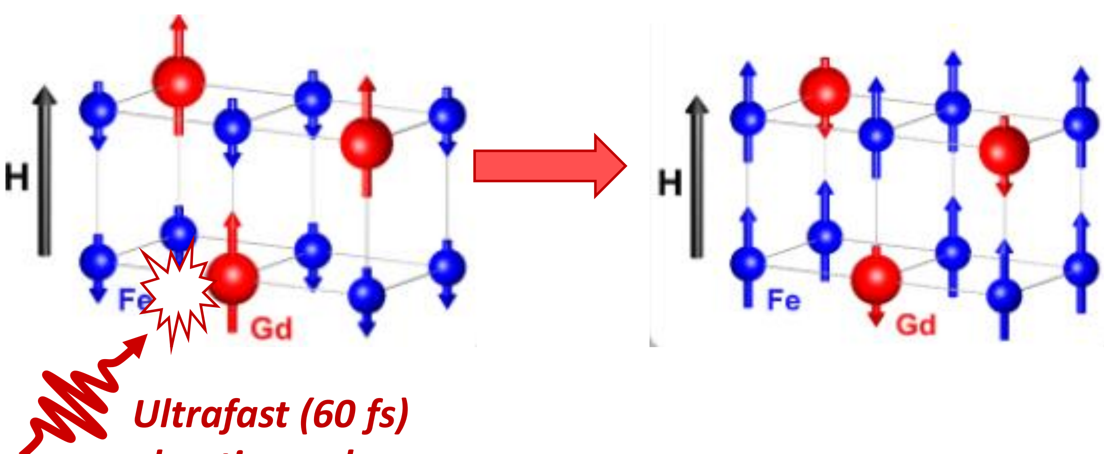
Ultrafast heating of GdFeCo?





Below
the compensation point

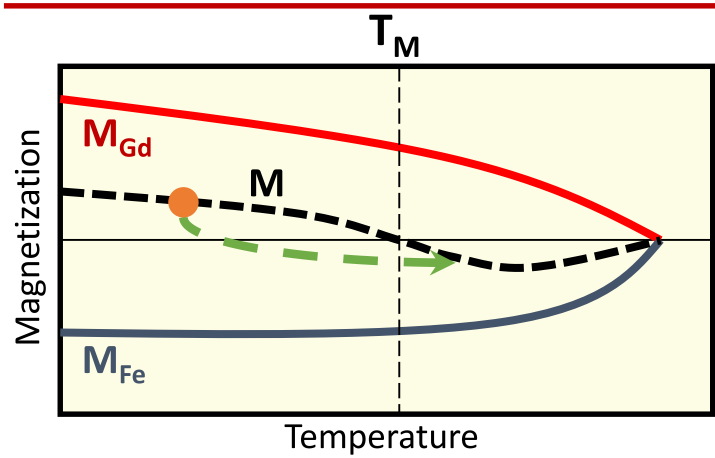
Above
the compensation point

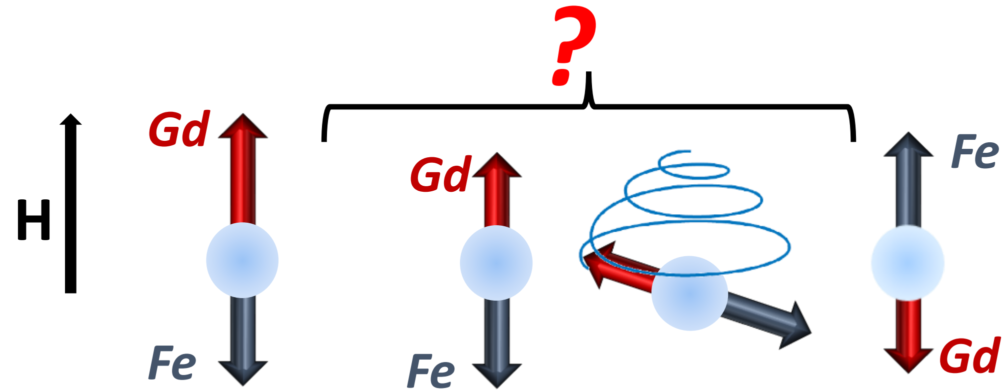


Ultrafast (60 fs)
heating pulse

What is the dynamics?

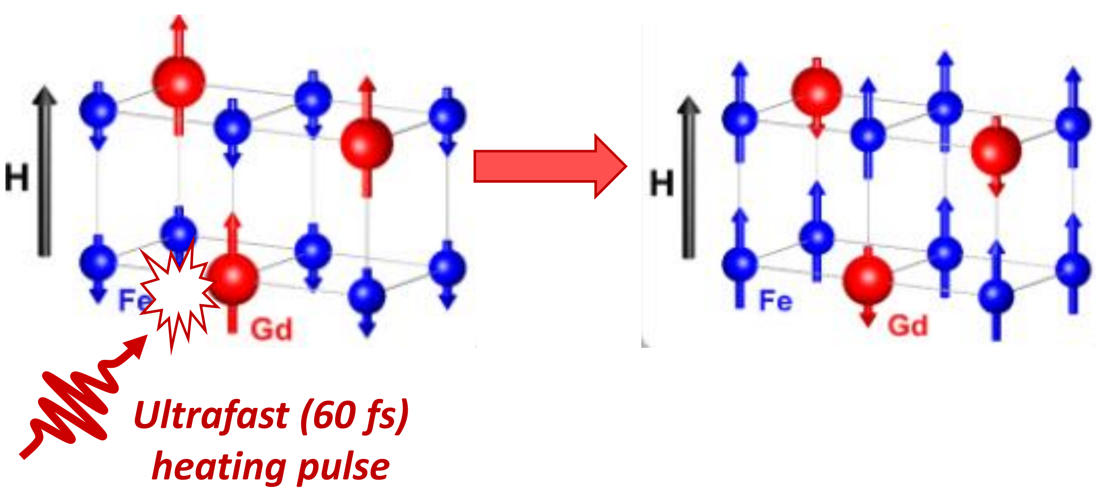
Ultrafast heating of GdFeCo?





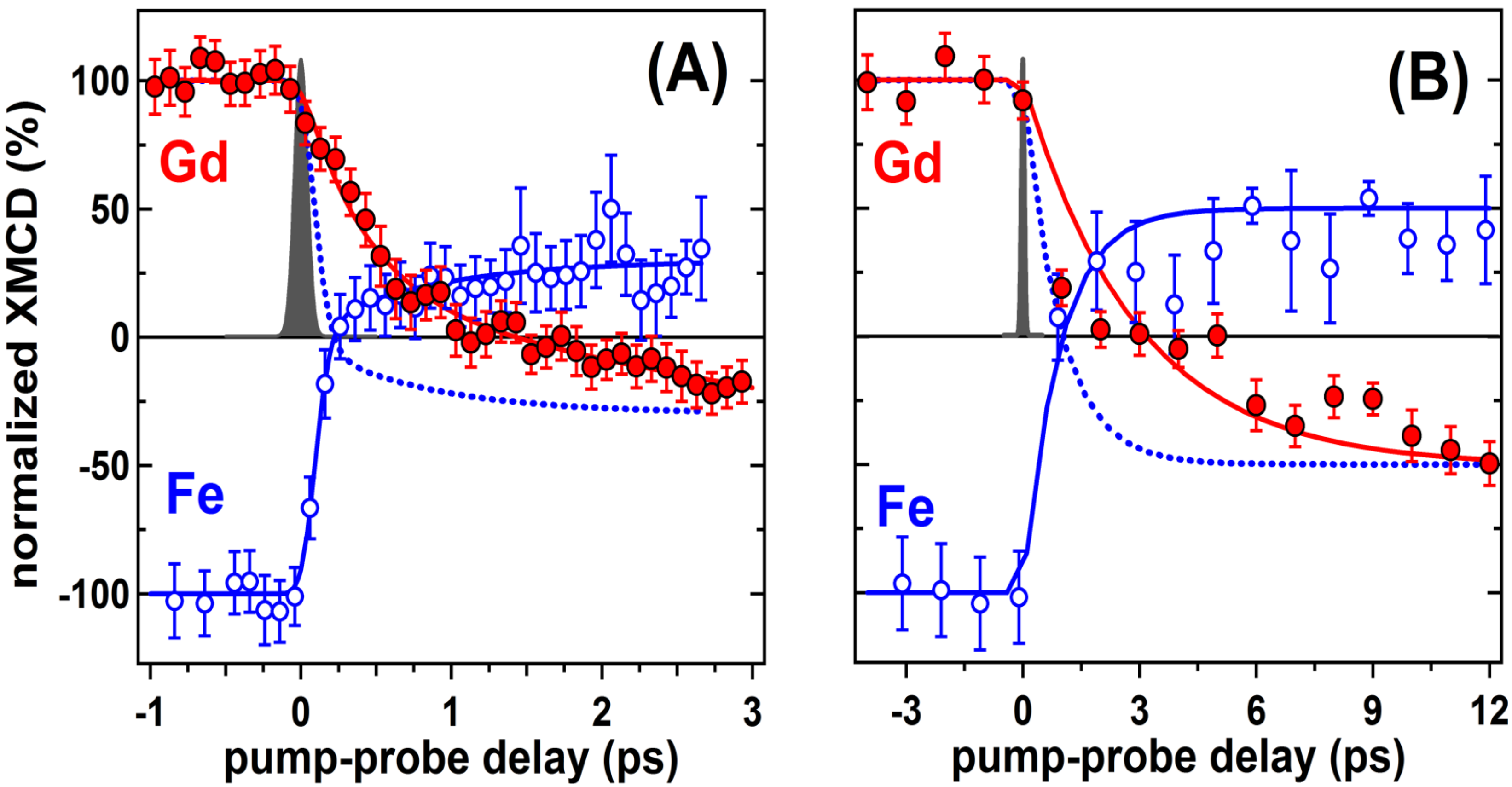
Below
the compensation point

Above
the compensation point



What is the dynamics?

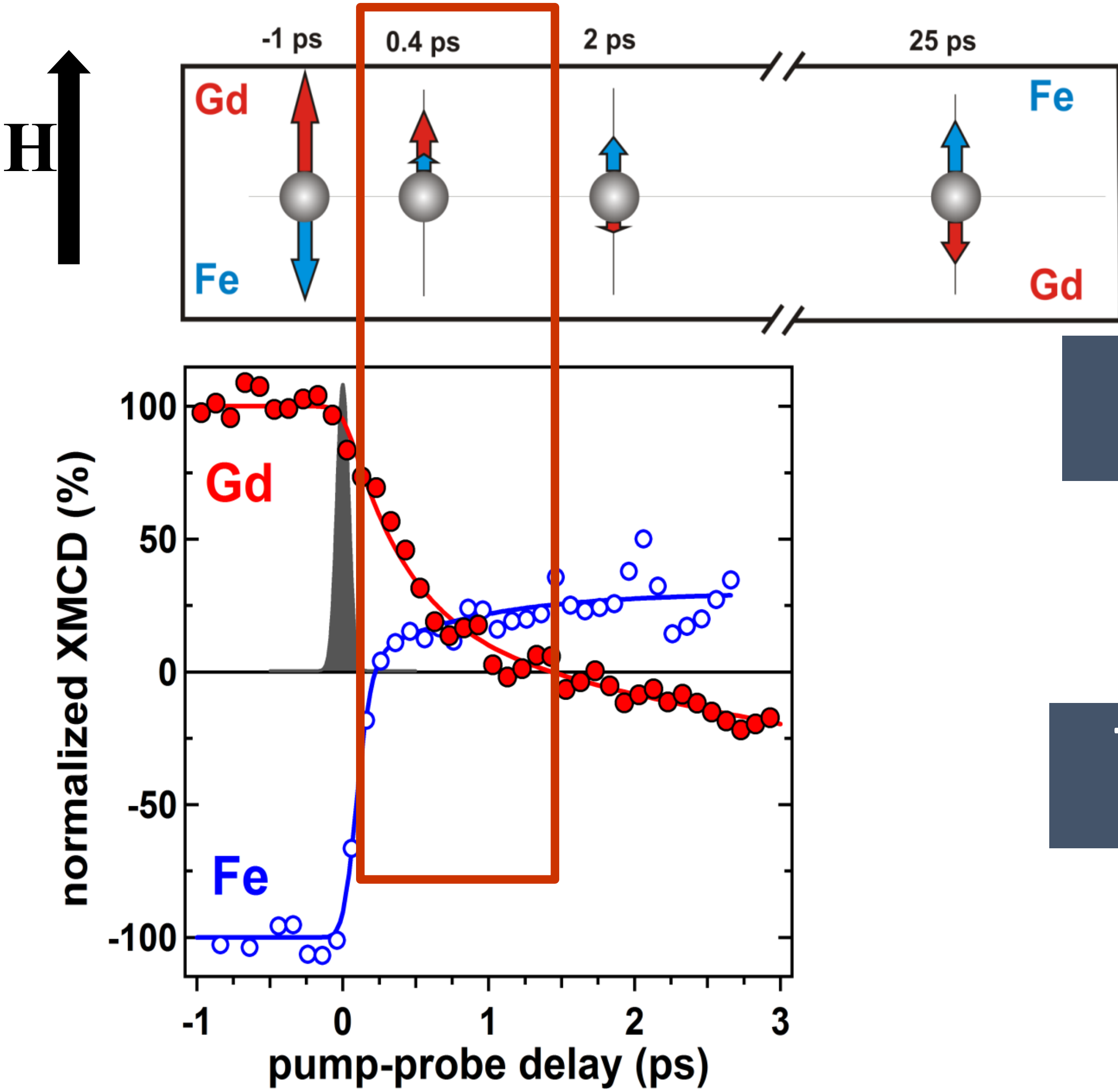
Experiment: Ultrafast dynamics of antiferromagnetically coupled sublattices



Different magnetization switching dynamics at Fe and Gd sites !!!

I. Radu et al, *Nature* **472**, 205-208 (2011).

Ultrafast "ferromagnetism" of antiferromagnetically coupled spins



$J_{Fe\text{-}Gd}$ ~ 140 fs

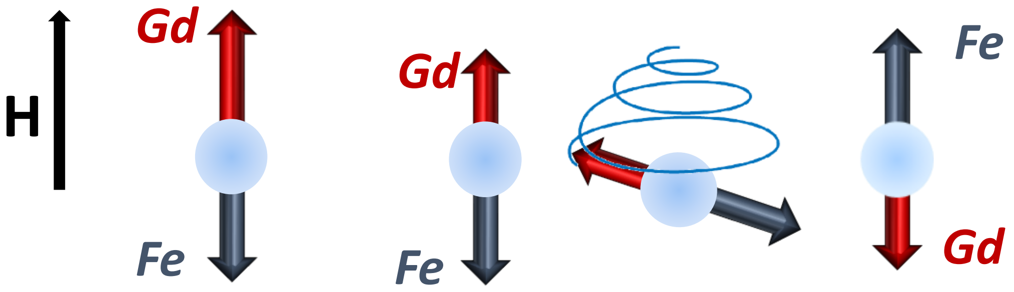
Transient ***FERROMAGNETIC*** ALIGNMENT for ~1.2 ps

The system evolves against the exchange interaction !!!

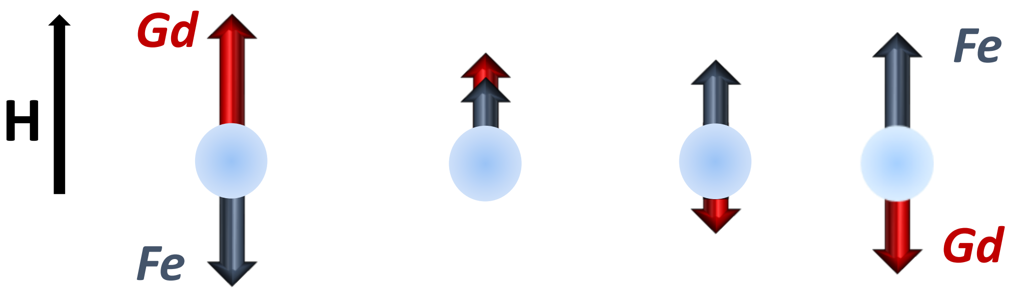
I. Radu et al, *Nature* **472**, 205-208 (2011).

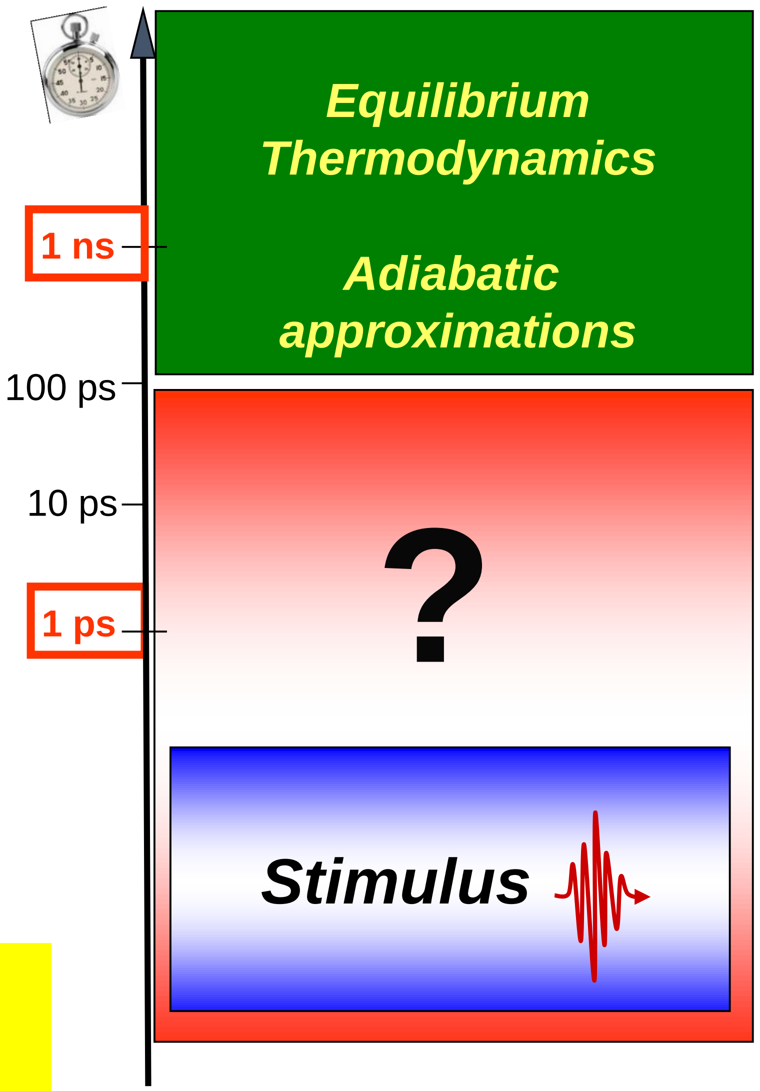
Ultrafast reversal of antiferromagnetically coupled spins

Expected thermodynamically



Observed experimentally

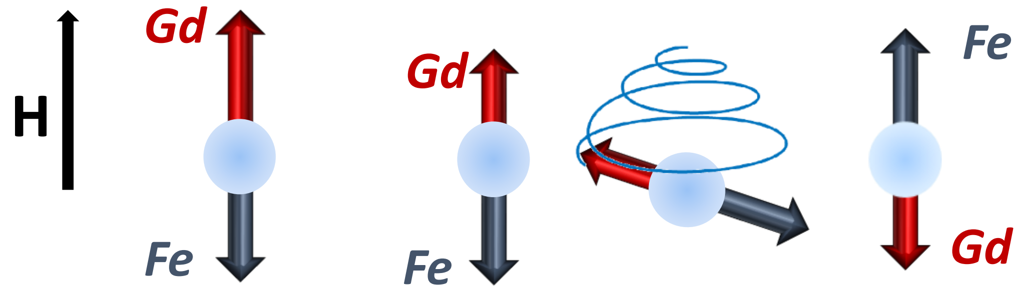




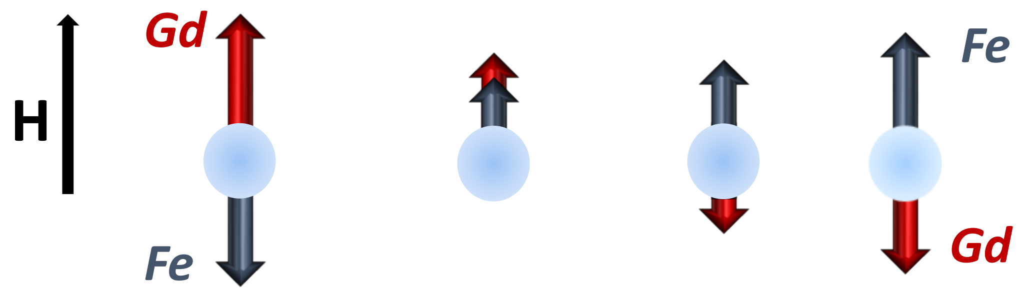
Fe is faster than Gd! **No precession!**
Ferromagnetic-like state!

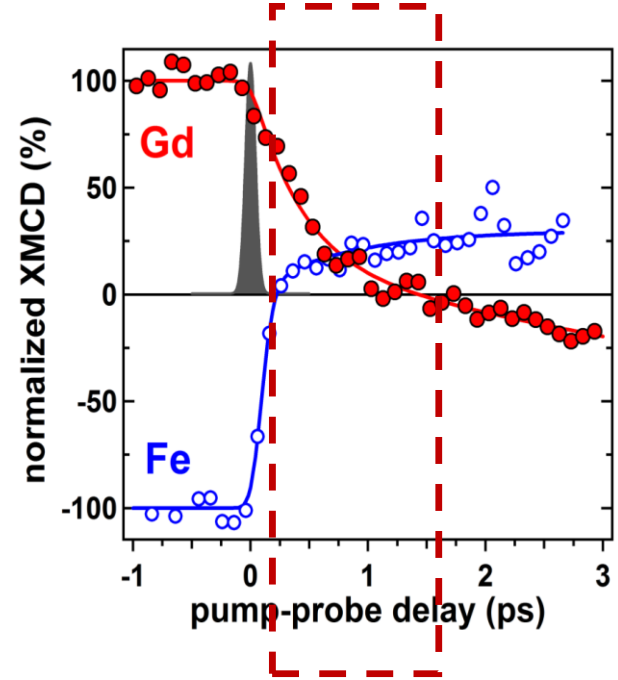
Ultrafast reversal of antiferromagnetically coupled spins

Expected thermodynamically



Observed experimentally





The system evolves against the exchange interaction !!!

Fe is faster than Gd! *No precession!*

Ferromagnetic-like state!

H≈0.3 T H_{ex}≈10 T

$H \ll H_{ex}$

Atomistic simulations of ultrafast spin dynamics

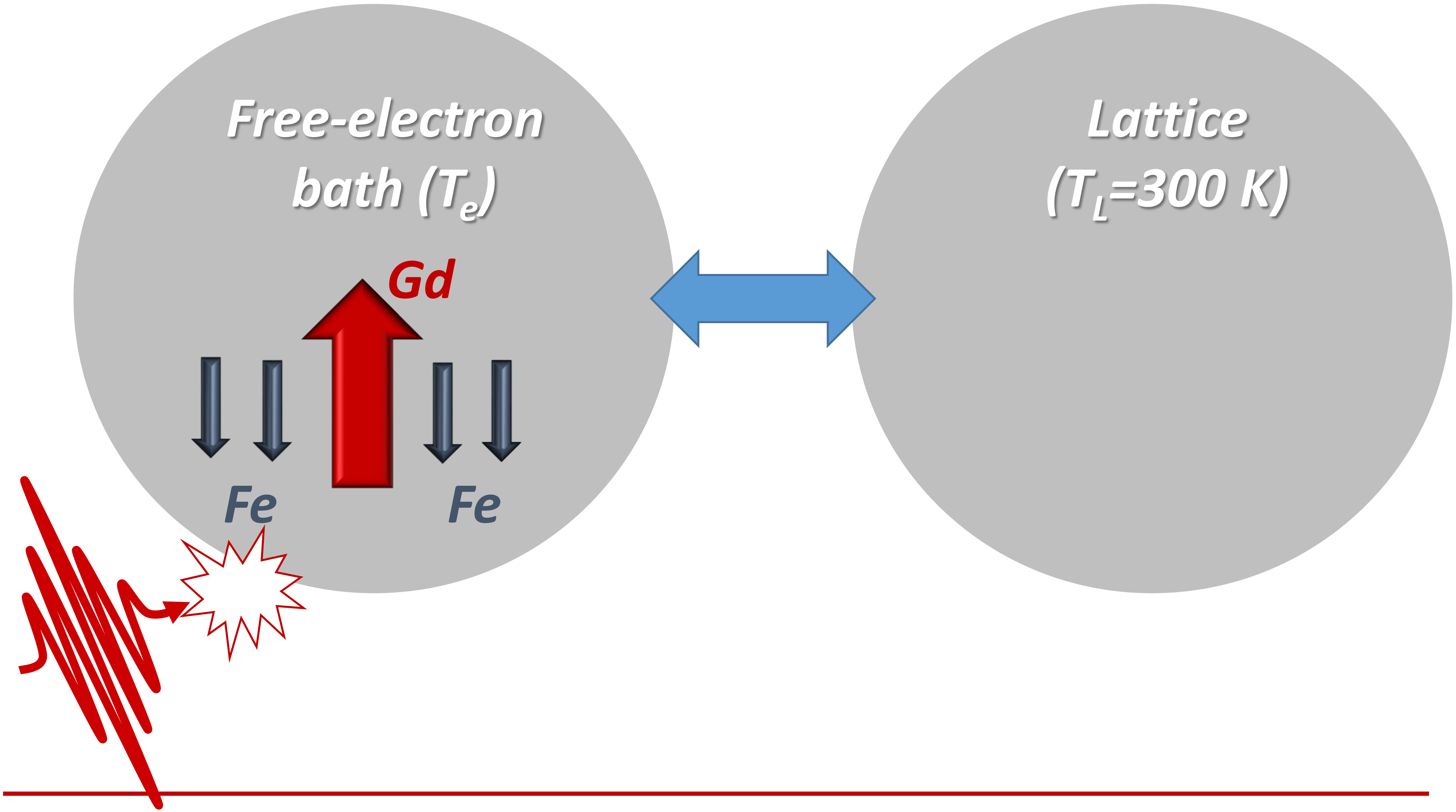
- *Localized atomistic spin model with 10^6 spins coupled with a Heisenberg exchange*

- *Exchange parameters (Fe-Fe, Gd-Gd, and Fe-Gd) obtained by fitting static M_{Fe} , M_{Gd} (T) dependencies*

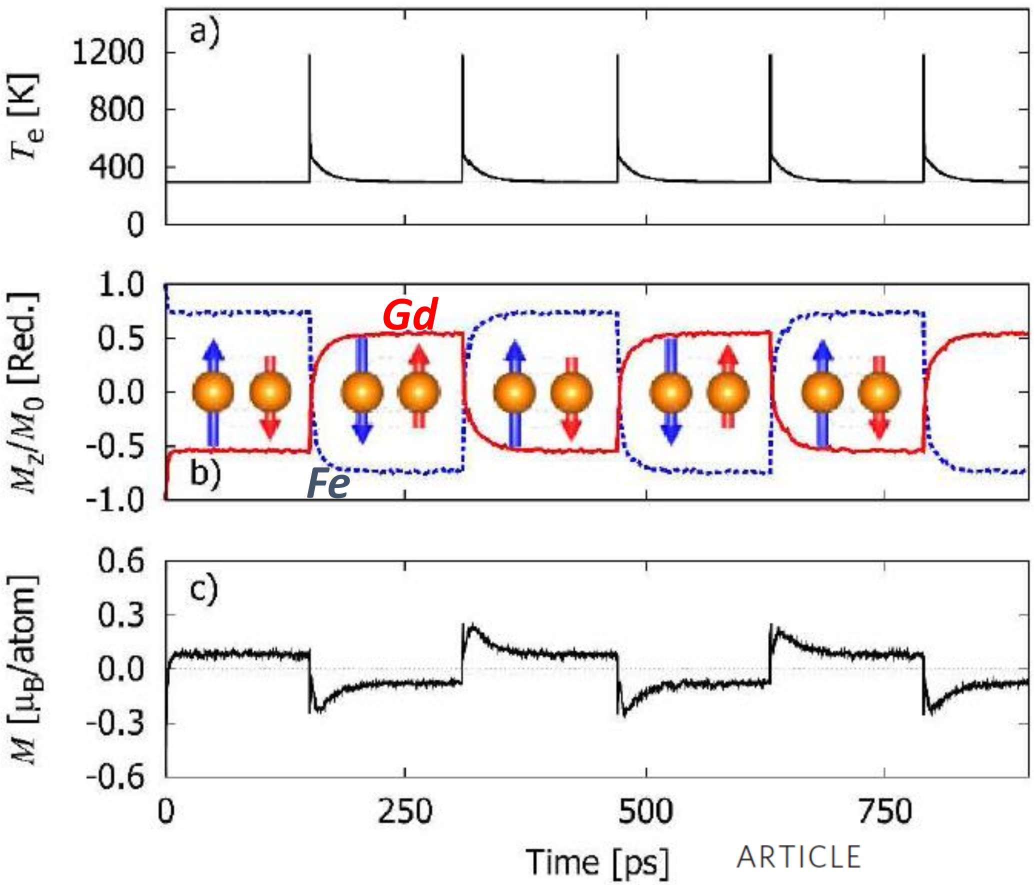
- *Stochastic term added to the effective field.*

- *No reversing field is present during the process*

Simulated model



Atomistic simulations: Ultrafast heating as a sufficient stimulus to reverse magnetization?



nature COMMUNICATIONS

ARTICLE

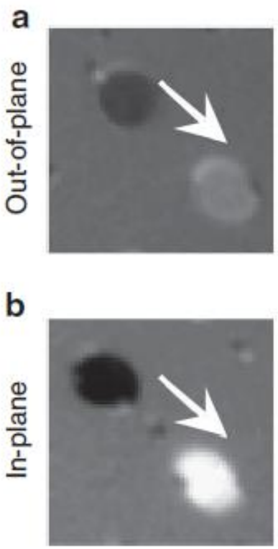
Received 11 Jul 2011 | Accepted 5 Jan 2012 | Published 7 Feb 2012

DOI:10.1038/ncomms1666

Ultrafast heating as a sufficient stimulus for magnetization reversal in a ferrimagnet

T.A. Ostler[1], J. Barker[1], R.F.L. Evans[1], R.W. Chantrell[1], U. Atxitia[2], O. Chubykalo-Fesenko[2], S.El Moussaoui[3], L. Le Guyader[3], E. Mengotti[3], L.J. Heyderman[3], F. Nolting[3], A. Tsukamoto[4], A. Itoh[4], D. Afanasiev[5], B.A. Ivanov[5], A.M. Kalashnikova[6], K. Vahaplar[7], J. Mentink[7], A. Kirilyuk[7], Th. Rasing[7] & A.V. Kimel[7]

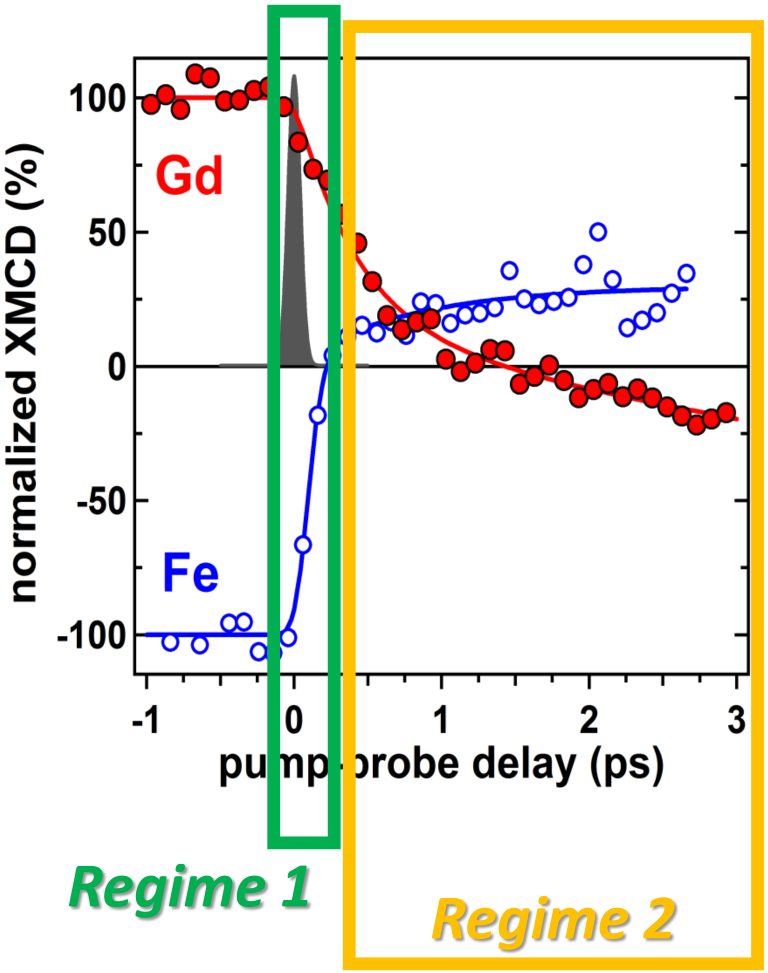
Do we need a magnetic field at all?



Ultrafast heating alone is a sufficient stimulus to reverse magnetization!

T. Ostler et al, *Nature-Communications*
DOI: 10.1038/ncomms1666 (2012).

Ultrafast spin dynamics in multi-sublattice magnets



Regime 1

- Temperature of electron gas is higher than the Curie temperature

$T_e >> T_C$

$$\frac{d\mathbf{M}_i}{dt} = -\gamma \mathbf{M}_i \times \mathbf{H}_i + \mathbf{R}_i,$$

$$\frac{dM_i}{dt} = -\frac{M_i - M_i^{(0)}}{\tau_i} \qquad \tau_i = \frac{\mu_i}{2\alpha\gamma k_{\mathrm{B}} T}$$

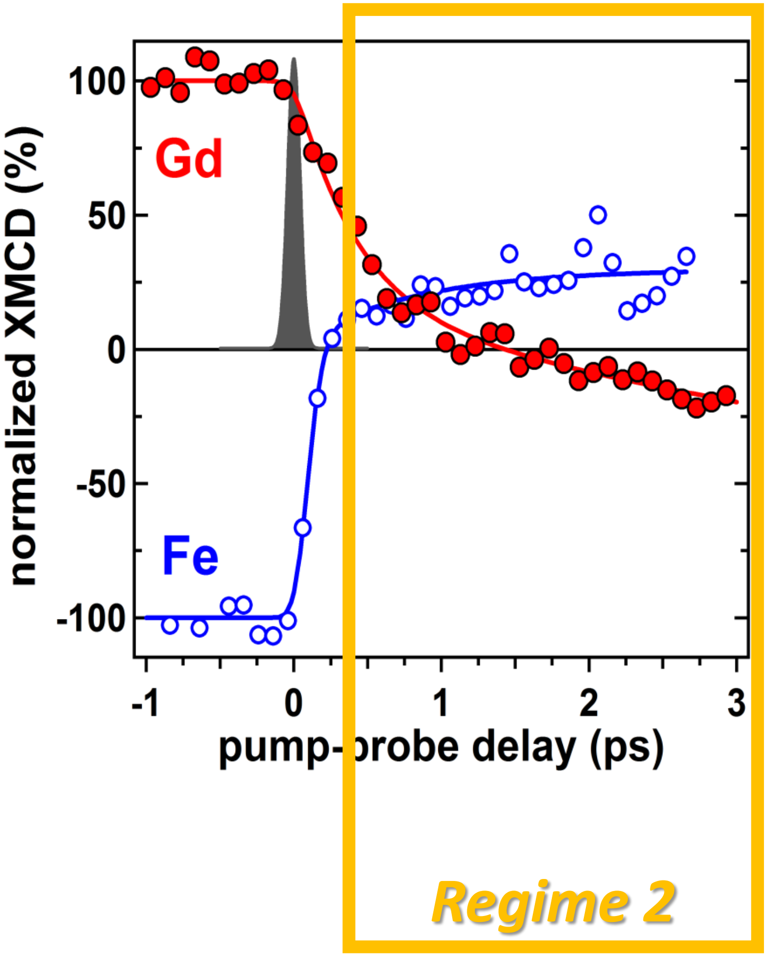
$$\mu_{\mathrm{Gd}} > \mu_{\mathrm{Fe}}$$

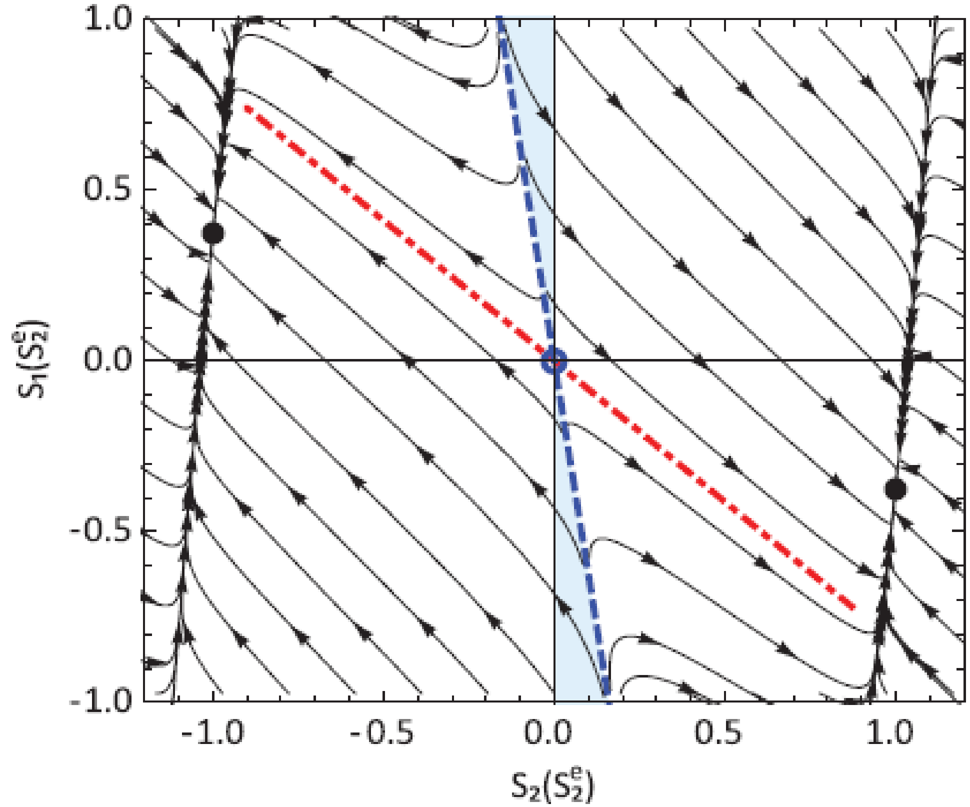
$$\tau_{\mathrm{Gd}} > \tau_{\mathrm{Fe}}$$

Brown Phys. Rev. 1963

Kubo et al. Prog. Theor. Phys. Suppl. 1970

Ultrafast spin dynamics in multi-sublattice magnets

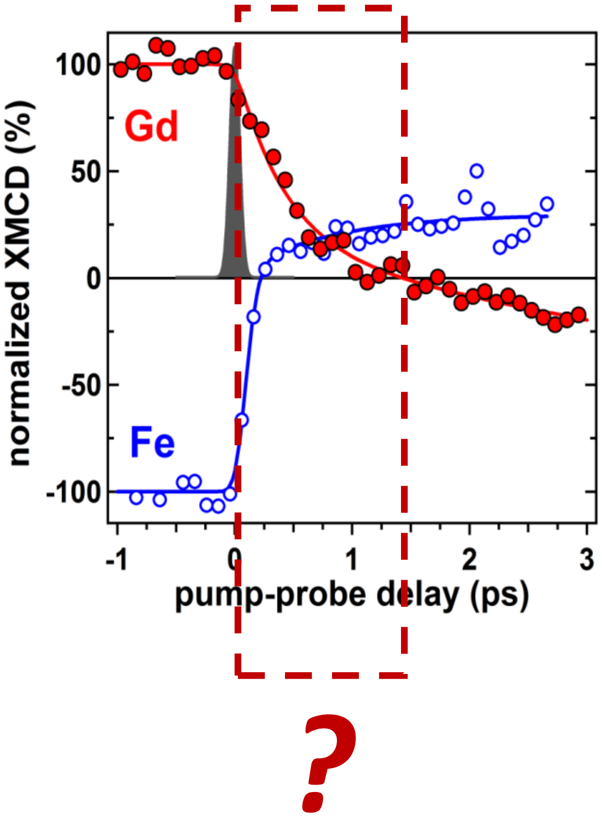




$$\frac{dM_{\mathrm{Fe}}}{dt} = -\frac{dM_{\mathrm{Gd}}}{dt}$$

J. Mentink et al
Physical Review Letters **108**, 057202 (2012).

Open questions

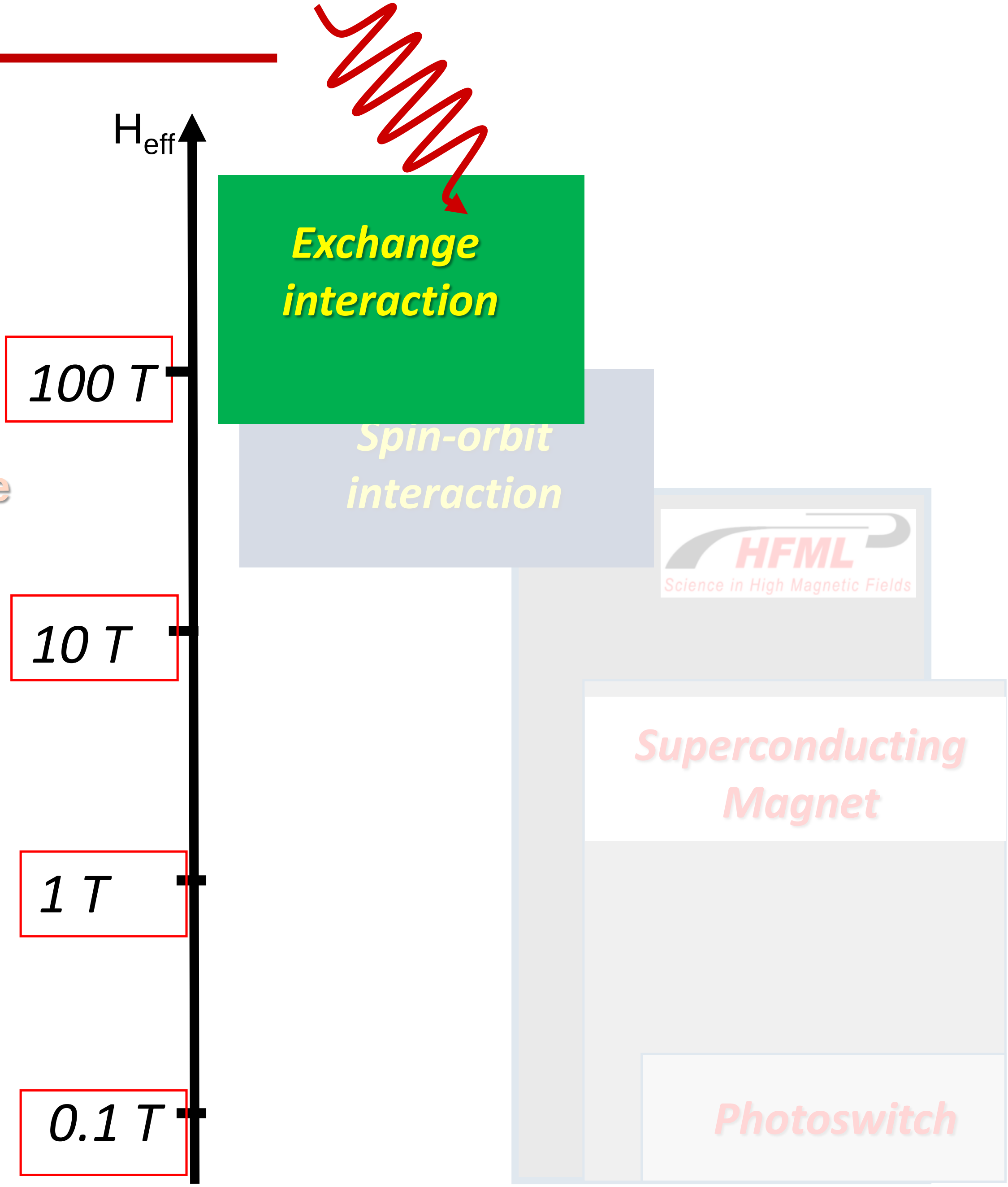


What is the effect of light on the exchange interaction?

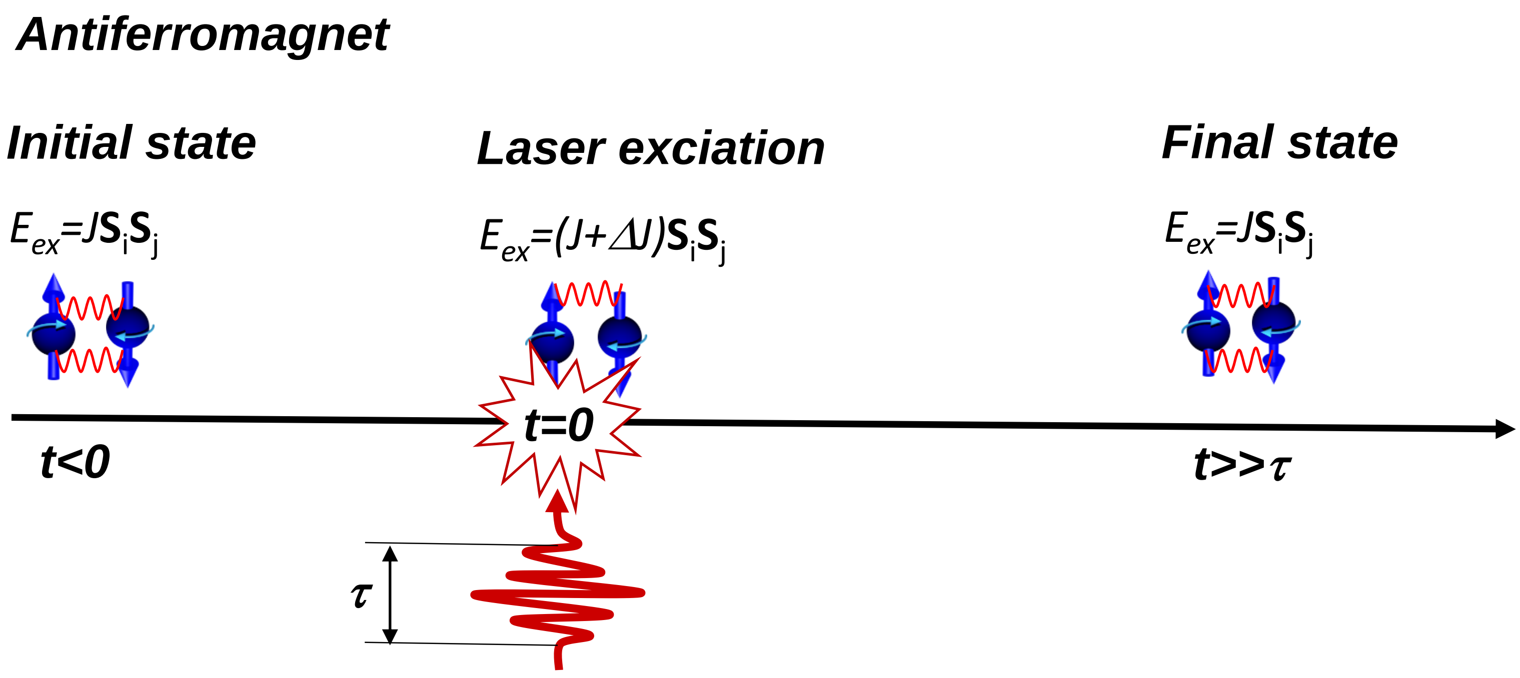
Questions

Can we harness the exchange interaction for optical control of spins?

Can light control the exchange interaction?



Experimental challenge:
how to demonstrate an ultrafast control of the exchange interaction

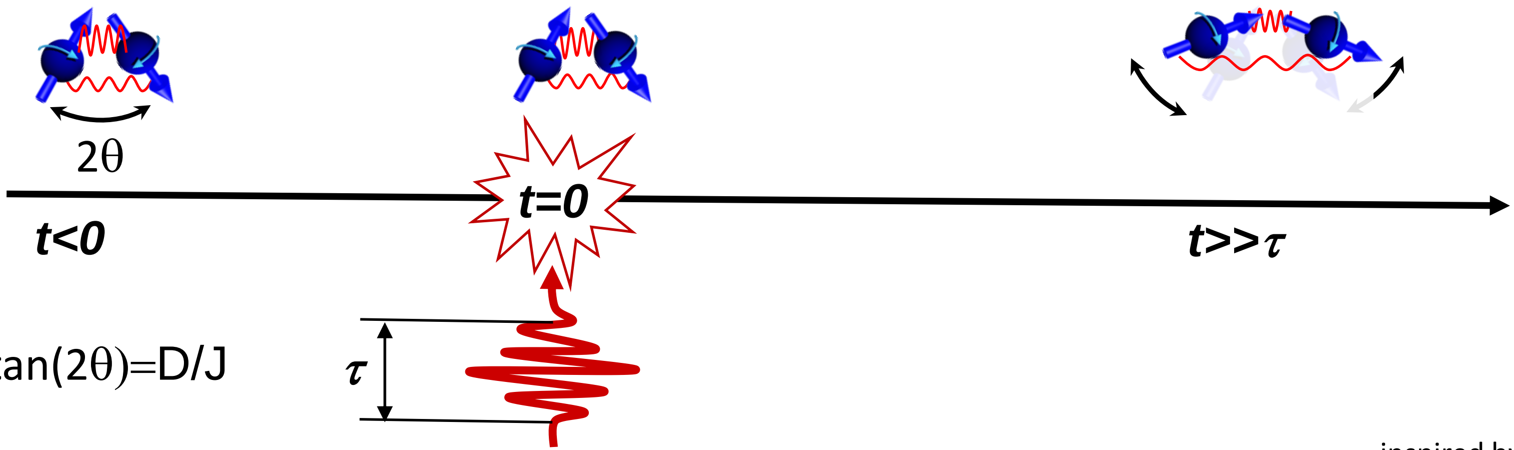


Experimental challenge:

how to demonstrate an ultrafast control of the exchange interaction

Canted Antiferromagnet

Initial state	***Laser exciation***	***Final state***
$E_{ex}=J\mathbf{S}_i\mathbf{S}_j + D[\mathbf{S}_i \times \mathbf{S}_j]$	$E_{ex}=(J+\Delta J)\mathbf{S}_i\mathbf{S}_j + (D+\Delta D)[\mathbf{S}_i \times \mathbf{S}_j]$	$E_{ex}=J\mathbf{S}_i\mathbf{S}_j + D[\mathbf{S}_i \times \mathbf{S}_j]$



$\tan(2\theta)=D/J$

$D/J \neq (D+\Delta D)/(J+\Delta J)$

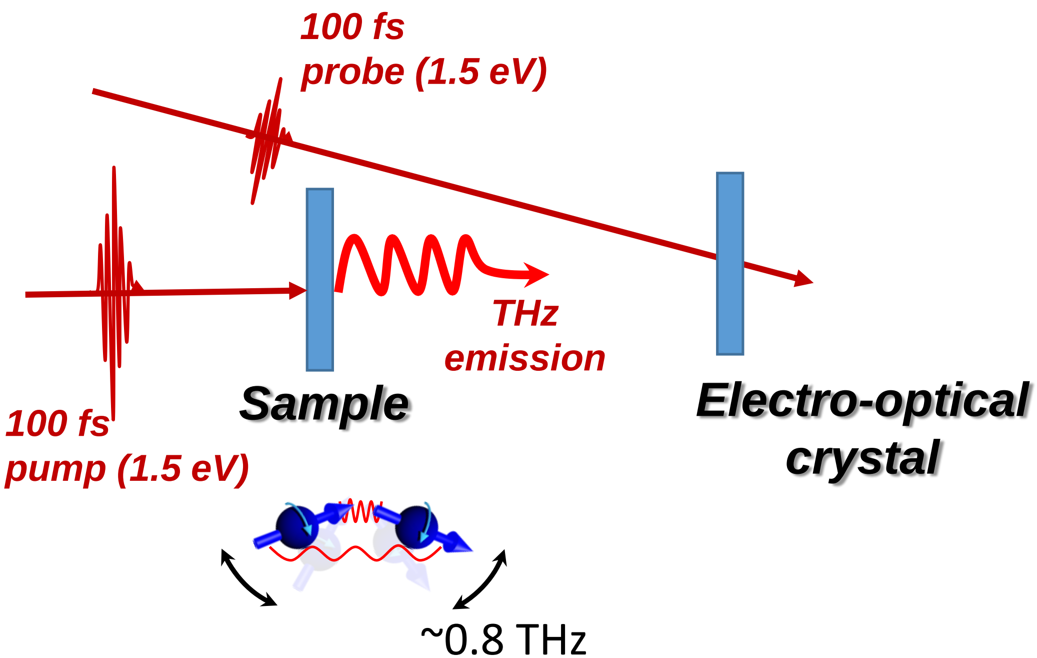
inspired by
S. O. Demokritov et al,
JETP Letters **41**, 38 (1985).

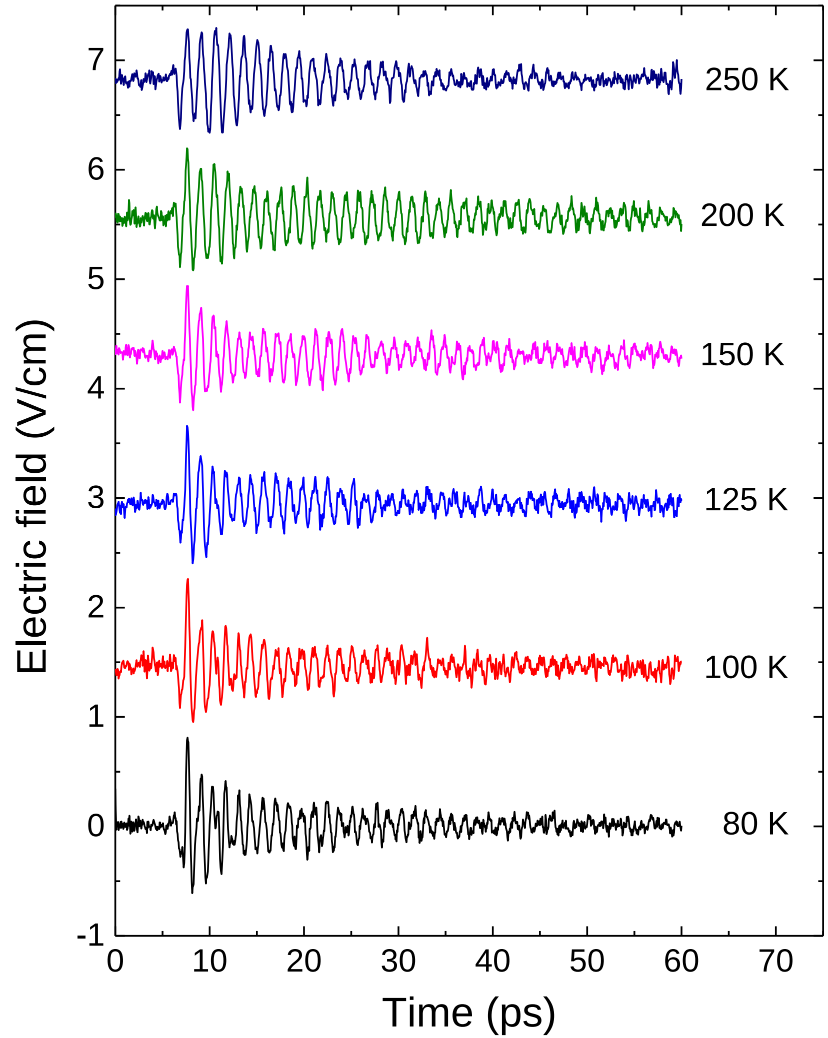
$$\mathbf{T}_{i,j} = -\gamma\left[\mathbf{S}_i \times \frac{\partial \Phi_{\text{IMR}}}{\partial \mathbf{S}_i}\right] = -\gamma \Delta J\left[\mathbf{S}_i \times \mathbf{S}_j\right]$$

α–Fe_2O_3, $FeBO_3$, $RFeO_3$ (R=Y, Er, Tm etc)

Solution: ***Laser-induced exciation of the antiferromagnetic resonance in weak ferromanets!***

Femtosecond excitation of the antiferromagnetic resonance in ErFeO3

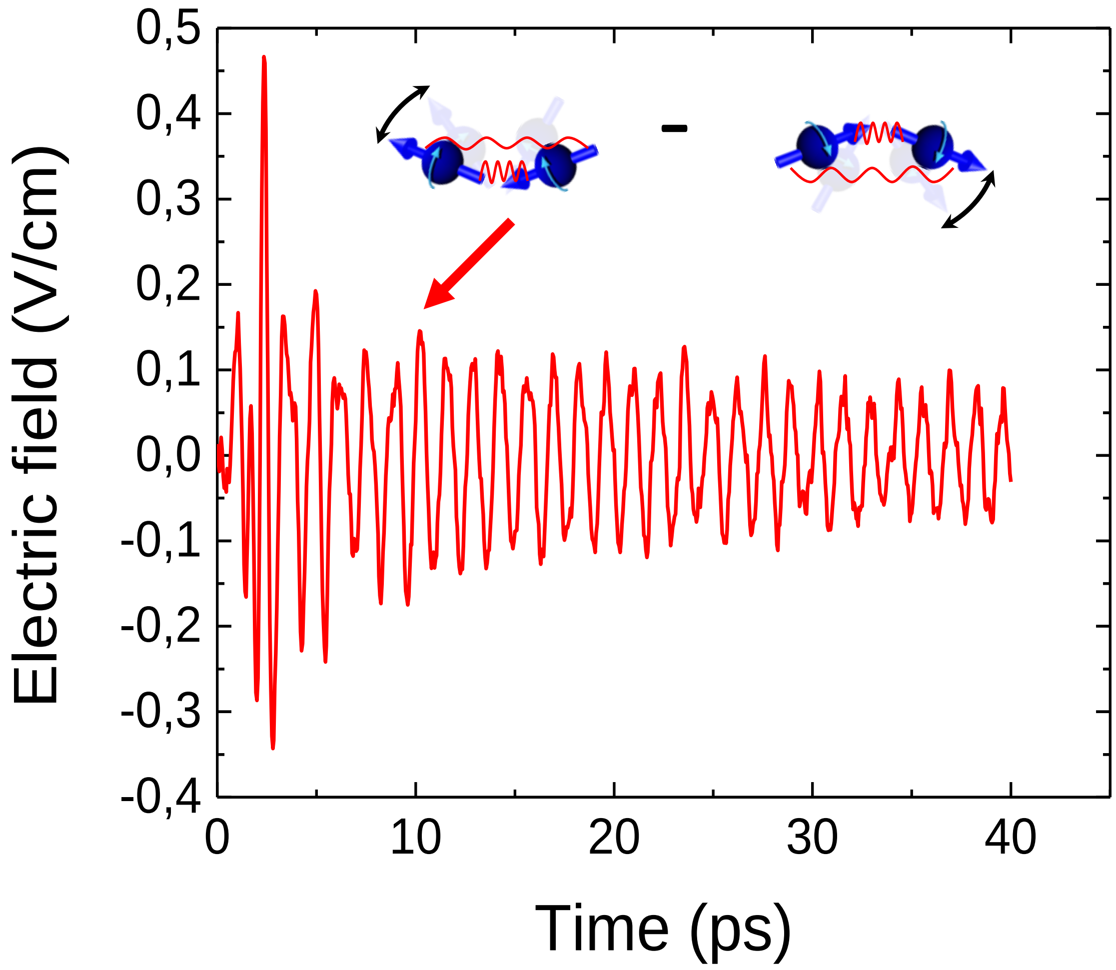




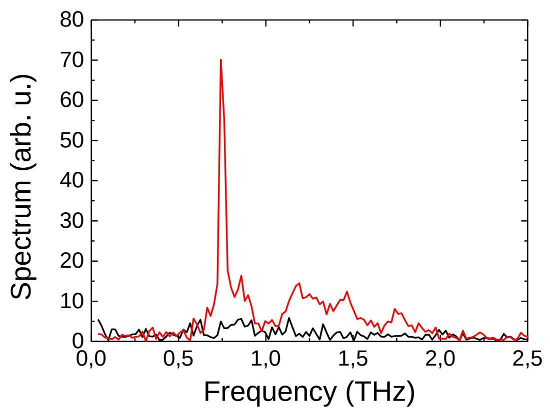
Is it spin resonance?

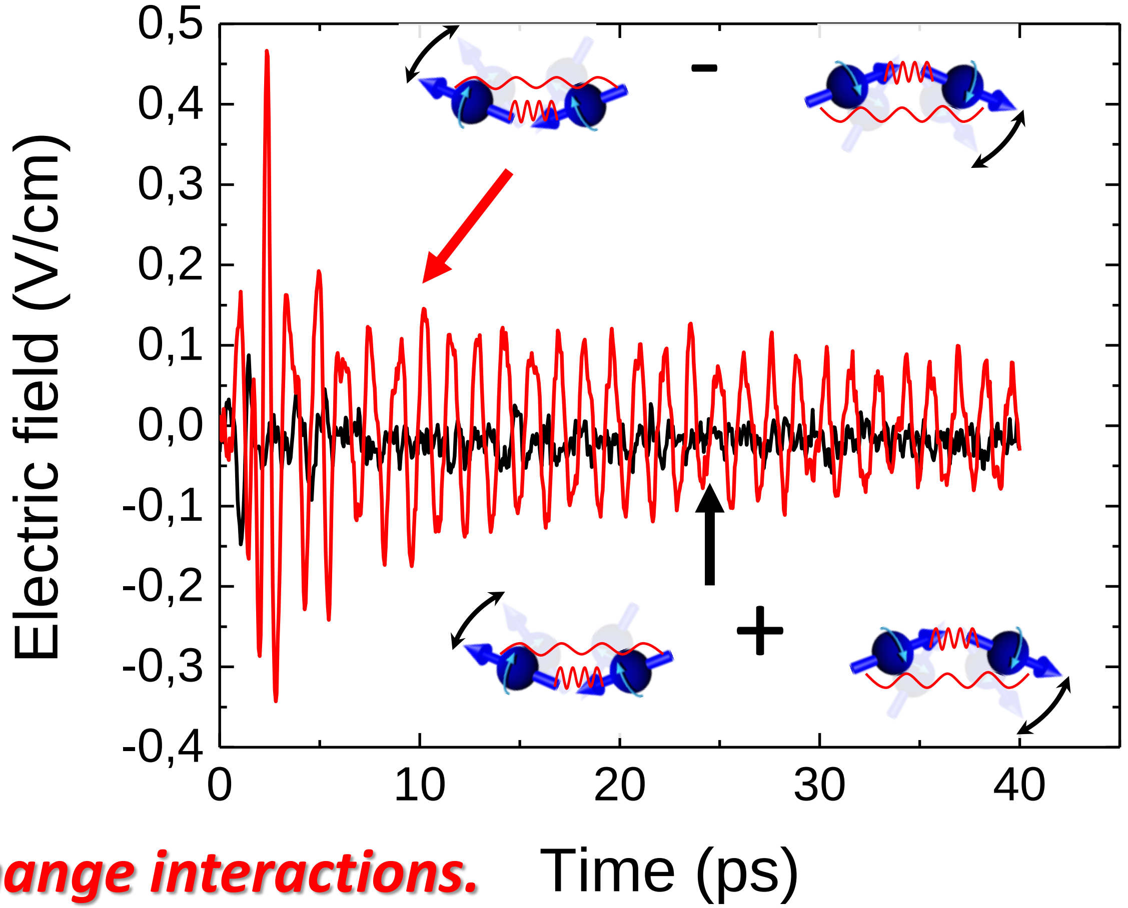
R. Mikhaylovskiy et al (in preparation).

Femtosecond excitation of the antiferromagnetic resonance in ErFeO3



Femtosecond excitation of the antiferromagnetic resonance in $ErFeO_3$





Light affects the exchange interactions.

D/J≠constant

How can light change the exchange interaction?

Light OFF

$$\Phi = \Phi_0 + \sum_{i,j} J_{ij} S_i S_j$$

Light ON

$$\Phi = \Phi_0 + \sum_{i,j} (J_{ij} + \Delta J) S_i S_j$$

Is it possible?

If yes $\Delta J = \alpha |E|^2$,

$$\Phi = \Phi_0 + \sum_{i,j} J_{ij} S_i S_j + \alpha |E|2 \sum_{i,j} S_i S_j$$

$\Delta J = \alpha |E|^2$

Dielectric permittivity

$$\varepsilon_{kl} = \frac{\partial^2 \Phi}{\partial E_k \partial E_l^*} = \varepsilon^{(0)} + \alpha \sum_{i,j} S_i S_j$$

$$\varepsilon = f(M^2)$$ ***Isotropic magneto-refraction***

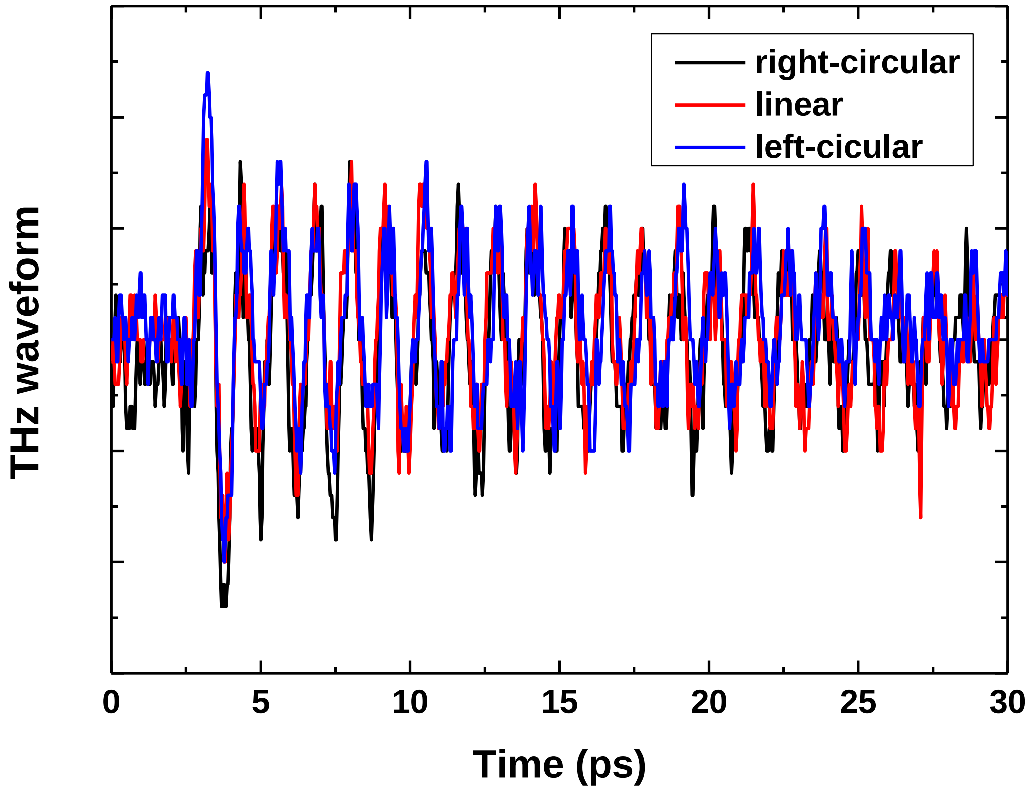
- ***Polarization insensitive***
- ***Orientation insensitive***
- ***Ultrafast***
- ***Any material***

Not impossible!

see also
S. O. Demokritov et al,
JETP Letters **41**, 38 (1985).

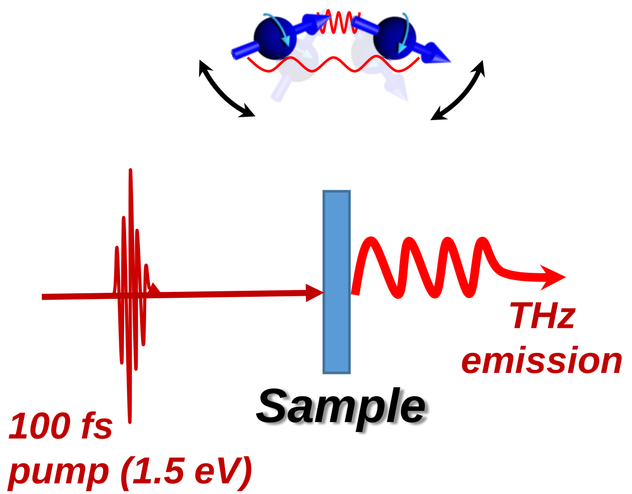
Is the optically controled exchange polarization insensitive?

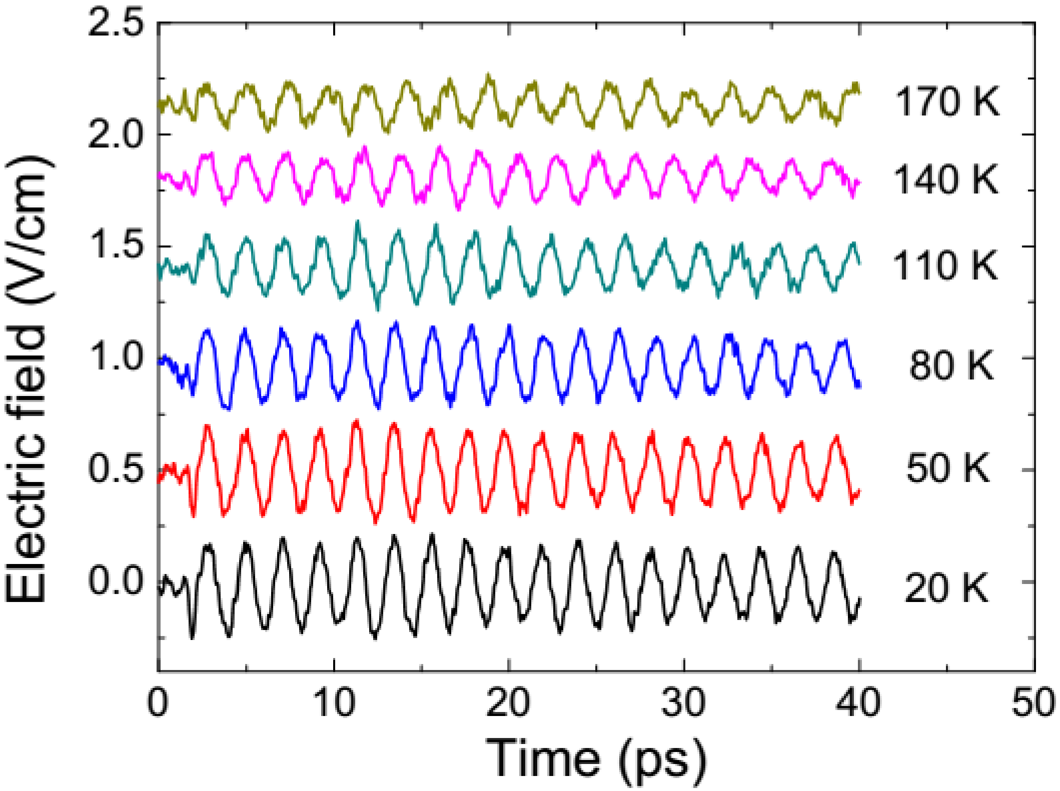
$TmFeO_3$



The effect of light on the exchange interactions D/J is polarization insentitive

Femtosecond excitation of the antiferromagnetic resonance in $FeBO_3$





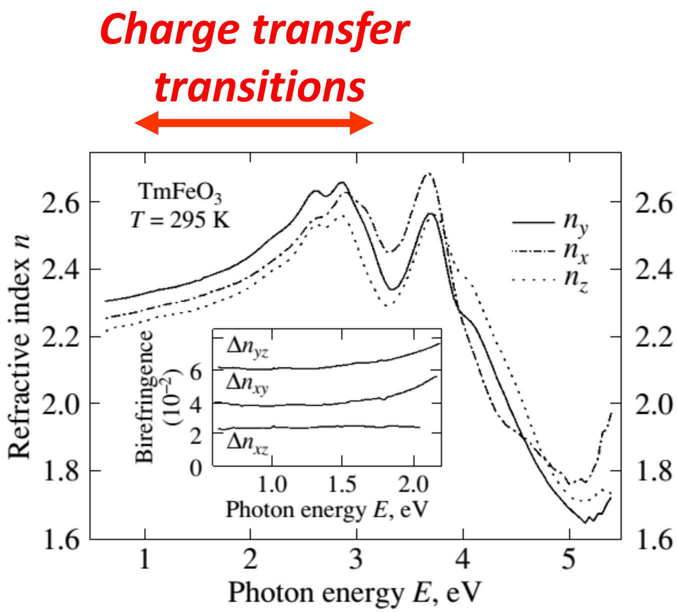
Light affects the exchange interactions.

D/J≠constant

R. Mikhaylovskiy et al (in preparation).

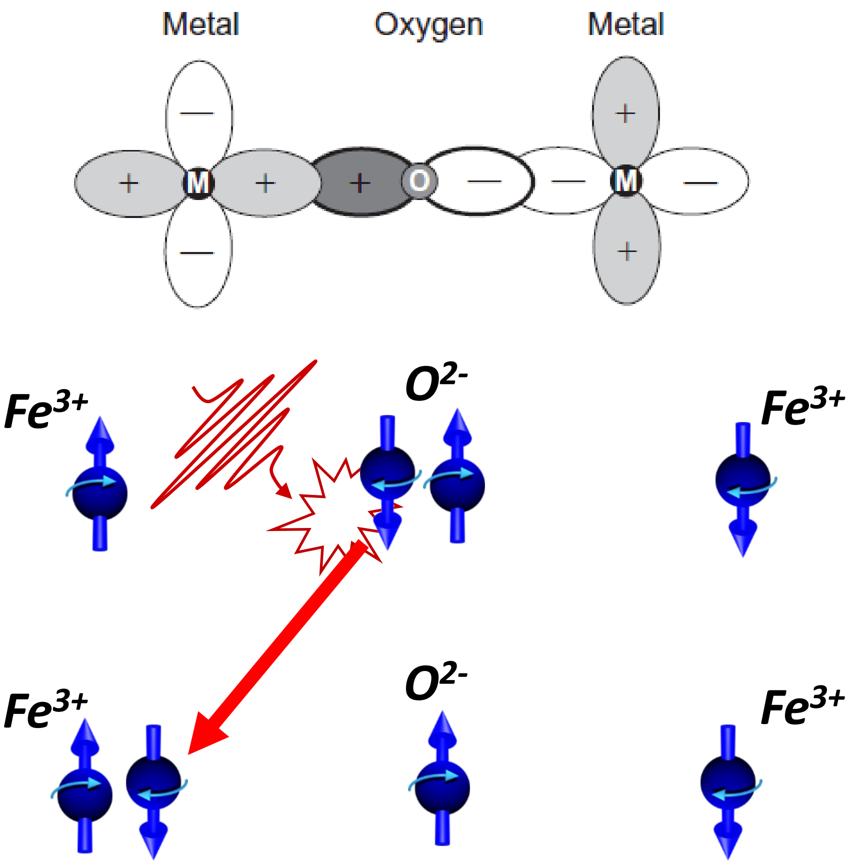
How can light change the exchange interaction?

$\alpha-Fe_2O_3$, $FeBO_3$, $RFeO_3$ (R=Y, Er, Tm etc)



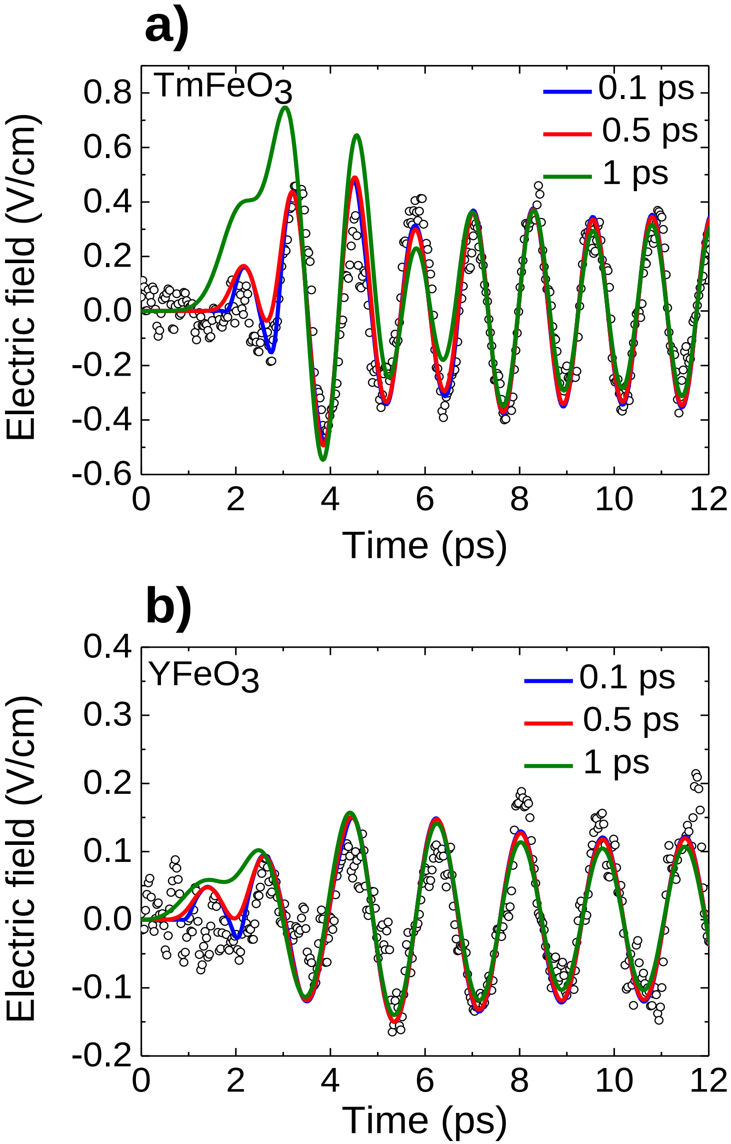
Phys. Sol. State **47** 2292 (2005).

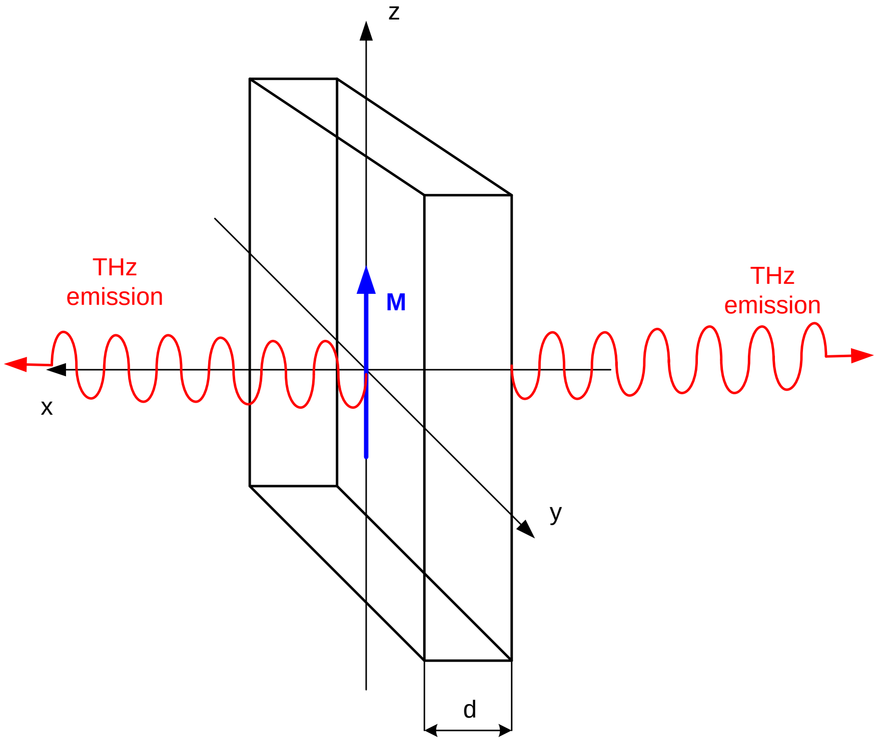
off-resonant pumping!



J. Stöhr and H. C. Siegmann
"Magnetism. From Fundamentals to nanoscale dynamics"
Springer (2006)

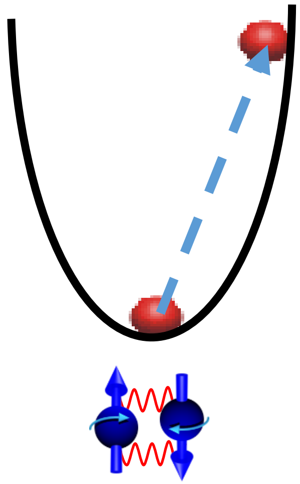
Is the optically controlled exchange ultrafast?





D/J changes about 0.01% and faster than 0.5 ps

$\Delta J/J > 0.01\%$. Is it small?



ρ_{Fe2O3}=5.25*10^3 kg/m^3

m_{Fe2O3}=160*1.6*10^{-27} kg≈2.5*10^{-25} kg

Pumped volume (1mm*1mm*100 μm)
V=10^{-10} m^3

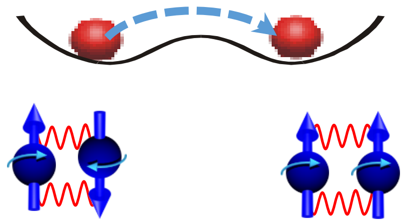
Pumped spin pairs $N=\rho_{Fe2O3}V/m_{Fe2O3} \approx 2*10^{18}$

Exchange energy of 1 spin $E_W=3kT_N \approx 4*10^{-20}$ J

Laser-induced exchange energy of 1 spin $\Delta E_W \approx 4*10^{-24}$ J

Total laser-induced exchange energy $N\Delta E_W \approx 8$ μJ

Do not look at spins.
Look at the energy!



ρ_{Fe}=7.8*10^3 kg/m^3

m_{Fe}=56*1.6*10^{-27} kg≈8*10^{-26} kg

Pumped volume (100μm*100μm*100 nm)
V=10^{-15} m^3

Pumped spins $N=\rho_{Fe}V/m_{Fe} \approx 10^{14}$

Exchange energy of 1 spin $E_W=3kT_C \approx 4*10^{-20}$ J

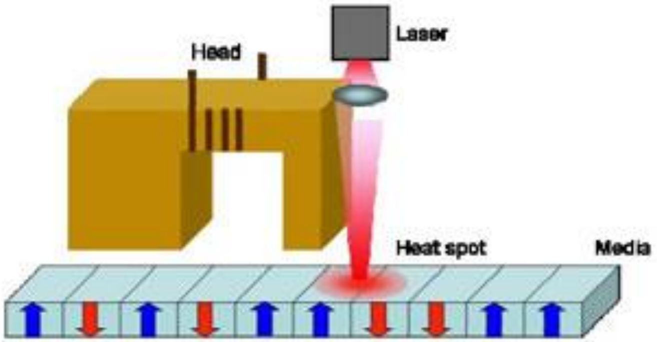
Total laser-induced exchange energy during 100 % demagnetization $E_W N/2 \approx 2$ μJ

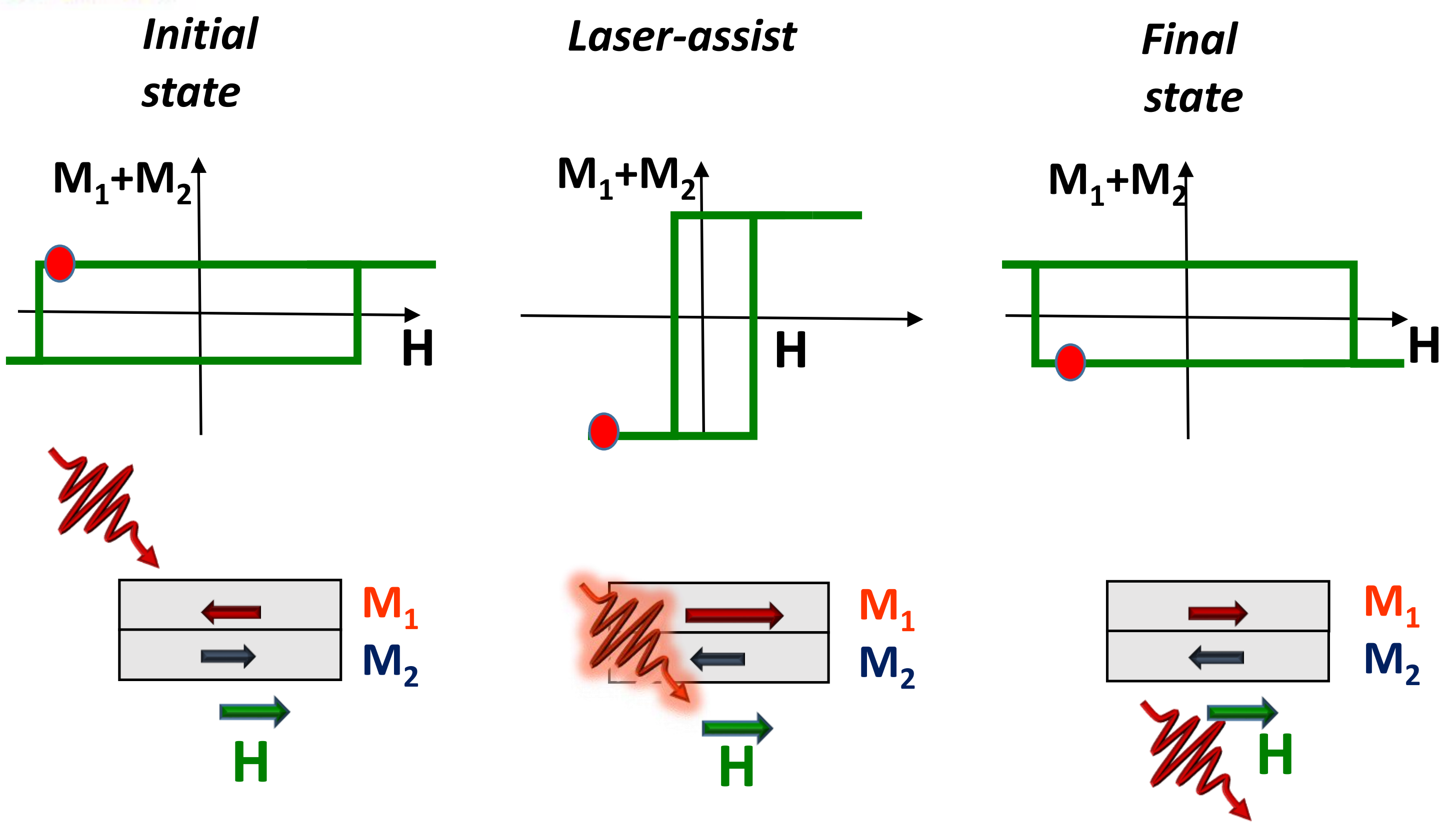
G. P. Ju et al., Phys. Rev. Lett. **93**, 197403 (2004).

J. U. Thiele, C. H. Back, Appl. Phys. Lett. 85, 2857 (2004).

T. Li et al., Nature **496**, 69 (2013).

Novel concept for magnetic recording: Laser-assisted Recording Without Heat

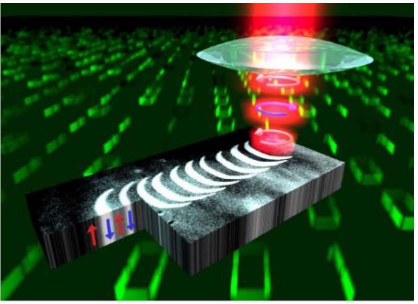


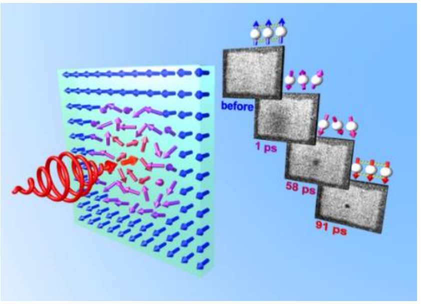


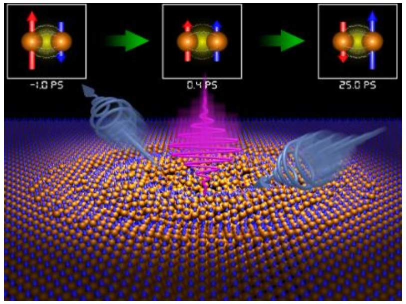
No Heat!

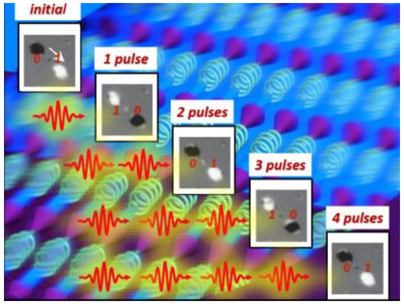
Conclusions

- *Effective fields of the exchange interaction can be harnessed for optical control of magnetism at sub-1ps time-scale*
- *Exchange interaction can be controlled ultrafast via inverse magneto refractive effect*
- *The mechanism of the control is universal*
- *The dynamics of the exchange interaction can be probed with the help of magneto-refractive effect*
- *Magneto-refraction is a key to magnetism at the time-scale of the exchange interaction*









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SEVENTH FRAMEWORK PROGRAMME

NMP "Go Fast"

Radboud University Nijmegen

erc

Starting Grant "Femtomagnetism"

The problem at different scales