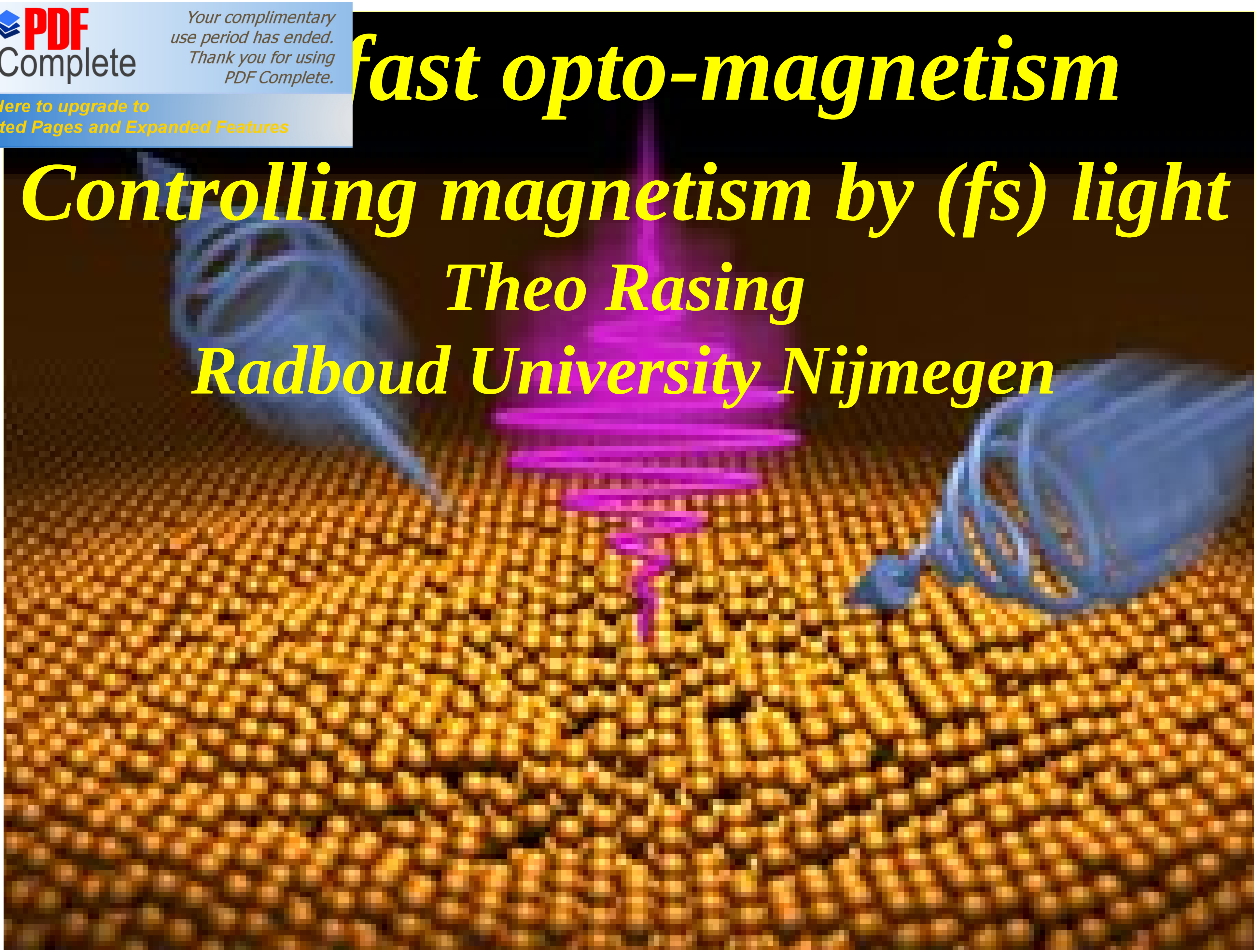
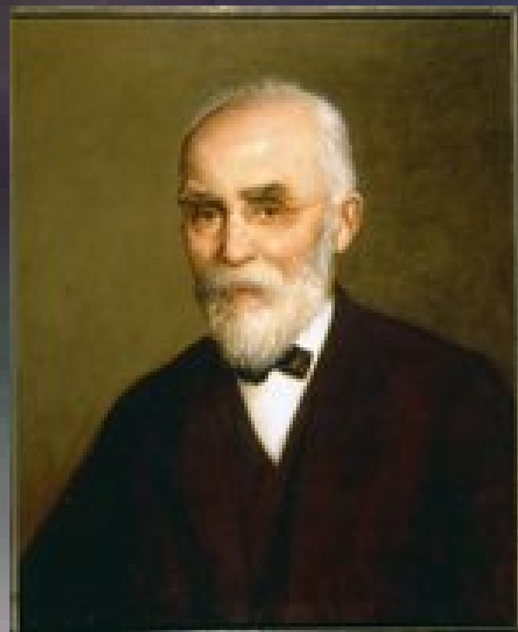
Magnetism and light


fast opto-magnetism
Controlling magnetism by (fs) light
Theo Rasing
Radboud University Nijmegen

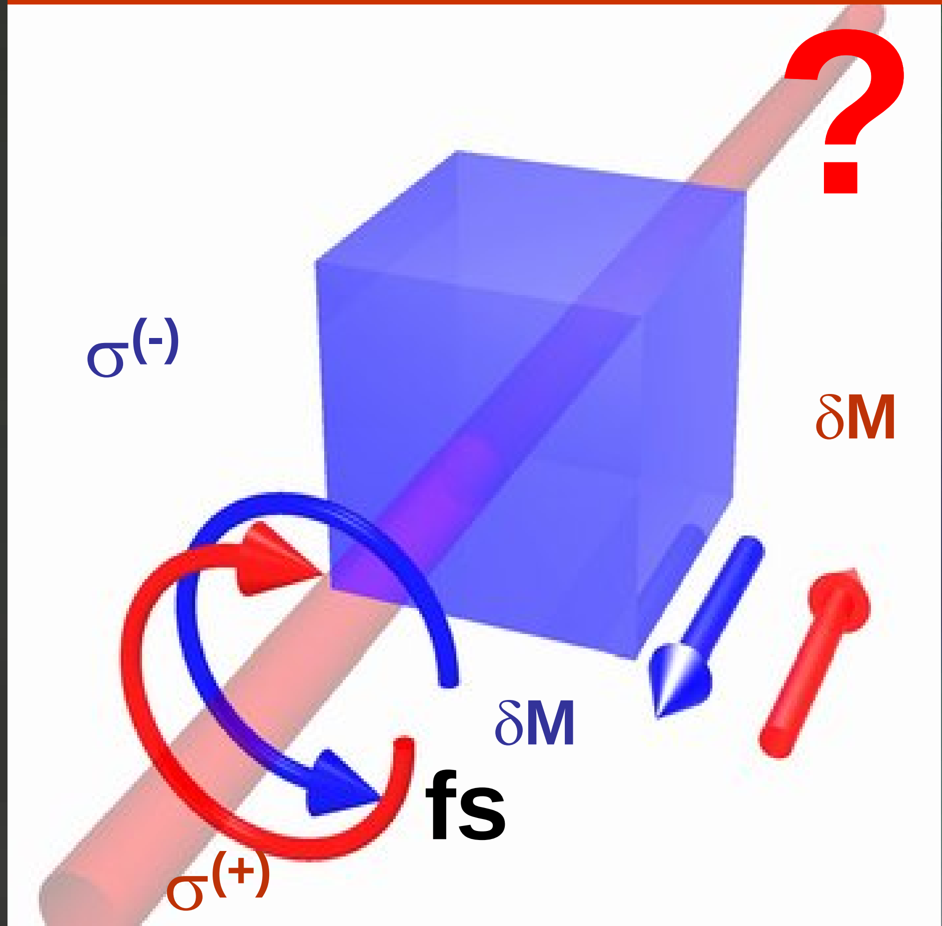
Magnetism and light



Th ... 02

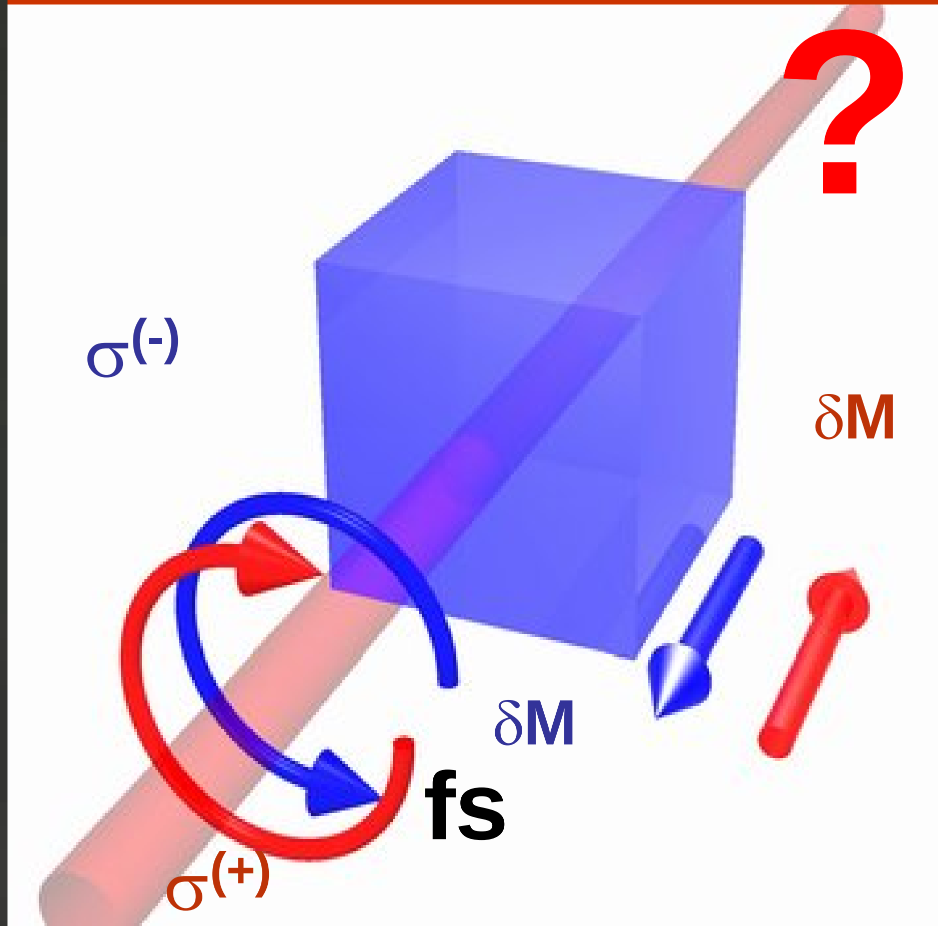
"in ... ary service they rendered by
th ... ce of magnetism upon
ra ... with Lorentz)

inverse?



Faraday effect

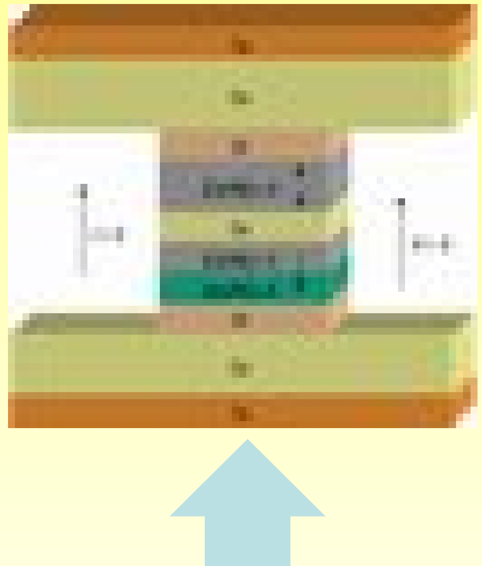
opto-magnetism



magneto-optics

gnetization reversal

magnetic field



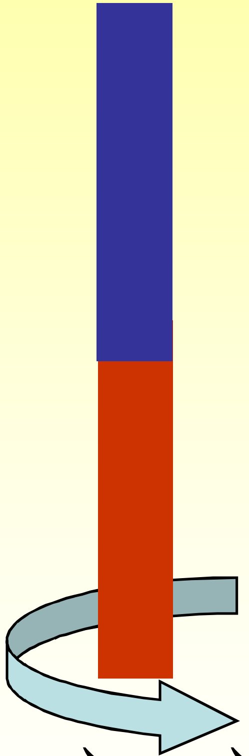
spin-polarized current

both slow!

~1ns

Haas effect

Magnetism and angular momentum



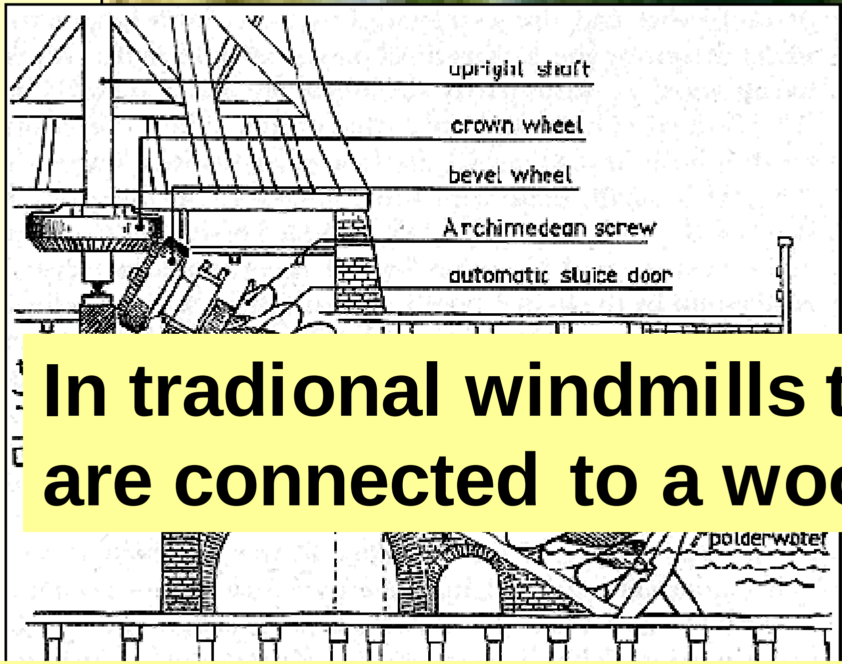
$$\vec{M} = \gamma \vec{L}$$

A. Einstein & W.J. de Haas,
Experimenteller Nachweis der Amperèschen Molekülströme,
Verhandl. Deut. Phys. Ges. **17**, 152ï 170 (1915).

...lity behind the Dykes

Traditional windmills rotate counter-clockwise

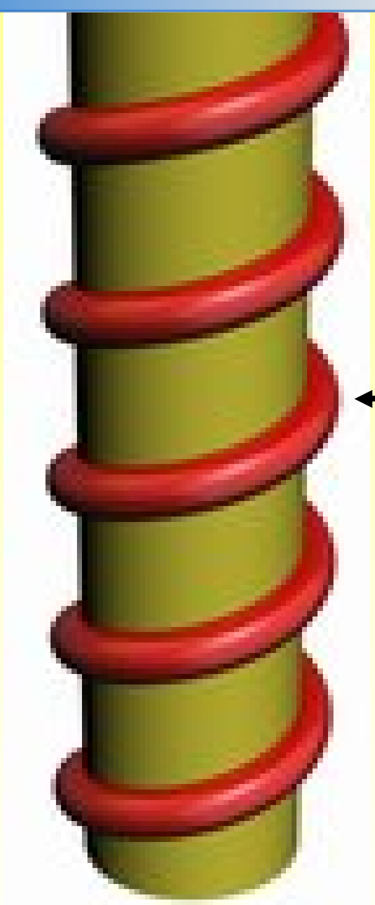
Modern windmills rotate clock-wise !



In tradional windmills the wings are connected to a wooden axle

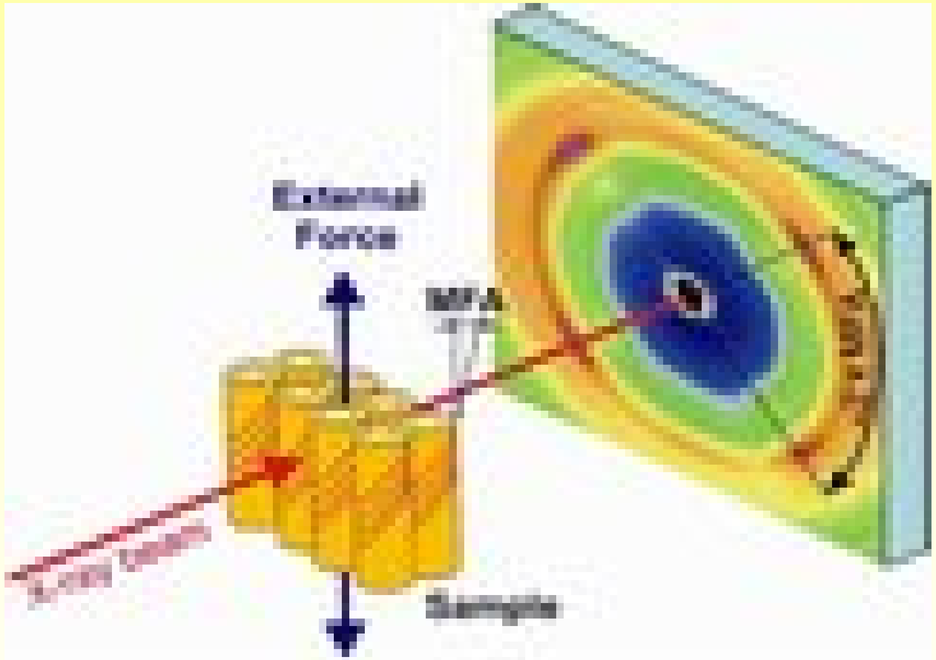
Experience:

counter-clock rotation increases lifetime of axle !



Wood cell

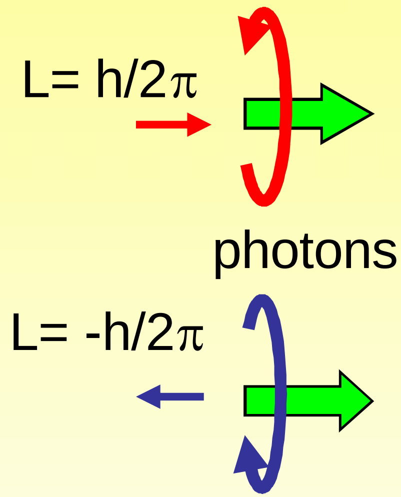
In situ wide-angle X-ray scattering (WAXS) on individual wood cells

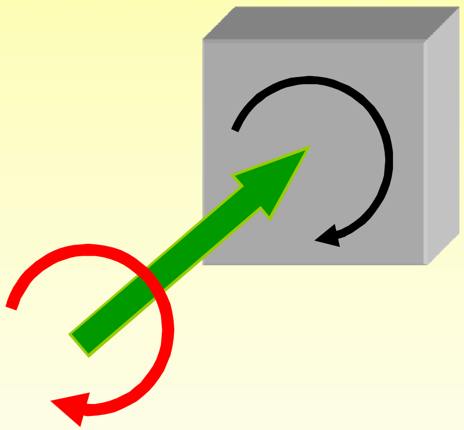


J. Keckes et al., Nature Materials 2, 811 (2003)

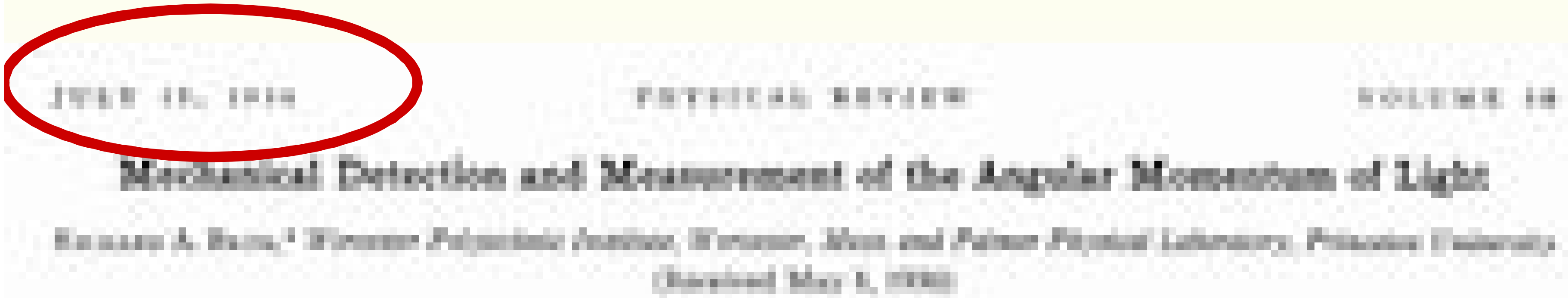
momentum of photon !

Beth's experiment

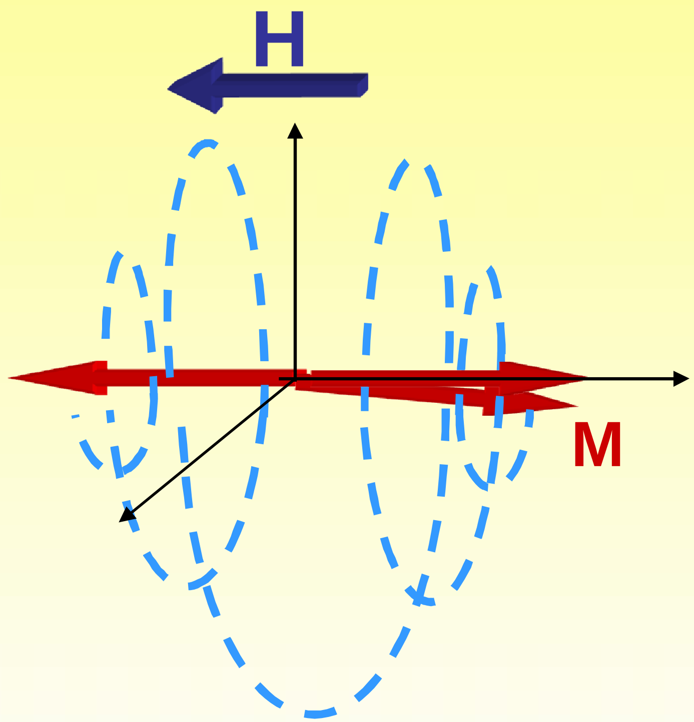


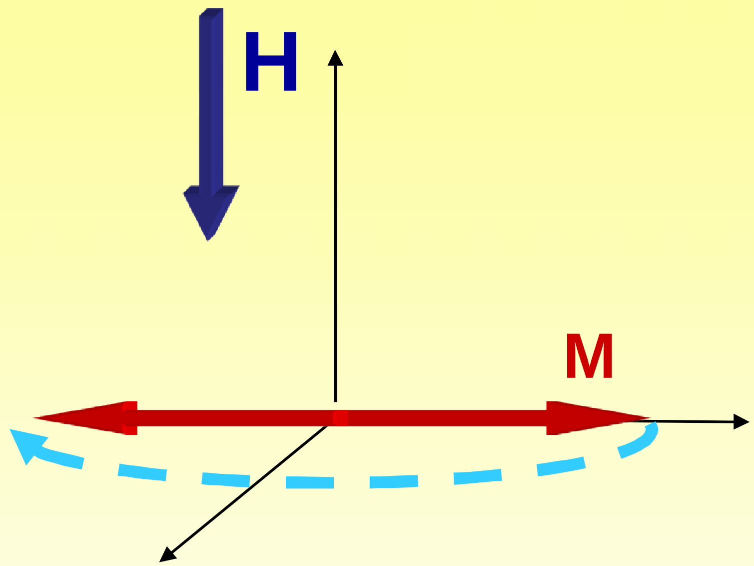


Transfer of chiral information !


Mechanical Detection and Measurement of the Angular Momentum of Light

…ms and time-scales of …tion reversal





Th. Gerrits et al., *Nature* **418**, 509 (2002).
S. Kaka, S. E. Russek, *Appl. Phys. Lett.* **80**, 2958 (2002).
H. W. Schumacher et al., *Phys. Rev. Lett*. **90**, 017201 (2003).

Reversal time~nanoseconds

Reversal time is determined by damping (ns) and spin-lattice relaxation ~ 100 ps

The shortest time achieved is 100 ps

Faster?

Spin dynamics?

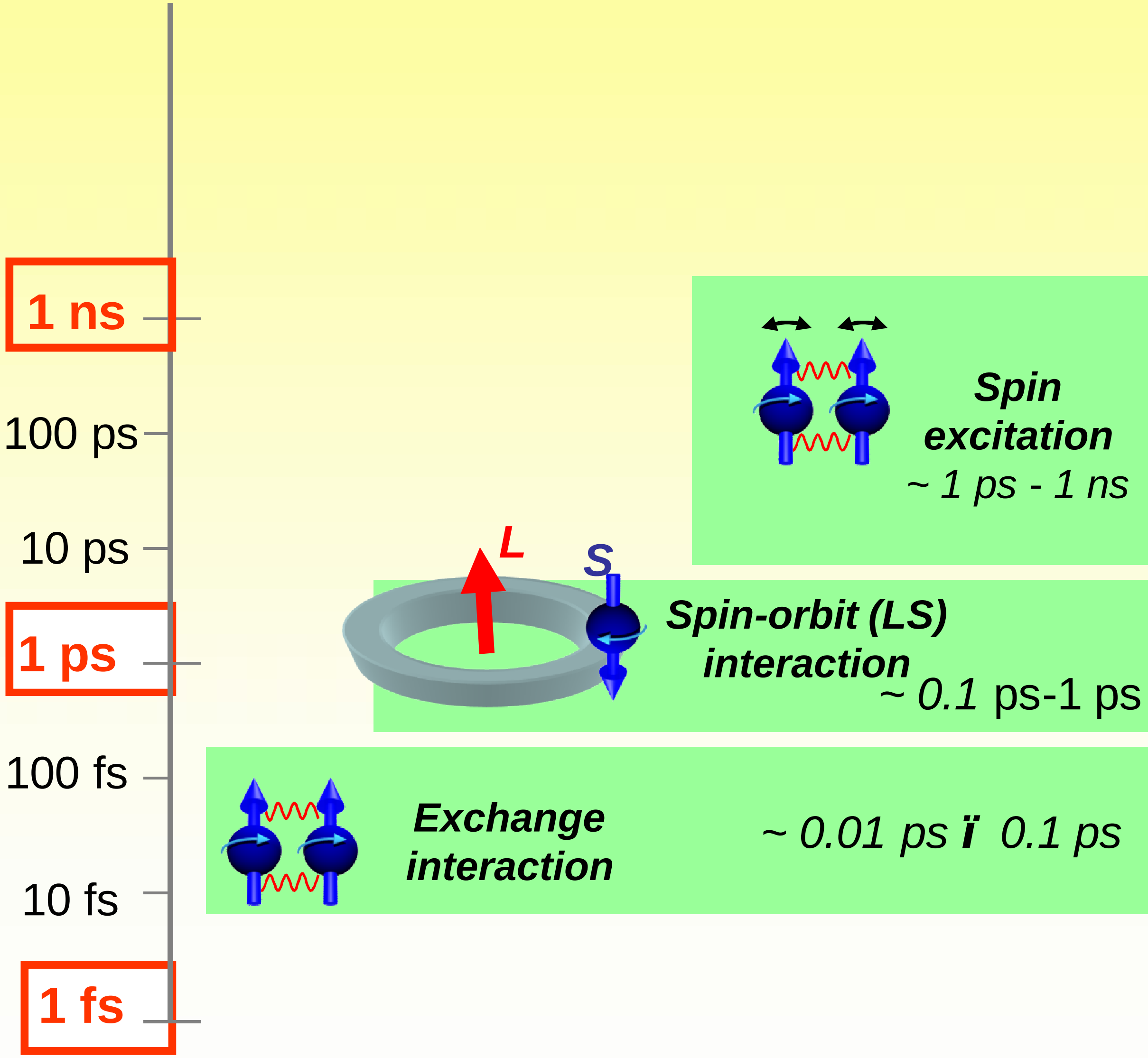
$$\gamma = g \cdot \frac{e}{2mc} = 2.8 \text{ GHz/kG}$$

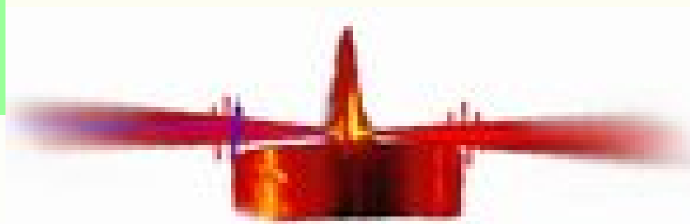
100ps ⟶ 0.36T

1ps ⟶ 36T ?

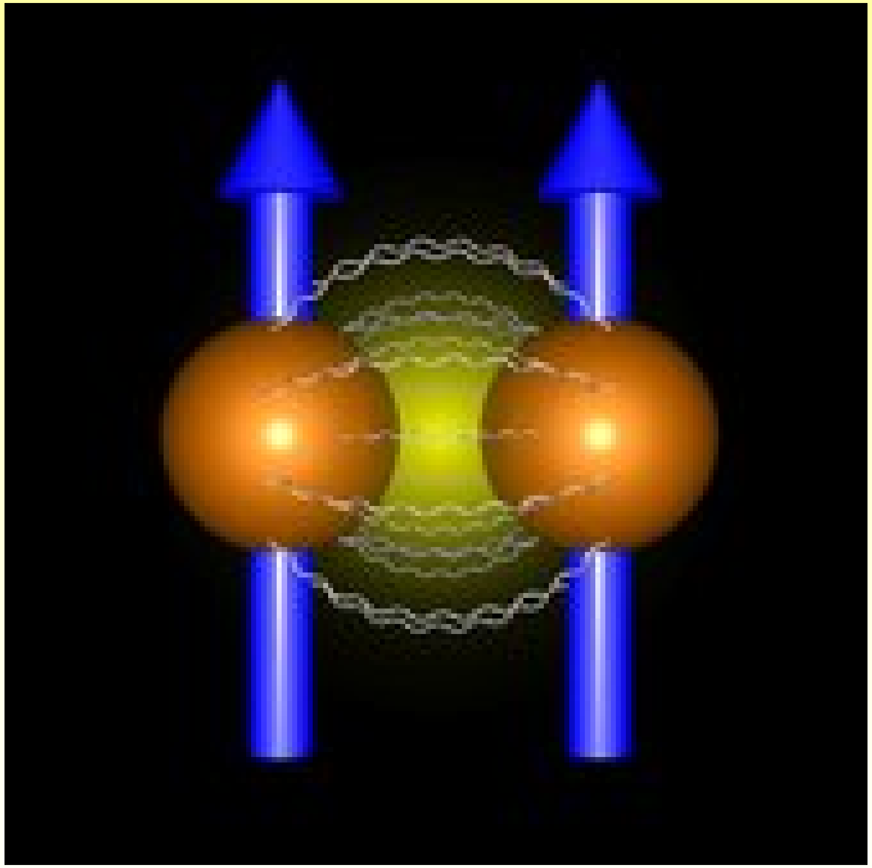

34Tesla

cales in magnetism

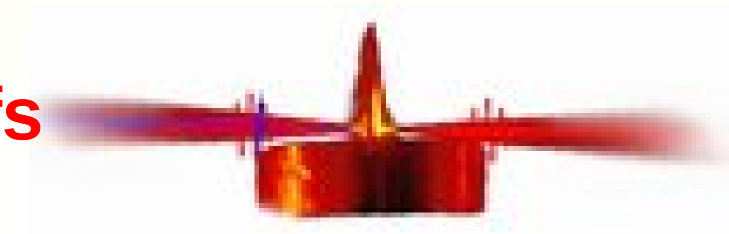




ew Mechanisms?



1-2eV,10-100fs



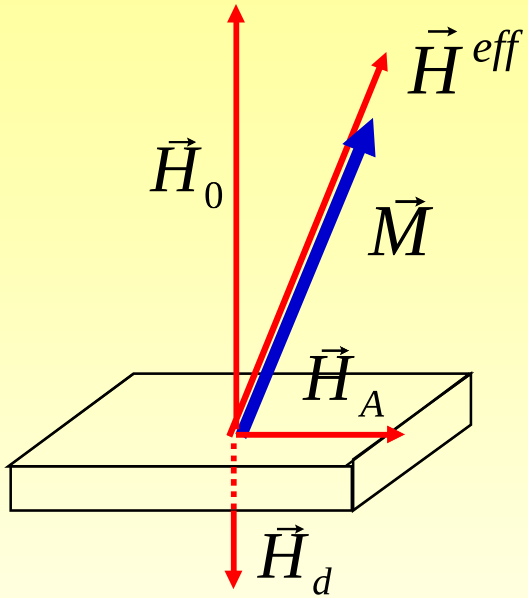
?

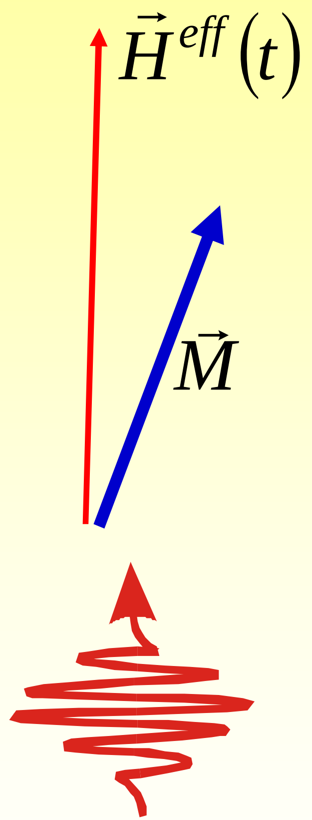
ntosecond camera

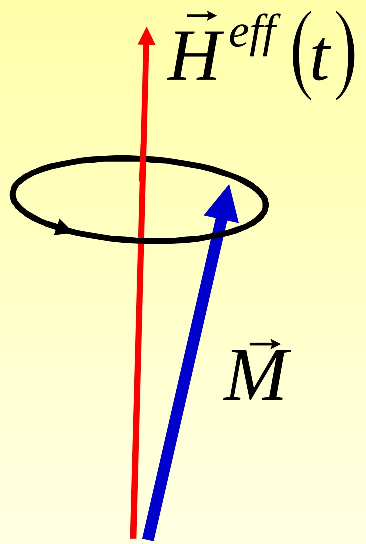
…uced spin dynamics

…e measurements

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







$$\vec{H}^{eff} = \vec{H}_0 + \underbrace{\vec{H}_A + \vec{H}_d}_{\text{laser-affected}}$$

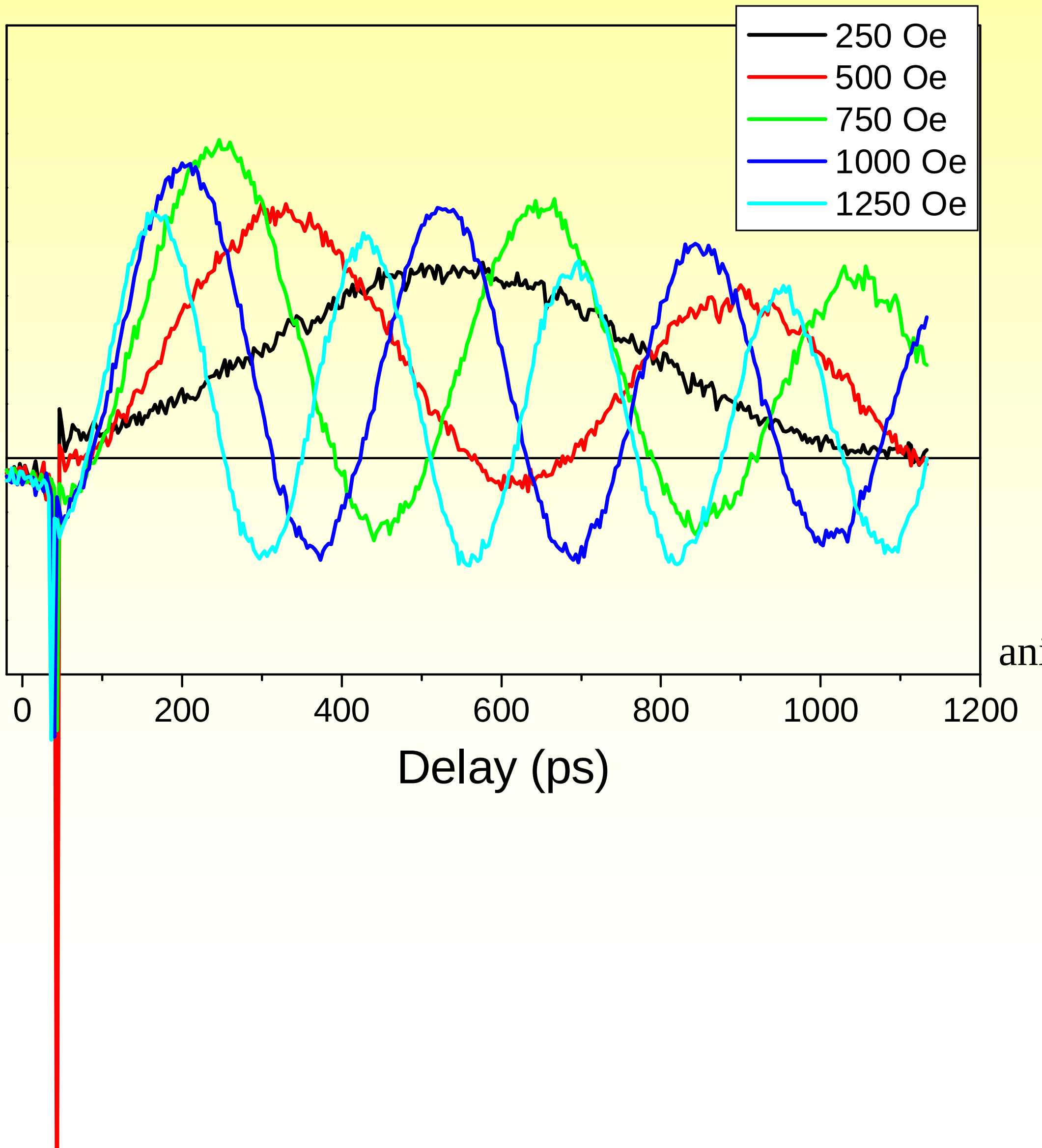
applied field ($\vec{H}_0$)

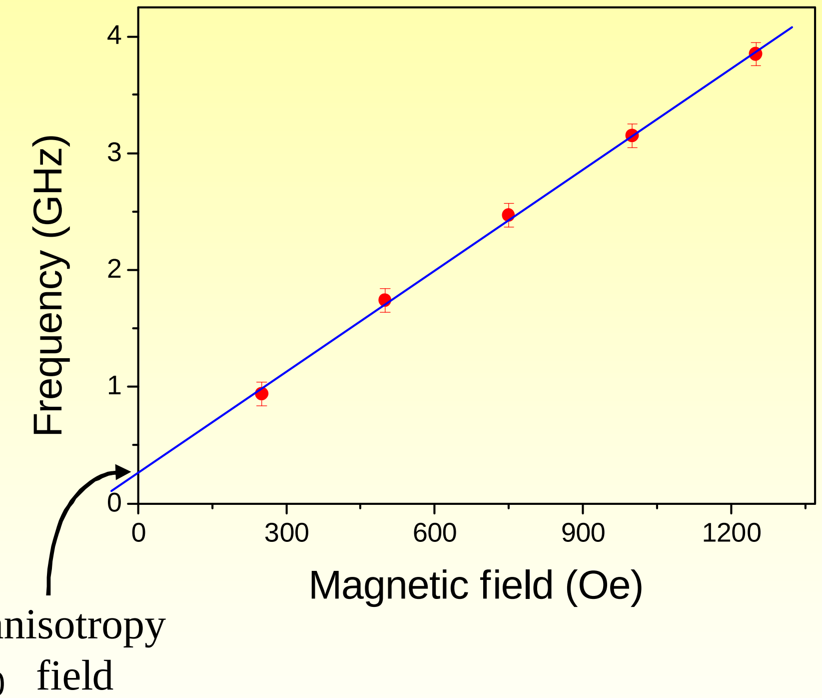
laser pulse

...nduced spin dynamics

thin film of magnetic garnet (~$Y_3Fe_5O_{12}$)

$$\omega = \gamma \left(H_A + H_0 \right)$$



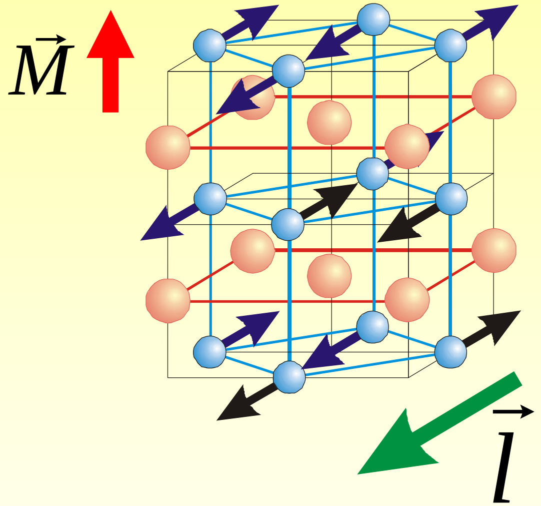


~GHz

Weak ferromagnet

Orthoferrites (RE)FeO_3

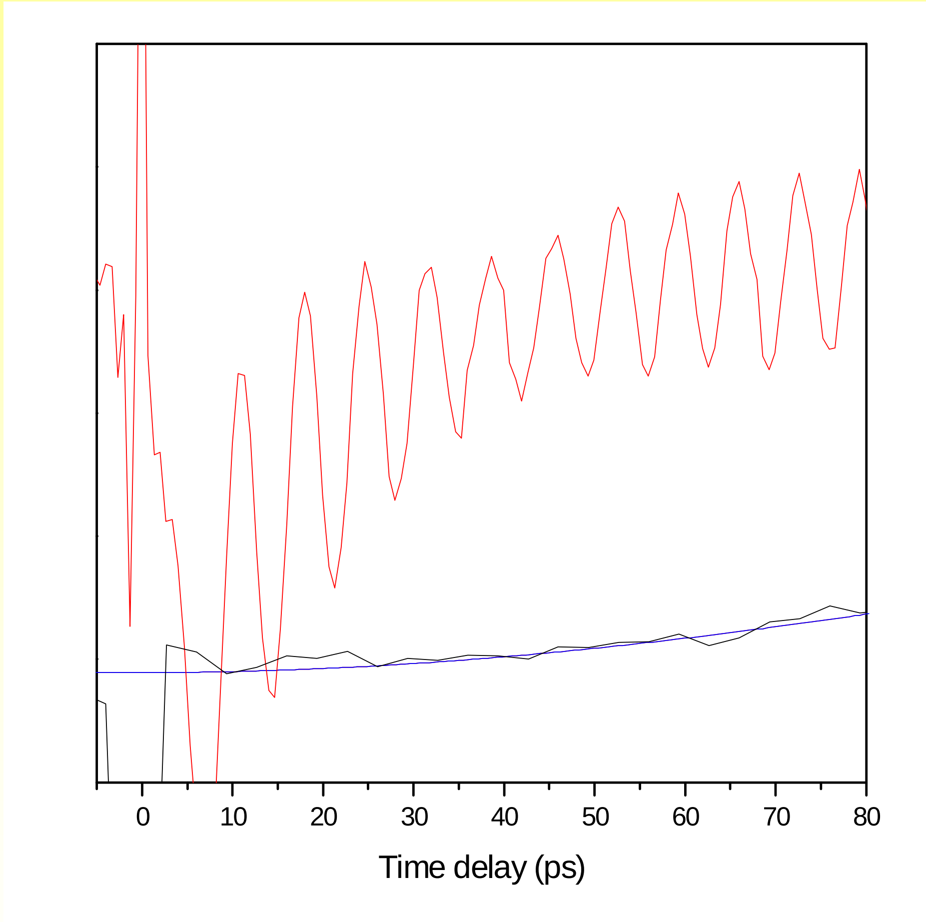
(canted antiferromagnets)



$4\pi M \approx 200$ G

low damping

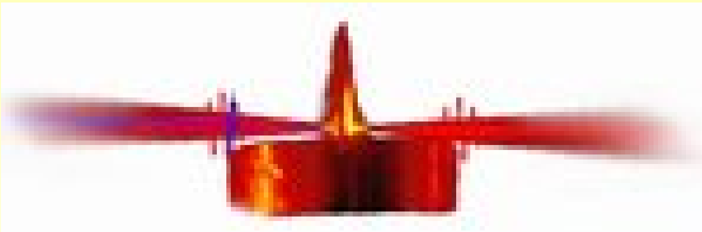
large magneto-optical effects



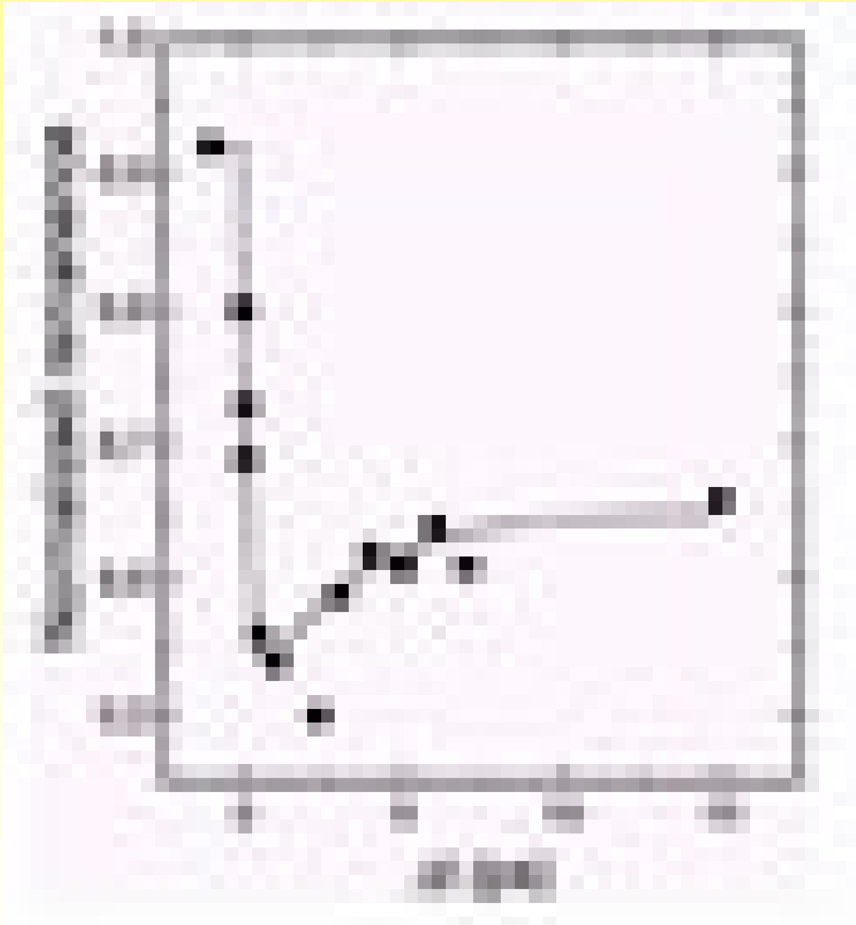
Kimel et al., Nature **429**, 850 (2004)

Period: 6 ps vs 550 ps in garnets !

repaire et al:



60fs

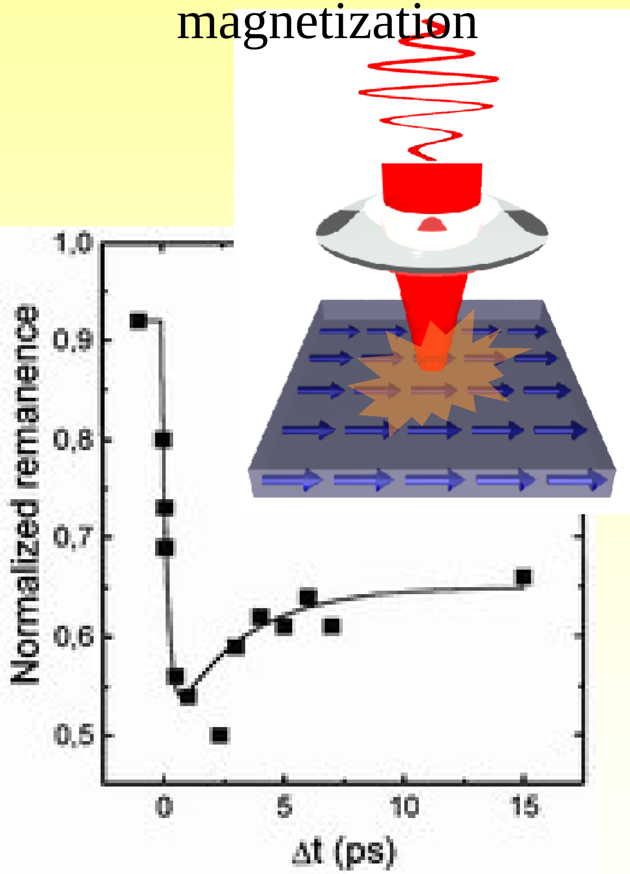


Magnetization is changed within a picosecond!!!

How is that possible?

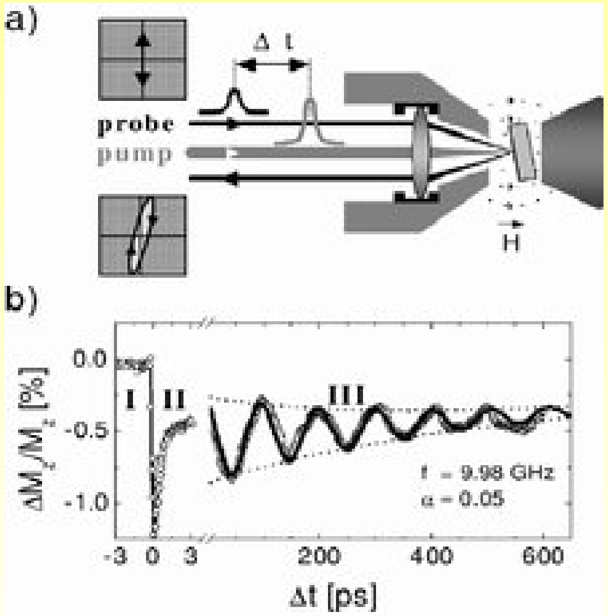
…t laser-induced effects

laser-induced collapse of magnetization



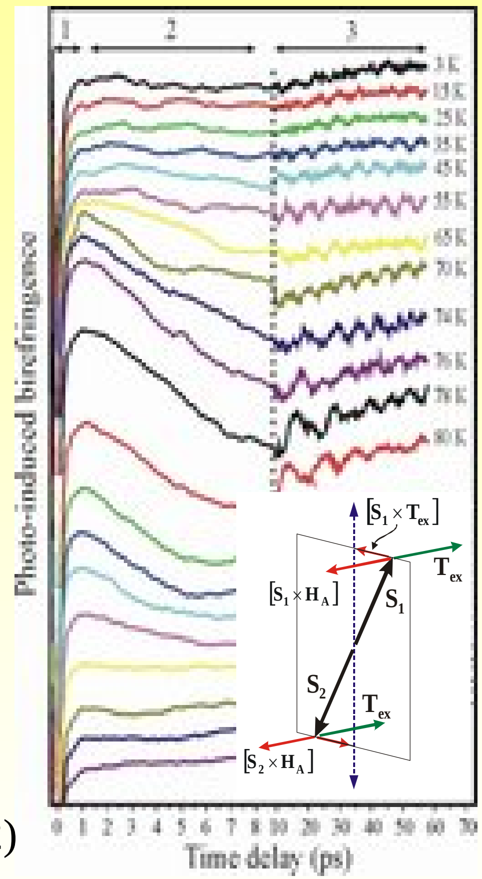
Beaurepaire et al, PRL **76**, 4250 (1996)

excitation and study of spin waves



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

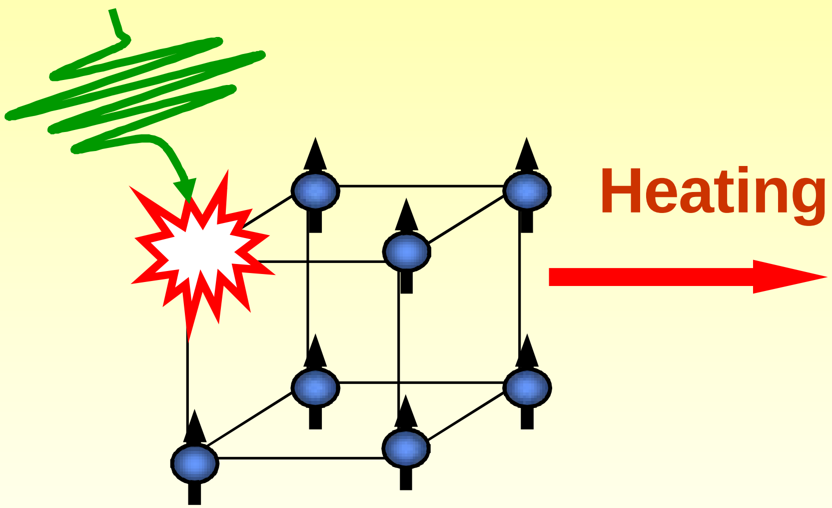
ultrafast phase transitions

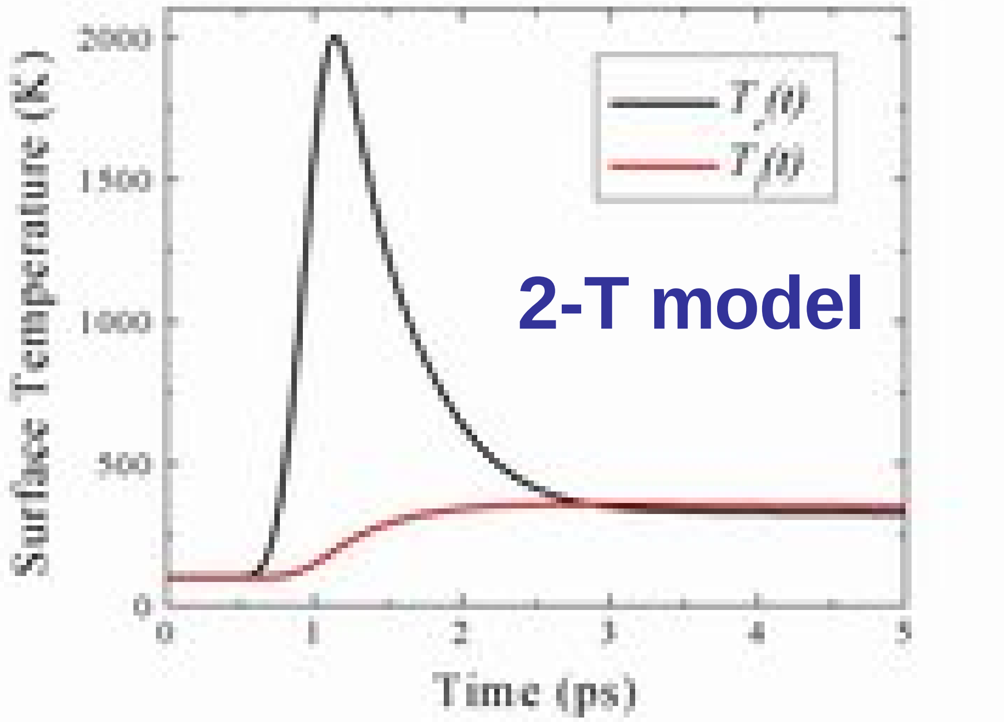


Kimel et al., Nature **429**, 850 (2004)
Ju et al, PRL **93**, 197403 (2004)
Thiele et al, APL **85**, 2857 (2004)
Kimel et al, Nature Phys **5**,727 (2009)

…ed dynamics: Excitation mechanism?

Ultrashort laser pulse



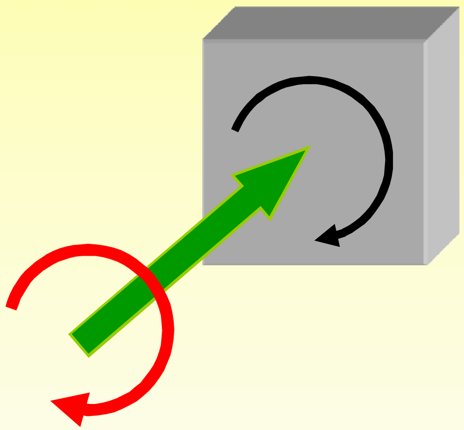


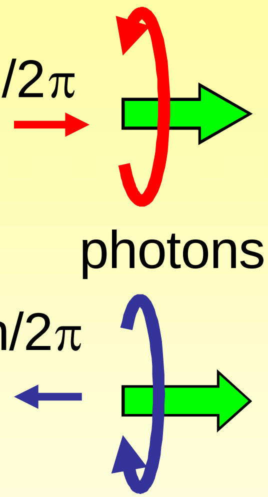
Solution: (only quenching !)

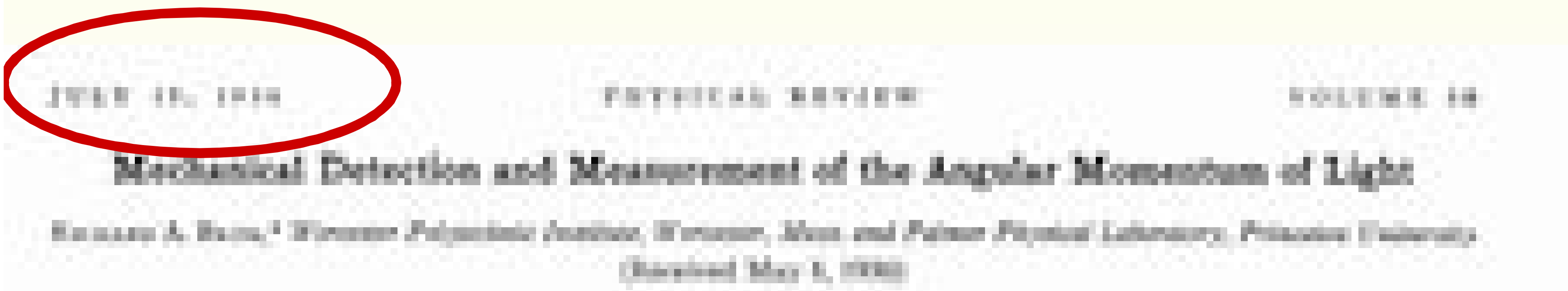
A nonthermal effect of photons on spins

momentum of photon !

Beth's experiment



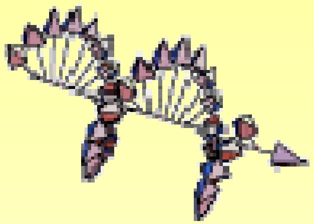



PHYSICAL REVIEW

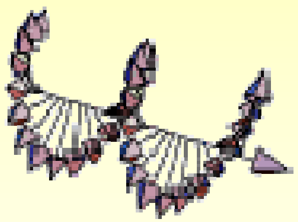
Mechanical Detection and Measurement of the Angular Momentum of Light

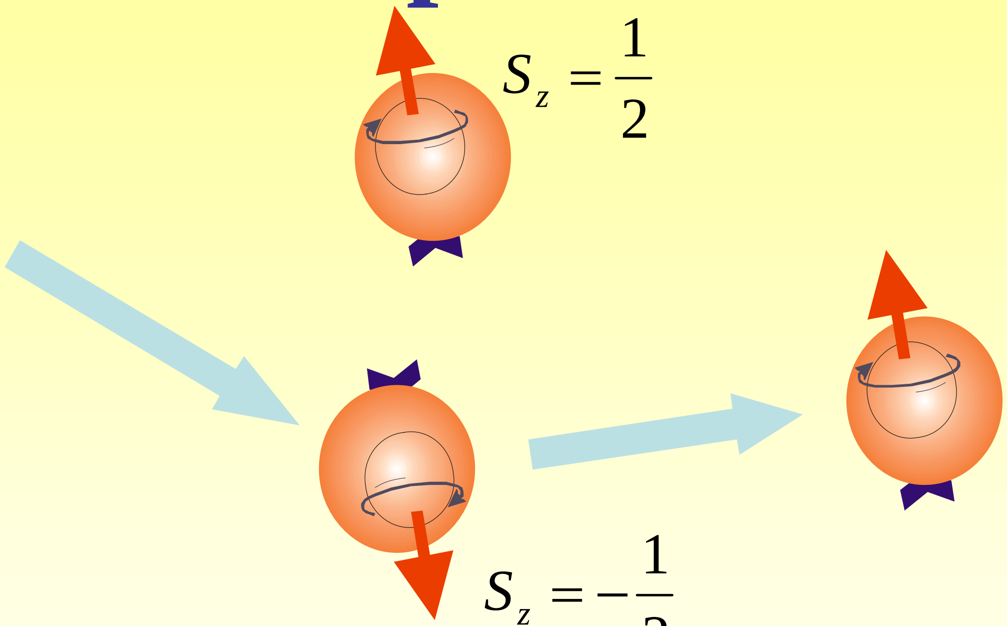
polarization, photon spin, and absorption

$S_z = +1$



$S_z = -1$





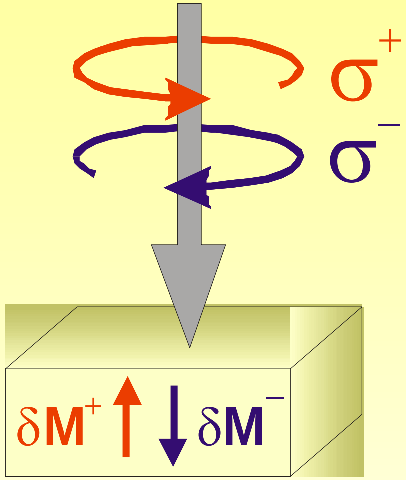
1 photon / site = 20000 K ΔT

very fast and easy?

~0.01 phot/site max
Ò0.01 efficiency

effect Ò 10^{-4}

ons magnetize a medium ?



Yes, they can!!!

$$\mathbf{M} = \frac{\varepsilon_0}{\mu_0} a \left[\mathbf{E} \times \mathbf{E}^* \right]$$

inverse Faraday effect !

L.P.Pitaevski: Electric forces in a transparant dispersive medium, Sov.Phys.JETP 12,1008-1013 (1961)

J.P.van der Ziel,P.S.Pershan&L.D.Malmstrom: Optically induced magnetization resulting from the inverse Faraday effect,Phys.Rev.Lett.15,190-193(1965)

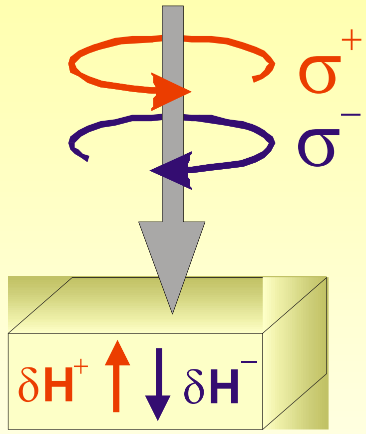
ynamics

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

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

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

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



Inverse Faraday effect

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

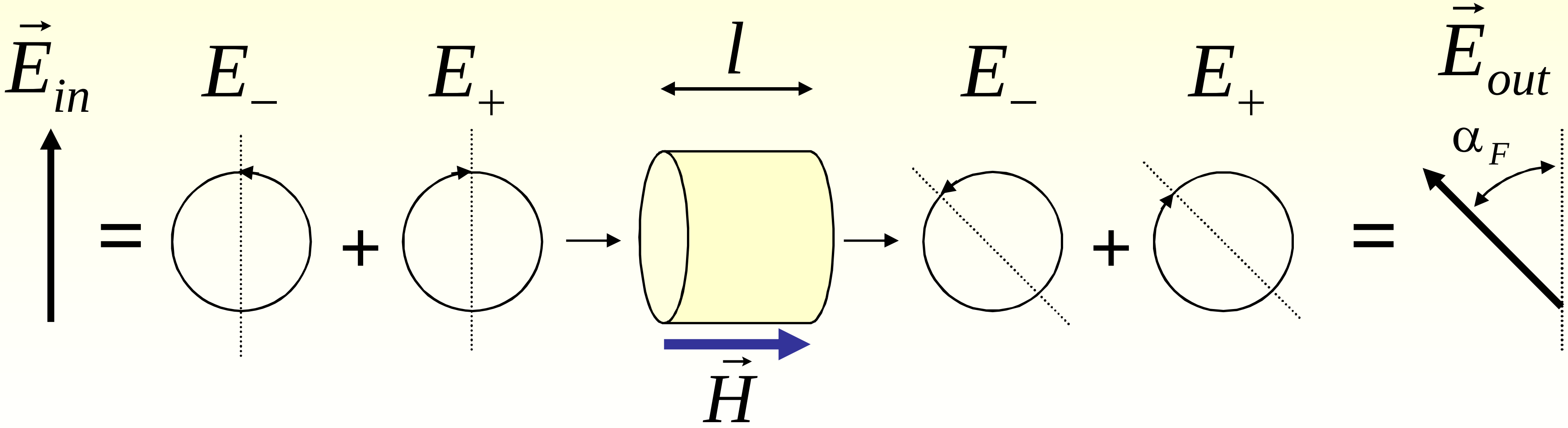
Faraday effect

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

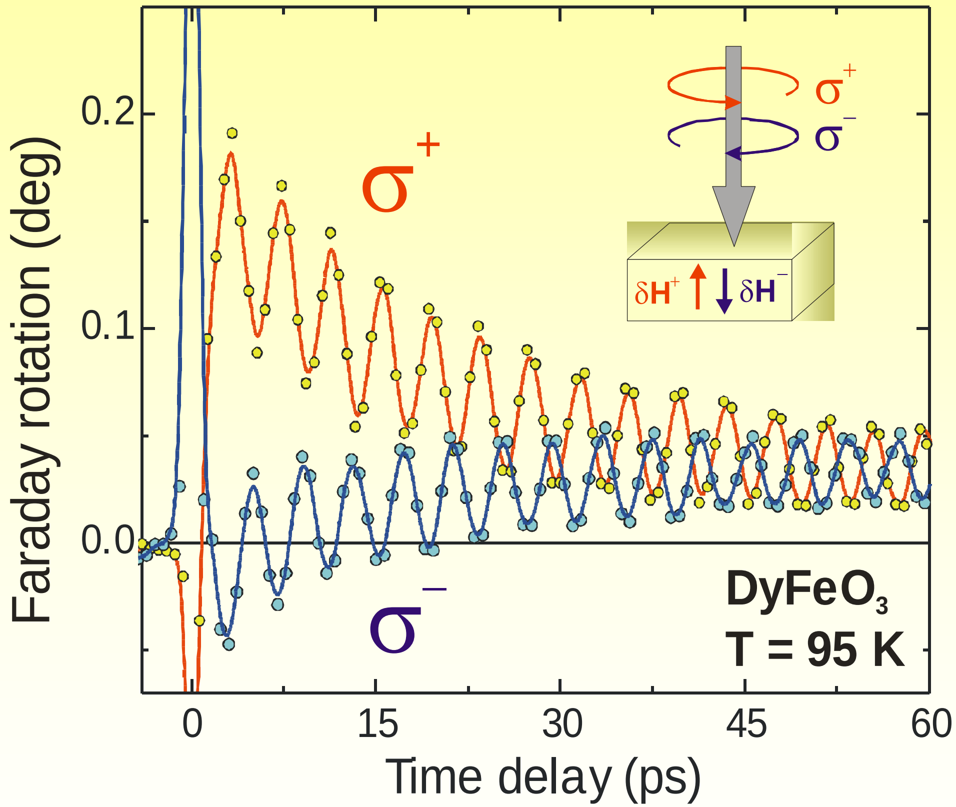
$$\vec{H}(0) = \frac{\varepsilon_0}{\mu_0} \alpha \left[\vec{E}(\omega) \times \vec{E}^*(\omega) \right]$$

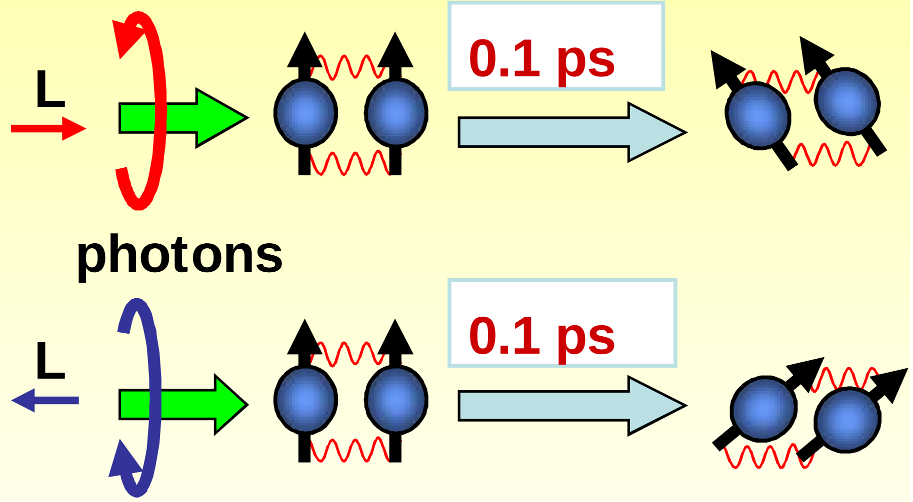
➡ **no absorption required!**

➡ **no angular momentum transfer!**



xcitation of spins in $DyFeO_3$

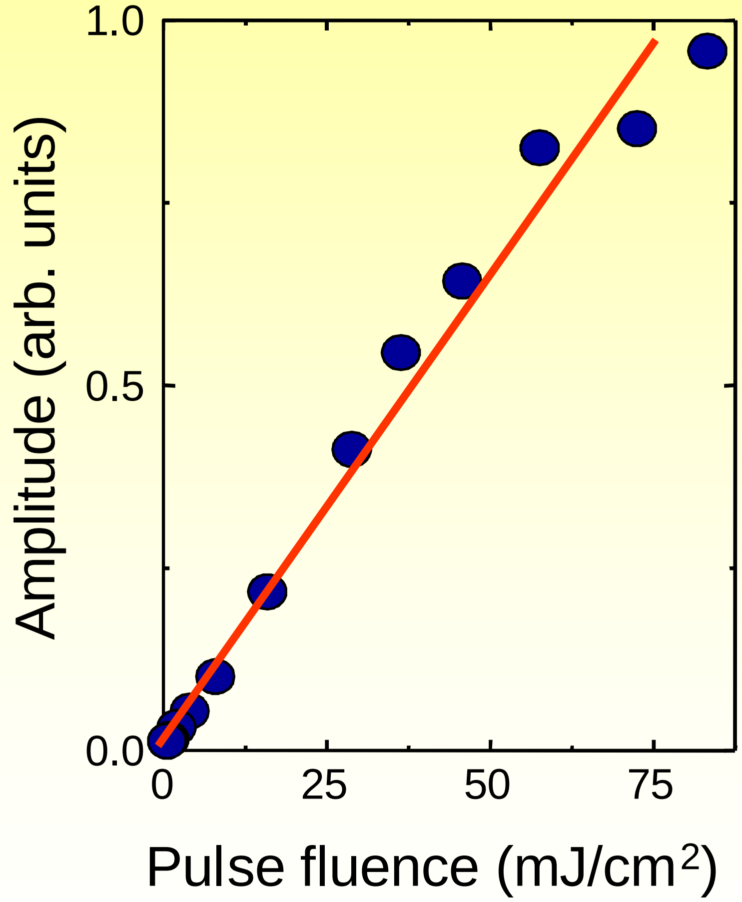




as strong as 1 T!

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

…of the laser-induced spin-waves

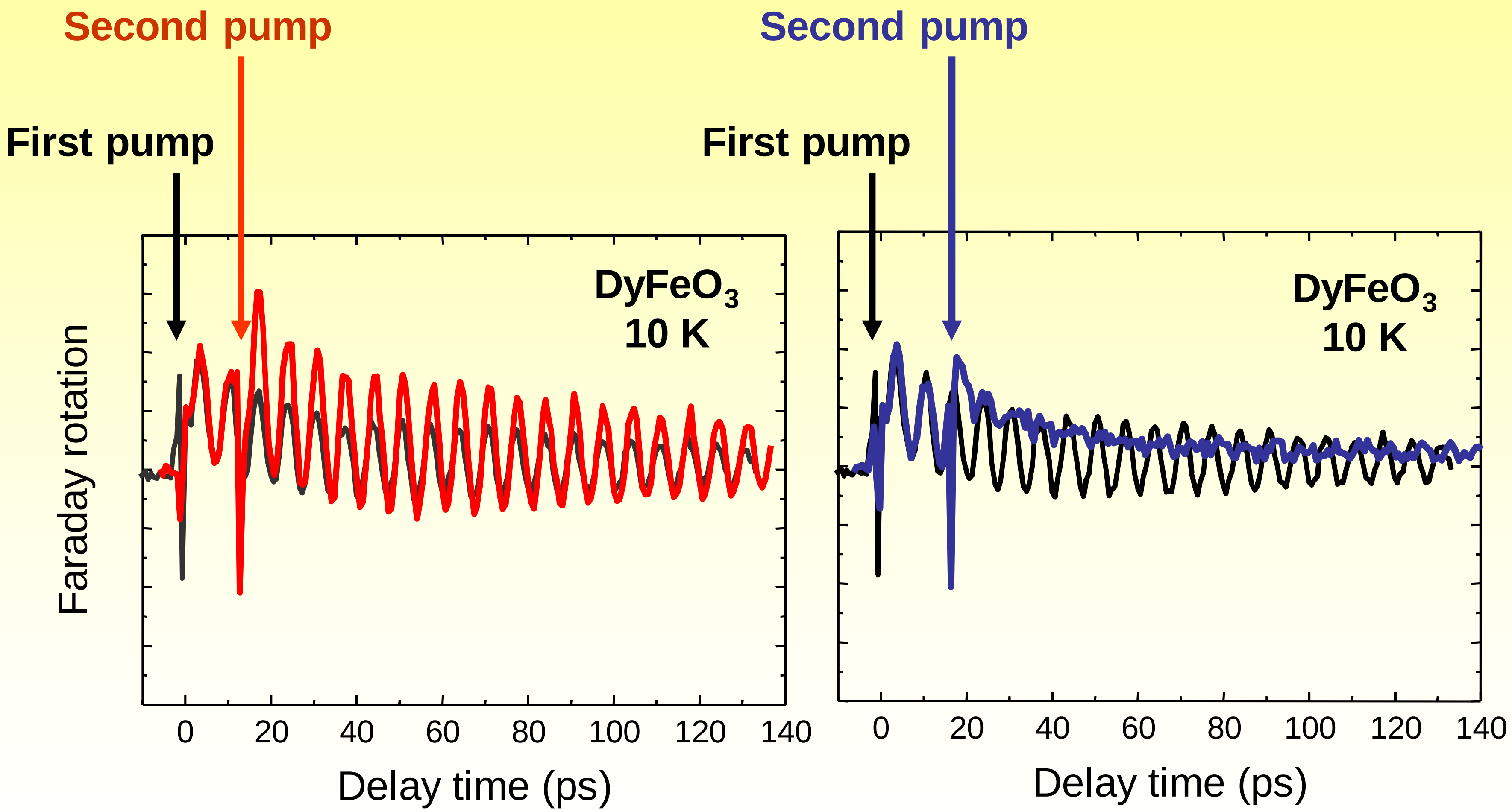


Inverse Faraday effect

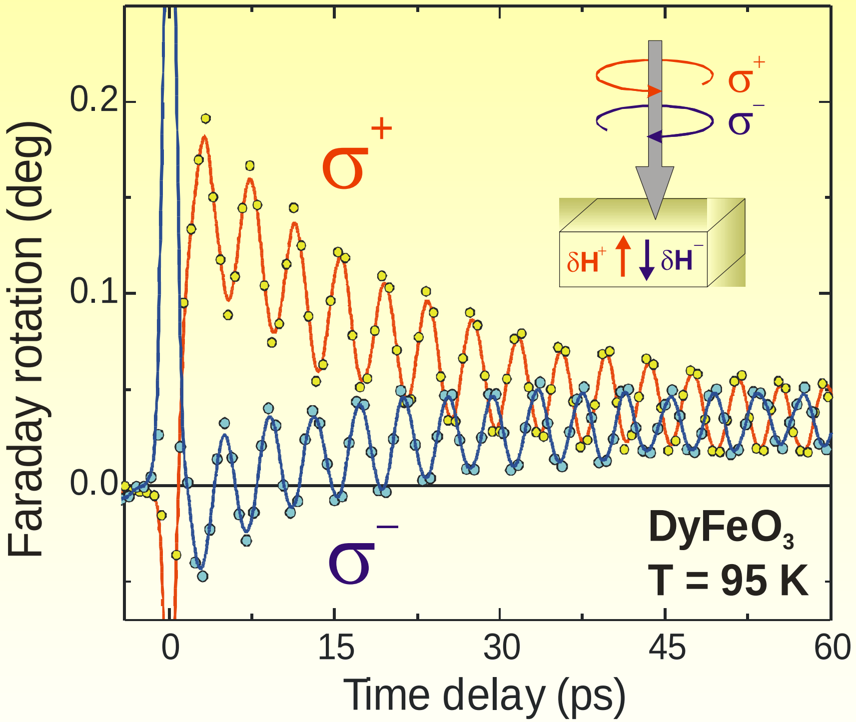
$$H_{eff}(0) = \alpha \frac{\varepsilon_0}{\mu_0} E(\omega) E^*(\omega)$$

Fields up to 5 T!

pump coherent control



itation of spins in $DyFeO_3$ via the Inverse Faraday effect



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

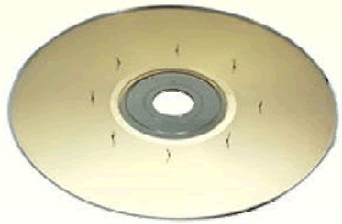
Referee A:

ñBut, unfortunately, the observed signal is so small that it seems impractical to utilize the inverse Faraday effect for the purpose of ultrafast control of magnetization in metallic materials.ò

eto-optical imaging + pulsed laser

Circularly polarized 40fs laser pulses

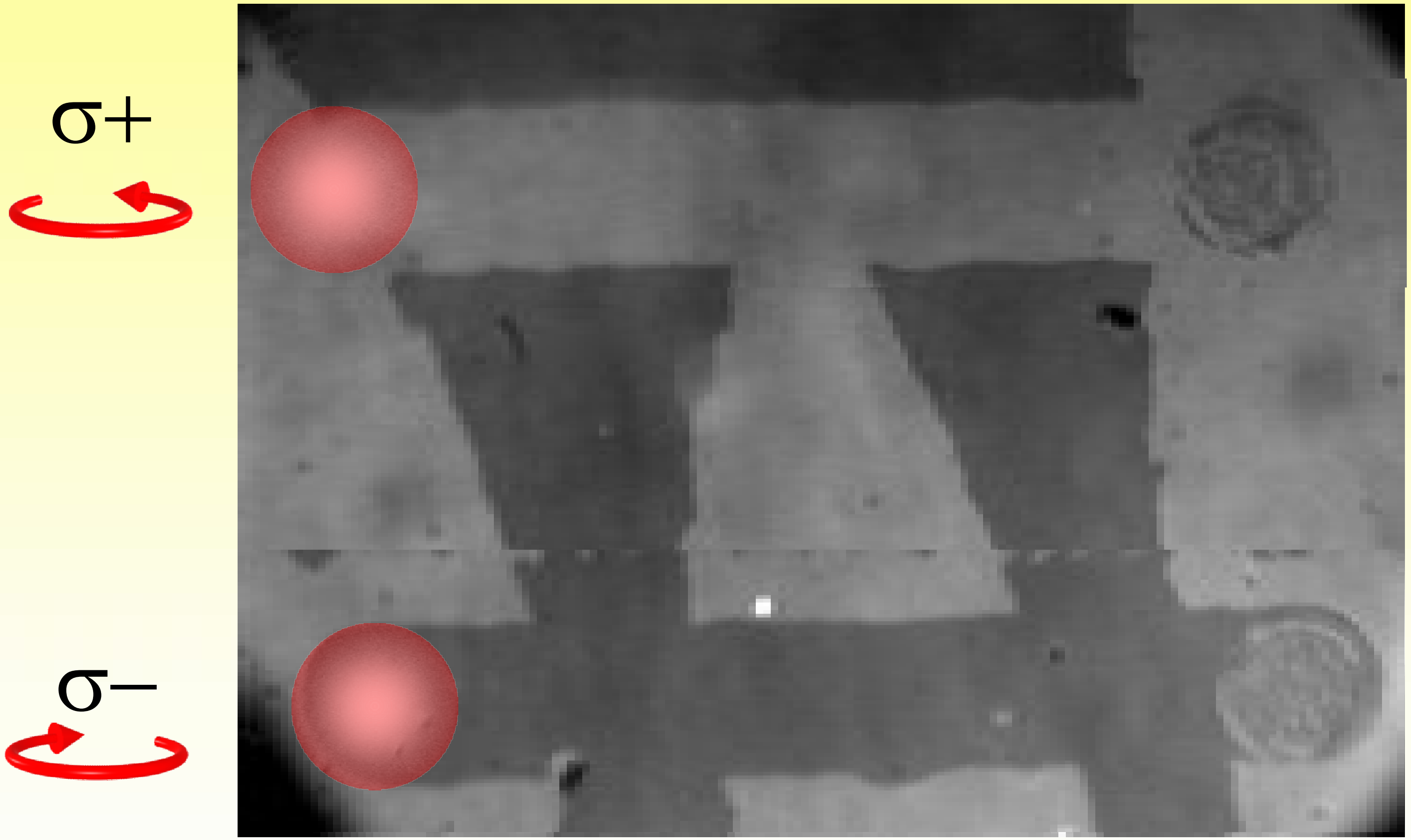
20 nm GdFeCo film



Magneto-Optical microscope

…anipulation of magnetization

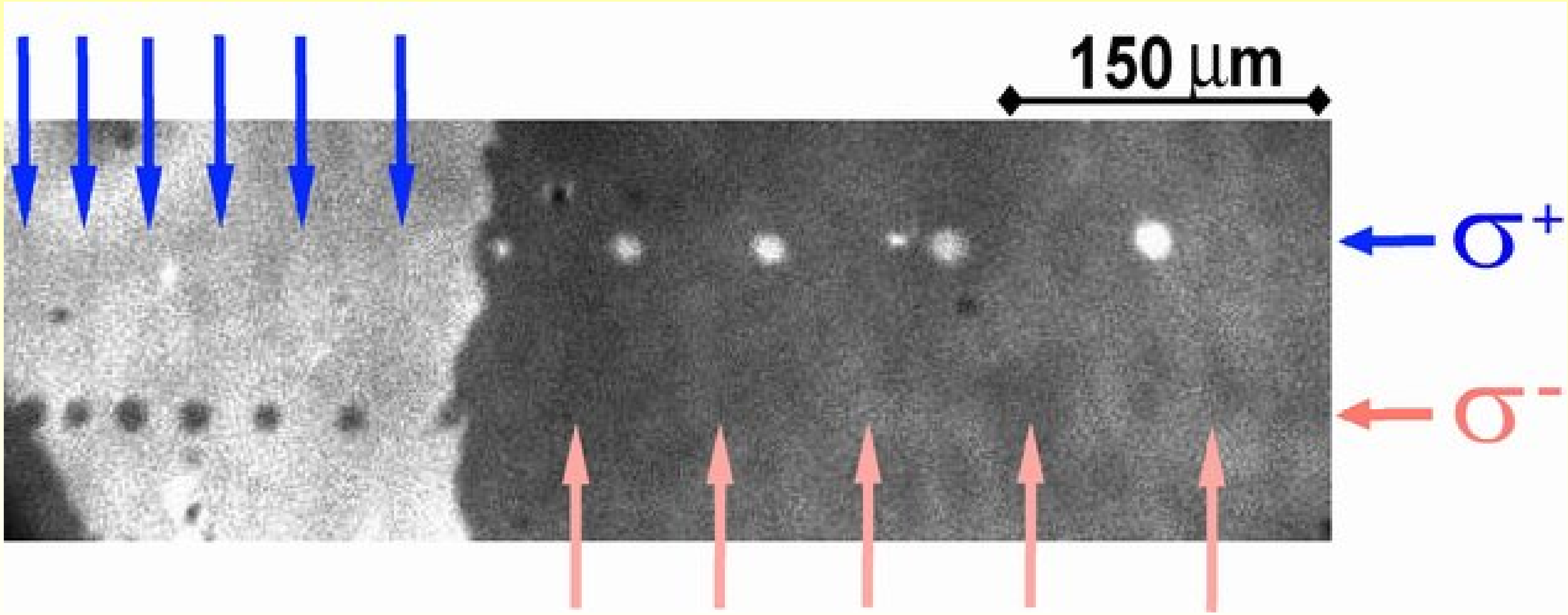
40 fs pulses, 1 kHz **GdFeCo** **$H_{ext} = 0$**



Reversal by 40fs laser pulses!

tion reversal in FeGdCo y a single 40 fs laser pulse

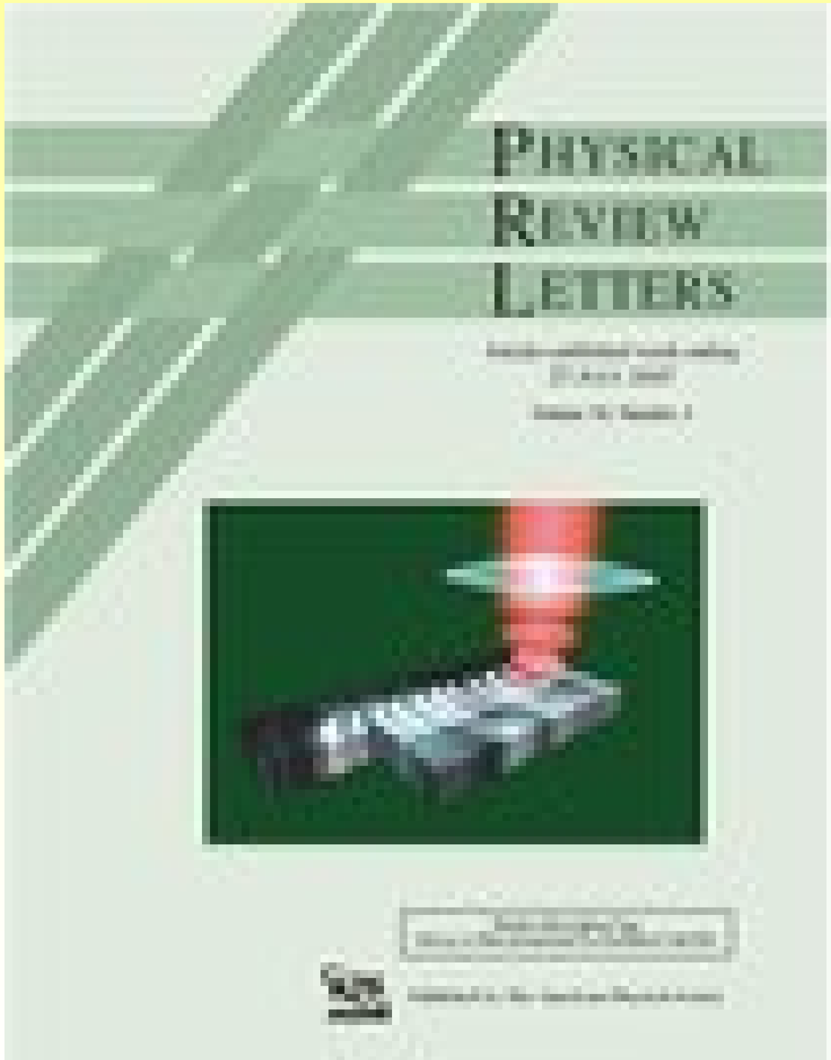
Sweeping the pulsed laser beam at high speed across the sample



Å*Each domain written with <u>single</u> 40 fs laser pulse*

C.D. Stanciu et al., PRL 99,047601 (2007)

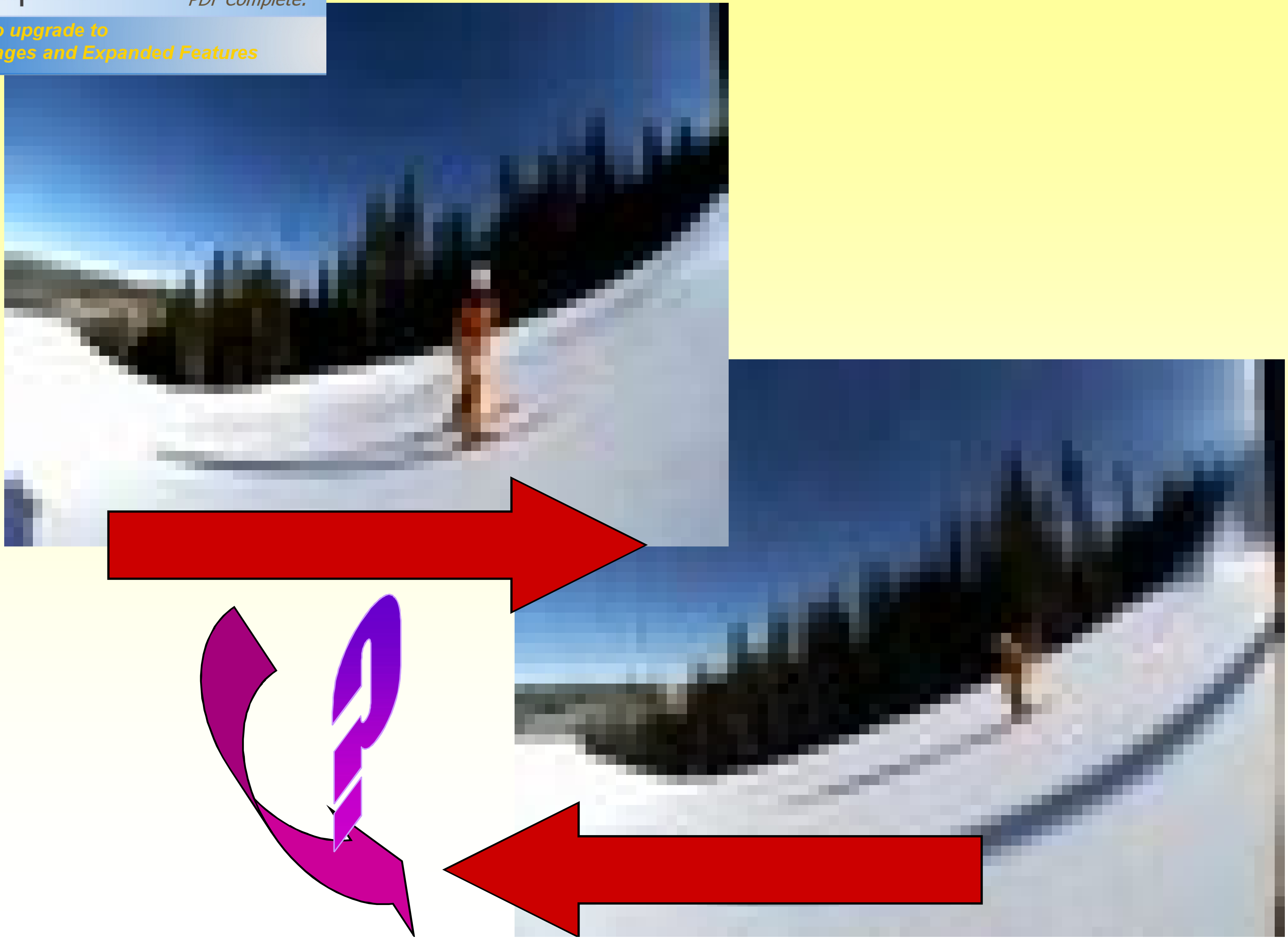
Ultrafast all optical recording



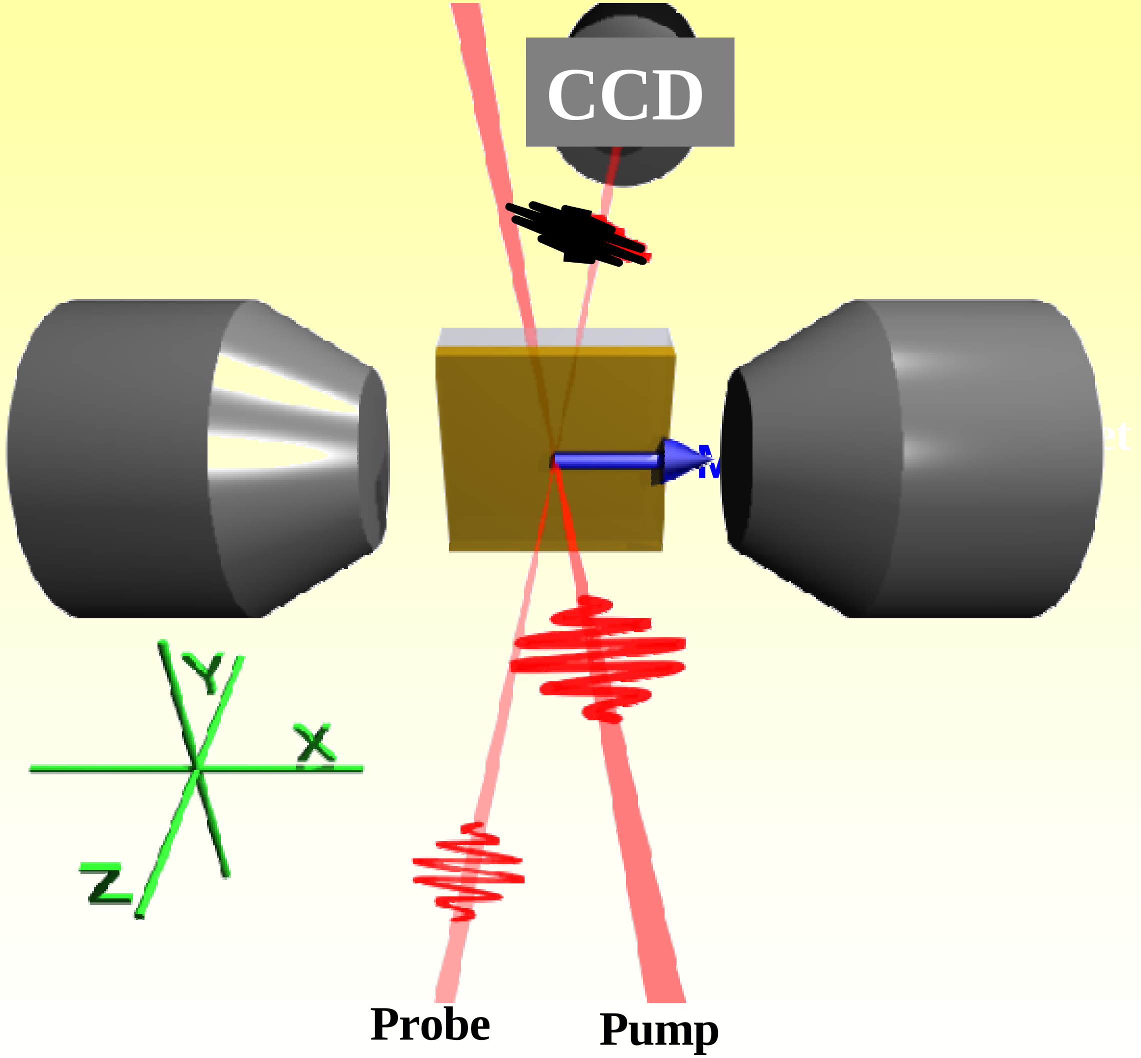
C.D. Stanciu et al., *patent* #P77323PC00, PRL **99**, 047601 (2007)

So,

- ***Light can reverse magnetization!***
- ***..and even a single 40fs pulse !***
- ***But what is the mechanism?***



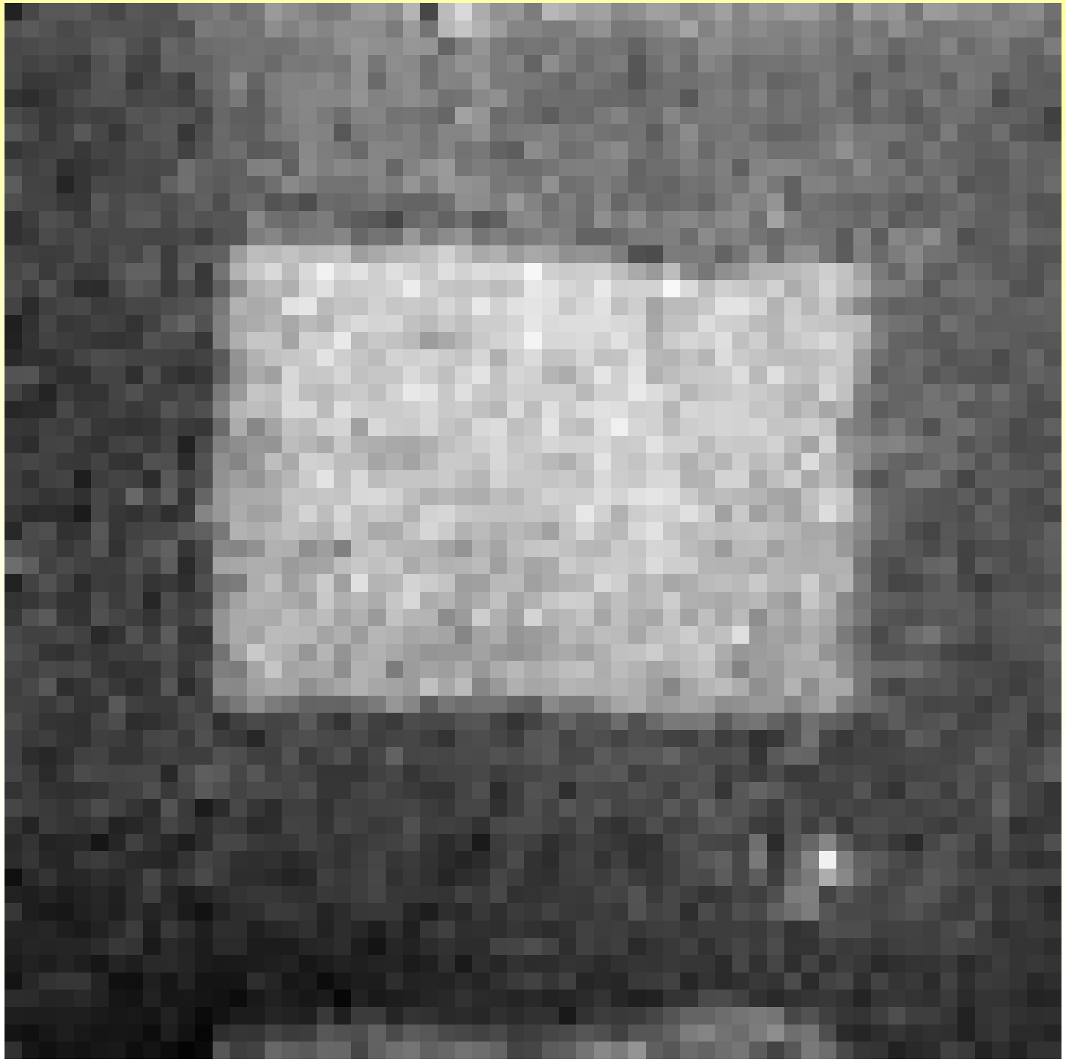
…t magneto-optical imaging



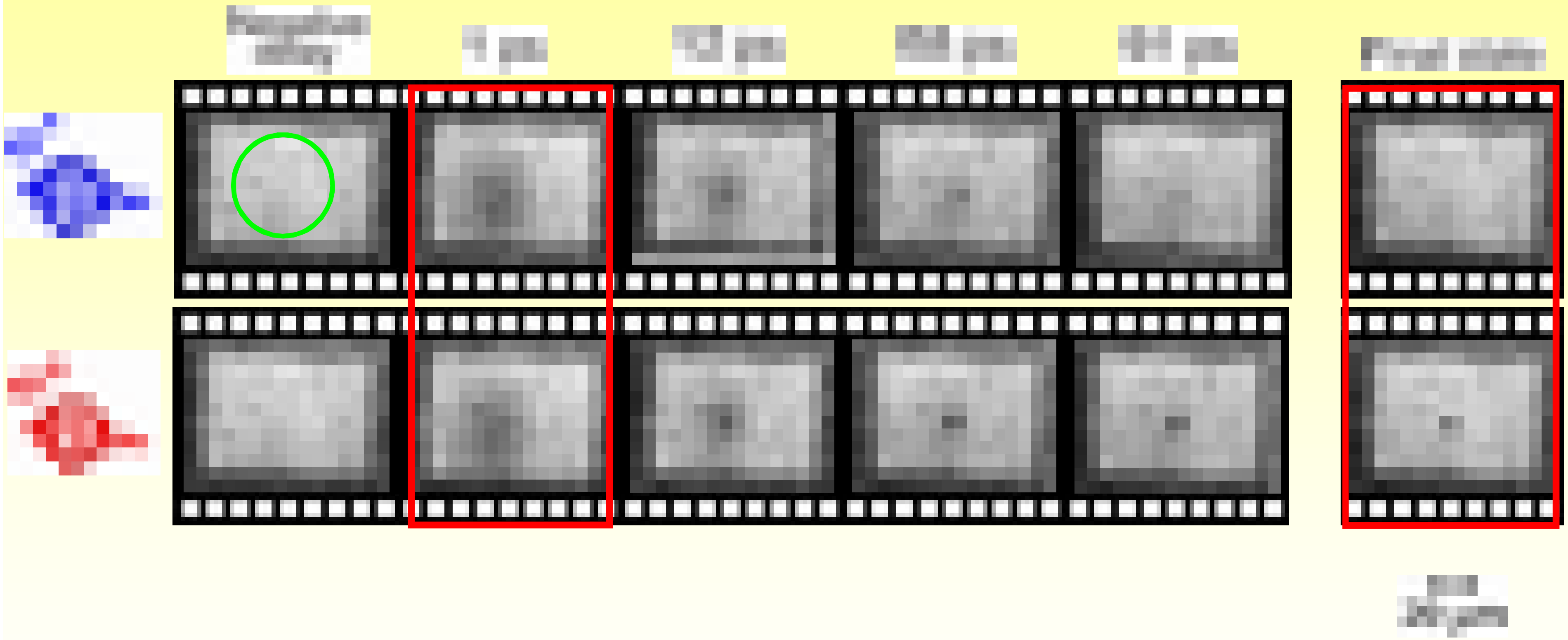
Dynamics of all-optical reversal

$Gd_{26}Fe_{64.7}Co_{9.3}$

ů -

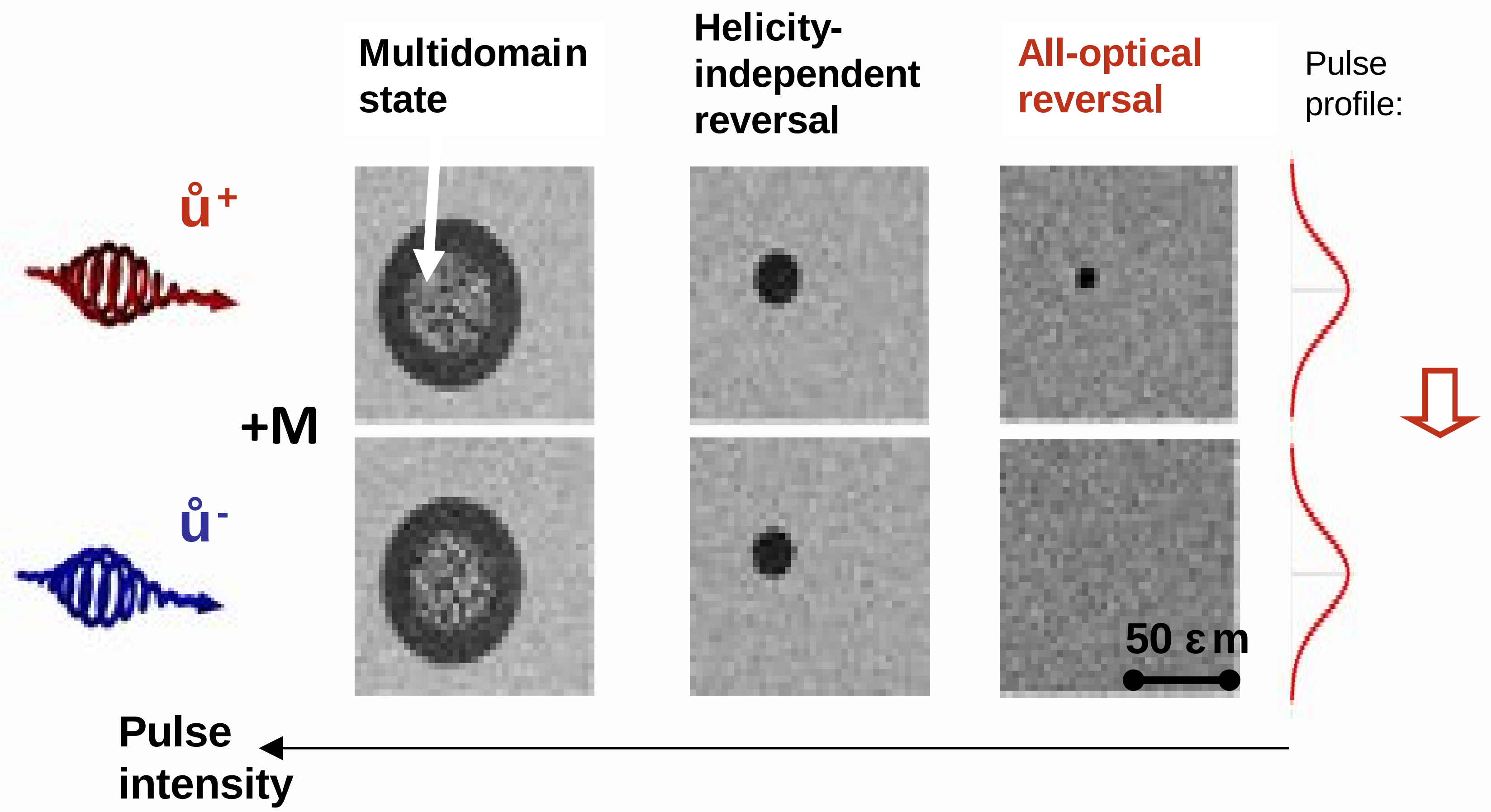


olution of the domains



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

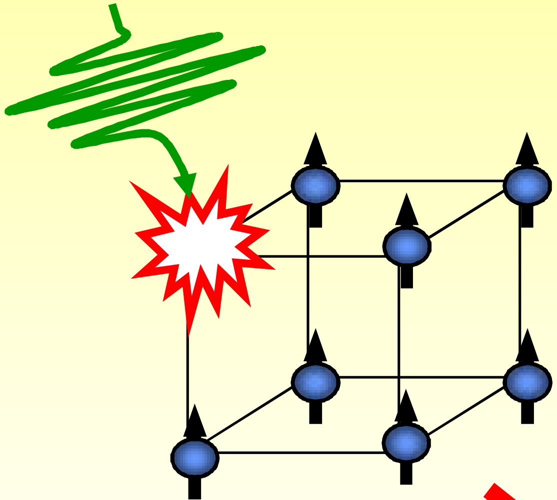
...le of the light intensity ...tical magnetization reversal



All-optical reversal in narrow (~5%) intensity range

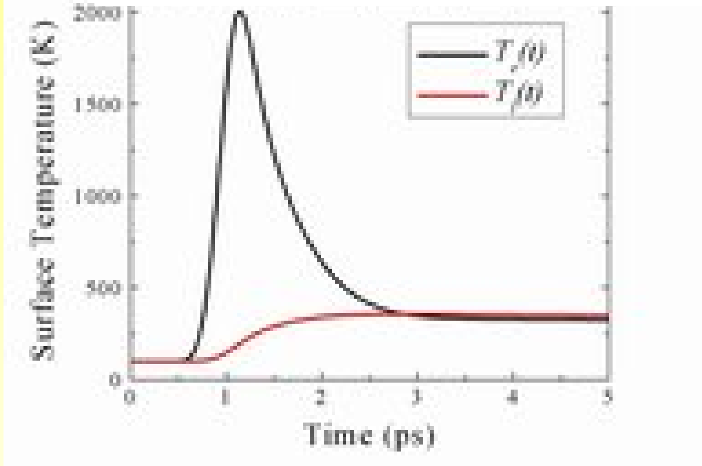
...ced dynamics: theory/simulations

Ultrashort laser pulse

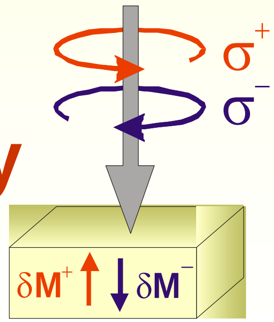


2-T model

Ultrafast demagnetization



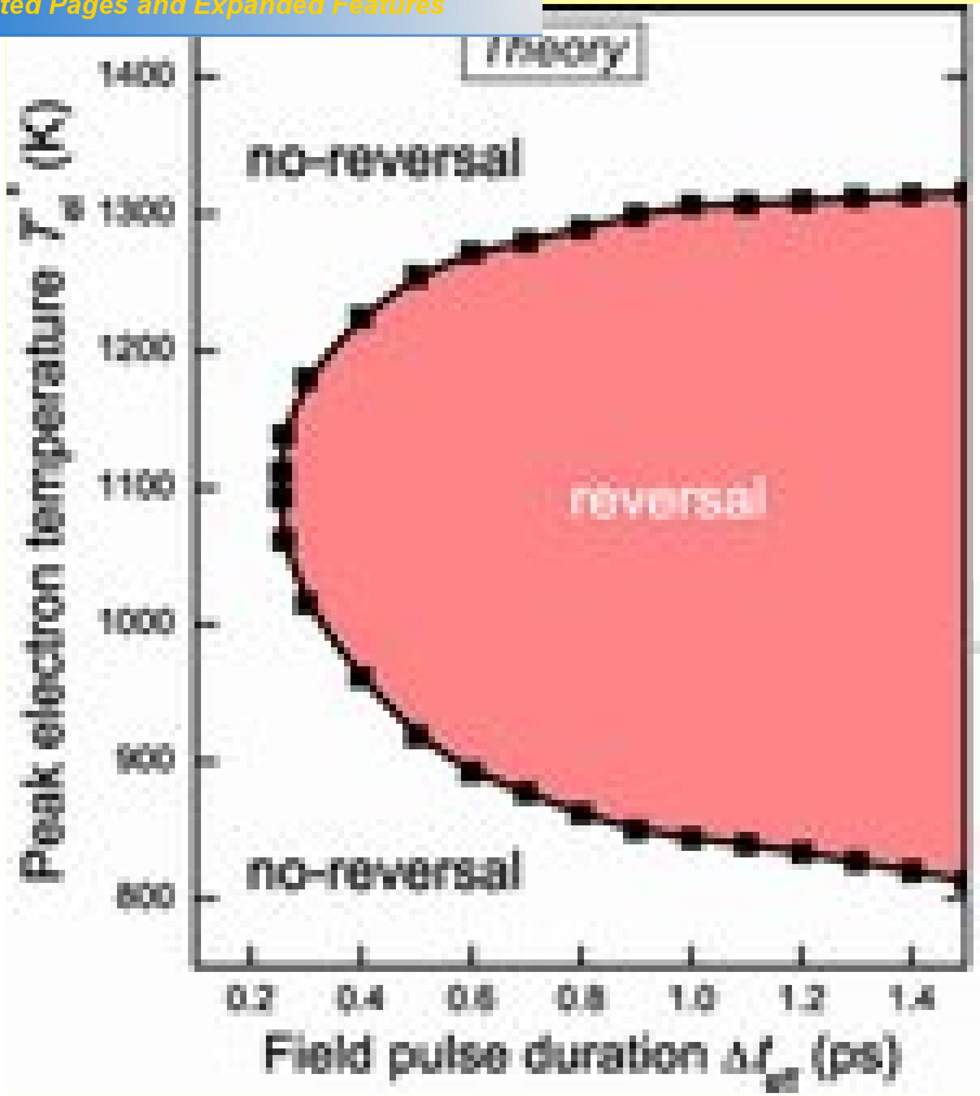
Inverse Faraday



[A. V. Kimel et al., Nature **435**, 655 (2005)]

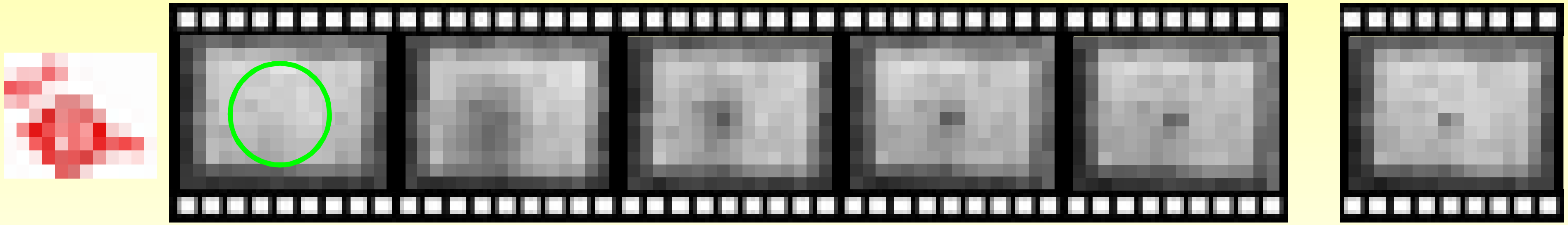
GdFeCo: 20T!

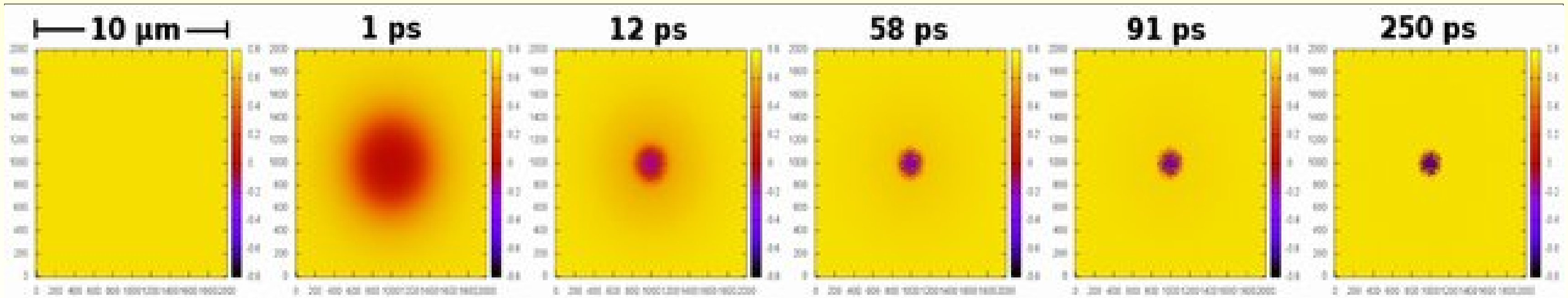
eory- Experiment



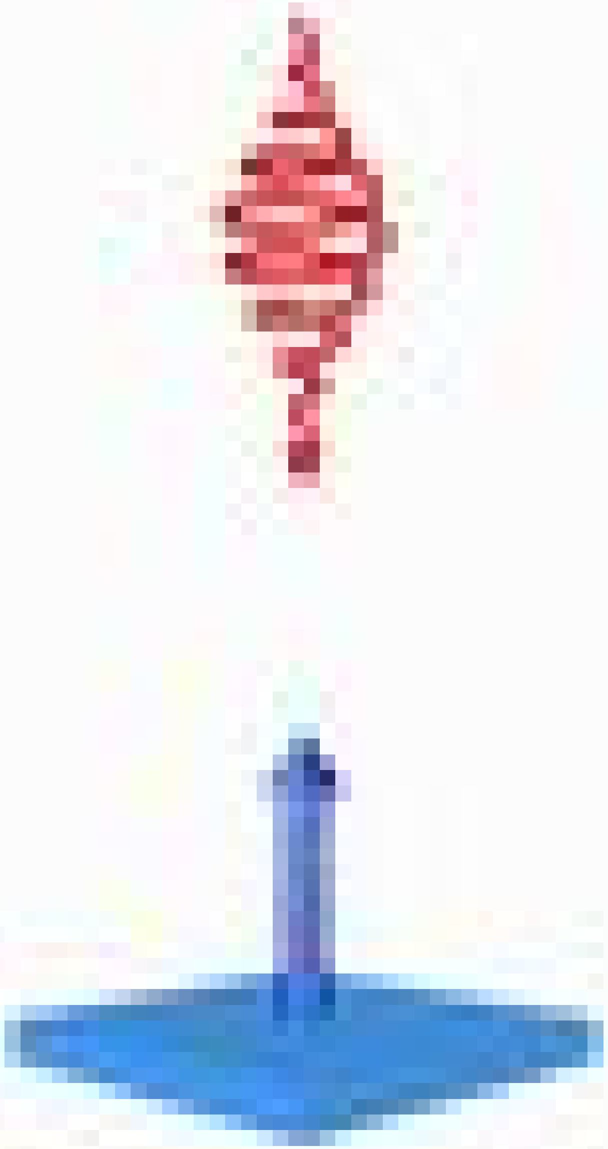
K. Vahaplar et al., **PRL 103,** 117201 (2009)

ion of the domains



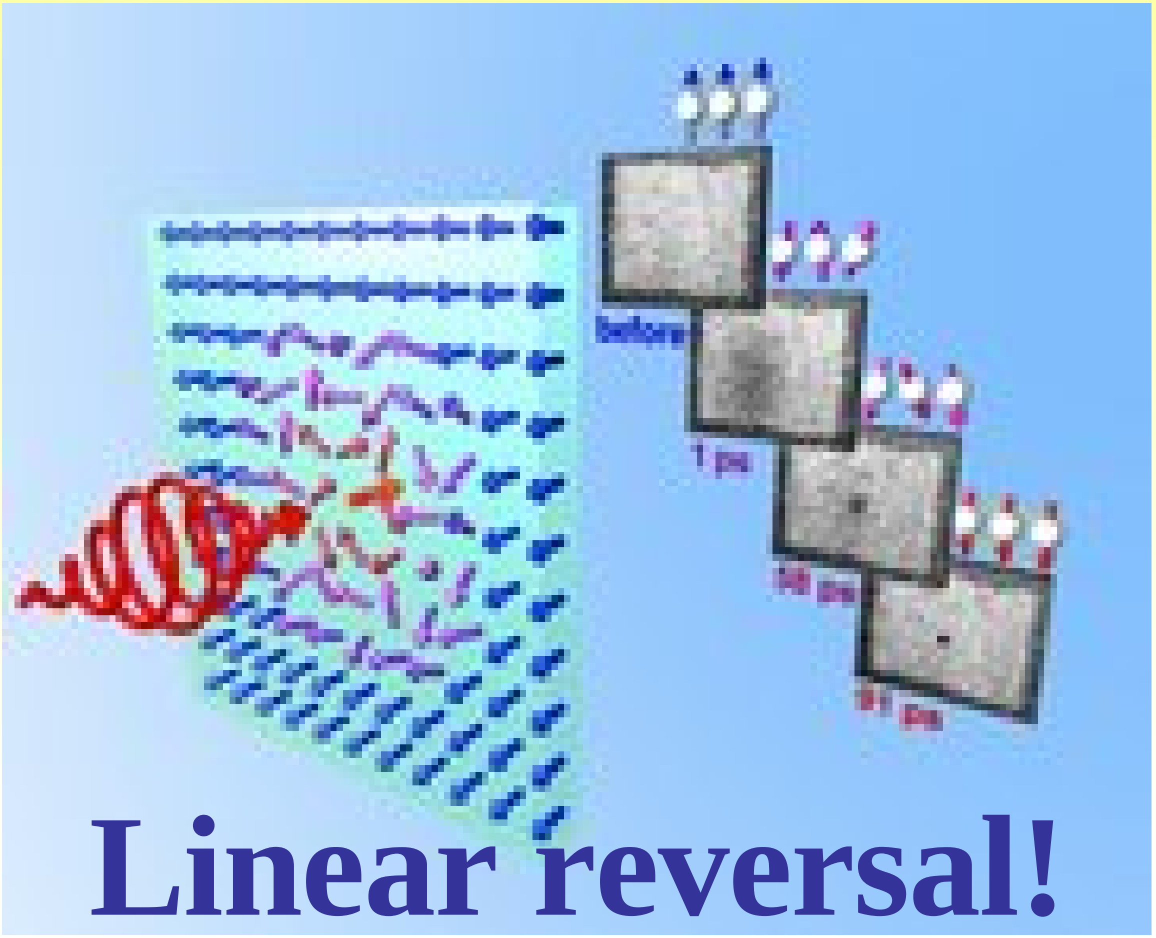


K. Vahaplar et al., Phys. Rev.B , 2010



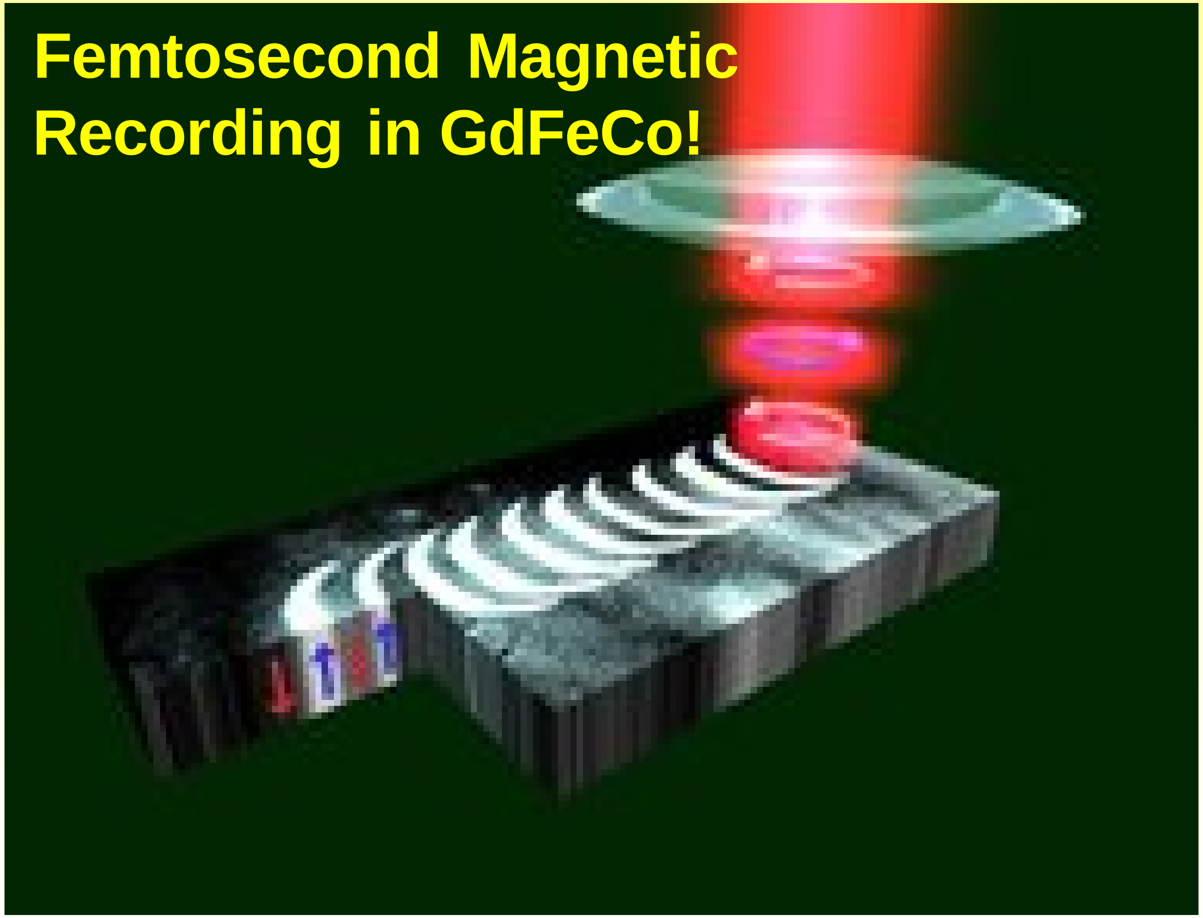
ew mechanism!

Done?

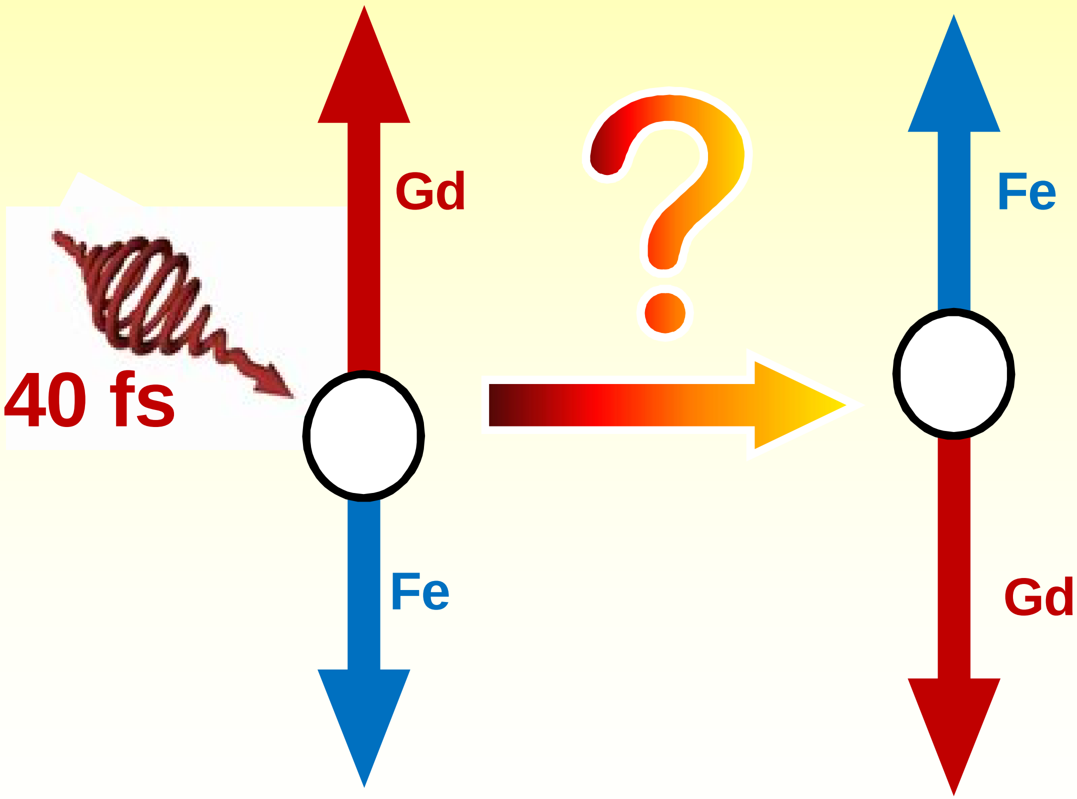


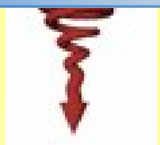
Linear reversal!

…near reversal: how?
multi-sublattice ferrimagnet!

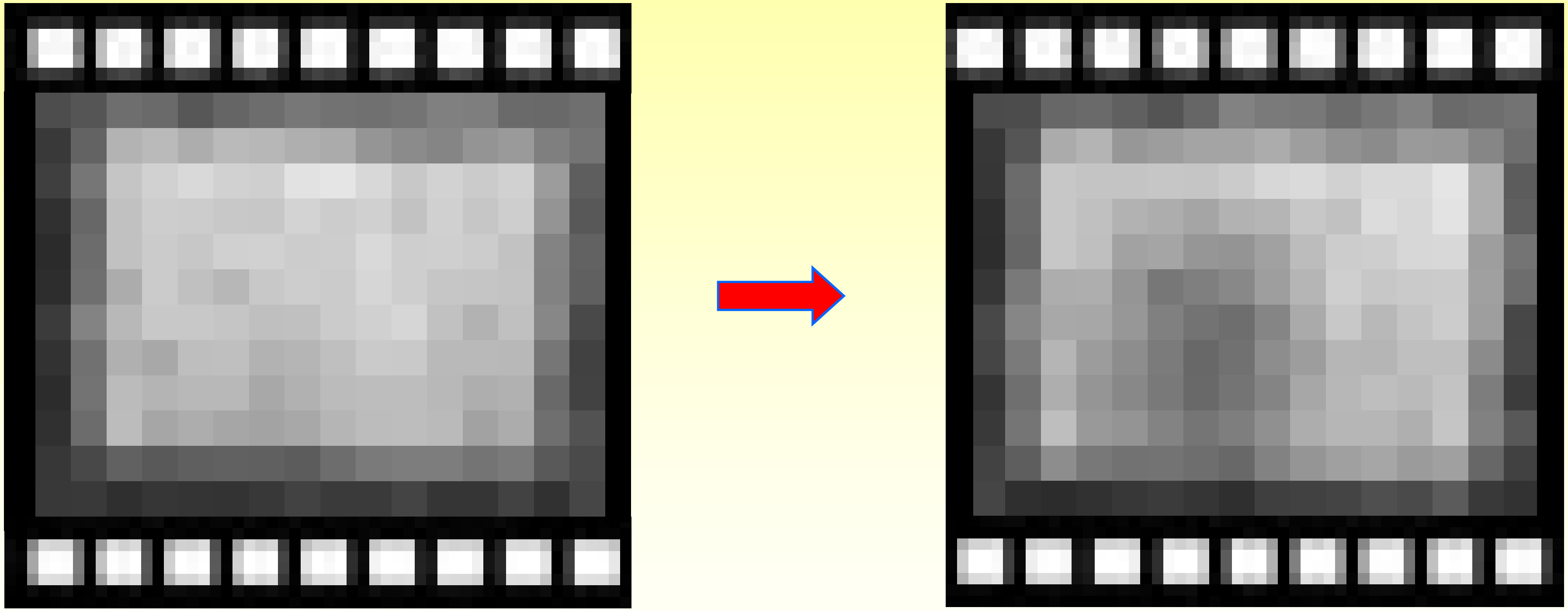


Ultrafast laser induced reversal in *multi*-sublattice magnets



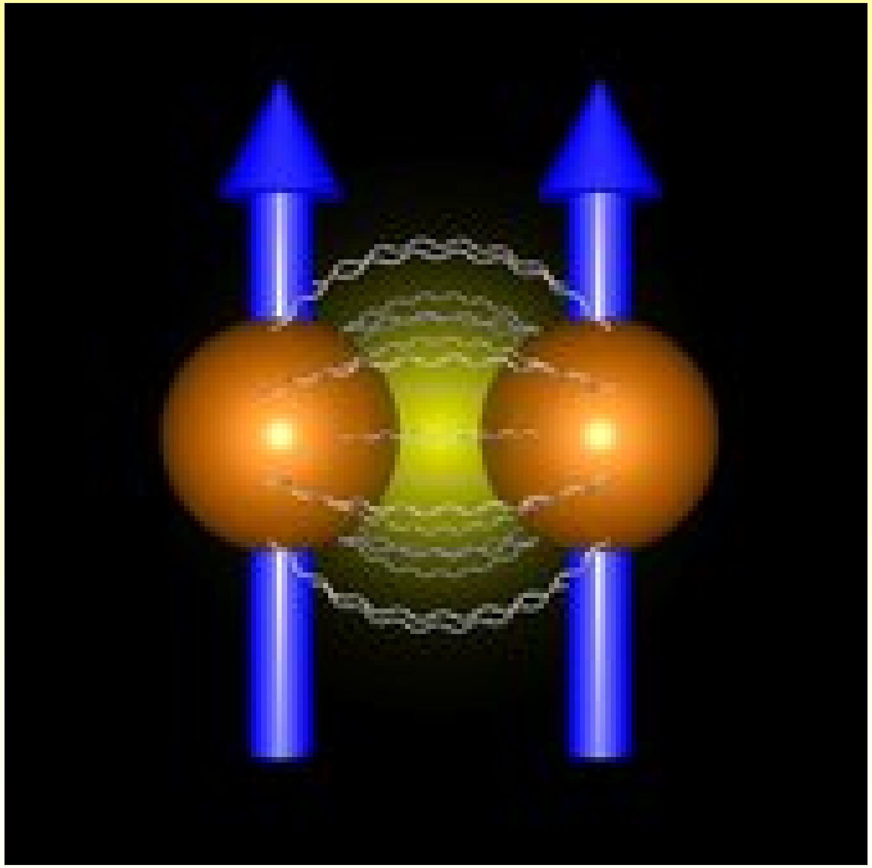


0é é é é 1ps?

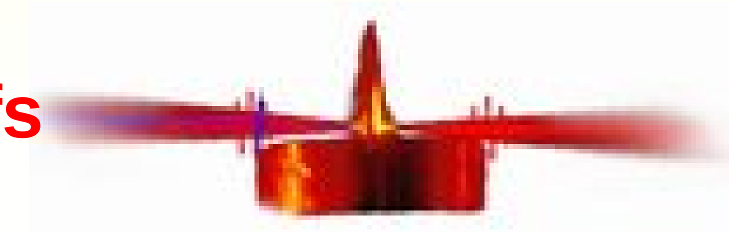


Magnetism at the timescale of the exchange interaction?

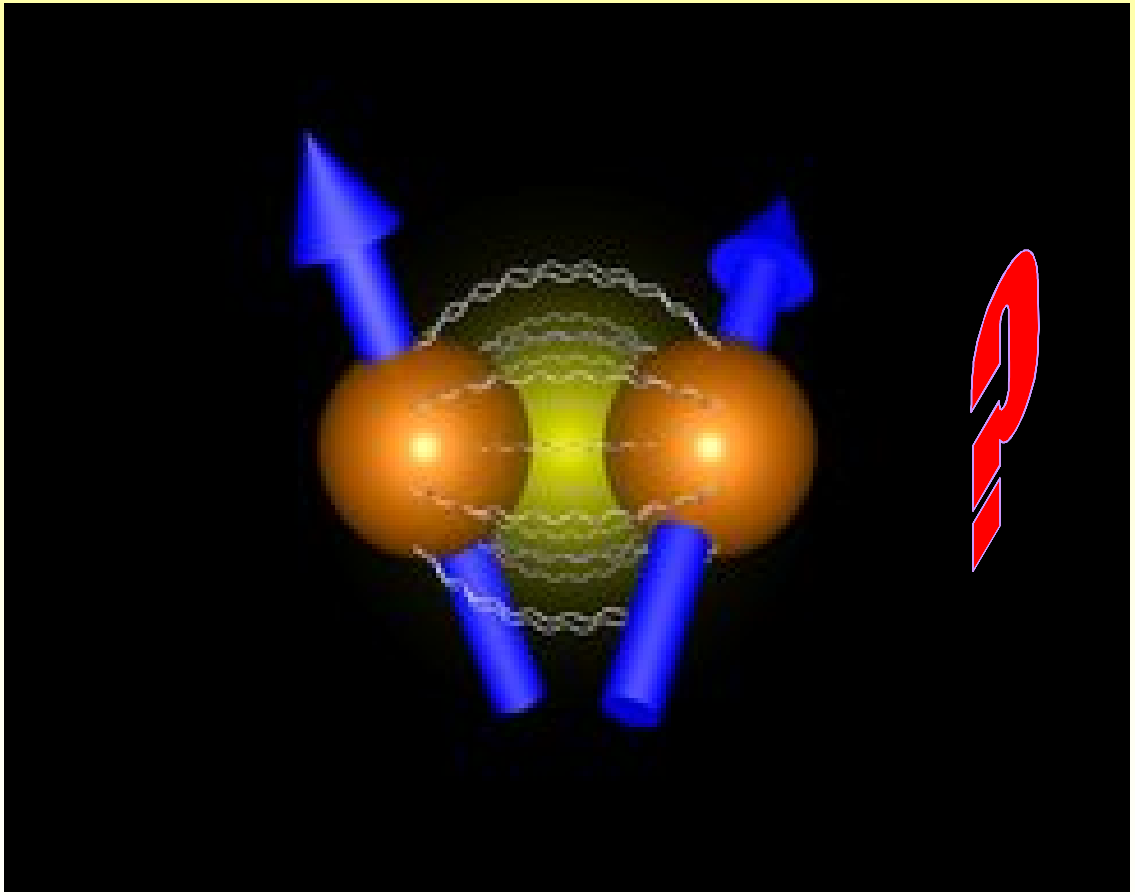
$_{Fe\text{-}Fe}=1.4\text{x}10^{-19}$ J ~ 40 fs



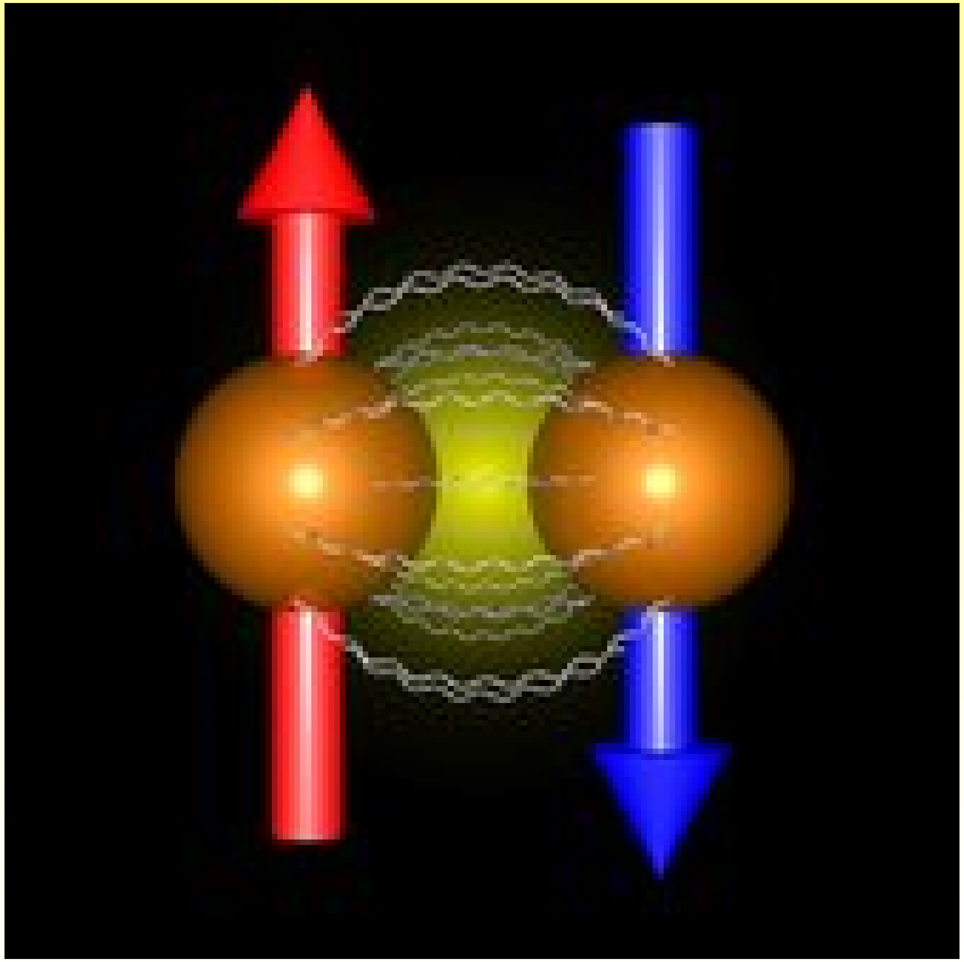
1-2eV,10-100fs



?

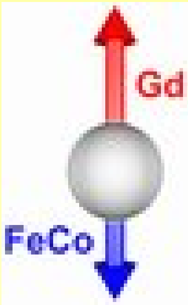


ferrimagnet

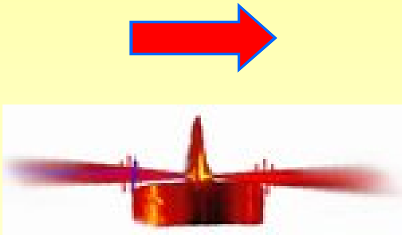


ñspins colouredò!

ment specific view

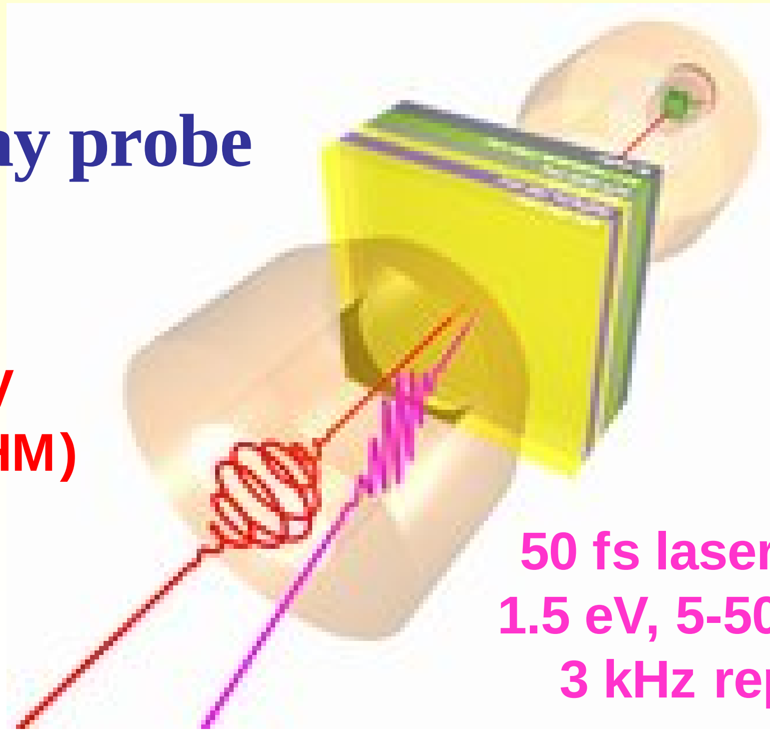


?



Laser pump ï X-ray probe

BESSY

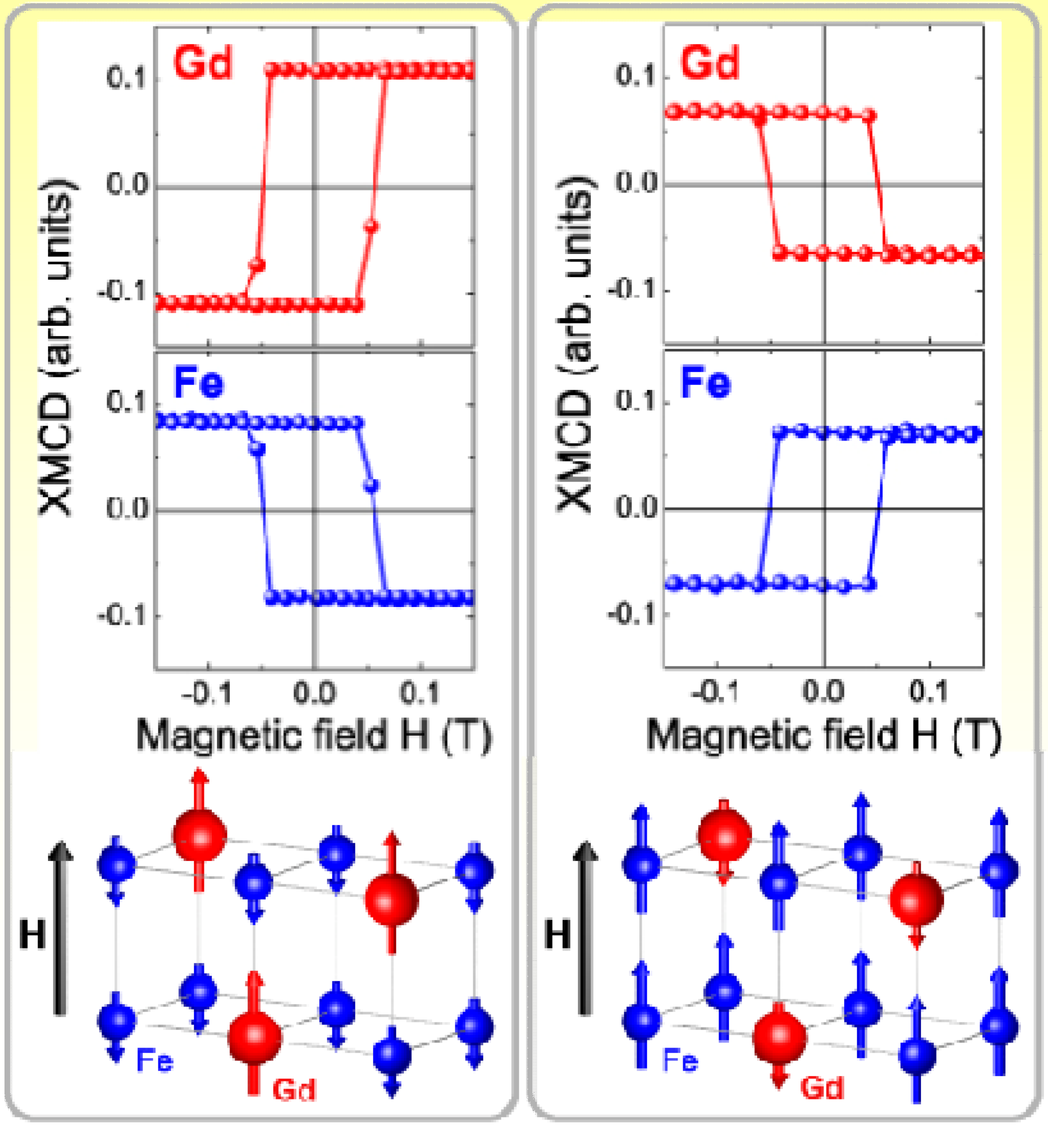


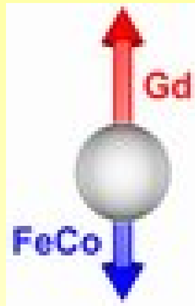
X-rays
400-1400 eV
10-50 ps (FWHM)

50 fs laser pulses
1.5 eV, 5-50 mJ/cm^2
3 kHz rep. rate

rimagnetic Rare Earth- Transition Metal

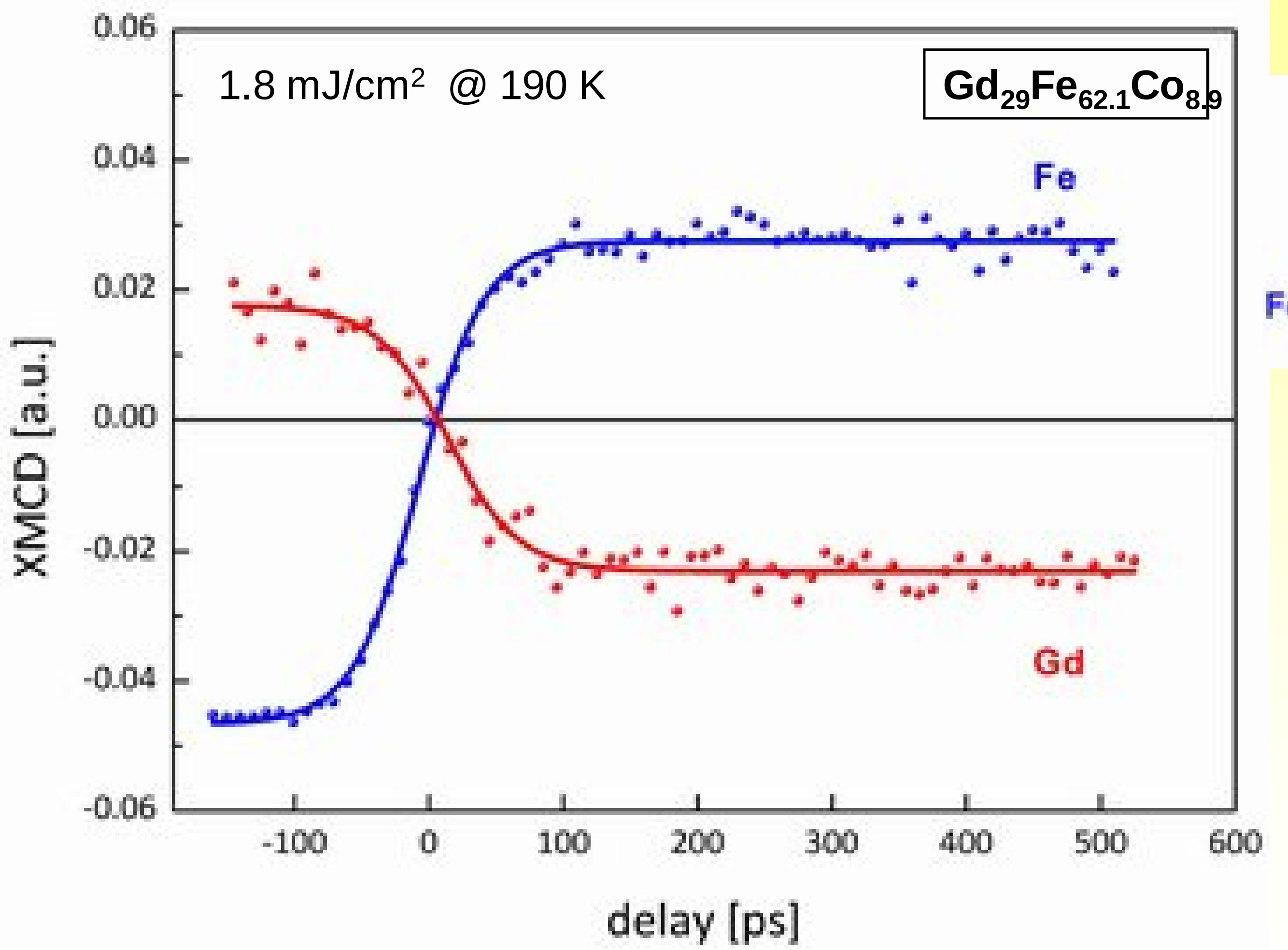
Below compensation point T = 82 K | **Above compensation point T = 350 K**

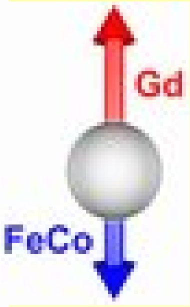




TR-XMCD @BESSY

» **Fe and Gd sub-lattices switch simultaneously within 50 ps.**

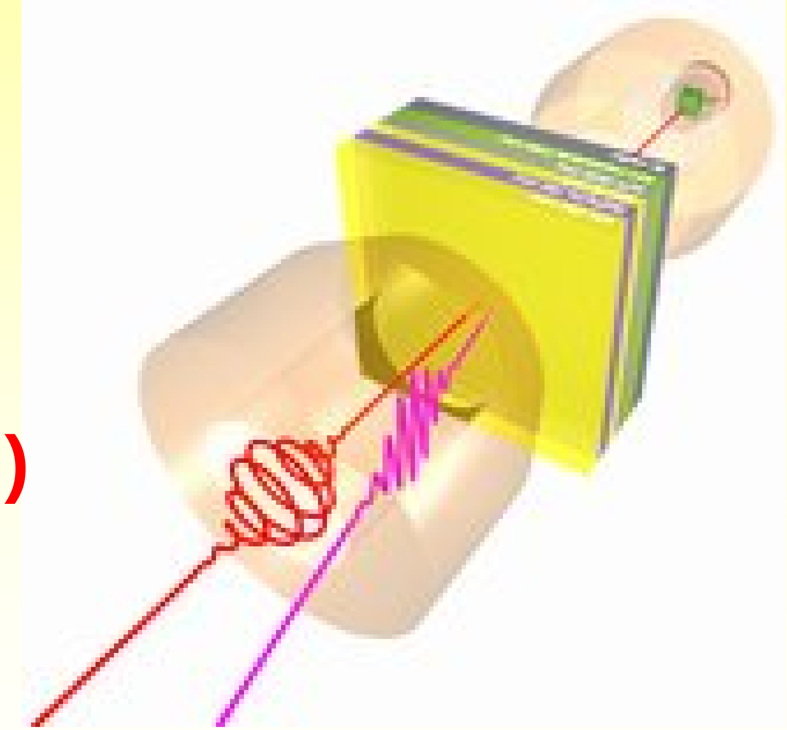




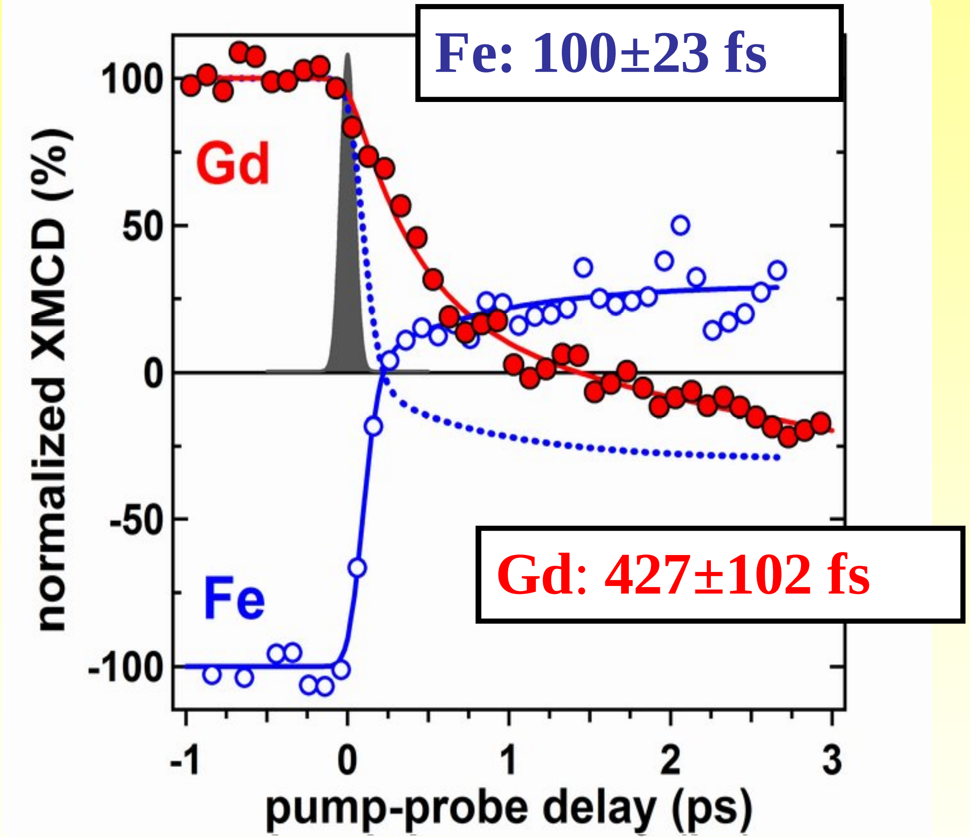
Canôt we look faster?

FEMTO-SLICING!

X-rays
400-1400 eV
100 fs (FWHM)

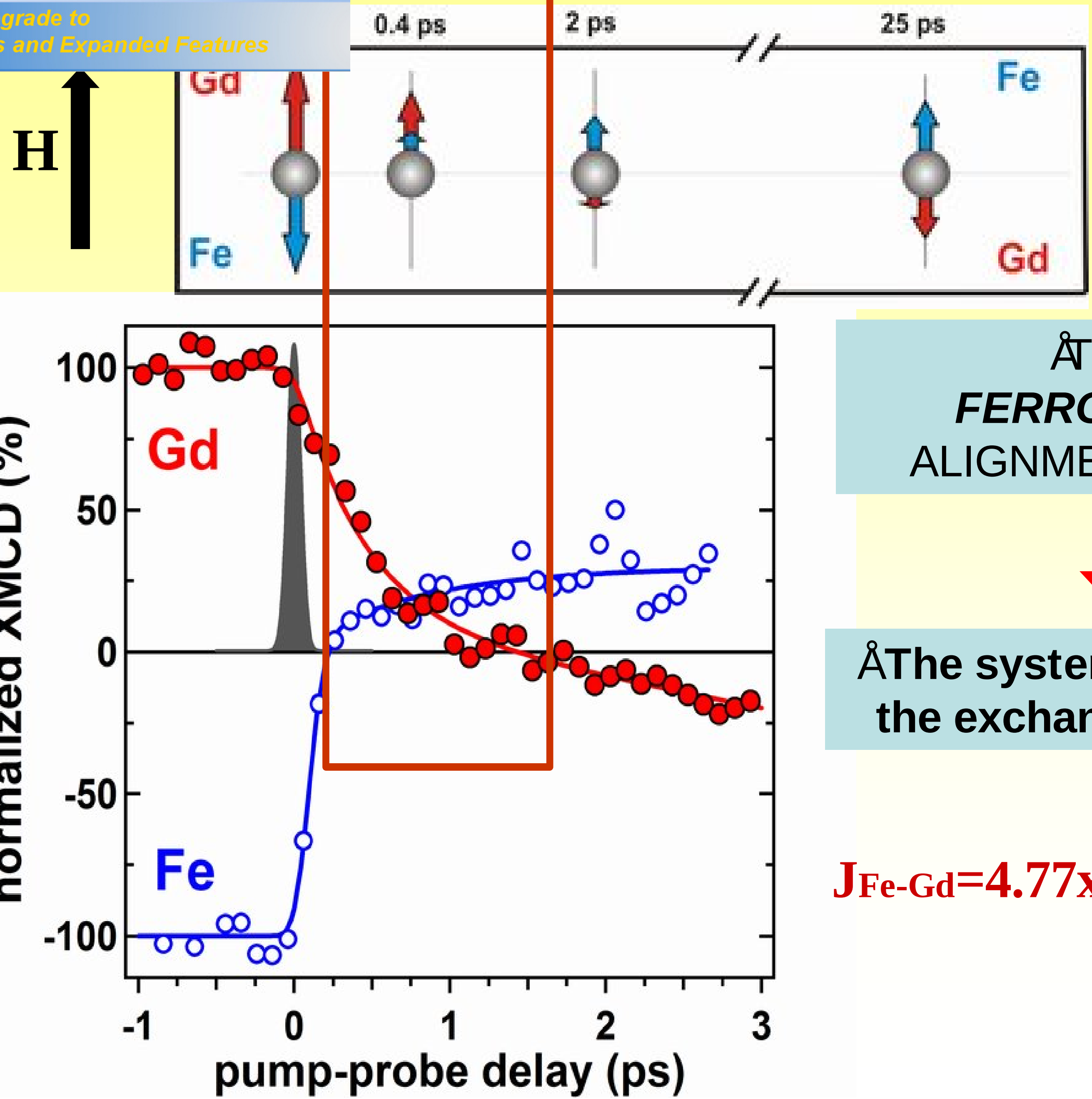


specific magnetization reversal



Different magnetization switching dynamics Fe and Gd !!!

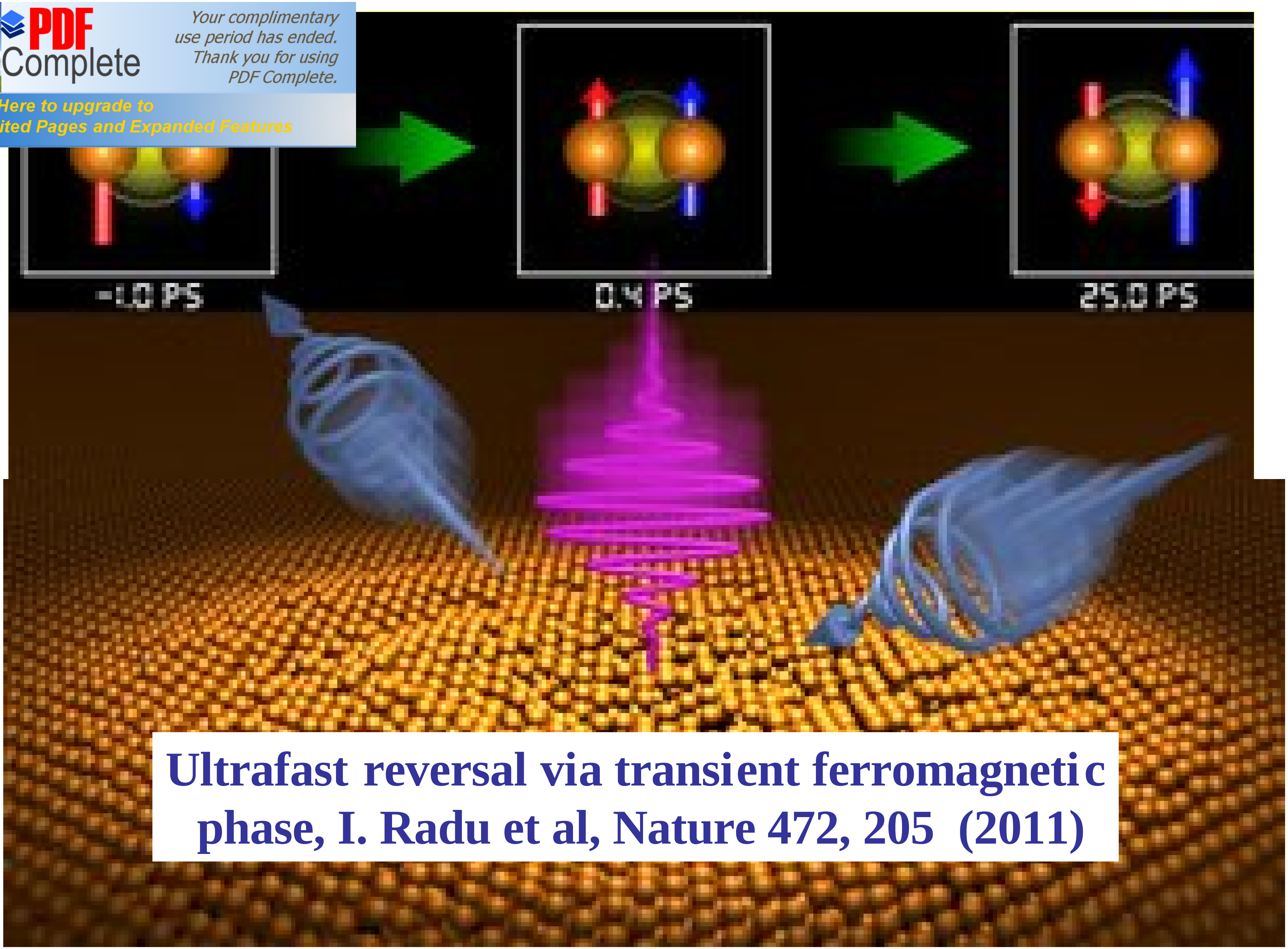
via a novel non-equilibrium state



ÅTransient
FERROMAGNETIC
ALIGNMENT for ~1.2 ps

ÅThe system evolves against the exchange interaction !!!

$J_{Fe\text{-}Gd}$=4.77x10^{-20} J ~ 140 fs

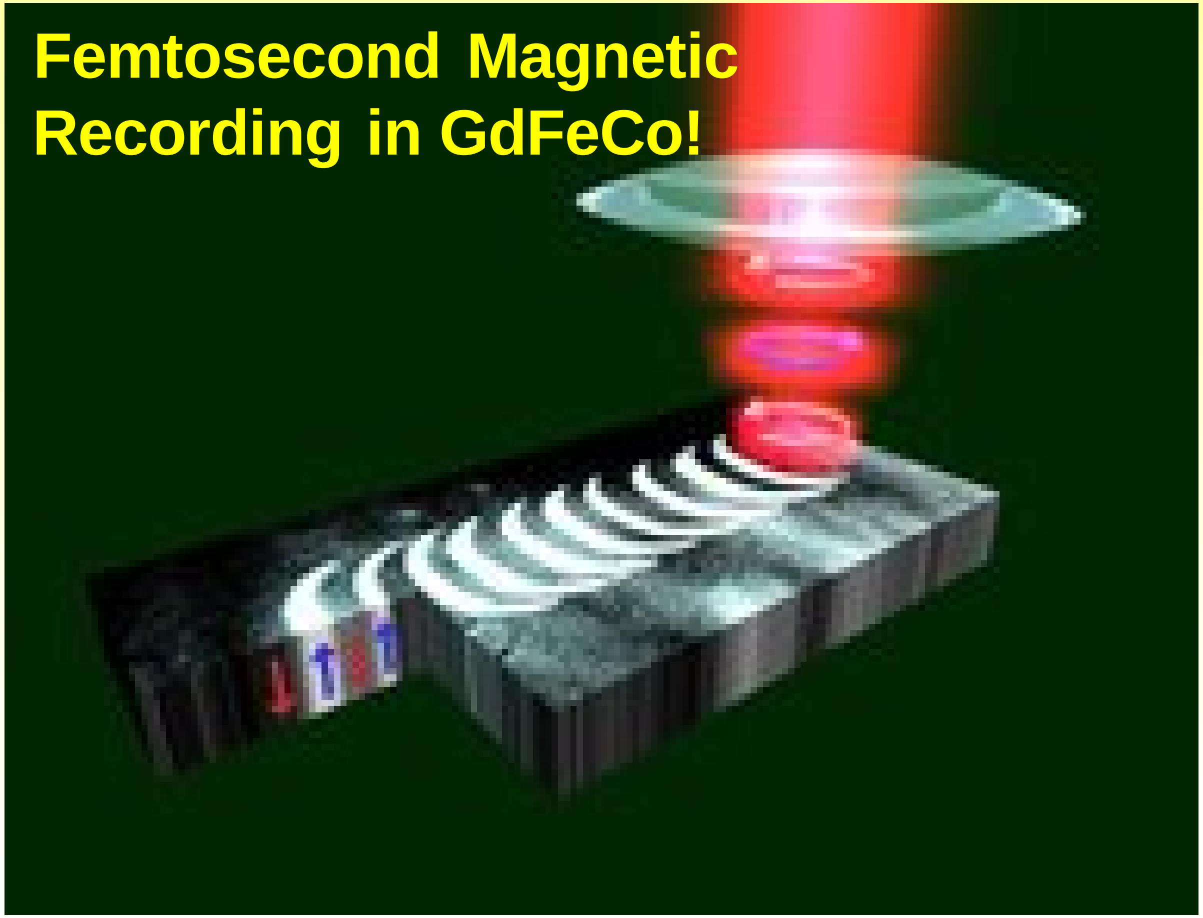


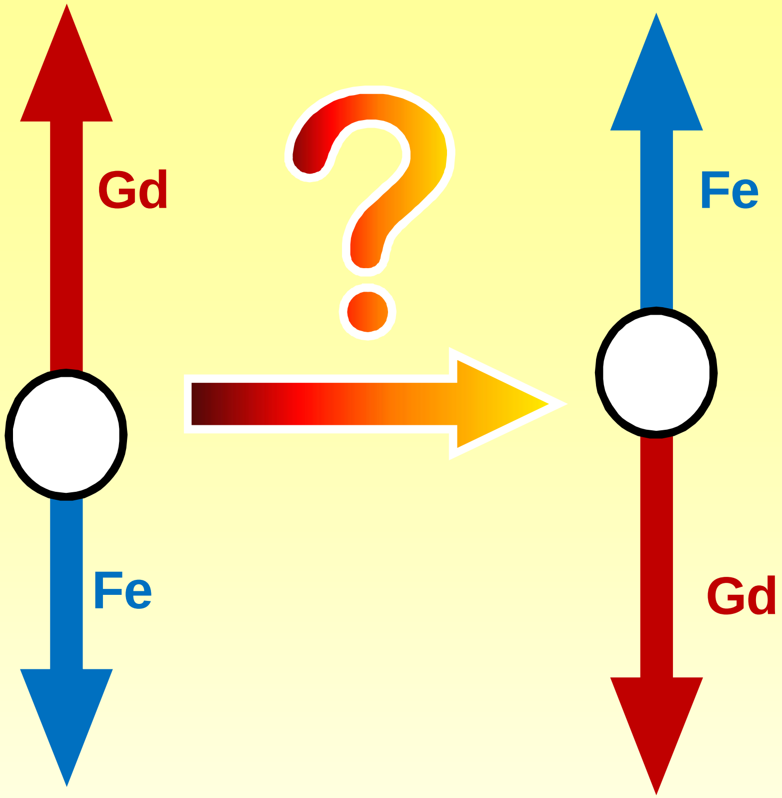
Ultrafast reversal via transient ferromagnetic phase, I. Radu et al, Nature 472, 205 (2011)

How to understand?

ear reversal: ferrimagnet!

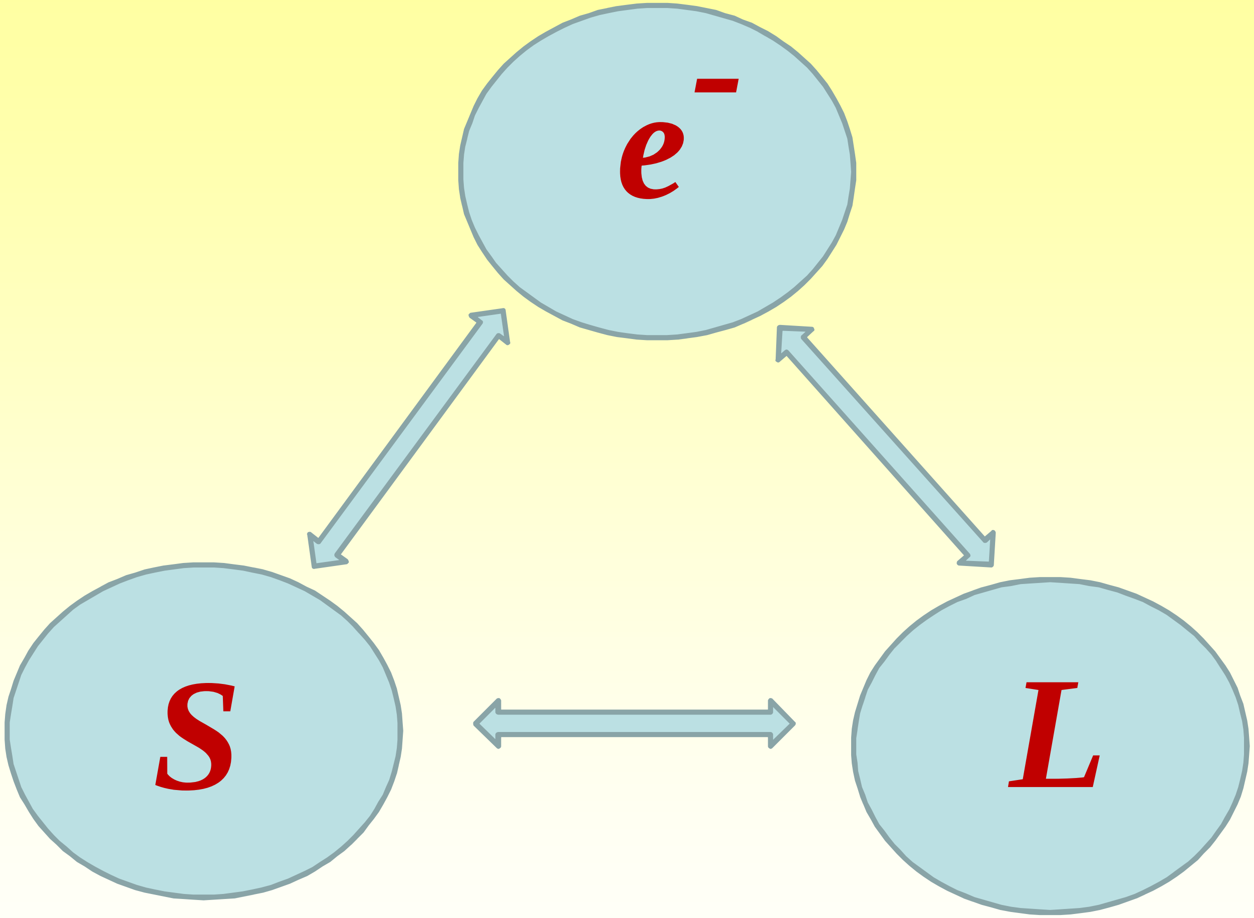
multi-sublattice theory?



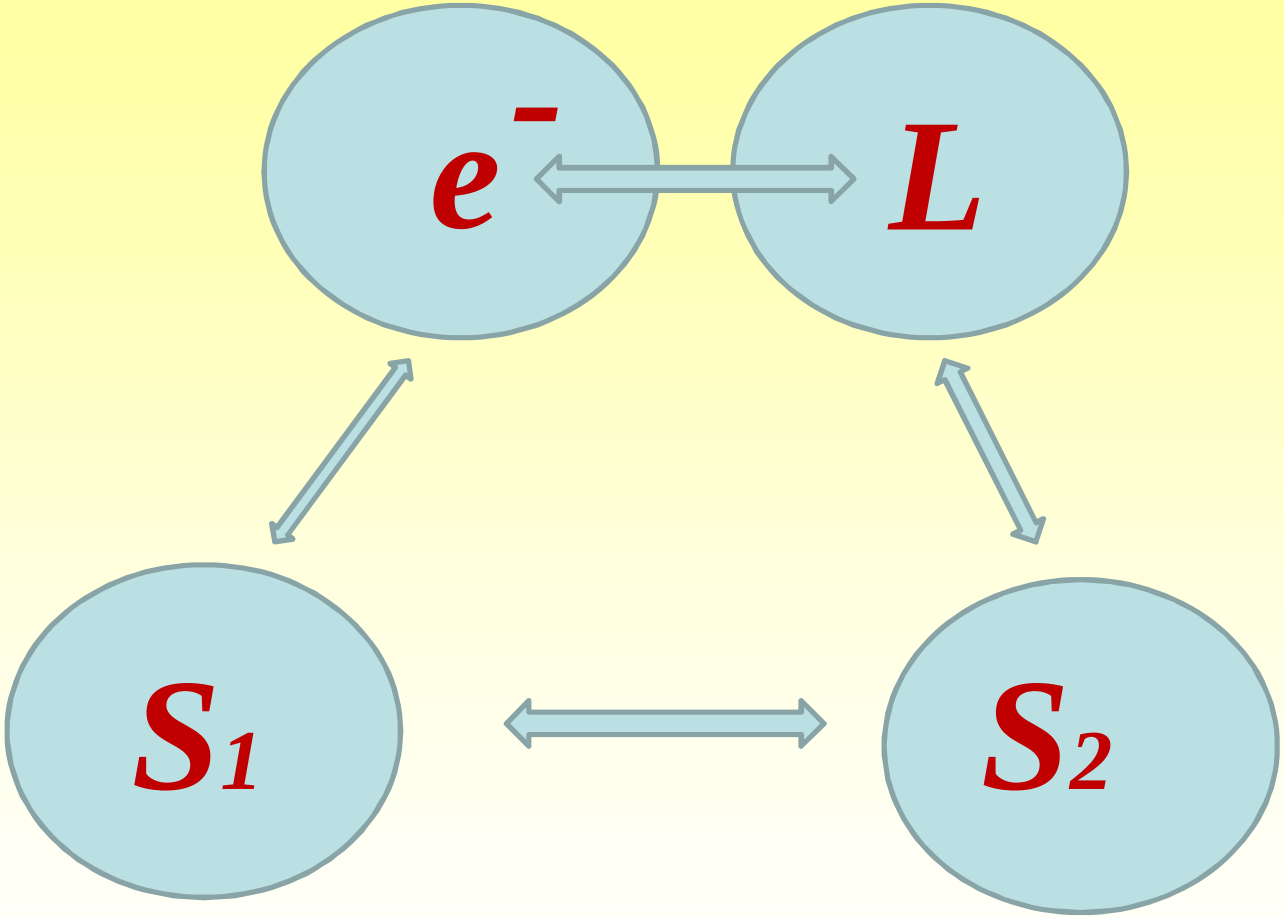


Angular momentum transfer?
Role of temperature?
Role of sublattices?
é ..

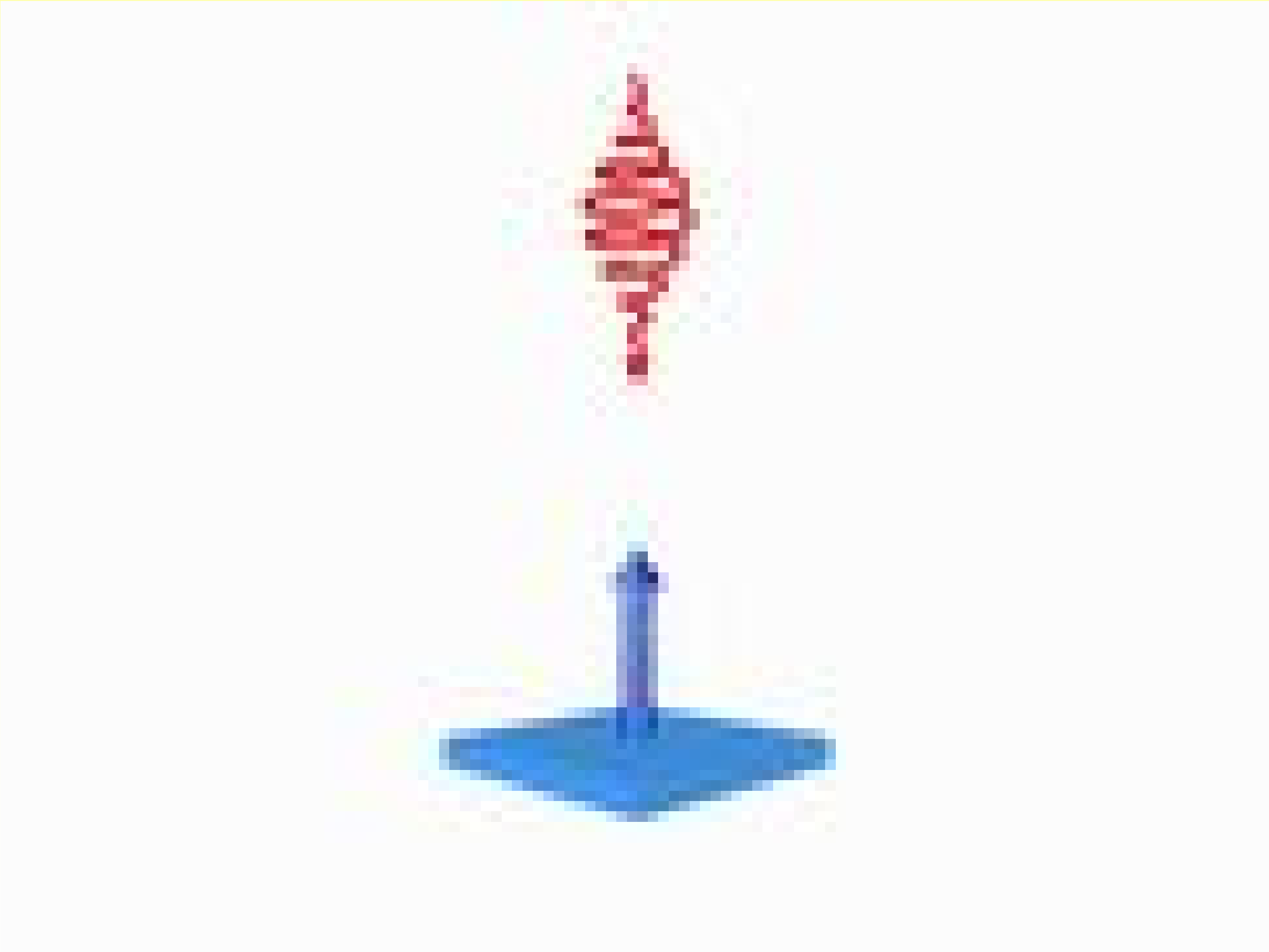
3-T model



ulti-sublattice



Longitudinal waves!!



Landau-Lifshitz dynamics

ON THE THEORY OF THE DISPERSION OF MAGNETIC PERMEABILITY IN FERROMAGNETIC BODIES.
By L. Landau and E. Lifshitz.

$$d\mathbf{S}/dt = -\gamma \mathbf{S} \times \mathbf{H}$$

$\gamma = g\frac{e}{2m}$ =0.28 Ghz/T

Typical laboratory fields ~ 1T
→ Reversal time ~ 1 ns!

Magnetism on the timescale of exchange:

→ ***LONGITUDINAL spin dynamics*** $\frac{d\mathbf{S}}{dt} =$?

omenological theory*

Å **Onsager** relations for spin dynamics

Generalized force $F_i = H_i(\mathbf{r}, t)$ =effective magnetic field

Generalized flux $J_i = dS_i(\mathbf{r}, t)/dt$

Å Equation of motion from symmetry relations

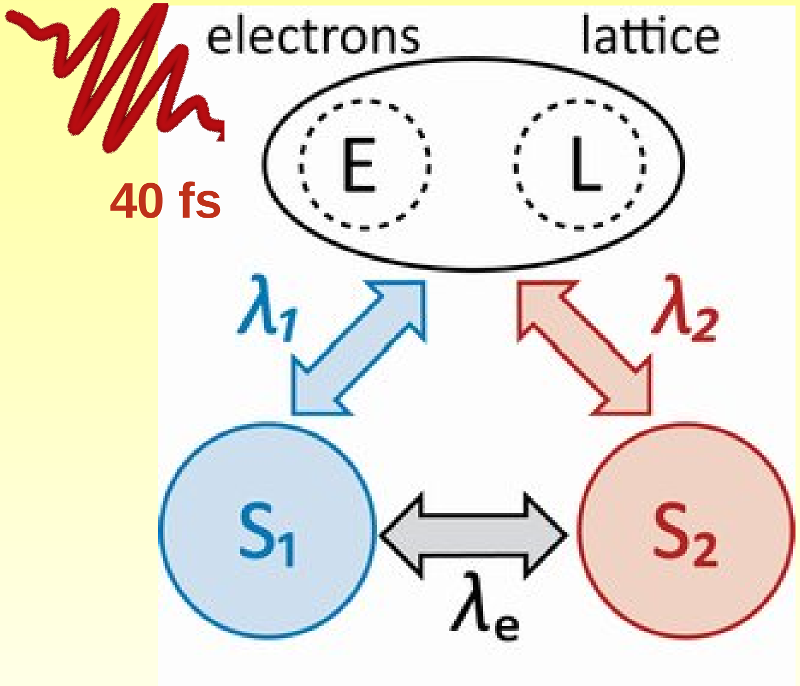
$$d\mathbf{S}/dt = -\gamma \mathbf{S} \times \mathbf{H} + \lambda^e \mathbf{H} + \ldots$$

Precession ñslowò

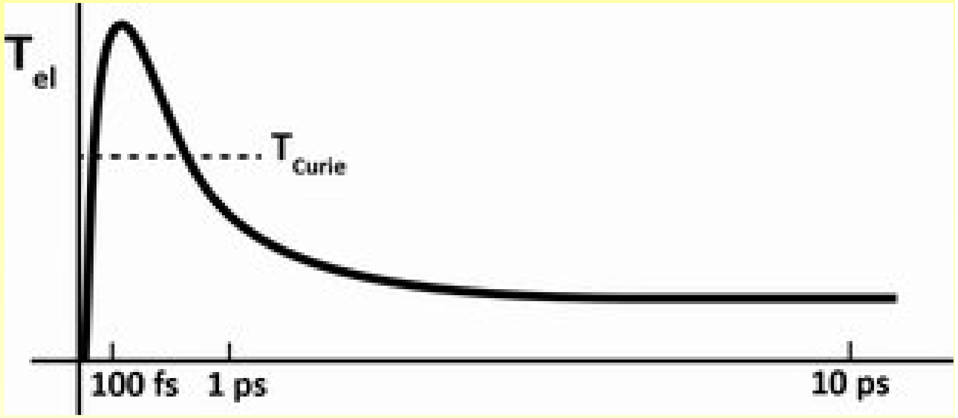
Longitudinal change |M| *FAST*

**Baryakhtar JETP 1984*

osecond laser excitation

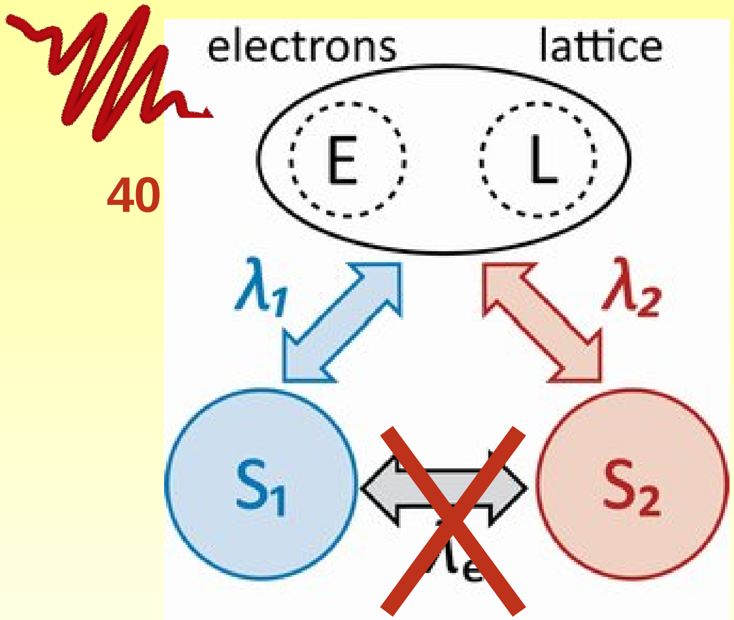


Ultrafast heating electrons



…erature dominated: $T >> T_{Curie}$

t~100 fs



Bloch relaxation

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

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

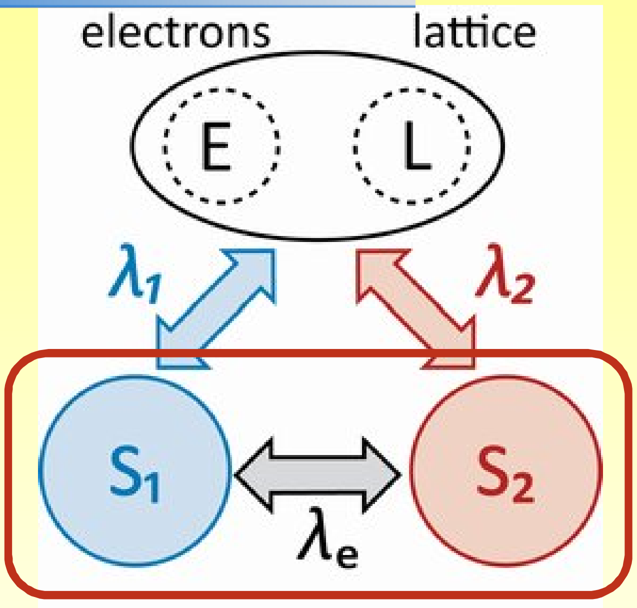
Dynamics scales with magnetic moment

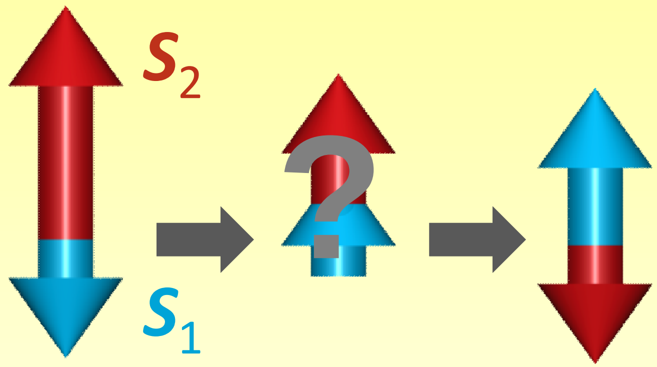
$$\mu_2 < \mu_1 \Rightarrow \tau_2 < \tau_1$$

$$\mu_{Fe} < \mu_{Gd} \rightarrow \tau_{Fe} < \tau_{Gd}$$

Distinct dynamics Gd and Fe

dominated: $T<T_{Curie}$ $t \sim 1$ ps





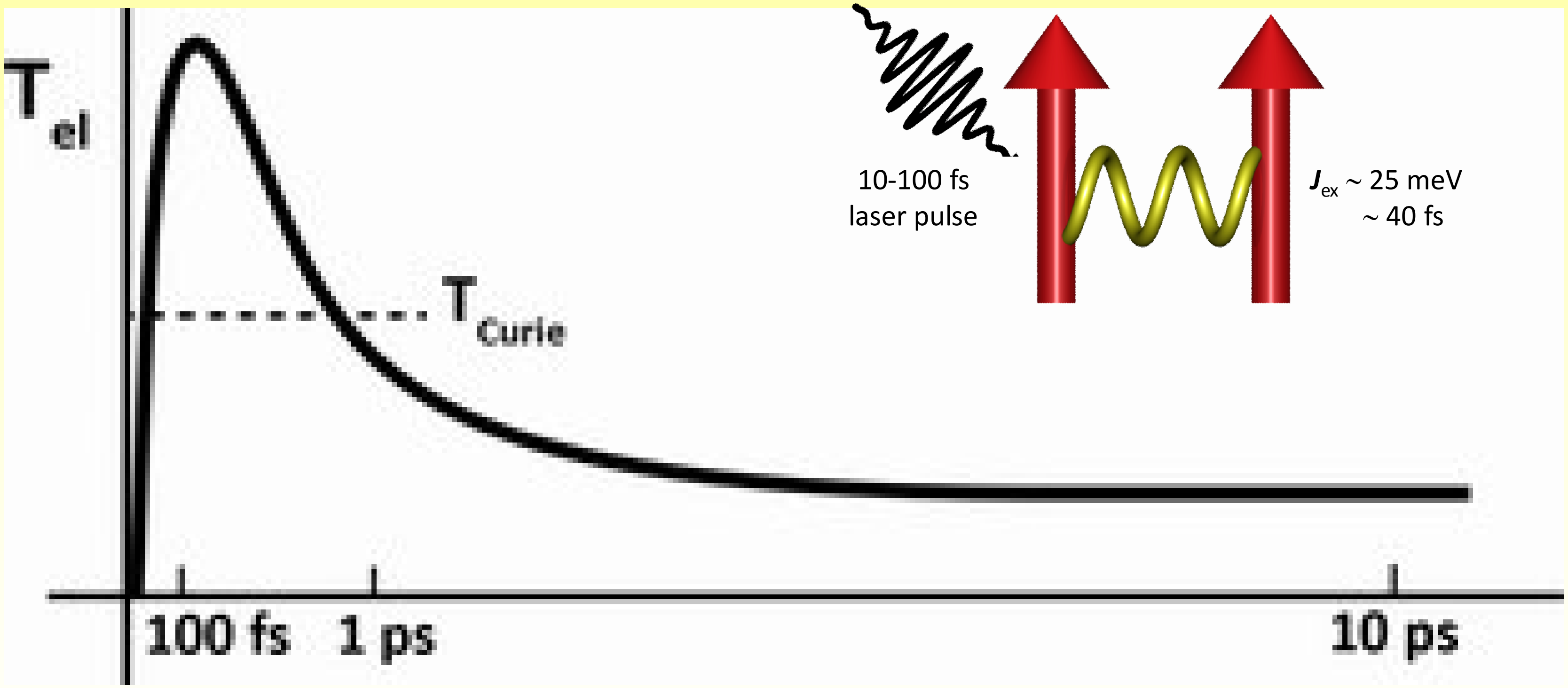
$$dS_1/dt = -dS_2/dt$$

Conservation total angular momentum

Ground state AFM, transient FM!

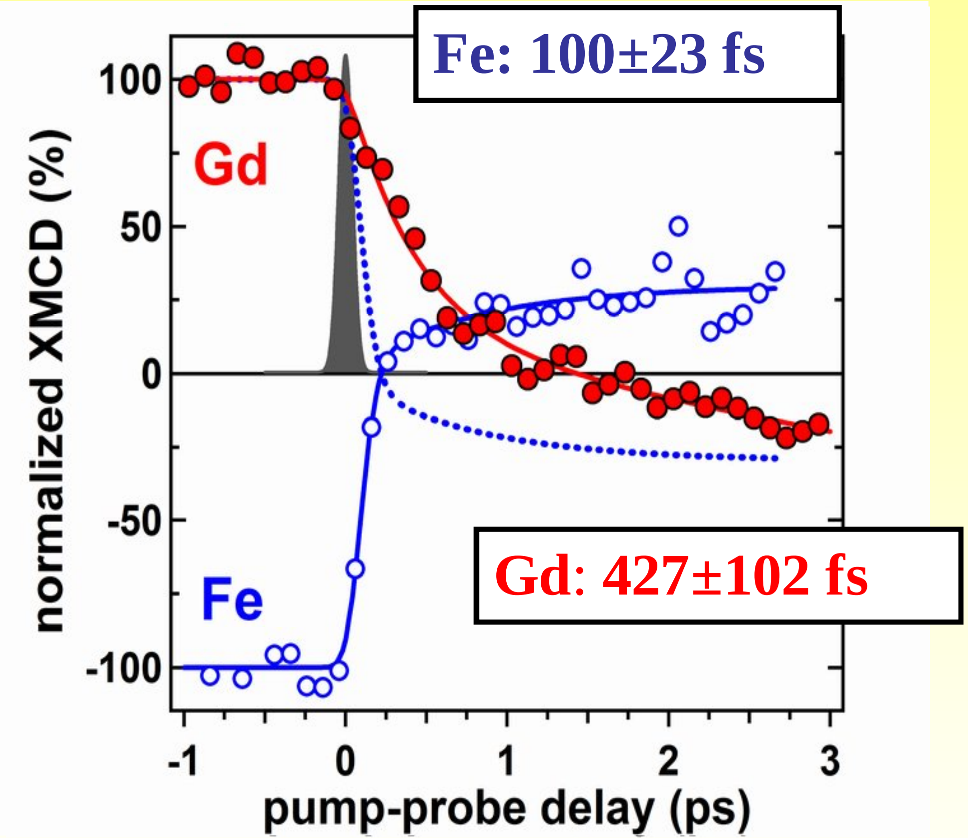
-induced spin dynamics

Ultrafast heating of electrons



Access to temperature and exchange dominated regime!

specific magnetization reversal



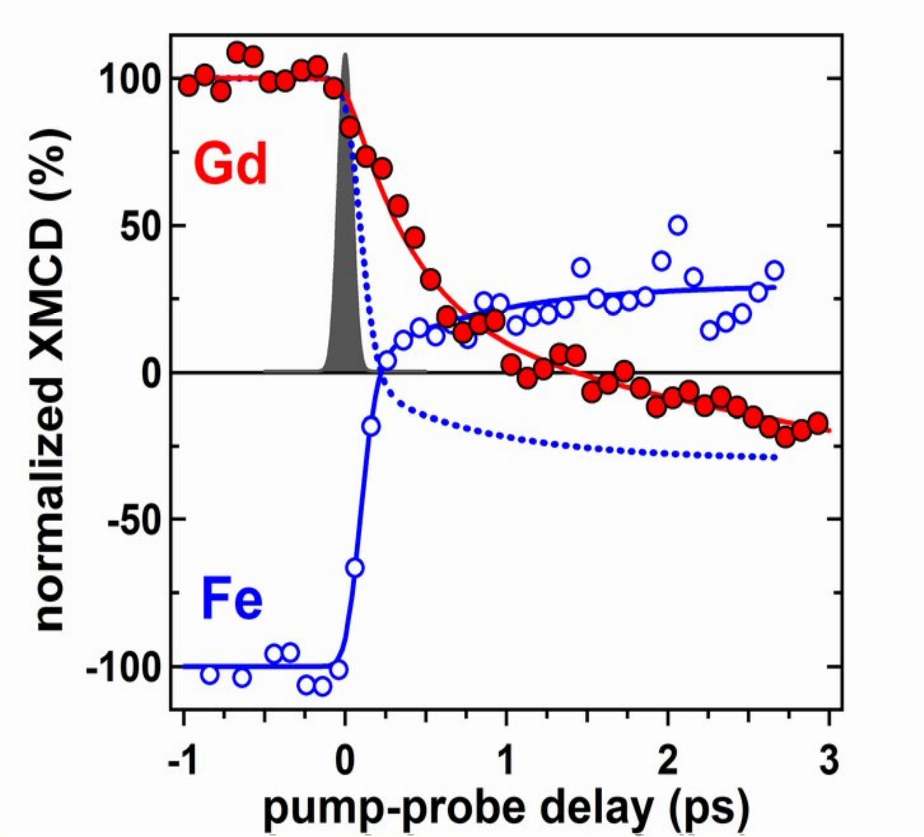
Different magnetization switching dynamics Fe and Gd !!!

Mentink:

$$\tau_i = \frac{\mu_i}{2\alpha\gamma k_B T}$$

Consequences?

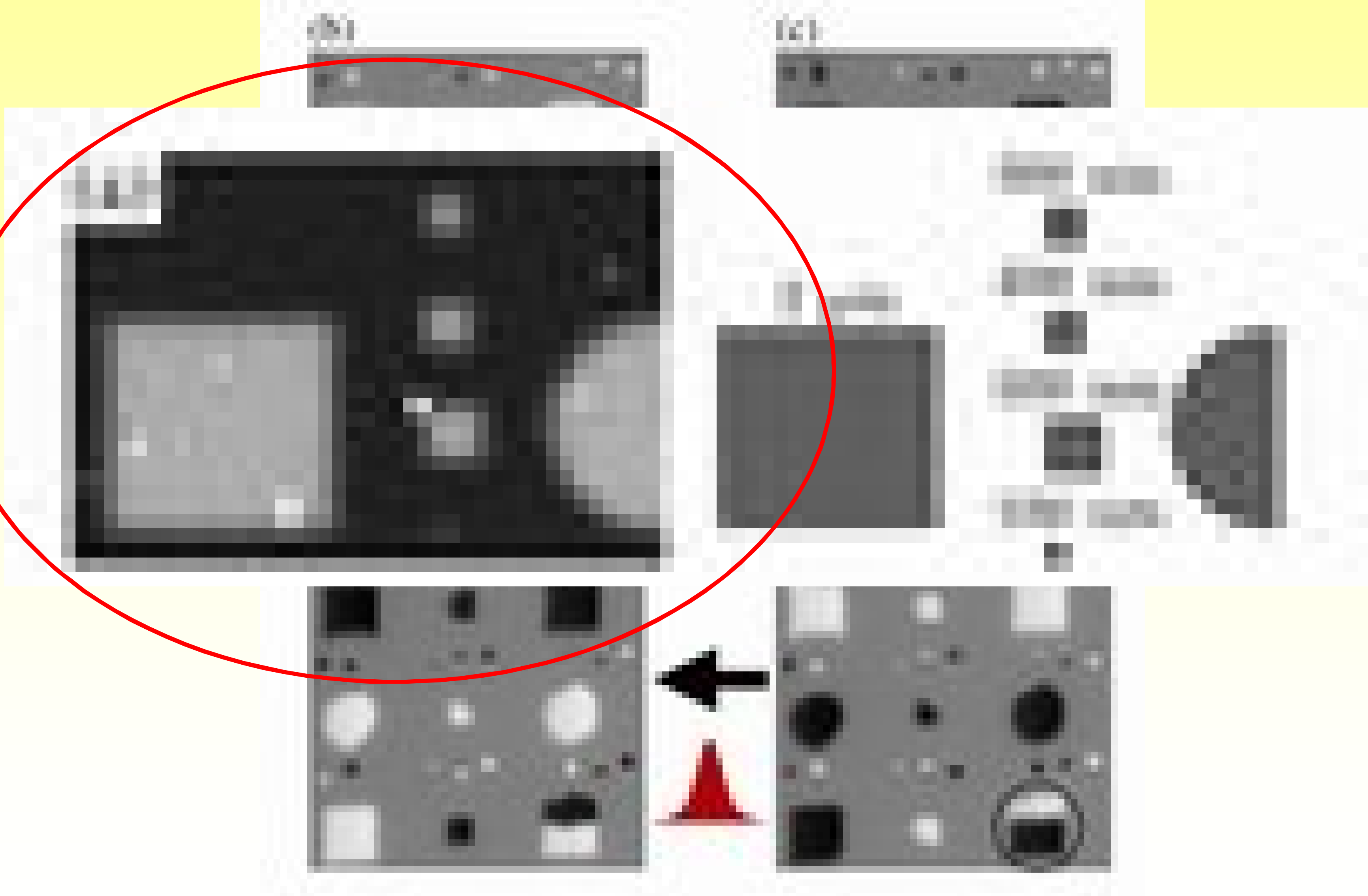
...uced magnetization reversal!



reversal of magnetization driven by exchange!!!

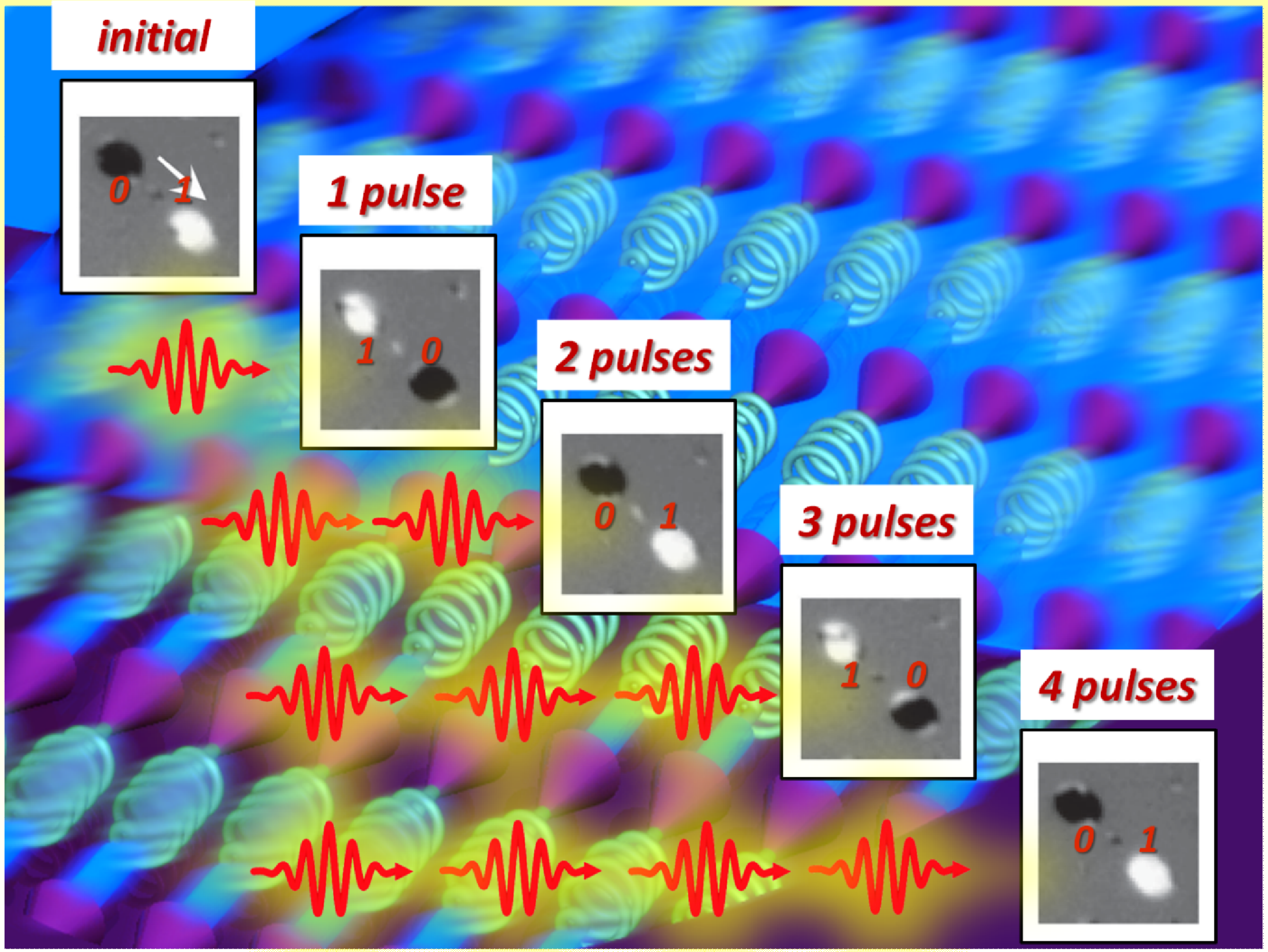
T. Ostler et al, Nature Comm. 3, 666 (2012)

...at induced switching



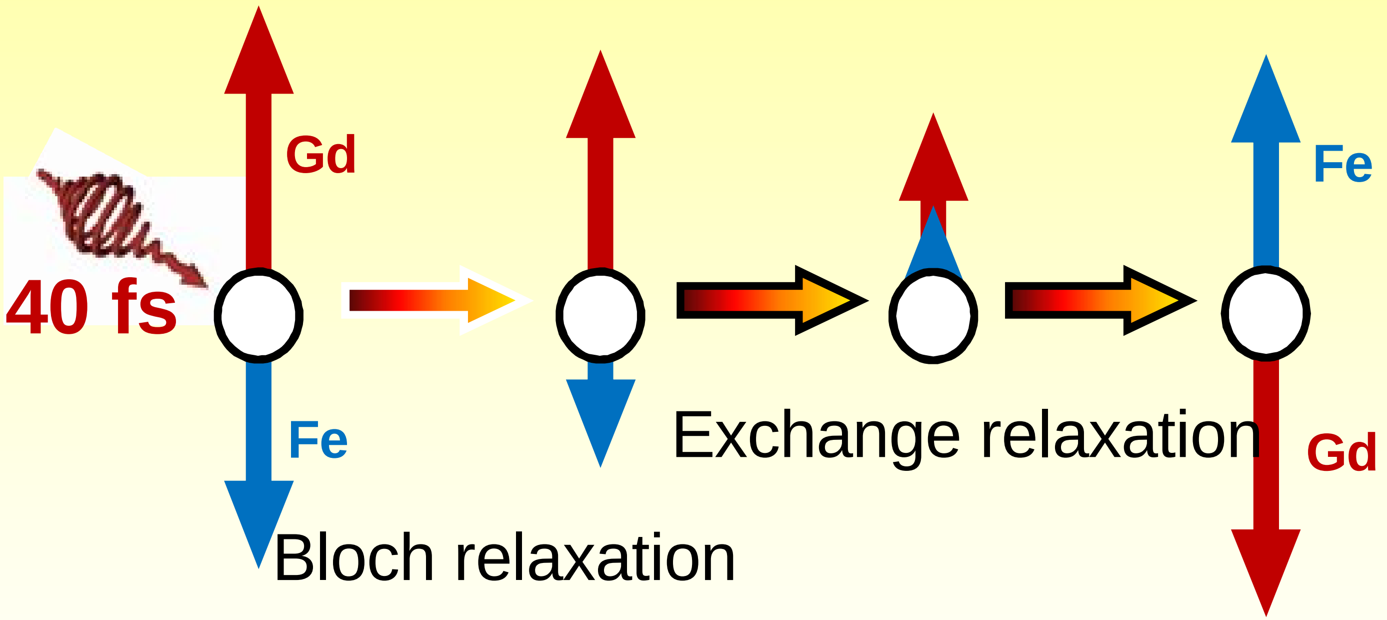
L. Le Guyader et al, APL to appear

ast *THERMAL* Switching



** Ostler et al., Nature Communications 2011*
ñMagnetization Reversalò Patent Pending

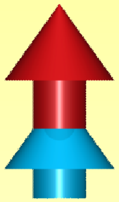
Ultrafast magnetism in multi-sublattice magnets



What about multi-sublattice ferromagnets?

: ultrafast demagnetization

FM coupling

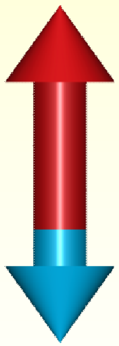


$$dS_1/dt = -\lambda_1 S_1/\chi_1 - \lambda_e(S_1/\chi_1 - S_2/\chi_2)$$

positive/negative

– Coupling makes one sublattice faster, other slower

AFM coupling



$$dS_1/dt = -\lambda_1 S_1/\chi_1 - \lambda_e(S_1/\chi_1 + |S_2|/\chi_2)$$

always positive

– Both sublattices faster than in uncoupled case!

J.H. Mentink *et al.*, *Phys. Rev. Lett.* (2012)

clude:

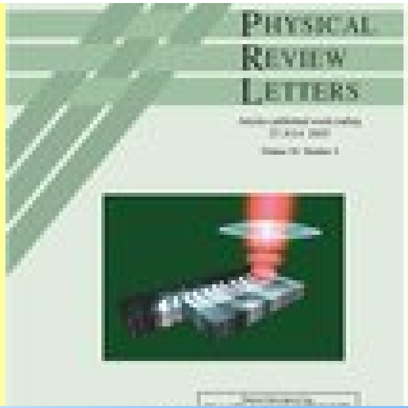
With light

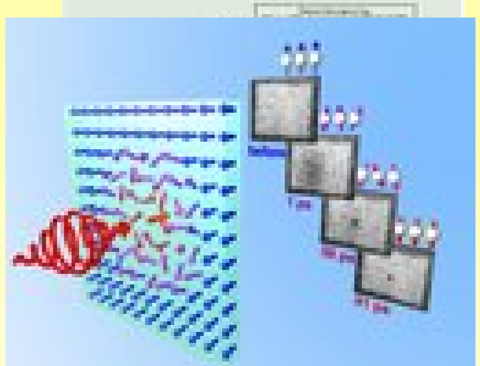
- **Coherent optical control of magnetism !**
- **All-optical ultrafast magnetic recording**
- **Novel (linear) ultrafast reversal path!**
- **Novel transient ferromagnetic state**
- **Heat driven deterministic switching**

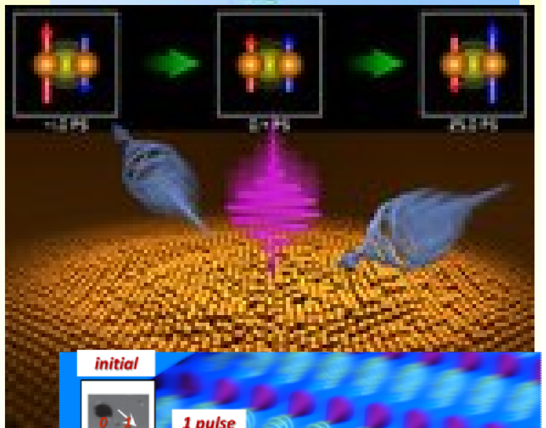
Future challenges

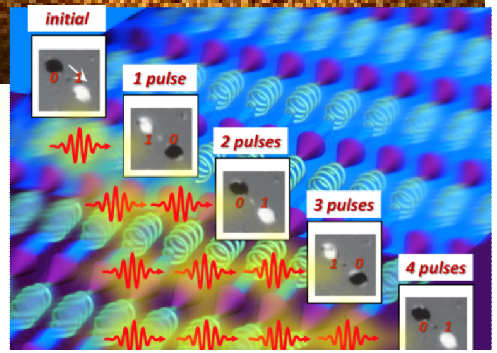
- **Femto magnetism!**
- **Combine chemical, magnetic**

  spatial and time resolution: X(Z)FEL!









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STW, NWO, EU,NanoNed, UltraMagnetron, FANTOMAS

*scopy of **S**olids and **I**nterfaces*