All-optical Control of Magnetism I

(including pump-probe techniques)

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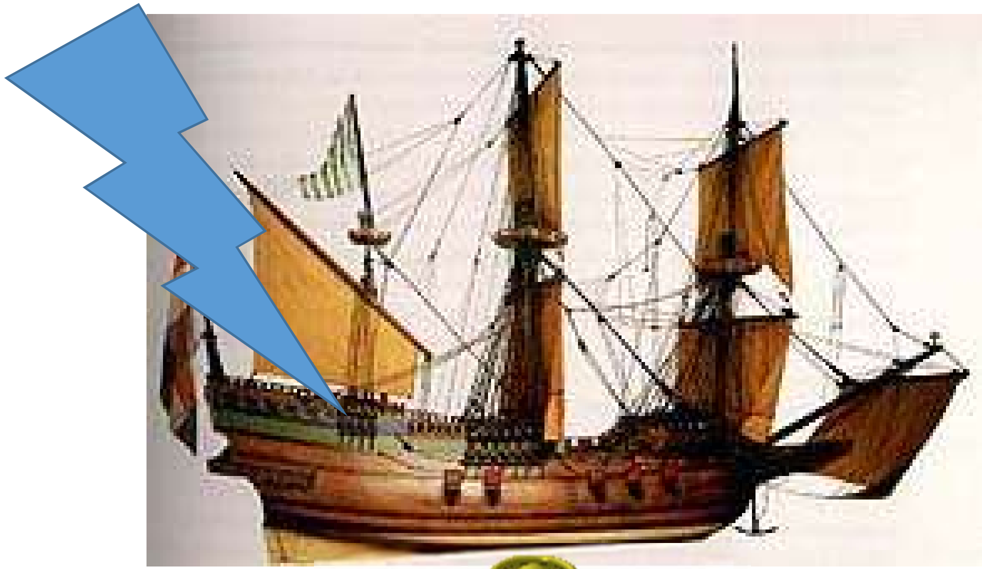
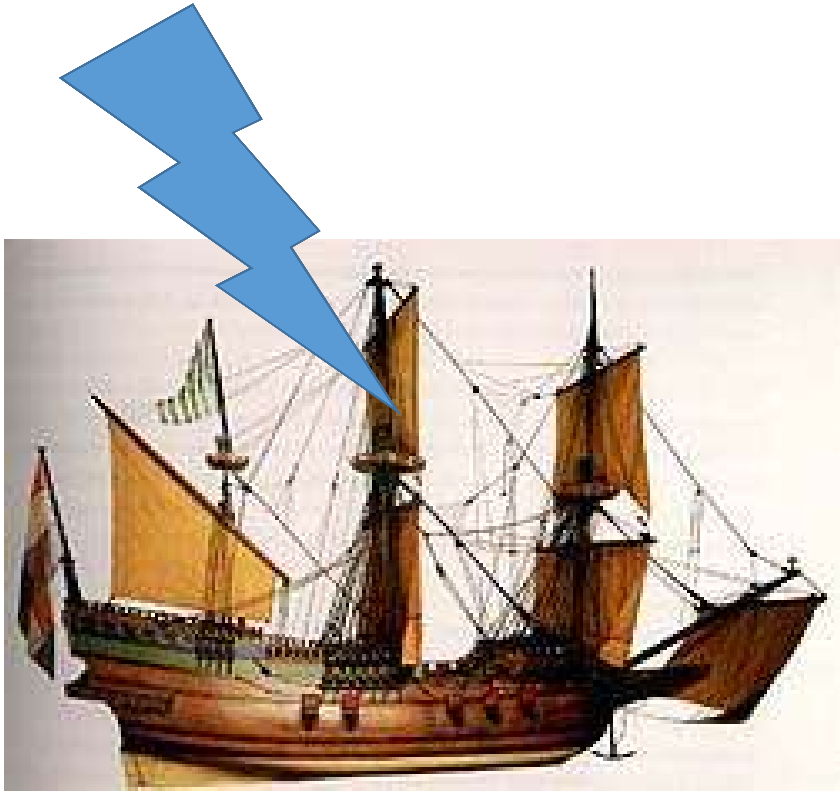
Institute for Molecules and Materials

1681: ship to Boston





Controlling magnetism by lightning

Controlling magnetism by light!

How does it work?

Can we control magnitude?

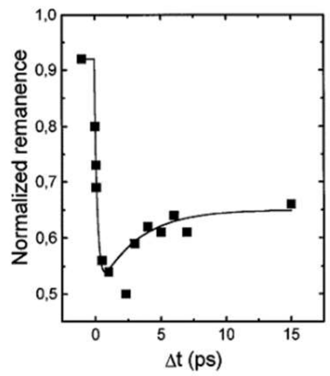
Can we control direction?

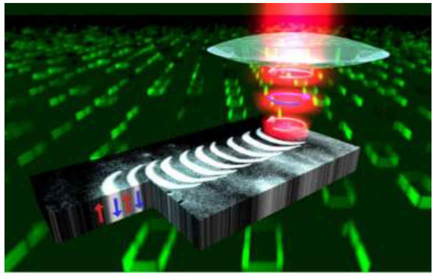
Can we switch?

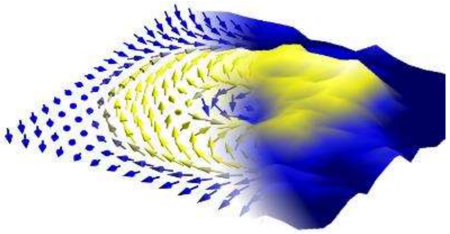
What about the nanoscale?

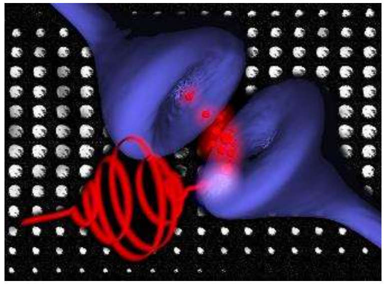
Lecture topics:

1. **Time scales and stimuli in magnetism**
2. **Laser induced effects**
    a. **Thermal effects**
    b. **Nonthermal opto-magnetic effects**
3. **Experiments**
    a. **AOS of Ferrimagnets**
    b. **AOS of Ferromagnets**
    c. **AOS of Dielectrics**
4. **Towards applications**
    a. **AOS at the nanoscale**
    b. **Neuromorphic applications**
5. **Outlook**

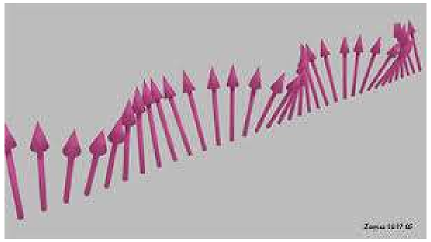




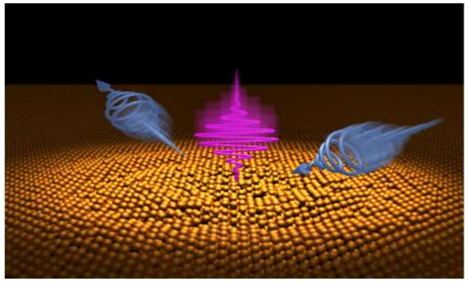




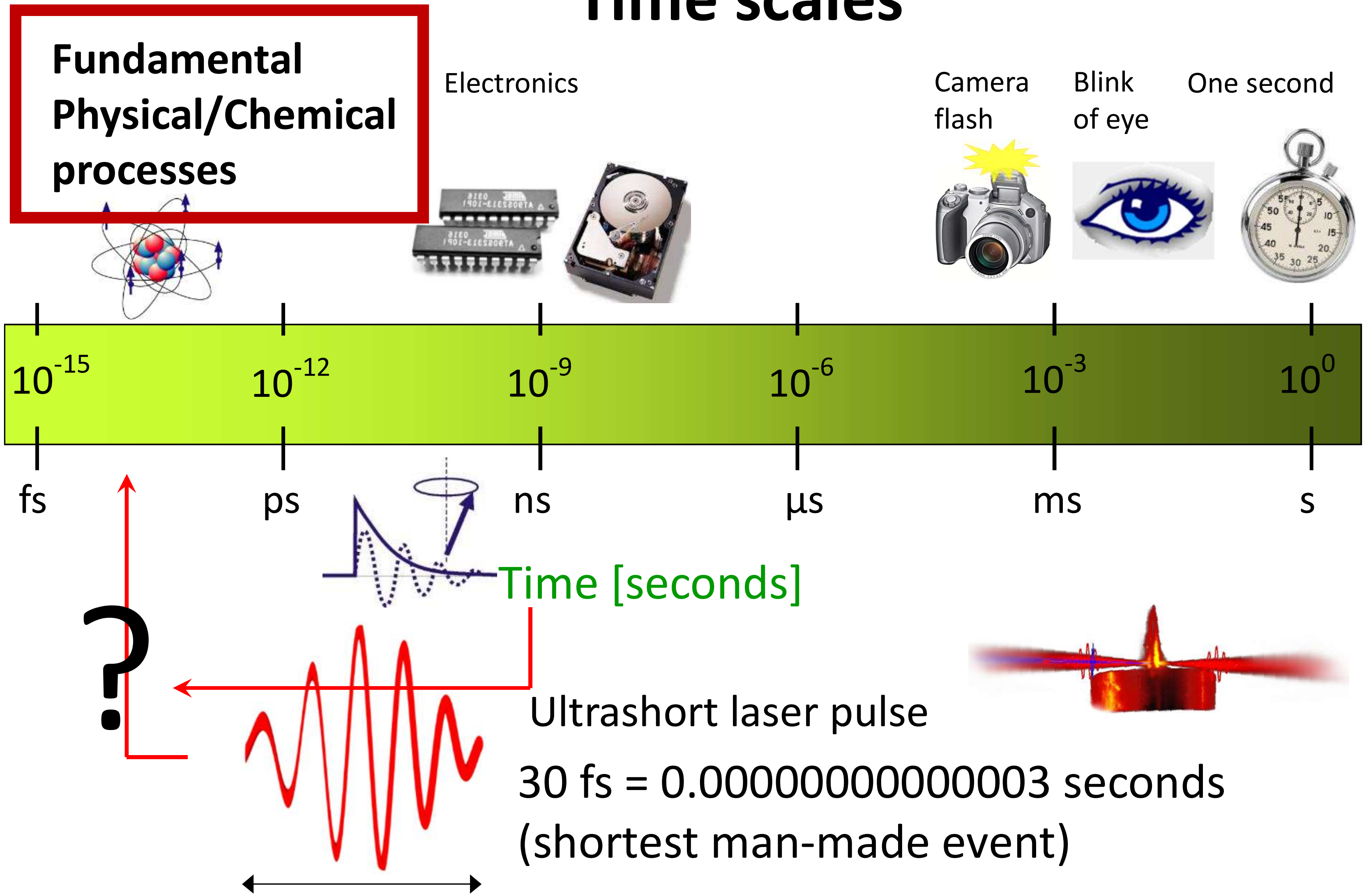
Lecture topics:



1. Introduction: stochastic/deterministic dynamics
2. Stroboscopic imaging.
3. Magneto-optical setups
   a. Faraday/Kerr effects
   b. XMCD
4. Examples
5. Outlook

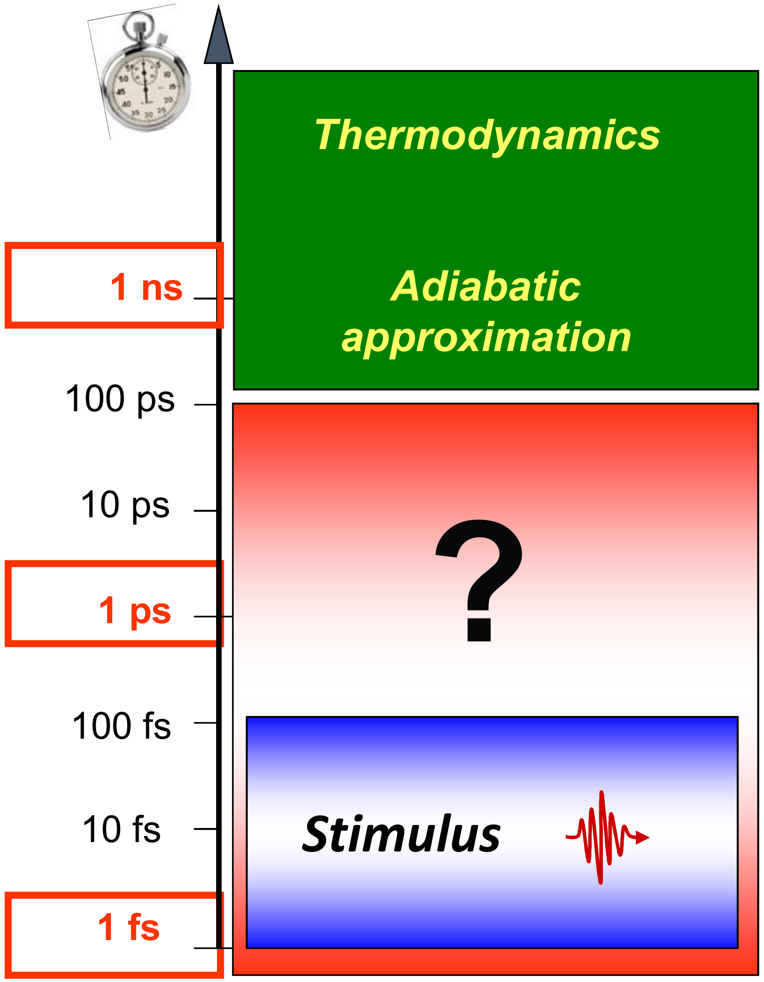


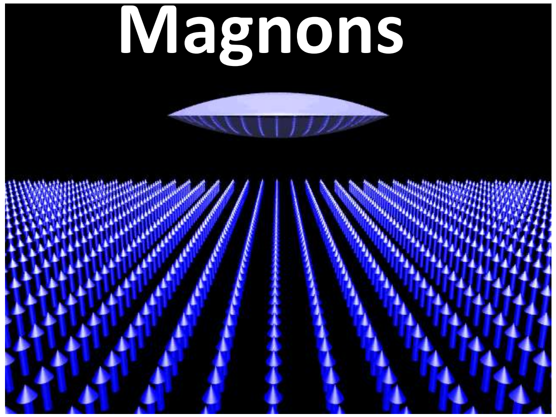
Time scales



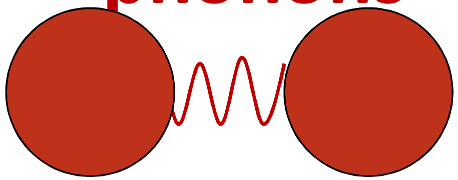
Fundamental Physical/Chemical processes
Electronics
Camera flash
Blink of eye
One second
10^-15
10^-12
10^-9
10^-6
10^-3
10^0
fs
ps
ns
µs
ms
s
Time [seconds]
?
Ultrashort laser pulse
30 fs = 0.00000000000003 seconds
(shortest man-made event)

How much is 1 fs in magnetism?

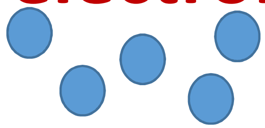




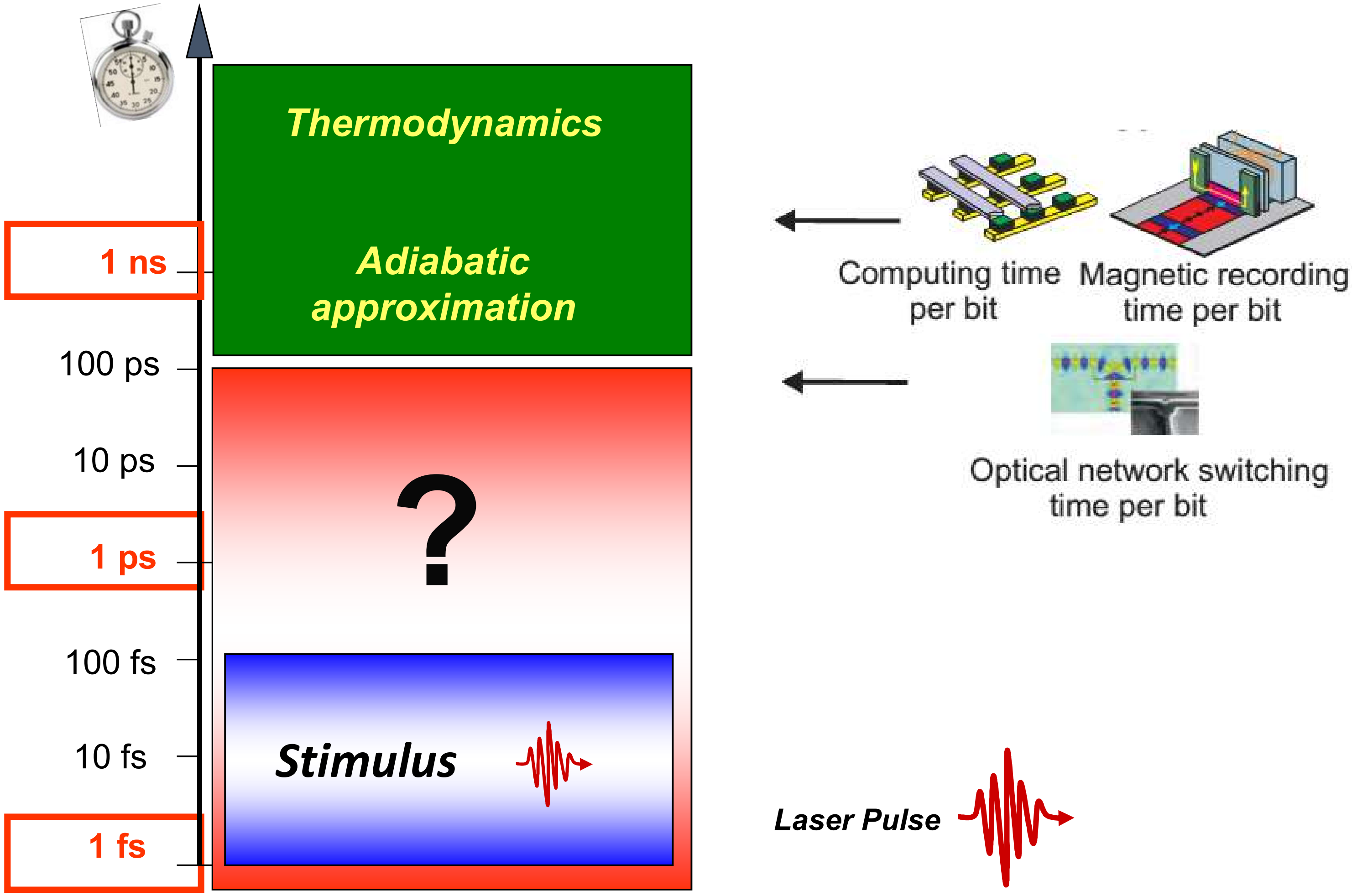
phonons



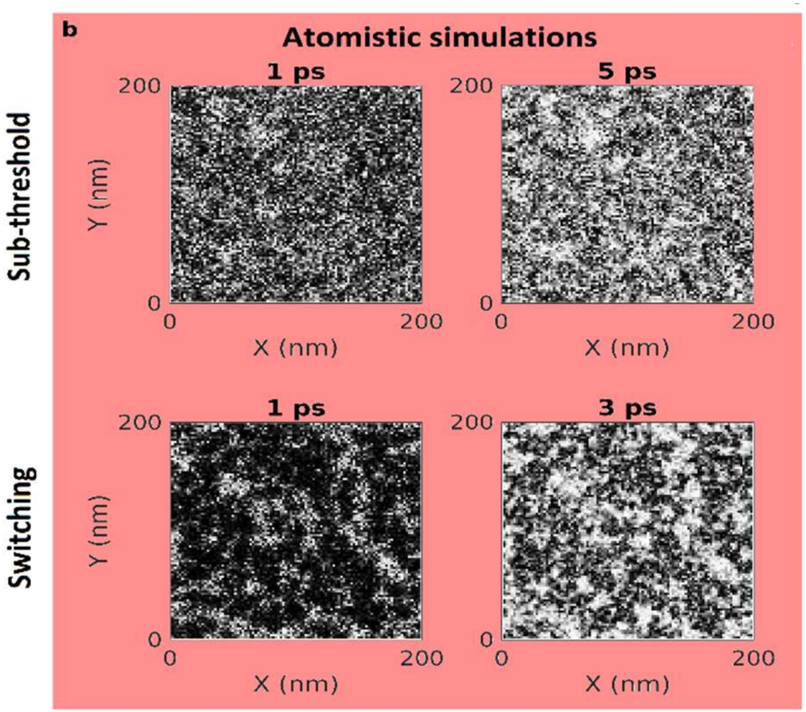
electrons

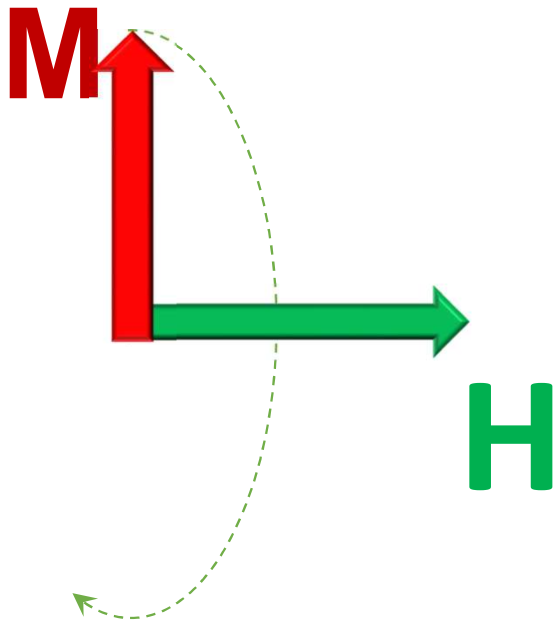


How much is 1 fs in technology?



stochastic/deterministic dynamics



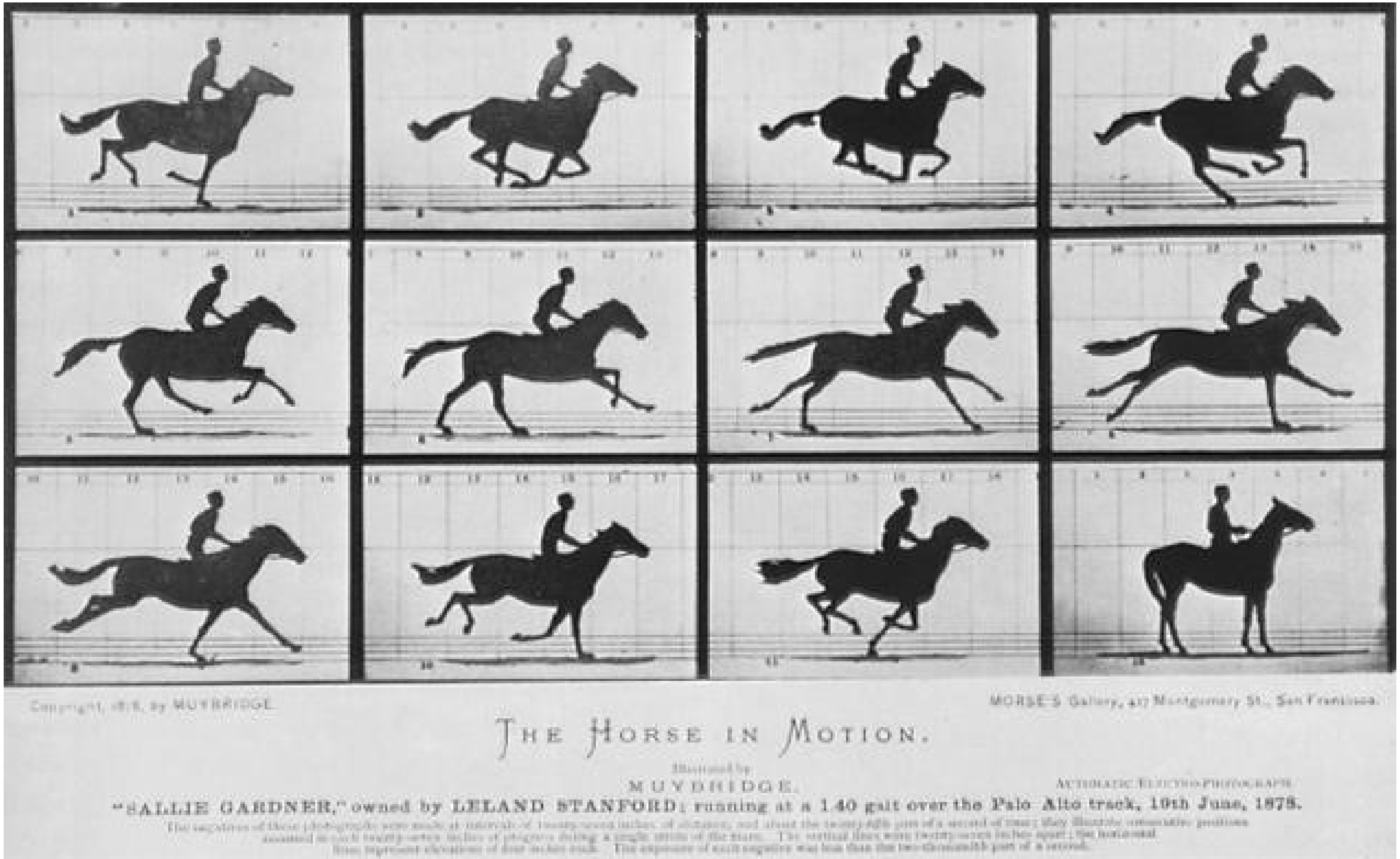


NUCLEATION OF MAGNETIC ORDER

COHERENT ROTATION OF MAGNETIZATION

Leland Stanford

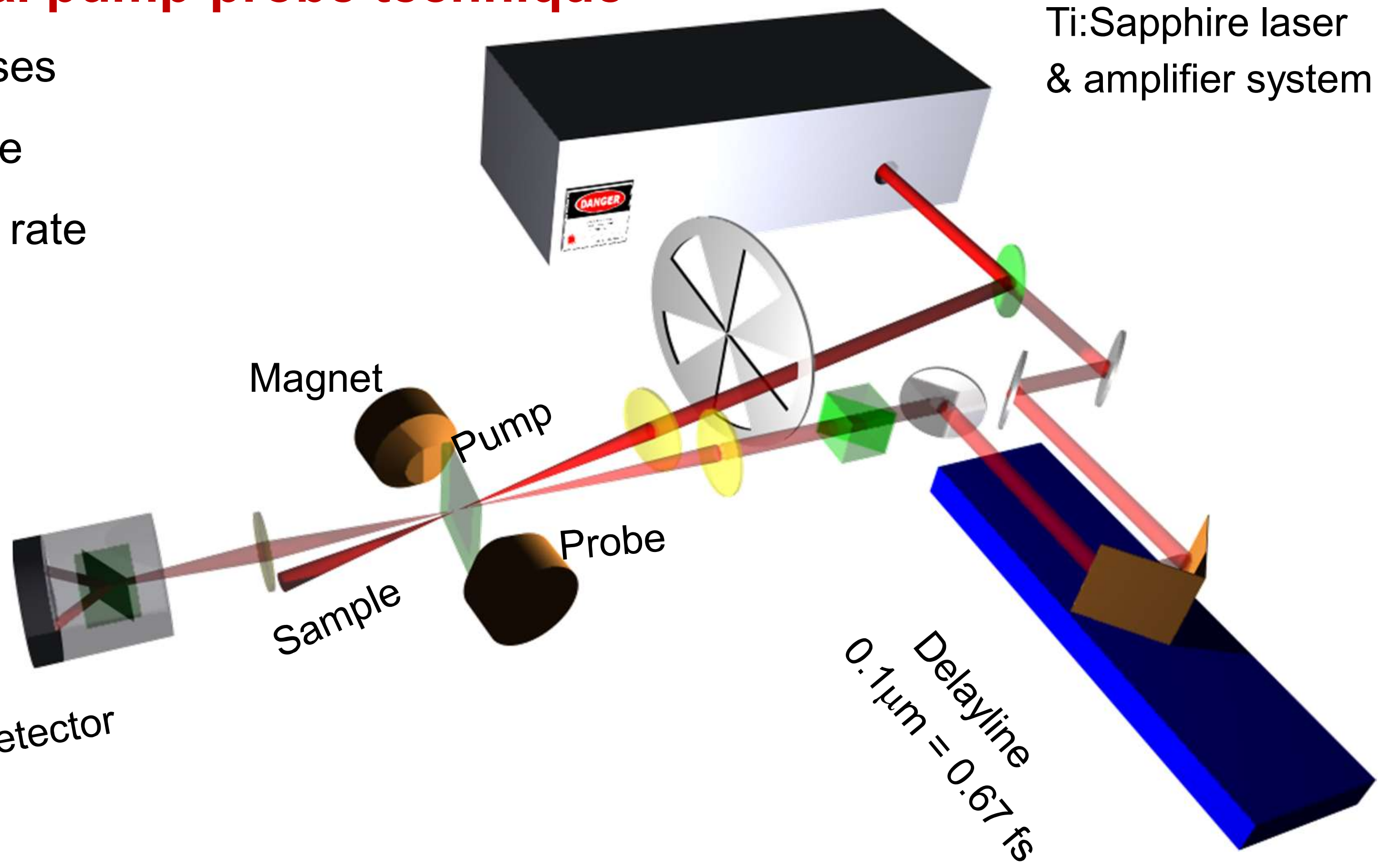
Edward Muybridge: The Horse in Motion



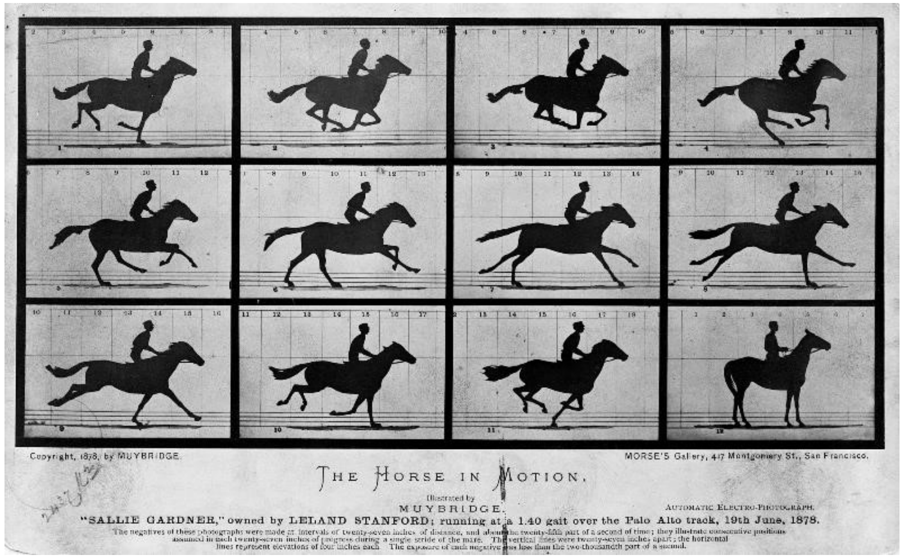
Experimental fs-pump-probe technique

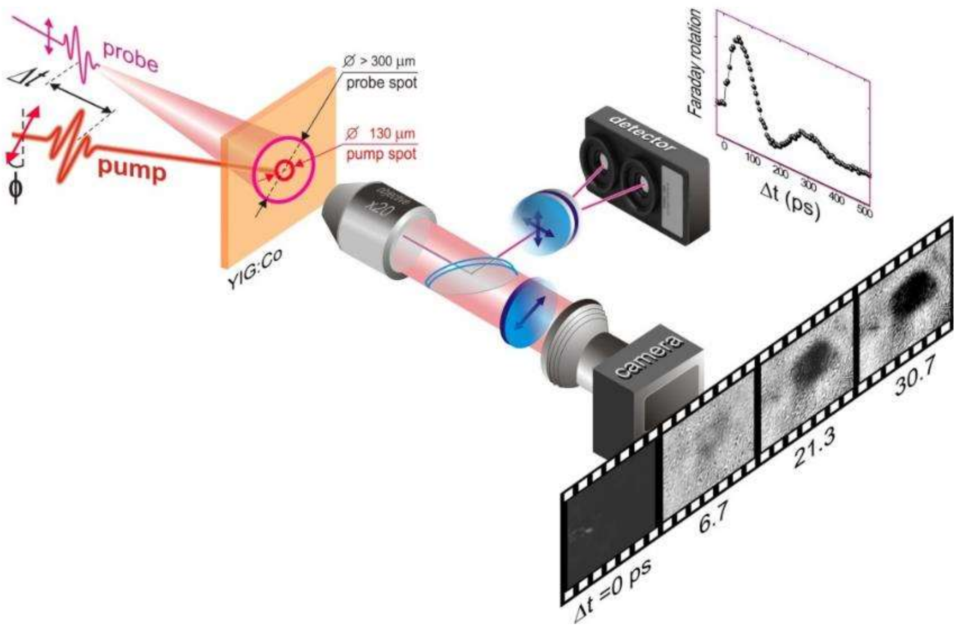
All-optical pump-probe technique

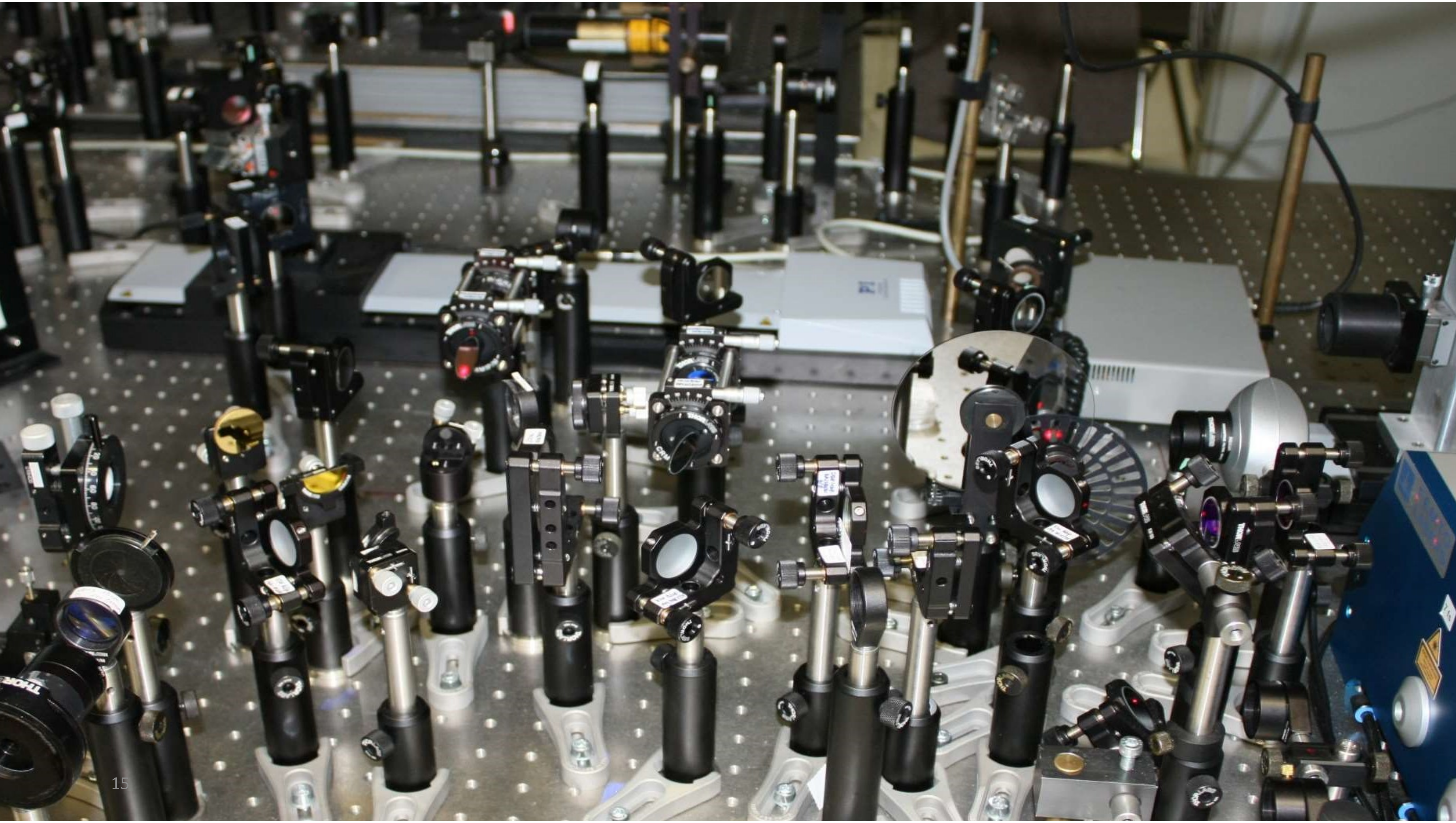
- 100fs pulses
- 20μJ/pulse
- 1kHz rep. rate



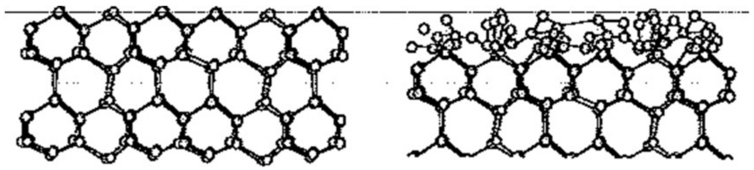
Revealing ultrafast dynamics with fs flashes

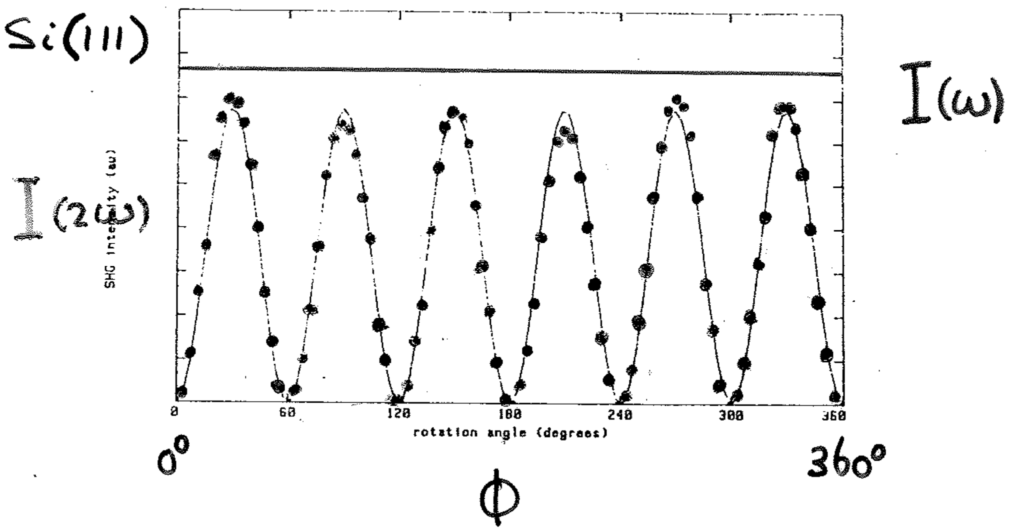


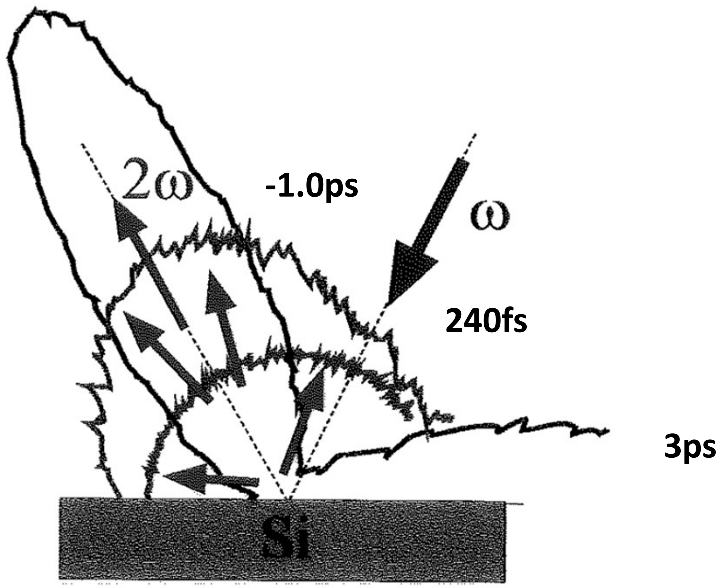




SHG studies of laser-induced surface melting

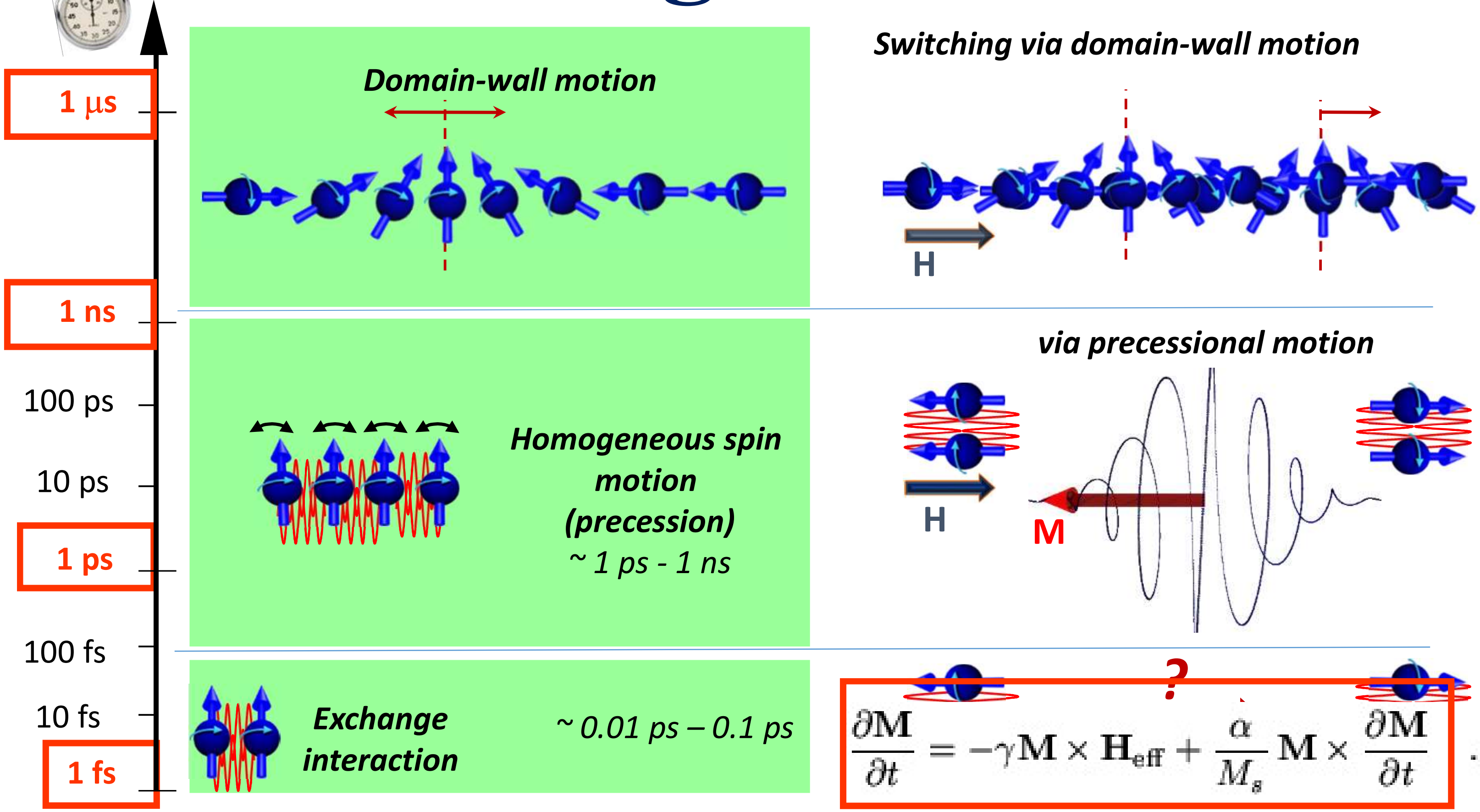






C.V. Shank et al, Phys.Rev.Lett.51, 900 (1983)

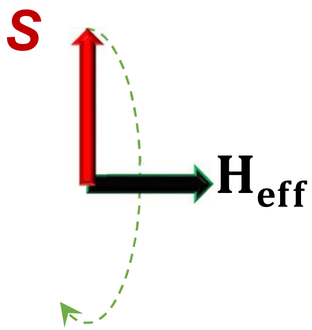
1. Time-scales in magnetism vs switching mechanisms

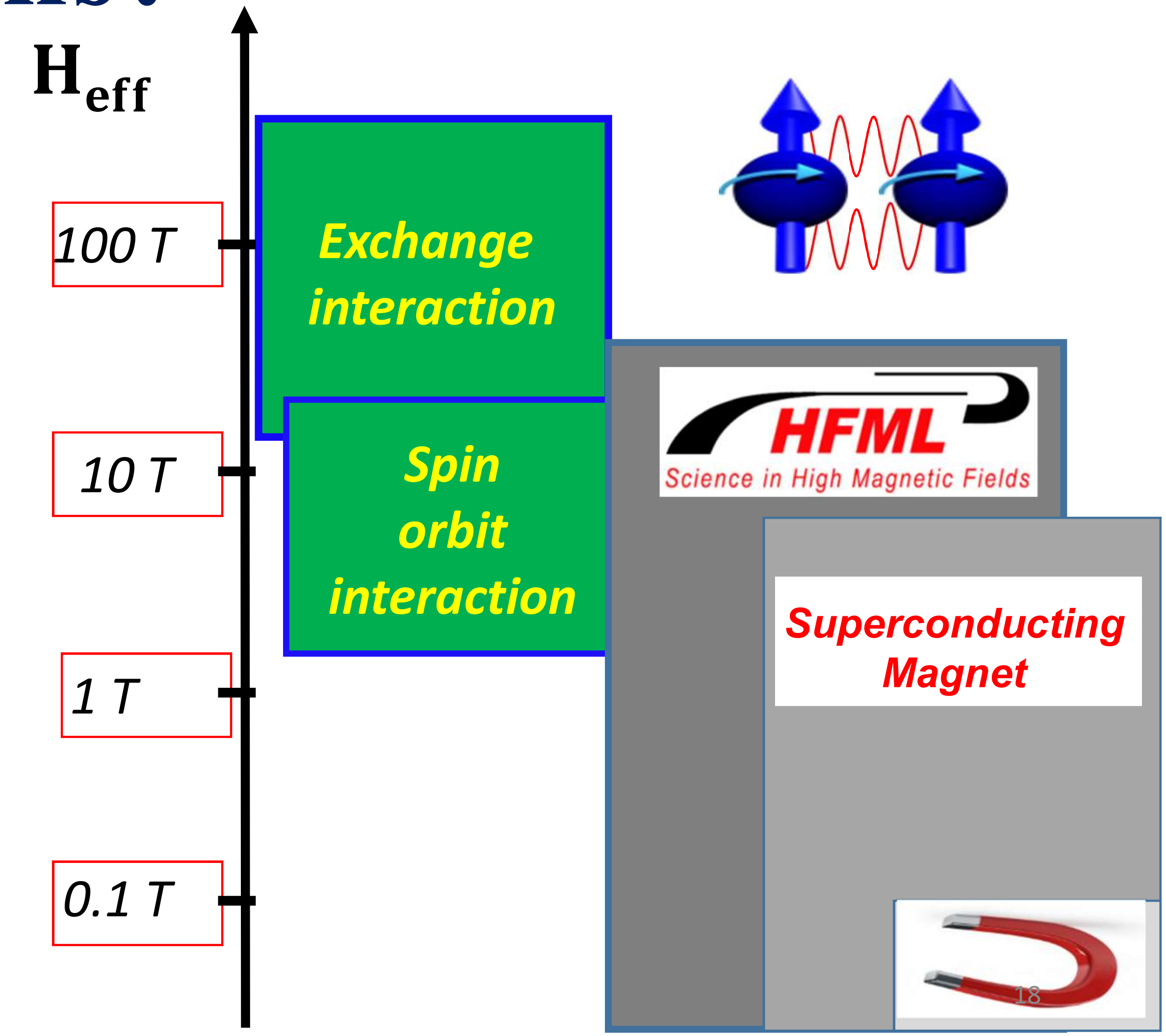


manipulating spins?

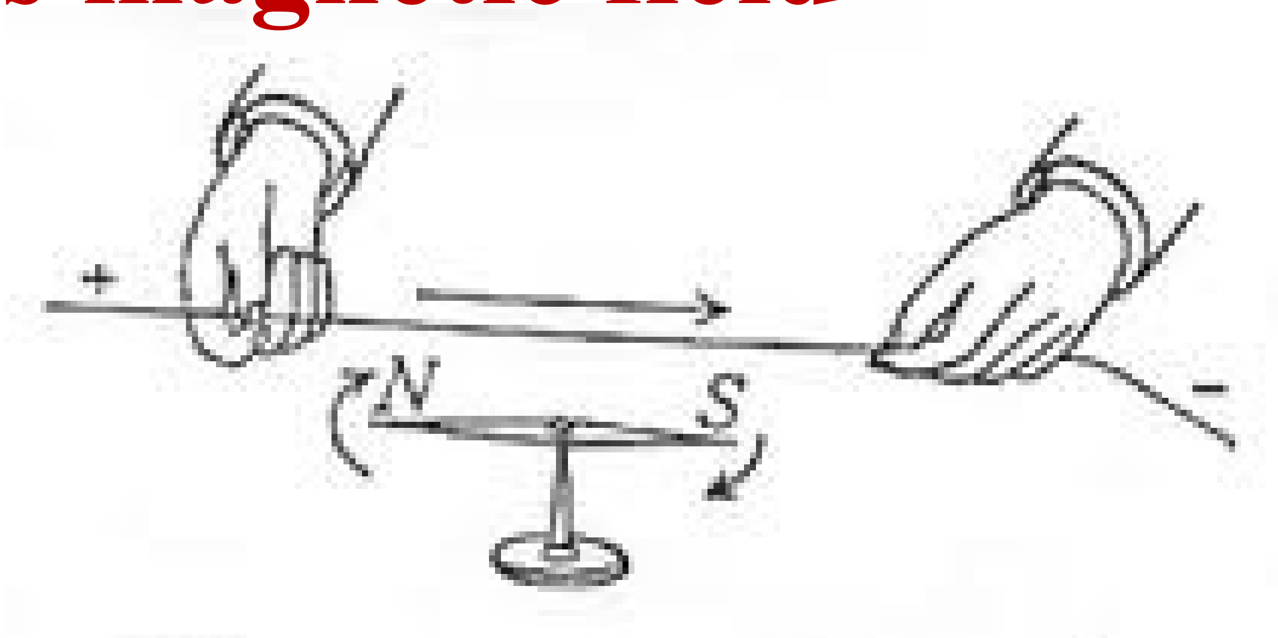
$$\mathbf{H}_{\mathrm{eff}} = \frac{\partial \mathcal{H}_i}{\partial \boldsymbol{S}_i} = \mathbf{H} + \alpha \boldsymbol{L}_i + Jij\boldsymbol{S}_j$$

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



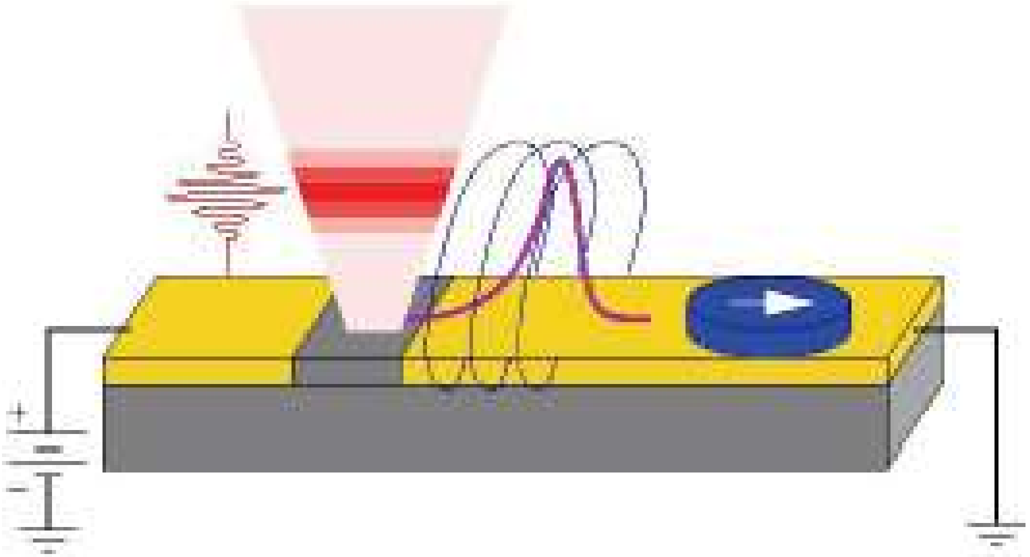


Oersted/Faraday: electrical current creates magnetic field



Current creates a magnetic field

optical switch for short current pulses:

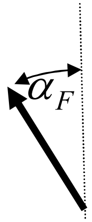


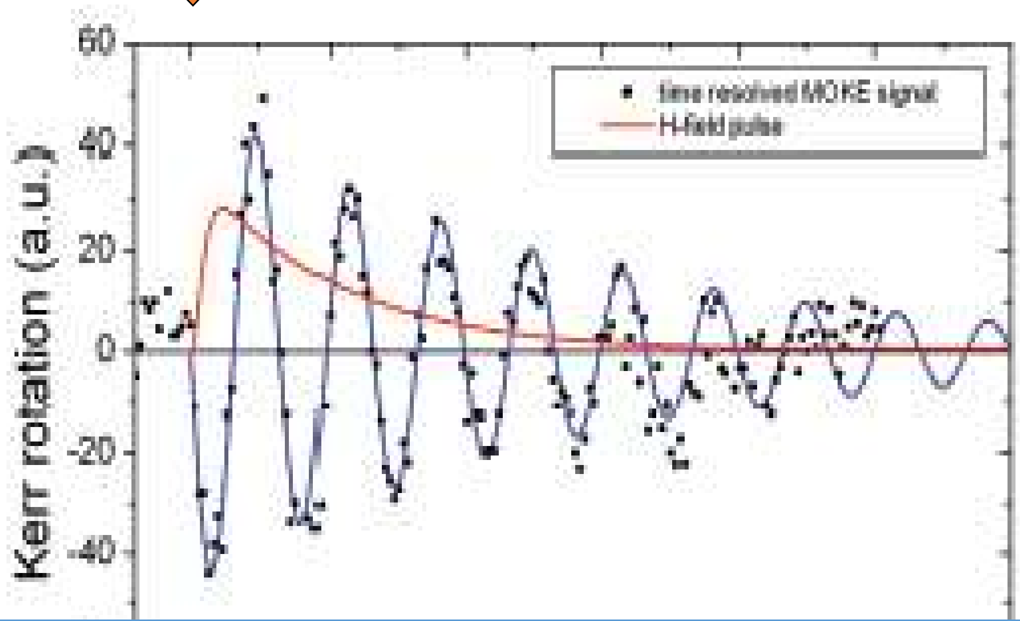
10 ps rise time   400 ps decay time

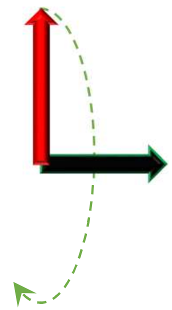
short magnetic field pulses!

magnetic precession

Magnetic fieldpuls



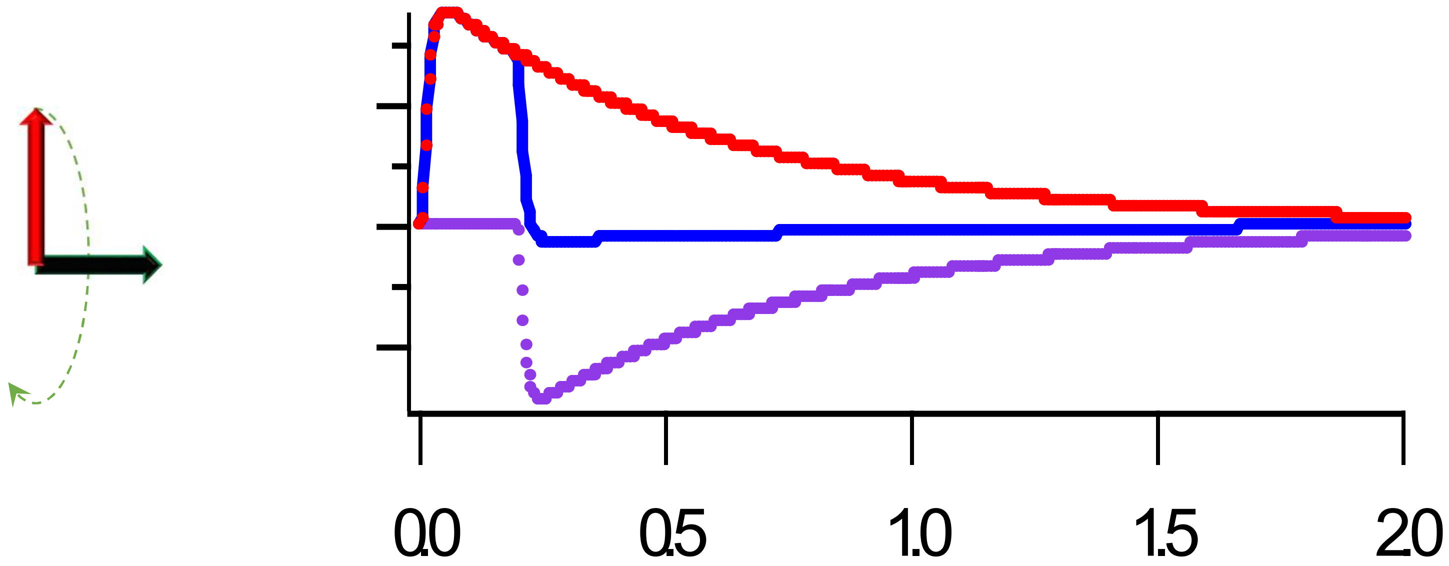




Th.Gerrits et al,
Nature 418, 509 (2002)

How to switch ?

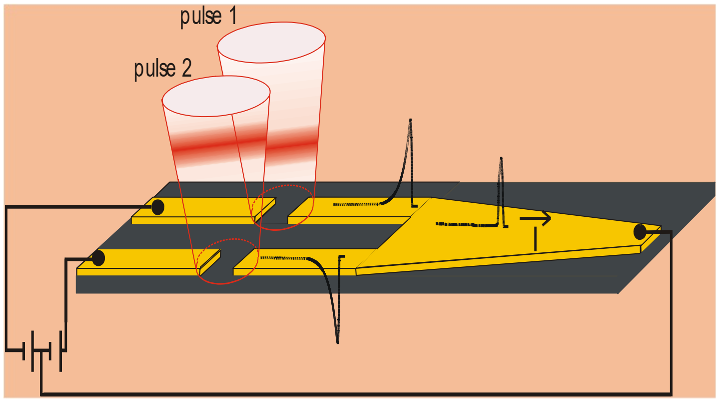
CONTROL: SHAPED pulse!

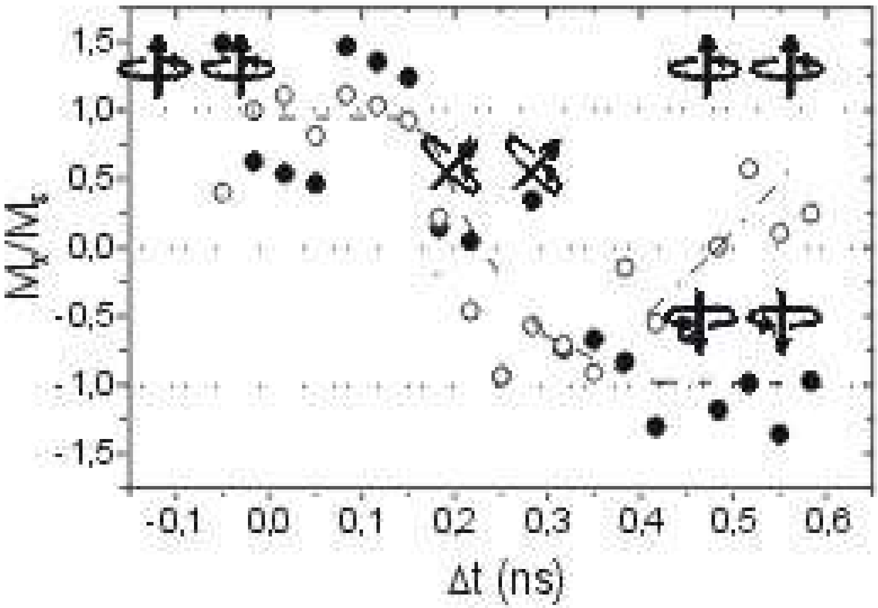


Switching: pulse length=half a precessional period!

Switching by controlling pulse width!

Switching within 200 ps !

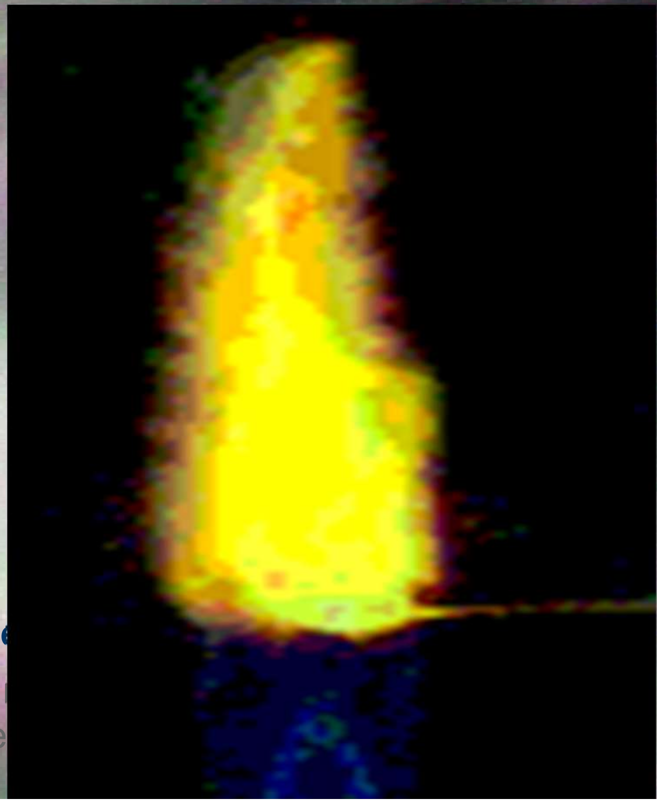


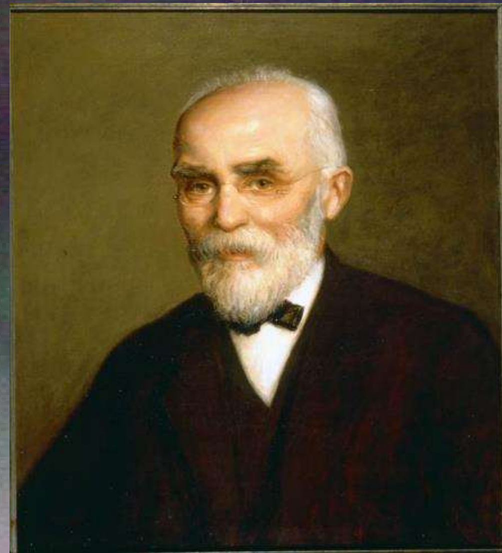


Th.Gerrits et al, Nature 418, 2002

Magnetism and light

Magnetism and light

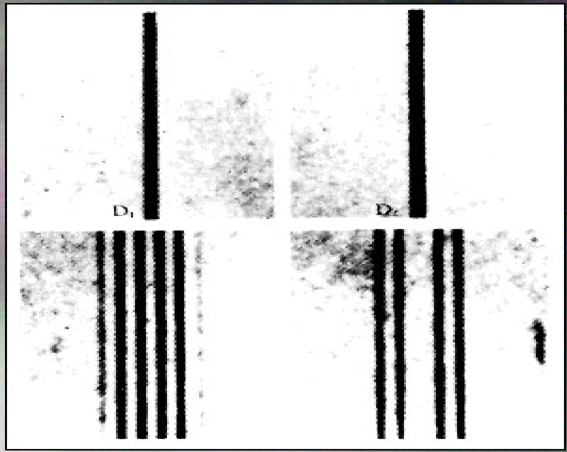


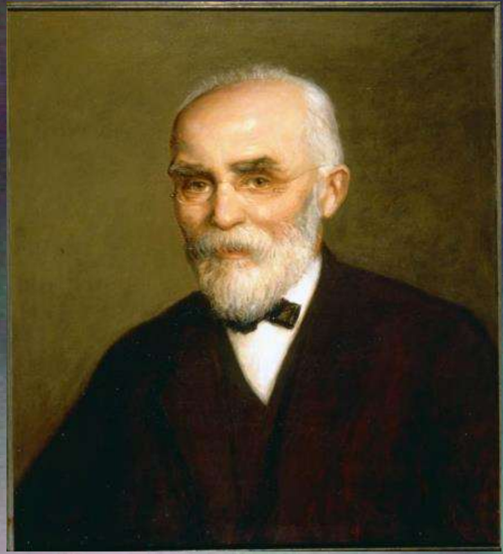


The

"in r … they rendered by their researches into the … phenomena" (together with Lorentz)

Magnetism and light





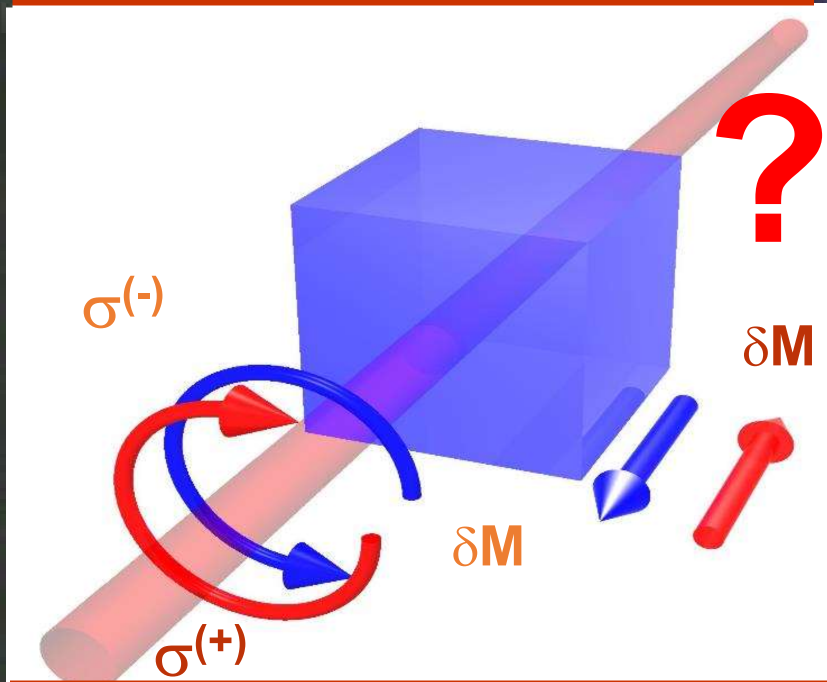
Zeeman effect

The Nobel Prize in Physics 1902

"in recognition of the extraordinary service they rendered by their researches into the influence of magnetism upon radiation phenomena" (together with Lorentz)

Magnetism and light

inverse?



Faraday effect

2.Ultrafast “demagnetization” by light

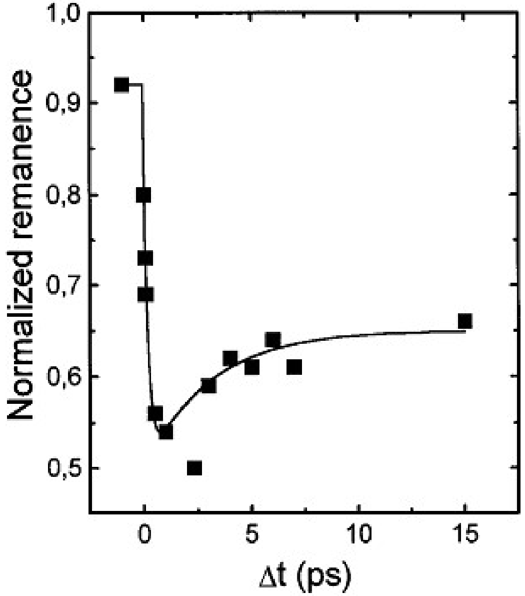


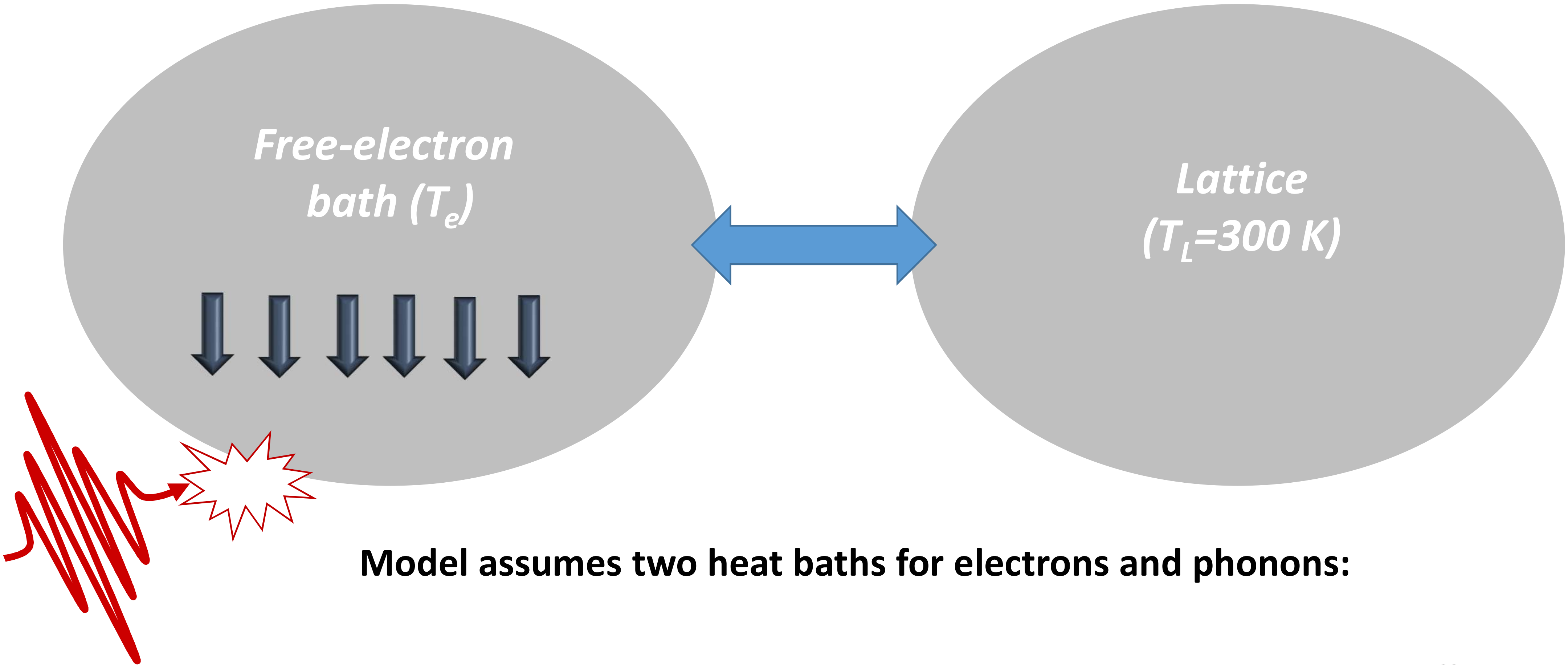
FIG. 2. Transient remanent longitudinal MOKE signal of a Ni(20 nm)/MgF_2(100 nm) film for 7 mJ cm^{-2} pump fluence. The signal is normalized to the signal measured in the absence of pump beam. The line is a guide to the eye.

VOLUME 76, NUMBER 22 PHYSICAL REVIEW LETTERS 27 MAY 1996

Ultrafast Spin Dynamics in Ferromagnetic Nickel

E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot
Institut de Physique et Chimie des Matériaux de Strasbourg, Unité Mixte 380046 CNRS-ULP-EHICS, 23, rue du Loess, 67037 Strasbourg Cedex, France
(Received 17 October 1995)

2-Temperature model

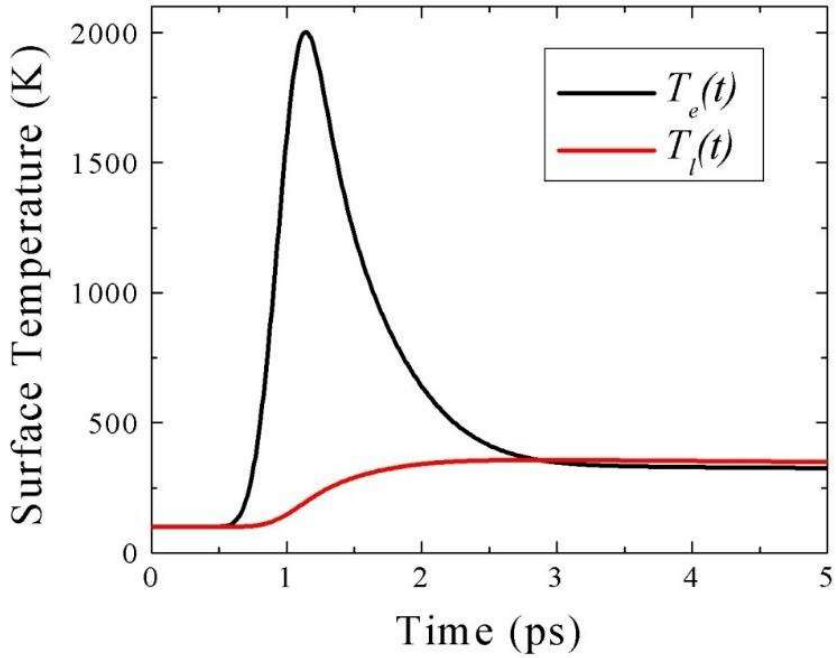


Model assumes two heat baths for electrons and phonons:

2-Temperature model

$$C_{\rm el}(T_{\rm el})\,\frac{\partial T_{\rm el}}{\partial t} = \nabla(\kappa\nabla T_{\rm el}) - g(T_{\rm el} - T_{\rm ph}) + S(z,t)$$

$$C_{\rm ph}(T_{\rm ph})\,\frac{\partial T_{\rm ph}}{\partial t} = g(T_{\rm el} - T_{\rm ph})$$



Coupled diffusion equations for T_{el} and T_{ph}

note that $C_{el} << C_{ph}$ – this is why electrons get so hot!

2-Temperature model

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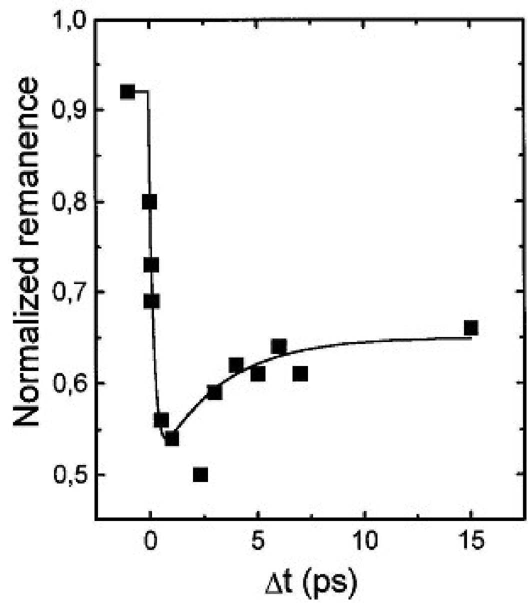
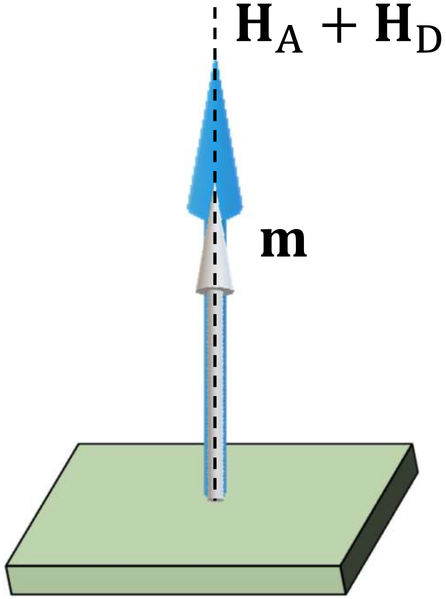


FIG. 2. Transient remanent longitudinal MOKE signal of a Ni(20 nm)/MgF$_2$(100 nm) film for 7 mJ cm^{-2} pump fluence. The signal is normalized to the signal measured in the absence of pump beam. The line is a guide to the eye.

Coupled diffusion equations for T_{el} and T_{ph}

note that C_{el} << C_{ph} – this is why electrons get so hot!

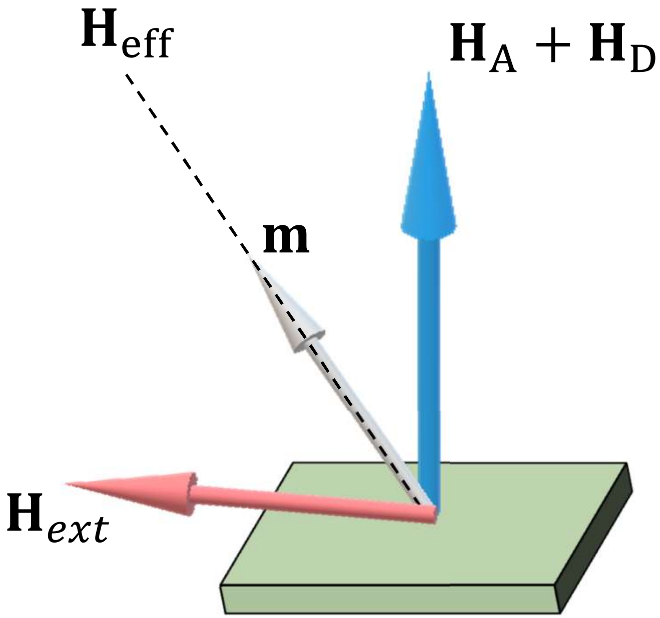
Laser-induced spin precession



$\mathbf{H}_\mathrm{D} = -4\pi\mathbf{m}_\perp$;

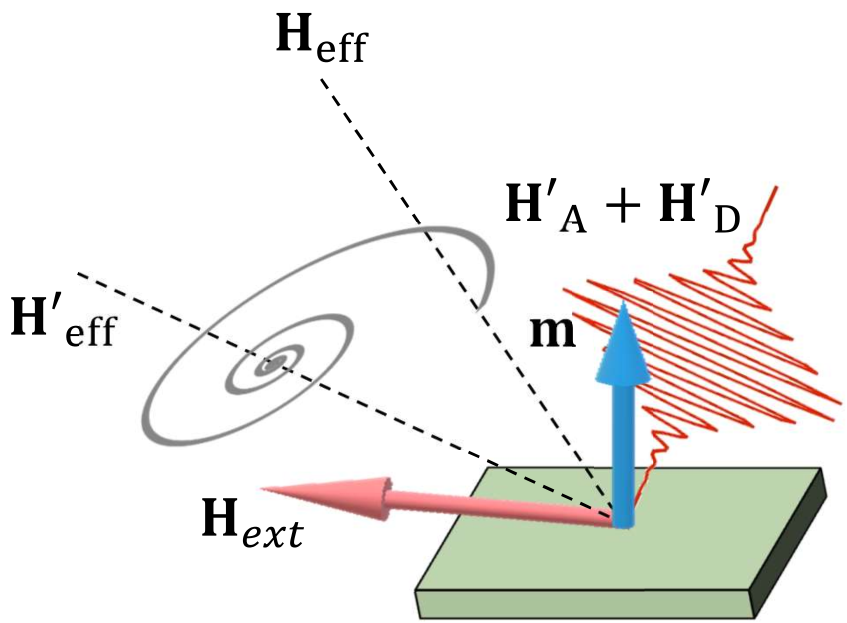
$\mathbf{H}_\mathrm{eff} = \mathbf{H}_\mathrm{A} + \mathbf{H}_\mathrm{D}$.

Laser-induced spin precession



$$\mathbf{H}_{\mathrm{eff}} = \mathbf{H}_{\mathrm{ext}} + \mathbf{H}_{\mathrm{A}} + \mathbf{H}_{\mathrm{D}}.$$

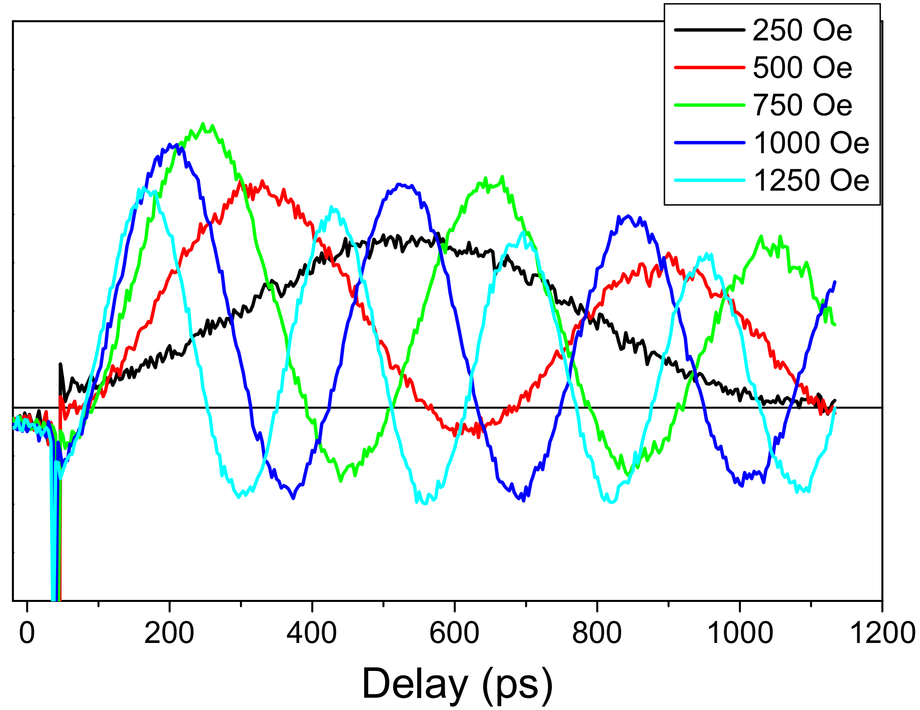
Laser-induced spin precession



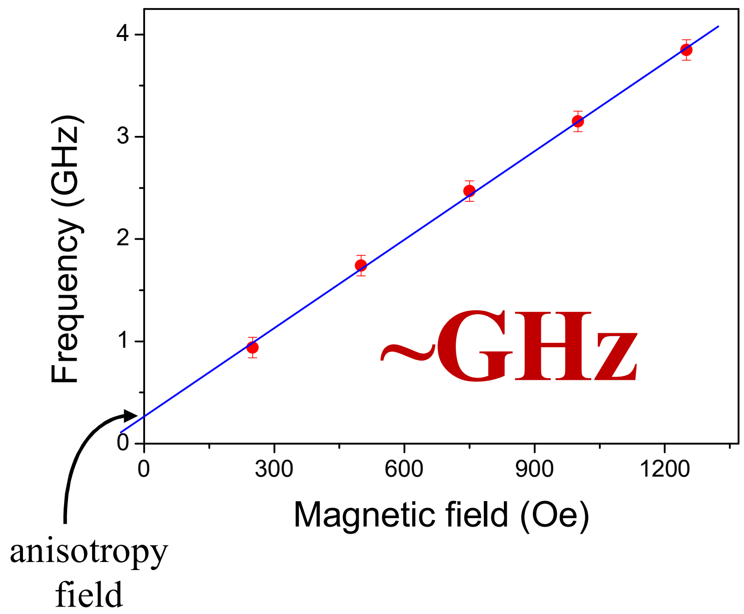
$$\mathbf{H'}_{\mathrm{eff}} = \mathbf{H}_{\mathrm{ext}} + \mathbf{H'}_{\mathrm{A}} + \mathbf{H'}_{\mathrm{D}}.$$

Laser-induced spin precession

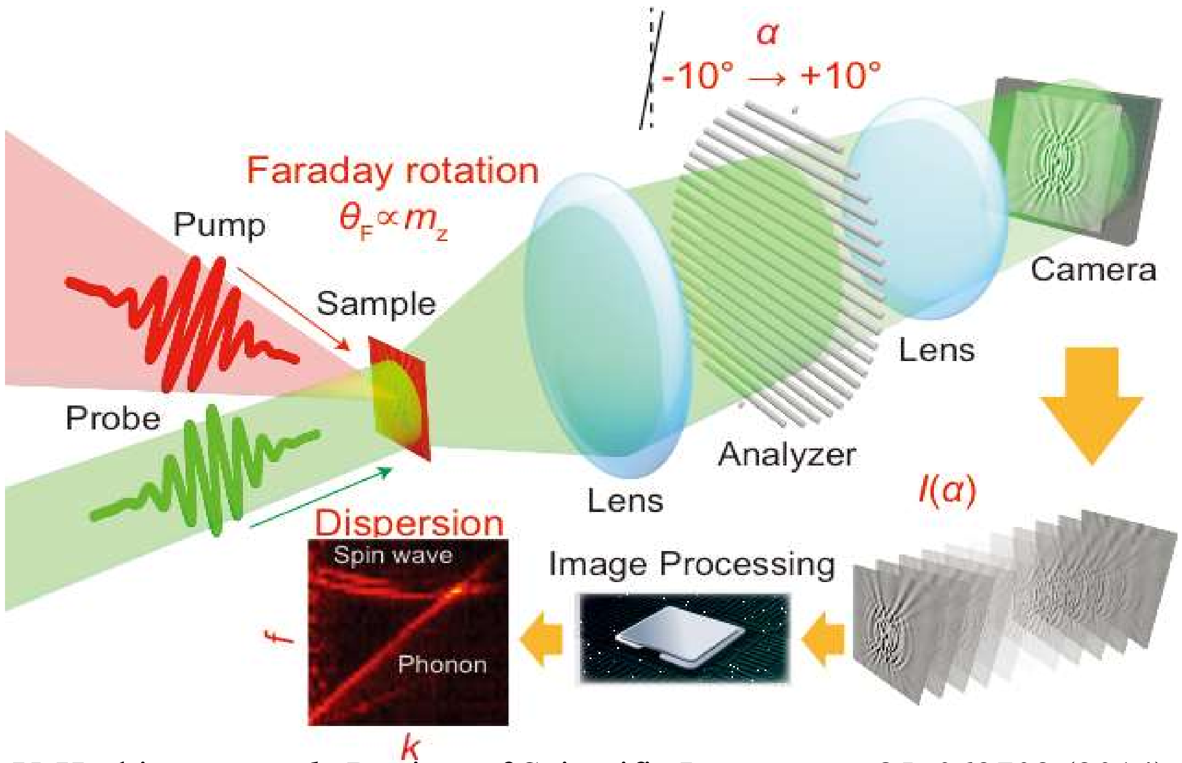
thin film of magnetic garnet (~$Y_3Fe_5O_{12}$)



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

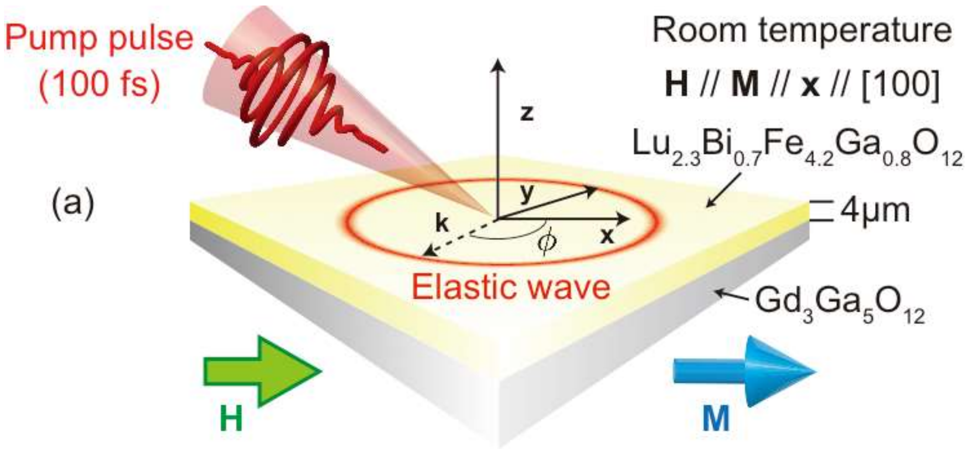


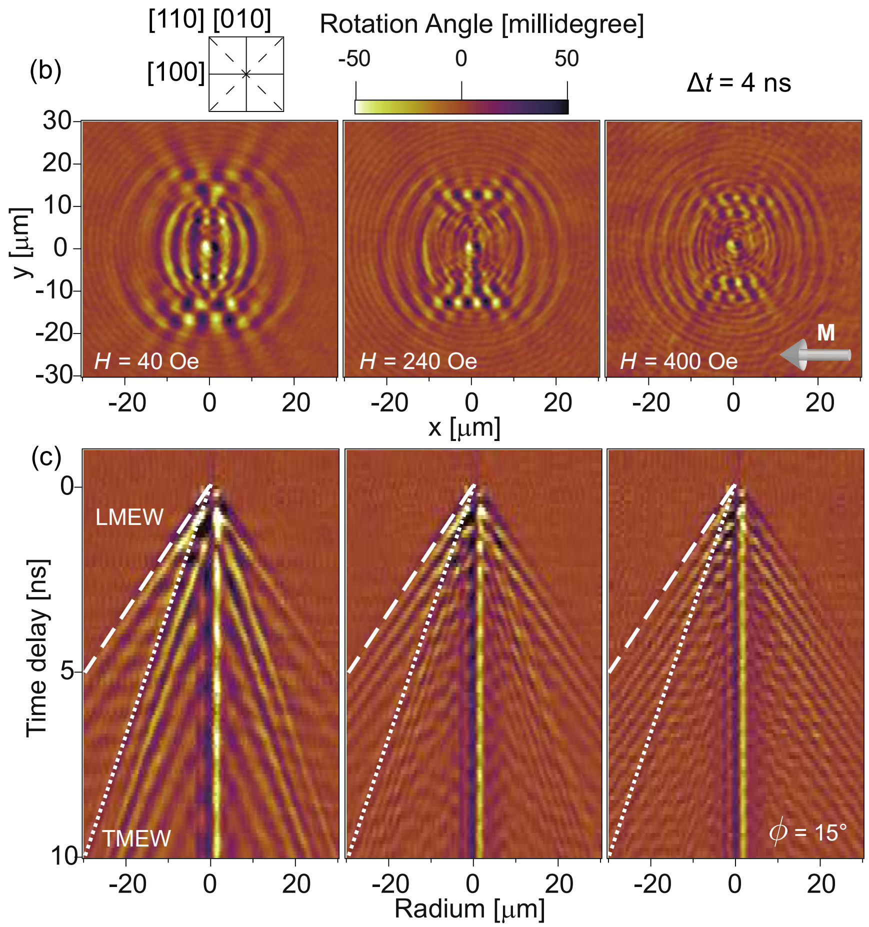
Time-resolved Magneto-optical Imaging



Y. Hashimoto, *et al.*, Review of Scientific Instruments 85, 063702 (2014).

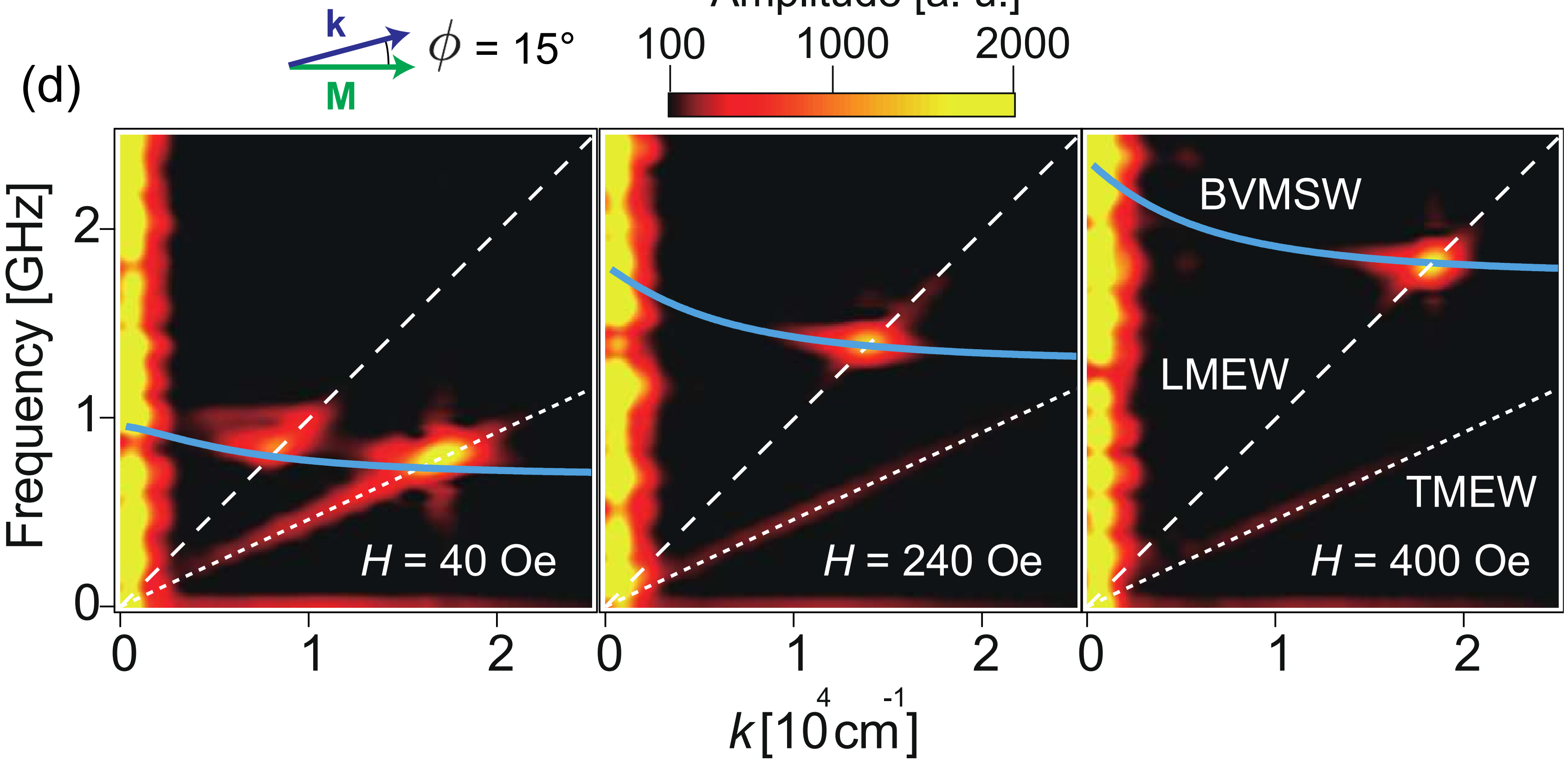
Propagation Dynamics of Optically-excited Spin Waves





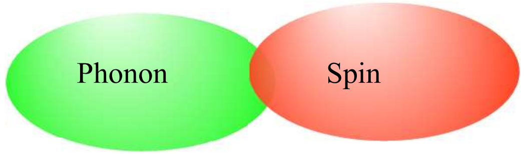
YIG sample

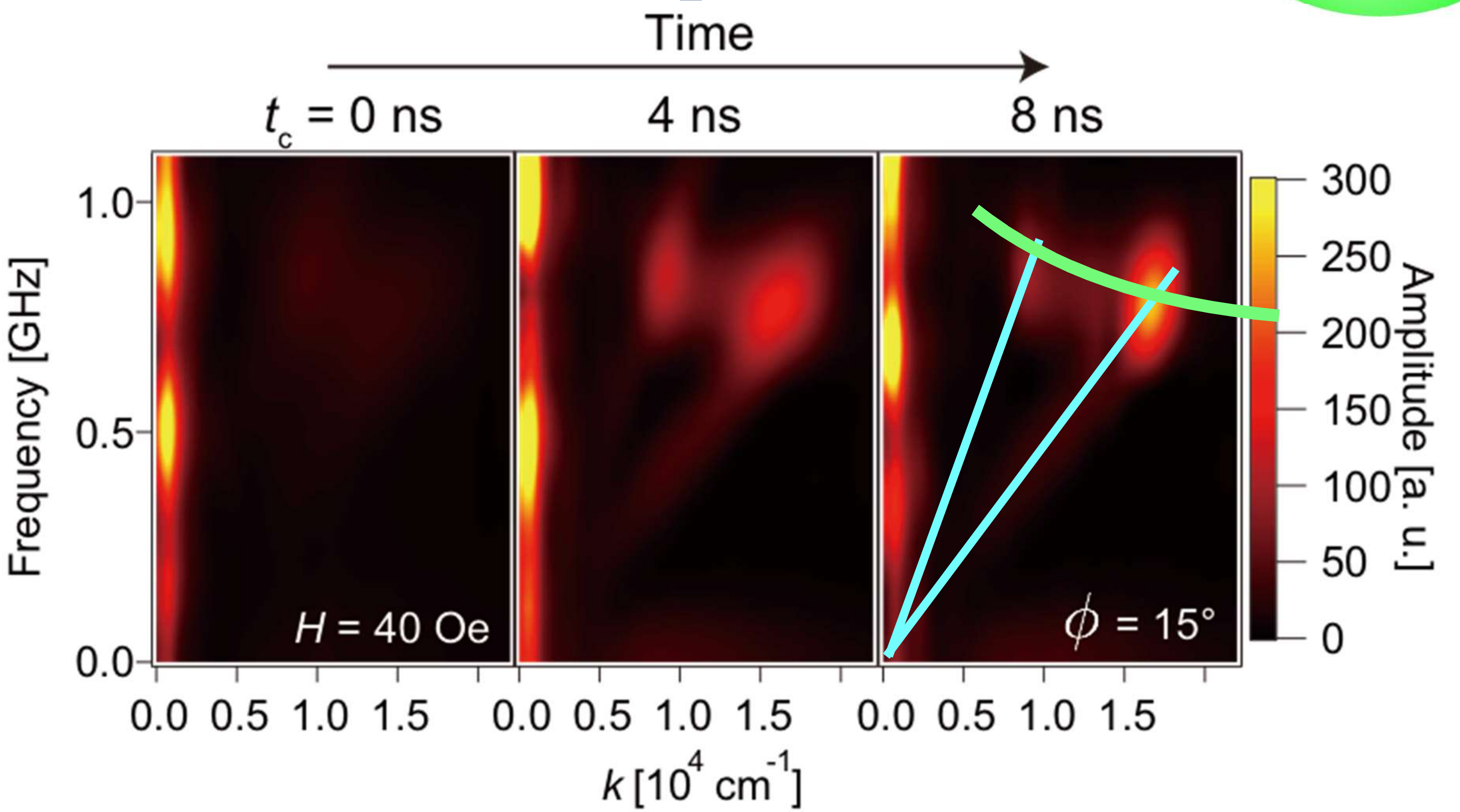
Spin-wave Tomography



Y. Hashimoto *et al*., Nature Communications **8**, 15859 (2017)

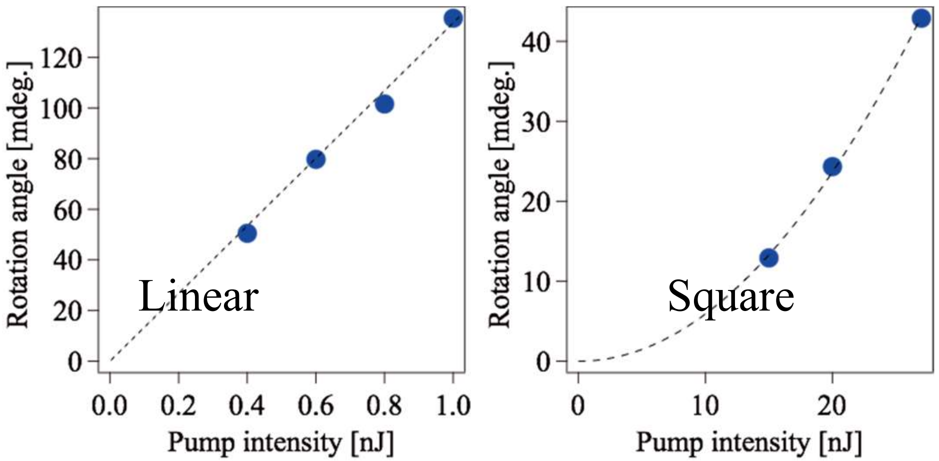
Coherent-energy Transfer from Elastic waves to Spin Waves



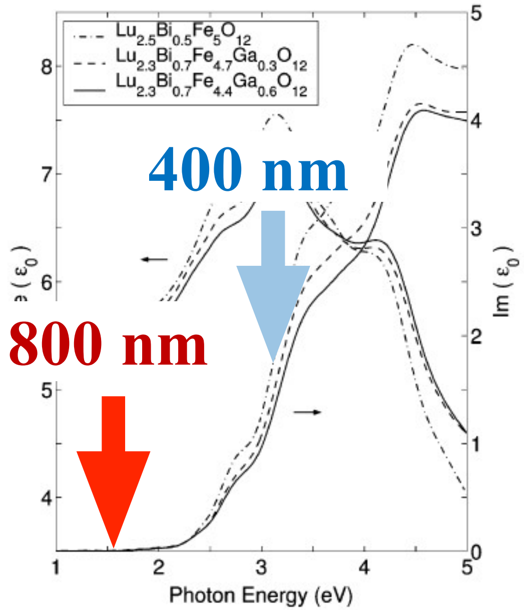


Fluence Dependence of Spin-wave Amplitude

400 nm (3.1 eV) **800 nm** (1.6 eV)



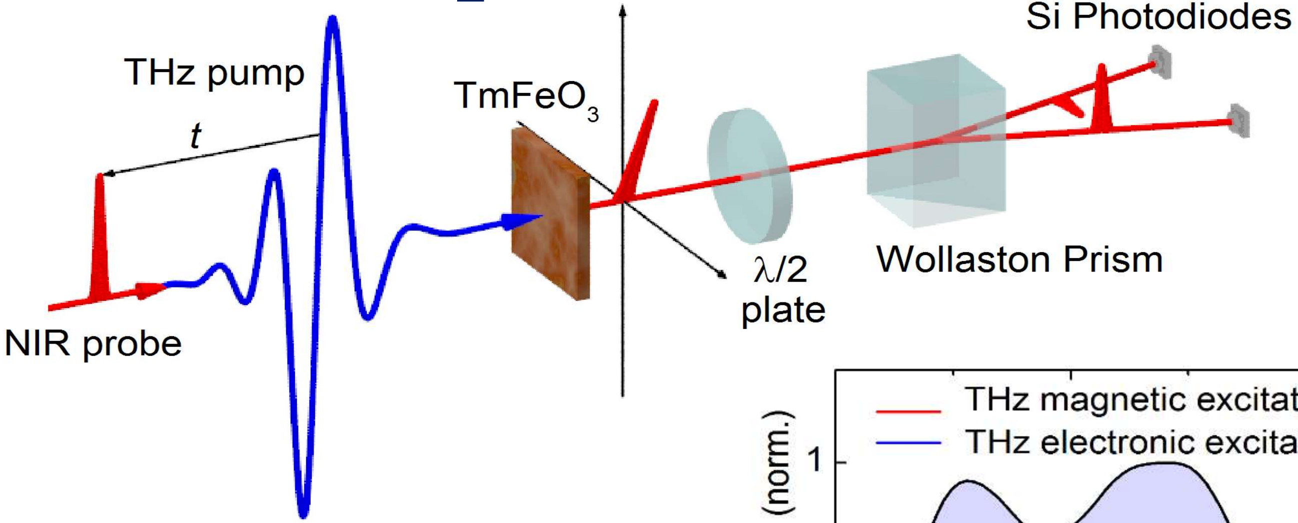
Single photon Two photon

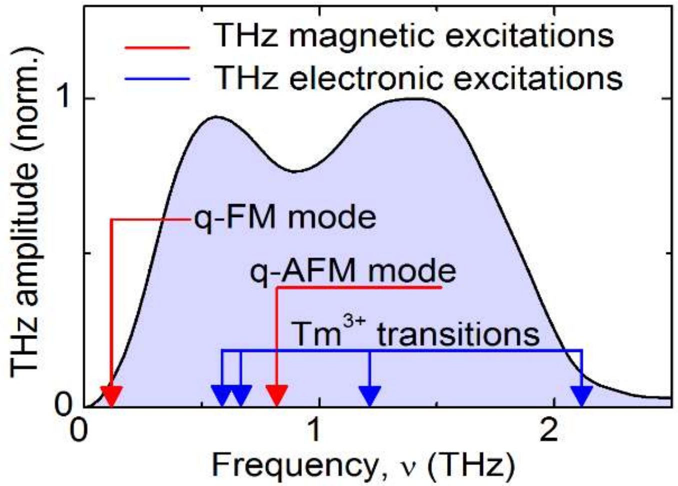


F. Hansteen, *et al.*, Thin Solid Films 455-456, 429 (2004).

Optical charge transfer transition near 400 nm (3.1 eV)

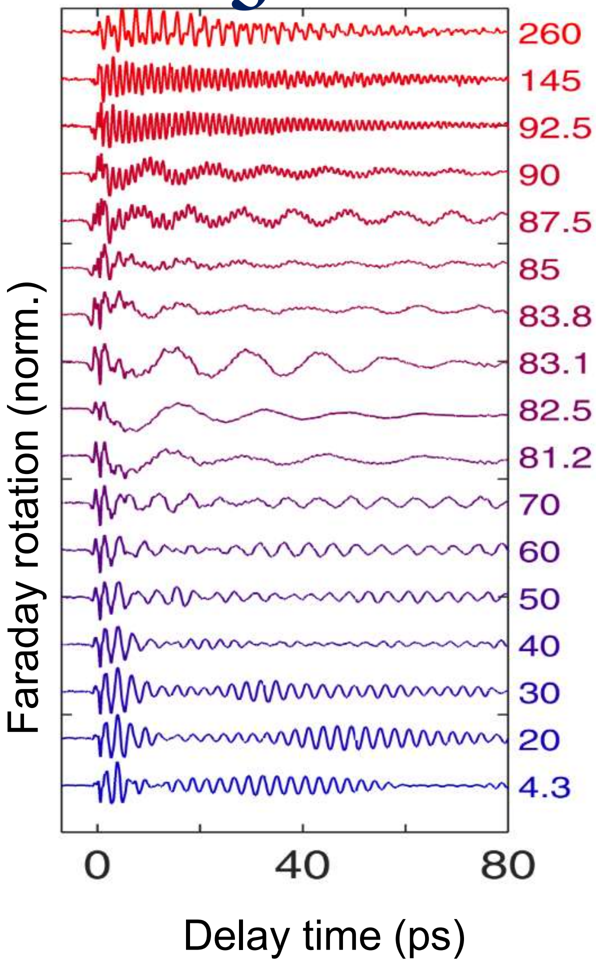
THz excitation of spin waves in $TmFeO_3$

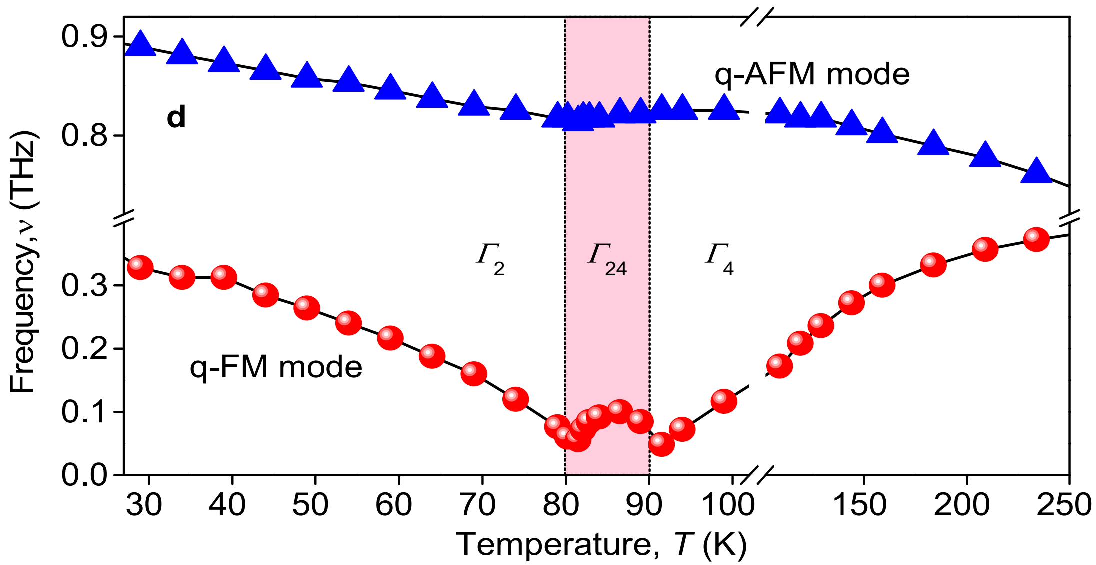




excitation via change in anisotropy

$TmFeO_3$: antiferromagnetic resonance





nature photonics

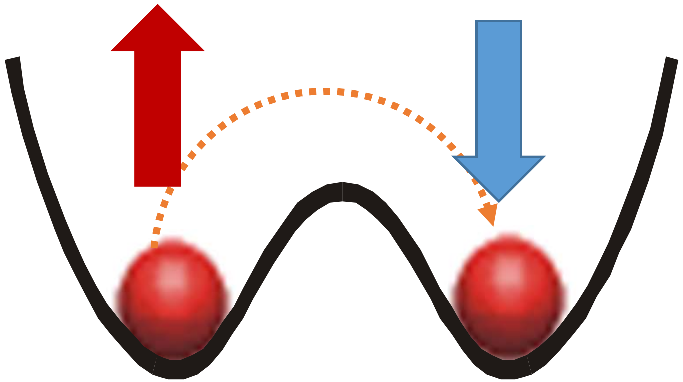
LETTERS

PUBLISHED ONLINE: 3 OCTOBER 2016 | DOI: 10.1038/NPHOTON.2016.181

Nonlinear spin control by terahertz-driven anisotropy fields

S. Baierl[1], M. Hohenleutner[1], T. Kampfrath[2], A. K. Zvezdin[3,4,5], A. V. Kimel[4,6], R. Huber[1]* and R. V. Mikhaylovskiy[6]*

All Optical Switching (AOS) by femtosecond laser pulses:



All-optical Control of Magnetism II

(including pump-probe techniques)

Theo Rasing

Radboud University Nijmegen

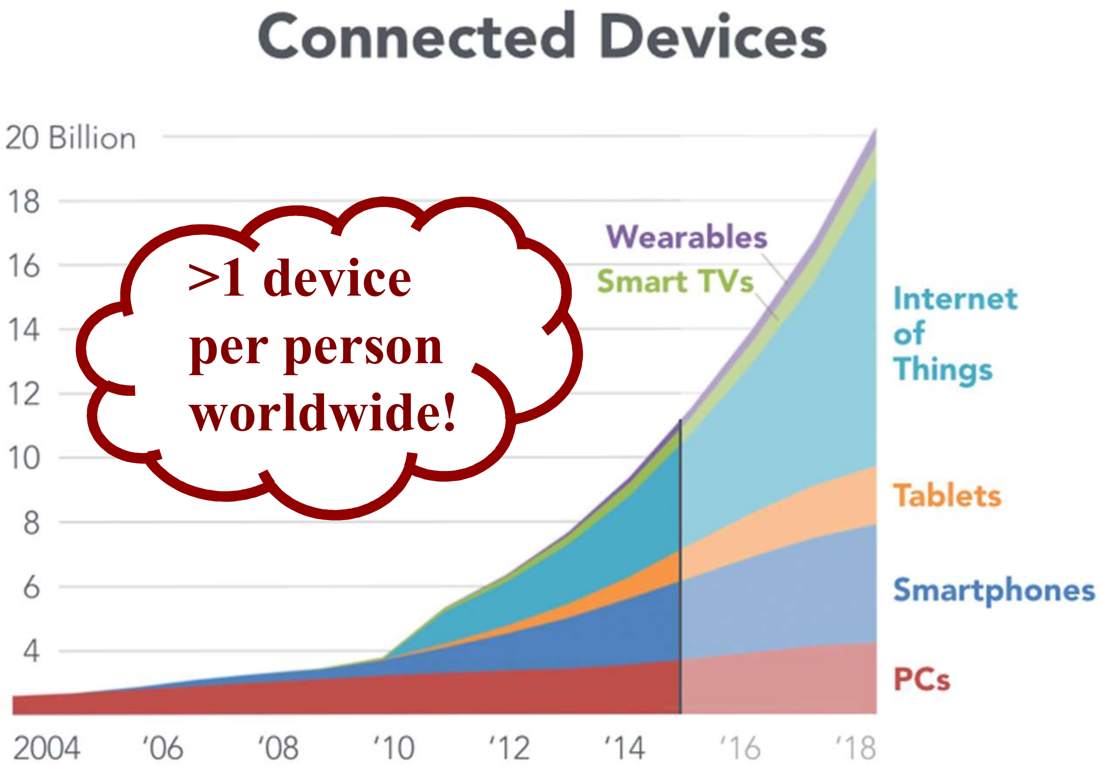
Institute for Molecules and Materials

Changes in society

Happening April 2005

Same Happening March 2013

Changes in society



March 2013

increase FUNCTIONALITY

Lots of data = Lots of energy

Hotel Palacky, Brno, Czech Republic

30 Google Searches =boil 1L water

7% of electricity produced in the world

Google (The Netherlands)

…

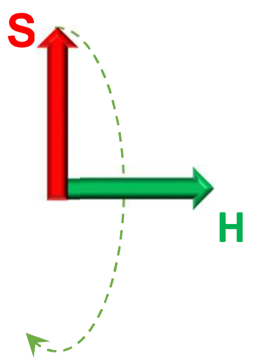
Facebook (Sweden)

~6 billion per day!

AOS by femtosecond laser pulses: *counterintuitive?*

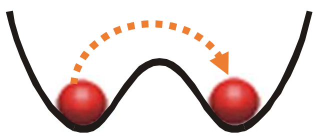
Simple single spin problem

$$\frac{\partial \boldsymbol{S}_i}{dt} = -\gamma \boldsymbol{S}_i \times \mathbf{B}_{\mathbf{eff}} + \frac{\lambda}{(S_i)^2} \boldsymbol{S}_i \times (\boldsymbol{S}_i \times \mathbf{B}_{\mathbf{eff}})$$



Intuitive estimate:

If 100 fs pulse reverses the magnetization, it should act as an effective magnetic field of about 90 Tesla (γ=28 GHz/T)!



Light acts as a magnetic field, which is either strong (>>1 Tesla) or stays long (>>100 fs).

Why?

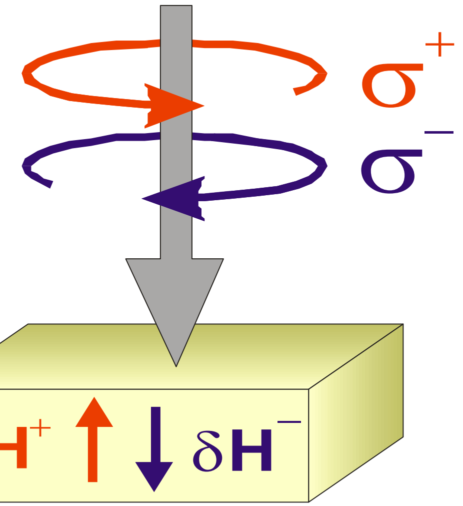
Thermodynamics of laser-matter interaction

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

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

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

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



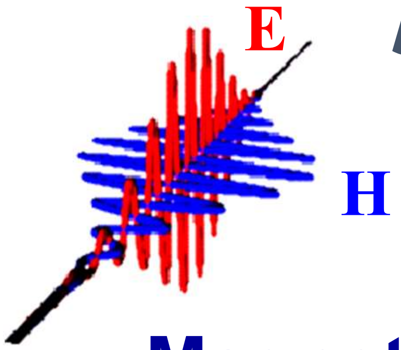
Inverse Faraday effect

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

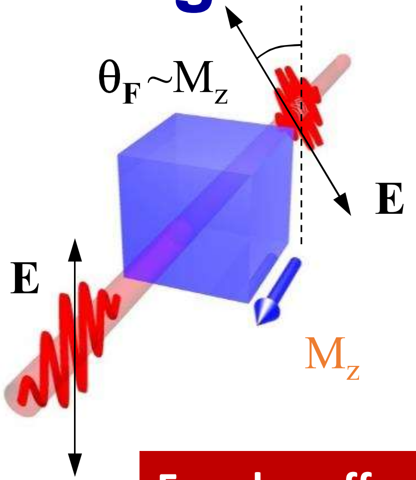
(see further lecture on Magneto Optics by Prof. Schaefer)

Magneto-optics and Opto-magnetism

both result from spin-orbit interaction!



Magneto-optics



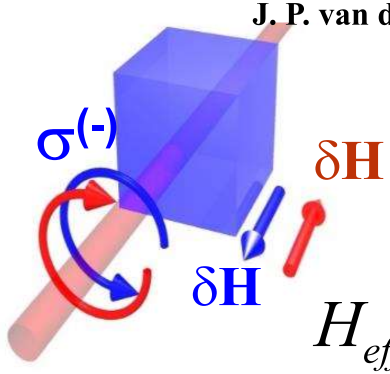
Faraday effect

$$\frac{\partial \varepsilon}{\partial M} = \alpha$$

$$\theta_F = \pi \frac{L}{\lambda} \frac{\alpha M}{\sqrt{\varepsilon}}$$

Opto-magnetism

L. P . Pitaevskii, Sov. Phys. JETP 12, 1008 (1961).
J. P. van der Ziel et al, Phys. Rev. Lett. 15,190 (1965).

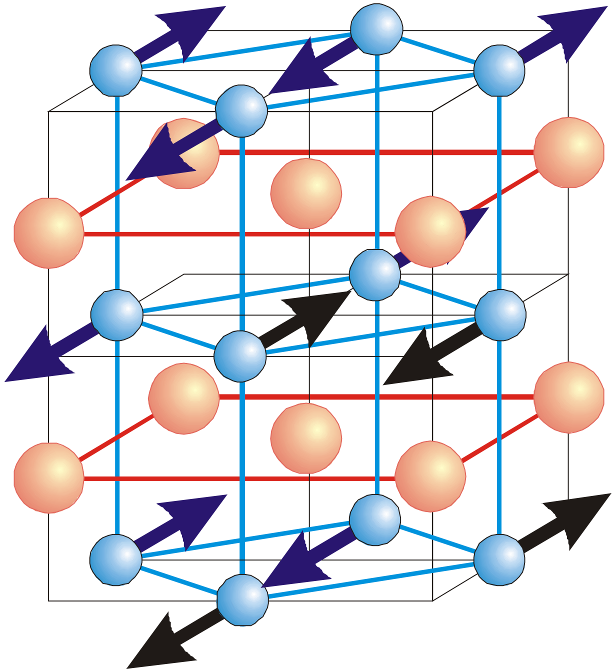


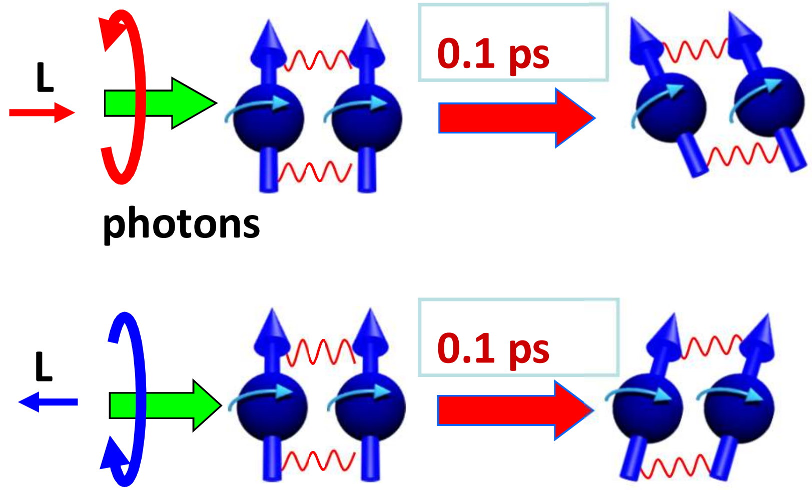
$$H_{eff}(0) = \alpha \frac{\varepsilon_0}{\mu_0} E(\omega) E^*(\omega)$$

Inverse Faraday effect

Ultrafast excitation of spins via IFE in $DyFeO_3$

(all-optical spin resonance)

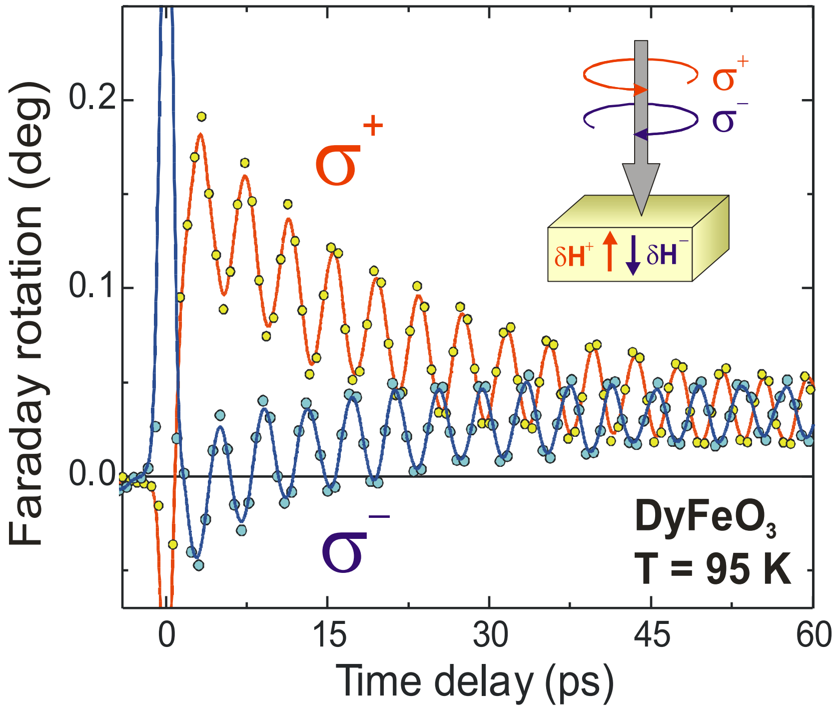


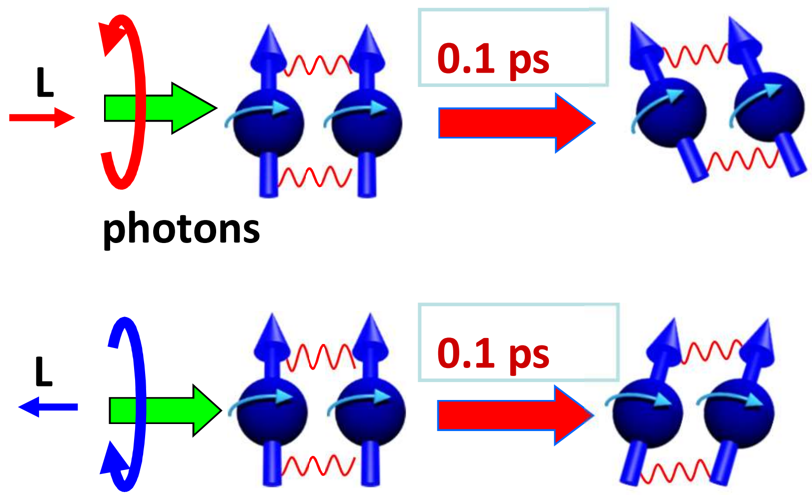


A.V. Kimel, A. Kirilyuk, P.A. Usachev, R.V. Pisarev, A.M. Balbashov, and Th. Rasing, **Nature 435**, 655-657 (2005)

Ultrafast excitation of spins via IFE in $DyFeO_3$

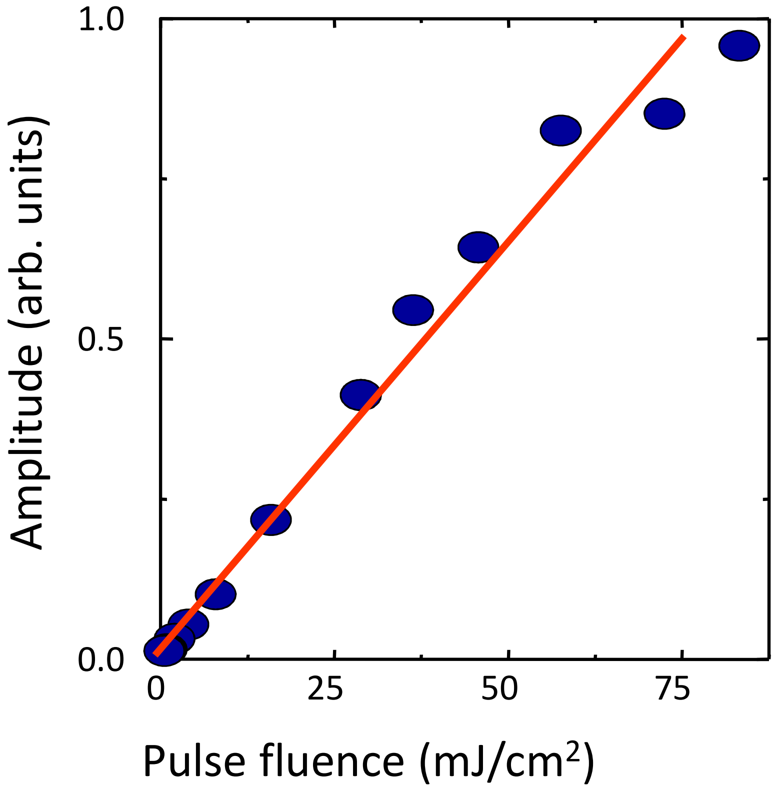
(all-optical spin resonance)





A.V. Kimel, A. Kirilyuk, P.A. Usachev, R.V. Pisarev, A.M. Balbashov, and Th. Rasing, **Nature 435**, 655-657 (2005)

Amplitude of the laser-induced spin-waves



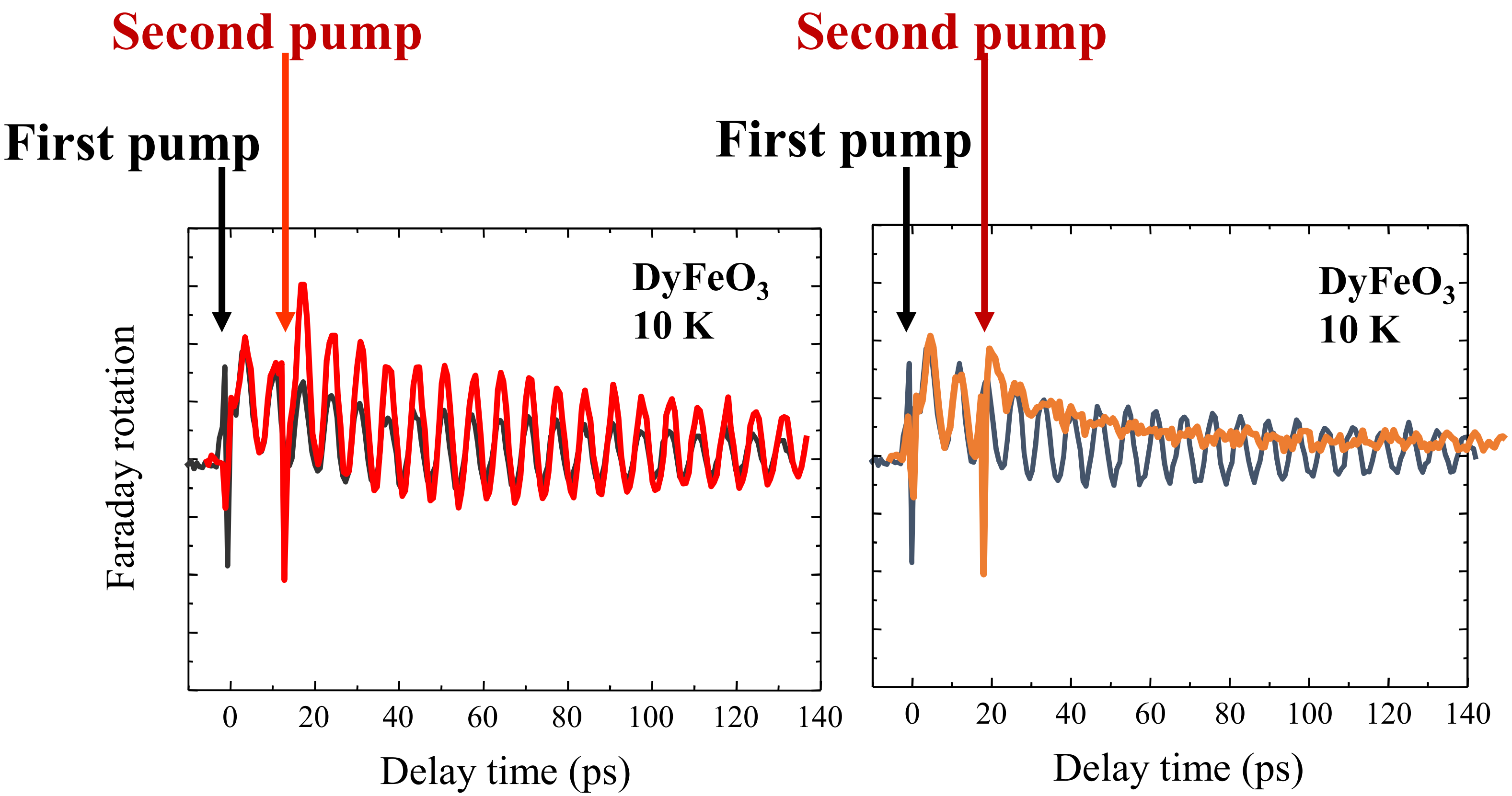
Inverse Faraday effect

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

Fields up to 5 T!
(even up to 20 T!)

Controlling ?

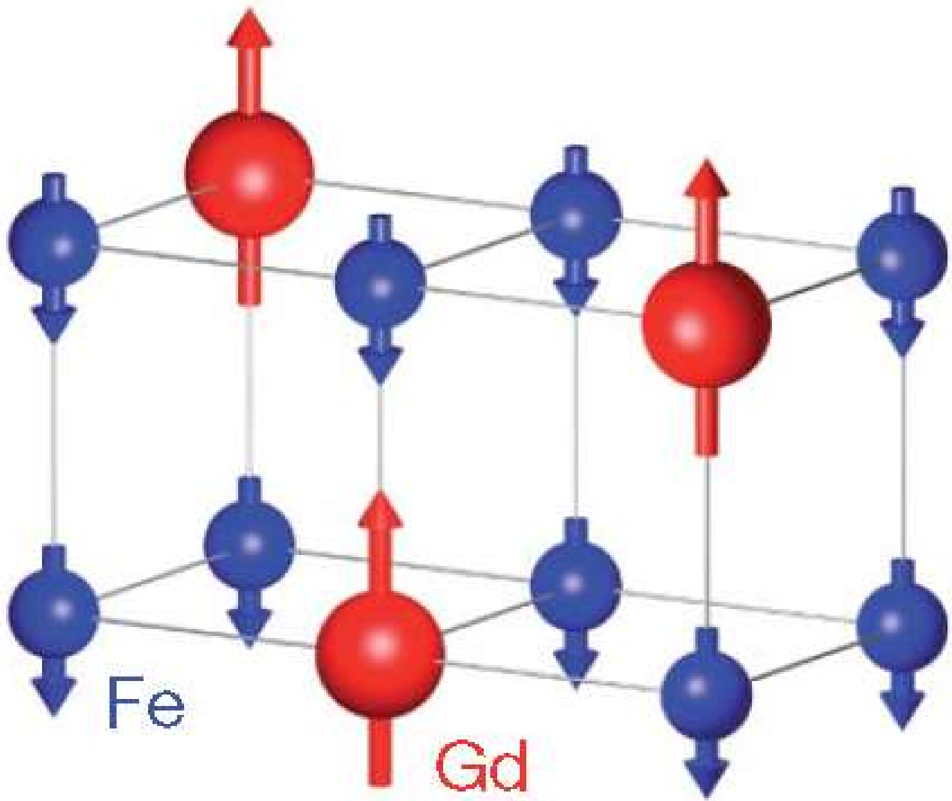
Double pump coherent control



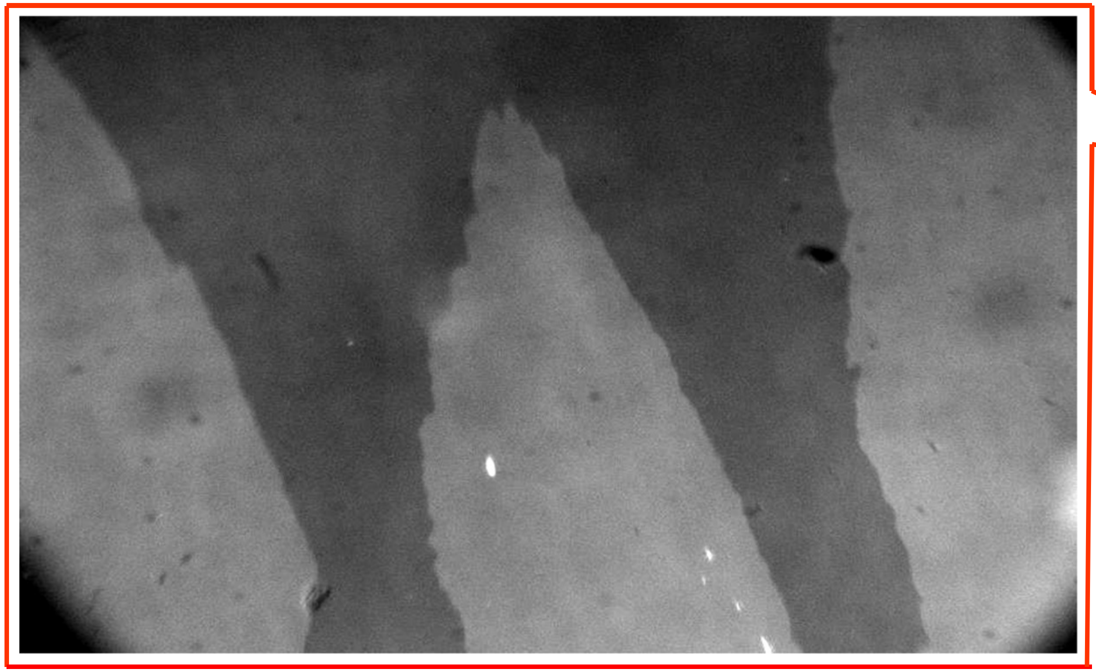
AOS of Ferrimagnetic Metals

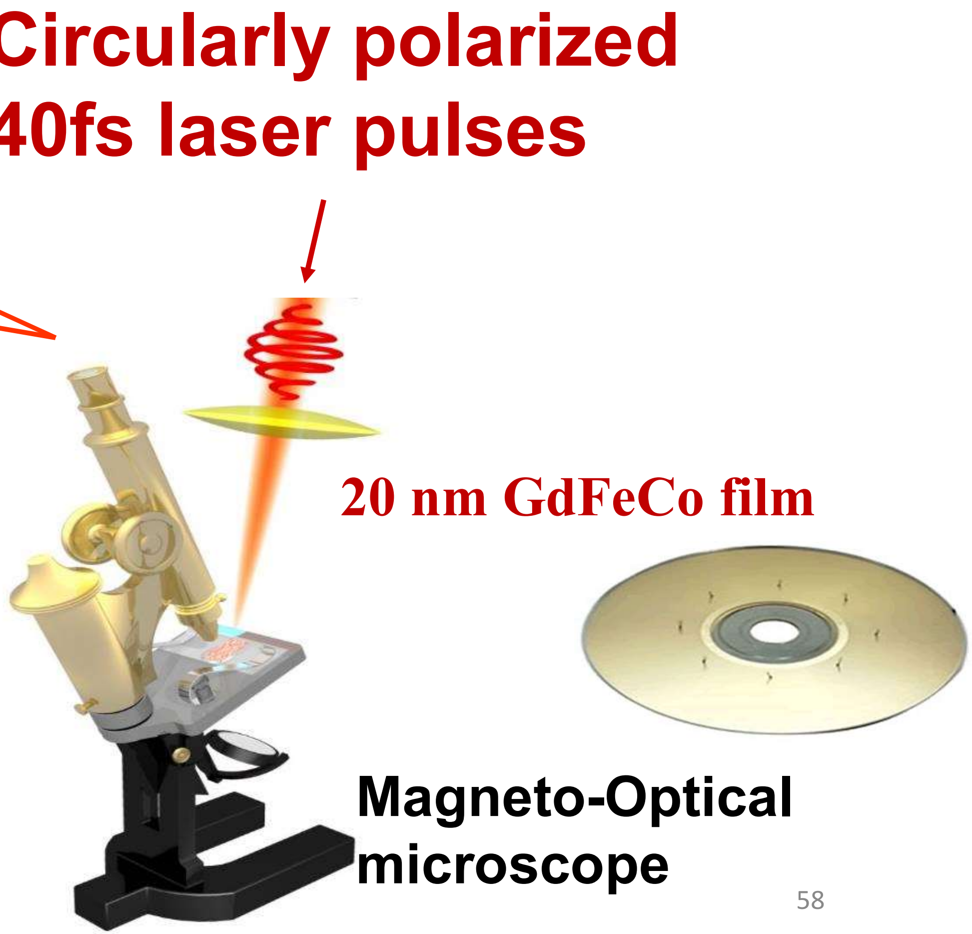
Femtosecond laser reversal of magnetization?

GdFeCo

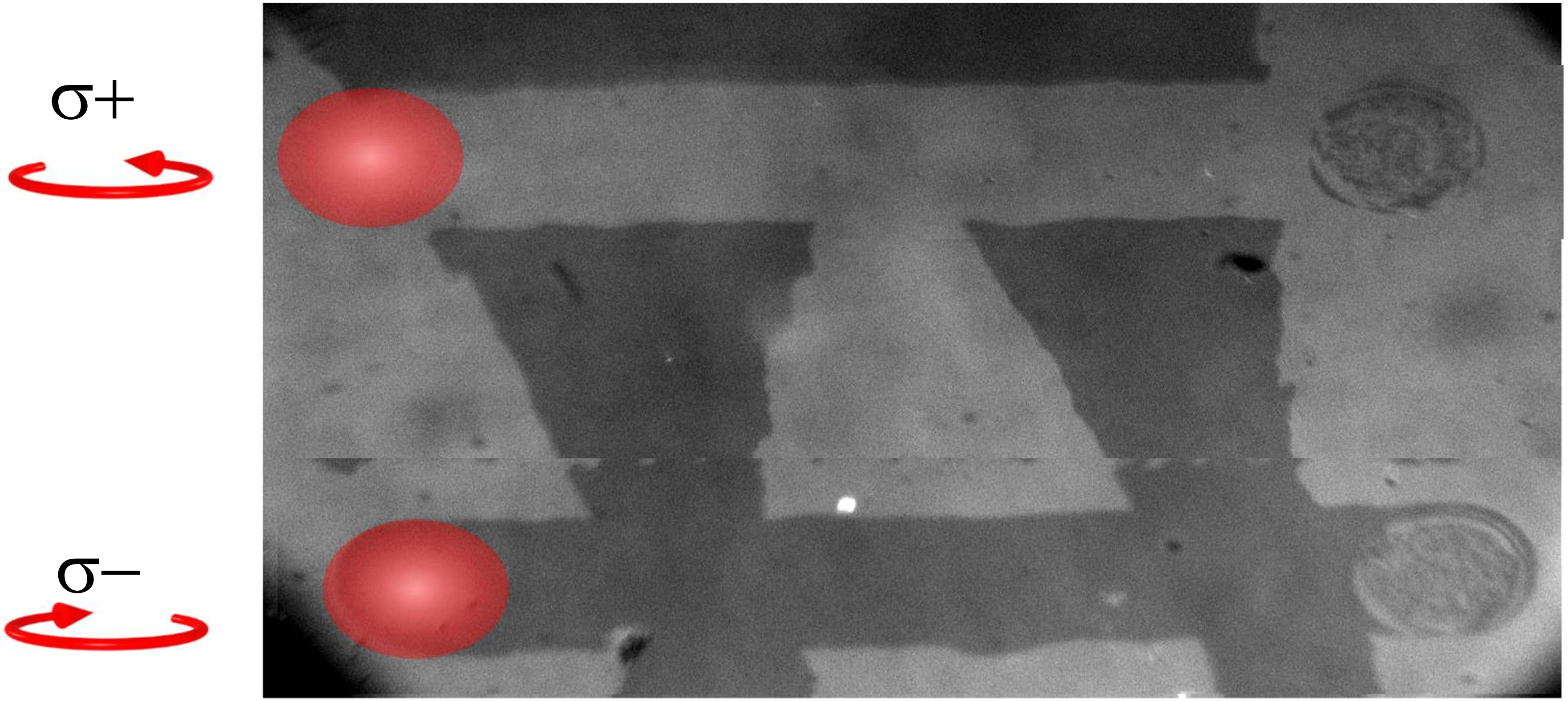


Polarization microscope + pulsed laser





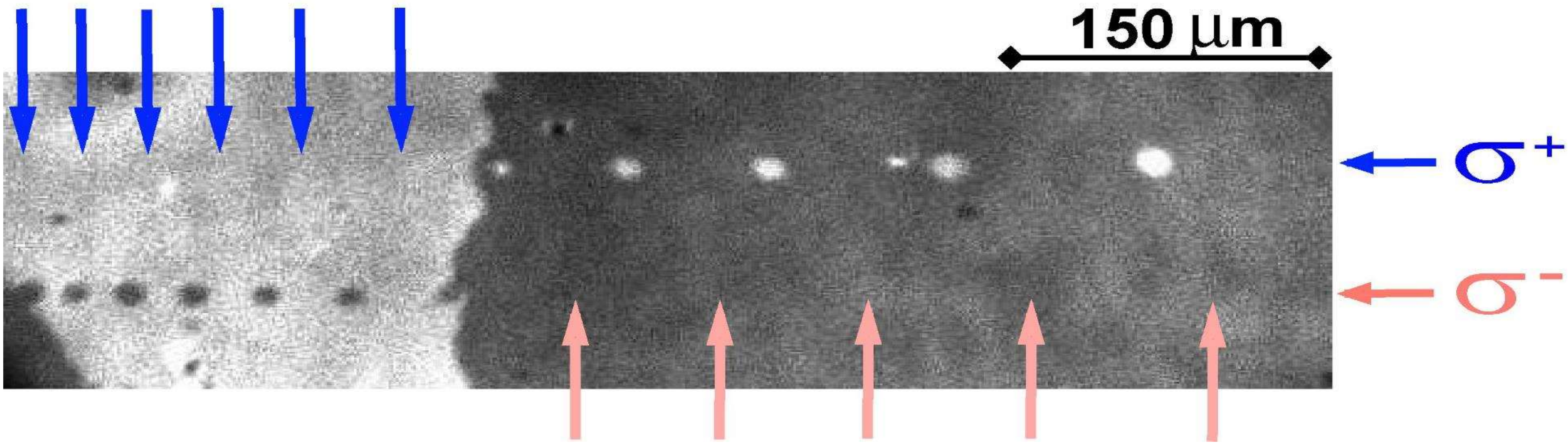
40 fs pulses, 1 kHz **GdFeCo** $H_{ext} = 0$



Reversal by 40fs laser pulsen!

switching of magnetization by single pulse!

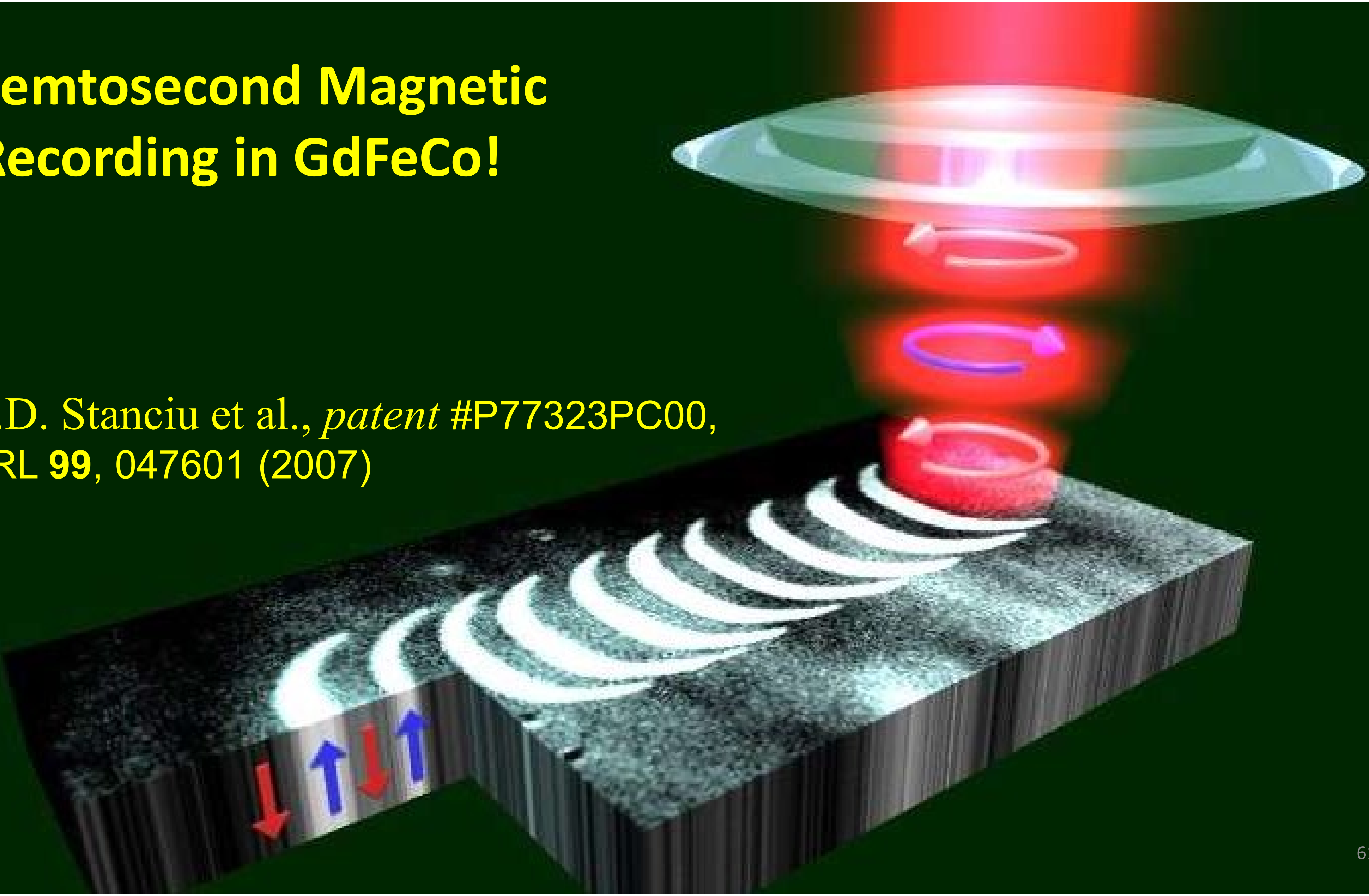
Sweeping the pulsed laser beam at high speed across the sample



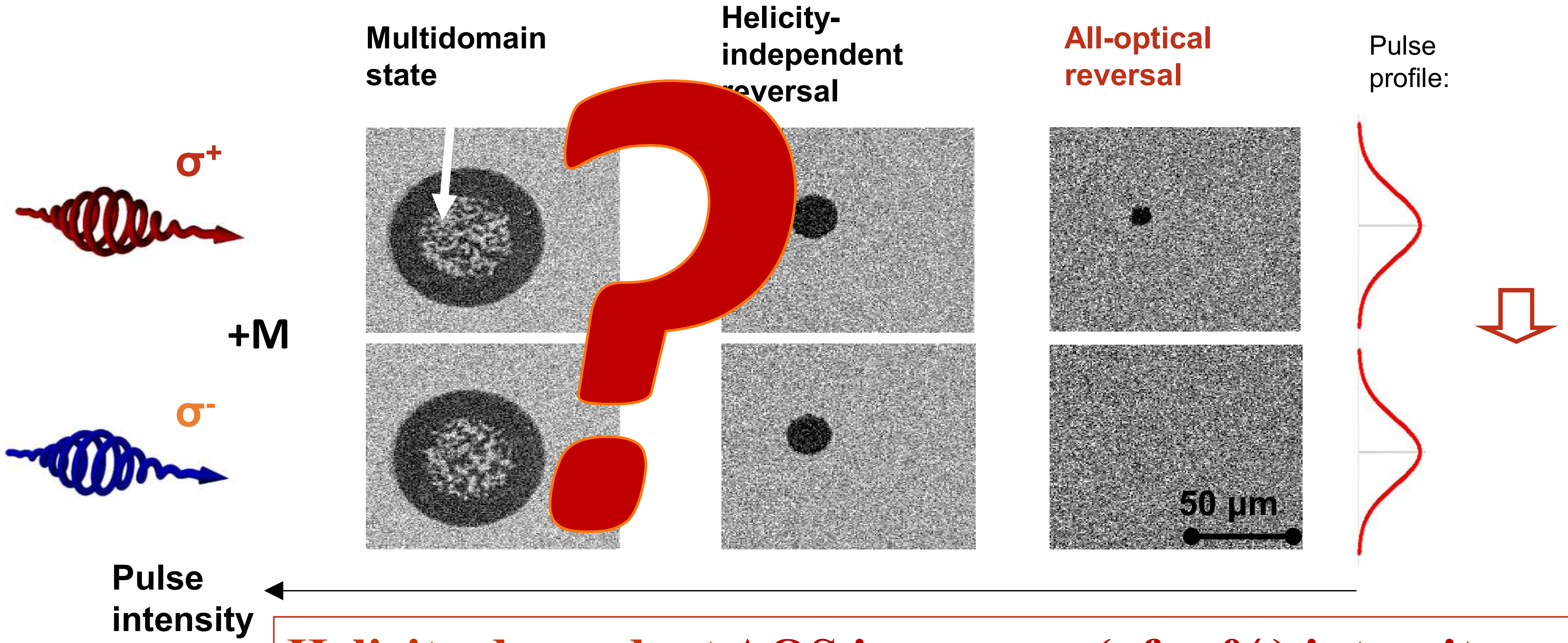
C.D. Stanciu et al., PRL 99,047601 (2007)

Femtosecond Magnetic Recording in GdFeCo!

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



AOS: role of light helicity/intensity



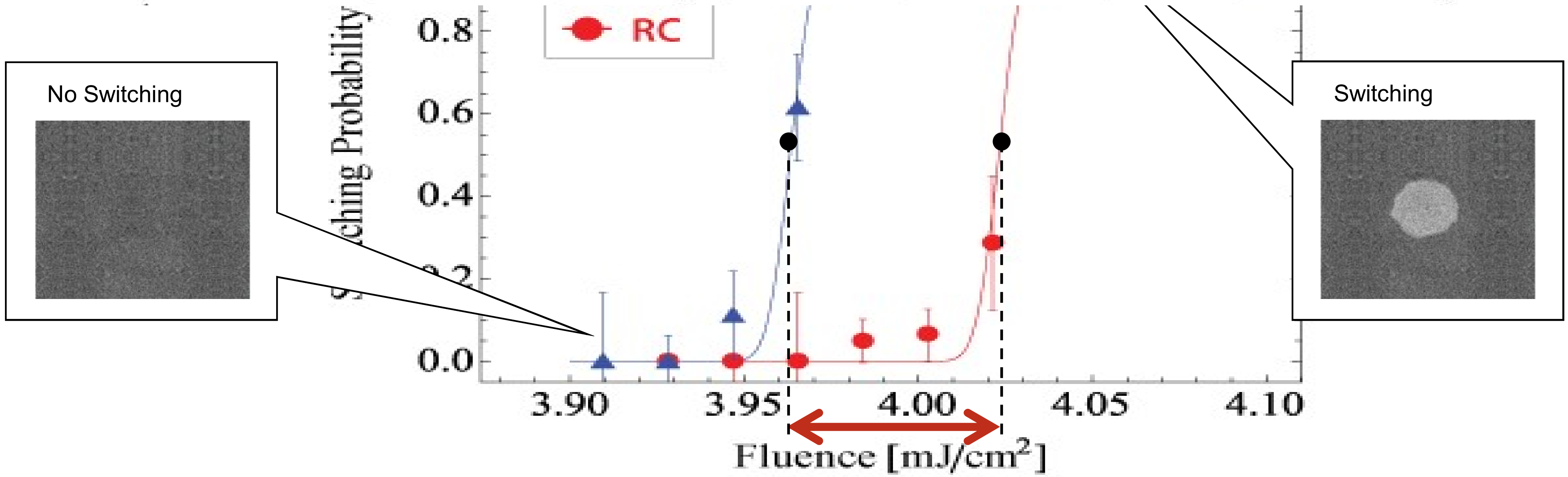
Helicity dependent AOS in narrow (~few%) intensity range

PRL 108, 127205 (2012) PHYSICAL REVIEW LETTERS week ending 23 MARCH 2012

Exci

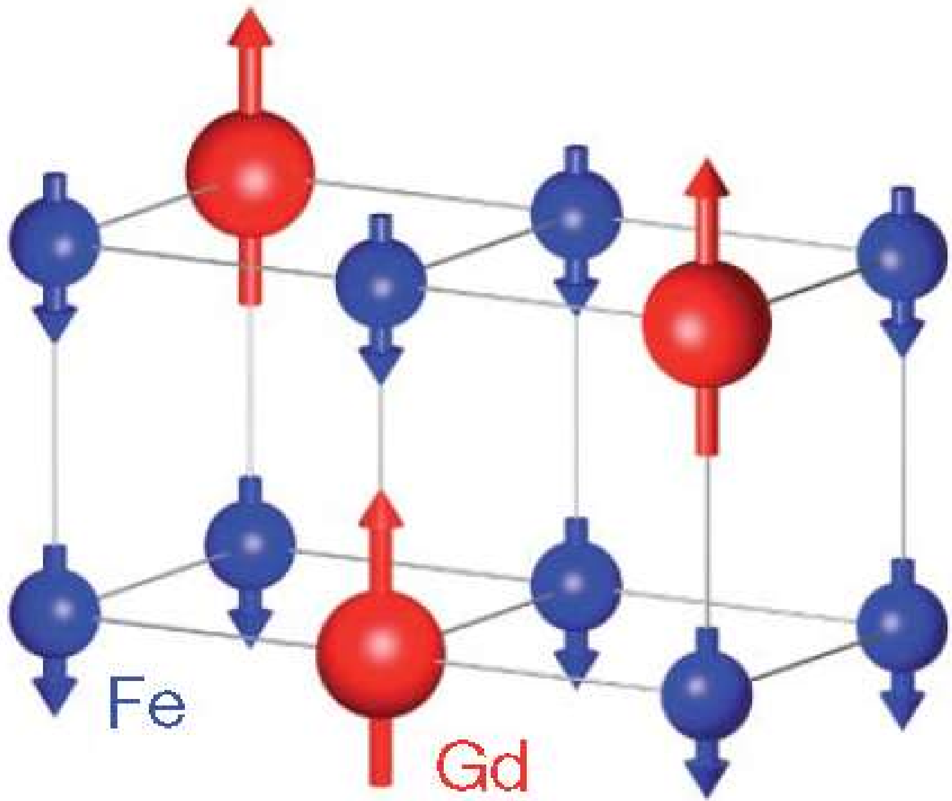
Role of Magnetic Circular Dichroism in All-Optical Magnetic Recording

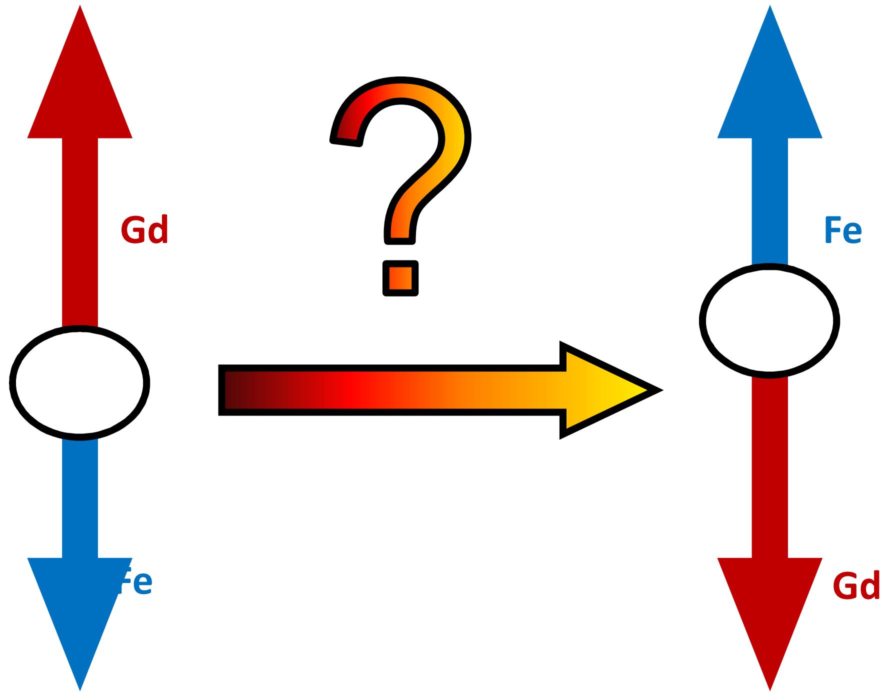
A. R. Khorsand,[1,*] M. Savoini,[1] A. Kirilyuk,[1] A. V. Kimel,[1] A. Tsukamoto,[2,3] A. Itoh,[2] and Th. Rasing[1]



Size of window is 1.5%.
Exactly equal to difference in absorption!

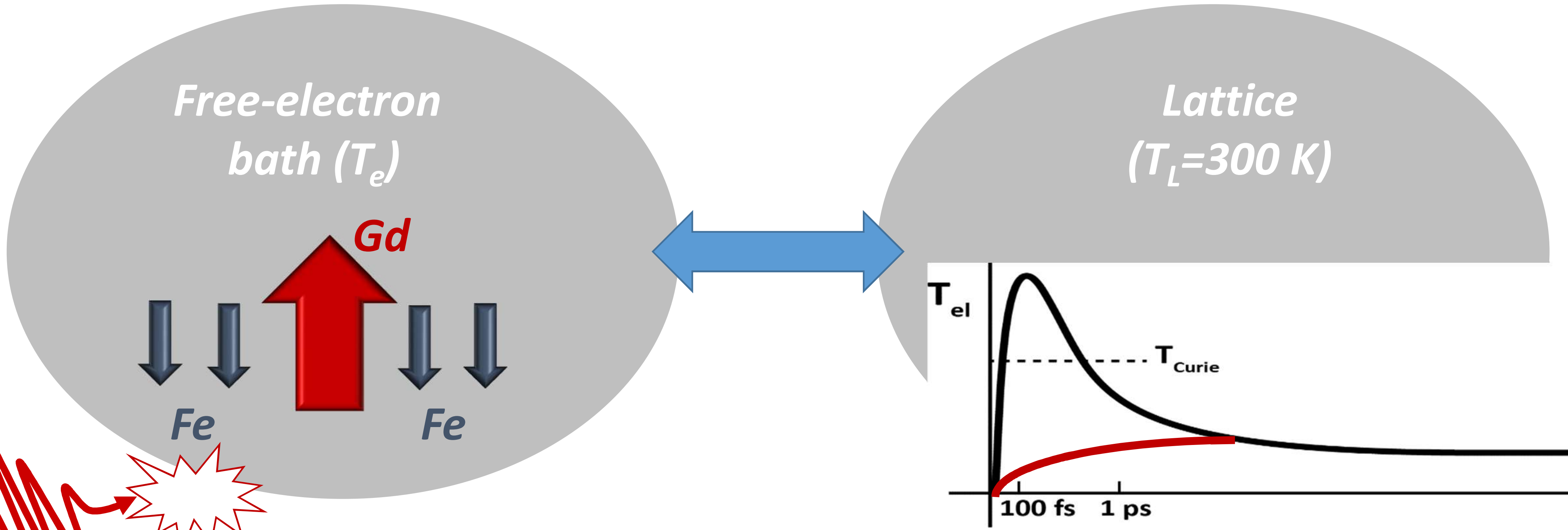
Femtosecond laser reversal: role of exchange?

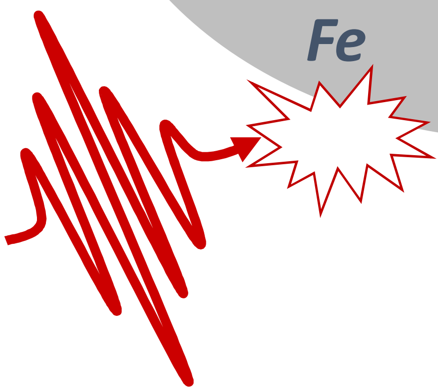




$J_{Fe\text{-}Gd} \sim$ 30-50T

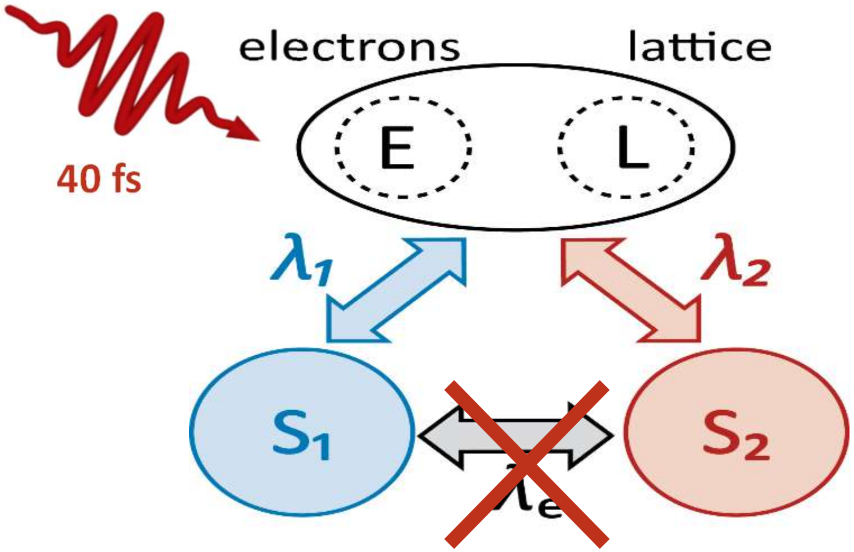
2-Temperature model





2-afm coupled sublattices!

Temperature dominated: *T >> T*$_{Curie}$*~100 fs*



Bloch relaxation

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

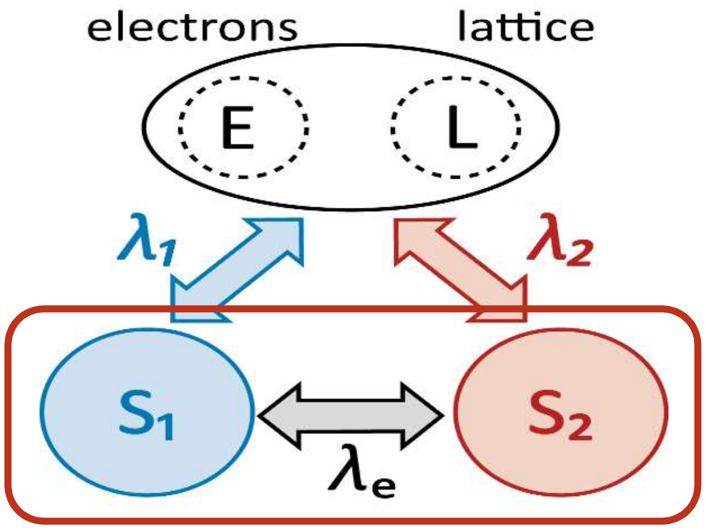
$$\tau_i = \mu_i/(2\alpha_i \gamma k_B T)$$

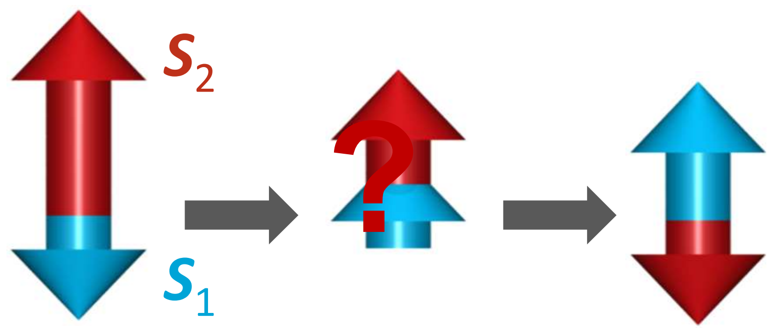
Dynamics scales with magnetic moment

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

Distinct dynamics of sublattices!

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



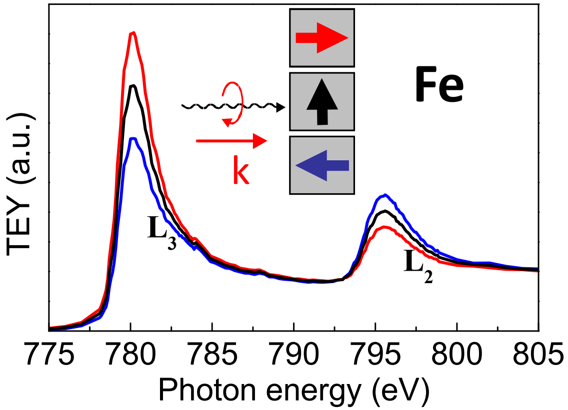


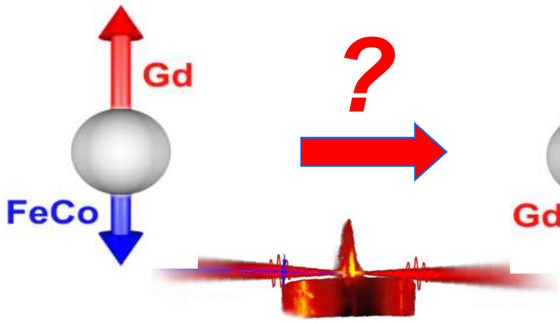
$$dS_1/dt = -dS_2/dt$$

Conservation total angular momentum

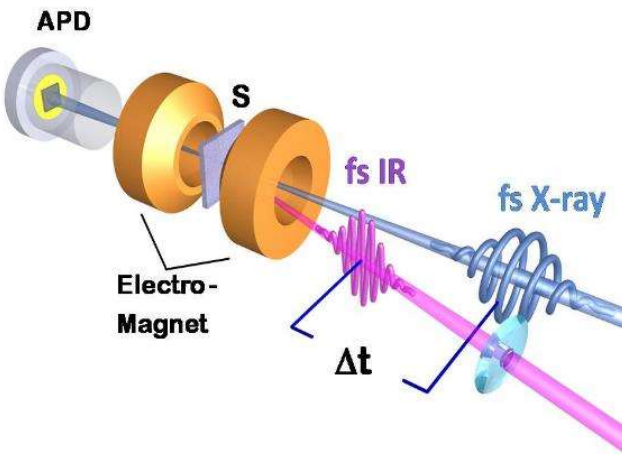
Ground state AFM, transient FM!

How to probe?
Element specific view: XMCD!





fs-Laser pump – X-ray probe



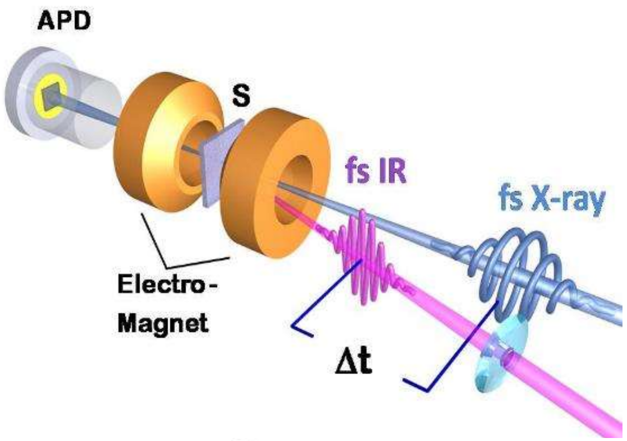
BESSY II

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

(for more details: see lecture Prof. Luning)

Femtosecond-XMCD!

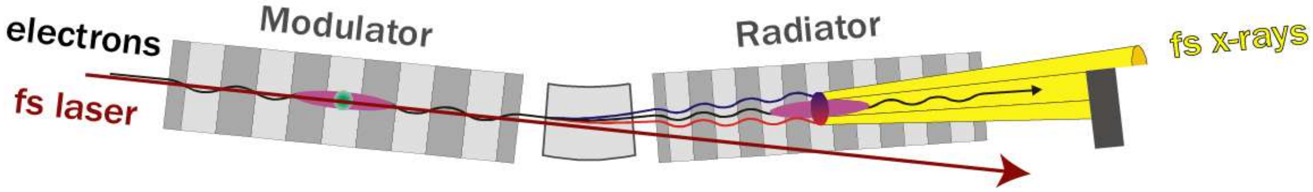
fs-Laser pump – X-ray probe



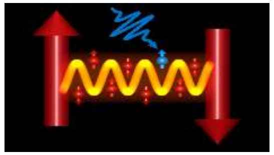
BESSY II

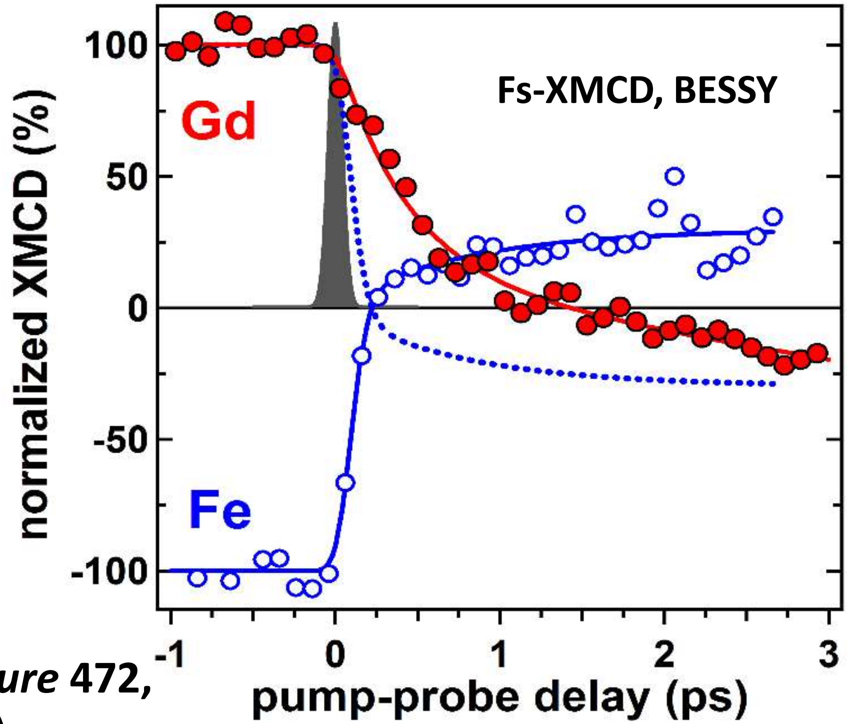
FEMTO-SLICING!

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

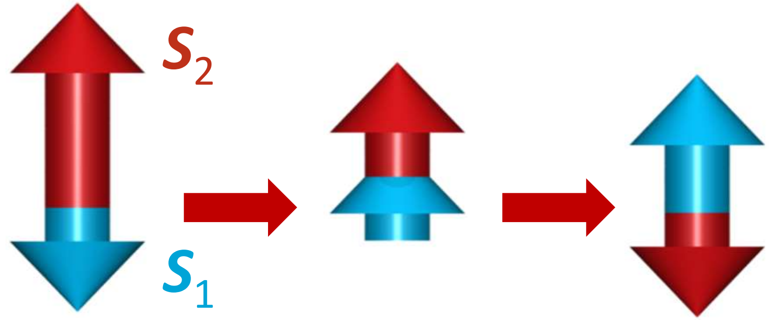


Laser heat induced magnetization reversal!





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



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

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

J.H. Mentink et al., PRL 057202, 2012

reversal of magnetization driven by exchange!!!

Ultrafast electrical pulse reverses magnetization!

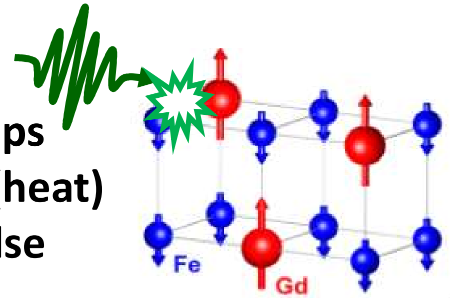
SCIENCE ADVANCES | RESEARCH ARTICLE

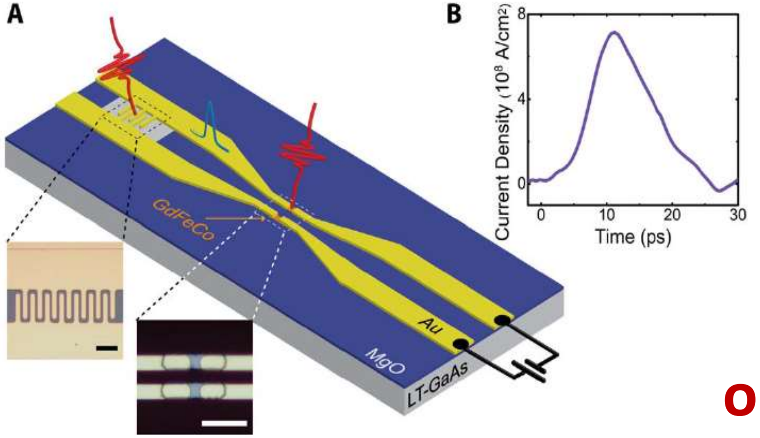
PHYSICS

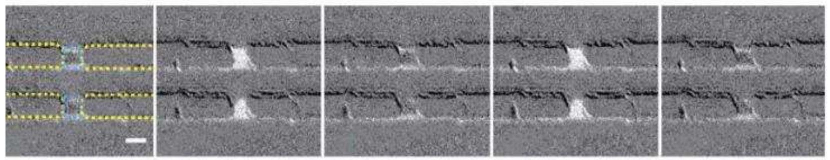
Ultrafast magnetization reversal by picosecond electrical pulses

Yang Yang,[1*†] Richard B. Wilson,[2*†] Jon Gorchon,[3,4*] Charles-Henri Lambert,[3] Sayeef Salahuddin,[3,4] Jeffrey Bokor[3,4†]

10 ps
laser (heat)
pulse



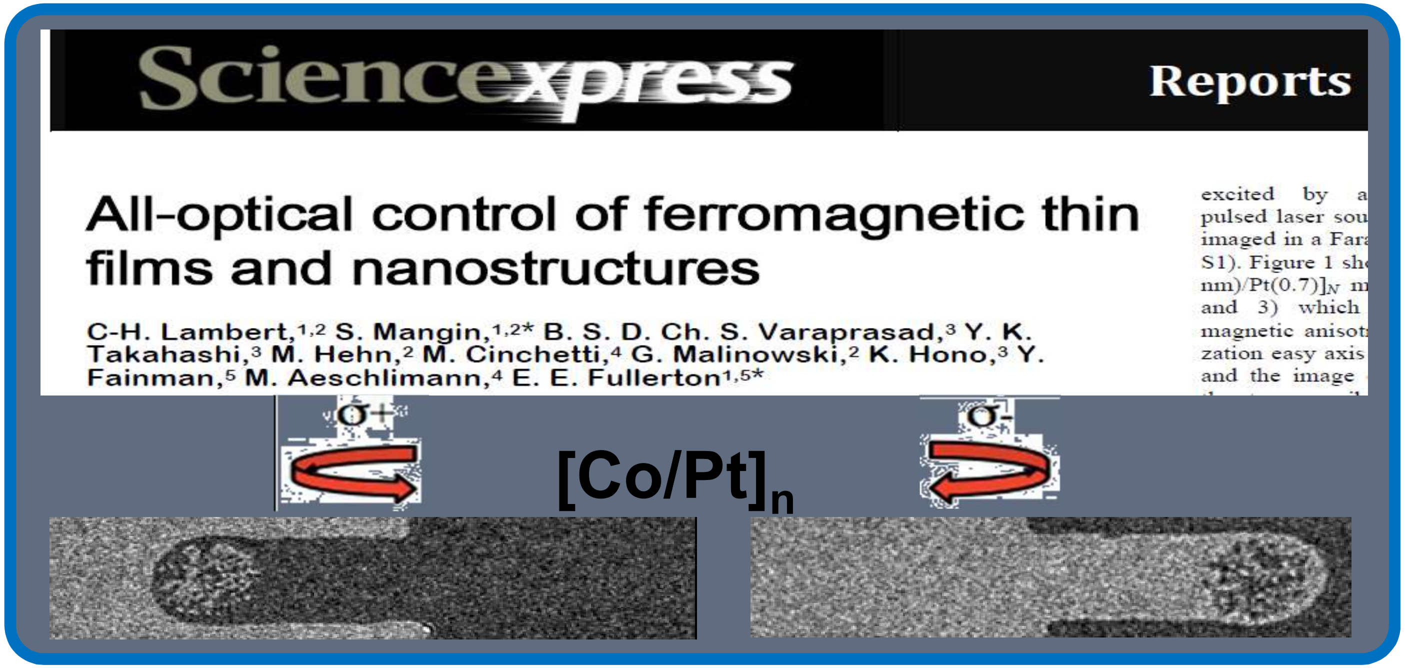




No hot, spin polarized
or spin-orbit coupled electrons!

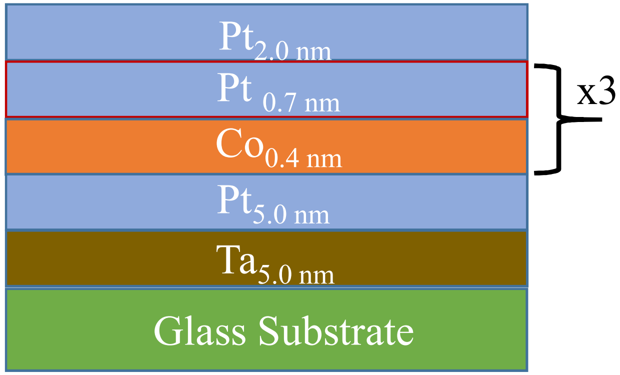
AOS of Ferromagnets

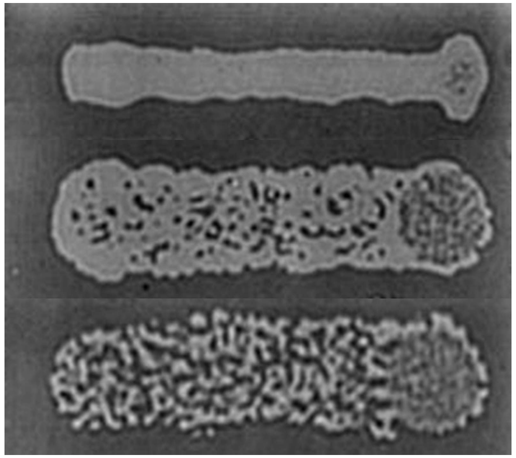
AOS of ferromagnetic CoPt (FePt)?



What's the mechanism?

HD-AOS in Co/Pt multilayer

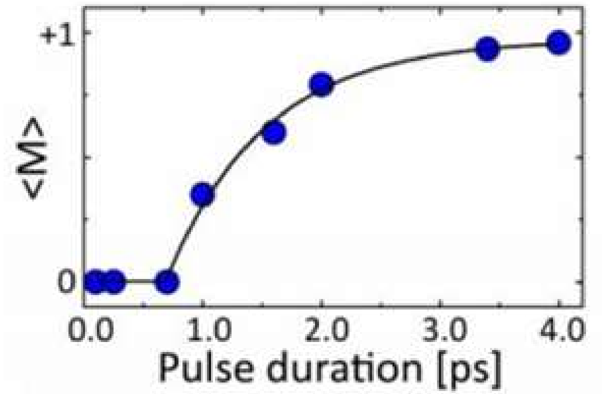


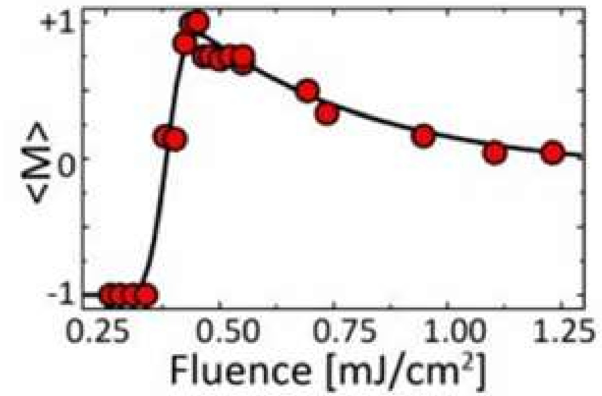


2.2 ps

1.6 ps

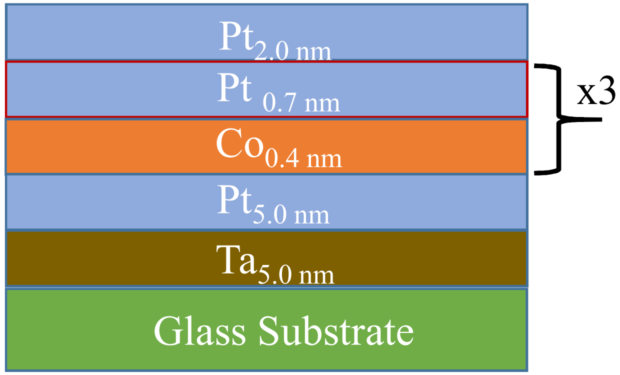
0.1 ps

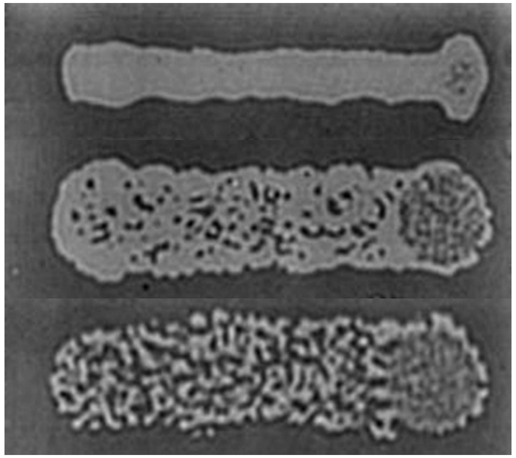




Y. Tsema et al, APL 2016, R. Medapalli et. al., Phys. Rev. B 96, 224421 (2017).

HD-AOS in Co/Pt multilayer

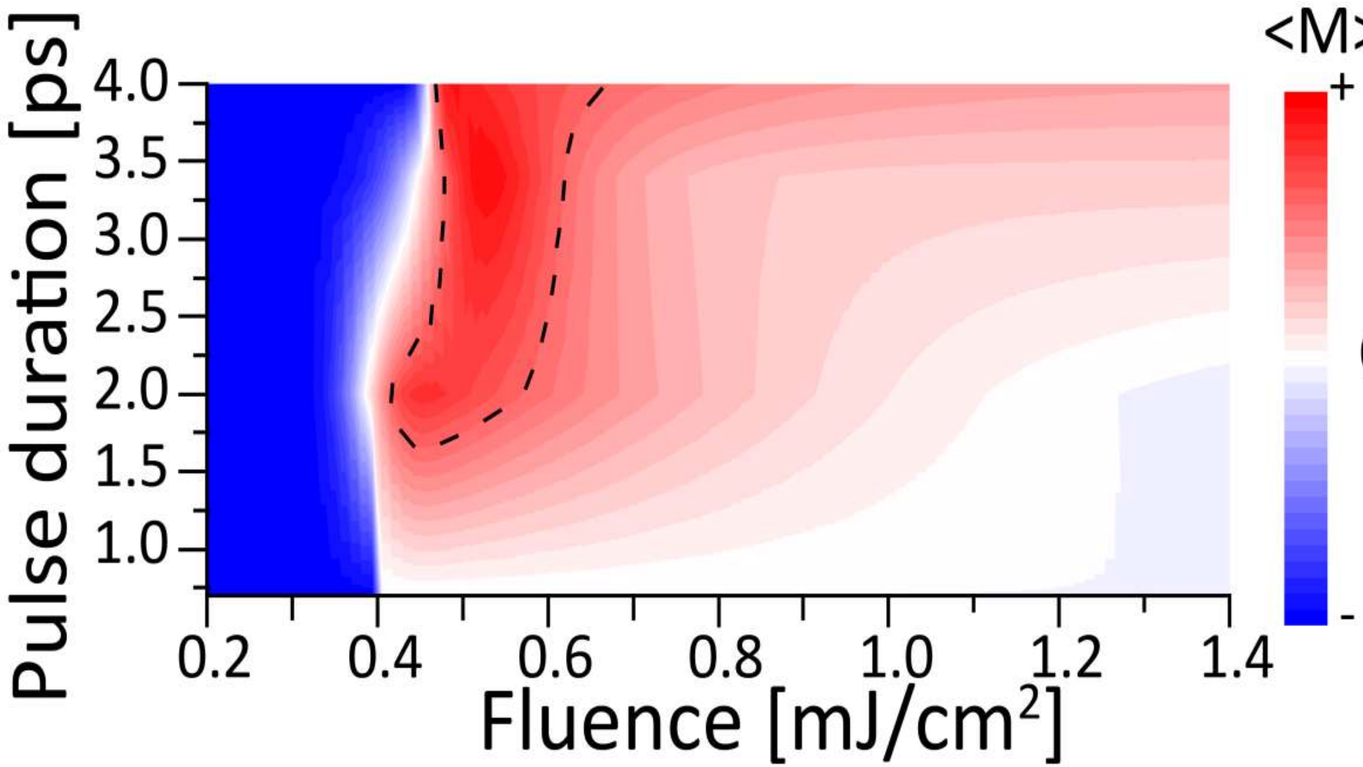




2.2 ps

1.6 ps

0.1 ps

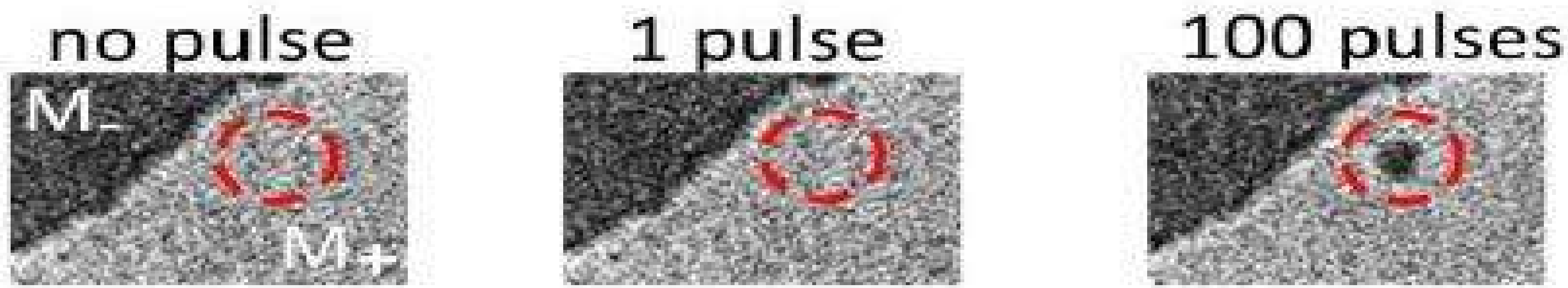


Y. Tsema et al, APL 2016, R. Medapalli et. al., Phys. Rev. B 96, 224421 (2017).

HD-AOS in CoPt: fs single-shot imaging

Mechanism of all-optical control of ferromagnetic multilayers with circularly polarized light

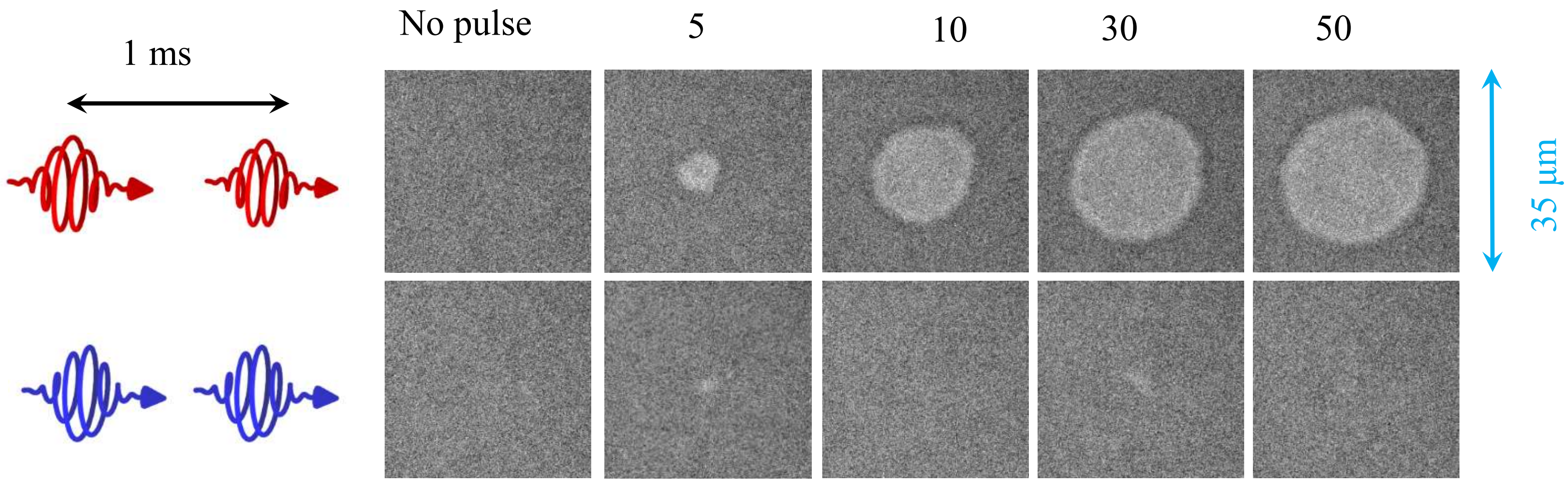
R. Medapalli,[1,*] D. Afanasiev,[2] D. K. Kim,[1] Y. Quessab,[1,3] S. Manna,[1] S. A. Montoya,[1] A. Kirilyuk,[2] Th. Rasing,[2] A. V. Kimel,[2] and E. E. Fullerton[1]



1) No single shot switching
2) Stochastic + deterministic
3) ~100 pulses

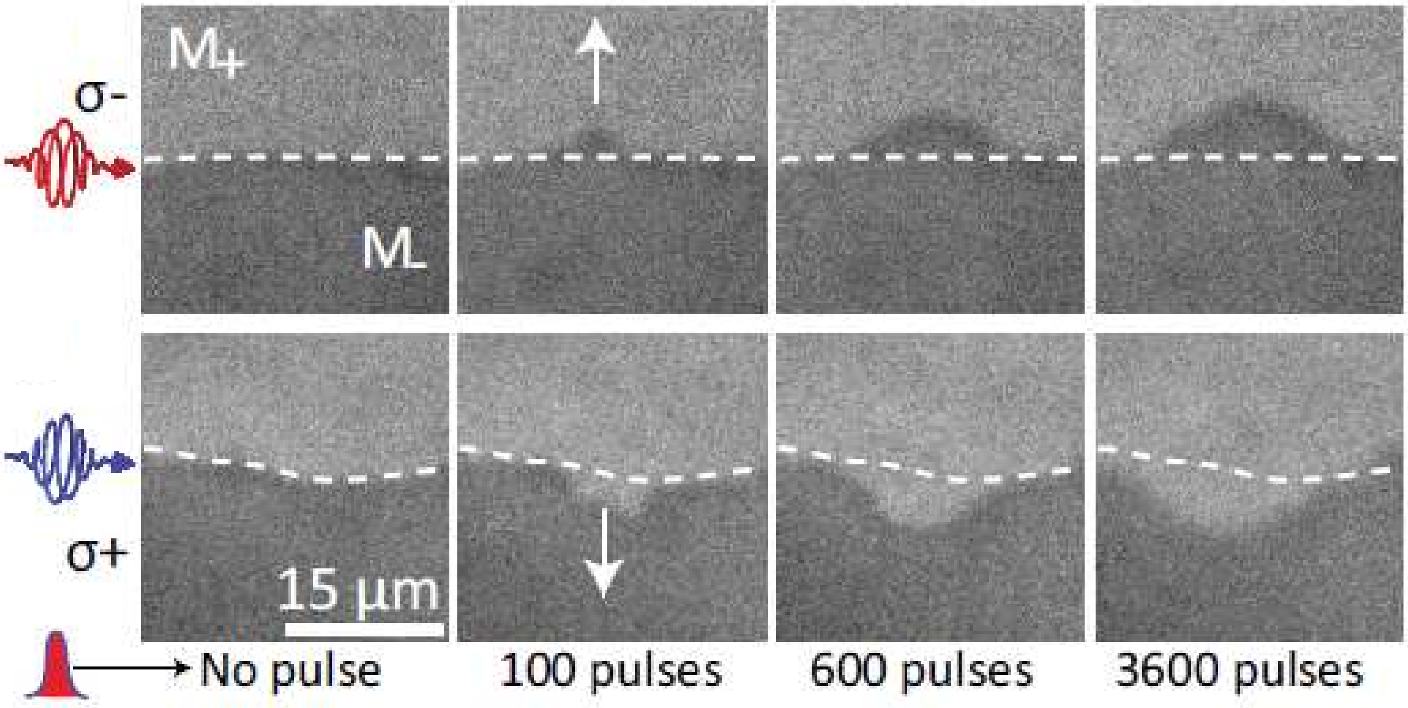
MECHANISM?

Multi-pulse induced HD-AOS



Stochastic nucleation & growth!!!

Deterministic displacement of domain walls



2 nm/pulse @ 0.4mJ/cm^2 takes many pulses!

R. Medapalli *et. al*., arXiv: 1607.02505, PRB 96, 224421 (2017).

HD-AOS in CoPt: mechanism

Magnetic recording in Co/Pt requires multiple pulses.

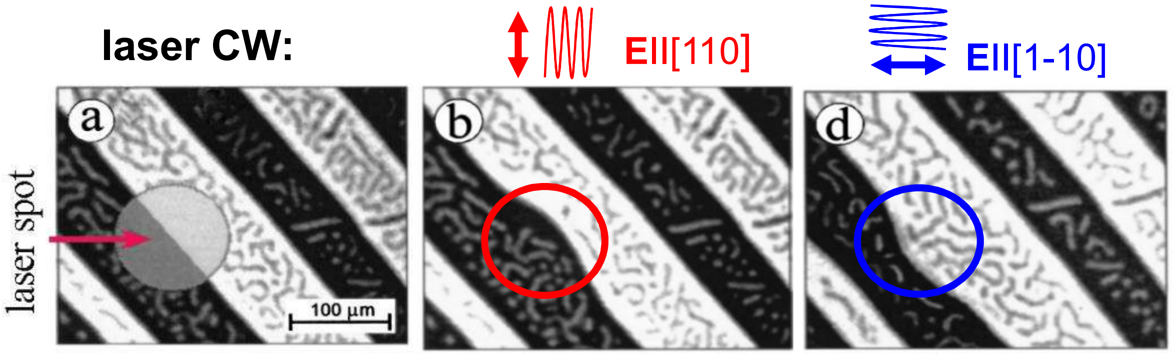
The first pulses form (stochastically) domains with reversed magnetization.

The following pulses cause helicity dependent domain wall motion.

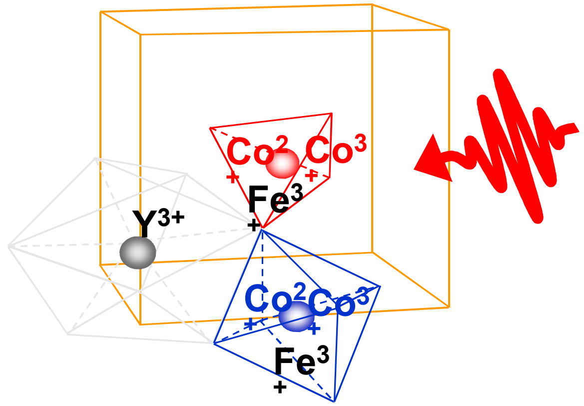
AOS of Dielectrics

Photo-magnetism of Co-substituted iron garnet

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



Light-induced slow (~µm/sec) motion of domain wall



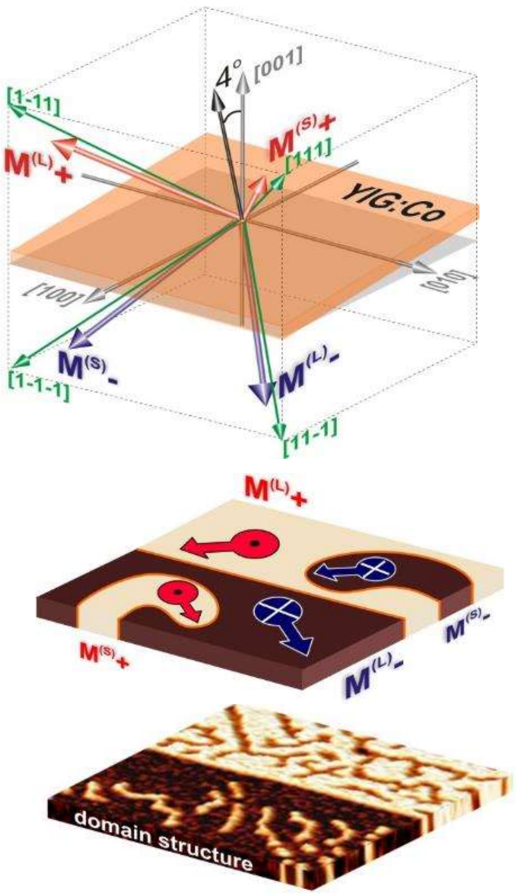
A.Chizhik et al. *PRB*, 57 (1998).

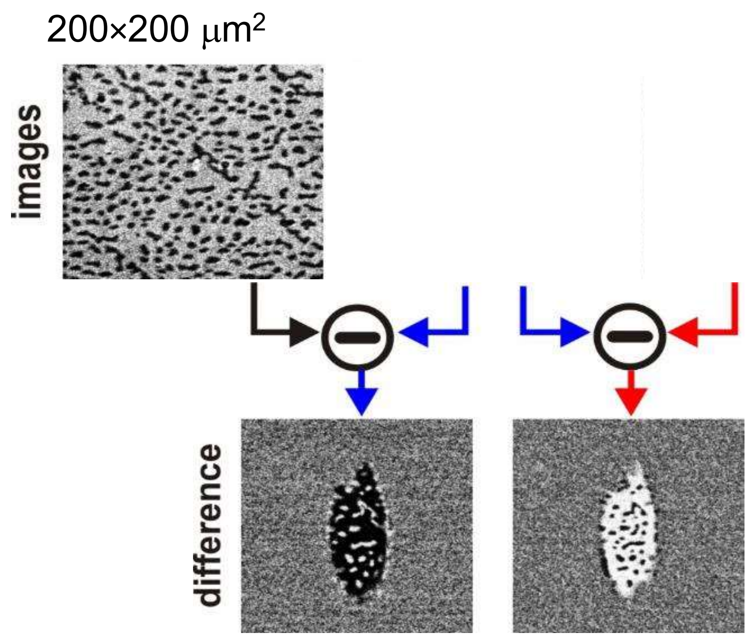
A.Stupakiewicz et al. *PRB*, 64 (2001).

Recording?
Heating?
Speed?

AOS in iron garnet

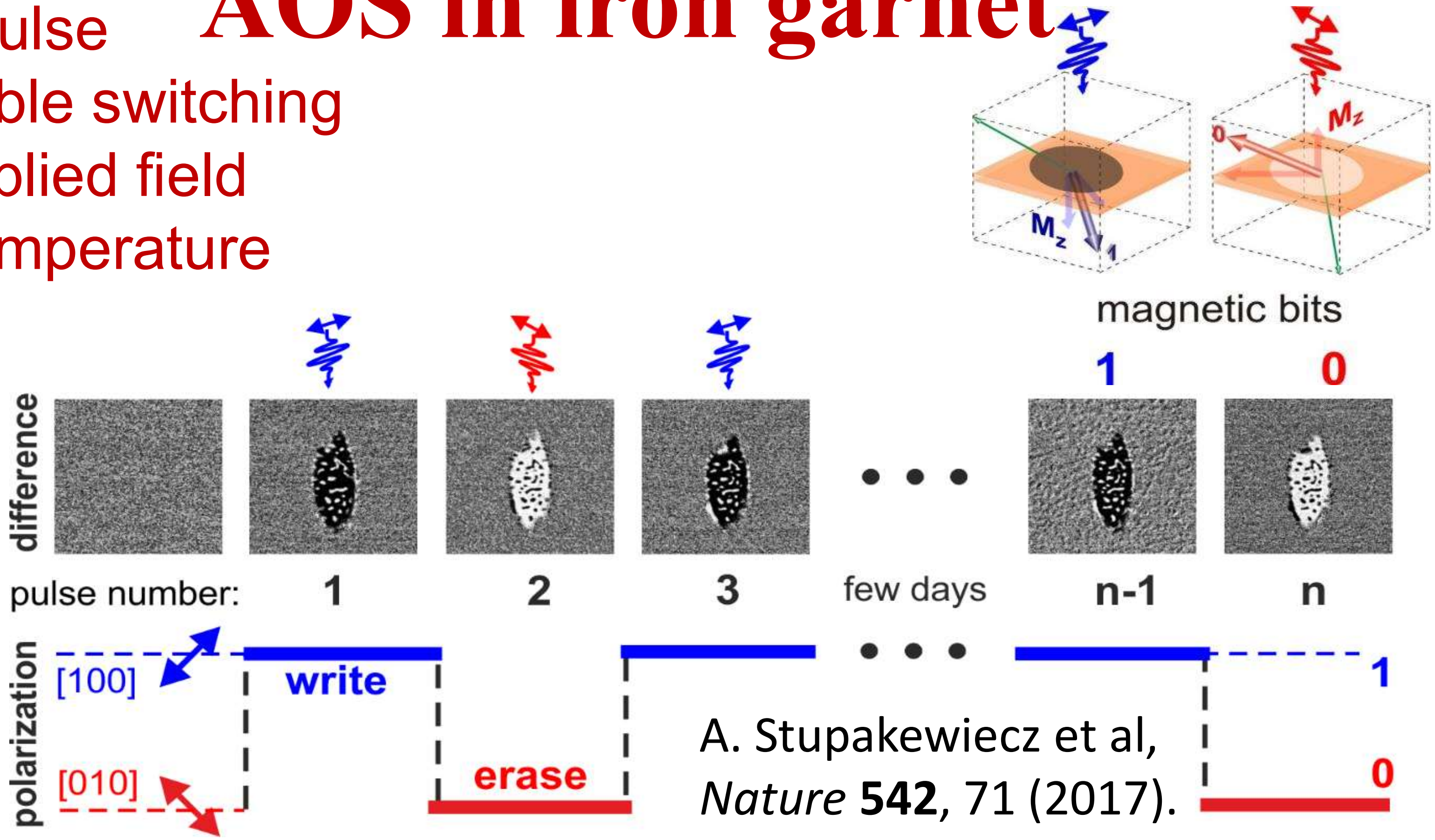
$Y_2CaFe_{3.9}Co_{0.1}GeO_{12}$ on GGG (001)
thickness d=7.5 μm)





AOS in iron garnet

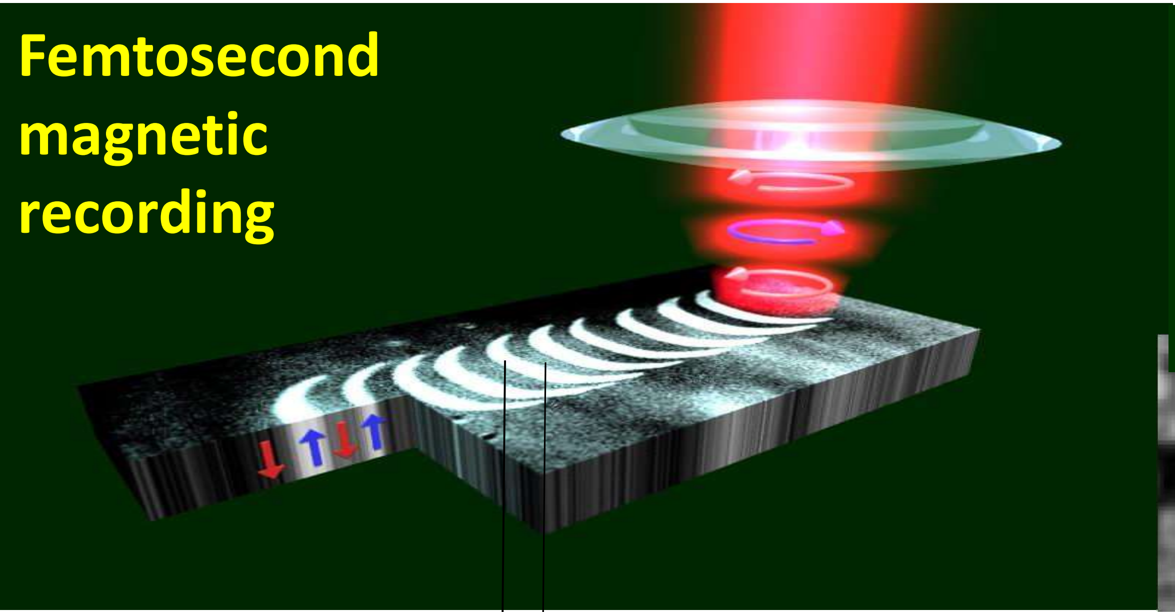
- ✓ single pulse
- ✓ repeatable switching
- ✓ zero applied field
- ✓ room temperature

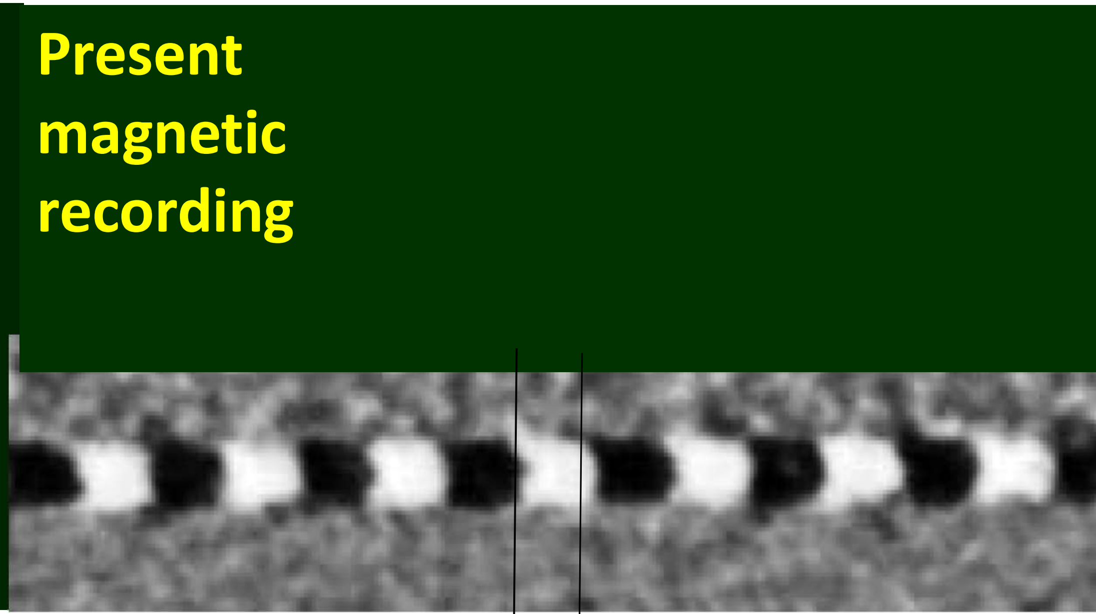


A. Stupakewiecz et al, *Nature* **542**, 71 (2017).

All-Optical Switching @ the nanoscale!

But.........



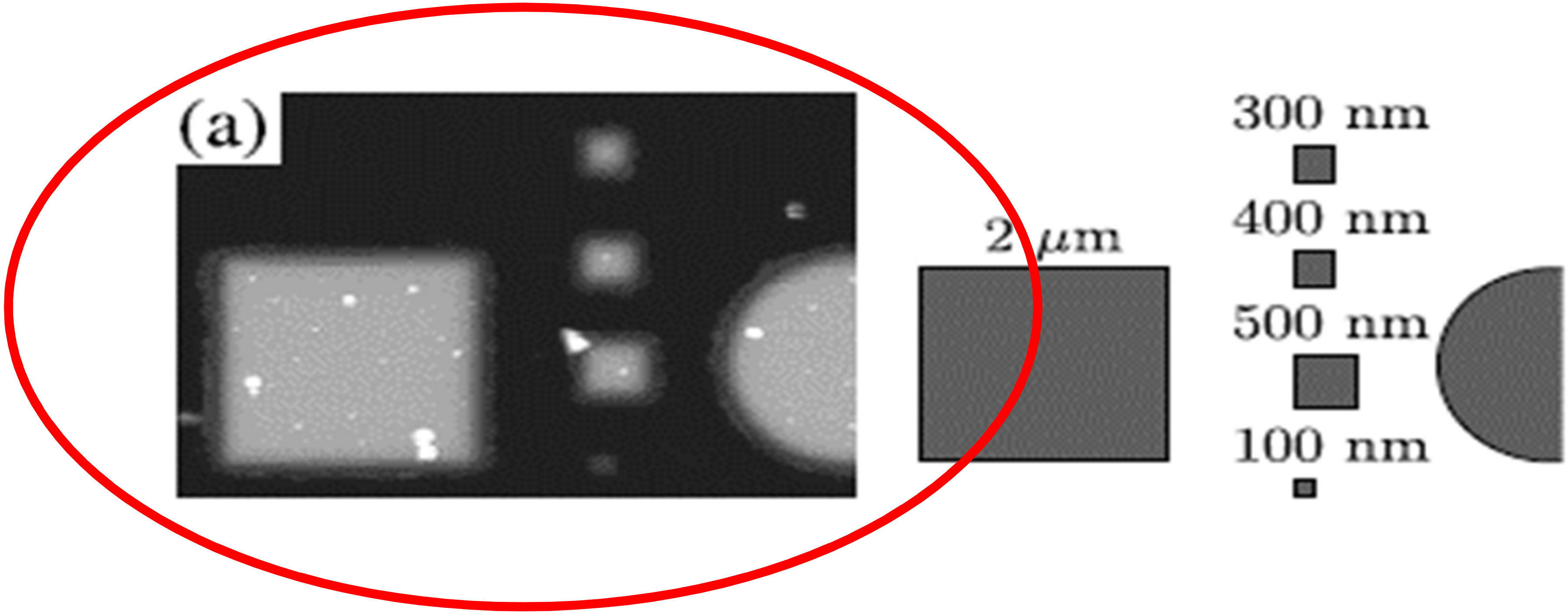


10 micron

100 nanometer!

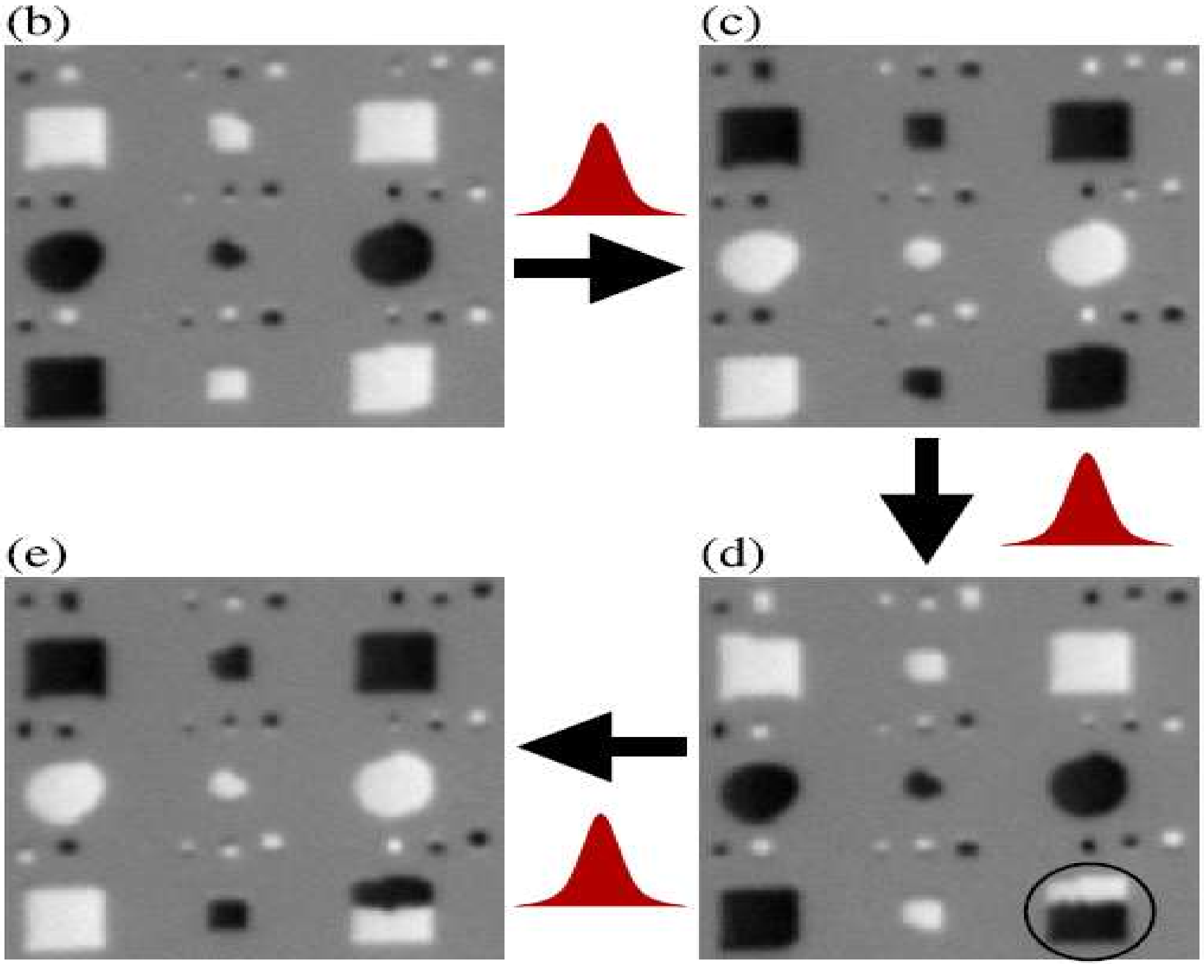
100 x smaller

All-Optical Switching @ the nanoscale⁉



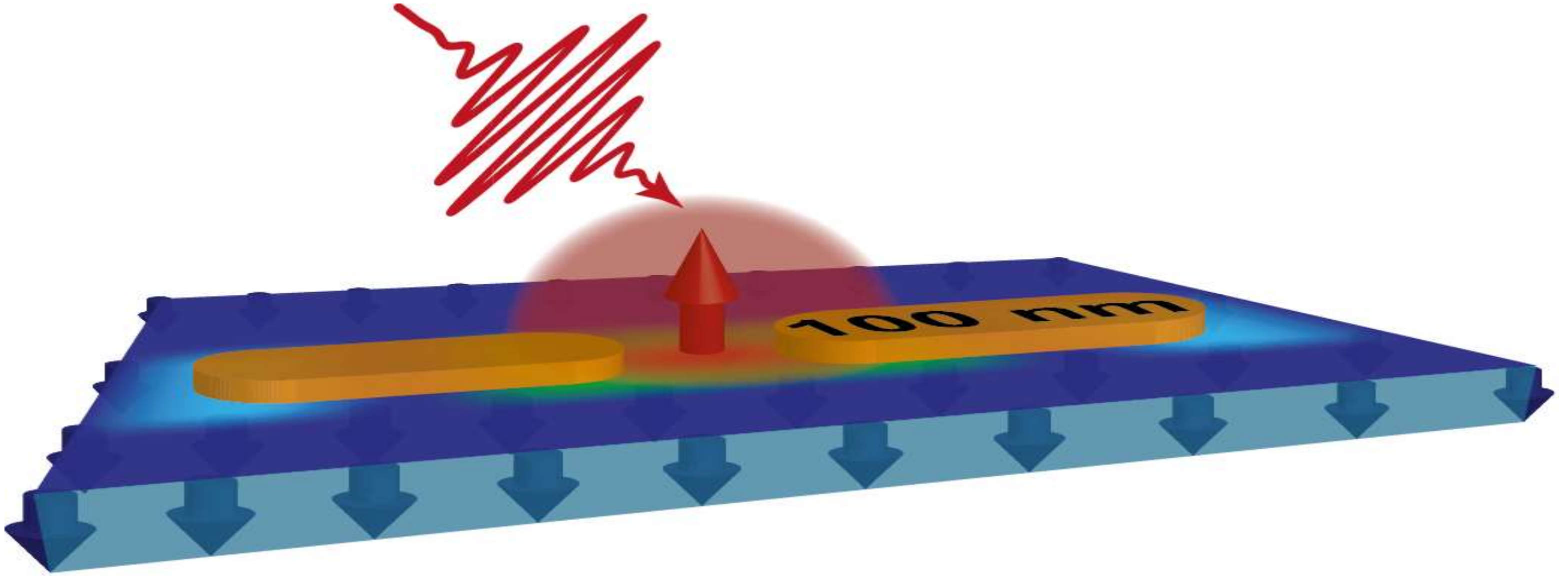
PEEM experiment SLS; L. Le Guyader et al, APL 2012, Nature Comm. 2015

All-Optical Switching @ the nanoscale?



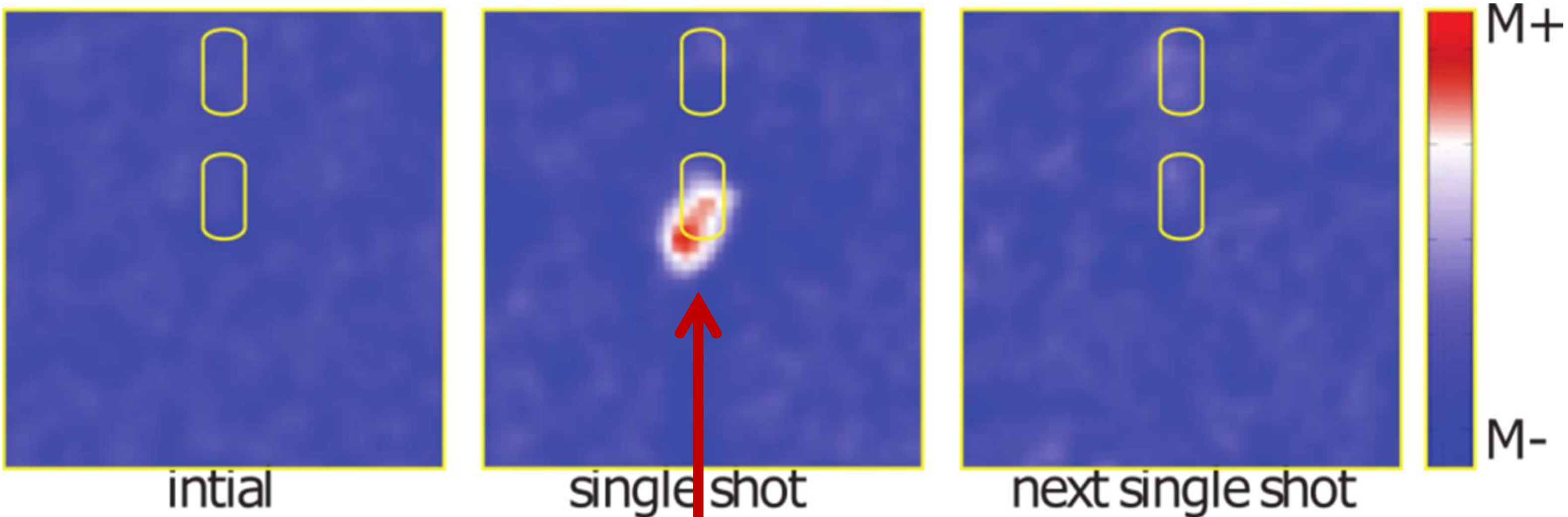
PEEM experiment SLS; L. Le Guyader et al, APL 2012, Nature Comm. 2015

Can't we go smaller?



plasmonic antenna!

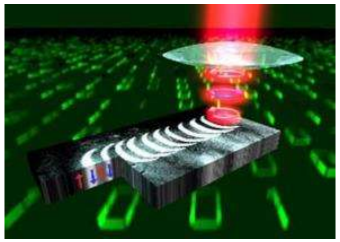
Nanoscale switching with plasmonic antennas
(with Bert Hecht, Wuerzburg)



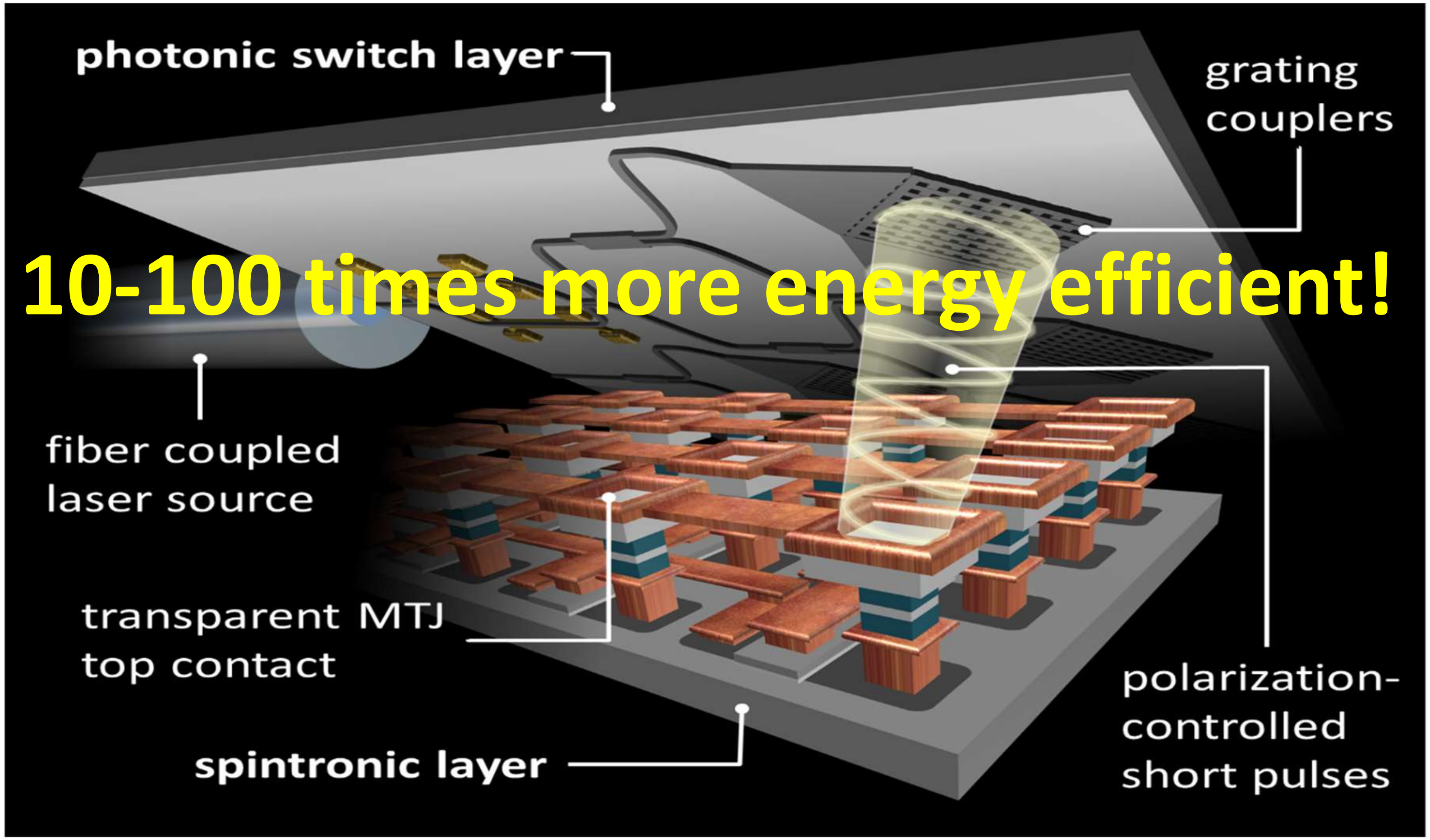
40 nm Switching!!

Tian-Min Liu et al, Nano Letters, 2015

Outlook:
speed and energy consumption in data storage

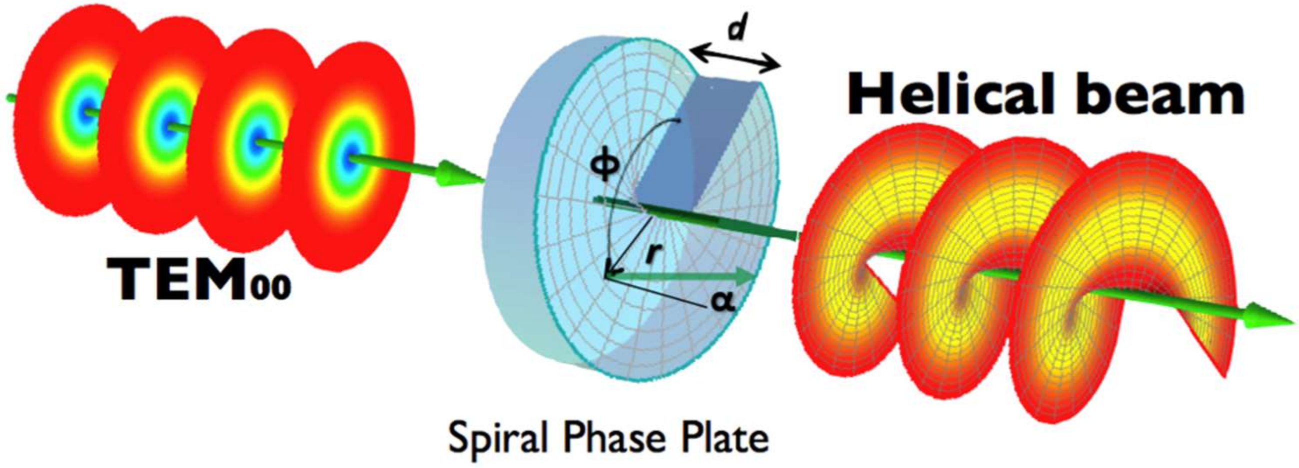
	(10 ns/bit)	0,05 $/GB	(>pJ/bit)
	(2 ns/bit)	0,65 $/GB	(>nJ/bit)
	(~ ps/bit)	?? $/GB	(~fJ/bit) (20x20nm)

Outlook: Spintronic-Photonic Integrated Circuit

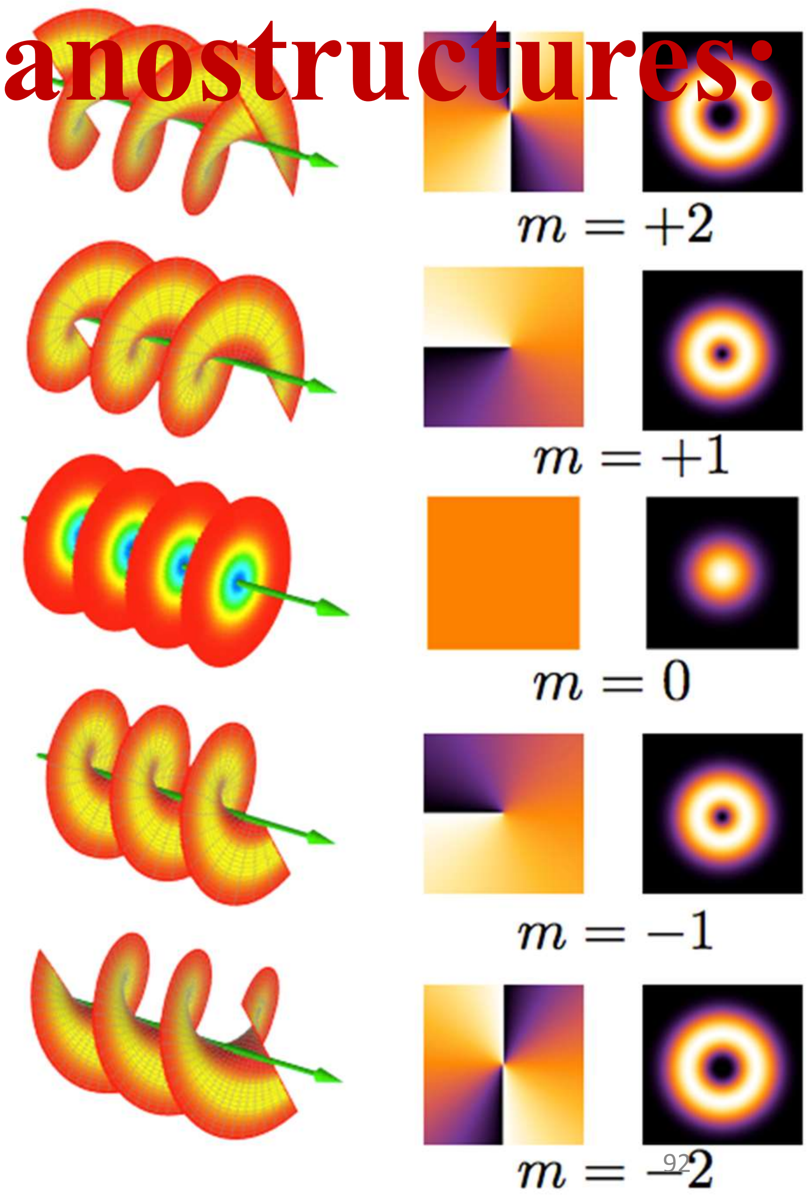


With: Aarhus University, IMEC, CEA SpinTEC, QuantumWise

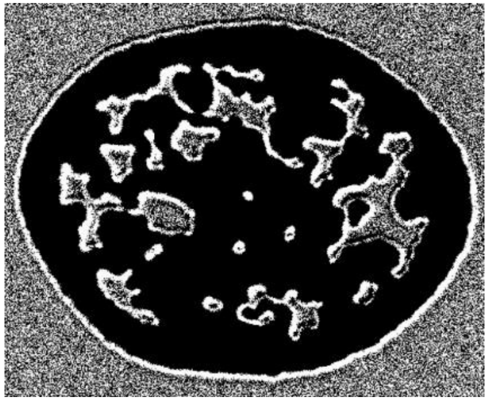
Towards more complex nanostructures:



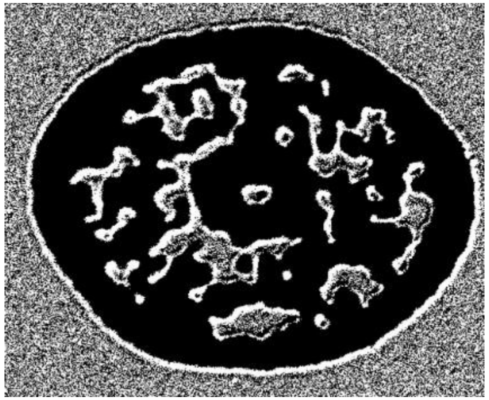
Laguerre-Gaussian Beams



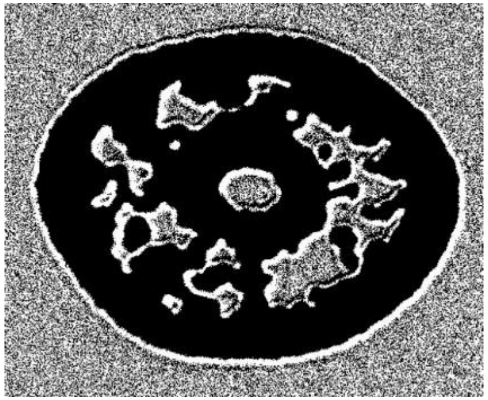
Donut Switching with L-G beams



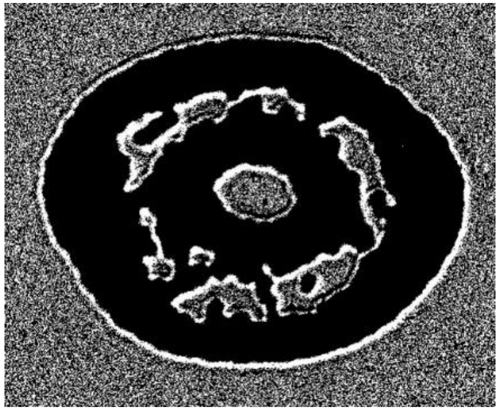
34.036



30.968

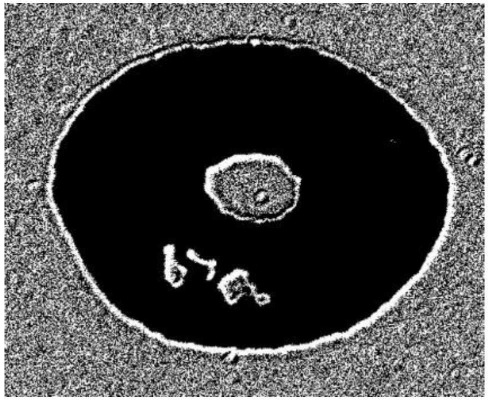


25.308

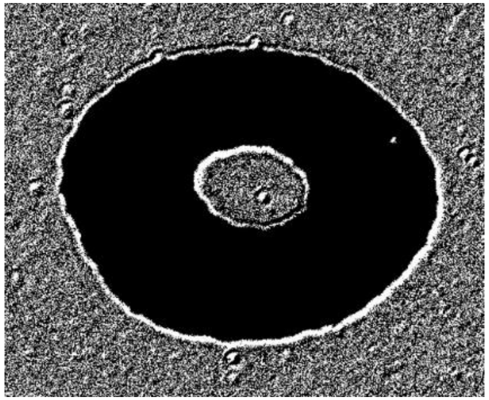


22.558

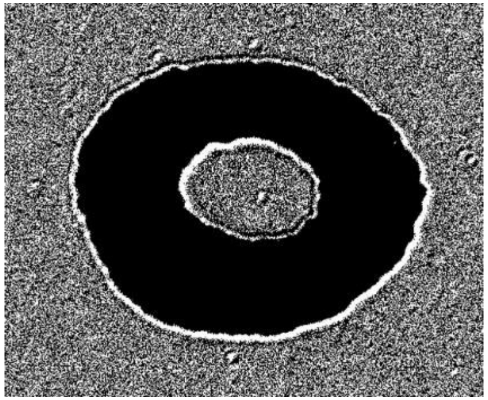
Fluence(mJ/cm^2)



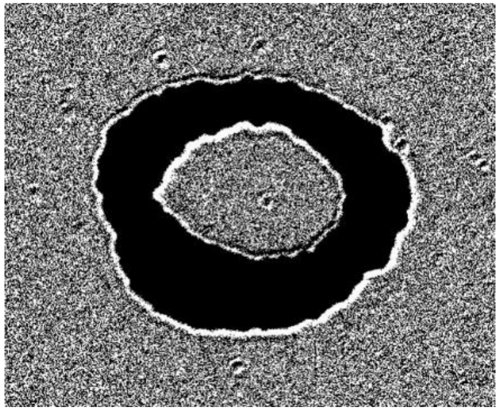
19.928



17.337



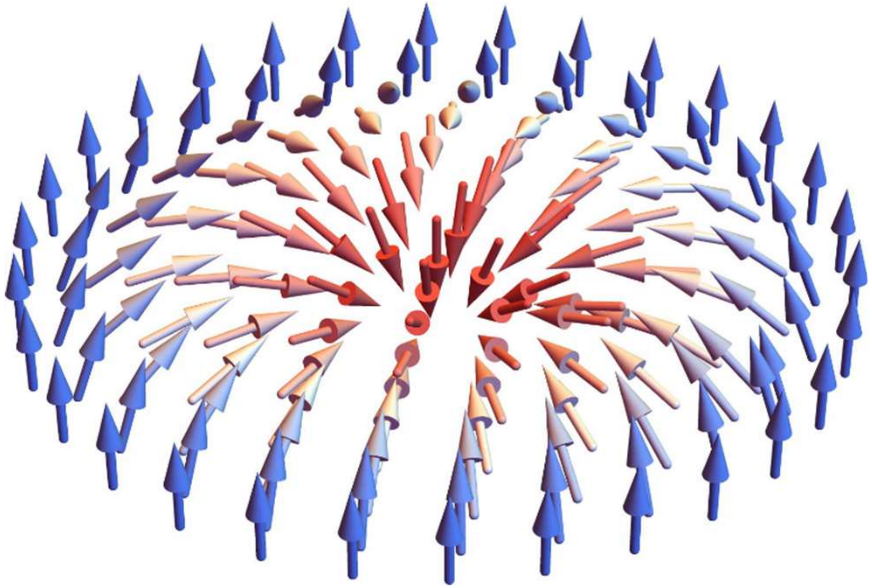
15.663



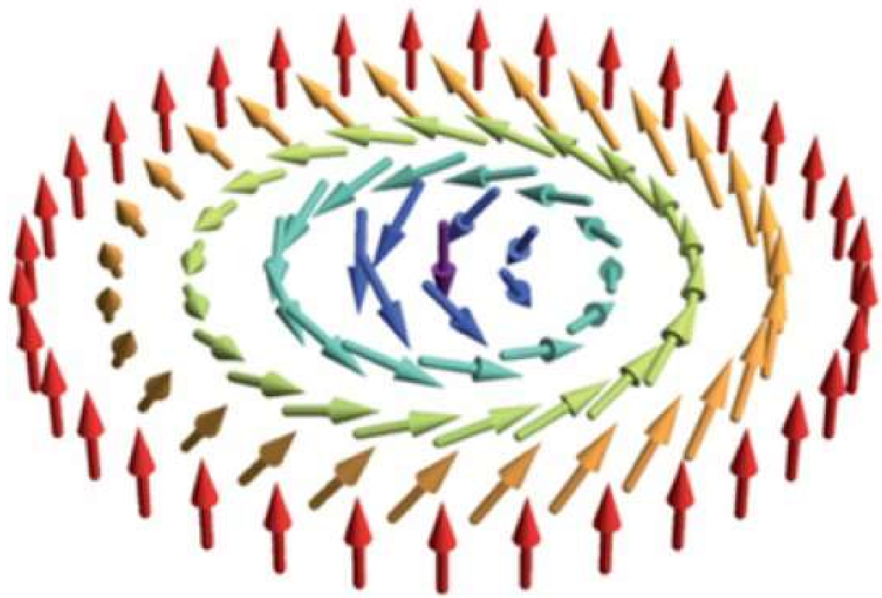
12.953

Fluence(mJ/cm^2)

Towards stable complex nanostructures:



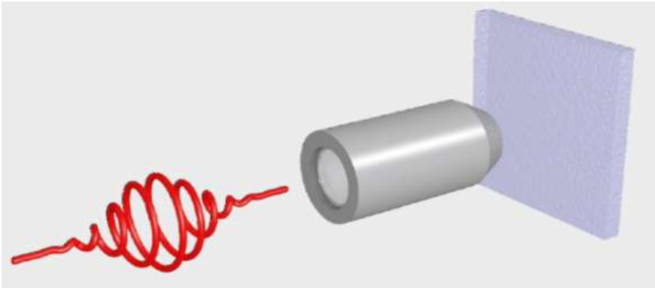
Neel skyrmion



Bloch skyrmion

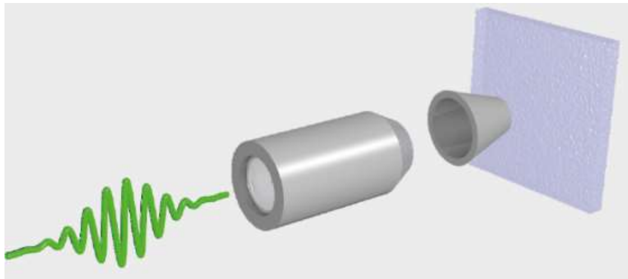
Opto-magnetic generation of Skyrmions

Single pulse illumination (λ = 800 nm)
through microscope objective (NA = 0.4)



+

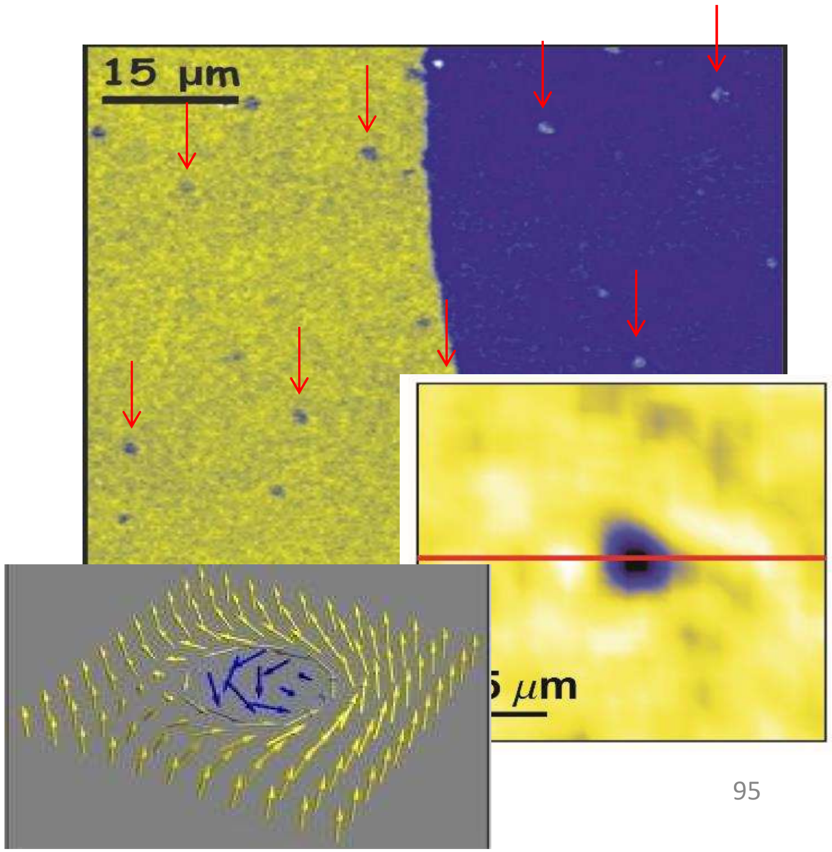
Read-out with Near-field microscopy
(λ = 532 nm, Resolution 80 nm)



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

=

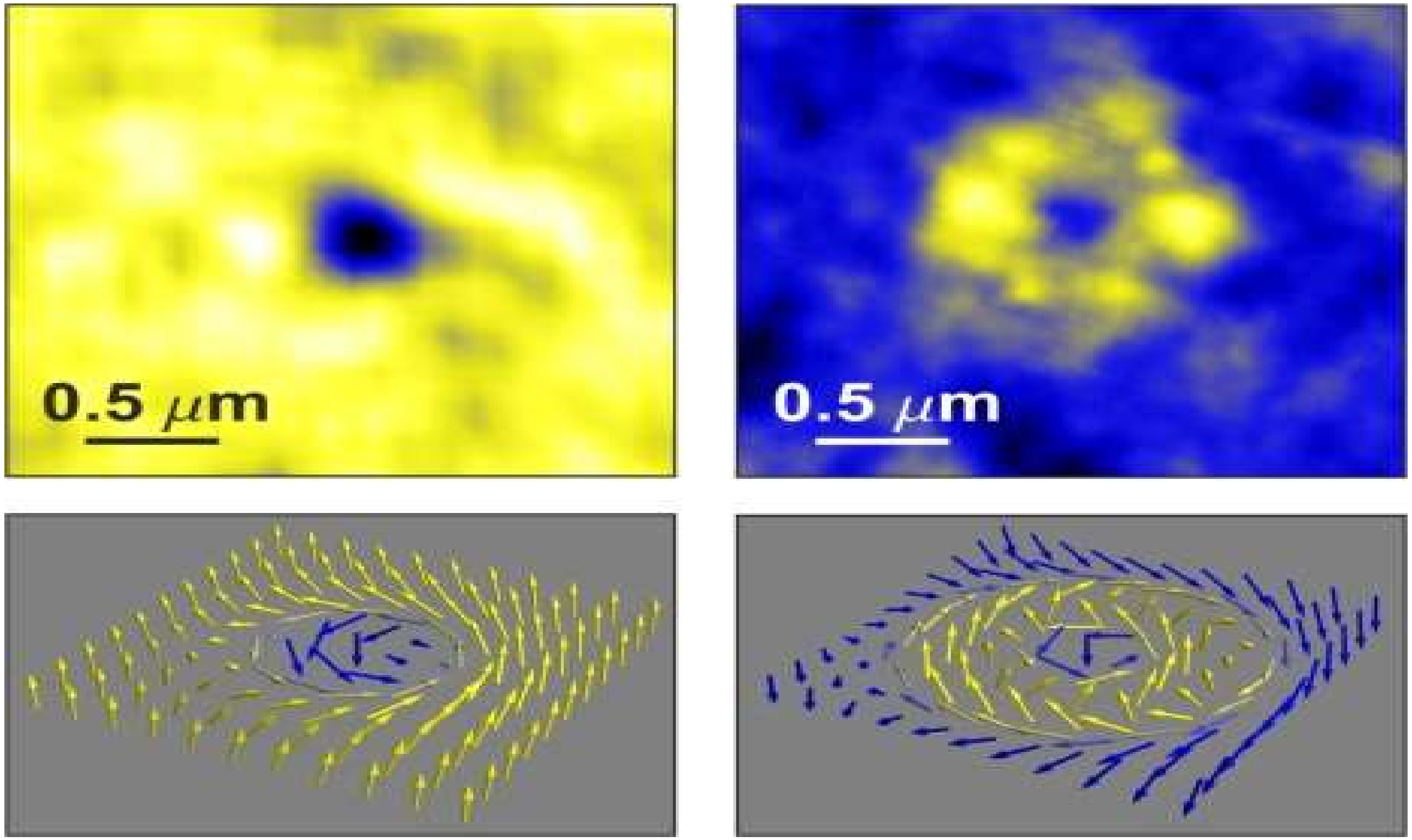
Sample: $Tb_{22}Fe_{69}Co_9$



Opto-magnetic generation of Skyrmions

Low fluence **High fluence**

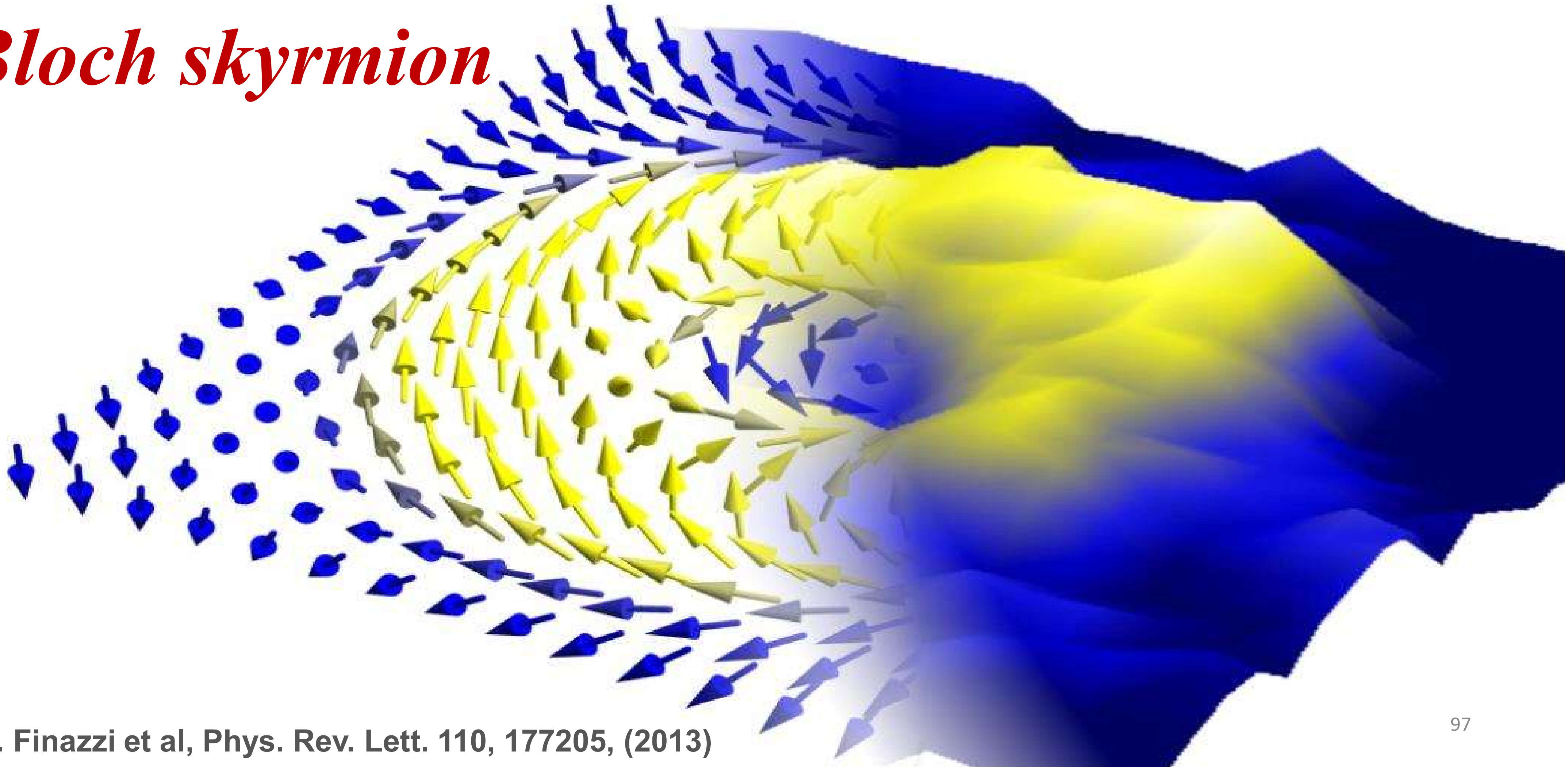
FeTb



?

Skyrmion generation model

Bloch skyrmion

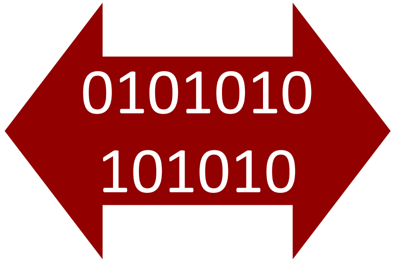


M. Finazzi et al, Phys. Rev. Lett. 110, 177205, (2013)

End of smaller and faster?

I. End of "Moore": too much heat

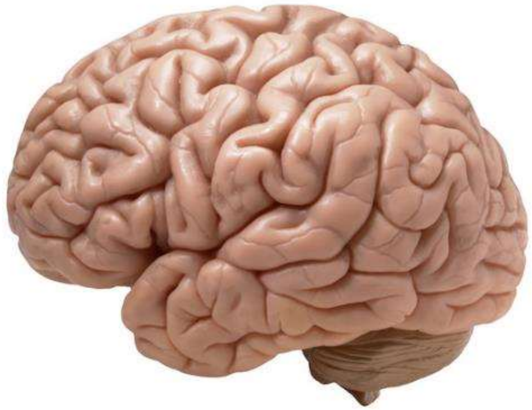
II. Higher density = too much energy



III. von Neumann bottleneck: transfer information back and forth

Create a new paradigm, beyond von Neumann

Supercomputer versus Brain:



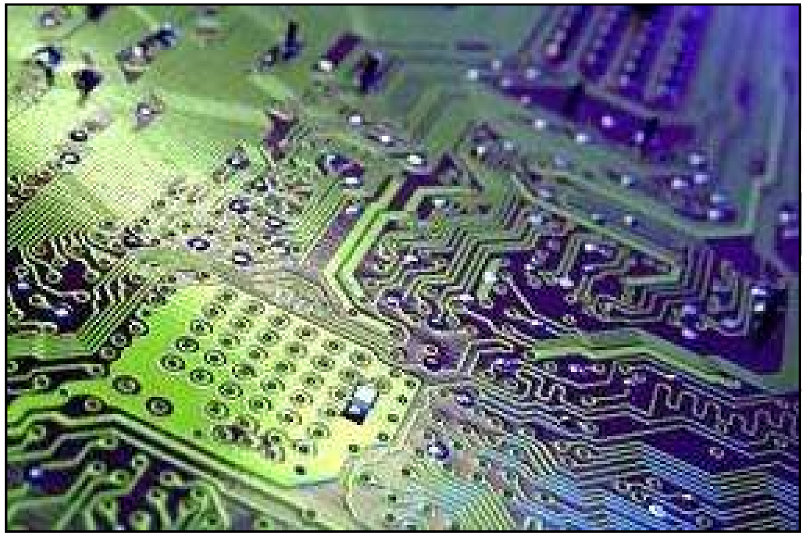
10 MW

Processing and storage
Separated and serial and 2D

10 W

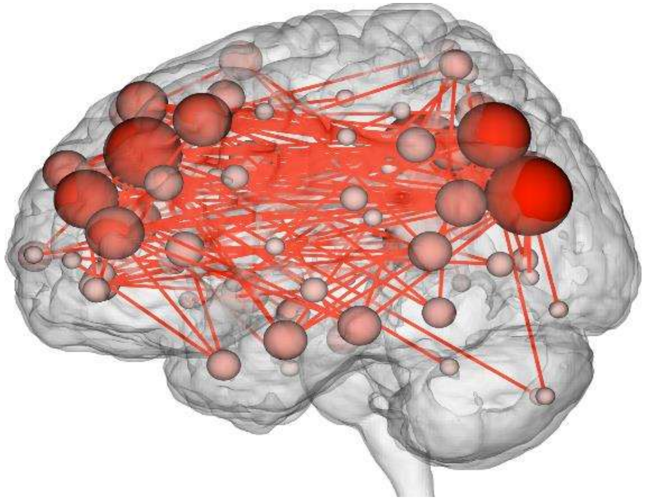
Processing and storage
Integrated and parallel and 3D!

Supercomputer versus Brain:



10 MW

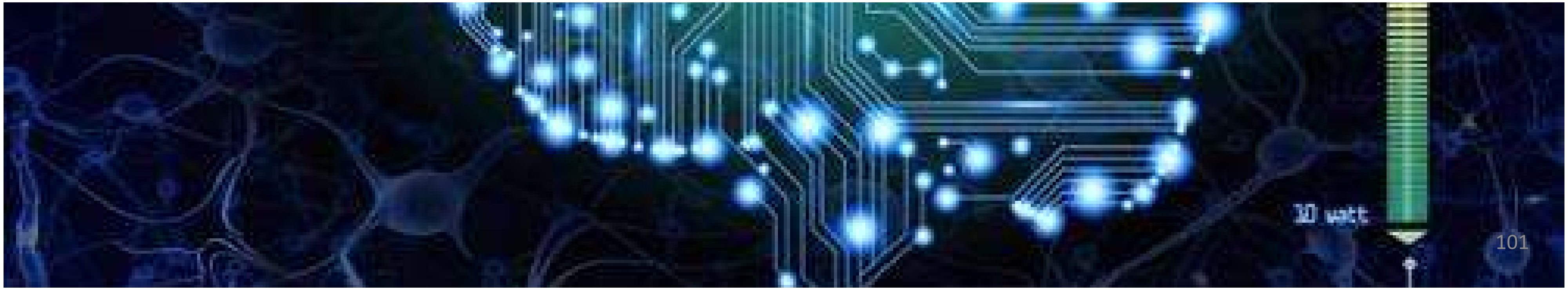
Processing and storage
Separated and serial and 2D



10 W

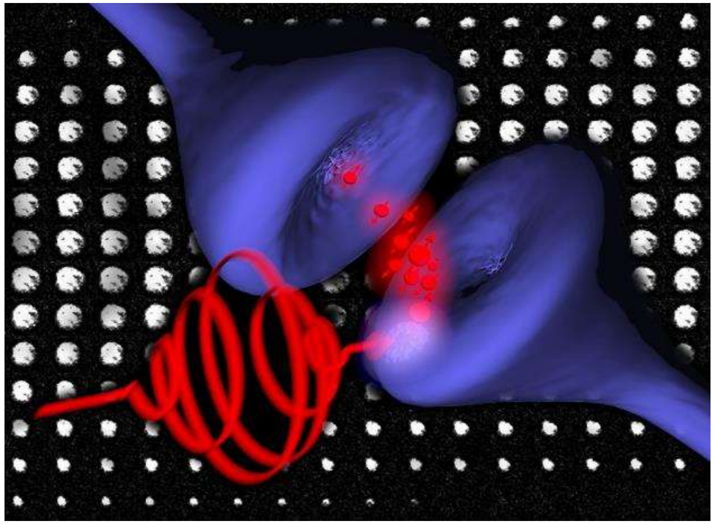
Processing and storage
Integrated and parallel and 3D!

Paradigm shift: ***to develop materials that "learn"***



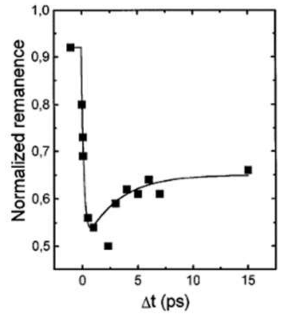
Neuromorphic Computing with Magneto-Optics?

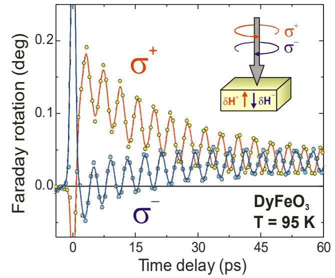
see: A. Chakravarty et al, Supervised learning of an opto-magnetic neural network with ultrashort laser pulses, Appl. Phys. Lett. 114, 192407 (2019)



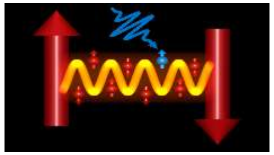
To conclude:

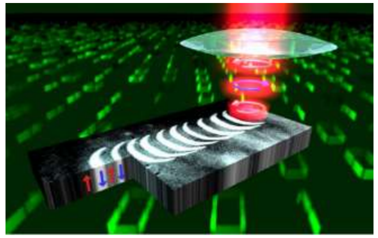
1. **Femtosecond optical excitation:**
pump/probe magnetism on timescale of exchange interaction

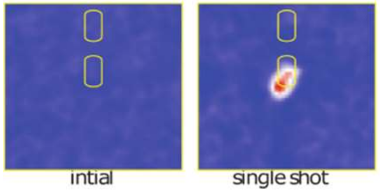


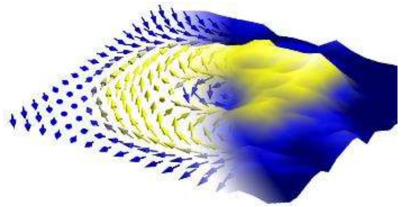


2. **Laser induced effects:**
   a. **Thermal effects**
   b. **Nonthermal opto-magnetic effects**

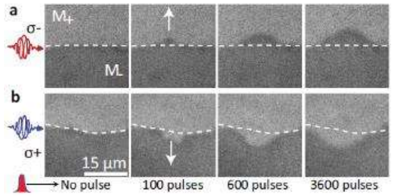




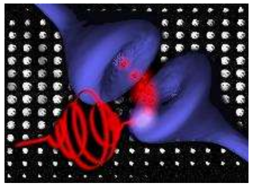


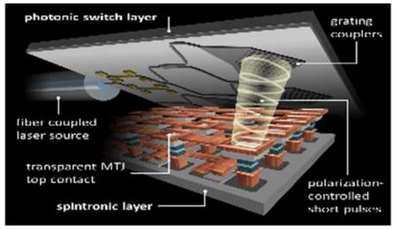


3. **AOS of Ferrimagnets, Ferromagnets antiferromagnets, metals, dielectrics**



4. **AOS at the nanoscale, O-MRAM, Neuromorphic applications**





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