Magnetization reversal:

from fundamental principles
to fundamental limits

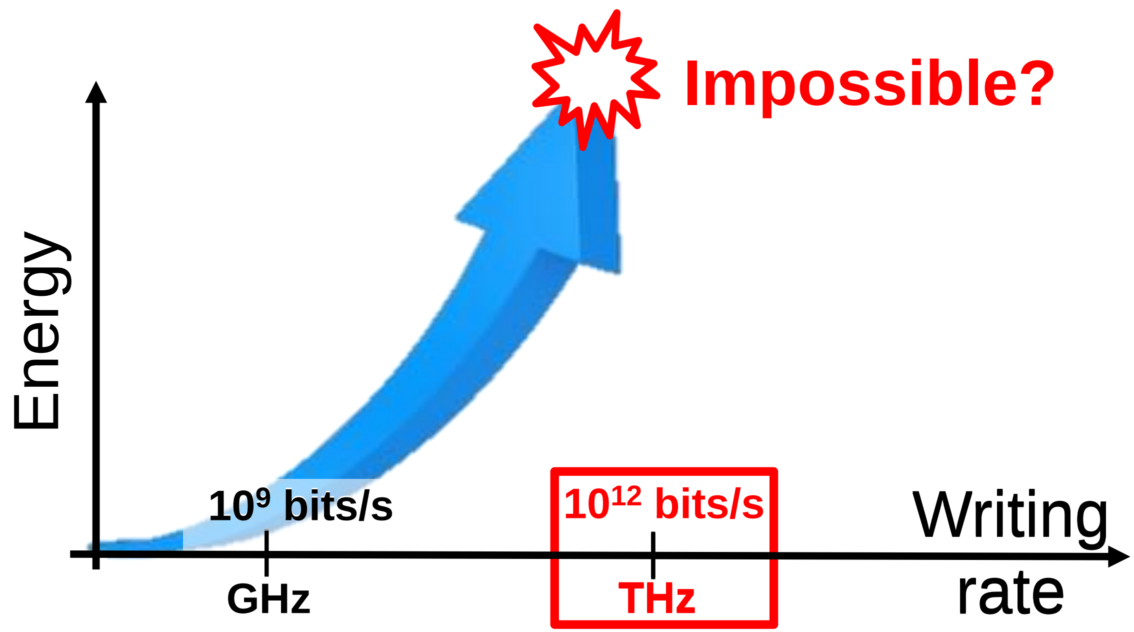
Alexey V. Kimel

Ultrafast Spectroscopy of Correlated Materials,

Radboud University, Nijmegen, The Netherlands

Fundamental Dilemma:

fast <u>or</u> energy efficient?



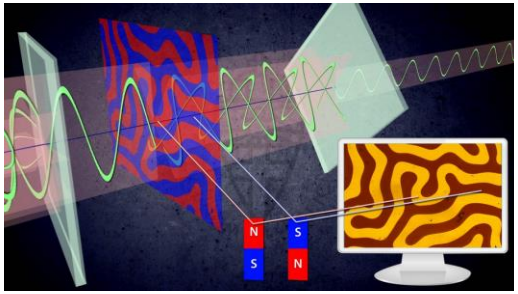
Challenge:

fast and energy efficient

Mission:

To discover new fundamental principles for the fastest possible writing of magnetic bits accompanied by minimal loss of energy





Magnetic recording: *experiment, theory, practice*

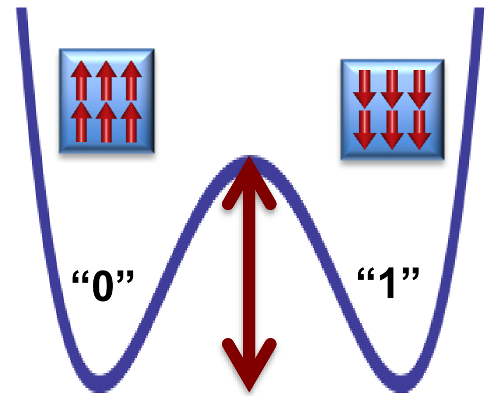
Practice

ns
0.1 nJ = 10^{-10} J

Experiment

physics?
ultrafast?
high density?
non-dissipative?

Theory

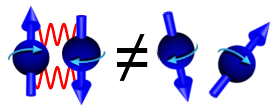


60 $k_BT \sim 10^{-19}$ J

Magnetism –
the strongest quantum mechanical phenomenon

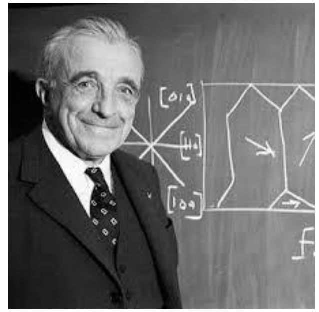
$S_z = \pm\hbar/2$

Spin
(1925)



$E_{ex}=-J\mathbf{S}_i\mathbf{S}_j$

Exchange interaction
(1926)

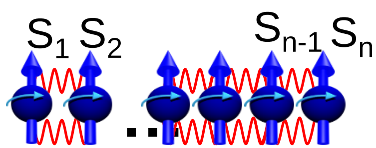


L. Néel

Antiferromagnetism
(1930)

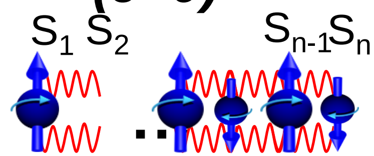
Ferrimagnetism
(1948)

Ferromagnet (J>0)



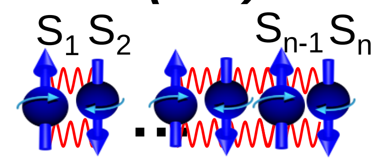
$\mathbf{M}= -\gamma\frac{\sum s_i}{V} \neq 0$

Ferrimagnet (J<0)



$\mathbf{M}\neq 0$

Antiferromagnet (J<0)



$\mathbf{M}= 0$

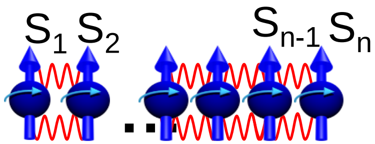
Macrospin approximation: *intuitive (classical) view of quantum (counter-intuitive) phenomenon*

$$dU = dW + dQ$$
$$dW = \mu_0 \mathbf{H} d\mathbf{M}$$
$$\mu_0 \mathbf{H}_{eff} = \left(\frac{\partial U}{\partial \mathbf{M}}\right)_\sigma$$

U - internal energy
W - work
Q - heat
σ - entropy

$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$

Ferromagnet (J>0)



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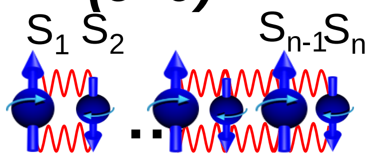
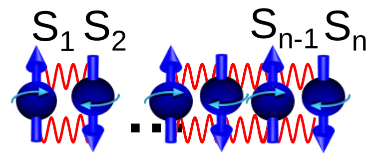
Ferrimagnet (J<0)



$\mathbf{L} = -\gamma \frac{\sum (\mathbf{S}\uparrow - \mathbf{S}\downarrow)}{V}$

Antiferromagnet (J<0)



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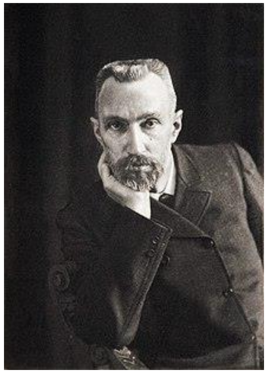


P. Curie (1894):

"the symmetries of the causes are to be found in the effects".

Cause	Effect	Energy (U)
F mechanical force	**dx** displacement	**Fdx**
E electric field	**dP** polarization	**EdP**
H magnetic field	**dM** magnetization	**HdM**

$$\mathbf{F} = -\frac{\partial U}{\partial \mathbf{x}}$$

Macrospin approximation: *intuitive (classical) view of quantum (counter-intuitive) phenomenon*

U - internal energy
W - work
Q - heat
σ - entropy
$\mathbf{T}$ - torque

$$\left.\begin{aligned} dU &= dW + dQ \\ dW &= \mu_0 \mathbf{H} d\mathbf{M} \end{aligned}\right\} \quad \mu_0 \mathbf{H}_{eff} = \left(\frac{\partial U}{\partial \mathbf{M}}\right)_\sigma$$

$$\frac{d\mathbf{S}}{dt} = \mathbf{T}$$

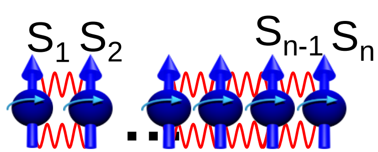
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} - \frac{\lambda}{M^2} \mathbf{M} \times \left(\mathbf{M} \times \mathbf{H}_{eff}\right)$$

Landau-Lifshitz equation (1935)

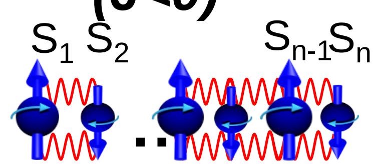
$$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$$

$$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$$

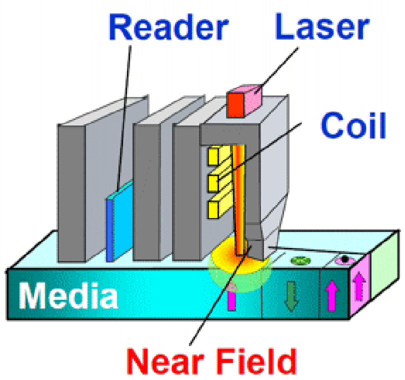
Ferromagnet (J>0)

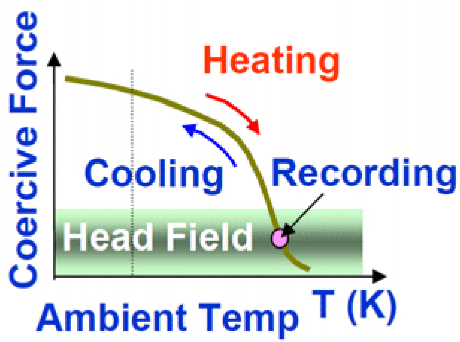


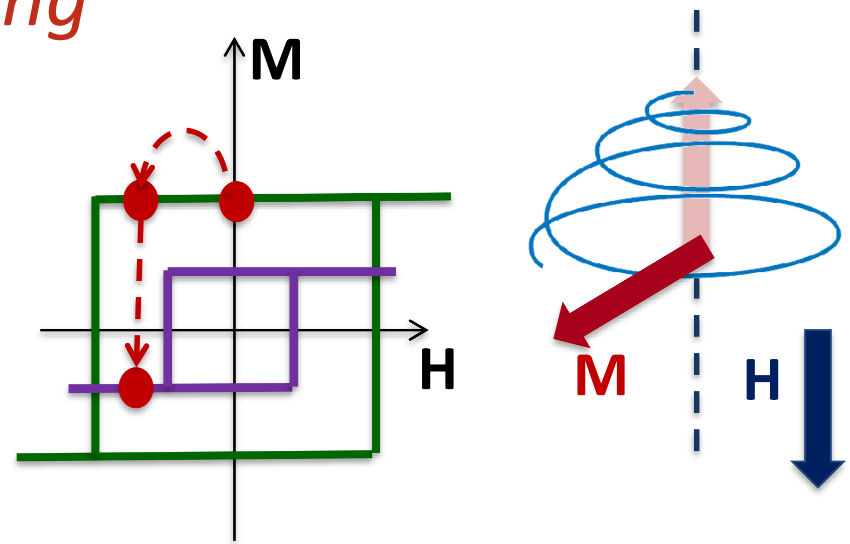
Ferrimagnet (J<0)



State-of-the-art in data storage:
heat assisted magnetic recording





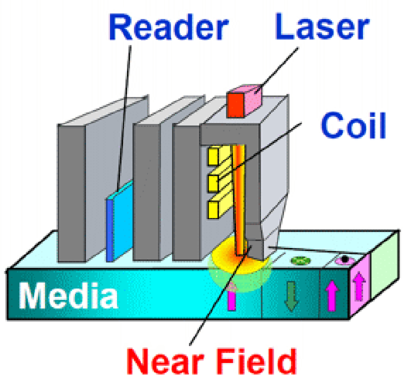


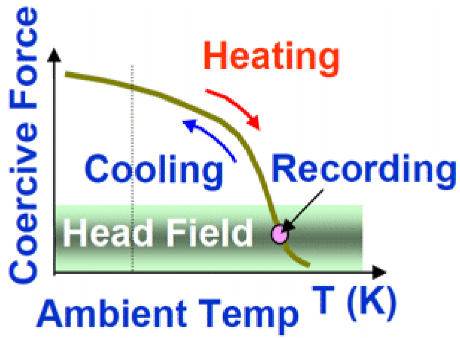
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} - \frac{\lambda}{M^2} \mathbf{M} \times \left(\mathbf{M} \times \mathbf{H}_{eff} \right)$$

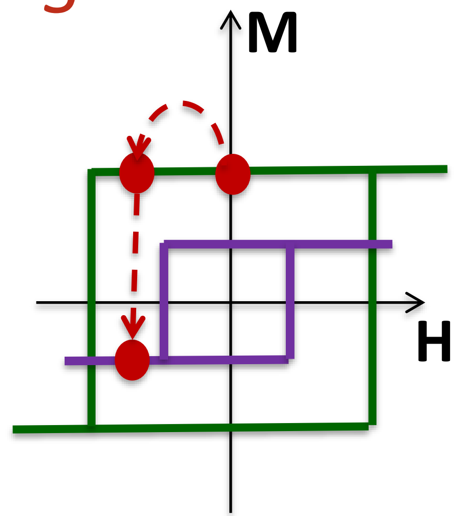
Magnetization reversal

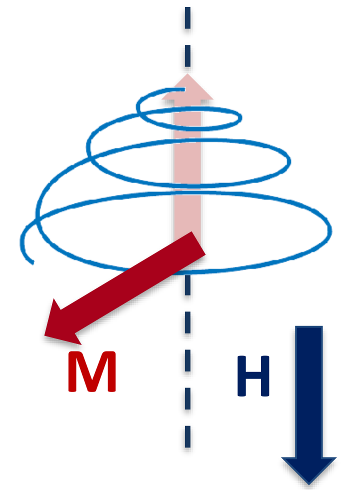
- with a magnetic field in a “wrong” direction;
- without any magnetic field and solely with heat;
- with no heat, no field .

State-of-the-art in data storage:
heat assisted magnetic recording









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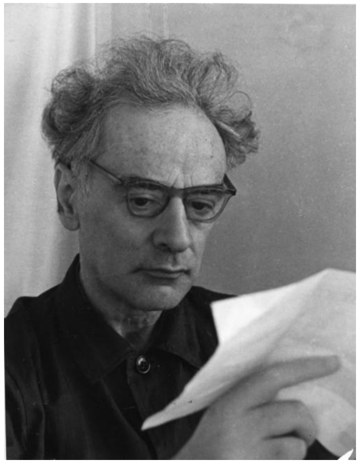


L. D. Landau
(*1908-1968*)

"Most important part of doing physics is the knowledge of approximations."

Macrospin approximation: *intuitive (classical) view of quantum (counter-intuitive) phenomenon*

$$-\mu_0 H_{eff}^{(j)} = {}^{\partial E_{ex}}/_{\partial S_i} \sim 1 - 1000\ \mathrm{T}$$

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} \qquad \frac{\gamma}{2\pi} = 28\ \mathrm{GHz/T}$$

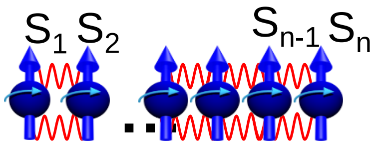
τ_{ex}=*30 fs -30 ps*

Nonequilibrium state **?** **Macrospin** *(classical)*

$t \sim \tau_{ex}$ | $t >> \tau_{ex}$

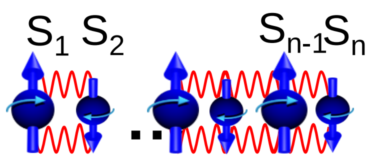
$$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$$

Ferromagnet (J>0)



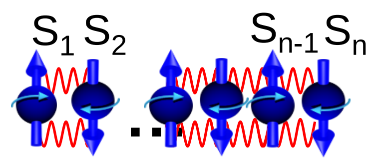
$$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$$

Ferrimagnet (J<0)

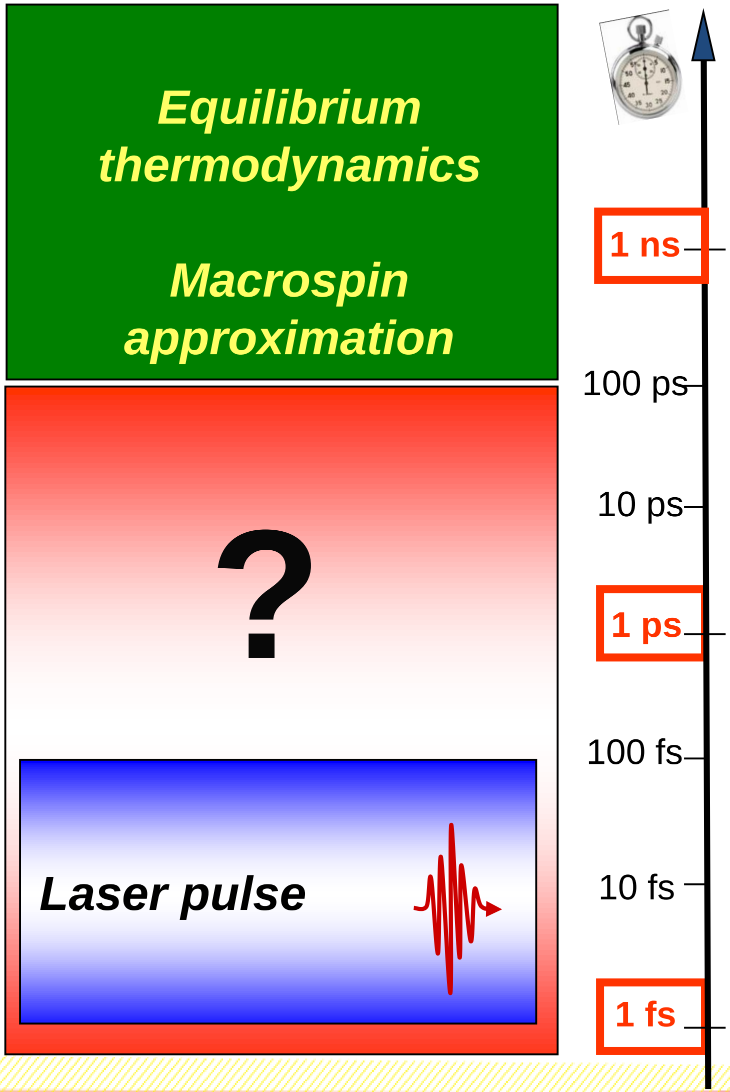


$$\mathbf{L} = -\gamma \frac{\sum(\mathbf{S}_{2i-1} - \mathbf{S}_{2i})}{V}$$

Antiferromagnet (J<0)

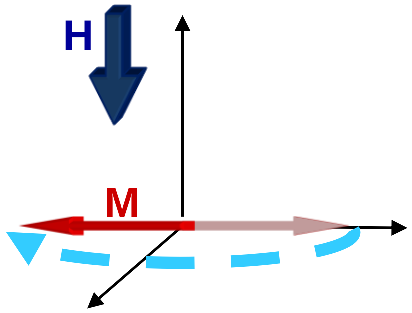


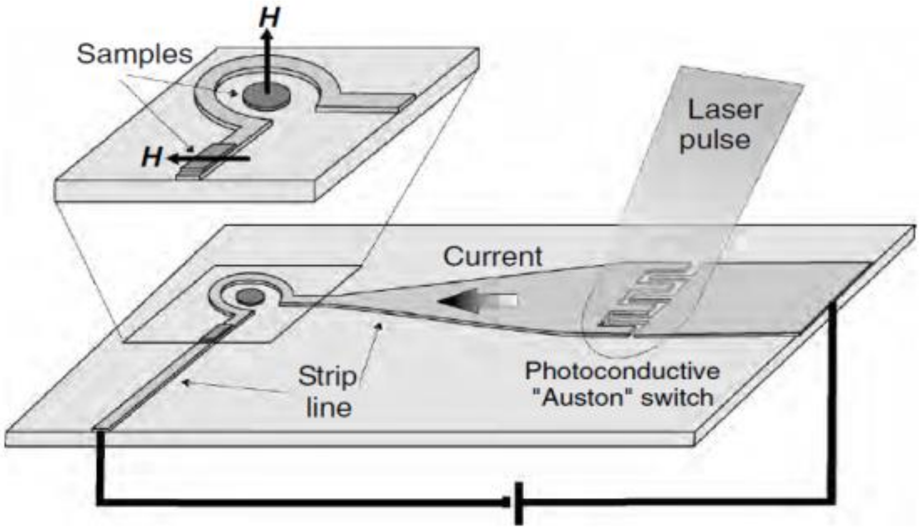
Ultrafast magnetism: *terra incognita of modern science*



Curie's principle fails!

Precessional switching





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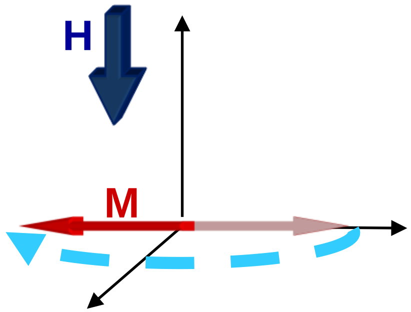
S. Kaka, S. E. Russek, Appl. Phys. Lett. **80**, 2958 (2002).
Th. Gerrits et al., Nature **418**, 509 (2002).
H. W. Schumacher et al., Phys. Rev. Lett. **90**, 017201 (2003).

The shortest time achieved is 100 ps!

Precessional switching



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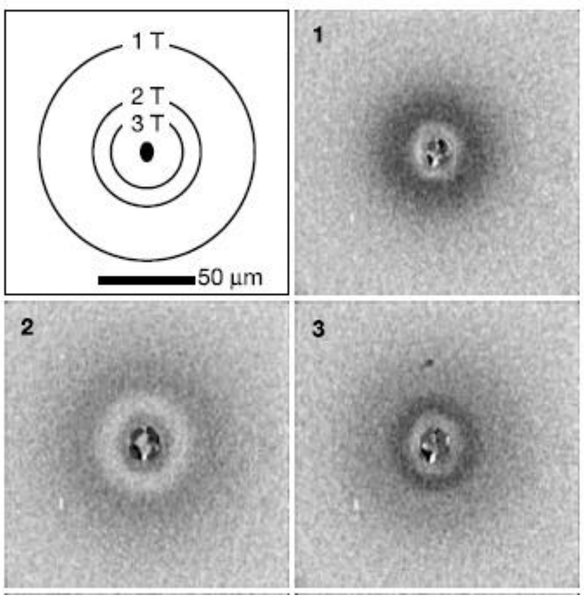
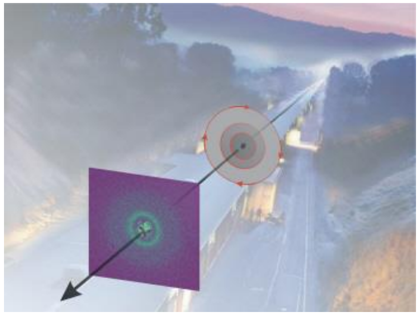


letters to nature

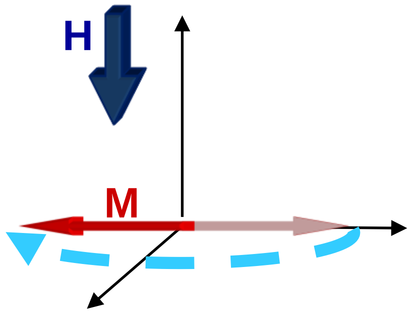
The ultimate speed of magnetic switching in granular recording media

I. Tudosa[1], C. Stamm[1], A. B. Kashuba[2], F. King[3], H. C. Siegmann[1], J. Stöhr[1], G. Ju[4], B. Lu[4] & D. Weller[4]



2.3 ps,
several T pulses

Precessional switching



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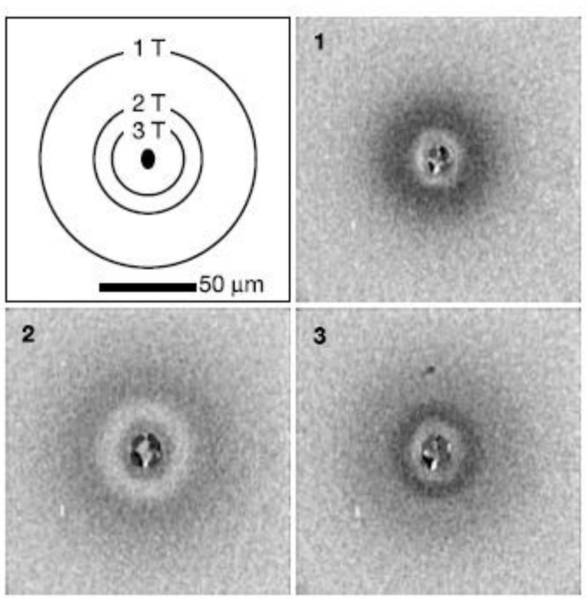

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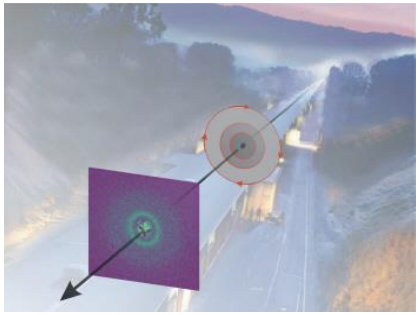
Applied physics

Speed limit ahead

C. H. Back and D. Pescia

Are there any limits to what science and technology can achieve? When it comes to recording data in magnetic media, the answer is yes: there is a natural limit to the speed at which data can be encoded.



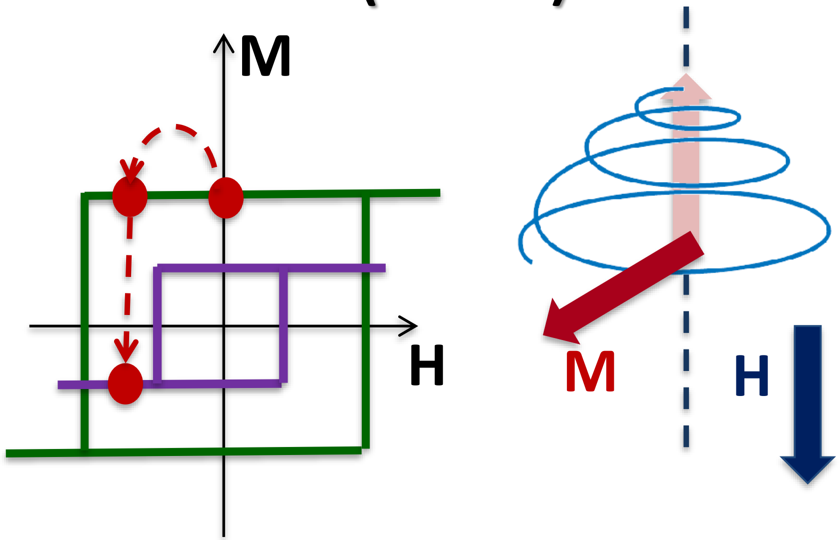
2.3 ps,
several T pulses

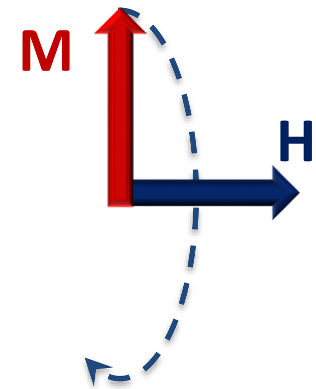
"No matter how short and strong the magnetic-field pulse, magnetic recording cannot be made ever faster."

New route for heat-assisted magnetic recording

Heat Assisted Magnetic Recording (HAMR)

Precessional Switching



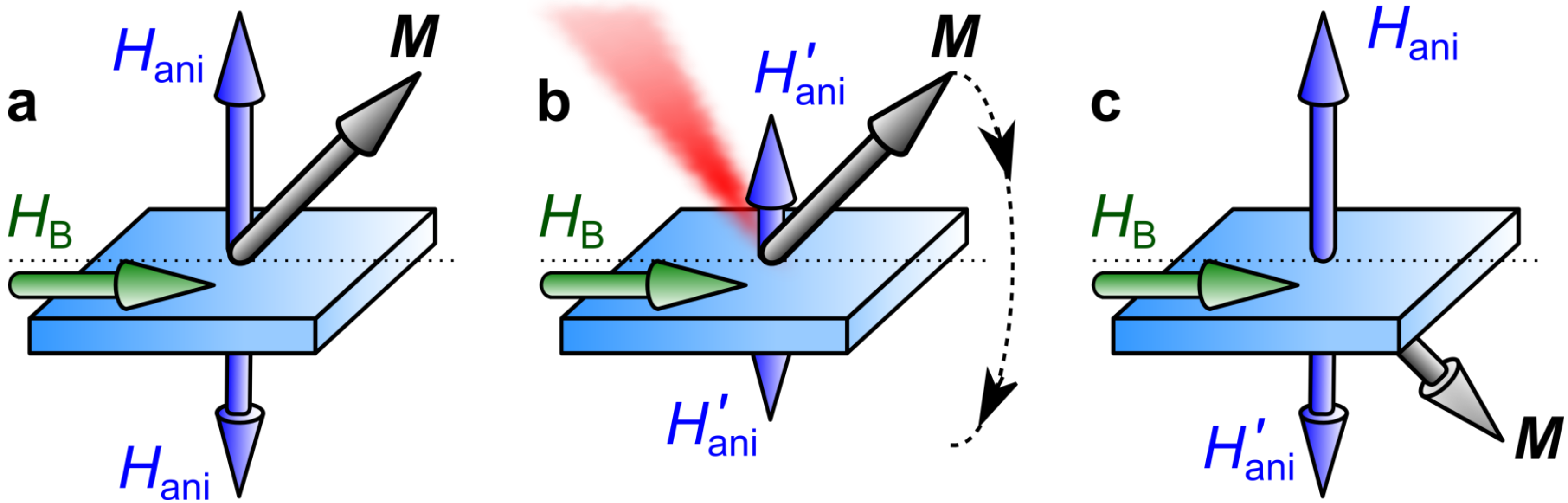


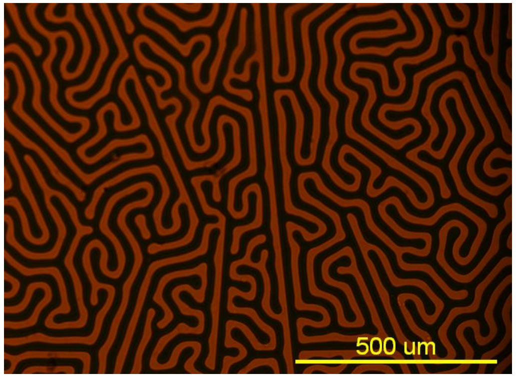
best spatial resolution

fastest route

Combine?

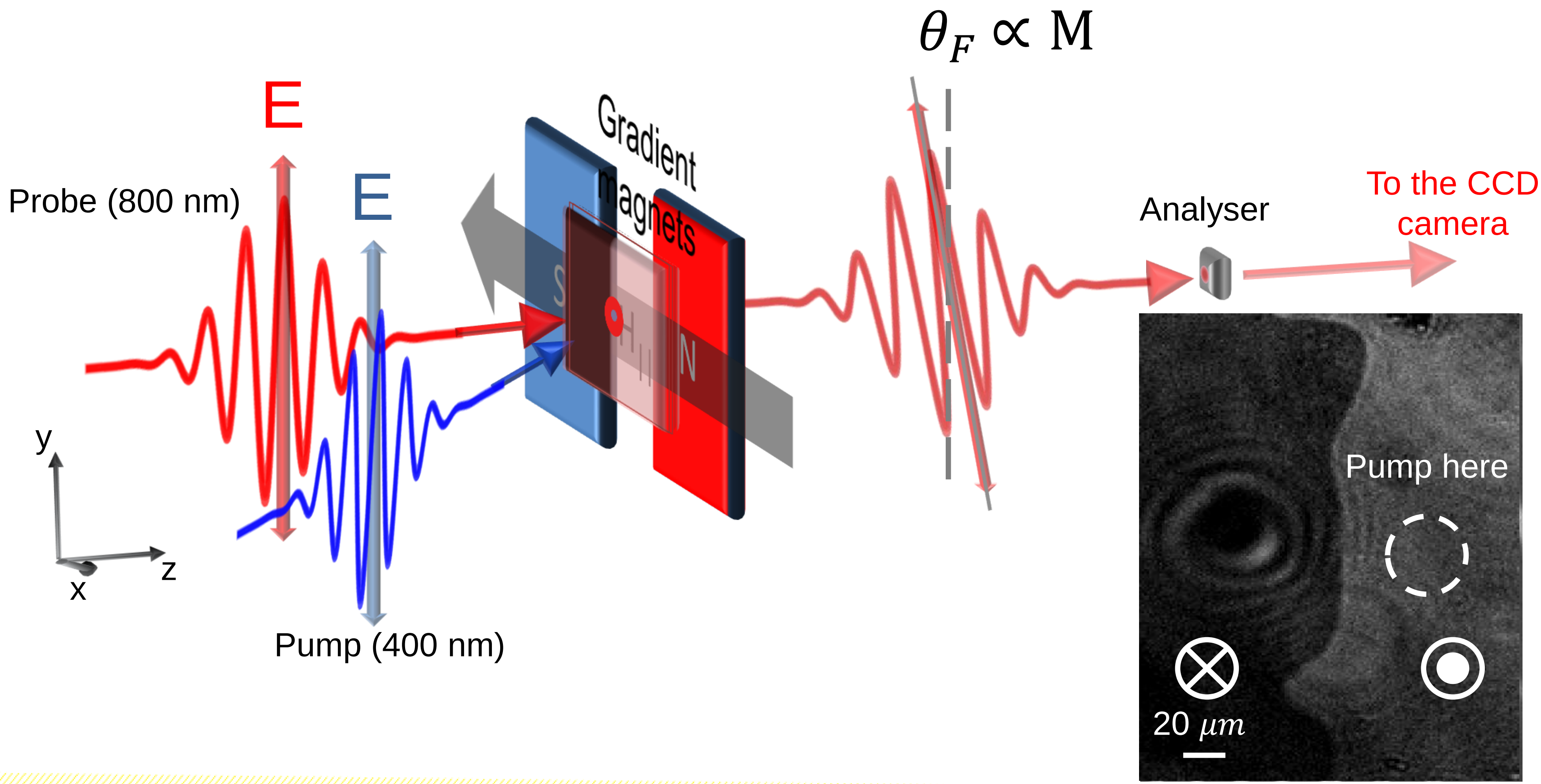
Heat-assisted magnetic switching



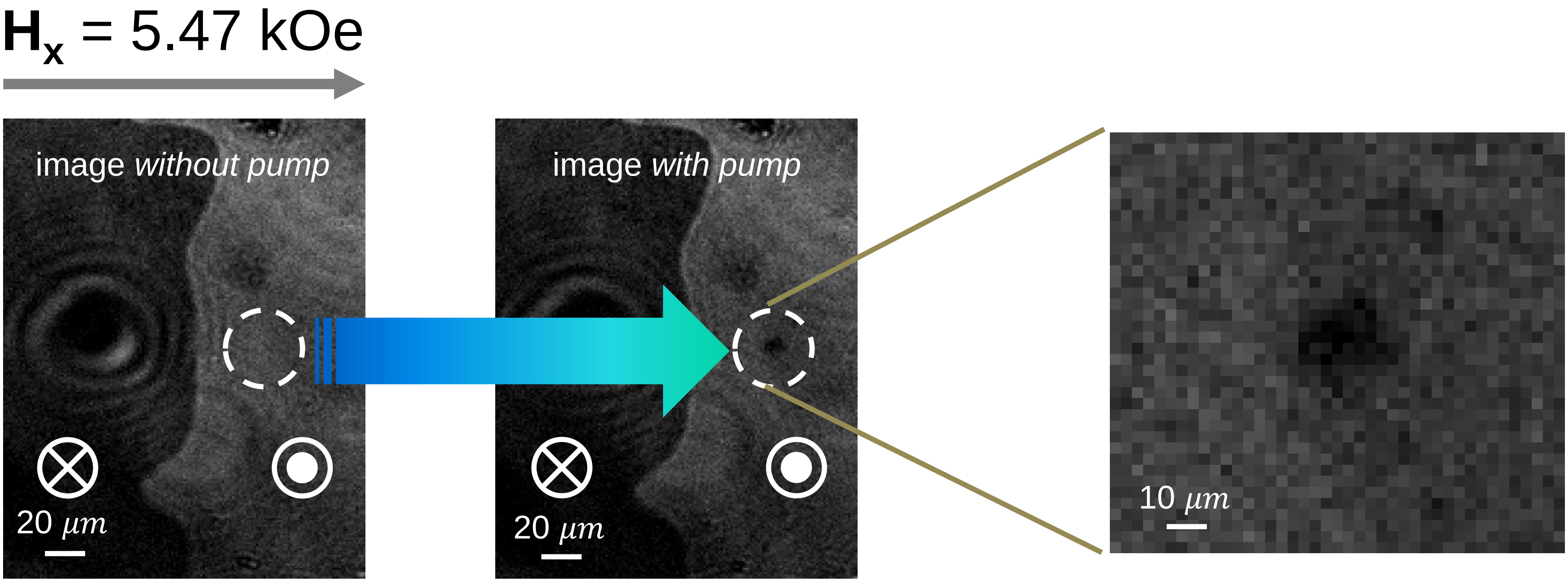


Bi-substituted Yttrium Iron Garnet (Bi:YIG)
Ferrimagnet with strong out-of-plane anisotropy
Low Gilbert damping

Experimental setup



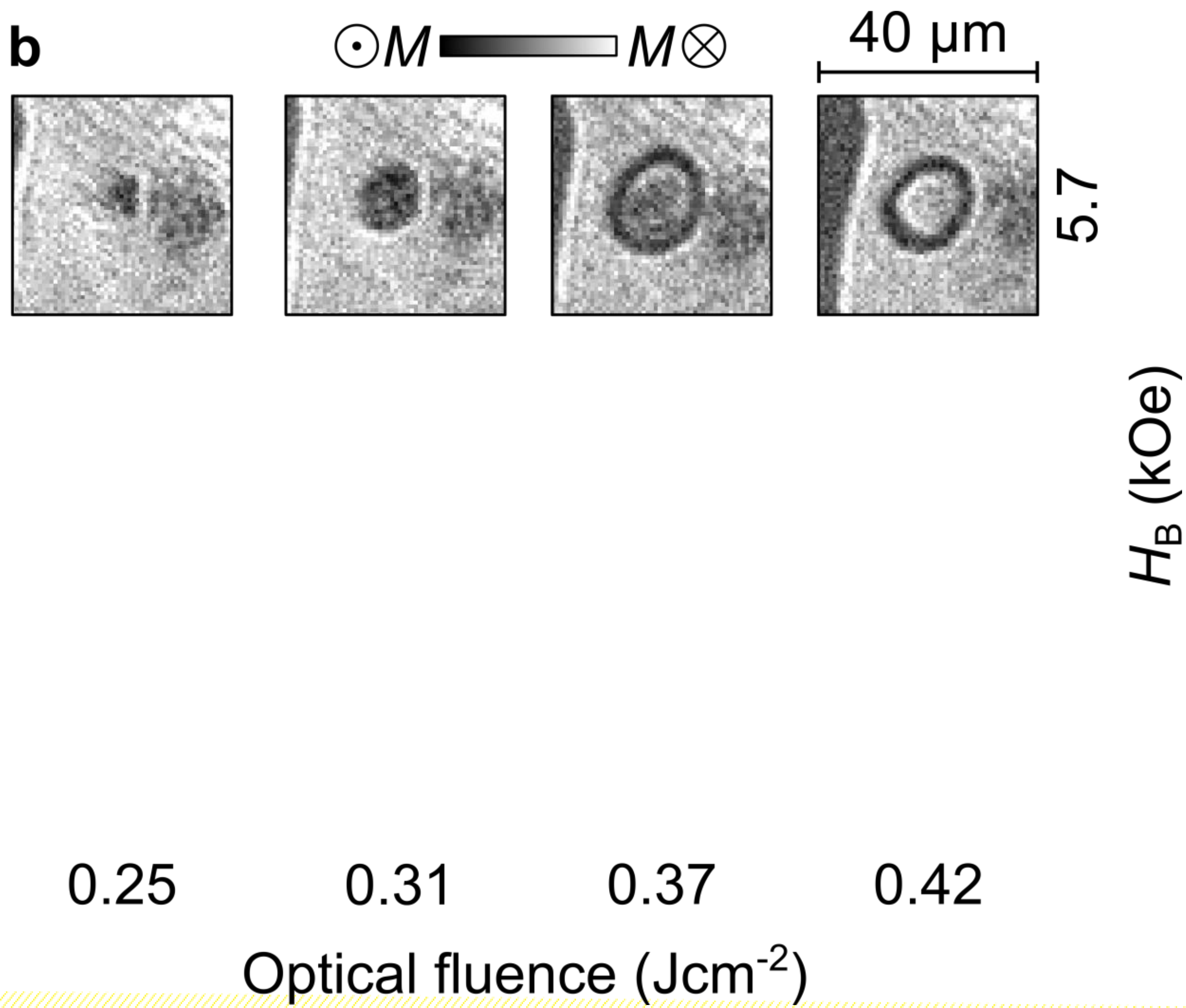
Heat-assisted magnetic switching



$\tau = 3.45$ ns

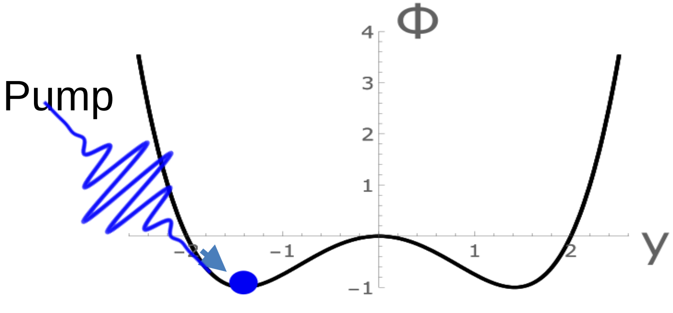
Swicthing as a function of pump and magnetic field

Inhomogenious switching!

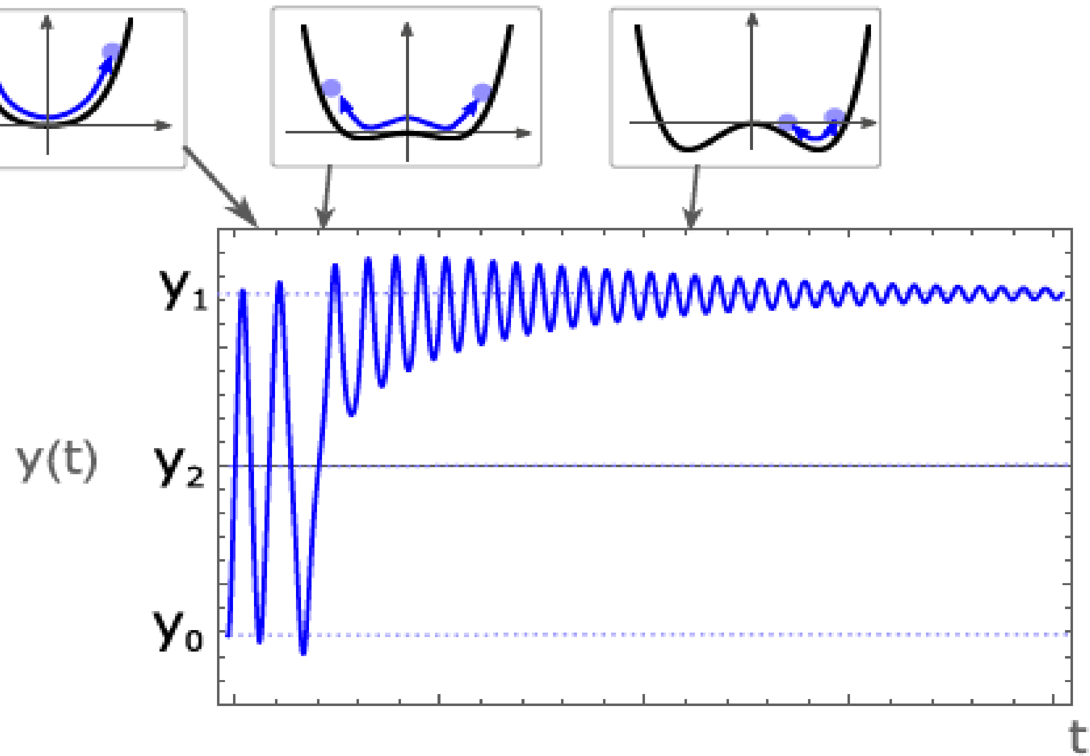


Toy model of the switching

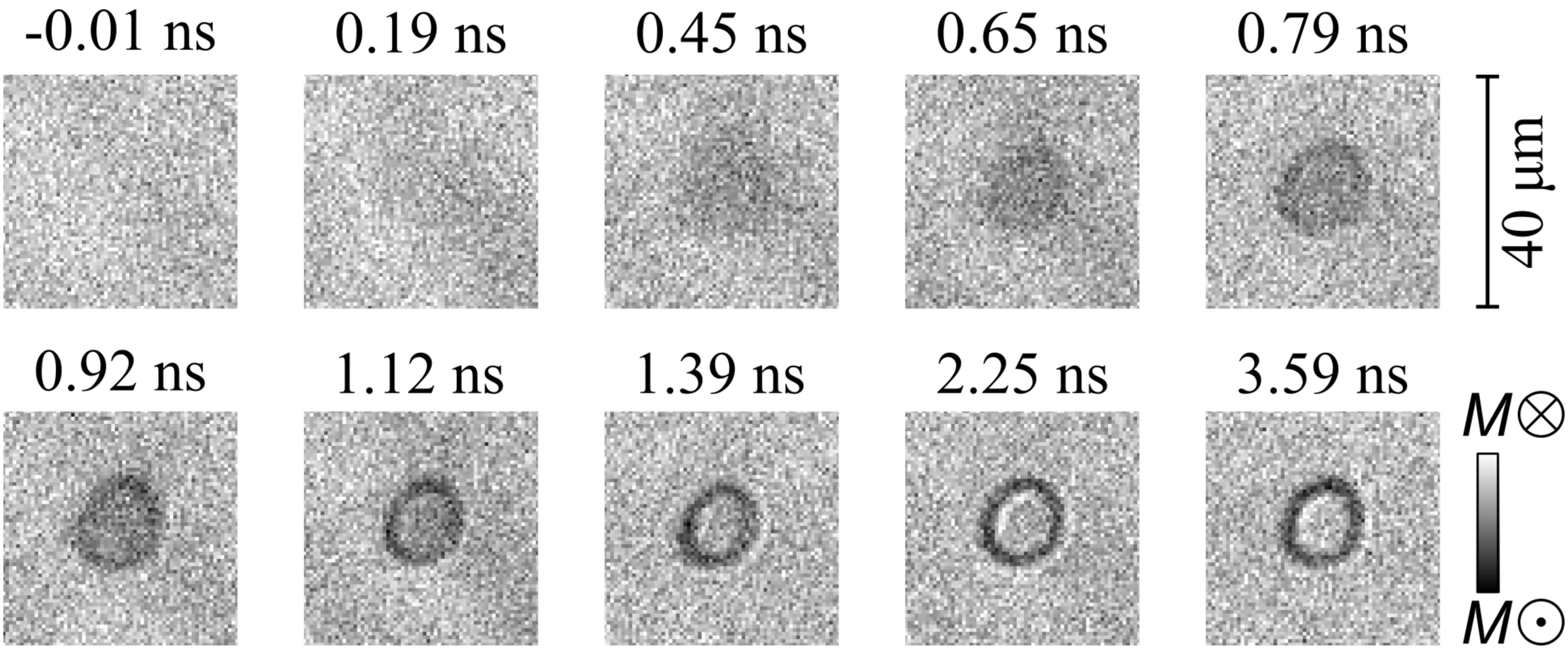
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} - \frac{\lambda}{M^2} \mathbf{M} \times \left(\mathbf{M} \times \mathbf{H}_{eff} \right)$$



Initial state
(y_0)

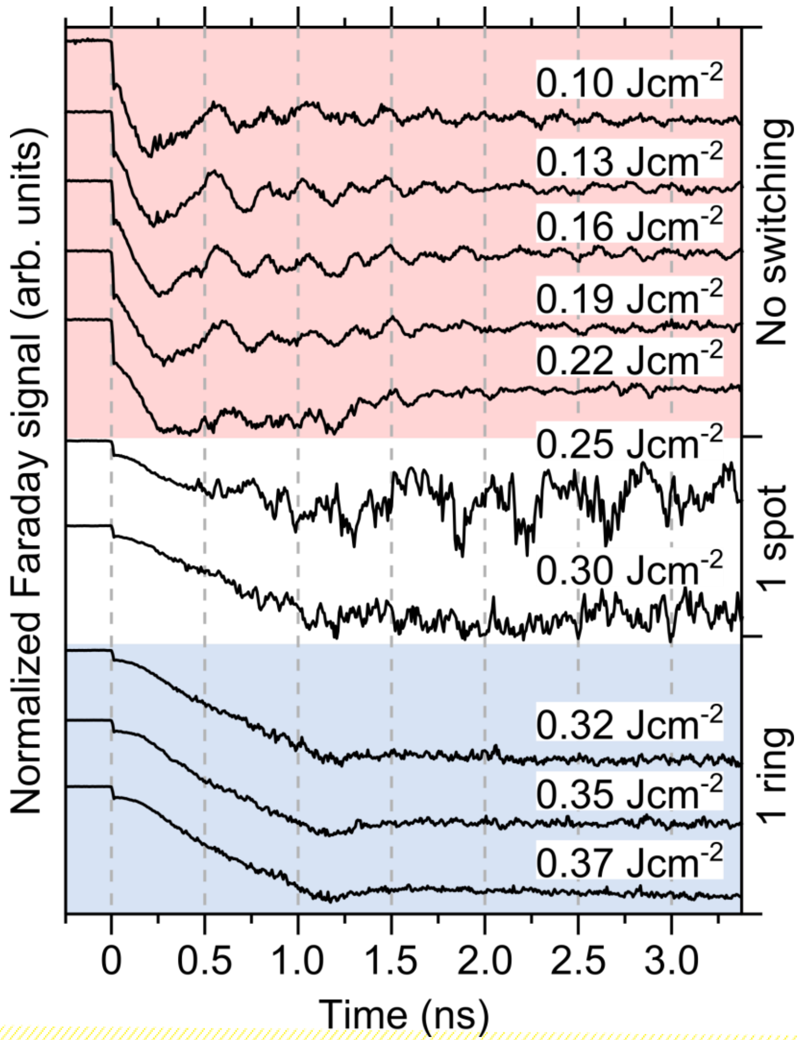


Dynamics of the switching



Huge damping!

Damping as a function of amplitude

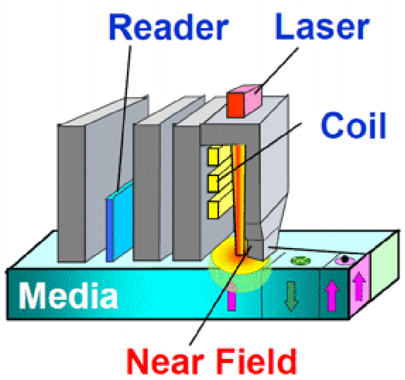


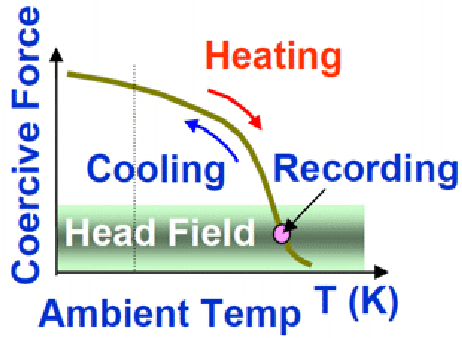
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} - \frac{\lambda}{M^2} \mathbf{M} \times \left(\mathbf{M} \times \mathbf{H}_{eff} \right)$$

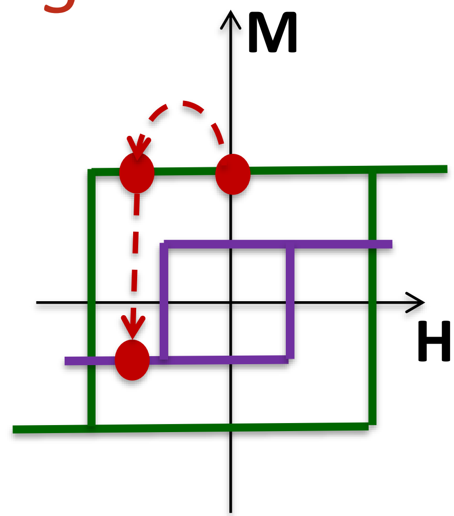
λ is a function of the amplitude!

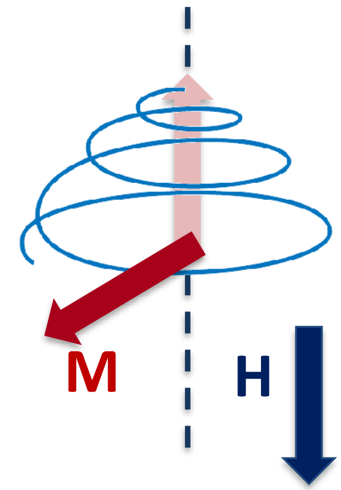
State-of-the-art in data storage:

heat assisted magnetic recording









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Magnetization reversal

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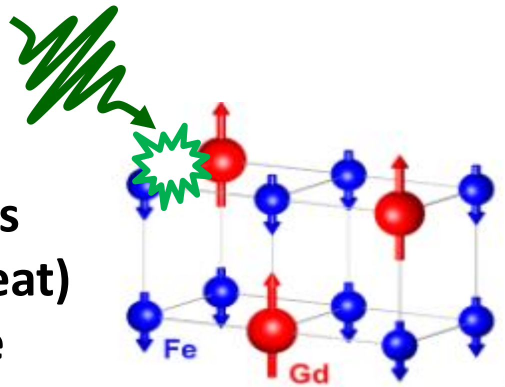
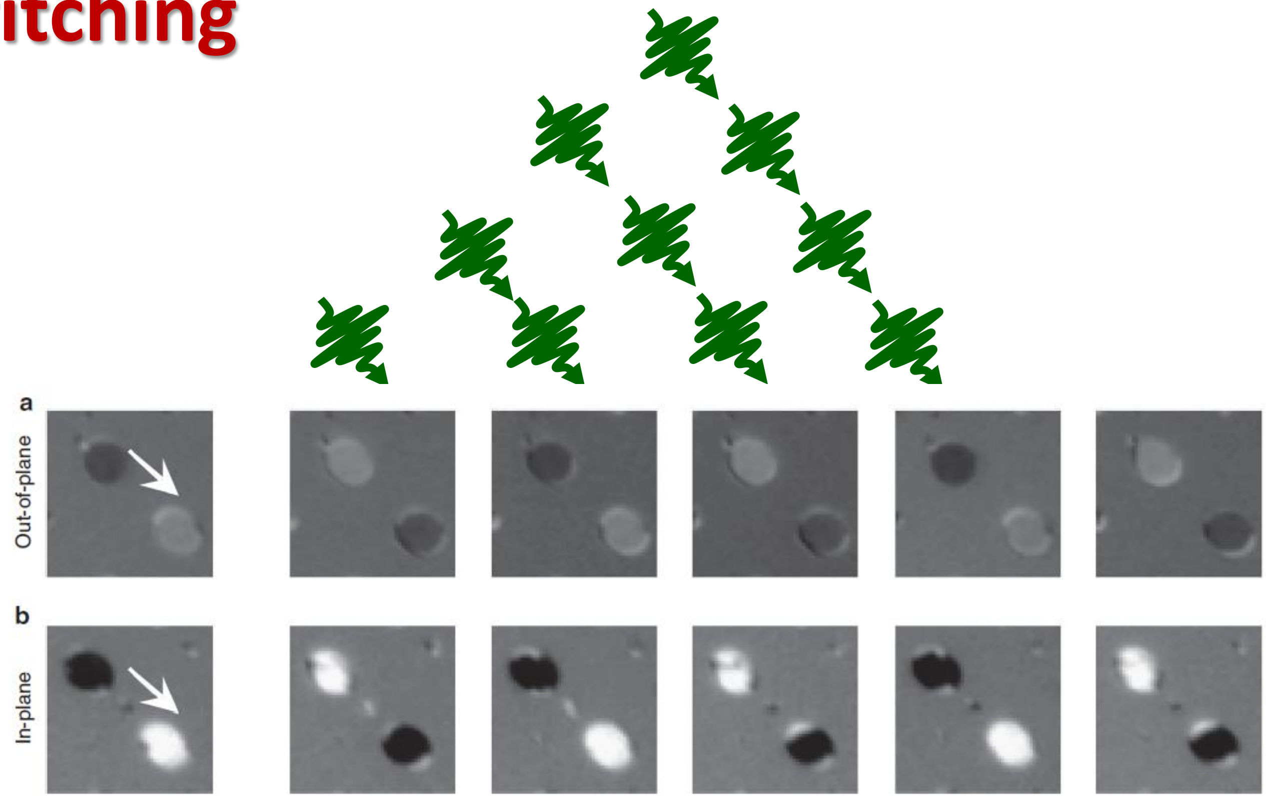
Toggle magnetic switching

Sub-ps
laser (heat)
pulse





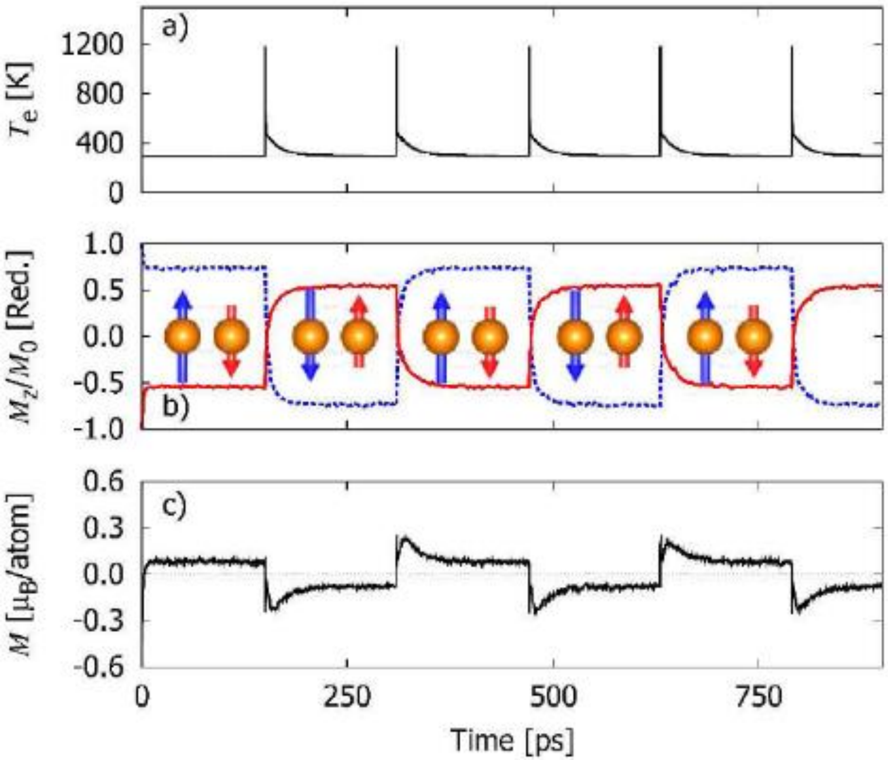
T. Ostler et al *Nature Comm.* **3**, 666 (2012).

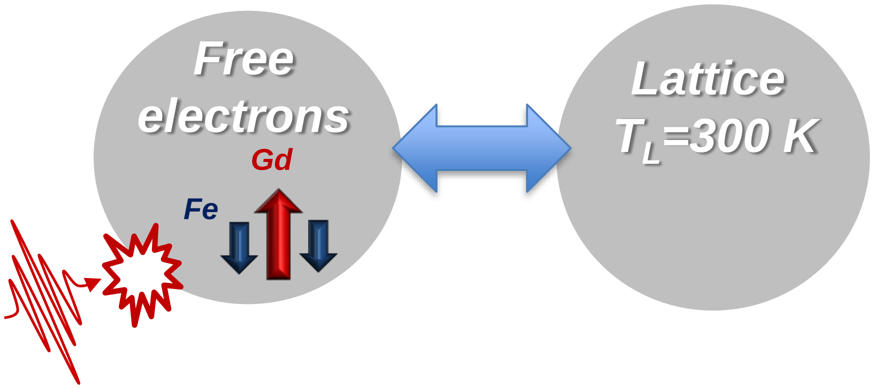
Ultrafast toggle switching of magnetization violates the Curie principle!

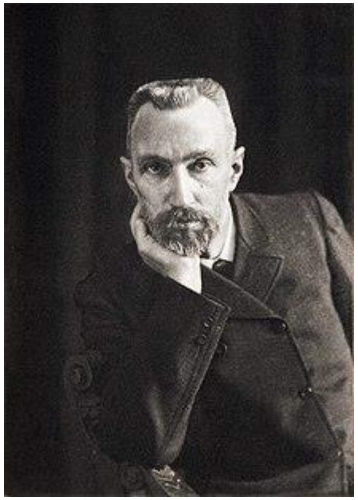
Heat as a sufficient stimulus for magnetization reversal

"Two-spin" model. Heat-induced reversal

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





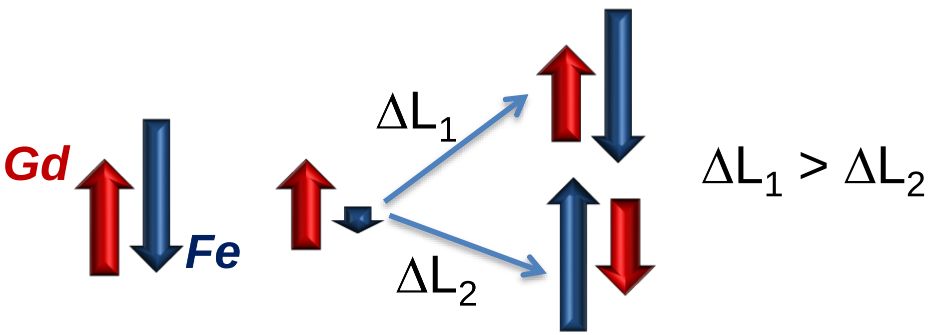


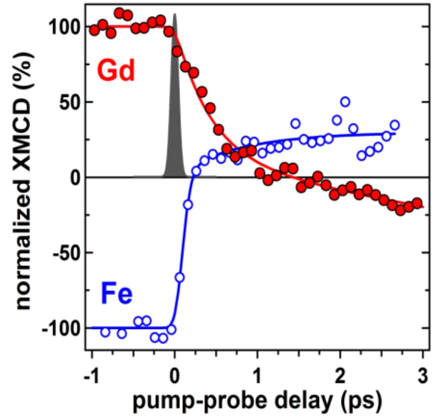
P. Curie (1894):

"the symmetries of the causes are to be found in the effects".

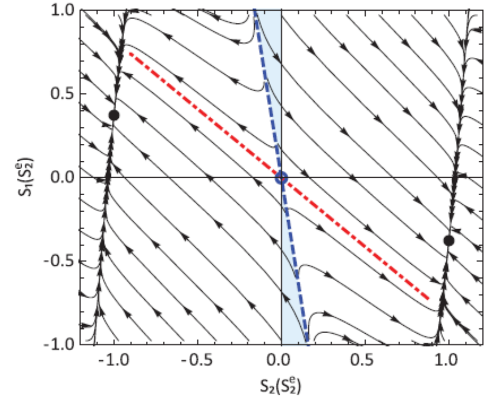
How can heat-induced magnetization reversal be possible at all?

Two-spin model and conservation of angular momentum





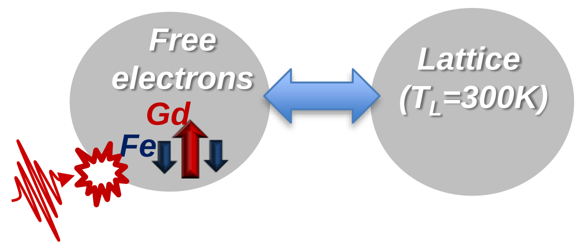
I. Radu et al, *Nature* **472** 205-208 (2011).



J. Mentink et al, *Phys. Rev. Lett.* **108**, 057202 (2012).

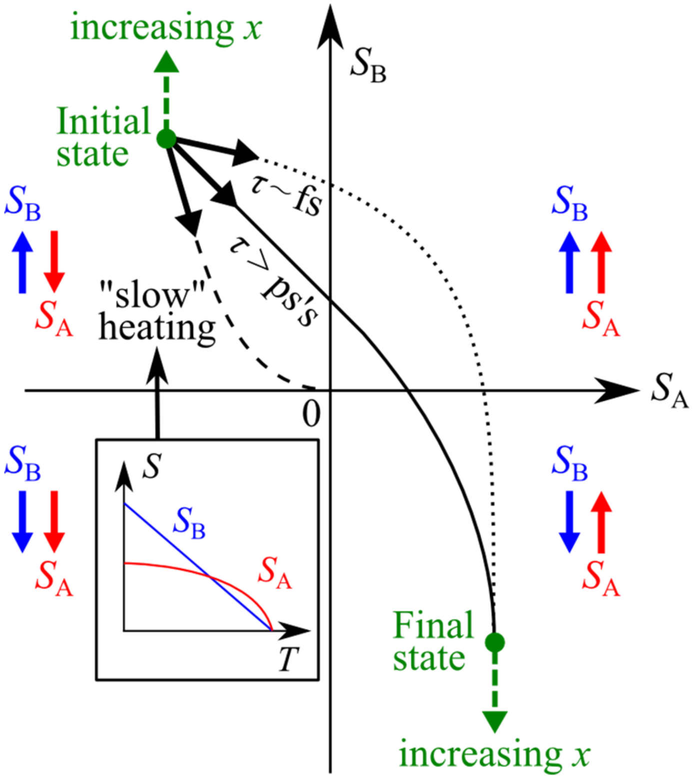
CREDIT: NIELS BOHR ARCHIVE, PHOTOGRAPH BY ERIK GUSTAFSON, COURTESY AIP EMILIO SEGRÈ VISUAL ARCHIVES, MARGRETHE BOHR COLLECTION

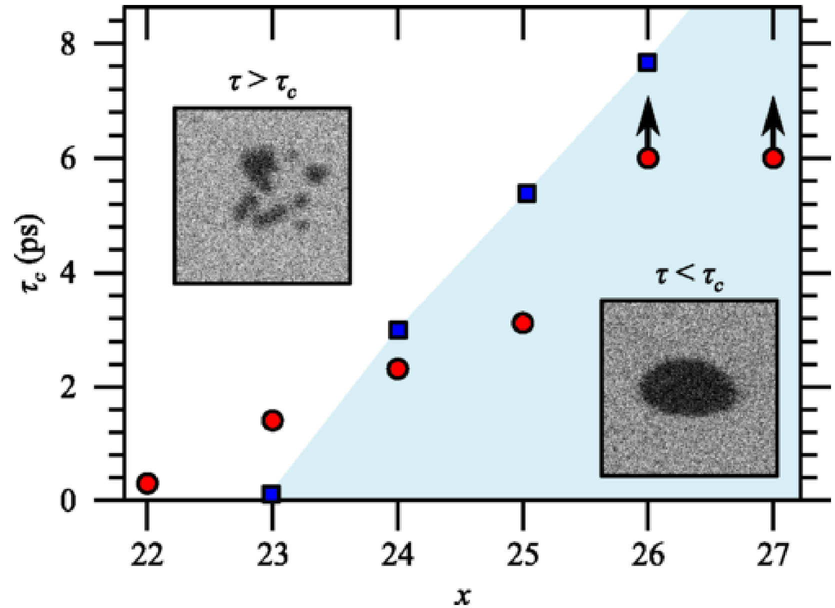
Physicists Wolfgang Pauli, left, and Niels Bohr demonstrating a "tippe top" toy in 1954. Tippe tops flip upside down to spin on their handle and are part of the "Secret Science of Toys" festival at the Fleet Science Center on Jan. 21.



1) **Hot electrons** ($t<\tau_{e\text{-}ph}$)
2) **Different demagnetizations** ($t<\tau_{Fe\text{-}Gd}$)
3) **Strongly non-equilibrium state** ($t\sim t_{e\text{-}ph}$ and $t<\tau_{Fe\text{-}Gd}$)
4) **Relaxation**

Femtosecond *vs* picosecond pulse excitation





C. Davies et al, arXiv:1904.11977 (2019).
Phys. Rev. Applied **13**, 024064 (2019).

Sublattices are brought out of mutual equilibrium, if excited faster than the Fe-Gd exchange interaction

SCIENCE ADVANCES | RESEARCH ARTICLE

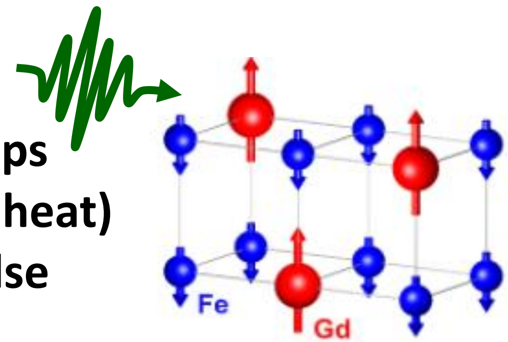
PHYSICS

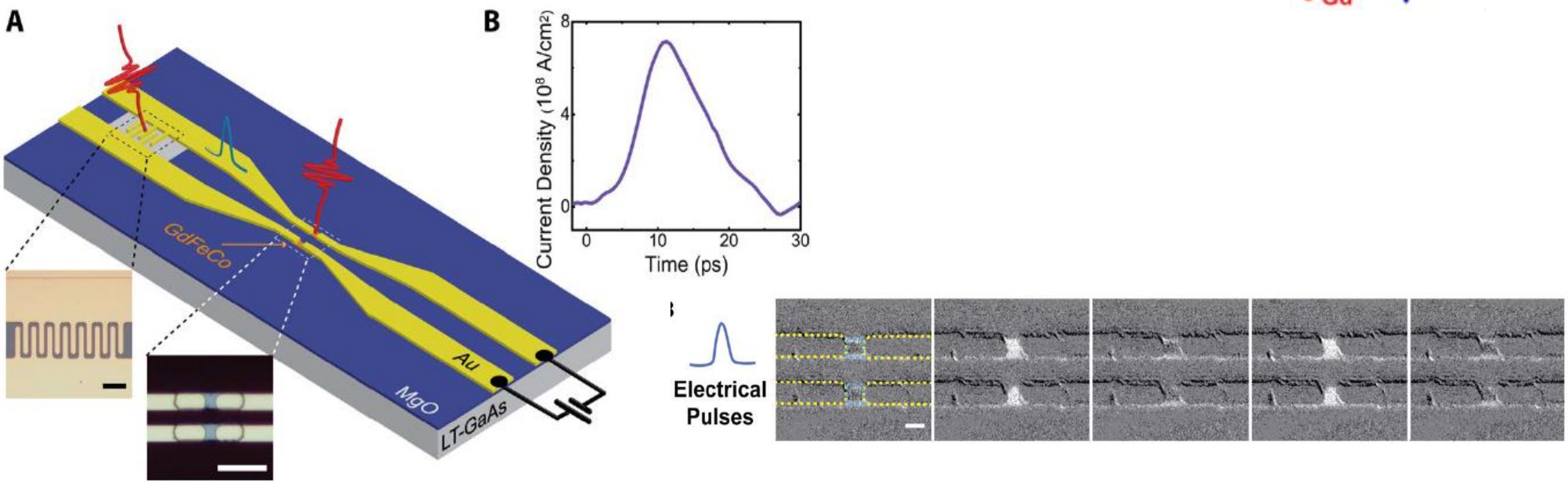
Ultrafast magnetization reversal by picosecond electrical pulses

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

Sci. Adv. e1603117 3 (2017).

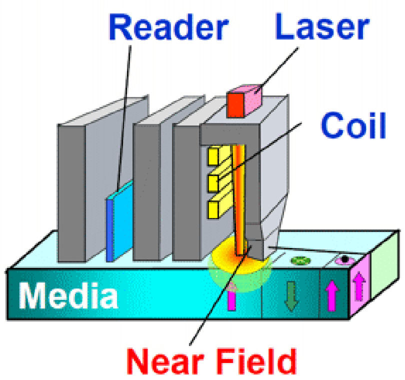
10 ps laser (heat) pulse

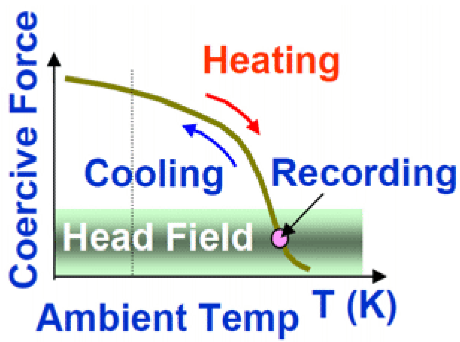


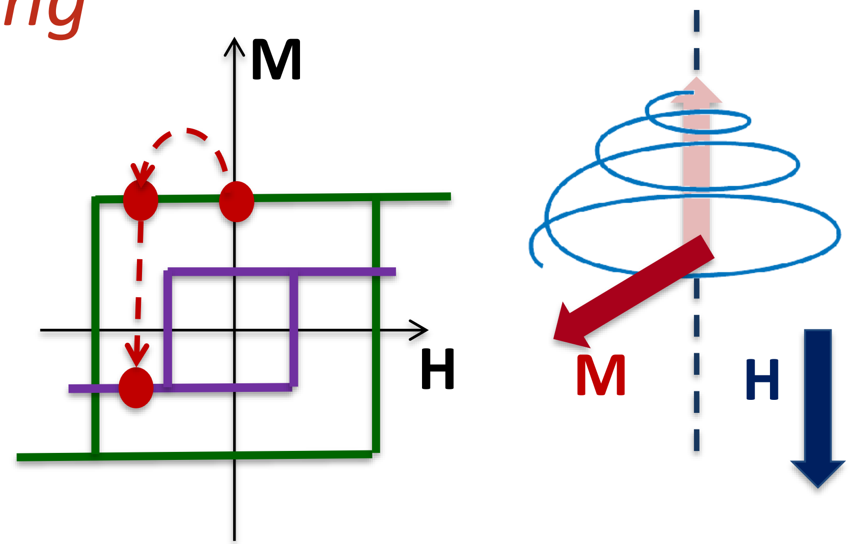


Ultrafast heating as a stimulus!

State-of-the-art in data storage:
heat assisted magnetic recording





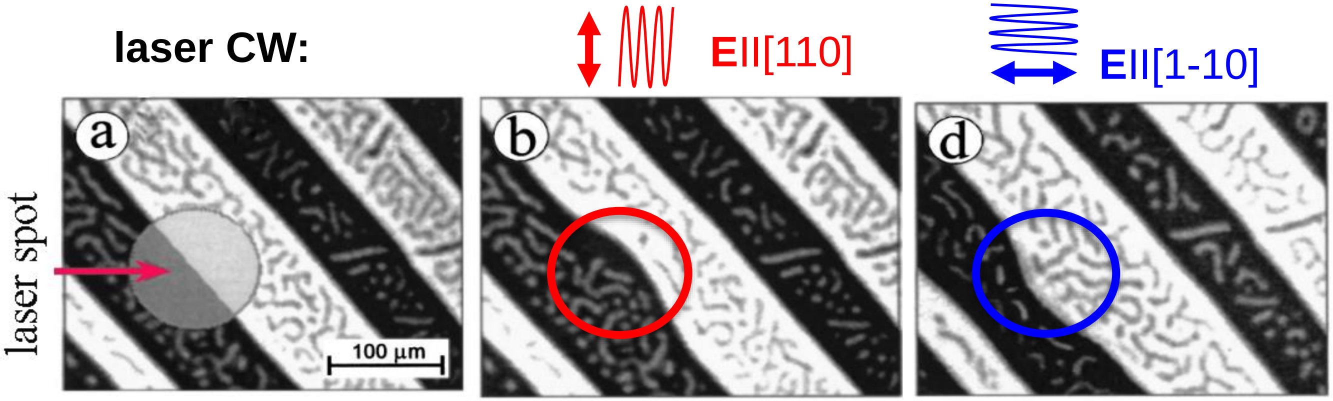


$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} - \frac{\lambda}{M^2} \mathbf{M} \times \left(\mathbf{M} \times \mathbf{H}_{eff} \right)$$

Magnetization reversal

- with a magnetic field in a “wrong” direction;
- without any magnetic field and solely with heat;
- with no heat, no field.

Photo-magnetism of Co-substituted iron garnet

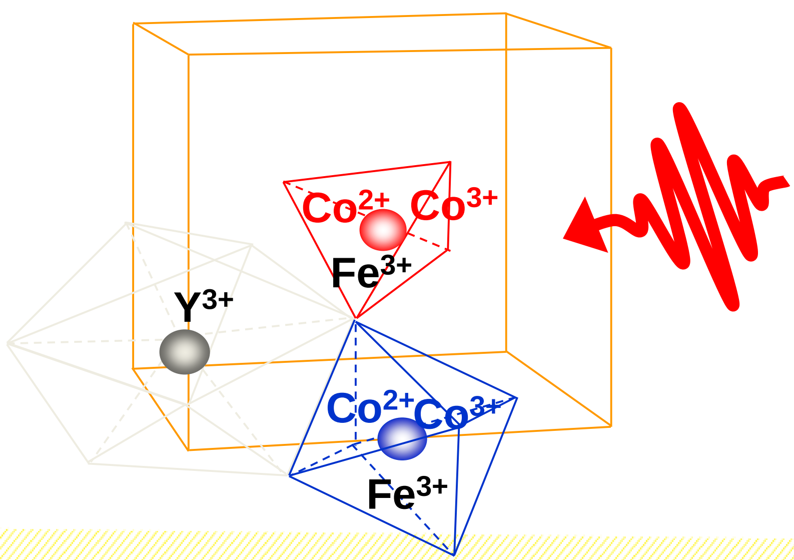


$Y_2CaFe_{3.9}Co_{0.1}GeO_{12}$ / GGG (001)

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

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

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

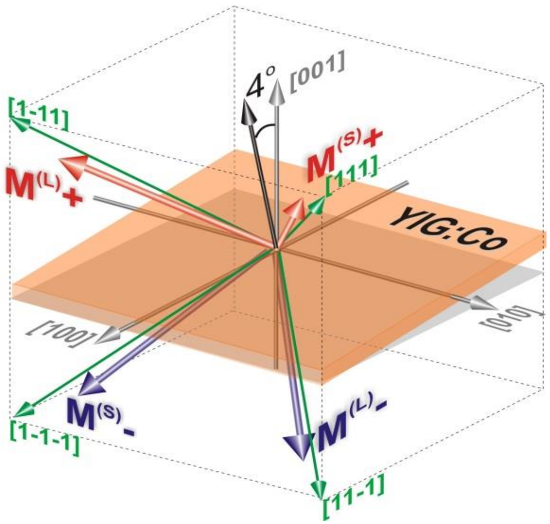


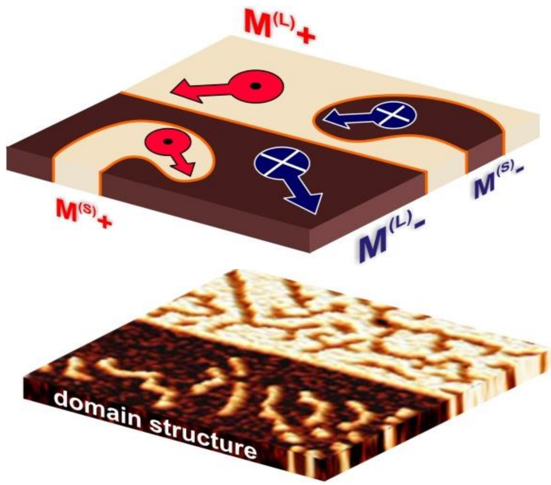
Recording?

Heating?

Speed?

Photo-magnetic recording in iron garnet





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

A. Stupakewiecz et al,
arXiv:1609.05223
Nature **542**, 71 (2017).

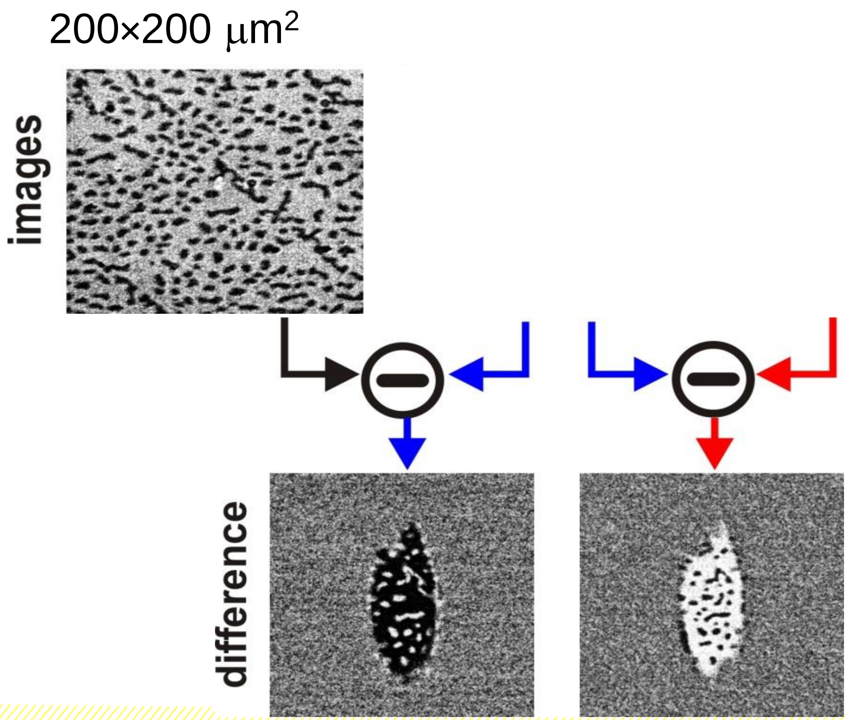
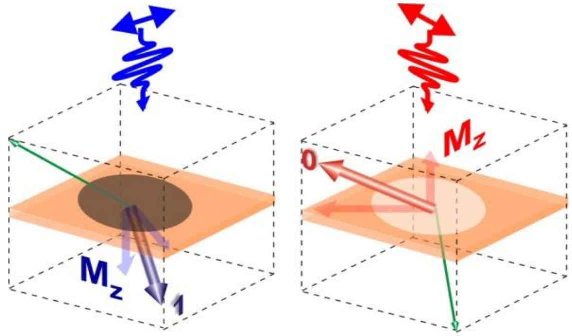
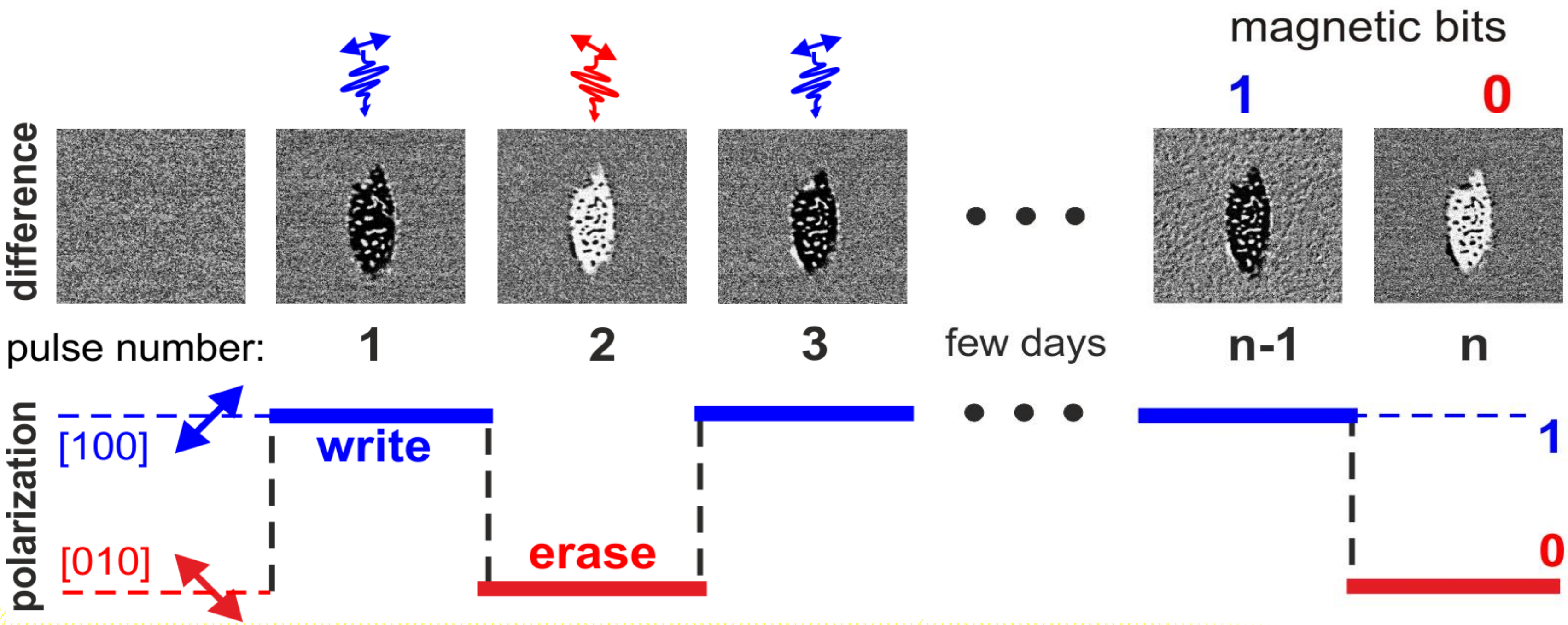


Photo-magnetic recording

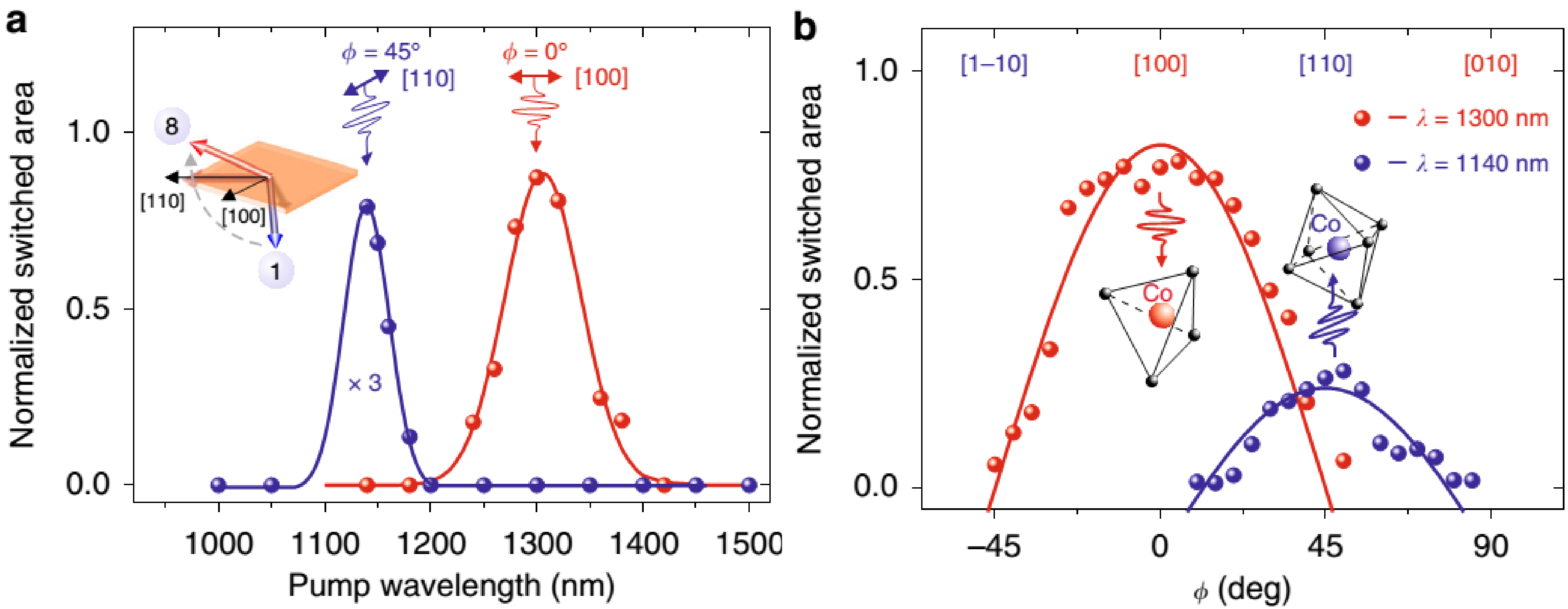
- ✓ single pulse
- ✓ repeatable switching
- ✓ zero applied field
- ✓ room temperature

A. Stupakewiecz et al,
arXiv:1609.05223
Nature **542**, 71 (2017).





Selection rules for magnetic writing with light on iron-garnet

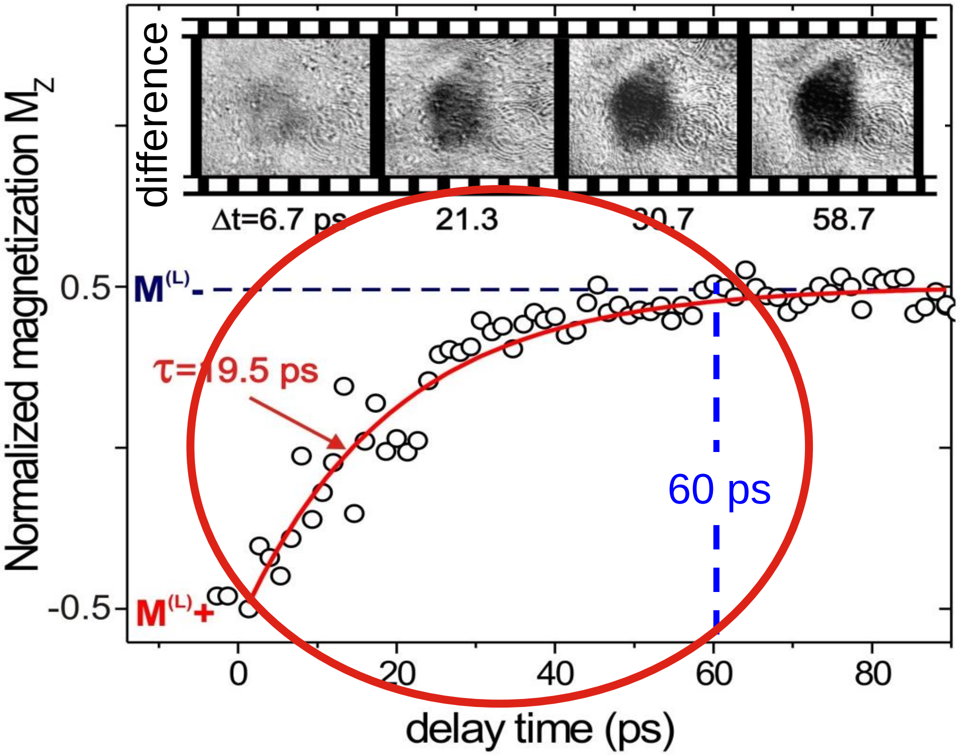


Optical resonant excitation of tetrahedral and octahedral Co^{2+} sublattices

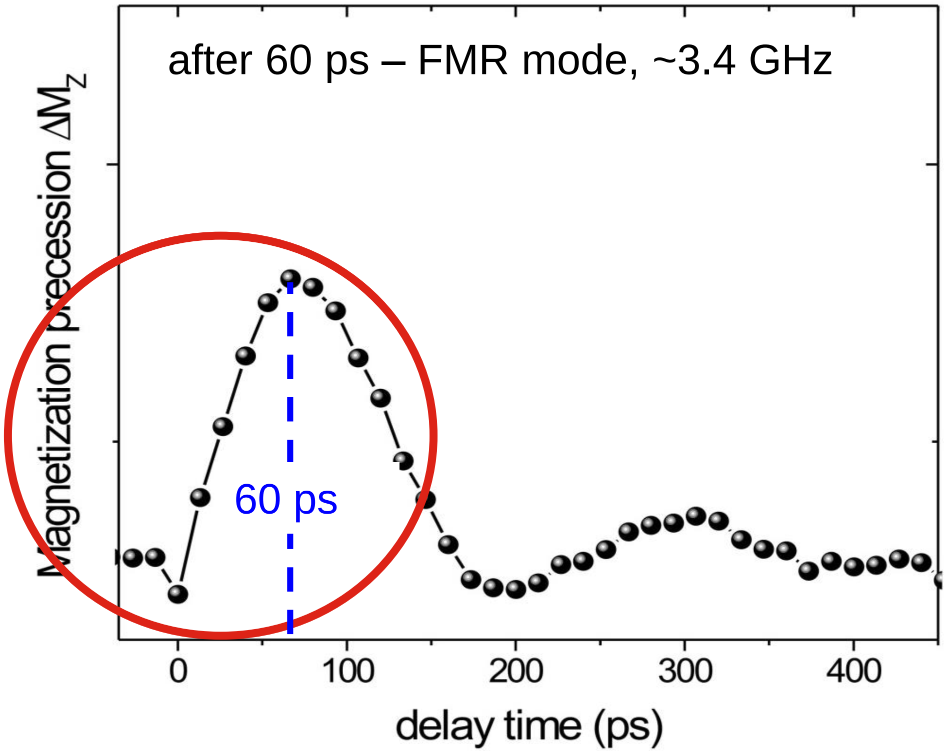
A. Stupakiewicz et al, *Nature Comm* **10**, 612 (2019).

Dynamics of the laser-induced switching in garnet

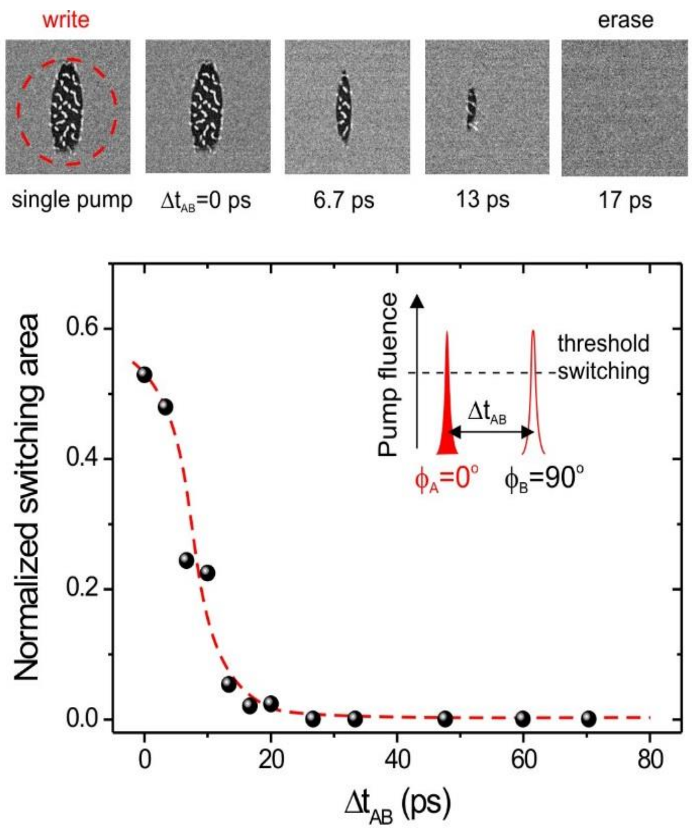
switched after the first quarter-period

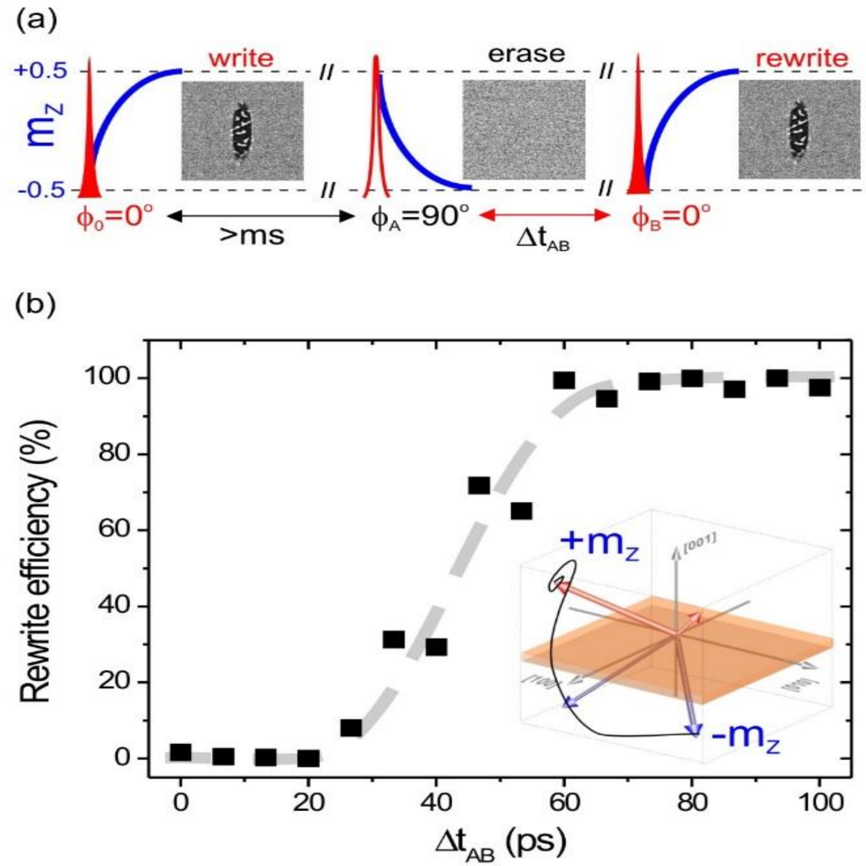


high Gilbert damping: α = 0.2



Fundamental limits of repetition rate of magnetic writing on $Y_3Fe_5O_{12}$:Co

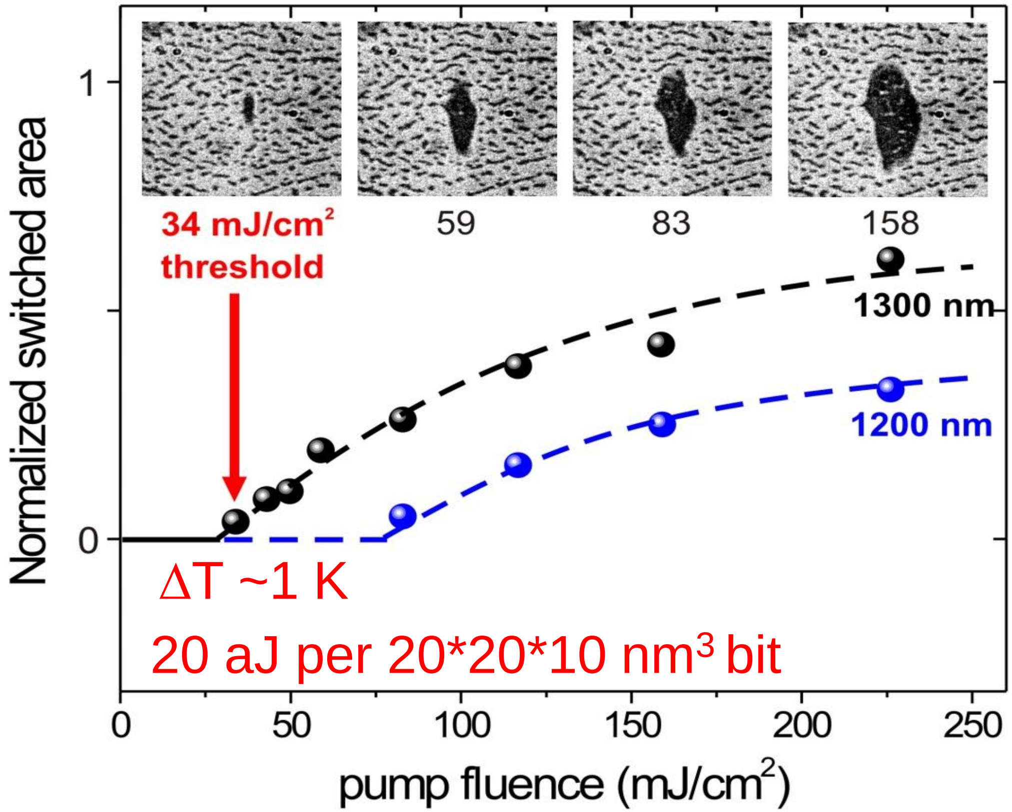


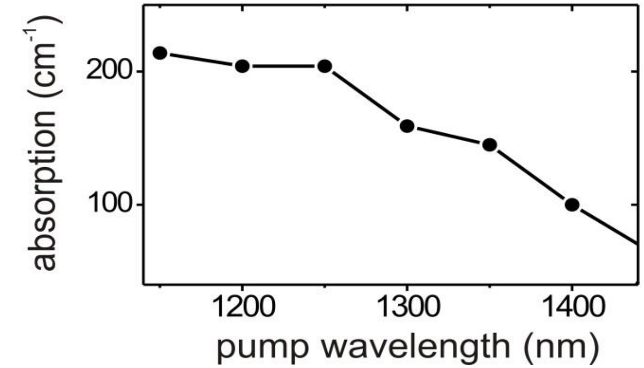


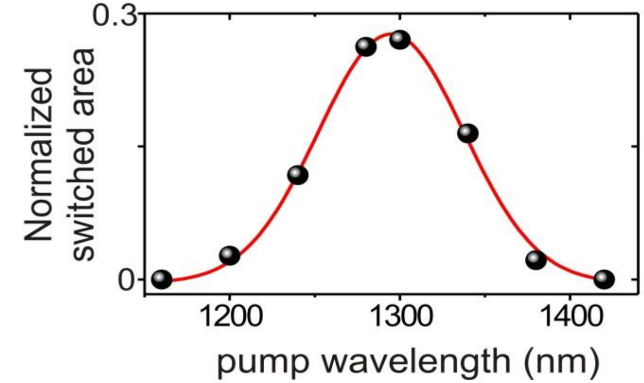
Rewriting at the frequency of 20 GHz (50 ps per bit)**!**

K. Szerenos et al. *Phys. Rev. Applied* **12**, 044057 (2020).

Efficiency of the photo-magnetic recording







Optical resonant excitation of tetrahedral Co^{2+}

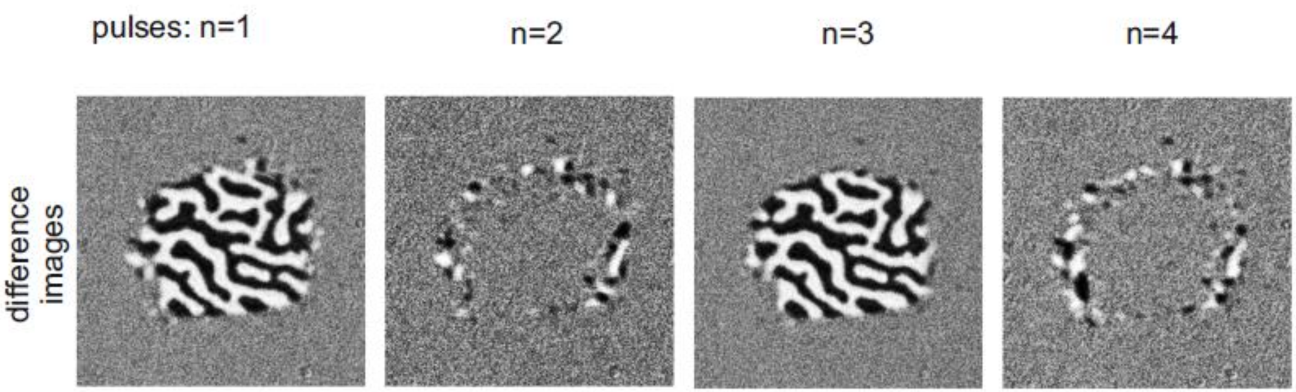
nature communications

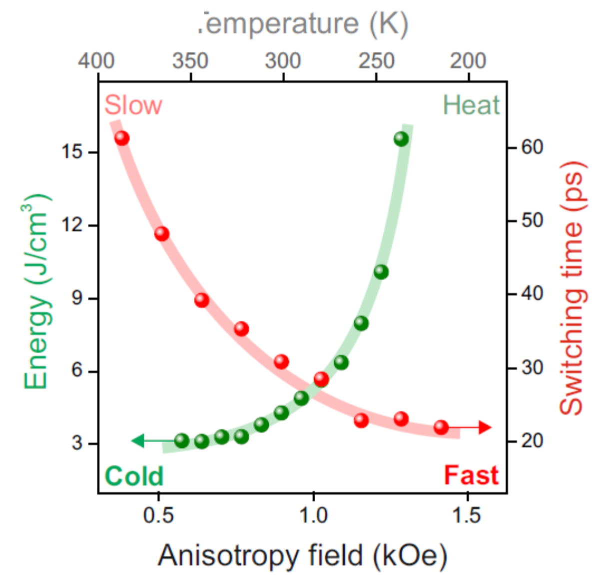
Article

https://doi.org/10.1038/s41467-024-48438-3

Ultrafast all-optical toggle writing of magnetic bits without relying on heat

T. Zalewski[1], A. Maziewski[1], A. V. Kimel[2] & A. Stupakiewicz[1]





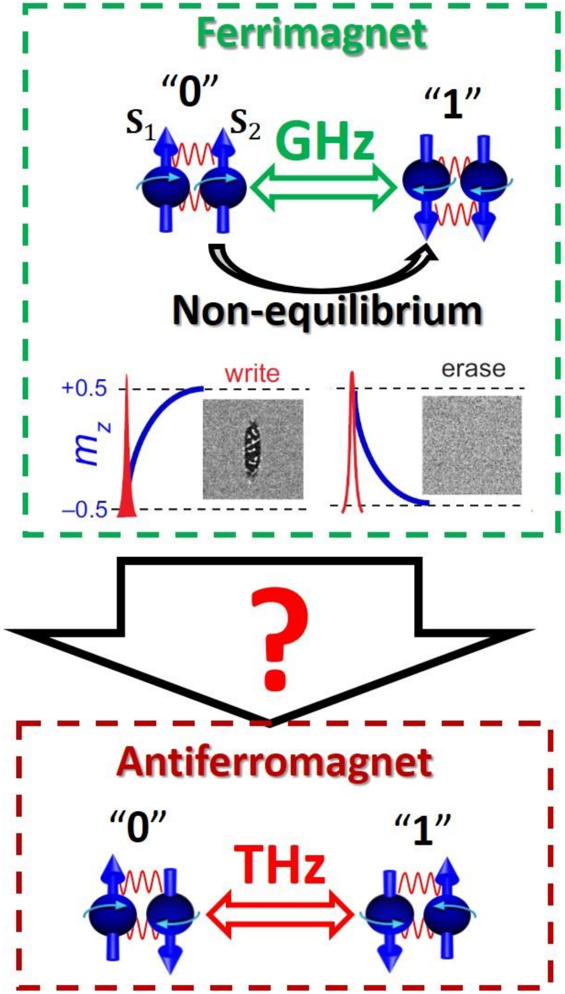
Summary

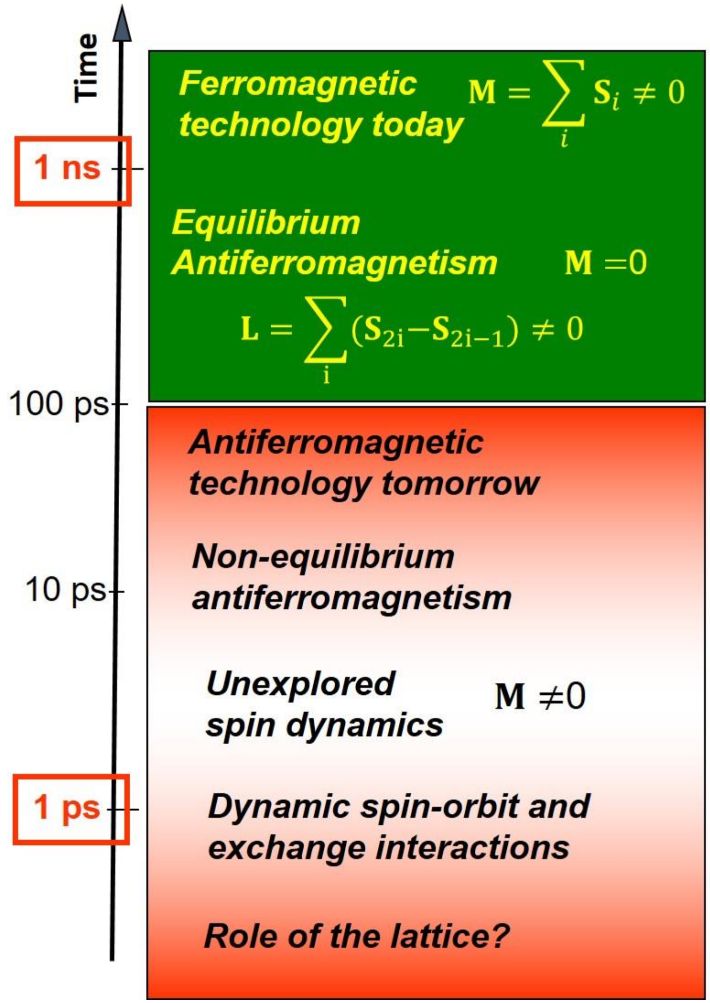
- Understanding magnetization reversal is the key for understanding the fundamental limits on the rate of writing of magnetic bits.

- Ultrafast magnetization reversal is a counter-intuitive process.

- If a stimulus is ultrafast, magnetization can be reversed with a "wrong" magnetic field, solely with heat or even without any heat.

Outlook – *ultrafast antiferromagnetism as the next challenge*





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