Tutorial:

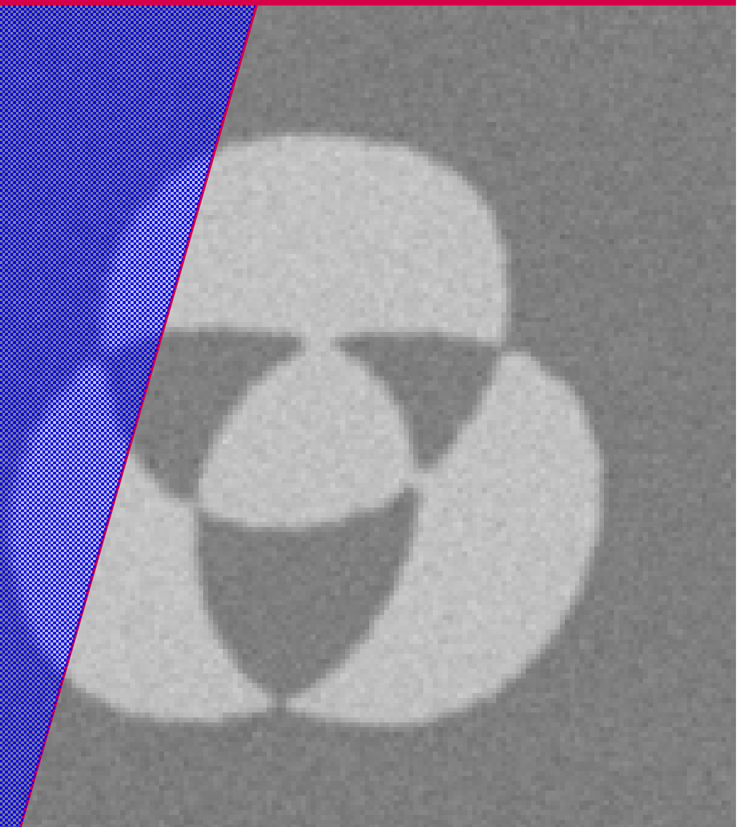
Merging Spintronics with Photonics

Laser-induced spin currents & all-optical switching of spintronic devices

Bert Koopmans

SPICE: Ultrafast Spintronics Workshop

SML, Mainz 2018



Institute for Photonic Integration
Materials · Devices · Systems

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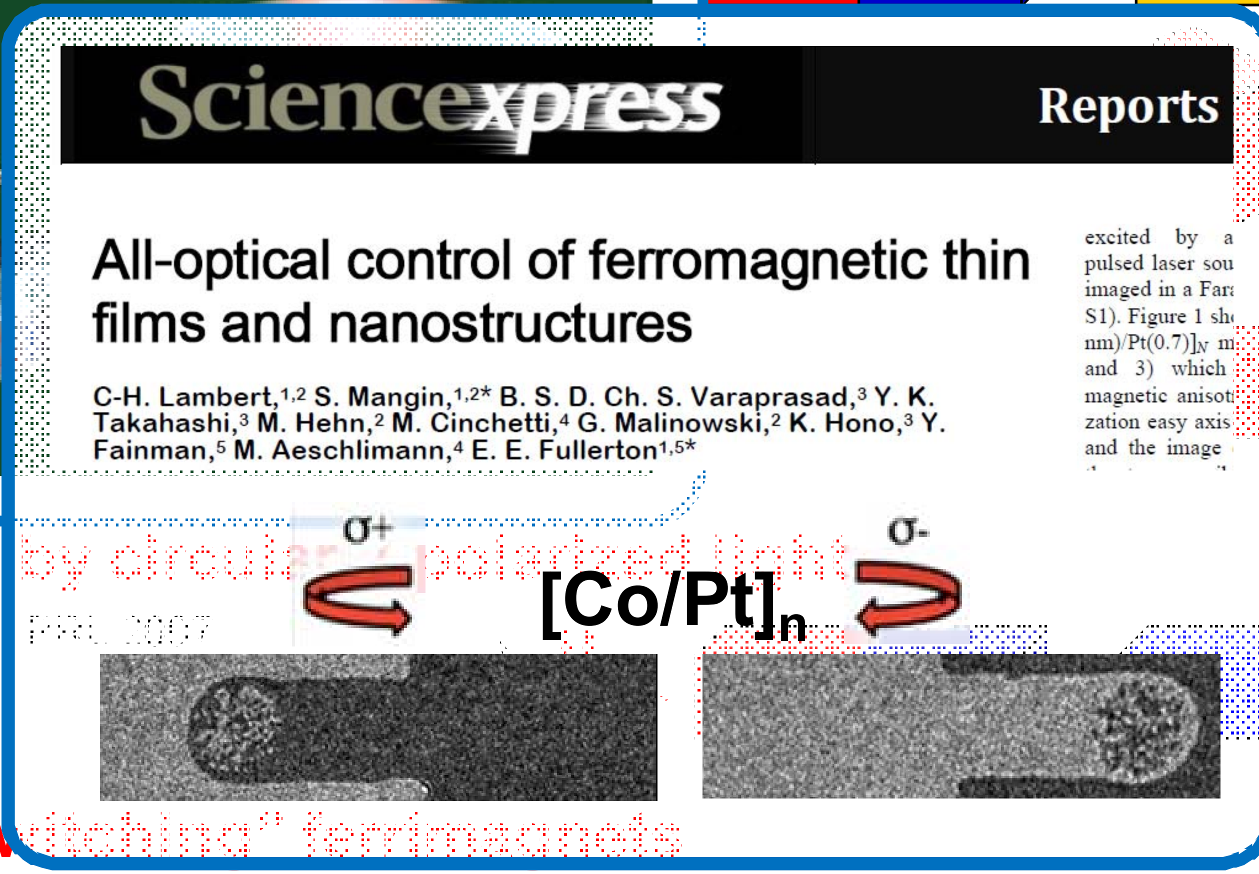
Where innovation starts

What happens after fs laser excitation?

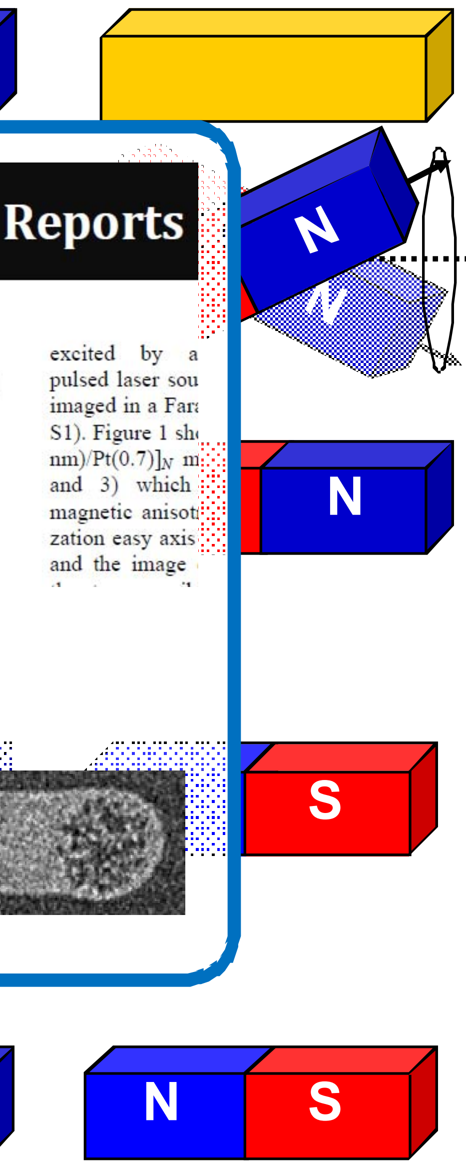


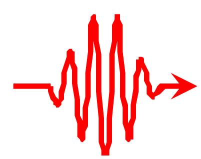
All-optical control of ferromagnetic thin films and nanostructures

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

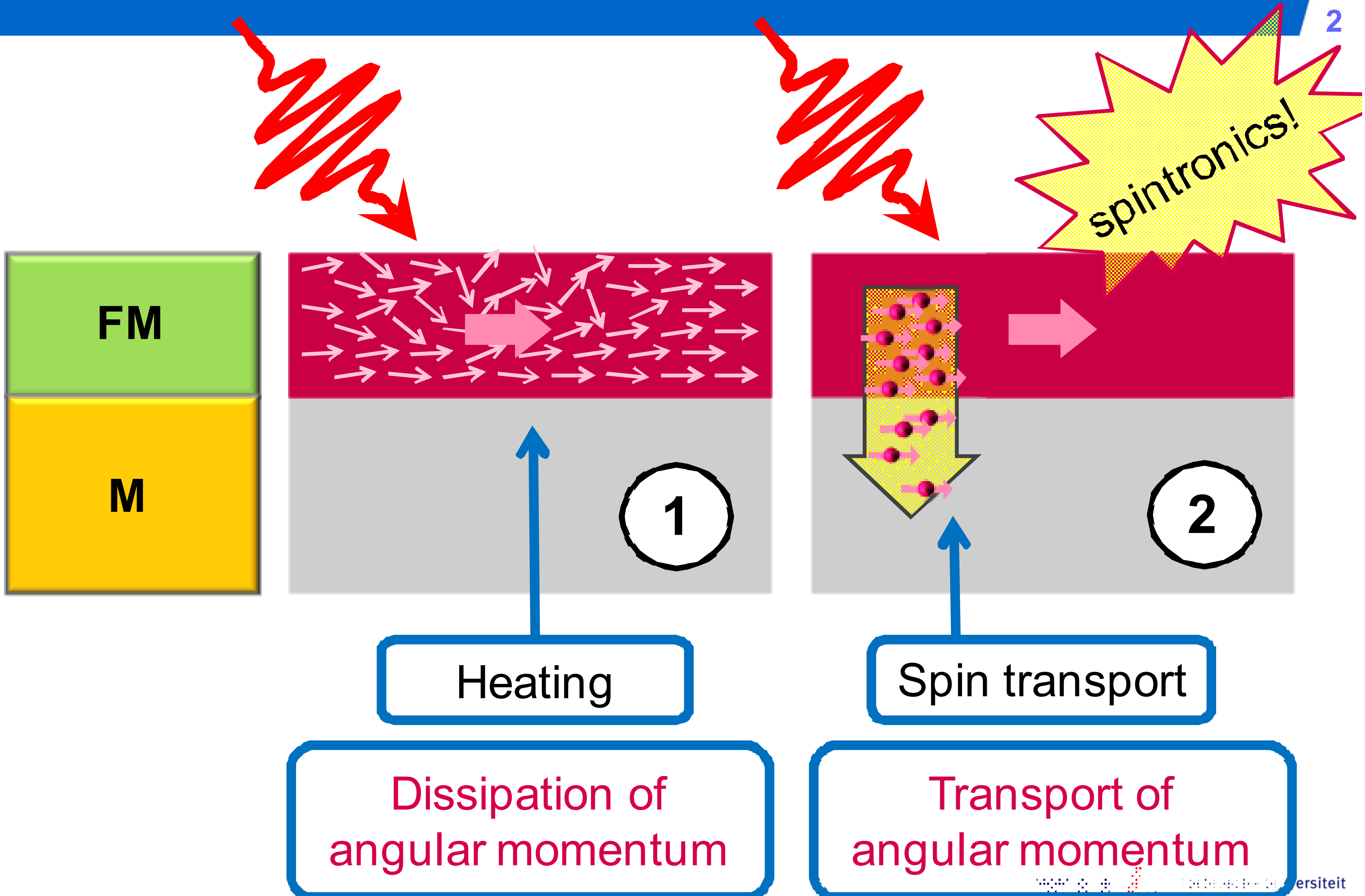
excited by a pulsed laser sou… imaged in a Fara… S1). Figure 1 sh… nm)/Pt(0.7)]$_N$ m… and 3) which … magnetic anisot… zation easy axis … and the image …

- **Switching by circular polarized light**
  - Stanciu et al. PRL 2007
- **“Toggle switching” ferrimagnets**
  - Radu et al., Nature 2011

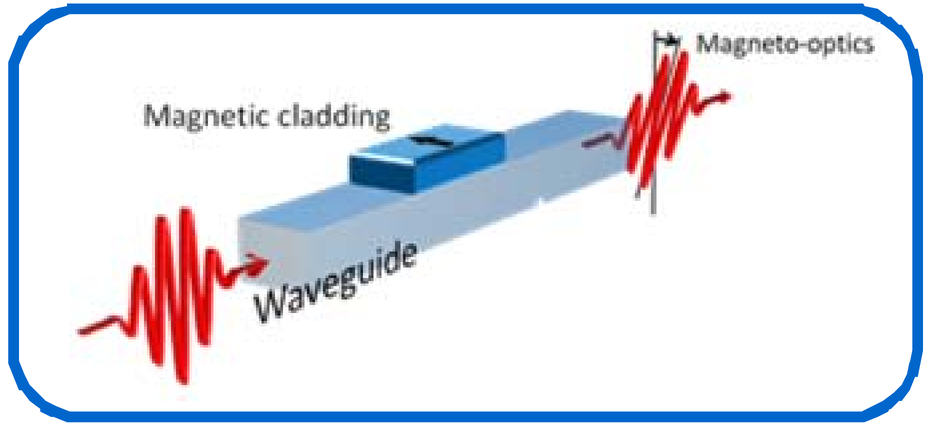


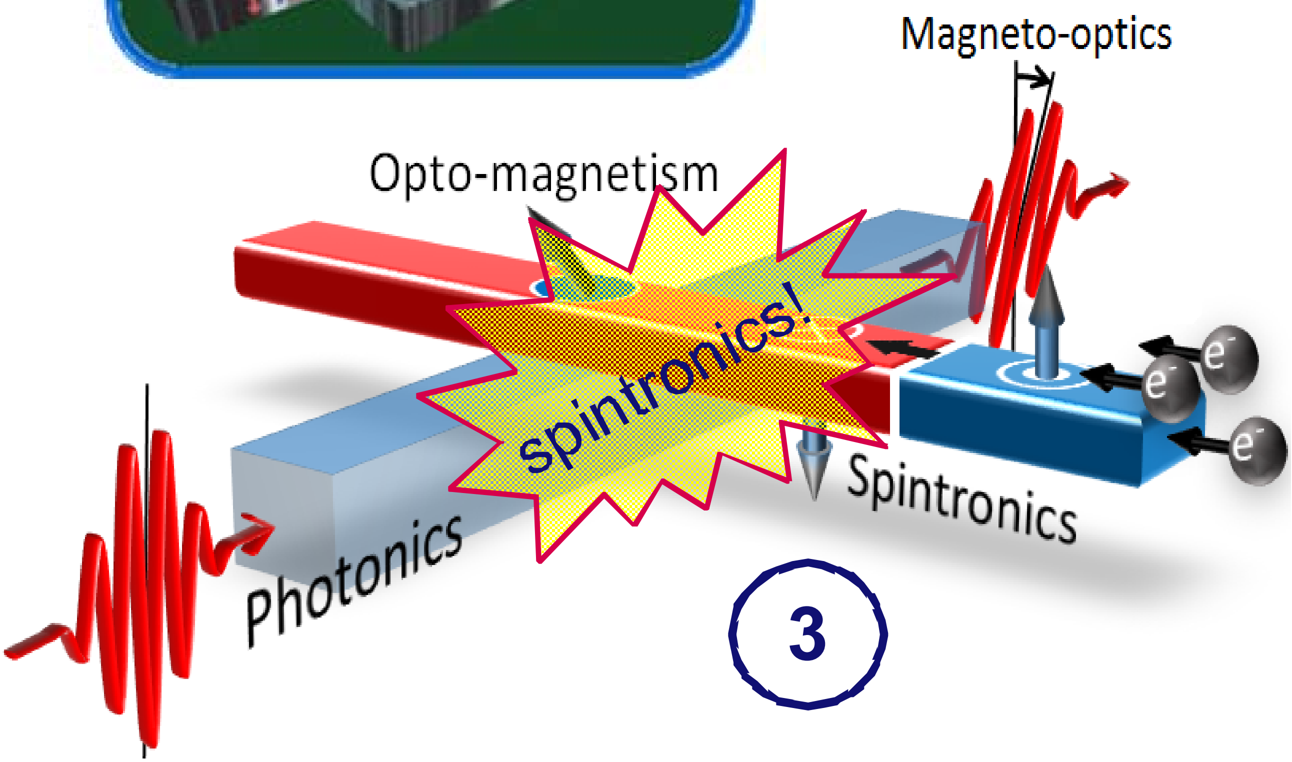
linear 

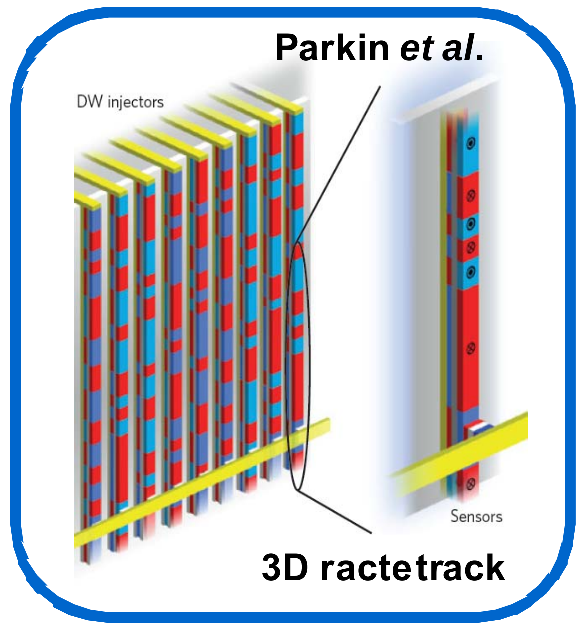
Outline: Local dynamics *vs.* spin transport



Outline: Towards Integrated MagnetoPhotonics







3

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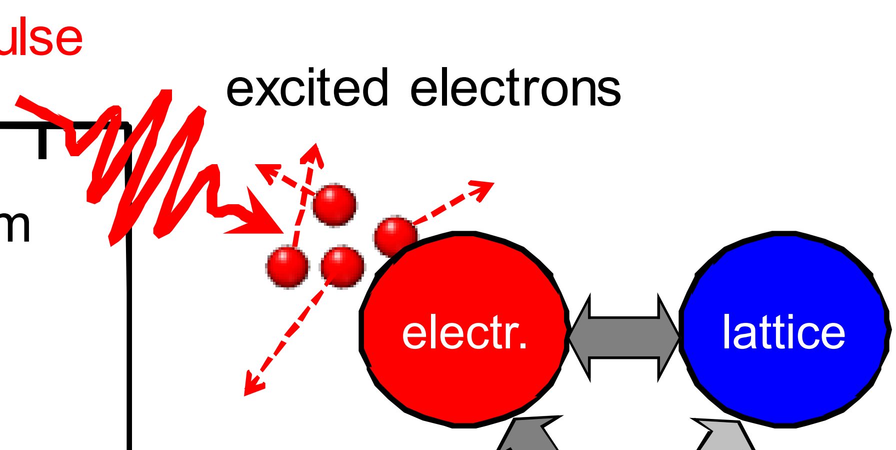
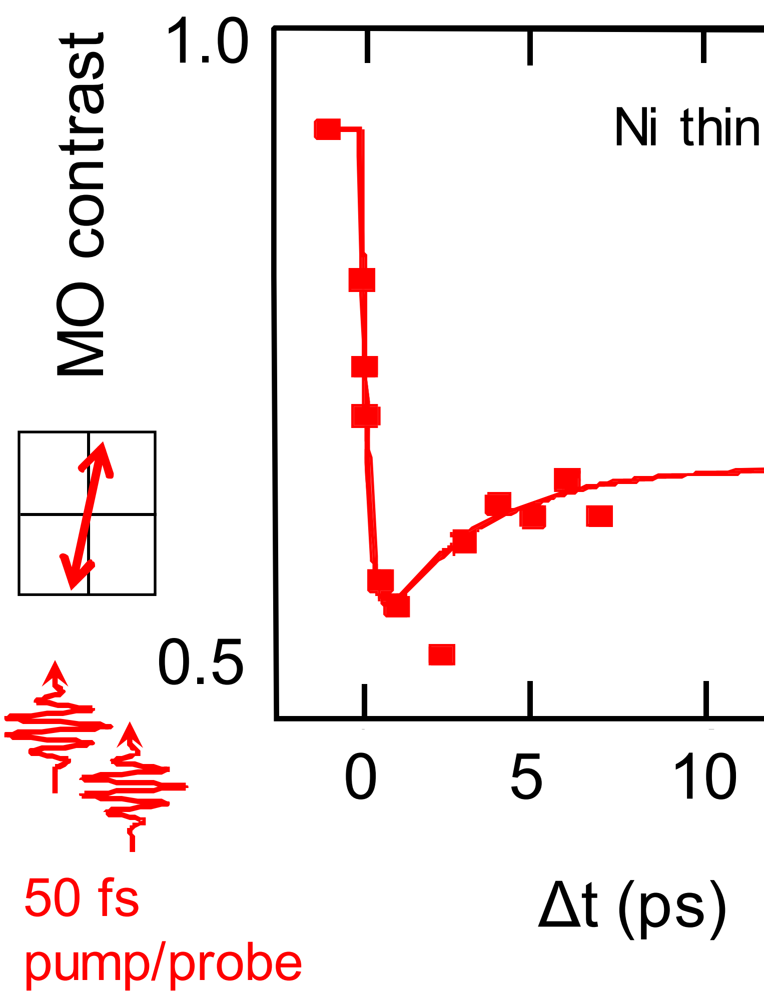
Essential ingredient: Fs loss of magnetization



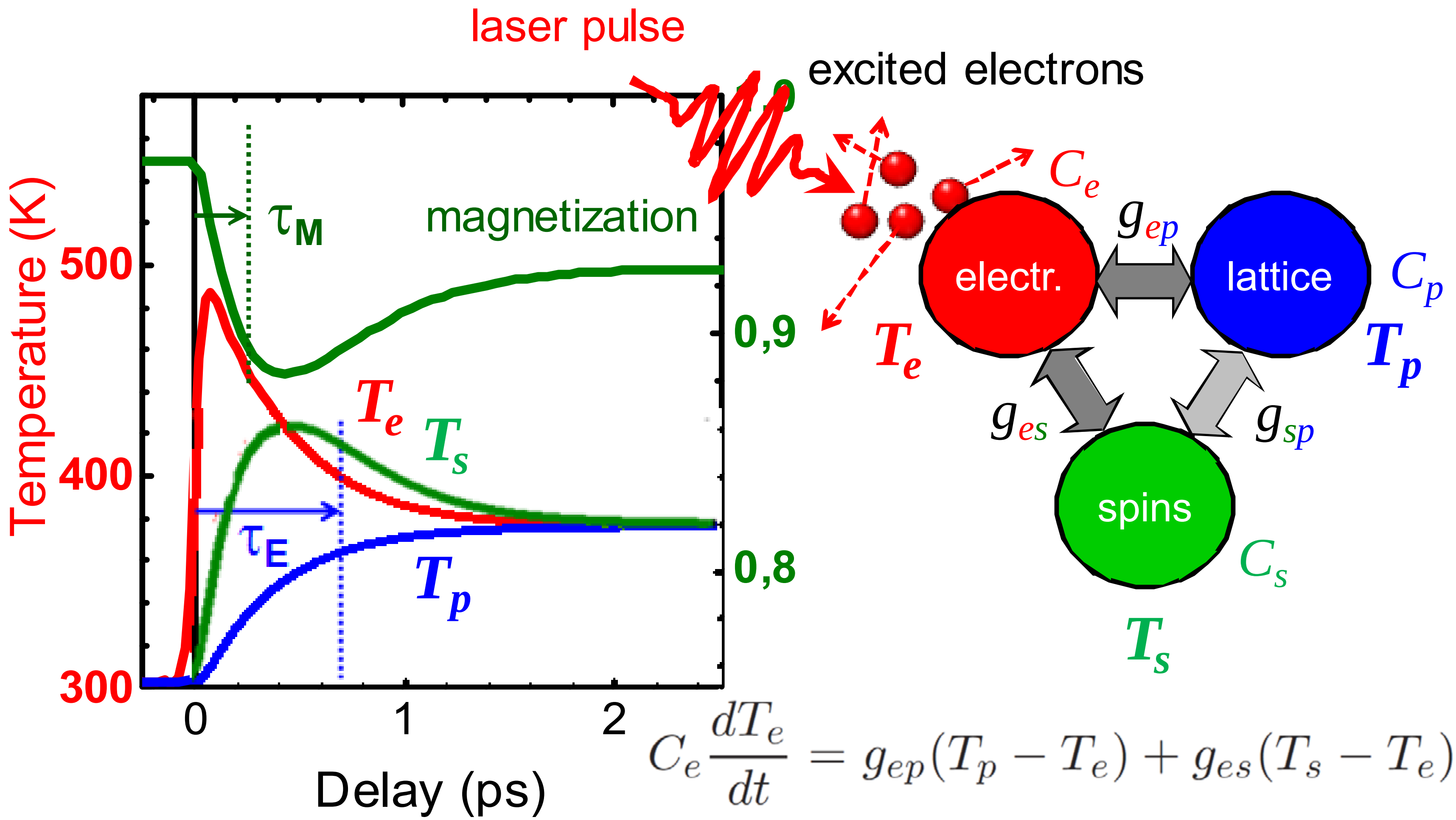


Eric Beaurepaire
1959-2018

Jean-Yves Bigot
1956-2018

E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot., Phys. Rev. Lett. 76, 4250 (1996)

3 Temperature Model



$$C_e \frac{dT_e}{dt} = g_{ep}(T_p - T_e) + g_{es}(T_s - T_e) + P(t)$$

$$C_p \frac{dT_p}{dt} = g_{ep}(T_e - T_p) + g_{sp}(T_s - T_p)$$

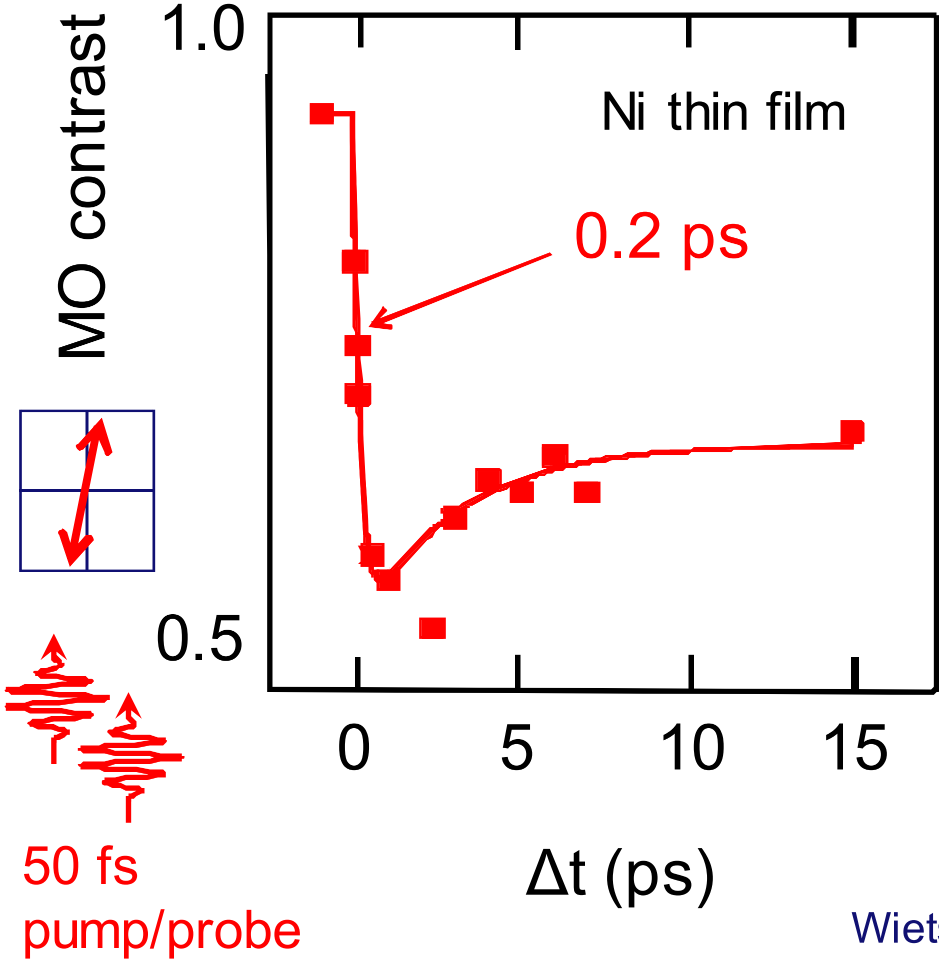
$$C_s \frac{dT_s}{dt} = g_{es}(T_e - T_s) + g_{sp}(T_p - T_s)$$

Different materials, different response

Weinelt (Tutorial)

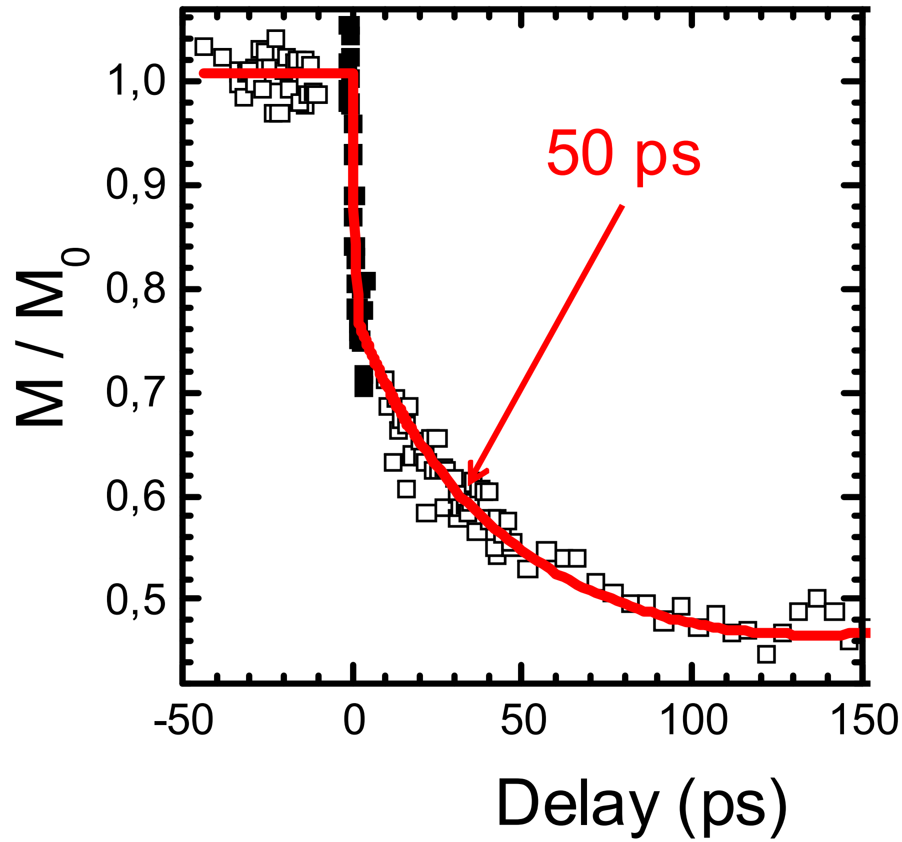
Nickel

3d, T_c = 630 K, μ_{at} = 0.6 μ_B



Gadolinium

4f, T_c = 295 K, μ_{at} = 7.5 μ_B



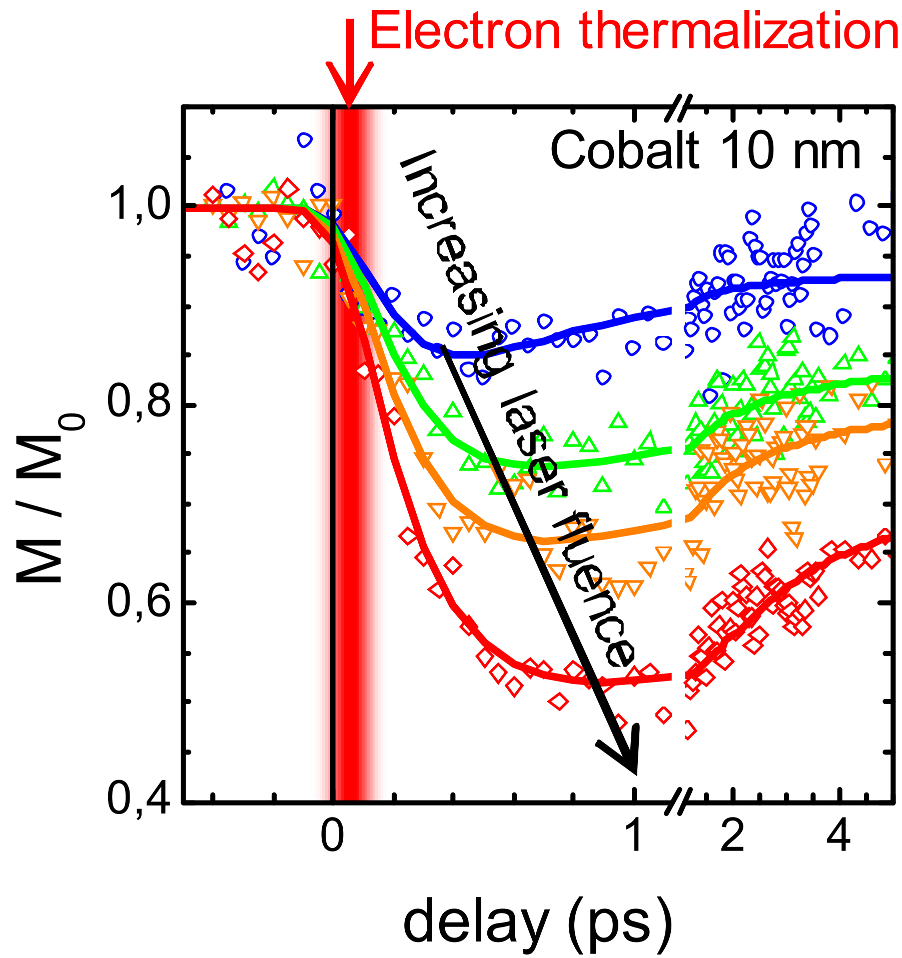
Wietstruk, Bovensiepen *et al.*, Phys. Rev. Lett. (2011)

E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot., Phys. Rev. Lett. 76, 4250 (1996)

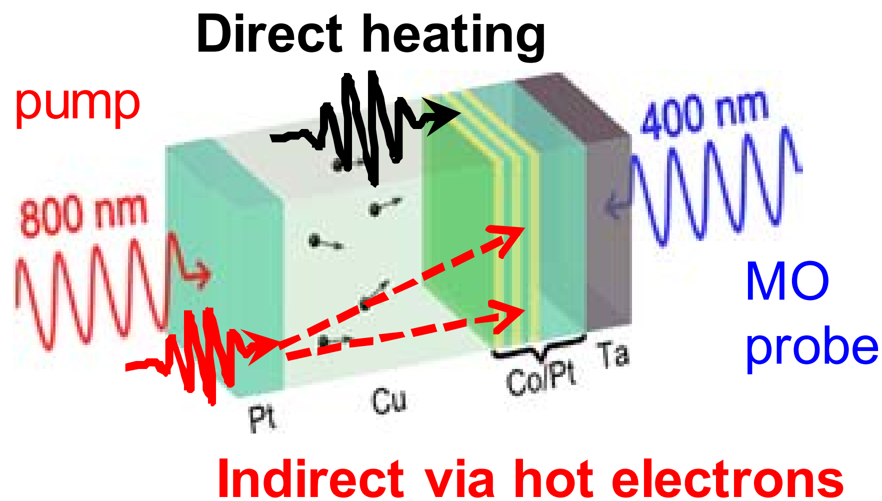
Claim: it's just (non-equilibrium) thermodynamics

- **Photons and hot e^- do not play a significant role**

Mangin (Tutorial), Bokor



BK, Tobias Roth et al., Nature Mat. 2010



Bergeard, Mangin, BK, Malinowski et al., Phys. Rev. Lett. 2016

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Proposed microscopic mechanisms / theories

- ~~Photon field + s.o. scattering~~
  - ~~Zhang & Huebner (PRL 2000 etc.)~~
  - ~~Bigot et al. (Nature Physics 2010)~~
- Superdiffusive spin transport
  - Battatio, Oppeneer, et al. (PRL 2010)
- Spin orbit-induced spin-flip scattering
  - Krieger, Sharma, Gross et al. (JCTC 2015) TDDF
  - Toews & Pastor (PRL 2015) many-body cluster
- Atomistic LLG
  - Chantrell, Nowak, Muenzenberger
- Landau-Lifzhitz-Bloch approach
  - Kazantseva, Atxitia, Chubykalo-Fesenko
- Phonon mediated Elliott-Yafet spin-flip scattering + Weiss
  - This lecture
- e-e mediated Elliott-Yafet spin-flip scattering + μ(T)
  - Mueller, Schneider, Rethfeld et al. PRL 2013

Lecture by Oppeneer

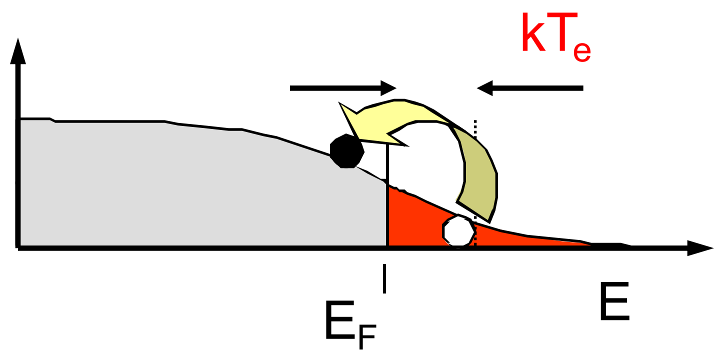
Lecture by Sharma

Angular momentum dumped in lattice – very similar results

Microscopic 3TM - Model Hamiltonian

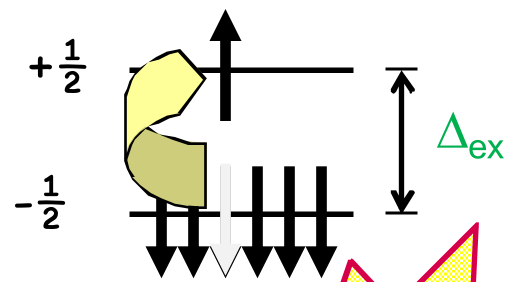
Koopmans et al., PRL 2005, Nat. Mater. 2010

- **electrons**



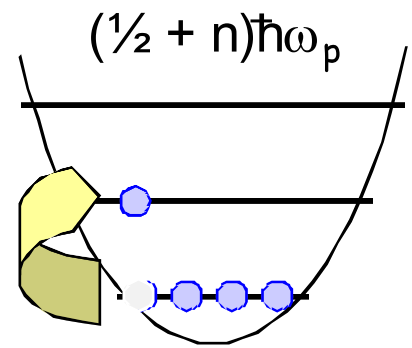
Spin-less free electrons

- **spins**



Mean field Weiss

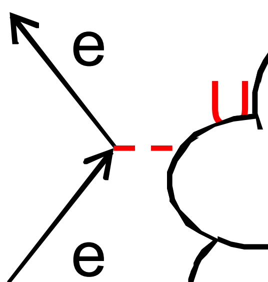
- **phonons**



Debye or Einstein

spintronics!

- **e-e**



Assumption

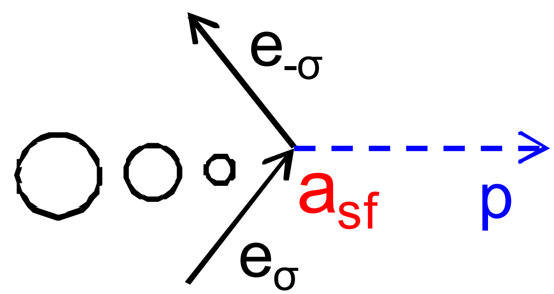
- **e-p**

.4 ps

Spintronics:

$$a_{sf} = \frac{\tau_0}{\tau_{sf}} = \frac{v_F^{\,2}\tau_0^{\,2}}{6 l_{sf}^{\,2}}$$

- **e-p + spin flip**



Spin-flip upon momentum scattering (Elliott-Yafet)

Using Golden Rule & Solve Boltzmann eqs.:

$$\begin{cases} c_e \dfrac{dT_e}{dt} = -g_{ep}\left(T_e - T_p\right) + P(z,t) \\ c_p \dfrac{dT_p}{dt} = g_{ep}\left(T_e - T_p\right) \\ \dfrac{dm}{dt} = Rm \dfrac{T_p}{T_C}\left(1 - m\coth\left(\dfrac{mT_C}{T_e}\right)\right) \end{cases}$$

ynamics

Wolfram Mathematica

For nickel:

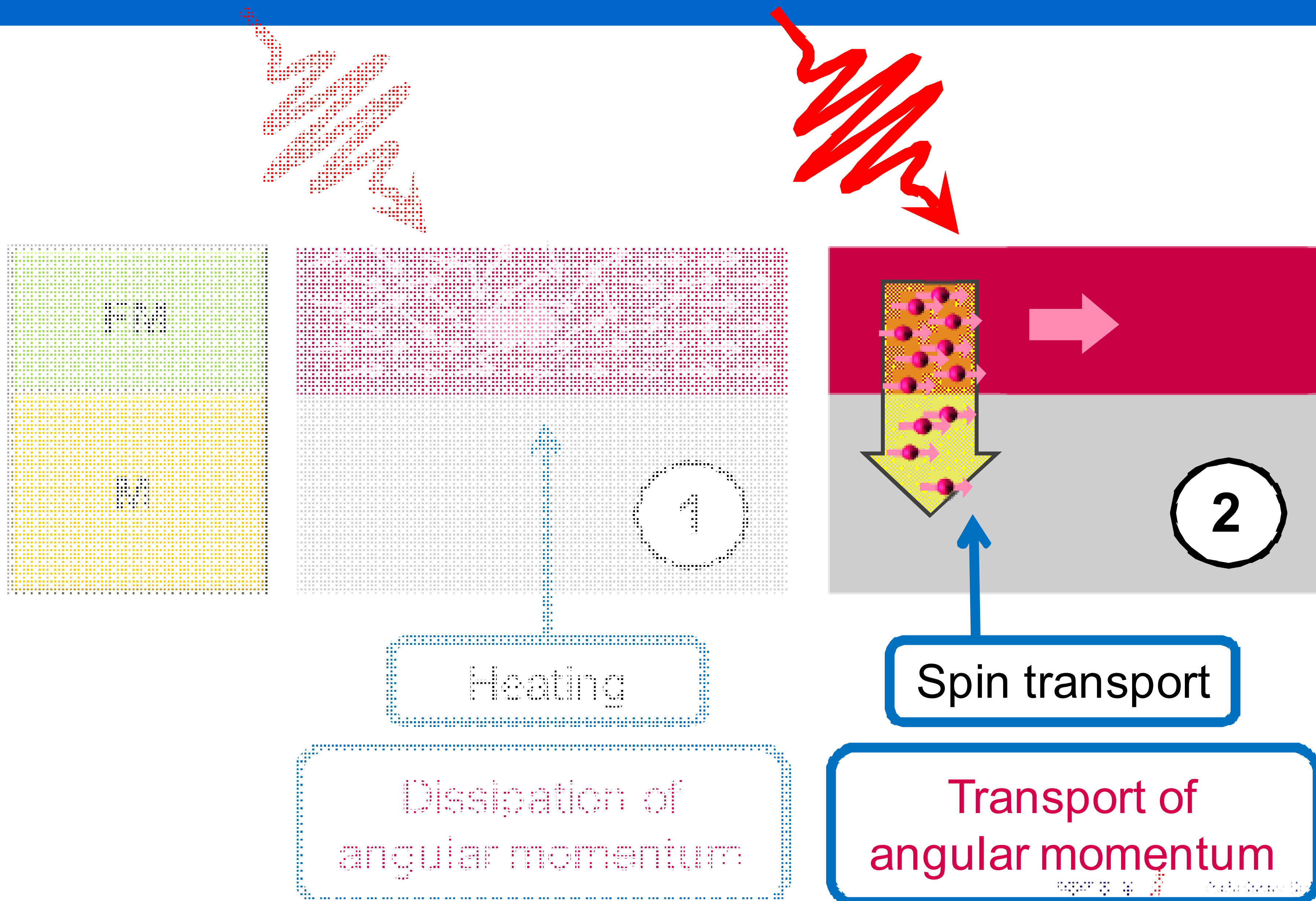
$$\begin{cases} T_C = 630 \text{ K} \\ \mu_{at} = 0.6 \\ E_D = 36 \text{ meV} \\ g_{ep} = \ldots, \text{ to fit } \tau_E \end{cases}$$

$$R = a_{sf} \frac{8 g_{ep} k T_C^{\,2}}{E_D^2 \mu_{at} / V_{at}} \approx a_{sf}\, 150 \text{ ps}^{-1}$$

$$m = \frac{M}{M_s}$$

τ ~ 60 fs for a_{sf} ~ 0.1

Outline: Local dynamics *vs.* spin transport



Fs laser-induced spin transport

Oppeneer
(Tutorial)

LETTERS

Control of speed and efficiency of ultrafast demagnetization by direct transfer of spin angular momentum

G. MALINOWSKI*, F. DALLA LONGA, J. H. H. RIETJENS, P. V. PALUSKAR, R. HUIJ
AND B. KOOPMANS
Department of Applied Physics, Center for NanoMaterials, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhover
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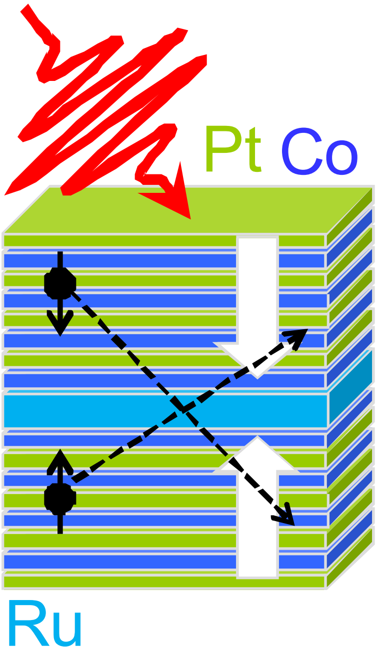
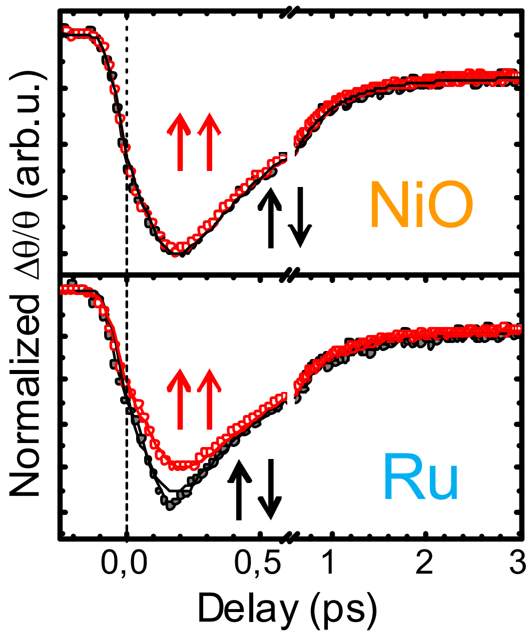
Greg Malinowski





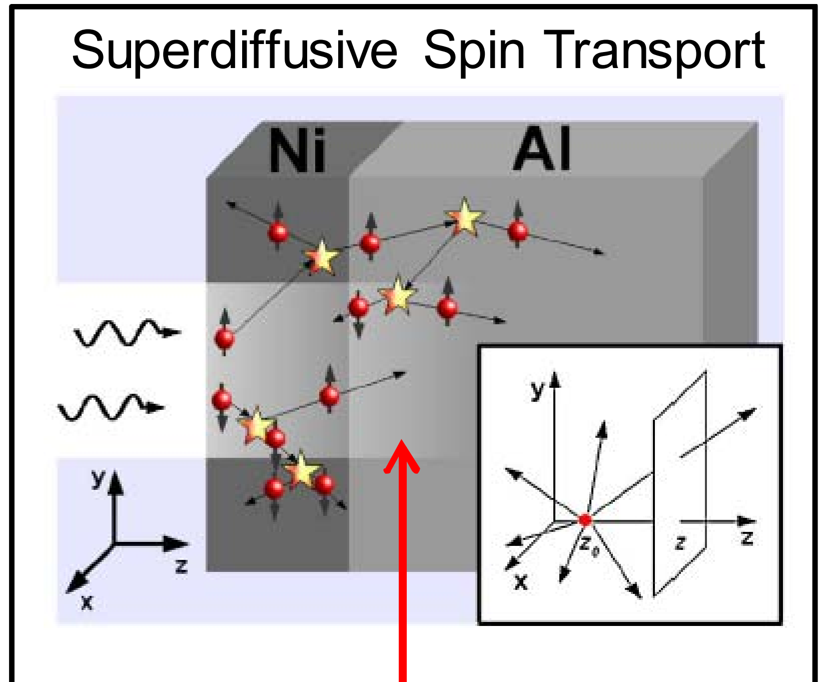
Malinowski et al. Nature Physics 2008

PRL 105, 027203 (2010) PHYS week ending 9 JULY 2010

Superdiffusive Spin Transport as a Mechanism of Ultrafast Demag ation

M. Battiato,* K. Carva,† and P. M. Oppeneer
Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden
(Received 31 March 2010; published 9 July 2010)

We propose a semiclassical model for femtosecond laser-induced demagnetization due to spin-polarized excited electron diffusion in the superdiffusive regime. Our approach treats the finite elapsed time and transport in space between multiple electronic collisions exactly, as well as the presence of several metal films in the sample. Solving the derived transport equation numerically we show that this mechanism accounts for the experimentally observed demagnetization within 200 fs in Ni, without the need to invoke any angular momentum dissipation channel.



Majority spins travel further

Battiato et al. PRL 2010

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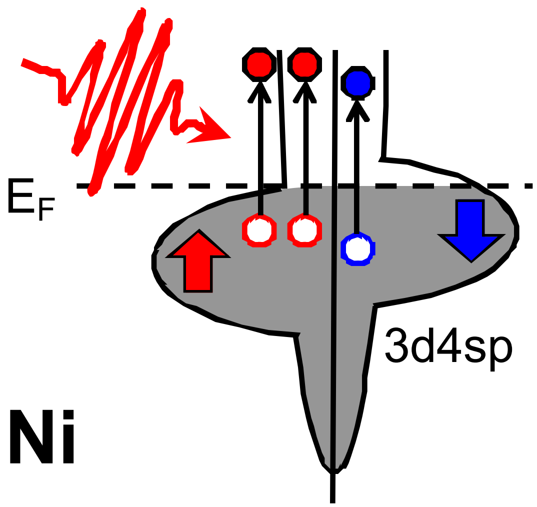
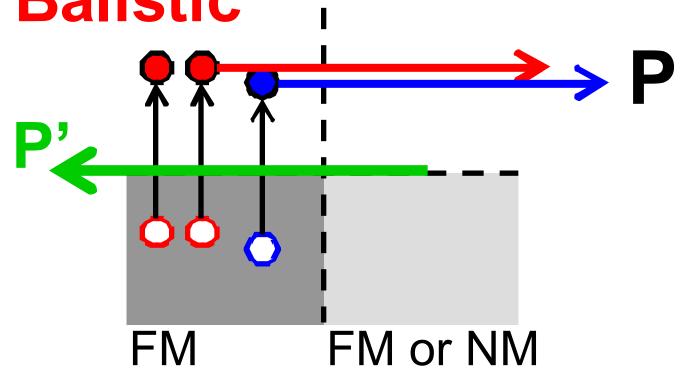
Optical generation of fs spin currents



Spin dep. life time:

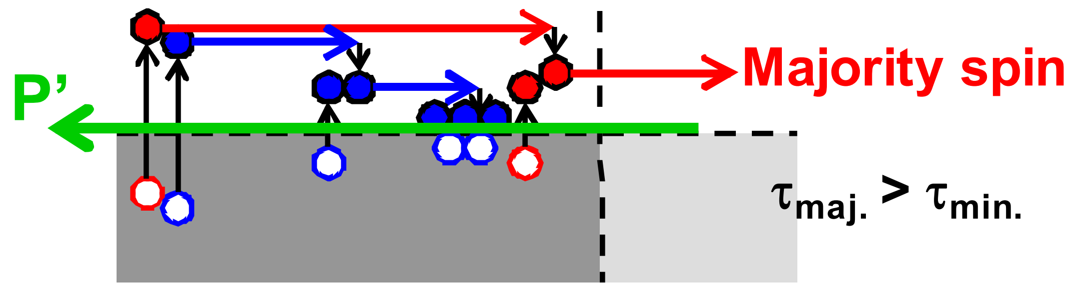
$t_{up} > t_{down}$

- **Balistic**



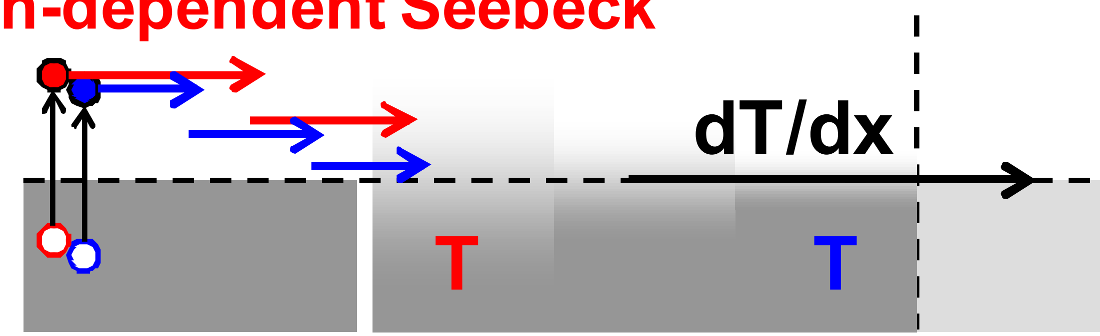
Due to:
- Matrix elements
- DOS
- Transmission
- Screening

- **Super-diffusive** Battiato, Oppeneer et al., PRL 2010



$\tau_{maj.} > \tau_{min.}$

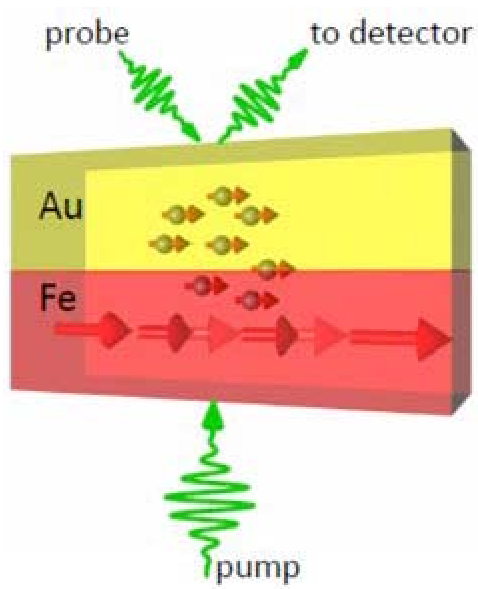
- **Spin-dependent Seebeck**



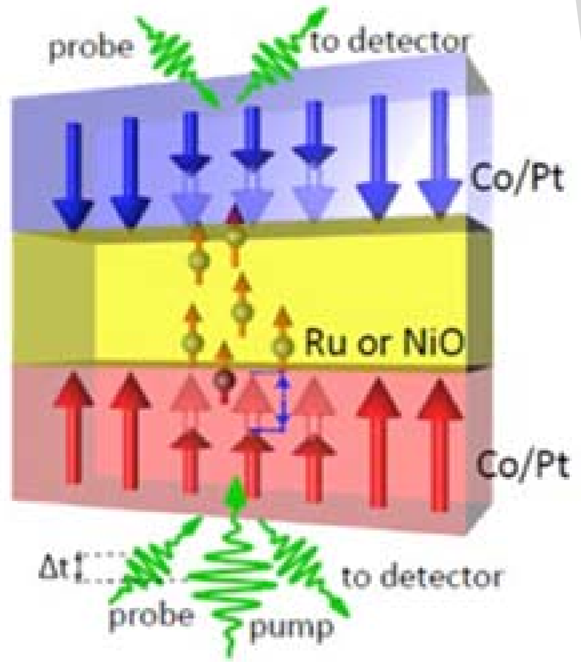
So pure spin current!

Fs spin currents confirmed

Spin accumulation



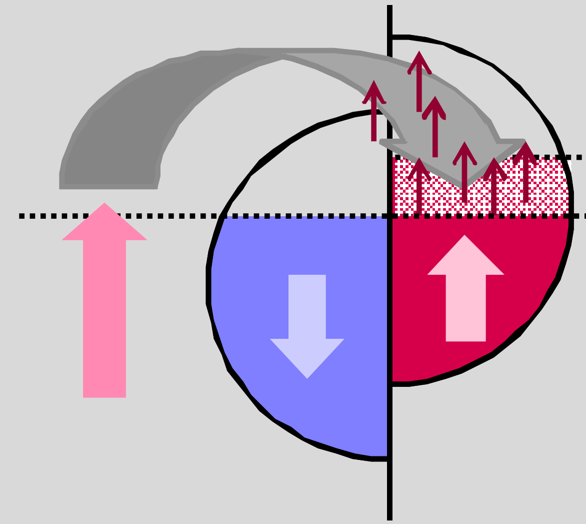
Magnetization



Melnikov et al., PRL 2011
Choi, Cahill et al., Nat. Comms.2014
Barkowski, BK, Aeschlimann, et al., submitted

Malinoswki et al., Nat. Phys. 2008
Rudolf et al., Nat. Comms. 2011

- strong non-equilibrium!
- huge splitting chemical potential…



- Local dissipation angular momentum (100 fs)
- Or spin currents (also fs time scale)

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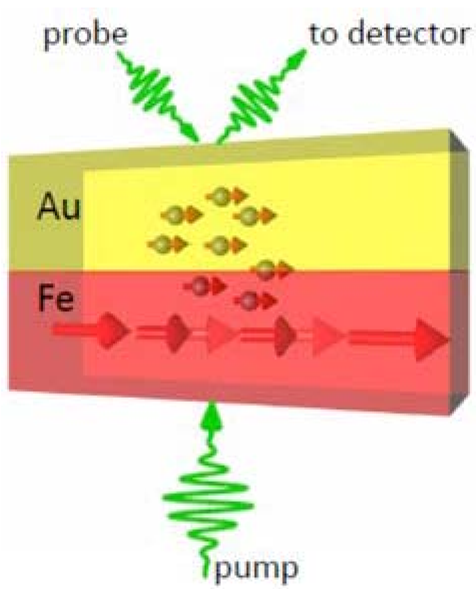
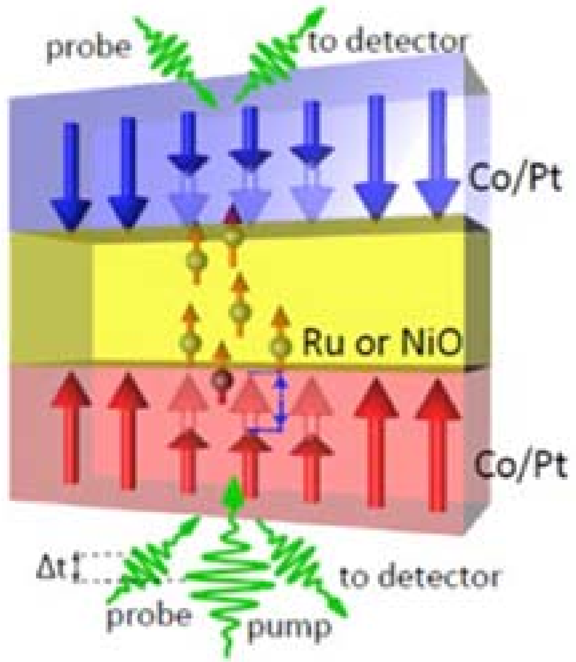
Fs spin currents confirmed

Spin accumulation



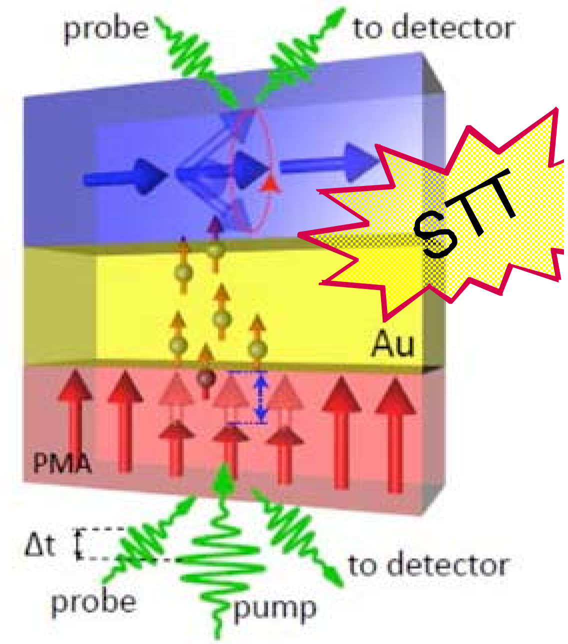
Melnikov et al., PRL 2011
Choi, Cahill et al., Nat. Comms.2014
Barkowski, BK, Aeschlimann, et al., submitted

Magnetization



Malinoswki et al., Nat. Phys. 2008
Rudolf et al., Nat. Comms. 2011

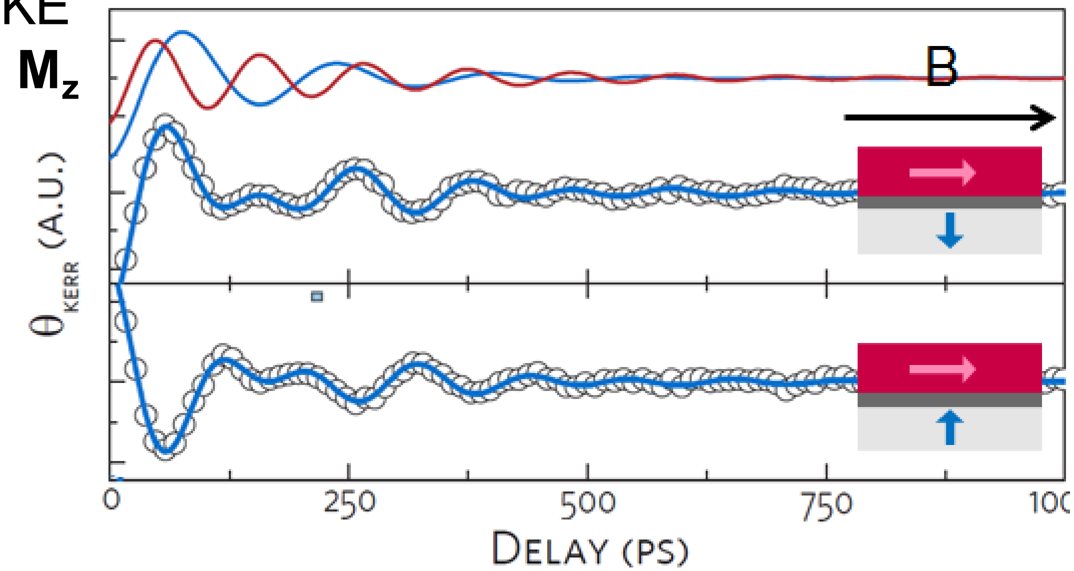
Torque

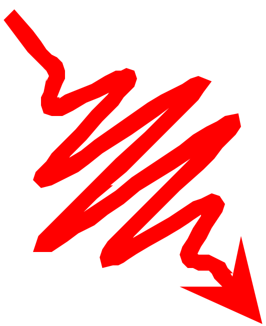


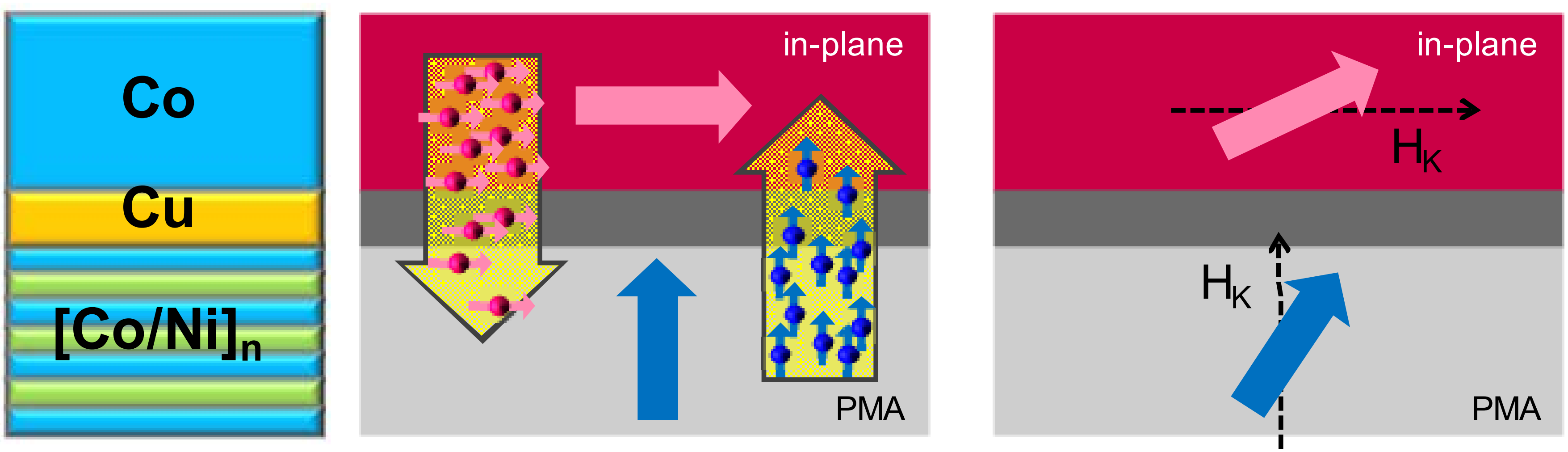
Schellekens et al., Nat. Comms. 2014
Choi et al., Nat Comms. 2014
Razdolski, Melnikov et al, Nat. Comms. 2017

Experimental demonstration Optical STT

Polar MOKE
measuring $\mathbf{M_z}$





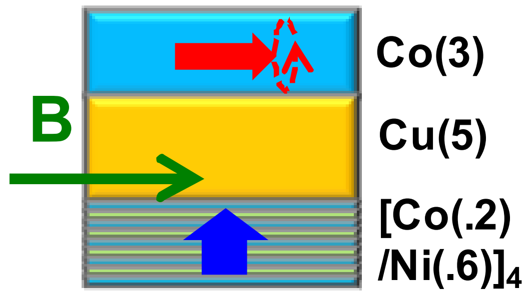


Schellekens, BK *et al*., Nature Comms. 2014
See also: Choi, Lee *et al.*, Nature Comms. 2014

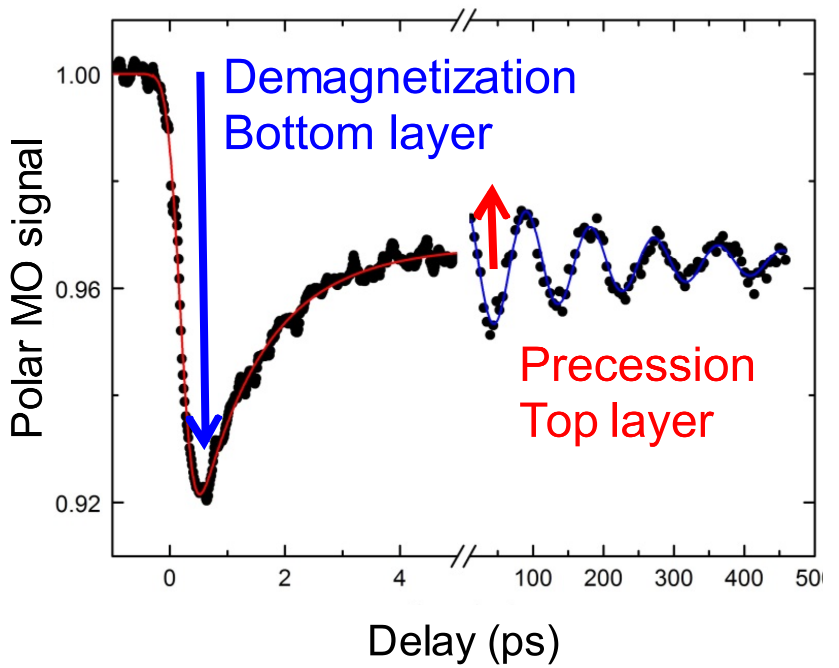
More quantitative studies

Materials engineering: Only bottom to top spin currents

$$\text{efficiency } \eta = \frac{\Delta M_{z,top}}{\Delta M_{z,bottom}}$$



$$\frac{\text{Canting angle}}{\Delta M/M_{bottom}}$$



Mark Lalieu, Paul Helgers et al., Phys. Rev. B (2017)

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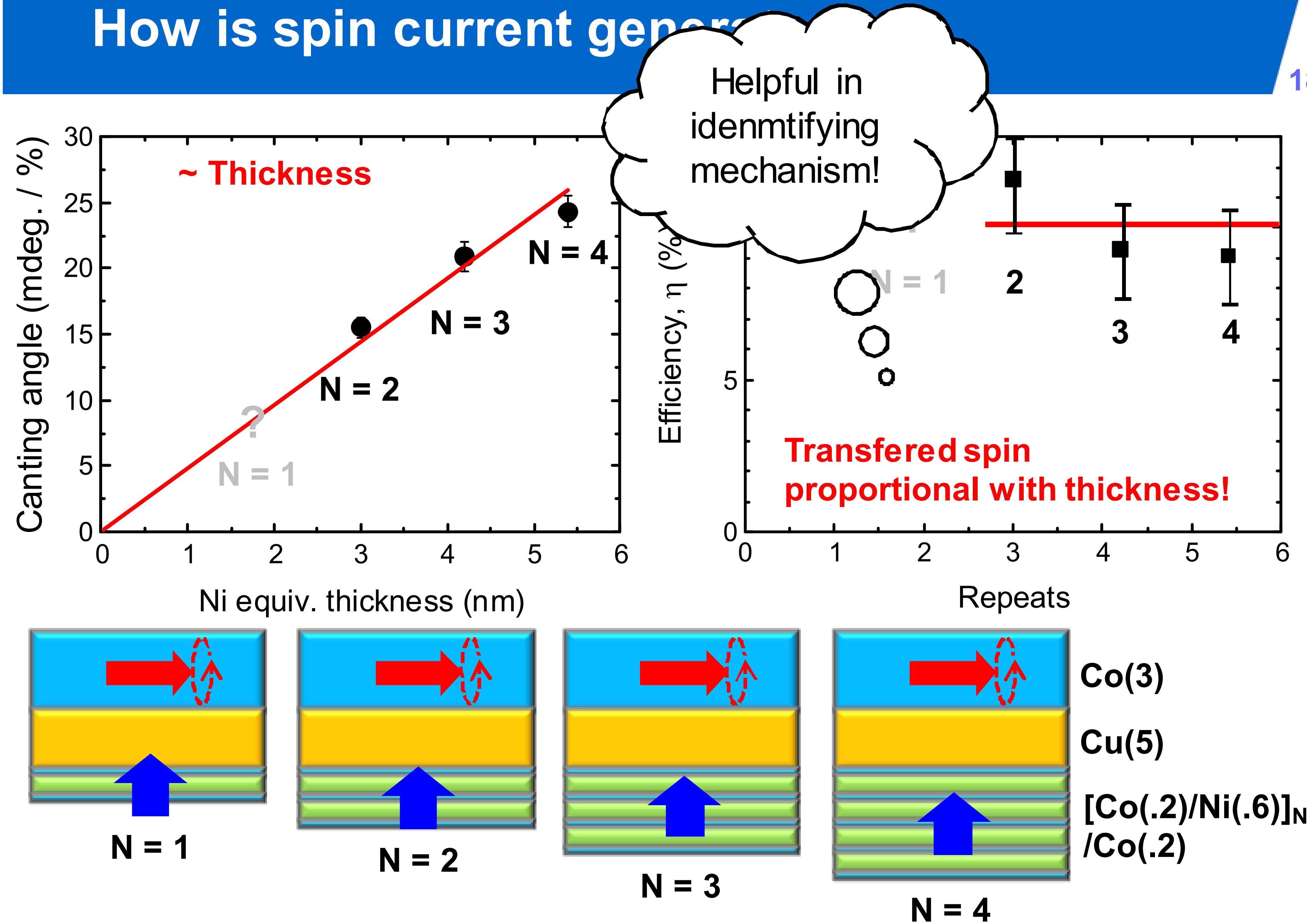
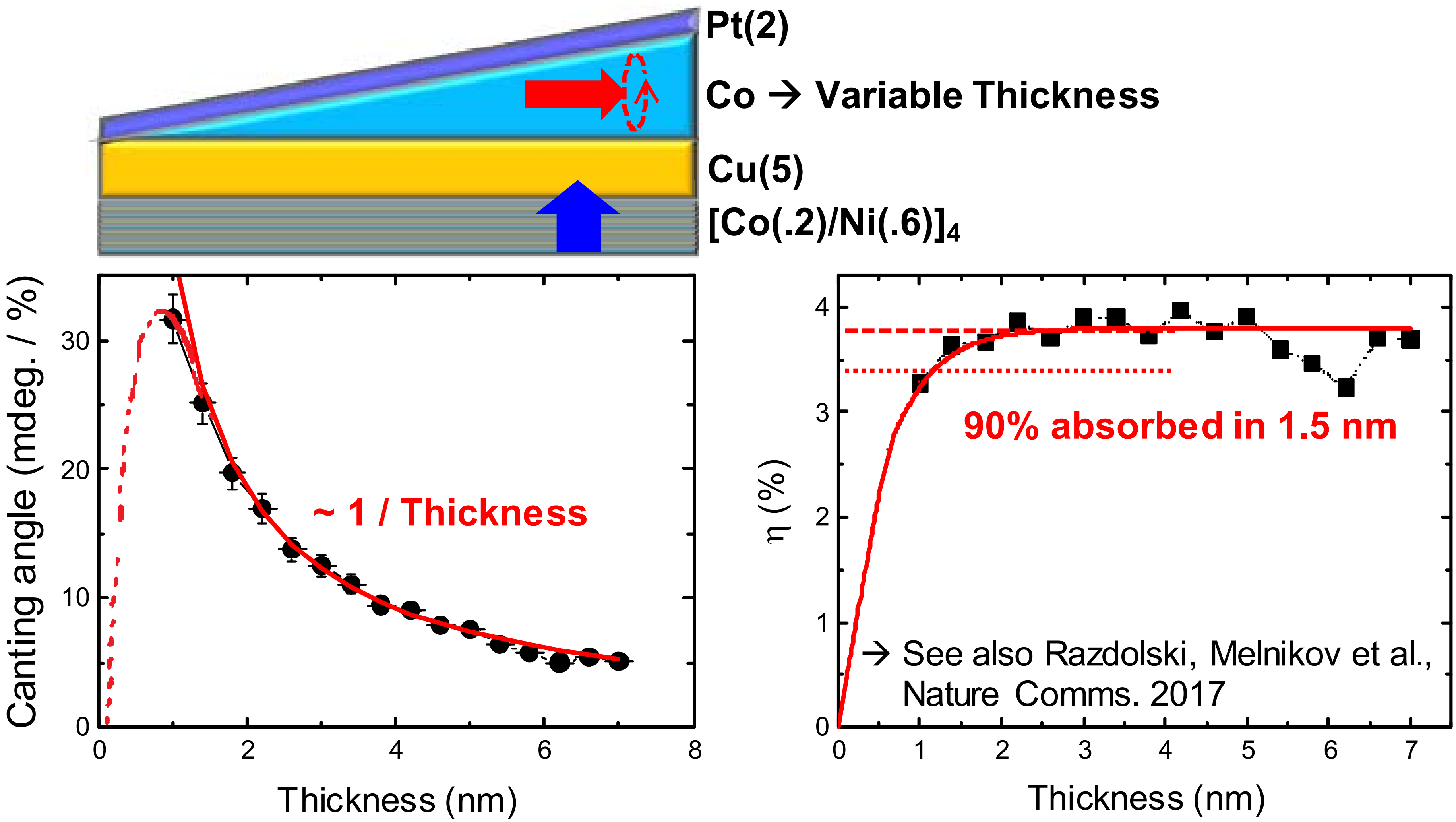
How is spin current gener



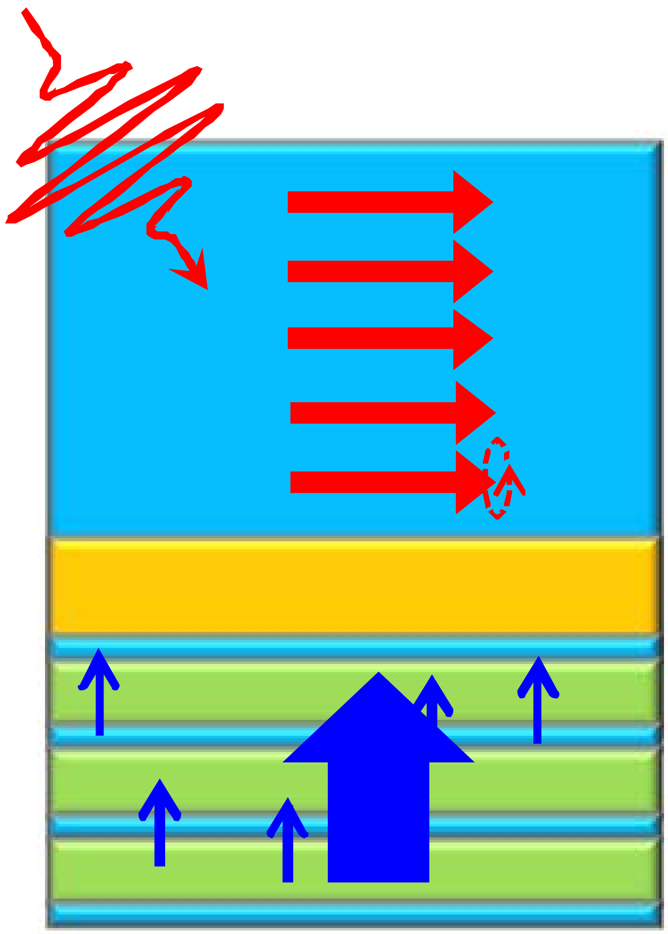
Mark Lalieu, Paul Helgers et al., Phys. Rev. B (2017)

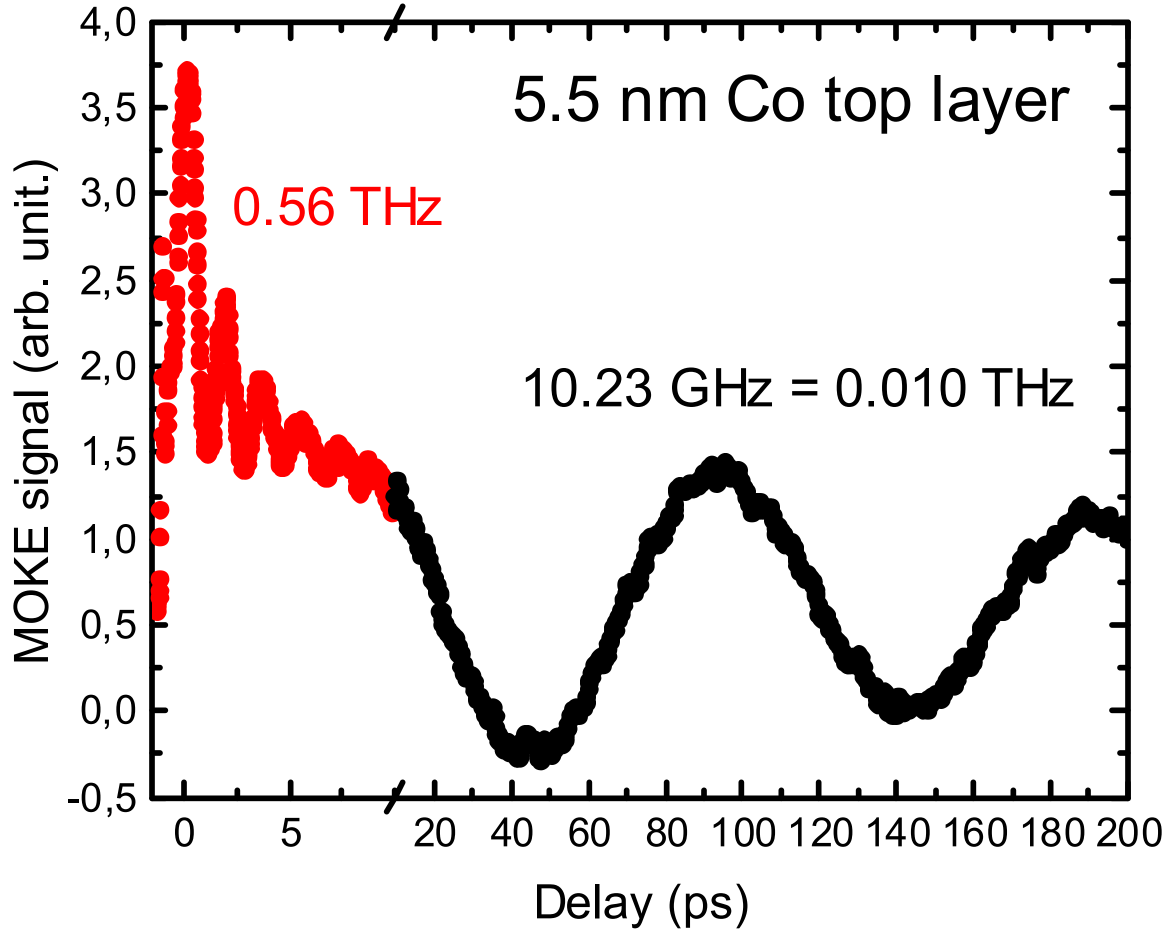
How is transverse momentum absorbed?



Mark Lalieu, Paul Helgers et al., Phys. Rev. B (2017)

Fs spin transport (and THz magnons)





Lalieu *et al*., Phys. Rev. B (2017)

Razdolski, Bovensiepen, Melnikov et al., Nat. Comms. 2017

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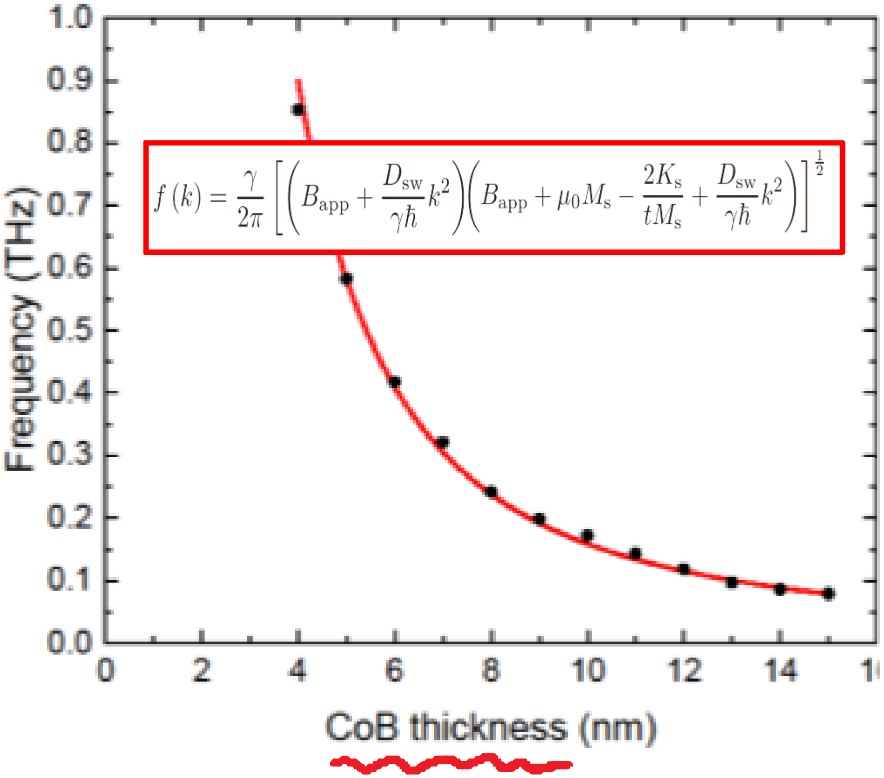
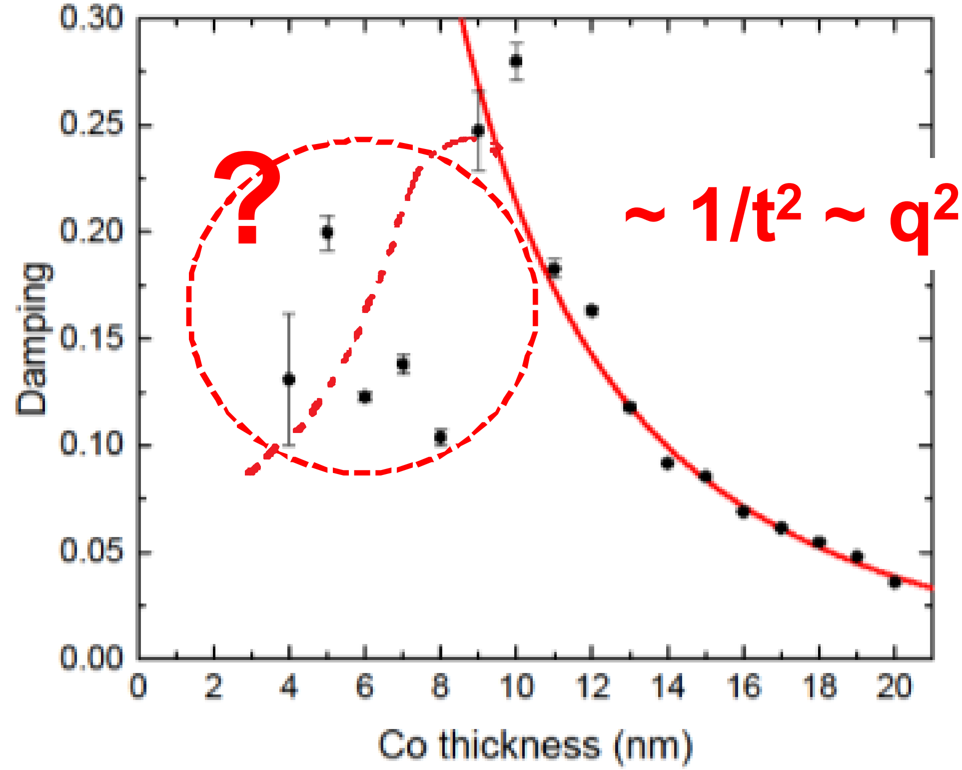
Resolving dispersion & q-dependent damping

Mark Lalieu, preprint





PHYSICAL REVIEW B **79**, 094415 (2009)

Transverse spin diffusion in ferromagnets

Yaroslav Tserkovnyak,[1] E. M. Hankiewicz,[2] and Giovanni Vignale[3]

[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*

[2]*Institut für Theoretische Physik und Astrophysik, Universität Würzburg, 97074 Würzburg, Germany*

[3]*Department of Physics and Astronomy, University of Missouri, Columbia, Missouri 65211, USA*

(Received 7 October 2008; revised manuscript received 8 January 2009; published 17 March 2009)

We discuss the dissipative diffusion-type term of the form $\mathbf{m}\times\nabla^2\partial_t\mathbf{m}$ in the phenomenological Landau-

$$\alpha(q) = \frac{\sigma_\perp q^2}{S} \sim \left(\frac{\mu_F/\Delta_{xc}}{p_F/q}\right)^2 \frac{\tau_\perp\Delta_{xc}}{1+(\tau_\perp\Delta_{xc})^2}$$

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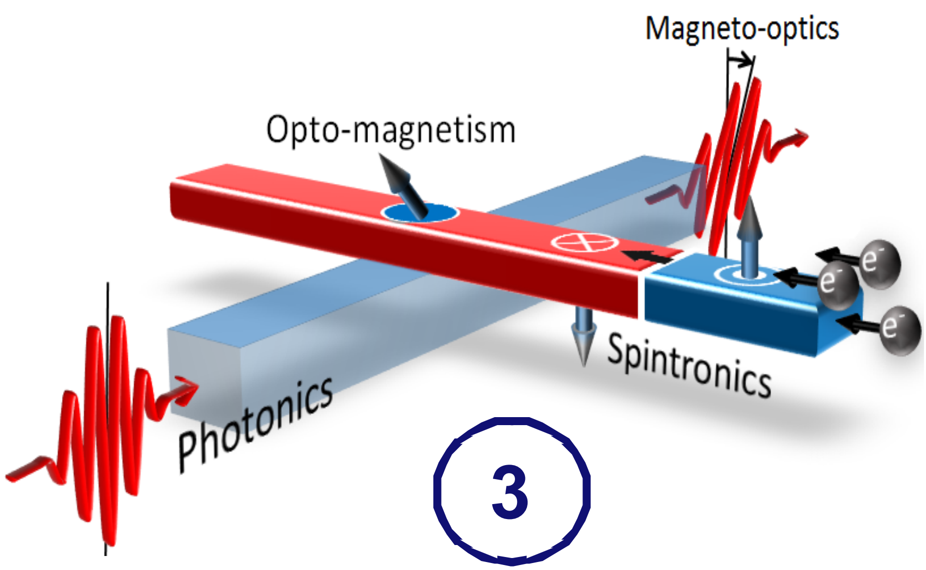
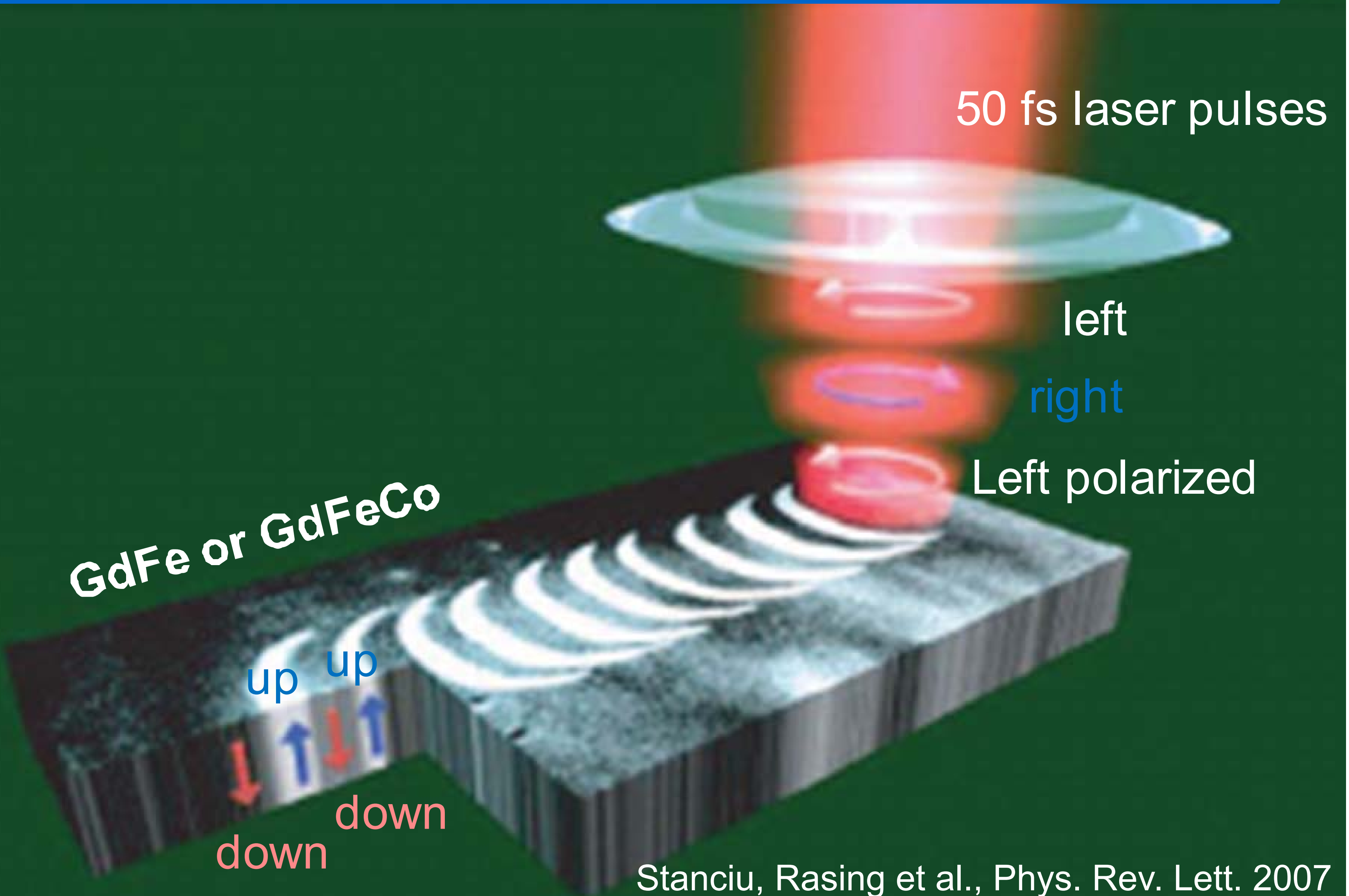
Outline

- Introduction: fs All-Optical Switching (AOS)
- AOS of spintronic materials
- Integration of “AOS” and spintronic functionality
- Conclusions & take home



Writing Magnetism with Light – Opto-magnetism

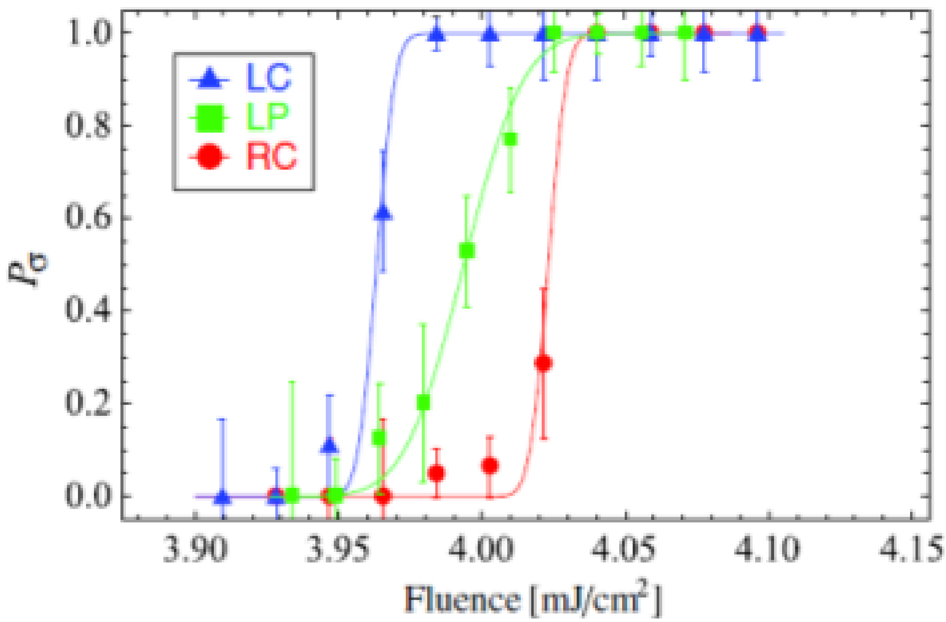


Stanciu, Rasing et al., Phys. Rev. Lett. 2007

Writing Magnetism with Light – Opto-magnetism

Toggle mechanism (linearly polarized!)

Ostler et al., Nature Comms. 2012



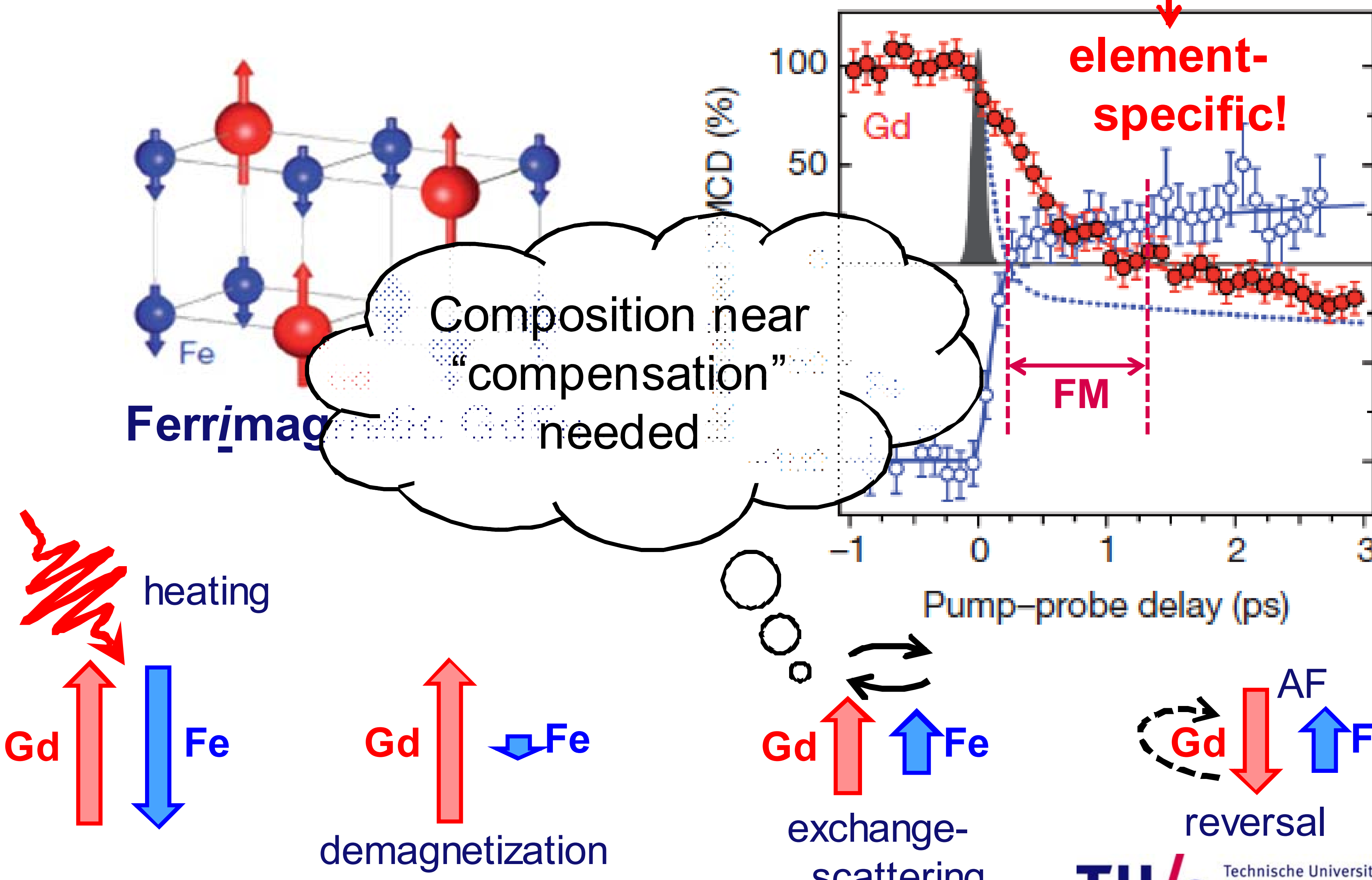
Helicity dependence just due to circular dichroism

Khorsand et al., Phys. Rev. Lett. 2012

s

Stanciu, Rasing et al., Phys. Rev. Lett. 2007

Detailed insight using fs X-ray pulses (XMCD)

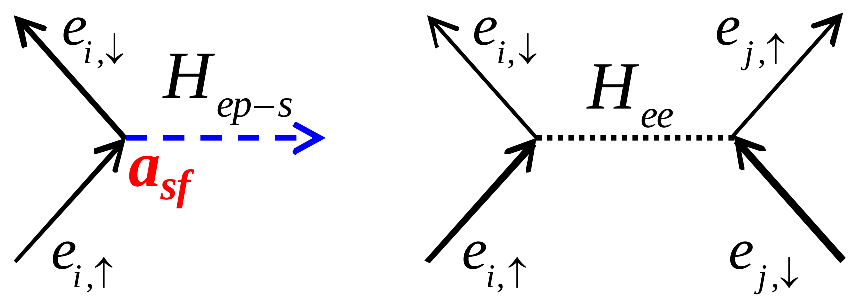


Radu et al., Nature 2011

AOS in Microscopic 3-Temparature model

$$H = H_e + H_p + H_s + H_{ee} + H_{ep} + H_{ep-s} \xrightarrow{\text{Golden rule}} \text{rate equations}$$

EY spin-flip + exchange scattering

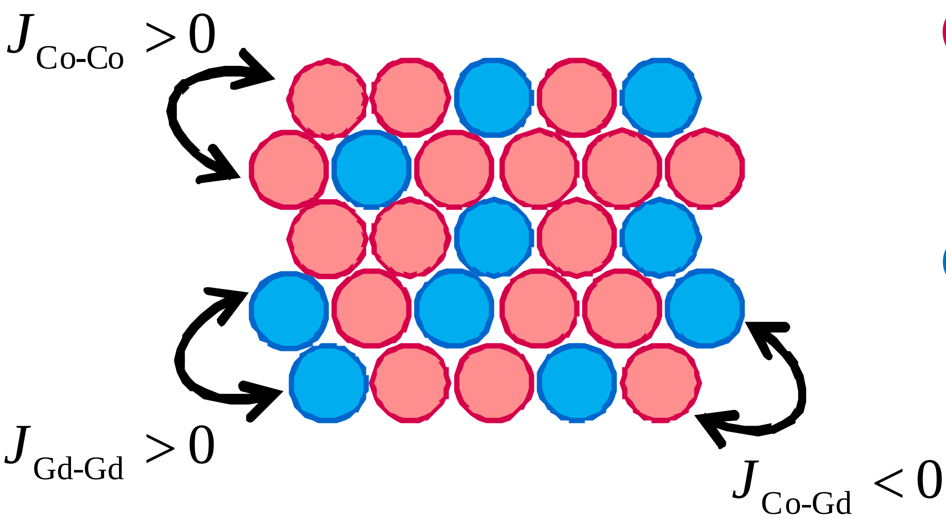


Spin-flip processes in 2 sub-lattice

$$\frac{dT_e}{dt} = \frac{g_{ep}}{C_e}\left(T_p - T_e\right) + \frac{P(t)}{C_e}$$

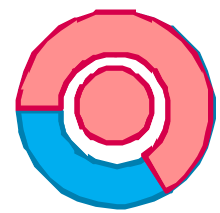
$$\frac{dT_p}{dt} = \frac{g_{ep}}{C_p}\left(T_e - T_p\right) + \frac{T_p - T_{amb}}{\tau_{diff}}$$

Electron and lattice



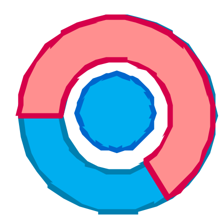
Cobalt

$$S_i = \frac{1}{2}, \ \mu_{at} = 1.6 \ \mu_B$$



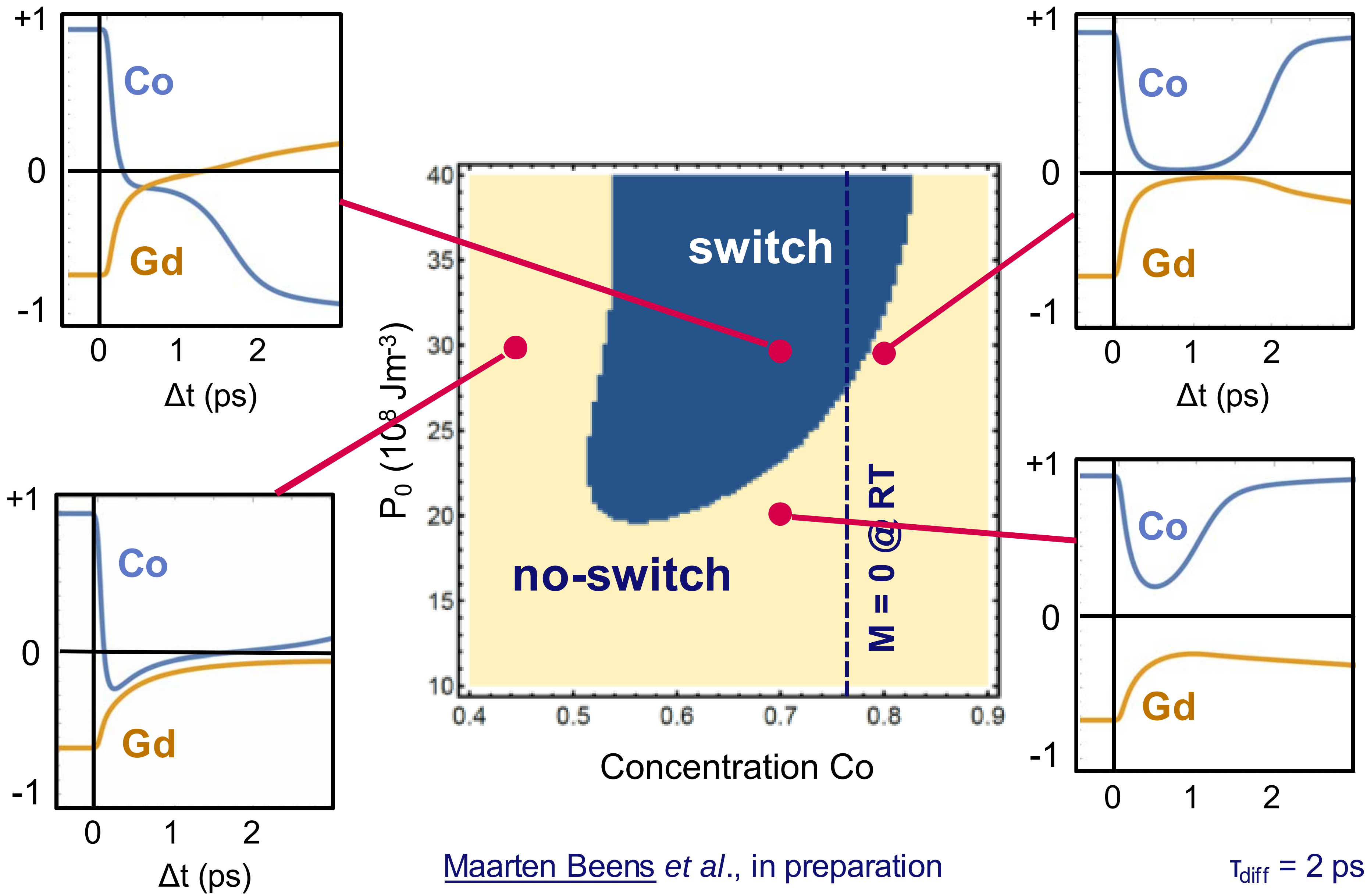
Gadolinium

$$S_i = \frac{1}{2}, \ \mu_{at} = 7.5 \ \mu_B$$



Similar to Schellekens *and BK*, PRB 87, 020407(R) (2013)

AOS phase diagram for Co_xGd_{1-x}

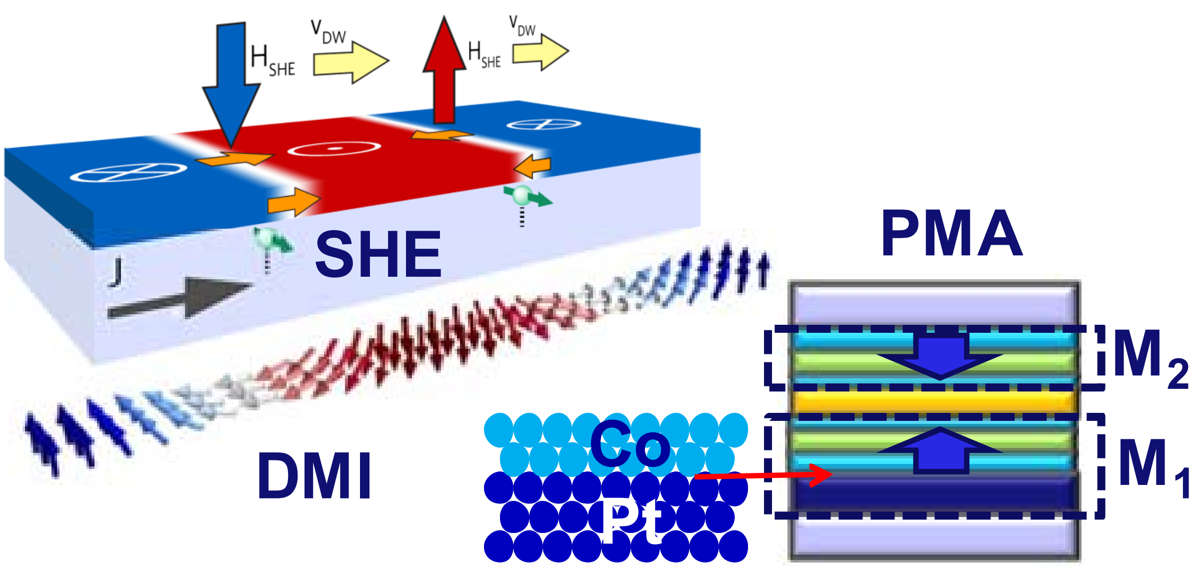


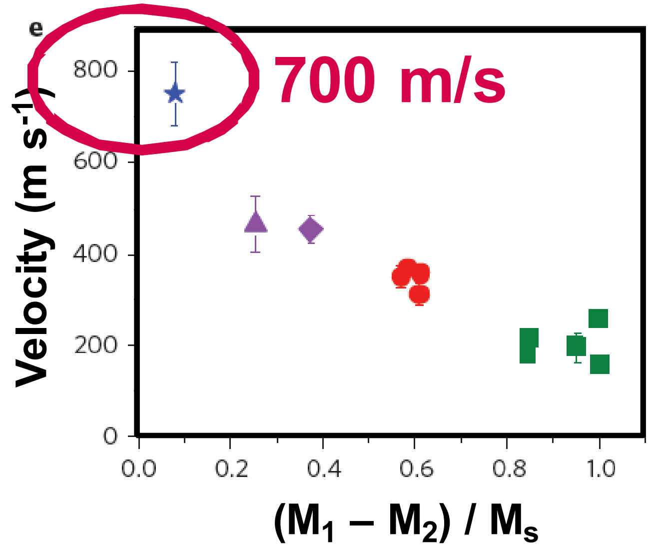
Maarten Beens *et al.*, in preparation

τ_{diff} = 2 ps

Requirements AOS *vs.* Fast CI-DWM

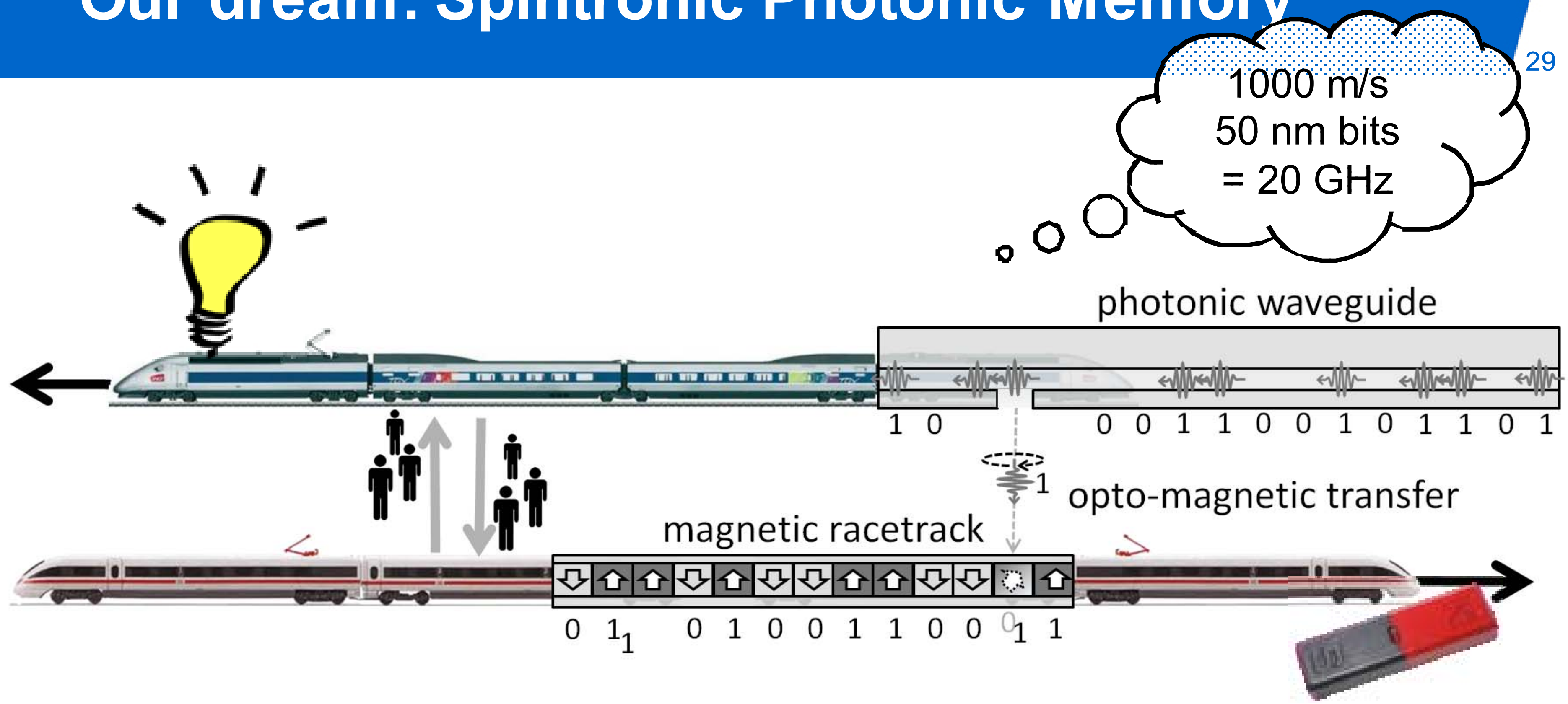
Requirements AOS	Fast CI-DWM
1. Anti-parallel sub-lattices = reduced M	1. Anti-parallel sub-lattices = reduced M
(2. Different (EY) demagnetization times)	2. Strong SOC → SHE
	3. Strong SOC → DMI
3. Exchange scattering	
4. PMA (useful)	4. PMA





Yang, Parkin et al., Nature Nanotechnol. (2015)

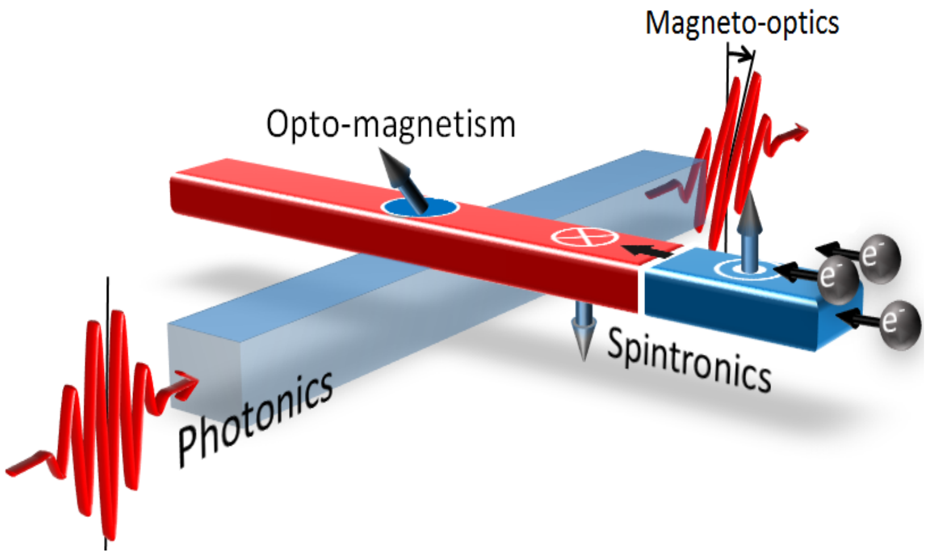
Our dream: Spintronic Photonic Memory



- **If we can engineer the proper magnetic stack**

Outline

- Introduction: fs All-Optical Switching (AOS)
- **AOS of spintronic materials**
- **Integration of "AOS" and spintronic functionality**
- **Conclusions & take home**



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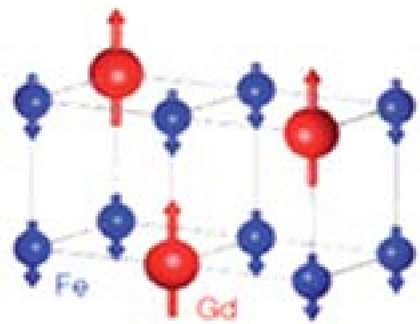
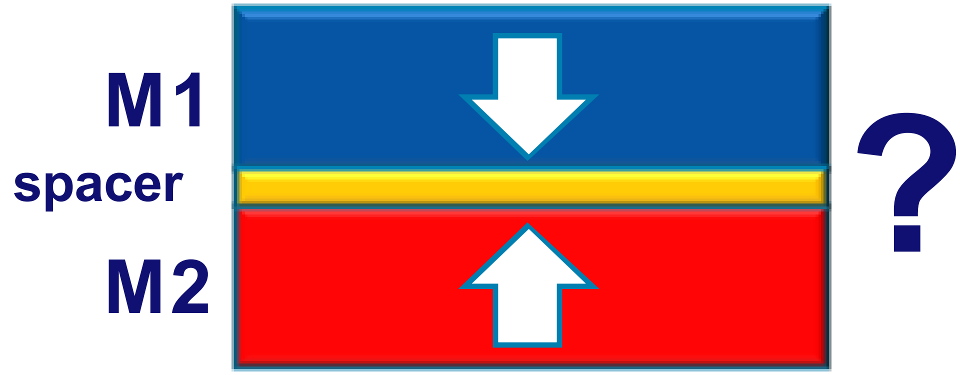
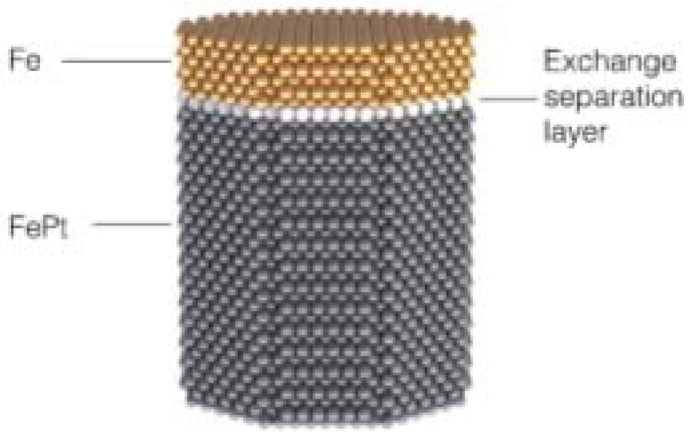
What about AOS of *synthetic* ferrimagnets?





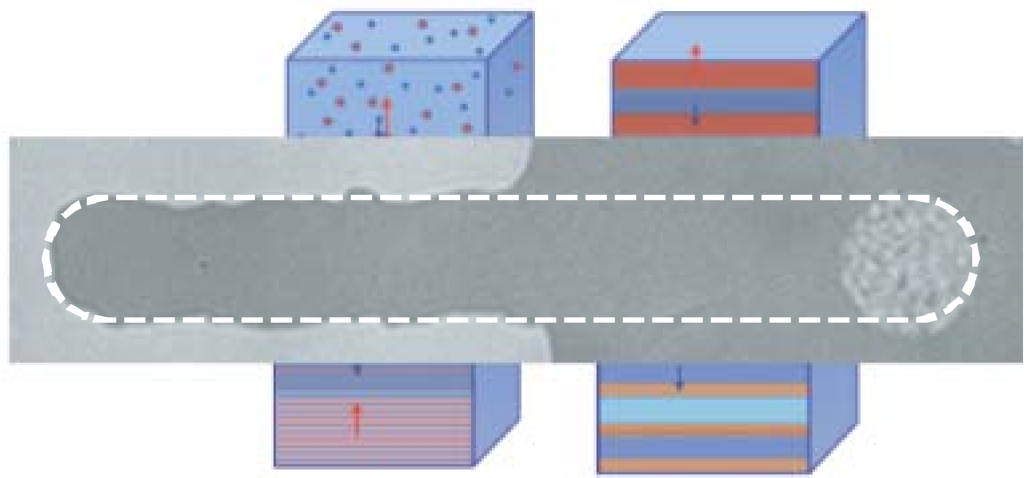
- **Theoretical predictions**



Evans, Chantrell *et al*. APL 2014 (Fe/FePt)

Gerlach, Nowak *et al*. PRB 2017 (Fe/Gd)

- **Experiments:**



Mangin *et al*., Nature Materials 2014

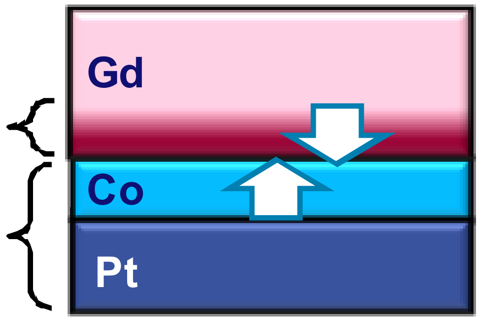
- **But no single-pulse switching…**

Pt/Co/Gd …

Partly inspired by Pham, Pizzini et al., EPL 2016

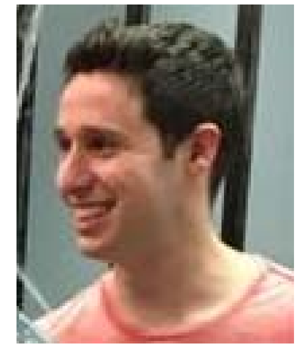
Proximity induced FM @ RT

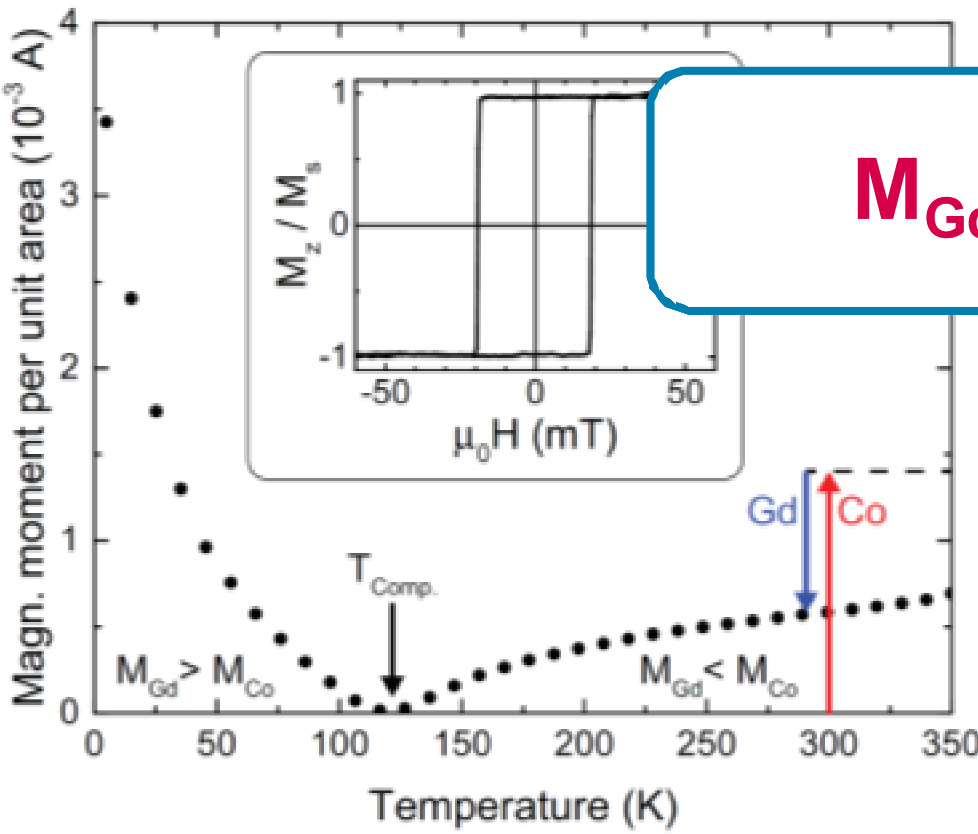
Strong spin-orbit (DMI & SHE)



few nm

~ 1 nm





M_{Gd}: 0.45 nm

VSM SQUID

→ 0.45 nm FM Gd @ RT

→ $M_{sat,Gd}$ = 1.8 MA/m
(bulk: 2.1 MA/m)

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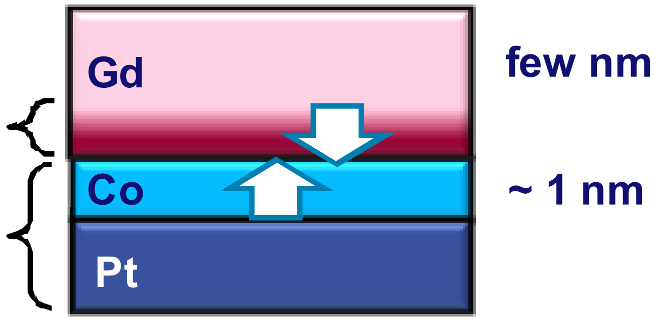
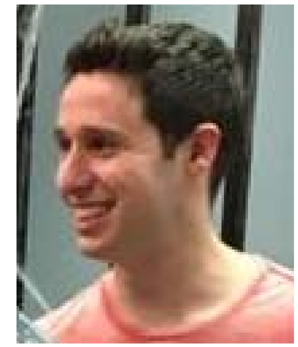
Pt/Co/Gd … Single-pulse toggle switching

Partly inspired by Pham, Pizzini et al., EPL 2016

Proximity induced FM @ RT

Strong spin-orbit (DMI & SHE)

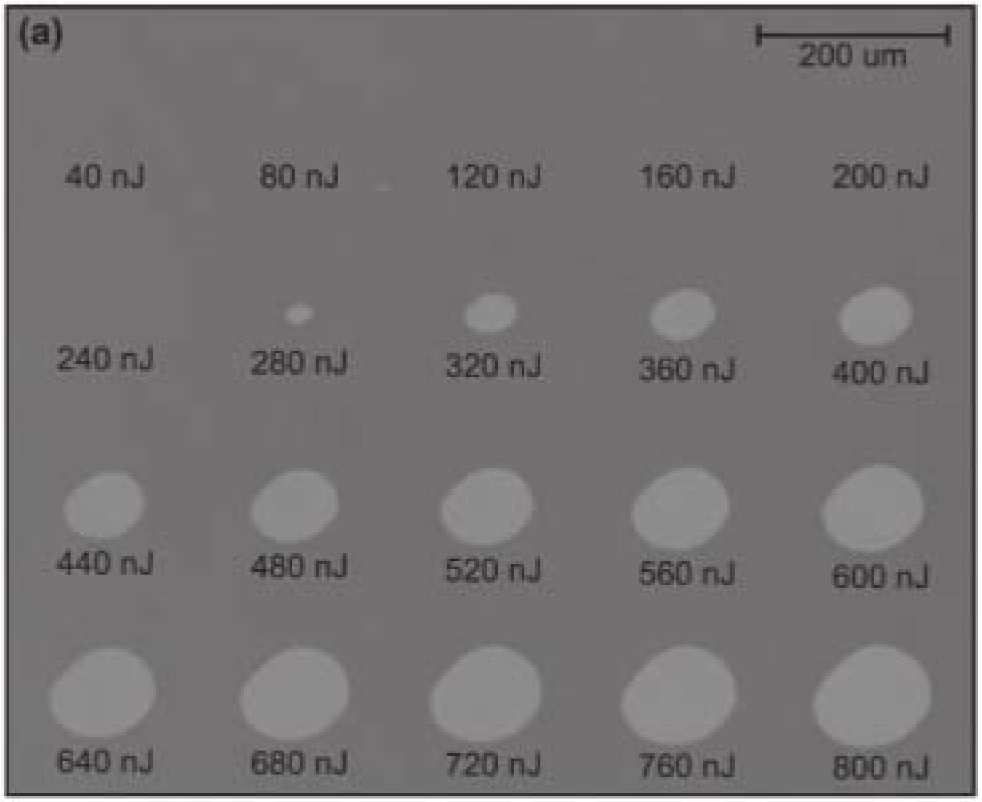


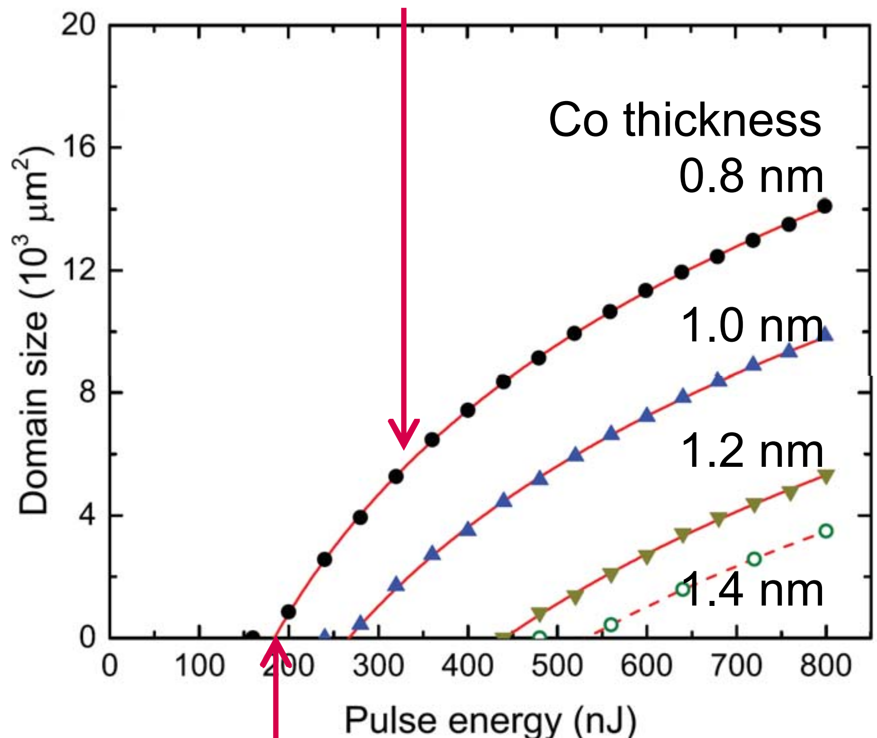


Mark Lalieu, Peeters, Lavrijsen *et al*., Phys. Rev. B 96, 220411 (Rapid) 2017

Fluence dependence

Fit assuming fixed threshold temperature





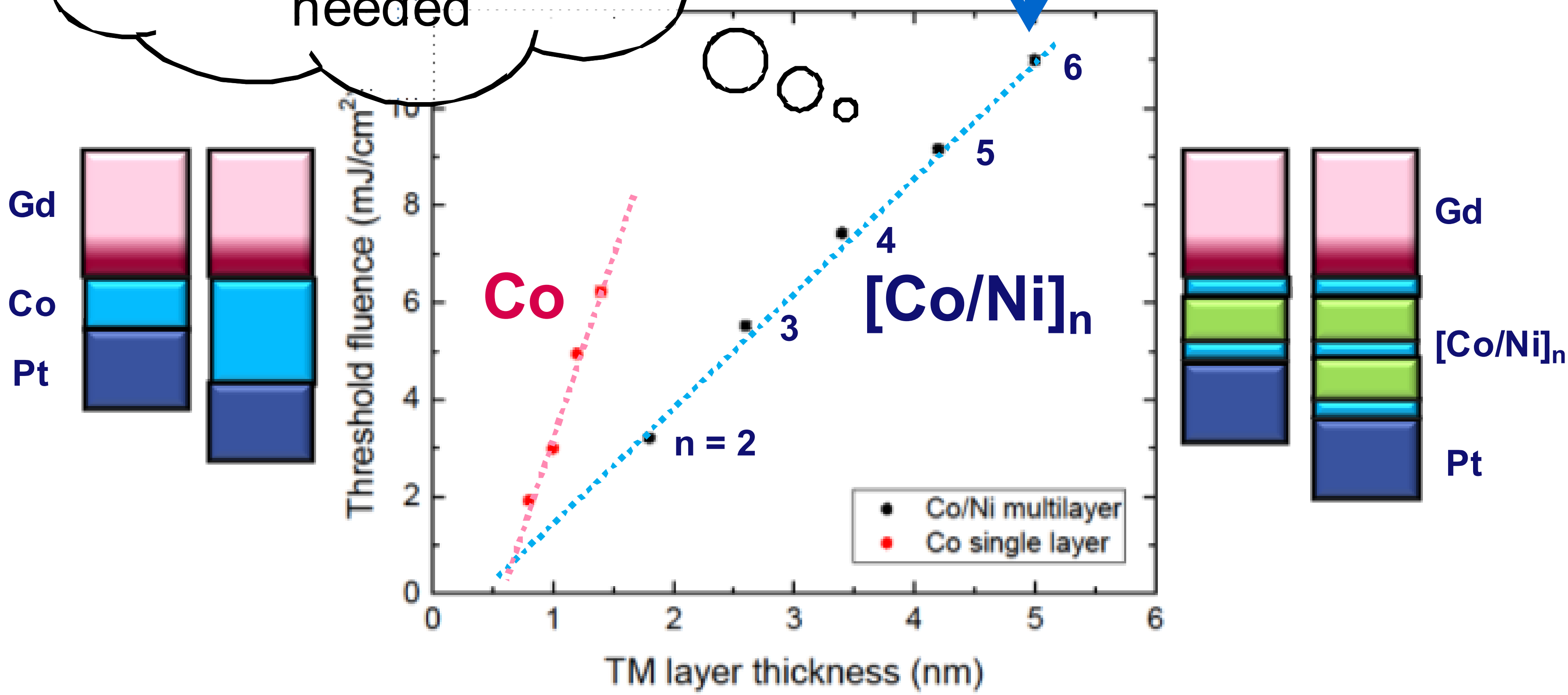
50 fJ for 50 x 50 nm^2

- **No helicty dependence**
- **> 10^7 successful switches and @ 100 kHz**

Mark Lalieu, Peeters, Lavrijsen *et al*., Phys. Rev. B 96, 220411 (Rapid) 2017

Sw… mpensation point

Alloys:
Composition near
"compensation"
needed



- **How come?**

Mark Lalieu, Maarten Beens *et al*., in preparation

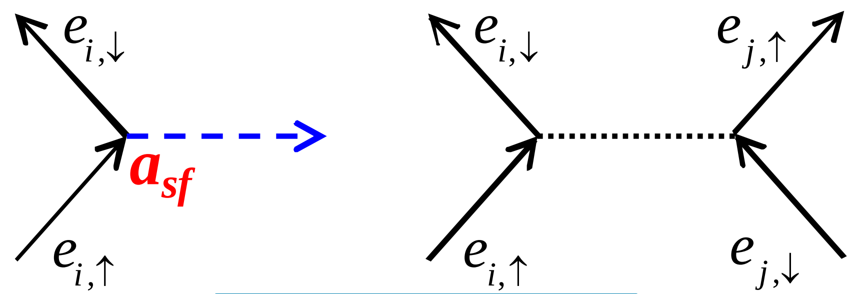
Layered multi-sublattice M3TM

$$\frac{dT_e}{dt} = \frac{g_{ep}}{C_e}\left(T_p - T_e\right) + \frac{P(t)}{C_e}$$

$$\frac{dT_p}{dt} = \frac{g_{ep}}{C_p}\left(T_e - T_p\right) + \frac{T_p - T_{amb}}{\tau_{diff}}$$

Electron and lattice

EY spin-flip + exchange scattering



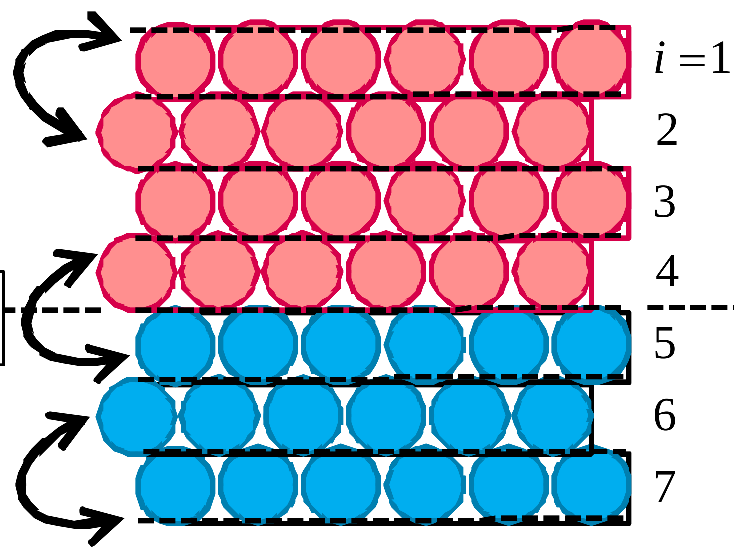
slab-wise M3TM

Cobalt

$J_{i,i} = J_{i,j} > 0$

$J_{i,i} = J_{i,j} < 0$

$J_{i,i} = J_{i,j} > 0$



$S_i = \frac{1}{2},\ \mu_{at} = 1.6\ \mu_B$

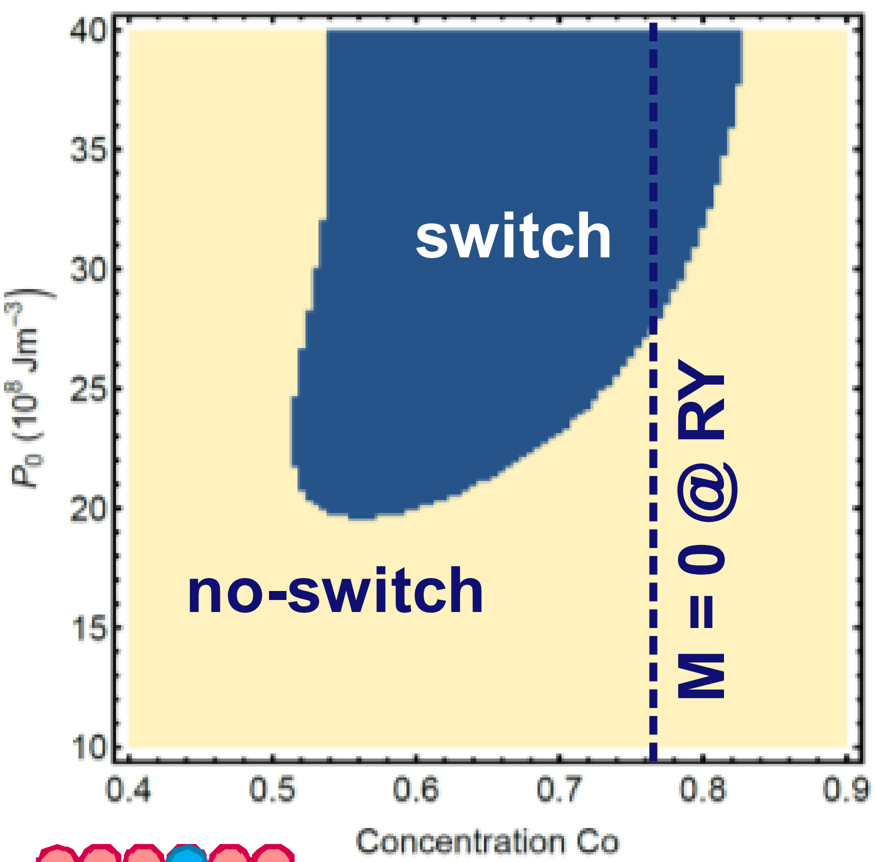
$S_i = \frac{1}{2},\ \mu_{at} = 7.5\ \mu_B$

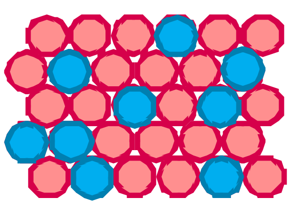
Gadolinium

Mark Lalieu, Maarten Beens *et al*., in preparation

AOS of alloy *versus* bi-layer

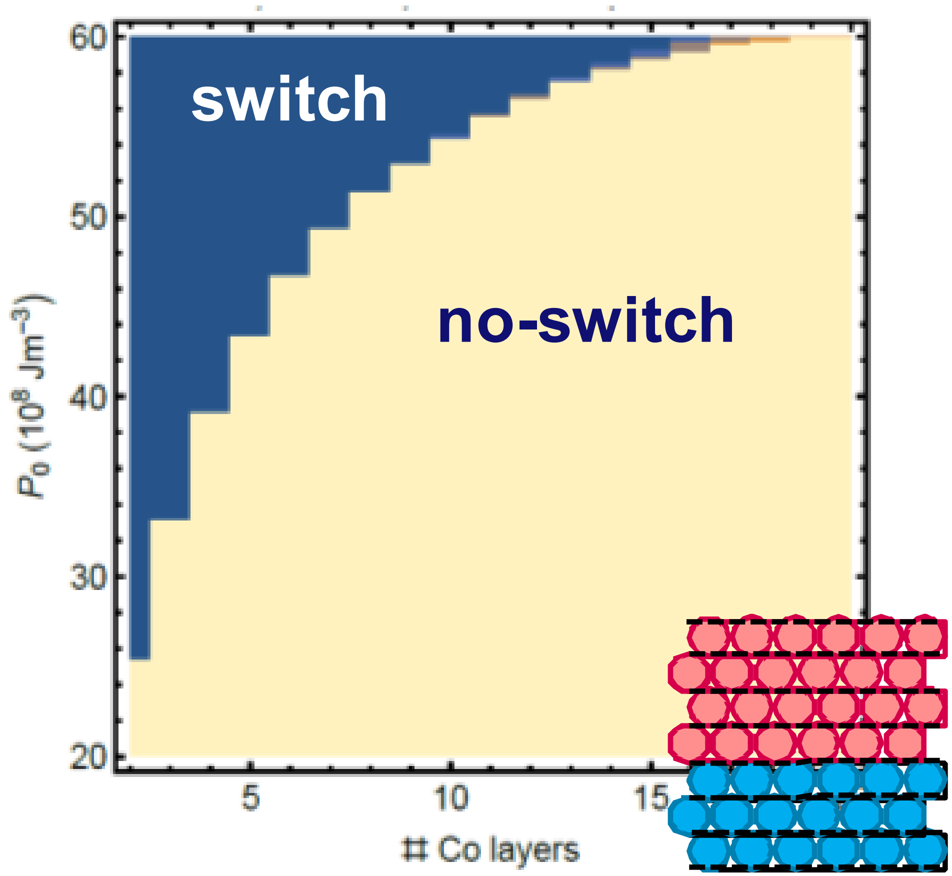
Alloy





Effective medium

Bi-layer

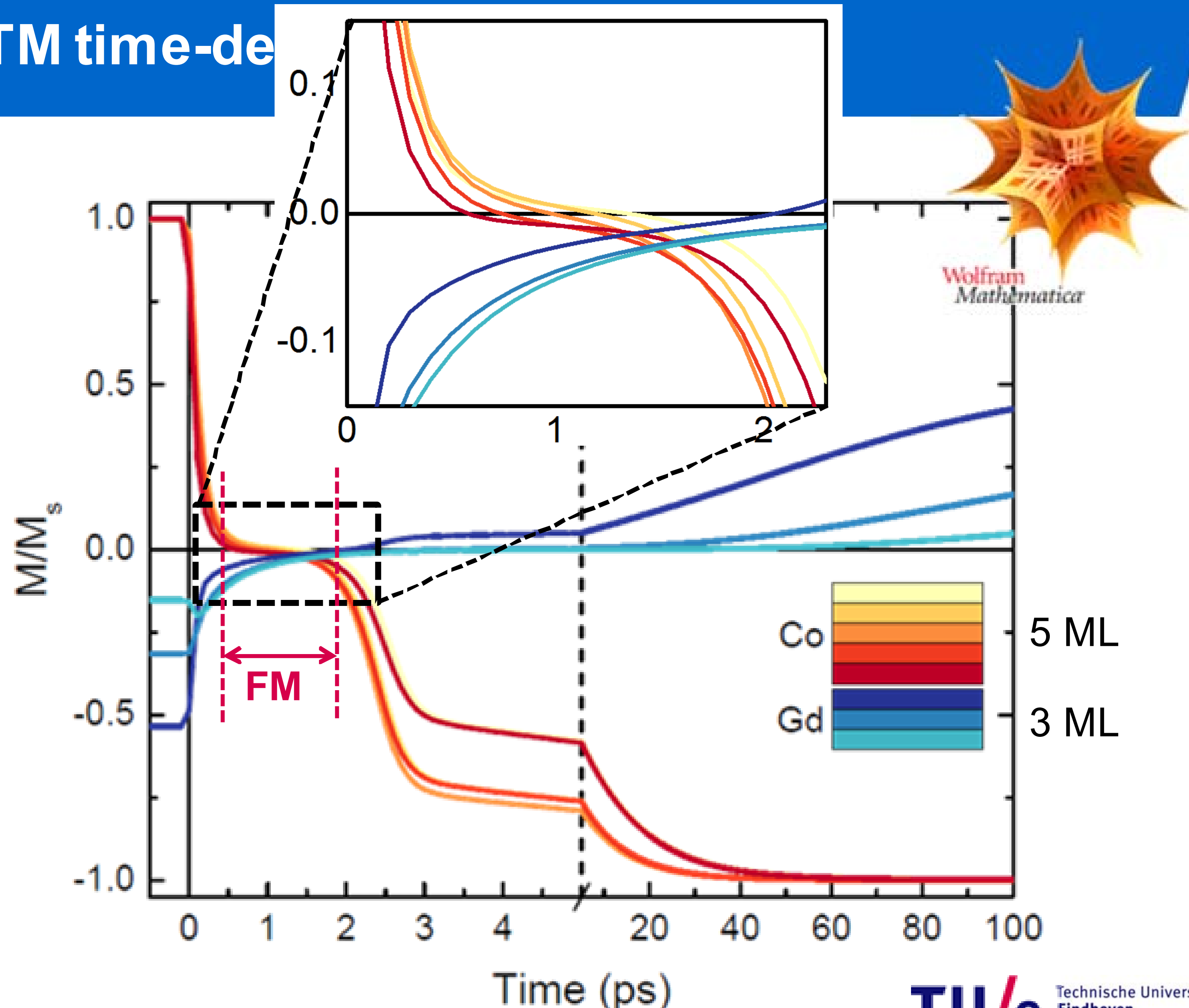


3 Gd layers

- **How come?**

Mark Lalieu, Maarten Beens *et al*., in preparation

M3TM time-de



Lalieu, Beens, Deenen, BK, to be published

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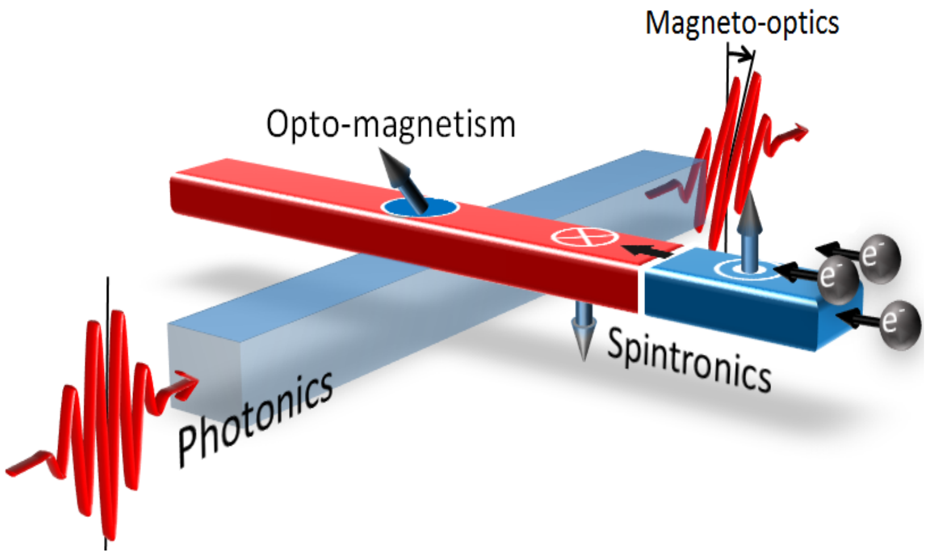
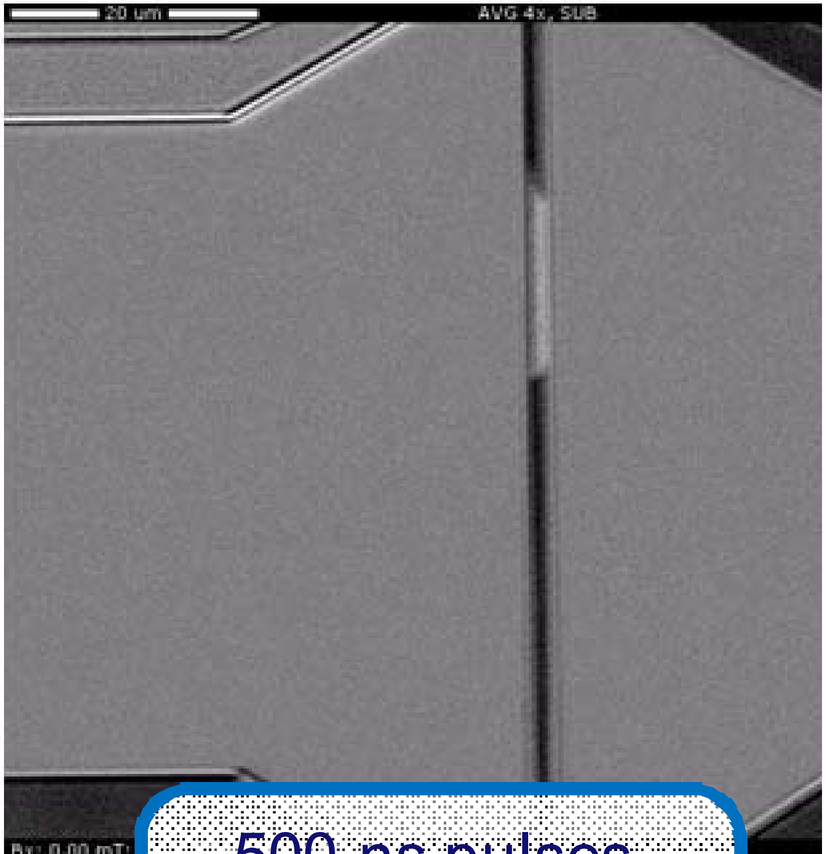
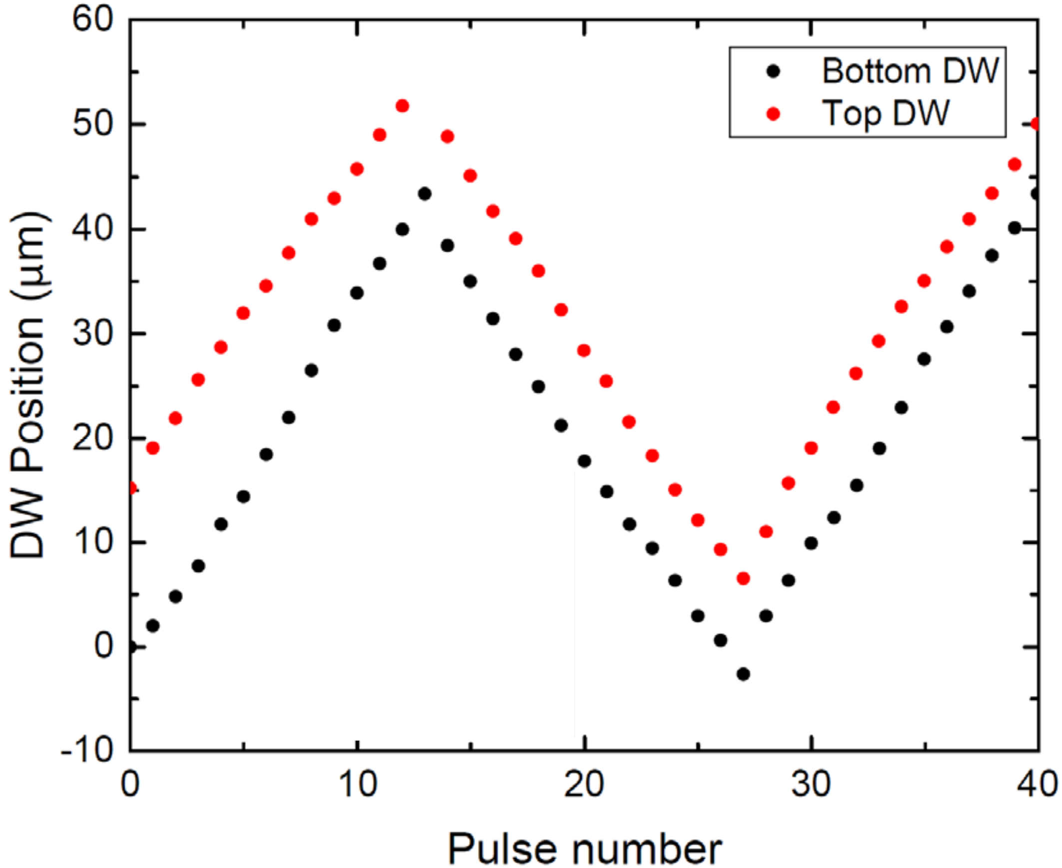


Current (SHE) induced motion in Pt/Co/Gd

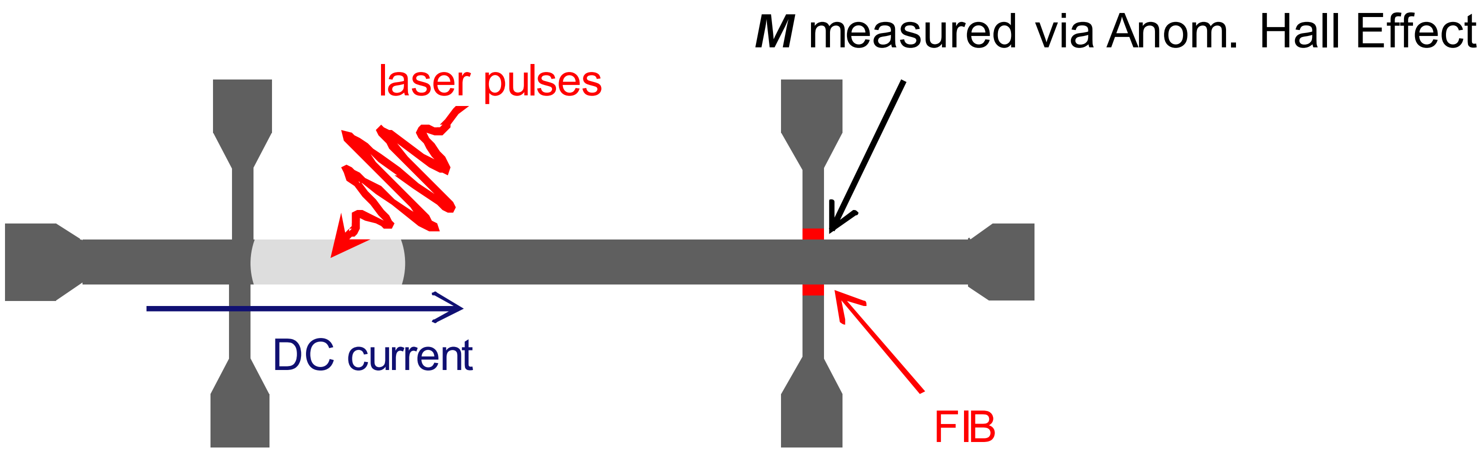


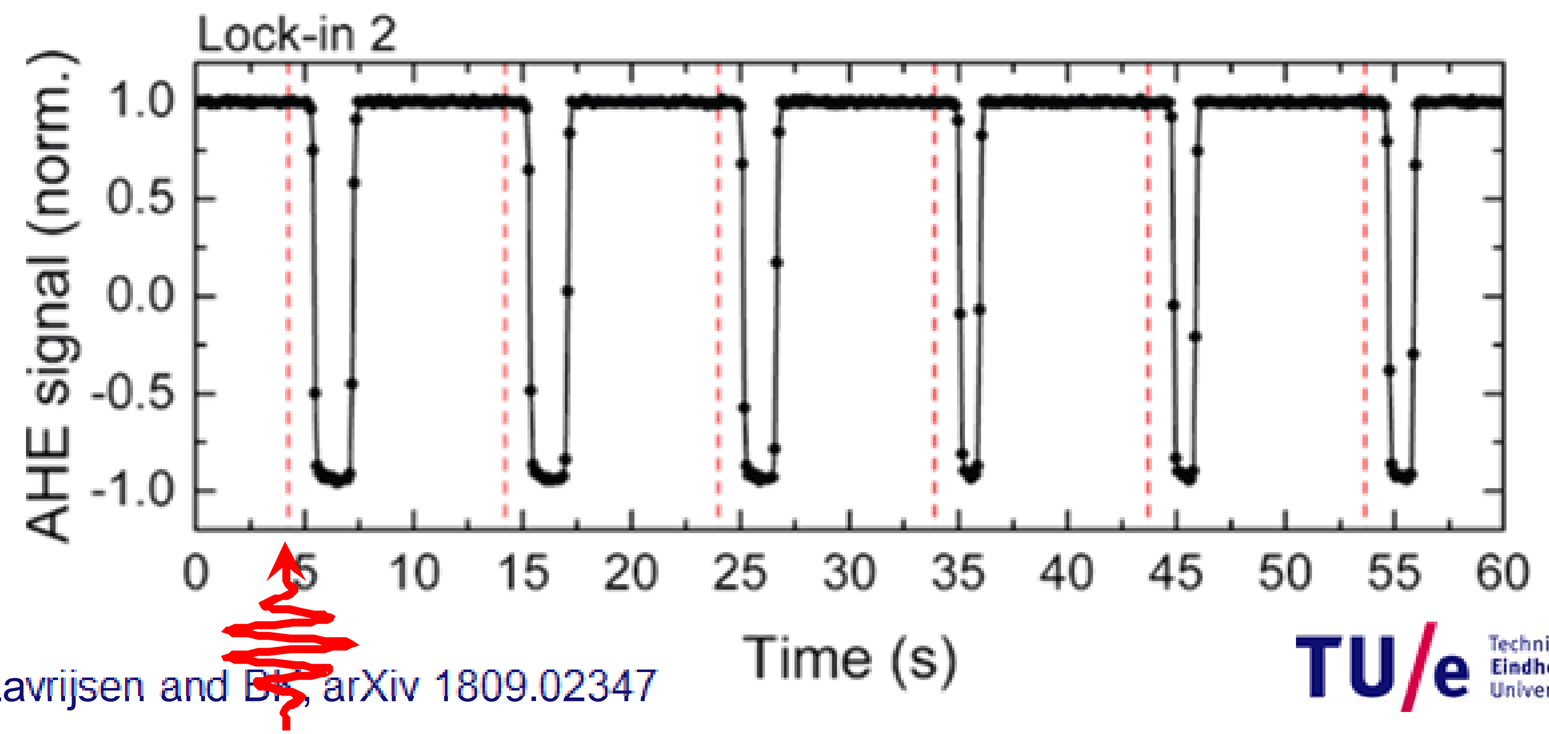
500 ns pulses
0.4×10^{12} A/m^2
v_{DW} = 8 m/s



Lalieu, Lavrijsen and BK, arXiv 1809.02347

All-optical writing “on the fly”

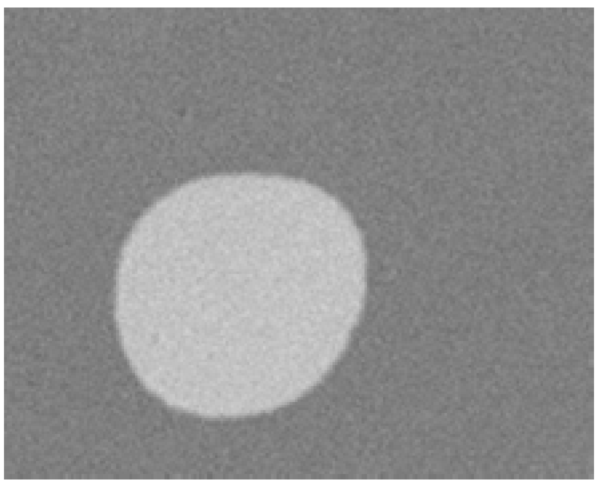




Lalieu, Lavrijsen and BK, arXiv 1809.02347

Conclusions & Take home

- **Converging of spintronics and fs magnetism rapidly progressing – two routes discussed**
- **First step towards integrated magneto-photonics**



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Mark Lalieu, Peeters, Lavrijsen *et al.*, Phys. Rev. B 96, 220411 (Rapid) 2017
M.L.M. Lalieu, R. Lavrijsen & BK, arXiv 1809.02347 (2018)
Lalieu, Deens, BK *et al.*, in preparation

Acknowledgements