Ultrafast switching of magnets

UppASD school 2022

Zhiwei Lu and **Danny Thonig**

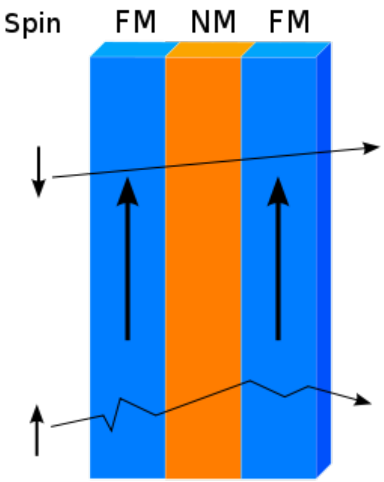
CONTENT

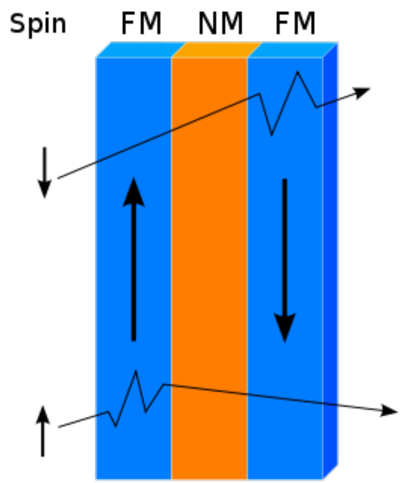
- Motivation of switching on ultrafast timescales
- Recap: Atomistic spin dynamics
- Energy barrier
  - Macrospin Switching
  - Macrospin Switching with inhomogeneous easy axis
  - Spin ice
- Domain wall
  - Spin transfer talk
- Internal-field-assisted switching
- Switching by Laser Pulse
  - Exchange vs damping
- Energy dissipation
- Conclusion

Based on:
[1] O. Eriksson et al. "*Atomistic Spin Dynamics - Foundations and Applications*" - Chapter 11, Oxford University Press, 2017

MOTIVATION OF SWITCHING ON ULTRAFAST TIMESCALES

Giant magneto resistant (Macroscopic switching)





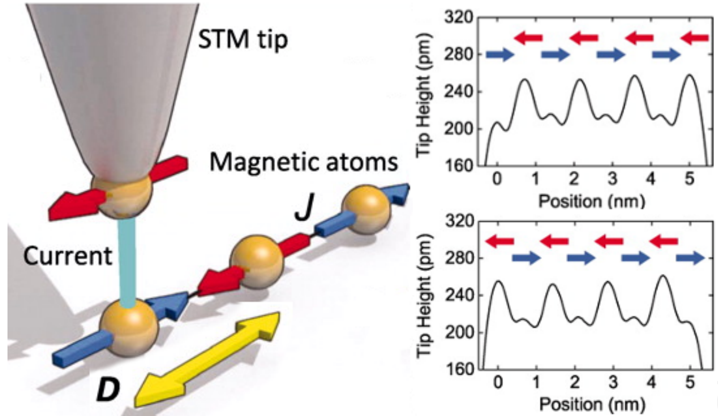
Albert Fert and Peter Grünberg -
The Nobel Prize in Physics 2007

https://www.informationweek.com/big-data/upcoming-data-storage-technologies-to-keep-an-eye-on

Writing information to a magnetic bit by changing the bit’s magnetization.

→ magnetization switching, or magnetization reversal

Atomic scale antiferromagnets (atomistic switching)



S. Loth et al., Science 335 6065 (2012)

aspects to the reversal process:

- Increase of switching speed (reduction of switching time)
- Minimise energy losses
- Minimise heating

An efficient switching mechanism involves a balance between the switching speed and the amount of external stimuli

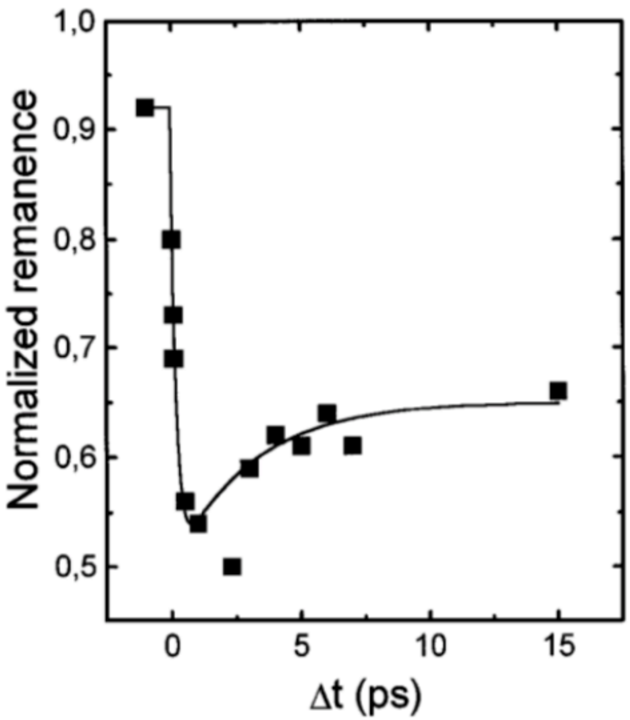
Such external stimuli could be magnetic fields, electrical currents, or heat.

Question to address: in which kinds of materials magnetization reversal can be controlled efficiently.

Optical controll

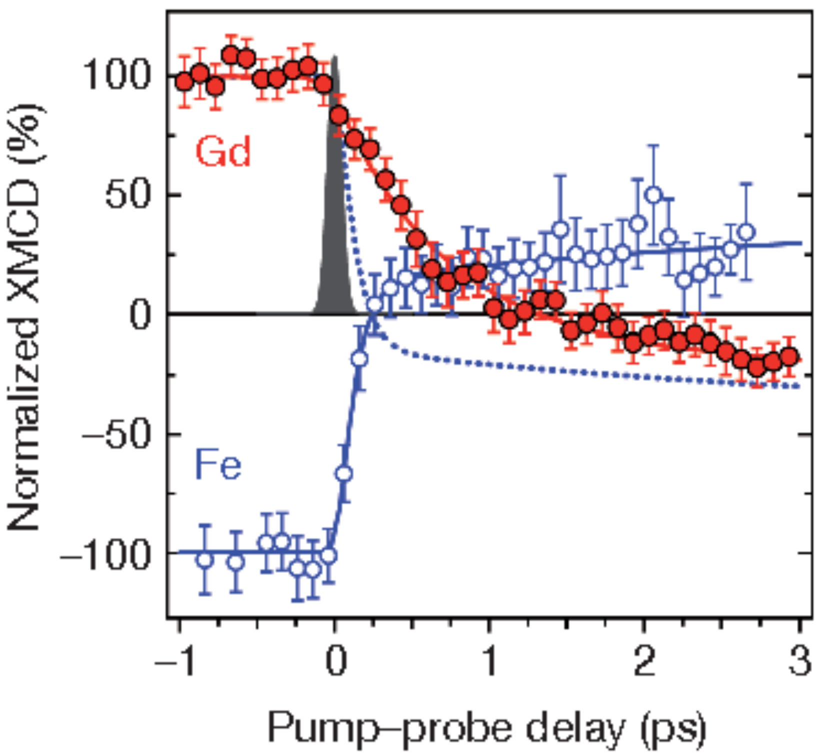
Demagnetisation

E. Beaurepaire et al. Phys. Rev. Lett., 76:4250 (1996).



All-optical switching

Radu et al., Nature 472 (2011)

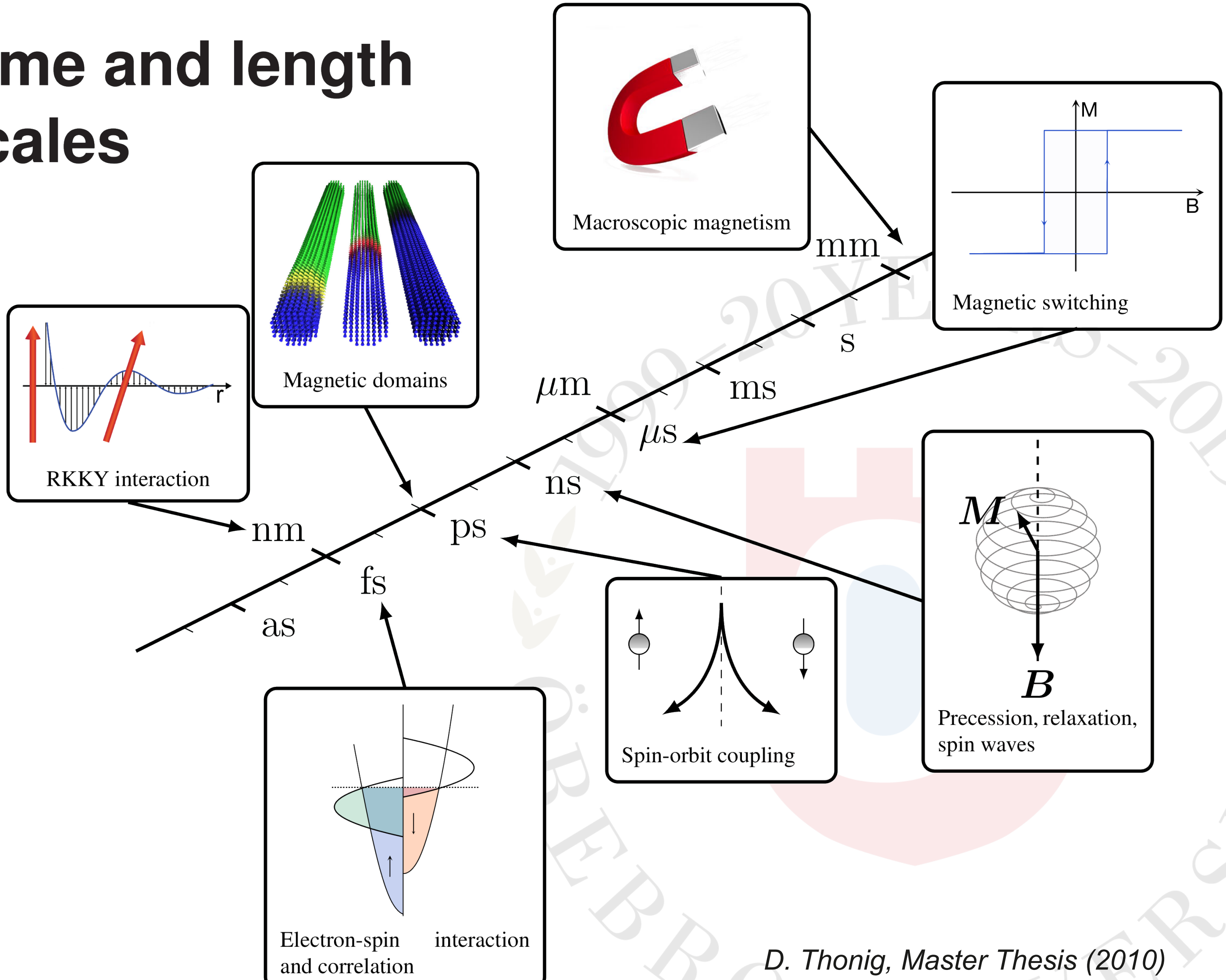


Unexpectedly fast drop in a Ni sample magnetization upon laser pulse illumination

The mechanisms behind these phenomena are far from trivial

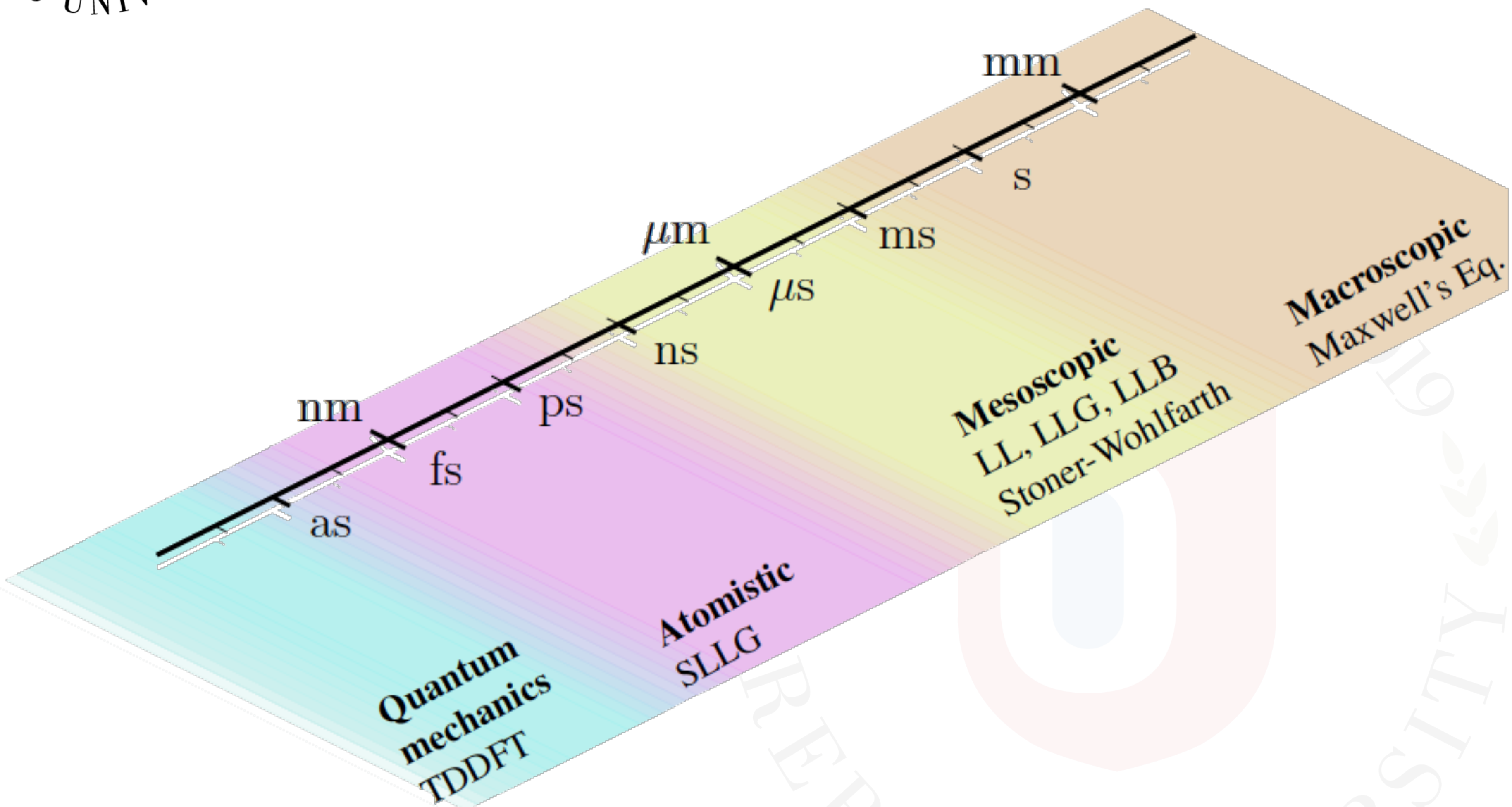
Where does the angular momentum transfers goes?

Time and length scales



D. Thonig, Master Thesis (2010)

MOTIVATION



D. Thonig, Master Thesis (2010)

ATOMISTIC SPIN DYNAMICS (RECAP)

Atomistic Landau-Lifshitz-Gilbert equation at $T = 0K$

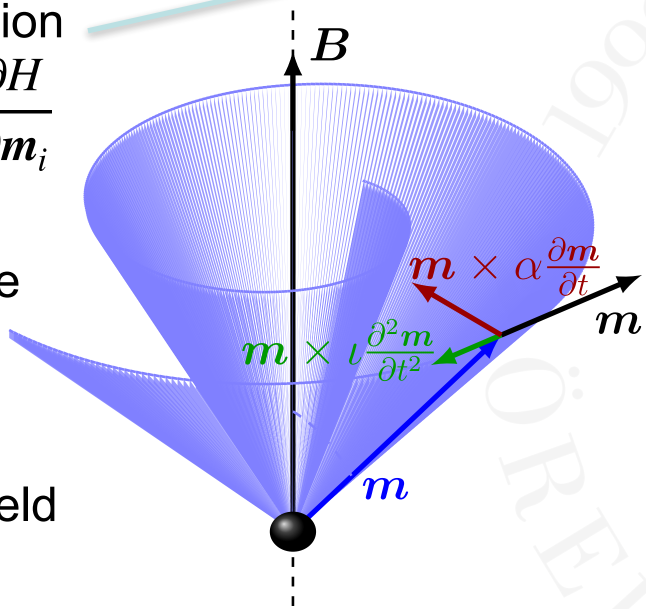
$$\frac{\partial \boldsymbol{m}_i}{\partial t} = \boldsymbol{m}_i \times \left(-\gamma \boldsymbol{B}_i + \boldsymbol{B}_i^{diss}\right)$$

Precession

$$\boldsymbol{B}_i = -\frac{\partial H}{\partial \boldsymbol{m}_i}$$

Dissipation

$$\boldsymbol{B}_i^{diss} = \frac{1}{|\boldsymbol{m}_i|}\alpha \frac{\partial \boldsymbol{m}_i}{\partial t}$$



D. Thonig, Diploma Thesis (2014)

Contains

- Exchange terms (like Heisenberg, DMI, biquadratic etc.)
- Anisotropy
- External magnetic field

Viscous damping with Gilbert damping α

Fluctuation-dissipation theorem

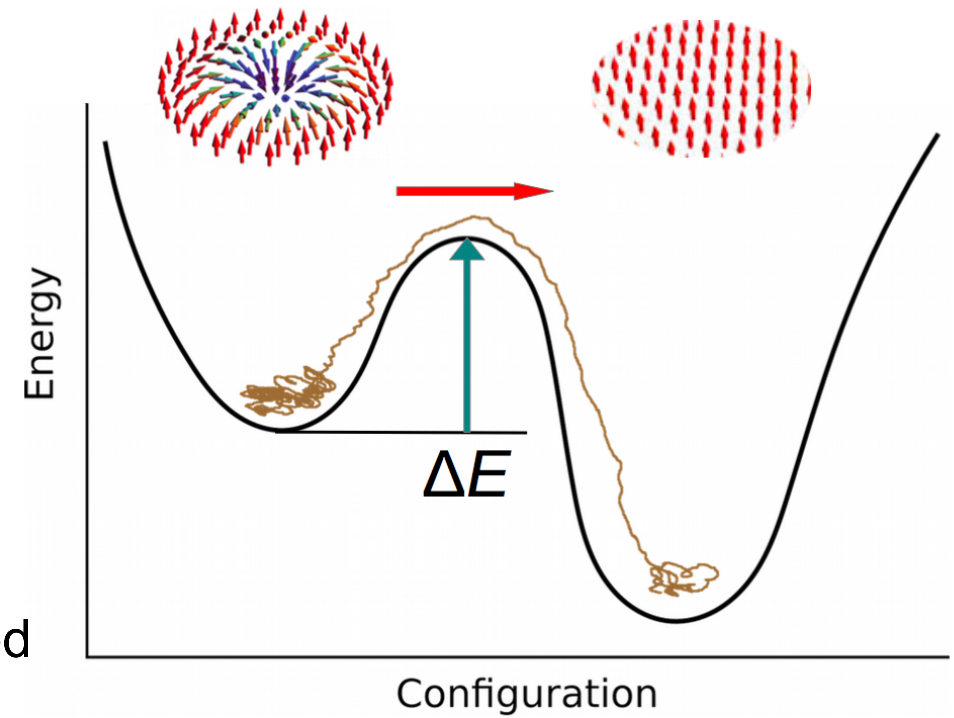
ENERGY BARRIERS

Ultrafast processes vs. the adiabatic approximation: probable break down (involves electron processes)

Most switching mechanisms via collective, or individual, motion of atomic spins across one or more energy barriers

Barriers from magnetic anisotropy K

- magnetostatic dipole interactions, (shape anisotropies)
- spin–orbit effects (magnetocrystalline anisotropies)



Method to calculate barrier

Geodesic Nudge Elastic Band Method

P. Bessarab et al., Comp. Phys. Comm. 196, 335 (2015)

Energy barrier $\Delta E \approx KV$ (V is volume of the system)

- Larger anisotropy - smaller switching rates (but large anisotropies keeps system stable against thermal fluctuations.
- Limit to how small a system can be, where energy barrier that is larger than the thermal effects

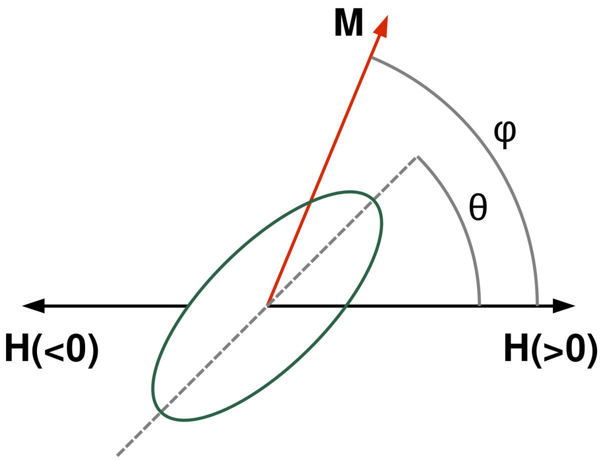
Superparamagnetism

Magnetization flips randomly direction under the influence of temperature. The typical time between two flips is called the **Néel relaxation time** τ_N. If $t >> \tau_N$, the magnetization in the superparamagnetic state appears to be in average zero. Compared to paramagnetism, an external magnetic field is able to magnetize the system and the magnetic susceptibility is large. The temperature for what $t == \tau_N$ is called the blocking temperature T_B

Switching rates from Arrhenius equation: $\tau_N = \tau_0 \exp\left(\frac{KV}{k_B T}\right)$

MACROSPIN SWITCHING

suffices to model a single spin (macro-spin) in an external magnetic field (coherent spin rotation)



https://en.wikipedia.org/wiki/Stoner–Wohlfarth_model

Stoner-Wohlfarth theory (1948)

- no description of dynamics
- but magnitude of the external field for a reversal to take place
- the energetics and hysteresis of the process

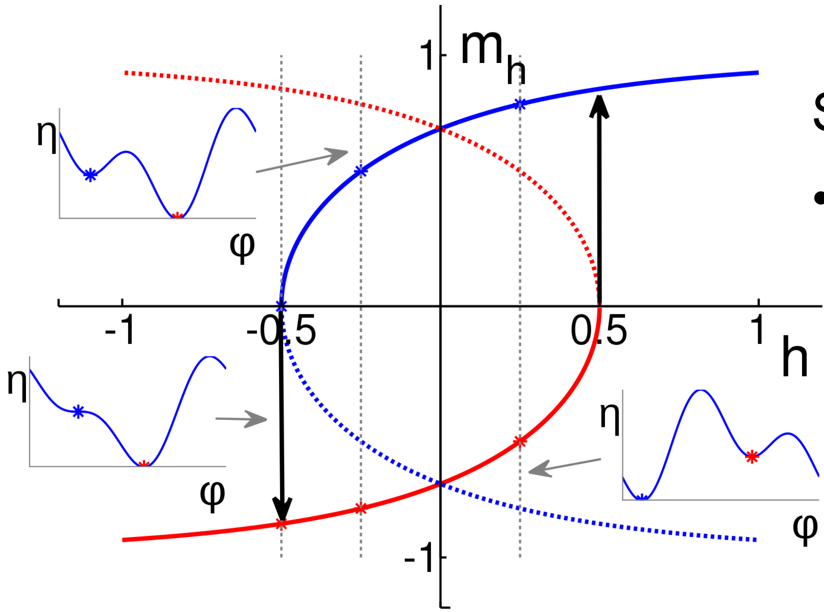
$$E = KV\sin^2(\phi - \theta) - \mu_0 M_s VH\cos(\phi)$$

M_s is the saturation magnetisation

Magnetization direction is in equilibrium if the forces on it are zero

In zero field: $\boldsymbol{M}$ is minimized when $\boldsymbol{M} \parallel \boldsymbol{e}^{MCA}$. In a large field, $\boldsymbol{M} \upuparrows \boldsymbol{H}$

suffices to model a single spin (macro-spin) in an external magnetic field (coherent spin rotation)



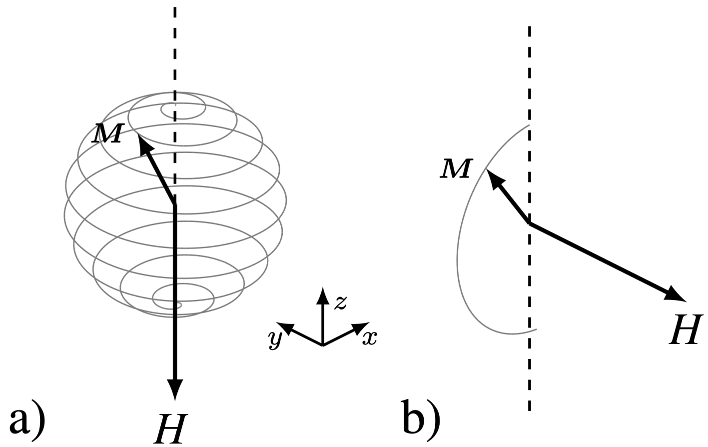
https://en.wikipedia.org/wiki/Stoner–Wohlfarth_model

Stoner-Wohlfarth theory (1948)

- $\partial E/\partial \phi = 0$ has two solution curves for each angle θ between easy axis and field.

If dynamics: Using LLG define before

Field only from anisotropy and external magnetic field (exchange not important)



D. Thonig, Master Thesis (2010)

Case a) - Antiparallel switching $\boldsymbol{H} \uparrow\downarrow \boldsymbol{M}$

$H < |\boldsymbol{B}|$ no reversal will take place

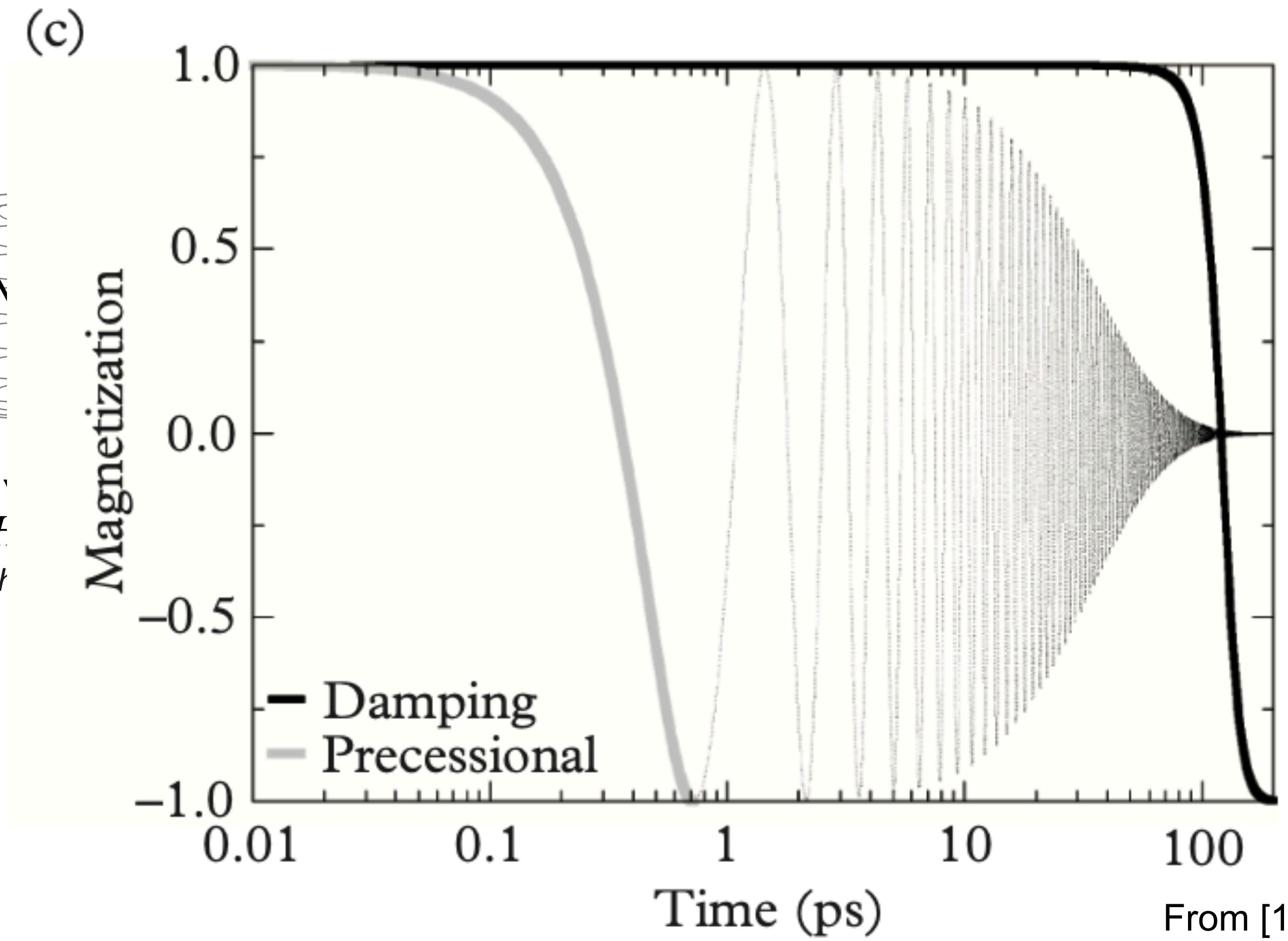
$H > |\boldsymbol{B}|$ reverse the direction of macrospin (Under finite thermal fluctuations)

Known also as damping switching

- Precession around the magnetic field with $\omega = \gamma B$
- Simultaneously relaxation towards the field axis at a rate proportional both $|\boldsymbol{B}|$ and to the Gilbert damping parameter α.
- Since $\alpha << 1$ - damping motion is much slower than the precessional motion - inefficient reveals

If dynamics: Using LLG define before

Field only from anisotropy and external magnetic field



g $\boldsymbol{H} \perp \boldsymbol{M}$

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From [1]

a)

D. Th

kfile K_1 in mRyd K_2in mRyd K^U/K^C

```
1 7  -0.020 0.00000 0.0 0.0 1.0 0.1
2 7  -0.020 0.00000 0.0 0.0 1.0 0.1
```

Mode (1 - uniaxial, 2 - cubic, 7 - both)

Uniaxes

inpsd.dat

```
…

posfile      ./posfile
momfile      ./momfile
exchange     ./jfile
anisotropy   ./kfile

…

hfield     0   0   2.0
Temp       0.0
damping    1.0

…

do_tottraj Y
do_avrg Y
…
```

Anisotropies

Magnetic field in Tesla

Temperature in K

Gilbert damping

Plotting the average magnetic moment trajectory

Task 1 and Task 2 of this tutorial …

inpsd.dat

```
…

do_bpulse      2
bpulsefile     ./bpulsefile

…
```

Pulse shape

1- exponential

2- gaussian

3- polexponential

4- square pulse

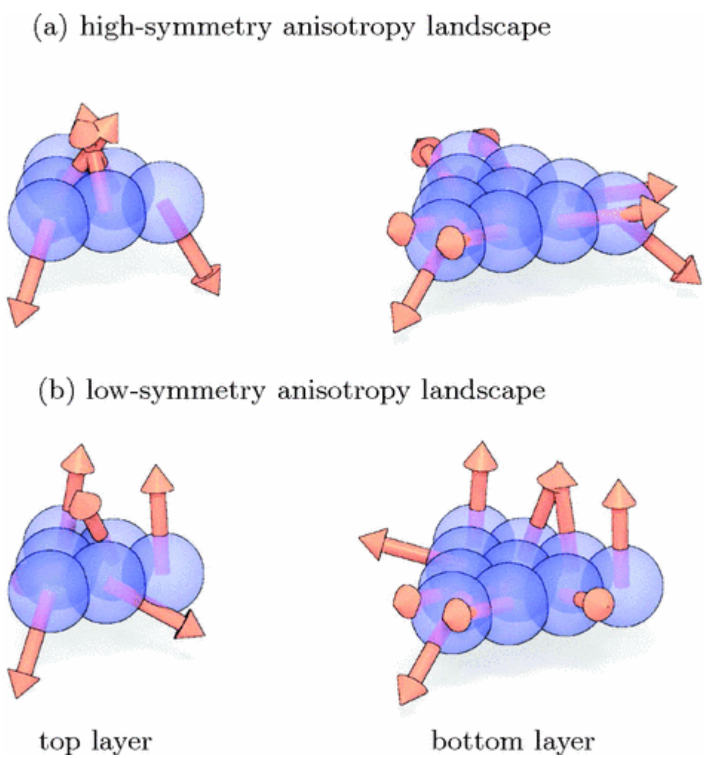
bpulsefile

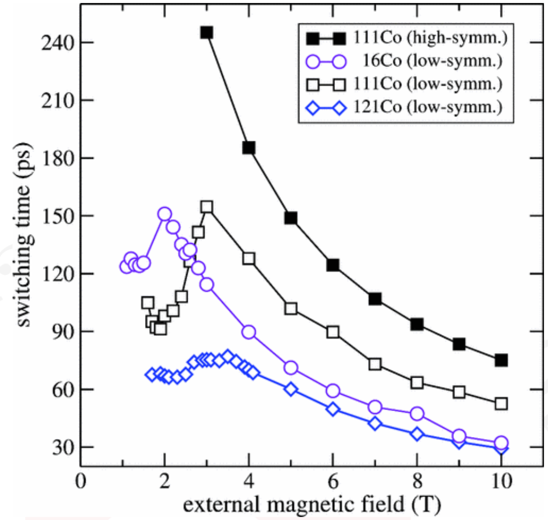
```
#Header
93.70 0 0    # Magnetic field amplitude (x,y,z)
0.0          # Not used
1            # Step between recalculation of field (1 is good)
10           # Number of pulse parameters to use
0.0          # Pulse parameter 1
5.0e-12      # Pulse parameter 2 (Center of pulse for Gaussian)
1.0e-12      # Pulse parameter 3 (Width of pulse for Gaussian)
0.0          # Pulse parameter 4
0.0          # Pulse parameter 5
1.0          # Pulse parameter 6 (Scaling factor for Gaussian)
0.0          # Pulse parameter 7
0.0          # Pulse parameter 8
0.0          # Pulse parameter 9
0.0          # Pulse parameter 10
```

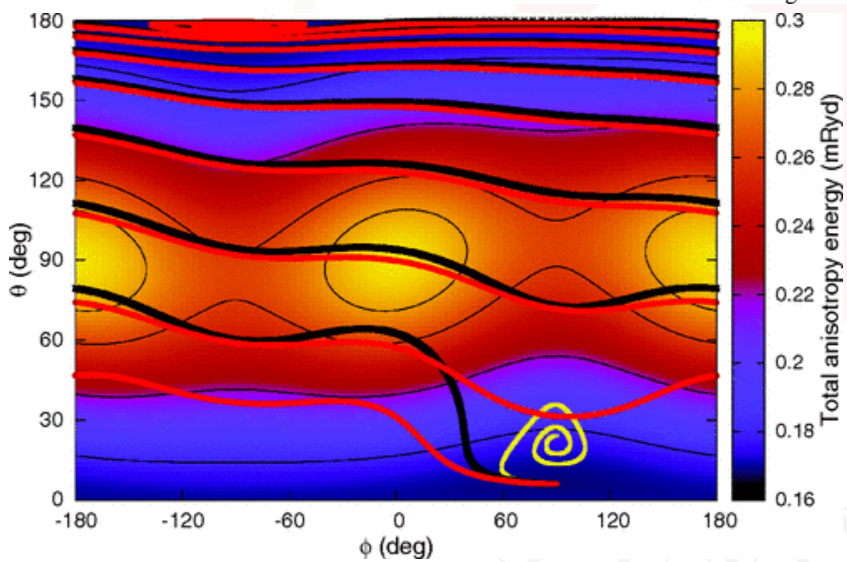
Task 3 of this tutorial …

MACROSPIN SWITCHING WITH INHOMOGENEOUS EASY AXIS

C. Etz et al. Phys. Rev. B **86**, 224401

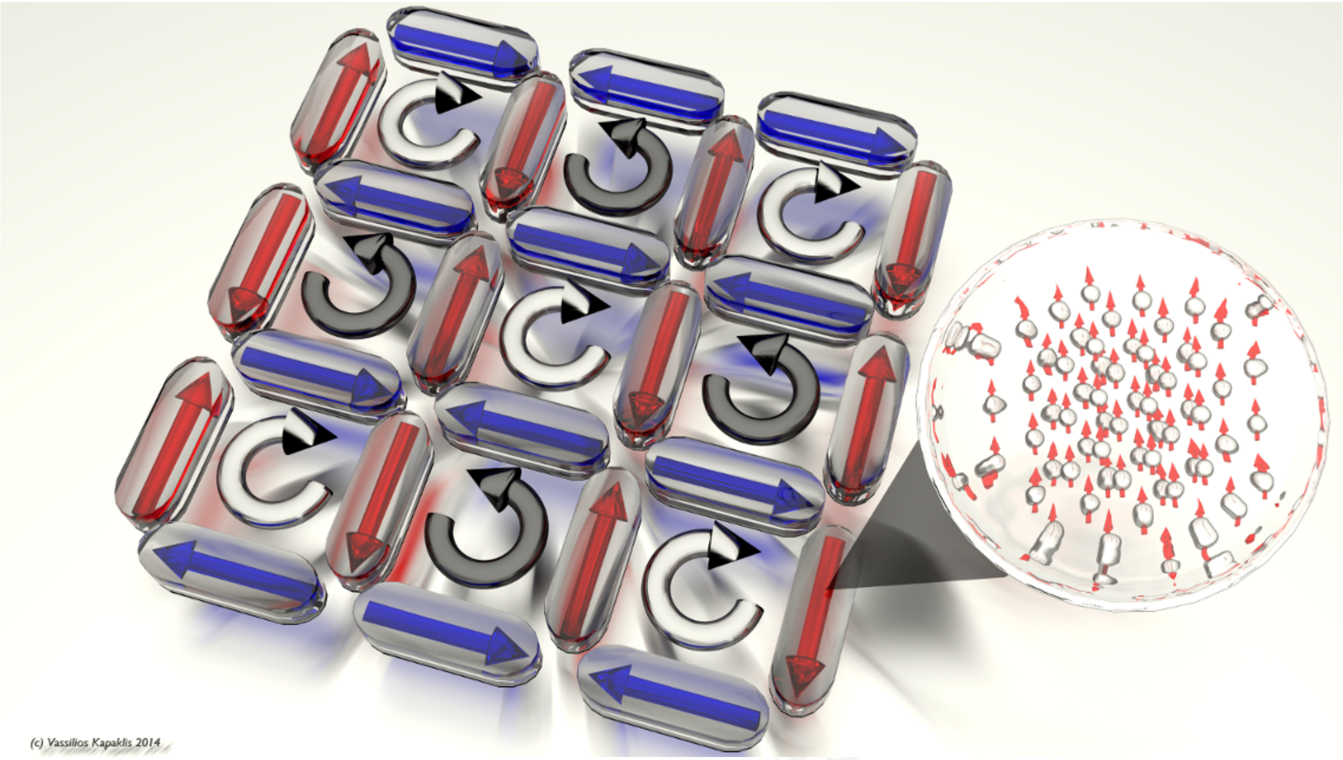


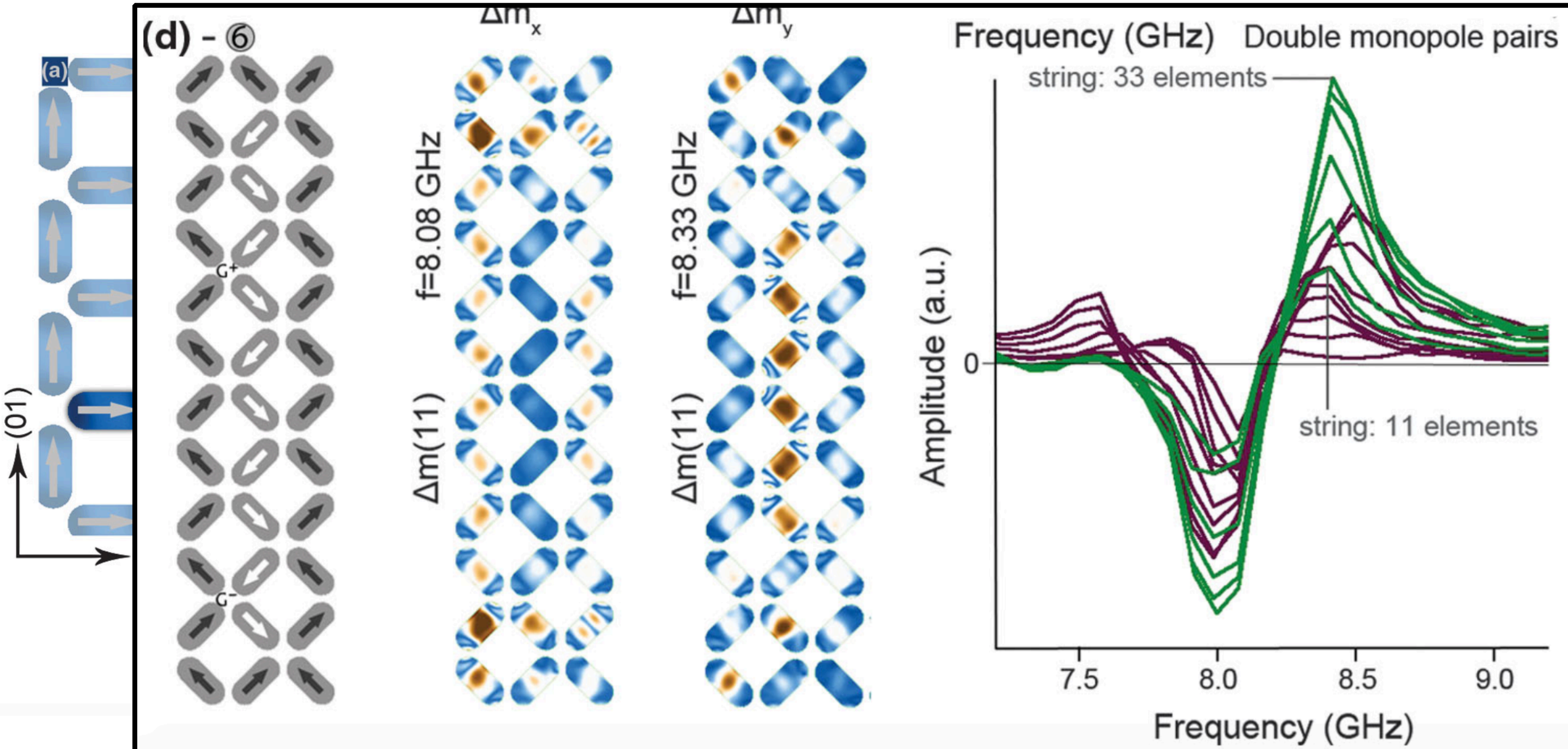




SPIN ICE

Spin ice is a low-dimensional arrangement of nanoislands in a single domain state. Why to apply micro magnetism?





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S. Gliga et al., Phys. Rev. Lett. 110, 117205 (2013)

DOMAINS AND DOMAIN WALLS

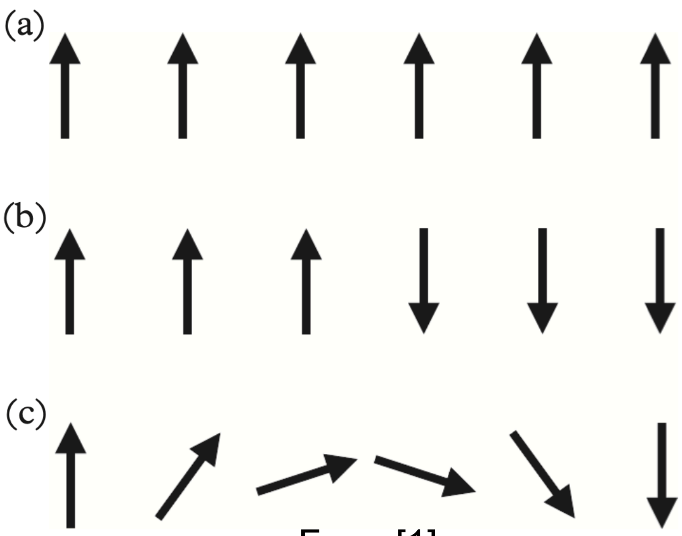
In real materials, both exchange and anisotropy energies are present

Suppose having two domain of opposite spin (b).

(a) $K = 0$, and $J > 0$, result in a ferromagnetic configuration.

(b) $K \neq 0$, and $J = 0$, result in an abrupt change of the magnetization.

(c) $K \neq 0$, and $J \neq 0$, give a smooth rotation of the magnetization: a domain wall



From [1]

Domain wall width when $K << J$: $d_{dw} = \pi\sqrt{\frac{A}{K}}$,

With micro magnetic exchange constant A

40 nm for body-centred cubic Fe

15 nm for hexagonal close-packed Co

1.9 nm for monolayer of Fe on a W(110)

The domain wall width is important for magnetization switching — it can determine how the actual reversal process behaves

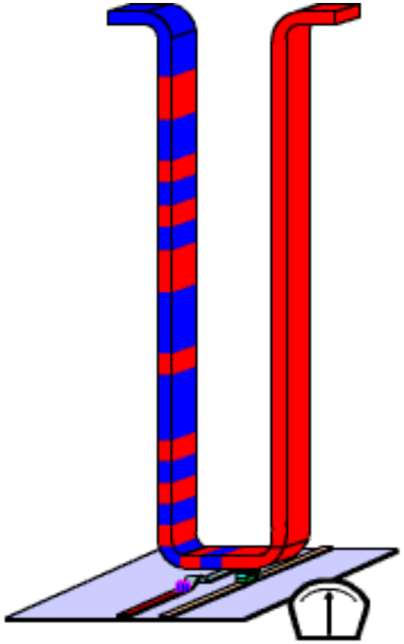
$d_{dw} >$ magnetic system: one domain will fit in the sample; single-domain ferromagnet (coherent macrospin switching)

$d_{dw} <$ magnetic system: several domains can form across the sample

SPIN TRANSFER TORQUE

Single domain switching vs. magnetic configuration of selected domains

Regardless of the type of external stimulus - reversal processes involve the motion of domain walls (DW)

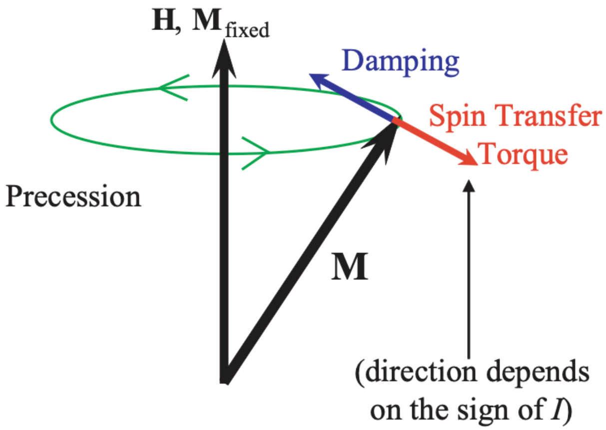


From https://physics.aps.org/story/v19/st14

The domain walls can be moved by applied magnetic fields or electric current (more efficient)

Material is spin polarized ⇒ difference between the amount of conduction electrons with majority and minority spin ⇒ current has polarization.

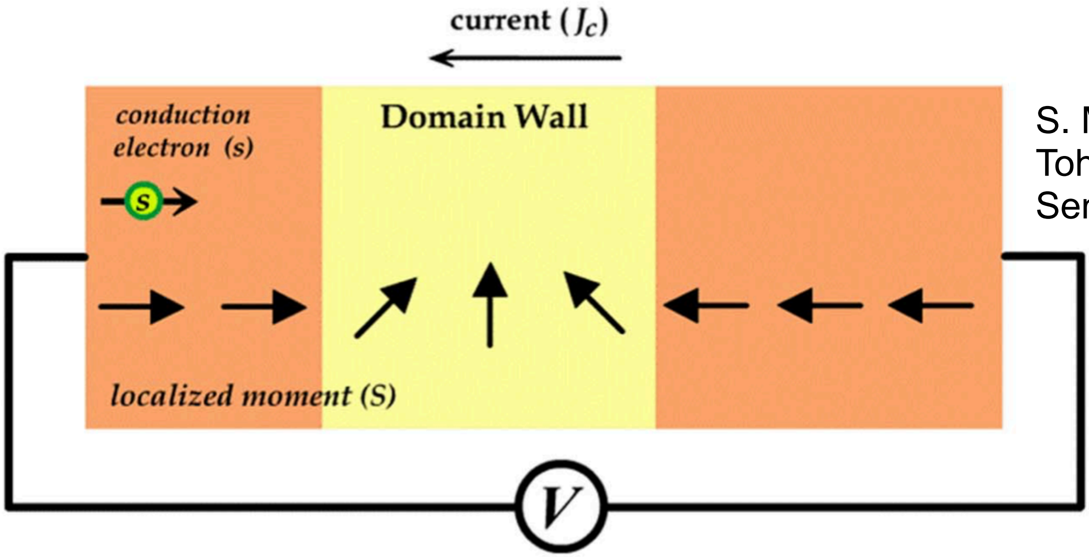
Spin polarized current passes through a domain wall ⇒ spins of the charge carriers will align with the changed magnetization ⇒ a transfer of angular momentum



domain wall is rotate towards the polarization of the current ⇒ magnetic moments rotate and the domain wall moves.

Spin-transfer torque (STT; Slonczewski, 1996)

D. C. Ralph et al., J. Mag. Mag. 320, 1190-1216 (2008)

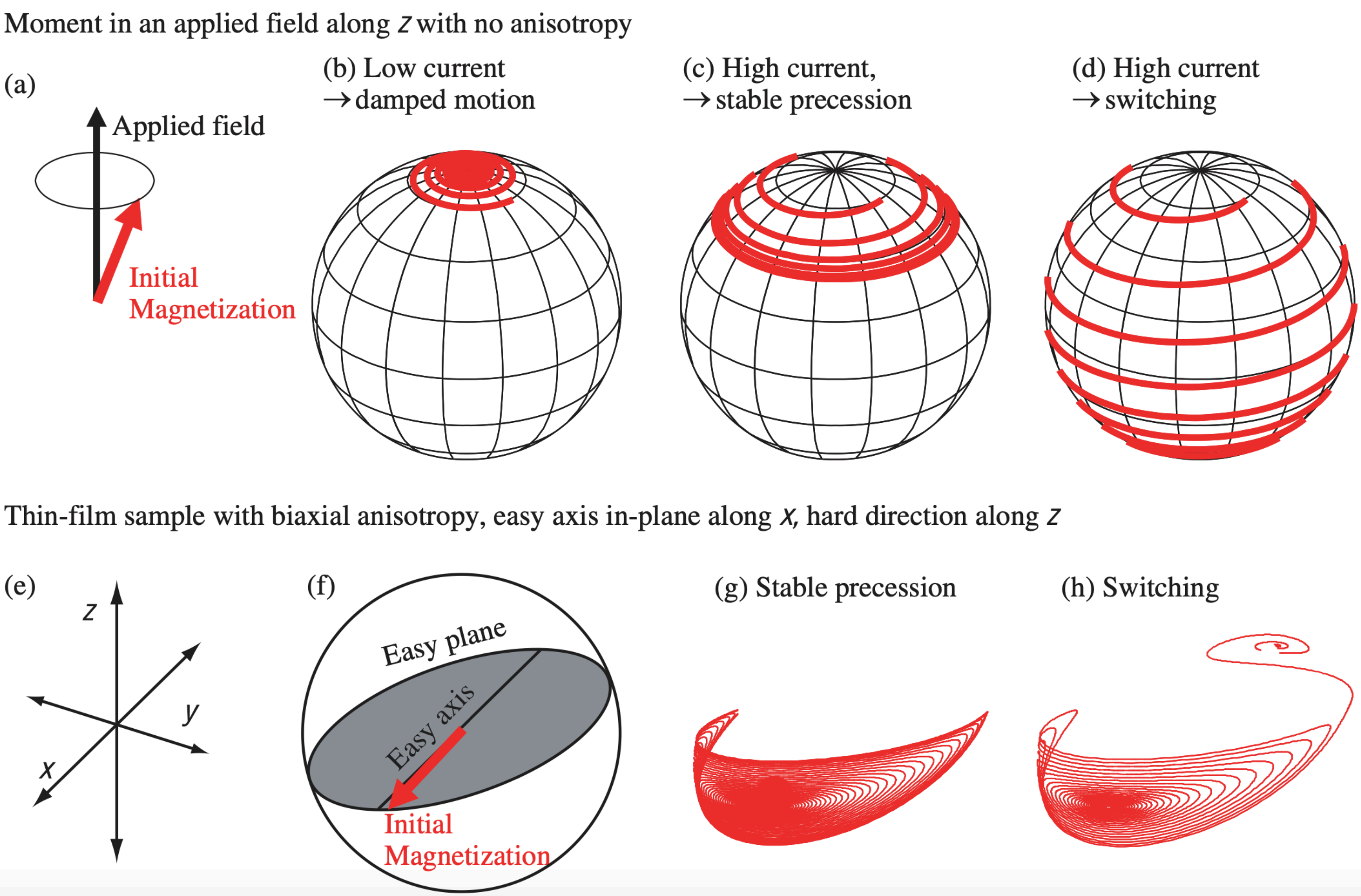


S. Maekawa et al.
Tohoku University
Sendai, Japan

$$\boldsymbol{u} = \frac{j_e P g \mu_B}{2e\,|\boldsymbol{m}_i|}$$

$$\frac{\partial \boldsymbol{m}_i}{\partial t} = \boldsymbol{m}_i \times \left(-\gamma \boldsymbol{B}_i + \boldsymbol{B}_i^{diss}\right) - \boldsymbol{m}_i \times \boldsymbol{m}_i \times \boldsymbol{u} \cdot \nabla \boldsymbol{m}_i - \beta \boldsymbol{m}_i \times \boldsymbol{u} \cdot \nabla \boldsymbol{m}_i$$

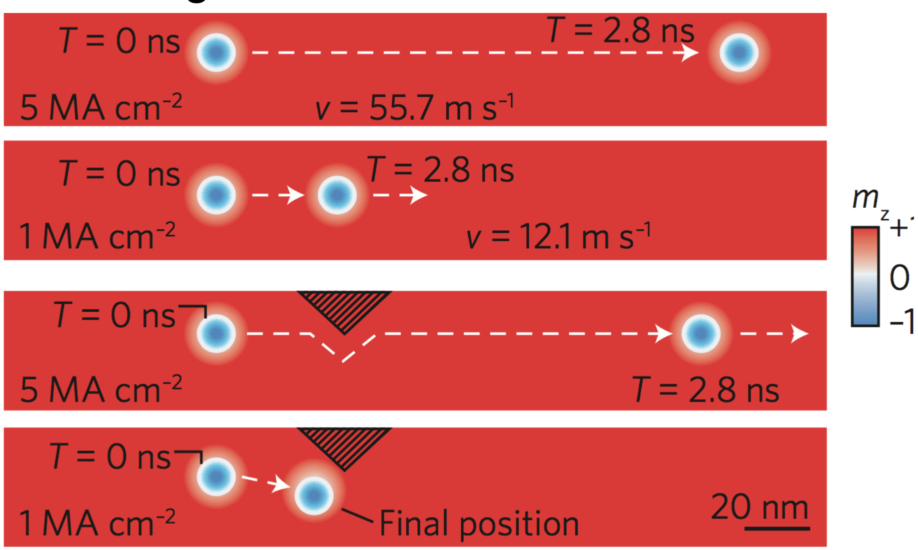
D. C. Ralph et al., J. Mag. Mag. Mat. 320, 1190-1216 (2008)

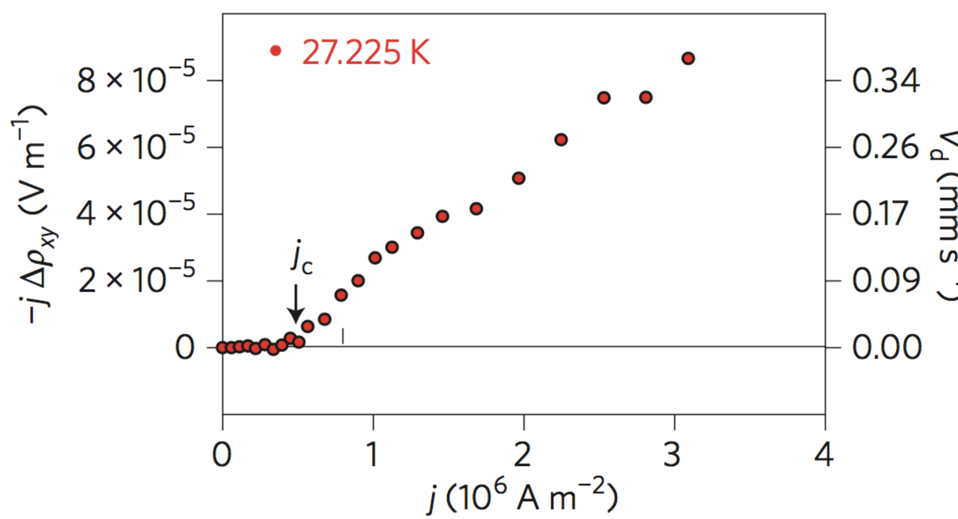


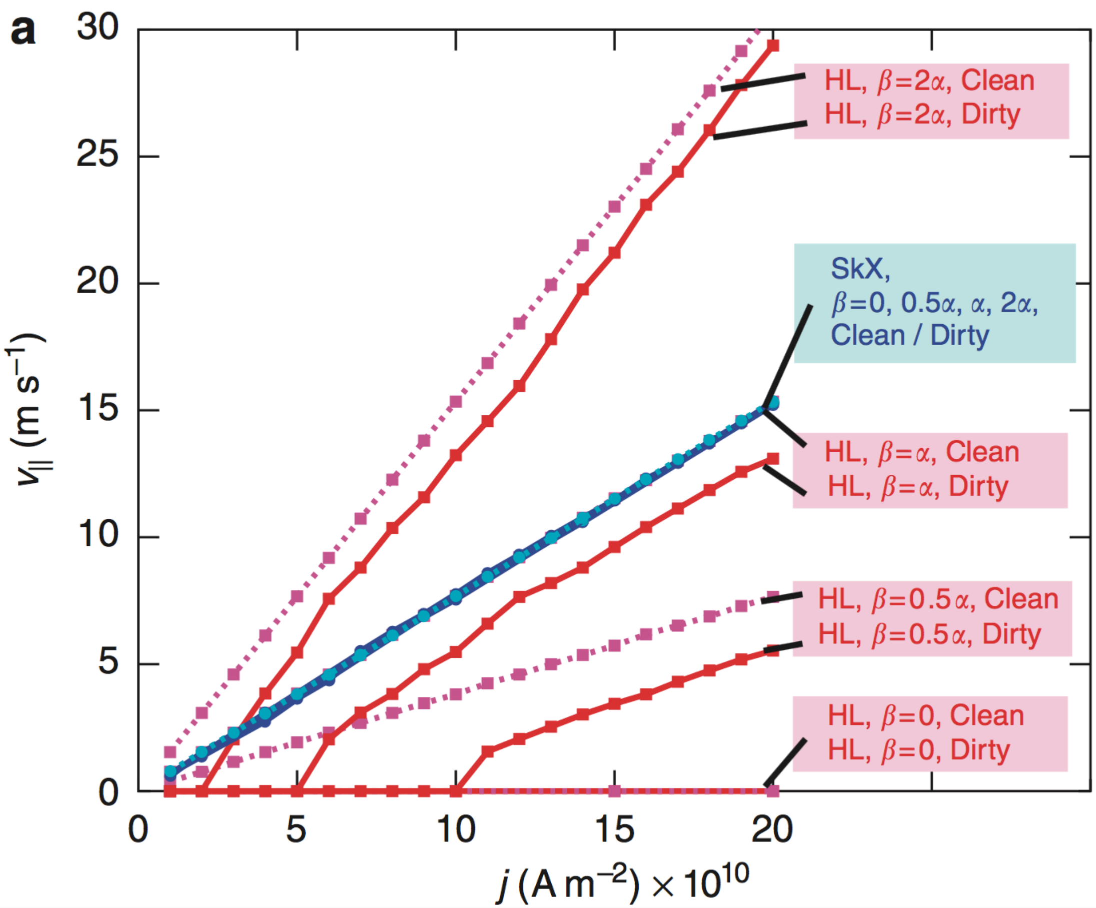
X. Zhang et al., *Scientific Reports* **5**, 9400 (2015)
N. Nagaosa et al., Nature Nanotechnology **8**, 899–911 (2013)

J. Iwasaki et al. *Nature Communications* **4**, 1463 (2013)
Spin Current (eds S. Maekawa et al.) 402–423 (Oxford Univ. Press, 2012)

- Skyrmion i) are basic building block of a new generation of spintronic devices and ii) can be moved or excited at low energy costs
- Motion due to same spin-transfer mechanism in both skyrmions and DWs (same spin-conservation rules). However, the depinning current, j_c is greatly reduced for SkX, allowing them to move with small currents and small speeds.







Depinning currents are significant for helical DWs, but practically zero for skyrmions.

weak influence of defects is ascribed to the role of the Magnus force for skyrmions and
the advantage of their flexibility to avoid pinning centres

Reason: smaller sizes and shorter spacings for skyrmions could allow faster information flows with similar current densities

X. Zhang et al., Scientific Reports ***5****, 9400 (2015)*
N. Nagaosa et al., Nature Nanotechnology ***8****, 899–911 (2013)*
J. Iwasaki et al. Nature Communications ***4****, 1463 (2013)*

How to setup STT in UppASD input?

inpsd.dat

```
…
restartfile ./restart.DOMAIN.DW
…
stt   A
jvec   0 100 0
…
```

STT mode

$\boldsymbol{u}$ in the $\boldsymbol{u} \cdot \nabla \boldsymbol{m}$ term

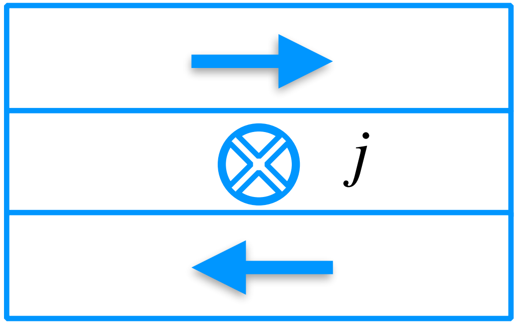
Task 4 of this tutorial …

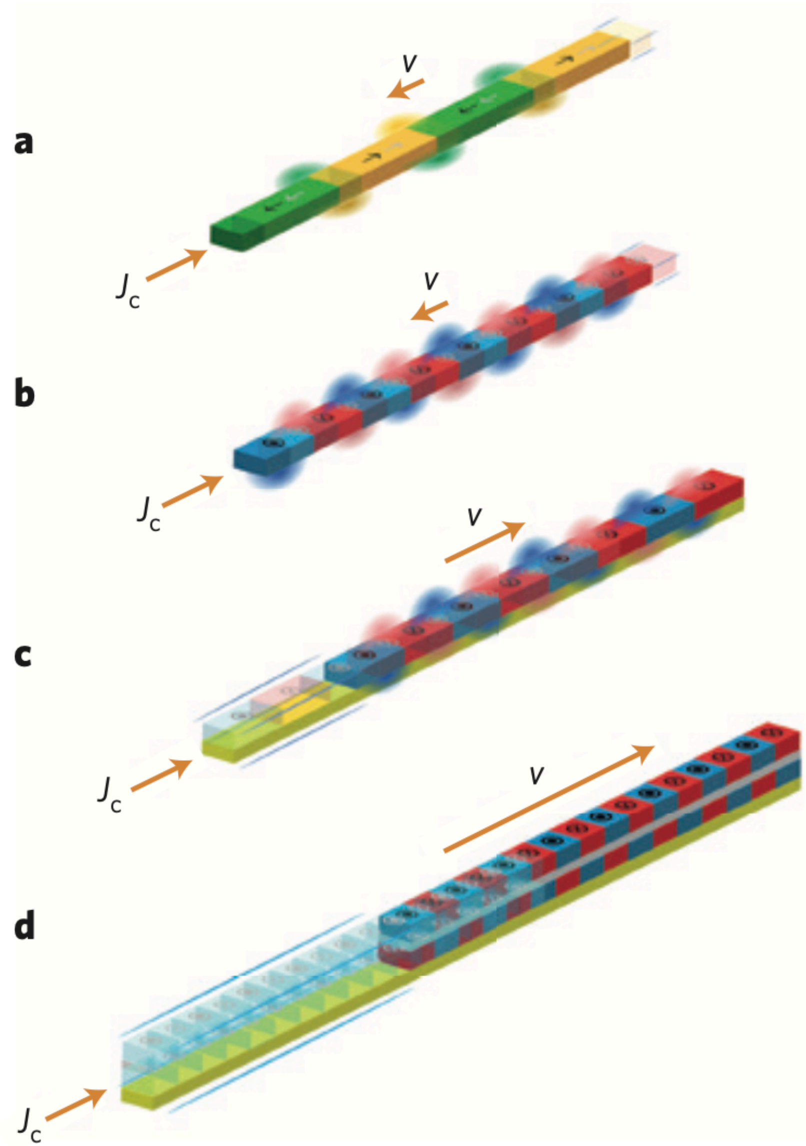
INTERNAL-FIELD-ASSISTED SWITCHING

Another way to improve the efficiency of macrospin switching is to use intrinsic fields $\boldsymbol{B}^{xc}$

Interatomic exchange field is very large ($> 100T$).

In antiferromagnets the intrinsic field can assist for switching when 180deg angle between the magnetic moments is lifted, e.g. in a trilayer structure



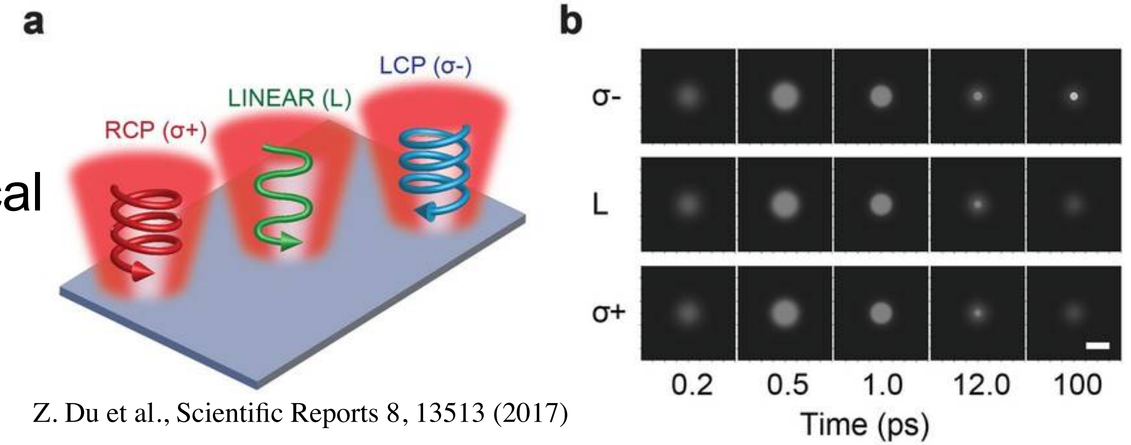


A. Bergman et al. Phys. Rev. B, 83, 224429, 2011

S. Parkin et al., Nature Nanotechnology10, 195–198 (2015)

SWITCHING BY LASER PULSE

possibility of inducing magnetization reversal by optical means, without an applied magnetic field



Z. Du et al., Scientific Reports 8, 13513 (2017)

Expect: circularly polarized light carries spin angular momentum ⇒reversal magnetization reversal

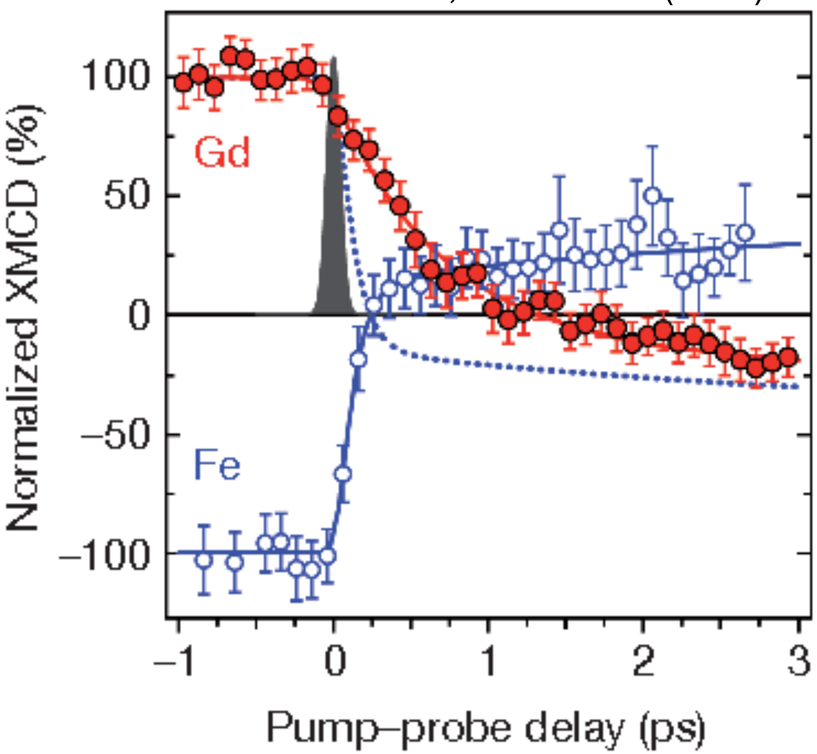
surprisingly, similar phenomena were observed when linearly polarized light,

Other mechanism: temperature pulse provided by the pump laser - ‘all-thermal control of magnetism’.

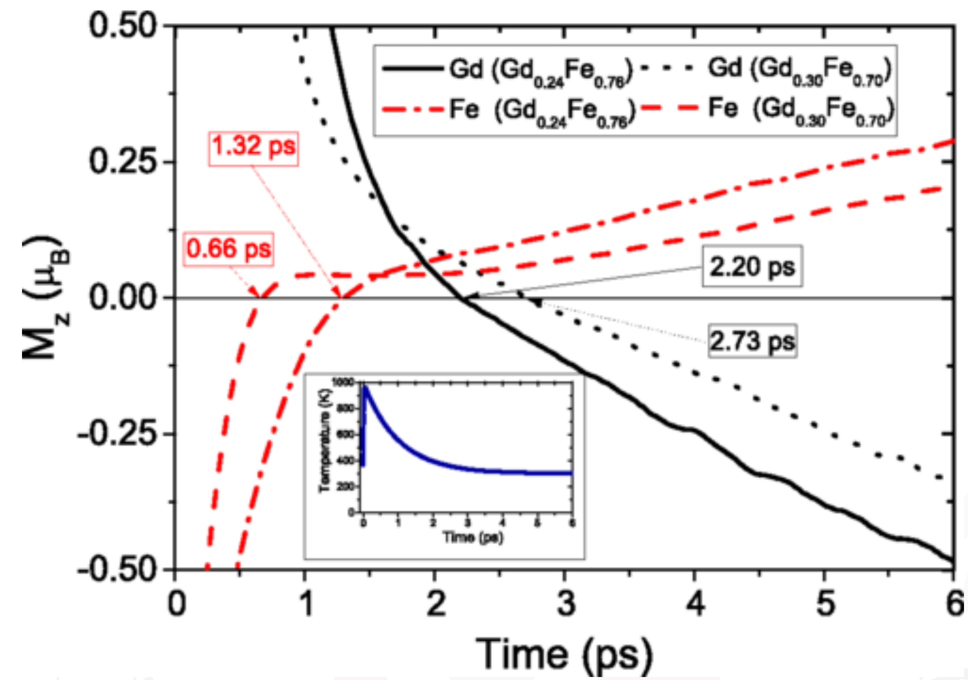
Sublattice moments: during the reversal process, the Fe and Gd moments, which initially were antiparallel, were parallel for a short period of time before they reached a stationary point where they became antiparallel again, albeit with a reversed total moment

SWITCHING BY LASER PULSE

Radu et al., Nature 472 (2011)



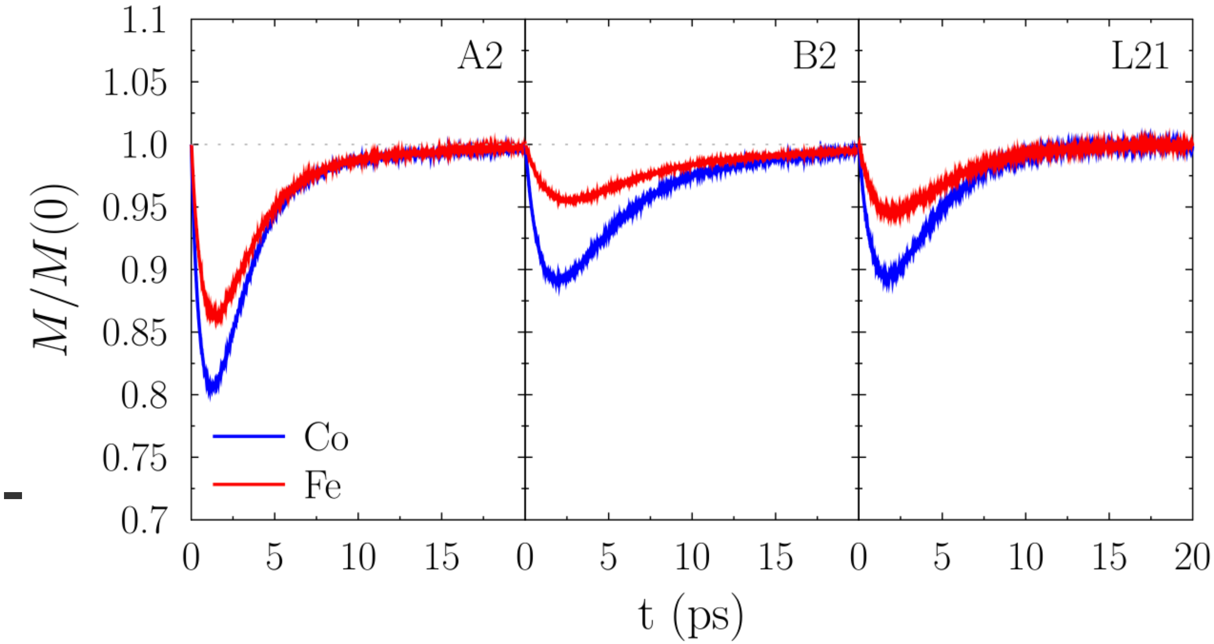
Chimata et al. Phys. Rev. B 92, 094411 (2015)



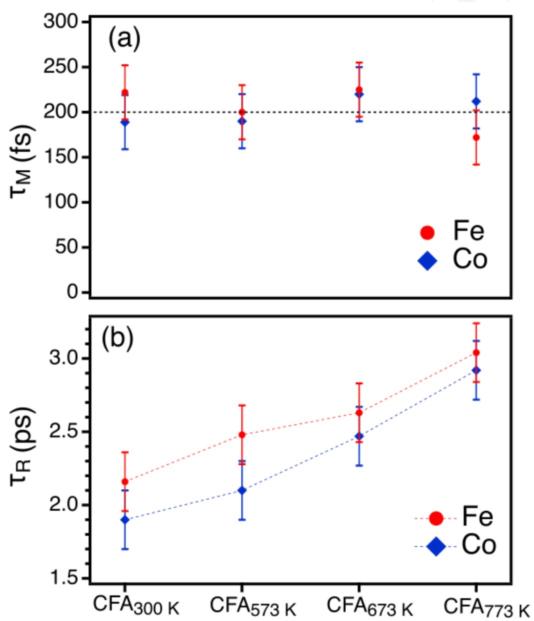
Since the time scales involved in these experiments are of the order of picoseconds, the ASD approach should be valid. This is also the approach taken by Chimata et al., who used both the three-temperature model and the LLG equation

Ultrafast magnetization dynamics in the half-metallic Heusler alloy Co_2FeAl

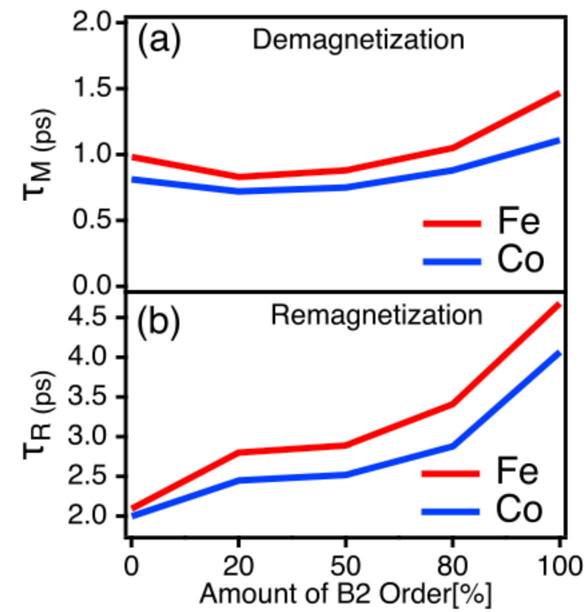
R. S. Malik et al., Phys. Rev. B **104**, L100408



Experiment



Theory



ENERGY DISSIPATION

From Lagrange-Rayleigh equation

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial\mathscr{L}(\boldsymbol{m},\dot{\boldsymbol{m}})}{\partial\dot{\boldsymbol{m}}}-\frac{\partial\mathscr{L}(\boldsymbol{m},\dot{\boldsymbol{m}})}{\partial\boldsymbol{m}}+\frac{\partial\mathscr{R}(\dot{\boldsymbol{m}})}{\partial\dot{\boldsymbol{m}}}=0,$$

The Lagrangian comprises a kinetic energy $\mathscr{T}[\boldsymbol{m},\dot{\boldsymbol{m}}]$ as well as a potential energy $\mathscr{U}[\boldsymbol{m}]$ part, whereas $\boldsymbol{B}=-\frac{\partial\mathscr{U}}{\partial\boldsymbol{m}}$.

With a general Rayleigh dissipation functional

$$\mathcal{R}=\frac{1}{2}\sum_i\sum_j\underline{\dot{m}}_i\eta_{ij}\underline{\dot{m}}_j$$

Since most experiments predict a uniform, isotropic dissipation transfer], the rate η simplifies to

$$\eta_{ij}=-\frac{\alpha}{\gamma m_s}\delta_{ij},$$

ENERGY DISSIPATION

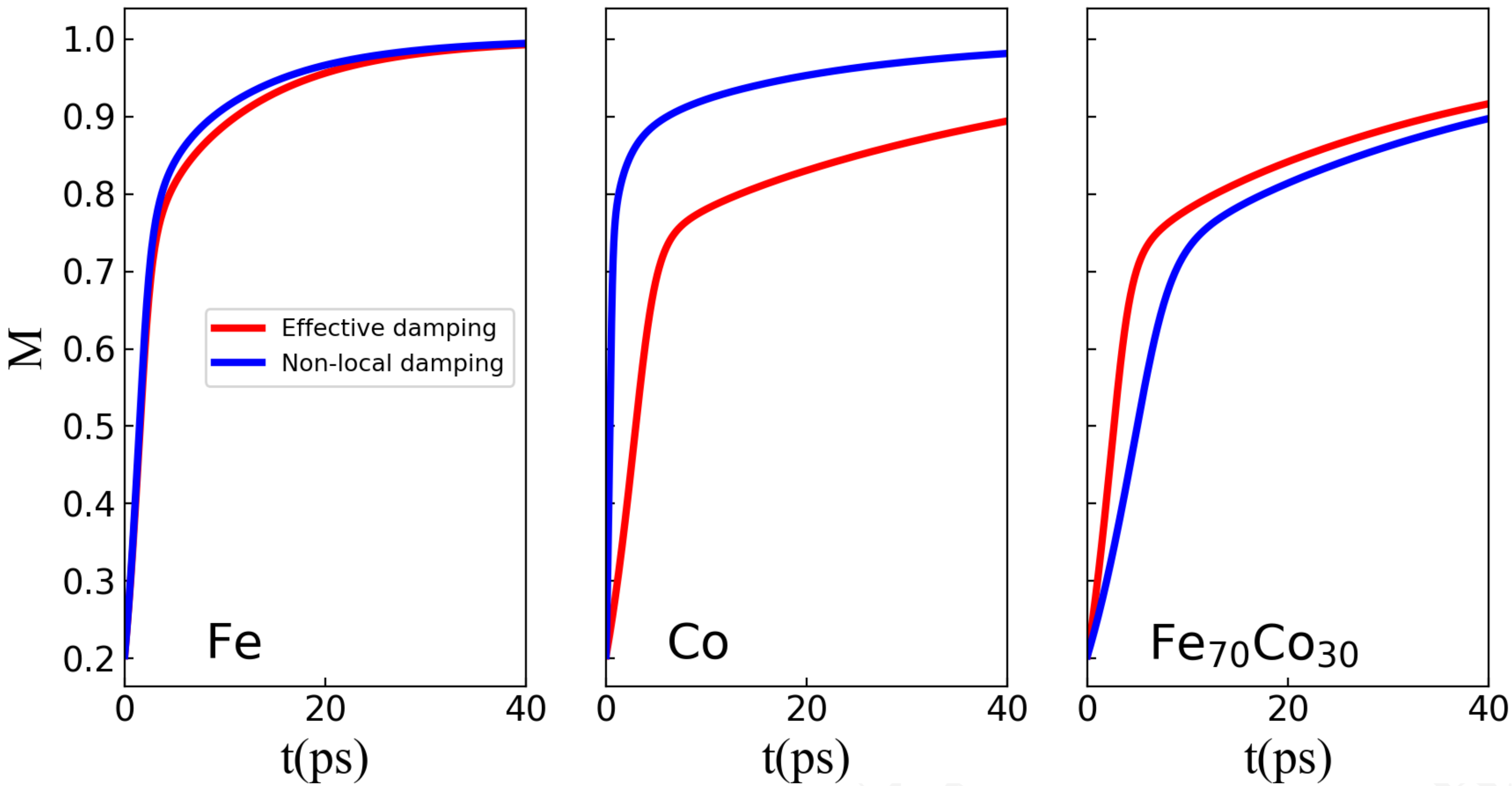
With $\frac{\partial \mathscr{U}[\boldsymbol{m}]}{\partial \dot{\boldsymbol{m}}} = 0$ and $\frac{\partial \mathscr{R}[\dot{\boldsymbol{m}}]}{\partial \dot{\boldsymbol{m}}} = -\boldsymbol{B}^{diss} = -\frac{\alpha}{\gamma m_s}\dot{\boldsymbol{m}}$, one notices a reduction of the effective field $\boldsymbol{B}$ by the 'damping field' $\boldsymbol{B}^{diss}$ and thus, a modification of the torque in field direction:

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathscr{T}(\boldsymbol{m},\dot{\boldsymbol{m}})}{\partial \dot{\boldsymbol{m}}} - \frac{\partial \mathscr{T}(\boldsymbol{m},\dot{\boldsymbol{m}})}{\partial \boldsymbol{m}} + \left(B - \frac{\alpha}{\gamma m_s}\dot{\boldsymbol{m}}\right) = 0.$$

That gives the Landau-Lifshitz Gilbert equation (see slide above)

With a general rate $\eta_{ij} = -\frac{\alpha_{ij}}{\gamma m_s}$ $\qquad$ $\boldsymbol{B}_i^{diss} = \sum_j \frac{1}{|\boldsymbol{m}_j|}\alpha_{ij}\frac{\partial \boldsymbol{m}_j}{\partial t}$

New way to tune the damping like macrospin switching!



Z. Liu et al., Manuscript in preparation

CONCLUSION

- Macrospin switching via damping or precision like switching
- Intrinsic field can drastically increase switching rates
- External sources causing switching are magnetic fields, currents, laser

Take home message: Depending on the timescale that need to be targeted, different switching protocols are possible.