MAX PLANCK INSTITUTE
FOR CHEMICAL PHYSICS OF SOLIDS

MAGNETISATION DYNAMICS

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European School of Magnetism 2022

Saarbruecken, 15th September 2022

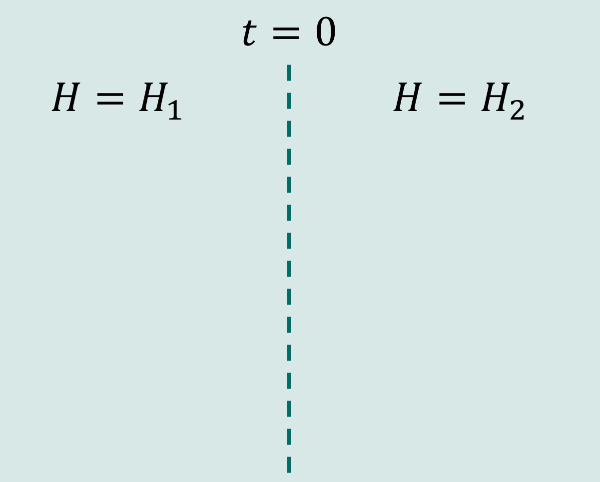
DYNAMICS – WHAT TIME SCALES?

Slow! Ultrafast!

10^{8}	10^{-9}	10^{-15}
Years	Nano-pico seconds	Femto seconds

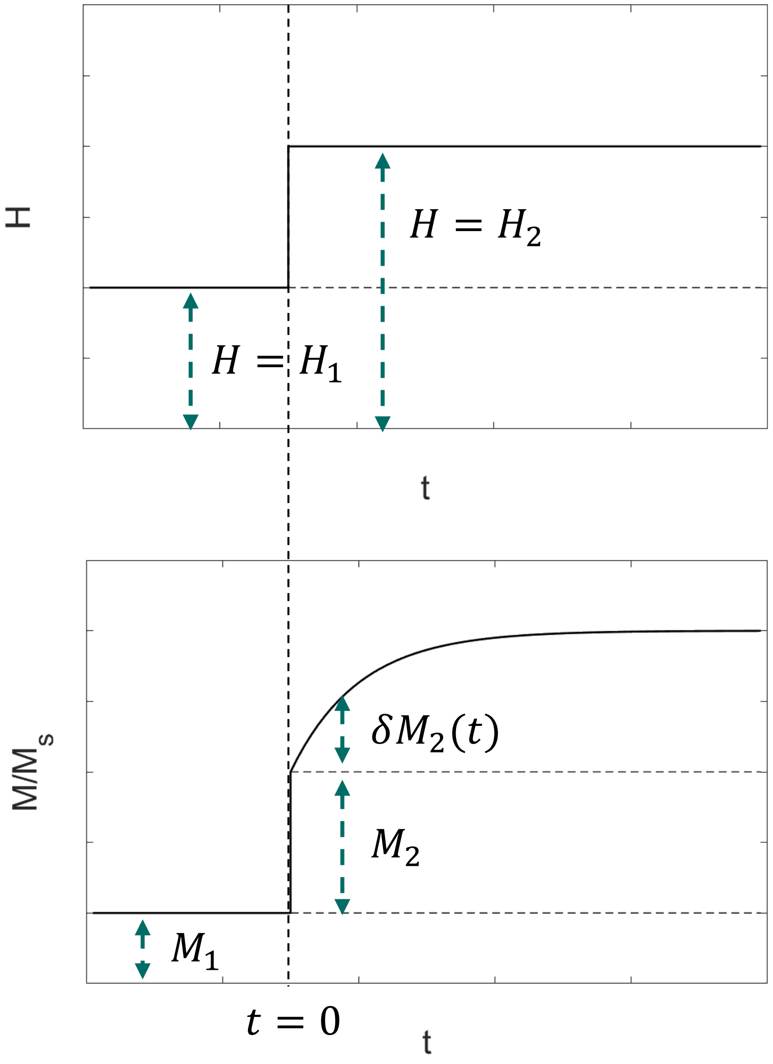
MAGNETISATION DYNAMICS: VISCOSITY

Imagine an abrupt change in field:



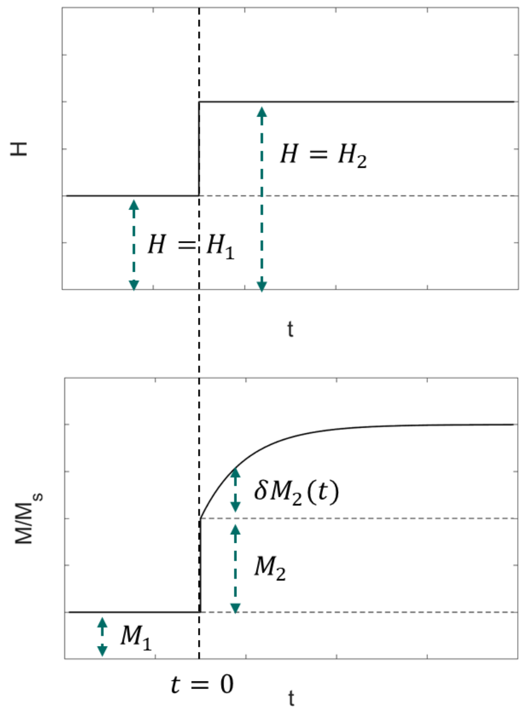
The magnetisation will vary with time:

$$I_n(t) = I_{n0}\left(1 - e^{-t/\tau}\right)$$



MAGNETISATION DYNAMICS: VISCOSITY

Three main causes of magnetic viscosity:



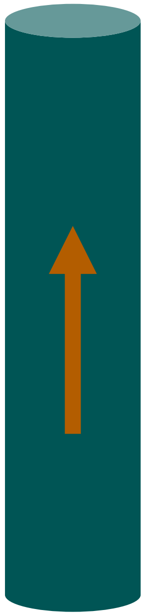
Eddy currents

Diffusion of impurities – allow domain walls to move

Temperature fluctuations

EDDY CURRENTS

Changing magnetisation leads to “Eddy currents”



Electromagnetic induction:

When a magnetic field changes, an electric field is created:

$$\int E dl = -\int\int \frac{dB}{dt} dS$$

$$2\pi r E(r) = -\mu_0 \pi r^2 \frac{dm}{dt}$$

$$E(r) = -\frac{\mu_0 r}{2}\frac{dm}{dt}$$

→ Eddy currents: $i(r) = -\frac{\mu_0 r}{2}\frac{dm}{dt}$

MAGNETISATION DYNAMICS: VISCOSITY

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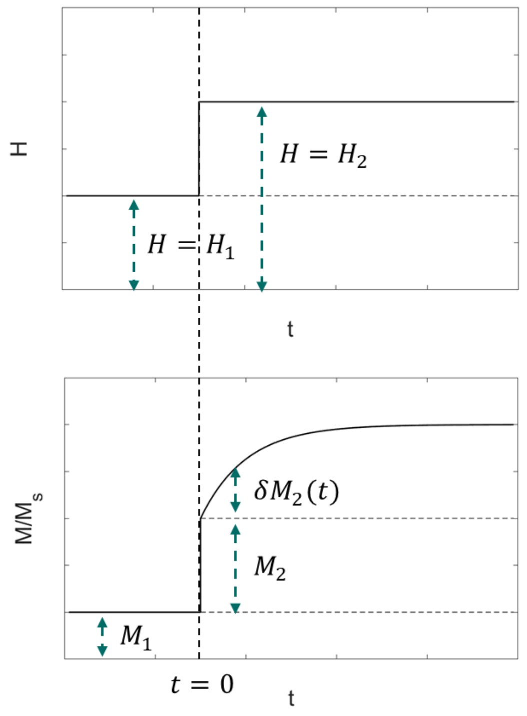


Eddy currents

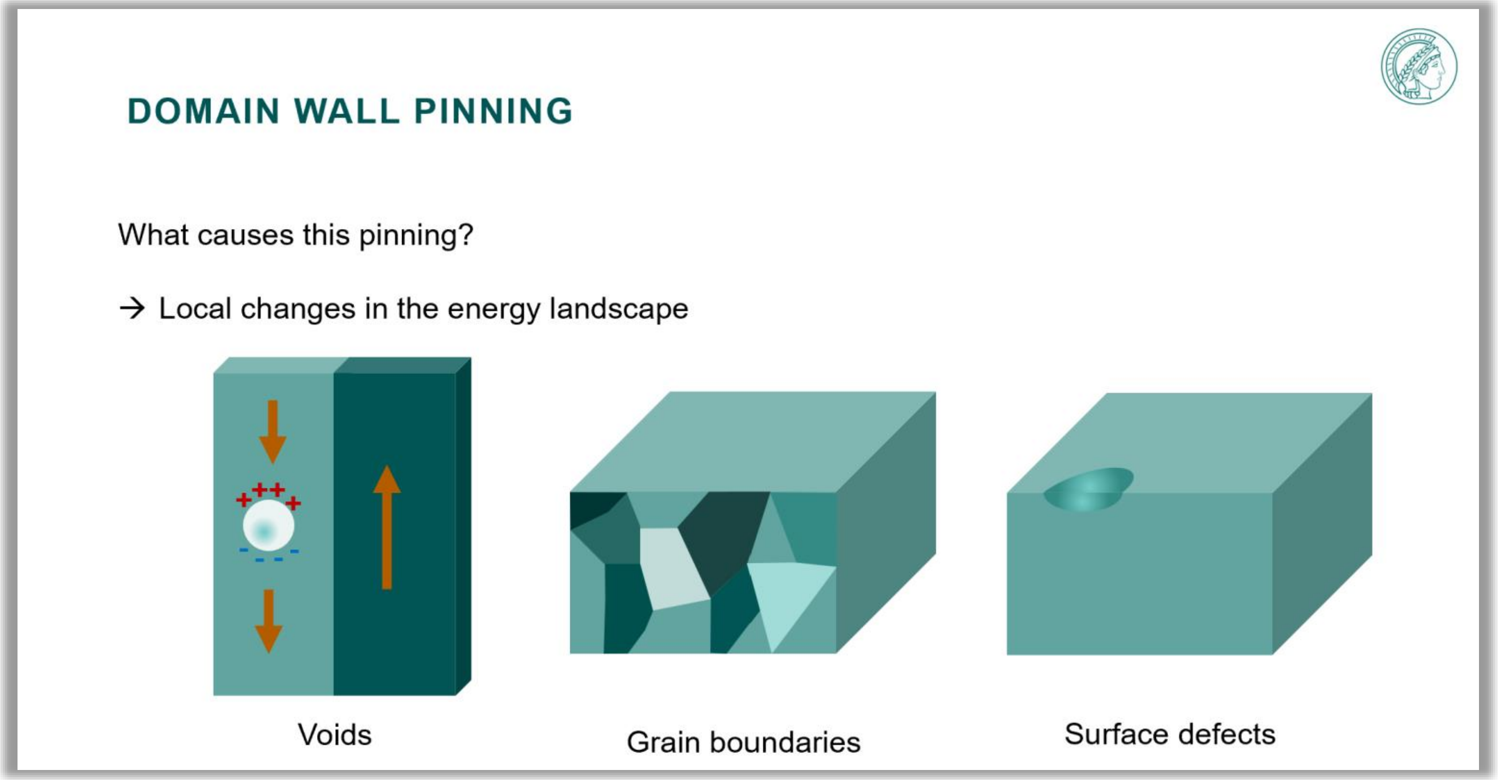
Diffusion of impurities – allow domain walls to move

Temperature fluctuations

DIFFUSION OF IMPURITIES

Remember from before:

Slowly over time, the impurities can adjust themselves



MAGNETISATION DYNAMICS: VISCOSITY

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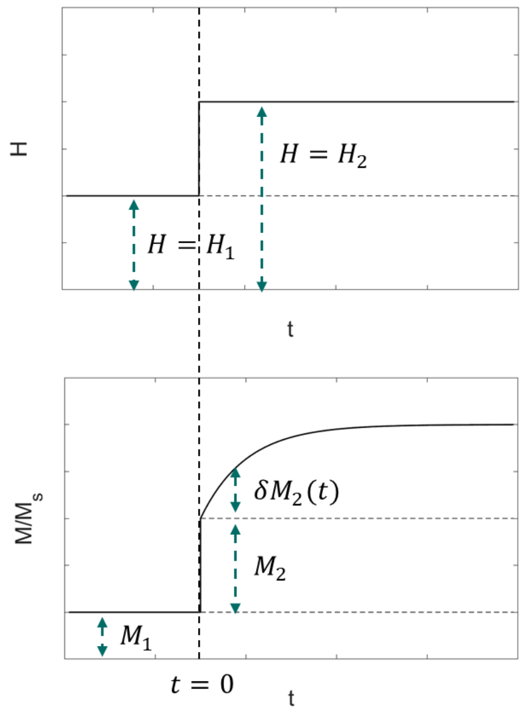


Eddy currents

Diffusion of impurities – allow domain walls to move

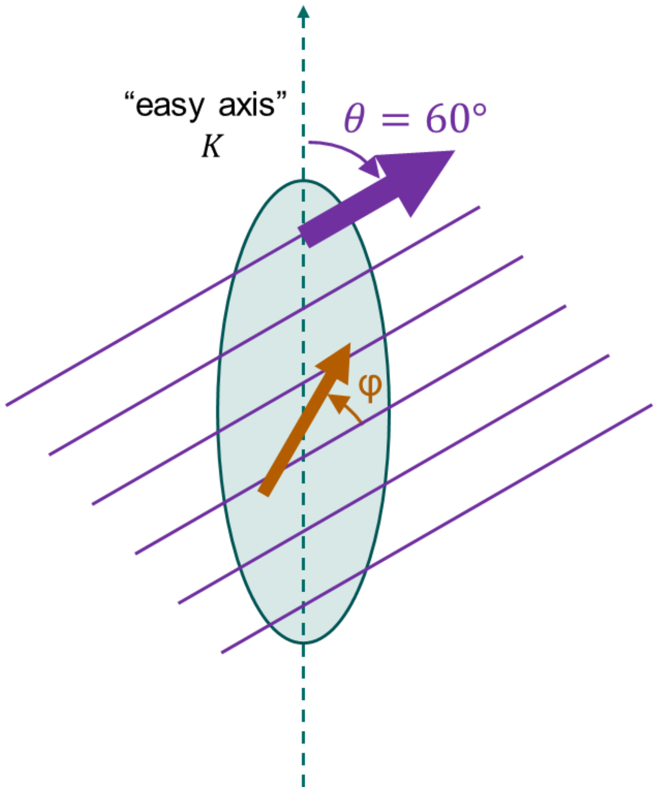
Temperature fluctuations

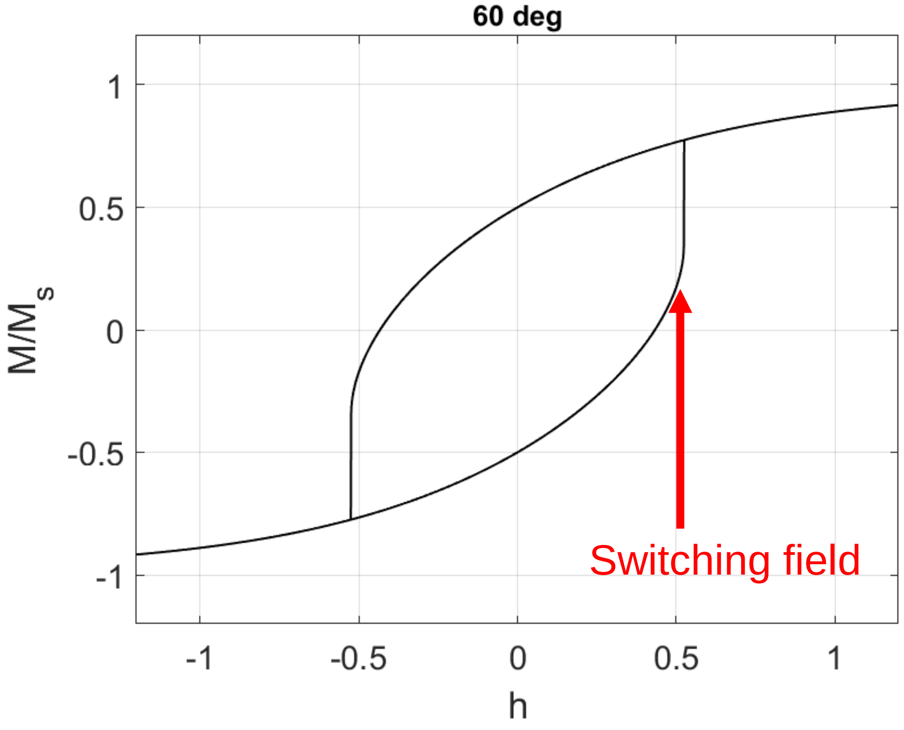
THERMAL FLUCTUATIONS: REVISITING STONER WOHLFAHRT

Reversal of single domain particle:

$$E = K\sin^2(\theta-\varphi) - \mu_0 H M_S K\cos\varphi$$

Anisotropy vs Magnetic field

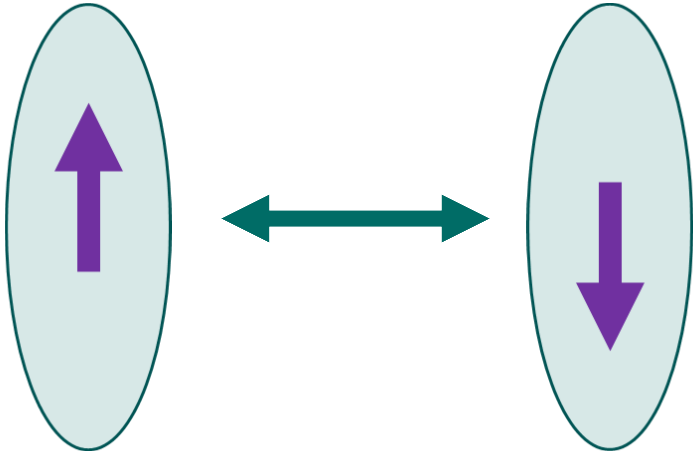




Zero-temperature model!

THERMAL FLUCTUATIONS: REVISITING STONER WOHLFAHRT

In reality, we have finite temperature

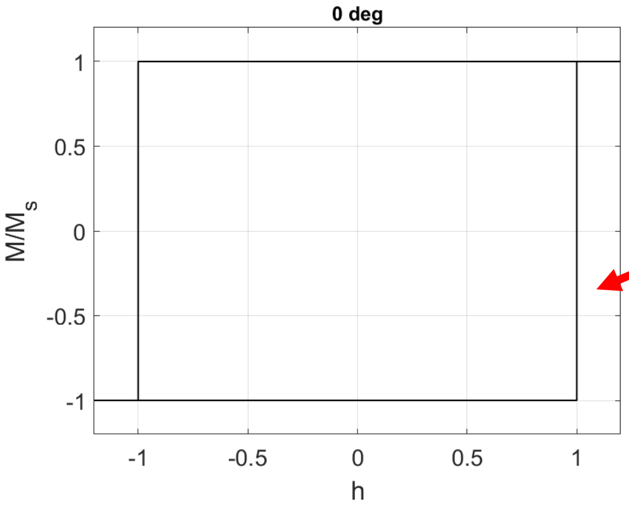


What is our energy barrier?

Rotate through the "hard axis" $\theta = 90°$:

$$E = v(K\sin^2(\theta - \varphi)) - \mu_0 H M_S \cos\varphi)$$

Anisotropy vs Magnetic field



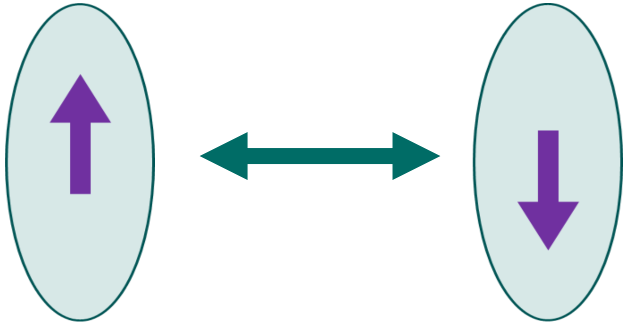
Switching field

Zero field energy barrier → $\Delta E \sim Kv$

Volume

THERMAL FLUCTUATIONS: REVISITING STONER WOHLFAHRT

In reality, we have finite temperature



What is our energy barrier?

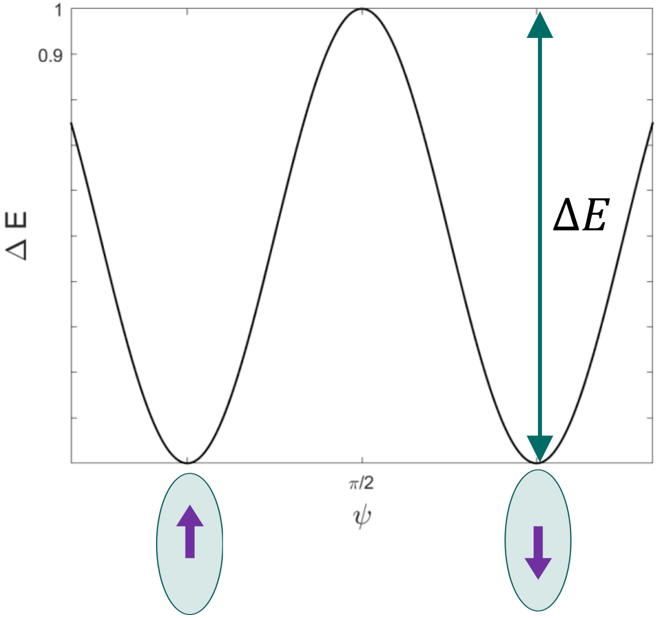
Rotate through the “hard axis” $\theta = 90°$:

$$E = v(K\sin^2(\theta - \varphi)) - \mu_0 H M_S \cos\varphi)$$

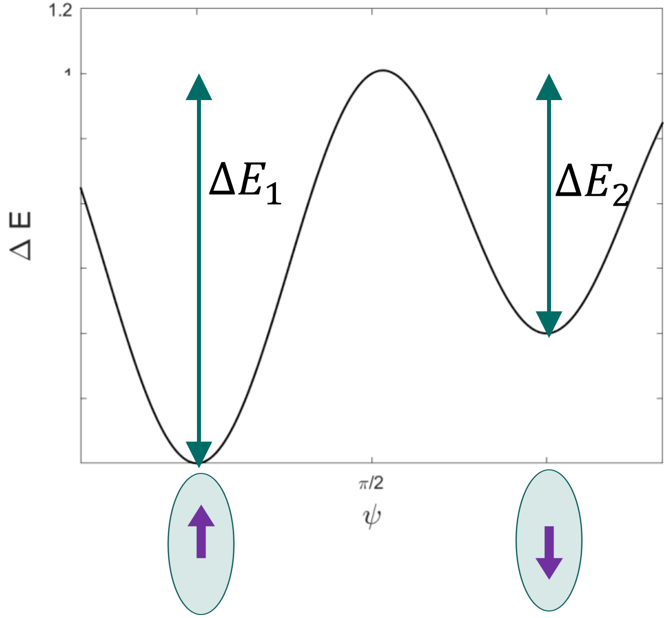
Anisotropy vs Magnetic field

Plot energy as a function of angle:

$H = 0$



$H > 0$



THERMAL FLUCTUATIONS:
REVISITING STONER WOHLFAHRT

In reality, we have finite temperature

$$E = v(K\sin^2(\theta - \varphi) - \mu_0 H M_S \cos\varphi)$$

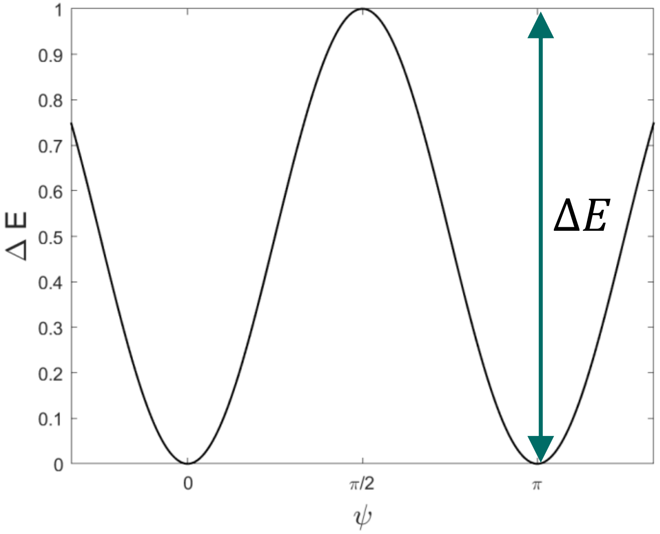
Anisotropy vs Magnetic field

Volume

Energy barrier → $\Delta E = vK$

Thermal activation → $E_{th} = \frac{k_B T}{2}$

$H = 0$



For a **small enough** particle,

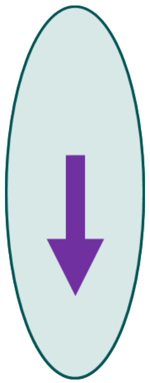
we can get spontaneous switching!

$T = 273\text{K} \quad \rightarrow \quad k_B T = 3.77e - 21\ \text{J}$

$K \sim 10^5 \frac{J}{m^3}$ for Co

$v = 1.9x10^{-26}\text{m}^3$ so $d = 1.7x10^{-9}$ m

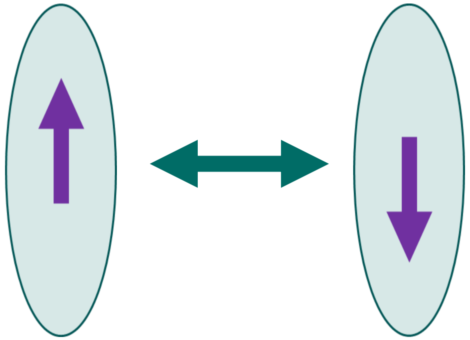
“superparamagnetism”



SUPERPARAMAGNETISM: TIME SCALES

What is the time scale of the oscillations?

i.e. time between two fluctuations?



Relaxation time ~ **Attempt frequency** and **Boltzmann probability**

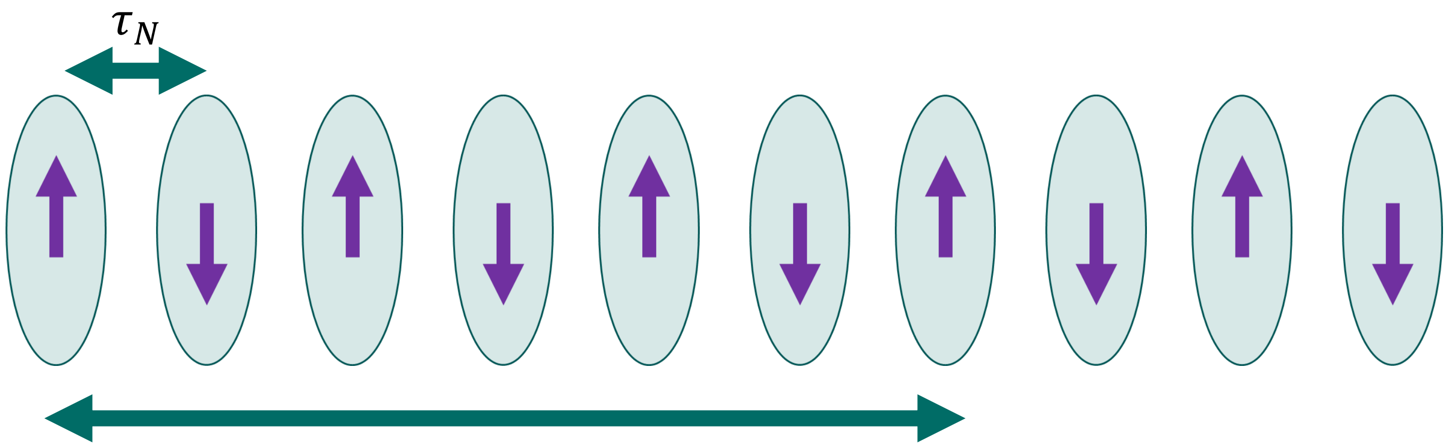
$$\tau_0 \qquad\qquad e^{\Delta/k_B T}$$

$$\sim 10^{-9} - 10^{-10}\ \mathrm{s}$$

Spin-flip / Neel relaxation time: $\tau_N = \tau_0 e^{\Delta/k_B T}$

Can range from nanoseconds to years!

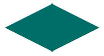
SUPERPARAMAGNETISM: BLOCKING TEMPERATURE



Imagine a superparamagnetic particle is measured over time τ_M

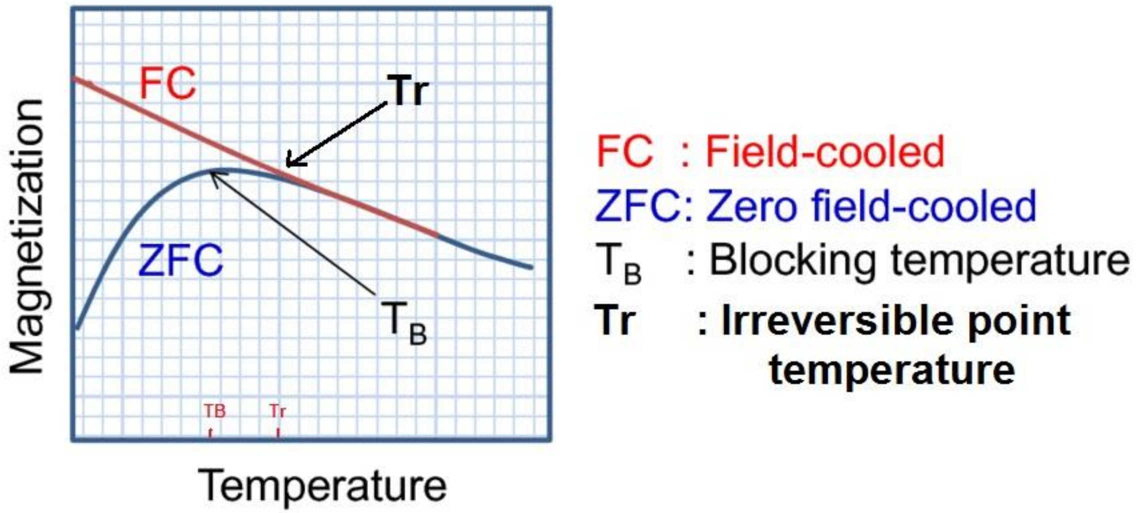
If $\tau_M \gg \tau_N$ then you measure zero!

$$\tau_M > \tau_N$$
$$\langle m \rangle \rightarrow 0$$



$$\tau_M < \tau_N$$
$$\langle m \rangle \rightarrow m$$

Magnet “blocked” in its initial state

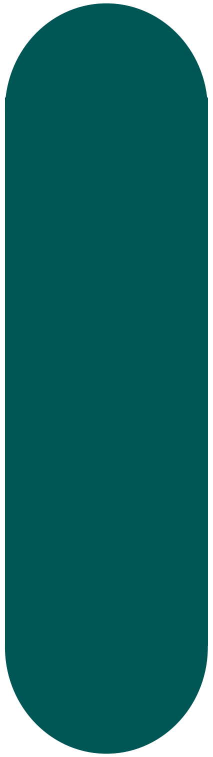


SUPERPARAMAGNETISM – OF NANOSTRUCTURES

Not only intrinsic anisotropy: can have fluctuations in small nanoislands:

For patterned nanostructures

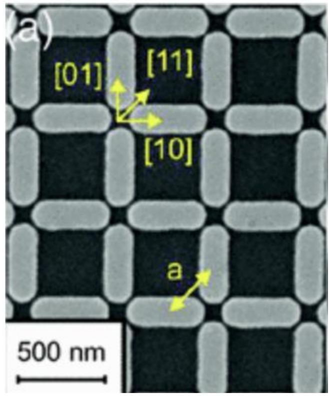
(shape anisotropy)

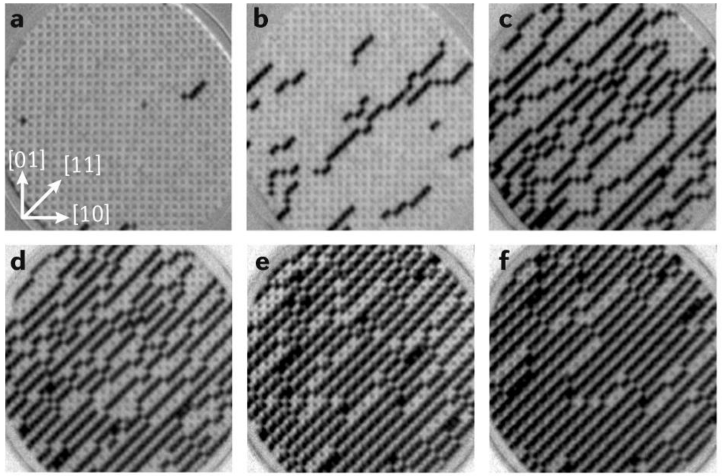


Blocking temperature: temperature at which the structures become thermally active.

Can tune with shape!

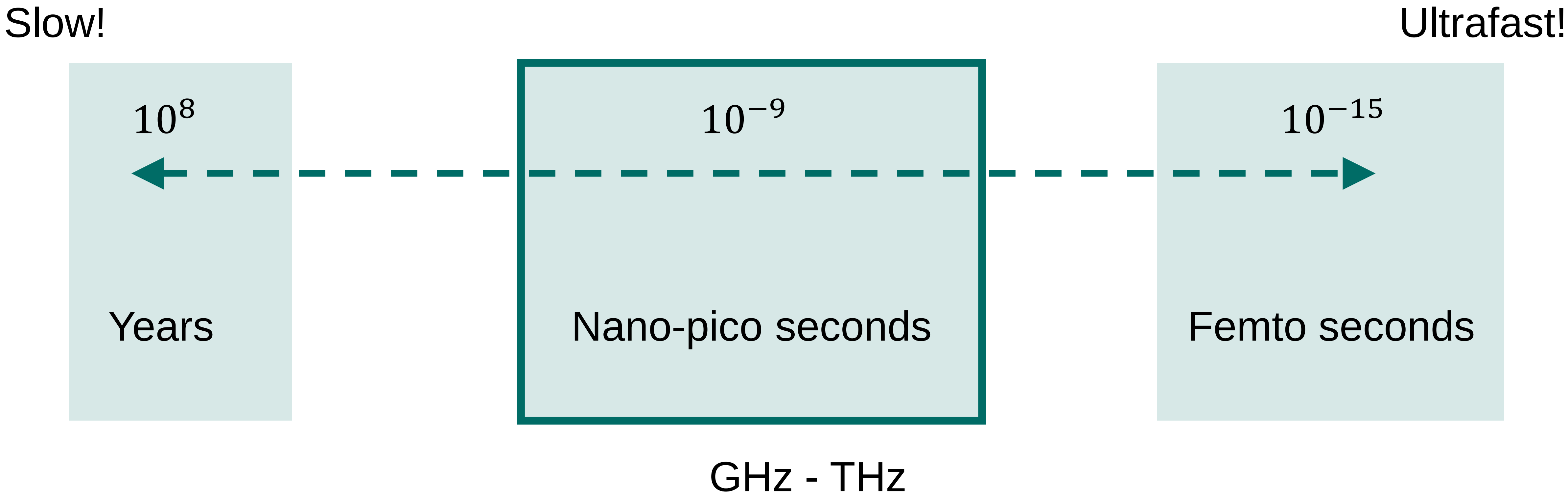
Artificial Spin ice





Farhan et al. Phys. Rev. Lett. 111, 057204 (2013).

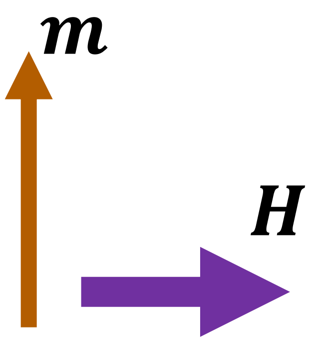
DYNAMICS – WHAT TIME SCALES?



FAST SPIN DYNAMICS:

Fast response of magnetisation to an excitation?

Let’s think about how the magnetisation reacts to a magnetic field:



What does the magnetic field apply?

The field applies a torque: $M \times H$

Because the magnetic moment has angular momentum

CONSIDER THE GYROMAGNETIC RATIO

What is the gyromagnetic ratio?

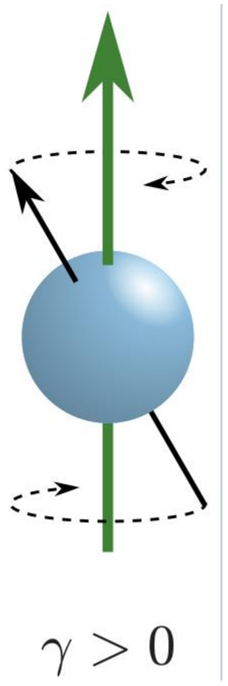
$$\frac{1}{\gamma}\frac{dM}{dt} = -M \times H$$

Ratio of magnetic moment to angular momentum $\gamma = \frac{\boldsymbol{\mu}}{\boldsymbol{L}}$

It determines the precession of the magnetisation based on an applied field

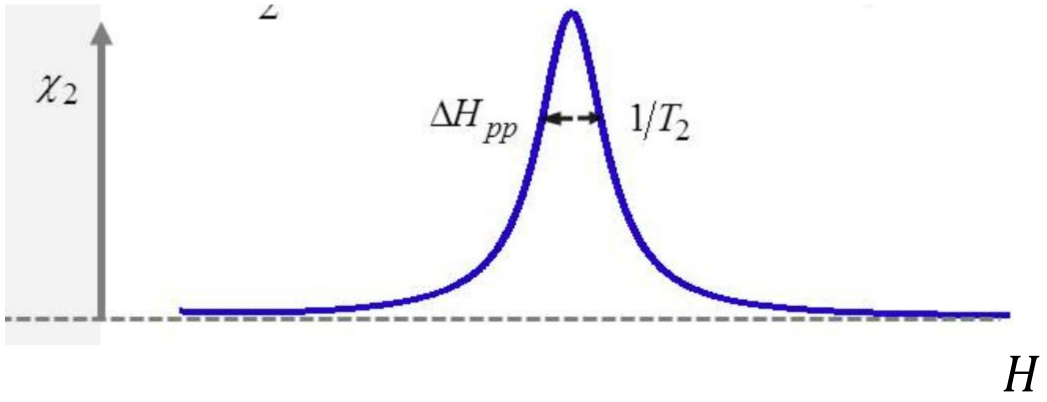
FERROMAGNETIC RESONANCE

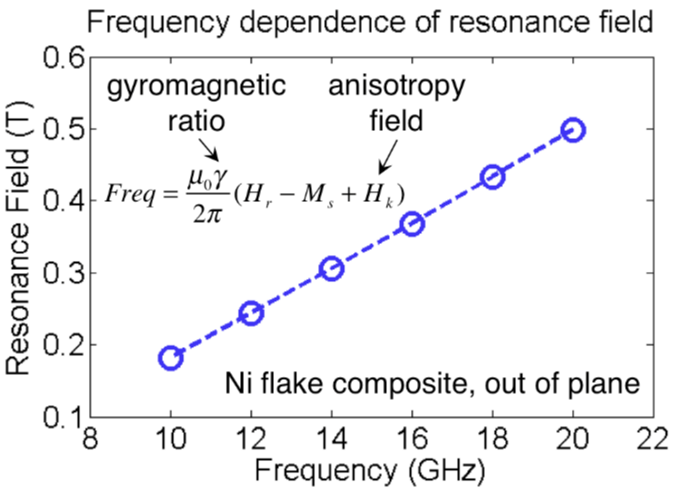
Ferromagnetic body under applied field strongly absorbs certain frequencies of field:



$$\omega = 2\pi f = \gamma B$$

γ = gyromagnetic ratio





BLOCH EQUATION

Effective field: includes all contributions!

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{eff}$$

Angle to the field: constant!

Precesses with angular velocity $\omega = \gamma|\boldsymbol{B}|$

~28 GHz/T

LANDAU LIFSHITZ GILBERT EQUATION

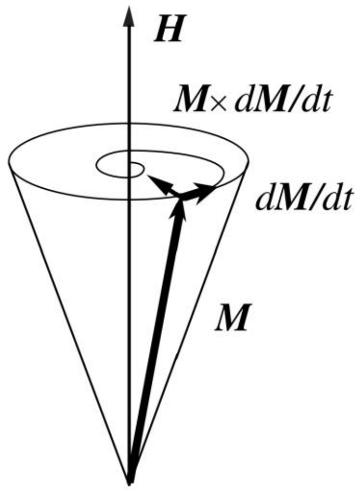
But! We see from Hysteresis loops that in the end, a magnetic field can saturate a sample

→ Energy dissipation (or damping)

→ → energy transferred to lattice vibrations, spin waves, & heating of conduction electrons

→ Include damping into effective field:

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{eff} - \lambda \boldsymbol{M} \times (M \times \boldsymbol{H}_{eff})$$



Which was rewritten as: (by Gilbert)

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{eff} - \frac{\alpha}{M_S} \lambda \boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}$$

$$\alpha = \frac{\lambda M_S}{\gamma}$$

→ **Gilbert damping factor**

LANDAU LIFSHITZ EQUATION

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{eff} - \frac{\alpha}{M_S} \lambda \boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}$$

What is alpha?

Determines the damping of a material

→ Affects the dynamics

Low damping materials:

CoFeB, Py, YIG

Depends on intrinsic and extrinsic effects

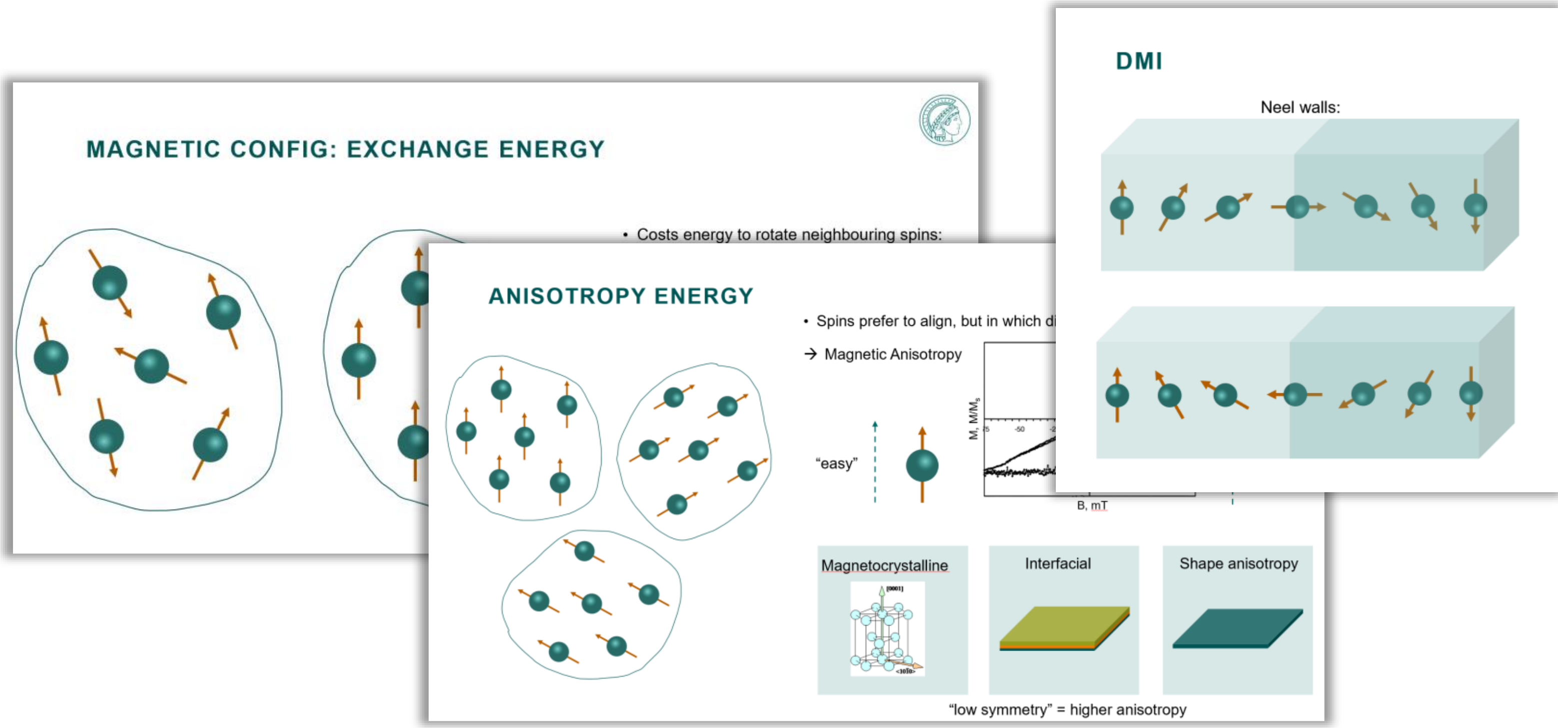
LANDAU LIFSHITZ EQUATION

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{eff} - \frac{\alpha}{M_S} \lambda \boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}$$

What is this effective field?

Composed of different contributions

Including magnetic field!



Interactions of spins – what happens in multi-spin systems?

GYROMAGNETIC RATIO & APPLICATIONS

Could you talk about the gyromagnetic ratio in terms of applications?

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{eff} - \frac{\alpha}{M_S} \lambda \boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}$$

→ **Typically, damping parameter optimised instead!**

Ratio of magnetic moment to angular momentum

$$\gamma = \frac{\boldsymbol{\mu}}{\boldsymbol{L}}$$

~28 GHz/T

→ Magnetism is fast!
→ However, not so easy to tailor…

MICROMAGNETICS WITH THE LLG

Micromagnetic simulations

Minimise energy or

Solve the LLG equation

Very robust for micromagnetic problems

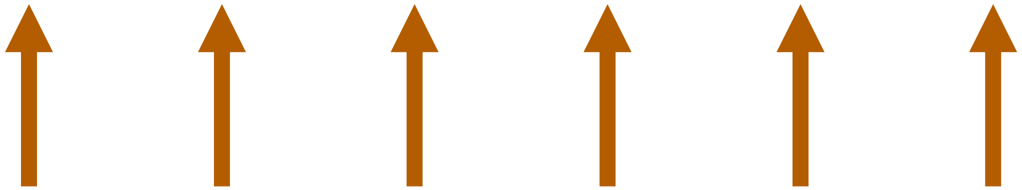
SPIN EXCITATIONS

Now we know how the magnetisation reacts to the magnetic field

We had ferromagnetic resonance: spins precess in phase…

What happens when we think about an excitation of the spin

We have the ground state:



SPIN EXCITATIONS

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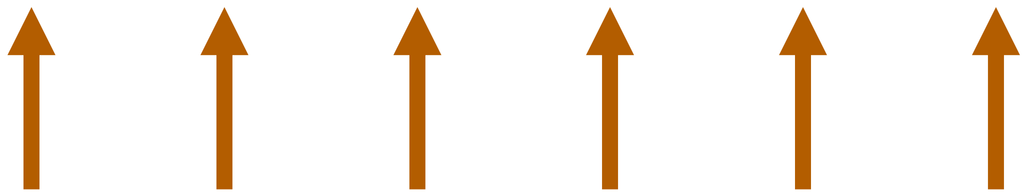
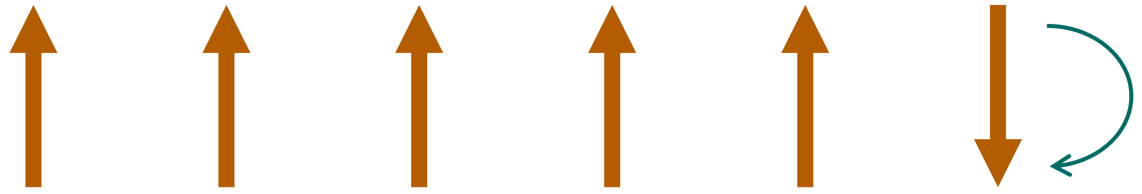
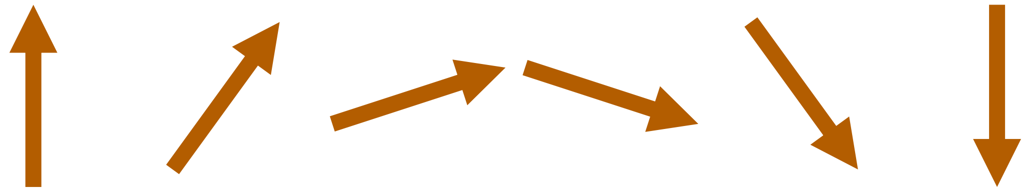


What is the smallest excitation of this ground state?



Flip a single spin

Can distribute over many spins:



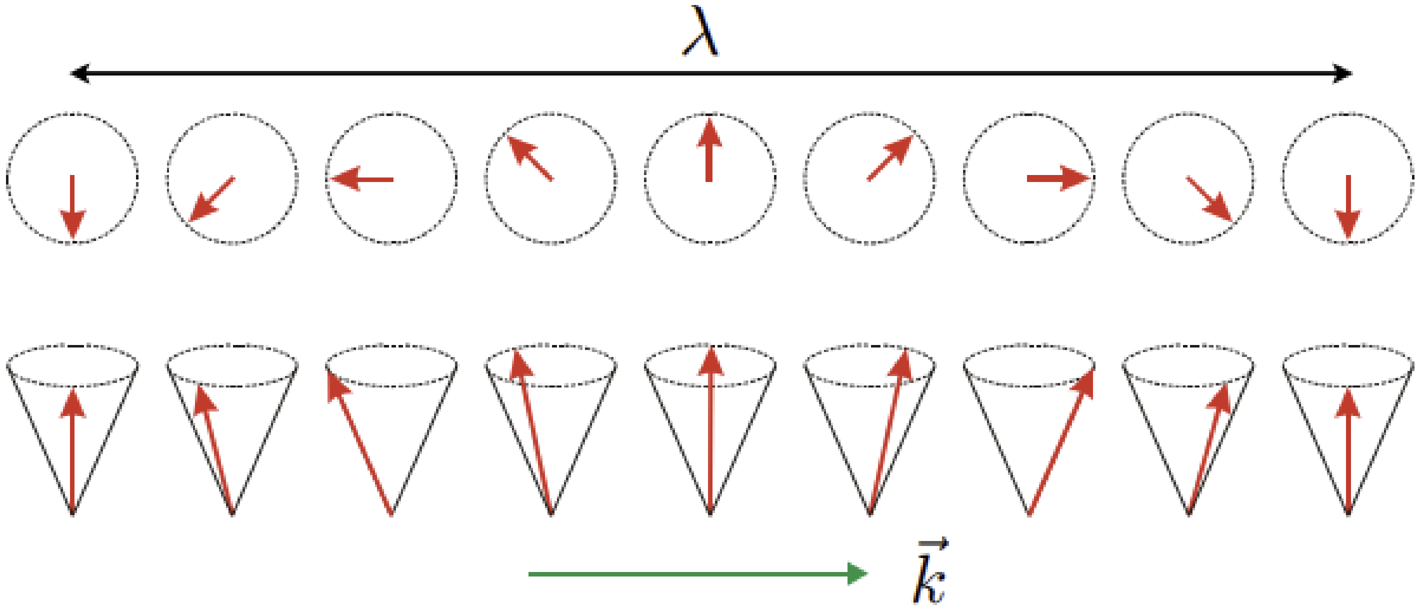
SPIN WAVES

What this leads to:

Spins all precessing at the same frequency

But: out of phase with one another:

→ Propagating spin waves

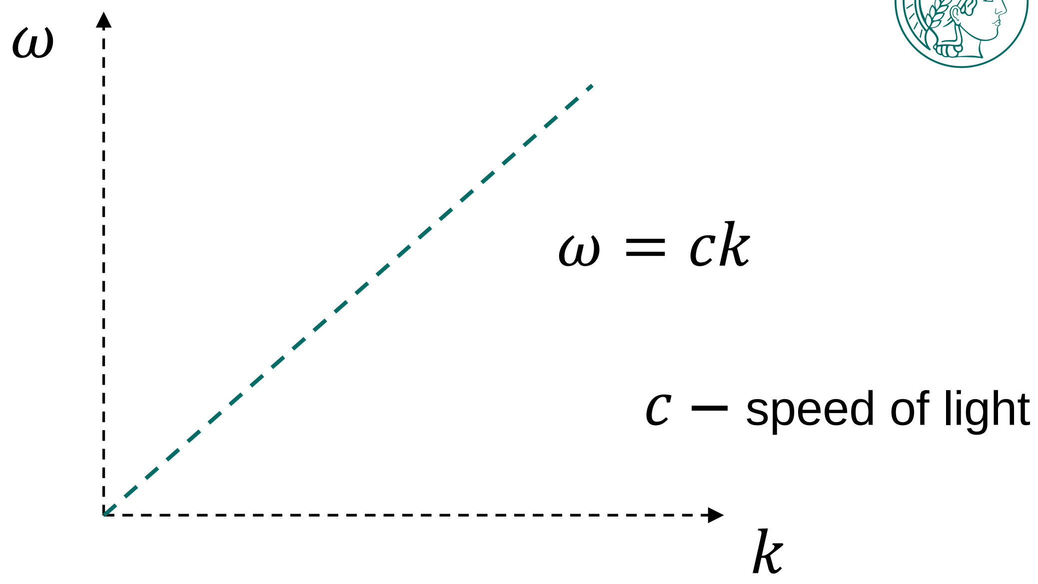


PROPERTIES OF SPIN WAVES

Let's think about "normal" waves

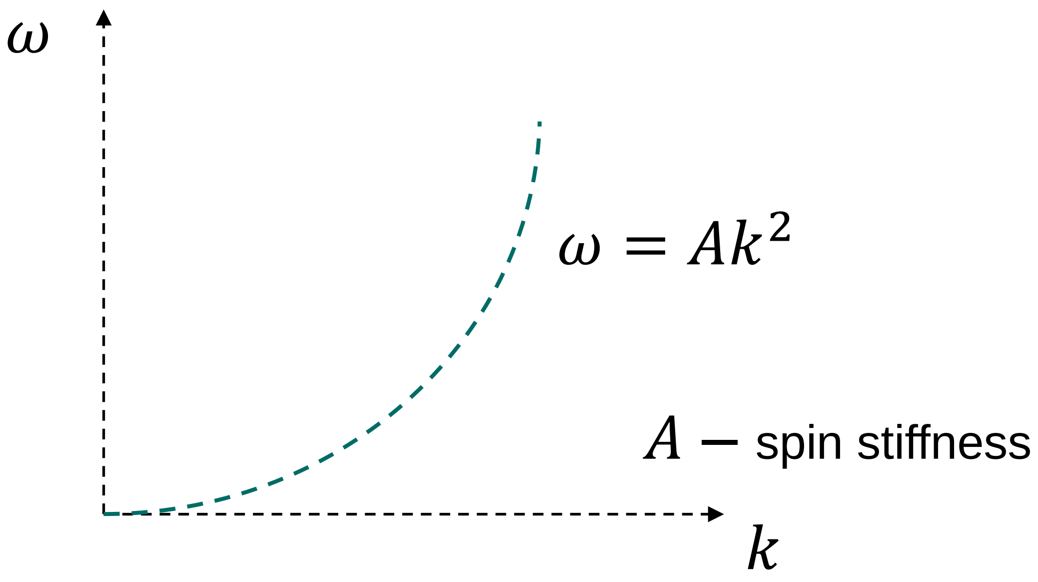
Take light as an example. What defines light?

Frequency, wavelength → dispersion relation

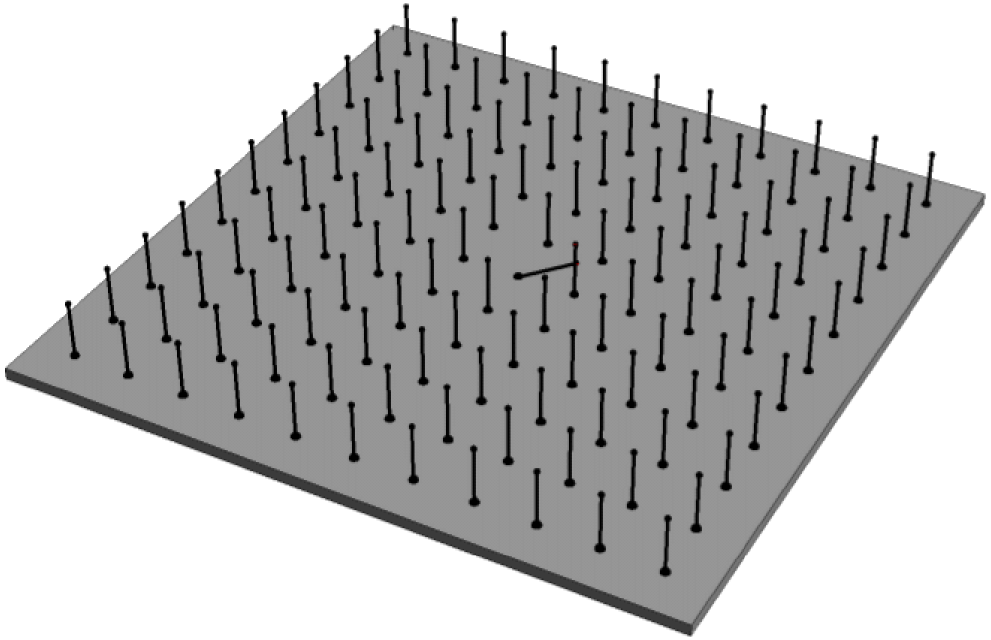


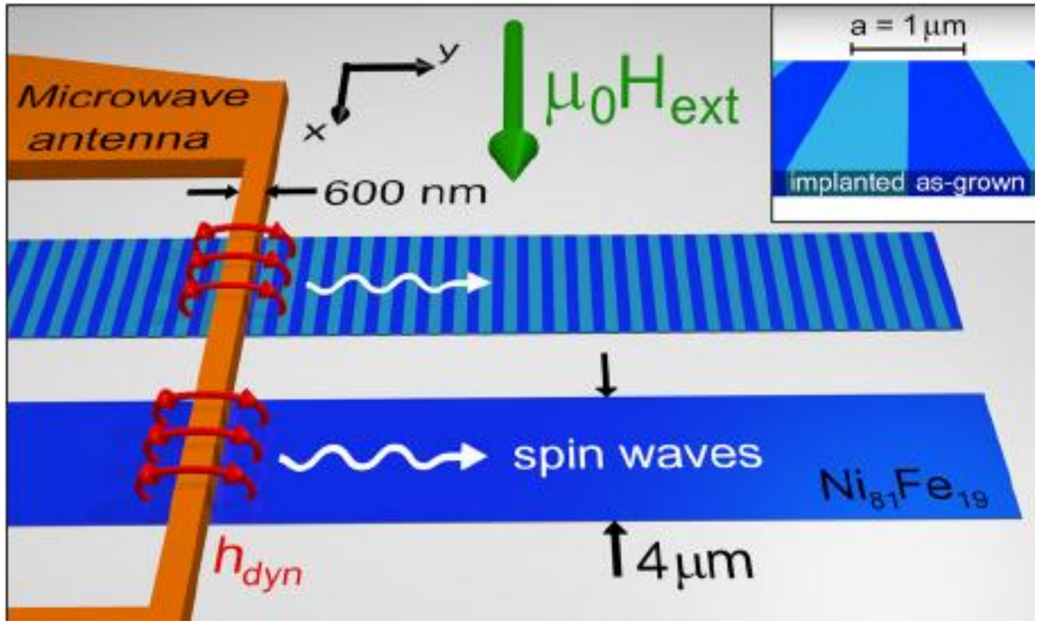
Quanta: the equivalent of a photon?

Magnons always present at finite temp



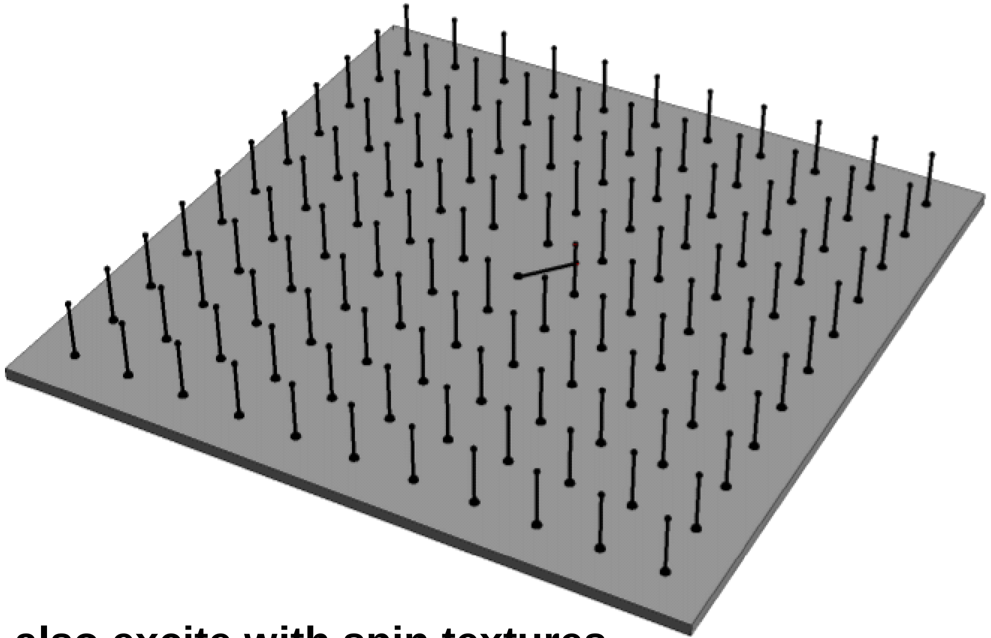
PROPERTIES OF SPIN WAVES





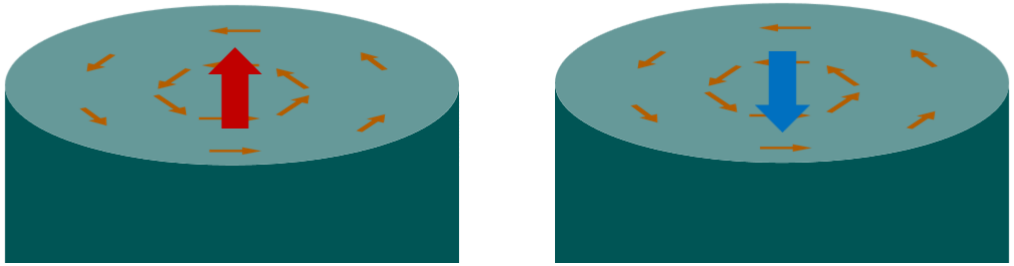
Excite spin waves with an antenna

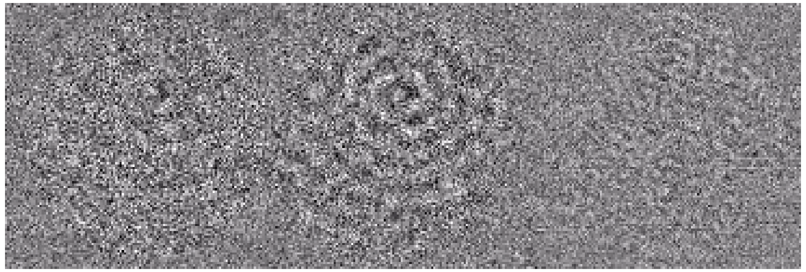
PROPERTIES OF SPIN WAVES

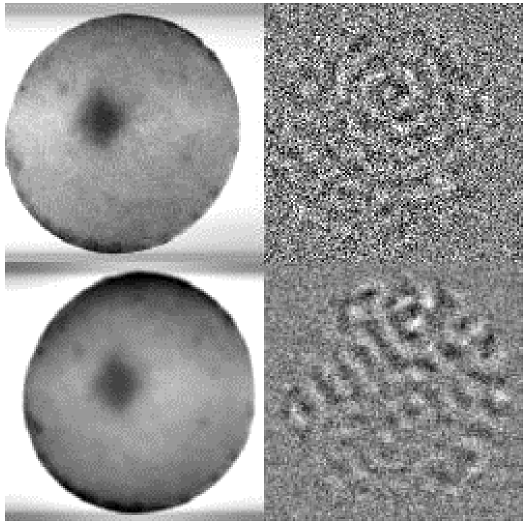


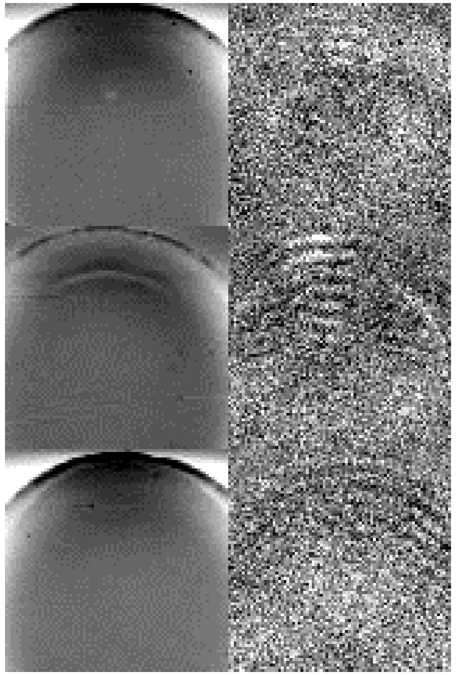
Can also excite with spin textures

→ nanoscale, ideal for spin wave excitation



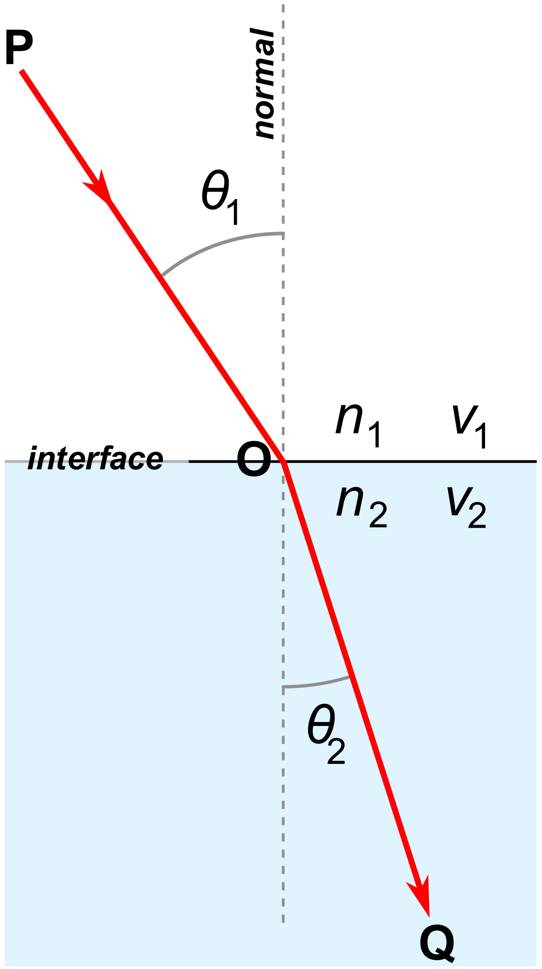






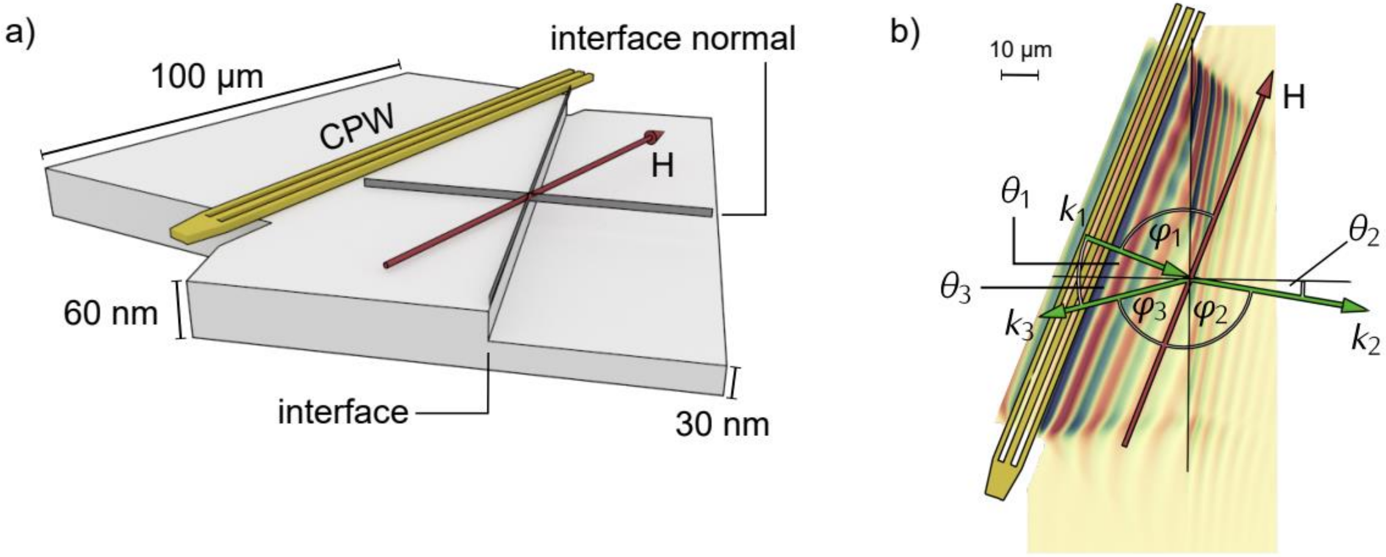
Mayr et al., *Nano Lett.* 2021, 21, 4 (2021)

PROPERTIES OF SPIN WAVES



In light, different materials have different refractive indices.

Snell's law In magnetic materials



Stigloher et al., Phys. Rev. Lett. 117, 037204 (2016)

“OPTIC-LIKE” EFFECTS IN SPIN WAVES

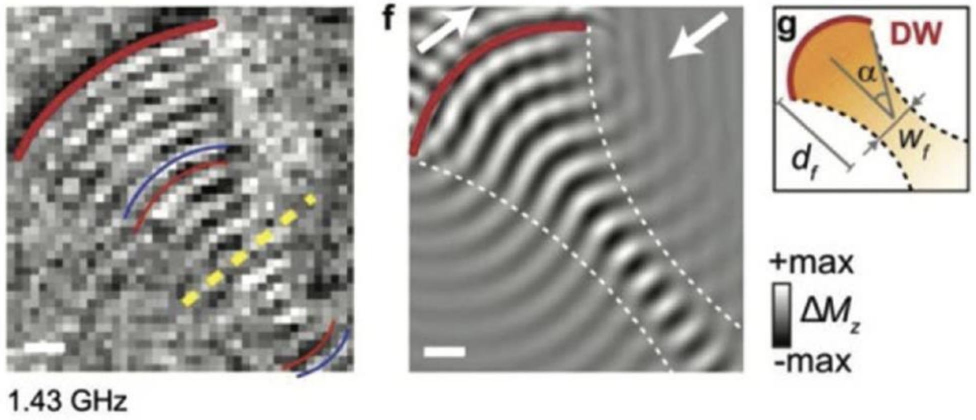
COMMUNICATION

ADVANCED MATERIALS
www.advmat.de

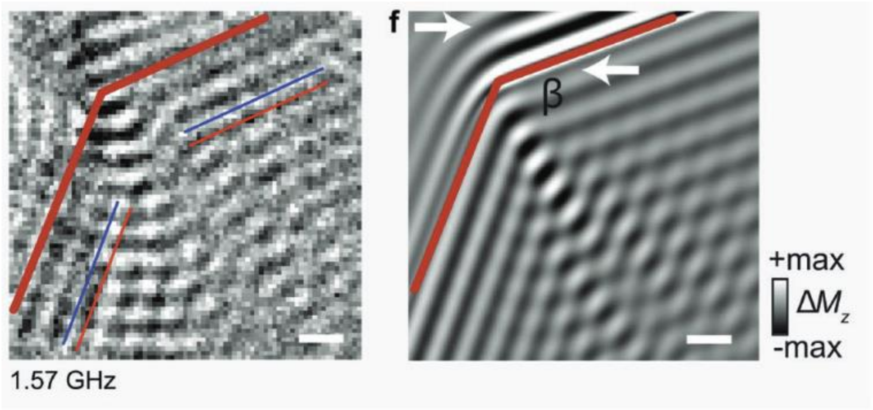
Optically Inspired Nanomagnonics with Nonreciprocal Spin Waves in Synthetic Antiferromagnets

Edoardo Albisetti, Silvia Tacchi, Raffaele Silvani, Giuseppe Scaramuzzi, Simone Finizio, Sebastian Wintz, Christian Rinaldi, Matteo Cantoni, Jörg Raabe, Giovanni Carlotti, Riccardo Bertacco, Elisa Riedo,* and Daniela Petti**

Spin wave lenses: domain wall used to excite spin waves



Pattern domain wall – define different waves

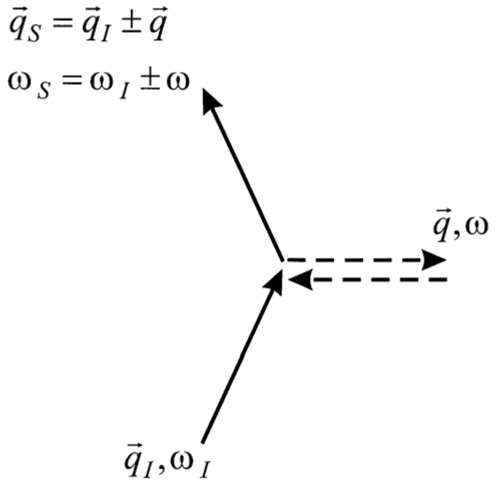


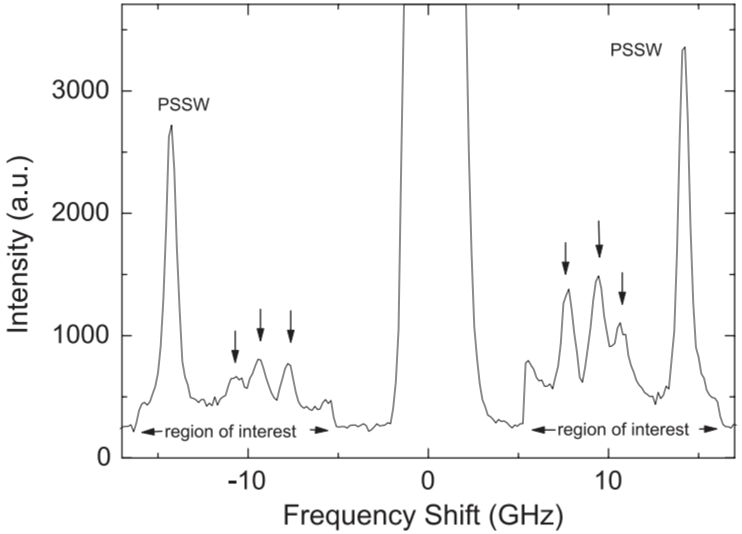
MEASURING SPIN WAVES

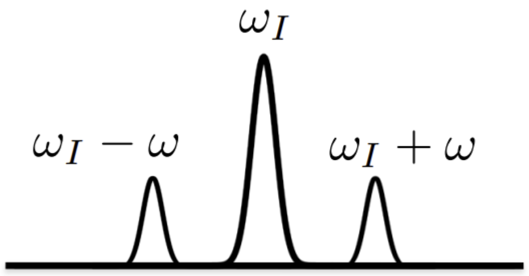
Brillouin Scattering

Scatter photons from surface spin waves of films

Reflected photons give information on spin waves that are created (Stokes) or annihilated (anti-Stokes)

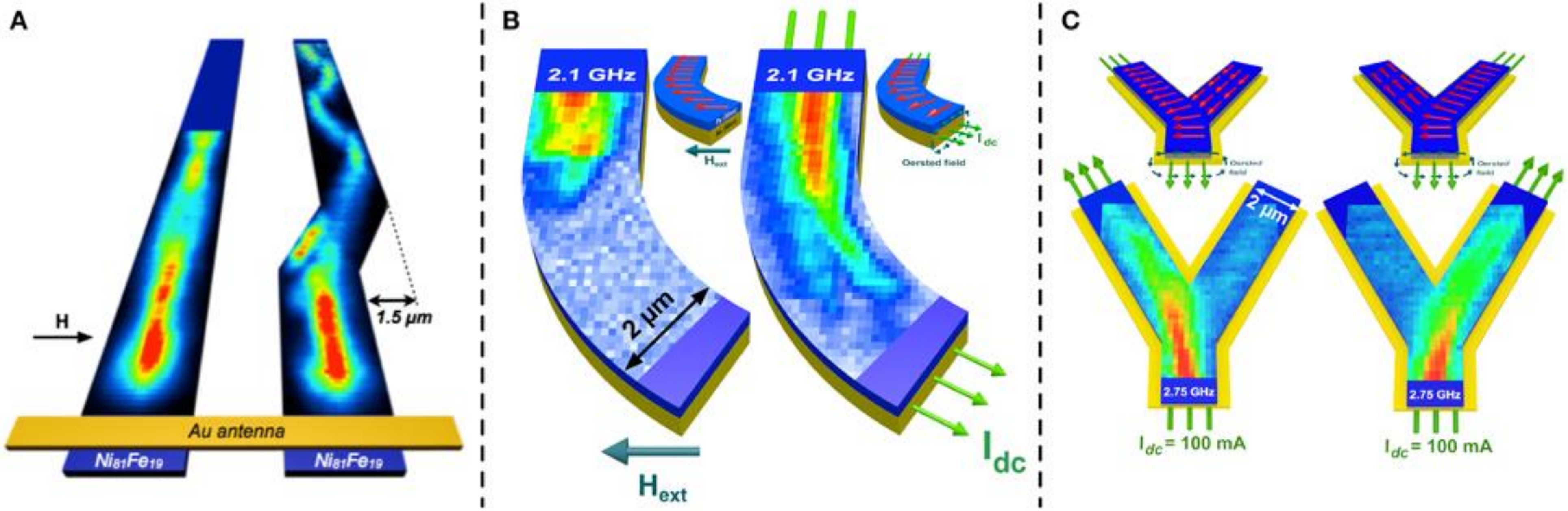






MEASURING SPIN WAVES

Brillouin Scattering – microfocused!



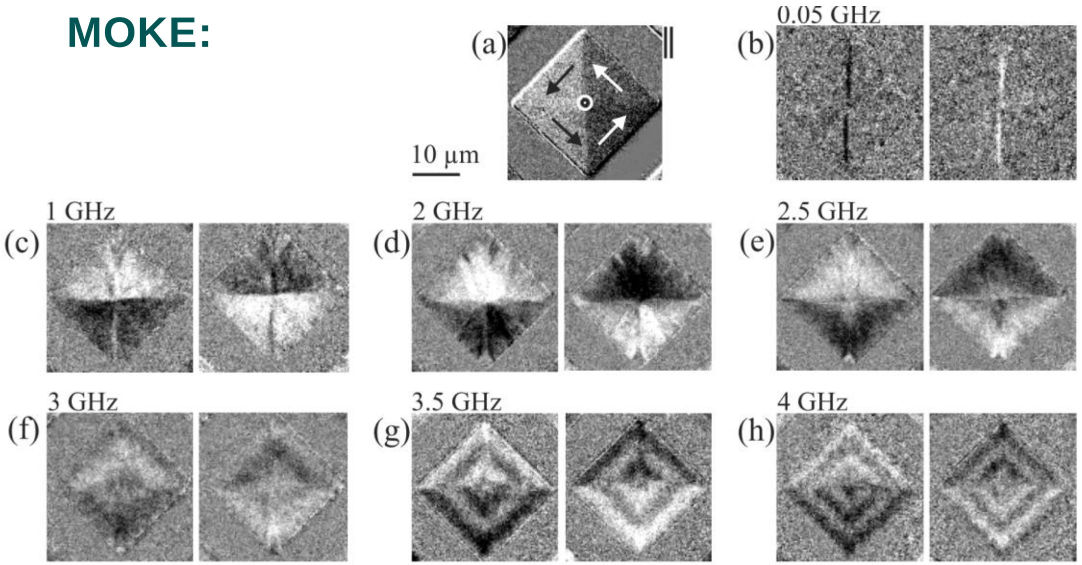
Sebastian et al., https://doi.org/10.3389/fphy.2015.00035

Not limited to coherent spin waves!

MEASURING SPIN WAVES

Or apply pump-probe techniques to measure *coherent* spin waves:

MOKE:

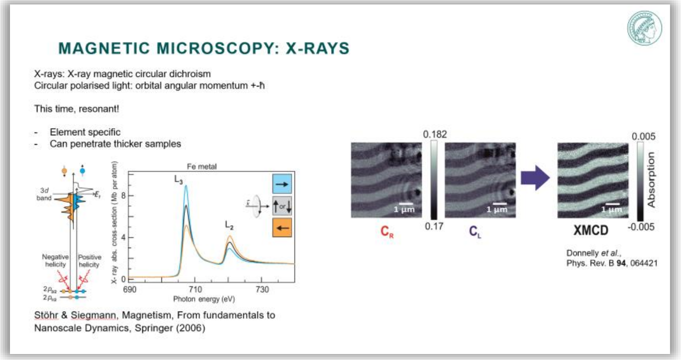


Time resolved MOKE

→ Pump probe rotation of linear polarised light

→ ps temporal resolution, 100s nm - µm spatial resolution

X-ray microscopy



Albisetti et al., *Adv. Mat.* 32, 1906439 (2020)

Synchrotron X-rays

→ Time resolved Scanning transmission X-ray microscopy

→ Pump-probe XMCD

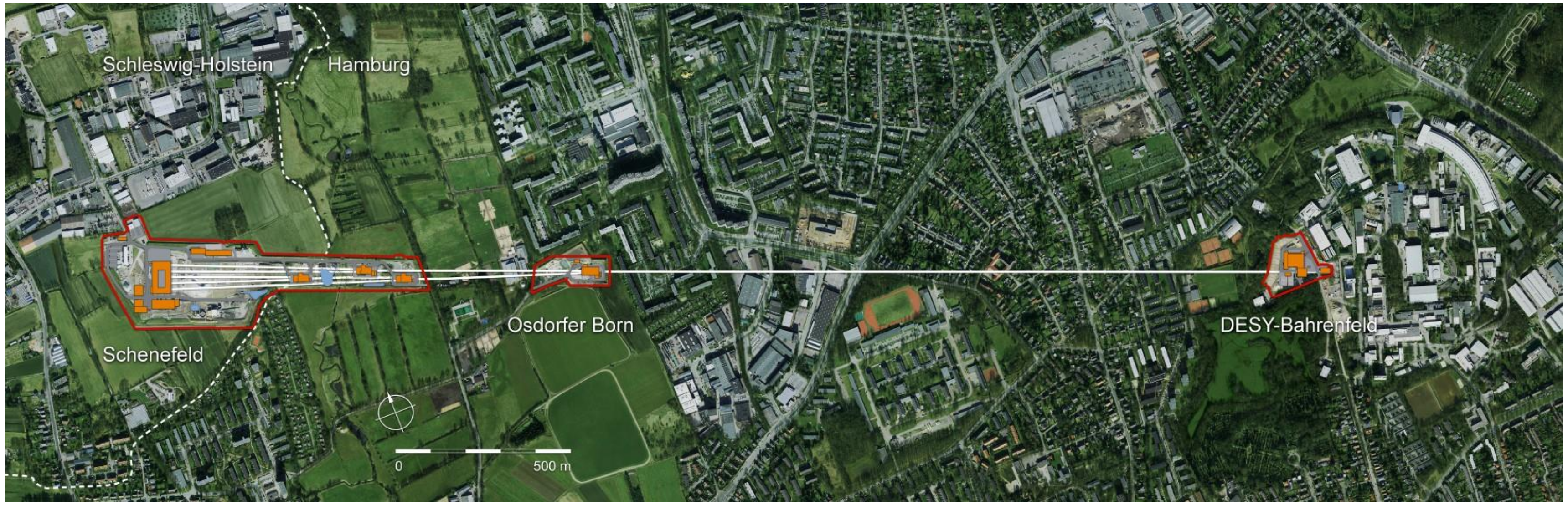
→ Ps temporal resolution, nm spatial resolution

MEASURING MAGNETISATION DYNAMICS – FASTER?

MEASURING MAGNETISATION DYNAMICS – FASTER?

Free electron laser

Very long accelerator: European XFEL 3.4 km long!



Ultra-bright, ultra-short X-ray pulses

10^{12} photons/s

~fs pulse length

MAGNONICS ROADMAP

IOP Publishing

Journal of Physics: Condensed Matter

J. Phys.: Condens. Matter **33** (2021) 413001 (72pp)

https://doi.org/10.1088/1361-648X/abec1a

Topical Review

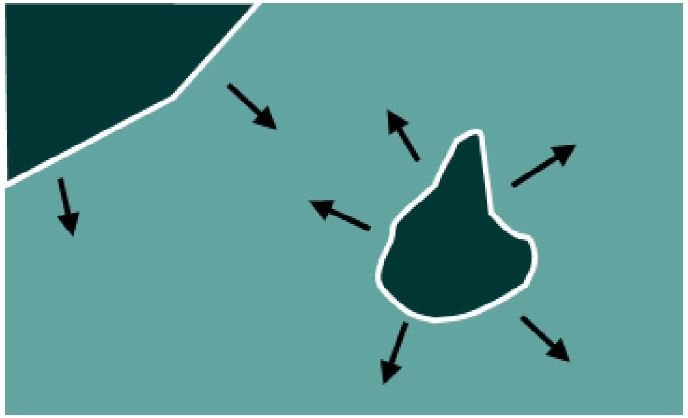
The 2021 Magnonics Roadmap

Anjan Barman[1,51,*], Gianluca Gubbiotti[2,51,*], S Ladak[3], A O Adeyeye[4], M Krawczyk[5], J Gräfe[6], C Adelmann[7], S Cotofana[8], A Naeemi[9], V I Vasyuchka[10], B Hillebrands[10], S A Nikitov[11], H Yu[12], D Grundler[13], A V Sadovnikov[11,14], A A Grachev[11,14], S E Sheshukova[11,14], J-Y Duquesne[15], M Marangolo[15], G Csaba[16], W Porod[17], V E Demidov[18], S Urazhdin[19], S O Demokritov[18], E Albisetti[20], D Petti[20], R Bertacco[20], H Schultheiss[21,22], V V Kruglyak[23], V D Poimanov[24], S Sahoo[1], J Sinha[25], H Yang[26], M Münzenberg[27], T Moriyama[28,29], S Mizukami[29,30], P Landeros[31,32], R A Gallardo[31,32], G Carlotti[33,34], J-V Kim[35], R L Stamps[36], R E Camley[37], B Rana[38], Y Otani[38,39], W Yu[40], T Yu[41], G E W Bauer[30,42], C Back[43], G S Uhrig[44], O V Dobrovolskiy[45], B Budinska[45], H Qin[46], S van Dijken[46], A V Chumak[45], A Khitun[47], D E Nikonov[48], I A Young[48], B W Zingsem[49] and M Winklhofer[50]

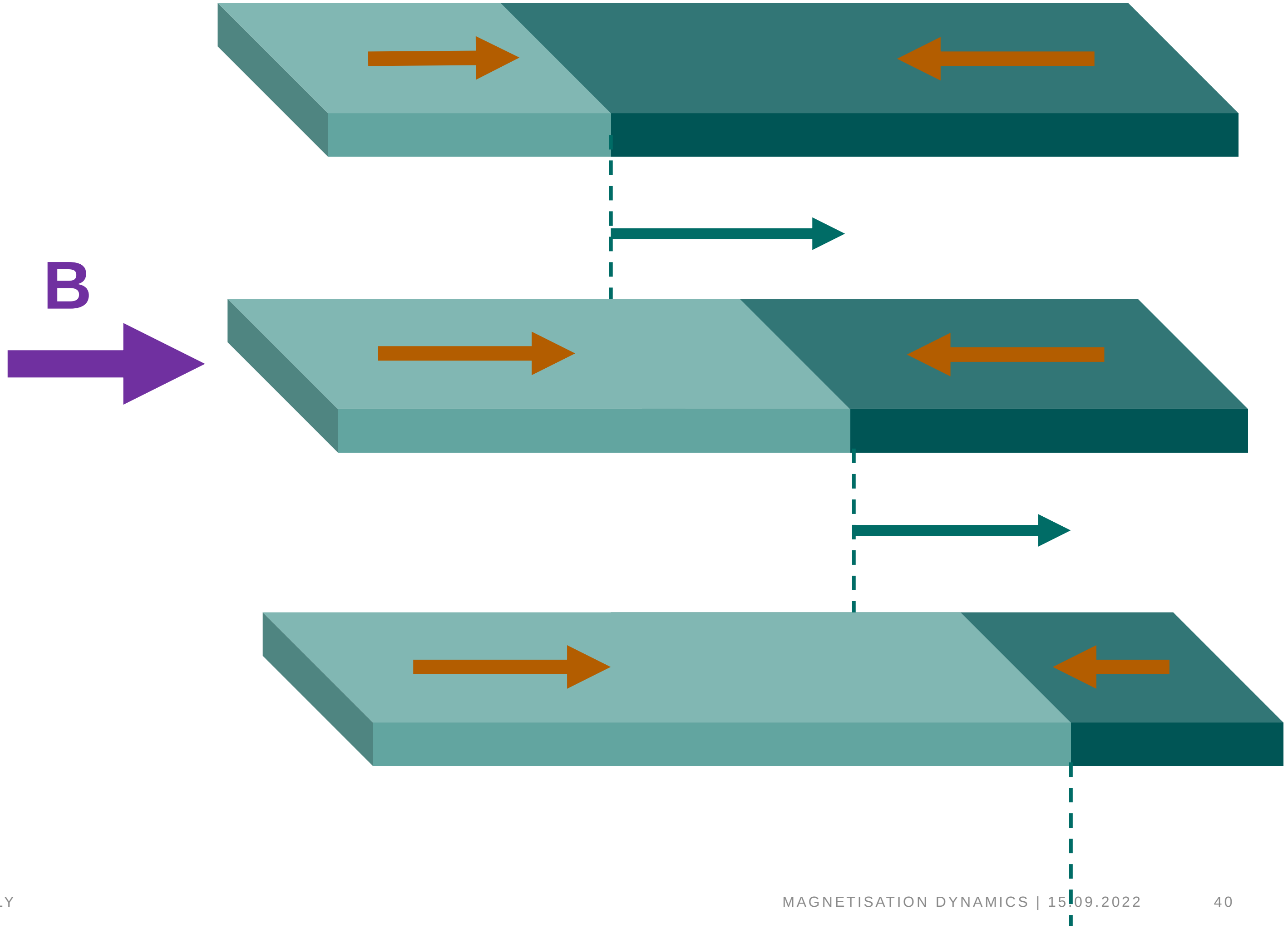
→ Sub-100 nm wavelength magnons
→ Manipulation on the nanoscale
→ Creation of sub-micrometre devices

“magnonics offers lower energy consumption, easier integrability and compatibility with CMOS structure”

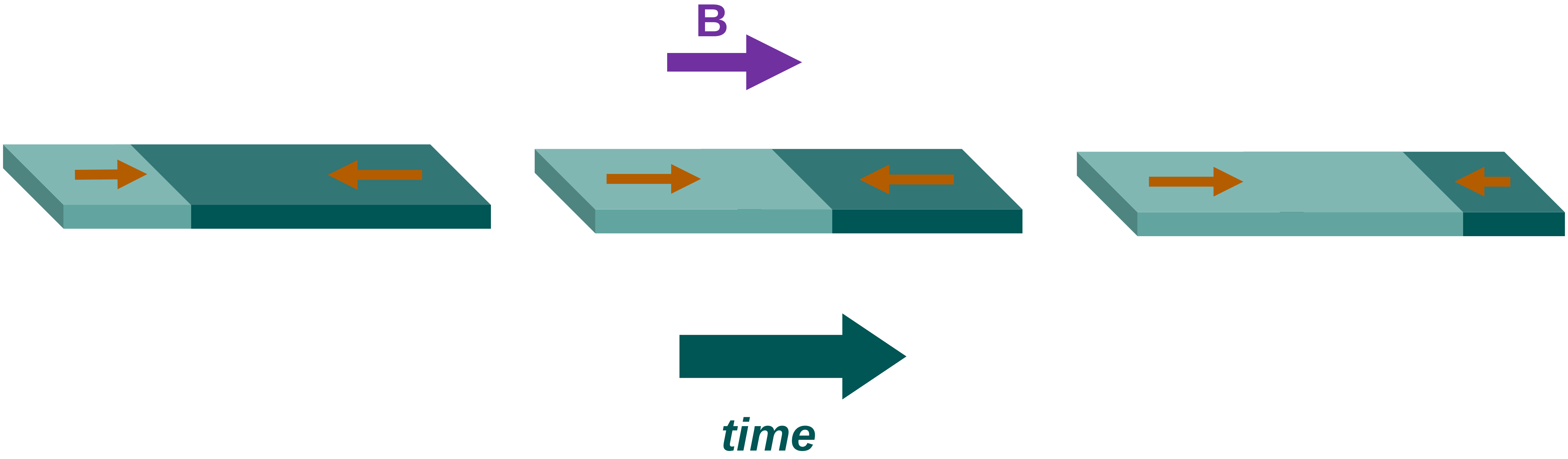
OTHER TYPES OF DYNAMICS:



Domain walls move
to grow domains

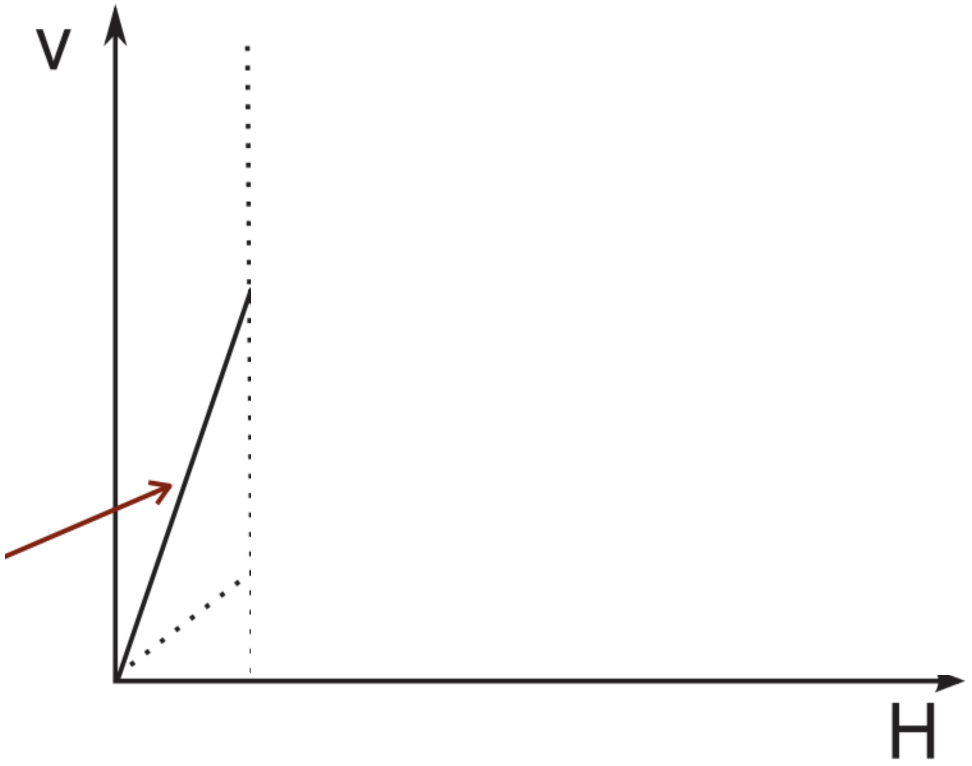


DOMAIN WALL DYNAMICS



As domain wall moves, Zeeman energy decreases: $E = -\mu_0 M \cdot H$

DOMAIN WALL DYNAMICS

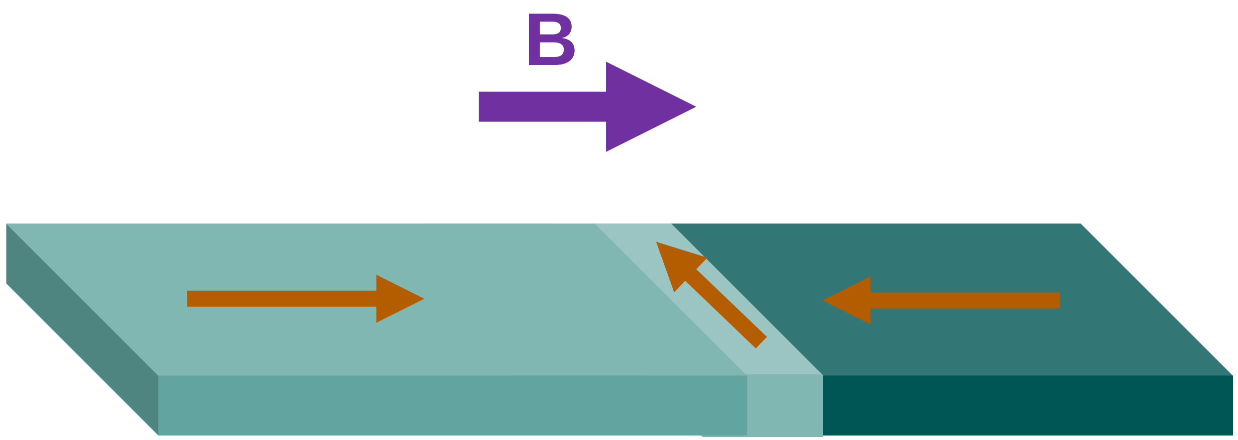


$$v = \frac{\gamma_0 H \lambda}{\alpha}$$

Steady state motion

"viscous regime"
When pinning doesn't dominate

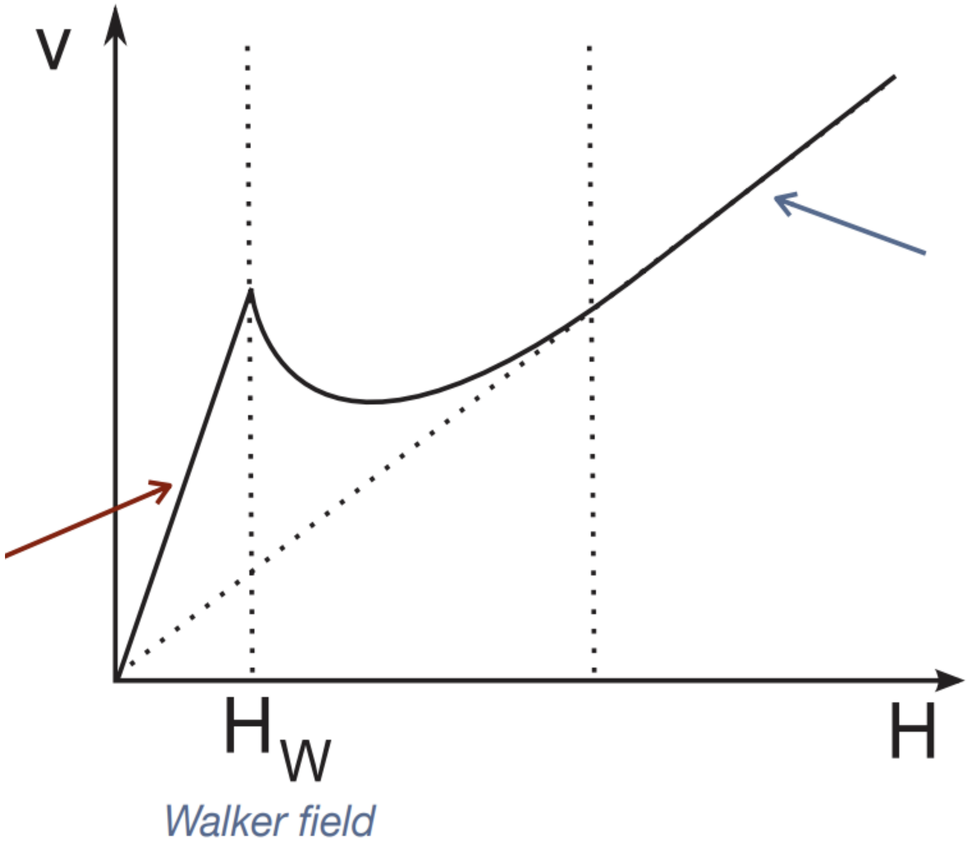
DOMAIN WALL DYNAMICS



$B \times M = 0$ $\boldsymbol{B} \times \boldsymbol{M} \neq \boldsymbol{0}$ $B \times M = 0$

Wall will feel a torque – start to tilt
For strong enough fields, the wall will start to precess!

DOMAIN WALL DYNAMICS



$$v = \frac{\alpha\gamma_0 H\lambda}{1+\alpha^2}$$

Precessional motion

$$v = \frac{\gamma_0 H\lambda}{\alpha}$$

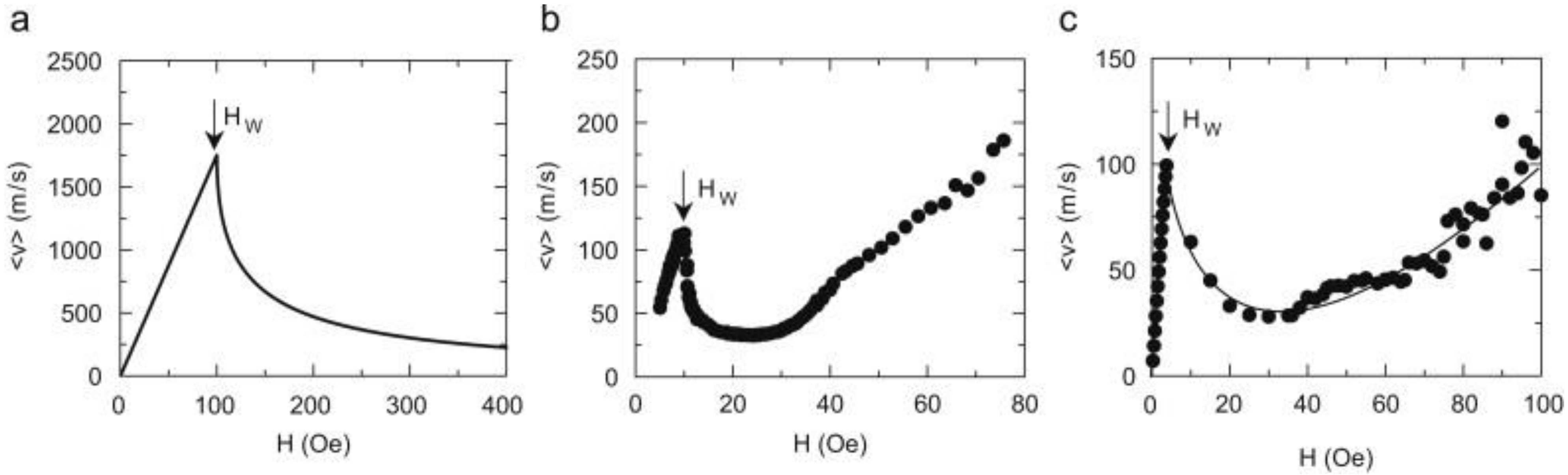
Steady state motion

"viscous regime"
When pinning doesn't dominate

$$H_C = \frac{\alpha M_S}{2}$$

WALKER BREAKDOWN: EXPERIMENTALLY

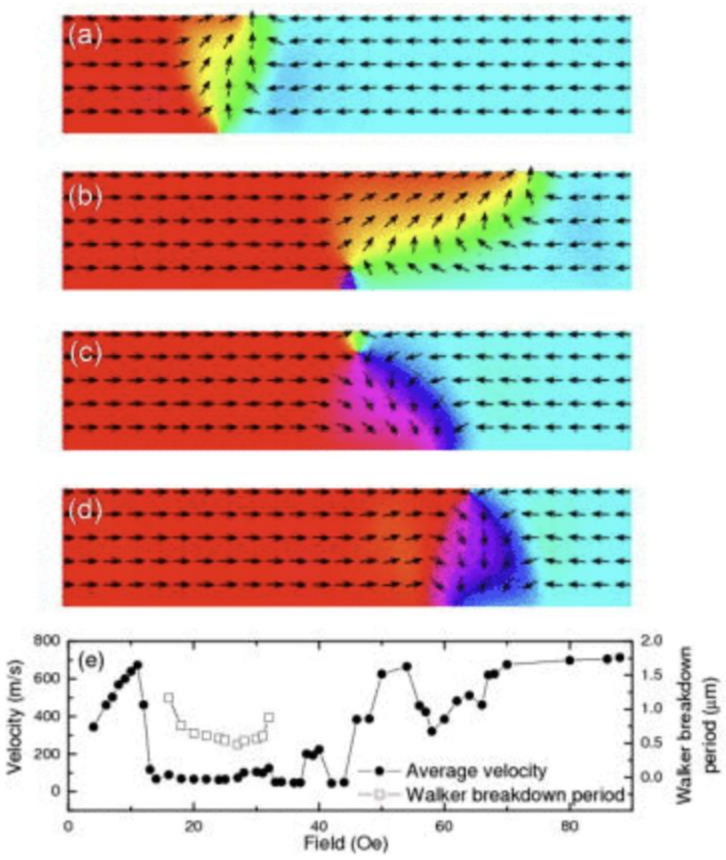
Experimentally confirmed in 500nm x 20 nm permalloy wire:



Domain wall propagated by spin-polarised current

Beach et al., JMMM 320, 1272 (2008)

IN REAL SYSTEMS: NANOWIRES



Burn & Atkinson Appl. Phys. Lett. **102**, 242414 (2013)

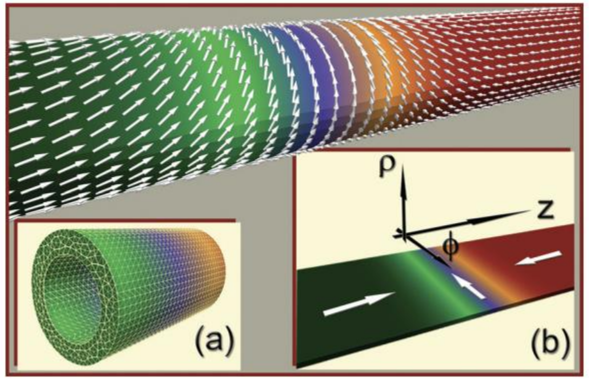
Edges play a role!

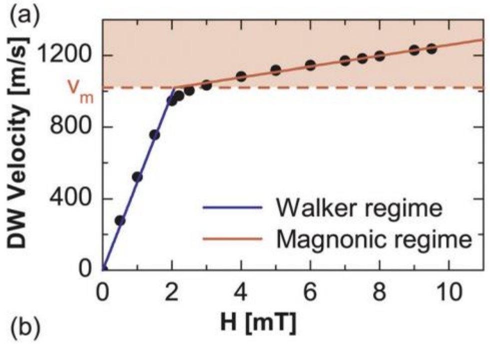
Can avoid by going to different geometries:

APPLIED PHYSICS LETTERS **99**, 122505 (2011)

Fast domain wall dynamics in magnetic nanotubes: Suppression of Walker breakdown and Cherenkov-like spin wave emission

Ming Yan,[1,a)] Christian Andreas,[1] Attila Kákay,[1] Felipe García-Sánchez,[1] and Riccardo Hertel[1,2]



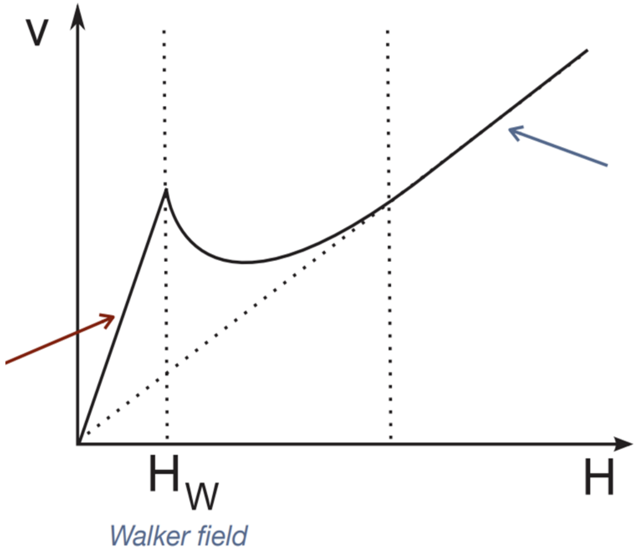


WALKER BREAKDOWN:

The Walker breakdown limits the maximum velocity of domain walls

→ Ferrimagnets!

→ At compensation temperature, Ms→ 0



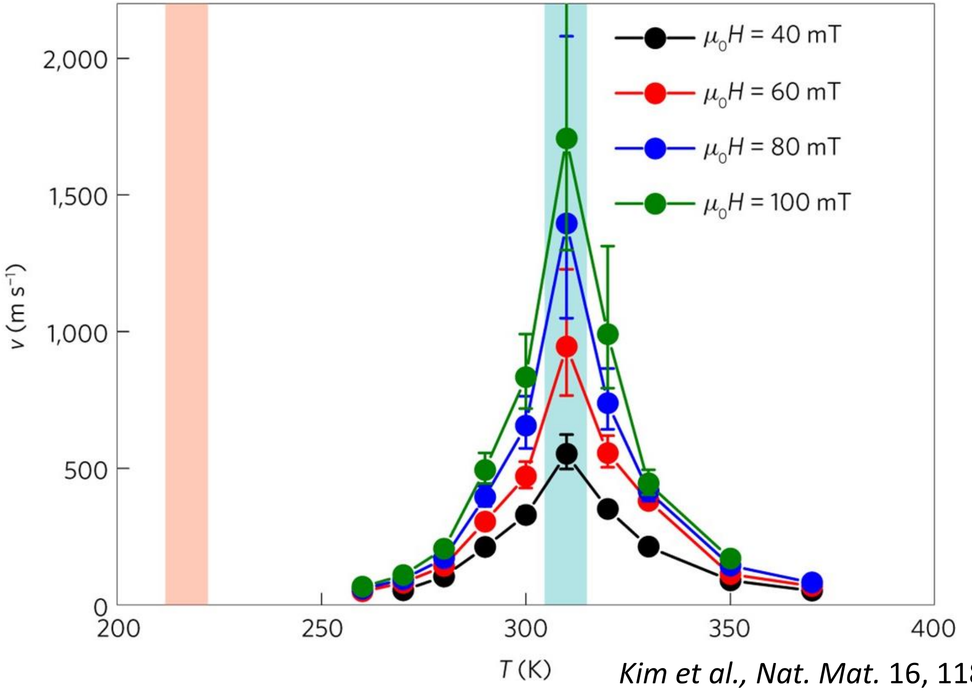
$$v = \frac{\gamma_0 H\lambda}{\alpha}$$

Steady state motion

$$v = \frac{\alpha\gamma_0 H\lambda}{1+\alpha^2}$$

Precessional motion

$$H_C = \frac{\alpha M_S}{2}$$



Kim et al., Nat. Mat. 16, 1187 (2017)

DYNAMICS – WHAT TIME SCALES?

Slow!

Ultrafast!

10^{8}

Years

10^{-9}

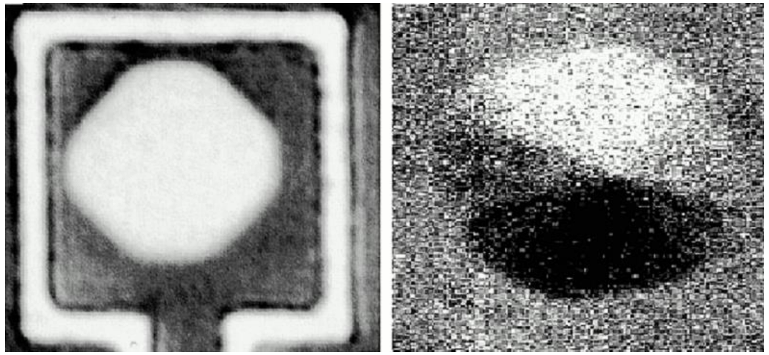
Nano-pico seconds

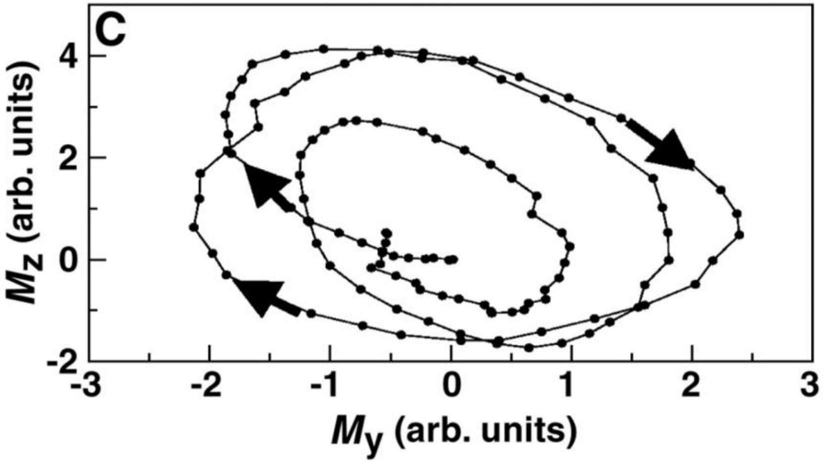
10^{-15}

Femto seconds

GHz - THz

SPIN-FLIP: HOW FAST CAN WE GO?





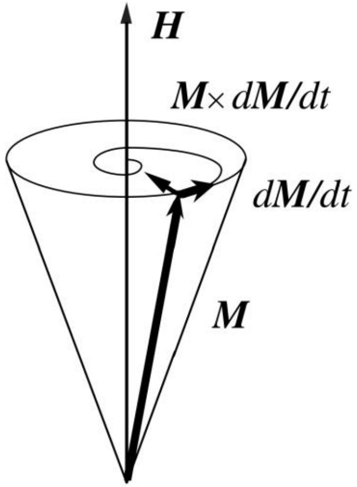
Acremann et al., Science, 290, 492 (2000)

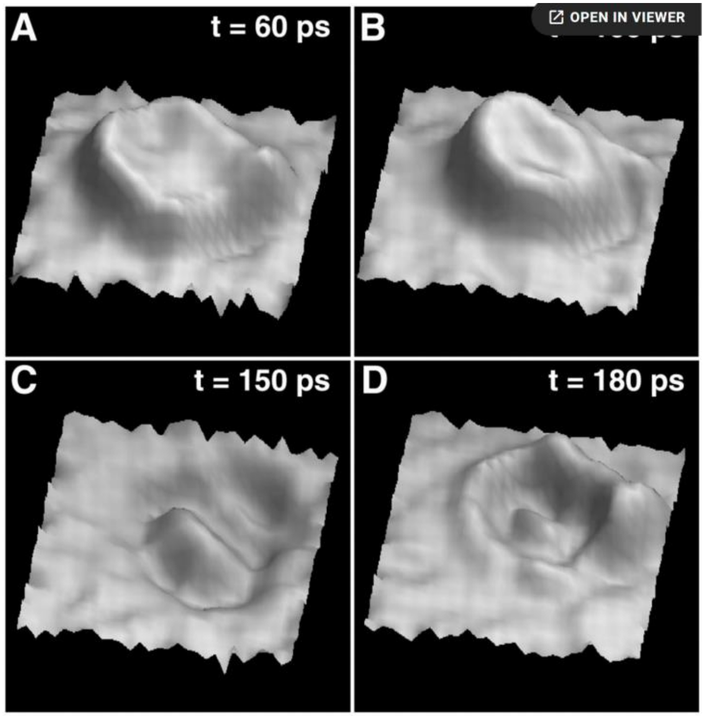
→ Time-resolved Vector MOKE

→ Mz field pulse

→ Larmor's theoreum: precessional orbit of the magnetisation

→ Microscopy: get spatial resolution:





SPIN-FLIP: HOW FAST CAN WE GO?

Does this precessional motion matter?

Yes – for devices it limits the speed!

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]

[1]*Stanford Synchrotron Radiation Laboratory, PO Box 20450, Stanford, California 94309, USA*
[2]*Landau Institute for Theoretical Physics, Kosygin str. 2, Moscow 117940, Russia*
[3]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309, USA*
[4]*Seagate Technology LLC, Pittsburgh, Pennsylvania 15222, USA*

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.

→ Limited to ~100s picoseconds

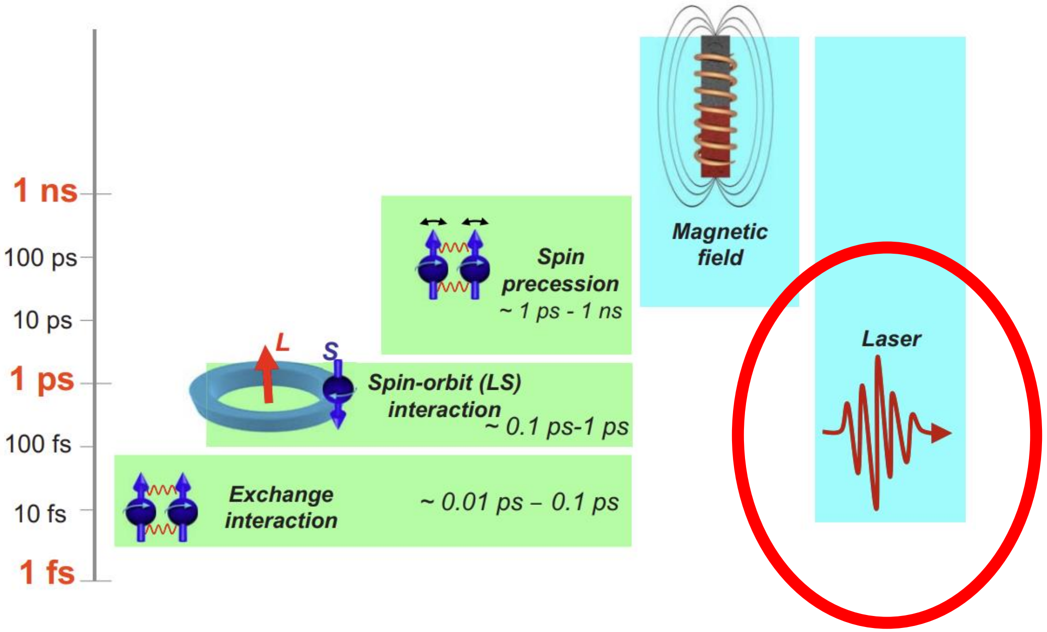
DIFFERENT TIME SCALES:

REVIEWS OF MODERN PHYSICS, VOLUME 82, JULY–SEPTEMBER 2010

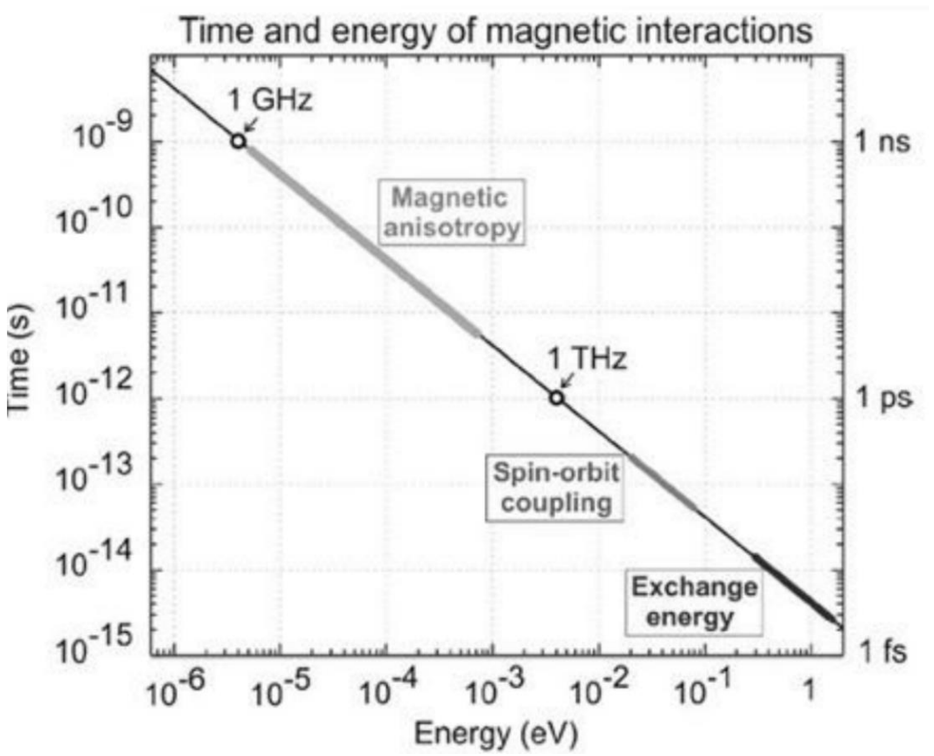
Ultrafast optical manipulation of magnetic order

Andrei Kirilyuk,* Alexey V. Kimel, and Theo Rasing

Radboud University Nijmegen, Institute for Molecules and Materials, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands



There are faster time-scales out there!



Stoehr et al., Magnetism Springer-Verlag, (2006)

GOING ULTRAFAST

So far, we have looked at **thermal** and **magnetic field/ current** driven dynamics

→ Indicate that it is limited to ~ns, ps.

→ However, when excited by a femtosecond laser, spin dynamics can be sub-pico second!

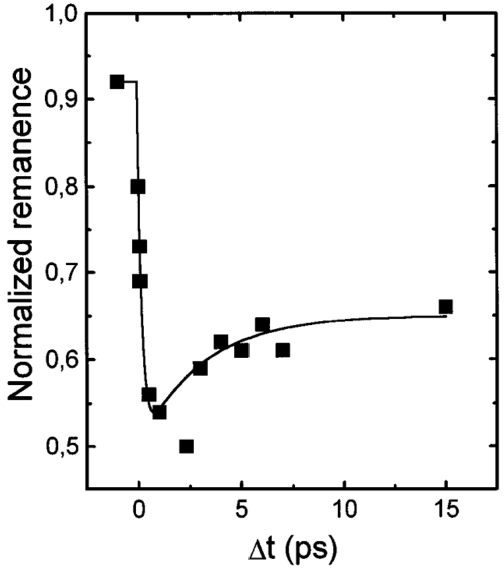
VOLUME 76, NUMBER 22 PHYSICAL REVIEW LETTERS 27 MAY 1996

Ultrafast Spin Dynamics in Ferromagnetic Nickel

E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot

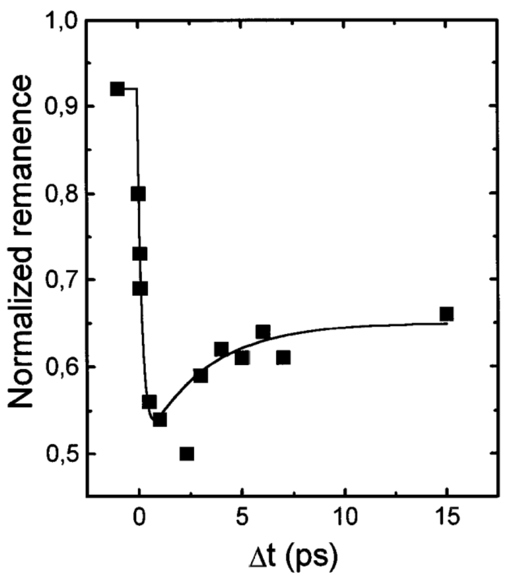
Institut de Physique et Chimie des Matériaux de Strasbourg, Unité Mixte 380046 CNRS-ULP-EHICS, 23, rue du Loess, 67037 Strasbourg Cedex, France

(Received 17 October 1995)



FEMTOSECOND DYNAMICS: ULTRAFAST DEMAGNETISATION

Nickel

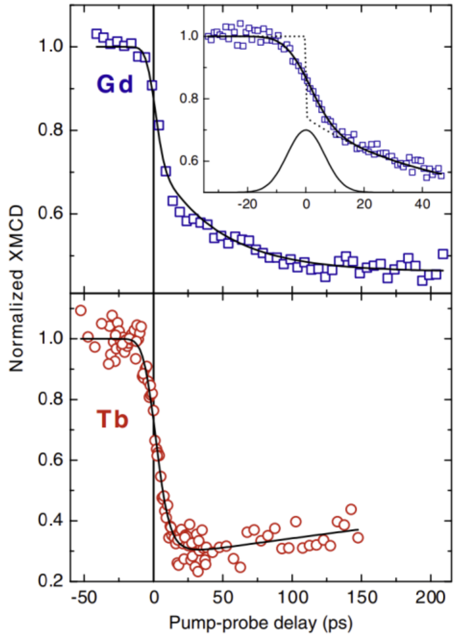


→ Demagnetisation in sub-ps time scale

→ Recovers ~ ps

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

Gadolinium



→ Demagnetisation in 10/100 ps timescale

Wietstruk et al. Phys. Rev. Lett. 106, 127401 (2011)

ULTRAFAST: WHAT'S HAPPENING?

Longer time scales:

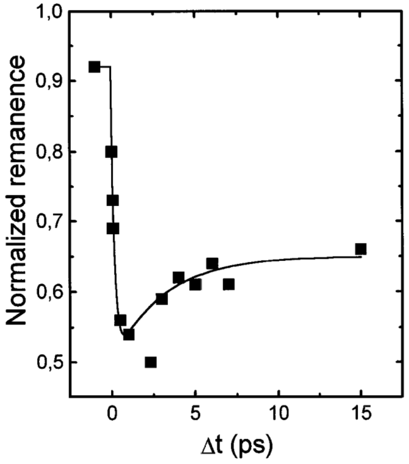
Spin & lattice in equilibrium

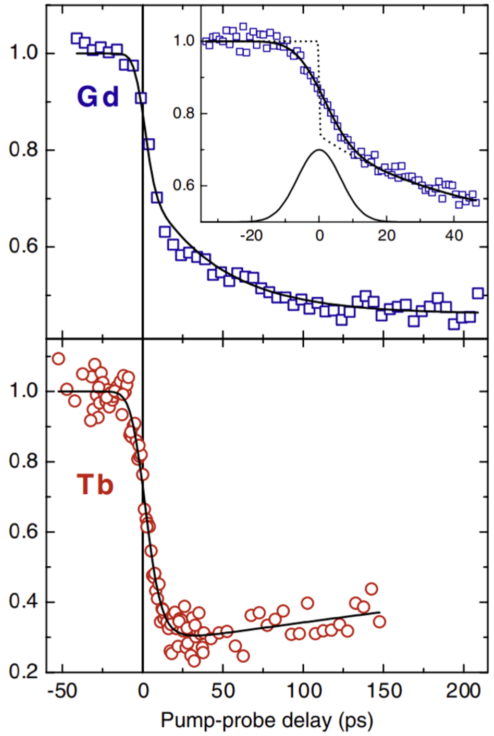
Fast time scales:

Lattice-driven spin demagnetisation!

Electrons act as heat bath for spin system

→ Effective heating of the spins above the Curie temperature



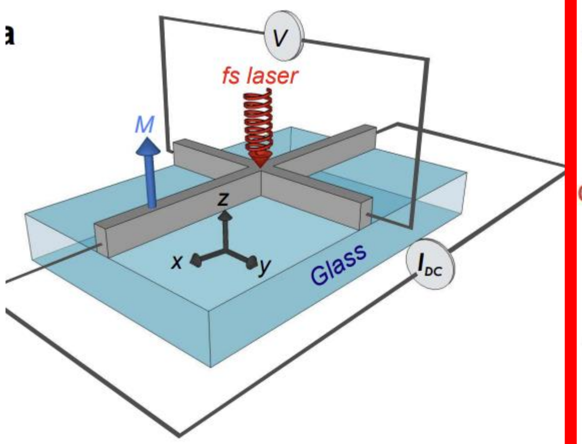


Ni vs Gd?

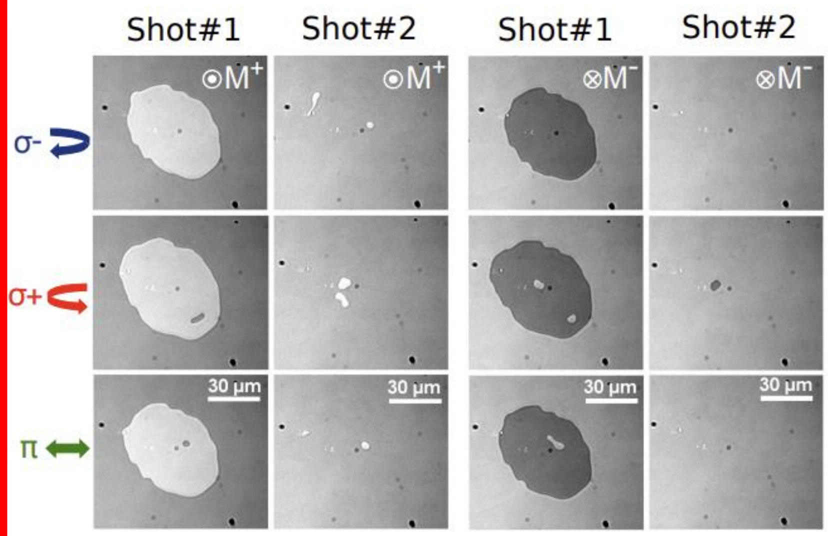
Magnetic moment ~ Angular momentum

Moment of Gd larger (7.3 vs 1.26 μB)
Rate of change of L ~ similar

ULTRAFAST DYNAMICS: SWITCHING?



Ferrimagnetic alloy, GdFeCo

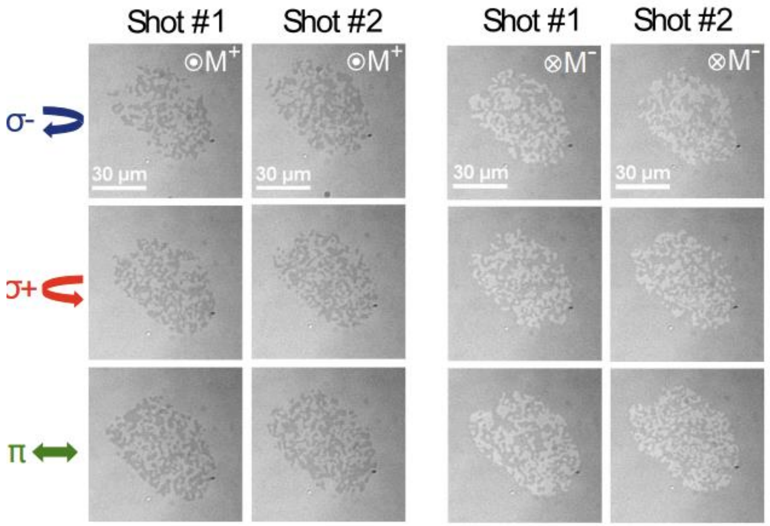


→ Helicity independent, single shot switching

→ Single shot: how fast?

Fast switching!

Ferromagnetic Co/Pt multilayers



→ Multi-pulse, helicity dependent optical switching

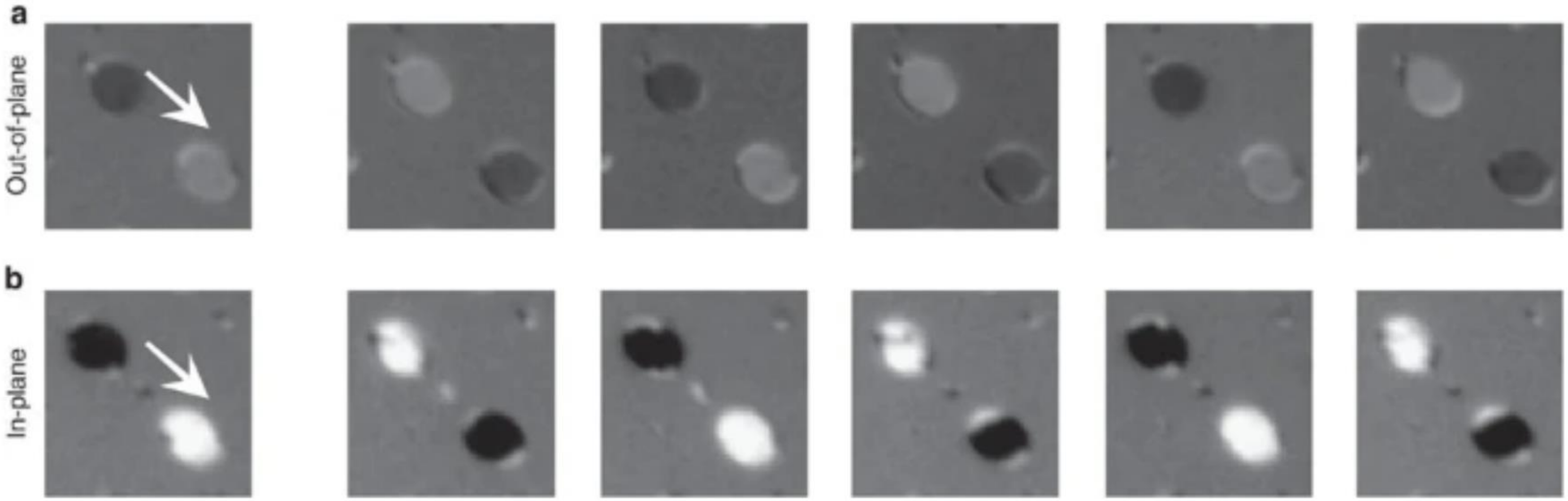
→ ~ms

El Hadri et al, Phys. Rev. B , 94, 064412 (2016)

ALL-OPTICAL SWITCHING

GdFeCo:

Reproducible switching back and forth



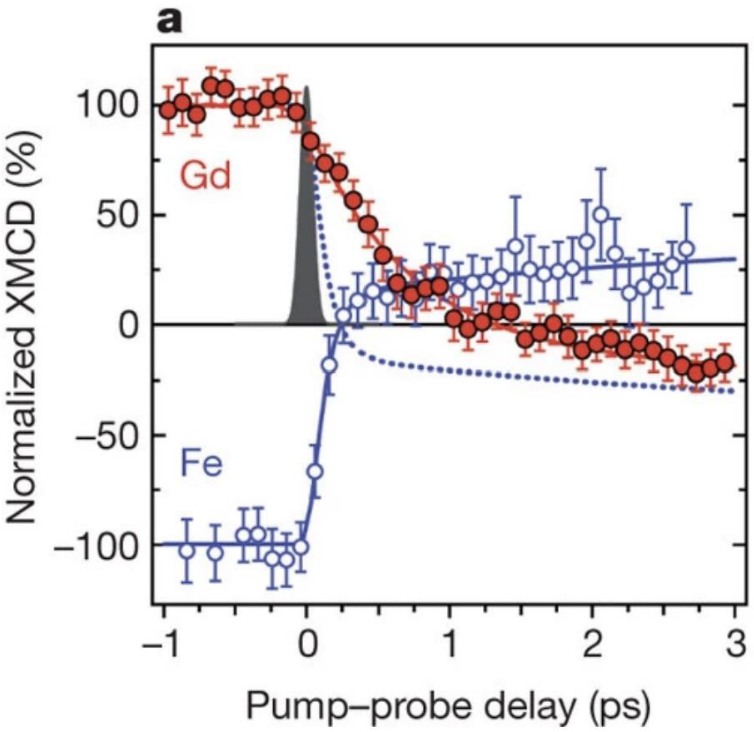
Ostler et al., Nat. Commun. 3, 666 (2012)

ULTRAFAST ALL-OPTICAL SWITCHING

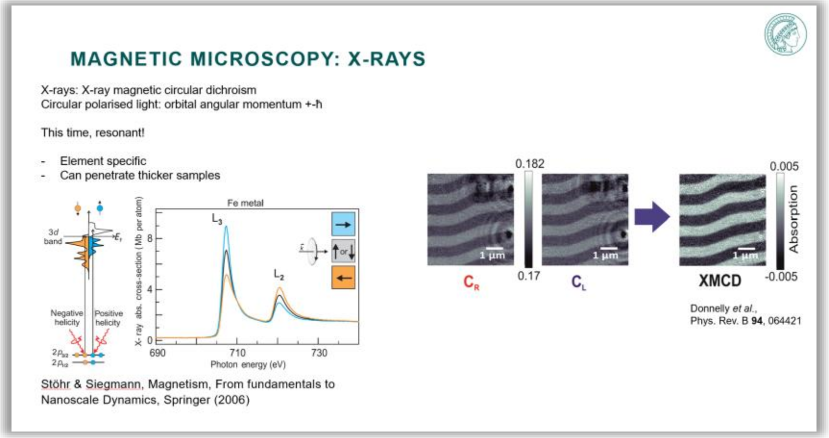
Key: ferrimagnet?

Use element-specific XMCD

Reveals:



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

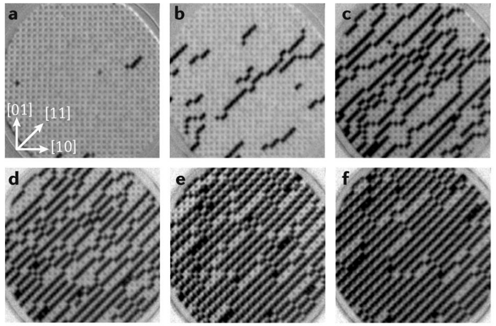


Fe and Gd demagnetise on different timescales
→ Transient ferromagnetic state
→ Drives robust switching process

DYNAMICS – WHAT TIME SCALES?

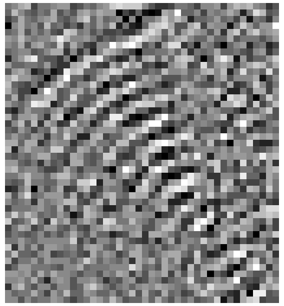
Slow! Ultrafast!

Years	Nano-pico seconds	Femto seconds
10^8 s	10^{-9}s	10^{-15}s
	GHz – THz	



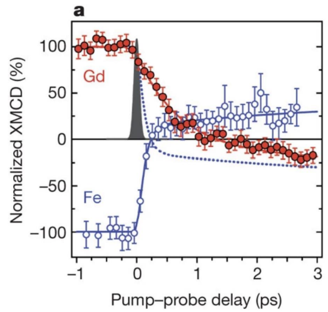
Magnetic viscosity

Superparamagnetism



Spin waves

Domain wall dynamics



Ultra-fast switching