ESM 2018
Krakow

MP - Magnetisation Processes

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Outline

- **MP1**
  Quasi-static processes, domain states, nontrivial spin textures

- **MP2**
  Precessional dynamics, dissipation processes, elementary and soliton excitations

- **MP3**
  Spin-transfer and spin-orbit torques, current topics in magnetization dynamics

MP1: Quasi-static processes

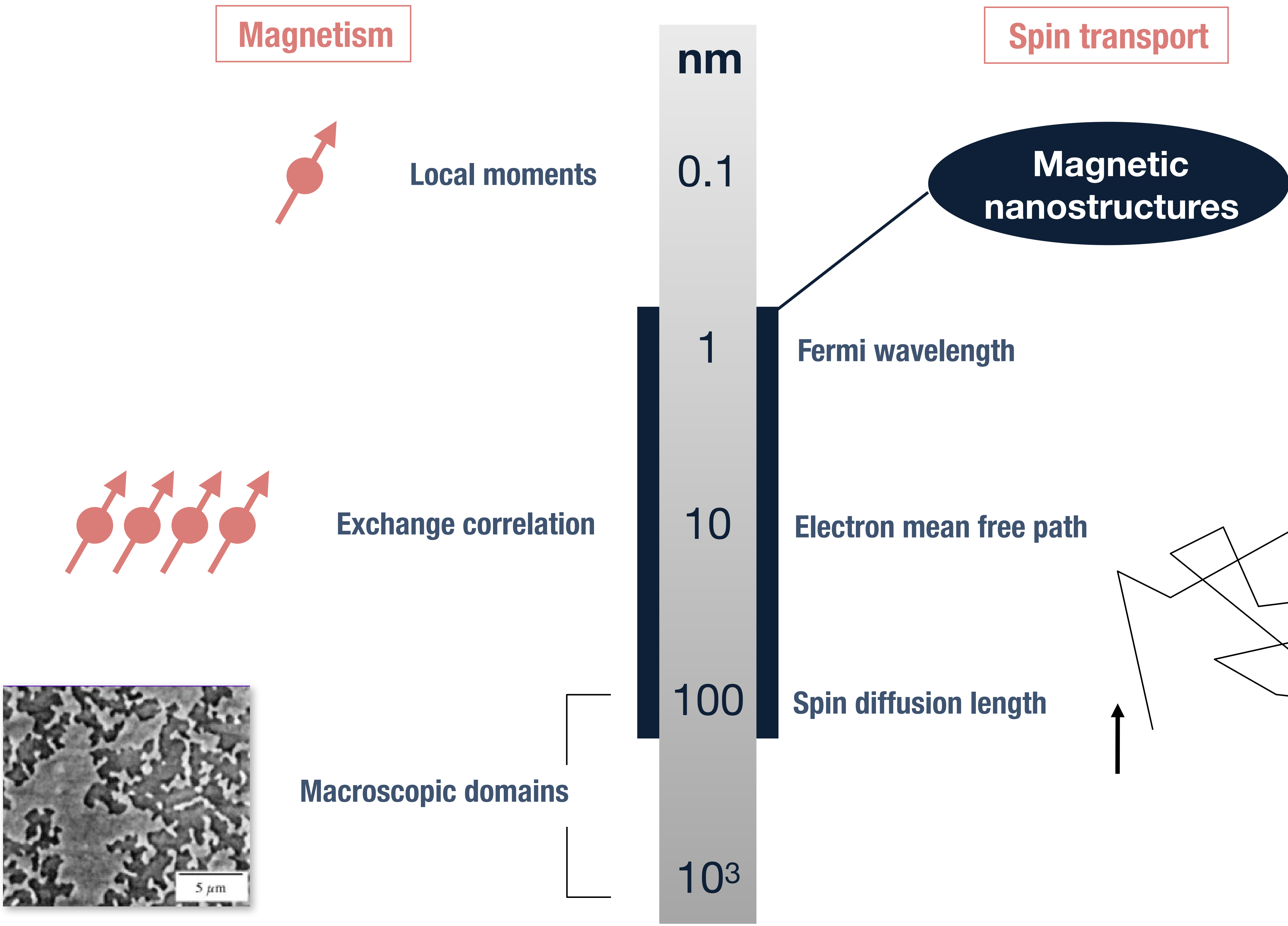
- Overarching theme: **Hysteresis loop**

- Energy landscapes
  Which magnetisation configurations are possible, favourable?

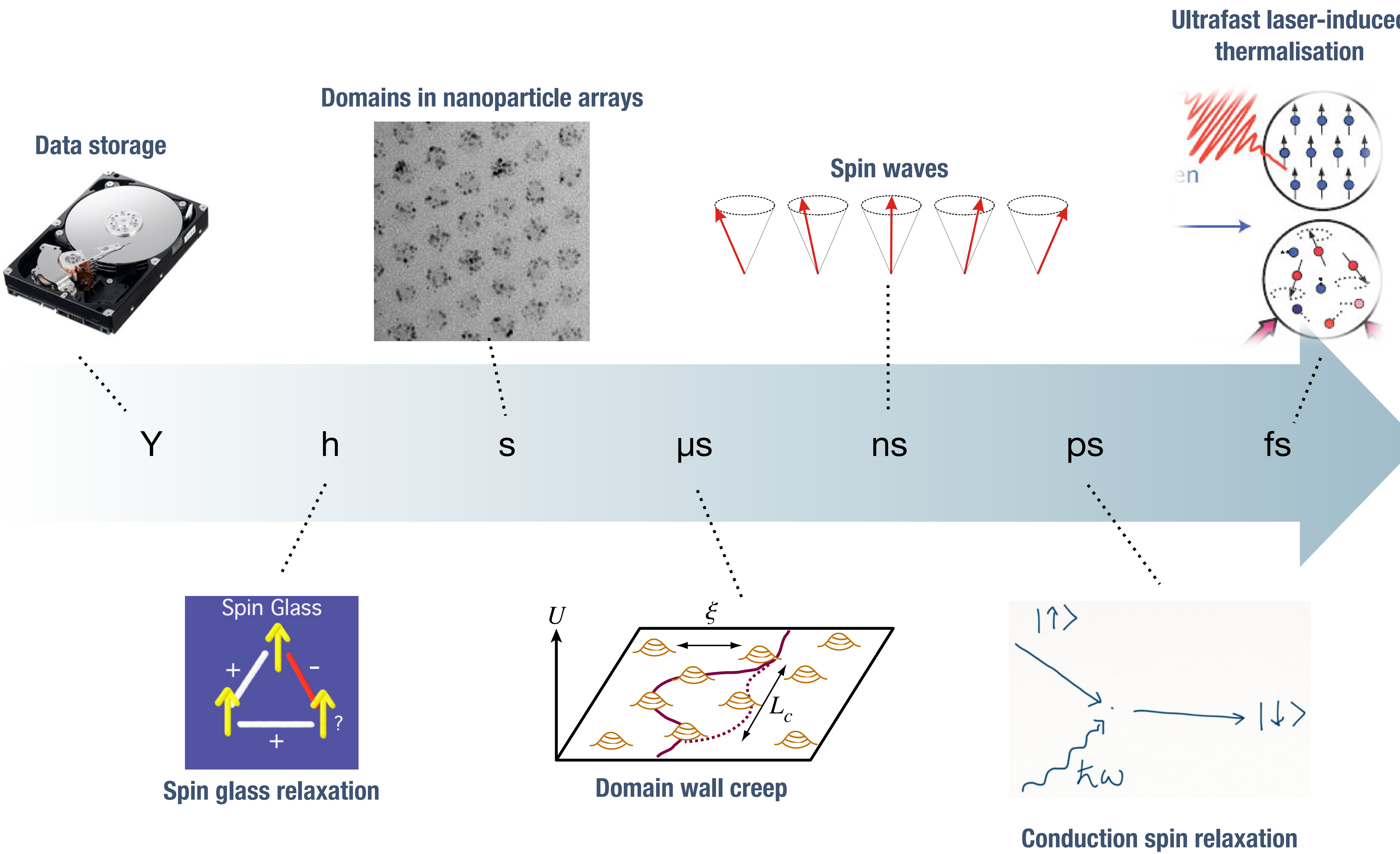
- Reversal mechanisms
  How do we navigate this energy landscape?

- Time-dependent and thermal effects
  "Slow" dynamics and the limits of what we mean by "quasi-static"

Length scales

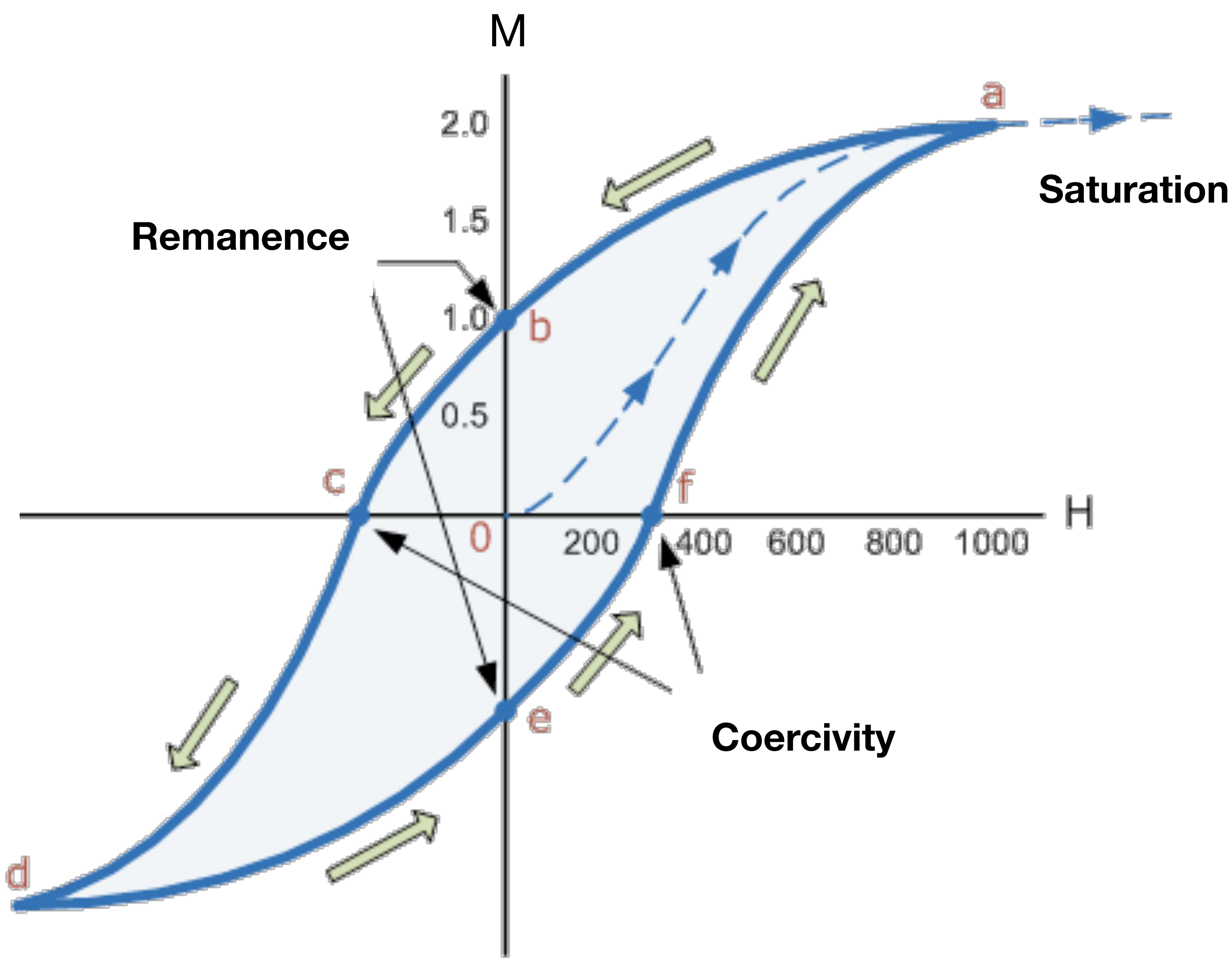


Time scales


Data storage
Domains in nanoparticle arrays
Spin waves
Ultrafast laser-induced thermalisation
Y
h
s
µs
ns
ps
fs
Spin Glass
+
-
?
+
Spin glass relaxation
U
ξ
L_c
Domain wall creep
$|\uparrow\rangle$
$|\downarrow\rangle$
$\hbar\omega$
Conduction spin relaxation

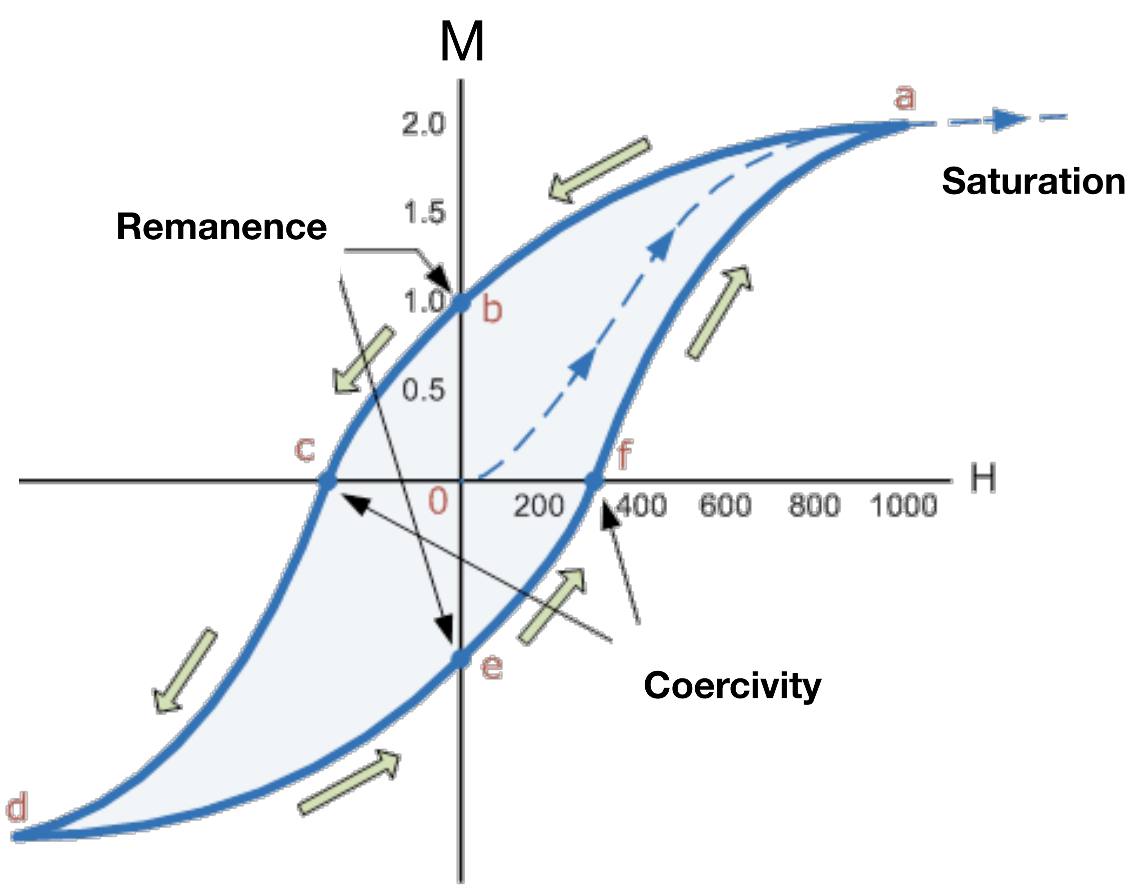
The hysteresis loop

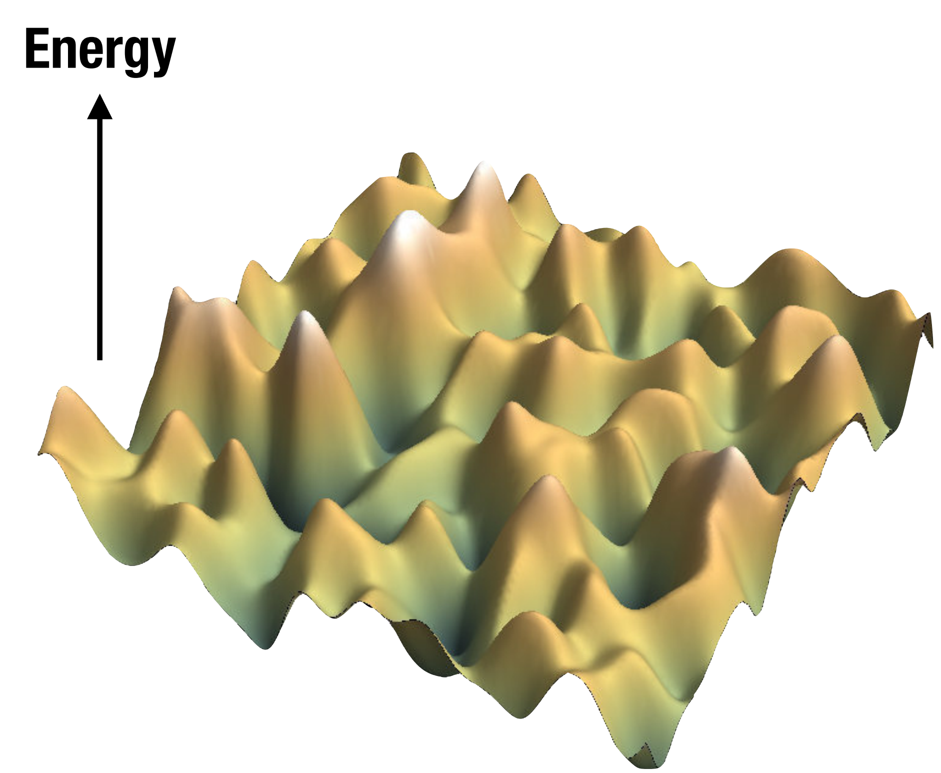
- Common characterisation of a magnetic material
- Captures physics across many length and time scales



“Quasi-statics”: Navigating the energy landscape

- As field is varied, magnetic system may move through a variety of metastable energy states
- “Quasi-static” processes dominated by energy considerations, rather than torques (i.e., precessional dynamics)
- “Slow” dynamics, compared with ns-scale of fs-scale processes

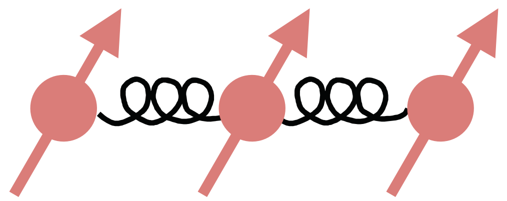




Energy terms - Brief overview

What contributes to the energy landscape?

Exchange

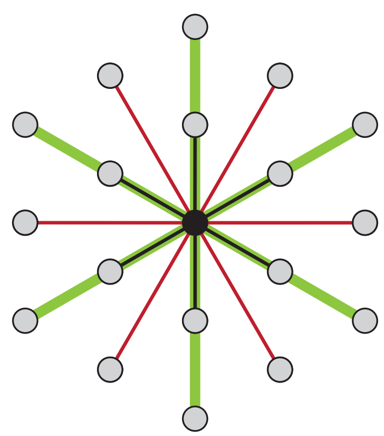


Atomistic

$$E_{\mathrm{ex}} = -J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$$

$J > 0$: ferromagnetic

$J < 0$: antiferromagnetic



J_1, J_2, J_3, …

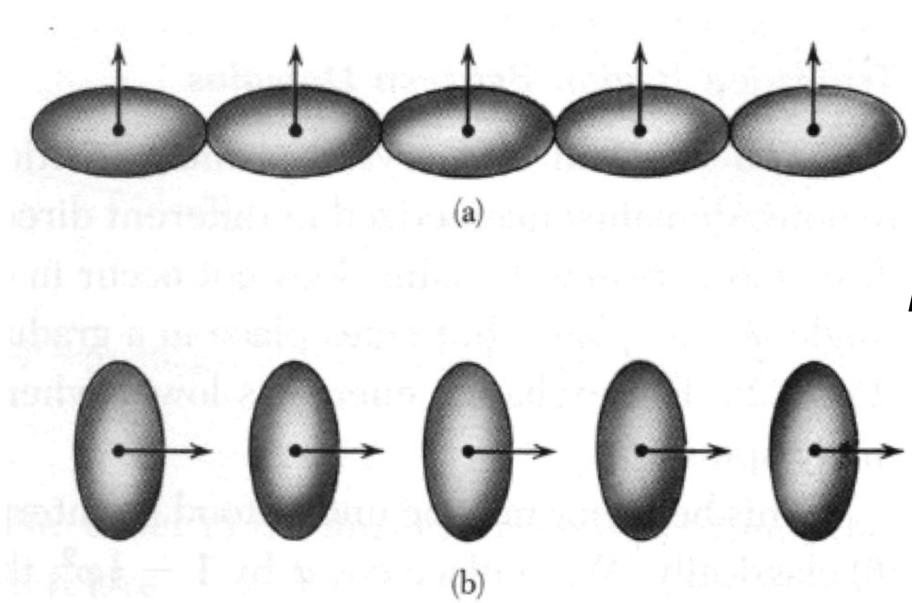
Micromagnetic

$$E_{\mathrm{ex}} = A\left(\nabla \mathbf{m}\right)^2$$

$$\mathbf{m} = \mathbf{M}/M_s$$

$$\|\mathbf{m}\| = 1$$

Anisotropy



E_1

$E_1 \neq E_2$

E_2

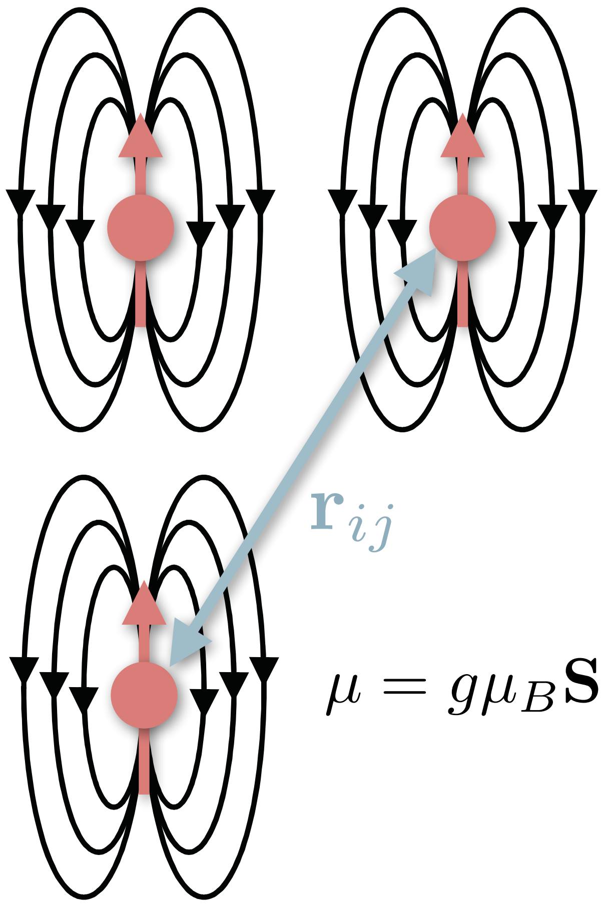
$$E_K = -K\left(\mathbf{m} \cdot \hat{\mathbf{e}}\right)^2$$

Uniaxial form shown, higher orders are possible

Energy terms - Brief overview

What contributes to the energy landscape?

Dipolar



$$\mu = g\mu_B \mathbf{S}$$

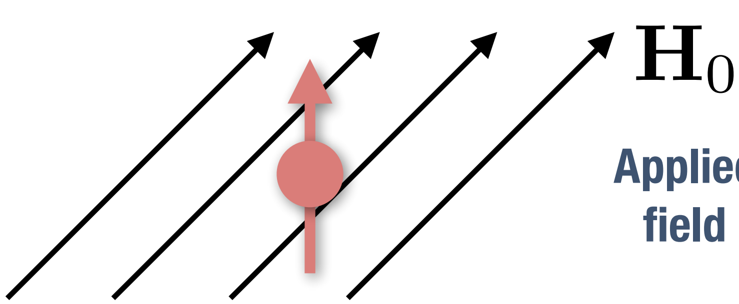
$$E_d = \mu_0 \left[\frac{\mu_i \cdot \mu_j}{r_{ij}^3} - \frac{3\left(\mu_i \cdot \mathbf{r}_{ij}\right)\left(\mu_j \cdot \mathbf{r}_{ij}\right)}{r_{ij}^5} \right]$$

$$E_d = -\frac{1}{2}\mu_0 \mathbf{M} \cdot \mathbf{H}_d \qquad \mathbf{H}_d = -\nabla \Phi_m$$

Demagnetising field

Magnetostatic potential

Zeeman



Applied field

$$E_Z = -\mu_0 \mathbf{M} \cdot \mathbf{H}_0$$

Energy terms - Brief overview

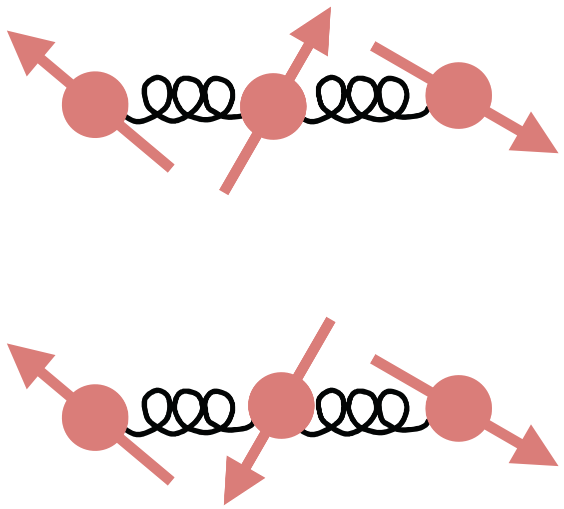
What contributes to the energy landscape?

Dzyaloshinskii-Moriya

E_1

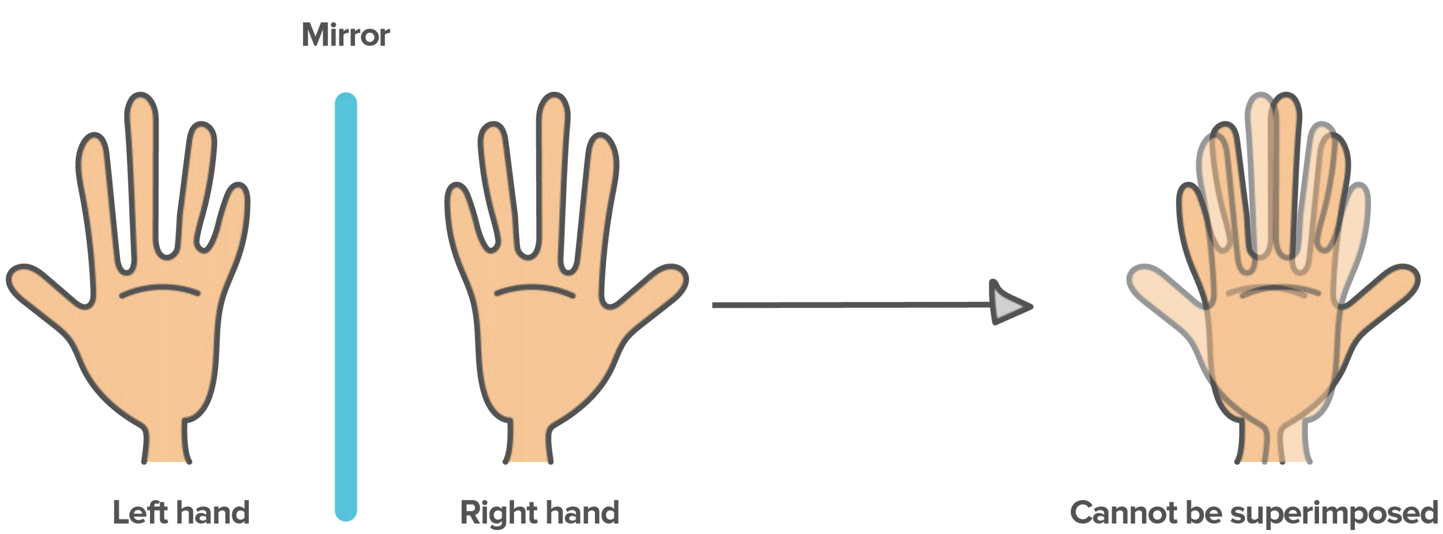
$E_1 \neq E_2$

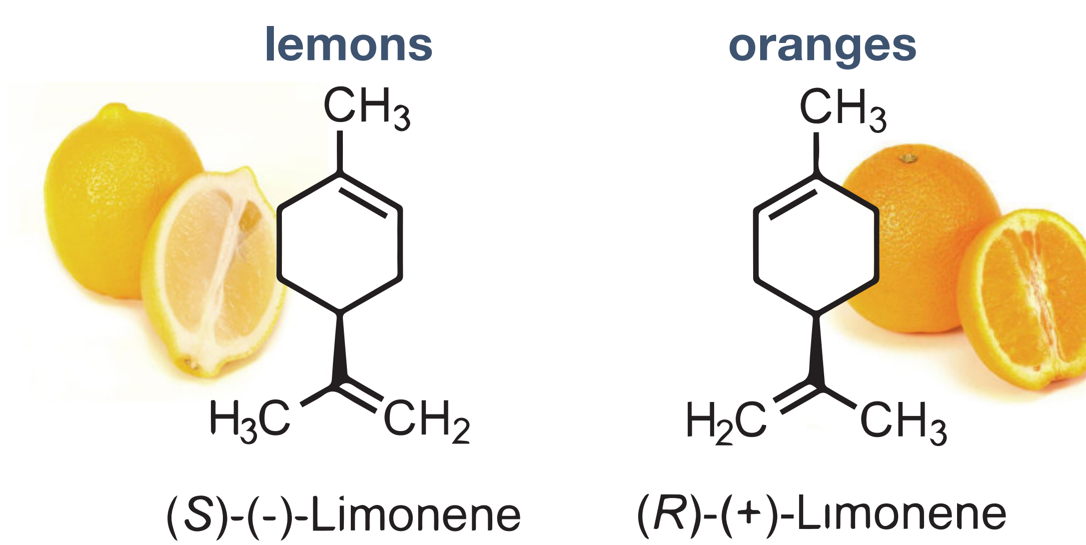
E_2



$$E_{\mathrm{DMI}} = D_{ij} \cdot \mathbf{S}_i \times \mathbf{S}_j$$

Example of a *chiral* interaction



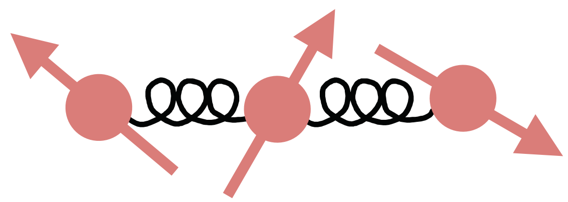


Energy terms - Brief overview

What contributes to the energy landscape?

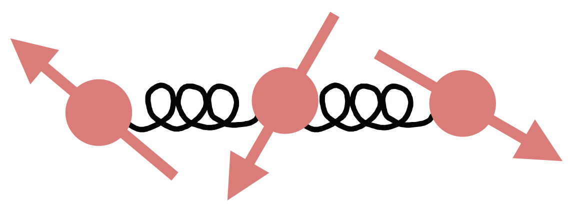
Dzyaloshinskii-Moriya

E_1



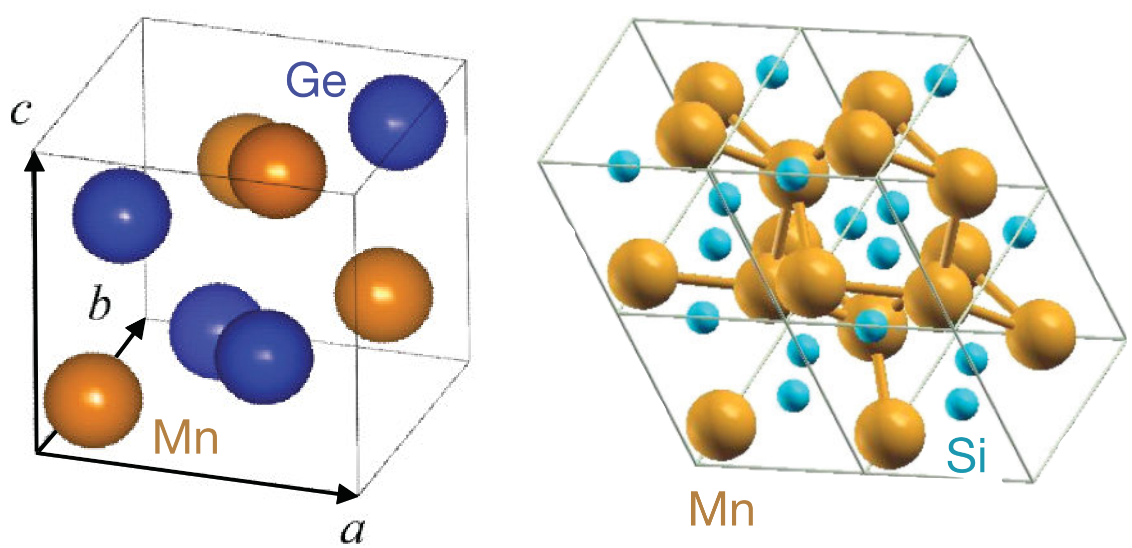
$E_1 \neq E_2$

E_2



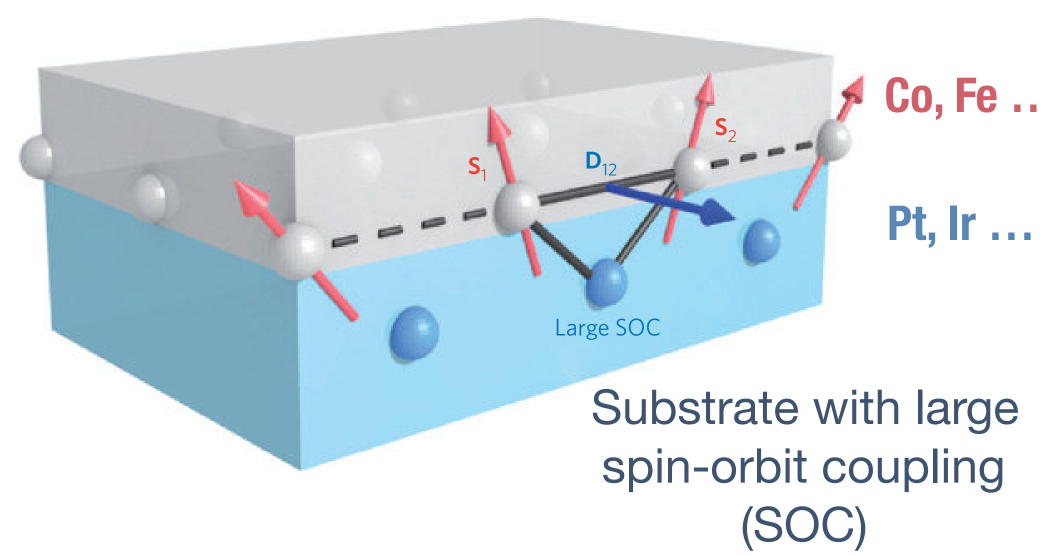
$$E_{\mathrm{DMI}} = D_{ij} \cdot \mathbf{S}_i \times \mathbf{S}_j$$

Non-centrosymmetric crystals (e.g., B20)



$$E_{\mathrm{DM}} = D\mathbf{m} \cdot (\nabla \times \mathbf{m})$$

Interface-induced



$$E_{\mathrm{DM}} = D\left[m_z\left(\nabla \cdot \mathbf{m}\right) - \left(\mathbf{m} \cdot \nabla\right) m_z\right]$$

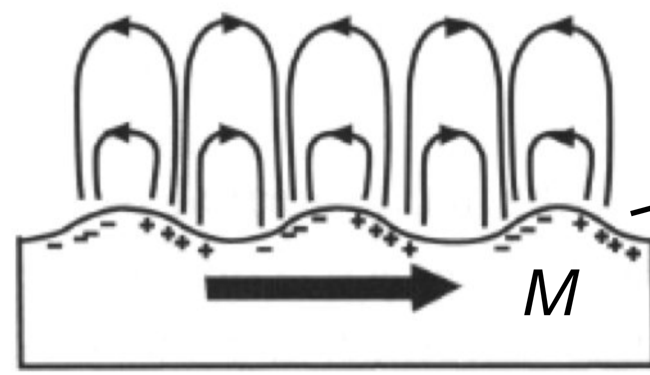
Energy terms - Interlayer coupling

Néel “Orange Peel” coupling

- Dipolar coupling due to induced magnetic charges at rough interfaces

Stray magnetic charges appear at surface of rough film

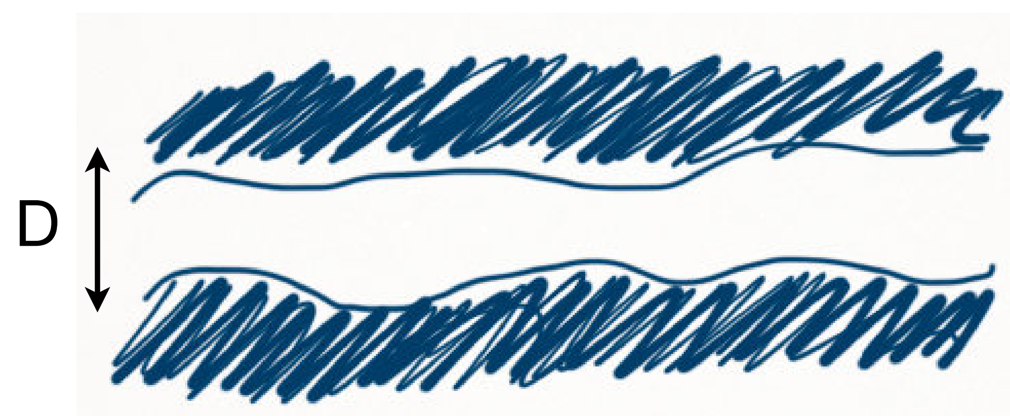
fringing fields



$$\sigma = \vec{M} \cdot \vec{n}$$

surface magnetic charge density

Similar phenomenon for rough interfaces in multilayer



Upper interface

Lower interface

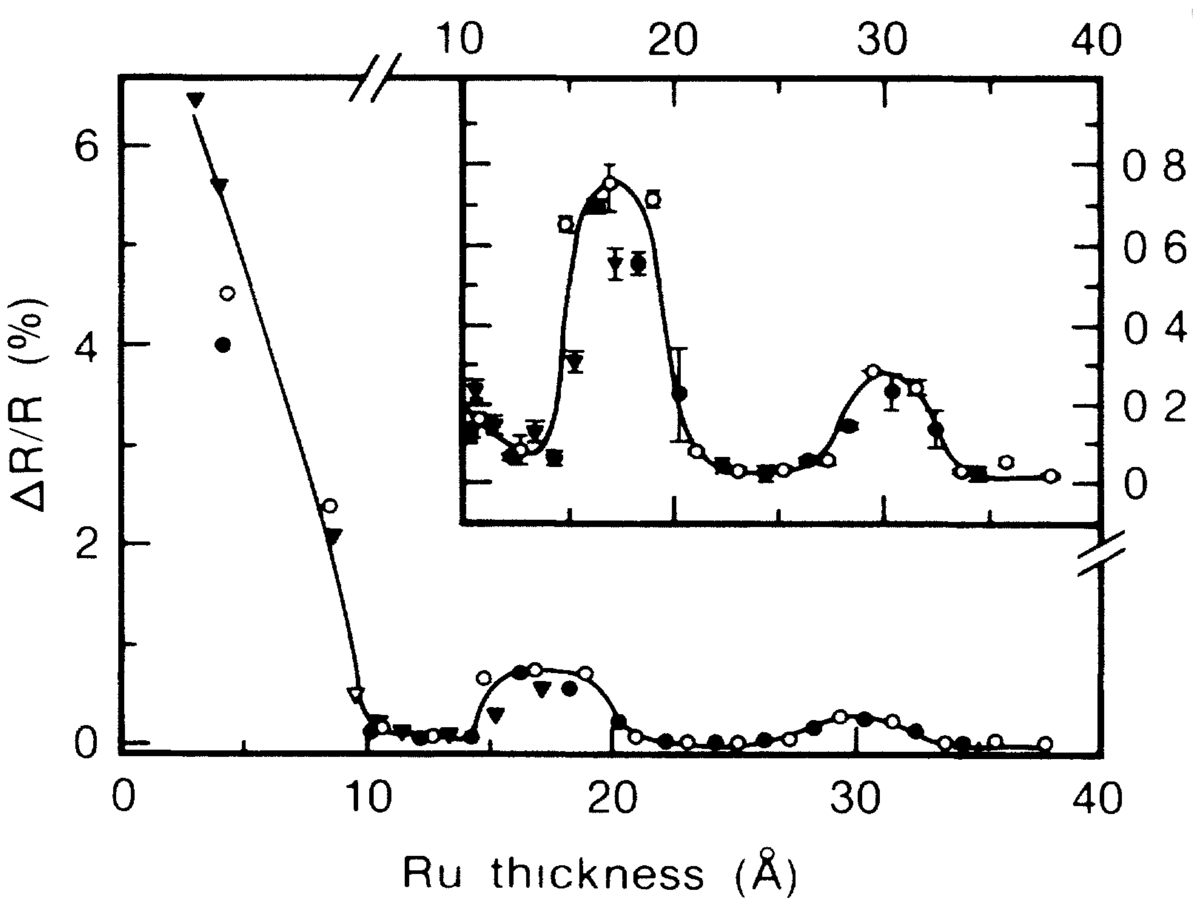
$$\mathcal{E} = \mu_0 \underbrace{\int d^2R}_{\text{Upper interface}} \underbrace{\int d^2R'}_{\text{Lower interface}} \frac{\sigma_U(\vec{R})\sigma_L(\vec{R}')}{\sqrt{D^2 + (\vec{R} - \vec{R}')^2}}$$

Energy terms - Interlayer coupling

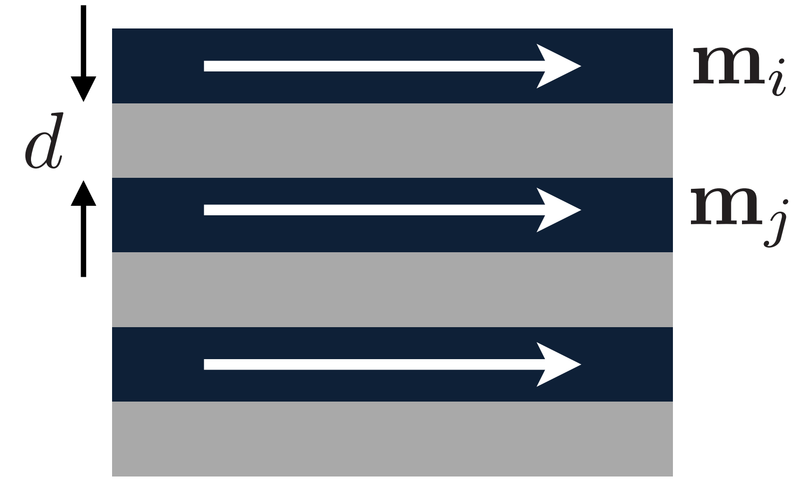
RKKY Coupling

- Indirect exchange coupling mediated by conduction electrons in spacer layer
- Related to *Ruderman-Kittel-Kasuya-Yosida* interaction between two magnetic impurities in an electron gas

GMR signal



$$E_{\text{RKKY}} = -J(d)\mathbf{m}_i \cdot \mathbf{m}_j$$



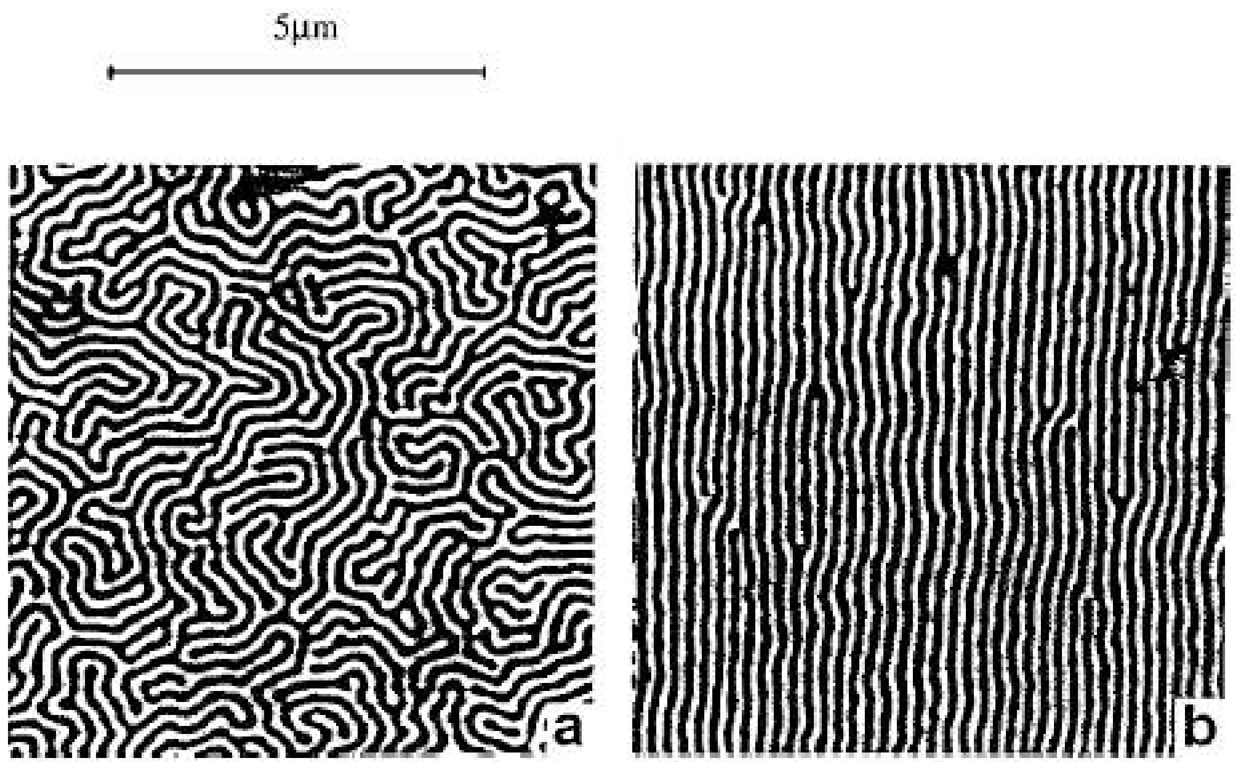
Fe/Cr, Co/Cr, Co/Ru, Co/Cu/, Fe/Cu, ...

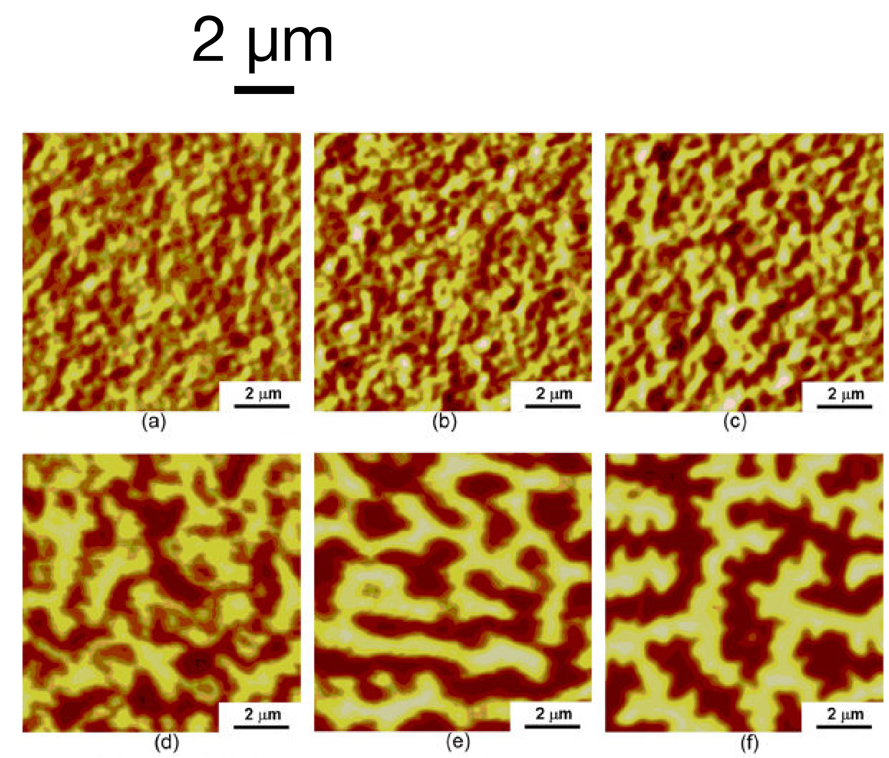
Coupling oscillates with spacer layer thickness

Magnetic states

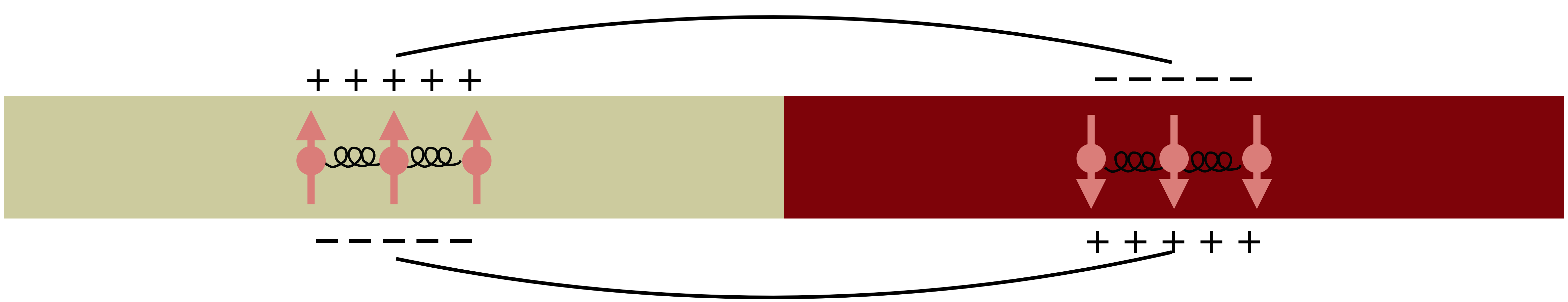
Domains

- On length scales of ~100 nm and above, magnetic order can be subdivided into different *domains*





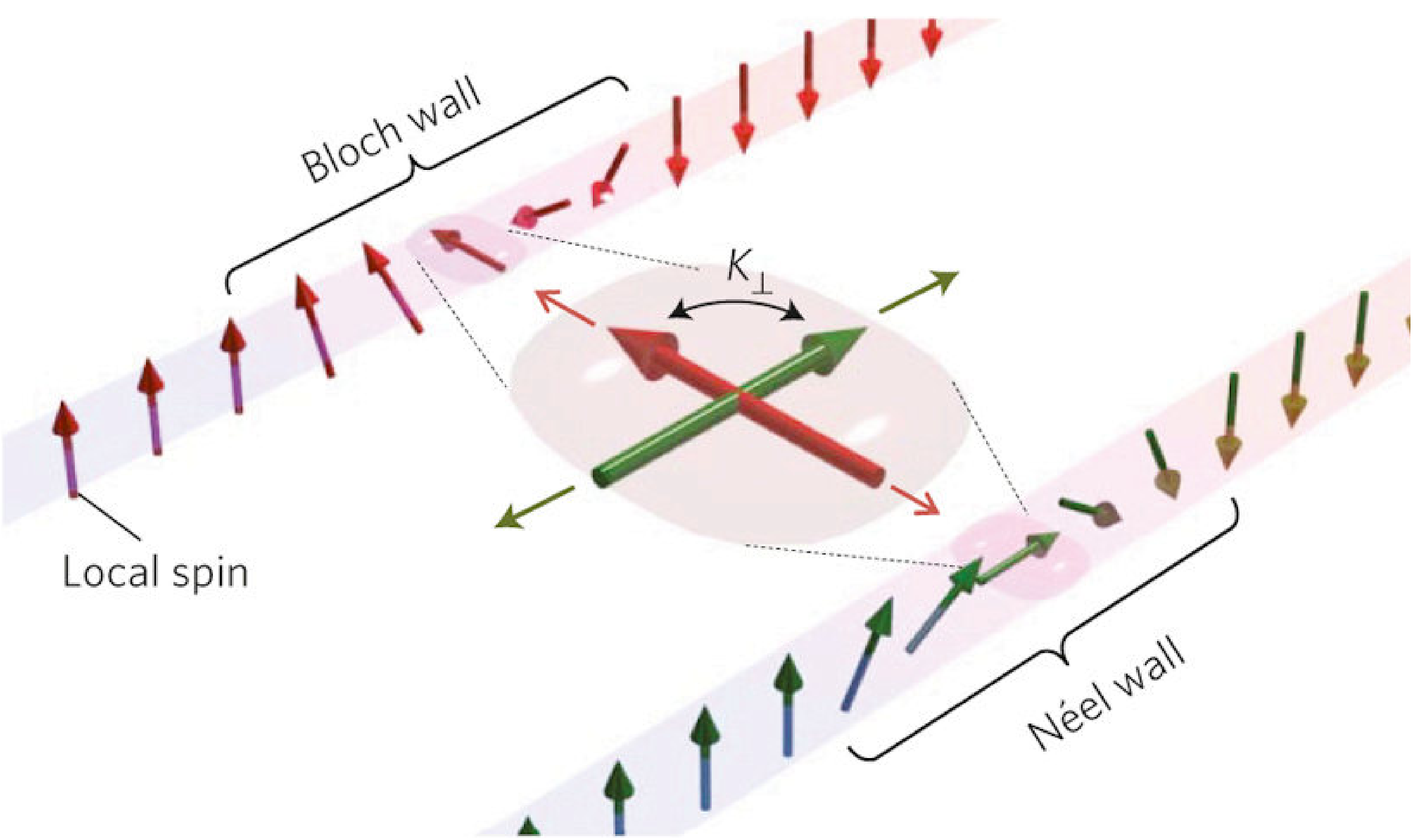
- Compromise between the short-range ferromagnetic exchange interaction and the long-range antiferromagnetic dipolar interaction

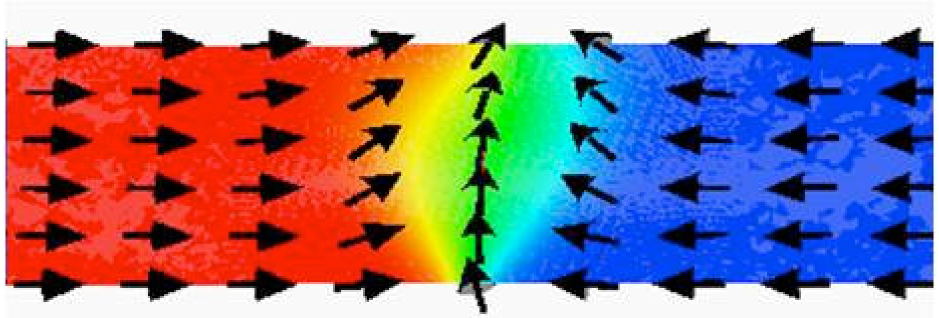


Magnetic states

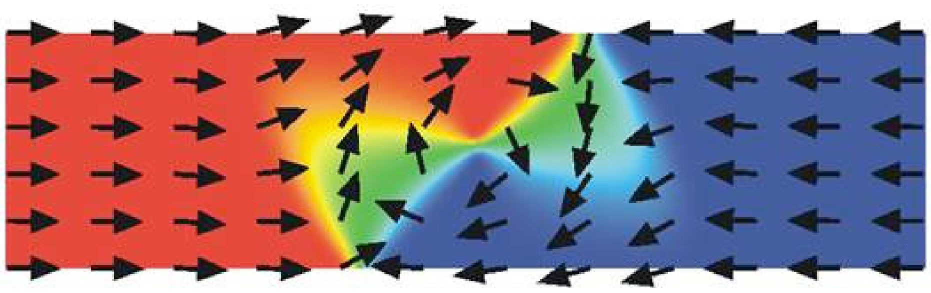
Domain walls

- The boundary between two magnetic domains is called a *domain wall*.
- Wall structure mainly determined by competition between the ferromagnetic exchange interaction (favours parallel alignment with neighbouring spins) and the uniaxial anisotropy (favours alignment along easy axis).
- Different wall types exist: **Bloch, Néel, Vortex, Transverse** ...
  Each minimises part of the dipolar energy





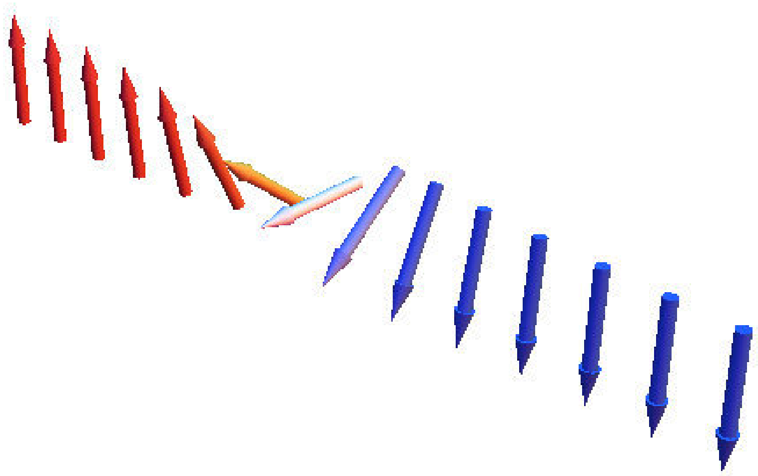
Transverse wall



Vortex wall

Magnetic states

Bloch walls

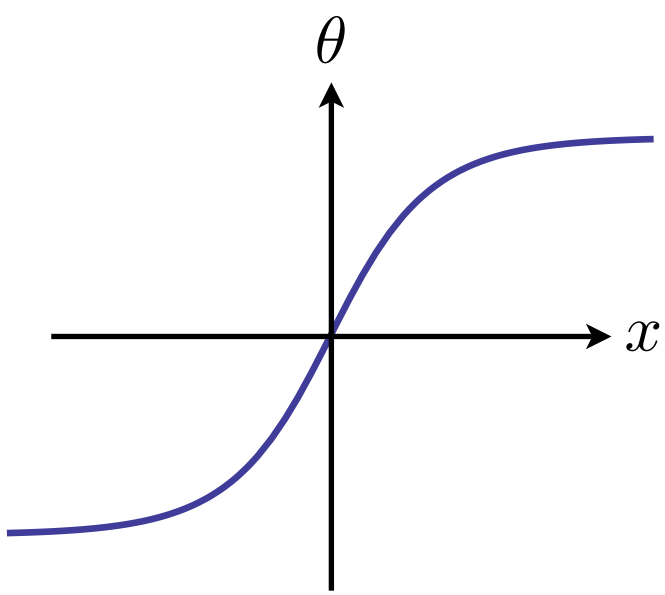


- Profile obtained by minimising the energy functional for the exchange and uniaxial anisotropy energies

  Suppose ***m*** varies along *x* axis, with anisotropy axis along *z*

  We seek to minimise

$$\mathcal{E} = \int dx \left[A \left(\frac{\partial \theta}{\partial x} \right)^2 + K_u \sin^2 \theta \right]$$



- Using variational calculus, obtain Euler-Lagrange equation for function that minimises integral

$$2A \frac{\partial^2 \theta}{\partial x^2} - K_u \sin 2\theta = 0$$

$$\Delta = \sqrt{A/K_u}$$

domain wall width

- Solution is example of a *topological soliton*

$$\theta(x) = 2 \tan^{-1} \left[\exp \left(x/\Delta \right) \right]$$

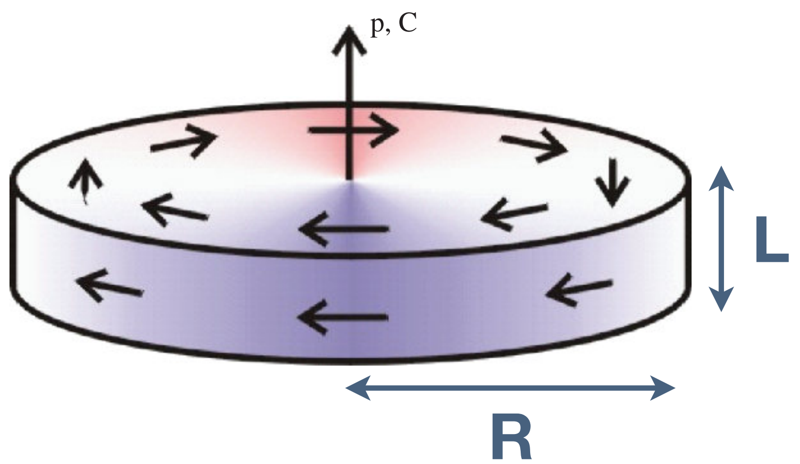
$$\sigma = 4\sqrt{AK_u}$$

domain wall energy density

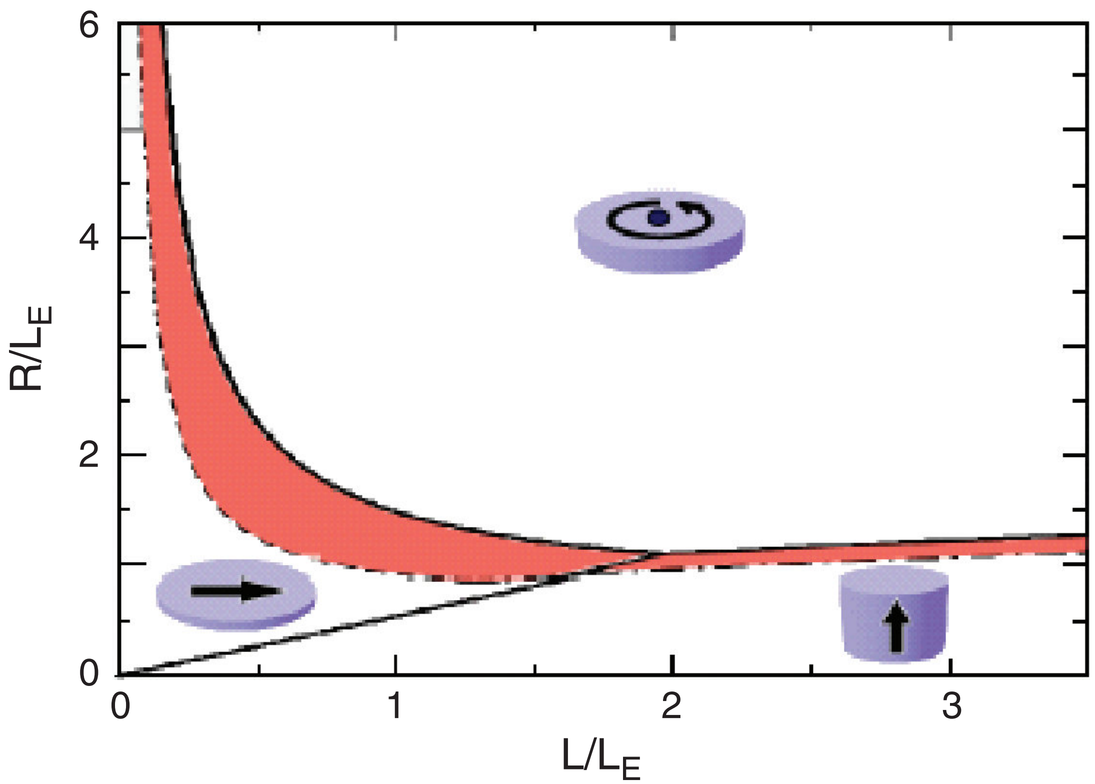
Magnetic states

Vortices

- In thin circular submicron magnetic elements ("*dots*"), dipolar energy can be minimised by forming **vortex states.**
- Magnetisation curls in the film plane and culminates perpendicular to the film plane at the vortex centre. Region with perpendicular component is called the **vortex core.**
- Another example of *topological solitons.*



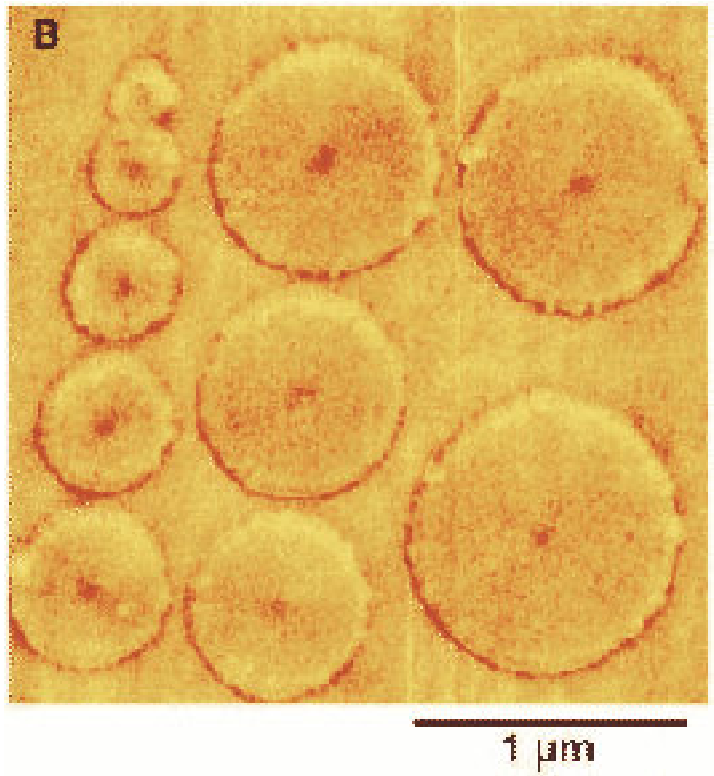
Phase diagram for existence of vortex state



L_E ~ 10-20 nm
(exchange length)

$$L_E = \sqrt{\frac{2A}{\mu_0 M_s^2}}$$

MFM images of vortex cores



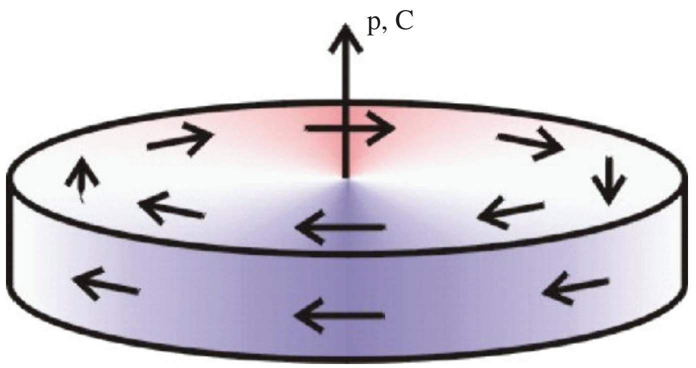
Magnetic states

Vortices

- Suitable *ansatz* for vortex profile:

$$\theta = \theta(\mathbf{r})$$
$$\phi(\mathbf{r}) = \varphi \pm \frac{\pi}{2}$$

sign determines chirality



$$\mathbf{m} = (\cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta)$$
$$\mathbf{r} = (r, \varphi)$$

- Profile minimises volume charges and surface charges at edges

$$-\nabla\cdot\mathbf{m} = 0$$

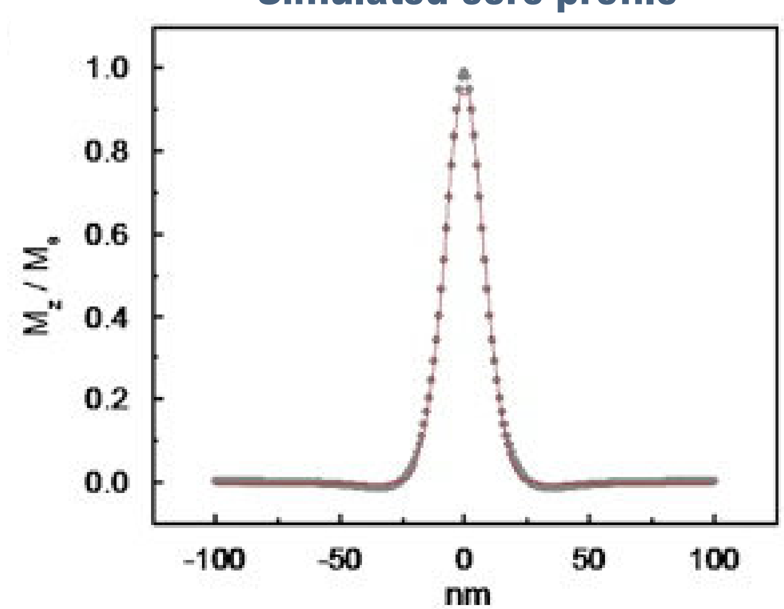
Volume charges vanish

$$\mathbf{m}\cdot\hat{\mathbf{r}} = 0$$

Edge surface charges vanish

- Energy costs: Vortex core leads to surface magnetic charges at the top and bottom surfaces, curling configuration costs exchange energy.
- The core profile results from a minimisation of these two energies.

Simulated core profile

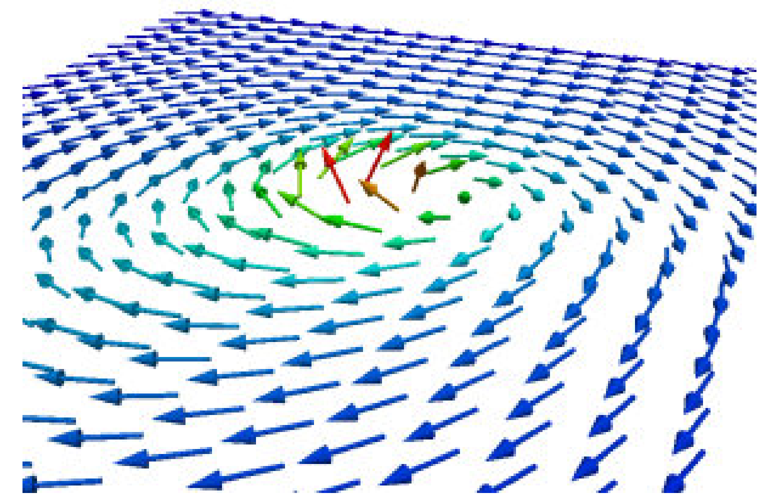


Magnetic states

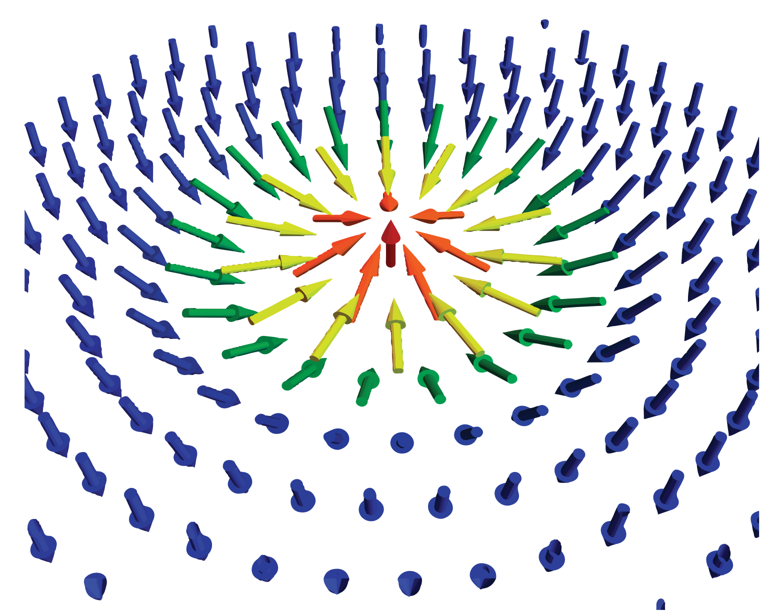
Skyrmions

- Skyrmions are like vortices but with m_z varying from +1 to -1
- Result from competition between exchange, anisotropy, and the chiral Dzyaloshinskii-Moriya interaction
- Another example of topological solitons

Vortex

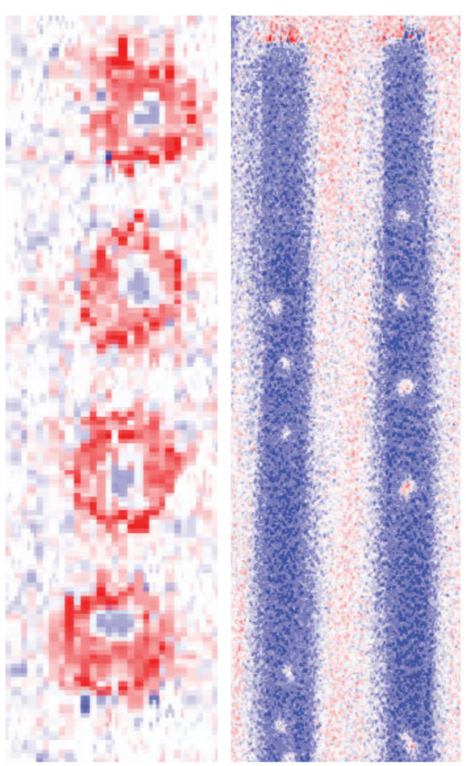


Skyrmion



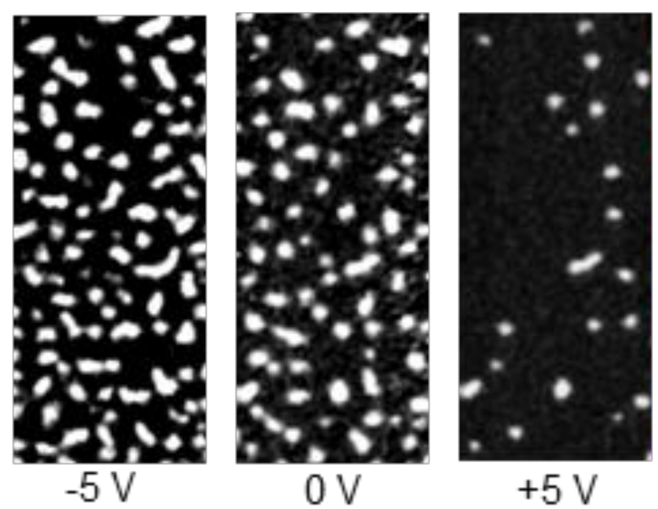
[Ir/Co (0.6 nm)/Pt]$_n$

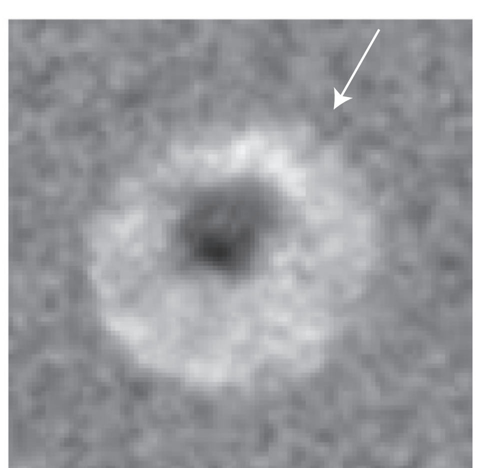
C Moreau-Luchaire et al, *Nat Nanotechnol* (2016)



Pt/Co/Ox

M Schott et al, *Nano Lett* (2017)





Pt/Co (1 nm)/MgO

O Boulle et al, *Nat Mater* (2016)

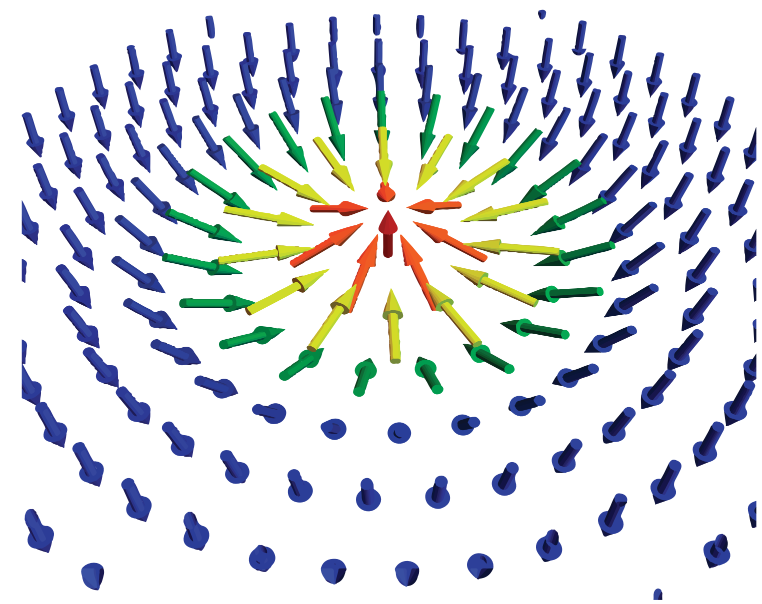
Magnetic states

Skyrmions

- Inexact but useful *ansatz* for skyrmion profile:

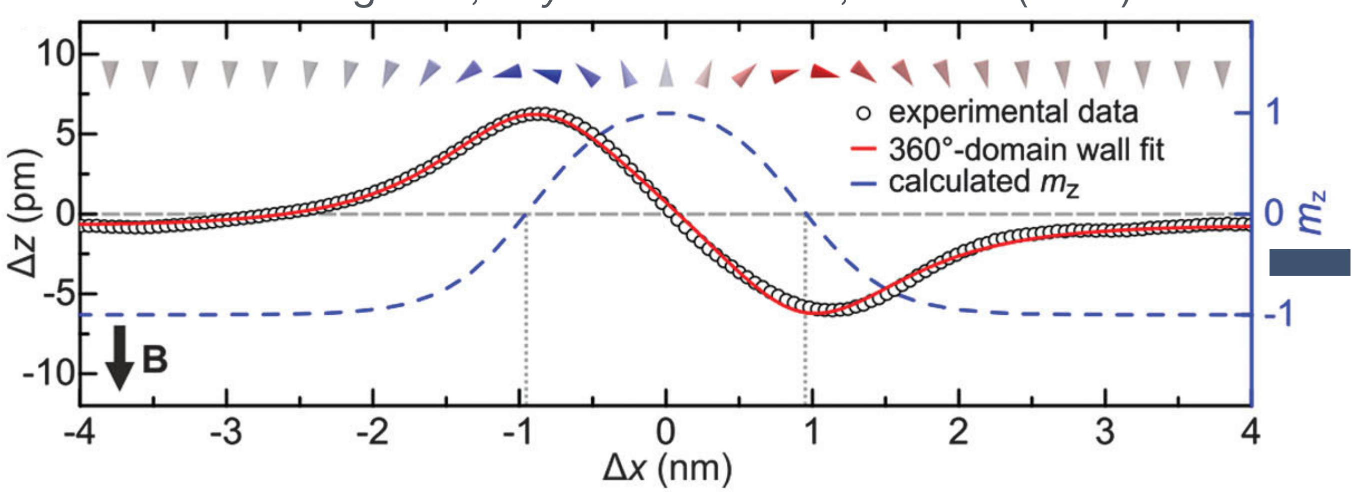
$$\cos\theta(r) = \frac{4\cosh^2 c}{\cosh 2c + \cosh(2r/\Delta)} - 1$$

Double wall



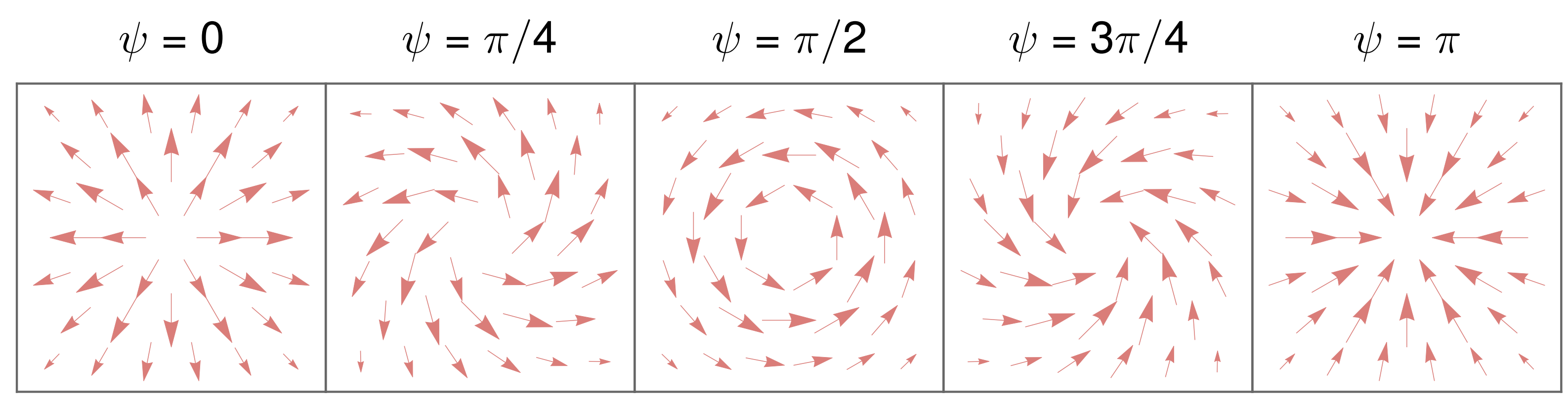
$$\mathbf{m} = (\cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta)$$
$$\mathbf{r} = (r, \varphi)$$

N Romming et al, *Phys Rev Lett* **117**, 177203 (2015)



$$\phi(\mathbf{r}) = \varphi + \psi$$

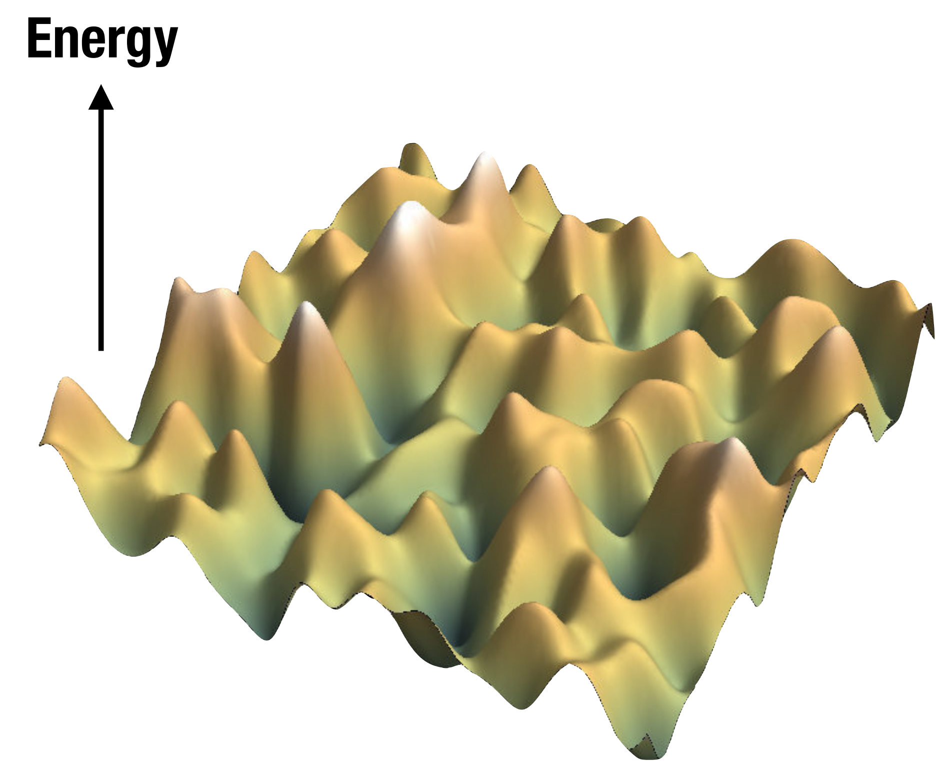
Helicity



Néel **Bloch** **Néel**

Reversal mechanisms

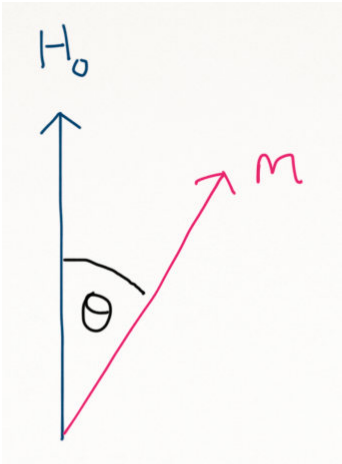
- Magnetization reversal involves navigating through an energy landscape
- May involve intermediate states with nontrivial magnetization configurations
- Intermediate states are metastable energy states
- Minimizing energies allow us to guess/predict/describe intermediate states

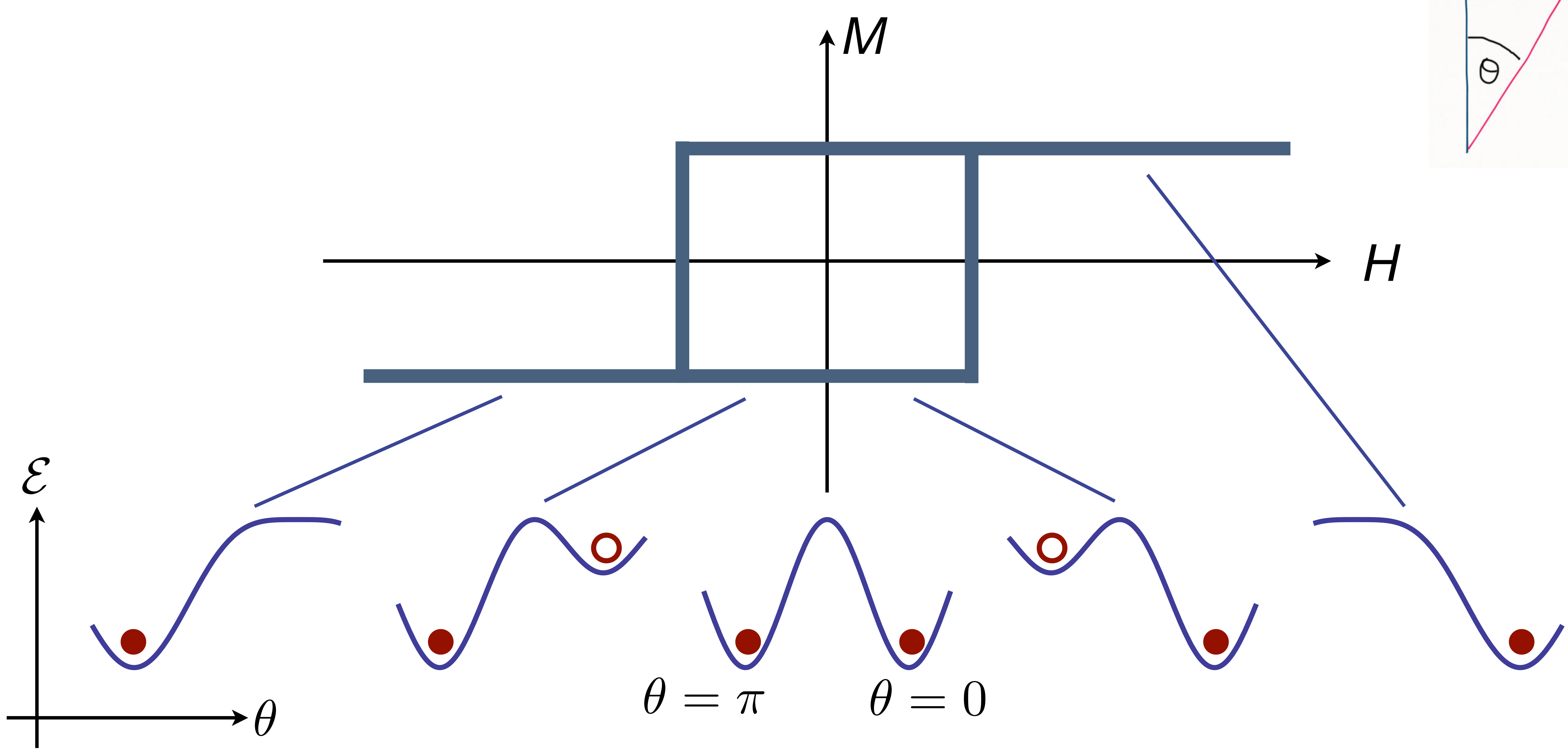


Coherent reversal

- The magnetic configuration at a given applied field represents the local energy minimum under that applied field.
- Simplest example that contains essential physics: magnetic nanoparticle with uniaxial anisotropy

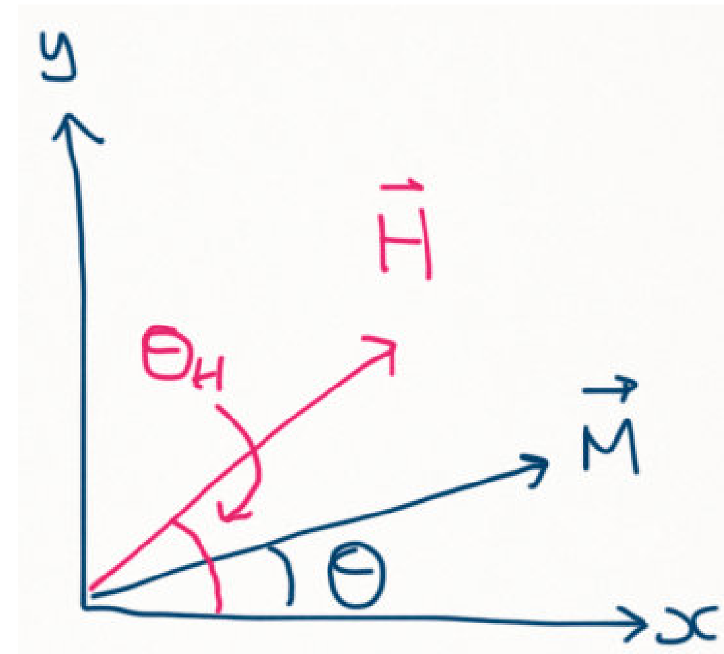
$$E = -\mu_0 H M_s \cos\theta - K_u \cos^2\theta$$





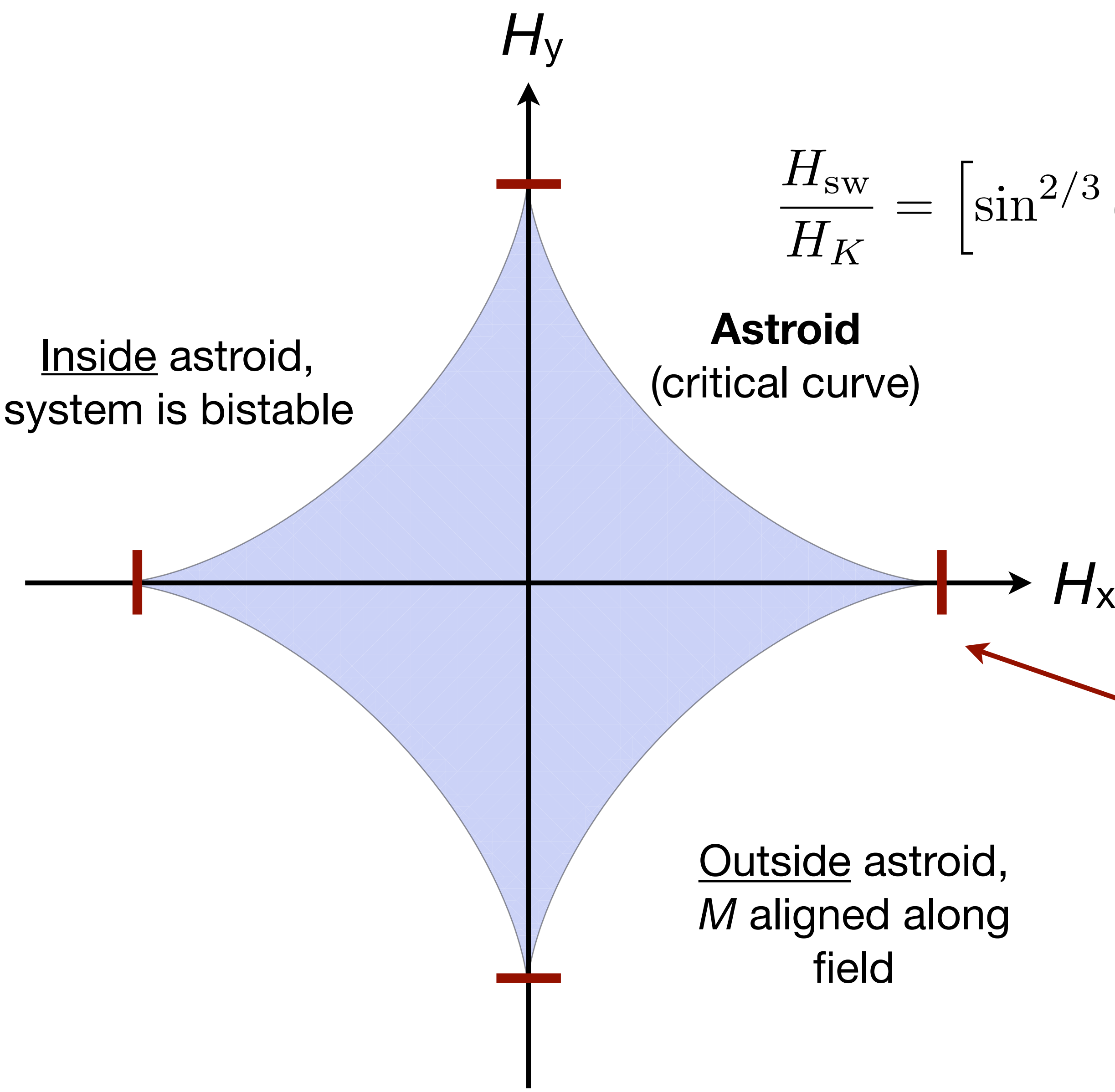
Coherent reversal: Stoner-Wohlfarth astroid

- Metastable states: Minimize Zeeman and anisotropy energy (in macrospin approximation) for arbitrary field angles



$$E = -\mu_0 H M_s \cos\left(\theta - \theta_H\right) - K_u \cos^2\theta$$

$$\frac{H_{\mathrm{sw}}}{H_K} = \left[\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right]^{-3/2}$$



Inside astroid, system is bistable

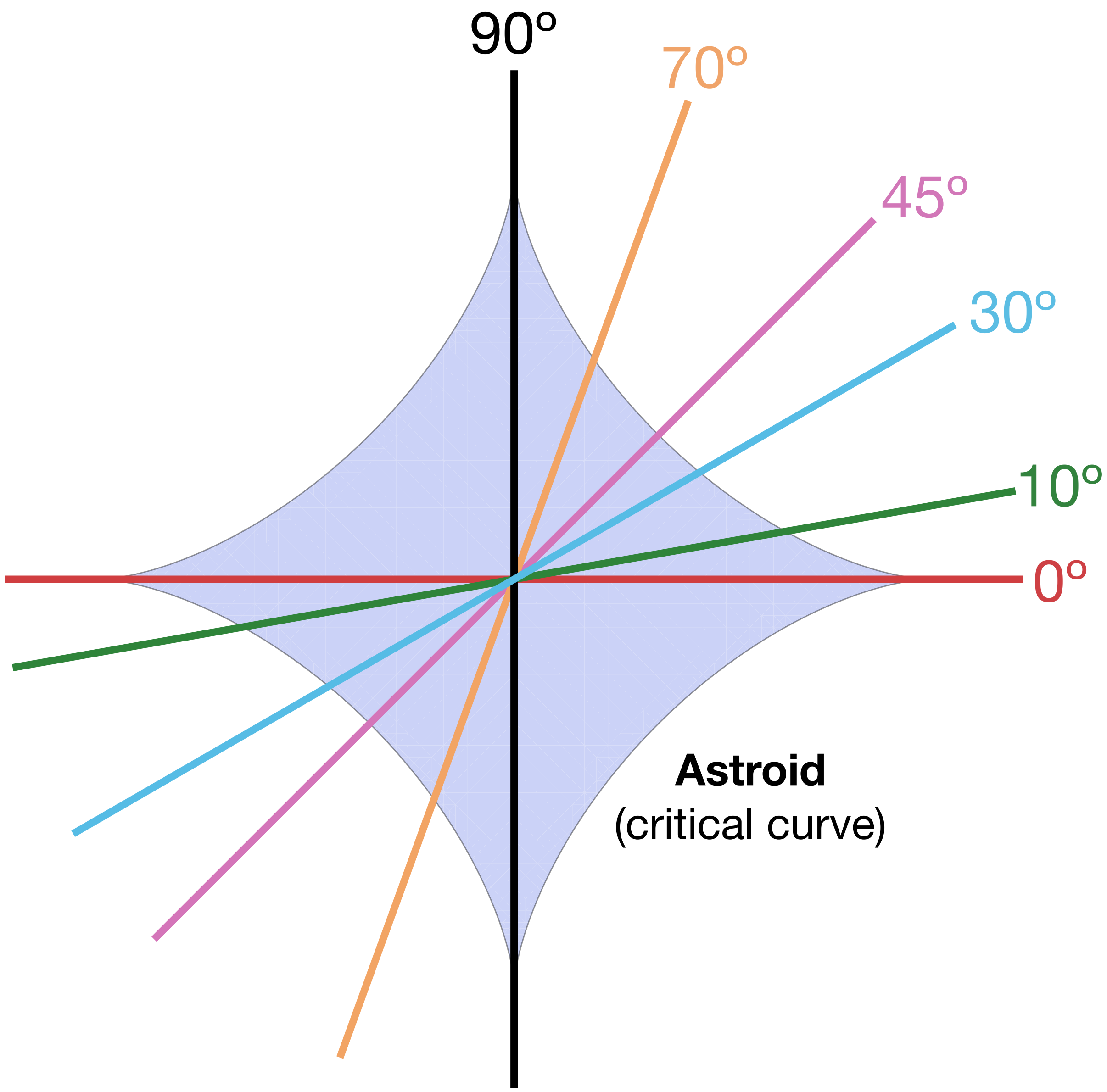
Astroid (critical curve)

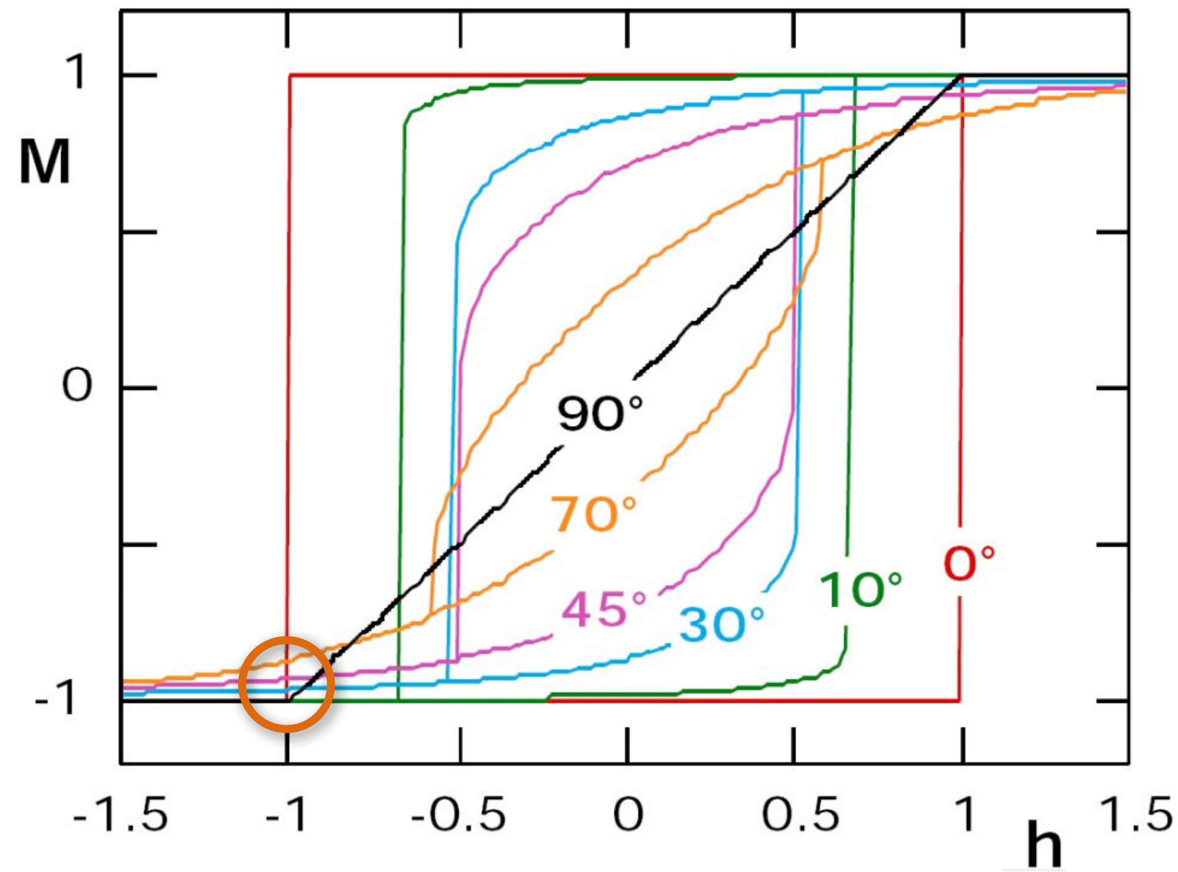
Outside astroid, *M* aligned along field

$$H_K = \frac{2K_u}{\mu_0 M_s}$$

Critical field

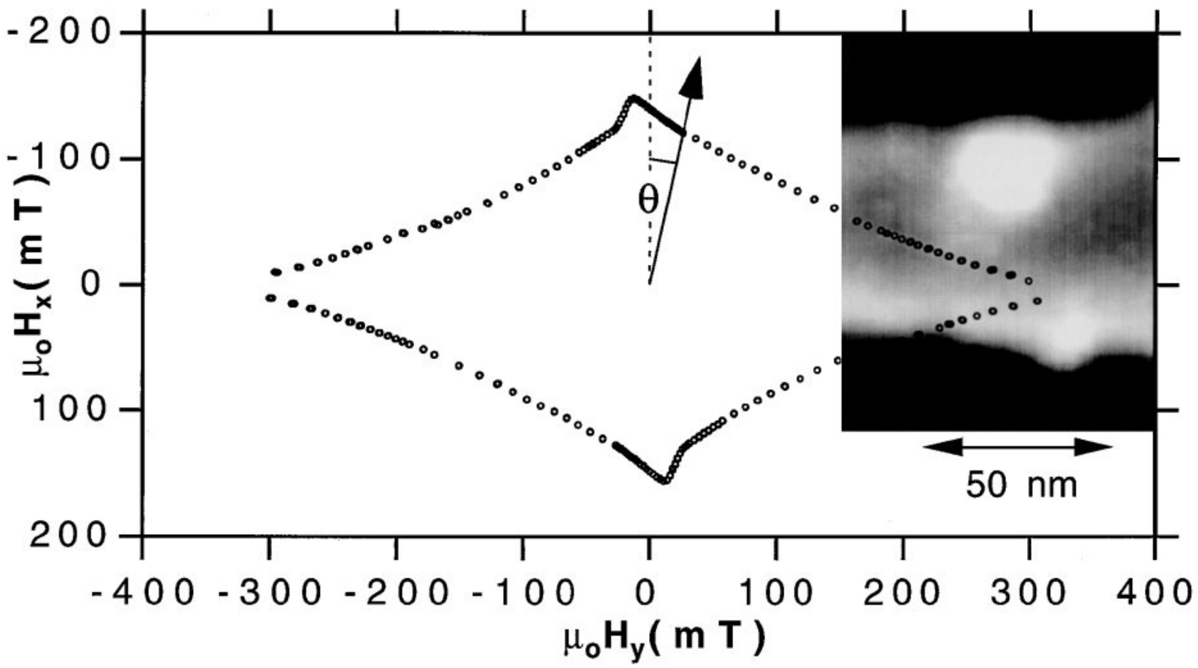
Stoner-Wohlfarth: Hysteresis loops





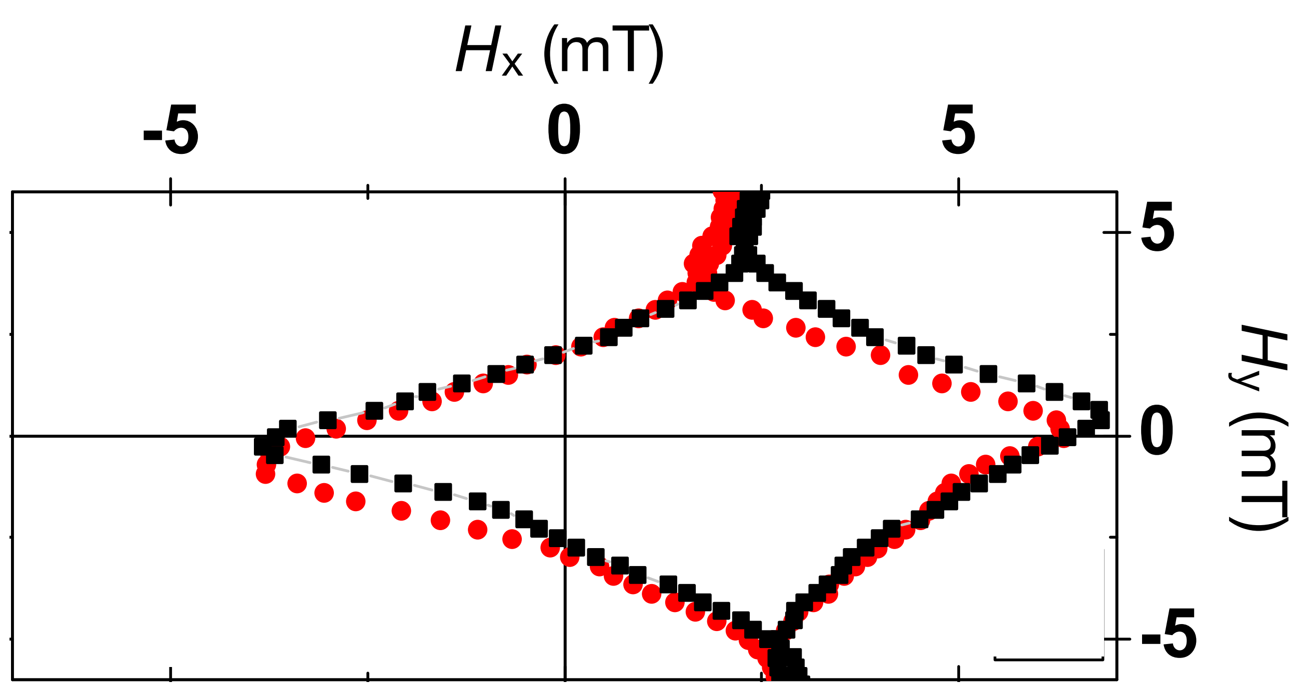
$$\frac{H_{\rm sw}}{H_K} = \left[\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right]^{-3/2}$$

Examples of astroids



- First experimental observation (2D system)
- 25 nm Co cluster

W Wernsdorfer et al, *Phys Rev Lett* **78**, 1791 (1997)

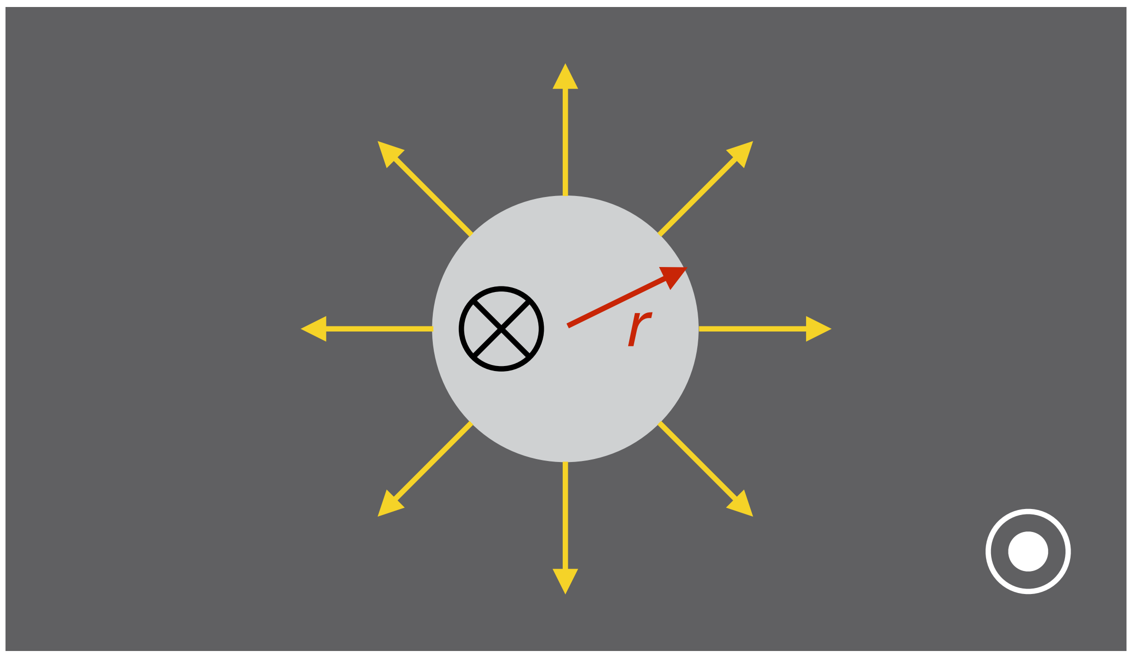


- Experimental astroid for magnetic nanopillar (200 x 100 x 2 nm)
- Magnetic tunnel junction, typical MRAM device

T Devolder et al, *Appl Phys Lett* **98**, 162502 (2011)

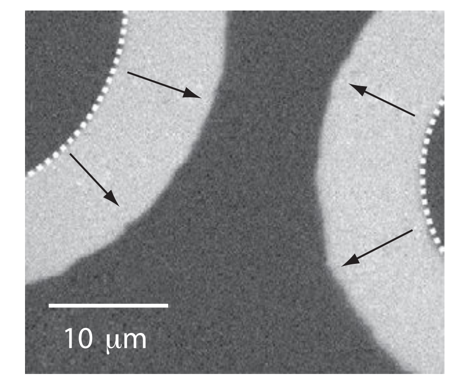
Domain wall nucleation and propagation

- In some circumstances it is more favourable to nucleate a domain wall, rather than rotate all moments coherently across sample



$\otimes H_0$

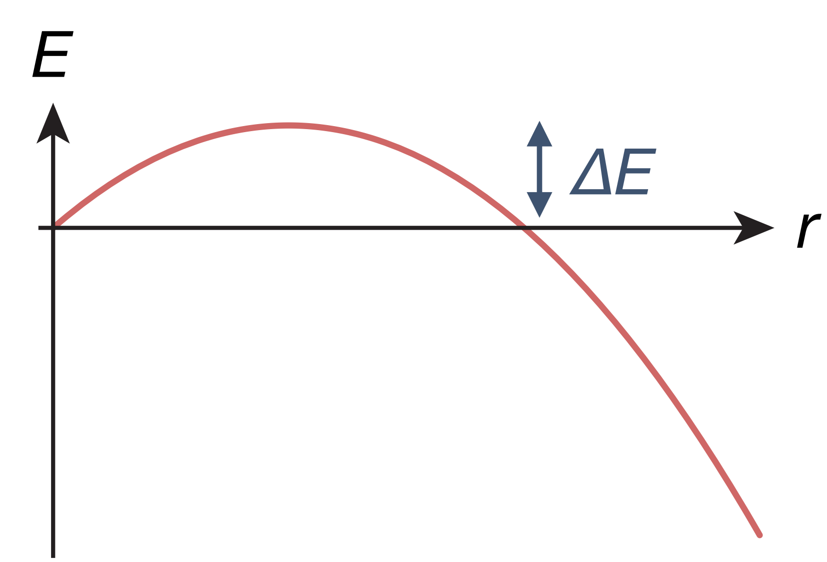
Kerr microscopy image of domain growth



- Need to balance energy cost in creating a domain wall with energy gain from Zeeman interaction

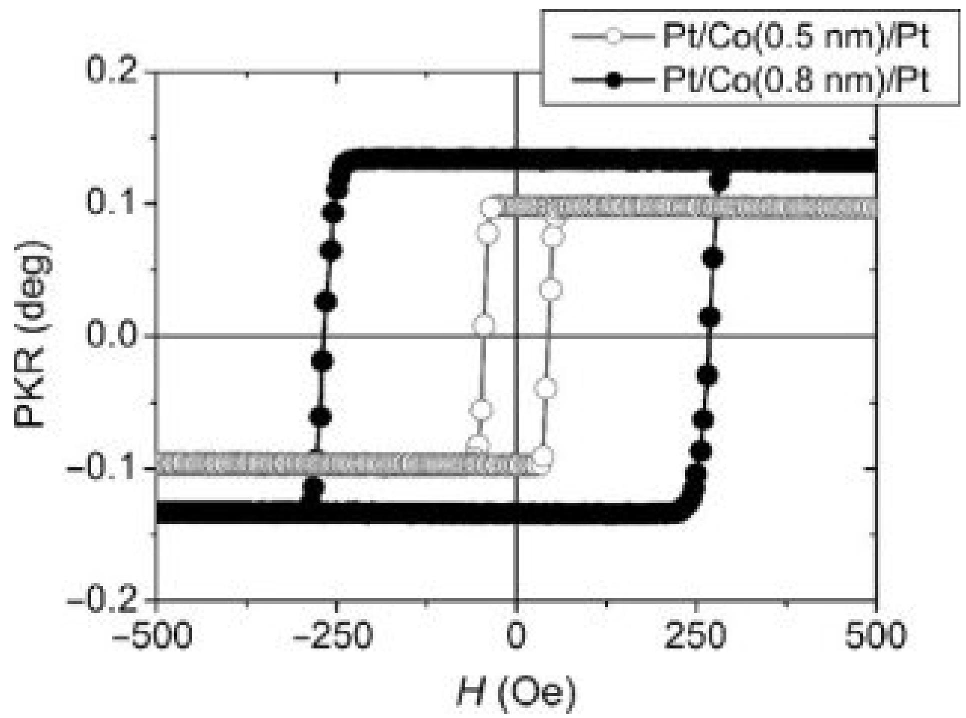
$$E(r) = \underbrace{(2\pi r d)\sigma}_{\text{Wall energy}} - \underbrace{(\pi r^2 d)(2\mu_0 M_s H_0)}_{\text{Zeeman energy}}$$

$$\sigma = 4\sqrt{AK_u}$$

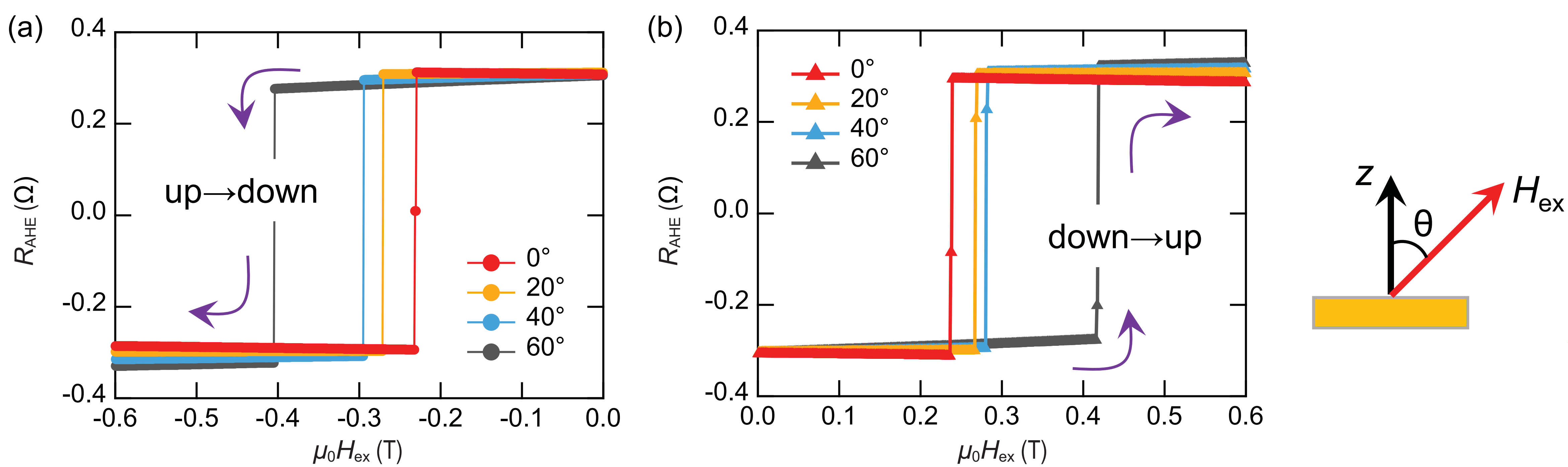


Domain wall nucleation and propagation

- Reversal through domain walls generally leads to lower coercivities than coherent reversal



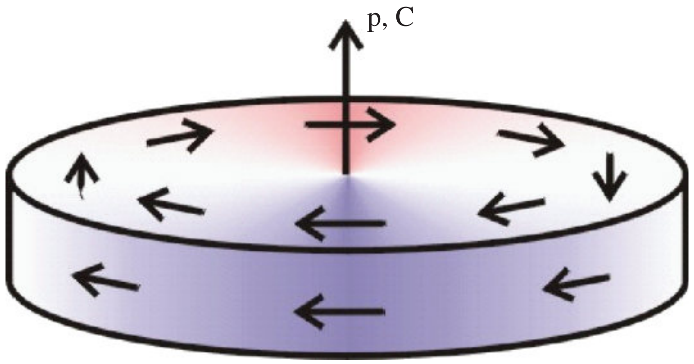
Courtesy of J Ferré, *Laboratoire de Physique des Solides*, Orsay

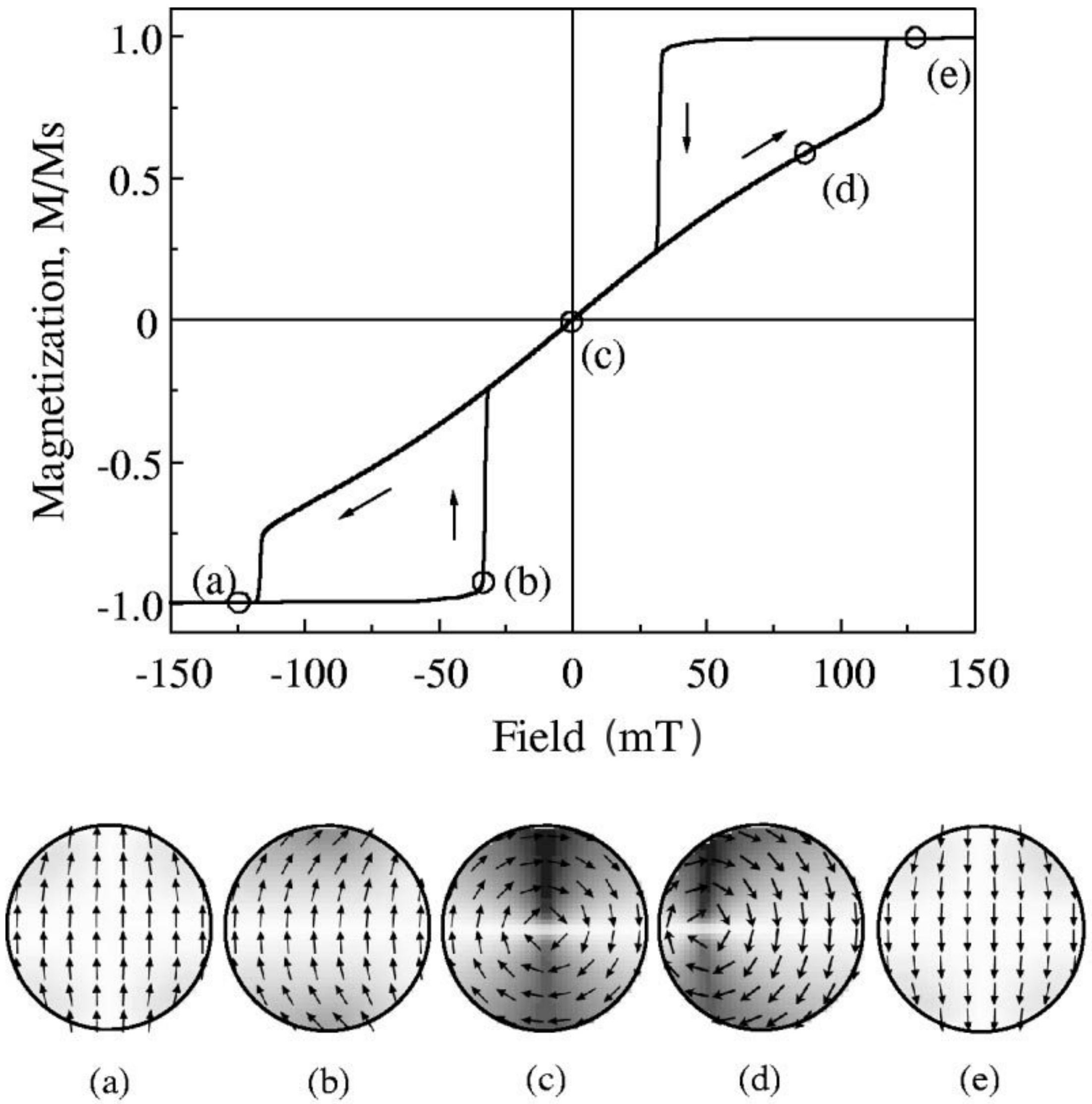


S Kim et al, *Phys Rev B* **95**, 220402 (2017)

Reversal in dots

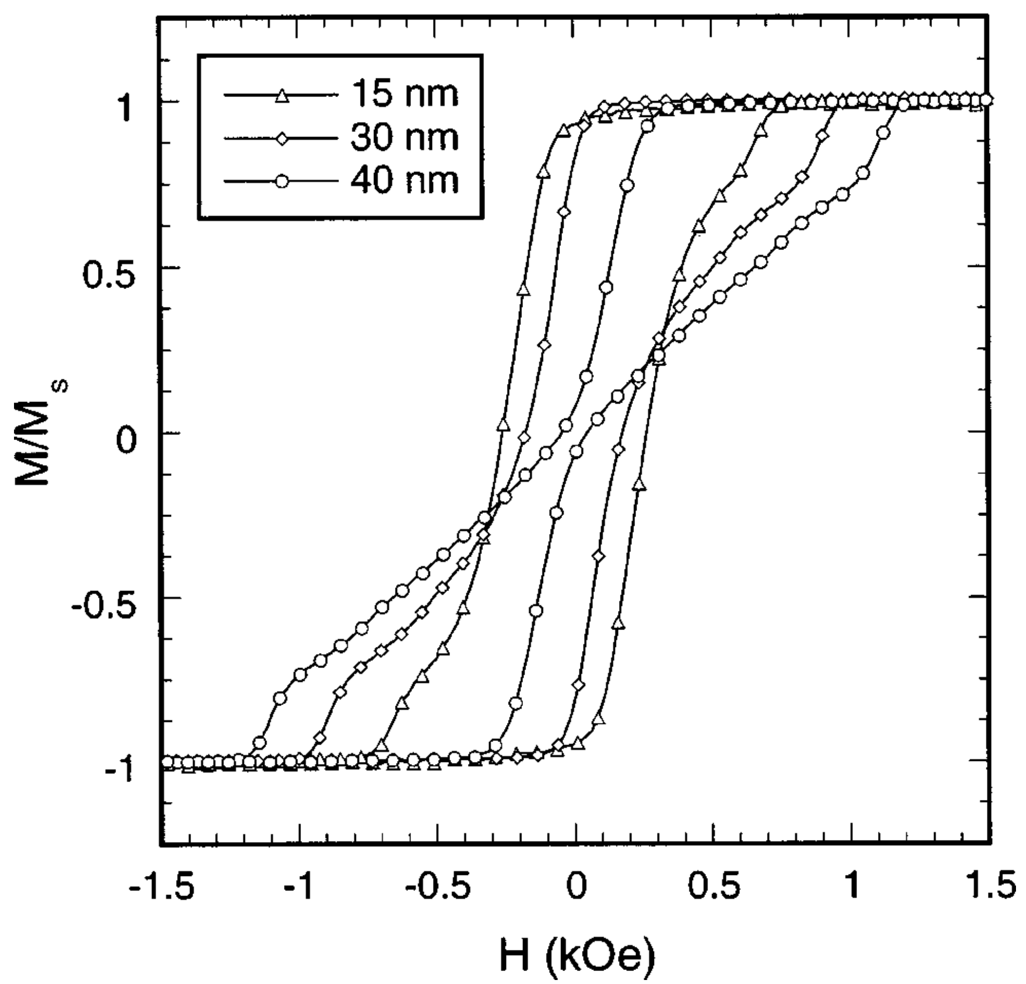
- In circular dots where vortices are metastable states, magnetisation reversal occurs through the nucleation and annihilation of vortices





K Guslienko et al, *Phys Rev B* **65**, 024414 (2001)

Reversal in Co dots

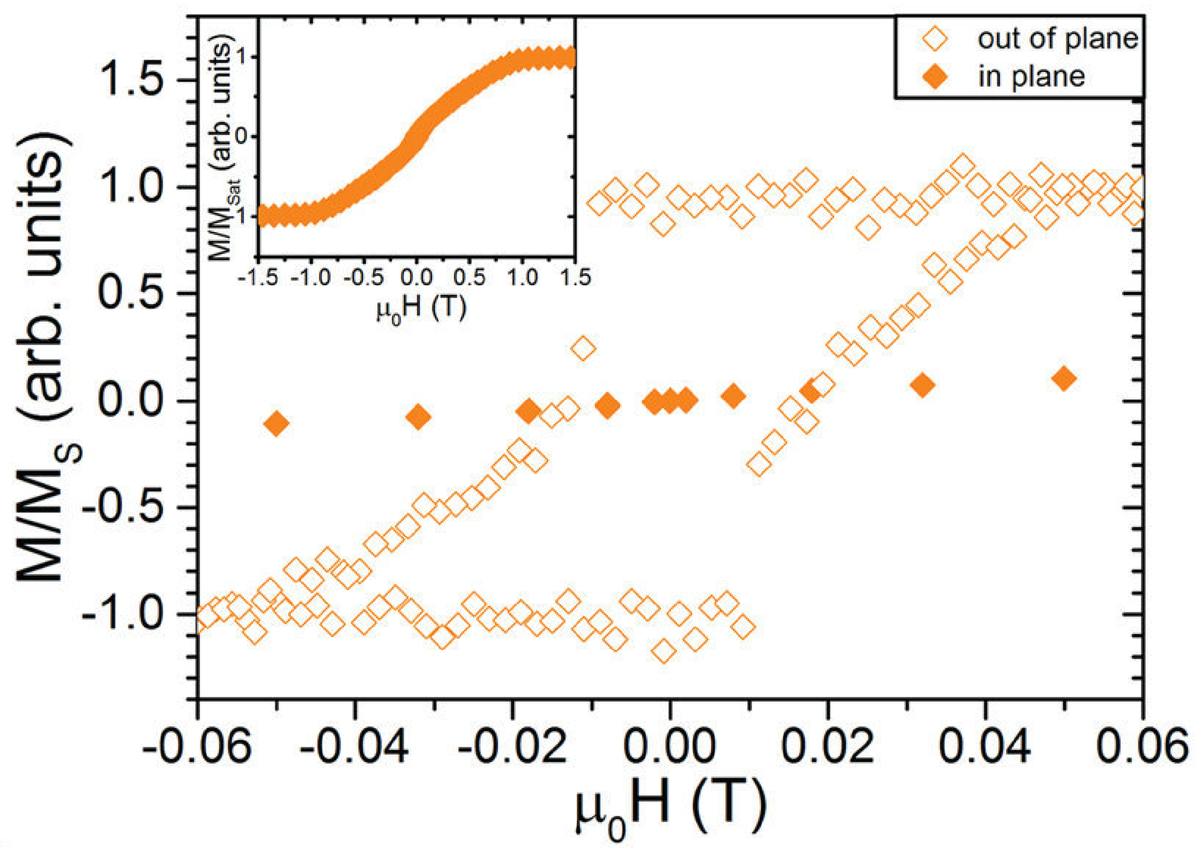


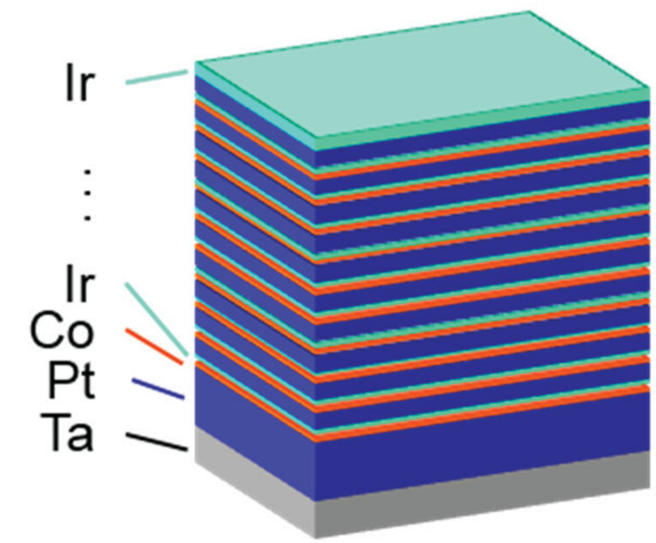
A Fernández & C Cerjan,
J Appl Phys **87**, 1395 (2000)

Reversal in dots

K Zeissler et al, *Sci Rep* **7**, 15125 (2017)

- In perpendicularly-magnetised dots with DMI, reversal can take place through skrymion nucleation and annihilation

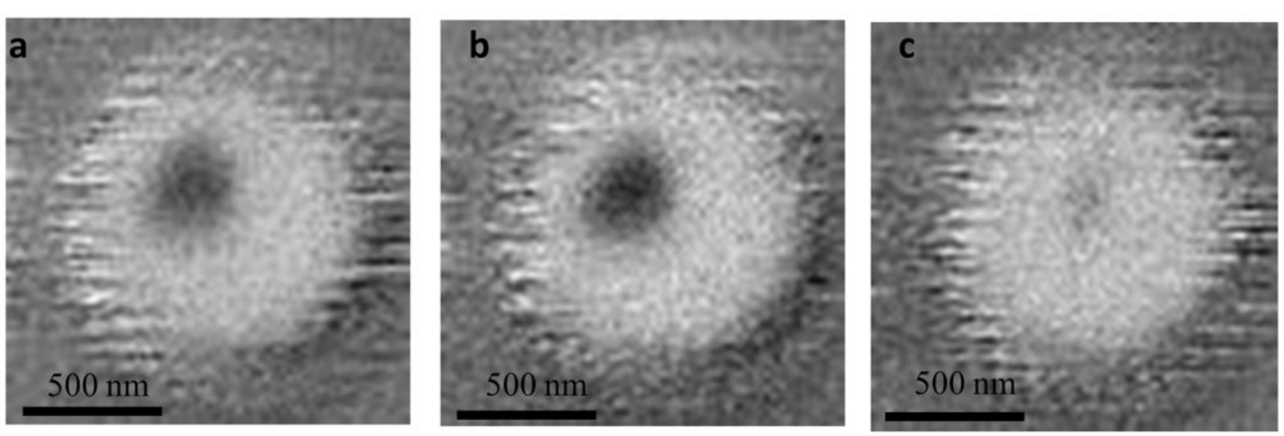




- 10 mT

- 20 mT

- 52 mT

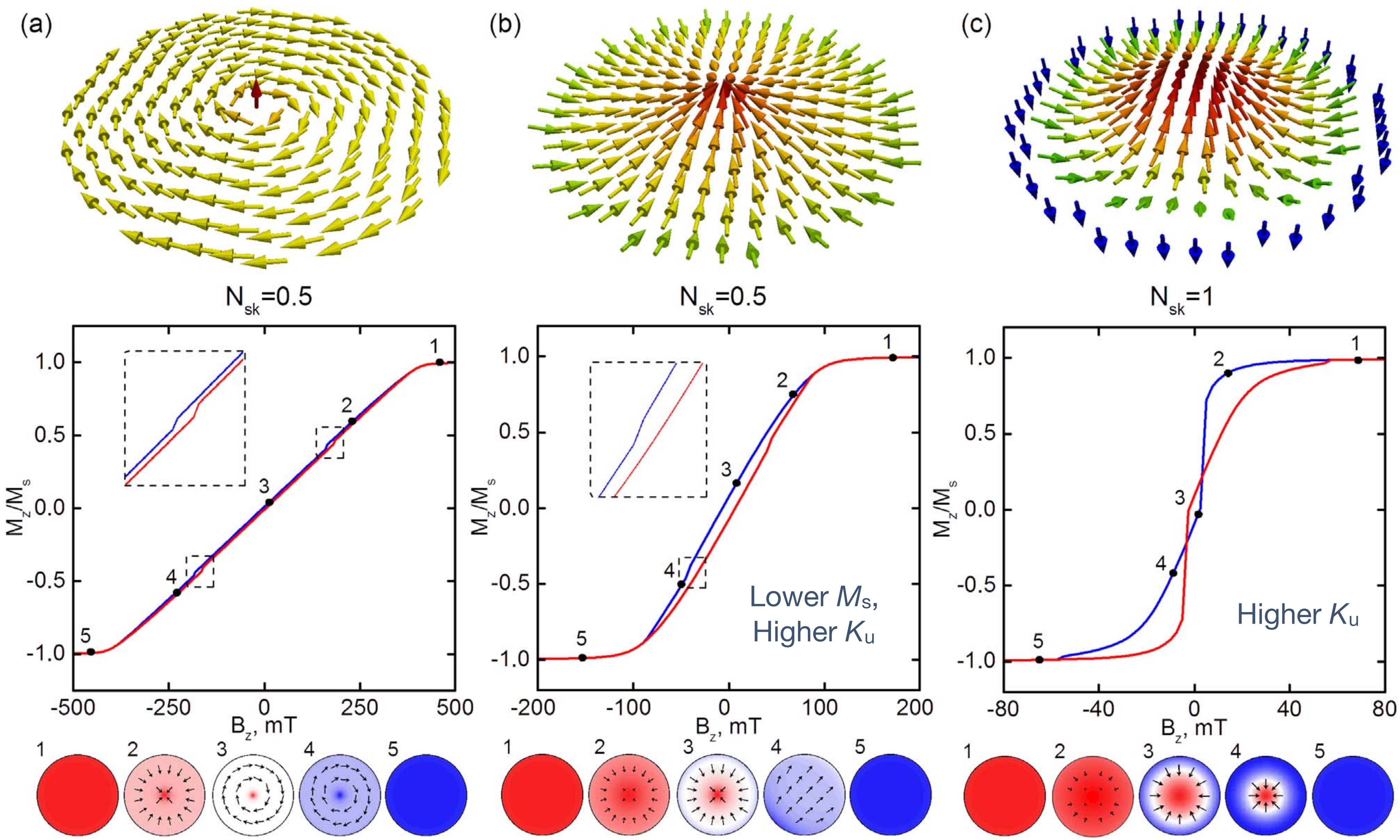


1 µm diameter dots

Reversal in dots

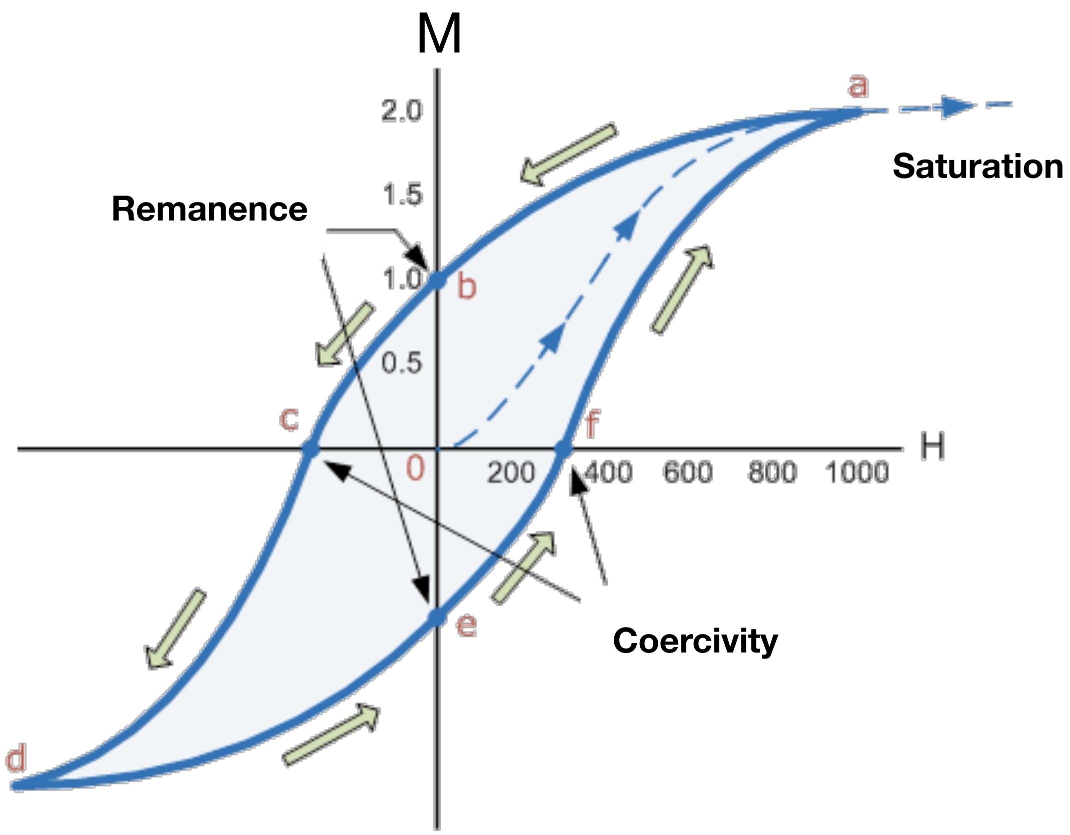
A G Kolesnikov, *J Magn Magn Mater* **429**, 221 (2017)

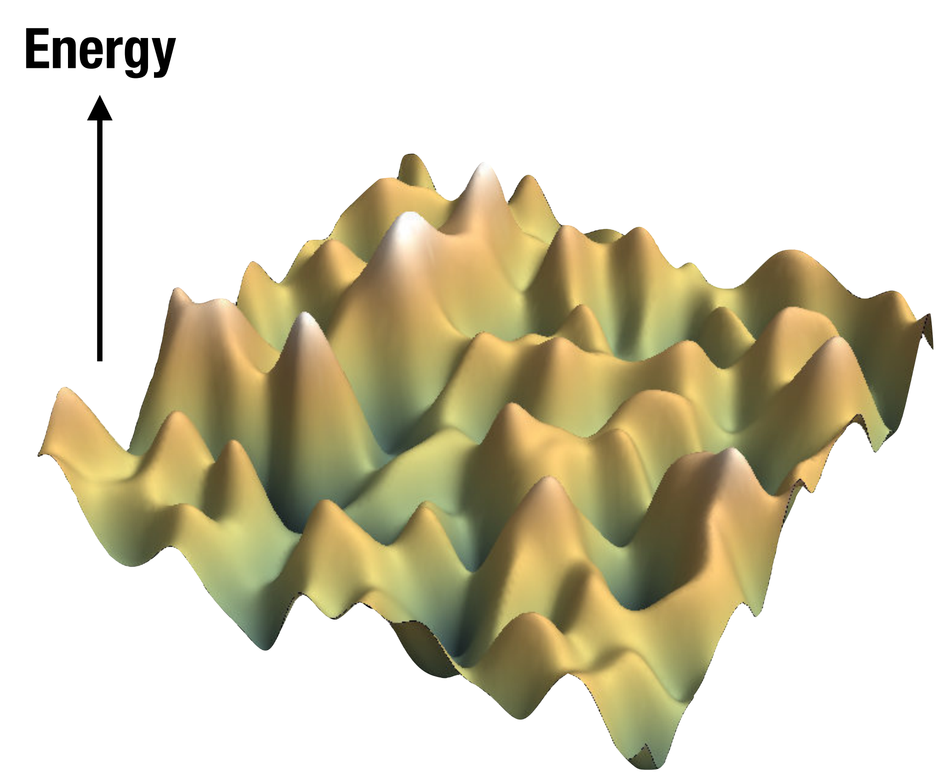
- Simulations show that intermediate states can depend strongly on magnetic parameters



Hysteresis: sweep rate

- Does it matter how *fast* we sweep the field?
- What does "quasi-statics" mean in this context?
- Slow dynamics … but slow compared to what?
- Fluctuations and energy barriers are the key

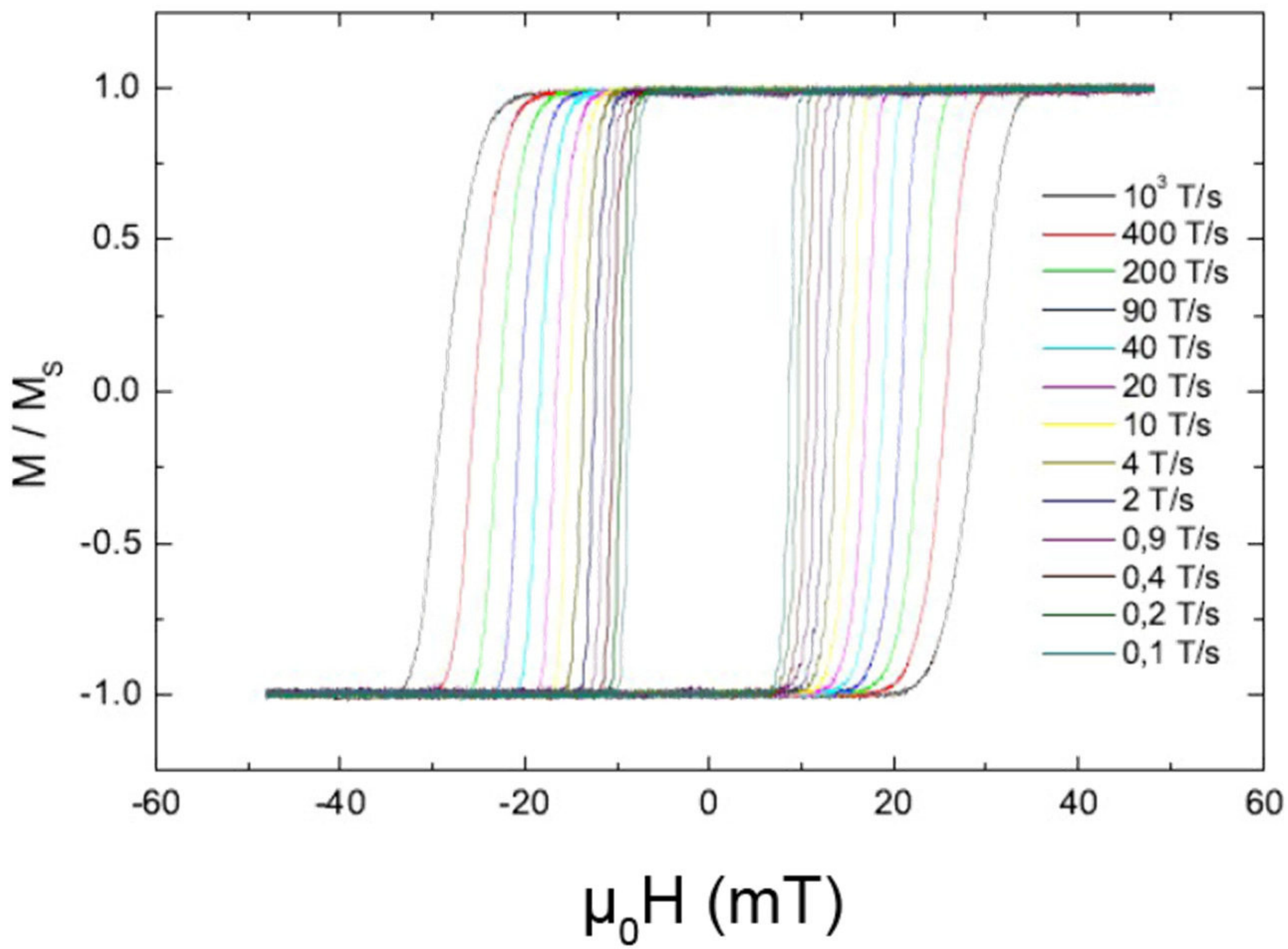




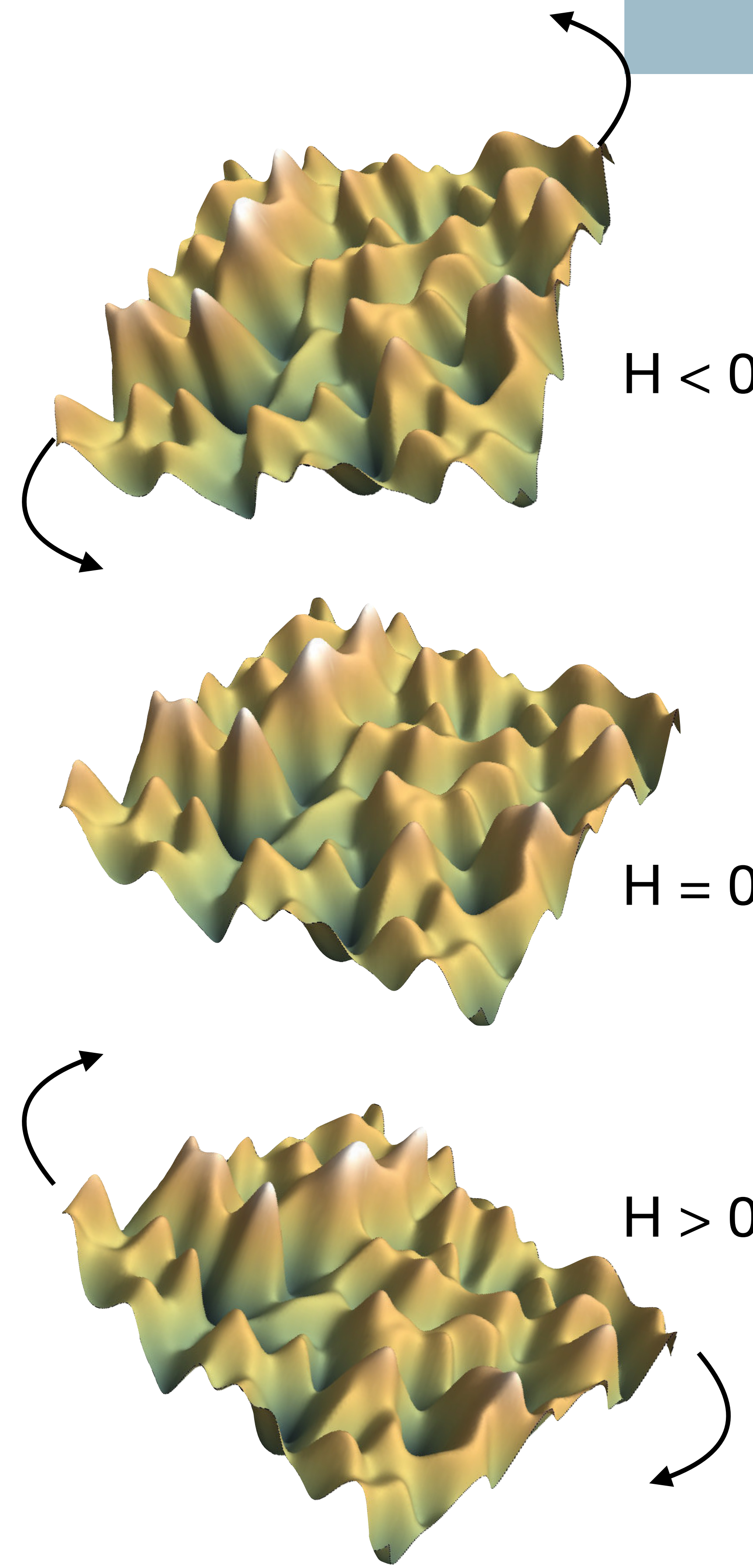
Sweep rates matter

- How fast you navigate the energy landscape matters

Hysteresis loop for a Pt/Co/Pt thin film



Courtesy of J Vogel, *Institut Néel*, Grenoble

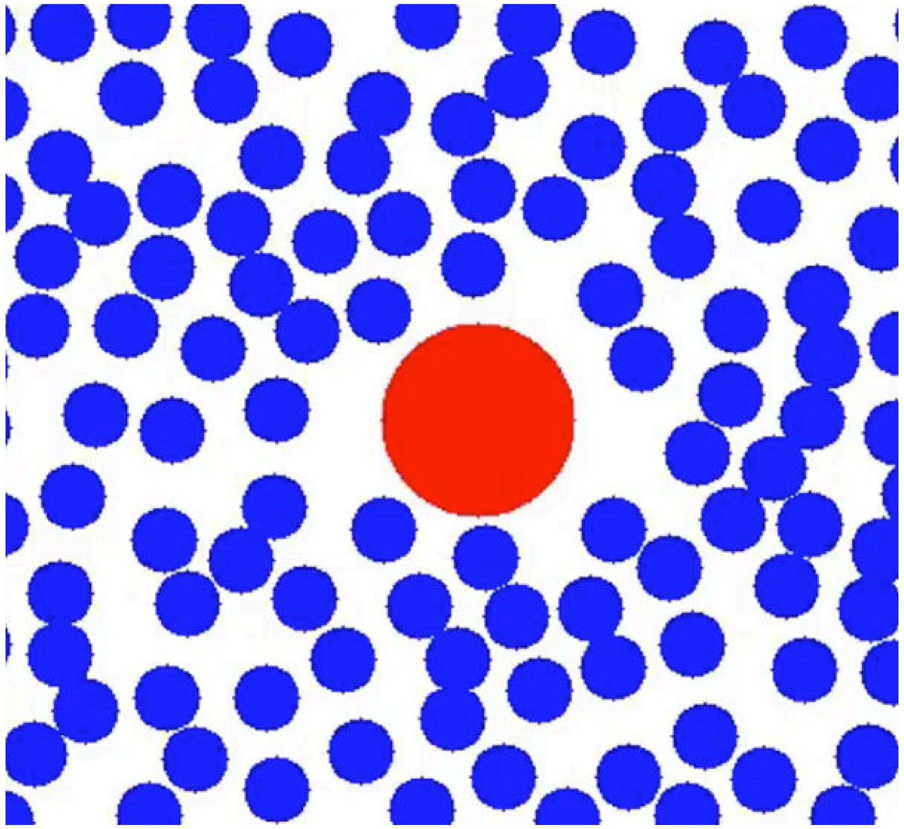


Thermal fluctuations

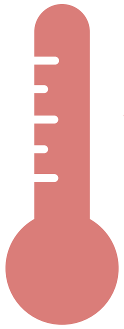
Brownian motion

R Brown, *Phil Mag* **4**, 161 (1828)

(Animation)



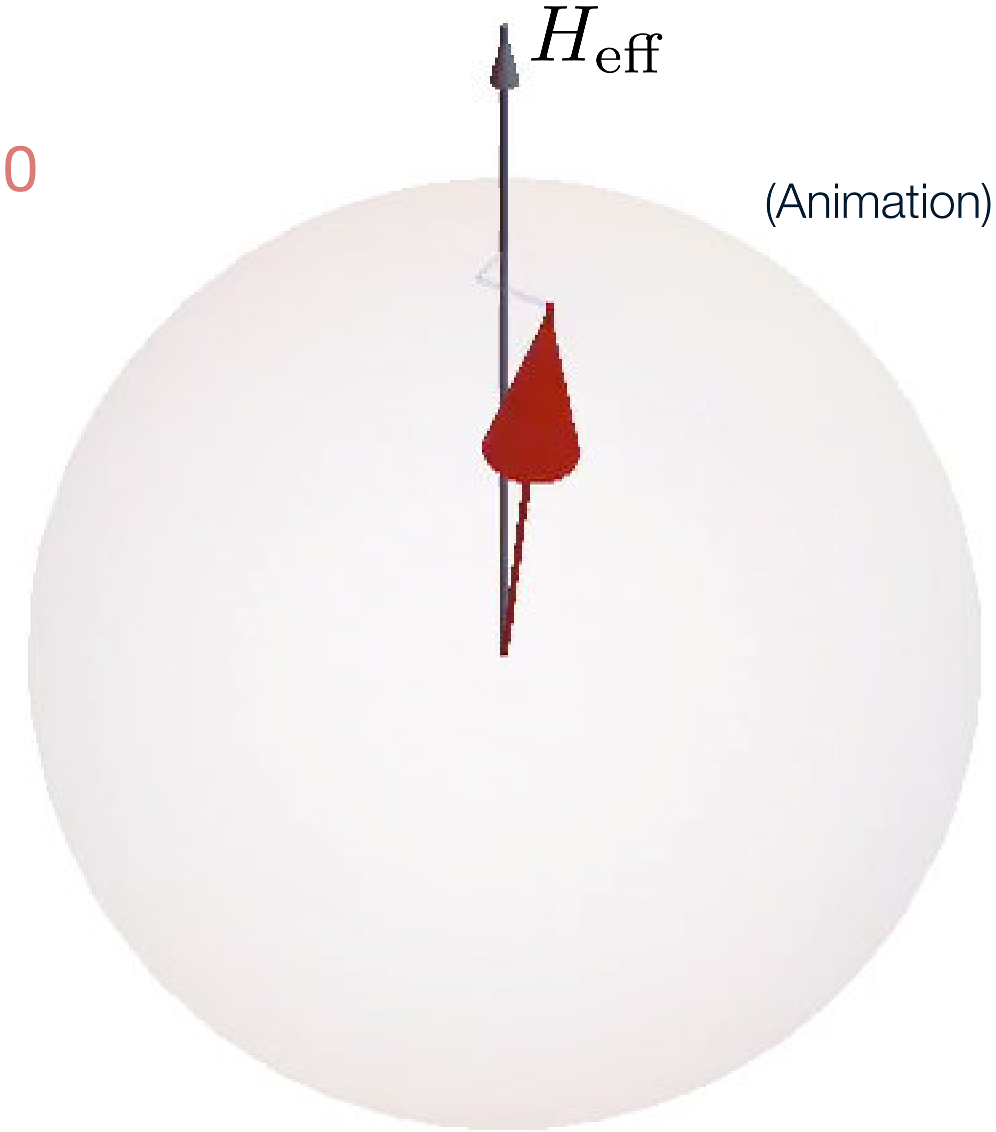
Particle (red) experiences random collisions (forces) due to thermal environment (blue)



Magnetisation precession

W F Brown, *Phys Rev* **130**, 1677 (1963)

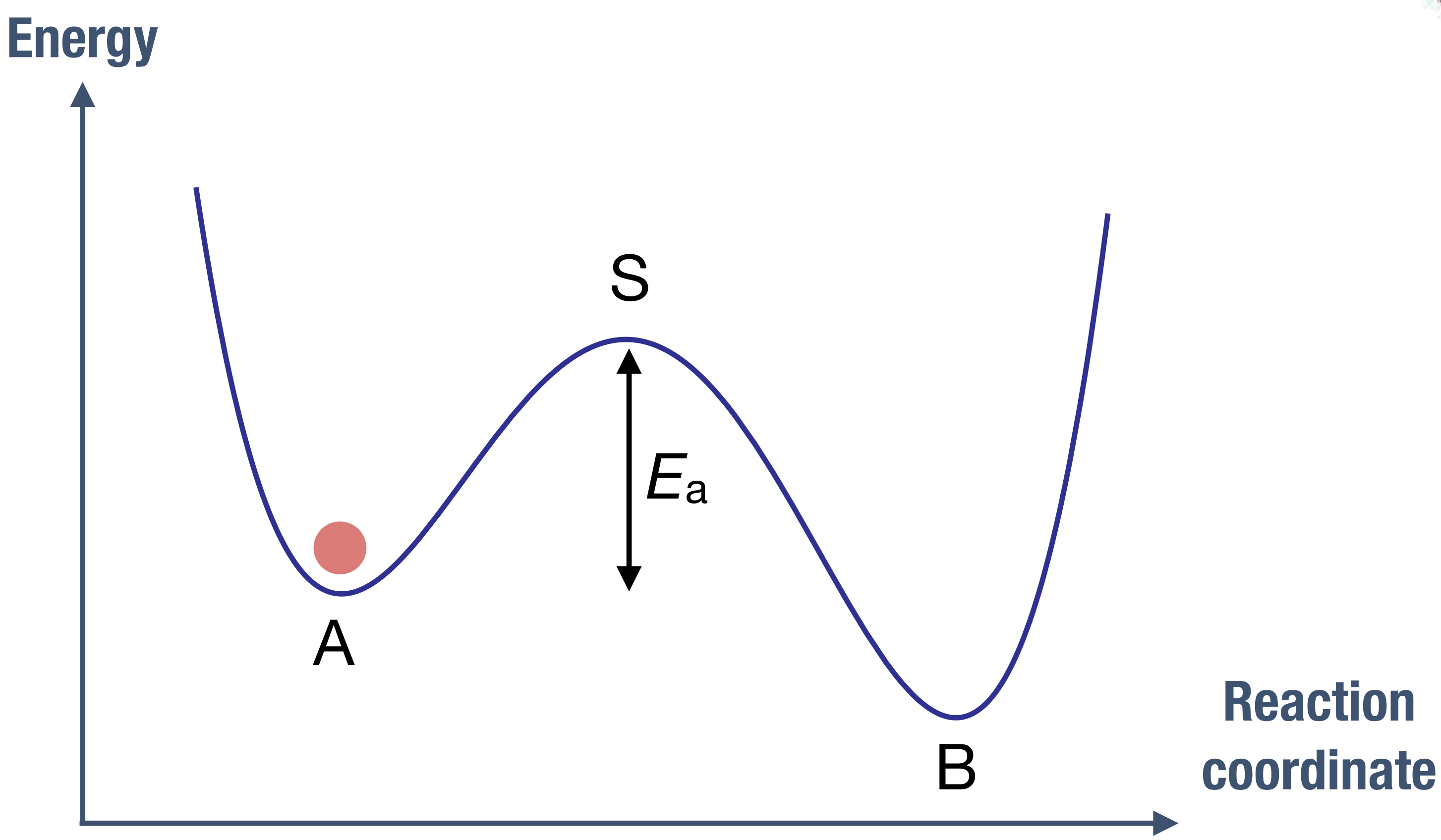
(Animation)

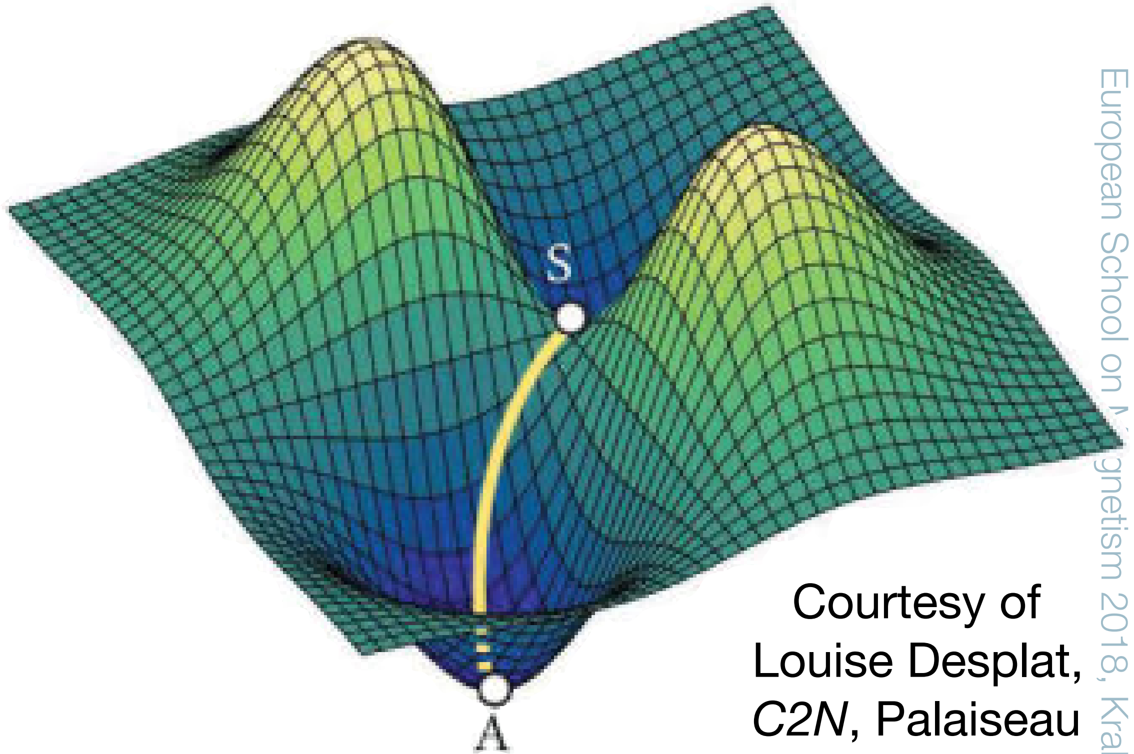


Precessing magnetic moment experiences random fields due to thermal environment

Thermal activation

- Thermal fluctuations give you a finite probability of escaping a metastable state. *How patient are you*?





Courtesy of Louise Desplat, *C2N*, Palaiseau

Arrhenius law

Transition rate out of well

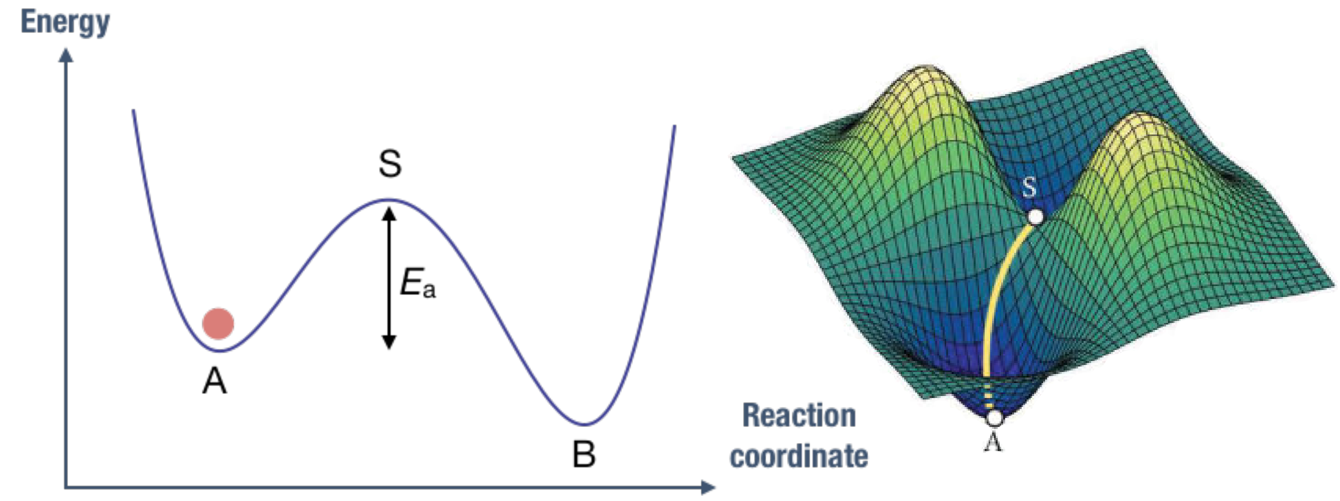
$$\frac{1}{\tau} = \frac{1}{\tau_0} \exp\left(-\frac{E_a}{k_B T}\right)$$

Attempt frequency (Prefactor)

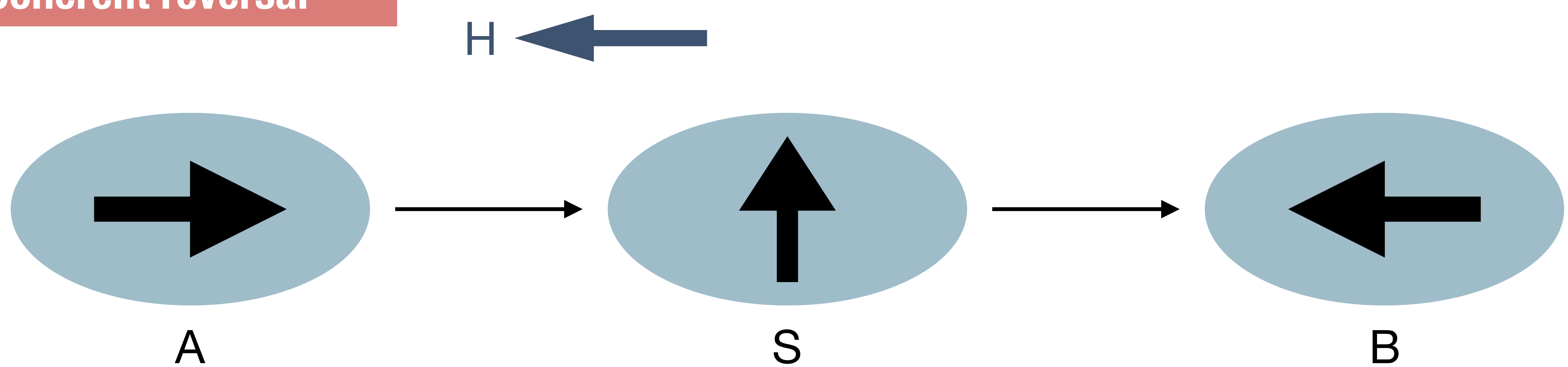
Probability function

$$P = \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right)$$

Activation pathways



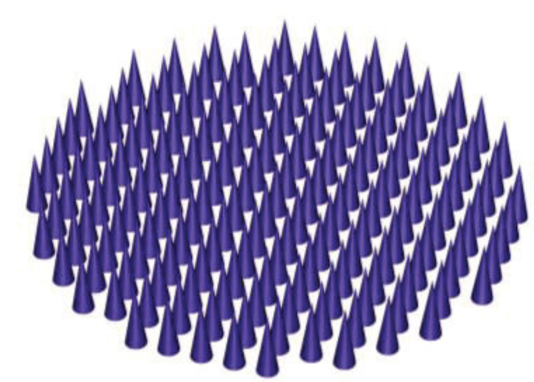
Coherent reversal



Skyrmion annihilation

Current research topic, subject of debate

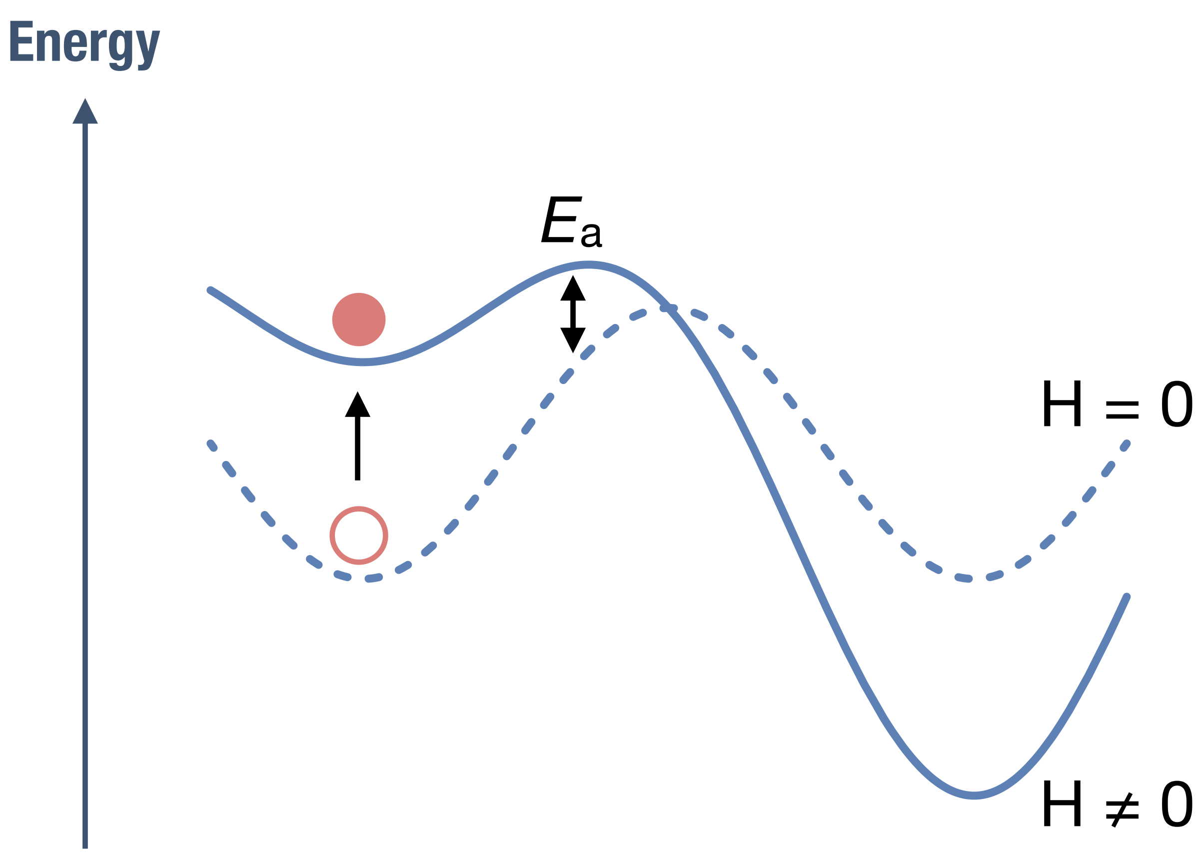
?



A S B

Magnetic aftereffect

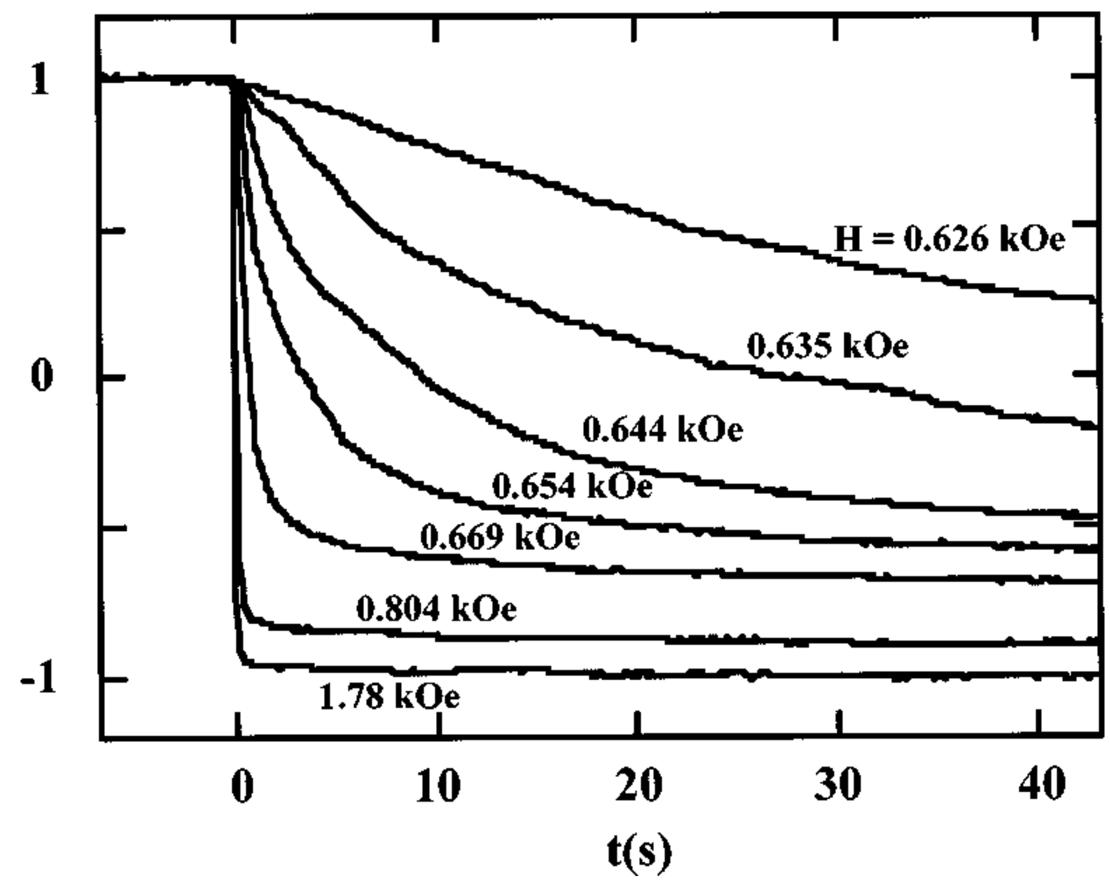
- Thermal effects necessarily introduce the notion of time into a measurement
- What happens when a field is suddenly applied? Thermal fluctuations eventually drive system into lower energy state



$$\frac{1}{\tau} = \frac{1}{\tau_0} \exp\left(-\frac{E_a}{k_B T}\right)$$

Magnetic aftereffect in ultrathin Co film

J-P Jamet et al, *Phys Rev B* **57**, 14320 (1998)



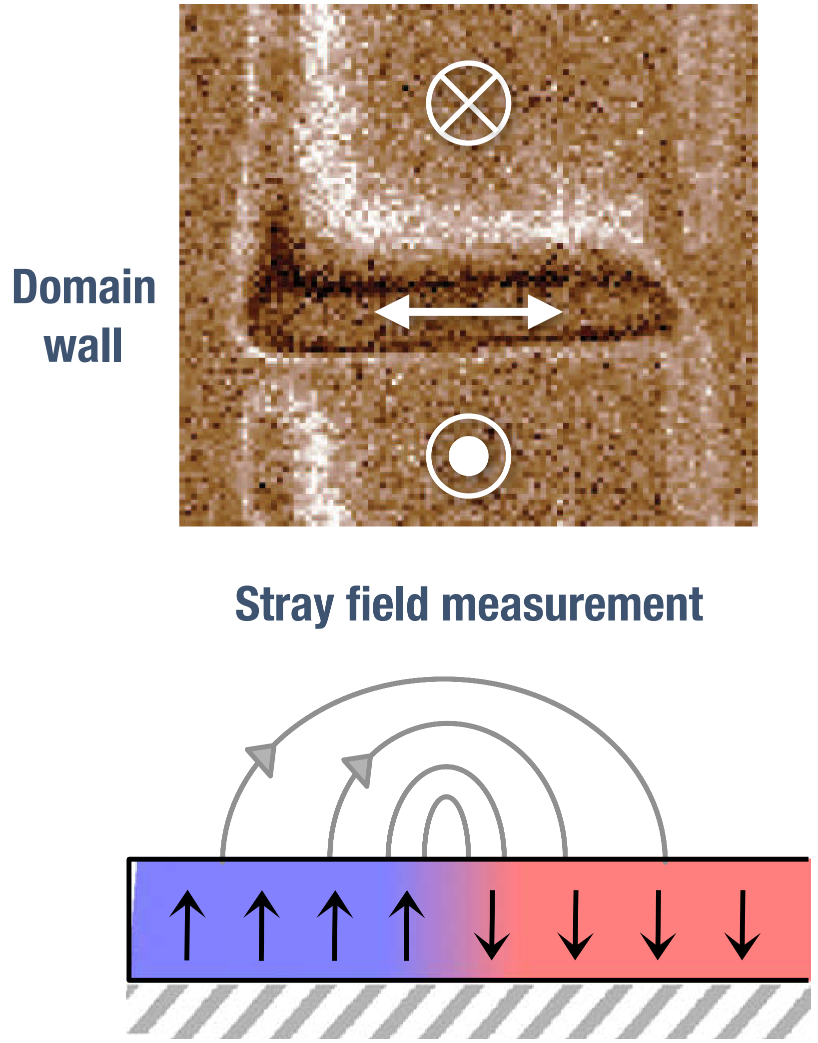
$$m(t) = 2\exp\left(-\frac{t}{\tau}\right) - 1$$

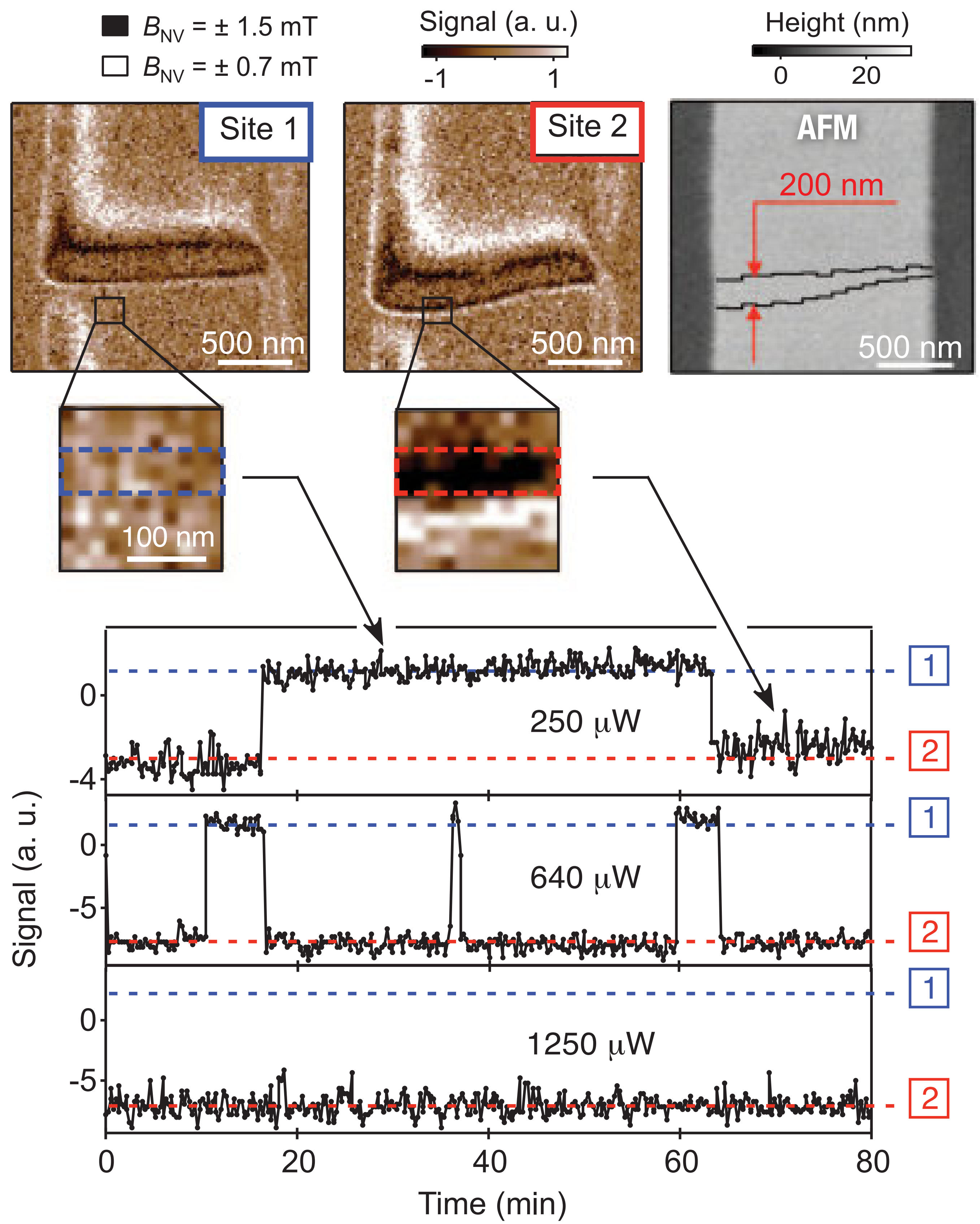
Domain wall hopping

J-P Tetienne et al, *Science* **334**, 1366 (2014)

- Thermally-activated domain wall hopping between two metastable states can be revealed using scanning probe techniques

Example:
Nitrogen-vacancy centre magnetometry on 1-nm thick CoFeB films

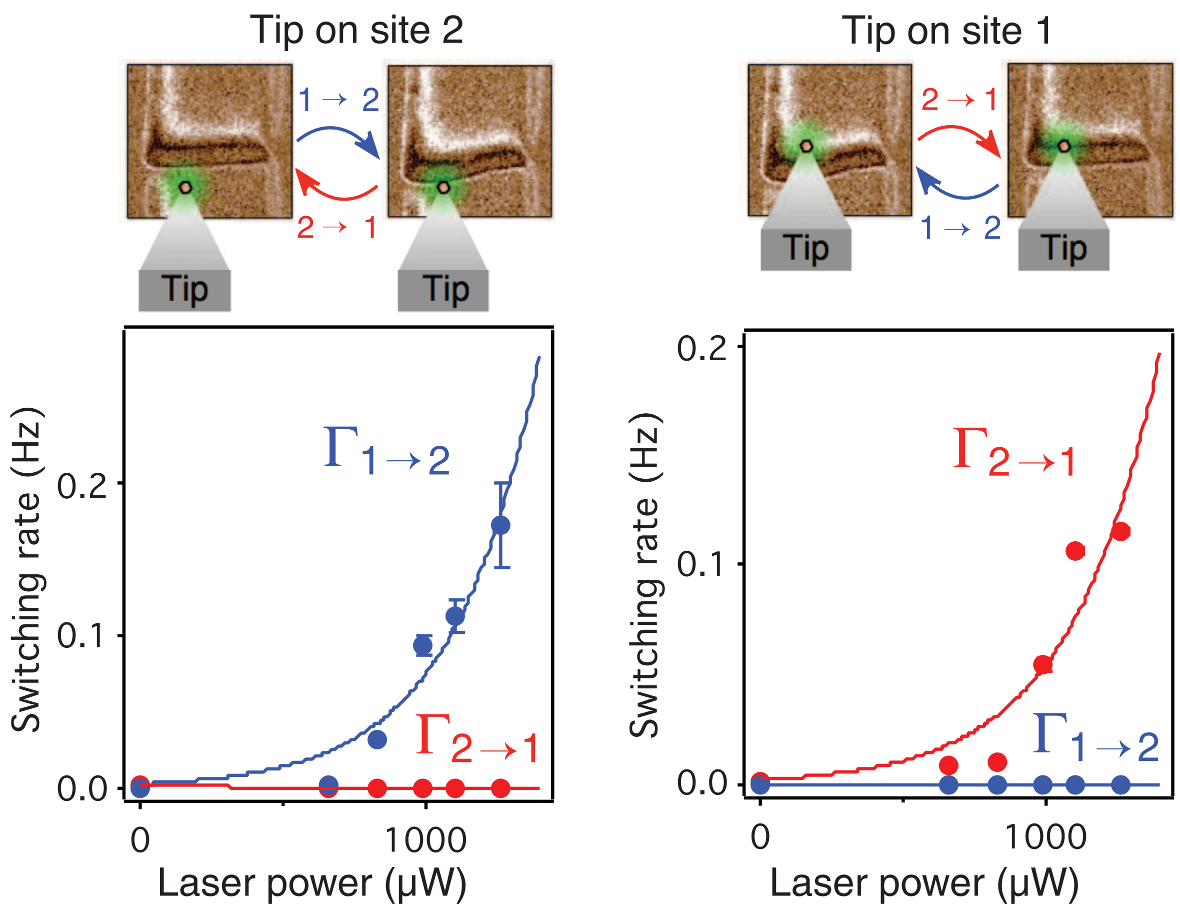


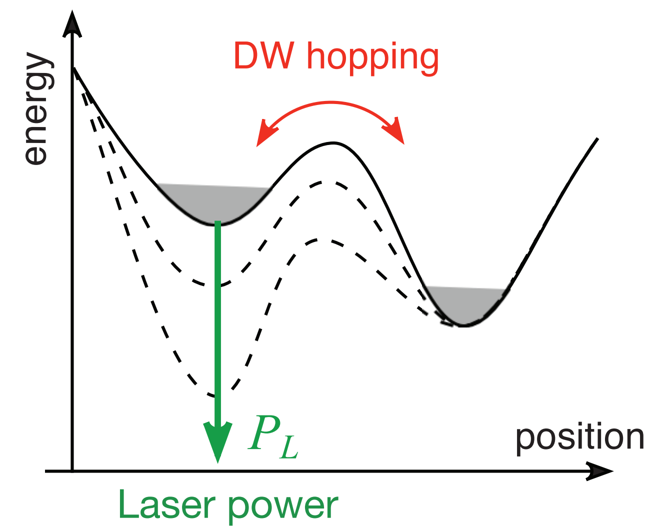


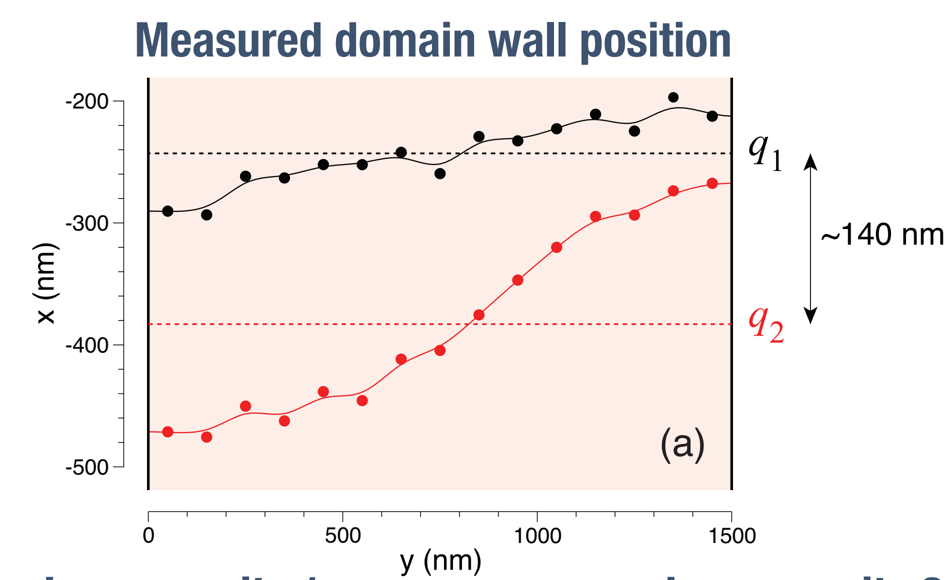
Domain wall hopping

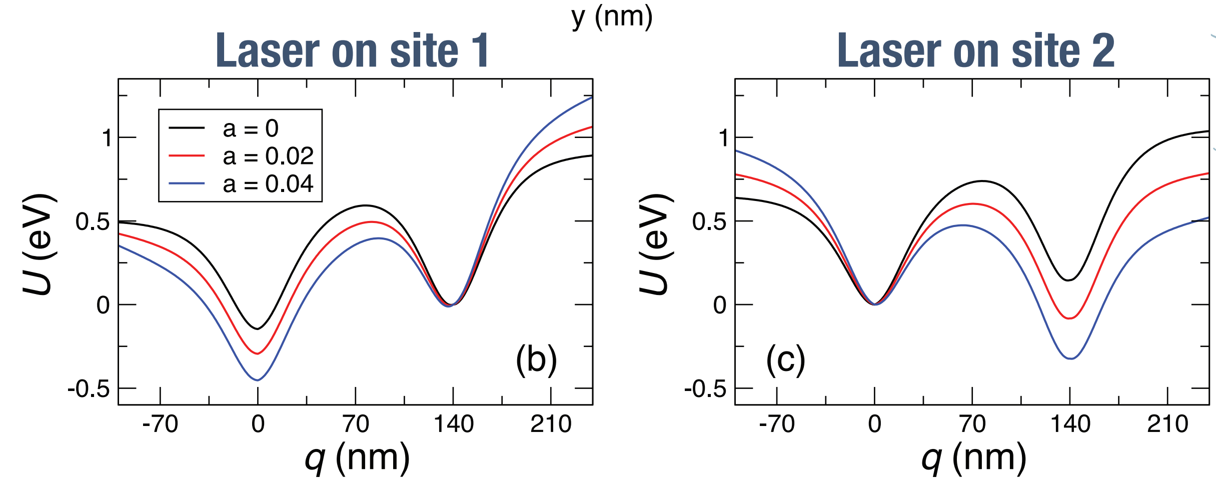
J-P Tetienne et al, *Science* **334**, 1366 (2014)

- Laser-induced heating can control hopping rates between two pinning sites









- Modelling with two-state system accounts for experimental results

$$\Gamma \equiv \frac{1}{\tau} = \frac{1}{\tau_0} \exp\left(-\frac{E_a}{k_B T}\right)$$

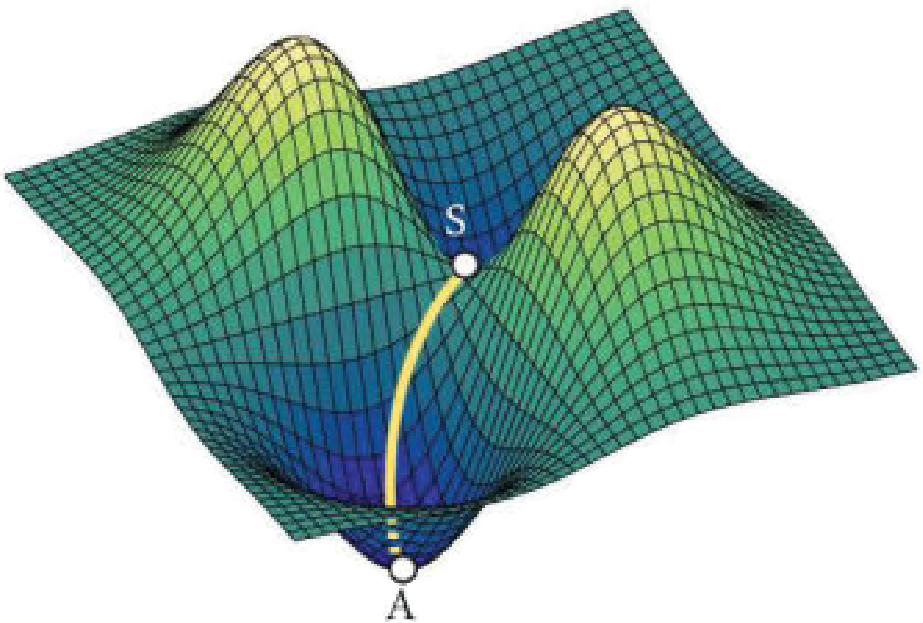
Transition state theory

J S Langer, *Ann Phys* **54**, 258 (1969)

- Connection to (higher-frequency) modes through the Arrhenius prefactor (attempt frequency)

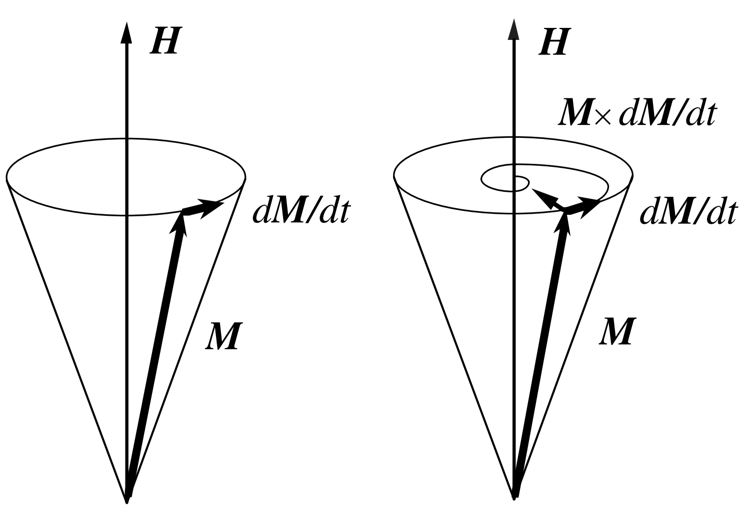
- <u>Example</u>: *Langer's theory of transition rates*

$$\Gamma \equiv \frac{1}{\tau} = \boxed{\frac{\lambda_+}{2\pi}\Omega_0} \exp\left(-\frac{E_a}{k_B T}\right)$$



Dynamical prefactor

Linearised dynamics at *S*,
rate of growth of unstable mode



$$\lambda_+$$

Ratio of curvatures

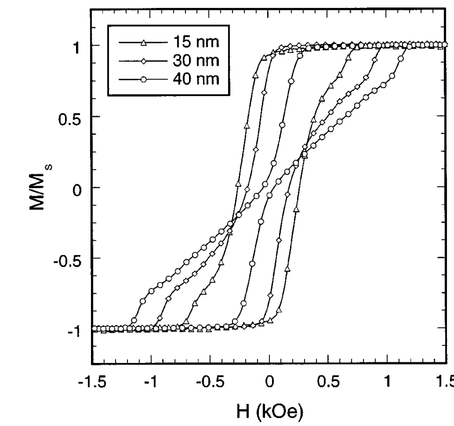
$$H = \left\{ \frac{\partial^2 E}{\partial \eta_i \partial \eta_j} \right\}$$

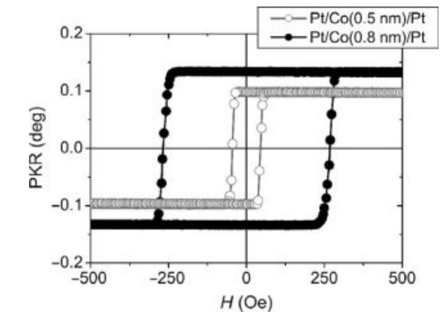
Hessian matrix

$$\Omega_0 = \sqrt{\frac{\det H^A}{|\det H^S|}} = \sqrt{\frac{\Pi_i \lambda_i^A}{\Pi_j |\lambda_j^S|}}$$

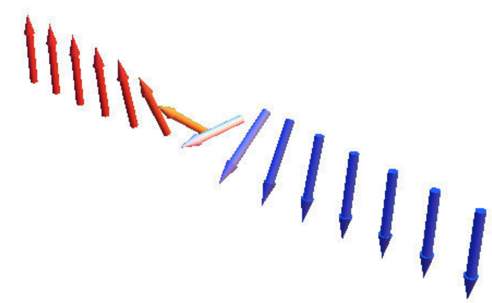
Ratio of products of eigenvalues of H

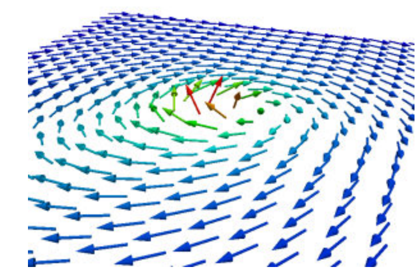
Summary



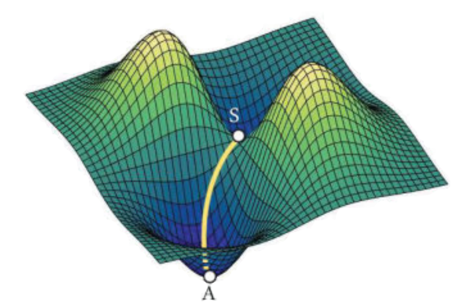


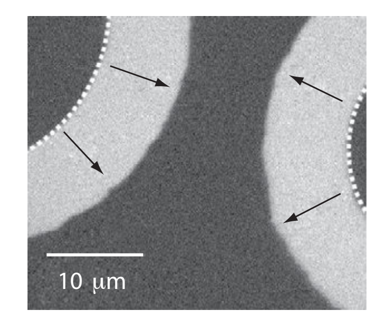
- Hysteresis loop as theme for quasi-statics



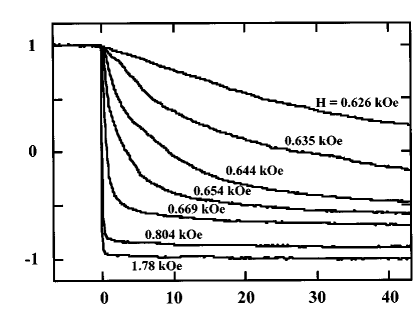


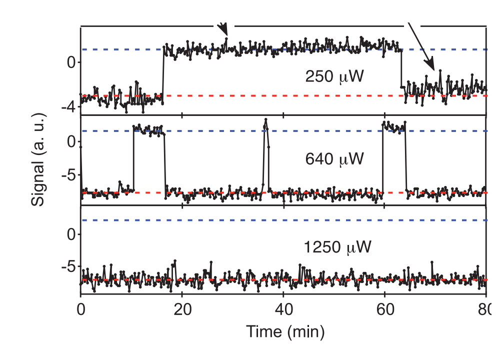
- Energy landscapes
  (Meta)stable magnetisation configurations
  Domain walls, vortices, skyrmions, …





- Reversal mechanisms
  Navigate energy landscape through nontrivial states
  Rotation; nucleation, propagation, annihilation



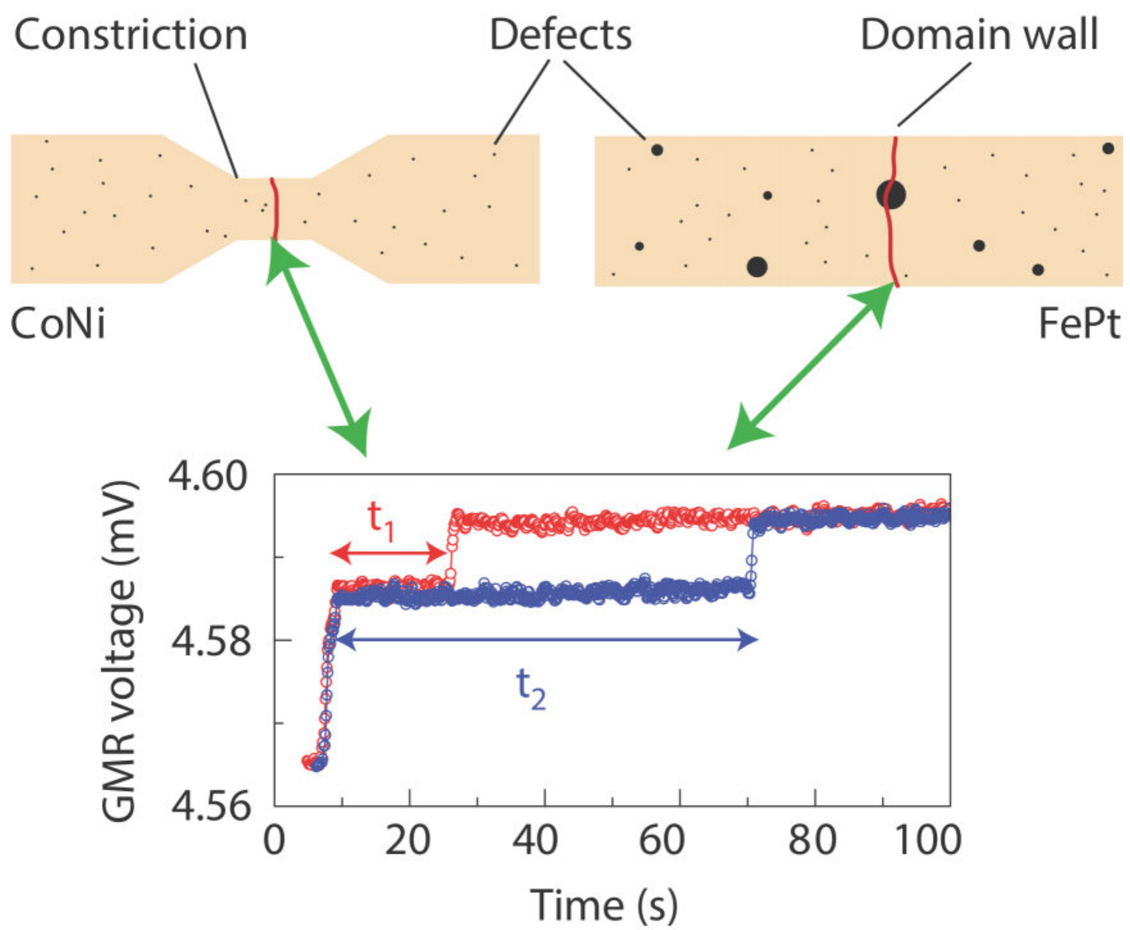


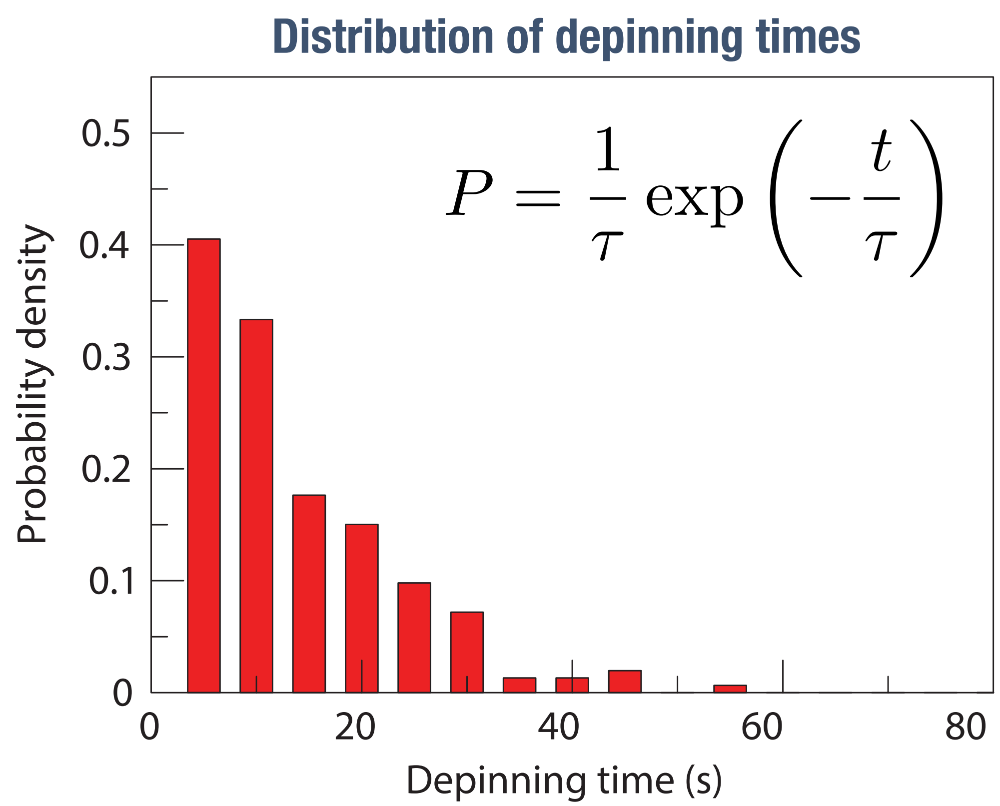
- Time-dependent and thermal effects
  Measurement times matter
  Fluctuations drive transitions out of metastable states

Domain wall depinning

C Burrowes et al, *Nat Phys* **6**, 17 (2010)

- Fluctuations can drive domain walls out of a local potential well
- Probability distribution of residence (depinning) times used to determine energy barriers

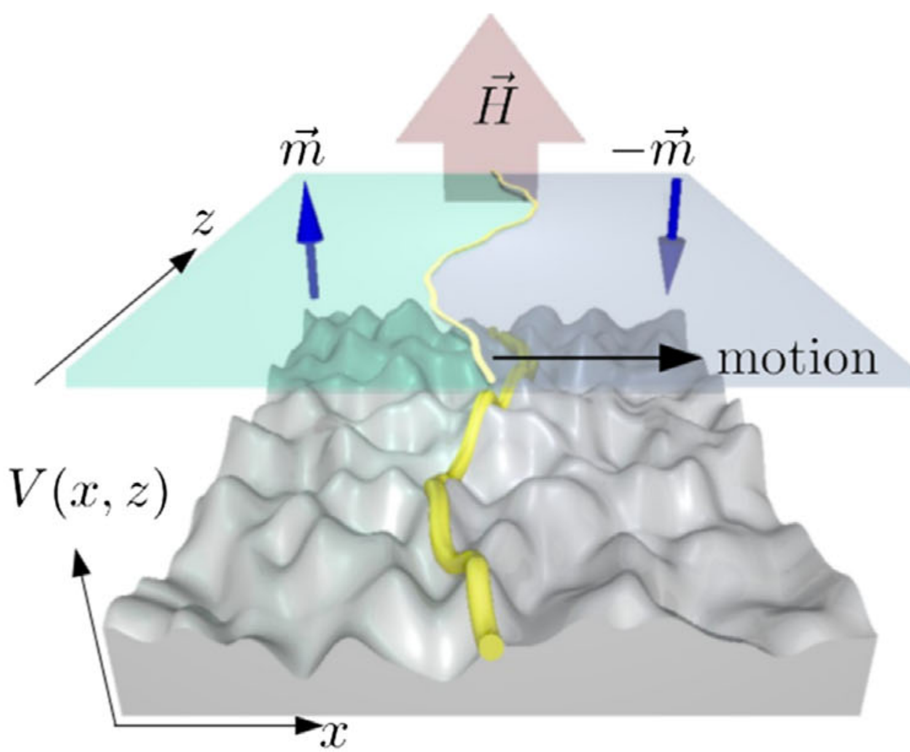




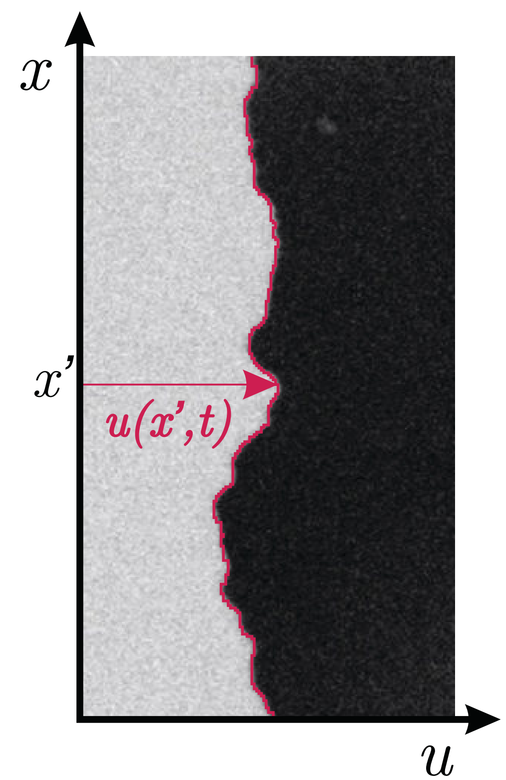
$$\frac{1}{\tau} = \frac{1}{\tau_0} \exp\left(-\frac{E_a}{k_B T}\right)$$

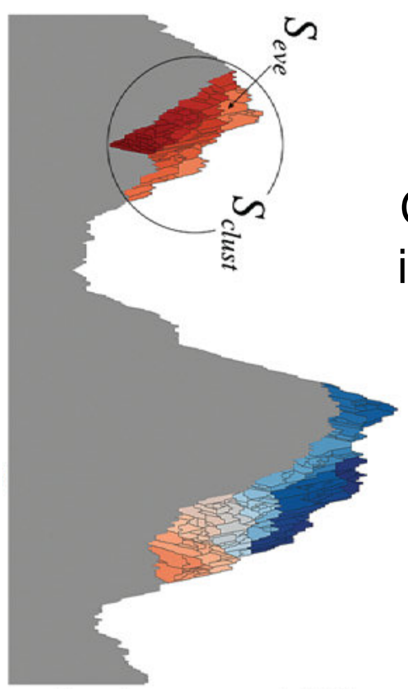
Domain wall creep

- In disordered films, motion is more complicated under low fields
- Competition between domain wall energy and disorder potential
- Creep motion occurs, involving thermally-activated avalanches
- Useful analogy: Elastic band moving across rough surface



V Jeudy et al, *Phys Rev Lett* **117**, 057201 (2016)





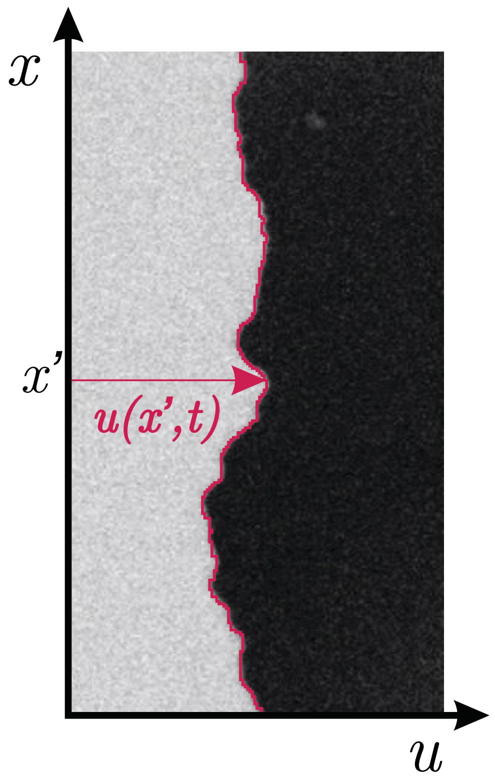
Colours indicate times

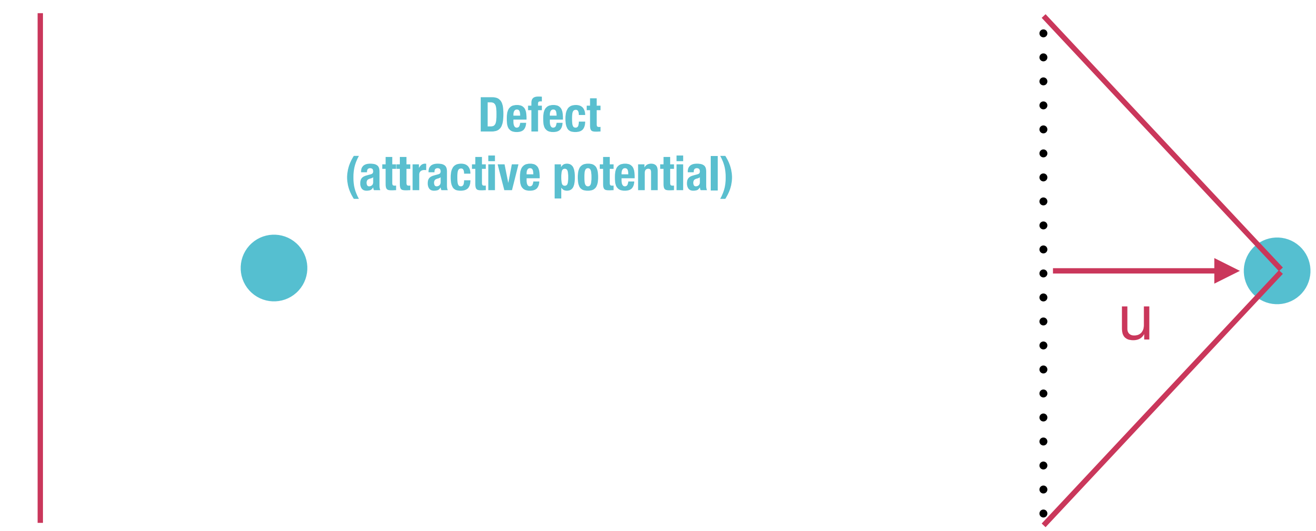
S Ferroro et al, *Phys Rev Lett* **118**, 147208 (2016)

Domain wall creep: Energetics

S Lemerle et al, *Phys Rev Lett* **80**, 849 (1998)

- Balance between increase in elastic energy and decrease in pinning energy





L

$$L + \delta L = L\sqrt{1 + \frac{4u^2}{L^2}}$$

Elastic energy

$$E_{\mathrm{el}} = \frac{1}{2}\sigma \int_0^L dx \left(\frac{\partial u}{\partial x}\right)^2 \simeq \frac{\sigma u^2}{L}$$

$\sigma = 4\sqrt{AK_u}$ Domain wall energy

Disorder (pinning) energy

$$E_{\mathrm{pin}} = -f_{\mathrm{pin}}\sqrt{\xi L n}$$

Characteristic strength of disorder

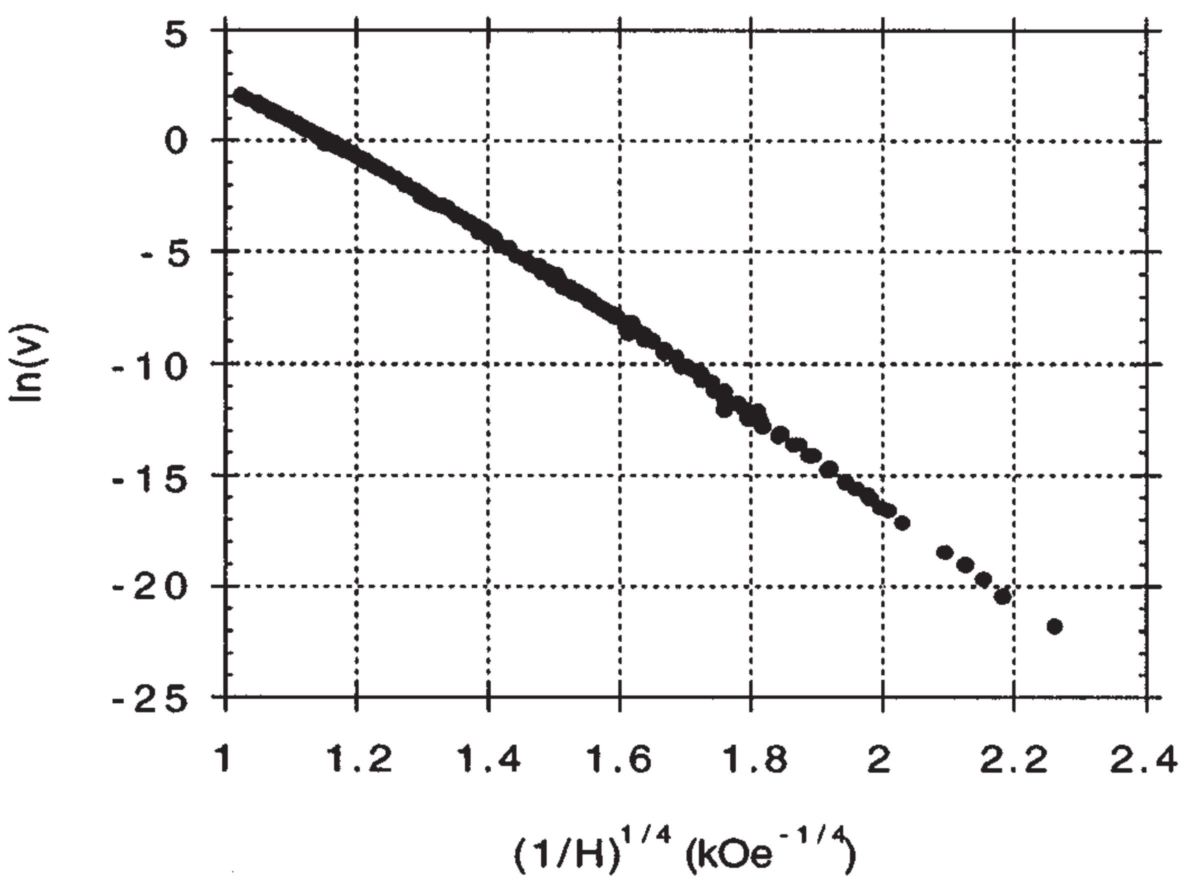
Characteristic length of disorder

Defect density

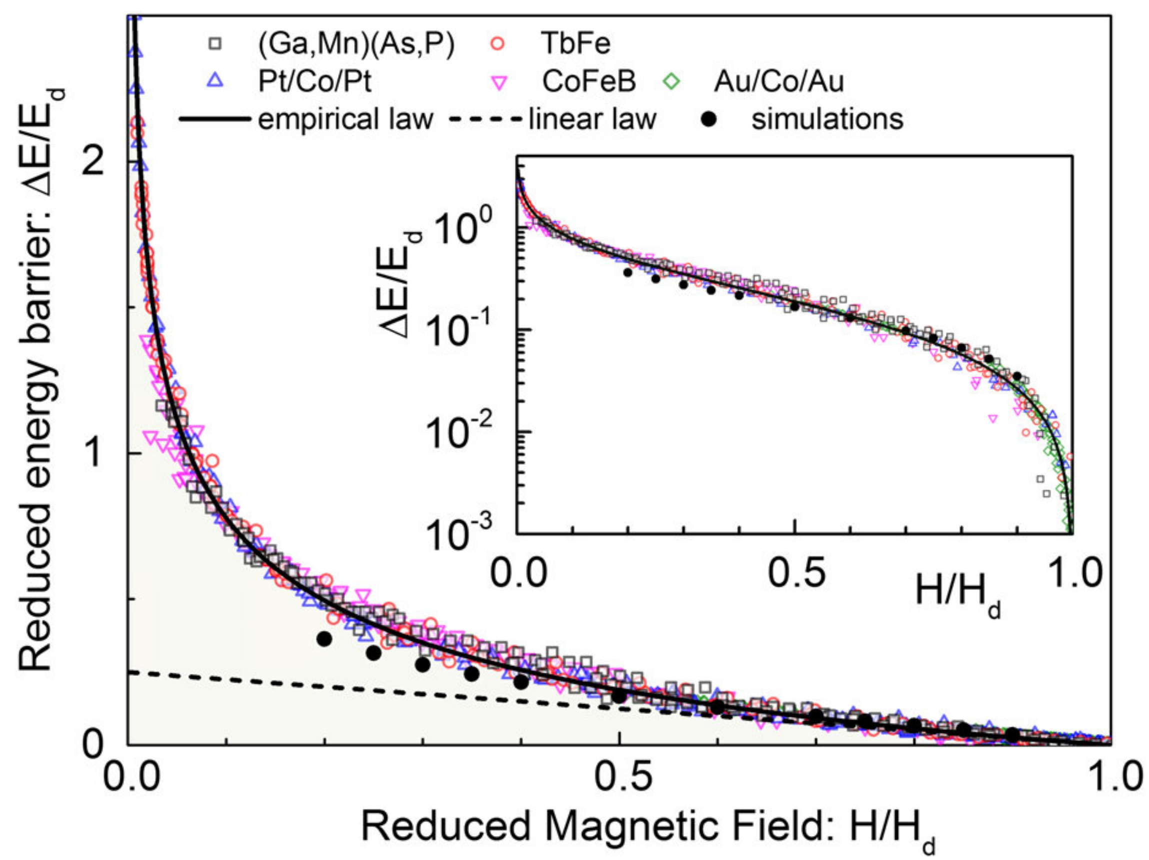
Domain wall creep: barriers and motion

- Energy barrier has power law dependence (μ = 1/4 for 2D systems)
- Avalanches – critical phenomena

S Lemerle et al, *Phys Rev Lett* **80**, 849 (1998)



V Jeudy et al, *Phys Rev Lett* **117**, 057201 (2016)



$$v = v_0 \exp\left(-\frac{\Delta E}{k_B T}\right)$$

$$\Delta E = k_B T_d \left[\left(\frac{H}{H_d}\right)^{-\mu} - 1\right]$$