MAX PLANCK INSTITUTE
FOR CHEMICAL PHYSICS OF SOLIDS

MAGNETIC REVERSAL

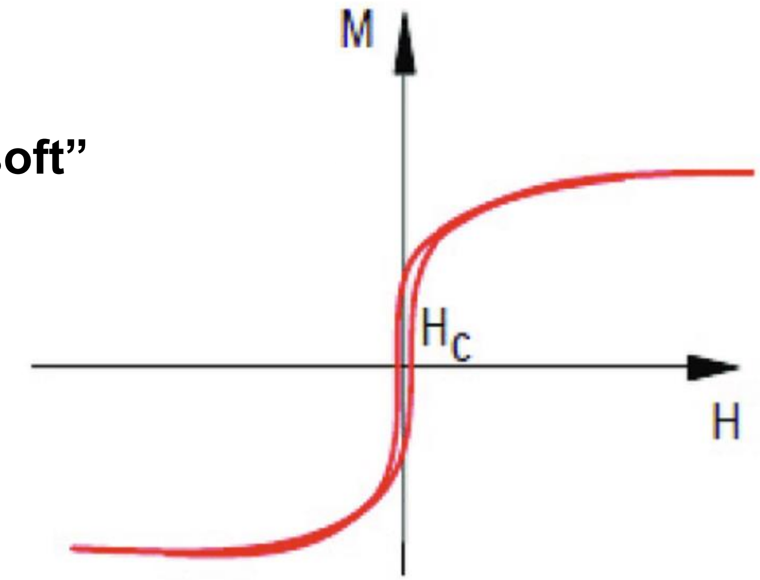
Claire Donnelly

European School of Magnetism 2022

Saarbruecken, 15th September 2022

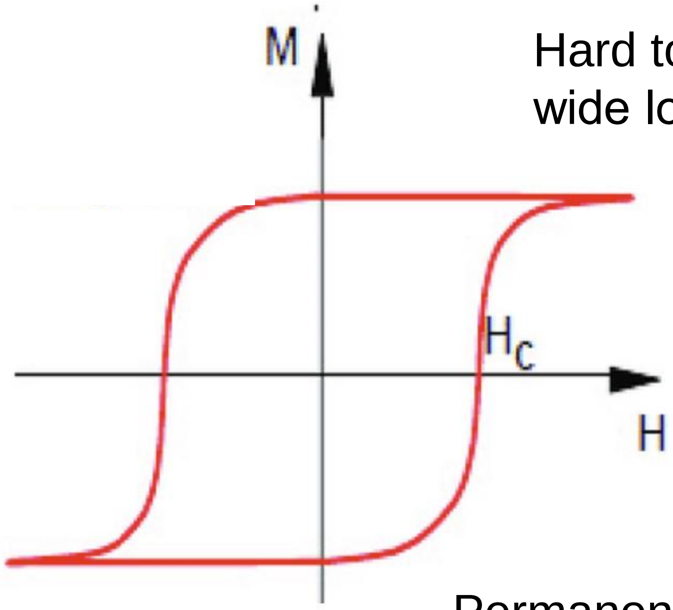
SOFT VS HARD MAGNETS:

Easy to switch:
narrow loop, “**soft**”



Sensors, transformer, magnetic shielding.
E.g. Permalloy, Iron, FeCo

Hard to switch:
wide loop, “**hard**”

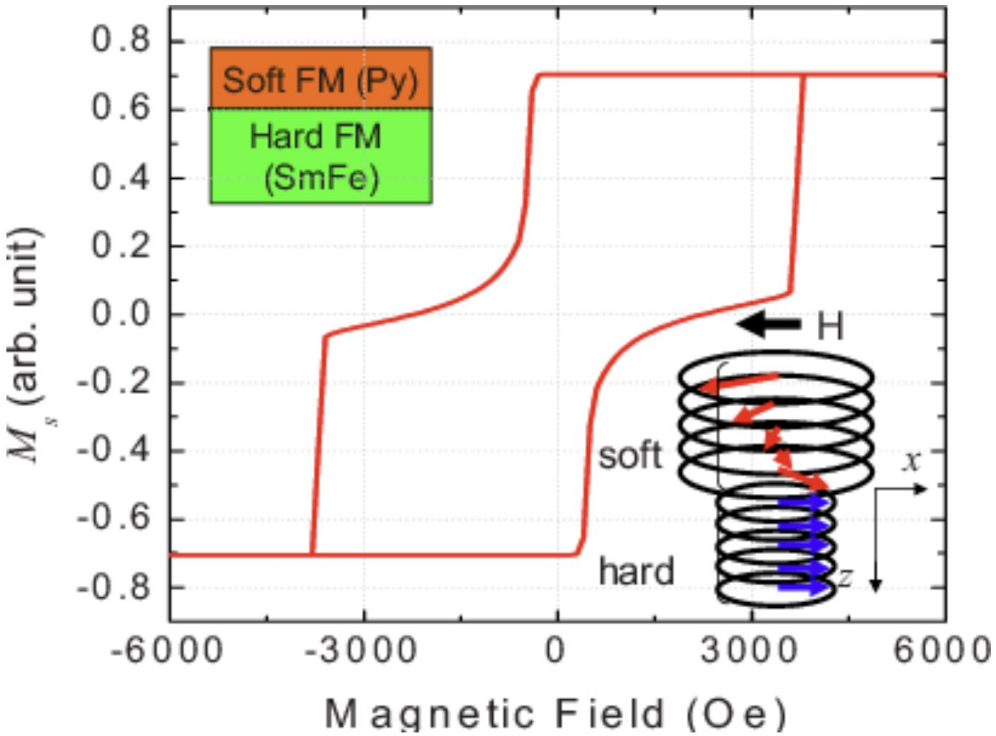


Permanent magnets, motors, magnetic recording
E.g. Co, NdFeB, CoSm

COMBINATION OF SOFT AND HARD?

Exchange spring!

Combination of hard & soft



Gu et al., PRB 81, 214435 (2010)

Idea:

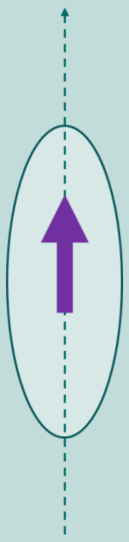
Hard magnets useful, however rare earth permanent magnets expensive

Combination of hard rare earths & “cheap” soft magnets

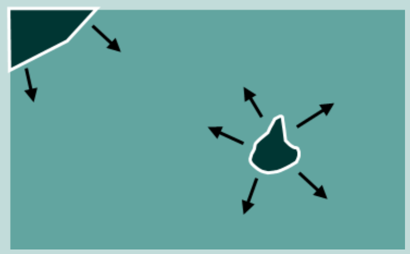
→ Higher Ms, higher Hc

OUR QUESTIONS FOR TODAY:

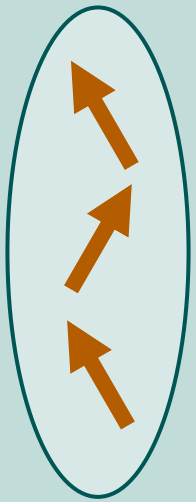
Reversal of a single particle



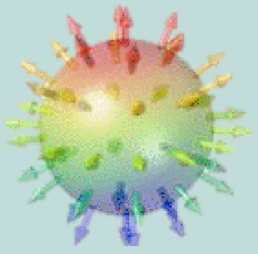
Domain wall motion



Alternative types of switching

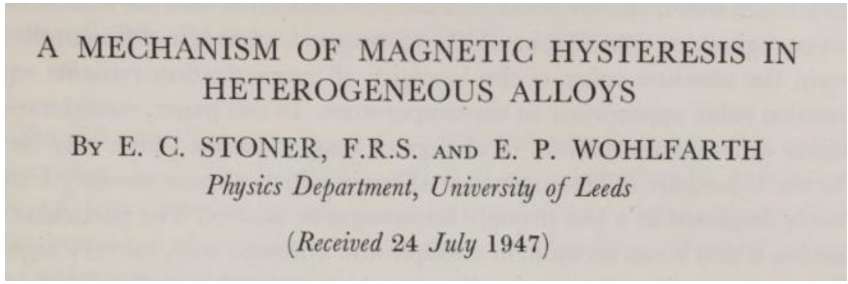


Topology in reversal



MAGNETIC REVERSAL: START WITH A SINGLE PARTICLE

“Stoner Wohlfarth Model”

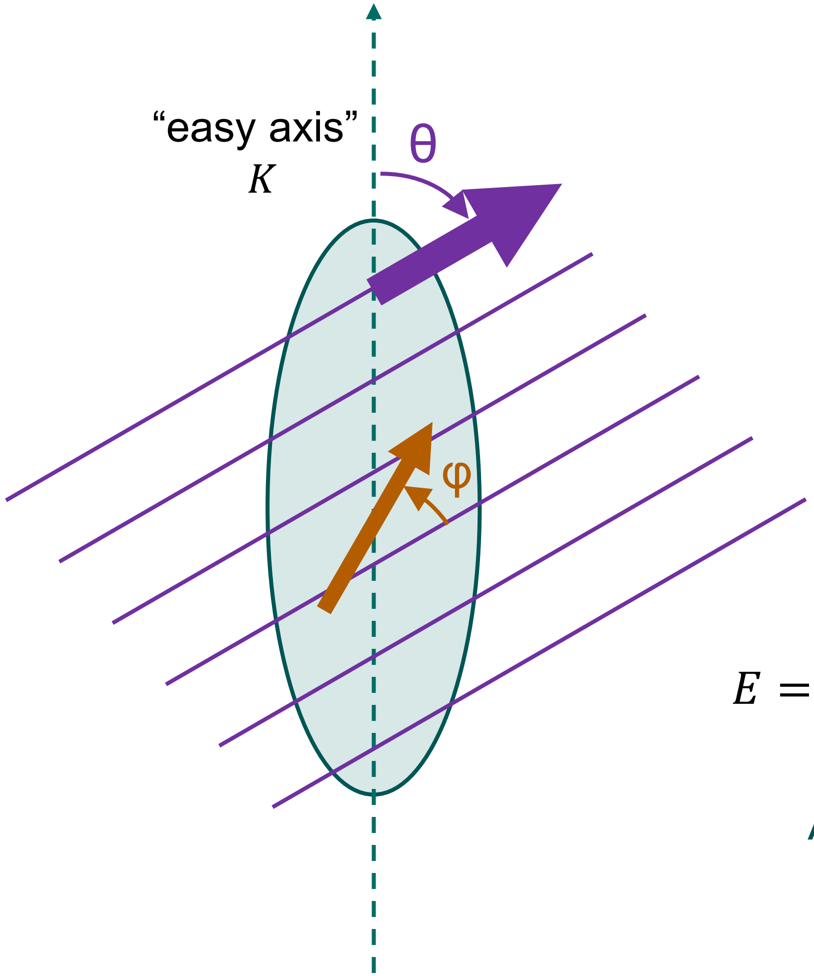


A MECHANISM OF MAGNETIC HYSTERESIS IN HETEROGENEOUS ALLOYS

BY E. C. STONER, F.R.S. AND E. P. WOHLFARTH

Physics Department, University of Leeds

(*Received* 24 *July* 1947)



Single domain particle with:

- Anisotropy K
- Magnetic field H

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

Anisotropy vs Magnetic field

“macro-spin” model

SINGLE PARTICLE: "SIMPLE" CASES

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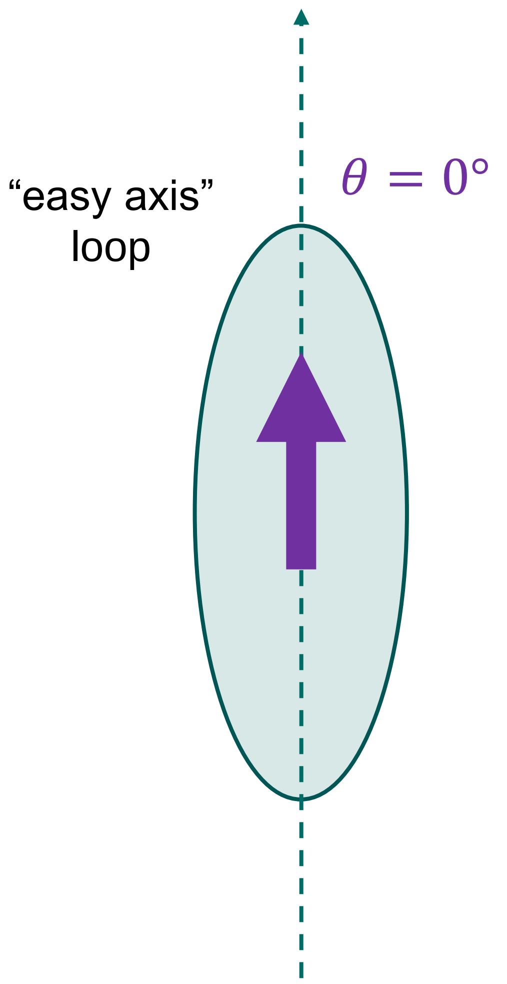

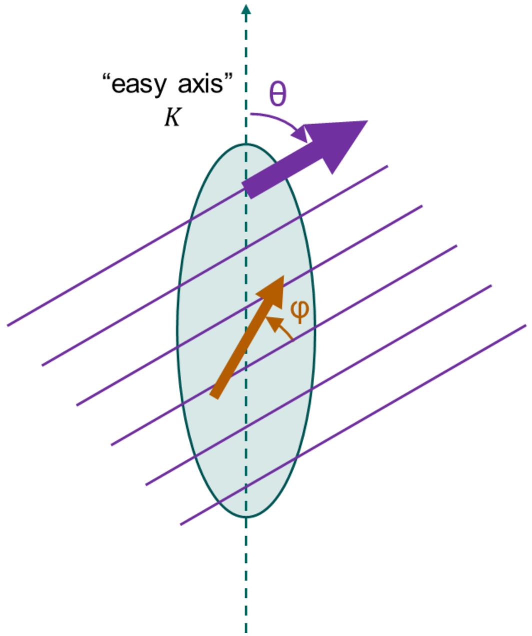

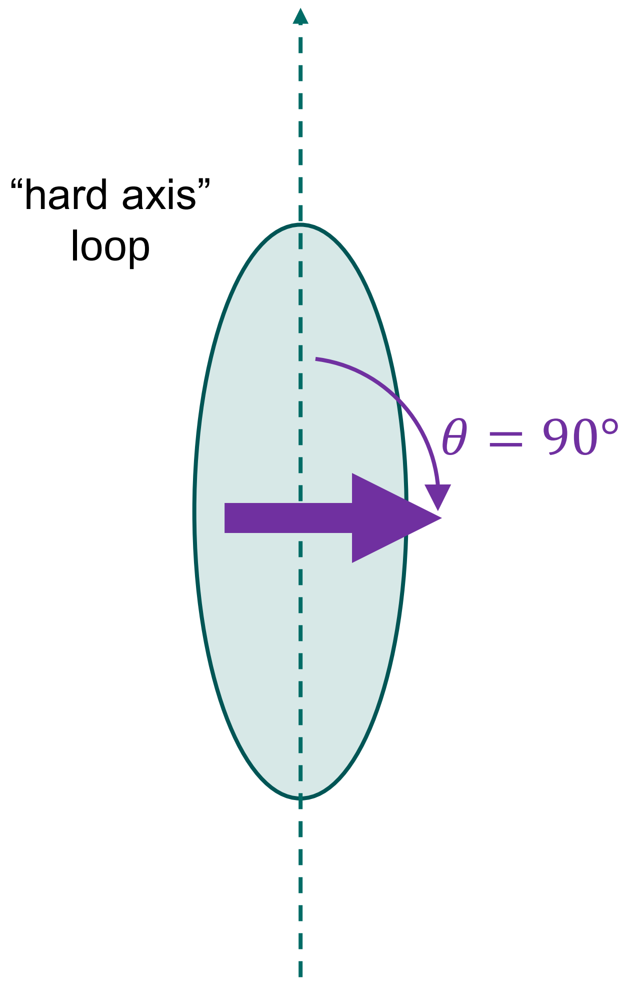

Reversal field larger for hard or easy axis?

SINGLE PARTICLE: “SIMPLE” CASES

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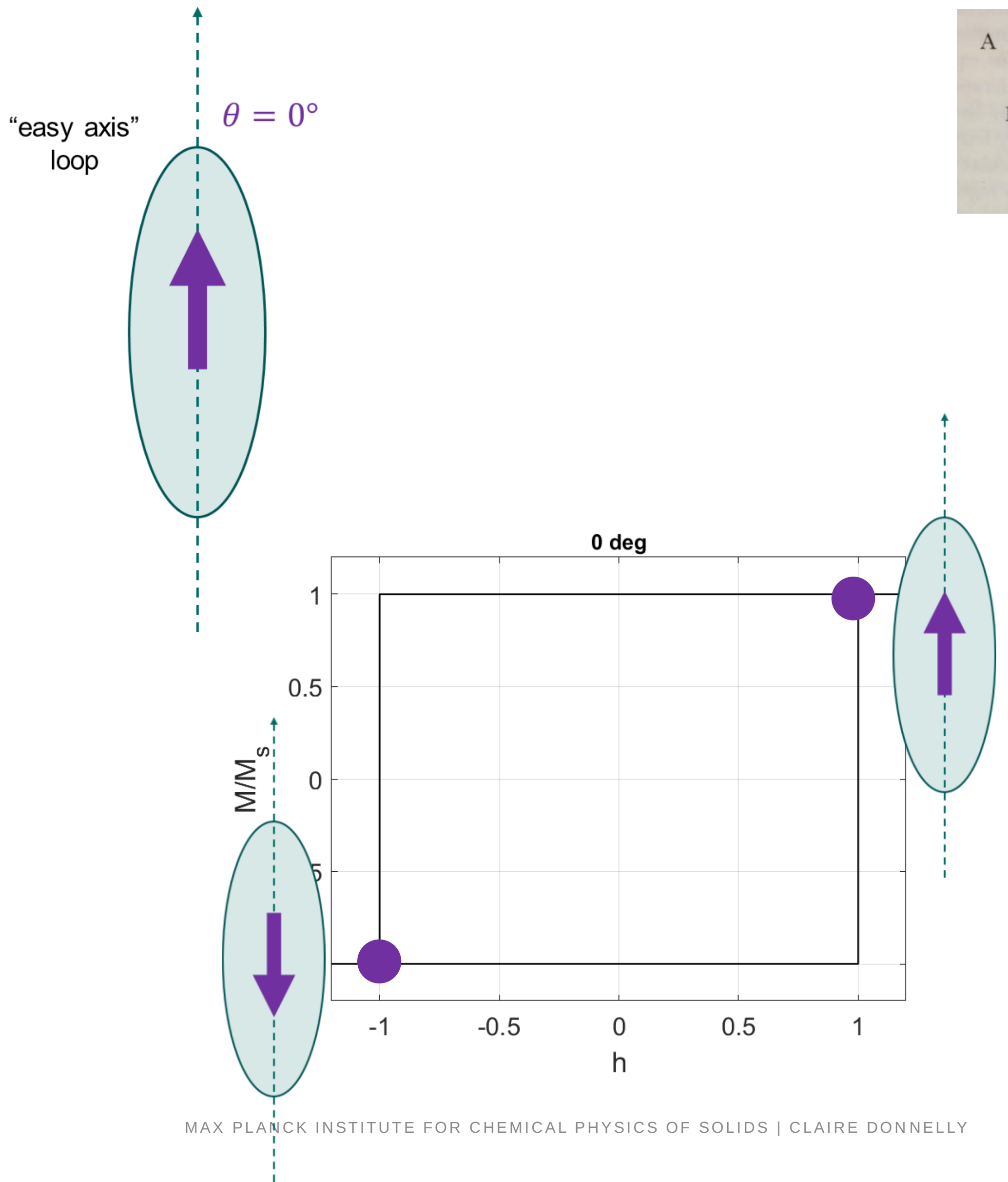
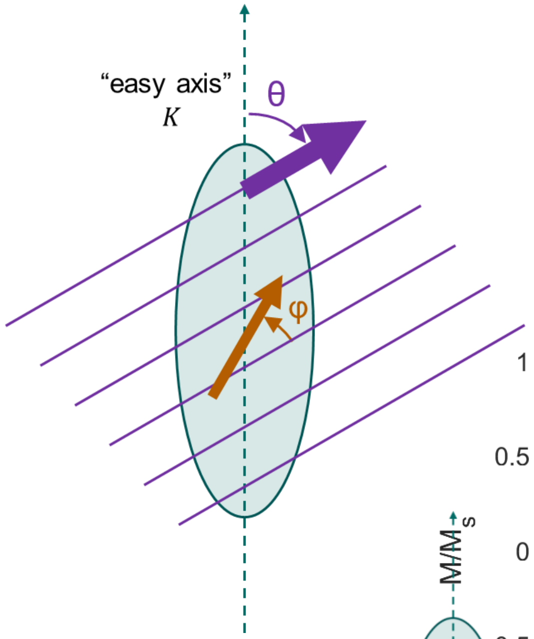
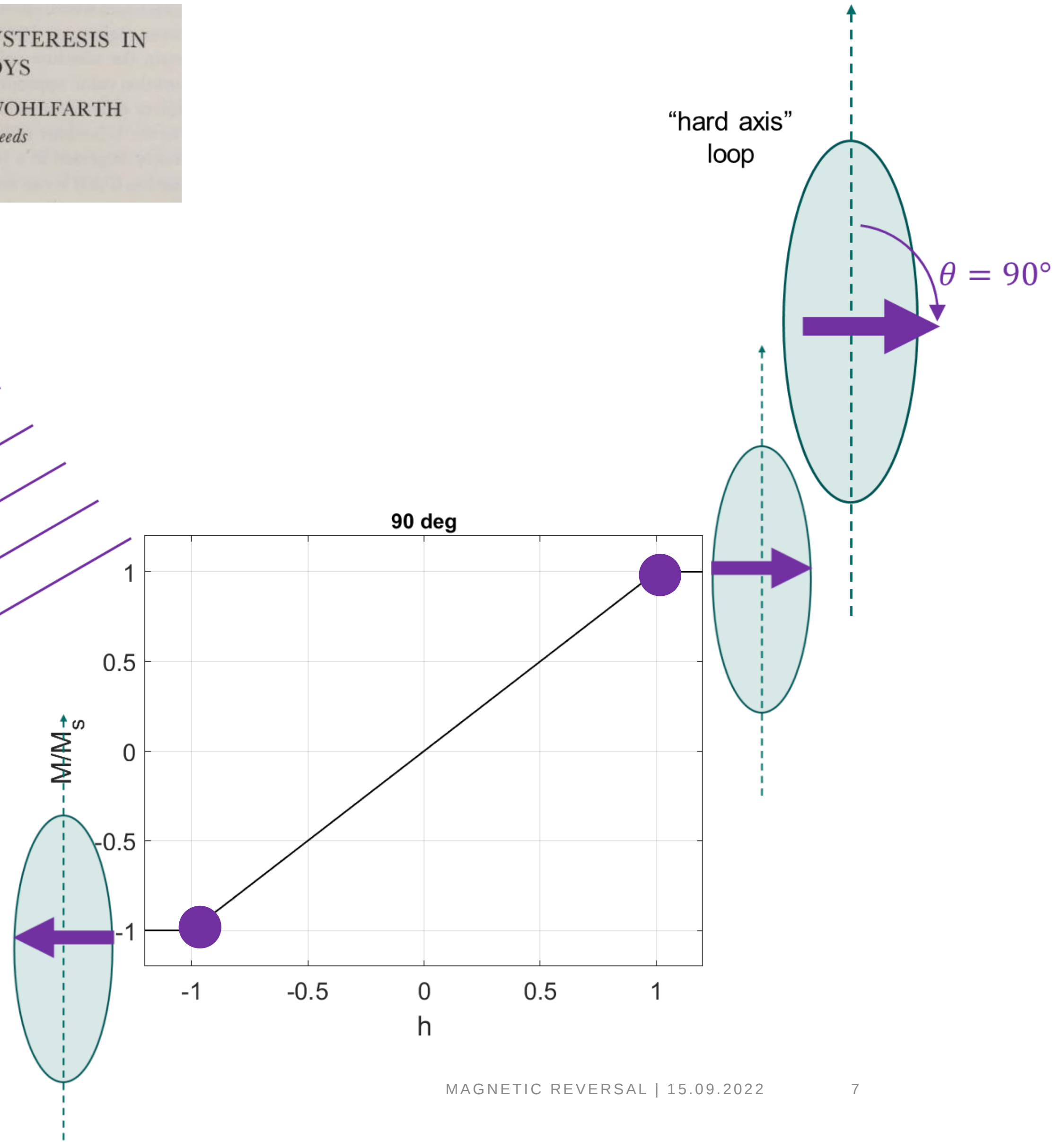


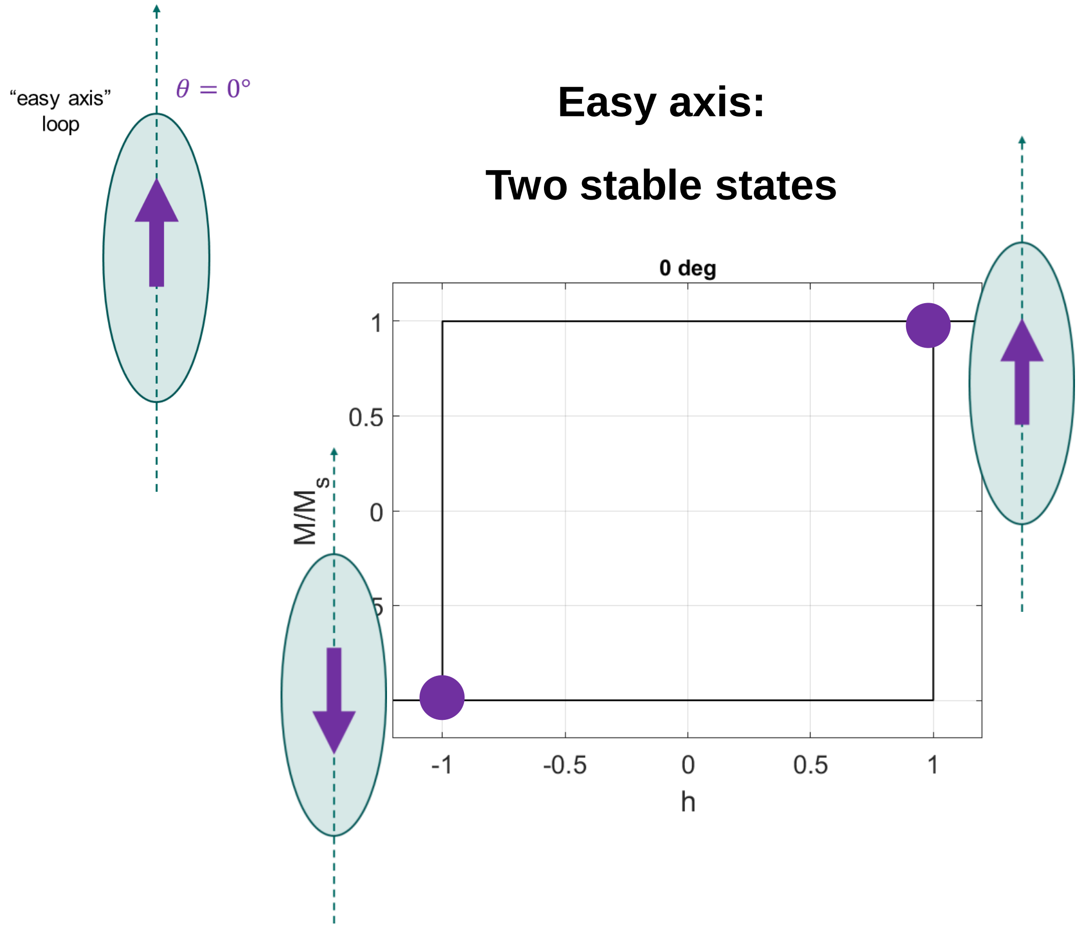




SINGLE PARTICLE: "SIMPLE" CASES

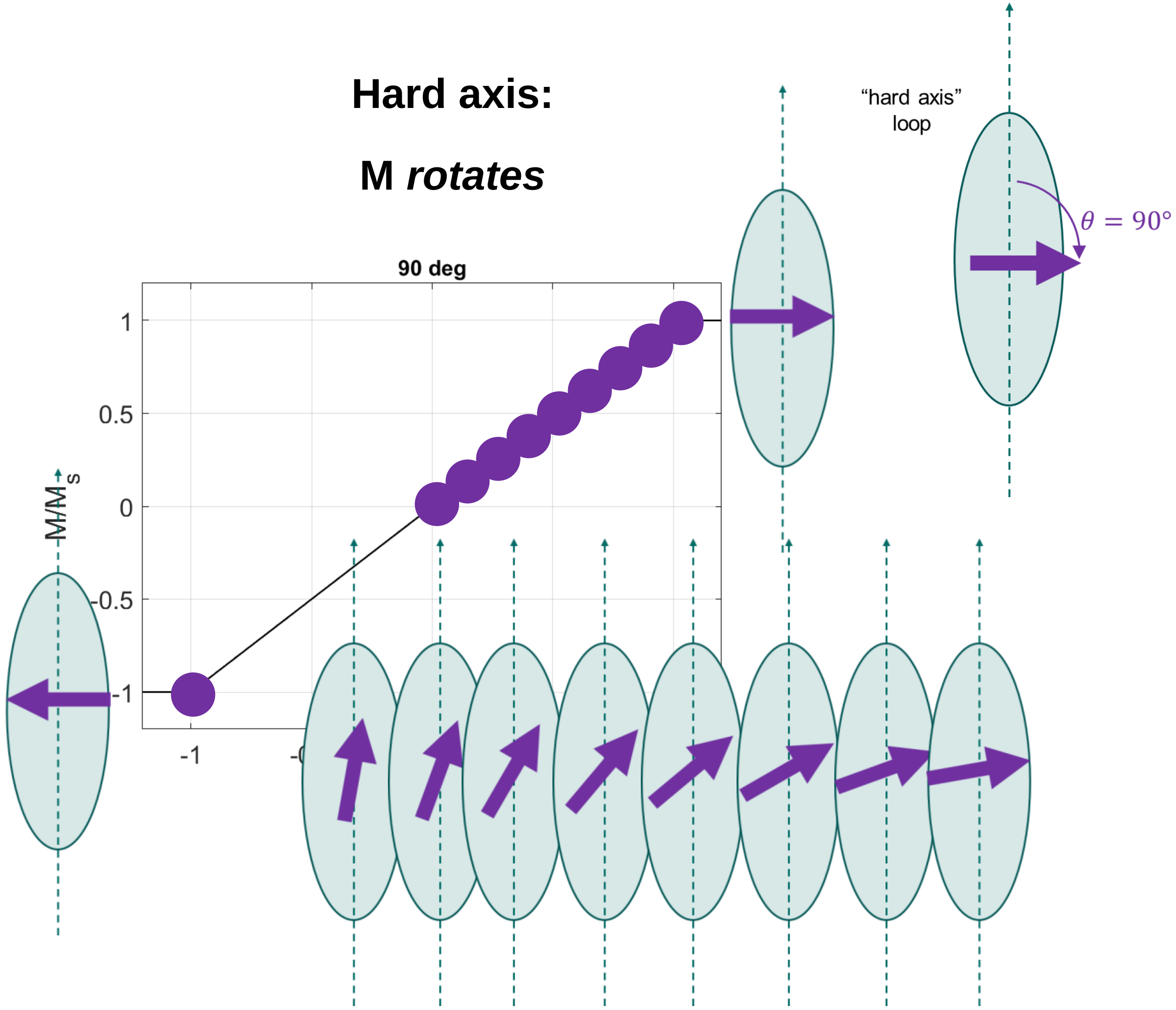
Easy axis:

Two stable states

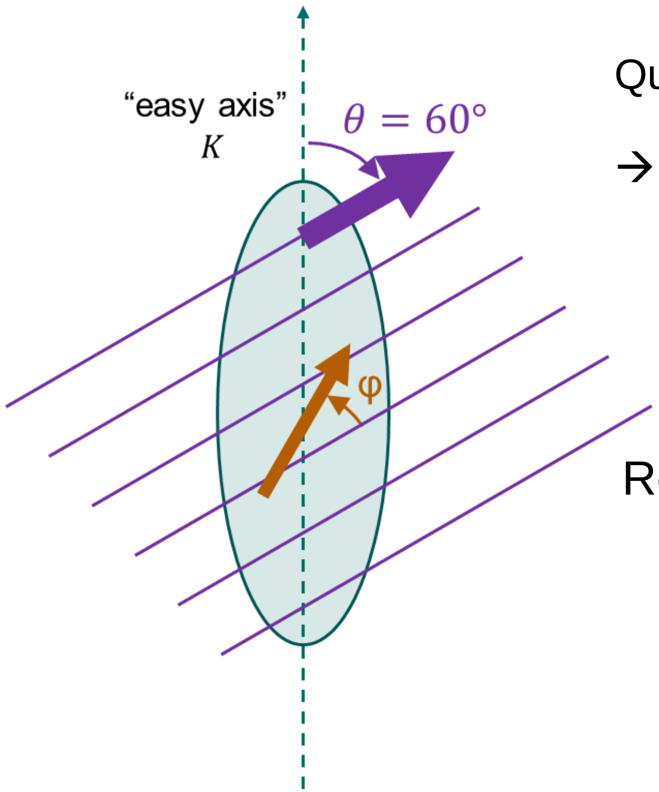


Hard axis:

M *rotates*



SINGLE PARTICLE: SOLVE FOR ARBITRARY ANGLES:



Question: which direction does the magnetisation point for a given field?

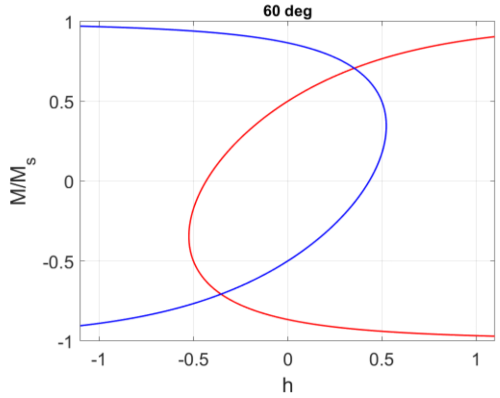
→ can *minimise energy*:

$$E = \underbrace{K \sin^2(\theta - \varphi)}_{\text{Anisotropy}} - \underbrace{\mu_0 H M_S \cos\varphi}_{\text{Magnetic field}}$$

Anisotropy vs Magnetic field

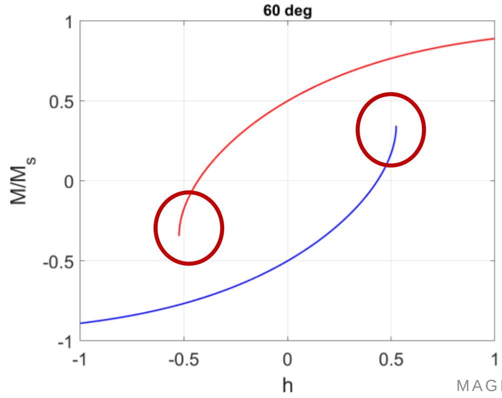
Rearranging, find solutions:

$$\frac{dE}{d\varphi} = 0$$



And determine if they are stable:

$$\frac{\mathrm{d}^2 E}{\mathrm{d}\varphi^2} > 0$$



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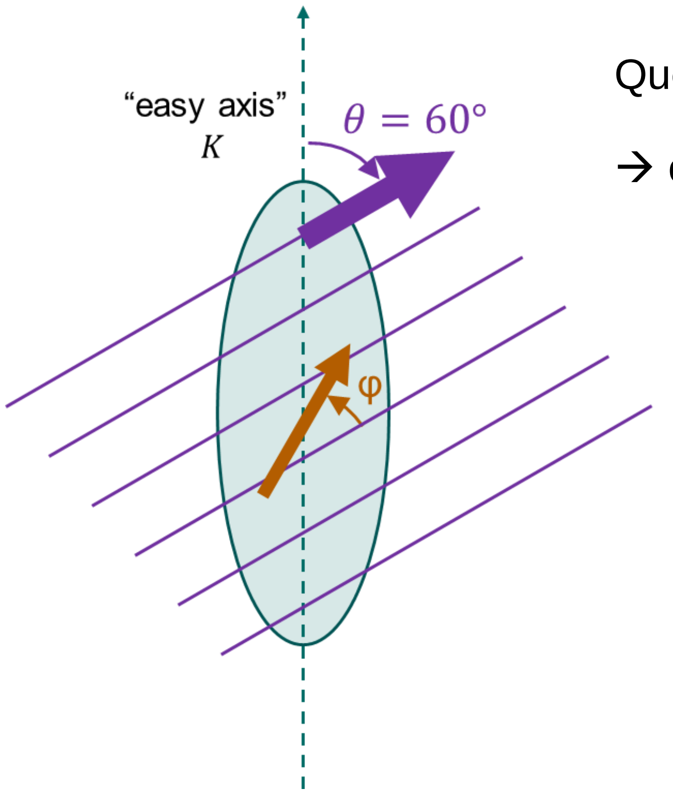
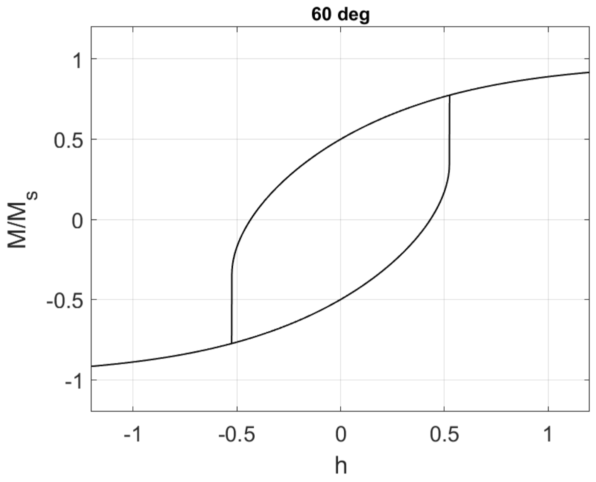


Question: which direction does the magnetisation point for a given field?

→ can *minimise energy*:

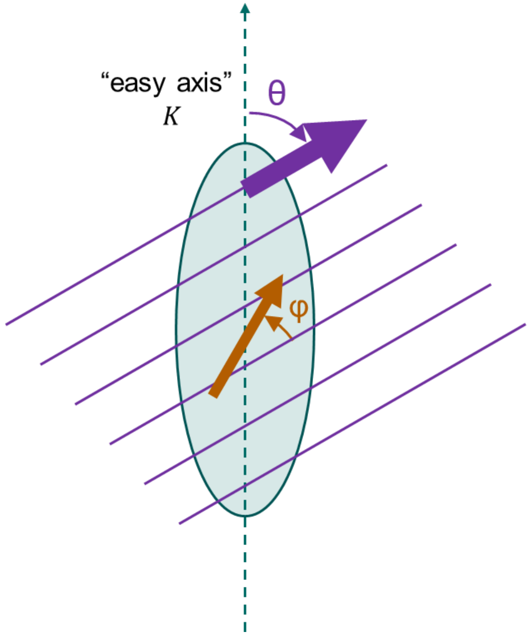
$$E = \underbrace{K\sin^2(\theta - \varphi)}_{\text{Anisotropy}} \text{ vs } \underbrace{- \mu_0 H M_S \cos\varphi}_{\text{Magnetic field}}$$

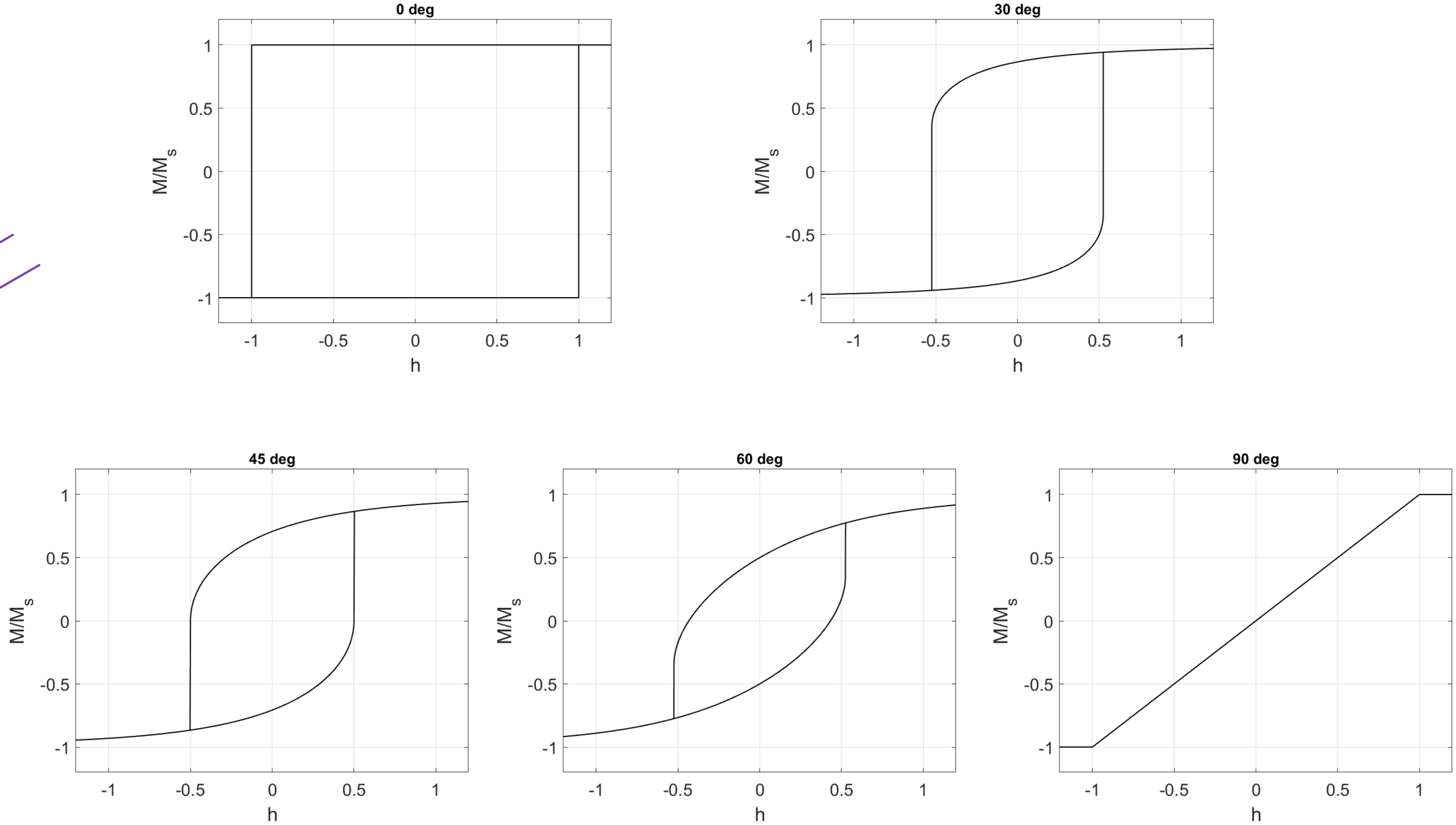
Giving our hysteresis loop!



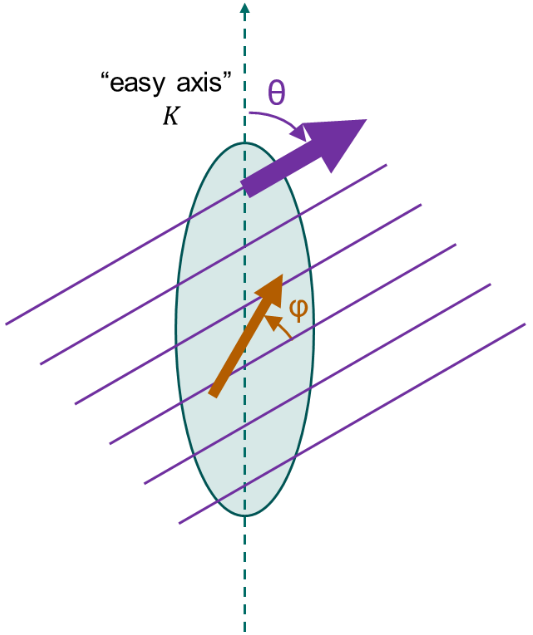
- Switching points - discontinuous
- Continuous rotation of m towards switching point

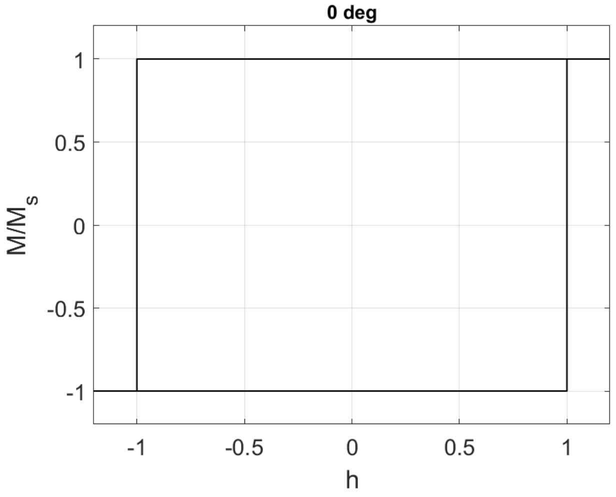
SINGLE PARTICLE: SOLVE FOR ARBITRARY ANGLES:

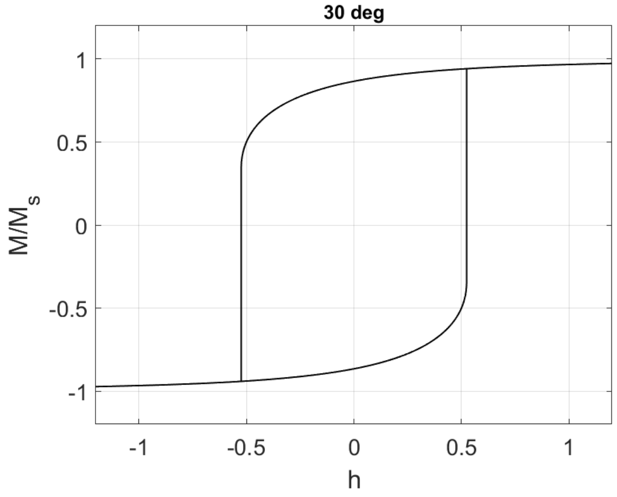




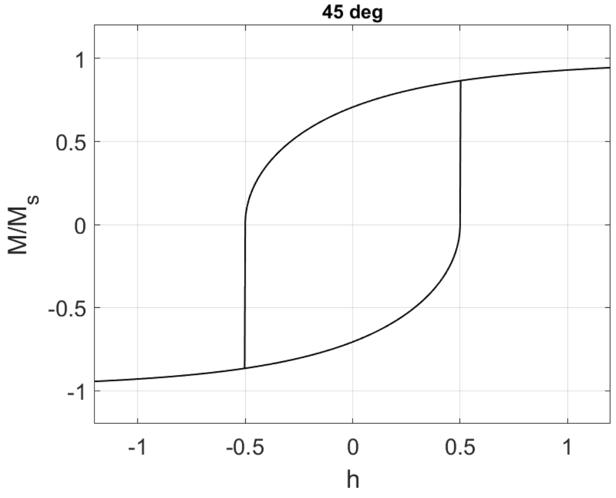
SINGLE PARTICLE: SOLVE FOR ARBITRARY ANGLES:

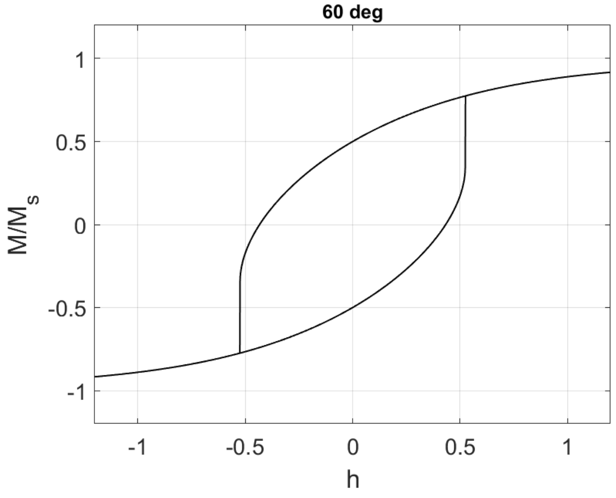


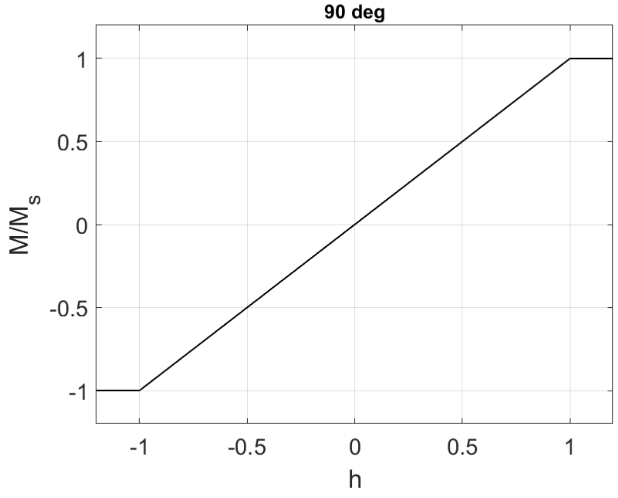




For all of these cases, we have the smooth rotation of the magnetisation… → coherent rotation





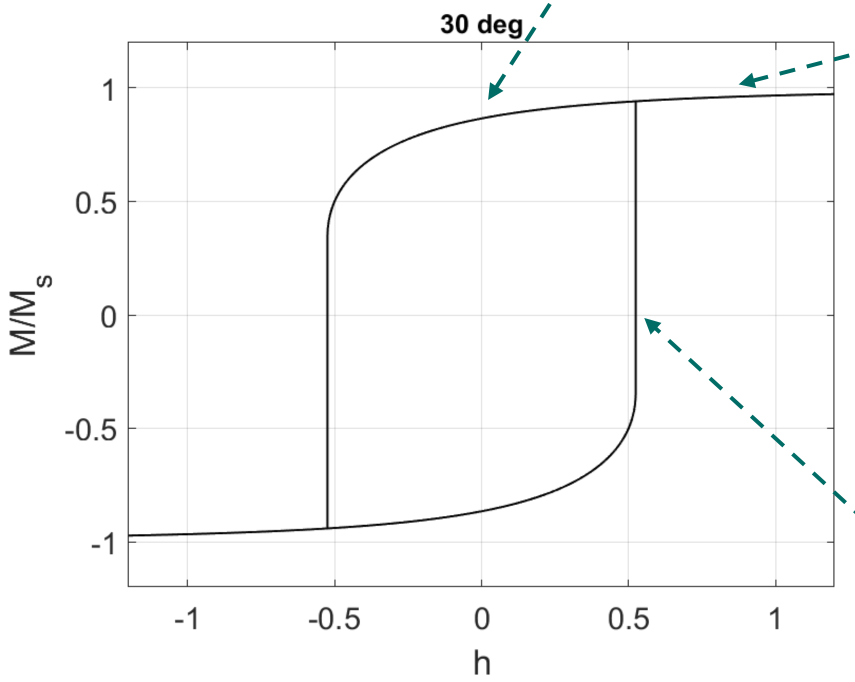


Max coercive field = anisotropy field

COERCIVITY:

Remanent magnetisation

Saturating field



Switching field:

When the magnetisation changes abruptly

Area of loop: Losses

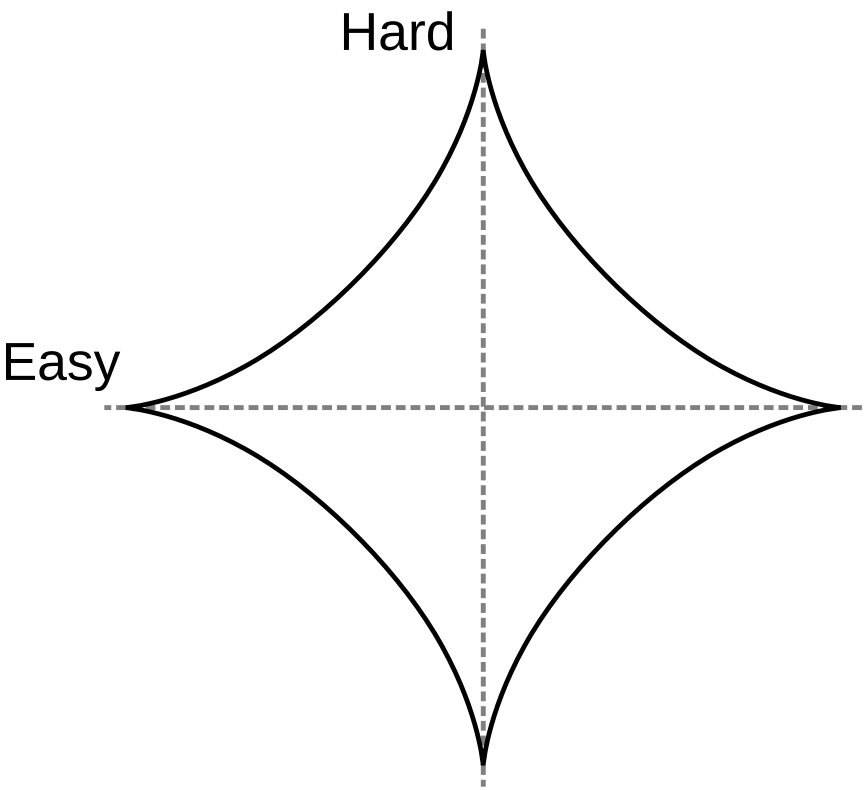
$$\int \mu_0 \boldsymbol{H}_{ext} \cdot \boldsymbol{m}$$

Note: Coercive field:

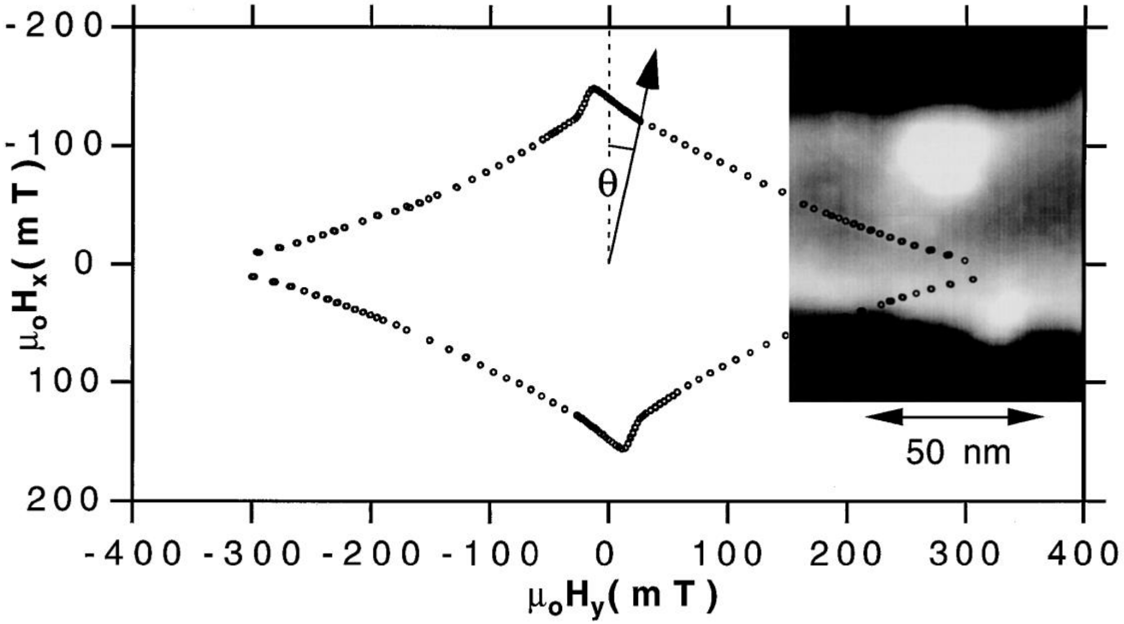
When M.H = 0

ASTEROID CURVE

Switching field as a function of angle:



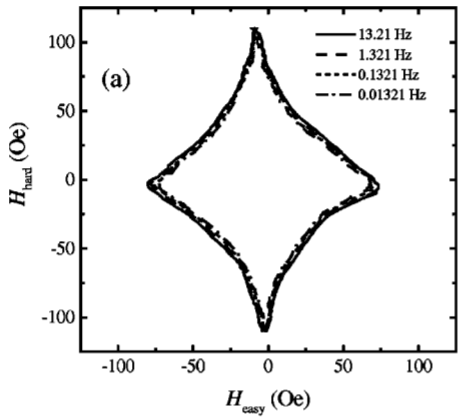
First experimental demonstration:
Ellipsoidal Co nanoparticle ~25 nm diameter



Wernsdorfer et al., PRL 78, 9 (1997)

MACRO SPIN FOR LARGER PARTICLES?

0.2x0.5 μm

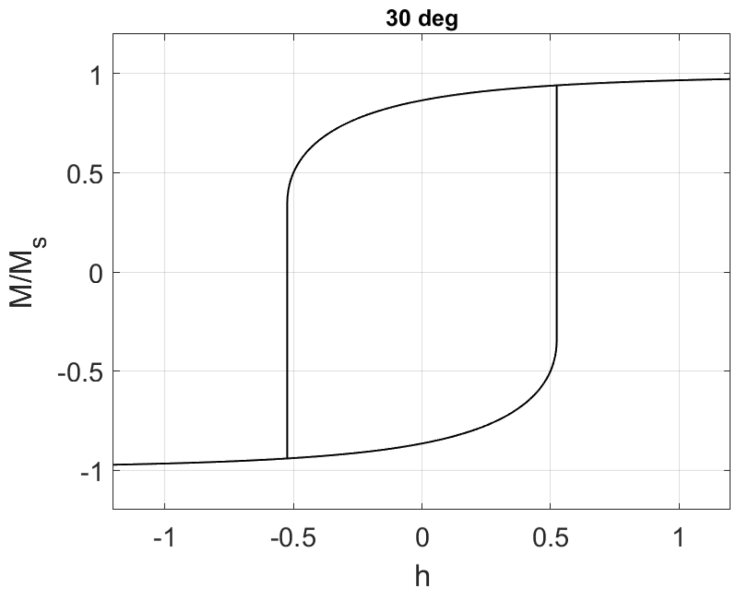


For flat particles (tunnel junctions)

Macro-spin model less applicable as size increases

Be careful when applying!

COERCIVITY: PARADOX



Max coercive field: reflective of anisotropy

→ But! Coercivity rarely this large! Difficult to get a coercive field that approaches anisotropy

Or, “Brown’s paradox”

→ Why does it switch prematurely? → size!

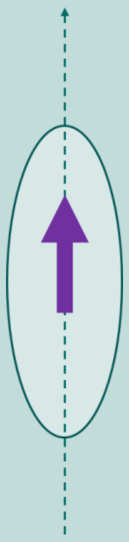
Can be described as: (William Brown, “Brown’s theorem”)

$$H_C \geq \underbrace{\left(\frac{2K_1}{\mu_0 M_S}\right)}_{\text{Magnetocrystalline}} - \underbrace{N M_S}_{\text{Shape}}$$

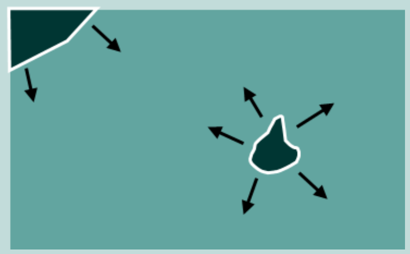
Anisotropies: Magnetocrystalline Shape

OUR QUESTIONS FOR TODAY:

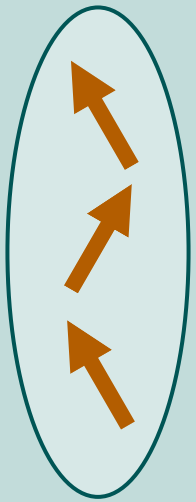
Reversal of a single particle



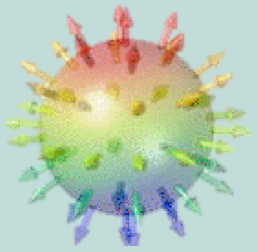
Domain wall motion



Alternative types of switching



Topology in reversal



BEYOND COHERENT ROTATION…

Can we assume coherent rotation?

→ Small particles, coherent rotation

→ Larger particles…?

Nucleation & propagation of domain walls

Intermediate configurations

LARGER SYSTEMS: INHOMOGENEOUS

Small region of inhomogeneous sample will switch first due to lower anisotropy

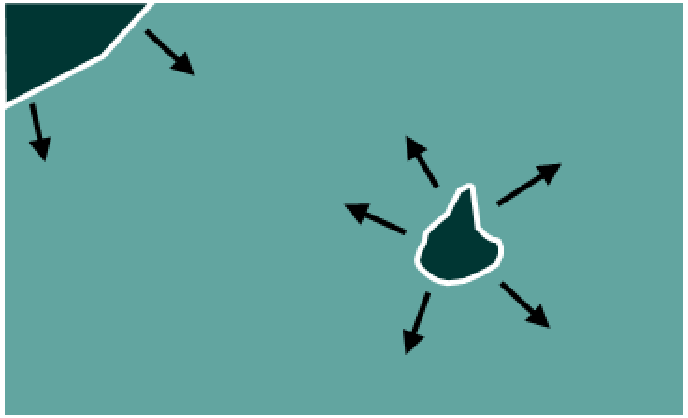
→ "nucleation field"

→ "Propagation field"

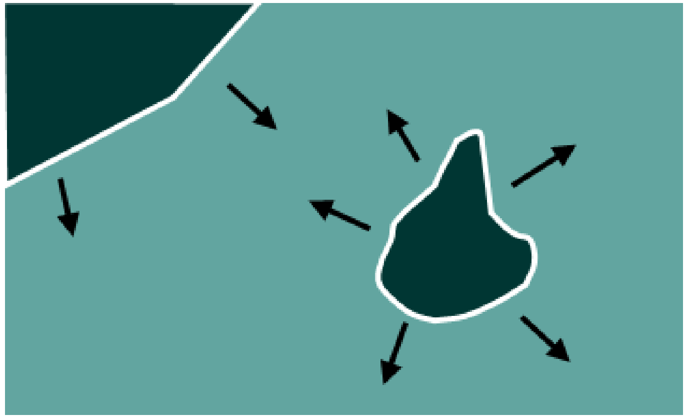
LARGER SYSTEMS: INHOMOGENEOUS

H ⊗

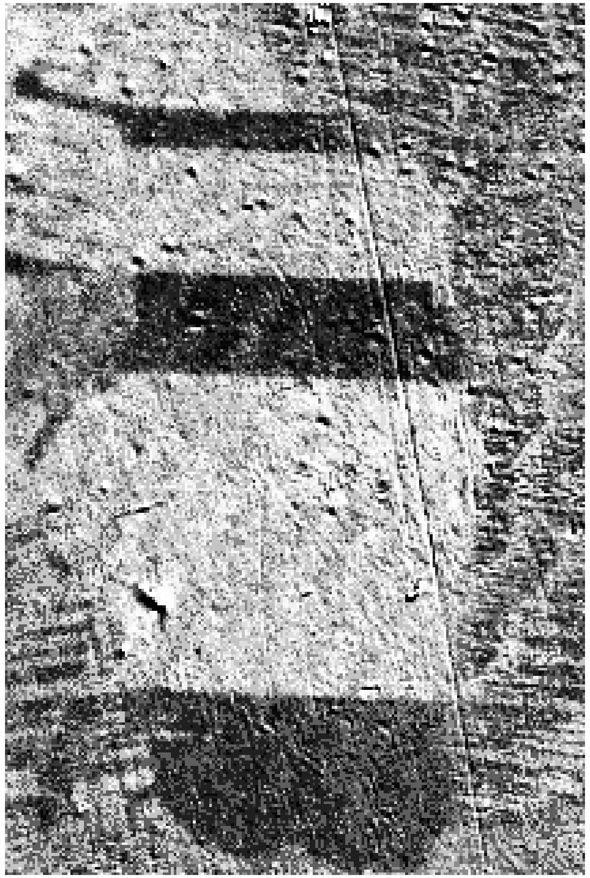
Surface charge effects



Internal defects

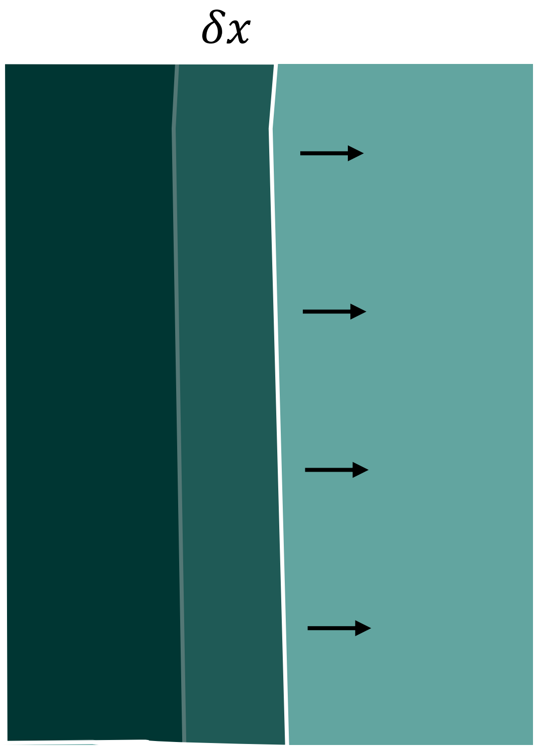


Domain walls move to grow domains



Seen experimentally in MOKE

DOMAIN WALL MOVES UNDER "PRESSURE"



As the wall moves δx:

$$\Delta E_Z = 2\mu_0 M H \delta x$$

(per unit area of wall)

We know that pressure:

$$p = \frac{F}{A} = \frac{Fx}{Ax}$$

Therefore:

$$p = \frac{E}{Ax} = 2\mu_0 M H$$

Leading to a velocity of

$$v_{DW} = \mu_0 \eta_{DW} (H - H_{dep})$$

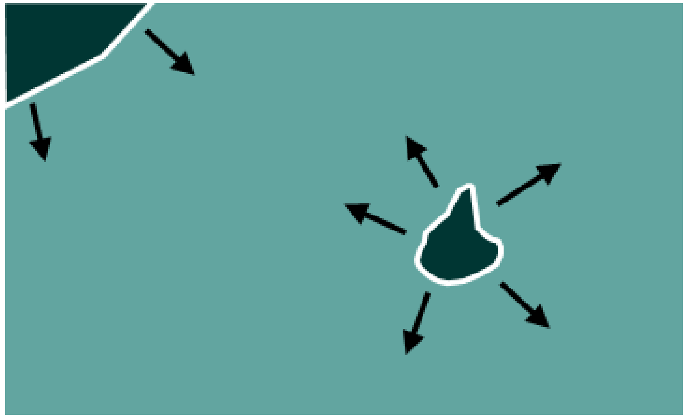
DW mobility
~1-1000 m /s /mT

"depinning field"

In a perfect system: domain walls move through system smoothly!

IN A NON-PERFECT SYSTEM:

Surface charge effects



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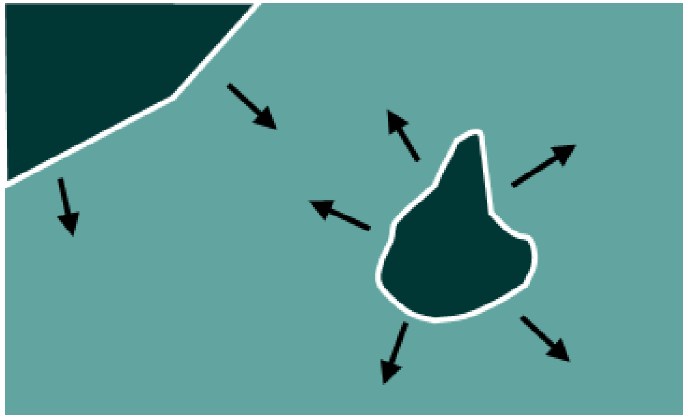
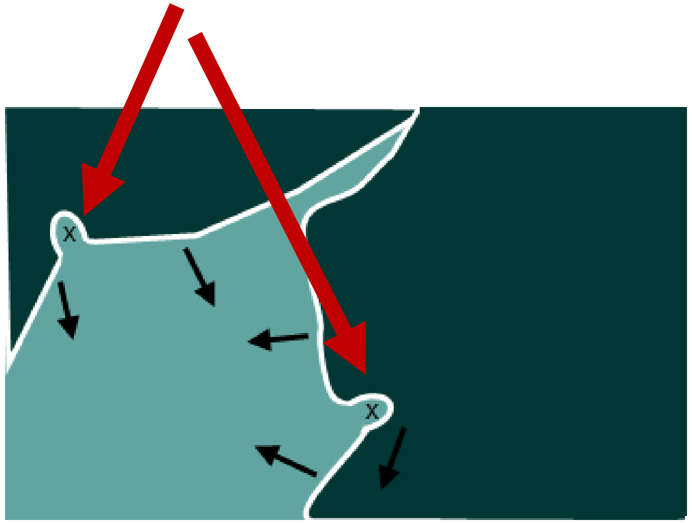


Domain walls move to grow domains

Pinning points: local defects

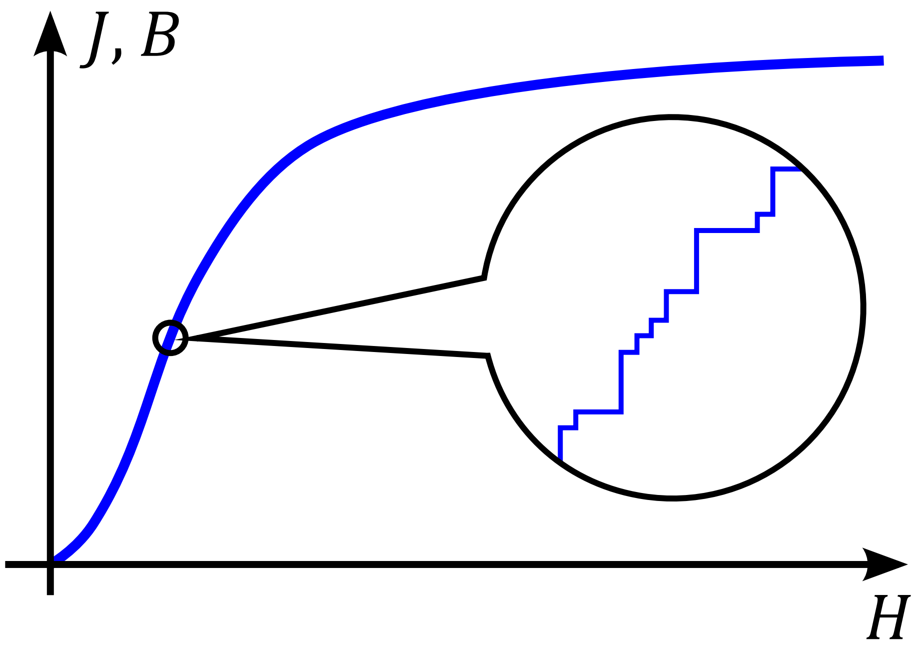


Until they get pinned by defects

→ ***Discontinuous motion***

BARKHAUSEN NOISE

First discovered by Barkhausen in 1919



Discrete jumps in the magnetisation

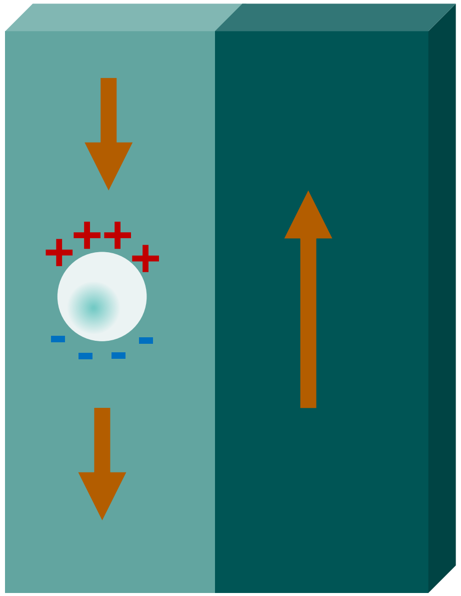
First evidence of ferromagnetic domains!

(pre-Bitter method!)

DOMAIN WALL PINNING

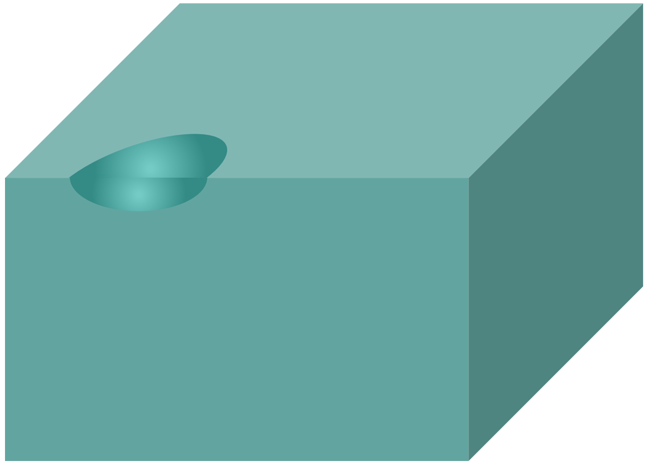
What causes this pinning?

→ Local changes in the energy landscape



Voids

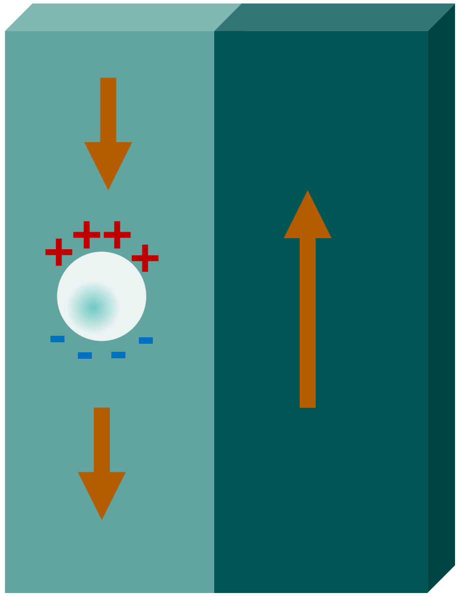
Grain boundaries



Surface defects

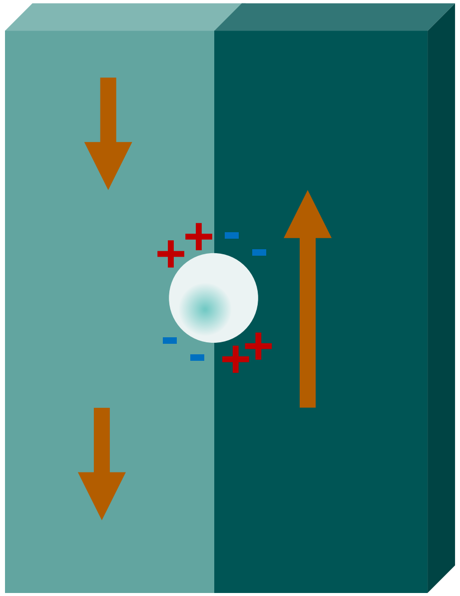
DOMAIN WALL PINNING: VOIDS

What causes this pinning? Voids:



Magnetostatic energy of a sphere:

$$E \propto \frac{1}{2}\frac{{M_S}^2}{3\mu_0}\frac{4\pi r^3}{3}$$



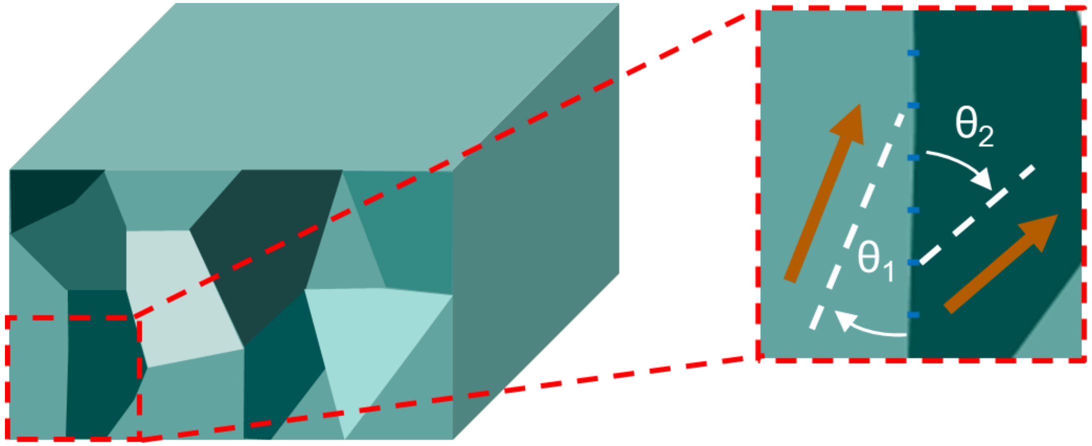
Domain wall intersecting void

→ Magnetostatic energy ~ halved!

DOMAIN WALL PINNING: GRAIN BOUNDARIES

Two grains with different anisotropies

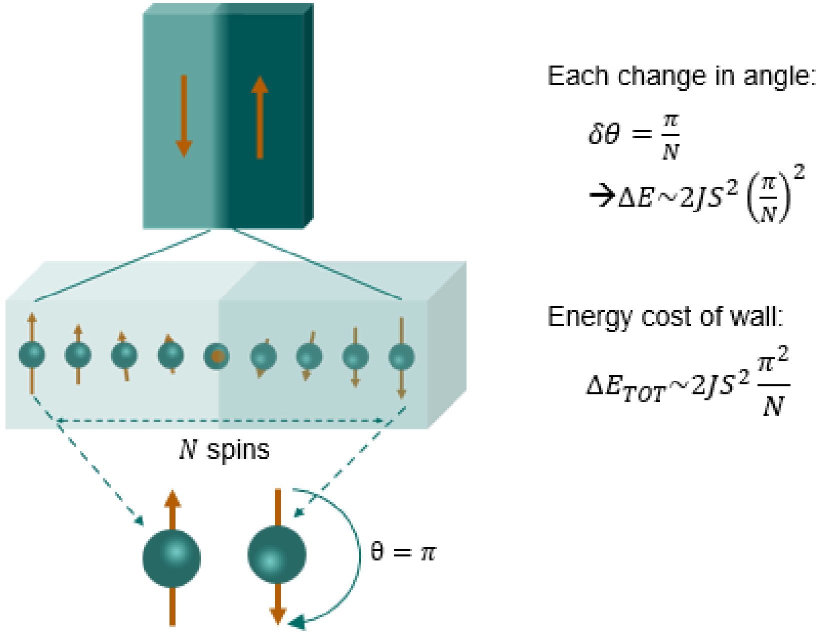
Without domain wall:



Magnetostatic energy of boundary:

$$E \propto (M_S(\cos\theta_1 - \cos\theta_2))^2$$

With domain wall:



Total angle of domain wall $< \pi$

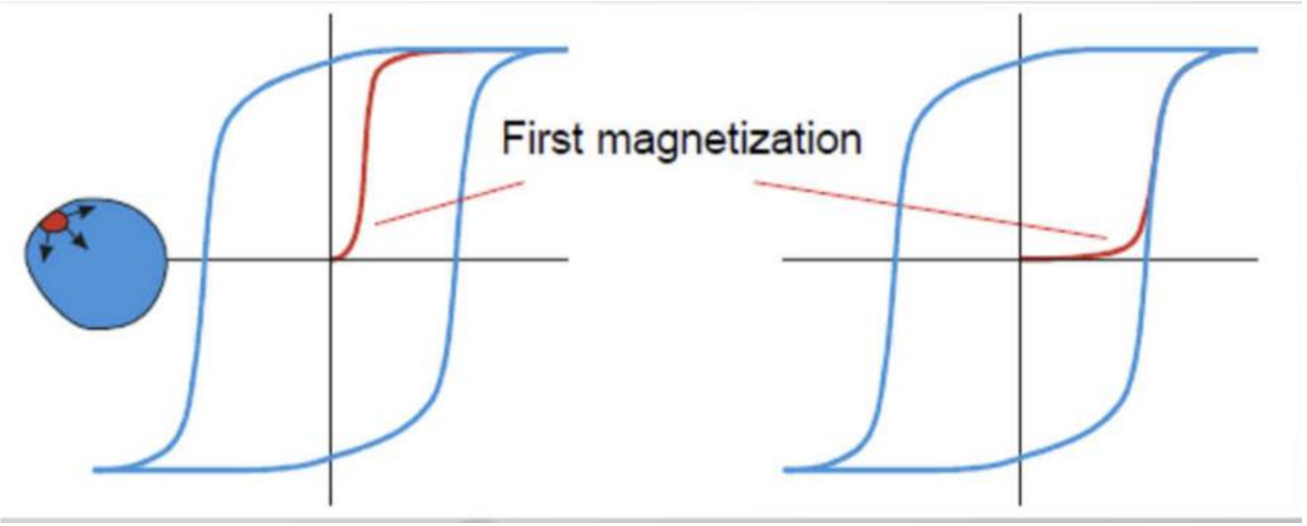
→ DW energy reduced

LARGE ANISOTROPIC SYSTEMS

Reversal stages:

1. Domain wall nucleation
2. Domain wall propagation
3. Coherent rotation

Can determine dominating factor by virgin magnetisation curves



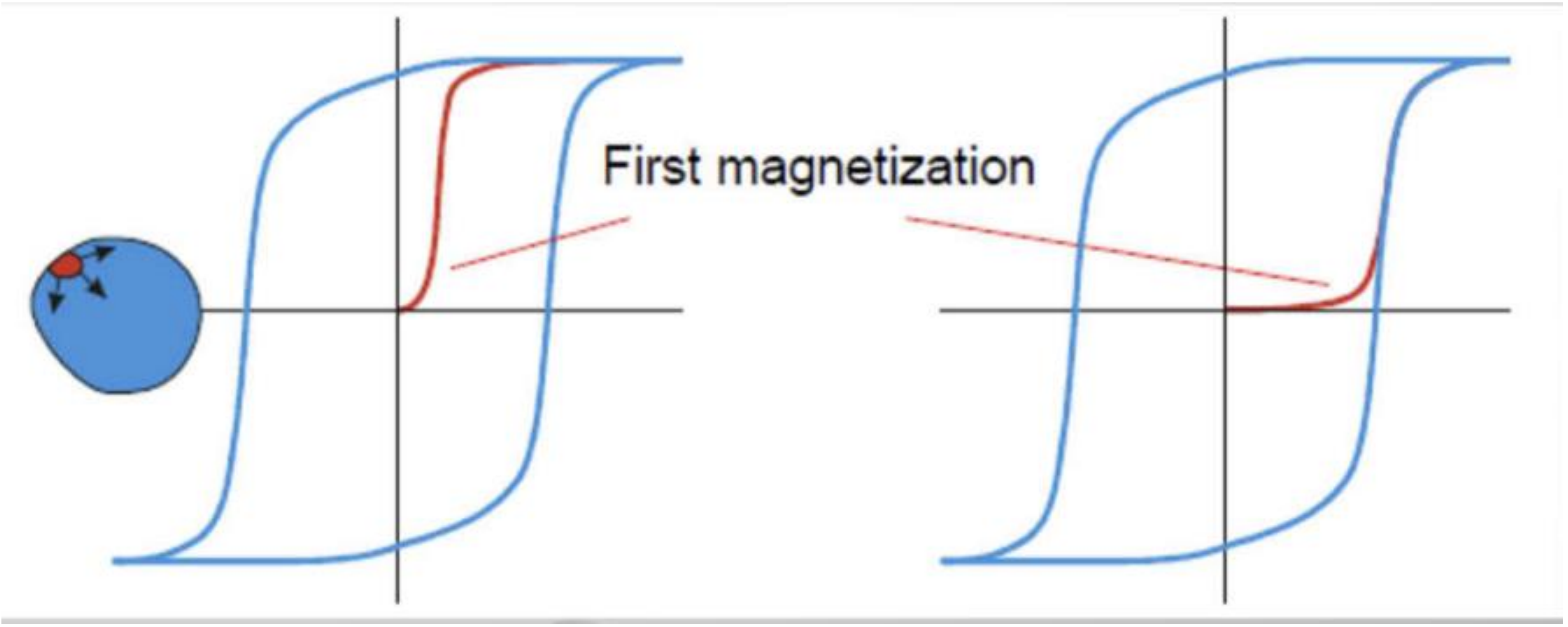
Nucleation field-limited

Depinning field-limited

Question:

Will a nucleation-limited switch give a square or rounded loop?

LARGE ANISOTROPIC SYSTEMS



Nucleation field-limited

Depinning field-limited

Few nucleation events needed
Followed by domain wall propagation → ~square loops

Many nucleation events needed
→ Rounded loops

THIN FILMS: NUCLEATING A DOMAIN WALL

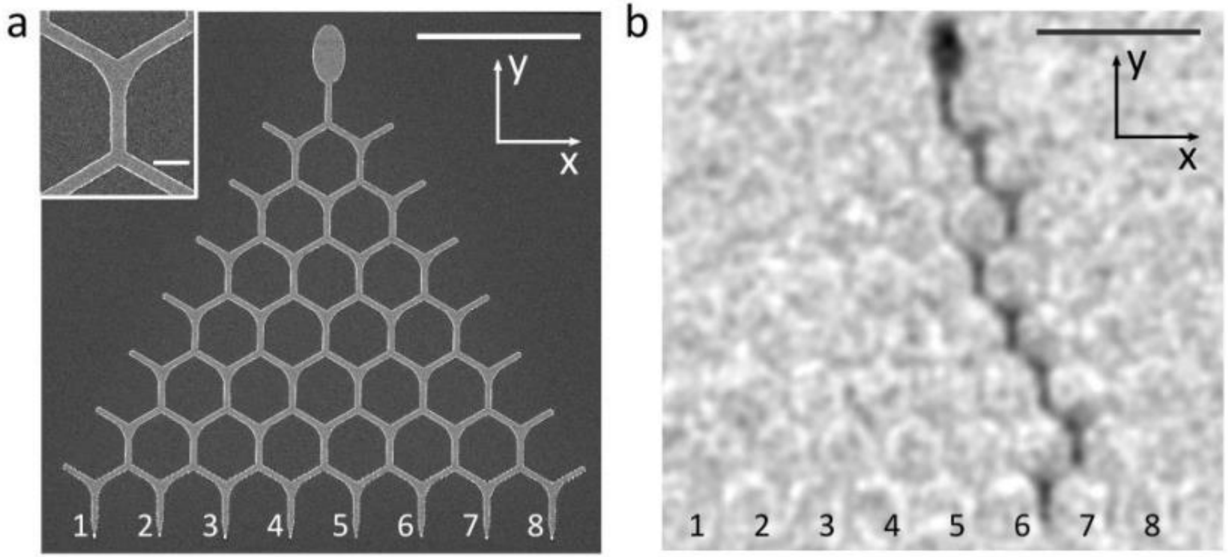
In a thin film:

Which has lower switching field?

THIN FILMS: NUCLEATING A DOMAIN WALL

In a thin film:

Region of low anisotropy: **nucleation pad**



Sanz-Hernández et al., Advanced Materials 33, 17 (2021)

QUESTION FROM Q&A:

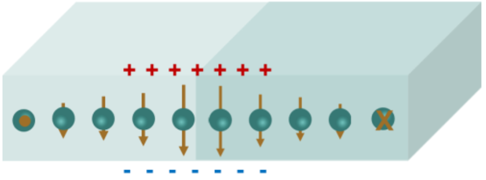
Amorphous ferromagnets are known as very soft magnetic materials. Compared with Permalloy thin films, why do amorphous ferromagnetics get more soft magnetic with increasing thickness, while the coercivity of premalloy thin films does not vary much with thickness?

Amorphous materials: neglect grain effects → Have shape anisotropy & surface effects

As film thickness increases:

Domain wall type changes

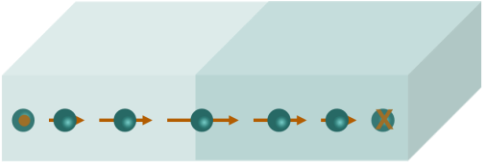
Bloch walls:



Surface charges

Stable for thick films

Neel walls:

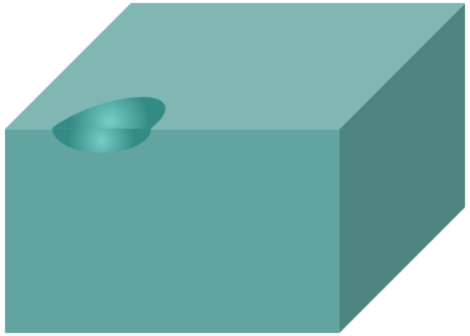


Volume charges

Stable for thin films

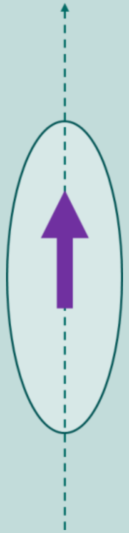
Shape anisotropy decreases

Surface defects less important

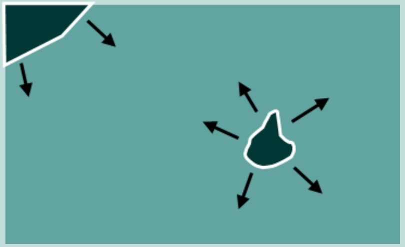


OUR QUESTIONS FOR TODAY:

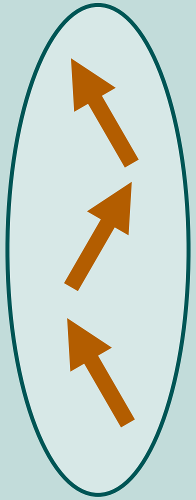
Reversal of a single particle



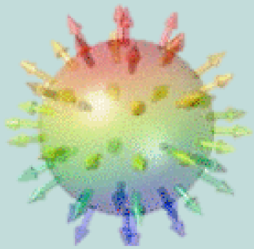
Domain wall motion



Alternative types of switching



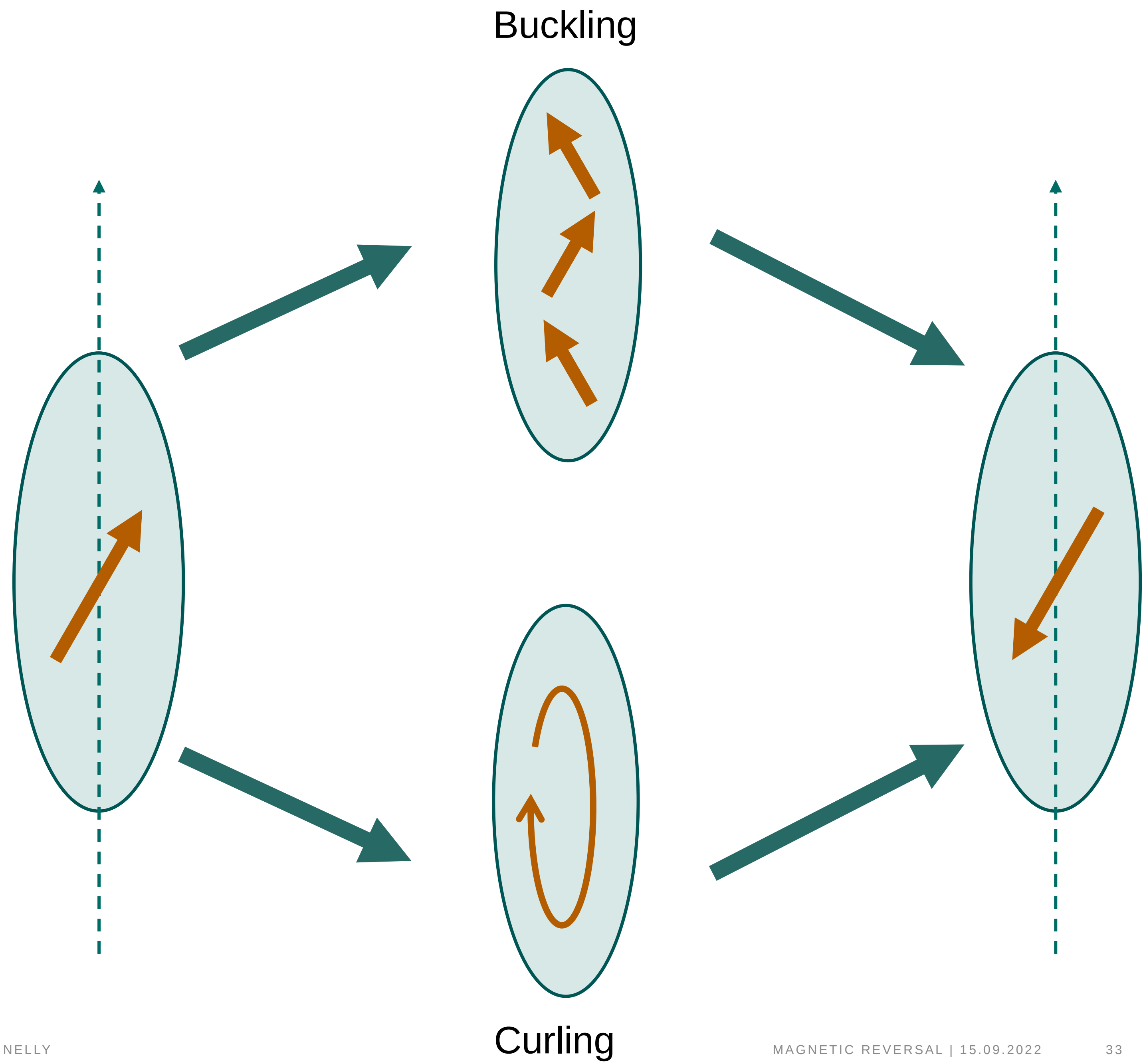
Topology in reversal



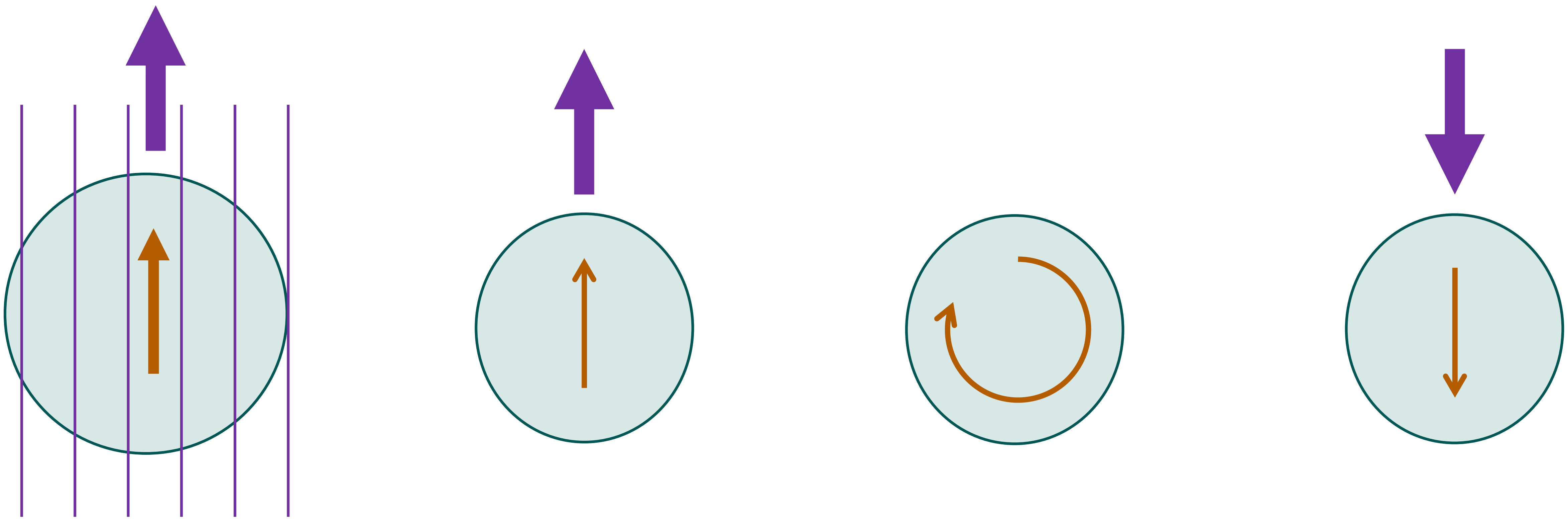
LARGER PARTICLES

Stoner Wohlfarth assumes macro spin – single domain

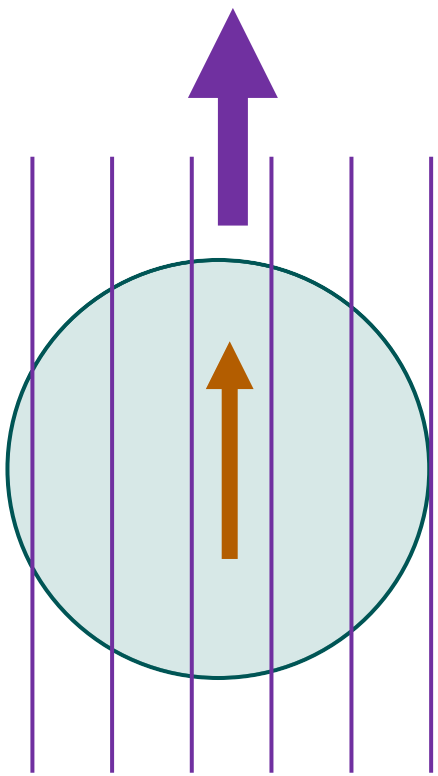
However, yesterday we realised that multi-domain states can be stable – if the sample is larger

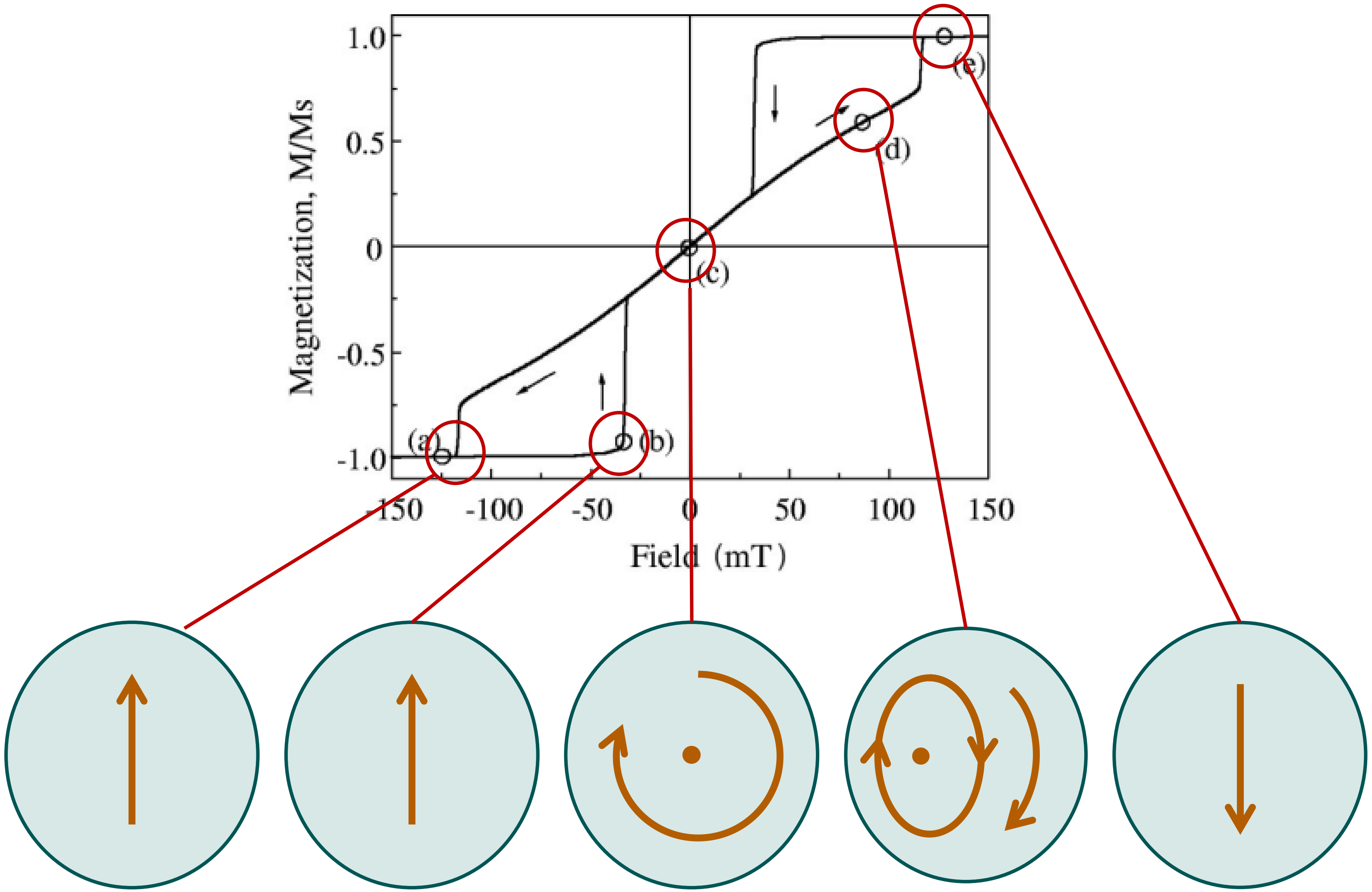


CURLING: A SOFT DISC



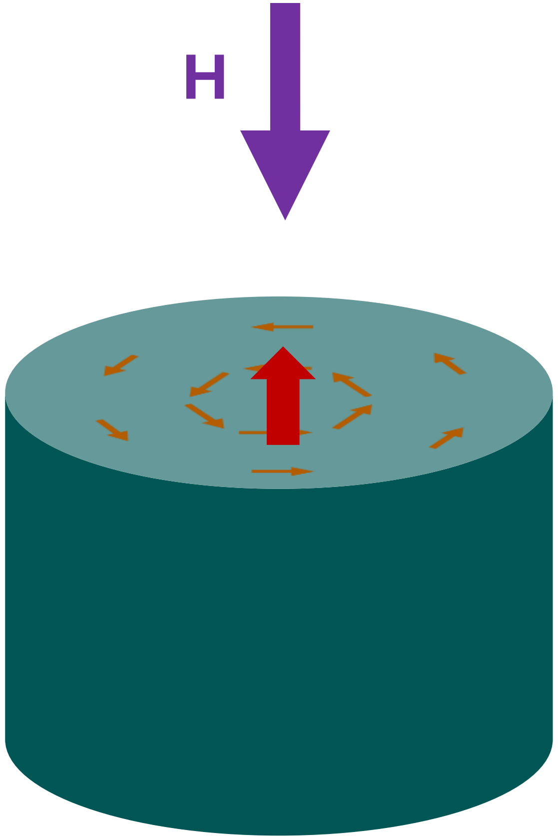
CURLING: A SOFT DISC





THE CORE OF A VORTEX:

Vortex core magnetisation reversal:

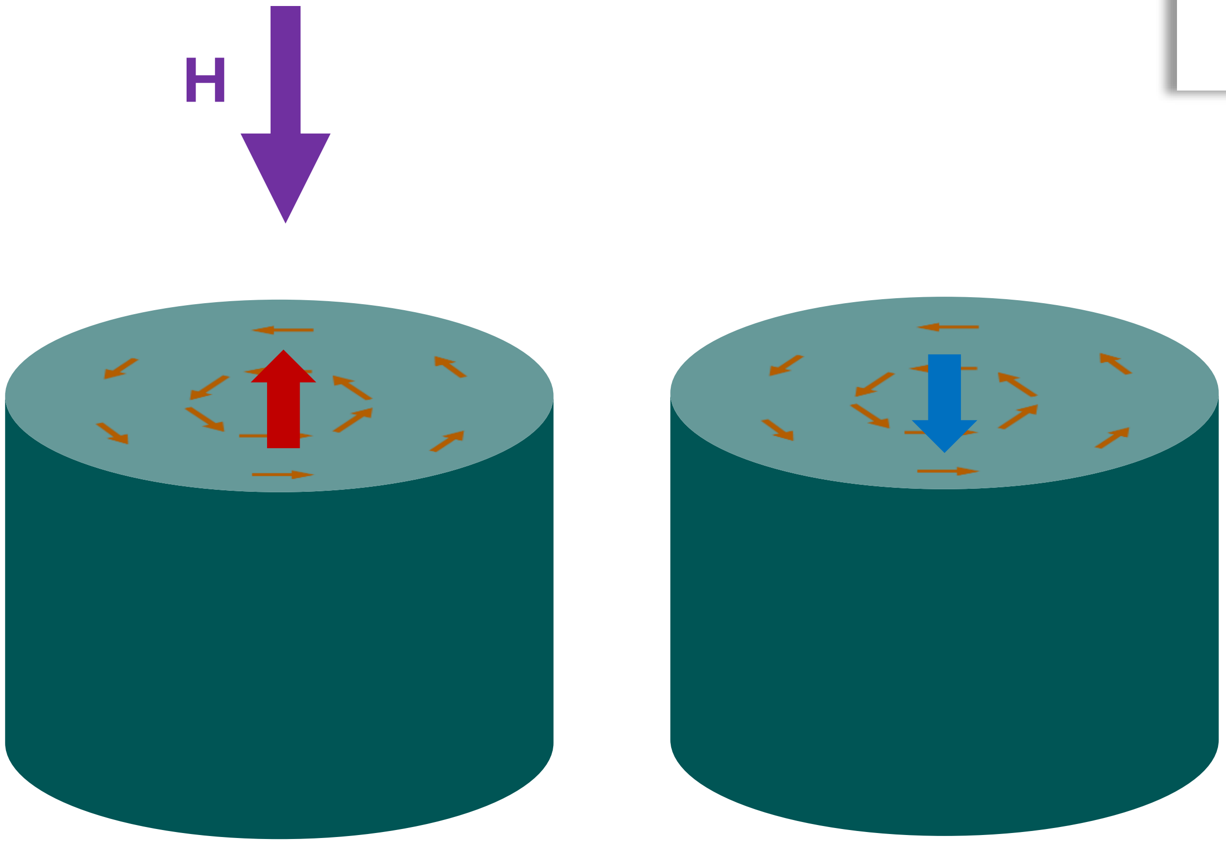


Magnetic field coupled to the vortex core only

Coherent reversal of vortex core magnetization is topologically impossible

THE CORE OF A VORTEX:

Vortex core magnetisation reversal:



Calculates over a surface

For a vortex:

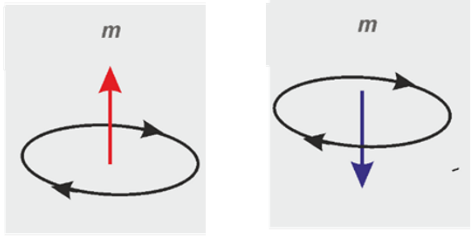
$$n = \frac{wp}{2}$$

w – winding number

p – polarisation

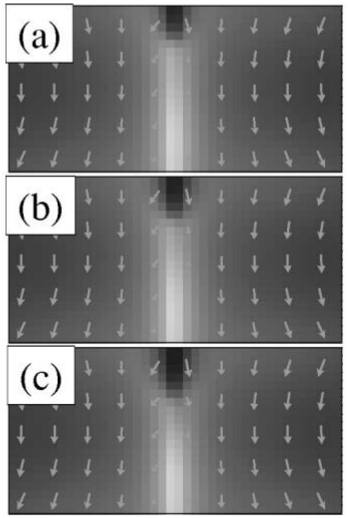
Tretiakov PRB 75, 012408 (2007)

$n = +\frac{1}{2}$ $\qquad$ $n = -\frac{1}{2}$



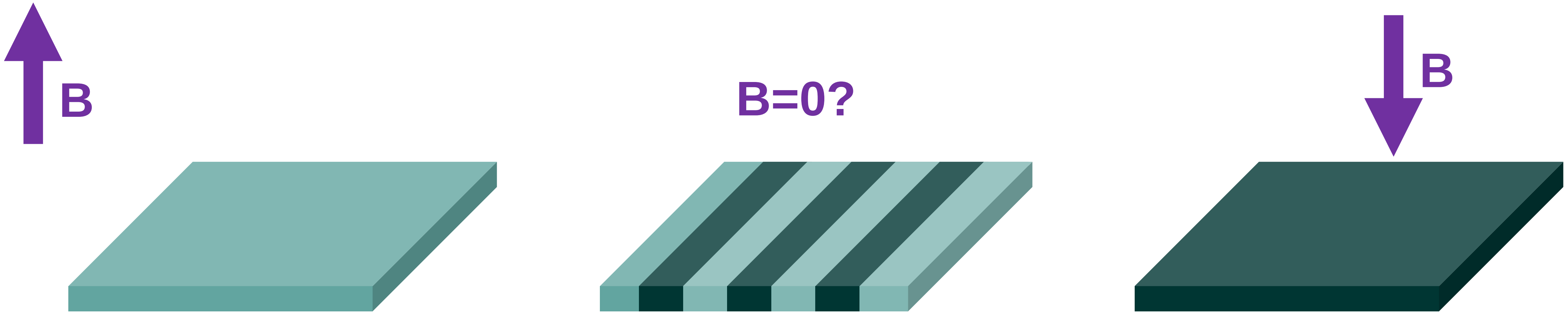
Reversal of core → change in topology

Mediated by a Bloch point



Thiaville et al.,
PRB **67**, 094410 (2003)

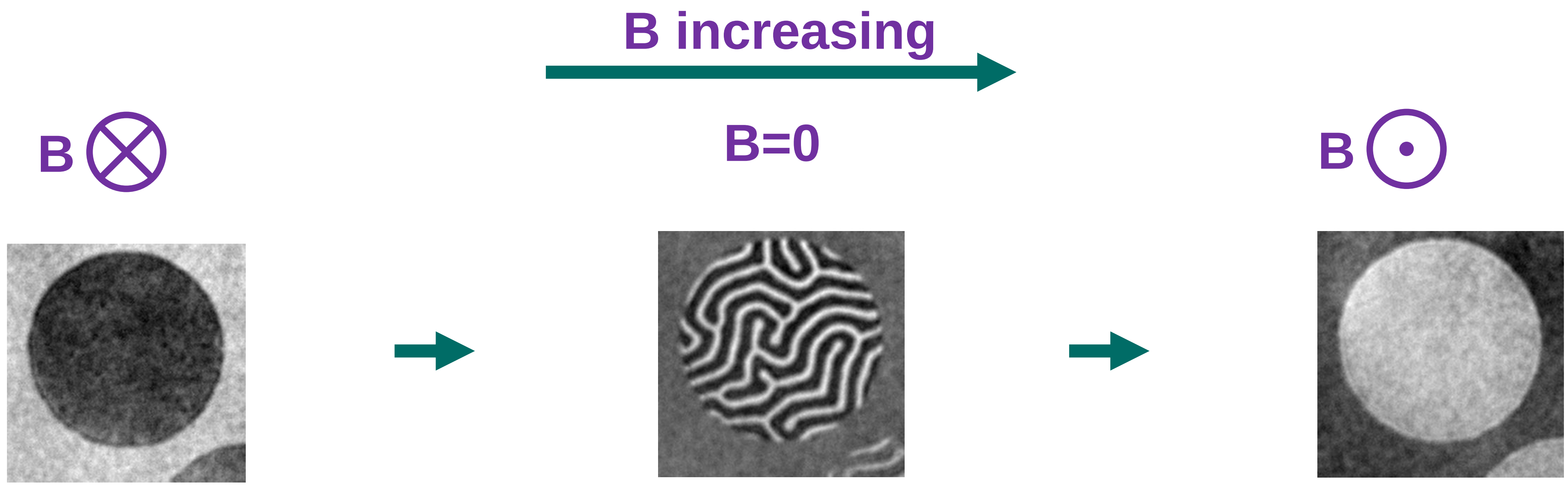
PERPENDICULAR ANISOTROPY



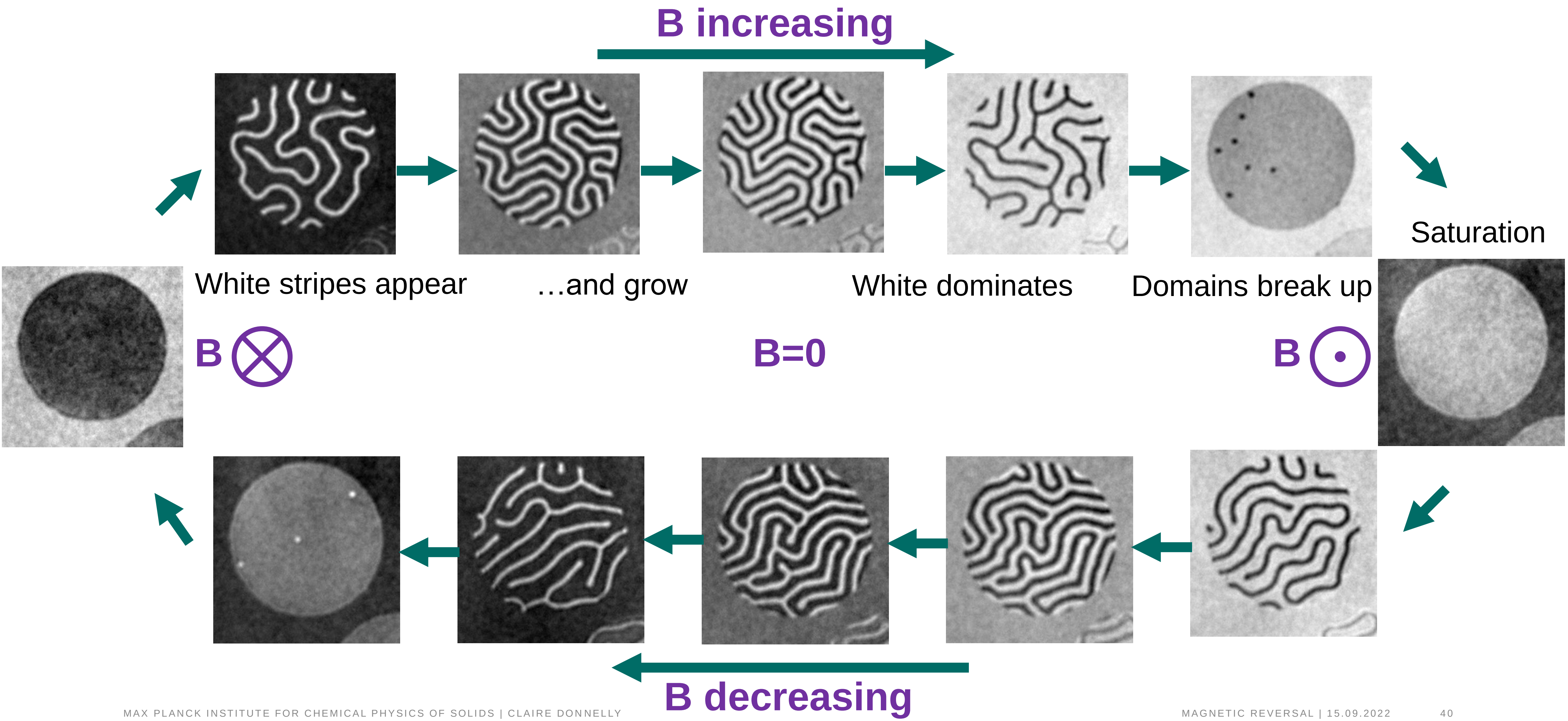
PERPENDICULAR ANISOTROPY

How do these evolve?

Let's look at some data:

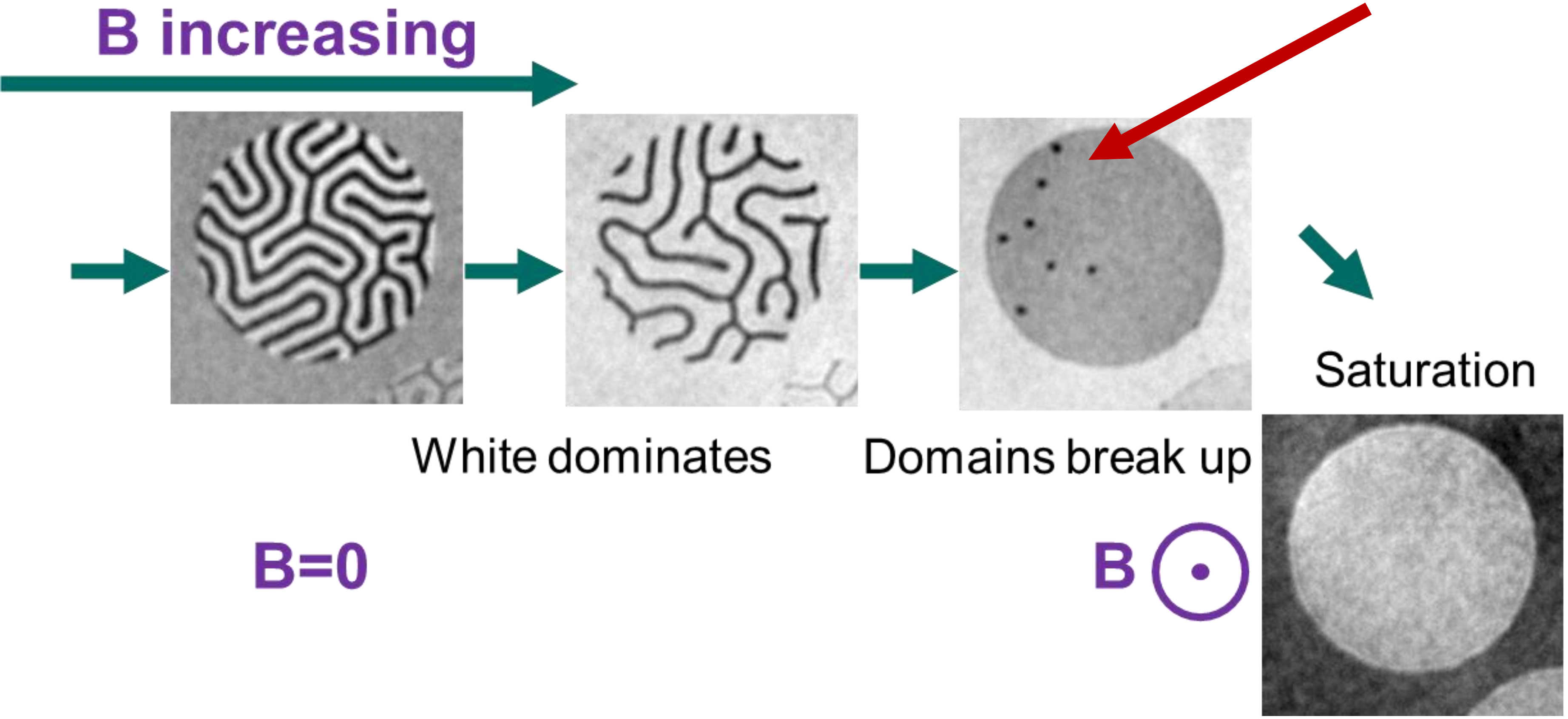


PERPENDICULAR ANISOTROPY

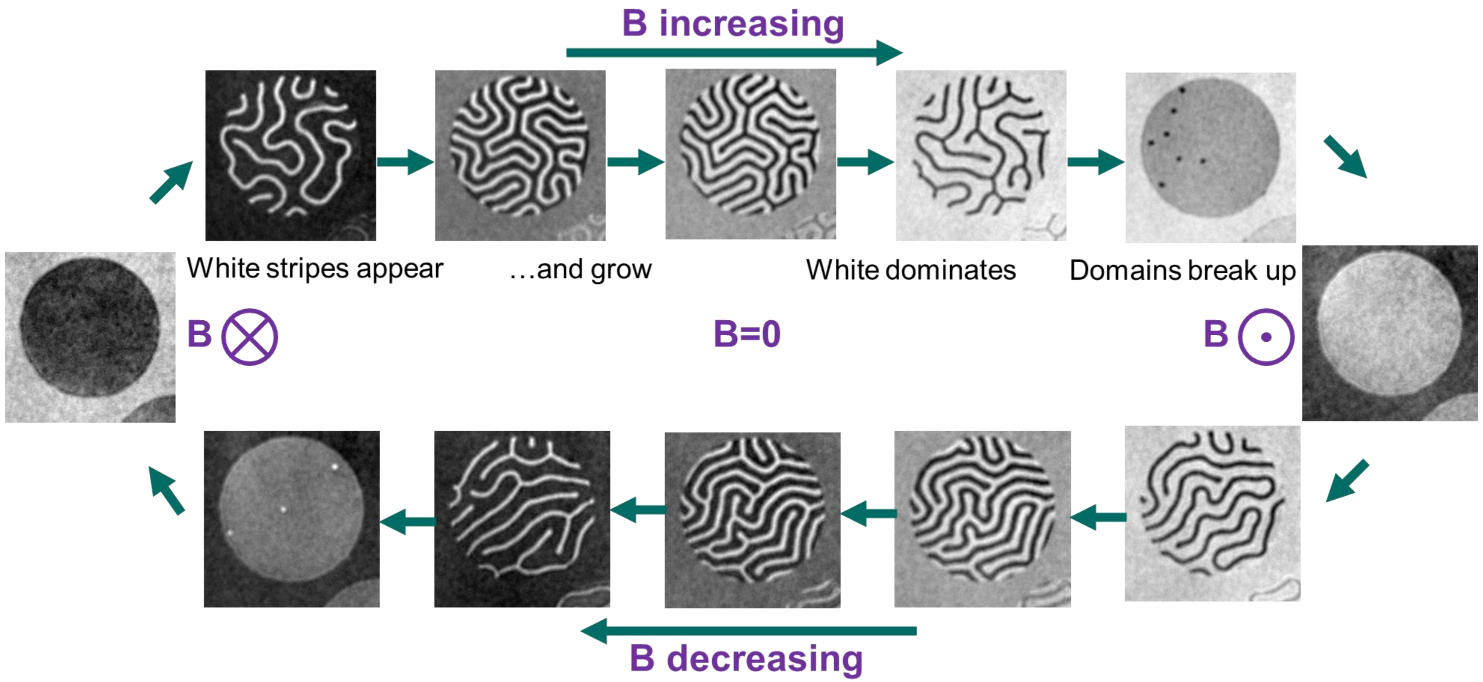


DOMAINS BREAK UP INTO

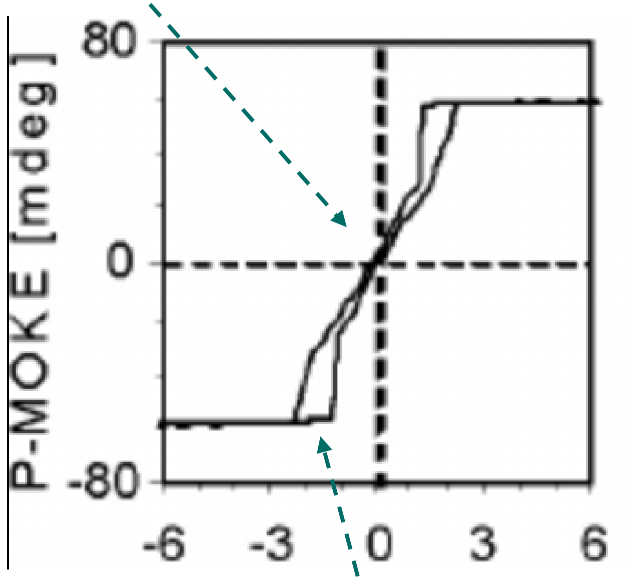
"Bubble domains" or skyrmions



PERPENDICULAR ANISOTROPY: HYSTERESIS

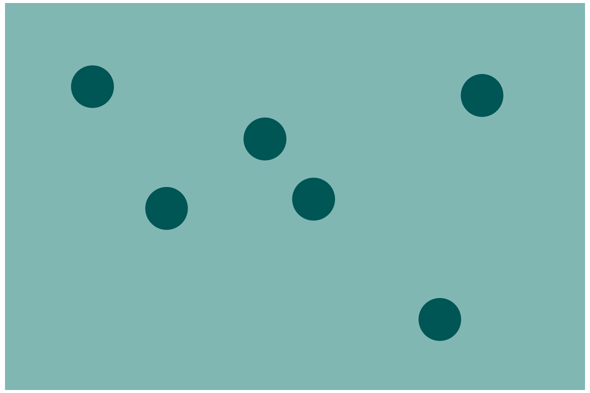


Linear: expansion of domains

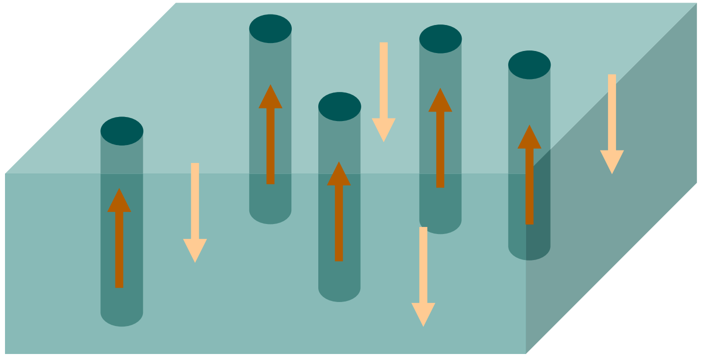


Abrupt: formation of bubbles/ domains

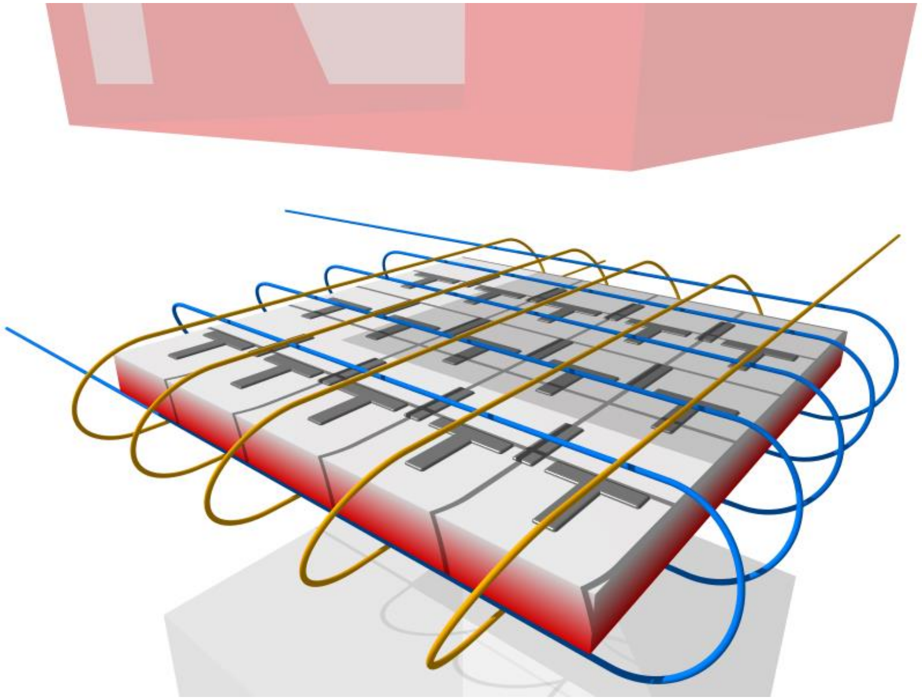
BUBBLE DOMAINS AND SKYRMIONS



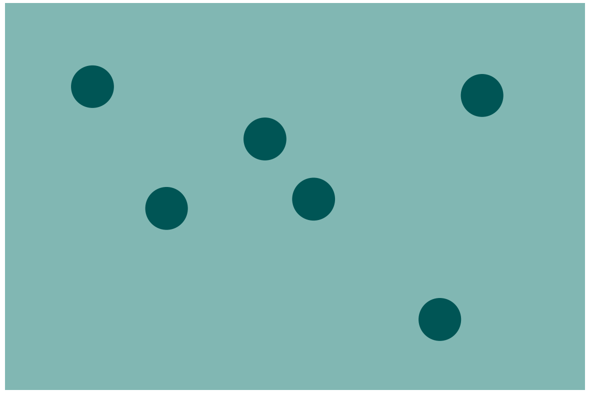
Cylindrical domains



Bubble domains: studied in 1970s, “Bubble memory” proposed

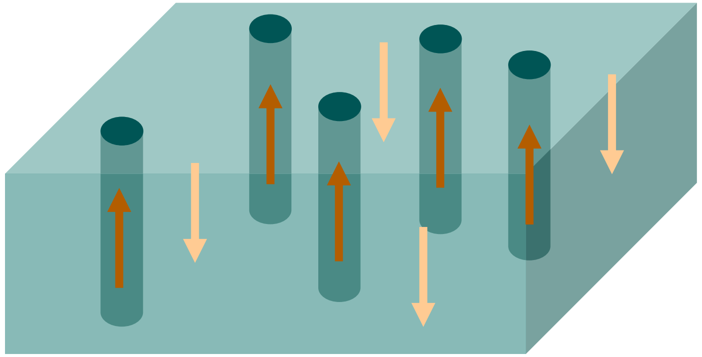


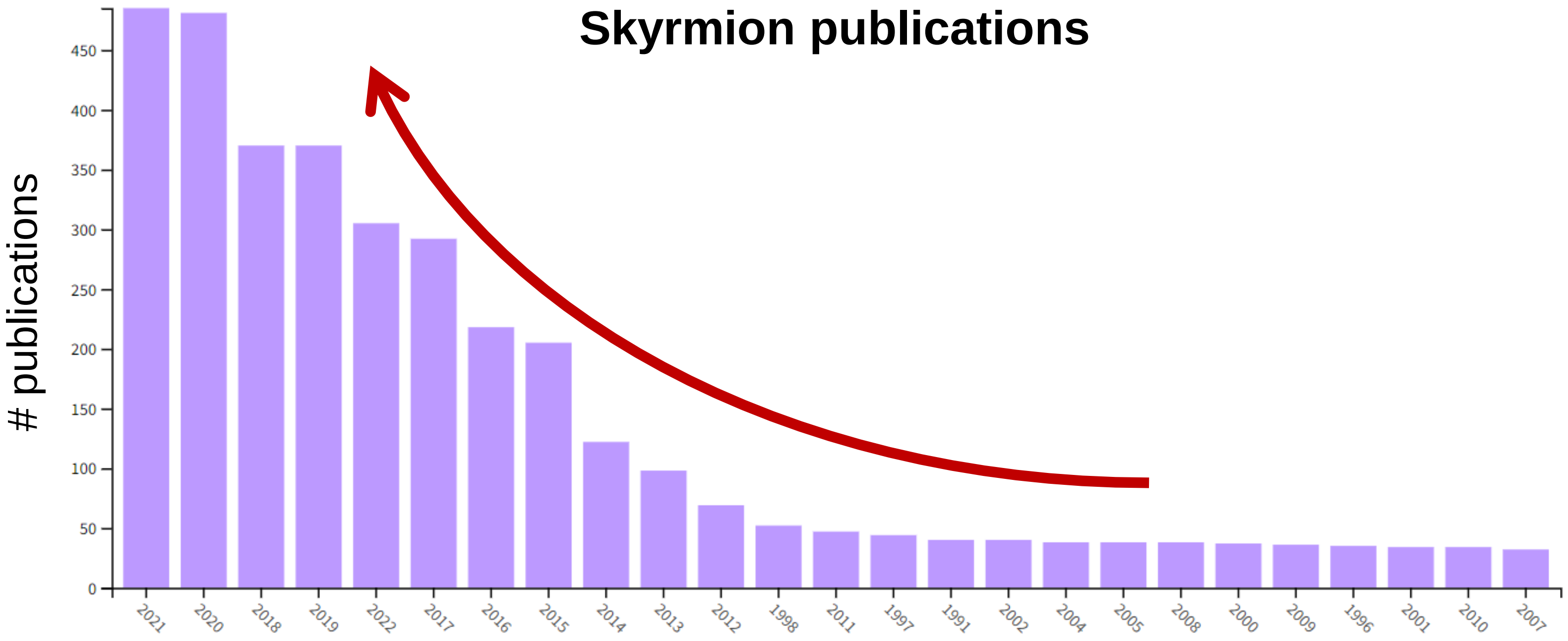
BUBBLE DOMAINS AND SKYRMIONS



Bubble domains: studied in 1970s, “Bubble memory” proposed

Cylindrical domains

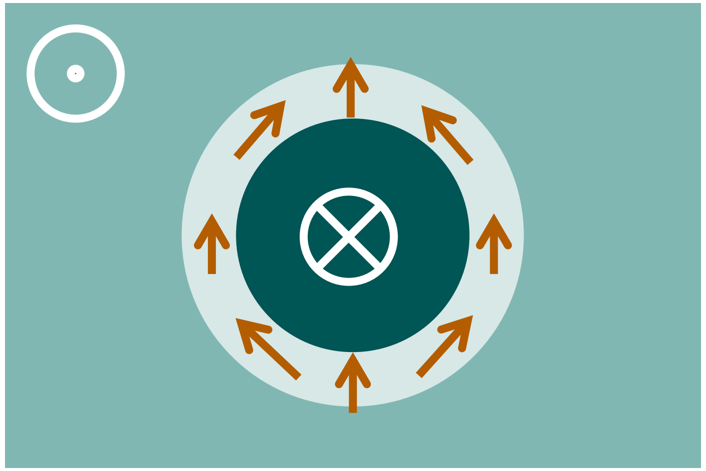


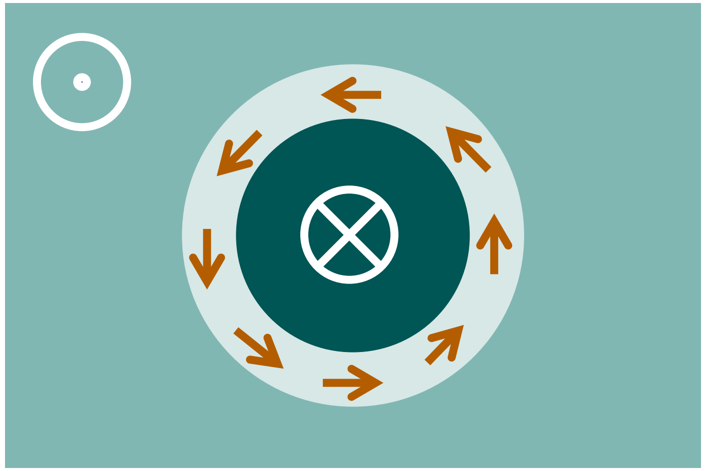


From webofscience.com

BUBBLES VS SKYRMIONS

Bubbles: can have different types of domain walls



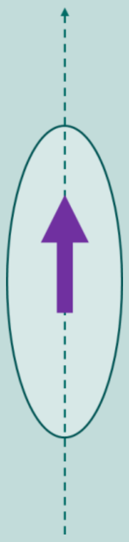


Skyrmions?

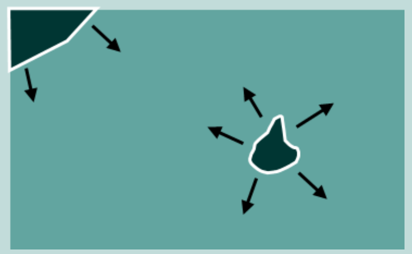
"Topologically non-trivial"

OUR QUESTIONS FOR TODAY:

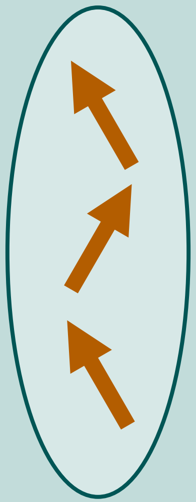
Reversal of a single particle



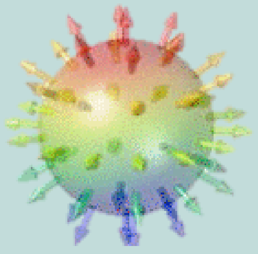
Domain wall motion



Alternative types of switching



Topology in reversal



UNDERSTANDING: TOPOLOGY

Key: *Smoothly deform!*

Meaning:

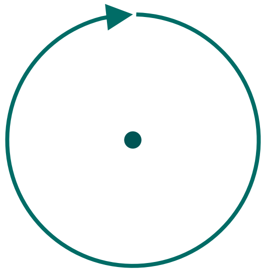
~

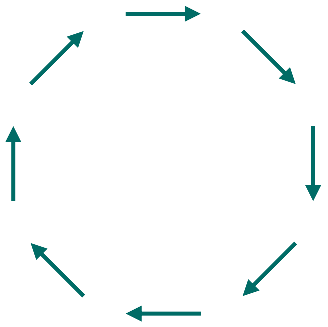
≠

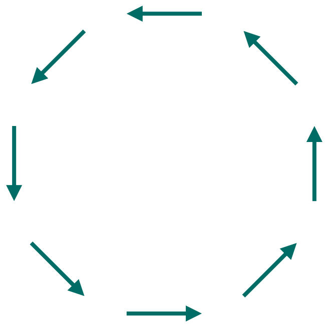
For magnetism?

→ *assume continuous vector field*

Let's start with 2D!
Winding number:







Are these topologically equivalent?

UNDERSTANDING: TOPOLOGY

Key: *Smoothly deform!*

Meaning:

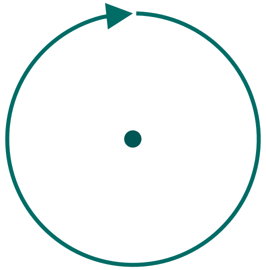
~

≠

For magnetism?

→ assume continuous vector field

Let's start with 2D!
Winding number:



Wind clockwise
→ W=+1

Wind clockwise
→ W=+1

Are these topologically equivalent?

UNDERSTANDING: TOPOLOGY

Key: *Smoothly deform!*

Meaning:

~

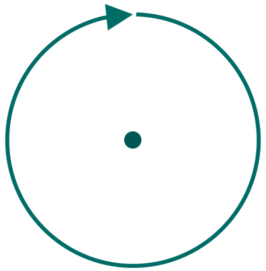
≠

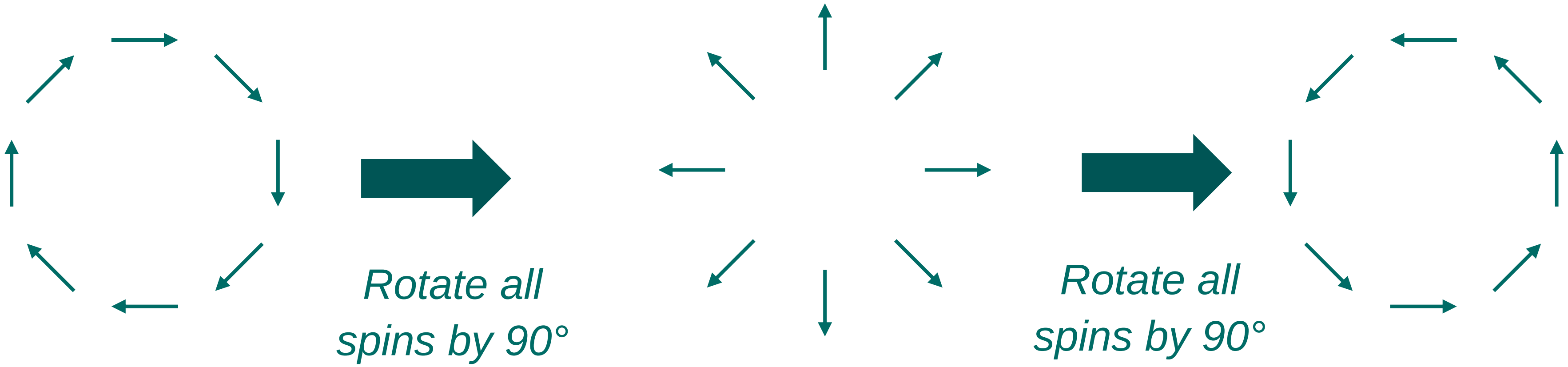
For magnetism?

→ assume continuous vector field

Let's start with 2D!

Winding number:





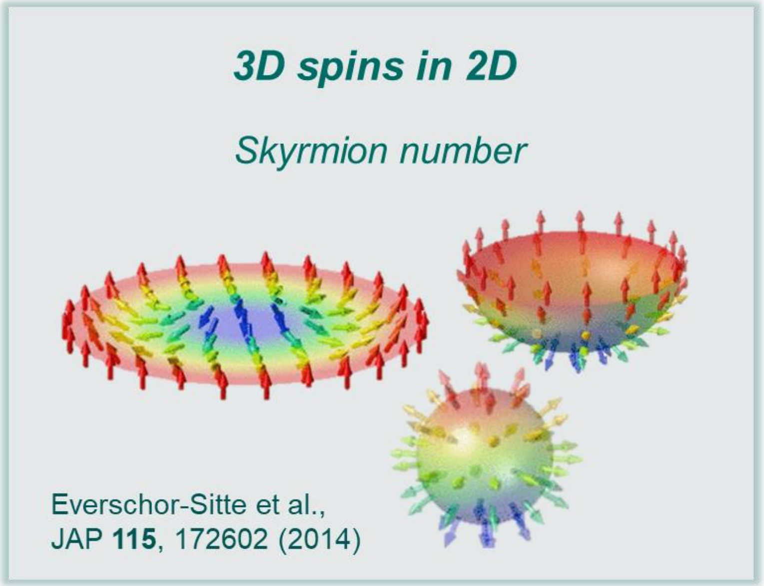
TOPOLOGY

Key: *Smooth unwinding!*

Meaning:

$\sim$

$\neq$



Skyrmion number:

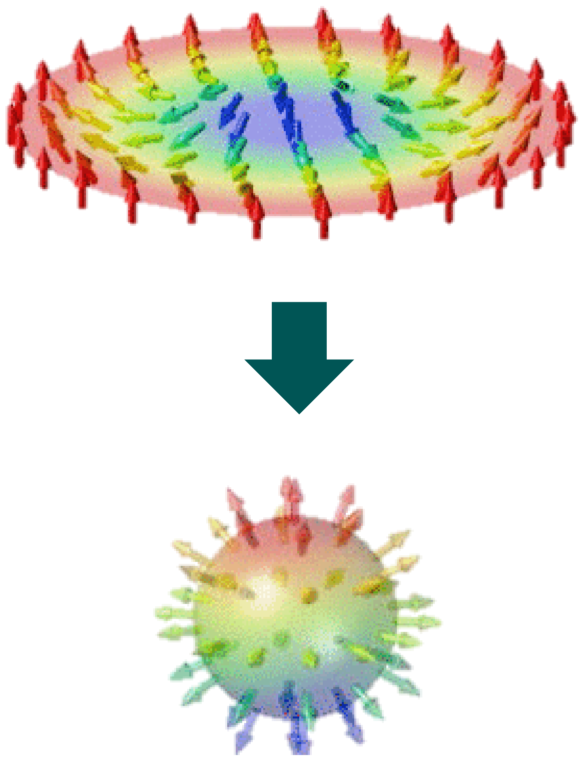
$$n = \frac{1}{4\pi}\int \mathbf{M}\cdot\left(\frac{\partial \mathbf{M}}{\partial x}\times\frac{\partial \mathbf{M}}{\partial y}\right)dxdy$$

Calculates over a surface

- Considers how many of the directions are present

SKYRMIONS & TOPOLOGY

Skyrmion number: How do the existing spins map onto the sphere?



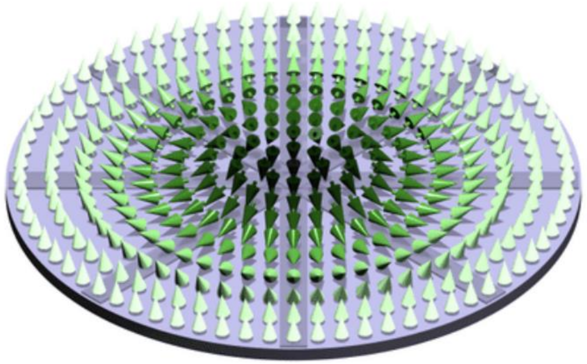
$$n = \frac{1}{4\pi}\int \mathbf{m}\cdot\left(\frac{\partial \mathbf{m}}{\partial x}\times\frac{\partial \mathbf{m}}{\partial y}\right)dxdy$$

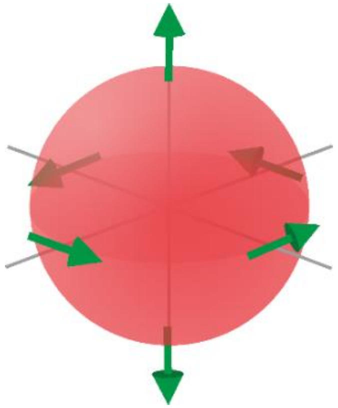
$$n = 1$$

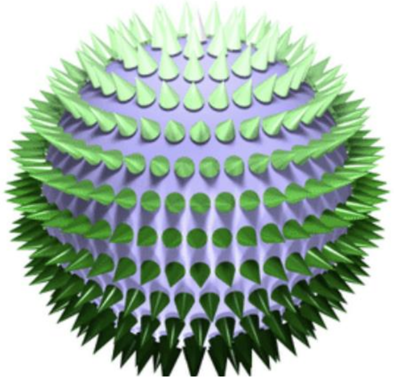
SKYRMIONS & ANTISKYRMIONS?

Skyrmion

$n = 1$

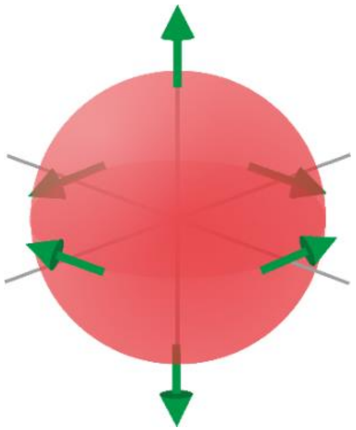






Anti-skyrmion

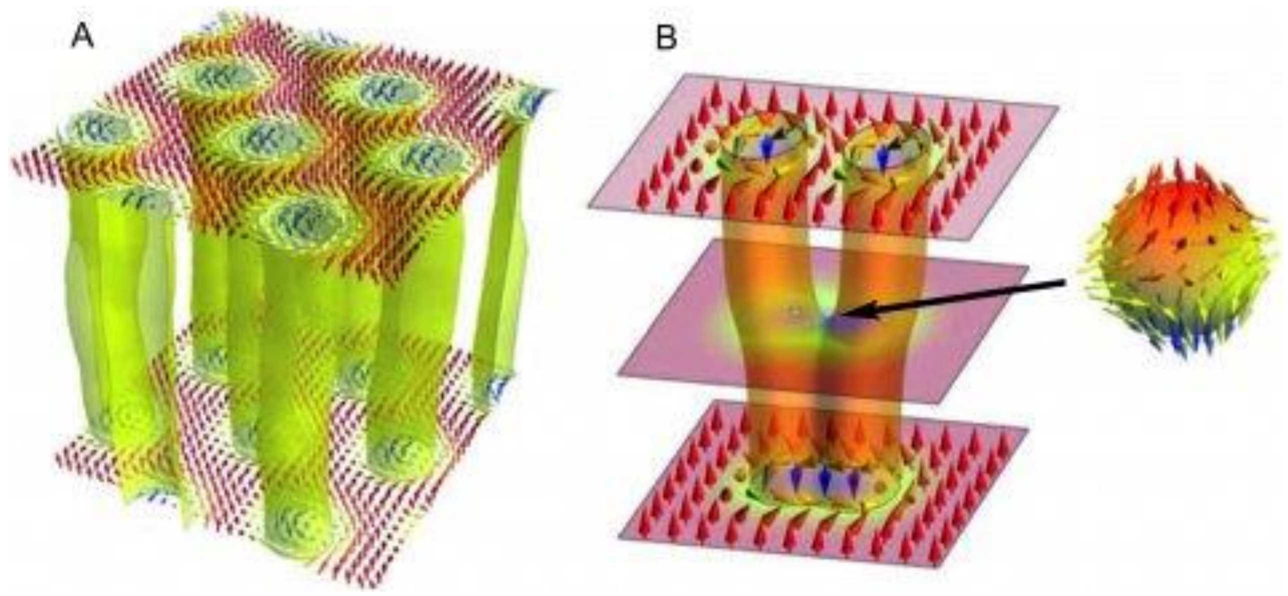
$n = -1$



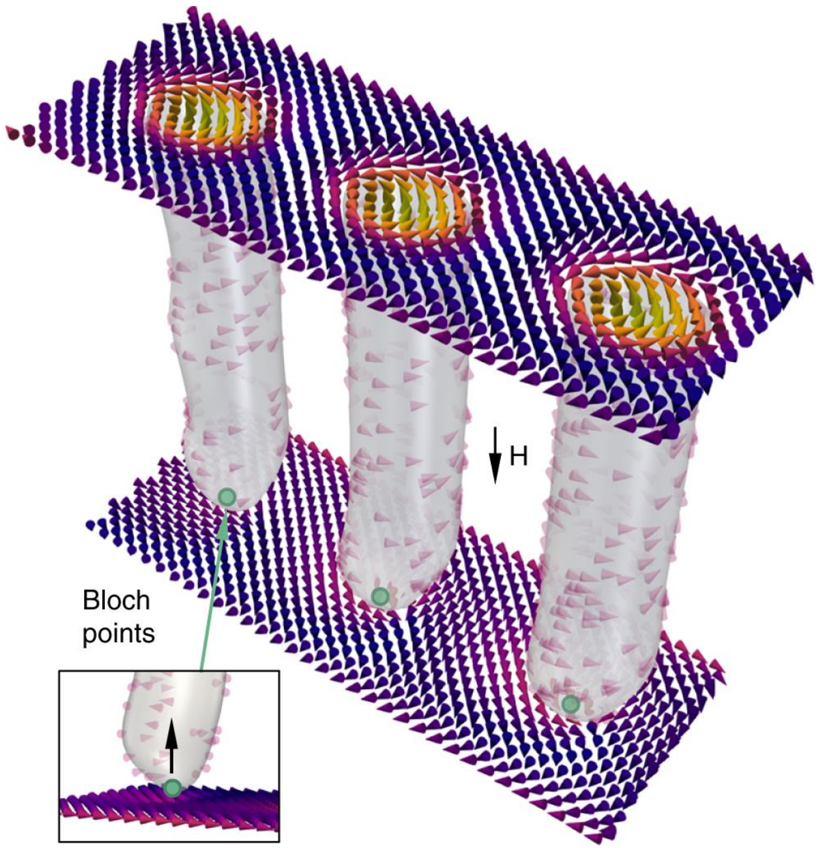
Hoffmann et al., Nat. Comm. 8, 308 (2017)

UNZIPPING A SKYRMION?

Requires a Bloch point singularity



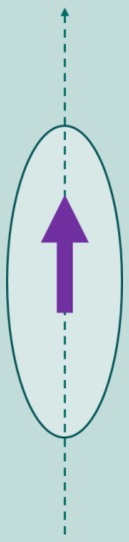
P. Milde et al., Science 340, 6136, (2013).



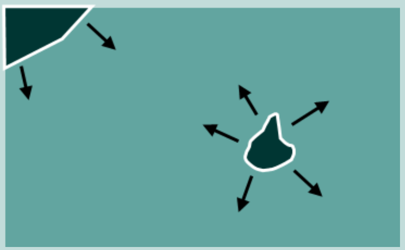
Birch et al. Nat. Comm. **11**, 1726 (2020)

OUR QUESTIONS FOR TODAY:

Reversal of a single particle



Domain wall motion



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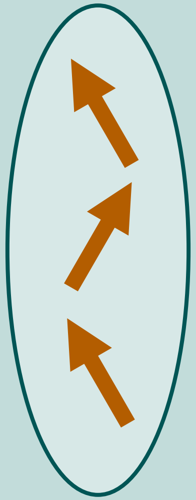

Topology in reversal