MAX PLANCK INSTITUTE
FOR CHEMICAL PHYSICS OF SOLIDS

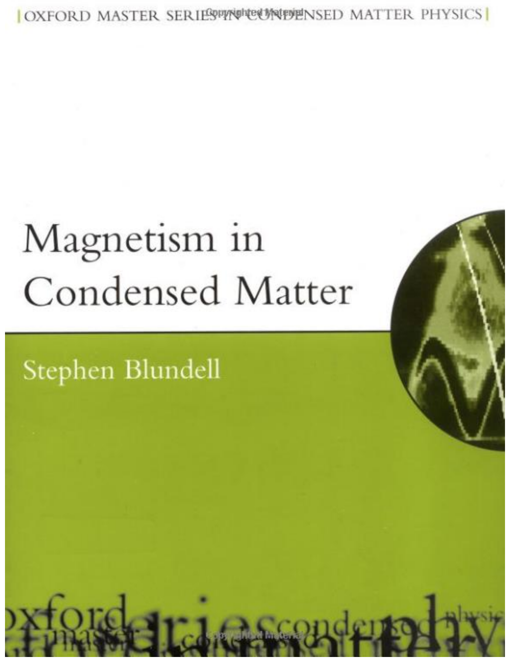
MAGNETISATION CONFIGURATIONS

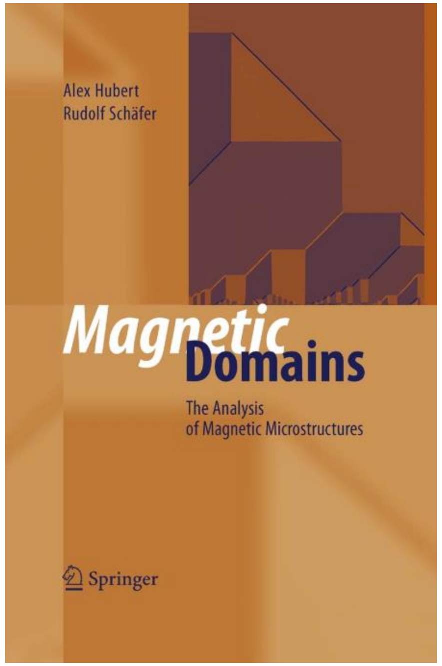
Claire Donnelly

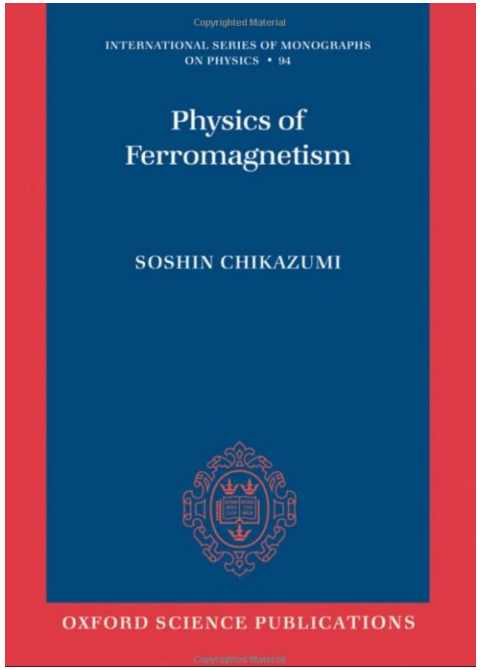
European School of Magnetism 2022

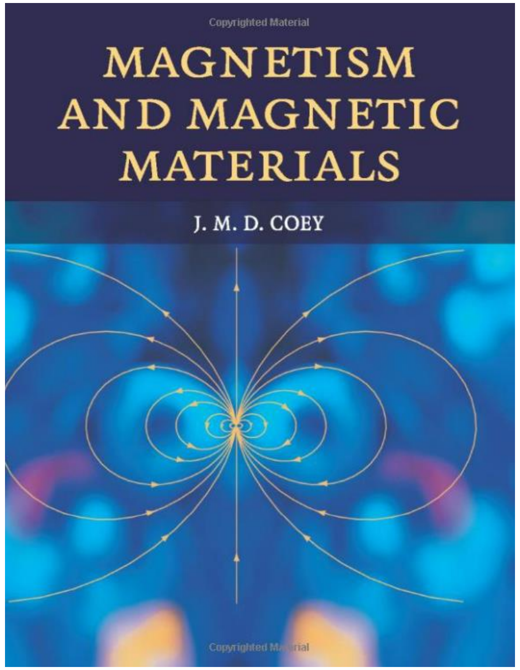
Saarbruecken, 14th September 2022

BOOKS FOR FURTHER READING:



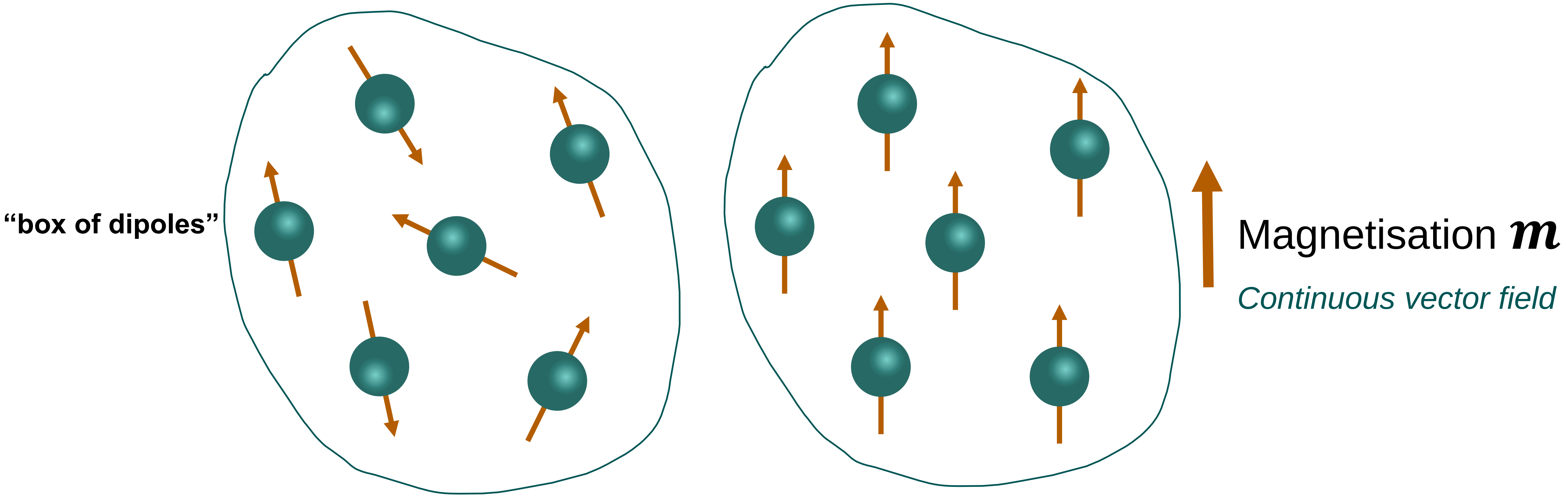






WHAT DO WE MEAN?

MAGNETISATION CONFIGURATIONS

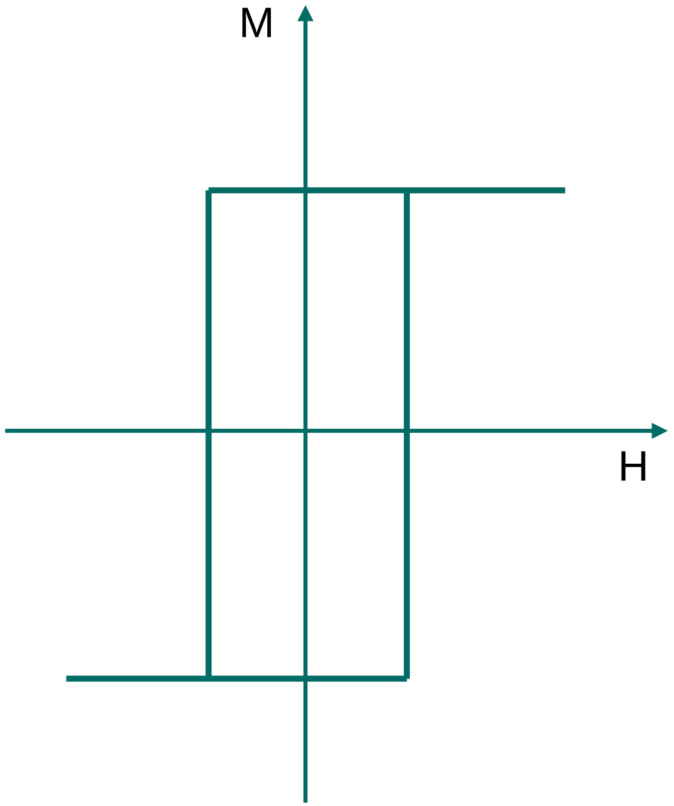


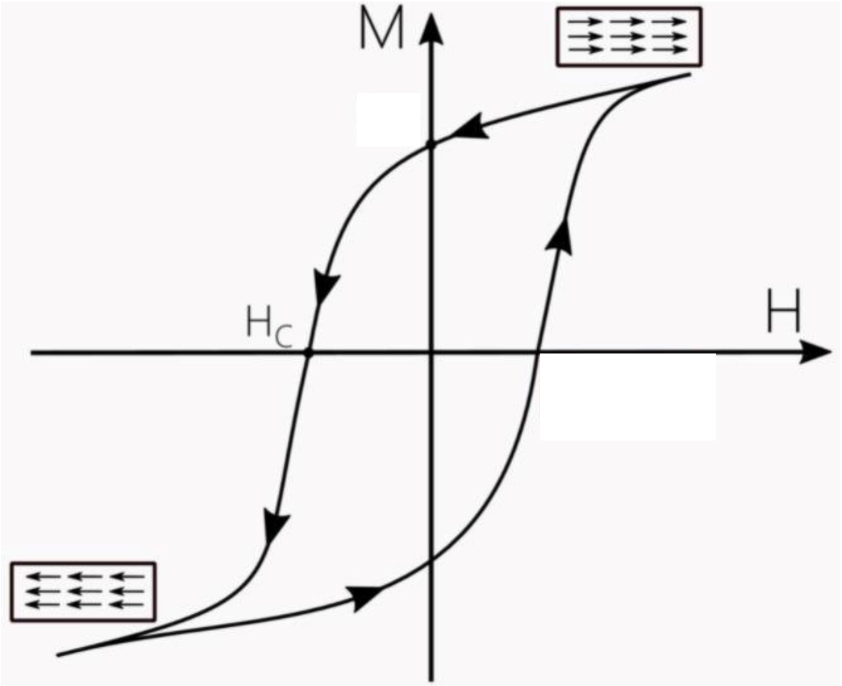
WHAT DO WE MEAN?

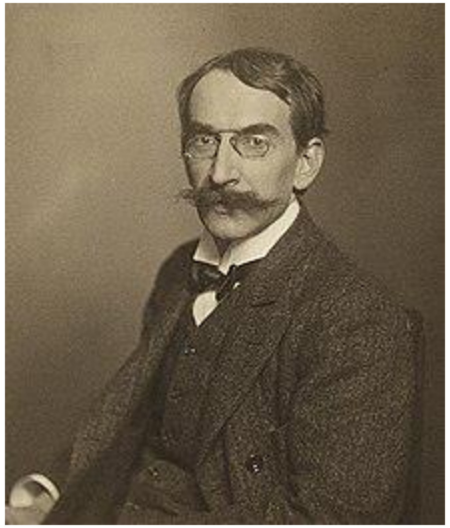
MAGNETISATION CONFIGURATIONS

What determines the magnetic configuration?

THE CONCEPT OF DOMAINS







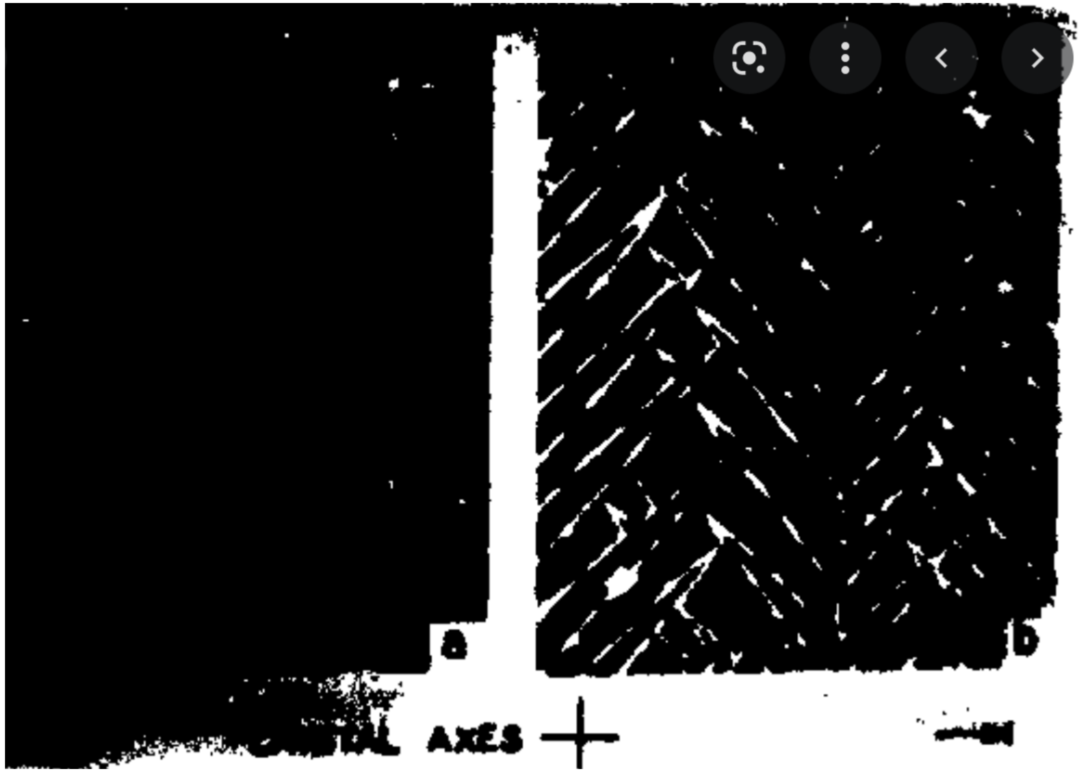
Pierre Weiss, 1907

Magnetic materials appear “non-magnetic”

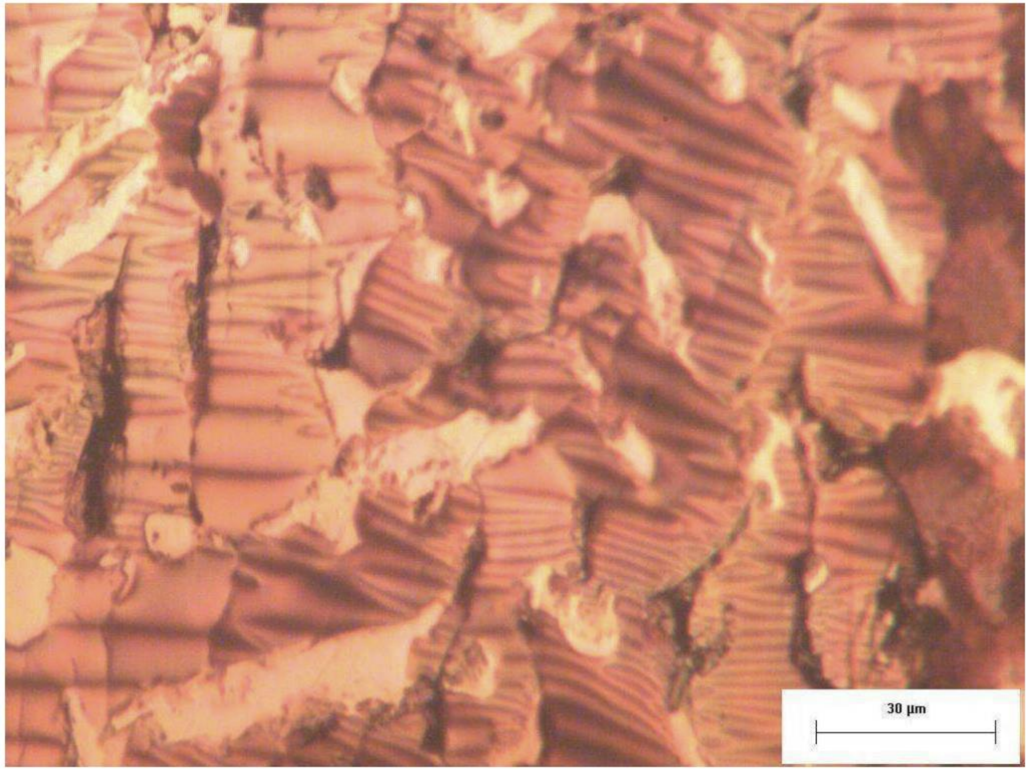
→ presence of magnetic domains

FIRST OBSERVED WITH THE BITTER METHOD

Put ferrofluid on top of a magnet



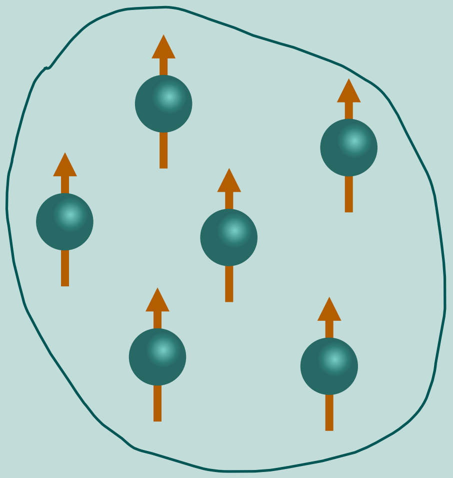
R. Patton, K. Strnat (1963)



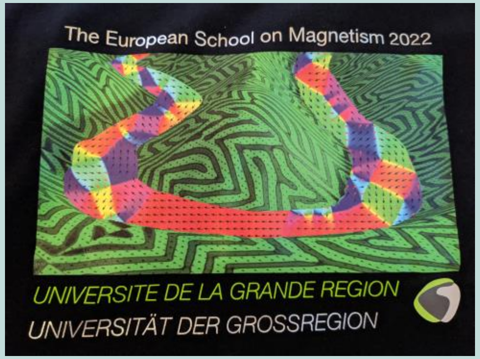
Lemos et al., Materials Science Forum Vol. 802 (2014)

OUR QUESTIONS FOR TODAY:

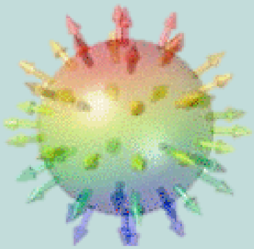
Why do domains form?



What drives different configurations?

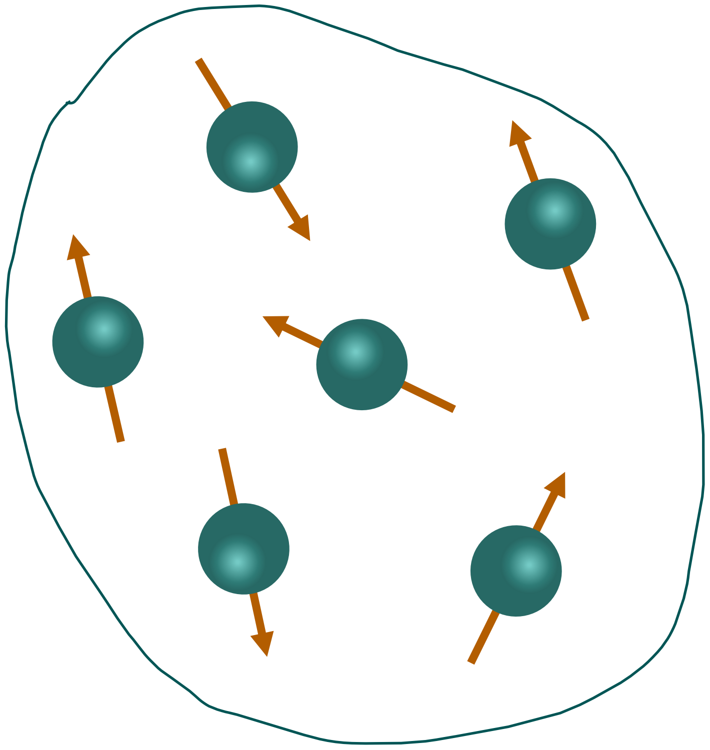


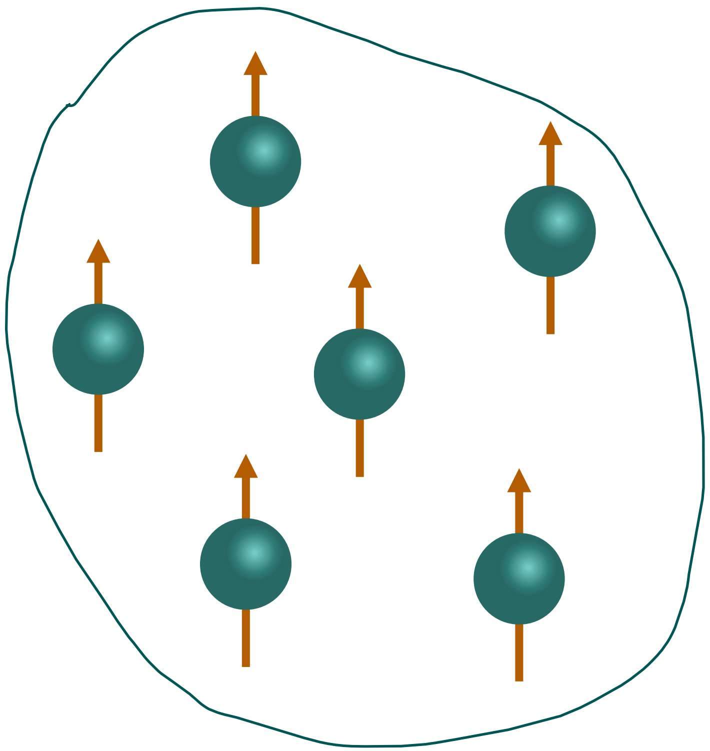
What about topology?



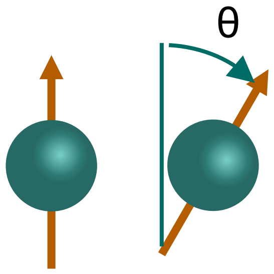
How can we observe these?

MAGNETIC CONFIG: EXCHANGE ENERGY





- Costs energy to rotate neighbouring spins:



Two neighbouring spins have exchange energy:

$$-2JS_1 \cdot S_2 = -2JS^2 \cos\theta$$

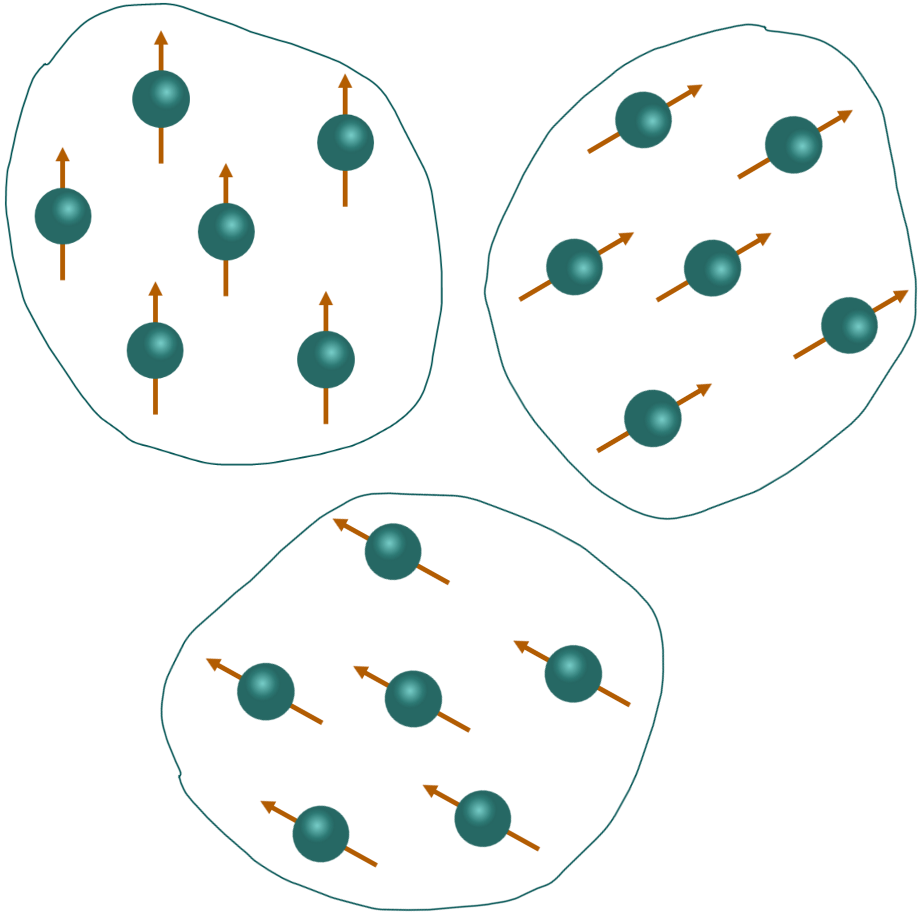
→ Prefer to align!

Can write the exchange energy in terms of **m**:

$$E_{EX} = A(\nabla \boldsymbol{m})^2$$

A = exchange constant

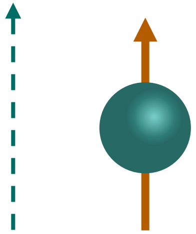
ANISOTROPY ENERGY

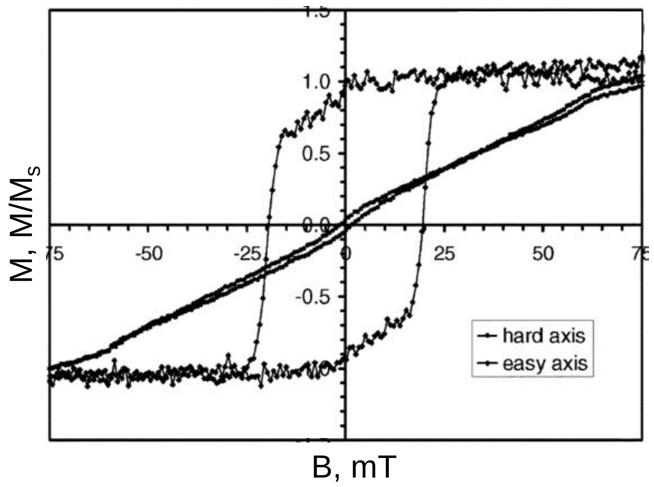


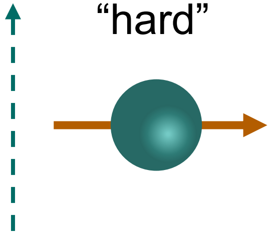
- Spins prefer to align, but in which direction?

→ Magnetic Anisotropy

"easy"

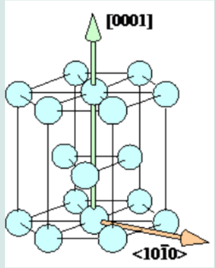






"hard"

Magnetocrystalline

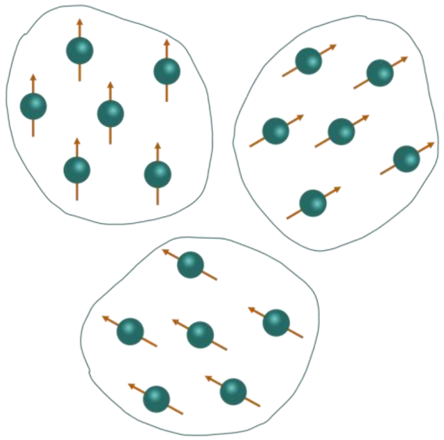


Interfacial

Shape anisotropy

"low symmetry" = higher anisotropy

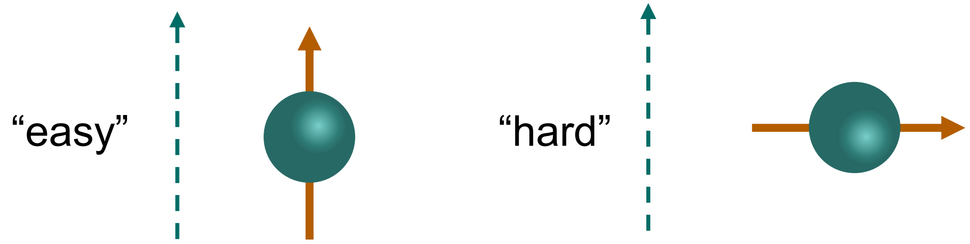
ANISOTROPY ENERGY



- Spins prefer to align, but in which direction?

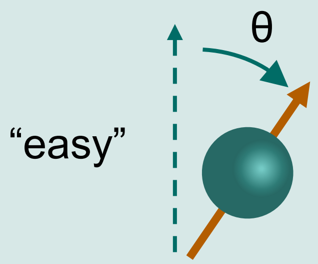
→ Magnetic Anisotropy in a crystal

“hard” vs “easy” axes



Magnetocrystalline anisotropy – spin-orbit coupling

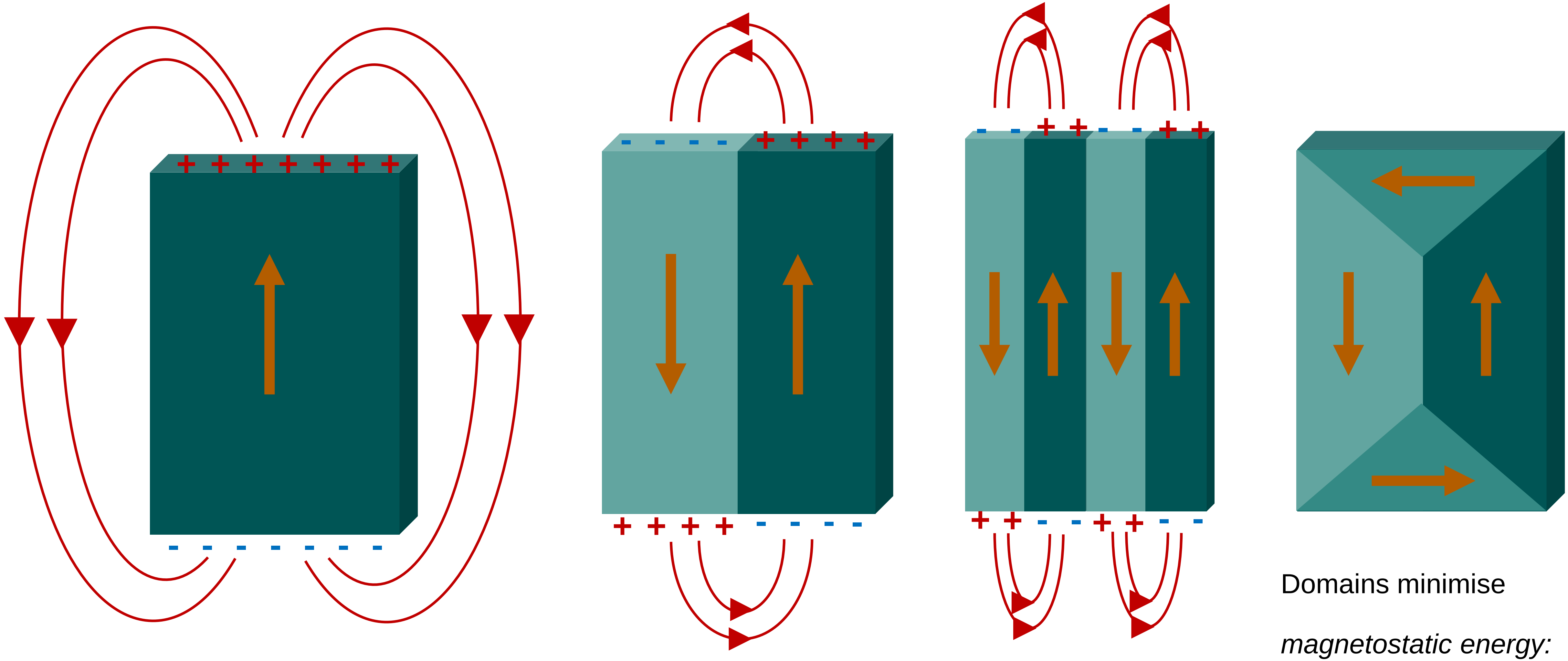
Depends on the crystal structure



For example, uniaxial anisotropy:

$$E = K_1 \sin^2 \theta + K_2 \sin^4 \theta$$

WHY DO DOMAINS FORM?

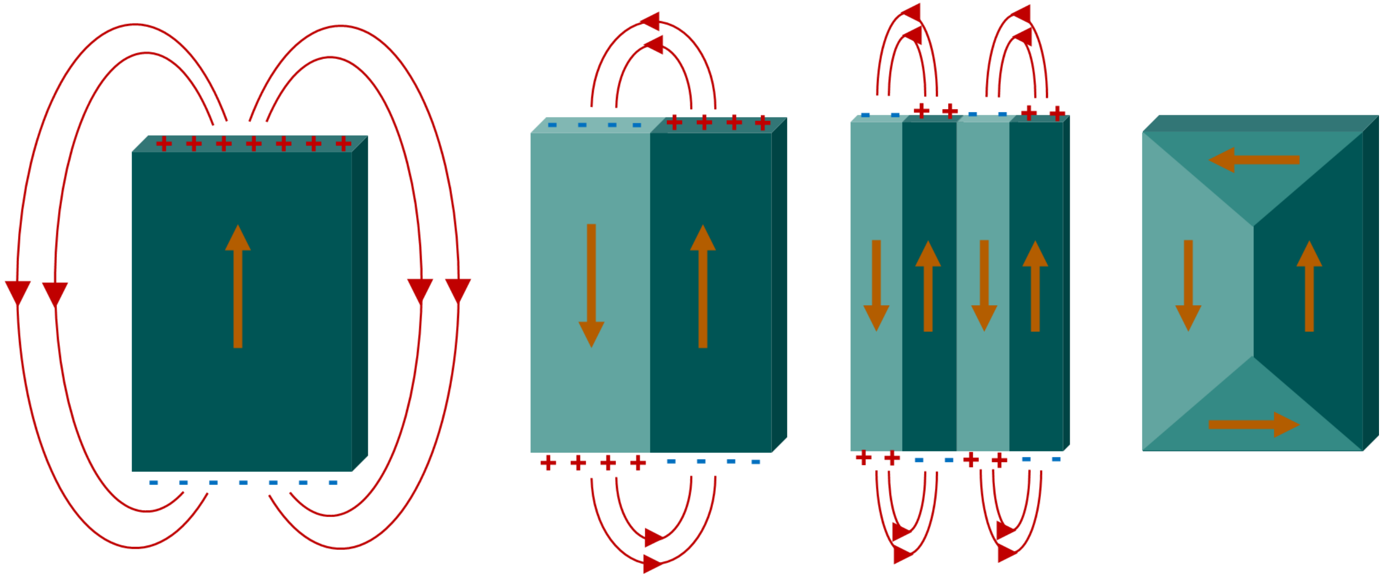


Stray field costs energy

Domains minimise

magnetostatic energy:

→ MAGNETOSTATIC ENERGY



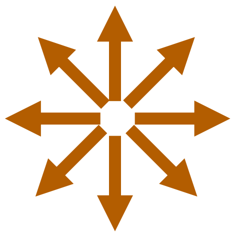
Can be thought of as two different charges:

Domains minimise *magnetostatic energy:*

$$E_{MS} = -\frac{\mu_0}{2} M \cdot H_d$$

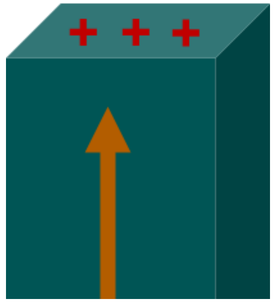
"Volume charges"

$$\rho = -\mu_0 \nabla \cdot M$$



"Surface charges"

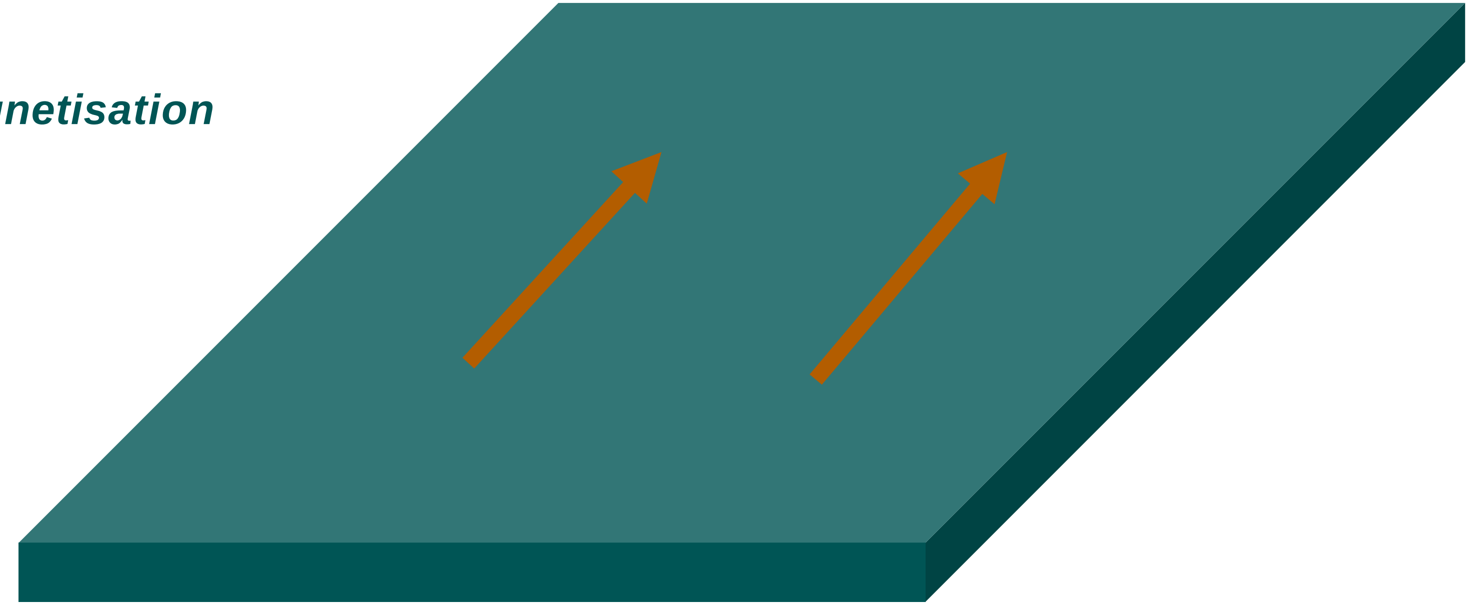
$$\sigma = \mu_0 \boldsymbol{m} \cdot \widehat{\boldsymbol{n}}$$



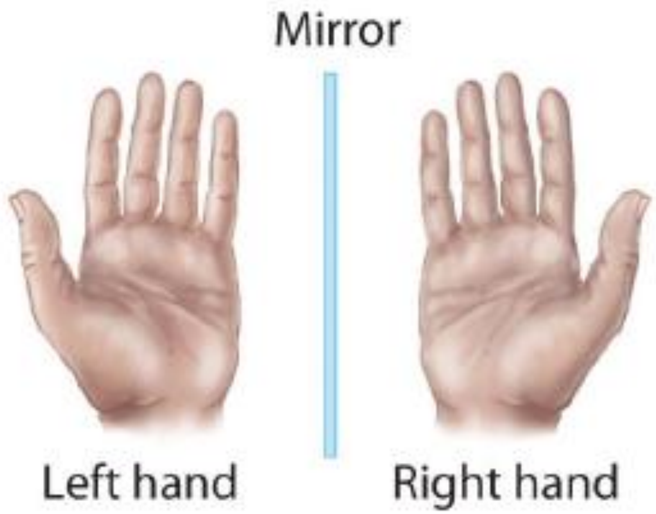
“THIN FILM”

Thin films with *no anisotropy*:

In plane magnetisation



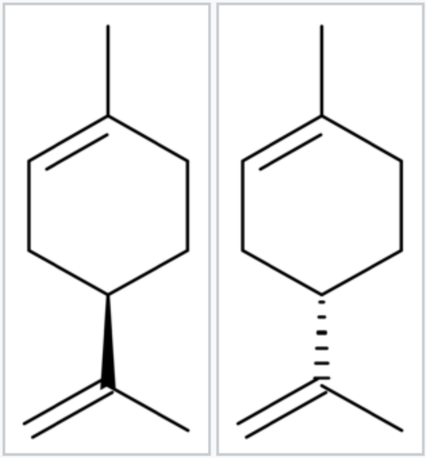
CHIRALITY: DZYALOSHINSKII–MORIYA INTERACTION



Breaking mirror symmetry

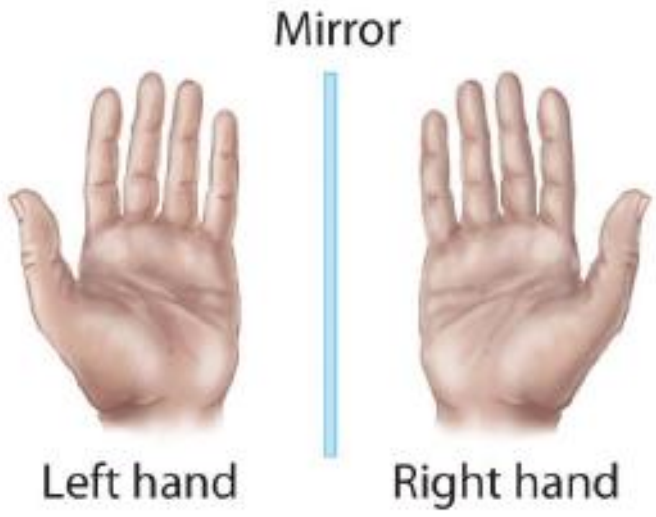
Can chirality exist in 2D?

Can have a strong impact on behaviour:



R-(+)-Limonene found in orange	*S*-(–)-Limonene found in lemon

CHIRALITY: DZYALOSHINSKII–MORIYA INTERACTION



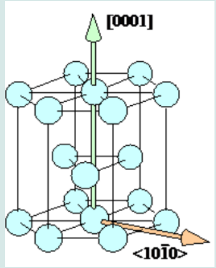
Breaking mirror symmetry

Can chirality exist in 2D?

How does this work for magnetism?

→ *Breaking of inversion symmetry*

Crystalline



Interfacial

$$H_{i,j}^{(\mathrm{DM})} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j).$$

DMI vector

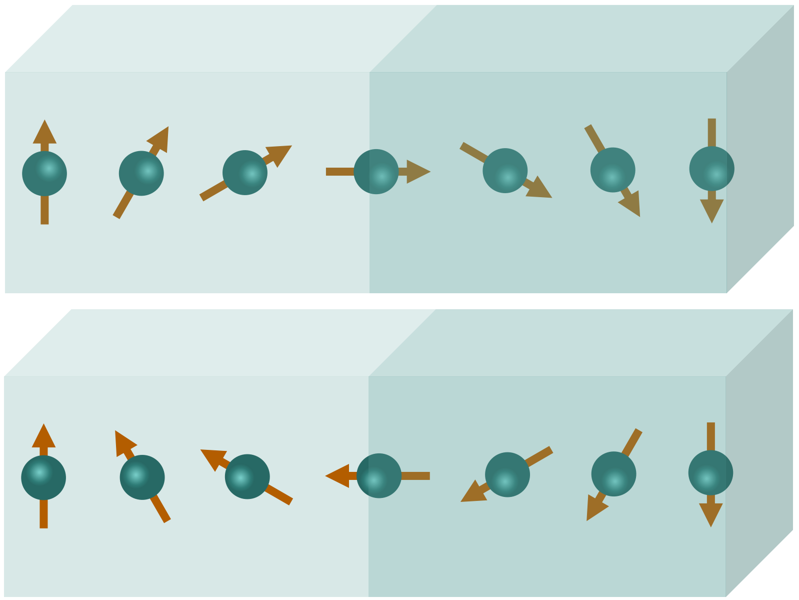
CHIRALITY: DMI

$$H_{i,j}^{(\mathrm{DM})} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j).$$

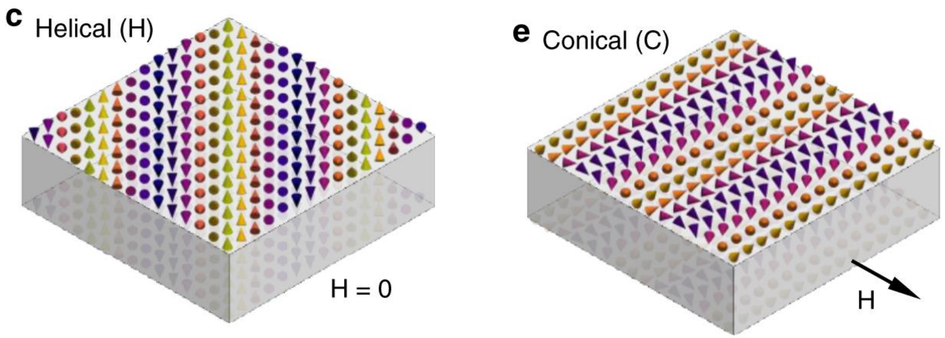
DMI vector

Depending on DMI vector:

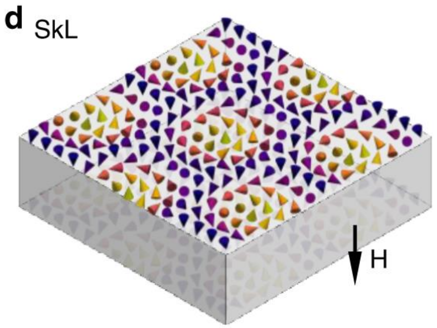
→ Preferential rotation of spins



Can lead to helical/ conical state:



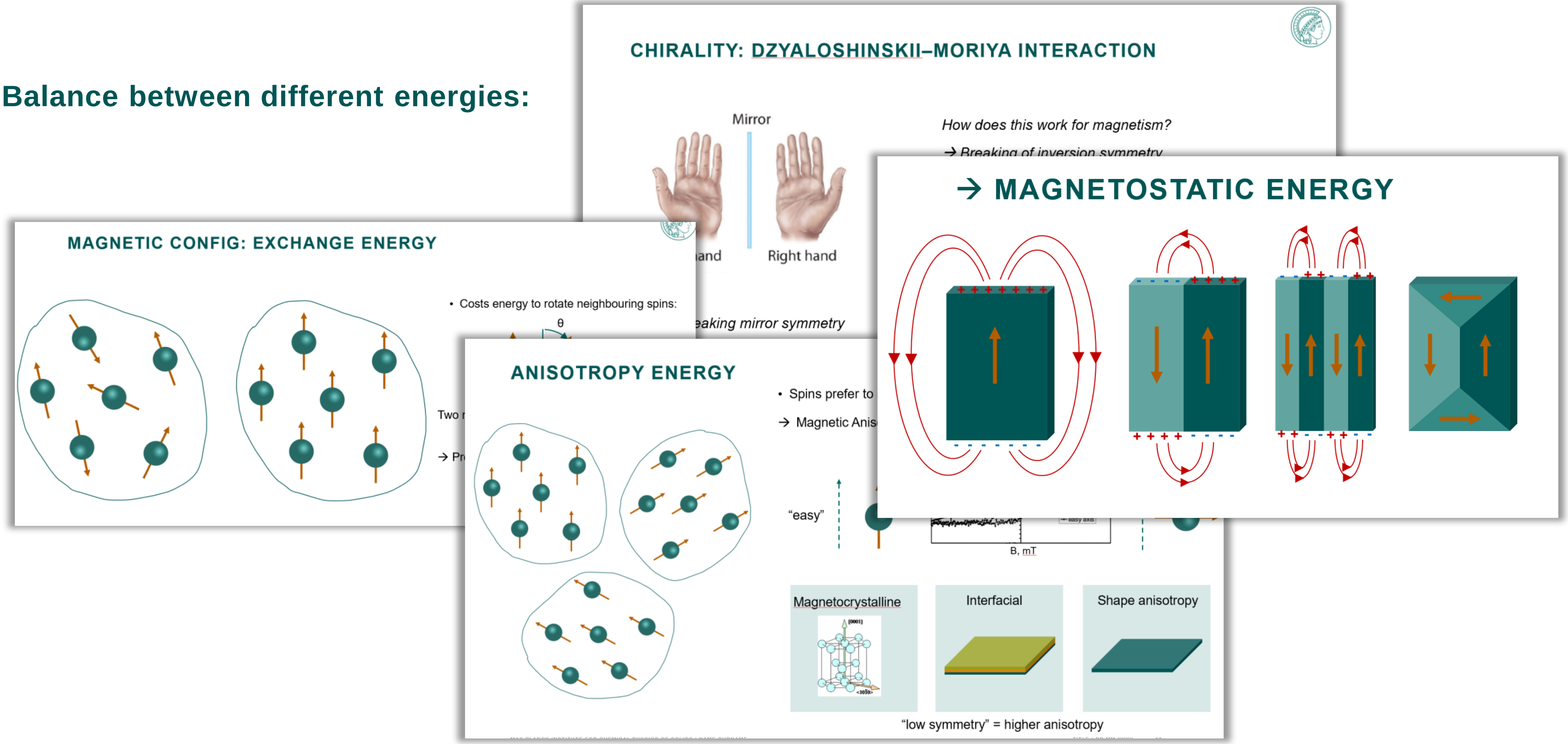
Or stabilisation of skyrmions! (lecture tomorrow)



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

DOMAIN STRUCTURE:

Balance between different energies:



MICROMAGNETIC DESCRIPTION

Describe energy of the system:

$$\varepsilon_{TOT} = \varepsilon_{EXCH} + \varepsilon_{ZEE} + \varepsilon_{MS} + \varepsilon_{ANI} + \varepsilon_{DMI}$$

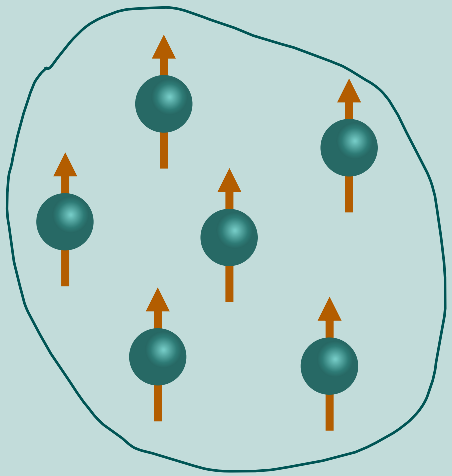
→ Can be combined with macro-spin model

→ And/or numerical simulations

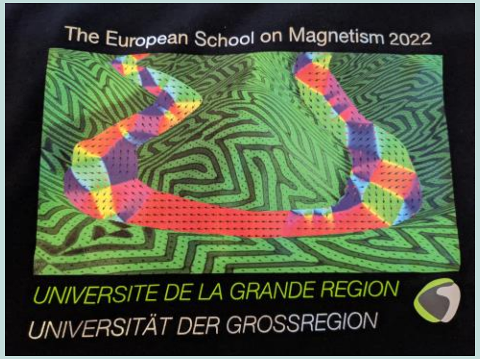
→ Continuum description

OUR QUESTIONS FOR TODAY:

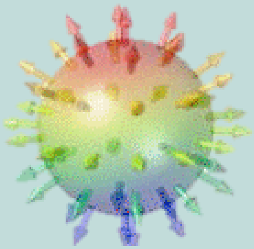
Why do domains form?



What drives different configurations?



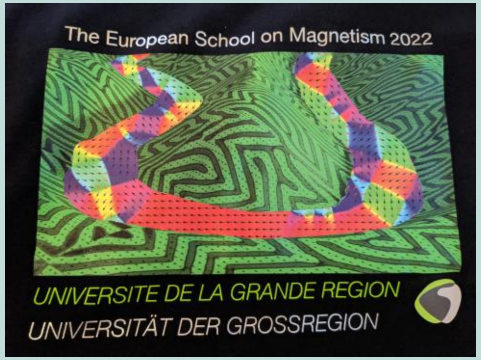
What about topology?



How can we observe these?

MAGNETISATION CONFIGURATIONS

What drives different configurations?



Questions:

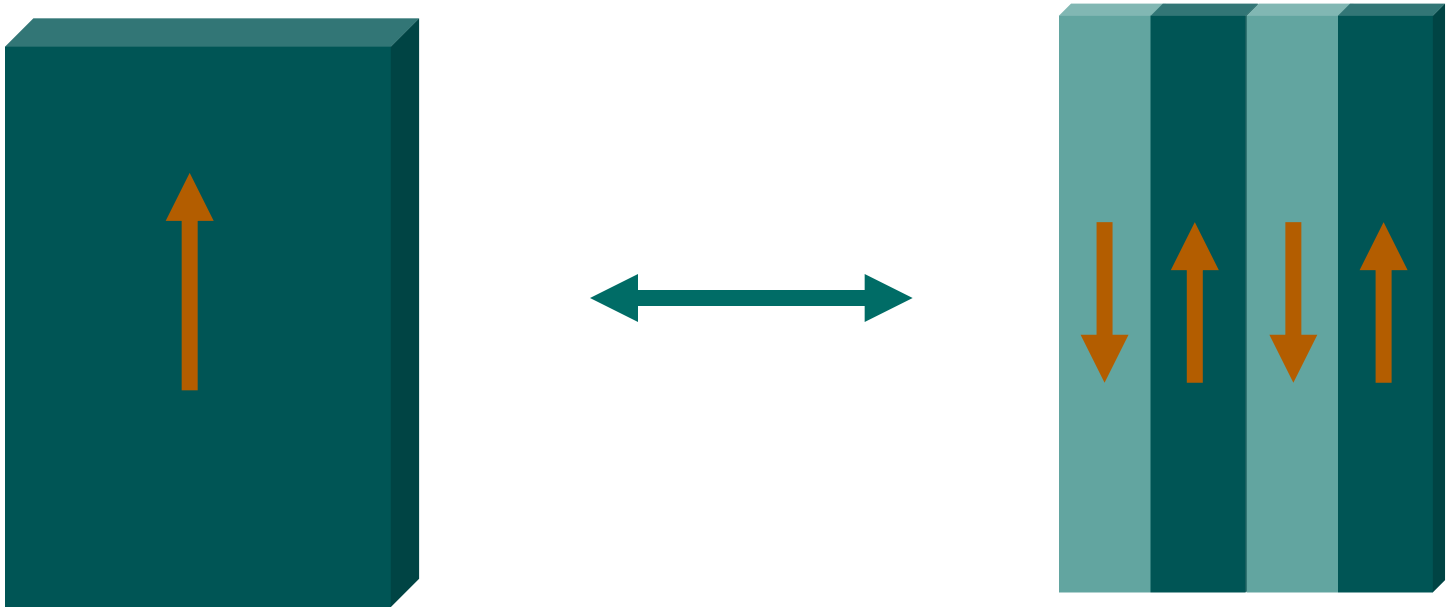
→ **What lengthscales?**

→ How big is a domain?

→ **What types of structures can we expect?**

WHAT DETERMINES THE SIZE OF THE DOMAINS?

(consider with anisotropy)

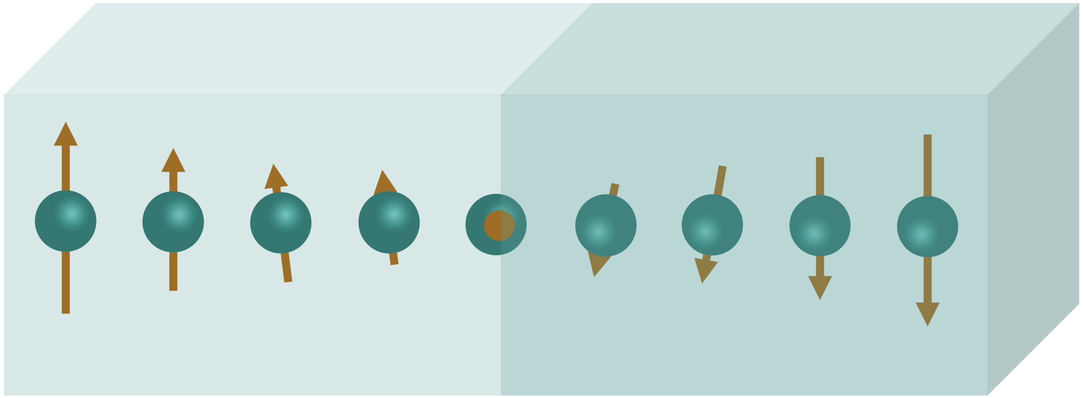


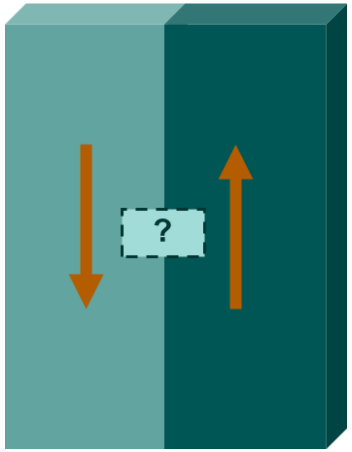
Energy of the domains vs energy of domain walls

AS WE INTRODUCE DOMAINS….

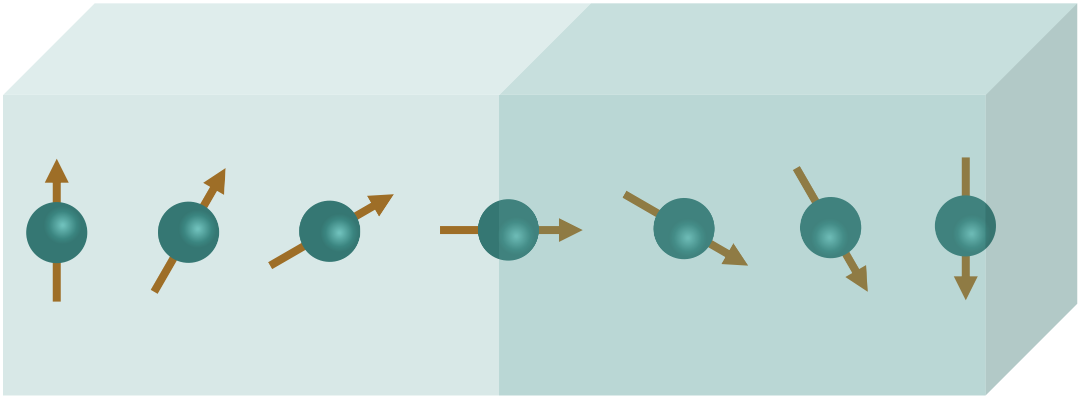
WE NEED DOMAIN WALLS

Bloch walls:





Neel walls:



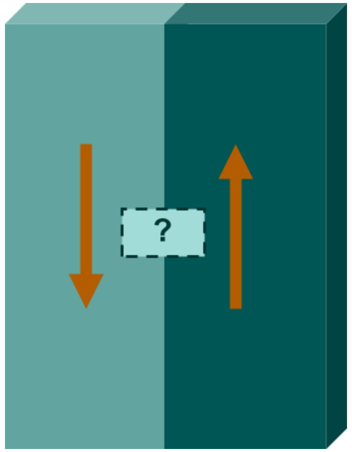
Size of domains: depends on energy of the domain wall

Question:

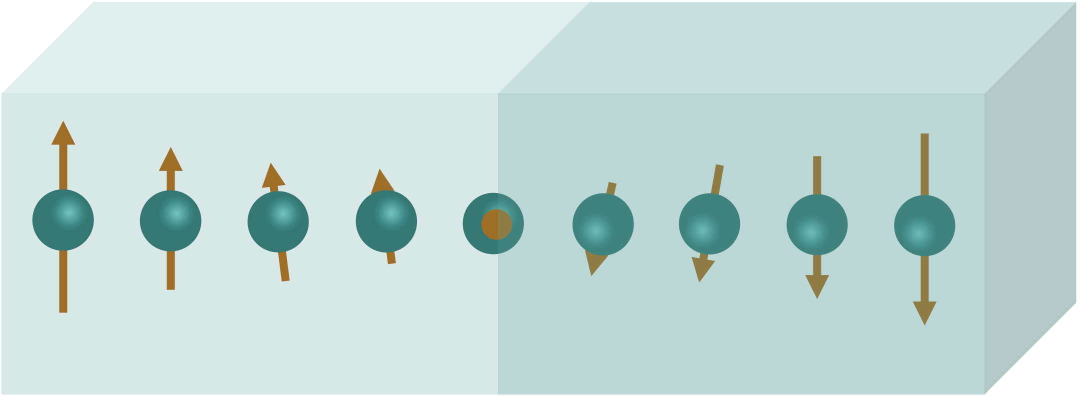
Which wall has higher magnetostatic energy?

AS WE INTRODUCE DOMAINS....

WE NEED DOMAIN WALLS

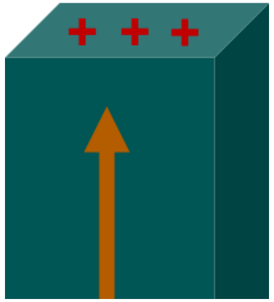


Bloch walls:

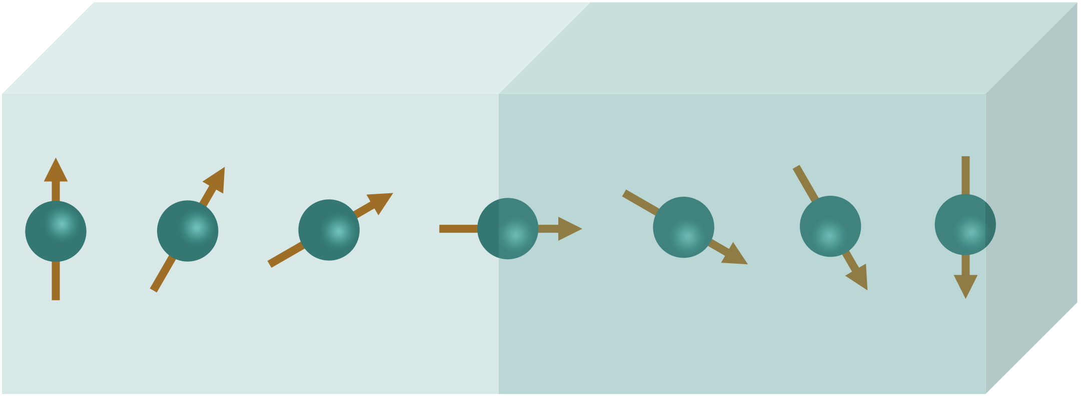


$$\sigma = \mu_0 \boldsymbol{m} \cdot \hat{\boldsymbol{n}}$$

"Surface charges"

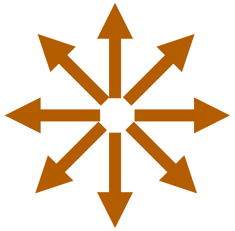


Neel walls:



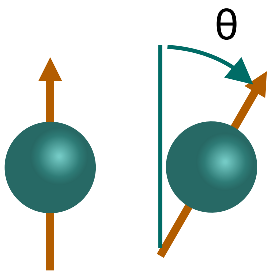
$$\rho = -\mu_0 \nabla \cdot M$$

"Volume charges"



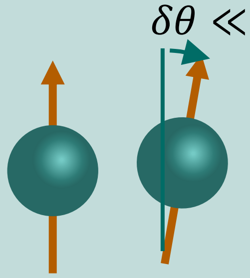
SIZE OF DOMAIN WALL: ENERGY BALANCE?

Remember: exchange energy:

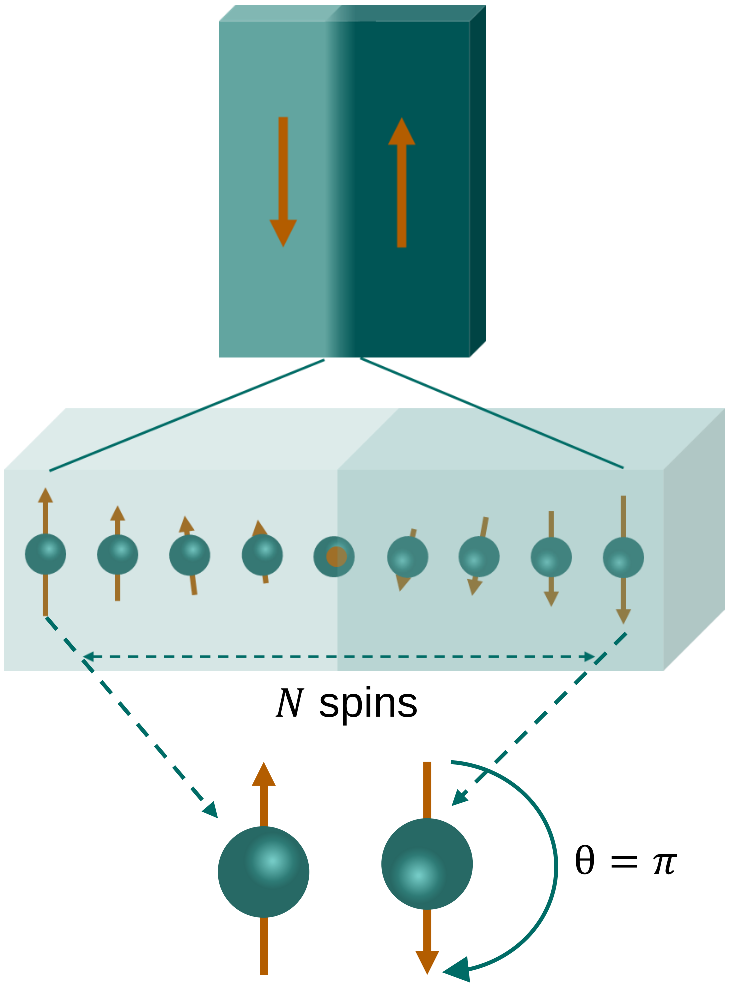


Two neighbouring spins have exchange energy:

$$-2JS_1 \cdot S_2 = -2JS^2 \cos\theta$$



$$\Delta E = 2JS^2 \cos\delta\theta$$
$$\sim 2JS^2 \delta\theta^2$$



We split the rotation over N spins

Each change in angle:

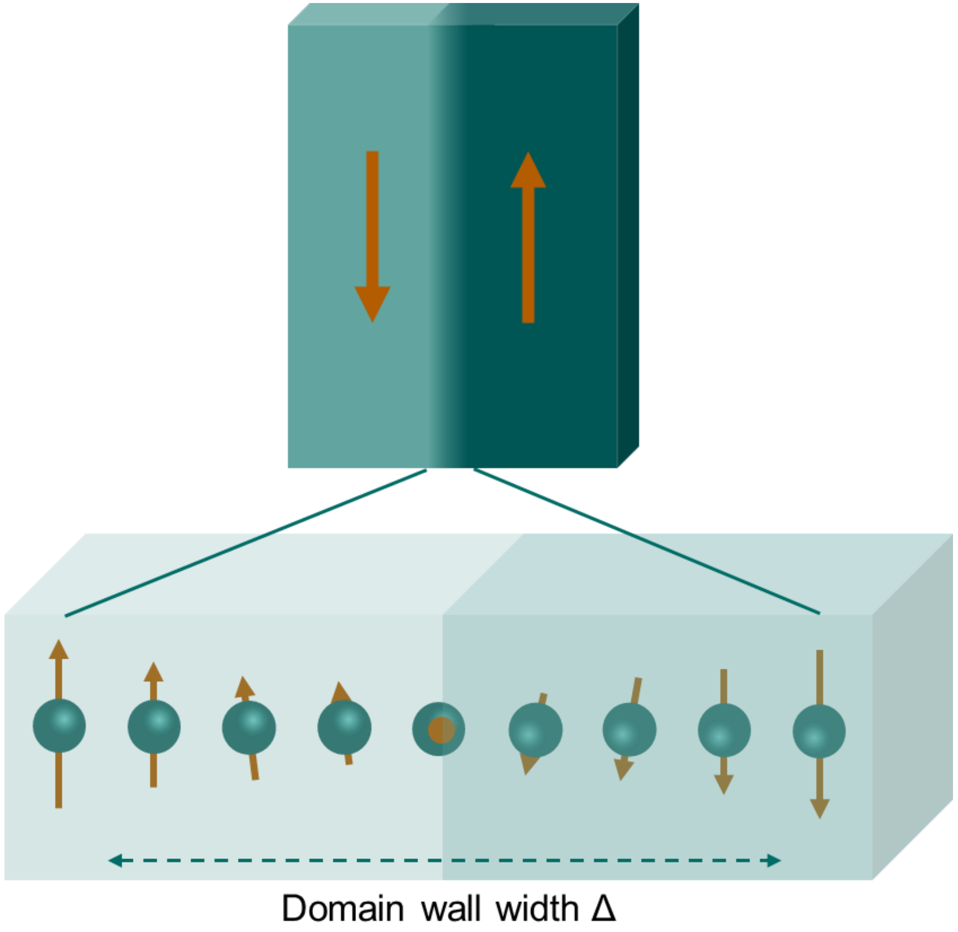
$$\delta\theta = \frac{\pi}{N}$$

$$\rightarrow \Delta E \sim 2JS^2 \left(\frac{\pi}{N}\right)^2$$

Energy cost of wall:

$$\Delta E_{EX} \sim 2JS^2 \frac{\pi^2}{N}$$

SIZES OF BLOCH WALLS

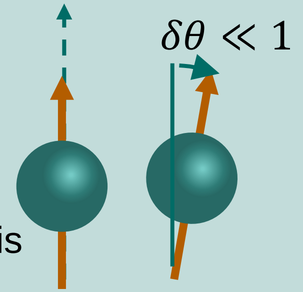


Not only Exchange… remember anisotropy:

$$\Delta E = \underbrace{2JS^2\theta^2}_{\text{Exchange energy}} + \underbrace{K\sin^2\theta}_{\text{Anisotropy energy}}$$

Domain //

Anisotropy axis



$$\Delta E = K\sin^2\delta\theta$$

Energy cost of wall:

$$\Delta E_{ANI} \sim KN$$

Domain wall width: $\Delta \sim \pi\sqrt{A/K}$

Hard: 2-3 nm → Soft: 10s to 100s nm

A – Exchange constant

K – Anisotropy constant

LENGTHSCALES

How quickly can the magnetisation rotate? → exchange length

In crystalline materials:

Magnetocrystalline exchange length:

$$l_{ex} = \sqrt{A/K_u}$$

Competition between exchange and anisotropy

In softer materials

Magnetostatic exchange length:

$$K_d = \frac{\mu_0 M_S^2}{2}$$

$$l_{MS} = \sqrt{A/K_d} \rightarrow l_{MS} = \sqrt{2A/\mu_0 M_S^2}$$

Competition between exchange and magnetostatics

LENGTHSCALES

How quickly can the magnetisation rotate? → exchange length

Magnetocrystalline exchange length:

$$l_{ex} = \sqrt{A/K_u}$$

Magnetostatic exchange length:

$$l_{MS} = \sqrt{2A/\mu_0 M_S^2}$$

Material	A (erg/cm)	M_s (emu/cm^3)	$4\pi M_s$ (kG)[a]	$l_{ex} = \frac{\sqrt{A}}{M_s\sqrt{2\pi}}$ (cm)[a]
Fe	10^{-6}	1700	~21.4	~2.3×10^{-7}
Magnetite	10^{-6}	500	~6.3	~8.0×10^{-7}
Soft magnetic material	10^{-6}	10^3	~12.6	~3.99×10^{-7}
Co	1.8×10^{-6}	1400	~17.6	~3.8×10^{-7}
Permalloy	1.3×10^{-6}	800	~10.1	~5.7×10^{-7}
Ferromagnetic material	10^{-6}	370	~4.6	~10.8×10^{-7}
Ni	10^{-6}	482	~6.1	~8.3×10^{-7}
Soft magnetic material	10^{-6}	550	~6.9	~7.3×10^{-7}
Permalloy	10^{-6}	800	~10.1	~4.99×10^{-7}

~2-10 nm

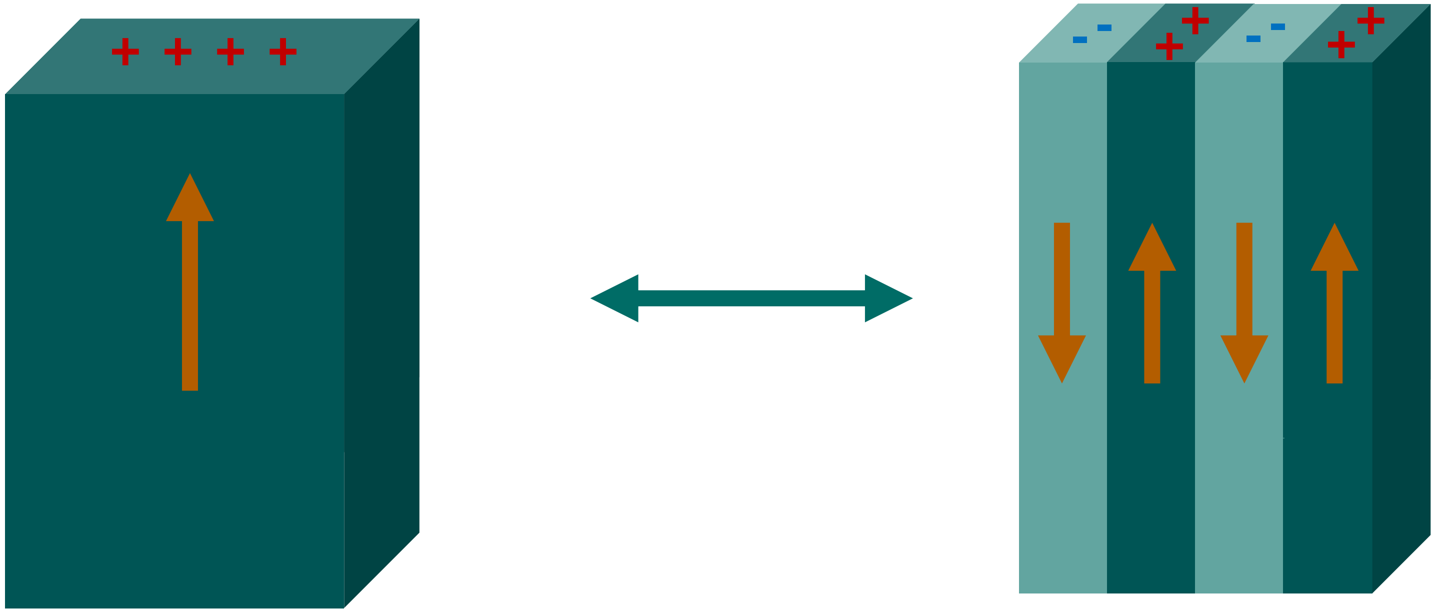
Abo et al., IEEE TRANSACTIONS ON MAGNETICS, VOL. 49, NO. 8, AUGUST 2013

SIZE OF DOMAINS:

We now have the size of our domain walls, but what about the domains?

Balance **energy of domain walls** vs **energy of domain**

What happens as we increase the film thickness?



SIZE OF DOMAINS:

Balance **energy of domain walls** vs **energy of domain**

Energy of domains:

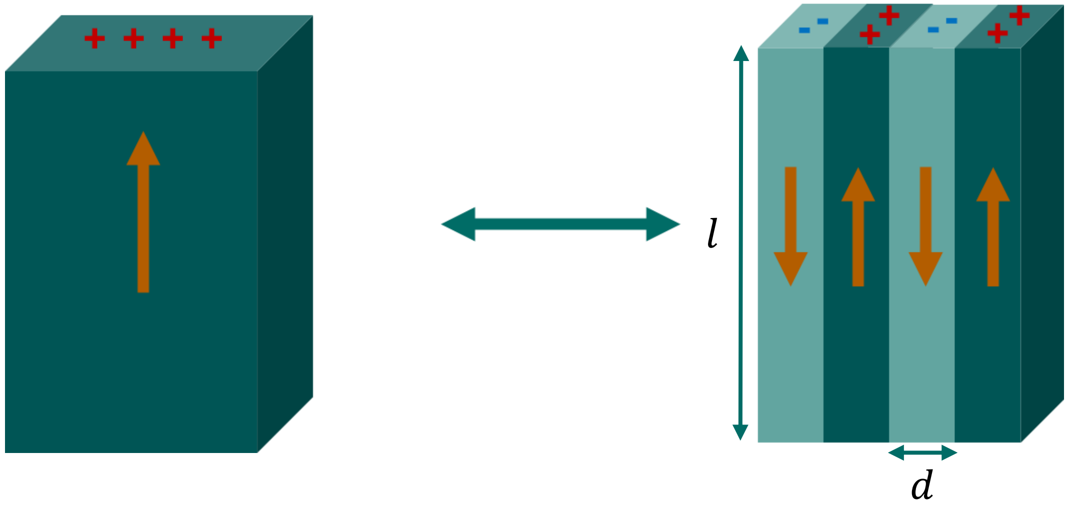
Magnetostatic energy:

(per unit area)

$$\varepsilon_{MS} = \frac{\mu_0 M_S^2}{2} l$$

Lowered if split into domains:

$$\varepsilon_{MS} = 1.08e5\ M_S^2 d$$



Energy of domain wall:

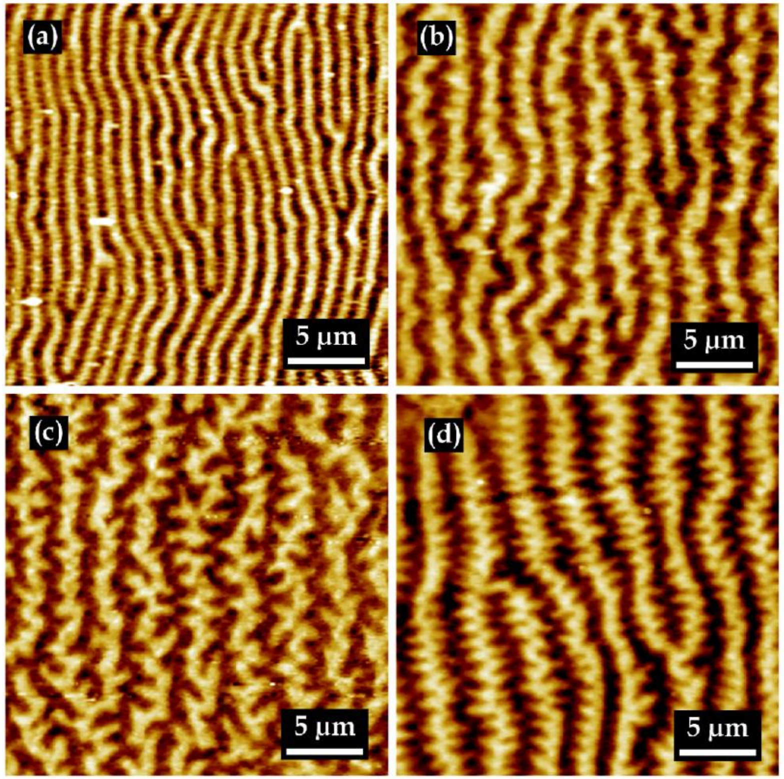
(per unit area)

$$\varepsilon_W = \frac{E_W l}{d}$$

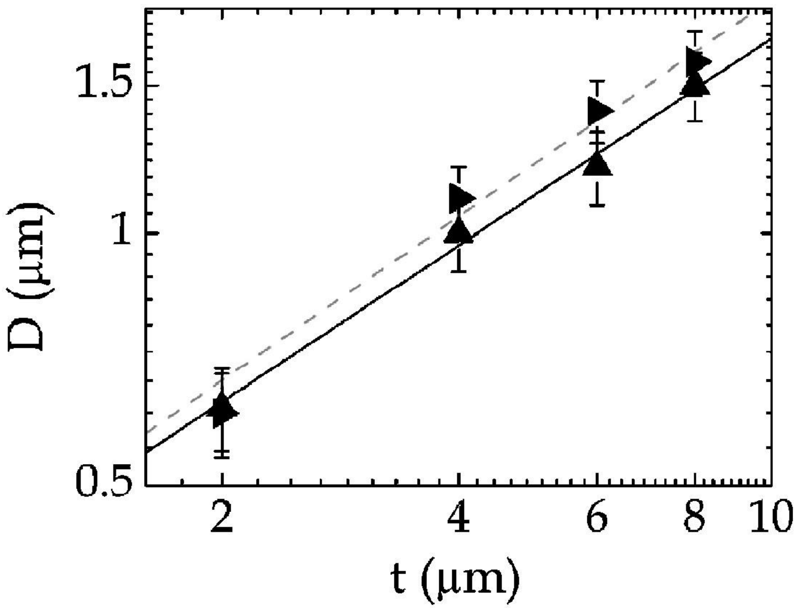
$$\rightarrow d \propto \sqrt{l}$$

SIZE OF DOMAINS

$t = 2\ \mu\mathrm{m}$ $t = 4\ \mu\mathrm{m}$

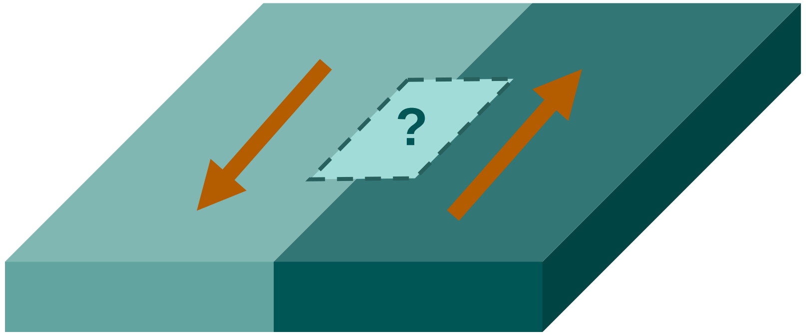


$t = 6\ \mu\mathrm{m}$ $t = 8\ \mu\mathrm{m}$

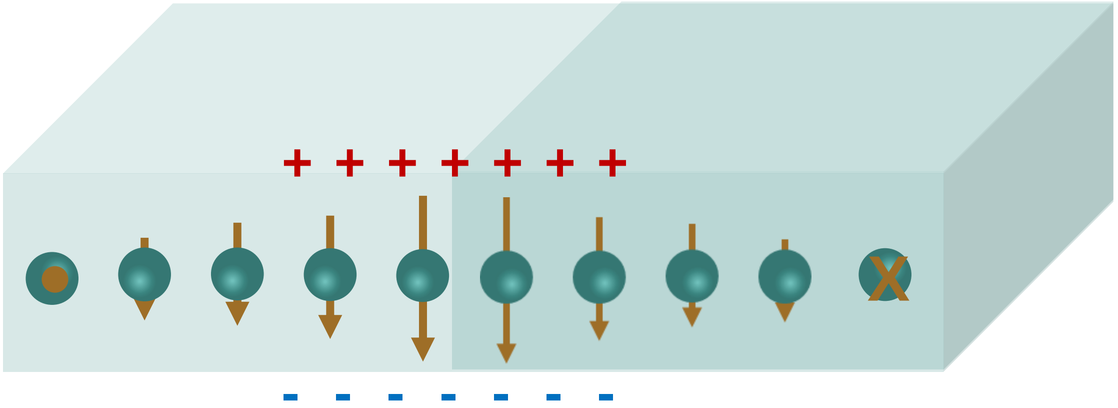


De Abril et al., Journal of Applied Physics **100**, 063904 (2006)

DIFFERENT TYPES OF DOMAIN WALLS?



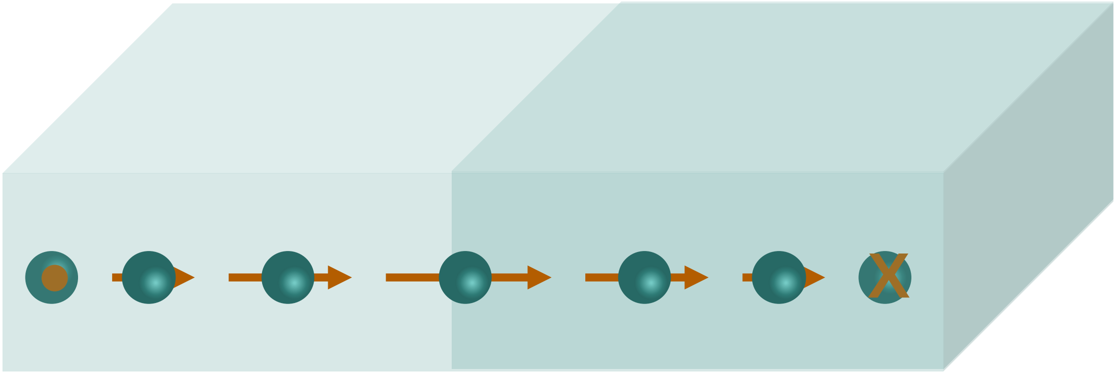
Bloch walls:



Surface charges

Stable for thick films

Neel walls:

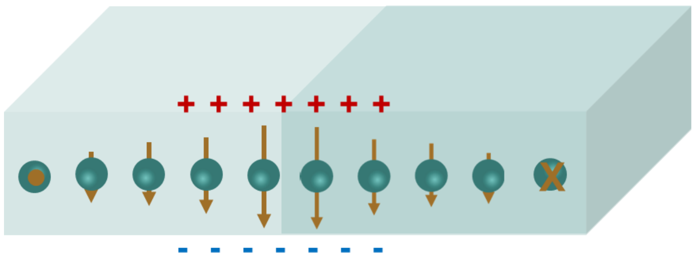


Volume charges

Stable for thin films

DIFFERENT TYPES OF DOMAIN WALLS?

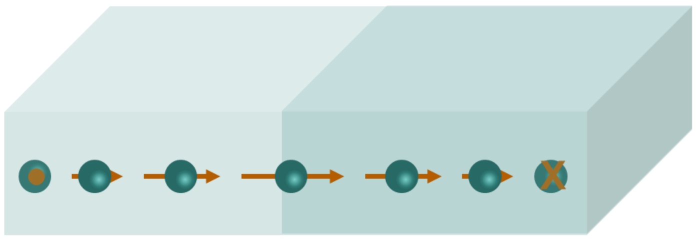
Bloch walls:



Surface charges

Stable for thick films

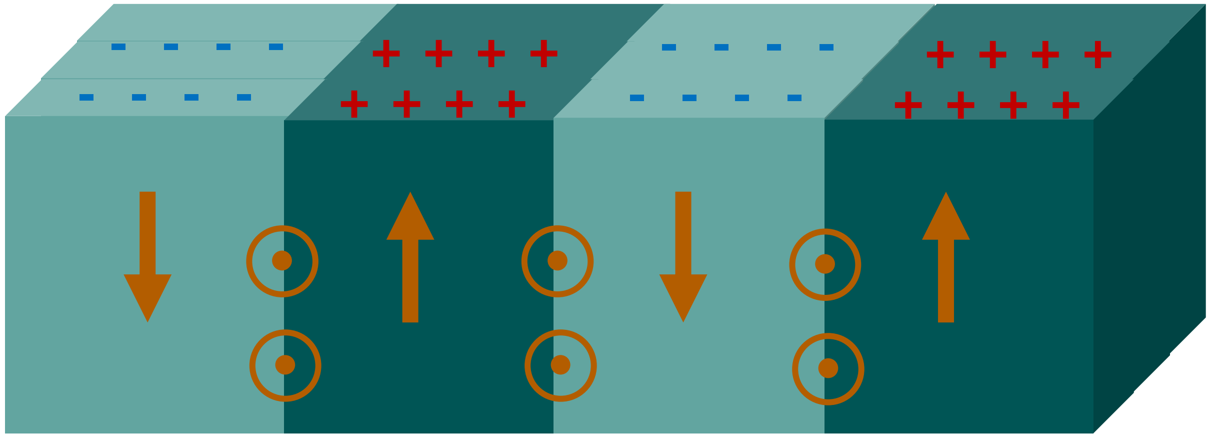
Neel walls:



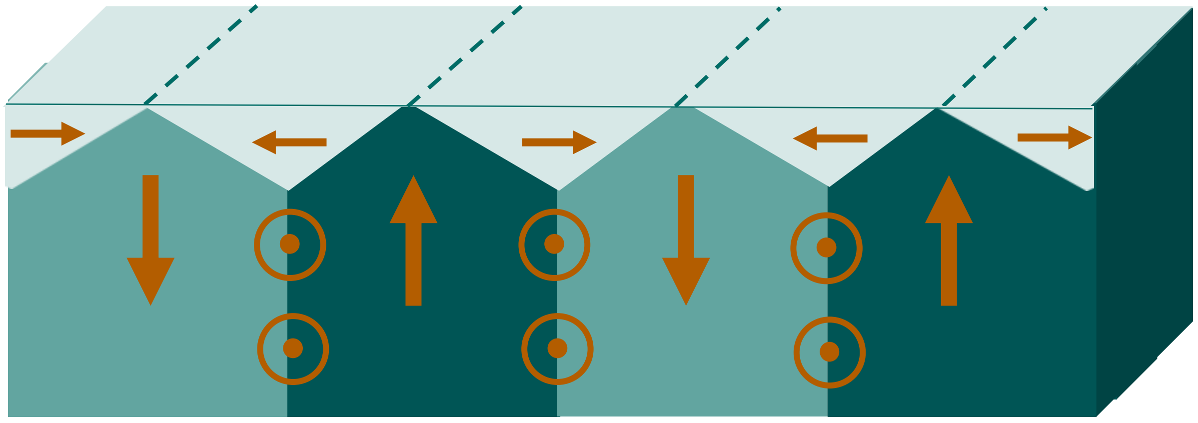
Volume charges

Stable for thin films

Combination of both:

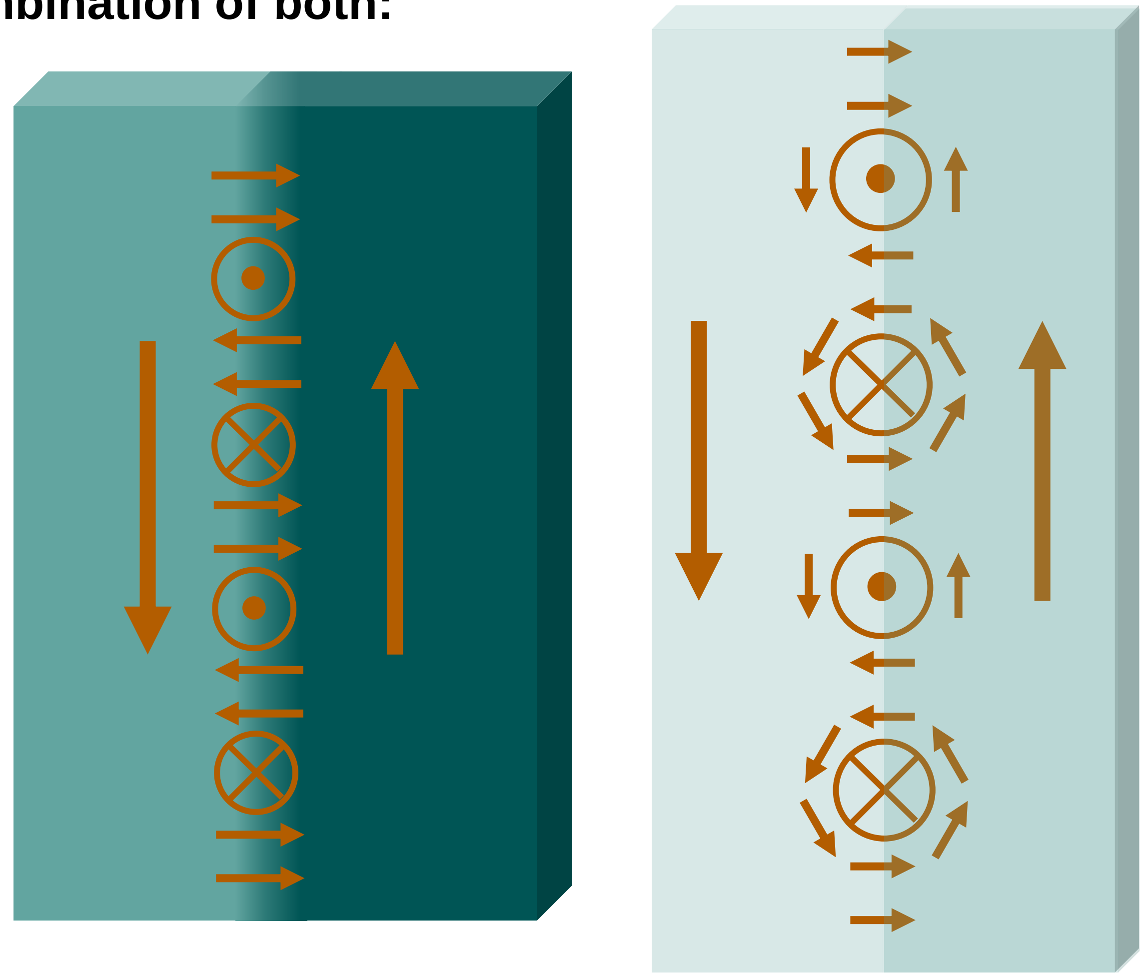


Closure domains:



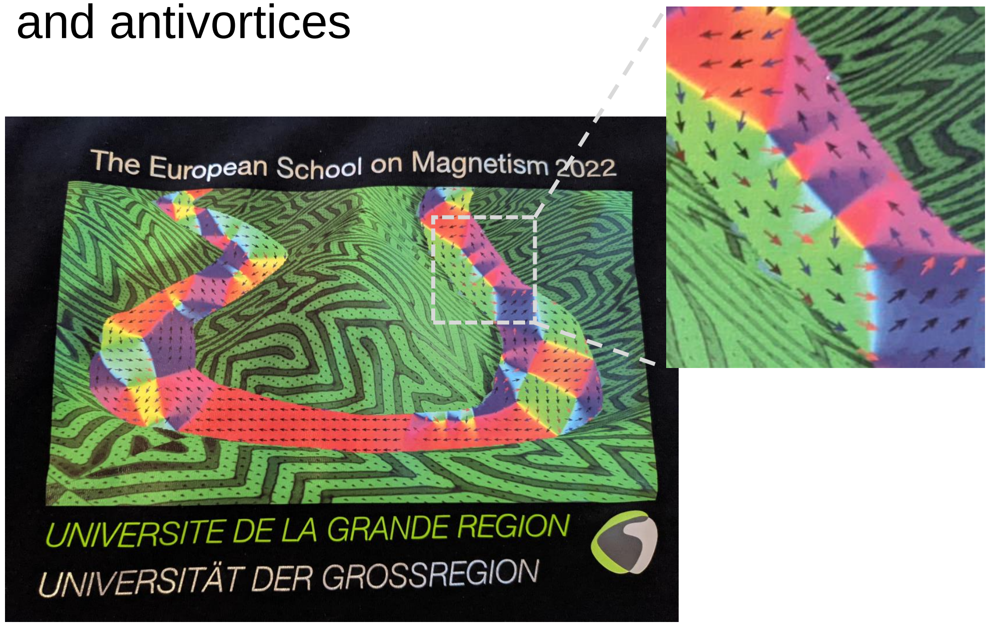
DOMAIN WALLS: BETWEEN THICK AND THIN?

Combination of both:



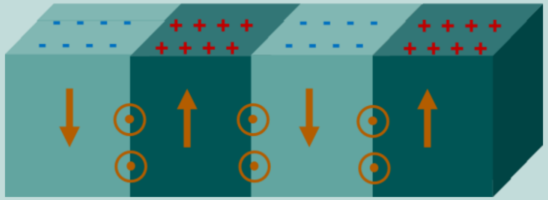
“Cross-tie wall”

Contains vortices
and antivortices



DIFFERENT SIZES OF MAGNETS

Bulk Magnets



Complex domains

Size >> domains

Mesoscale magnets

?

Size ~ domains

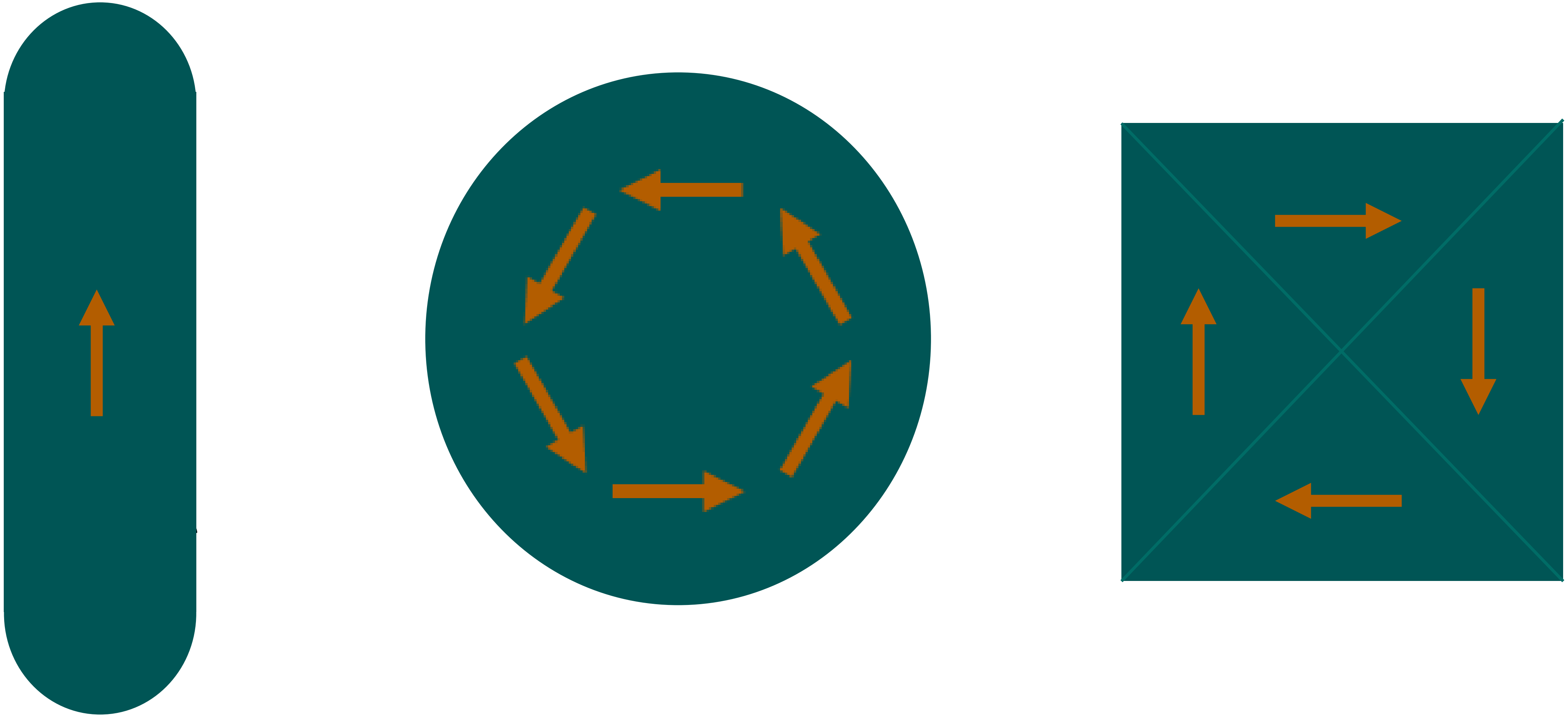
Nanoscale magnets

Single domain

Size < domains

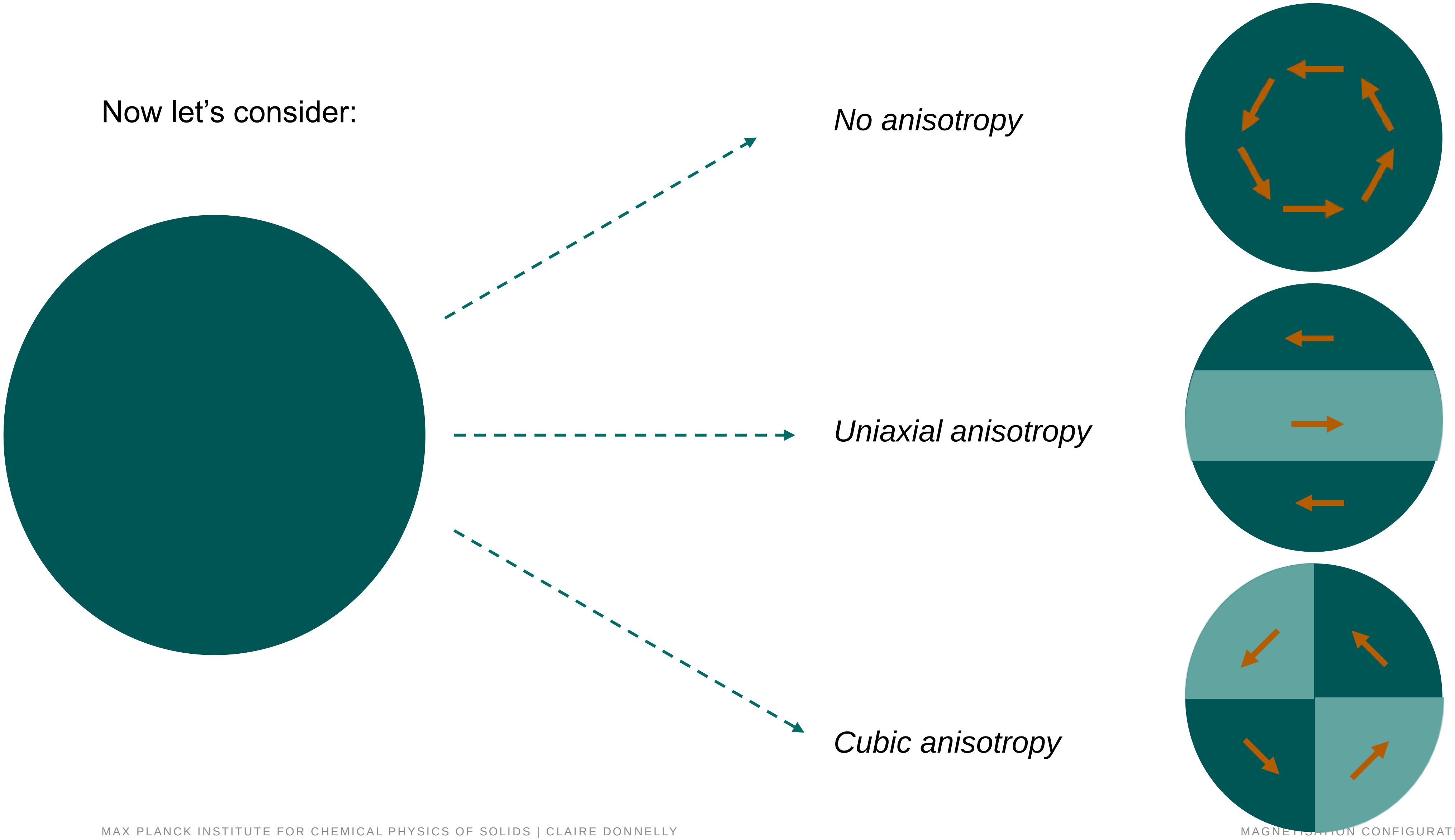
SHAPE ANISOTROPY

SHAPE ANISOTROPY



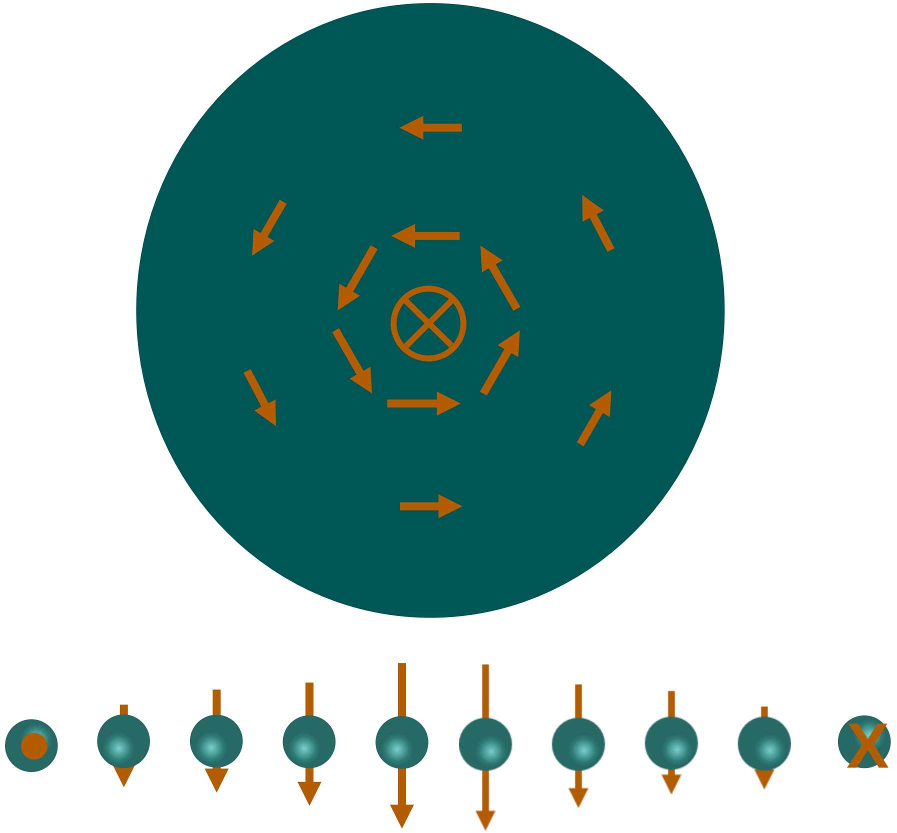
SHAPE ANISOTROPY

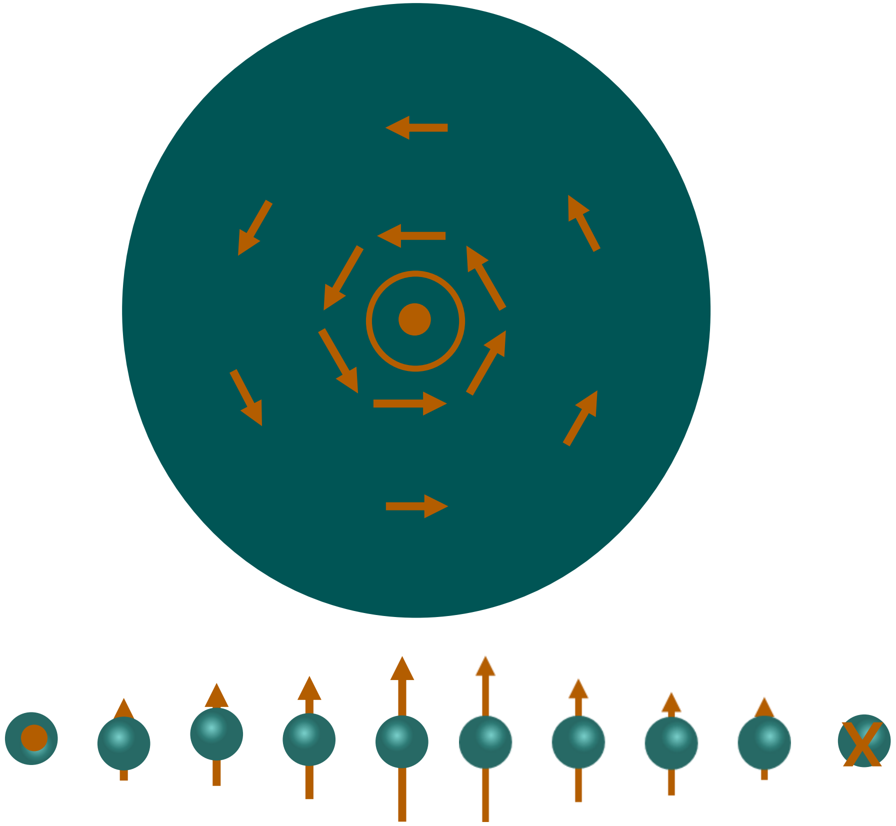
Now let’s consider:



VORTEX:

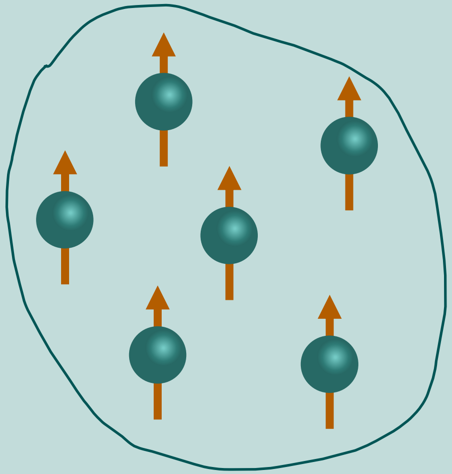
What happens in the centre of the vortex?



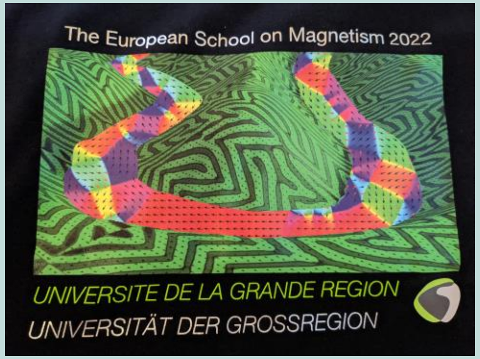


OUR QUESTIONS FOR TODAY:

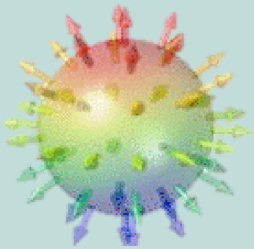
Why do domains form?



What drives different configurations?



What about topology?



How can we observe these?

UNDERSTANDING: TOPOLOGY

Key: *Smoothly deform!*

Meaning:

$\sim$

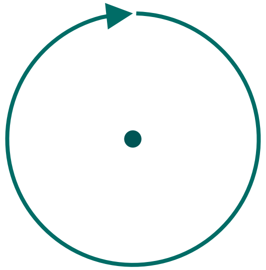
$\neq$

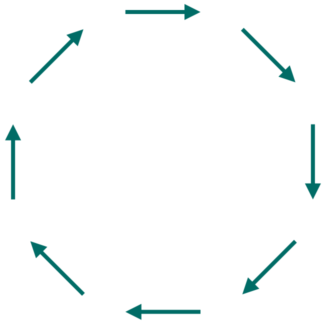
For magnetism?

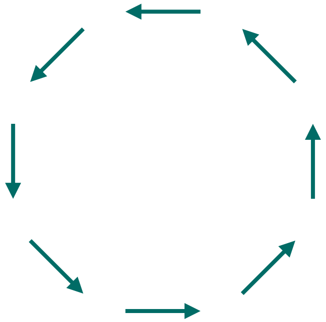
→ *assume continuous vector field*

Let’s start with 2D!

Winding number:







Are these topologically equivalent?

UNDERSTANDING: TOPOLOGY

***Key:** Smoothly deform!*

Meaning:

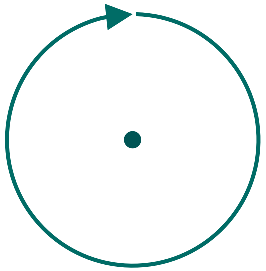
~

≠

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:

~

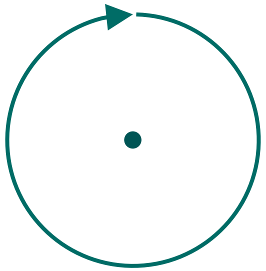
≠

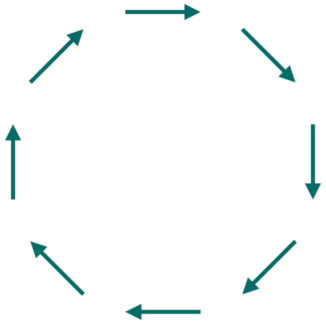
For magnetism?

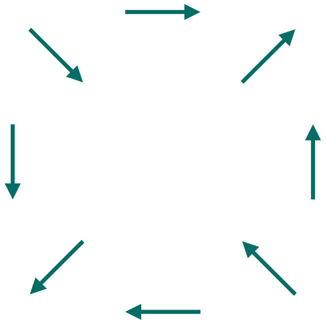
→ *assume continuous vector field*

Let's start with 2D!

Winding number:







UNDERSTANDING: TOPOLOGY

Key: *Smoothly deform!*

Meaning:

~

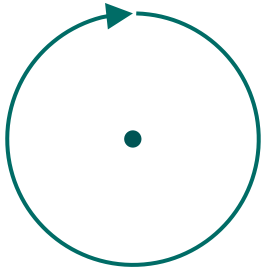
≠

For magnetism?

→ assume continuous vector field

Let's start with 2D!

Winding number:



↓ ↙ ← ↖ ↑ ↗ → ↘

Wind clockwise
→ W=+1

↑ ↖ ← ↙ ↓ ↘ → ↗

Wind anti-clockwise
→ W=-1

TOPOLOGY

***Key:** Smooth unwinding!*

Meaning:

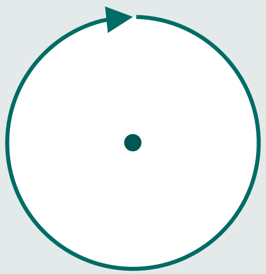
~

≠

Now to higher dimensions:

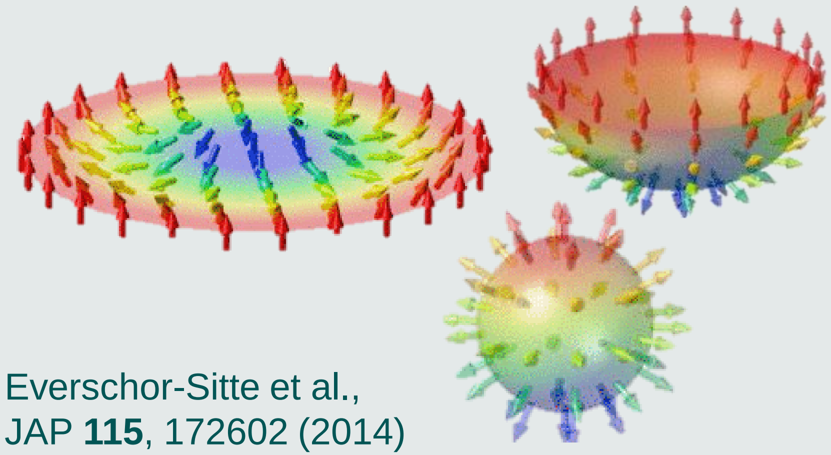
2D spins in 2D

Winding number



3D spins in 2D

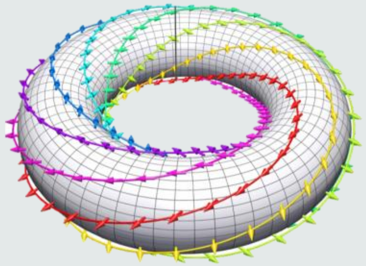
Skyrmion number



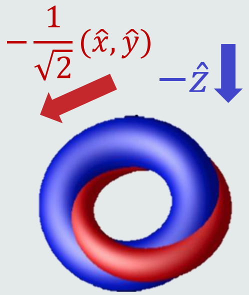
Everschor-Sitte et al.,
JAP **115**, 172602 (2014)

3D spins in 3D

Hopf Index



Rybakov et al.,
arXiv:1904.00250



Sutcliffe PRL 118,
247203 (2017)

TOPOLOGY

***Key:** Smooth unwinding!*

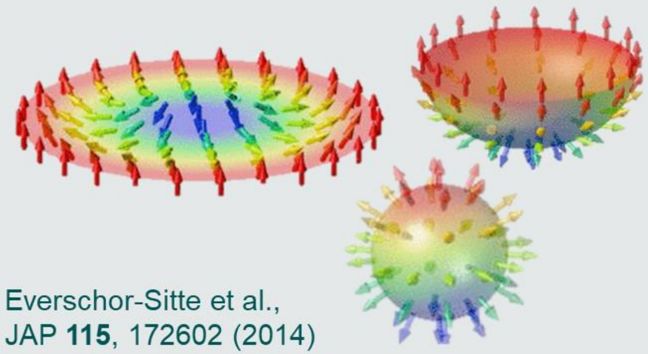
Meaning:

$\sim$

$\neq$

3D spins in 2D

Skyrmion number



Everschor-Sitte et al.,
JAP **115**, 172602 (2014)

Skyrmion number:

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

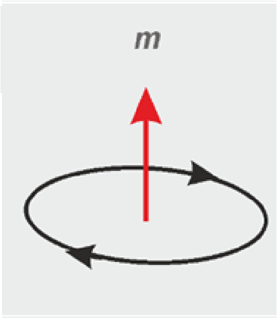
Calculates over a surface

For a vortex:

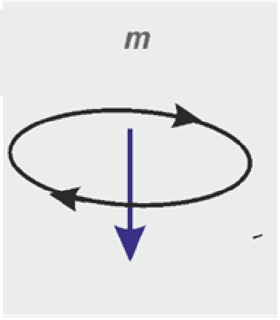
$$n = \frac{wp}{2}$$

w – winding number
p – polarisation
Tretiakov PRB 75, 012408 (2007)

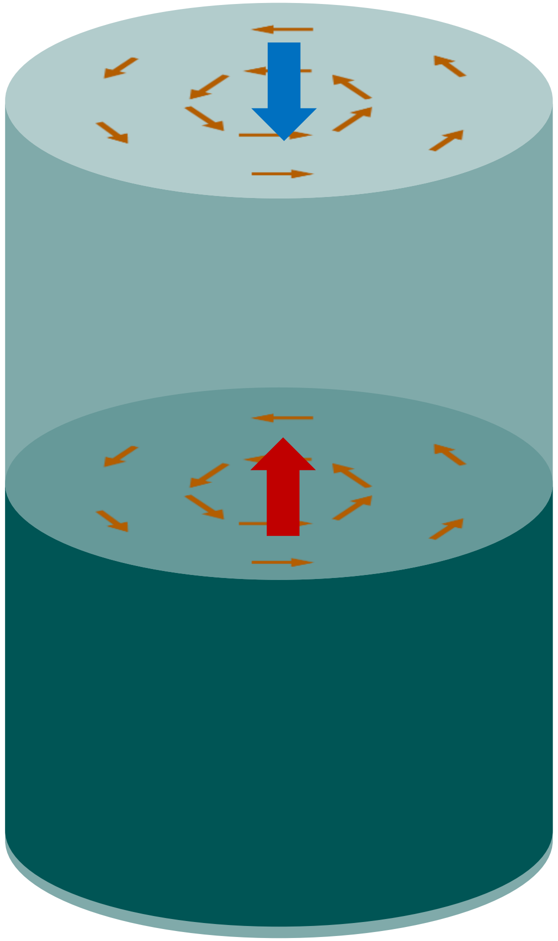
$$n = +\frac{1}{2}$$



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

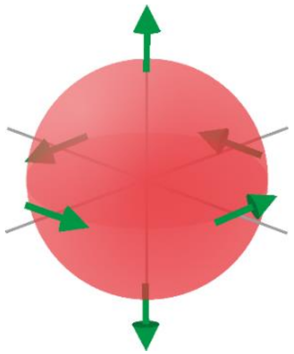


TOPOLOGY OF VORTICES IN 3D



Change of polarisation = change in skyrmion #

Bloch point!

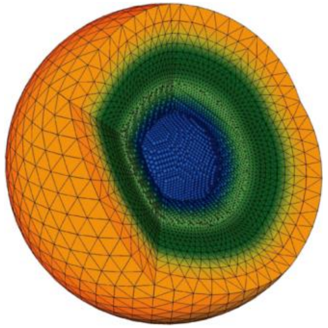


- **Topological defect in 3D**
- **Cannot be described by micromagnetics alone!**

III. THE MULTISCALE PROBLEM

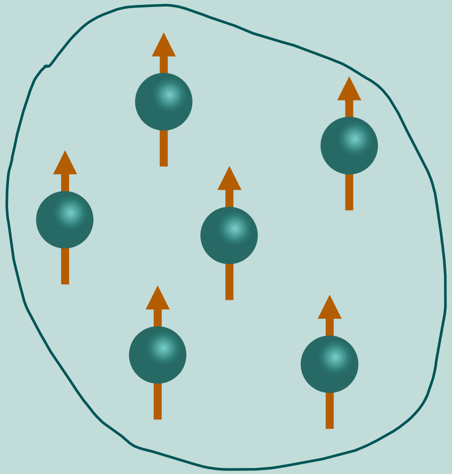
It appears that all difficulties connected with Bloch points stem from micromagnetic theory. If an atomistic Heisenberg model is used, nothing prevents neighboring atomistic magnetic moments from being strongly misaligned.

Andreas et al., Phys. Rev. B **89**, 134403 (2014)

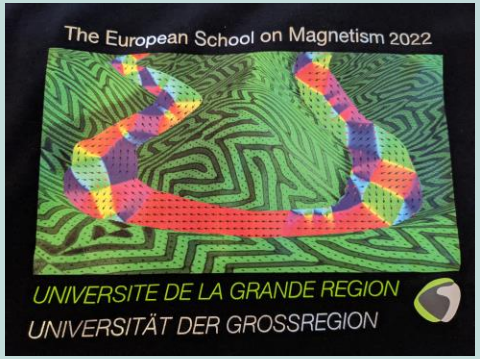


OUR QUESTIONS FOR TODAY:

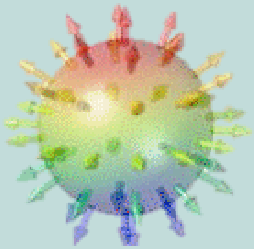
Why do domains form?



What drives different configurations?

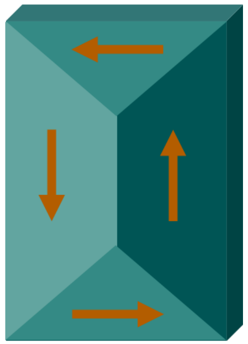


What about topology?



How can we observe these?

OBSERVING MAGNETIC DOMAINS



$$B = \mu_0(M + H)$$

$\boldsymbol{M}$ probes

Magneto-optics, spin-polarised STM, spin-polarised SEM

Optical regime

X-rays

$\boldsymbol{B}$ probes

Neutrons, electrons, scanning probe, Bitter method…

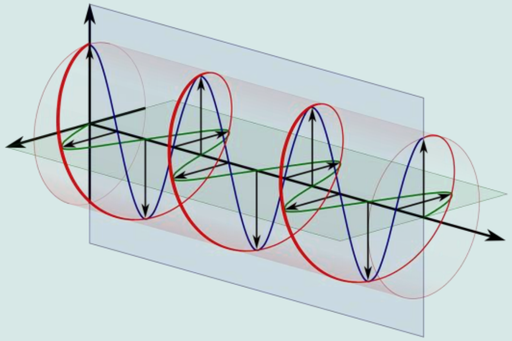
Electrons

MFM

Key consideration: spatial resolution!

MAGNETIC MICROSCOPY: MAGNETO-OPTICS

Circular polarised light:

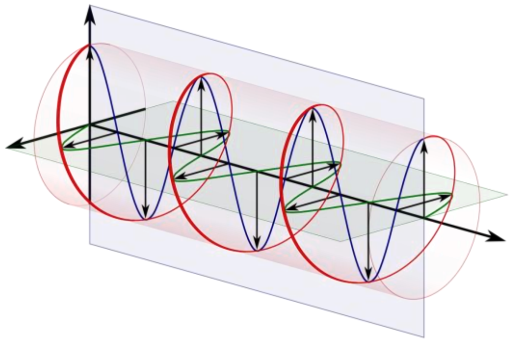


Coupling of the
photon's angular momentum
to
angular momentum of an electron

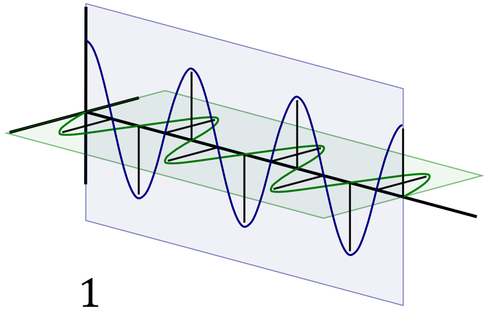
Angular momentum = $\pm\hbar$

Dichroism: *Refractive index dependent on:*
Circular polarisation and *Direction of magnetisation*

Circular polarised light:

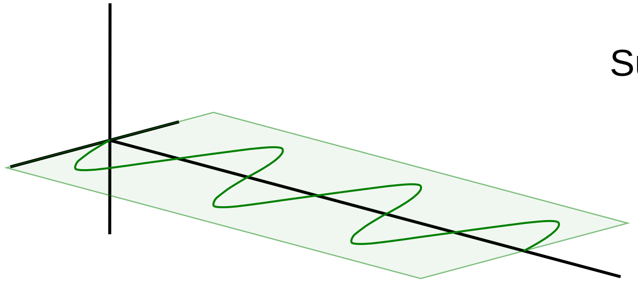


Superposition of linear H and V



$$|\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm i|V\rangle)$$

Linear polarised light:

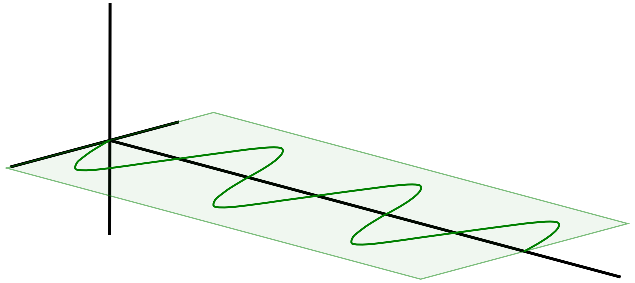


Superposition of circular C+ and C-

$$|H\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)$$

MAGNETIC MICROSCOPY: MAGNETO-OPTICS

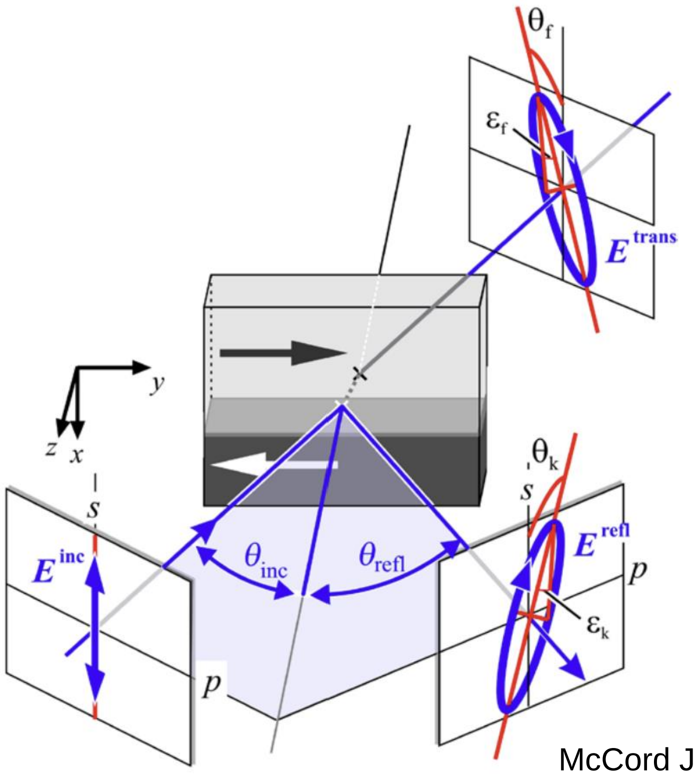
Linear polarised light incident on magnetic material:



→ *Rotation* of the linear polarisation
→ Ellipticity of the light

Measure this rotation → probe the magnetisation // k

***In transmission*: Faraday effect**



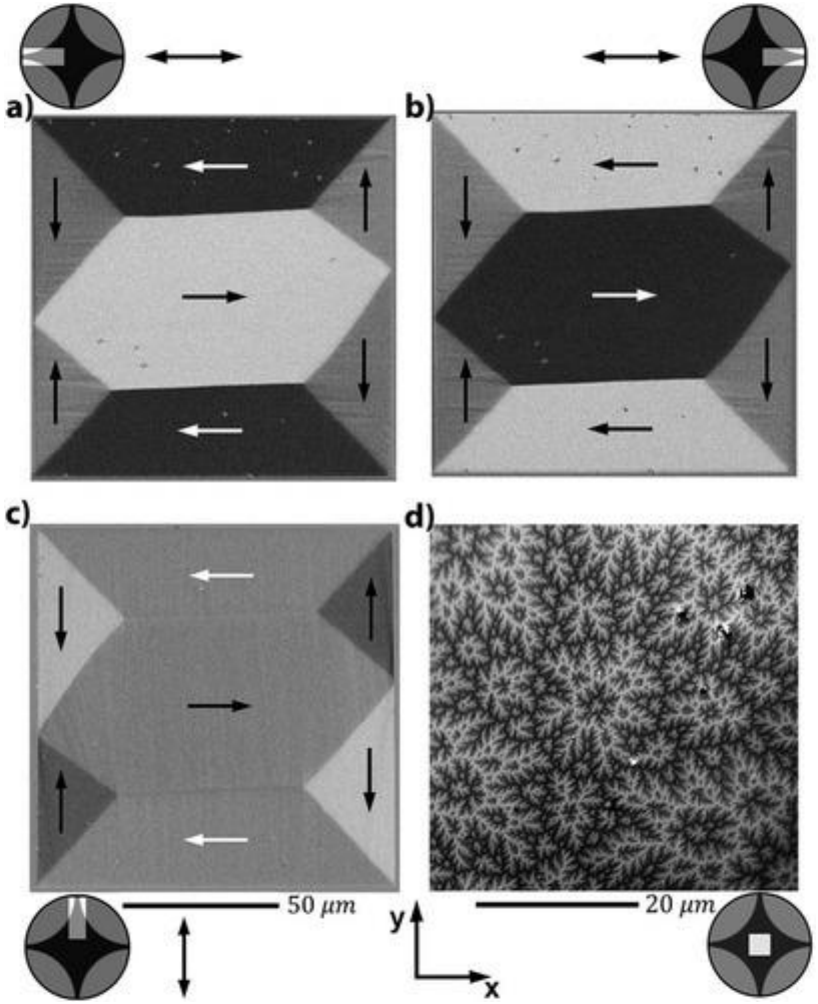
McCord J. Phys. D: Appl. Phys. 48 (2015) 333001

***In reflection:* Kerr effect**

Spatial resolution:

limited by wavelength of light
~hundreds of nanometres

MOKE MICROSCOPY



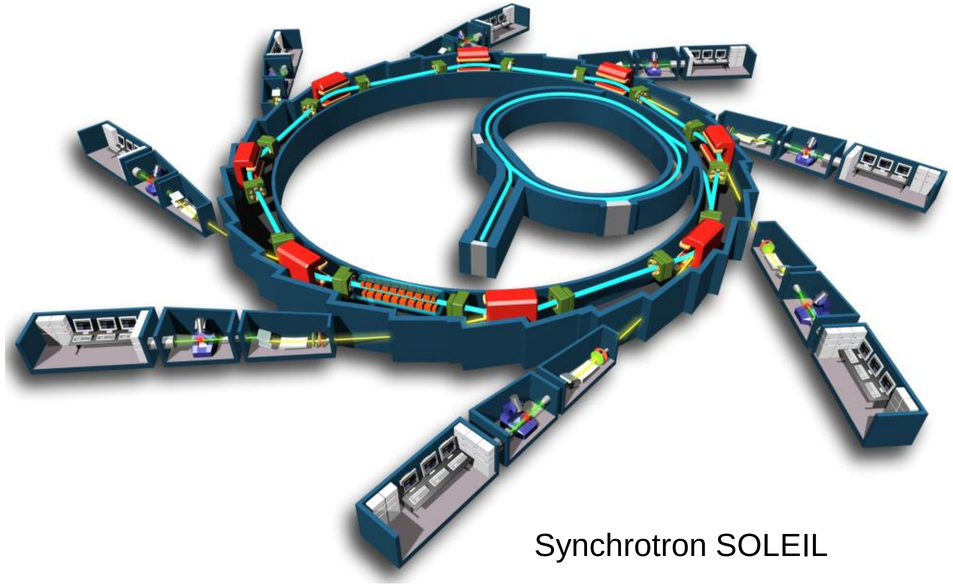
MOKE signal
depends on **k**

Soldatov & Schaefer, Review of Scientific Instruments **88**, 073701 (2017)

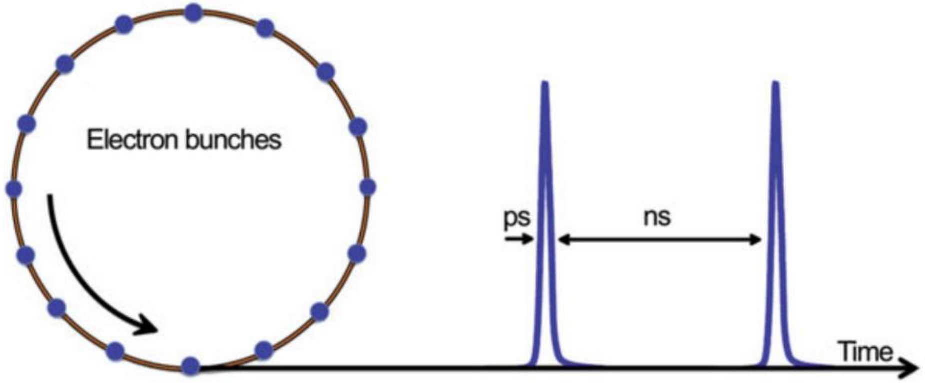
MAGNETIC MICROSCOPY: X-RAYS

Synchrotron light sources:

Swiss Light Source, PSI



Synchrotron SOLEIL



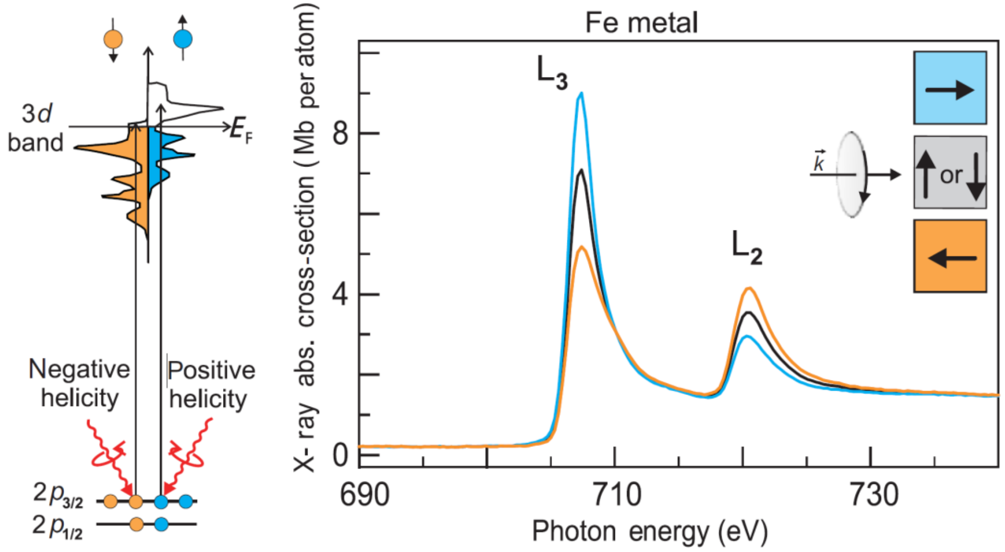
Balerna, Mobilio Intro. Synch. Rad

MAGNETIC MICROSCOPY: X-RAYS

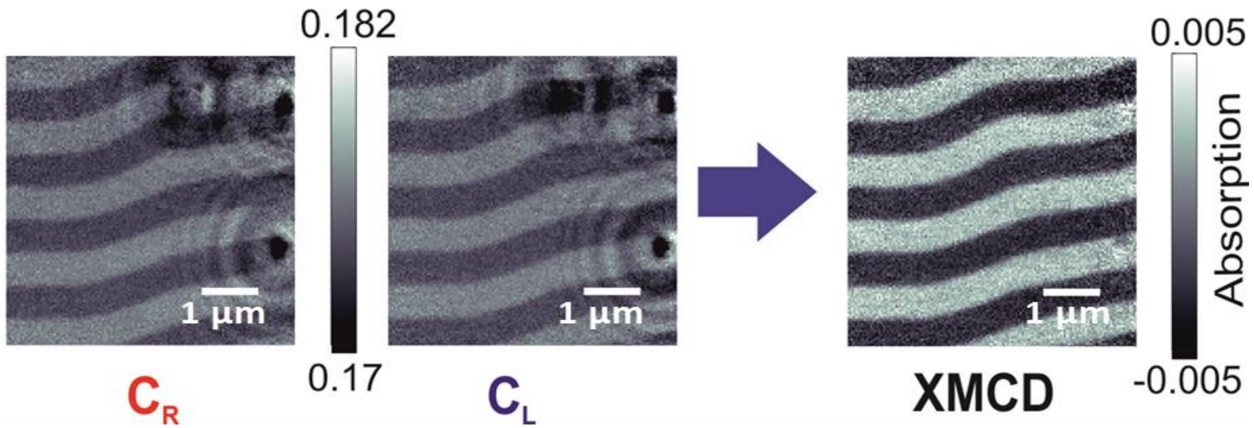
X-rays: X-ray magnetic circular dichroism
Circular polarised light: angular momentum ±ħ

This time, resonant!

- Element specific
- Can penetrate thicker samples



Stöhr & Siegmann, Magnetism, From fundamentals to Nanoscale Dynamics, Springer (2006)



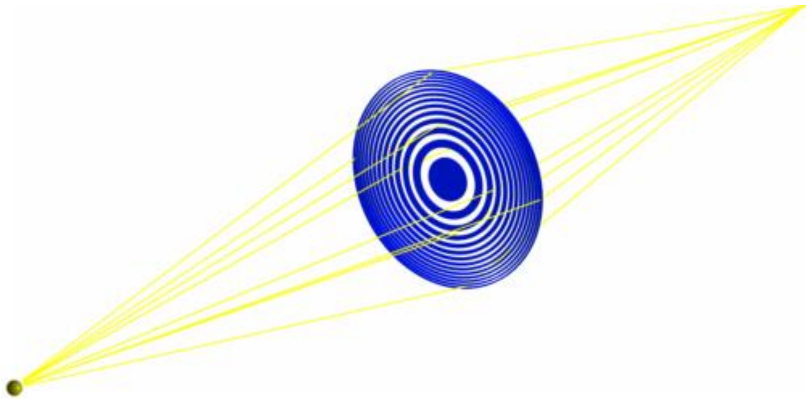
Donnelly et al., PRB **94**, 064421 (2016)

MAGNETIC MICROSCOPY: X-RAYS

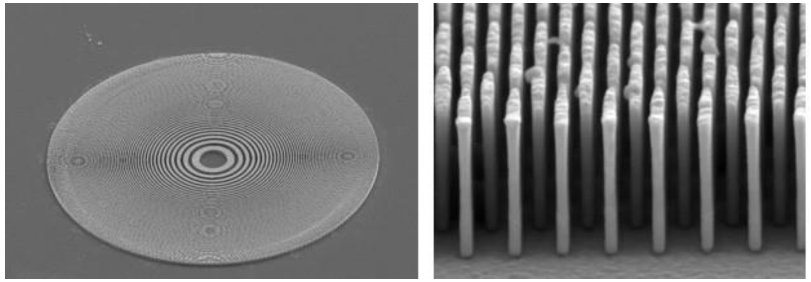
Advantage of X-rays: highly penetrating, so can look through “thick” samples

Also disadvantage: small refractive index means hard to create optics!

Fresnel Zone Plate:

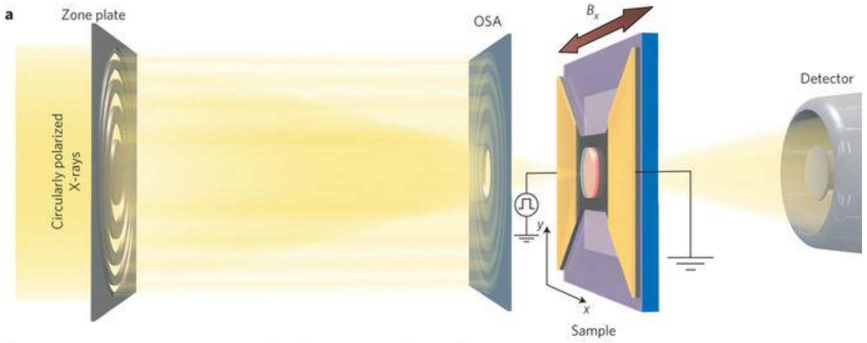


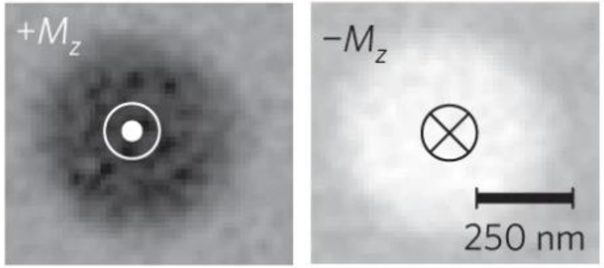
Nanofabrication determines spatial resolution



STXM

(Scanning Transmission X-ray Microscopy)



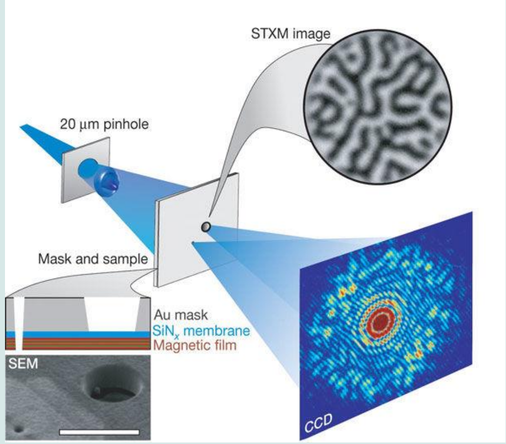


Baumgartner et al., Nat. Nano. **12**, 980 (2017)

MAGNETIC MICROSCOPY: X-RAYS

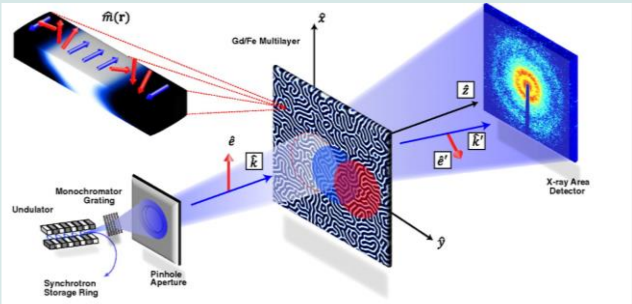
Alternative ways to obtain high resolution:

Holography



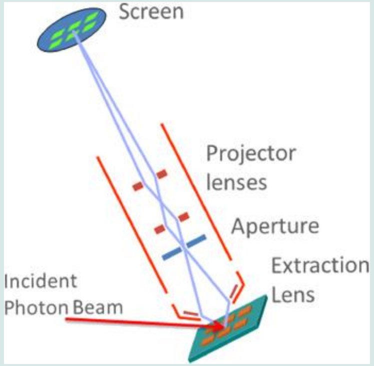
Eisebitt et al., Nature **432**, 885 (2004)

Coherent diffractive imaging



Tripathi et al., PNAS **108**, 33 (2011)

Photo emission electron microscopy



Cheng et al., Rep. Progr. Phys. **25**, 2 (2012)

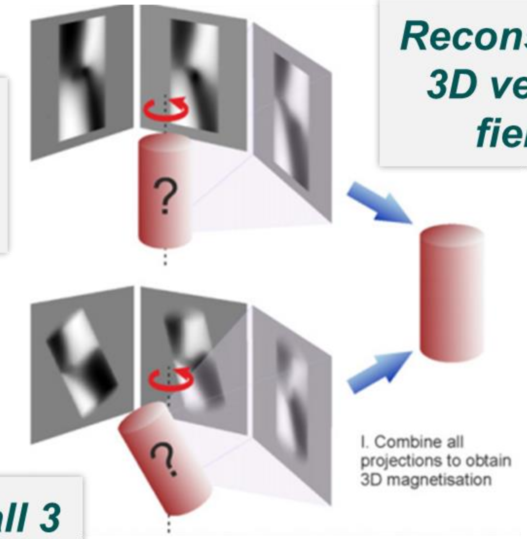
Spatial resolution: not limited by wavelength! But by signal/ focusing optics, depending on technique

~ 20 nm routinely achievable

3D MAGNETIC IMAGING

Magnetic tomography

2D projections of $\vec{m}$ or $\vec{B}$



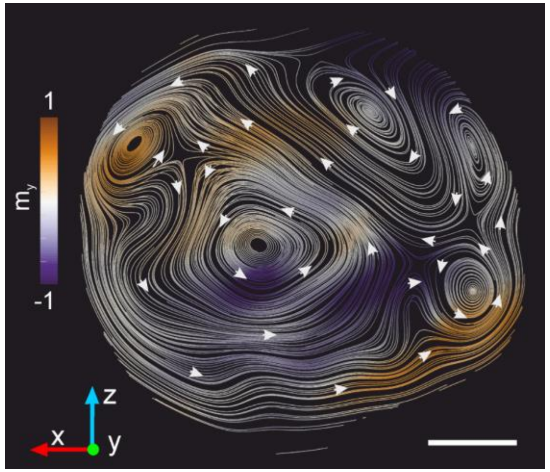
Reconstruct 3D vector field

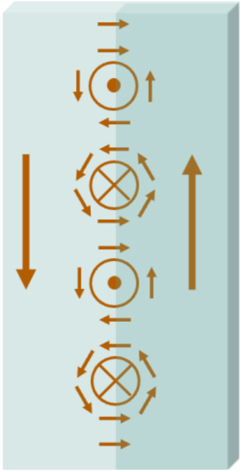
Measure all 3 components by rotating

Donnelly et al., NJP (2018)

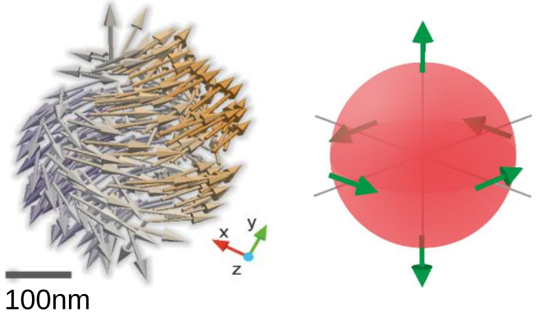
Review on 3D magnetic imaging:
Donnelly & Scagnoli, J. Phys. D. **32**, 213001 (2020)

Cross-tie: vortices & antivortices



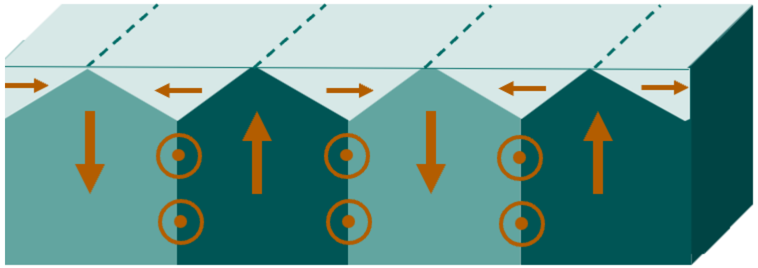


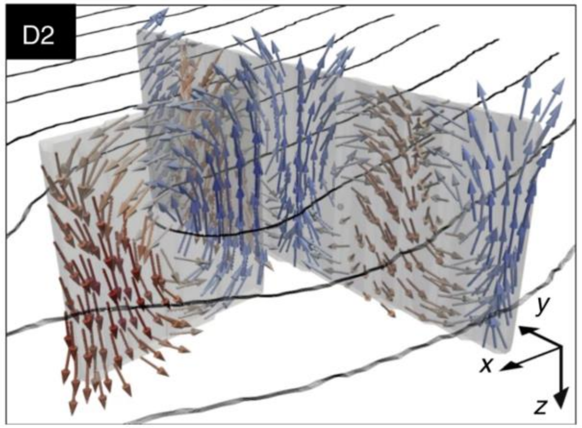
Bloch point singularities



Donnelly et al., Nature **547** 328 (2017)

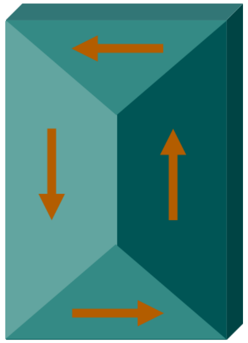
Closure domains:





Hierro Rodriguez et al., Nat. Comm. **11** 6382 (2020)

OBSERVING MAGNETIC DOMAINS



$$B = \mu_0(M + H)$$

$\boldsymbol{M}$ probes

Magneto-optics, spin-polarised STM, spin-polarised SEM

Optical regime

X-rays

$\boldsymbol{B}$ probes

Neutrons, electrons, scanning probe, Bitter method…

Electrons

MFM

Key consideration: spatial resolution!

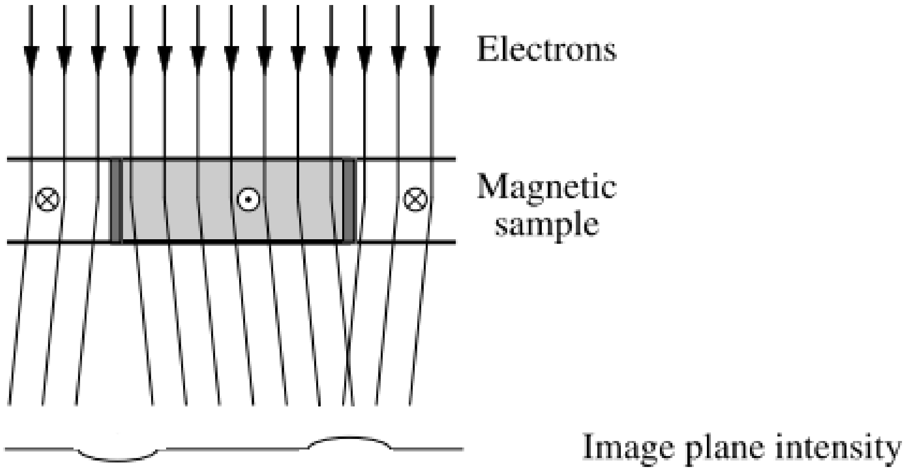
MAGNETIC MICROSCOPY: ELECTRON IMAGING

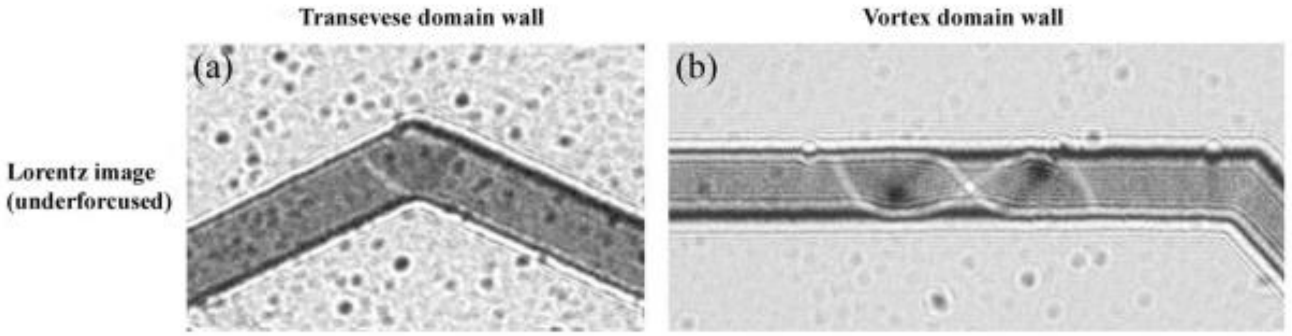
Lorentz microscopy:

Transmission electron microscopy:

Electrons deflected by Lorentz force:

$$\boldsymbol{F}_{Lorentz} = q(\boldsymbol{v} \times \boldsymbol{B})$$





Togawa et al., Proc. SPIE 7036, Spintronics, 703617 (2008)

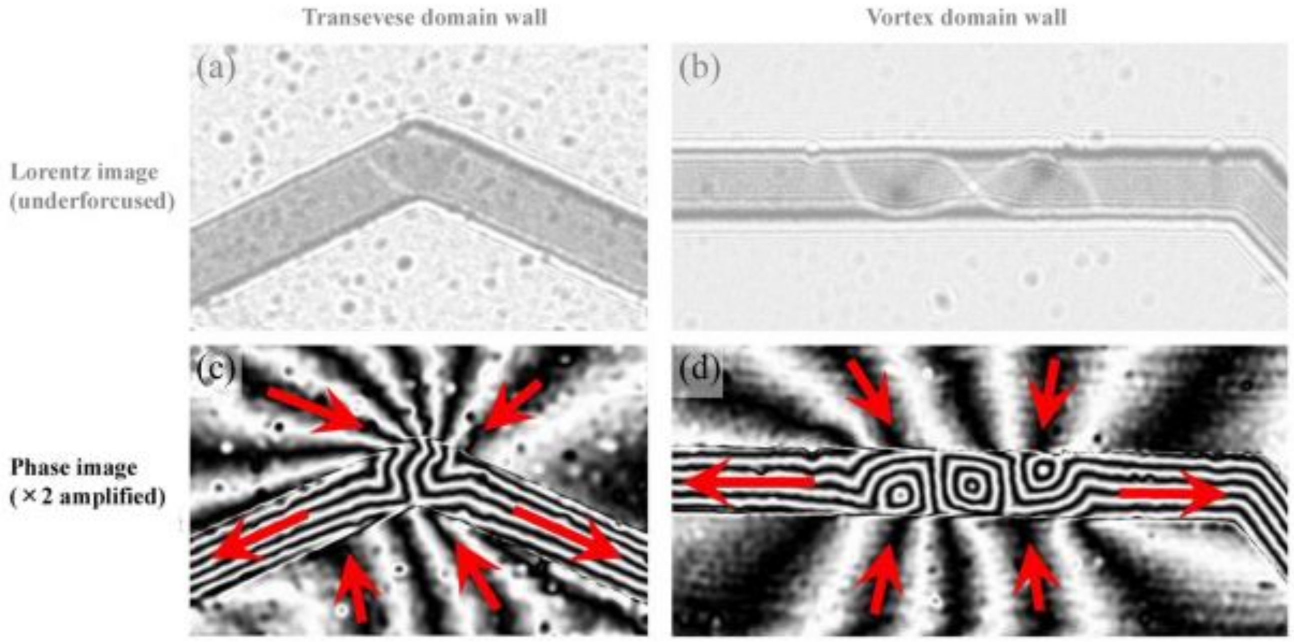
MAGNETIC MICROSCOPY: ELECTRON IMAGING

Electron holography:

Aharonov–Bohm effect:

Electrically charged particle affected by an electromagnetic potential, which leads to a change in phase of the wavefunction of the particle.

→ If you can reconstruct the phase of an electron, you can directly reconstruct the magnetic vector potential → in-plane components of magnetic field B



Togawa et al., Proc. SPIE 7036, Spintronics, 703617 (2008)

Spatial resolution: single digit nm

Wavelength of an electron ~ pm. Not the limiting factor!

MAGNETIC MICROSCOPY: SCANNING PROBE TECHNIQUES

MAGNETIC FORCE MICROSCOPY (MFM)

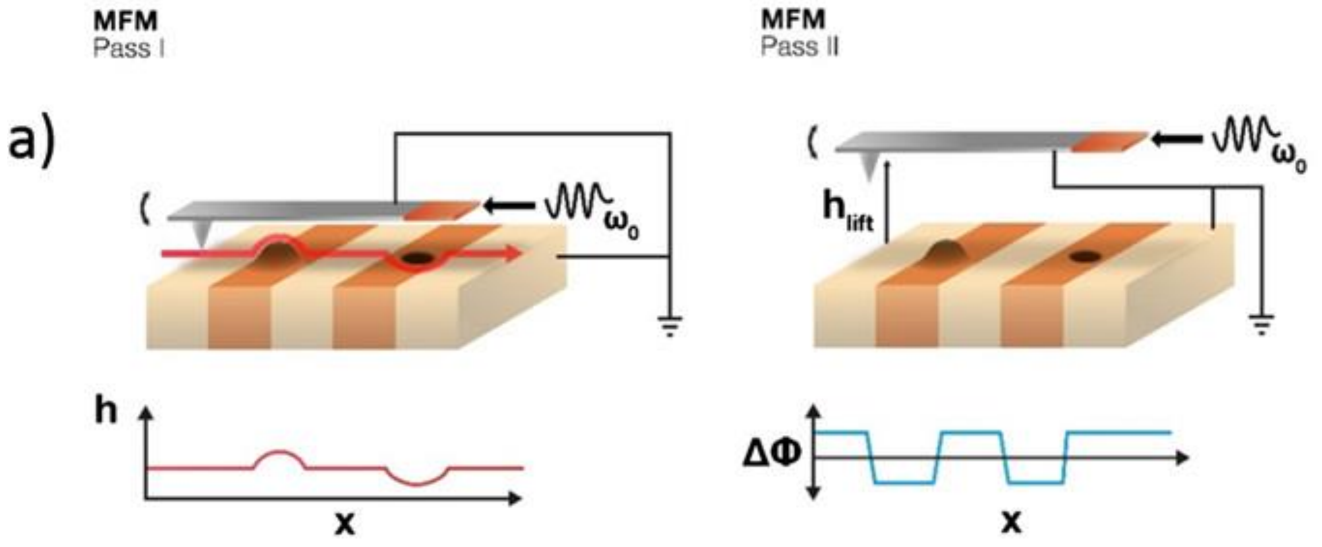
Scan an oscillating cantilever with magnetic tip over surface of a sample

First pass: get topography

(van der Waals)

Second pass lifted higher:

get long-range magnetic



Kasakova et al., Journal of Applied Physics **125**, 060901 (2019)

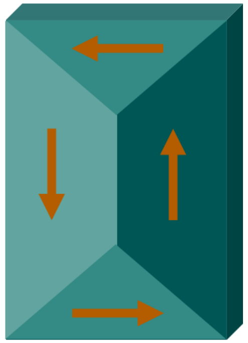
Tip acts as a dipole moving in a gradient of magnetic field:

Tip sample interactions change the cantilever oscillation, observed as a phase shift in the oscillation

Spatial resolution: determined by tip. Roughly 50 nm (down to ~10 nm)

Measure surface charges

OBSERVING MAGNETIC DOMAINS



$$B = \mu_0(M + H)$$

$\boldsymbol{M}$ probes

Magneto-optics, spin-polarised STM, spin-polarised SEM

Optical regime ✓

X-rays ✓

$\boldsymbol{B}$ probes

Neutrons, electrons, scanning probe, Bitter method…

Electrons ✓

MFM ✓

Key consideration: spatial resolution!

MAGNETIC MICROSCOPY COMPARISON