e-ESM, an online higher-education Magnetism event

MAGNETIC DOMAINS AND DOMAIN WALLS

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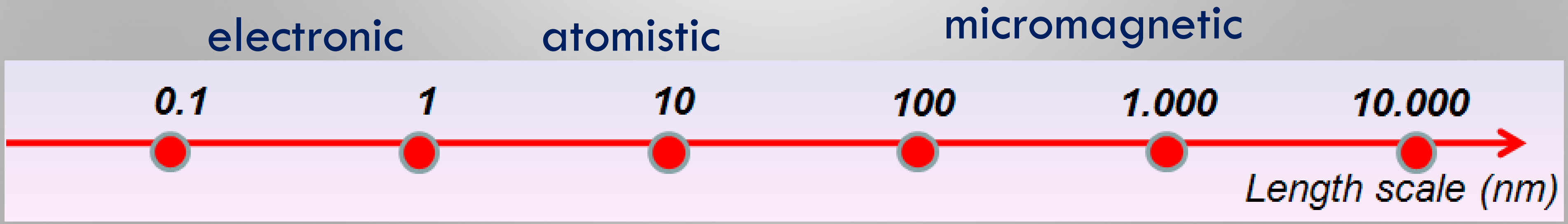
SCALES IN MAGNETISM



Magnetism processes at different scales

Quantum

Single-domain

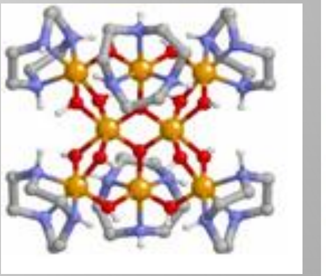
Multi-domain

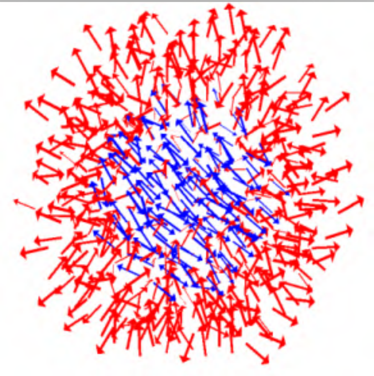
1nm 100nm 1000nm

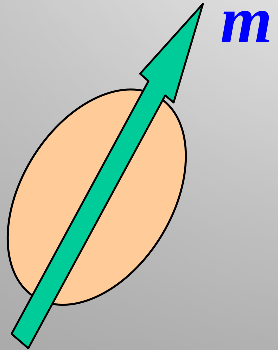
exchange energy

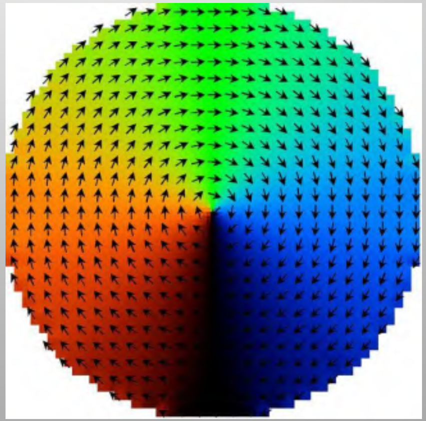
magnetostatic energy

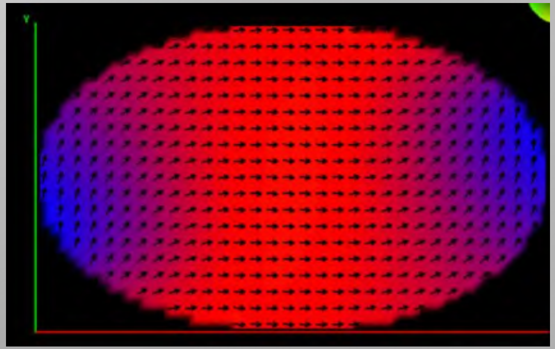
Surface dominating Core dominating Vortex state Inhomogeneous state



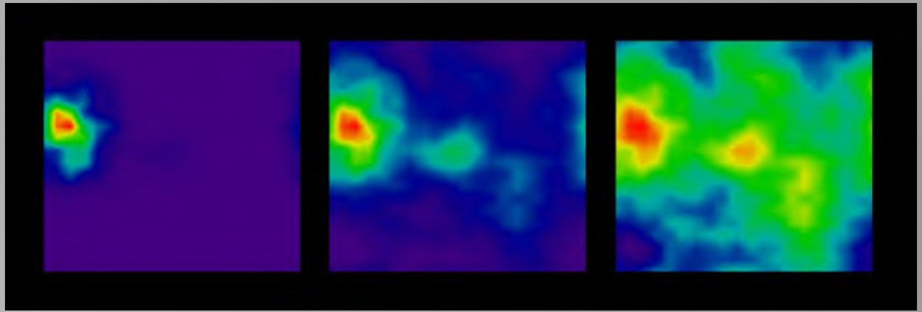




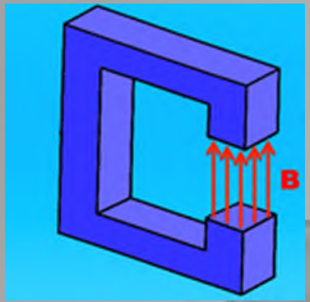




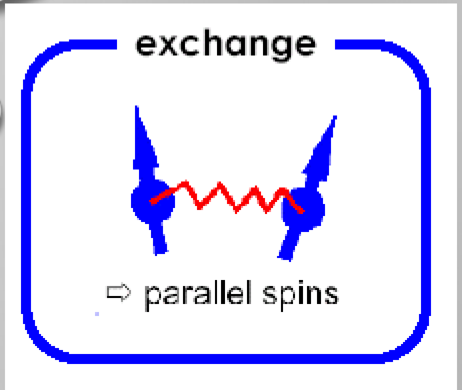
The sequence of nucleation-propagation-pinning-depinning
is governed by atomistic defects: inclusions, grain boundaries, interfaces etc.

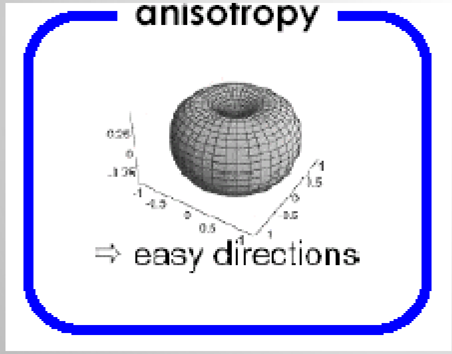


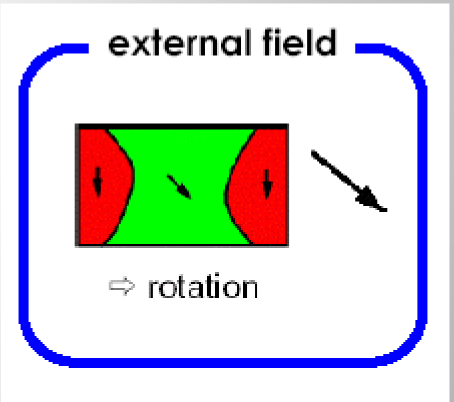
Magnets design

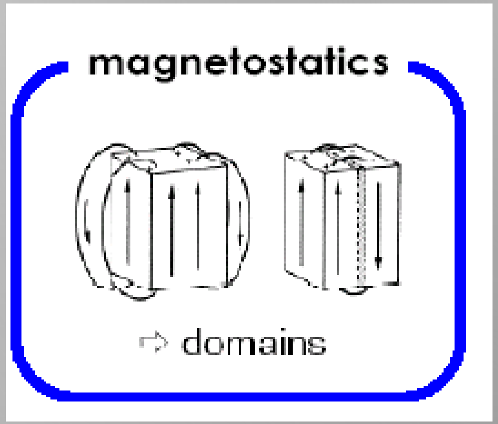


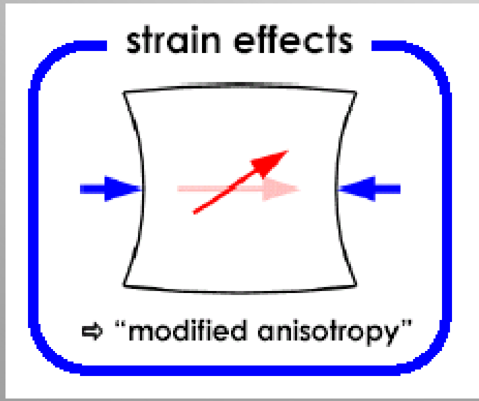
MAGNETIC ENERGIES

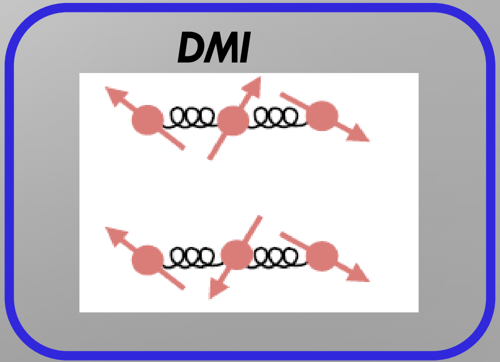


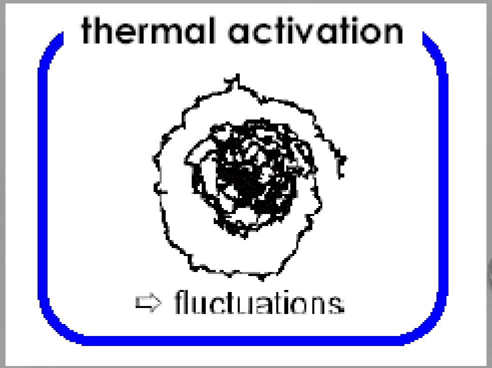












The relevance of different energies depend on the system dimensions

Classical micromagnetic sumulations:

W.F.Brown "Micromagnetics" 1963

Classical approximation of continuous magnetic media

Consists of the minimization of total magnetic energy:

$$E_{ext} = -\mu_0 \int_V \vec{H}_{ext}(\vec{r})\vec{M}(\vec{r})dV$$ External field

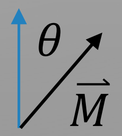
$$E_{ani} = -\int_V K_{ani}(\vec{r})[\vec{m}(\vec{r})\vec{e}(\vec{r})]^2 dV$$ Uniaxial Anisotropy

$$E_{ex} = \int_V A_{ex}(\vec{r})\left[(\nabla m_x)^2 + \left(\nabla m_y\right)^2 + (\nabla m_z)^2\right] dV$$ Exchange

$$E_{magn} = -\frac{\mu_0}{2}\int_V \vec{M}(\vec{r})\vec{H}_{magn}(\vec{r})dV$$ Magnetostatic

$$E_{DMI} = D\int_V \left[m_z\left(\vec{\nabla}\cdot\vec{m}\right) - \left(\vec{m}\cdot\vec{\nabla}\right)m_z\right]dV$$ DMI

$$\vec{H}_{eff} = -\frac{\partial E_{tot}}{\partial \vec{M}}$$ Total effective field



$\frac{\partial E_{tot}}{\partial \theta}$=0 $\leftrightarrow$ $MH_{eff}\sin\theta = 0$ $\longleftrightarrow$ $\left[\vec{M}\times\vec{H}_{eff}\right] = 0$ Brown's equilibrium condition

Magnetostatic energy

(Maxwell equations in the static limit):

$$\vec{H}_{magn} = -grad\ \Phi_{magn}$$

$$\Delta\Phi_{magn} = \begin{cases} 4\pi\nabla\vec{M} & inside \\ 0 & outside \end{cases}$$ Volume charges

Boundary conditions:

$$\Phi_{magn}^{outside}\Big|_\Sigma = \Phi_{magn}^{inside}\Big|_\Sigma$$

$$\left(\frac{\partial\Phi_{magn}^{inside}}{\partial\vec{n}} - \frac{\partial\Phi_{magn}^{outside}}{\partial\vec{n}}\right)_\Sigma = 4\pi\vec{M}\vec{n}$$ Surface charges

FORMAL SOLUTION OF THE MAGNETOSTATIC PROBLEM

Magnetostatic energy
(Maxwell equations in the static limit):

$$\vec{H}_d = -grad\ \Phi_d$$

$$\Delta\Phi_d = \begin{cases} 4\pi\nabla\vec{M} & inside \\ 0 & outside \end{cases}$$

Volume charges

Boundary conditions:

$$\Phi_d^{outside}\Big|_\Sigma = \Phi_d^{inside}\Big|_\Sigma$$

$$\left(\frac{\partial\Phi_d^{inside}}{\partial\vec{n}} - \frac{\partial\Phi_d^{outside}}{\partial\vec{n}}\right)_\Sigma = 4\pi\vec{M}\vec{n}$$

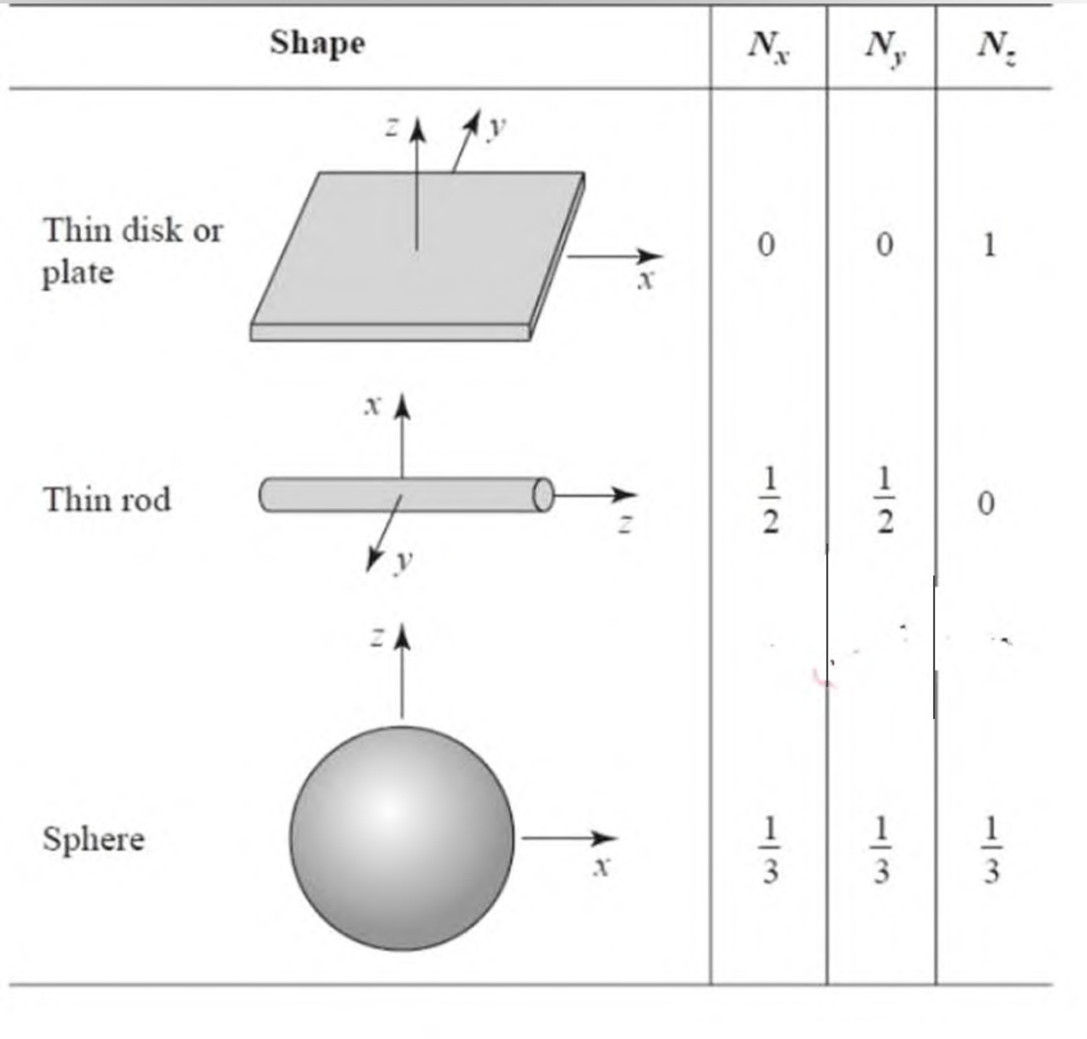
Surface charges

$$\boxed{\vec{H}_d(\vec{r}) = -\,grad\ \Phi_d(\vec{r})}$$ where

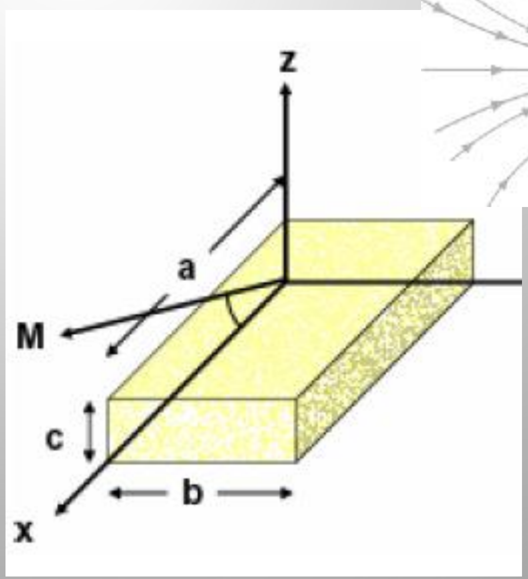
$$\boxed{\Phi_d(\vec{r}) = \frac{M_s}{4\pi}\left[\int \frac{-\mathrm{div}\ \vec{m}(\vec{r}')}{|\vec{r}-\vec{r}'|}\,dV' + \int \frac{\vec{m}(\vec{r}')\cdot\vec{n}(\vec{r}')}{|\vec{r}-\vec{r}'|}\,dS'\right]}$$

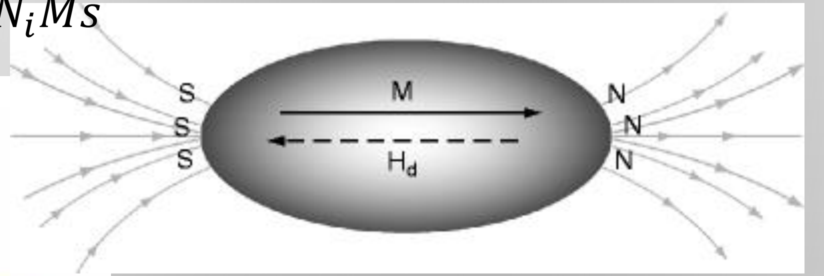
THE CONCEPT OF SHAPE SHAPE ANISOTROPY

$$H_i = H_a - N_i Ms$$



Shape	N_x	N_y	N_z
Thin disk or plate	0	0	1
Thin rod	$\frac{1}{2}$	$\frac{1}{2}$	0
Sphere	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$

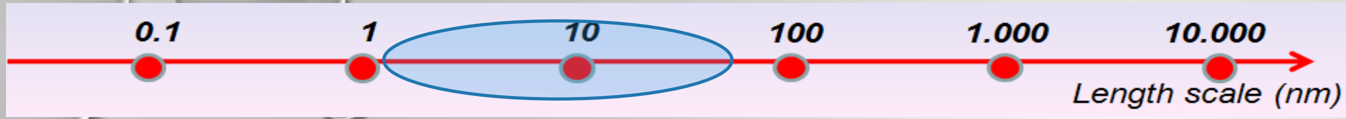




$$E_{magn} = \frac{1}{2}\mu_0 (N_c - N_a) M_s^2 \sin^2(\theta)$$

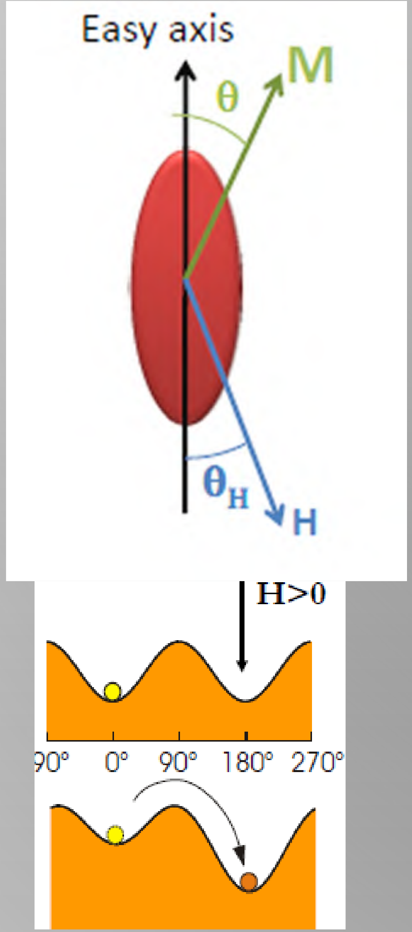
Shape anisotropy acts similar to magnetocrystalline anisotropy

But the concept is valid for saturated objects only



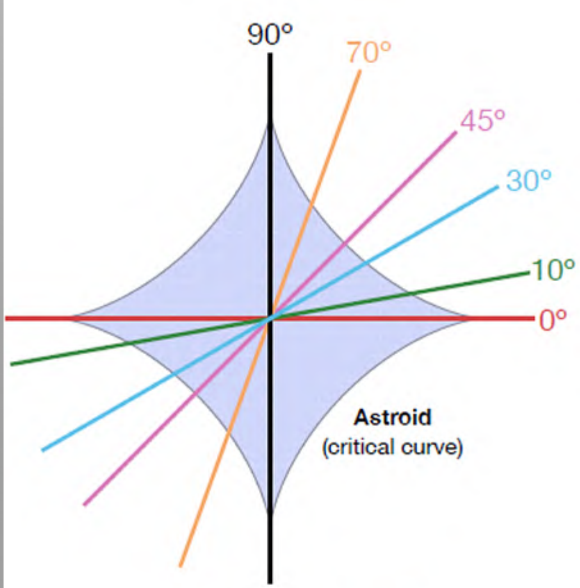
NANOPARTICLES: THE STONER-WOLFARTH MODEL FOR COHERENT REVERSAL

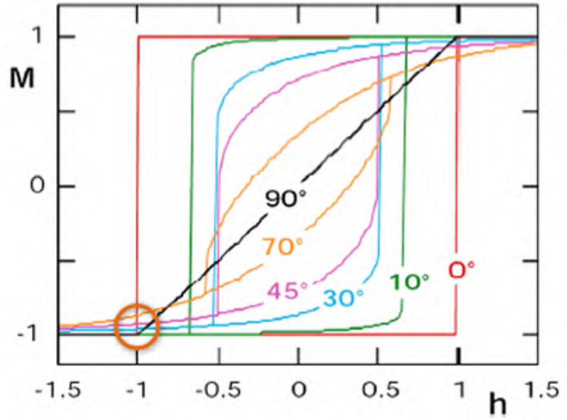
The maximum coercive field is equal to the anisotropy field



$$E = K_{eff}\sin^2\theta - \mu_0 M_S H\cos(\theta+\theta_H)$$

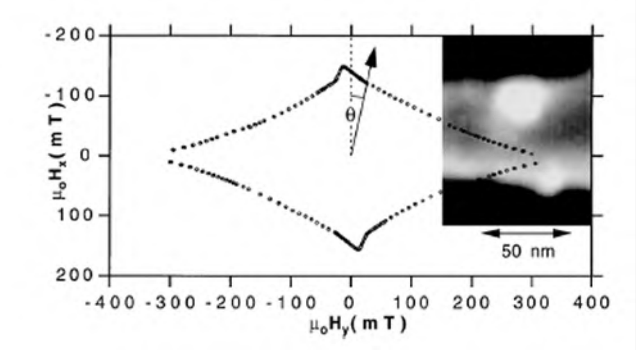
$$H_K(H_A) = \frac{2K}{M_s}$$ Anisotropy field





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

Real measurement
Nano-SQUID Co 25 nm



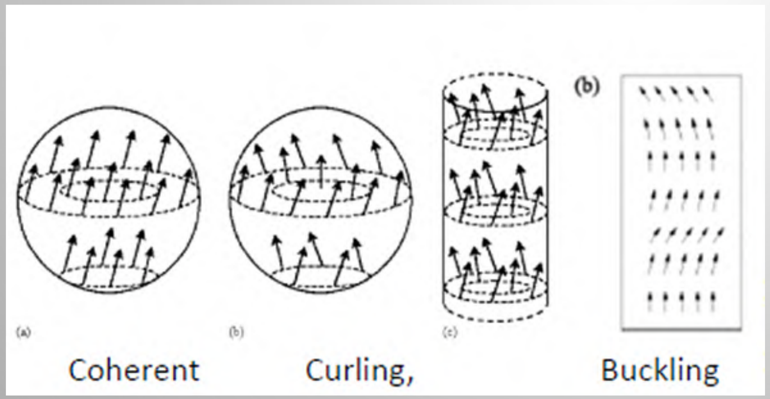
Wernsdorfer et al
PRL 78 (1997)

BROWN'S PARADOX

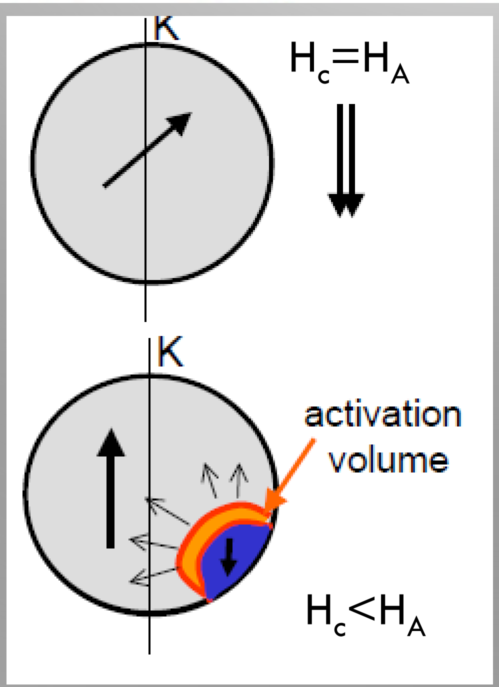
Brown's paradox

In most systems $H_c \lll \frac{2K}{\mu_0 M_s}$

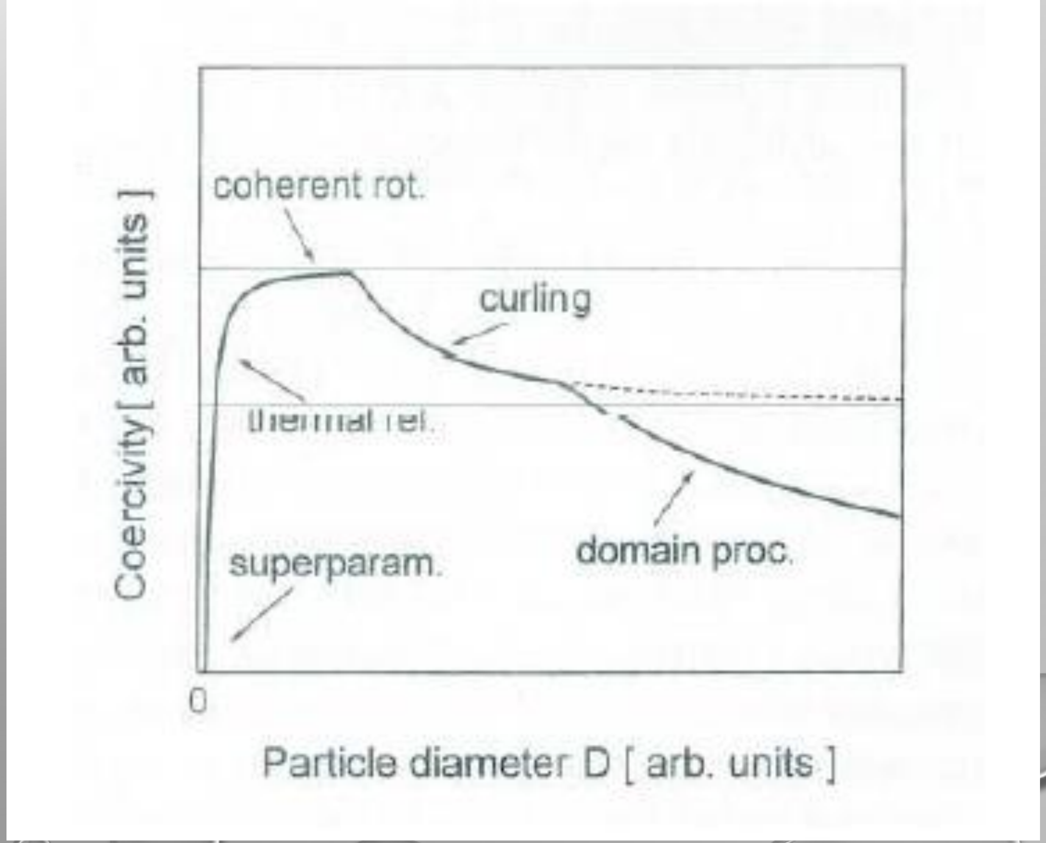
For nanomagnets: Non-uniform reversal modes



For larger systems: Nucleation (on defects and thermal nucleation)



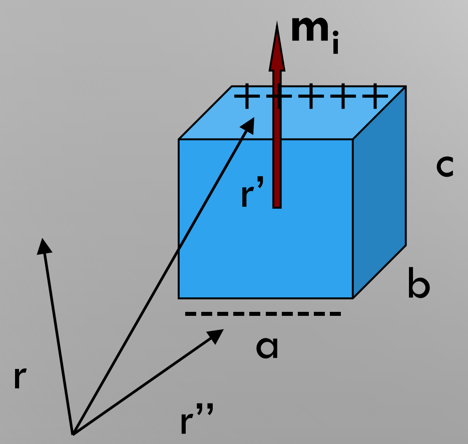
Pinning an depinning of structures.



FORMAL SOLUTION

$$\boxed{\vec{H}_d(\vec{r}) = -\,grad\ \Phi_d(\vec{r})}$$ where

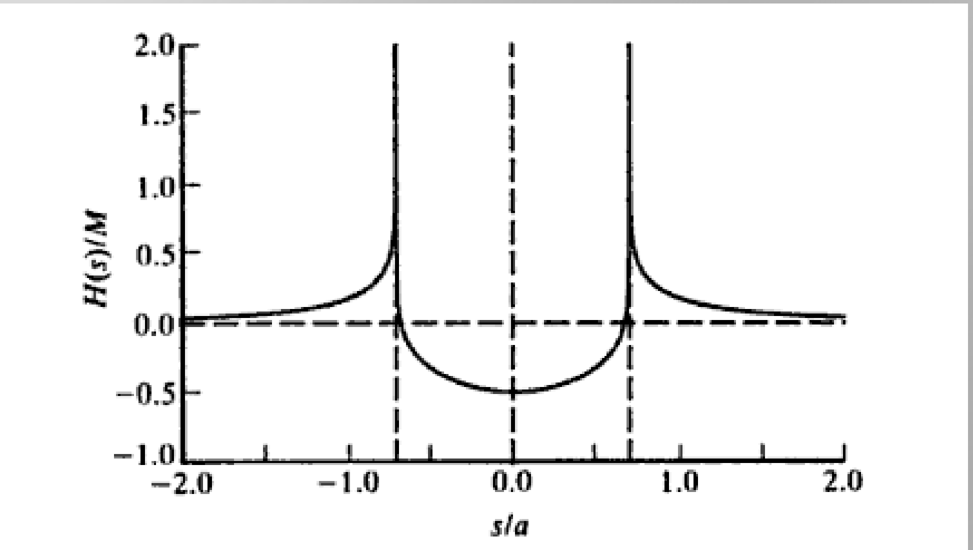
$$\boxed{\Phi_d(\vec{r}) = \frac{M_s}{4\pi}\left[\int \frac{-\mathrm{div}\ \vec{m}(\vec{r}\,')}{\left|\vec{r}-\vec{r}\,'\right|}\,dV' + \int \frac{\vec{m}(\vec{r}\,')\cdot\vec{n}(\vec{r}\,')}{\left|\vec{r}-\vec{r}\,'\right|}\,dS'\right]}$$



SATURATED CUBE

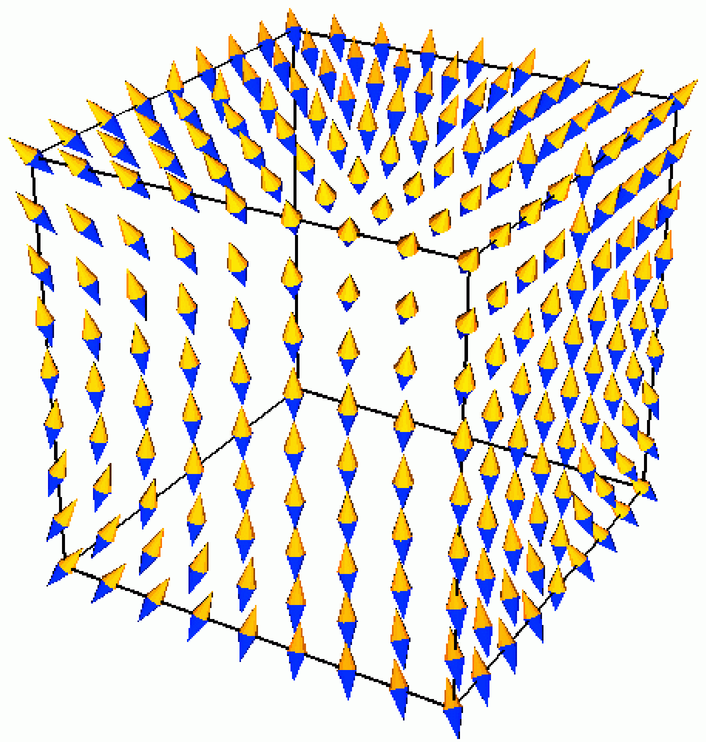
On the cube side:

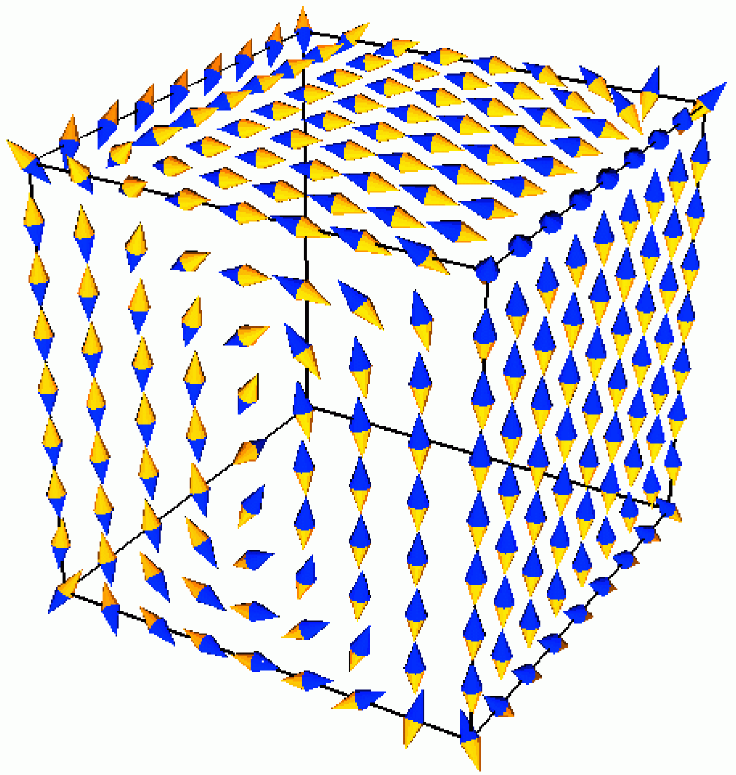
$$\phi(\vec{r}) \propto \frac{M}{4\pi}\left(\iint_{\Sigma} \frac{dx'\,dy'}{\left|\vec{r}-\vec{r}\,'\right|} + \iint_{\Sigma'} \frac{dx''\,dy''}{\left|\vec{r}-\vec{r}\,''\right|}\right)$$



•The magnetostatic fields are stronger at the corners.

M-MAG STANDARD PROBLEM (FROM OOMMF WEBPAGE)


Longitudinal flower state

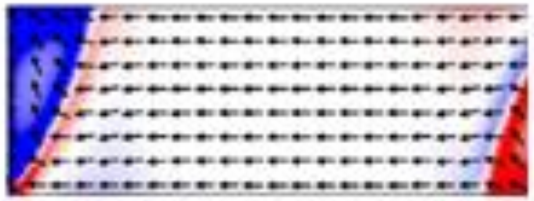

Transverse vortex state

See also M.A.Schabes abd H.N.Bertram "Magnetisation processes in ferromagnetic cubes", J.Appl. Phys. 64 (1988) 1347.

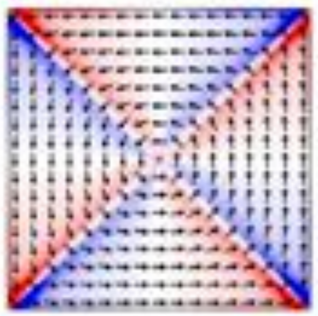
POLE AVOIDANCE PRINCIPLE

The minimization of the magnetostatic energy leads to the "avoidance" of surface charges = Magnetisation parallel to surfaces

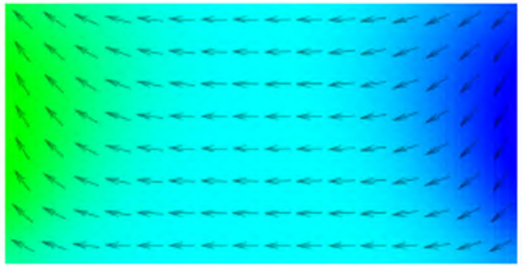
C-state

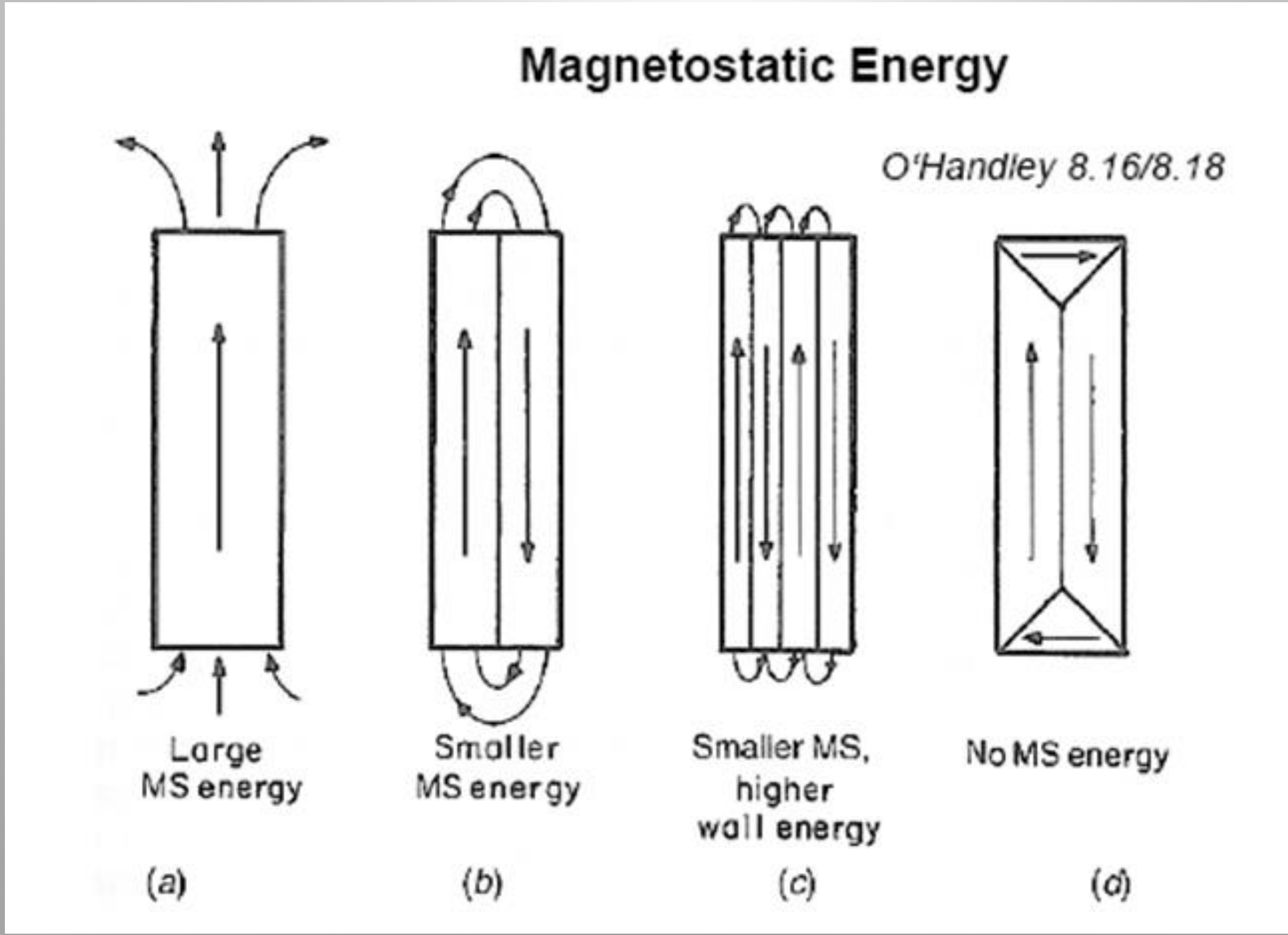


Vortex

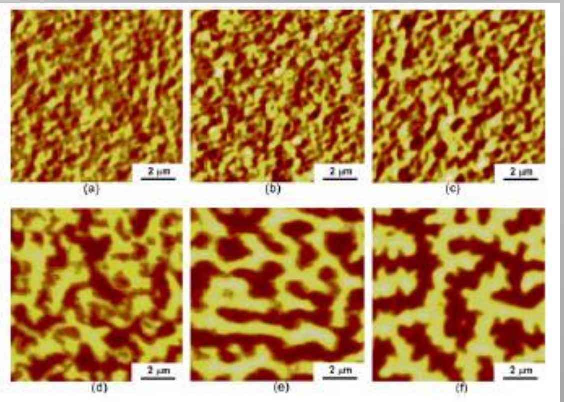


S-state




Magnetostatic Energy
O'Handley 8.16/8.18
Large
MS energy
Smaller
MS energy
Smaller MS,
higher
wall energy
No MS energy
(a)
(b)
(c)
(d)

THE CONCEPT OF DOMAINS

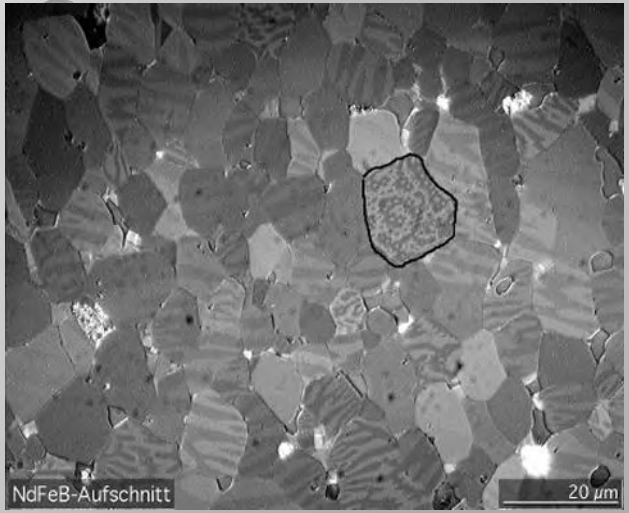


The concept of **domain:**

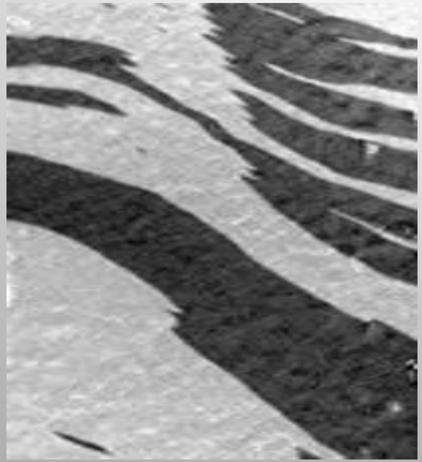
Postulated by Pierre Weiss in 1907 to explain why ferromagnetic bodies can appear non-magnetic.

DOMAINS

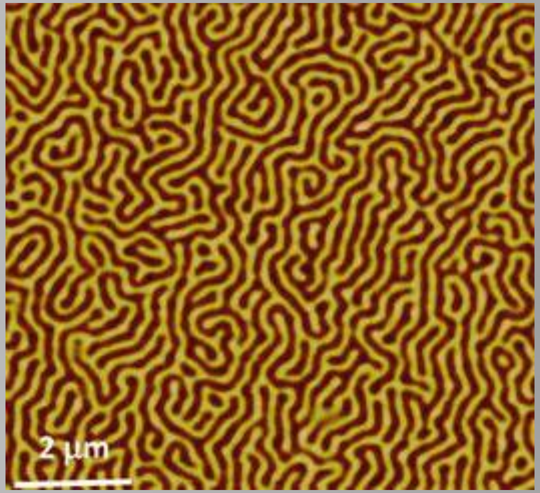
- Hard magnet: NiFeB

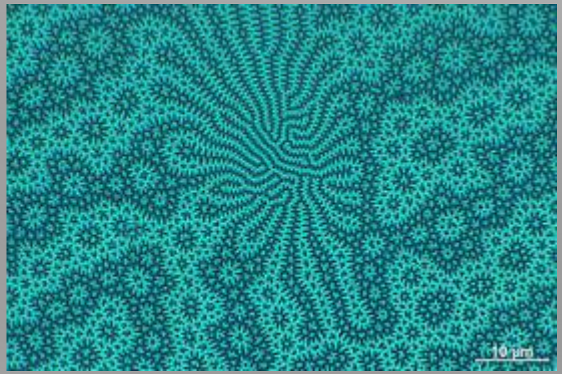


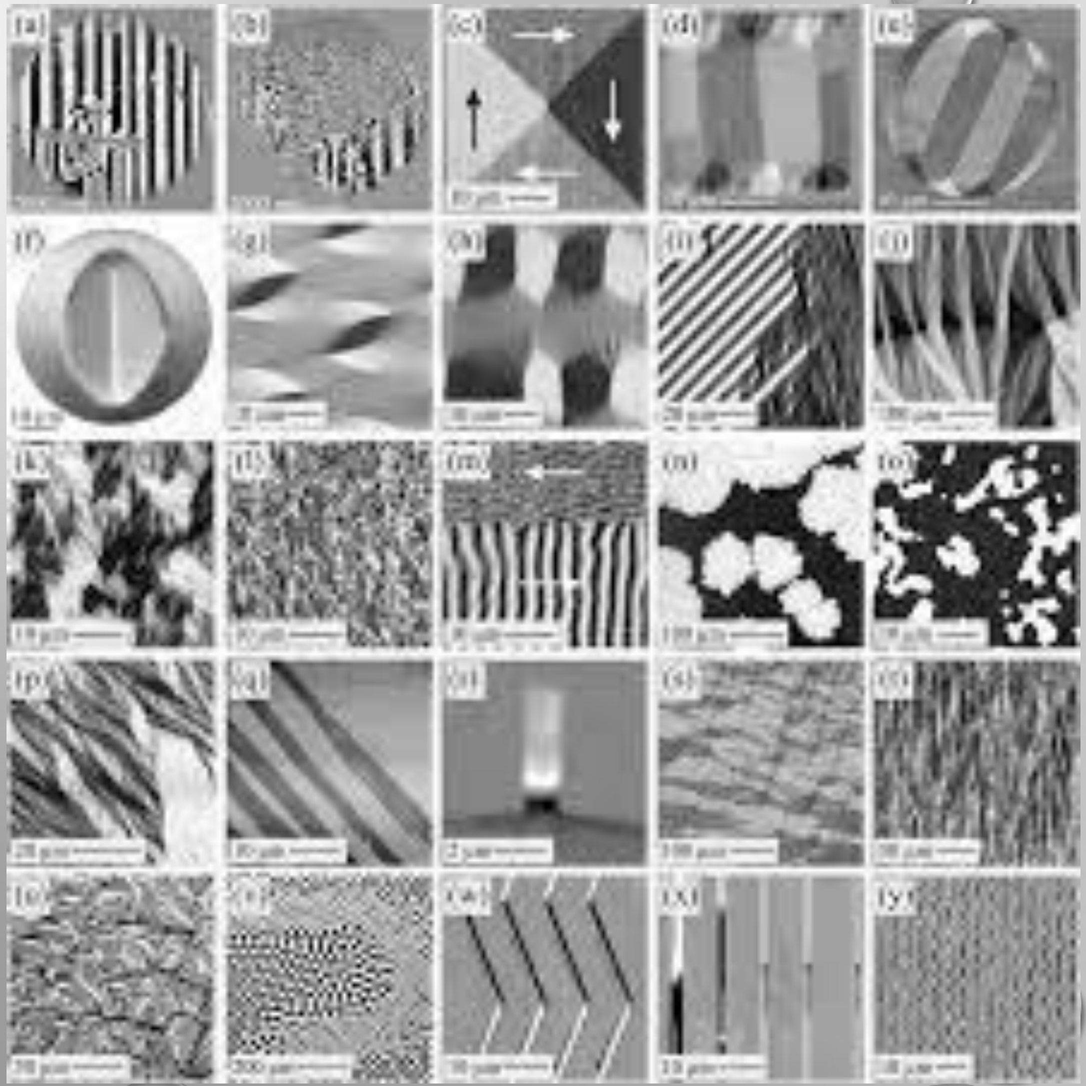
Soft magnetic material: finemet (FeSiB)



Systems with PMA: stripe domains







A huge number if domain patterns is very surprising!

DOMAIN THEORY CH. KITEL

“Domain structure has its origin in
the possibility of Lowering the energy of a system by going from a saturated configuration such as (a) with high magnetic energy to a domain configuration, such as (c) or (e), with a lower energy.”

Ch.Kitel Rev. Modern Phys 21 (1949)

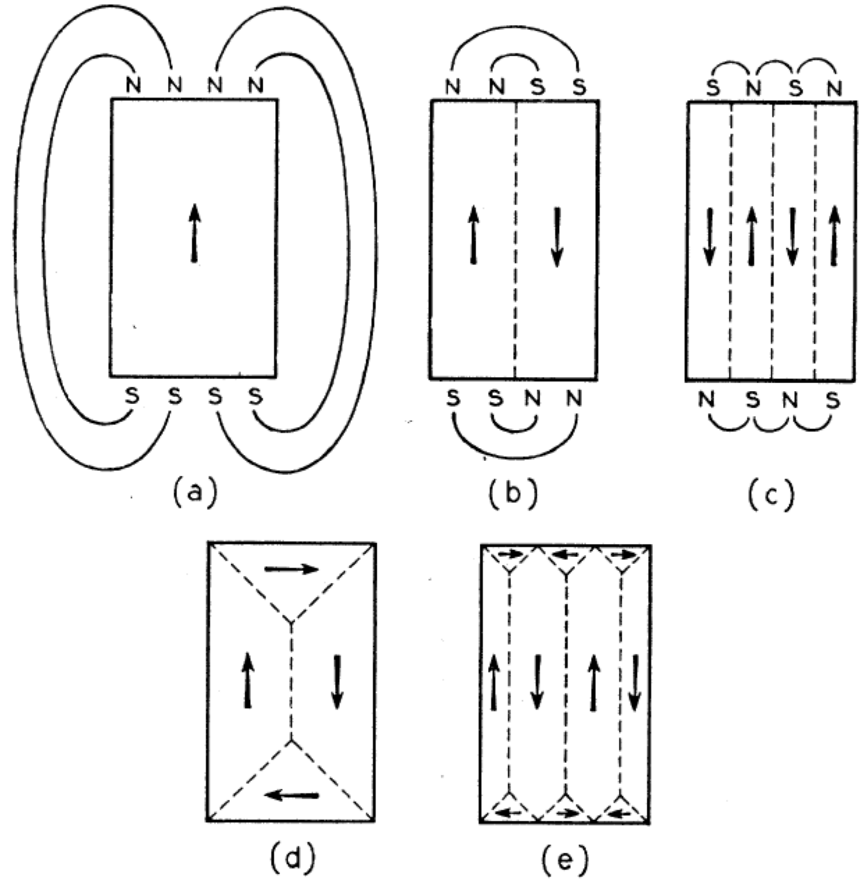
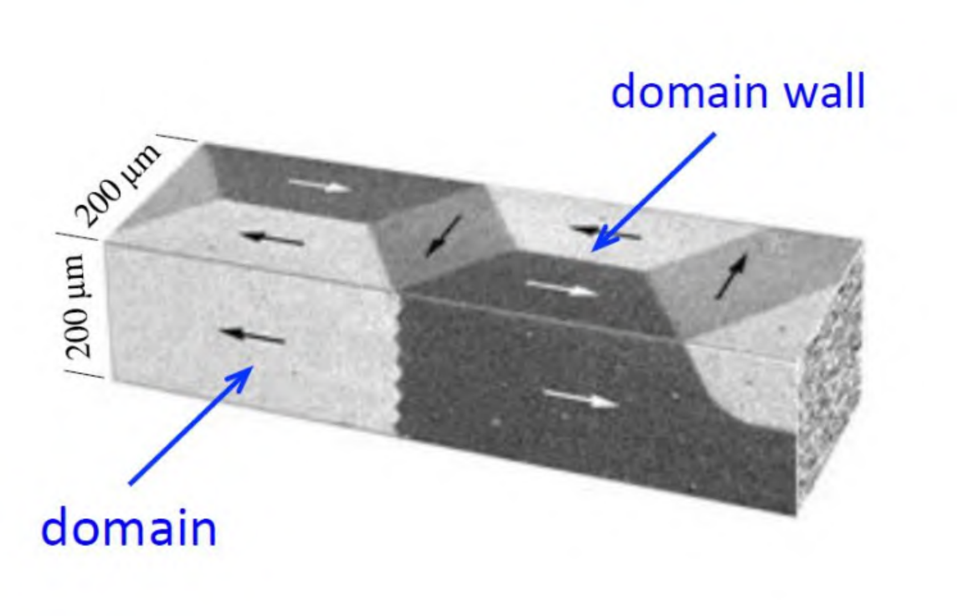
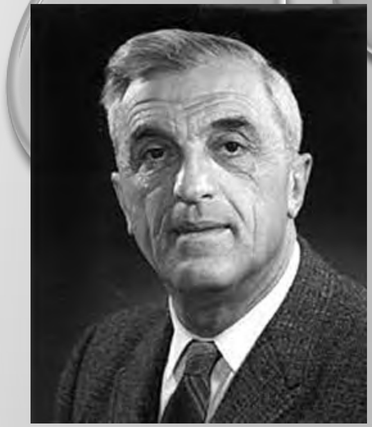


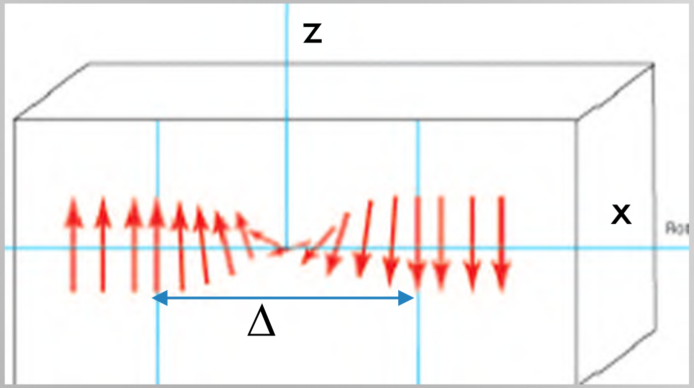
FIG. 9. The origin of domains.

DOMAINS





BLOCH DOMAIN WALL



$$\mathcal{E} = \int dx \left[A \left(\frac{\partial \theta}{\partial x} \right)^2 + K_u \sin^2 \theta \right] \longrightarrow 2A\frac{\partial^2 \theta}{\partial x^2} - K_u \sin 2\theta = 0$$

$$\vec{m} = (0, \sin\theta\,,\ \cos\theta)$$

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

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

Domain wall width

Δ=2 nm (very hard materials) ---- more than 1000 nm (very soft materials)

4 nm (FePt), 12 nm (hcp Co)

$E_{DW} = 4\sqrt{AK_u}$ Domain wall energy (density per area)

$E_{DW} = 4\sqrt{AK_u} - \pi D$ (with DMI)

Different in cubic materials: 90 degrees walls (100) e.a.

and depends on the e.a. orientations For (111) e.a. we can have 71 and 109 degrees domain walls

NEEL AND BLOCH DOMAIN WALLS

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

DW angle $\phi = \pi/2 \quad m_x = 0$ Bloch wall

$\phi = 0 \quad m_y = 0$ Neel wall

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

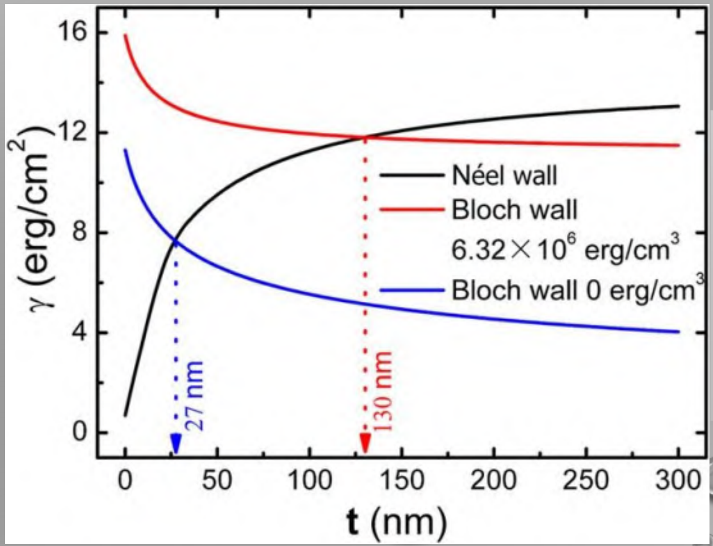
Domain wall width

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

For ultrathin films $K_u \to K_u - 2\pi M_s^2$

The magnetostatic energies are different

- ✓ Neel DW creates volume charges
- ✓ Bloch DW creates surface charges

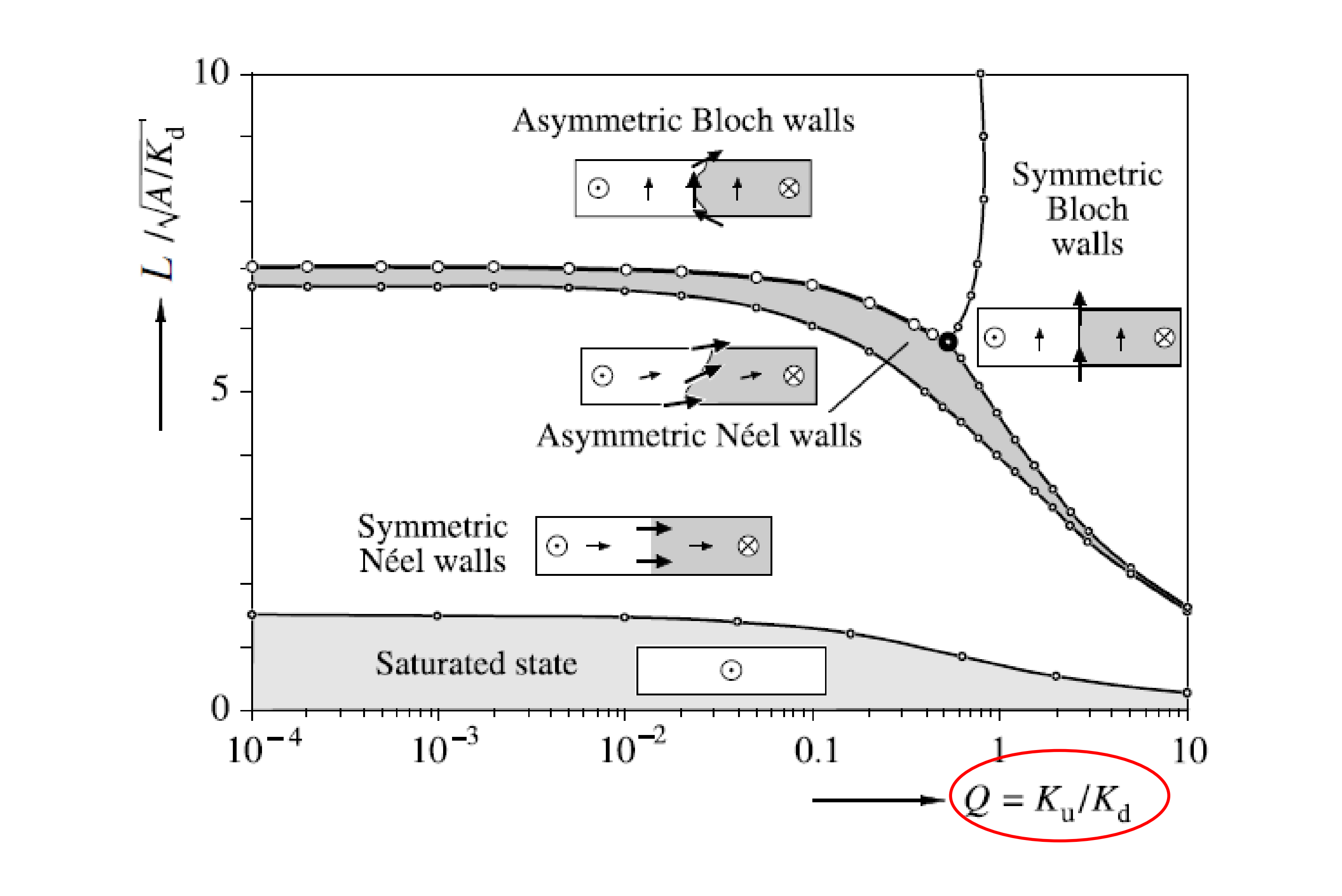


F.Xu et al
Sci Rep
6, 20140 (2016)

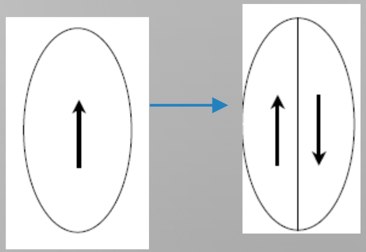
Colr samples

Neel domain wall is stable in ultrathin films

DOMAIN WALL DIAGRAM IN SYSTEMS WITH PERPENDICULAR ANISOTROPY



DOMAINS

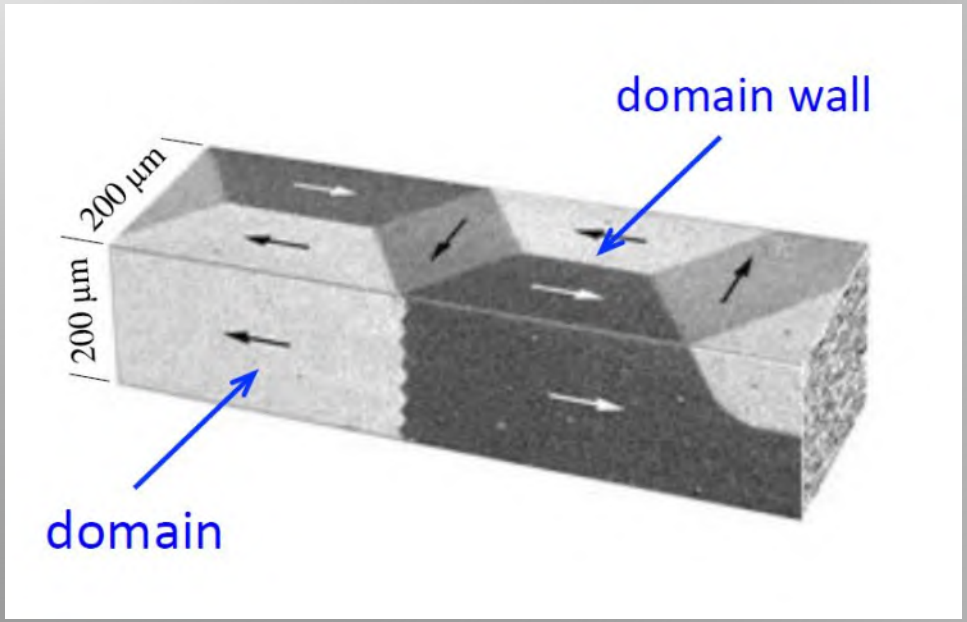


$$2\pi R^2\sqrt{AK} = \frac{1}{2}VNM_s^2$$

Criterium for a single domain particle

$$R_{sd} = 9\sqrt{AK}/\mu_0 M_s^2$$

For spherical nanoparticles



Important Length scales:

- *Domain wall width*

$$\delta_o = (A/K_1)^{1/2}$$

- Exchange correlation length

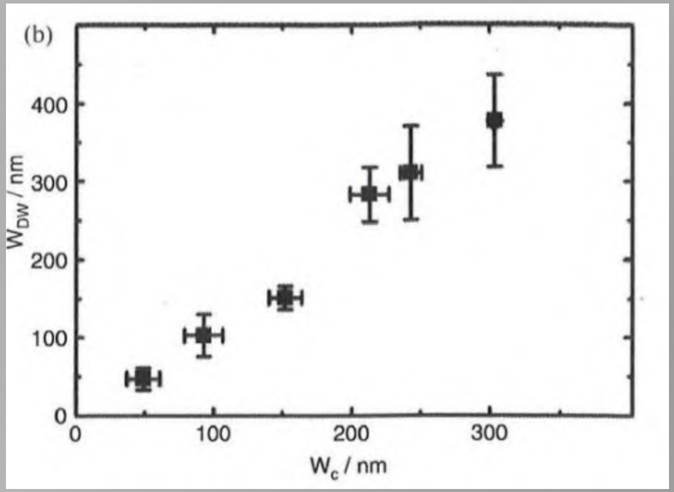
$$l_o = (A/\mu_o M_s^{\,2})^{1/2}$$

- *Critical nanoparticle diameter to form domains*

$$R_{sd} = 9\sqrt{AK}/\mu_0 M_s^2$$

SOME MATERIALS

	M_s MA m^{-1}	A pJ m^{-1}	K_1 kJ m^{-3}	δ_w nm	γ_w mJ m^{-2}	κ	l_{ex} nm
$Ni_{80}Fe_{20}$	0.84	10	0.15	2000	0.01	Q.01	3.4
Fe	1.71	8	50	40	2.6	0.12	1.5
Co	1.44	10	530	14	9.3	0.46	1.9
$Nd_2Fe_{14}B$	1.28	8	4900	3.9	25	1.54	2.0

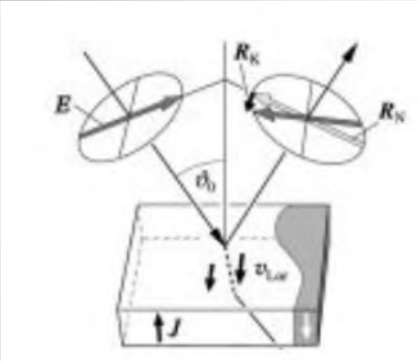


Py nanowires: Dw width decreases with stripe width

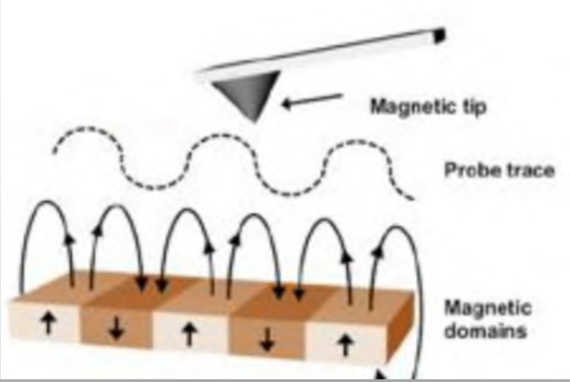
Backes D *et al Appl. Phys. Lett.* 91 (2007)

DOMAIN OBSERVATION TECHNIQUES

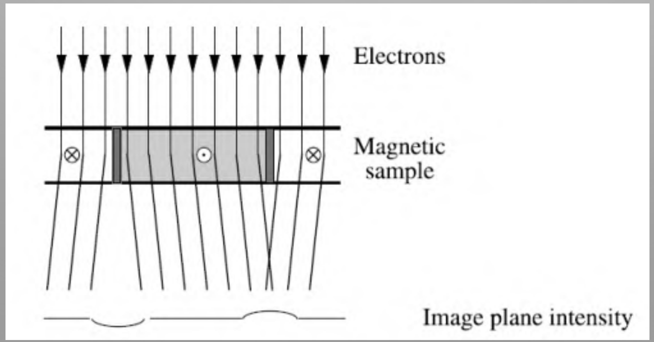
- ✓ Magneto-optical Kerr effect



- ✓ Magnetic force microscopy



- ✓ Transmission electron microscopy (holography)

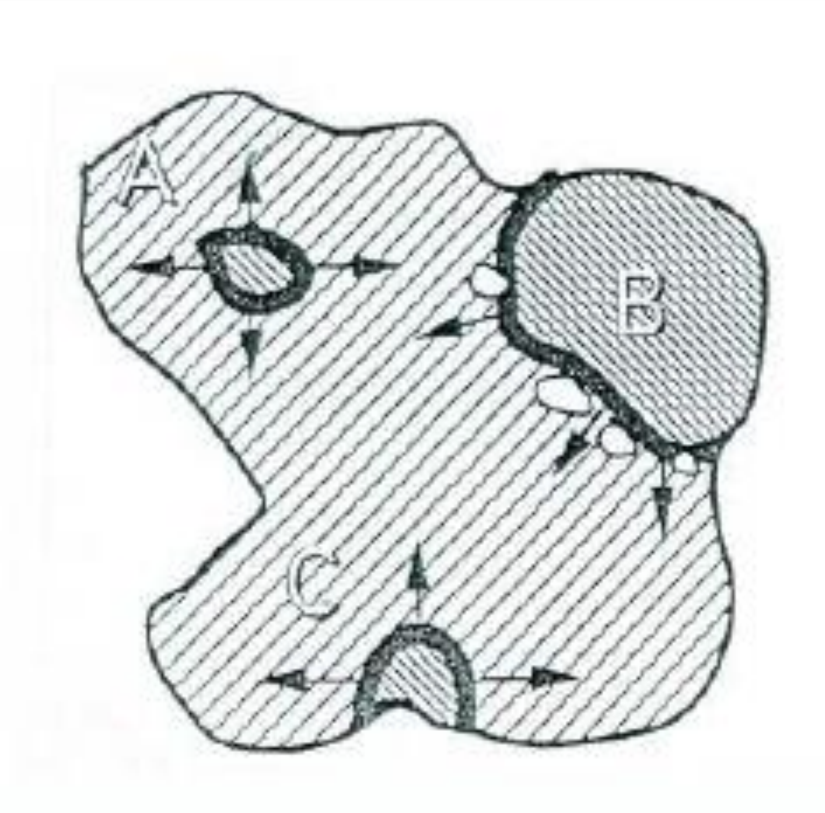


- ✓ X-ray microscopy (XMCD)

- ✓ Spin-polarized STM

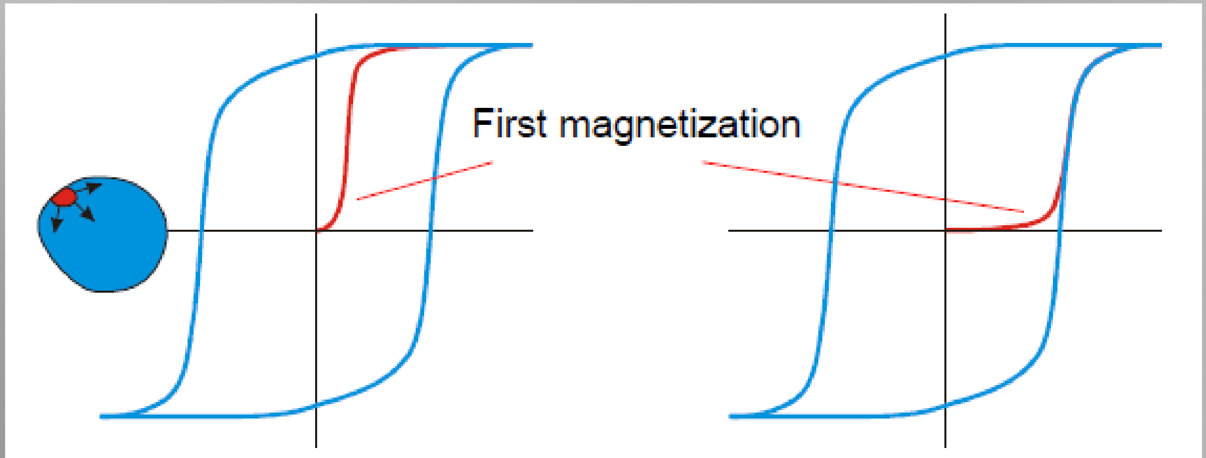
COERCIVITY TYPE MECHANISMS

Rotation, nucleation, DW propagation, pinning, depinning



Nucleation-type coercivity

Pinning-type coercivity



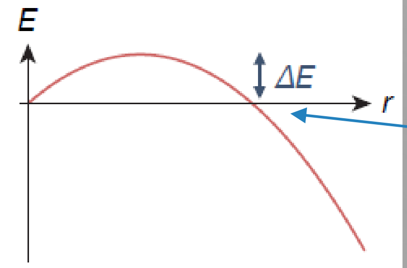
NUCLEATION AND DOMAIN WALL PROPAGATION THEORIES

Nucleation mechanism

The concept of nucleation volume

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

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



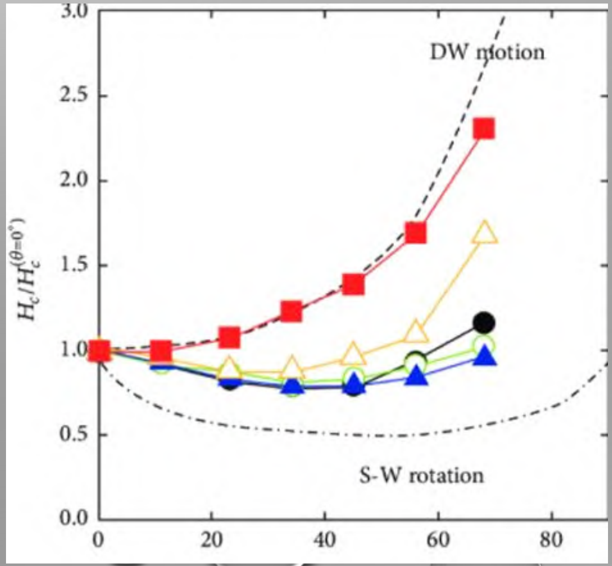
Nucleation size

DW nucleation + propagation

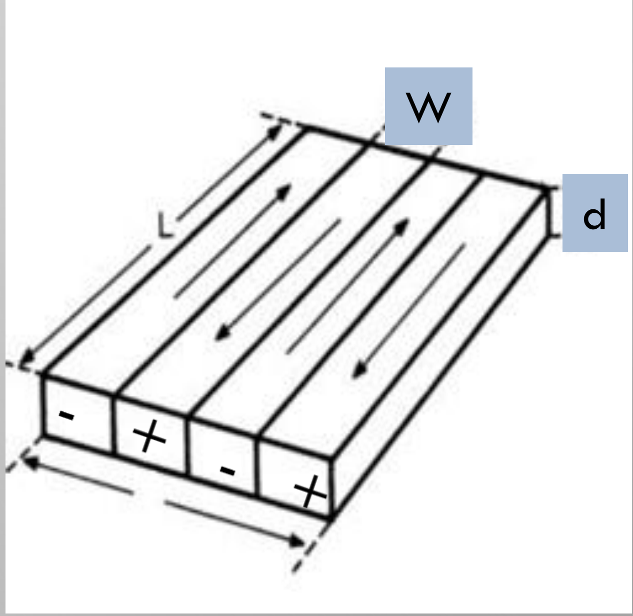
$$H_c(\theta_H) = \frac{H_c(0)}{\cos(\theta)}$$

Angular dependence of coercivity

DW energy > thermal energy



SIMPLEST CASE (ULTRA-THIN FILMS)



Energy per unit volume

$$E_{DW} = 4\sqrt{AK}L/w$$

$$E_{Mag} = 1.7(\frac{dw}{L^2})\mu_0 M_s^2$$

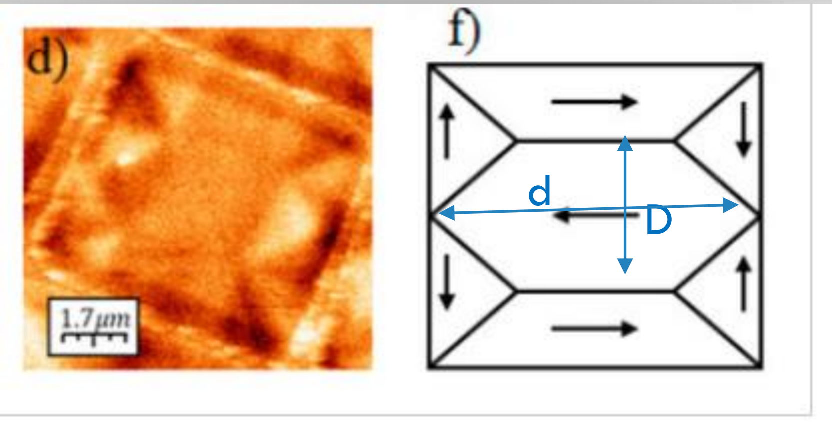
$$w \approx L\left(\frac{L\sigma_{DW}}{\mu_0 M_s^2 d}\right)^{1/2}$$

Kittel structure for in-plane magnetisation

(more correct magnetostatic, summing surface charges

$$w \approx \frac{\pi^3 L\sigma_{DW}}{4\mu_0 M_s^2 d}$$

LANDAU MODEL FOR CLOSURE DOMAINS



FeB nanoelements
Magnet-optic image)
R.Alvarez-Sanchez
Magnetochemistry 2020, 6(4), 50

For uniaxial anisotropy
Including only 180-degree walls

The total energy= energy of domain walls –energy of closure domains

Can be of magnetostrictive origin

The wall energy (per unit area) $E_{DW} = 4\sqrt{AK}L/D$

Anisotropy energy of closures $E_a = KD/2$

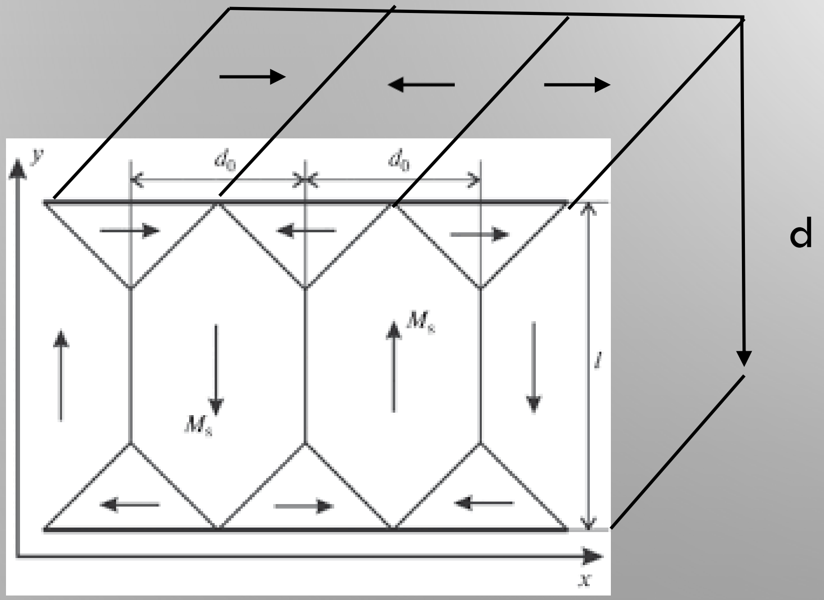
Minimizing the total energy with respect to D gives

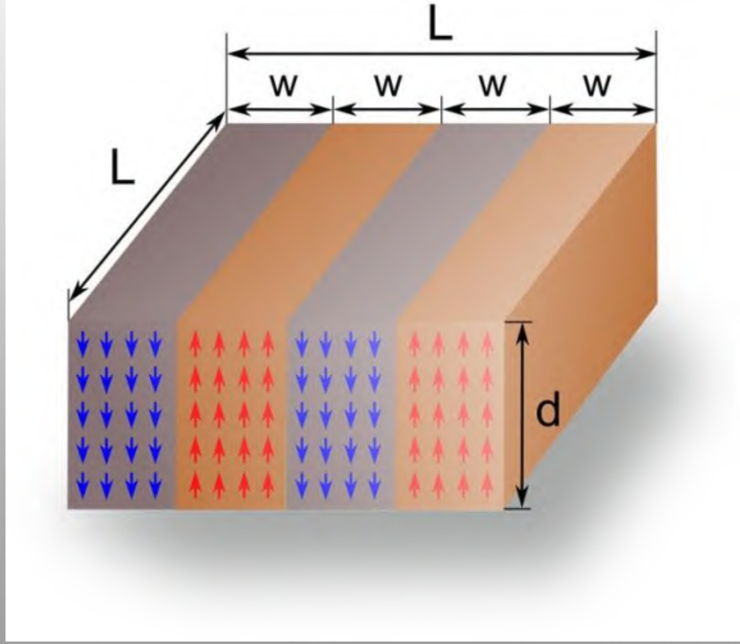
$$w = 2\left[2d\sqrt{A/K}\right]^{1/2}$$

equiibrium domain width

LANDAU AND KITTEL STRUCTURES

$$Q=\frac{2K}{\mu_0 M_s^2}$$





CHECK!!!!!!!!!!!

Q<<1

Q>>1 Magnetic charges on the surface

$$w = 2\left[2d\sqrt{A/K}\right]^{1/2}$$

$$w = 4\left[\pi d\sqrt{AK}/1.7M_s^2\right]^{1/2}$$

DOMAINS IN PERPENDICULAR MAGNETIC MATERIALS

$$Q = \frac{2K}{\mu_0 M_s^2}$$

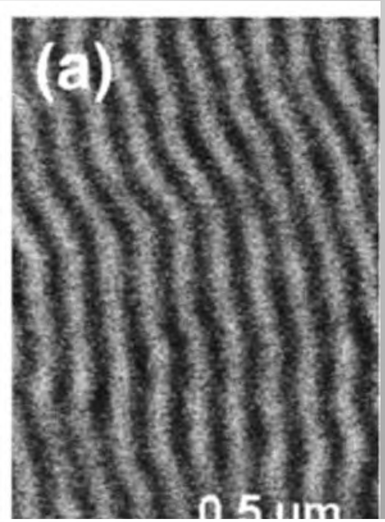
Q<1 D(thickness)>Dcr periodic (in-plane) stripe domains

Q>1 domains magnetized in different directions out-of plane

Y.Samson et al JAP 85 (1999)

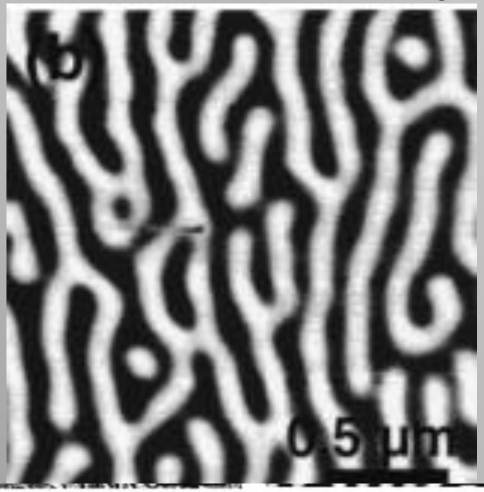
Stripe domains

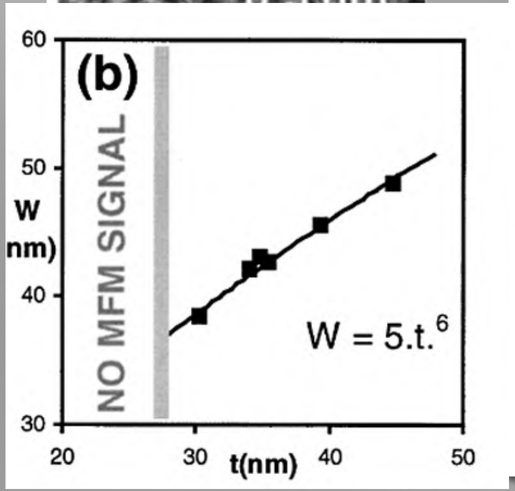
FePd weak PMA

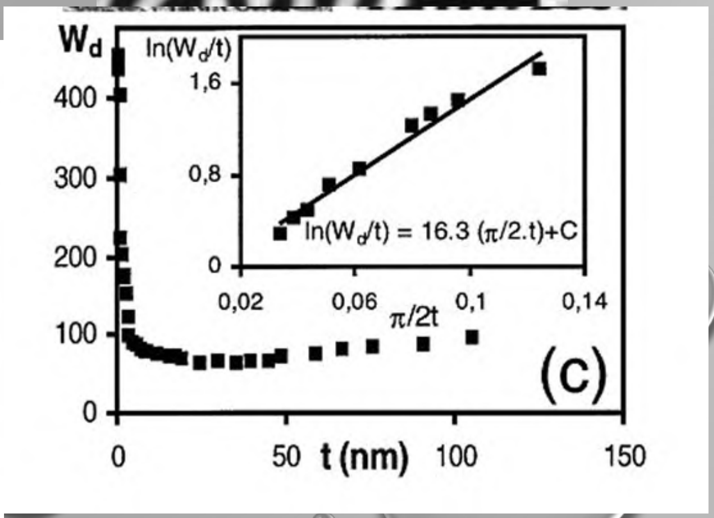


Laberinth domains
With bubbles

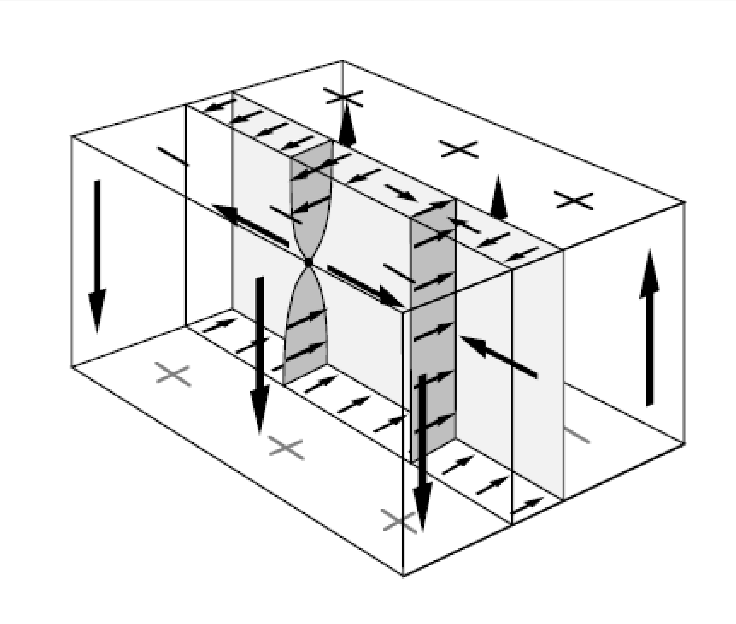
FePd strong PMA

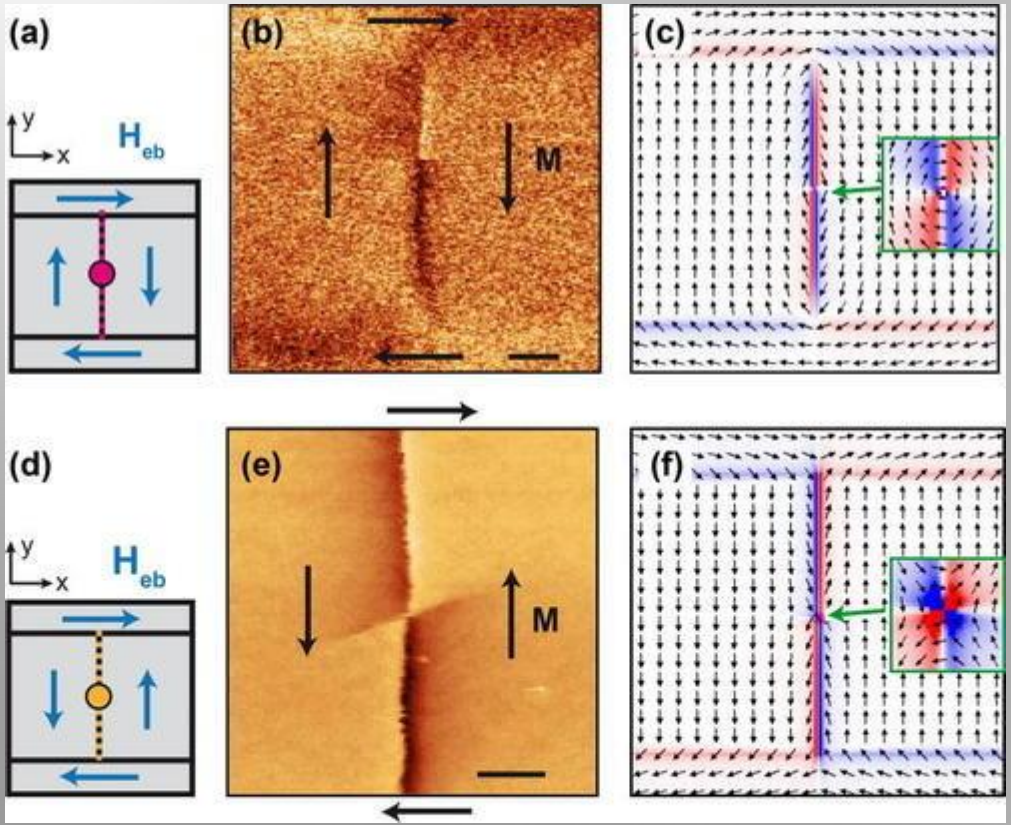






BLOCH LINES

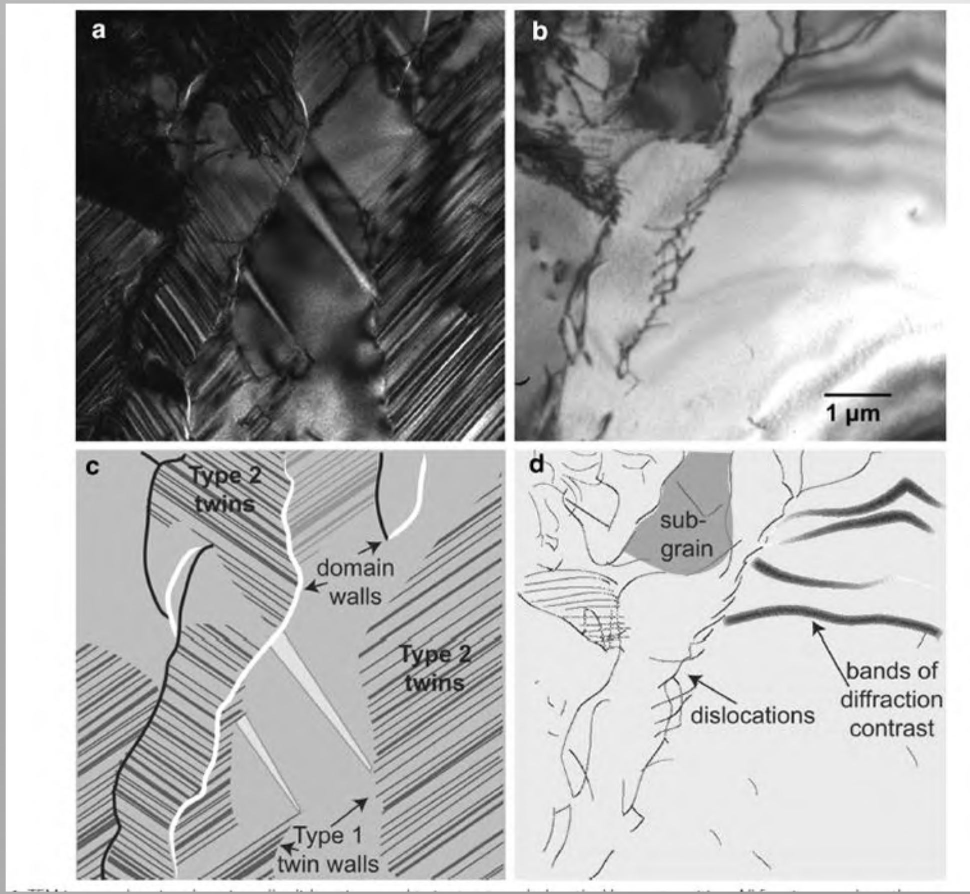




E.Albisetti et al APL 113 (2018)162401

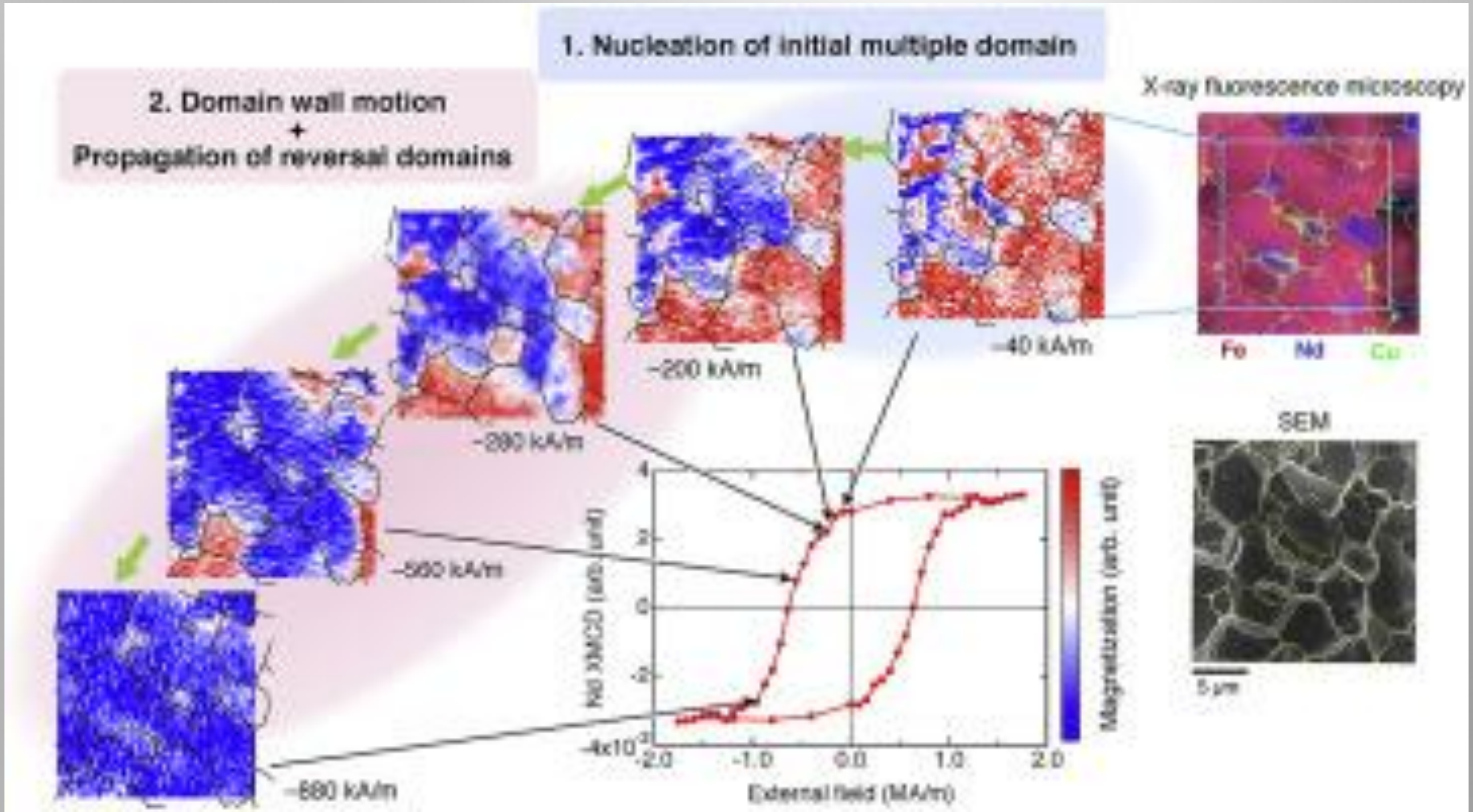
DOMAINS AND STRUCTURE

Domains are strongly related to nanostructure (grains, boundaries, dislocations etc.)



Magnetite, TEM
A-Lindquist et al
Earth, Planets and Space (2019) 71:5

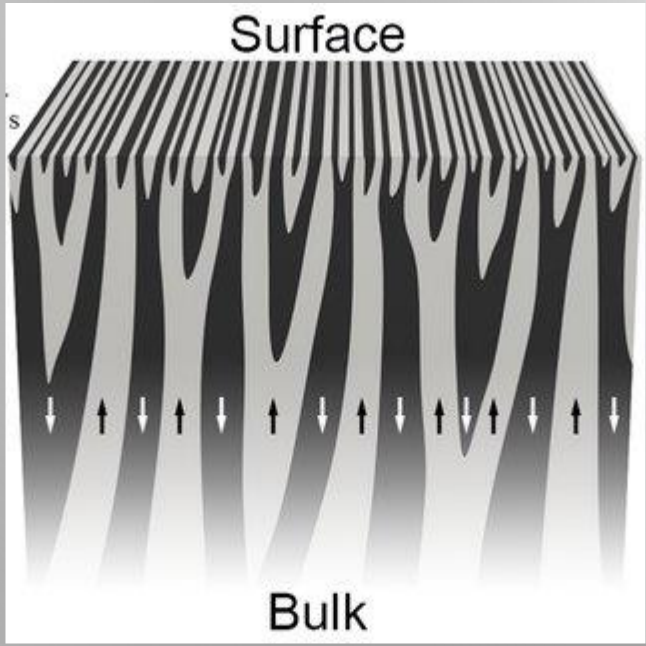
DOMAINS IN HARD MAGNETIC MATERIALS



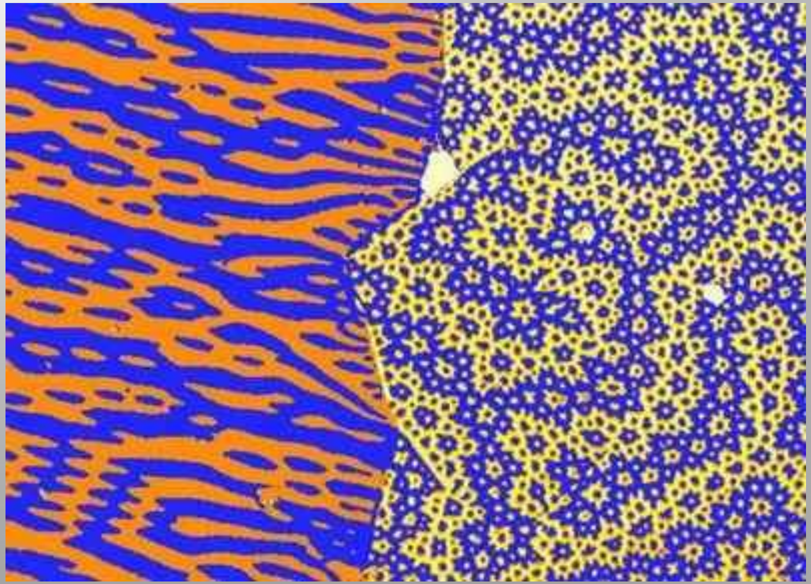
Suzuki et al
Acta Materialia
106 (2016) 155

NdFeB, XMCD

DOMAIN BRANCHING

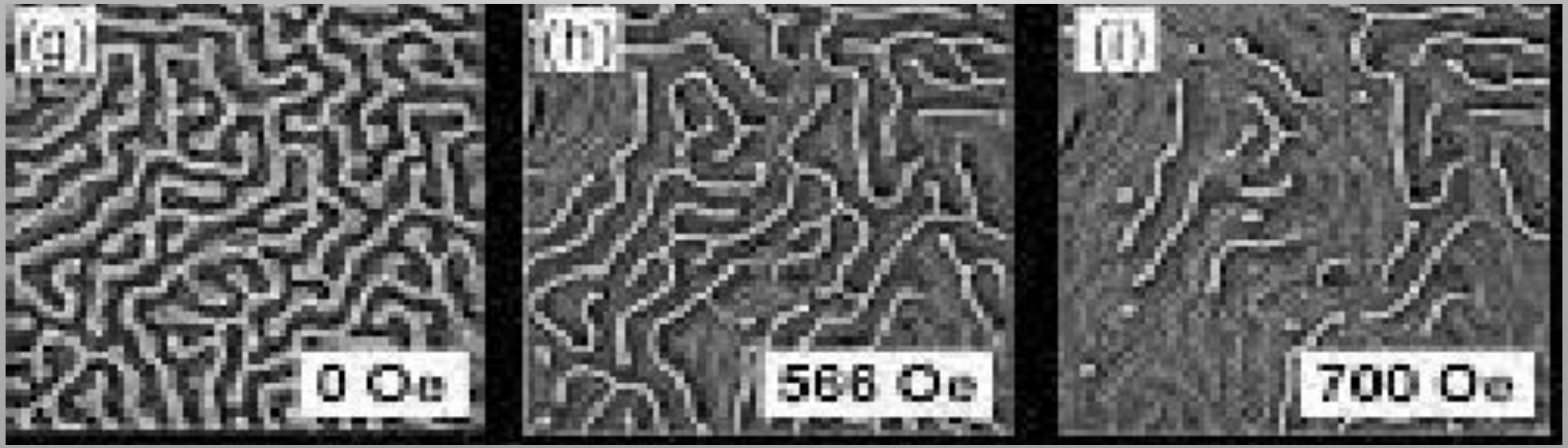


NdFeB



(especially in hard materials, depends on the mis-orientation of grains with respect to the surface

FORMATION OF SKYRMIONS (BUBBLES) FROM LABYRINTH DOMAINS



Typical for large anisotropy magnetic films

TbCo, TEM images, J.Zhang et al APL, 116 (2020)

SOFT MATERIALS: RANDOM ANISOTROPY MODEL

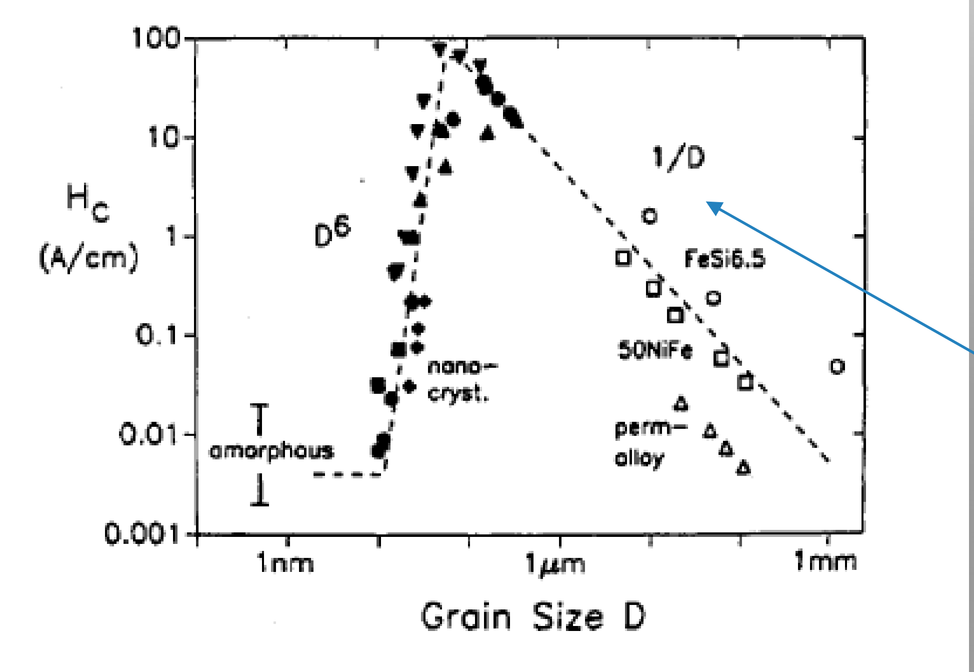
Exchange correlation length is much larger than the grain size

Mostly demagnetize by domain wall propagation

$$< K >= \frac{K}{\sqrt{N}}, \quad N = \frac{L^3_{ex}}{D^3}$$

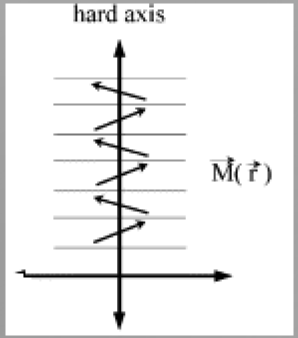
Number of grains within exchange correlation length

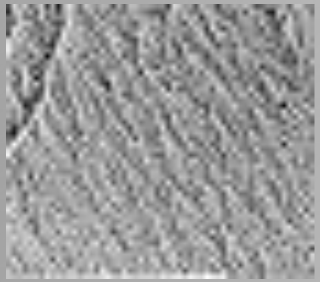
$$< K > \propto K_1 D^6$$



Nucleation model

Magnetisation ripple





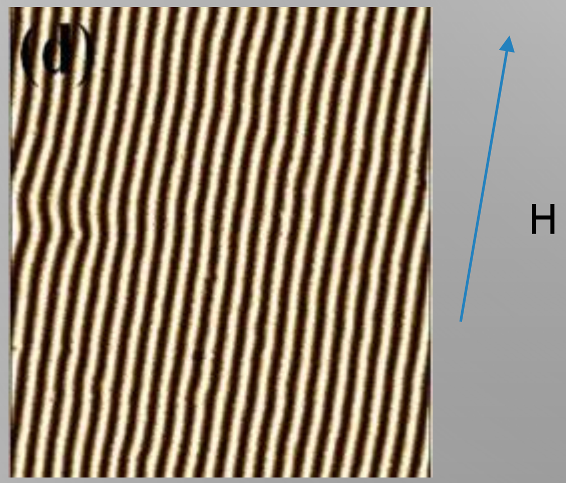
TEM image: NiFe
L.Heyderman et al JMMM

DOMAINS IN SOFT MAGNETIC MATERIALS

e.g. zero-magnetostrictive alloys

Laminar structure

Induces anisotropies can be produced by annealing under field or stress



W.Wu et al Appl. Surf.Sci. 346, (2015) 567

FeCoAlON films

DOMAINS IN SOFT MAGNETIC MATERIALS

e.g. amorphous alloys

Magnetic anisotropies are due to internal long-range (quenching) stresses produced by preparation techniques

$$K_u = \frac{3}{2}\lambda_s \sigma v$$

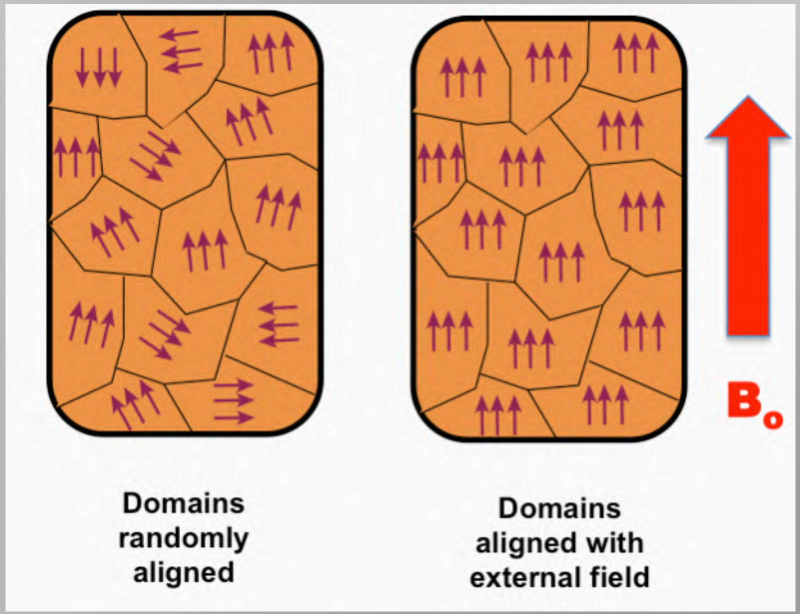
Magnetostriction constant   stress   volume

Typical domains have laminar (10-100 μm) or zig-zag structures

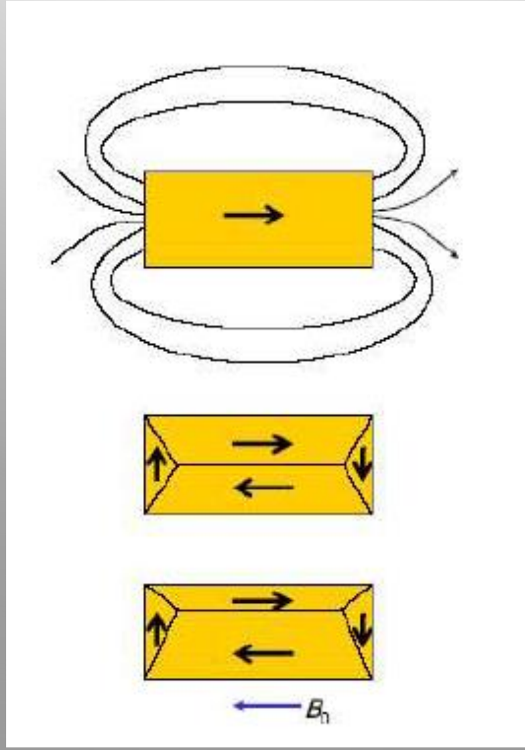
N.Ilin et al Solid State Phen 312, 275 (2020)
FeCuNbSiB amorphous robbons.

GROWTH OF DOMAINS UNDER MAGNETIC FIELD

Rotation



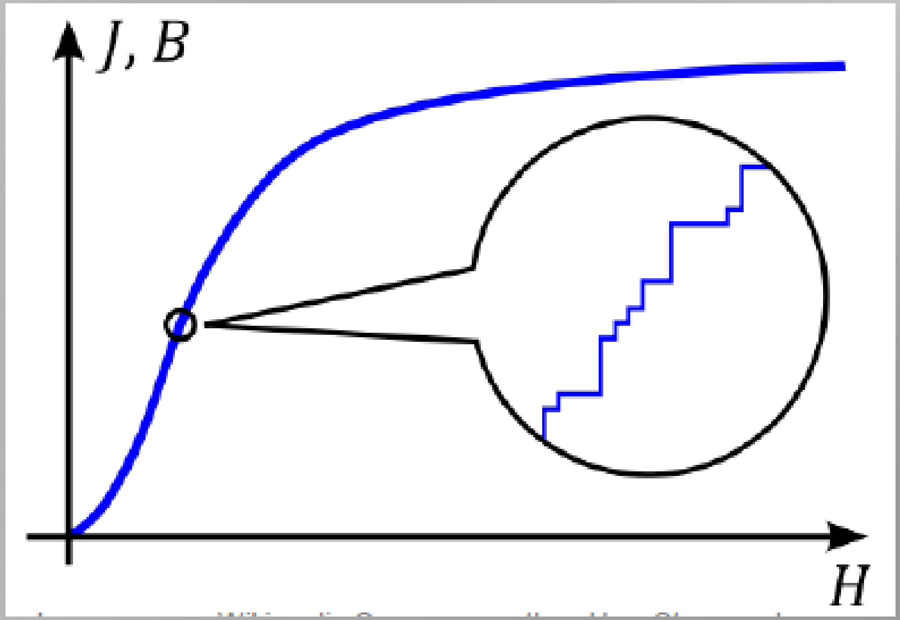
Domain wall propagation

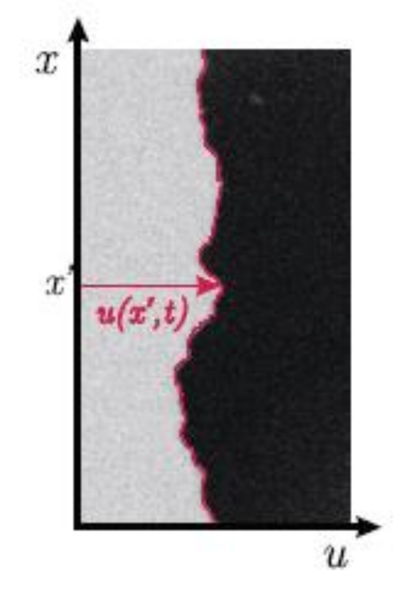


Steel

BARKHAUSEN EFFECT

R.M.Bozorth PRB 34 (1929)





Domain wall as an elastic band in a Random potential : creep motion

Disorder (pinning) energy

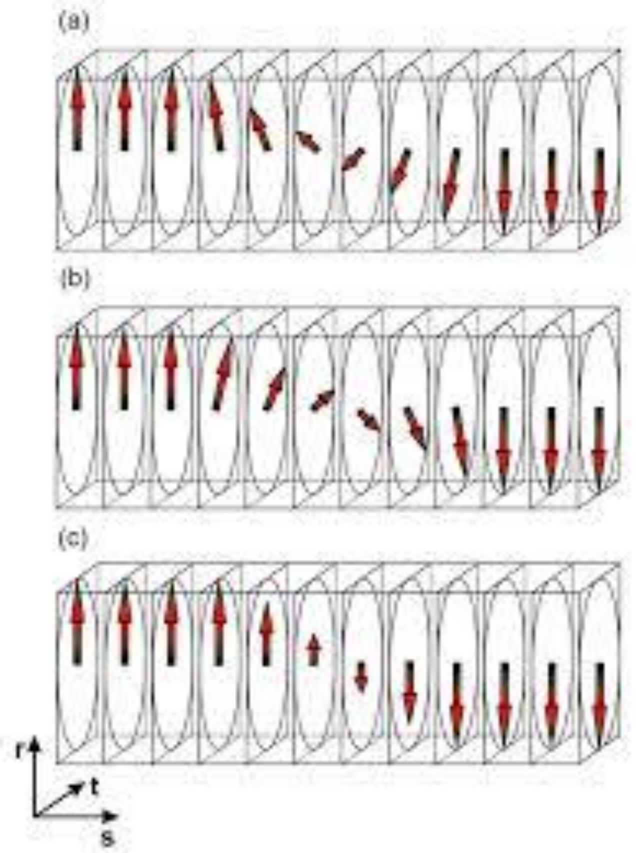
$$E_{\mathrm{pin}} = -f_{\mathrm{pin}}\sqrt{\xi L n}$$

Characteristic strength of disorder

Characteristic length of disorder

Defect density

DOMAIN WALLS



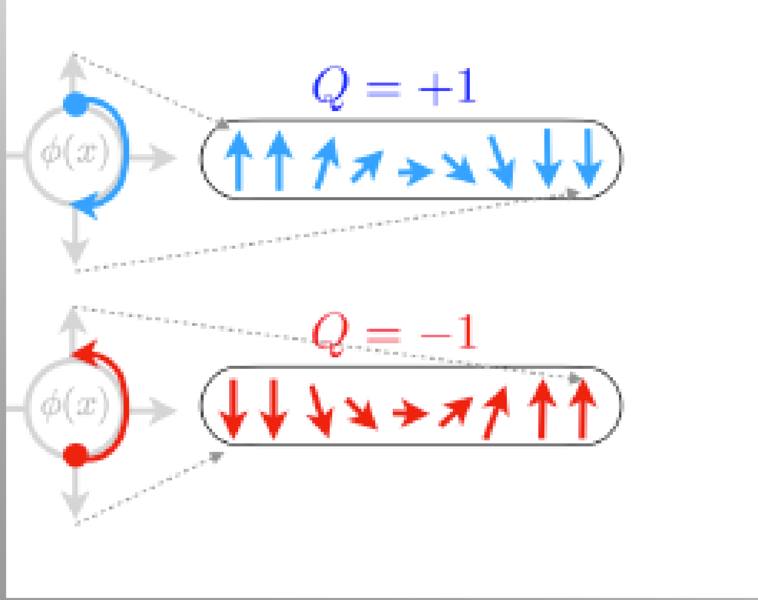
Bloch DW

Neel DW

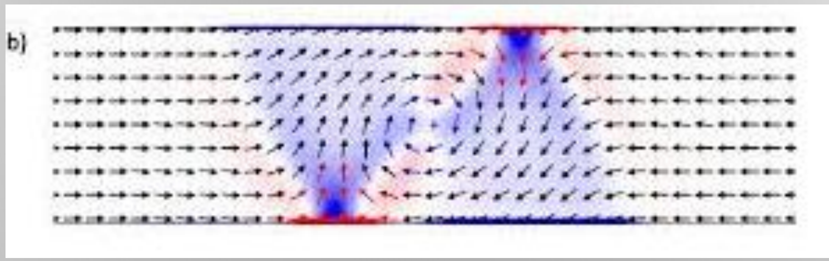
Linear DW

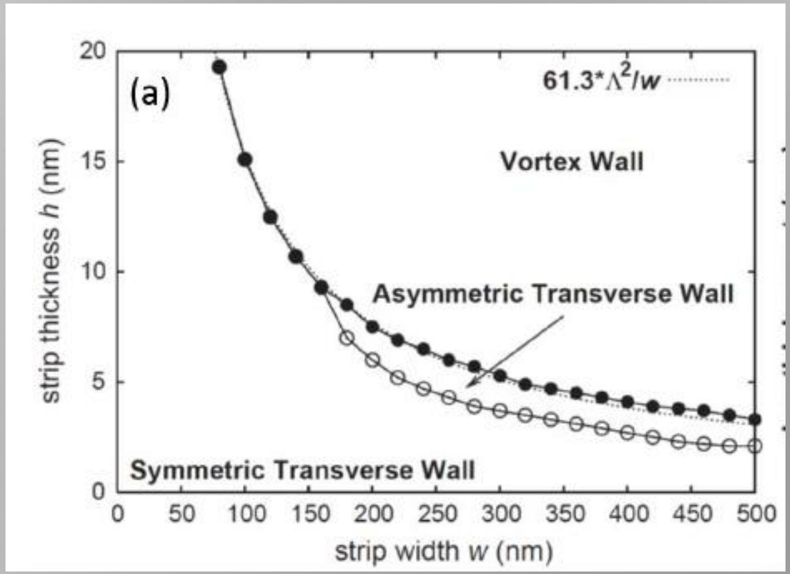
$$Q = -\nabla_x \theta$$

Topological charge

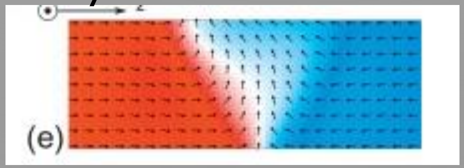


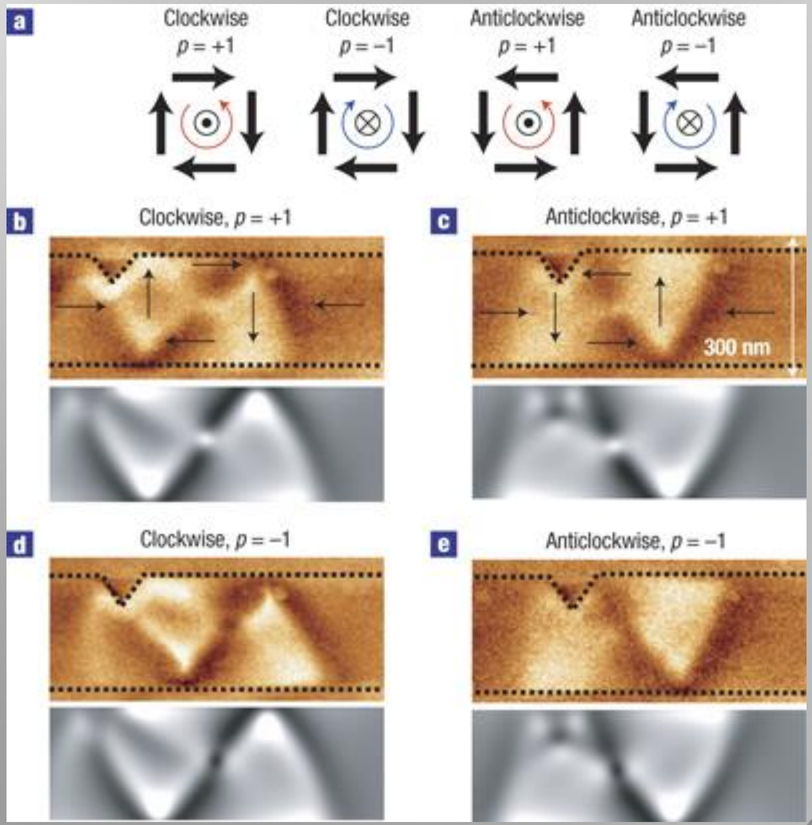
VORTEX DOMAIN WALLS





Asymmetric transverse DW

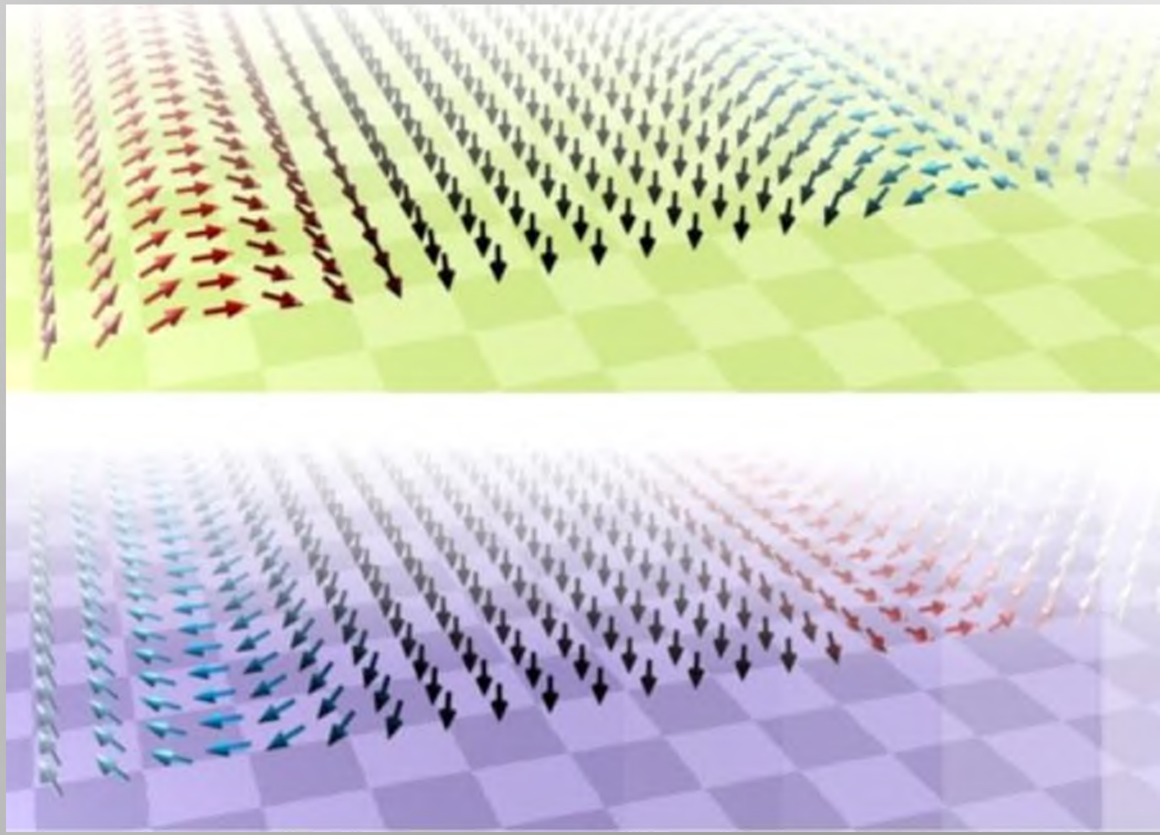




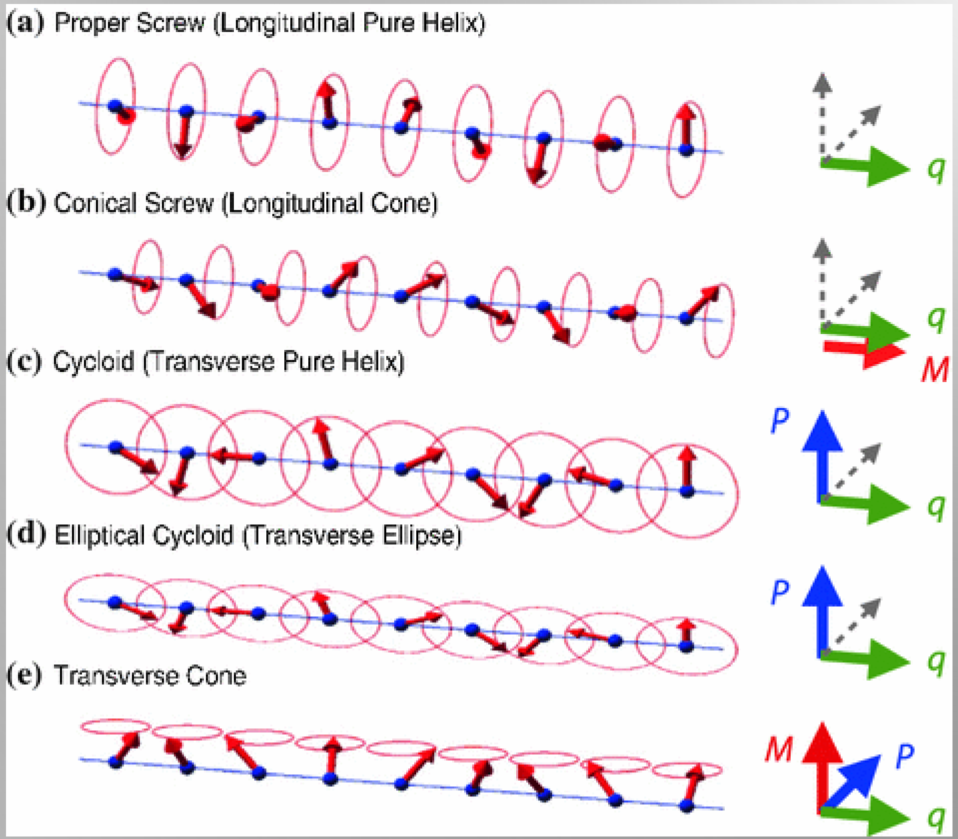
R.Moriya et alNature Physics 4(5) (2008)

CHIRAL DOMAIN WALLS (SYSTEMS WITH DMI)

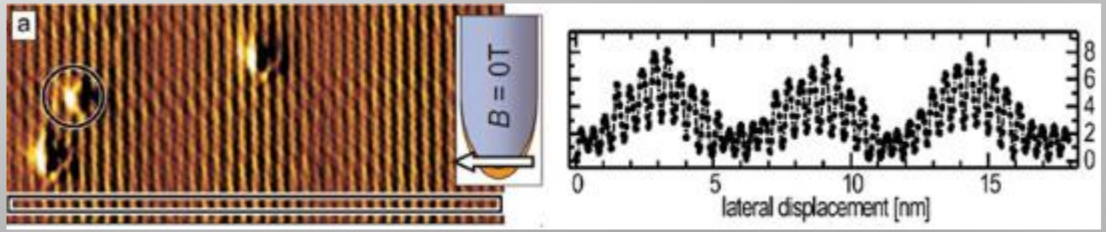
DMI favors only one chirality for Neel domain walls



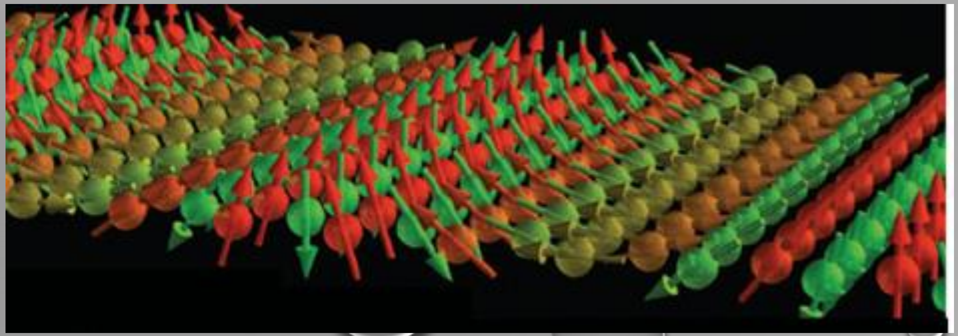
SPIN SPIRALS



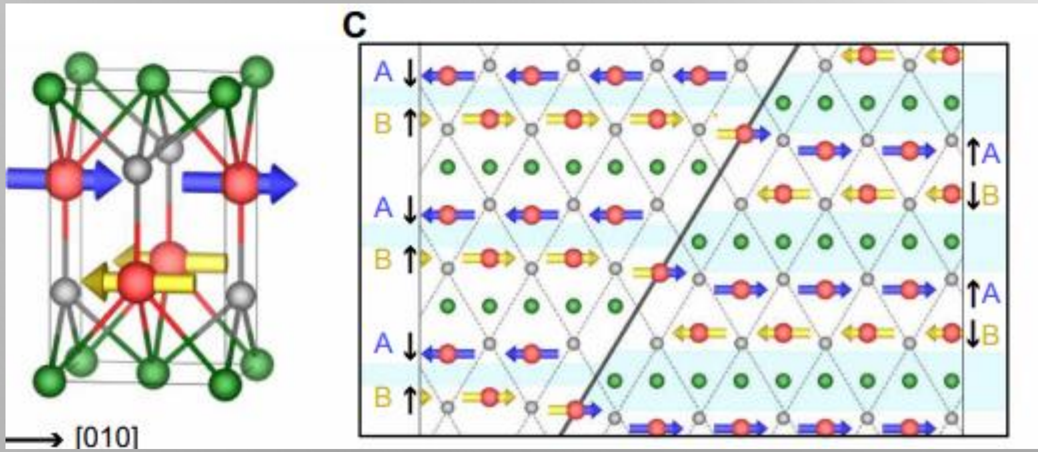
Competition Ferromagnetic and antiferromagnetic interactions

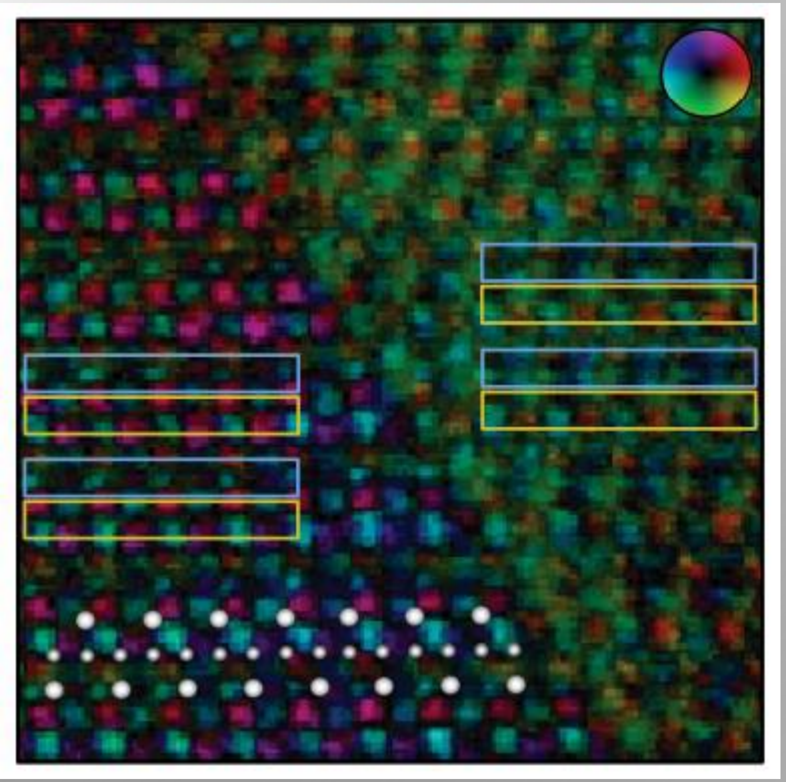


Spin-polarised STM, monolayer of Mn on W surface
Group of WIesendanger



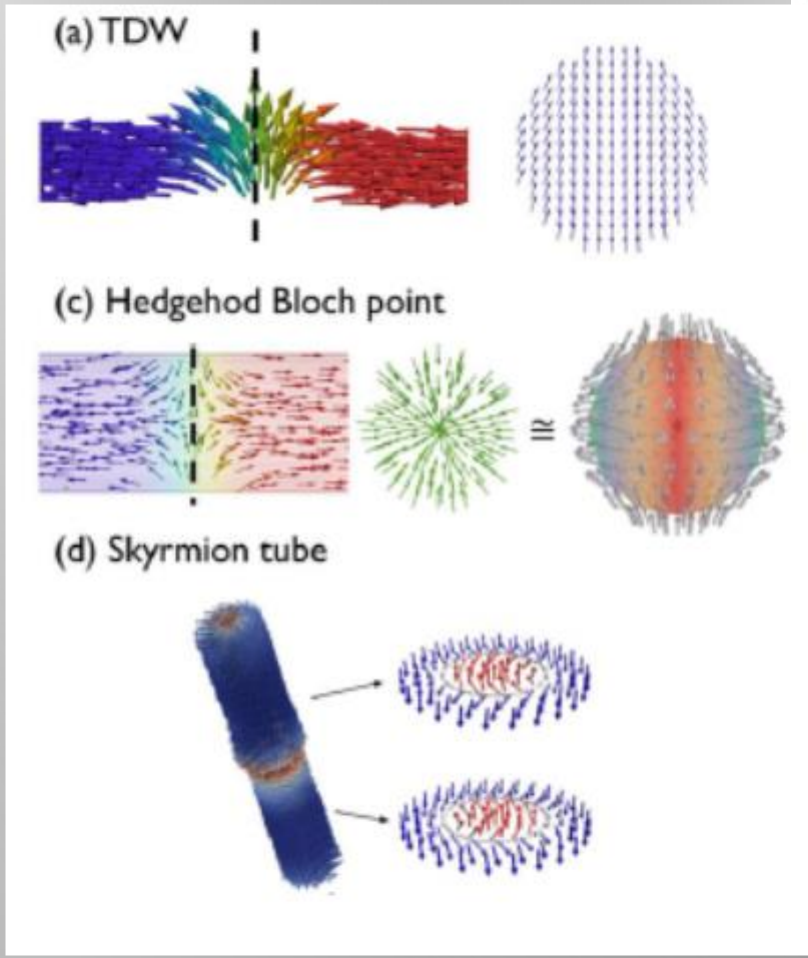
ATOMICALLY SHARP DOMAIN WALLS IN ANTIFERROMAGNETS

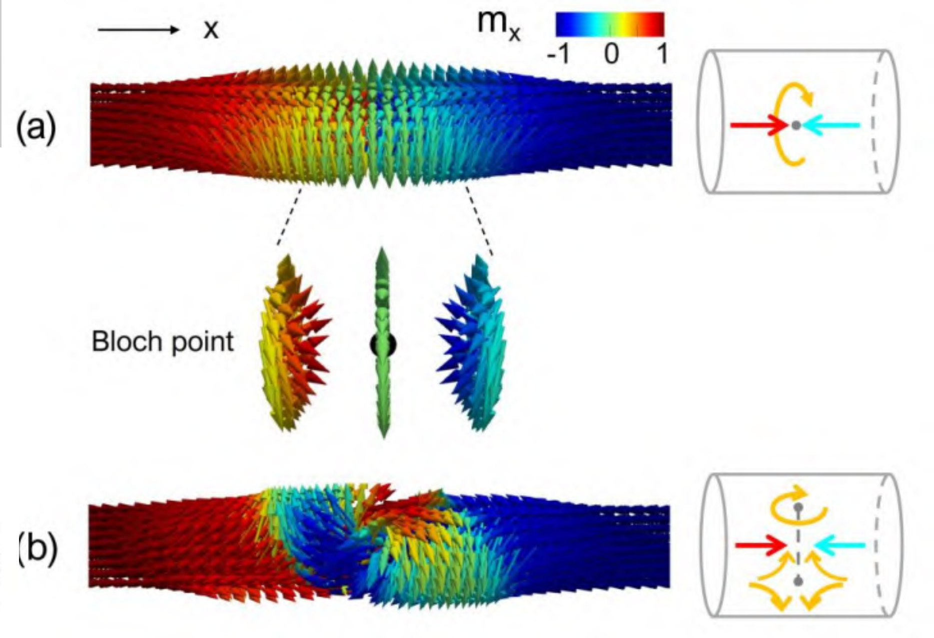




differential phase-contrast (DPC)–STEM image of CuMnAs
Krizek et al., Sci. Adv. 8, eabn3535 (2022)

3D DOMAIN WALLS IN CYLINDRICAL NANOWIRES

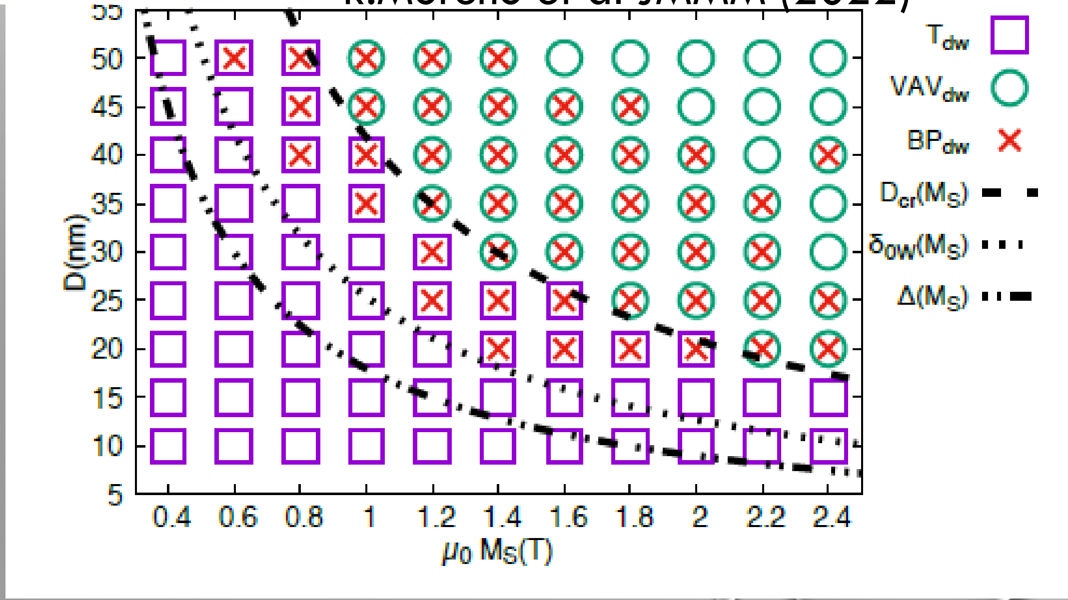




Bloch point domain wall

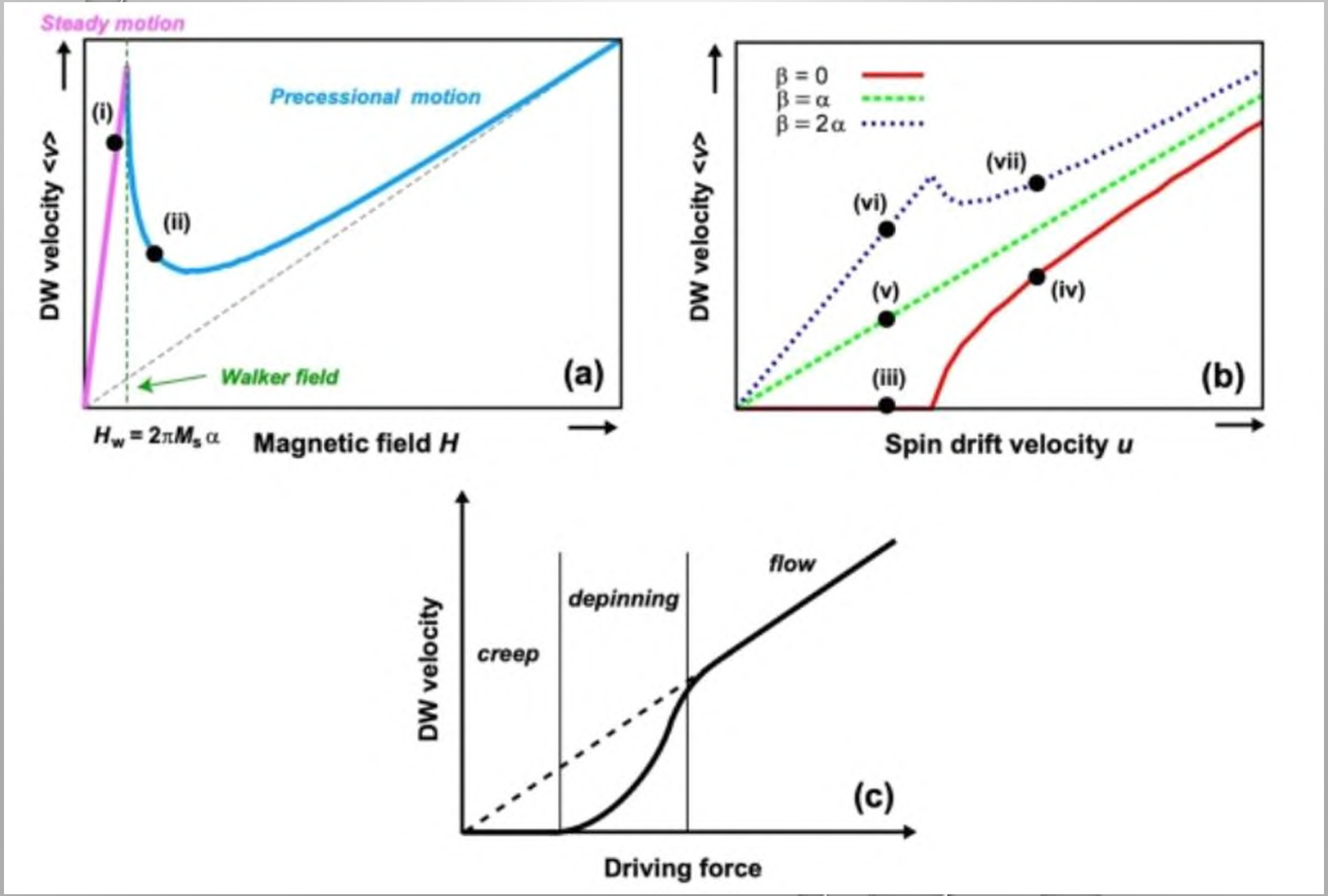
Vortex-antivortex domain wall

R.Moreno et al JMMM (2022)



MESSAGES

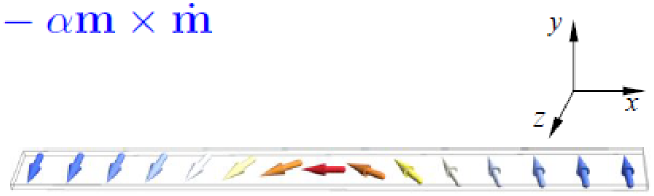
- MAGNETISATION STATES DEPEND STRONGLY ON THE COMPETITION OF ENERGIES AND SYSTEM SIZE
- MAGNETIC DOMAINS ARE RESULTS OF MAGNETOSTATIC ENERGY MINIMIZATION, DOMAIN TYPE (STRIPE, LABYRINTH ETC.) AND SIZE IS DEPENDS ON THE THIN FILMS THICKNESS AND Q-FACTOR
- DOMAIN ARE SEPARATED BY DOMAIN WALLS: NEEL (THIS FILMS) AND BLOCH (THICKER FILMS)
- DMI SELECTS DOMAIN WALL CHIRALITY
- MORE COMPLEX DOMAIN WALLS (VORTEX, BLOCH POINT ETC.)


Steady motion
Precessional motion
(i)
(ii)
DW velocity <v>
Walker field
(a)
$H_w = 2\pi M_s \alpha$
Magnetic field H
$\beta = 0$
$\beta = \alpha$
$\beta = 2\alpha$
(vii)
(vi)
(v)
(iv)
(iii)
DW velocity <v>
(b)
Spin drift velocity u
flow
depinning
creep
DW velocity
(c)
Driving force

Domain wall motion

$$\dot{\mathbf{m}} = -\gamma\ \mathbf{m}\times\mathbf{H}_{\text{eff}} - \alpha\mathbf{m}\times\dot{\mathbf{m}}$$

$$E = \int [A(\nabla\mathbf{m})^2 - Km_z^2 + \underbrace{K_d m_y^2}_{K_d=\frac{\mu_0}{2}M_s^2} - \mathbf{M}\cdot\mathbf{H}_{\text{ext}}]d^3x$$



$m_y = 0 \to$ stray-field-free wall

$$\mathbf{m} = -\gamma(\sin\theta\cos\phi,\ \sin\theta\sin\phi,\ \cos\theta)$$

$$\dot{\theta} - \alpha\dot{\phi}\sin\theta = \frac{2\gamma}{M_s}[-\frac{A}{\sin\theta}\nabla\cdot(\sin^2\theta\nabla\phi) + \frac{K_d}{2}\sin\theta\sin 2\phi]$$

$$\dot{\phi}\sin\theta + \alpha\dot{\theta} = \frac{2\gamma}{M_s}\left\{A\left[\nabla^2\theta - \frac{1}{2}\sin 2\theta(\nabla\phi)^2\right] - \frac{K+K_d\sin^2\phi}{2}\sin 2\theta\right\} + \gamma H\sin\theta$$