Domains
Domain walls
Spin textures

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Me ☺

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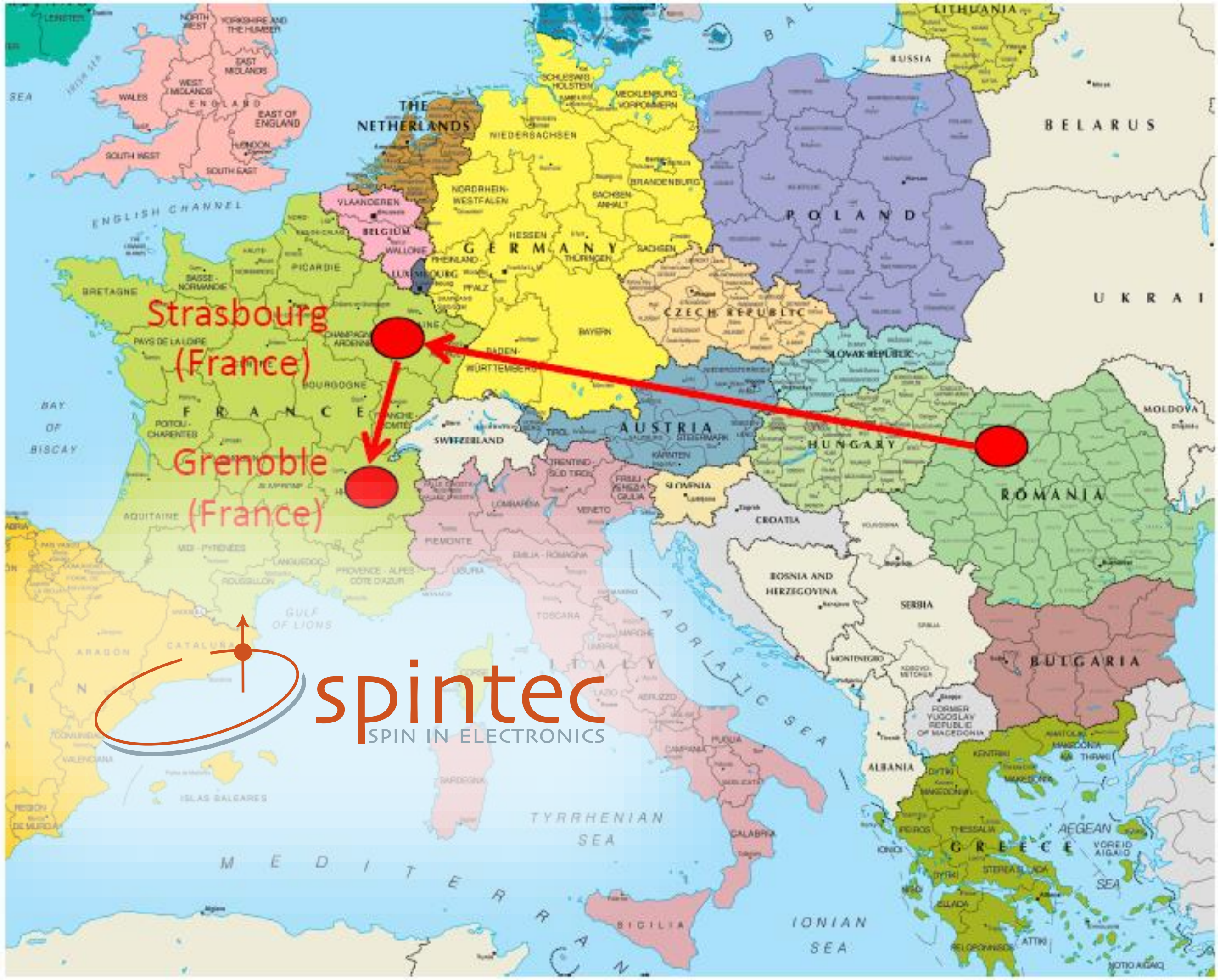
cea irig

cnrs

GRENOBLE INP UGA



Cluj-Napoca / ESM 1999 2^{nd}
Brasov / ESM 2003 3^{rd}
Cluj-Napoca / ESM 2007 5^{th}

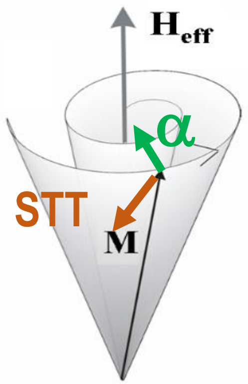
Me ☺

Micromagnetic modeling of spintronic devices

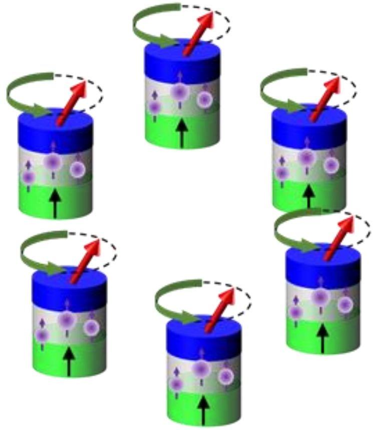
Landau-Lifshitz-Gilbert equation + various flavors

STT, SOT,…

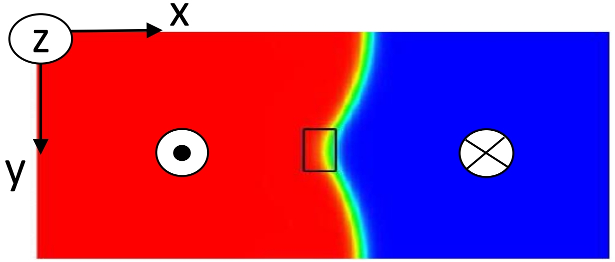
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0(\mathbf{M} \times \mathbf{H}_{\mathbf{eff}}) + \frac{\alpha}{M_S}\left(\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}\right) + \left(\frac{\partial \mathbf{M}}{\partial t}\right)_{add}$$



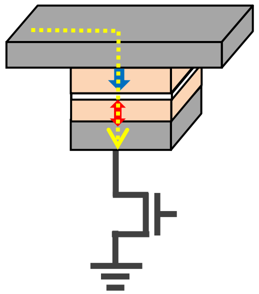
Spin torque nanososcillators



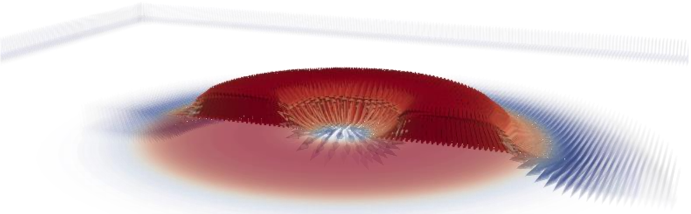
Domain walls



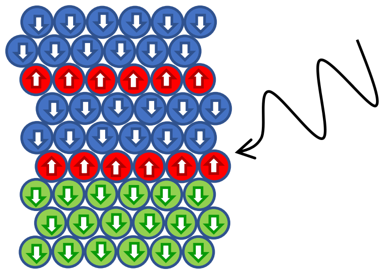
STT- MRAM



Skyrmions and chiral structures

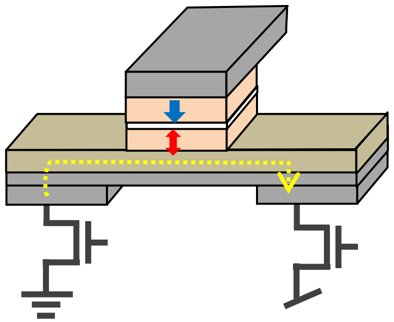


All optical swiching



Tb1/Co2 + FeCoB

SOT- MRAM



Few questions awaiting answers

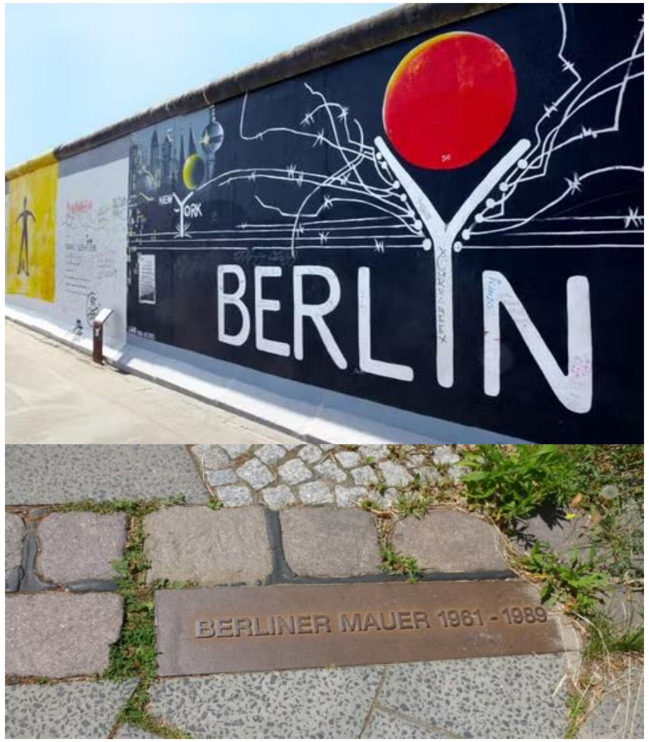
- How to define domains, walls, spin textures?
- What are their origins?
- Which is their internal structure ?
- What are their properties ?

A very broad topic. My objective : open doors for you and not be exhaustive

Very famous domains and walls

Ancient time

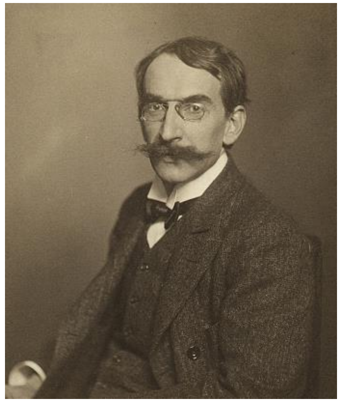
More recently



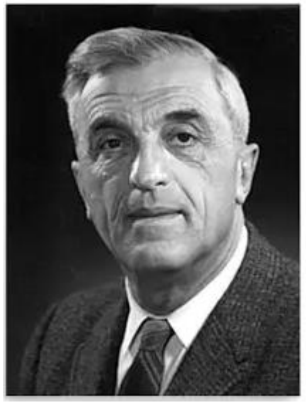
Virtual

An old story written by …

Bloch and Néel domain walls



Pierre WEISS
1865-1940



Felix BLOCH
1905-1983
Nobel Price 1952

Louis NEEL
1904-2000
Nobel Price 1970

Domain theory of ferromagnetism
Weiss mean field theory

Weiss, Pierre; Foëx, Gabriel (1931). Le Magnétisme

Zur Theorie des Austauschproblems und der Remanenzerscheinung der Ferromagnetika.

Von **F. Bloch** in Leipzig [1]).

Mit 2 Abbildungen. (Eingegangen am 14. September 1931.)

Die Slatersche Methode zur Behandlung der Austauschaufspaltung und Termsystemeinteilung beim Mehrkörperproblem wird analog zur Jordan-Kleinschen Theorie umgeformt in eine nichtlineare Wellengleichung im dreidimensionalen Raum, wobei das Absolutquadrat der Wellenfunktion anschaulich als „Spindichte" gedeutet werden kann (§ 1 und 2). Vernachlässigt man den q-Zahlcharakter der Wellenfunktion, so stellt die Wellengleichung analog zur Hartreeschen Methode eine klassisch-anschauliche Annäherungsgleichung für das Verhalten der Spindichte dar, die zur Diskussion der Remanenz- und Hysteresiserscheinungen verwendet wird (§ 4 und 5). Ferner wird im Anschluß an das

F. Bloch, Zur Theorie der Austauschproblems und der Remanenzerscheinung der Feromagnetika, Z. Phys. 74 (1932) 295–335.

ACADÉMIE DES SCIENCES.

SÉANCE DU LUNDI 8 AOUT 1955.

PRÉSIDENCE DE M. GASTON JULIA.

MAGNÉTISME. — *Énergie des parois de Bloch dans les couches minces.* Note (*) de M. **Louis Néel.**

On montre que l'énergie d'une paroi de Bloch, située dans une couche mince continue, augmente d'abord à mesure que l'épaisseur de la couche diminue, passe par un maximum puis reprend sa valeur normale quand la couche est devenue excessivement mince.

Comme l'a montré F. Bloch (1), la paroi séparant deux domaines élémentaires, d'aimantation spontanée J_1 et J_2, possède une épaisseur finie $2a_0$ à l'intérieur de laquelle l'aimantation spontanée tourne progressivement de la direction de J_1 à la direction de J_2. Donnons en effet à la paroi une épaisseur arbitraire $2a$. L'énergie de cette paroi est la somme de deux termes dont le

L. Néel, Energie des parois de Bloch dans les couches minces, C. r. hebd. séances Acad. sci. 241 (1955) 533–538.

Timeline and key concepts for magnetic material

1900

Maxwell equations

Weiss magnetic domains

Bloch & Néel walls

Quantum theory

Stoner–Wohlfarth model

.
.
.

1990

Microscopy technics
MFM
MOKE
Lorentz
Holography
Spin TEM
NV magnetometry
Modelling
µmagnetism
atomistic SD
Band structures, ab-initio ….
.
.
.

2000

Dynamics
Ferromagnetic resonance , magnonics

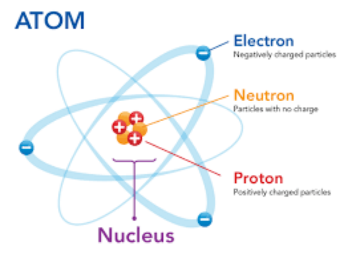
Field driven
Current driven (STT, SOT, VCMA, Seebeck, acoustic)

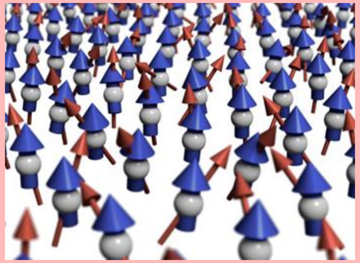
DMI interaction

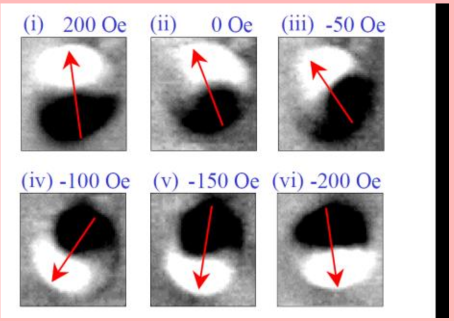
Spintronics, Spinorbitronics, Skyrmionics,…
.
.
.
Phonon-magnon-spin-photon… coupling

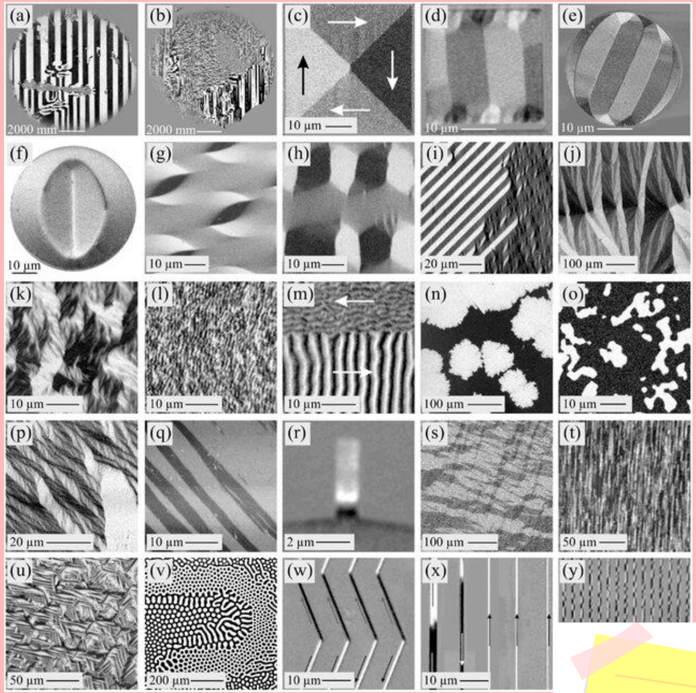
Scale and processes

elementary	individual magnetic moments	single domain coherent rotation	multi-domains wall nucleation/propagation	permanent magnets
quantum	**atomistic**	**nanoscopic**	**microscopic**	**macrosopic**

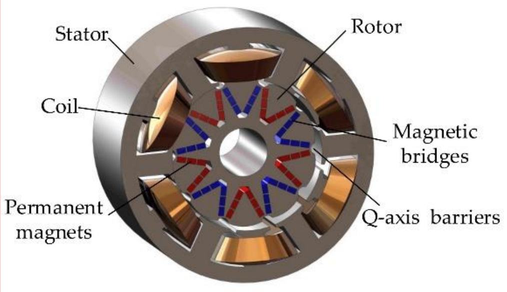








Schäfer, R. (2021).



Local interactions : exchange, MCA

Bousquet
Ronnow
Weiler
Atkinson
lectures

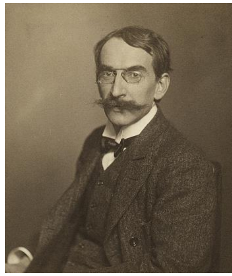
Long range interactions: magnetostatic

Fruchart lecture

Starting point : quantum physics

Magnetic domains ← exchange

Pierre WEISS
1865-1940



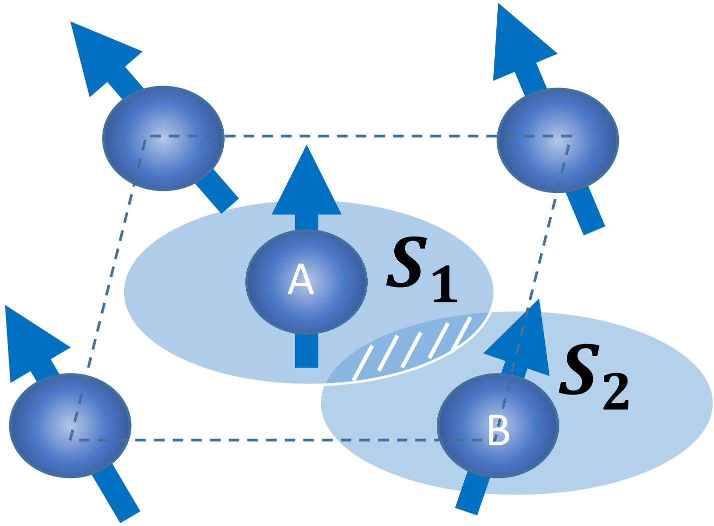
Solid state material : transition metals, rare earth materials, band vs localized magnetism, magnetic moments

Exchange integral: electrostatic interaction, overlapping of electrons wave functions $\psi_A(\boldsymbol{r}_1)$ and $\psi_B(\boldsymbol{r}_2)$

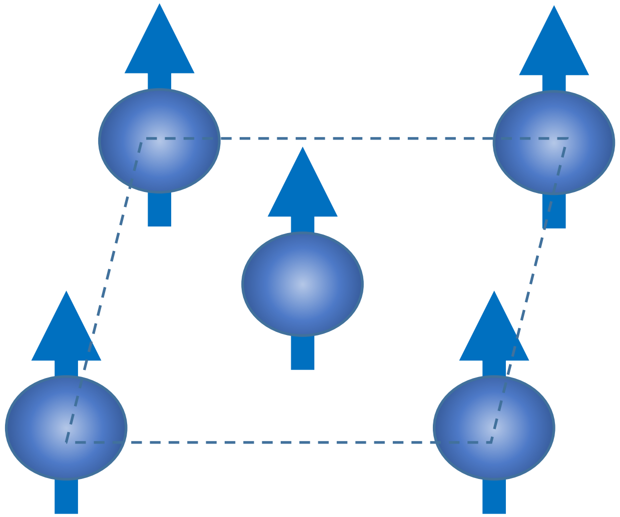
$$J_{12} = \frac{e^2}{4\pi\varepsilon_0}\iint d\boldsymbol{r}_1 d\boldsymbol{r}_2\, \psi_A^*(\boldsymbol{r}_1)\, \psi_B^*(\boldsymbol{r}_2)\left[\frac{Z^2}{|\boldsymbol{R}_A-\boldsymbol{R}_B|}-\frac{Z}{|\boldsymbol{R}_A-\boldsymbol{r}_2|}-\frac{Z}{|\boldsymbol{R}_B-\boldsymbol{r}_1|}+\frac{1}{|\boldsymbol{r}_1-\boldsymbol{r}_2|}\right]\psi_B(\boldsymbol{r}_1)\psi_A(\boldsymbol{r}_2)$$

$$\mathcal{H} = -\sum_{i<j} J_{ij}\, \boldsymbol{S_i}\cdot\boldsymbol{S_j}$$

Werner
HEISENGERG
1901-1976
Nobel Price 1932



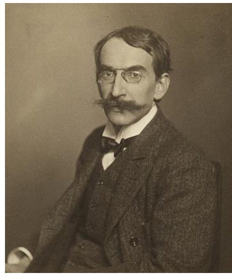
$$J_{ij} > 0$$



ferromagnetic order ($T< T_C$)
parallel alignment

Magnetic domains ← exchange

Pierre WEISS
1865-1940



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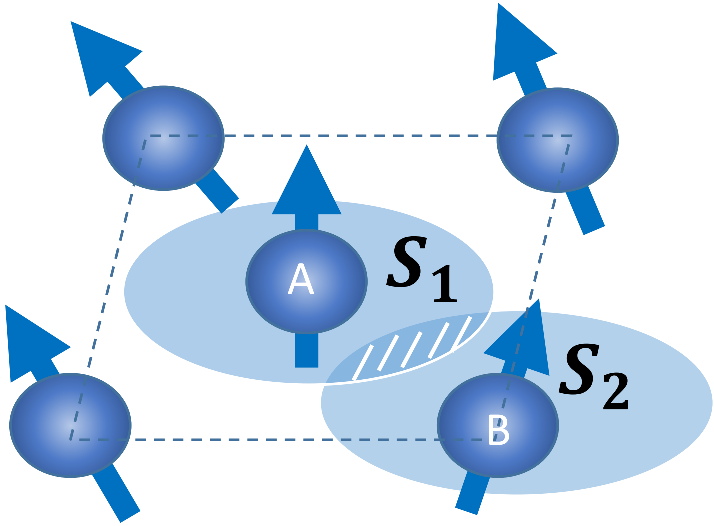
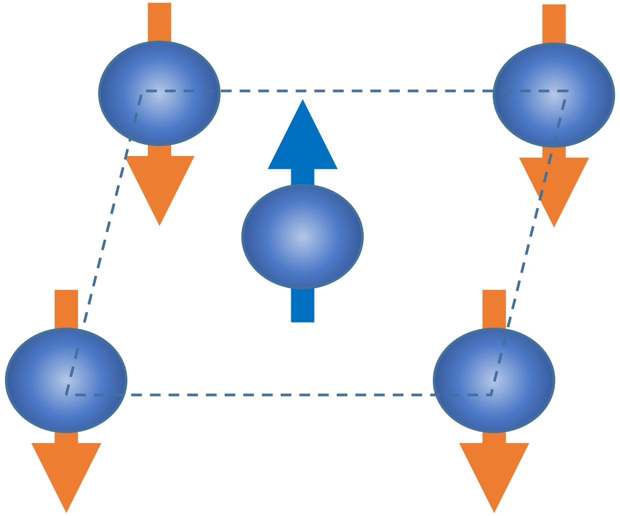
$$\mathcal{H} = -\sum_{i<j} J_{ij}\, \boldsymbol{S_i}\cdot\boldsymbol{S_j}$$



$J_{ij} < 0$



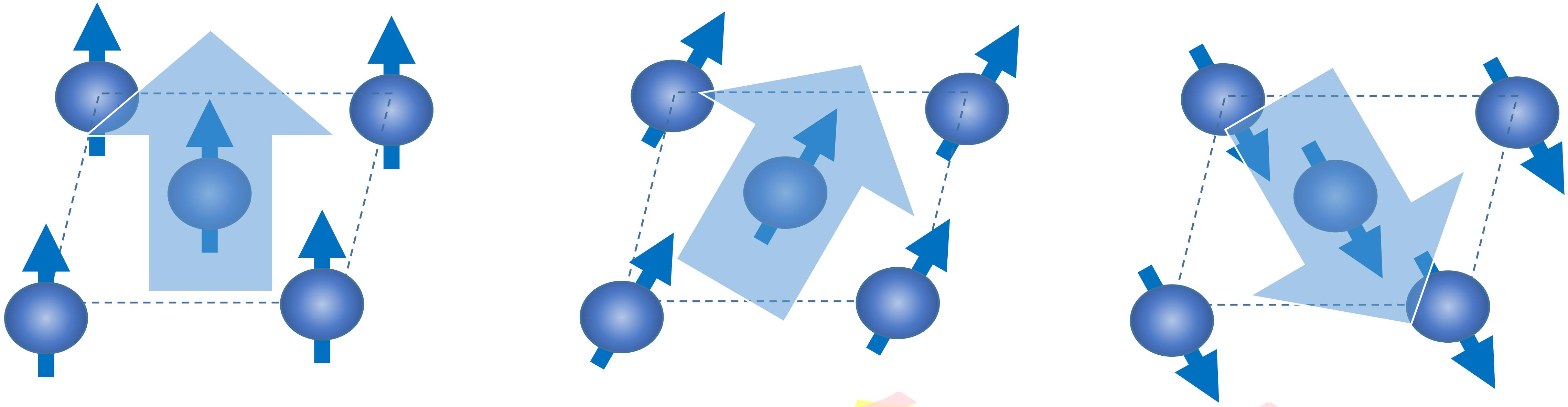
antiferromagnetic order (T< T_N)
antiparallel alignment

Werner
HEISENGERG
1901-1976
Nobel Price 1932

Magnetic domains ← exchange

Ferromagnetic order
$T < T_C$

2D picture: the exchange is an isotropic interaction
→ no preference for the orientation of the magnetic moments



→ parallel alignment at large scale is favorable
→ spontaneously one single magnetic domain : far too ideal

magnetization

$$\boldsymbol{M}(\boldsymbol{r}) = \frac{\sum_i \mu_i}{V}$$

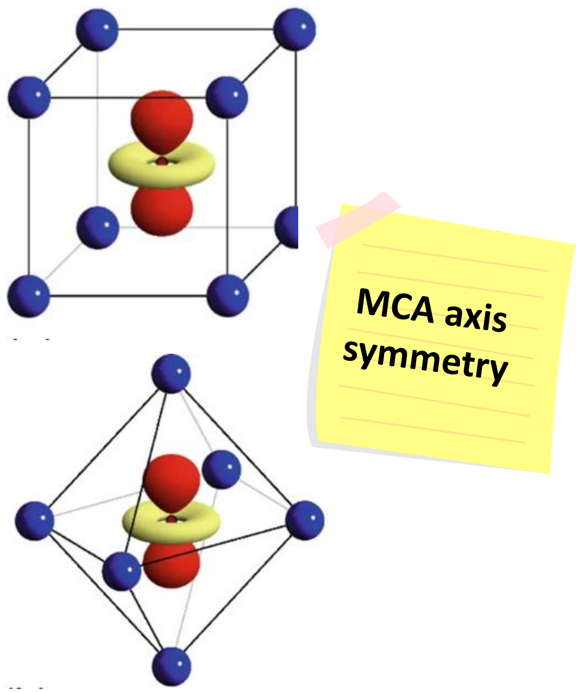
domain = uniform magnetization

$$|\boldsymbol{M}(\boldsymbol{r})| = M_s$$

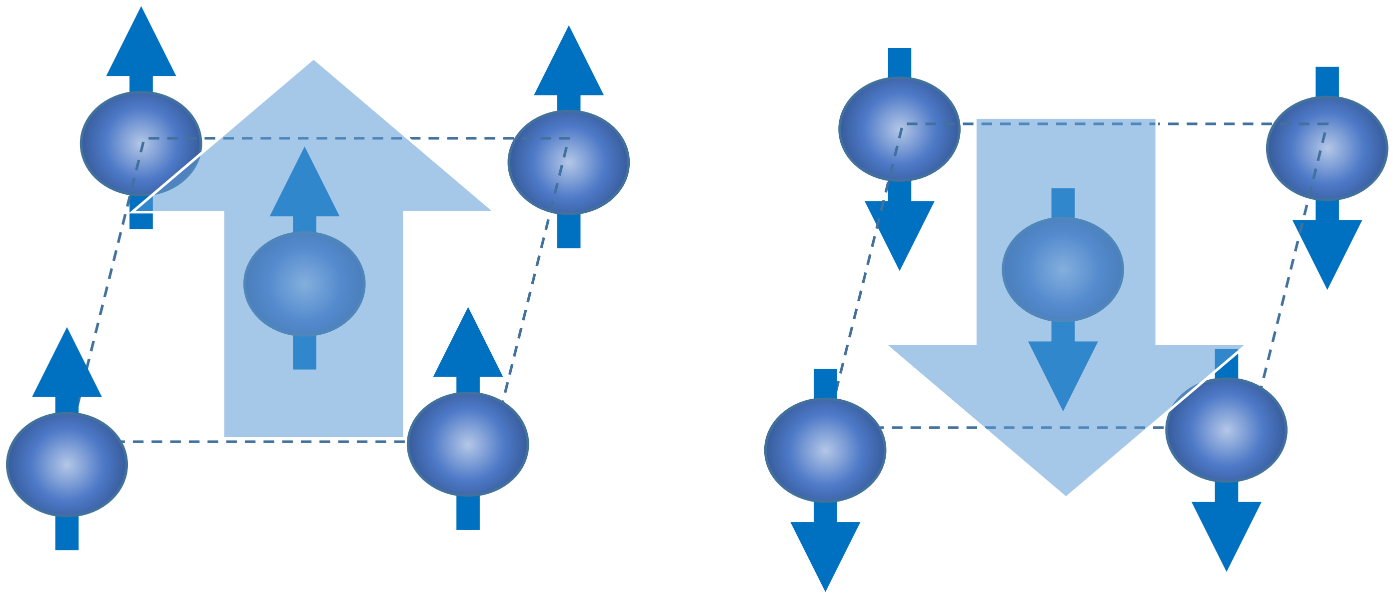
Magnetic domains ← magneto-crystalline anisotropy (MCA)

Ferromagnetic order
$T < T_C$

3D picture : charges have periodic arrangement in a crystal
→ crystal electric field acts on the electrons (orbital orientation)
→ additional terms in Hamiltonian



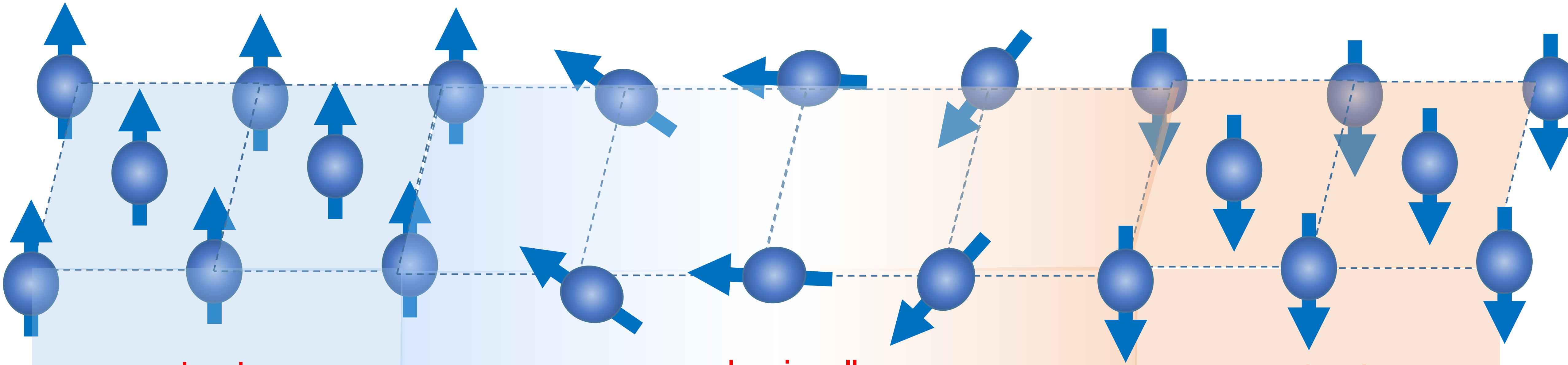
3d orbital (z2)
in crystalline
environments



→ magneto-crystalline anisotropy : few orientations are more favorable than others

→ several magnetic domains distinguished by the alignment with the MC axis

Magnetic domains and walls : a battle between exchange & anisotropy



domain
uniform magnetization

$$\boldsymbol{M} = M_s \begin{pmatrix} 0 \\ 0 \\ +1 \end{pmatrix}$$

domain wall
gradual variation of the magnetization

$$\boldsymbol{M}(\boldsymbol{r}) = M_s \begin{pmatrix} m_x\,(\boldsymbol{r}) \\ m_y\,(\boldsymbol{r}) \\ m_z\,(\boldsymbol{r}) \end{pmatrix}$$

domain
uniform magnetization

$$\boldsymbol{M} = M_s \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$$

wall = magnetization variable (r)

→ ferromagnetic systems host magnetic domains and walls

Magnetic domains and walls : a real and complex world

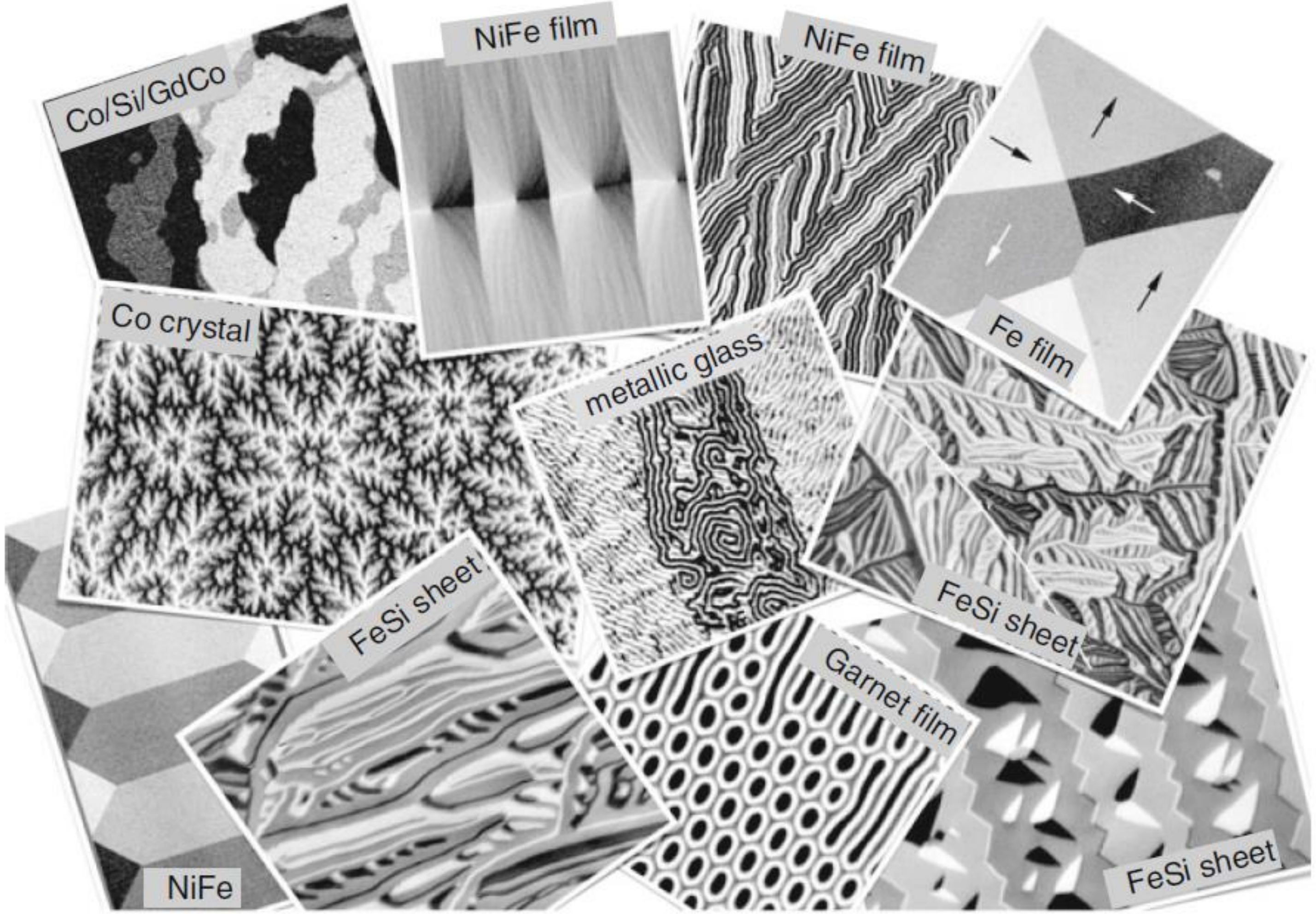
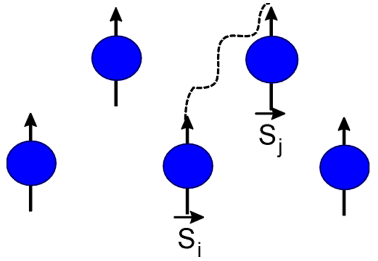


Fig. 2 Collection of domain images, obtained by Kerr microscopy on various magnetic materials. (Most domain images are adapted by permission from Ref. [1] (c) Springer 1998)

Schäfer, R. (2021). Magnetic Domains https://doi.org/10.1007/978-3-030-63210-6_8

Domains and walls : a battle between interactions / Gibb's free energy

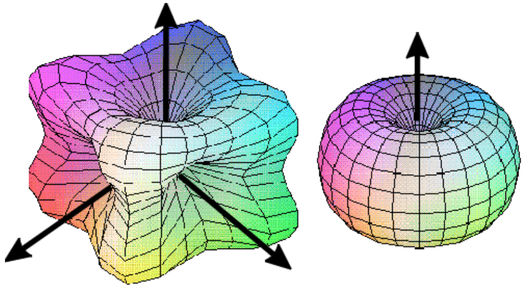
Exchange interaction
magnetic order ($T<T_c$)
parallel alignment of spins
short range interaction but very strong



$$\int_{\Omega} A_{ex} \left(\nabla \boldsymbol{m}(\boldsymbol{r},t)\right)^{2} dV$$

$A_{ex} \sim J_{ij}$

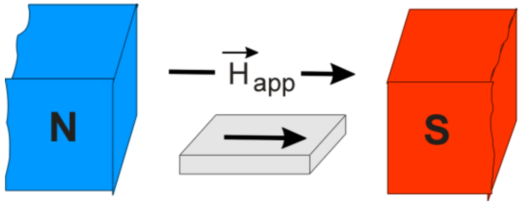
Magnetocrystalline anisotropy
easy axis and hard axis
Impact of the crystal symmetry
local interaction



$$\int_{\Omega} K_u \left[1-\left(\boldsymbol{u_k}\cdot \boldsymbol{m}(\boldsymbol{r},t)\right)^{2}\right] dV$$

K_u ~symmetry

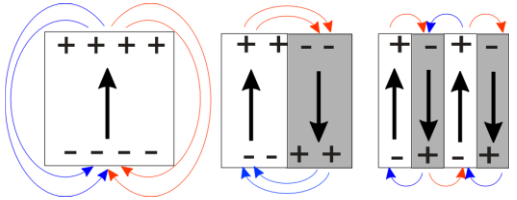
Zeeman interaction
Externally applied field
local interaction



$$-\mu_0 M_S \int_{\Omega} \boldsymbol{m}(\boldsymbol{r},t)\cdot \boldsymbol{H_{app}}(\boldsymbol{r},t)\, dV$$

Magnetostatic interaction
Maxwell's equations
long range interaction

Shape anisotropy



$$-\frac{1}{2}\mu_0 M_S \int_{\Omega} \boldsymbol{m}(\boldsymbol{r},t)\cdot \boldsymbol{H_D}(\boldsymbol{r},t)\, dV$$

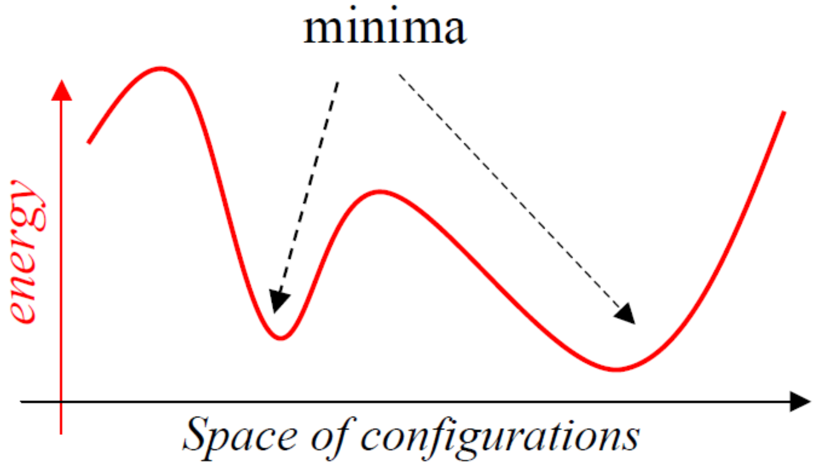
6^{th} *fold integral*

Magnetic domains and walls ← stable state

Magnetization distribution:

$$\boldsymbol{M}(\boldsymbol{r},t), = M_S\boldsymbol{m}(\boldsymbol{r},t) \;\; \boldsymbol{r} \in \boldsymbol{\Omega}$$

$$|\boldsymbol{m}(\boldsymbol{r},t)|=1$$



Gibb's free energy:

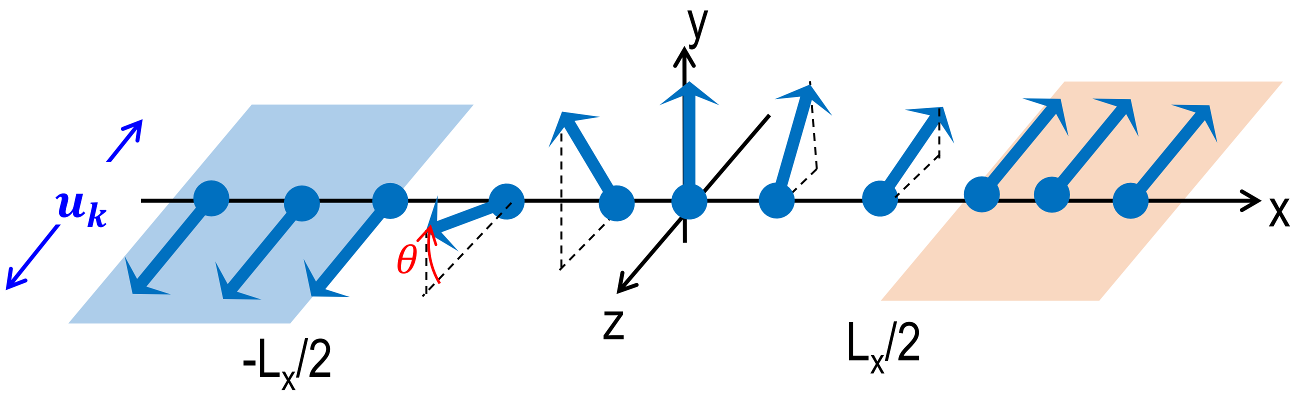
$$E_{total} = \int_{\Omega} \left[\varepsilon_{ex} + \varepsilon_K + \varepsilon_{app} + \varepsilon_D\right] dV$$

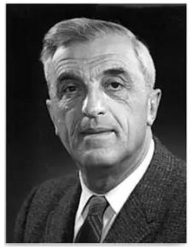
Magnetic stable state = minimum of the Gibb's free energy functional

$$\boldsymbol{m} \rightarrow \boldsymbol{m}+\delta\boldsymbol{m} \qquad \delta E_{total}(\boldsymbol{m}) = 0 \qquad \delta^2 E_{total}(\boldsymbol{m}) > 0$$

← variational principle

Bloch wall : a 3D model wall





Bloch wall : invariance along y and z

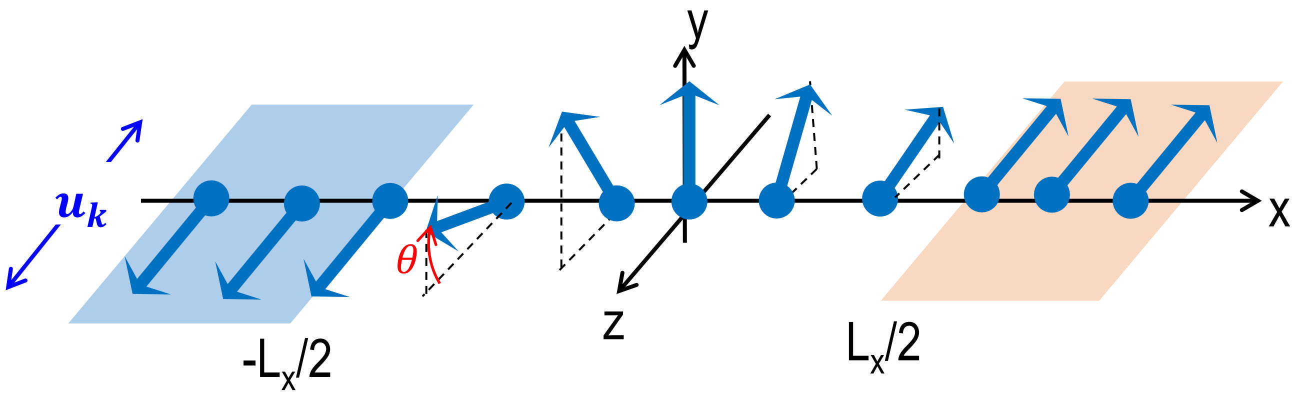
$$\boldsymbol{M}(\boldsymbol{x}) = M_s \begin{pmatrix} m_x(x) \\ m_y(x) \\ m_z(x) \end{pmatrix} = M_s \begin{pmatrix} 0 \\ \sin\theta(x) \\ \cos\theta(x) \end{pmatrix}$$

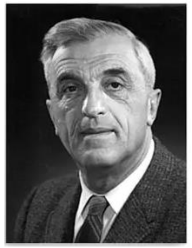
Exchange energy:

$$E_{ex} = \int_\Omega A_{ex} \left(\nabla \boldsymbol{m}(\boldsymbol{r},t)\right)^{\boldsymbol{2}} dV = A_{ex} \int_\Omega \begin{bmatrix} \left(\frac{\partial m_x}{\partial x}\right)^2 + \left(\frac{\partial m_x}{\partial y}\right)^2 + \left(\frac{\partial m_x}{\partial z}\right)^2 \\ + \left(\frac{\partial m_y}{\partial x}\right)^2 + \left(\frac{\partial m_y}{\partial y}\right)^2 + \left(\frac{\partial m_y}{\partial z}\right)^2 \\ + \left(\frac{\partial m_z}{\partial x}\right)^2 + \left(\frac{\partial m_z}{\partial y}\right)^2 + \left(\frac{\partial m_z}{\partial z}\right)^2 \end{bmatrix} dxdydz$$

$$E_{ex} = A_{ex} L_y L_z \int_{-L_x/2}^{+L_x/2} \left[\left(\frac{\partial m_y}{\partial x}\right)^2 + \left(\frac{\partial m_z}{\partial x}\right)^2\right] dx = A_{ex} L_y L_z \int_{-L_x/2}^{+L_x/2} \left(\frac{d\theta}{dx}\right)^2 dx$$

Bloch wall : a 3D model wall





Bloch wall : invariance along y and z

$$\boldsymbol{M}(\boldsymbol{x}) = M_s \begin{pmatrix} m_x(x) \\ m_y(x) \\ m_z(x) \end{pmatrix} = M_s \begin{pmatrix} 0 \\ \sin\theta(x) \\ \cos\theta(x) \end{pmatrix}$$

$$\boldsymbol{u_k} = (0,0,1)$$

MCA energy:

$$E_K = \int_\Omega K_u \left[1 - (\boldsymbol{u_k} \cdot \boldsymbol{m}(\boldsymbol{r}, t))^2\right] dV = K_u \int_\Omega \left[1 - (u_{kx} m_x + u_{ky} m_y + u_{kz} m_z)^2\right] dxdydz$$

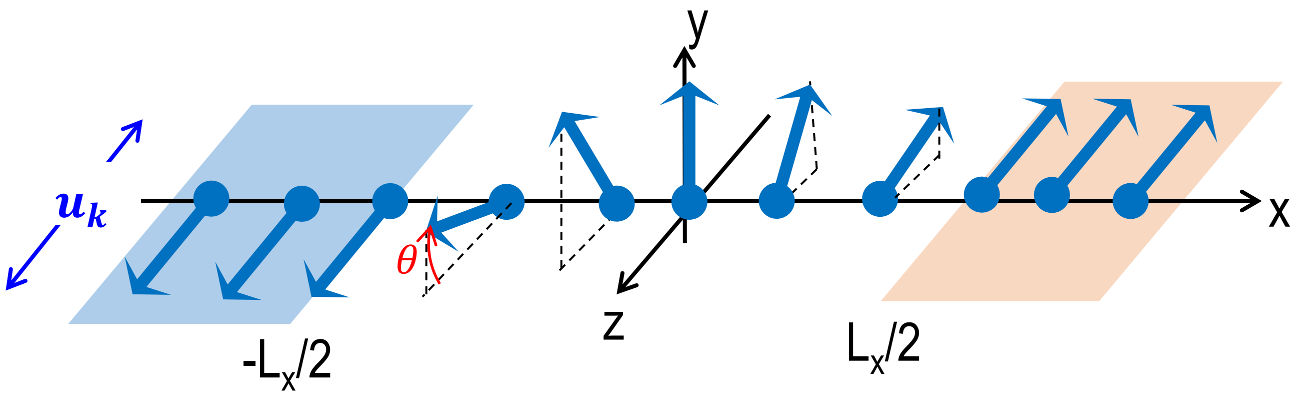
$$E_k = K_u L_y L_z \int_{-L_x/2}^{+L_x/2} [1 - m_z^2] dx = K_u L_y L_z \int_{-L_x/2}^{+L_x/2} sin^2 \theta dx$$

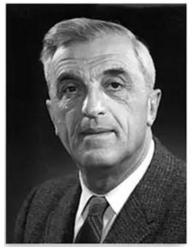
Magnetostatic energy : $E_D = 0$

Volume charges: $\rho = -\nabla \cdot \boldsymbol{m}(\boldsymbol{r}, t)$ ✓ because of the symmetry $\rho = 0$

Surface charges: $\sigma = \boldsymbol{n} \cdot \boldsymbol{m}(\boldsymbol{r}, t)$ ✓ 3D sample, the surface is at ∞

Bloch wall : a 3D model wall





Bloch wall : invariance along y and z

$$\boldsymbol{M}(\boldsymbol{x}) = M_s \begin{pmatrix} m_x(x) \\ m_y(x) \\ m_z(x) \end{pmatrix} = M_s \begin{pmatrix} 0 \\ \sin\theta(x) \\ \cos\theta(x) \end{pmatrix}$$

$$E_{tot} = \int_{-L_x/2}^{+L_x/2} \left[A_{ex} \left(\frac{d\theta}{dx} \right)^2 + K_u sin^2\theta \right] dx$$

$$\varepsilon_{tot}(\theta) = \frac{E_{tot}}{L_y L_z} = \int_{-L_x/2}^{+L_x/2} \left[A_{ex} \left(\frac{d\theta}{dx} \right)^2 + K_u sin^2\theta \right] dx$$

✓ Use the variational principle to find the θ function minimising the ε_{tot}

$$\theta \rightarrow \theta + \delta\theta$$

$$\delta\varepsilon_{tot} = \varepsilon_{tot}(\theta + \delta\theta) - \varepsilon_{tot}(\theta) \rightarrow 0$$

$$\int_{-\infty}^{+\infty} \left[2A_{ex} \frac{d\theta}{dx} \frac{d\delta\theta}{dx} + 2K_u sin\theta cos\theta \delta\theta \right] = 0$$

✓ Boundary conditions $\theta\left(-\frac{L_x}{2}\right) = 0$, $\theta\left(+\frac{L_x}{2}\right) = \pi$

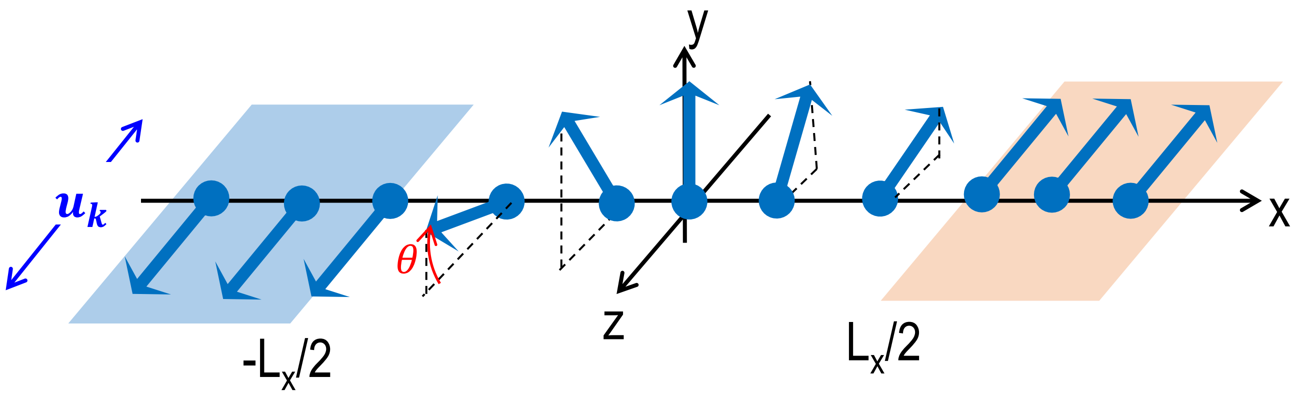
$$\frac{d\theta}{dx}\left(\pm\frac{L_x}{2}\right) = 0$$

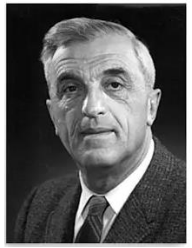
$$-A_{ex}\left(\frac{d\theta}{dx}\right)^2 + K_u (sin\theta)^2 = 0$$

$$\frac{d\theta}{dx} = \pm\sqrt{\frac{K_u}{A_{ex}}} sin\theta$$

→ two solutions with the same energy

Bloch wall : a 3D model wall





Bloch wall : invariance along y and z

$$\boldsymbol{M}(\boldsymbol{x}) = M_s \begin{pmatrix} m_x(x) \\ m_y(x) \\ m_z(x) \end{pmatrix} = M_s \begin{pmatrix} 0 \\ \sin\theta(x) \\ \cos\theta(x) \end{pmatrix}$$

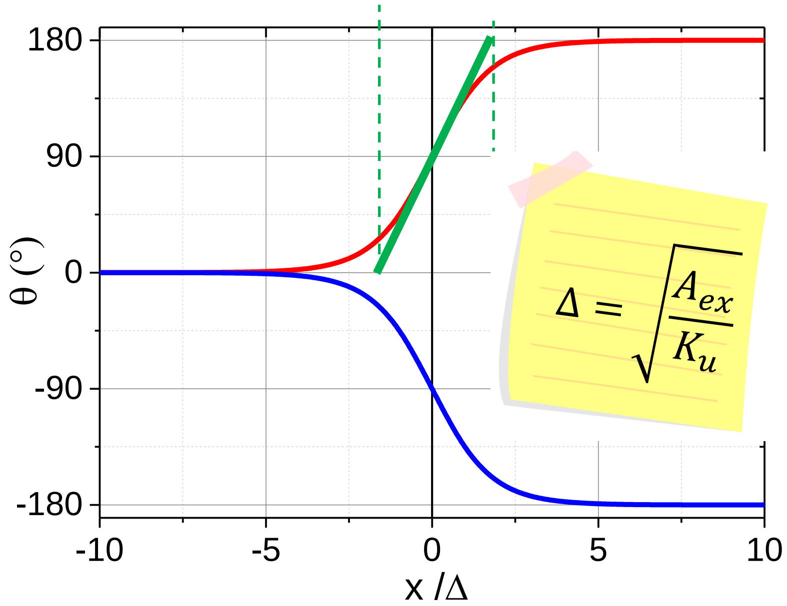
$$\theta(x) = \pm 2atan\left(e^{\frac{x}{\Delta}}\right)$$

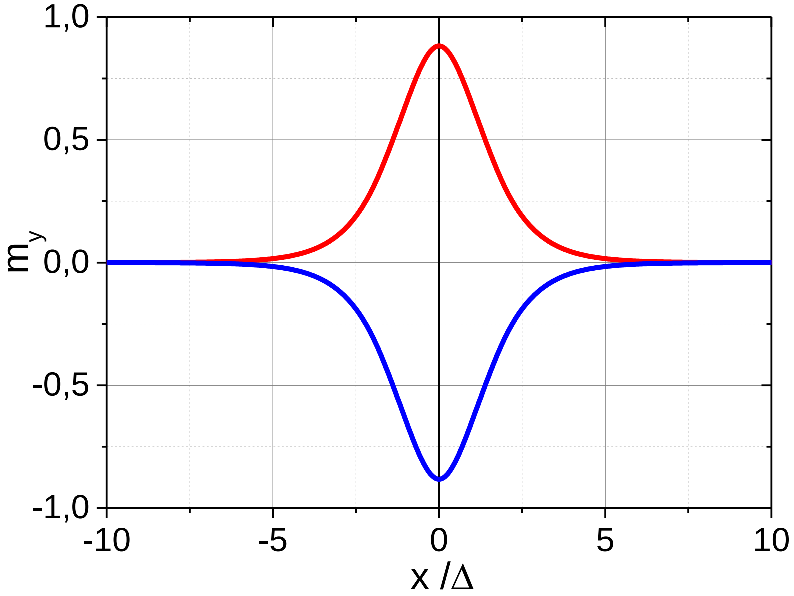
Bloch wall parameter: $\Delta = \sqrt{\frac{A_{ex}}{K_u}}$

$\Delta \sim 1 \ldots .100nm \ldots$

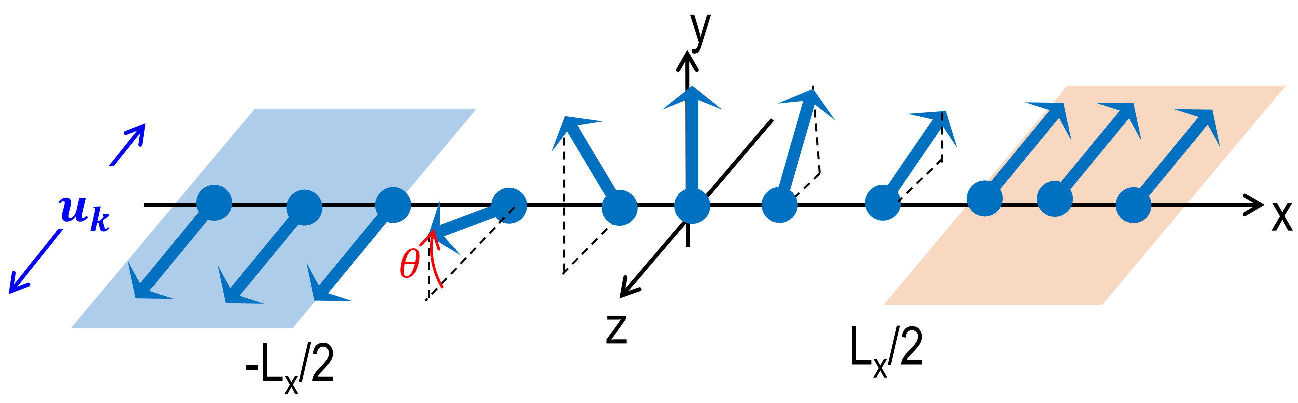
Bloch wall width: $\delta = \pi\Delta$

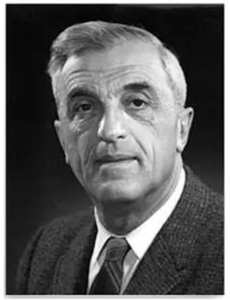
Bloch wall energy $\gamma_B = 4\sqrt{A_{ex}K_u}$





Bloch wall becomes Néel wall when finite size



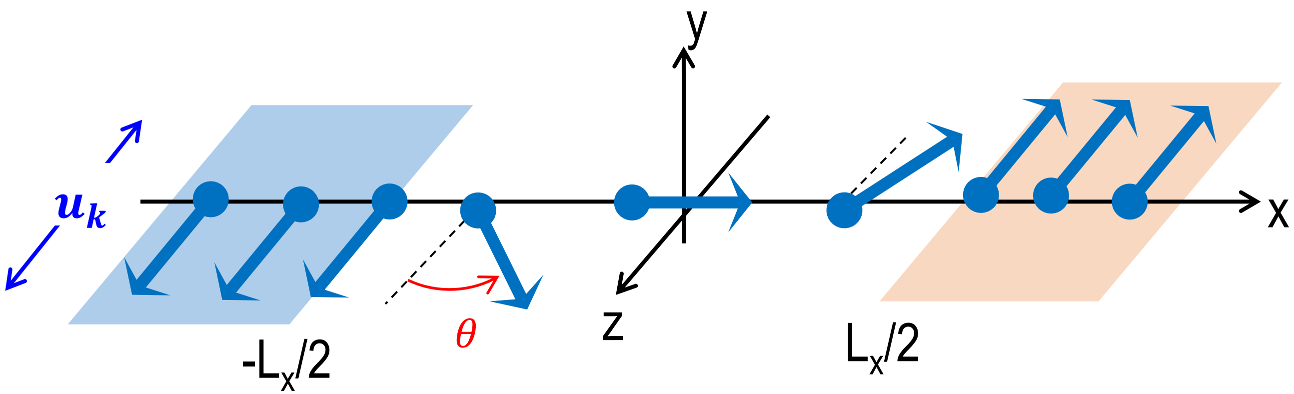


Bloch wall : invariance along y and z

$$\boldsymbol{M}(\boldsymbol{x}) = M_s \begin{pmatrix} m_x(x) \\ m_y(x) \\ m_z(x) \end{pmatrix} = M_s \begin{pmatrix} 0 \\ \sin\theta(x) \\ \cos\theta(x) \end{pmatrix}$$

No volume charges: $\rho = -\nabla \cdot \boldsymbol{m}(\boldsymbol{r},t)$=0

Surface charges: $\sigma = \boldsymbol{n} \cdot \boldsymbol{m}(\boldsymbol{r},t)$



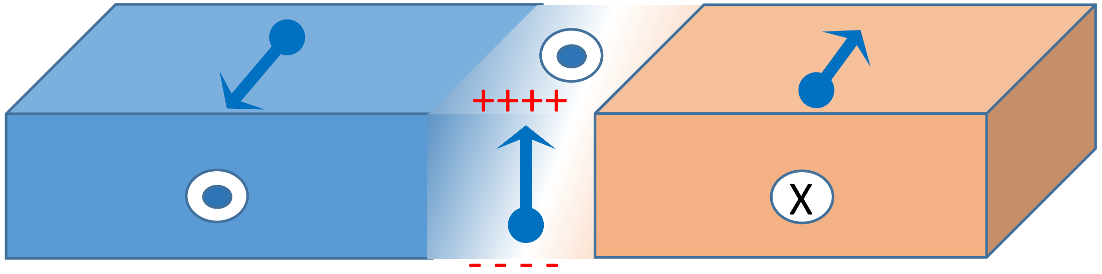
Néel wall : invariance along y and z

$$\boldsymbol{M}(\boldsymbol{x}) = M_s \begin{pmatrix} m_x(x) \\ m_y(x) \\ m_z(x) \end{pmatrix} = M_s \begin{pmatrix} \sin\theta(x) \\ 0 \\ \cos\theta(x) \end{pmatrix}$$

Volume charges: $\rho = -\nabla \cdot \boldsymbol{m}(\boldsymbol{r},t) = -\frac{d\sin\theta(x)}{dx}$

No surface charges: $\sigma = \boldsymbol{n} \cdot \boldsymbol{m}(\boldsymbol{r},t)$=0

Bloch wall becomes Néel wall when finite size

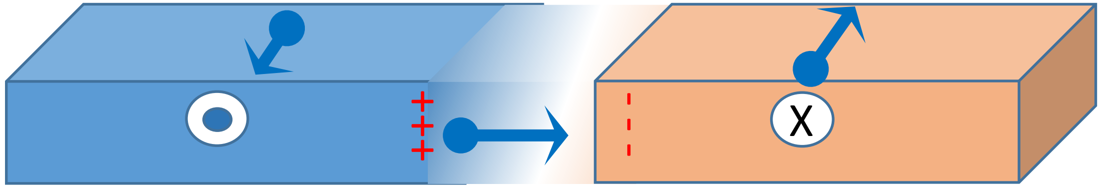


thicker layers

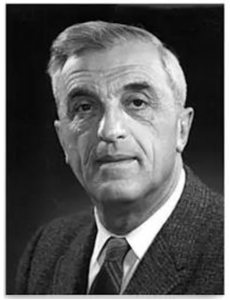
Magnetostatics is important

$$l_{ex} = \sqrt{\frac{2A_{ex}}{\mu_0 M_s^2}}$$

Exchange length



thinner layers



Bloch wall : invariance along y and z

$$\boldsymbol{M}(\boldsymbol{x}) = M_s \begin{pmatrix} m_x(x) \\ m_y(x) \\ m_z(x) \end{pmatrix} = M_s \begin{pmatrix} 0 \\ \sin\theta(x) \\ \cos\theta(x) \end{pmatrix}$$

No volume charges: $\rho = -\nabla \cdot \boldsymbol{m}(\boldsymbol{r}, t) = 0$

Surface charges: $\sigma = \boldsymbol{n} \cdot \boldsymbol{m}(\boldsymbol{r}, t)$

Néel wall : invariance along y and z

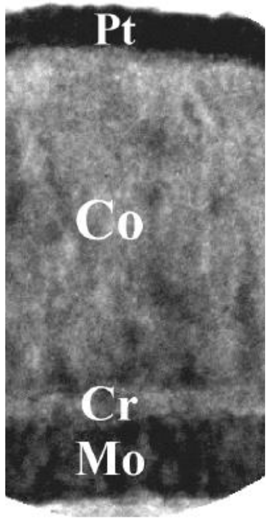
$$\boldsymbol{M}(\boldsymbol{x}) = M_s \begin{pmatrix} m_x(x) \\ m_y(x) \\ m_z(x) \end{pmatrix} = M_s \begin{pmatrix} \sin\theta(x) \\ 0 \\ \cos\theta(x) \end{pmatrix}$$

Volume charges: $\rho = -\nabla \cdot \boldsymbol{m}(\boldsymbol{r}, t) = -\frac{d \sin\theta(x)}{dx}$

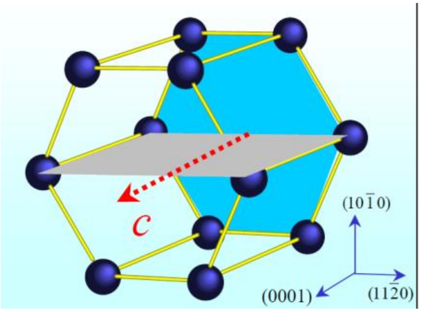
No surface charges: $\sigma = \boldsymbol{n} \cdot \boldsymbol{m}(\boldsymbol{r}, t) = 0$

Domain wall in thin films with in plane MCA

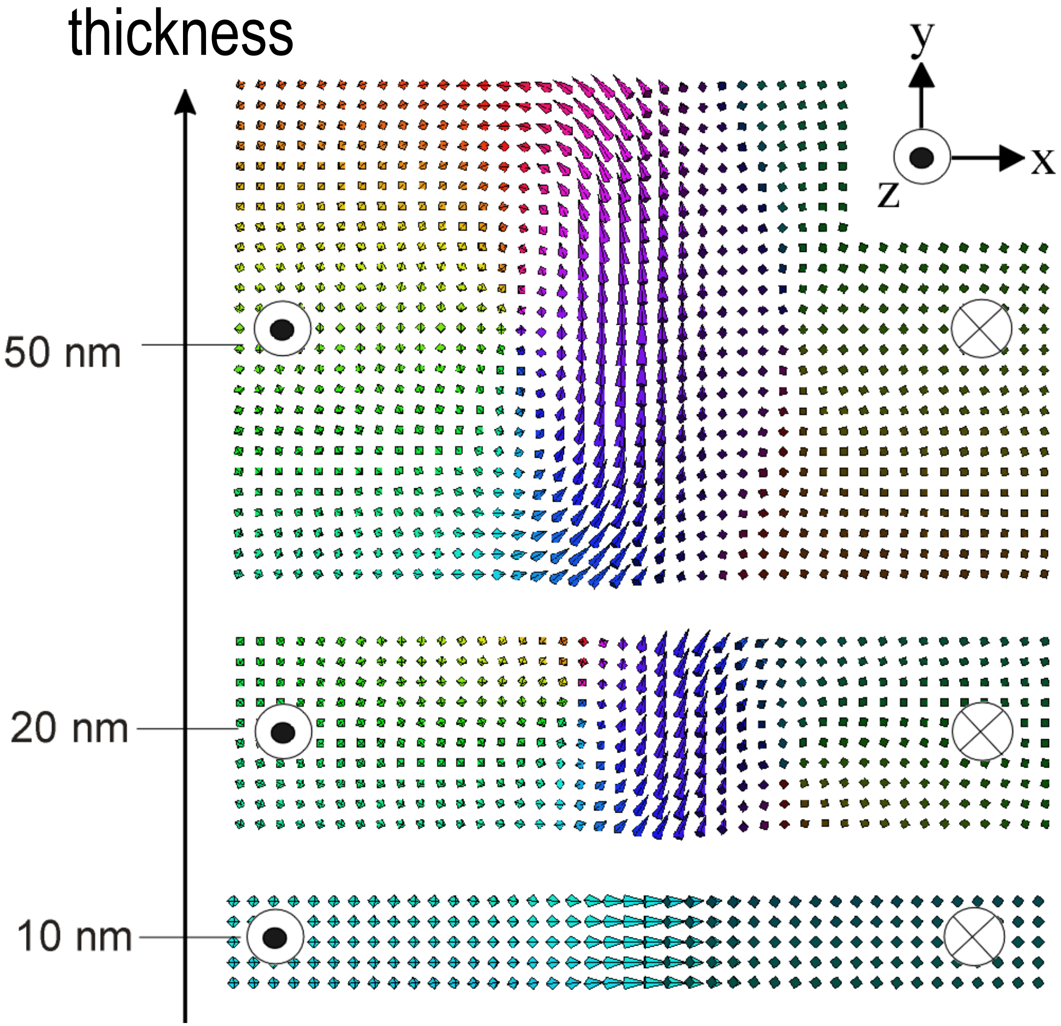
TEM cross section



MgO(110)



In-plane uniaxial MCA



LD Buda PhD (Univ. Strasbourg 2001)

2D micromagnetic simulation

$Co(10\bar{1}0)$ parameters

$M_S = 1400kA/m$

$K_U = 500kJ/m^3$

$A_{ex} = 14pJ/m$

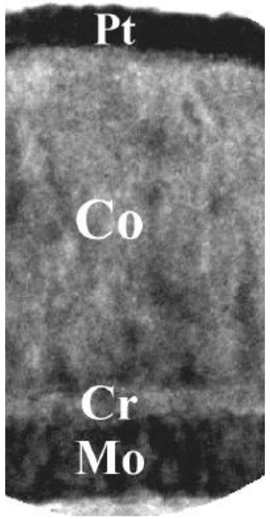
$\Delta = 5.29nm$

$l_{ex} = 3.37nm$

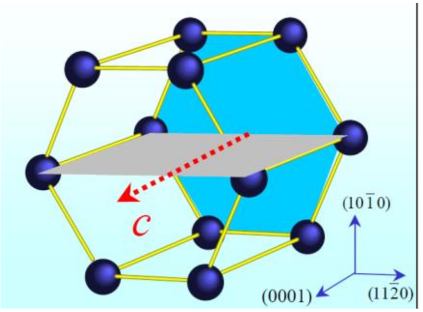
DW structure mixing Bloch & Néel

Domain wall in thin films with in plane MCA

TEM cross section

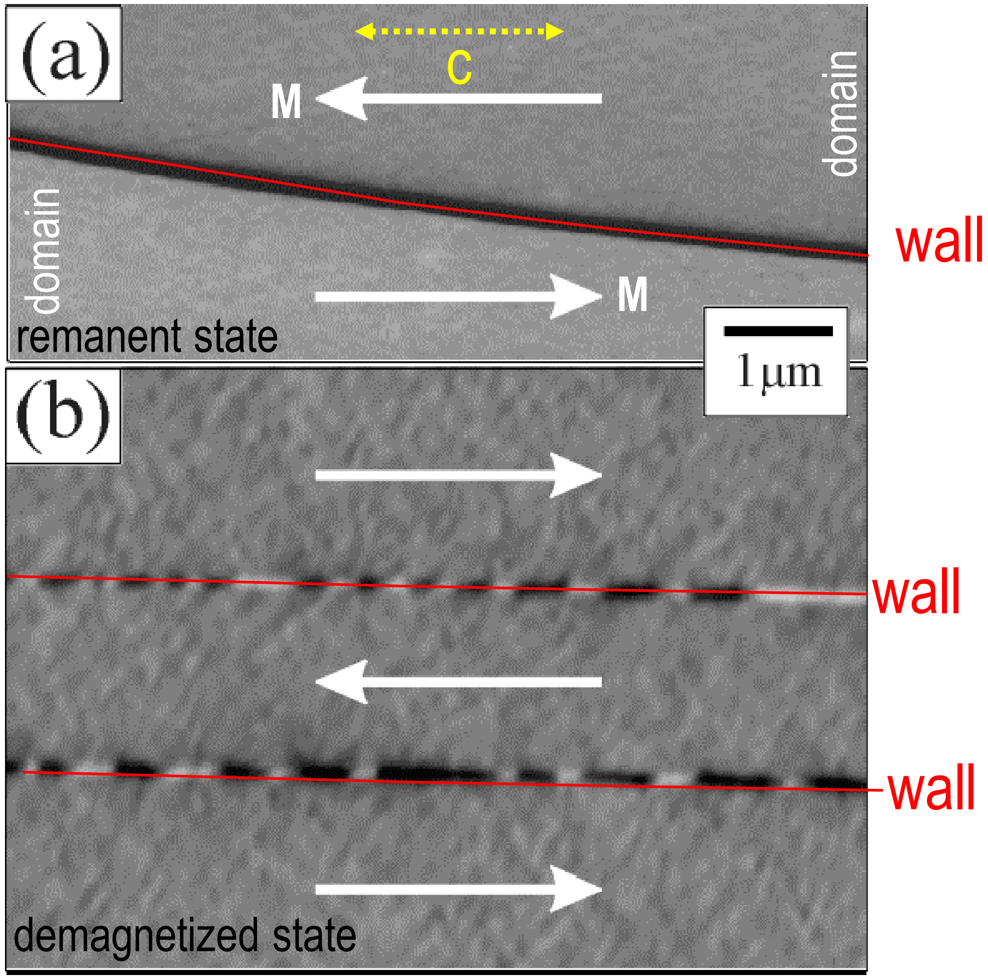


MgO(110)



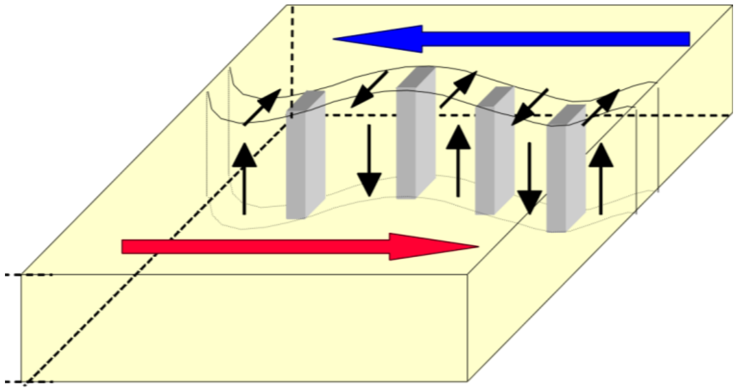
In-plane uniaxial MCA

MFM images : epitaxial 50nm thin film of Co(1010)



MFM resolution limit

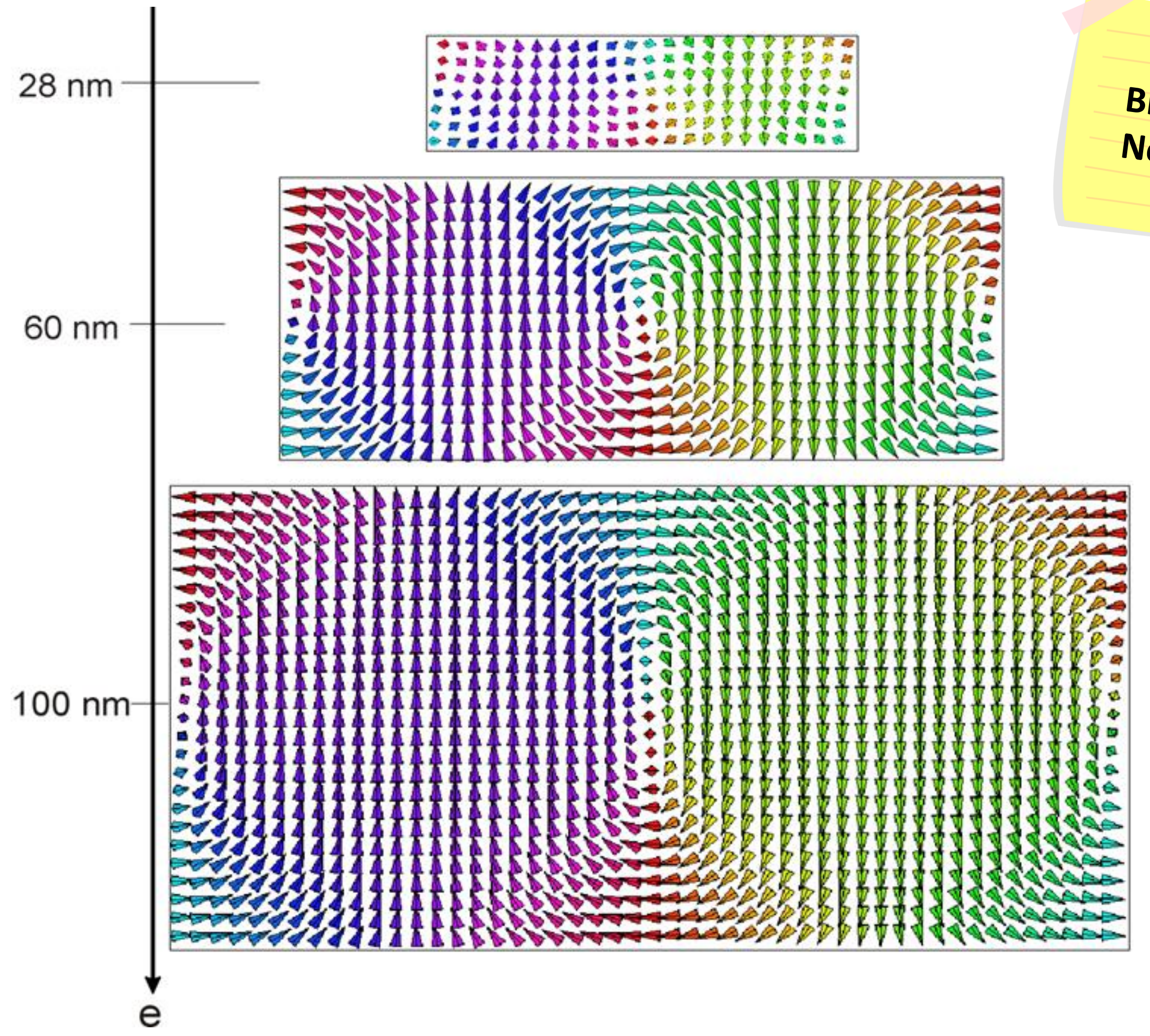
both chiralities exist +singularities



IL Prejbeanu PhD (Univ. Strasbourg 2001)

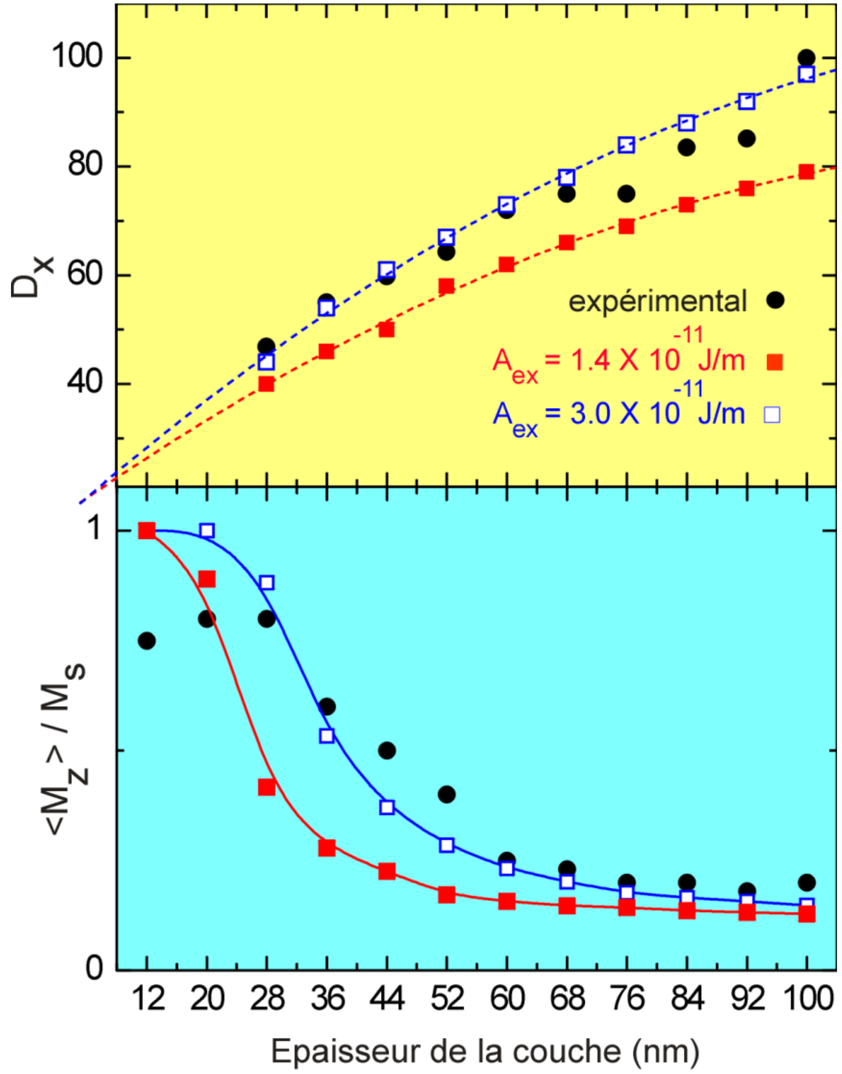
Domain wall in thin films with out of plane MCA

Co, Q=0.5



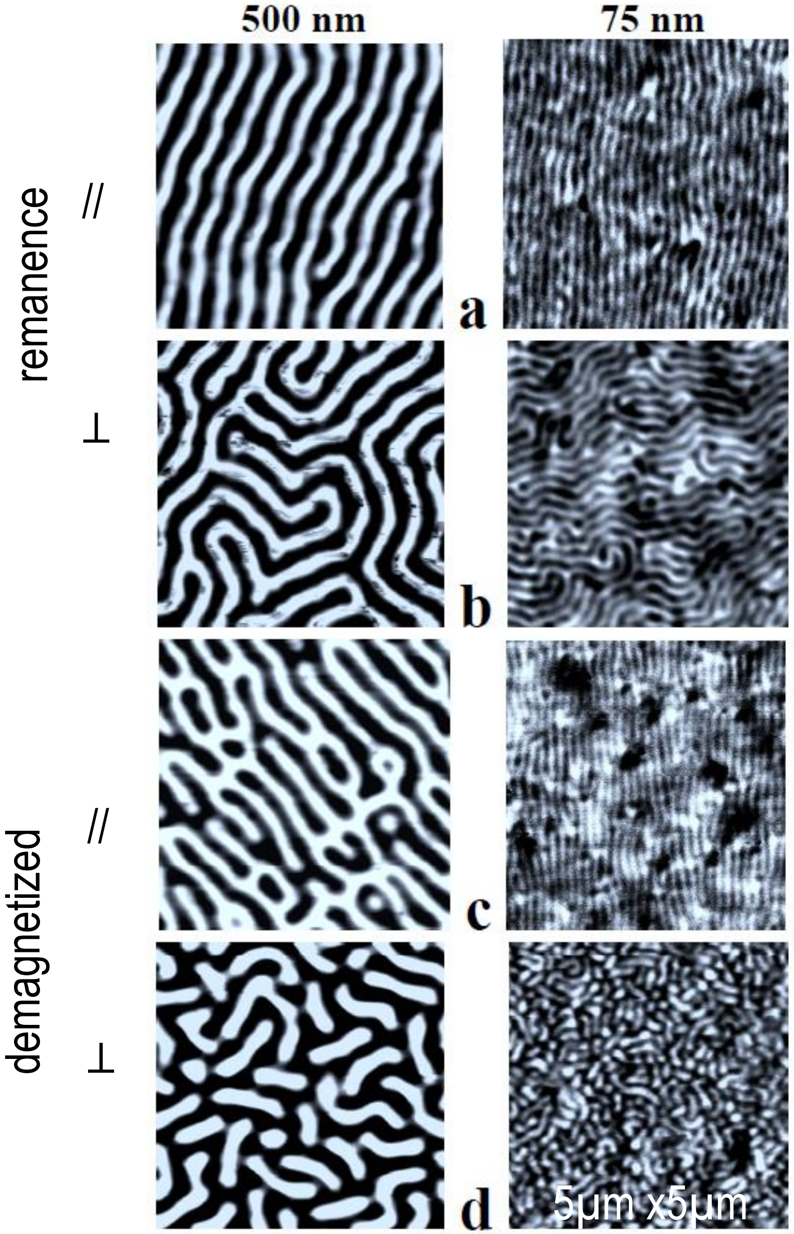
Bloch DW
Néel caps

$M_S = 1400 kA/m$
$K_U = 600 kJ/m^3$

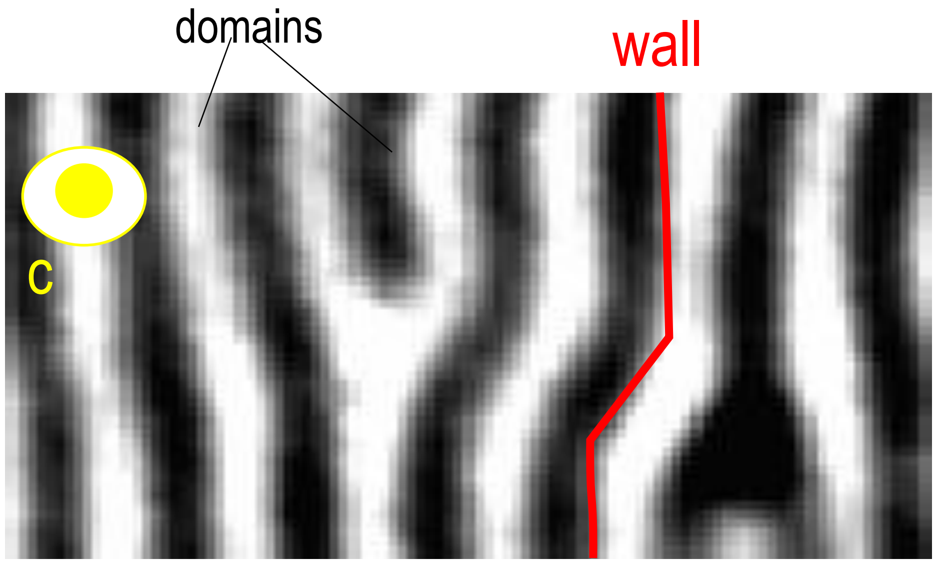


*Kittel, PR **70**, 965 (1946)*

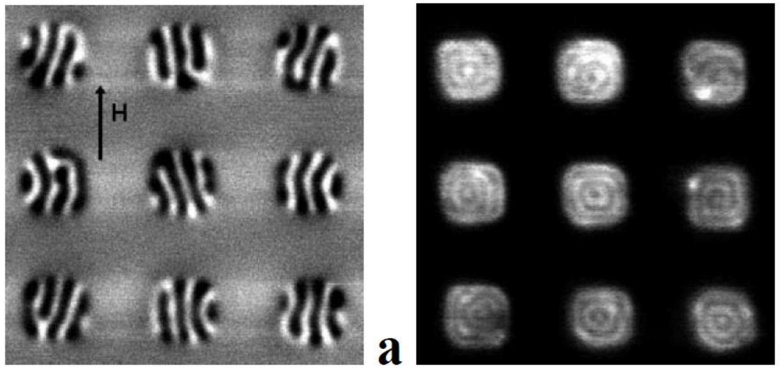
Domain wall in thin films with out of plane MCA



Epitaxial thin film of Al2O3/ Ru(5nm)/Co(0001) (hcp)



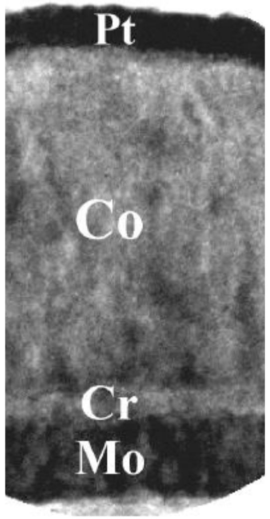
500nm square dots
Co(0001) t=150nm



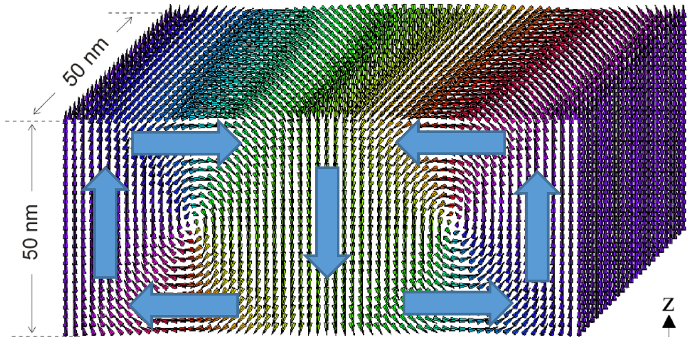
M. Hehn PhD (Univ. Strasbourg 1997)

Domain wall in nanowires with MCA

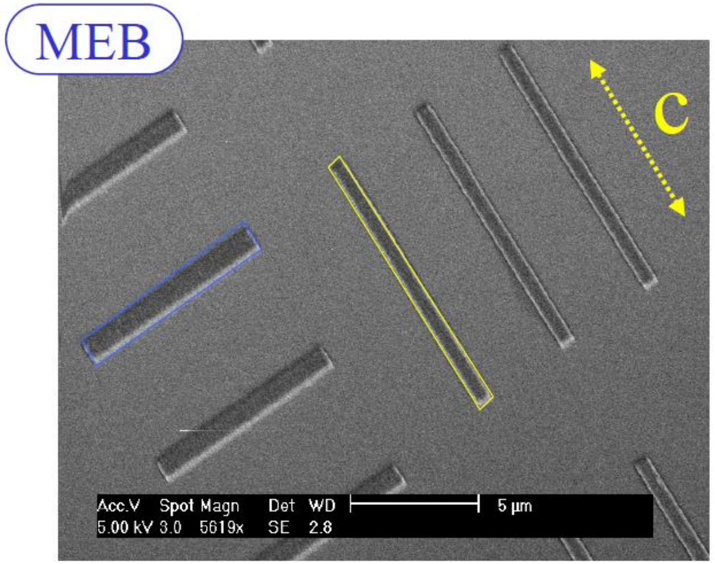
TEM cross section

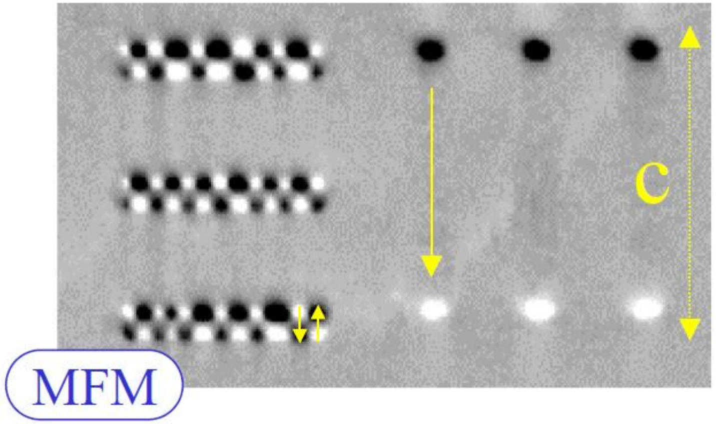


MgO(110)



MFM images : nanowire of Co(1010)

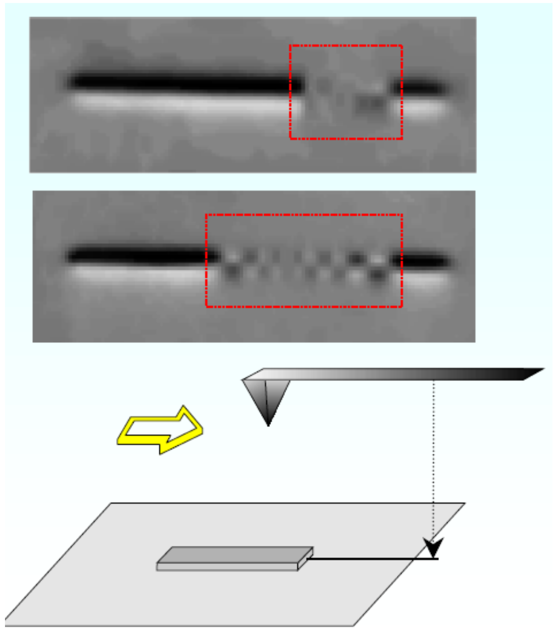




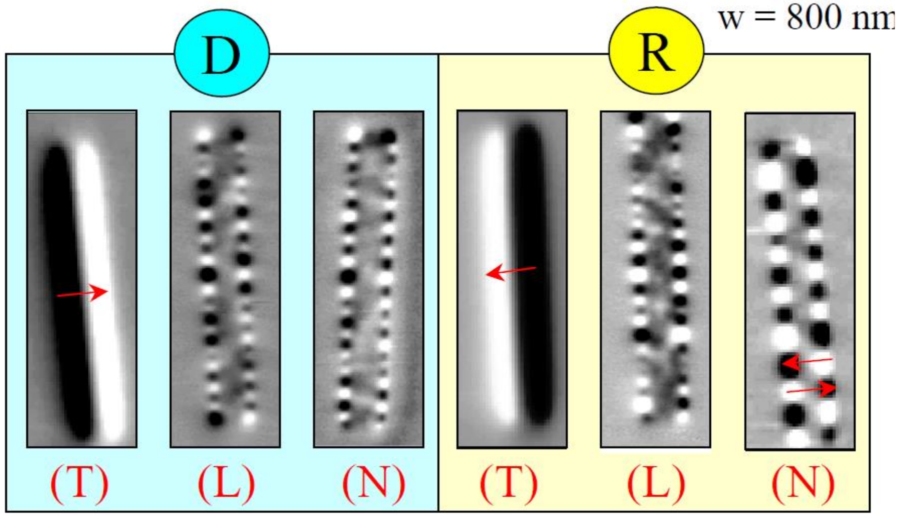
IL Prejbeanu PhD (Univ. Strasbourg 2001)

MFM surface charges

Multiple states

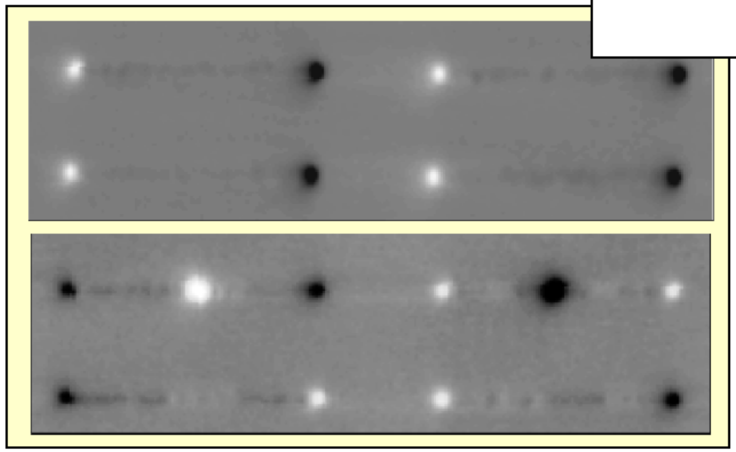


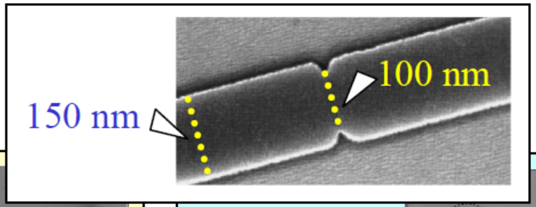
t = 60 nm
w = 800 nm



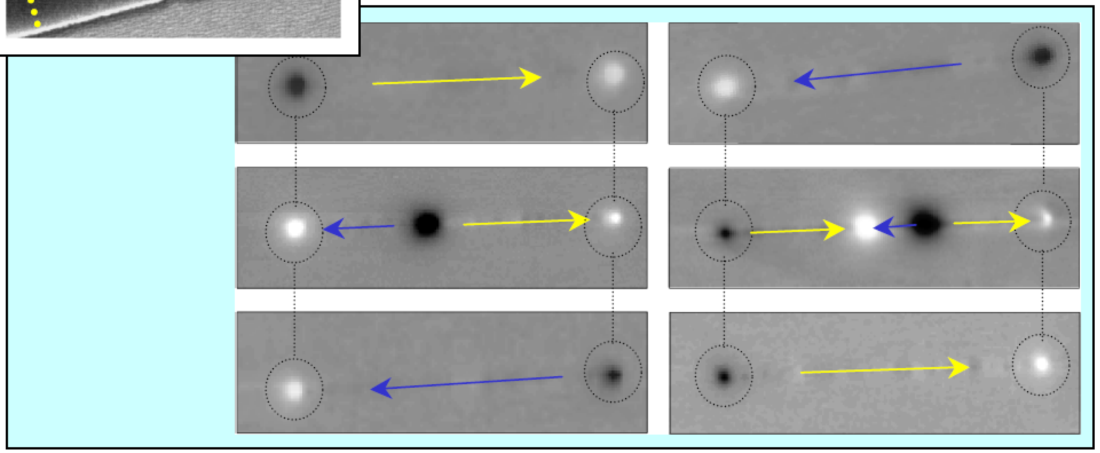
Domain wall in thin nanowires with MCA

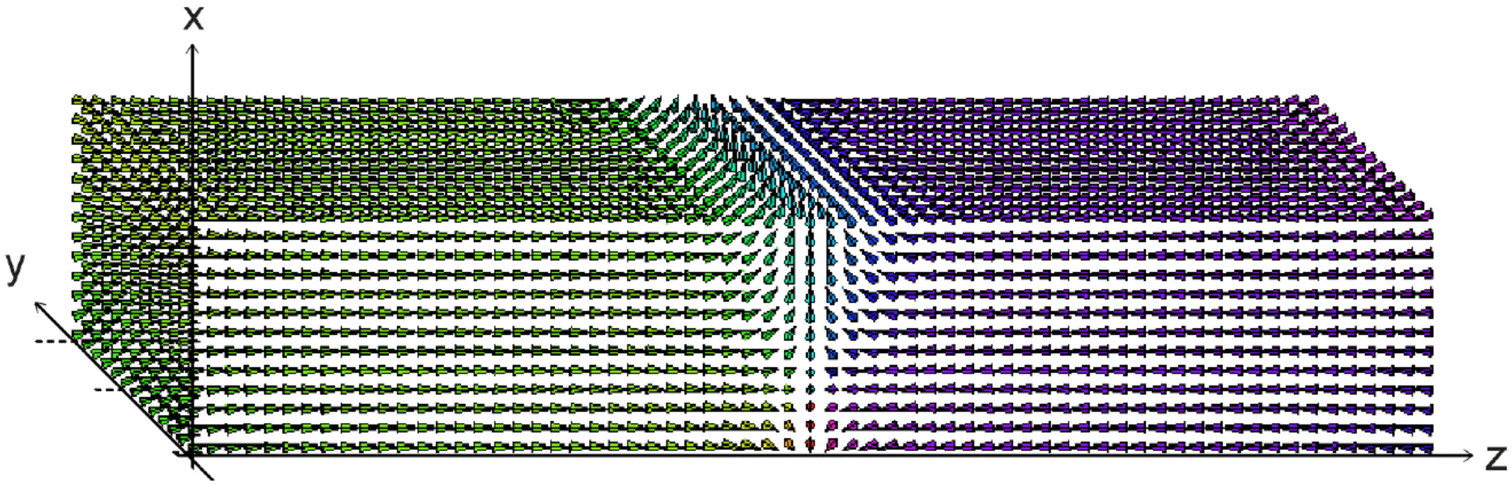
Pinning





During the field reversal





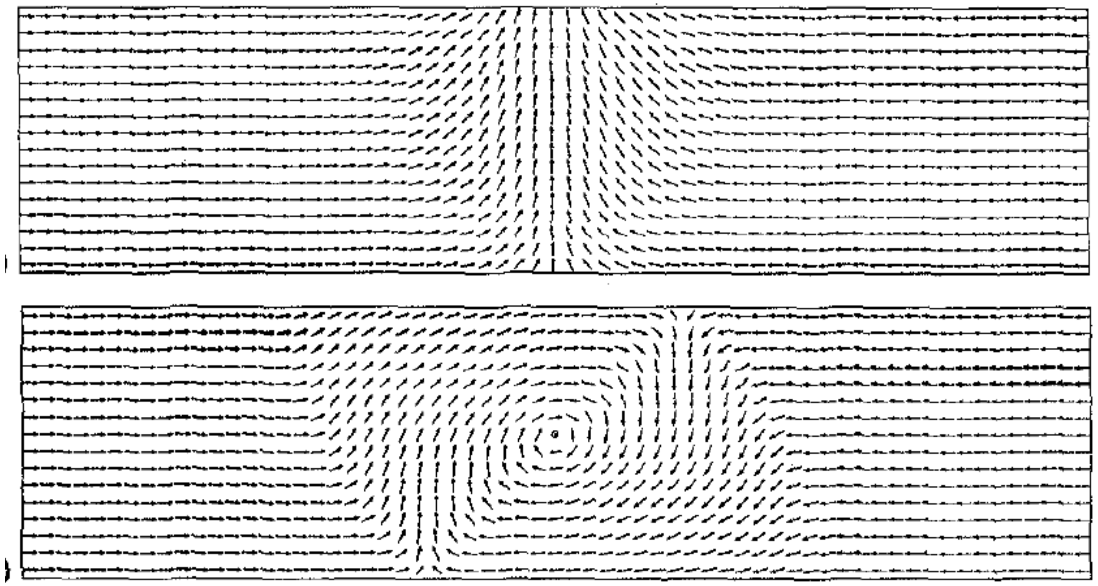
IL Prejbeanu PhD (Univ. Strasbourg 2001)

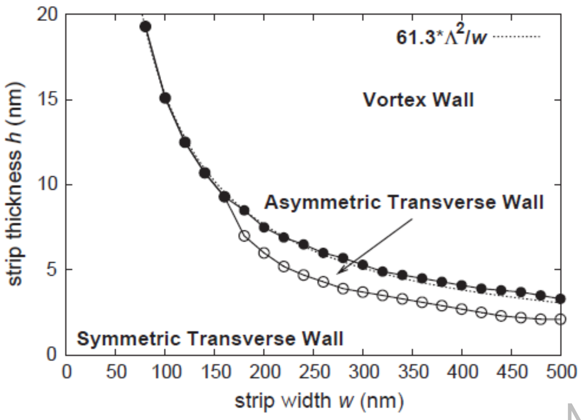
Domain wall in thin nanowires no MCA

R. D. McMichael et al. IEEE Trans.Mag.(1997)

Micromagnetic simulation

$Ni_{80}Fe_{20}$ width = 250 nm/ thickness 32nm





NiFe parameters

$M_S = 800kA/m$

$no\ MCA$

$A_{ex} = 10pJ/m$

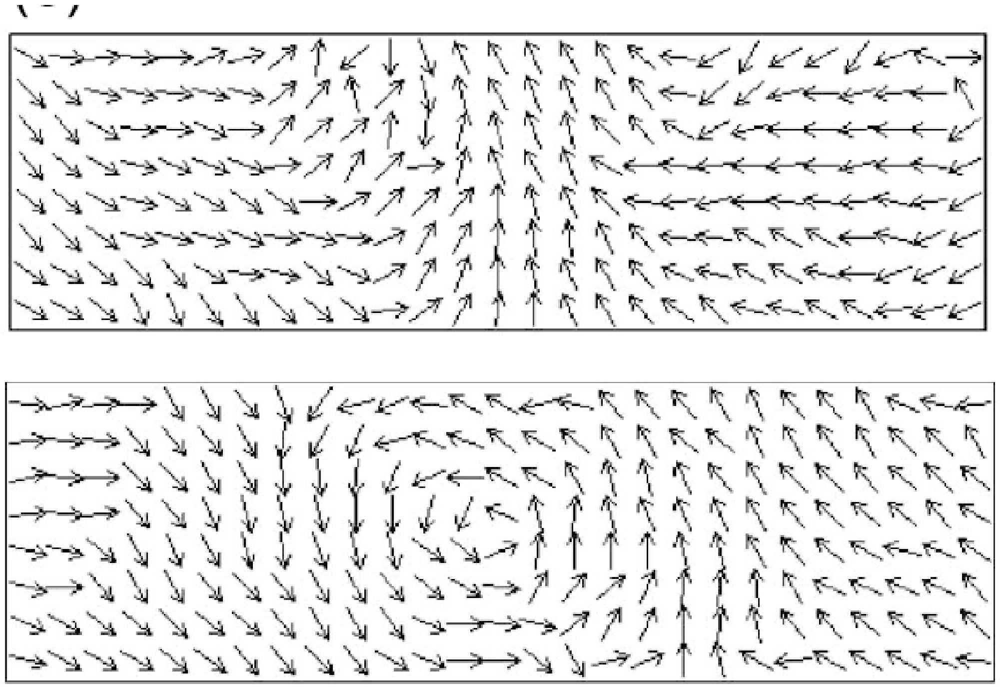
$\Delta \to \infty$

$l_{ex} = 4nm$

Nakatani et la. JMMM (2005)

Spin-polarized scanning electron microscopy

$Ni_{80}Fe_{20}$ width = 500 nm/ thickness 10nm

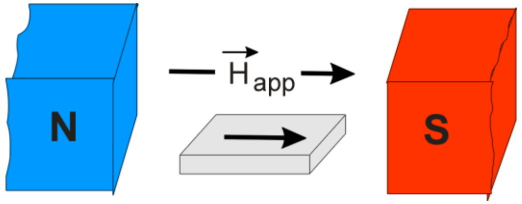


Reconstruction 3D structure

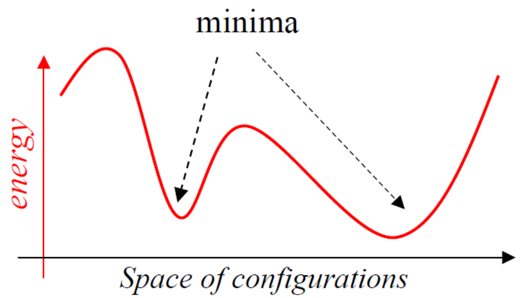
M. Klaui et al, Phys Rev. Lett (2005)

Hysteresis in thin films

Zeeman interaction



Energy landscape depends on the applied field (conservative term)



Thermal fluctuations play a role!

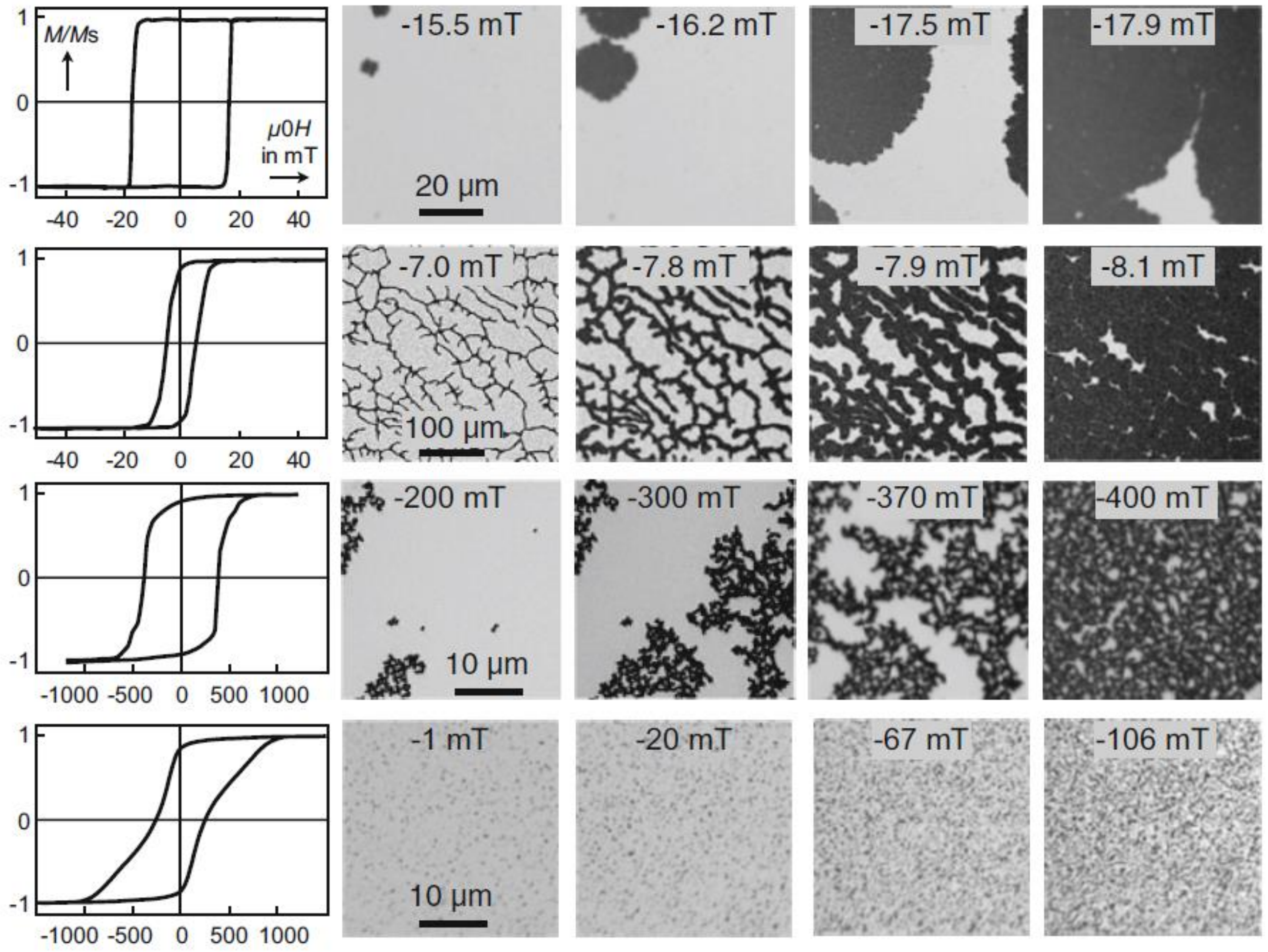


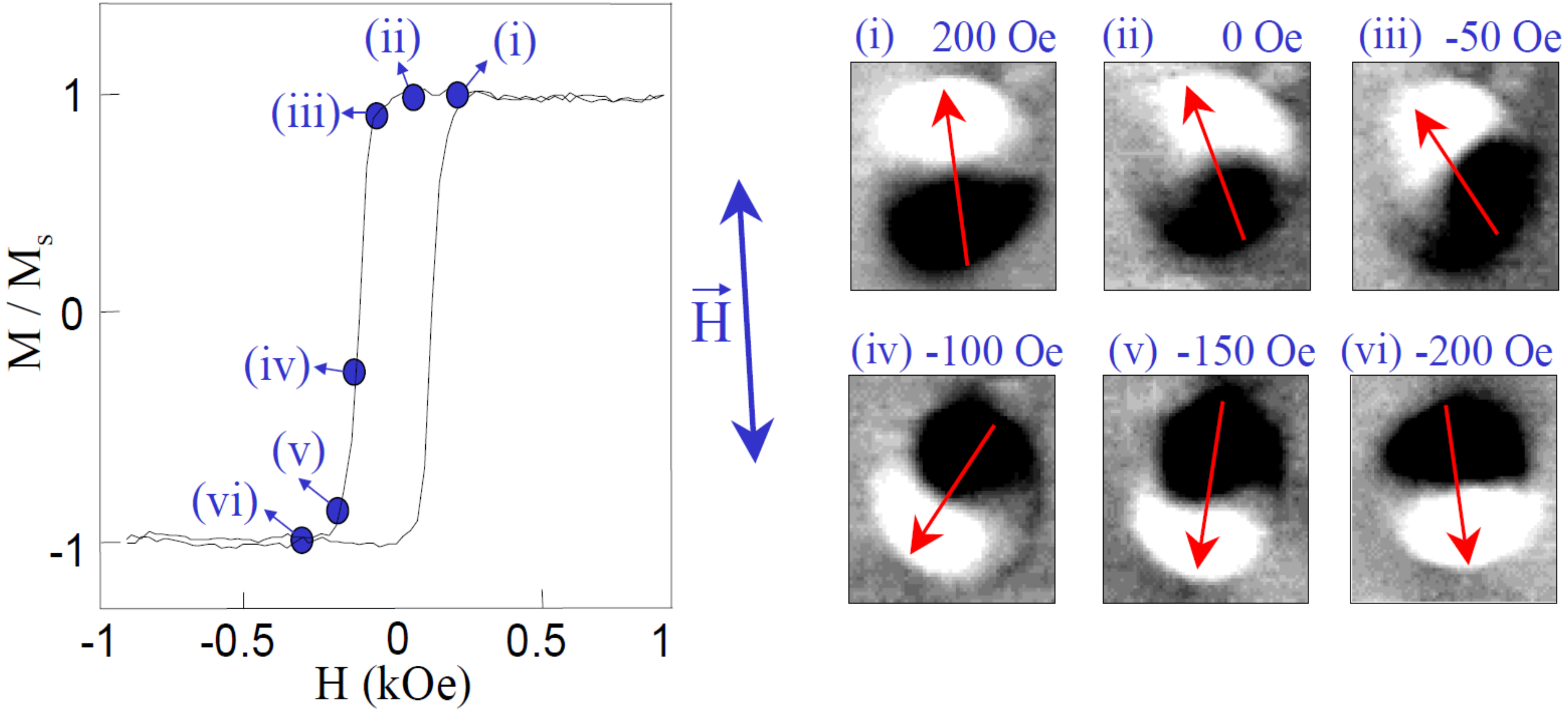
Fig. 3 Domain nucleation and growth in magnetic films with strong perpendicular anisotropy, together with the hysteresis loops along which the domains were imaged. **First row**: [Co (0.3 nm)/Pt (0.7 nm)]$_3$ multilayer (sample courtesy *D. Makarov*, Dresden). **Second row**: Pt (3 nm)/Co (1 nm)/Pt (1.5 nm) trilayer (sample courtesy *P.M. Shepley and T.A. Moore*, Leeds). **Third row**: FePt film, 16 nm thick (sample courtesy *P. He and S.M. Zhou*, Tongji [4]). **Fourth row**: FePd(11 nm)/FePt (24 nm) double layer (Sample courtesy *L. Ma and S.M. Zhou*, Tongji [3])

DW nucleation propagation

Hysteresis in nanostructures (1)

Finite size effects
Shape anisotropy is important

Co t=10 nm, diameter 500 nm



shape
Size
important

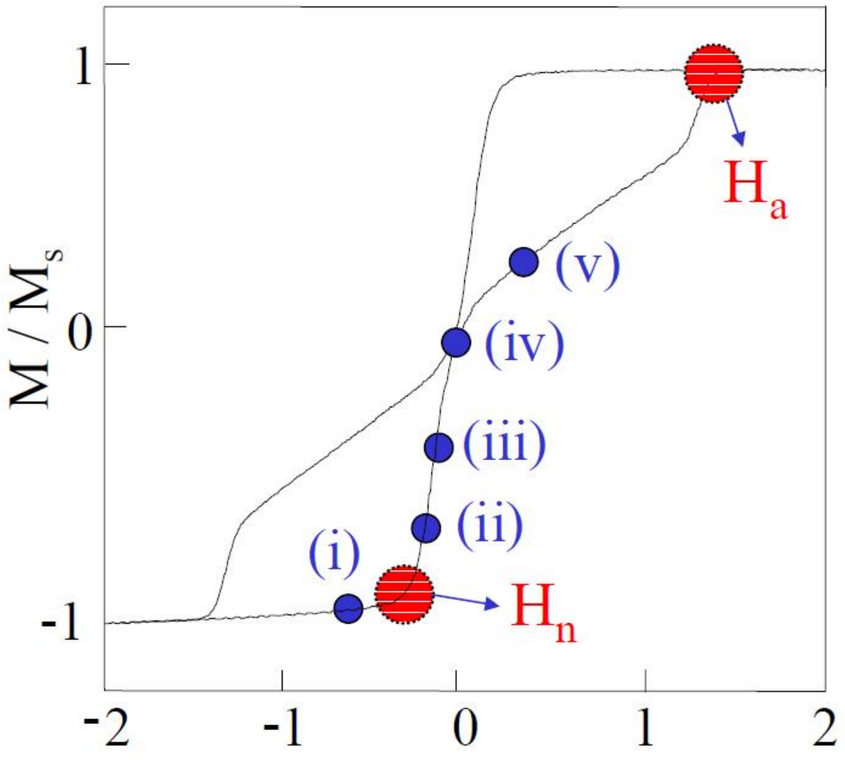
Stoner–
Wohlfarth
like

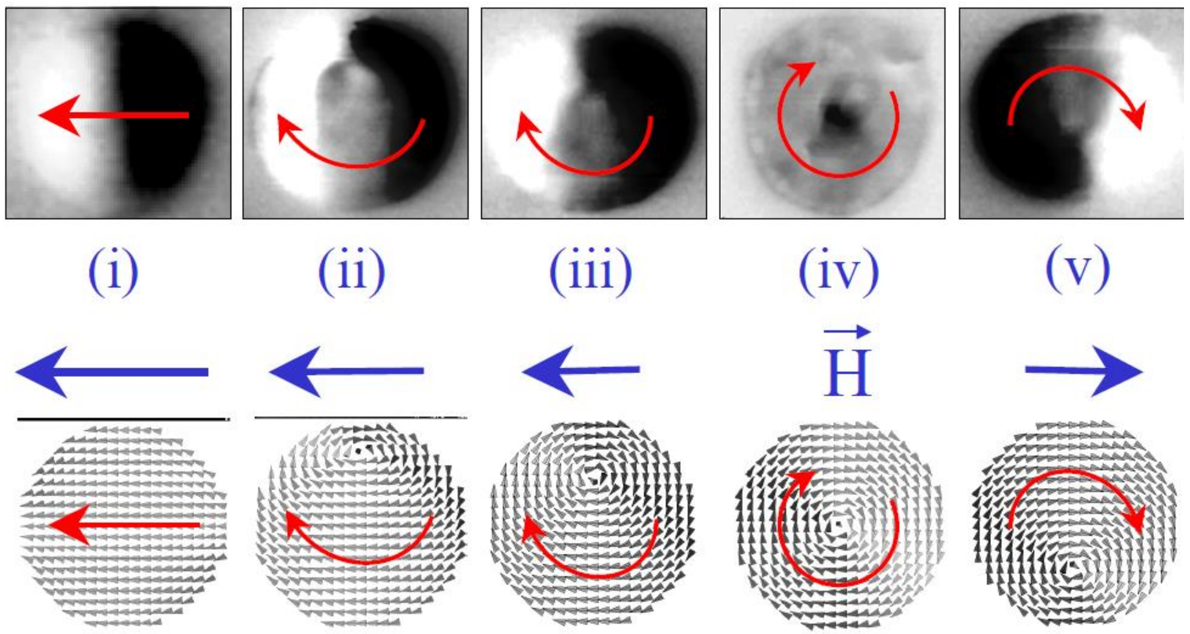
IL Prejbeanu PhD (Univ. Strasbourg 2001)

Hysteresis in nanostructures (2)

Finite size effects
Space to put "wall"

Co t=30 nm, diameter 500 nm

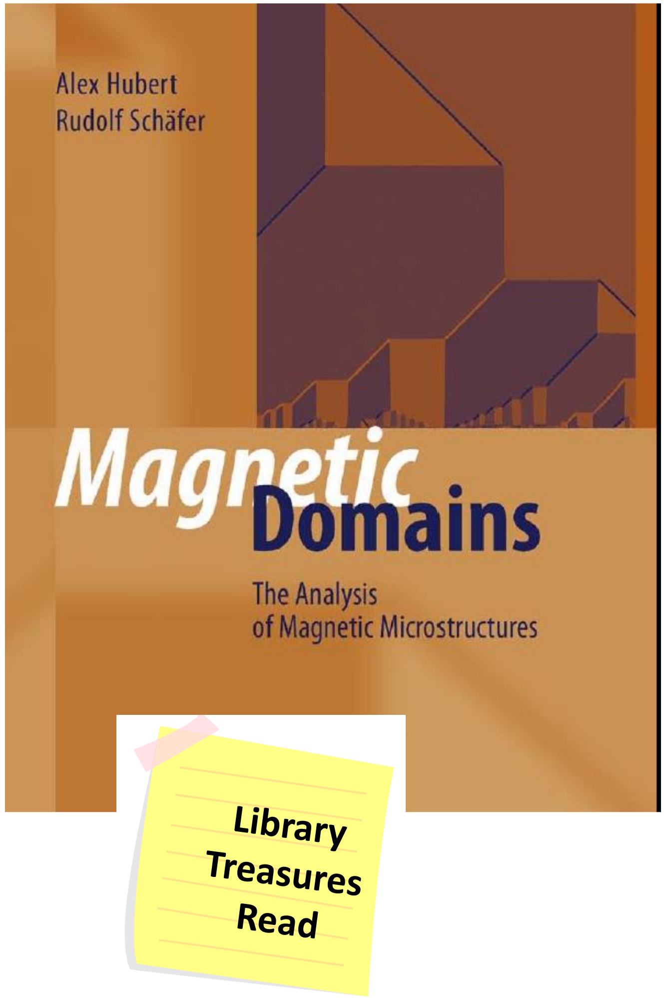


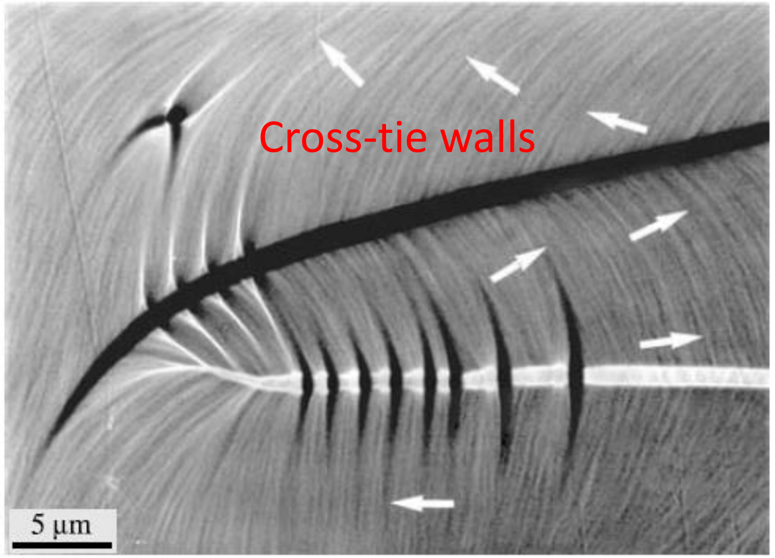


vortex =demag signature

IL Prejbeanu PhD (Univ. Strasbourg 2001)

A very good book





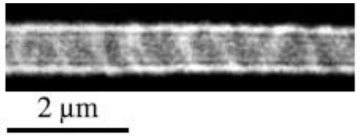


Fig. 2.26. Lorentz picture of a polycrystalline Permalloy film showing the streaky *ripple* texture perpendicular to the mean magnetization in the domains and *cross-tie* walls. The convergent wall displays diffraction fringes as shown in the enlargement. (Courtesy *S. Tsukahara* [261])

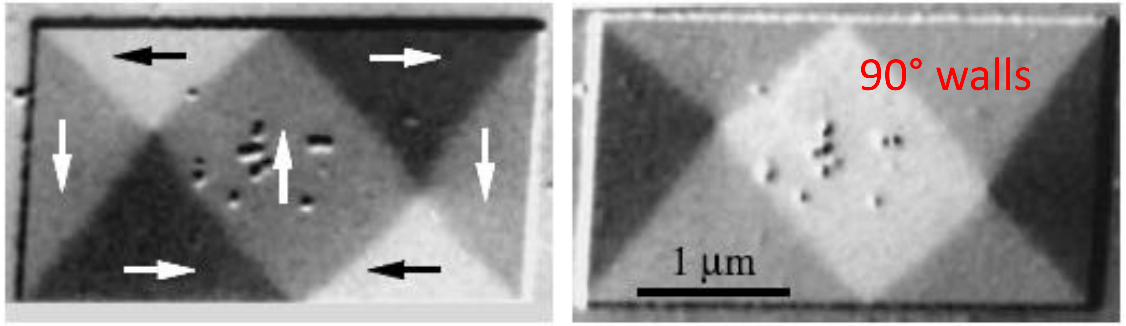
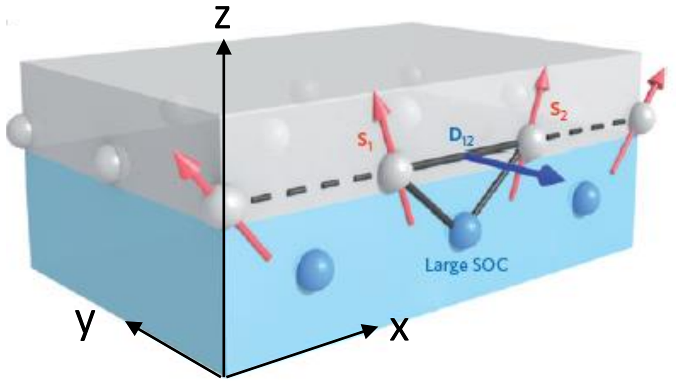


Fig. 2.30. Differential phase images showing orthogonal magnetization components of a Permalloy element of 60 nm thickness. (Courtesy *S. McVitie* and *J.N. Chapman* [273])

Interfaces and additional interaction

Dzyaloshinskii-Moriya interaction

Antisymmetric exchange / symmetry breaking

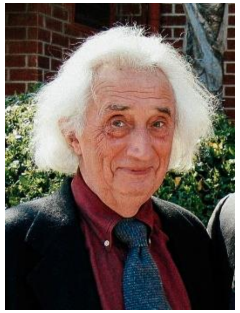


A Fert t al., Nature Nanotechnology (2013)

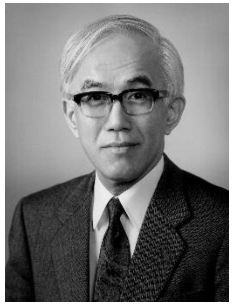
3-site indirect exchange mechanism between two atomic spins $\mathbf{S_1}$ and $\mathbf{S_2}$ with a neighboring atom with strong spin-orbit coupling :

$$H_{DM} = -\mathbf{D}_{12} \cdot (\mathbf{S}_1 \times \mathbf{S}_2)$$

Non collinear configuration



I. Dzyaloshinskii



T. Moriya

From a normal ferromagnetic state with $\mathbf{S_1}$ parallel with $\mathbf{S_2}$, the DMI tilts **S1** with respecte to $\mathbf{S_2}$ by a rotation around the $\mathbf{D_{12}}$.

Mott insulators, spin glasses, interfaces thin layers (top & bottom layers are important)

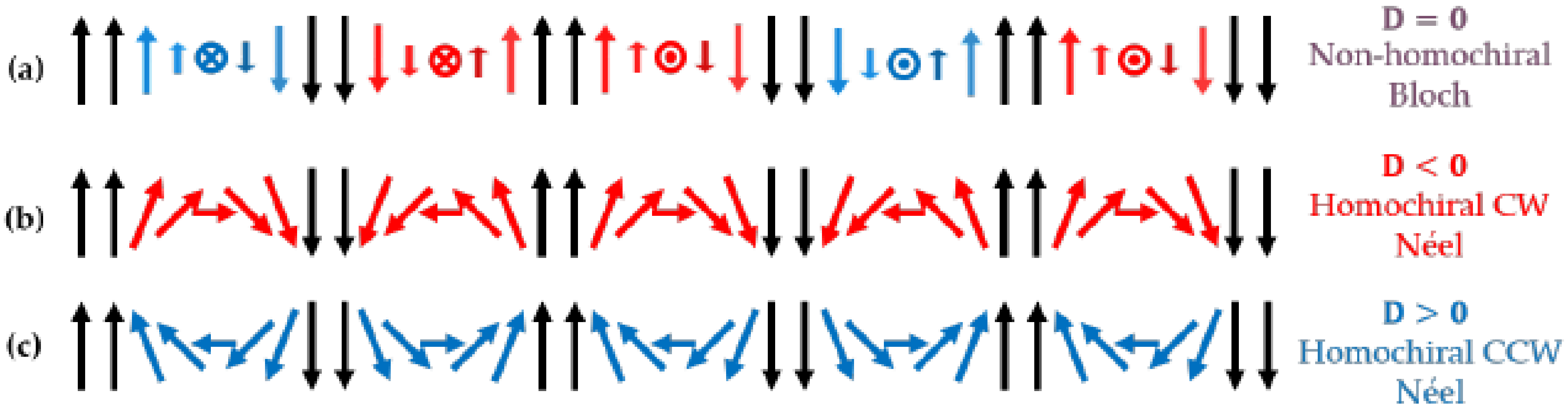
Pt /Co(0.6) /AlOx

Isotropic samples in-plane x0y $\quad \mathbf{D} = DM\left(\hat{\mathbf{z}} \times \hat{\mathbf{r}}_{12}\right)$

$$E_{DM}(\mathbf{m}) = \iiint \left[D\left(m_z \frac{\partial m_x}{\partial x} - m_x \frac{\partial m_z}{\partial x} \right) + D\left(m_z \frac{\partial m_y}{\partial y} - m_y \frac{\partial m_z}{\partial y} \right) \right] dV$$

A. Thiaville et al., Europhys. Lett., (2013)

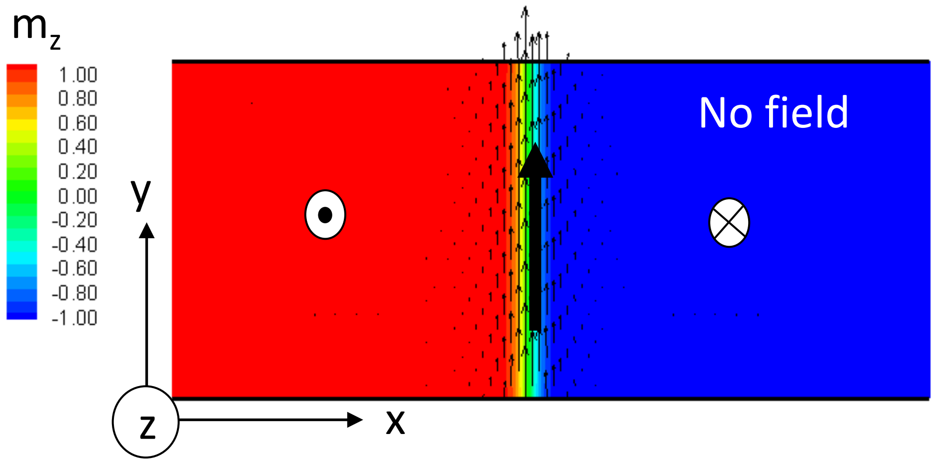
Dzyaloshinskii Moriya wall (3rd type)

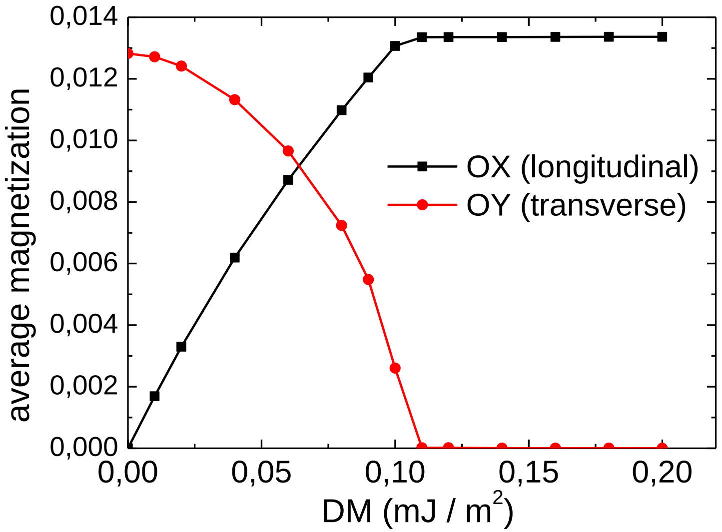


DMI sign!

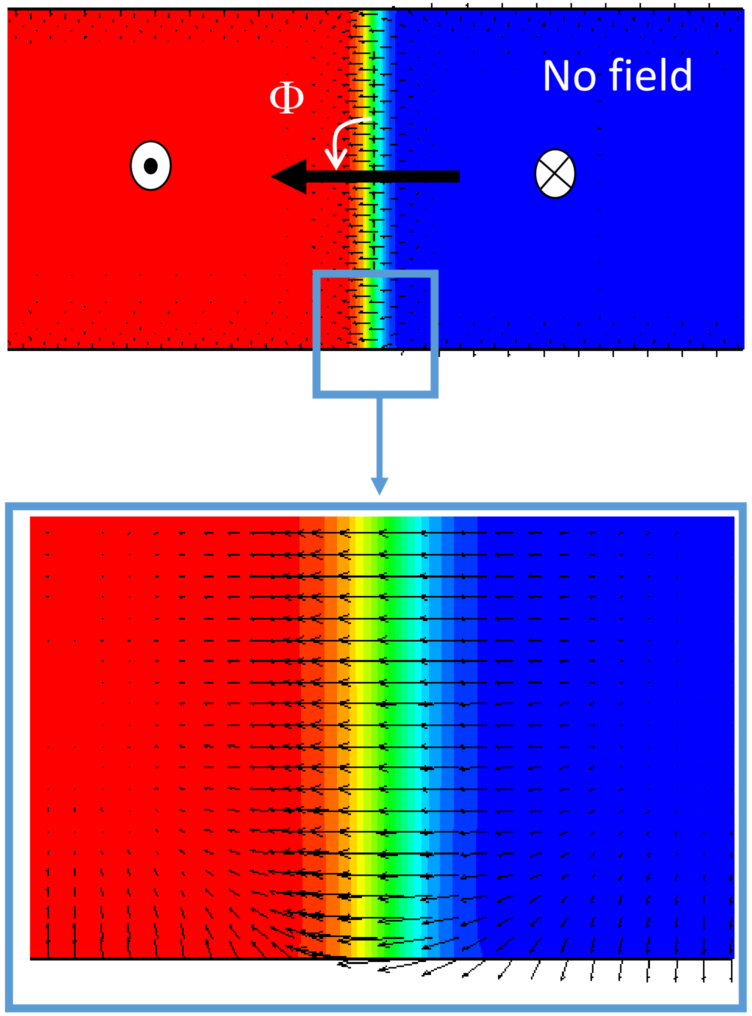
Dzyaloshinskii Moriya wall (3rd type)

no DMi





Large DM=2.0 mJ/m²



Co (0.6*nm*) parameters

$M_S = 1090kA/m$

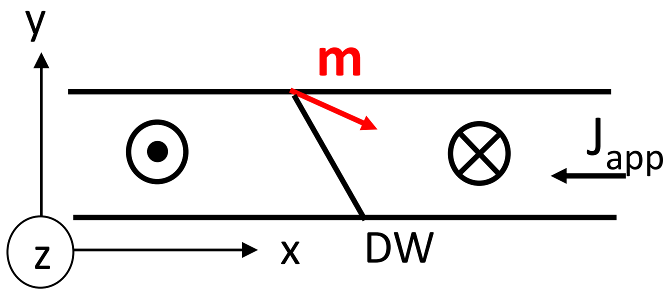
$K_U = 1245\ kJ/\ m^3$

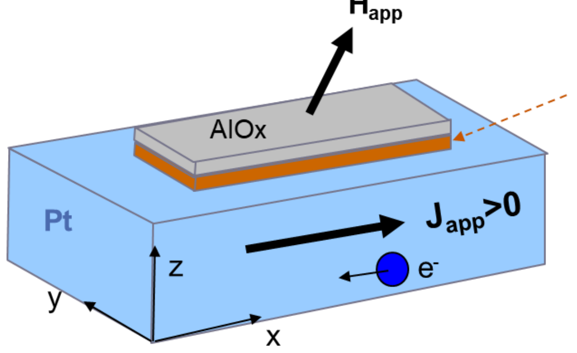
$A_{ex} = 10pJ/m$

$\Delta = 2.8\ \ nm$

$l_{ex} = 3.66\ nm$

DW dynamics - basics





LLG equation – describing the dynamics (phenomenologically)
- includes many terms

$$\frac{d\boldsymbol{m}}{dt} = -\gamma_0(\boldsymbol{m}\times\boldsymbol{H_{eff}}) + \boldsymbol{\alpha}\left(\boldsymbol{m}\times\frac{d\boldsymbol{m}}{dt}\right)$$

Precession + Damping (α)

$$\boldsymbol{H_{eff}} = \boldsymbol{H_{ex}} + \boldsymbol{H_{DMI}} + \boldsymbol{H_K} + \boldsymbol{H_{dem}} + \boldsymbol{H_{app}}$$

$$+\ (\boldsymbol{u}\cdot\nabla)\boldsymbol{m} - \beta(\boldsymbol{m}\times(\boldsymbol{u}\cdot\nabla)\boldsymbol{m})$$

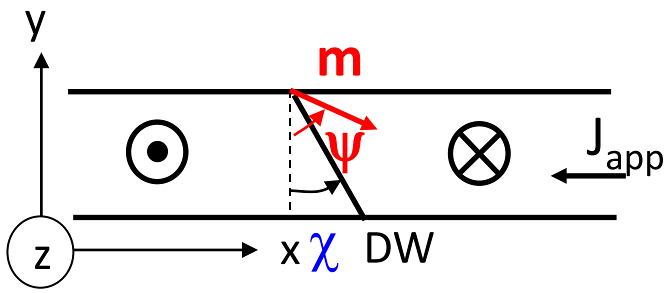
STT Levy-Zhang term, e flow in a gradient of magnetization
$u \sim J_{app}$

$$-\gamma_0 H_{DL}(\boldsymbol{m}\times(\boldsymbol{m}\times\hat{\boldsymbol{y}})) + \gamma_0 H_{FL}(\boldsymbol{m}\times\hat{\boldsymbol{y}})$$

SOT terms
Spin Hall Effect, Rashba effect
Damping-like and Field like
$\sim J_{app}$

LLG enhanced!

DW dynamics - basics



$$\theta(x) = 2atan\left(e^{\frac{x-q}{\Delta(\psi)}}\right)$$

- The DW is described by 3 variables (q, ψ, χ), w is the width of track
- A standard Bloch DW profile is assumed
- no STT Levy-Zhang, no FL
- DMI is included by adding the term - πD sin(ψ-χ) in the DW energy
- Dynamical equations are derived using a Lagrangian approach

$$\frac{d\psi}{dt} + \frac{\alpha\, cos\chi}{\Delta}\frac{dq}{dt} = \gamma_0 H_z + \frac{\pi}{2}\gamma_0 H_{DL} sin\psi$$

$$\frac{dq}{dt}\frac{cos\chi}{\Delta} - \alpha\frac{d\psi}{dt} = \frac{1}{2}\gamma_0 H_K sin2(\psi-\chi) + \frac{\pi D\gamma_0}{2\mu_0 M_S\Delta}cos(\psi-\chi) - \frac{1}{2}\gamma_0 H_y sin\psi$$

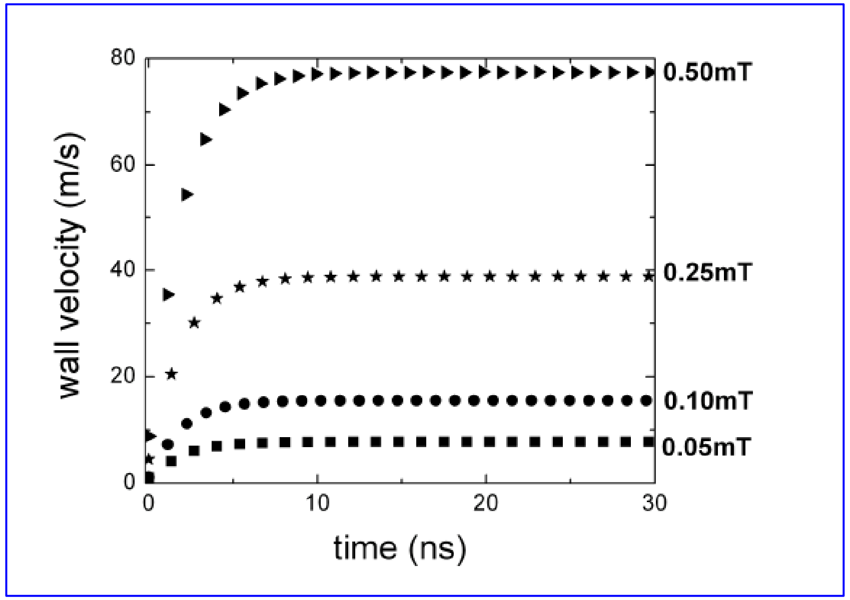
$$\frac{d\chi}{dt}\frac{\alpha\mu_0 M_S\Delta\pi^2}{6\gamma_0}\left(tan^2\chi + \left(\frac{w}{\pi\Delta}\right)^2\frac{1}{cos^2\chi}\right) = -\sigma tan\chi + \pi D cos(\psi-\chi) + \mu_0 H_K M_S\Delta\, sin2(\psi-\chi)$$

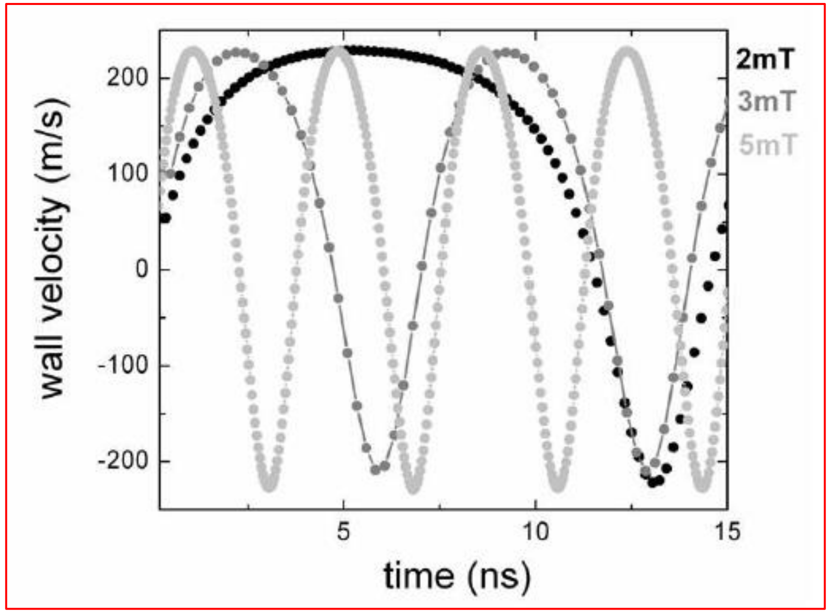
DW tilt due DMI

[Boulle *et al.*, JAP, **112**, *053901* (2012)]

DW dynamics - Hz

No DMI



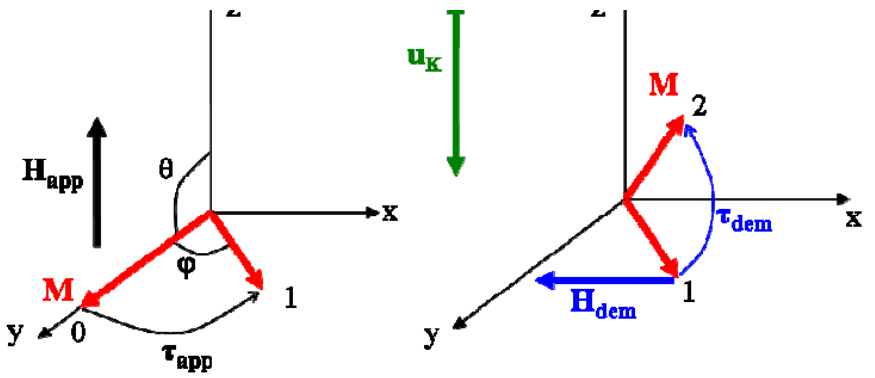


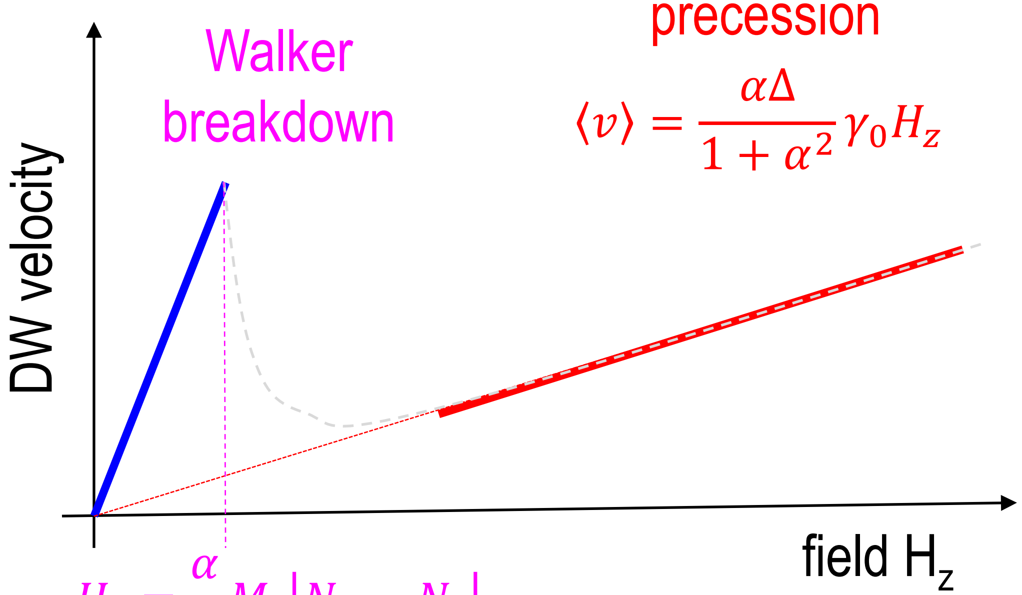
translation

$$v = \frac{\Delta}{\alpha}\gamma_0 H_z$$

precession

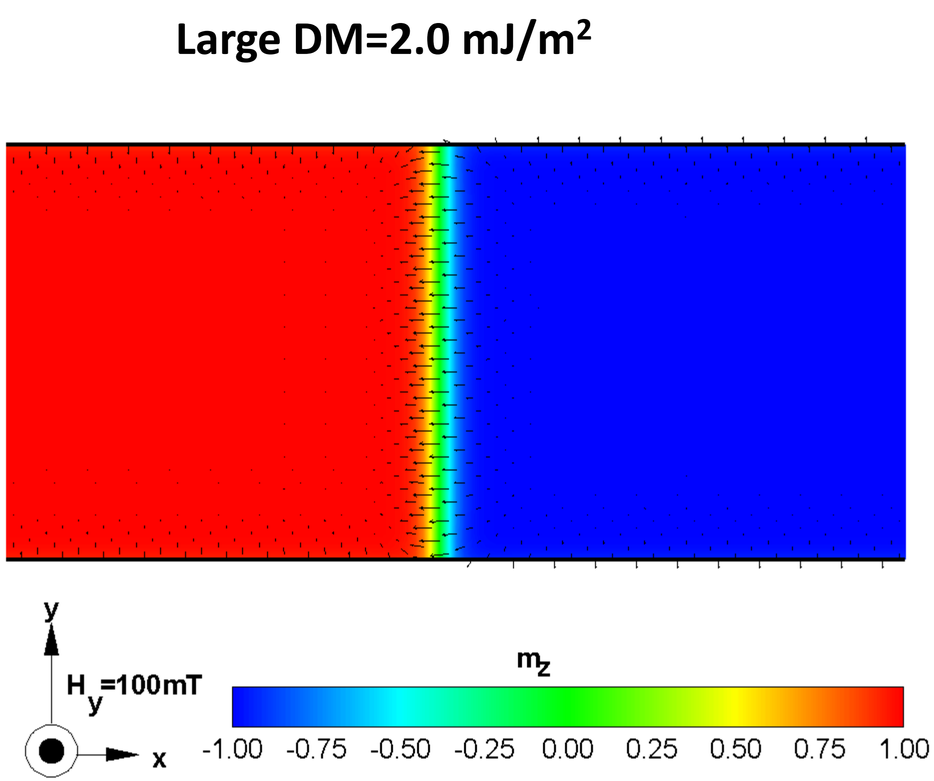
$$\langle v \rangle = \frac{\alpha\Delta}{1+\alpha^2}\gamma_0 H_z$$

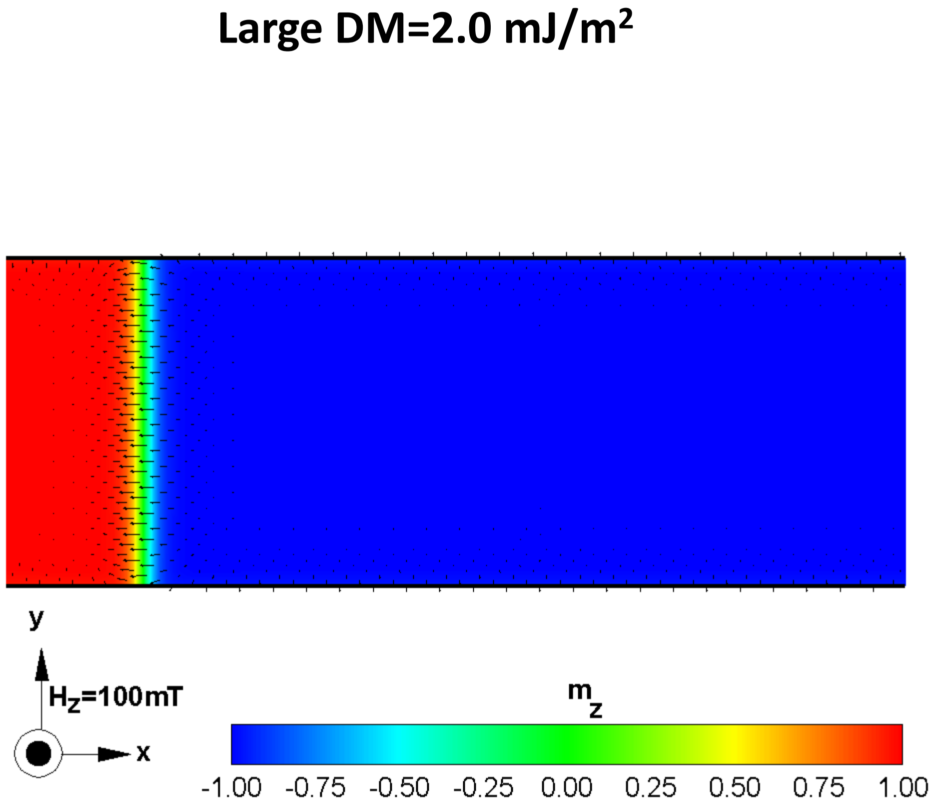




$$H_c = \frac{\alpha}{2} M_S |N_y - N_z|$$

Dzyaloshinskii Moriya wall (3^{rd} type)

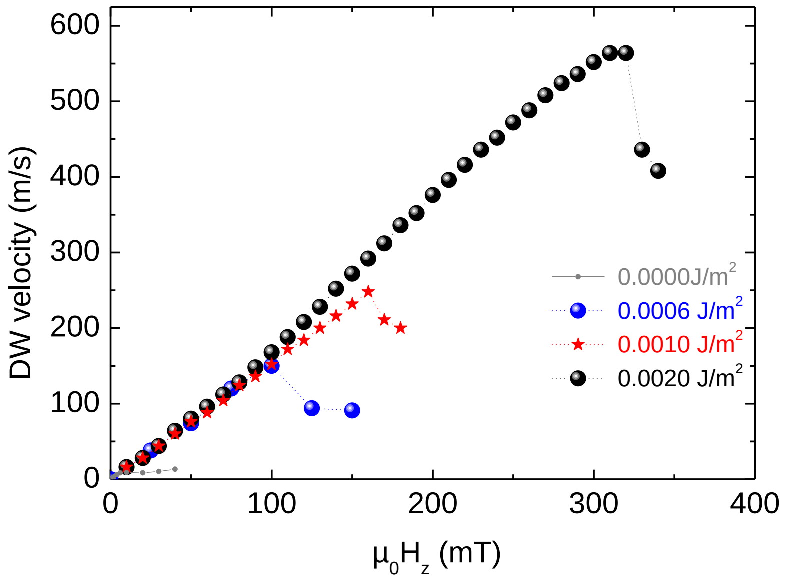


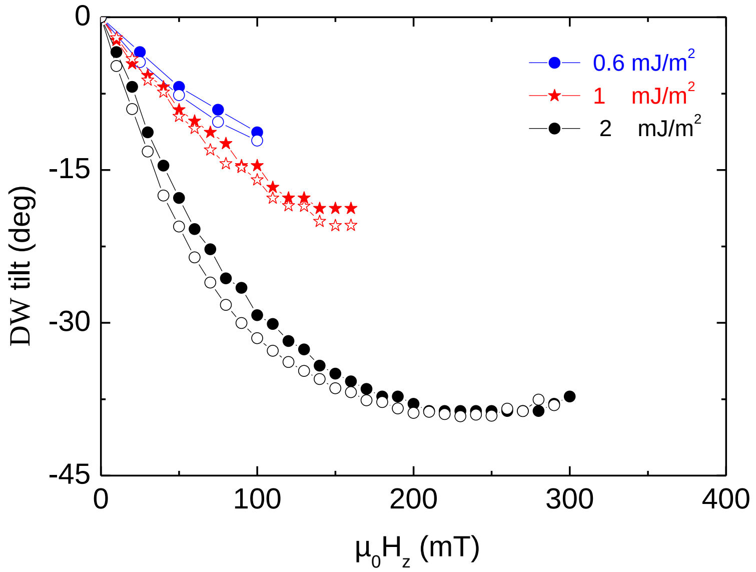


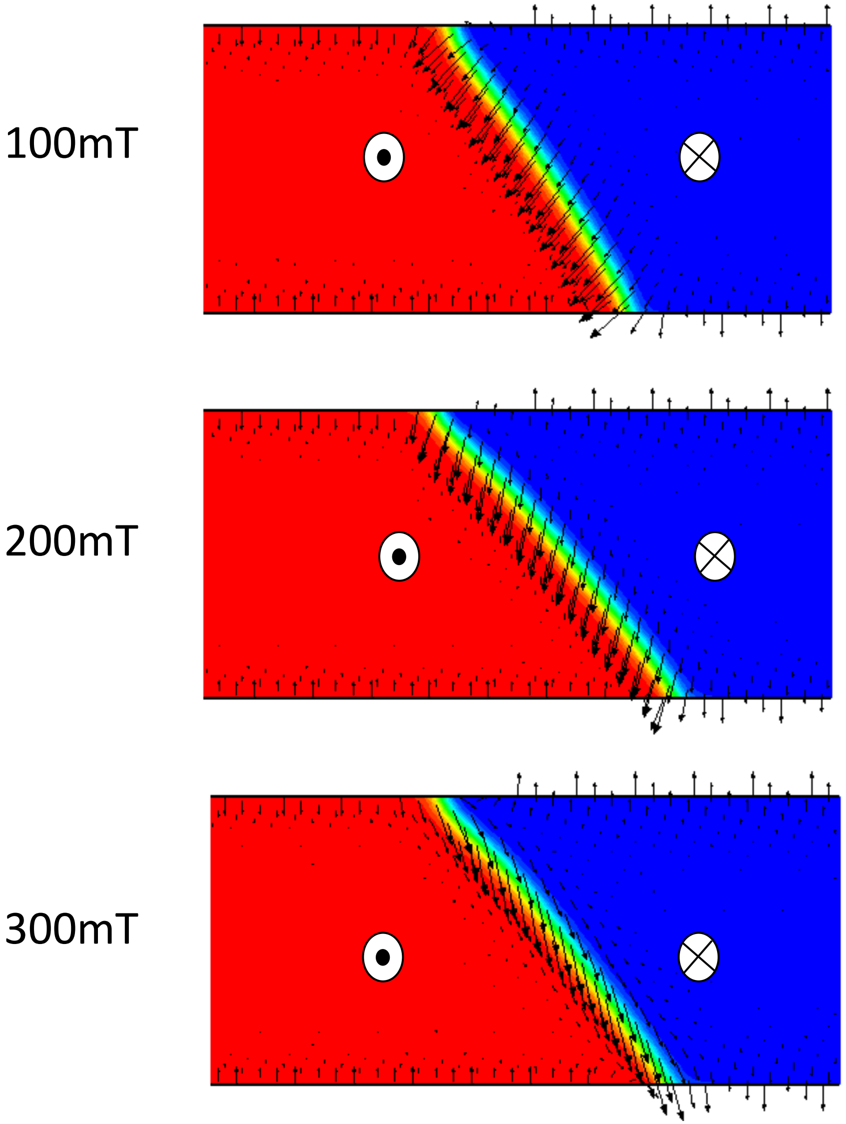
deformation static

Dw tilt motion

Dzyaloshinskii Moriya wall – control by applied field

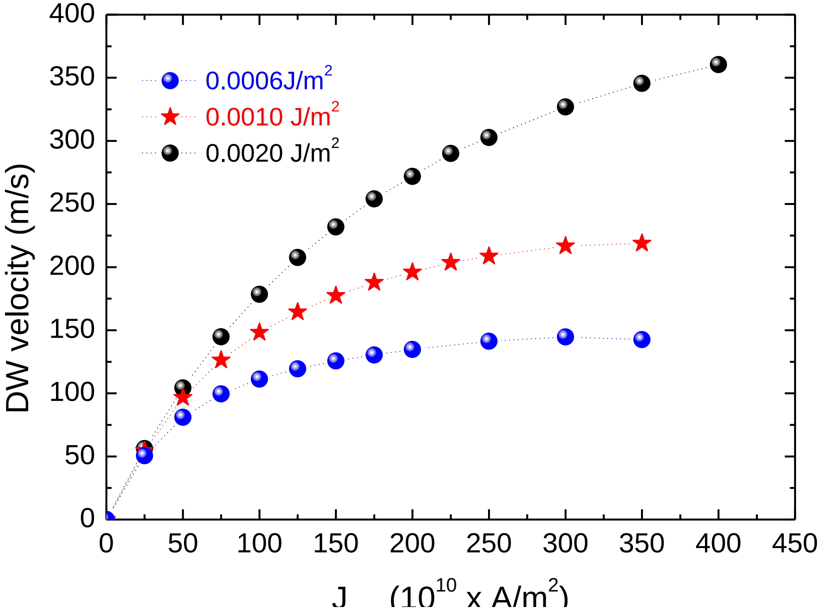


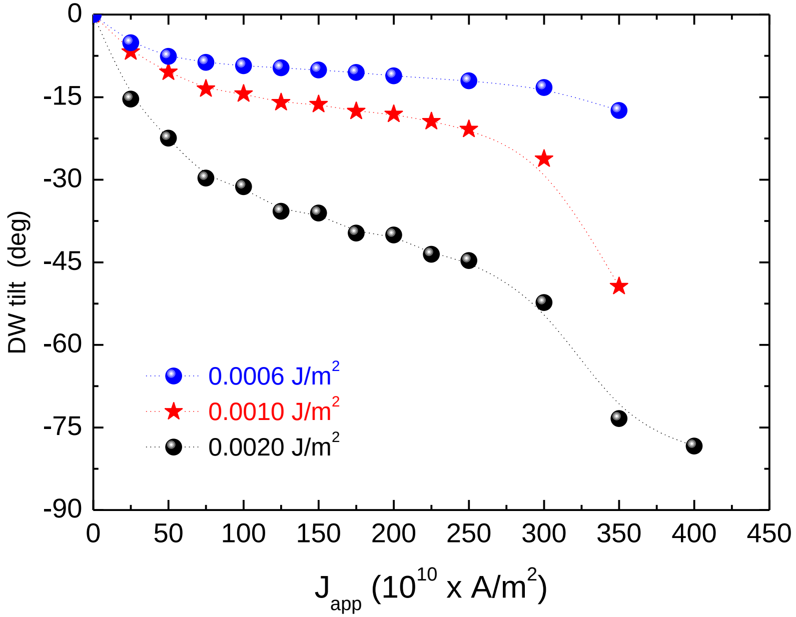


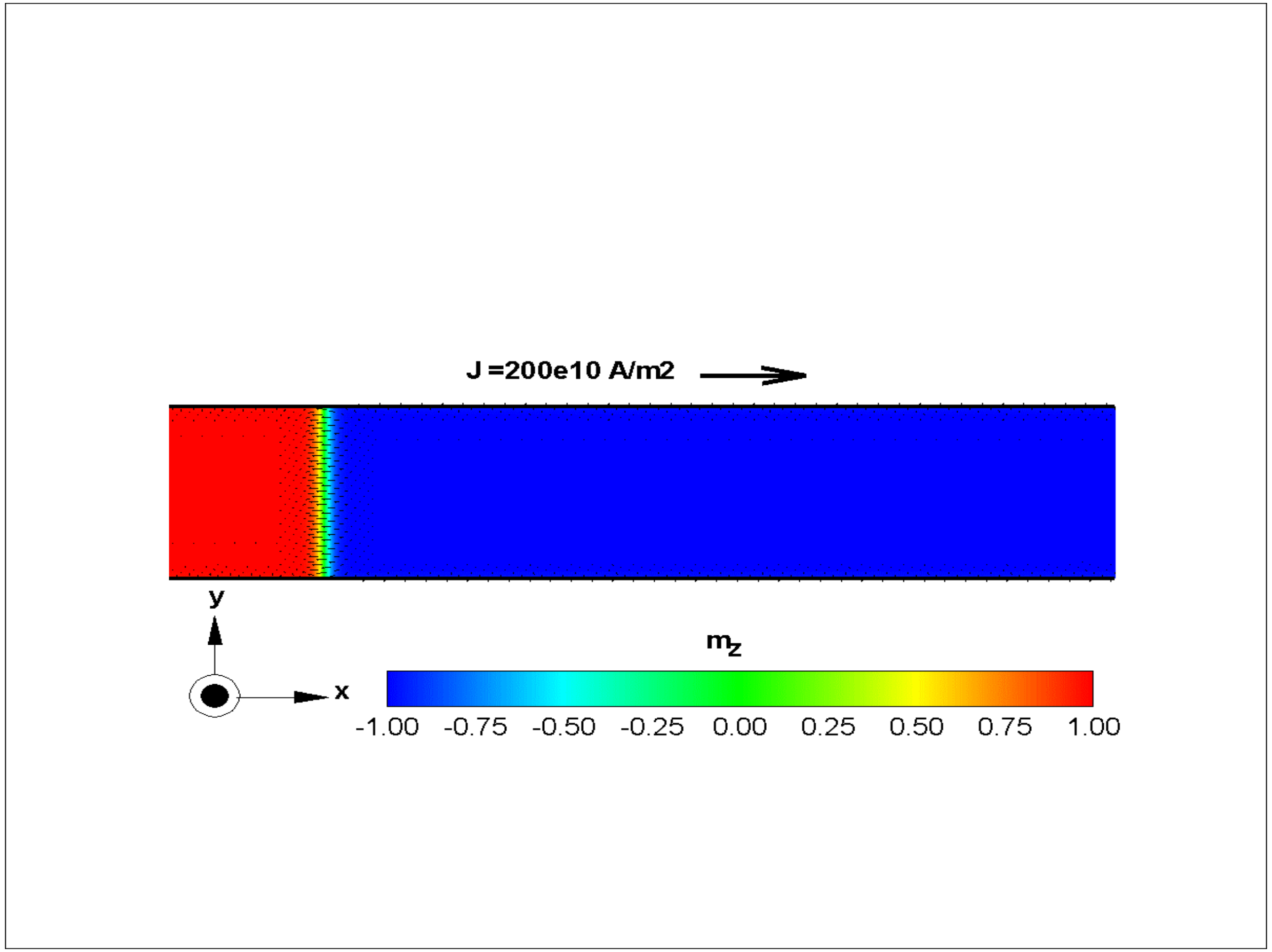


Elastic Internal structure! Very large speed!

Dzyaloshinskii Moriya wall – control by SOT





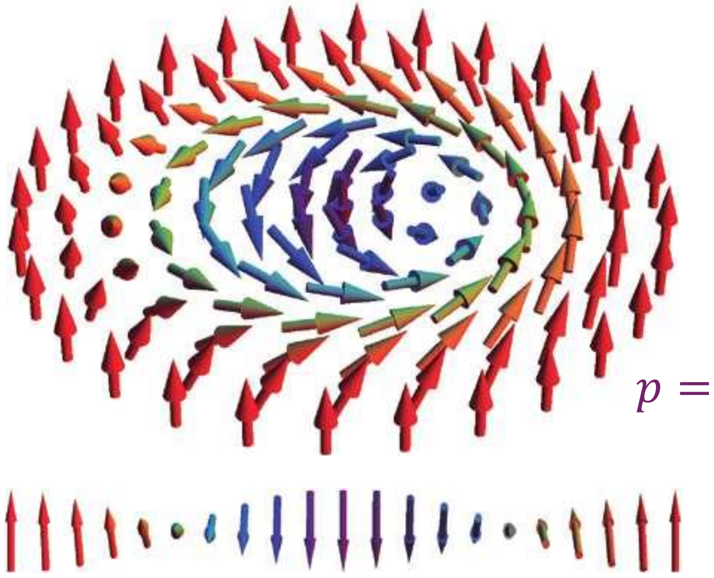


Elastic Internal structure! Very large speed!

Skymions – topological twists

T.H.R. SKYRME

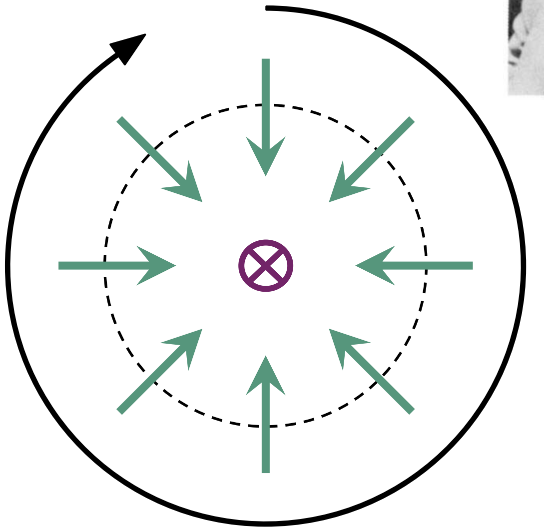
Magnetic skyrmion = small, 2D, circular domain enclosed by a <u>chiral</u> DW



Bloch skyrmion

$p = -1$

Néel skyrmion



Topological charge: $N_{sk} = \frac{1}{4\pi} \iint \boldsymbol{m} \cdot \left(\frac{\partial \boldsymbol{m}}{\partial x} \times \frac{\partial \boldsymbol{m}}{\partial y} \right) dxdy \;\; = p \cdot W$ ⟹ $\boldsymbol{N_{sk} = p = \pm 1}$

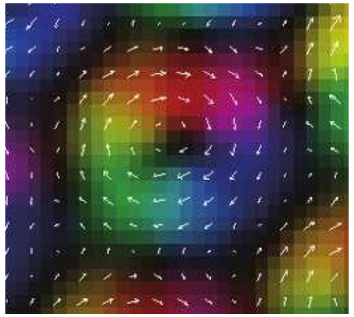
Winding number (W)

Core polarity (p)

Skymions – real sample

Bulk crystals

FeGe **[1]**

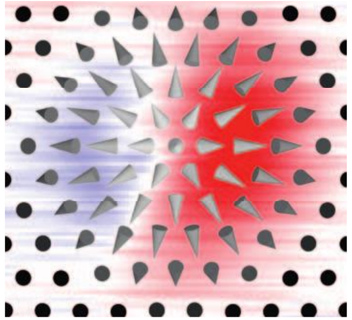


40 nm

- Bloch skyrmions
- Size = 20 nm – 90 nm
- $T < 300\ K$
- Bulk inversion asymmetry

Ultra-thin epitaxial films

Ir(111)/PdFe **[2]**

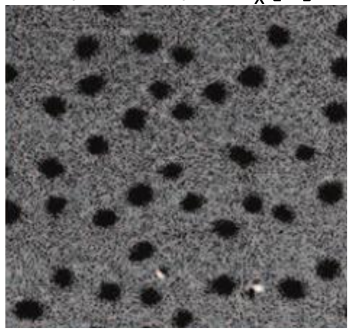


~ 2 nm

- Néel skyrmions
- Size < 10 nm
- $T \sim 5\ K$
- Structural inversion asymmetry

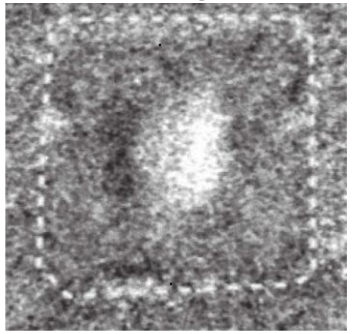
Ultra-thin sputtered films

Ta/FeCoB/TaO_x **[3]**



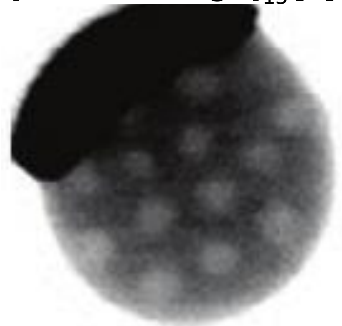
20 µm

Pt/Co/MgO **[4]**



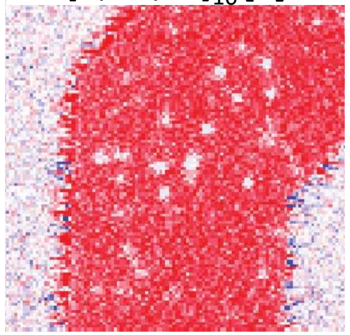
200 nm

$[Pt/CoFeB/MgO]_{15}$ **[5]**



500 nm

$[Ir/Co/Pt]_{10}$ **[6]**

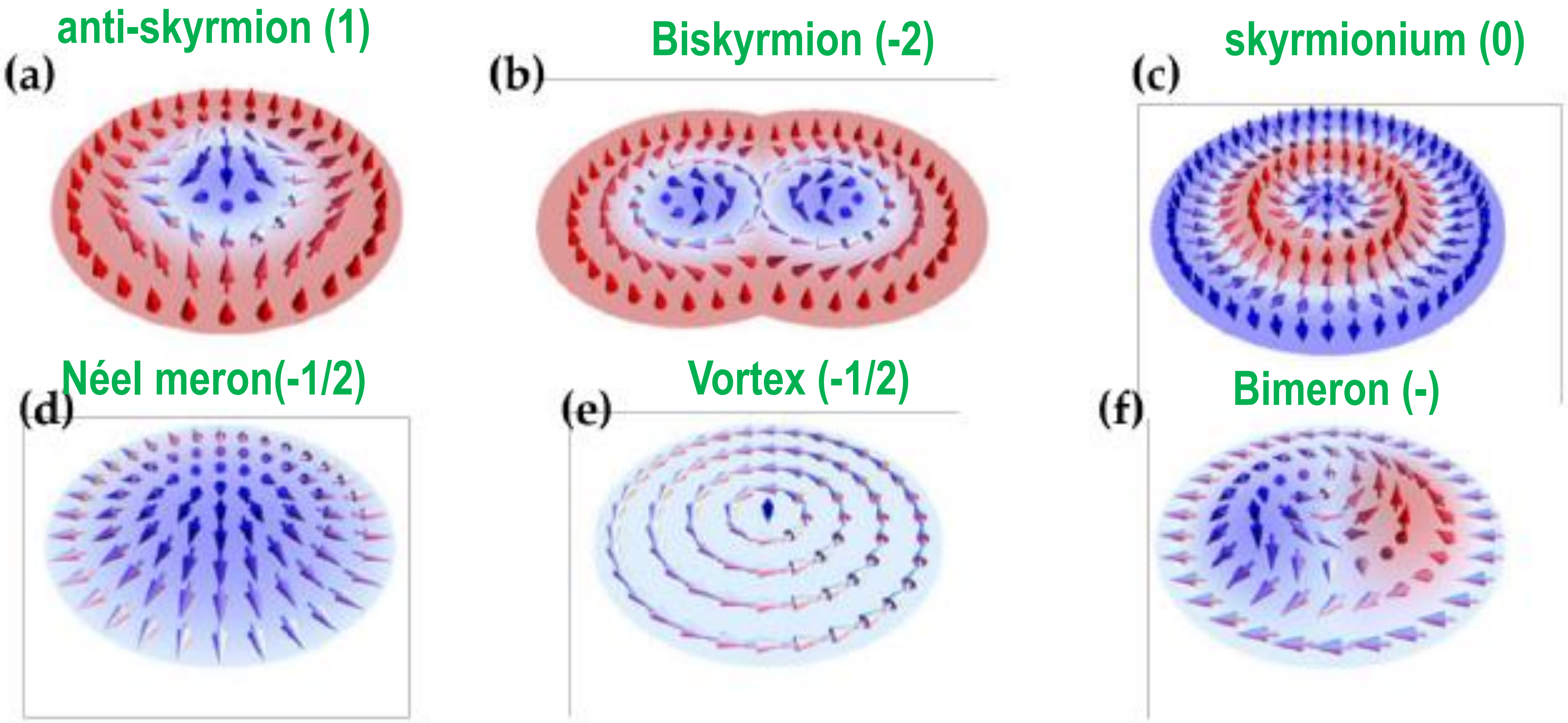


500 nm

- Néel skyrmions
- Size = 30 nm – 2 µm
- $T = 300\ K$
- Structural inversion asymmetry

[1] Yu *et al.*, Nat. Mater. **10**,106 (2011) **[2]** Romming *et al.*, Science **341**,636 (2013) **[3]** Jiang *et al.*, Science **349**,283 (2015)
[4] Boulle *et al.*, Nat. Nanotech. **11**,449 (2016) **[5]** Woo *et al.*, Nat. Mater. **15**,501 (2016) **[6]** Moreau-Luchaire *et al.*, Nat. Mater. **11**,444 (2016)

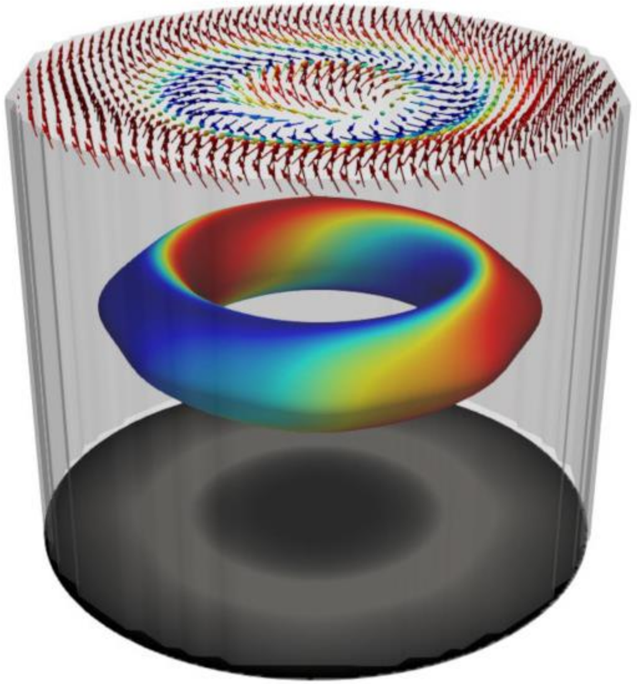
Spin textures – 2D



Large variety

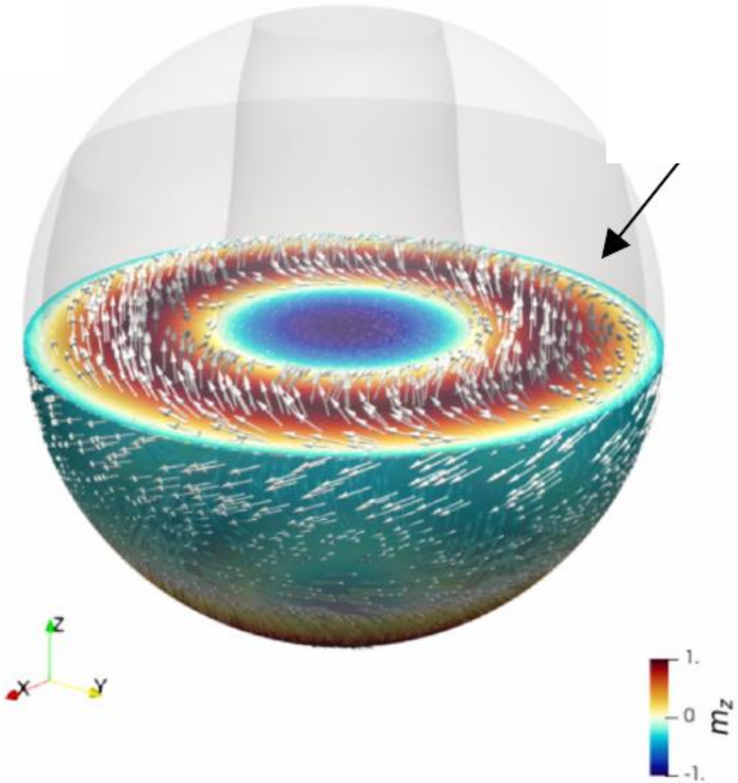
Spin textures - 3D

hopfion

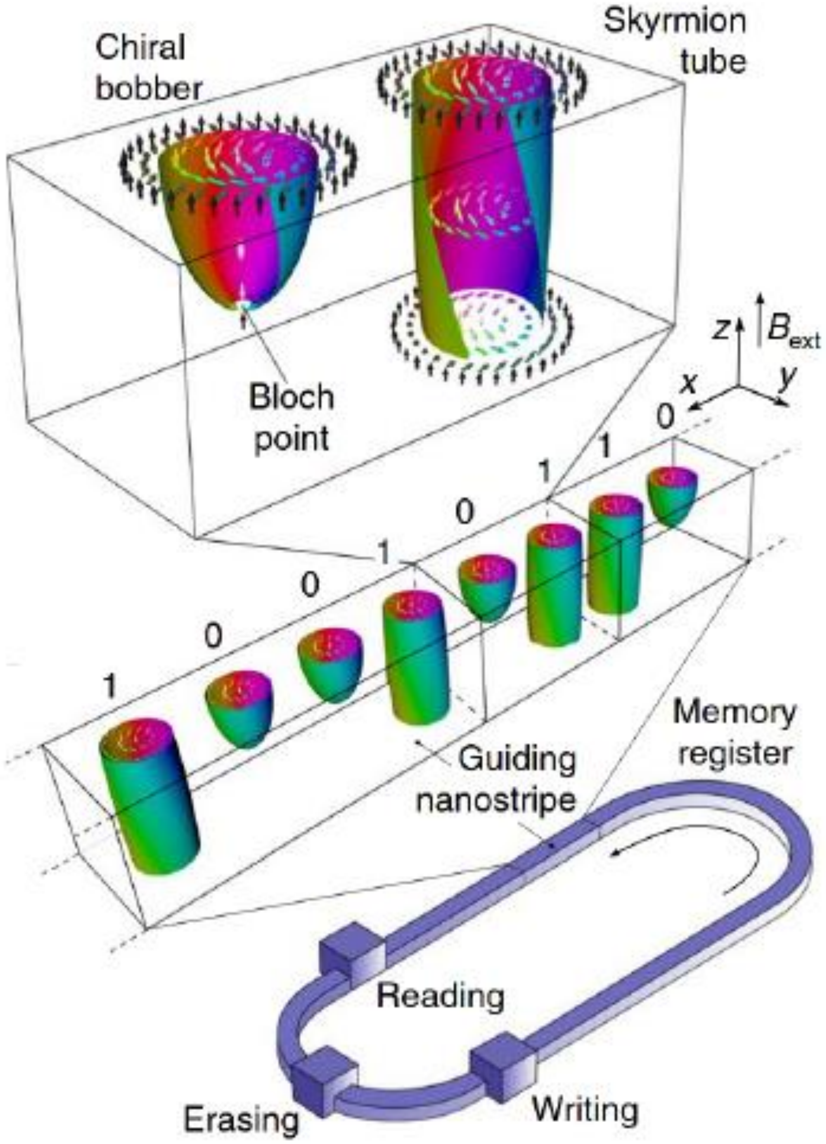


https://newscenter.lbl.gov/2021/04/08/spintronics-tech-a-hopfion-away/

3D skrmion



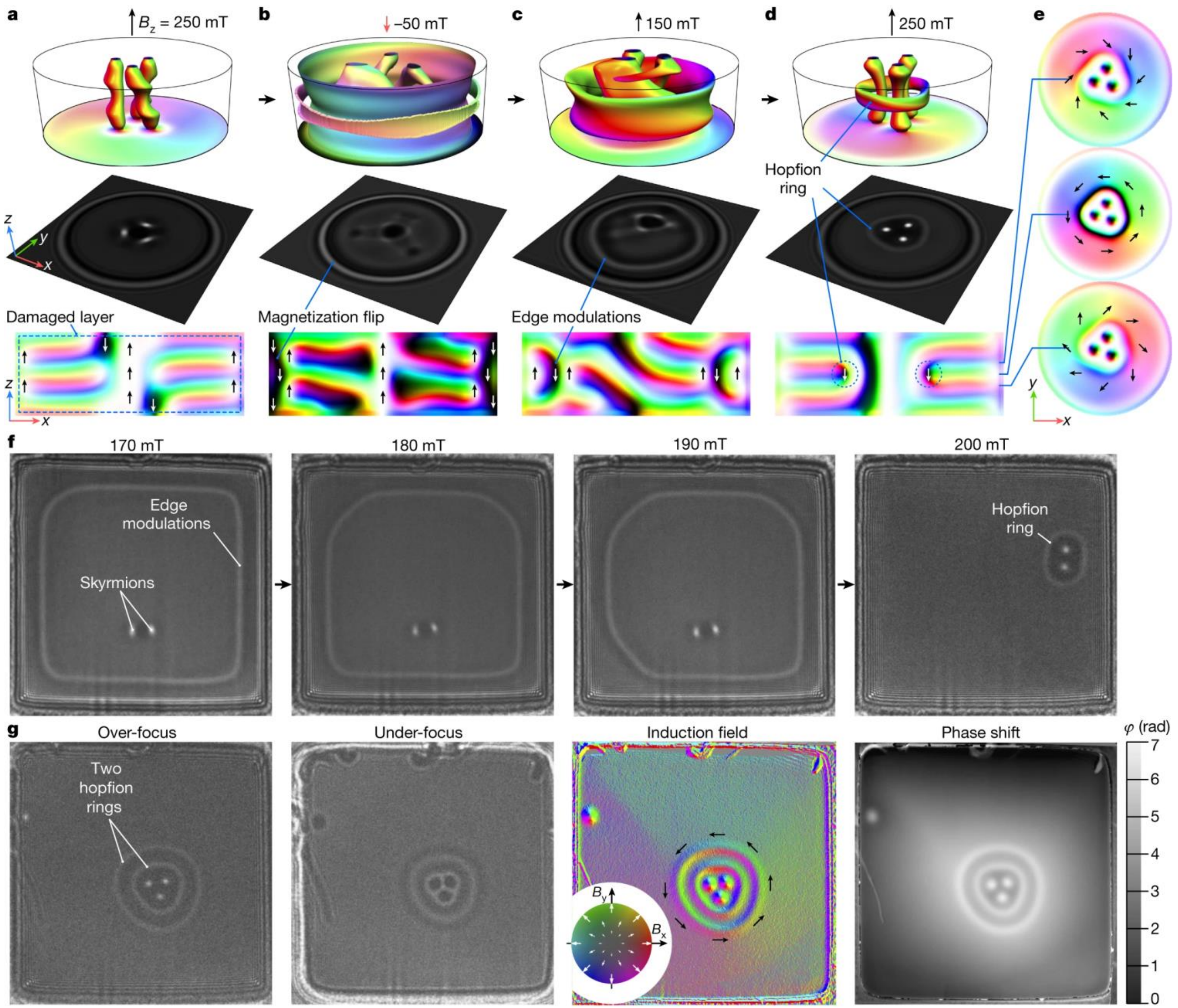
Swapneel PATHAK
PhD Univ. Strasbourg (2021)



F. Zheng et al., *Nat. Nanotechnol.*, **13**, 451 (2018)

Spin textures – 3D

Hopfion rings on skyrmion strings in FeGe samples of confined geometry.



Experimental over-focus Lorentz images recorded in an FeGe plate of dimensions 1 µm × 1 µm and with a thickness of 180 nm.

Zheng et al. *Nature* **623**, 718–723 (2023)

Spin textures - 3D

3D exotic shapes

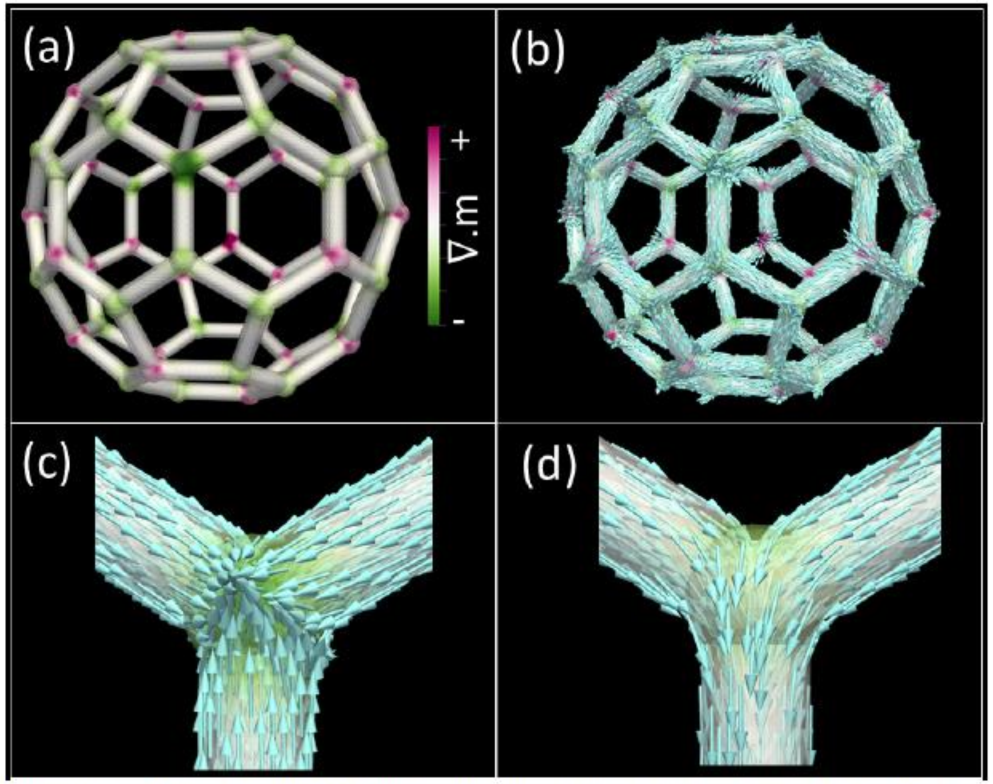
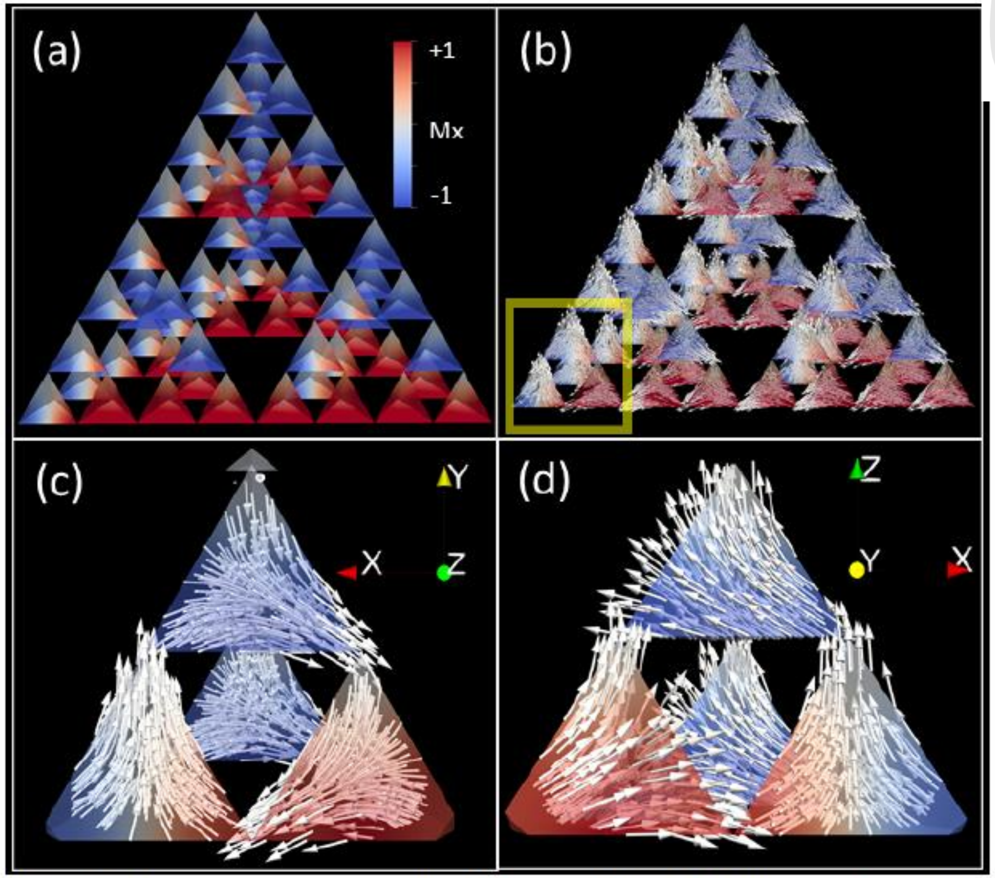
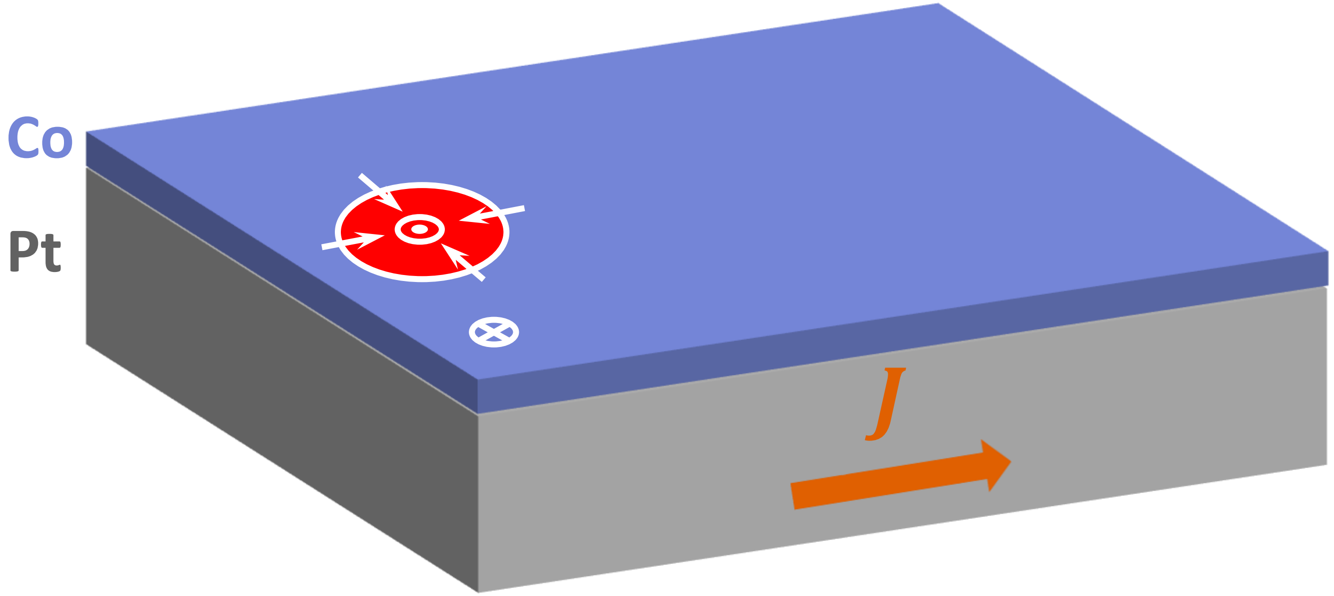


Figure 6.22: Relaxed magnetization structure of a hollow buckyball with side length, $L = 100\,\mathrm{nm}$ (a) the charges at vertices are visualized by plotting the volume charge density $\nabla \cdot \boldsymbol{m}$ (b) The local magnetization is plotted by means of arrows (c) Zoomed-in view of one of the triple charged vertices (d) Zoomed-in view of a single charge vertex structure.

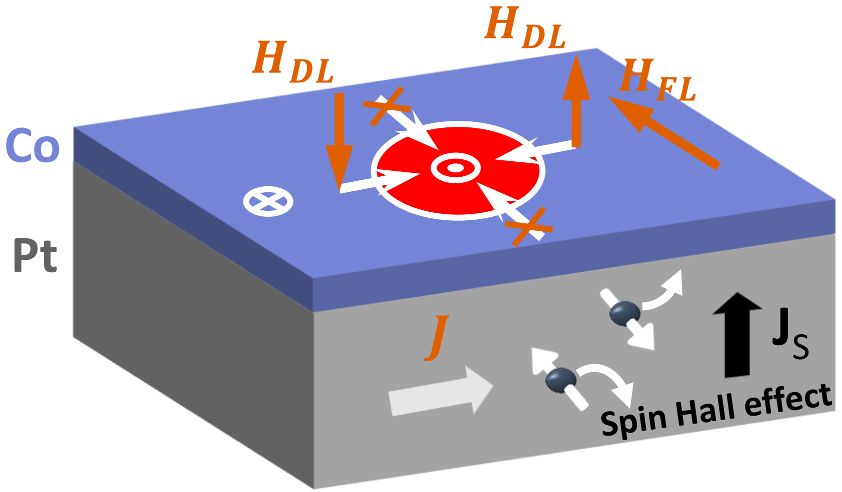


Rajgowrav CHEENIKUNDIL PhD Univ. Strasbourg (2021)

Skymions – SOT driven dynamics



Skymions – SOT driven dynamics



Current J flows in the stack → spin Hall + Rashba effects

→ **spin-orbit torque (SOT)**

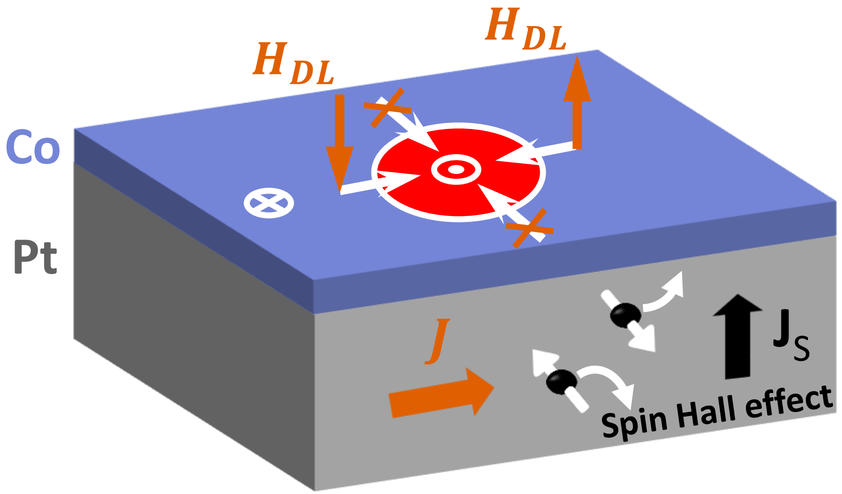
- Damping-like torque (DL)

$$\boldsymbol{T}_{DL} = -\gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{DL}), \quad \mu_0\boldsymbol{H}_{DL} = C_{DL}J[(\hat{\boldsymbol{z}} \times \hat{\boldsymbol{j}}) \times \boldsymbol{m}]$$

- Field-like torque (FL)

$$\boldsymbol{T}_{FL} = -\gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{FL}), \quad \mu_0\boldsymbol{H}_{FL} = C_{FL}J(\hat{\boldsymbol{z}} \times \hat{\boldsymbol{j}})$$

Skymions – SOT driven dynamics



Current J flows in the stack → spin Hall + Rashba effects
→ **spin-orbit torque (SOT)**

- Damping-like torque (DL)

$$\boldsymbol{T}_{DL} = -\gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{DL}), \quad \mu_0 \boldsymbol{H}_{DL} = C_{DL} J[(\hat{\boldsymbol{z}} \times \hat{\boldsymbol{j}}) \times \boldsymbol{m}]$$

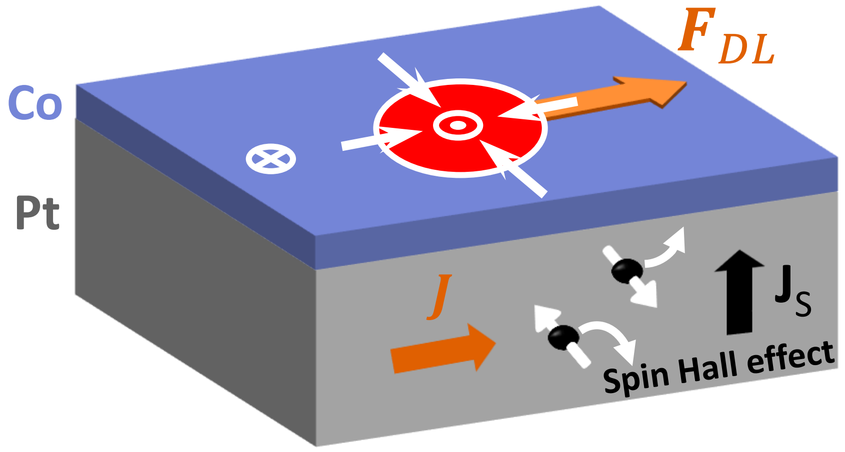
Landau-Lifshitz-Gilbert equation:

$$\frac{\partial \boldsymbol{m}}{\partial t} = -\gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{eff}) + \alpha\left(\boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t}\right) - \gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{DL})$$

⇩ *Rigid skyrmion*

Thiele equation: $\boldsymbol{F}_{DL} + \boldsymbol{G} \times \boldsymbol{v} - \alpha \boldsymbol{D} \boldsymbol{v} = \boldsymbol{0}$

Skymions – SOT driven dynamics



Current J flows in the stack → spin Hall + Rashba effects
→ **spin-orbit torque (SOT)**

- Damping-like torque (DL)

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Landau-Lifshitz-Gilbert equation:

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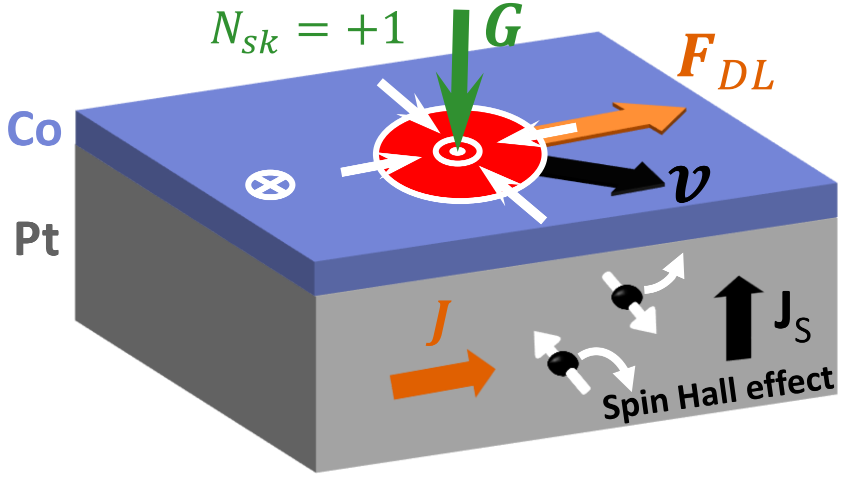
⇩ *Rigid skyrmion*

Thiele equation: $\boldsymbol{F}_{DL} + \boldsymbol{G} \times \boldsymbol{v} - \alpha \boldsymbol{D} \boldsymbol{v} = \boldsymbol{0}$

Skymions – SOT driven dynamics



Current $\boldsymbol{J}$ flows in the stack → spin Hall + Rashba effects
→ **spin-orbit torque (SOT)**

- Damping-like torque (DL)

$$\boldsymbol{T}_{DL} = -\gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{DL}), \quad \mu_0\boldsymbol{H}_{DL} = C_{DL}J[(\hat{\boldsymbol{z}} \times \hat{\boldsymbol{j}}) \times \boldsymbol{m}]$$

Landau-Lifshitz-Gilbert equation:

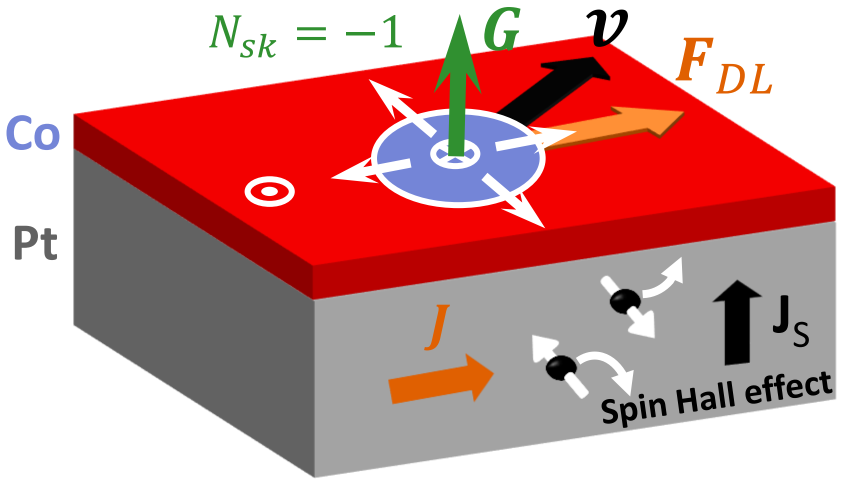
$$\frac{\partial \boldsymbol{m}}{\partial t} = -\gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{eff}) + \alpha\left(\boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t}\right) - \gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{DL})$$

⇩ *Rigid skyrmion*

Thiele equation: $\boldsymbol{F}_{DL} + \boldsymbol{G} \times \boldsymbol{v} - \alpha \boldsymbol{D}\boldsymbol{v} = \boldsymbol{0}$

$$\boldsymbol{G} = -4\pi\left(\frac{M_s t}{\gamma}\right) N_{sk}\hat{\boldsymbol{Z}} \quad \text{(gyrotropic vector)}$$

Skymions – SOT driven dynamics



Current J flows in the stack → spin Hall + Rashba effects
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- Damping-like torque (DL)

$$\boldsymbol{T}_{DL} = -\gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{DL}), \quad \mu_0 \boldsymbol{H}_{DL} = C_{DL} J[(\hat{\boldsymbol{z}} \times \hat{\boldsymbol{j}}) \times \boldsymbol{m}]$$

Landau-Lifshitz-Gilbert equation:

$$\frac{\partial \boldsymbol{m}}{\partial t} = -\gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{eff}) + \alpha\left(\boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t}\right) - \gamma_0(\boldsymbol{m} \times \boldsymbol{H}_{DL})$$

⇩ *Rigid skyrmion*

Thiele equation: $\boldsymbol{F}_{DL} + \boldsymbol{G} \times \boldsymbol{v} - \alpha \boldsymbol{D} \boldsymbol{v} = \boldsymbol{0}$

$$\boldsymbol{G} = -4\pi\left(\frac{M_s t}{\gamma}\right) N_{sk} \hat{\boldsymbol{z}}$$ (gyrotropic vector)

Skyrmion Hall effect (SkHE)

⇩ *Circular skyrmion with $R \gg \Delta$*

Skyrmion velocity

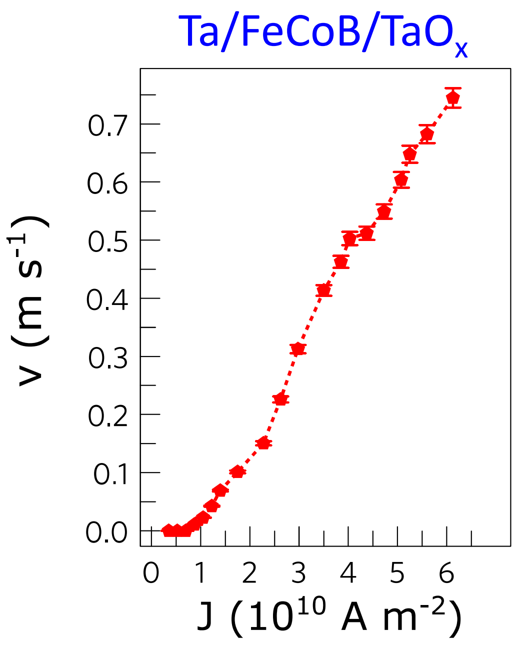
$$v = \frac{\gamma\pi}{4} \frac{R}{\sqrt{(\alpha R/2\Delta)^2 + 1}} C_{DL} J$$

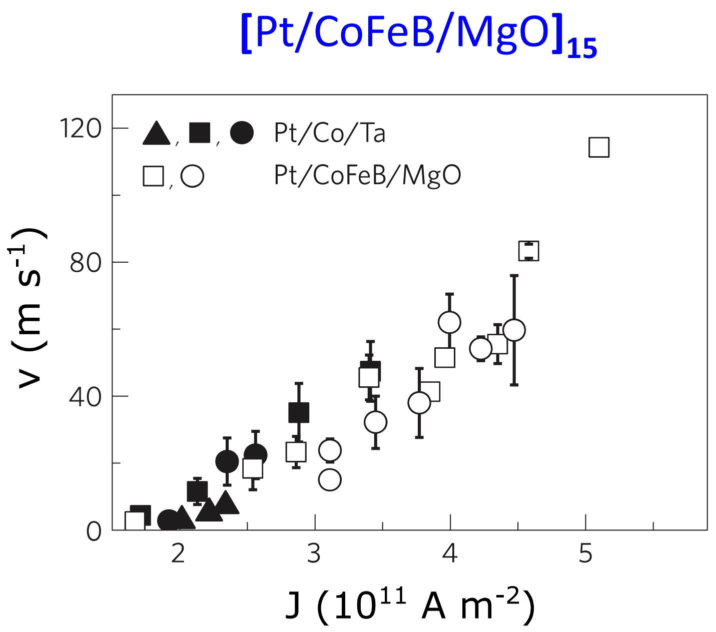
Skyrmion Hall angle

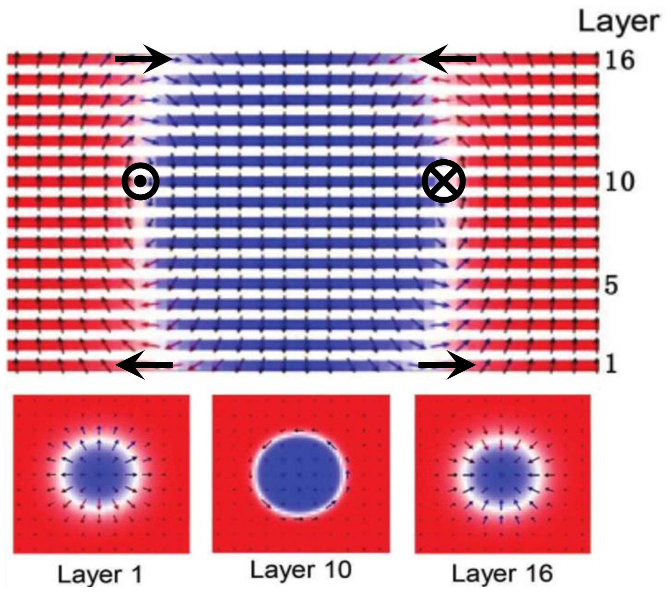
$$\tan \theta_{SkH} = \frac{2\Delta}{\alpha R}$$

$$\theta_{SkH} = (\boldsymbol{F}_{DL}, \boldsymbol{v})$$

Skymions – SOT driven dynamics







- Diameter ~ 1 µm
- Velocity ~ 1 m s^{-1}
- **Single-layer** HM/FM/NM

- Diameter ~ 110 nm
- Velocity ~ 100 m s^{-1}
- **Multilayer [**HM/FM/NM**]$_N$**

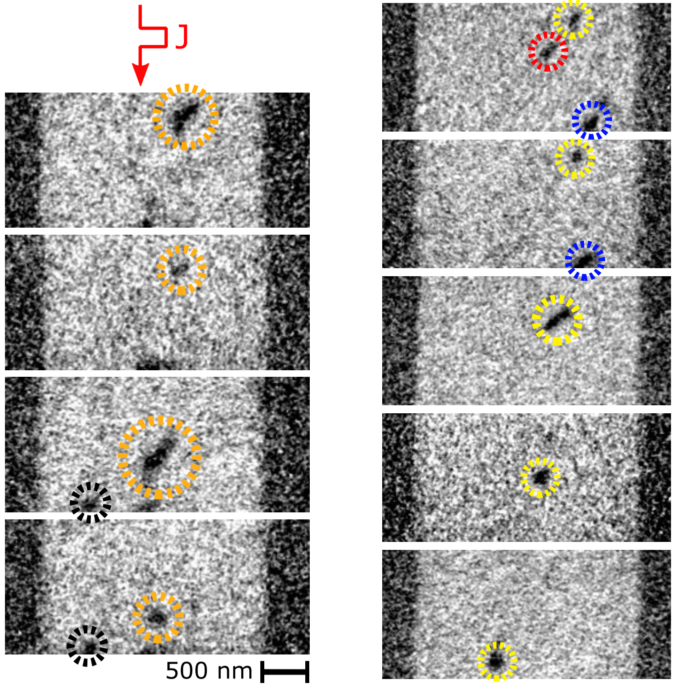
- Inter-layer stray fields → Twisted spin textures with hybrid chiralities
- Complex motion
- Dissipated power $P = RI^2 \propto N$

Jiang *et al.*, Nat. Phys. **13**,162 (2017) Woo *et al.*, Nat. Mater. **15**,501 (2016) Li *et al.*, Adv. Mat. **31**, 1807683 (2019)

Skymions – SOT driven dynamics

Pt/Co/MgO

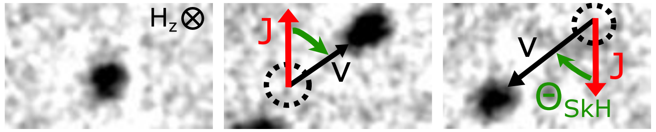
XMCD-PEEM images



11 ns pulse, J = 5.6x10^11^ A m^-2^, $\mu_0 H_z \approx -5$ mT

Romeo Juge
PhD Univ. Grenoble Alpes (2020)

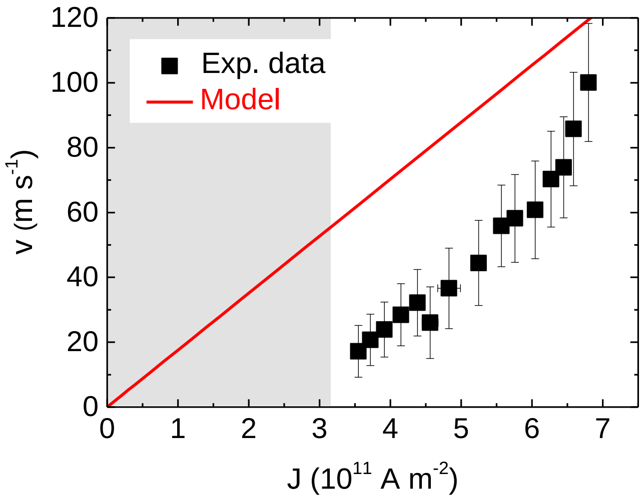
- Overall direction consistent with dynamics of left-handed Néel skyrmion driven by SOTs
- Skyrmion Hall effect



- Irregular current-driven motion due to pinning effects
  - Nucleation/annihilation events
  - Distortion

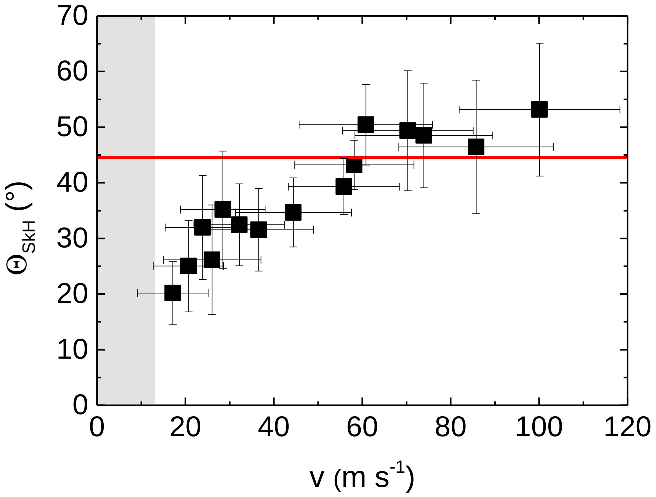
Skyrmion velocity

$$v = \frac{\gamma\pi}{4} \frac{R}{\sqrt{(\alpha R/2\Delta)^2 + 1}} C_{DL} J$$

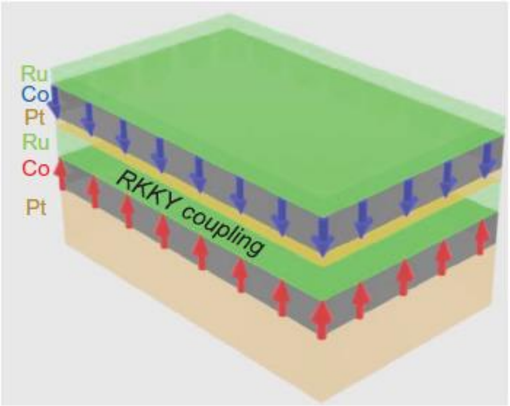


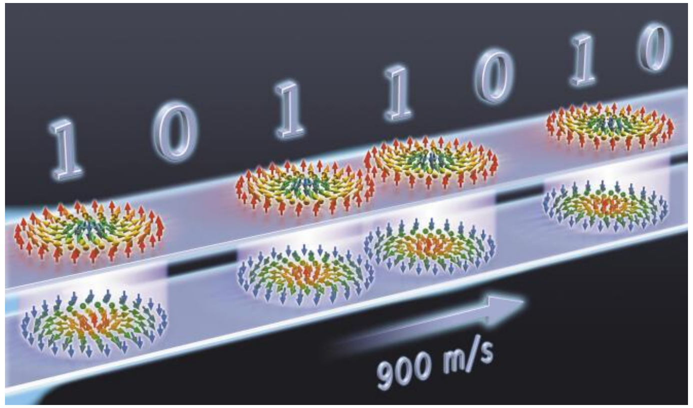
Skyrmion Hall angle (SkHA)

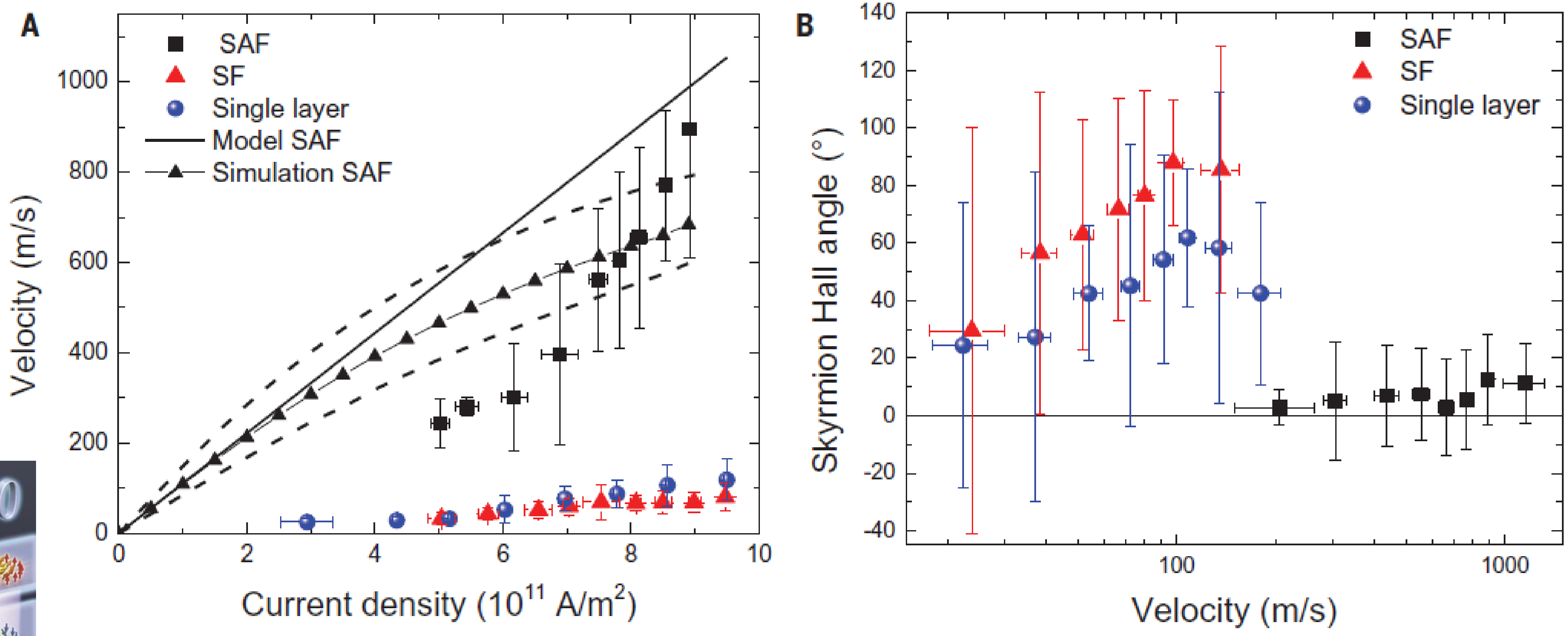
$$\tan \theta_{SkH} = \frac{2\Delta}{\alpha R}$$



Skymions – SOT driven dynamics







Pham et al. , Science 384 (2024)

Domains & Domain walls & Spin textures

- How to define them?
- What are their origins?
- Which is their internal structure ?
- What are their properties ?

Fundamental interactions

Energy
Dynamics
1D, 2D, 3D

Field
STT
SOT
DMI …

Materials
Experiments

Models

Theories

An old but still surprising topic..... and many flavors to discover


Q
&
A


THANK
YOU