Magnetic vortices, skyrmions, etc.

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Collaborators

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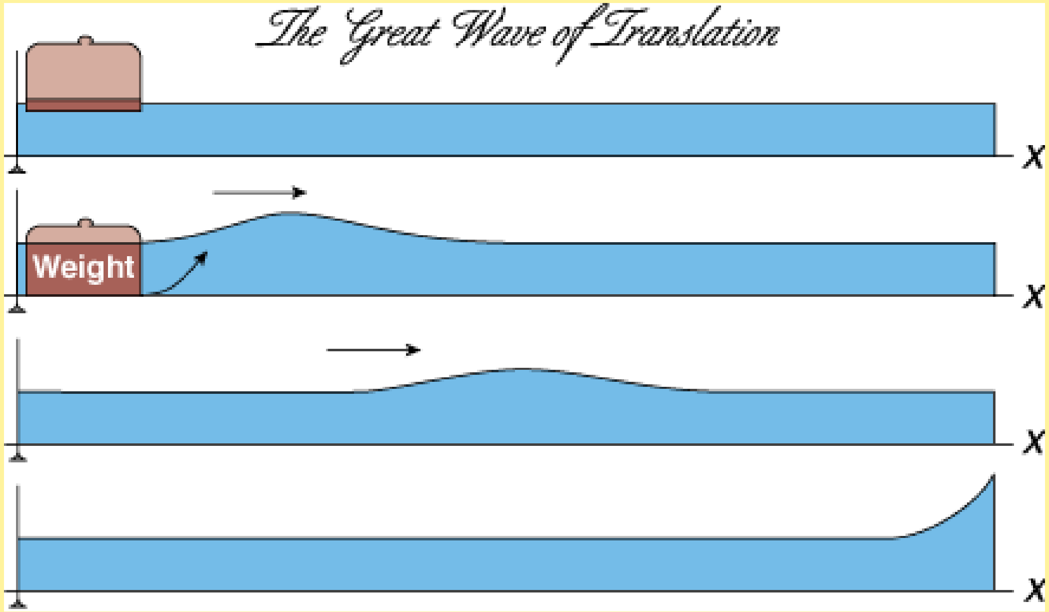
Outline

1. Solitons and magnetic vortices
2. Topological properties of vortices, etc
3. Formation of a skyrmion

Solitons

Waves in a narrow channel travel long distances without changing their shape

J. S. Russell, Report of the Fourteenth Meeting of the British Association for the Advancement of Science (Murray, London, 1844), pp. 311-390.



John Scott Russell (1808–1882)

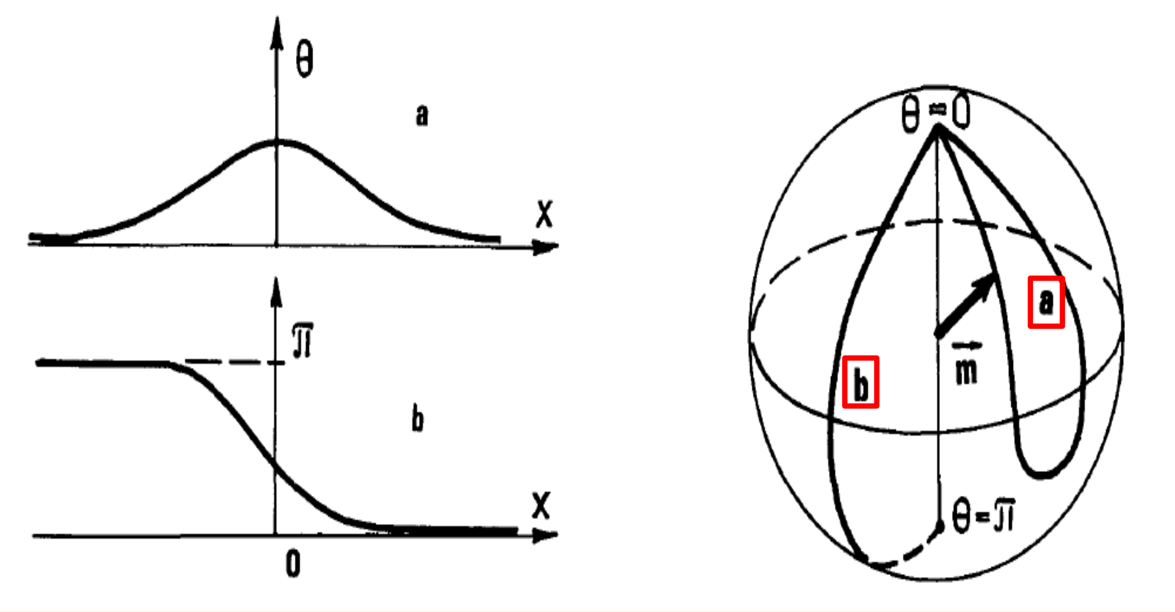
Solitons are collective excitations that are solutions of differential equations

Topological solitons (or topological defects): those whose stability is guaranteed topologically

Examples of solitons

http://www.youtube.com/watch?v=Ud7STKWNmQw

Solitons in a one-dimensional magnet



a) Dynamic soliton: topologically unstable, since curve a on the sphere can be deformed continuously to a point (the ground state)(these configurations are said to be topologically equivalent)

b) Topological soliton: curve b cannot be deformed to a point

Kosevich Phys. Repts. 194, 117 (1990).)

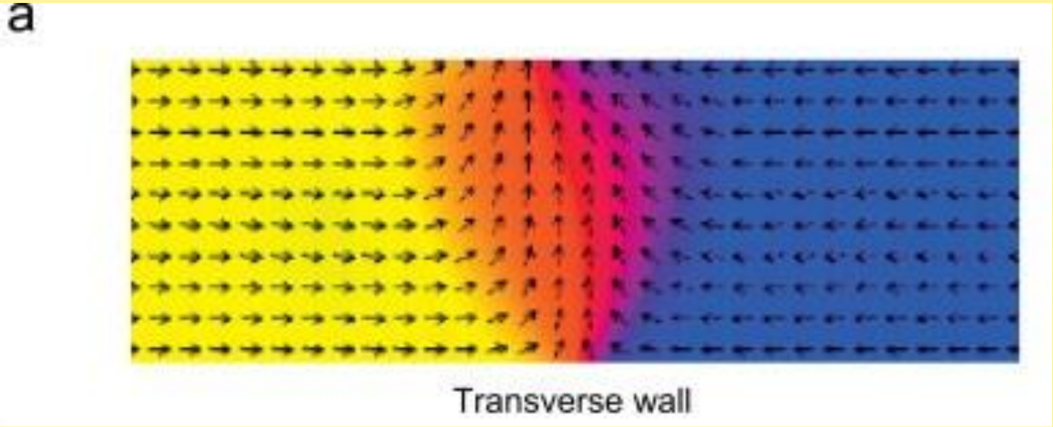
Real systems

Two configurations are topologically equivalent when they can transformed into one another without overcoming an infinite energy barrier

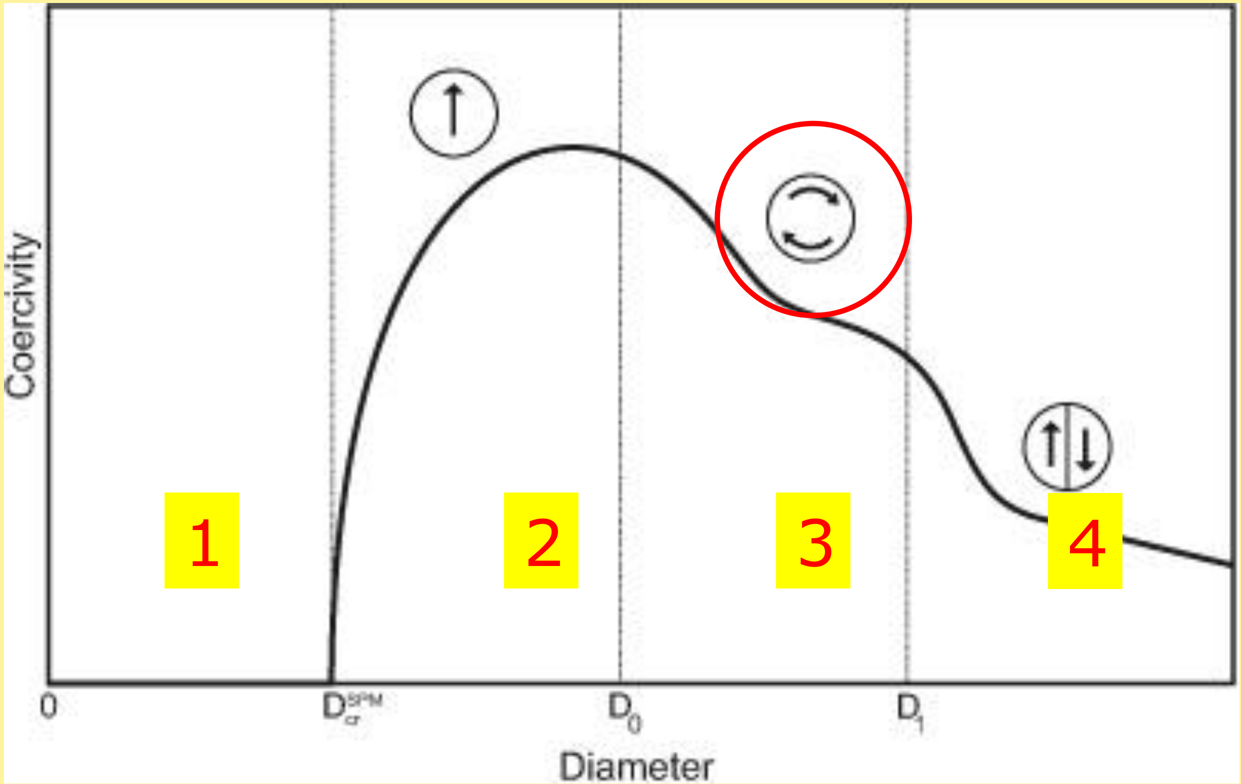
Considerations:

a) In real systems, the energy barriers are not infinite;

b) Real systems have finite dimensions, therefore, e.g., one can always expel a domain wall from a sample



Spin structures in nanoobjects



Four regimes:

1) superparamagnetic;

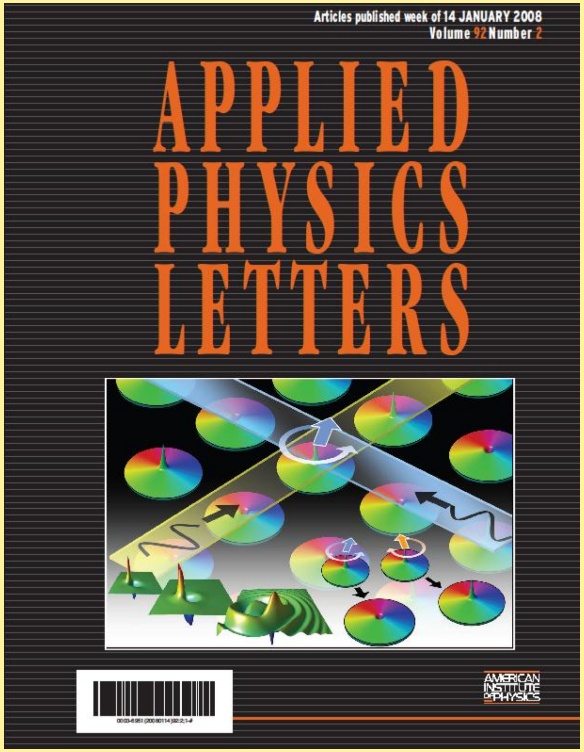
2) single-domain FM;

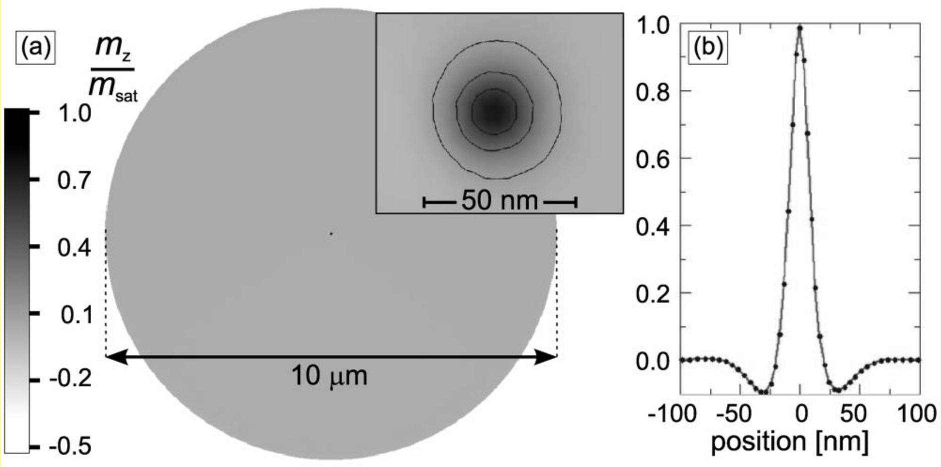
3) vortex state;

4) multidomain FM

Schematic curve of coercivity vs. diameter for soft magnetic particles.

Properties of magnetic vortices





Computed vortex and core profile Bode, PRL 100, 029703 (2008)

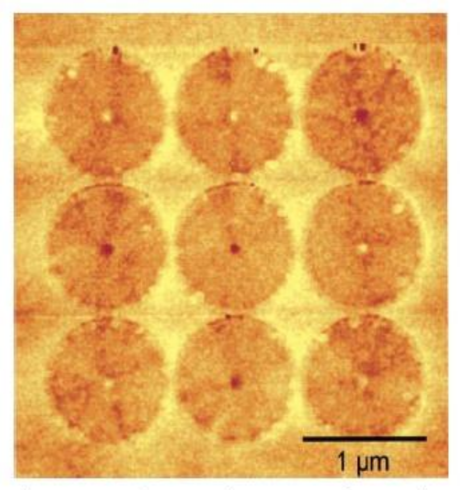
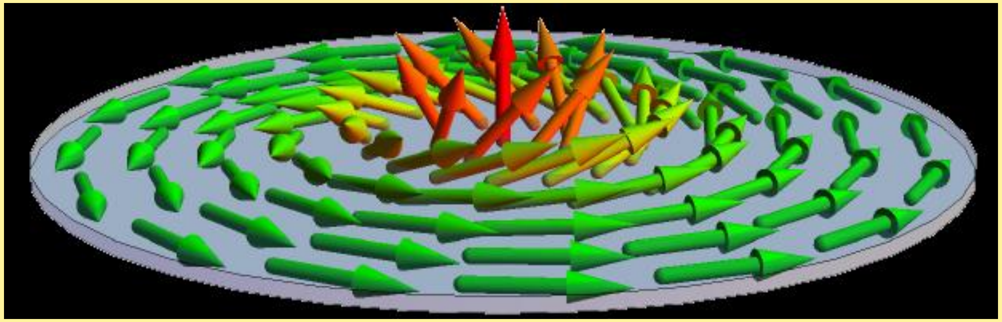


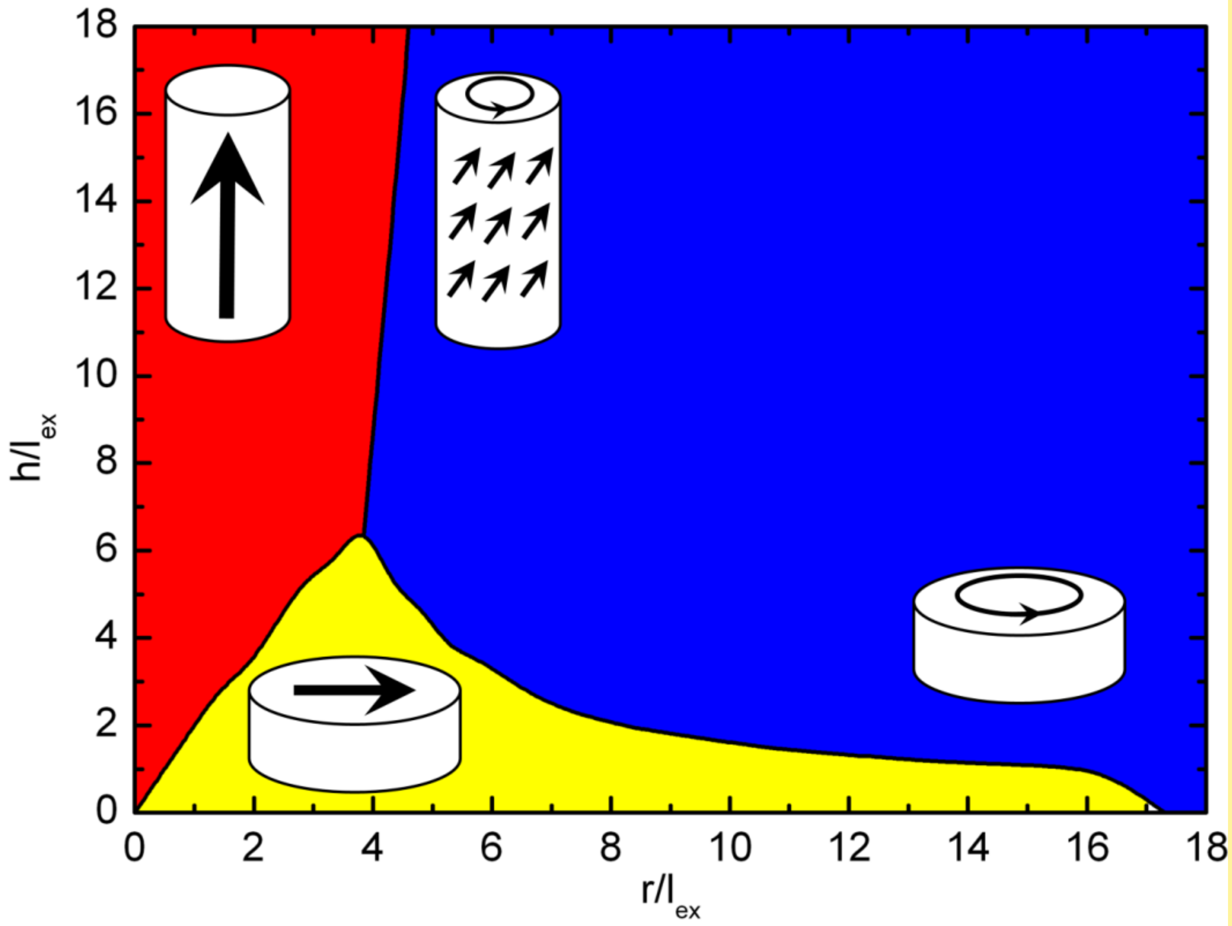
Fig. 2. MFM image of an array of permalloy dots 1 μm in diameter and 50 nm thick.

Shinjo et.al., Science 289, 930 (2000)



Pigeau

Circular nanodots:phase diagram



Different spin configurations

Graph:
Height vs. thickness

Novais JAP 110, 053917 (2011)

Micromagnetic simulations

The properties of nanoscopic or microscopic magnetic samples may be simulated numerically. In the Micromagnetism approach, the magnetic medium is treated as a continuum.

The total energy is a sum of the terms of exchange, anisotropy, magnetostatic and Zeeman:

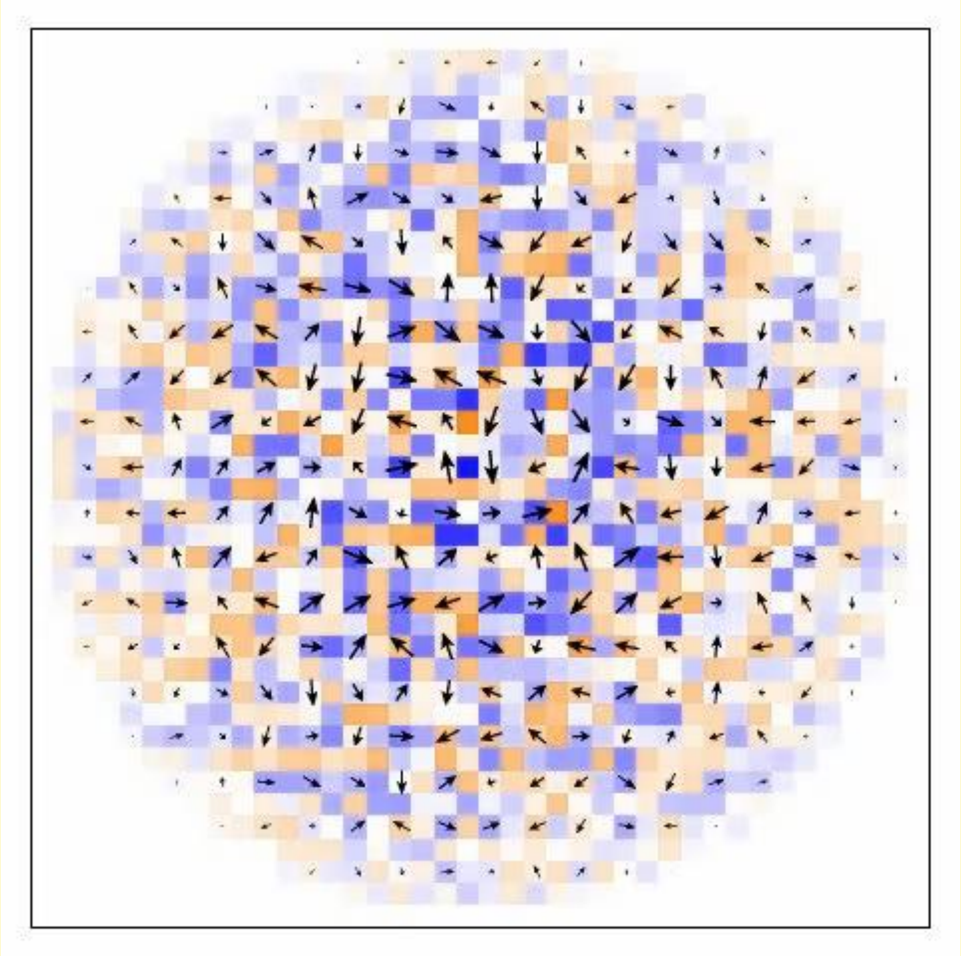
$$E_{\mathrm{tot}} = E_{\mathrm{ex}} + E_A + E_{\mathrm{ms}} + E_{\mathrm{ext}}$$

or

$$E = \int_V \left\{ A\left[\nabla\left(\frac{\mathbf{M}}{M_s}\right)\right]^2 + K_1 sin^2(\theta) - \frac{\mu_0}{2}\mathbf{M}\cdot\mathbf{H}_d(M) - \mu_0\mathbf{M}\cdot\mathbf{H}\right\} dV$$

The spin configuration is found by minimizing the total energy E_{tot}

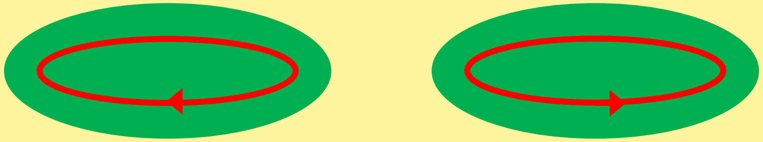
Formation of a vortex on a permalloy nanodisk



Properties of magnetic vortices

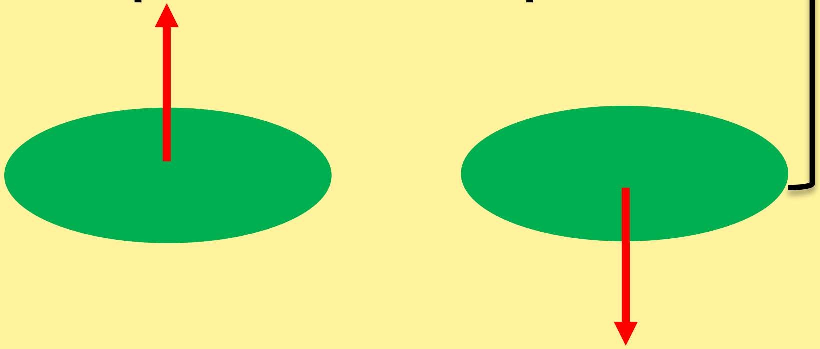
- Circulation:

c=+1 (CCW) c=-1 (CW)



- Polarity:

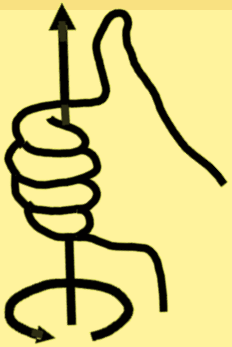
p=+1 p=-1



Combining c and p:

chirality or handedness:

$cp=\pm 1$



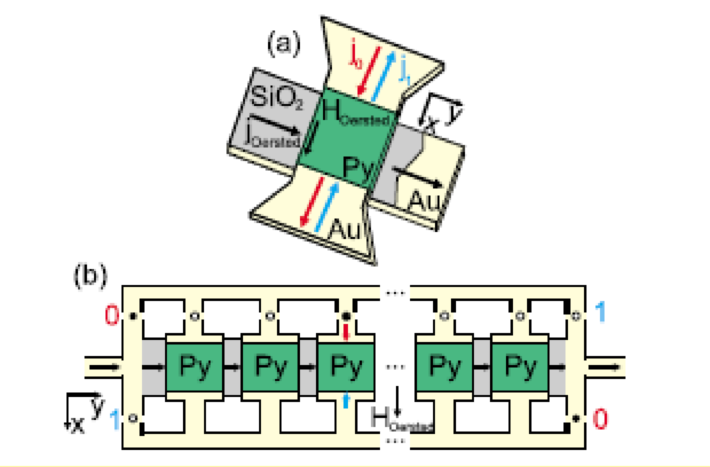
a. Applications of vortex systems: Vortex Random-access Memory (VRAM)

Vortices may store 1 bit using

a) Polarity
b) Circulation (CW or CCW)
c) Chirality

Or else store 2 bits using, e.g.,

a) Polarity and circulation



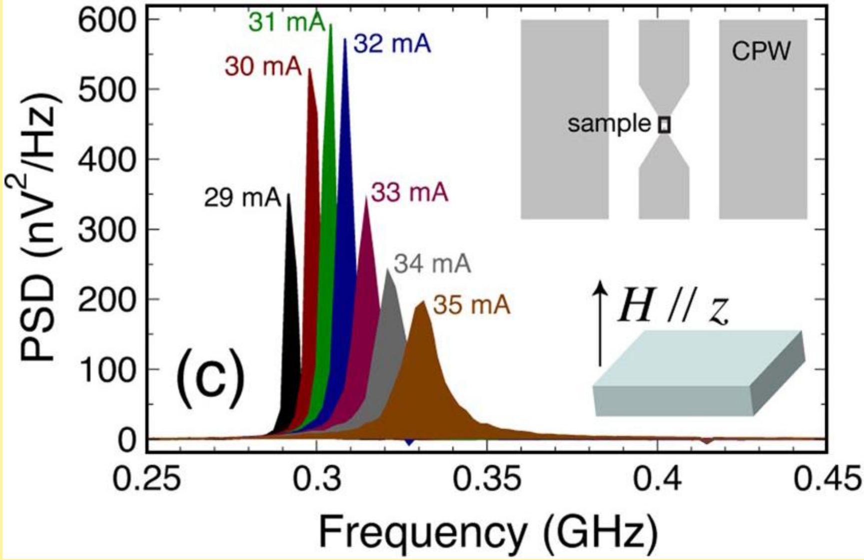
e.g. Bohlens, Appl. Phys. Lett. 93, 142508 (2008)

b. Applications of vortex systems : spin torque nano-oscillators (STNOs)

Polarized spin currents can induce periodic motion of vortex cores (gyrotropic motion), also emitting RF

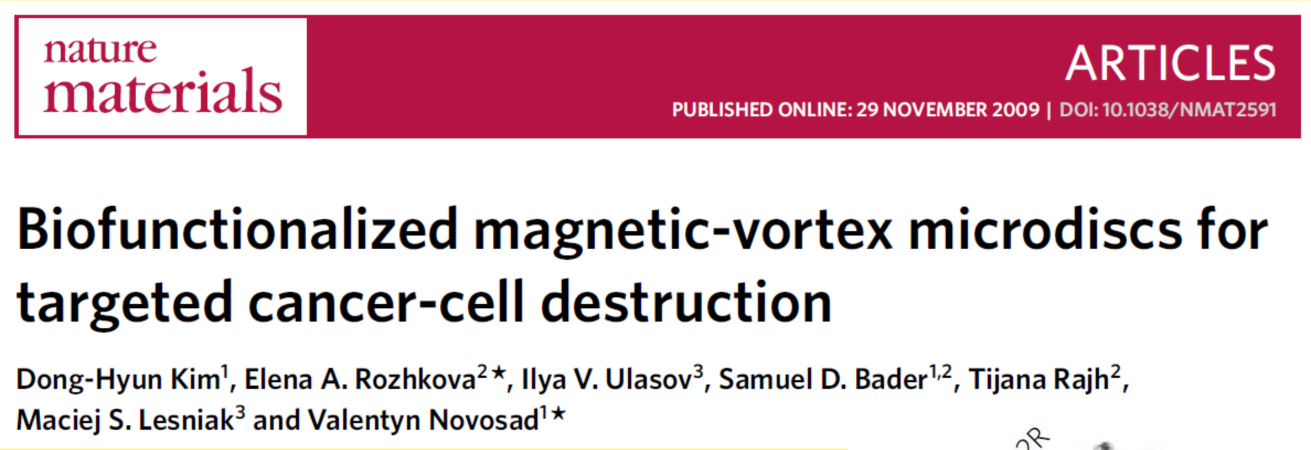
(Pufall 2007, Mistral 2008)

Coupling of vortices in spin valve nanopillar may increase rf power



Mistral PRL 100 257201 (2008)

c. Applications of vortex systems : destruction of cancer cells



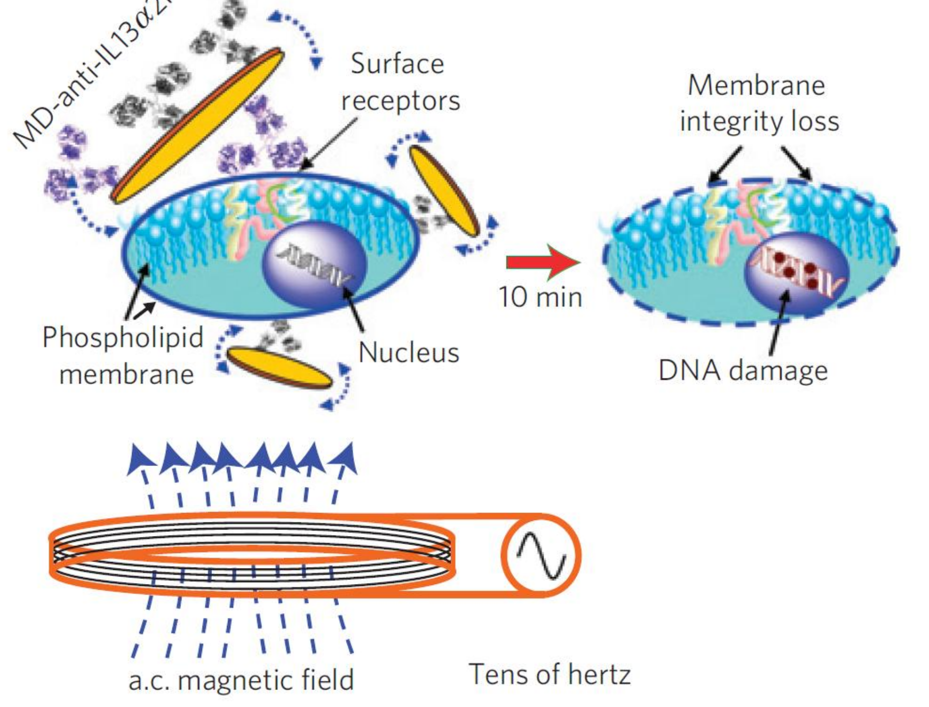
nature materials

ARTICLES

PUBLISHED ONLINE: 29 NOVEMBER 2009 | DOI: 10.1038/NMAT2591

Biofunctionalized magnetic-vortex microdiscs for targeted cancer-cell destruction

Dong-Hyun Kim[1], Elena A. Rozhkova[2]*, Ilya V. Ulasov[3], Samuel D. Bader[1,2], Tijana Rajh[2], Maciej S. Lesniak[3] and Valentyn Novosad[1]*



Torque $\tau = \mathbf{m} \times \mathbf{H}$

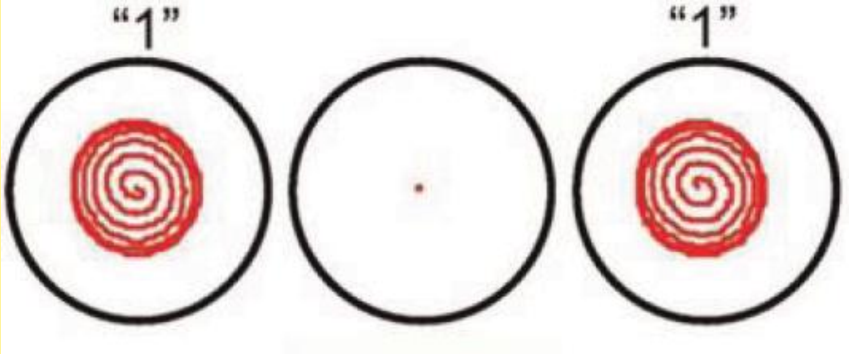
Oscillation of the disks induces programmed cell death

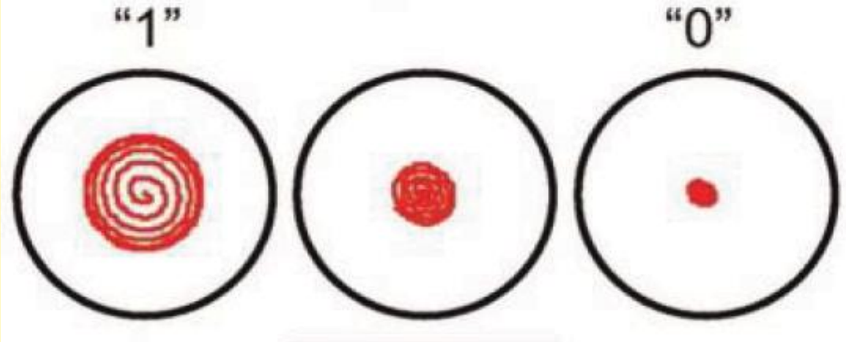
Kim, Nature Mater. 9 165, (2010)

d. Applications of vortex systems: logic gates

Logic Operations Based on Magnetic-Vortex-State Networks

Hyunsung Jung,[†] Youn-Seok Choi,[†] Ki-Suk Lee,[†] Dong-Soo Han,[†] Young-Sang Yu,[†] Mi-Young Im,[‡]
Peter Fischer,[‡] and Sang-Koog Kim[†,*]





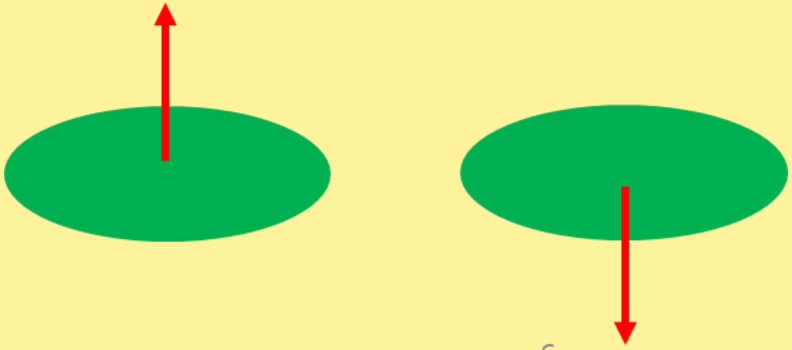
The output of the center disk is controlled by the input to disks 1 and 3

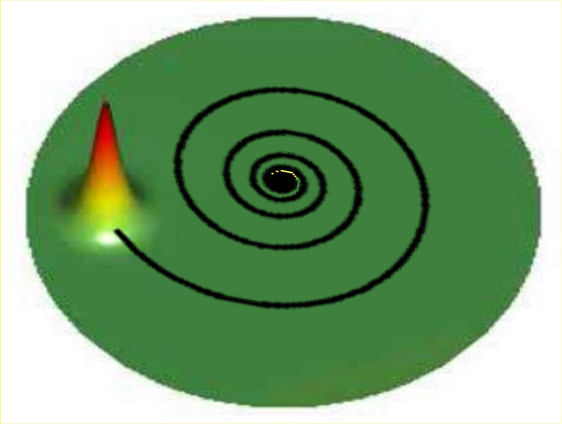
VOL. 6 ▪ NO. 5 ▪ 3712–3717 ▪ 2012 ACS NANO

Gyrotropic motion of vortex cores

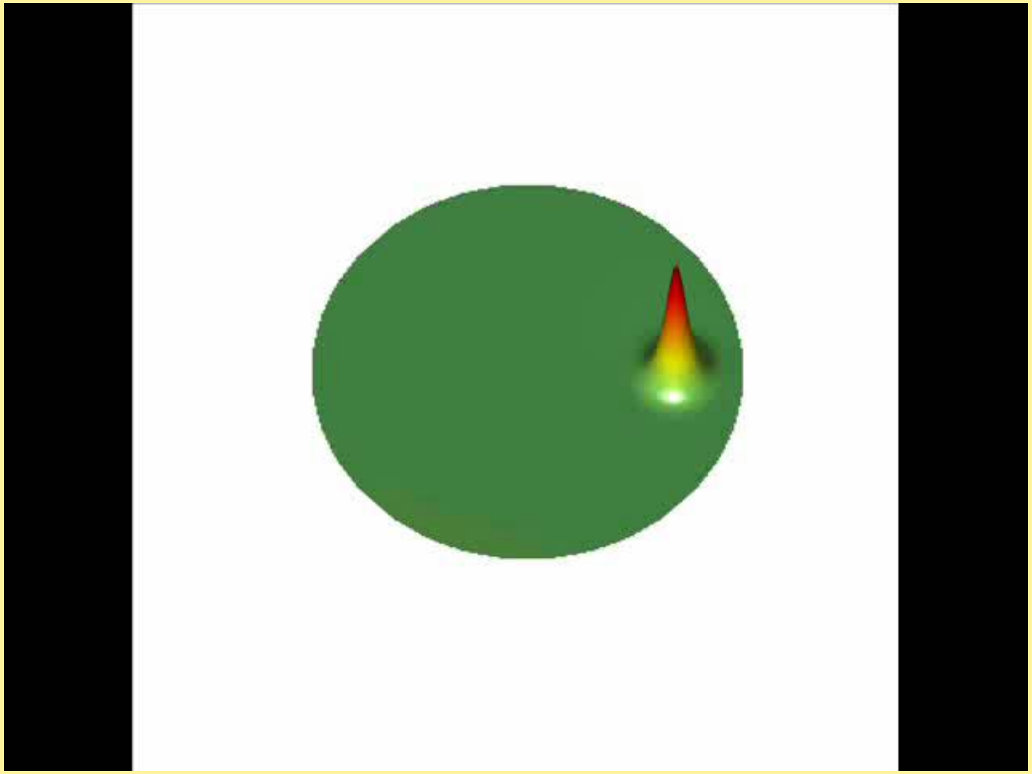
The vortex core performs a spiral-like motion with a frequency related to the disk aspect ratio β=h/R

The direction of the translation is defined by the polarity p (up or down)





Gyrotropic motion of a vortex core



Translation motion of magnetic vortex core displaced from the equilibrium position (zero damping)

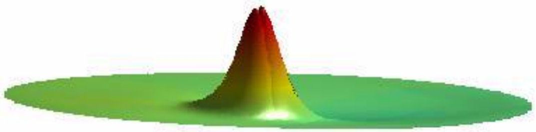
JOURNAL OF APPLIED PHYSICS **112**, 113911 (2012)

Magnetic vortex echoes

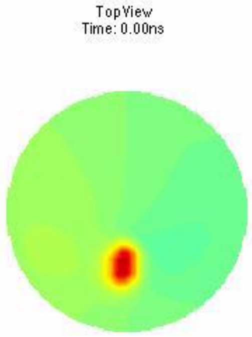
F. Garcia,[1] J. P. Sinnecker,[2] E. R. P. Novais,[2] and A. P. Guimarães[2,a)]

The vortex core motion of a inhomogeneous assembly of nanodisks produces an echo that may be used to characterize it

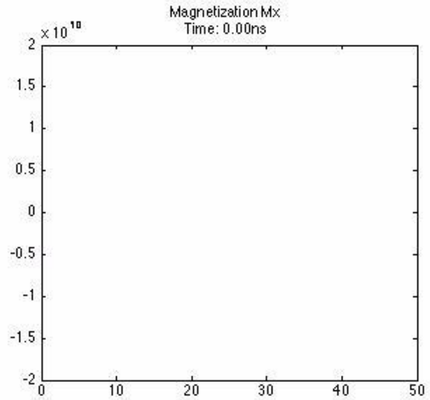
This is analogous to the NMR spin echo



Superposed image of several disks

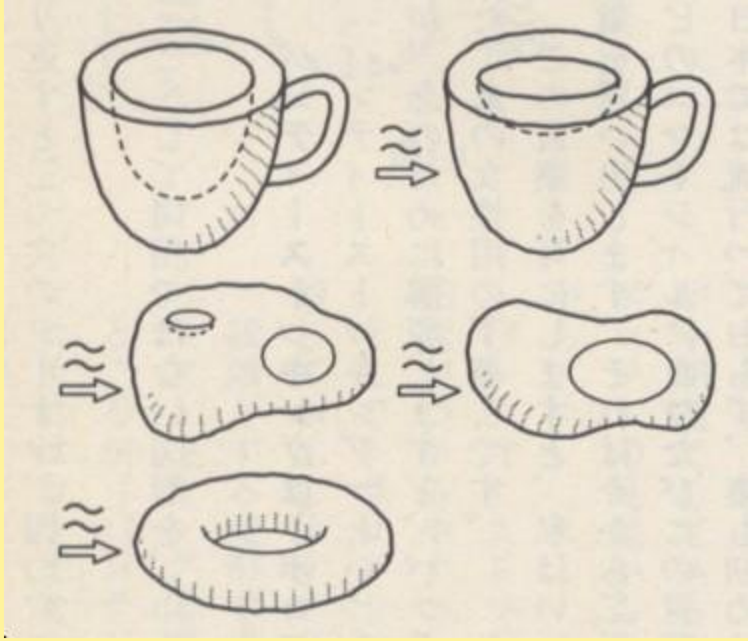


Projection of the image of the disks



The evolution of the total magnetization

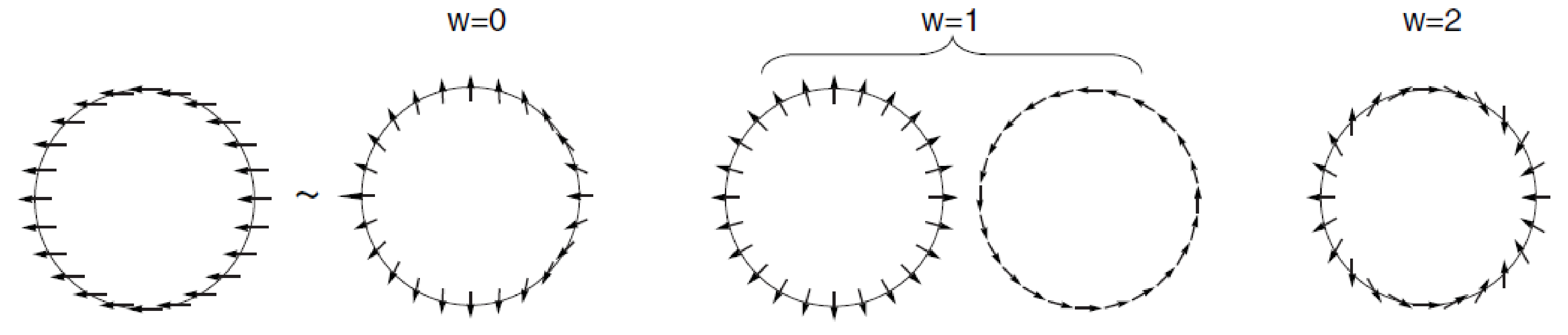
Topology?!



Jwilson.coe.uga.edu

Remember: in topological terms, one coffee cup=one donut

Winding number



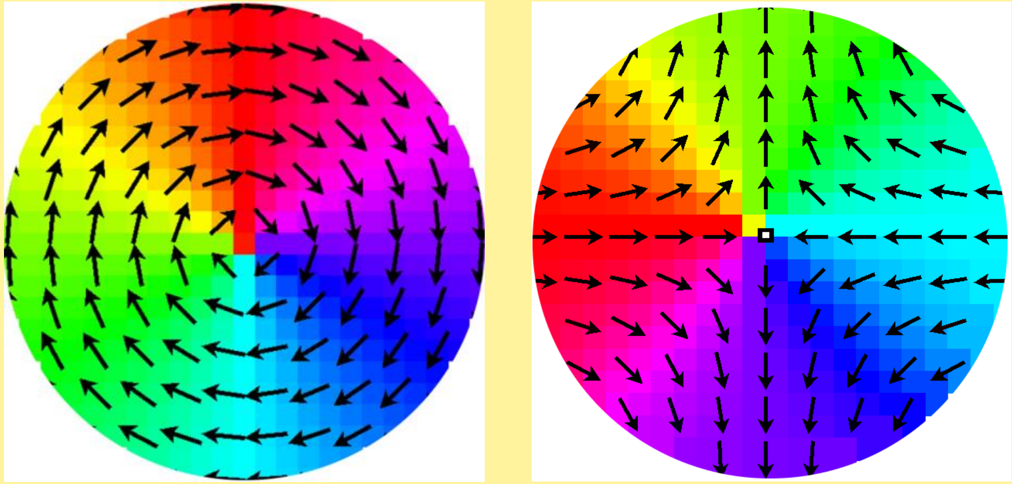
The <u>winding number</u> is the total variation of the magnetization angle $\Delta\varphi$ as one moves counterclockwise around a circle, divided by 2π

One cannot deform a given spin configuration into another of different winding number

A <u>topological defect</u> exists if one cannot deform a spin configuration into the ferromagnetic state

Braun Adv. Phys. 61, 1–116 (2012)

Vortices and antivortices



Vortex

Antivortex

When a vortex and an antivortex meet, they annihilate.

n=1

p=±1

n=-1

p=±1

Winding number n and skyrmion number q

The winding number: total variation of the magnetization angle $\Delta\varphi$ as one moves counterclockwise around a circle divided by 2π

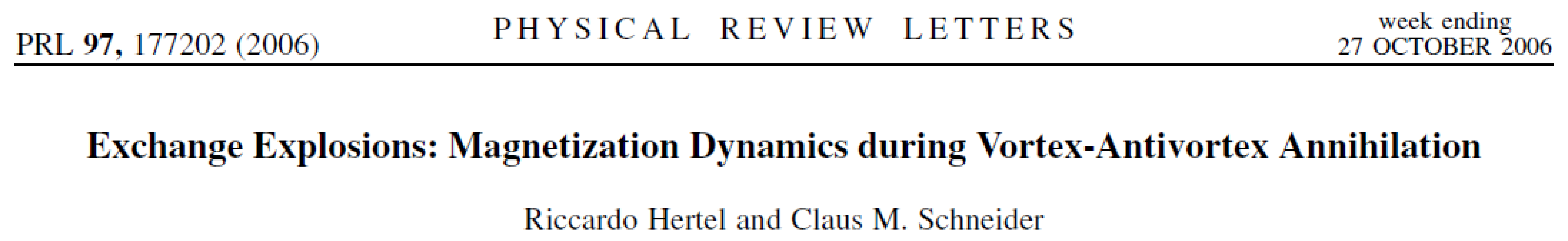
$$n = \Delta\varphi/2\pi$$

The winding number of a vortex is 1

The skyrmion number q is

$$q = np/2$$

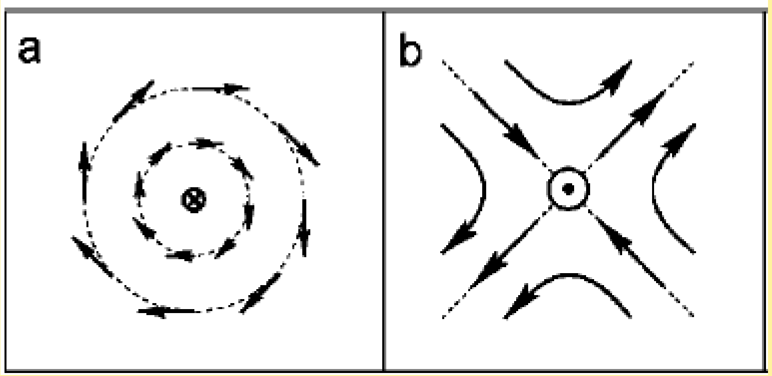
where p is the polarity



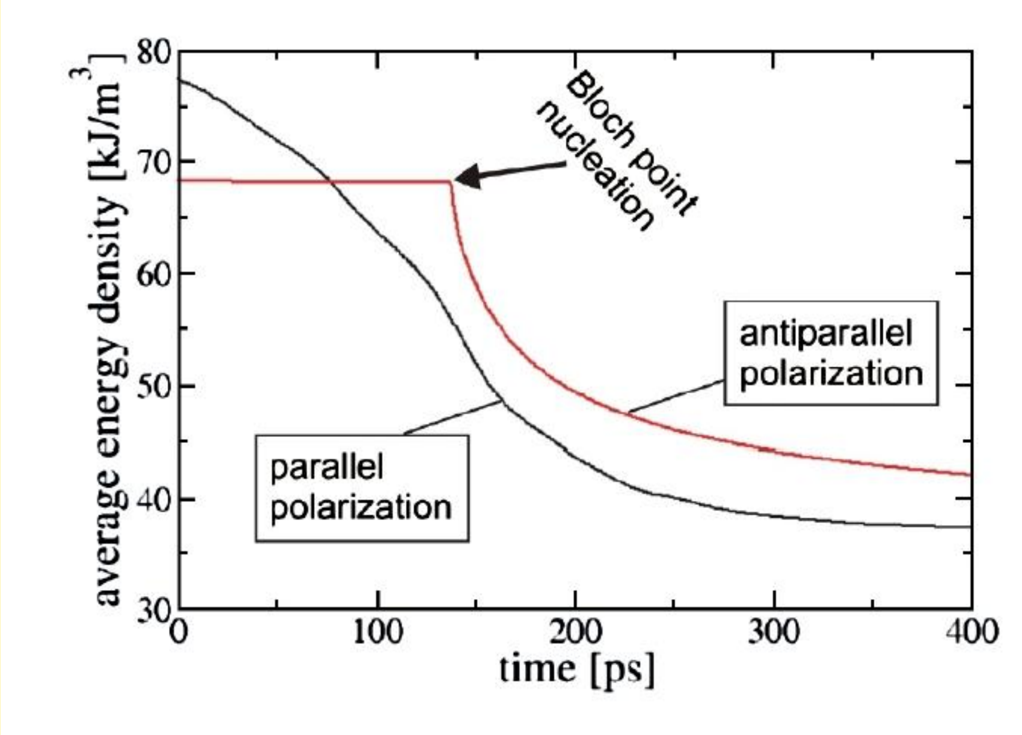
PRL **97,** 177202 (2006) PHYSICAL REVIEW LETTERS week ending 27 OCTOBER 2006

Exchange Explosions: Magnetization Dynamics during Vortex-Antivortex Annihilation

Riccardo Hertel and Claus M. Schneider



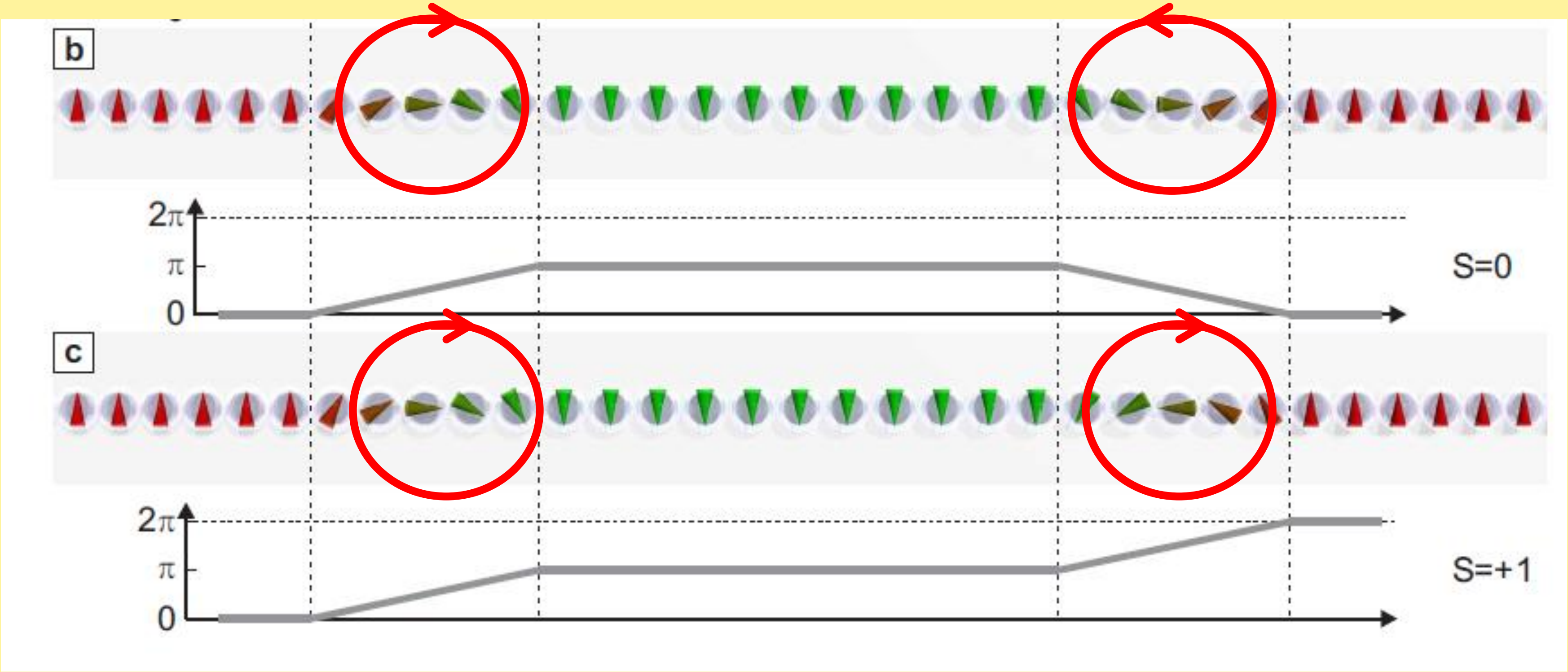
Vortex and antivortex



When the sum of the skyrmion numbers of the vortex and the antivortex is not zero, the annihilation releases a burst of energy

Annihilation of a vortex and the conservation of the skyrmion number

1D Domain walls and skyrmions

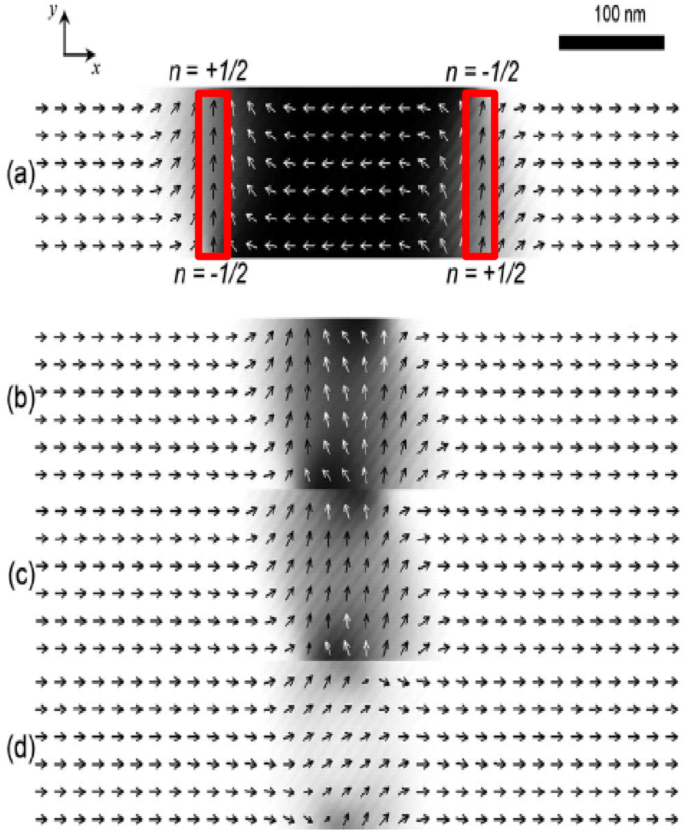


The importance of the winding number (and the total skyrmion number S)
In b) the total skyrmion number S is zero
In c) S=1 and the one-dimensional domain walls need a higher field to be annihilated – a skyrmion is formed

Menzel, Thesis, Hamburg (2011)

2D Domain walls

1)

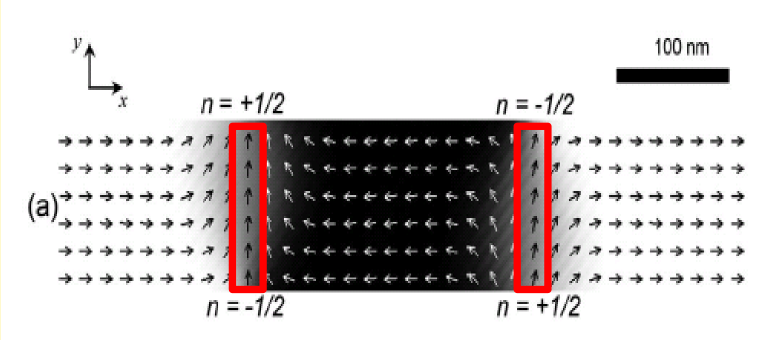


2)

Effect of applied field on domain walls with different topologies: 1) Σq =0, the walls disappear; 2) Σq ≠0 topologically protected

Kunz, APL94, 132502 (2009)

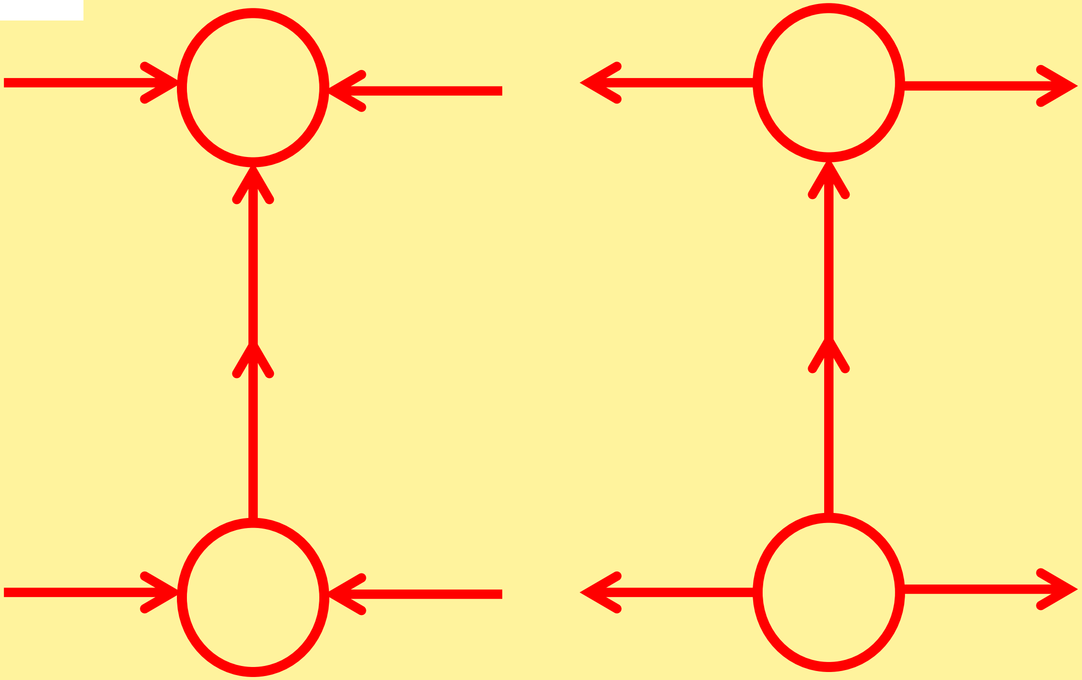
Edge defects in a domain wall I



This is a representation of the first stripe (previous slide)

A DW is composed of 2 or more defects with winding numbers

+1/2 or -1/2



n=+1/2

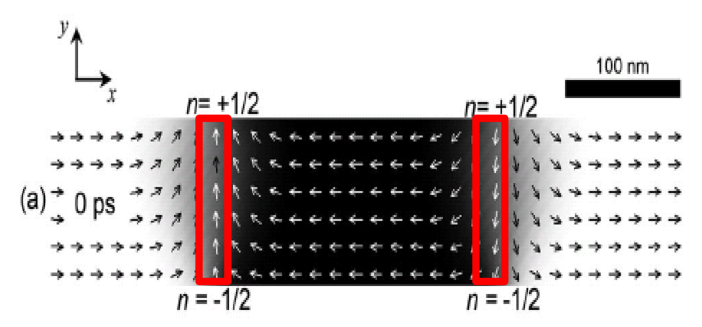
n=-1/2

n=-1/2

n=+1/2

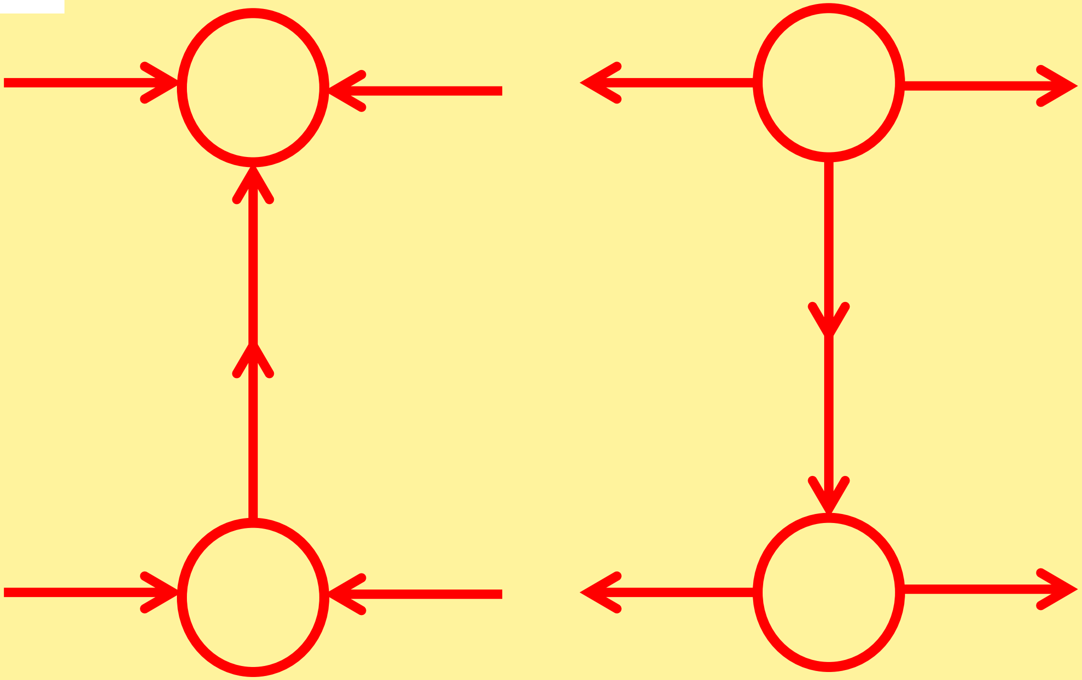
Opposite charges annihilate

Edge defects in a domain wall II



This is a representation of the second stripe (previous slide)

If the total charge on each edge does not add to zero, a 360o wall is formed, and a higher field is necessary to destroy it



n=+1/2

n=+1/2

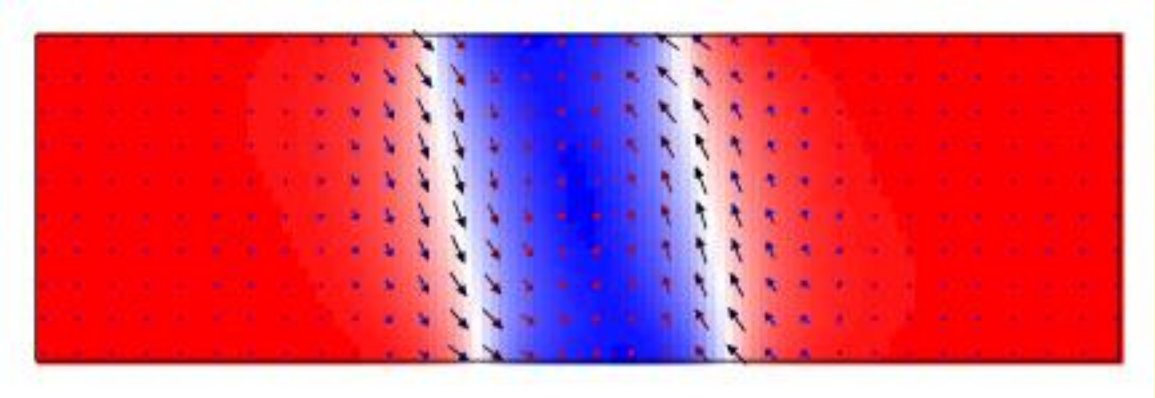
n=-1/2

n=-1/2

Charges do not add to zero

Collapse of two DWs: formation of a skyrmion

01

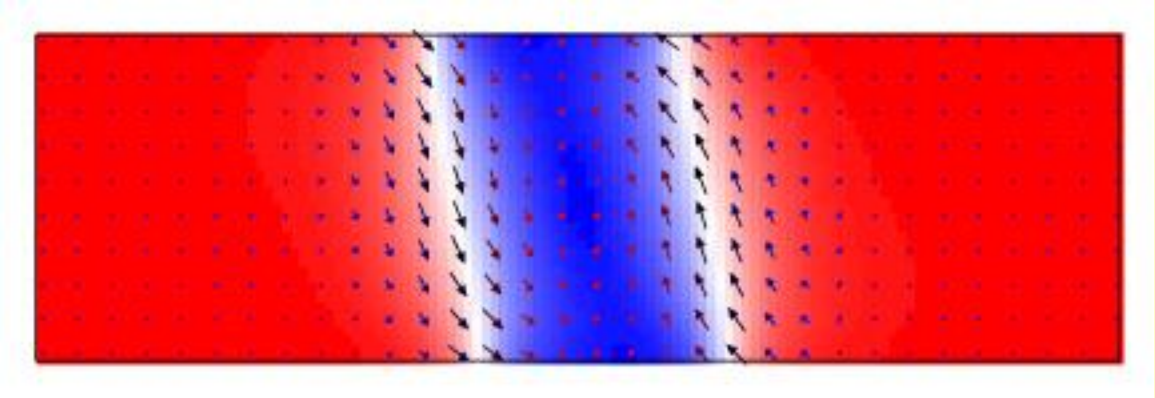


Micromagnetic simulation of a stripe with perpendicular anisotropy, topologically protected, with increasing perpendicular applied field

Garcia, unpublished (2013)

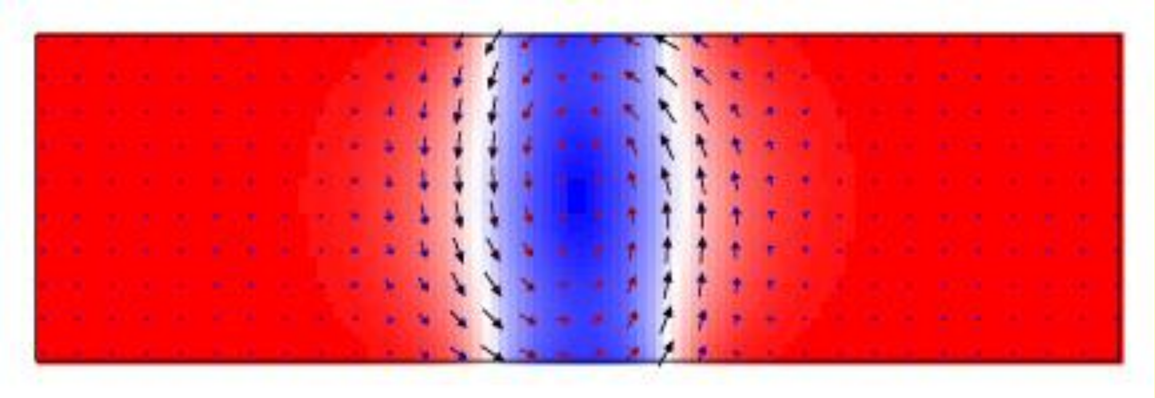
Collapse of two DWs: formation of a skyrmion

01

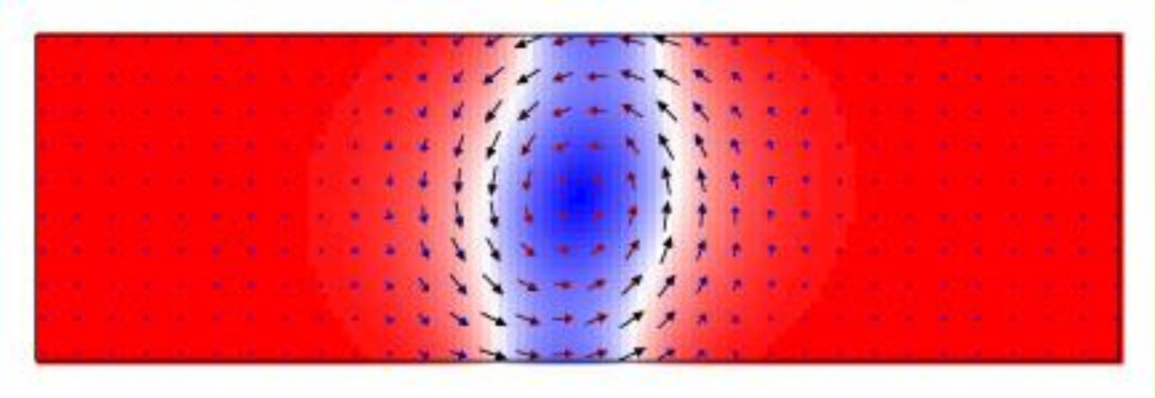


Collapse of two DWs: formation of a skyrmion

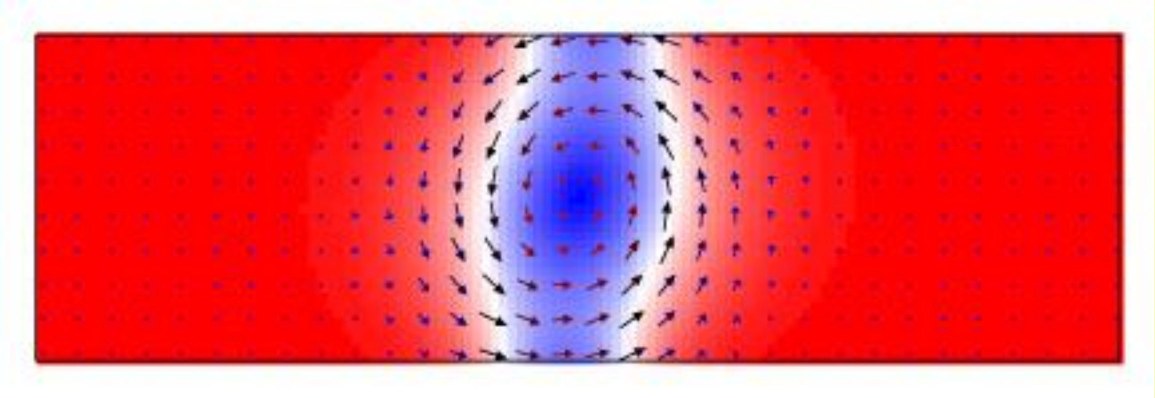
02



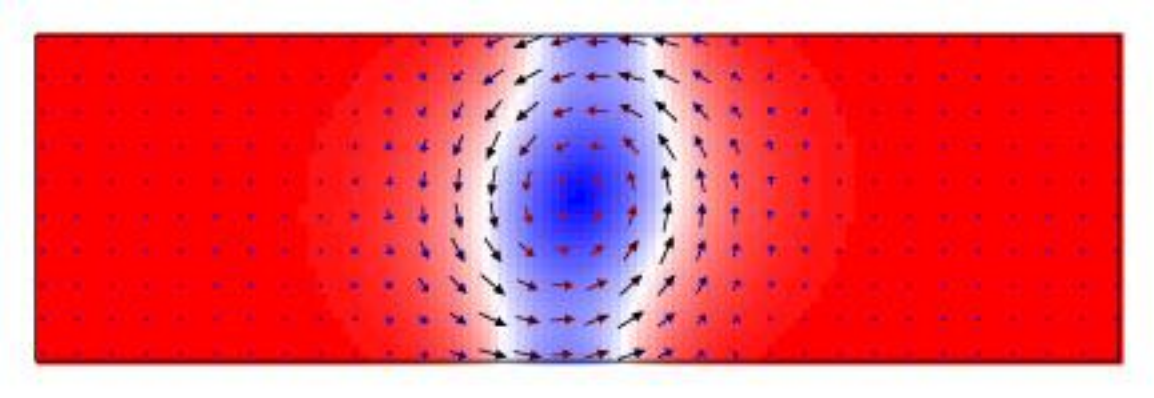
Collapse of two DWs: formation of a skyrmion
03



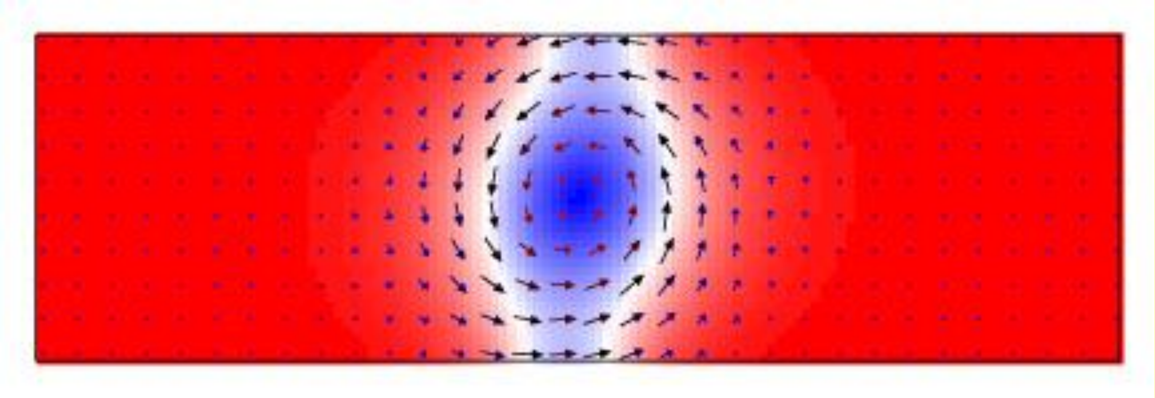
Collapse of two DWs: formation of a skyrmion
04



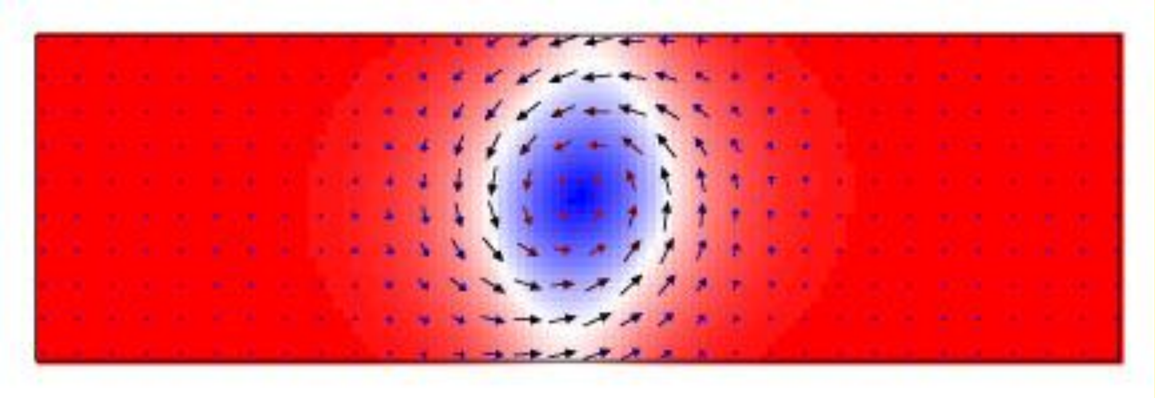
Collapse of two DWs: formation of a skyrmion
05



Collapse of two DWs: formation of a skyrmion
06

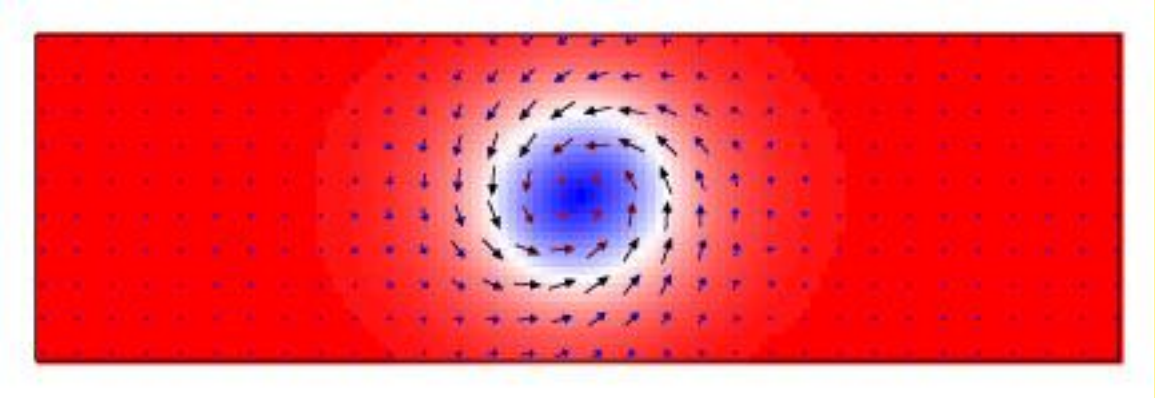


Collapse of two DWs: formation of a skyrmion 07



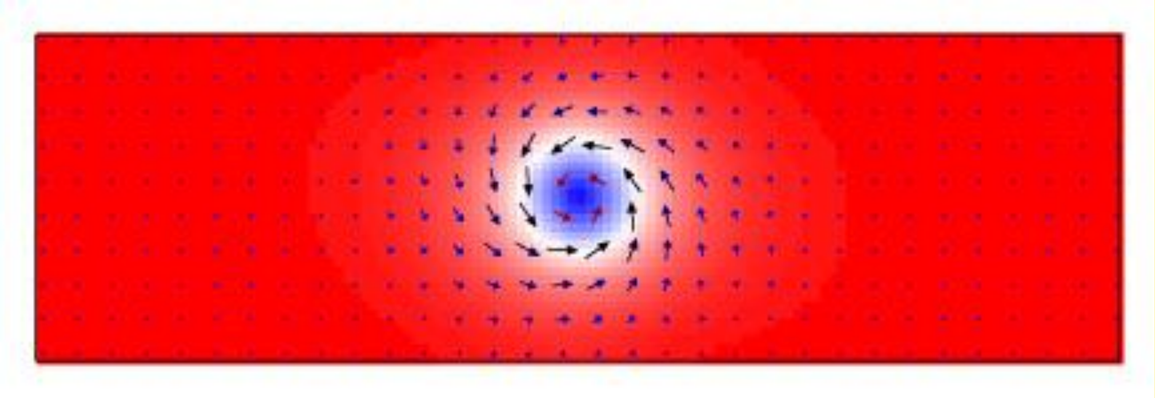
Collapse of two DWs: formation of a skyrmion

08



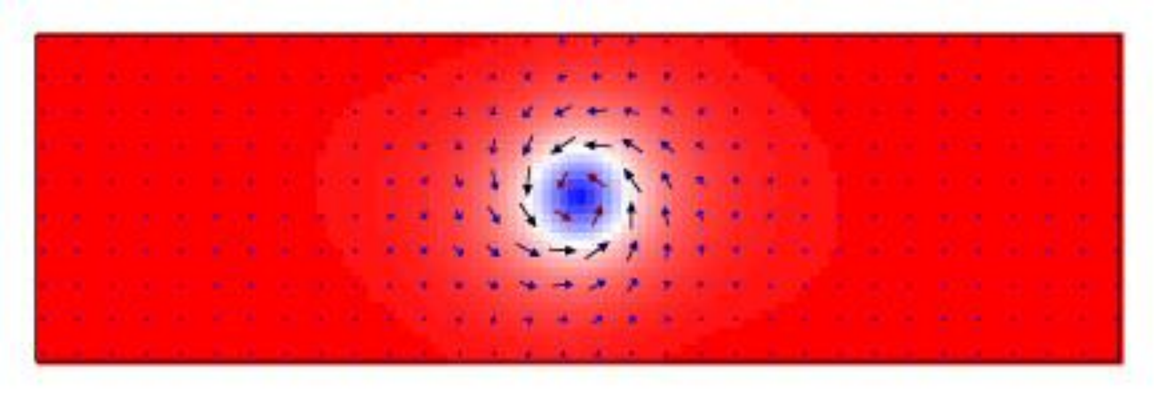
Collapse of two DWs: formation of a skyrmion

09



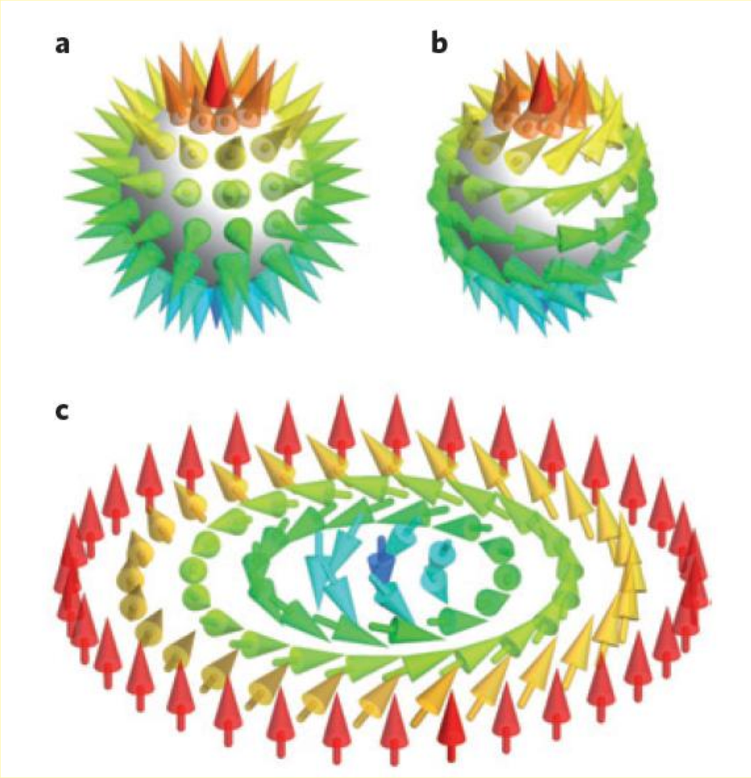
Collapse of two DWs: formation of a skyrmion

10



Skyrmions

A class of solitons found in liquid crystals, Bose-Einstein condensates, quantum Hall magnets, thin magnetic films, and materials with Dzyaloshinsky-Moriya (DM) interaction, named after T.H.R. Skyrme (1922–1987)

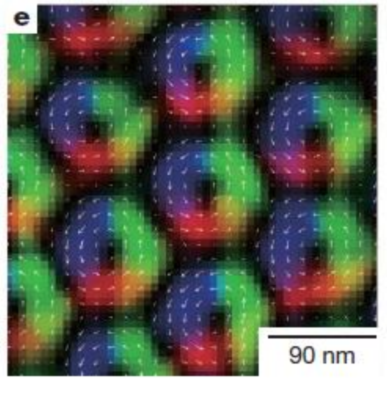


T.H.R. Skyrme, Nucl. Phys. 31, 556–569 (1962).

Skyrmion lattices and isolated skyrmions

Skyrmion lattices:

Nanolayers of materials with intrinsic chirality (cubic helimagnets Fe0.5Co0.5Si and FeGe (Yu (2010, 2011)) and with induced chirality (Fe/W bilayers) Heinze (2011))

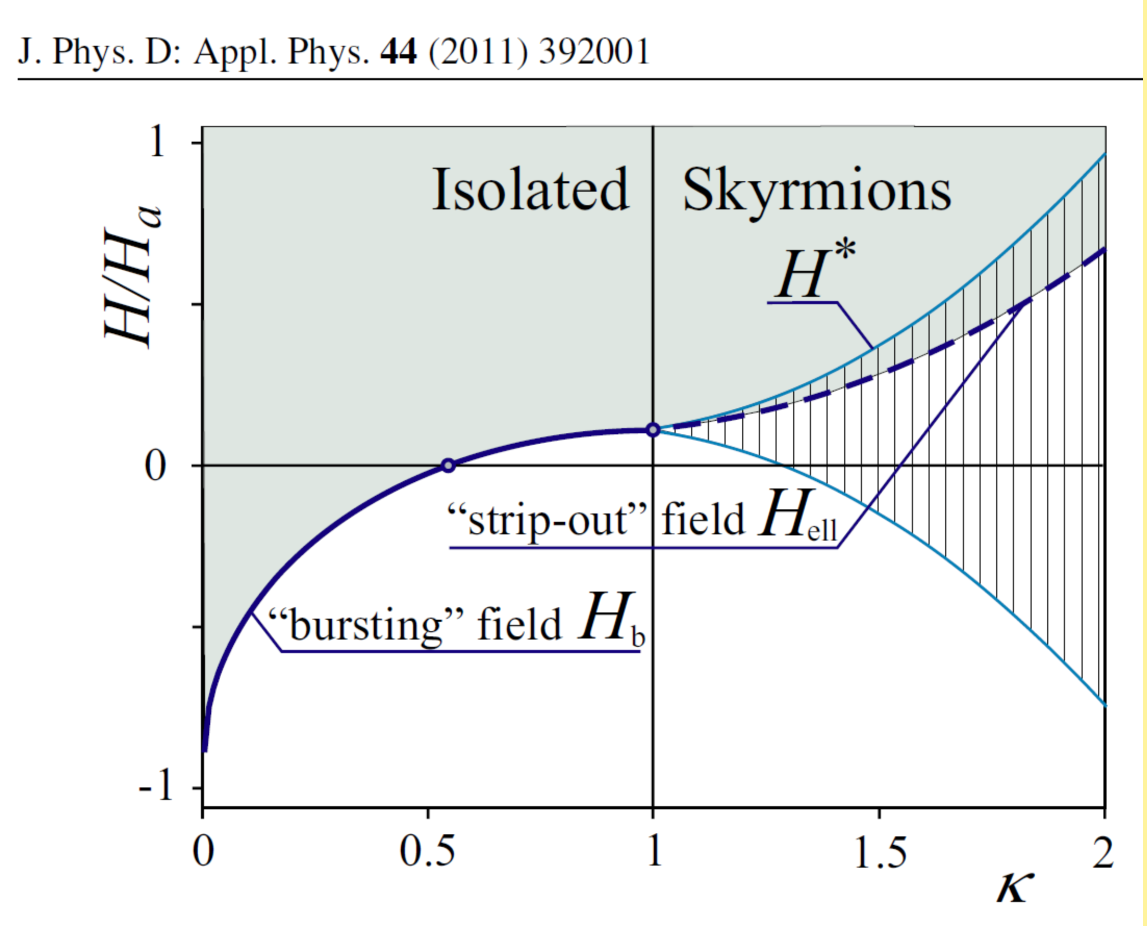


Isolated skyrmions:

Nanolayer of Fe0.5Co0.5Si (L = 20 nm) for $H \approx$ 50mT (Yu (2010, 2011).

Kiselev J. Phys. D: Appl. Phys. 44 (2011) 392001

Skyrmion phase diagram (Applied field Vs. Kappa)



Ha=K/M

κ=πD/4sqrt(AK)

D – Dzyaloshinsky-Moriya Coefficient

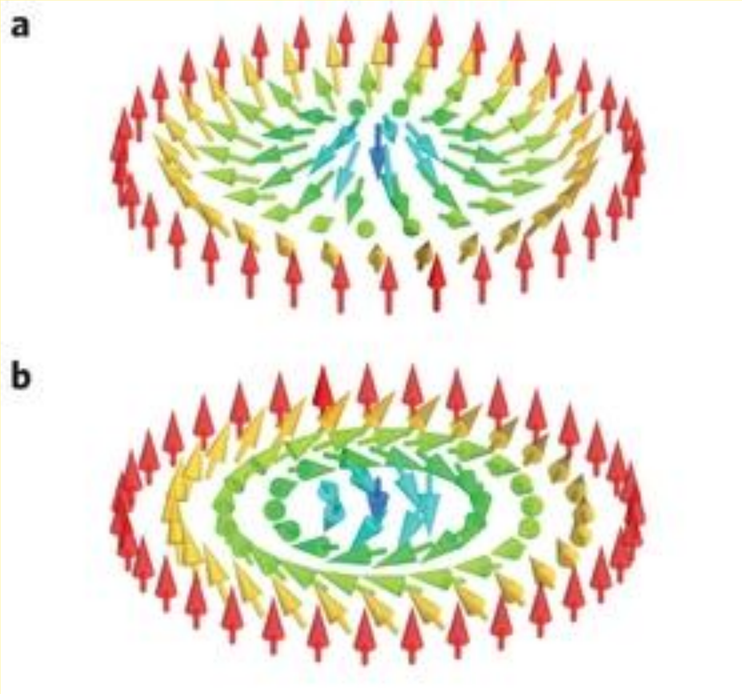
K – anisotropy

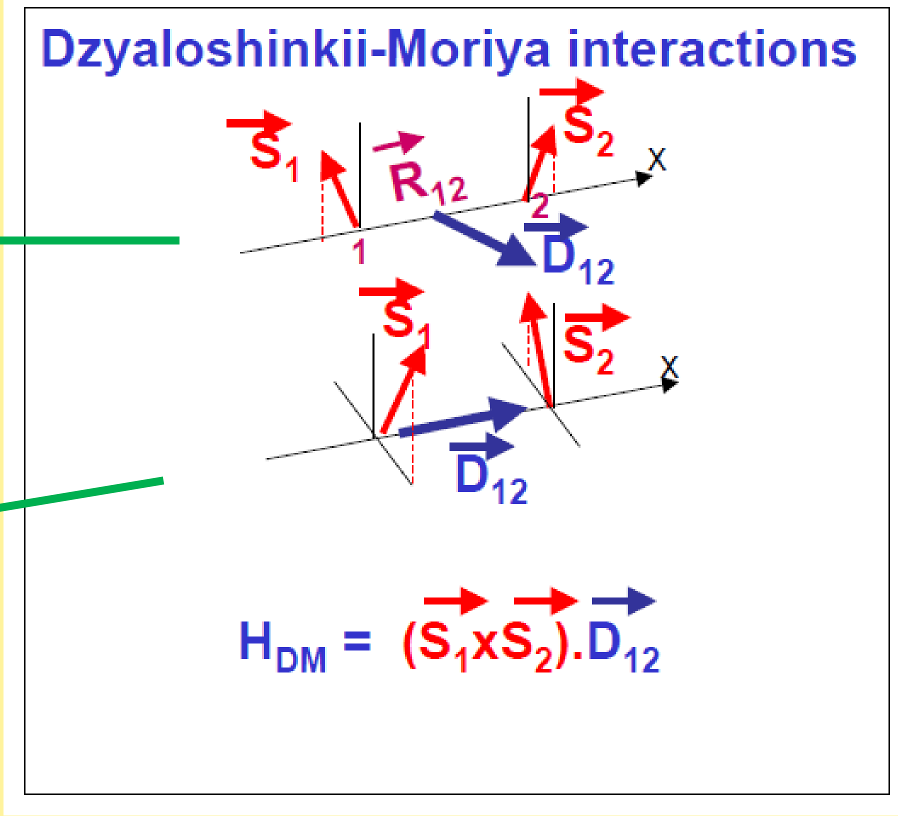
A – exchange stiffness

Kiselev J. Phys. D: Appl. Phys. 44 (2011) 392001

Diagram for film of thickness L (fixed ratios K/M and L/W_{DW})
(in the hatched area spatially modulated skyrmion phases are stable)

Dzyaloshinskii–Moriya interactions



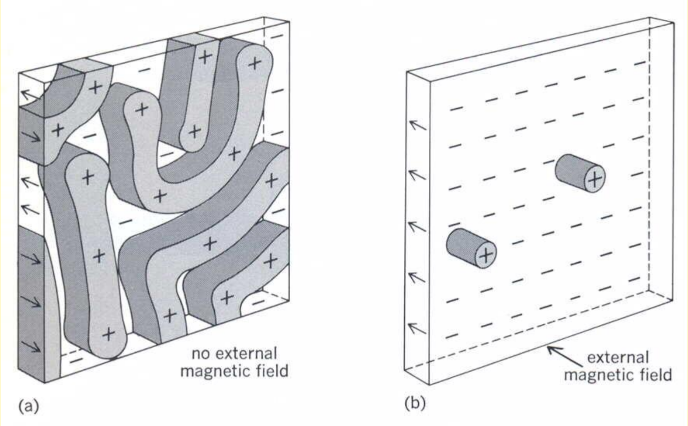

Dzyaloshinkii-Moriya interactions

$$H_{DM} = (\vec{S}_1 x \vec{S}_2).\vec{D}_{12}$$

Fert 2012

Magnetic bubbles

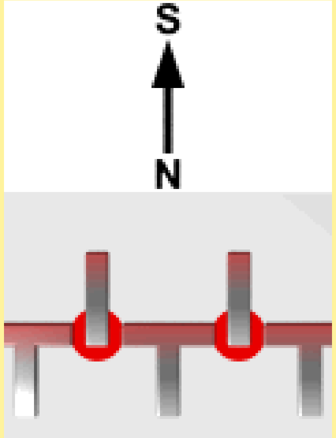
Cylindrical domains with perpendicular magnetization in magnetic films (e.g., of ferrite, garnet)



H=0 H≠0

Bubble radius of the order of 1 micron

Applications to magnetic memories studied in the 1960s and 1970s



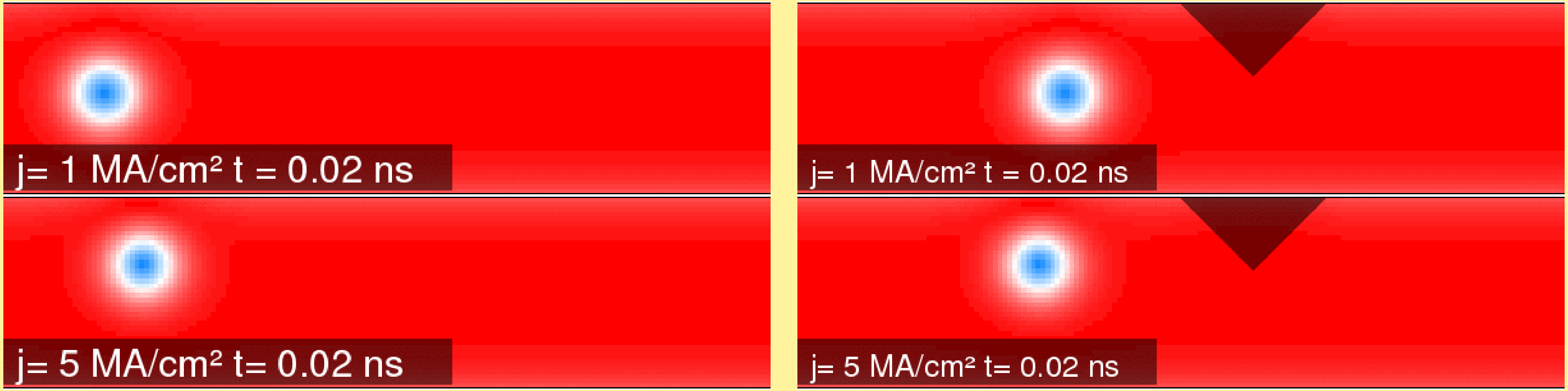
Wikipedia

Skyrmions on the track

Albert Fert, Vincent Cros and João Sampaio

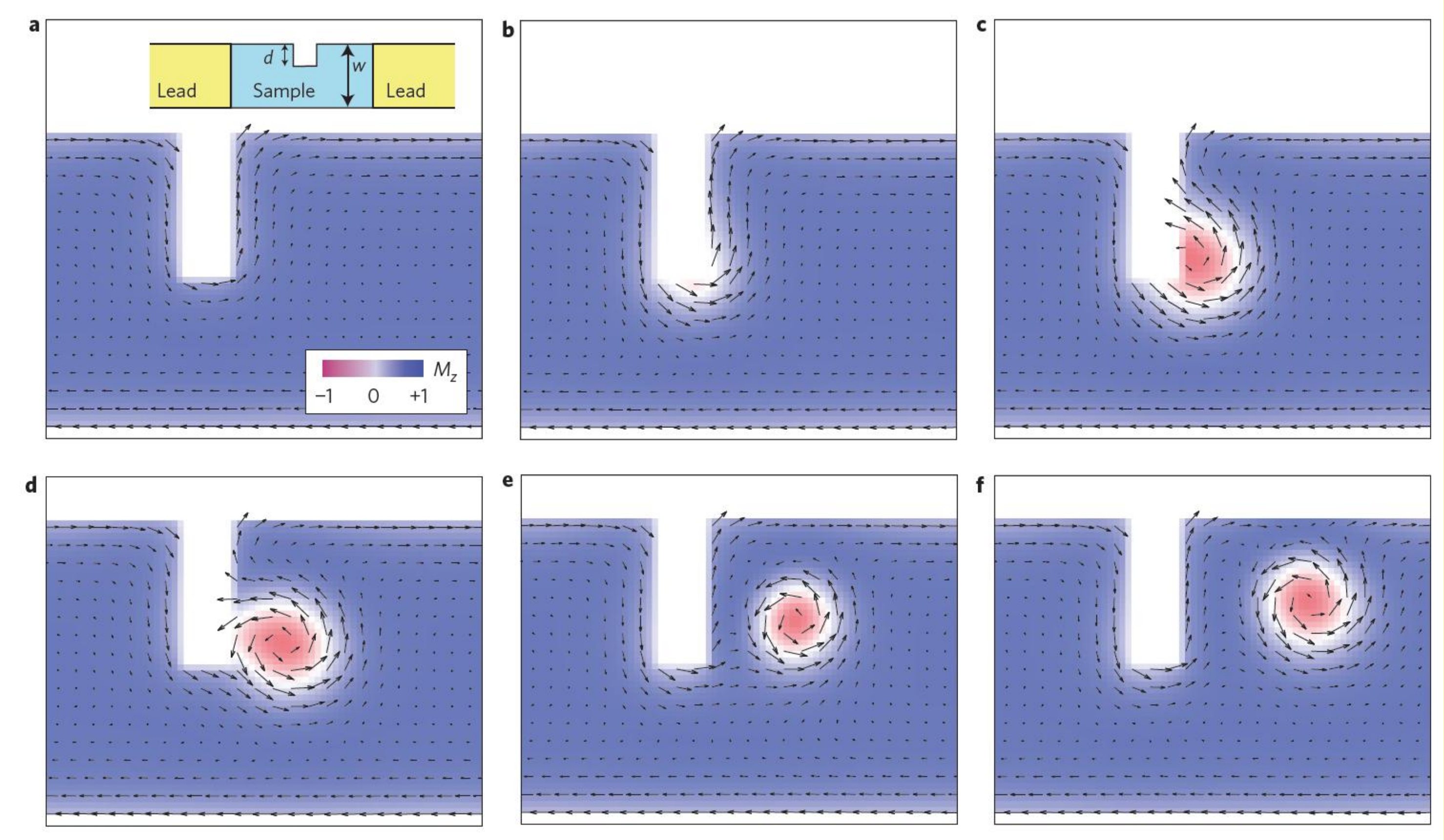
Magnetic skyrmions are nanoscale spin configurations that hold promise as information carriers in ultradense memory and logic devices owing to the extremely low spin-polarized currents needed to move them.

NATURE NANOTECHNOLOGY | VOL 8 | MARCH 2013 |

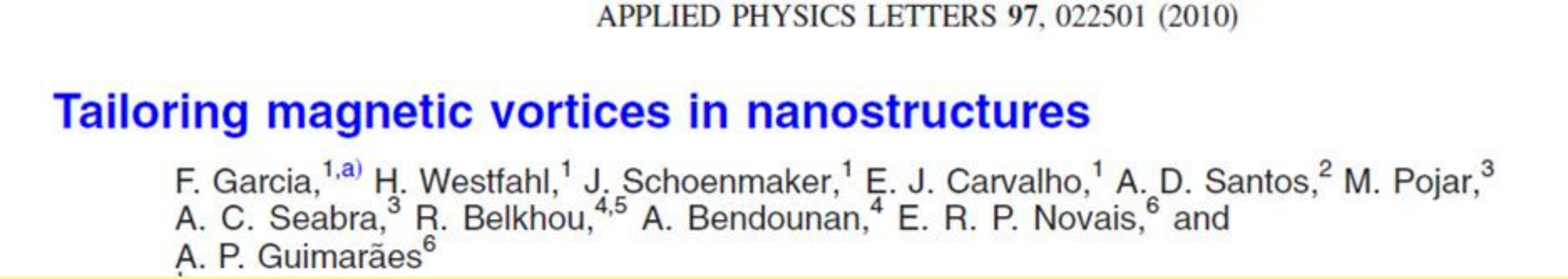


Current-induced motion of a skyrmion on a Co stripe – low depinning currents

Creation of skyrmions



Iwasaki et al. Nat. Nano. 8 (2013)

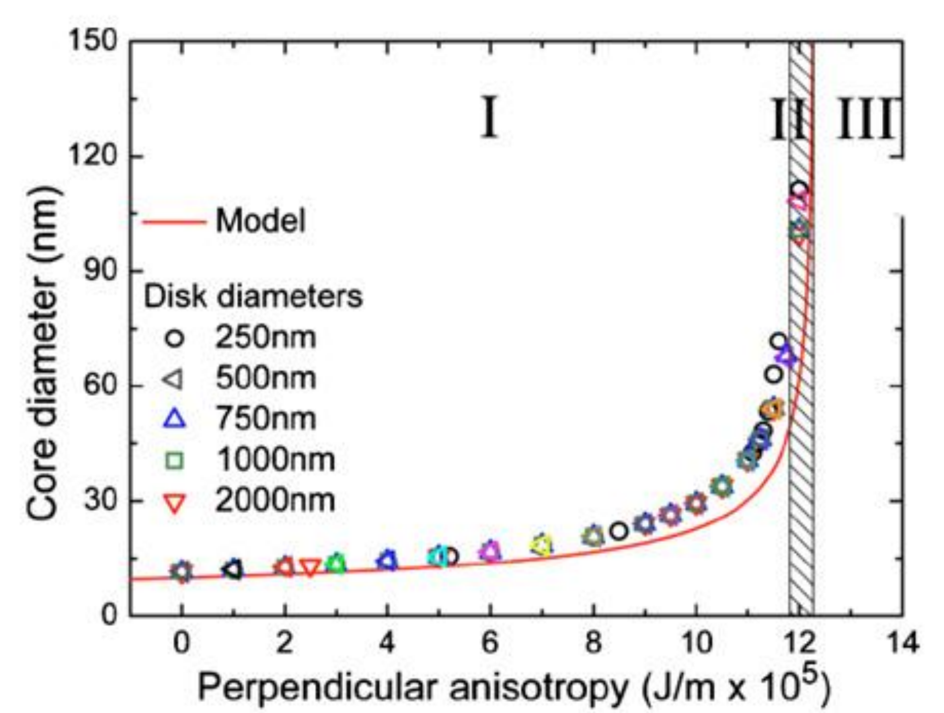

APPLIED PHYSICS LETTERS 97, 022501 (2010)

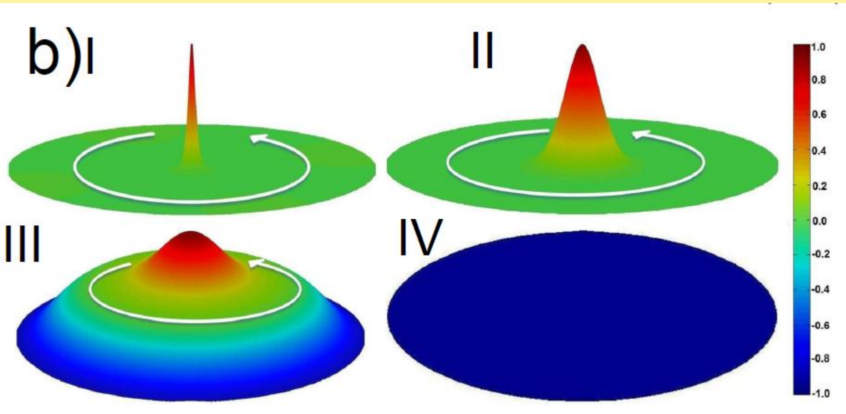
Tailoring magnetic vortices in nanostructures

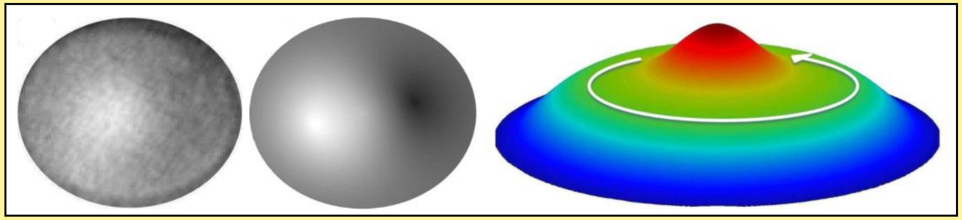
F. Garcia,[1,a)] H. Westfahl,[1] J. Schoenmaker,[1] E. J. Carvalho,[1] A. D. Santos,[2] M. Pojar,[3]
A. C. Seabra,[3] R. Belkhou,[4,5] A. Bendounan,[4] E. R. P. Novais,[6] and
A. P. Guimarães[6]

Tuning the properties of the vortex:

Varying the Co thickness in Co/Pt multilayers, the anisotropy K_z can be increased, and the vortex core diameter also increases.

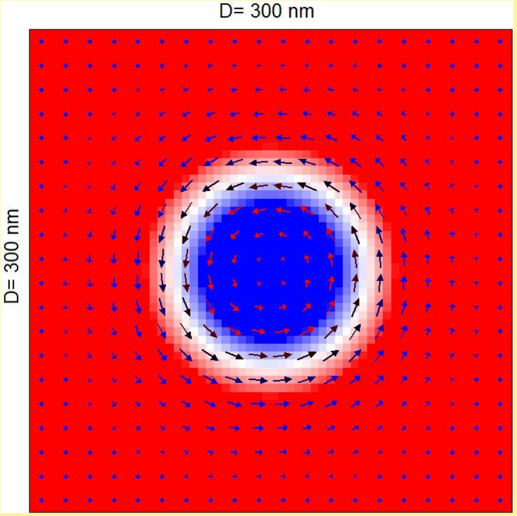


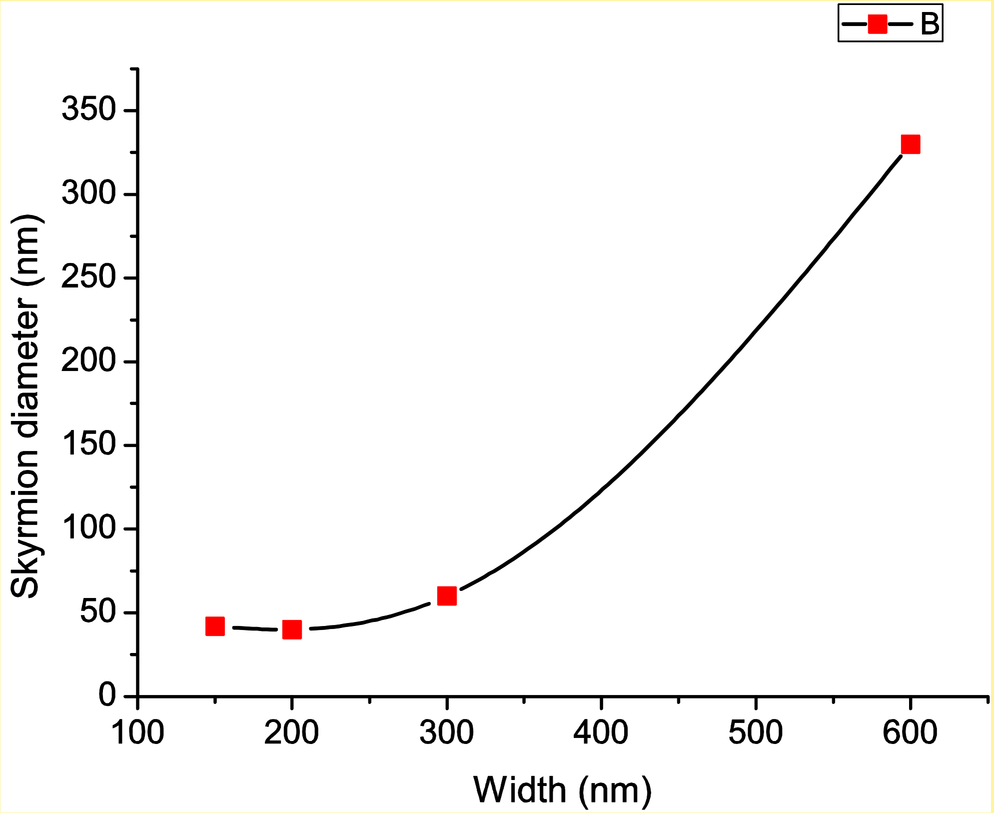



1 2 3

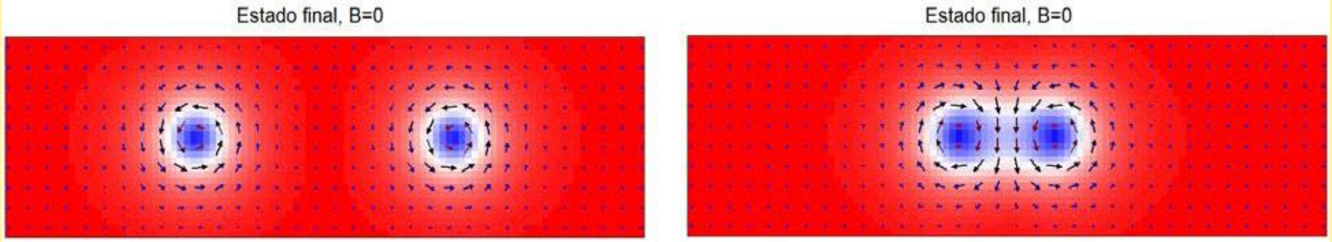
1.PEEM image, 2. simulation, 3. simulation

Skyrmions without DM



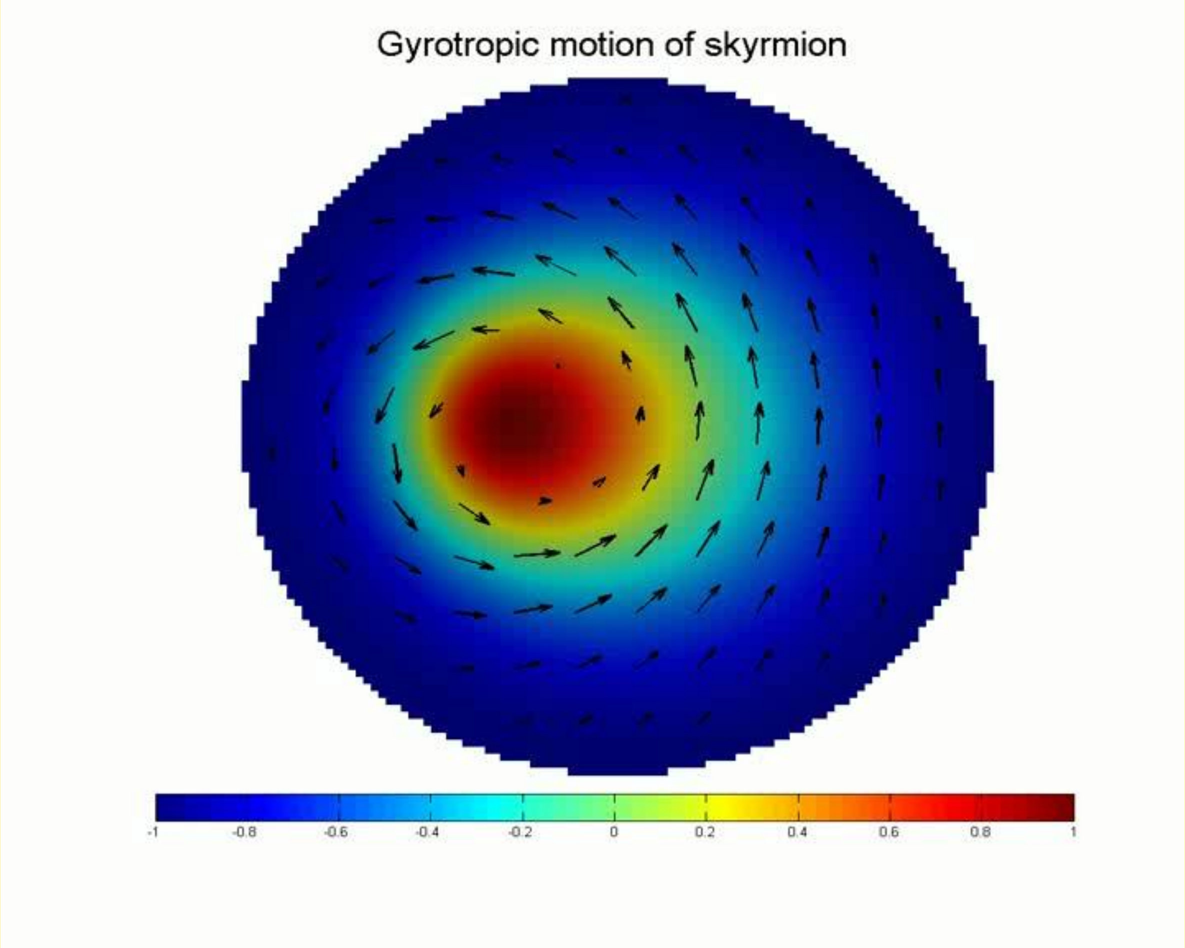


Diameter vs. stripe width



Novais , unpublished (2013)

Motion of a skyrmion



Simulation of the motion of a skyrmion in a CoPt disk, with perpendicular anisotropy Kz=1.2X10^{6} J /m^{3}

Novais , unpublished (2013)

Summary

Topological properties of magnetic systems are relevant for their dynamic behavior

Magnetic vortices and skyrmions are topological defects

Skyrmions are stable structures, topologically protected, related to magnetic vortices and to magnetic bubbles

Skyrmions may be stable with or without DM interaction

Skyrmions may be displaced through the action of polarized currents, with much smaller current densities than domain walls

Skyrmions may have applications in memory devices

Some general References

A. P. Guimarães, Principles of Nanomagnetism, Springer (2009)

K. Y. Guslienko, J. Nanoscience Nanotechnol., 8 2745-2760 (2008)

A.M. Kosevich et al. Phys. Repts. 194, Nos. 3 & 4 117—238 (1990).

Menzel, Thesis, Hamburg University (2011)

Thank you!