MAGNETIC STRUCTURES

DOMAIN WALLS, VORTICES, SKYRMIONS ETC

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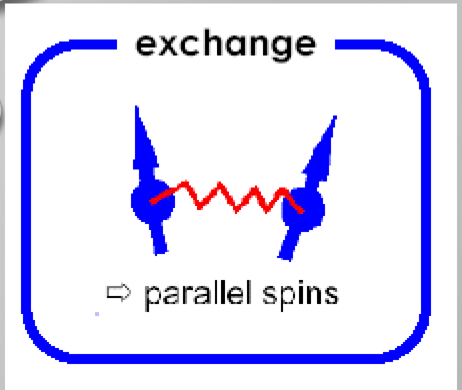
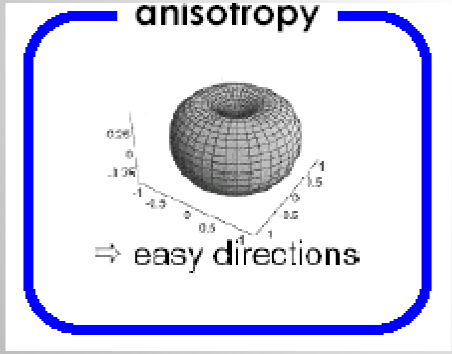
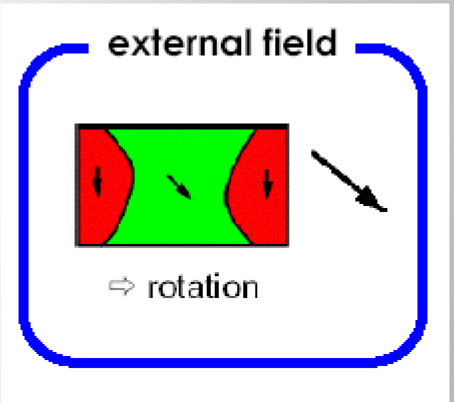
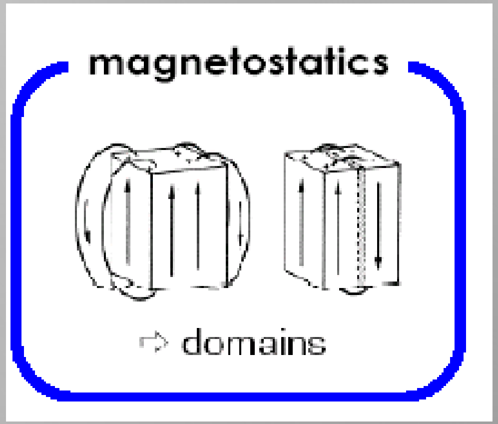
CSIC, SPAIN

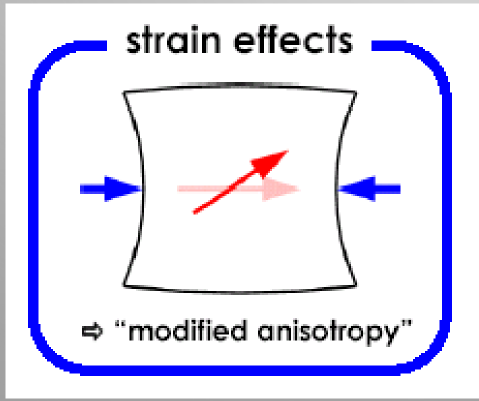
MAGNETIC ENERGIES

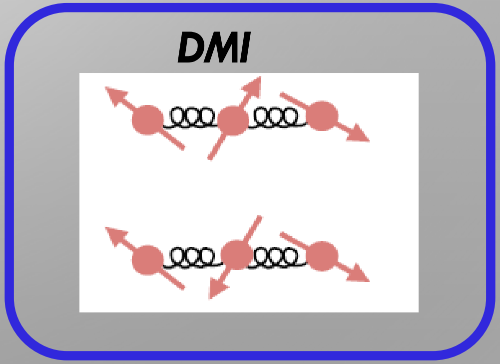


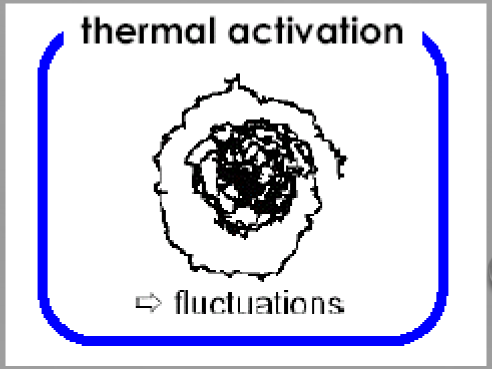












The relevance of different energies depend on the system dimensions

Important Length scales:

- *Domain wall width*

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

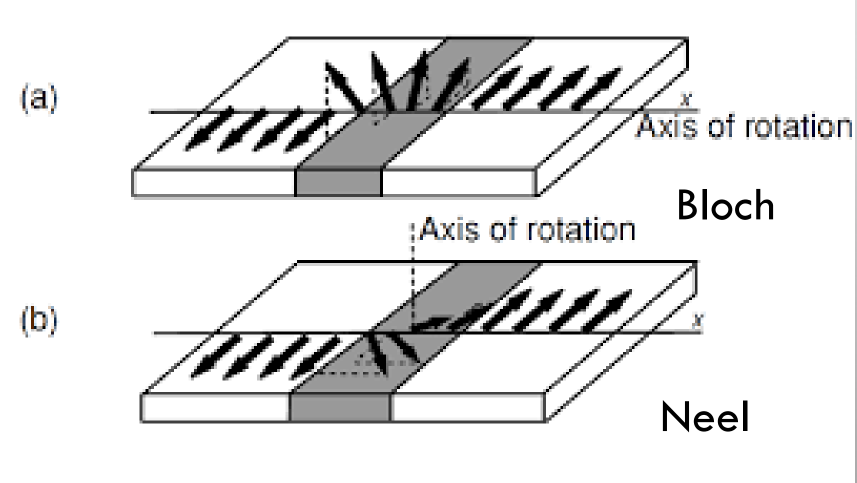
- Exchange correlation length

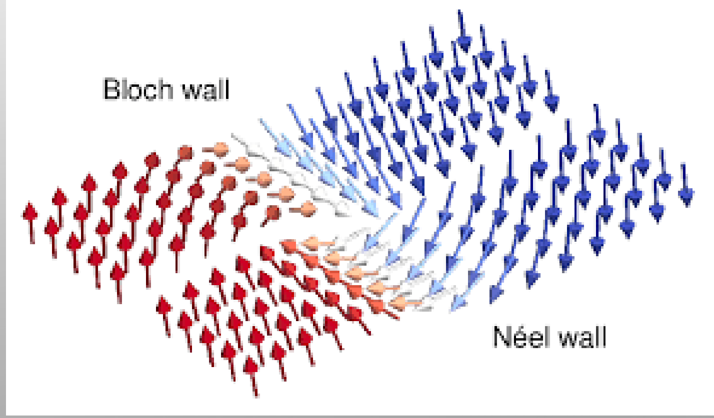
$$l_o = (A/\mu_o M_s^2)^{1/2}$$

- *Critical nanoparticle diameter to form domains*

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

NEEL AND BLOCH DOMAIN WALLS

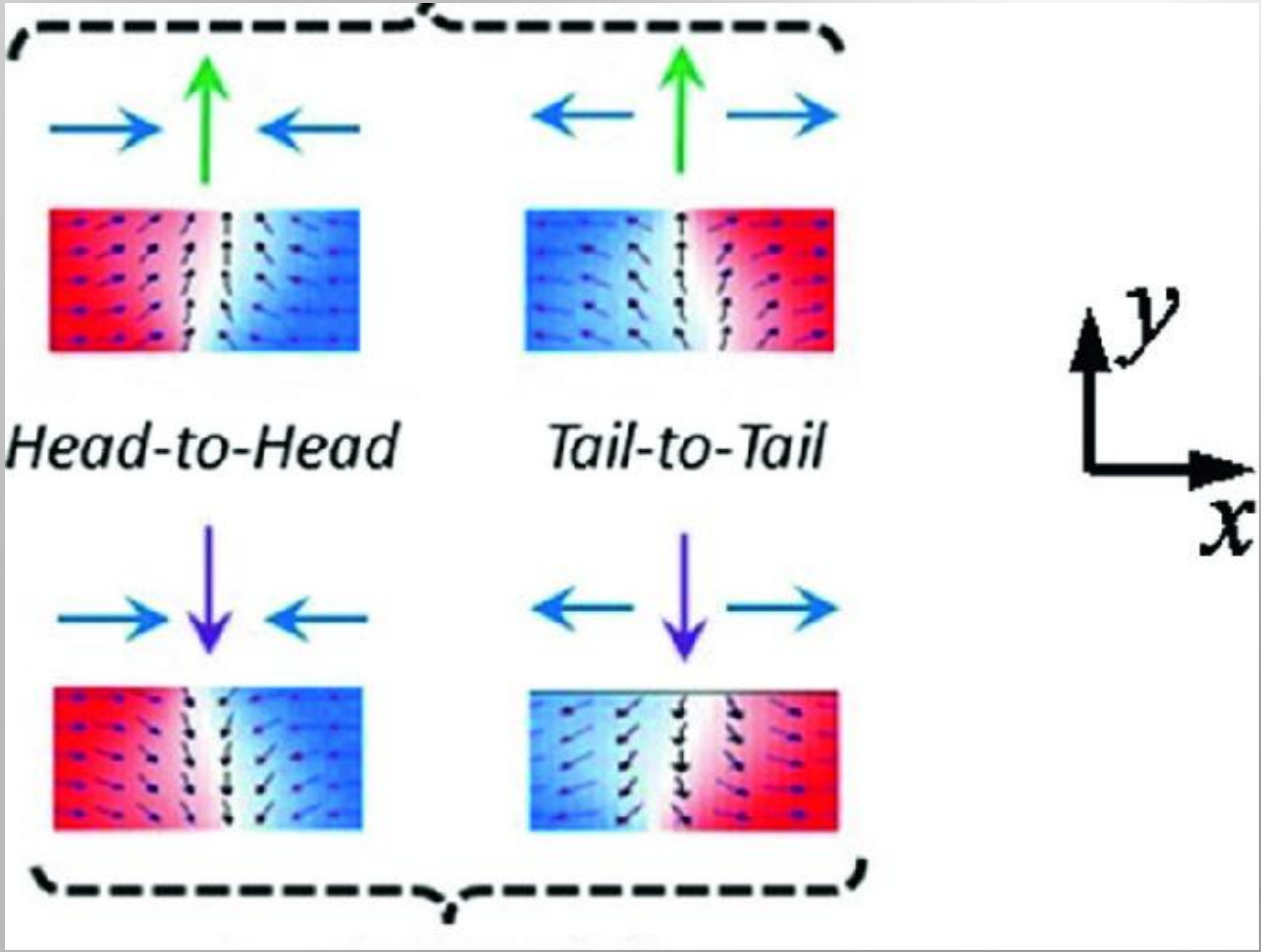




In-plane materials

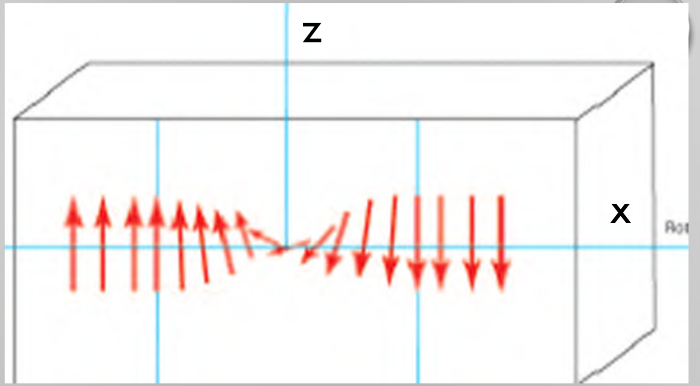
Out-of-plane materials

IN-PLANE (NEEL) DOMAIN WALLS



Carry “magnetic” charges

1D MODEL



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

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

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

$m_z = \tanh(x/\Delta)$; $m_y = 1/\cosh(x/\Delta)$

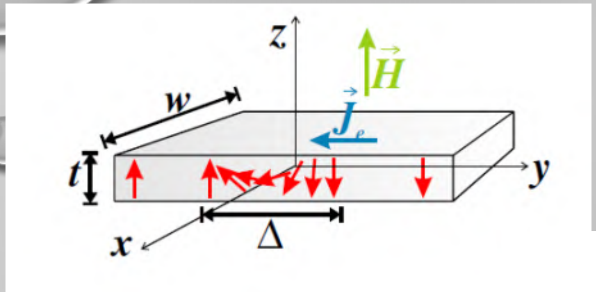
$m_z = \tanh(x/\Delta)$; $m_x = 1/\cosh(x/\Delta)$

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

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

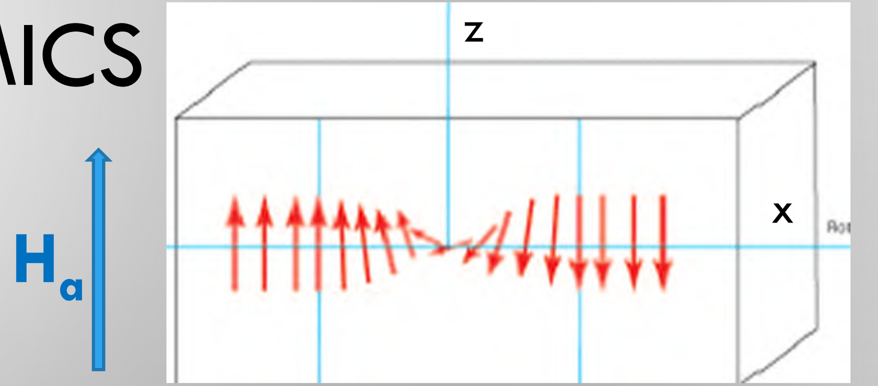
$$\Delta = \sqrt{A/K_u}$$

1D MODEL: DYNAMICS



$$\frac{d\mathbf{m}}{dt} = \gamma_0 \mathbf{H}_{eff} \times \mathbf{m} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt}$$

$$\mathbf{H}_{eff} = -\frac{1}{\mu_0 M_s}\frac{\delta E}{\delta \mathbf{m}}$$



Applied field tilts magnetic moments out-of-plane

In spherical coordinates

$$\dot{\theta} + \alpha \sin\theta \dot{\varphi} = \gamma_0 H_{\varphi},$$

$$\alpha\dot{\theta} - \sin\theta \dot{\varphi} = \gamma_0 H_{\theta},$$

Bloch domain wall

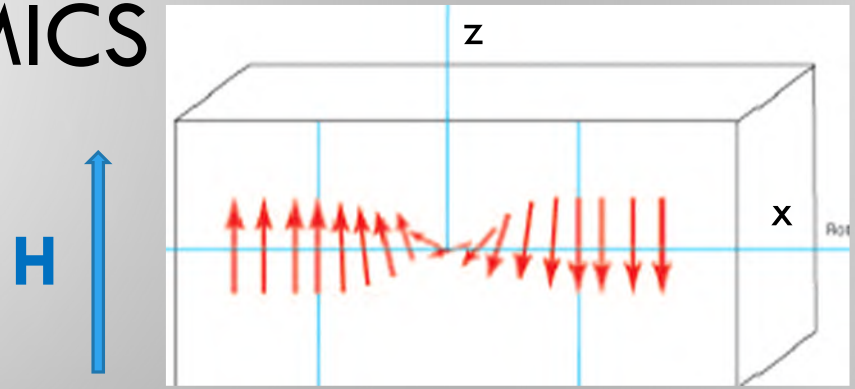
Collective coordinate approach:

$$\theta(x,t) = 2\tan^{-1} exp\left(\frac{x - q(t)}{\Delta(t)}\right); \qquad \varphi(x,t) = \phi(t).$$

$$\alpha\frac{\dot{q}}{\Delta} + \dot{\phi} = \gamma_0 H_a$$

$$\frac{\dot{q}}{\Delta} - \alpha\dot{\phi} = \gamma_0 H_K \frac{\sin 2\phi}{2}$$

1D MODEL: DYNAMICS



$$\dot{\phi} = \frac{\gamma_0}{1+\alpha^2}\left(H_a - \frac{\alpha}{2} H_K \sin 2\phi\right)$$

if $H_K = 0$

$$\dot{\phi} = \frac{\gamma_0 H_a}{1+\alpha^2}$$

Precession and movement with a constant velocity

$H_K \neq 0$

$$\dot{\phi} \doteq 0$$

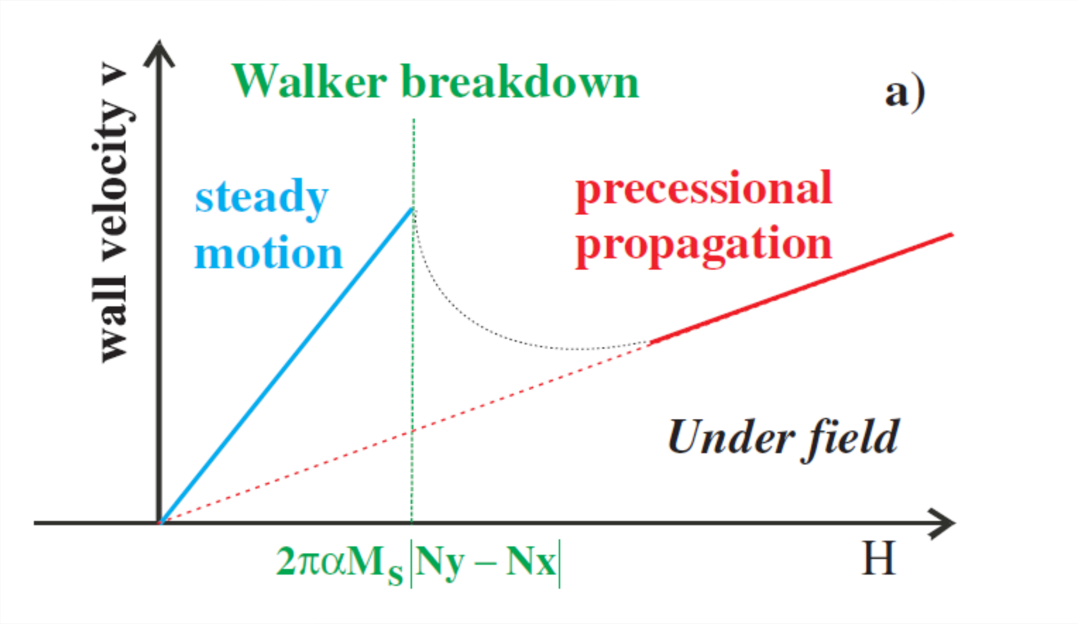
Defines stationary domain wall angle, it exists if $H_a < \frac{\alpha H_K}{2}$ Walker field

In soft materials $H_K = 4\pi M_s^2 (N_x - N_y)$

Velocity below Walker field

The Walker break-down field $H_W = 2\pi\alpha M_s \left(N_x - N_y\right)$

WALKER BREAKDOWN PHENOMENON



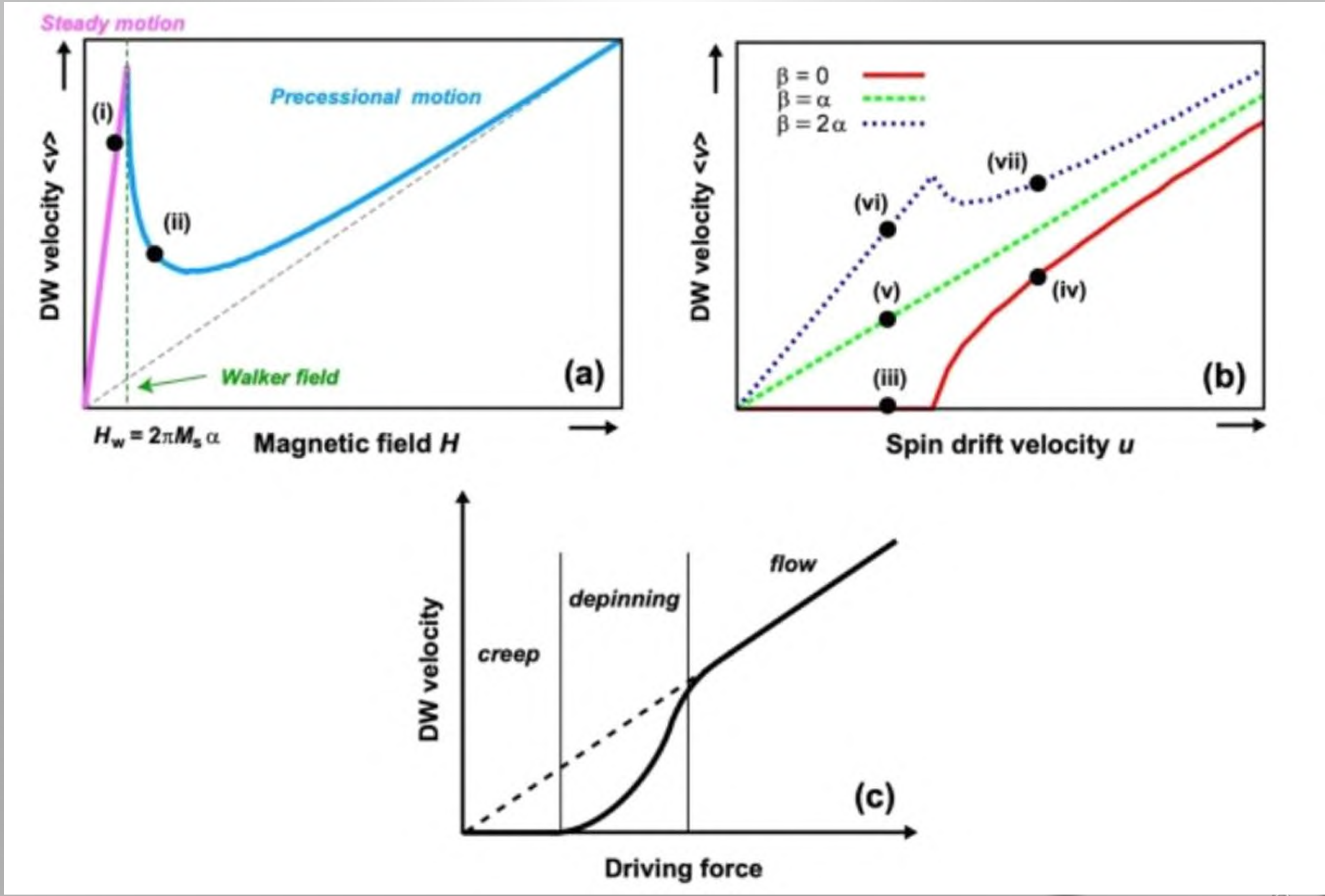
Below Walker breakdown

$$v = \frac{\gamma \Delta H_a}{\alpha}$$

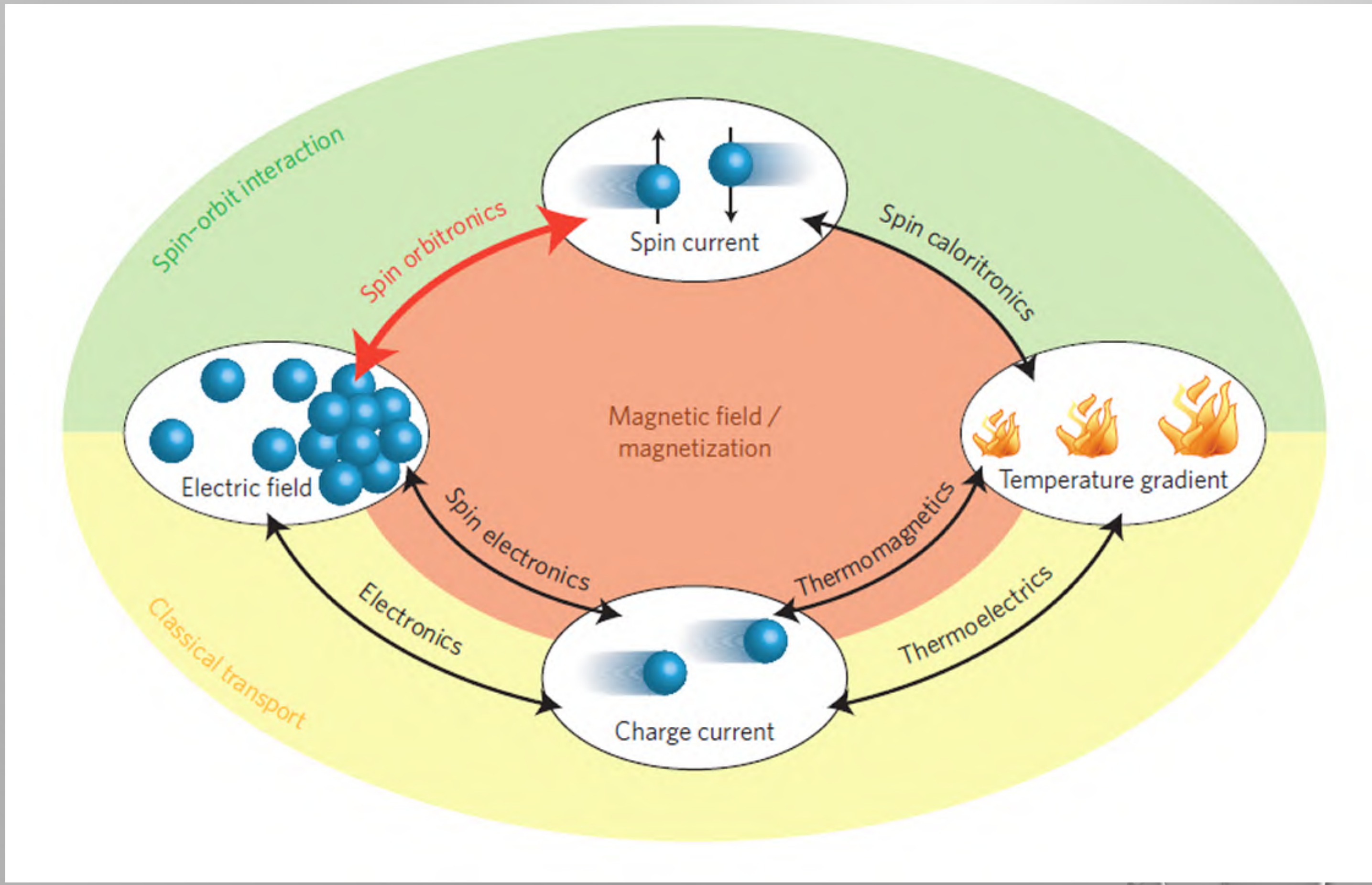
Above Walker limit
(averaging over precessional period)

$$v = \frac{\gamma \Delta \alpha H_a}{(1 + \alpha^2)}$$

WALKER BREAKDOWN PHENOMENON

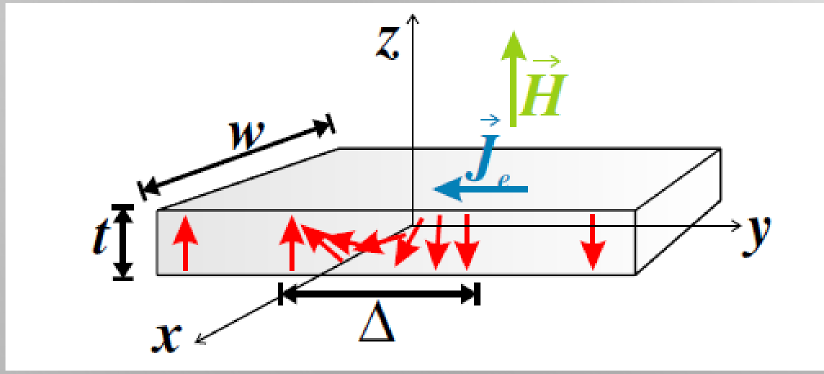


DOMAIN WALL MOTION



1. Field
2. Current
3. Thermal gradient
4. Laser

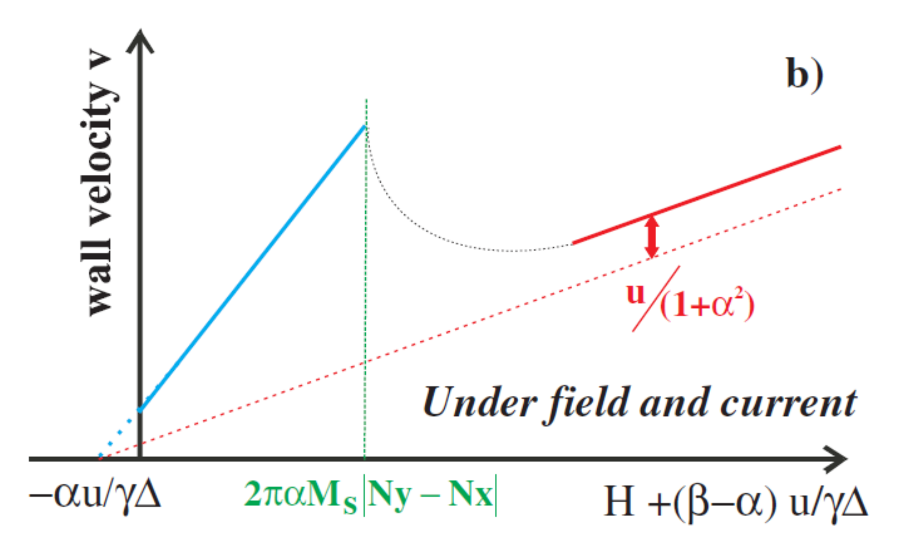
WITH CURRENT



Zhang-Li model

$$\frac{\partial \vec{M}}{\partial t} = \gamma \vec{H}_{eff} \times \vec{M} + \frac{\alpha}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial t} - u \frac{\partial \vec{M}}{\partial y} + \frac{\beta u}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial y}$$

$$\left| H + (\beta - \alpha) \frac{u}{\gamma \Delta} \right| \leqslant H_W$$

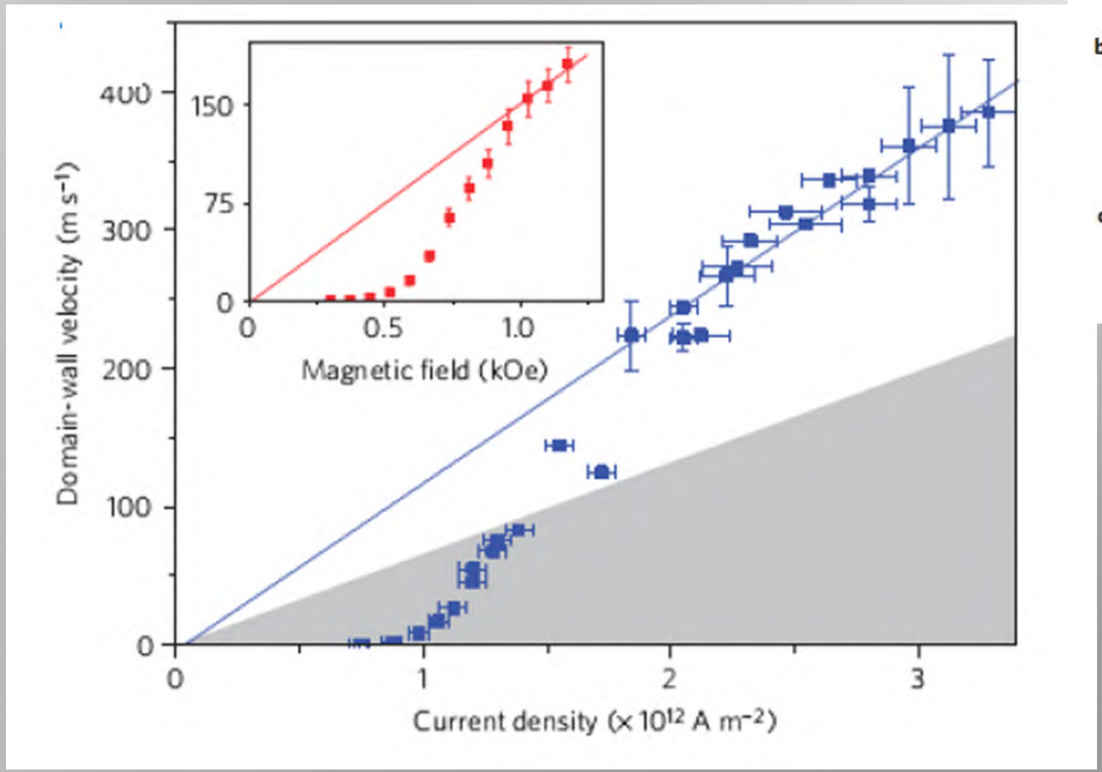


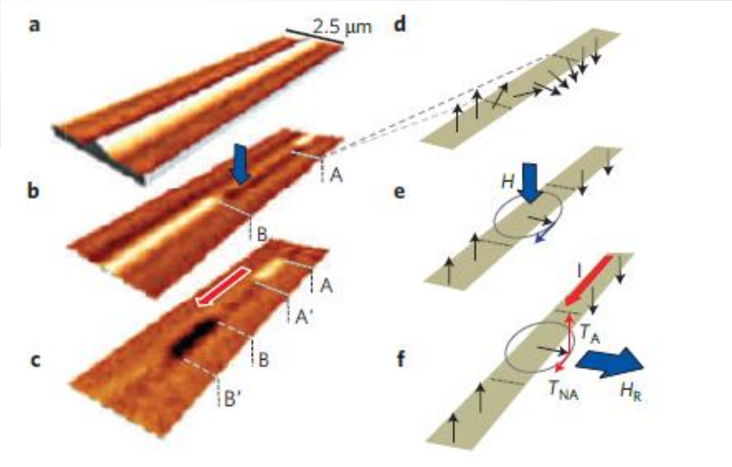
A.Mougin et al EPL 78 (2007) 57007

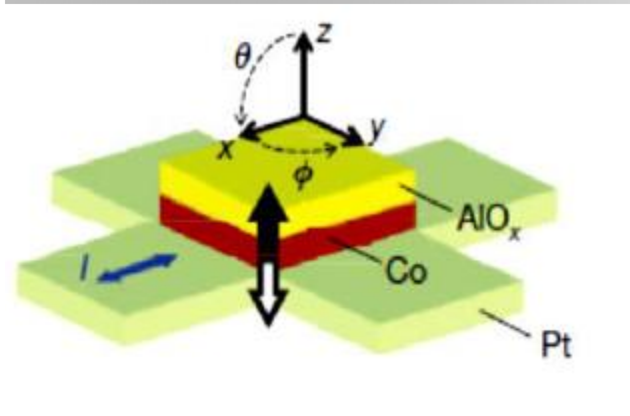
SPIN-ORBIT TORQUE

Pt/Co/AlO multilayers with spin-orbit field-like torque

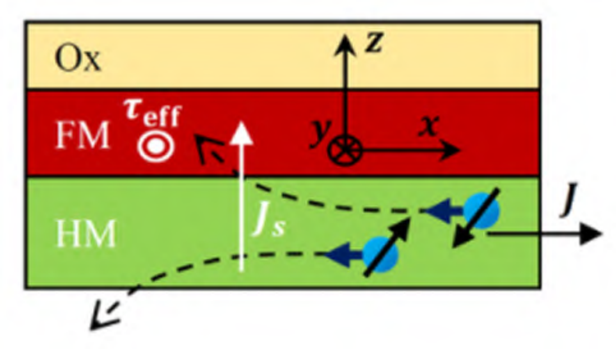
I.Miron Nature 2011



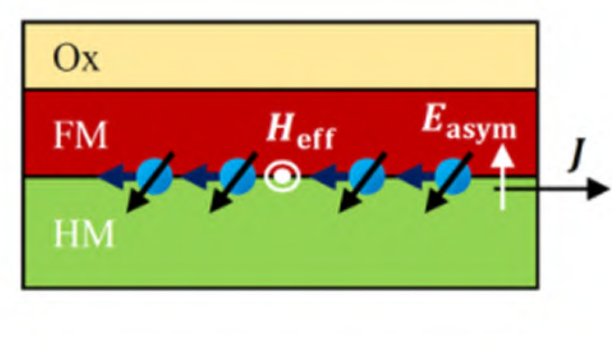




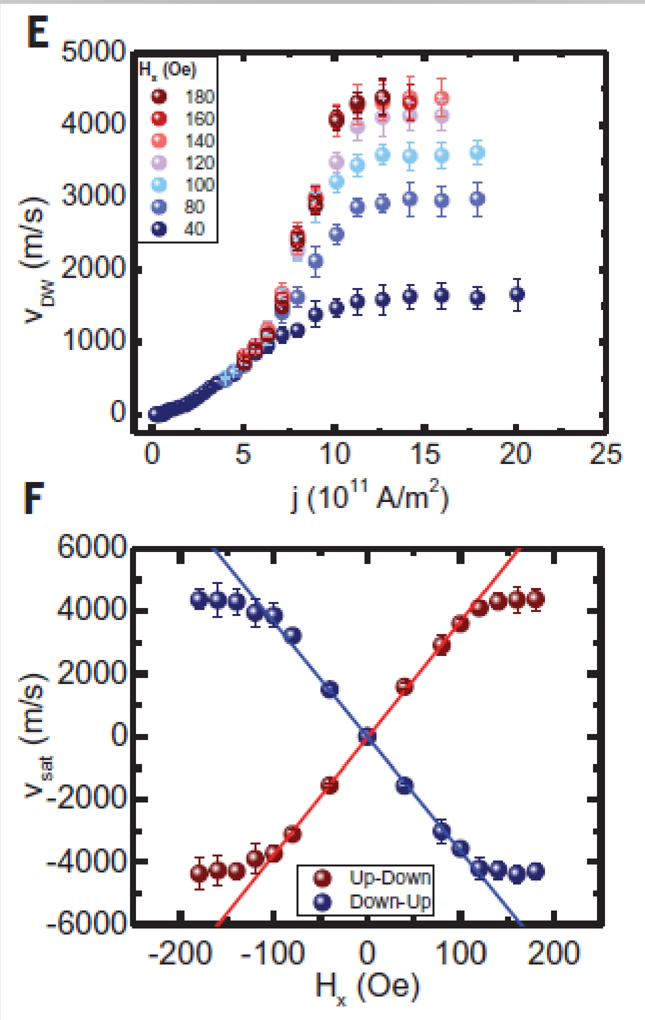
Spin-Hall effect

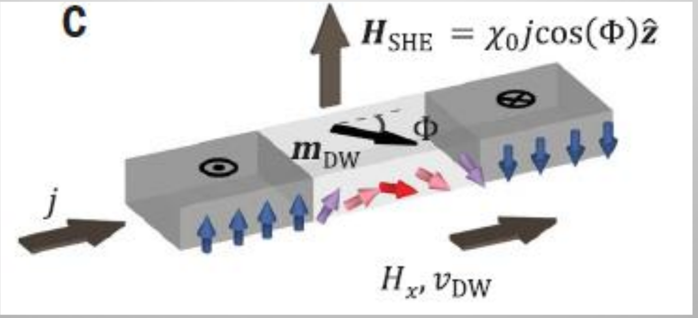


Rashba field



“RELATIVISTIC” DOMAIN WALL VELOCITY



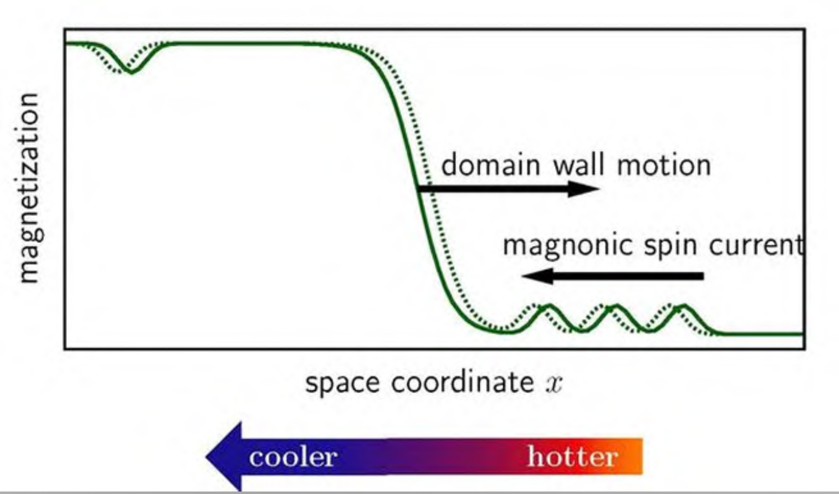


$$\frac{\partial^2\theta}{\partial t^2} - c_{\mathrm{m}}^2\frac{\partial^2\theta}{\partial x^2} + \frac{c_{\mathrm{m}}^2}{\Delta_0^2}\sin\theta = 0$$

Caretta *et al.*, *Science* **370**, 1438–1442 (2020)

Ferrimagnetic Bi-YIG
Low damping

DOMAIN WALL MOTION BY SPIN-SEEBECK EFFECT (TEMPERATURE GRADIENTS)



D. Hinzke and U. Nowak

Phys. Rev. Lett. 107, 027205 (2011)

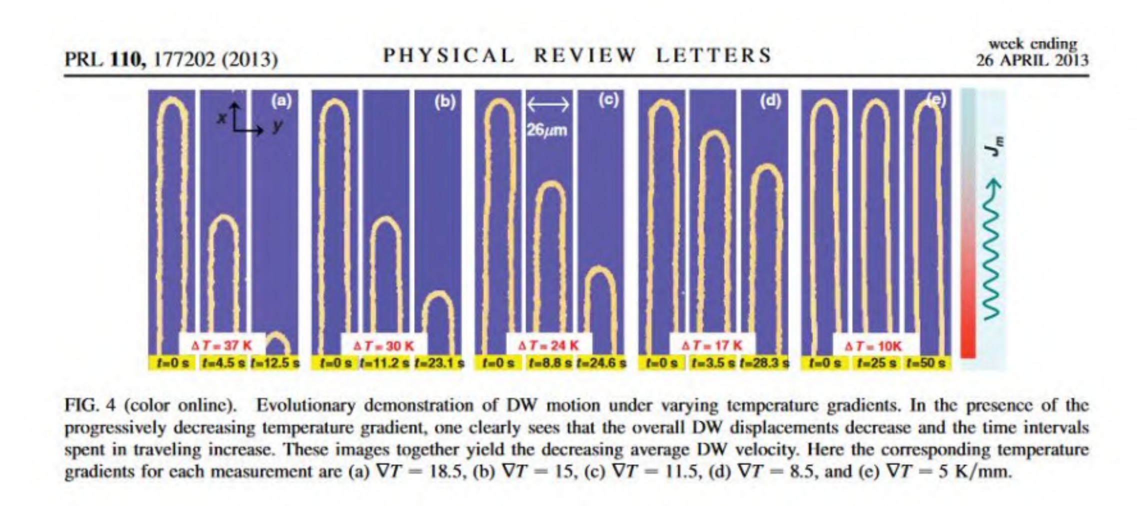
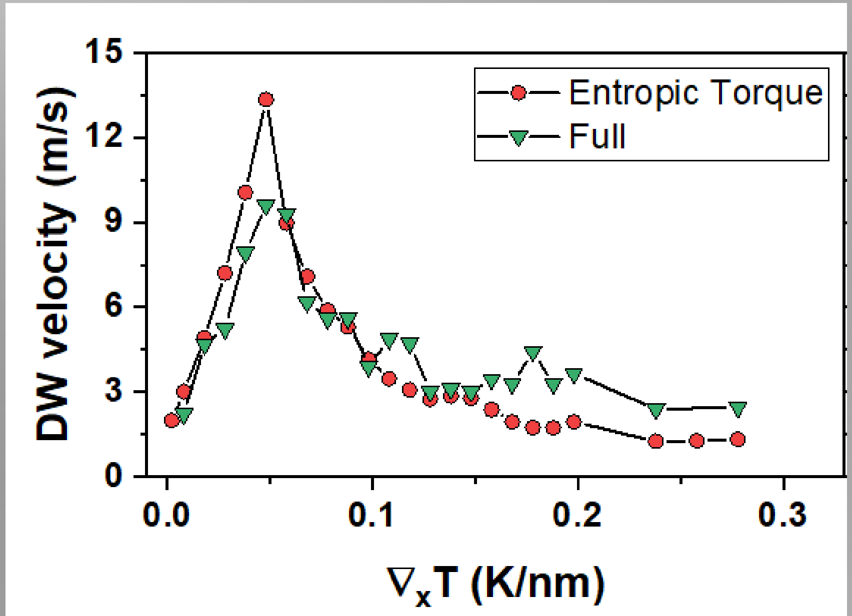

PRL 110, 177202 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

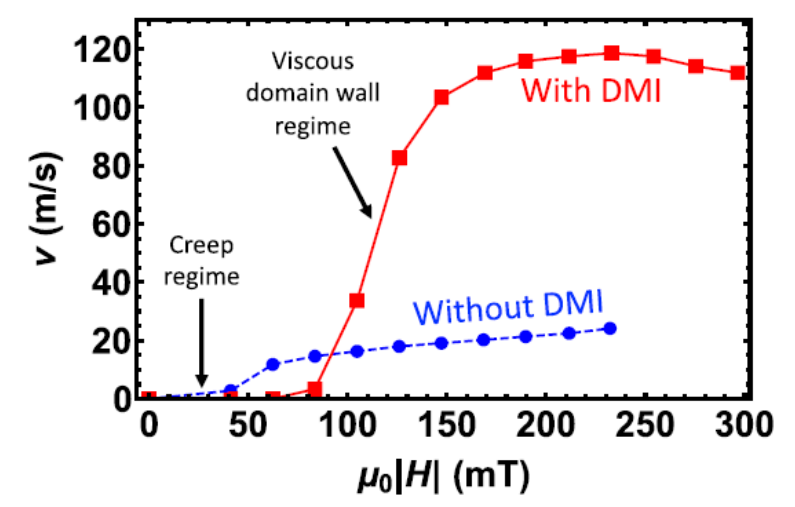
FIG. 4 (color online). Evolutionary demonstration of DW motion under varying temperature gradients. In the presence of the progressively decreasing temperature gradient, one clearly sees that the overall DW displacements decrease and the time intervals spent in traveling increase. These images together yield the decreasing average DW velocity. Here the corresponding temperature gradients for each measurement are (a) $\nabla T = 18.5$, (b) $\nabla T = 15$, (c) $\nabla T = 11.5$, (d) $\nabla T = 8.5$, and (e) $\nabla T = 5$ K/mm.

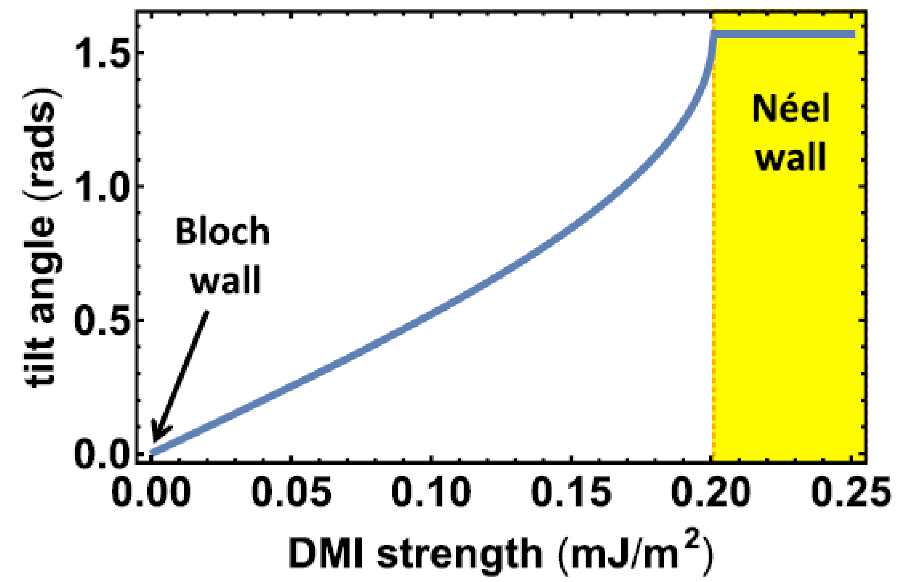


W.Jiang et al

DOMAIN WALLS WITH DMI

$$\sigma_{\text{Néel}} = 4\sqrt{AK} \pm \pi D, \quad \text{and} \quad \sigma_{\text{Bloch}} = 4\sqrt{AK}.$$

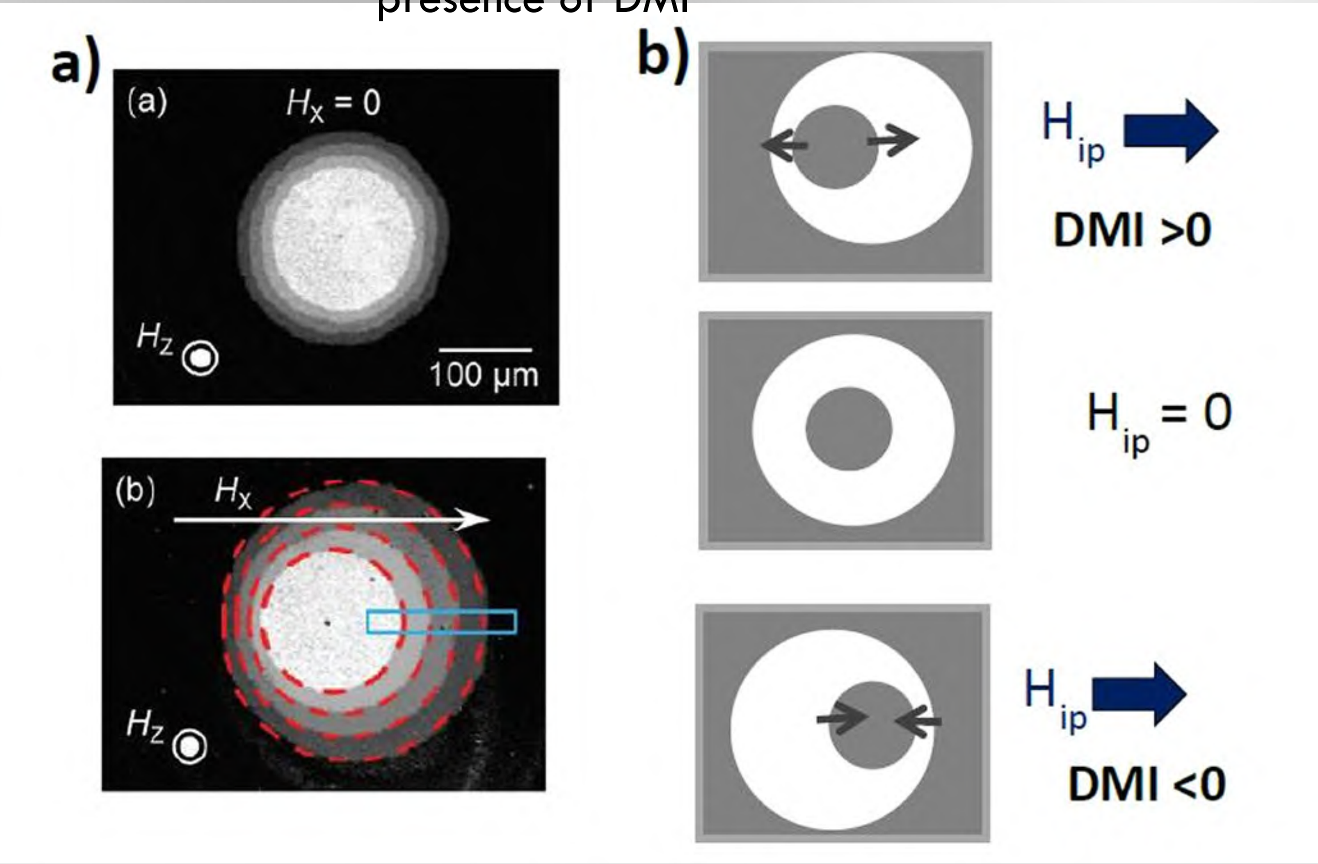




Surface Science Reports 78 (2023) 100605

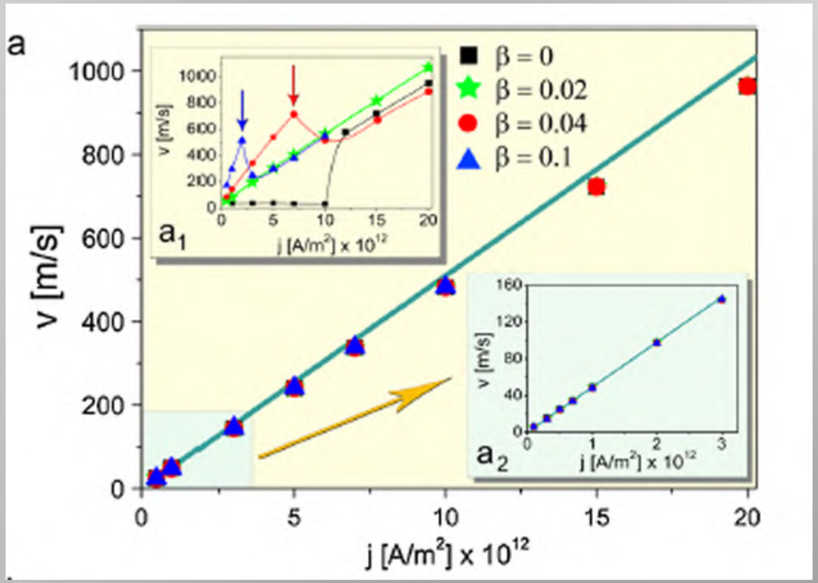
DW MOTION IN THE PRESENCE OF DMI

Asymmetric bubble expansion in the presence of DMI

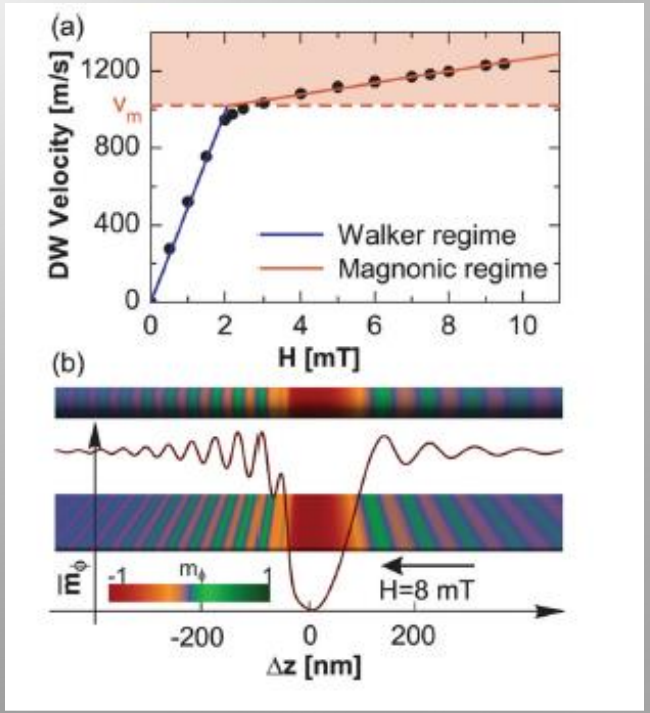


S.Je et al (2013)

DYNAMICS OF TRANSVERSE DWS IN CYLINDRICAL NANOWIRES AND NANOTUBES
THE ABSENCE OF THE WALKER BREAKDOWN PHENOMENON AND CHIRAL EFFECTS

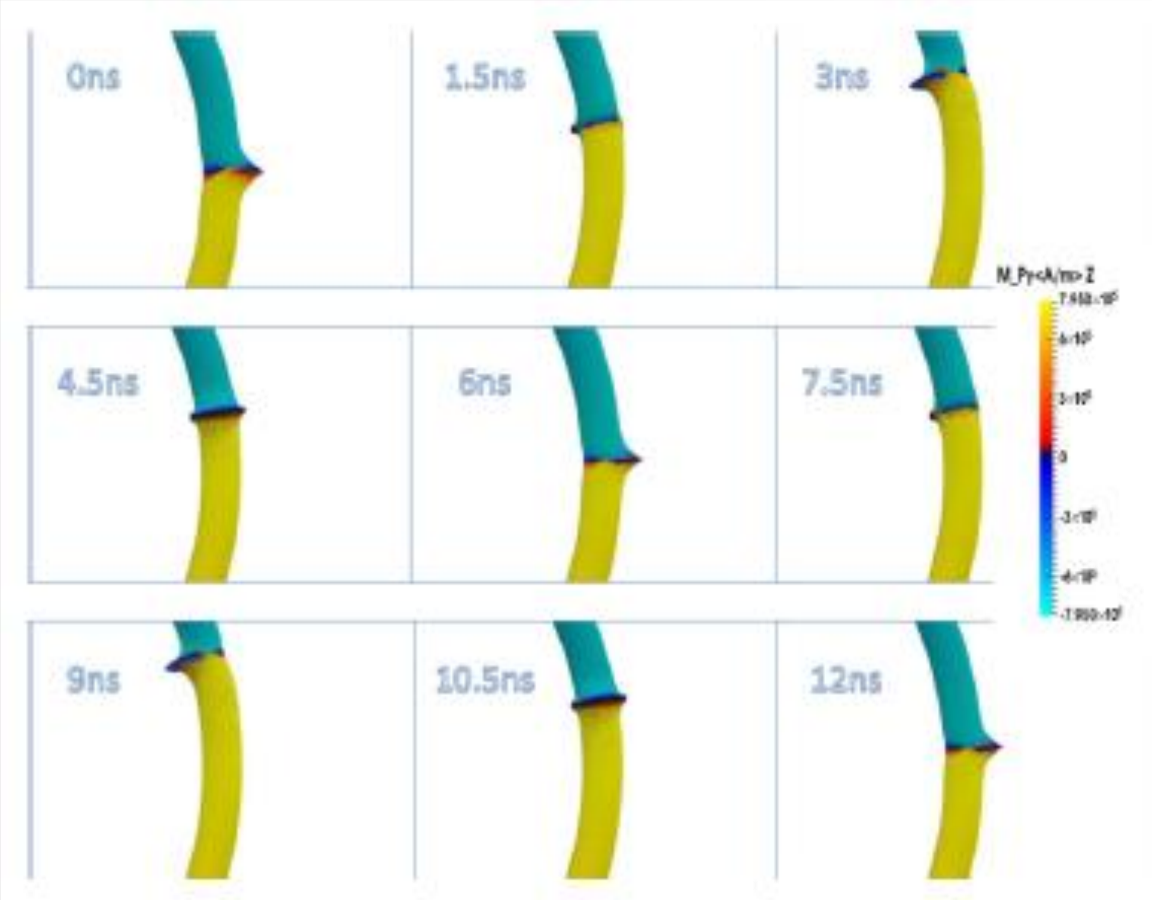


M.Yan et al PRL 104, 057201 (2010)



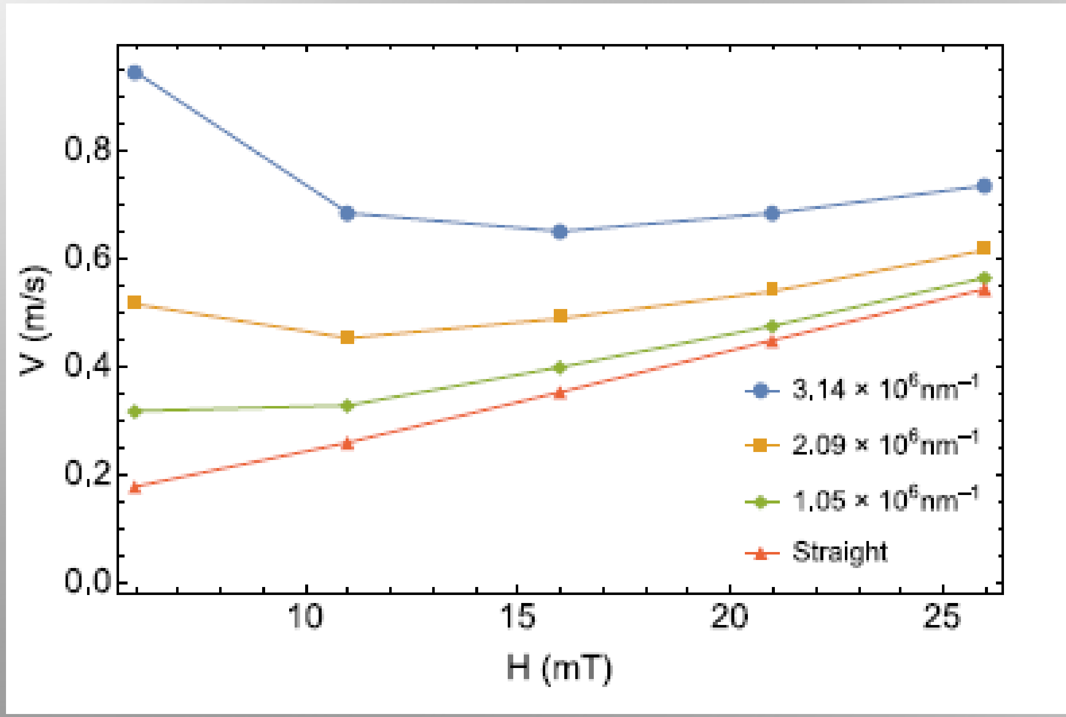
R.Hertel, J.Phys: Cond Mat 28 (2016)

DYNAMICS IN BENT NANOWIRE



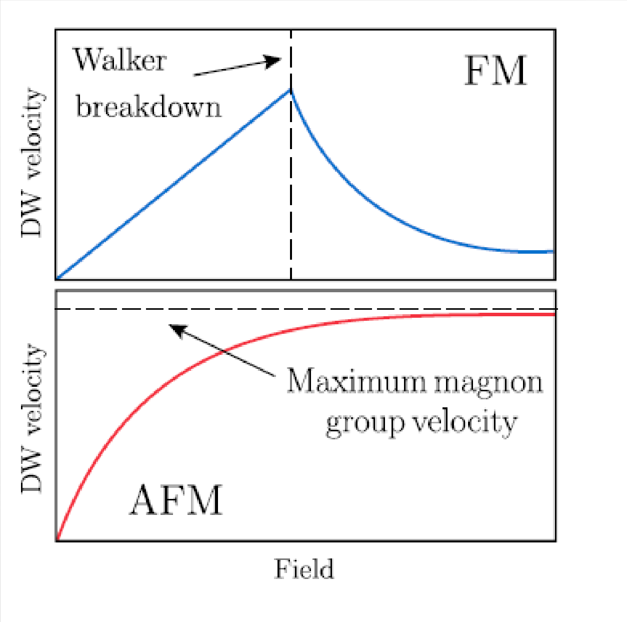
Oscillations along and around NW with Walker breakdown

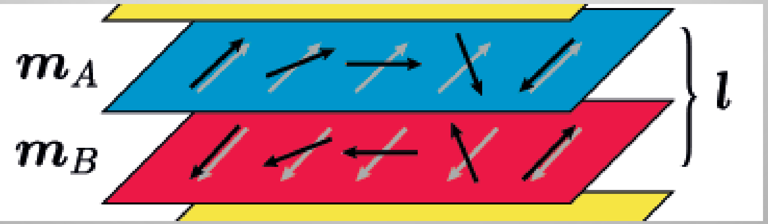
The recovery of the Walker breakdown with curvature



R.Moreno et al PRB 96, 184401 (2017)

MAGNETIC DOMAIN WALLS WITHOUT WALKER BREAKDOWN: ANTIFERROMAGNETS





Sigma-model

$$\boldsymbol{m}, \boldsymbol{l} = \left(\boldsymbol{m}_{\rm A} \pm \boldsymbol{m}_{\rm B}\right)/2$$

m (magnesation)<<l (Neel vector)

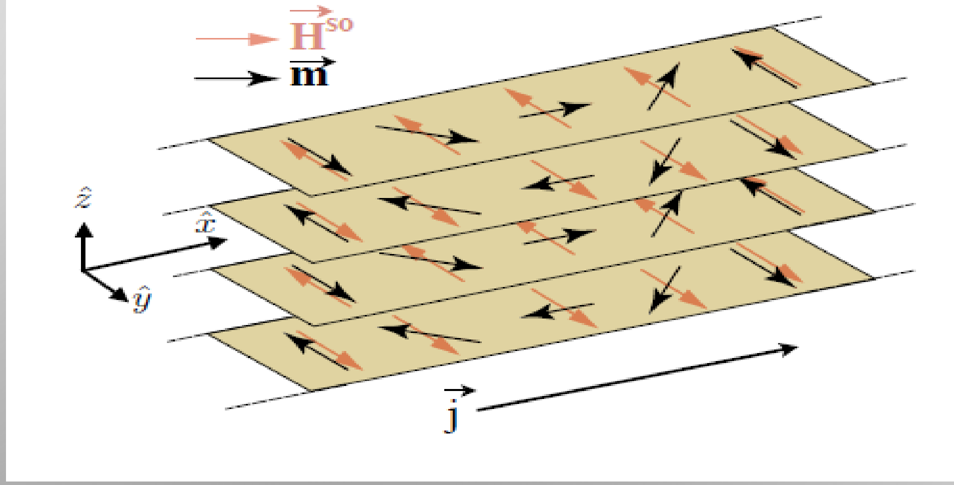
Field directly cannot move DW

In certain materials spin-polarized current acts as staggered field

$$w = \frac{1}{2} A\, \boldsymbol{m}^2 + \frac{1}{8} a \left(\partial_x \boldsymbol{l}\right)^2 + w_{\rm a}\left(\boldsymbol{l}\right) - 2\gamma\hbar \left(\boldsymbol{l} \cdot \boldsymbol{H}^{\rm SO}\right)$$

ANTIFERROMAGNETIC DOMAIN WALLS

$$\dot{\boldsymbol{l}} = \gamma\, \boldsymbol{H}_m^{\rm eff} \times \boldsymbol{l}, \qquad \dot{\boldsymbol{m}} = \left(\gamma\, \boldsymbol{H}_l^{\rm eff} - \alpha\, \dot{\boldsymbol{l}}\right) \times \boldsymbol{l},$$



$$\frac{1}{c^2}\theta_{tt} - \theta_{xx} + \frac{1}{2\Delta_0^2}\sin 2\theta = -H_{SOT}\sin\theta - \alpha\theta_t$$

Sine-Gordon equation

ext (SOT) field

dissipation

AFM DOMAIN WALLS AS "RELATIVISTIC SOLITONS"

$$\frac{1}{c^2}\theta_{tt} - \theta_{xx} + \frac{1}{2\Delta_0^2}\sin 2\theta = -H_{SOT}\sin\theta - \alpha\theta_t$$

Sine-Gordon equation

ext (SOT) field

dissipation

When dissipation is counter-balanced by external field

$$\theta = 2\tan^{-1} exp\left[\frac{x - Vt}{\Delta}\right]$$

$$V = \frac{H_{SOT}\Delta(V)}{\alpha}$$

Stationary velocity

Domain wall width $\Delta = \Delta_0\sqrt{1 - V^2/c^2}$

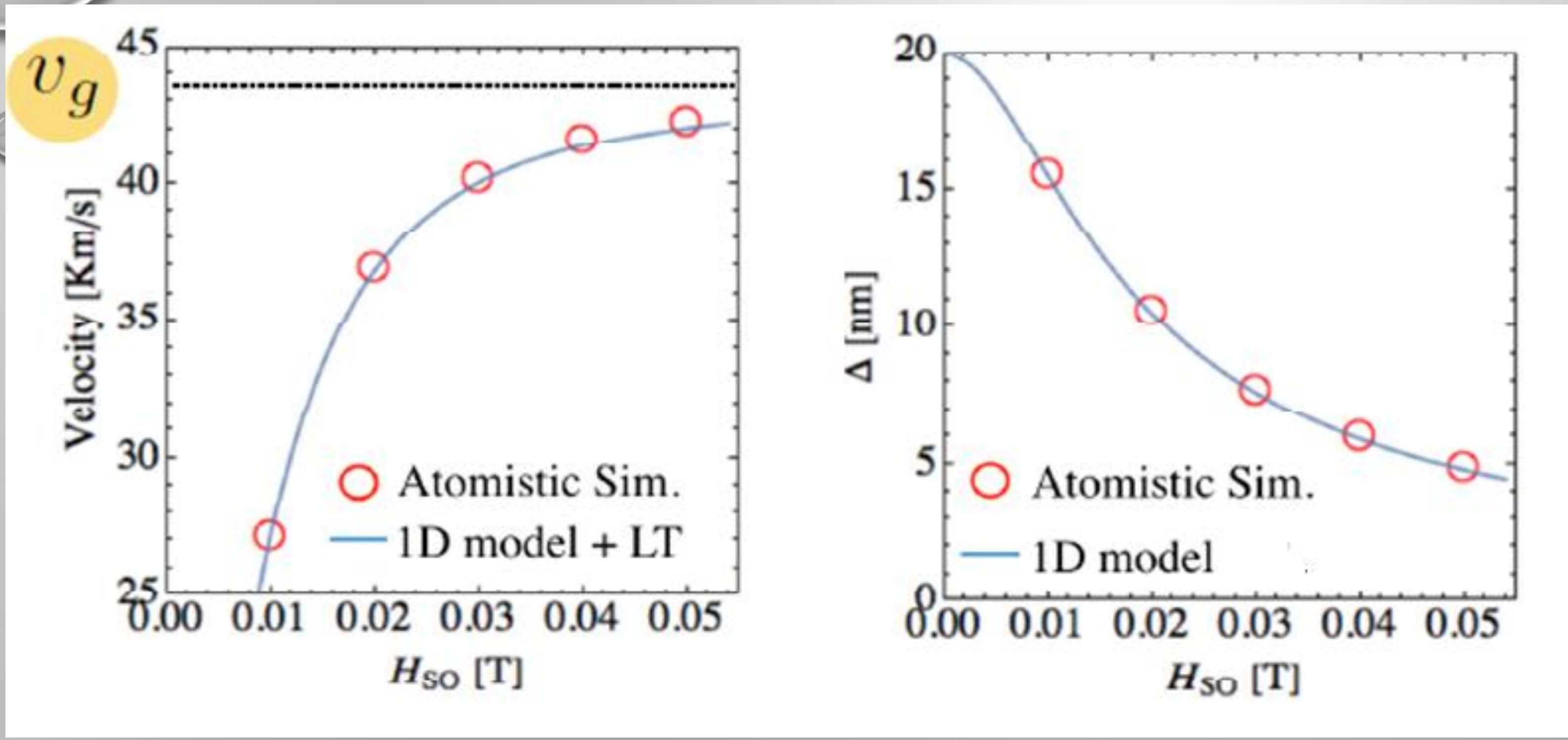
Domain wall width at rest

"Light" speed

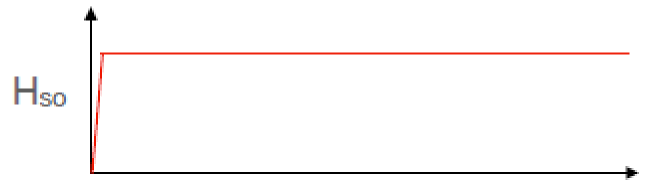
c=43.3 km/s –spin wave group velocity

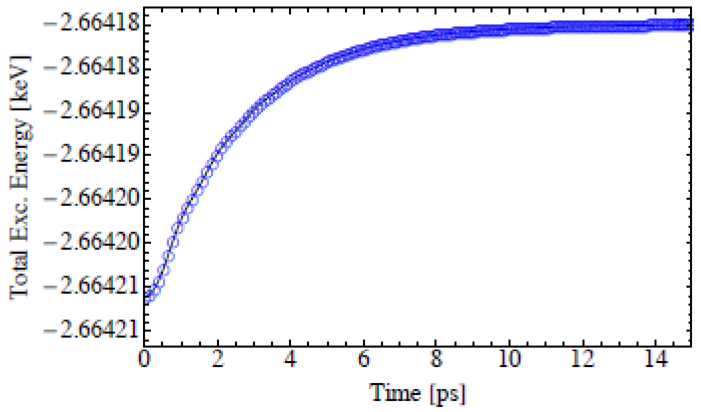
R.Rama-Eiroa et al, (in revision)
arXiv:2109.09003

Domain wall velocity and width in Mn2Au



$$E(v_s) = \frac{E_0}{\sqrt{1-(v_s/c)^2}},$$

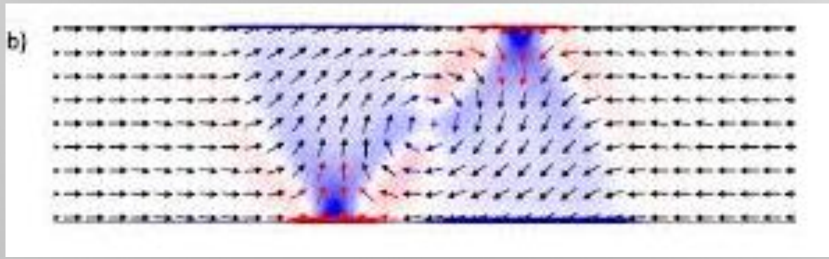


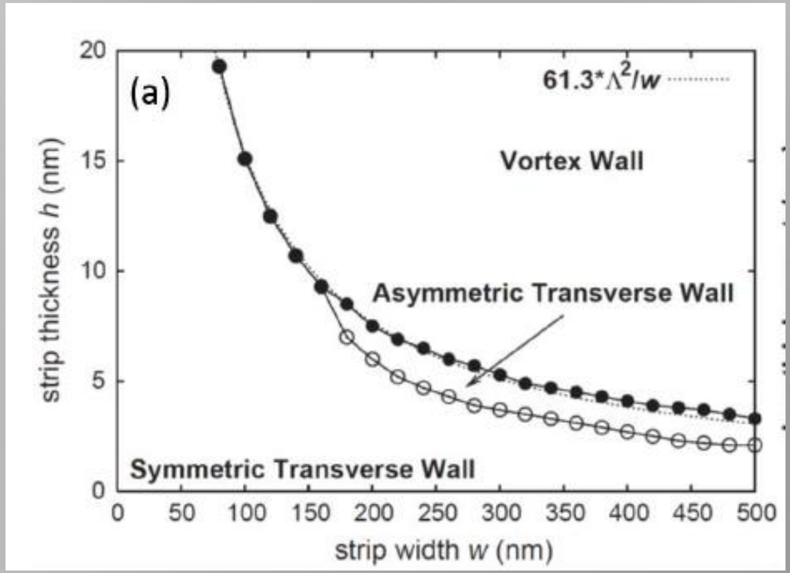


- ✓ Velocity increases up to 40 km/s (limited by spinwave emission)
- ✓ Domain width decreases down to 4 nm (relativistic effect)
- ✓ Domain wall is “charged” with exchange energy

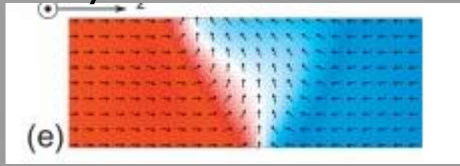
R.Otxoa, …O.C.-F.
Comm.Phys. 3, 31 (2020)

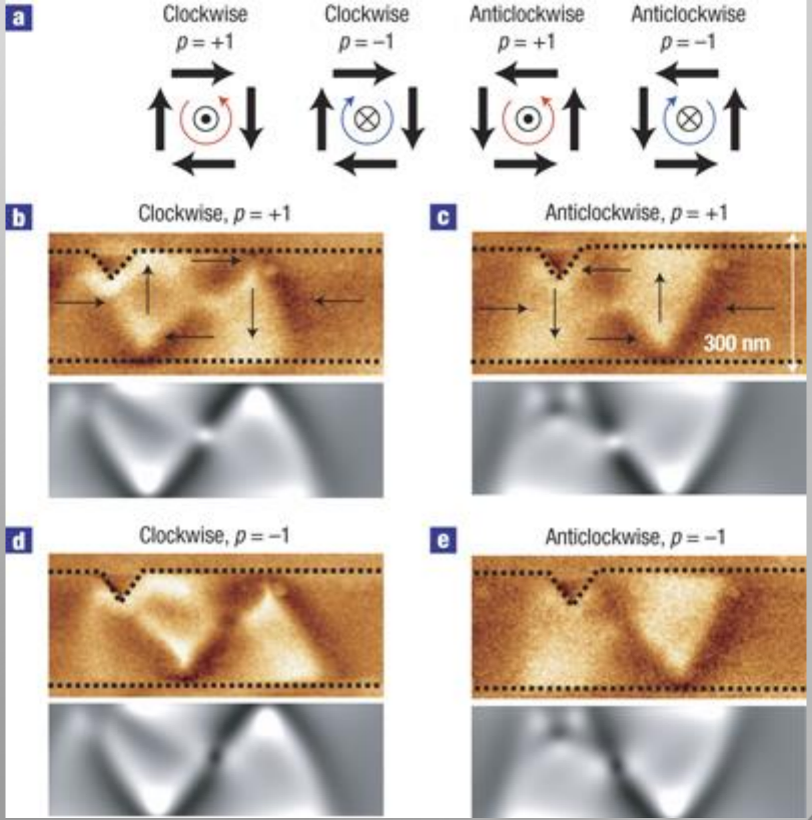
VORTEX DOMAIN WALLS





Asymmetric transverse DW





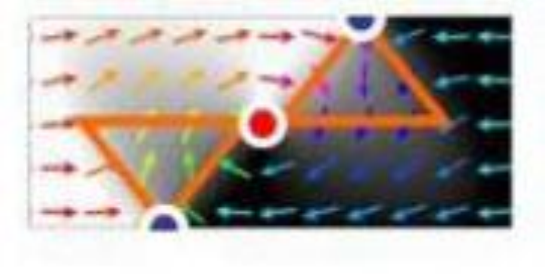
R.Moriya et alNature Physics 4(5) (2008)

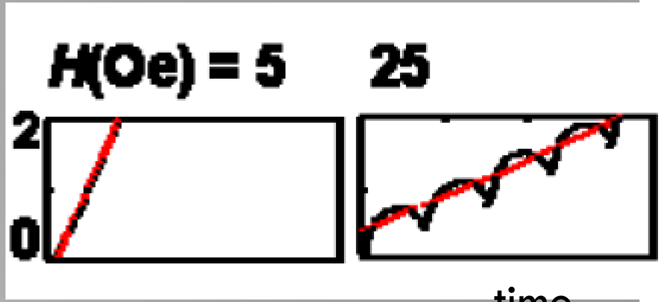
DOMAIN WALL PROPAGATION IN WIRES

Transverse DW

Head-to-head domain wall

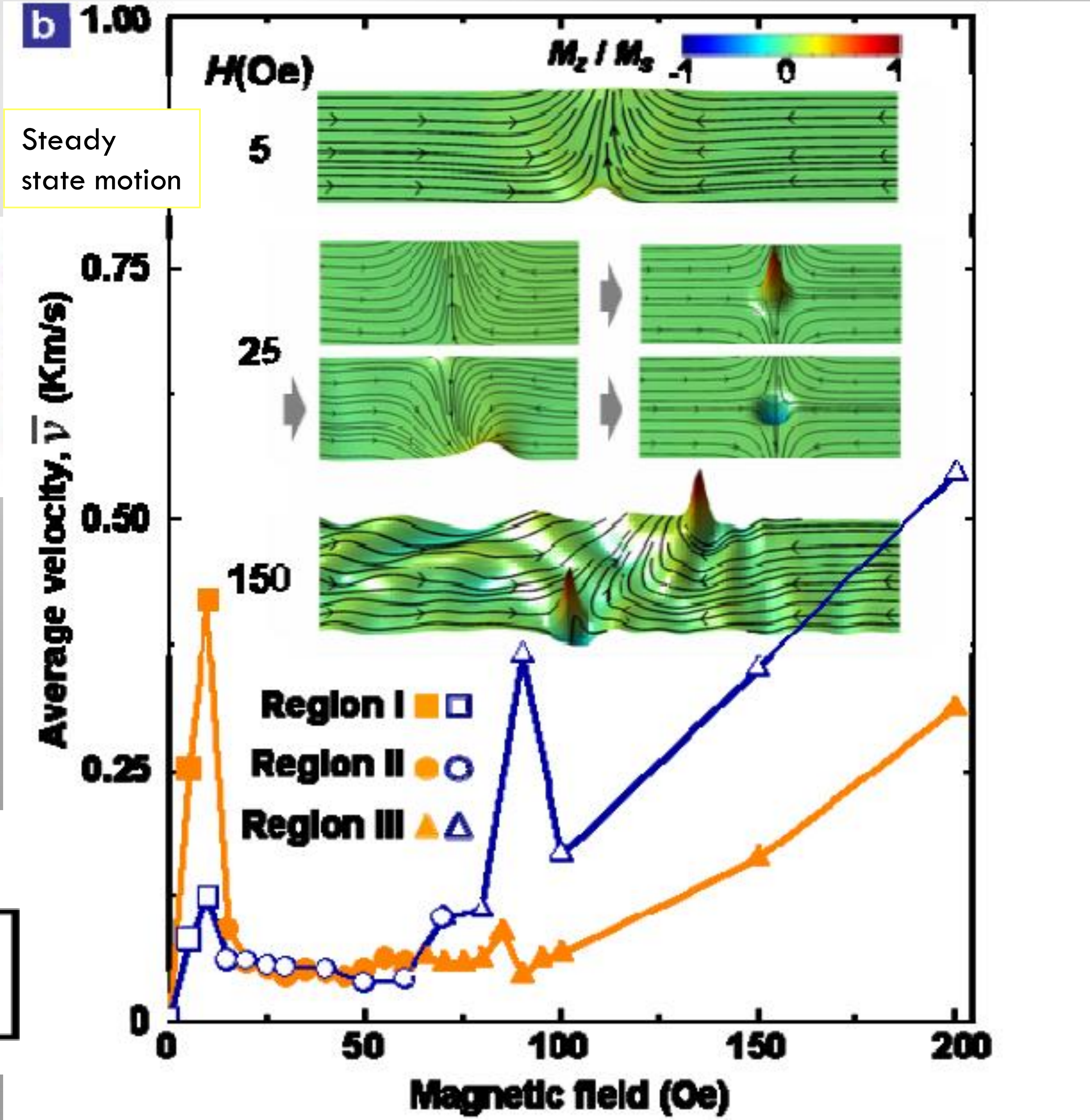
Vortex domain wall



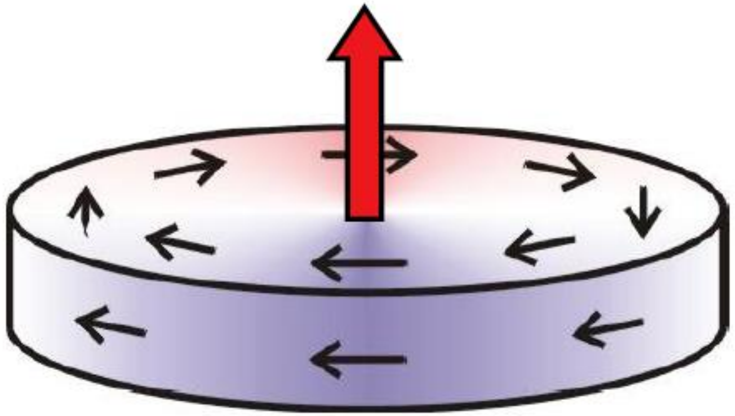


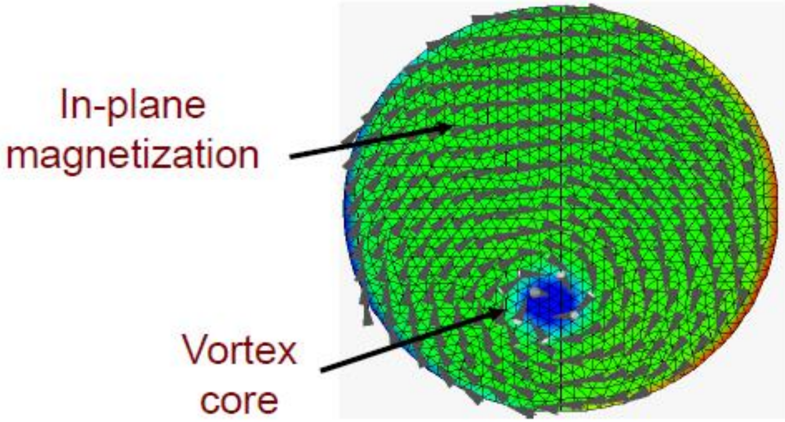
Courtesy K.Guslienko

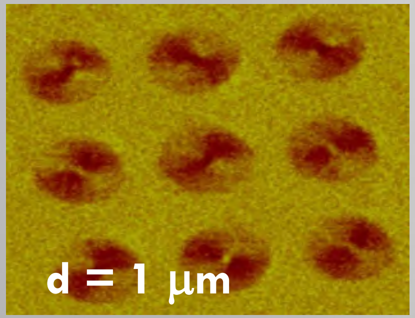
Steady state motion



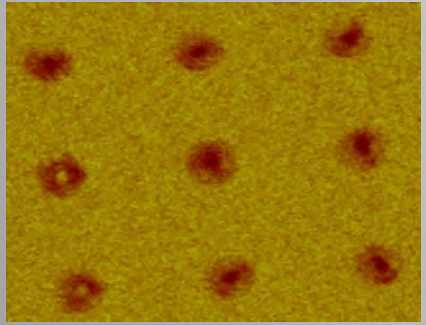
Magnetic vortices in soft magnetic dots







MFM Images:
Thickness = 60 nm



Magnetic Vortex Integers:

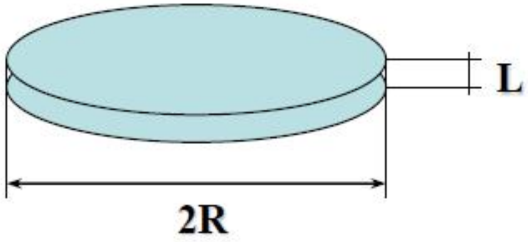
Vorticity (topological charge): q = ±1
degree of mapping of XY plane to the magnetization unit sphere

Chirality (CCW, CW): C = ±1

Polarization: p = ±1

M-ground state depends on:

- Dot geometry and shape: L and R
- Material: A, K and M_s

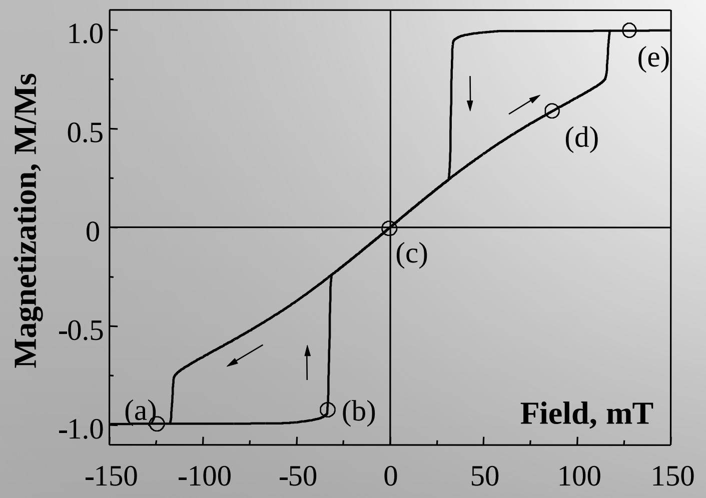


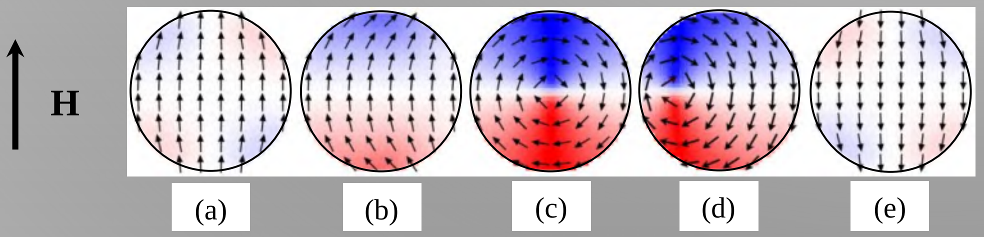
Skyrmion mumber: S = qp/2

Courtesy K.Guslienko

Magnetic Vortex State in circular ferromagnetic dot

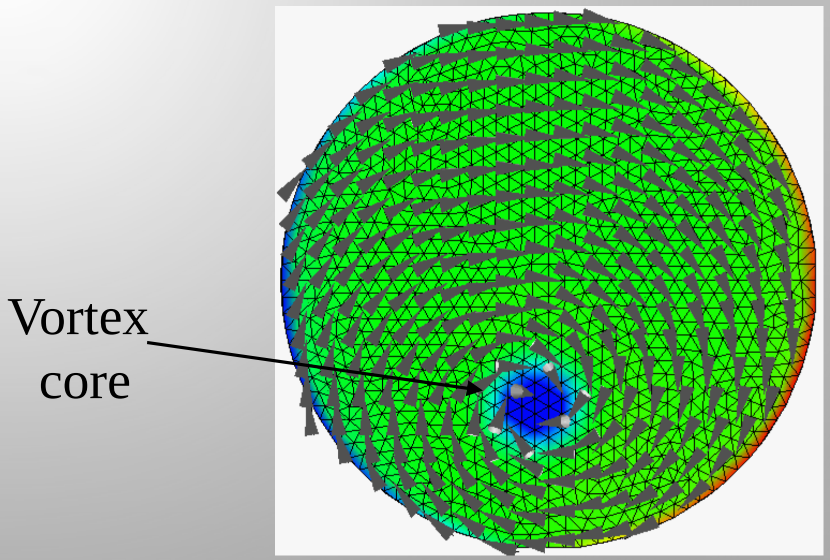
Micromagnetic calculations: hysteresis loop and field-evolution of the vortex spin structure

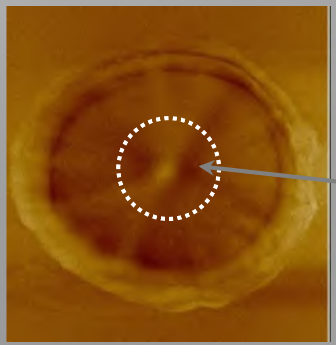


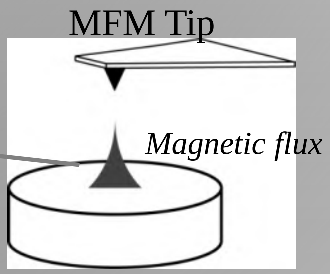


V. Novosad et al. IEEE Trans. Magn., 2001

Experiments: hysteresis loop and MFM observation of the vortex state in remanence

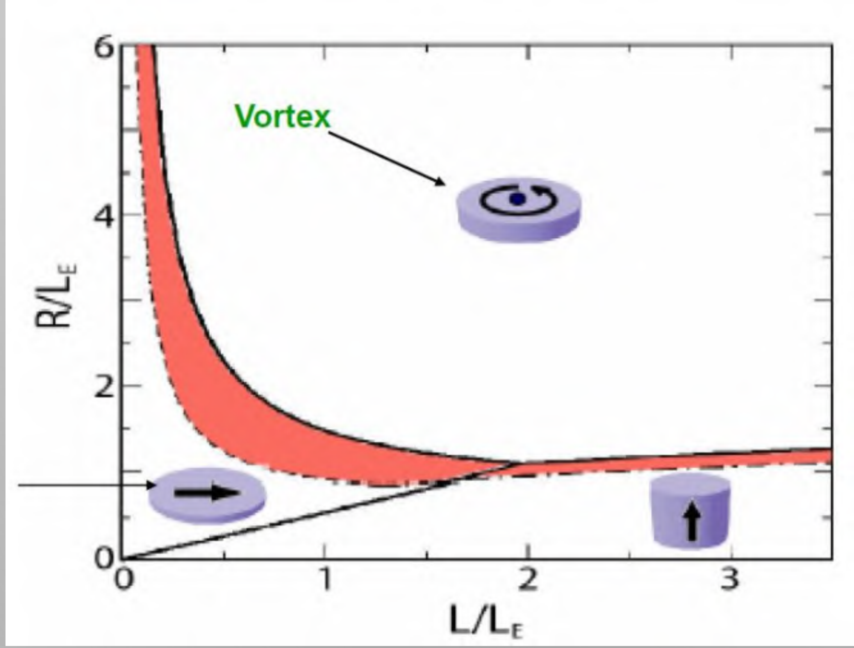




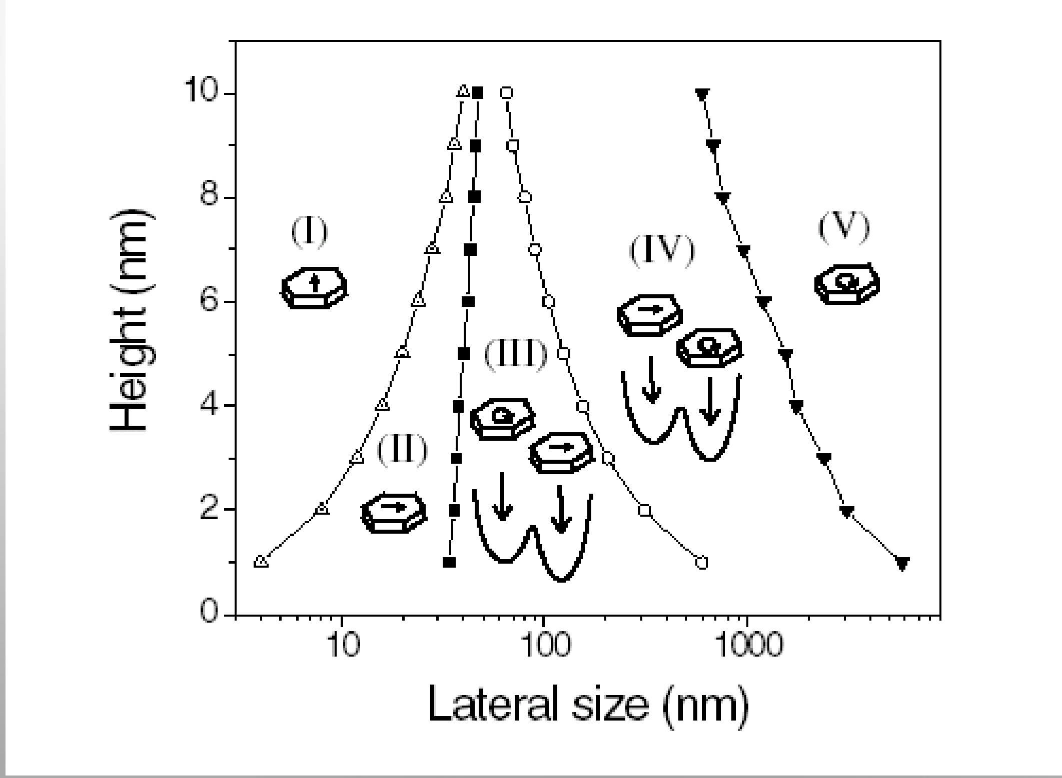


⇨ **Magnetization reversal due to formation of the magnetic vortex state in circular dot**

General stability diagram for soft dots



Stability diagram in Co dots



K.Guslienko

THIELE EQUATION

LLG equation $$\partial_t \vec{m} = \gamma_0 \vec{H}_{eff} \times \vec{m} + \alpha \vec{m} \times \partial_t \vec{m}$$

$\times \vec{m}$

`solved' form $$\vec{H}_{eff} = \{\vec{m} \times \partial_t \vec{m} + \alpha \partial_t \vec{m}\} / \gamma_0 + \lambda \vec{m}$$

ASSUME a magnetization structure in RIGID MOTION

$$\vec{m}(\vec{r},t) = \vec{m}_0(\vec{r} - \vec{R}(t)) \qquad \partial_t \vec{m} = -\sum_j V_j \frac{\partial \vec{m}_0}{\partial x_j}$$

$$E = \mu_0 M_s \int dV\, \vec{H}_{eff} \vec{m}$$

Force on the structure $$F_i = -\frac{dE}{dR_i} = \mu_0 M_s \int \vec{H}_{eff} \cdot \frac{\partial \vec{m}}{\partial R_i} = -\mu_0 M_s \int \vec{H}_{eff} \cdot \frac{\partial \vec{m}_0}{\partial x_i}$$

Gyrotropic term Damping term

$$F_i = \frac{\mu_0 M_s}{\gamma_0} \sum_j V_j \int \left(\vec{m}_0 \times \frac{\partial \vec{m}_0}{\partial x_j} + \alpha \frac{\partial \vec{m}_0}{\partial x_j} \right) \cdot \frac{\partial \vec{m}_0}{\partial x_i}$$

THIELE EQUATION (CONT.)

$$\vec{F}_{gyro} + \vec{F}_{dissip} + \vec{F} = \vec{0}$$

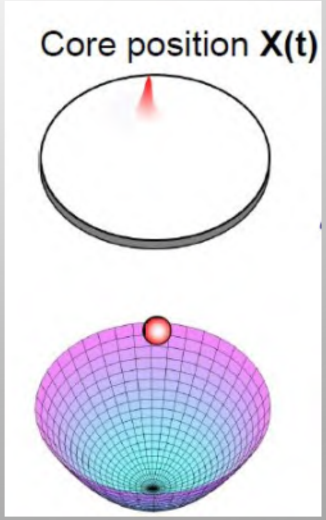
$$G \times \vec{V} + \alpha \overleftrightarrow{D}\vec{V} = \vec{F}$$

THIELE EQUATION FOR VORTEX

$$-\mathbf{G}\times\frac{d\mathbf{X}}{dt}-\hat{D}\frac{d\mathbf{X}}{dt}+\frac{\partial W(\mathbf{X})}{\partial\mathbf{X}}=0$$

$\mathbf{G}$: gyrovector $\mathbf{G}=-pq|G|\hat{\mathbf{z}}$

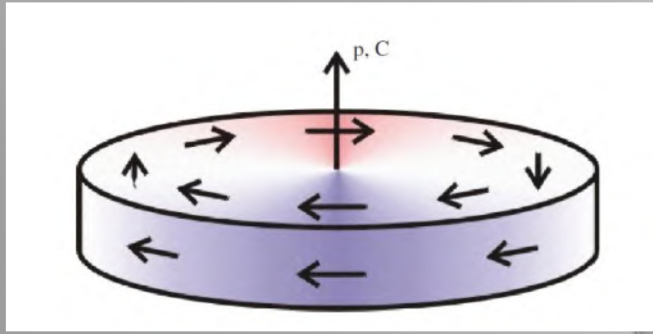
$$G=2\pi qpLM_s/\gamma,$$



Belyavin-Polyakov ansatz

(simplified Usov's form)

$$m_\rho=0,\quad m_\varphi=\sin\Theta(\rho)=\frac{2b\rho}{b^2+\rho^2}\quad \text{if } \rho\le b,$$
$$m_\varphi=1\quad \text{if } \rho>b,\quad m_z=\pm\cos\Theta(\rho)$$



For thin dots L<<R

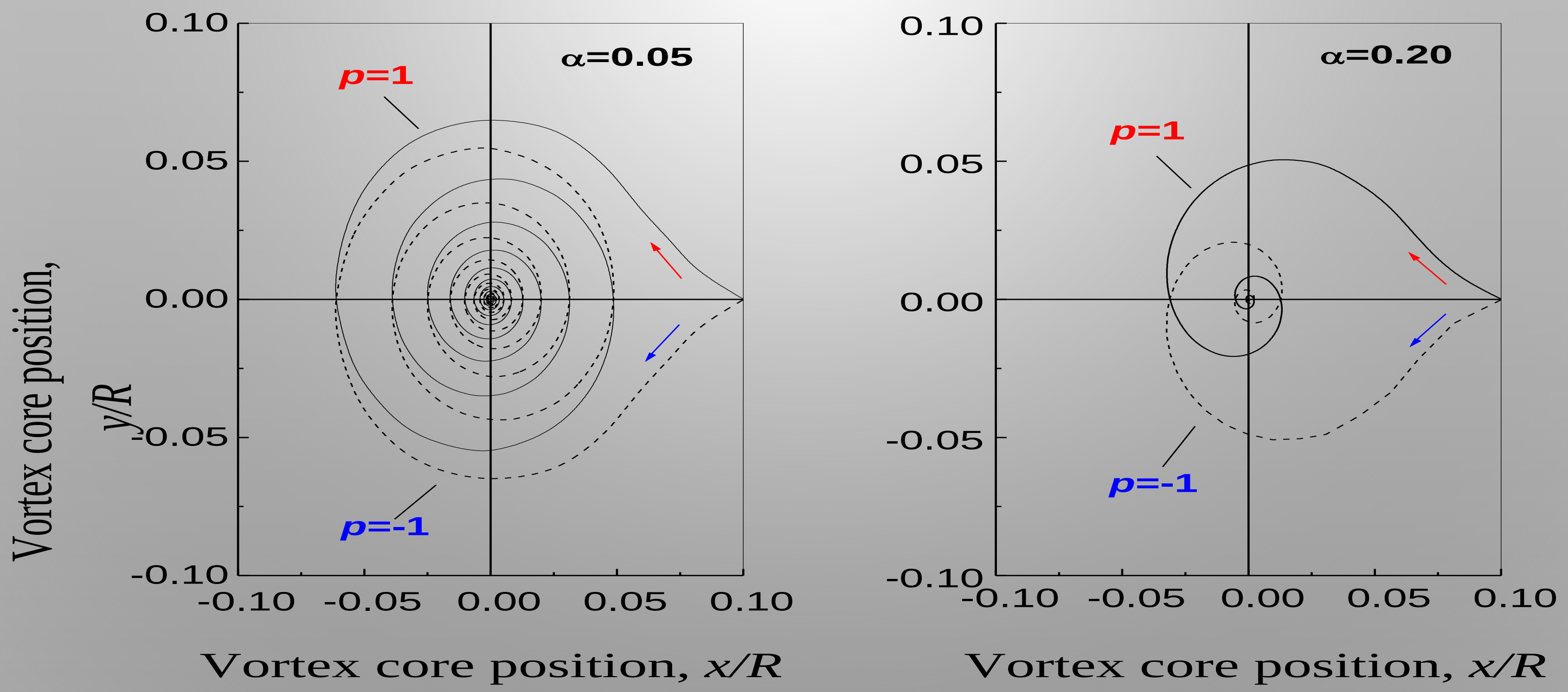
ω_0 ~ 100-500 MHz

$$\omega_0=\frac{5}{9\pi}\frac{L}{R}\omega_M\qquad \omega_M=\gamma 4\pi M_s\approx 30\ GHz$$

Guslienko et al., *JAP* **91**, 8037, 2002; *PRL* **96**, 067205 (2006)

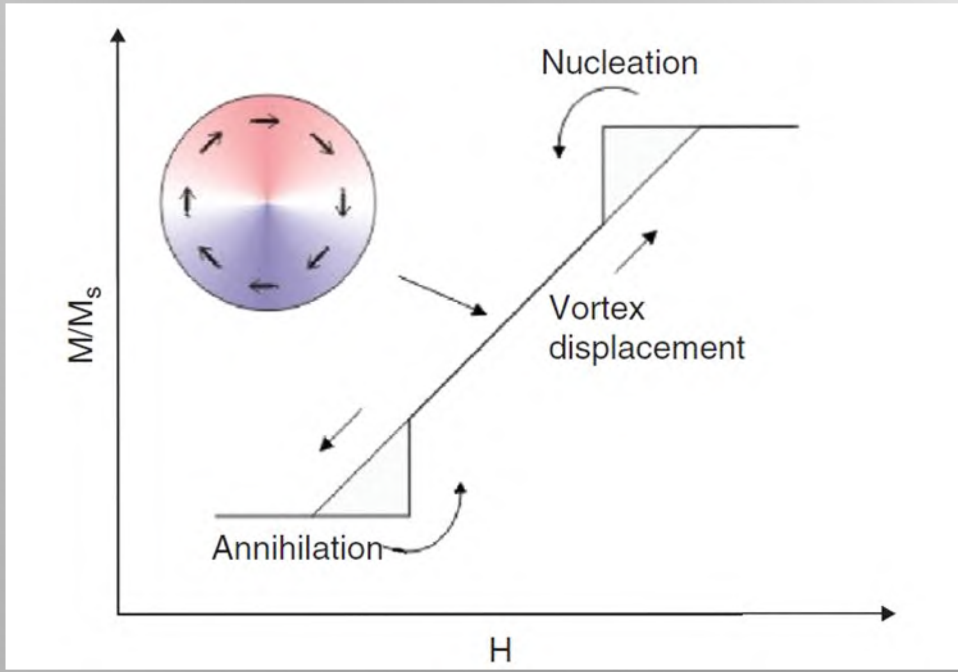
Vortex translation mode in a circular dot

Vortex core trajectory

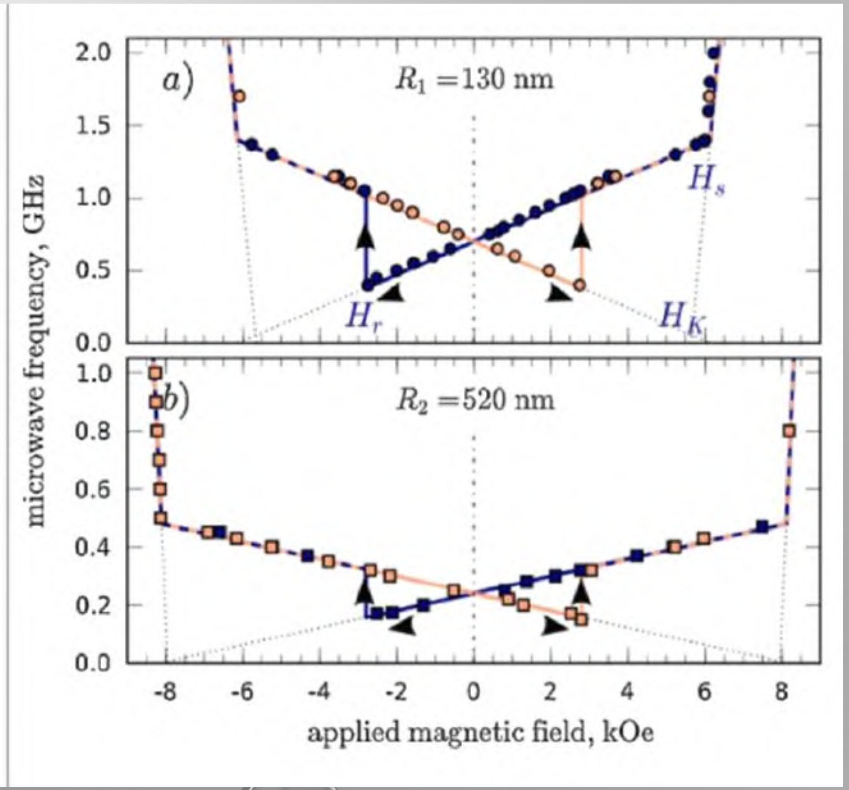


The "*translational mode*" of the vortex excitations corresponds to the spiral vortex core rotation around the dot center. Its direction (counter-clockwise or clockwise) is defined by the combination of the vortex polarization and chirality.

VORTEX HYSTERESIS



Perpnendicular field: Goes through Bloch point



. de Loubens et al. PRL, 2009

ULTRAFAST CORE REVERSAL IN IN-PLANE FIELDS

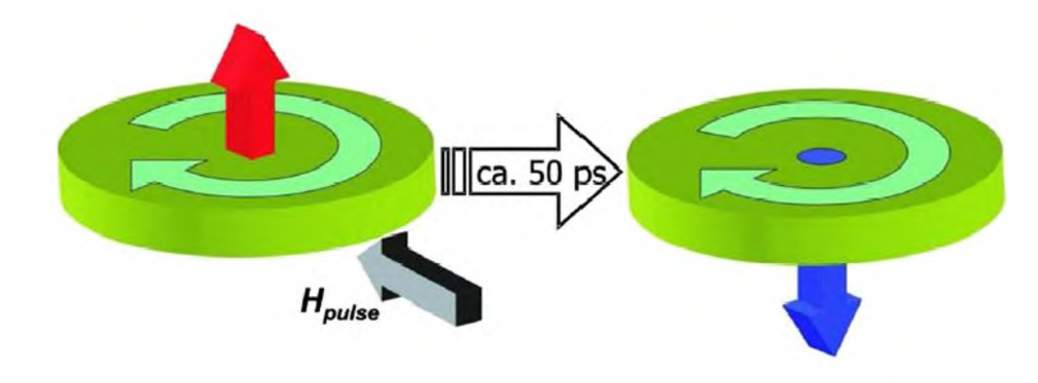
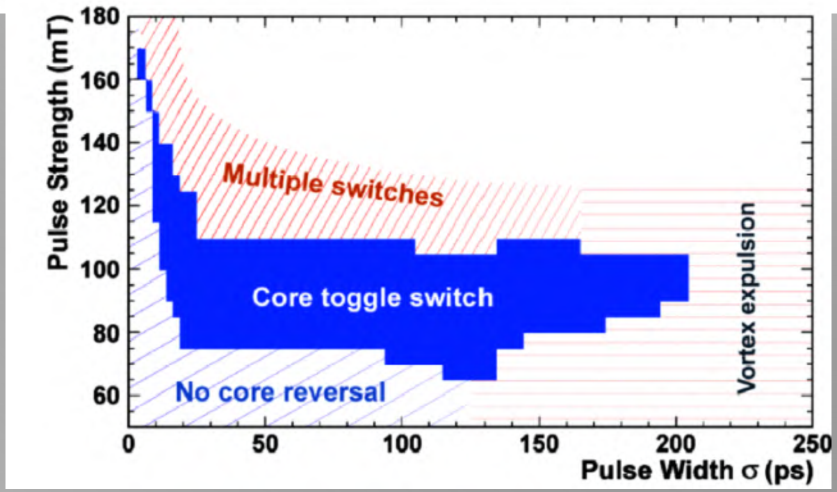
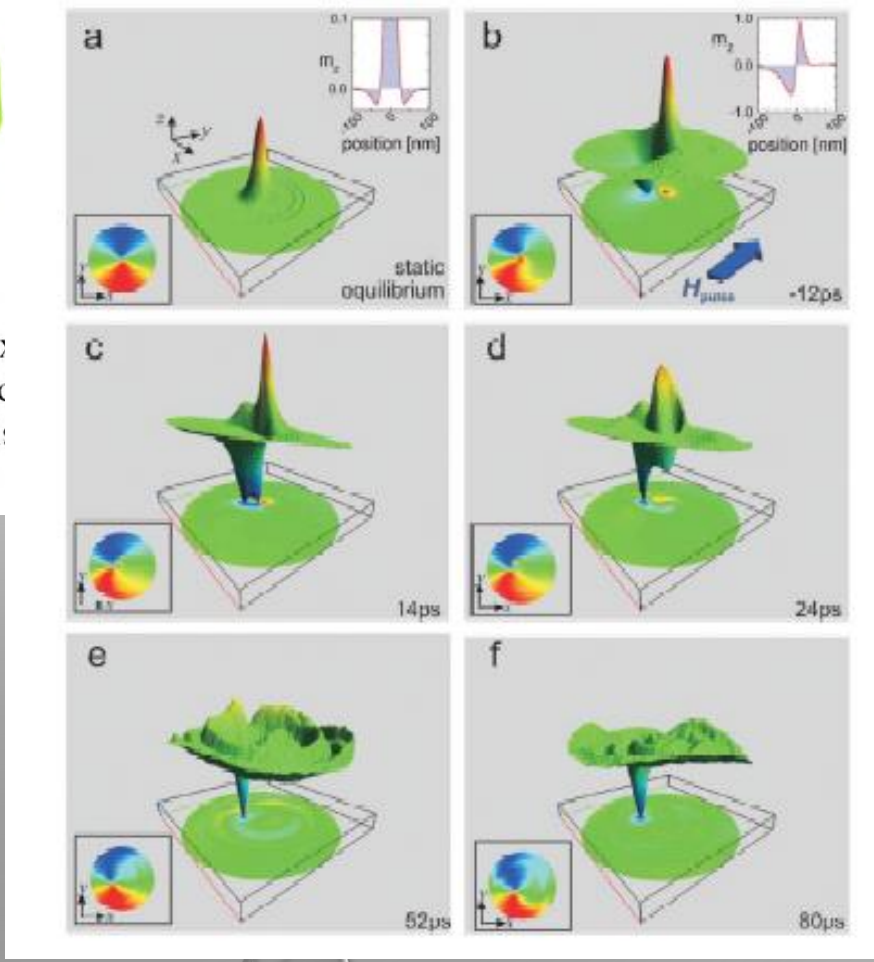


FIG. 1 (color online). Schematics of a field-pulse driven vortex core switching. The vortex core magnetization can be switched by a short magnetic field pulse applied in the film plane. This switching process requires only 40–50 ps.



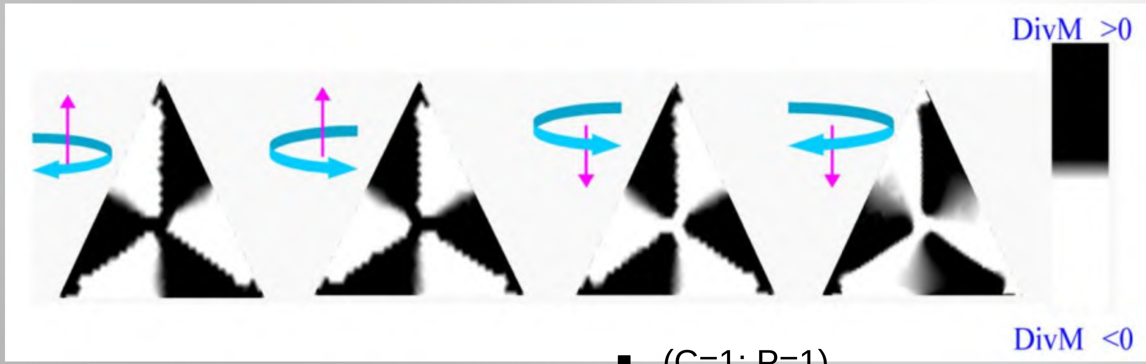


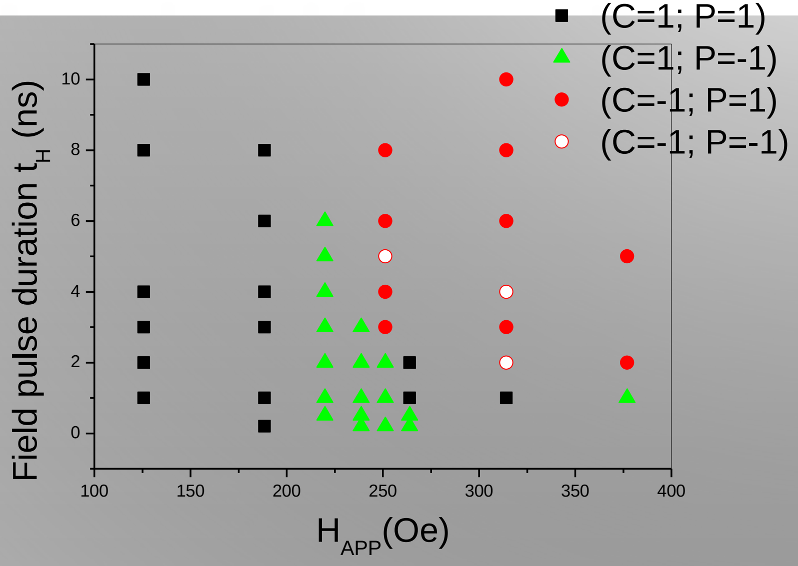
R.Hertel et al PRL 98 (2007) 117201

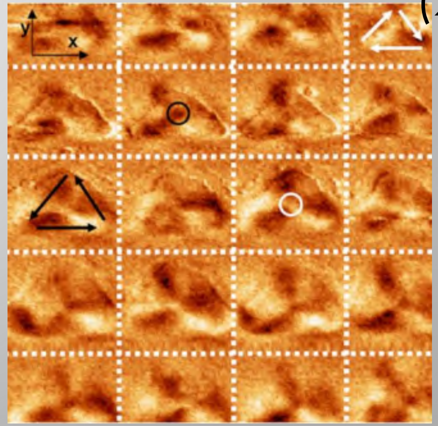
Experimental observation with synchrotron:
B.Van Wayenberge, Nature 444 (2006)

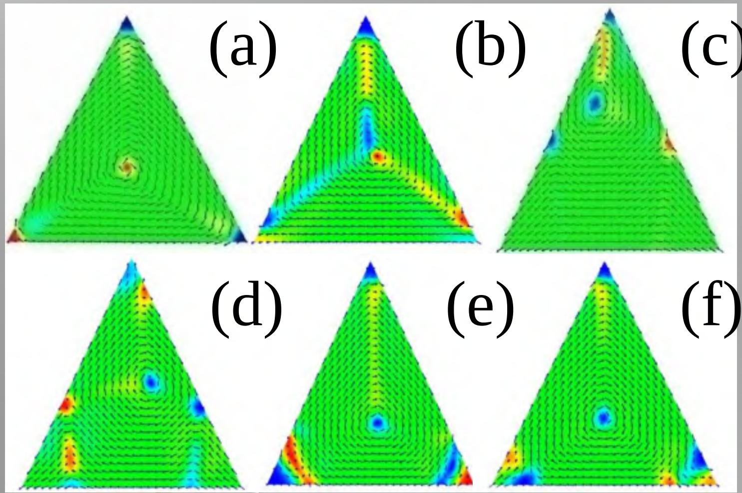
CONTROL OF THE VORTEX STATES IN TRIANGULAR DOTS

M.Jaafar et al
Phys. Rev. B 81, 054439 (2010)





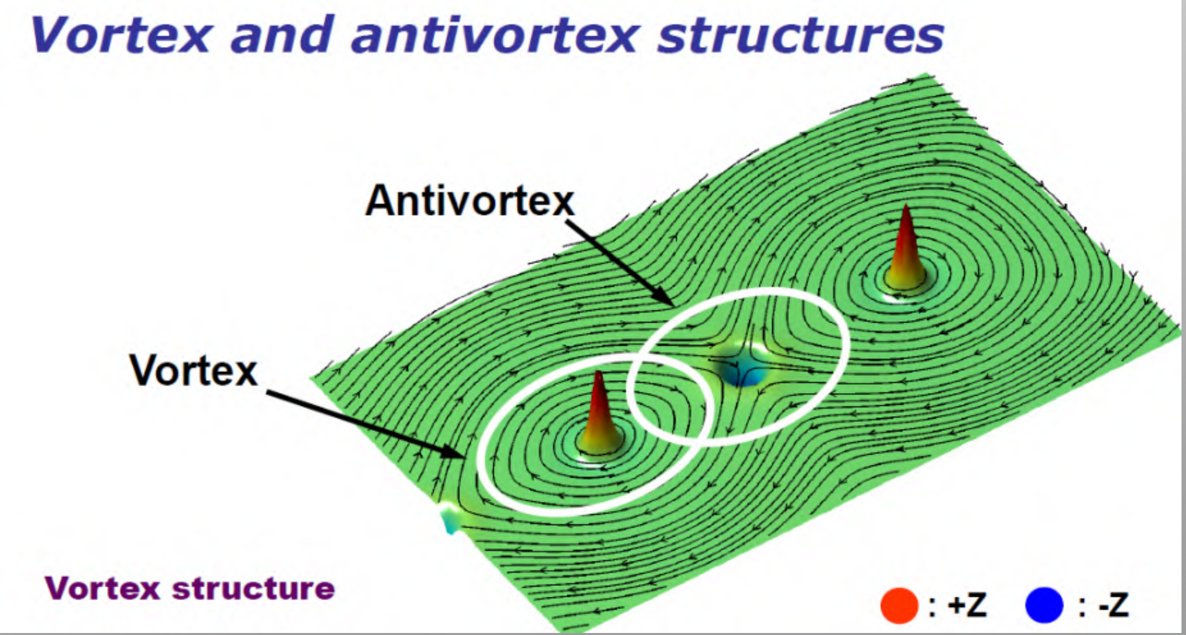




*Small fields + small duration -> core reversal

* Larger fields + larger duration -> chirality reversal

VORTEX AND ANTIVORTEX STRUCTURES



Topological charge
Antivortex -1

TOPOLOGICAL MAGNETIC SOLITONS

Skyrmion number
(topological charge)

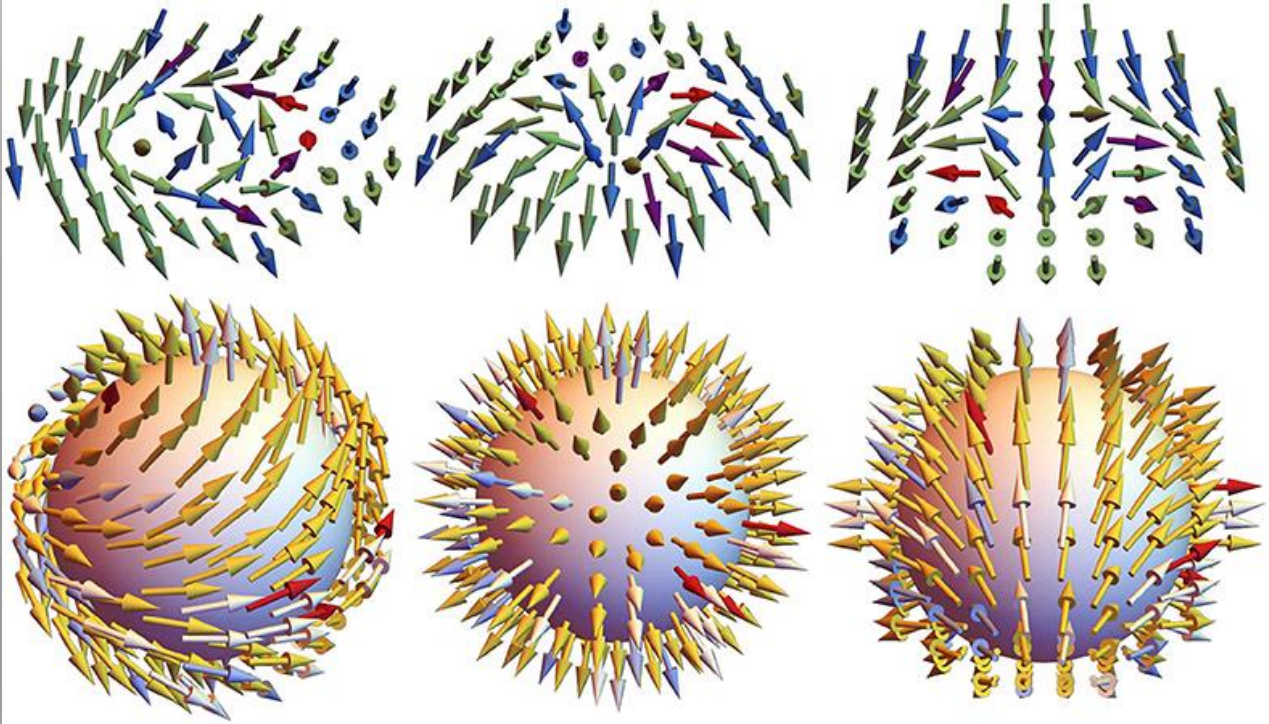
↓

Gyrovector

$$S = \frac{1}{4\pi}\int dxdy\,\mathbf{m}\cdot\left(\partial_x\mathbf{m}\times\partial_y\mathbf{m}\right)$$

Vortex S=1/2
Skyrmion S=1

Bloch skyrmion | Neel skyrmion | antiskyrmion



One of the farther of quantum chromodynamics the nuclear physicist T.H.R. Skyrme

Stability of mesons and baryons through topological protection

Particles are characterised by a topological integer (topological charge or topological quantum number) that cannot be changed by continuous field deformation

Also discussed in liquid crystals, Bose-Einstein condensates etc.

Skyrme (1962):

WHEN DO SKYMIONS EXIST?

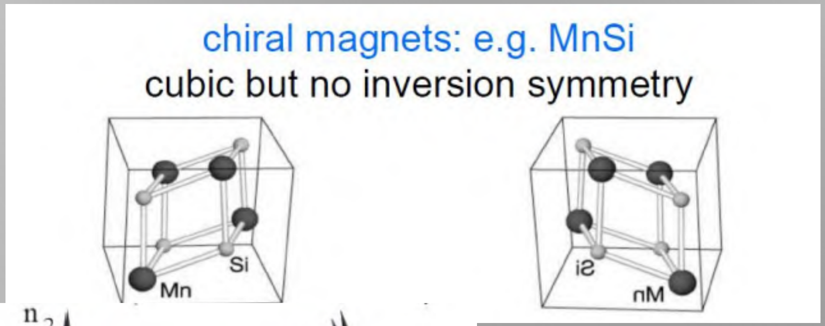
CHIRAL MAGNETS OR HELLIMAGNETS

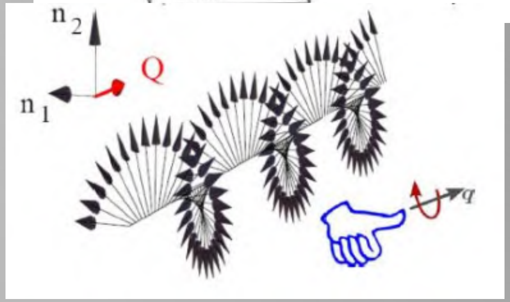
- ✓ Intrinsic broken centro-symmetric symmetry

Strong intrinsic Dzyaloshinskii-Moriya interactions (DMI)

MnSi, FeCoSi, FeGe etc.   Fe monolayer at Ir

Low temperature skymion lattices

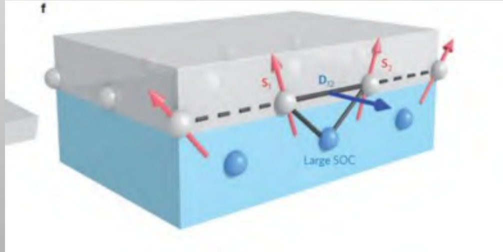




THIN MULTILAYES: TRANSITION METALS COUPLED WITH LARGE SOC METALS

- ✓ DMI due to capping via materials with strong SOC

Fe (Co)/Pt, Fe(Co)/Pd, Fe(Co)/Ir , FePd/Ir



Or no ons (BUBBLE DOMAINS)

Or Both

Of course larger but stable at room temperatures!

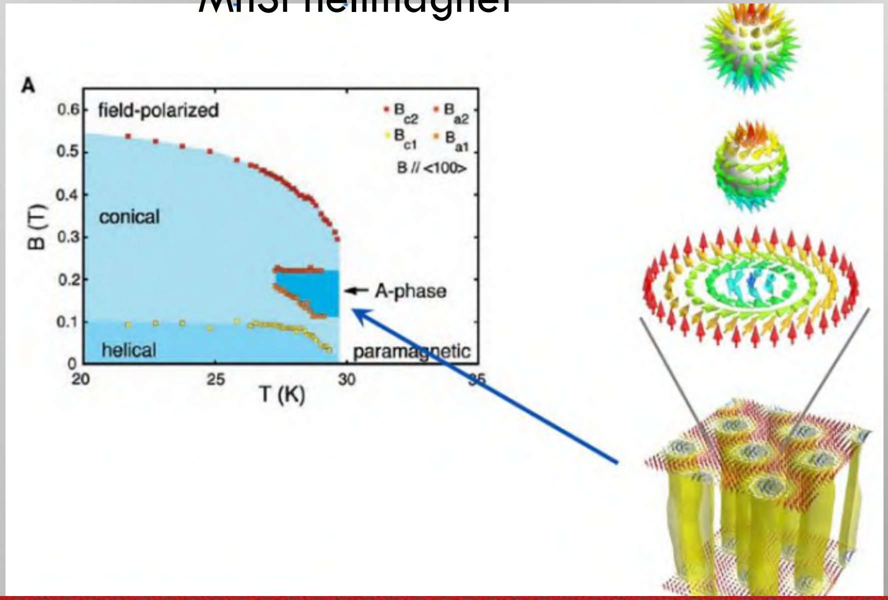
CLASSICAL BUBBLE DOMAINS ARE SKYRMIONS (same topological charge)

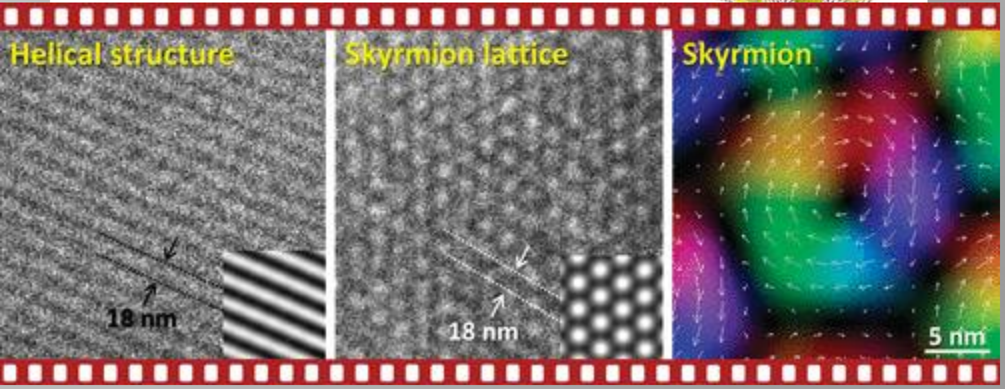
- ✓ Four-spin exchange interaction (2D materials)

Frustrated exchanged interaction.

SKYRMIONS

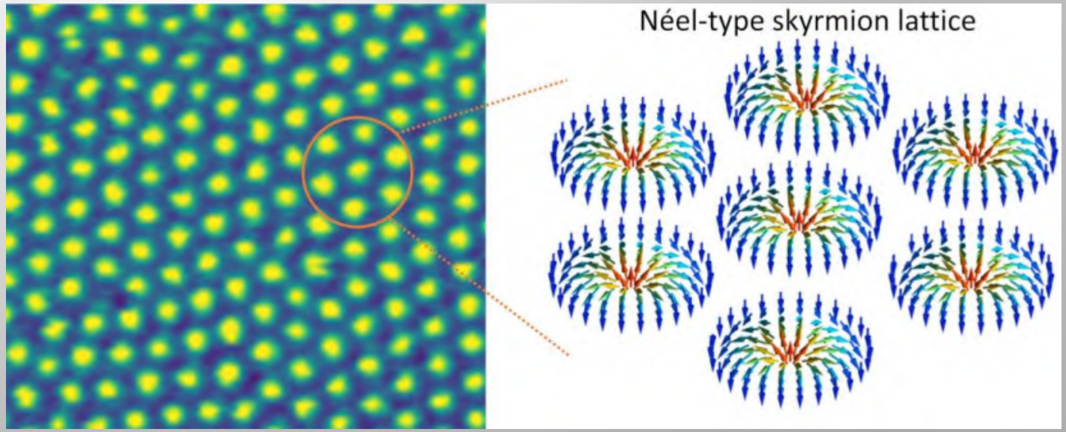
MnSi helimagnet





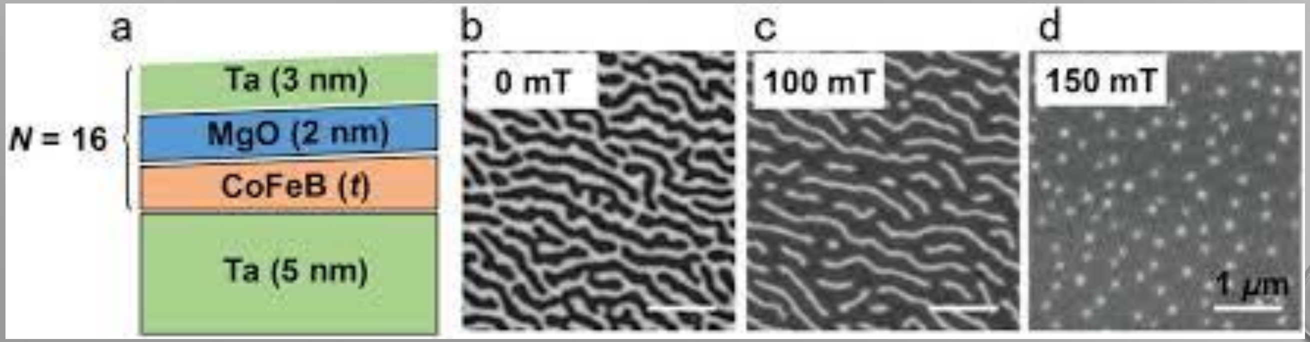
A.Tonomura Nano Lett. 2012, 12, 3, 1673–1677

Hongrui Zhang et al, Science Adv (2022)



FeGeTe
(2D material)

Multilayers

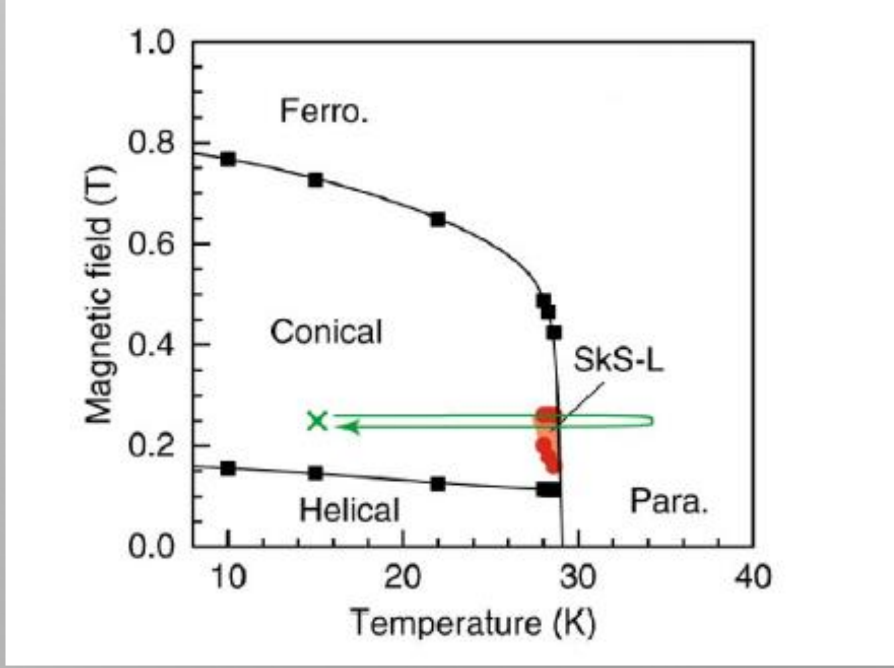


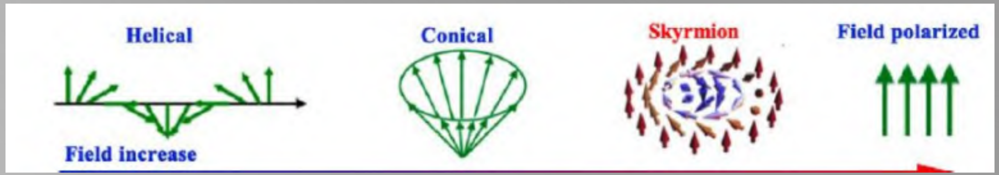
W.Li et al Adv Mater (2019)

SYSTEMS WITH DMI

MnSi phase diagram

F.Kagawa et al Nature Comm. 8 (2017)





STABILITY OF SKYRMIONS: THEORETICAL APPROACH

- Rohart and Thiaville PRB 2013 (cylindrical domains Wall theory of Dzyaloshinkii)

D>Dc skyrmion is stable

$$D_c = (2/\pi)\mu_0 M_s^2 l_{ex}\sqrt{Q-1}$$

- A linear ansatz for the polar angle inside the core raidus R_c

$\Theta(\rho) = \pi\rho / 2R_c$ for $\rho \leq 2R_c$ and π otherwise

$$D_c = (1/\pi)\sqrt{\lambda}\mu_0 M_s^2 l_{ex}\sqrt{Q-1} \qquad Q = 2K / \mu_0 M_s^2$$

Q> 1 and D>D_c skyrmion is a ground state

D<D_c skyrmion is a metastable state

THEORETICAL APPROACH II

- Belyavin-Polyakov soliton

$$\cos\Theta(\rho) = p\frac{R_c^2 - \rho^2}{R_c^2 + \rho^2} \qquad D_c = \mu_0 M_s^2 R\left[\left(\frac{l_{ex}}{R}\right)^2 \frac{1}{c} + \frac{1}{2}(Q-1)c\left\{(1+c^2)\ln\left(1+\frac{1}{c^2}\right) - 1\right\}\right]$$

For small radius c_0

$$D_c^* = 2\mu_0 M_s^2 l_{ex}\sqrt{Q-1}\ln(1/c_0)$$

- The most general ansatz

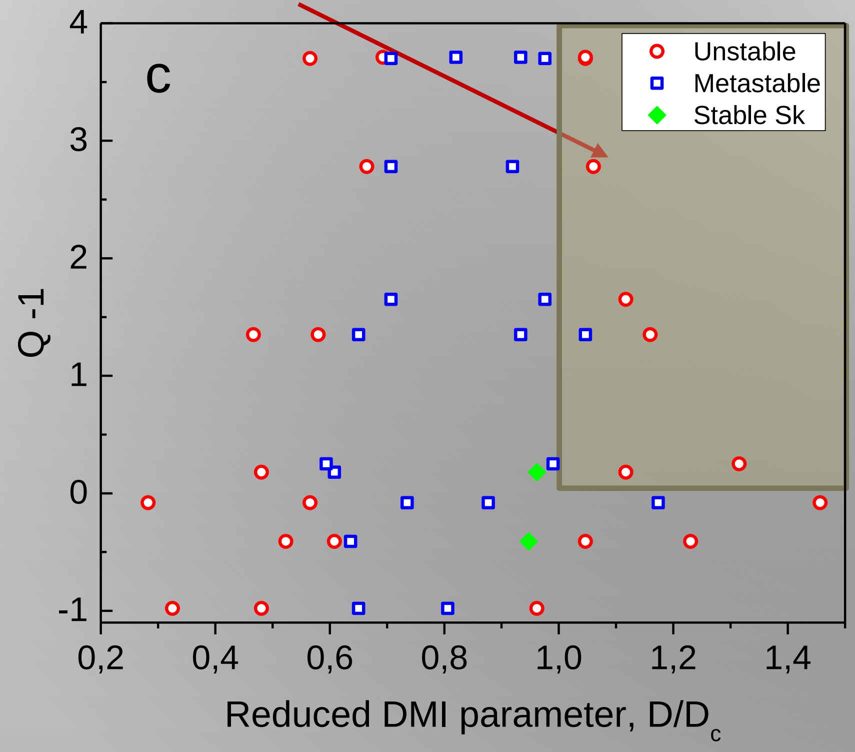
$$\Theta(\rho) = 2\arctan e^{p\frac{(\rho - R_c)}{\Delta}} \qquad \Delta = \sqrt{A/K_{eff}}$$

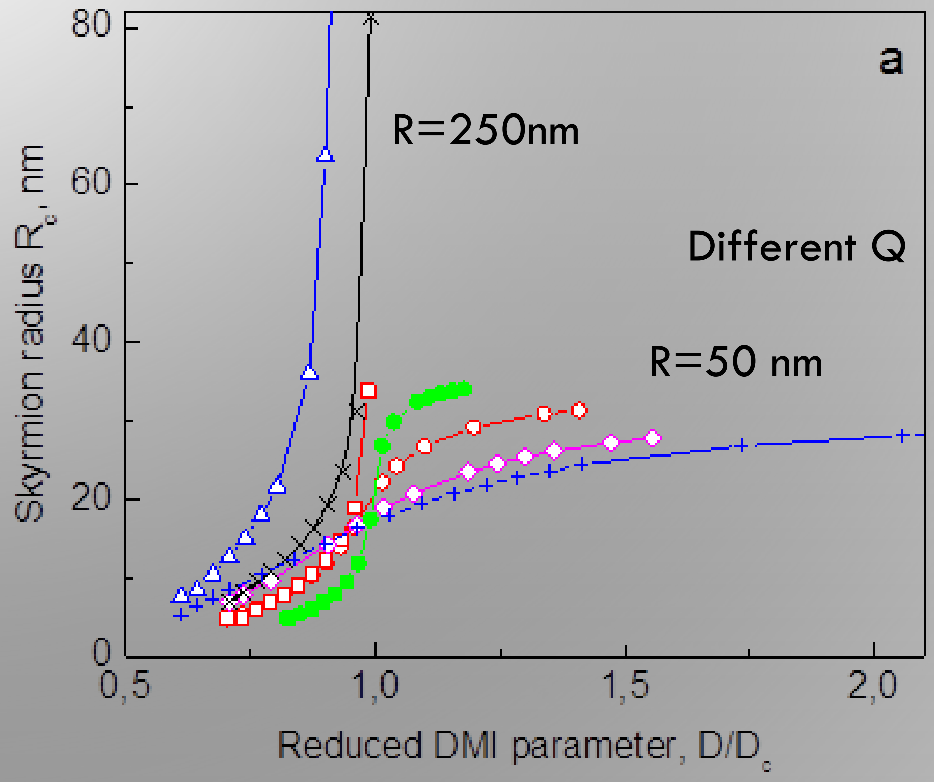
STABILITY DIAGRAM: MOST OF SKYRMIONS ARE METASTABLE

Dot R=250 nm

$$D_c = (2/\pi)\mu_0 M_s^2 l_{ex}\sqrt{Q-1}$$

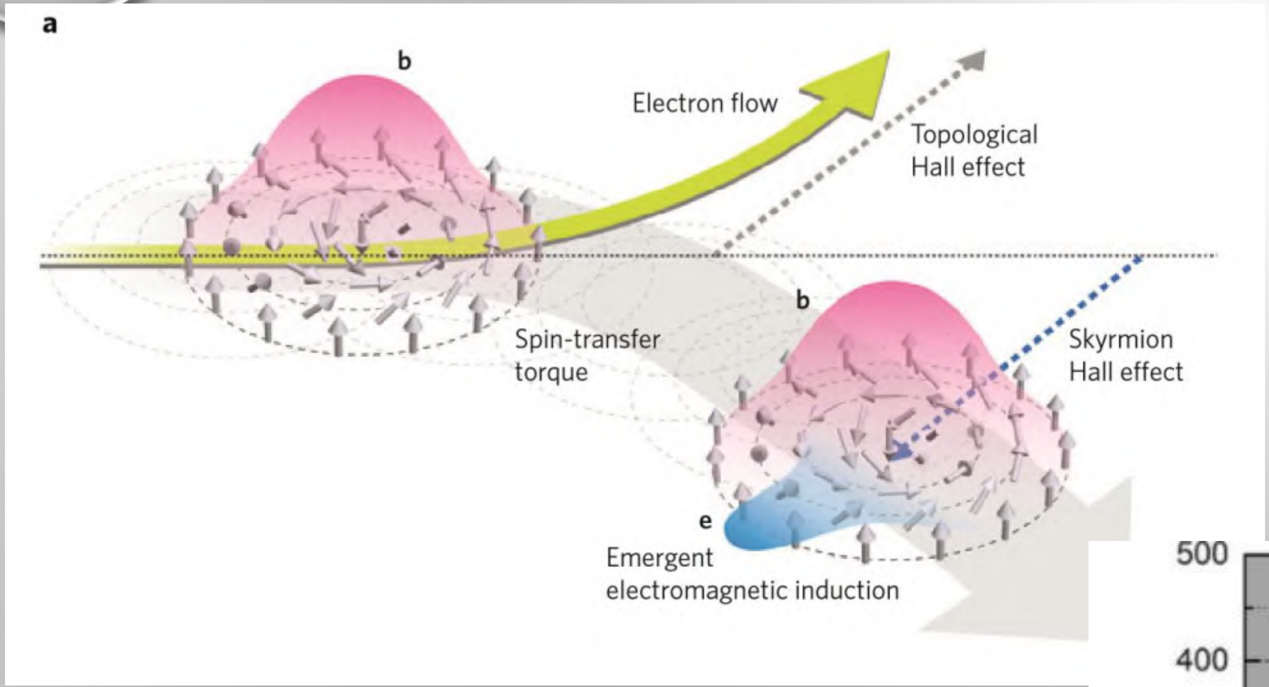
J. Sampaio,, Nature Nanotechn. **8**, 839 (2013).

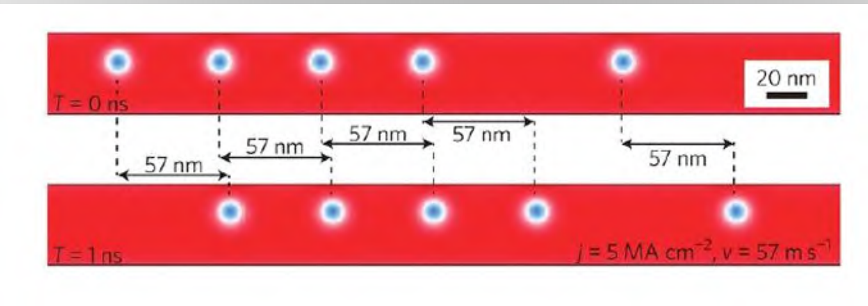




J. Magn. Magn. Mater. 465, 471 (2018)

Topological effects in skymions

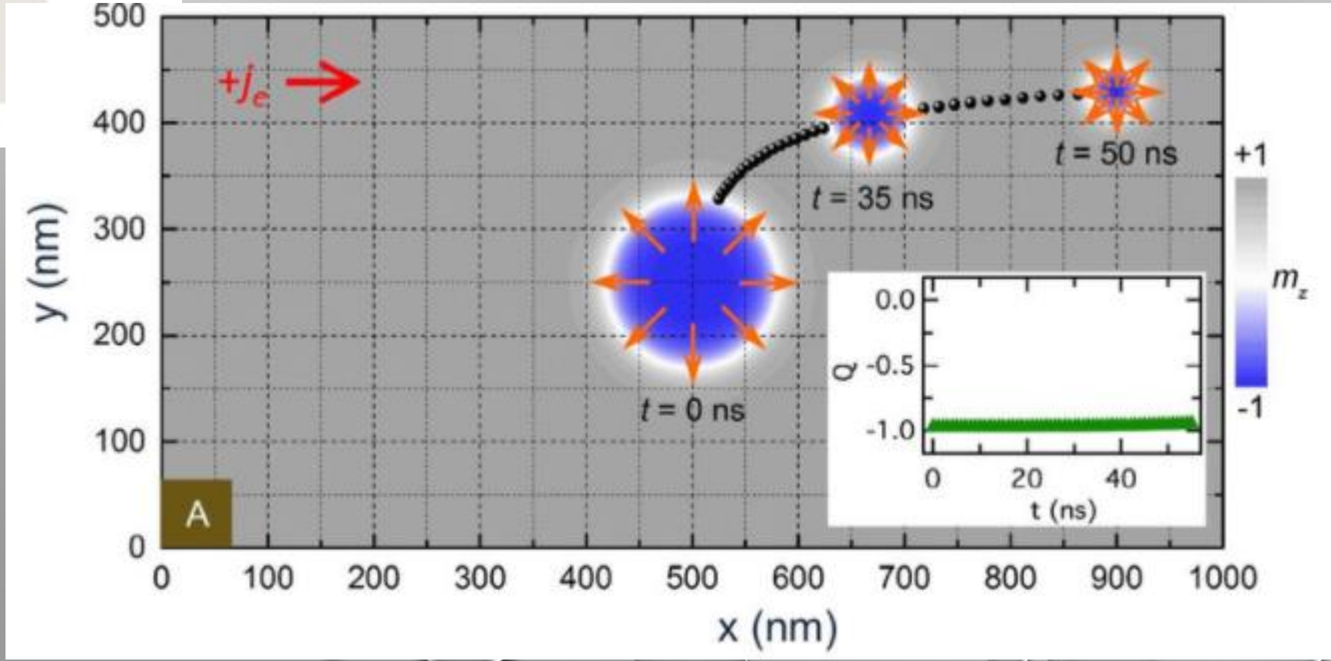




Micromagnetic simulations:
W.Jang et al (2017)

$$\vec{v} \times \vec{G} + \overleftrightarrow{D}\,\vec{v} - \vec{\nabla}_{\vec{X}} U\left(\vec{X}\right) = 0,$$

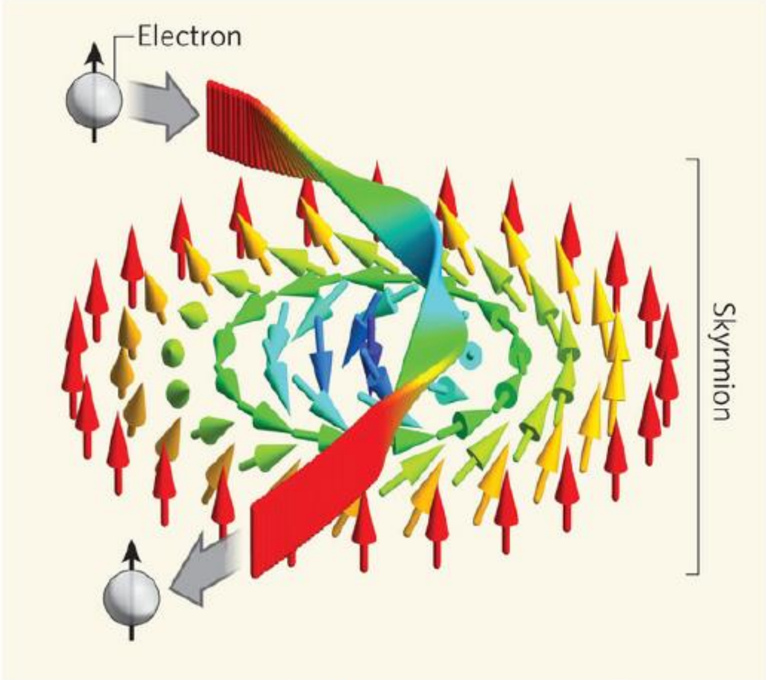
$$\vec{G} = -\frac{4\pi t M_s}{|\gamma|}(\pm 1)\,\hat{z}.$$



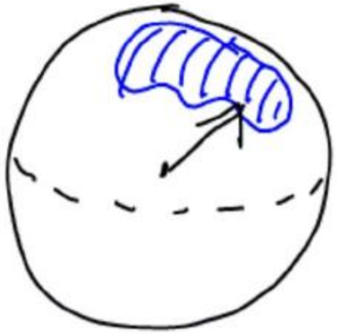
Emergent electric and magnetic fields

coupling of electrons to skyrmions by Berry phases

Resulting field (magnetic and electric) proportional to topological charge



geometric phase of spin
=
spin size * area on unit-sphere enclosed by spin



electron spin follows magnetic texture

⇨ Berry phase proportional to winding number

Berry phase as Aharonov Bohm phase ⇨ emergent electrodynamics

Volovik 87

Perspectives

Prediction : Skyrmions are attractive candidates for transporting information because they are :

- ✓ only a few nanometers in size
- ✓ very stable,
- ✓ easily created
- ✓ easily manipulated with spin-polarized currents that consume little power.

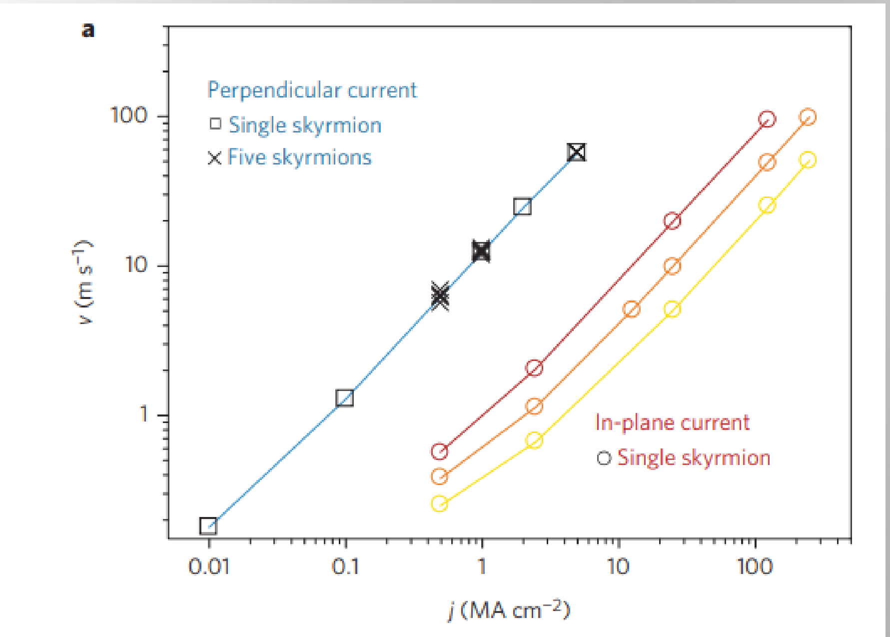
Possibility of electric generation and operation of skyrmions
Detection through Hall effect due to emerging fields

We need individual skyrmions (not lattices), i.e. nanostructuring

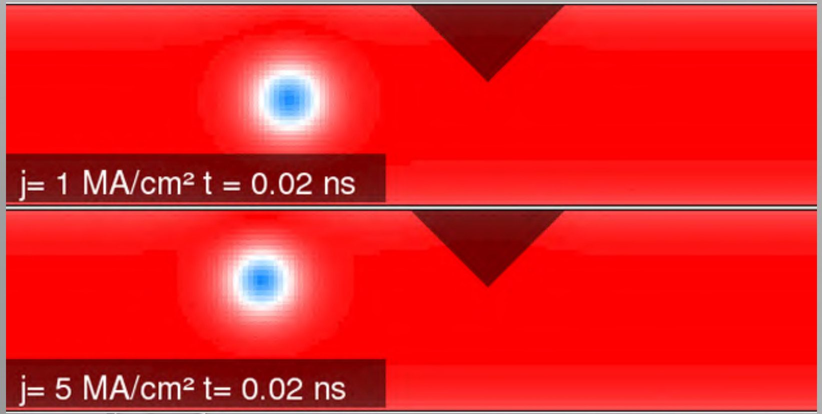
Challenge:
find suitable materials with stable at room temperature, small skyrmions operating at small currents but with large velocities

SKYRMIONS: PROPERTIES

J.Sampaio Nat. Nanotech. 8, 839 (2013).



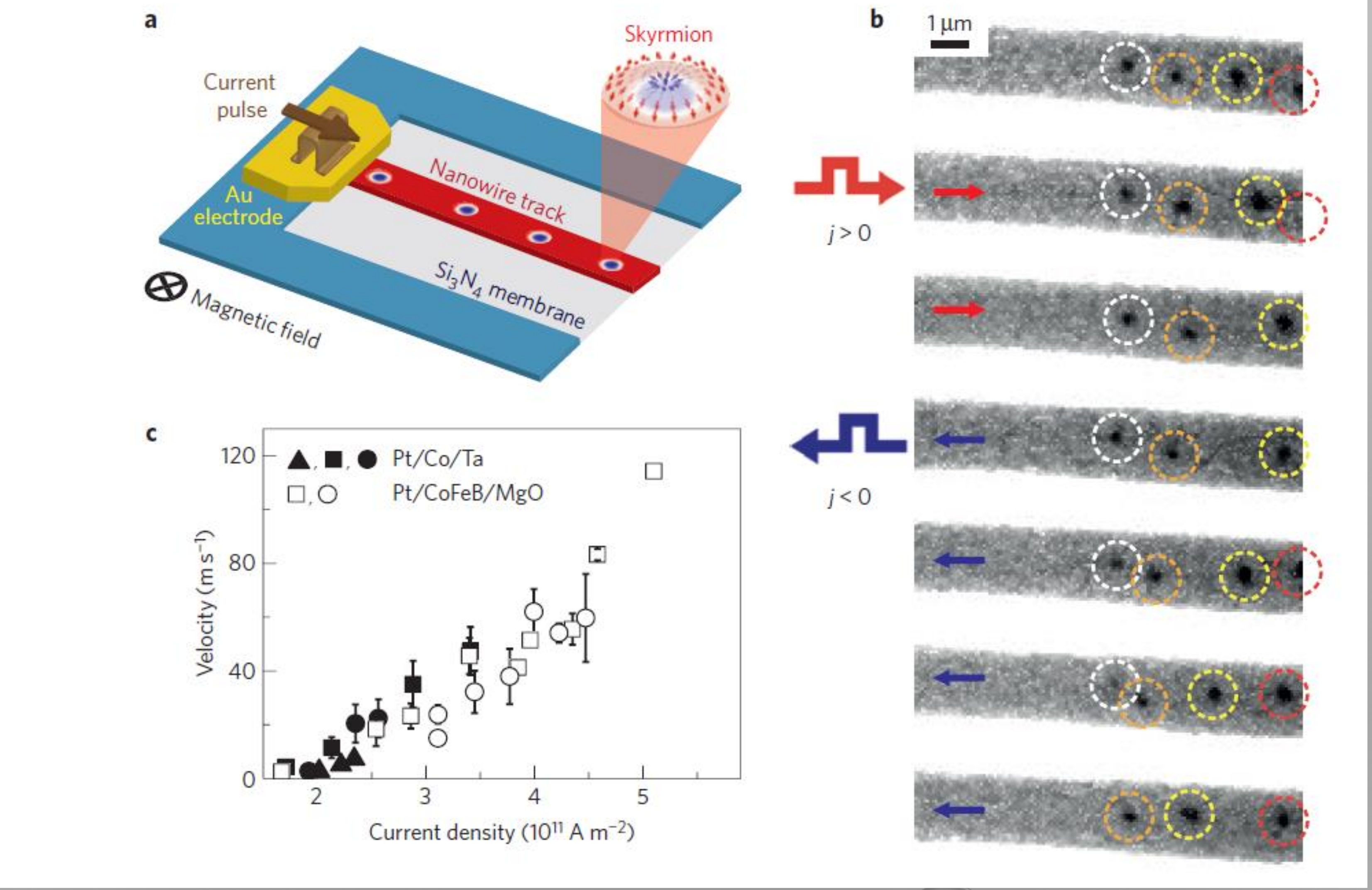
- ✓ Stability against perturbations (topological protection)
- ✓ More stable against thermal effects
- ✓ Less current for motion



Writing: Local Field (MFM), electric field, laser

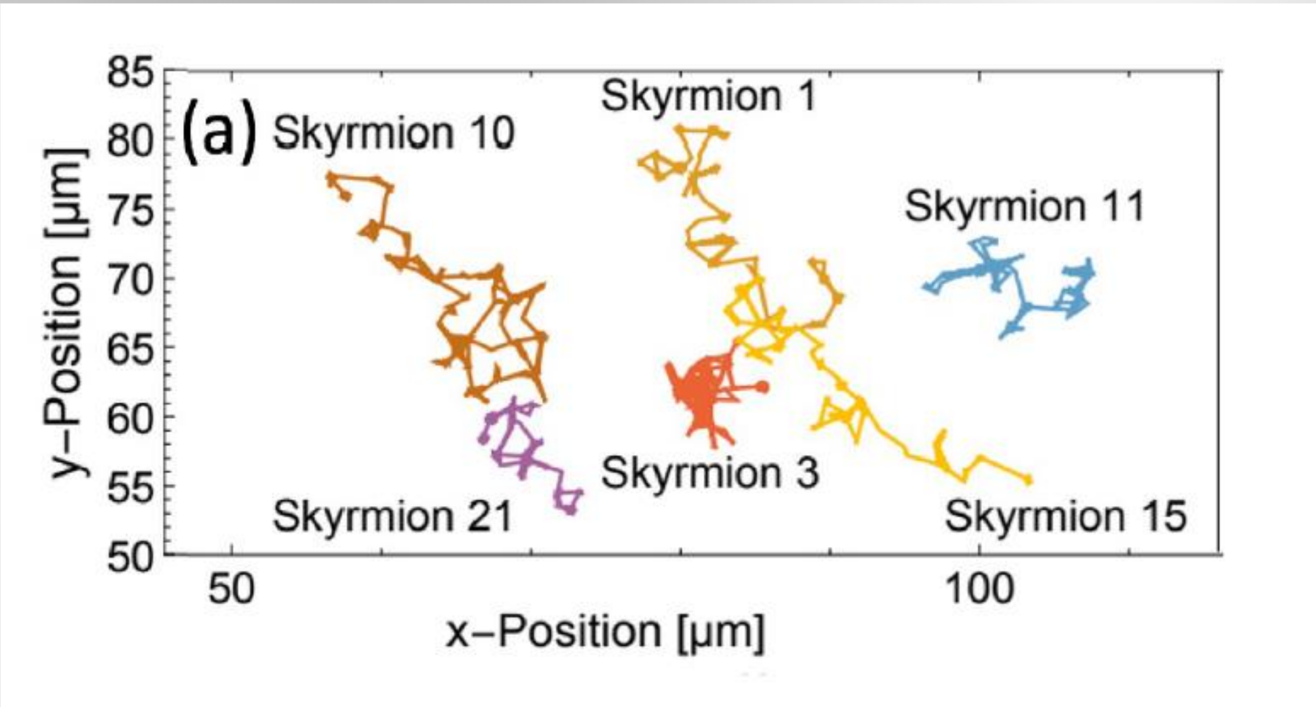
Reading (electrical (Hall effect)

Room-temperature, velocities suitable for applications
Motion under spin-polarised currents and spin-Hall effect



S.Woo et al Nature Mat (2016)

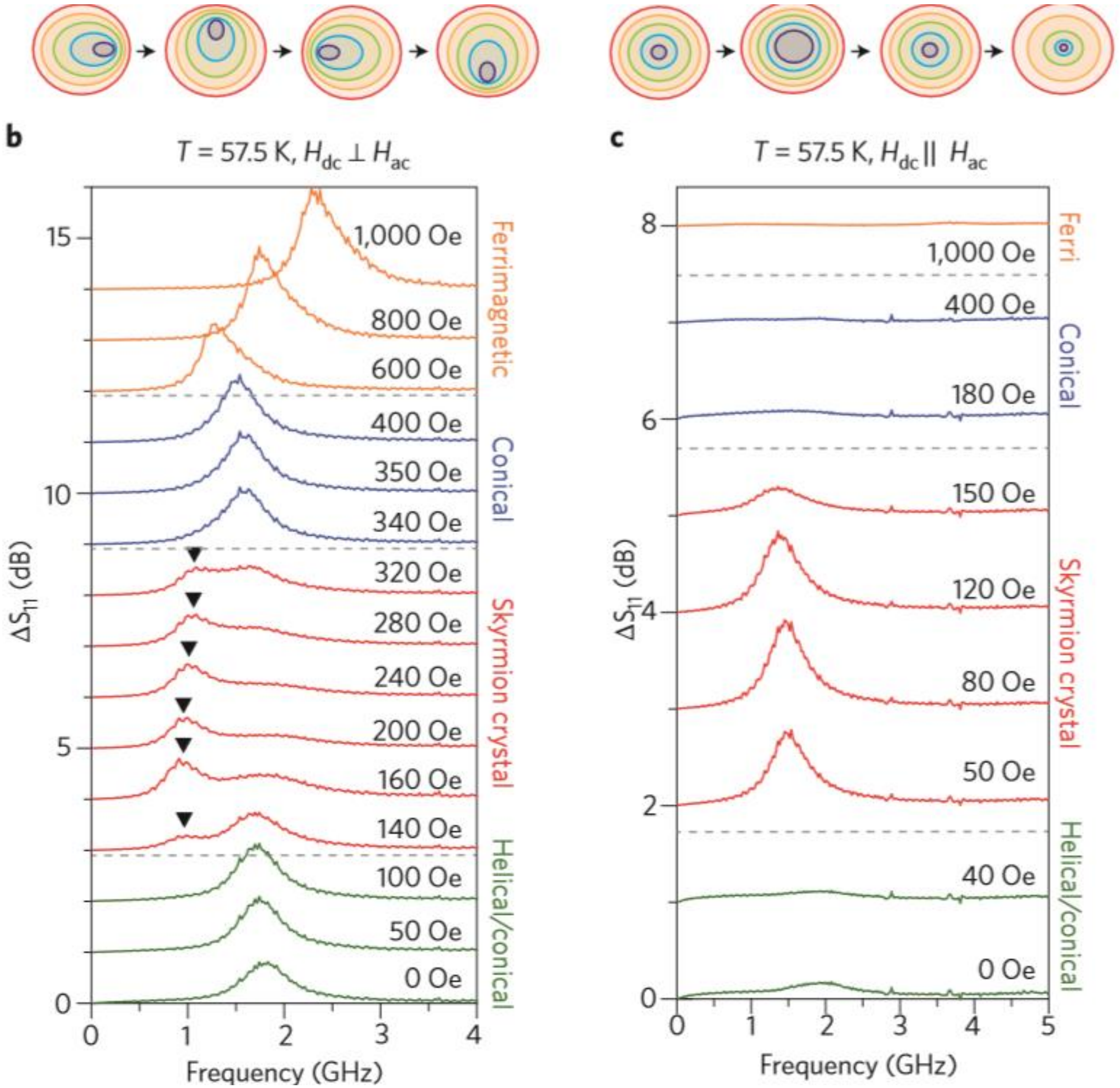
THERMAL SKYRMION DIFFUSION



Group of M.Klaui

Dynamics: two modes

Gyrotropic & Breathing

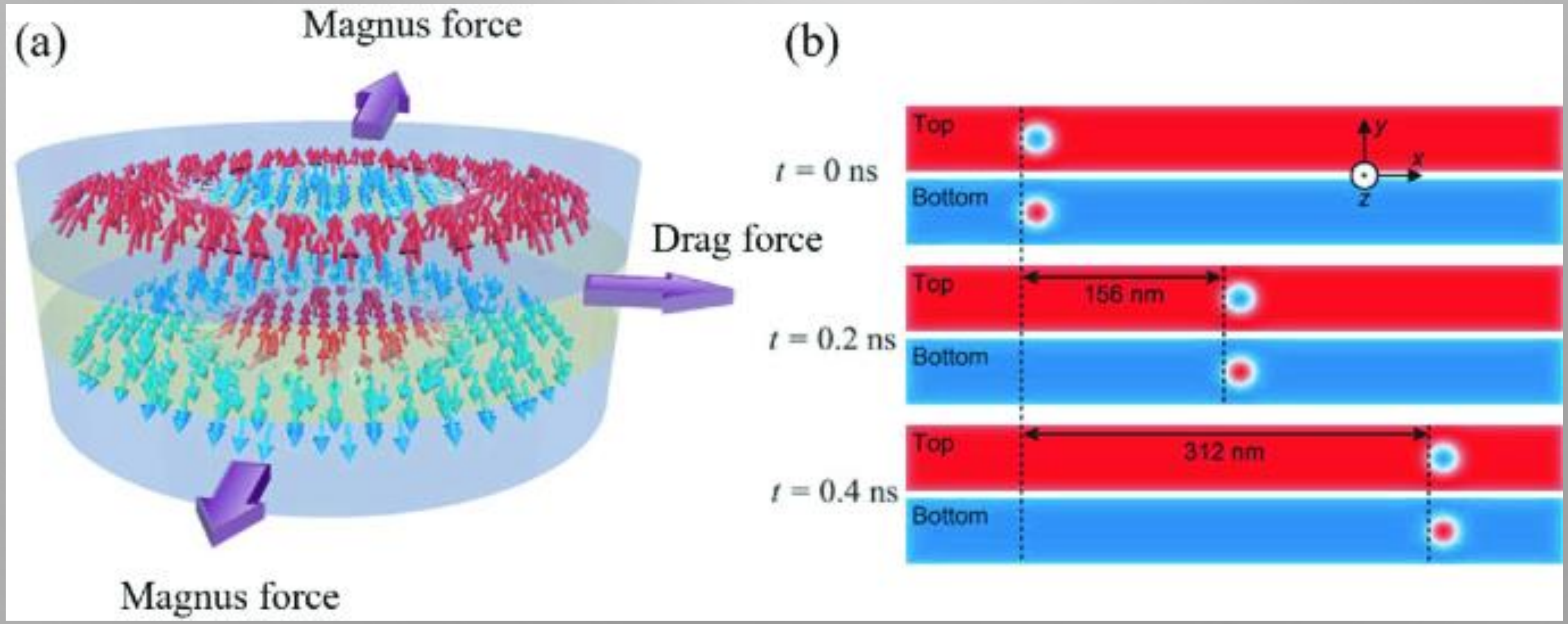


Skyrmions also have non-neglidgible mass

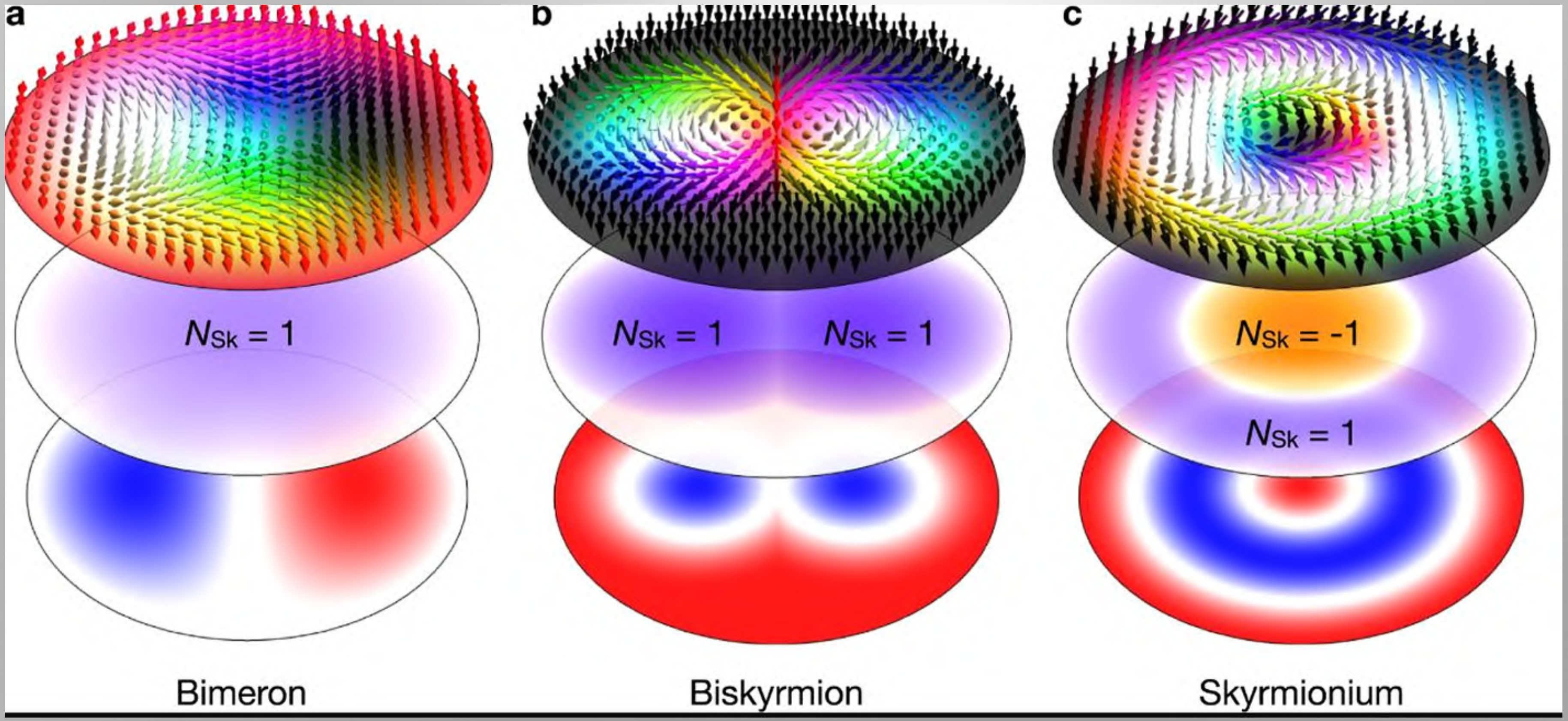
ANTIFERROMAGNETIC SKYRMIONS

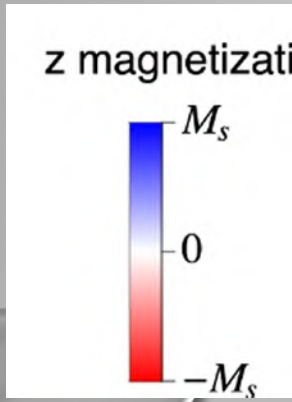
No skyrmion Hall angle

L.Shen
Topics in Applied Physics
book series (TAP,volume 138)

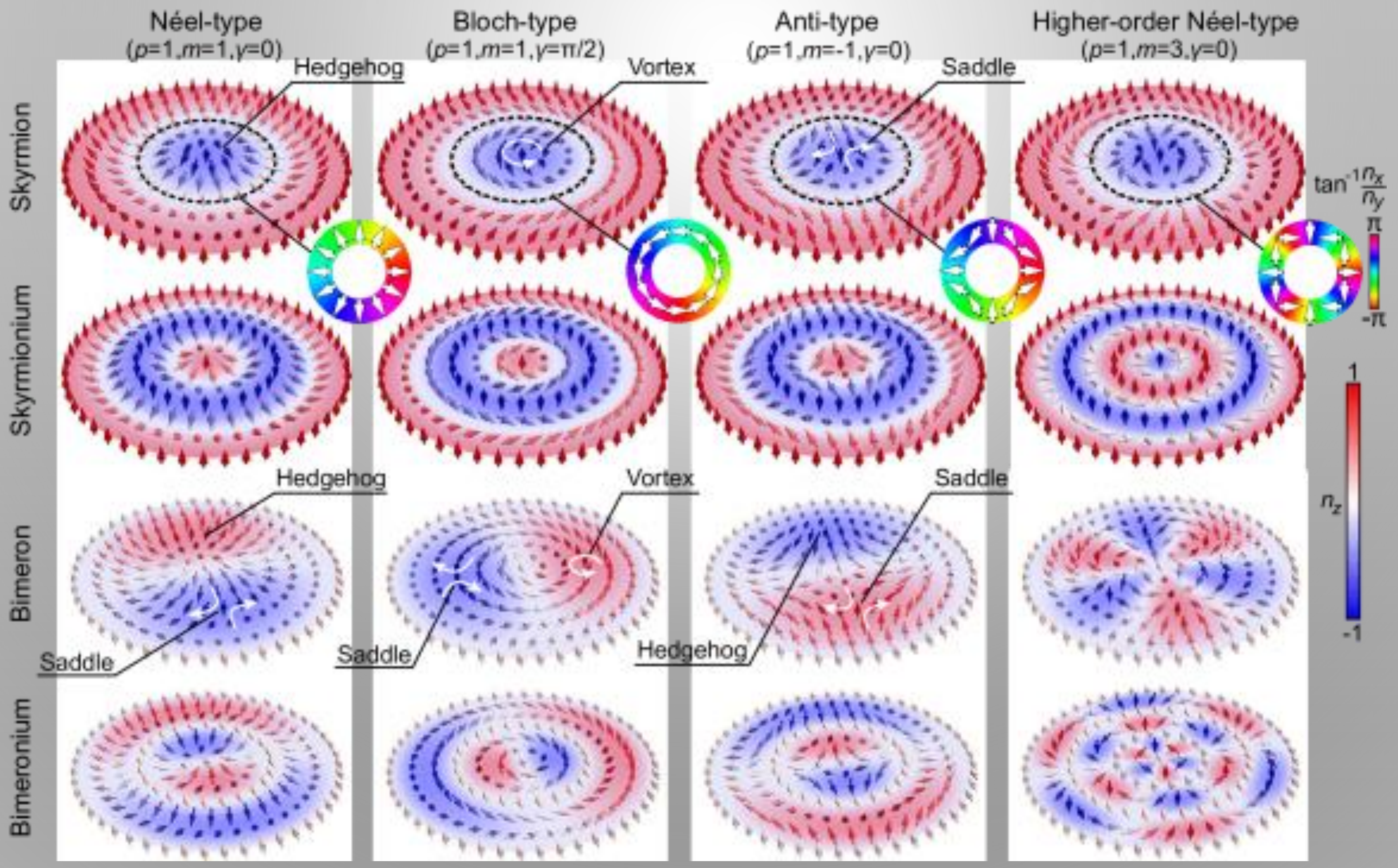


MORE STRUCTURES





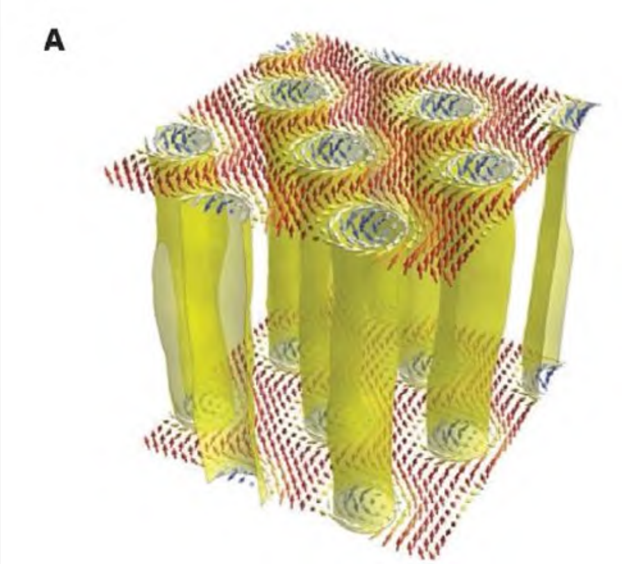
B.Gobel et al Physics Reports 895 (2021)

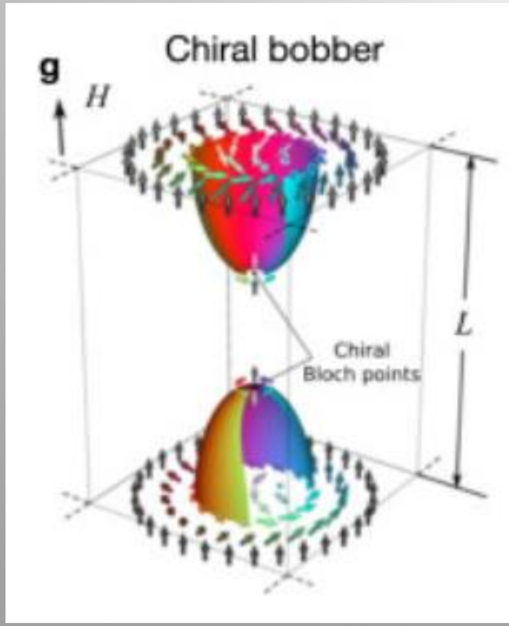


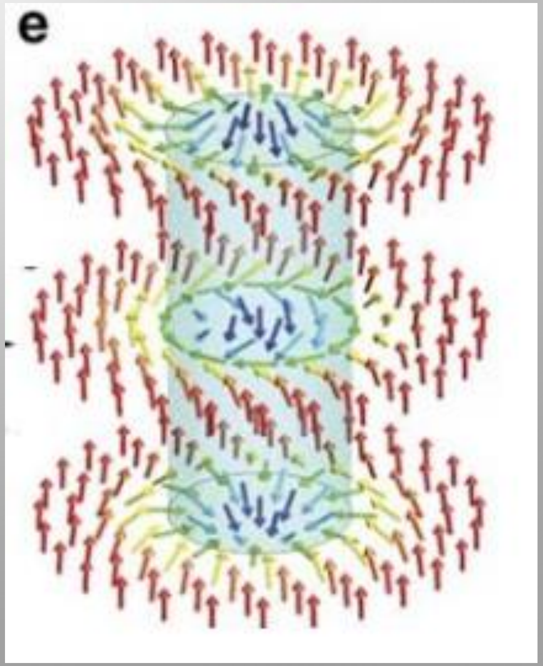
Yijie Shen et al arXiv

3D STRUCTURES

NATURAL 3D STRUCTURES IN THICK FILMS







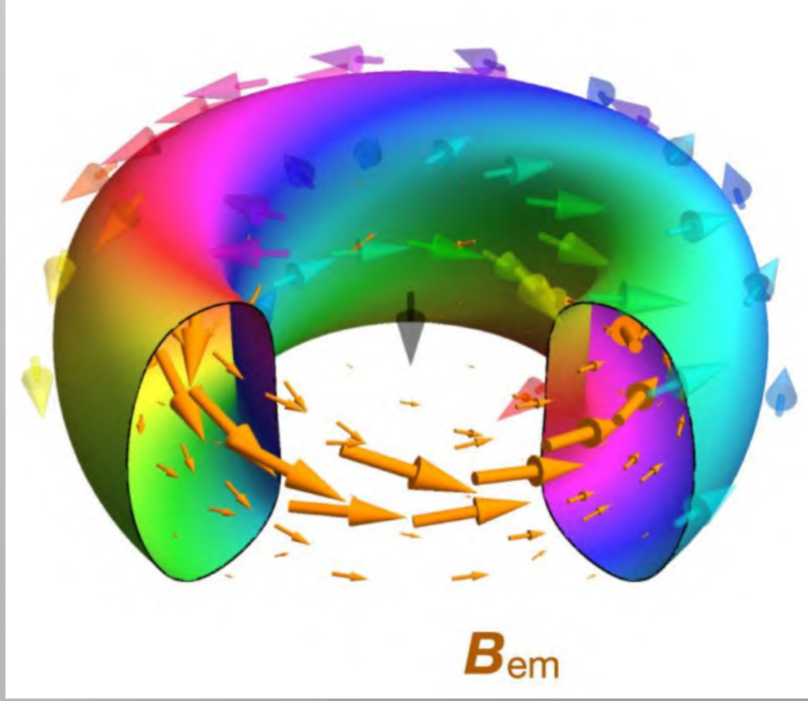
P.Milde et al Science 340 (2013)

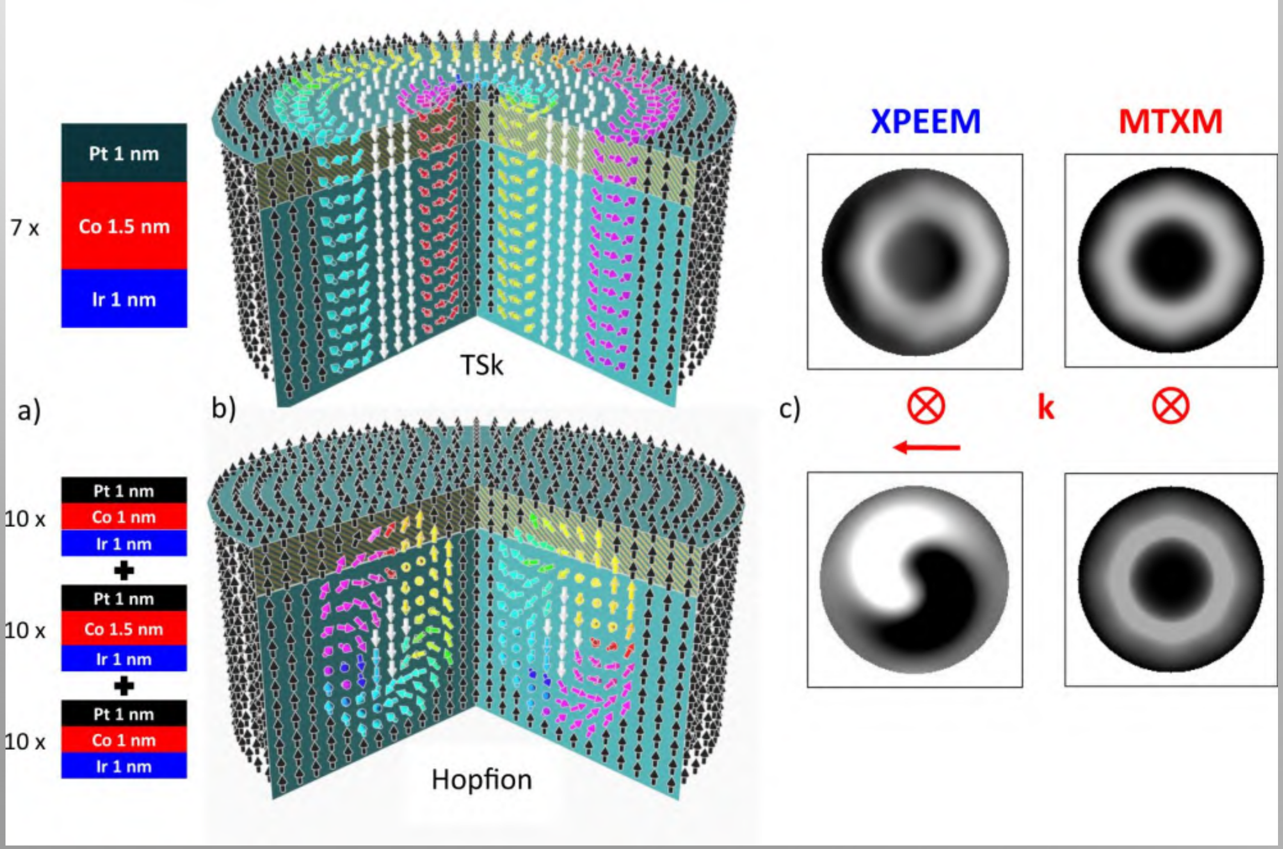
Interfacial DMI

Intrinsic DMI

HOPFIONS

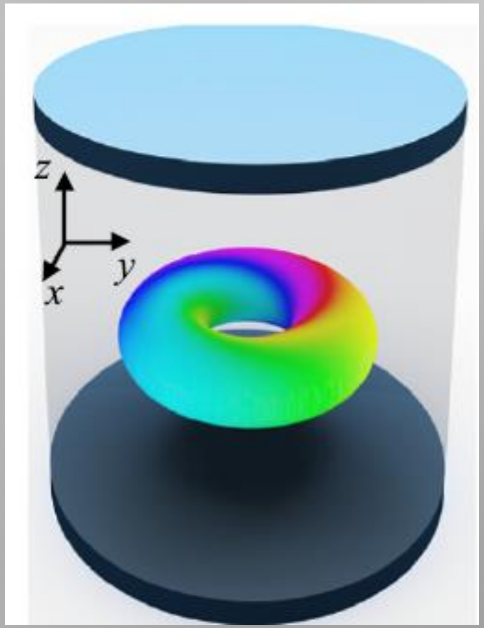
Twisted skyrmion tubes



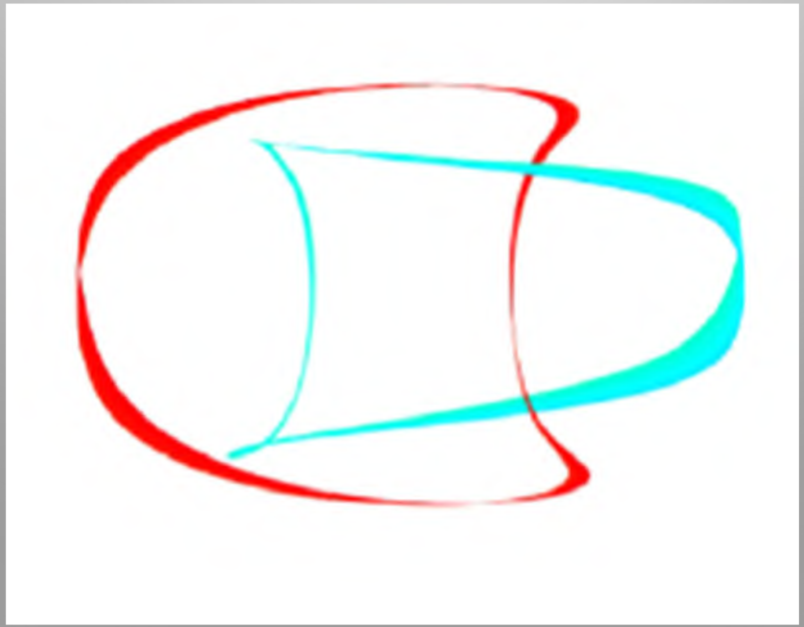


N-Kent et a Nature Com 12, : 1562 (2021)

HOPFIONS



Preimages S_x=1 and S_x=-1



$$Q_H = -\frac{1}{4\pi^2}\int dV\mathbf{A}\,\mathbf{B}$$

$$B_i = \frac{1}{8\pi}\epsilon_{ijk}\mathbf{s}\cdot(\nabla_j\mathbf{s}\times\nabla_k\mathbf{s})$$

Emergent field

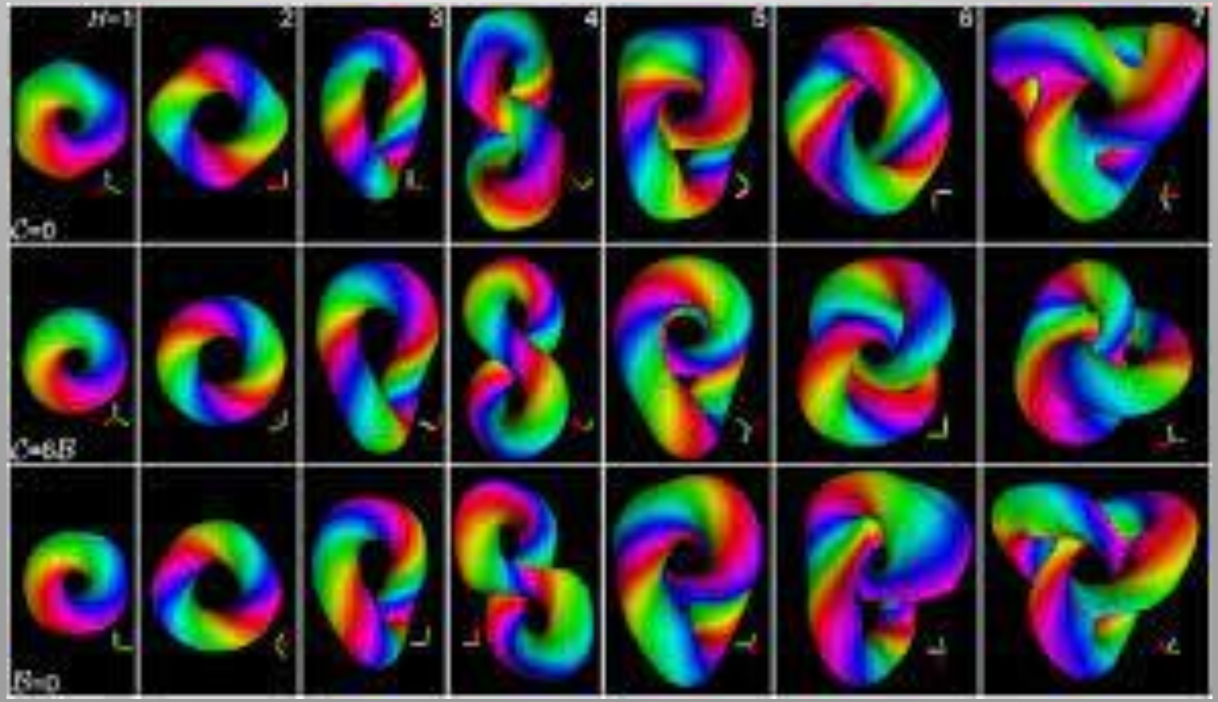
$$rot\,\boldsymbol{A} = \boldsymbol{B}$$

Gauge invariance for

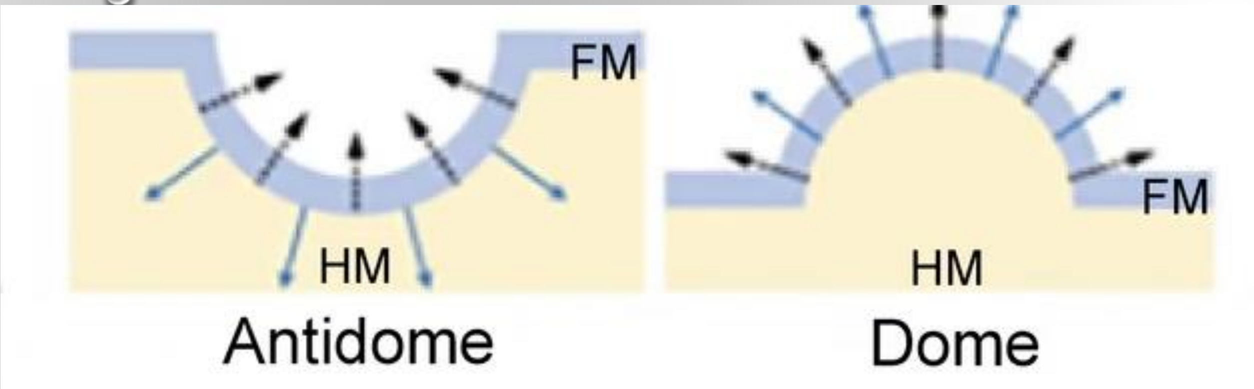
$$div\,\boldsymbol{B} = 0$$

Y.Liu et al PHYSICAL REVIEW B 98, 174437 (2018)

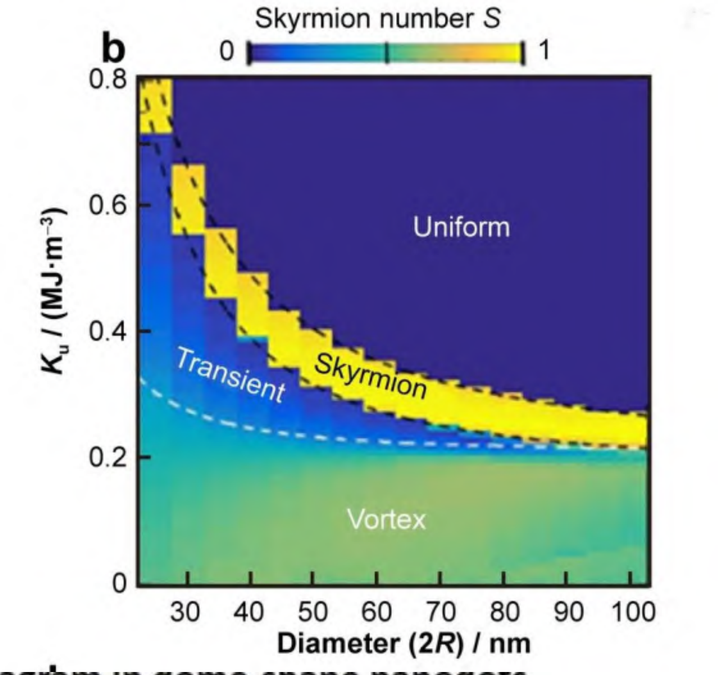
HOPFIONS OF HIGHER ORDERS



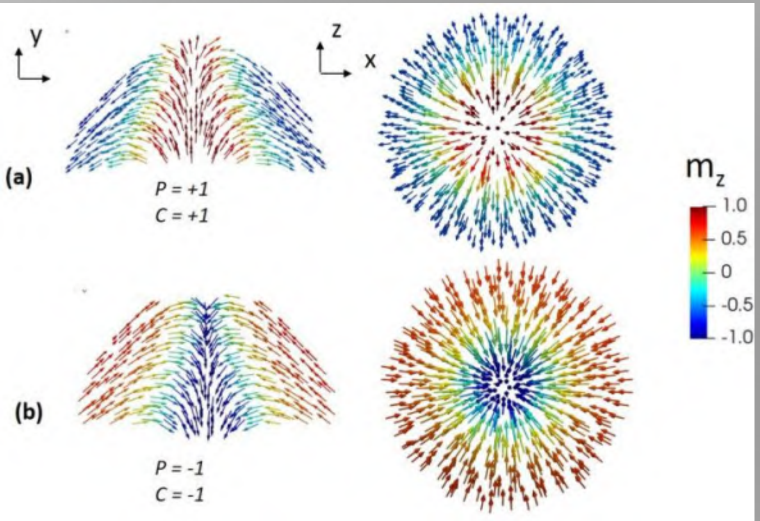
CURVED GEOMETRIES

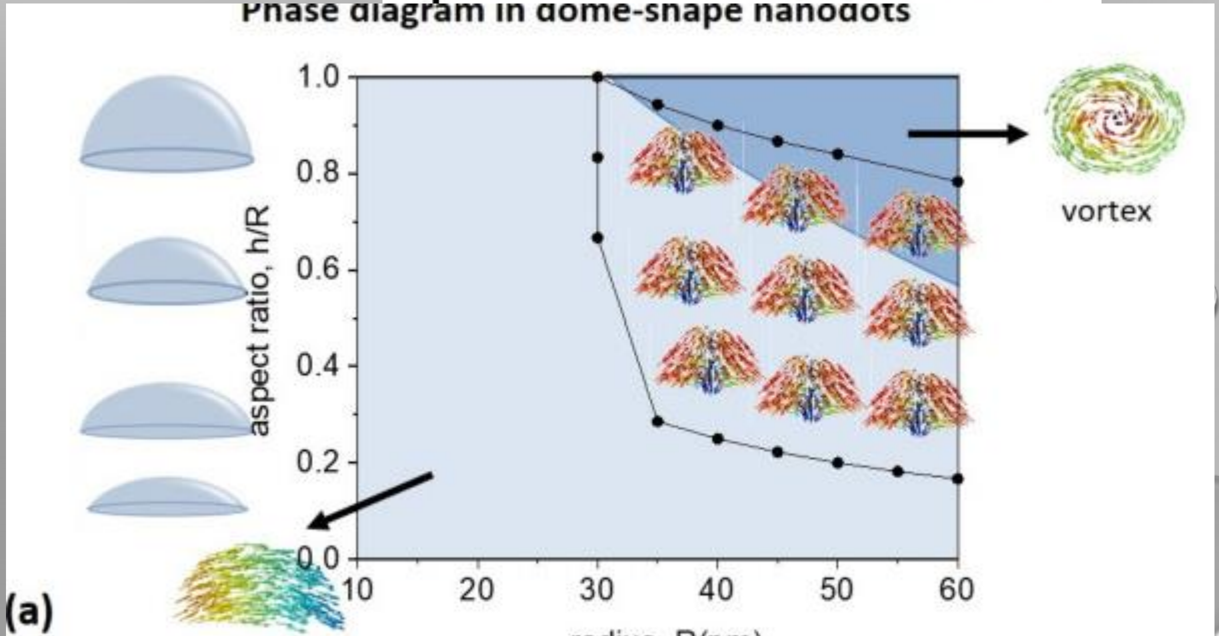


Y.Liu et al Rare Metals 41, 2184 (2022)

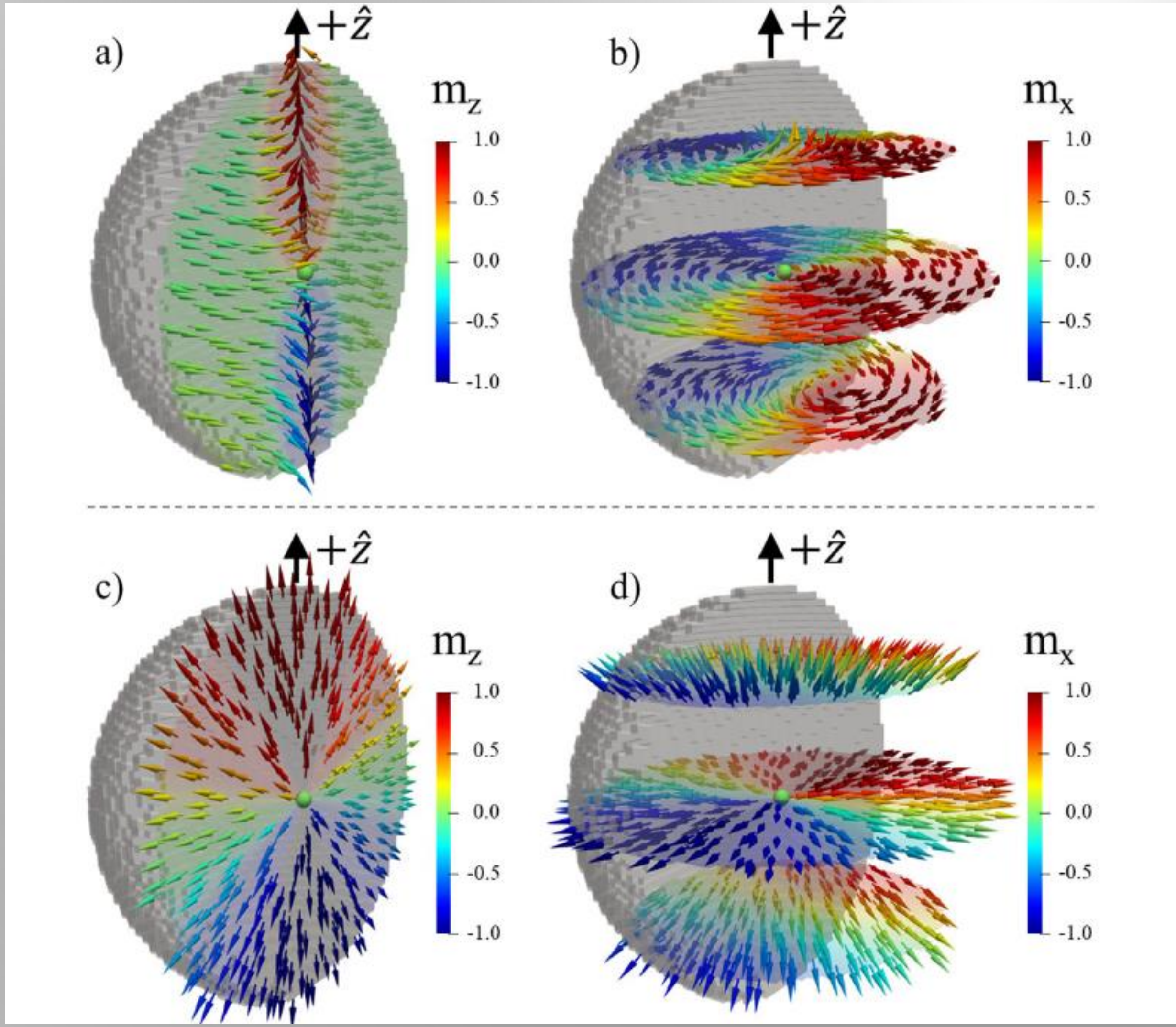


E.Berganza et al Sci Rep. 2022; 12: 3426.





BLOCH POINTS

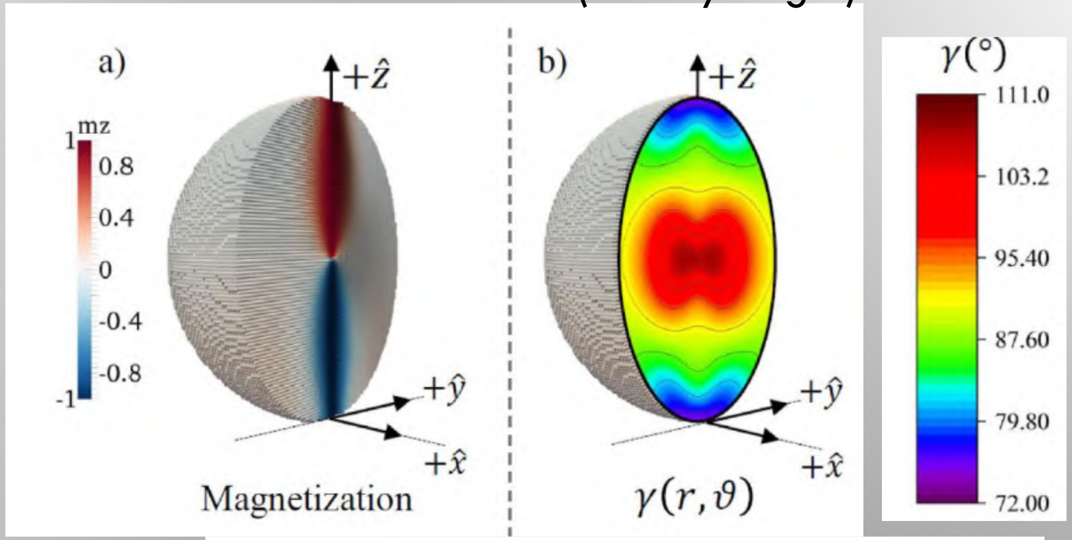


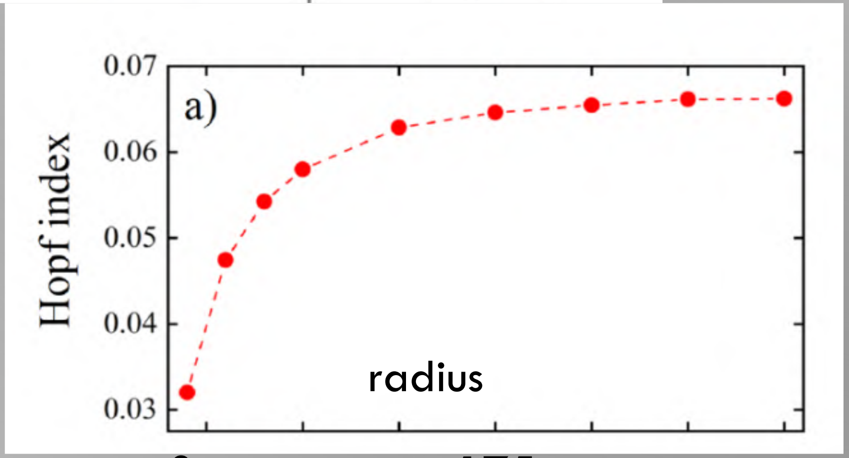
Bloch point of the Bloch type (spiral)

Bloch point of the Neel type (radial or hedgehog)

ON THE “TOPOLOGICAL CHARGE” OF THE BLOCH POINT

(helicity angle)





0 175nm

$$Q_H = -\frac{1}{4\pi^2}\int dV\mathbf{A}\,\mathbf{B}$$

Hoph index (3D topological charge)

Gyrovector $\mathbf{B} = rot\ \mathbf{A}$

$$Q_H = -\frac{q}{4\pi}\int_0^{\pi} d\vartheta \sin\vartheta\,(1+\cos\vartheta)[\gamma(\mathrm{R},\vartheta)-\gamma(0,\vartheta)],$$

Zero for radial BP

Non-zero - for spiral BP

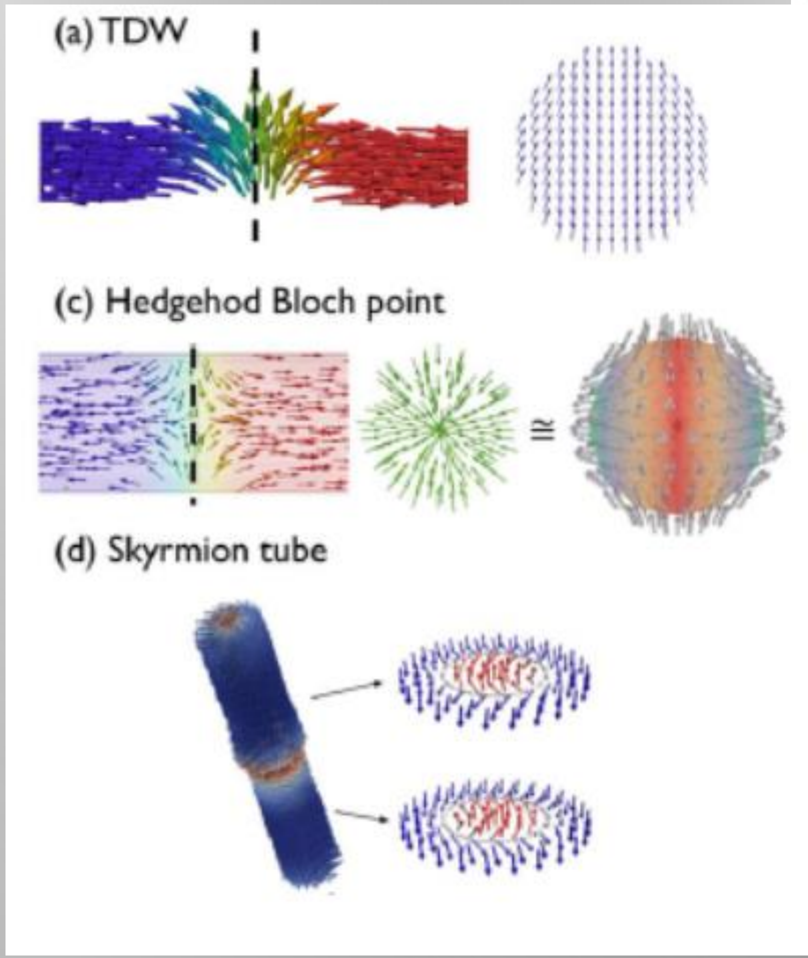
polarity

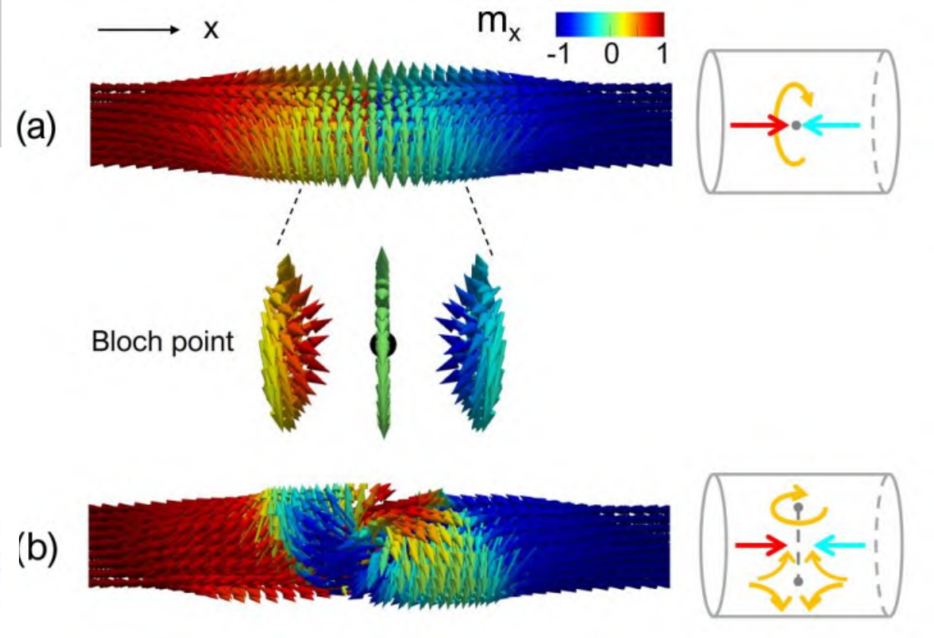
$$\oint \mathbf{B}d\mathbf{S} = -4\pi pq$$

Winding number

F.Tejo et al Sci. Rep. (2021) 21714

DOMAIN WALLS IN CYLINDRICAL NANOWIRES

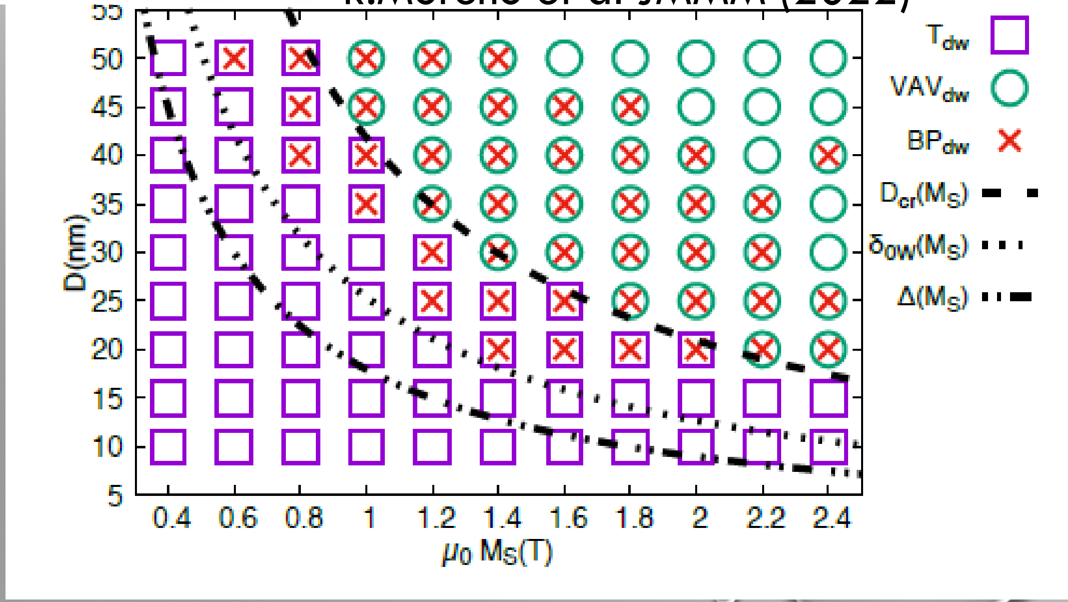




Bloch point domain wall

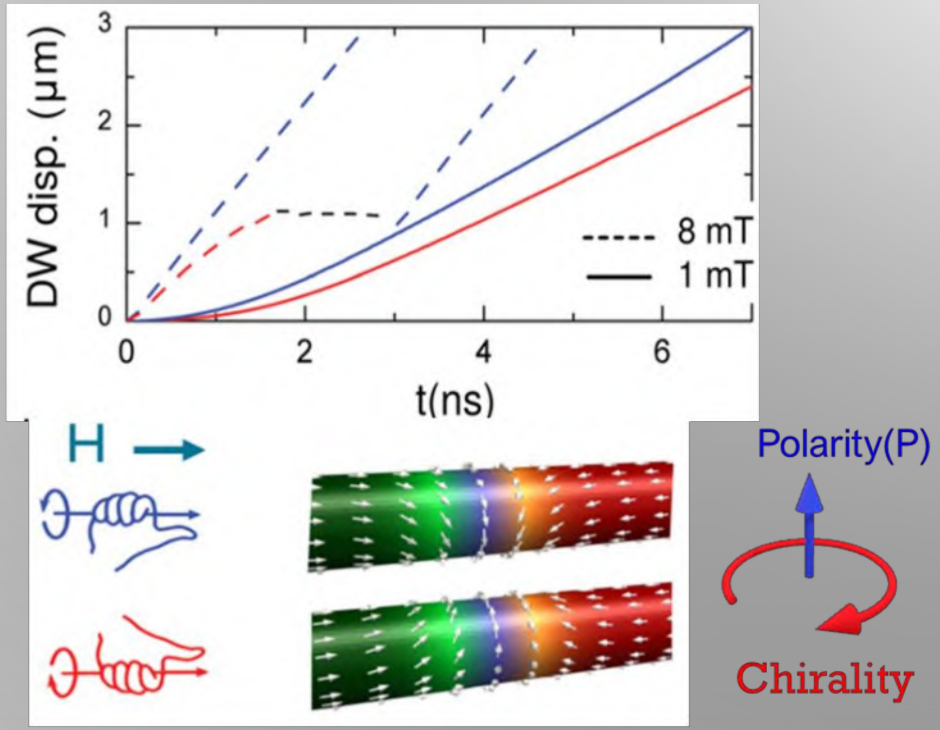
Vortex-antivortex domain wall

R.Moreno et al JMMM (2022)

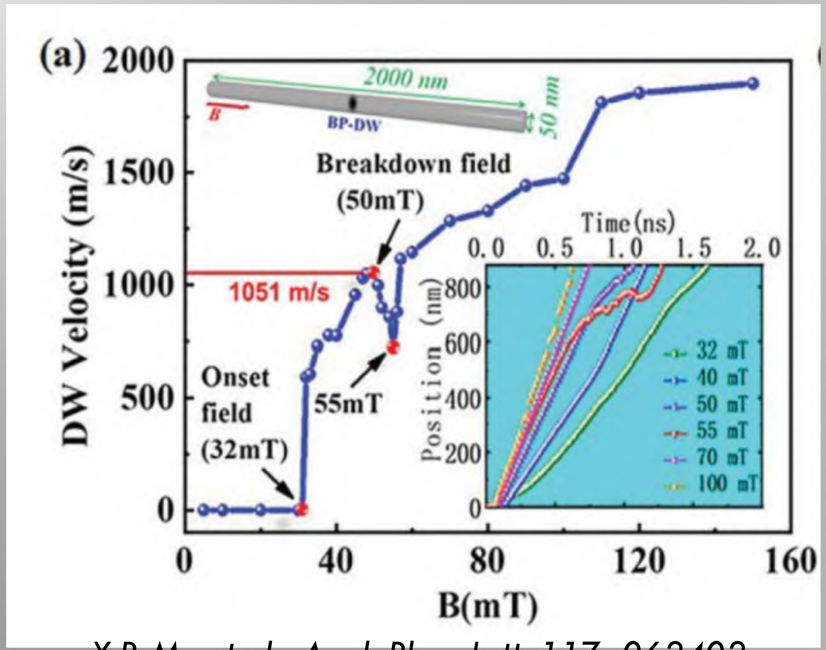


DYNAMICS OF BLOCH POINT DW IN CYLINDRICAL NANOWIRES

High velocities can be achieved > 1 km/s
(limited by spin-Cherenkov effect?)



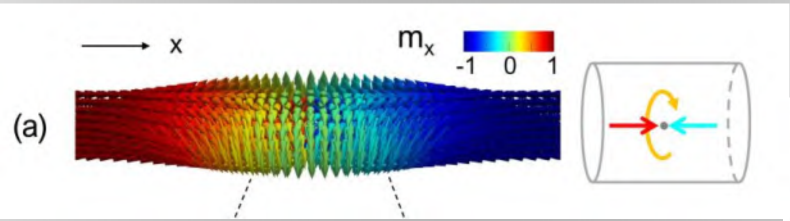
R. Hertel *et al*, J. *Phys.: Condens. Matter* **28** 483002 2016



X.P. Ma et al., Appl. Phys. Lett. 117, 062402 (2020);

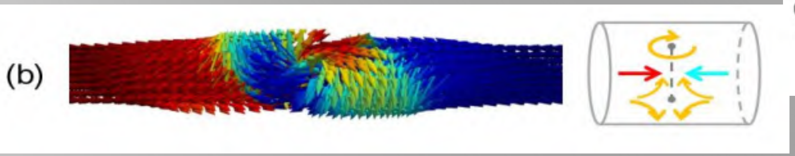
Propagation above magnonic limit?

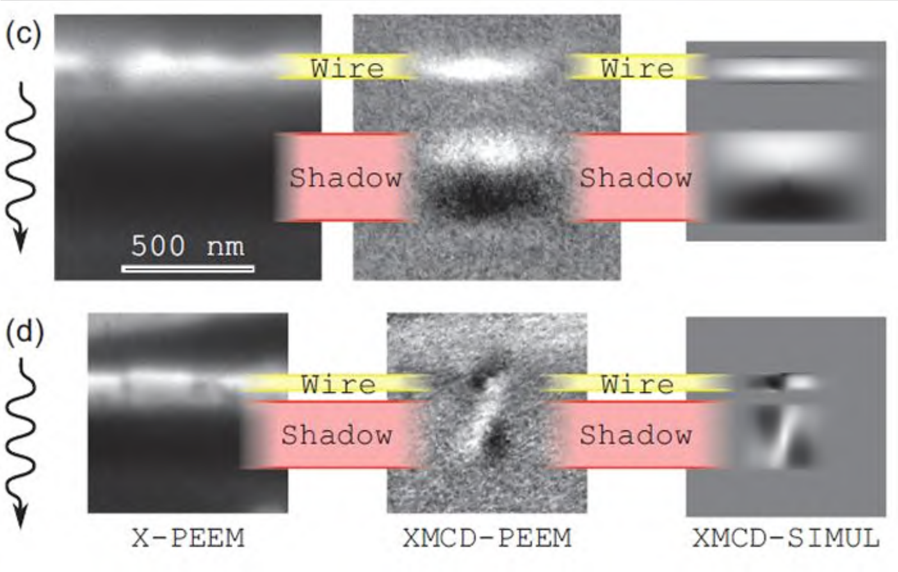
BLOCH-POINT VERSUS VORTEX-ANTIVORTEX DOMAIN WALL



BPW

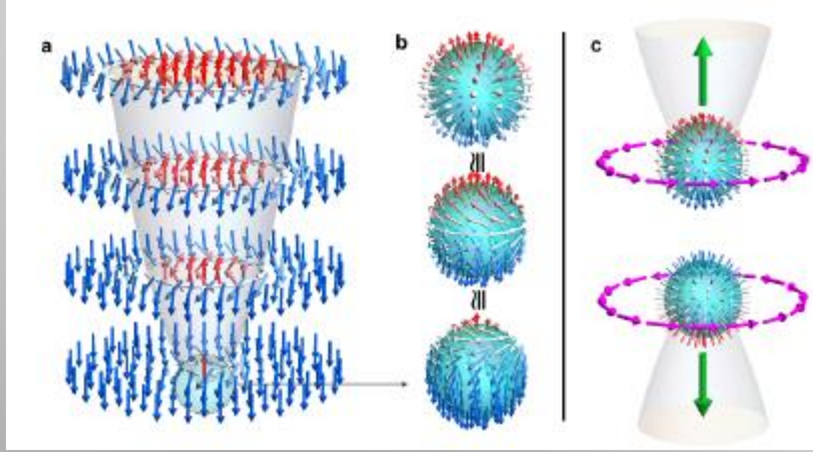
VADW





DaCol et al., PRB 89, 180405(R) (2014)

3D Skyrmion



M. Charilaou, et al Phys. Rev. Lett. **121** 097202 (2018).

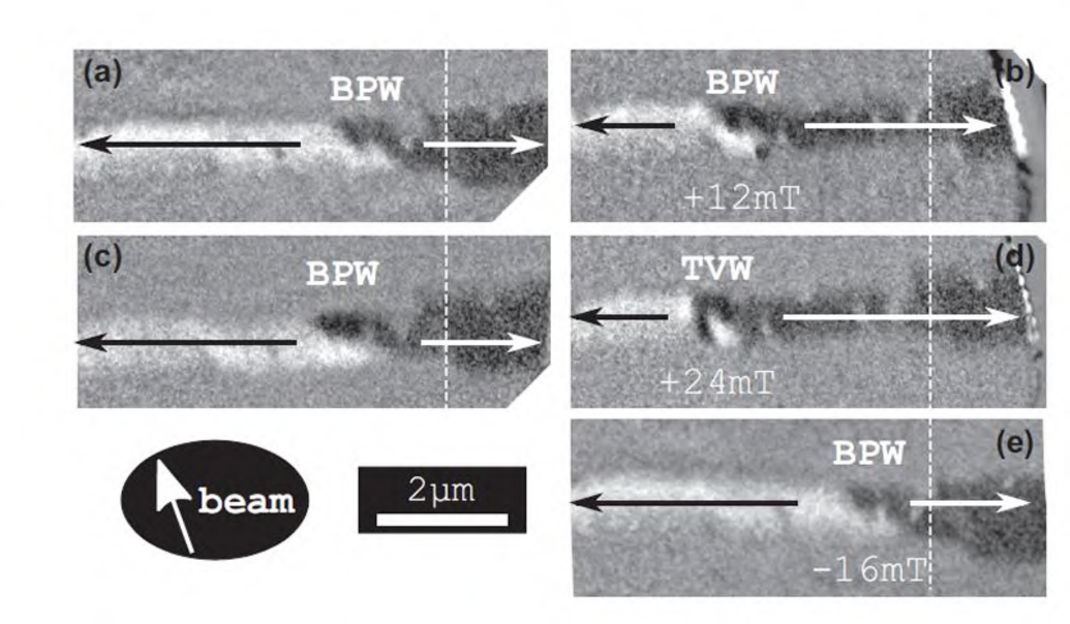
Non-trivial topology

Emerging electromagnetic fields

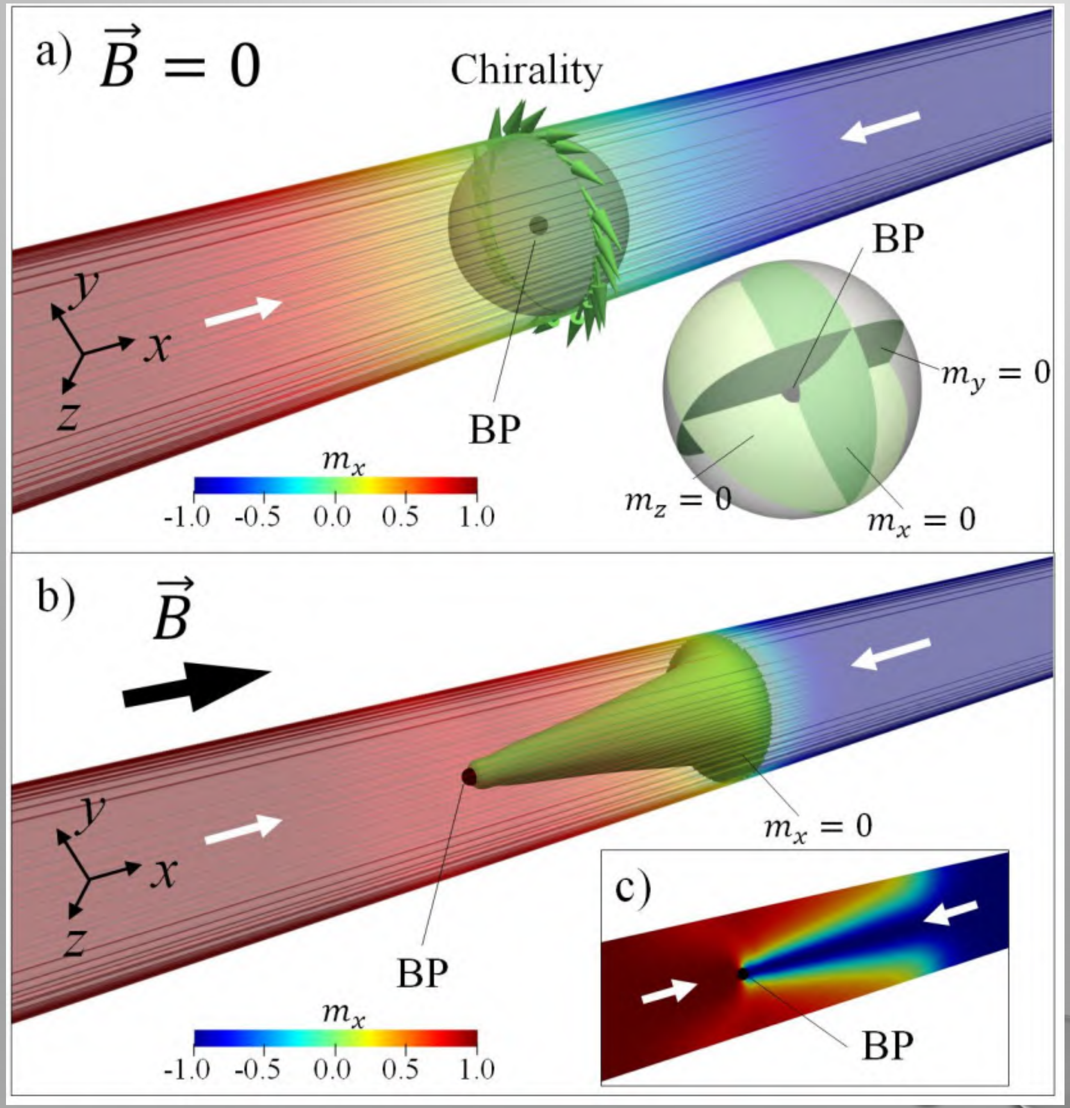
PHYSICAL REVIEW B **99**, 024433 (2019)

Bloch-point-mediated topological transformations of magnetic domain walls in cylindrical nanowires

A. Wartelle,[1,*] B. Trapp,[1] M. Staňo,[1,†] C. Thirion,[1] S. Bochmann,[2] J. Bachmann,[2,3] M. Foerster,[4] L. Aballe,[4] T. O. Menteş,[5] A. Locatelli,[5] A. Sala,[5] L. Cagnon,[1] J.-C. Toussaint,[1] and O. Fruchart[6,‡]

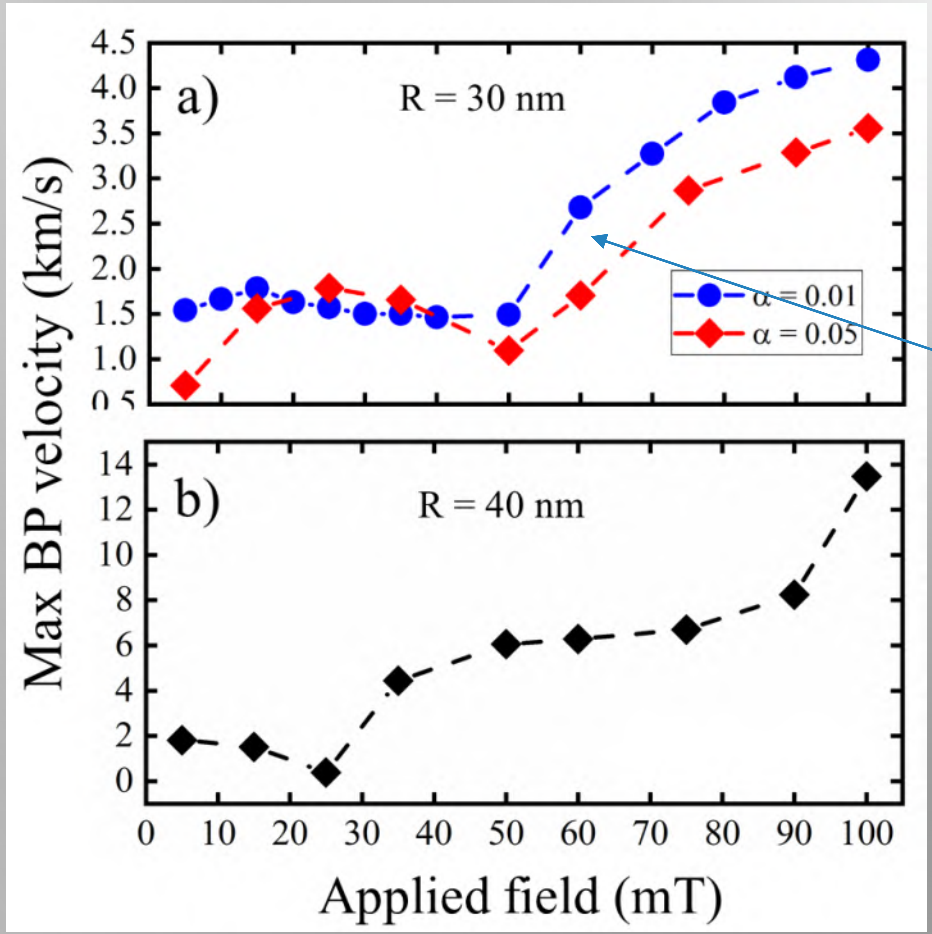


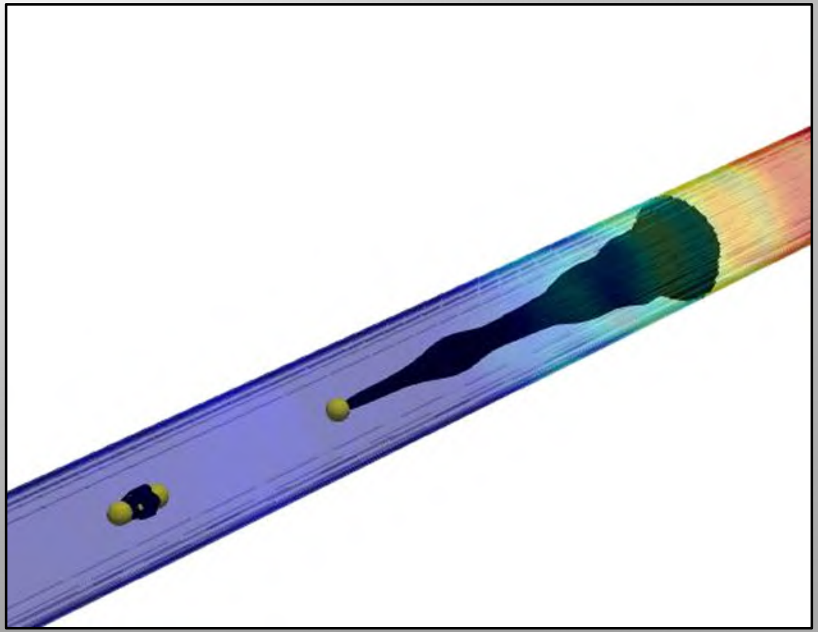
FE MAGNETIC CYLINDRICAL NANOWIRE



BLOCH-POINT DOMAIN WALL VELOCITY

- LARGER FOR SMALLER DAMPING
- LARGER FOR LARGER DIAMETER





The elongation of DW cone is due to large difference
In magnetostatic field in the middle and in the center

MESSAGES

- STABILIZAITON OF MAGNETISATION STRUCTURES DEPEND STRONGLY ON THE COMPETITION OF ENERGIES AND SYSTEM SIZE
- DOMAIIN WALLS: WALKER BREAKDOWN EFFECT AND SEARCH FOR SYSTEMS WITHOUT IT
- FINITE-SIZE SYSTEMS: POSSIBILITY TO STABILIZE ADDITIONAL STRUCTURES (VORTICES, BLOCH POINTS IN 3D ETC)
- DMI INTRODUCES MORE VARIETY (SKYRMIONS, HOPHIONS ETC.)
- IMPORTANCE OF GYROTROPIC EFFECTS (VORTEX, SKYRMION HALL EFFECT)

CHIRAL DOMAIN WALLS (SYSTEMS WITH DMI)

DMI favors only one chirality for Neel domain walls