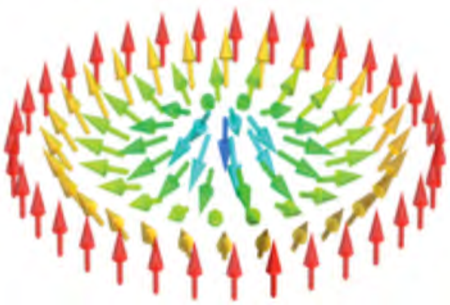
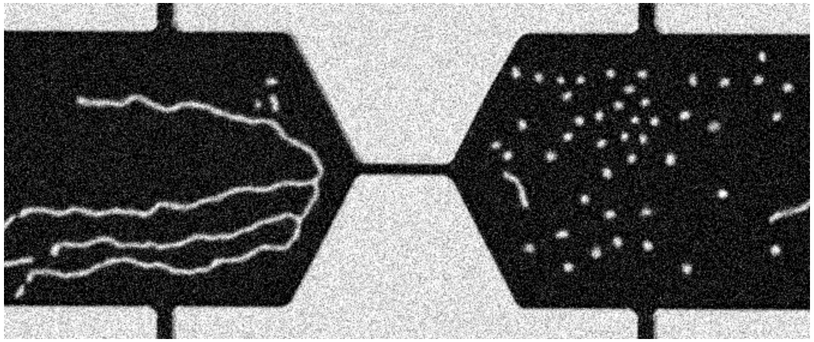
Manipulating Magnetic Skyrmions



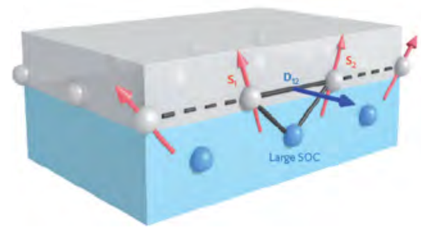


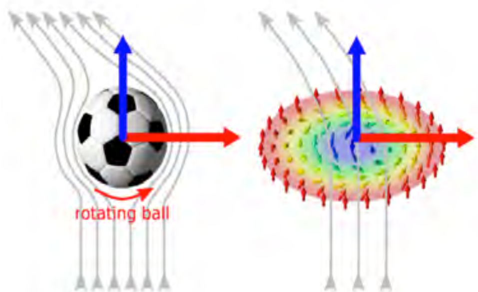
Axel Hoffmann

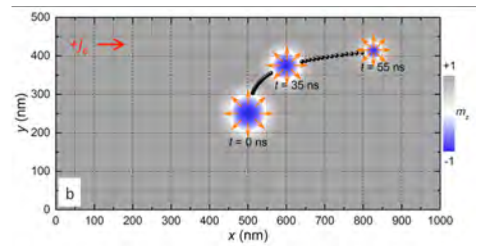
Materials Science Division
Argonne National Laboratory

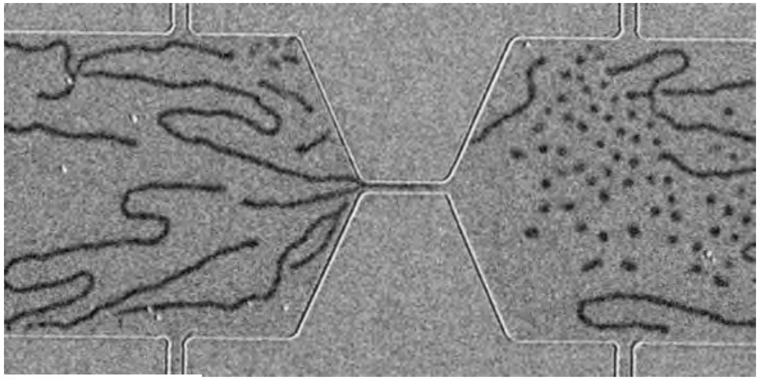
Outline

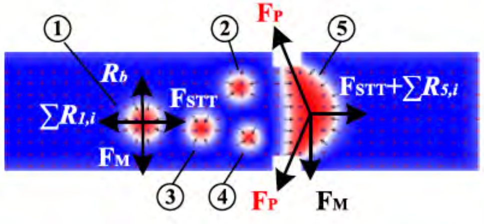
- Magnetic Skyrmions
- Moving Skyrmions
- Generating Skyrmions
- Neuromorphic Ideas
- Conclusions

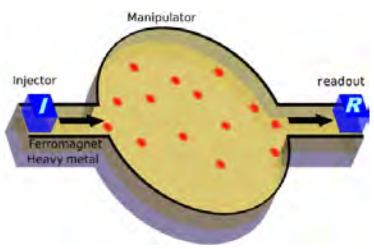




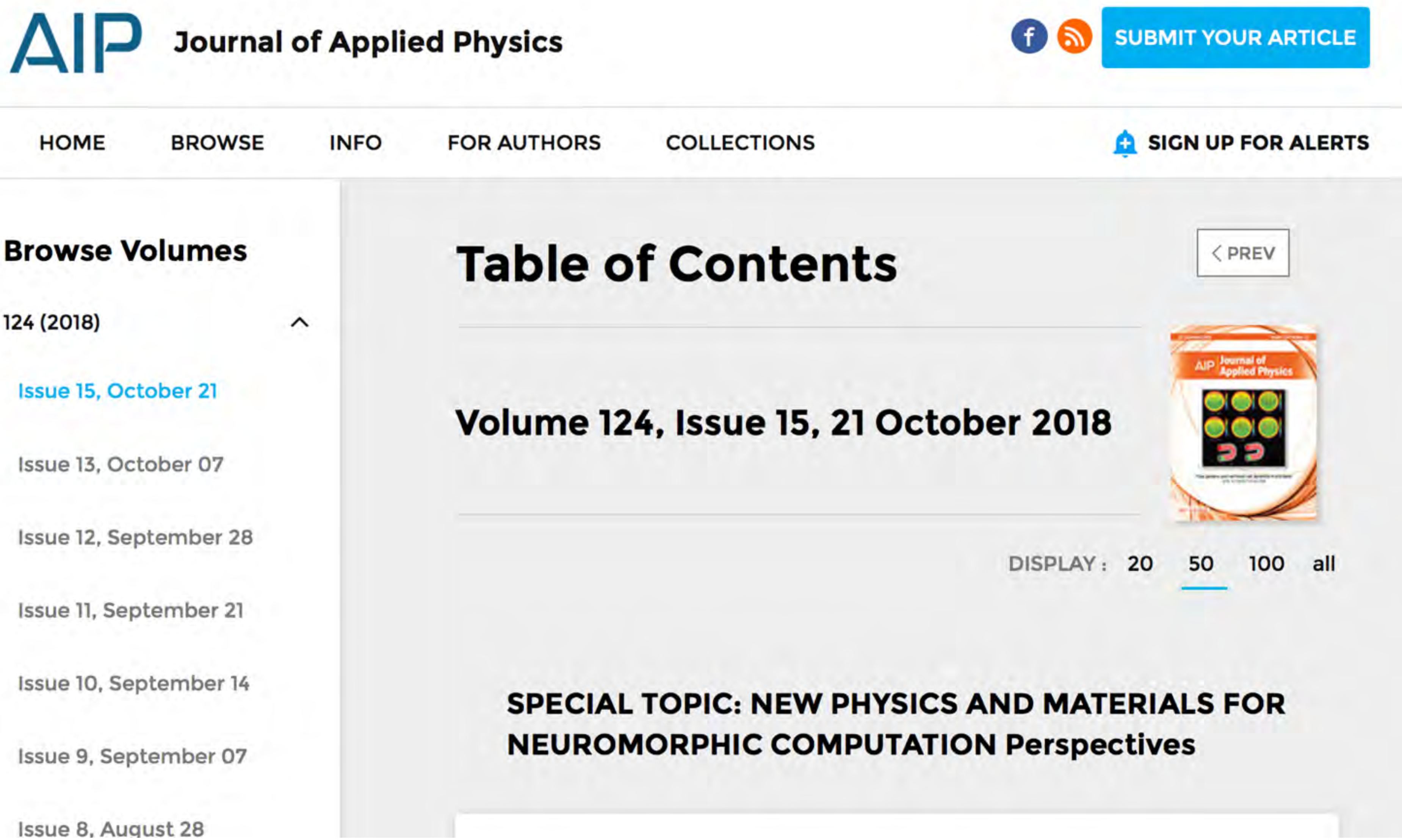








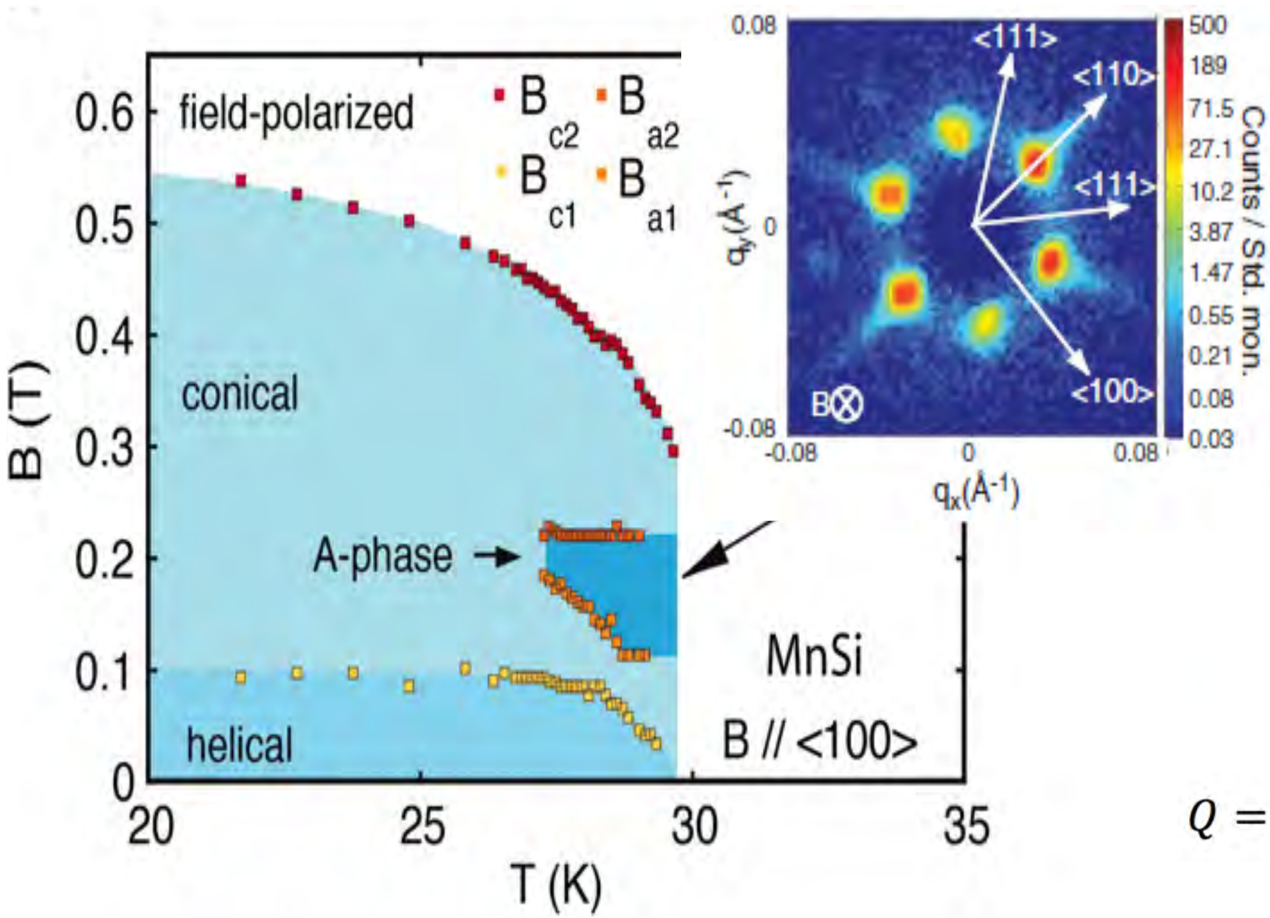
Journal of Applied Physics: Special Topic



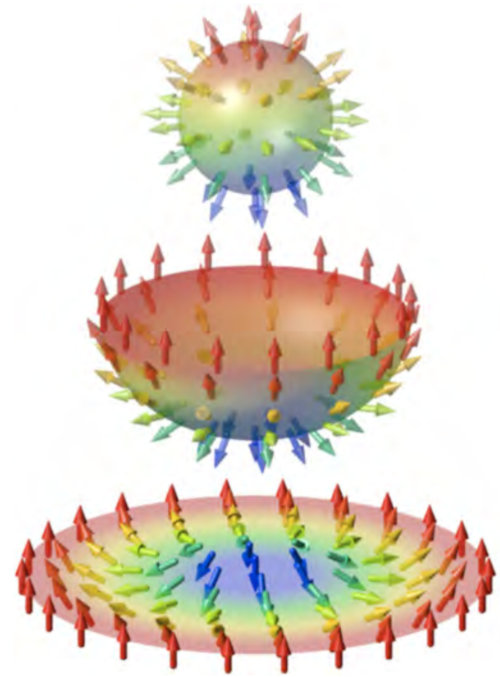
Magnetic Skyrmions

Recent Review: W. Jiang *et al.*, Phys. Rep. **704**, 1 (2017)

Discovery of Magnetic Skyrmions



S. Mühlbauer *et al.*, Science **323**, 915 (2009)



Topological Charge

$$Q = \frac{1}{4\pi}\int \mathbf{m}\cdot(\partial_x\mathbf{m}\times\partial_y\mathbf{m})dxdy$$

Q = ±1

Charge Current Manipulation of Skyrmions

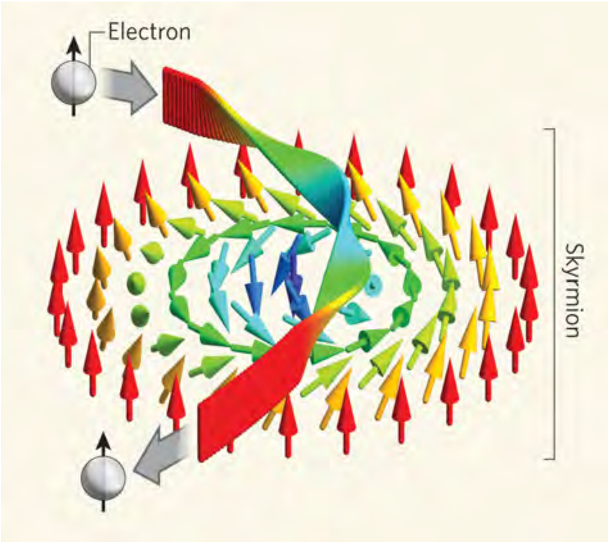
Emergent Magnetic Field

J. Zang *et al.*, Phys. Rev. Lett. **107**, 136804 (2011)

$$h_i = \frac{\hbar c}{2e}\delta_{iz}\mathbf{n}\cdot(\partial_x\mathbf{n}\times\partial_y\mathbf{n}) = \pm\frac{\hbar c}{2e}$$

$$h \approx \frac{\Phi_0}{\pi R^2} \approx \frac{\Phi_0}{\pi a^2}(\frac{D}{J})^2$$

$h \sim 100$ T



Back-action moves skyrmion

- Ultralow threshold Current

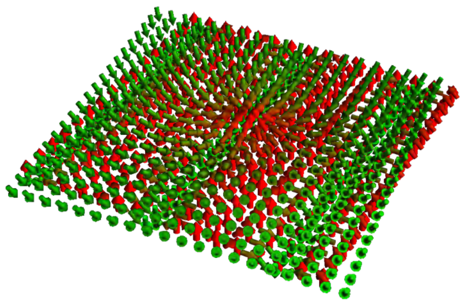
$j_c \approx 10^6 \mathrm{A}\cdot\mathrm{cm}^{-2}$ Domain Wall

$j_c \approx 0.2\mathrm{A}\cdot\mathrm{cm}^{-2}$ Skyrmion

Skyrmions are Stabilized by Chiral Interactions

W. Jiang *et al.*, Phys. Rep. **704**, 1 (2017)

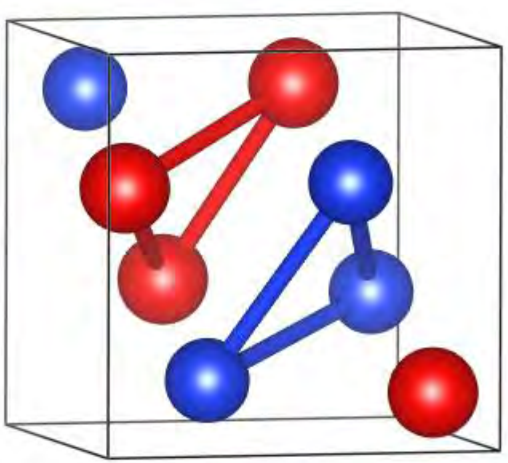
$$H = \sum_{<ij>} -J\mathbf{S}_i \cdot \mathbf{S}_j + \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j) - \sum_i \mathbf{B} \cdot \mathbf{S}_i$$



Ferromagnetic Helical Spiral Skyrmion

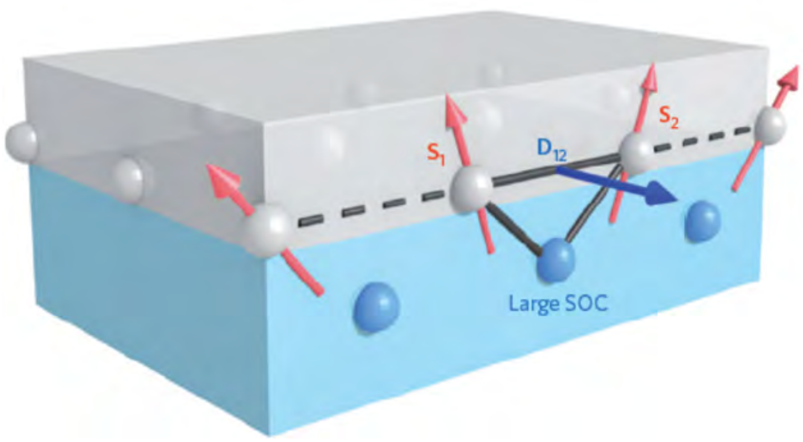
Dzyaloshinskii-Moriya Interaction (DMI) requires Inversion Symmetry Breaking

Bulk



e.g., B20 compounds (MnSi, etc.)

Multilayers



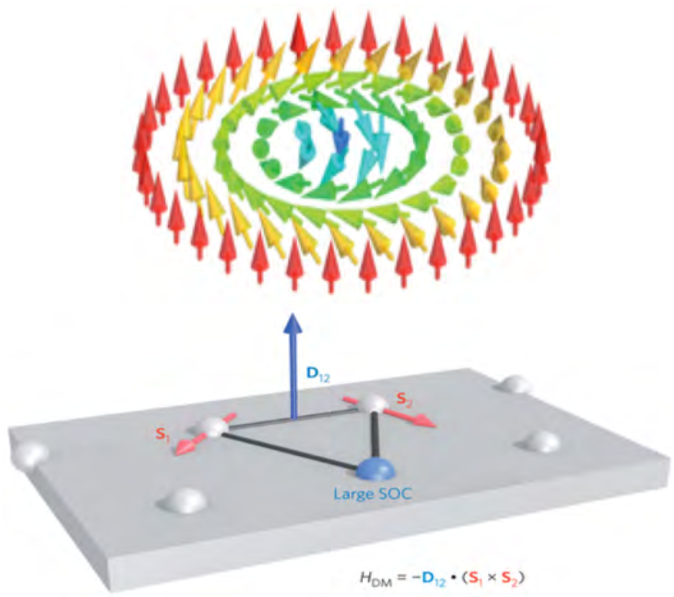
e.g., Co/Pt, $Ni_{80}Fe_{20}$/Ta, etc.

Stabilizing Skyrmions

Broken inversion symmetry leads to Dzyaloshinskii-Moriya Interaction (DMI) $H_{dmi} = -D_{ij} \cdot (S_i \times S_j)$

Bulk DMI

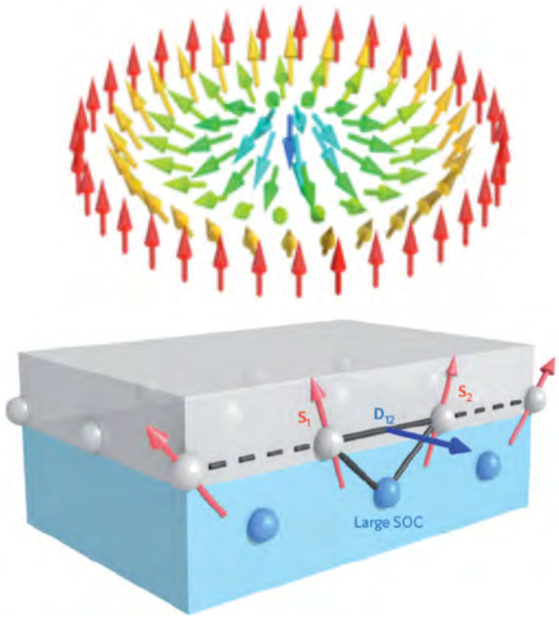
Vortex-like (Bloch)



B20 compound MnSi, FeGe, FeCoSi

Interfacial DMI

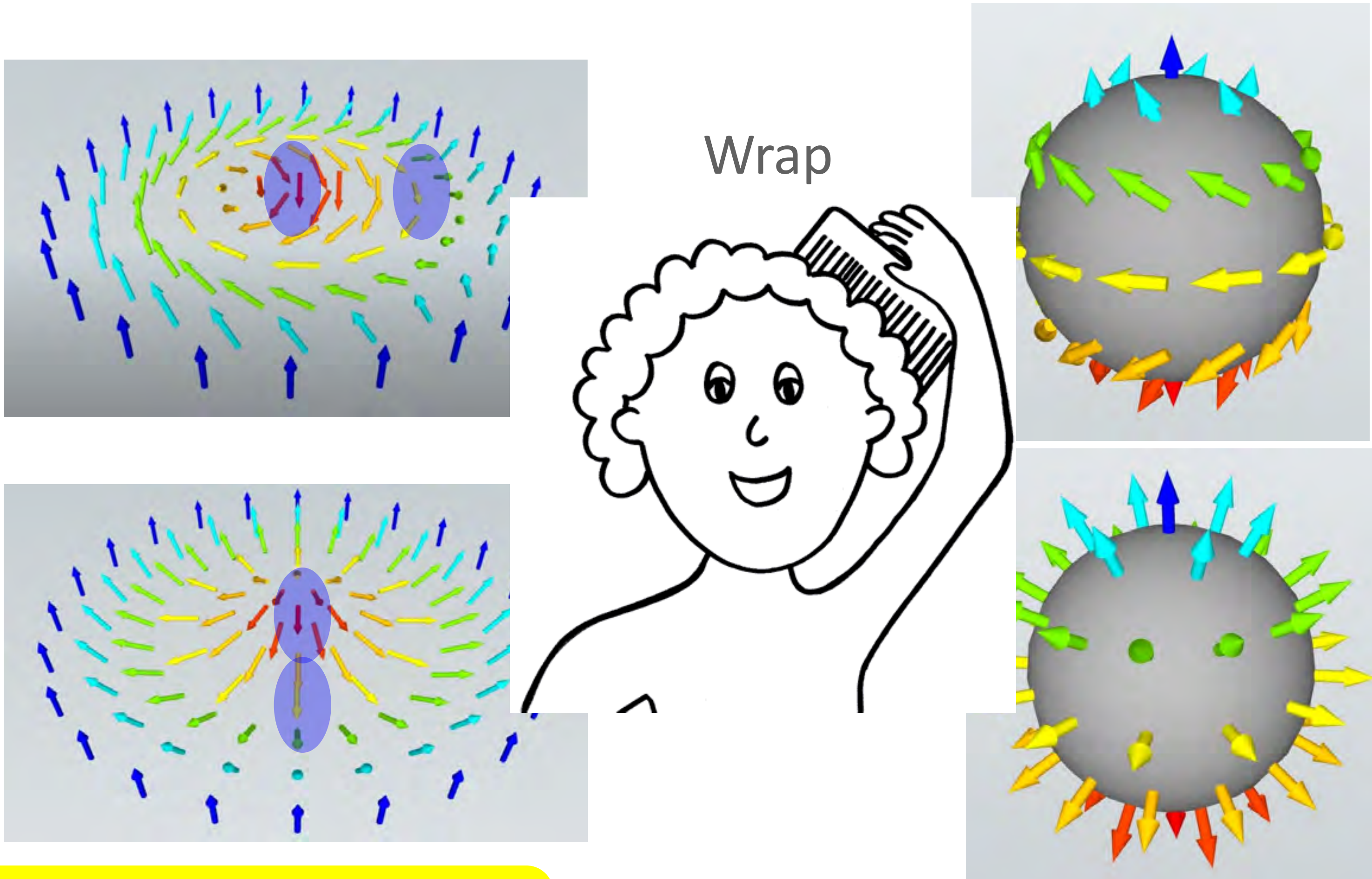
Hedgehog (Néel)



Ta/CoFeB/MgO, Pt/Co/MgO, Ir/Fe/Pd

A. Fert *et al.*, Nature Nano. 8, 152 (2013)

Topological Nature of Skyrmions



$$\frac{1}{4\pi}\int d^2x n\cdot(\partial_x n\times\partial_y n)=\pm1$$

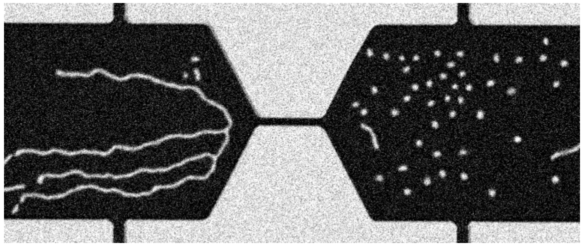
Topological Charge

Courtesy of Jiadong Zang

Skyrmions at Room Temperature

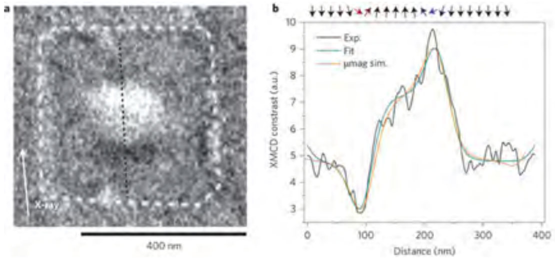
"Single" Layer

$TaO_x/CoFeB/Ta$: ≈ 1 µm



W. Jiang *et al.*, Science **349**, 283 (2015)

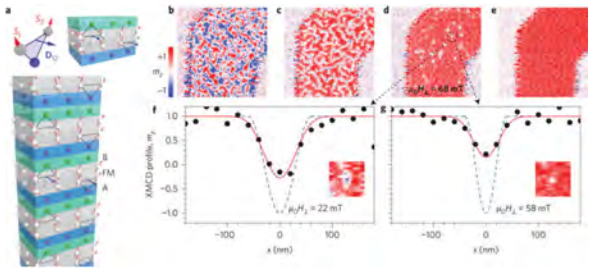
$Pt/Co/MgO$: ≈ 130 nm



O. Boulle *et al.*,
Nature Nanotechn. **11**, 449 (2016)

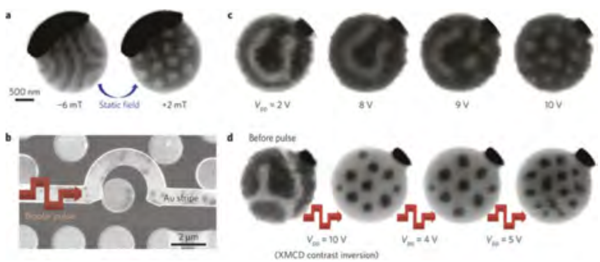
Multilayer

$(Ir/Co/Pt)_{10}$: ≈ 30–90 nm



C. Moreau-Luchaire *et al.*,
Nature Nanotechn. **11**, 444 (2016)

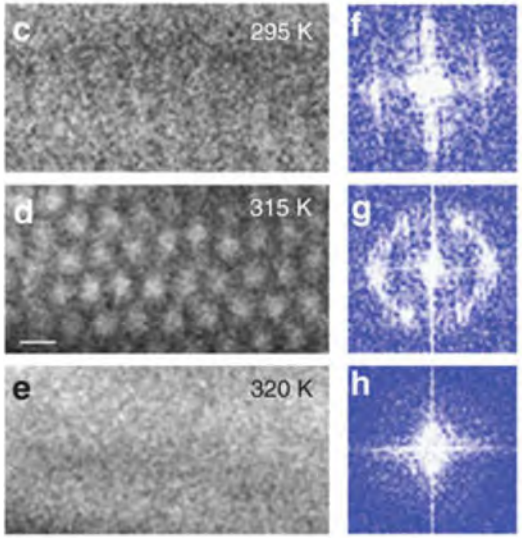
$(Pt/Co/Ta)_{15}$ and $(Pt/CoFeB/MgO)_{15}$:
≈ 100 nm



S. Woo *et al.*,
Nature Mater. **15**, 501 (2016)

Bulk

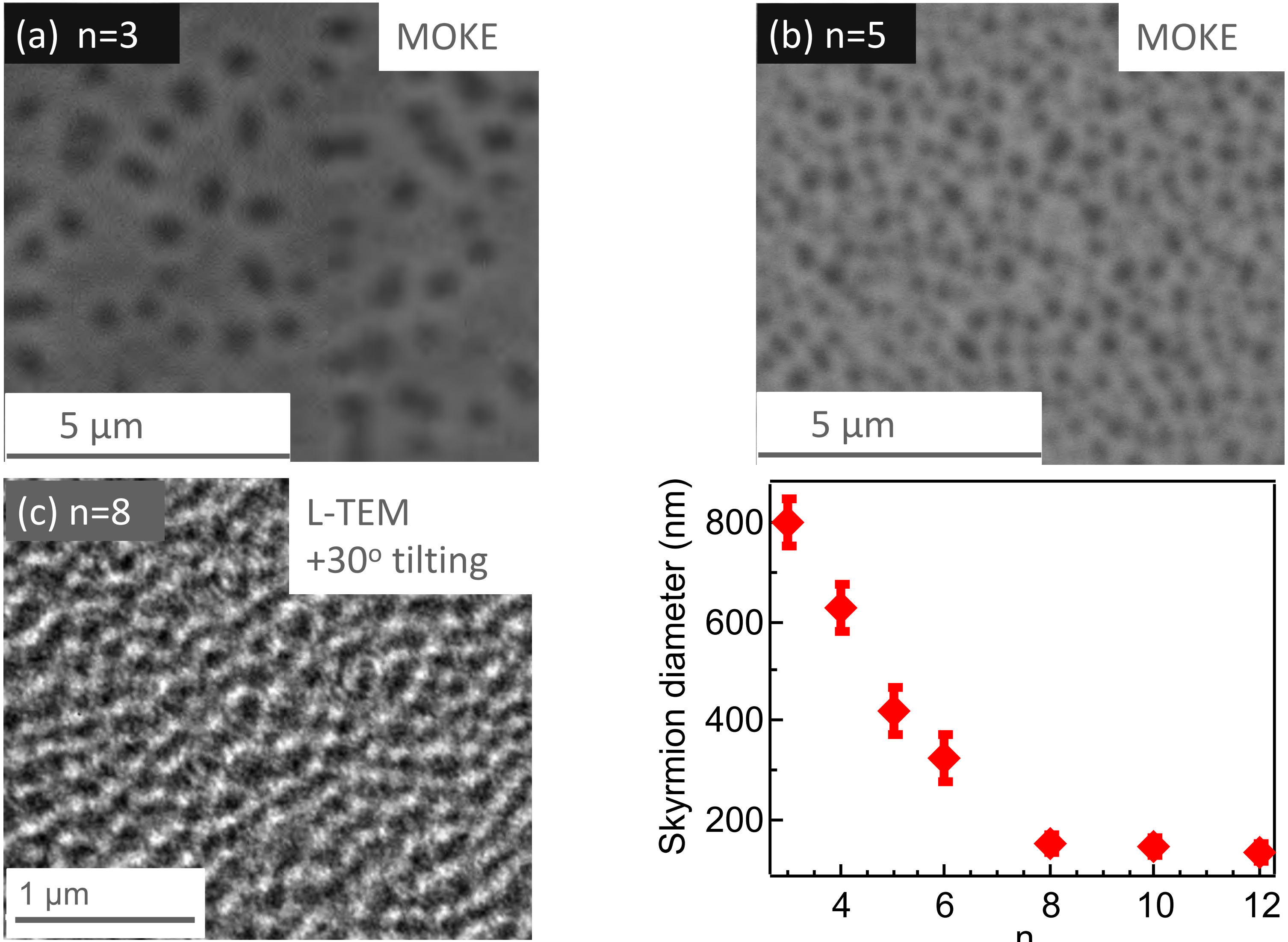
$Co_8Zn_9Mn_3$:
≈ 115–180 nm



Y. Tokunaga *et al.*,
Nature Comm. **6**, 7638 (2015)

Size Dependence on Number of Multilayers

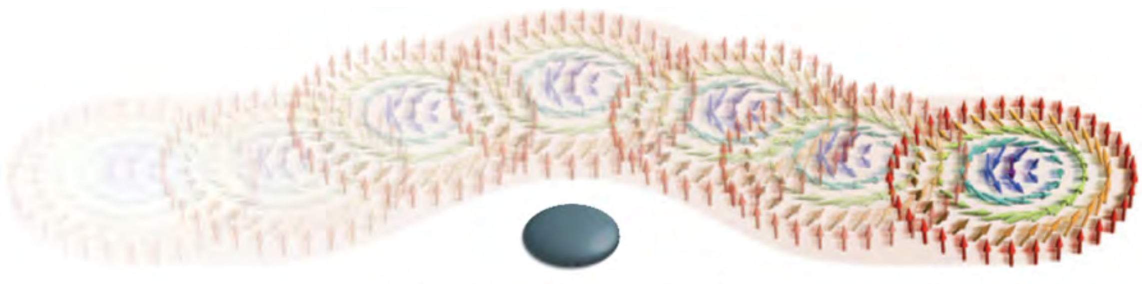
Sample: Ta 2.0nm/ (Pt 1.5 nm/Co 1.0 nm/Ir 1.0 nm)n/ Pt 2.0 nm



Moving Skyrmions

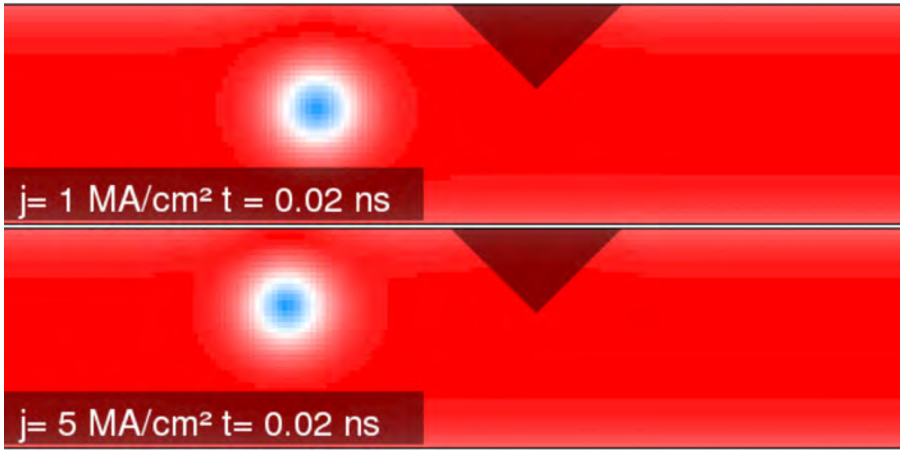
Weak Pinning of Skyrmion Motion

Skyrmions can move around defects



A. Rosch,
Nature Nano. 8, 160 (2013)

Micromagnetic Simulations

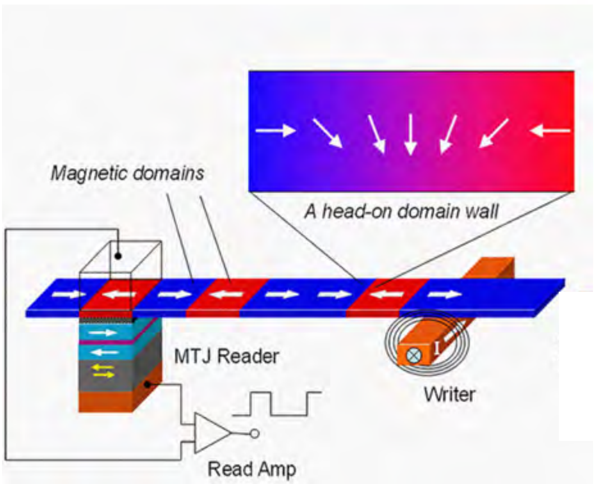


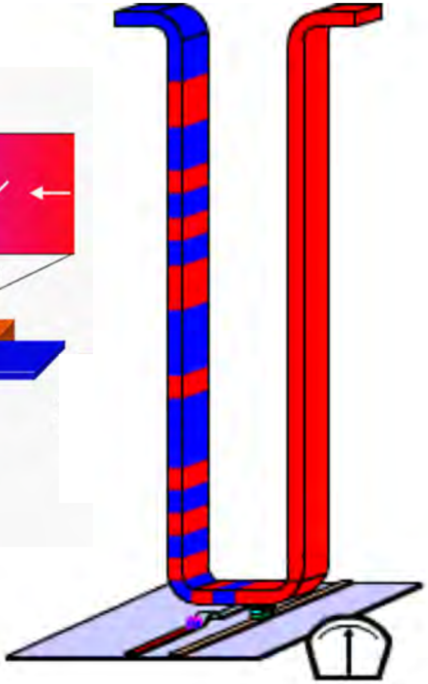
A. Fert *et al.*,
Nature Nano. 8, 152 (2013)

Encoding Information in Spin Textures

W. Jiang *et al.*, Phys. Rep. **704**, 1 (2017)

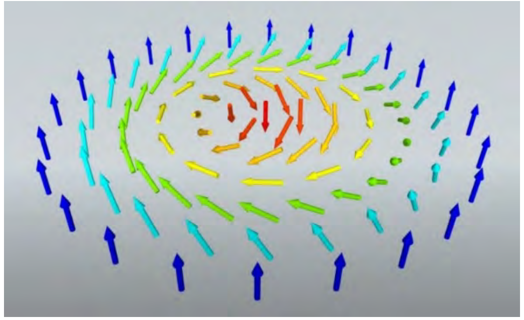
Racetrack Memory

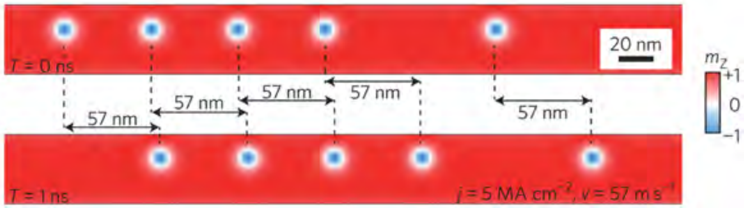




S. S. P. Parkin, M. Hayashi, and L. Thomas, Science **320**, 190 (2008)

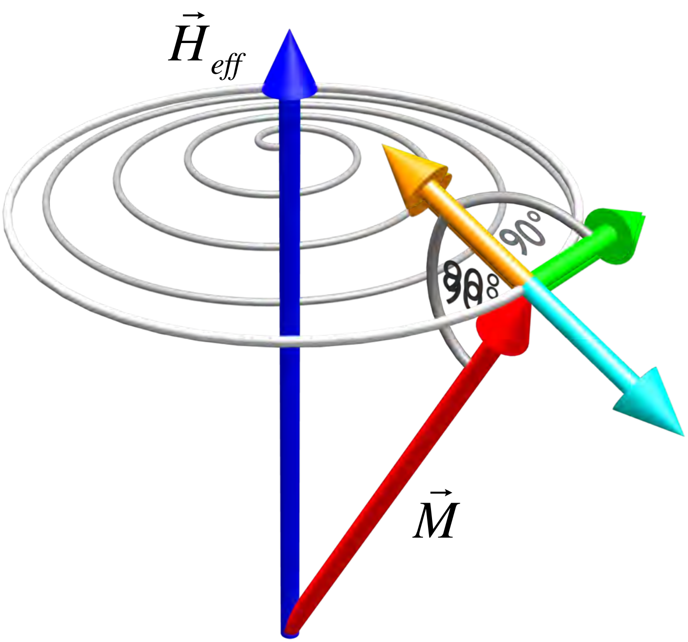
Skyrmions





A. Fert *et al.*, Nature Nano. 8, 152 (2013)

Magnetization Dynamics with Spin-(Orbit) Torques

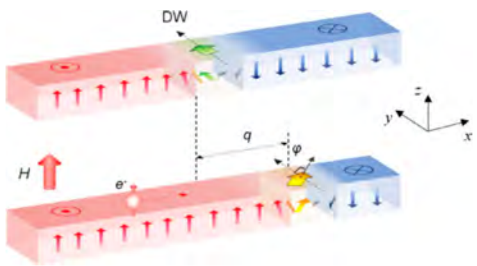


Landau-Lifshitz-Gilbert equation:

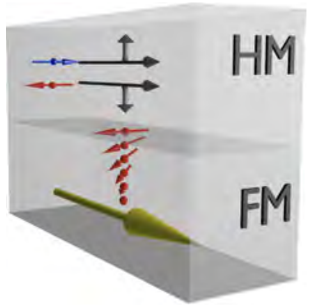
$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff} + \frac{\alpha}{M_S}\left(\vec{M} \times \frac{d\vec{M}}{dt}\right) + \frac{\gamma \hbar \vec{J}_S}{2eM_S d_F}$$

$$\vec{J}_S = \frac{\mathrm{Re}(G_{mix})}{e}\vec{M} \times (\vec{M} \times \vec{\mu}_S) + \frac{\mathrm{Im}(G_{mix})}{e}\vec{M} \times \vec{\mu}_S$$

damping-like | field-like



Spin accumulation generated
within magnetic layer
or adjacent layer



Thiele Equation

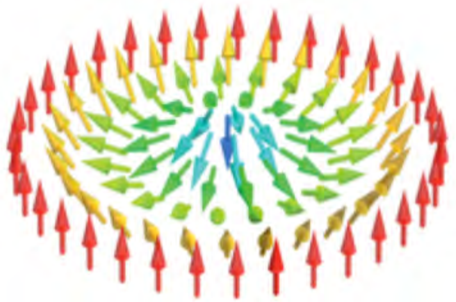
A. A. Thiele, Phys. Rev. Lett. **30**, 230 (1972)

Landau-Lifshitz-Gilbert equation

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff} + \frac{\alpha}{M_S}\left(\vec{M} \times \frac{d\vec{M}}{dt}\right) + \frac{\gamma \hbar \vec{J}_S}{2eM_S d_F}$$

+

Rigid Skyrmion Texture



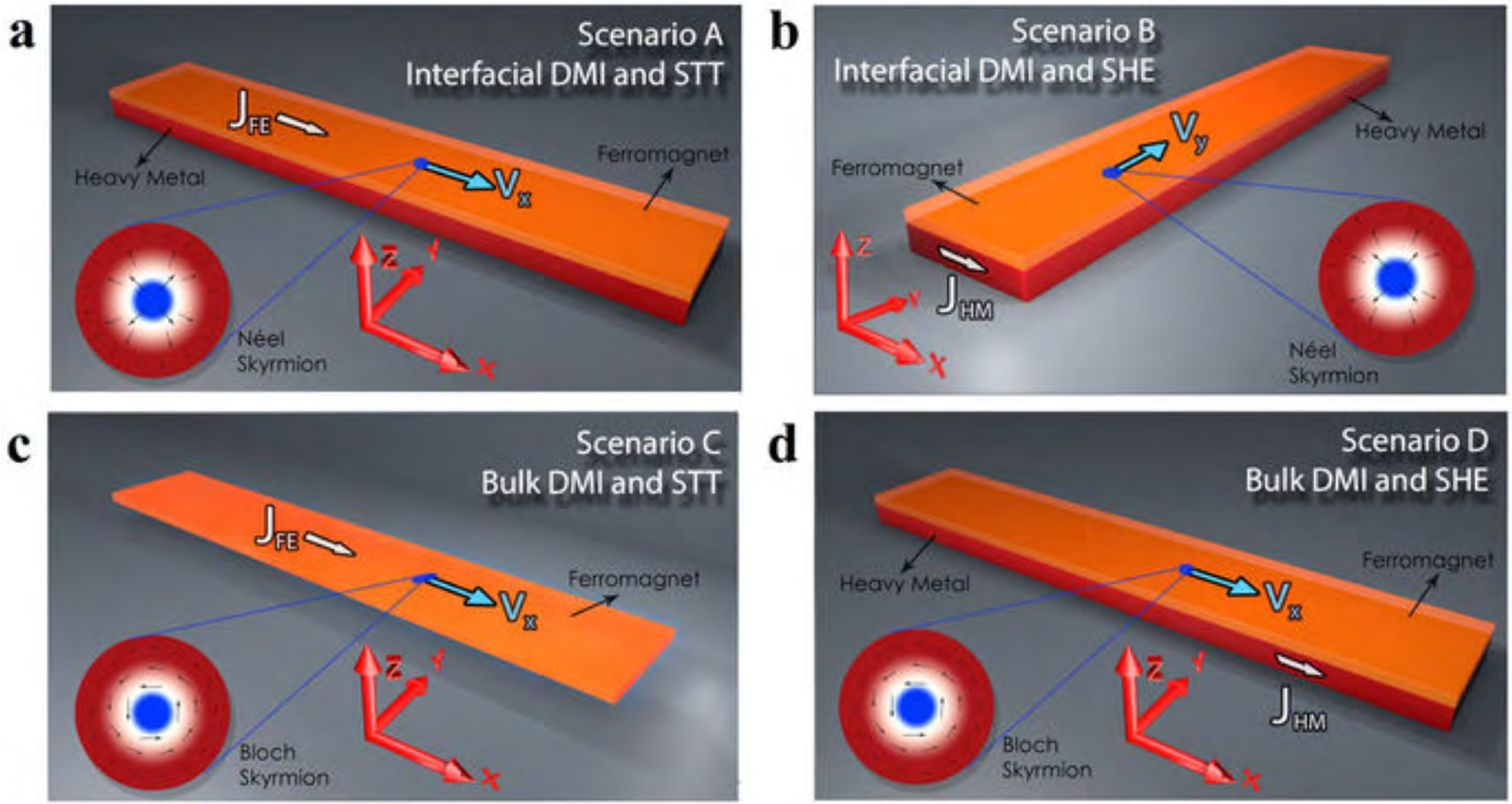
→

$$G \times v - \alpha D \cdot v + 4\pi \overleftrightarrow{B} J_c = 0$$

$$G = (0,0,-4\pi Q) \qquad Q = \frac{1}{4\pi}\int \mathbf{m} \cdot \left(\partial_x \mathbf{m} \times \partial_y \mathbf{m}\right) dxdy$$

R. Tomasello *et al.*, Sci. Rep. **4**, 6784 (2014)

Net Force Depends on Skyrmion Structure and Spin Torque Mechanism



R. Tomasello *et al.*, Sci. Rep. **4**, 6784 (2014)

Skyrmion Hall Effect

Classic Hall effect

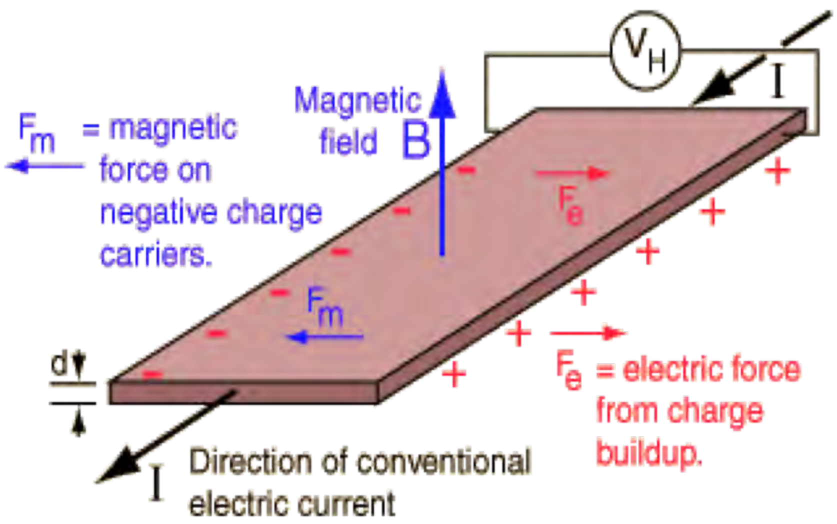
Electric charge q_e

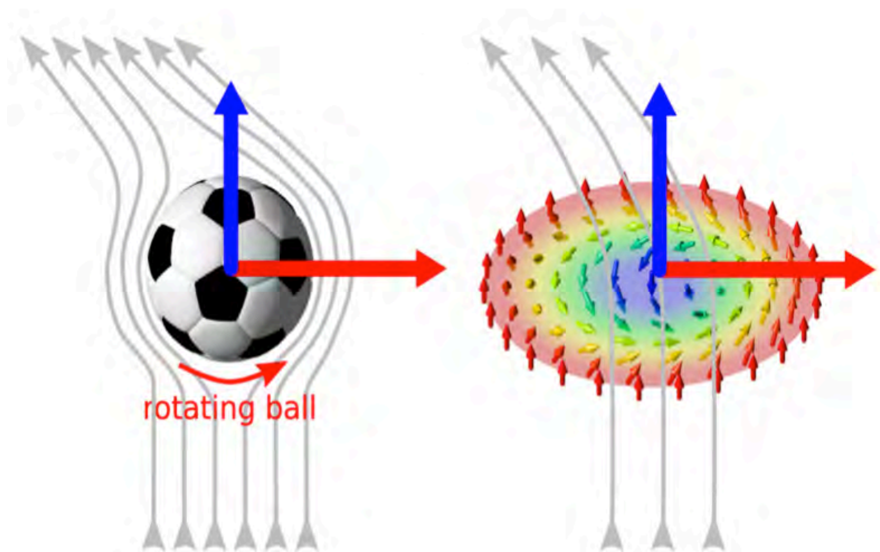
Lorentz force $q_e(v \times B)$

Skyrmion Hall effect

Topological charge q_t

Magnus force $4\pi q_t(v \times e_z)$



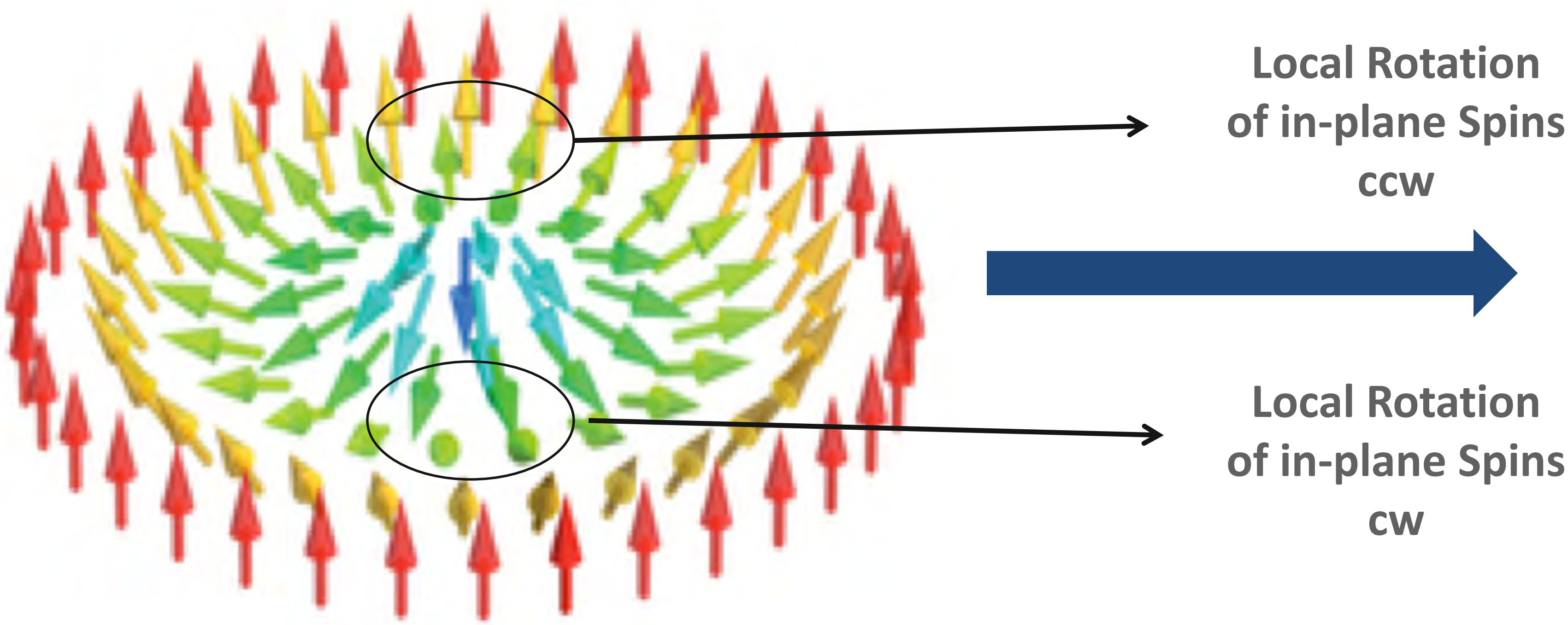


K. Everschor-Sitte and M. Sitte, J. Appl. Phys. **115**, 172602 (2014)

Motion of Rotating Objects

Famous Brazilian Expert:
Roberto Carlos

Skyrmion in Motion



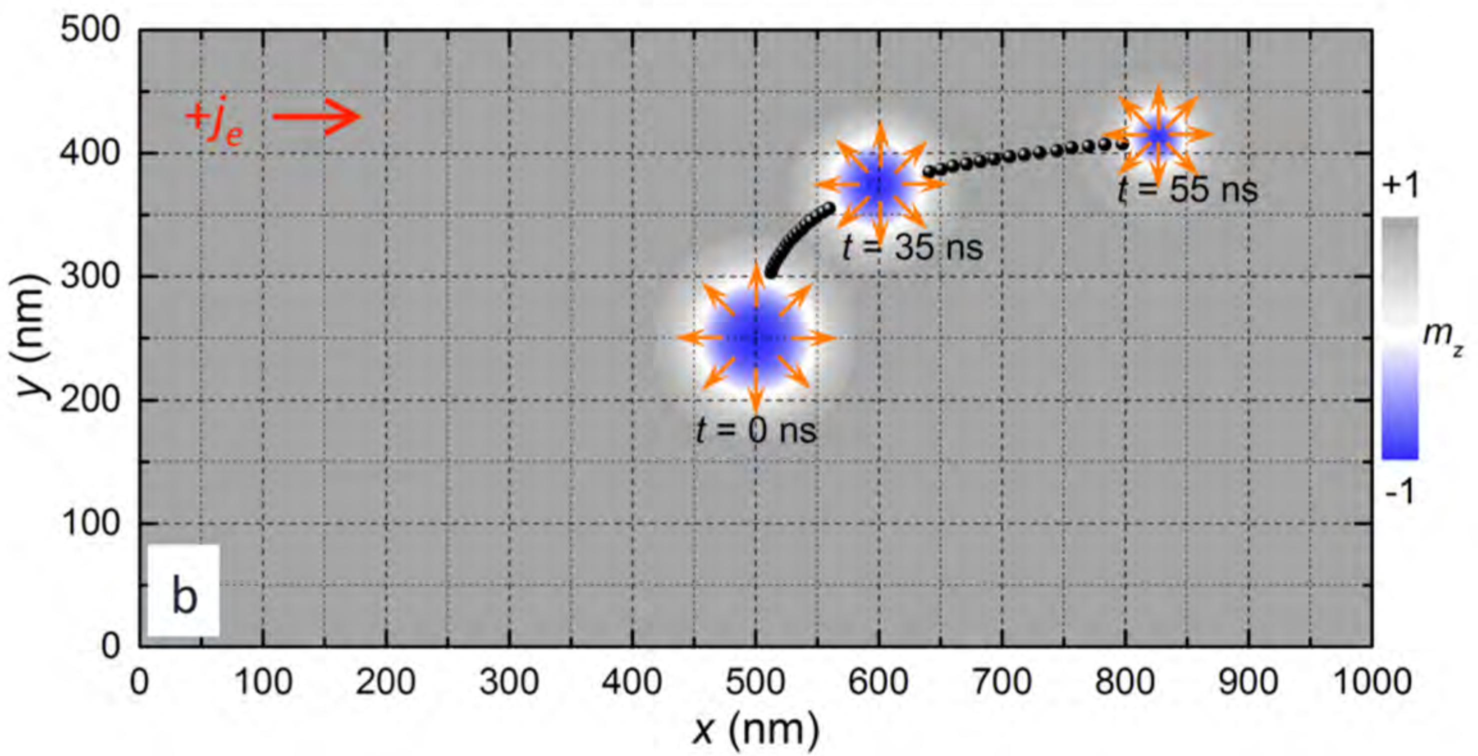
- Different rotation sense on both sides
- Looks like “opposite fields” => magnetic field gradient
- Results in transverse motion

Micromagnetic Simulation

W. Jiang *et al.*,
Nature Phys. **13**, 162 (2017)

Thiele Equation: $G \times v - \alpha D \cdot v + 4\pi \overleftrightarrow{B} J_c = 0$

$G = (0, 0, -4\pi Q)$ $\quad Q = \frac{1}{4\pi} \int \mathbf{m} \cdot (\partial_x \mathbf{m} \times \partial_y \mathbf{m}) dxdy$

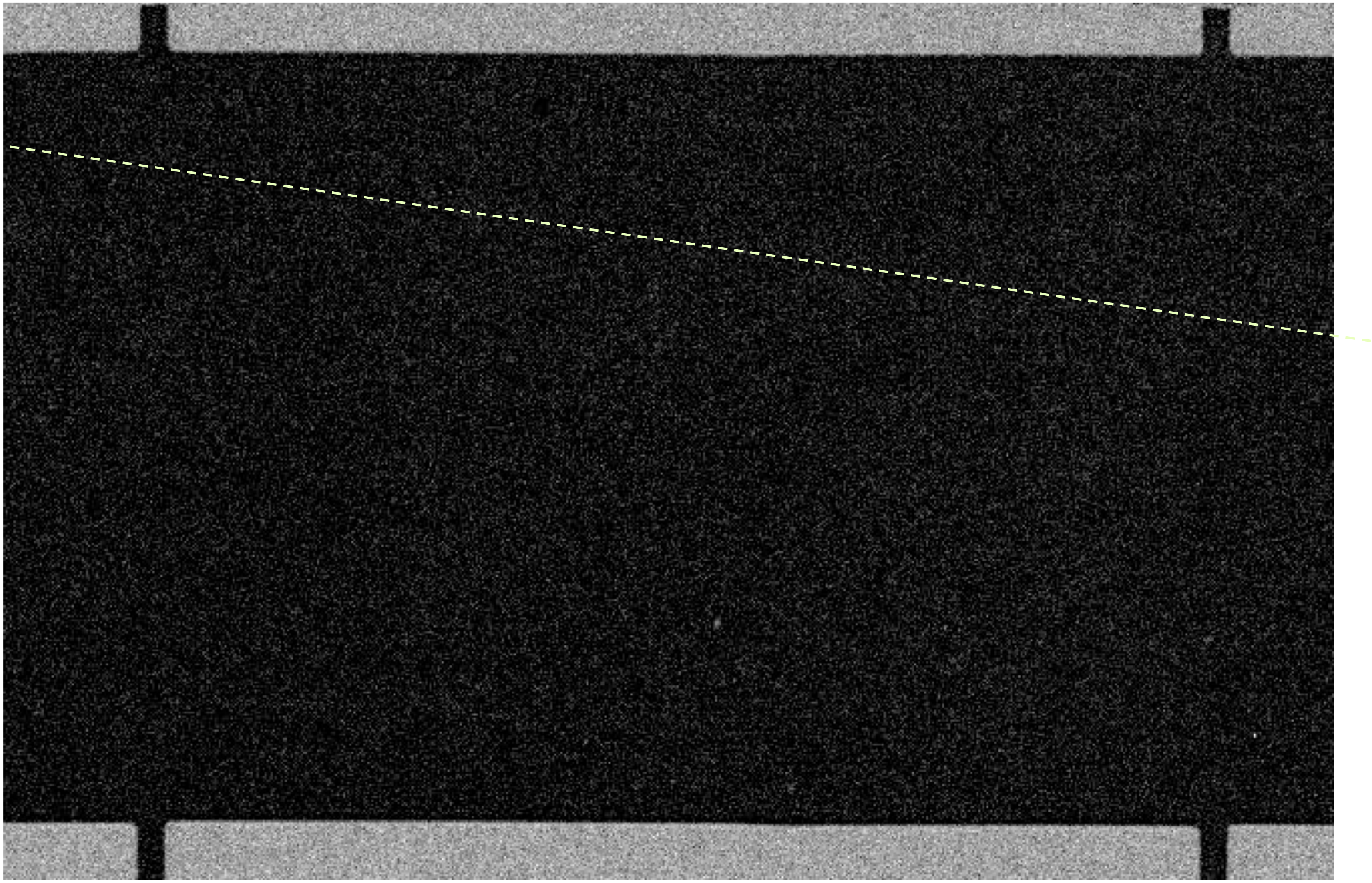


$$\frac{v_y}{v_x} = \frac{1}{\alpha D}$$

Skyrmion Motion with Homogeneous Current

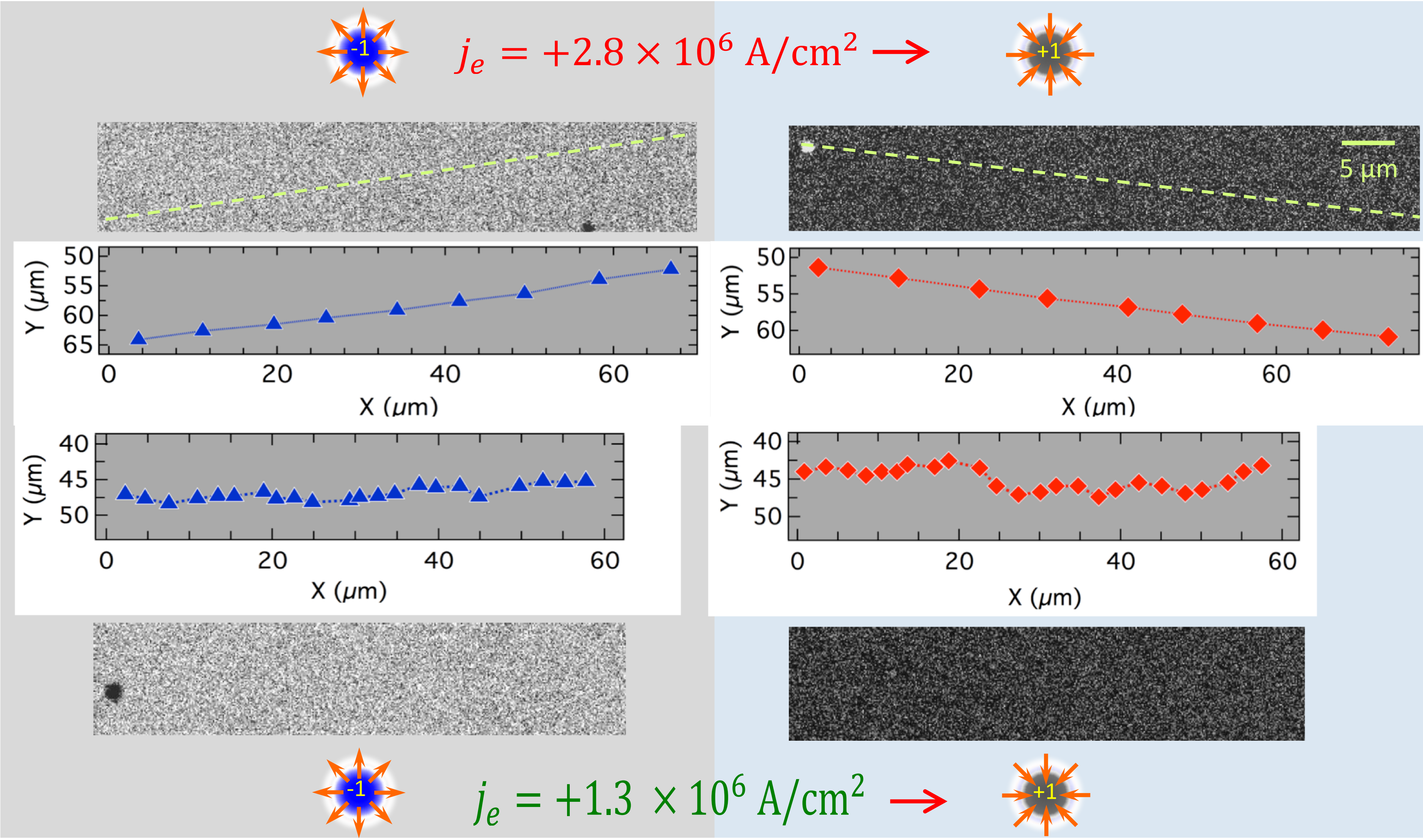
$j_e = +2.8 \times 10^6\ \mathrm{A/cm^2}$

W. Jiang *et al.*,
Nature Phys. **13**, 162 (2017)

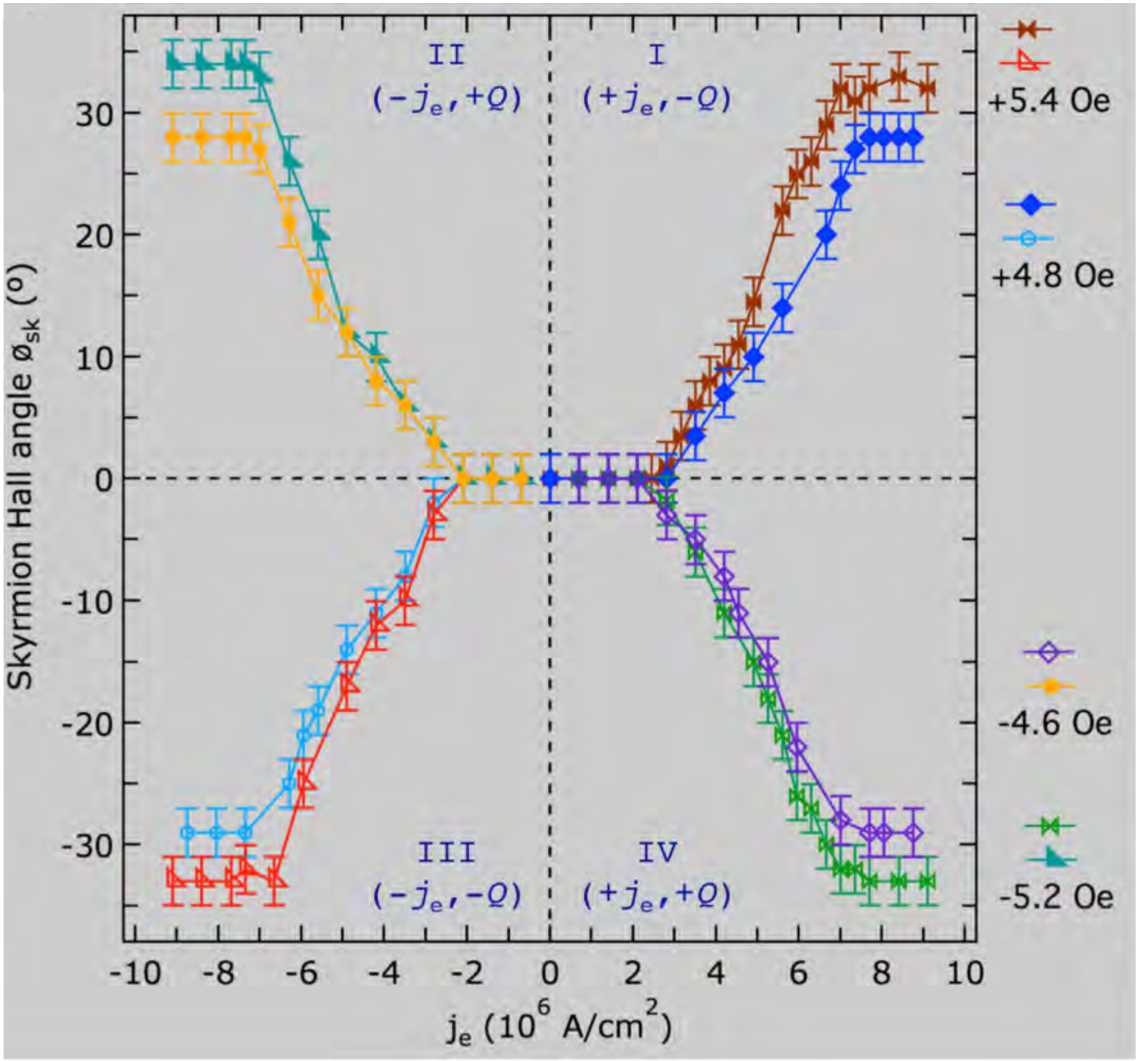


Current Dependence of Motion

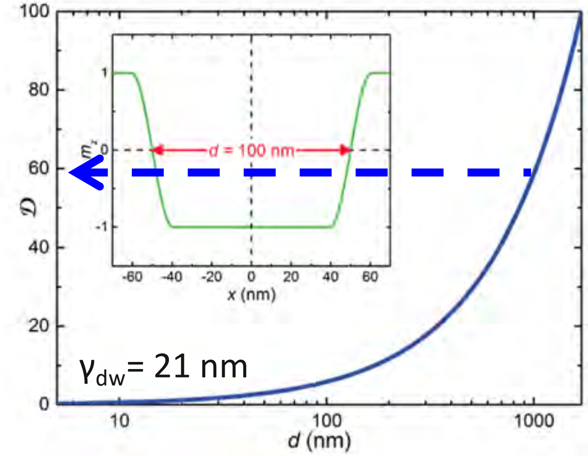
W. Jiang *et al.*,
Nature Phys. **13**, 162 (2017)



Drive dependent Skyrmion Hall angle



$$\mathcal{D} = \frac{\pi^2 d}{8\gamma_{dw}}$$



$$\frac{v_y}{v_x} = \frac{1}{\alpha D} \approx 0.83$$

$$\Phi_{sk} \approx 40^\circ$$

W. Jiang *et al.*,
Nature Phys. **13**, 162 (2017)

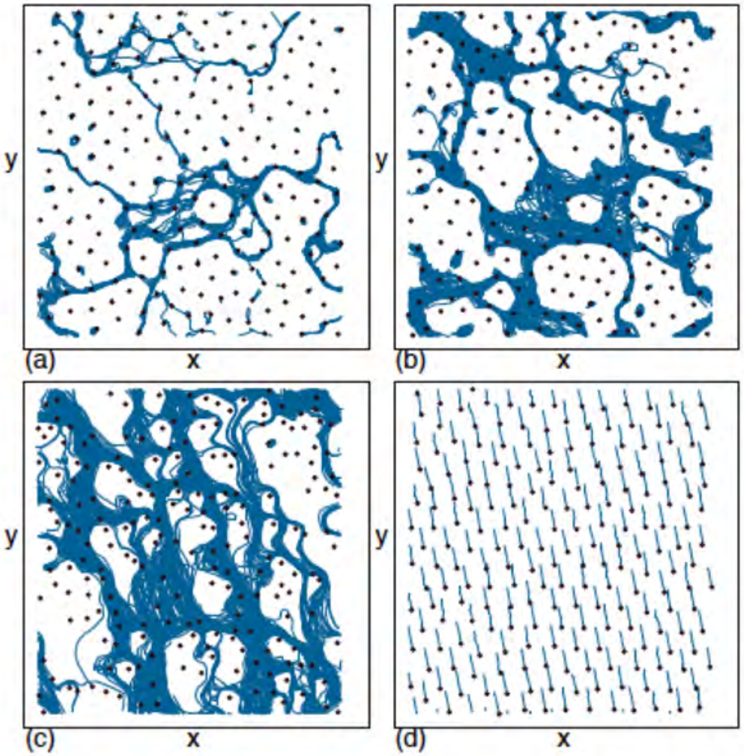
Numerical Simulations

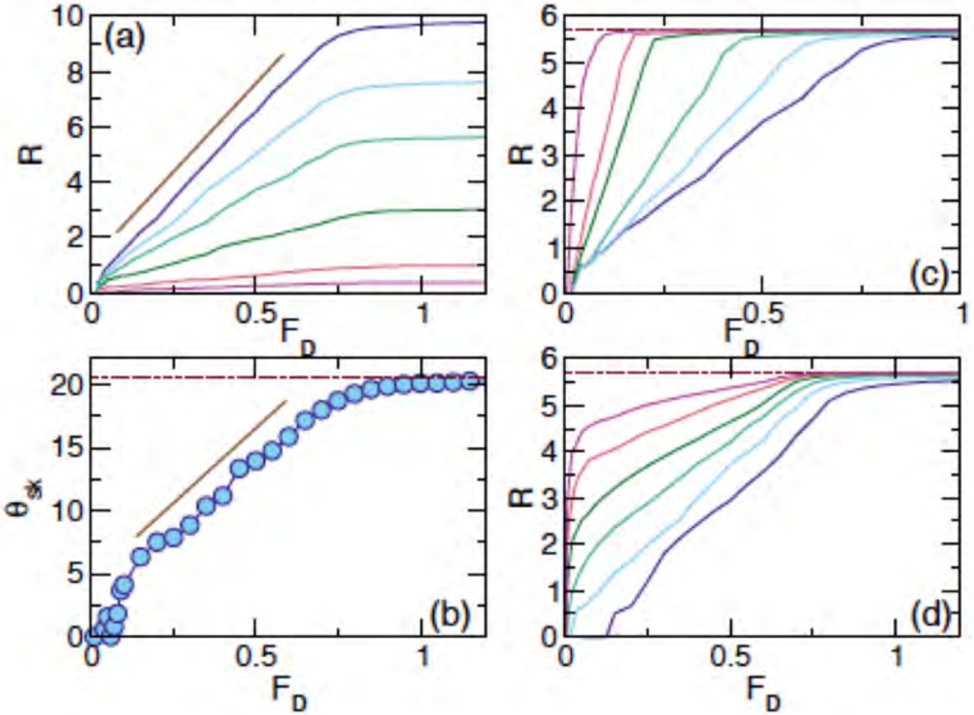
Noise fluctuations and drive dependence of the skyrmion Hall effect in disordered systems

C Reichhardt and C J Olson Reichhardt

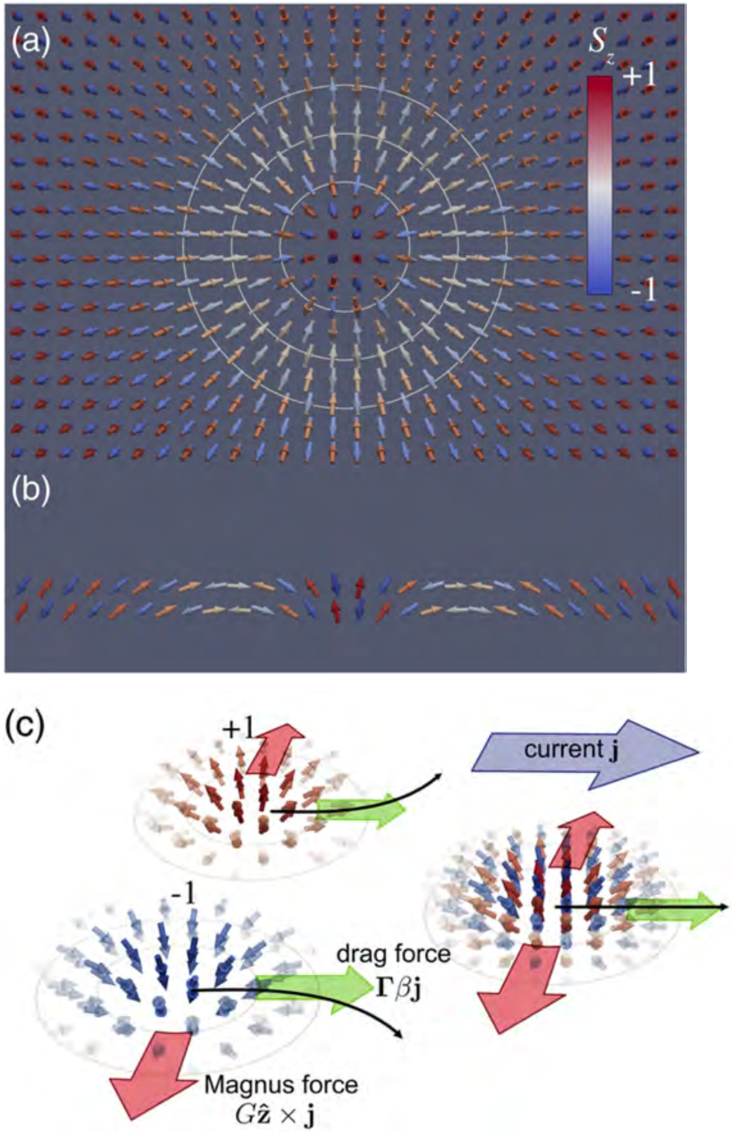
Theoretical Division and Center for Nonlinear Studies, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

New J. Phys. **18**, 095005 (2016)



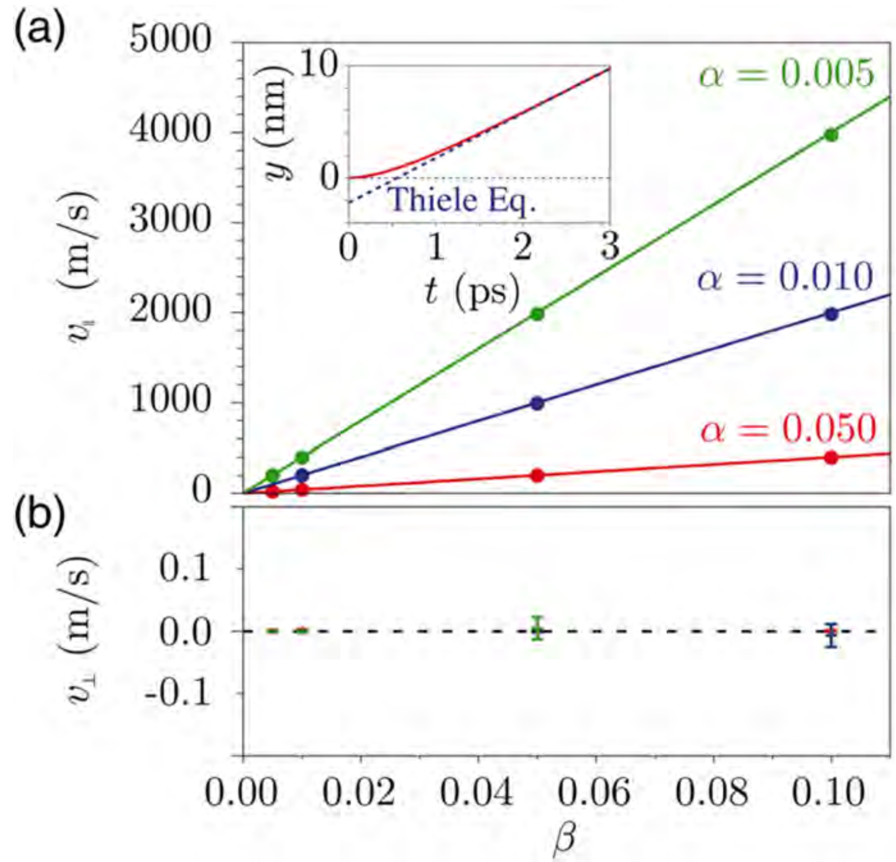


Antiferromagnetic Skyrmions



Avoid Skyrmion Hall Effect

No transverse velocity!

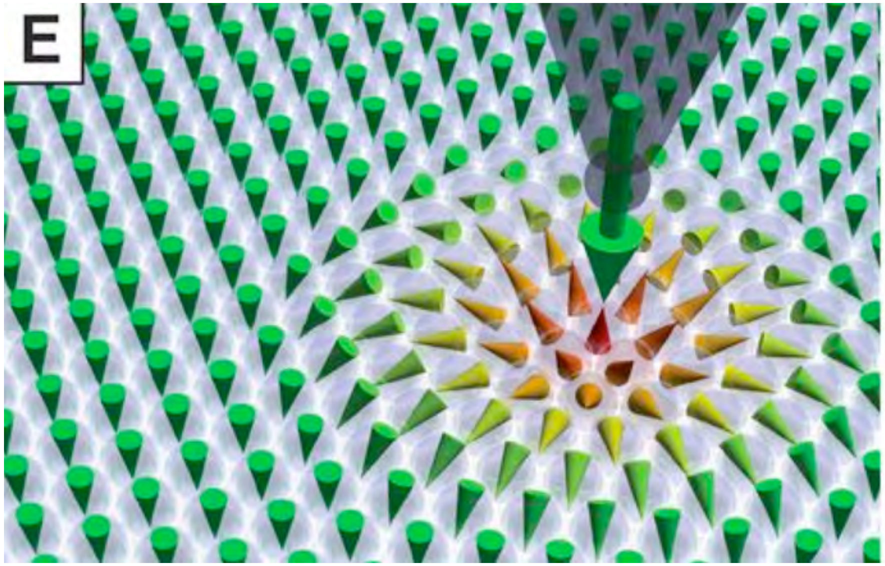


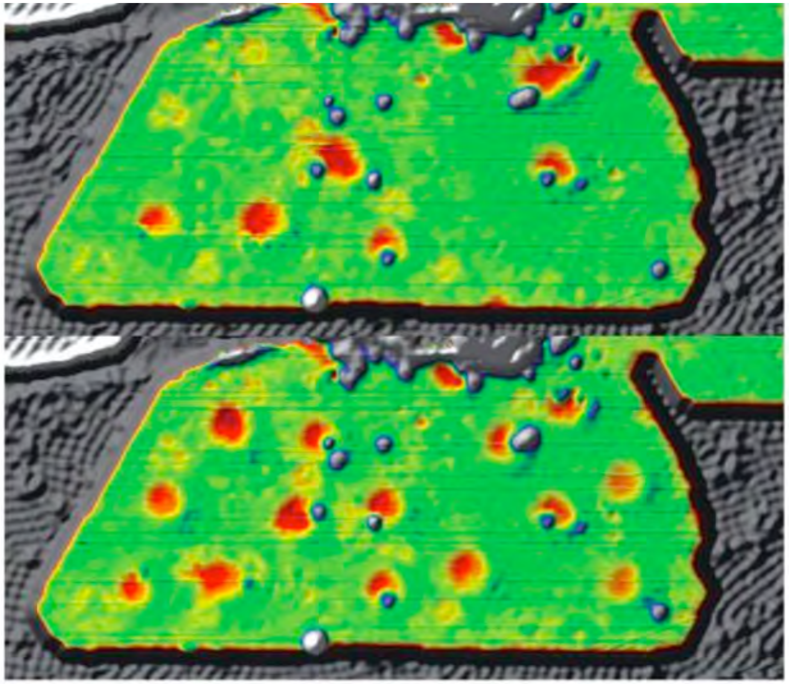
J. Barker and O. A. Tretiakov,
Phys. Rev. Lett. **116**, 147203 (2016)

Generating Skyrmions

Generating Individual Skyrmions

Using spin-polarized scanning tunneling microscope



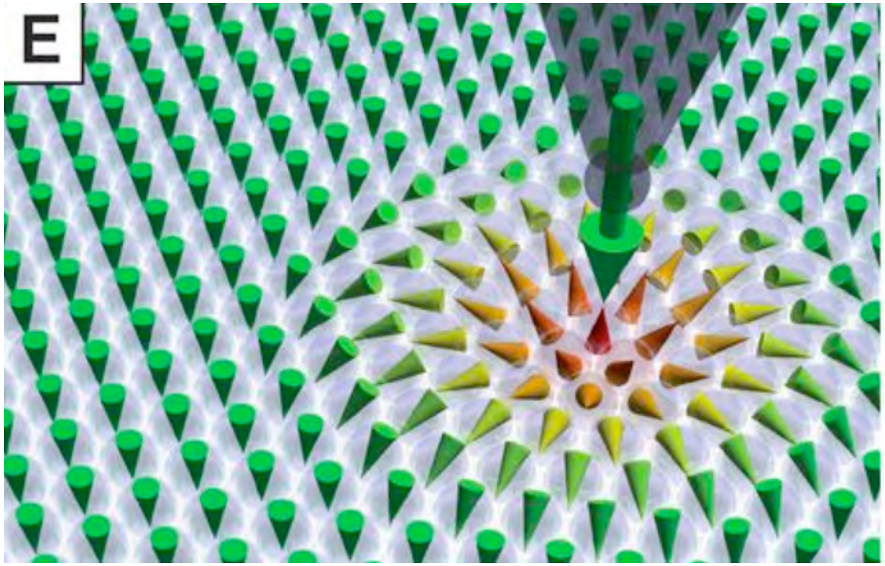


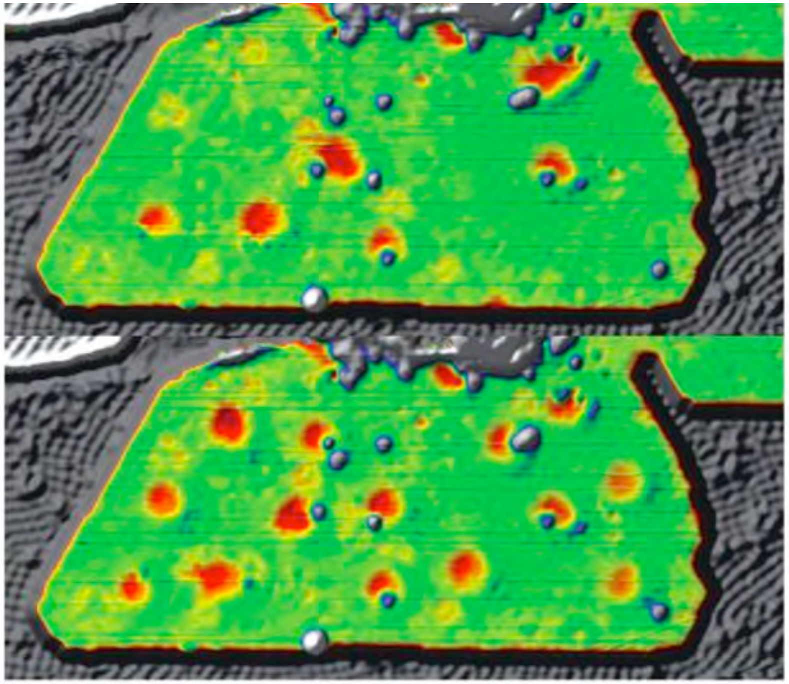
N. Romming, et al., Science **341**, 636 (2013)

Spin-transfer torque switches skyrmion core reversibly

Generating Individual Skyrmions

Using spin-polarized scanning tunneling microscope

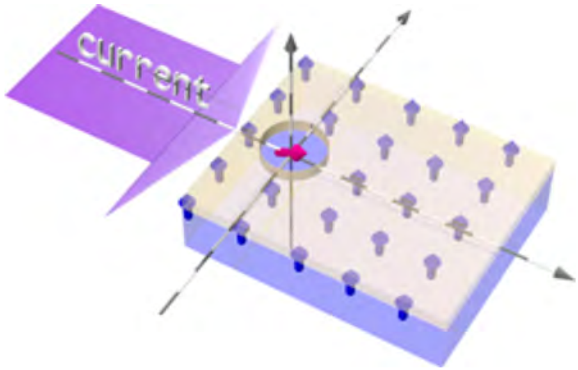




Applied Goal:

Use Topological Charge instead of Electronic Charge in Information Technologies

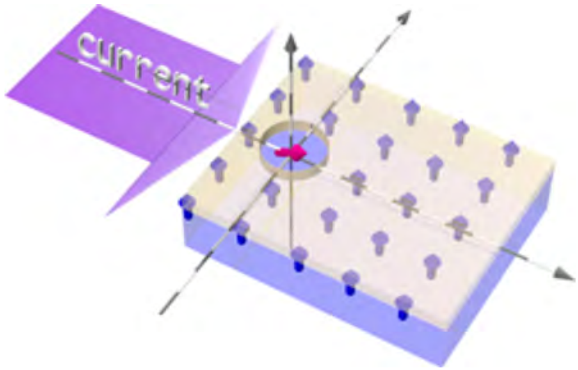
Inhomogeneities may Nucleate Skyrmions



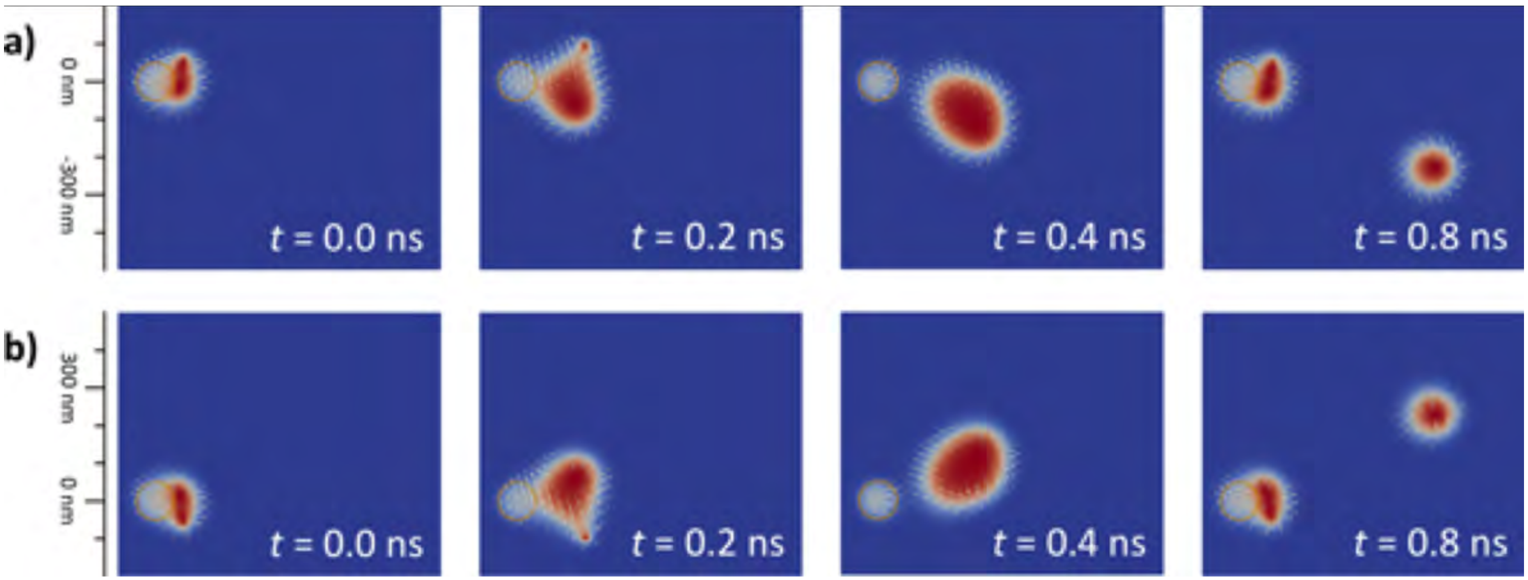
Without DMI:
Nucleation of skyrmion/anti-skyrmion pair

K. Everschor-Sitte, et al., New J. Phys. **19**, 092001 (2017)

Inhomogeneities may Nucleate Skyrmions



With DMI or anti-DMI:
Stabilize only one of the two pair-partners



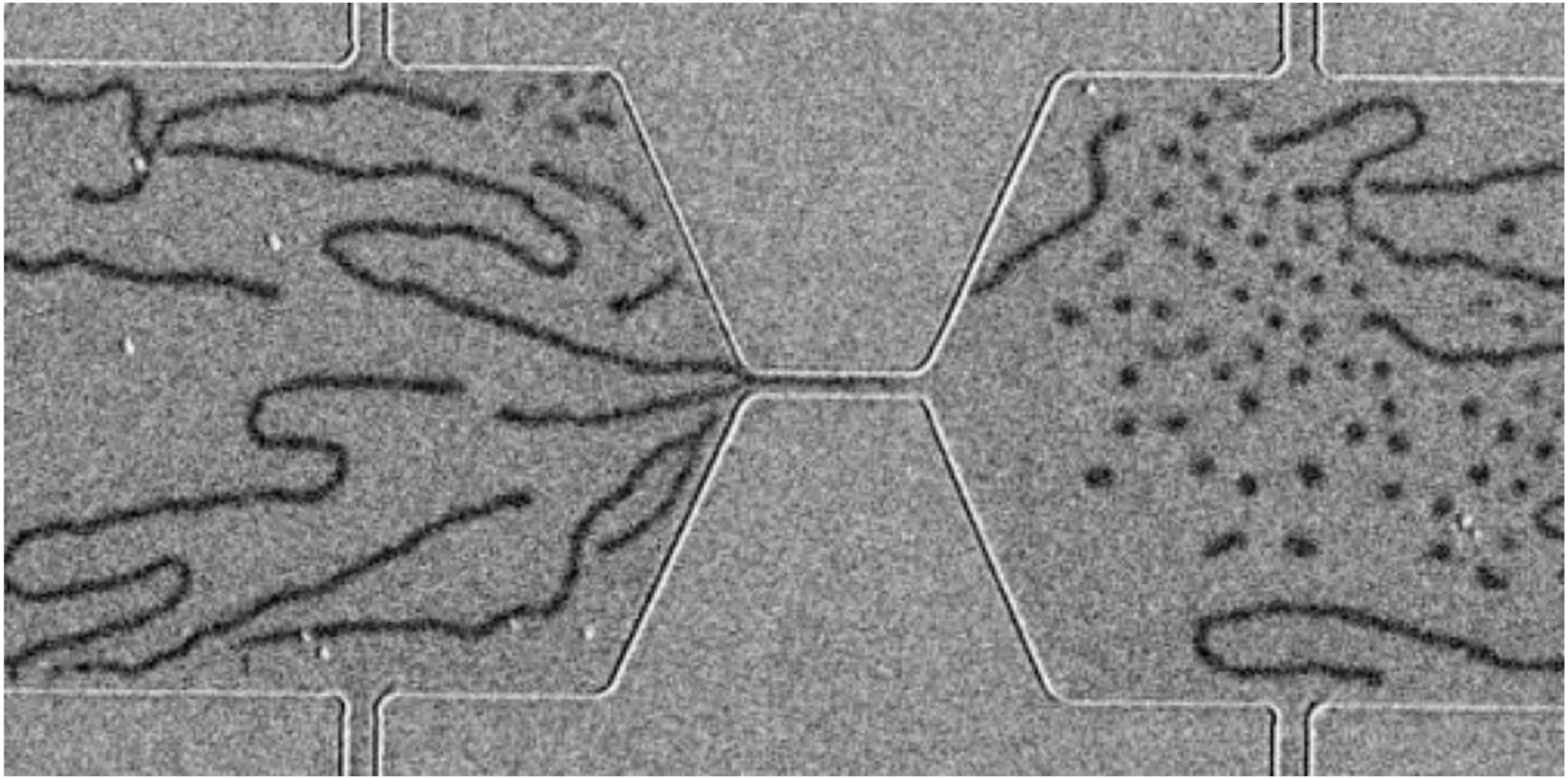
DMI

anti-DMI

K. Everschor-Sitte, et al., New J. Phys. **19**, 092001 (2017)

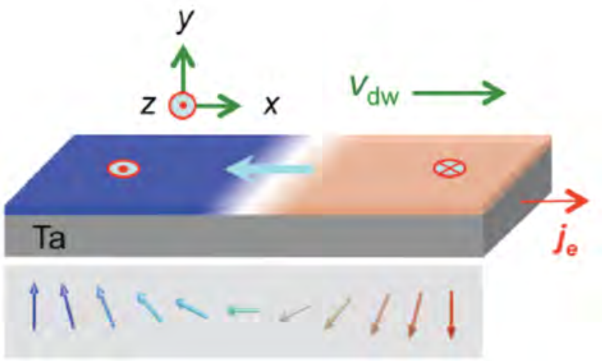
Skyrmion Generation from Inhomogeneous Current

$B_\perp$ = +0.46 mT, *DC current* J_e = + 6.8 × 10^4 A/cm^2
TaO_x/CoFeB/Ta

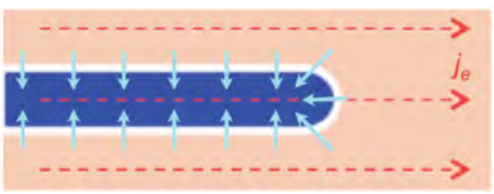


W. Jiang *et al.*, Science **349**, 283 (2015)

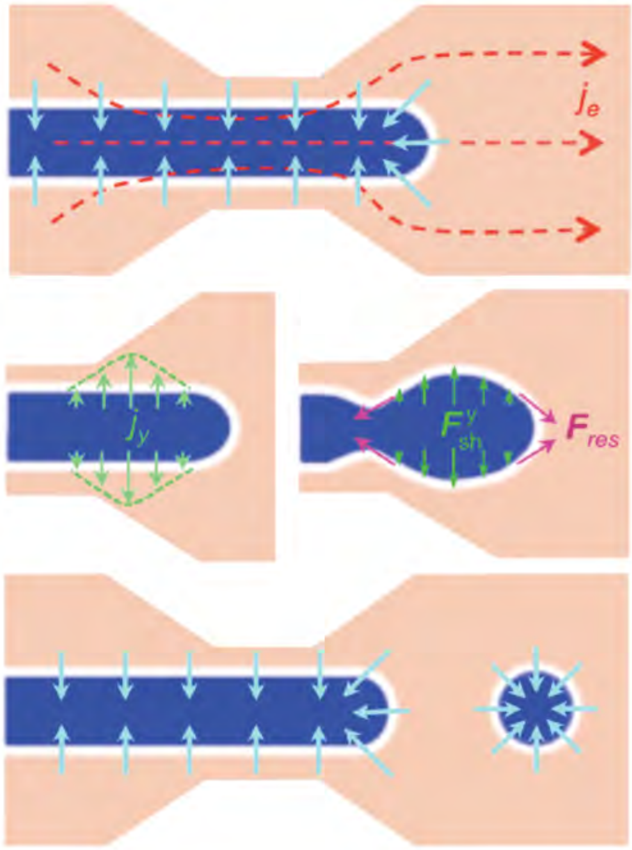
Inhomogeneous Chiral Spin Orbit Torques



Stripe Domain with Homogeneous Current

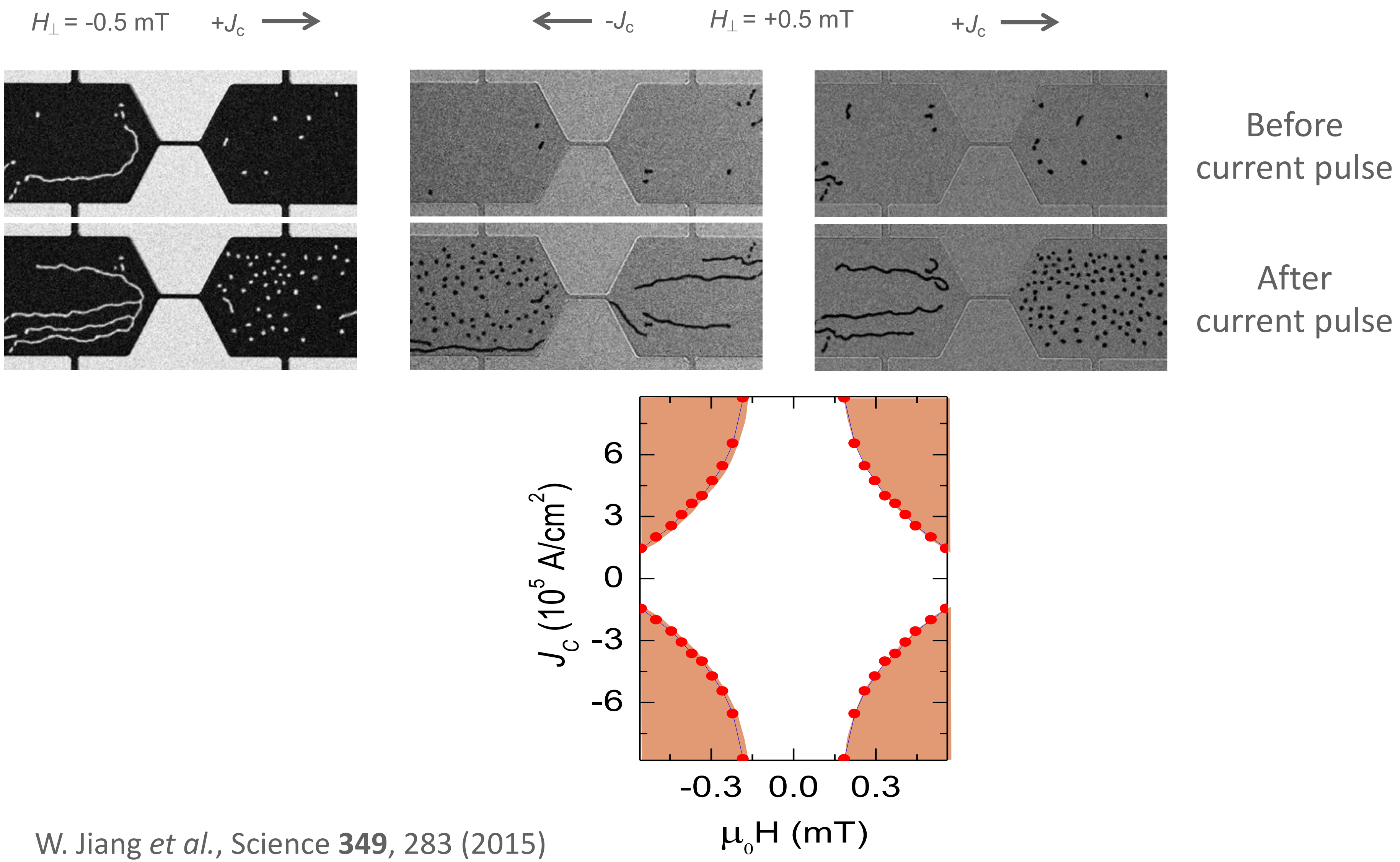


Stripe Domain with Inhomogeneous Current



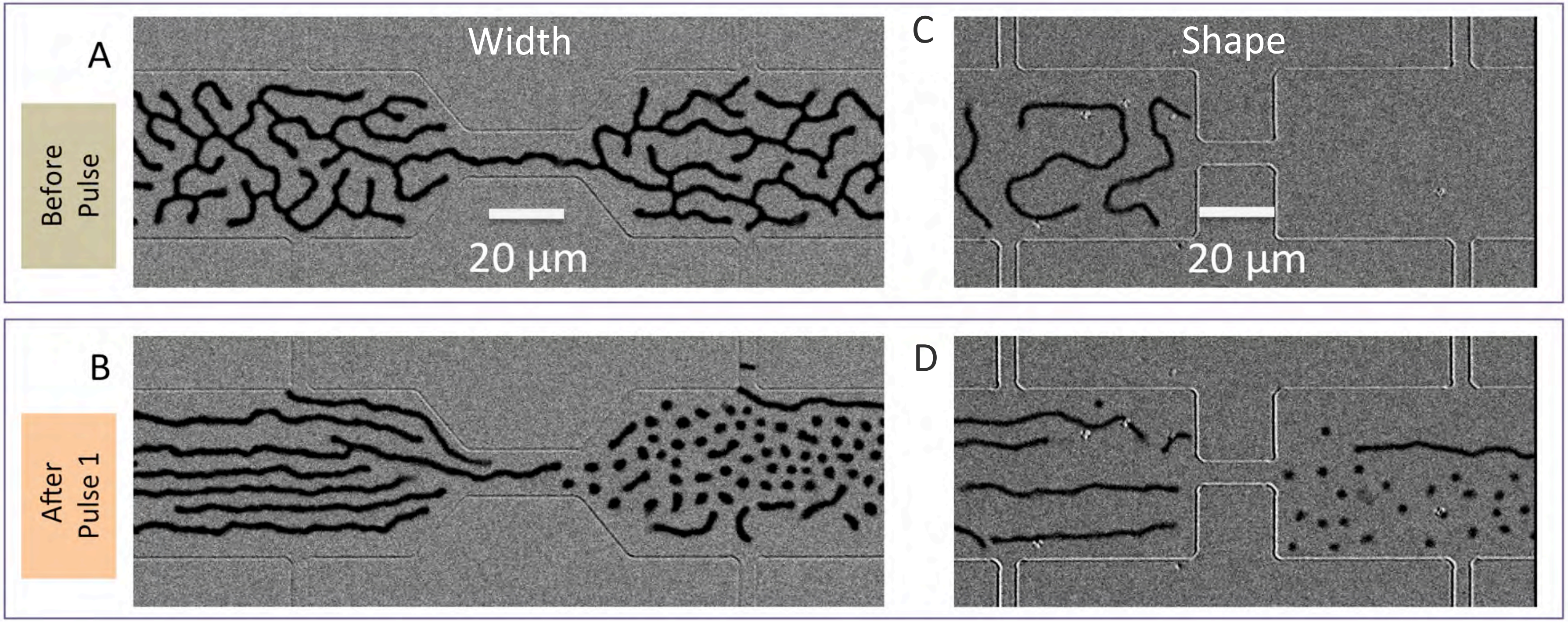
W. Jiang *et al.*, Science **349**, 283 (2015)

Skyrmion Generation Phase Diagram



W. Jiang *et al.*, Science **349**, 283 (2015)

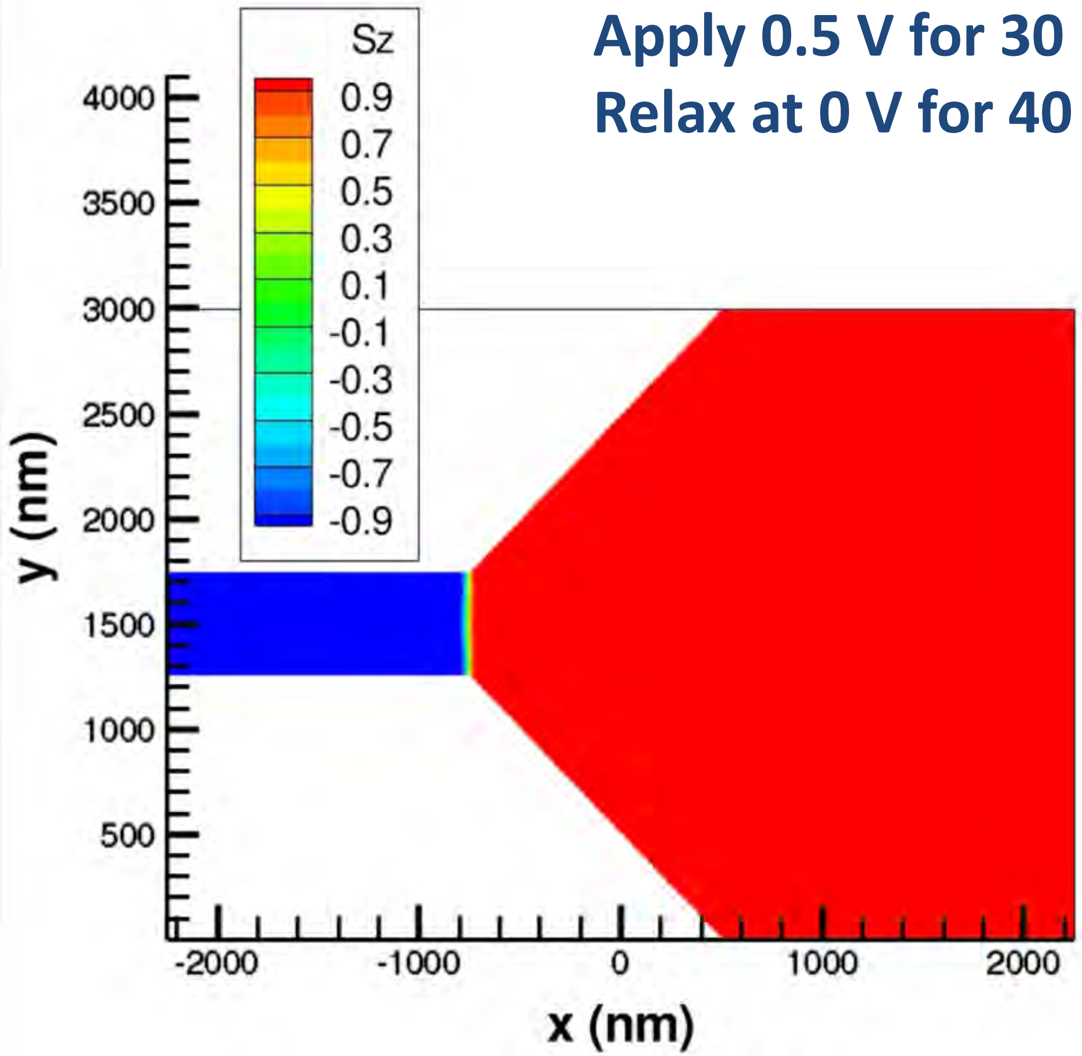
Different Geometries



Skyrmion generation is robust
Spatially divergent currents are the key

W. Jiang *et al.*, Science **349**, 283 (2015)

Micromagnetic Simulation of Transformation



Apply 0.5 V for 30 ns

Relax at 0 V for 40 ns

H = 5 Oe

M_s = 650 emu/cm^3

H_a = 8868 Oe

A = 3 μerg/cm

DMI = 0.5 erg/cm^2

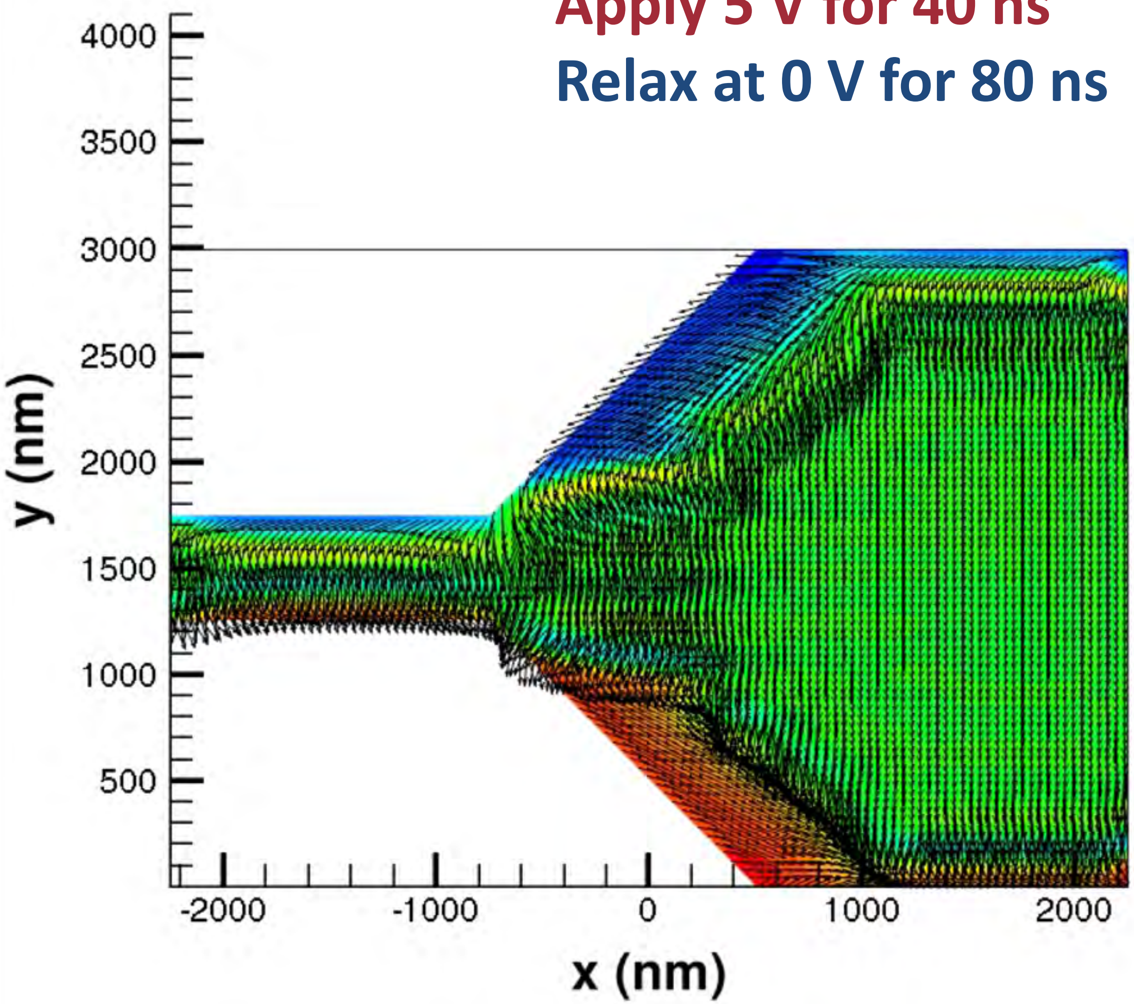
α = 0.02

σ_{Ta} = 0.83 MS

θ_{sh} = 10%

O. Heinonen *et al.*,
Phys. Rev. B **93**, 094407 (2016)

Micromagnetic Simulation of Transformation



Apply 5 V for 40 ns

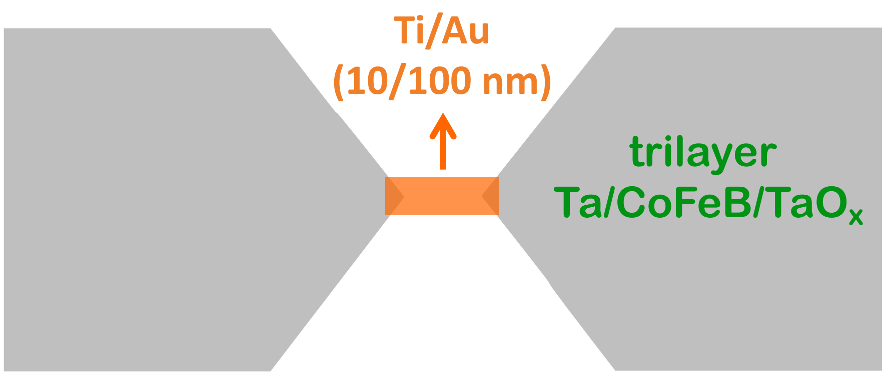
Relax at 0 V for 80 ns

$H = 5$ Oe
$M_s = 650$ emu/cm^3
$H_a = 8868$ Oe
$A = 3$ μerg/cm
DMI = 0.5 erg/cm^2
$\alpha = 0.02$
$\sigma_{Ta} = 0.83$ MS
$\theta_{sh} = 10\%$

Two distinct mechanisms for skyrmion generation!

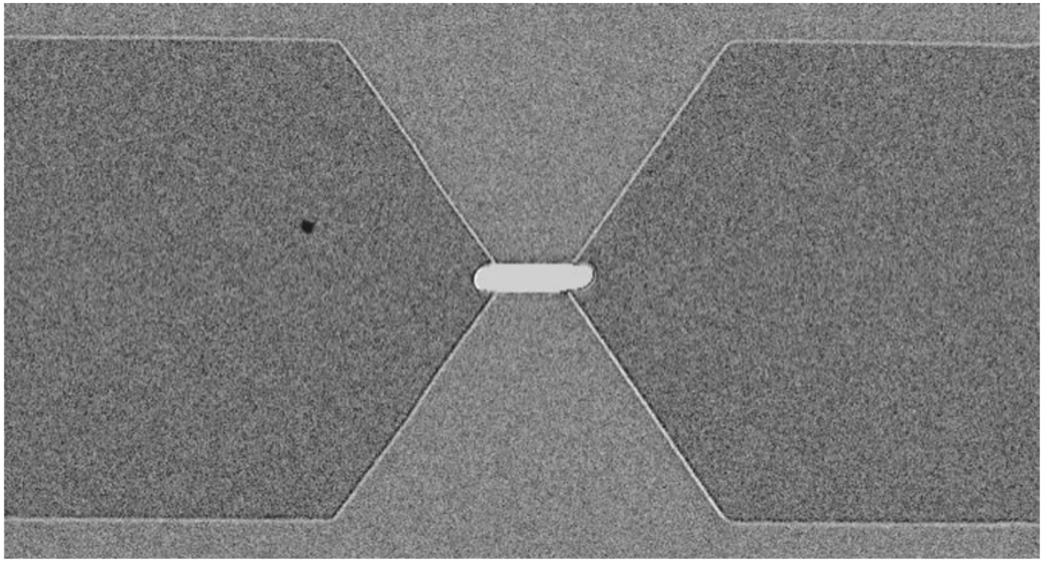
O. Heinonen *et al.*,
Phys. Rev. B **93**, 094407 (2016)

Creation of Skyrmions via Nonmagnetic Contacts



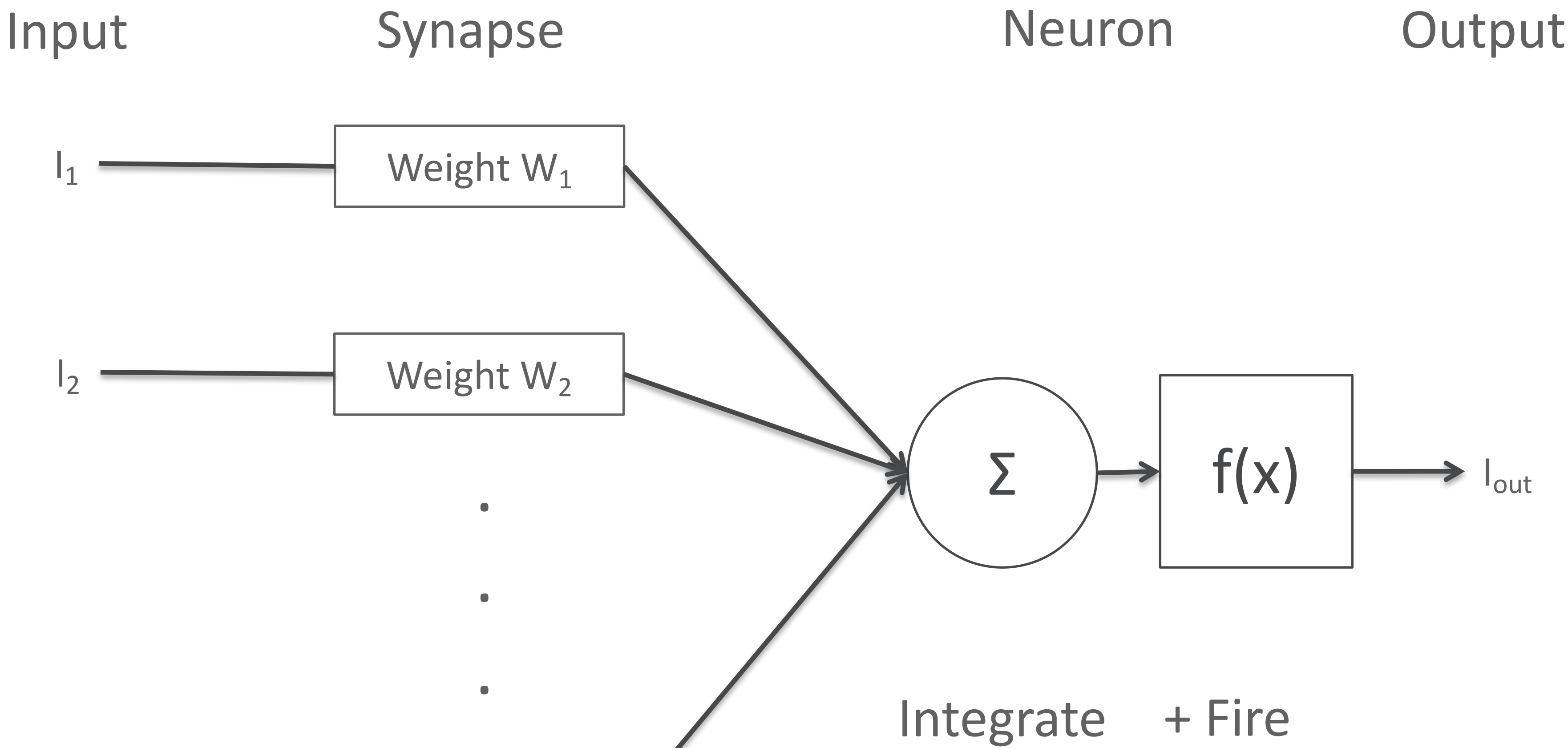
No stripe domains through
No heat involved
Only divergence of current
Requires Larger Currents

Pulse current: 15 V of duration 1 ms at 1 Hz

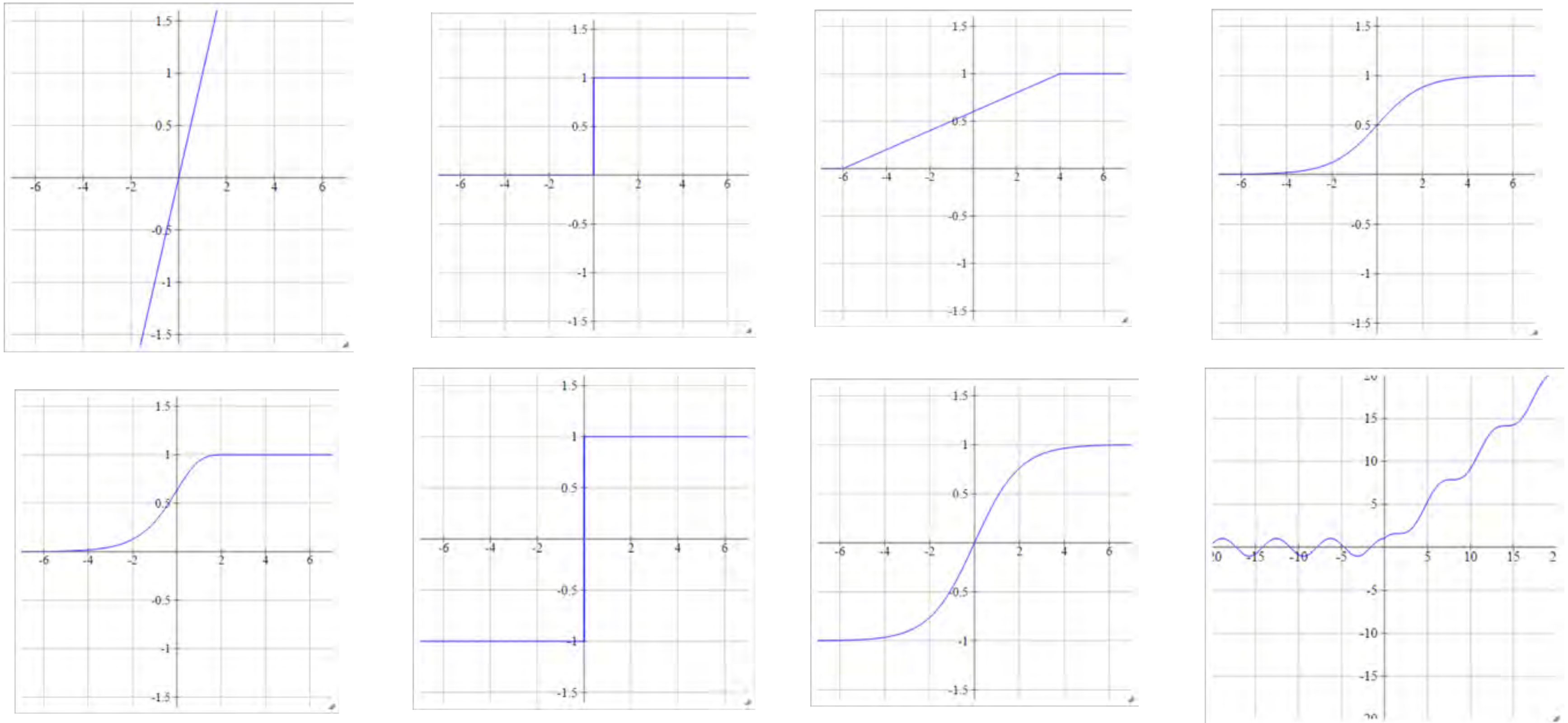


Skyrmions meet Neuromorphic

Basic Neuromorphic Concept



Possible Transfer Functions



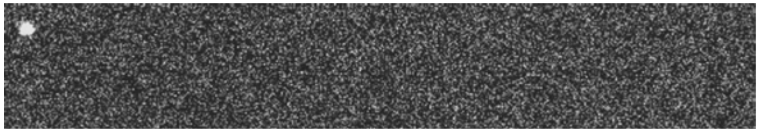
https://stats.stackexchange.com/questions/115258/comprehensive-list-of-activation-functions-in-neural-networks-with-pros-cons

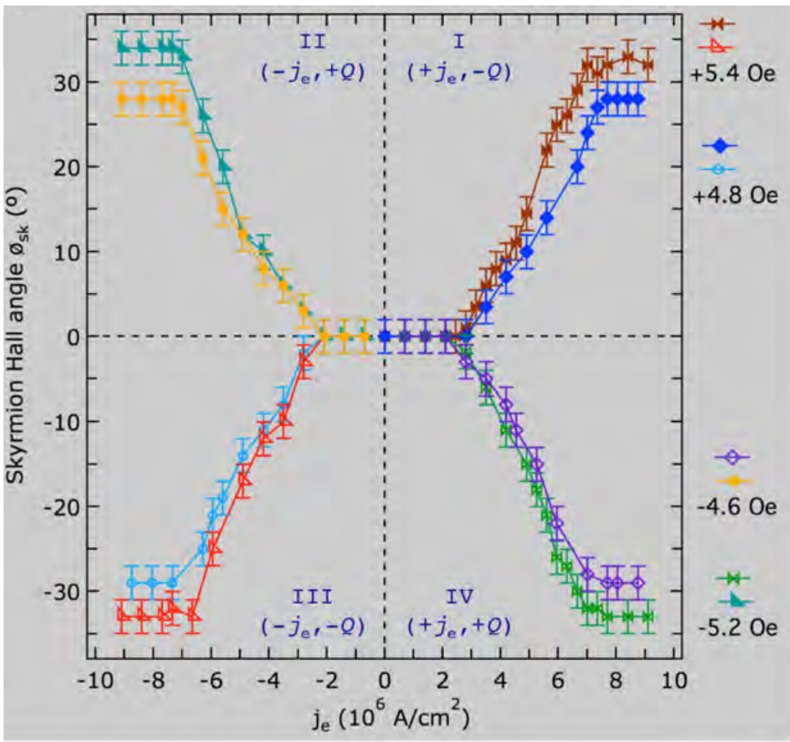
Neural network algorithms adjust weights of synapses AND transfer function during training!

What nonlinear behavior can be used with skyrmions?

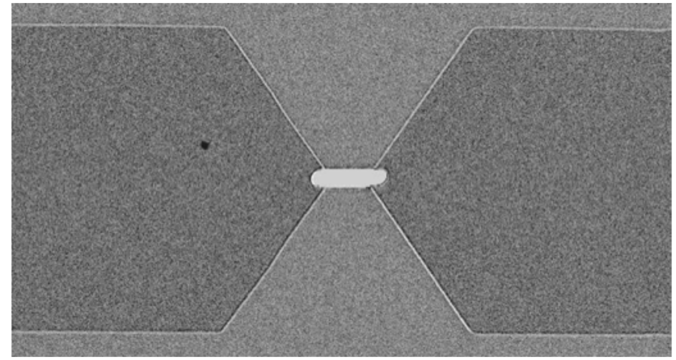
Nonlinear Phenomena

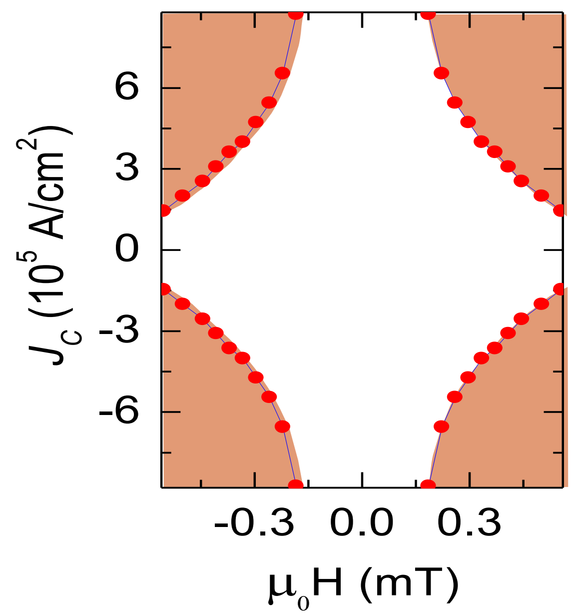
Transverse Motion



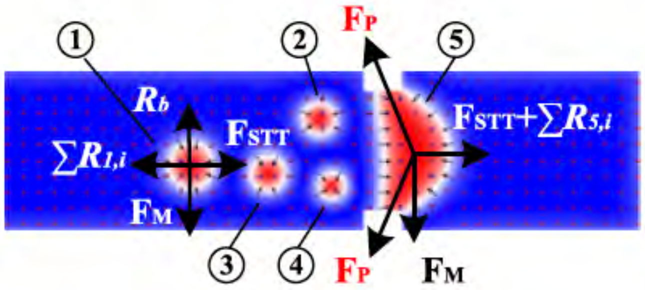


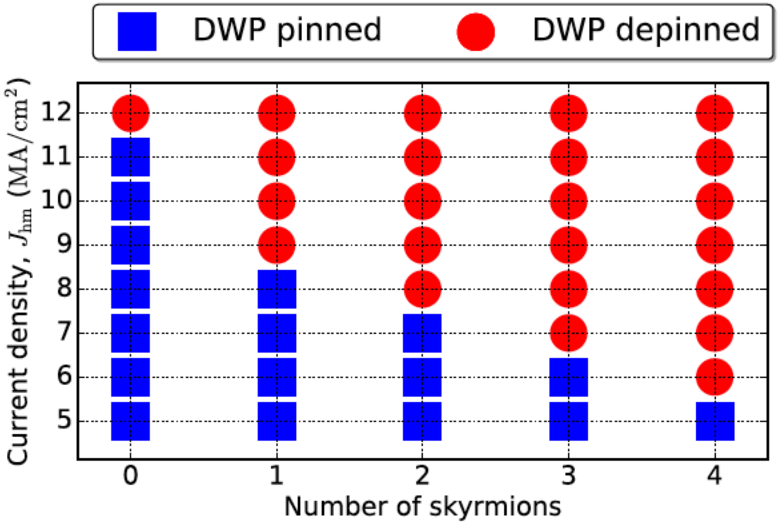
Generation and Depinning

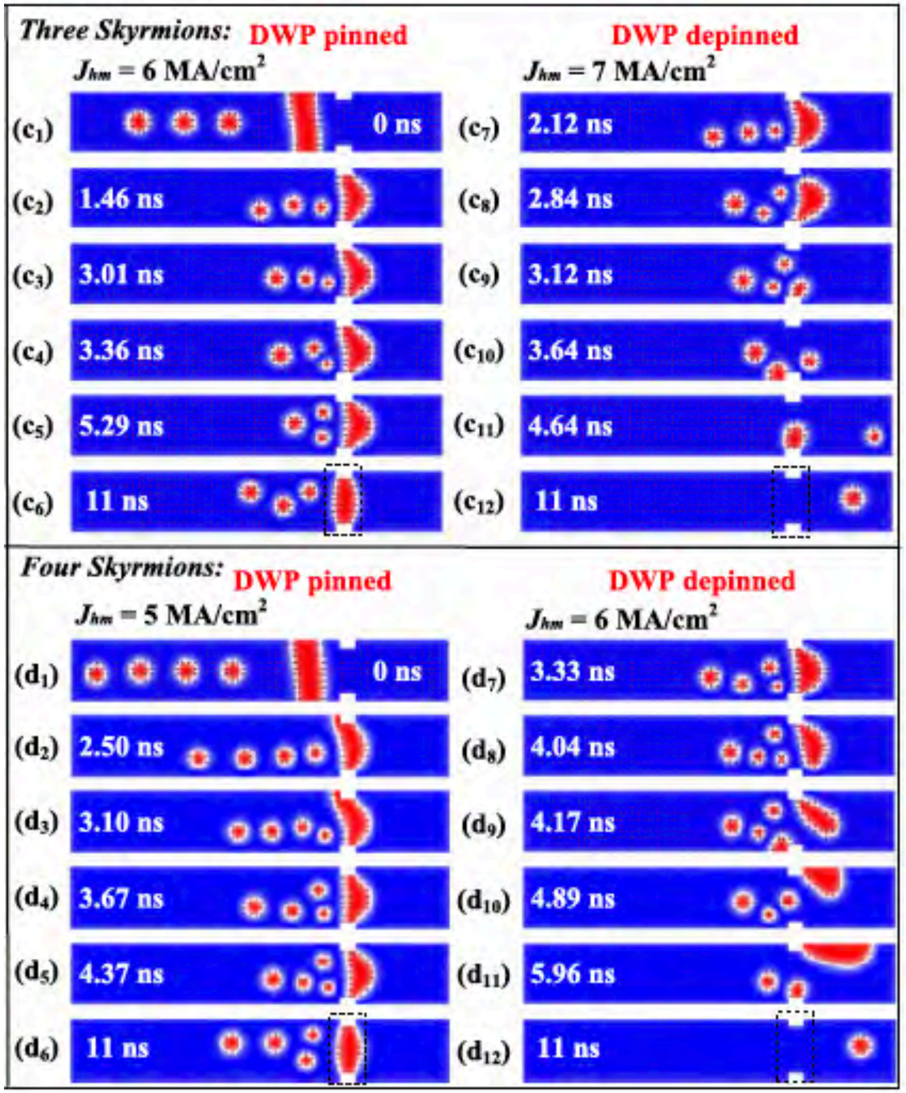




Depinning due to skyrmion accumulation





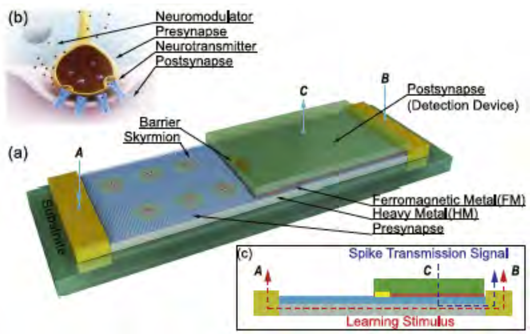


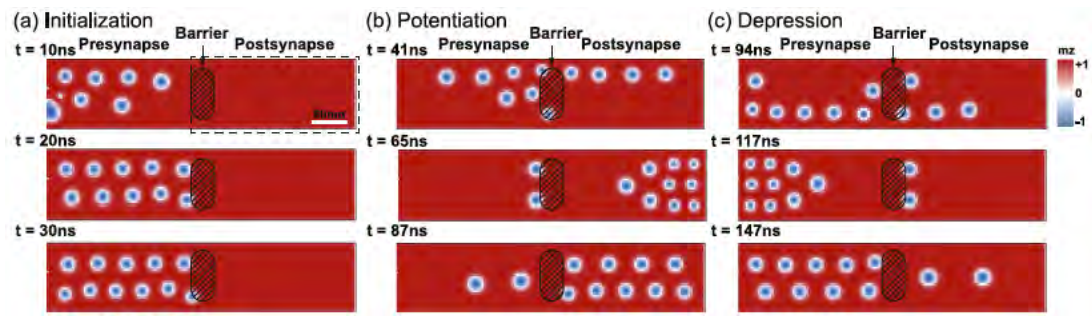
Tunable Transfer Function!

Z. He, S.Angizi , and D.Fan
IEEE Magn. Lett. **8**, 4305705 (2017)

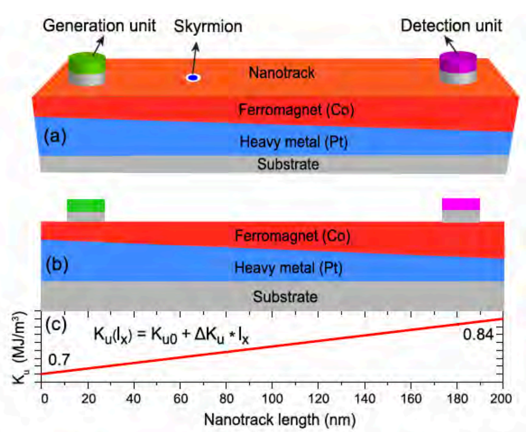
More complex ideas along these lines

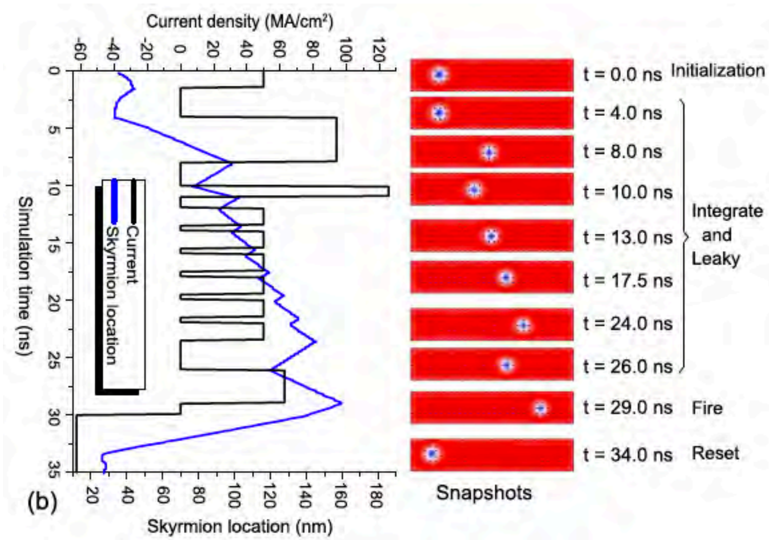
Modulating DMI or anisotropy locally





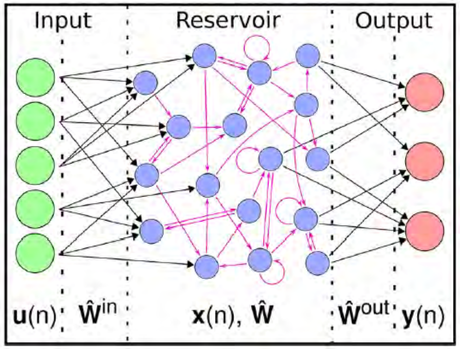
Y.Huang, *et al.*, Nanotechn. **28**, 08LT02 (2017)





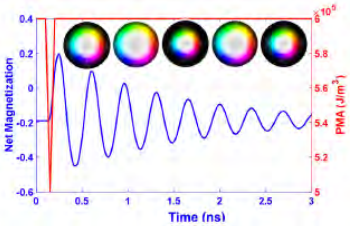
S. Li, *et al.*, Nanotechn. **28**, 31LT01 (2017)

Reservoir Computing

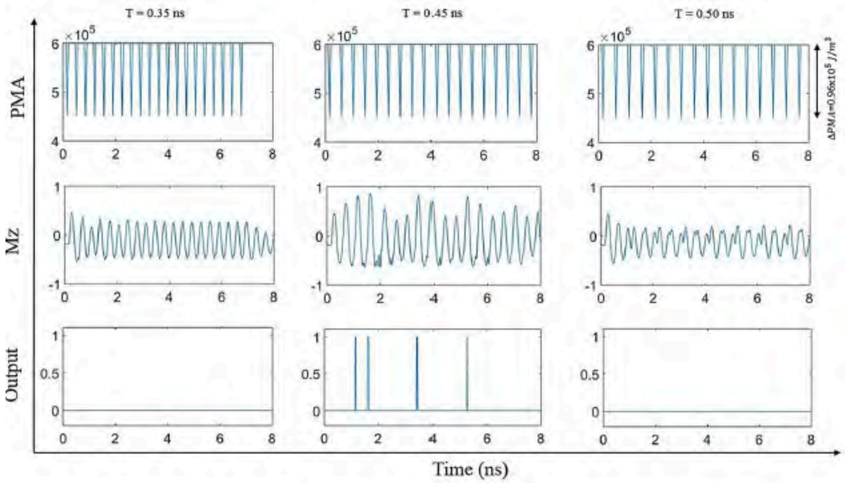


G.Bourianoff *et al.*, AIP Adv. **8**, 055602 (2018)

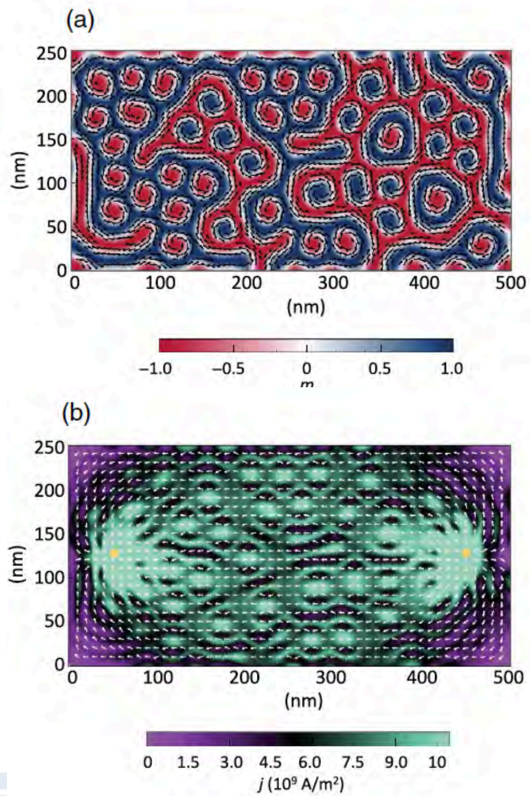
Dynamics



Md.Ali Azam *et al.*, J. Appl. Phys **124**, 152122 (2018)



Complex Spin Textures

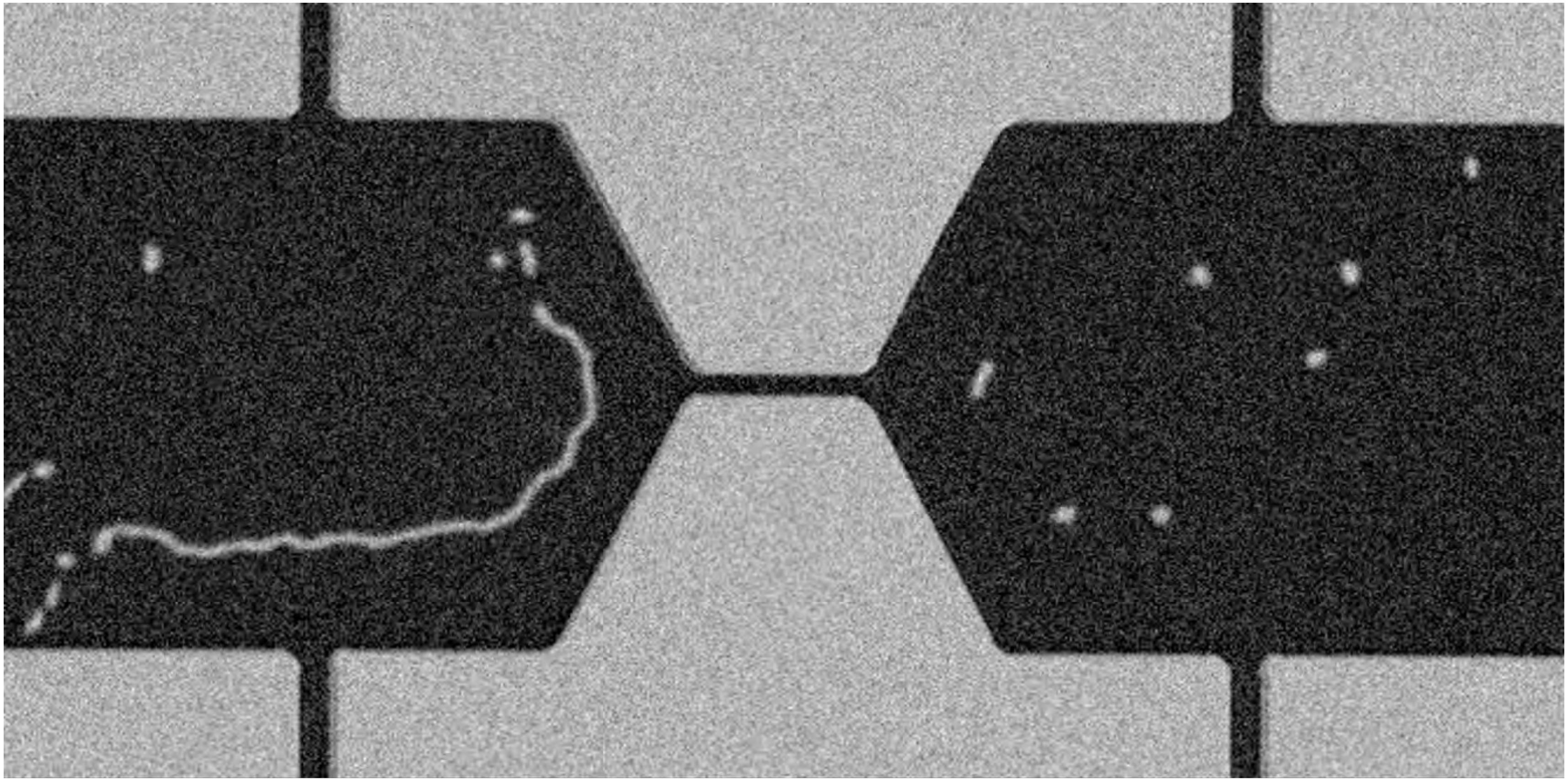


D.Prychynenko *et al.*, Phys Rev. Appl. **9**, 014034 (2018)

Stochastic Behavior

$H_{\perp} = -0.5$ mT

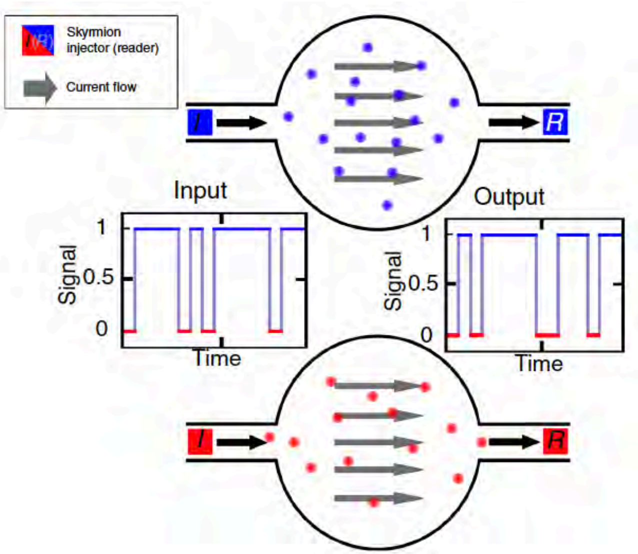
$+ J_c$ ⟶

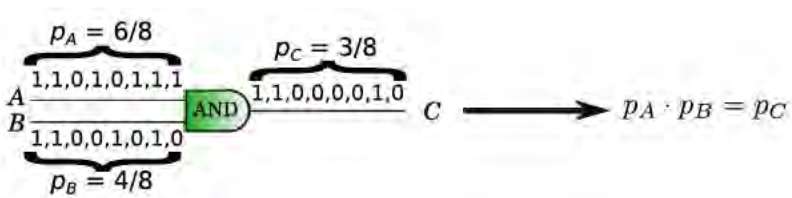


W. Jiang *et al.*, Science **349**, 283 (2015)

Skyrmion Reshuffler

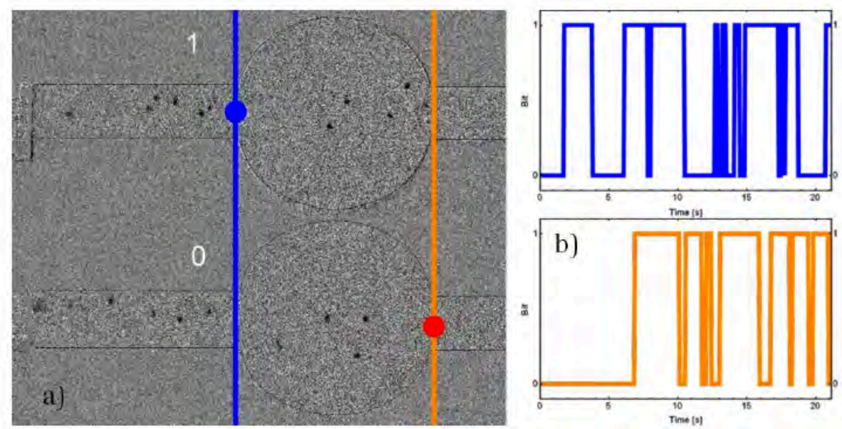
Theoretical Concept





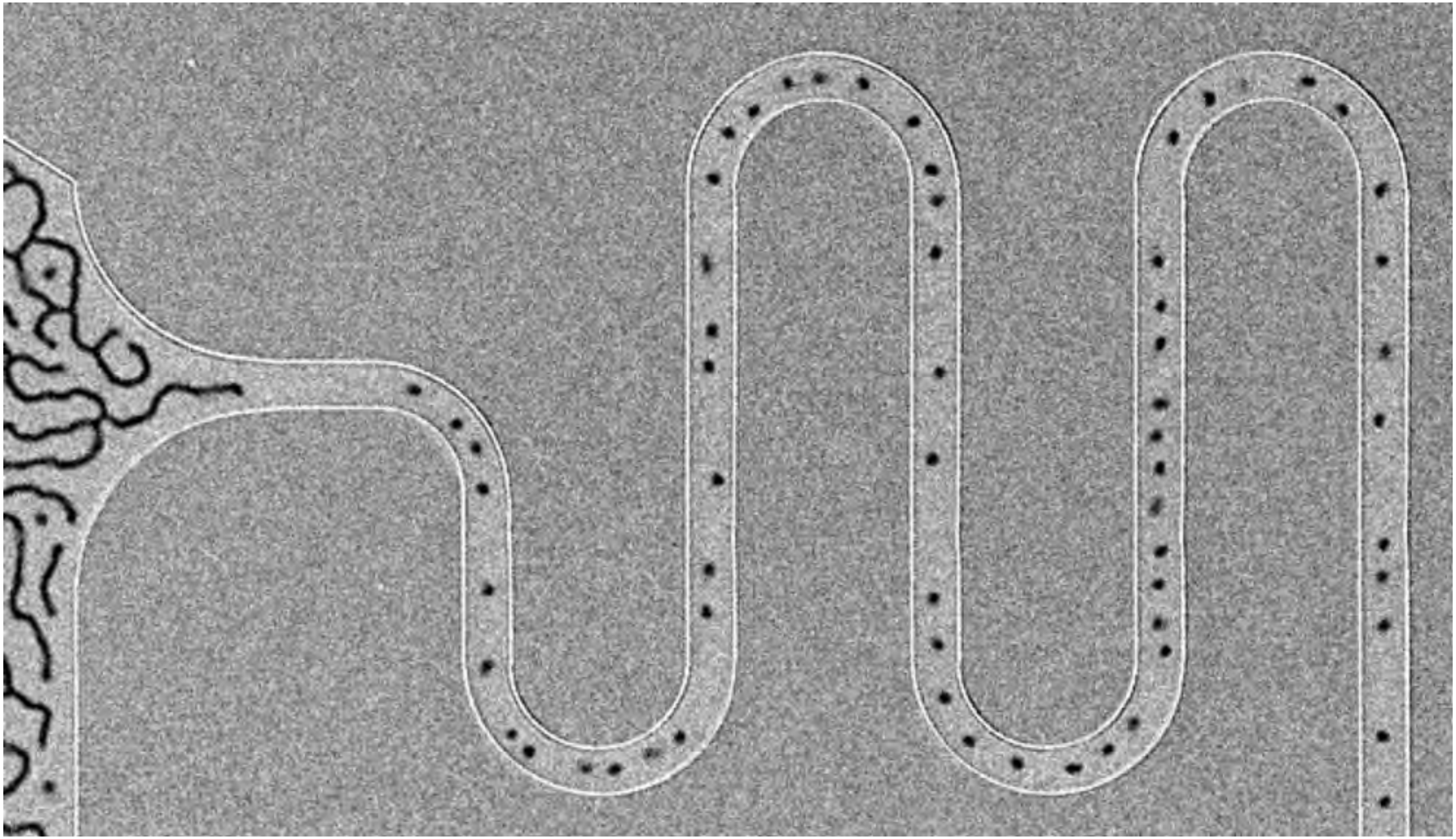
D. Pinna *et al.*, Phys. Rev. Appl. **9**, 064018 (2018)

Experimental Demonstration

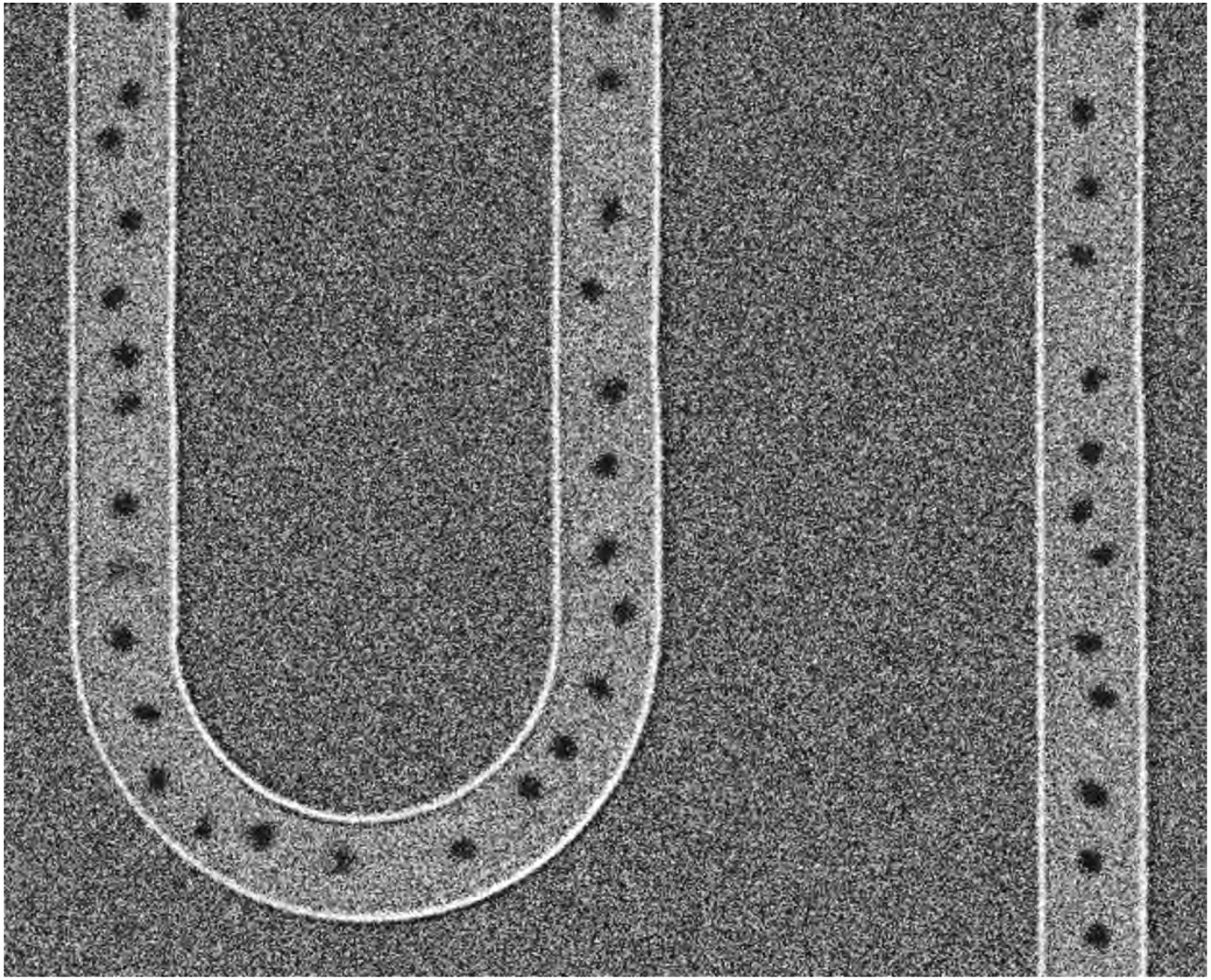


J.Zázvorka *et al.*, arXiv: 1805.05924

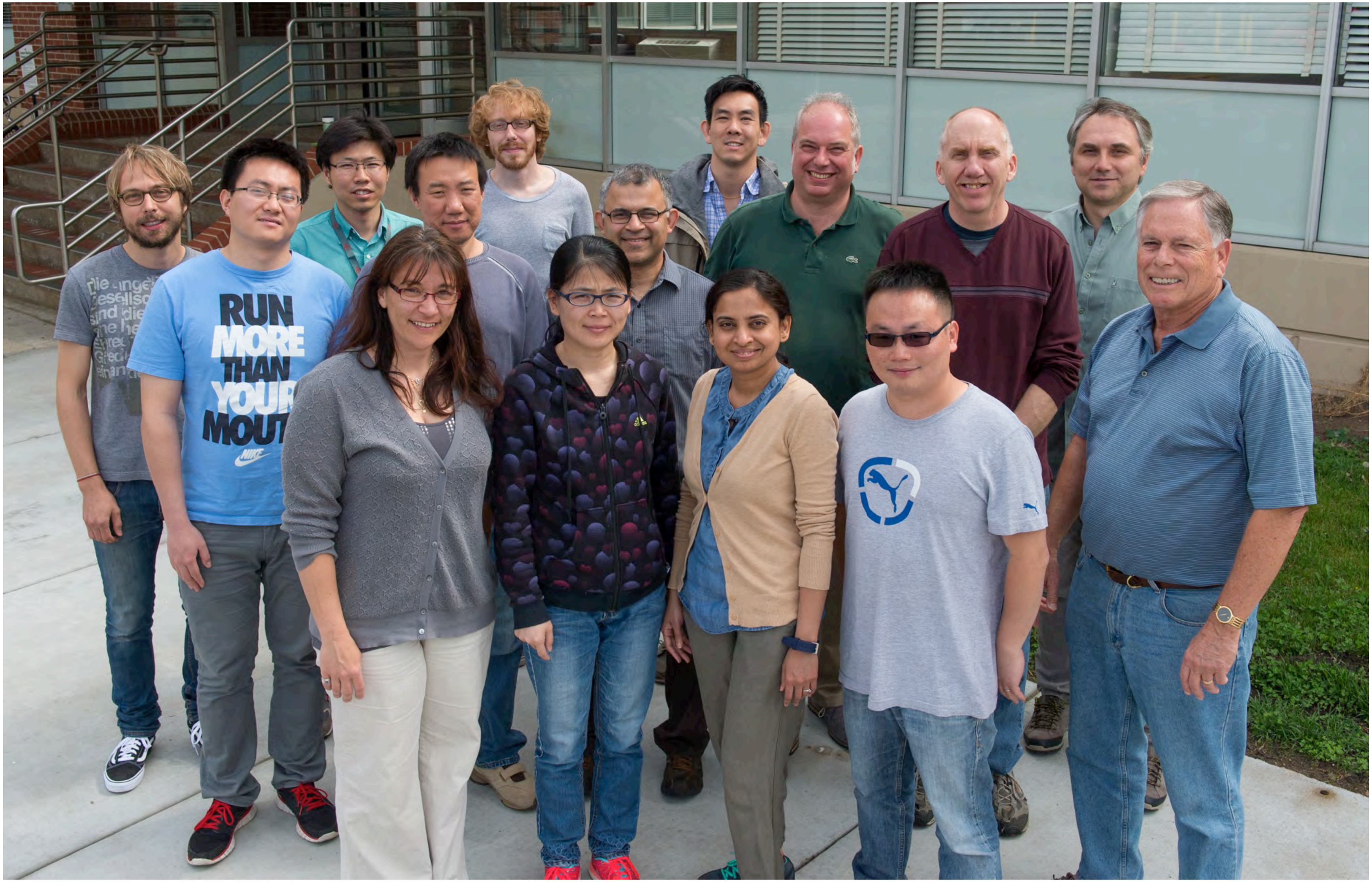
Just the Beginning of the Fun!



Just the Beginning of the Fun!



Magnetic Films Group at Argonne



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Xichao Zhang and Yan Zhou

The University of Hong Kong

Xiao Wang and Xuemei Cheng

Bryn Mawr College

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DOE-BES Materials Science and Engineering Division

Conclusions

- **Magnetic Skyrmions**
  - Use interfacial interactions to stabilize them at room-temperature
- **Motion of Skyrmions**
  - Spin-orbit torques provide very efficient driving force
  - Topological charge gives rise to strong gyroscopic forces: skyrmion Hall effect
- **Generating Skyrmions**
  - Inhomogeneities in spin textures or driving force can nucleate new skyrmions
- **Skyrmions for Neuromorphic Computing**
  - Can exhibit threshold and non-linear behavior
  - Stochastic motion