STABILIZING AND CONTROLLING ROOM TEMPERATURE MAGNETIC SKYRMIONS

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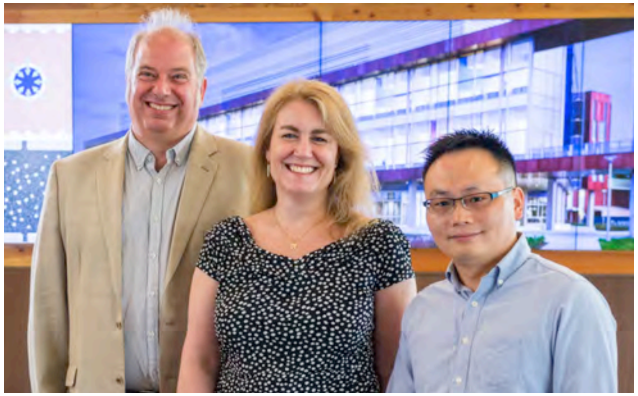
Materials Sciences and Engineering Division.

ACKNOWLEDGEMENTS



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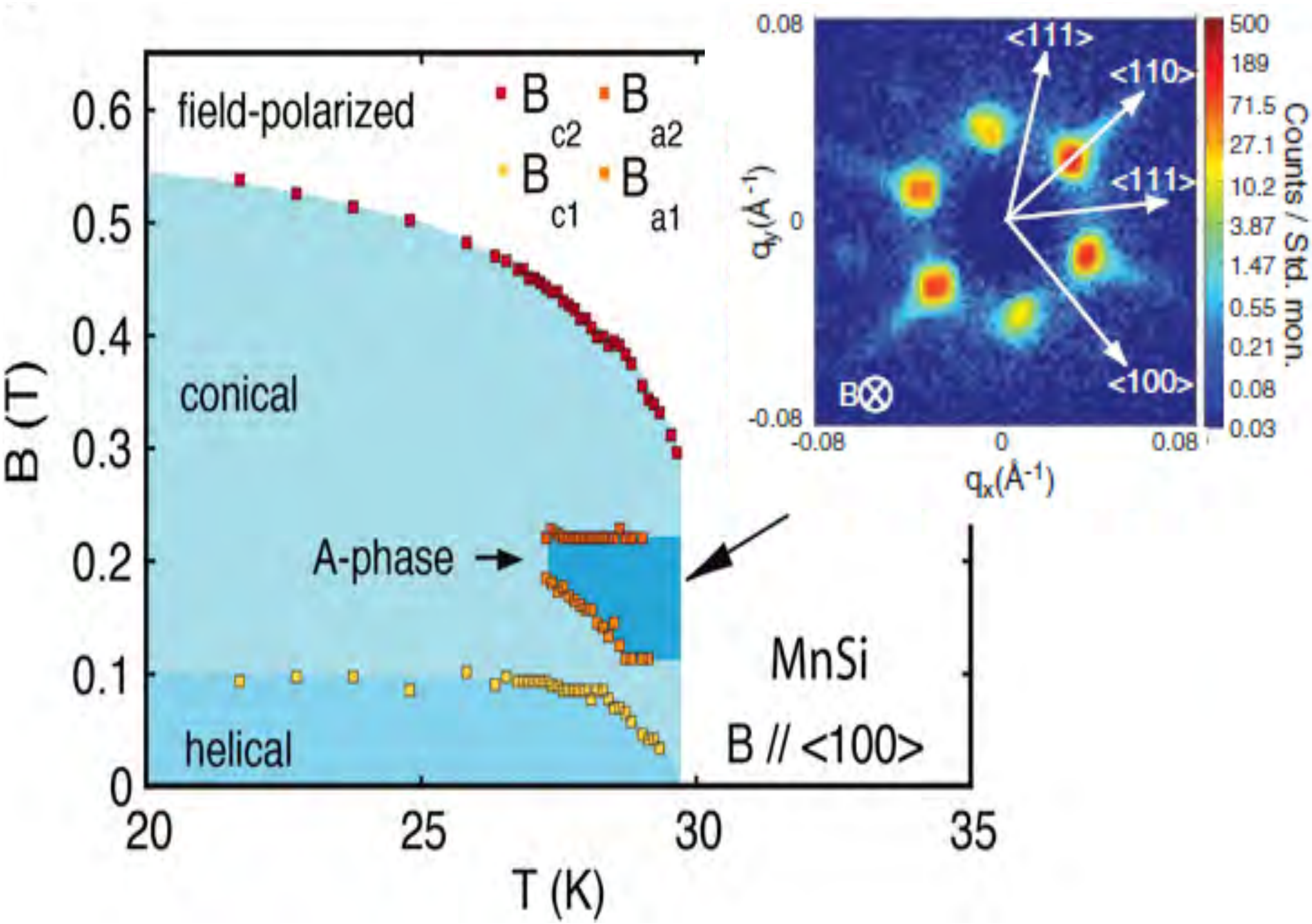
DISCOVERY OF MAGNETIC SKYRMIONS

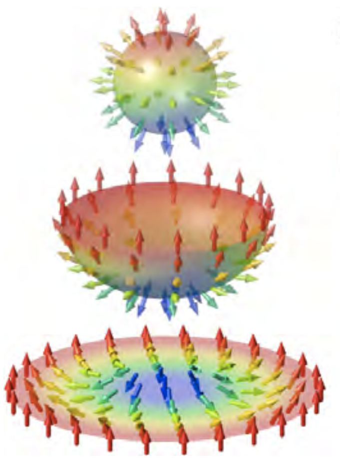


S. Mühlbauer *et al.*, Science **323**, 915 (2009)

MAGNETIC SKYRMIONS

Non-Trivial Topology

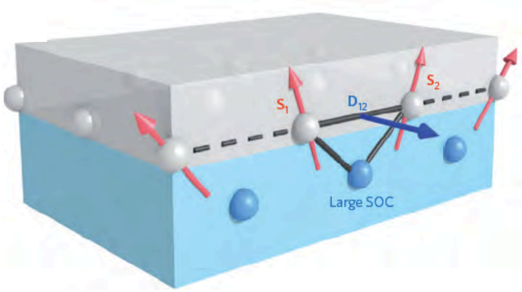
Topological Charge



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

$$Q = \pm 1$$

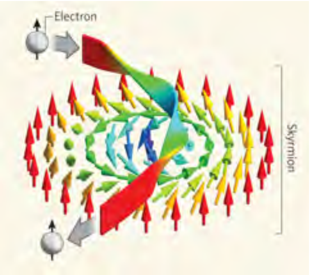
Stabilized by Chiral Dzyaloshinkii-Moriya Interaction



$$\mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

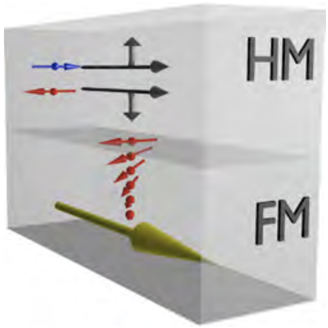
Efficient Manipulation by Electric Charge Currents

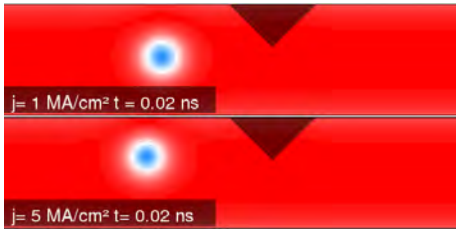
Emergent Magnetic Field



$$h \approx \frac{\Phi_0}{\pi R^2} \approx \frac{\Phi_0}{\pi a^2} \left(\frac{D}{J}\right)^2 \qquad h \sim 100\ \mathrm{T}$$

Motion due to Spin Hall Effect

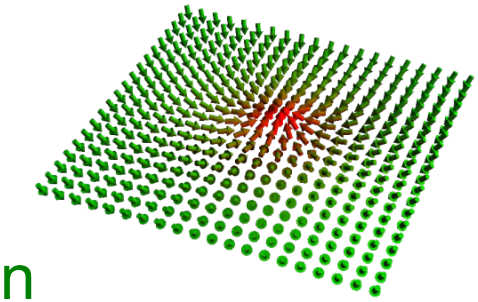




A. Fert *et al.*, Nature Nano. 8, 152 (2013)

SKYRMIONS ARE STABILIZED BY CHIRAL INTERACTIONS

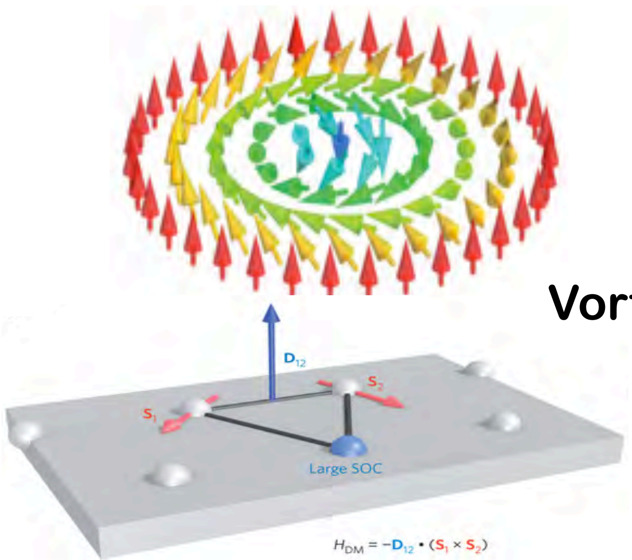
$$H = \sum_{<ij>} -J\mathbf{S}_i \cdot \mathbf{S}_j + \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j) - \sum_i \mathbf{B} \cdot \mathbf{S}_i$$



Ferromagnetic   Helical Spiral   Skyrmion

Dzyaloshinskii-Moriya Interaction (DMI) requires Inversion Symmetry Breaking

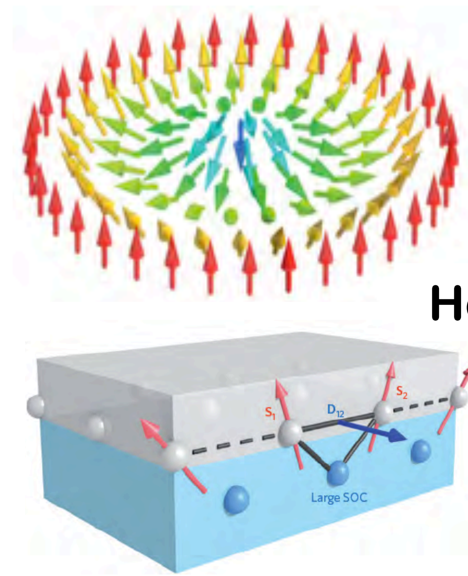
Bulk DMI



Vortex-like

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

Interfacial DMI



Hedgeho g

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

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

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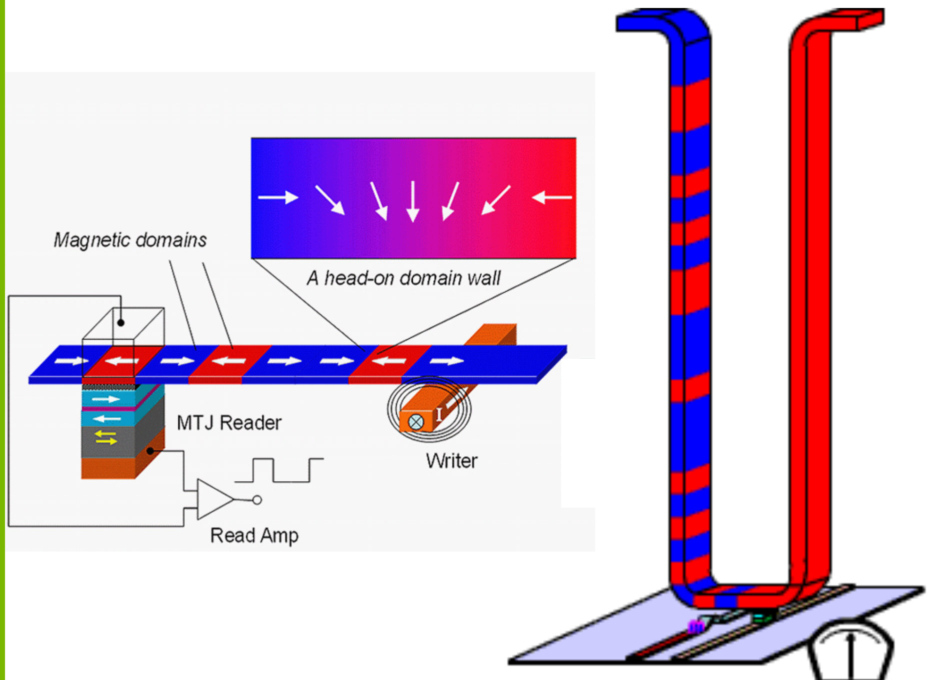
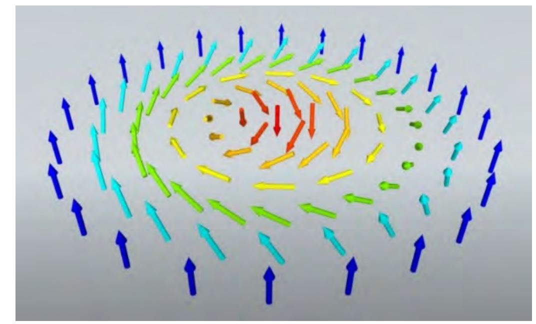
ENCODING INFORMATION IN SPIN TEXTURES

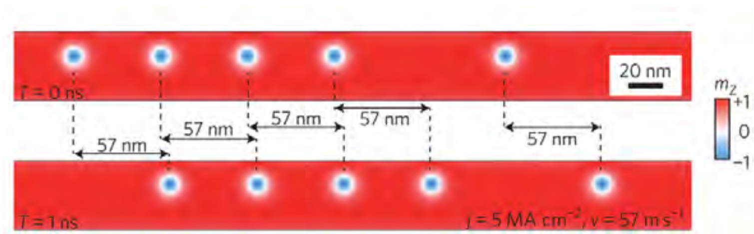
Racetrack Memory



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

Skyrmions

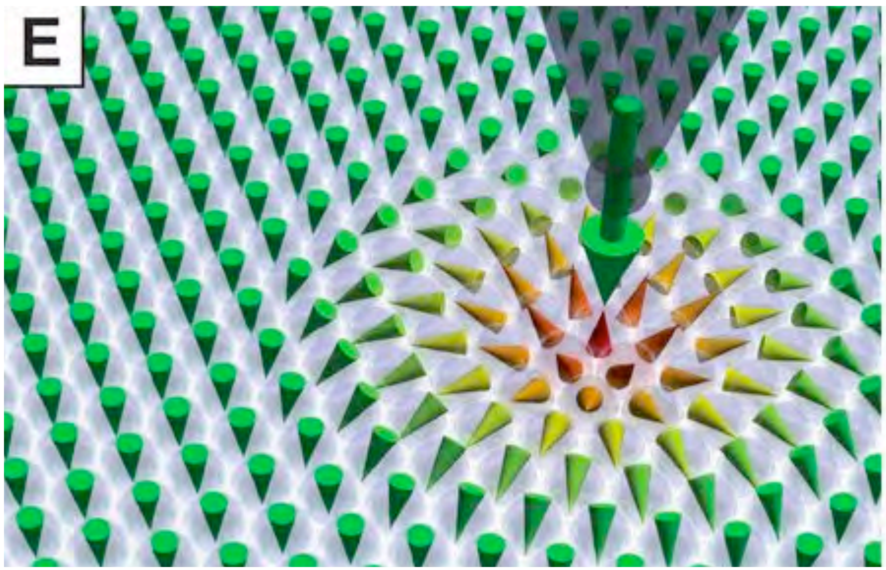


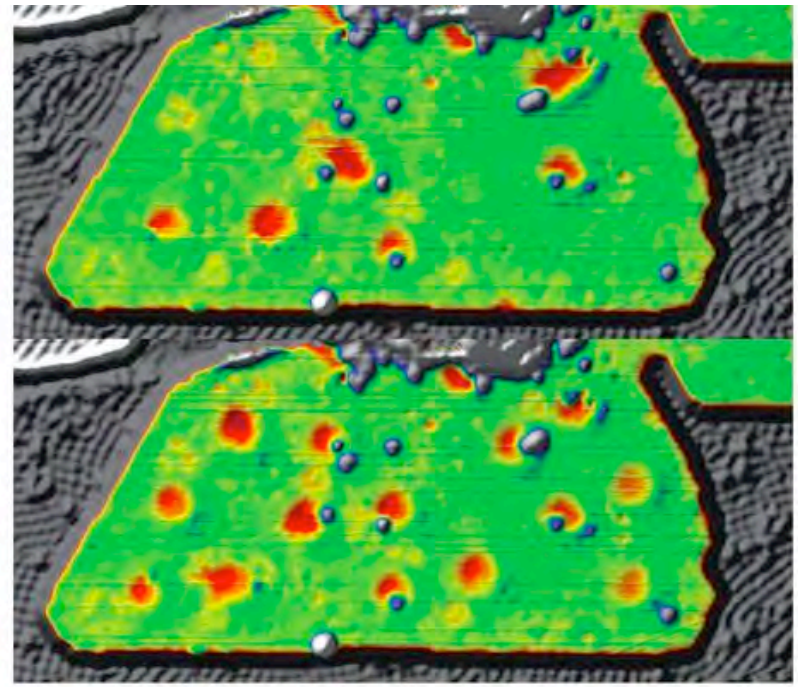


A. Fert *et al.*, Nature Nano. 8, 152 (2013)

GENERATING INDIVIDUAL SKYRMIONS

Using spin-polarized scanning tunneling microscope





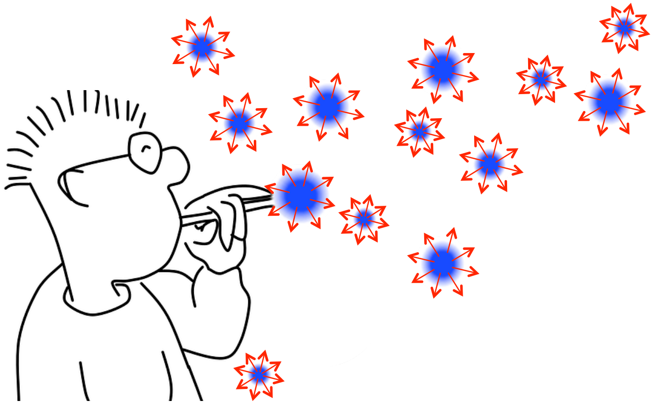
N. Romming, et al., Science **341**, 636 (2013)

Spin-transfer torque switches skyrmion core reversibly

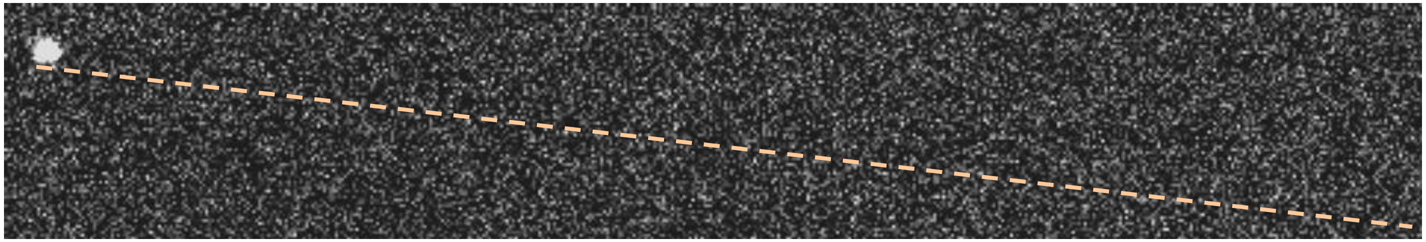
HOW TO EXPERIMENTALLY CREATE AND/OR MANIPULATE **ROOM-TEMPERATURE** MOBILE SKYRMIONS IN **COMMON MATERIAL SYSTEMS**.

TOPICS

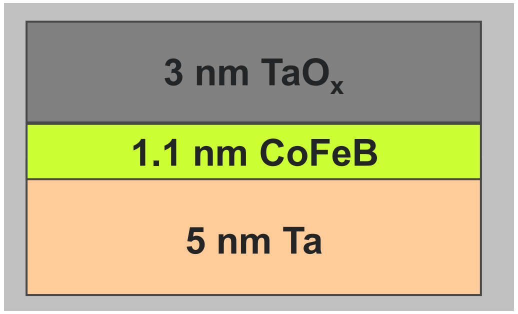
Blowing Magnetic Skyrmion Bubbles

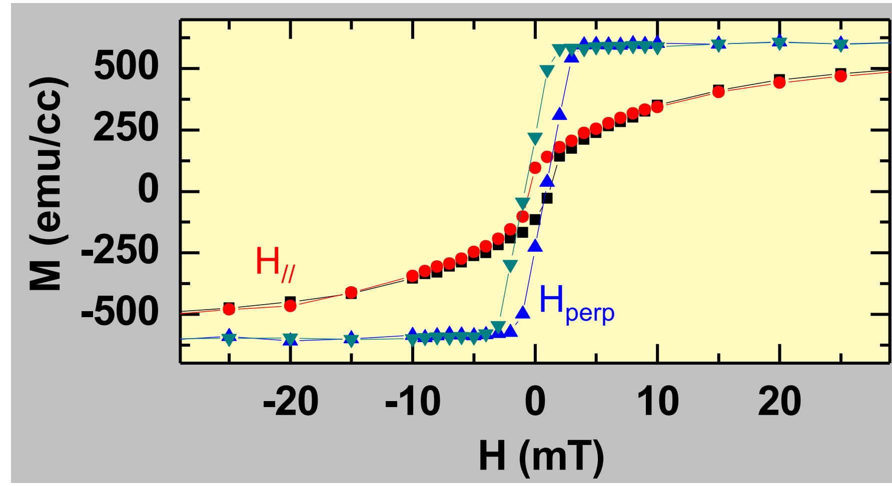


Skyrmion Hall Effect

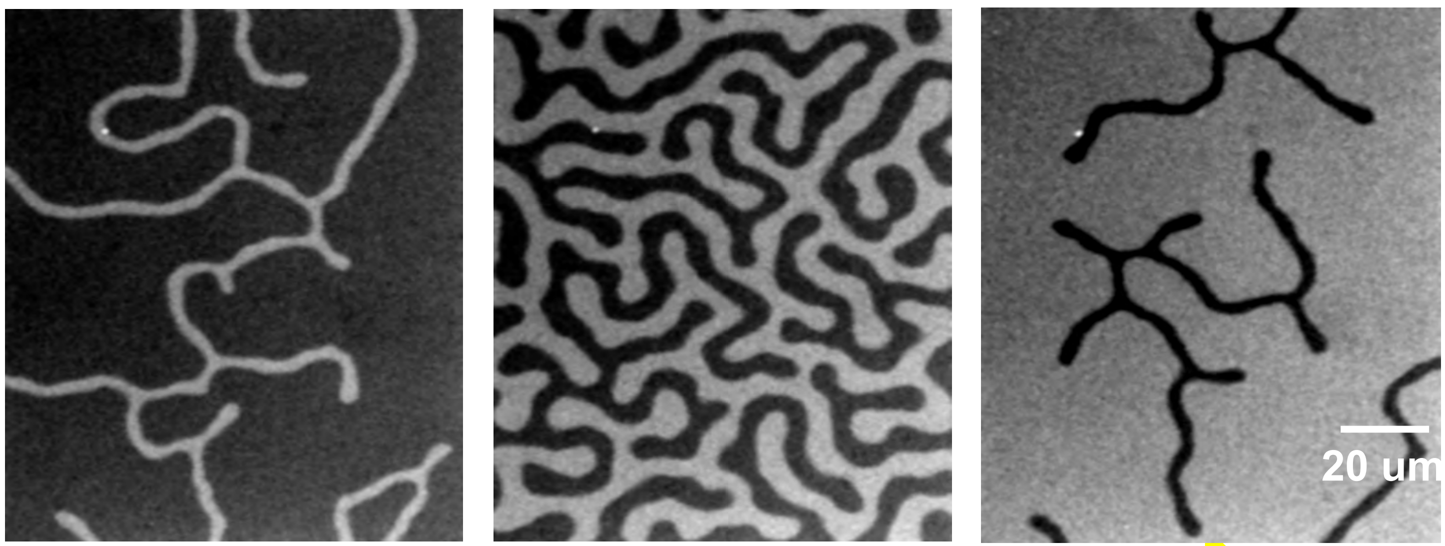


FERROMAGNETIC FILMS WITH PERPENDICULAR ANISOTROPY





Polar
Magneto
Optic
Kerr
Effect
(MOKE)
Imaging



Increasing Magnetic Field

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

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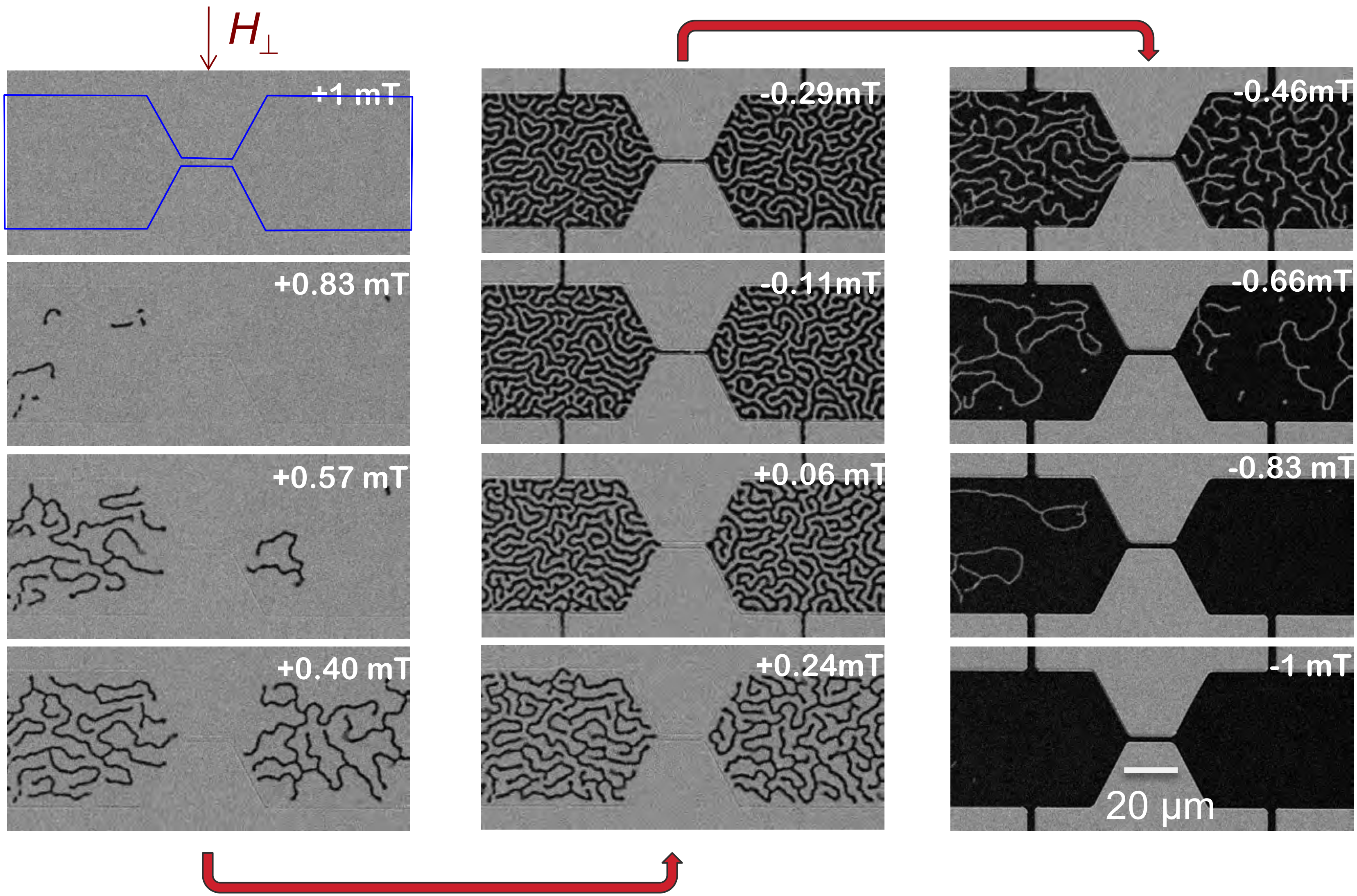
DOMAIN EVOLUTION WITH MAGNETIC FIELD

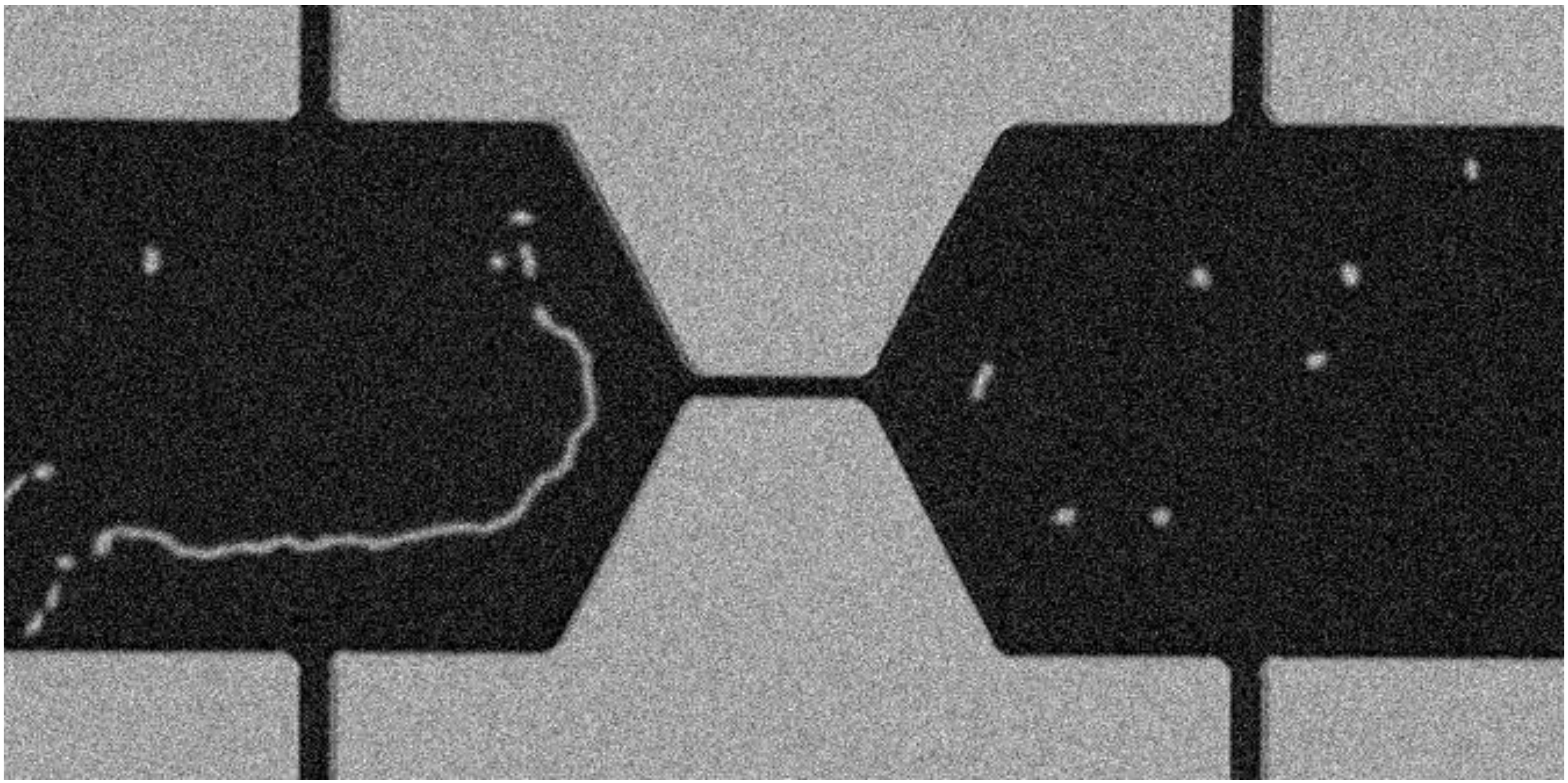


W. Jiang *et al.*, Science **349**, 283 (2015)

BLOWING MAGNETIC SKYRMION BUBBLES

$H_{\perp}$ = - 0.5 mT

J_c = **+** 0.5 MA/cm^2 ⟶



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

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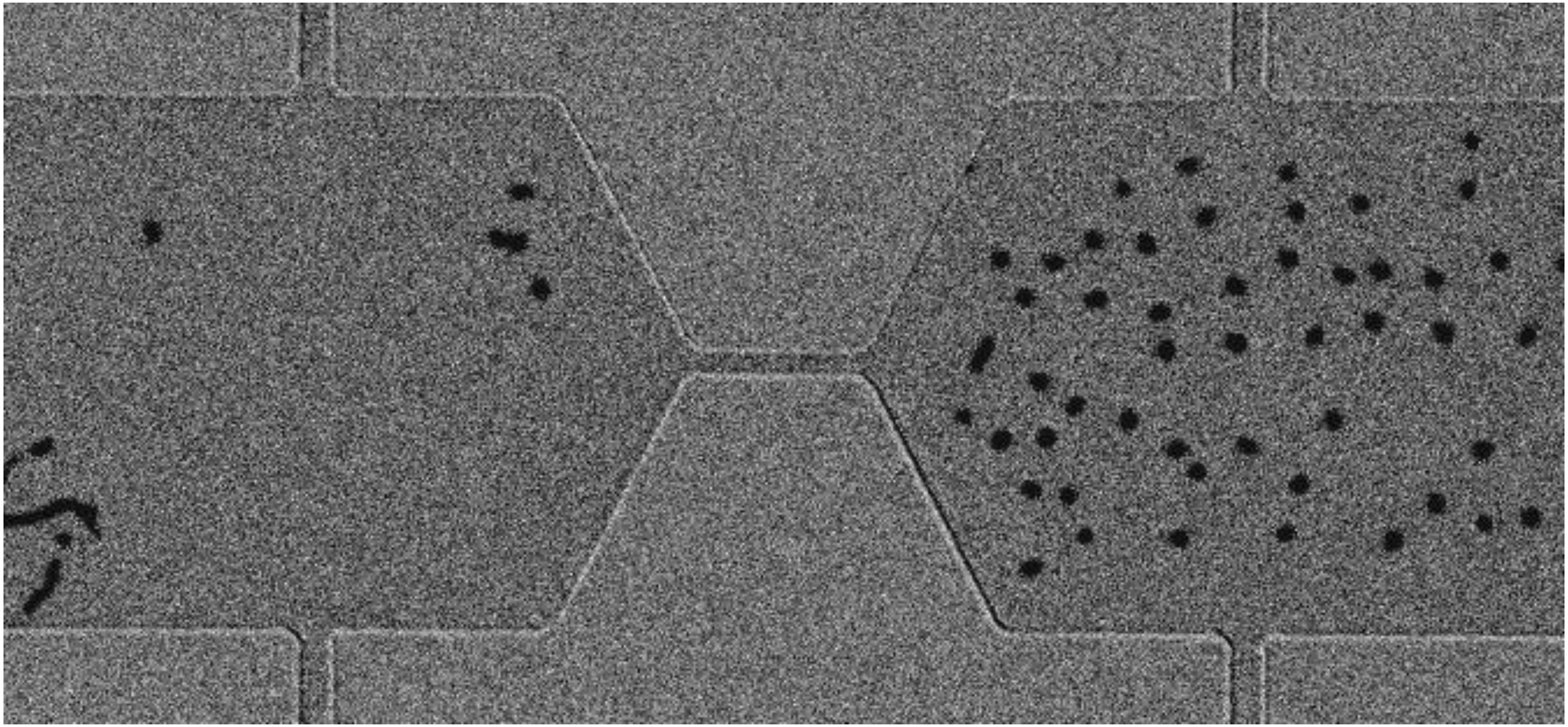
BLOWING MAGNETIC SKYRMION BUBBLES

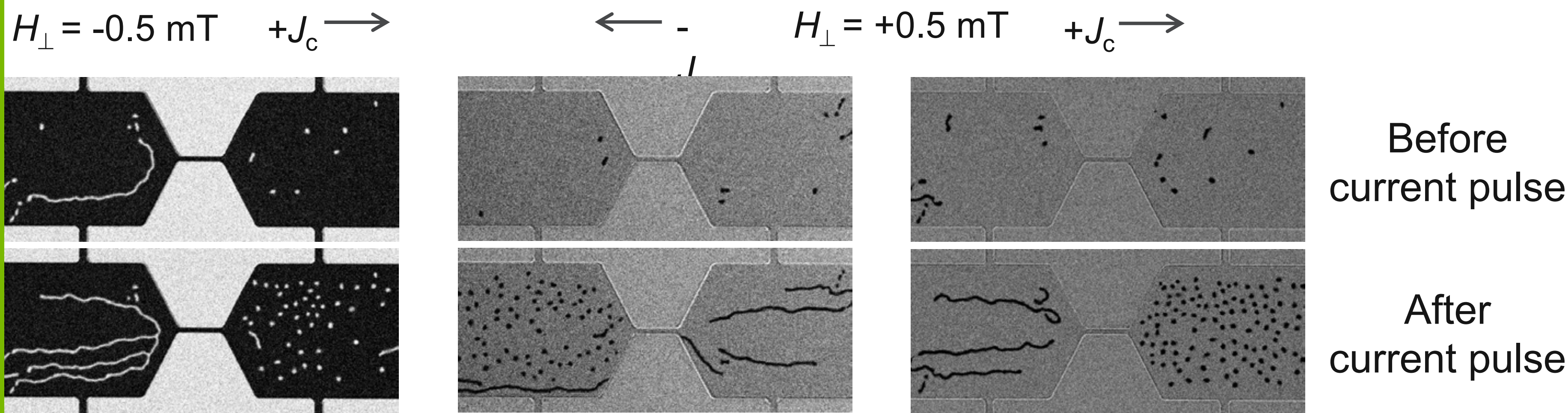
$H_{\perp} = +0.5$ mT

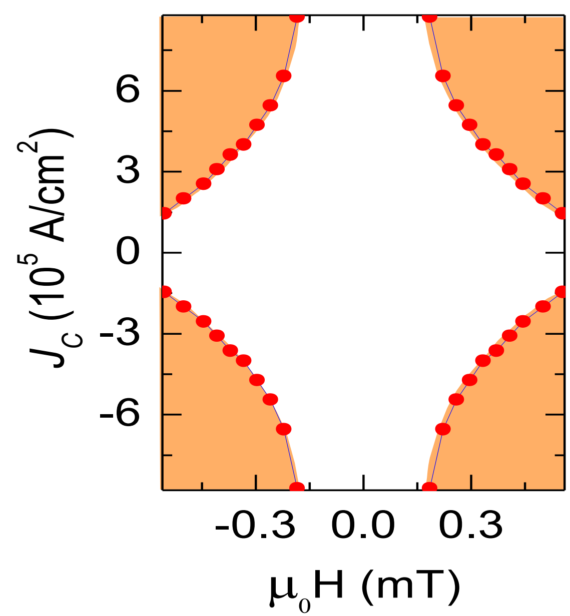
$J_c = +0.5$ MA/cm^2 ⟶



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

SKYRMION GENERATION PHASE DIAGRAM





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

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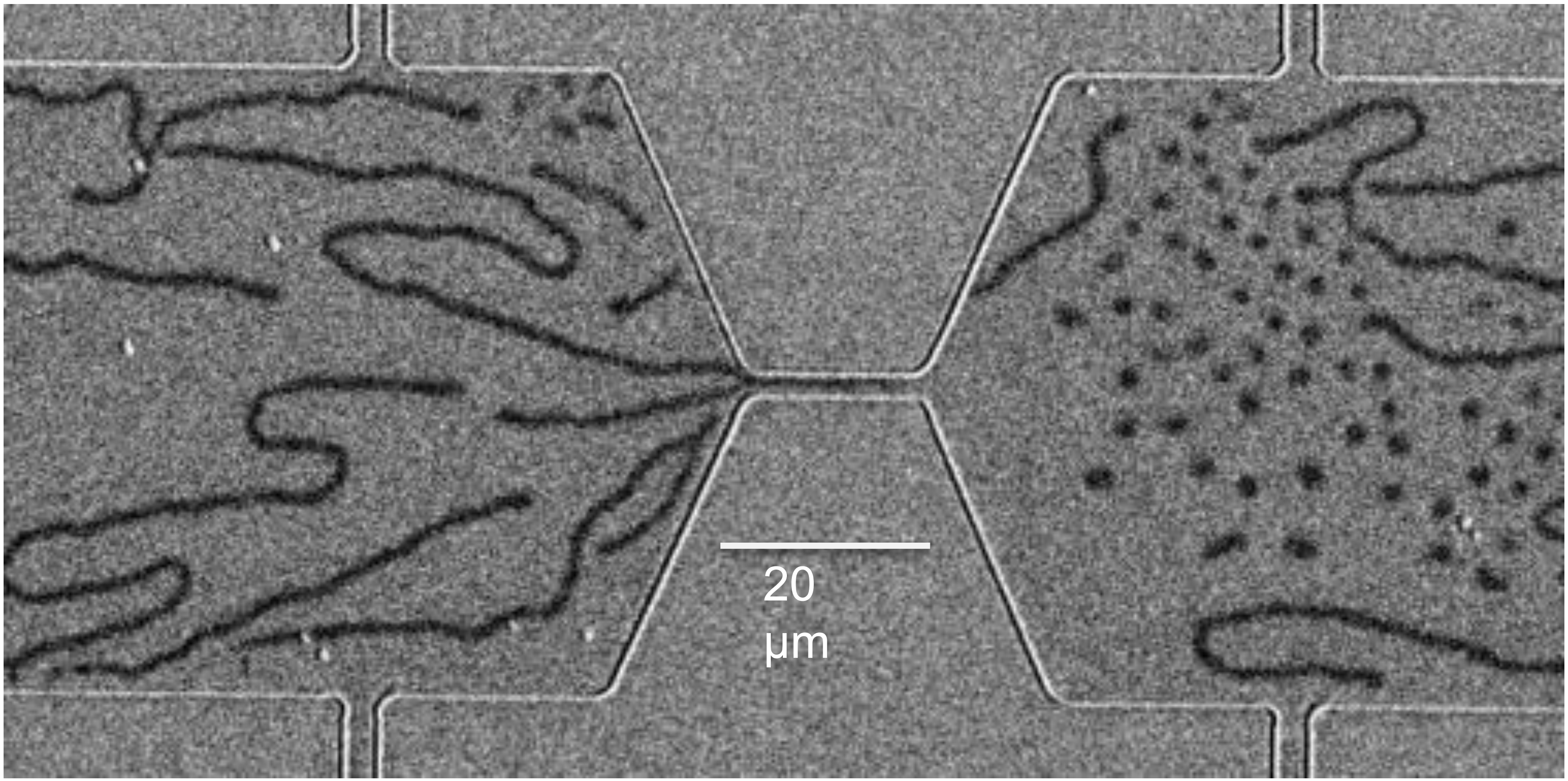
LOW CURRENT TRANSFORMATION DYNAMICS

$B_{\perp}$ = +0.46 mT, *DC current* J_e = + 0.068 MA/cm^2



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

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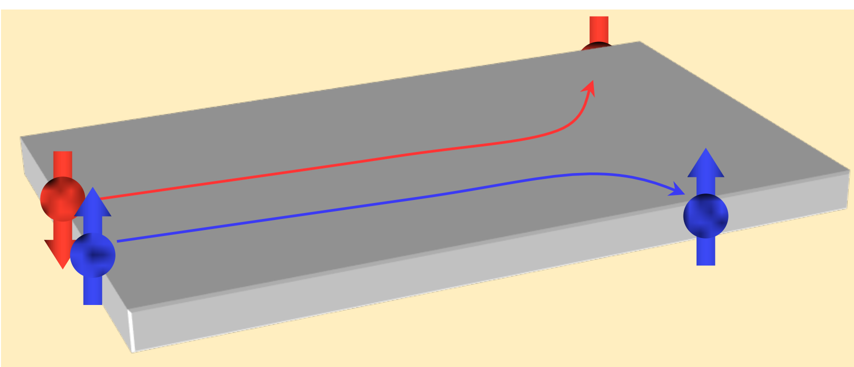
SPIN HALL EFFECT

Spin Hall

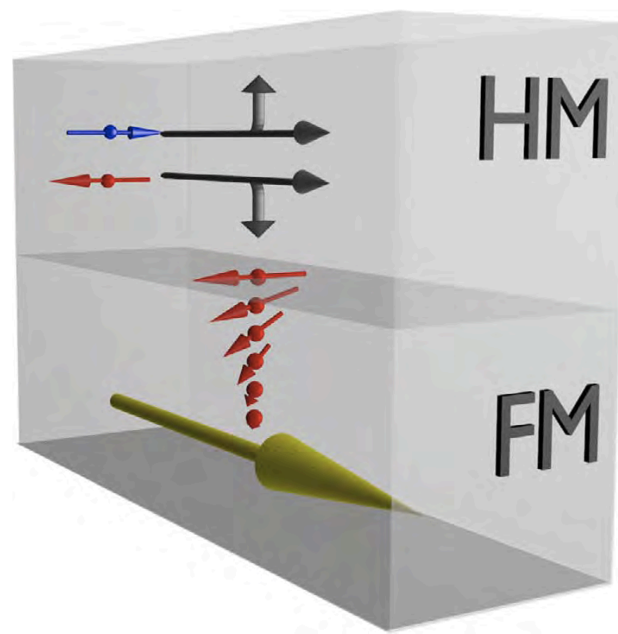
Charge Current

⇓

Transverse Spin Imbalance



Spin Orbit Torque On Adjacent Ferromagnet

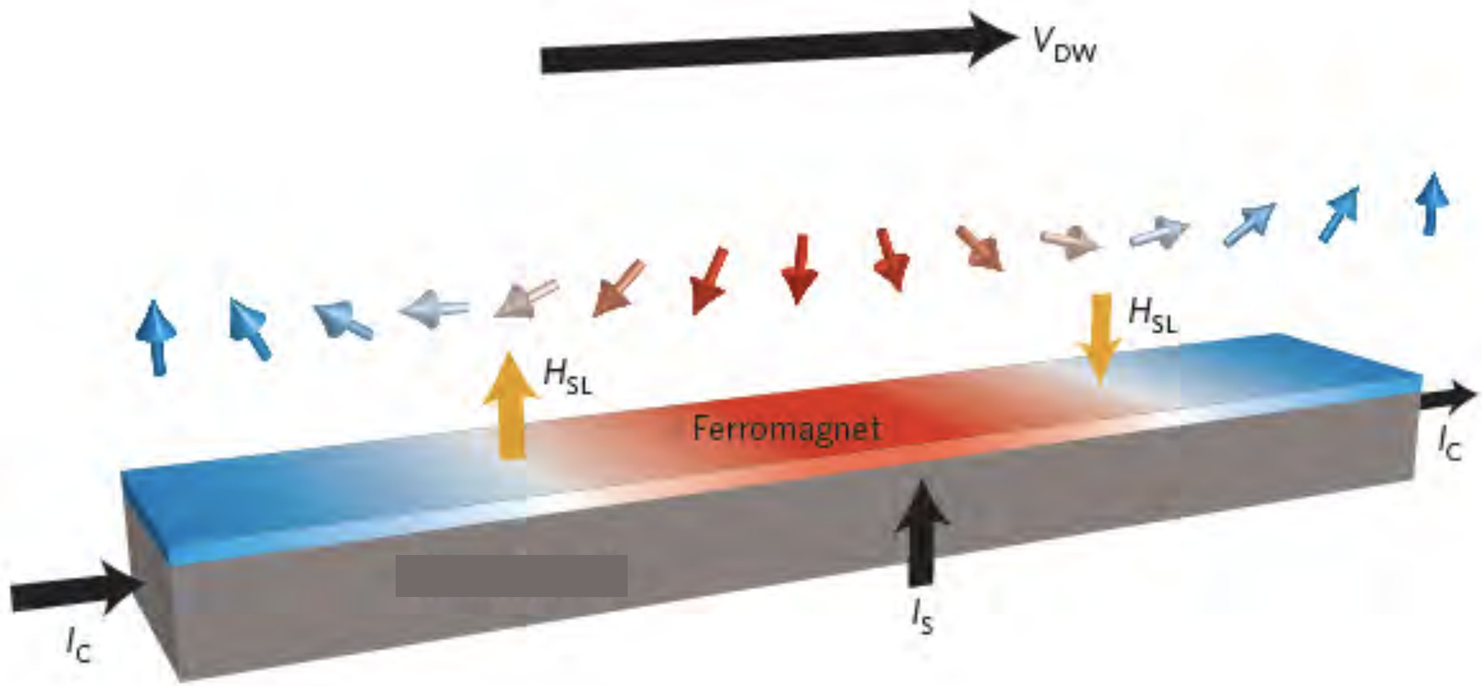


Ta

CoFeB

Recent Review: **Axel Hoffmann, IEEE Trans. Magn. 49, 5172 (2013)**

CHIRAL DOMAIN WALL TORQUES

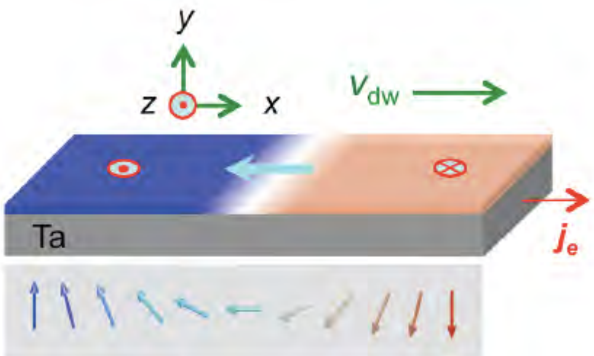


DMI + Spin Hall
= Efficient Torque

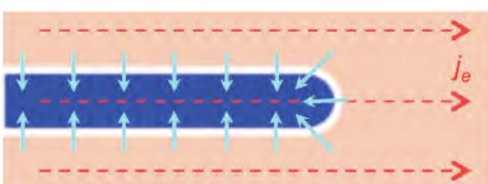
S. Emori, et al., Nat. Mater. **12**, 611 (2013)

K.-S. Ryu, et al., Nat. Nanotechn. **8**, 527 (2013)

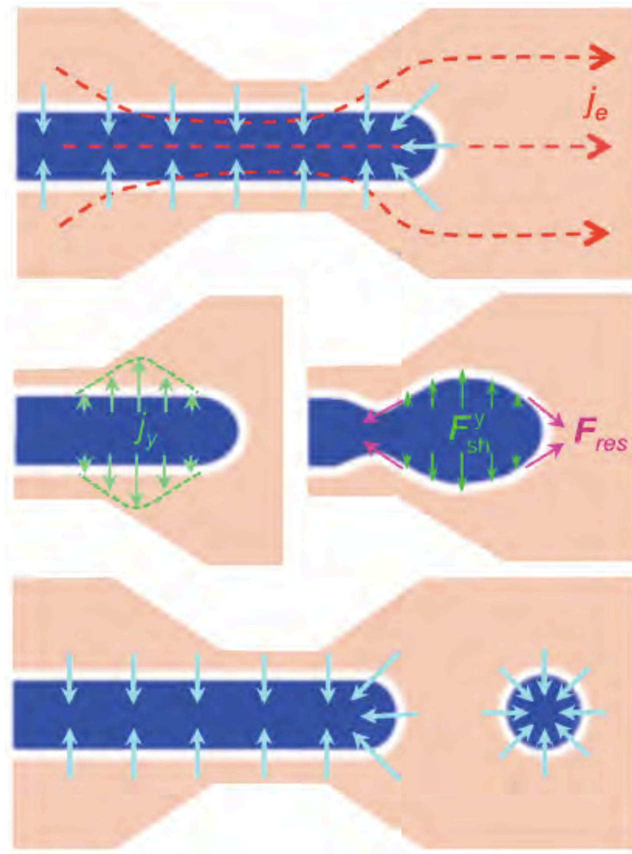
INHOMOGENEOUS CHIRAL SPIN ORBIT TORQUES



Stripe Domain with Homogeneous Current



Stripe Domain with Inhomogeneous Current



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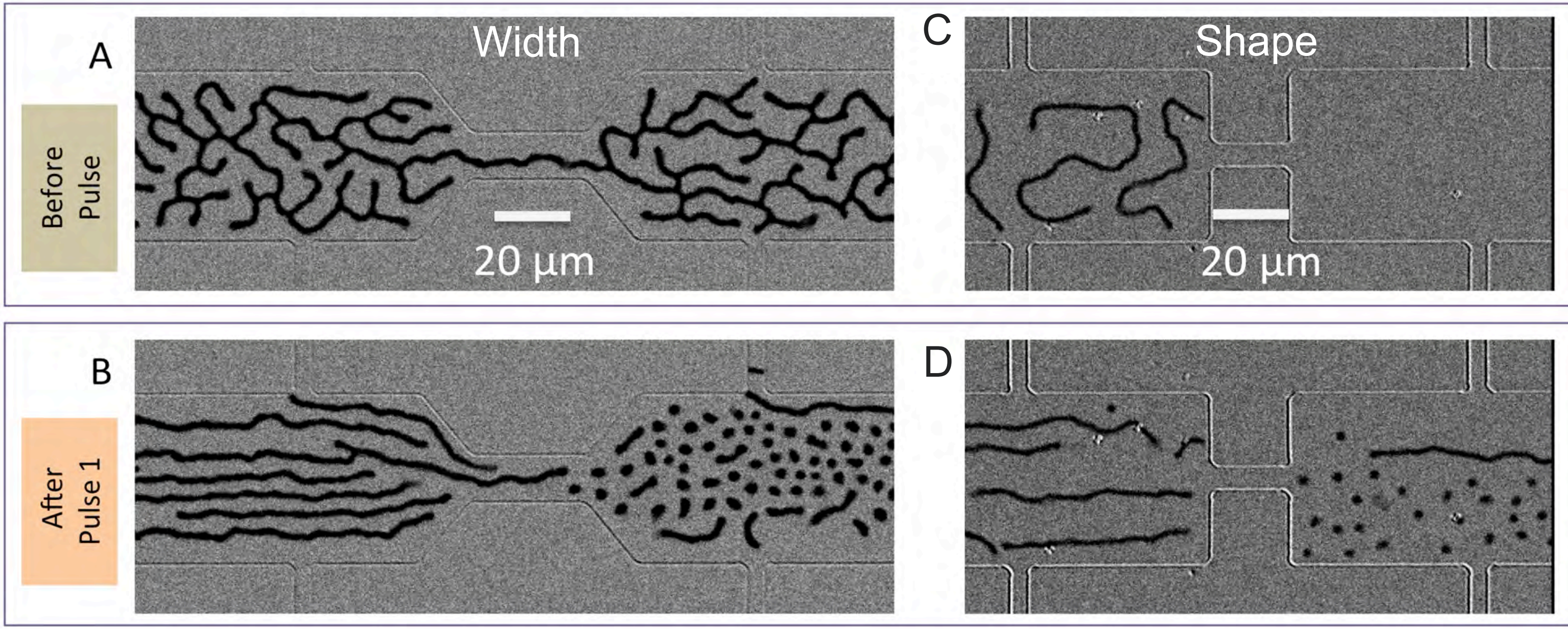
DIFFERENT GEOMETRIES

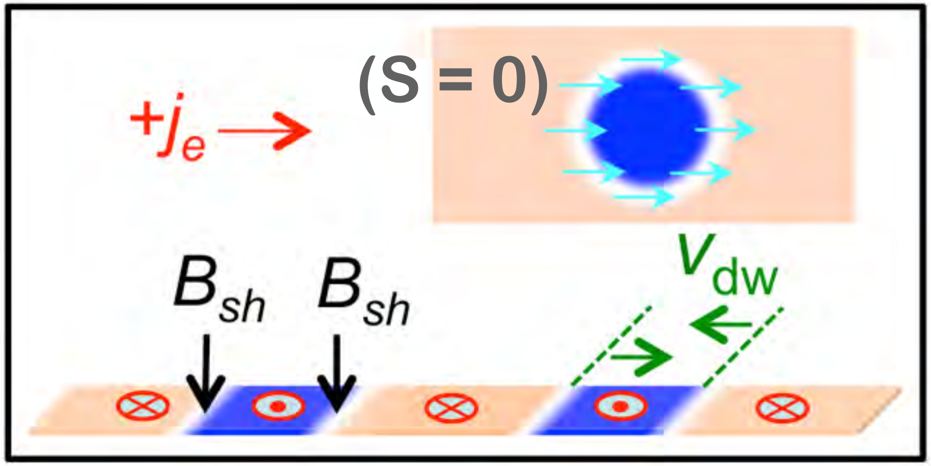


Skyrmion generation is robust
Spatially divergent currents are the key

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

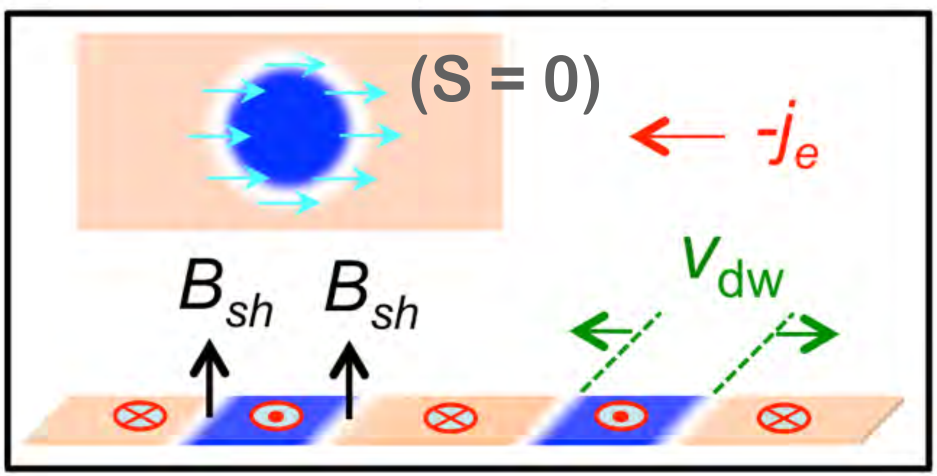
TOPOLOGICALLY TRIVIAL BUBBLES

(S = 0) bubble stabilized by in-plane magnetic fields



$$\vec{B}_{sh} = B_{sh}^0\left(\hat{m}\times(\hat{z}\times\hat{j}_e)\right)$$

Shrinking



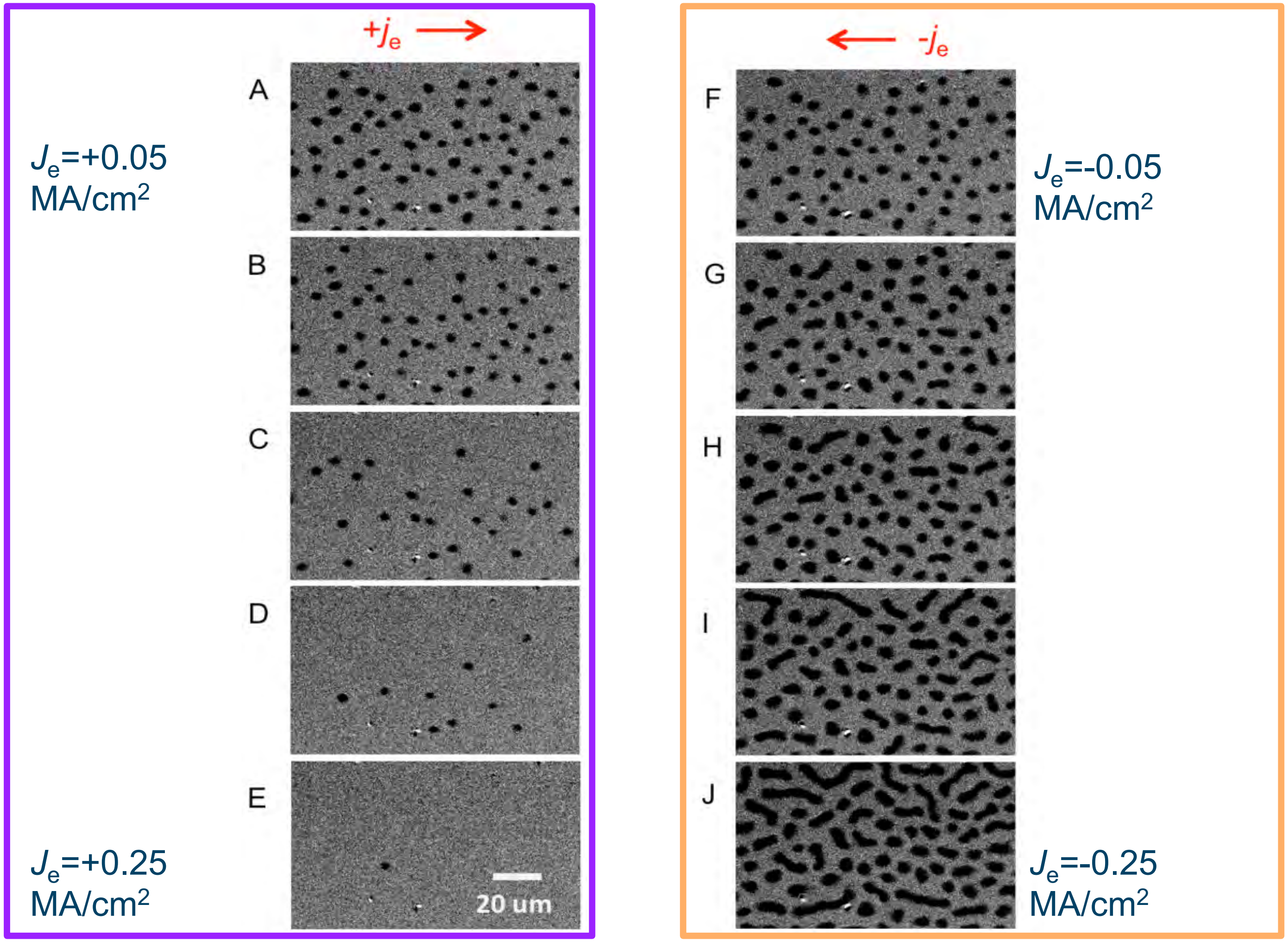
Expansion

J. Choi, et al., PRL (2007)
O. Lee et al., PRB (2014)
S. Emori, et al., Nat. Mater. (2013)
K.-S. Ryu, et al., Nat. Nano. (2013)
S. Emori, et al., PRB. (2014)

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

RESPONSE TO CURRENTS WITH IN-PLANE MAGNETIC FIELDS

$B_{//}$=10 mT



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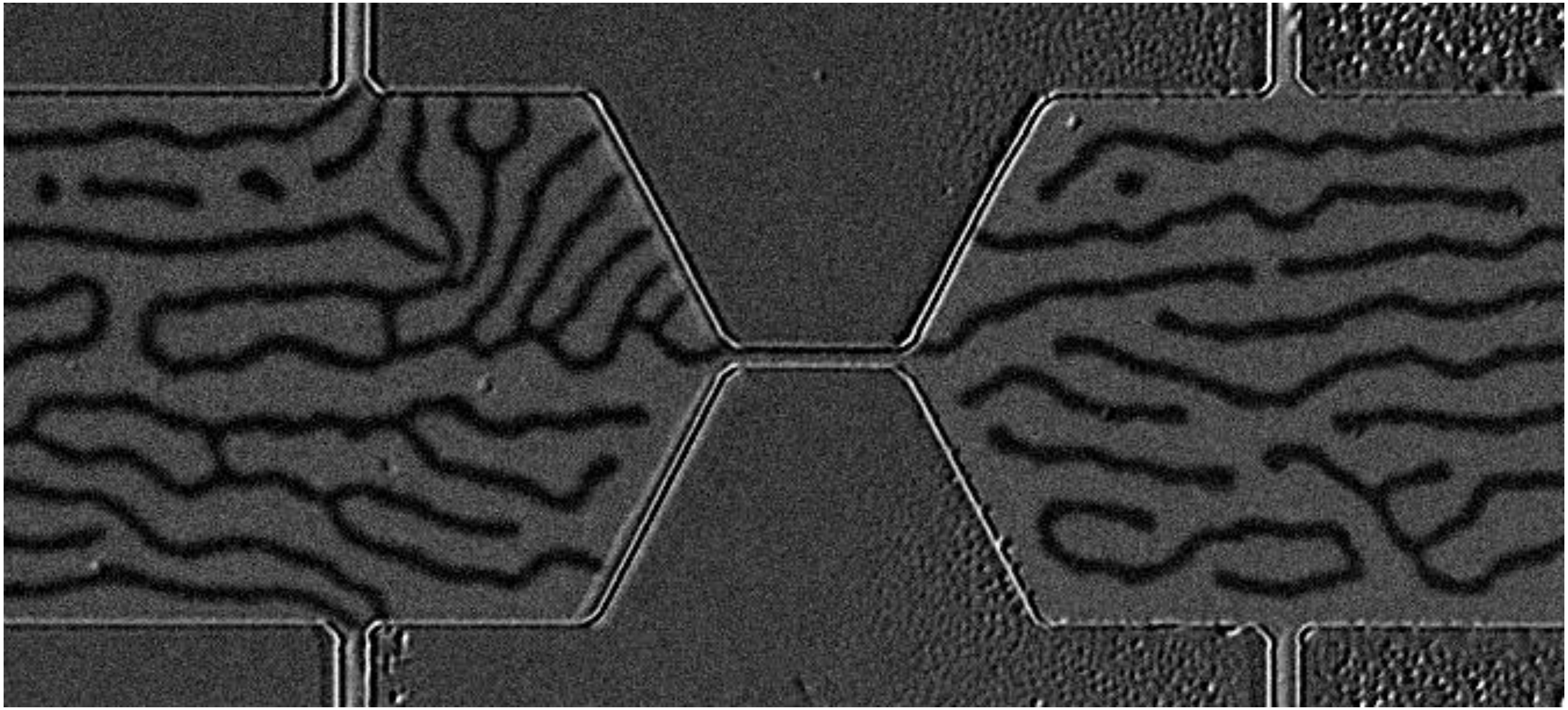
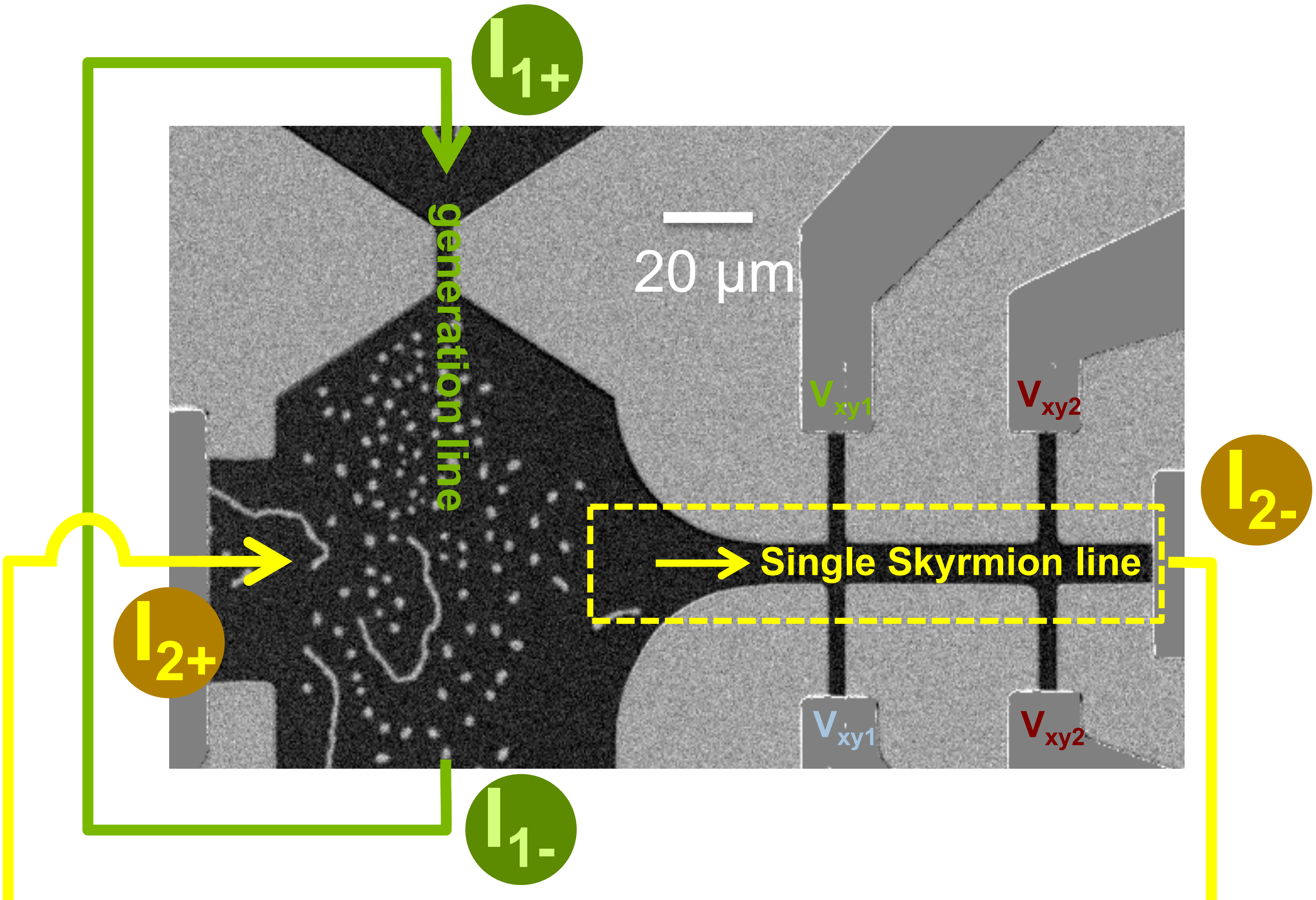
NO BUBBLE FORMATION WITHOUT UNIFORM CHIRALITY

$B_{//} = 5$ mT $J_e = + 0.5$ MA/cm^2



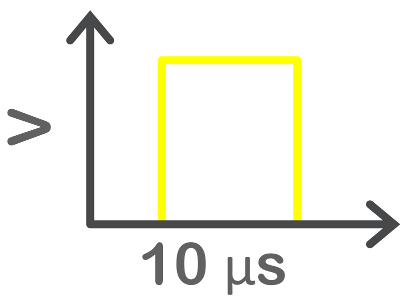
W. Jiang *et al.*, Science **349**, 283 (2015)

INVESTIGATING INDIVIDUAL SKYRMIONS

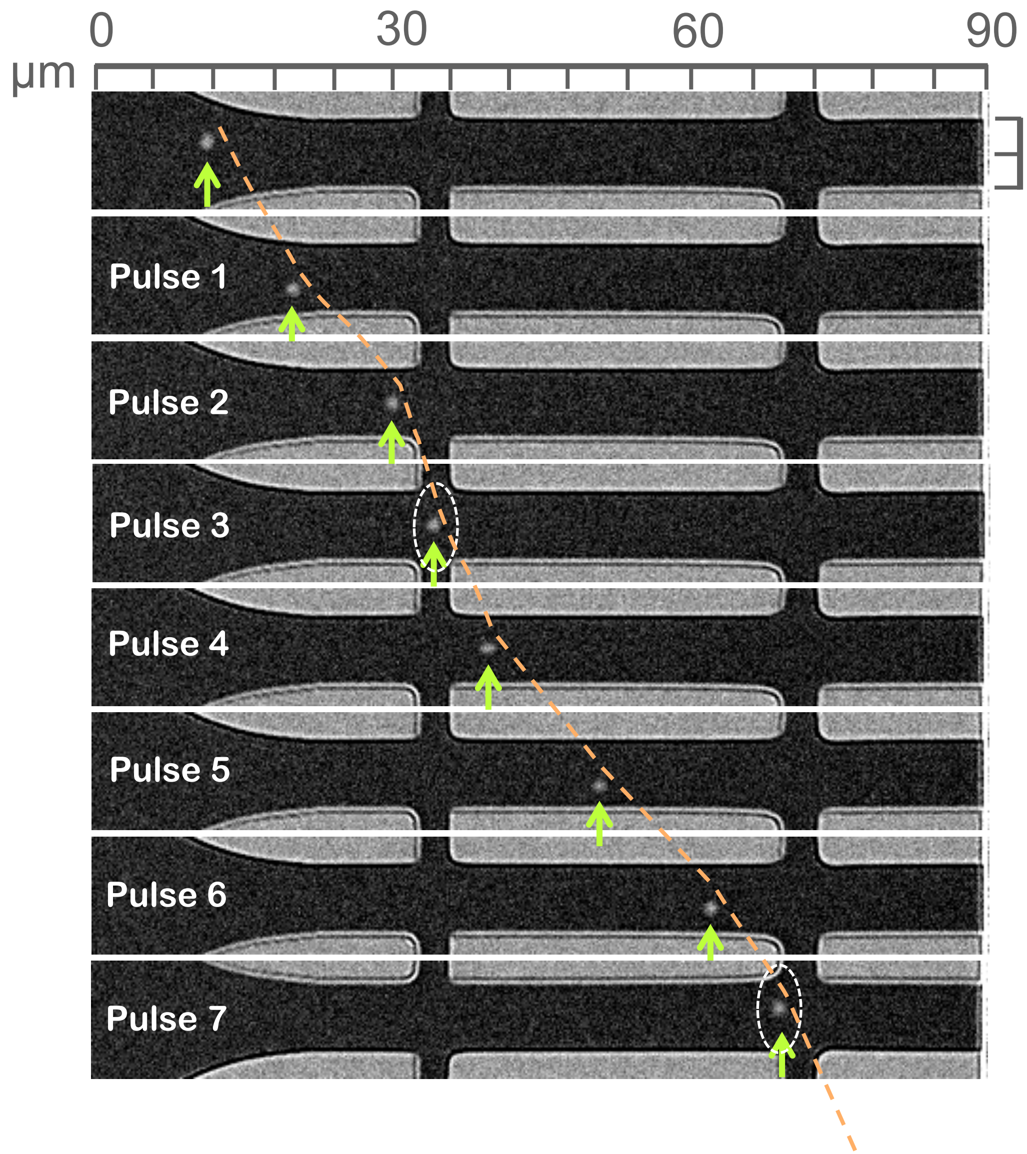


W. Jiang *et al.*, AIP Advances 6, 055602 (2016)

MOTION OF INDIVIDUAL SKYRMIONS



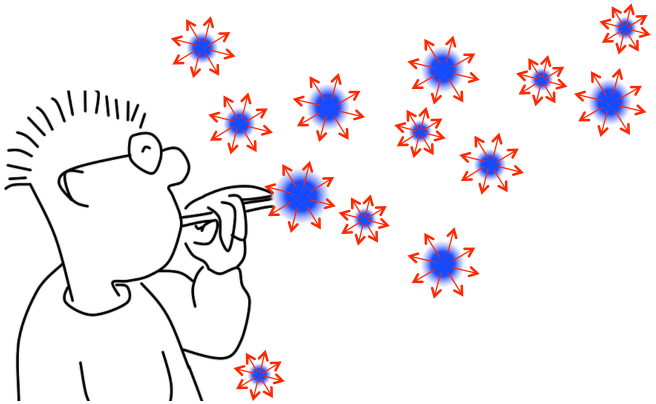
J_e = + 0.5 MA/cm²



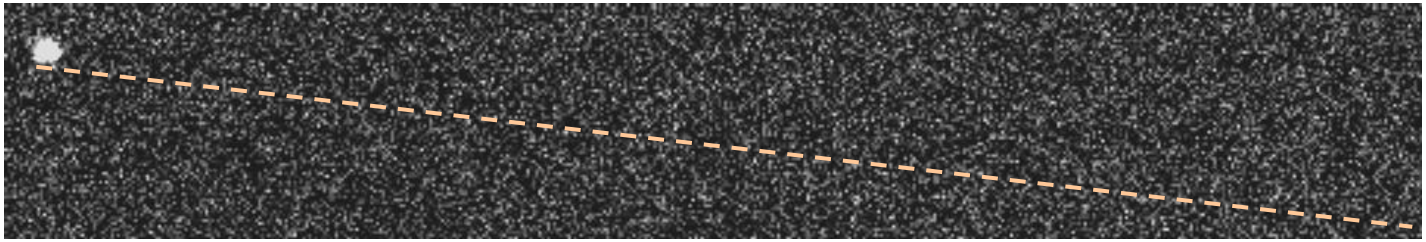
W. Jiang *et al.*, AIP Advances 6, 055602 (2016)

TOPICS

Blowing Magnetic Skyrmion Bubbles



Skyrmion Hall Effect



SKYRMION HALL EFFECT

Classic Hall effect

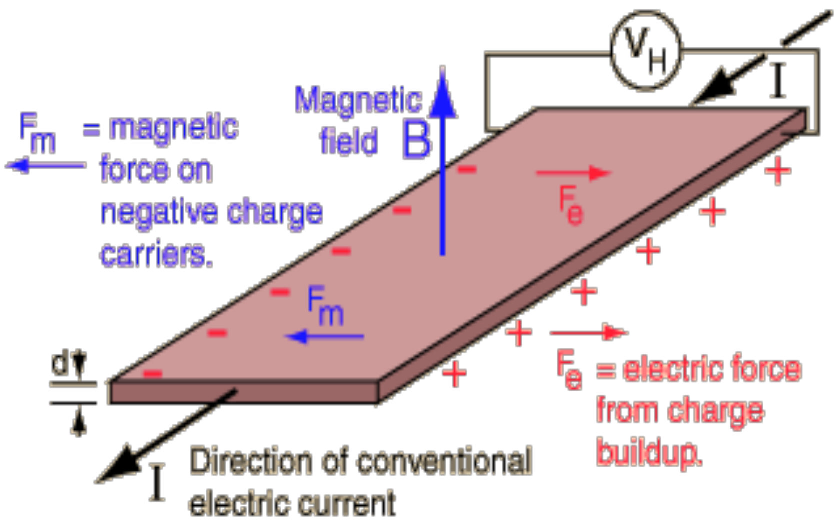
Electric charge q_e

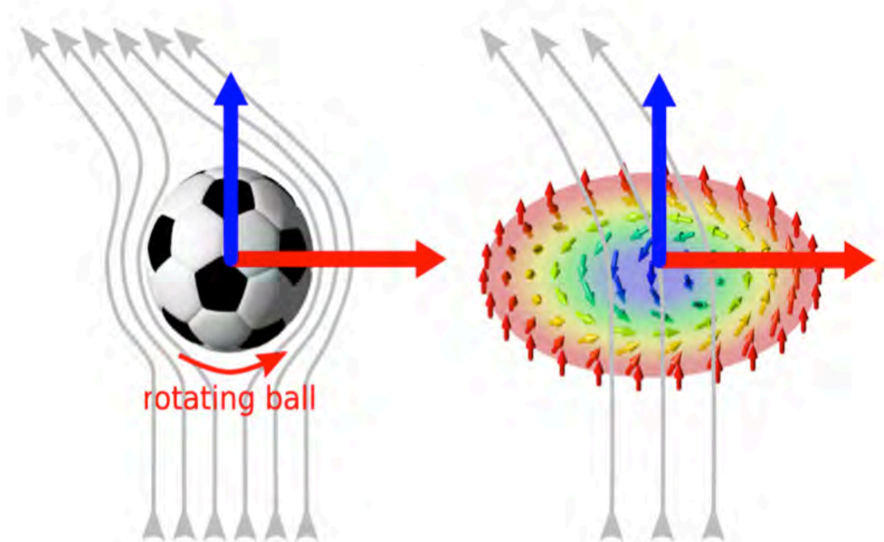
Lorentz force $q_e(v \times B)$

Skyrmion Hall effect

Topological charge q_t

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

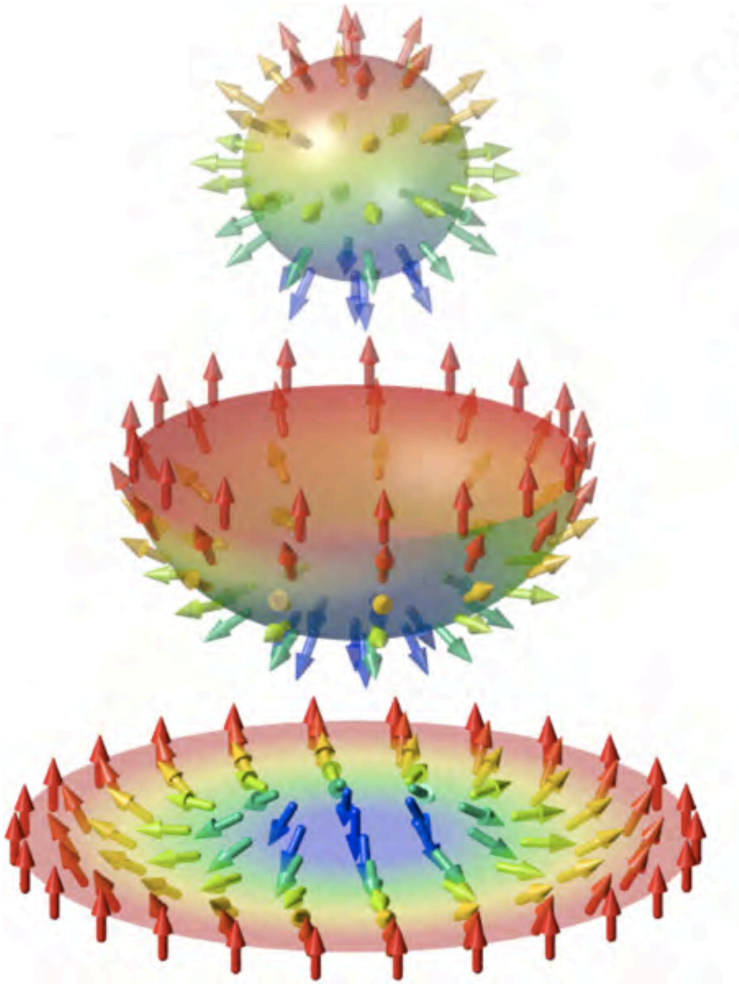




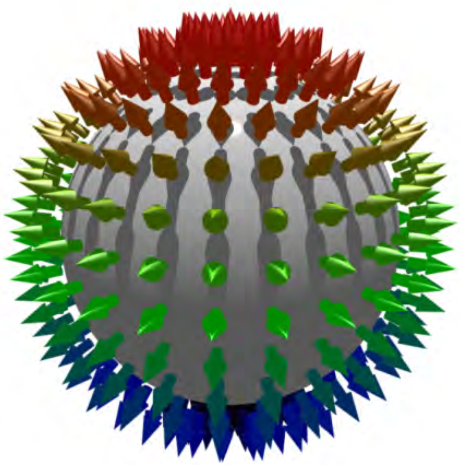
K. Everschor-Sitte and M. Sitte,
J. Appl. Phys. **115**, 172602 (2014)

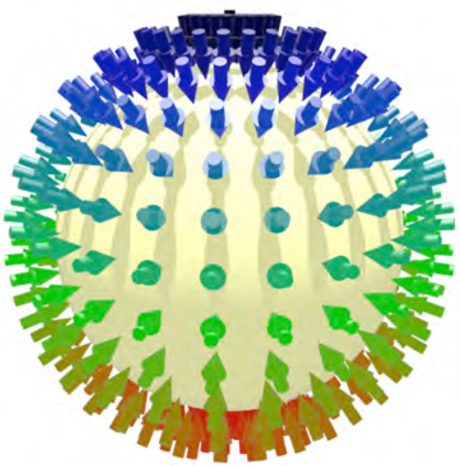
TOPOLOGICAL CHARGE

Is there a Hall effect due to topological charge?



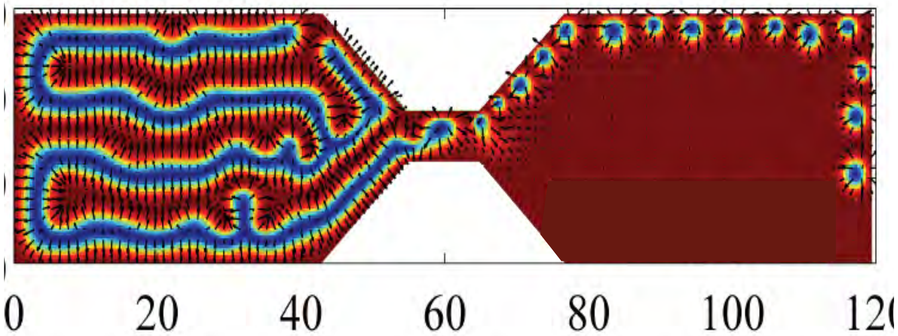
K. Everschor-Sitte and M. Sitte

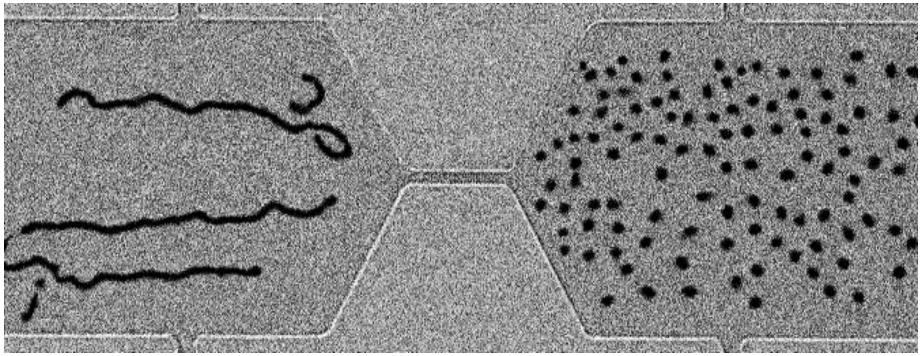




Electrons (-1) / holes (+1)

Skyrmion Hall Effect

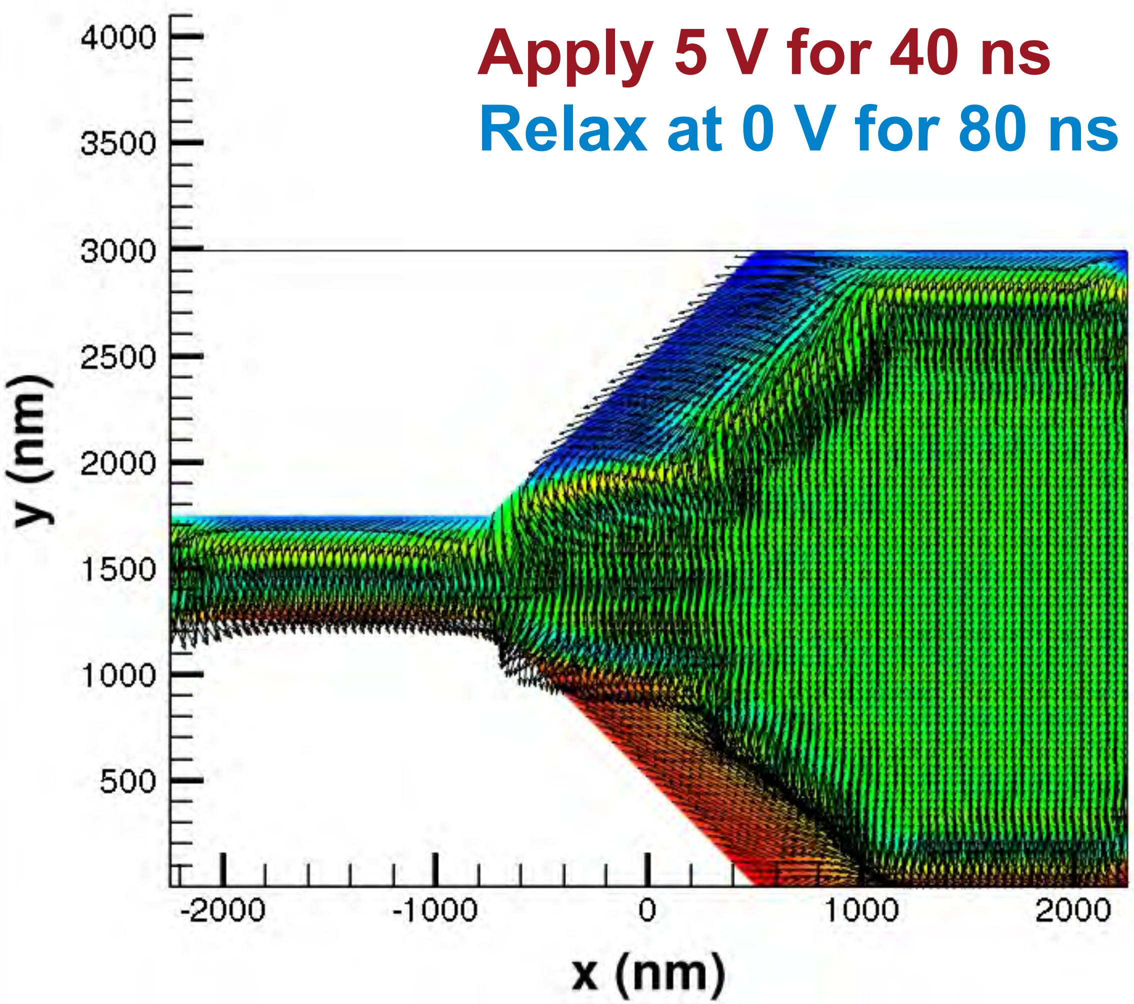




Shi-Zeng Lin, Phys. Rev. B **94**, 020402 (2016)

- Small J ➔ creep motion
- Bigger J ➔ steady motion (inaccessible)
- Complication from inhomogeneous currents

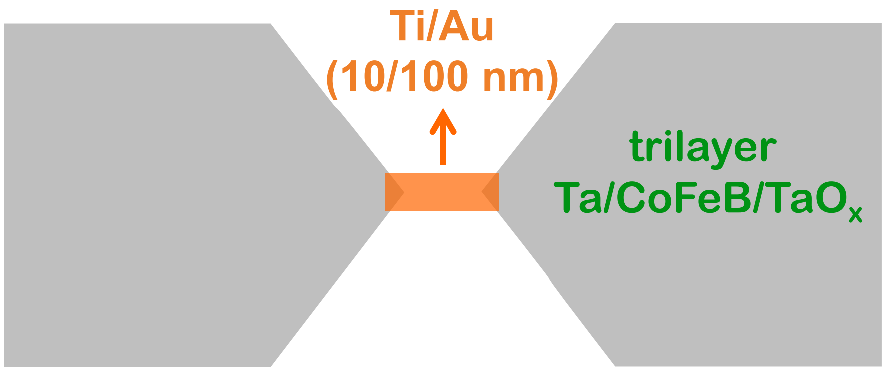
MICROMAGNETIC SIMULATION OF TRANSFORMATION



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%

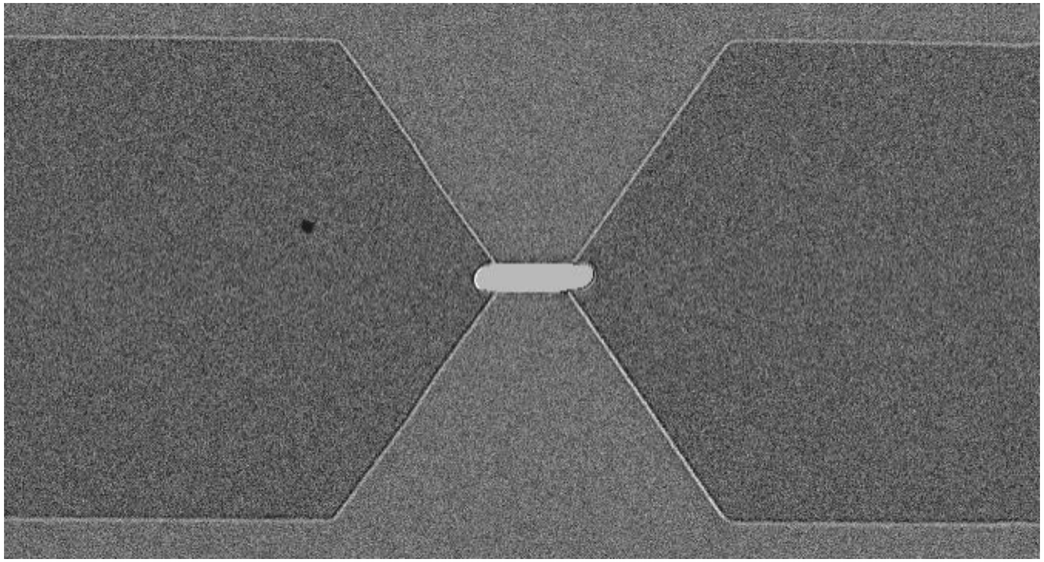
O. Heinonen *et al.*, Phys. Rev. B **93**, 094407 (2016)

CREATION OF SKYRMIONS VIA NONMAGNETIC CONTACTS

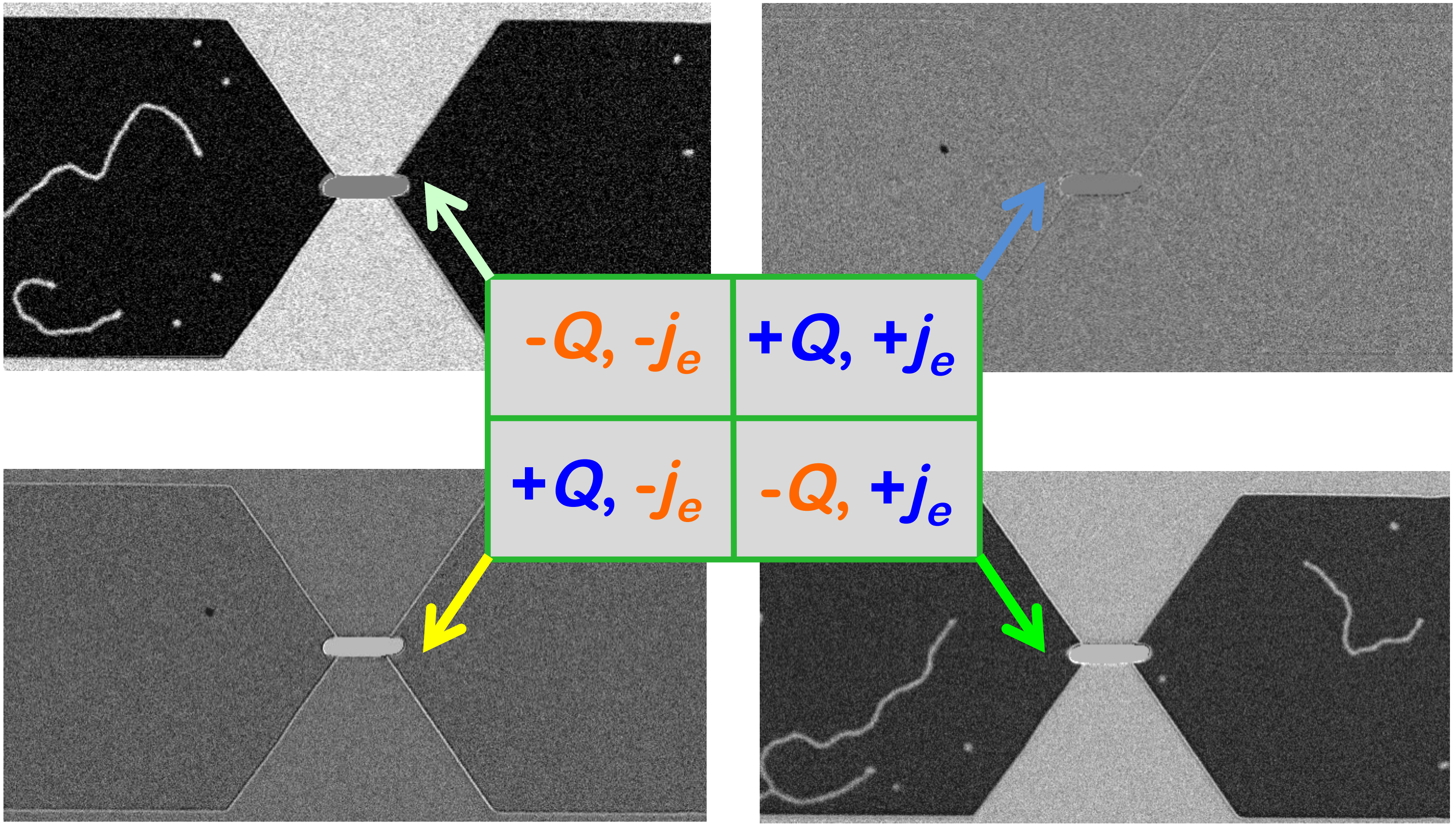


No stripe domains through
No heat involved
Only divergence of current
Requires Larger Currents

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



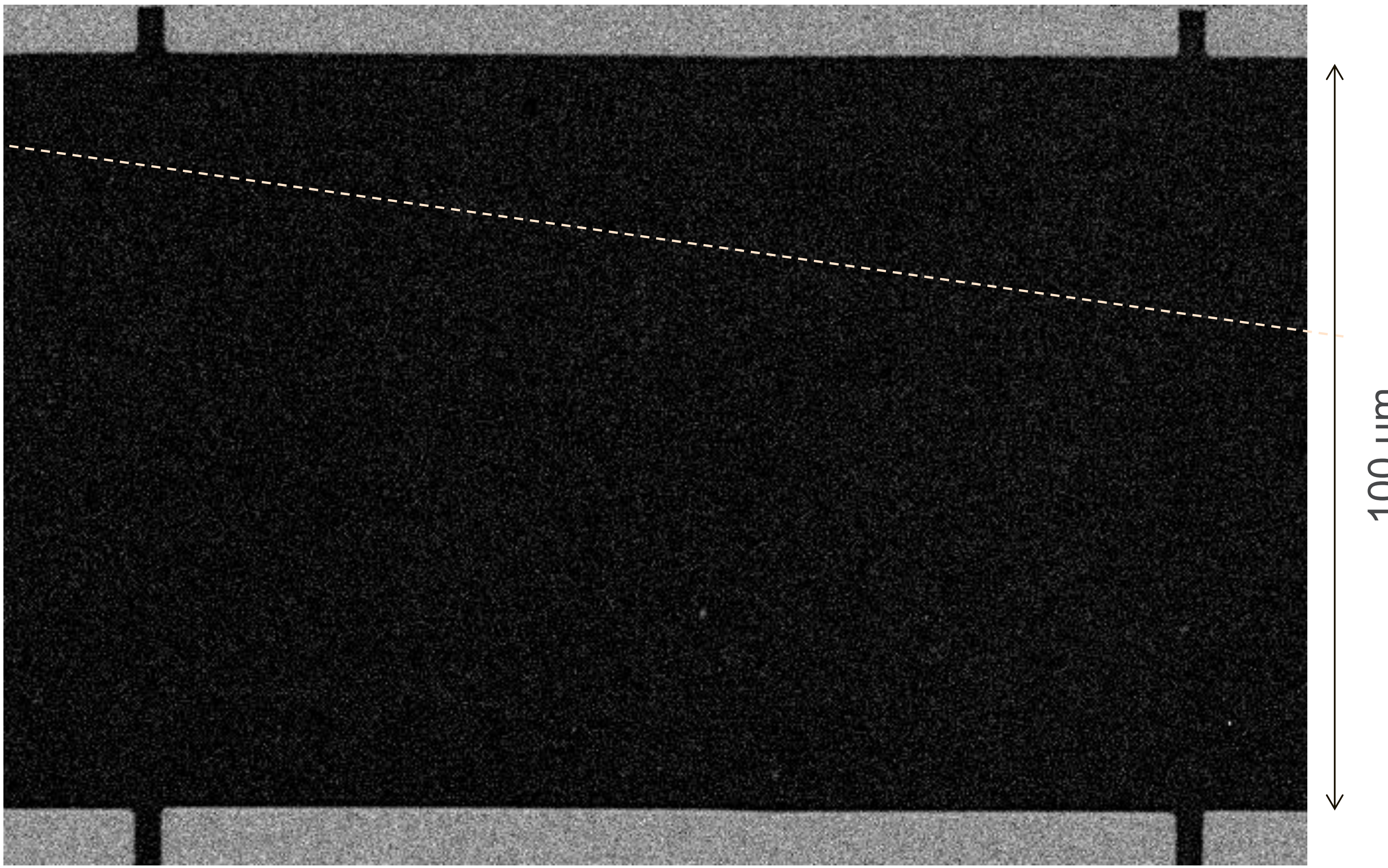
Skyrmion Hall Effect



Topological charge behaves as electronic charge
Skyrmion Hall effect in real space

SKYRMION MOTION WITH HOMOGENEOUS CURRENT

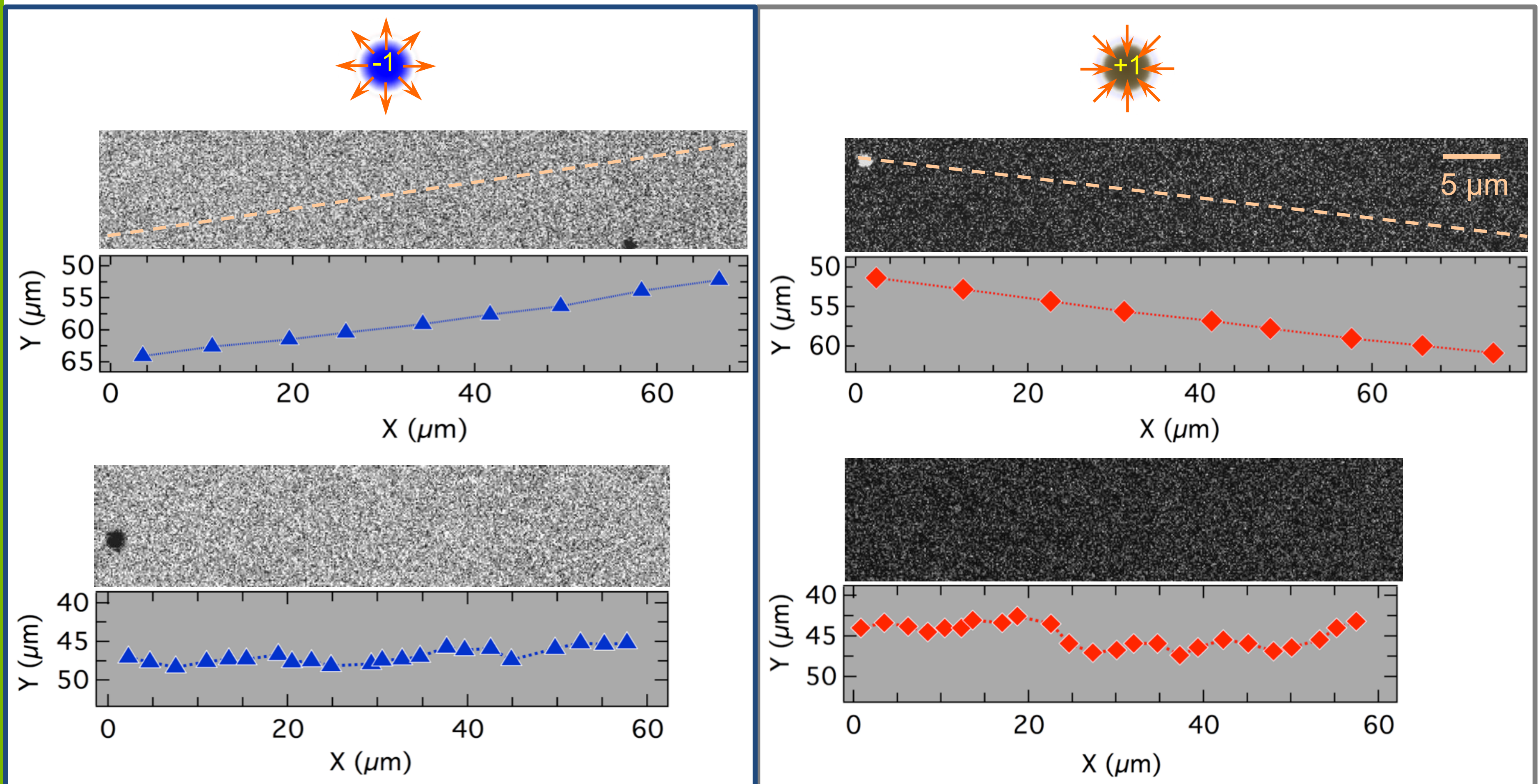
$$j_e = +2.8 \times 10^6 \text{ A/cm}^2$$



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

CURRENT DEPENDENCE OF MOTION

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



$$j_e = +1.3\ \times 10^6\ \mathrm{A/cm^2} \longrightarrow$$

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

EVOLUTION OF VELOCITY/HALL ANGLE ON CURRENTS

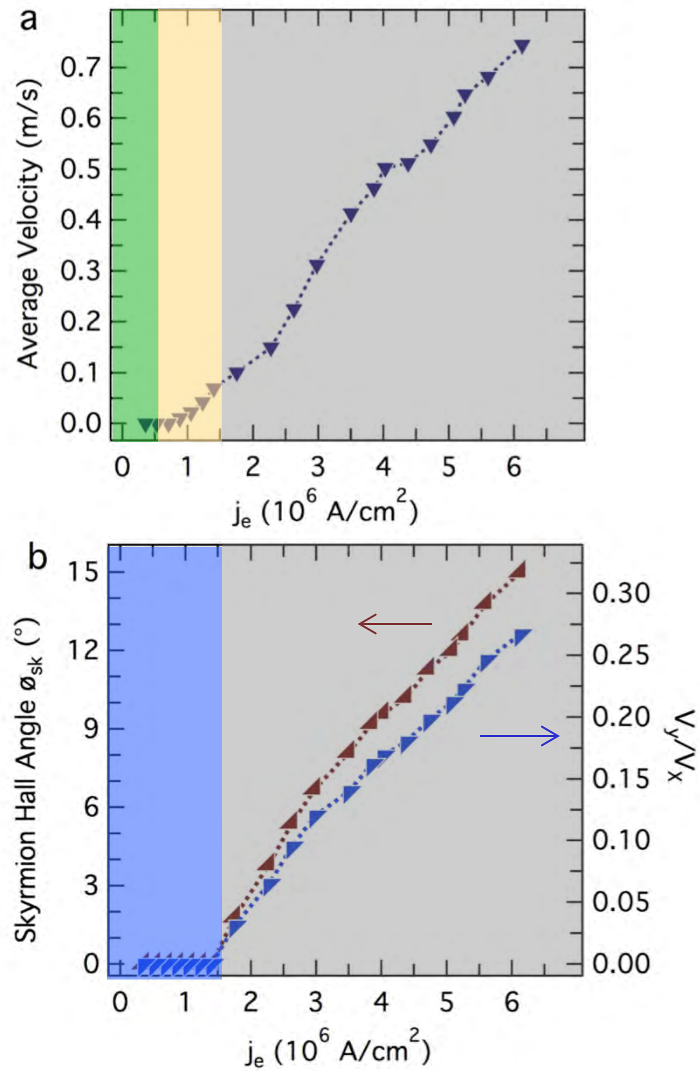
Skyrmion is pinned

(stochastic) hopping

Drive-dependent Skyrmion Hall angle

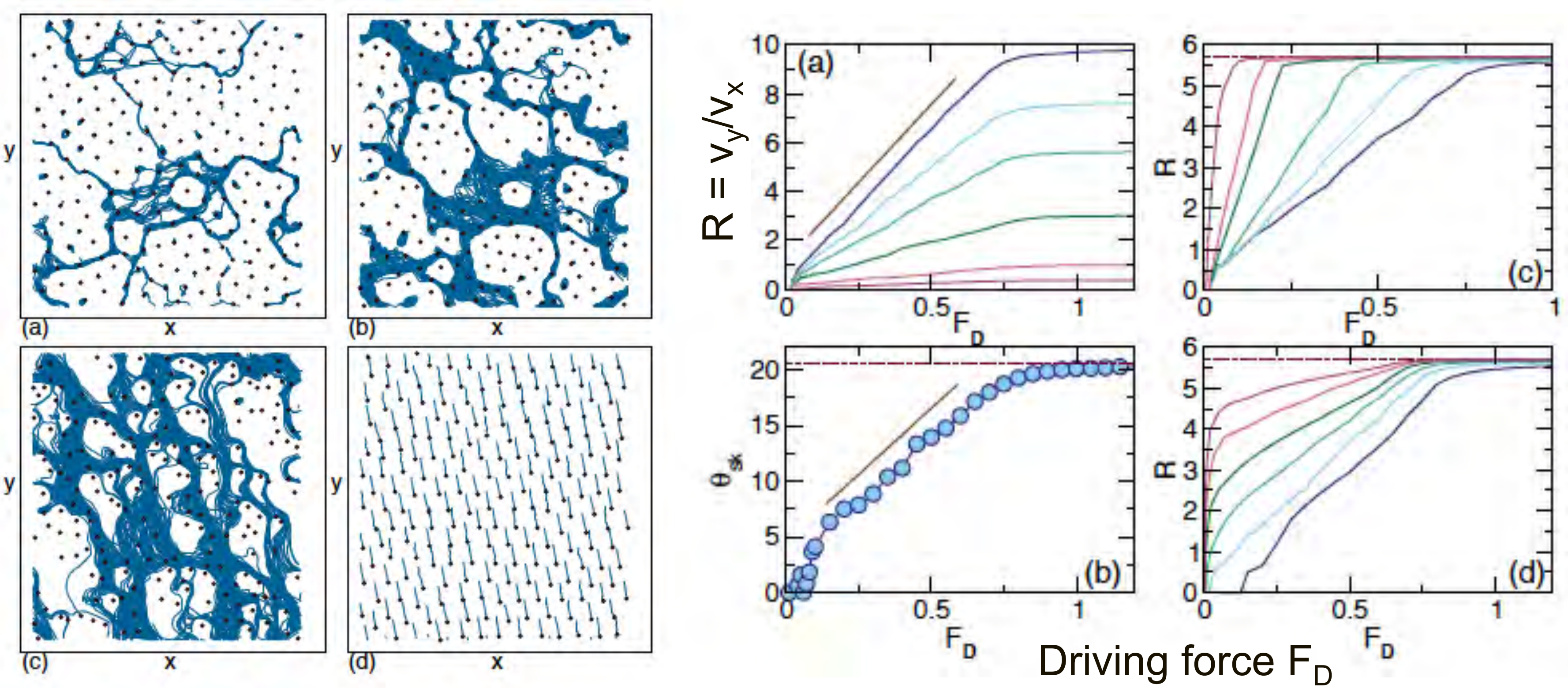
rather than predicted constant value

$$\frac{v_y}{v_x} = \tan\left(\Phi_{sk}\right) = \frac{1}{\alpha D}$$



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

PARTICLE-BASED SIMULATION MODEL

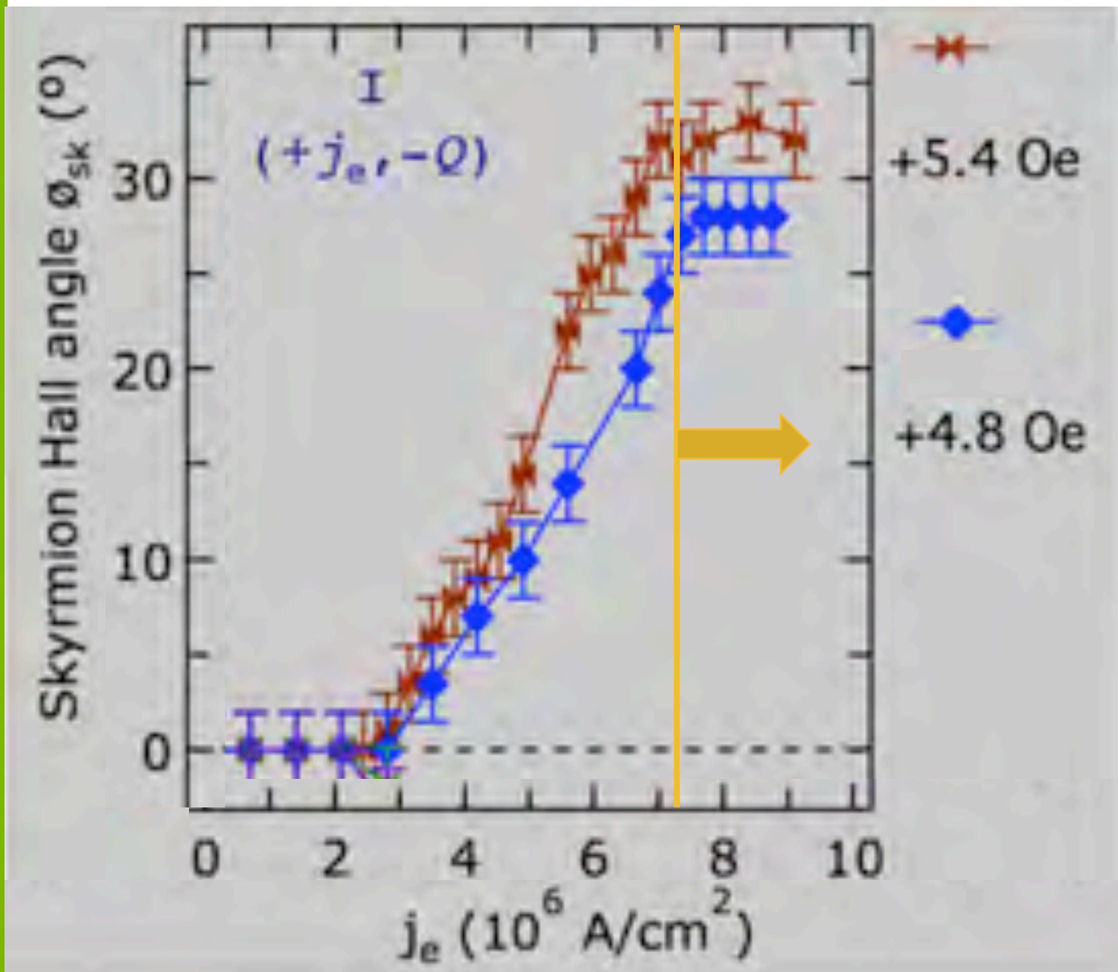


- For small intrinsic Hall angles, the Hall angle increases linearly with external drive.

- At sufficiently high drives, the skyrmions enter a free flow regime,
  => *R* saturates to the disorder-free limit.

C. Reichhardt and C. J. Olson Reichhardt, New Journal of Physics, 18 (2016)

DRIVE-DEPENDENT SKYRMION HALL ANGLE



Skyrmion Hall angle eventually

Flow regime is reached

$H = 5.4$ Oe, $d = 800 \pm 300$ nm

$$\Phi_{sk} = 32 \pm 2^{\circ}$$

$H = 4.8$ Oe, $d = 1100 \pm 300$ nm

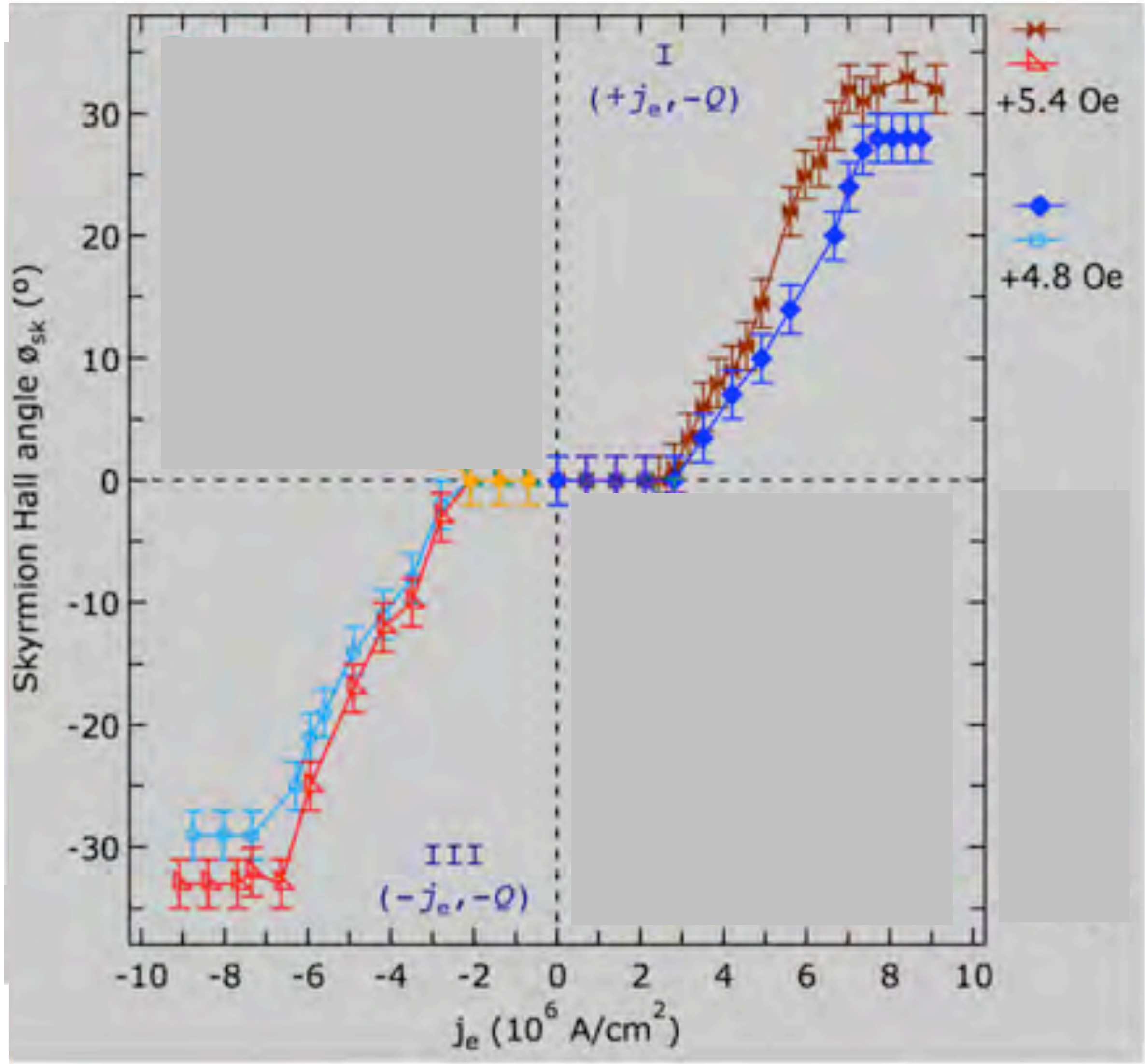
$$\Phi_{sk} = 28 \pm 2^{\circ}$$

Final Skyrmion Hall angle depends on the skyrmion size

field

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

DRIVE-DEPENDENT SKYRMION HALL ANGLE

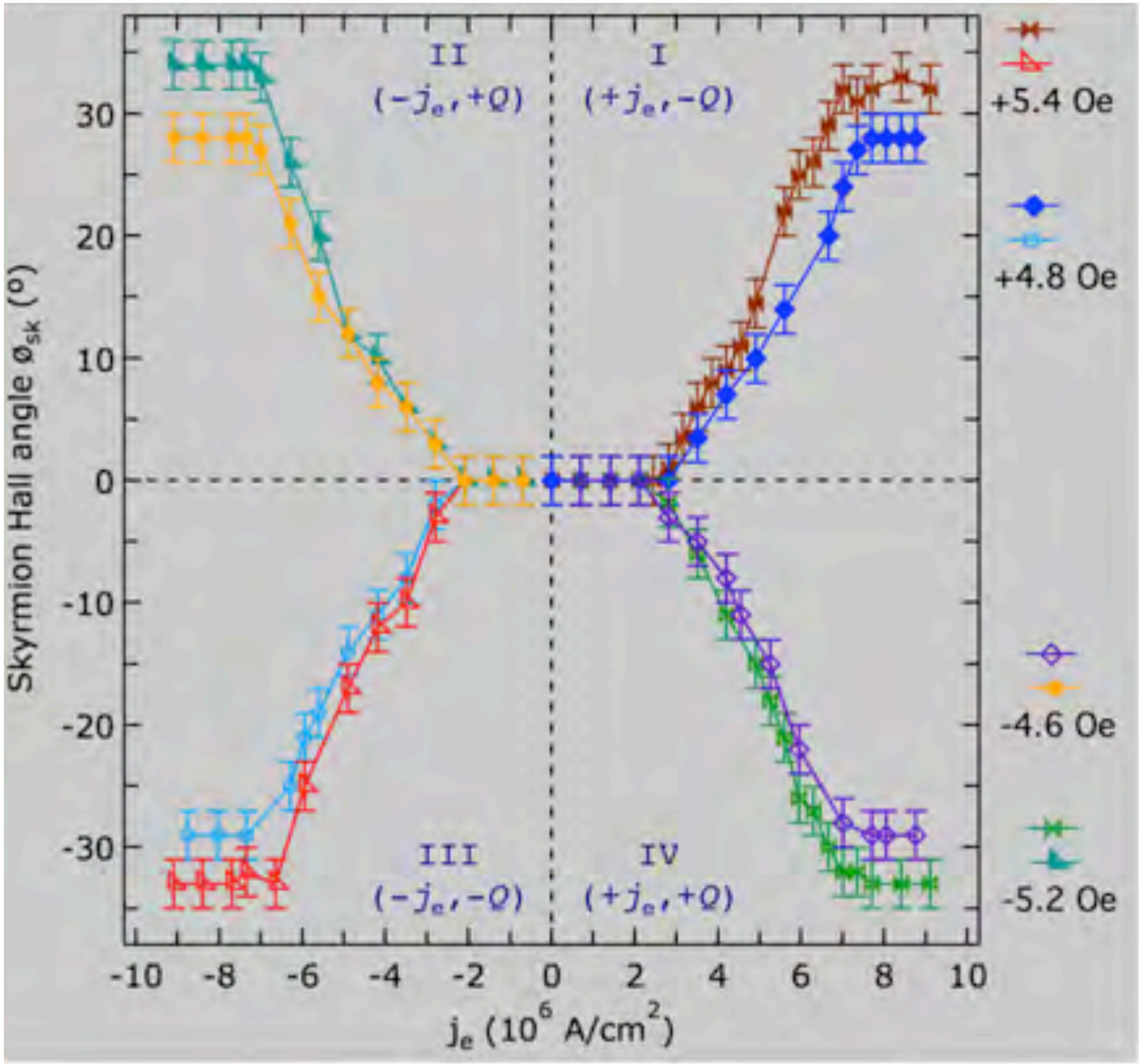


The sign of the Skyrmion Hall angle changes with

- **Current direction**

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

DRIVE-DEPENDENT SKYRMION HALL ANGLE



The sign of the Skyrmion Hall angle changes with

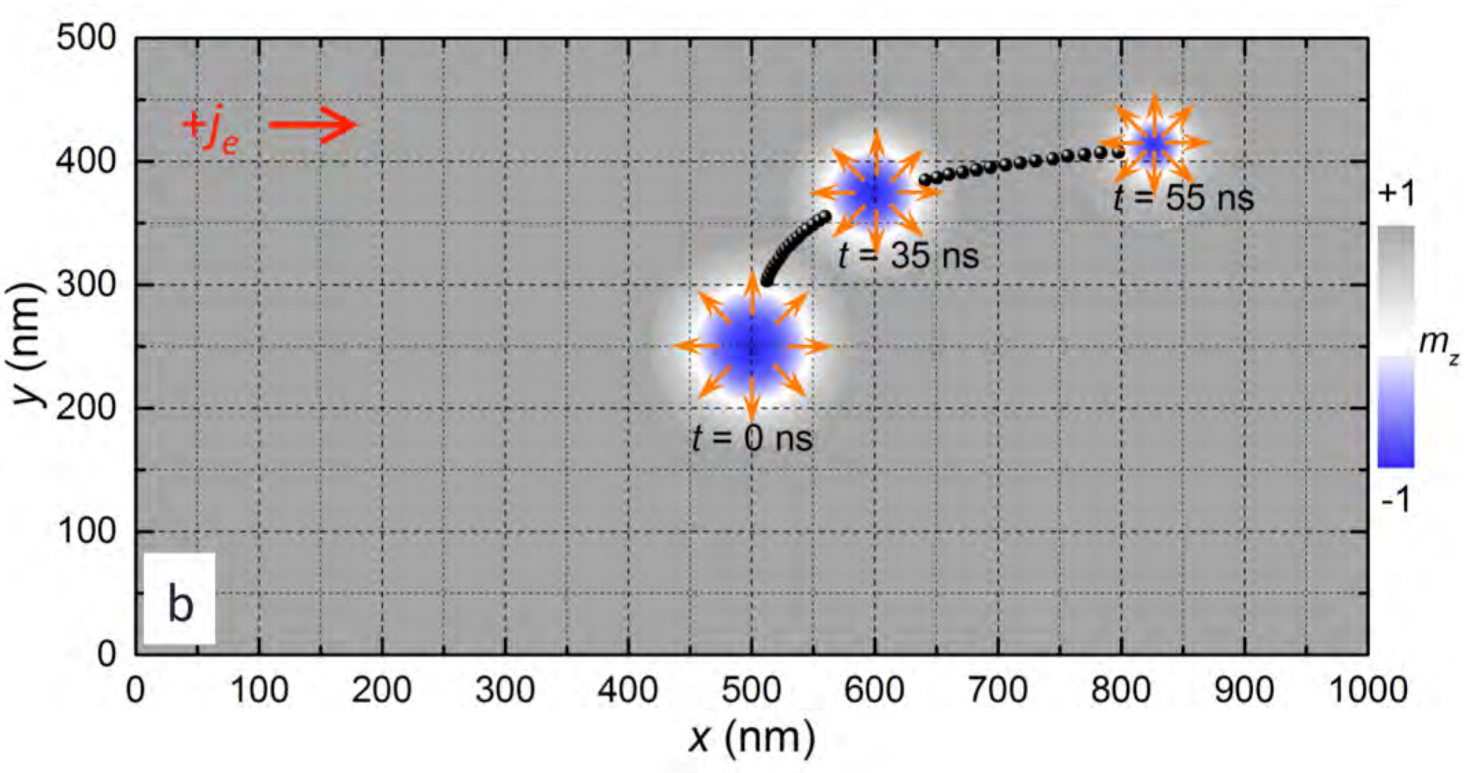
- Current direction
- Topological charge Q

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

SKYRMION HALL EFFECT

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

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

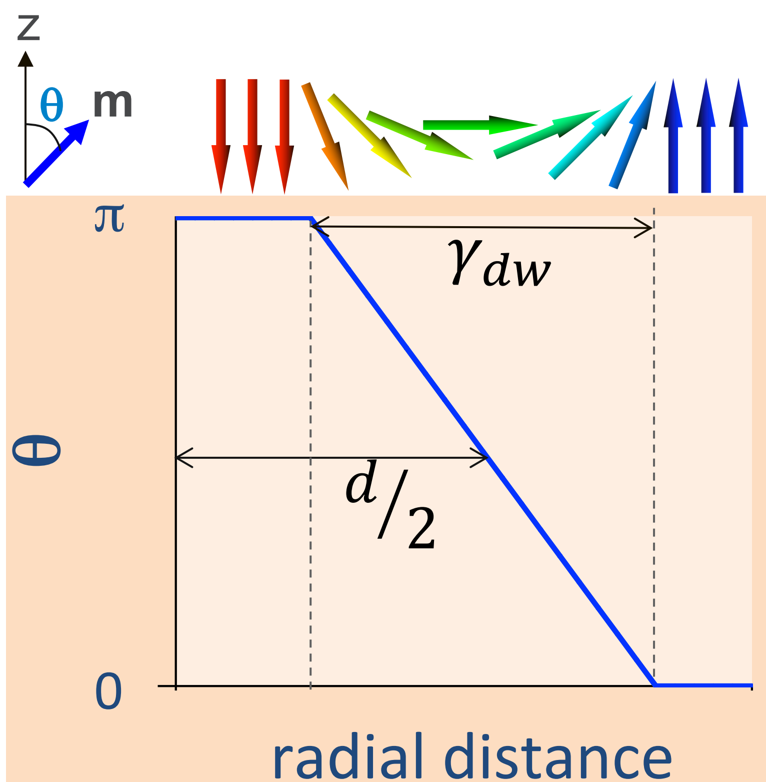


$$\frac{v_y}{v_x} = \frac{1}{\alpha D}$$

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

DISSIPATIVE FORCE TERM – ISOLATED SKYRMIONS

$$\overleftrightarrow{\mathcal{D}} = 4\pi \begin{pmatrix} \mathcal{D}_{ii} & \mathcal{D}_{ij} \\ \mathcal{D}_{ji} & \mathcal{D}_{jj} \end{pmatrix} \quad \mathcal{D} = \boldsymbol{\mathcal{D}_{ij}} = \frac{\mathbf{1}}{\mathbf{4\pi}} \int_{\textbf{unit cell}} \frac{\boldsymbol{\partial} \mathbf{m}}{\boldsymbol{\partial i}} \cdot \frac{\boldsymbol{\partial} \mathbf{m}}{\boldsymbol{\partial j}} \boldsymbol{dxdy}$$



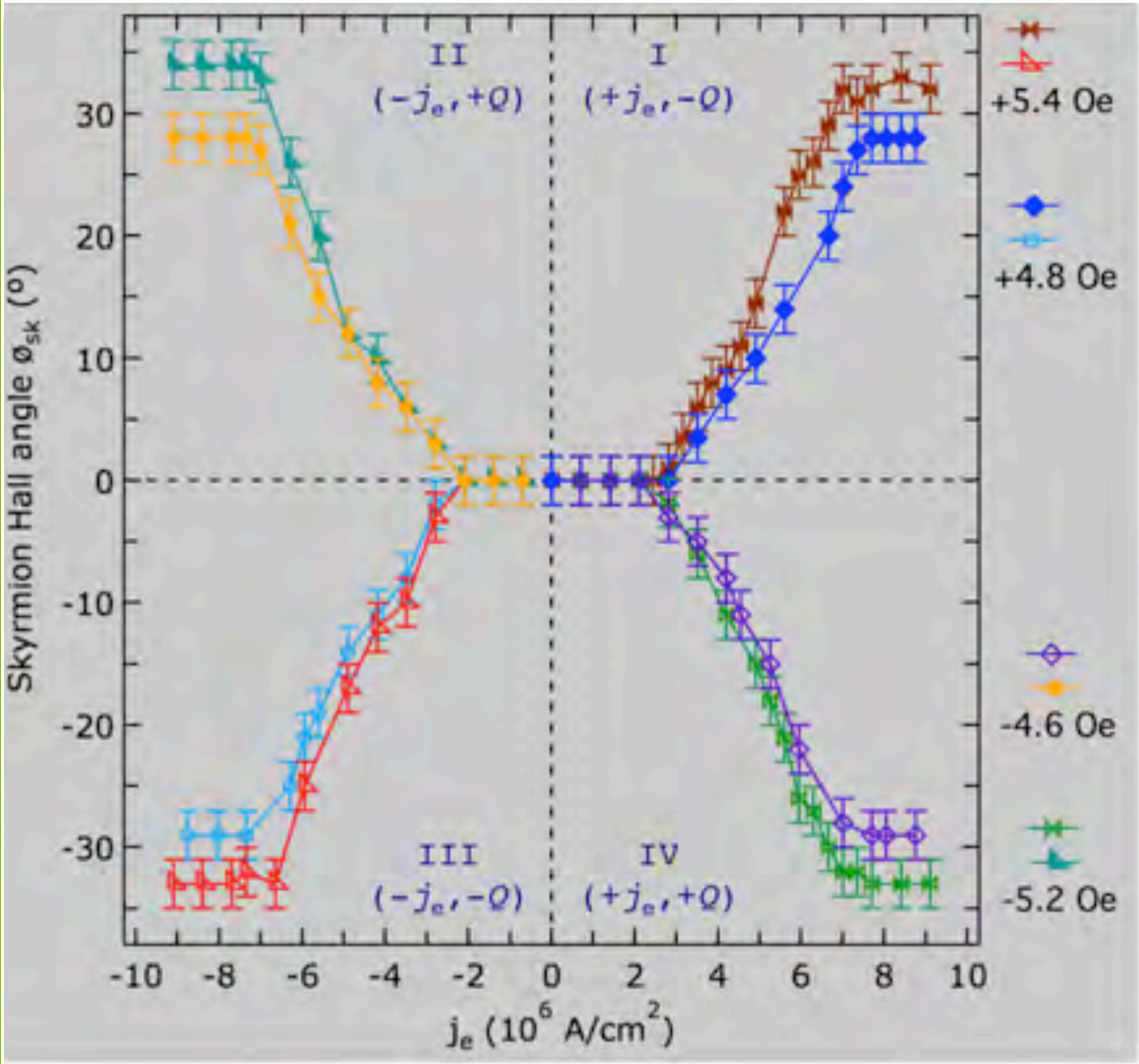
$$\mathcal{D} = \frac{\pi^2 d}{8\gamma_{dw}}$$

d	γ_{dw}	D	v_y/v_x	Φ_{sk}
10 nm	10 nm	1.2	40	89°
100 nm	10 nm	12	4	76°
1000 nm	10 nm	123	0.4	22°

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

Argonne NATIONAL LABORATORY

DRIVE-DEPENDENT SKYRMION HALL ANGLE



$\gamma_{dw} \approx \sqrt{A/K_{eff}} \approx 21$ nm

$\alpha \approx 0.02$

$H = 5.4$ Oe, $d = 800 \pm 300$ nm

$\Phi_{sk} = 32 \pm 2^{\circ}$

$\Phi_{sk} \approx 47 \pm 11^{\circ}$

$H = 4.8$ Oe, $d = 1100 \pm 300$ nm

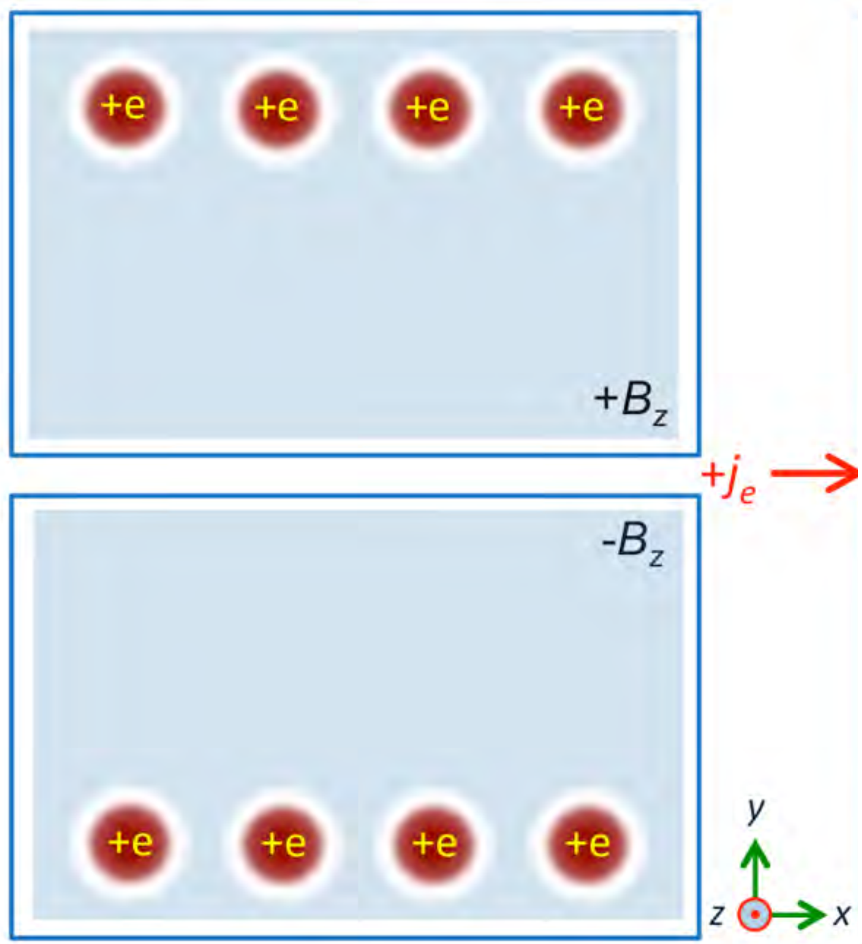
$\Phi_{sk} = 28 \pm 2^{\circ}$

$\Phi_{sk} \approx 38 \pm 8^{\circ}$

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

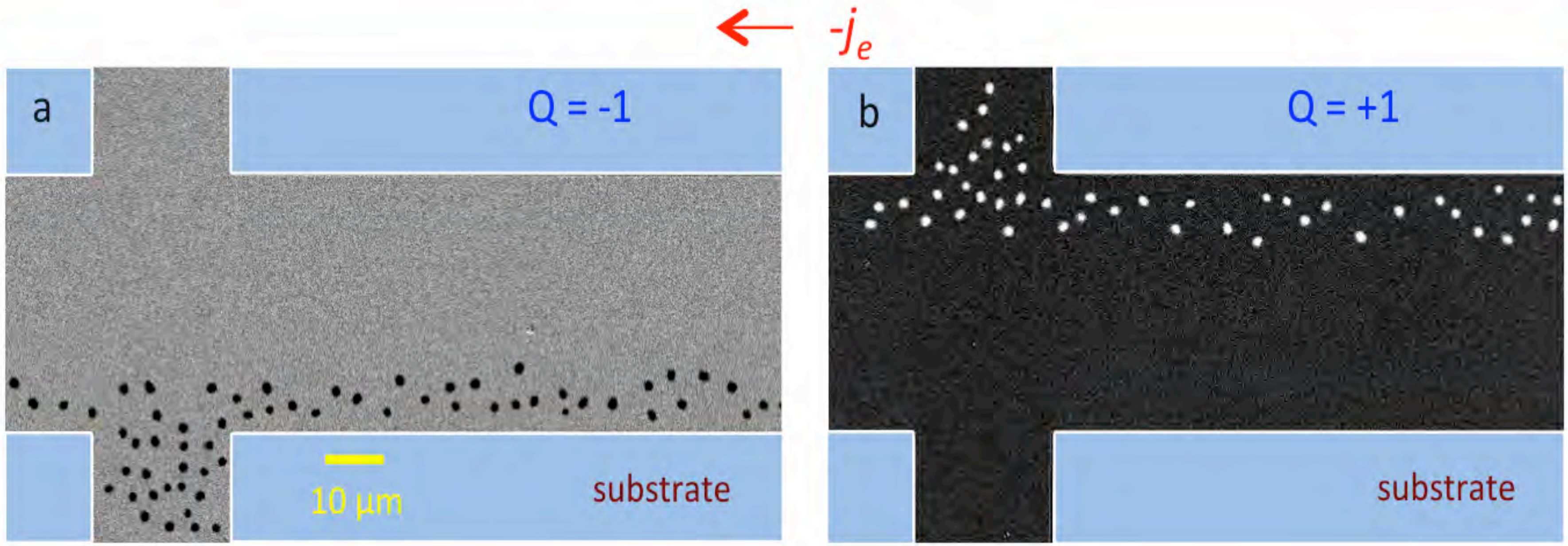
Classic Hall effect
Electric charge q_e
Lorentz force

Skyrmion Hall effect
Topological charge Q
Magnus force



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

SKYRMION ACCUMULATION

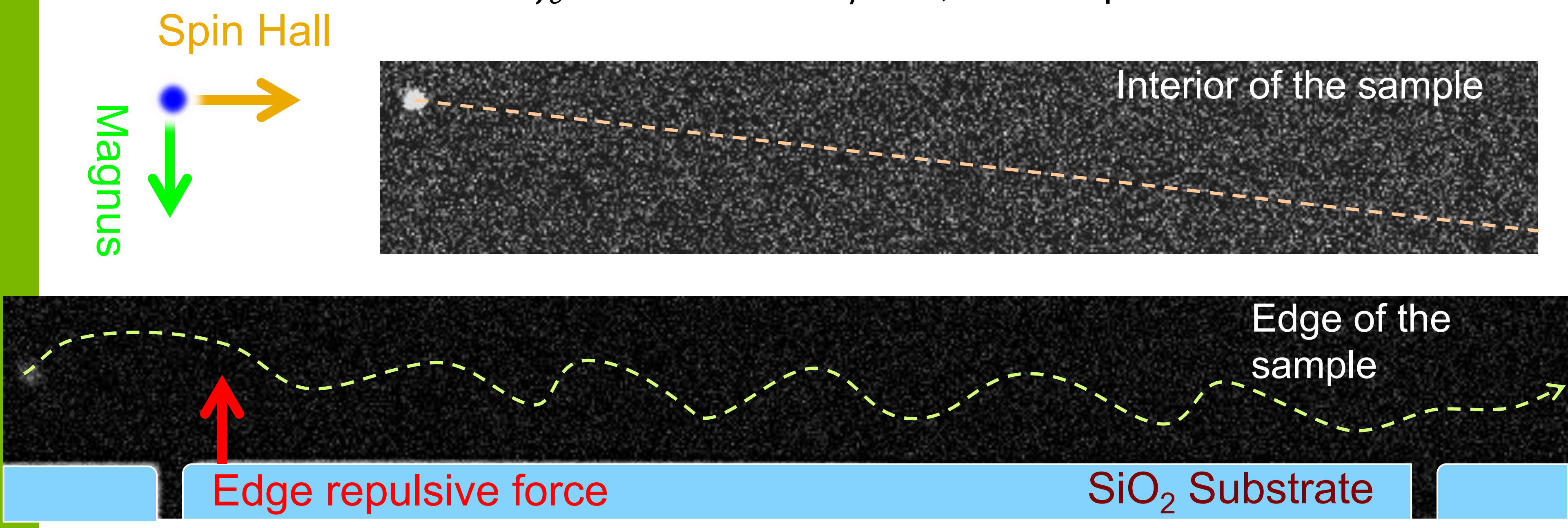


Accumulation of skrymions along one wire edge is observed.

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

SKYRMION MOTION: EDGE VS. INTERIOR

$j_e = +2.8 \times 10^6\ \mathrm{A/cm^2}$, Δt = 50 μs

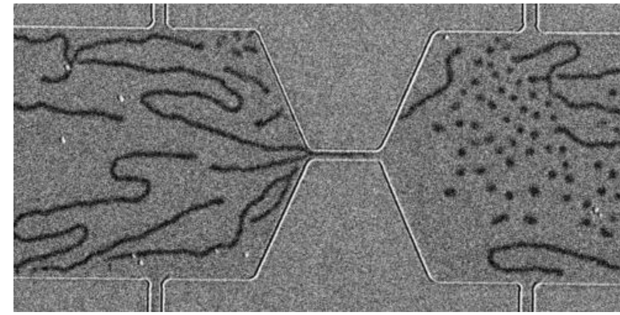


Oscillatory skyrmion edge transport: Competition between edge repulsive force and magnus force

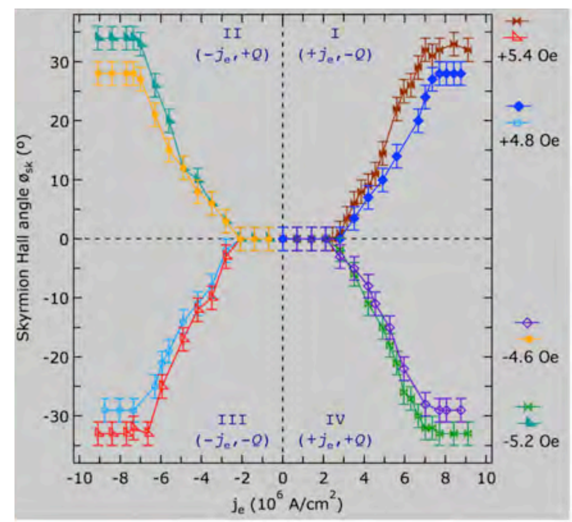
W. Jiang *et al.*, Nature Physics 13, **162** (2017)

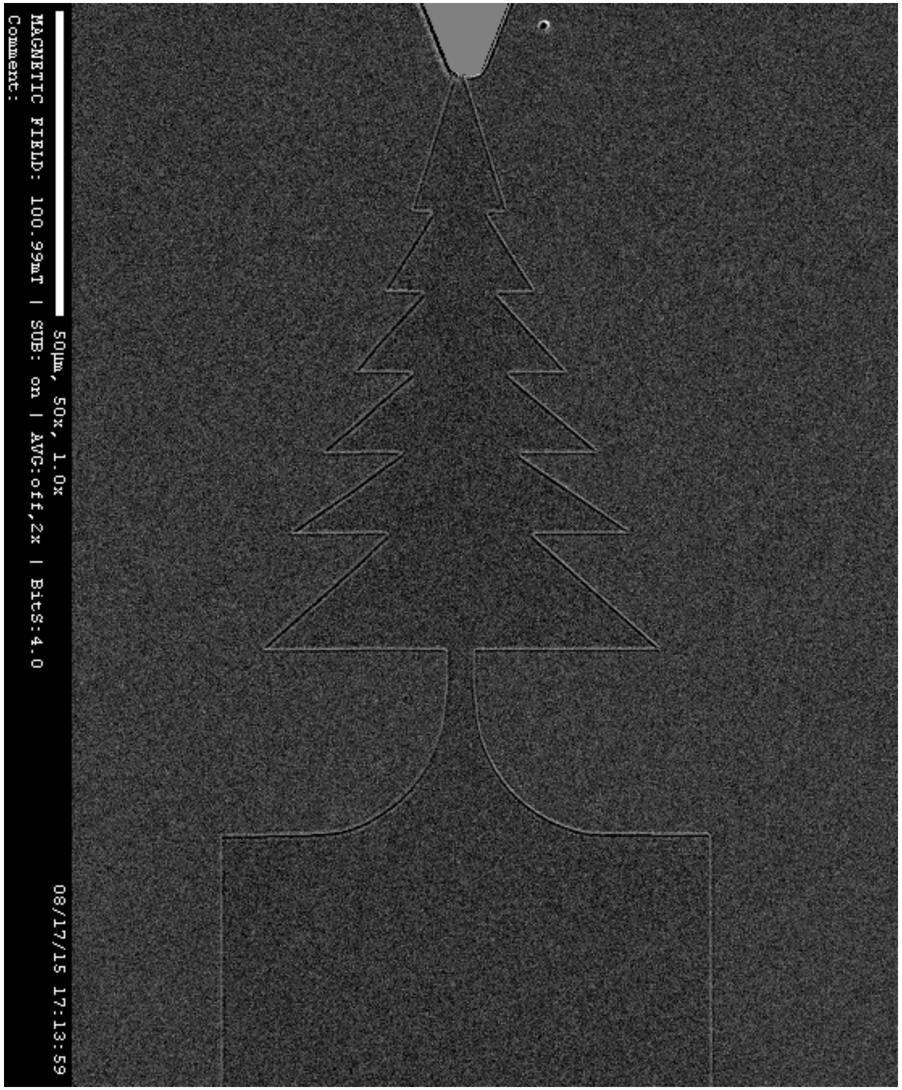
CONCLUSIONS

- Magnetic Skyrmions at RT
  - Use inhomogeneous currents for generating skyrmions



- Skyrmion Hall Effect
  - **Low current**: Linear dependence of skrymion Hall angle (creep regime).
  - **High current**: Saturation of skyrmion Hall angle (flow regime).
  - Magnitude of skyrmion Hall angle Φ_{sk} consistent with size of skyrmion.
  - Sign of Φ_{sk} changes with sign of Q.





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