Room Temperature Magnetic Skyrmions Imaged by Transmission X-Ray Microscopy

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Stefan Eisebitt

Brookhaven National Laboratory – MIT Workshop on Synchrotron Science

July 25, 2017

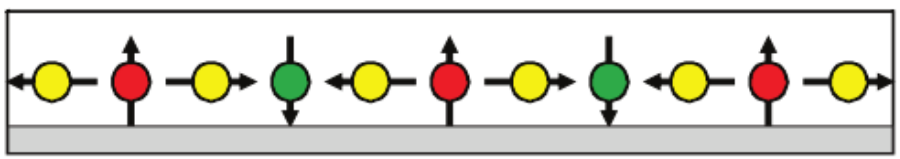
Chiral Exchange & Magnetic Skyrmions

Heisenberg Exchange:

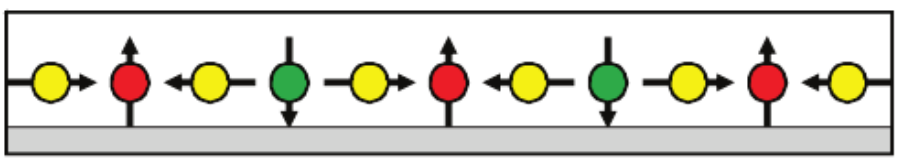
$$E_H = -\sum_{i,j} J_{ij}(\boldsymbol{S}_i \cdot \boldsymbol{S}_j)$$

Dzyaloshinskii-Moriya Interaction:

$$E_{DMI} = -\sum_{i,j} \boldsymbol{D}_{ij} \cdot (\boldsymbol{S}_i \times \boldsymbol{S}_j)$$

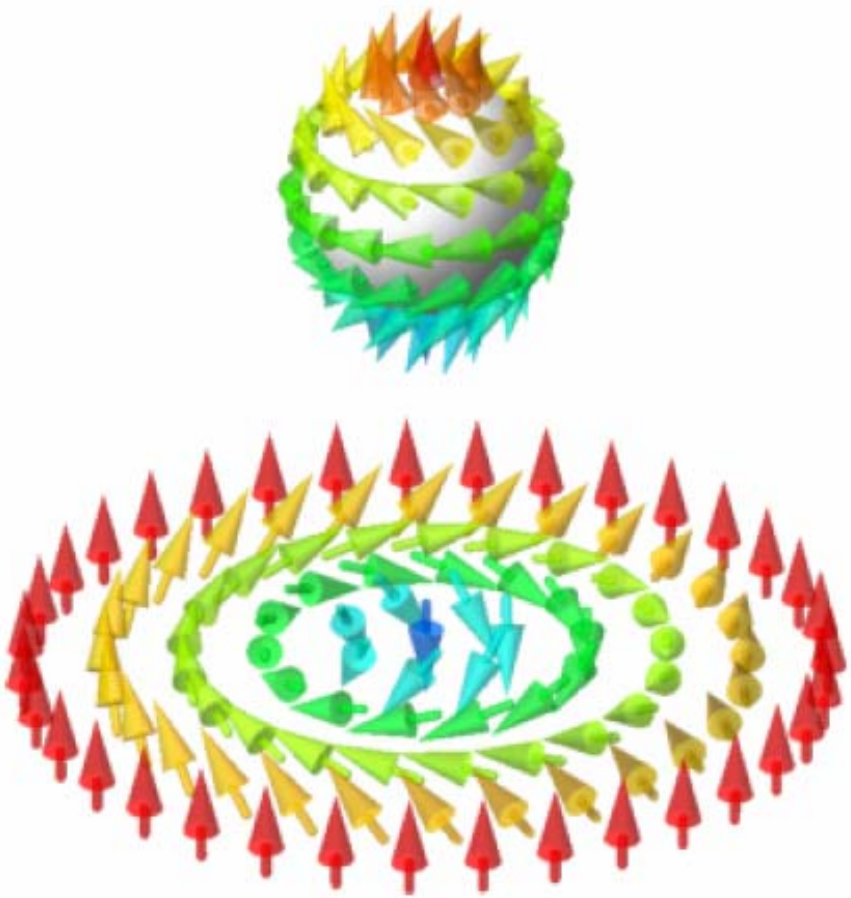


spin spiral with unique rotational sense



spin spiral with opposite rotational sense

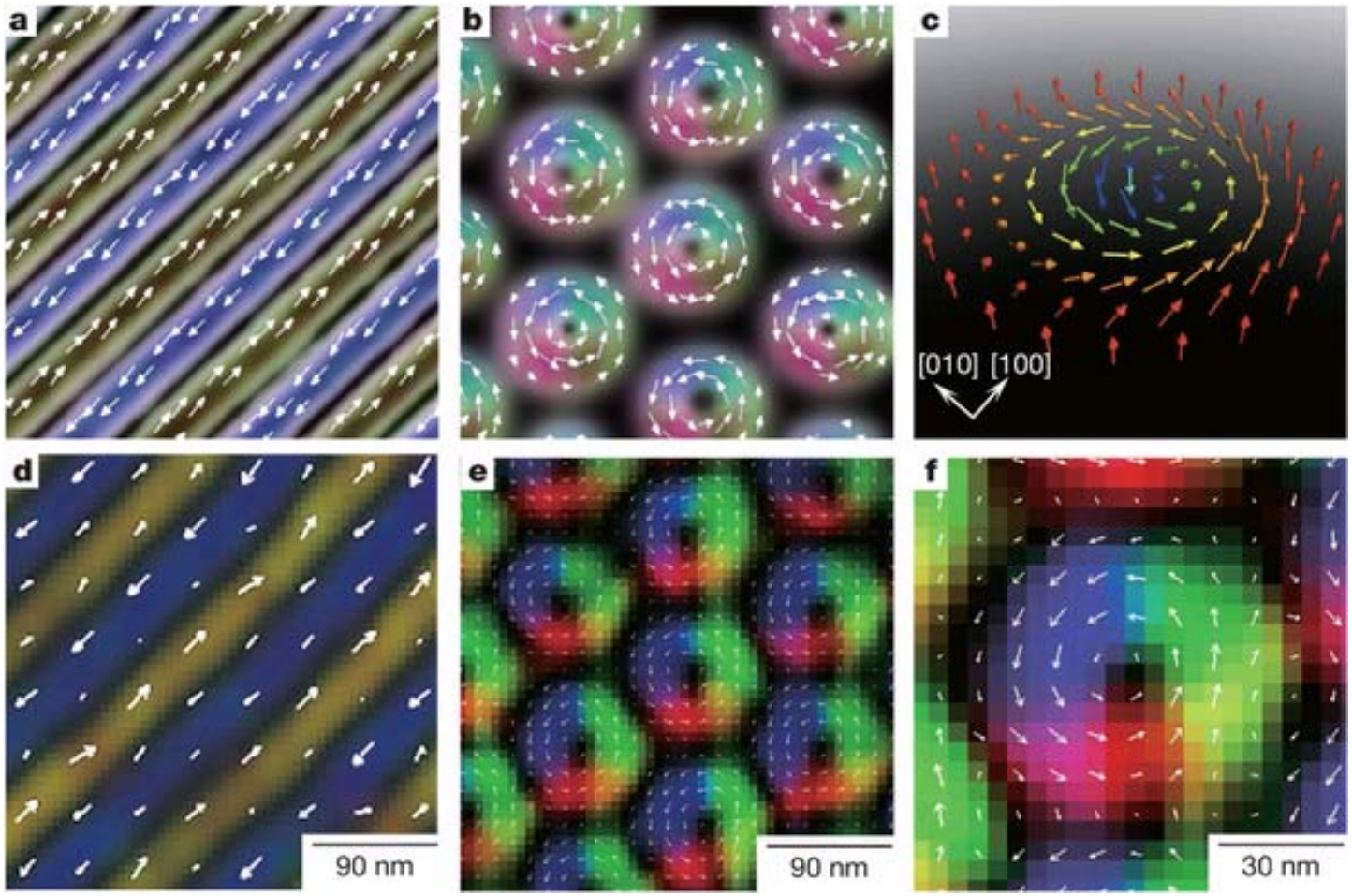
K. von Bergmann, et. al.
J. Phys: Condens. Matter **26** 394002 (2014).



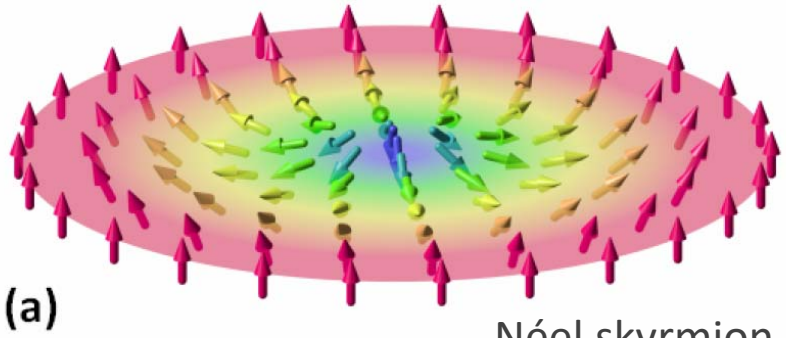
K. Everschor, Ph.D. Dissertation.
Köln University, 2012.

Chiral Ferromagnets & Skyrmions

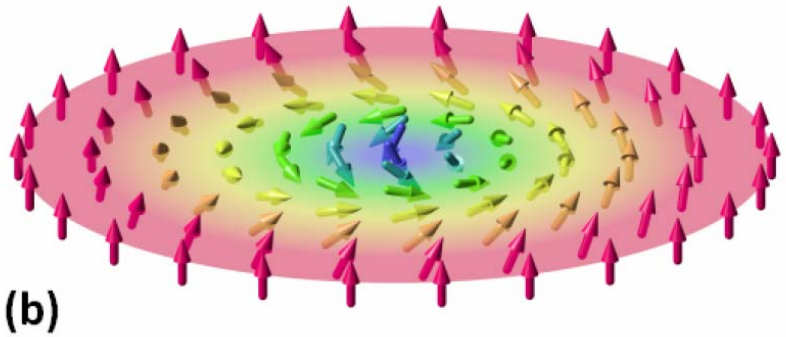
$Fe_{0.5}Co_{0.5}Si$, at T~20 K, Nature 465, 901–904 (2010)



Magnetic Skyrmions – Topological Properties



Néel skyrmion

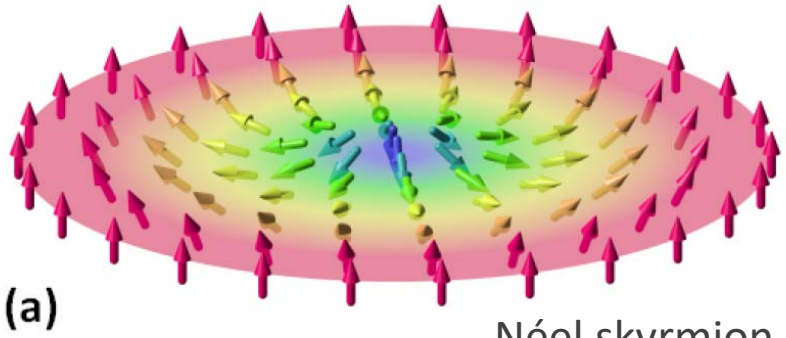


Bloch skyrmion

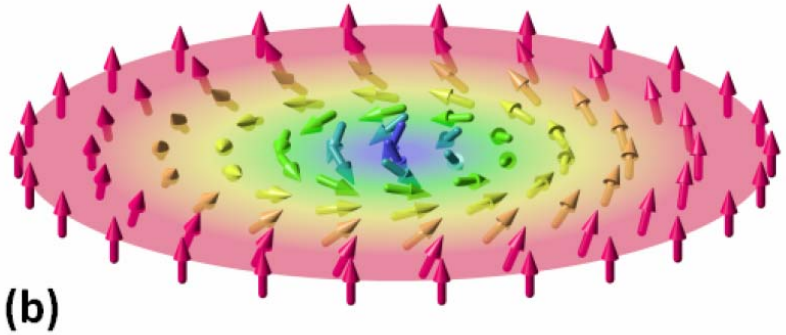
Topologically protected particle-like spin configuration:

$$S = \frac{1}{4\pi} \int_A \boldsymbol{n} \cdot \left(\frac{\partial \boldsymbol{n}}{\partial x} \times \frac{\partial \boldsymbol{n}}{\partial y} \right) dx\, dy$$

Magnetic Skyrmions – Topological Properties



Néel skyrmion



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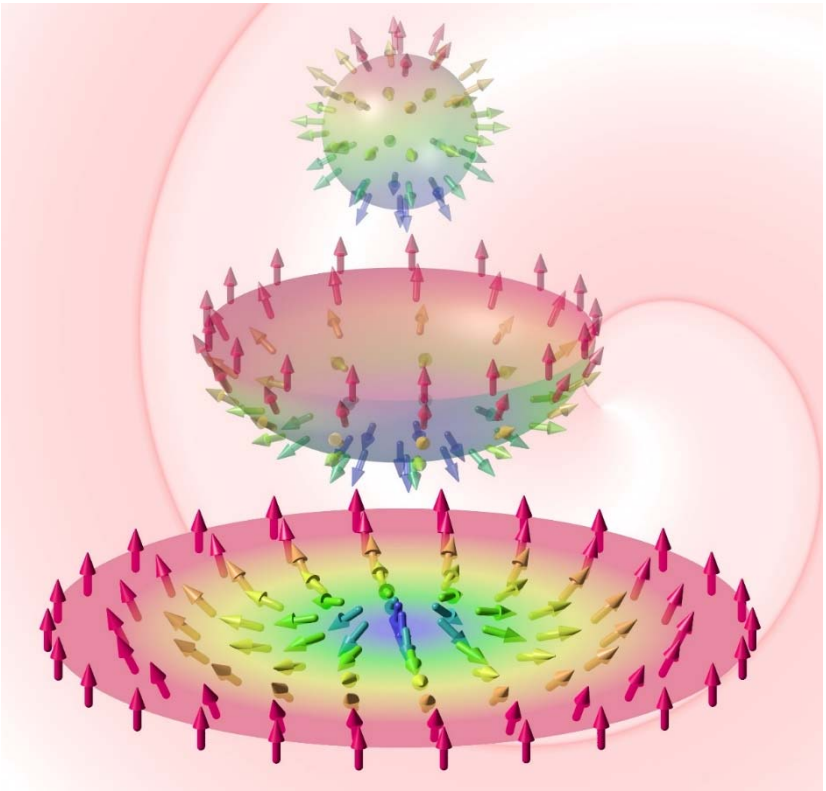
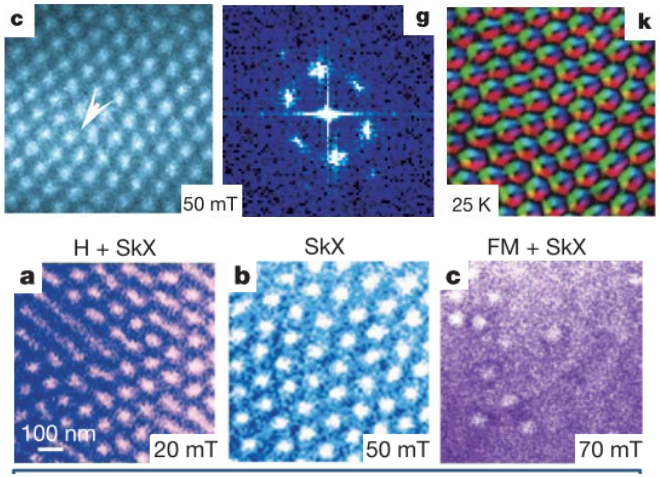


K. Everschor, U. Mainz

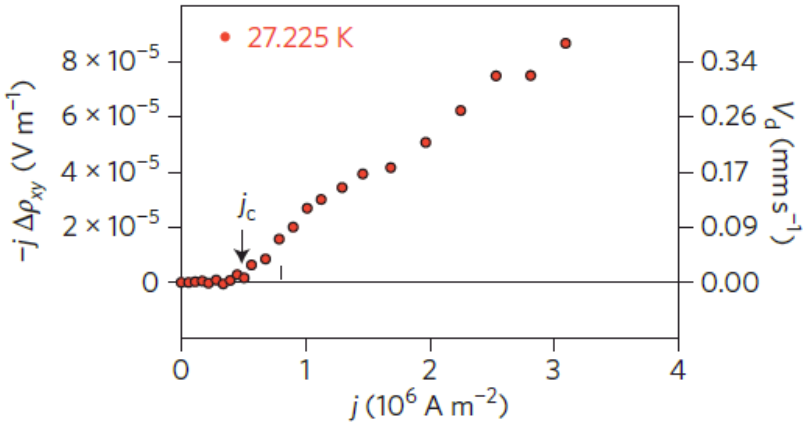
Key Behaviors of Skyrmions

Lattice formation



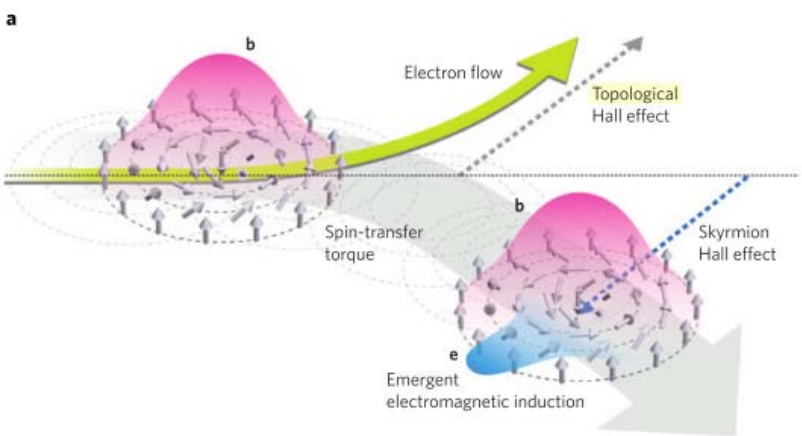
X. Z. Yu, *et. al.*, Nat. Lett. **465** 901 (2010).

(low-threshold) Current-driven motion



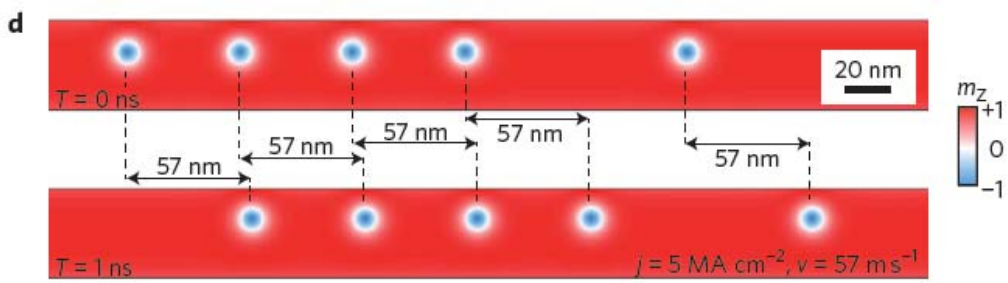
Schulz, T. *et al. Nature Phys.* **8,** 301–304 (2012).

Emergent electrodynamics



N. Nagaosa and Y. Tokura, *Nat. Nanotech.* **8,** 899 (2013).

Device applications



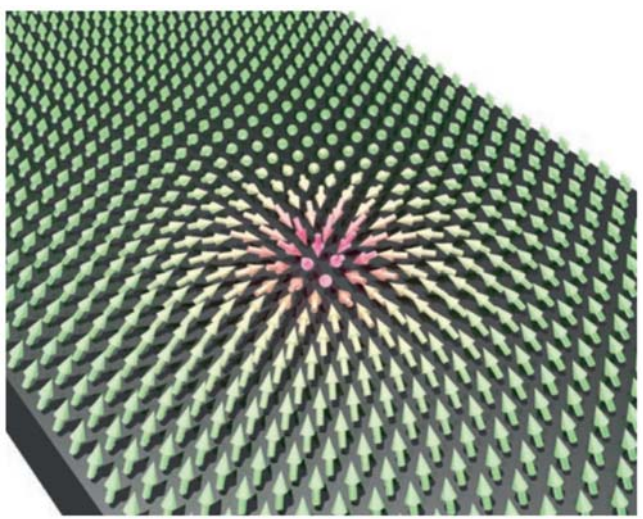
A. Fert, *et. al., Nat. Nanotech.* **8** 152 (2013).

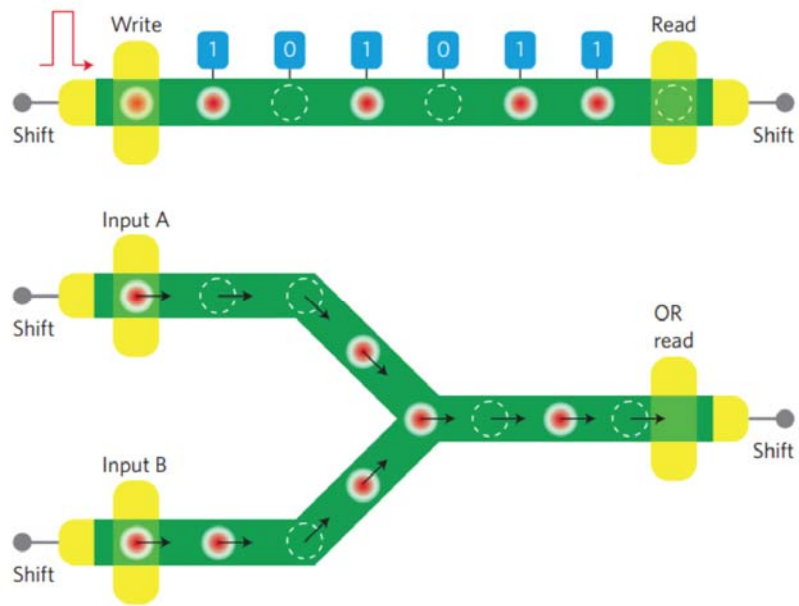
Magnetic Skyrmions

Magnetic Skyrmions: Nanoscale particle-like spin textures with high current-driven mobility

- Topologically-protected winding of spins with size down to a few nm
- Efficiently driven by spin Hall torques in racetrack devices

$$S = \frac{1}{4\pi}\int_A \boldsymbol{n}\cdot\left(\frac{\partial \boldsymbol{n}}{\partial x}\times\frac{\partial \boldsymbol{n}}{\partial y}\right)dx\,dy$$



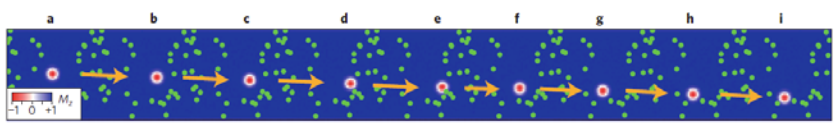


Krause & Wiesendanger, Nature Mater. 15, 493 (2016).

Magnetic Skyrmions

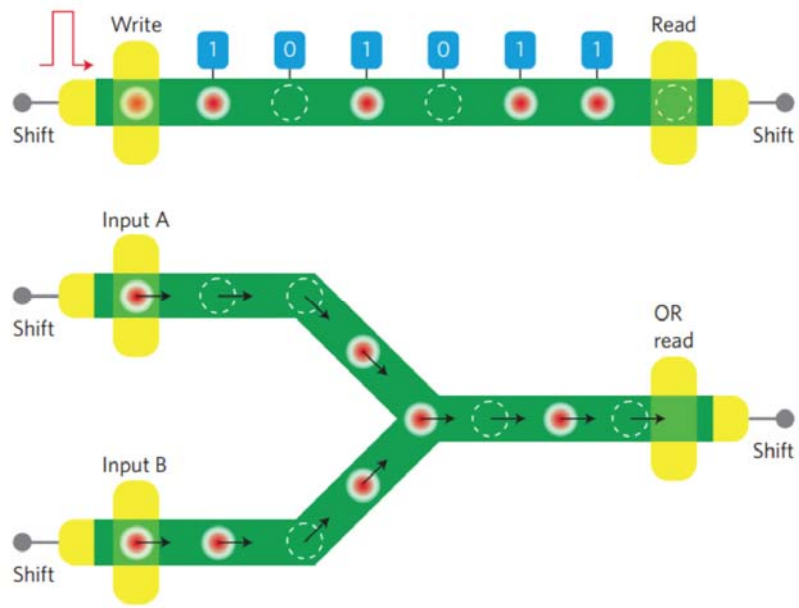
Magnetic Skyrmions: Nanoscale particle-like spin textures with high current-driven mobility

- Topologically-protected winding of spins with size down to a few nm
- Efficiently driven by spin Hall torques in racetrack devices
- Less sensitive to defects than domain walls, leading to low threshold currents



J. Iwasaki, *et. al., Nat. Nanotech.* **8** 742 (2013).

A. Fert, *et. al., Nat. Nanotech.* **8** 152 (2013).



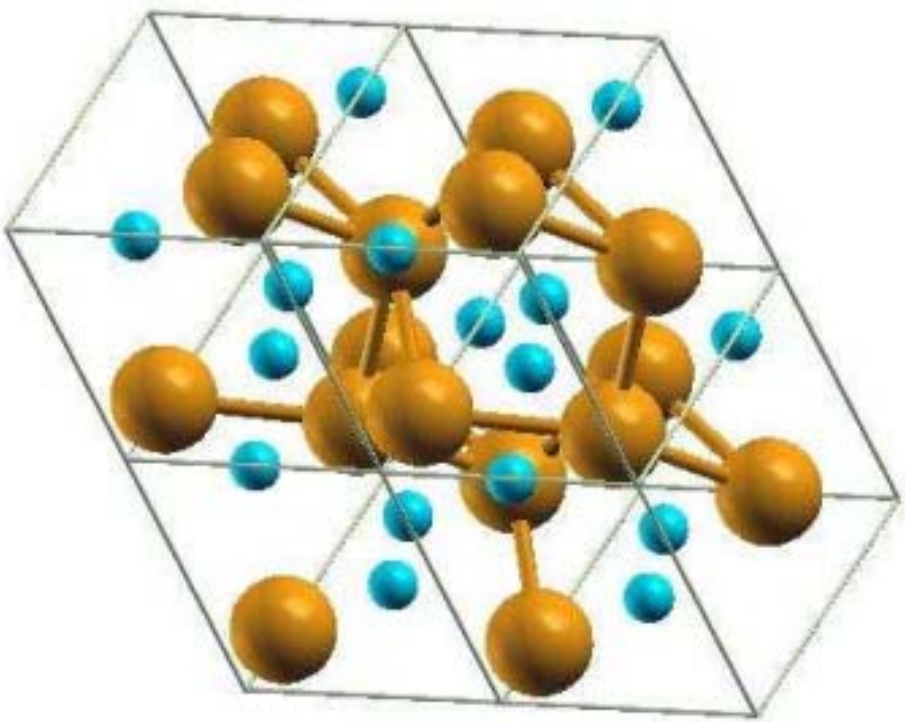
Magnetic skyrmions can serve nanoscale current-driven bits in spin memory and logic devices

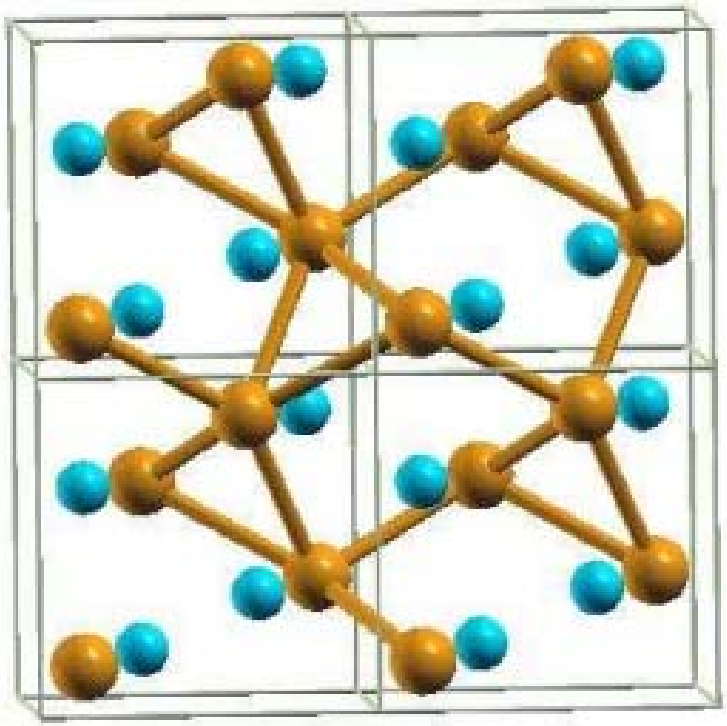
Krause & Wiesendanger, Nature Mater. 15, 493 (2016).

Bulk Helimagnets

B20 compounds: magnetically-ordered materials with bulk inversion asymmetry

MnSi, FeCoSi, FeGe

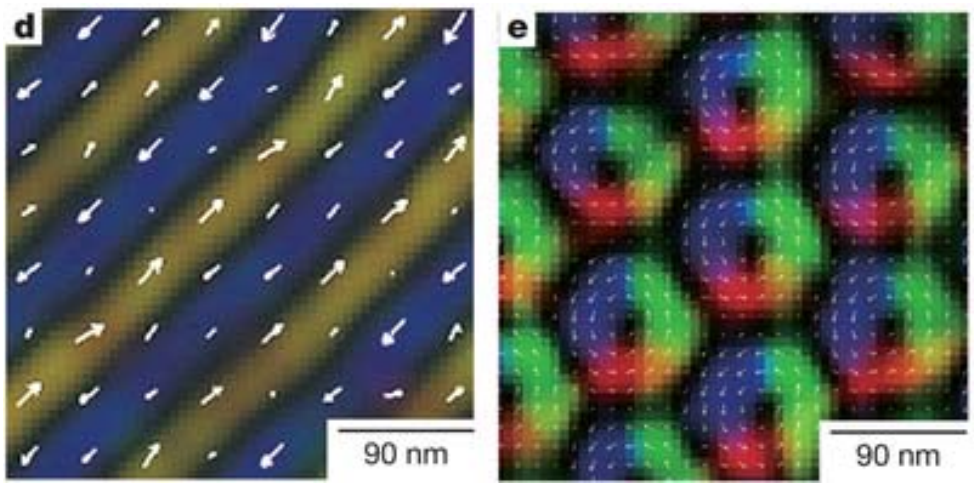




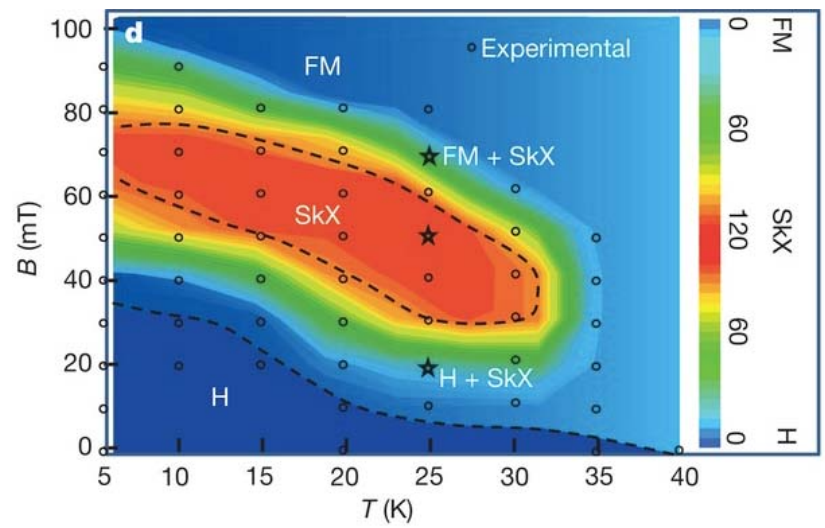
T. Jeong *et al.,* Phys. Rev. B **70**, 075114 (2004)

Spin Textures in Bulk Helimagnets

$Fe_{0.5}Co_{0.5}Si$



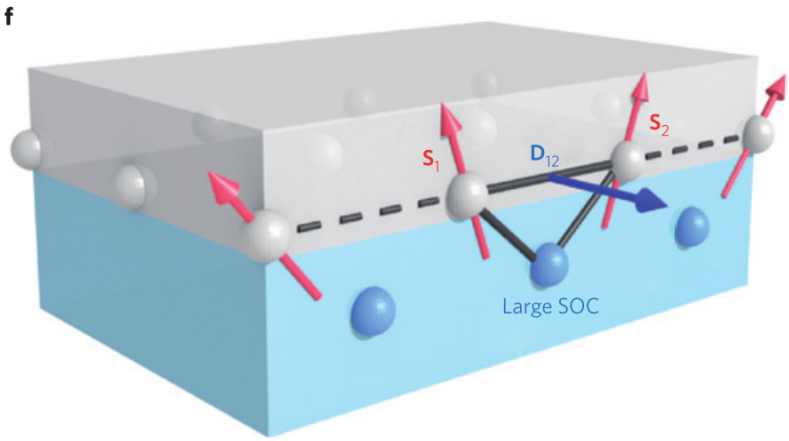
M. Uchida, et.al., Science **311**, 359 (2006).
X.Z. Yu, et.al., Nature **465,** 901 (2010).



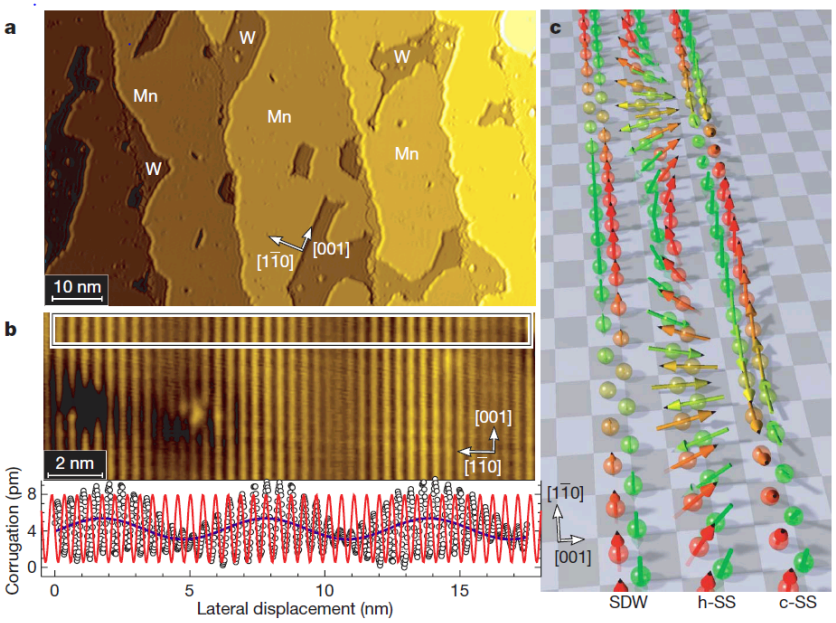
Yu, X. Z. et al. *Nature* **465**, 901–904 (2010).

Limited to a narrow range of temperature and magnetic field

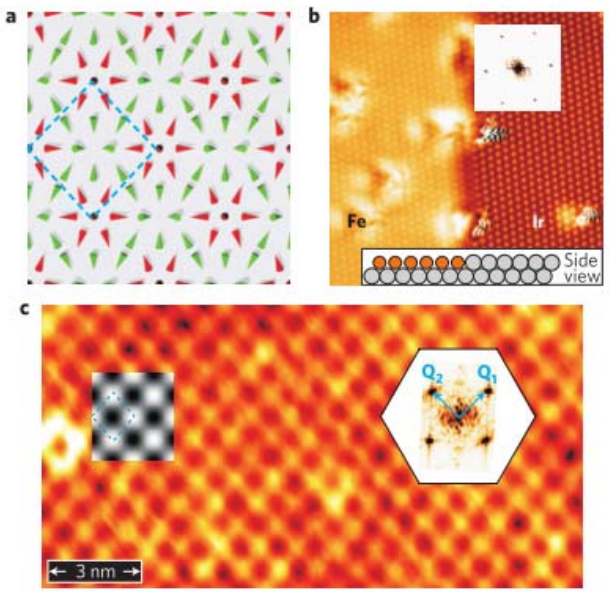
DMI at Interfaces



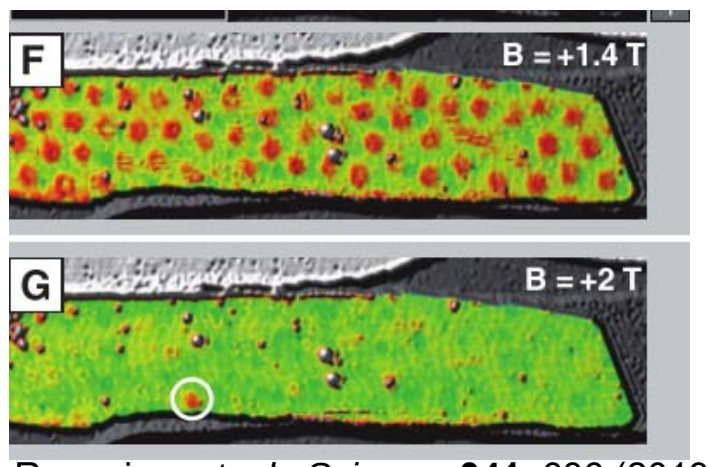
A. Fert *et al*, Nature Nanotechnology, 2013



M. Bode, Nature 447, 190 (2007)



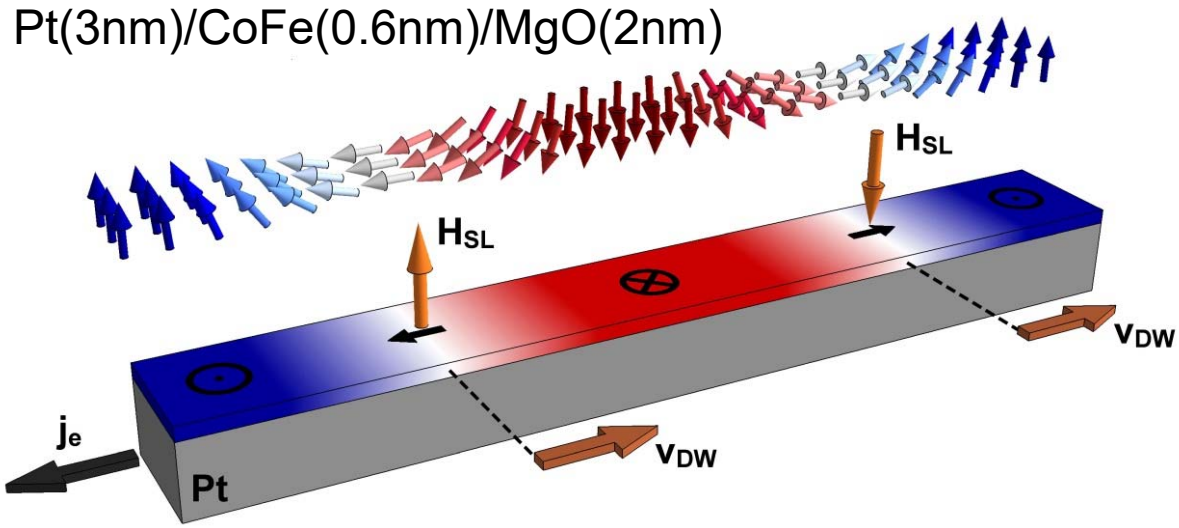
S. Heinze, *et. al.*, *Nat. Phys.* **7** 713 (2011).

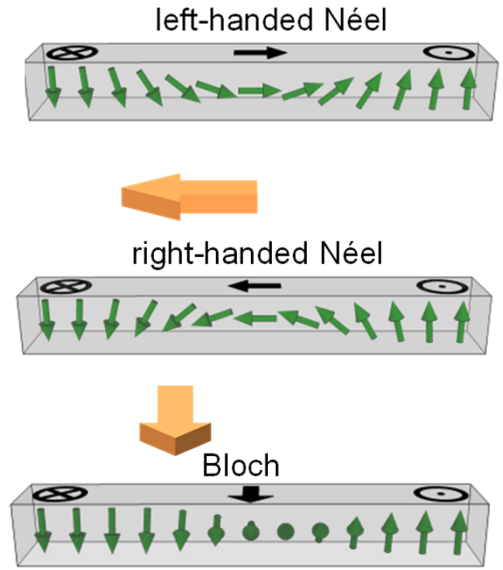


N. Romming, *et. al.*, *Science*. **341**, 636 (2013).

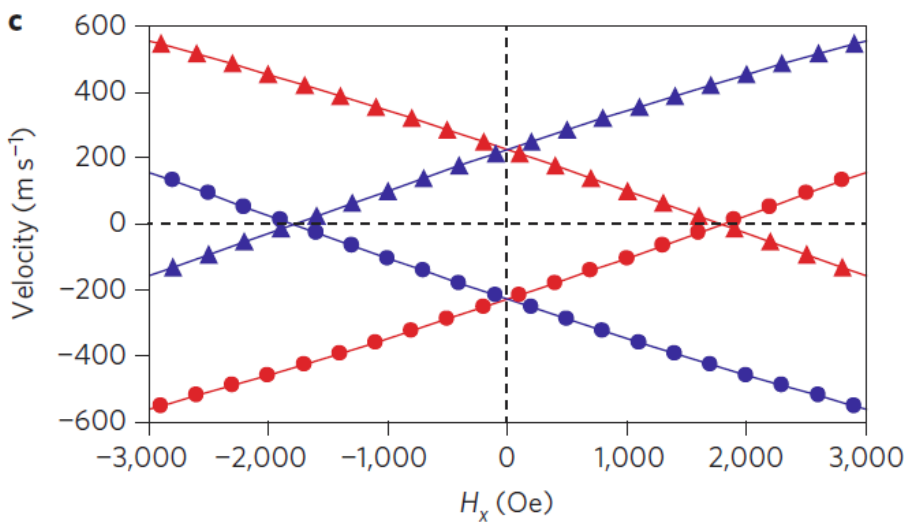
Chiral Domain Walls in Ultrathin Films

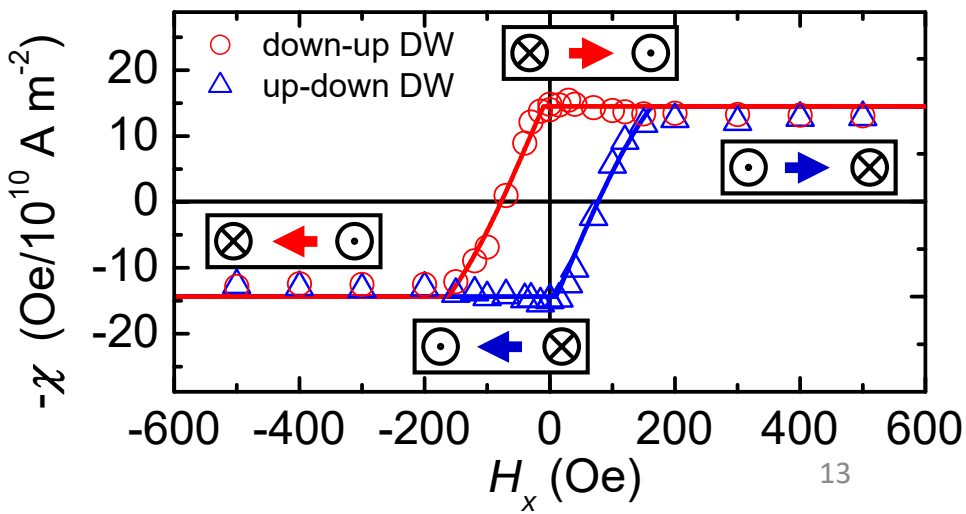
Pt(3nm)/CoFe(0.6nm)/MgO(2nm)





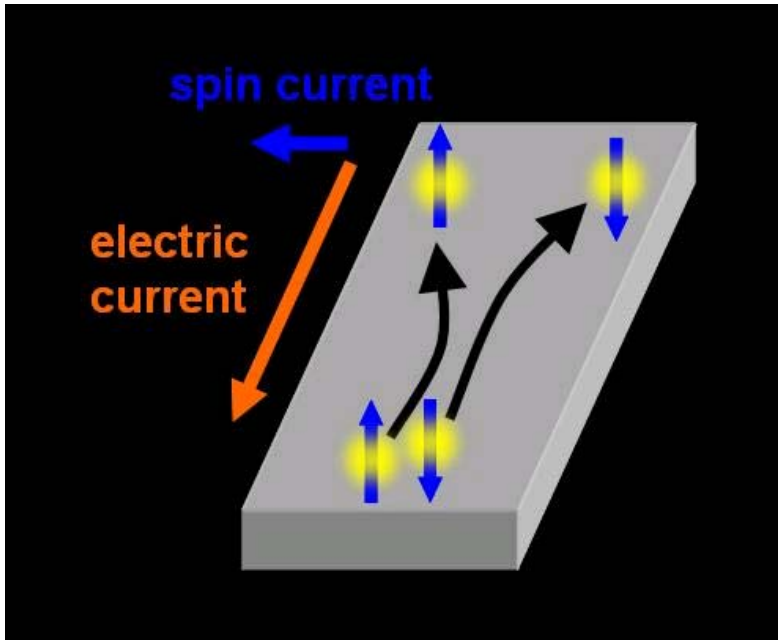
S. Emori, et al., Nat. Mater **12**, 611 (2013) ;
K.-S. Ryu, et al., Nat. Nano. **8**, 527 (2013) ;
S. Emori, et al., PRB. **90**, 184427 (2014)

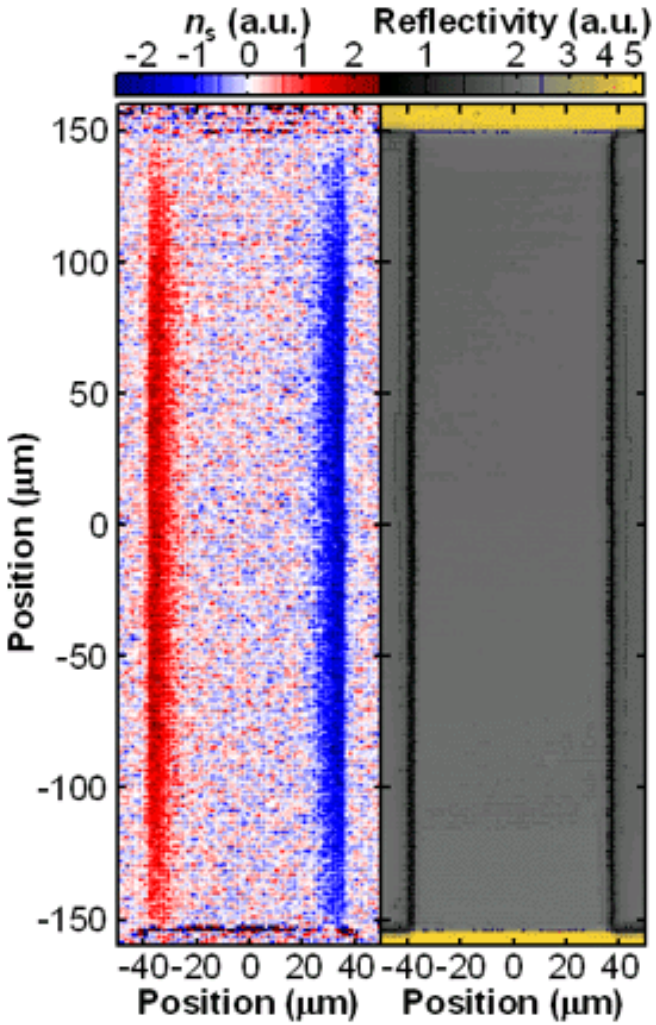




Spin Hall Effect (SHE)

Spin-dependent skew scattering in a heavy metal





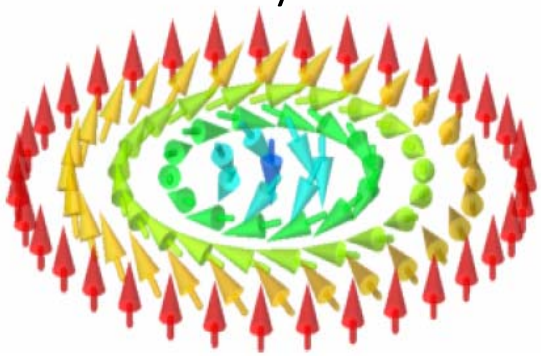
D'yakonov and Perel', *Sov. Phys. JETP Lett.* 13, 467, (1971).

Hirsch, *Phys. Rev. Lett.*, 83, 1834, (1999).

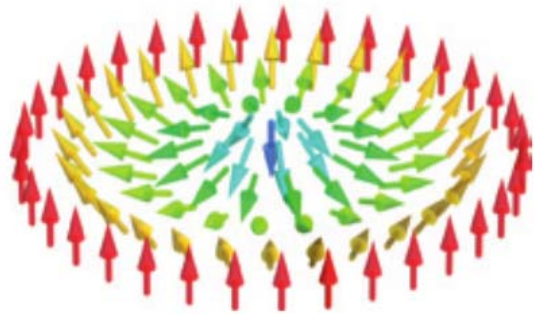
Y. K. Kato, R. C.Myers, A. C. Gossard, and D. D. Awschalom, *Science*, vol. 306, 1910 (2004)

Chiral Ferromagnets & Skyrmions

Bloch Skyrmion

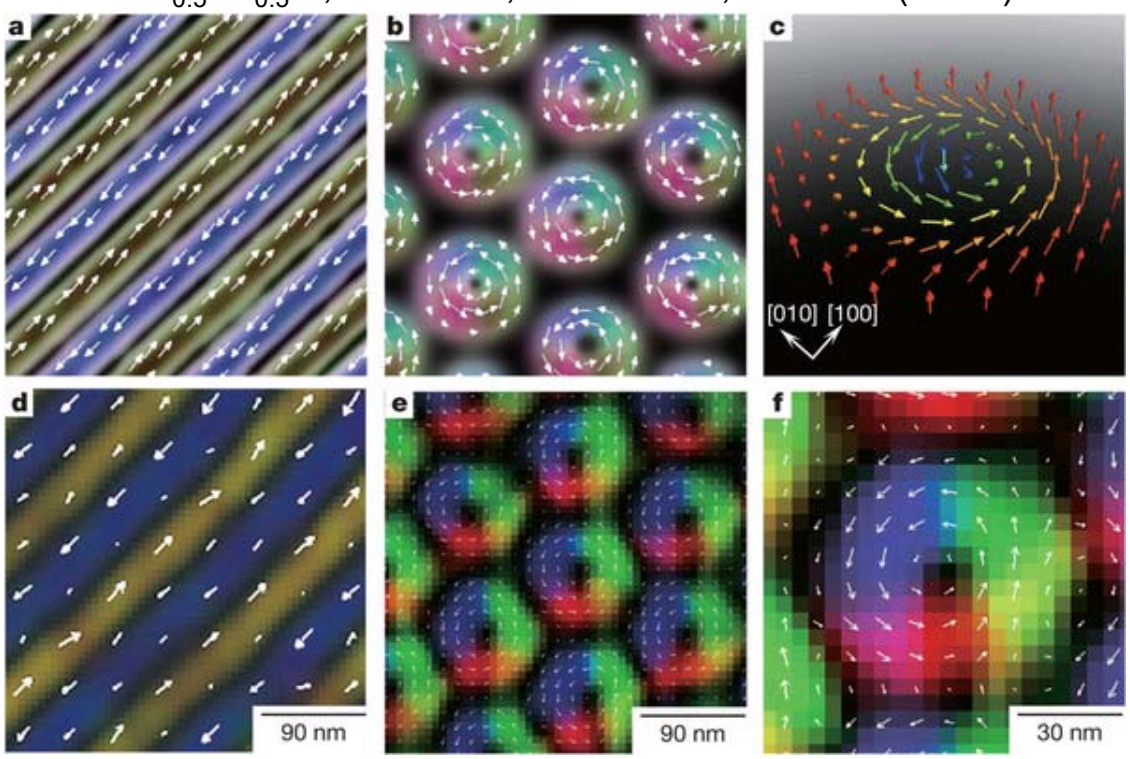


Néel Skyrmion



K. Everschor,
Ph.D. Dissertation.

$Fe_{0.5}Co_{0.5}Si$, at T~20 K, Nature 465, 901–904 (2010)



Threshold

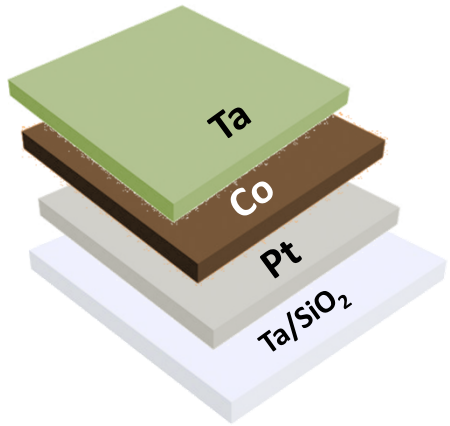
$$\frac{H_{DMI}}{H_{\perp}} > \frac{2}{\pi}$$

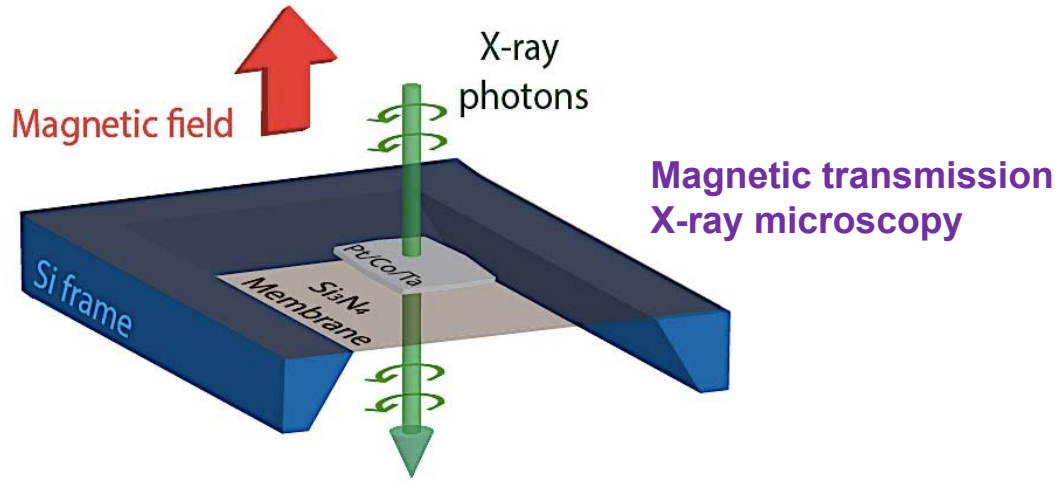
Pt/Co(Fe)

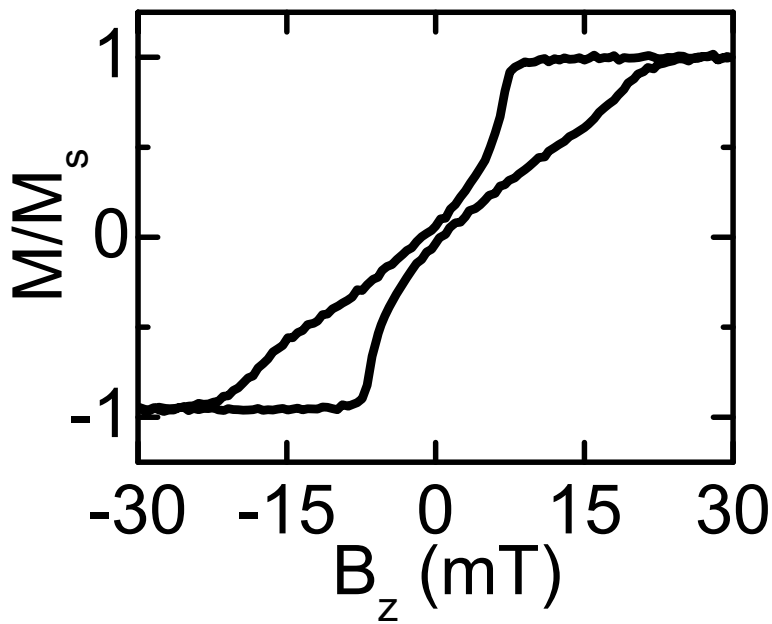
$$\frac{H_{DMI}}{H_{\perp}} \approx 0.45$$

S. Emori, et al., Nat. Mater **12**, 611 (2013)
S. Emori, et al., PRB. **90**, 184427 (2014)

Magnetic Transmission X-Ray Microscopy



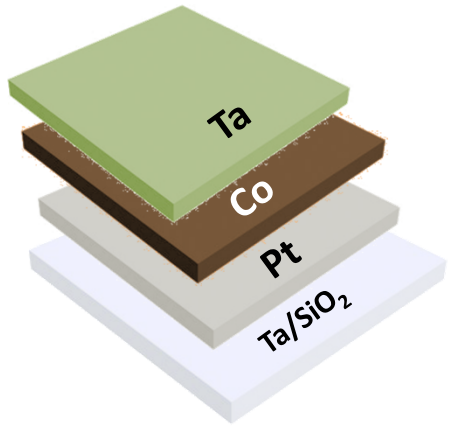


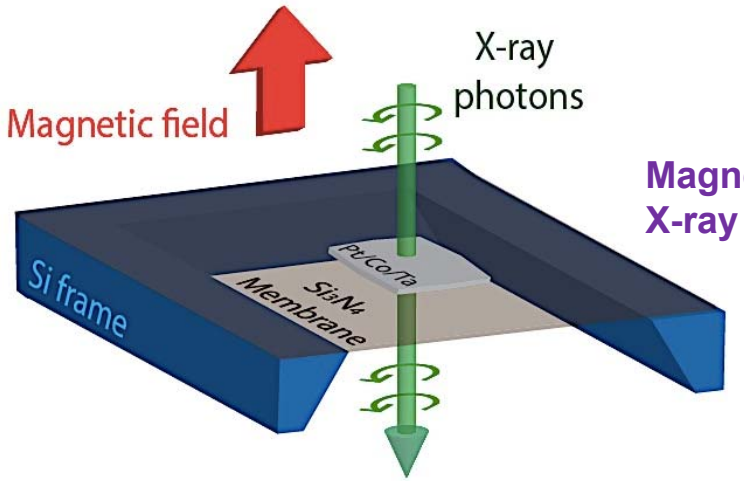


S. Woo, et al., *Nature Mater.* 15, 503 (2016).

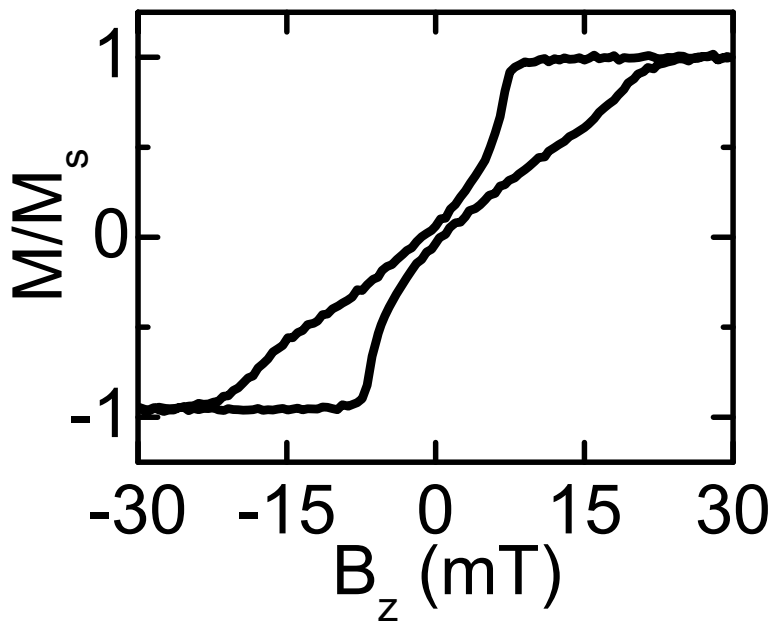
With Peter Fischer, Mathias Kläui

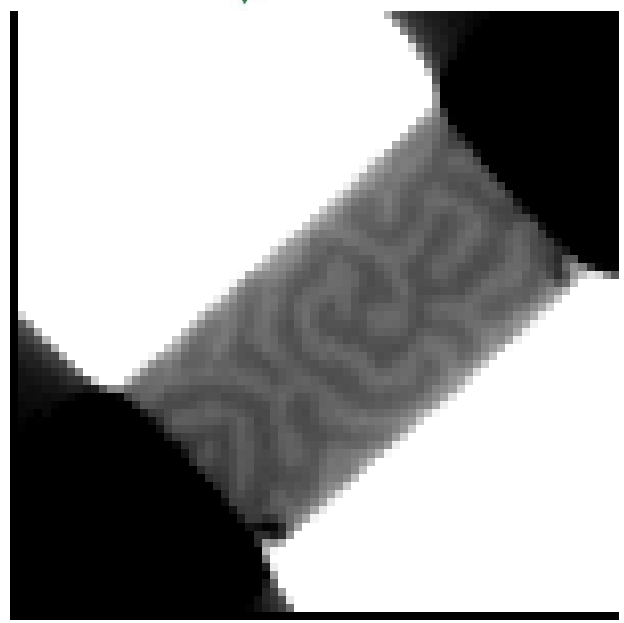
Magnetic Transmission X-Ray Microscopy





Magnetic transmission X-ray microscopy

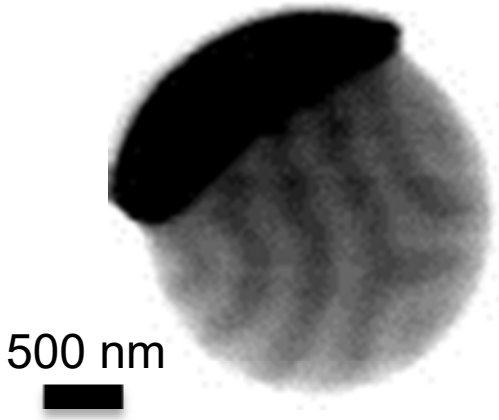




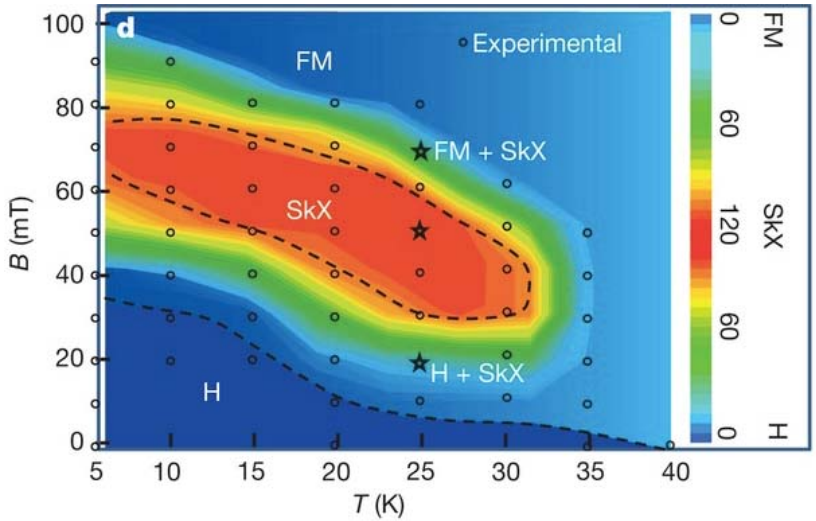
S. Woo, et al., *Nature Mater.* 15, 503 (2016).

With Peter Fischer, Mathias Kläui

Skyrmion Lattice Formation



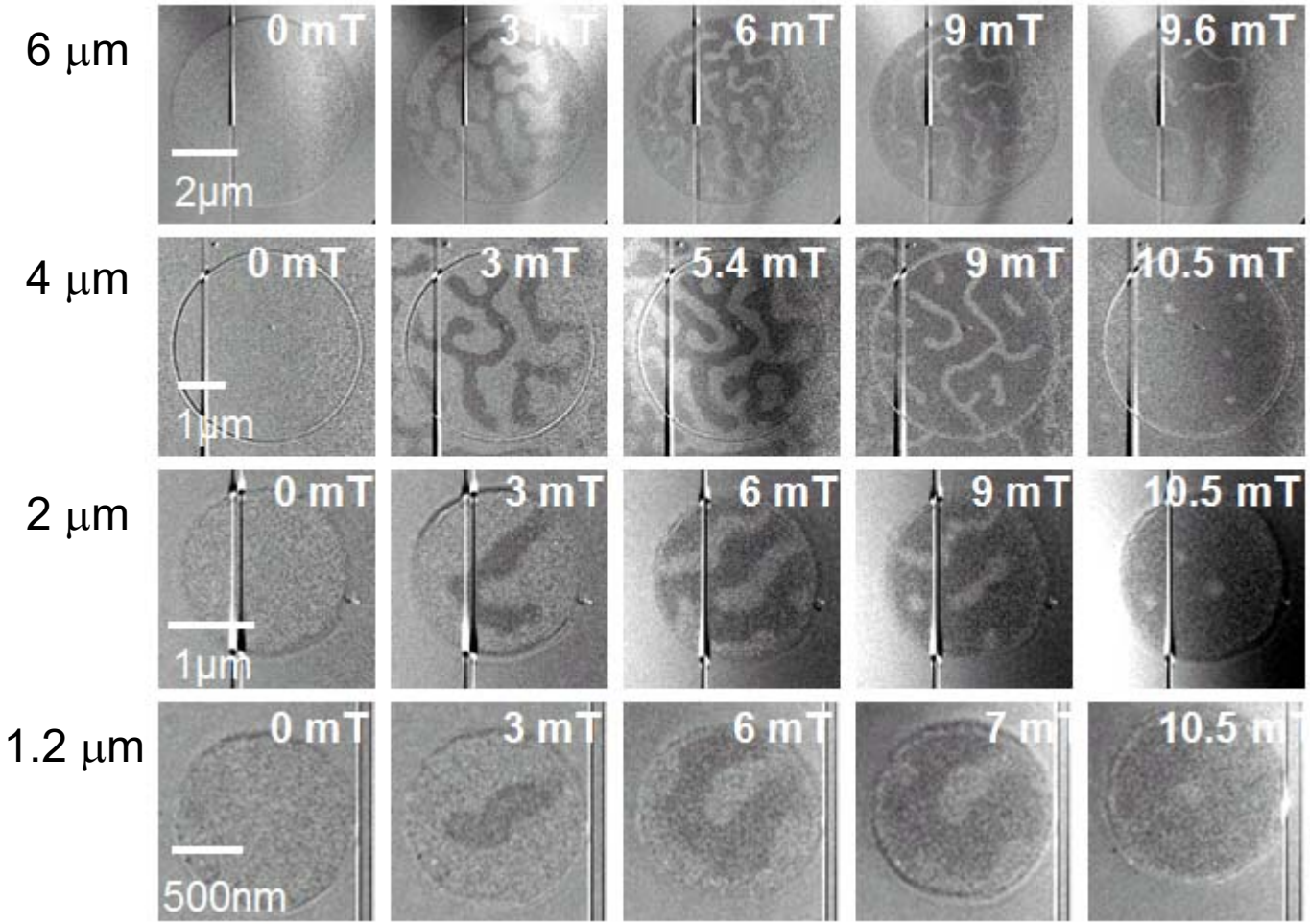
- Quasistatic transformation between stripe & skyrmion lattice phase
- Skyrmion lattice is stable at room temperature and zero applied field



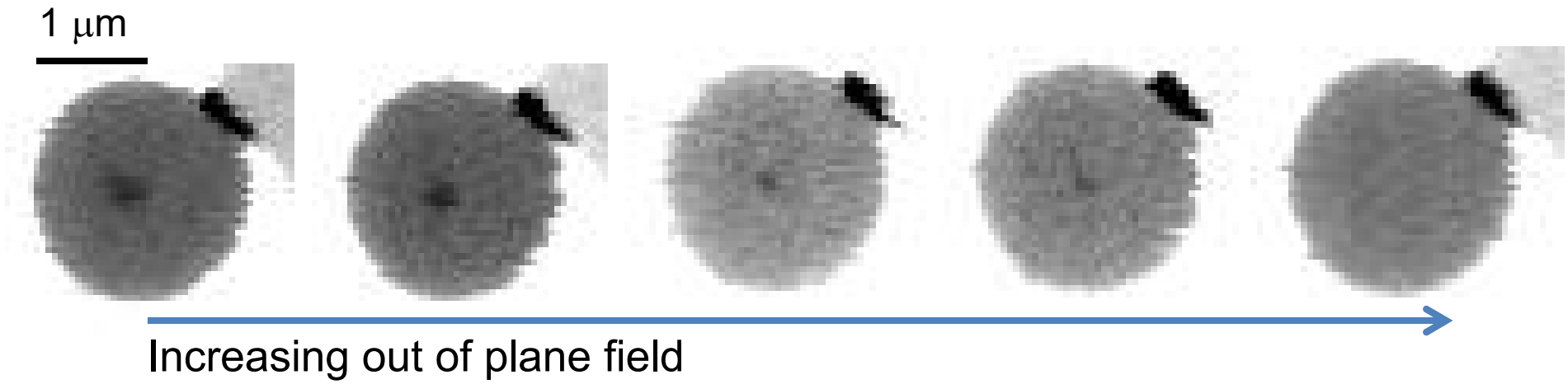
Yu, X. Z. et al. *Nature* 465, 901–904 (2010).

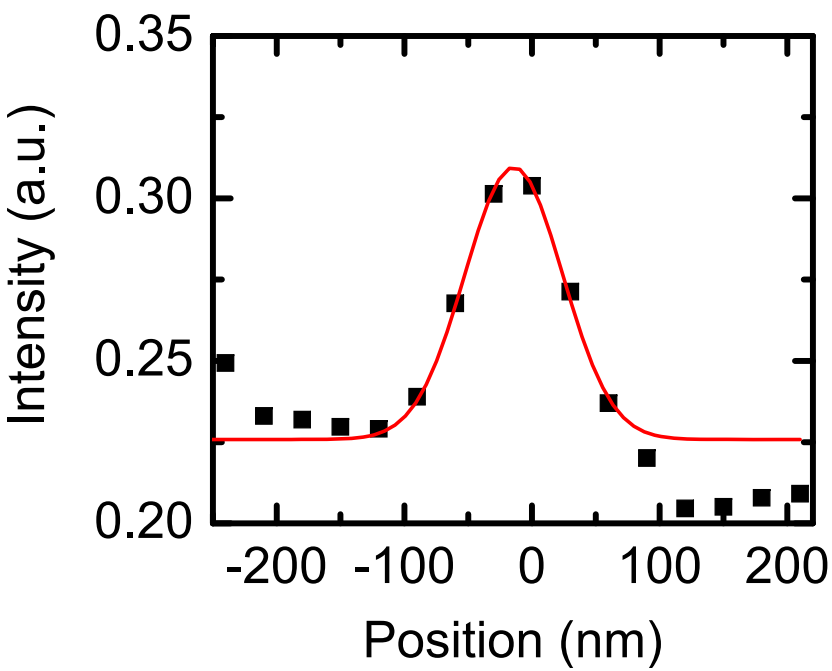
S. Woo, et al., *Nature Mater.* 15, 503 (2016).

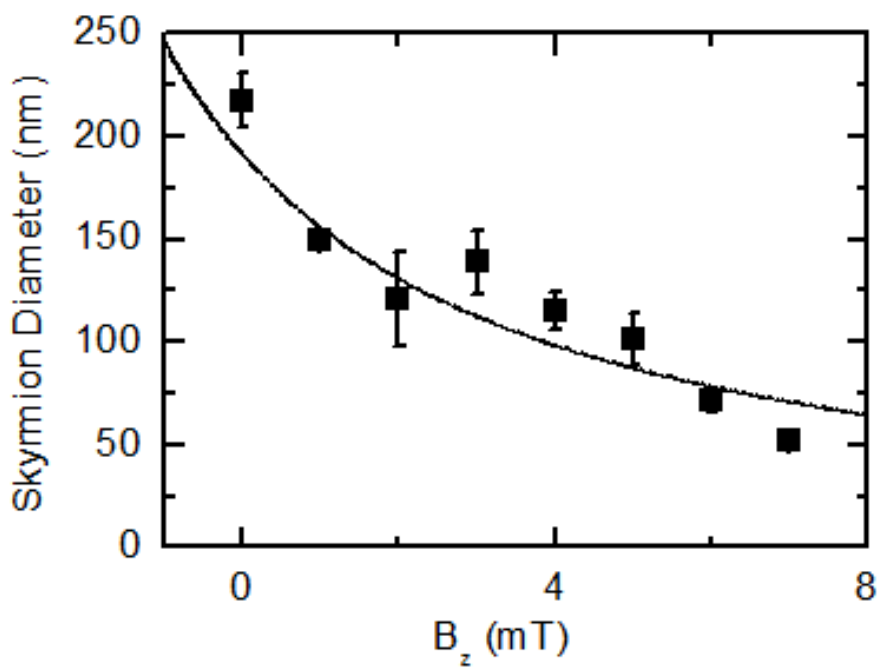
Skyrmions in confined geometries



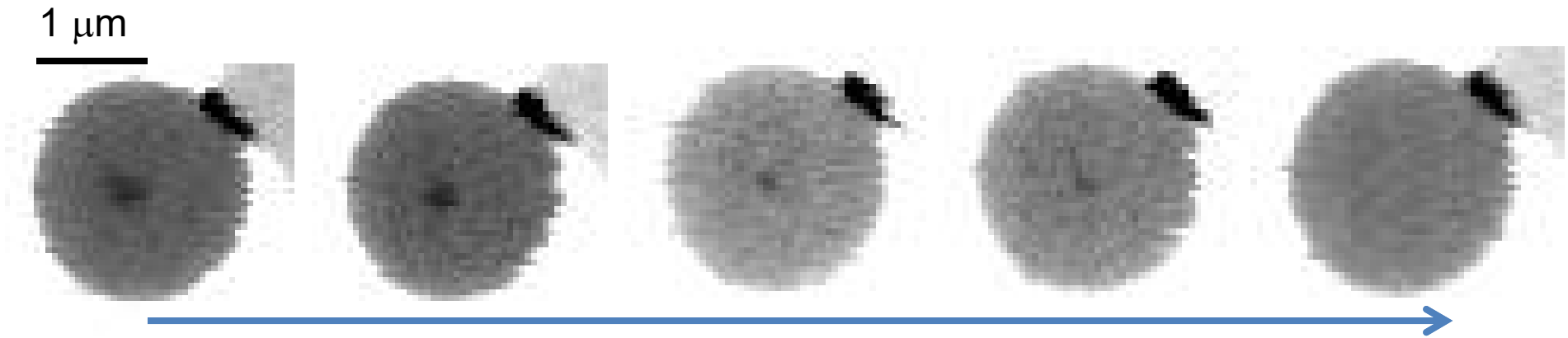
Skyrmion diameter versus field



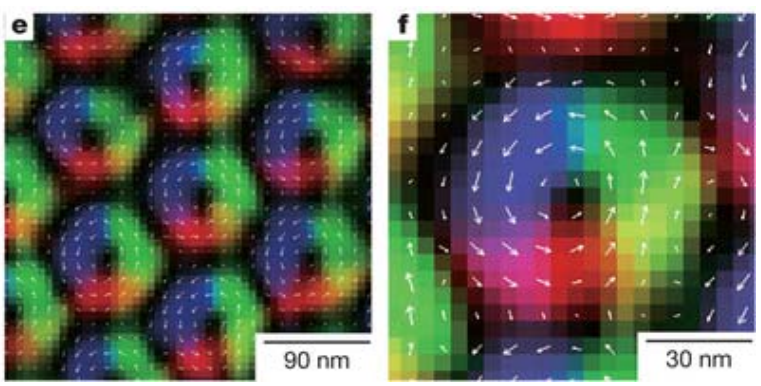


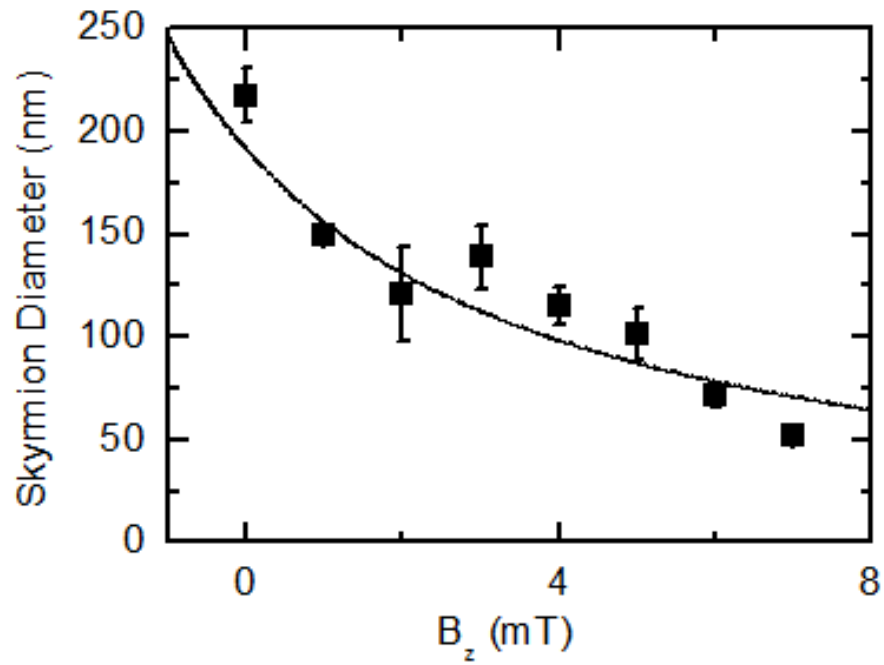


Skyrmion diameter versus field

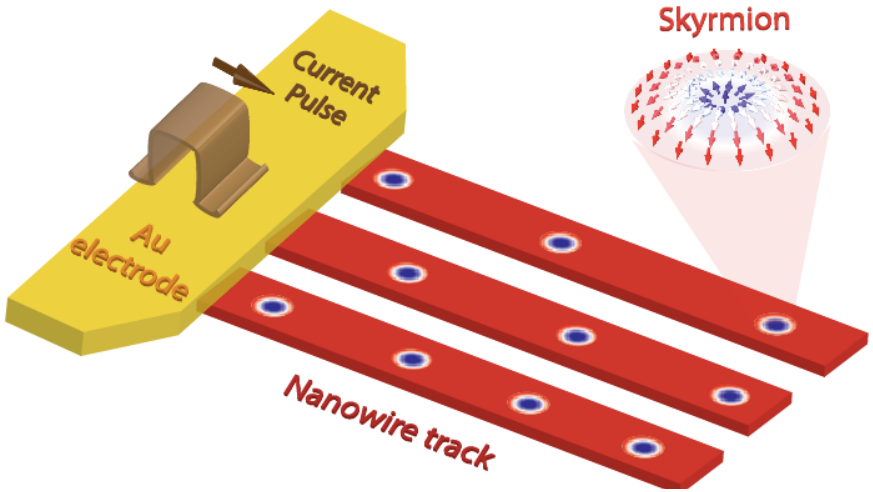


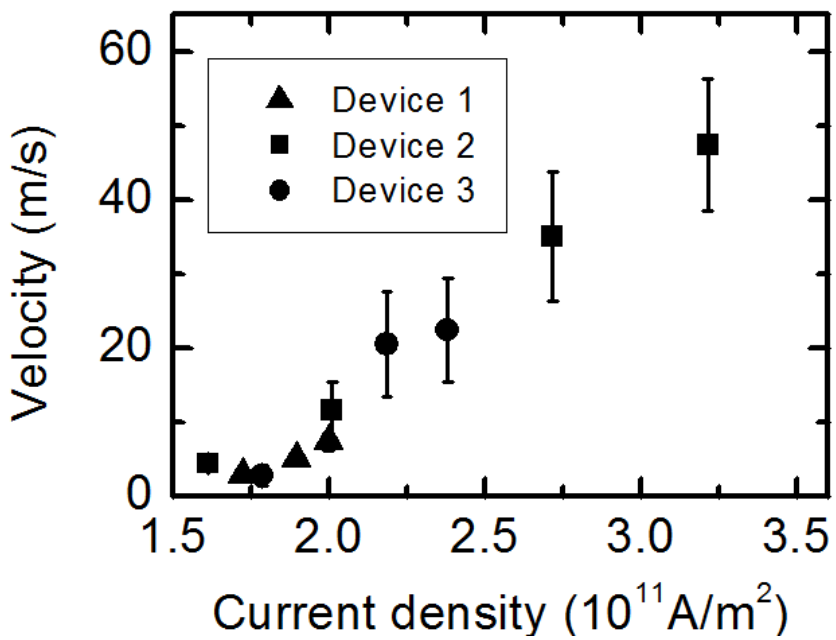
$Fe_{0.5}Co_{0.5}Si$, Nature 465, 901–904 (2010)

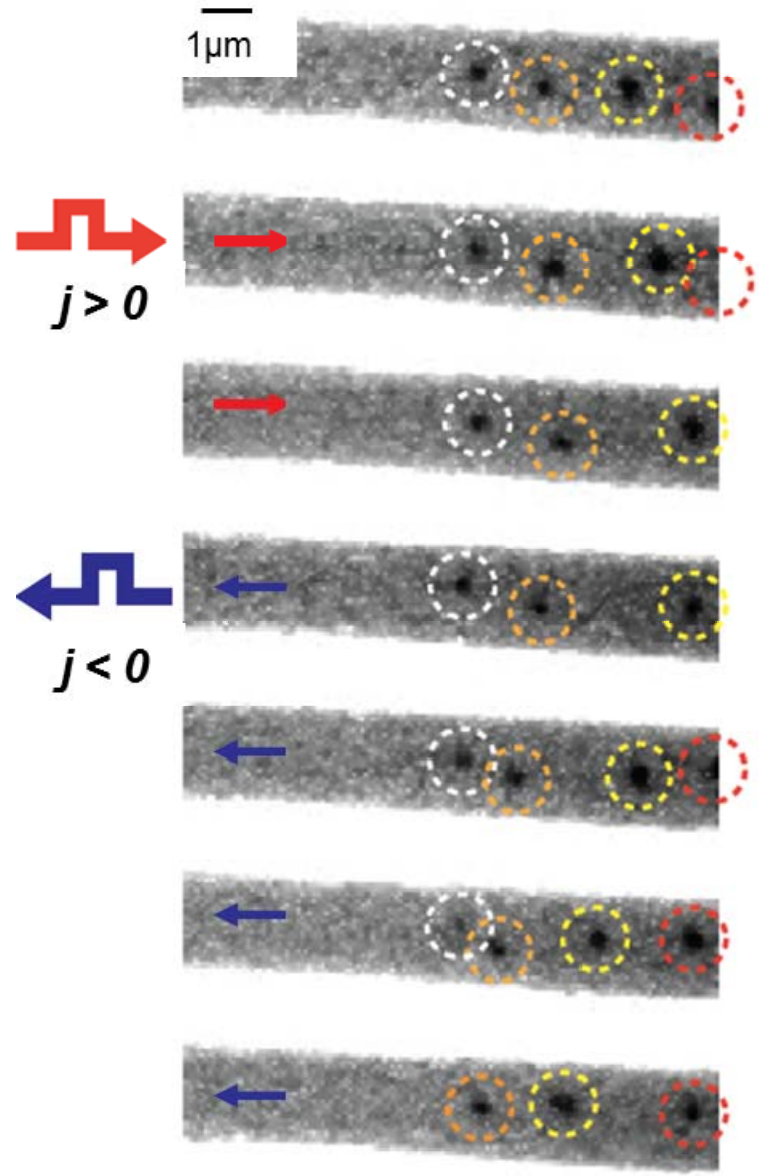




Current-driven skyrmions in a racetrack

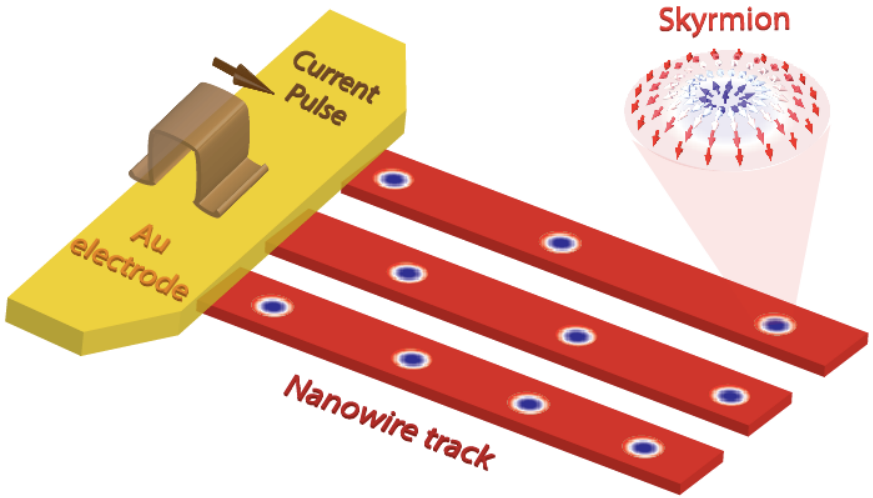


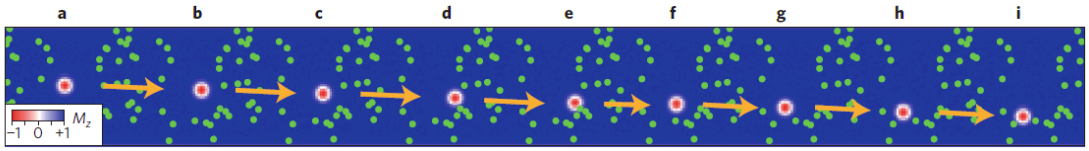




S. Woo, et al., *Nature Mater.* 15, 503 (2016).

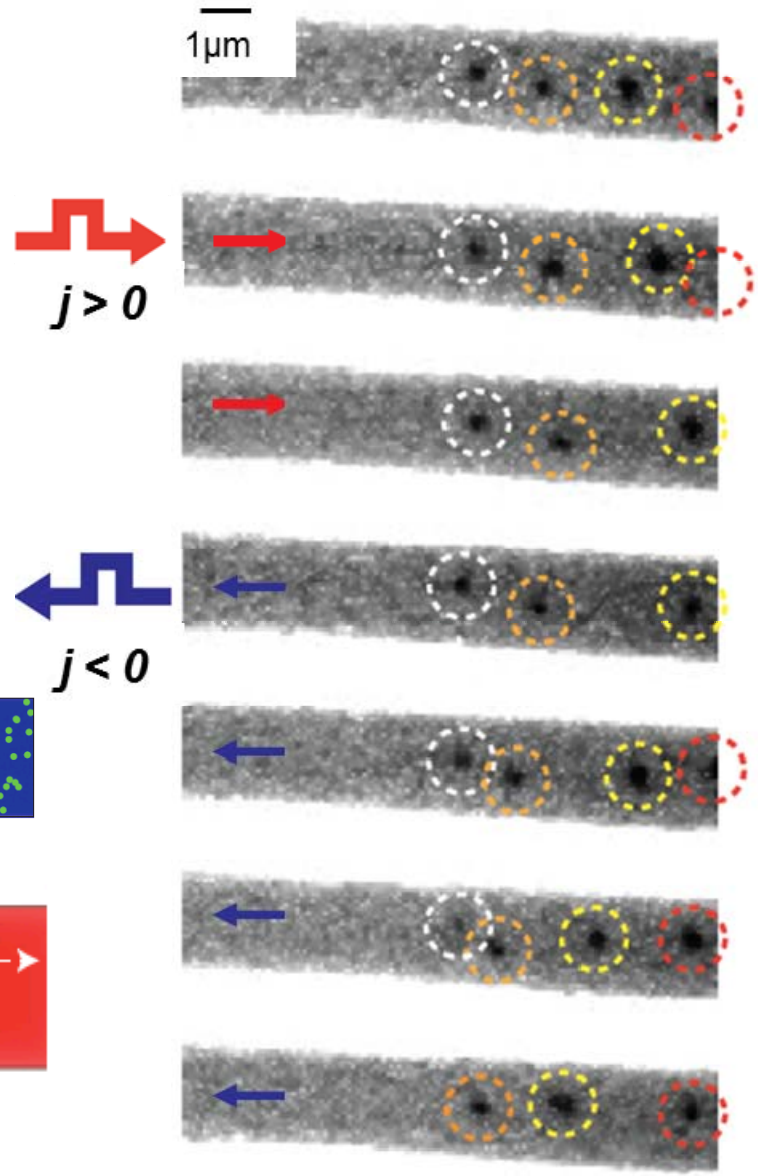
SHE-driven motion





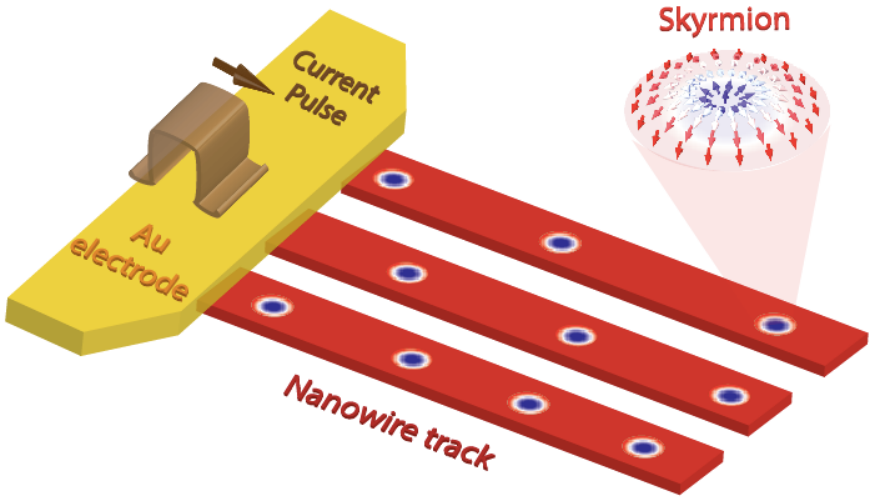
J. Iwasaki, *et. al., Nat. Nanotech.* **8** 742 (2013).

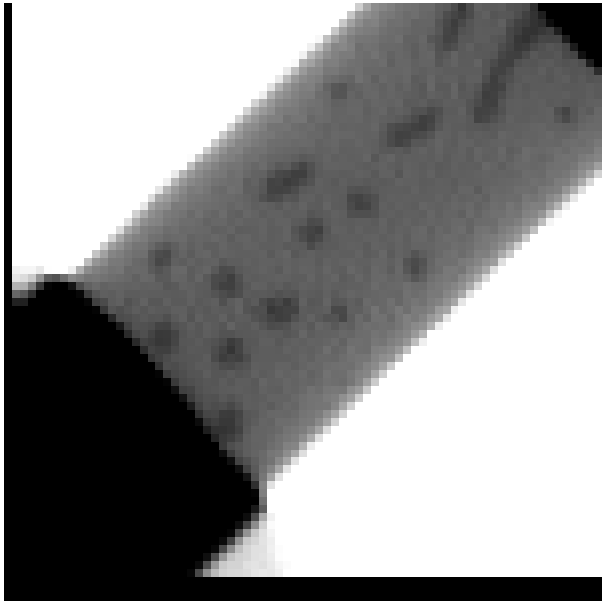
A. Fert, *et. al., Nat. Nanotech.* **8** 152 (2013).

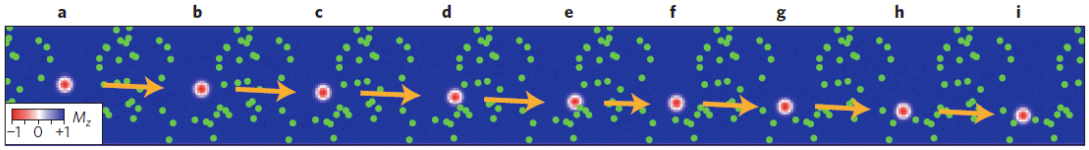


S. Woo, et al., *Nature Mater.* 15, 503 (2016).

SHE-driven motion







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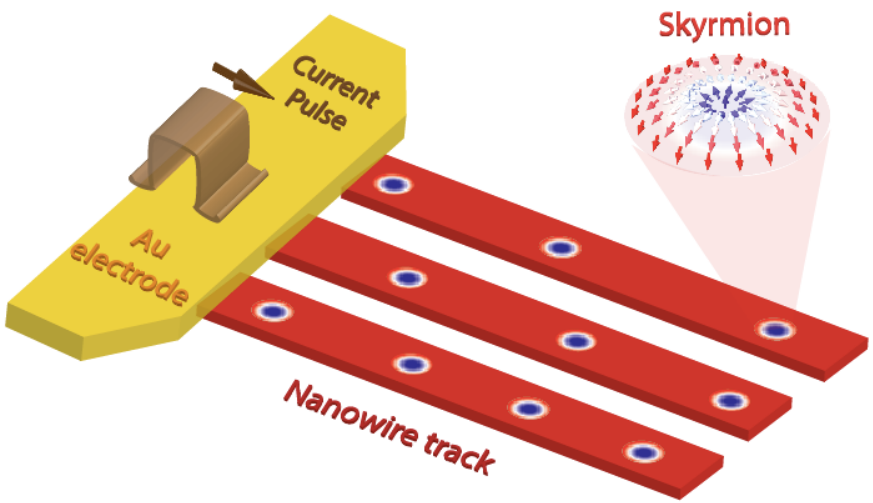
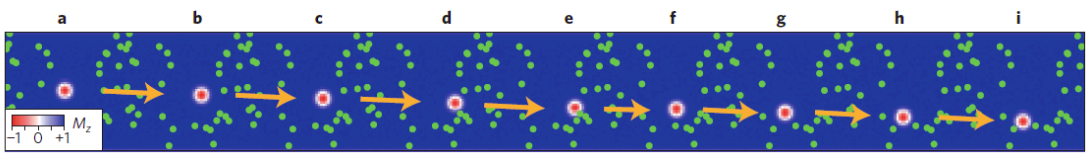
Pt/Co/Ta versus Pt/CoFeB/MgO





J. Iwasaki, *et. al., Nat. Nanotech.* **8** 742 (2013).

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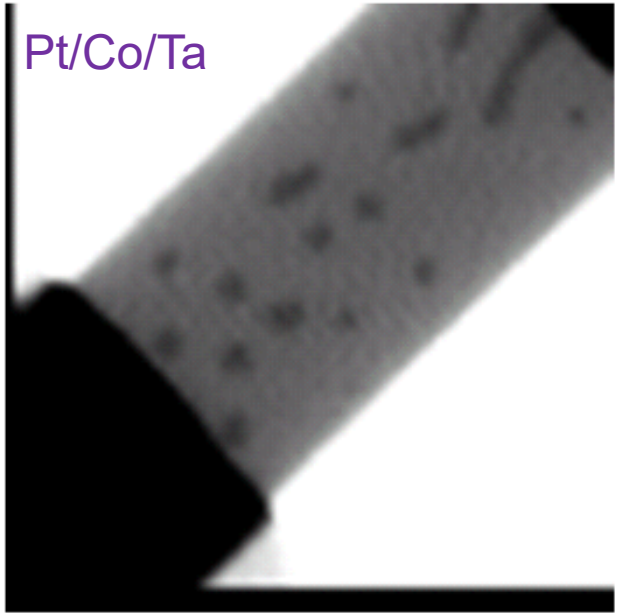

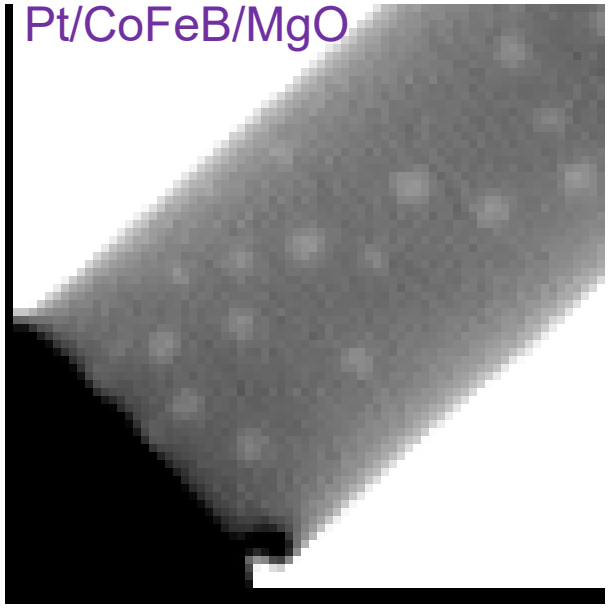

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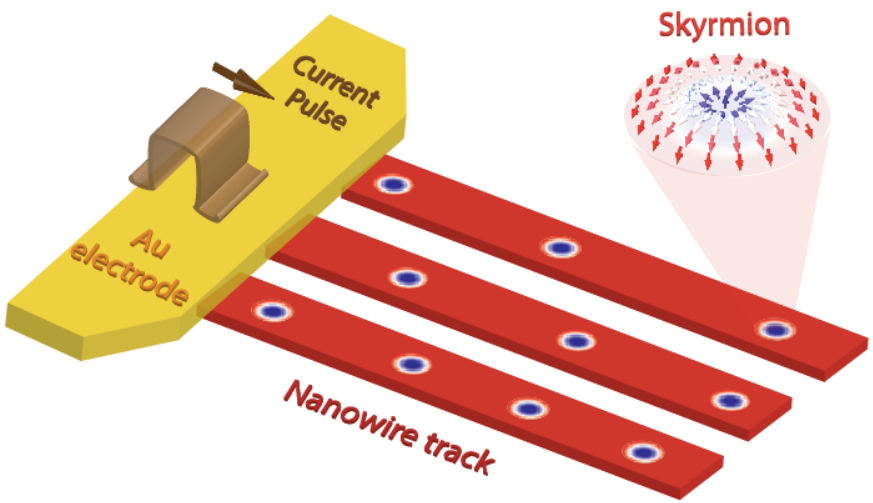
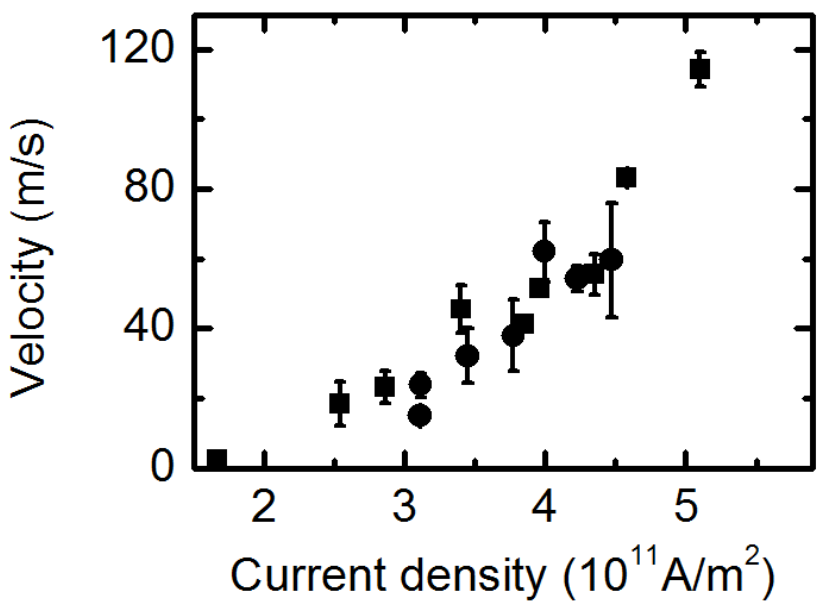
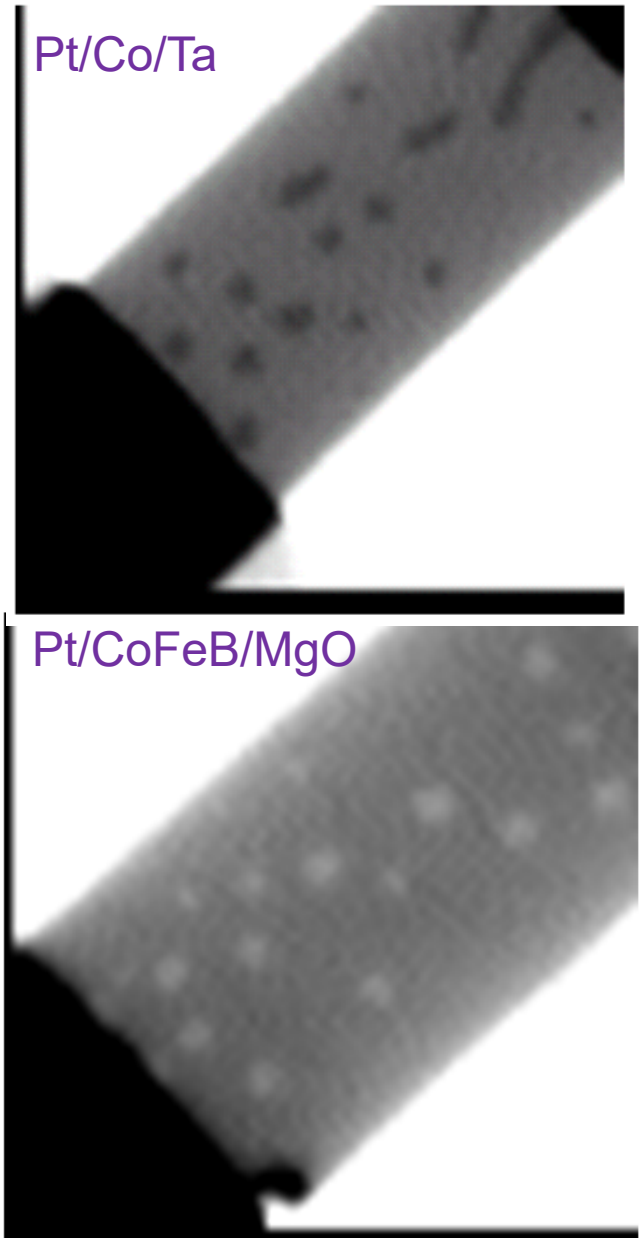
Pt/Co/Ta versus Pt/CoFeB/MgO

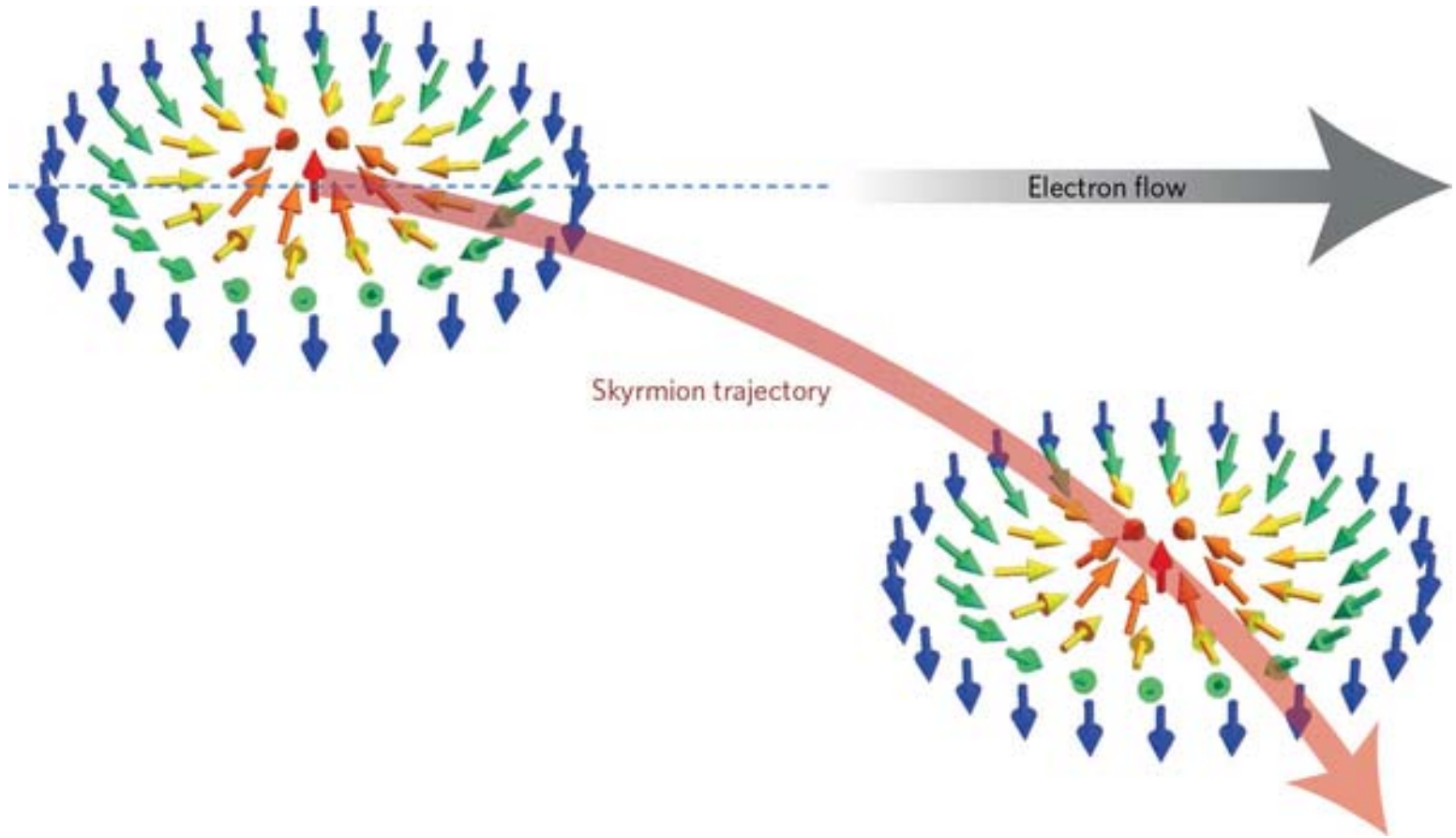






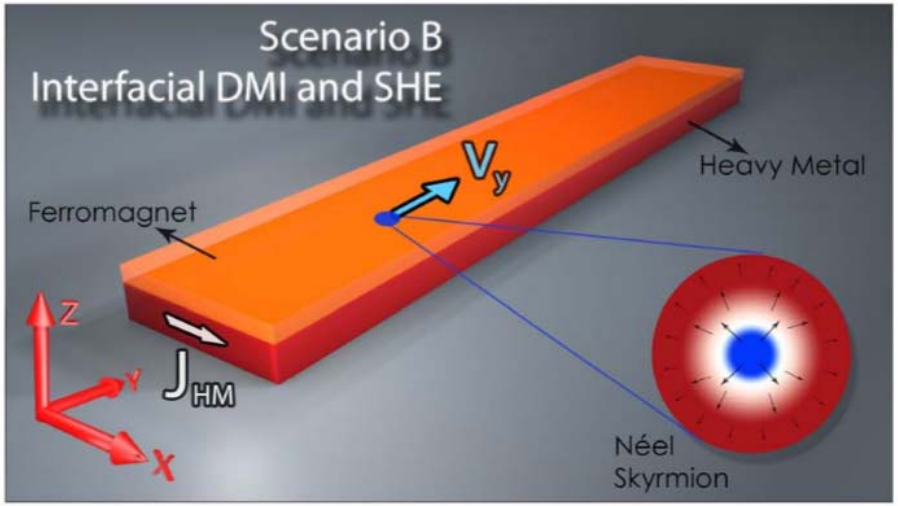
S. Woo, et al., *Nature Mater.* 15, 503 (2016).

Skyrmion Hall Effect



G. Chen, Nature Physics 13, 112 (2017)

Skyrmion Hall Effect



$$\mathbf{G} \times \mathbf{v} - \alpha_G \overleftrightarrow{\mathcal{D}} \cdot \mathbf{v} + 4\pi B \overleftrightarrow{\mathcal{R}}(\phi_0 = 0) \cdot \mathbf{j}_{\mathbf{HM}} = 0$$

$$v_x = \frac{\alpha_G \mathcal{D} B}{1 + \alpha_G{}^2 \mathcal{D}^2} j_{HM}$$

$$v_y = \frac{B}{1 + \alpha_G{}^2 \mathcal{D}^2} j_{HM}$$

$$\tan\phi = \frac{2\Delta}{\alpha R}$$

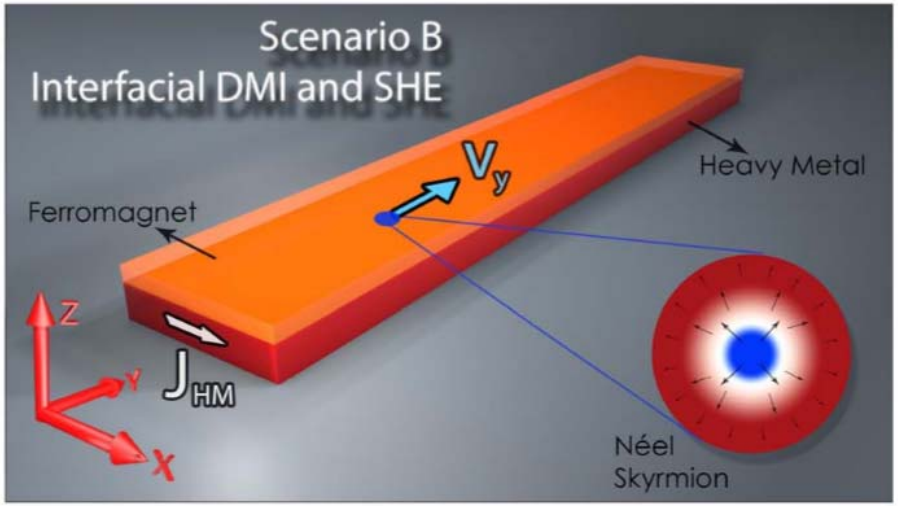
DW width

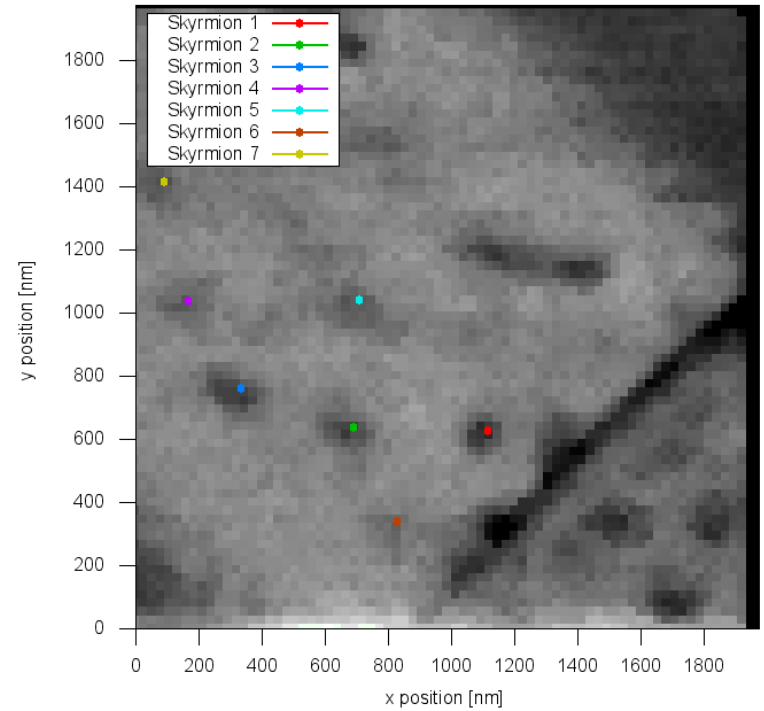
damping

radius

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

Skyrmion Hall Effect





$$\mathbf{G} \times \mathbf{v} - \alpha_G \overleftrightarrow{\mathcal{D}} \cdot \mathbf{v} + 4\pi B \overleftrightarrow{\mathcal{R}}(\phi_0 = 0) \cdot \mathbf{j}_{\mathbf{HM}} = 0$$

$$\phi \approx 20^o \rightarrow \alpha \approx 0.4$$

$$v_x = \frac{\alpha_G \mathcal{D} B}{1 + \alpha_G{}^2 \mathcal{D}^2} j_{HM}$$

$$v_y = \frac{B}{1 + \alpha_G{}^2 \mathcal{D}^2} j_{HM}$$

$$\tan\phi = \frac{2\Delta}{\alpha R}$$

DW width

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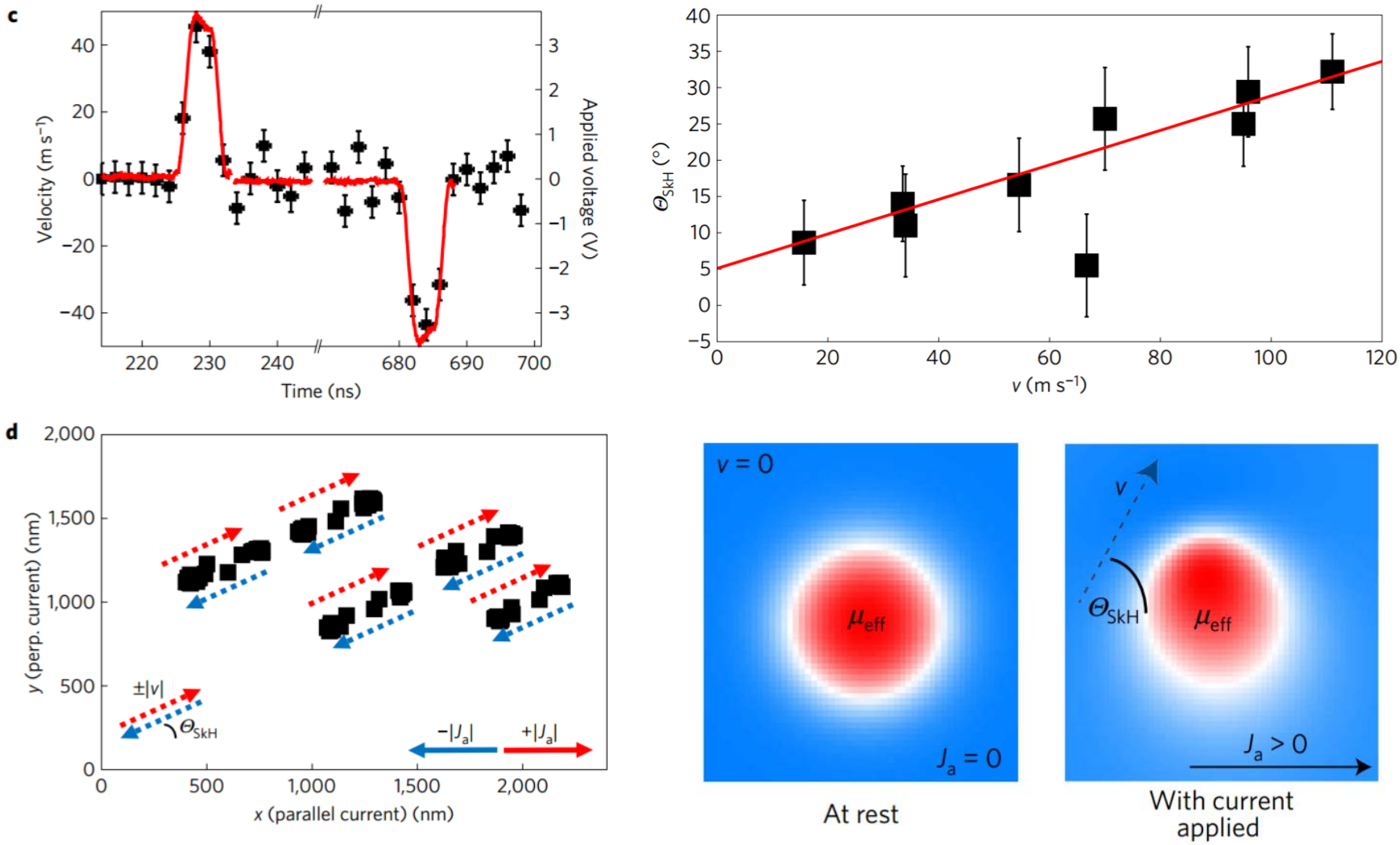
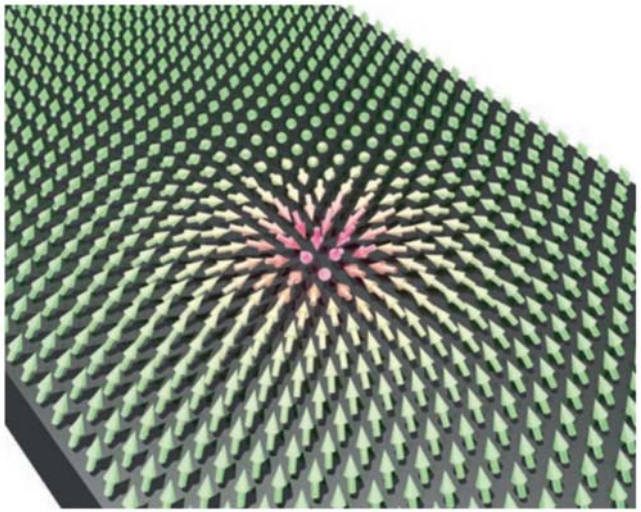
R. Tomasello, et al., Sci. Repts. 4, 6784 (2014)

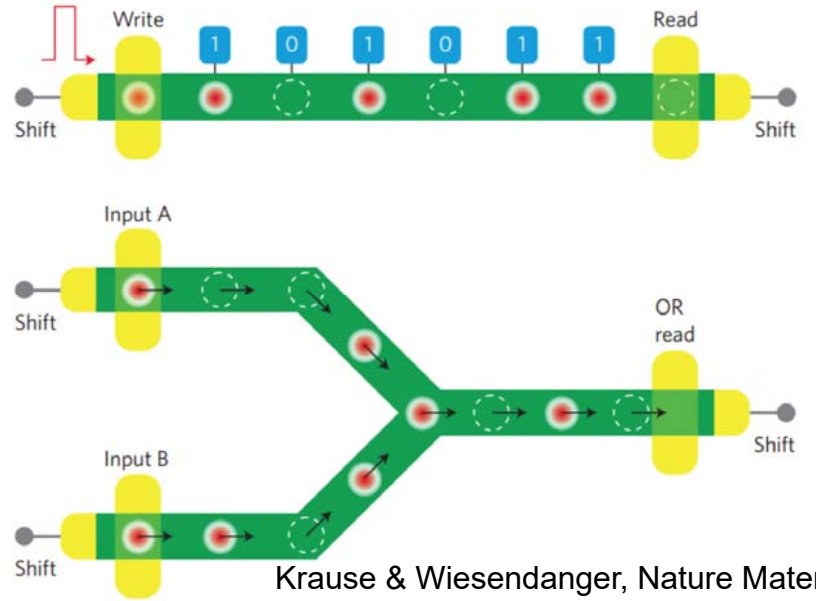
K. Litzius, et al., Nature Physics AOP (2016)

Skyrmion Hall Effect

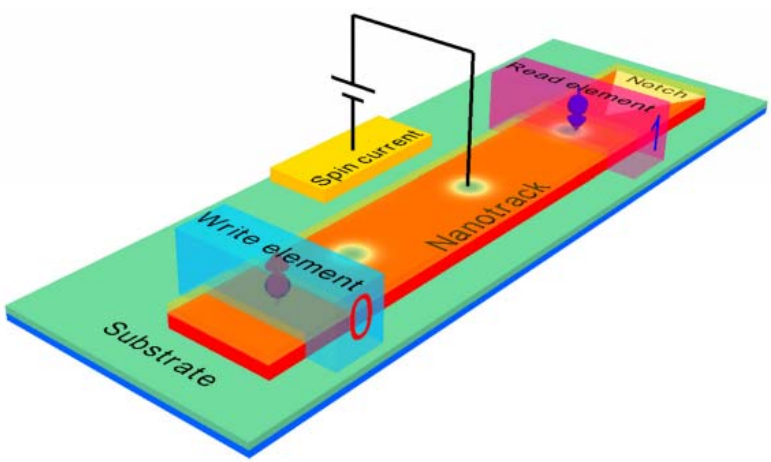


Skyrmion Writing by Spin Orbit Torque

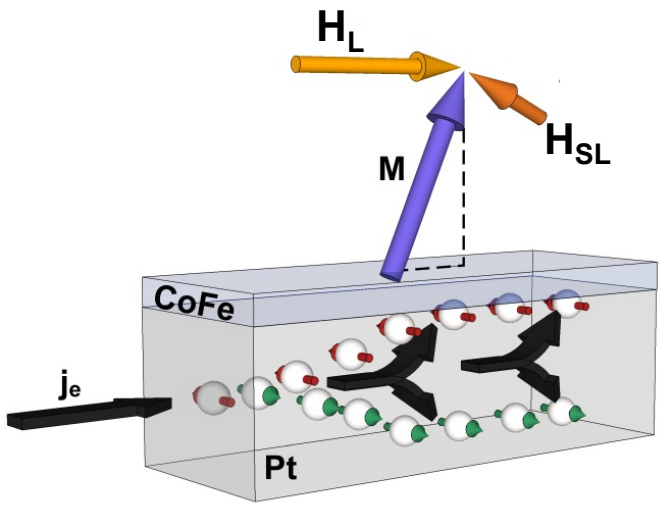




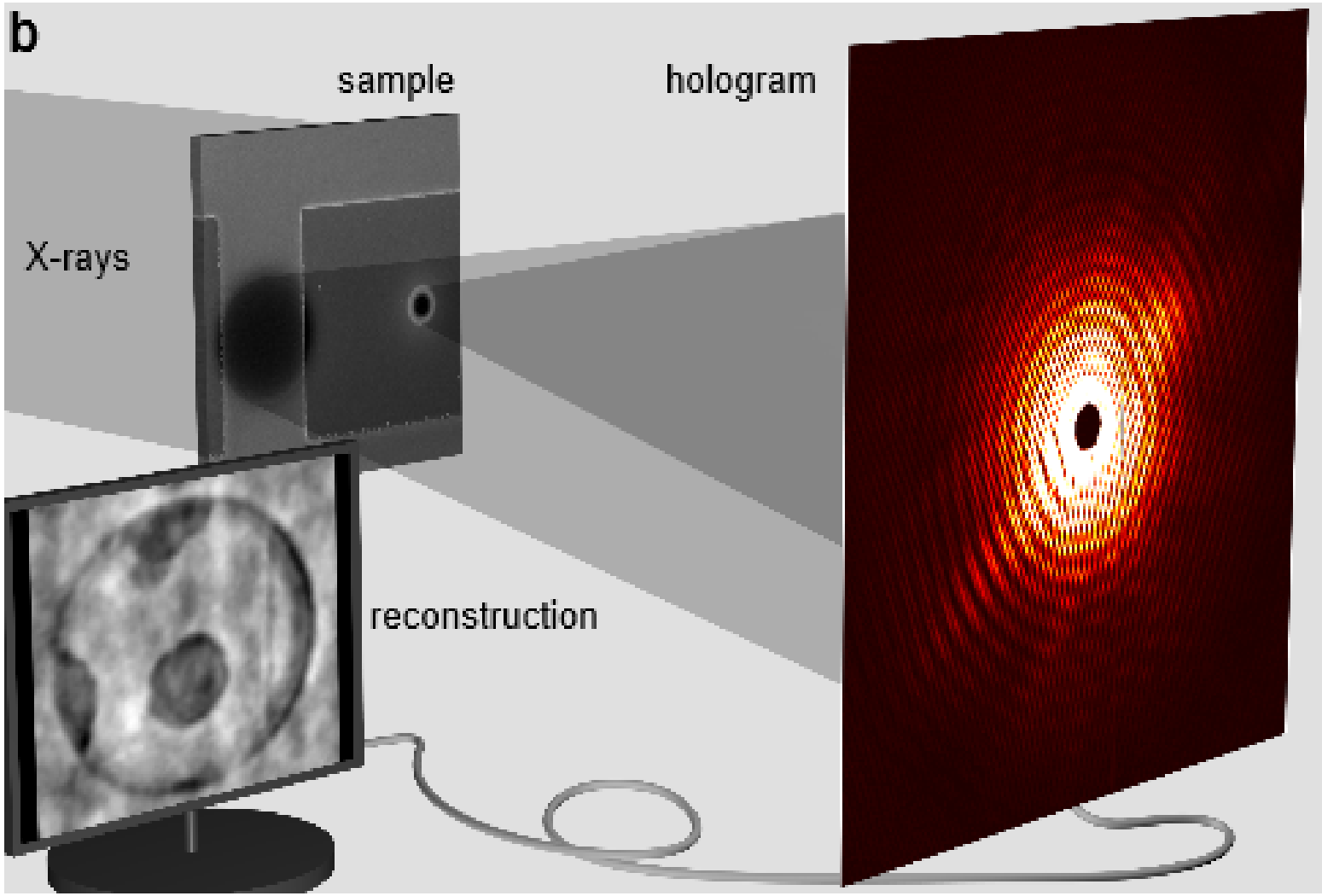
Krause & Wiesendanger, Nature Mater. 15, 493 (2016).



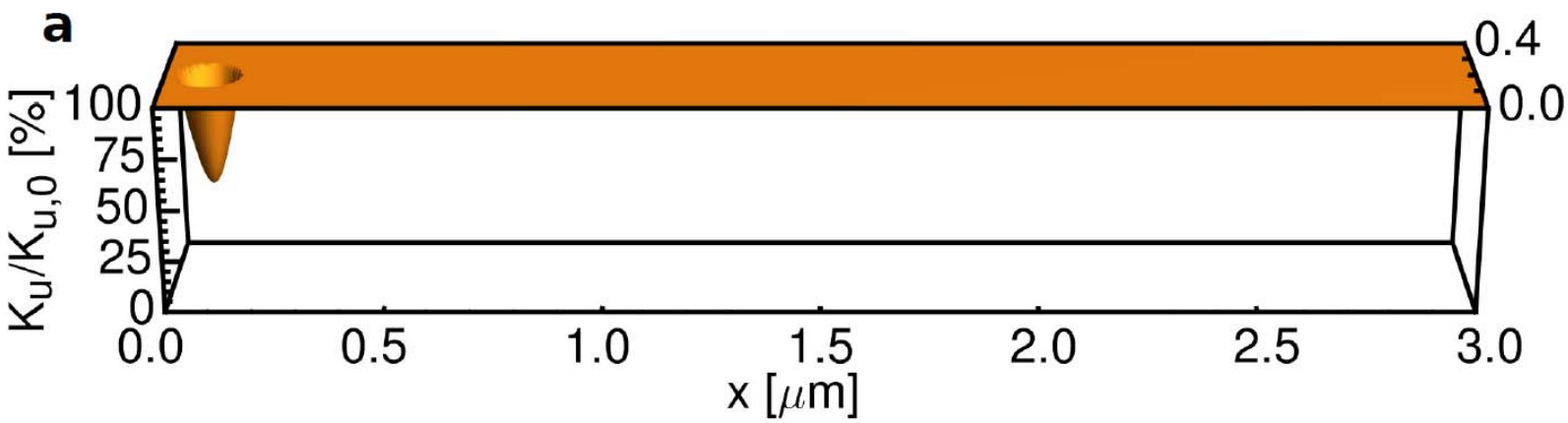
X. Zhang, et al., Sci. Rept. 5:7643 (2015)



X-Ray Holography



A skyrmion racetrack



F. Buettner, et al., Nature Nanotechnology, in press (2017)

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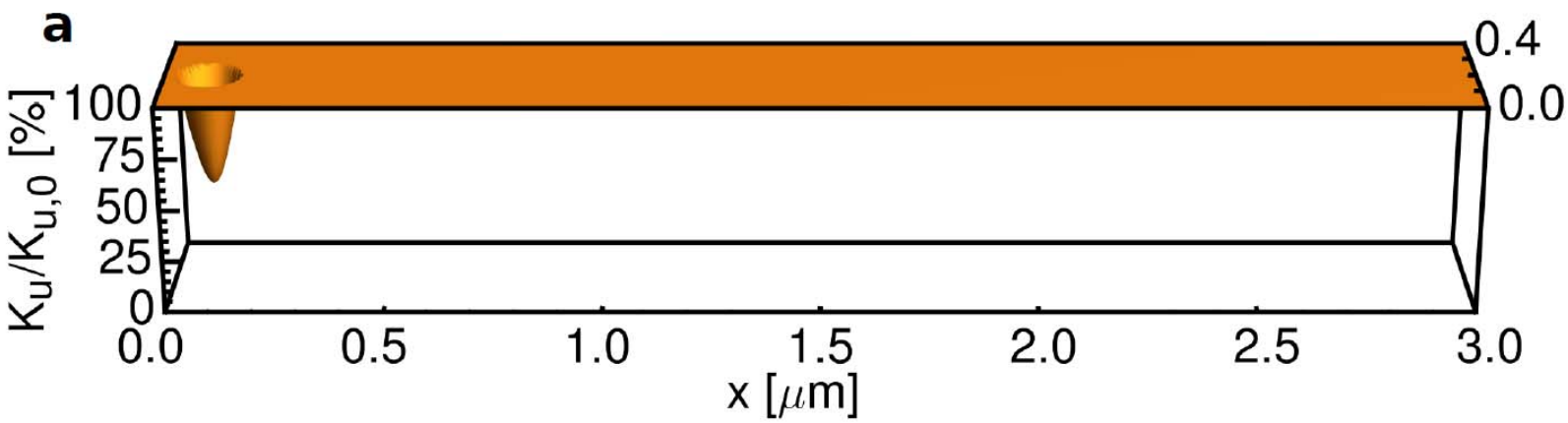

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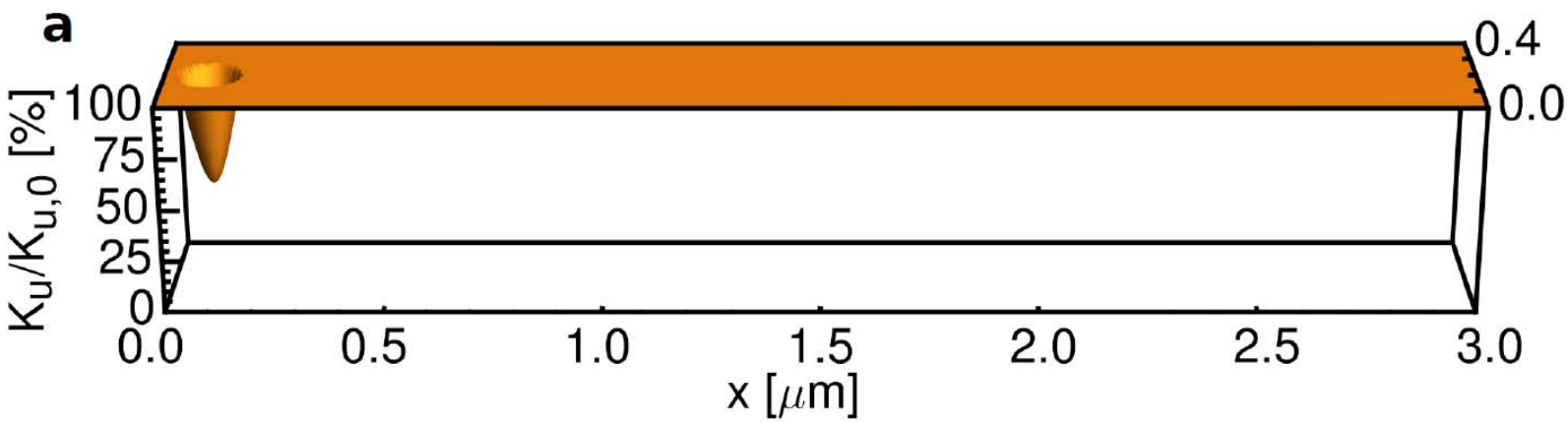

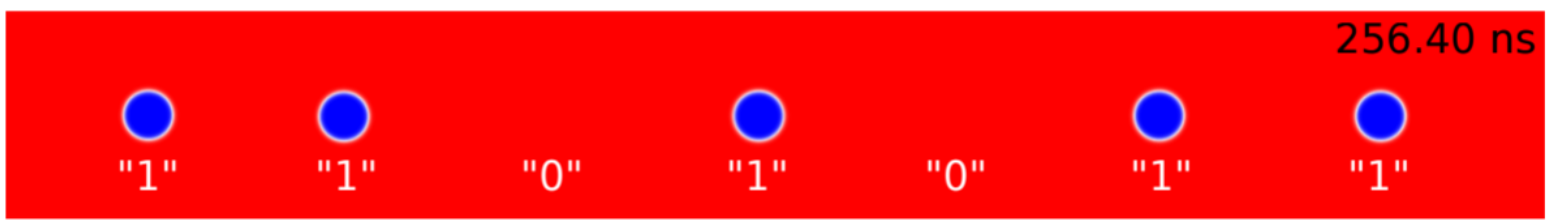

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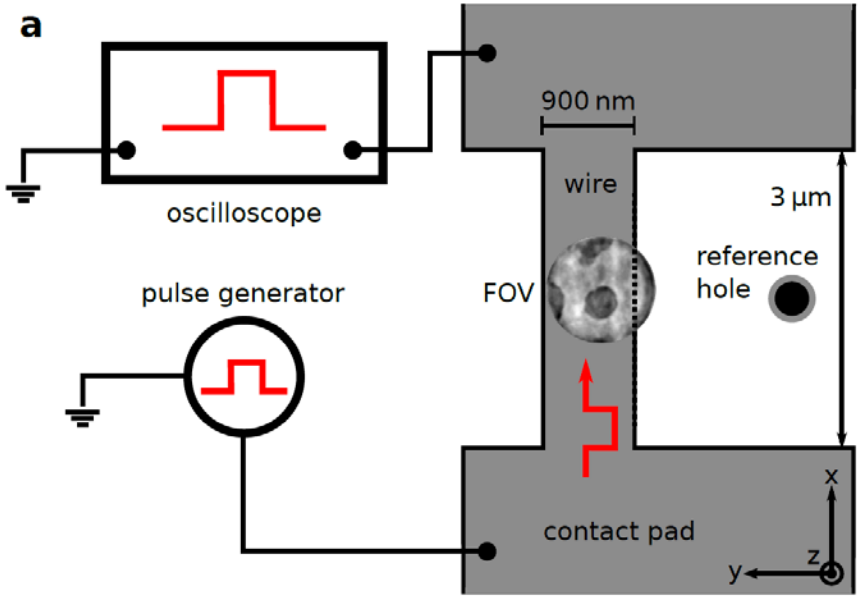

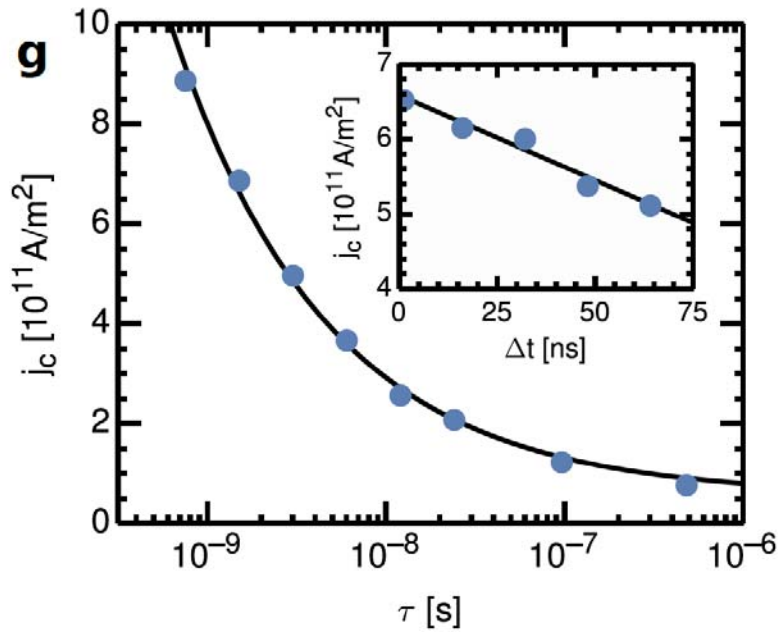

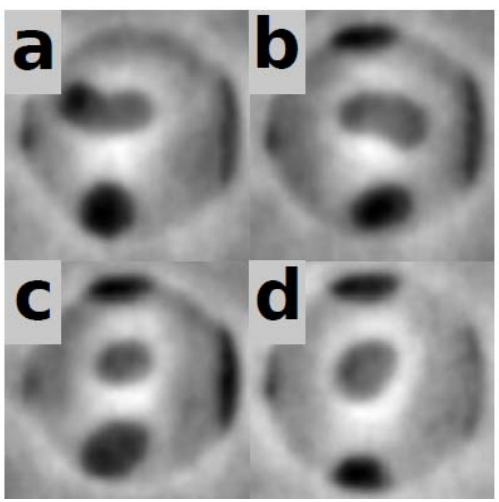

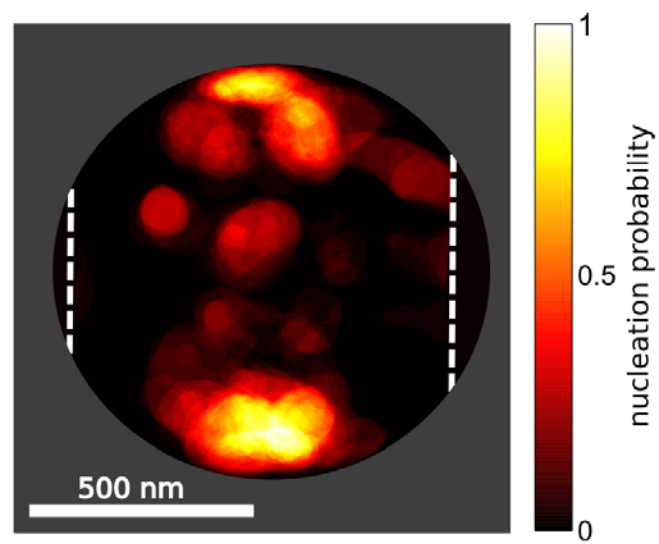

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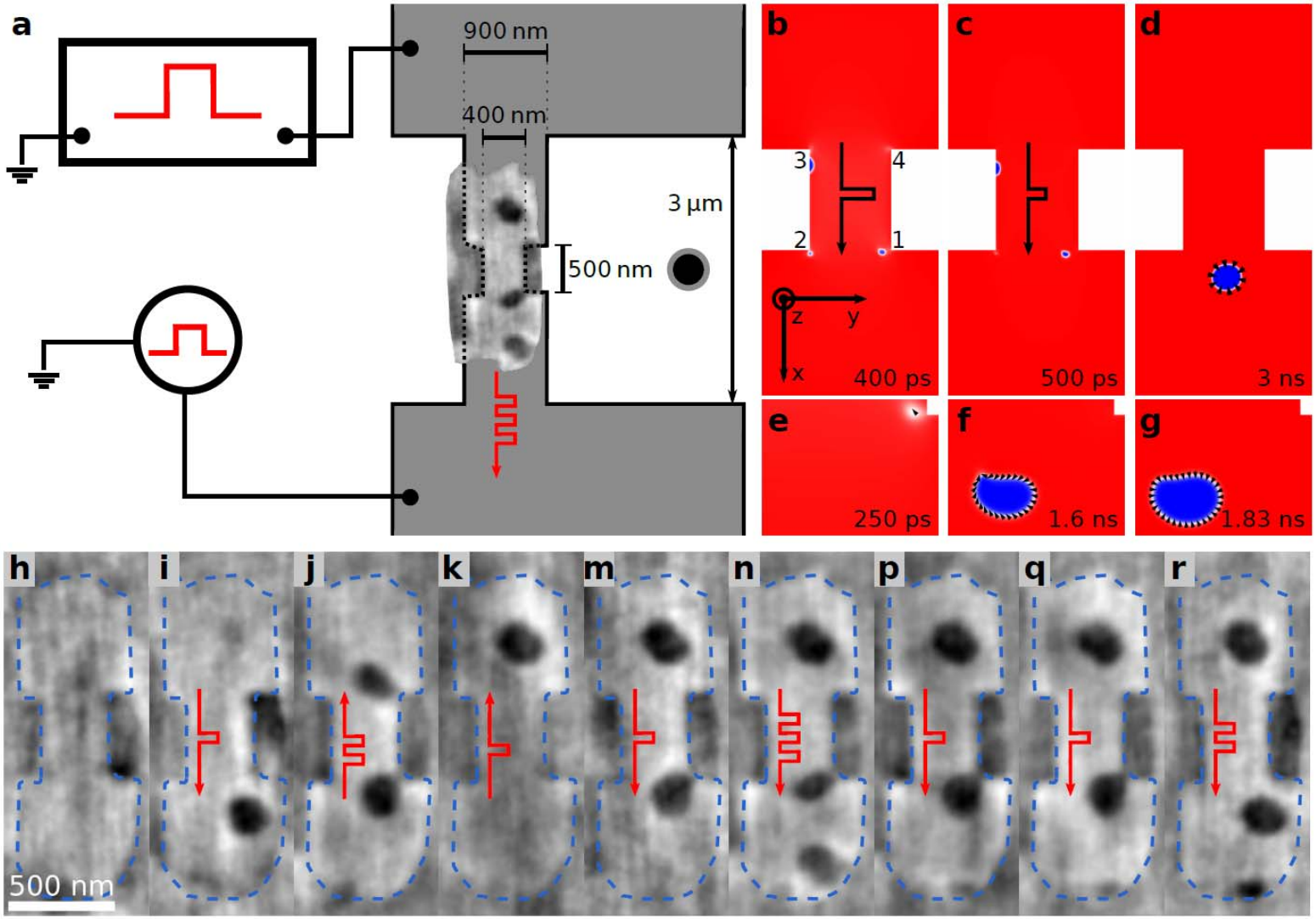

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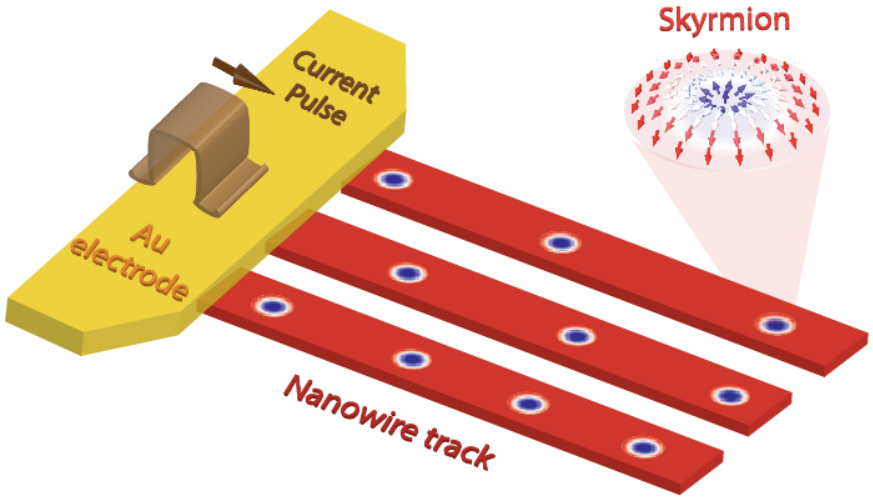
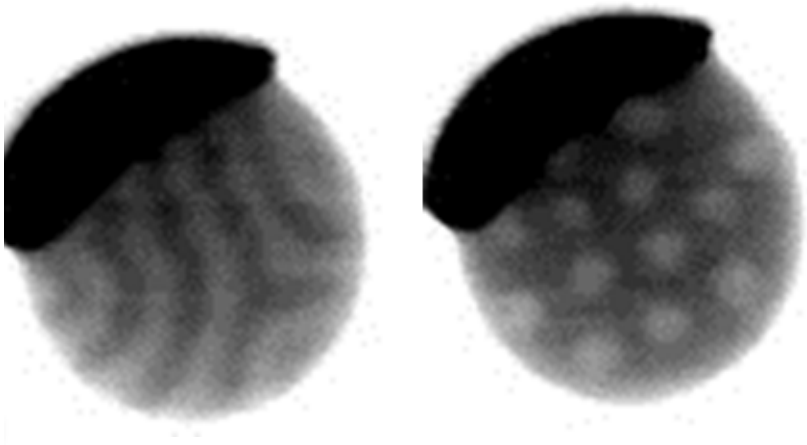
Summary





- **Skyrmions can be engineered and stabilized at room temperature in ultrathin transition metal films & multilayers**
- **Skyrmion velocities exceeding 100 m/s obtained via SHE**
- **Properties of any skyrmion in any material accessible through new analytical model**

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