Magnetism and Topology

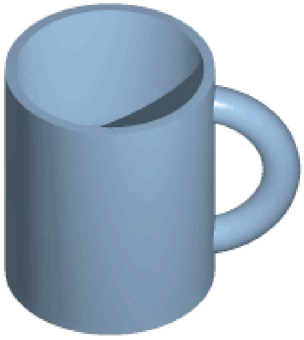
Yoshi Tokura

RIKEN Center for Emergent Matter Science (CEMS)

Department of Applied Physics, University of Tokyo

Topological spin textures – real & momentum space-

- Spin chirality
- Skyrmions
- Magnetic topological insulators



Wikipedia

Collaborators

- ***RIKEN (Japan)***

  X. Z. Yu, , S. Seki N. Nagaosa, Y. Tokunaga,
  D. Okuyama, Y. Taguchi, M. Kawasaki,
  D. Morikawa, T. Arima, N. Ogawa, M. Kubota
  W. Koshibae

- ***Univ. of Tokyo (Japan)***

  Y. Kanazawa, Y. Onose,
  S. Ishiwata, A. Tsukazaki,
  M. Ichikawa, Y. Shiomi, K. Shibata,
  F. Kagawa, Y. Okamura, M. Mochizuk
  R. Yoshimi, J.G. Checkelsky

Xiuzhen Yu   Naoya Kanzawa

- ***Sung Kyun Kwan Univ. (Korea)***

  J. H. Han, J. H. Park

- ***MPI (Germany)***

  D. S. Inosov, J. H. Kim, B. Keimer

- ***PSI (Switzerland)***

  J. White, N. Egetenmeyer, J. Gaviland

- ***Groningen Univ. (Holland)***

  M. Mostovoy

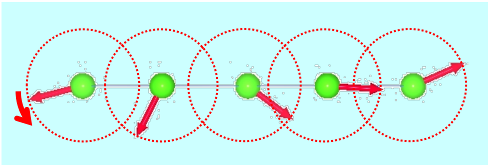
- ***JAEA (Japan)***

  K. Kakurai, S. Wakimoto

- ***NIMS (Japan)***

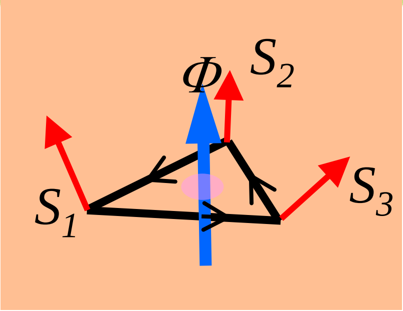
  Y. Matsui, K. Kimoto, W. Z. Zhang

Toward dissipation-less electronics and materials



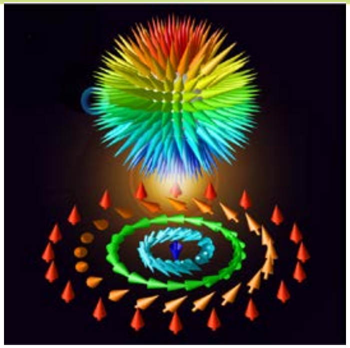
Vector spin chirality

Control of mangetism by polarization current



Scalar spin chirality

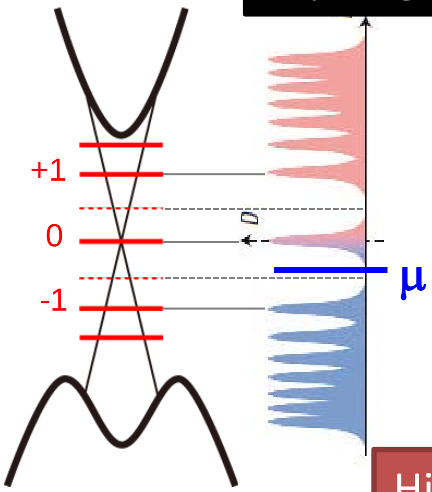
continuum



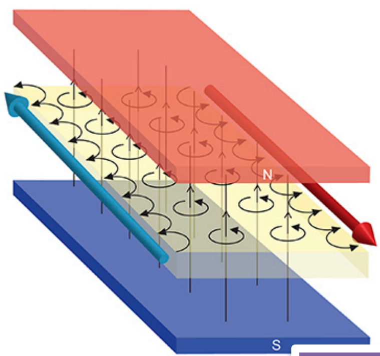
Skyrmions

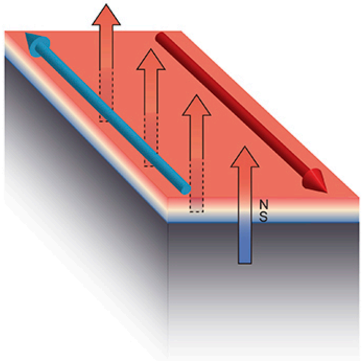
Huge fictitious magnetic field acting on moving electrons

Topological insulators – Dirac electron state on surface/interface-



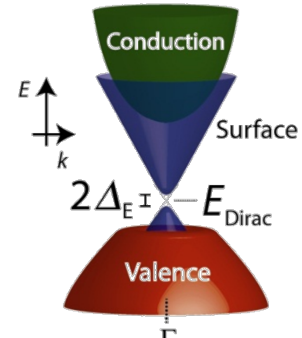
High T





Nondissipative edge conduction

Qunatum Hall effect

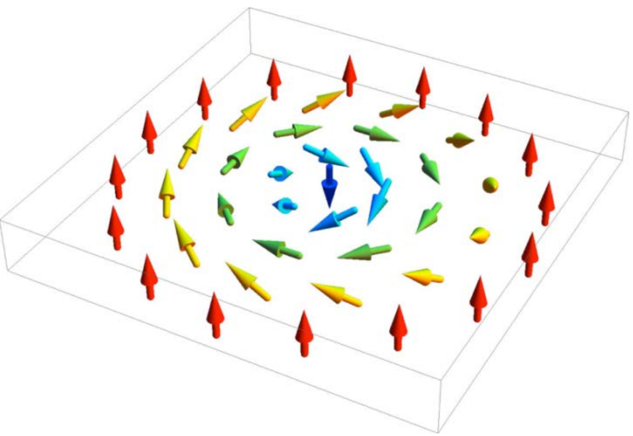


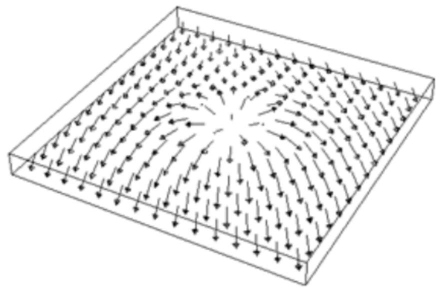
Quatum anomalous Hall effect

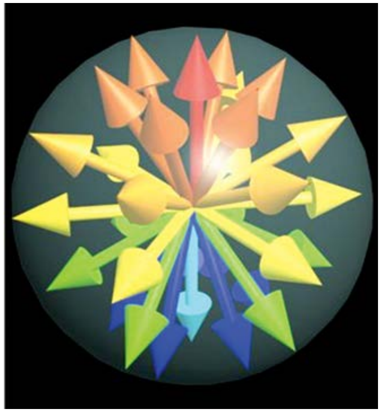
Zero H

What is magnetic skyrmion?

5 ~ 100 nm





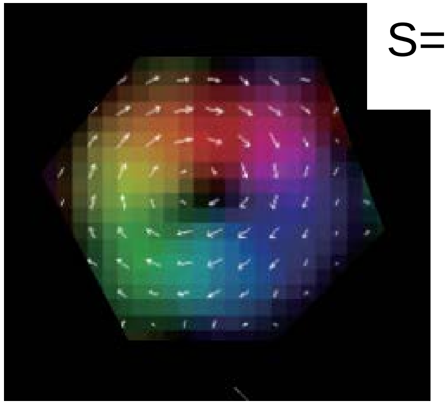


Topologically-stable spin vortex
with particle-like nature

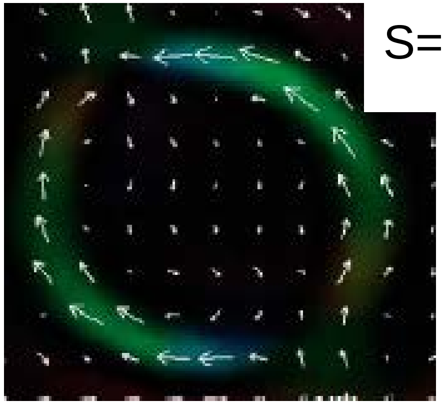
"skyrmion number"

$$\boxed{S = \frac{1}{4\pi}\int \vec{n}\cdot\frac{\partial\vec{n}}{\partial x}\times\frac{\partial\vec{n}}{\partial y}\mathrm{d}\vec{r} = -1}$$

Lateral component of
M of some bubbles



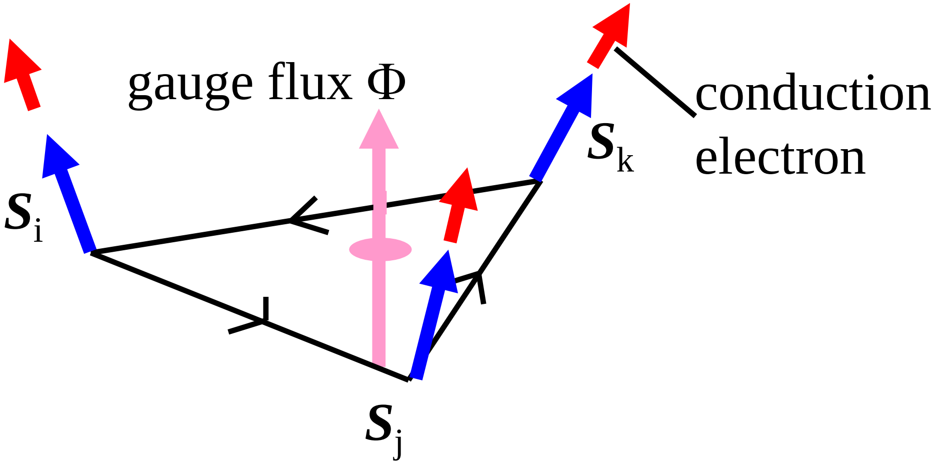
S=-1



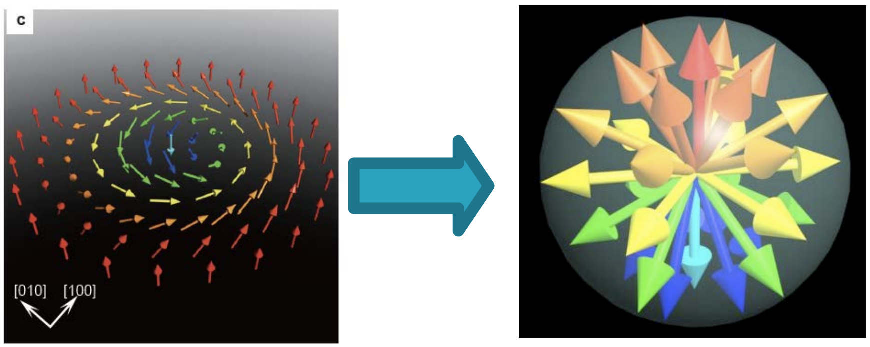
S=0

a pair of
Bloch lines

Skyrmion



Mapping to a sphere

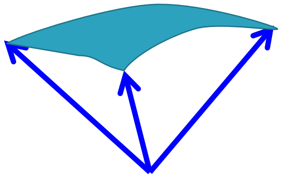


Solid angle $\Omega = 4\pi$

<u>Cf. Spin chirality</u>

$$\vec{S}_i \cdot (\vec{S}_j \times \vec{S}_k)$$

$= 1/2\ \Omega$ Solid angle



Continuum approximation

Total spin Chirality

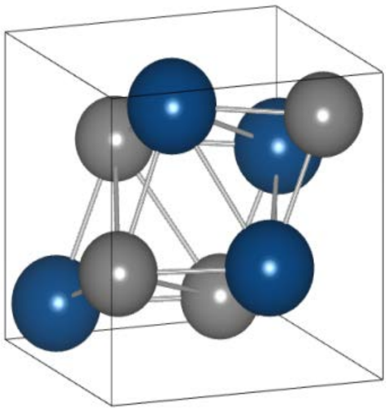
$$= \frac{1}{4\pi S^3} \int d^2\mathbf{r}\,\mathbf{S} \cdot (\nabla_x \mathbf{S} \times \nabla_y \mathbf{S})$$

$= N_S$ Skyrmion number

Skyrmion carries emergent magnetic field.

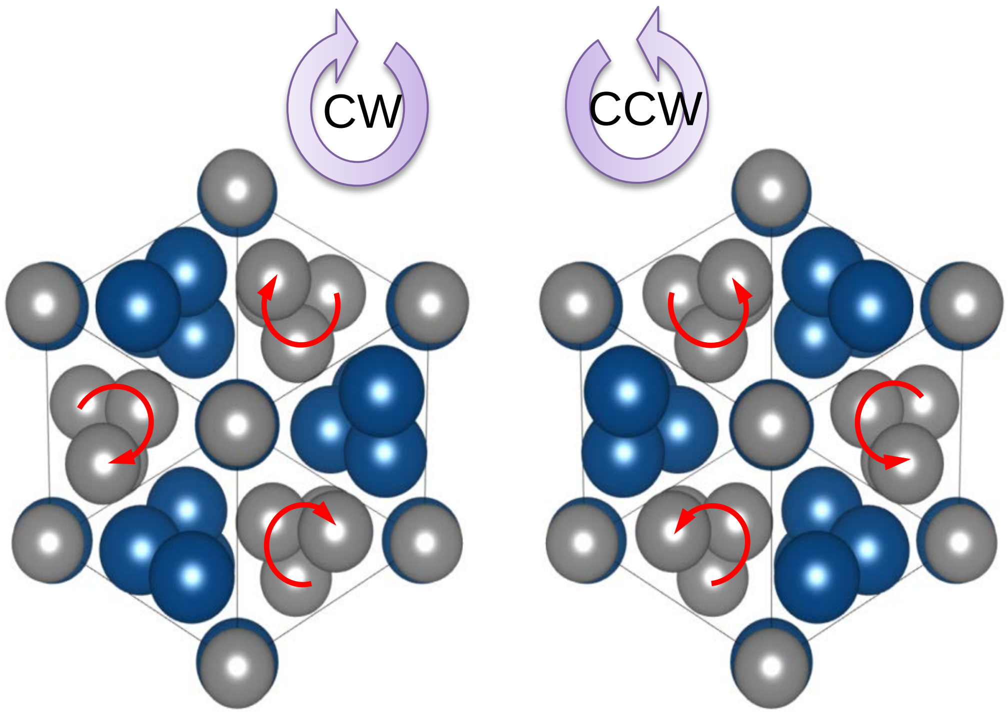
Helical spin order in B20-type crystals

Crystal structure



- ● : Transition-metal element
- ● : Group 14 element

  - Cubic ($P2_13$)
  - Noncentrosymmetric



Chiral lattice structure

Magnetic structure

$$H = \sum \left(-J\vec{S}_i \cdot \vec{S}_j + \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \right)$$

Ferro + DM

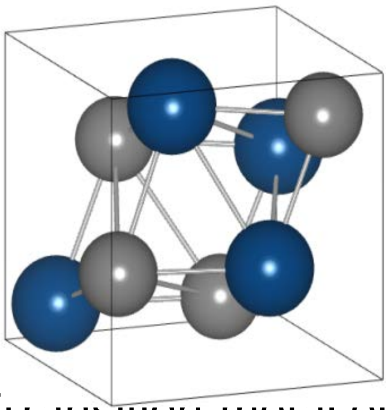
Dzyaloshinsky-Moriya

Helical spin structure

Long period～aJ/D～10nm-300nm

Helical spin order in B20-type crystals

Crystal structure



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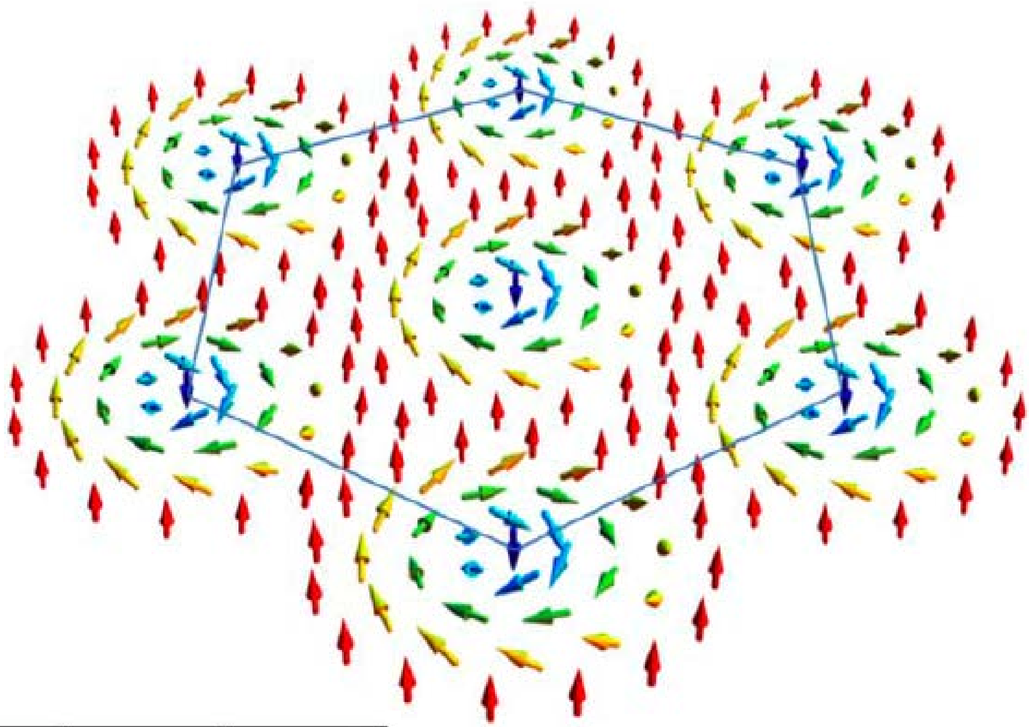
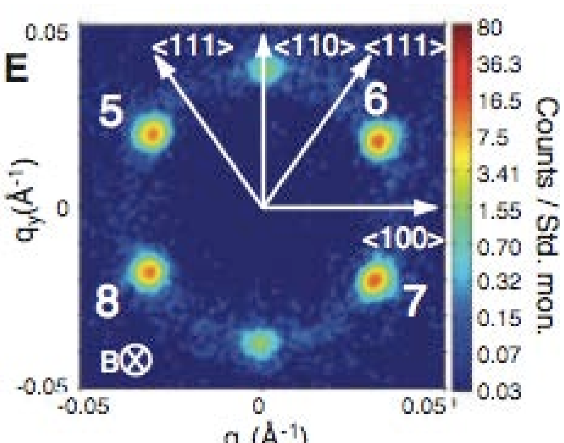
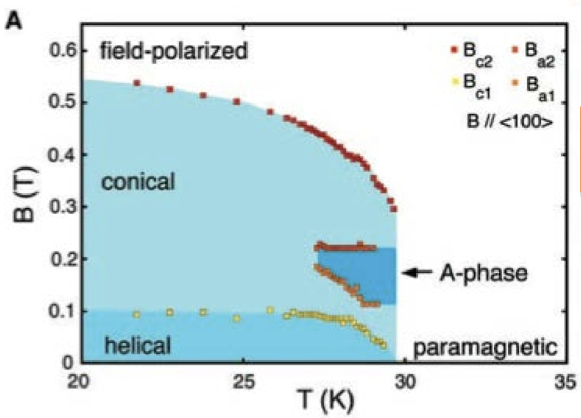


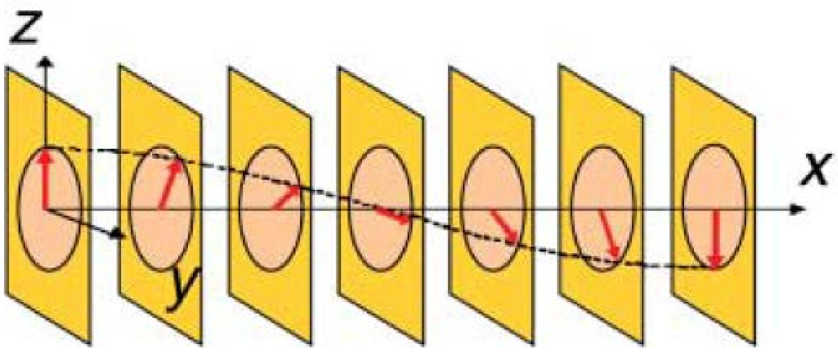




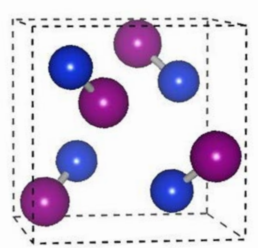
MnSi

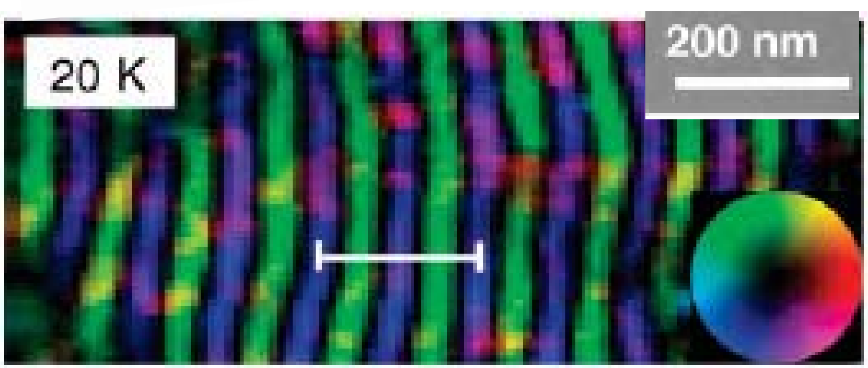
S. Mühlbauer *et. al.*, Science 323 915 (2009)

Toward real space observation of Skyrmion structure



F





M. Uchida, Y. Onose, Y. Matsui, Y. Tokura, Science (2006)

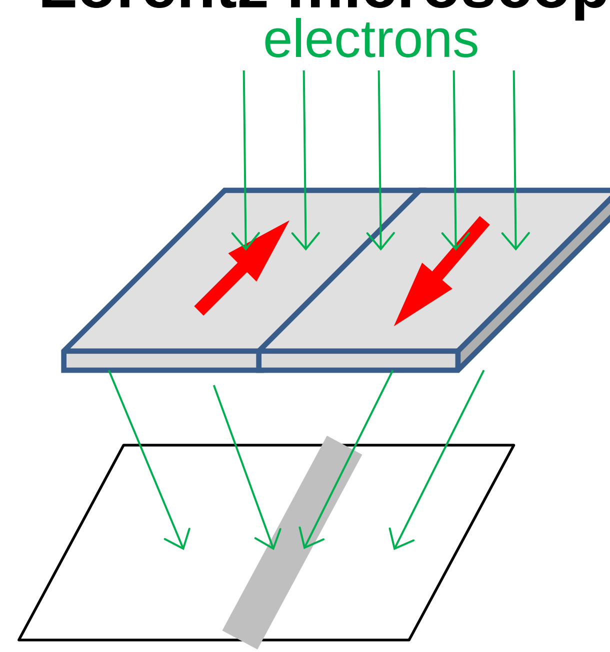
$$H = \sum \left(\underline{\underline{-J\vec{S}_i \cdot \vec{S}_j}} + \underline{\underline{\vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)}} \right)$$

Ferro + DM

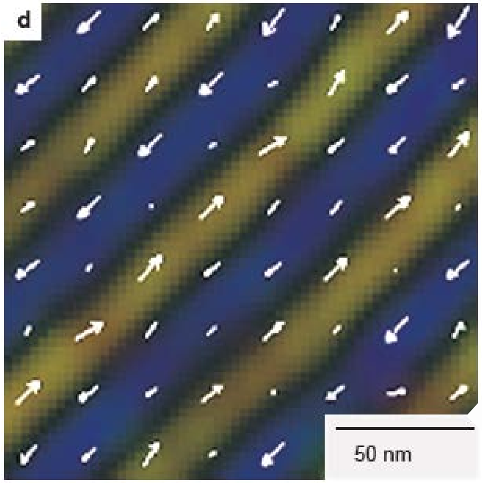
Helical spin structure

Long period～aJ/D～$10nm$-$300nm$

Lorentz microscope

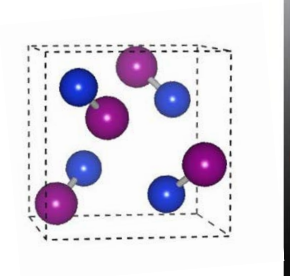


Real Space Observation of Skyrmion crystal

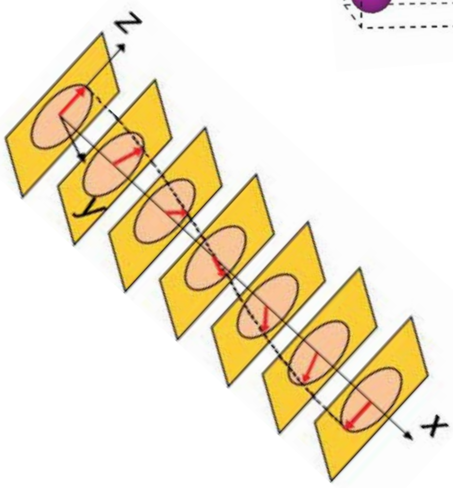


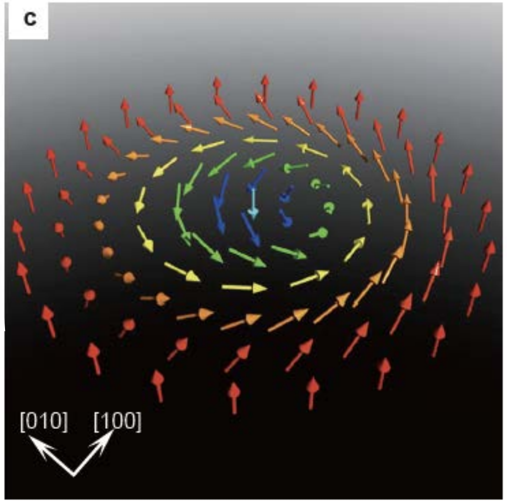
$Fe_{0.5}Co_{0.5}Si$

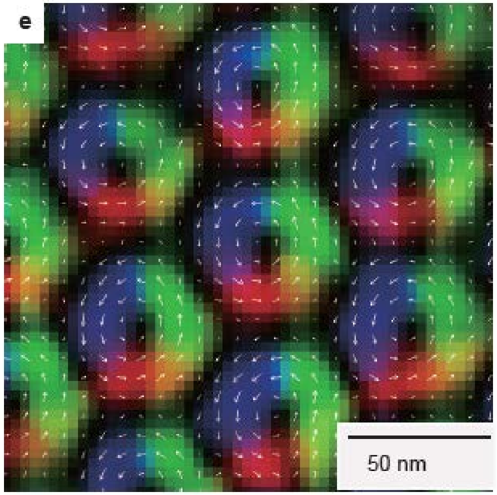
T=25K



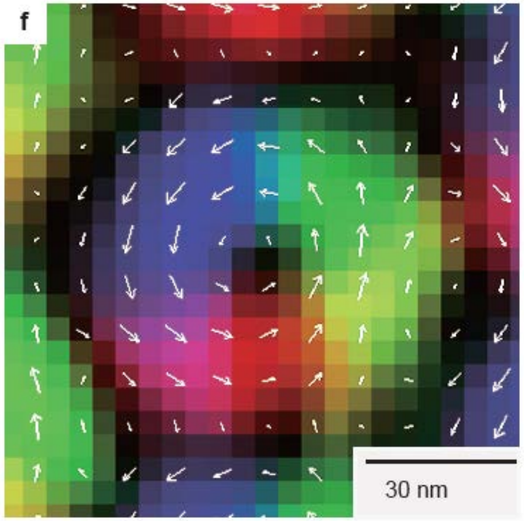
H=0







H=50mT

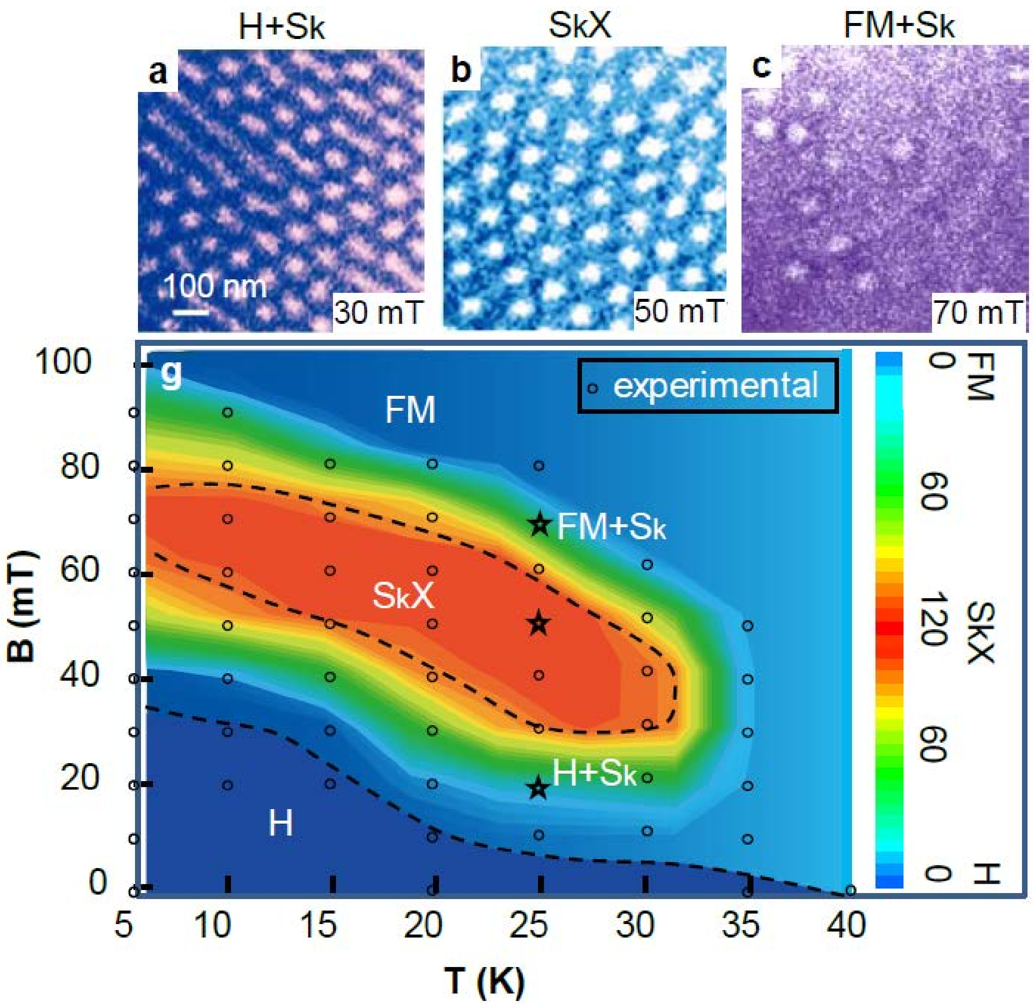


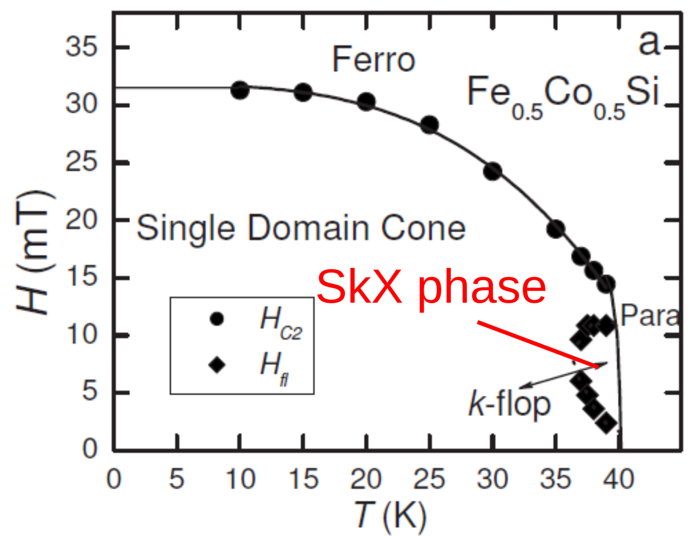
X.Z. Yu, Y.T *et al.* Nature *(2010).*

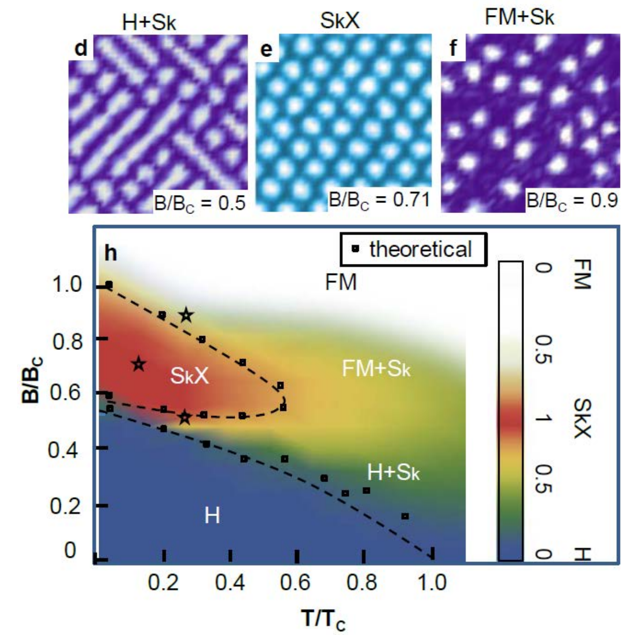
H-T Phase diagram

Bulk sample

20nm-thick film (Lorentz TEM)







Skx: Skyrmion Crystal

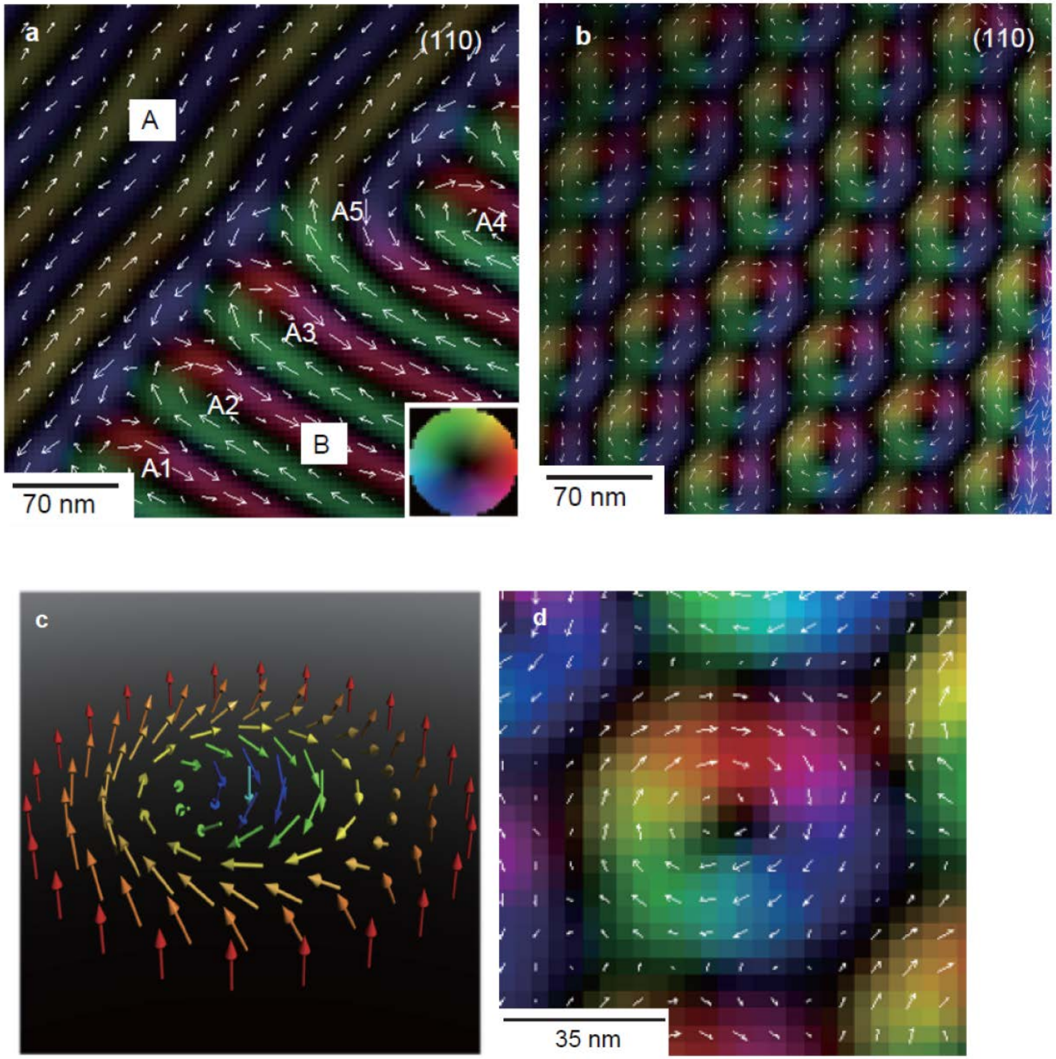
2D simulation

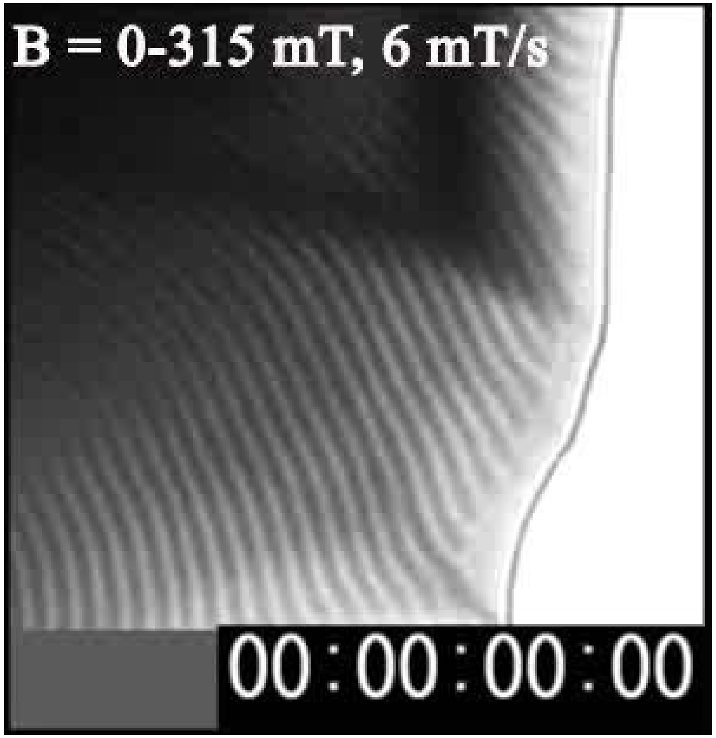
FeGe: from helical to skyrmion crystal at 260K

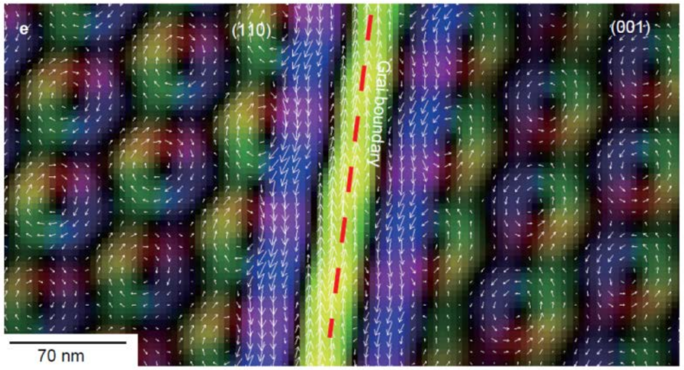
X.Z. Yu et al. Nat. Mater.(2010)

H=0

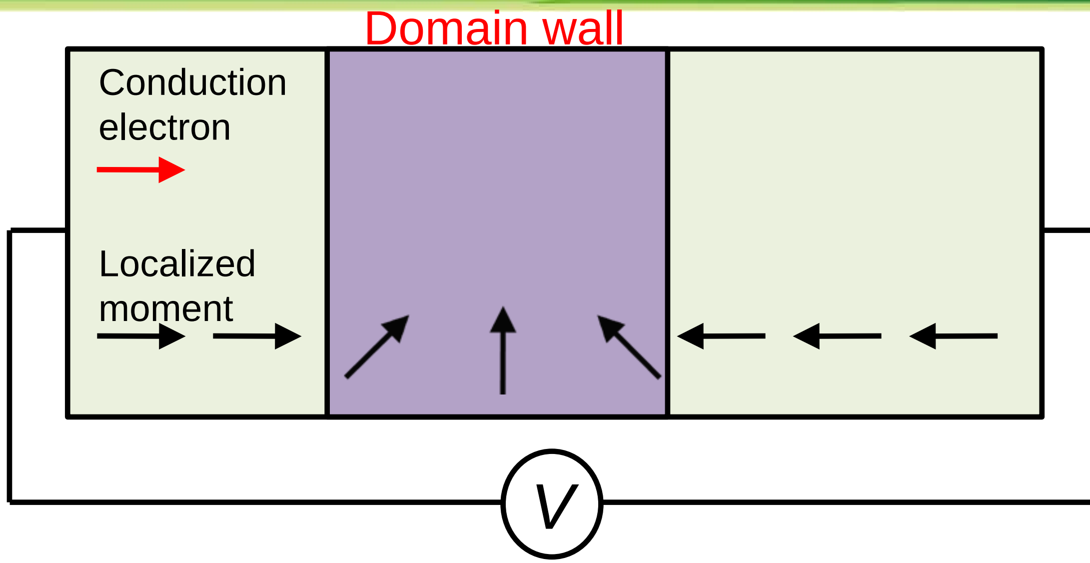
H=0.1T





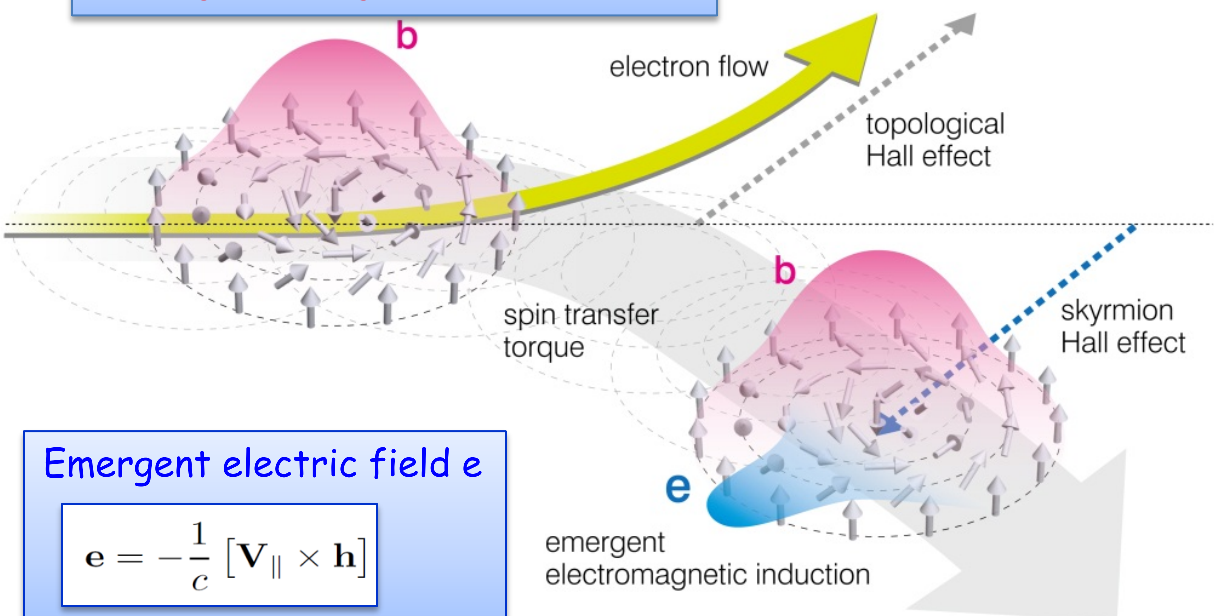


Current drive of skyrmions and emergent EM field



Domain wall motion
by spin transfer torque

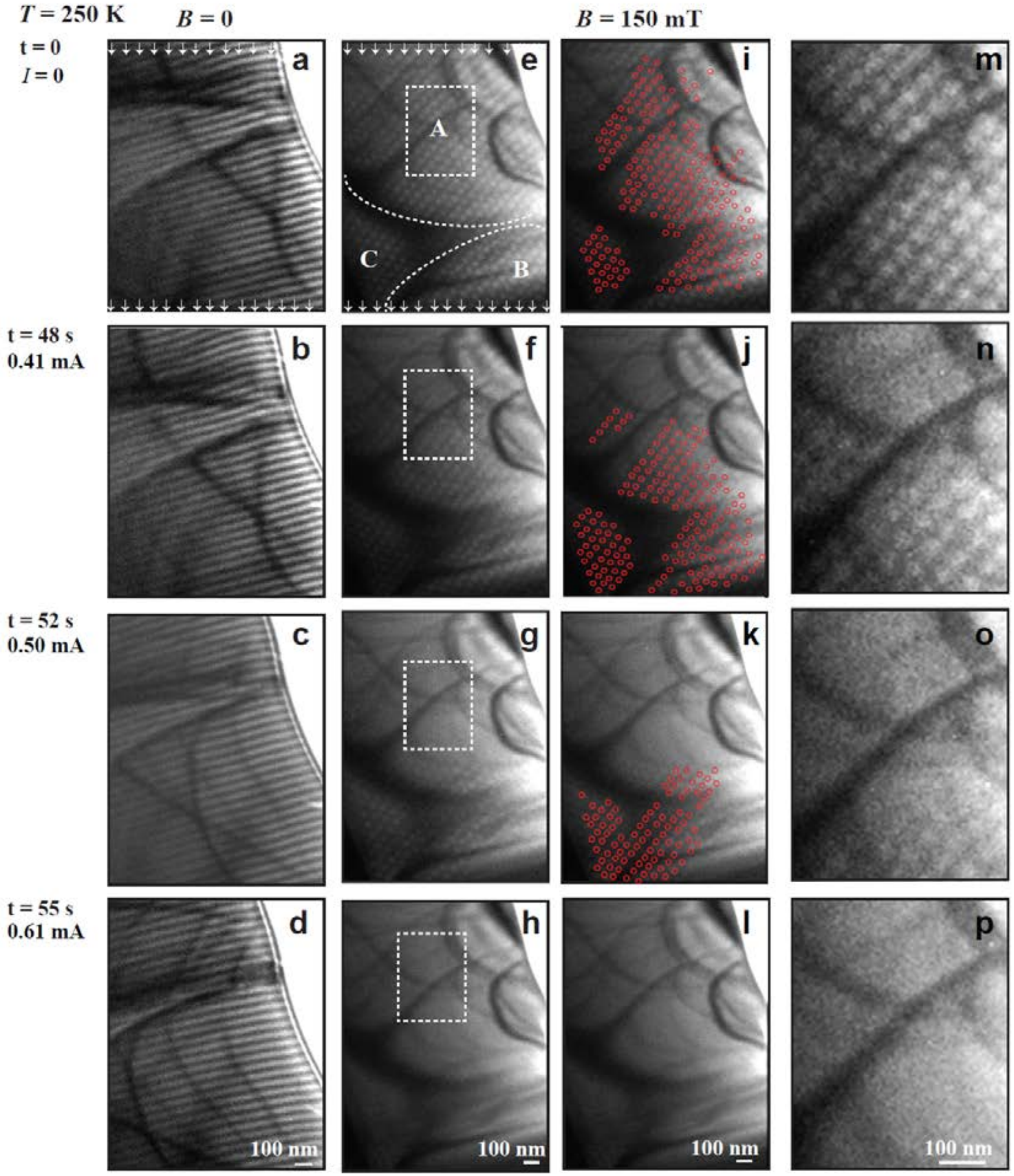
Topological Hall effect (THE)
Emergent magnetic field *b*

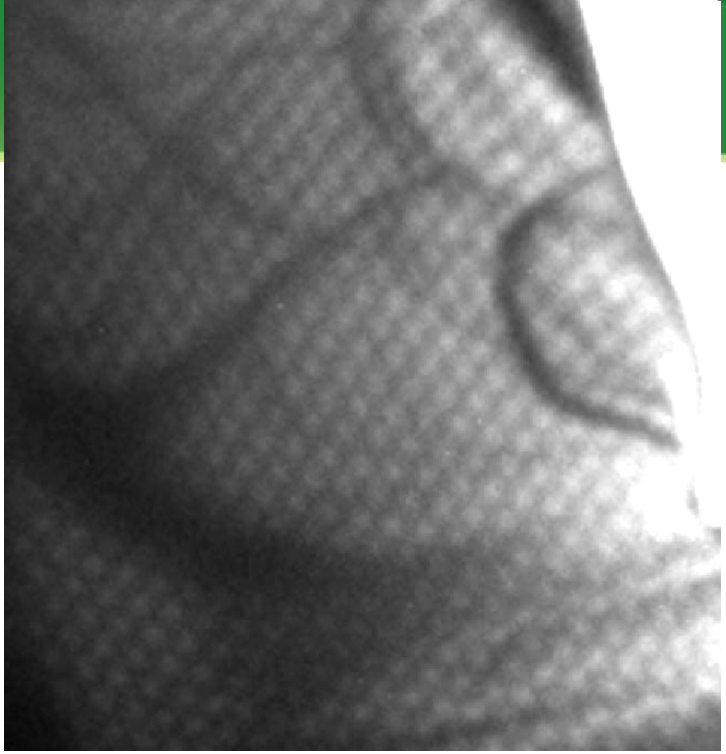


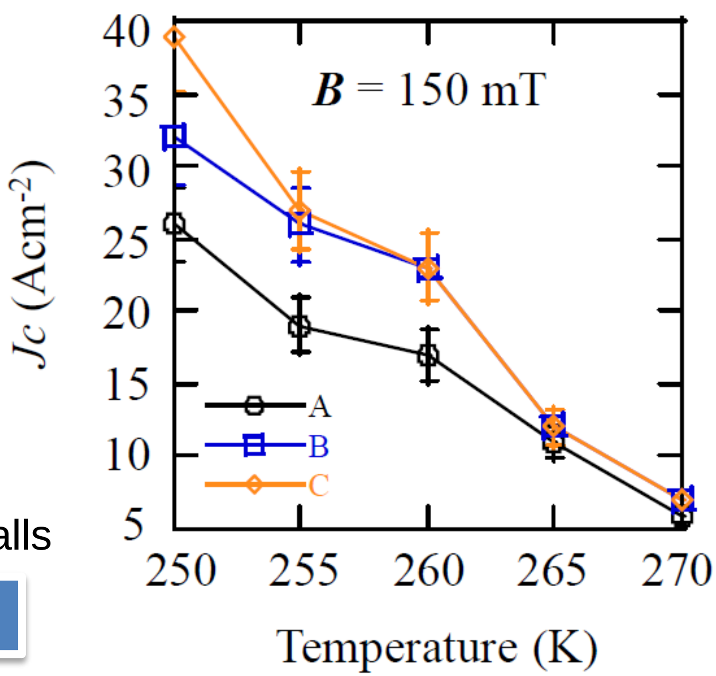
-counteraction of THE
→ skyrmion Hall effect

Emergent electric field *e*

$$\mathbf{e} = -\frac{1}{c}\left[\mathbf{V}_{\|} \times \mathbf{h}\right]$$







J_c<100A/cm^2

J_c~10^7A/cm^2 for ordinary domain walls

no intrinsic / minimal extrinsic pinning effect on SkX

Zoology of skyrmions

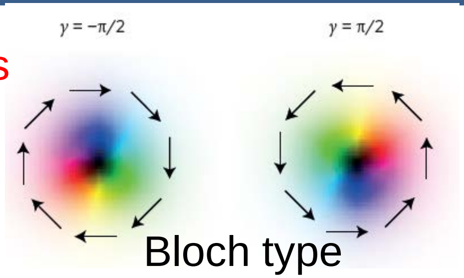
Generators of magnetic skyrmions

(a) Relativistic Dzyaloshinskii–Moriya (DM) interaction in non-centrosymmetric magnets

chiral-lattice magnets

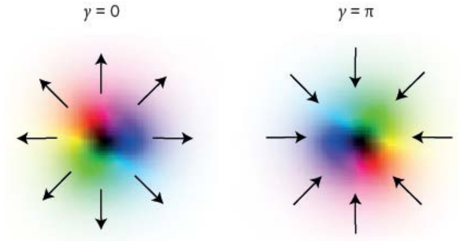
B20 copounds

Cu_2OSeO_3



Bloch type

interface ferromag.



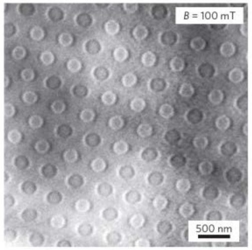
Neel type

(b) Long-ranged magnetic dipolar interactions in magnetic thin films with perpendicular easy axis anisotropy

M-type ferrite, $(LaSr)_3Mn_2O_7$, etc.

Generalization of Garel-Doniach model

helicity degree of freedom



X.Z. Yu *et al. PNAS, 109, 8856 (2012).*

(c) Frustrated exchange interactions

Multiple-q state with q=<111>/<100>

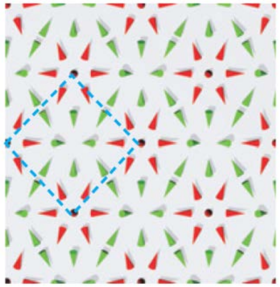
$SrFeO_3$ (Ishiwata et al.)

helicity degree of freedom

T.Ohkubo et al. PRL 108, 017206 (2012).

(d) 4-spin exchange interactions + DM

Fe monolayer on Ir (111)



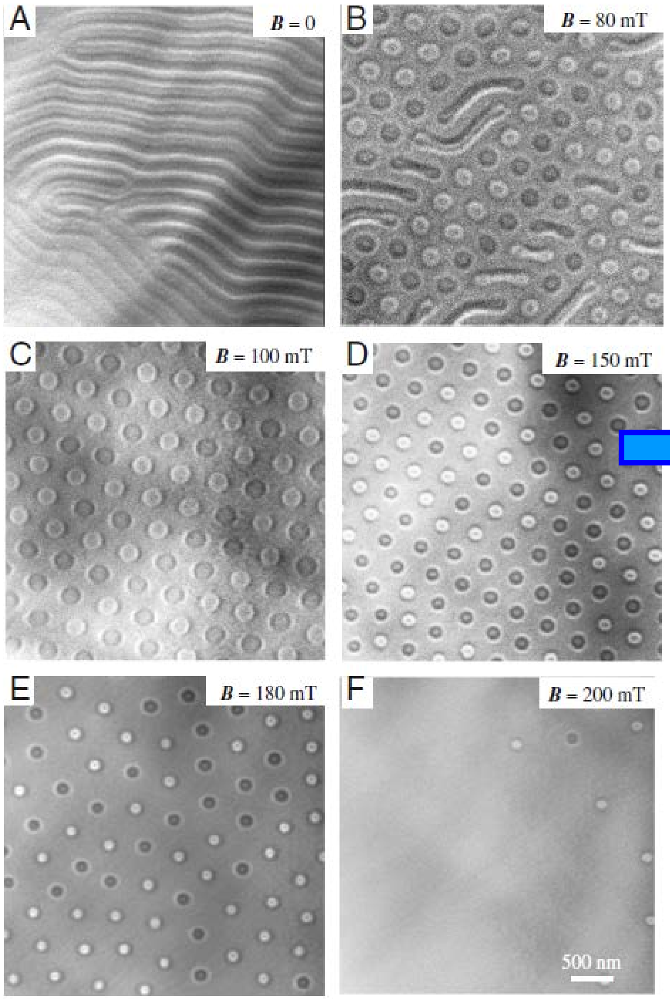
S. Hinze et al., Nature Physics 7, 713 :(2011).

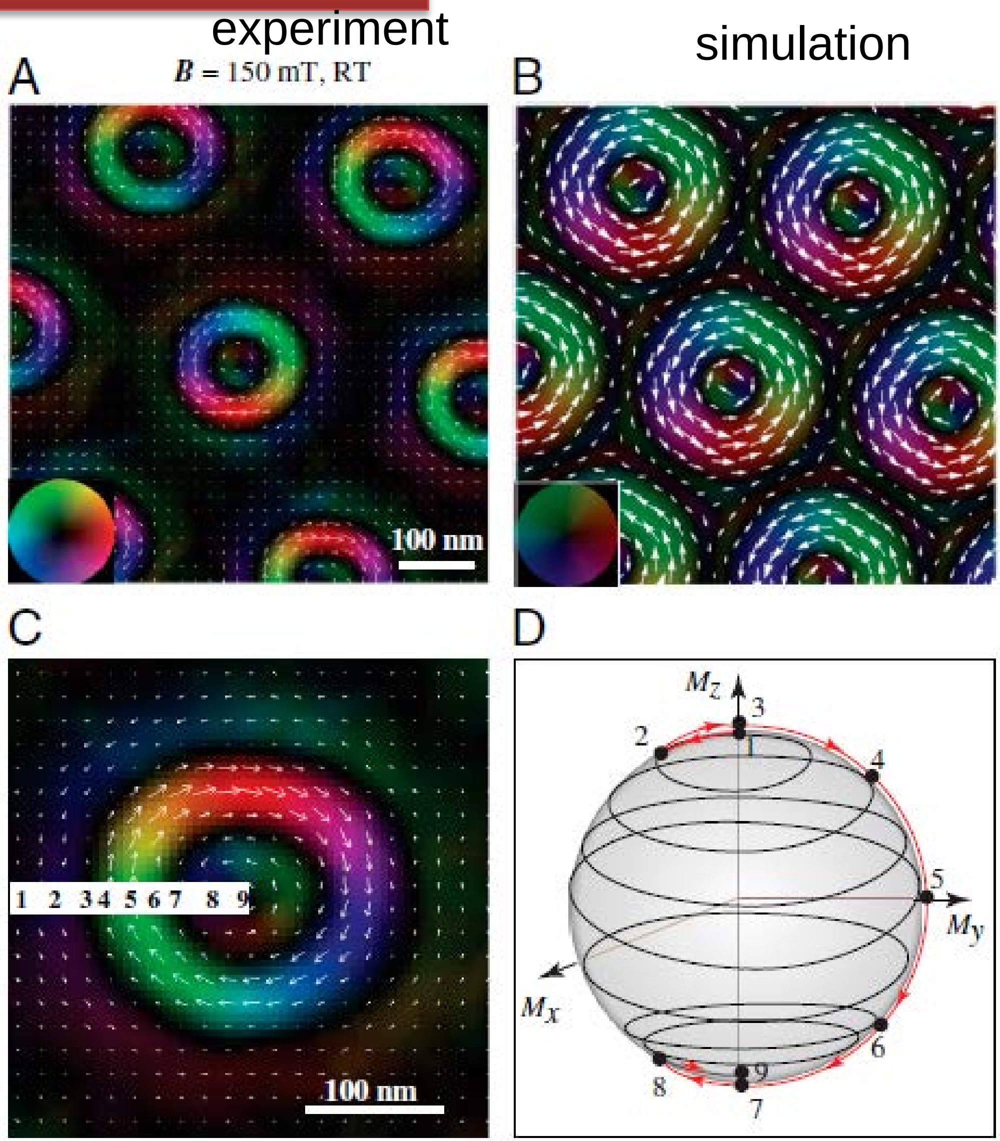
Dipolar interaction also generates skrymions with variable helicities

Yu et al. PNAS (2012)

Room temperature

M-type ferrite





$BaFe_{12\text{-}x\text{-}0.05}Sc_xMg_{0.05}O_{19}$

Biskyrmions in layered manganites

In centrosymmetric CMR manganite

A bound state of two skyrmions with opposite helicities

can be driven also with low current!

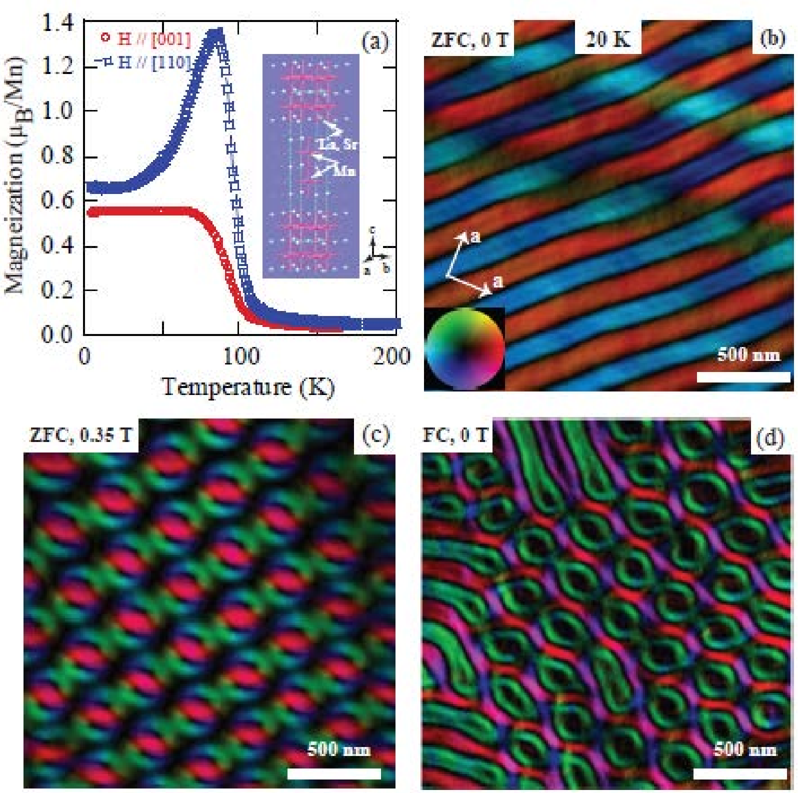
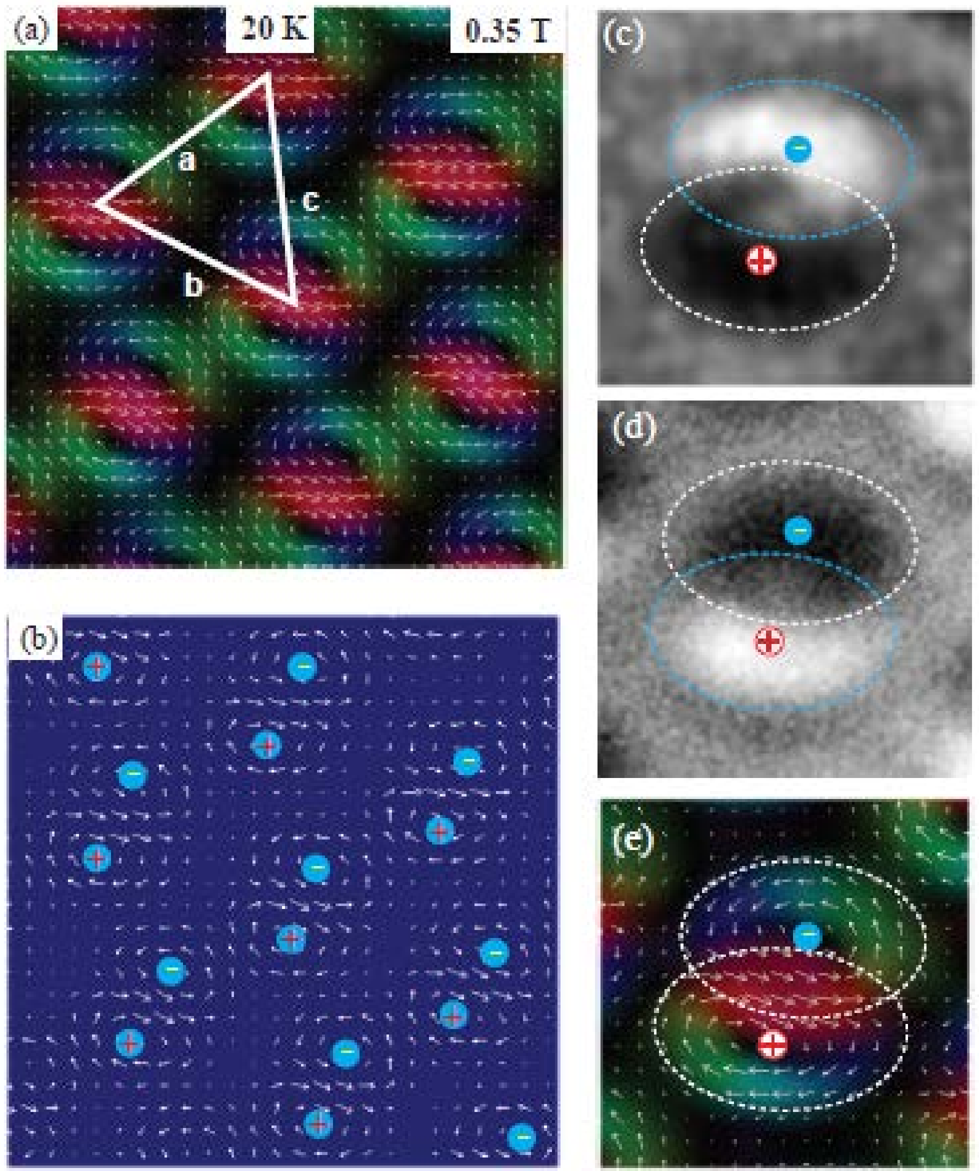
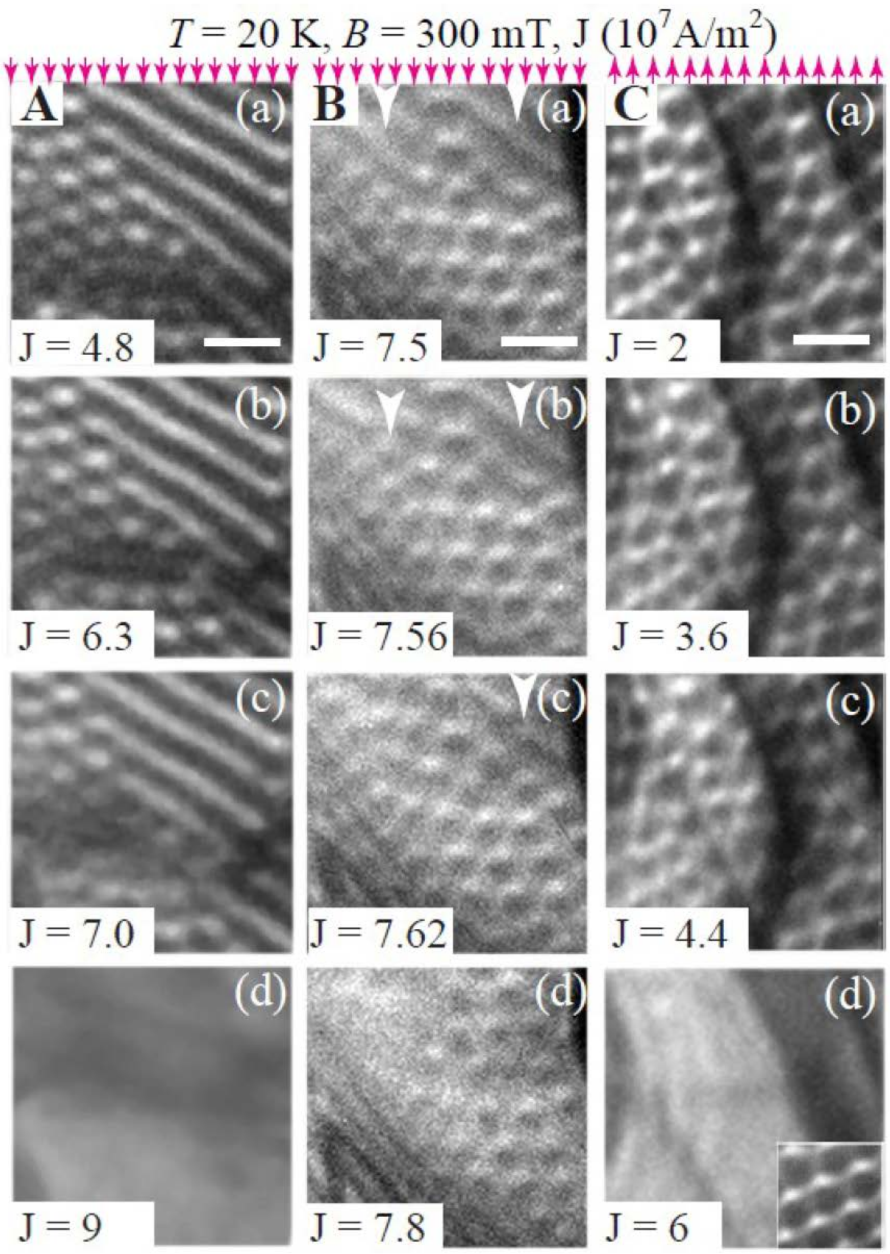
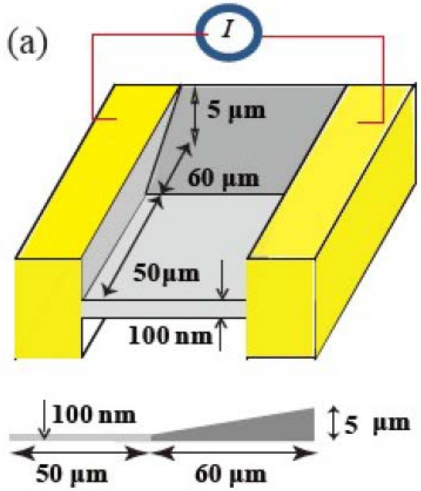


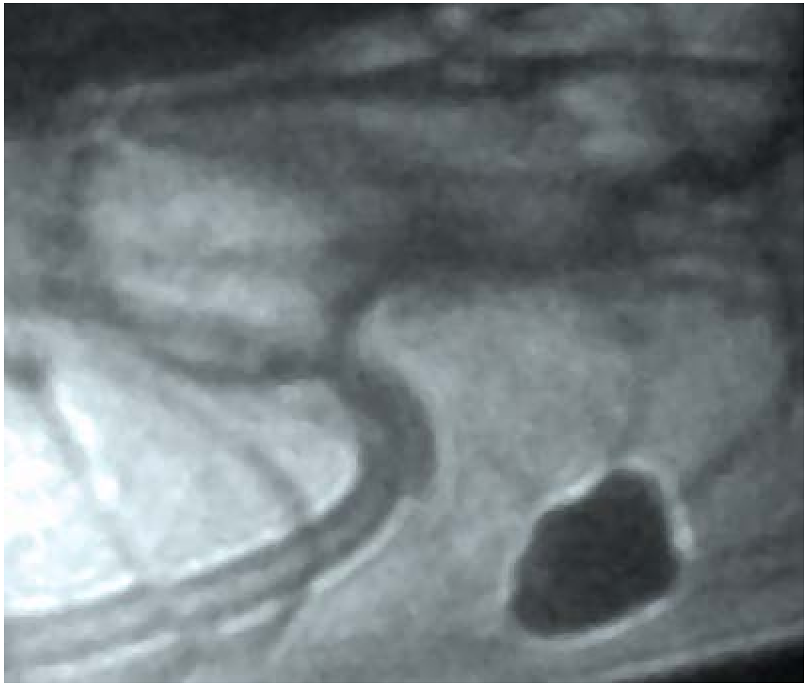
FIG. 1



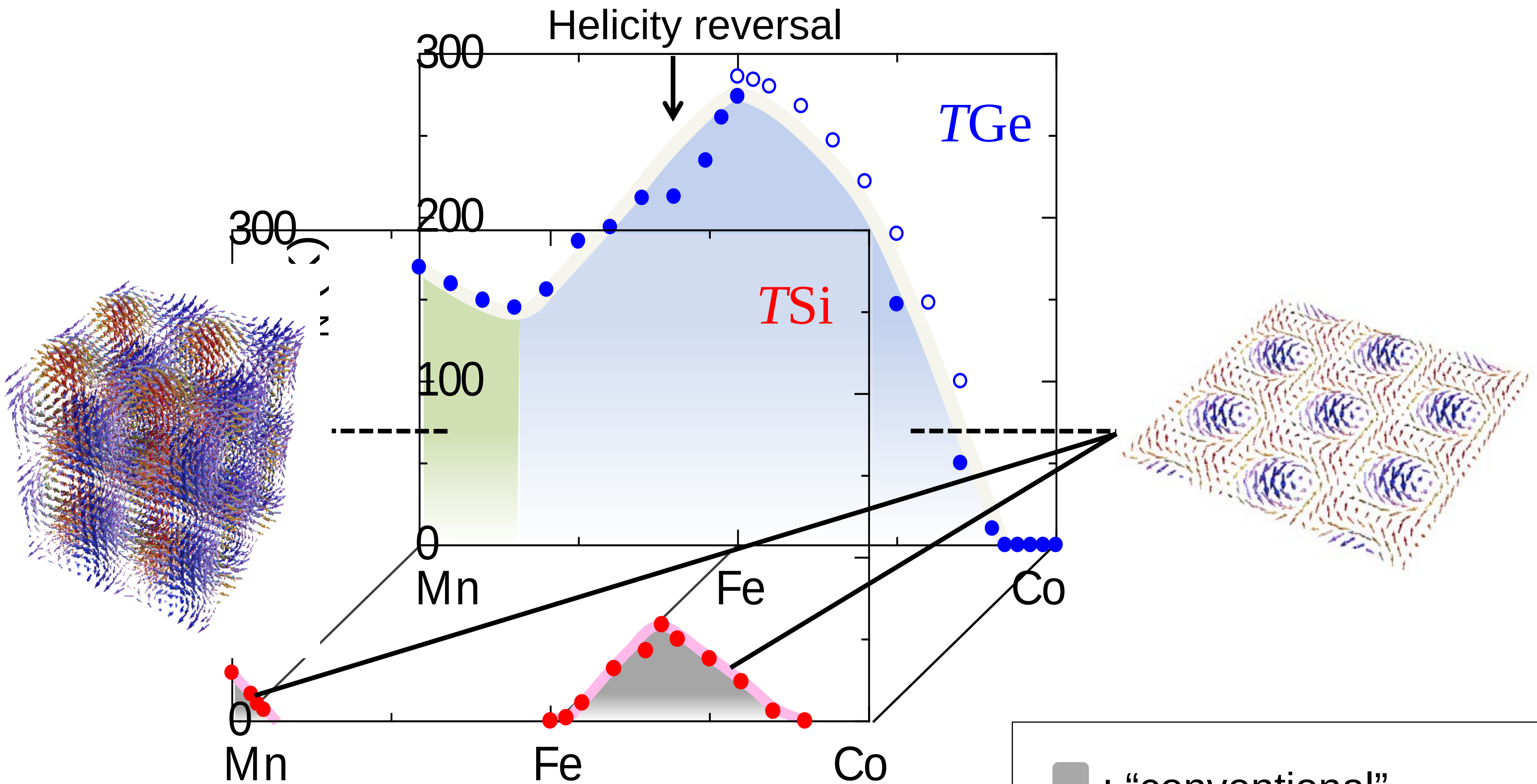
Current induced transformation from screw to biskyrmion







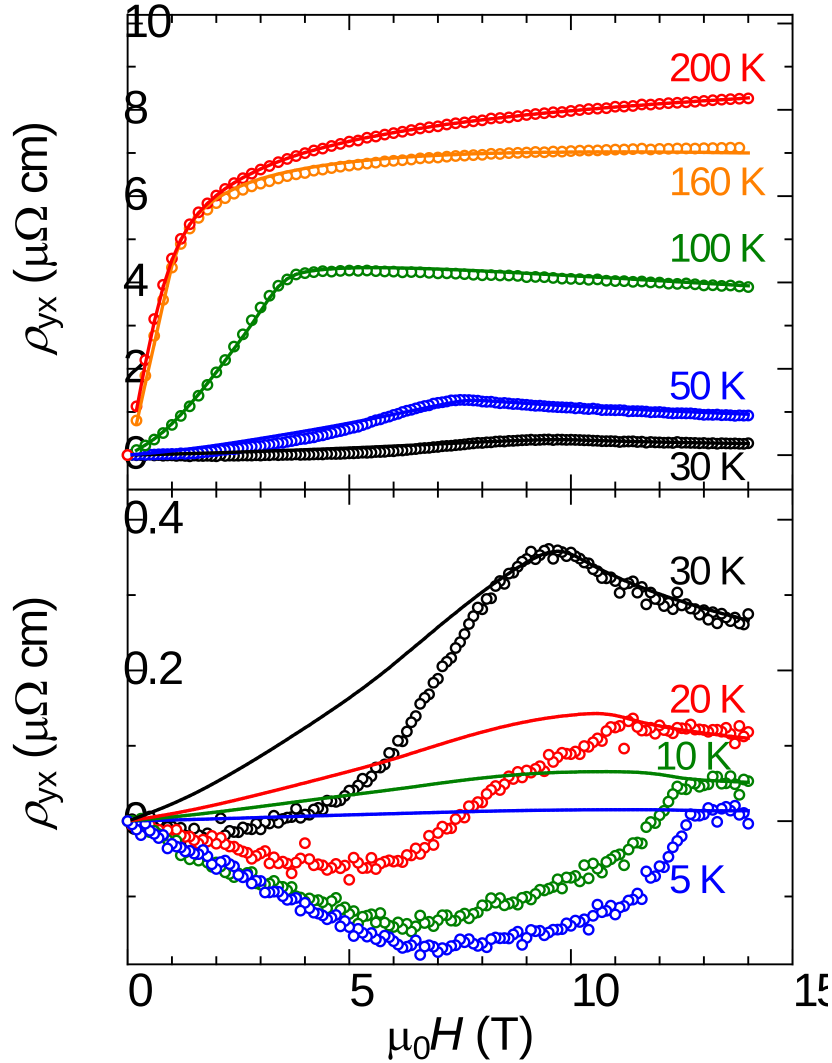
Magnetic phase diagram in *B*20 compounds



: "conventional" helical/skyrmion phase

: "new" skyrmion phase

Topological Hall effect in MnGe



$H > H_C$

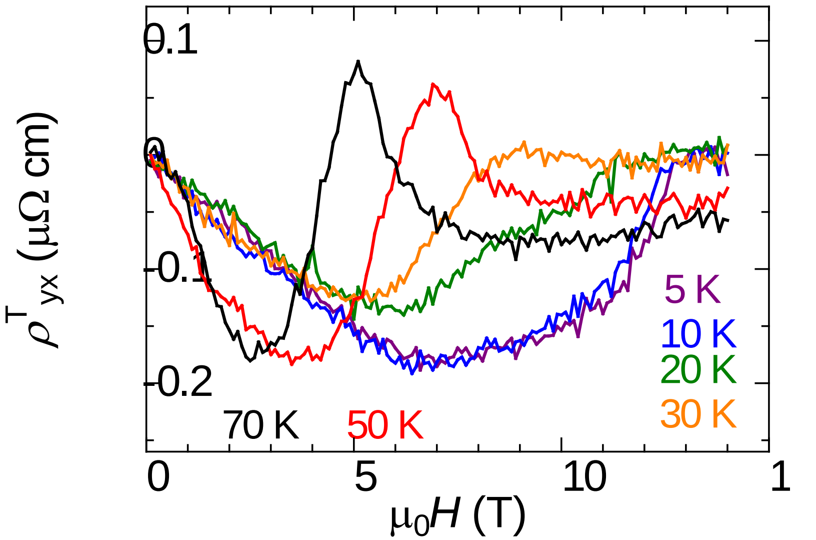
Induced ferromagnetic state
→"Conventional" anomalous Hall effect

Solid lines : estimate of

$$\rho_{yx}^{A} = R_0 B_z + \mu_0 R_S M_z$$

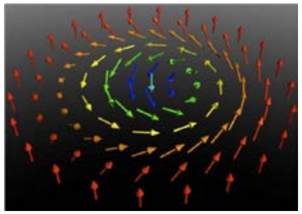
$$\mu_0 R_S = S_A \rho_{xx}^2$$

Components of THE



Nearly temperature independent

Real-space fictitous magnetic field in a skyrmion spin texture



Solid angle $\Omega = 4\pi$

In strong coupling case

One skyrmion $\longleftrightarrow$ One magnetic flux ϕ_0

$$\phi_0 = h/e$$

Emergent **magnetic field**

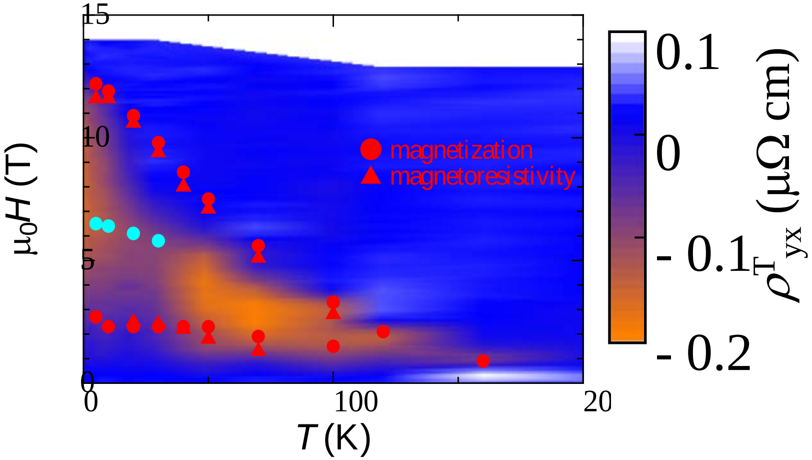
$$\mathbf{B}^z_{\mathrm{eff}} = -\phi_0/A$$

A: skyrmion size

one skyrmion/nm²

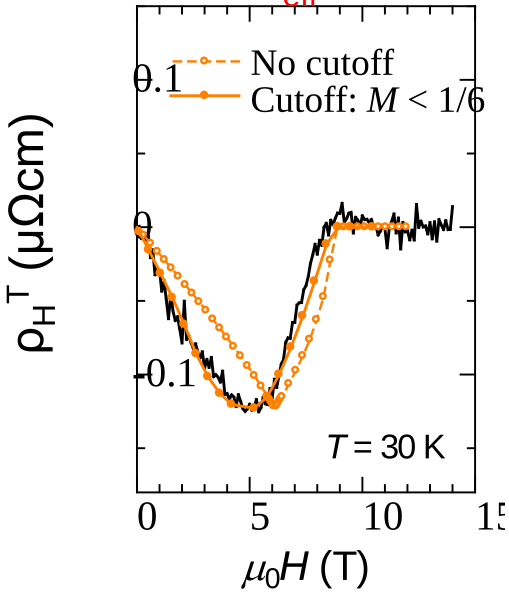
B_{eff}~4000T

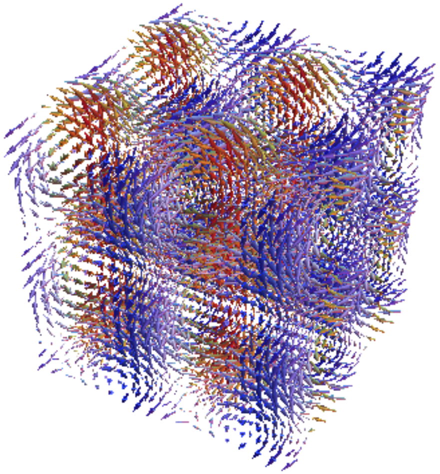
High skyrmion density ⇄ Large topological Hall Effect



MnGe topological Hall effect

B_{eff}~100-1000T !

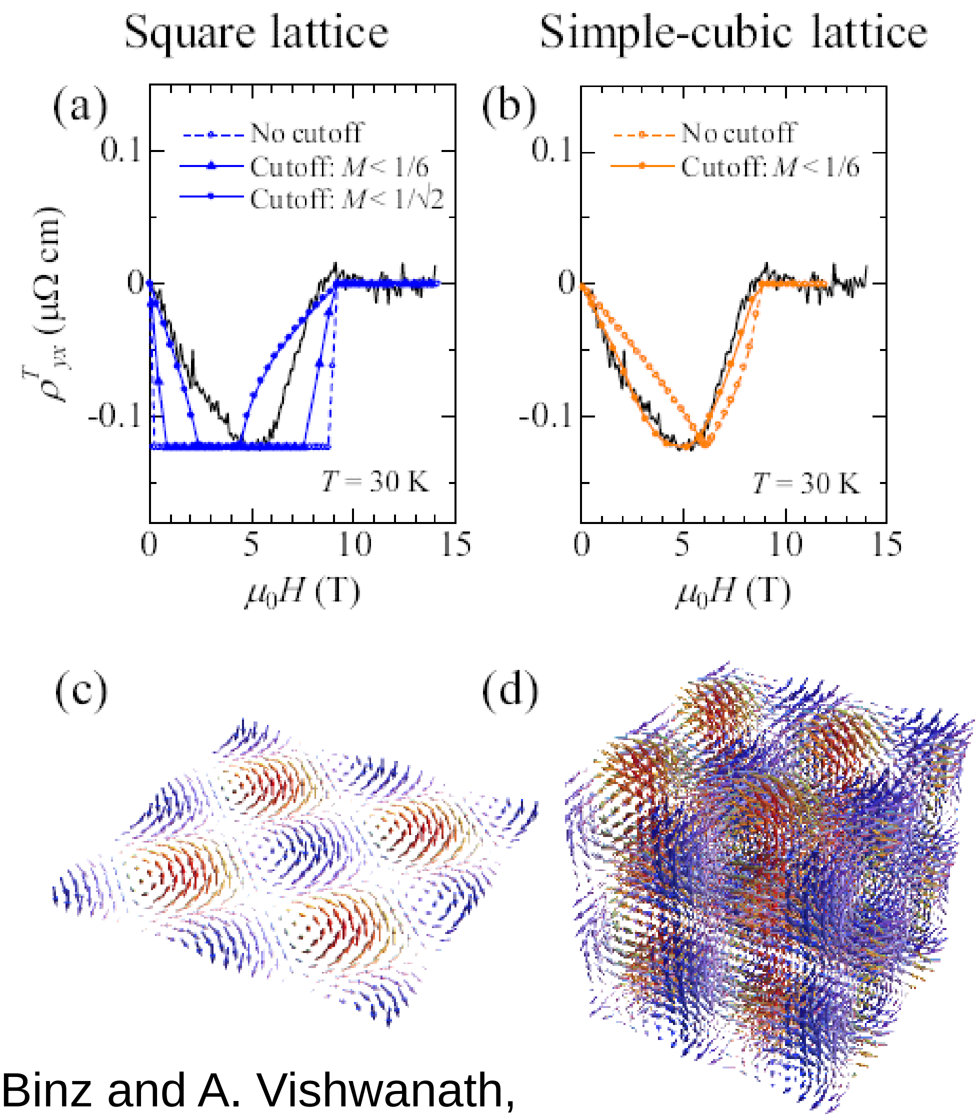


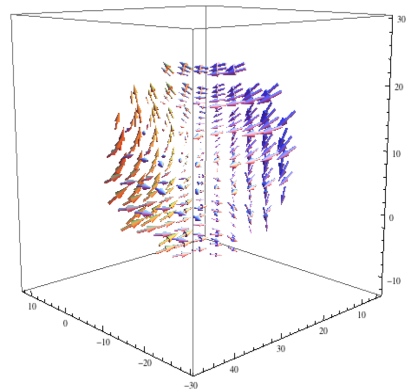


3D skyrmion X

Possible 2D (meron) or 3D (hedgehog) Skyrmion Xtal at B=0

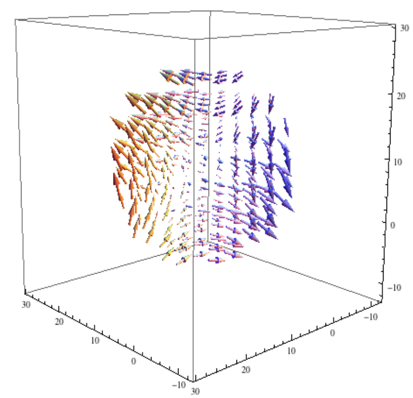
$$M^{SC}(r) = (\sin y + \cos z,\ \sin z + \cos x,\ \sin x + \cos y)$$





b-field magnetic monopole & antimonople ?

div **b** ≠ 0



Cf. B. Binz and A. Vishwanath, Physica B 403, 1336 (2008).

Thiele eqation of Skyrmion

$$\boldsymbol{G}\boldsymbol{e}_z \times (\boldsymbol{v}_s - \boldsymbol{v}_d) + \boldsymbol{\mathcal{D}}(\beta \boldsymbol{v}_s - \alpha \boldsymbol{v}_d) + \boldsymbol{F} = 0$$

Skyrmion (texsture) drift velocity

spin current

external force

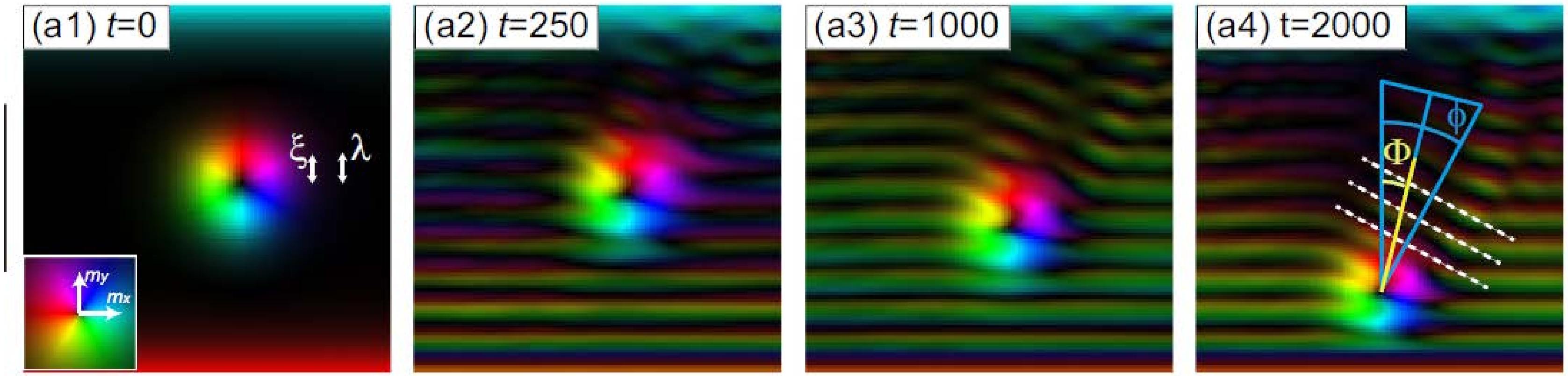
$$G = \int \boldsymbol{m_r} \cdot (\partial_x \boldsymbol{m_r} \times \partial_y \boldsymbol{m_r}) dxdy$$

: Gyrocoupling vector

Skyrmion, non-coplanar curved DW

$$\mathcal{D}_{ij} = \int (\partial_i \boldsymbol{m_r} \cdot \partial_j \boldsymbol{m_r}) dxdy$$

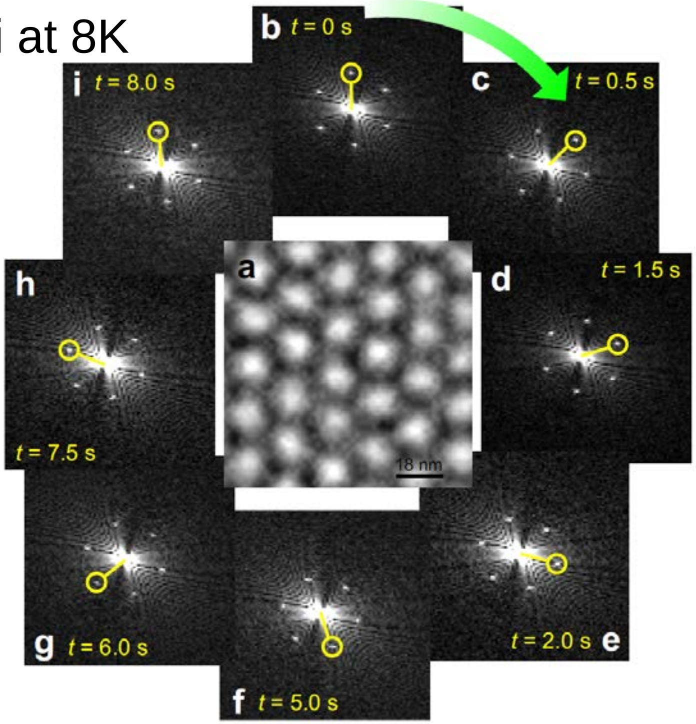
: Dissipation tensor

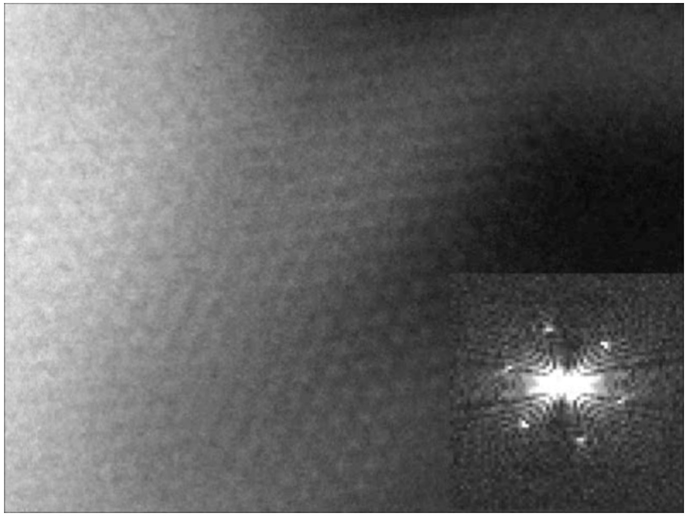


J. Iwasaki, A.J. Beekman, and N. Nagaosa, PR B 89, 064412 (2014).

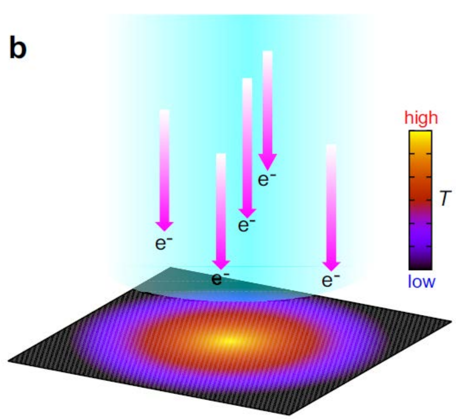
Ratchet motion of skyrmion microcrystals

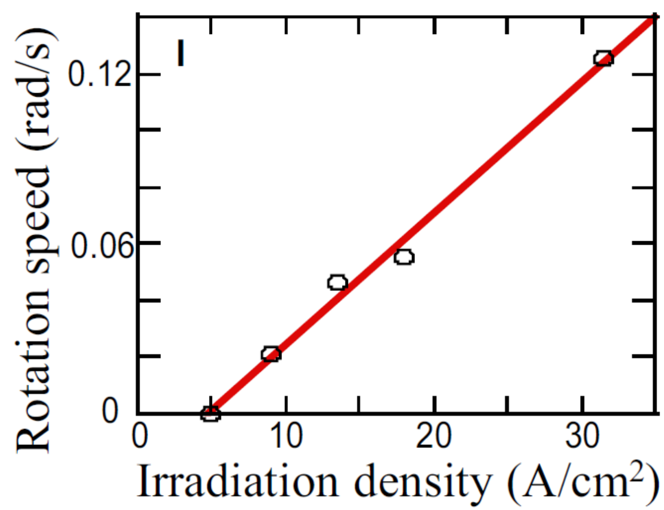
MnSi at 8K



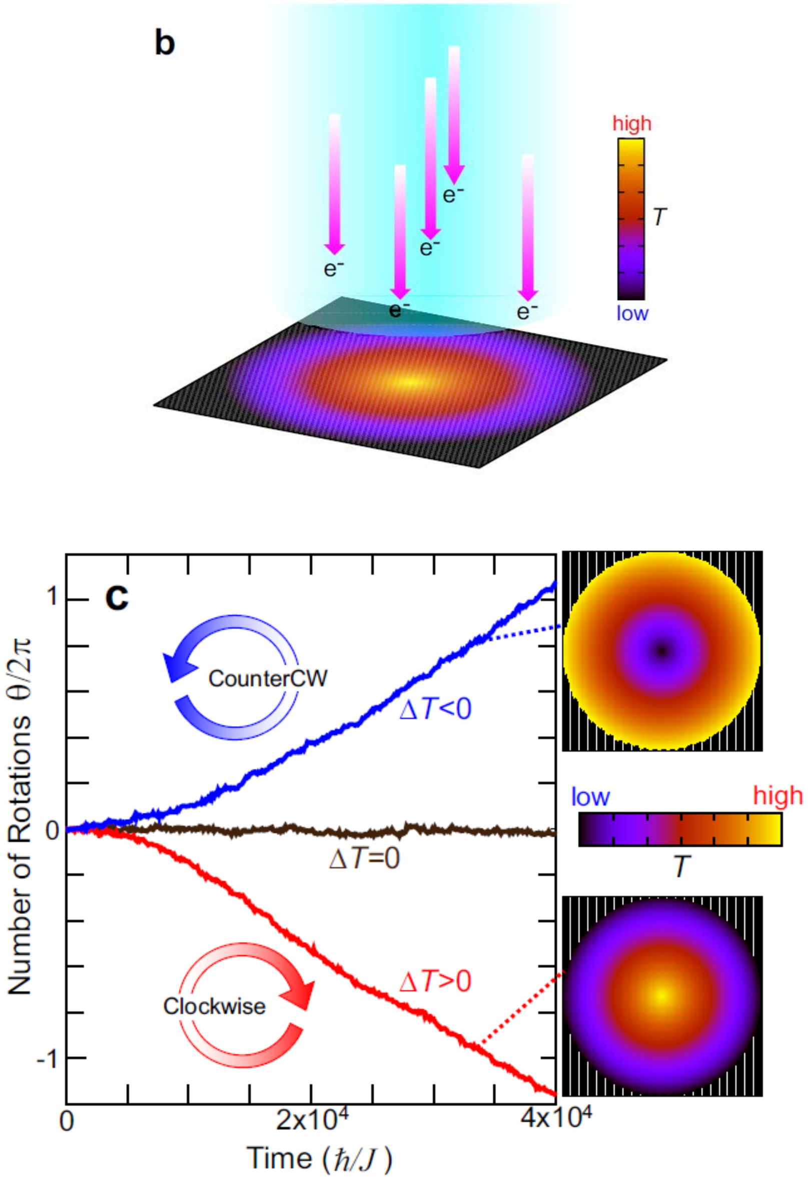


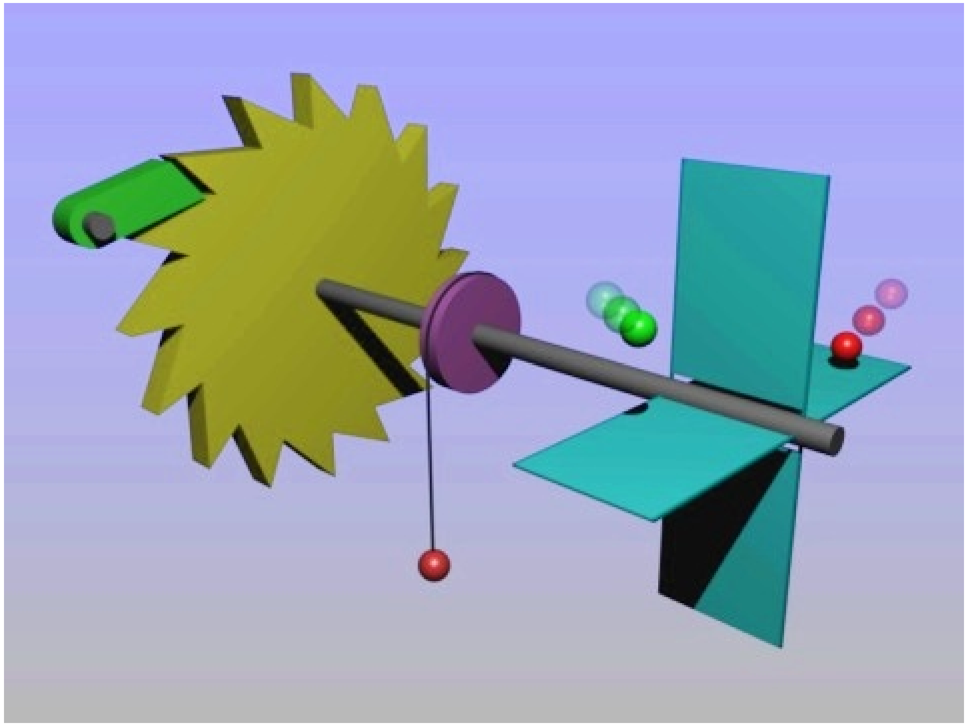
MnSi at 8K





Thermally-driven Fynman's ratchet



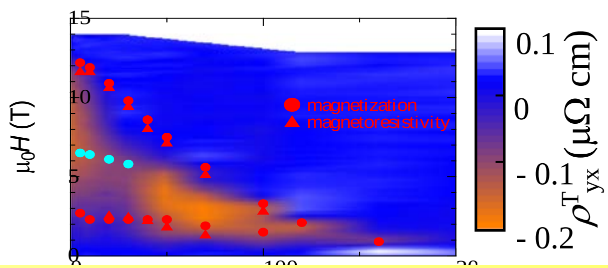


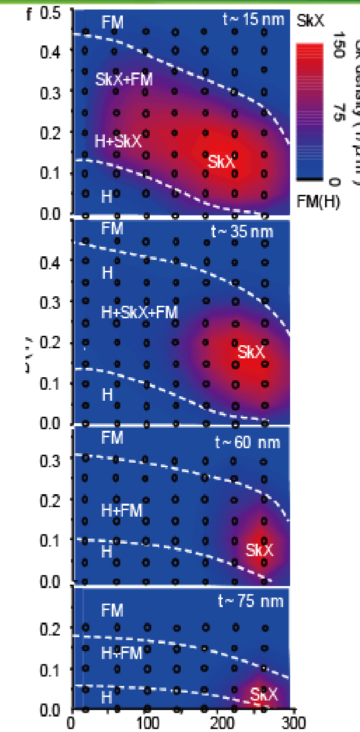
~ toward Skyrmionics ~

Stabilization Skrymions and Skyrmion Xtal in form of thin films

Topological Hall effect as probe/detection for SkX

emergent EM fields





Skyrmion transport phenomena

- low-current drive of Skyrmions (<100A/cm^2)
- optical (inverse Faraday) control, E-drive (multiferroics)

Versatility of skyrmion forms (vorticity, helicty, molecule, monopole)

How to create, amplyfy, and utilize Emergent ElectroMagnetic Field.