Skyrmion Dynamics in Thin Films of Chiral Magnets

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Skyrmions and topological transport phenomena

Skyrmions in multiferoics toward *E*-control

Forced and spontaneous dynamics of skyrmions

Collaborators

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- ***Tohoku Univ. (Japan)***

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  K. Kakurai, S. Wakimoto

- ***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. Gavilano

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

  M. Mostovoy

- ***Fudan Univ. (Peoples R China)***

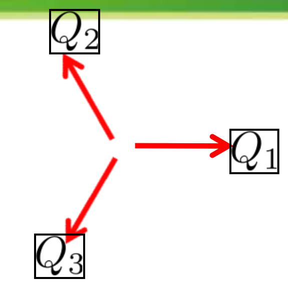
  Yufan Li, Xiofeng Jin

Skyrmion Crystal

Superposition of three Helix without phase shift

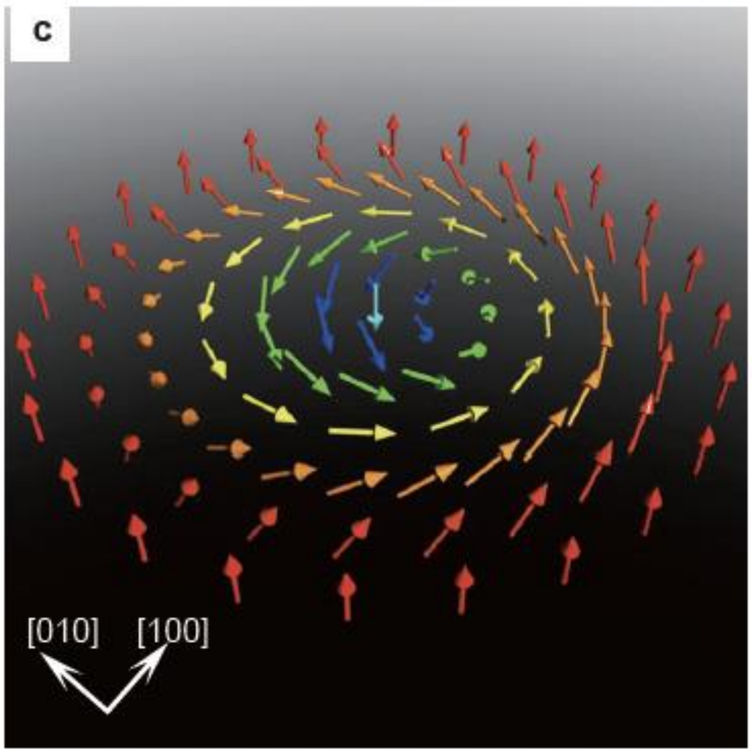
$$M(r) \approx M_f + \sum_{i=1}^{3} M_{Q_i}(r+\Delta r)$$

$$M_{Q_i}(r+\Delta r) = A[n_{i1}\cos(Q_i \cdot r) + n_{i2}\sin(Q_i \cdot r)]$$



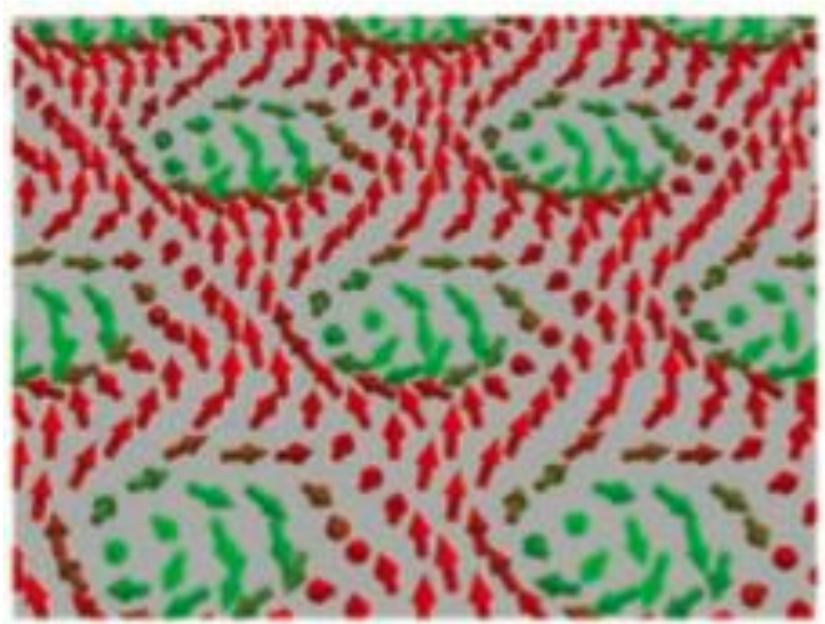
$$Q_1 + Q_2 + Q_3 = 0$$

Skyrmion



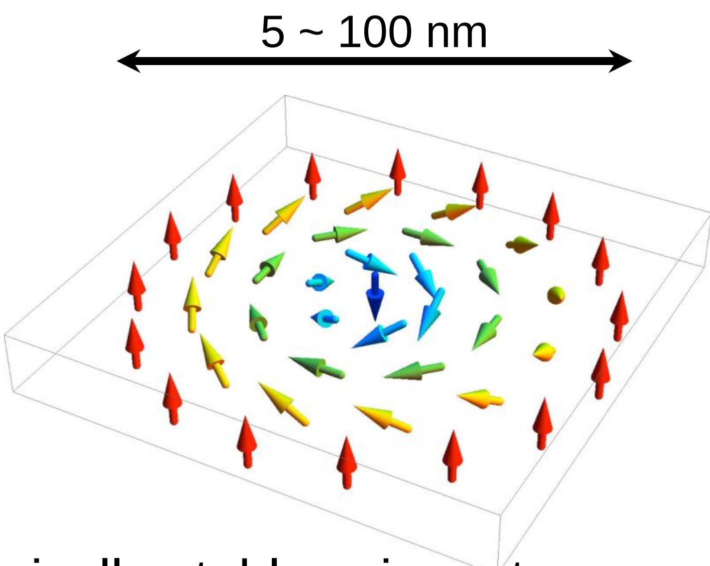
Skyrmion crystal

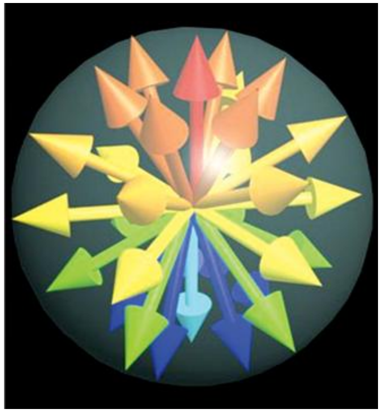
3-flod-Q



S. Muhlbauer et al. Science 323, 915 (2009).

What is magnetic skyrmion?



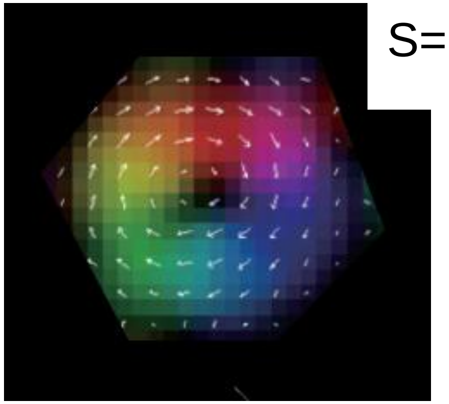


Topologically-stable spin vortex
with particle-like nature

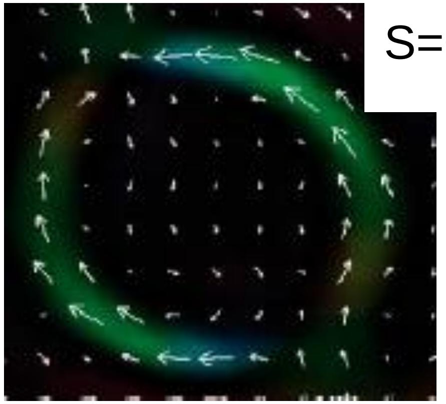
"skyrmion number"

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

Lateral component of
M ofsome bubbles



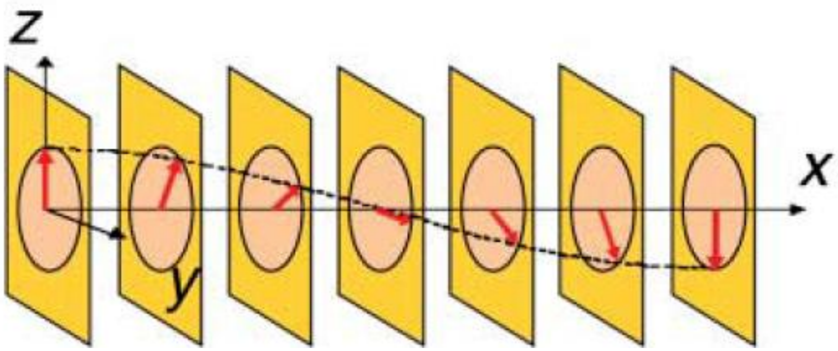
S=-1



S=0

a pair of
Bloch lines

Toward real space observation of Skyrmion structure



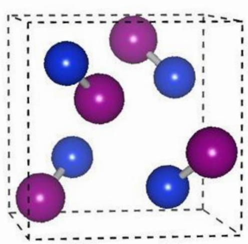
$$H = \sum \left(-J\vec{S}_i \cdot \vec{S}_j + \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \right)$$

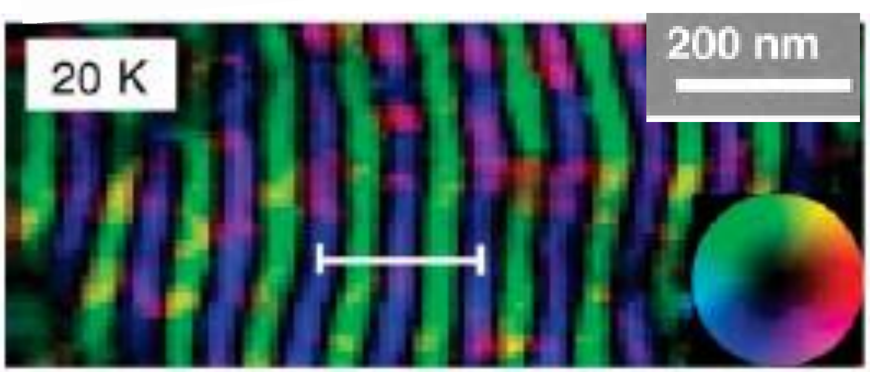
Ferro + DM

Helical spin structure

Long period～aJ/D～10nm-300nm

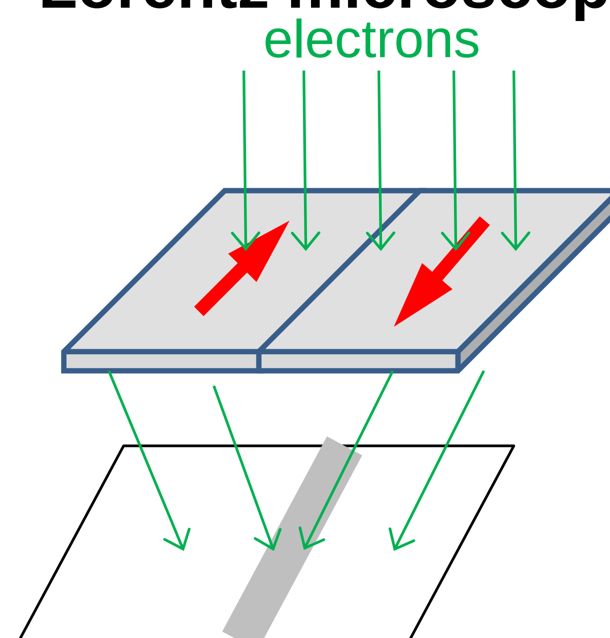
F





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

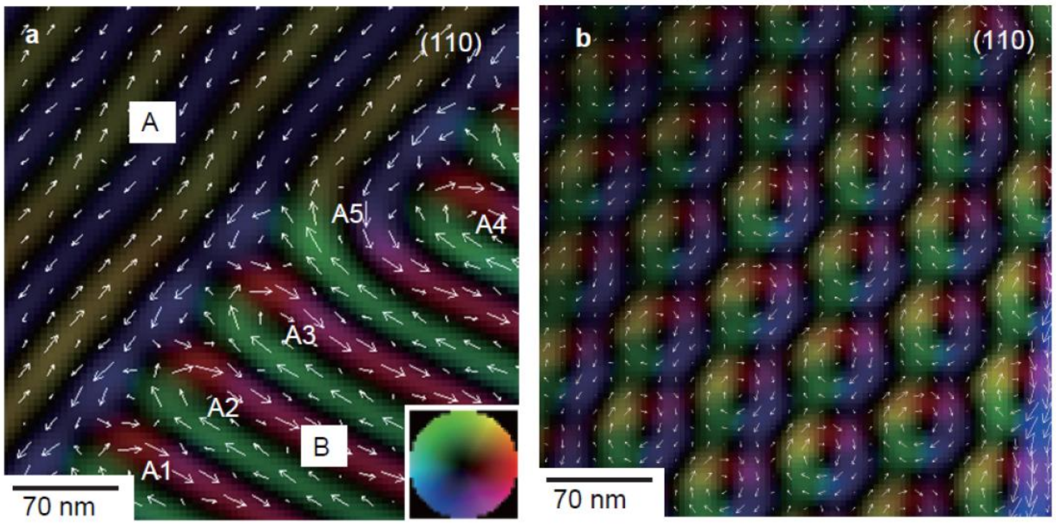
Lorentz microscope

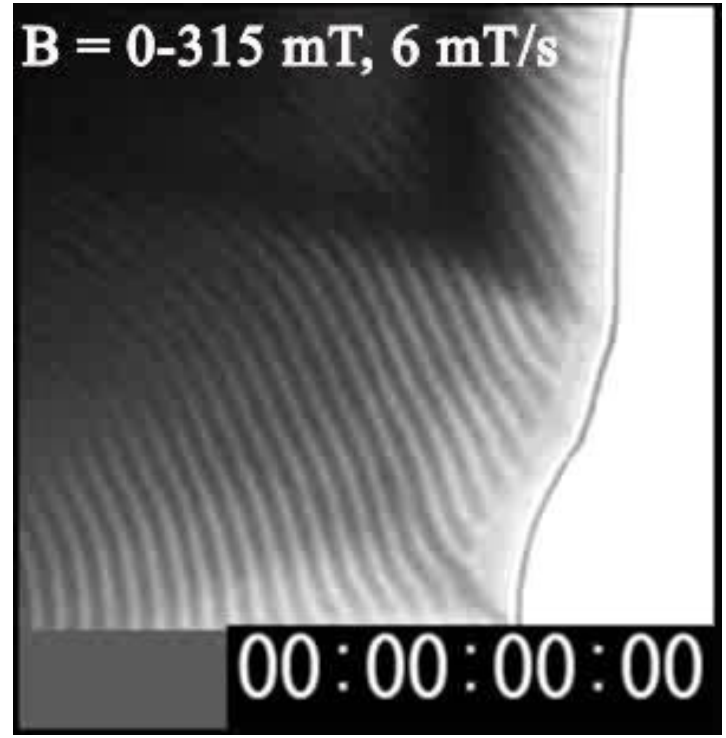


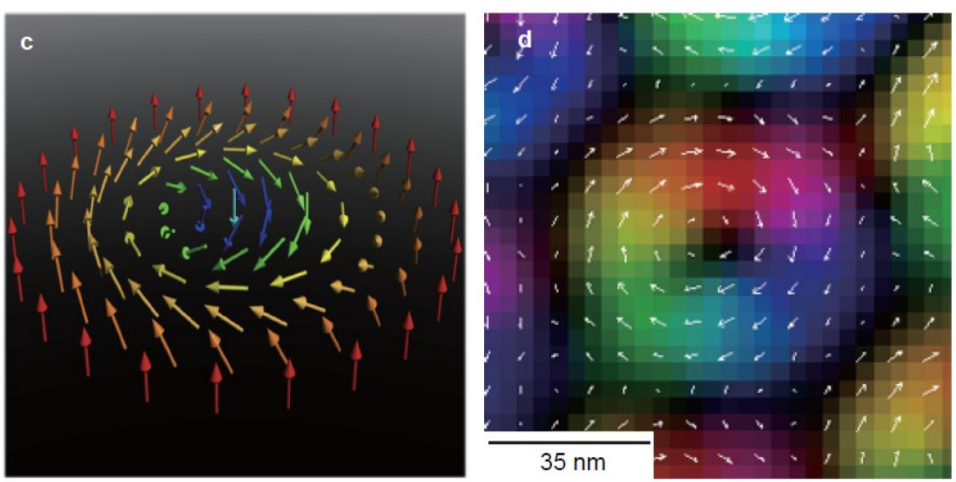
FeGe: from helical to skyrmion crystal at 260K

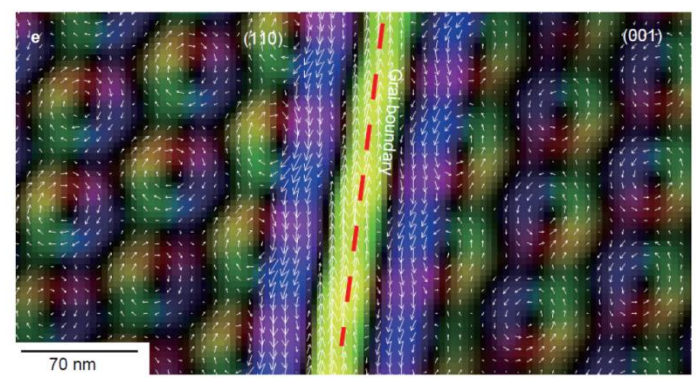
X.Z. Yu et al. Nat. Mater.(2011)

H=0 ⊙ H=0.1T









Near room-temperature formation of SkX in FeGe

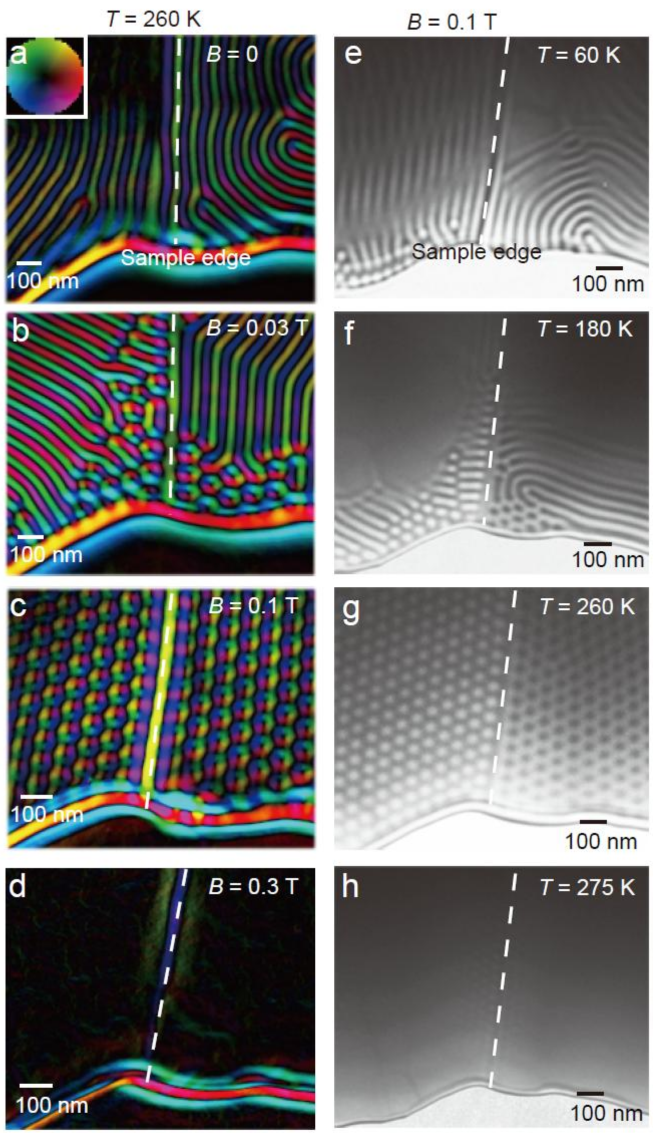


FIG. 2 Yu *et al.*

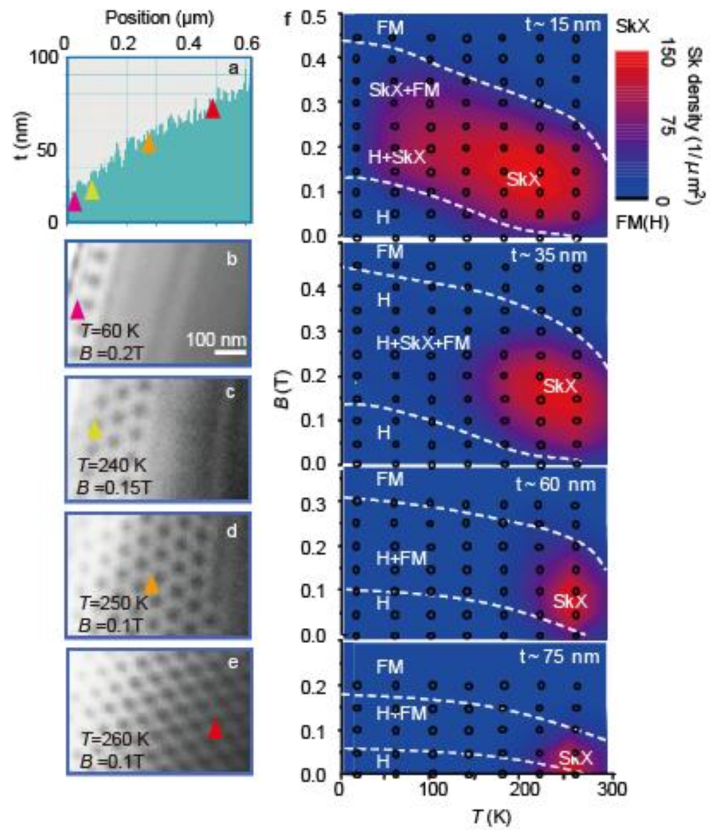


FIG. 3 Yu *et al.*

t = 15 nm

t = 35 nm

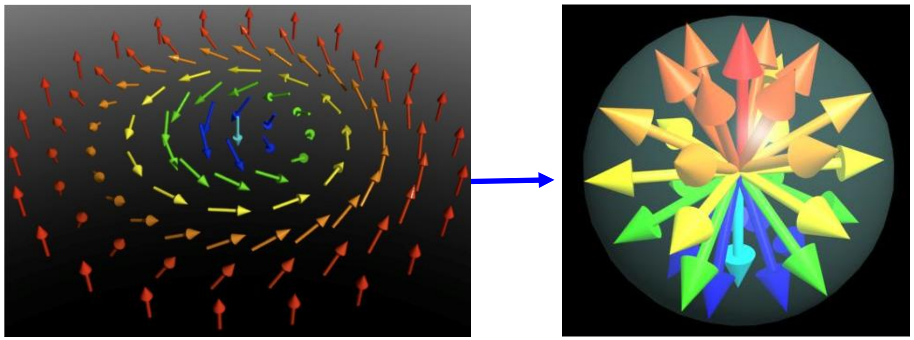
t = 60 nm

t = 75 nm

-Near room-temperature formation of SkX
-Stability of SkX depend largely on the thickness.

X. Z. Yu, N. Kanazawa, Y. Onose, K. Kimoto, W.Z. Zhang ,
S. Ishiwata, Y. Matsui, and Y. Tokura, Nature Mater. 10 106 (20

Real-space fictitous magnetic field in a skyrmion spin texture



scalar spin chirality

Solid angle $\Omega = 4\pi$

In srong coupling case

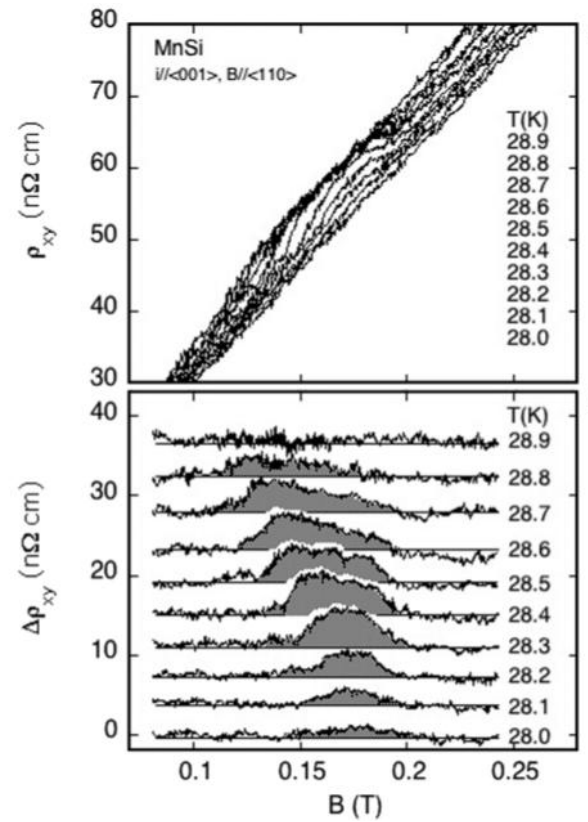
One skyrmion ⟷ One magnetic flux ϕ_0

$$\phi_0 = h/e$$

Emergent **magnetic field**

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

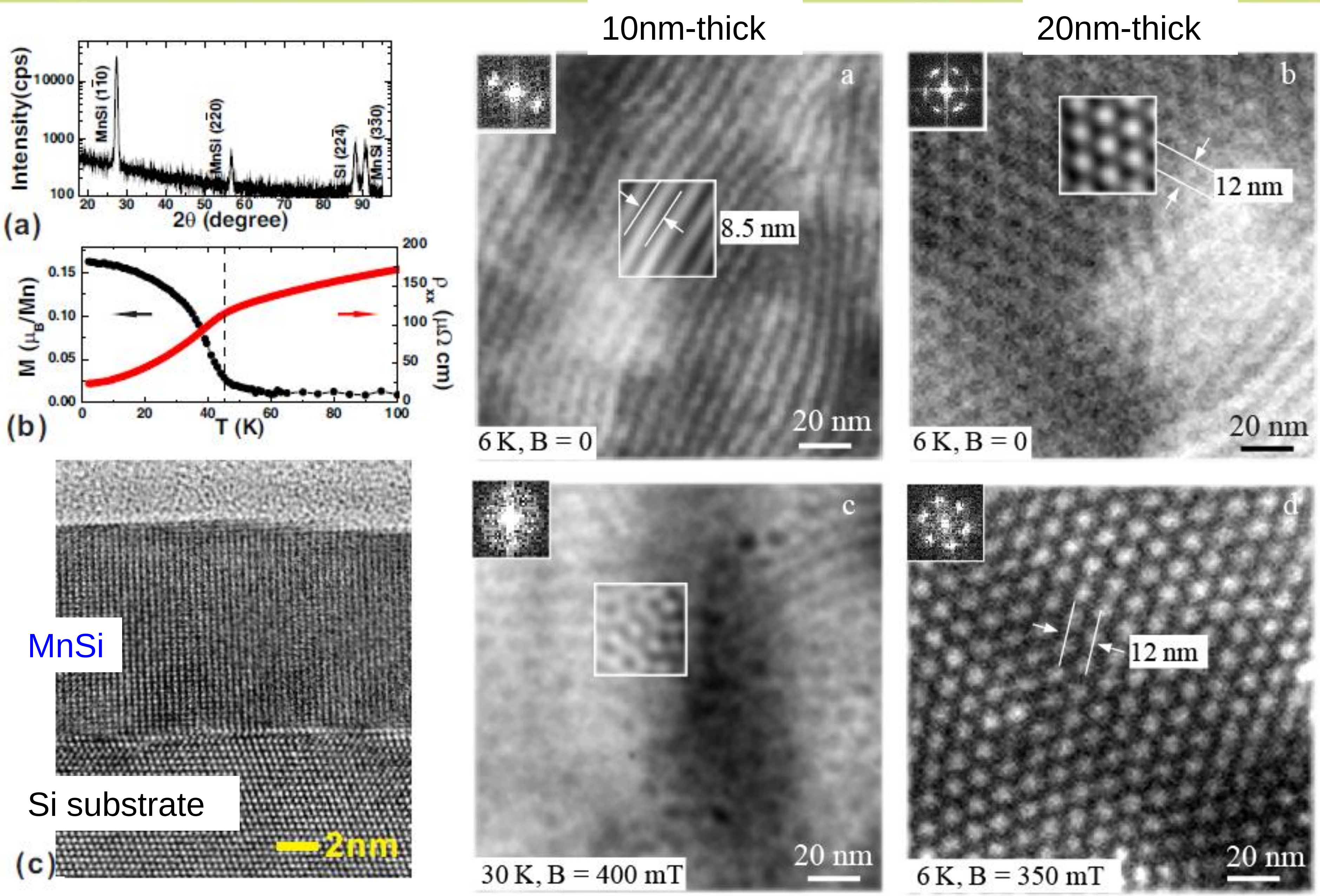
A: skyrmion size



A. Neubauer *et al*, PRL 102 186602 (2009)

High skyrmion density ⇄ Large topological Hall Effect

Ultrathin epitaxial thin films of MnSi



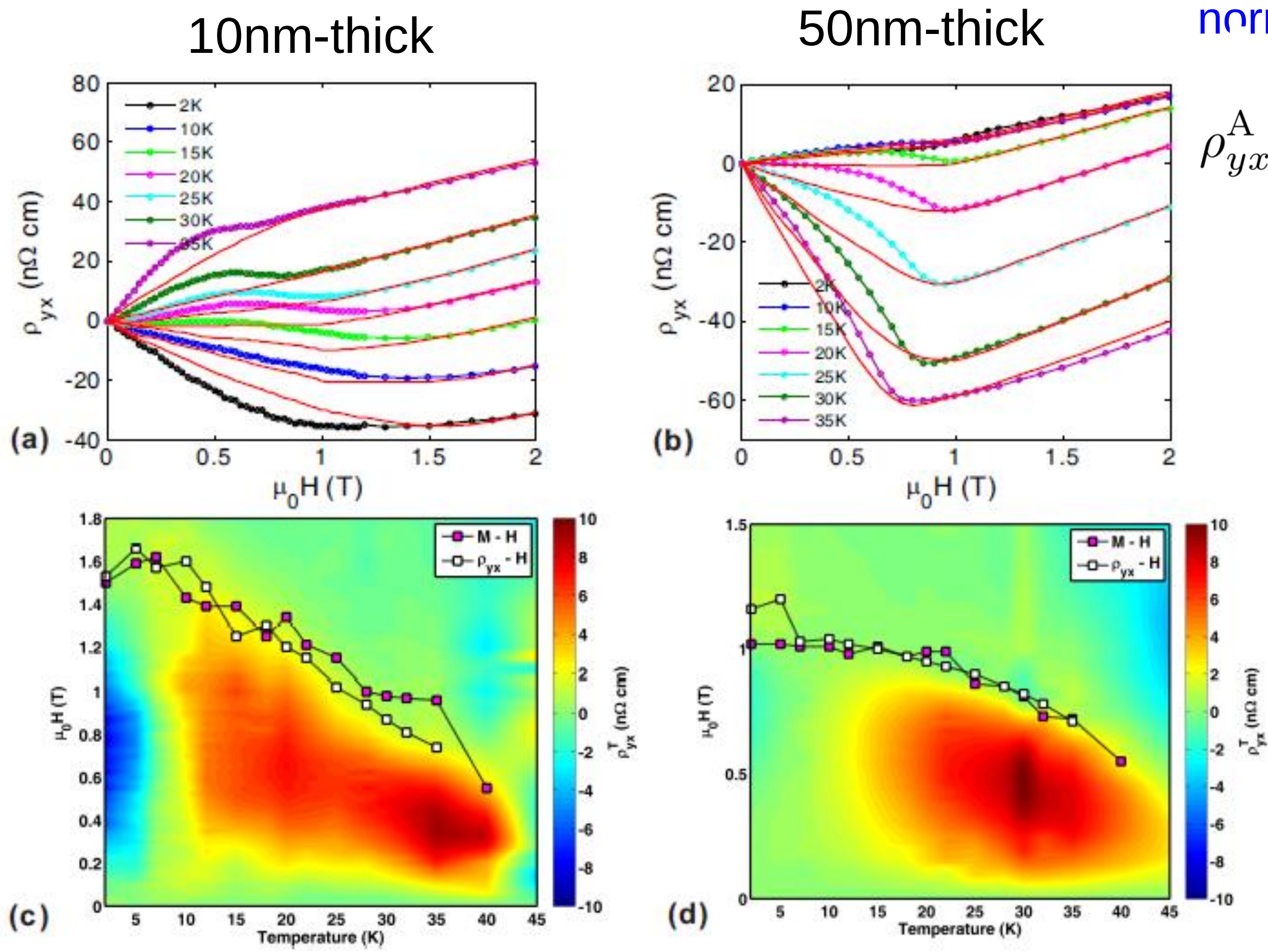
Skyrmion phase mapping by topological Hall resistivity

Yufan Li, Kanazawa,Kagawa

Conventional anomalous + normal Hall effects

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

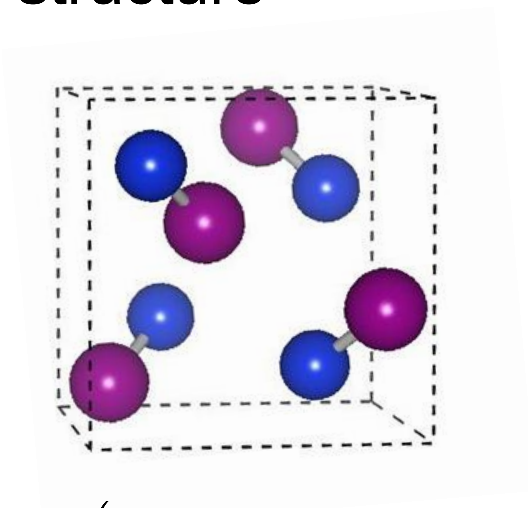
$$\mu_0 R_S = S_A \rho^2_{xx}$$



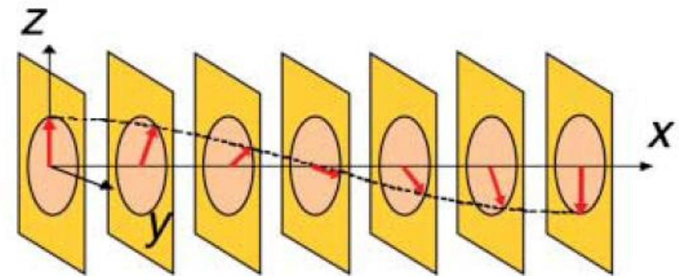
See also the late paper on FeGe thin film;
S. X. Huang and C. L. Chien、Phys. Rev. Lett. **108**, 267201 (2012)

Magnetic phase daigrams of B20 TMSi, TMGe

B20 structure



Cubic but noncentros
(Chiral)



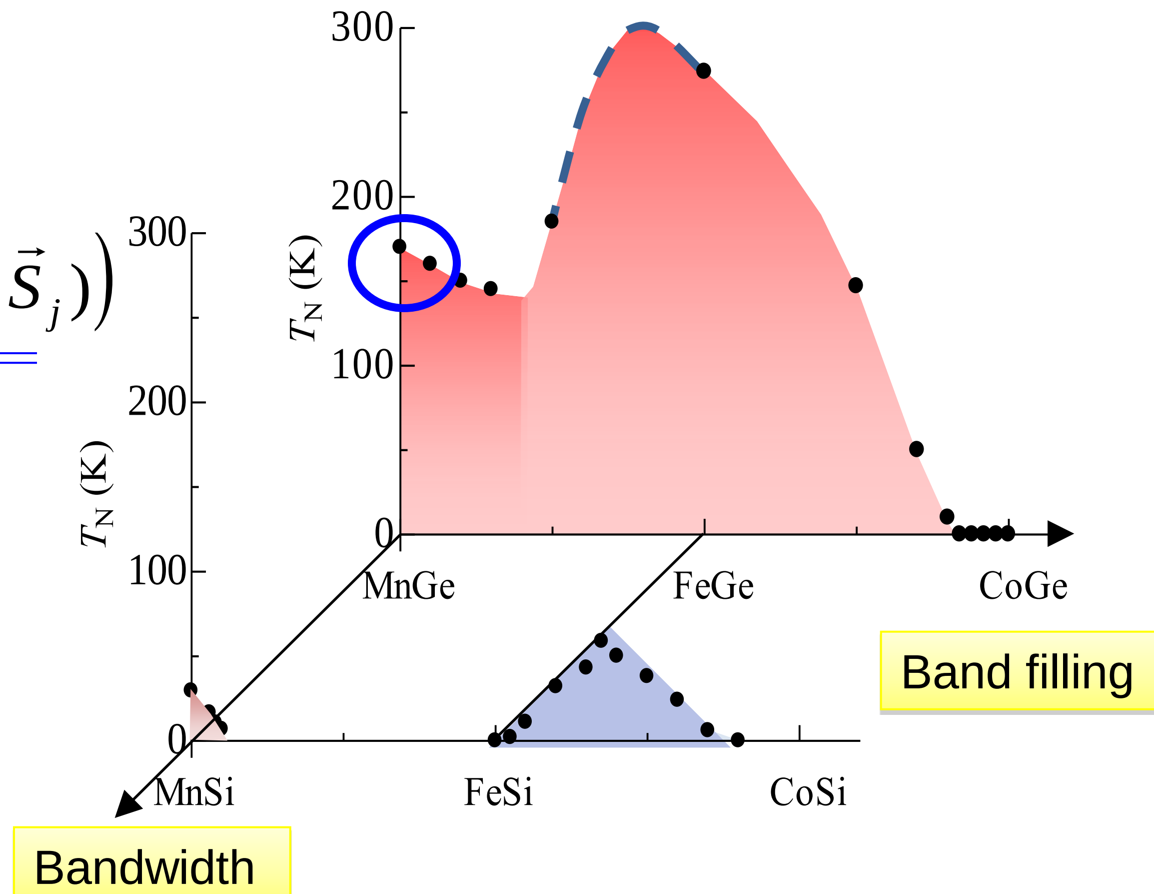
$$H = \sum \left(-J\vec{S}_i \cdot \vec{S}_j + \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \right)$$

Ferro + DM

Helical spin structure

Long period～aJ/D

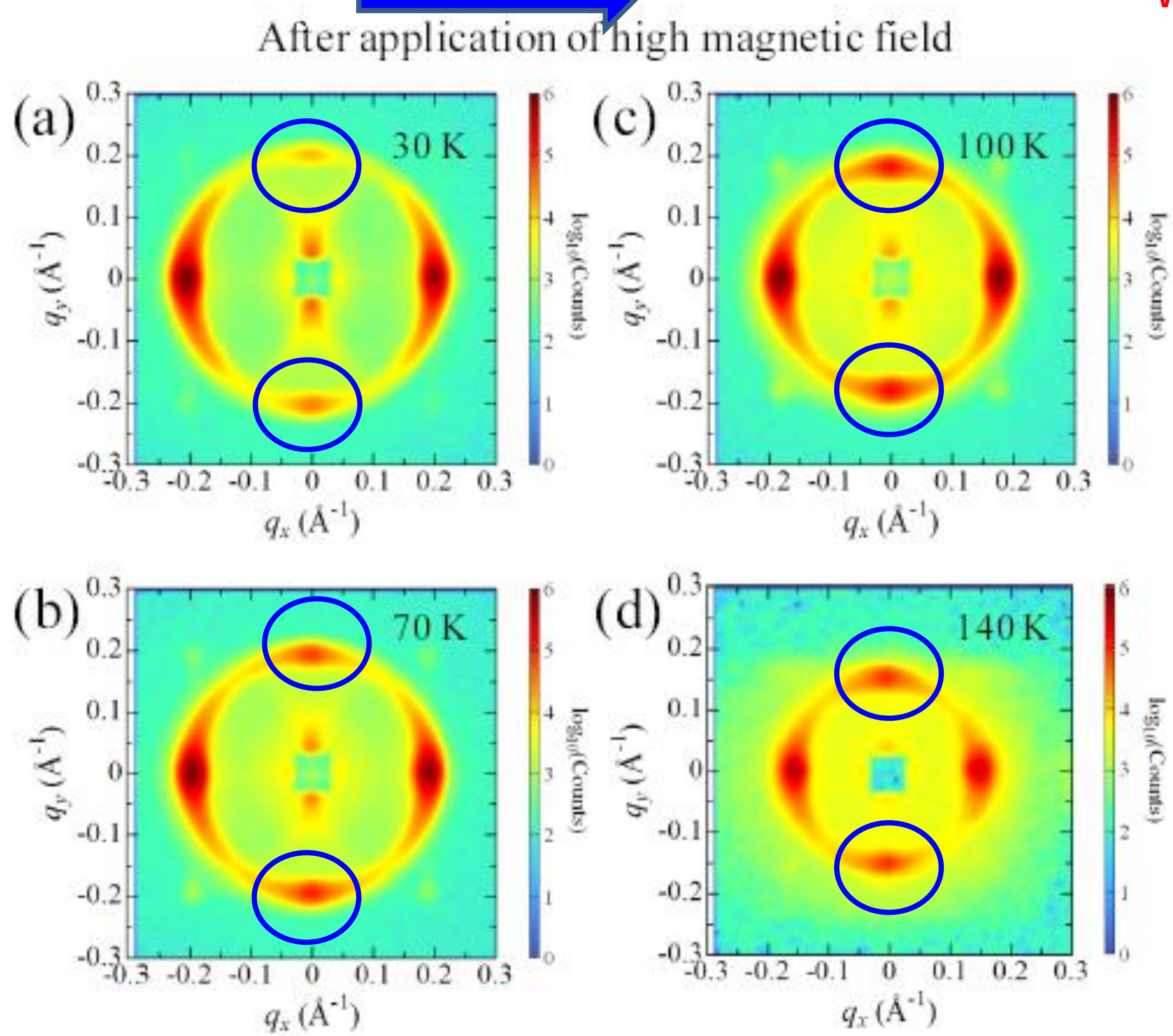
～*10nm-300nm*



Small angle neutron scattering on MnGe (polyXtal)

B (10T) then B=0

in collaboration with Keimer group

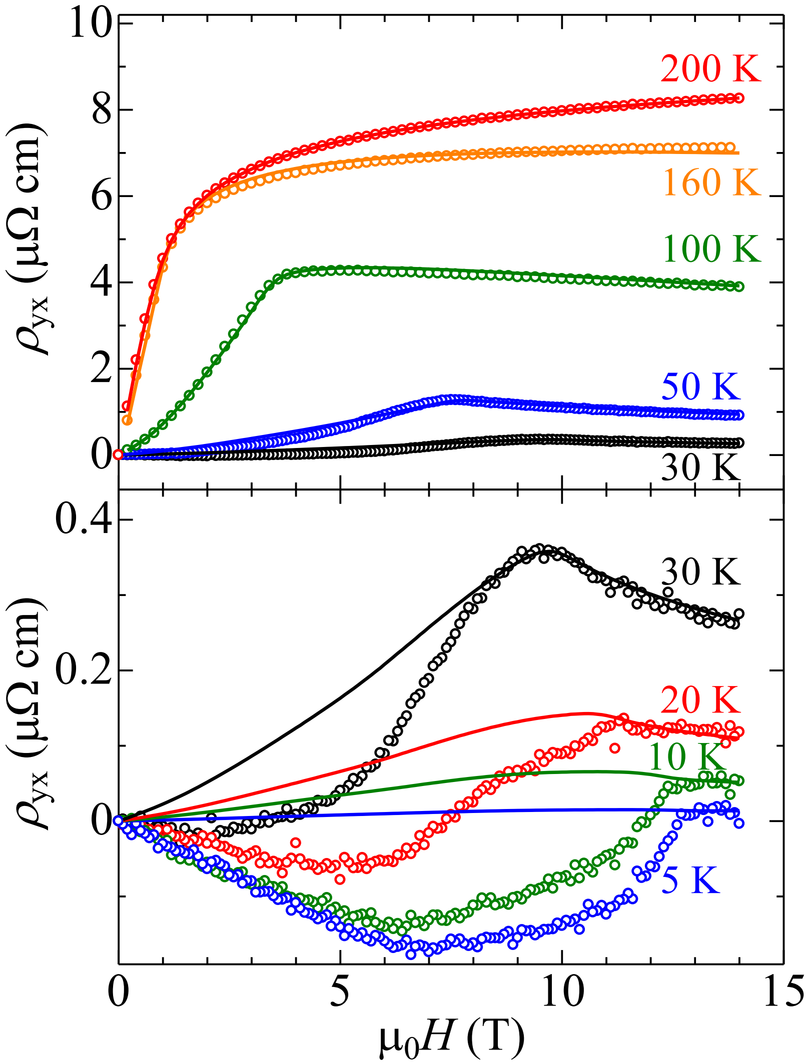


λ=3 - 6nm

q's//<100>

Evidence for multiple-q structure even at B=0

Topological Hall effect in MnGe



$H > H_C$

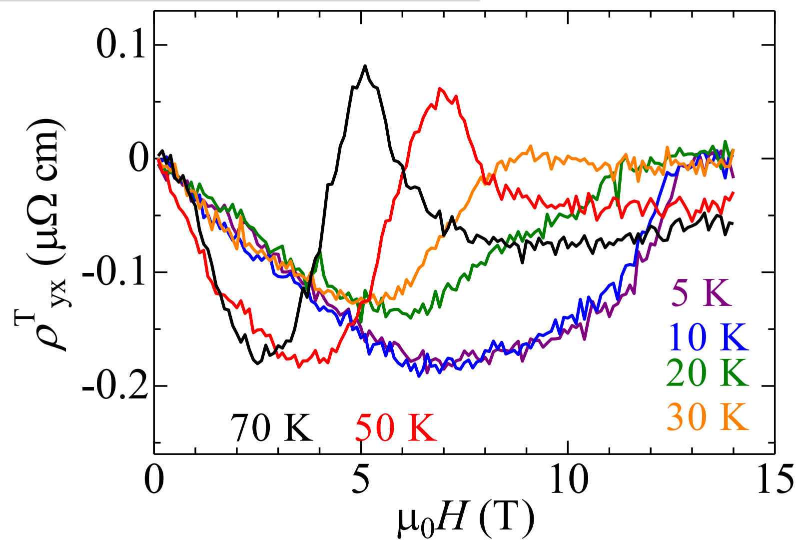
Induced ferromagnetic state
→"Conventional" anomalous Hall effect

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

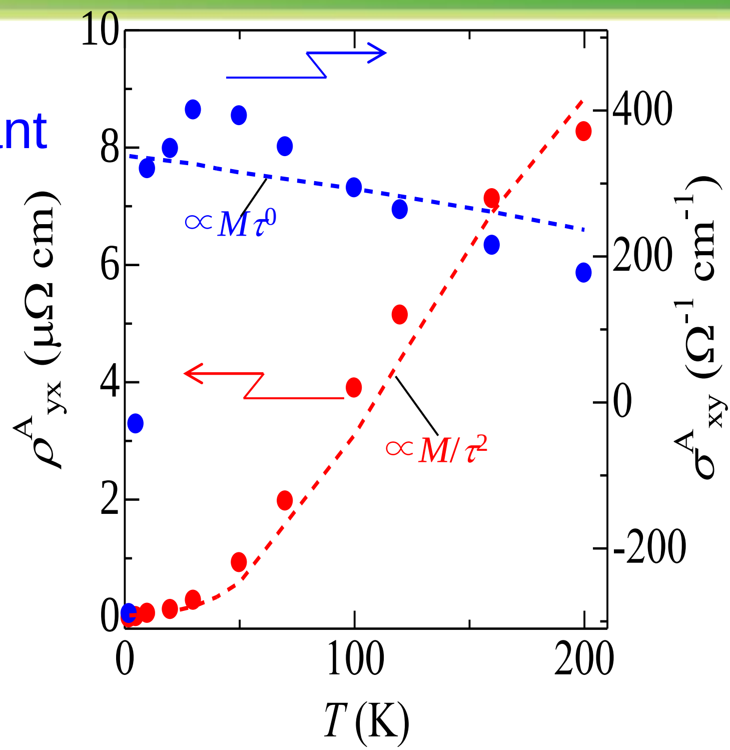


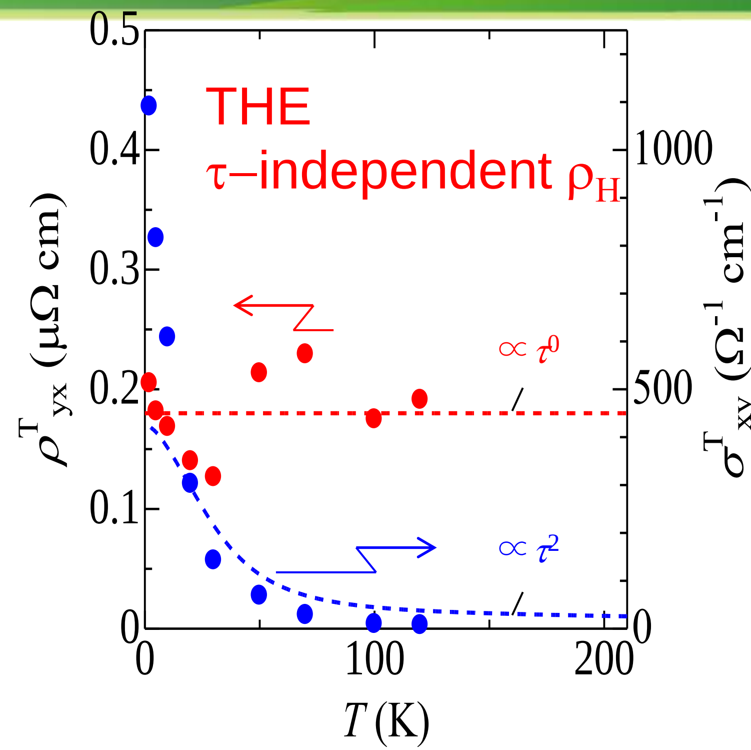
Nearly temperature independent

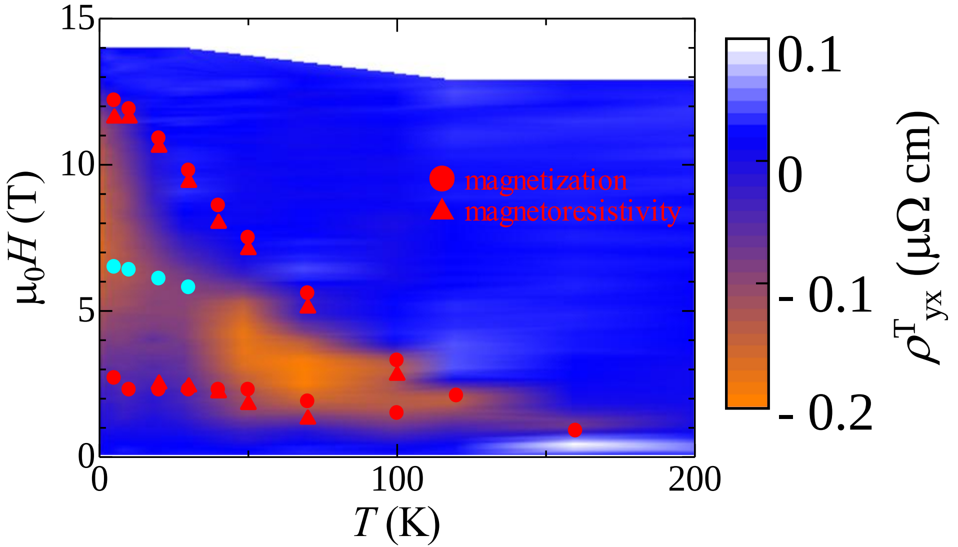
topological Hall effects via Skyrmion lattice

AHE

σ_H constant



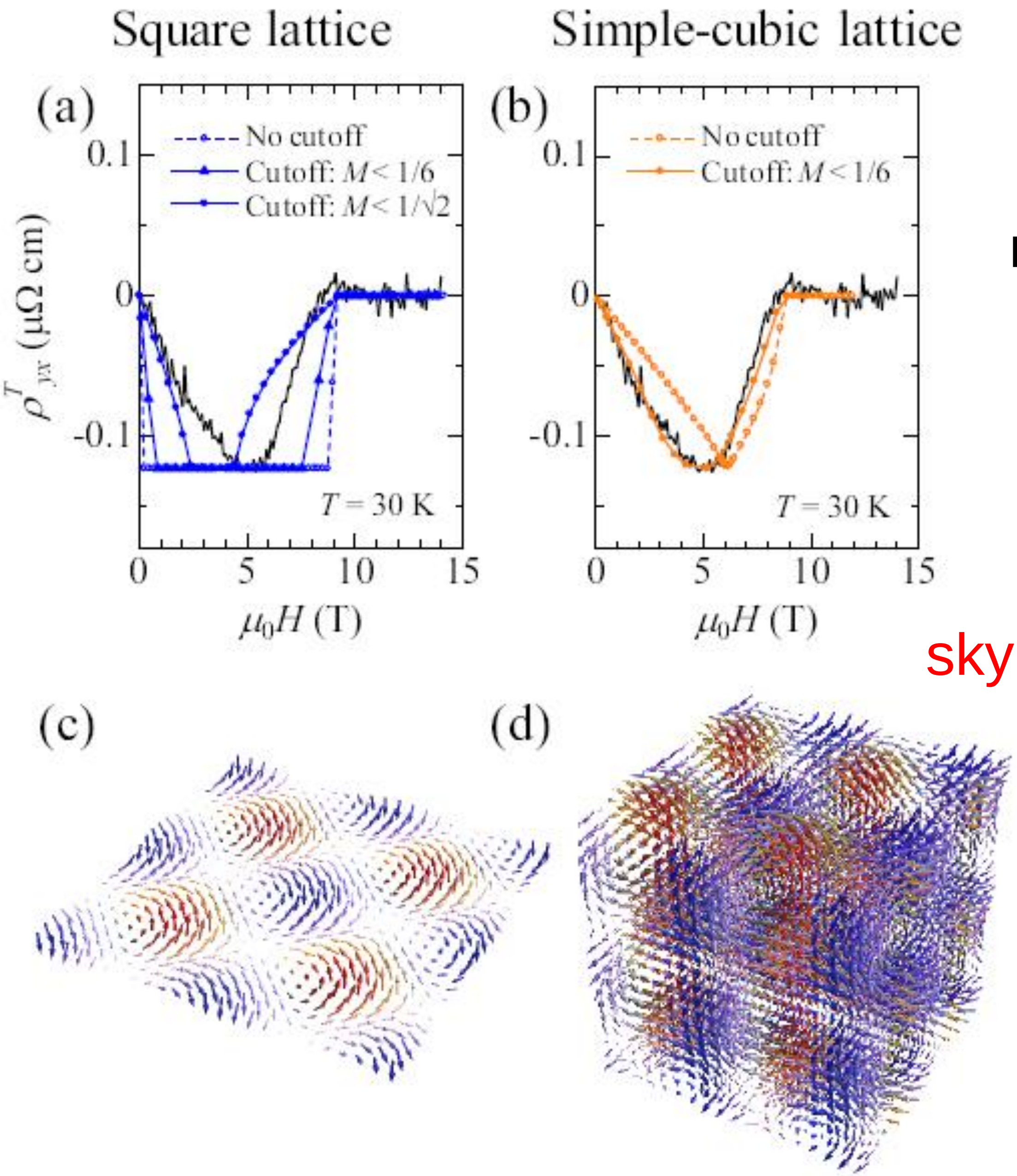




MnGe

SkX subsistent to ground state

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

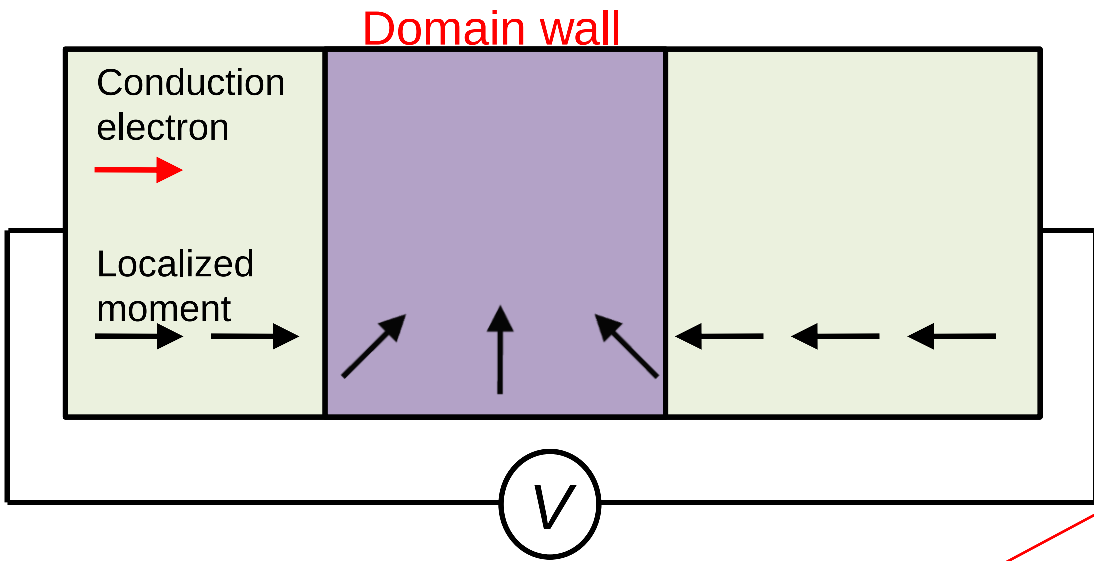


B. Binz and A. Vishwanath, Physica B 403, 1336 (2008).

skyrmion-antiskyrmion

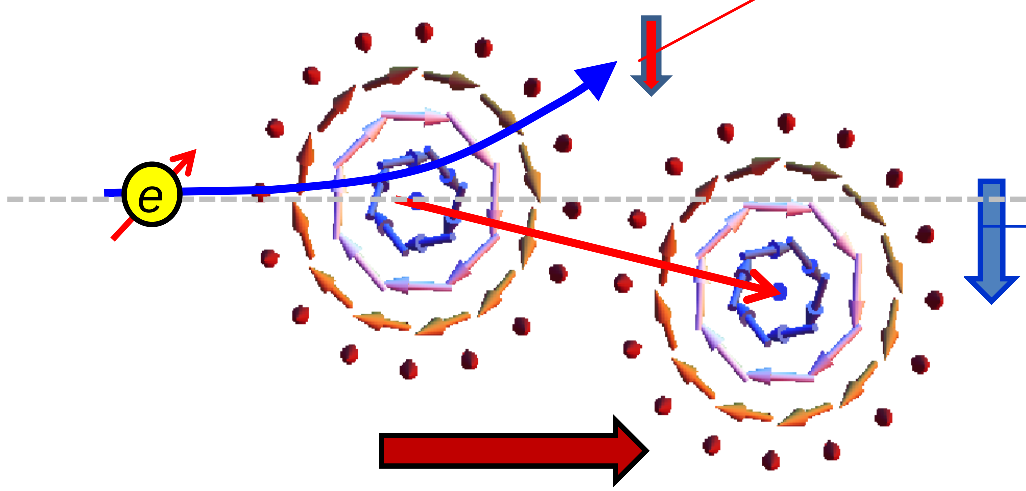
Current drive of skyrmions and emergent EM field

Domain wall motion by spin transfer torque



Topological Hall effect
Emergent magnetic field
h

Skyrmion motion by spin transfer torque



-Emergent electric field

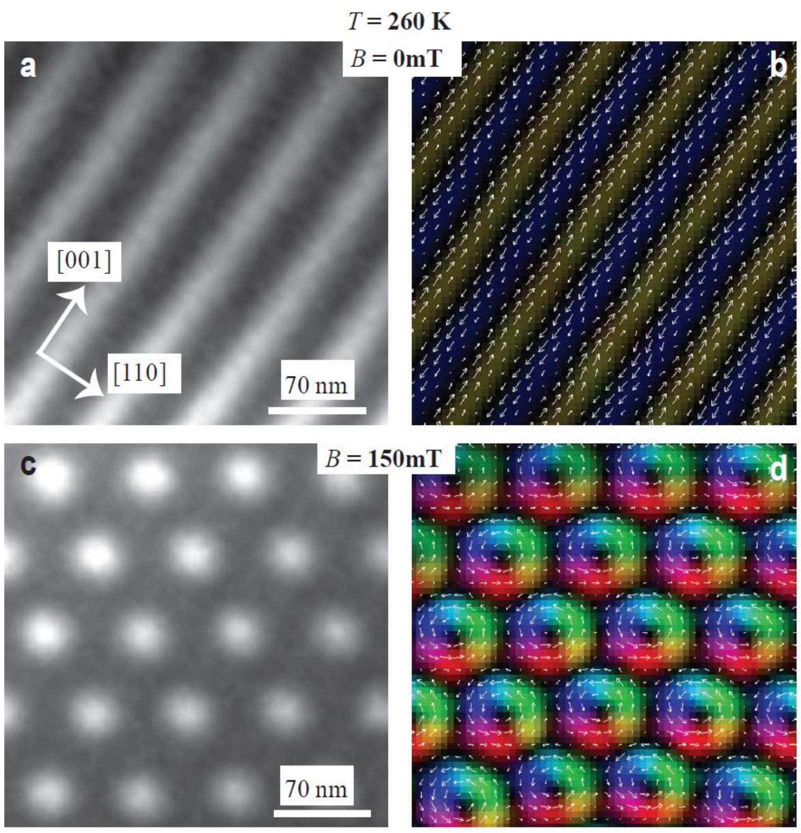
$$\mathbf{e} = -\frac{1}{c}\left[\mathbf{V}_{\|} \times \mathbf{h}\right]$$

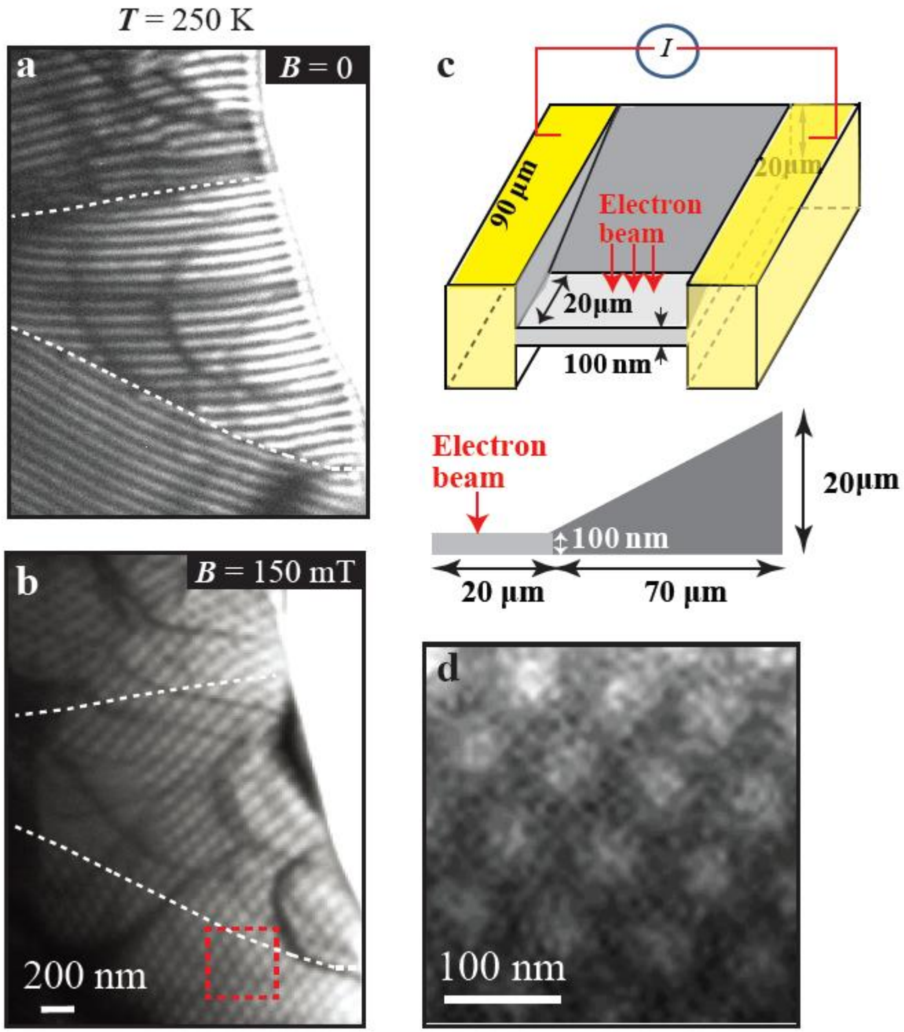
→ appears as reduction of topological Hall effect

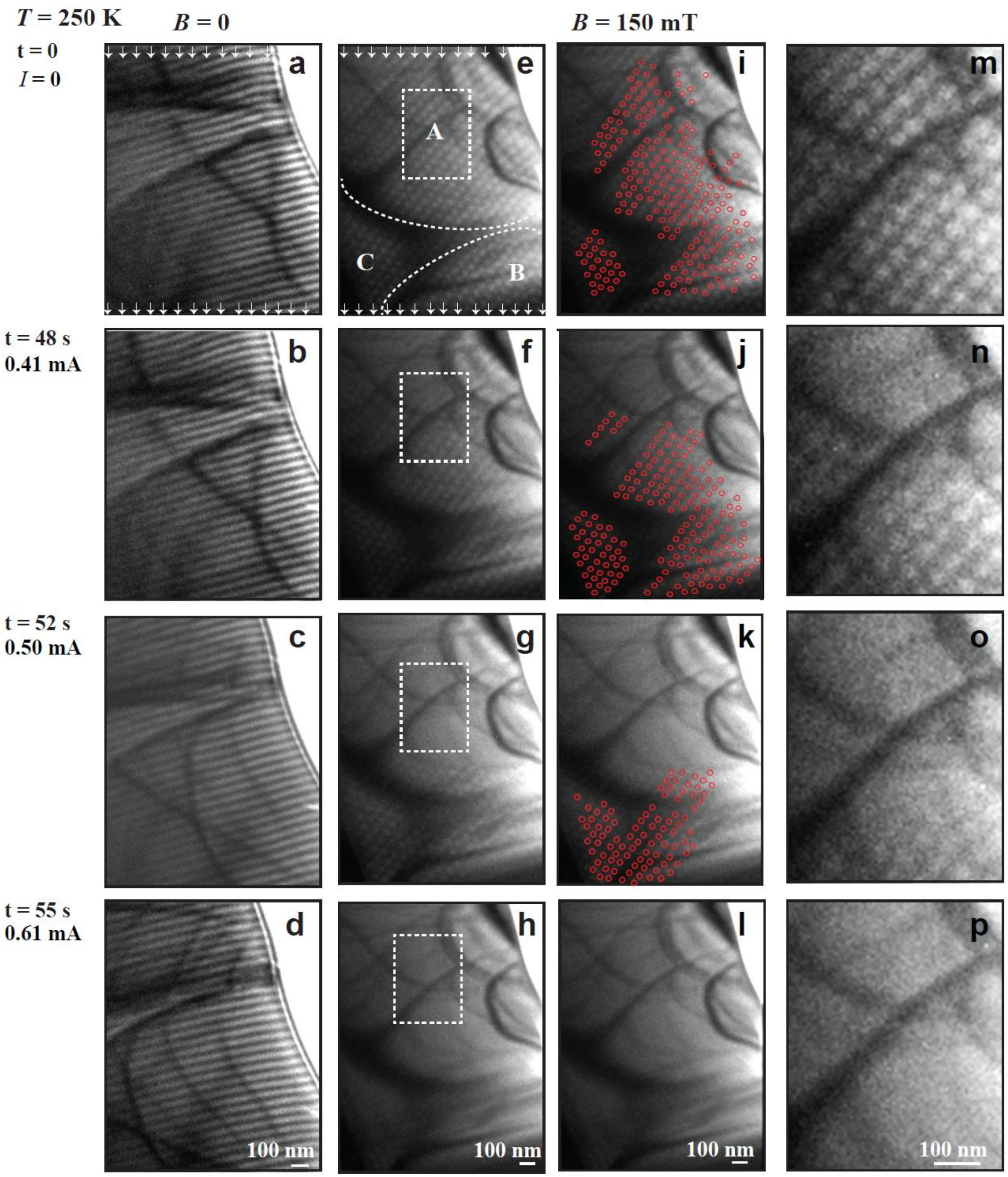
-counteraction of topological Hall effect (THE)

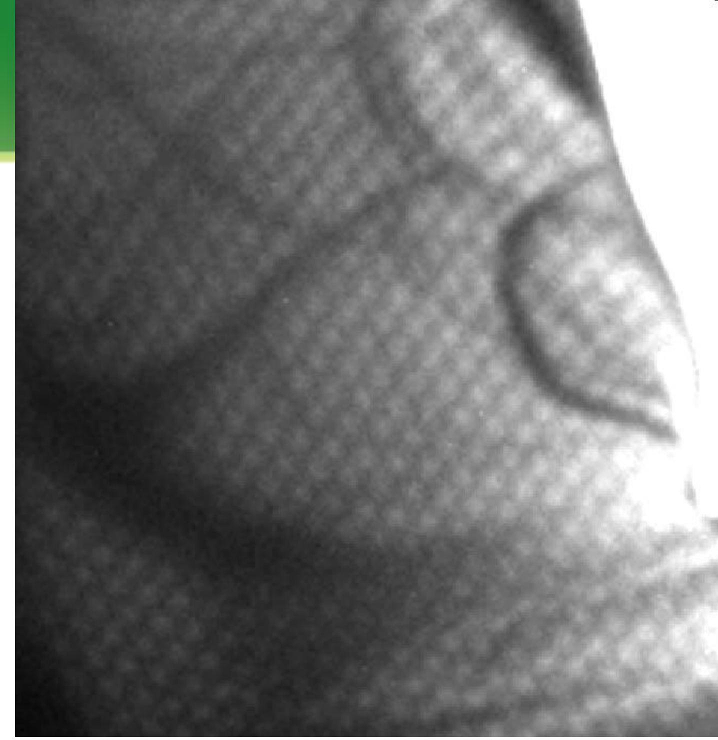
→ skyrmion Hall effect

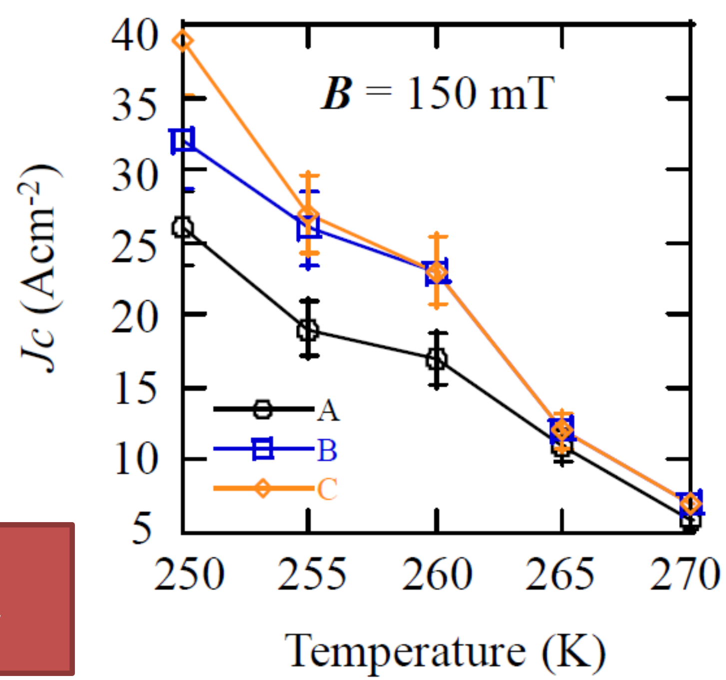
Current driven skyrmion flow in FeGe film











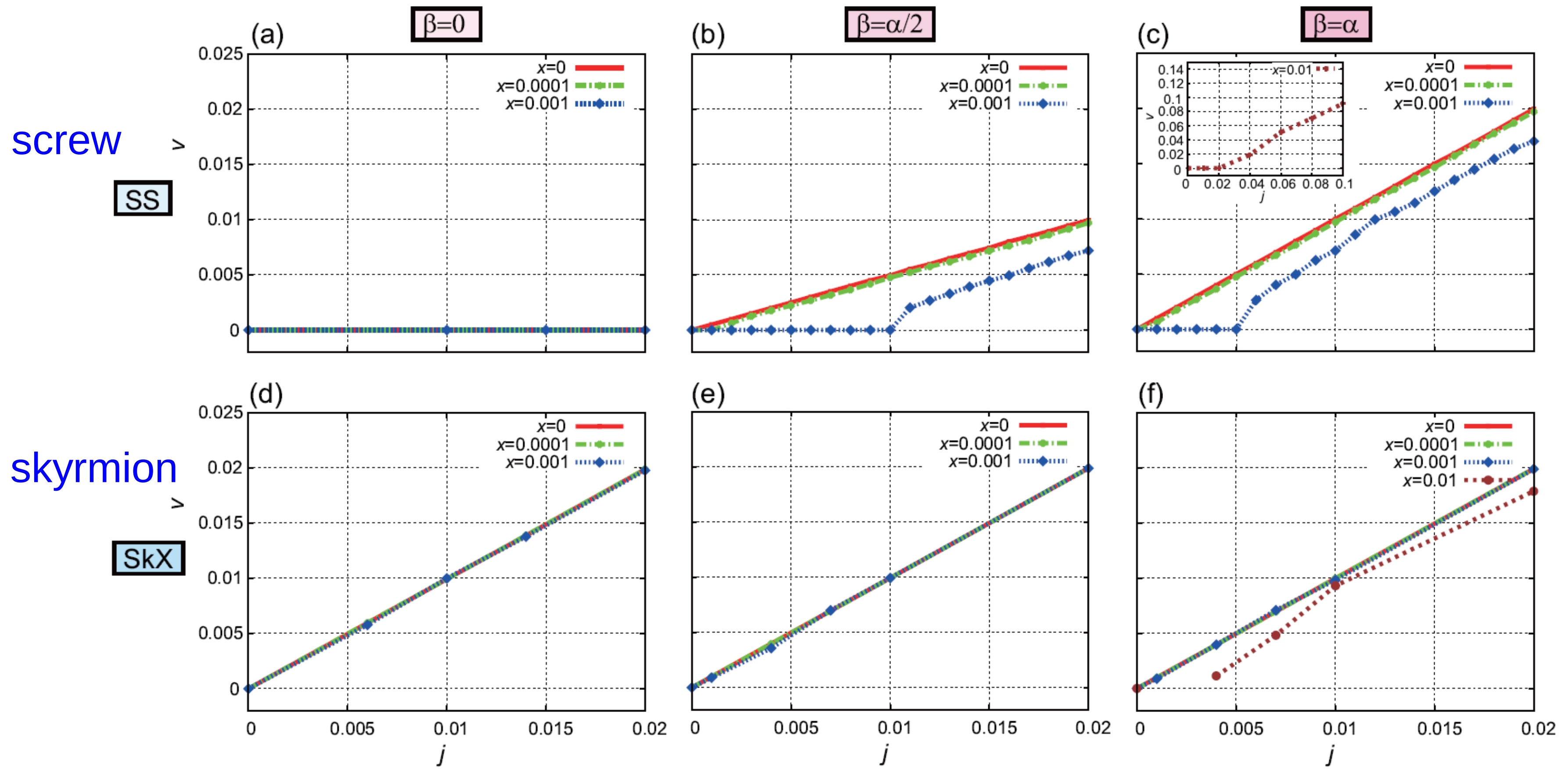
J_c<40A/cm^2 !!for skyrmion (not skrew)
>10^5 orders of magnitude smaller than Jc for DW

No pinning effect on skyrmion motion

LLG

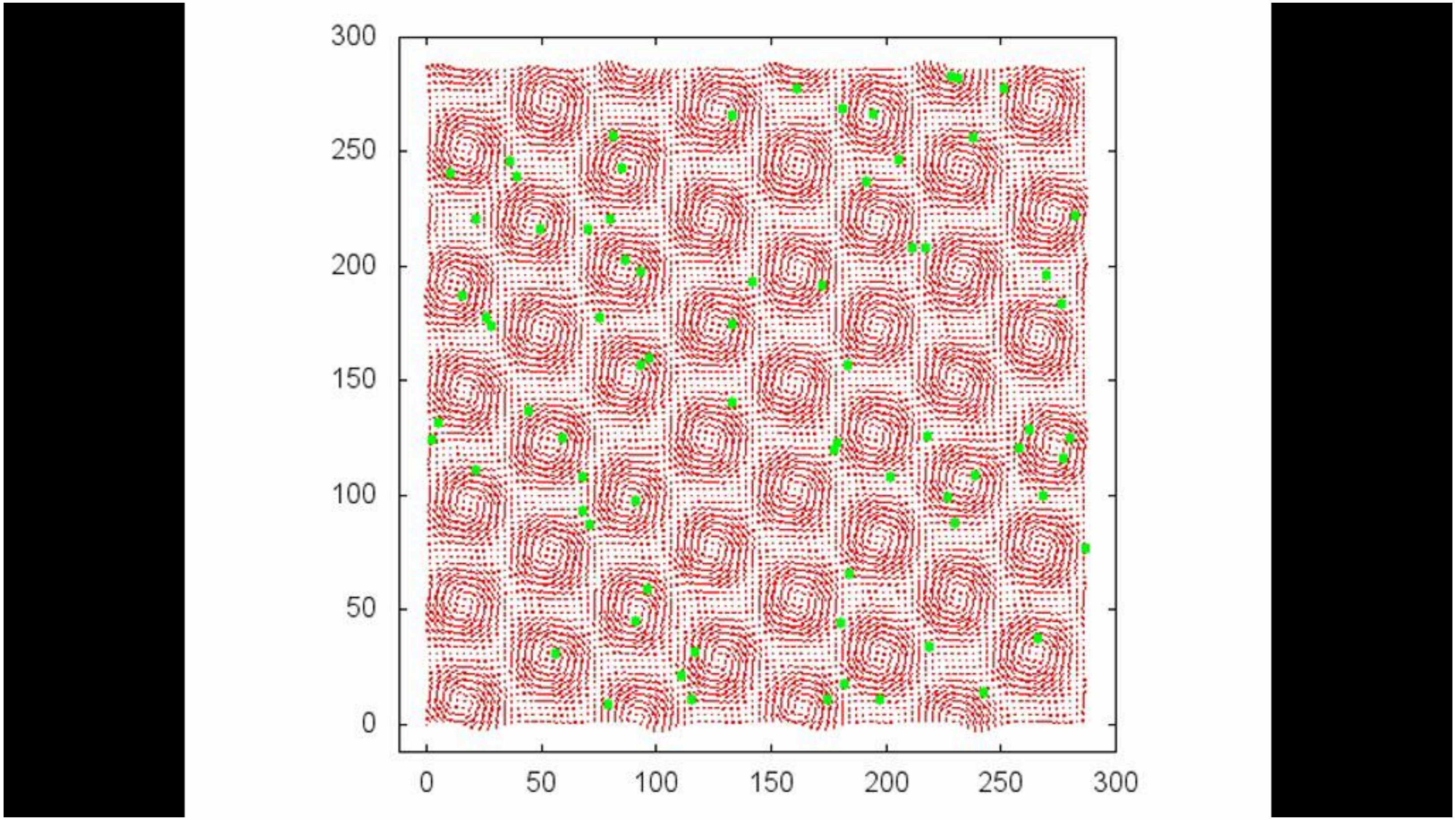
$$\frac{\mathrm{d}\vec{M}_{\vec{r}}}{\mathrm{d}t} = \gamma \vec{M}_{\vec{r}} \times B^{\mathrm{eff}}_{\vec{r}} - \frac{\alpha}{M}\vec{M}_{\vec{r}} \times \frac{\mathrm{d}\vec{M}_{\vec{r}}}{\mathrm{d}t} - \frac{pa^3}{2eM}\left(\vec{j}\cdot\vec{\nabla}\right)\vec{M}_{\vec{r}} - \frac{pa^3\beta}{2eM^2}\left[\vec{M}_{\vec{r}} \times \left(\vec{j}\cdot\vec{\nabla}\right)\vec{M}_{\vec{r}}\right],$$

Iwasaki-Mochizuki-Nagaosa (2012)



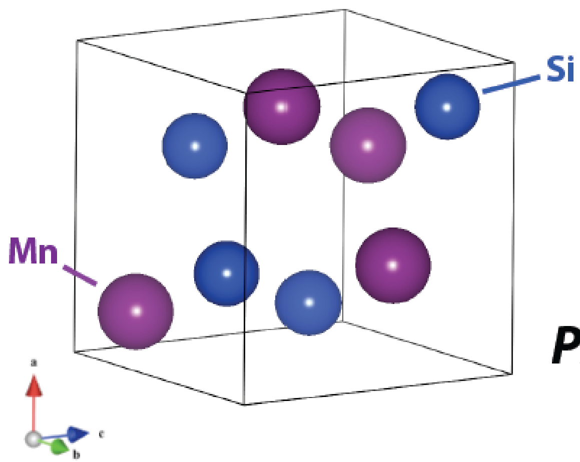
no (minimal) pinning effect on SkX

Simulation of current-driven skrymions under pinning sites



Cu_2OSeO_3 : Chiral Magnetic Insulator

MnSi



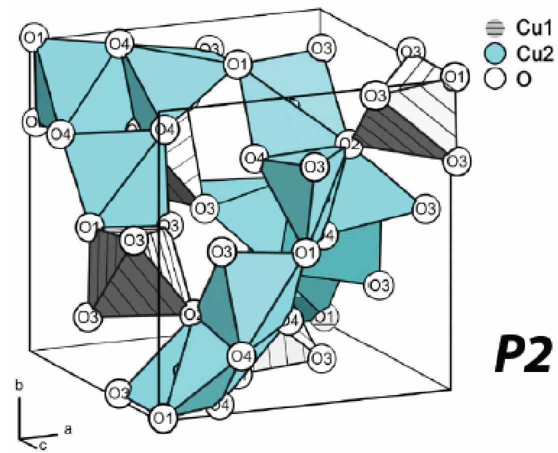
$P2_13$

Metal

Transport Properties

- Topological Hall Effect

Cu_2OSeO_3



$P2_13$

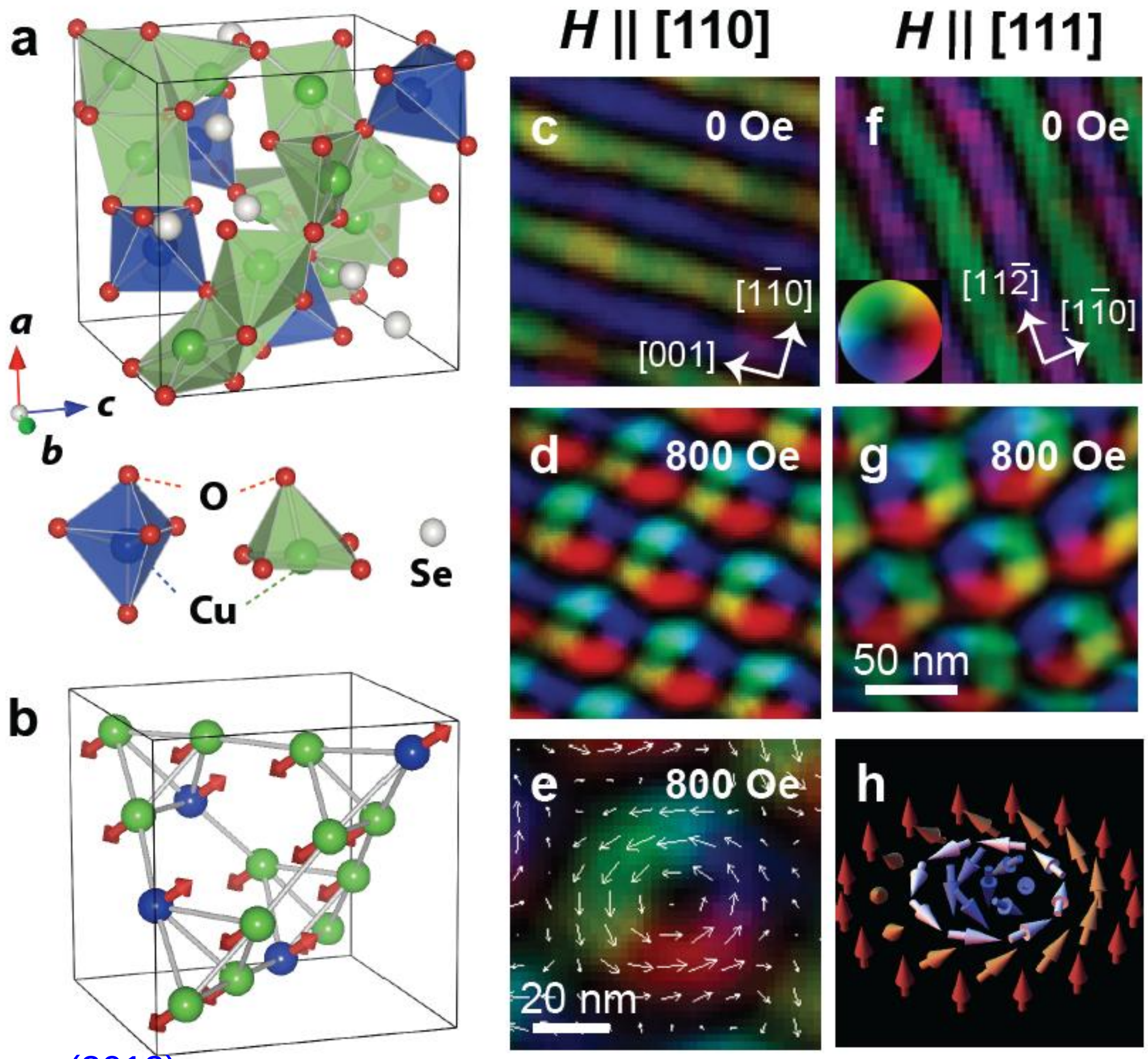
Insulator

Dielectric & Optical Properties

- Multiferroic order & ME effect?
- Novel collective excitation?
- Directional dichroism?

c.f. JWG Bos,CV Colin, and TTM Plastra, PRB (2010).

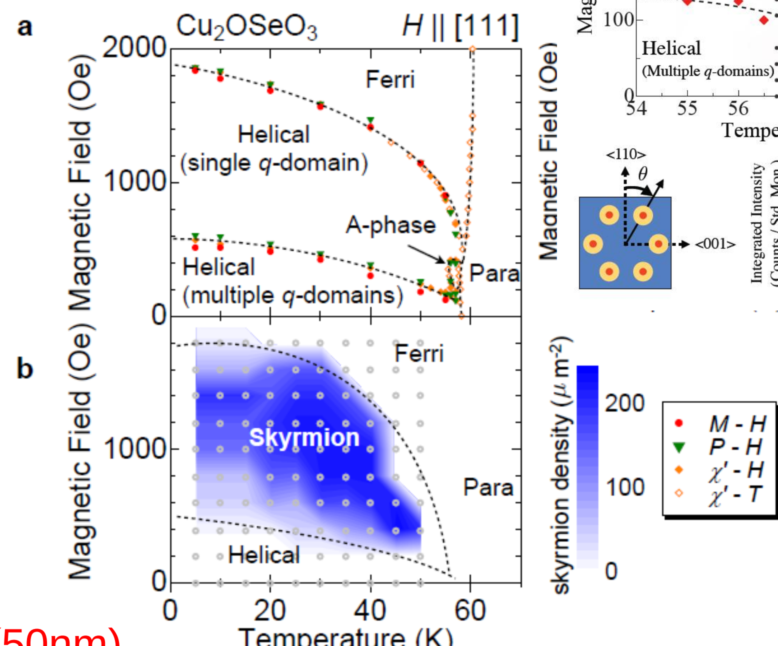
Lorentz TEM observation of thin flake of Cu_2OSeO_3

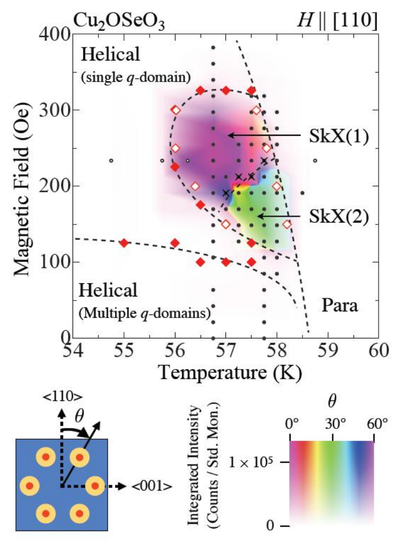


Seki et al. Science (2012)

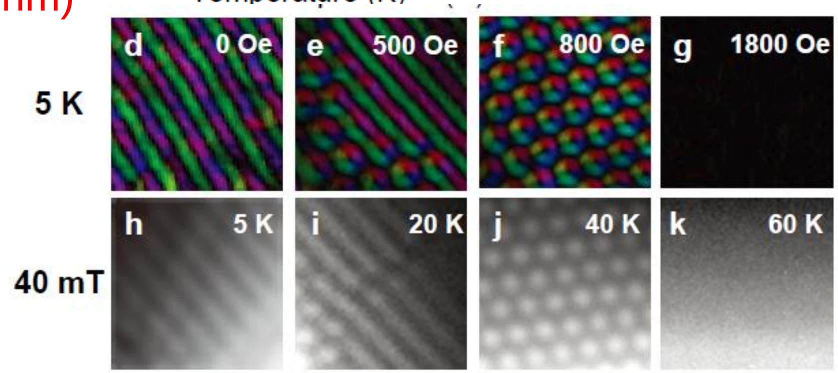
Skyrmion crystal phase: bulk vs. thin film

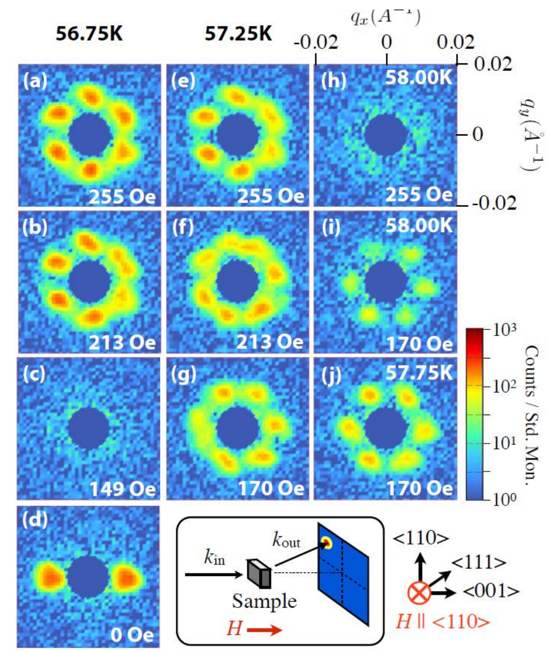
bulk





film (50nm)



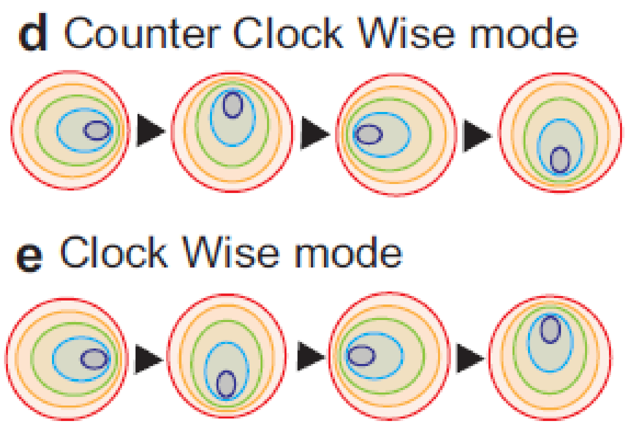


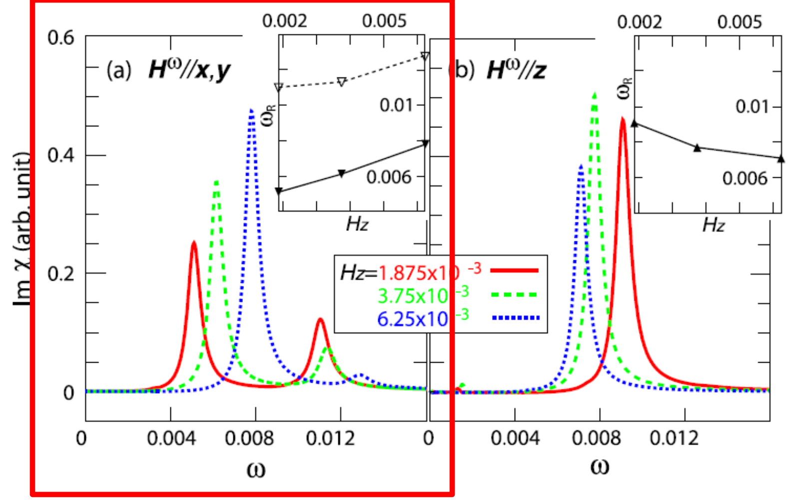
Seki et al. PRB (RC), 85, 220406(2012).

See also Adams et al. PRL, 108, 237204 (2012).

H//x,y on skyrmions

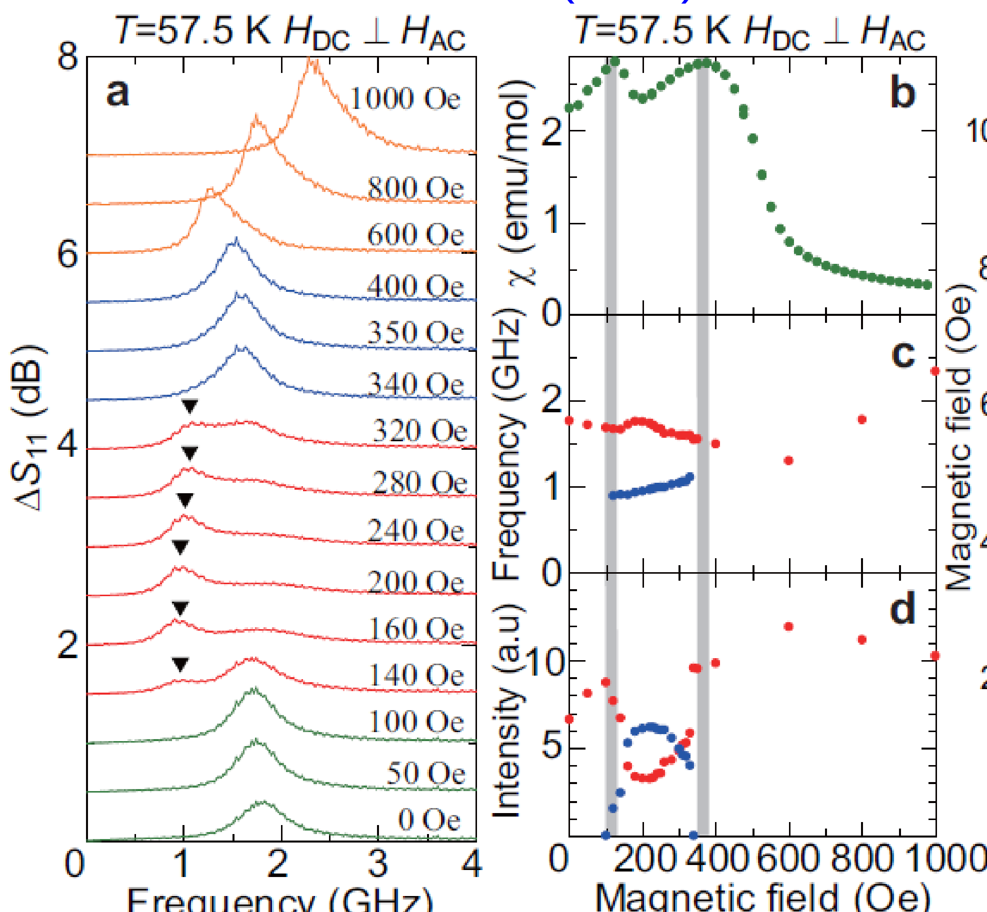
$H^{\omega}//xy$

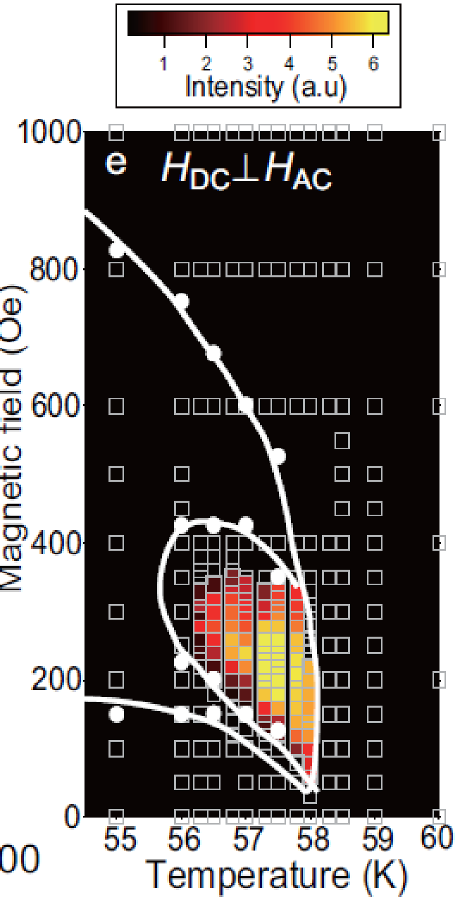


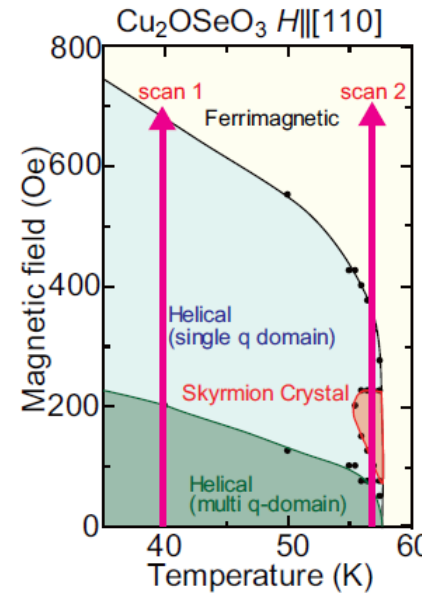


Mochizuki PRL (2012)

Onose et al. PRL (2012)



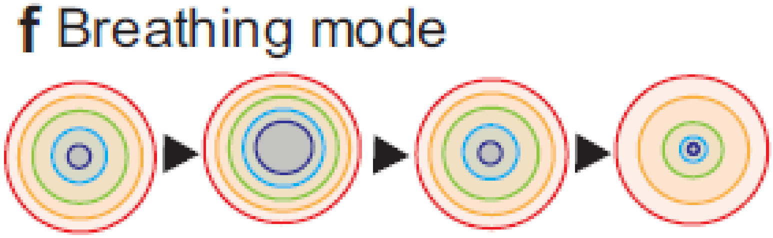


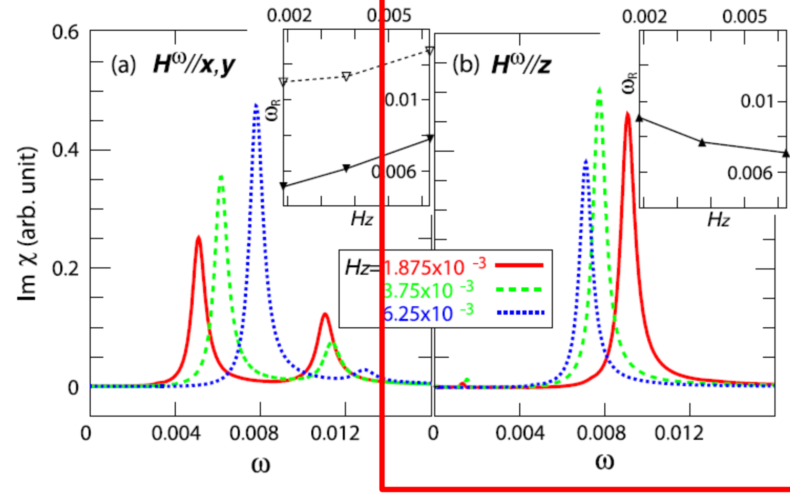


H//z on skyrmions

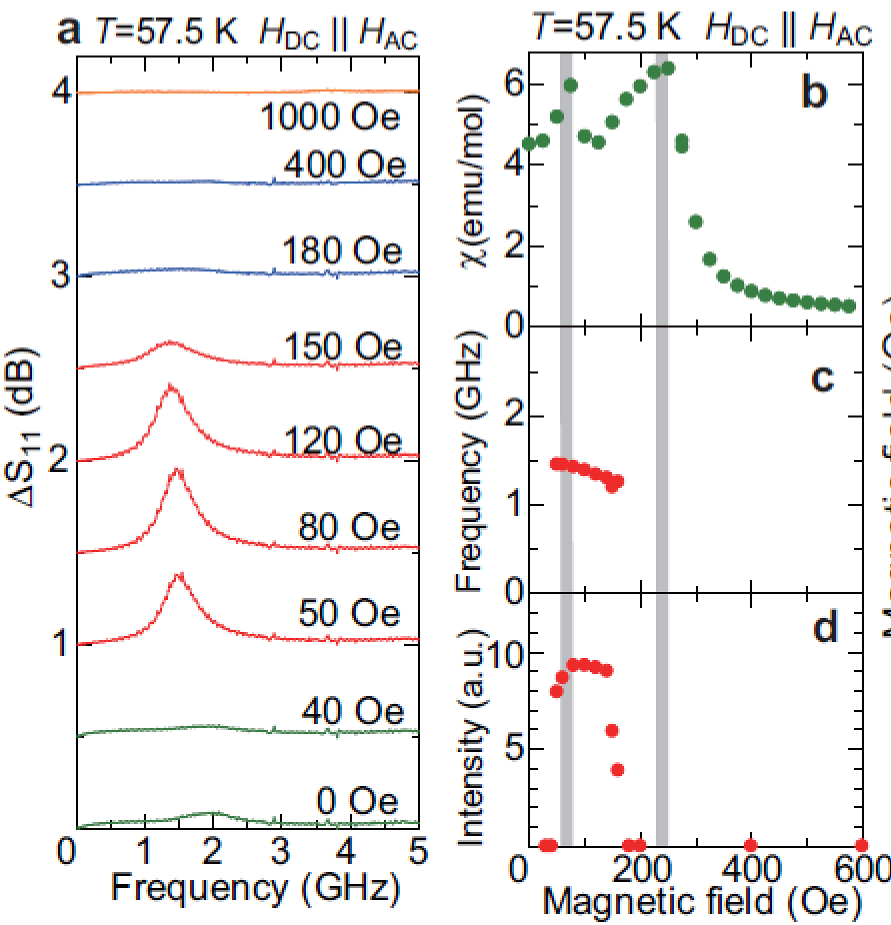
Onose et al. PRL (2012)

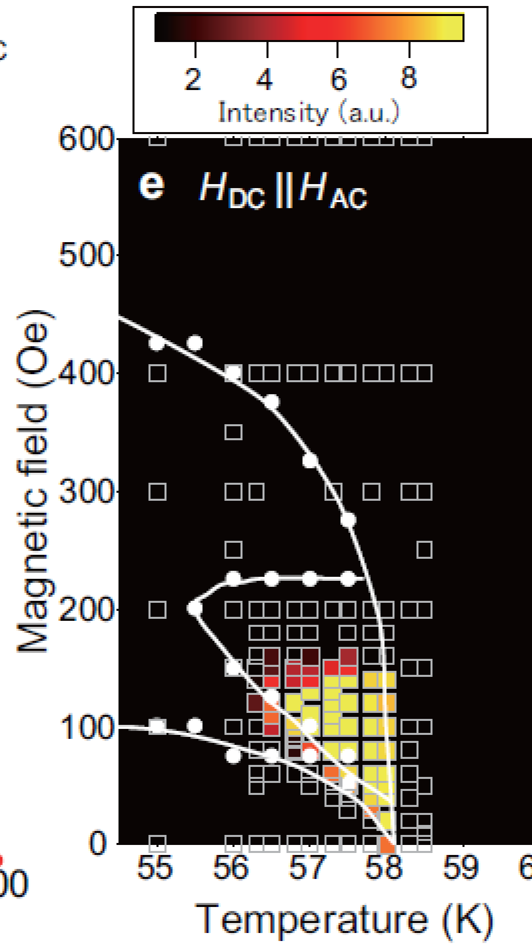
$H^{\omega}//c$

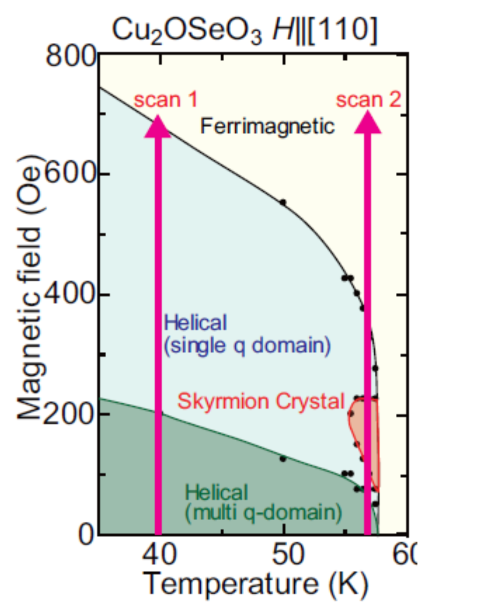




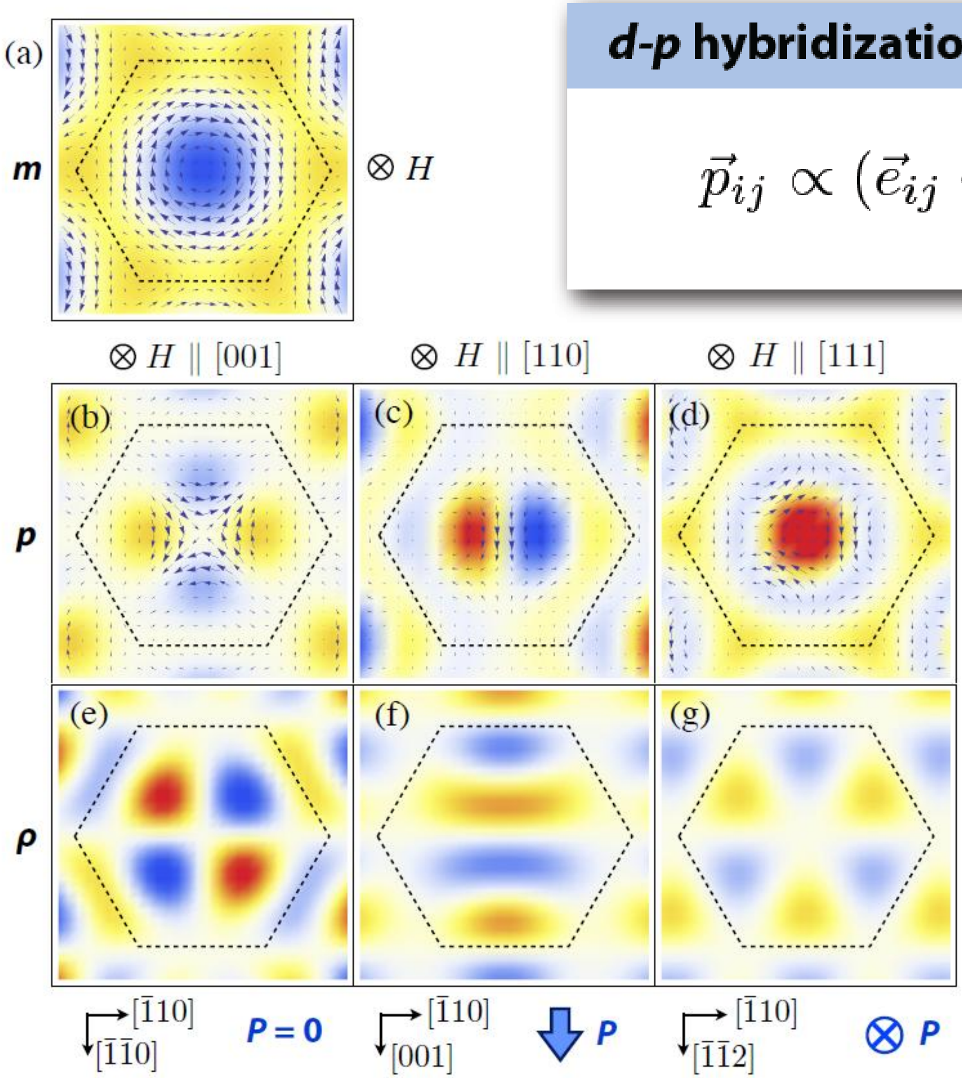
Mochizuki PRL (2012)





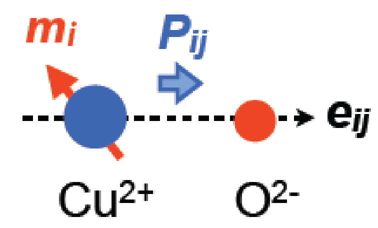


Cu_2OSeO_3: *P* and ρ distributions in skyrmion



d-p hybridization model

$$\vec{p}_{ij} \propto (\vec{e}_{ij} \cdot \vec{m}_i)^2 \vec{e}_{ij}$$



polarization P

E-field drive

charge ρ

quadrupole

dipole

Seki et al. PRB (2012)

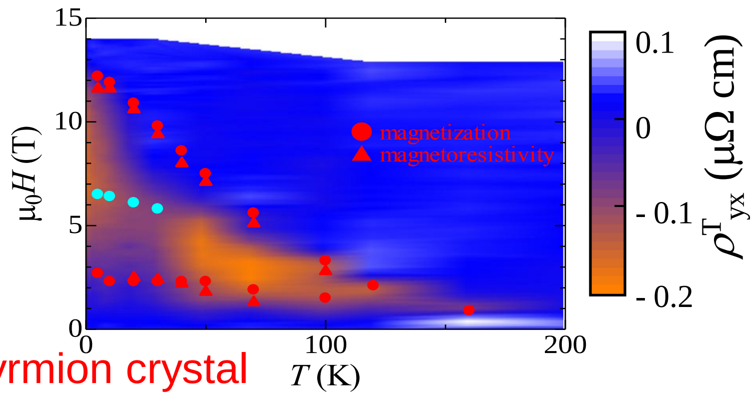
Electrodynamics of Skyrmions ~ toward Skyrmionics ~

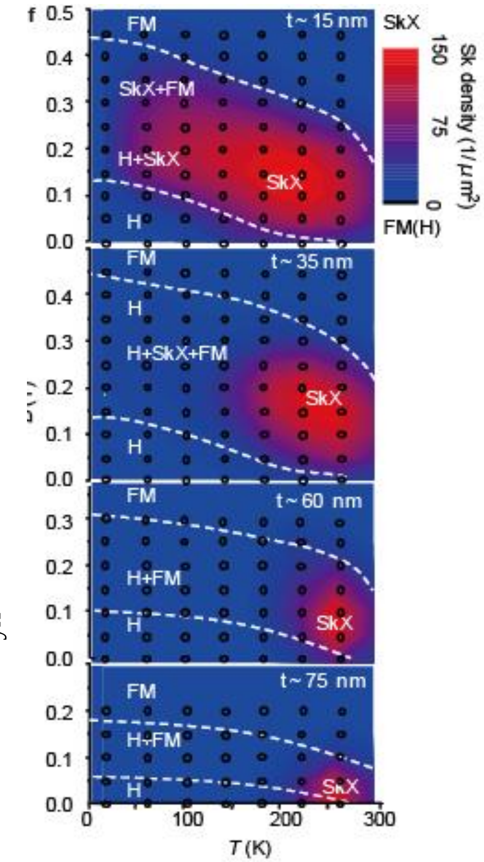
Stabilization Skrymions and Skyrion Xtal in form of thin films

Topological Hall effect as probe for SkX

emergent EM fields

MnGe
zero-field skyrmion crystal





Skyrmion transport and dynamics

toward skyrmionics

- current-drive of Skyrmions (~10A/cm^2)
- multiferroic skyrmions, E-drive/optical-control of Skyrmion
- spontaneous ratchet motion in thermal equilibrium