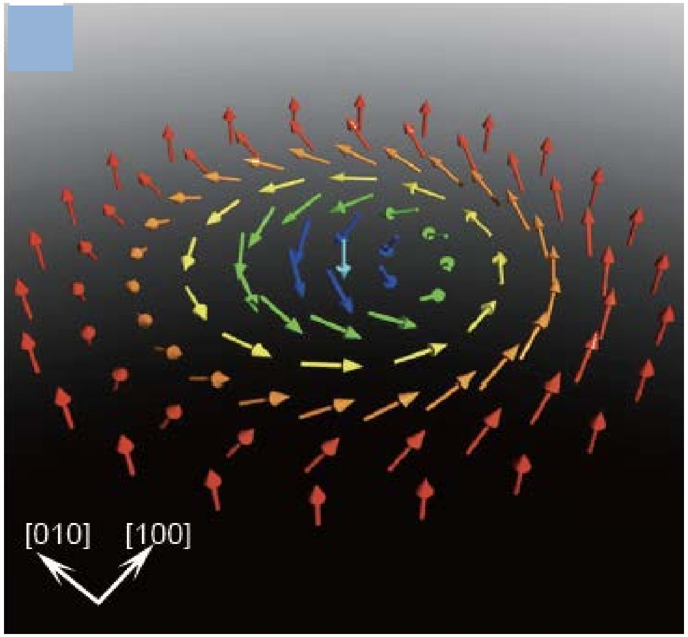
Skyrmion Dynamics and Topological Transport Phenomena

Yoshi Tokura
RIKEN Center for Emergent Matter Science (CEMS)
Department of Applied Physics, University of Tokyo

CEMS

"skyrmion" , the concept originally introduced by Tony Skyrme (1922-87) to describe the state of nucleon: to model a particle as a topological soliton



Skyrmions and topological transport phenomena

Skyrmions in multiferoics toward *E*-control and light control

Collaborators

- ***RIKEN (Japan)***

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

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

  Y. Kanazawa, Y. Onose, S. Ishiwata, A. Tsukazaki, M. Ichikawa, Y. Shiomi, K. Shibata, F. Kagawa, Y. Okamura, M. Mochizuki

- ***NIMS (Japan)***

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

Xiuazhen Yu

Naoya Kanzawa

Shinichiro Seki

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

  J. H. Han, J. H. Park

- ***MPI (Germany)***

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

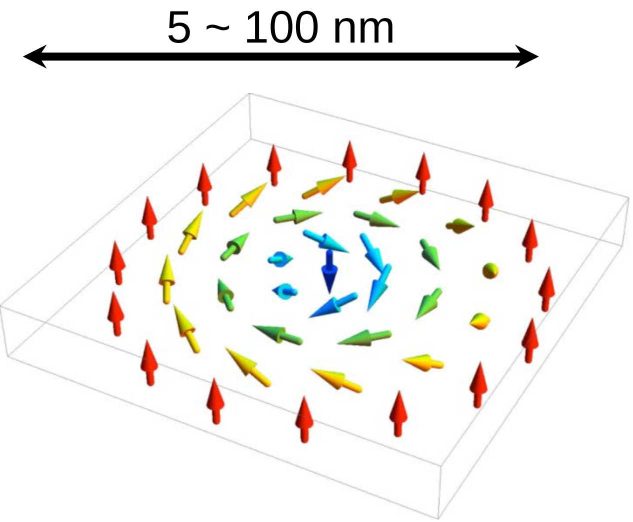
- ***PSI (Switzerland)***

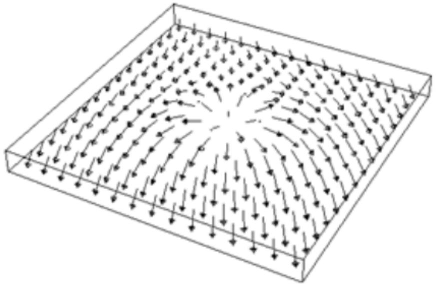
  J. White, N. Egetenmeyer, J. Gavilano

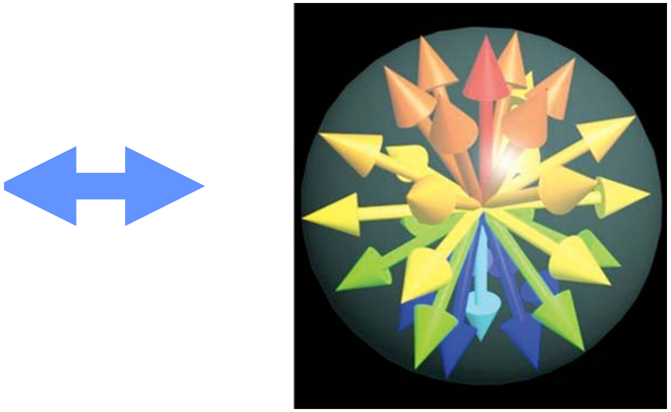
- ***Groningen Univ. (Holland)***

  M. Mostovoy

What is magnetic skyrmion?





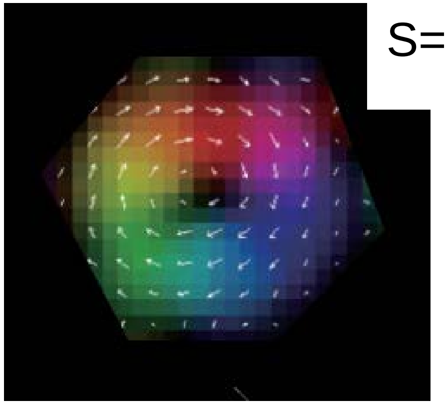


Topologically-stable spin vortex
with particle-like nature

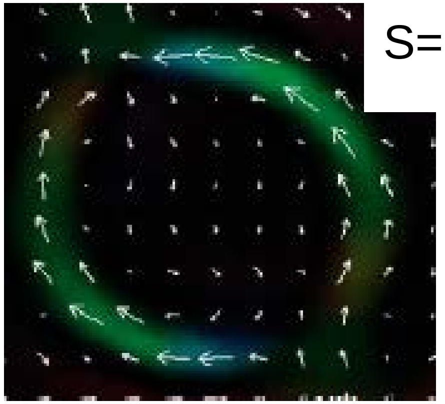
“skyrmion number”

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

Lateral component of
M of some bubbles



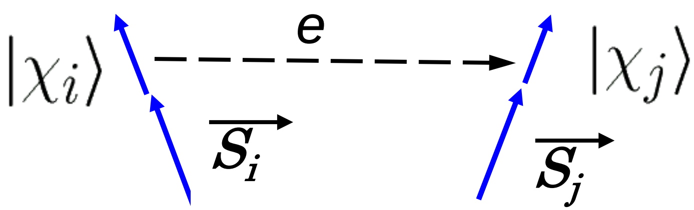
S=-1



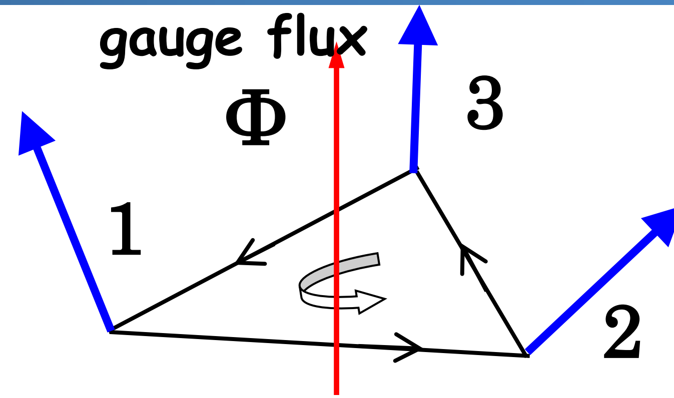
S=0

a pair of
Bloch lines

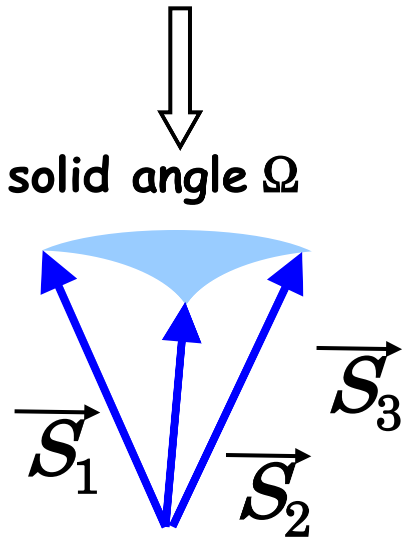
Spin Chirality



$$t_{ij} = t\langle\chi_i|\chi_j\rangle$$
$$= t[\cos(\frac{\theta_i}{2})\cos(\frac{\theta_j}{2}) + \sin(\frac{\theta_i}{2})\sin(\frac{\theta_j}{2})e^{i(\phi_i-\phi_j)}]$$
$$= t\cos(\frac{\theta_{ij}}{2})\exp(ia_{ij})$$



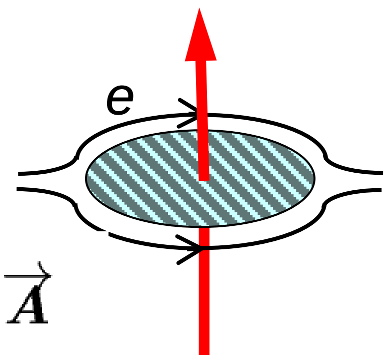
non-coplanar spin structure



Fictitious "magnetic field" $\Phi = \frac{1}{2}\,\underline{\Omega}$

$$= 2\vec{S}_1\cdot\vec{S}_2\times\vec{S}_3$$

Aharonov - Bohm effect

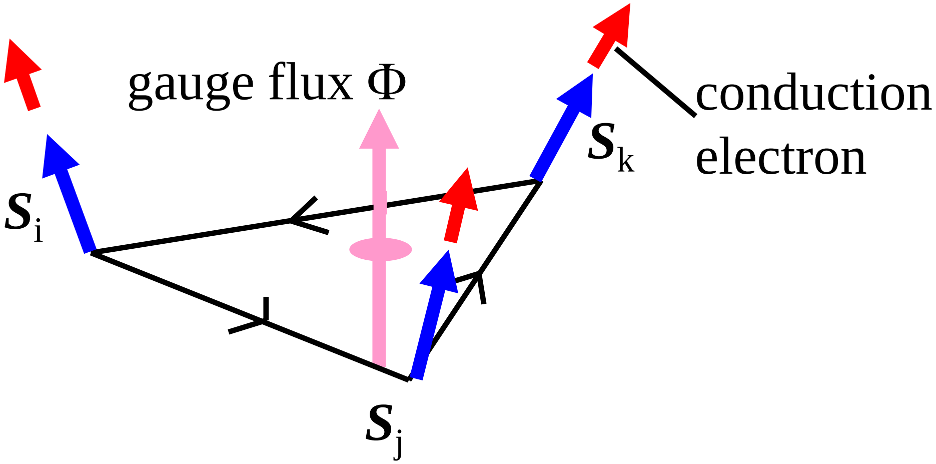


$$\vec{B} = \mathrm{rot}\ \vec{A}$$

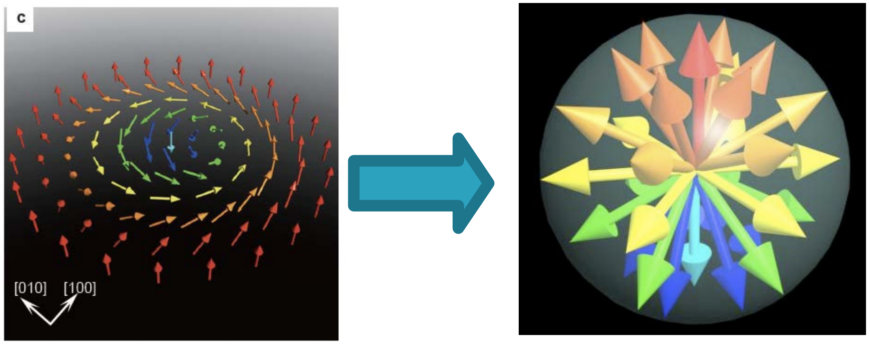
$$-\frac{ie}{\hbar}\oint\vec{A}d\vec{r} = -2\pi i\cdot\frac{\Phi}{\Phi_0}$$

$$\Phi_0 = \frac{h}{e}$$: flux quantum

Skyrmion



Mapping to a sphere

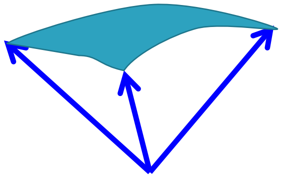


Solid angle $\Omega = 4\pi$

Cf. Spin chirality

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

$= 1/2\ \Omega$ Solid angle



Continuum approximation

Total spin Chirality

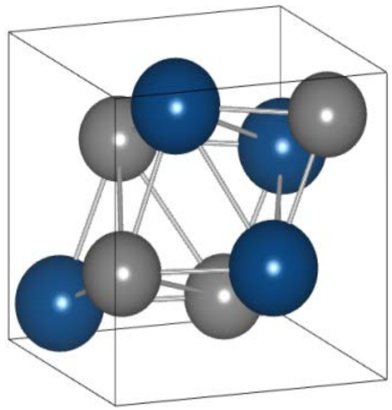
$$= \frac{1}{4\pi S^3} \int d^2\mathbf{r}\, \mathbf{S} \cdot (\nabla_x \mathbf{S} \times \nabla_y \mathbf{S})$$

$$= N_S$$ Skyrmion number

Skyrmion carries emergent magnetic field.

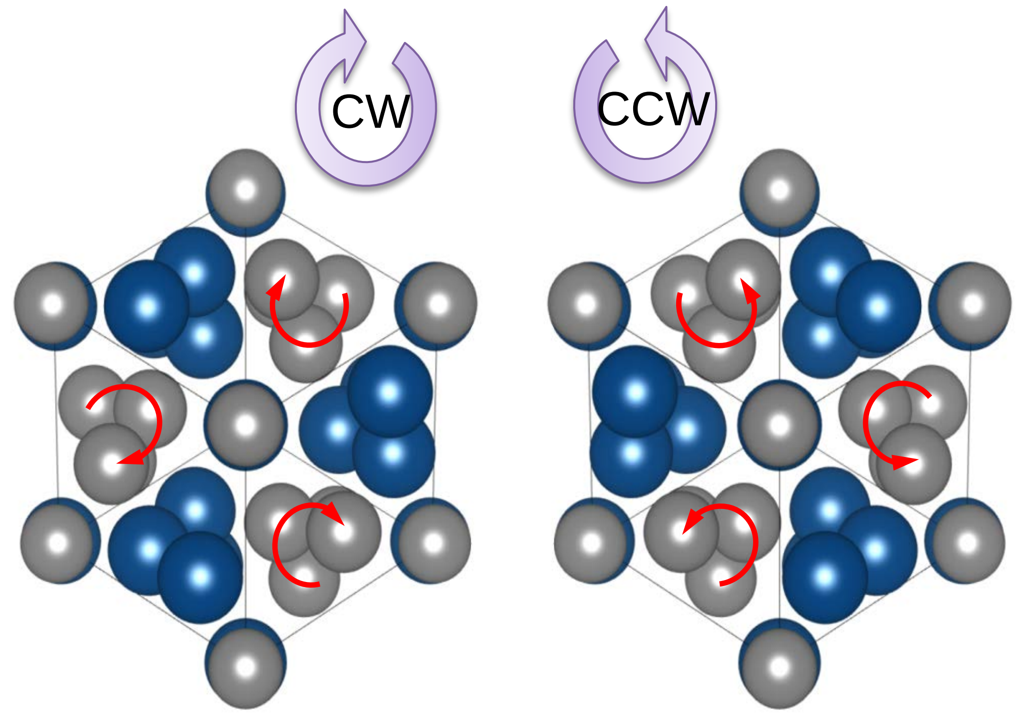
Helical spin order in B20-type crystals

Crystal structure



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

- Cubic ($P2_13$)
- Noncentrosymmetric



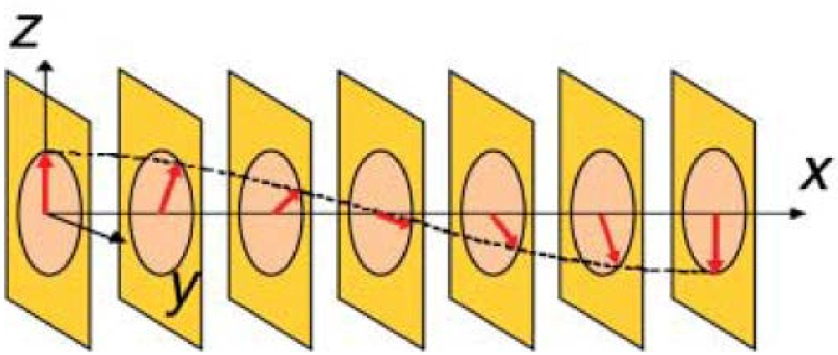
Chiral lattice structure

Magnetic structure

<u>Three well-separated energy scales</u>

ferromagnetic interaction($\boldsymbol{S}_i \cdot \boldsymbol{S}_j$) > Dzyaloshinsky-Moriya interaction($\boldsymbol{S}_i \times \boldsymbol{S}_j$) > magnetic anisotopy
→one-handed helical spin structure
(a long wavelength 17.5 – 230 nm, weakly locked helix direction <111> or <100>)

Toward real space observation of Skyrmion structure



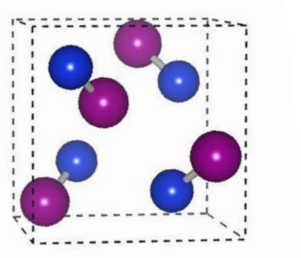
$$H = \sum \left(-J\vec{S}_i \cdot \vec{S}_j + \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \right)$$

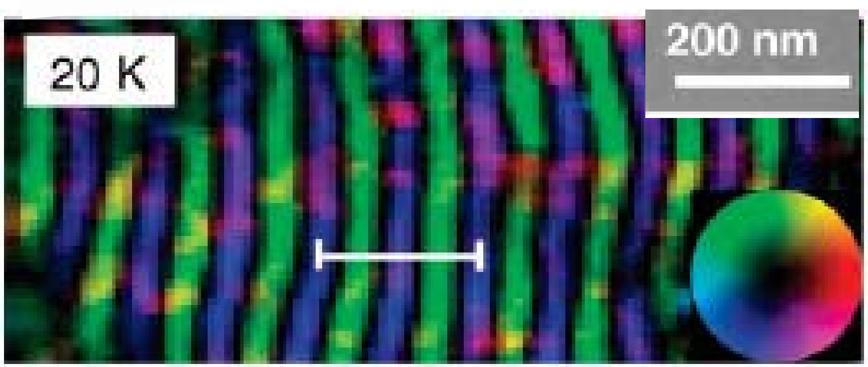
Ferro + DM

Helical spin structure

Long period～aJ/D～$10nm$-$300nm$

F

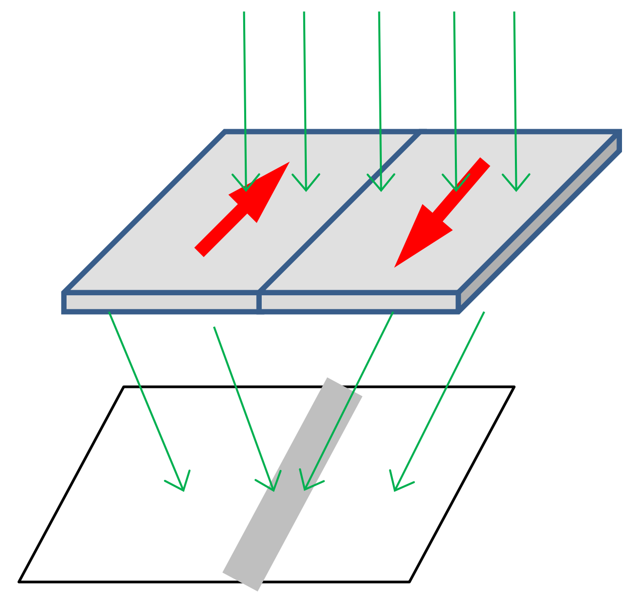




M. Uchida, Y. Onose, Y. Matsui, Y. Tokura, Science (2006)

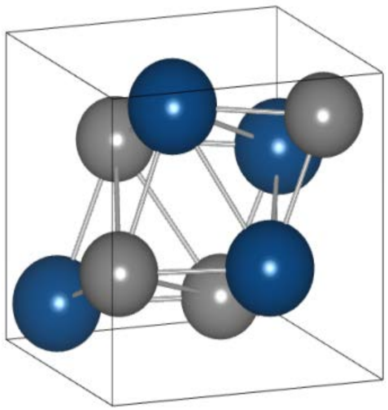
Lorentz microscope

electrons



Helical spin order in B20-type crystals

Crystal structure



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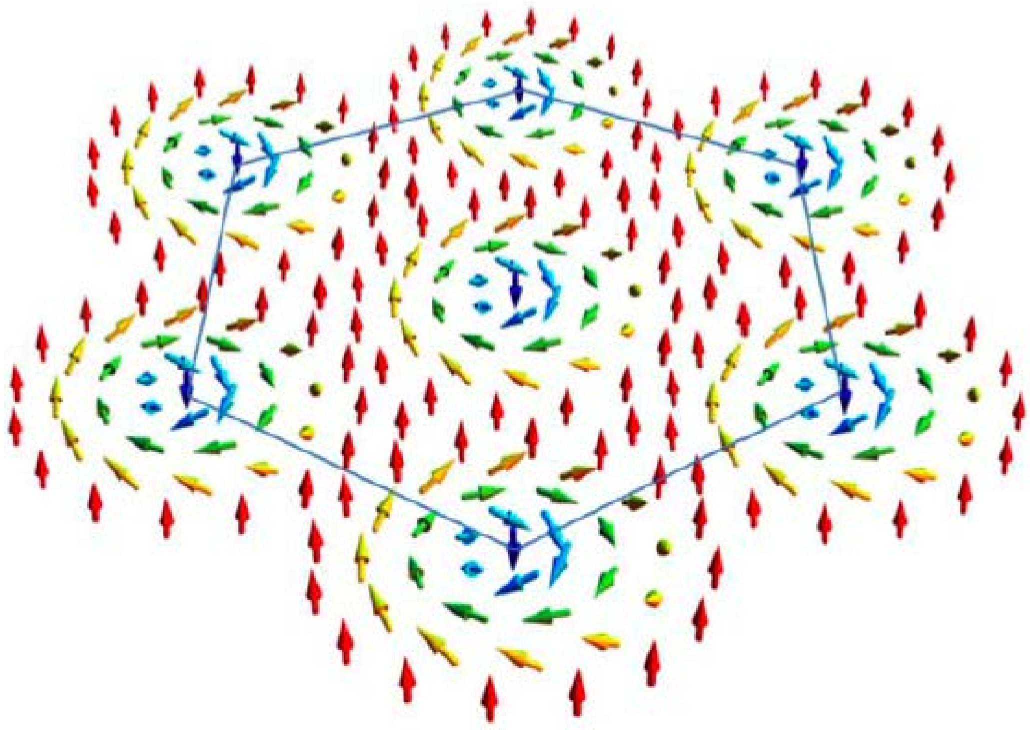

Magnetic structure

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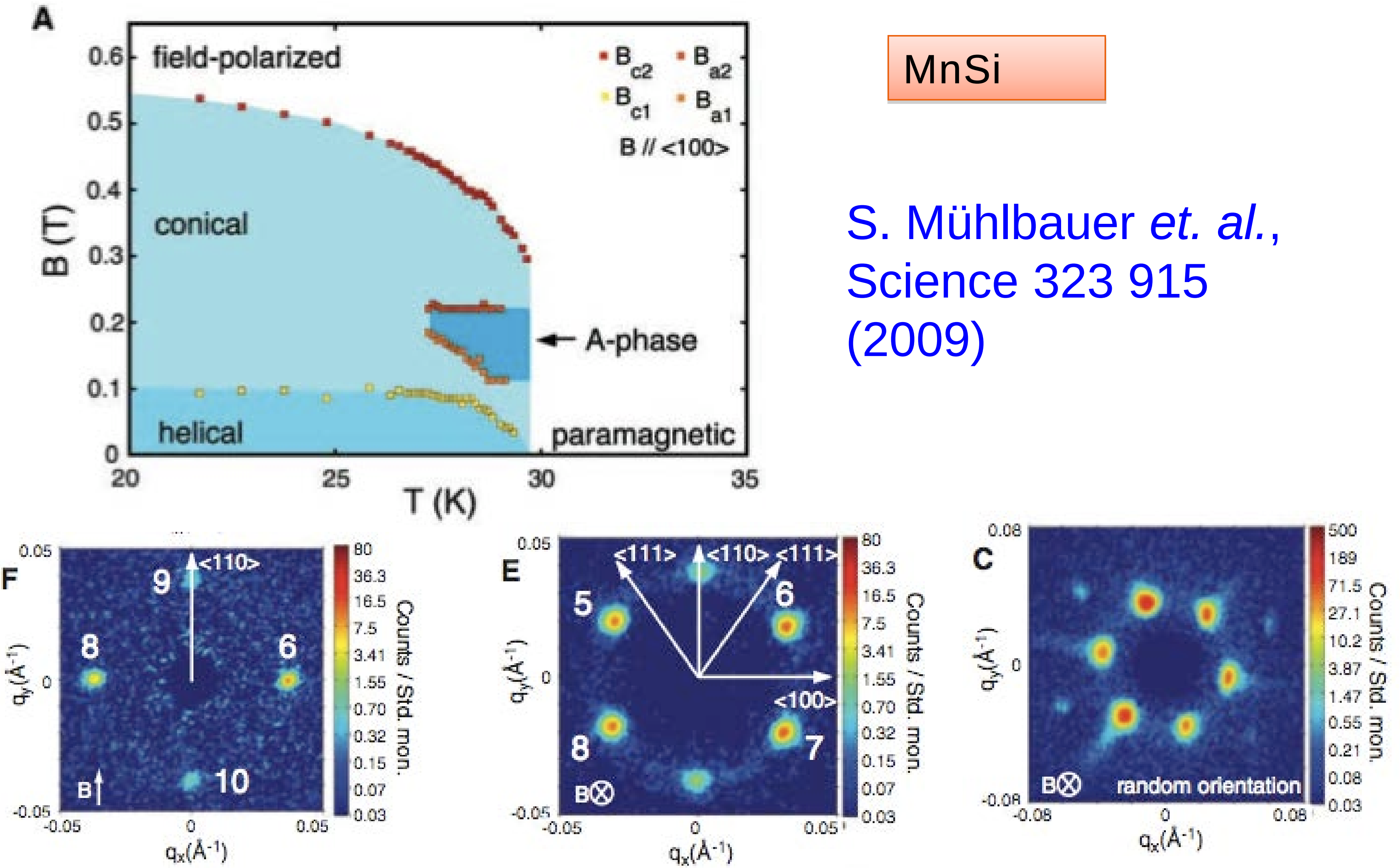
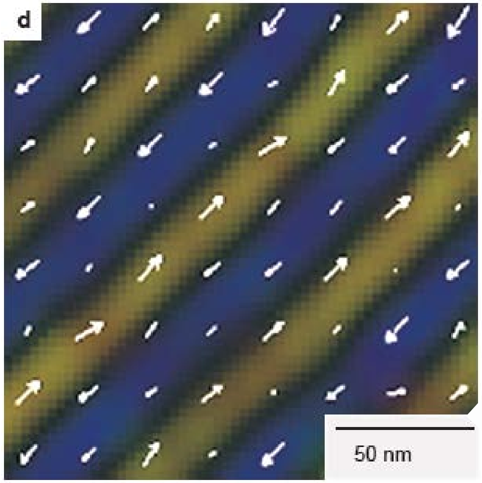
Small angle neutron scattering for Skyrmion Xtal

MnSi

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



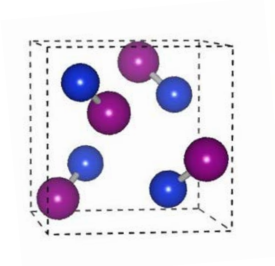
Real Space Observation of Skyrmion crystal

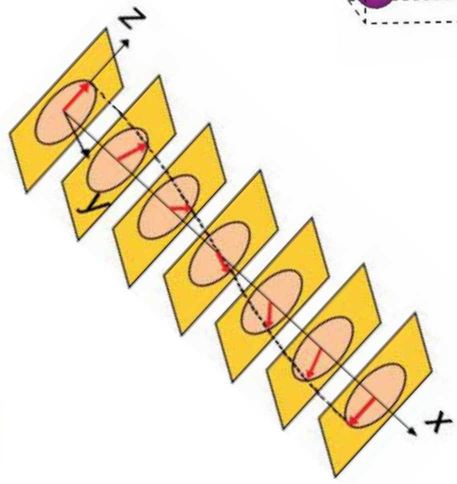


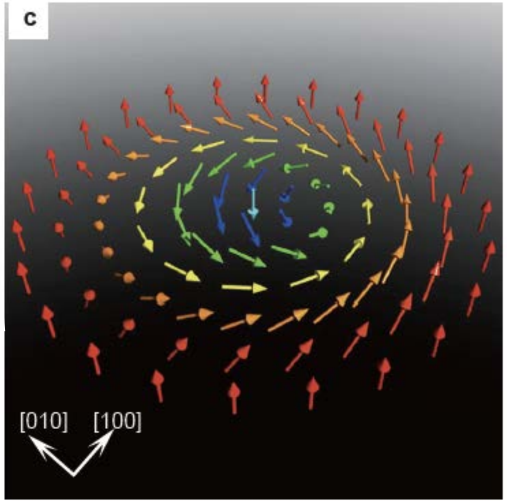
$Fe_{0.5}Co_{0.5}Si$

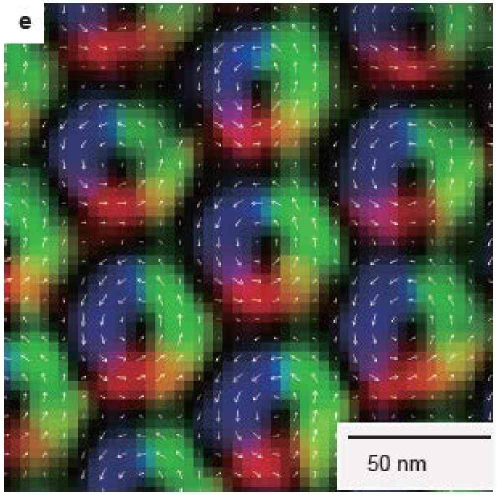
T=25K

H=0

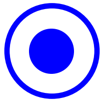


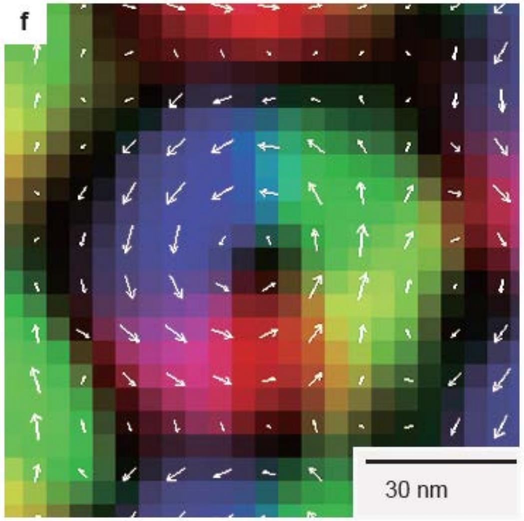






H=50mT



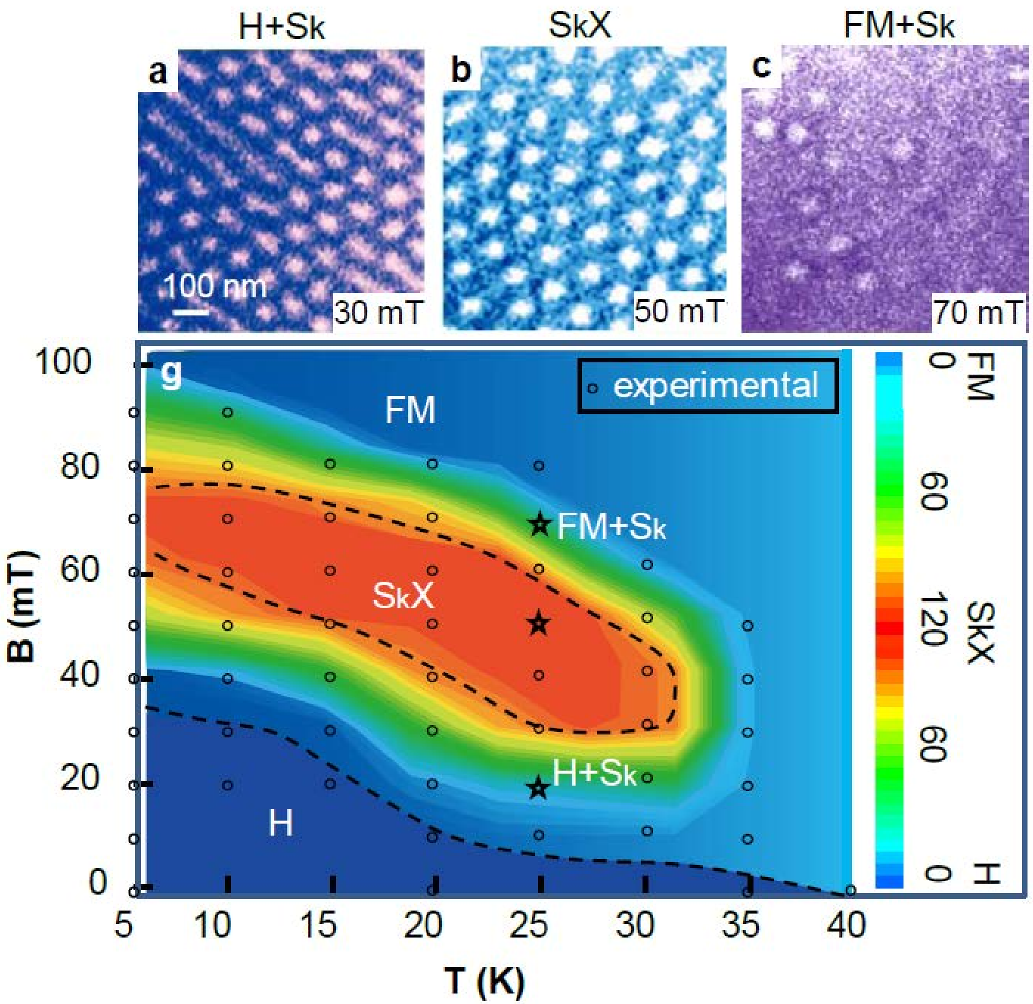


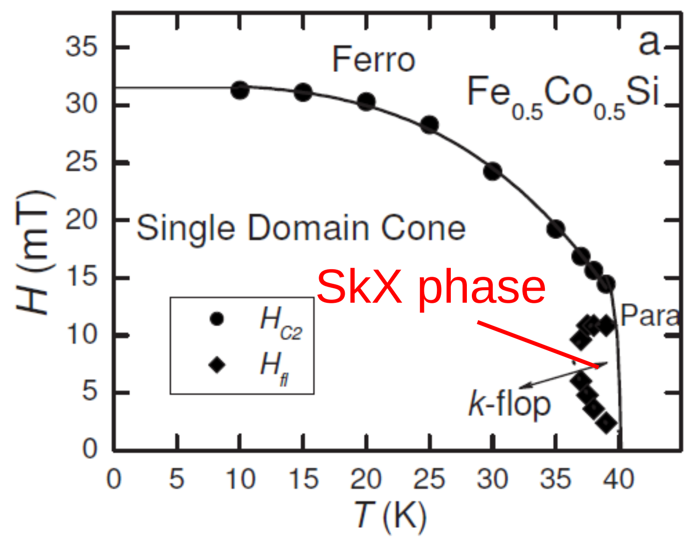
X.Z. Yu, Y.T *et al.* Nature *(2010).*

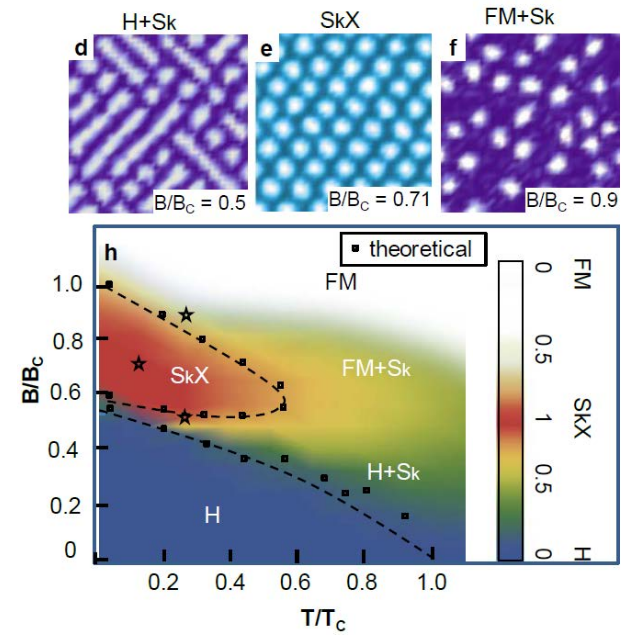
H-T Phase diagram

Bulk sample

20nm-thick film (Lorentz TEM)







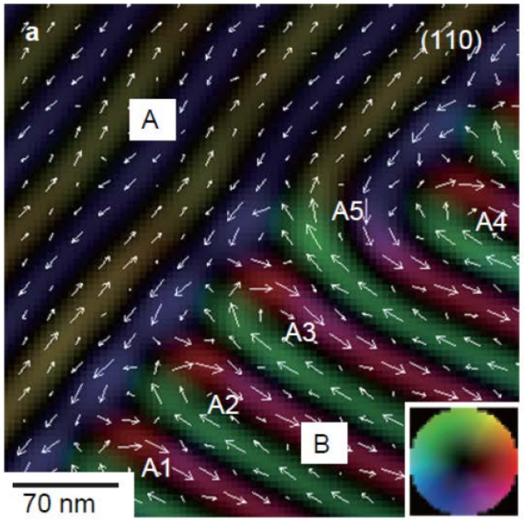
Skx: Skyrmion Crystal

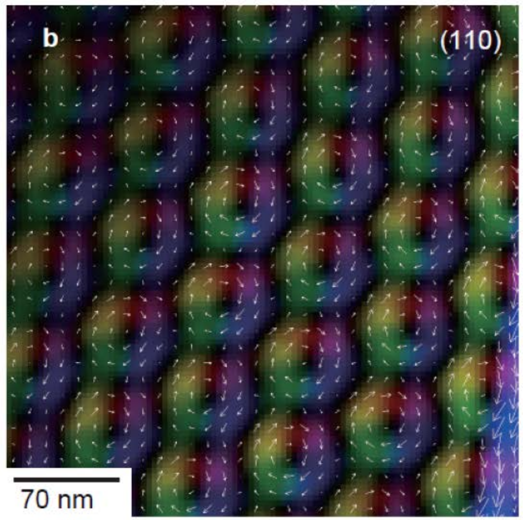
2D simulation

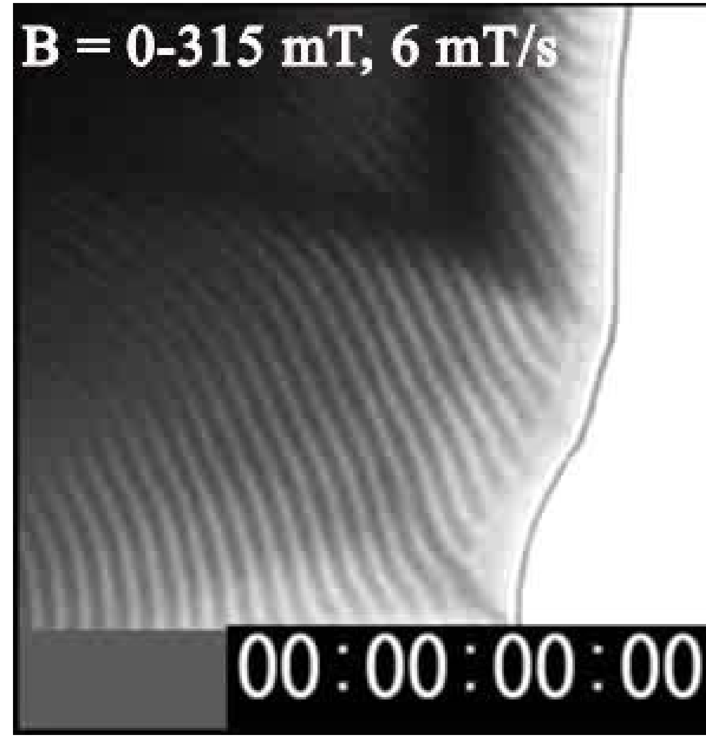
FeGe: from helical to skyrmion crystal at 260K

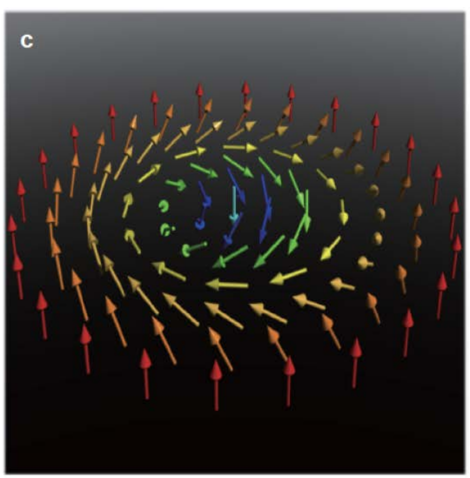
X.Z. Yu et al. Nat. Mater.(2010)

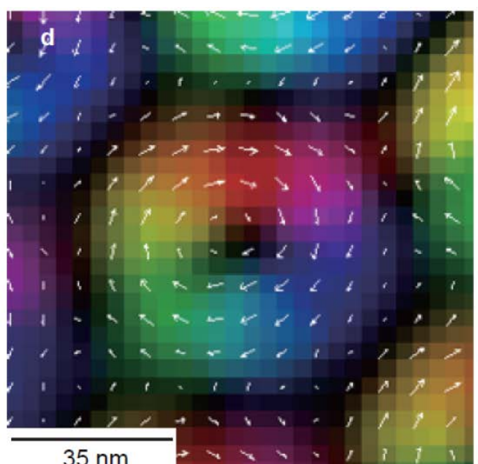
H=0 ⊙ H=0.1T

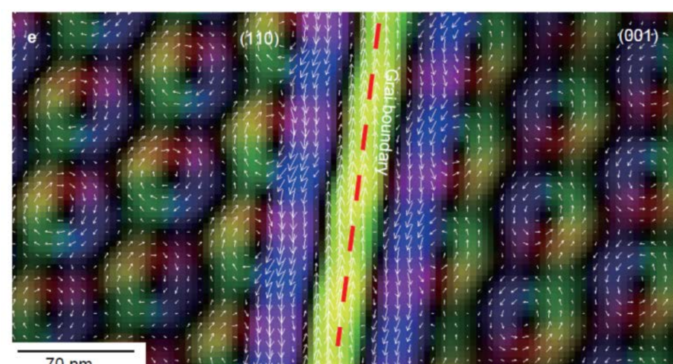




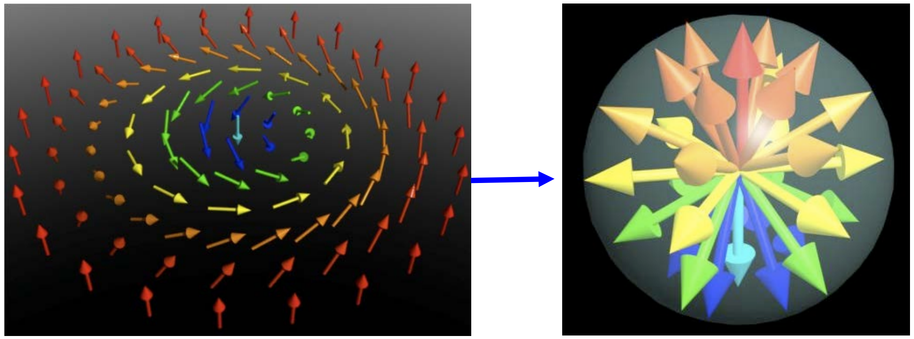








Real-space fictitous magnetic field in a skyrmion spin texture



Solid angle $\Omega = 4\pi$

In srong coupling case

One skyrmion ⟷ One magnetic flux ϕ_0

$$\phi_0 = h/e$$

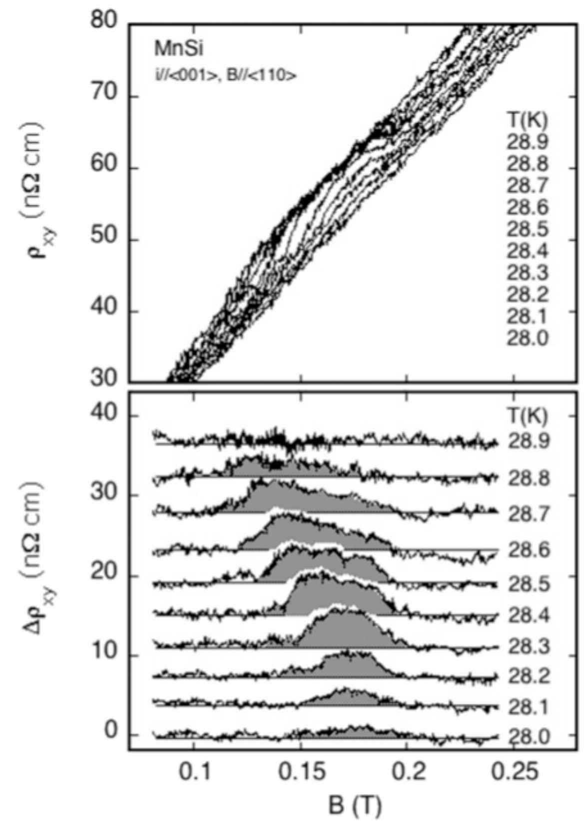
Emergent **magnetic field**

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

A: skyrmion size

one skyrmion/nm^2

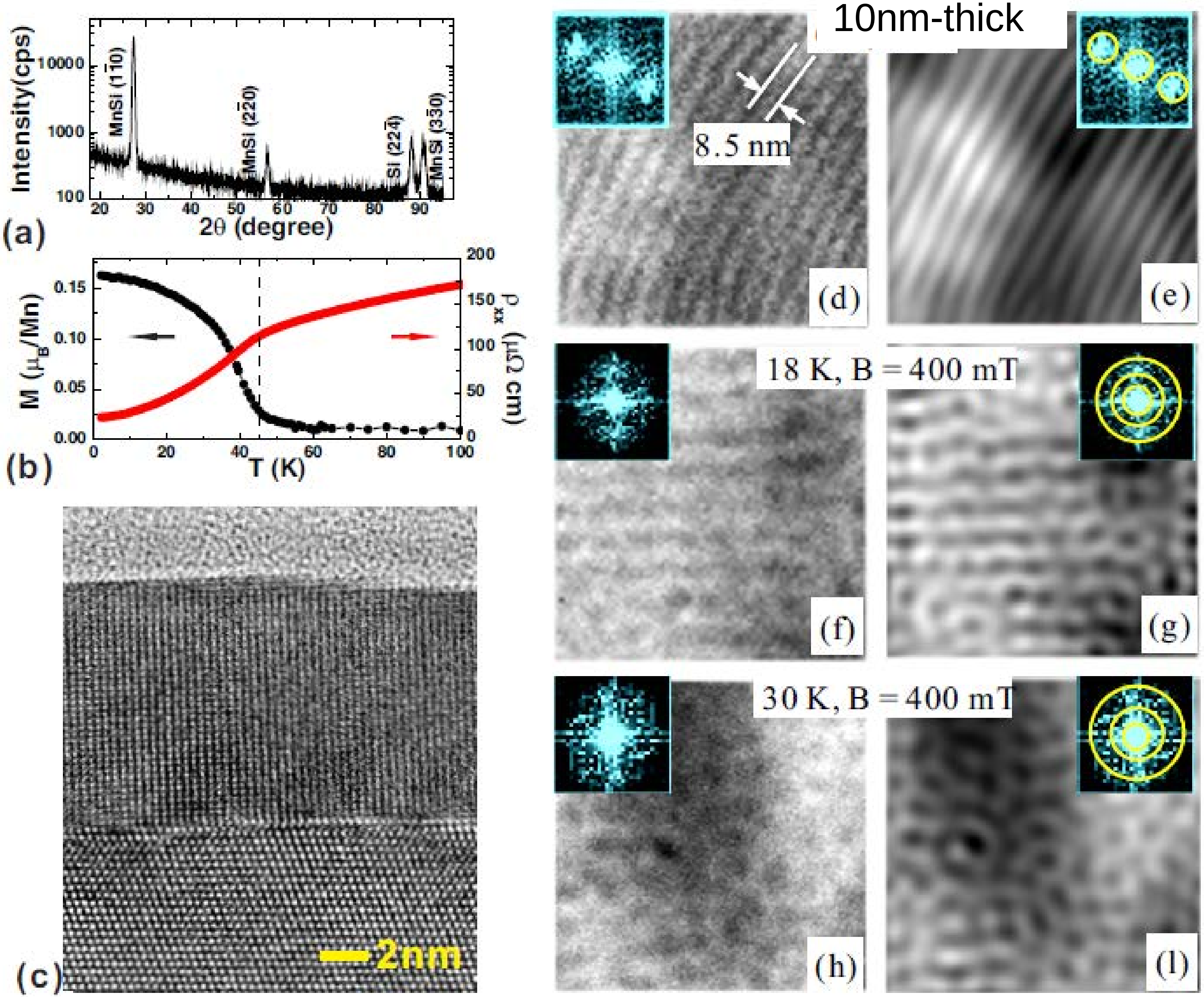
B_{eff}~4000T



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

High skyrmion density ⇄ Large topological Hall Effect

Ultrathin epitaxial thin films of MnSi



MnSi

Si substrate

Skyrmion phase mapping by topological Hall resistivity

Yufan Li, Kanazawa,Kagawa et al. PRL (2013)

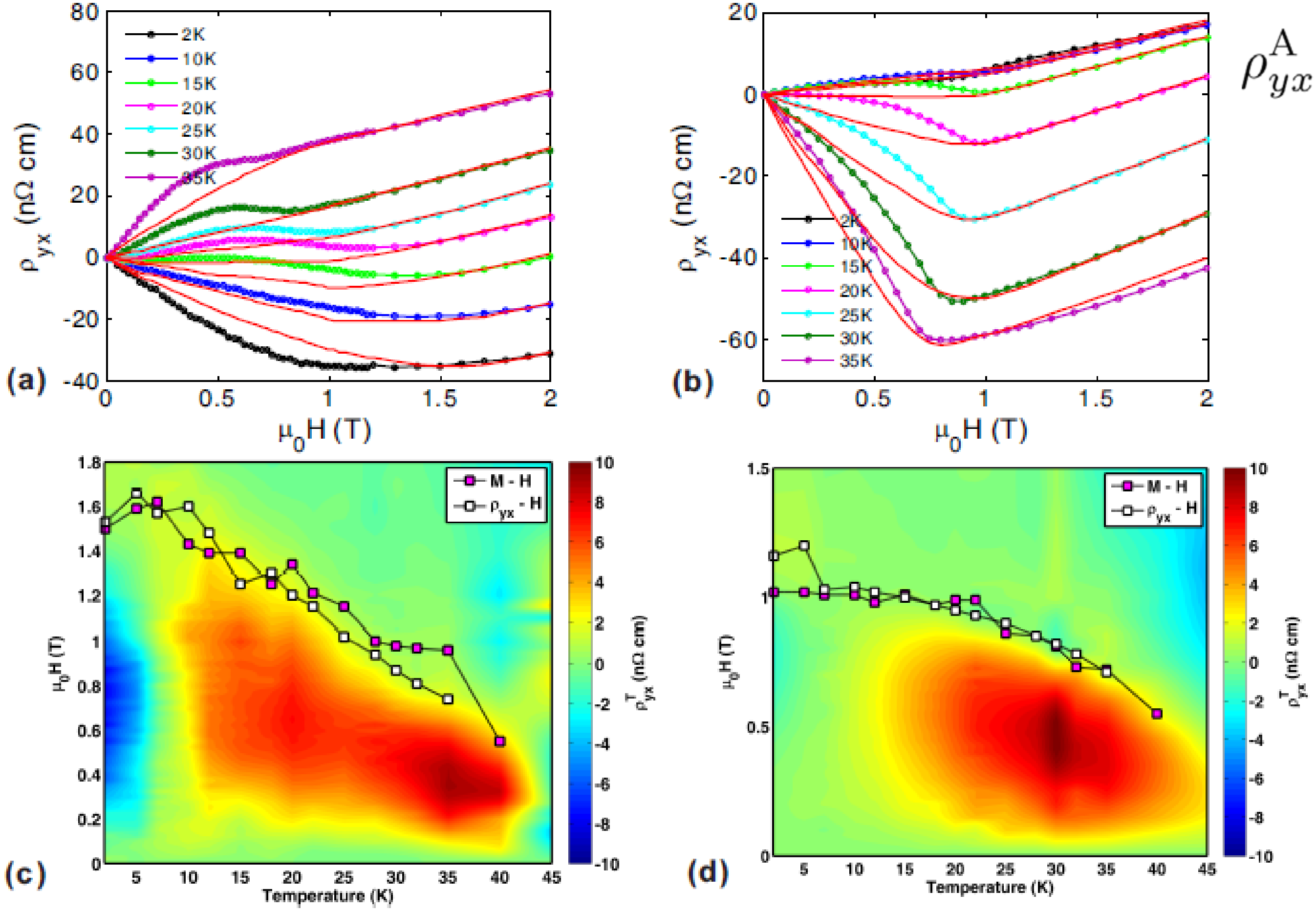
10nm-thick

50nm-thick

Conventional anomalous + normal Hall effects

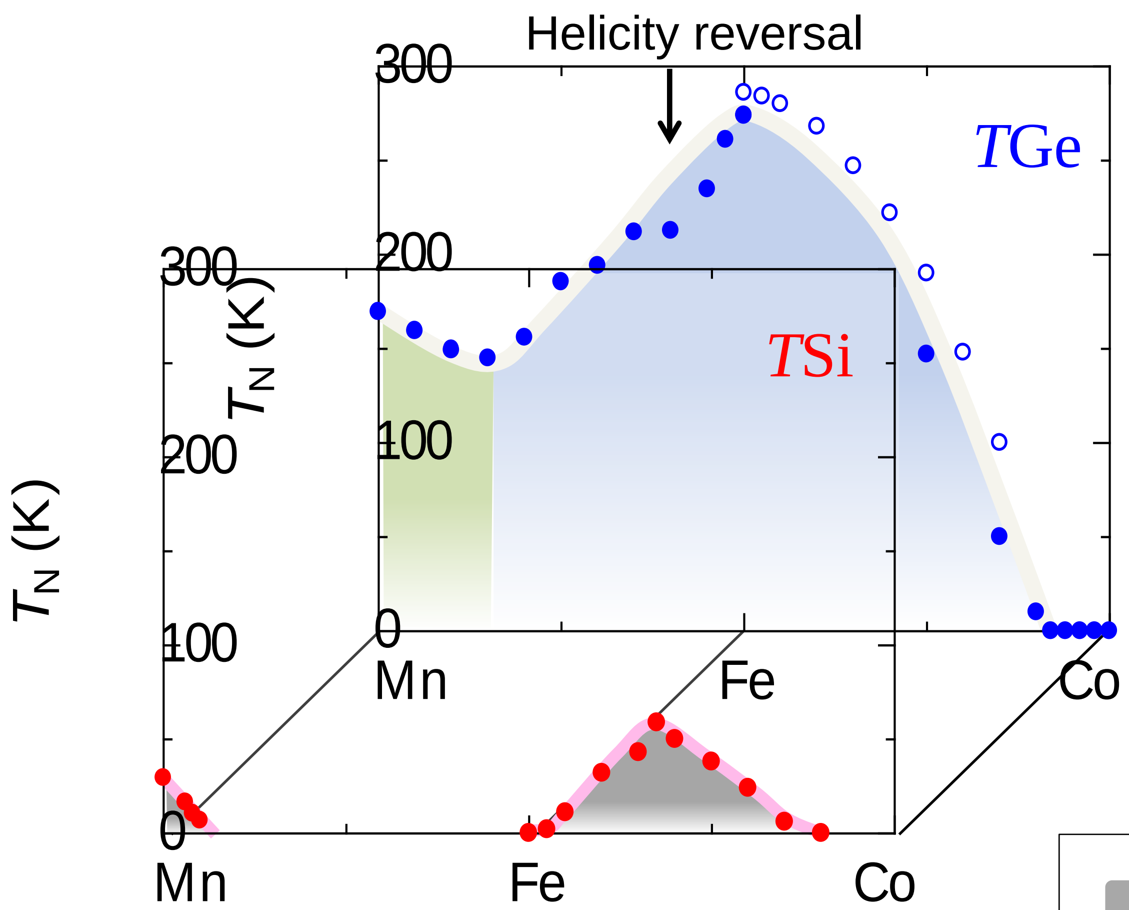
$$\rho_{yx}^{\mathrm{A}} = R_0 B_z + \mu_0 R_S M_z$$

$$\mu_0 R_S = S_{\mathrm{A}} \rho_{xx}^2$$



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

Magnetic phase diagram in *B*20 compounds



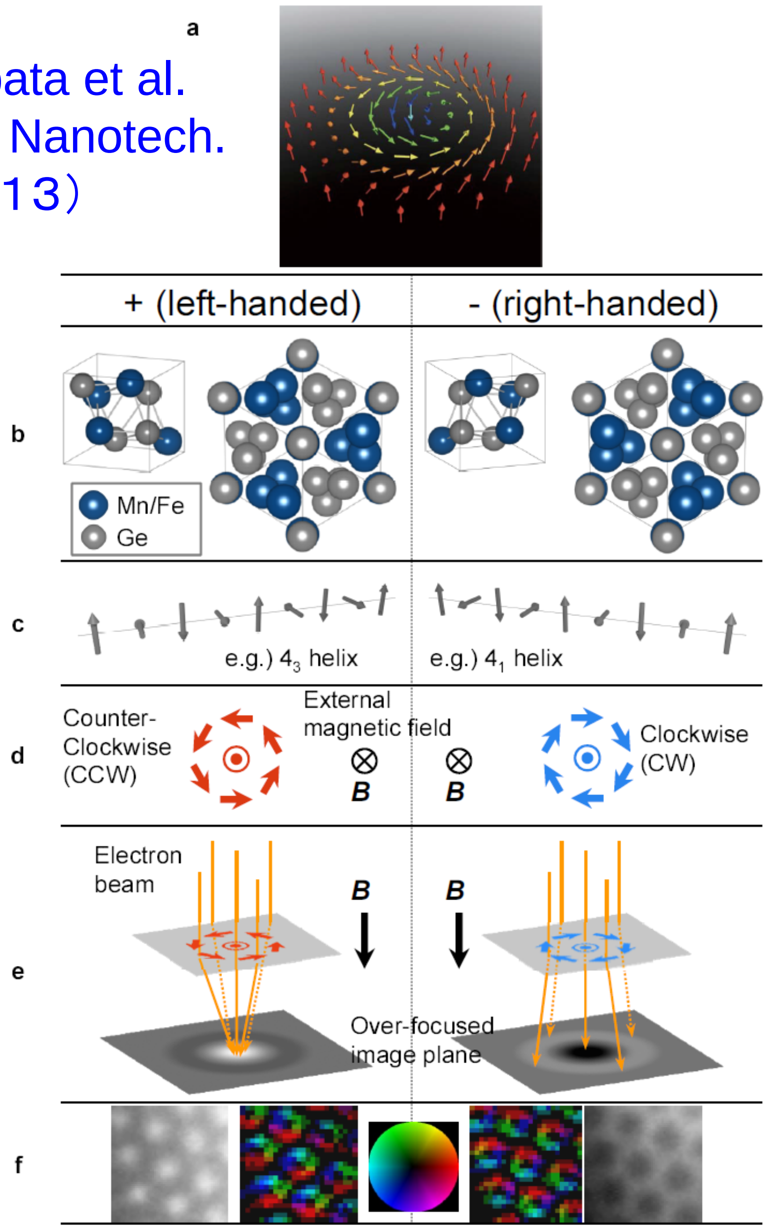
: "conventional" helical/skyrmion phase

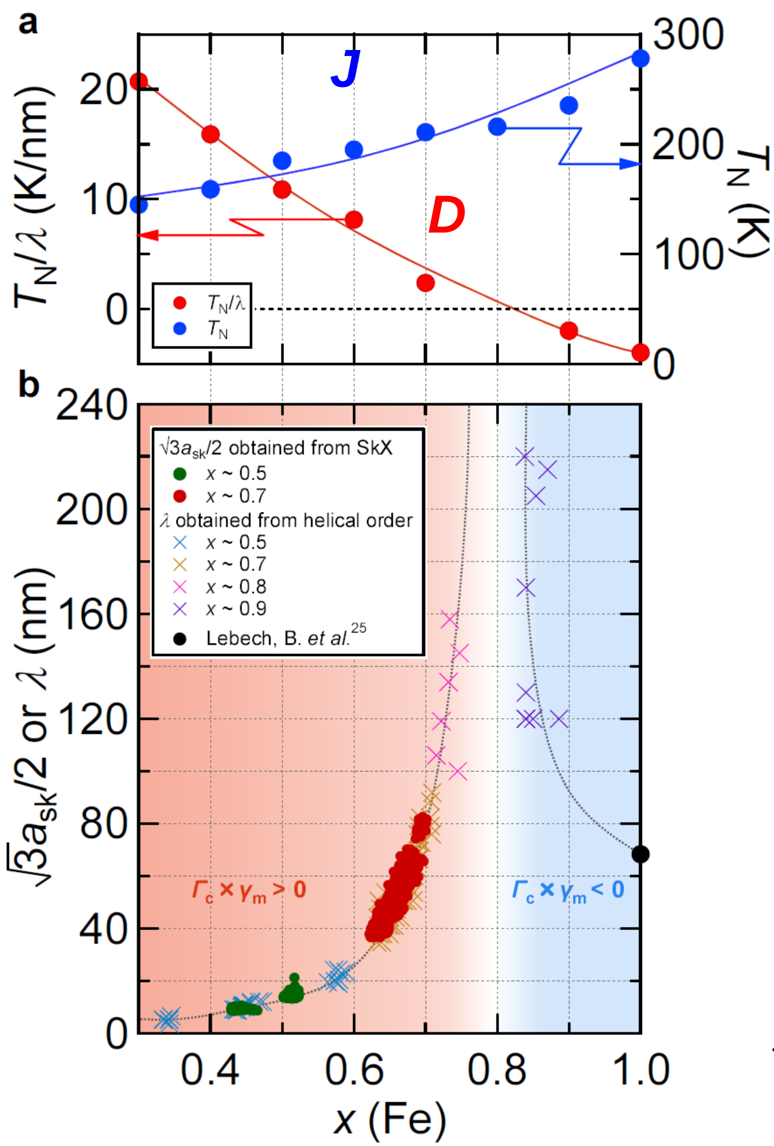
: "new" skyrmion phase

$Mn_{1-x}Fe_xGe$ (Control of DM interaction)

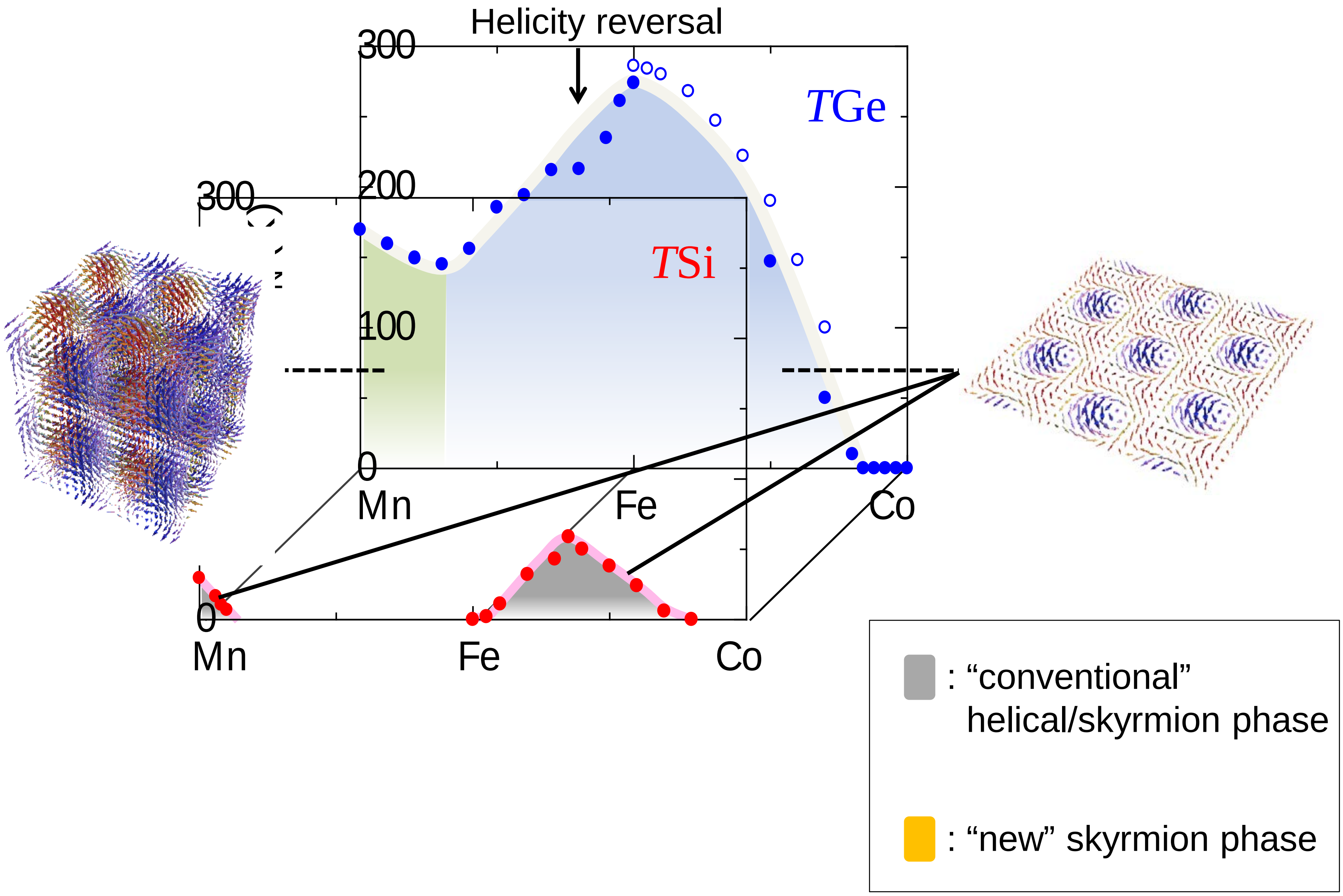
Shibata et al.
Nat. Nanotech.
(2013)

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



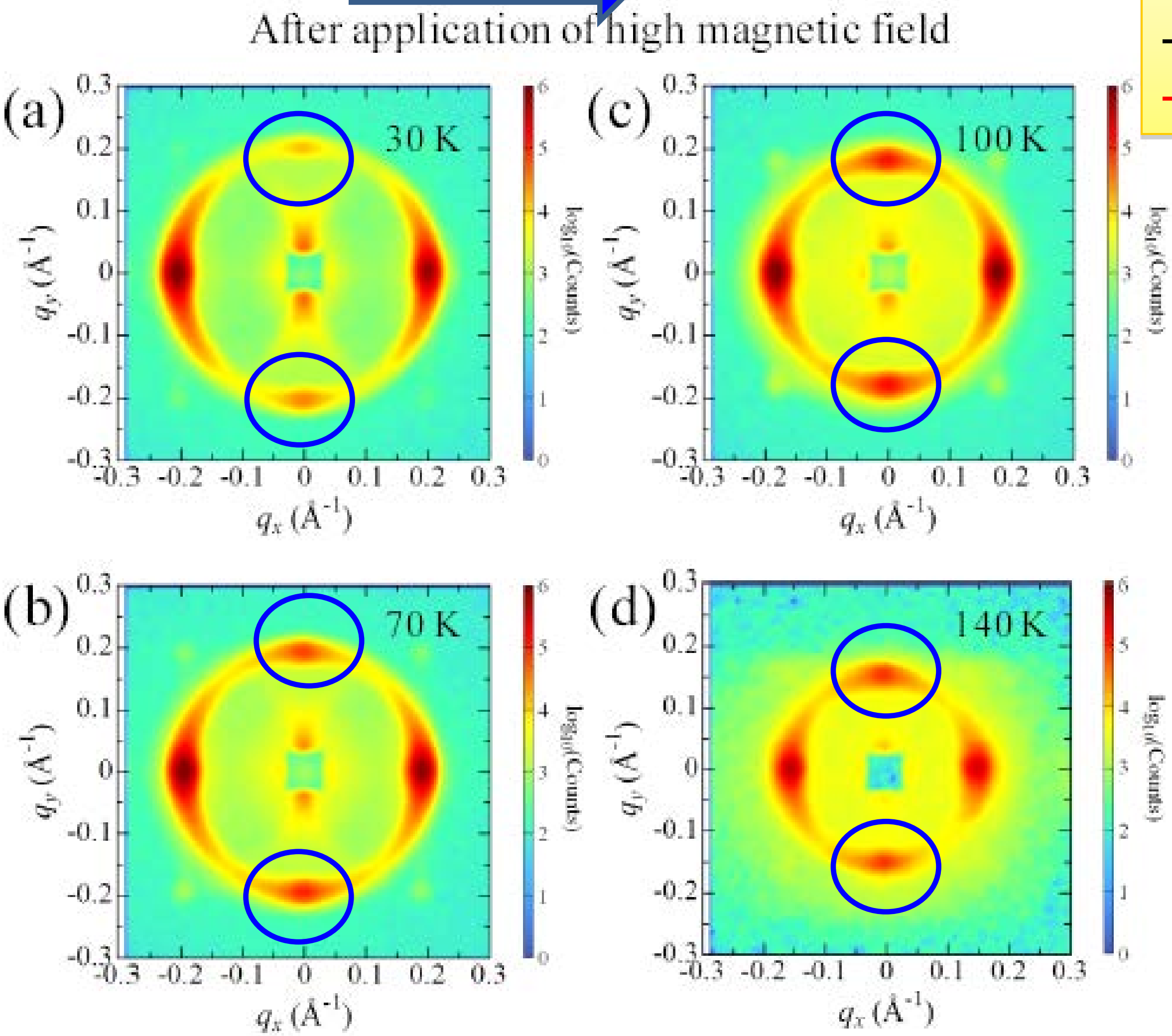


Magnetic phase diagram in *B*20 compounds



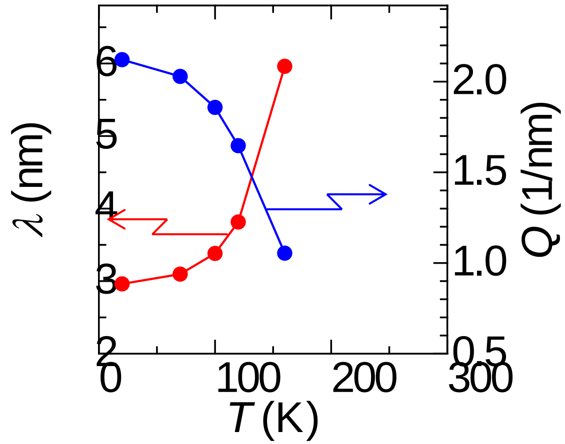
Small angle neutron scattering on MnGe (polyXtal)

B (10T) then B=0



- T_N=170 K
- Helical structure
- modulation vector : Q ||<100>
- Helical period : λ = 3 nm – 6 nm

Helical period

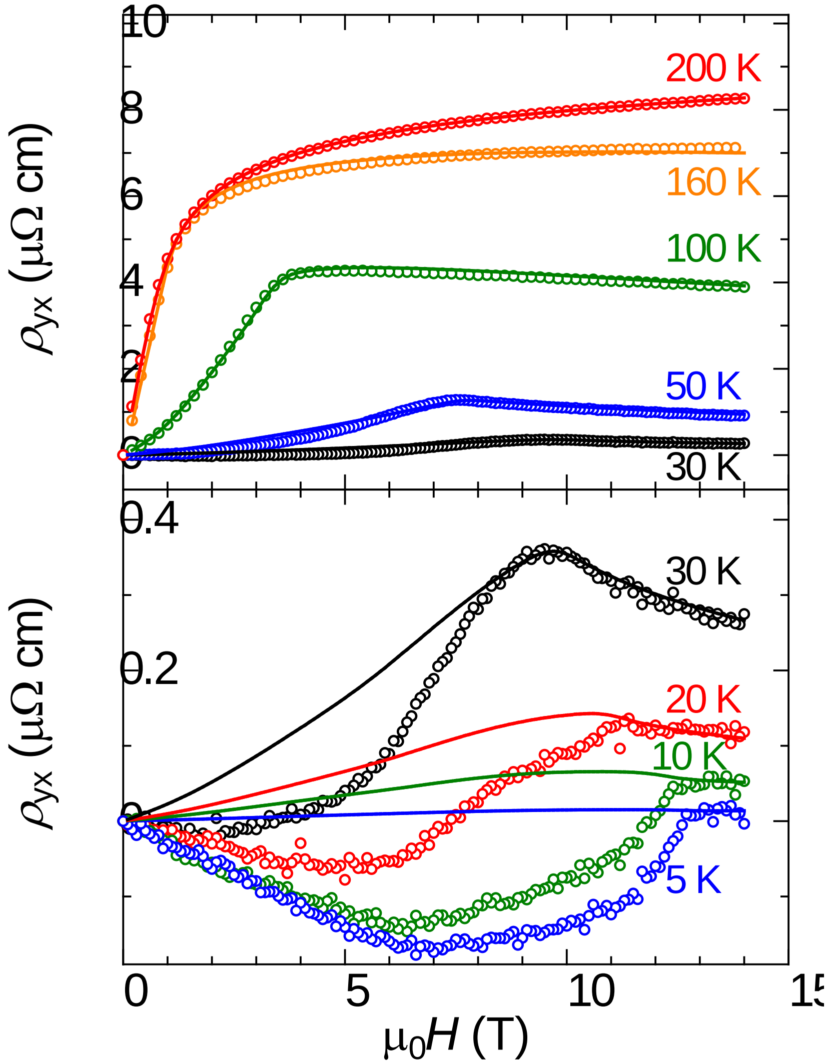


Huge topological Hall effect?

Evidence for multiple-q **<100>** structure even at B=0

in collaboration with Keimer group

Topological Hall effect in MnGe



H > H_C

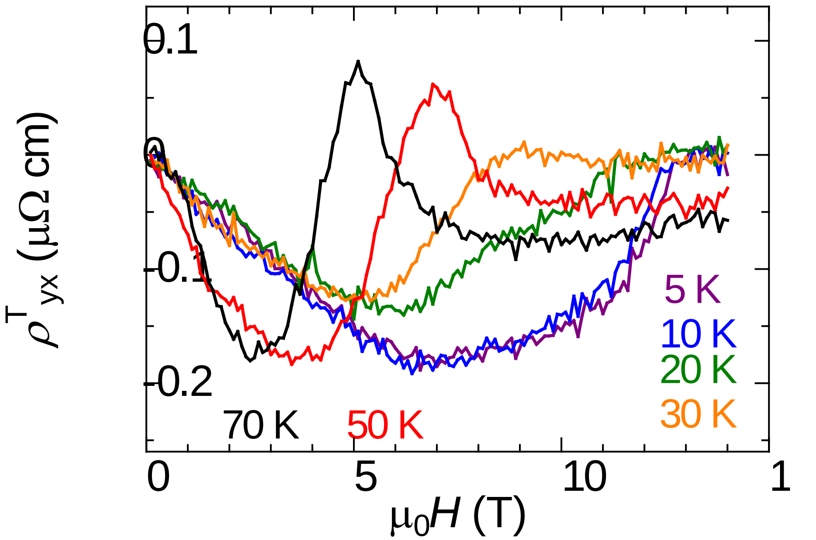
Induced ferromagnetic state
→"Conventional" anomalous Hall effect

Solid lines: estimate of

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

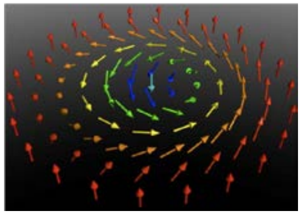
$$\mu_0 R_S = S_A \rho_{xx}^2$$

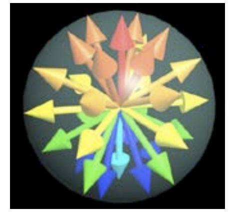
Components of THE



Nearly temperature independent

Real-space fictitous magnetic field in a skyrmion spin texture





Solid angle $\Omega = 4\pi$

In strong coupling case

One skyrmion ⟷ One magnetic flux ϕ_0

$$\phi_0 = h/e$$

Emergent **magnetic field**

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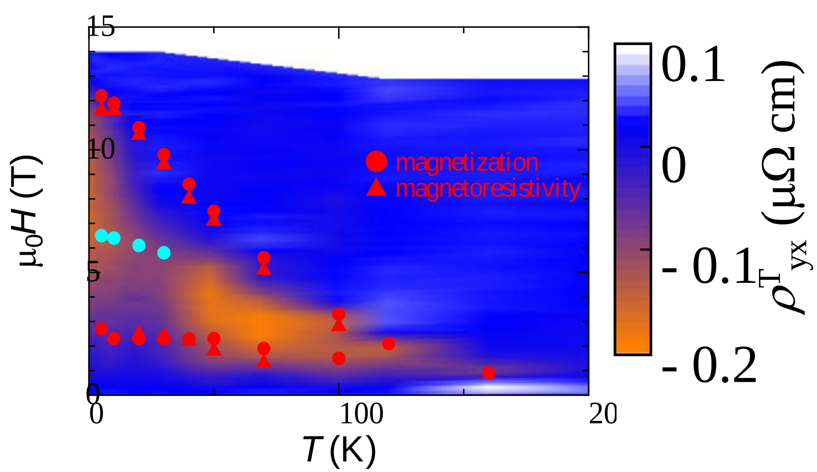
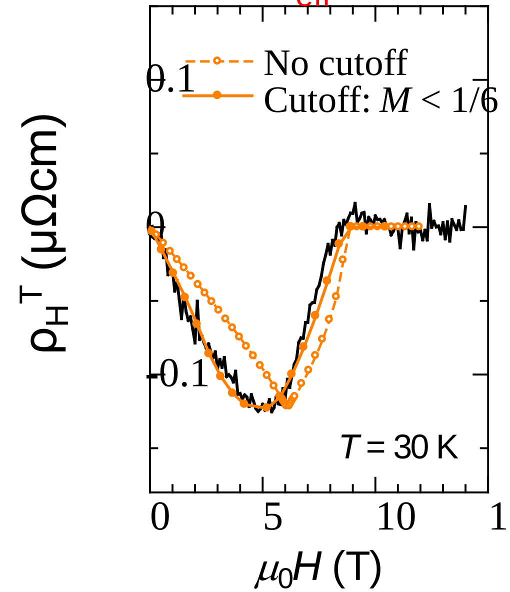
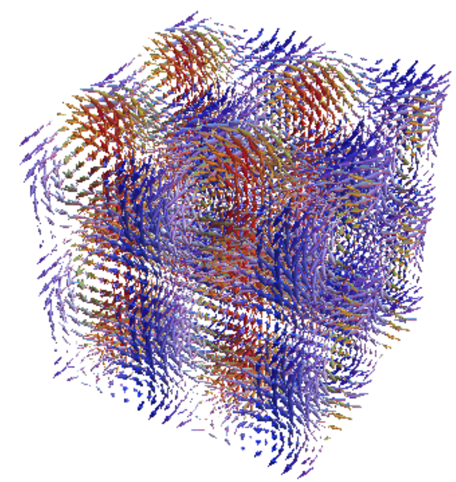


MnGe topological Hall effect

B_{eff}~100-1000T !





3D skyrmion X

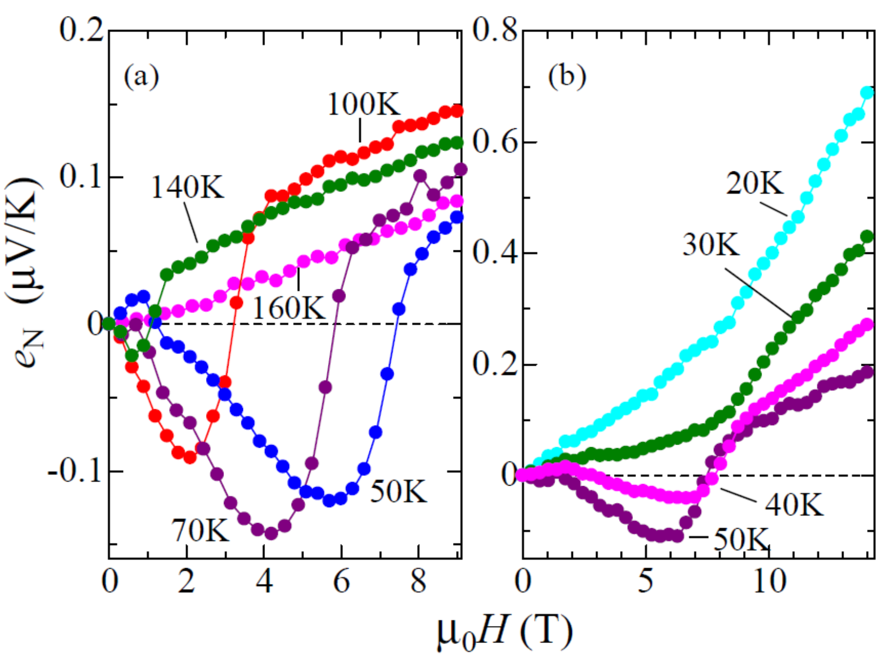
Topological Nernst Effect

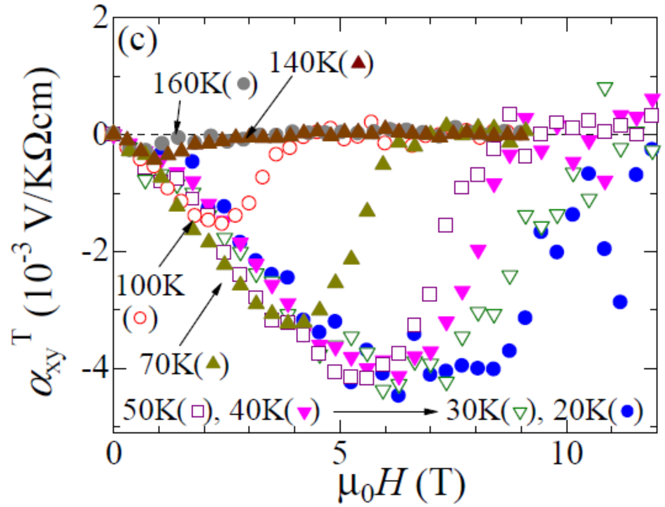
Nernst effect $e_N = E_y/|\nabla_x T|$

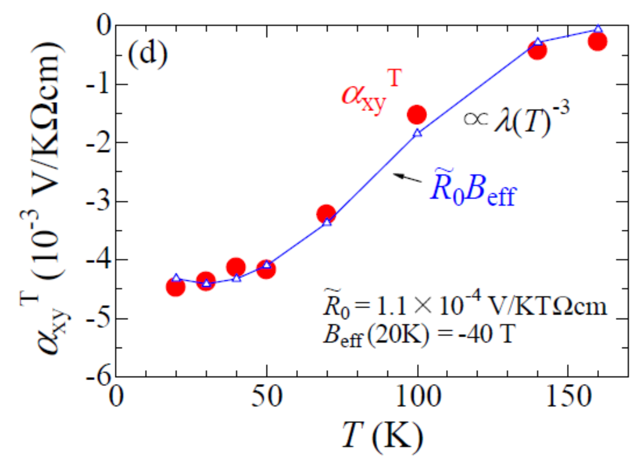
$$\alpha_{xy} = \sigma_{xx}\left[e_N + S_{xx}\left\{(\sigma_{xy}/\sigma_{xx}) + (\kappa_{xy}/\kappa_{xx})\right\}\right]$$

$$\alpha_{xy}^T = \frac{\pi^2}{3}\frac{k_B^2 T}{e}\left(\frac{\partial \sigma_{xy}^T}{\partial \varepsilon}\right)_{\varepsilon=\mu} \approx \tilde{R}_0 B_{eff}$$

Mott relation: $\boldsymbol{\alpha} = eL_0T(\partial\boldsymbol{\sigma}/\partial\varepsilon)_{\varepsilon=\mu}$



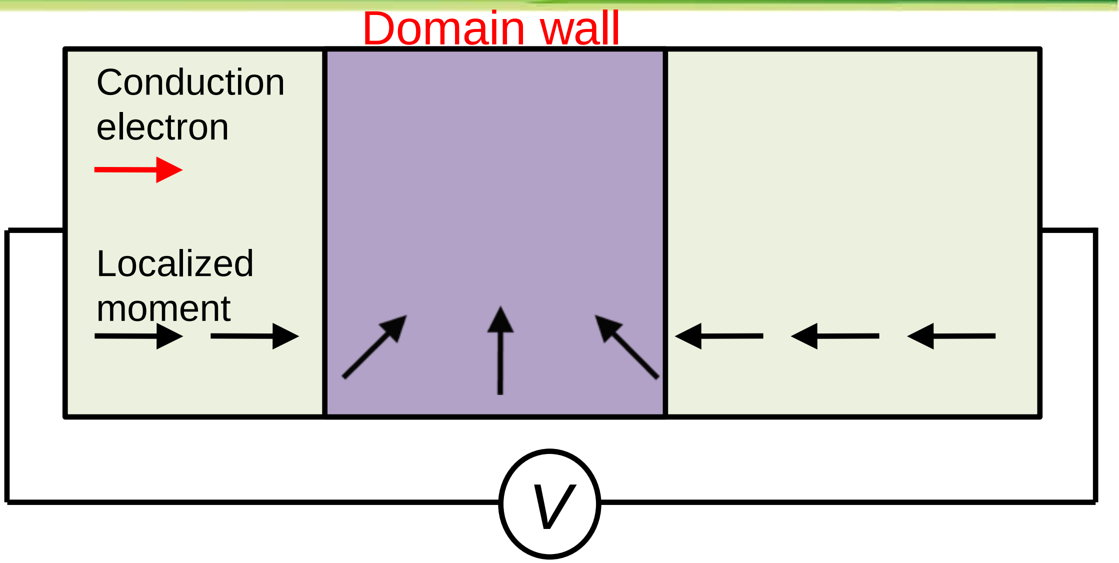




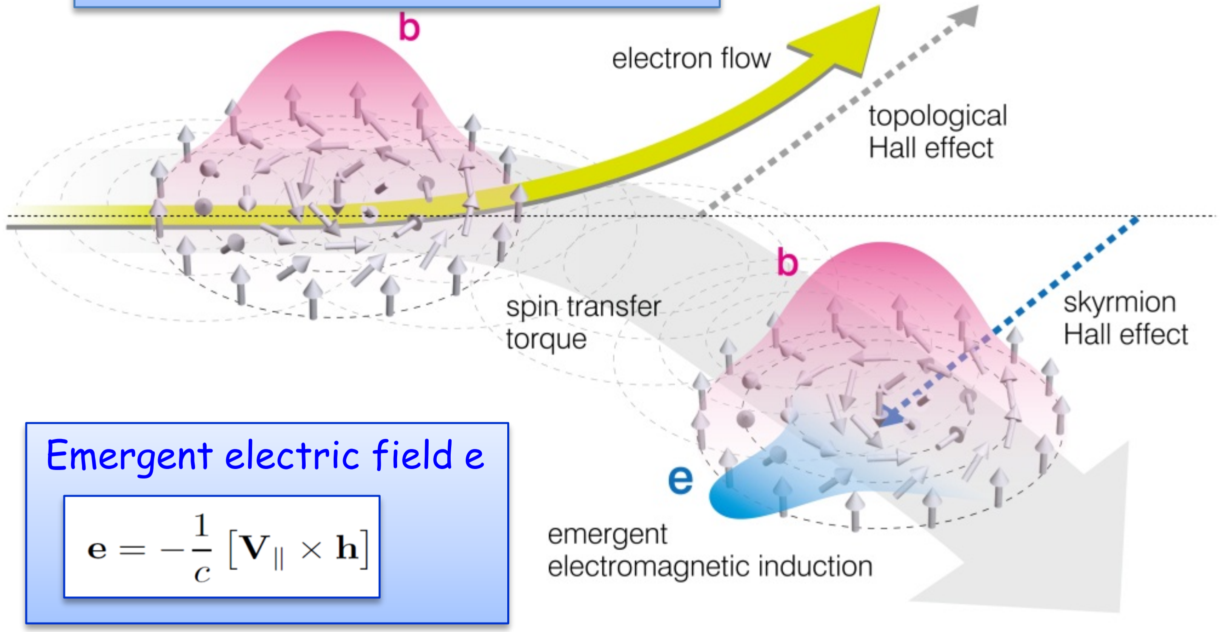
Shiomi et al. PRB (2013)

Current drive of skyrmions and emergent EM field

Domain wall motion
by spin transfer torque



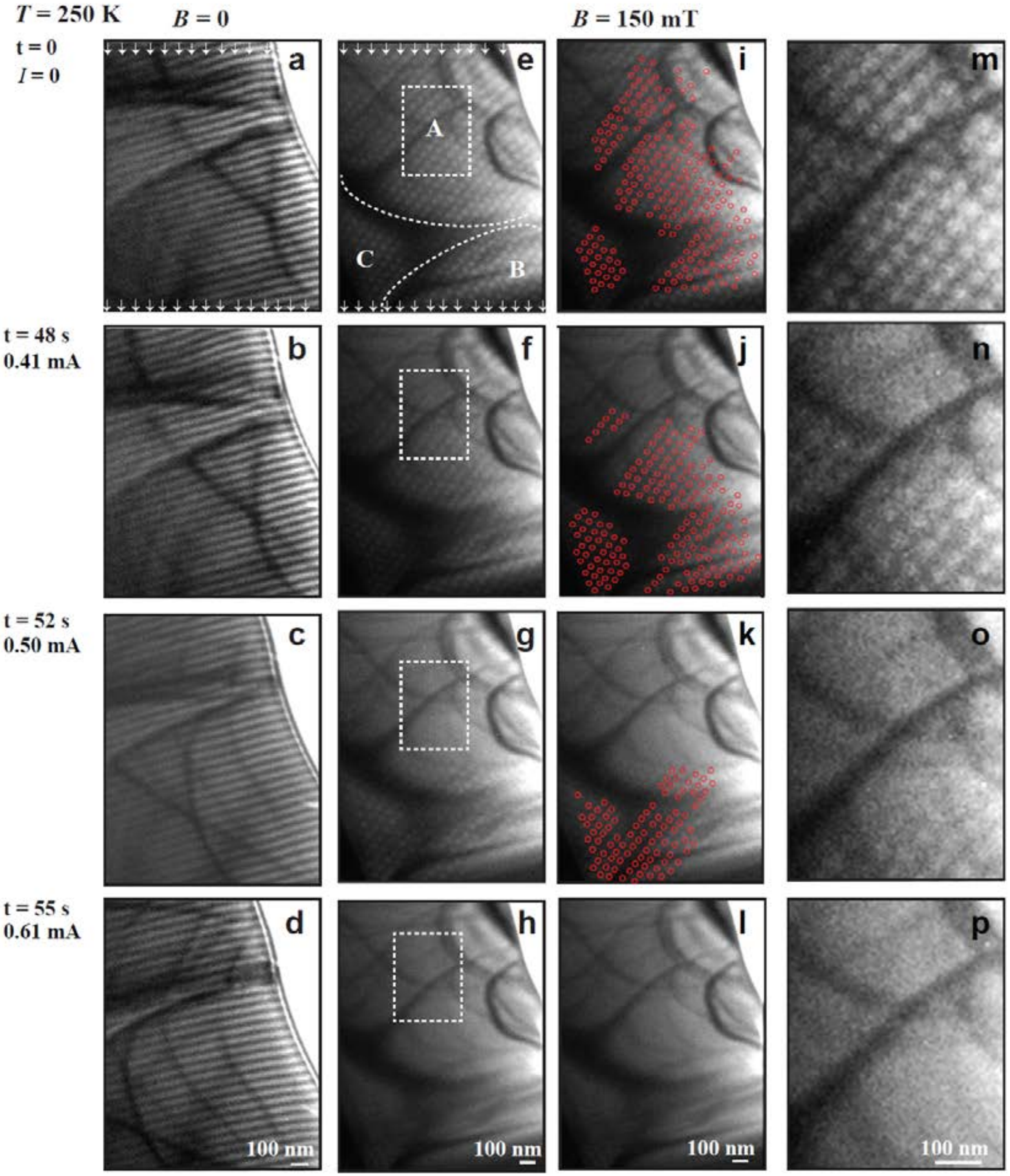
Topological Hall effect (THE)
Emergent magnetic field *b*

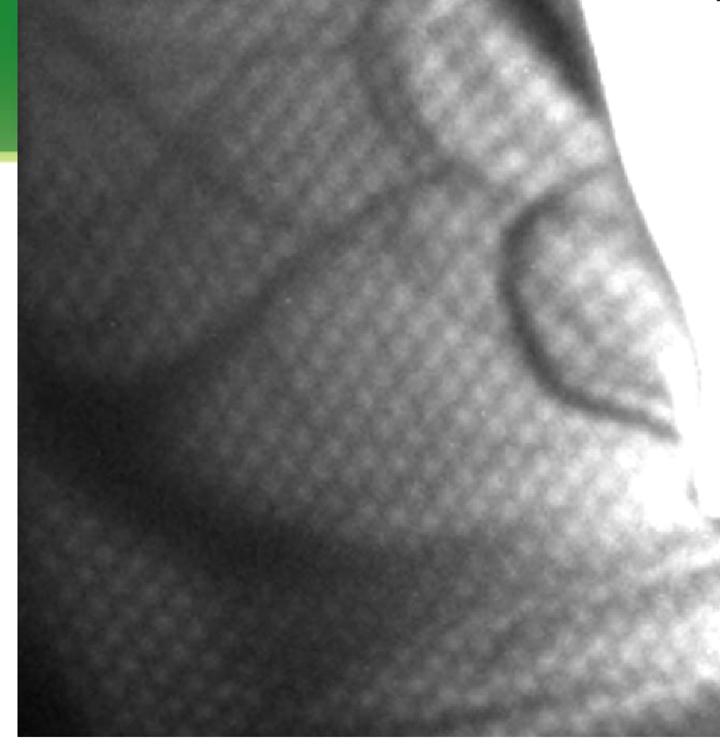


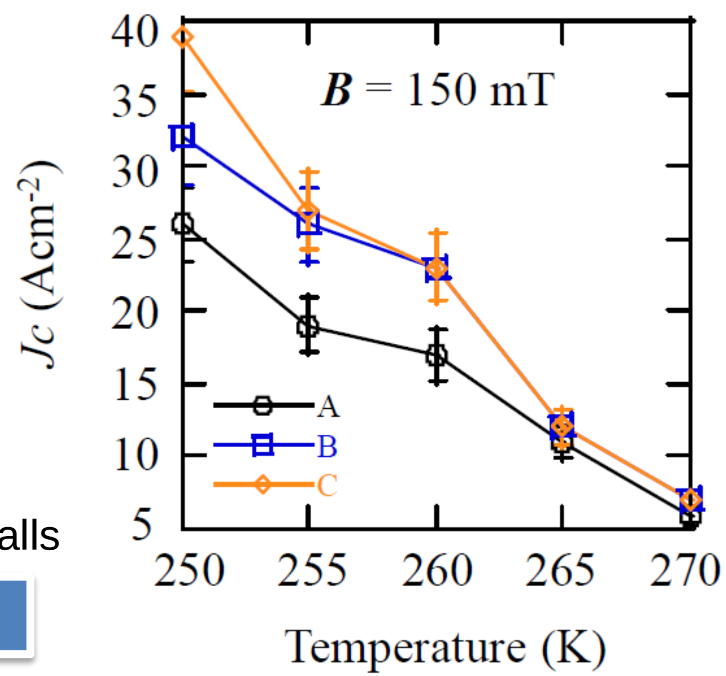
-counteraction of THE
→ skyrmion Hall effect

Emergent electric field *e*

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







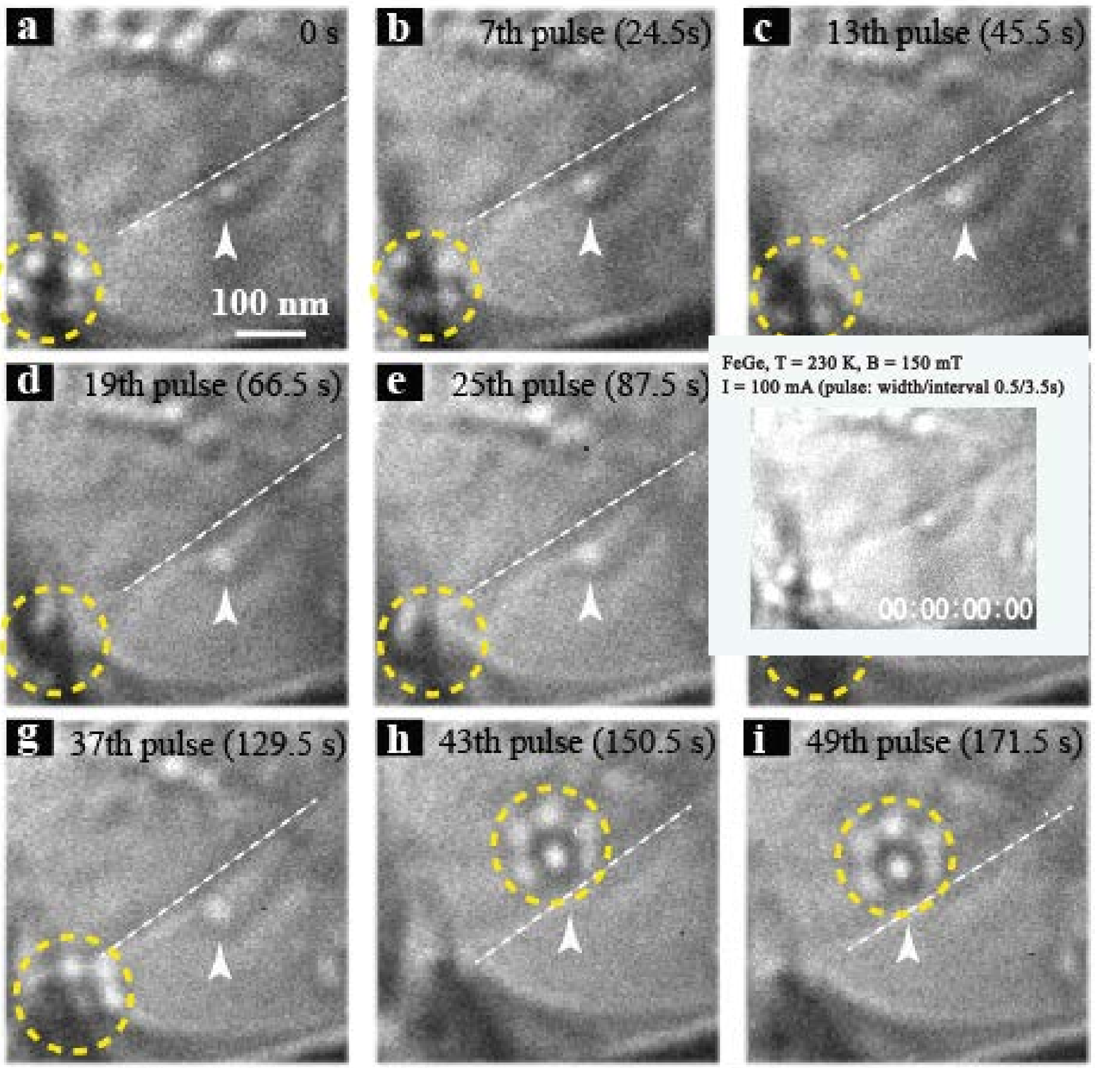
J_c<100A/cm^2

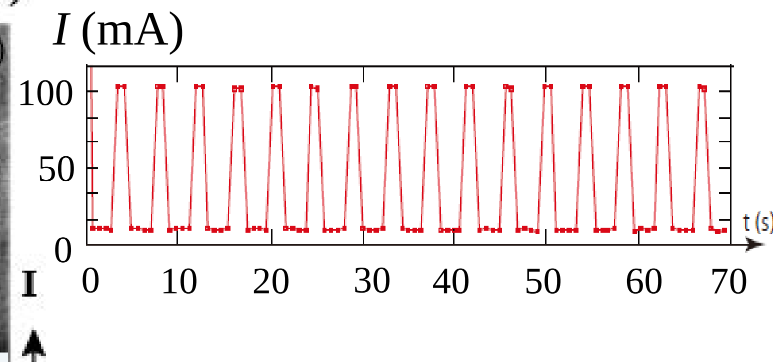
J_c~10^{7}A/cm^2 for ordinary domain walls

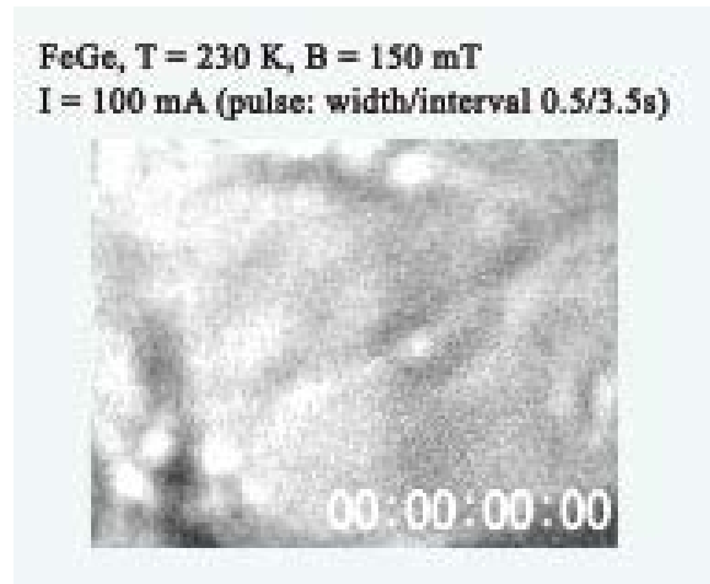
no intrinsic / minimal extrinsic pinning effect on SkX

Manipulation of single skyrmion in FeGe by pulse currents

T = 230 K, B = 150 mT, I = 100 mA (pulse width/interval = 0.5/3.5 s)



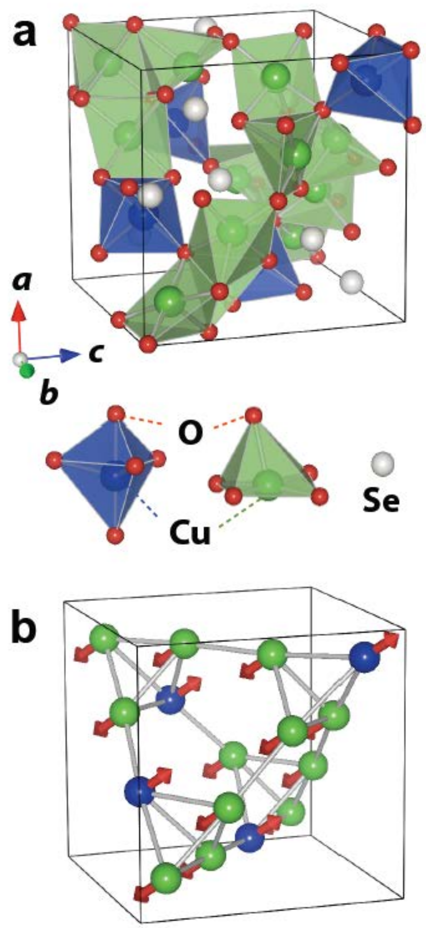


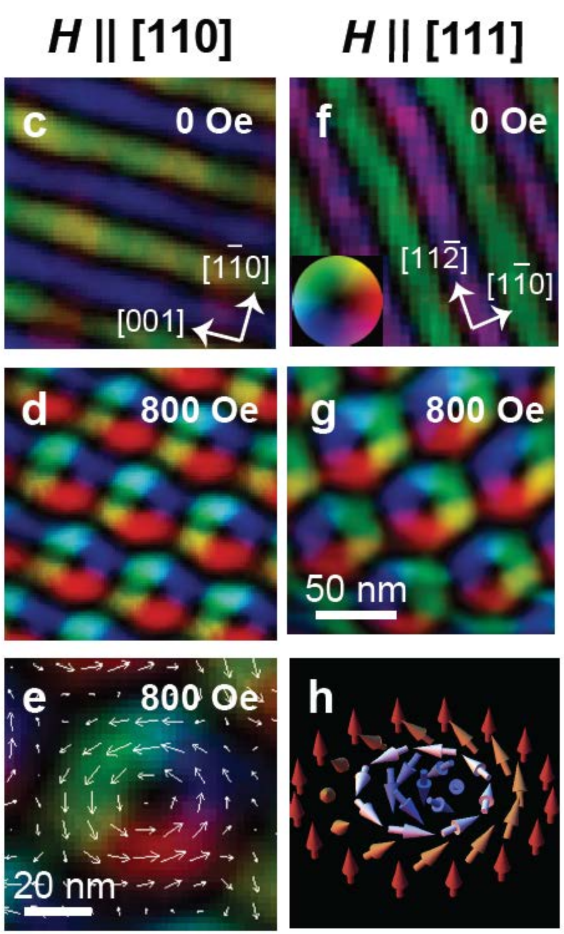


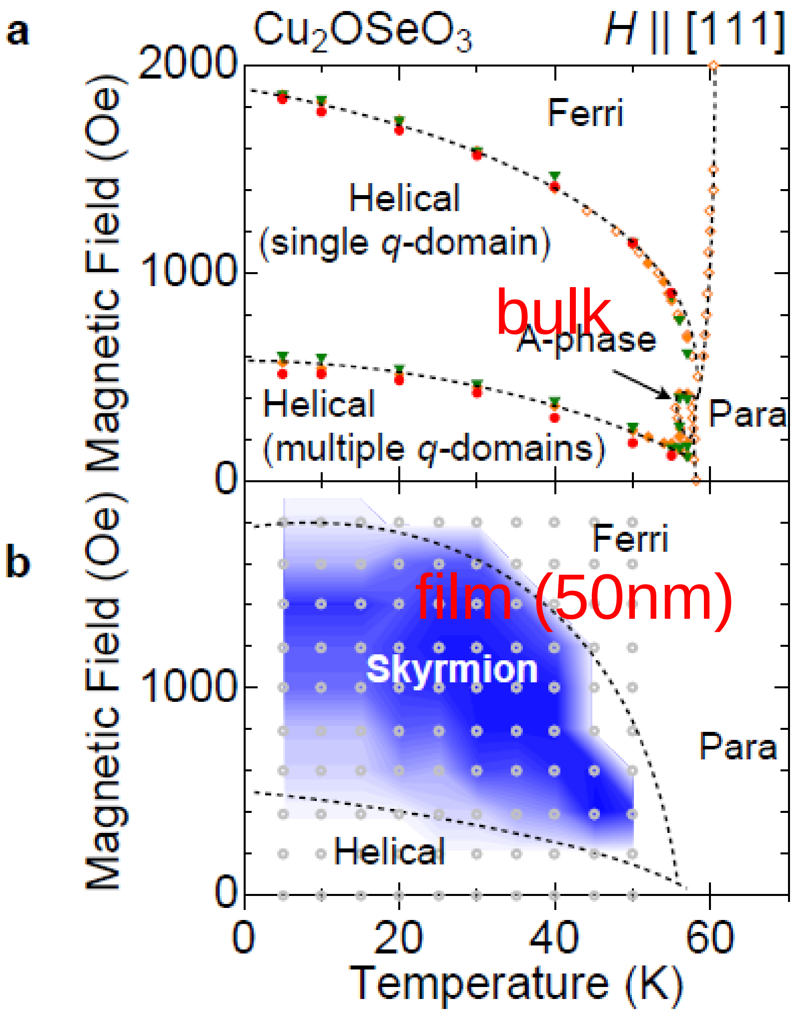
Lorentz TEM observation of thin flake of Cu_2OSeO_3

space group $P2_13$ the same as B 20 (MnSi)

Mott insulator with quantum spins





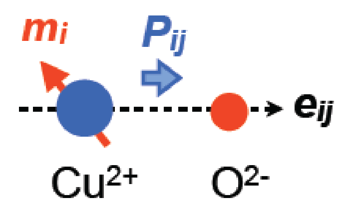


Cu_2OSeO_3 : *P* distribution in skyrmion

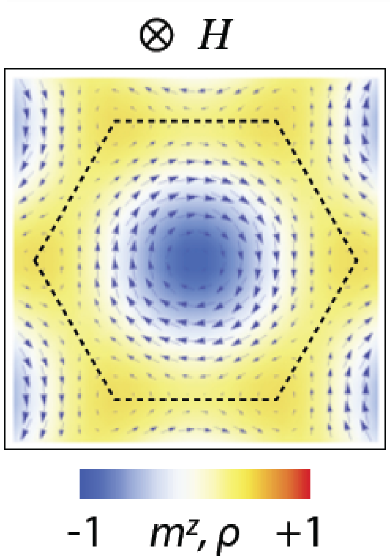
S. Seki *et al.*, PRB(2012)

d-p hybridization model

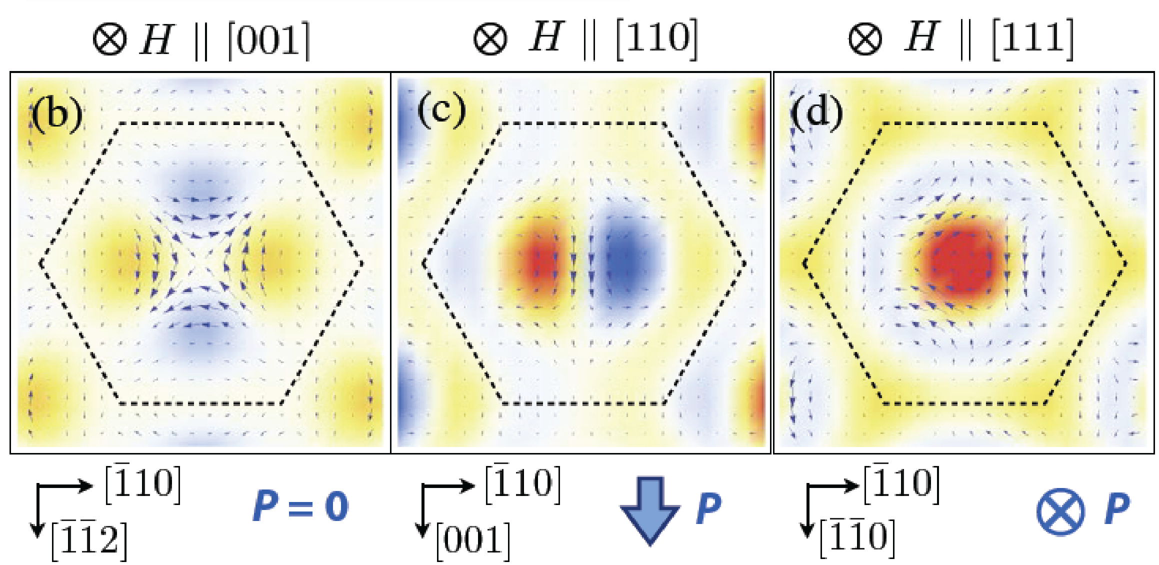
$$\vec{p}_{ij} \propto (\vec{e}_{ij} \cdot \vec{m}_i)^2 \vec{e}_{ij}$$



Local *M*



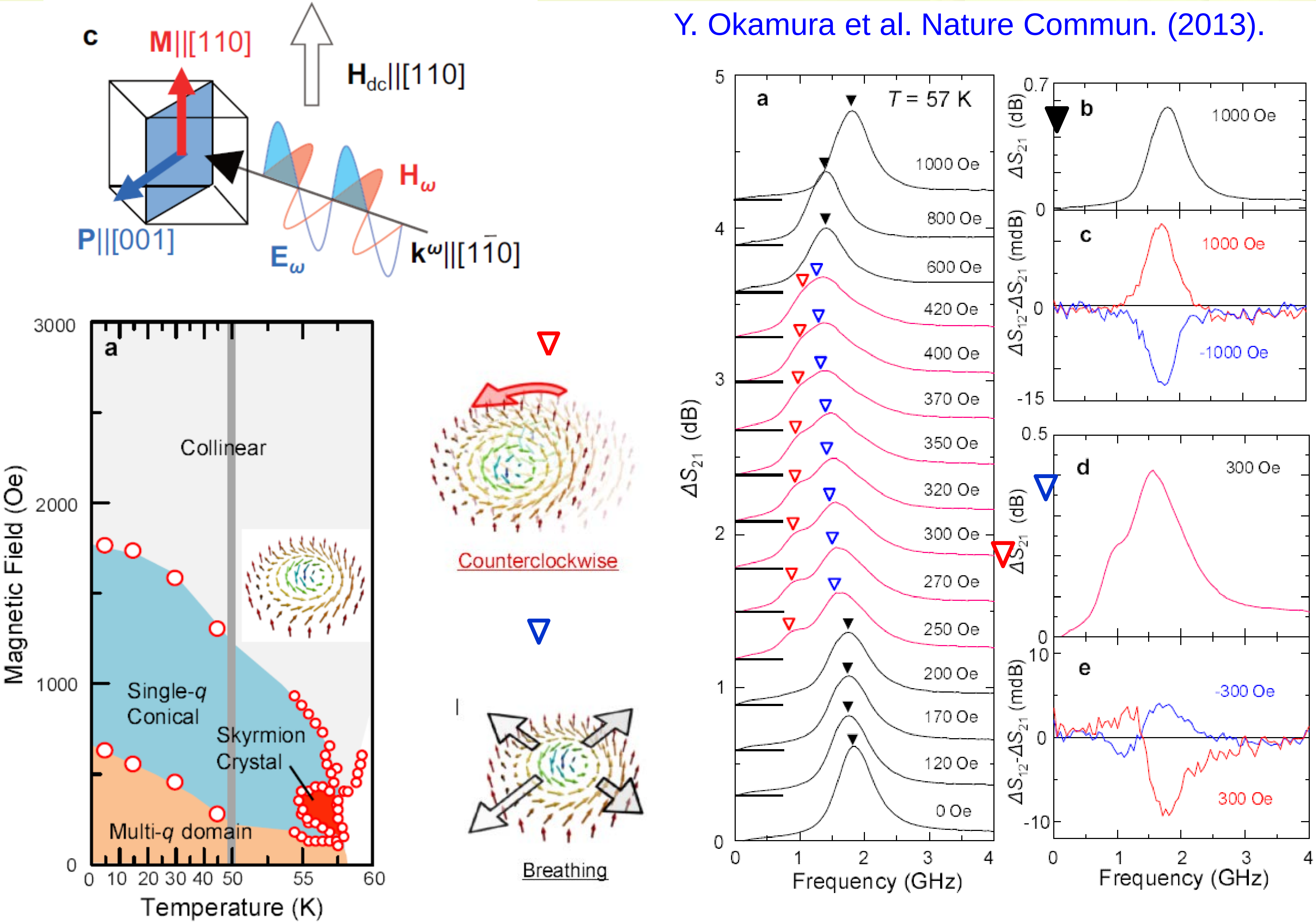
Local *P*



Skyrmion particle can locally carry **electric dipole** or **quadrupole**

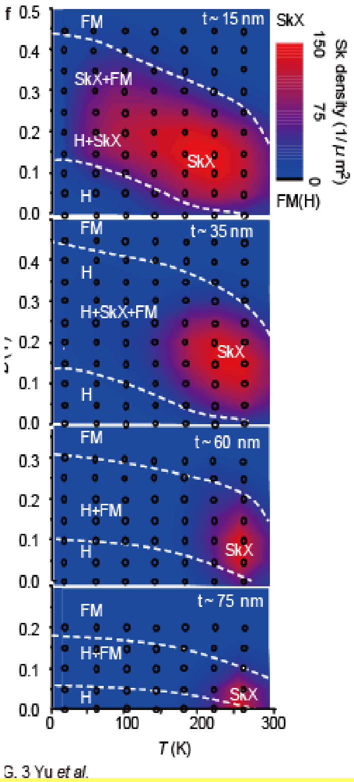
Skyrmion excitations as electromagnons showing directional dichroism

Y. Okamura et al. Nature Commun. (2013).



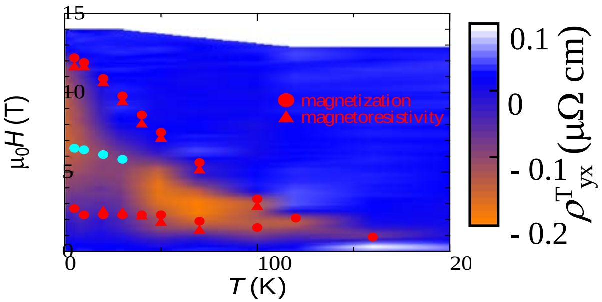
Electrodynamics of Skyrmions ~ toward Skyrmionics ~

Stabilization Skrymions in form of thin films, not only DM but also uniaxial magnets



Topological Hall effect as probe/detection for SkX

emergent EM fields



Skyrmion transport phenomena

- low-current drive of Skyrmions (<100A/cm^2)
  processing speed ∝ I*(Sk density); energy-cost per bit∝ *I*
- optical, e-beam (spin-current) control,; E-drive (multiferroics)