Science of Magnetic Skyrmions

Yoshi TOKURA
RIKEN Advance Science Instituite
Department of Applied Physics, University of Tokyo,

The 3rd energy revolution based on emergent electromagnetism in solids

Topological spin textures to host magneto-electric coupling

Observation of skyrmions

Skyrmion dynamics toward skyrmionics

Collaborators

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

  Y. Kanazawa, N. Nagaosa, Y. Onose,
  T. Arima, S. Ishiwata, A. Tsukazaki,
  M. Ichikawa, M. Kawasaki, S. Seki
  Y. Shiomi, K. Shibata, F. Kagawa,
  Y. Okamura, M. Mochizuki

- ***RIKEN (Japan)***

  X. Z. Yu, Y. Tokunaga, Y. D. Okuyama, Y. Taguchi

- ***NIMS (Japan)***

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

- ***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

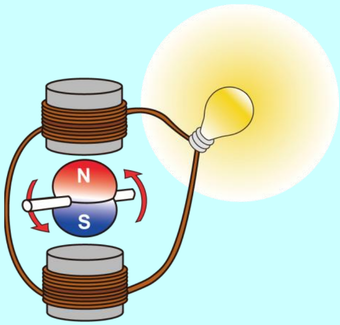
- ***Groningen Univ. (Holland)***

  M. Mostovoy

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

  Yufan Li, Xiofeng Jin

Three Energy Revolutions

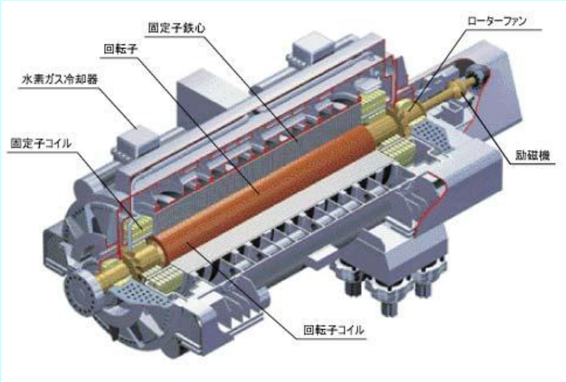


Ⅰ： Stream energy / electromagnetic induction

conversion from mechanical to electromagnetic energy
based on classic electromanetism

Electromagnetic induction $\mathrm{rot}\, E = -\partial B / \partial t$

（E and H fields are not independent.）



Ⅱ： Nuclear energy

nuclear generator/ electromagnetic induction
based on nuclear physics/relativistic quantum mechanics

conversion from mechanical to electromagnetic energy

http://www.kyuden.co.jp/effort_thirmal_new_i_karita.html

Ⅲ： Solid state electronics

energy conversion among light , heat, and information **(without mechanics)**
based on emergent electromagnetism (relativistic quantum mechanics in a solid)

Energy Innovations for sustainable society

Impact of ×3j ump   e.g. T_c=30K (214) to T_c=90K (123)

Magic "4"

Ultimate functions

superconductors
＞400 K ←135K

Thermoelectricity
ZT＞4 ←1.3

Solar cell
＞40 % ←15%

battery
＞400 Wh/kg ←130Wh/kg

Dissipation-less electronics

If attained・・・

Transfer the electricity power without loss

Cool the world directly via electricity with high efficiency

Get the energy from the Sun

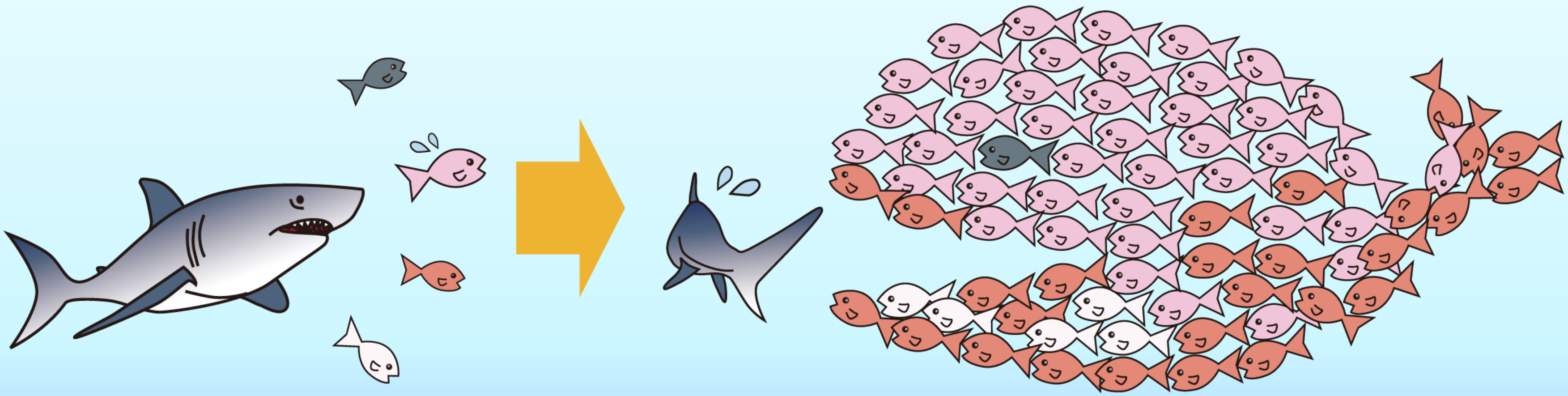
Carry the electric power to everywhere toward mobile IT society

Save the energy for the computer

What is Emergent Matter Science？

"More is different" *P.W.Anderson* ～beyond reductionism～

Surprising phenomena/functions in condensed matter/molecular assembly, never anticipated from the individual components, e.g., electrons, spins, and molecules.

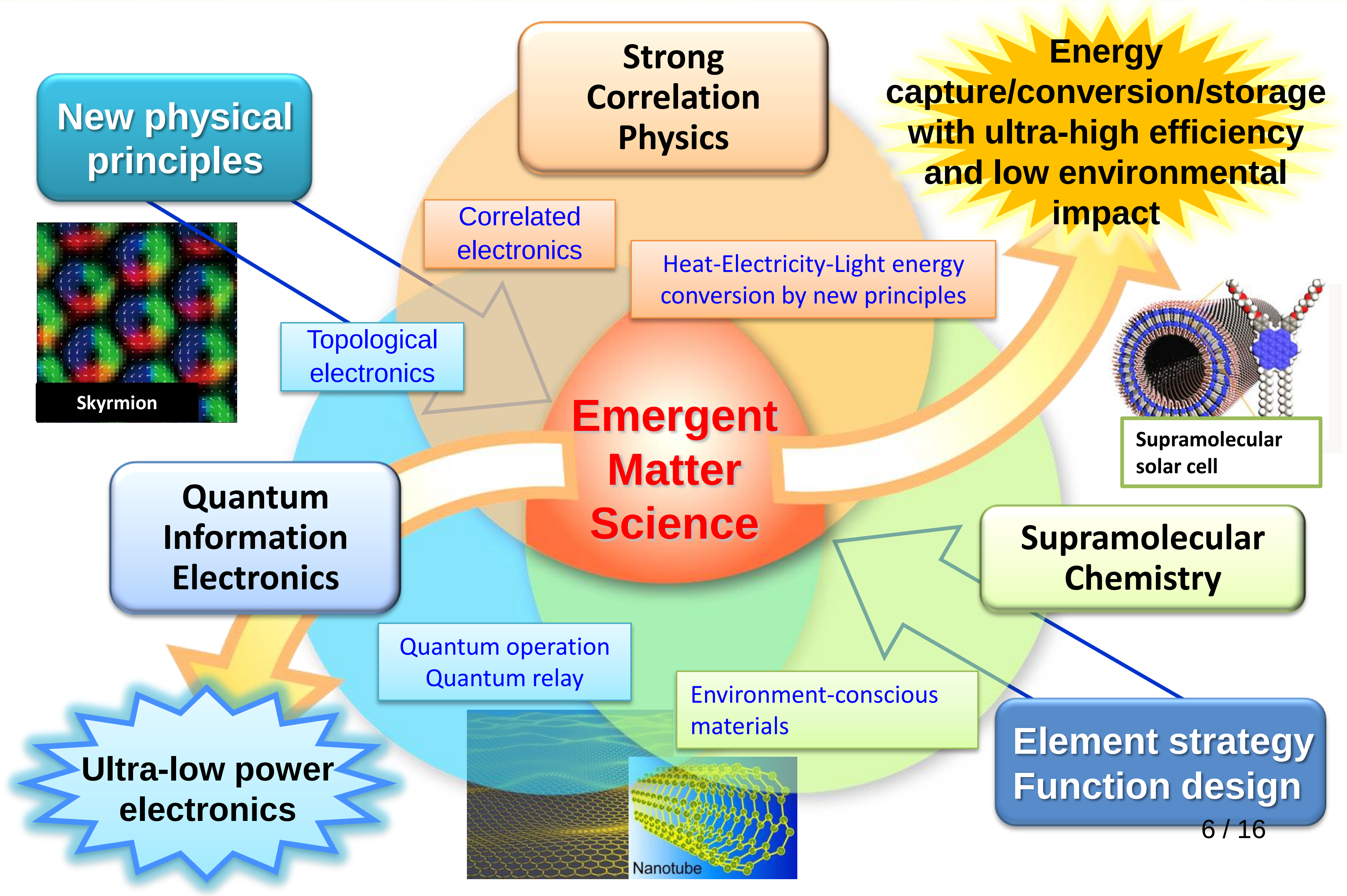


Colossal responses in **Strong Correlation Physics**

Element strategy/molecular design in **Supramolecular Chemistry**

Integrated functions in **Quantum Information Electronics**

Emergent Matter Science



Magneto-electric effect as another electronics"

Pierre Curie's Conjecture（1894）

There should be materials whose magnetism is induced by electric field and whose polarization by magnetic field.

electric control of magentism ⟷ magnetic control of electricity

$$M_\alpha = G_{\beta\alpha} E_\beta \qquad P_\alpha = G_{\alpha\beta} B_\beta$$

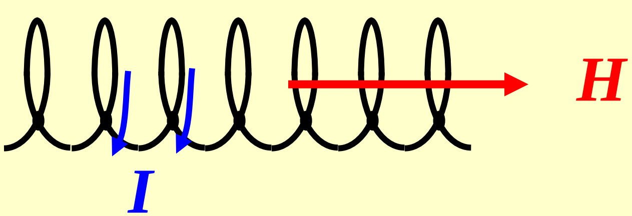
図２　研究室でのキュリー夫妻

［出典］ワインバーグ（本間三郎訳）：電子と原子核の発見、日本経済新聞（1986）

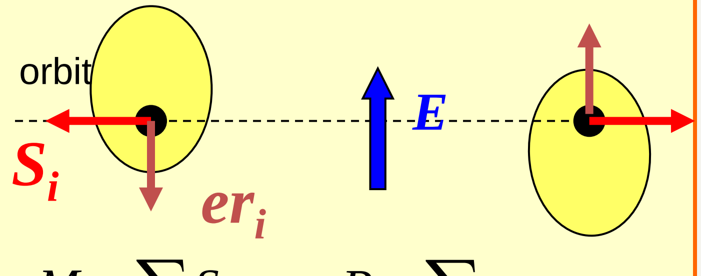
Observation on Cr_2O_3

I.E.Dzyaloshinskii, Sov.Phys.-JETP **10**, 628 (1959)
D.N.Astrov, Sov.Phys.-JETP **11**, 708 (1960)

Biot-Savart's law

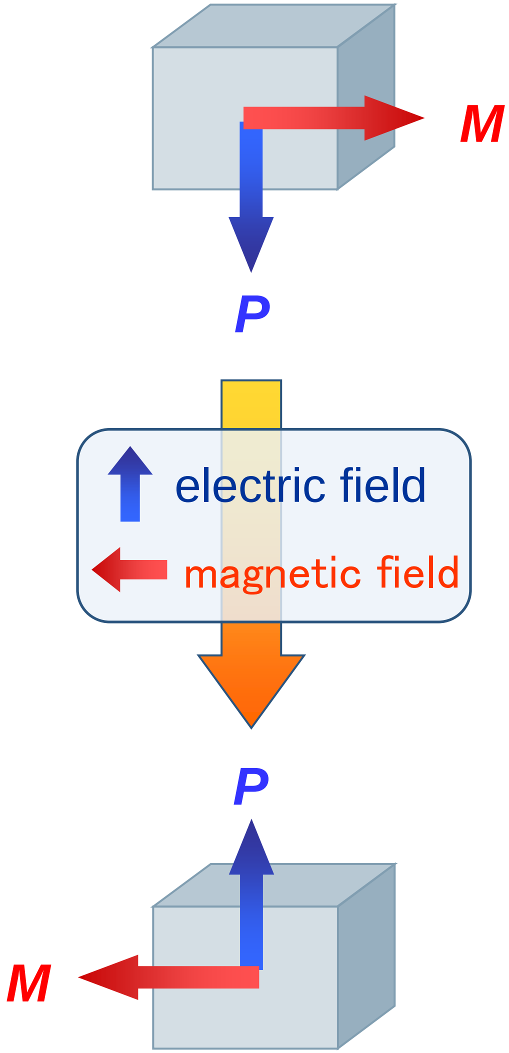


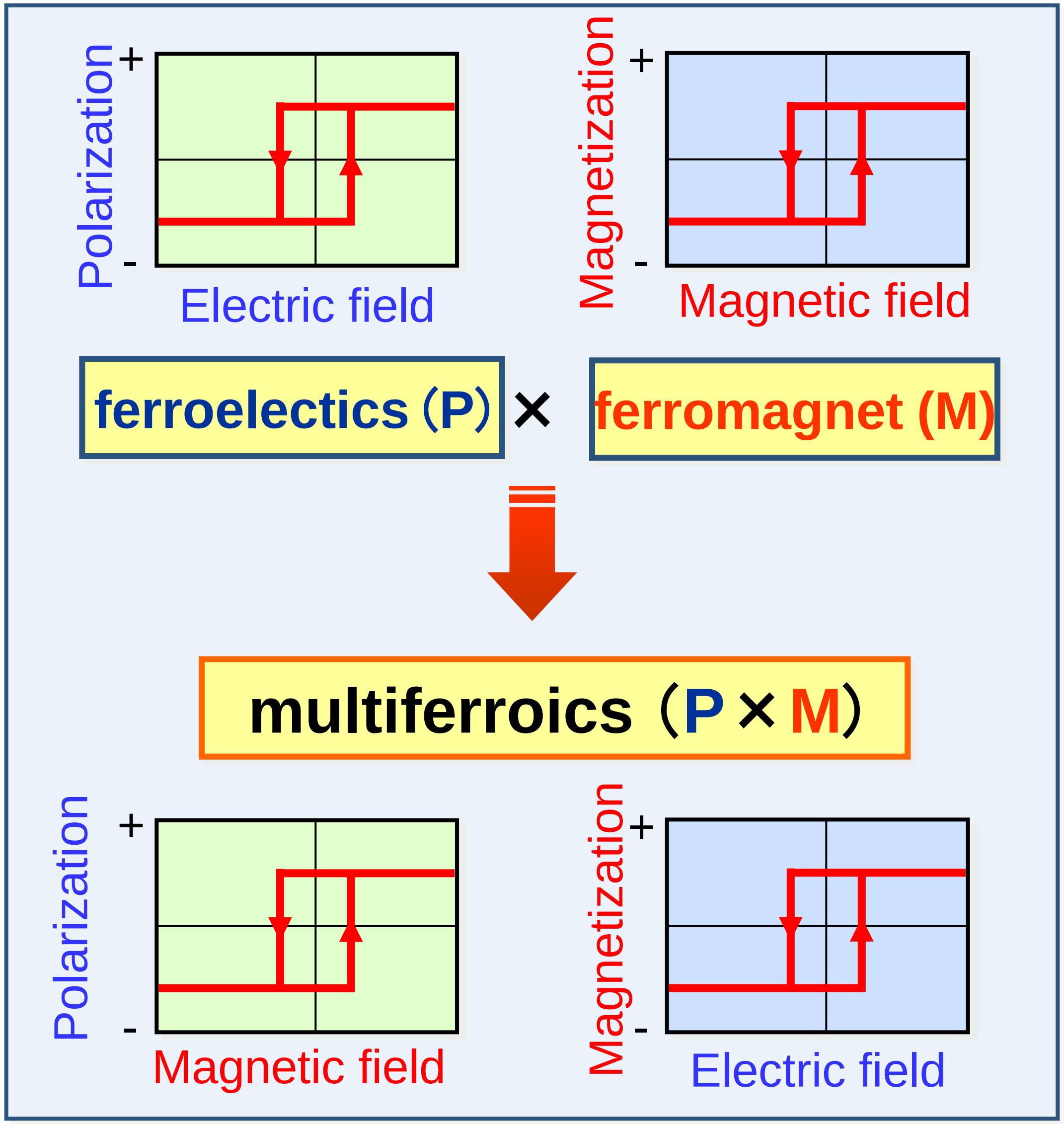
spin-orbit interaction



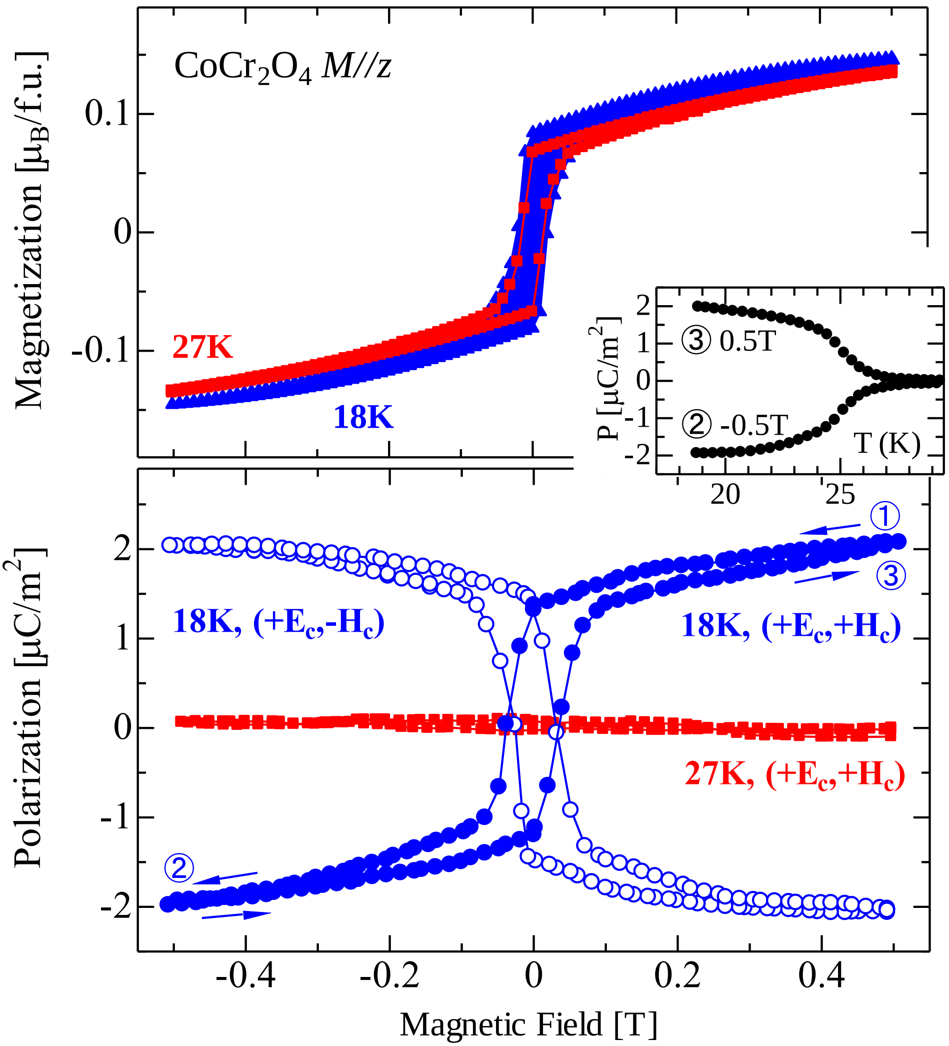
$$M = \sum_i S_i \qquad P = \sum_i er_i$$

Importance of Multiferroics

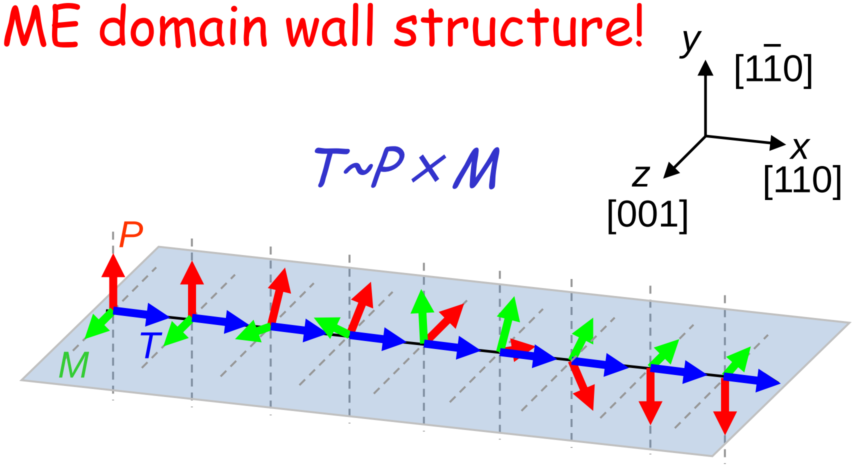


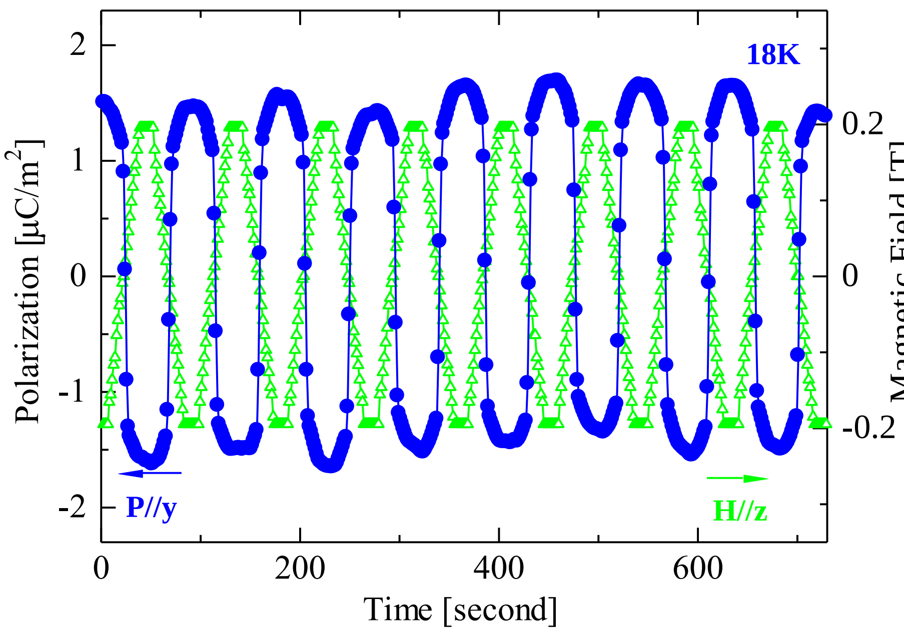


Polarization reversal upon magnetization reversal



ME domain wall structure!



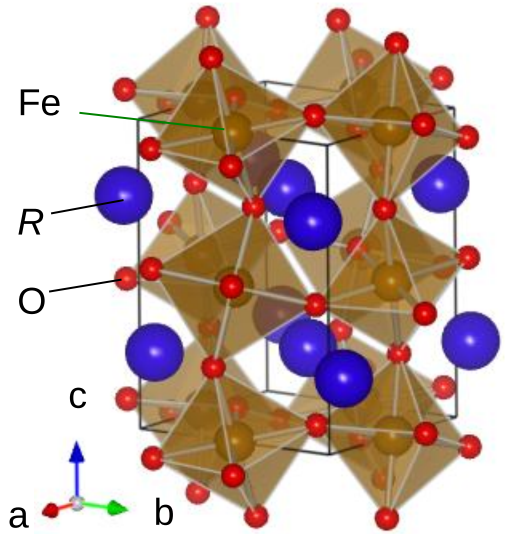


Yamasaki et al. PRL (2006)

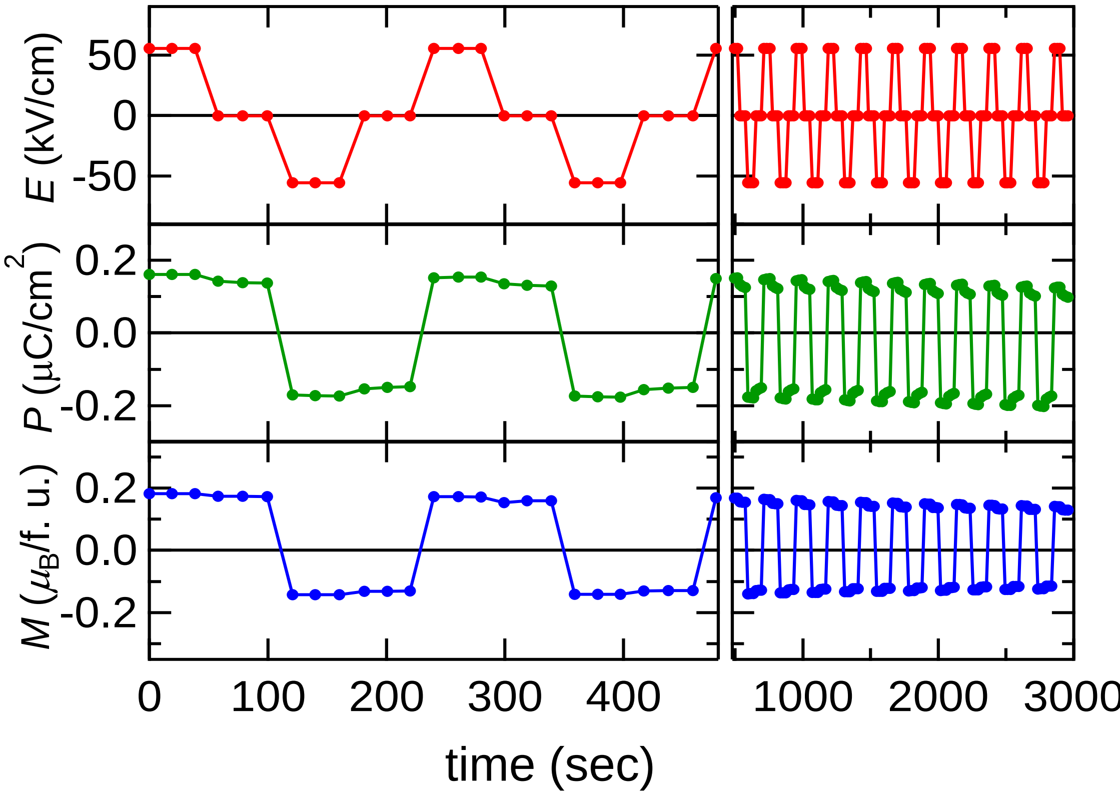
Perfect magnetization reversal by electric field; no power loss

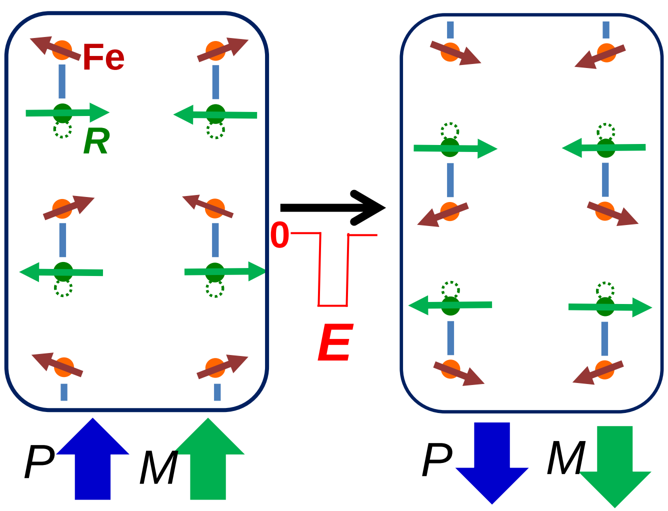
Tokunaga et al. Nature Physics (2012)

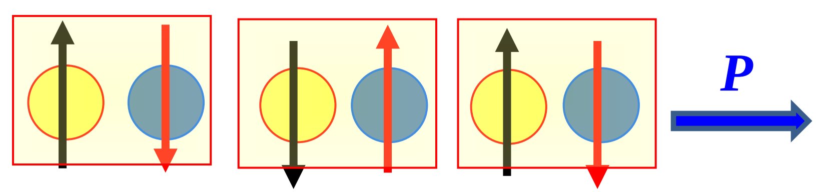
$R\mathrm{FeO}_3$



"GdFeO_3-type" distortion

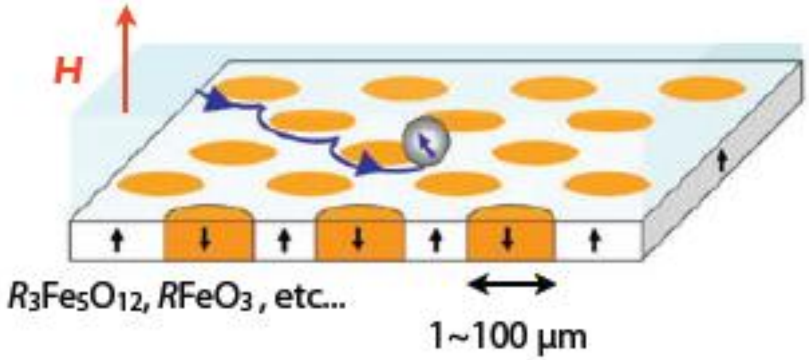






exchange-striction mechanism

Magnetic bubbles （up to 1980's)



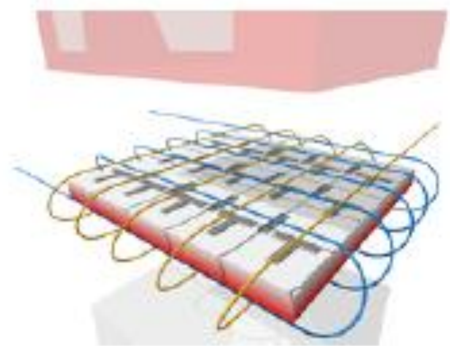
cf. Bubble Memory
(by Intel, IBM, Sharp etc...)

Cylinder-like domain in ferromagnets (**Bubble**)
→ Existence of bubble used as a bit (0 / 1)

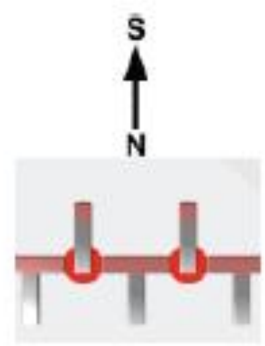
How does bubble memory work ?

gradient of B

Bubble can be driven by magnetic field gradient



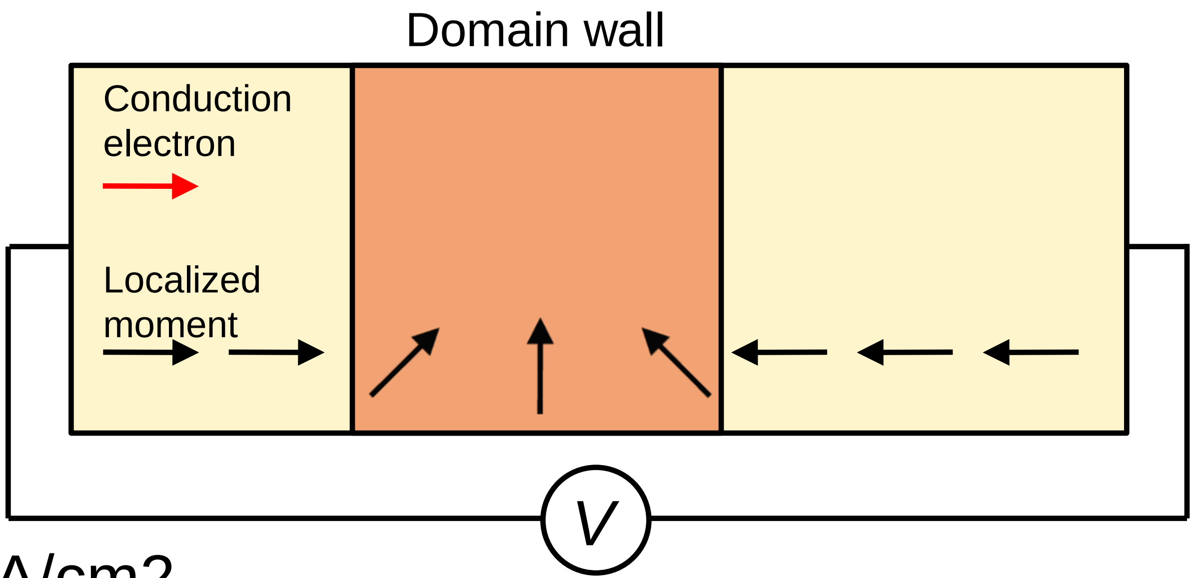
Metallic wire to generate magnetic field + ferromagnetic "guide lane"



Rotation of magnetic field causes bubble motion along guide

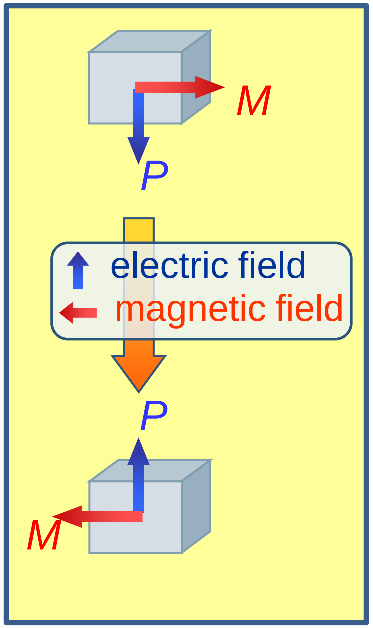
Toward electrical control of magnetism

Domain wall motion by spin transfer torque



10^6-10^8A/cm2

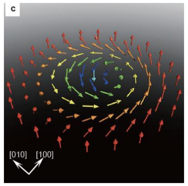
need lower power consumption

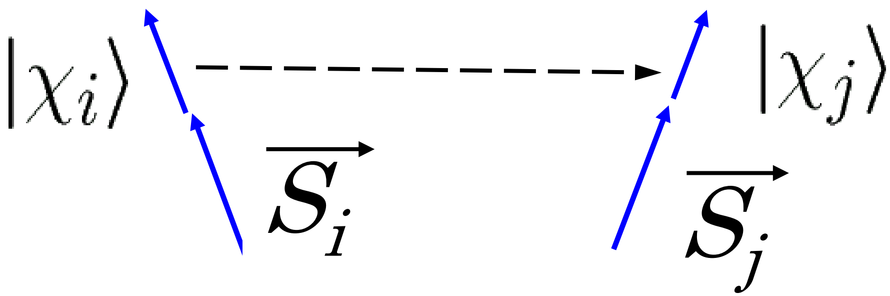


① Multiferroic= ferroelectric + ferromagetic

② nanometric topological spin texture

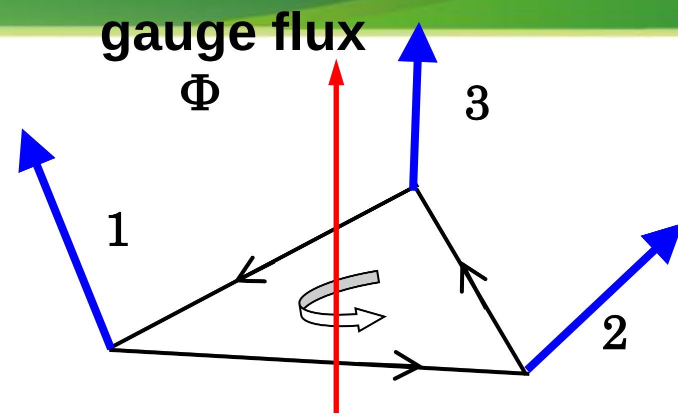
lower-current drive or E-field drive?





$$|\chi_i\rangle = \begin{bmatrix} \cos\frac{\theta_i}{2} \\ e^{i\phi_i}\sin\frac{\theta_i}{2} \end{bmatrix}$$

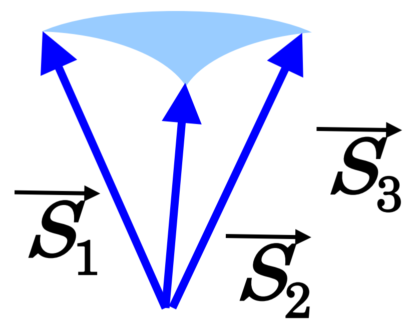
$$\begin{aligned} t_{ij} &= t\langle\chi_i|\chi_j\rangle \\ &= t[\cos(\frac{\theta_i}{2})\cos(\frac{\theta_j}{2}) + \sin(\frac{\theta_i}{2})\sin(\frac{\theta_j}{2})e^{i(\phi_i-\phi_j)}] \\ &= t\cos(\frac{\theta_{ij}}{2})\exp(ia_{ij}) \end{aligned}$$



non-coplanar spin structure

⇓

solid angle Ω



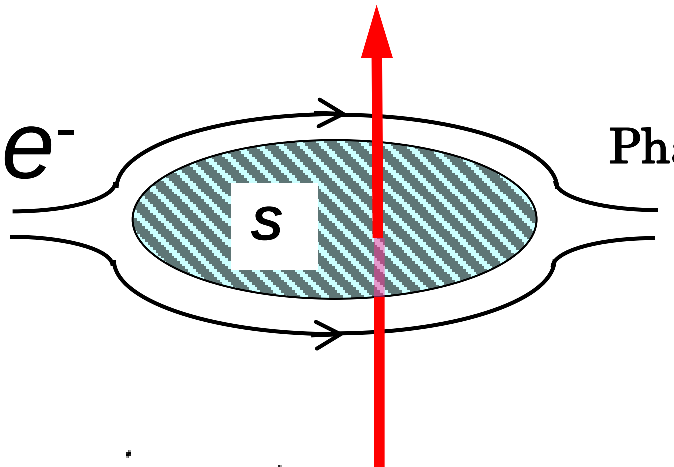
Berry phase
Φ= Ω/2

$= 2S_1\cdot(S_2\times S_3)$

Quantum Berry phase and spin chirality

Aharonov - Bohm effect

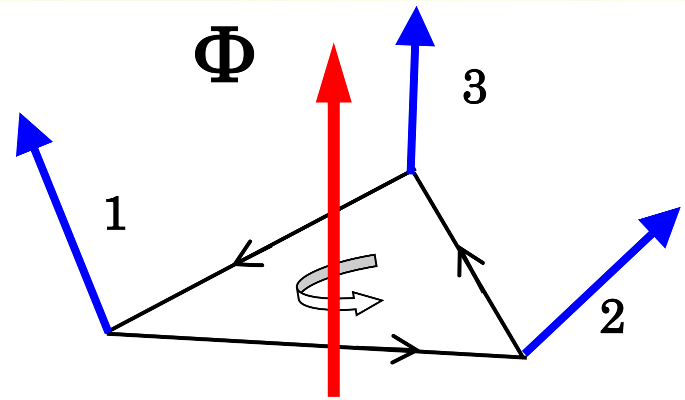
$$\vec{B} = \mathrm{rot}\ \vec{A}$$



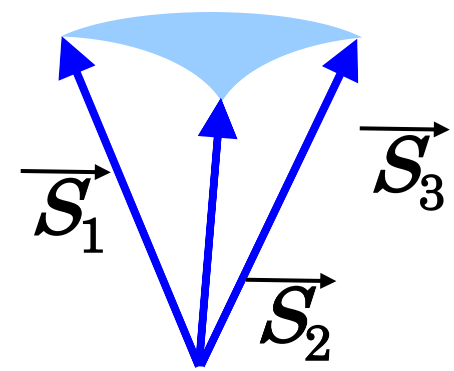
Phase difference

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

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

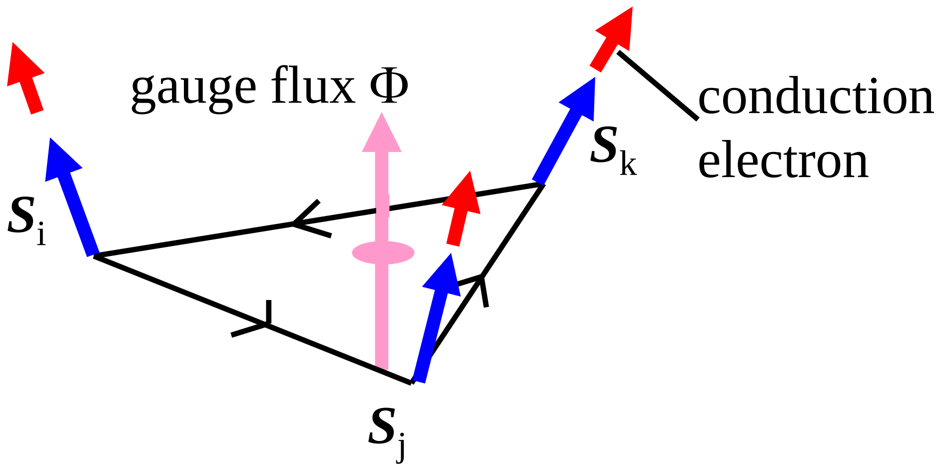


Solid angle Ω

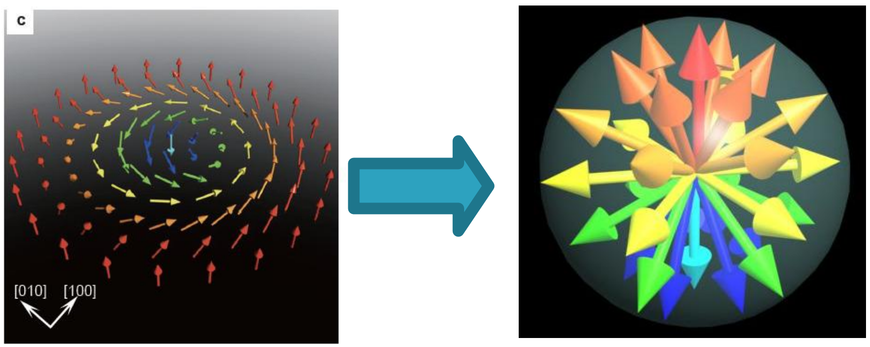


$$\Phi = \frac{1}{2}\Omega$$

Skyrmion



Mapping to a sphere

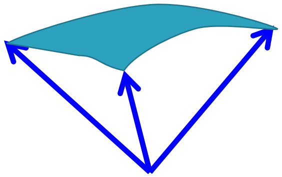


Solid angle $\Omega = 4\pi$

Cf. Spin chirality

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

$= 1/2\ \Omega$ Solid angle



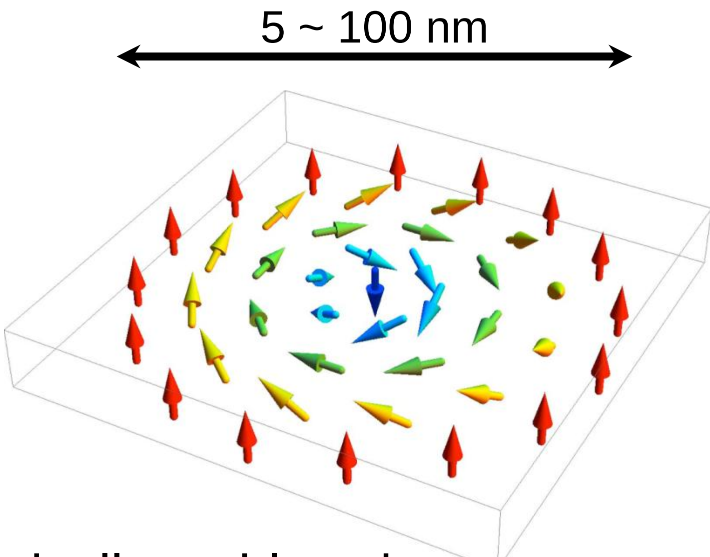
Continuum approximation

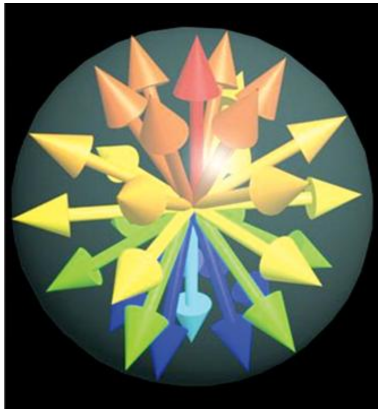
Total spin Chirality

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

$$= N_S$$ Skyrmion number

What is magnetic skyrmion?



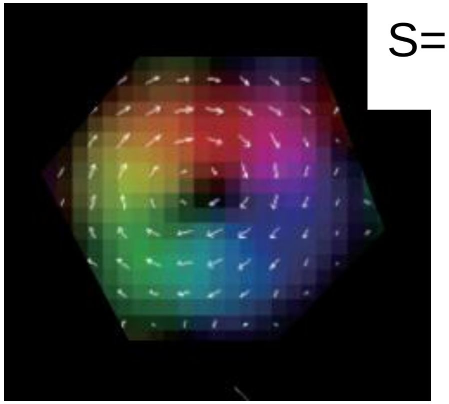


Topologically-stable spin vortex
with particle-like nature

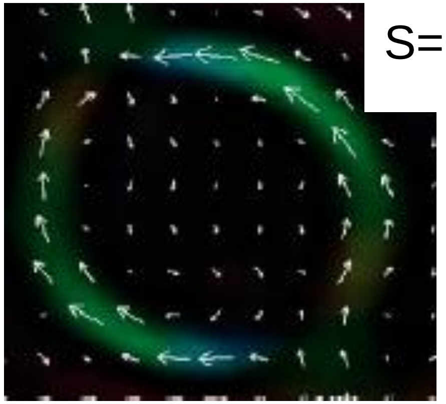
"skyrmion number"

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

Lateral component of
M ofsome bubbles



S=-1

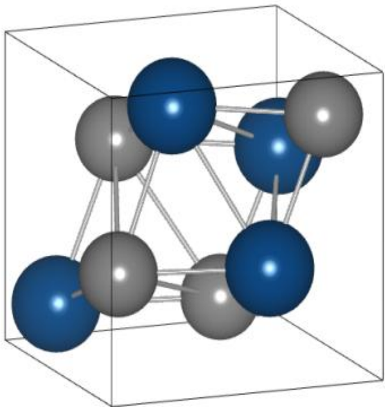


S=0

a pair of
Bloch lines

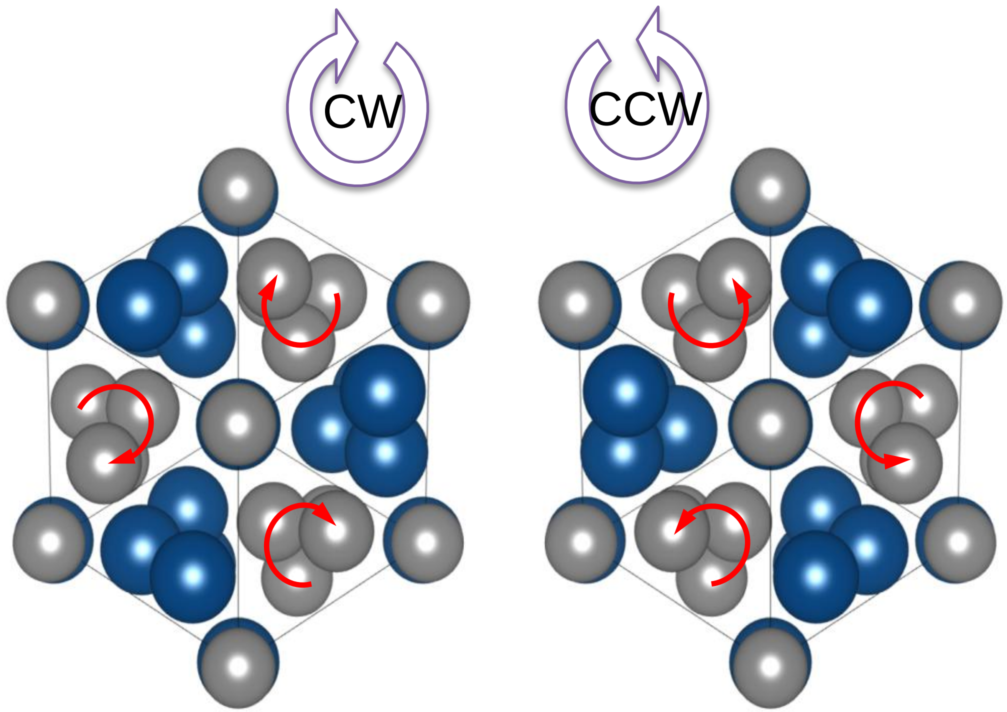
Helical spin order in B20-type crystals

Crystal structure



● : Transition-metal element
● : Group 14 element

- Cubic ($P2_13$)
- Noncentrosymmetric



Chiral lattice structure

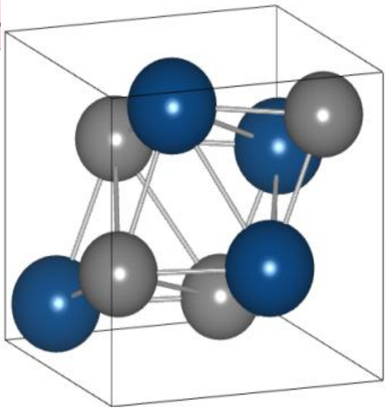
Magnetic structure

<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>)

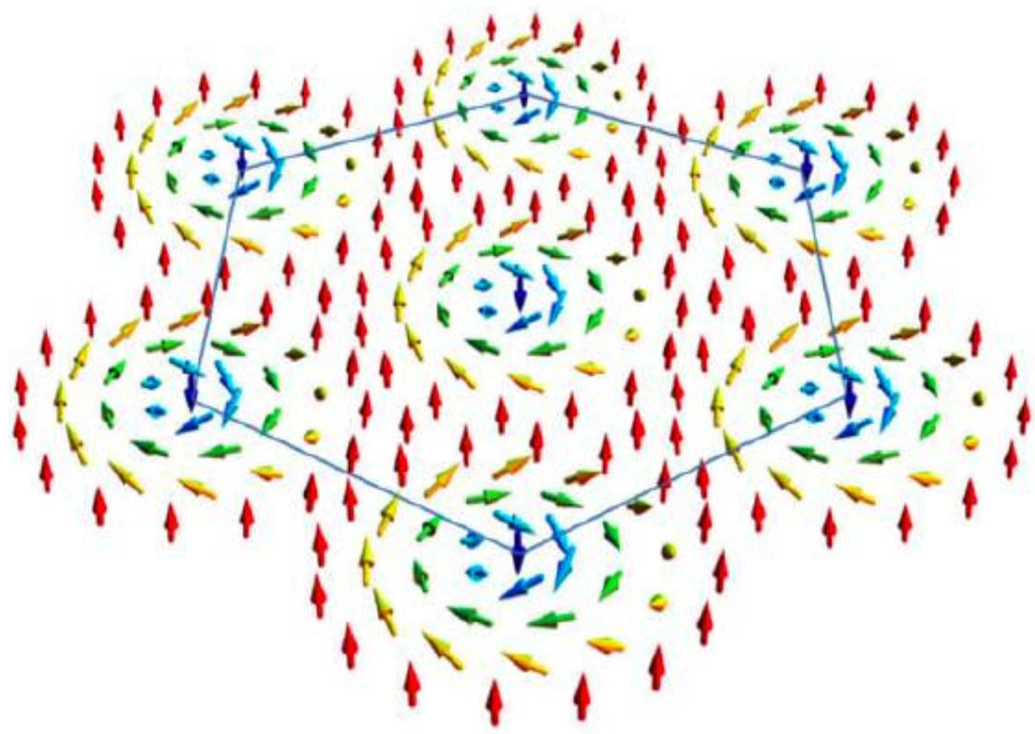
Helical spin order in B20-type crystals

Crystal structu



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

  - Cubic ($P2_13$)
  - Noncentrosymmetric



Magnetic structure

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

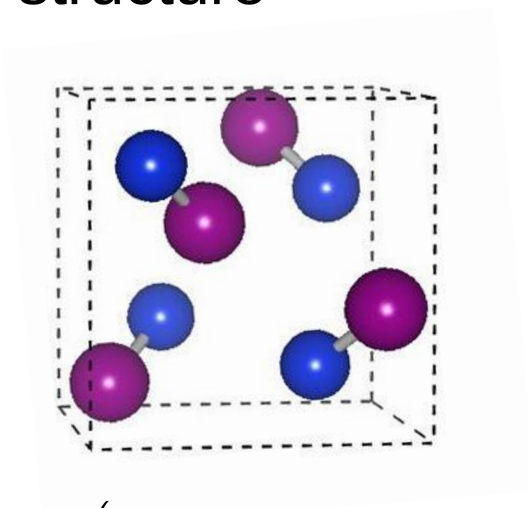
ferromagnetic interaction($\boldsymbol{S}_i \cdot \boldsymbol{S}_j$) > Dzyaloshinsky-Moriya interaction($\boldsymbol{S}_i \times \boldsymbol{S}_j$) > magnetic aniso

→one-handed helical spin structure

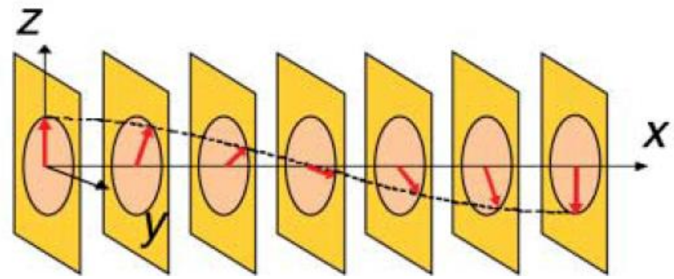
(a long wavelength 17.5 – 230 nm, weakly locked helix direction <111> or <100>)

Magnetic phase daigrams of B20 TMSi, TMGe

B20 structure



Cubic but noncentros
(Chiral)



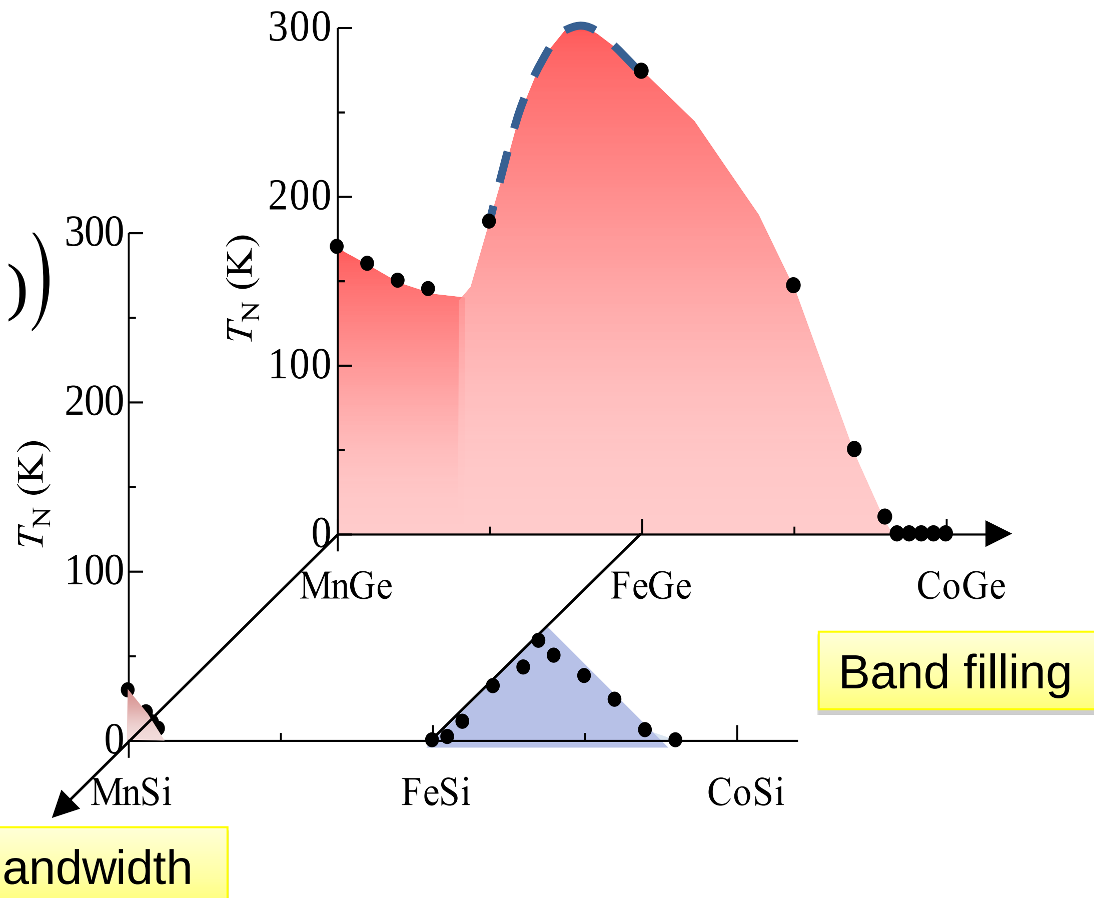
$$H=\sum\left(-J\vec{S}_i\cdot\vec{S}_j+\vec{D}_{ij}\cdot(\vec{S}_i\times\vec{S}_j)\right)$$

Ferro + DM

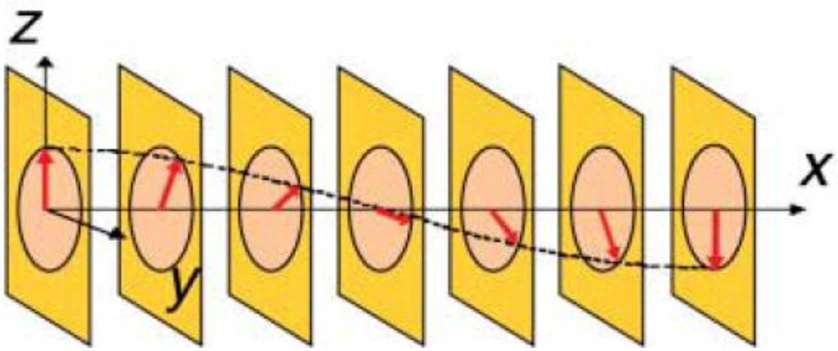
Helical spin structure

Long period～aJ/D

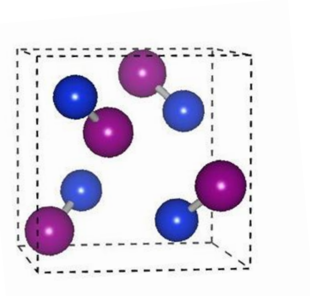
～$10nm\text{-}300nm$

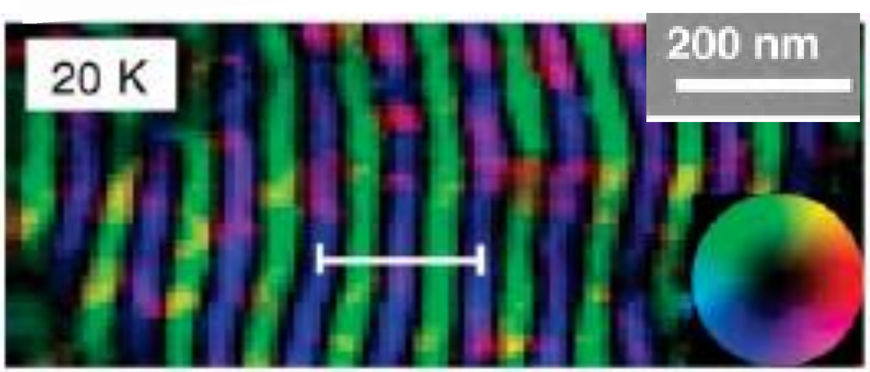


Toward real space observation of Skyrmion structure



F





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

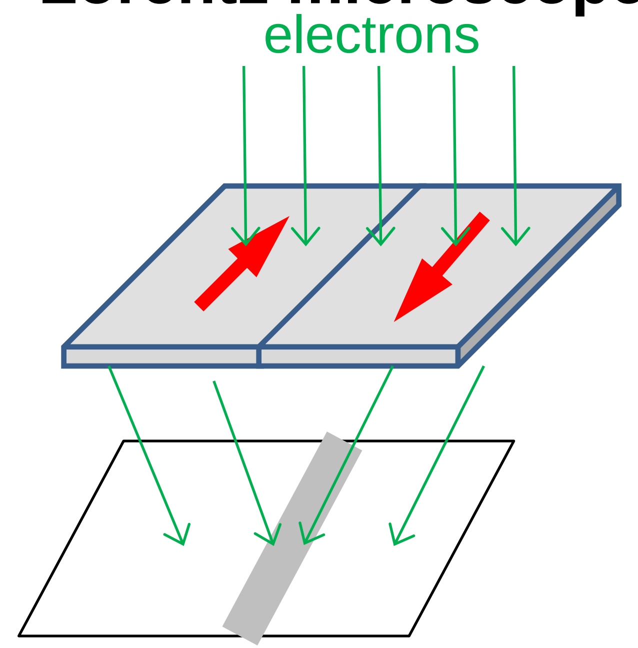
$$H = \sum \left(-J\vec{S}_i \cdot \vec{S}_j + \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \right)$$

Ferro + DM

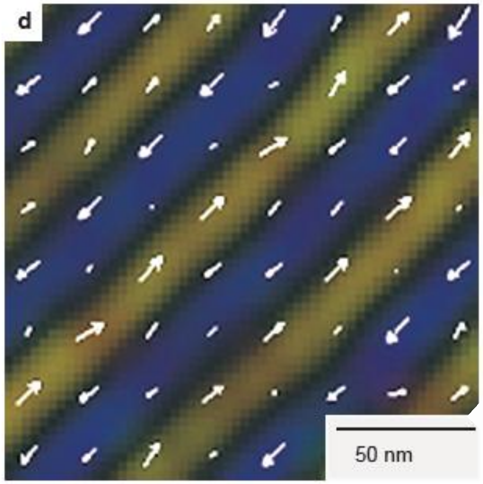
Helical spin structure

Long period～*aJ/D*～*10nm-300nm*

Lorentz microscope

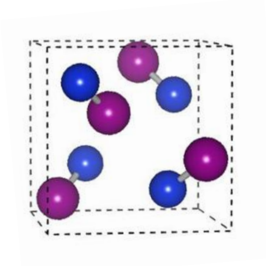


Real Space Observation of Skyrmion crystal

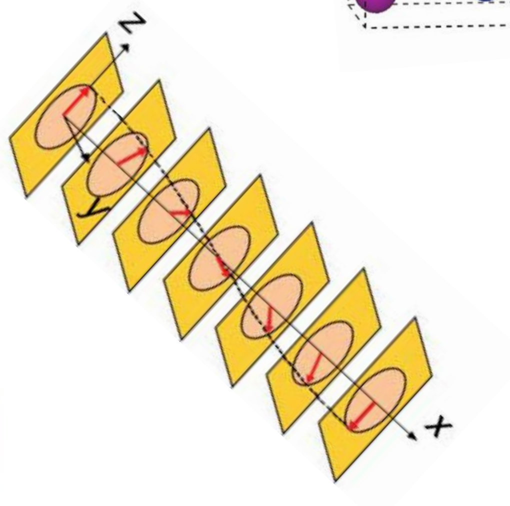


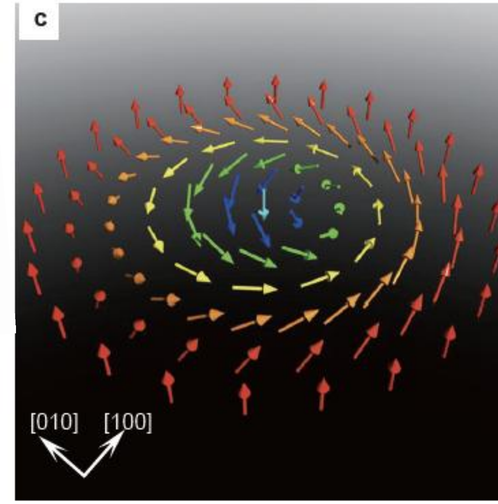
$Fe_{0.5}Co_{0.5}Si$

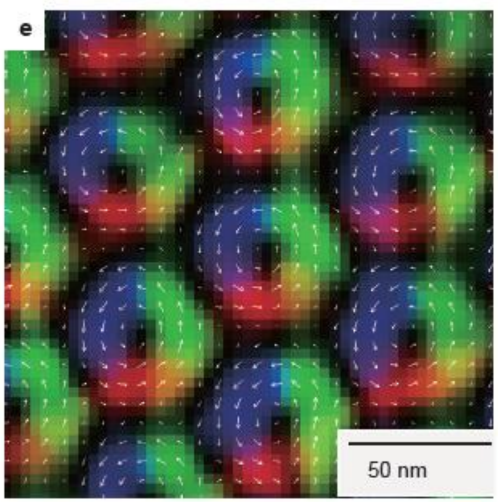
T=25K



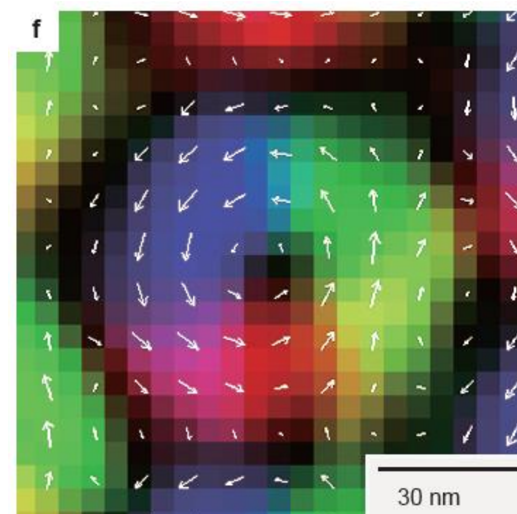
H=0







H=50mT

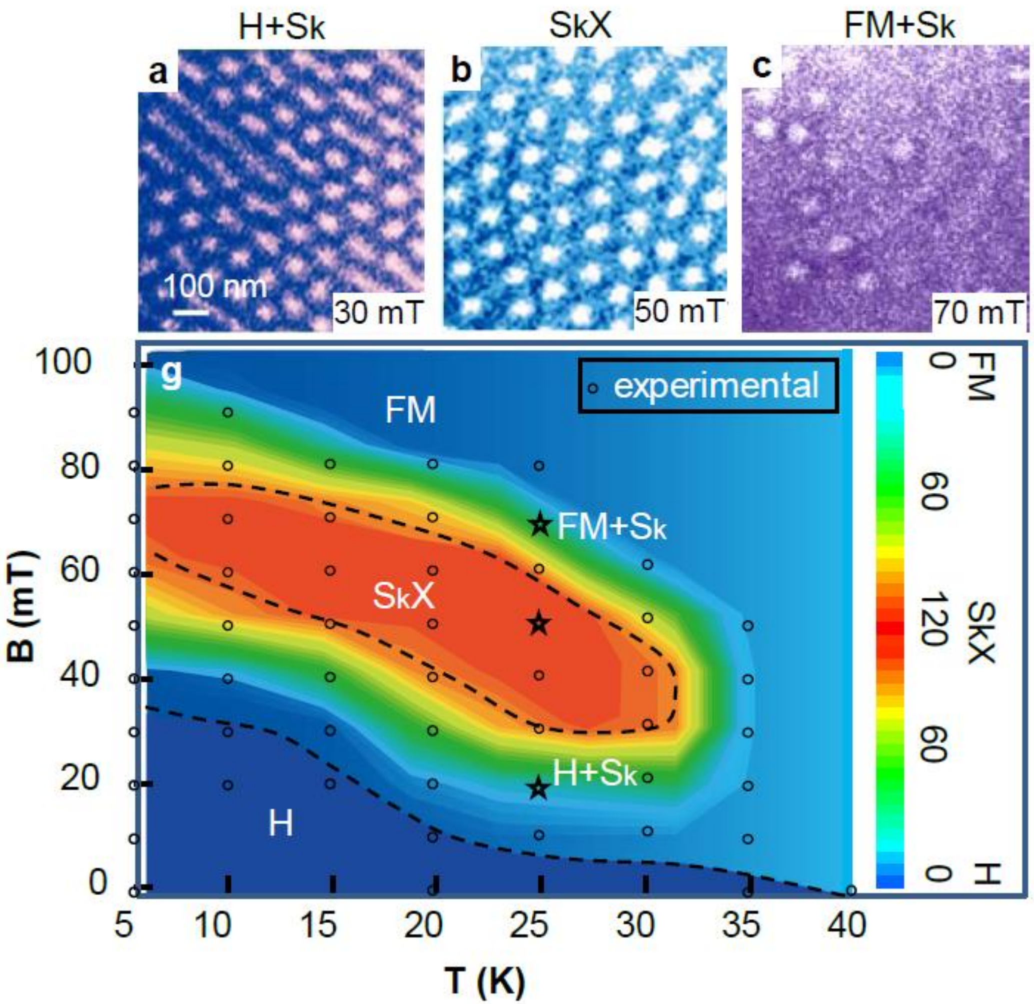


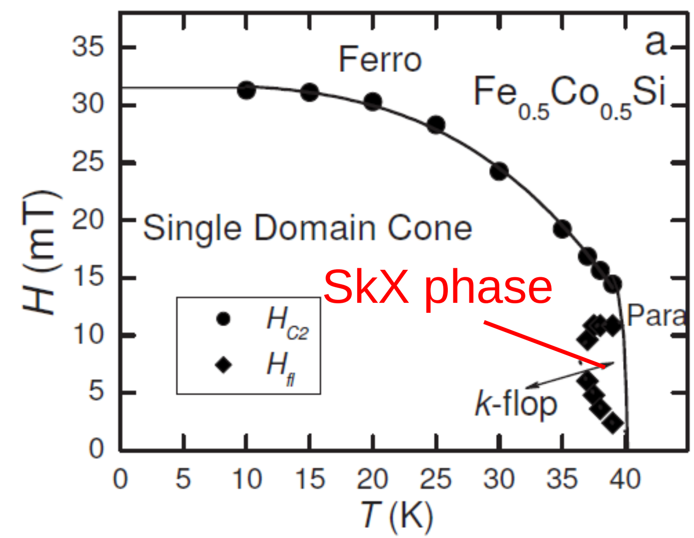
X.Z. Yu, Y.T *et al.* Nature *(2010).*

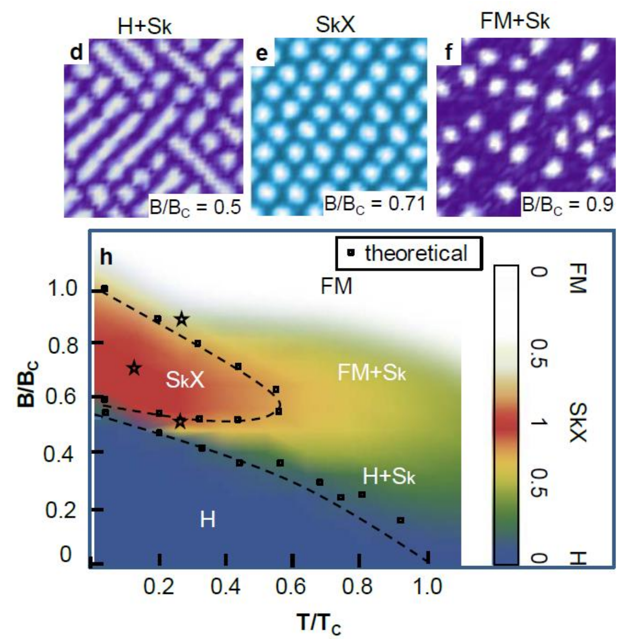
H-T Phase diagram

Bulk sample

20nm-thick film (Lorentz TEM)







Skx: Skyrmion Crystal

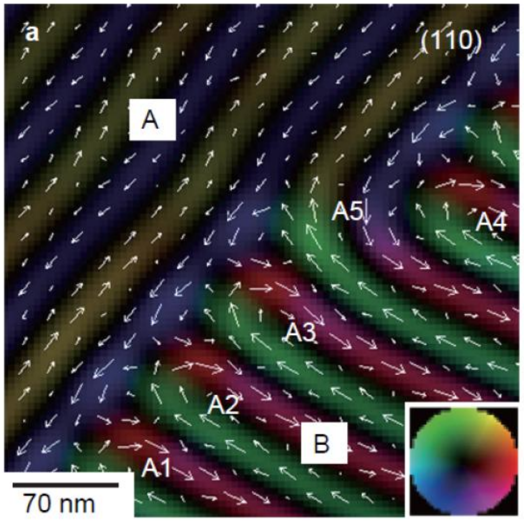
2D simulation

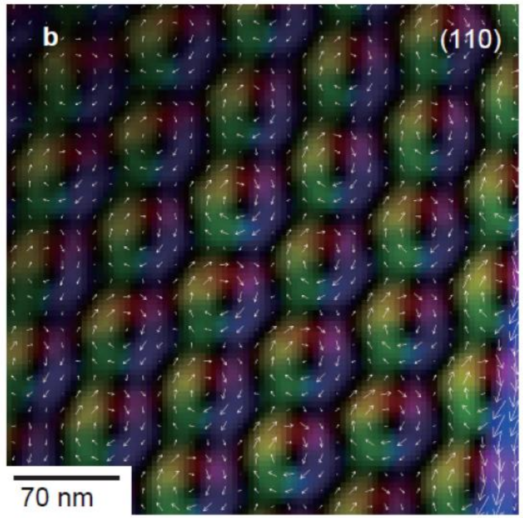
FeGe: from helical to skyrmion crystal at 260K

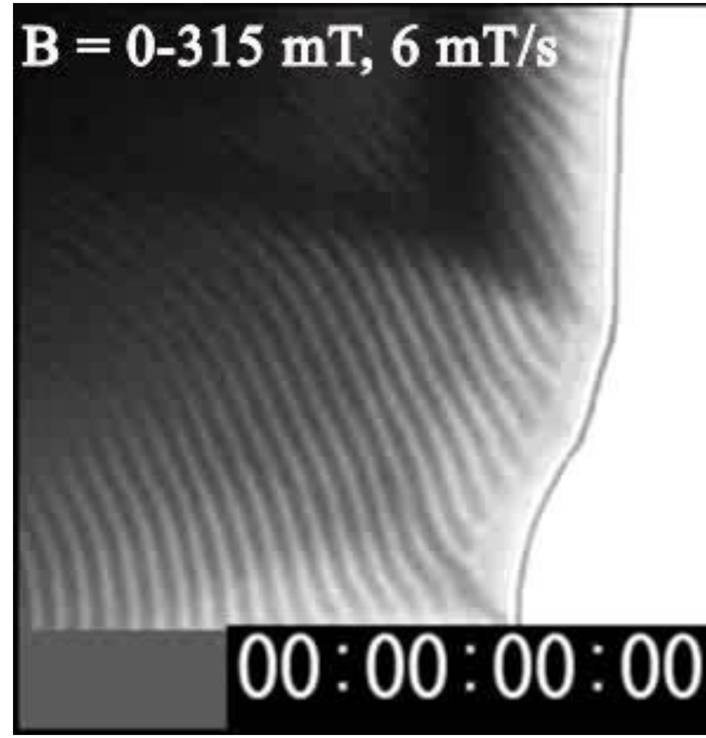
X.Z. Yu et al. Nat. Mater.(2010)

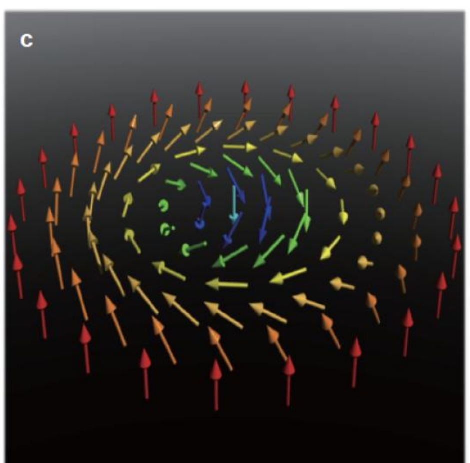
H=0

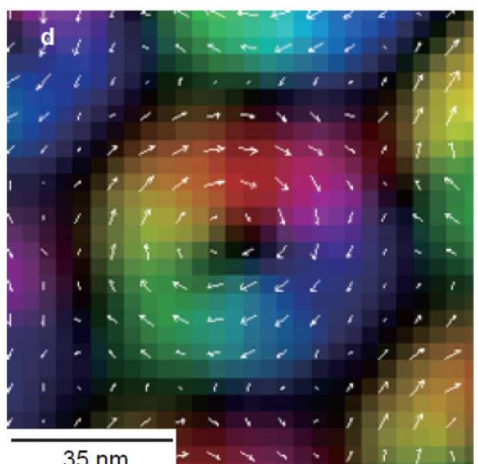
⊙ H=0.1T

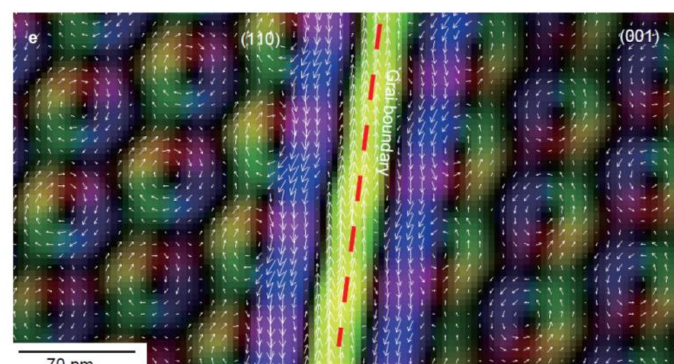












Near room-temperature formation of SkX in FeGe

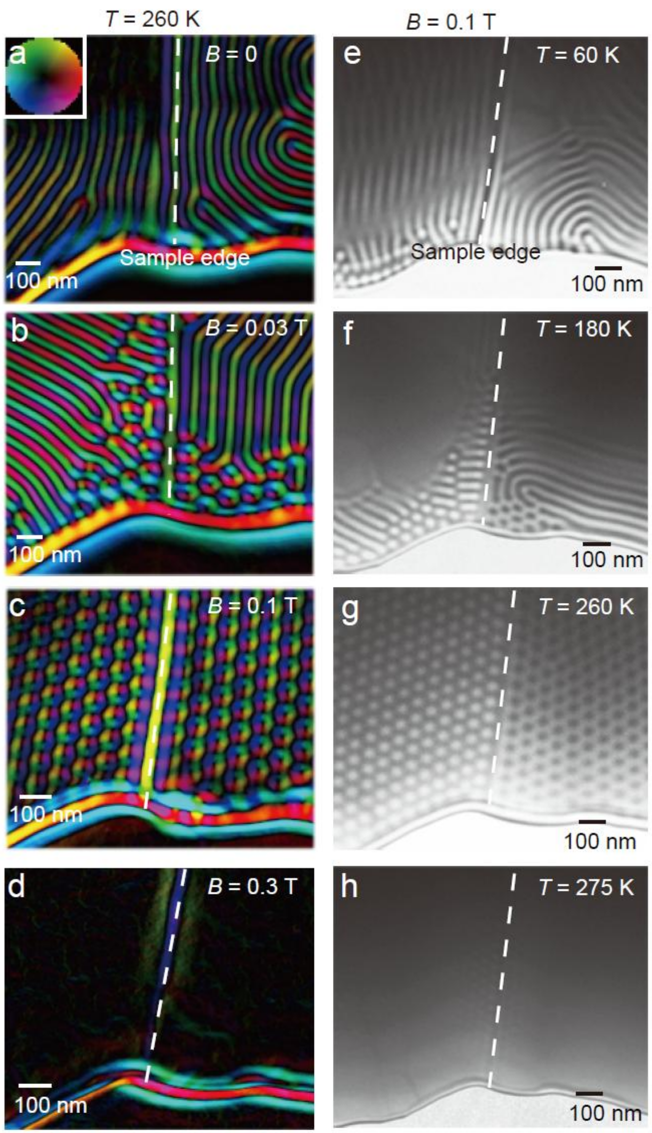


FIG. 2 Yu *et al.*

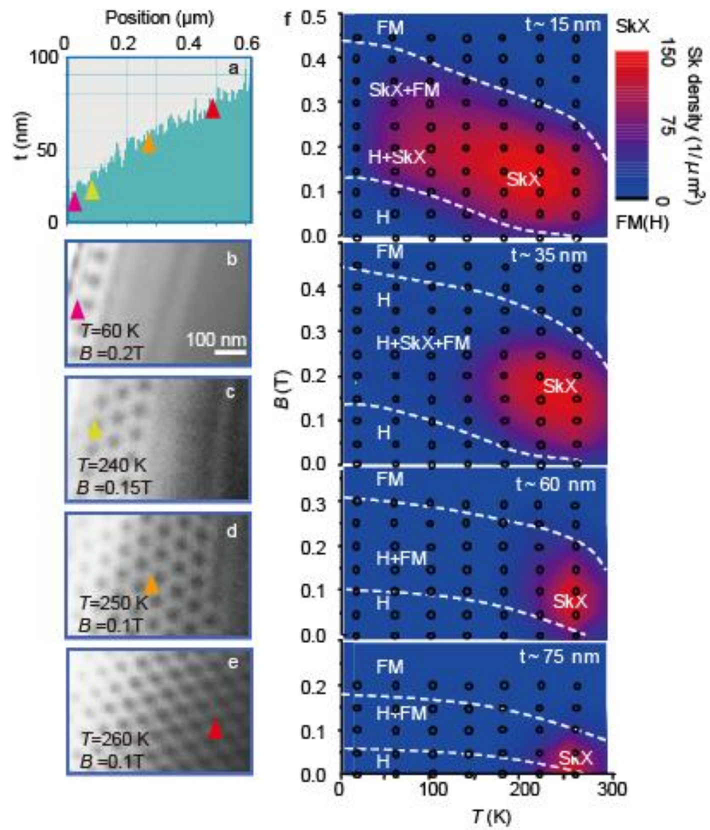


FIG. 3 Yu *et al.*

t = 15 nm

t = 35 nm

t = 60 nm

t = 75 nm

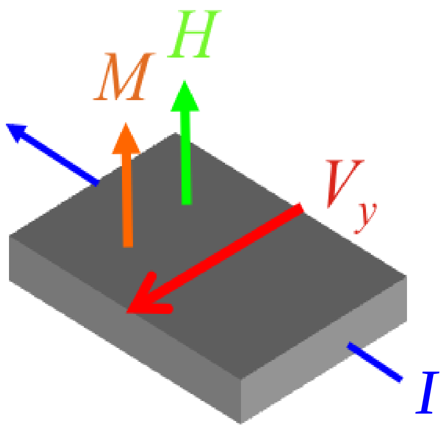
-Near room-temperature formation of SkX

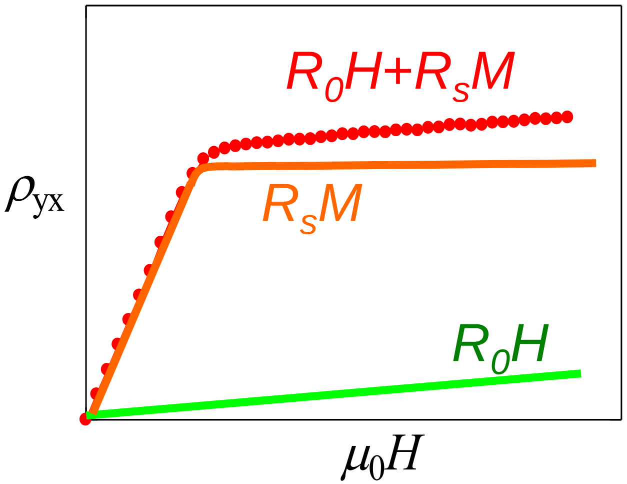
-Stability of SkX depend largely on the thickness.

X. Z. Yu, N. Kanazawa, Y. Onose, K. Kimoto, W.Z. Zhang ,
S. Ishiwata, Y. Matsui, and Y. Tokura, Nature Mater. 10 106 (201

Hall effect in magnetic materials

e.g.) Anomalous Hall effect in Ni





Empirical relation

$$\rho_{yx} = \boxed{R_0 B_z} + \boxed{\mu_0 R_S M}$$

Normal Hall effect
due to Lorentz force

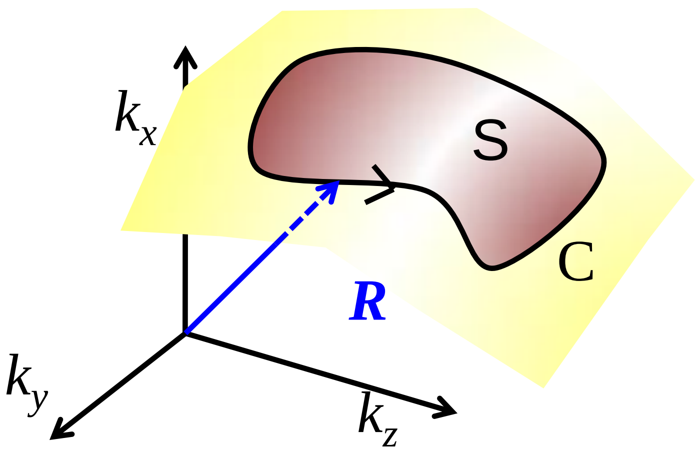
Anomalous Hall effect
proportional to *M*

× due to the magnetic field by *M*
→*too small*

✔ due to the Berry phase in *k*-space

Berry phase and Hall effect

Band structure (k-space)



Berry phase

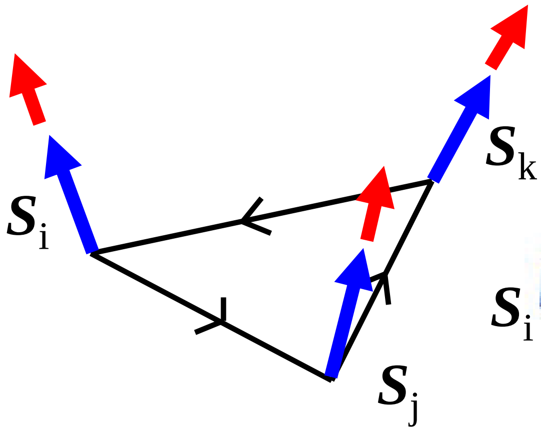
$$\gamma = \int_S d\mathbf{S} \cdot \mathbf{b}(\mathbf{k})$$

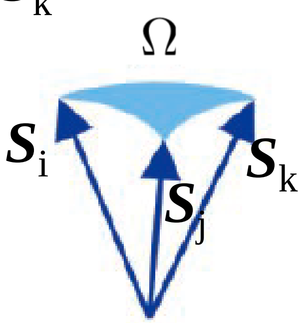
Equation of motion

$$\dot{\mathbf{r}} = \frac{\partial \epsilon_n(\mathbf{k})}{\hbar \partial \mathbf{k}} - \dot{\mathbf{k}} \times \mathbf{b}(\mathbf{k})$$

Anomalous Hall effect($\rho_{yx} = \mu_0 R_S M$)

Spin texture (r-space)





Berry phase

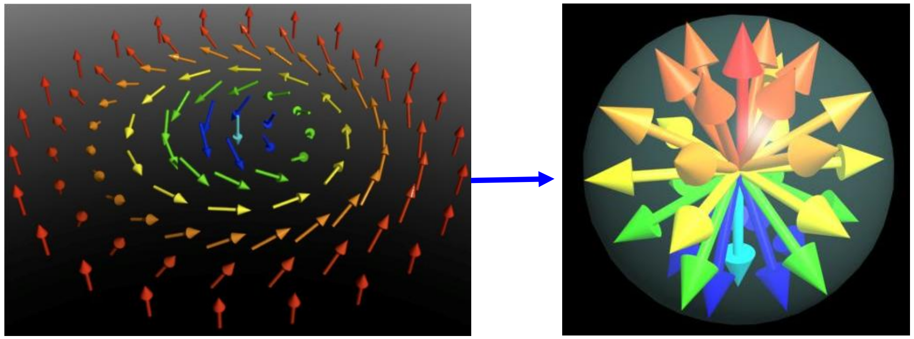
$$\gamma = \int_S d\mathbf{S} \cdot \mathbf{b}(\mathbf{r}) = \frac{\Omega}{2} = 2\mathbf{s}_i \cdot (\mathbf{s}_j \times \mathbf{s}_k)$$

Equation of motion

$$\hbar \dot{\mathbf{k}} = -e\mathbf{E} - e\dot{\mathbf{r}} \times \mathbf{B} - \hbar \dot{\mathbf{r}} \times \mathbf{b}(\mathbf{r})$$

Topological Hall effect

Real-space fictitous magnetic field in a skyrmion spin texture



Solid angle $\Omega = 4\pi$

In srong coupling case

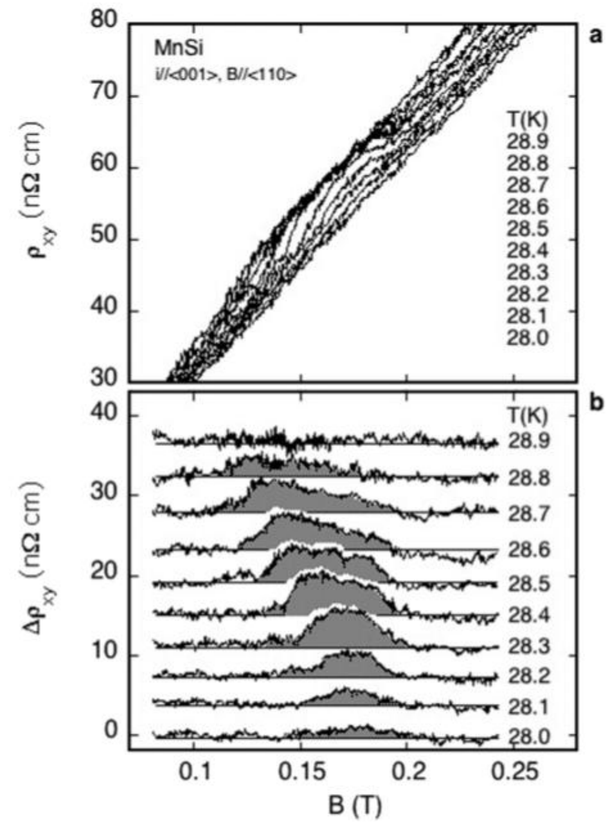
One skyrmion ⟷ One magnetic flux ϕ_0

$$\phi_0 = h/e$$

Emergent **magnetic field**

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

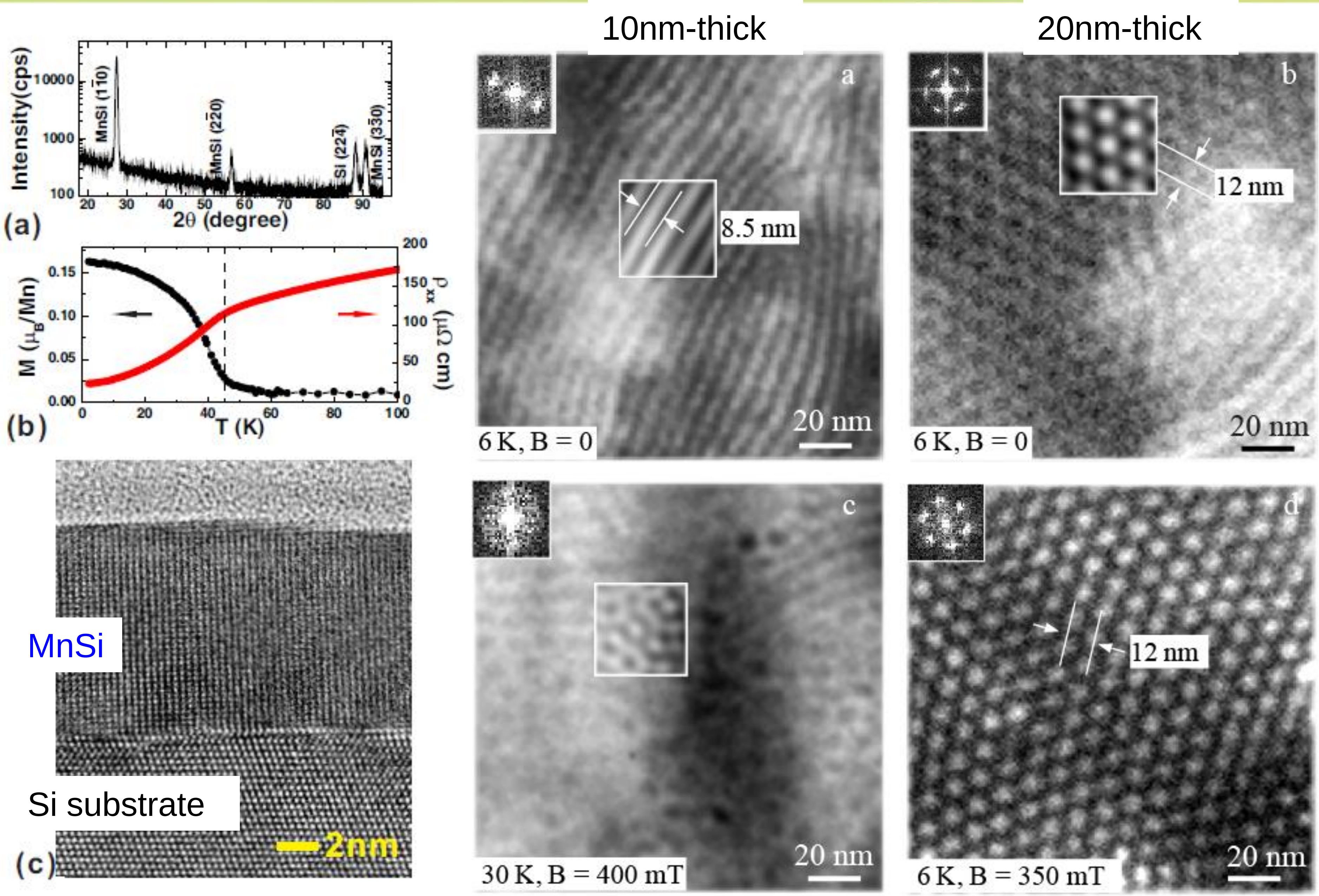
A: skyrmion size



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

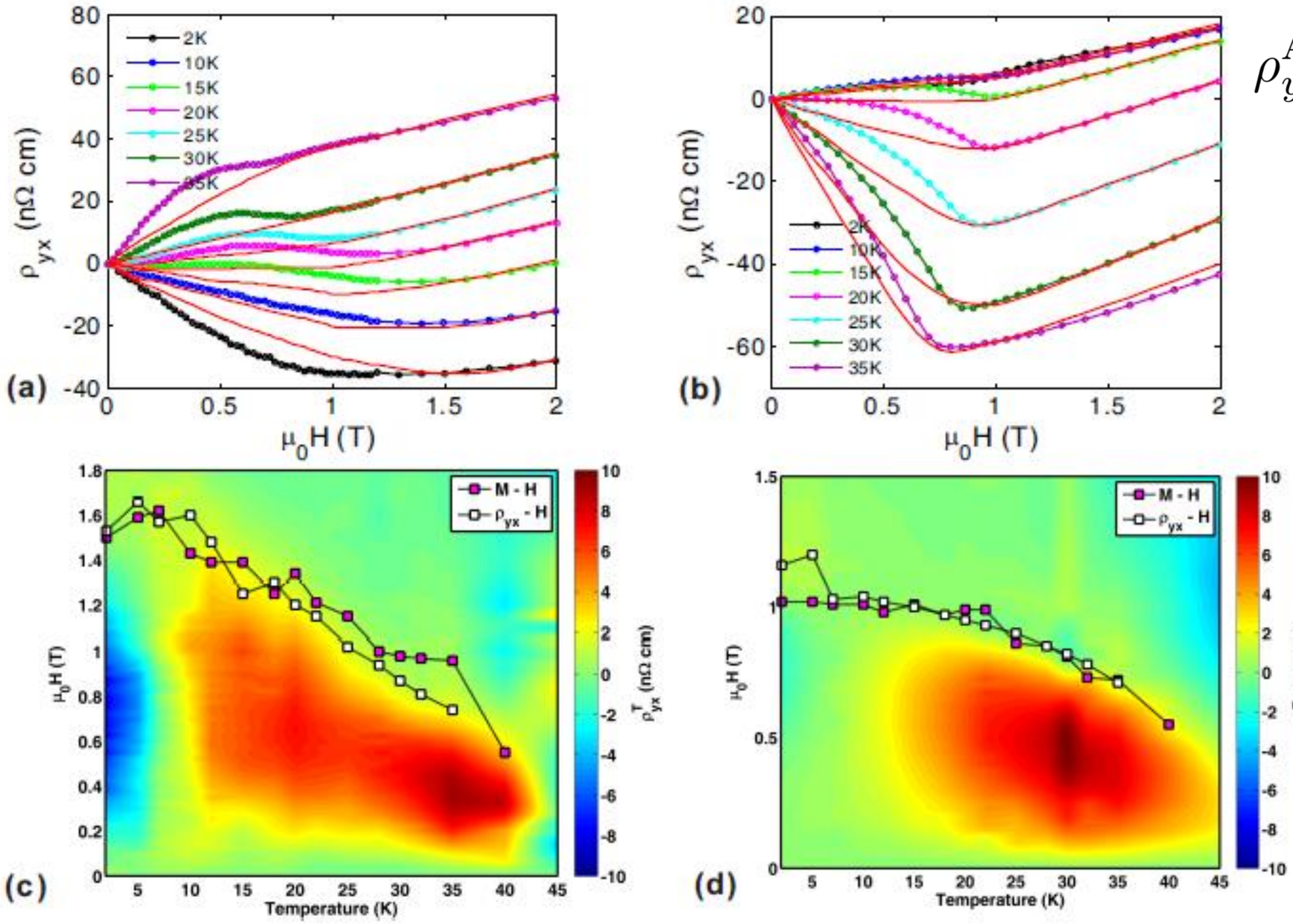
10nm-thick

50nm-thick

Conventional anomalous + normal Hall effects

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

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

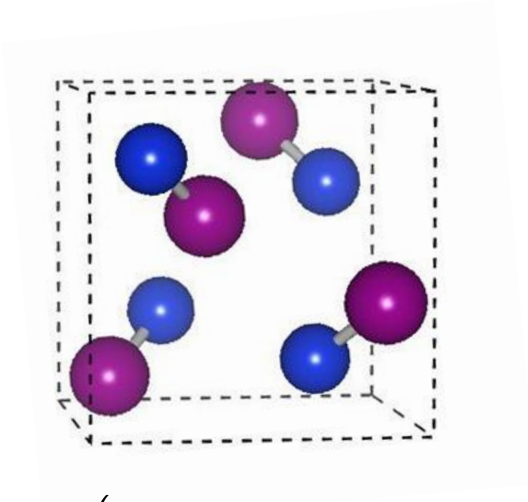


See also the late paper on FeGe thin film;

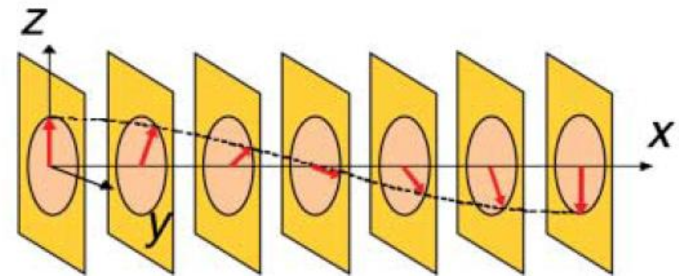
S. X. Huang and C. L. Chien、Phys. Rev. Lett. **108**, 267201 (2012)

Magnetic phase daigrams of B20 TMSi, TMGe

B20 structure



Cubic but noncentros
(Chiral)

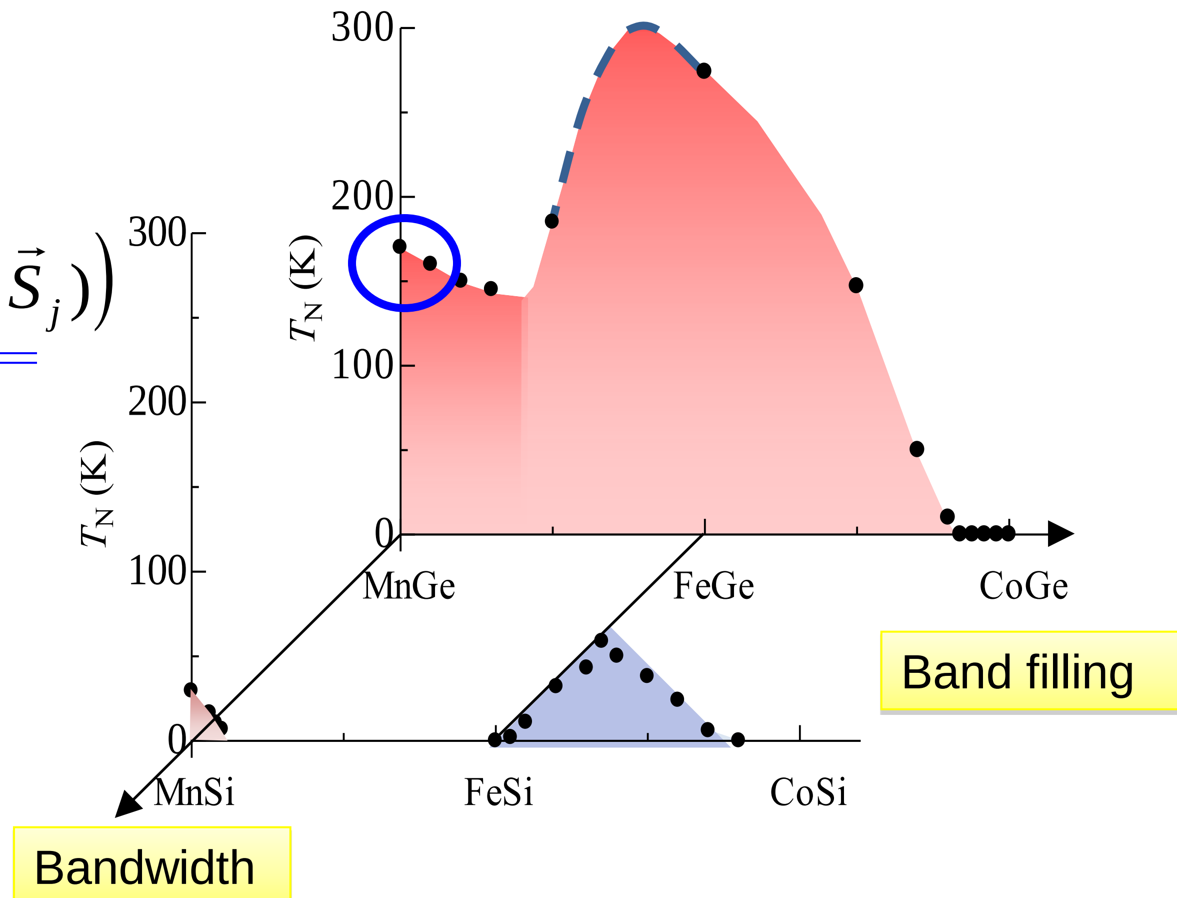


$$H = \sum \left(-J\vec{S}_i \cdot \vec{S}_j + \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \right)$$

Ferro + DM

Helical spin structure

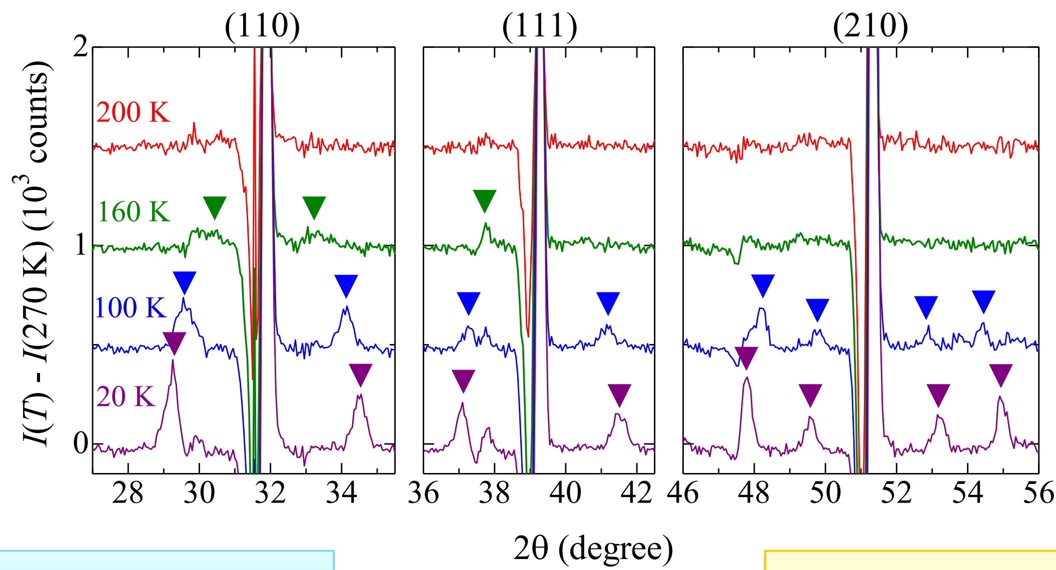
Long period～aJ/D
～$10nm$-$300nm$



Neutron diffraction patterns at H = 0

Powder neutron diffraction patterns

MnGe

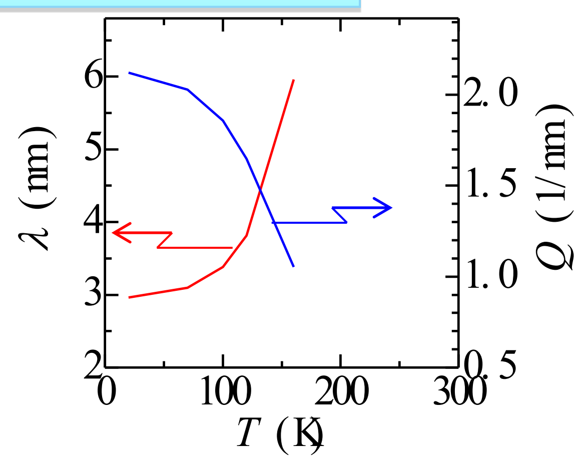


Magnetic Bragg peaks

$$|\mathbf{q}| = |\mathbf{Q} \pm \mathbf{Q}_m|$$

N. Kanazawa, Y. Onose, T. Arima, D. Okuyama, K. Ohoyama, S. Wakimoto, K. Kakurai, S. Ishiwata, and Y. Tokura, PRL 106 156603 (2011).

Helical period



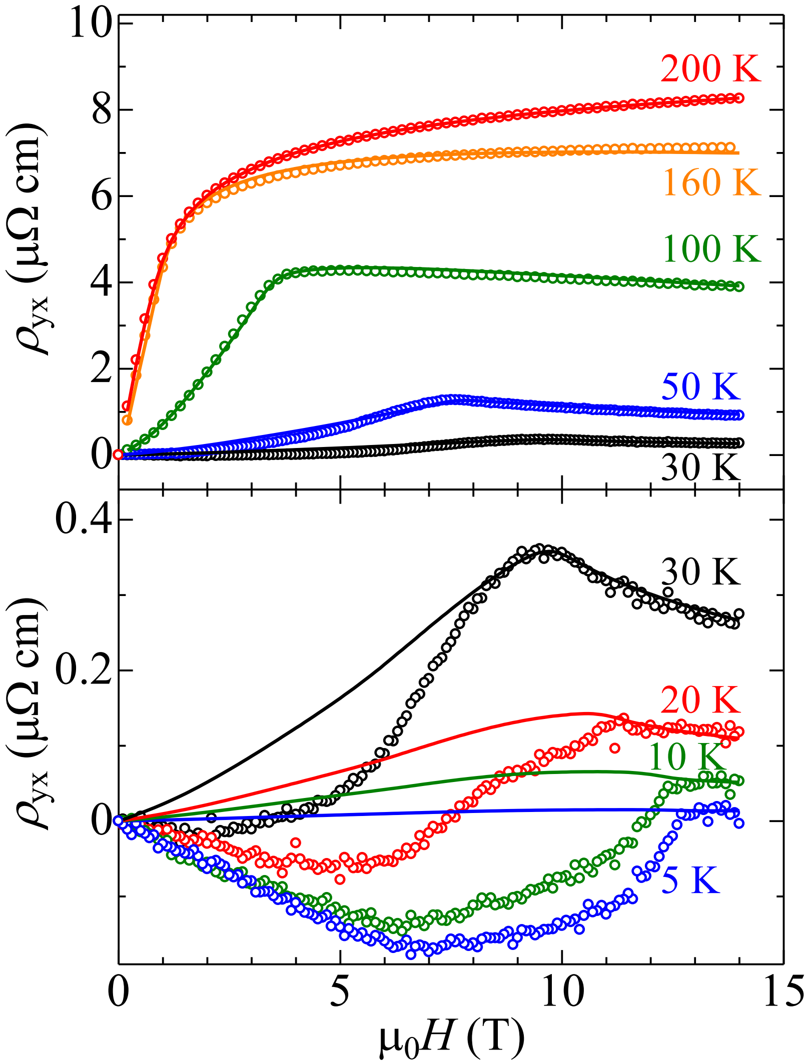
- T_N=170 K
- Helical structure
- modulation vector : Q ||<100>
- Helical period : λ = 3 nm – 6 nm

→ Large topological Hall effect

Cf) MnSi : λ = 17.5 nm

ρ^T_{yx} ~ - 4.5 nΩ cm

Topological Hall effect in MnGe



H > H_C

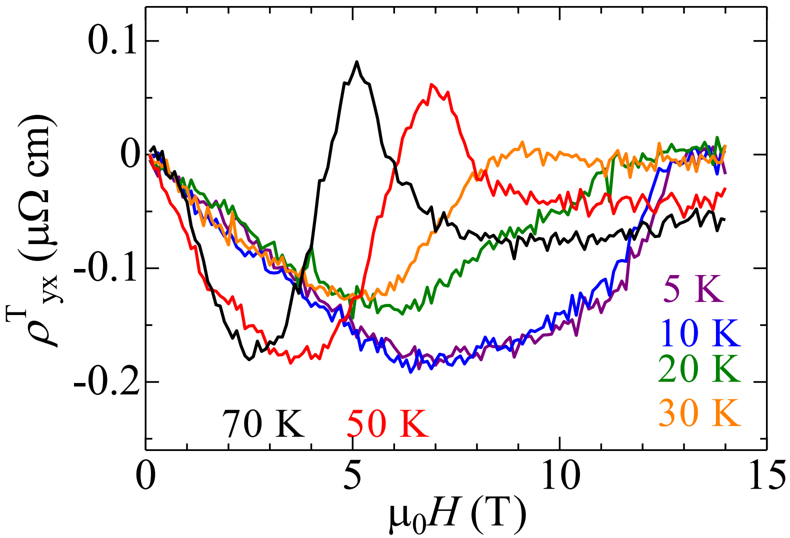
Induced ferromagnetic state
→"Conventional" anomalous Hall effect

Solid lines: estimate of

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

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

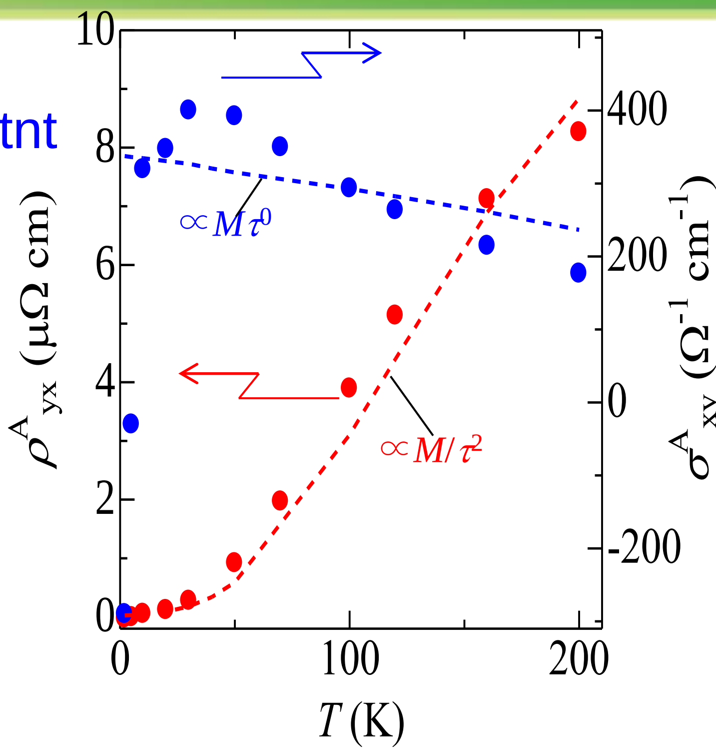
Components of THE



Nearly temperature independent

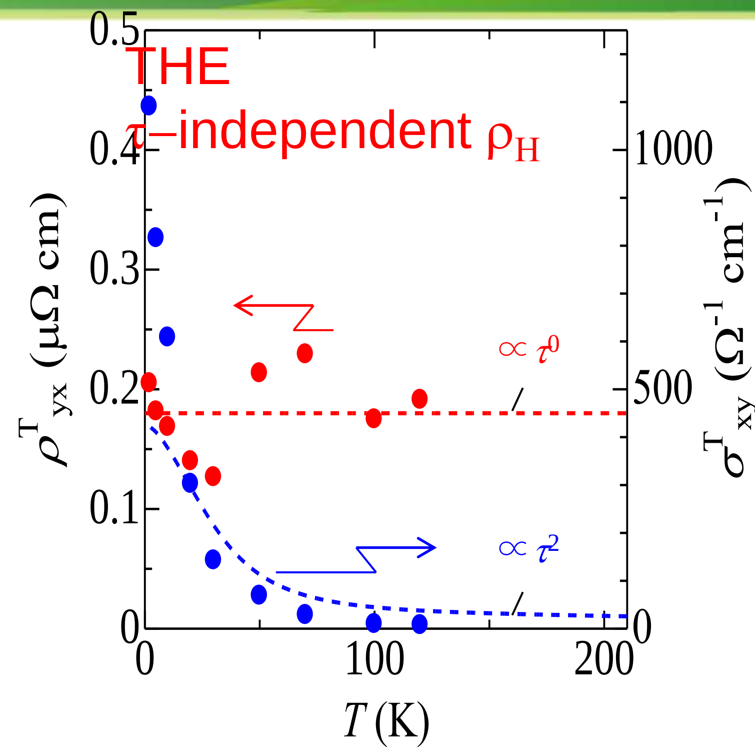
AHE

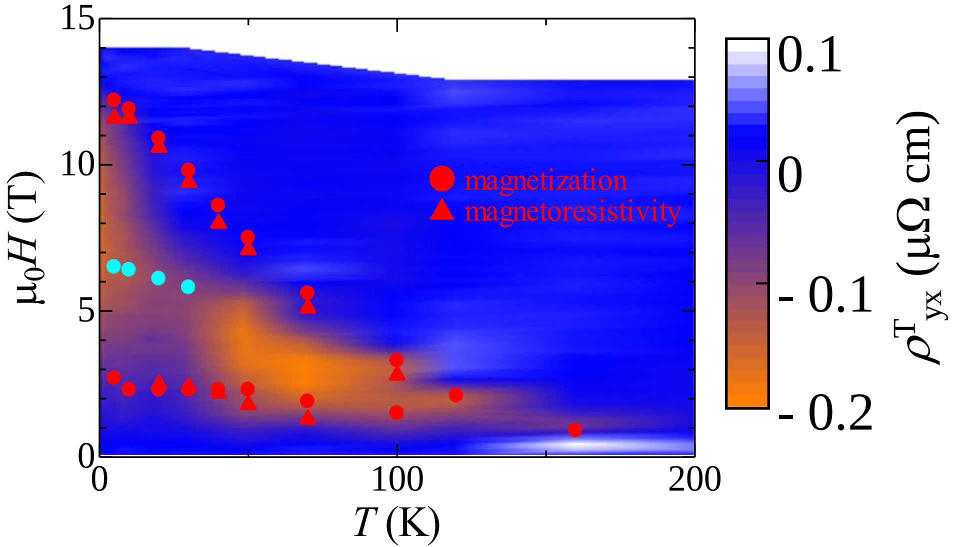
σ_H constatnt



THE

τ–independent ρ_H



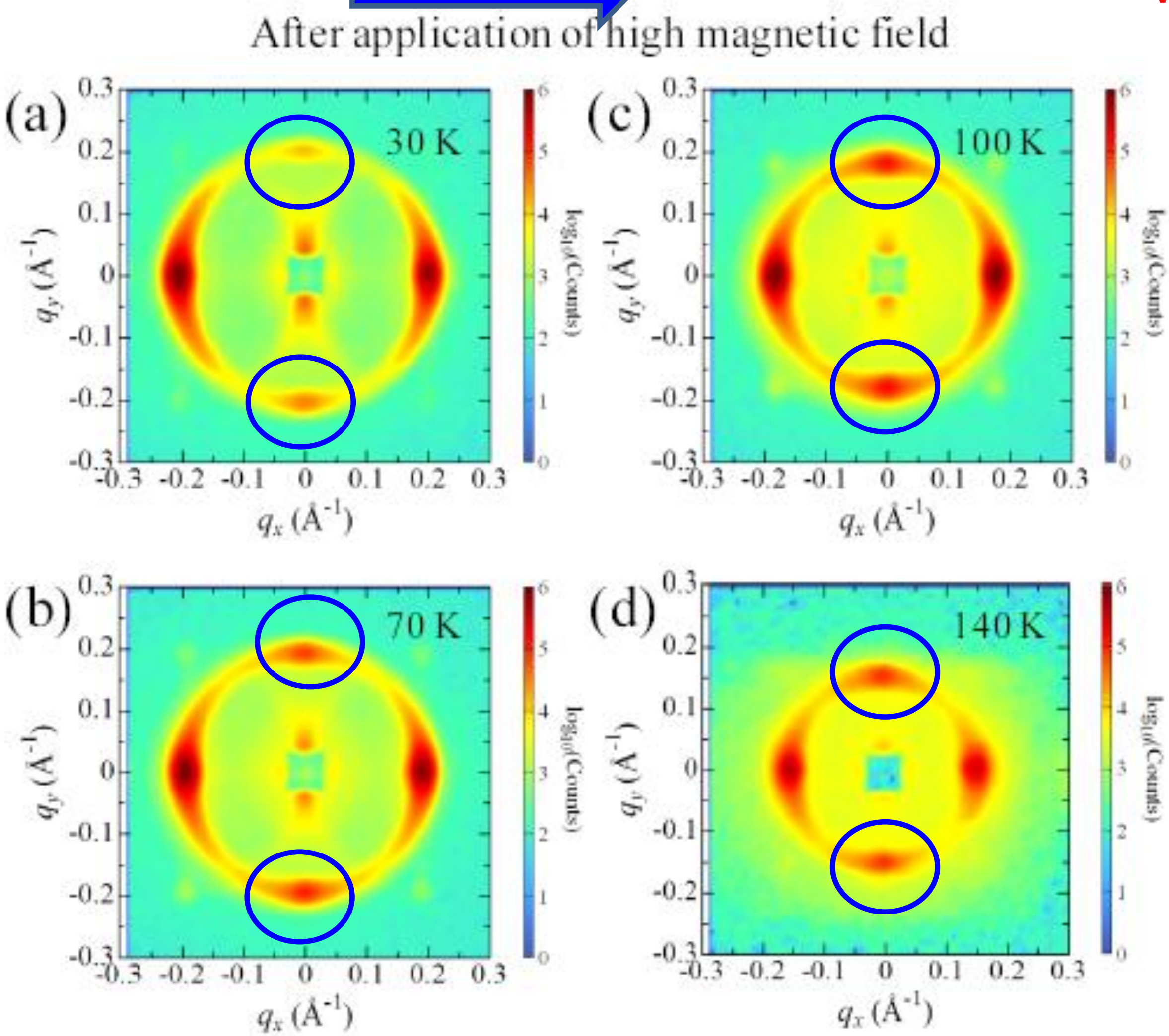


MnGe

SkX subsistent to ground state

B (10T) then B=0

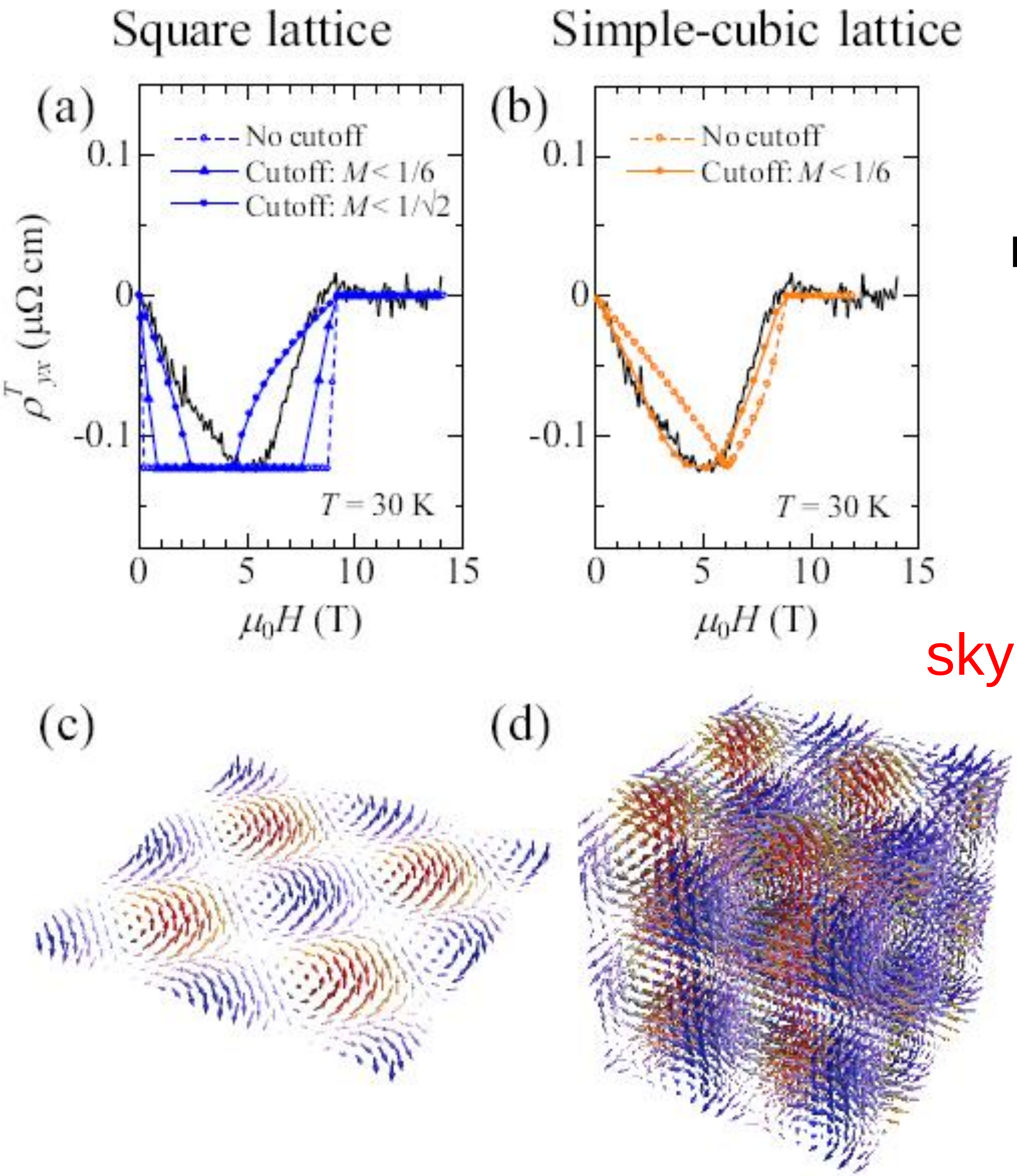
in collaboration
with Keimer group



q’s//<100>

Evidence for multiple-q structure even at B=0

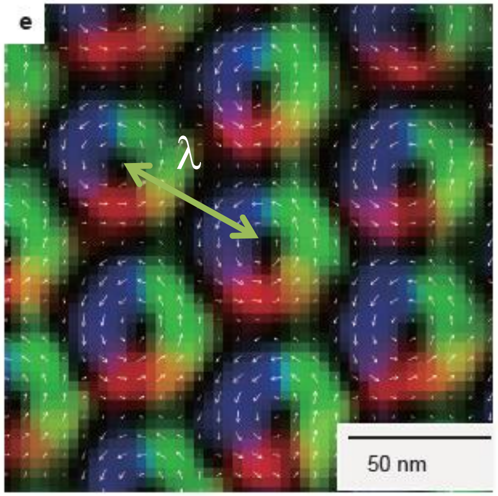
Possible 2D (meron) or 3D (hedgehog) Skyrmion Xtal at B=0



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

skyrmion-antiskyrmion

Fictitiuous magnetic flux



one flux quantum/(nm)^2~4000T !
(double-excahnge model)

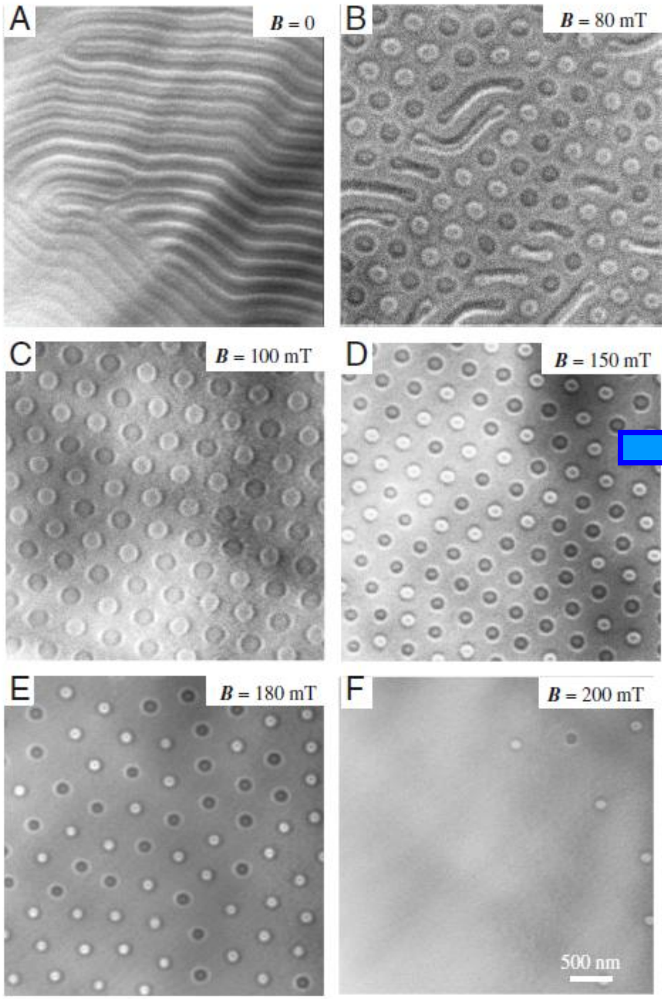
$\Delta\rho_{yx} \propto \Phi$ (Sk density)

	λ(magnetic) [nm]	Φ(cal.) [T]	$\Delta\rho_{yx}$(topological) [nΩcm]
FeGe	70	1	5
MnSi	18	28	5
MnGe	3.0	1100	200
$Nd_2Mo_2O_7$ (reference)	~0.5	~40000	6000

Pendulum like syrmions in ubiquitous magnet: M-type ferrite

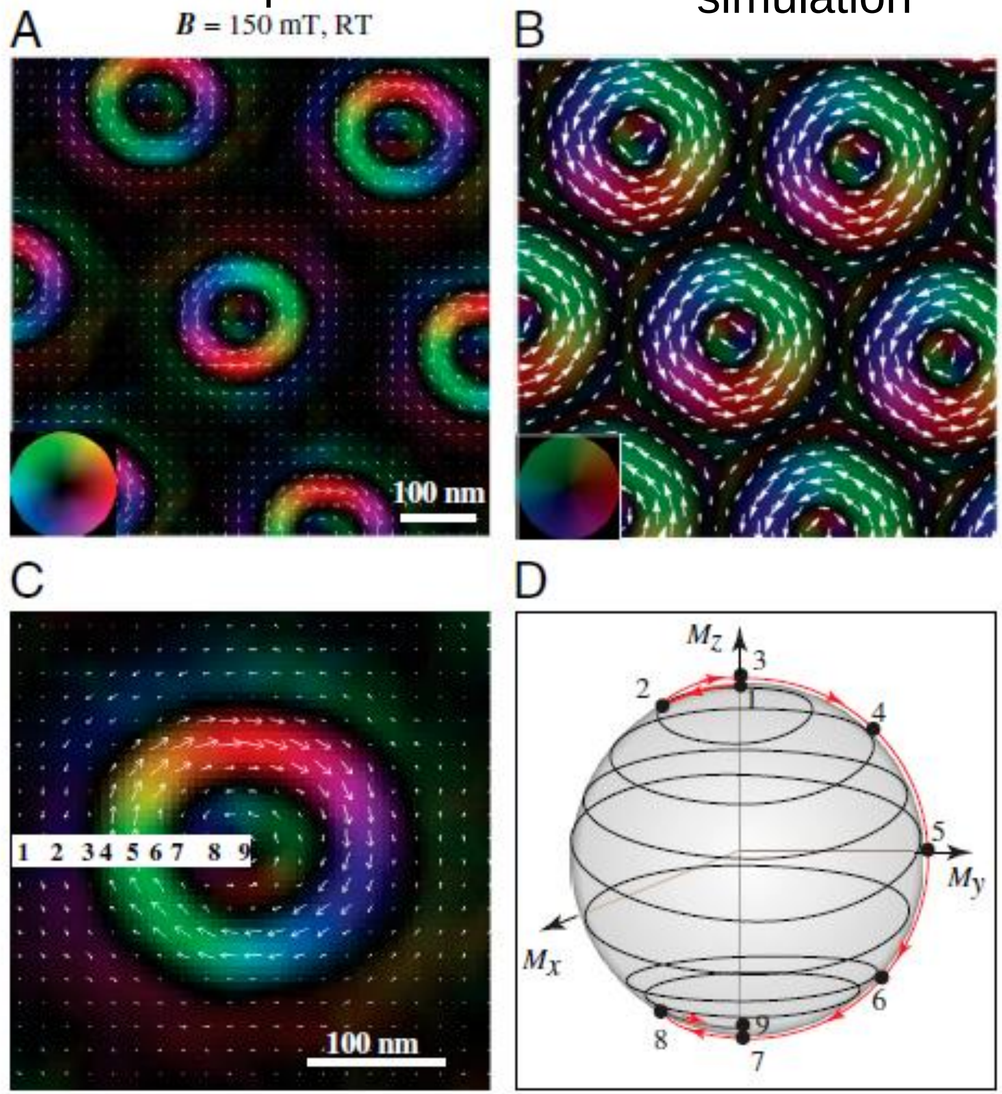
Yu et al. PNAS (2012)

Room temperature



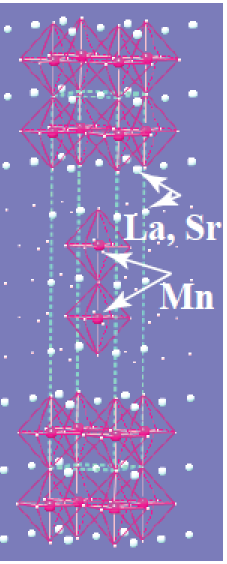
experiment

simulation



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

Biskyrmions in layered manganites



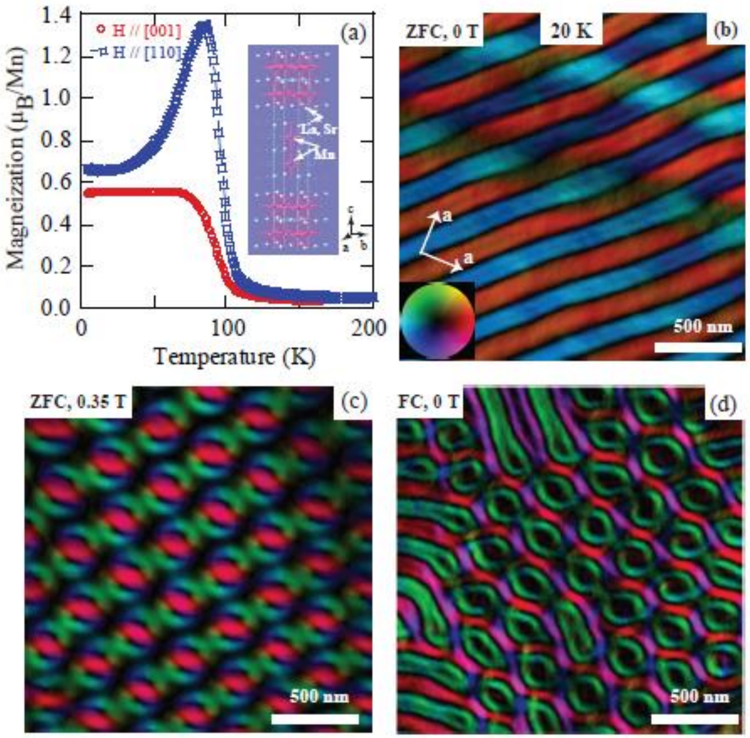
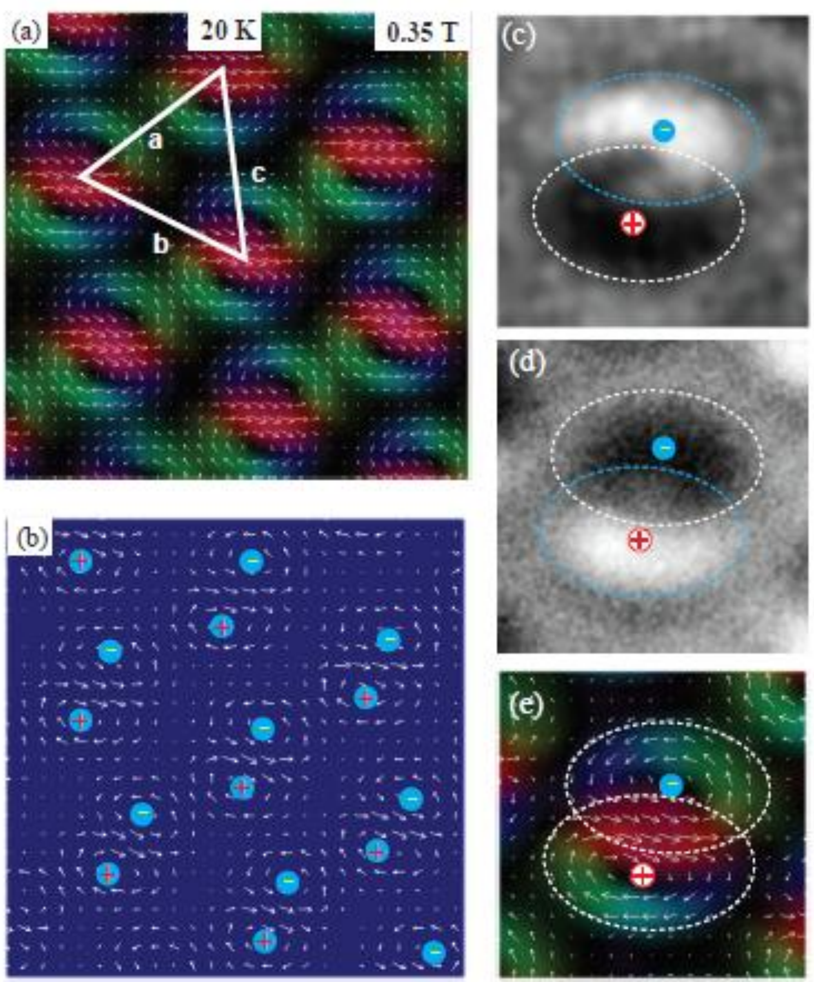
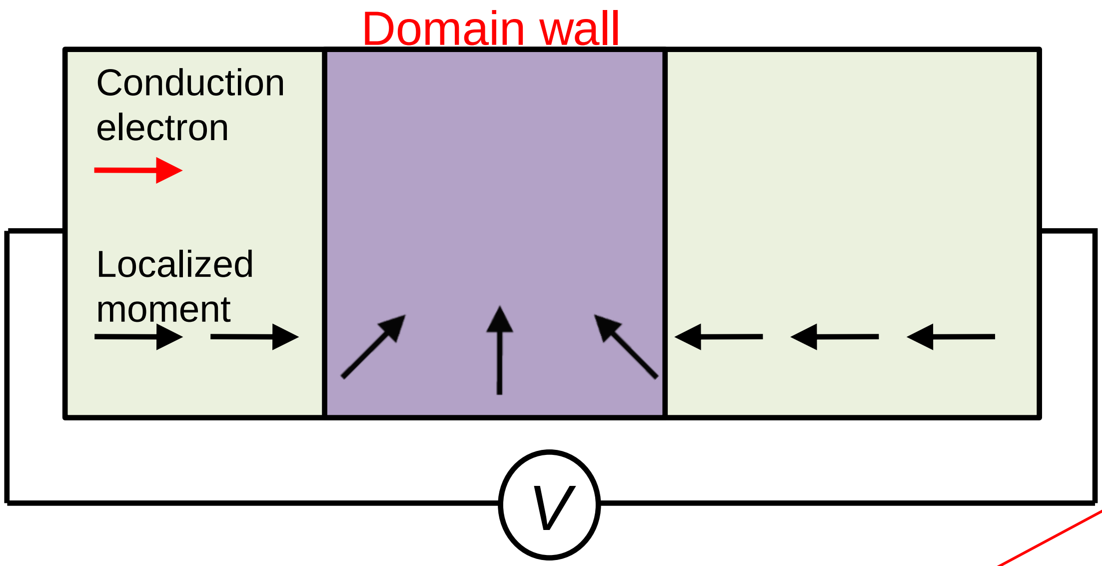


FIG. 1

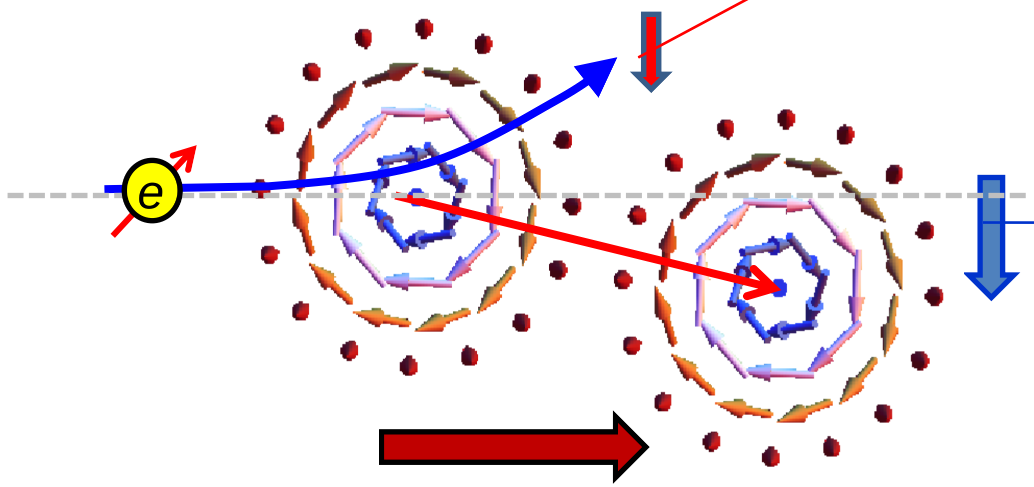


Current drive of skyrmions and emergent EM field

Domain wall motion by spin transfer torque



Skyrmion motion by spin transfer torque



Topological Hall effect
Emergent magnetic field
h

-Emergent electric field

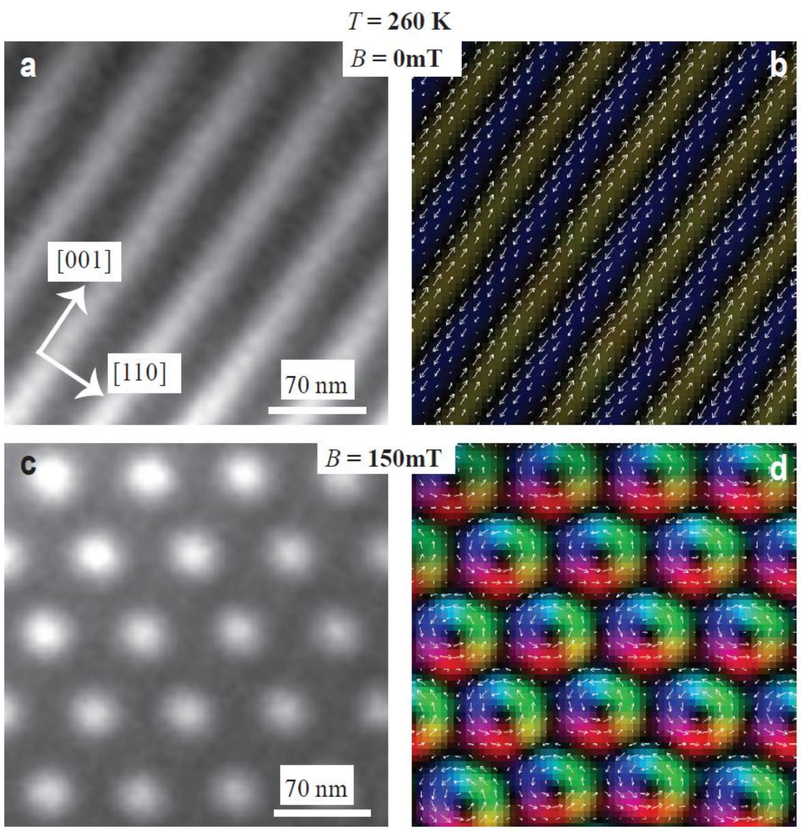
$$\mathbf{e} = -\frac{1}{c}\left[\mathbf{V}_{\parallel} \times \mathbf{h}\right]$$

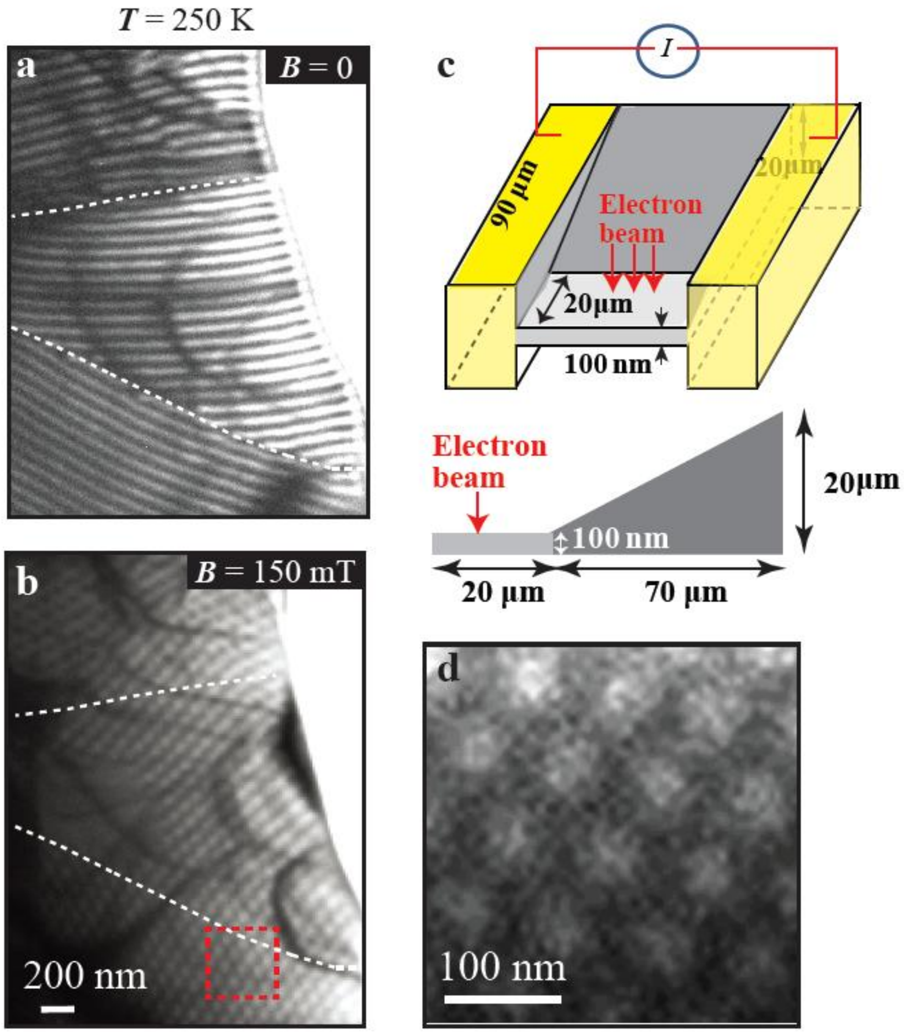
→ appears as reduction of topological Hall effect

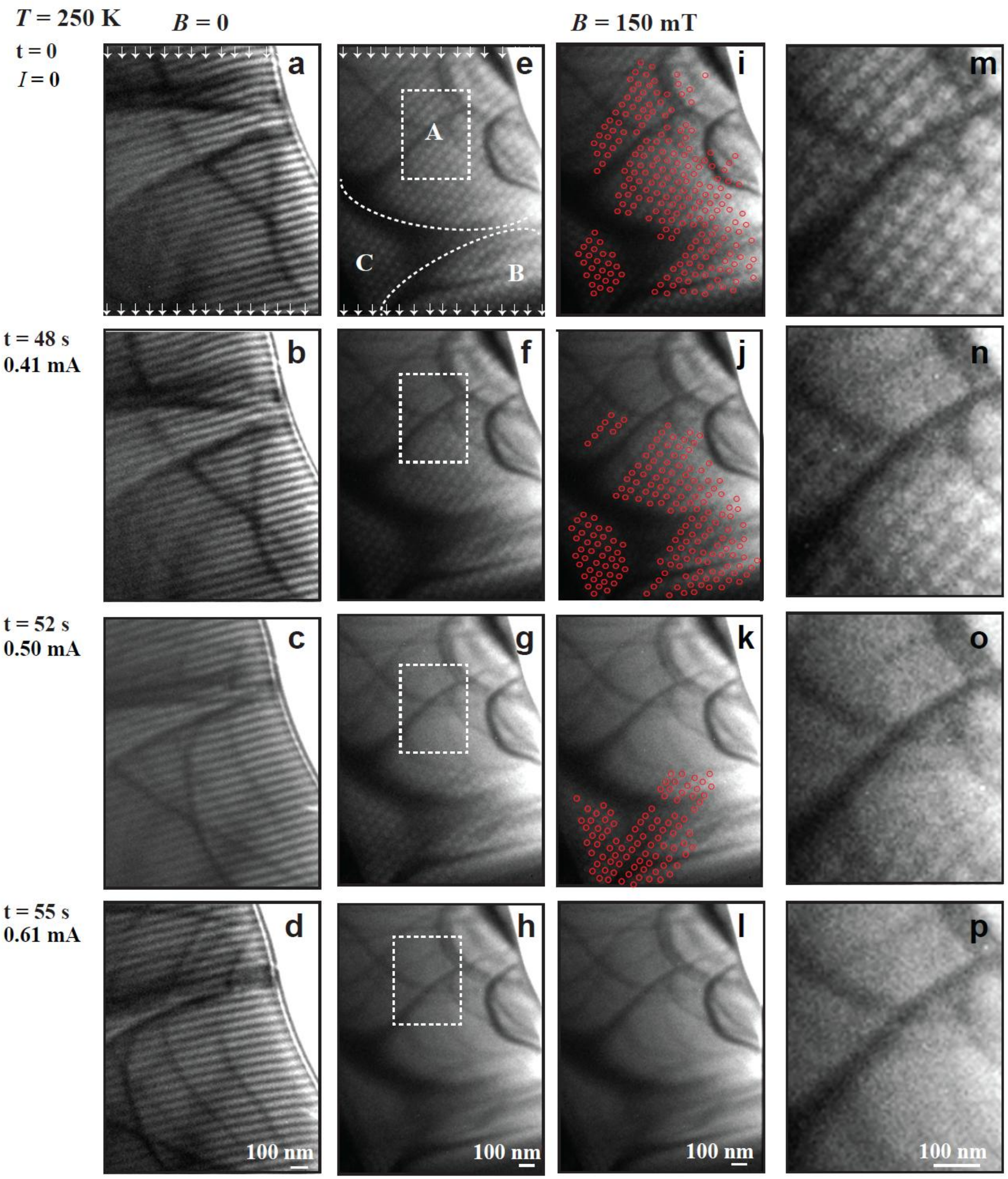
-counteraction of topological Hall effect (THE)

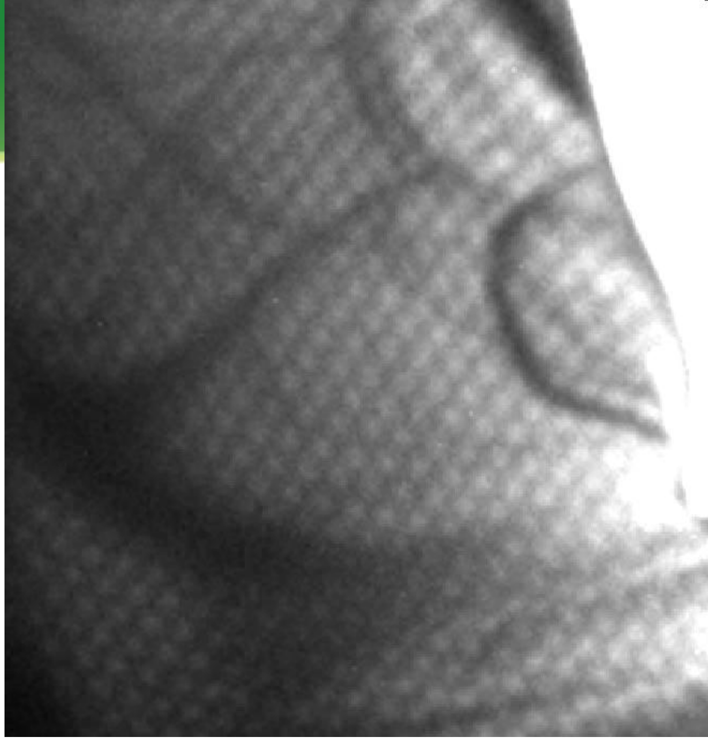
→ skyrmion Hall effect

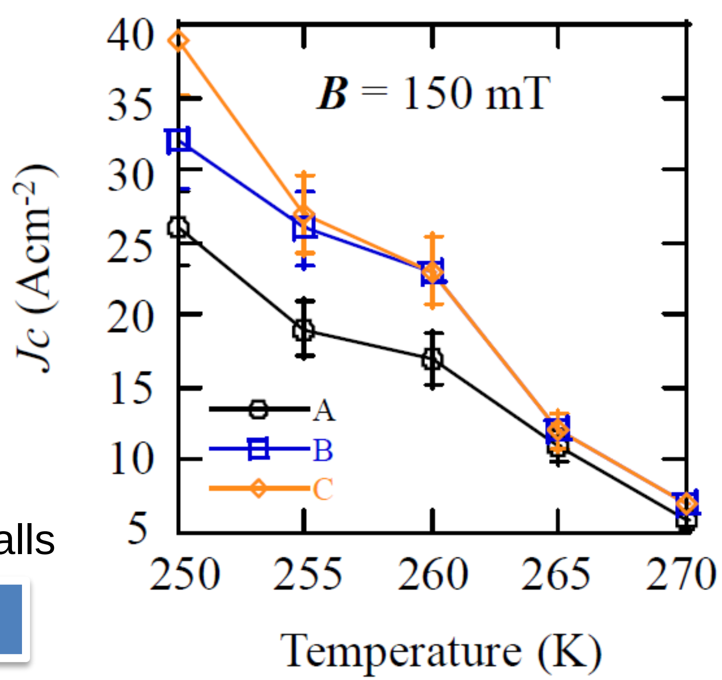
Current driven skyrmion flow in FeGe film











J_c<100A/cm^2

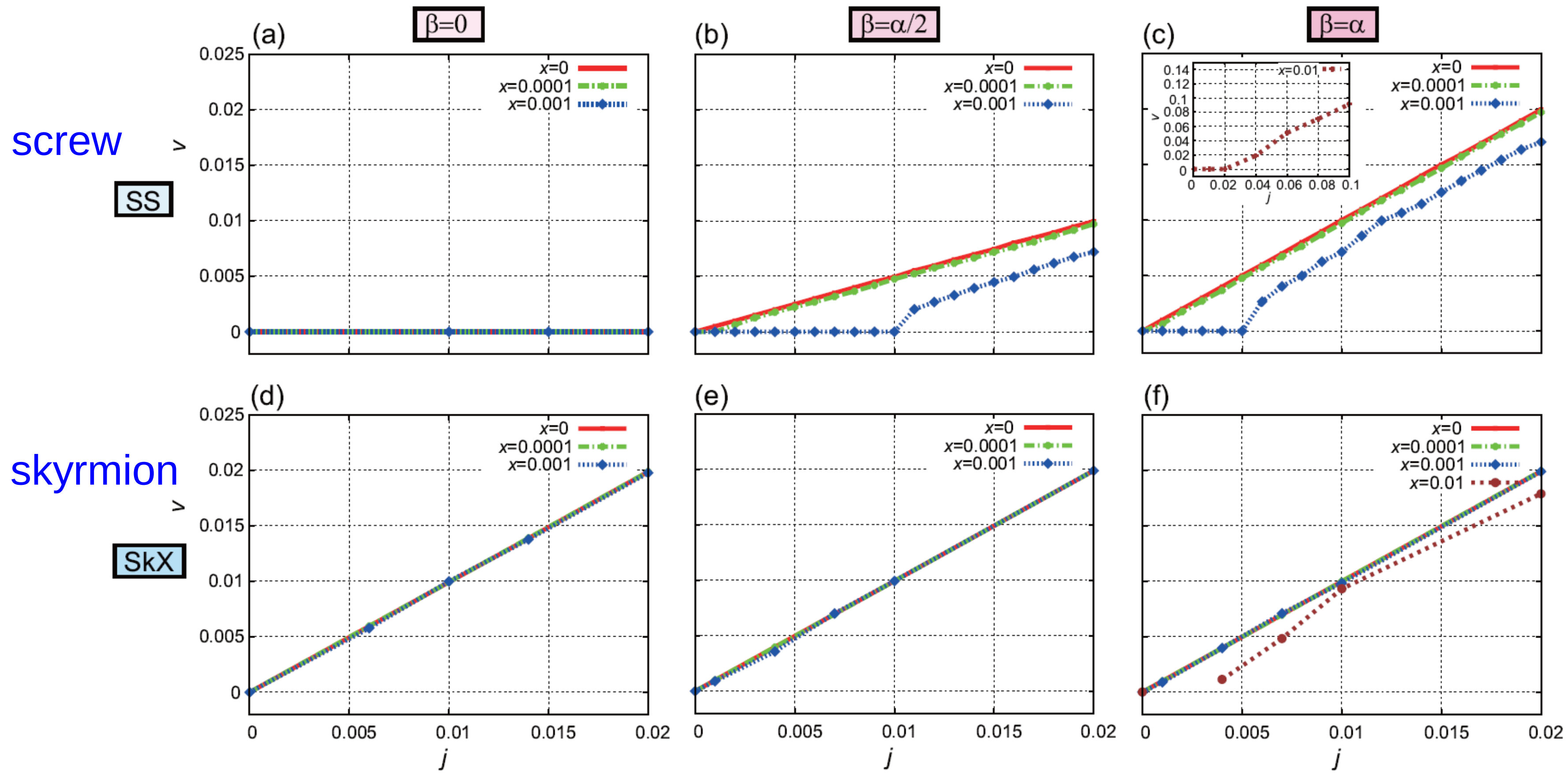
J_c~10^{7}A/cm^2 for ordinary domain walls

no intrinsic / minimal extrinsic pinning effect on SkX

No pinning effect on skyrmion motion

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

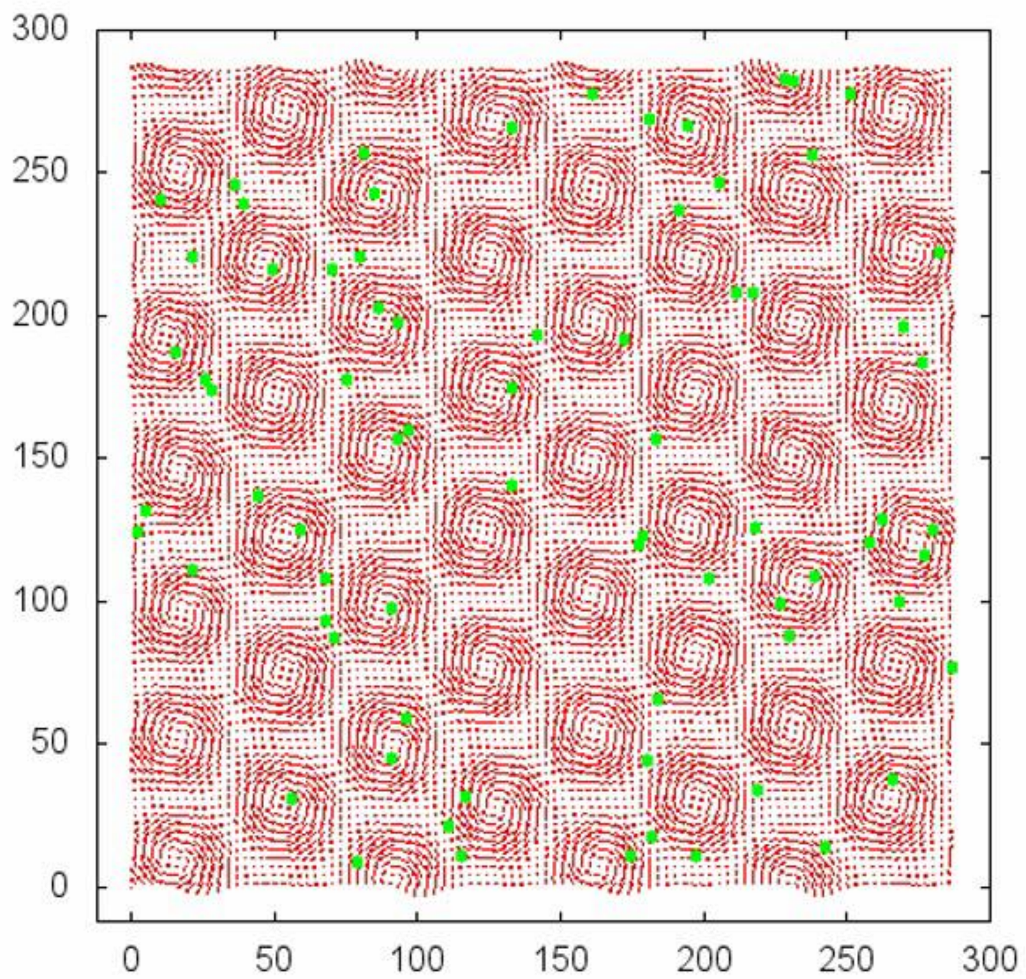
Iwasaki-Mochizuki-Nagaosa (2012)



no (minimal) pinning effect on SkX

Simulation of current-driven skrymions under pinning sites

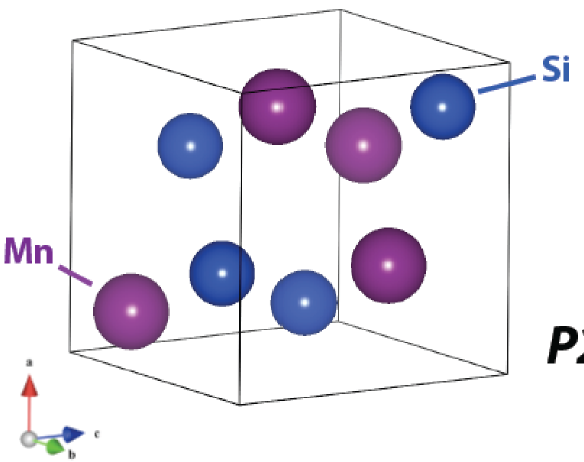
Iwasaki-Mochizuki-Nagoasa



No intrinsic pinning of skyrmions!

Cu_2OSeO_3 : Chiral Magnetic Insulator

MnSi



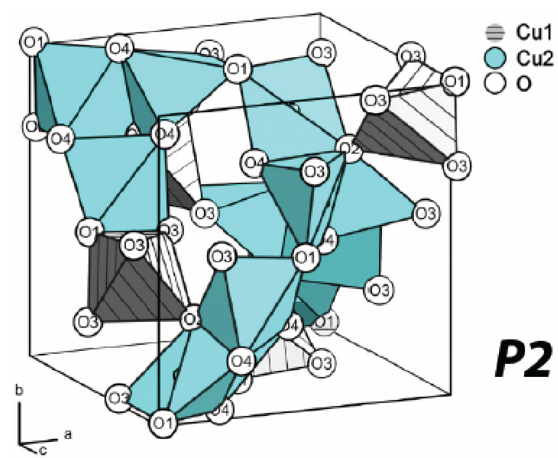
$P2_13$

Metal

Transport Properties

- Topological Hall Effect

Cu_2OSeO_3



$P2_13$

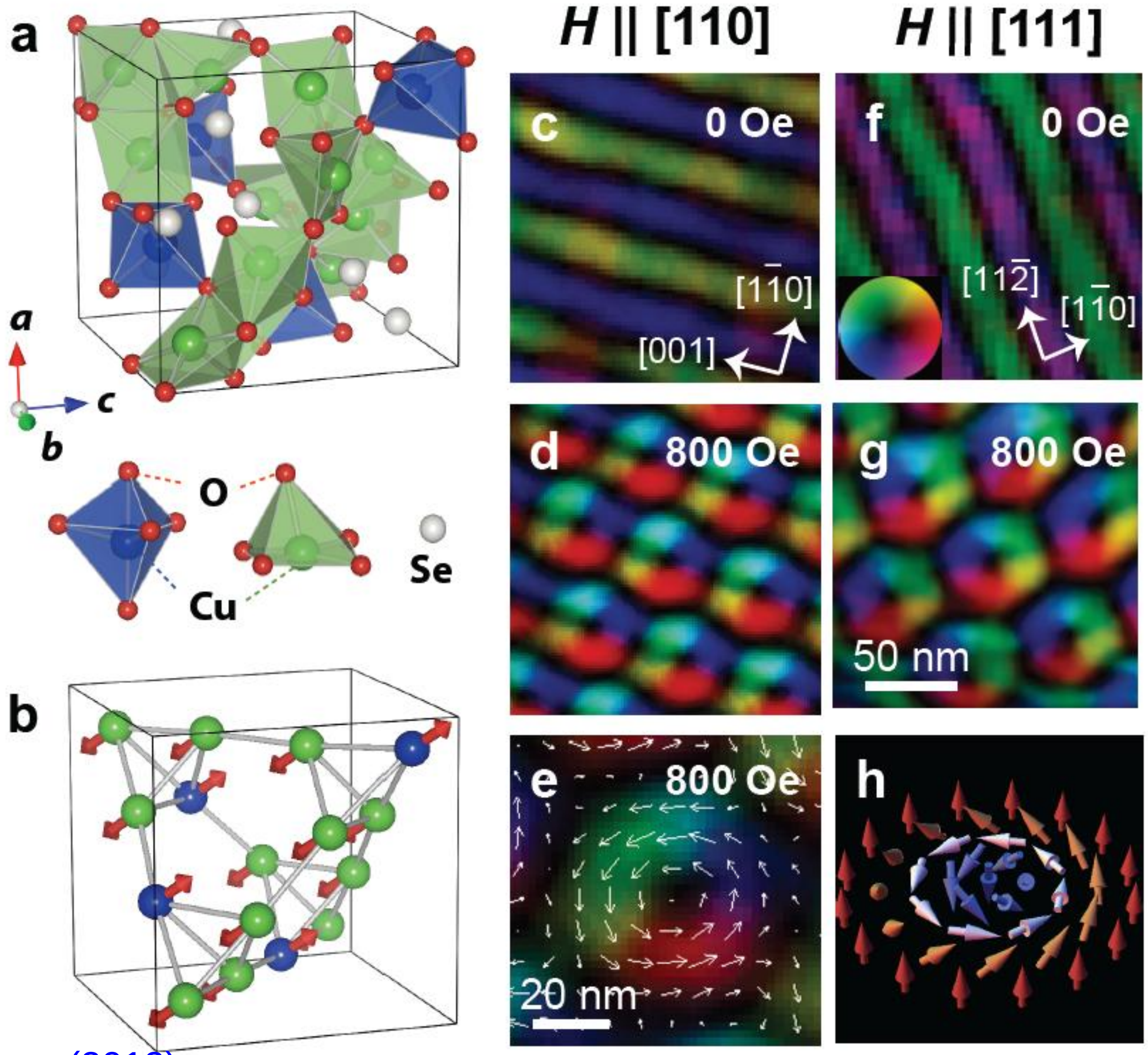
Insulator

Dielectric & Optical Properties

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

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

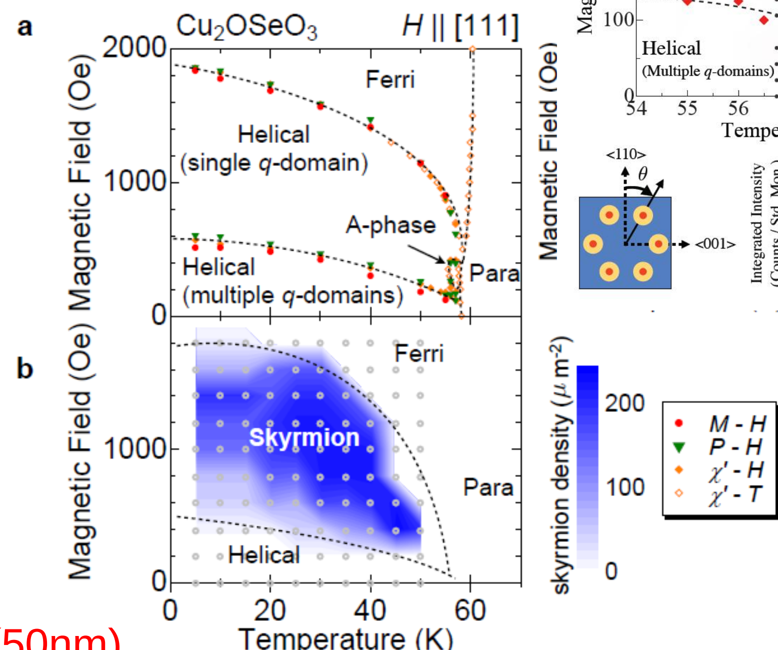
Lorentz TEM observation of thin flake of Cu_2OSeO_3

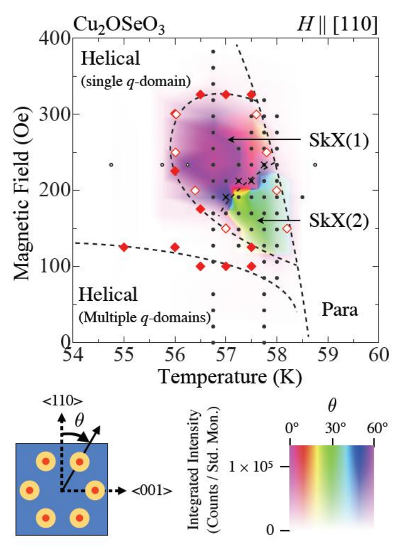


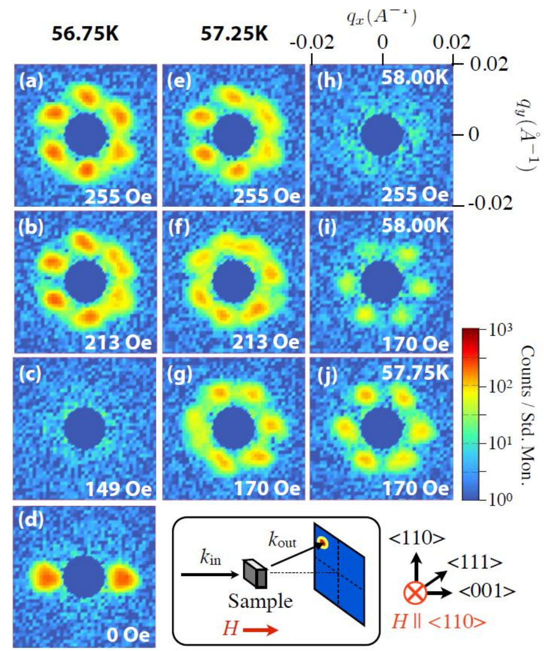
Seki et al. Science (2012)

Skyrmion crystal phase: bulk vs. thin film

bulk



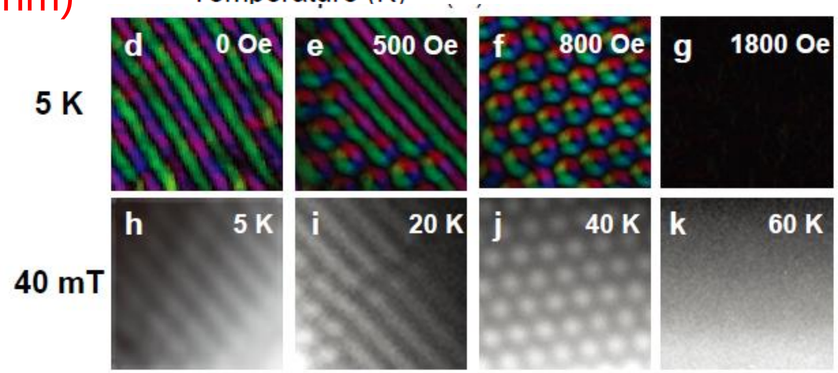




Seki et al. PRB (RC), 85, 220406(2012).

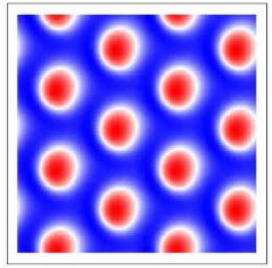
See also Adams et al. PRL, 108, 237204 (2012).

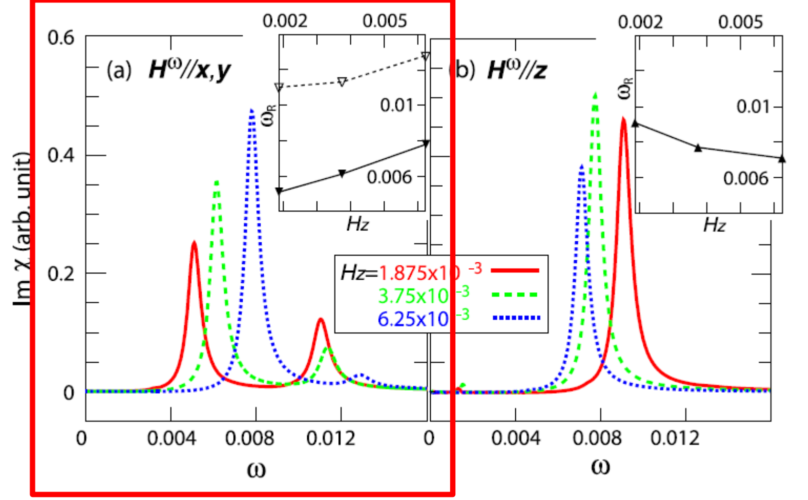
film (50nm)



H//x,y on skyrmions

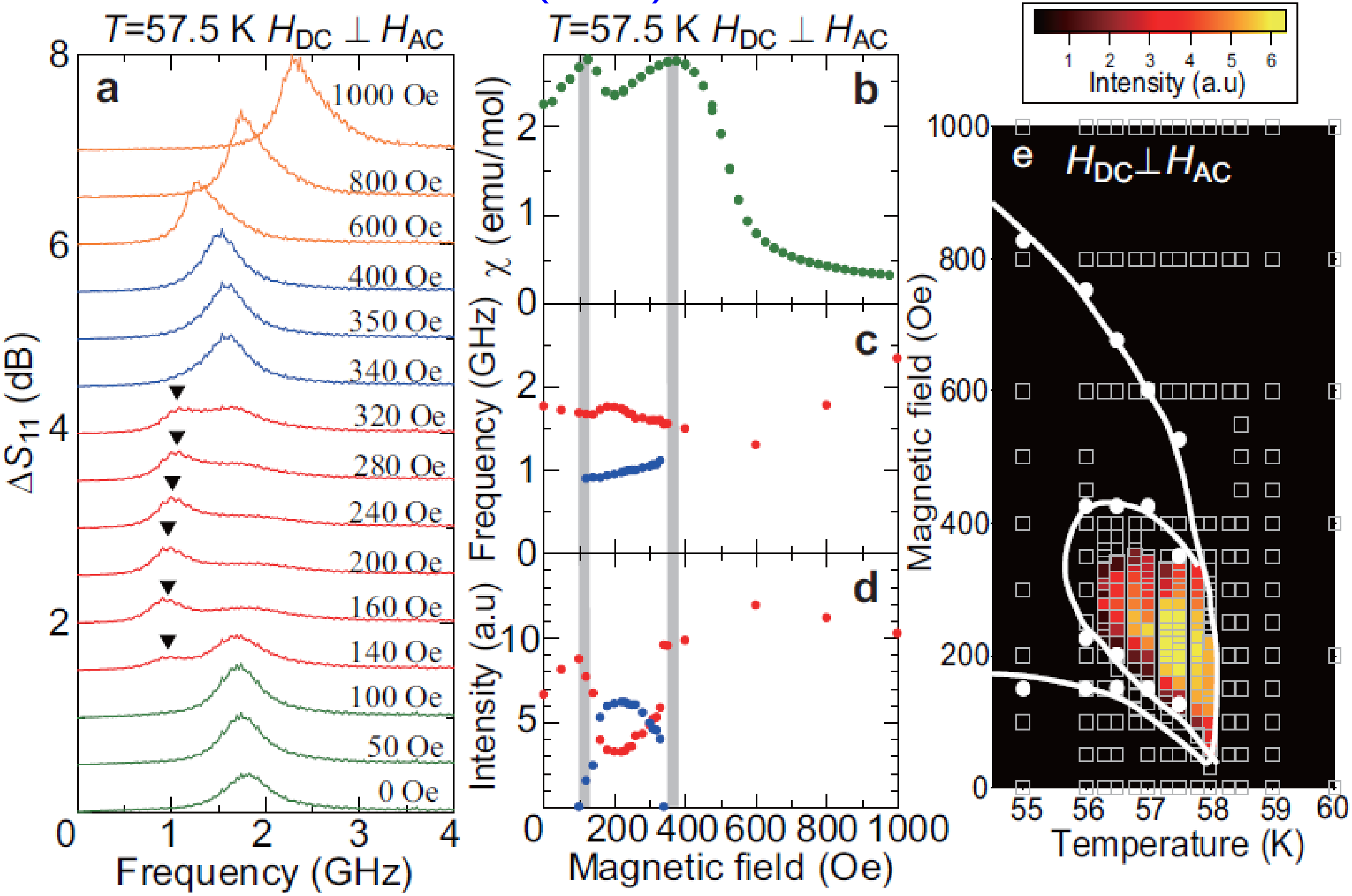
$H^{\omega}//xy$

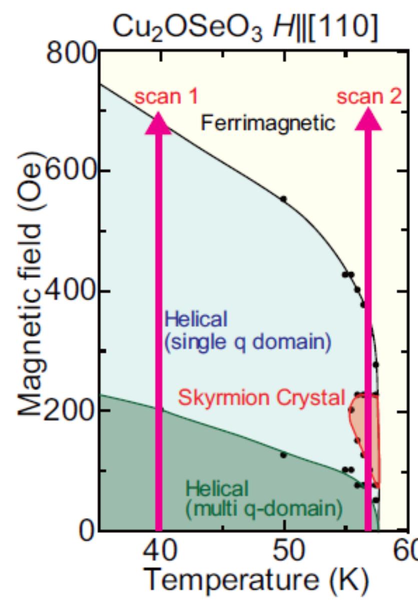




Mochizuki PRL (2012)

Onose et al. PRL (2012)

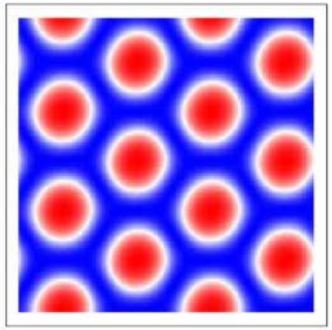


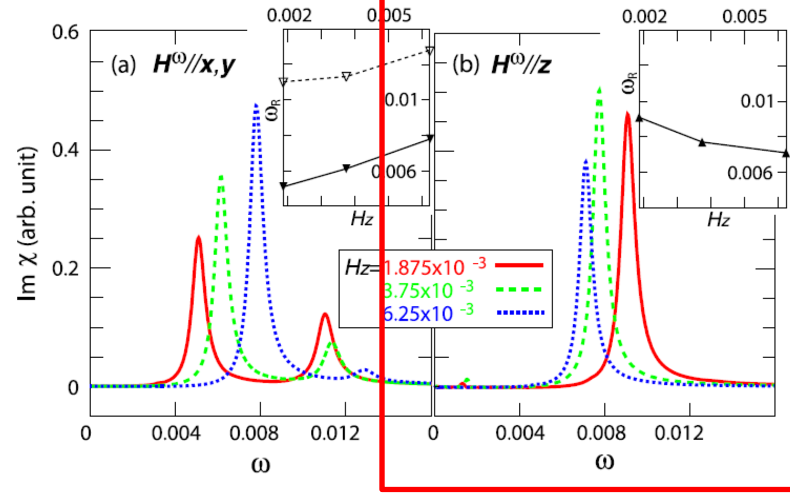


H//z

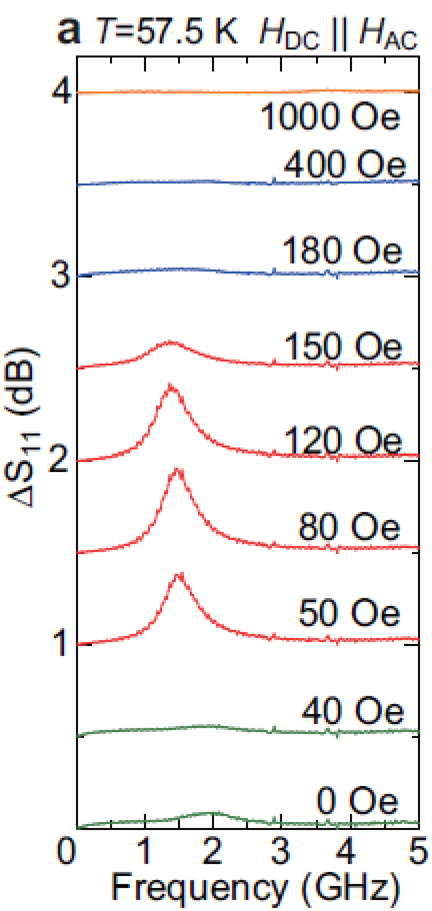
Onose et a

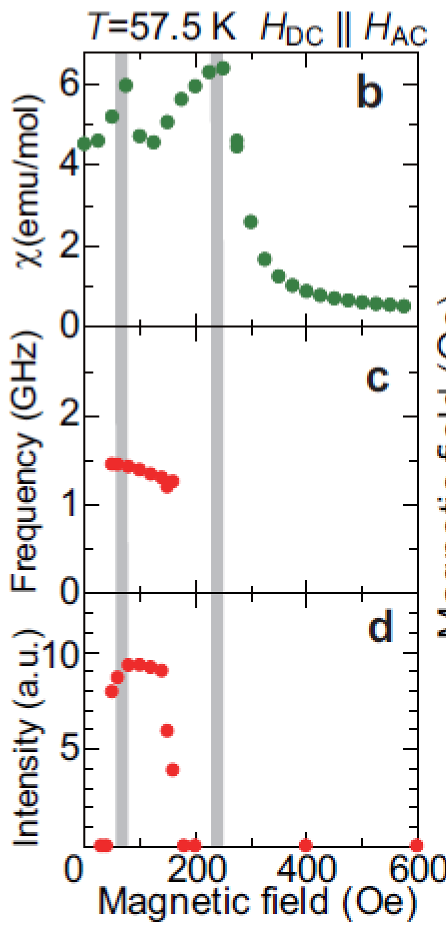
$H^{\omega}//c$

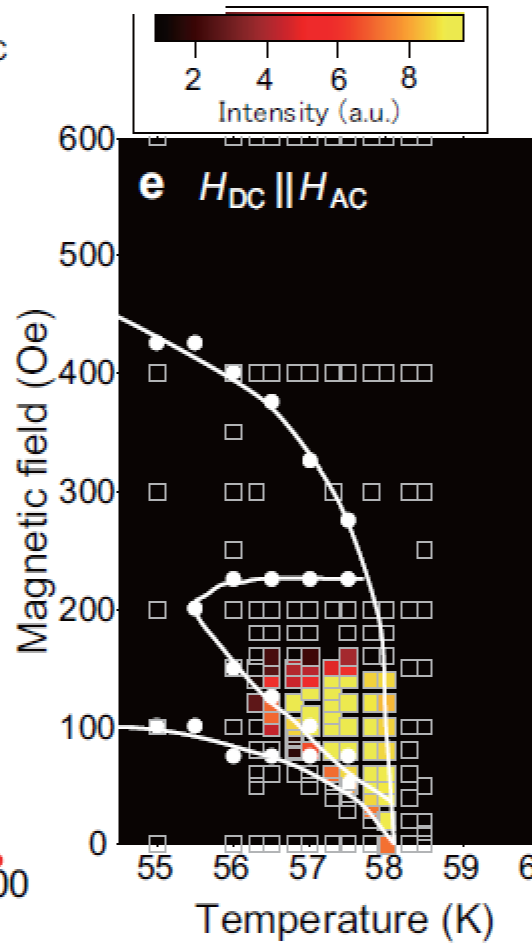


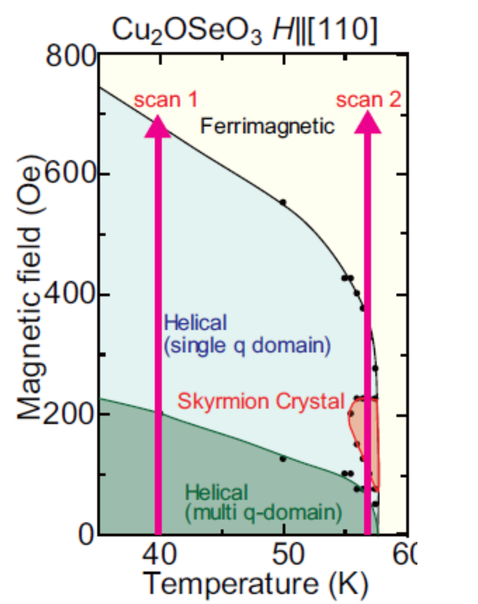


Mochizuki PRL (2012)

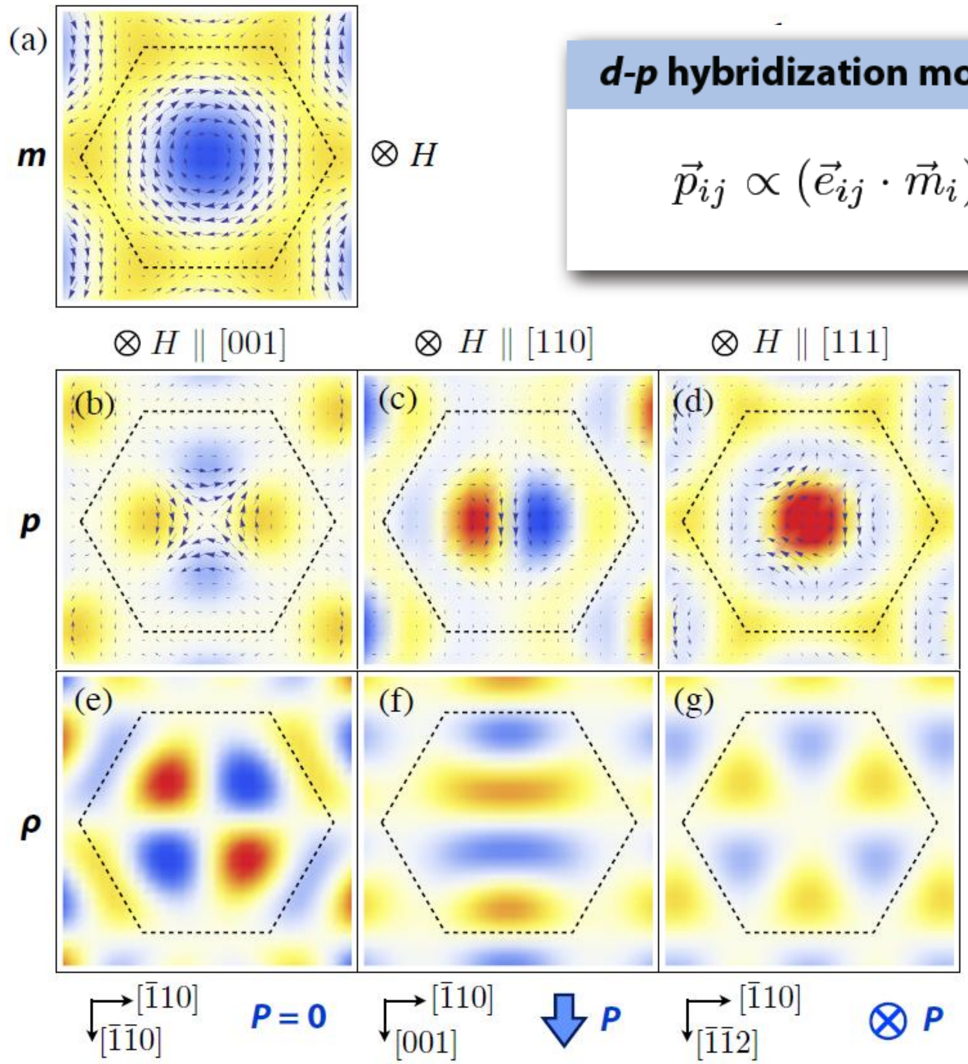






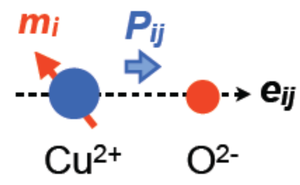


Cu_2OSeO_3: *P* and ρ distributions in skyrmion



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

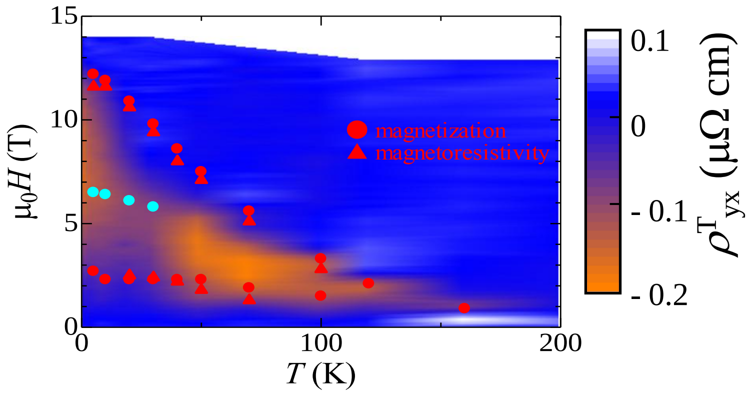
dipole

Seki et al. PRB (2012)

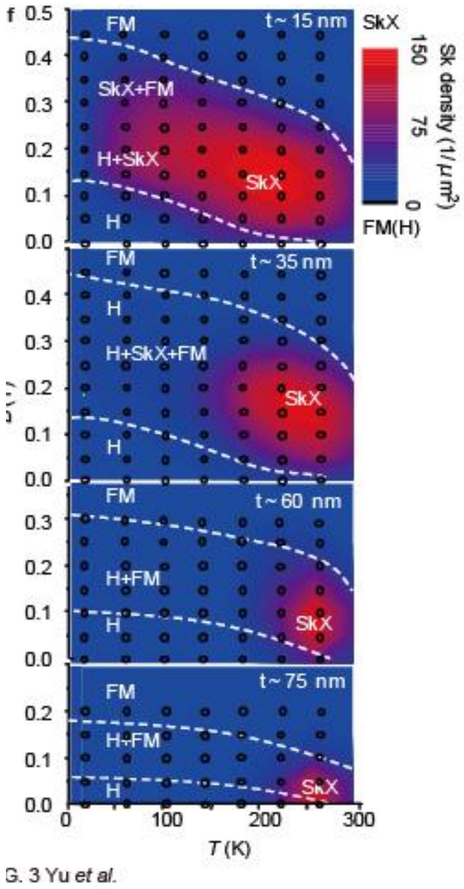
Toward skyrmionics

Skyrmions as stabilized in a thin film form

Emergent EM fields hosted by skyrmions



MnGe
3D Skyrmion crystals
at zero field



Skyrmion transport and dynamics

- Ultra-low current driven skyrmion motion (~10A/cm^2)
- Skyrmions in insulators/multiferroics toward E- control
- Ratchet motion of skyrmions in thermal equlibrium
- Electric generation and operation of skyrmions