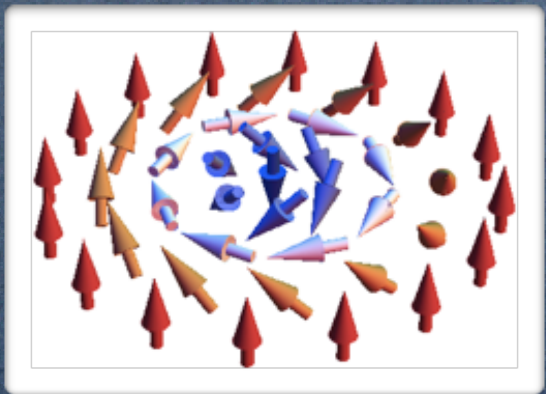
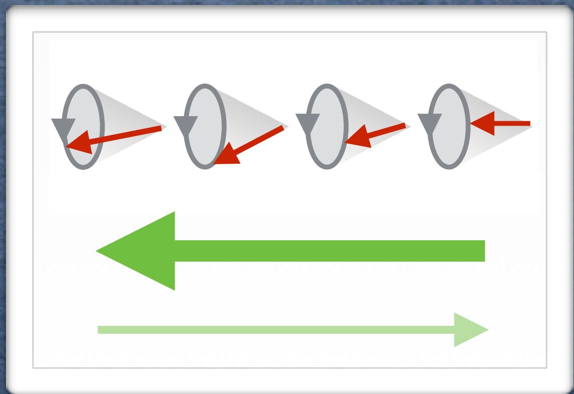
Chirality and Ferromagnetism

Shinichiro Seki

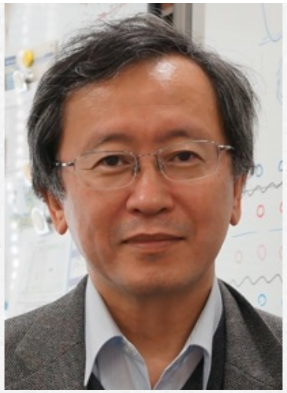
RIKEN, Center for Emergent Matter Science (CEMS), Japan
PRESTO, Japan Science and Technology Agency (JST)





Collaborators

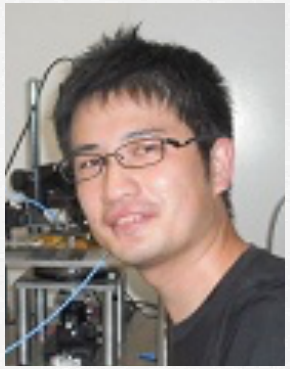
RIKEN CEMS



Y. Tokura

R. Takagi

X. Z. Yu



K. Kondou

Y. Otani, G. Tatara, N. Ogawa, F. Kagawa,
N. Nagaosa, M. Kawasaki, T. Arima

東京大学 THE UNIVERSITY OF TOKYO

N. Kanazawa
K. Shibata
S. Ishiwata

Y. Okamura

AOYAMA GAKUIN

M. Mochizuki

MAX-PLANCK-GESELLSCHAFT

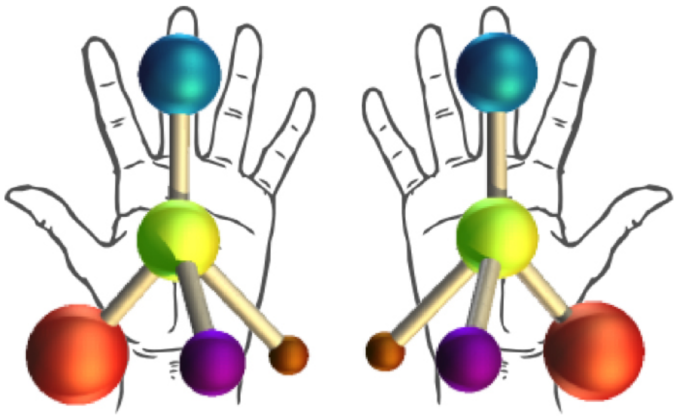
B. Keimer
J. -H. Kim
D. S. Inosov

TECHNISCHE UNIVERSITÄT MÜNCHEN

R. Georgii

Today's Topic

What happens from interplay between chiral-lattice and ferromagnetism in **insulating** system ?

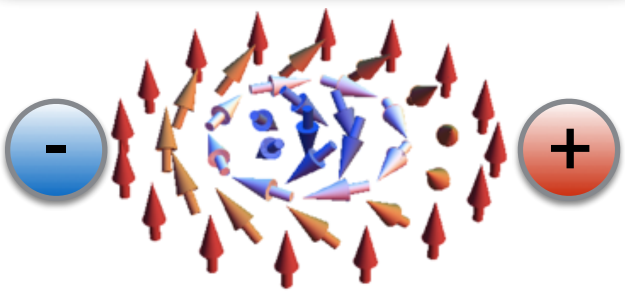


+

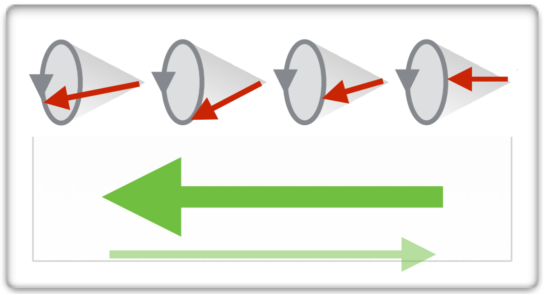
Chirality

Ferromagnetism

Multiferroic Skyrmions

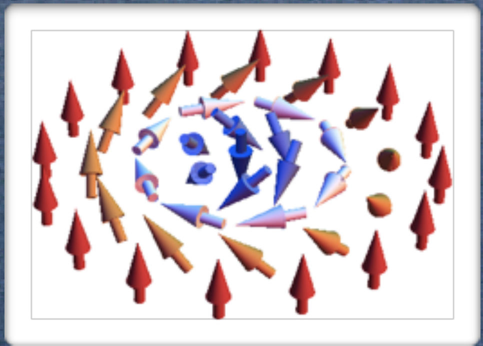


Spin-wave Diode

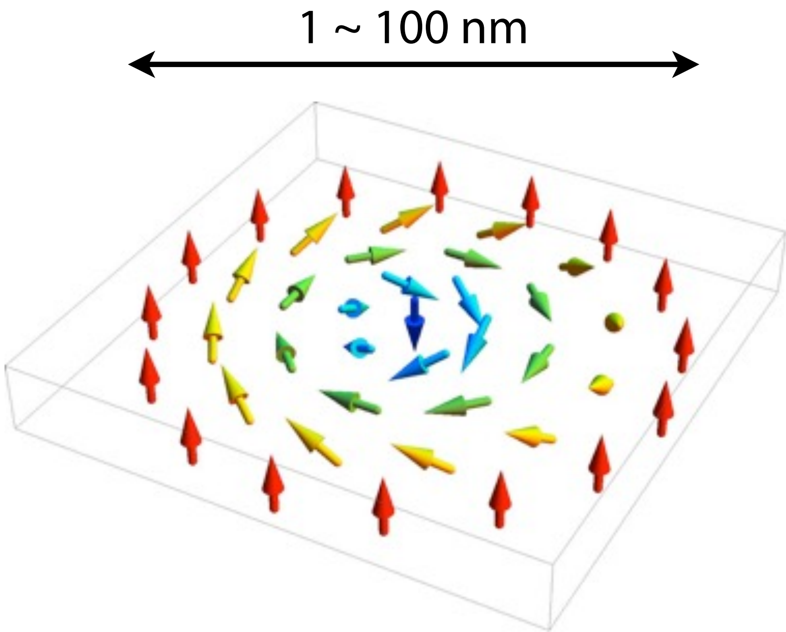


Outline

1. Multiferroic Skyrmions
2. Spin-wave Diode
3. Summary & Perspective



What is magnetic skyrmion?



Topologically-stable **spin vortex**
with **particle-like** nature

“skyrmion number”

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

Particle nature + Nanometric scale
= New information carrier for memory device?

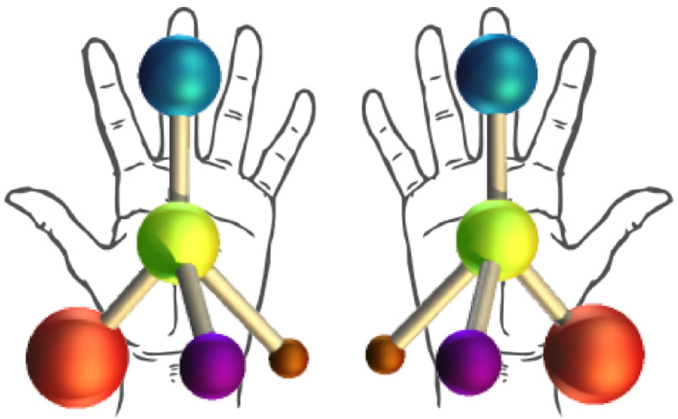
cf. Racetrack memory, bubble memory etc...

A. Fert, V. Cross, and J. Sampaio, Nature Nanotech. **8**, 152 (2013).

Skyrmions in Chiral Magnets

Muhlbauer *et al.*, Science (2009).
Rossler *et al.*, Nature (2006).

left-handed　　right-handed



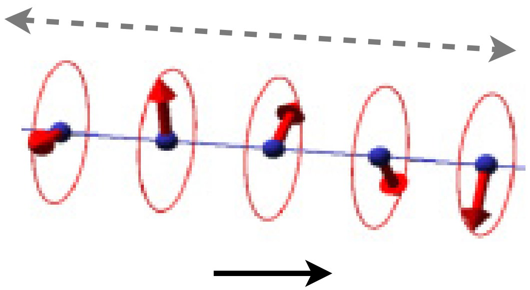
$$\mathcal{H} = \sum_{i,j} \underline{J\vec{S}_i \cdot \vec{S}_j} + \sum_{i,j} \underline{\vec{D} \cdot (\vec{S}_i \times \vec{S}_j)} + \alpha$$

Ferromagnetic Exchange

Dyakishinskii-Moriya(D-M) Interaction

Helical (ground state)

modulation period : *J/D*



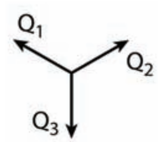
single *q*

$$\mathbf{M}^h_{\mathbf{Q}_i}(\mathbf{r}) = A[\mathbf{n}_{i1}\cos(\mathbf{Q}_i\mathbf{r}) + \mathbf{n}_{i2}\sin(\mathbf{Q}_i)\mathbf{r}]$$

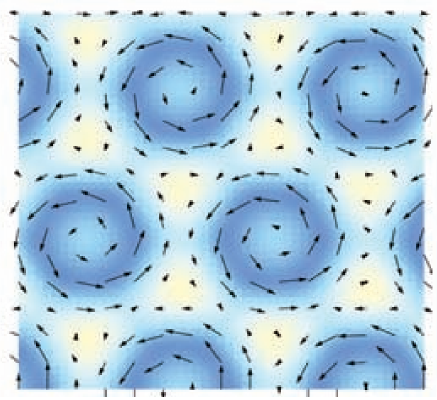
Thermal Fluctuation
+
Magnetic Field

Skyrmion Crystal

triple *q*



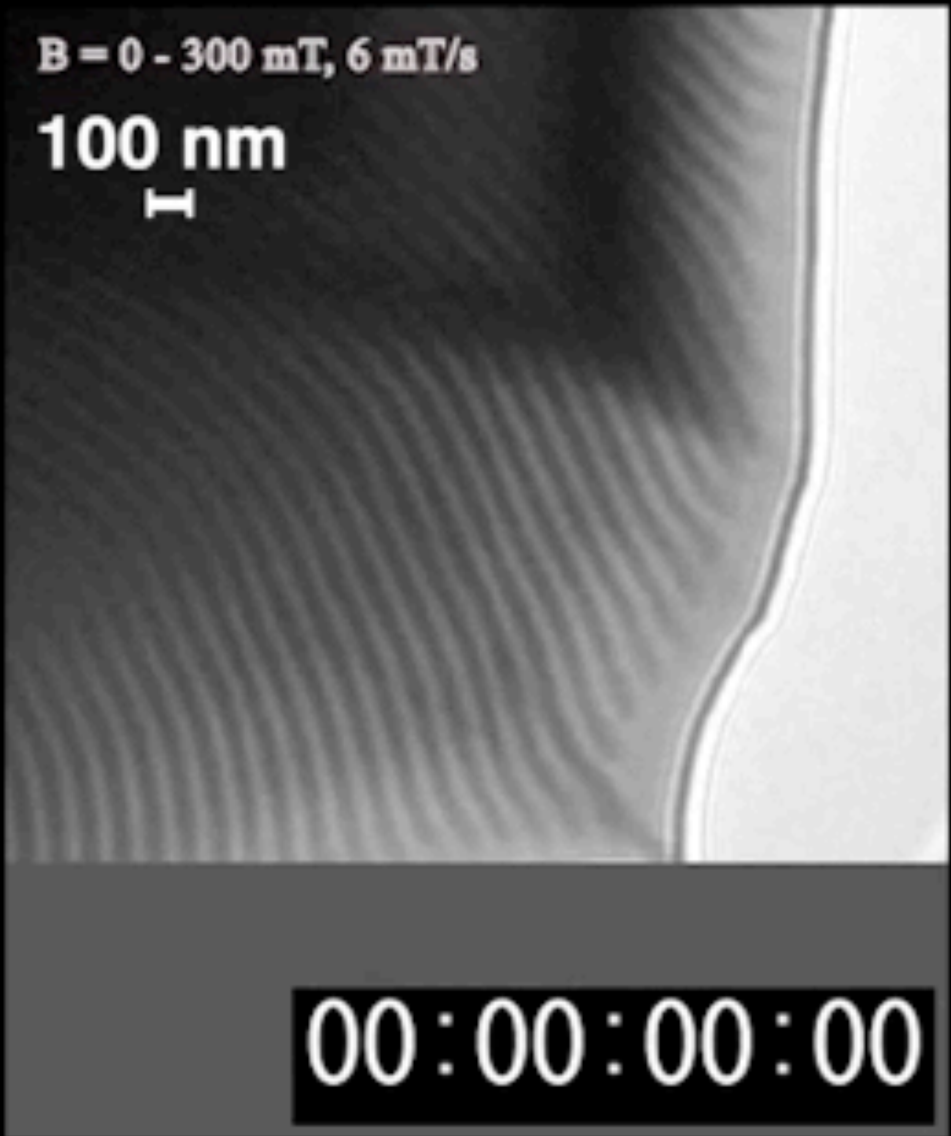
◉ *H*

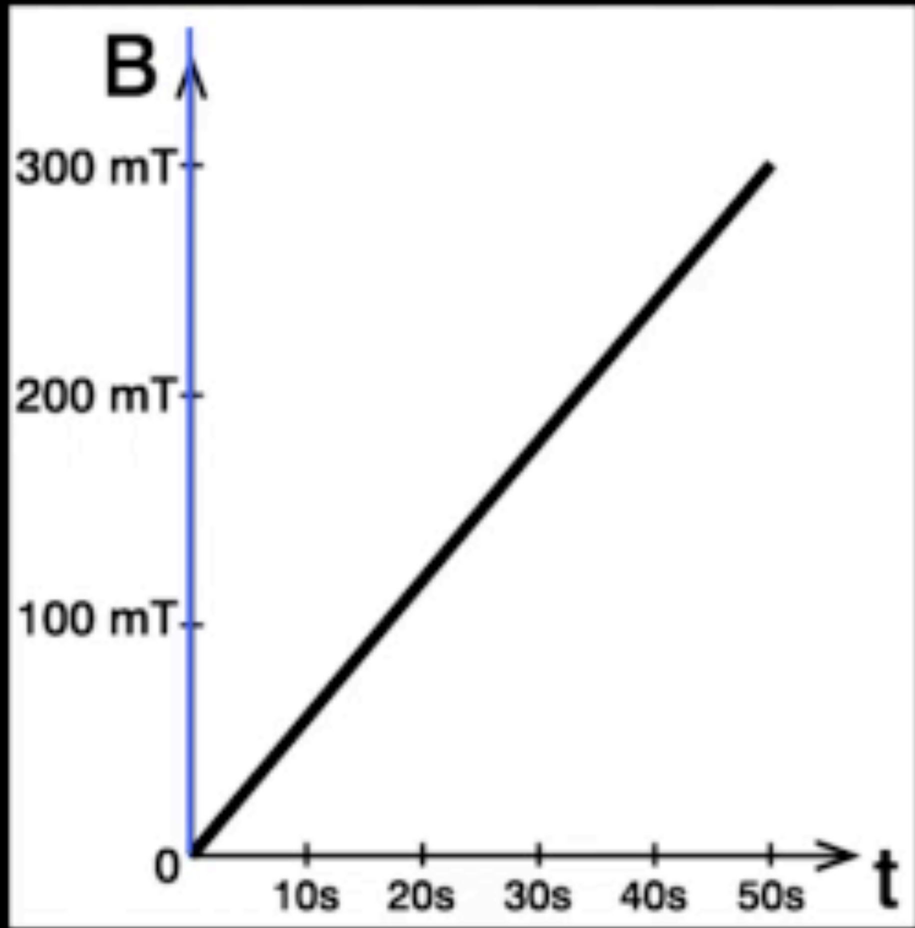


$$\mathbf{M}(r) \approx \mathbf{M}_f + \sum_{i=1}^{3} \mathbf{M}^h_{\mathbf{Q}_i}(\mathbf{r} + \Delta\mathbf{r}_i)$$

Observation of skyrmion in real-space (FeGe)

X. Z. Yu





Observation by Lorentz TEM
(magnetic field stabilizes and destabilizes skyrmions)

From Metal to Insulator…

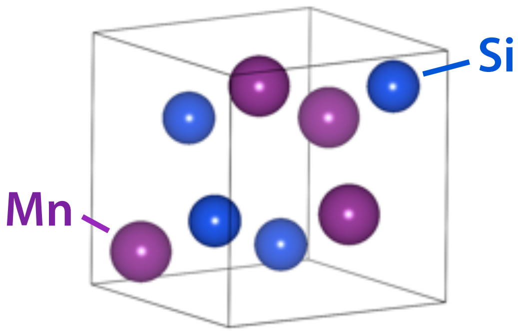
Metal (B20-Alloys)

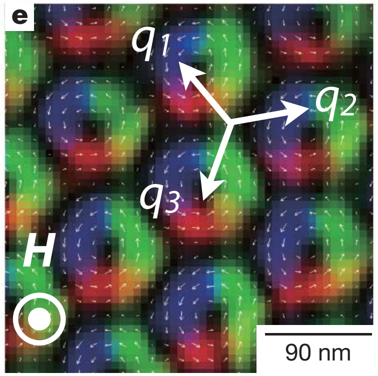
MnSi, $Fe_{1-x}Co_xSi$, FeGe etc...

Muhlbauer *et al.*, Science (2009).
Yu *et al.*, Nature (2010).

Skyrmion Lattice

- **Chiral cubic ferromagnet** (*P*2_1*3*)



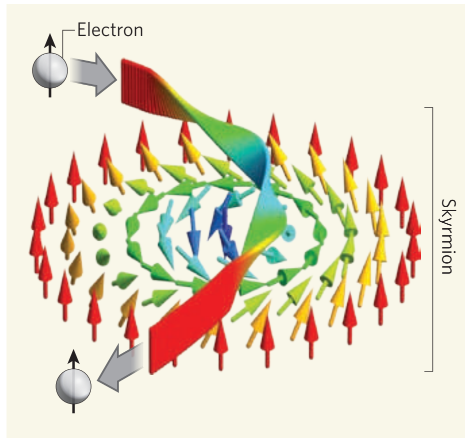


Transport Properties

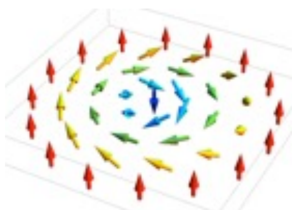
- Topological Hall Effect
- **Current-driven** control of skyrmion

Neubauer *et al.*, PRL (2009).

Jonietz *et al.*, Science (2010).



Insulator



P (?)

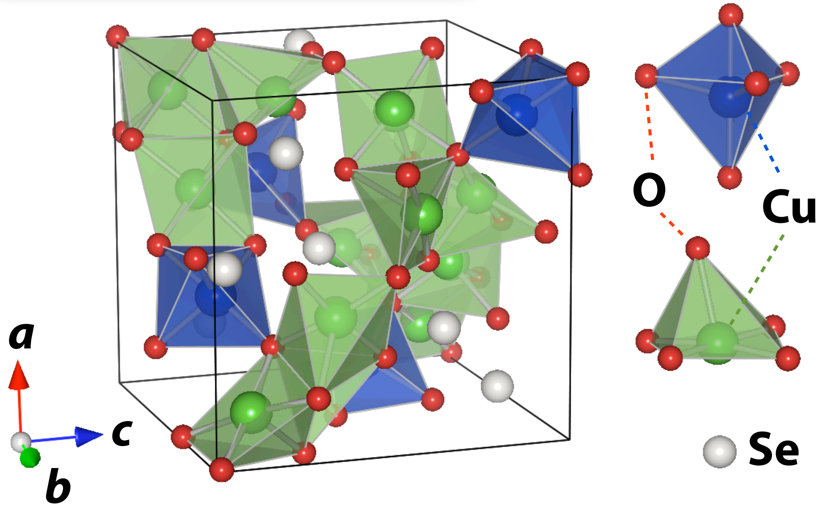
Dielectric & Optical Properties

- Multiferroic nature and magnetoelectric effects?
- Novel collective excitation?
- **Electric-field-driven** control of skyrmion?

Cu_2OSeO_3 : Chiral magnetic insulator

Crystal Structure

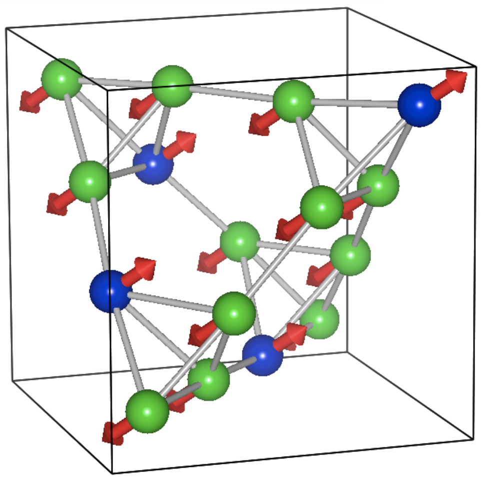
Meunier *et al.*, J. Appl. Cryst. (1976).
Effenberger *et al.*, Monatsch. Chem. (1986).



- **Chiral cubic lattice (*P*2_1*3* : same as B20-alloys)**
- Two distinctive Cu^{2+} ($S = 1/2$) sites

Spin Structure

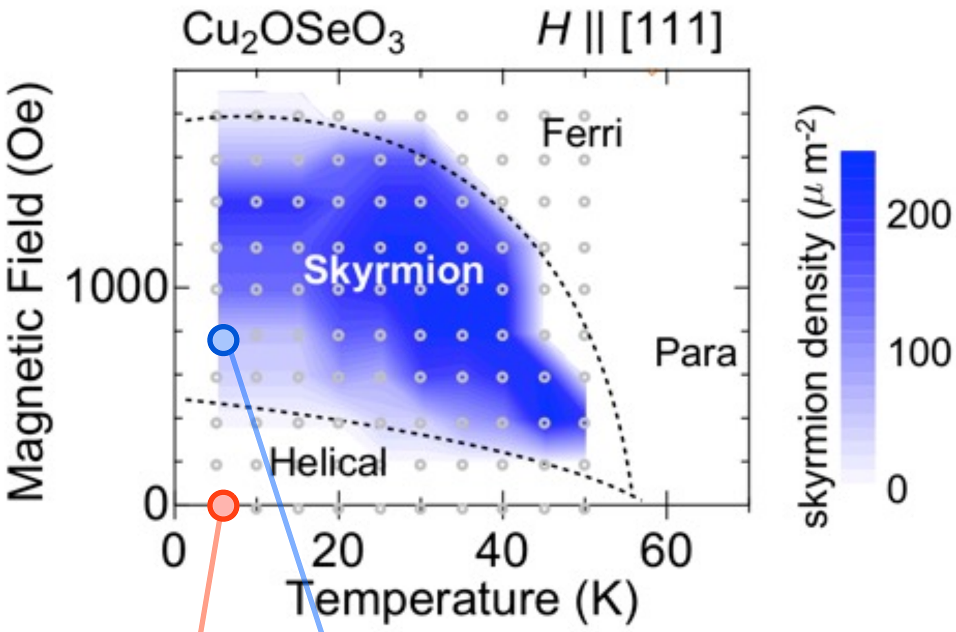
Kohn *et al.* J. Phys. Soc. Jpn. (1977).
Bos *et al.*, Phys. Rev. B (2008).



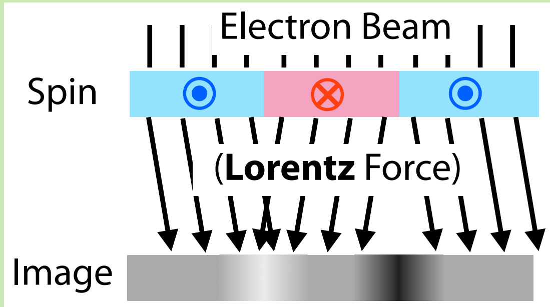
- **Ferrimagnetic** order (3-up, 1-down) below 58K
  (reported from powder neutron diffraction)
- D-M interaction may cause helimagnetism **(?)**

Cu_2OSeO_3 : Lorentz TEM (Thin Film)

S. Seki *et al.*, Science **336**, 198 (2012).

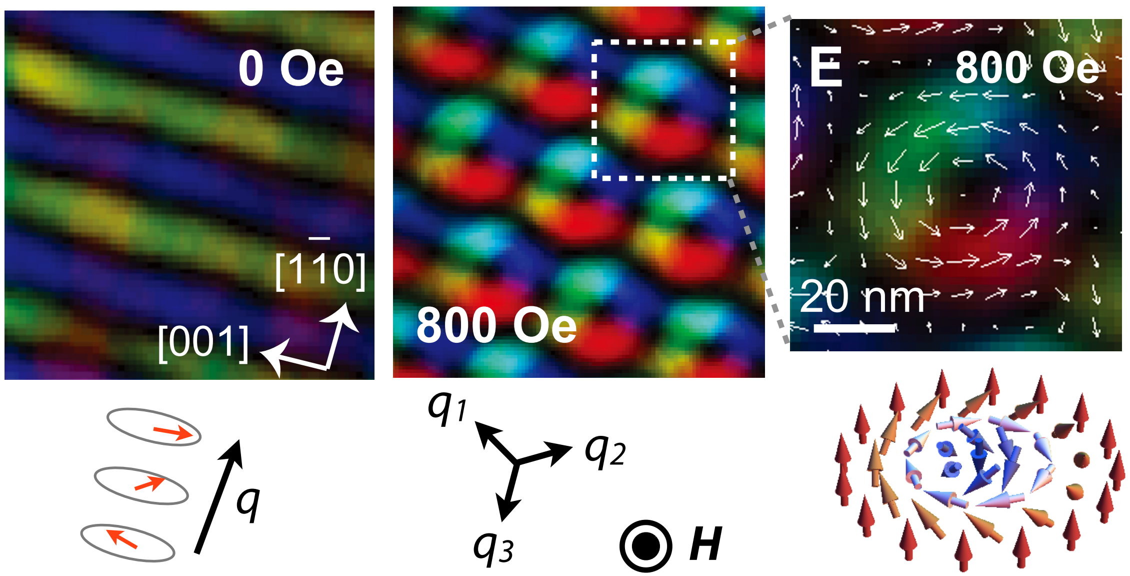


In-plane component of local magnetization can be detected



(@5 K)

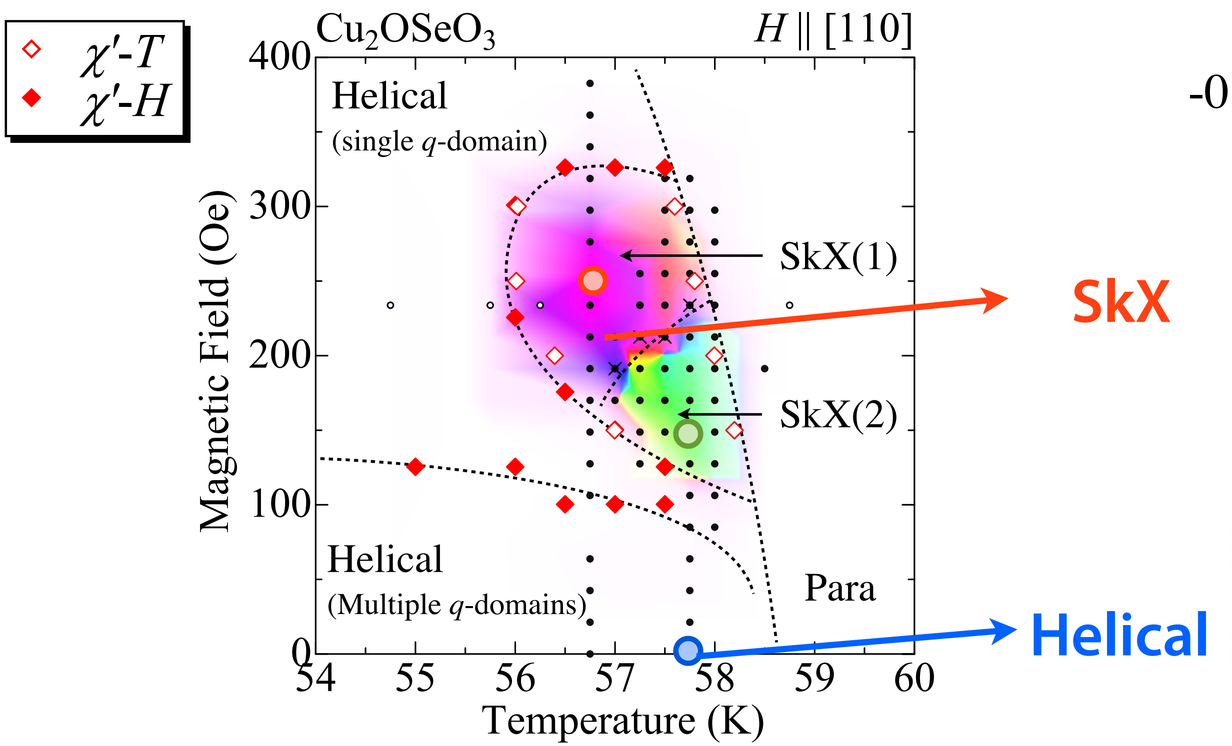
(Sample thickness : ~100 nm)

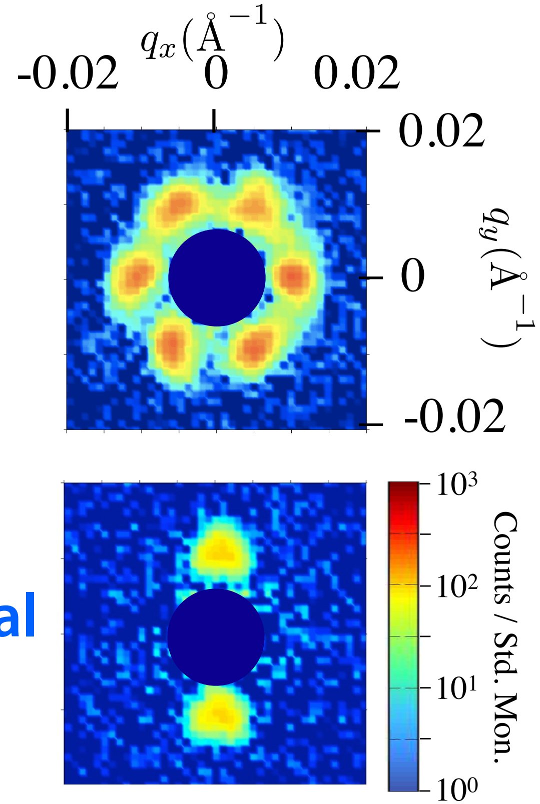


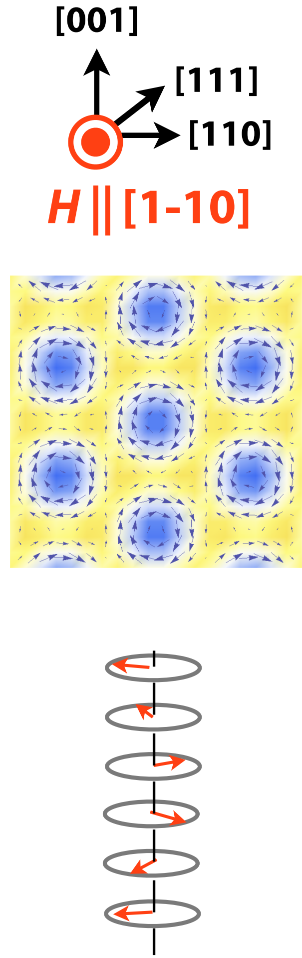
- **Helimagnetic ground state**
- **Skyrmion lattice** is formed under *H*
- Spin modulation period : ~ **50nm**

Cu_2OSeO_3 : Small Angle Neutron Scattering (Bulk)

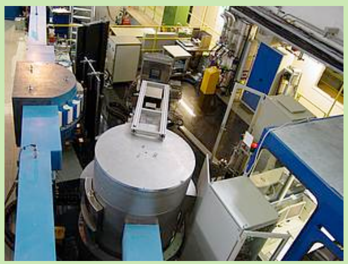
S. Seki *et al.*, Phys. Rev. B **85**, 220406 (R) (2012).
T. Adams *et al.*, Phys. Rev. Lett. **108**, 237204 (2012).

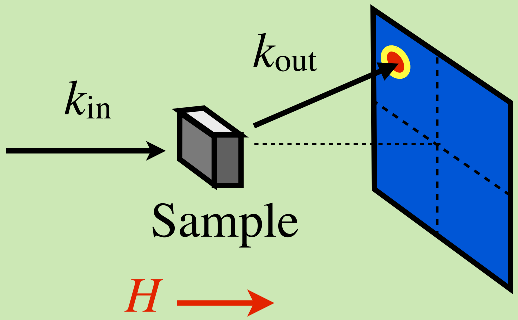






MIRA FRM2
@ München



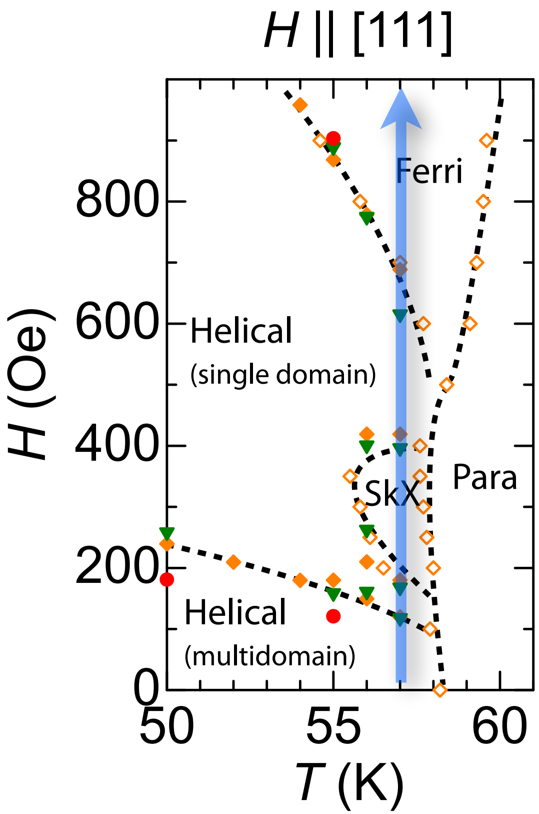


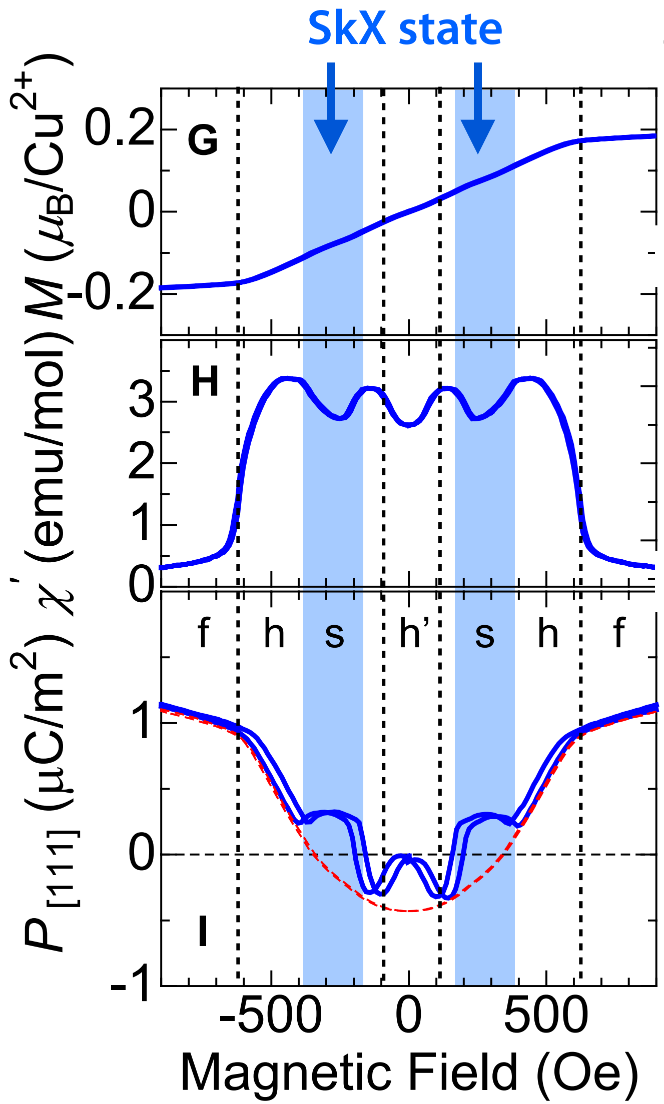
with Keimer Group and R. Georgii

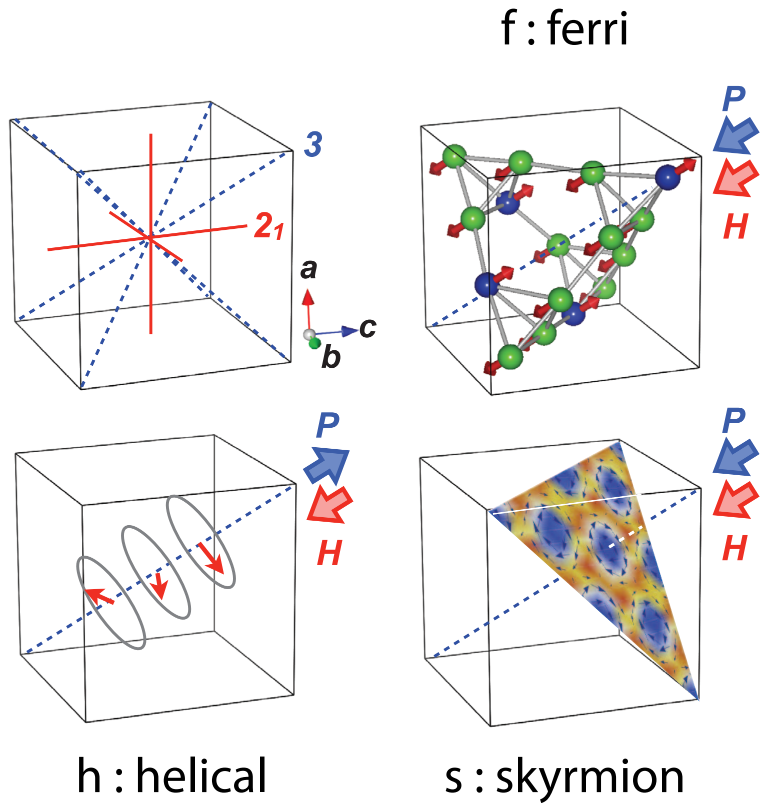
- **Helical** spin texture for $H = 0$
- **Skyrmion** lattice spin state for "A-phase" just below T_c

Cu_2OSeO_3 : Multiferroic Skyrmions

S. Seki *et al.*, Science **336**, 198 (2012).

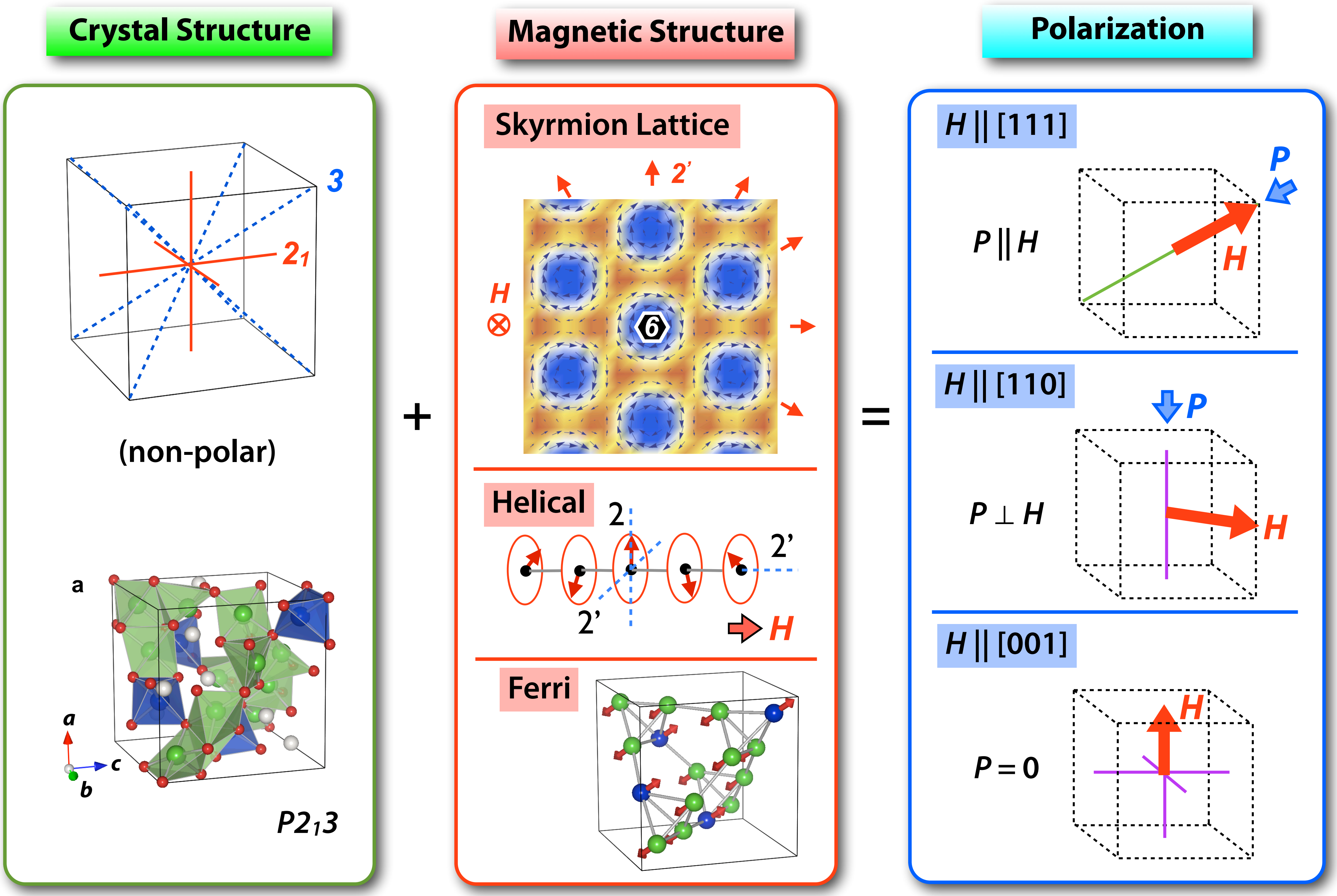






All of ferrimagnetic, helimagnetic, and **skyrmion crystal** state induce **electric polarization**

Cu_2OSeO_3 : Symmetry Analysis

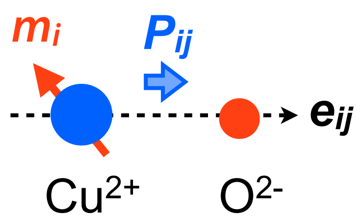


Cu_2OSeO_3 : Charge distribution in skyrmion

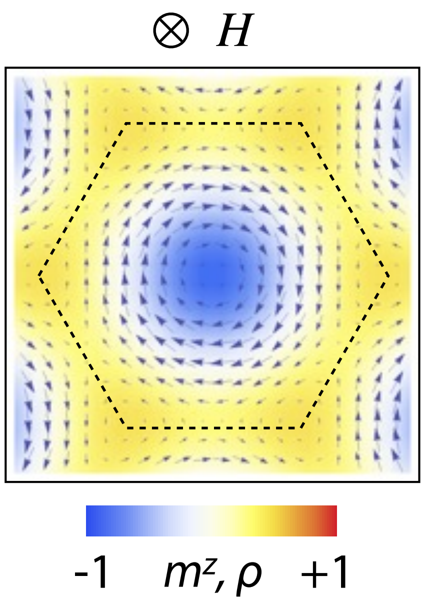
S. Seki *et al.*, Phys. Rev. B **86**, 060403 (R) (2012).

***d-p* hybridization model**

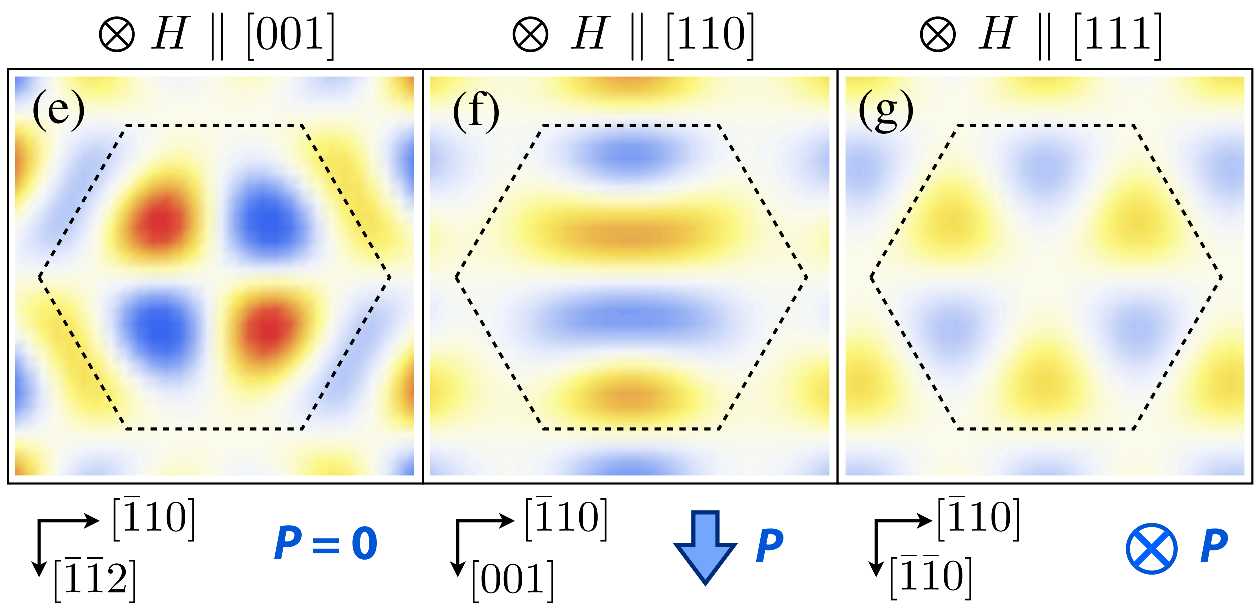
$$\vec{p}_{ij} \propto (\vec{e}_{ij} \cdot \vec{m}_i)^2 \vec{e}_{ij}$$



Local *M*



Local charge (-div *P*)

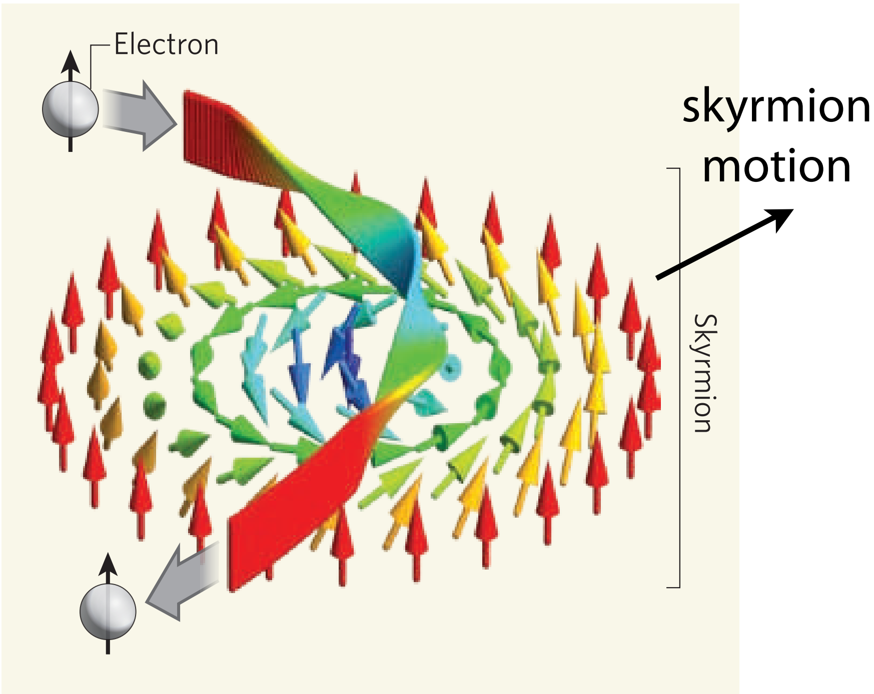


Skyrmion particle can locally carry **electric dipole** or **quadrupole**

Electric manipulation of skyrmion

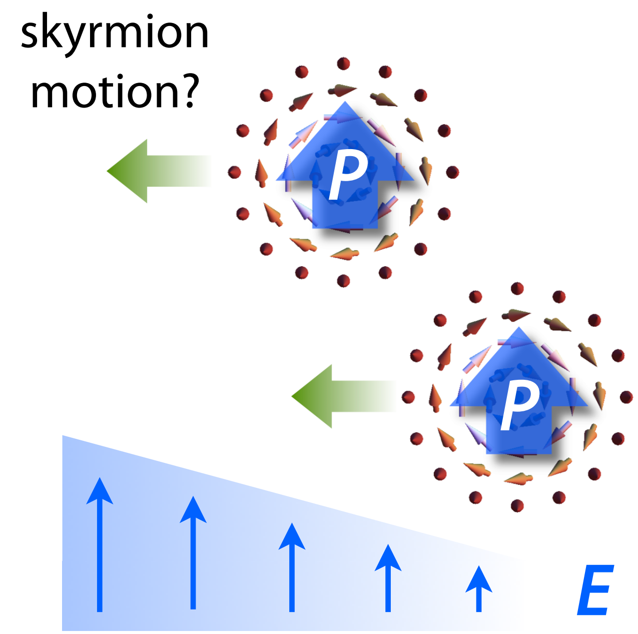
Current-driven

Neubauer *et al.*, PRL (2009).
Jonietz *et al.*, Science (2010).



Metal

Electric-field-driven (?)



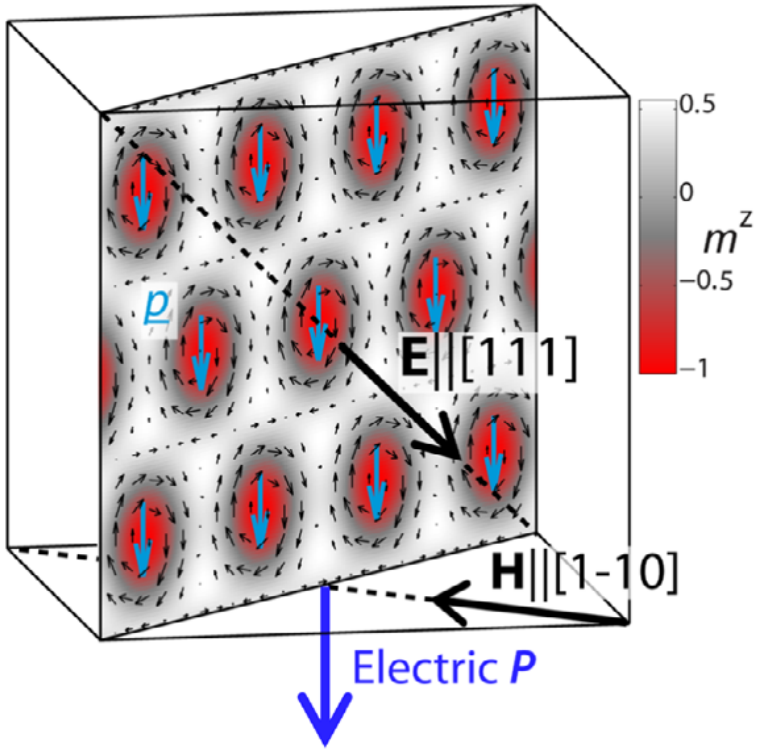
Insulator

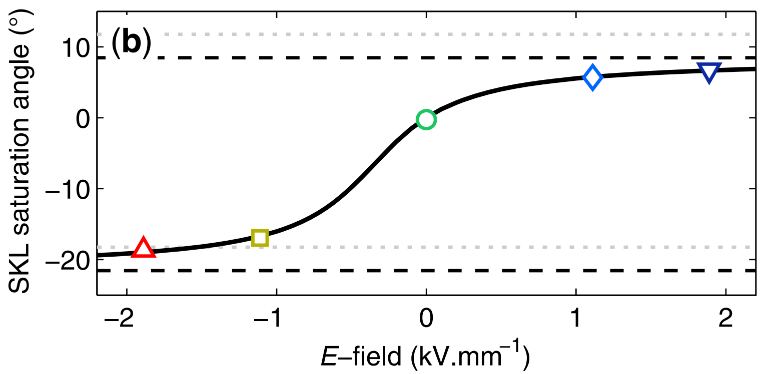
Only negligible joule heat loss
→ Energetically more efficient ??

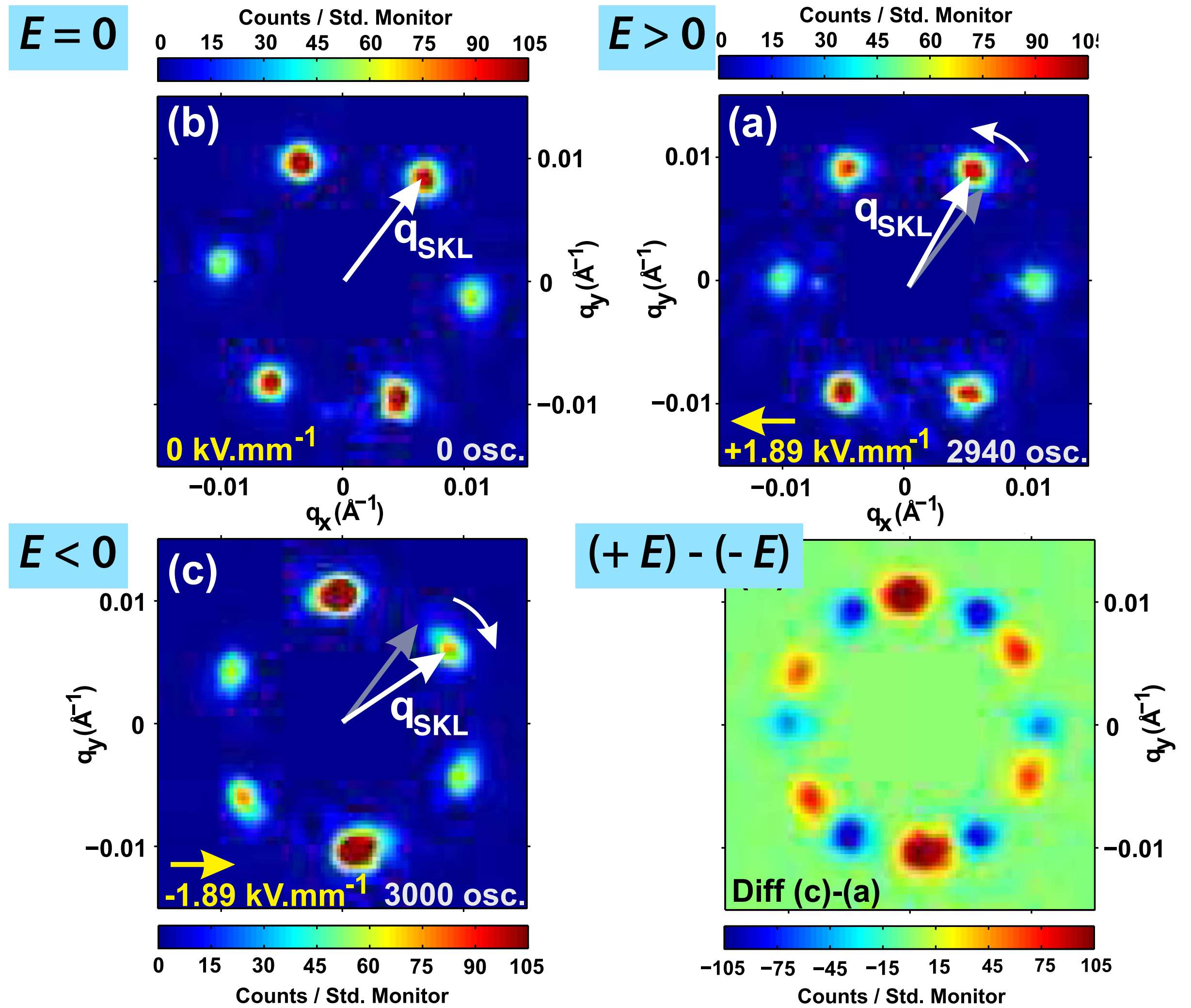
Electric field induced rotation of skyrmion lattice

J. S. White *et al.*, J. Phys.: Condens. Matter **24**, 432201 (2012).

J. S. White *et al.*, Phys. Rev. Lett. **113**, 107203 (2014).



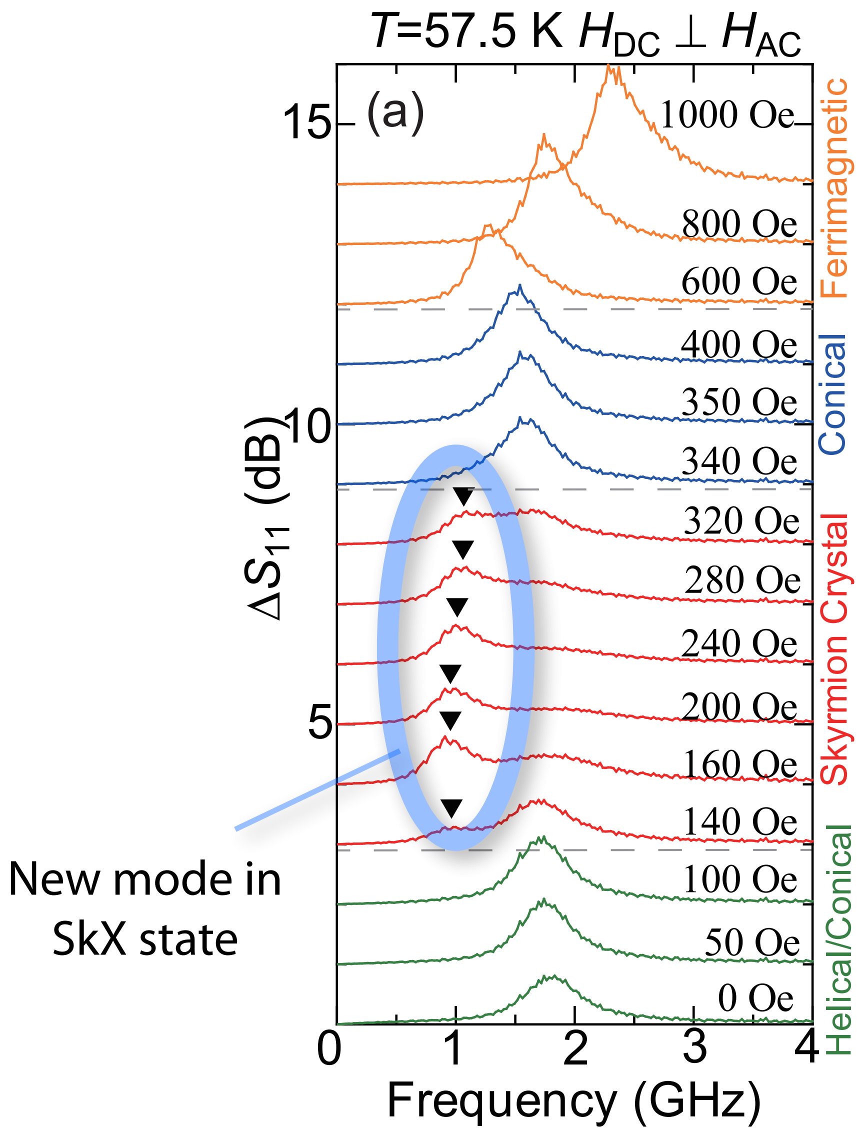


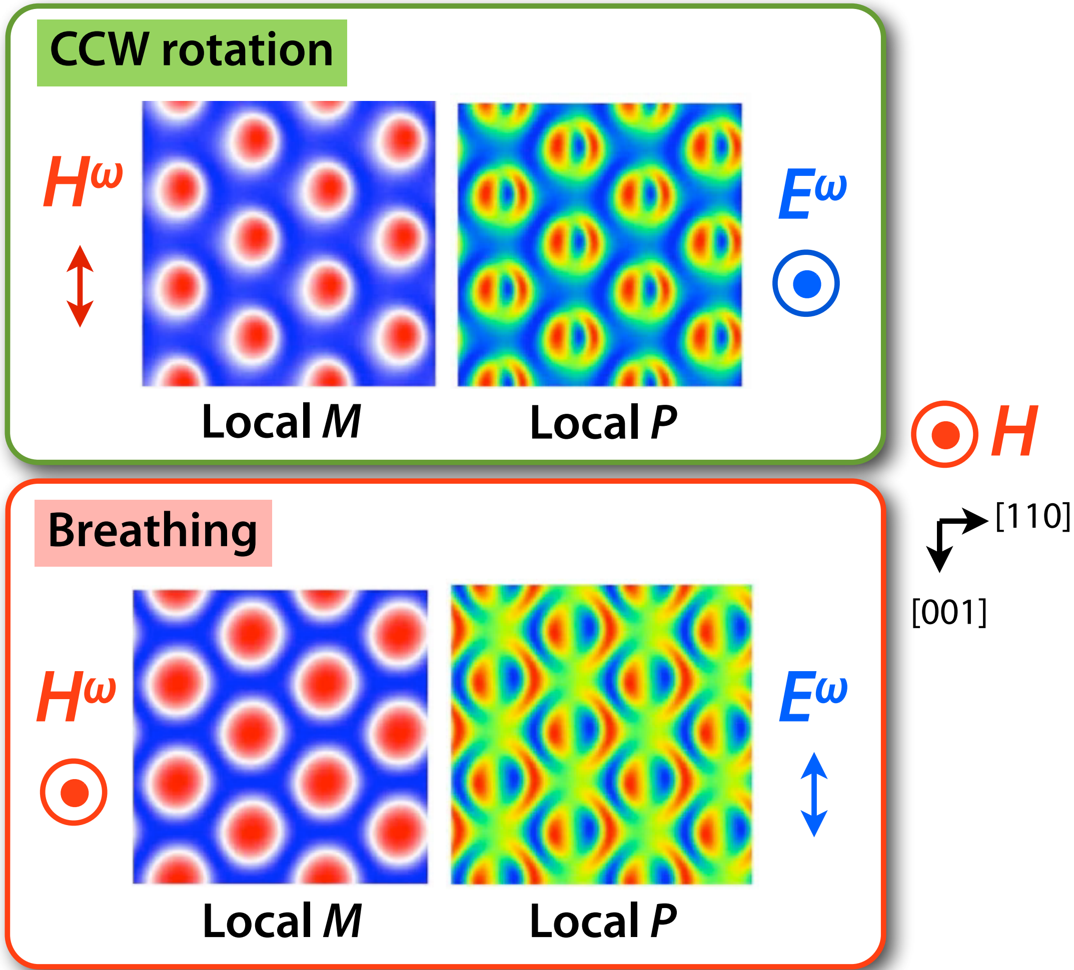


Application of electric field **rotates** skyrmion crystal

H^ω- and E^ω-induced Resonance of Skyrmion Lattice

M. Mochizuki *et al*., Phys. Rev. Lett. **108**, 017601 (2012).
Y. Onose, S. S *et al*., Phys. Rev. Lett. **109**, 037603 (2012).
Y. Okamura, S. S *et al*., Nature Comm. **4**, 2391 (2013).
T. Schwarze *et al*., Nature Mater. **14**, 478 (2015).





Collective mode of skyrmion crystal can be excited not only by H^ω, but **also by E^ω via magnetoelectric coupling**

Electromagnon
in skyrmion crystal

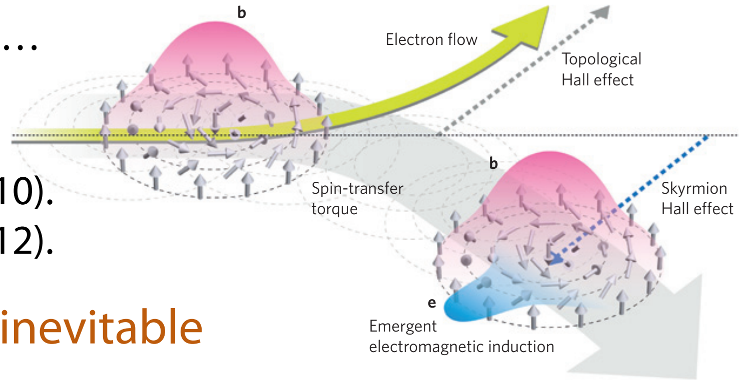
Various Methods to Manipulate Skyrmions

Metal (B20 alloys)

MnSi, FeGe, $Fe_{1-x}Co_xSi$ etc…

Electric Current

F. Jonietz *et al.*, Science (2010).
X. Z. Yu *et al.*, Nature Comm. (2012).

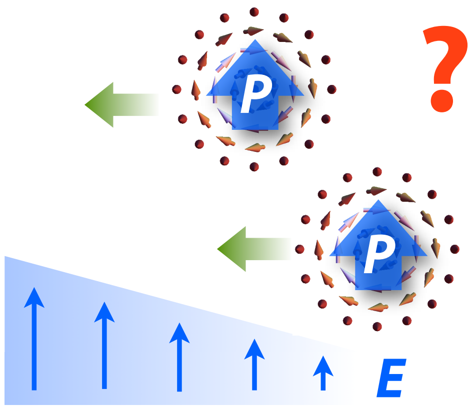


▷ Energy loss due to **Joule heating** is inevitable

Insulator (Cu_2OSeO_3)

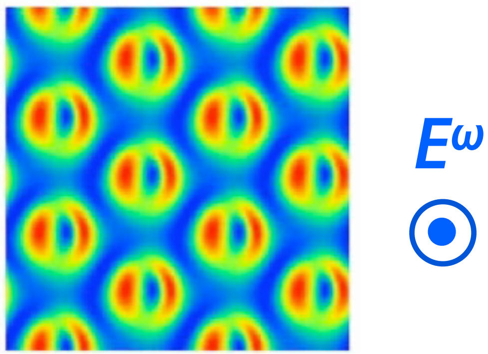
Electric Field

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



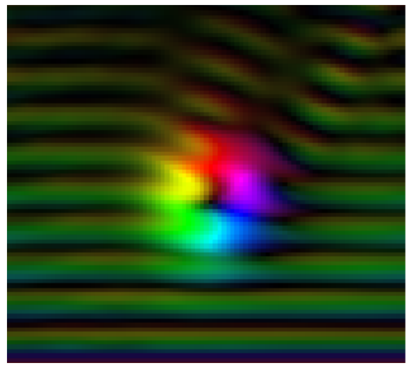
Oscillating Electric Field

Okamura, Seki *et al.*,
Nature Comm. (2013).



Spin-wave

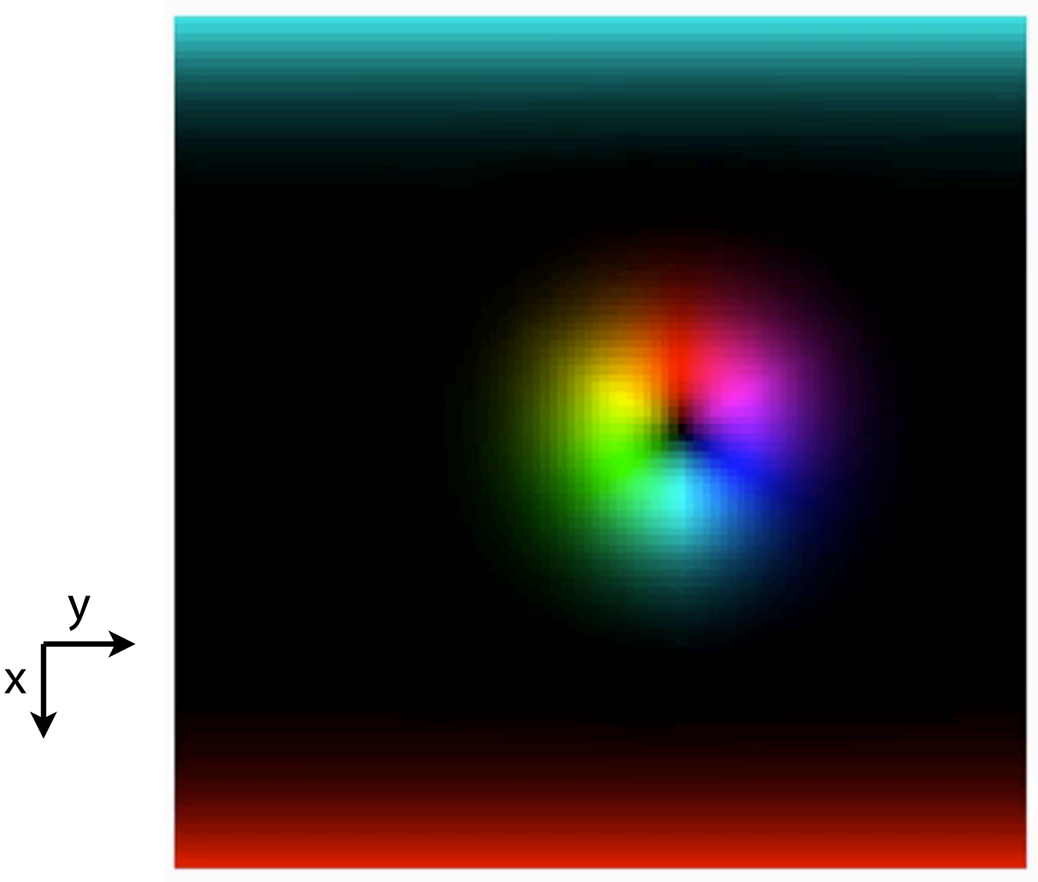
Mochizuki, Seki *et al.*,
Nature Mater. (2014).

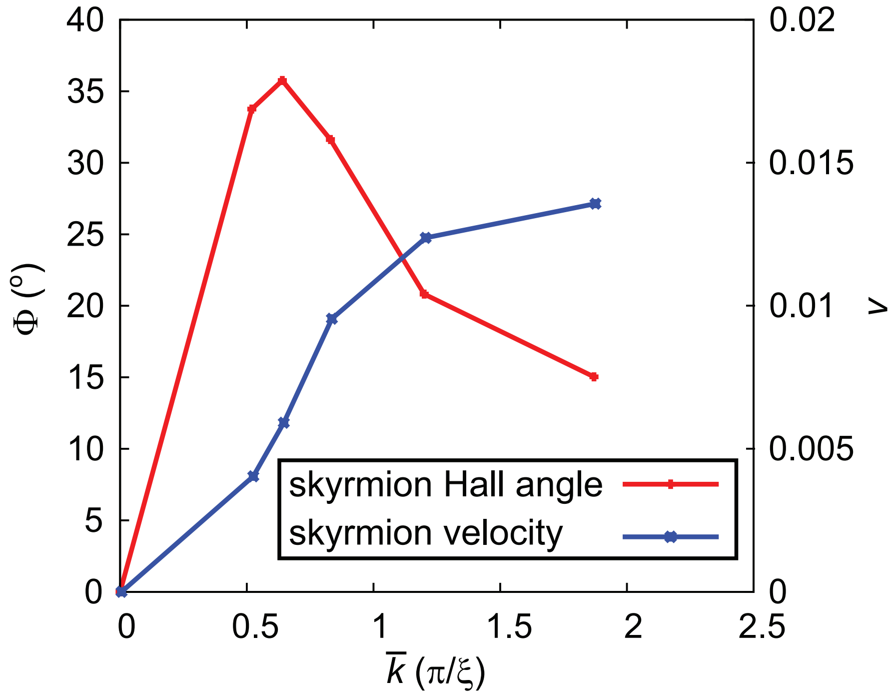


▷ Energetically more **efficient** approach ?

Interplay between skyrmions and spin-wave

Lin *et al.*, Phys. Rev. Lett. **112**, 187203 (2014).
Iwasaki *et al.*, Phys. Rev. B **89**, 64412 (2014).
C. Schutte *et al.*, Phys. Rev. B **90**, 094423 (2014).





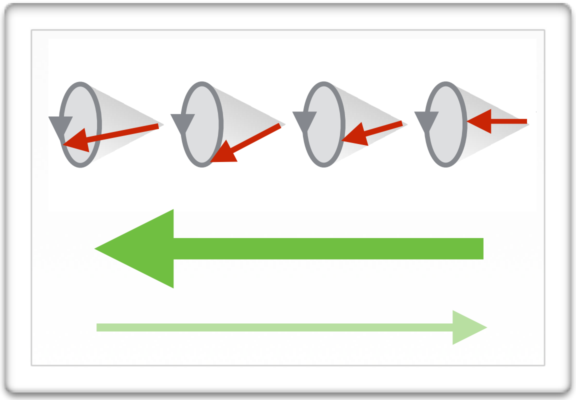
(a)

- Skyrmions are **dragged** through momentum exchange process
- Skyrmions are also deflected along transverse direction, due to **Magnus force**
- Energetically efficient way to manipulate skyrmions **without Joule heat loss ?**

How does spin-wave propagate in chiral crystal??

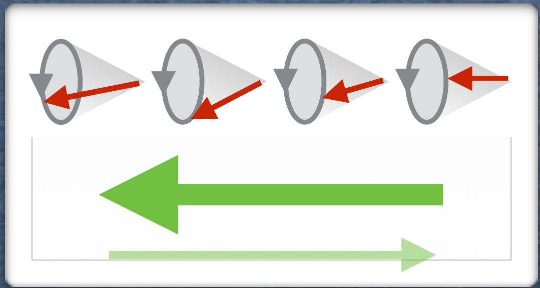
(experimentally unexplored before…)

Spin-wave "Diode"



Outline

1. Multiferroic Skyrmions
2. Spin-wave Diode
3. Summary & Perspective

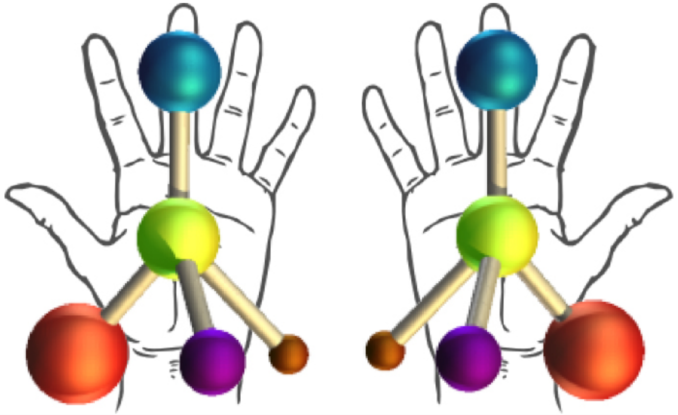


Outline

1. Multiferroic Skyrmions
2. Spin-wave Diode
3. Summary & Perspective

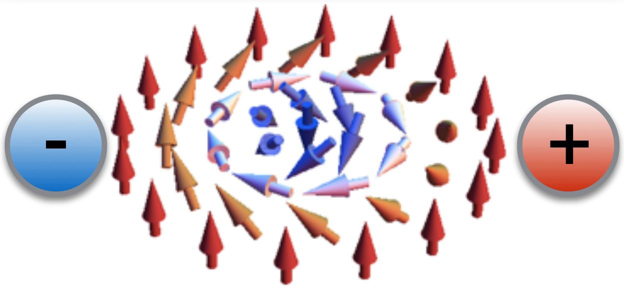
Summary

S. Seki *et al.*, Science **336**, 198 (2012).
S. Seki *et al.*, arXiv 1505.02868.



+

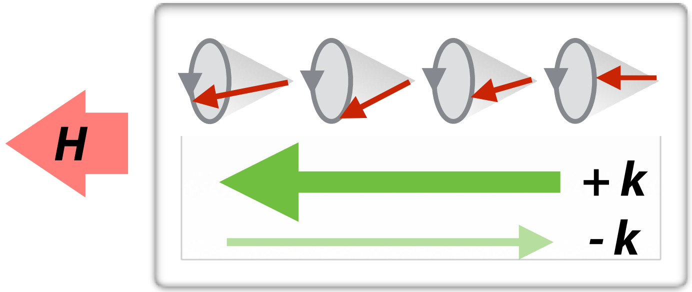
Multiferroic Skyrmions



- Skyrmions in insulator carries **electric dipole**
- ***E*- or *E*^ω^- induced manipulation** of skyrmion is possible, without Joule heat loss

→ **Energy-efficient skyrmion memory ?**

Spin-wave Diode

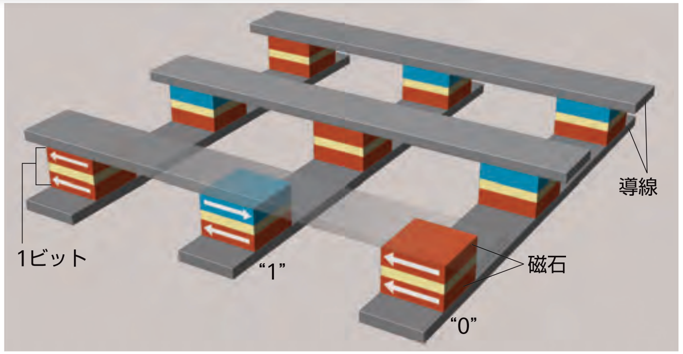


- Spin-wave propagating along spin direction has **chirality**
- Such a spin-wave shows **nonreciprocal propagation** in chiral-lattice materials

→ **Perfect spin-current diode ?**

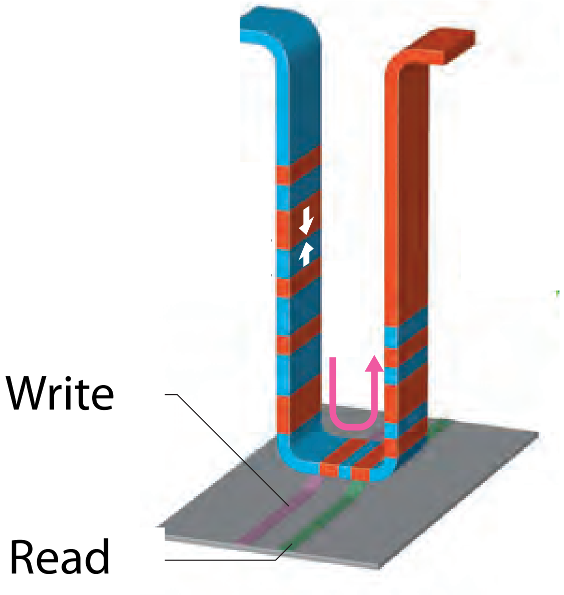
Toward Application…

MRAM



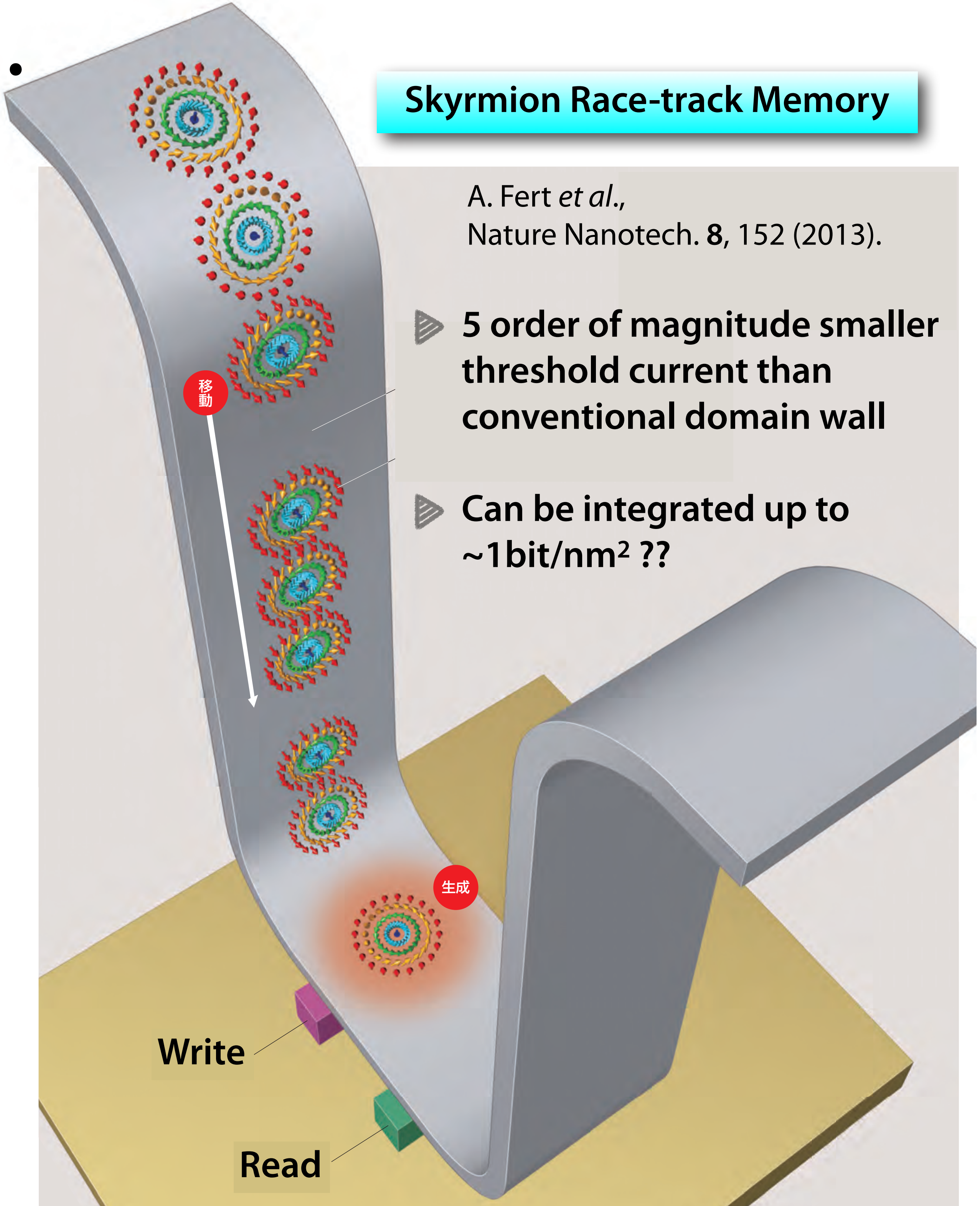
Race-track Memory

S. S. P. Parkin *et al.*, Science **320**, 190 (2008).



- **Only 1 transistor / 1000 bits**

Skyrmion Race-track Memory



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

- **5 order of magnitude smaller threshold current than conventional domain wall**
- **Can be integrated up to ~1bit/nm^2 ??**