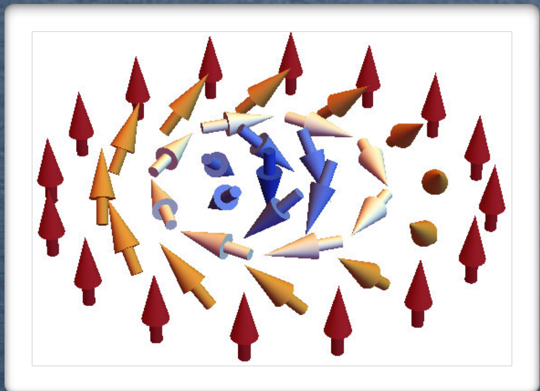
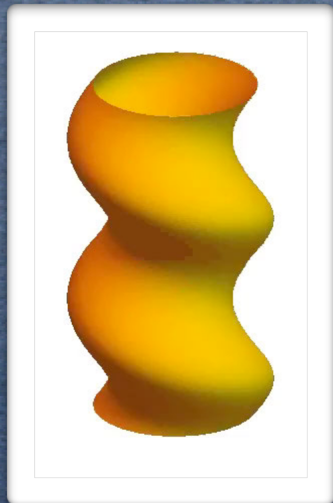
Novel materials with magnetic skyrmions and their three-dimensional dynamics

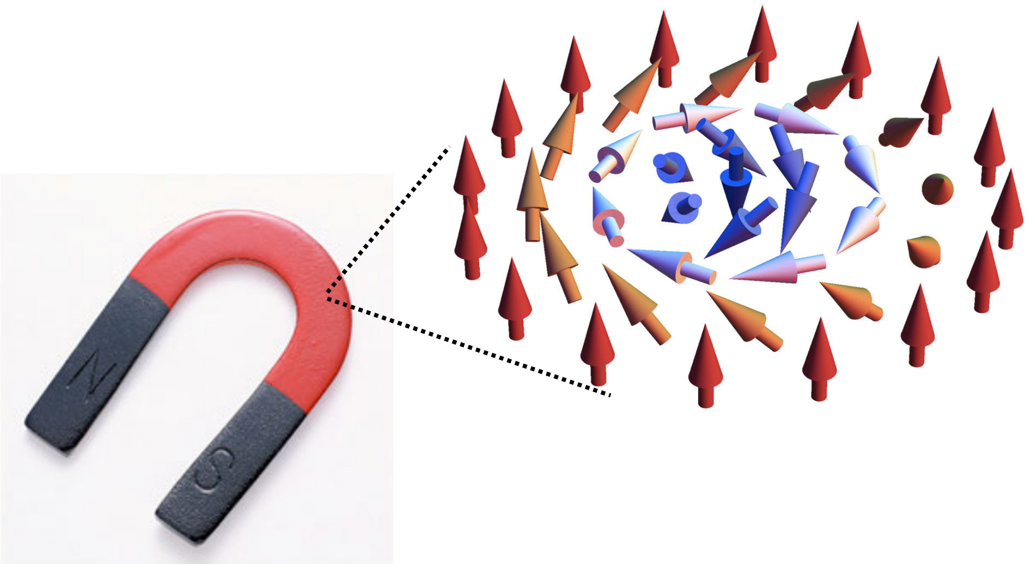
Shinichiro Seki

Department of Applied Physics, University of Tokyo, Japan





Today's Topic



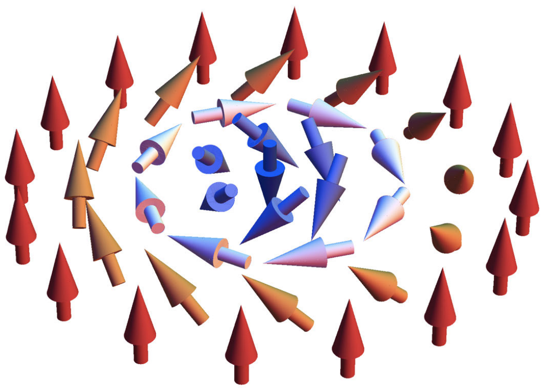
"Magnetic Skyrmion"

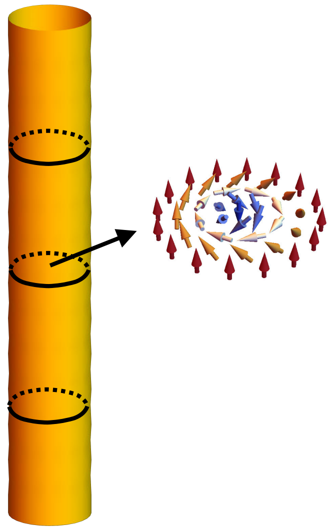
Today's Topic

What kind of function can be expected from magnetic vortices?

Particle

String



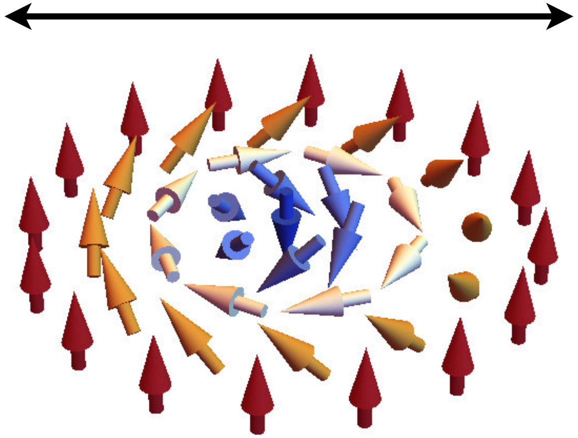


What is magnetic skyrmion?

Rossler *et al.*, Nature (2006).
A. Fert *et al.*, Nature Nanotech.(2013).

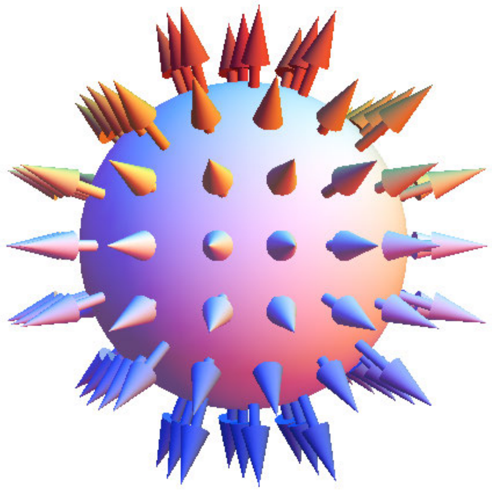
Magnetic Skyrmion

1 ~ 100 nm



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

Skyrmion Number



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

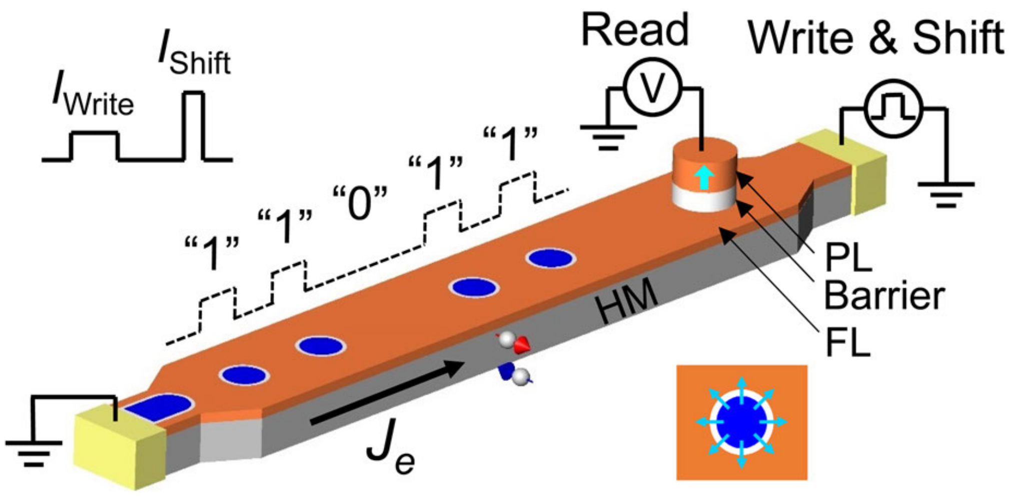
Particle nature + Nanometric scale
= New information carrier for memory device?

cf. Racetrack memory, bubble memory etc...

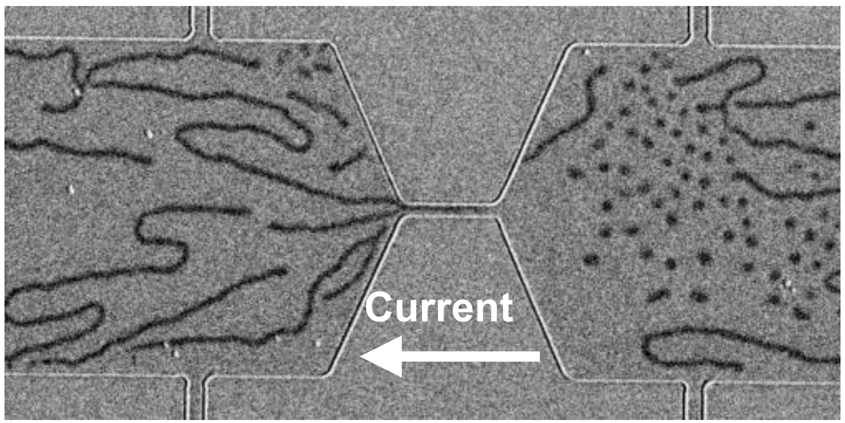
Skyrmion Particle as Information Bit

Skyrmion Memory

G. Yu *et al.*, Nano Lett. **17**, 261 (2017).

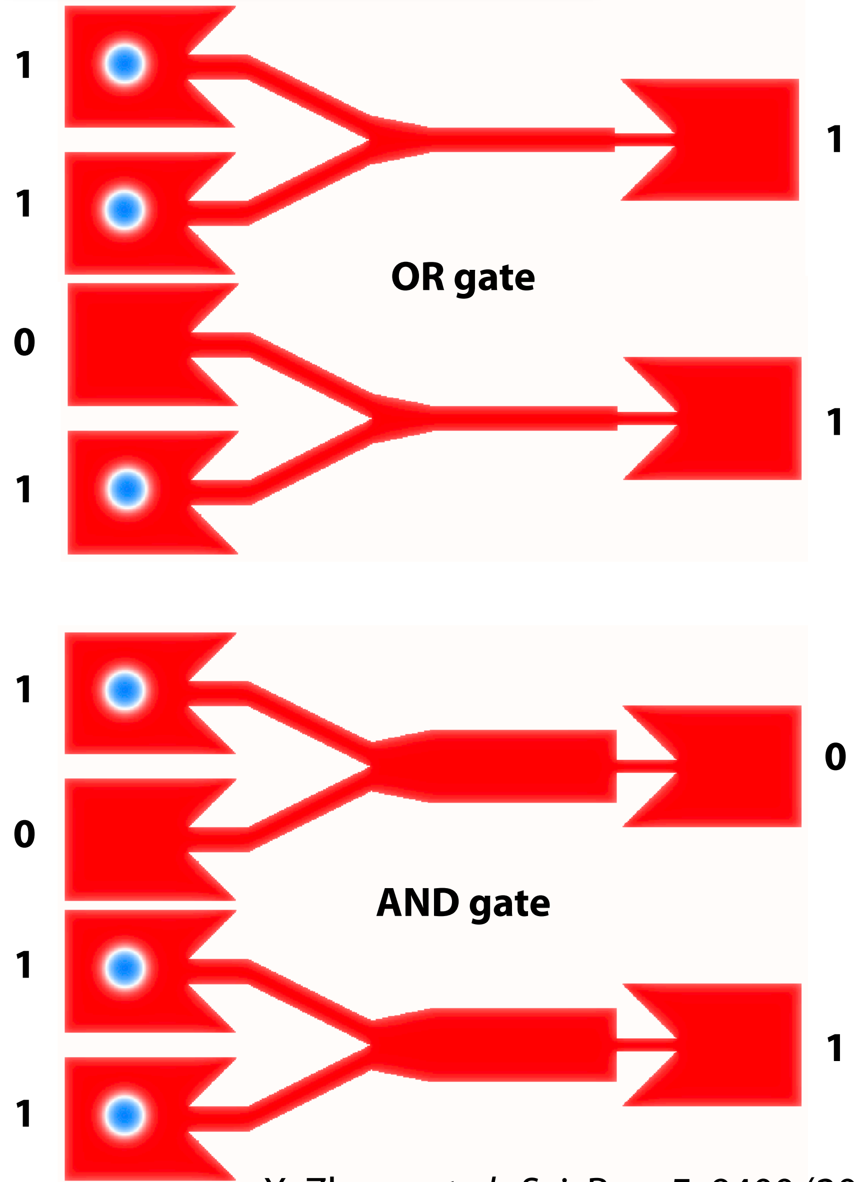


- **Skyrmions can be driven by electric current**



W. Jiang *et al.*, Science **349**, 283 (2015).

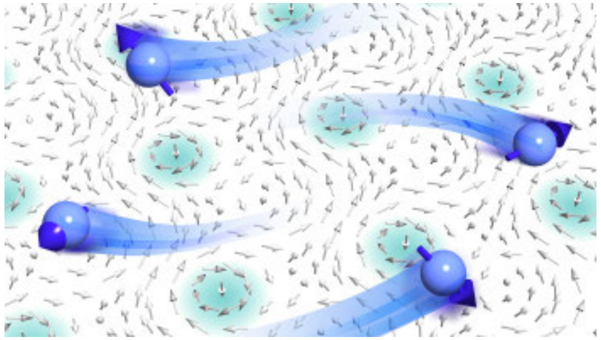
Skyrmion Logic Gate

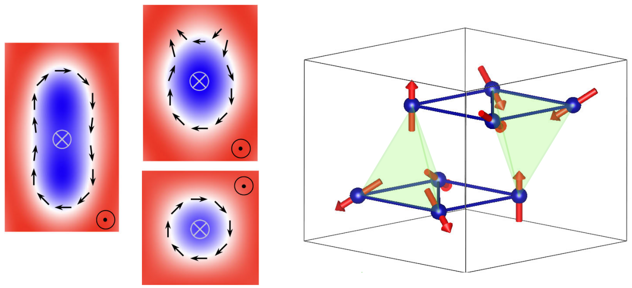


X. Zhang *et al.*, Sci. Rep. **5**, 9400 (2015).

Outline

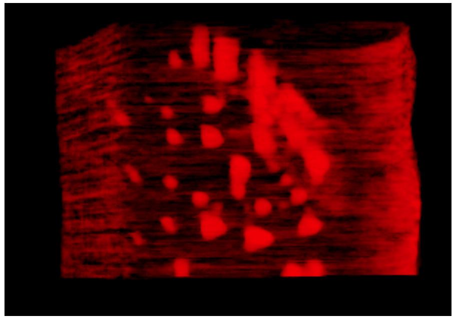
Nanometric skyrmions in centrosymmetric magnets

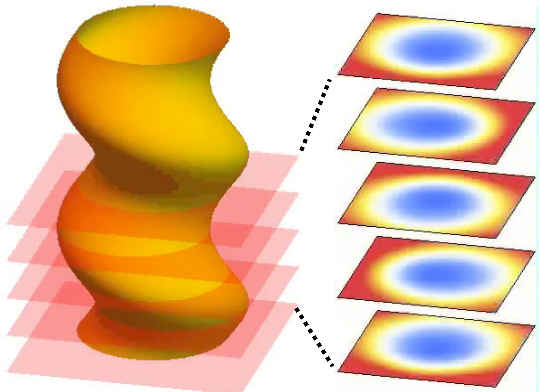




N. D. Khanh, …, S. Seki, Nature Nanotech. **15**, 444 (2020).
H. Takagi, …, S. Seki, Nature Physics **19**, 961 (2023).
H. Yoshimochi, …, S. Seki, Nature Physics (2024).

3D visualization and dynamics of skyrmion strings





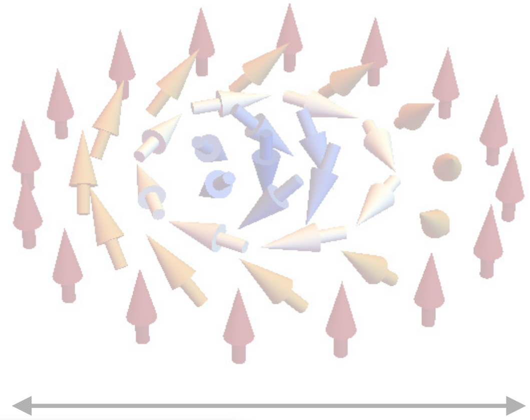
S. Seki *et al.*, Nature Materials **21**, 181 (2022).
S. Seki *et al.*, Nature Comm. **11**, 256 (2020).

Magnetic skyrmions in noncentrosymmetric system

Noncentrosymmetric systems

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

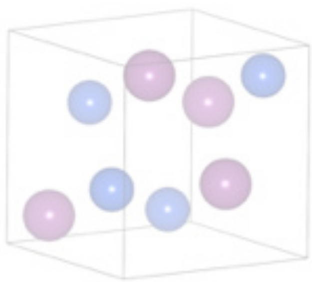
Exchange — Dzyaloshinskii-Moriya



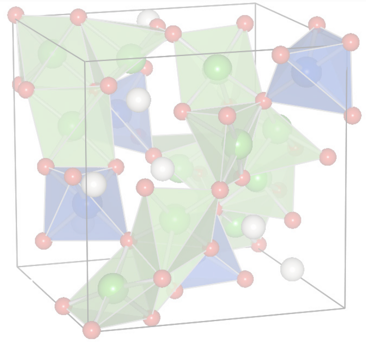
Can we realize smaller skyrmions in centrosymmetric system ?

Mn

$P2_13$



Muhlbauer *et al.*, Science (2009).



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

- **Broken inversion symmetry** is essential
- **Skyrmion diameter is $\lambda_{sk} \sim J/D$ (10 - 100 nm, typically)**

Skyrmions mediated by itinerant electrons

Localized Spins with Itinerant Electrons

$$\mathcal{H} = -\sum_{i,j,\sigma} t_{ij} c^{\dagger}_{i\sigma} c_{j\sigma} + J \sum_{i,\sigma,\sigma'} c^{\dagger}_{i\sigma} \boldsymbol{\sigma}_{\sigma\sigma'} c_{i\sigma'} \cdot \mathbf{S}_i$$

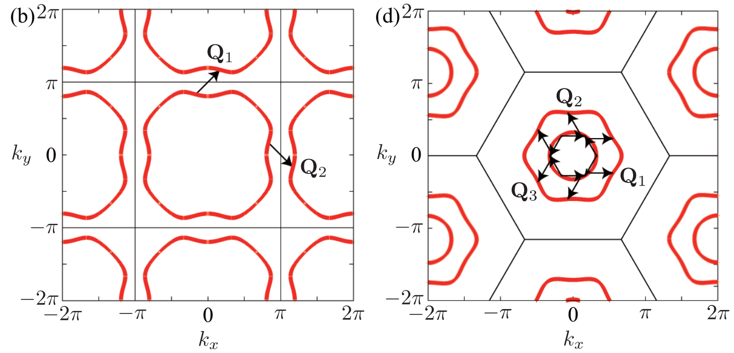
$$\simeq 2\sum_{\nu} \left[\underbrace{-\tilde{J}\mathbf{S}_{\mathbf{Q}_\nu} \cdot \mathbf{S}_{-\mathbf{Q}_\nu}}_{\text{RKKY}} + \underbrace{\tilde{K}(\mathbf{S}_{\mathbf{Q}_\nu} \cdot \mathbf{S}_{-\mathbf{Q}_\nu})^2}_{\text{Four-spin}} \right]$$

RKKY **Four-spin**

S. Hayami, Y. Motome *et al.*, Phys. Rev. B **95**, 224424 (2017).
Z. Wang, S.-Z. Lin, C. D. Batista *et al.*, Phys. Rev. Lett. **124**, 207201 (2020).
J. Bouaziz *et al.*, Phys. Rev. Lett. **128**, 157206 (2022).
S. Hayami *et al.*, J. Phys. Soc. Jpn. **91**, 023705 (2022).

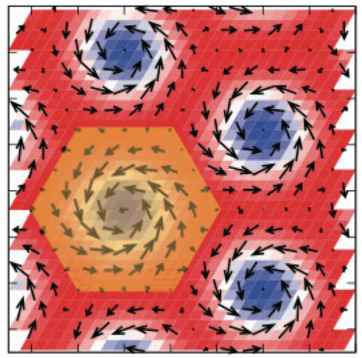
\+

High-symmetry Lattice



Multiple-number of equivalent nesting vectors

- Skyrmion can be stabilized even in **centrosymmetric system**
- Skyrmion size is determined by **nesting vector (~ a few nm)**

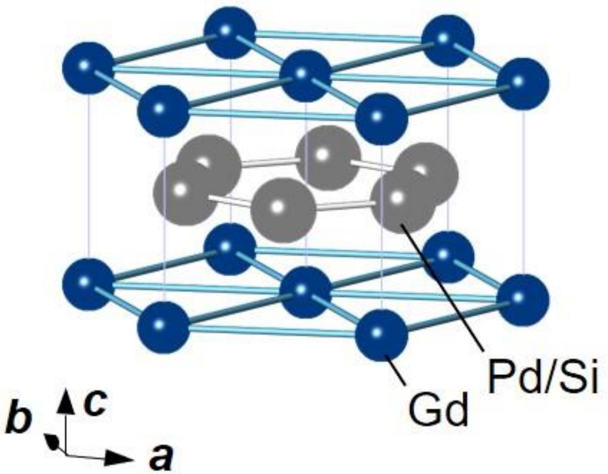


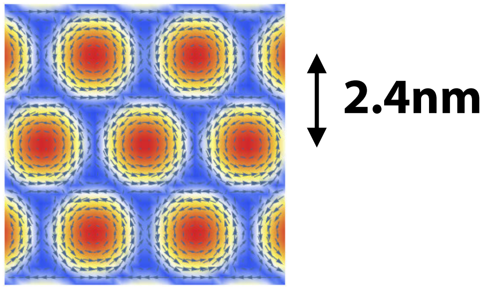
Design Strategy → **Rare-earth alloys with highly-symmetric lattice**

Gd-based Centrosymmetric Skyrmion-hosting Magnets

Gd_2PdSi_3

Triangular lattice

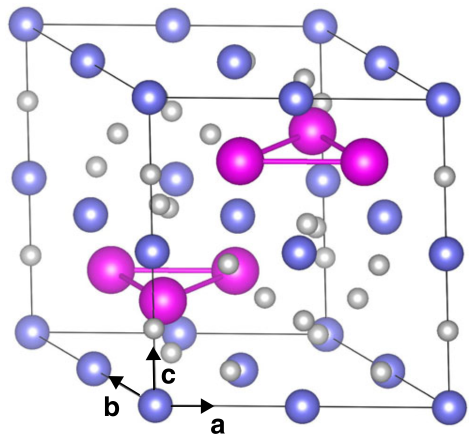


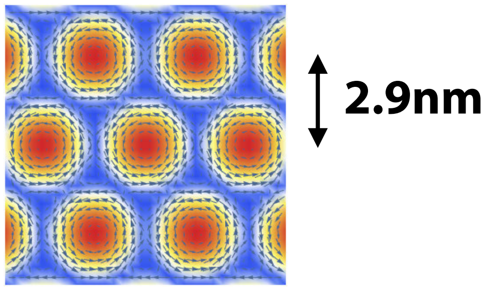


T. Kurumaji *et al.*,
Science **365**, 914 (2019).

$Gd_3Ru_4Al_{12}$

Breathing Kagome lattice

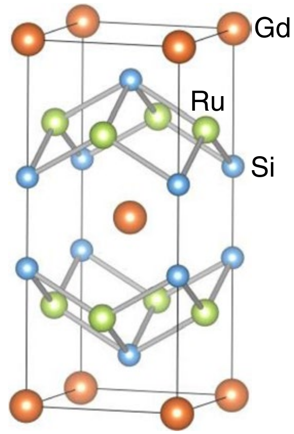


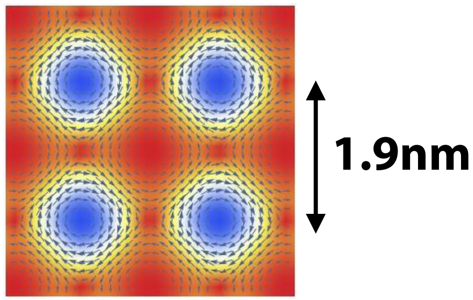


M. Hirschberger *et al.*,
Nat. Comm. **10**, 5831 (2019).

$GdRu_2Si_2$

Square lattice





N. D. Khanh, S. Seki *et al.*,
Nat. Nanotech. **15**, 444 (2020).

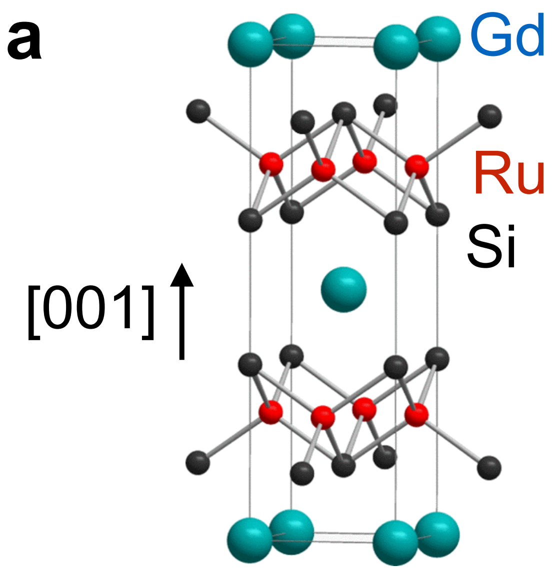
Gd^{3+} (L=0, S=7/2) intermetallics with highly-symmetric lattice
ubiquitously host skyrmions with small diameter

$GdRu_2Si_2$: Skyrmions in centrosymmetric tetragonal magnet

N. D. Khanh, X. Z. Yu, … , S. Seki, Nature Nanotech. **15**, 444 (2020).

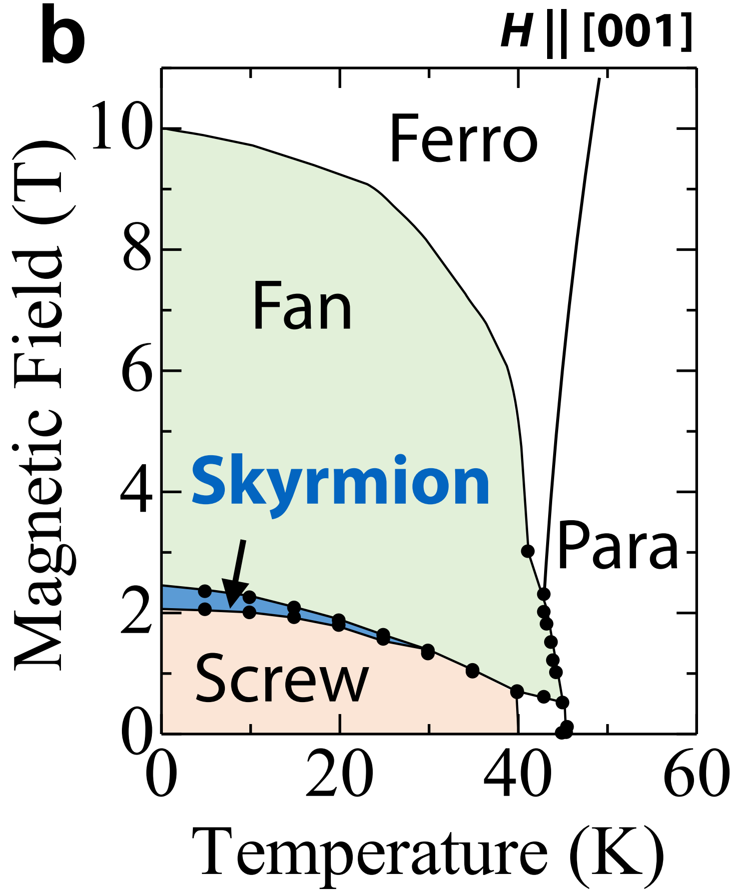
Crystal structure

$I4/mmm$

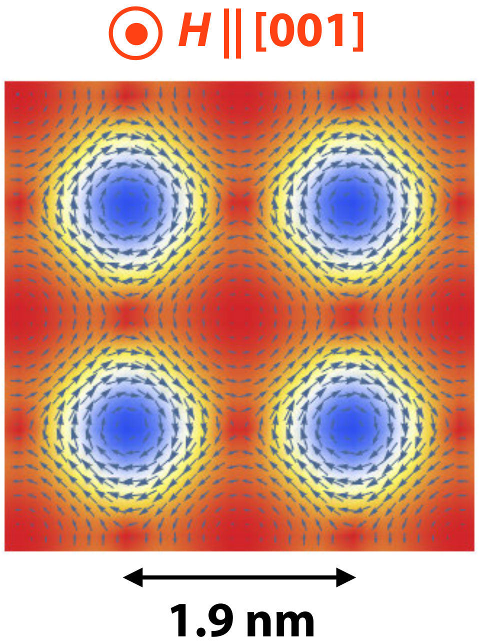


- **Centrosymmetric tetragonal**
- Gd^{3+} Heisenberg spin

Magnetic phase diagram



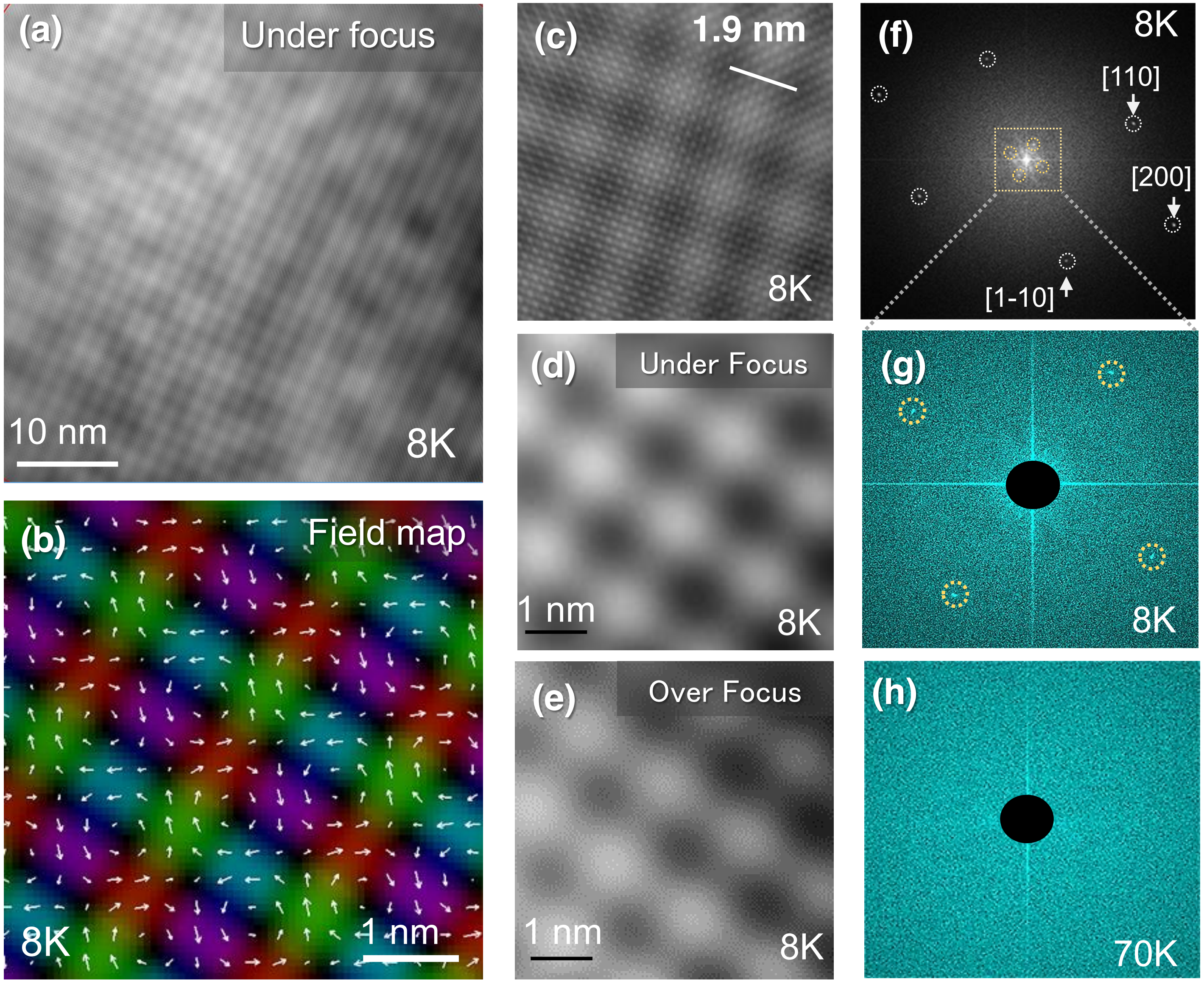
N. D. Khanh



- **Square skyrmion lattice (λ_{sk} ~ 1.9 nm) is stabilized under *H* || [001]**

$GdRu_2Si_2$: Lorentz TEM (Real-space spin texture)

N. D. Khanh, X. Z. Yu, … , S. Seki, Nature Nanotech. **15**, 444 (2020).



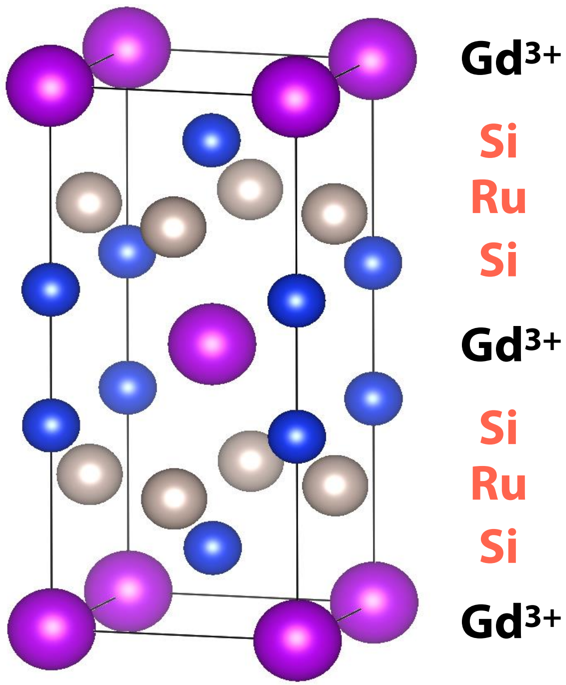
X. Z. Yu

Square lattice of **skyrmions with λ_{sk} ~ 1.9nm** (**smallest** value ever reported for bulk material)

Skyrmion-hosting compounds with $ThCr_2Si_2$ structure

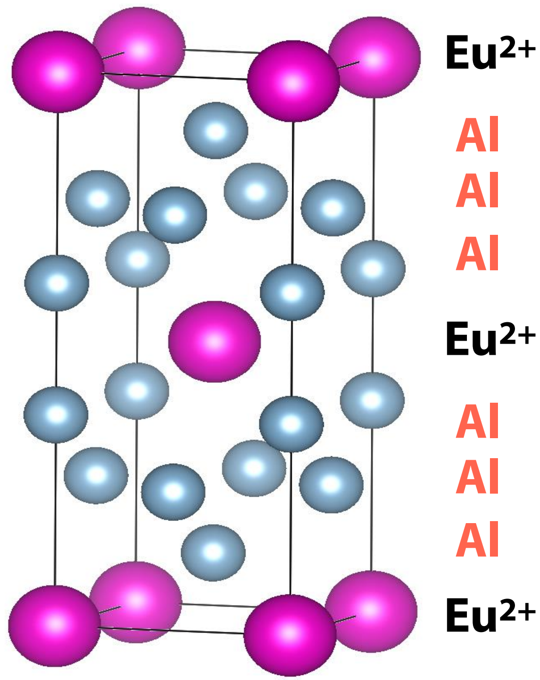
$GdRu_2Si_2$

N. D. Khanh, … , S. Seki
Nature Nanotech. **15**, 444 (2020).



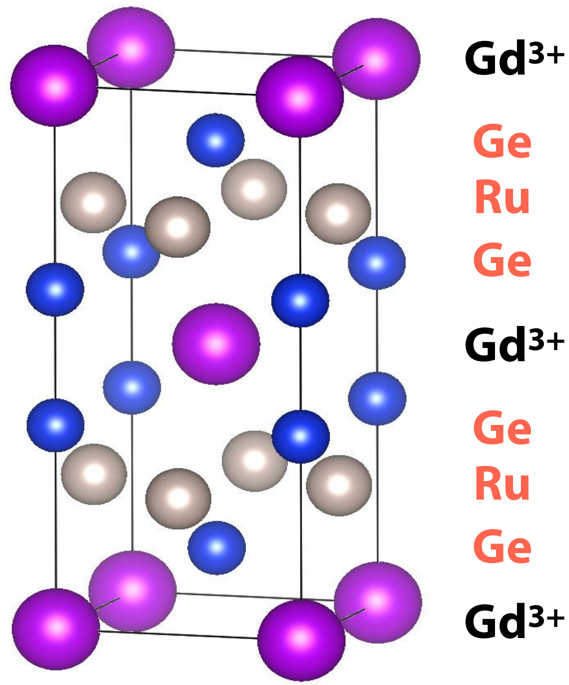
$EuAl_4$

R. Takagi, …, S. Seki
Nature Comm. **13**, 1472 (2022).



$GdRu_2Ge_2$

H. Yoshimochi, …, S. Seki
Nature Physics (2024).

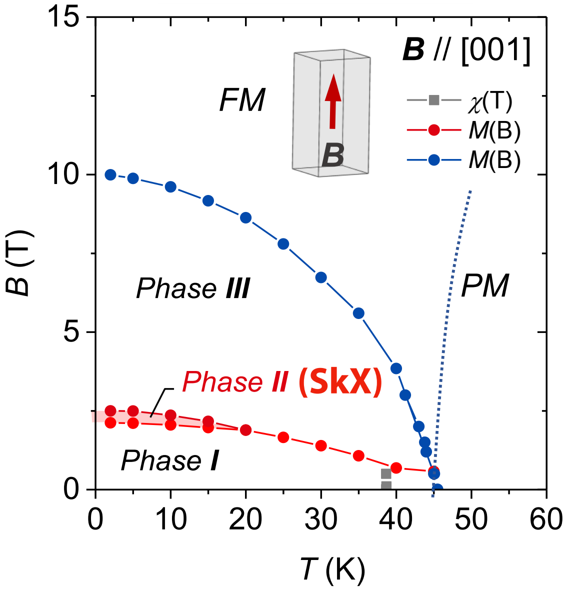


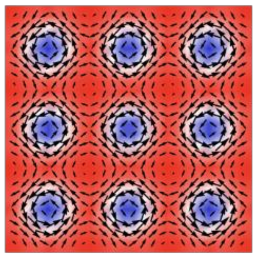
Multiple skyrmion phases are observed in $EuAl_4$ and $GdRu_2Ge_2$

Skyrmion-hosting compounds with $ThCr_2Si_2$ structure

$GdRu_2Si_2$

N. D. Khanh, … , S. Seki
Nature Nanotech. **15**, 444 (2020).

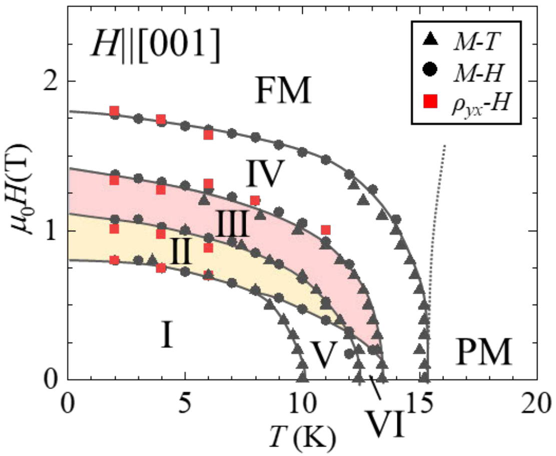


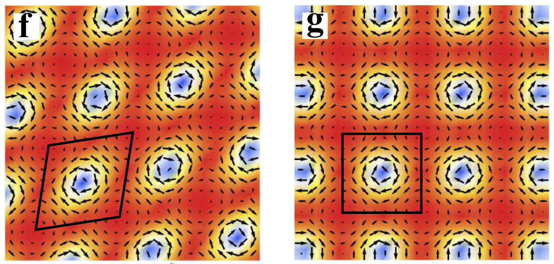


square

$EuAl_4$

R. Takagi, …, S. Seki
Nature Comm. **13**, 1472 (2022).

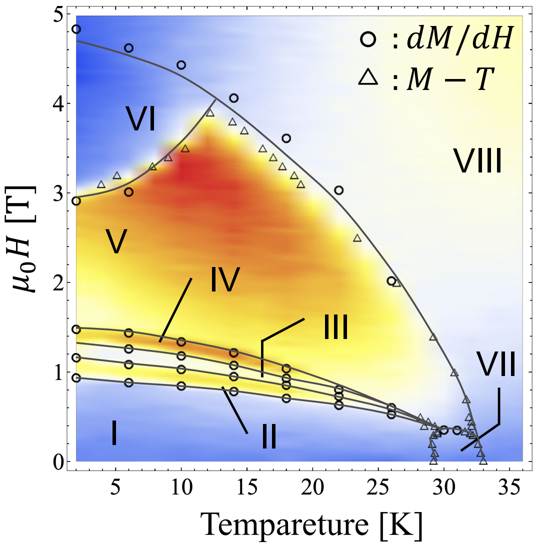


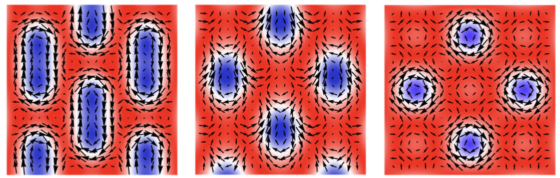


rhombic **square**

$GdRu_2Ge_2$

H. Yoshimochi, …, S. Seki
Nature Physics (2024).



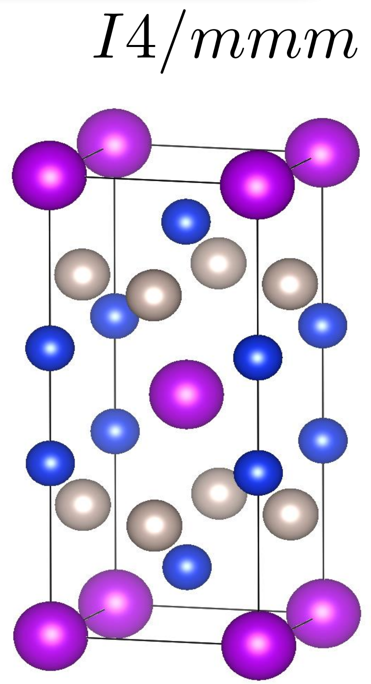


Multiple skyrmion phases are observed in $EuAl_4$ and $GdRu_2Ge_2$

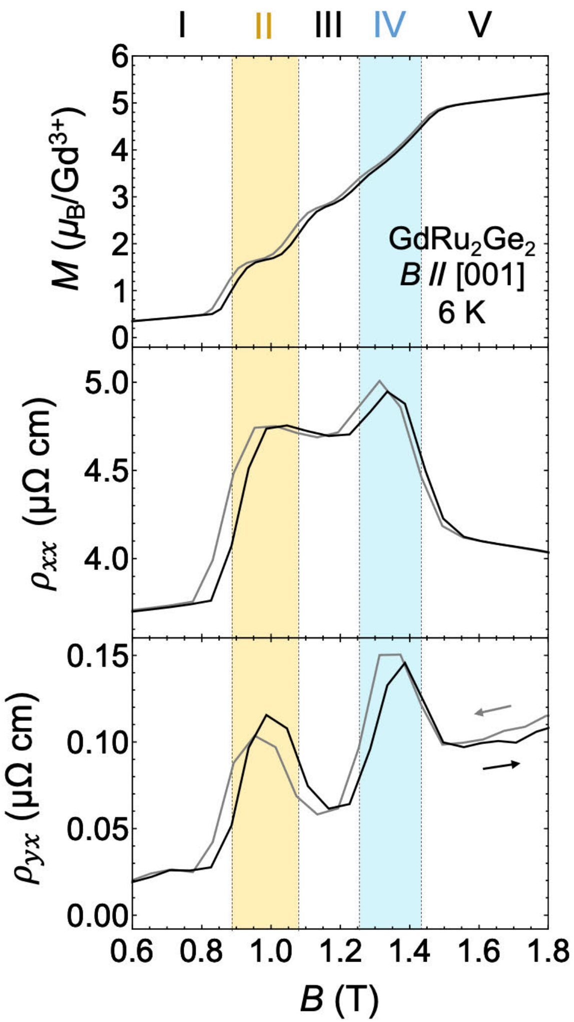
$GdRu_2Ge_2$: Multiple-step metamagnetic transition

H. Yoshimochi, … , S. Seki, Nature Physics (2024).

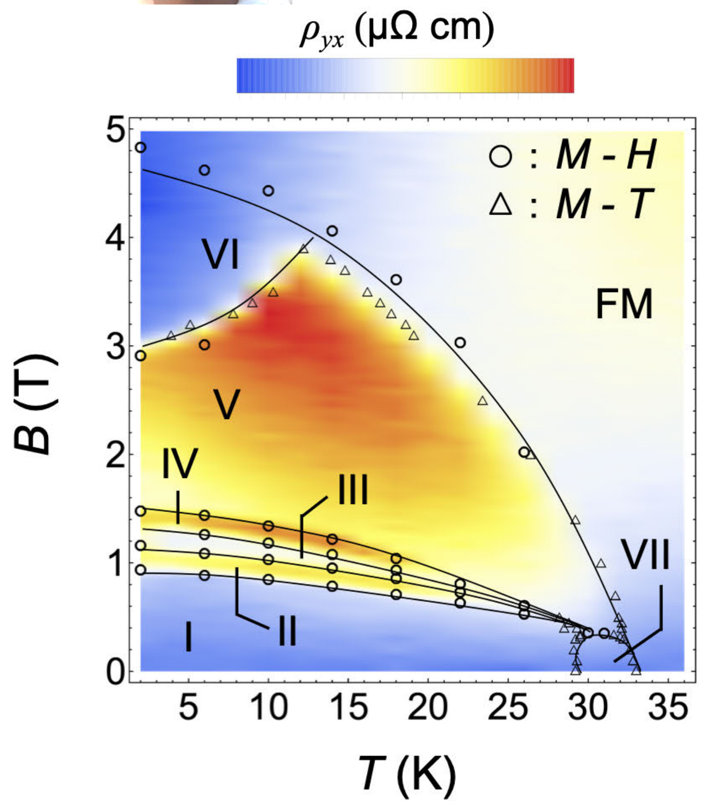
Crystal structure



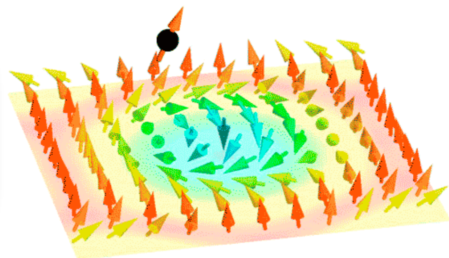
- **Centrosymmetric tetragonal**
- Gd^{3+} Heisenberg spin



H. Yoshimochi (D3)

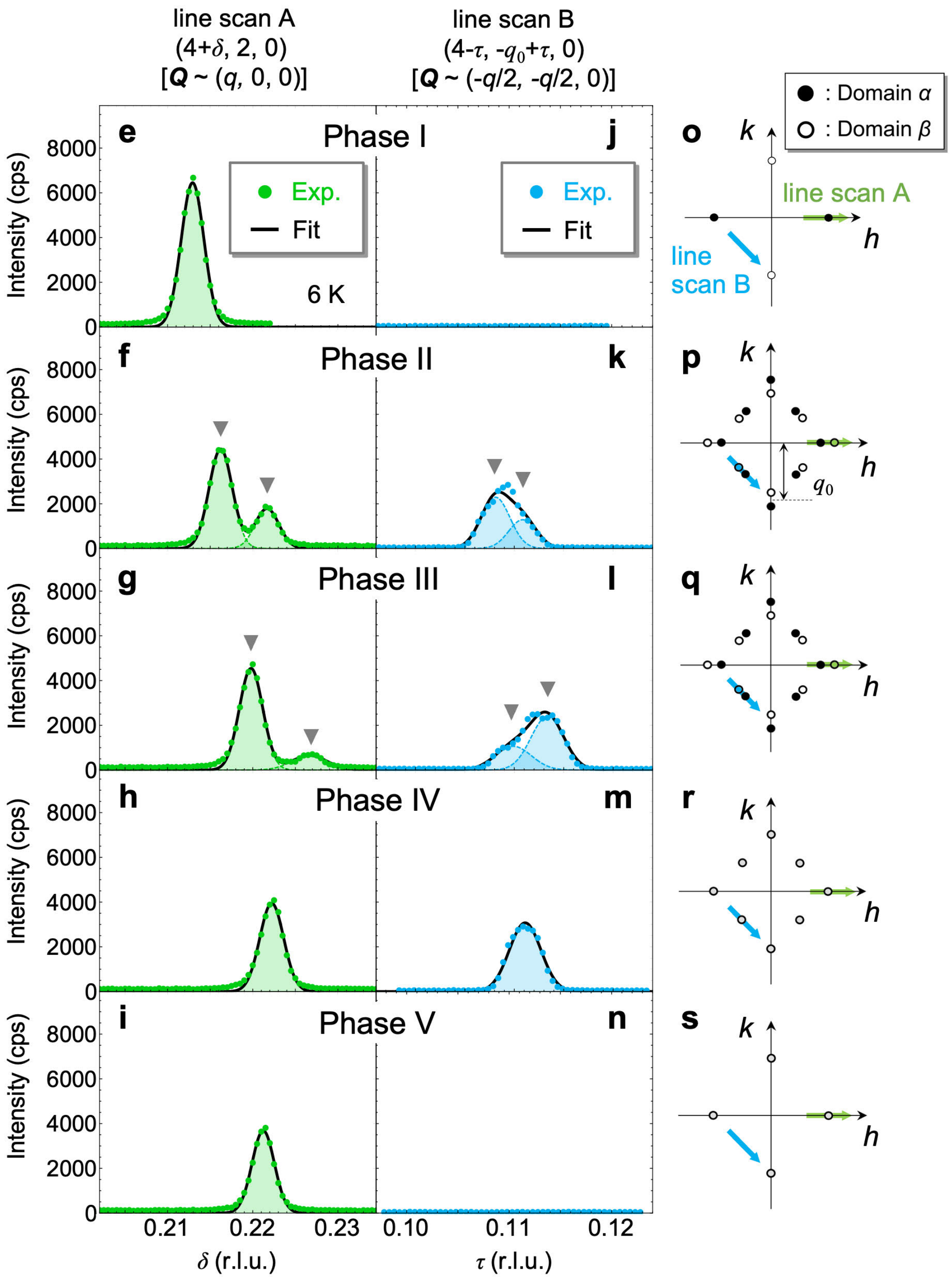


- *M* profile shows **three** intermediate steps
- ρ_{yx} shows **two** peak structure (Phase **II & IV** : **topological Hall effect** ?)



$GdRu_2Ge_2$: Magnetic structure (Resonant X-ray scattering)

H. Yoshimochi, … , S. Seki, Nature Physics (2024).

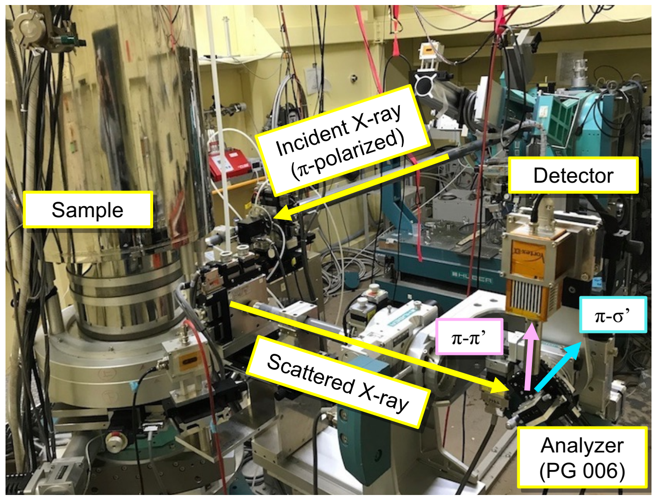


▶ **$Q_1 + Q_2$ peak is identified in Phases II, III, and IV**

double-*Q* magnetic order

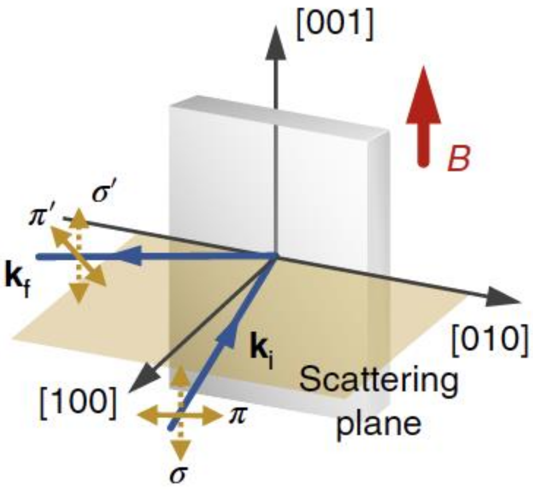
H. Yoshimochi

with Nakajima & Arima Lab.



KEK BL-3A

$GdRu_2Ge_2$: Magnetic structure (Resonant X-ray scattering)

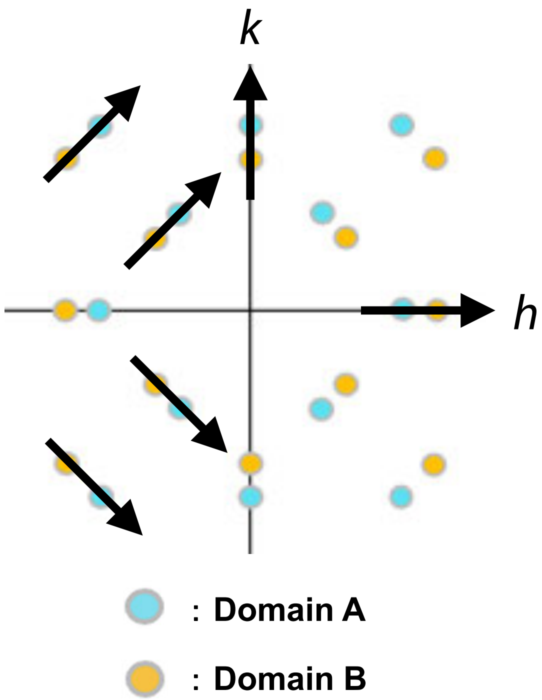


Magnetic structure : $\mathbf{m}(\mathbf{r}) = \sum_i \mathbf{m}_{\mathbf{Q}_i} \exp(i\mathbf{Q}_i \cdot \mathbf{r}) + c.c.$

$$I(\mathbf{Q}_i) \propto |(\mathbf{e}_i \times \mathbf{e}_f) \cdot \mathbf{m}_{\mathbf{Q}_i}|^2$$

Incident X-ray polarization **Scattered** X-ray polarization

→ **Each m_{Qi} can be identified by polarization analysis**

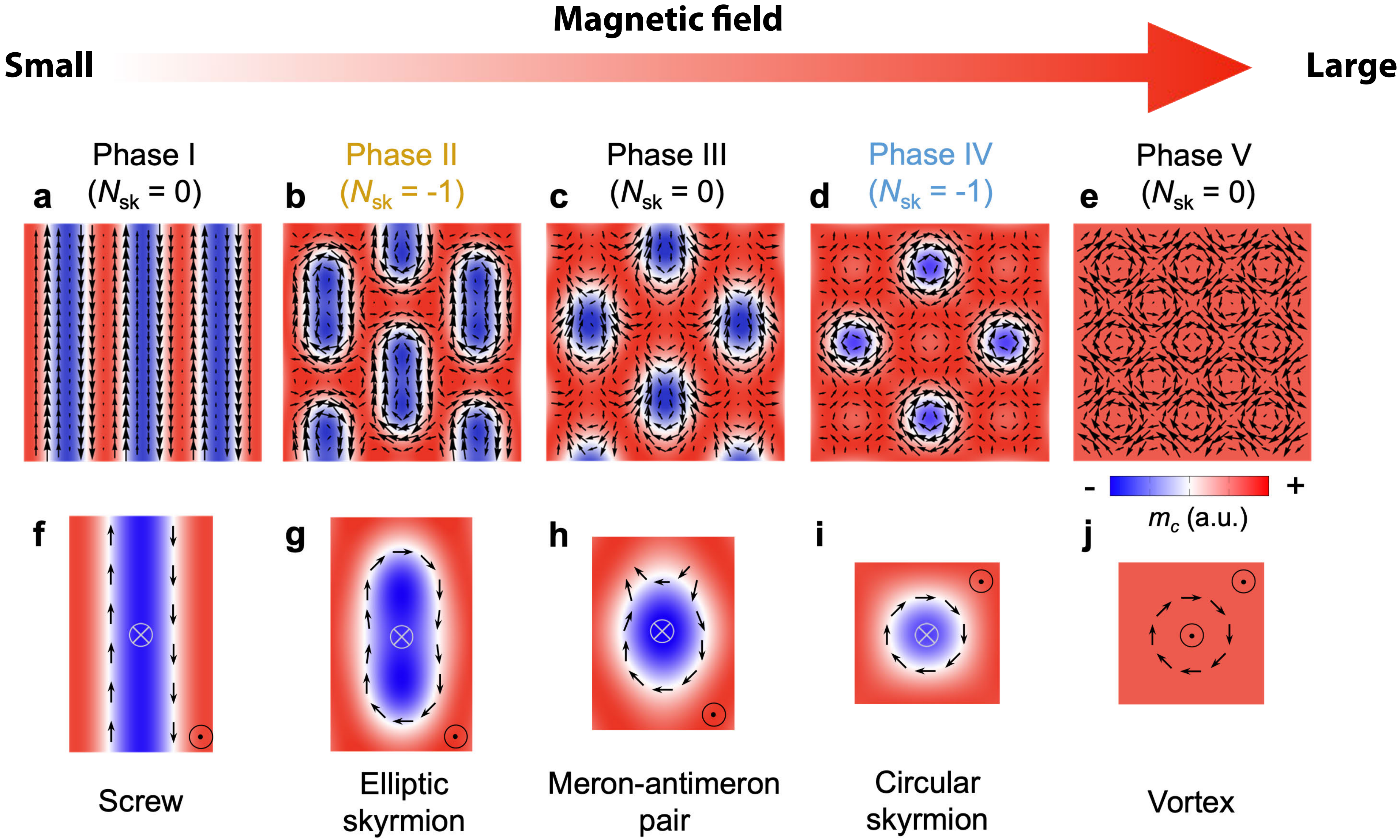


	(*q* 0 0)	(*q*/2 *q*/2 0)	(*q q* 0)	(0 0 0)
Phase II	m_x^1 = 1.0000 m_z^1 = 0.8865 m_x^2 = 0.5302 m_z^2 = 0.2201	$m_{[1\bar{1}0]}$ = 0.3852 m_z = 0.5900	$m_{[\bar{1}10]}$ = 0.082 m_z = 0.1524	m_z^0 = 0.2346 $M_z^{sat.}$
Phase III	m_x^1 = 0.7256 m_z^1 = 0.4386 $m_{//q}^1$ = 0.3027 m_x^2 = 0.4438 m_z^2 = 0.2326	$m_{[1\bar{1}0]}$ = 0.1394 m_z = 0.5768 $m_{//q}$ = 0.1021		m_z^0 = 0.4106 $M_z^{sat.}$
Phase IV	m_x = 1.0250 m_z = 0.4217	$m_{[1\bar{1}0]}$ = 0.2845 m_z = 0.5545	$m_{[1\bar{1}0]}$ = 0.0592 m_z = 0.1338	m_z^0 = 0.5718 $M_z^{sat.}$
Phase V	m_x = 0.4413			m_z^0 = 0.7206 $M_z^{sat.}$

$GdRu_2Ge_2$: Magnetic structure (Resonant X-ray scattering)

H. Yoshimochi, … , S. Seki, Nature Physics (2024).

Multiple-step topological transitions among skyrmion and meron crystal states

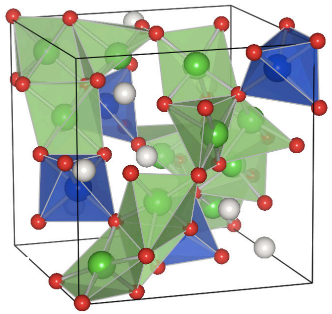


Summary

N. D. Khanh, …, S. Seki Nature Nanotech. **15**, 444 (2020).
R. Takagi, …, S. Seki Nature Comm. **13**, 1472 (2022).
H. Yoshimochi, …, S. Seki Nature Physics (2024).

Old strategy

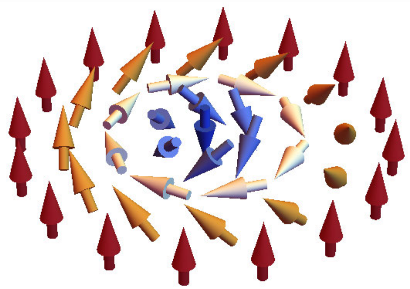
S. Seki *et al.*, Science (2012).



Noncentrosymmetric

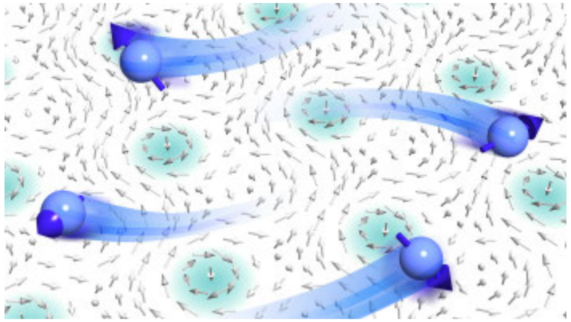
$$\vec{D}\cdot(\vec{S}_i \times \vec{S}_j)$$

DM interaction



10 - 200 nm

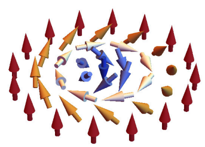
New strategy



Itinerant electron
+ Highly symmetric lattice

$$\tilde{J}\mathbf{S}_{\mathbf{Q}_\nu}\cdot\mathbf{S}_{-\mathbf{Q}_\nu}$$

RKKY interaction

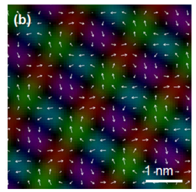


< 3 nm

One order of magnitude smaller skyrmion size

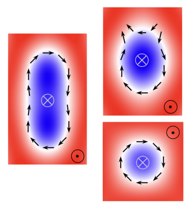
Higher information density

"Smallest" size of skyrmion



$GdRu_2Si_2$
N. D. Khanh, … , S. Seki
Nature Nanotech. (2020).

Rich variety of topological quasiparticles



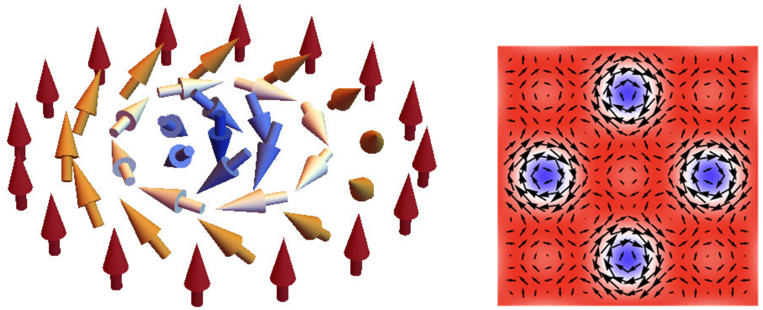
$GdRu_2Ge_2$
H. Yoshimochi, … , S. Seki
Nature Physics (2024).

Further search of RKKY-induced multi-*q* spin order

4*f* system

$GdRu_2Si_2$ & $GdRu_2Ge_2$

N. D. Khanh, …, S. Seki Nature Nanotech. (2020).
H. Yoshimochi, …, S. Seki Nature Physics (2024).

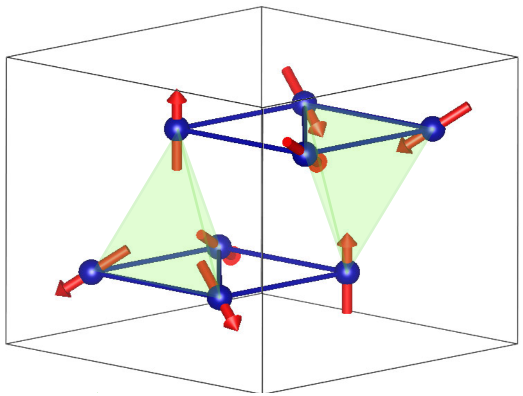


double-*Q* skyrmion lattice

3*d* system

$CoTa_3S_6$ & $CoNb_3S_6$

H. Takagi, …, S. Seki
Nature Physics **19**, 961 (2023).



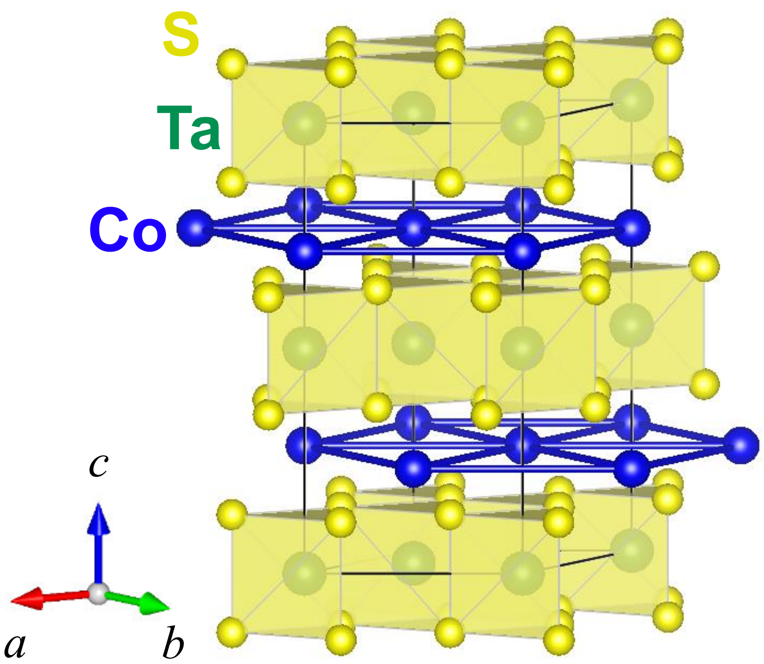
Triple-*Q* non-coplanar AFM order

$CoTa_3S_6$: Intercalated van der Waals antiferromagnet

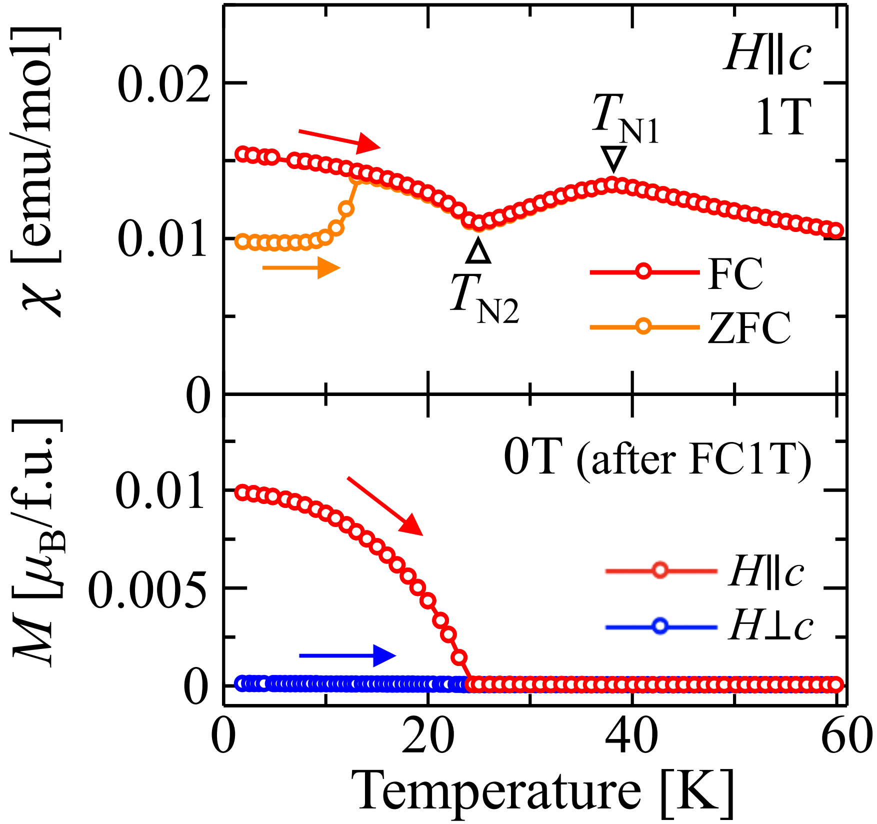
S. S. P. Parkin *et al.*, Phil. Mag. B **41**, 65 (1980).

H. Takagi, …, S. Seki, Nature Physics **19**, 961 (2023).

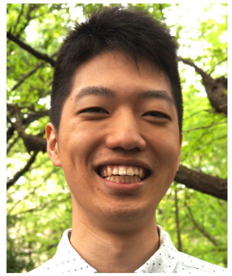
$P6_322$



2H-TaS_2 + Co-intercalation



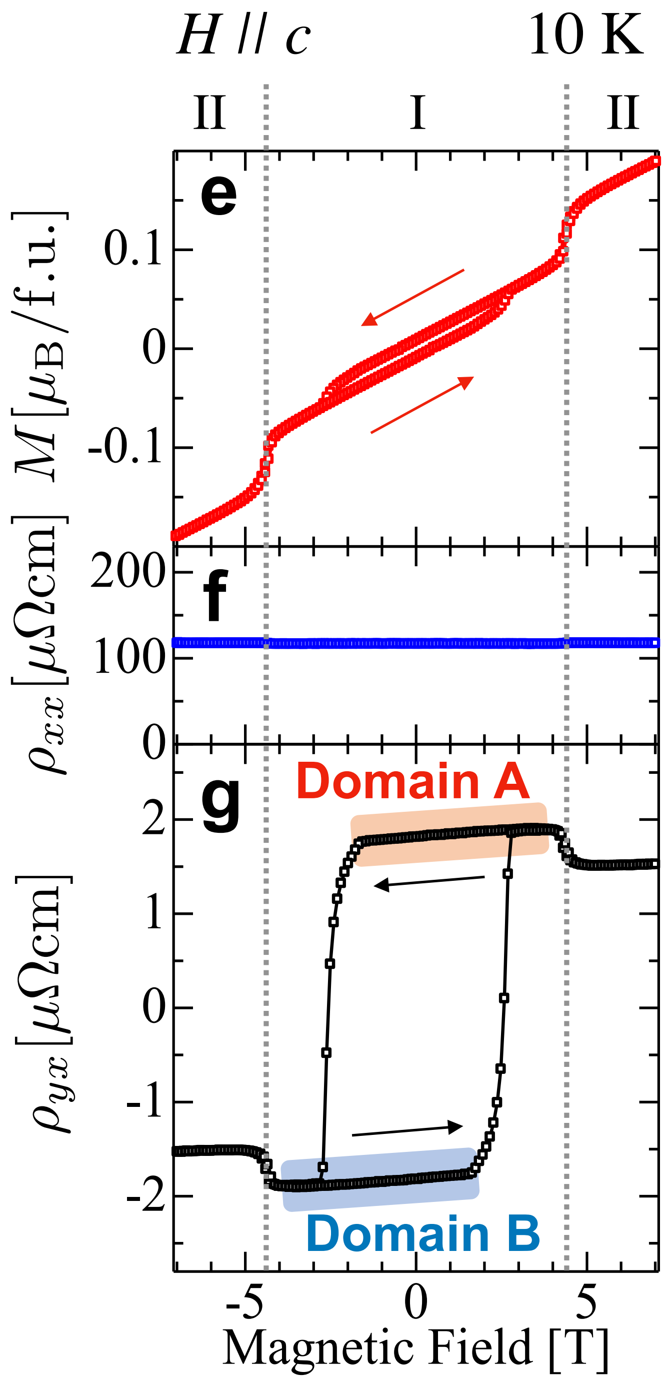
- **Chiral hexagonal crystal structure**
- AFM order below T_N ~ 36K
- **Weak spontaneous *M* || [001]** (~ 0.01μ_B/Co)

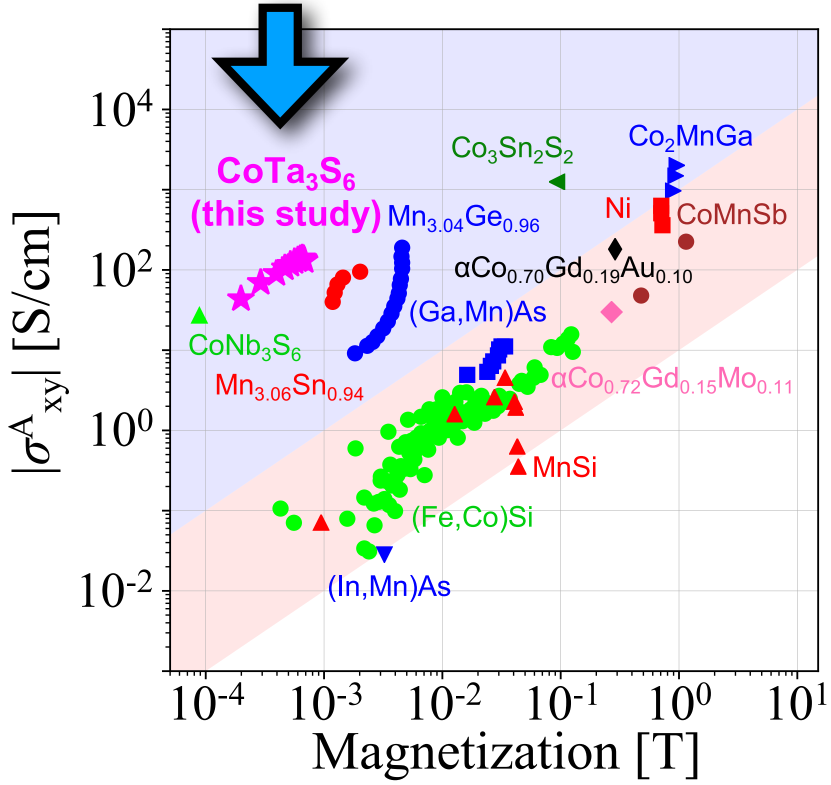


H. Takagi

$CoTa_3S_6$: Giant spontaneous Hall effect

H. Takagi, …, S. Seki, Nature Physics **19**, 961 (2023).





- **Giant spontaneous Hall effect, not proportional to *M***
  (ρ_{yx}/ρ_{xx} ~ 2%)

→ **Time-reversal-symmetry-broken** AFM order?

Magnetic Structure Analysis by Neutron Scattering

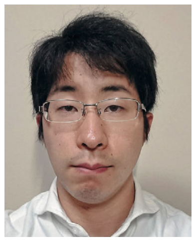
➢ JRR-3

https://jrr3.jaea.go.jp/

5G PONTA

Polarized Neutron Scattering

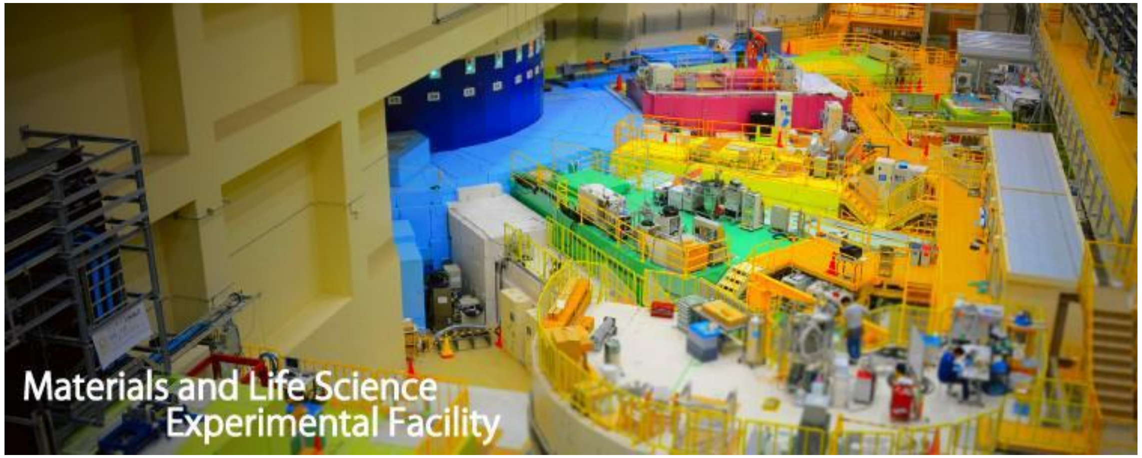
https://sites.google.com/view/issp-nsl/home



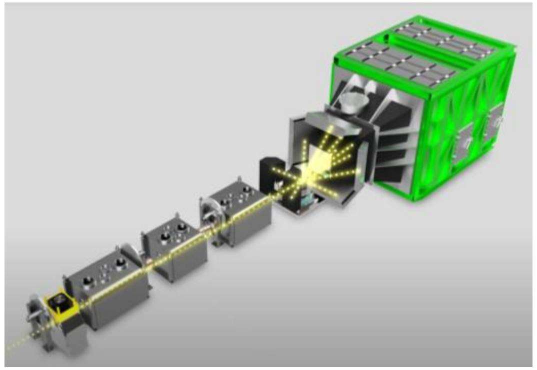
T. Nakajima, H. Saito
(ISSP, University of Tokyo)

➢ J-PARC

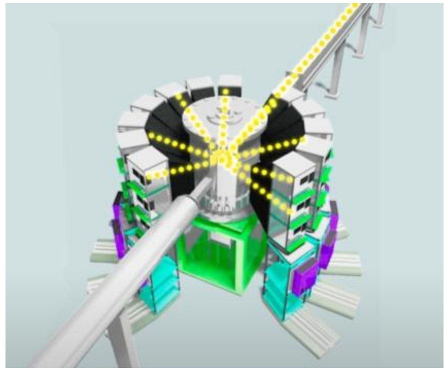
https://mlfinfo.jp/ja/



BL15 (TAIKAN)



BL18 (SENJU)



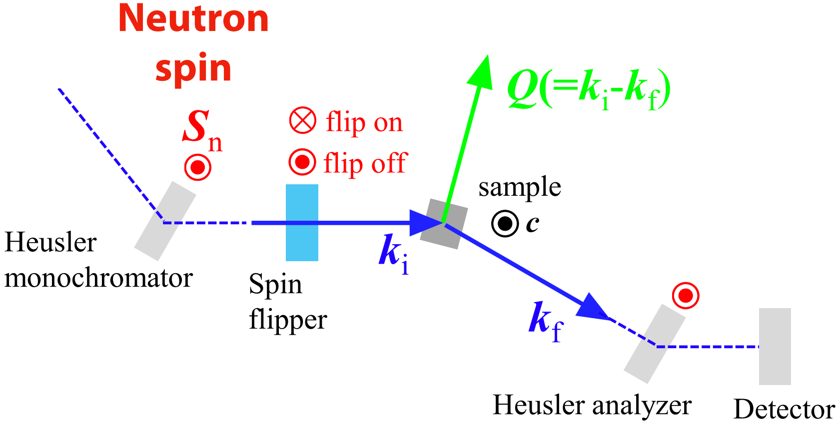
CROSS YouTube

K. Ohishi
(CROSS)

R. Kiyanagi
(J-PARC)

$CoTa_3S_6$: Polarized neutron scattering

@ 5G PONTA, JRR-3

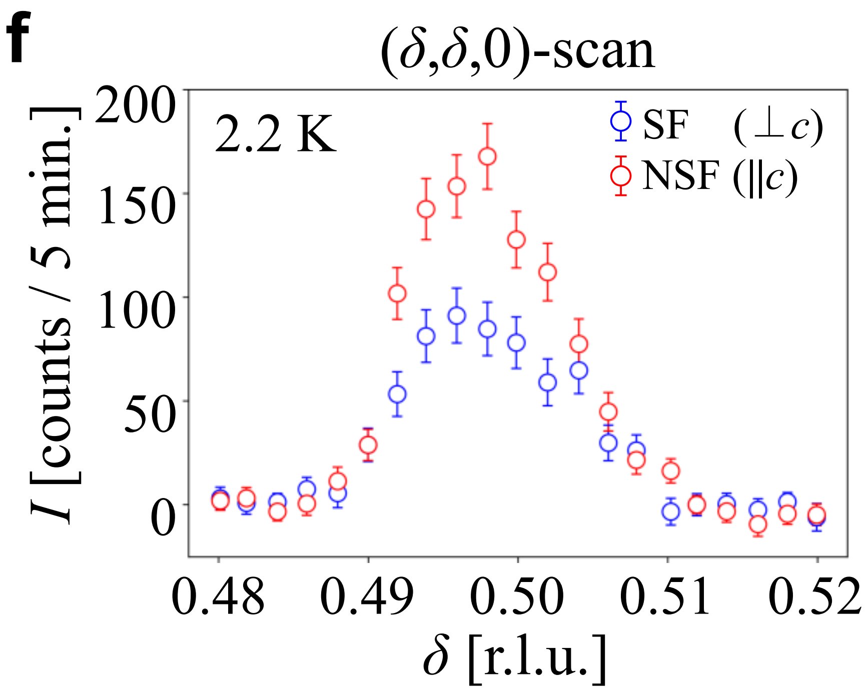


Spin-flip (SF) scattering

▶ $(m_q \perp S_n)$ and $(m_q \perp Q)$ → **In-plane spin component**

Non-spin-flip (NSF) scattering

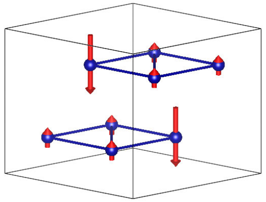
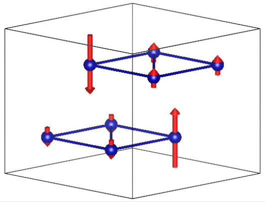
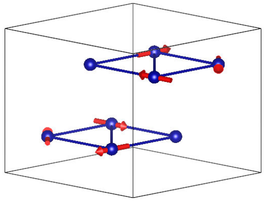
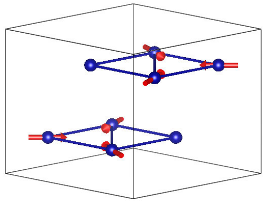
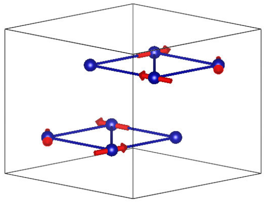
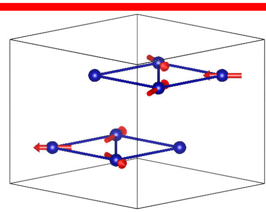
▶ $(m_q \parallel S_n)$ and $(m_q \perp Q)$ → **Out-of-plane spin component**



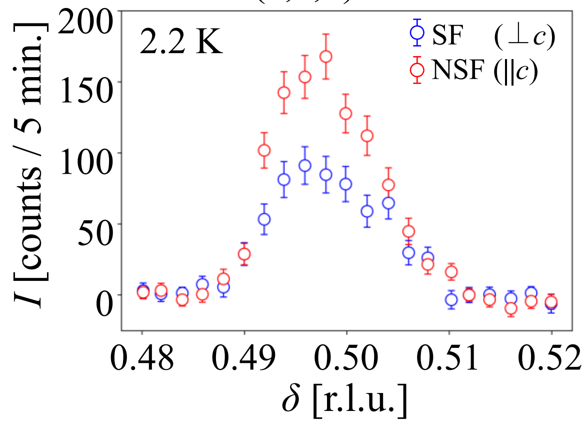
▶ **Both in-plane and out-of-plane spin components coexist**

▶ **Non-coplanar spin texture ?**

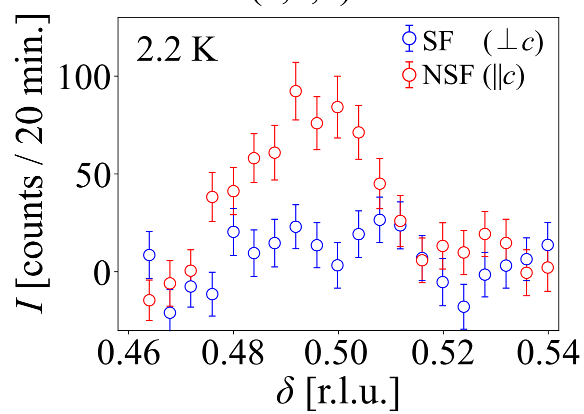
$CoTa_3S_6$: Representation Analysis

Basis	MPG	σ (M=0)	$\tilde{\boldsymbol{m}}^{\perp}(\frac{1}{2}\,0\,0)$	$\tilde{\boldsymbol{m}}^{\perp}(\frac{1}{2}\,\frac{1}{2}\,0)$	Channel	Structure
1	62'2'	$\begin{pmatrix}\sigma_{xx} & \sigma_{xy} & 0\\ -\sigma_{xy} & \sigma_{yy} & 0\\ 0 & 0 & \sigma_{zz}\end{pmatrix}$	$\frac{4}{3}S\mathbf{e}_Z$	$-\frac{8}{3}S\mathbf{e}_Z$	NSF	
2	6'22'	$\begin{pmatrix}\sigma_{xx} & 0 & 0\\ 0 & \sigma_{yy} & 0\\ 0 & 0 & \sigma_{zz}\end{pmatrix}$	$-\frac{4\sqrt{3}}{3}Si\mathbf{e}_Z$	0	NSF	
3	62'2'	$\begin{pmatrix}\sigma_{xx} & \sigma_{xy} & 0\\ -\sigma_{xy} & \sigma_{yy} & 0\\ 0 & 0 & \sigma_{zz}\end{pmatrix}$	$2\sqrt{3}Si\mathbf{e}_Y$	0	SF	
4	622	$\begin{pmatrix}\sigma_{xx} & 0 & 0\\ 0 & \sigma_{yy} & 0\\ 0 & 0 & \sigma_{zz}\end{pmatrix}$	0	0	-	
5	6'22'	$\begin{pmatrix}\sigma_{xx} & 0 & 0\\ 0 & \sigma_{yy} & 0\\ 0 & 0 & \sigma_{zz}\end{pmatrix}$	$2S\mathbf{e}_Y$	0	SF	
6	6'22'	$\begin{pmatrix}\sigma_{xx} & 0 & 0\\ 0 & \sigma_{yy} & 0\\ 0 & 0 & \sigma_{zz}\end{pmatrix}$	0	$-4S\mathbf{e}_Y$	SF	

(1/2,1/2,0) (δ,δ,0)-scan

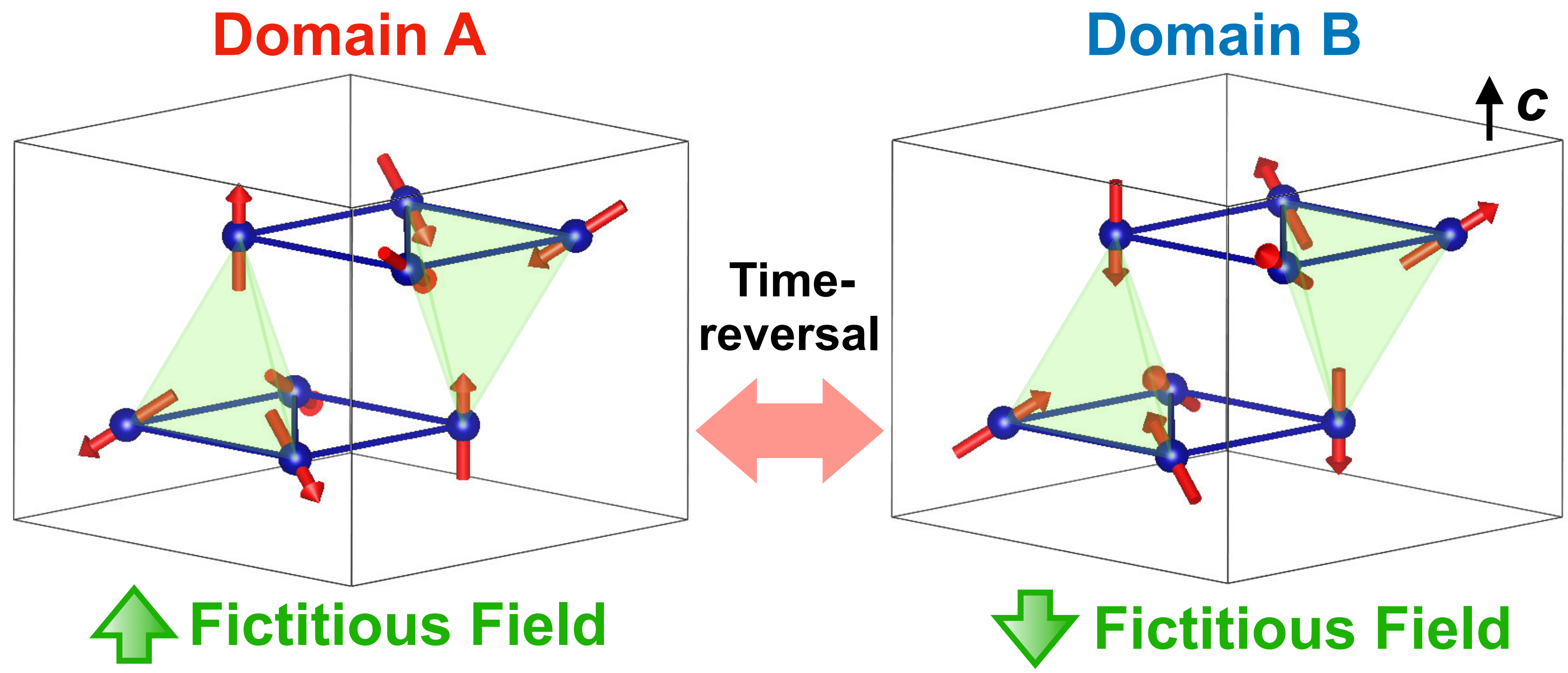


(1/2,0,0) (δ,0,0)-scan



Magnetic structure is described by linear combination of Bases 1 and 6

$CoTa_3S_6$: "All-in-all-out" non-coplanar AFM order



$$32'$$

$$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ -\sigma_{xy} & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{zz} \end{pmatrix}$$

- Time-reversal symmetry is **broken**
- Magnetic symmetry allows **non-zero σ_{xy}**
  → **Fictitious magnetic field** along [001]

Spontaneous topological Hall effect

Fictitious field due to **real-space Berry phase**

$$|\mathbf{b}| \propto \underline{\mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k)}$$

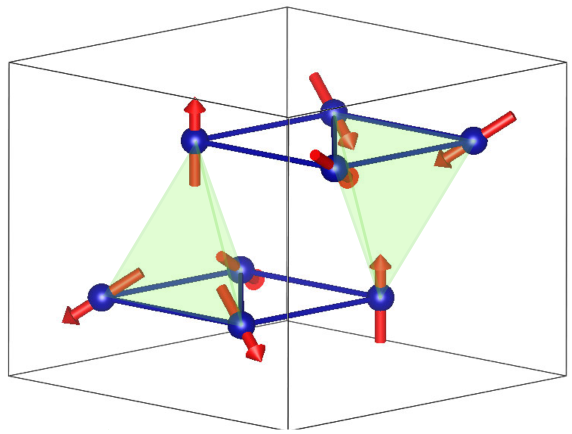
scalar spin chirality

$CoTa_3S_6$: RKKY-driven triple-Q spin texture ?

"All-in-all-out" non-coplanar AFM order

Spontaneous **topological** Hall effect

H. Takagi, …, S. Seki
Nature Physics **19**, 961 (2023).



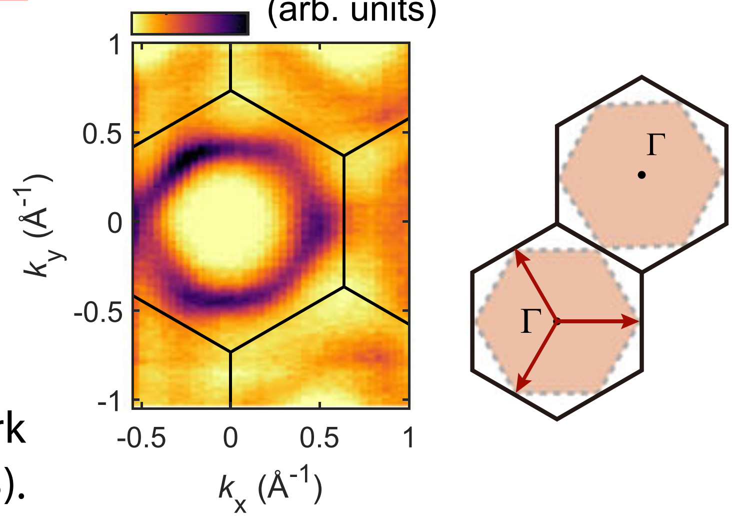
RKKY-driven triple-Q order ?

$$H = -t\sum_{\langle i,j\rangle} c^{\dagger}_{i\alpha} c_{j\alpha} - J\sum_{i} \boldsymbol{S}_i \cdot c^{\dagger}_{i\alpha} \boldsymbol{\sigma}_{\alpha\beta} c_{i\beta}.$$

3 **nesting** vectors with 3/4 filling

P. Park, …, C. D. Batista, J-G. Park
Nature Commun. **14**, 8346 (2023).

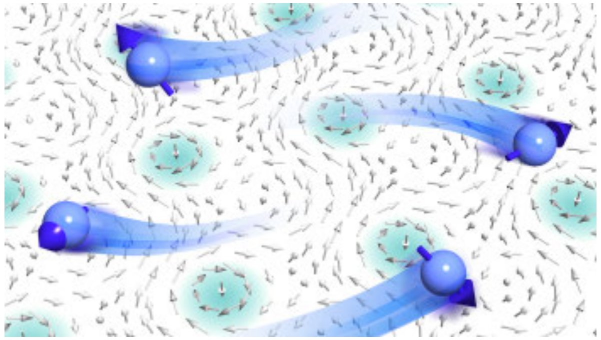
Fermi-surface (ARPES)

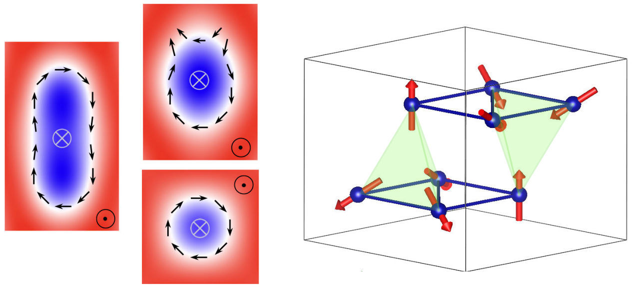


RKKY-driven mechanism also works well in 3*d* electron systems !

Outline

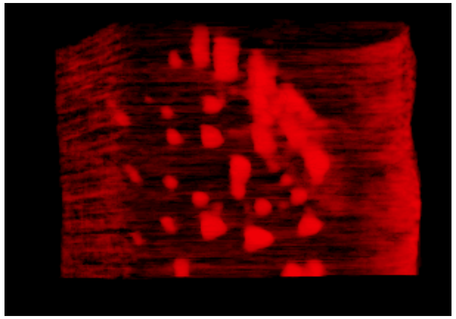
Nanometric skyrmions in centrosymmetric magnets

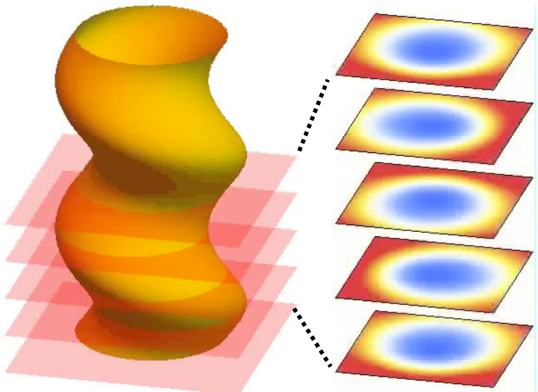




N. D. Khanh, …, S. Seki, Nature Nanotech. **15**, 444 (2020).
H. Takagi, …, S. Seki, Nature Physics **19**, 961 (2023).
H. Yoshimochi, …, S. Seki, Nature Physics (2024).

3D visualization and dynamics of skyrmion strings

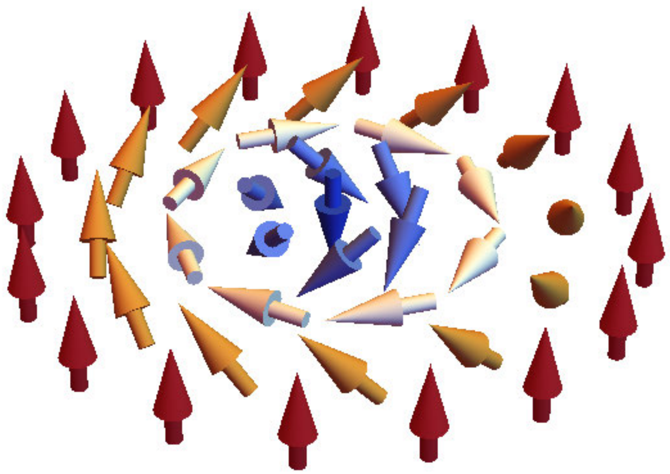




S. Seki *et al.*, Nature Materials **21**, 181 (2022).
S. Seki *et al.*, Nature Comm. **11**, 256 (2020).

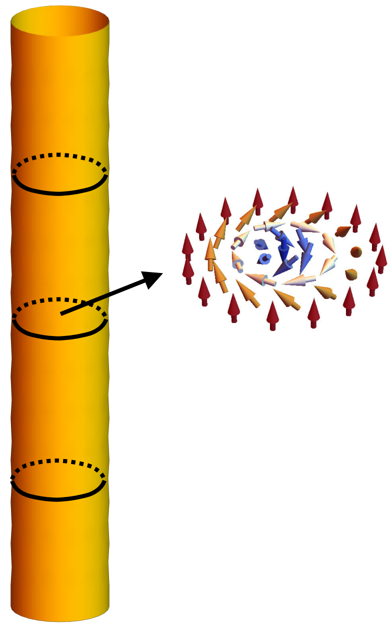
Skyrmion Particle and Skyrmion String

2D system



▶ **Skyrmion particle**

3D system



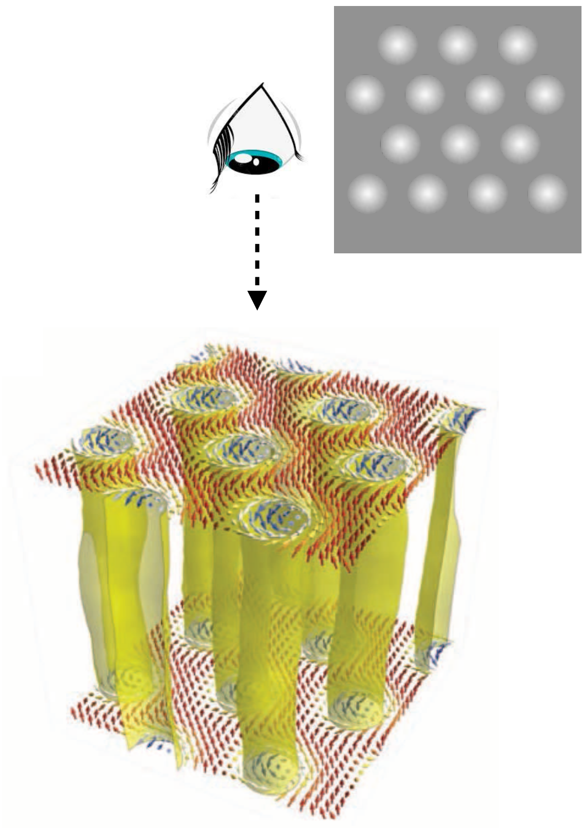
▶ **Skyrmion string**

Information bit

Information Transmission Line ?

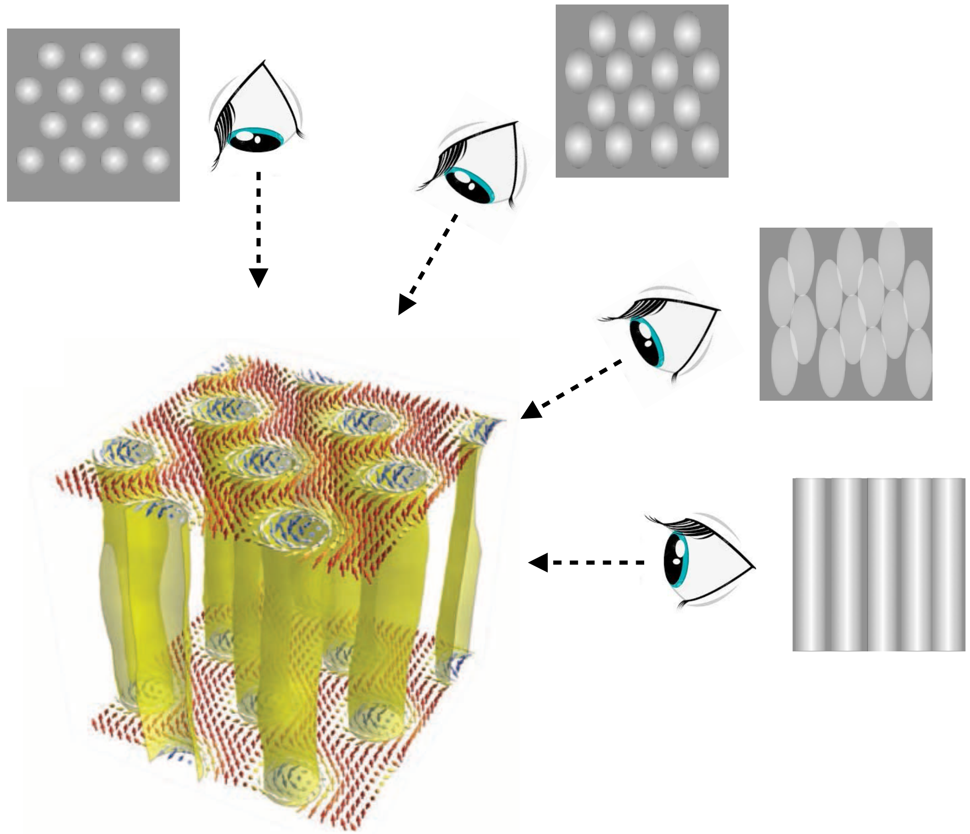
How to visualize 3D spin texture ?

Traditional approach



- Only **2D** information is obtained (averaged over depth direction)

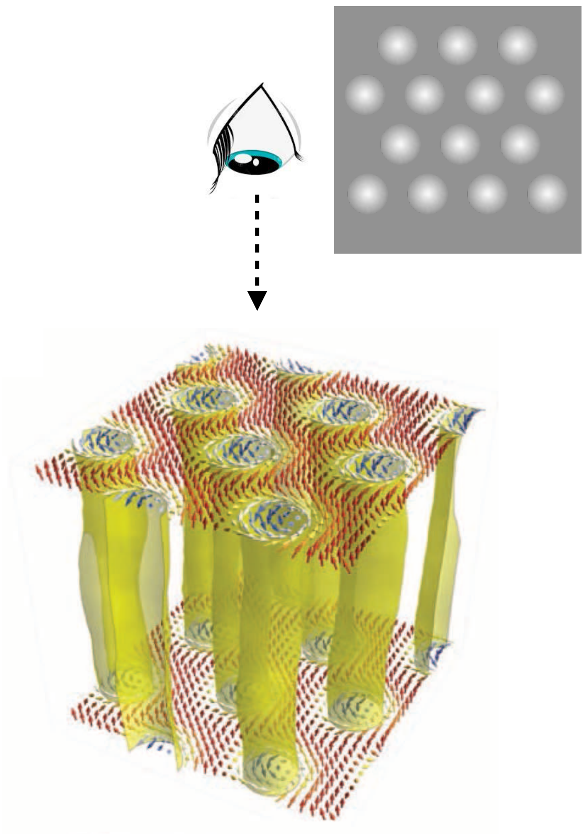
New approach



- **3D** distribution of local *M* is estimated from 2D images taken from various angles

How to visualize 3D spin texture ?

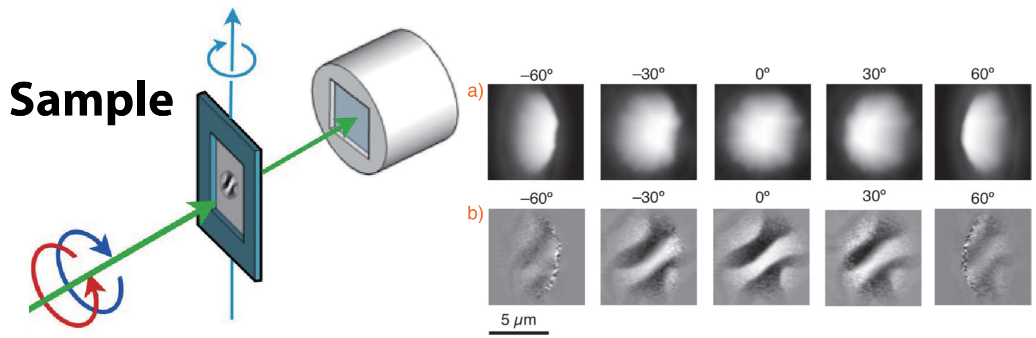
Traditional approach



▶ Only **2D** information is obtained (averaged over depth direction)

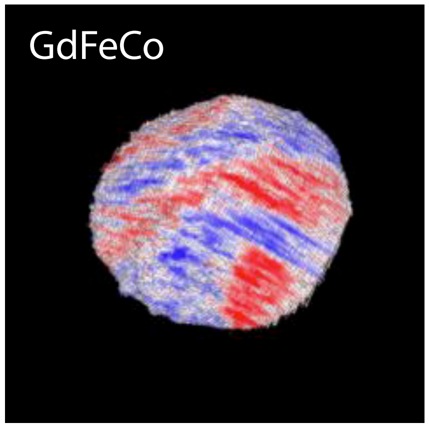
New approach

X-ray magnetic tomography



C. Donnelly *et al.*, Nature **547**, 328 (2017).

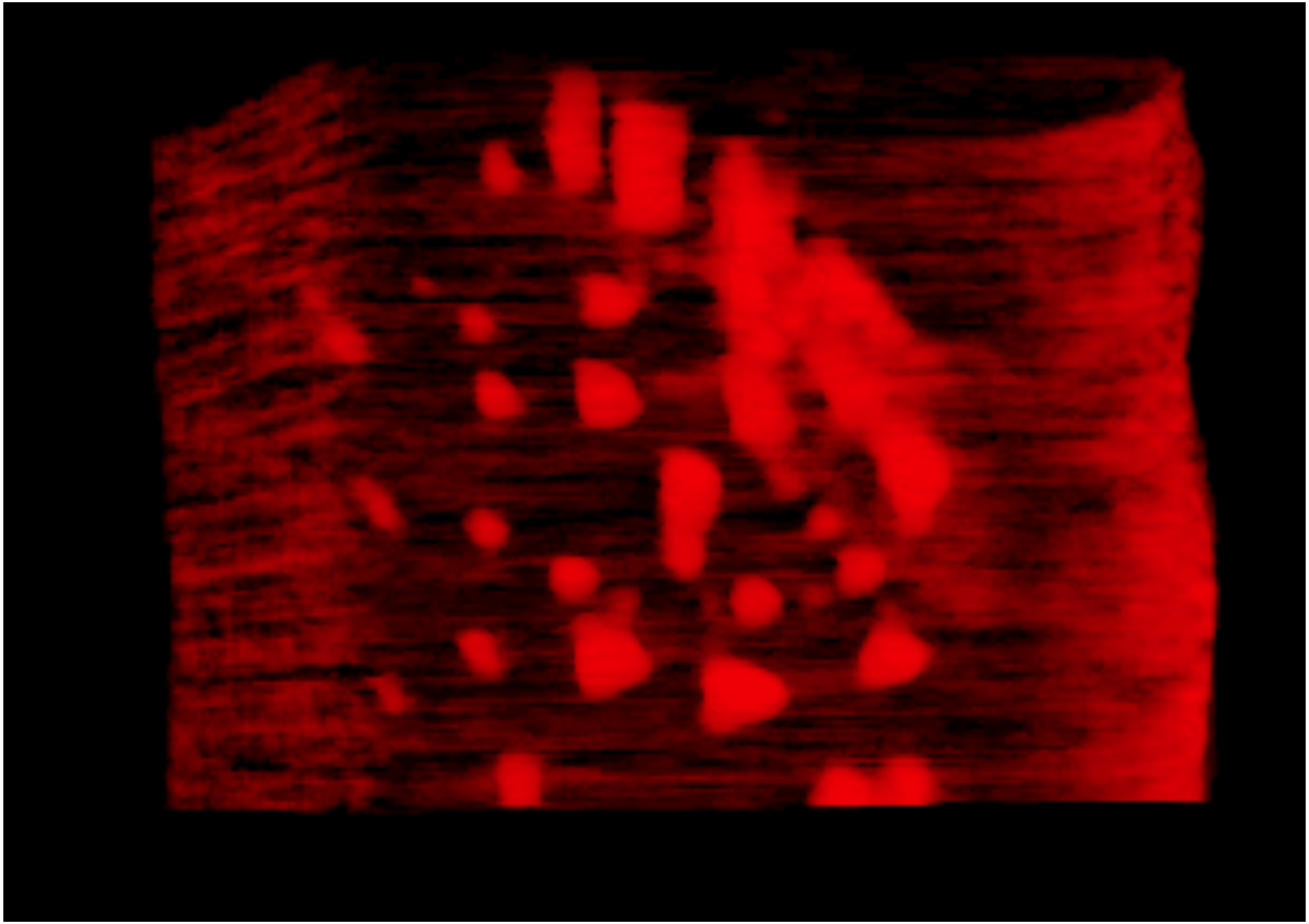
M. Suzuki, T. Ono *et al.*, APEX **11**, 036601 (2018).



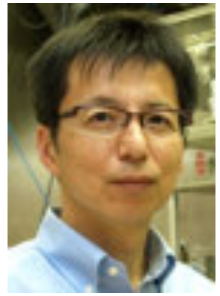
▶ **3D** distribution of local *M* is estimated from 2D images taken from various angles

$Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$: Reconstructed 3D distribution of $m_{[001]}$

S. Seki, M. Suzuki, T. Ono *et al.*, Nature Materials **21**, 181 (2022).



BL39XU@Spring8



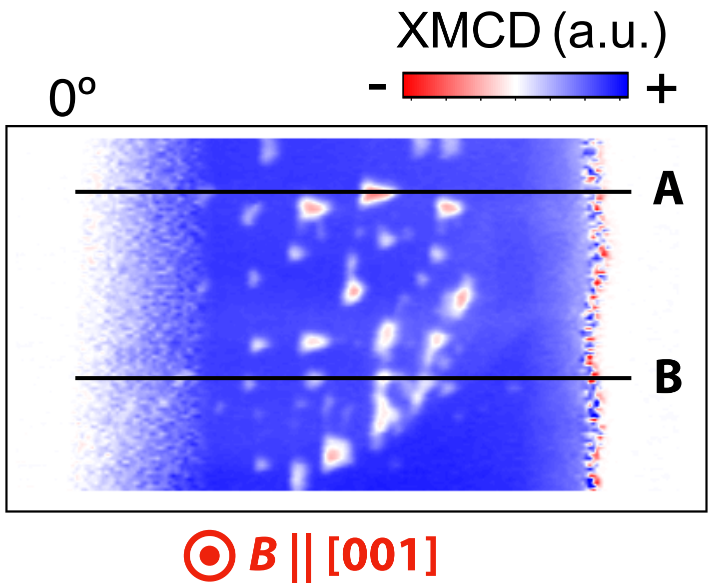
M. Suzuki
(SPring8)

T. Ono
(Kyoto Univ.)

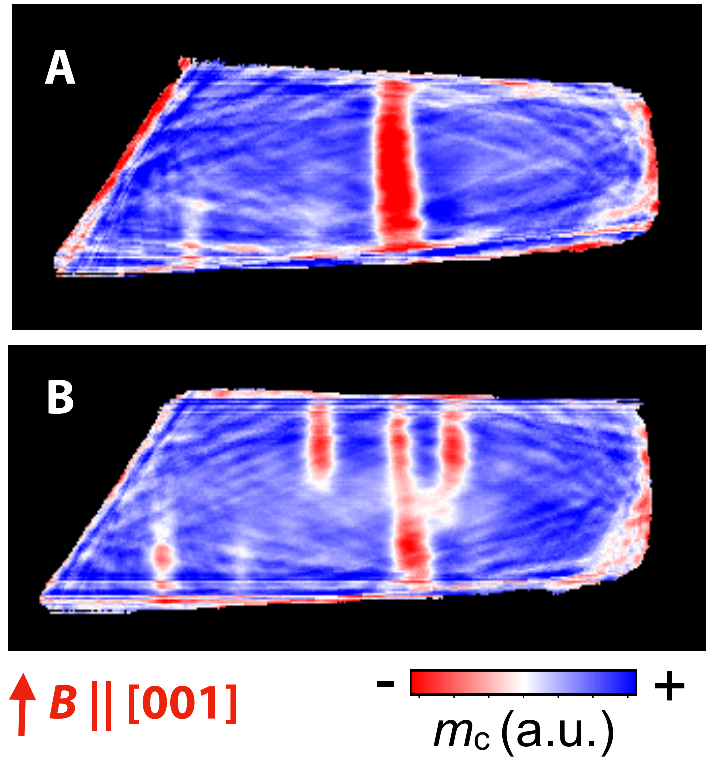
$Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$: 3D shape of skyrmion strings

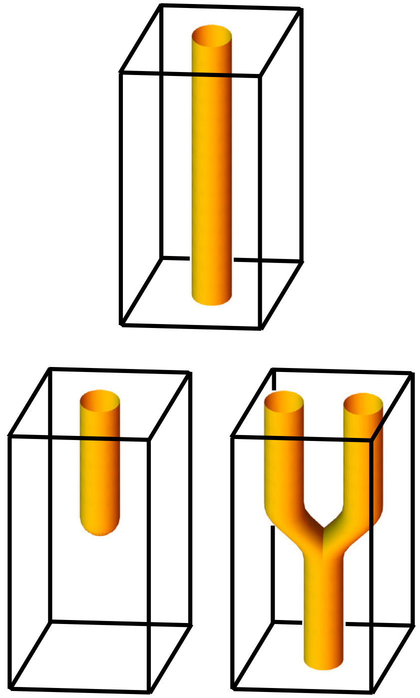
S. Seki, M. Suzuki, T. Ono *et al.*, Nature Materials **21**, 181 (2022).

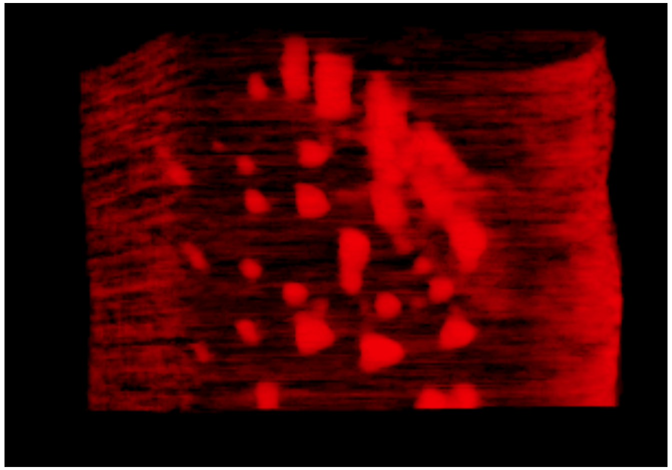
Top view



Side-view (Cross-section of reconstructed $m_{[001]}(r)$)



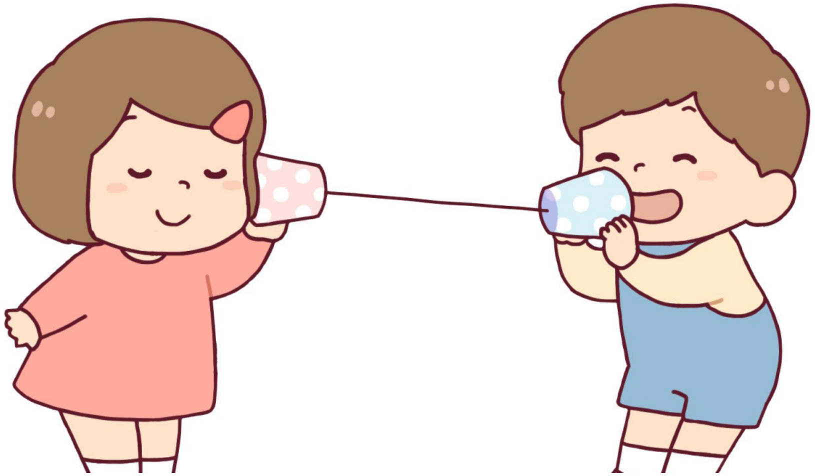


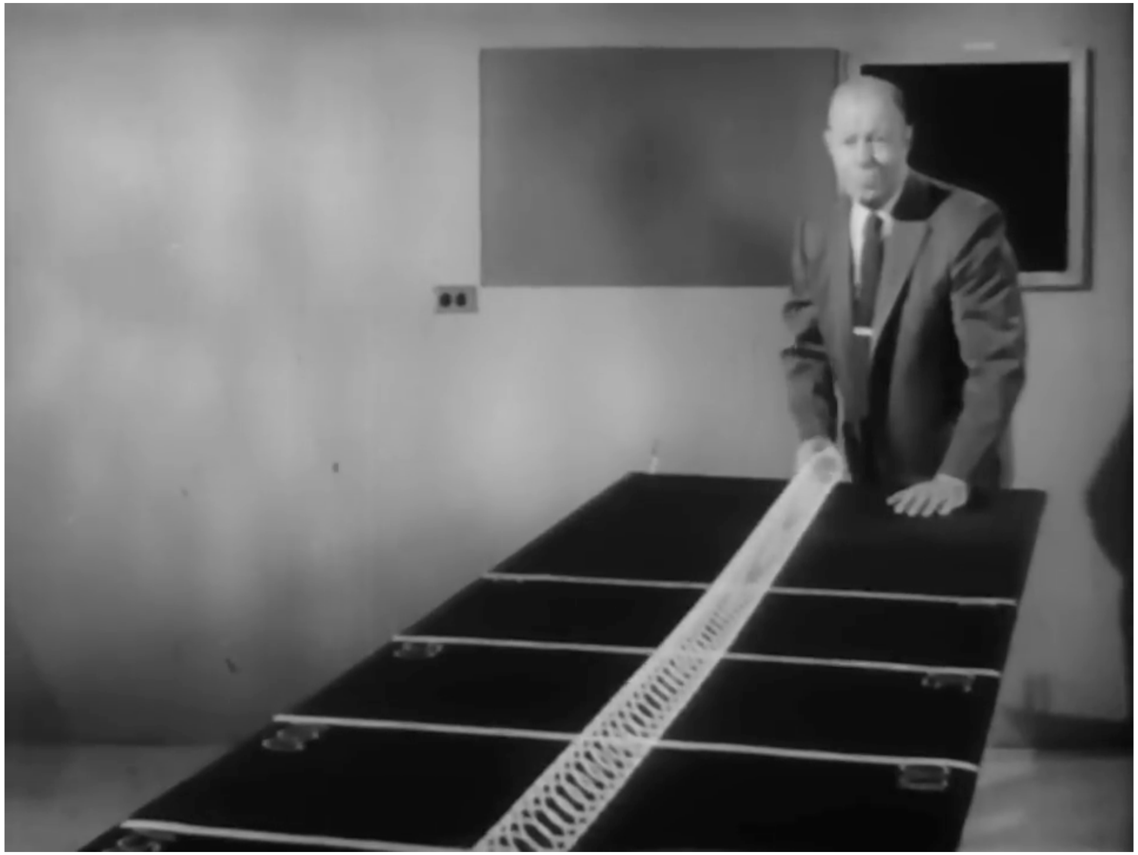


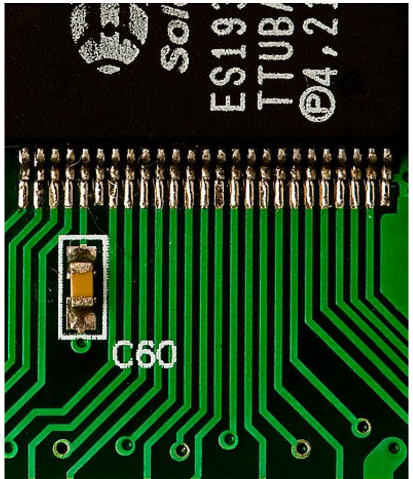
- **3D shape of skyrmion strings is directly visualized!**
- **Interrupted and Y-shaped strings are also identified (“Emergent magnetic monopole”)**

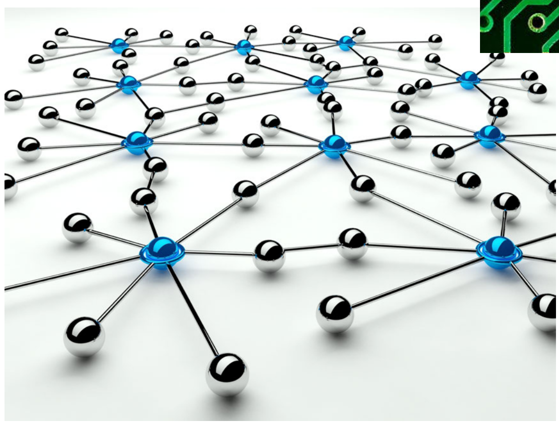
cf. Wolf *et al.*, Nature Nanotech. **17**, 250 (2022). [vector electron tomography]

Skyrmion String as Signal Transmission Line ?



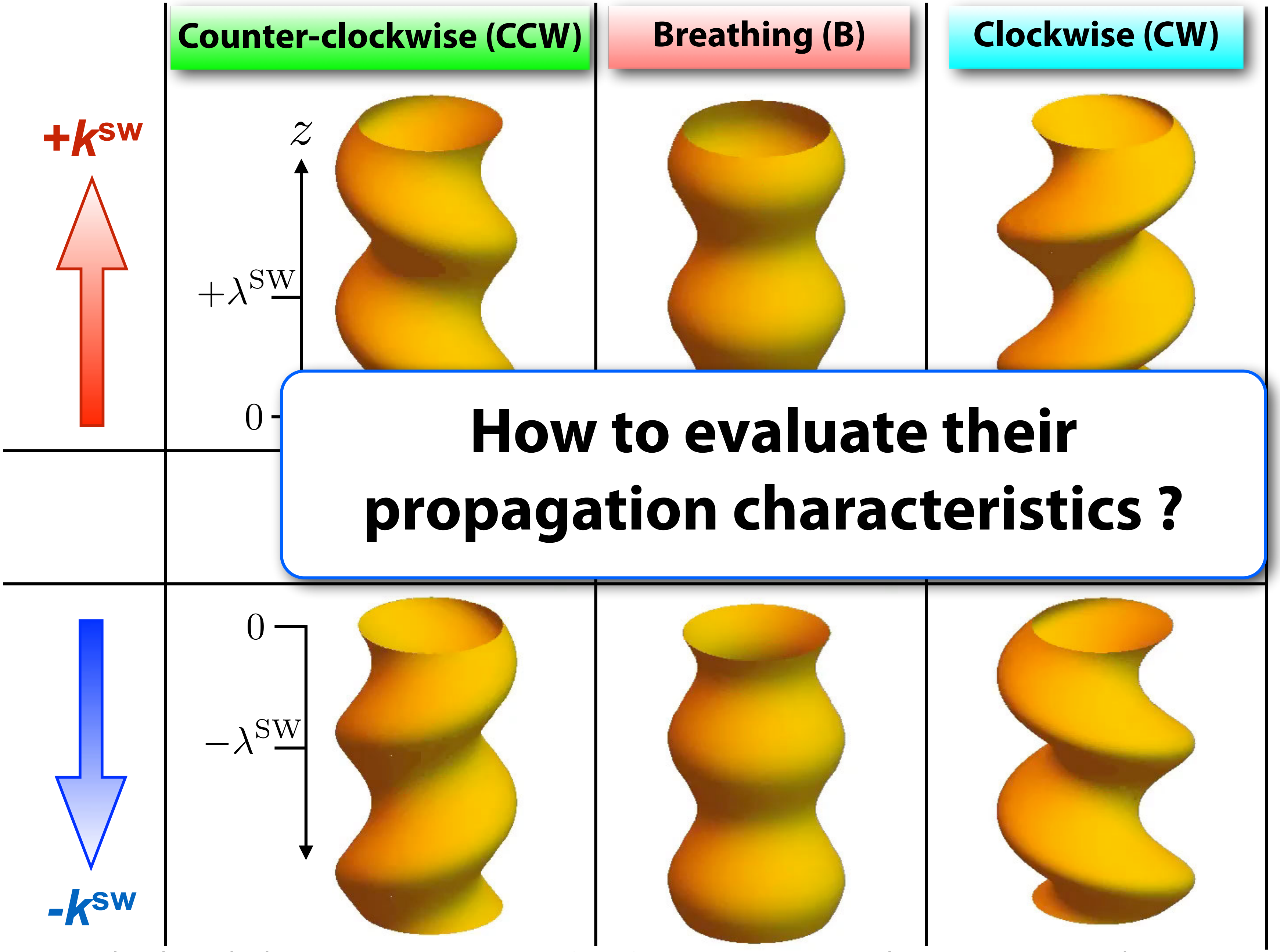






How about propagation characteristics of excitation on skyrmion strings ?

Propagating excitation modes on skyrmion strings



How to evaluate their propagation characteristics ?

M. Mochizuki
(Waseda Univ.)

M. Garst
(KIT)

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

Propagating Spin Wave Spectroscopy

V. Vlaminck and M. Bailleul,
Science **322**, 410 (2008).
Phys. Rev. B **81**, 014425 (2010).

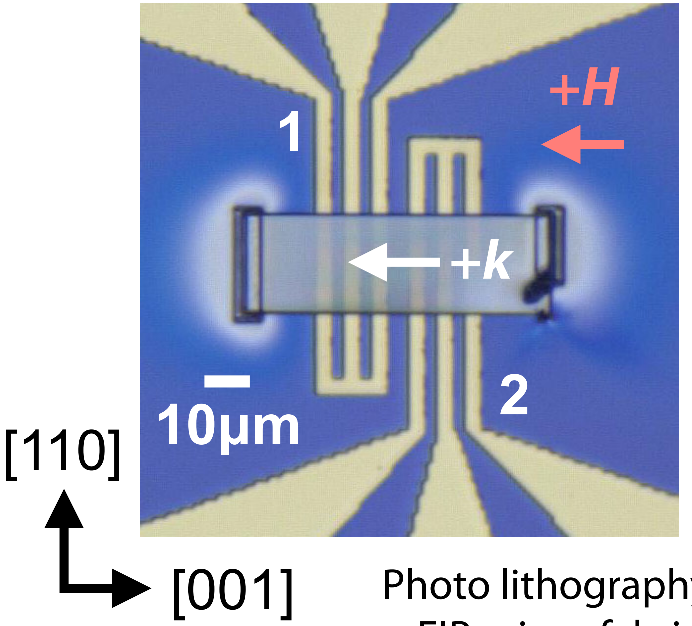
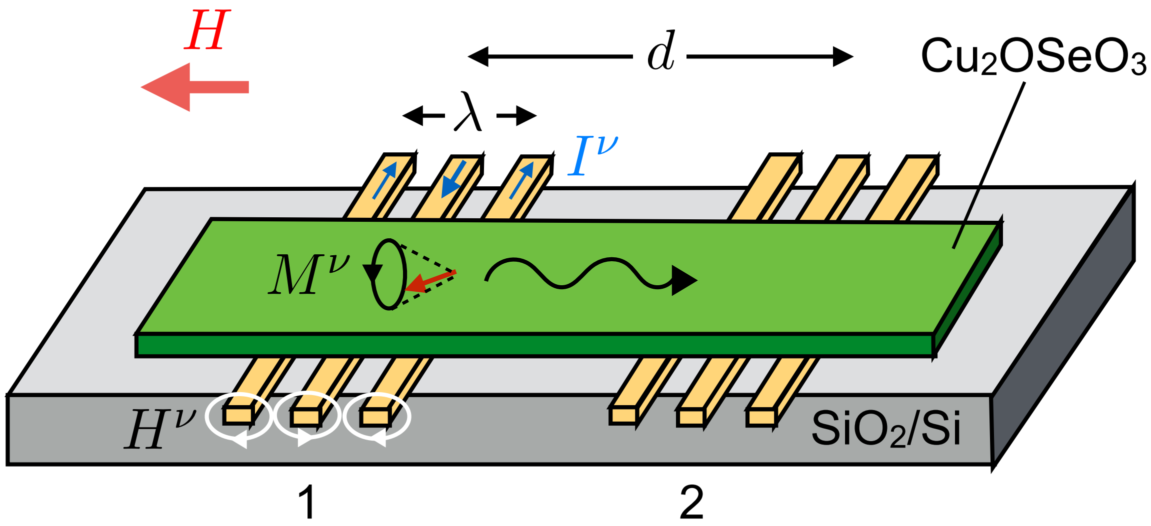


Photo lithography
+ FIB micro-fabrication



- Wavelength : λ~12µm
- Propagation gap : d ~ 20 µm

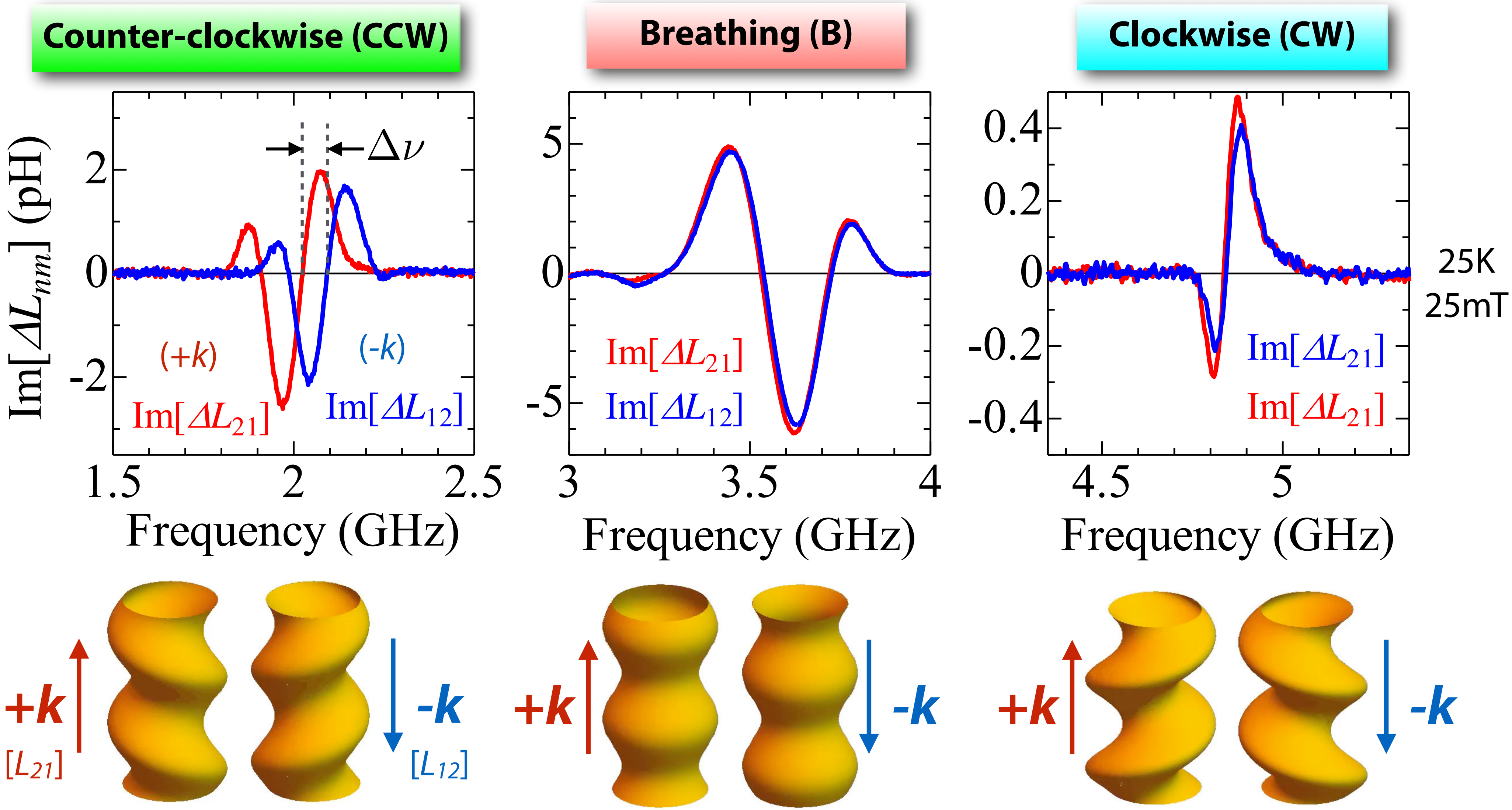
Vector Network Analyzer
+ Probe Station

$$V_n = \sum_m L_{nm} \frac{dI_m}{dt}$$

- Self-inductance (ΔL_{11}) : Magnon Excitation efficiency
- Mutual-inductance (ΔL_{21}) : Magnon **Propagation**

Propagating excitation on skyrmion strings

<u>S. Seki</u>, M. Garst *et al.*, Nature Communications **11**, 256 (2020).

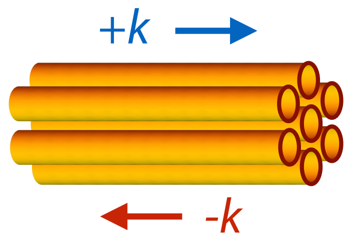


- **Three excitation modes are identified (i.e. consistent with theory)**
- **Decay length is more than 1000 times longer than skyrmion string diameter**

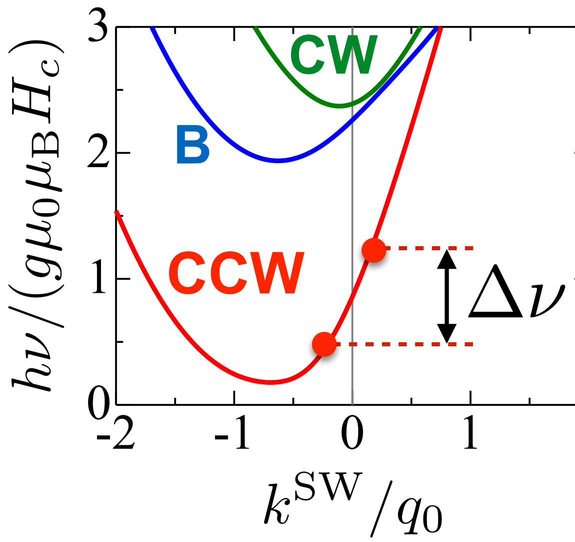
Nonreciprocal propagation of skyrmion string excitation

Theory

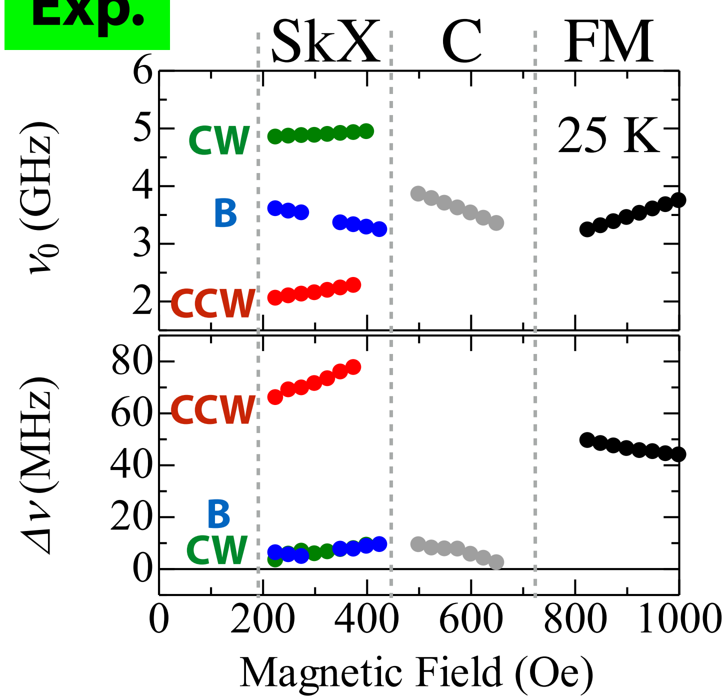
M. Garst & J. Waizner



- **Mode-dependent asymmetric dispersion**
- **CCW mode hosts largest asymmetry**

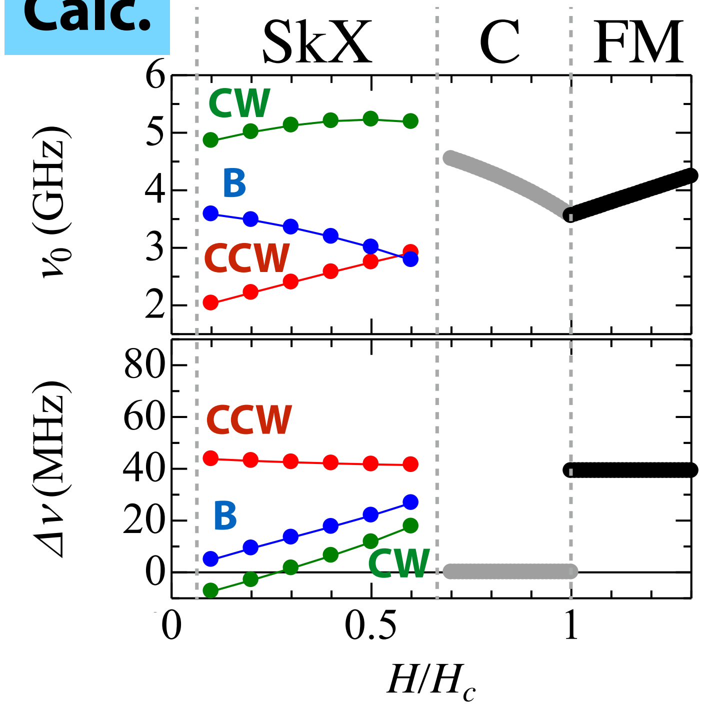


Exp.



Consistent!

Calc.

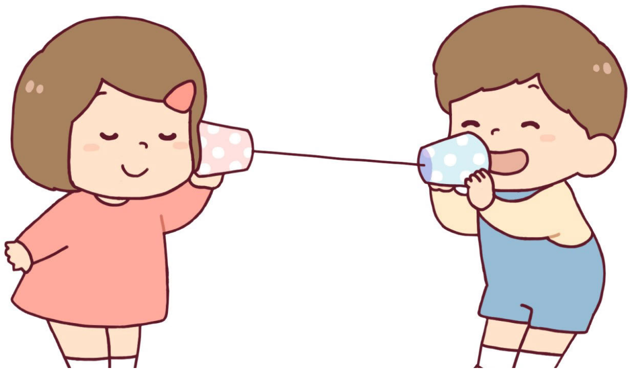


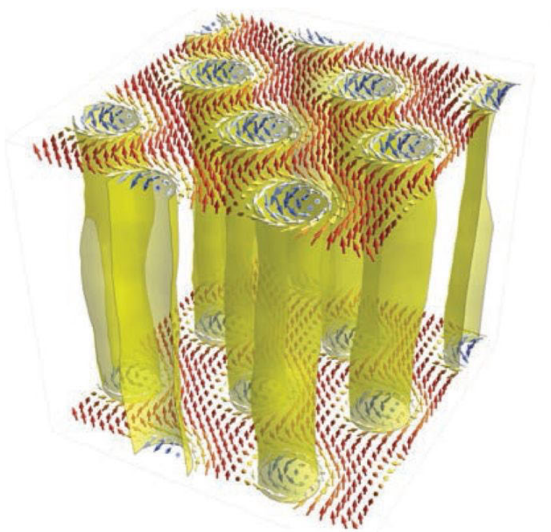
S. Seki, M. Garst *et al.*, Nature Commun. **11**, 256 (2020).

Skyrmion string as information transmission line ?

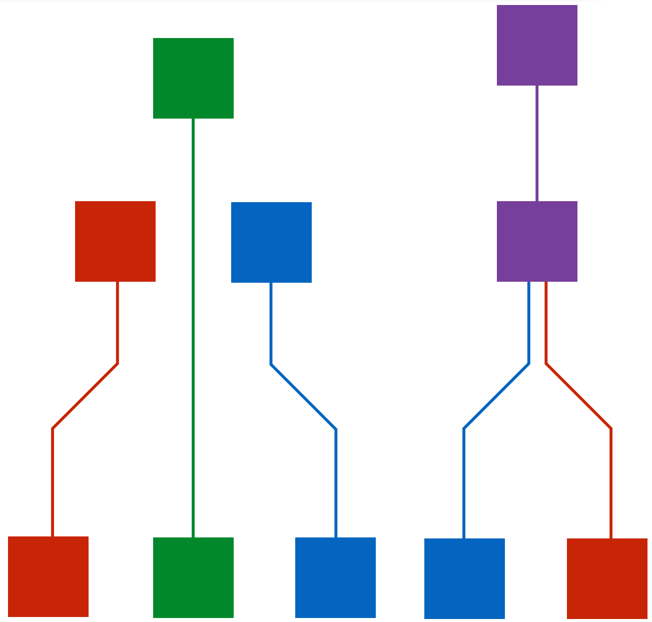
- Robust and flexible (due to topological protection)
- Excitation modes propagating through string path

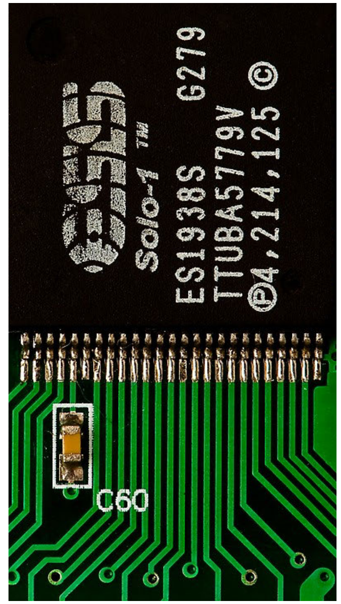
Ideal for information transmission line?





Skyrmion string network



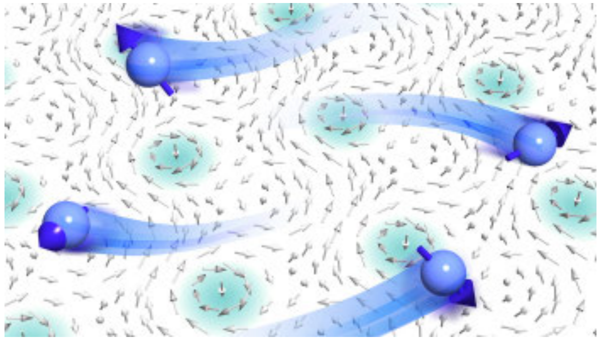


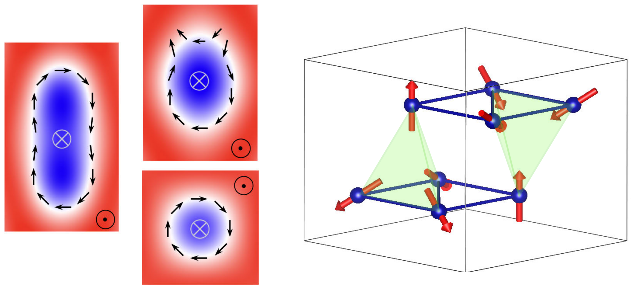
Signal transmission line (Skyrmion String)

Signal processing component

Outline

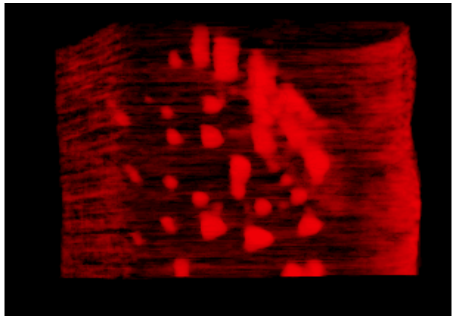
Nanometric skyrmions in centrosymmetric magnets

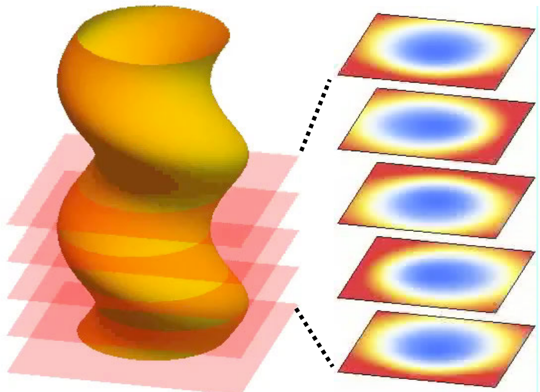




N. D. Khanh, …, S. Seki, Nature Nanotech. **15**, 444 (2020).
H. Takagi, …, S. Seki, Nature Physics **19**, 961 (2023).
H. Yoshimochi, …, S. Seki, Nature Physics (2024).

3D visualization and dynamics of skyrmion strings

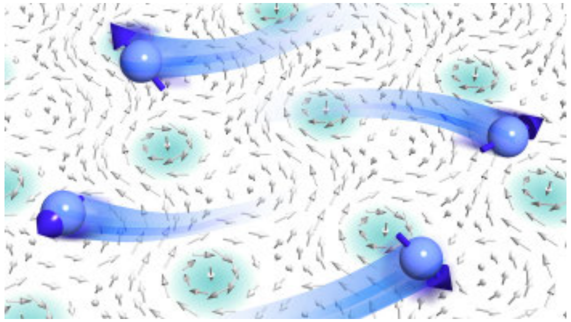


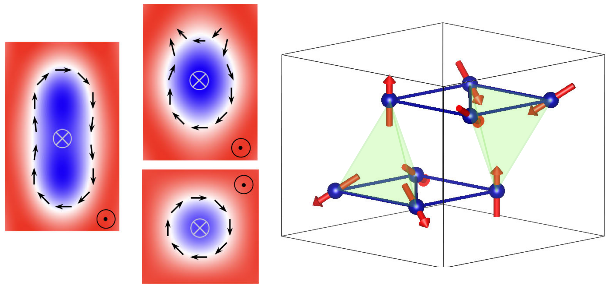


S. Seki *et al.*, Nature Materials **21**, 181 (2022).
S. Seki *et al.*, Nature Comm. **11**, 256 (2020).

Summary

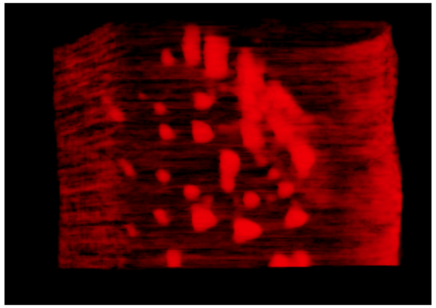
Nanometric skyrmions in centrosymmetric magnets





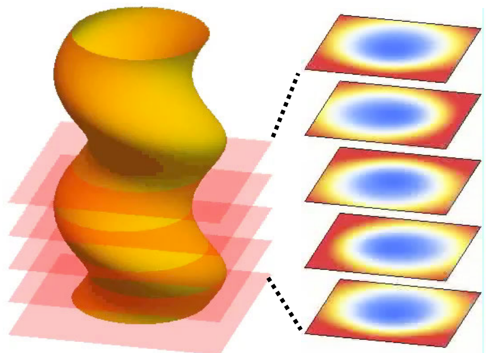
N. D. Khanh, …, S. Seki Nature Nanotech. **15**, 444 (2020).
Y. Yasui, …, S. Seki Nature Commun. **11**, 5925 (2020).
R. Takagi, …, S. Seki Nature Commun. **13**, 1472 (2022).
H. Takagi, …, S. Seki Nature Physics **19**, 961 (2023).
H. Yoshimochi, …, S. Seki Nature Physics (2024).

Direct visualization of 3D shape of skyrmion strings



S. Seki *et al.*, Nature Materials **21**, 181 (2022).

Information transfer by skyrmion string excitations



S. Seki *et al.*, Nature Comm. **11**, 256 (2020).

- **Magnetic skyrmion particle and string may be unique information media for novel spintronic devices**

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Our team

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N. D. Khanh (staff)

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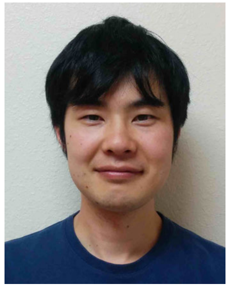
M. Mochizuki (theory)

M. Garst (theory)

J. S. White (Diffraction)

東京大学 THE UNIVERSITY OF TOKYO



Y. Otani (spin wave)

S. Hayami (theory)

Y. Motome (theory)

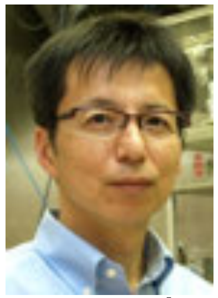
T. Nakajima (diffraction)

R. Arita, T. Kurumaji

T. Arima, T. Koretsune

K. Ishizaka, T. Nomoto

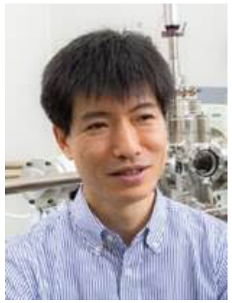
京都大学 KYOTO UNIVERSITY

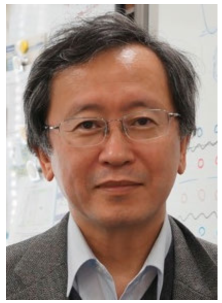


T. Ono, M. Suzuki (Tomography)

JASRI SPring-8

RIKEN CEMS





X. Z. Yu (TEM)

T. Hanaguri (STM)

Y. Tokura

Y. Yasui, K. Kondou

& etc etc…

Thank you!

e-mail:
seki@ap.t.u-tokyo.ac.jp