Topological effects on magnetic excitations in magnetic materials

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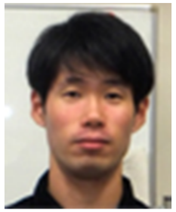
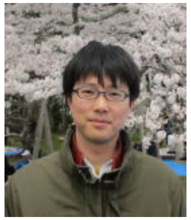
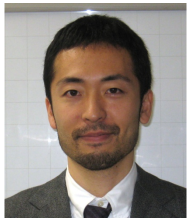
Yoshinori Onose

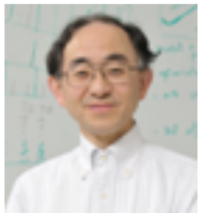
Collaborators

- Transport & crystal growth: T . Ideue, Y. Shiomi, S. Ishiwata, S. Seki


- Microwave: Y. Okamura

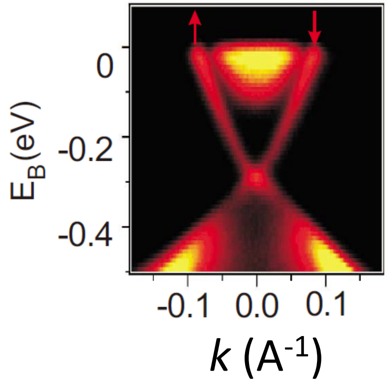
- Theory: H. Katsura, N. Nagaosa

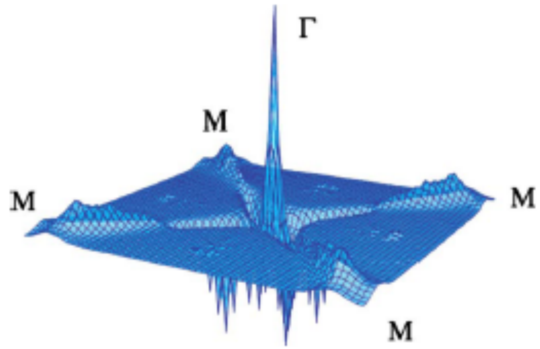
- Group Leader: Y. Tokura

Novel electromagnetic phenomena due to the topology of electronic state

- •Quantum Hall effect
- •Topological Insulator
- •Anomalous Hall effect
- •Spin Hall effect
- •etc



Hasan group



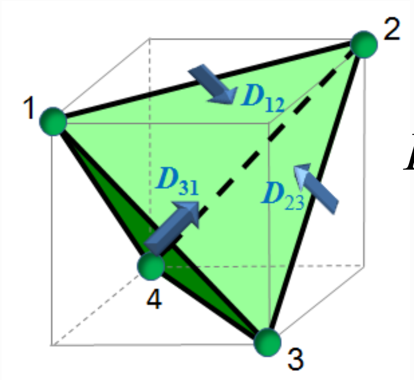
Fang-Nagaosa

How about topological phenomena relevant to magnetic oscillation (magnon)??

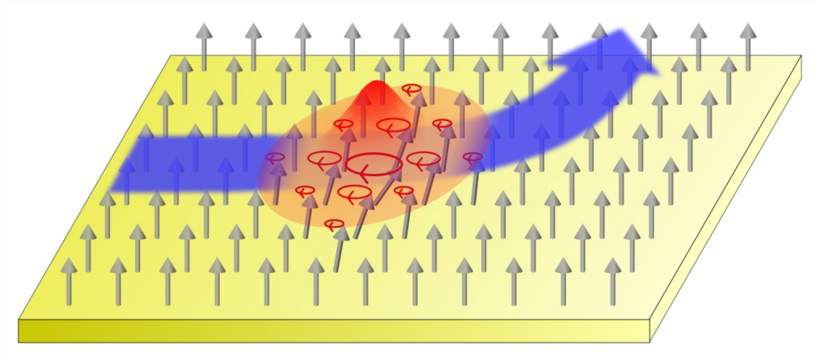
Contents of this talk

Observation of magnon Hall effect

Dzyaloshinskii-Moriya interaction



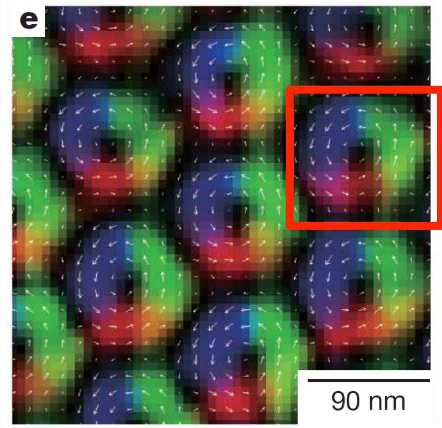
$$H_{DM} = D \cdot (\vec{S}_1 \times \vec{S}_2)$$

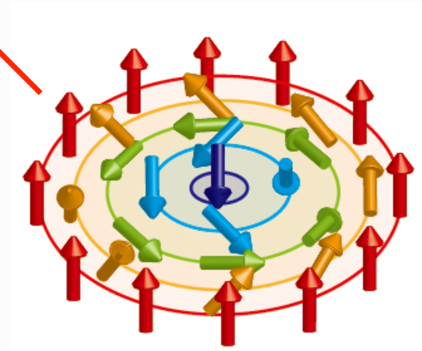


Y. Onose *et al.*, Science 2010

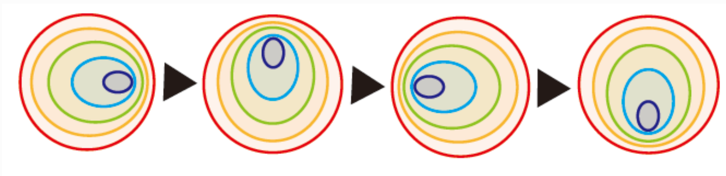
T. Ideue, Y. Onose *et al.*, PRB 2012

Observation of Magnetic excitations in skyrmion crystal

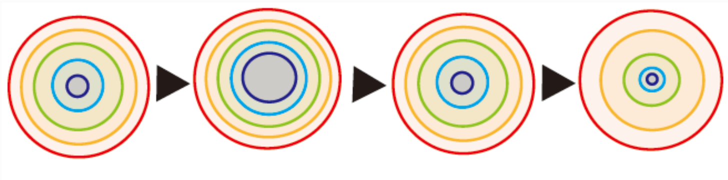




Rotation mode



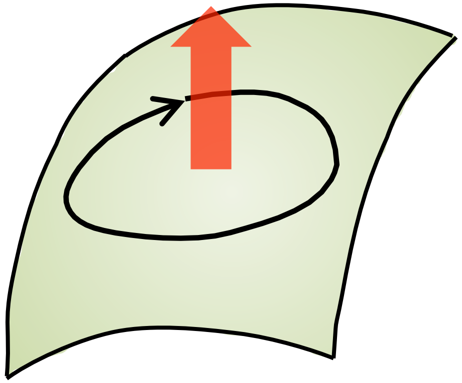
Breathing mode



Y. Onose *et al.*, PRL 2012

Observation of magnon Hall effect

Quantum phase=Effective magnetic field

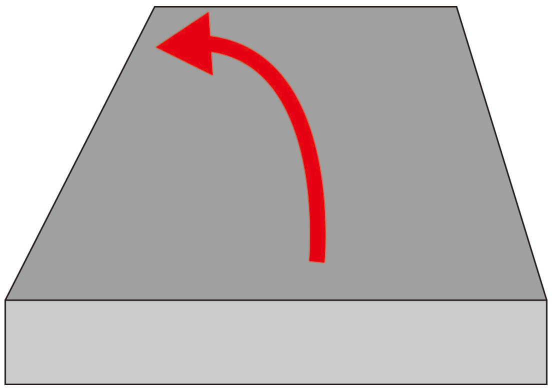


Motion in topologically twisted space

Additional quantum phase (Berry phase)

$$\psi = A\exp(i\mathbf{k}\cdot\mathbf{r}) \rightarrow A\exp(i\mathbf{k}\cdot\mathbf{r} + i\alpha)$$

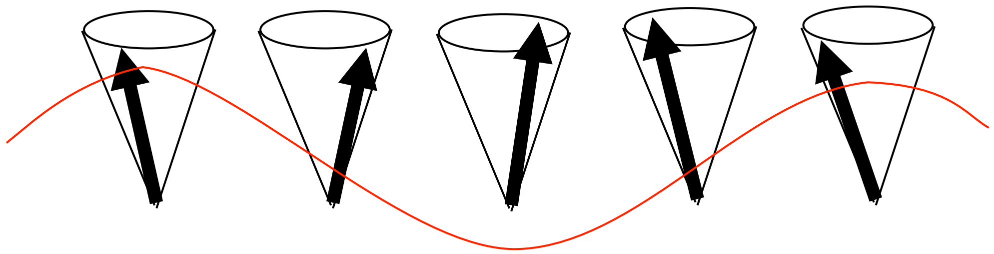
Berry phase induced Hall effect



- Topological Hall effect in skyrmion lattice
- Anomalous Hall effect in ferromagnets
- Spin Hall effect in metals and semiconductors
- etc.

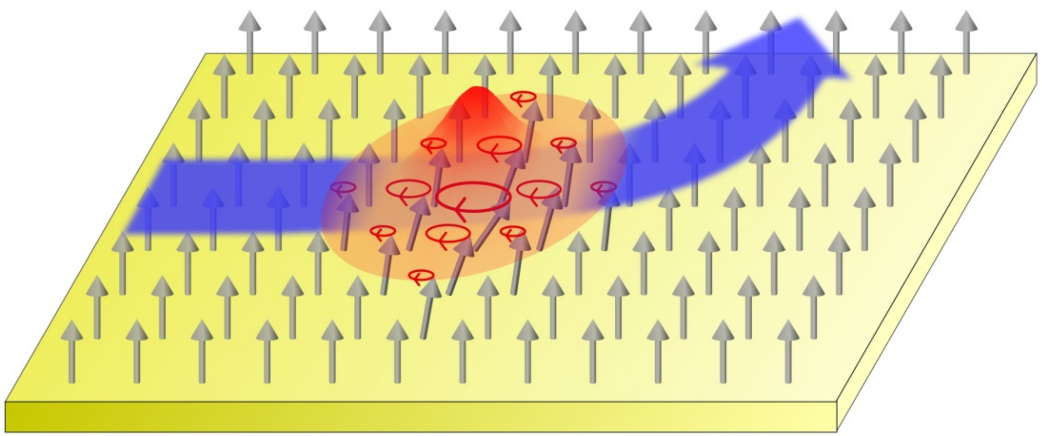
Berry phase-induced Hall effect for magnons??

Magnon: quantum of spin wave
no charge, spin S=1



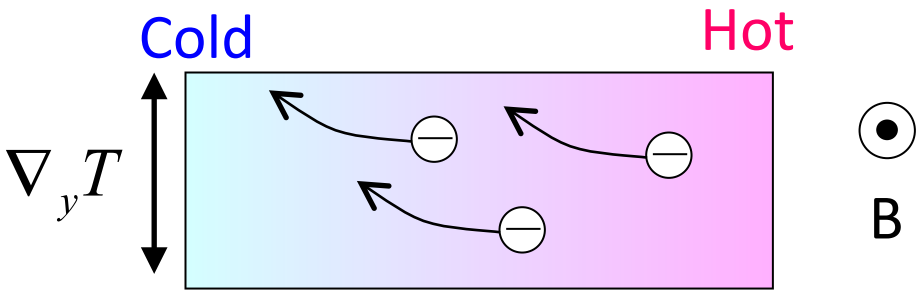
Lorentz force $\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) = 0$ (q=0 for magnon)

Berry phase of magnon ⇨ Hall effect



Thermal Hall conductivity

Thermal Hall conductivity in metal



Electronic thermal current is deflected when B is applied.

Transverse *T* gradient $\nabla_y T$

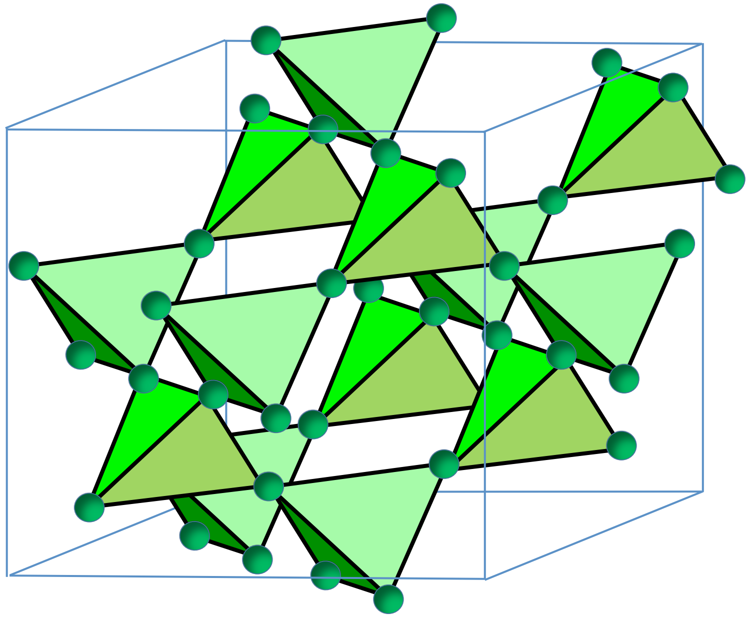
Thermal Hall conductivity in insulator

$$\kappa = \kappa_{\text{electron}} + \kappa_{\text{phonon}} + \kappa_{\text{magnon}}$$

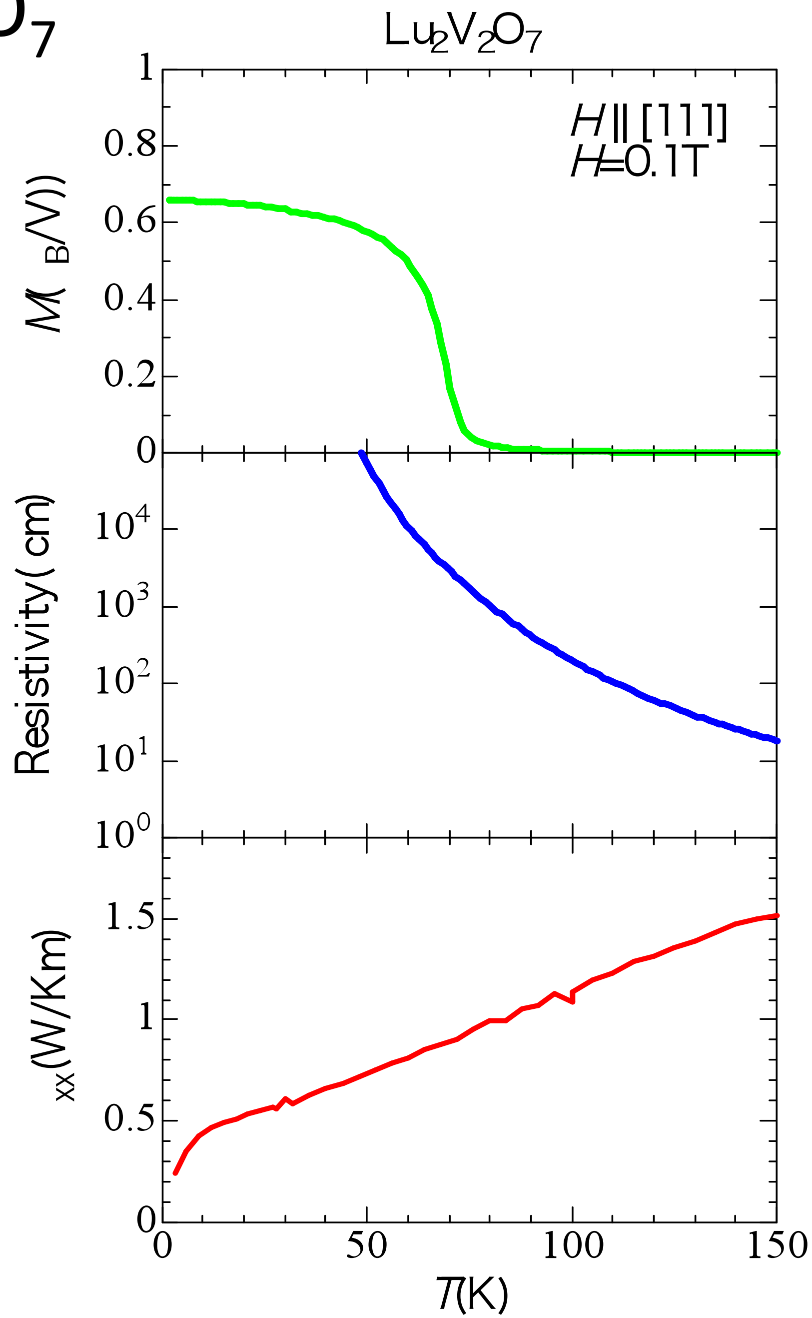
Thermal Hall conductivity κ_{xy}

Hall effect of magnon (or phonon)

Target material -$Lu_2V_2O_7$

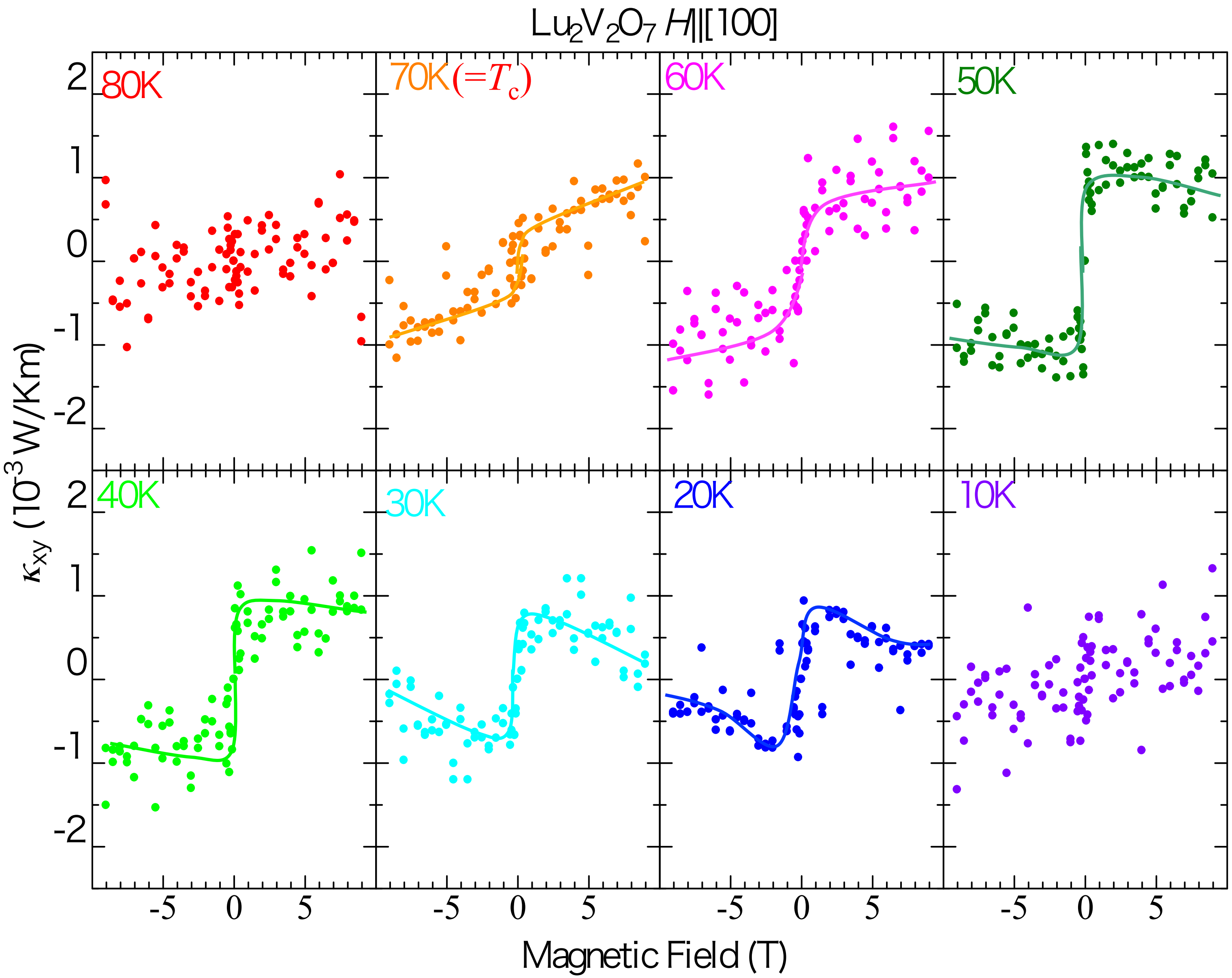


- ✓Pyrochlore Lattice
- ✓Collinear ferromagnet
- ✓insulator



Thermal Hall conductivity for $Lu_2V_2O_7$

Y. Onose *et al.*, Science **329,** 297 (2010).



Discussion

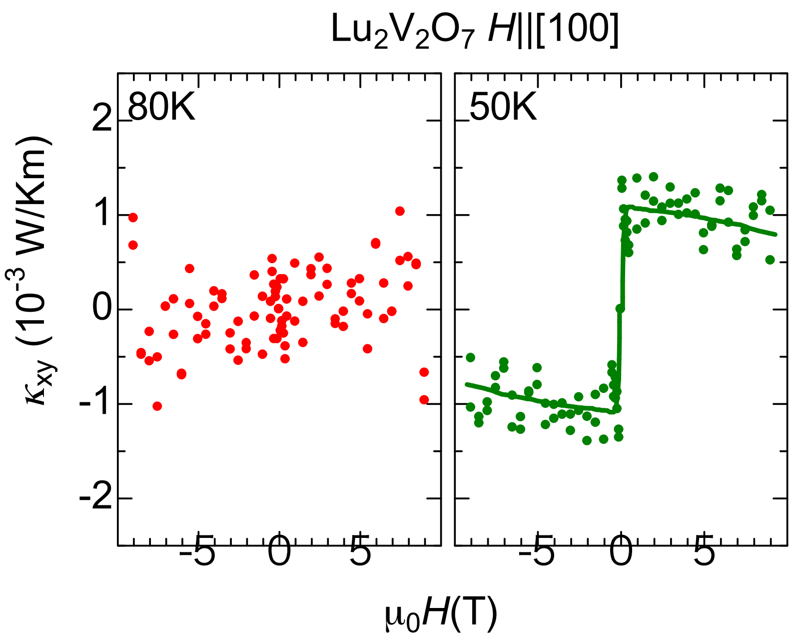
Origin of thermal Hall conductivity?

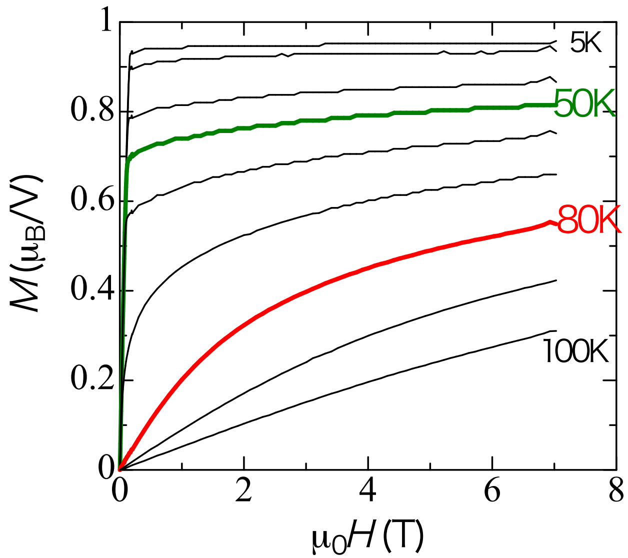
✓Possibility of electronic origin can be ruled out by Wiedemann Franz law.

κ_{xx}^{e}<10^{-5} W/Km below 100K

✓κ_{xy} decreases with *H* at low *T*. → Opening of magnon gap

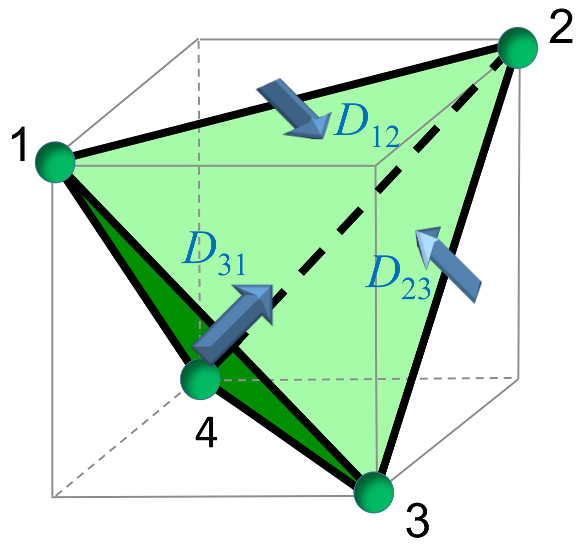
✓κ_{xy} is observed only below T_C. Coherent magnon propagation is crucial





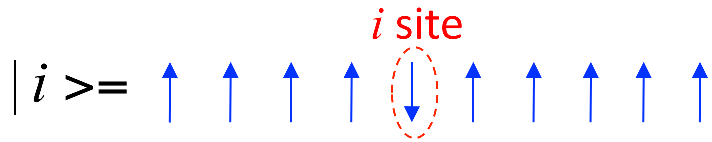
Theory of magnon Hall effect based on DM interaction

Katsura & Nagaosa



Dzyaloshinskii-Moriya vectors in Pyrochlore Lattice

Localized magnon state



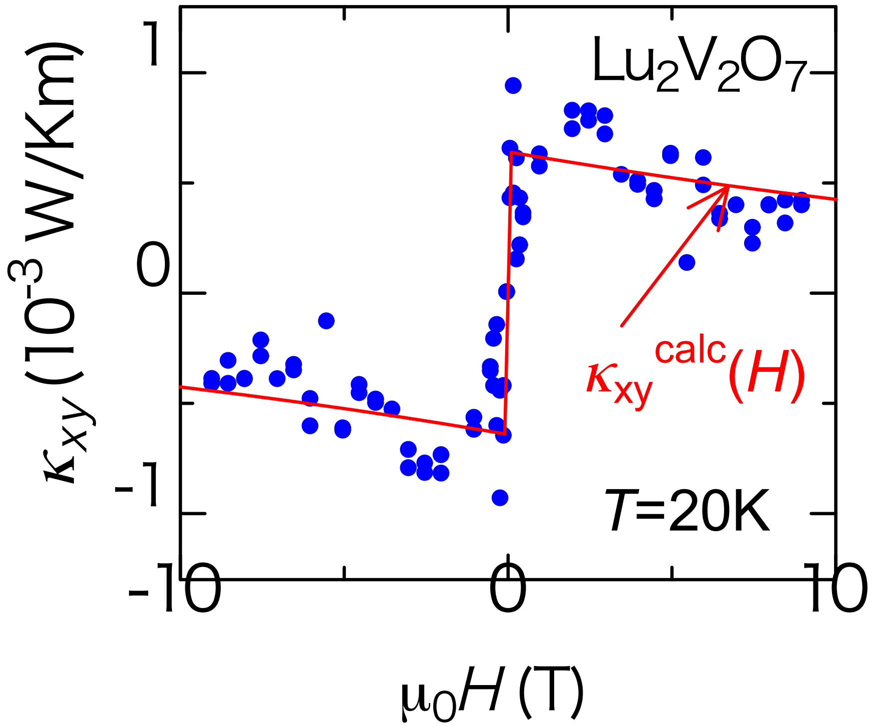
"transfer integral" of localized magnons

$$< j\,|-J\vec{S}_i \cdot \vec{S}_j + \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)\,|\,i >= -(\widetilde{J}/2)\,e^{i\phi_{ij}}$$

$$\widetilde{J}e^{i\phi_{ij}} = J + i\overrightarrow{D}_{ij} \cdot \vec{n}$$

Magnons acquire Berry phase owing to DM interaction.

Fitting to Experimental data



From fitting, we obtain

D/J=0.38

Cf. D/J=0.19 for $CdCr_2O_4$

Theoretical formula of κ_{xy}(Matsumoto & Murakami)

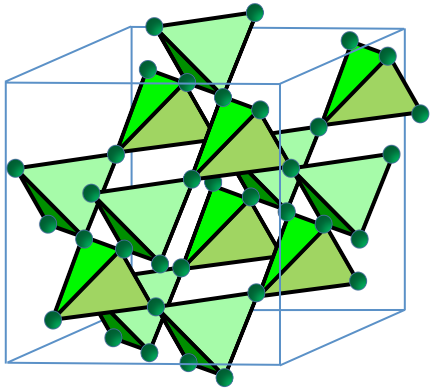
$$\kappa^{xy} = -\frac{k_B^2 T}{\hbar V}\sum_{n,\boldsymbol{k}} c_2(\rho_n)\Omega_{n,z}(\boldsymbol{k})$$

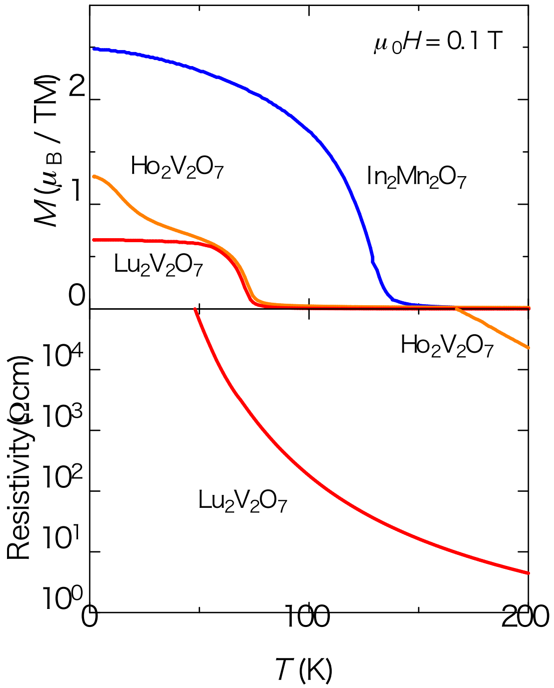
ρ_n: Bose distribution function, Ω_{nz}: Berry curvature

$$c_2(\rho) = (1+\rho)(\log\frac{1+\rho}{\rho})^2 - (\log\rho)^2 - 2\mathrm{Li}_2(-\rho)$$

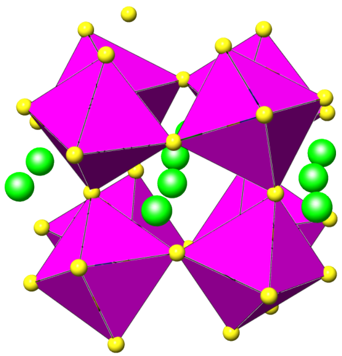
Various ferromagnetic insulators

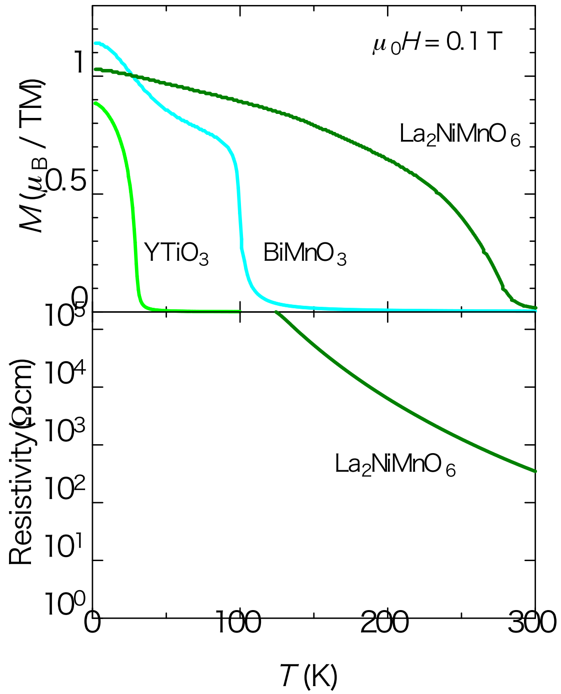
Pyrochlore ferromagents



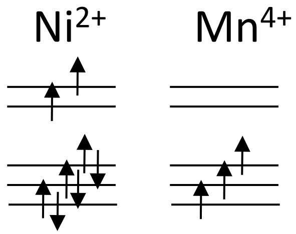


Perovskite ferromagnets

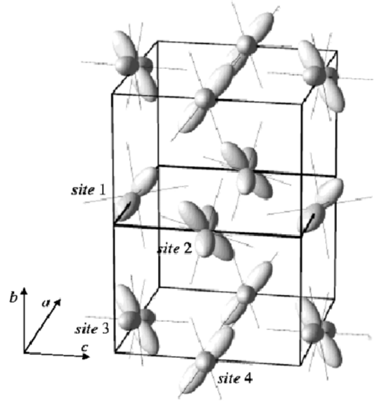




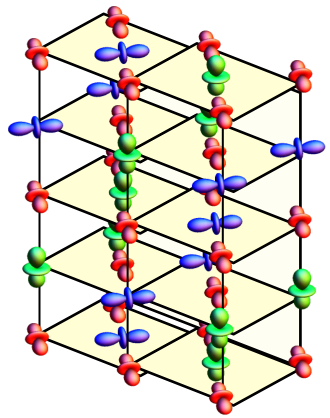
La_2NiMnO_6:

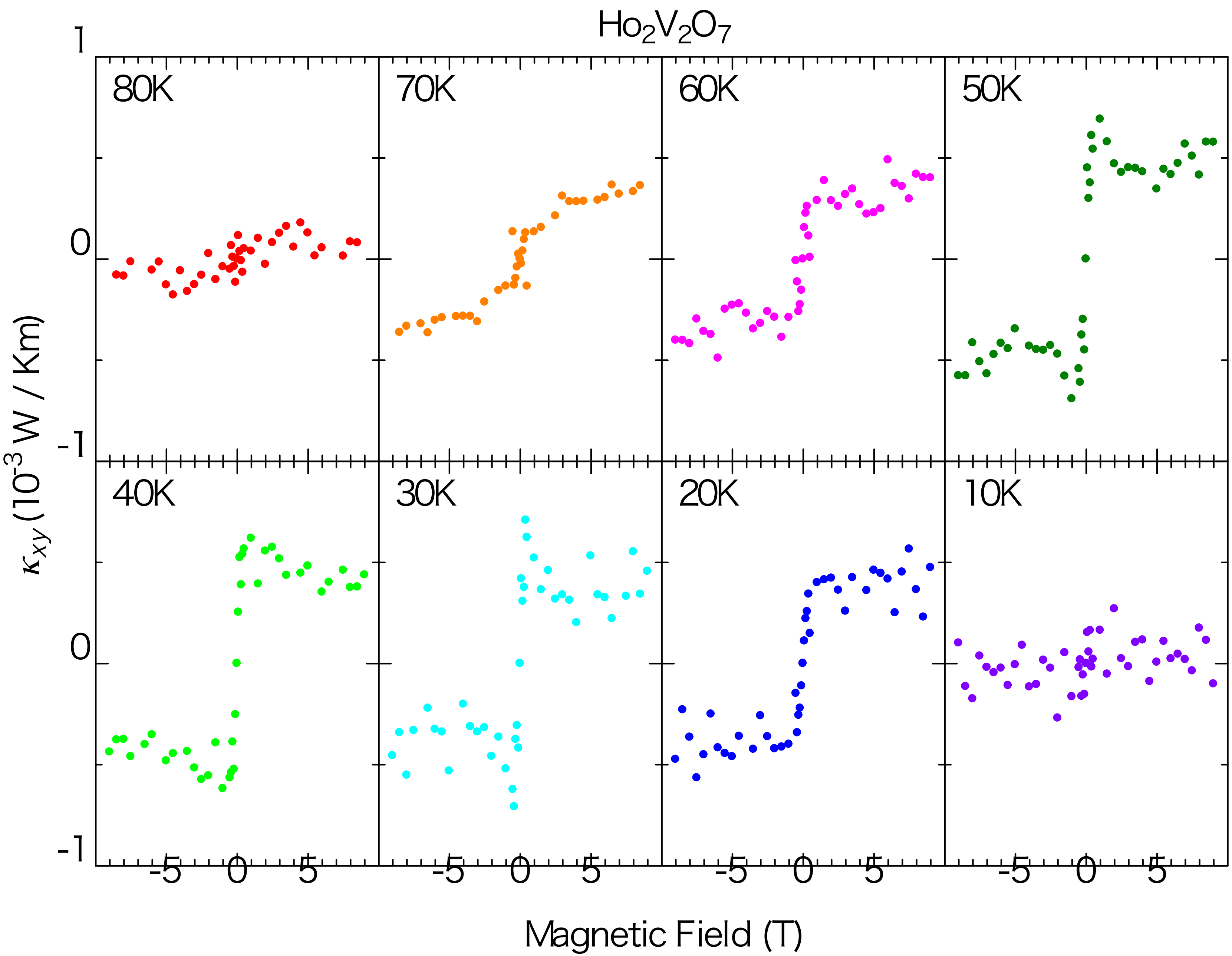


$YTiO_3$ Akimitsu *et al.*, 2001

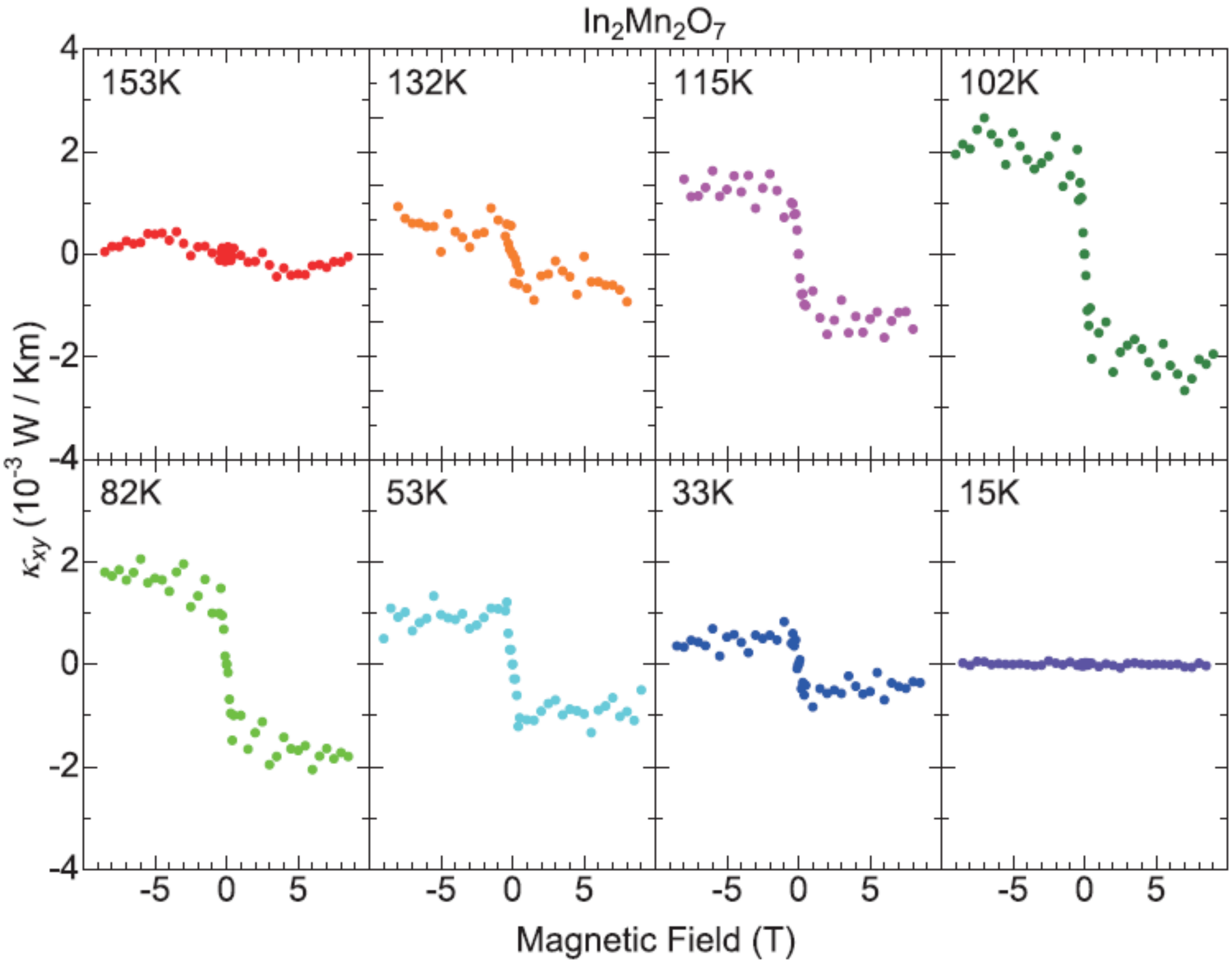


$BiMnO_3$ Atou *et al.* 1999

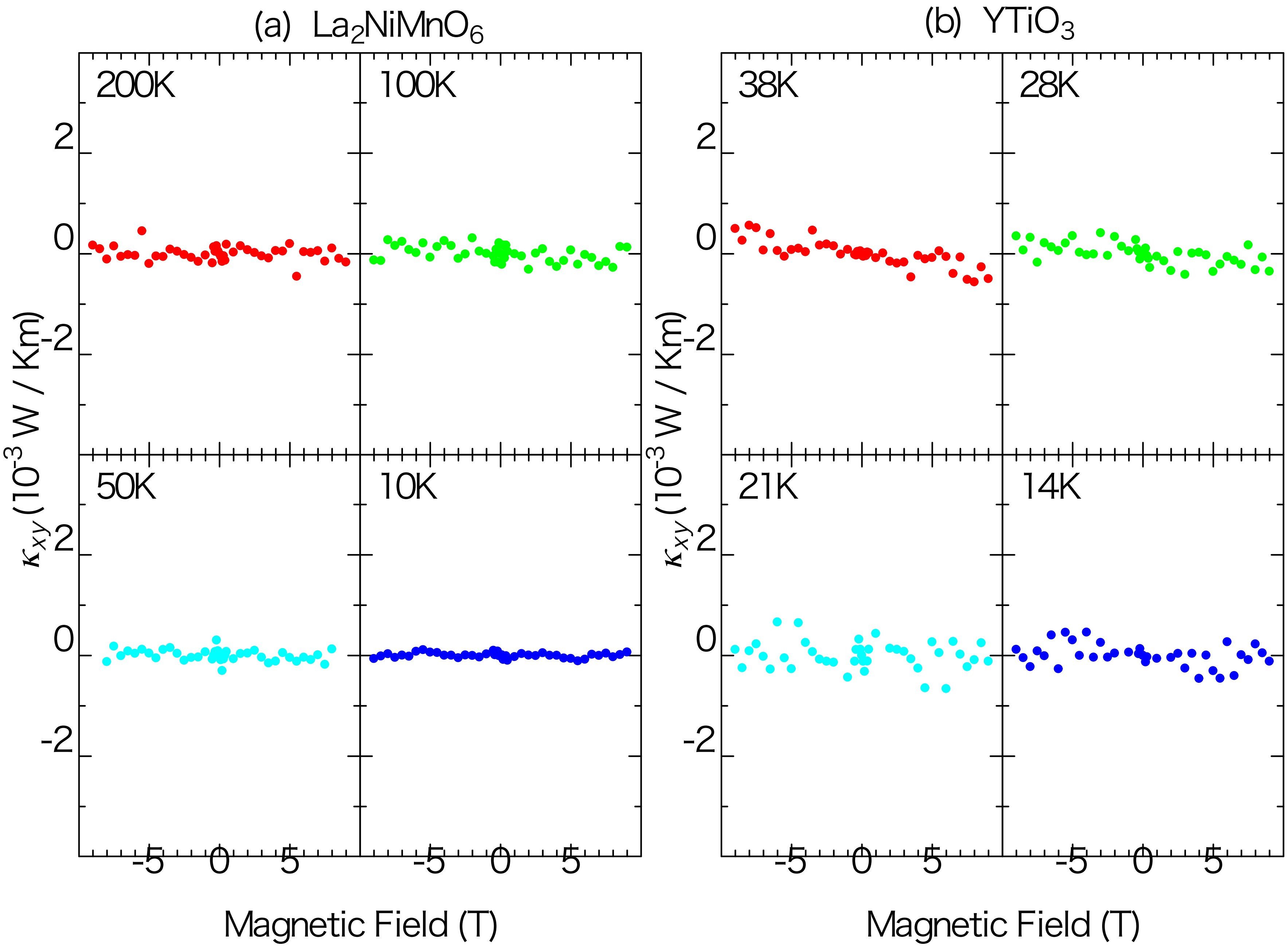


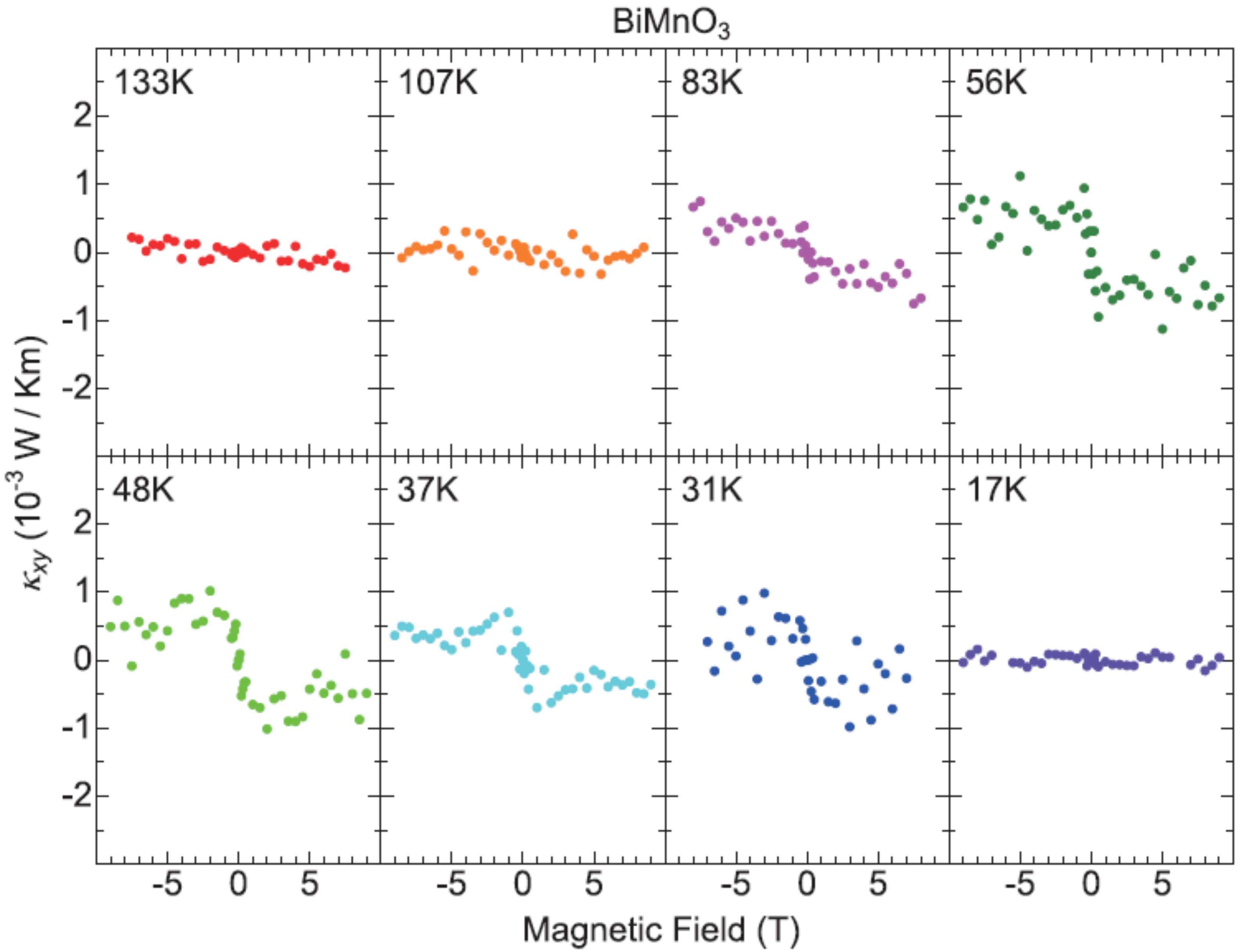


$Ho_2V_2O_7$
80K
70K
60K
50K
40K
30K
20K
10K
1
0
-1
0
-1
-5
0
5
κ_{xy} (10^{-3} W / Km)
Magnetic Field (T)



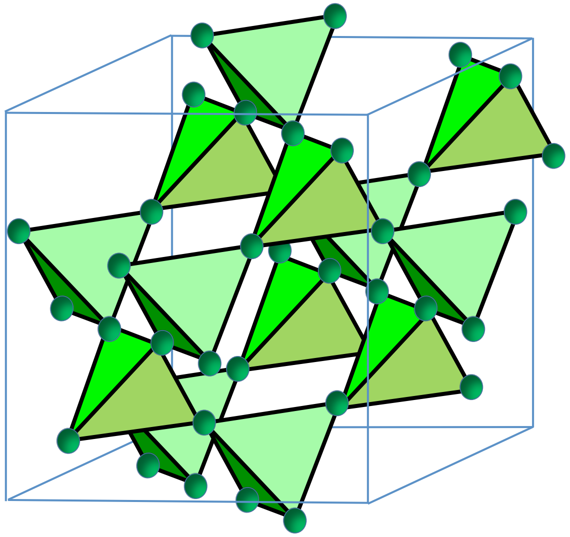
In2Mn2O7
153K
132K
115K
102K
82K
53K
33K
15K
κxy (10-3 W / Km)
Magnetic Field (T)
4
2
0
-2
-4
-5
0
5

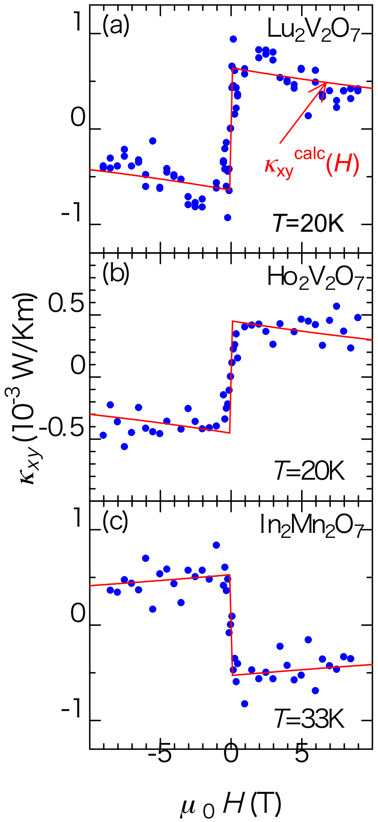

(a) La2NiMnO6
(b) YTiO3
200K
100K
50K
10K
38K
28K
21K
14K
κxy (10-3 W / Km)
2
0
-2
-5
5
Magnetic Field (T)



BiMnO3
133K
107K
83K
56K
48K
37K
31K
17K
κxy (10-3 W / Km)
Magnetic Field (T)

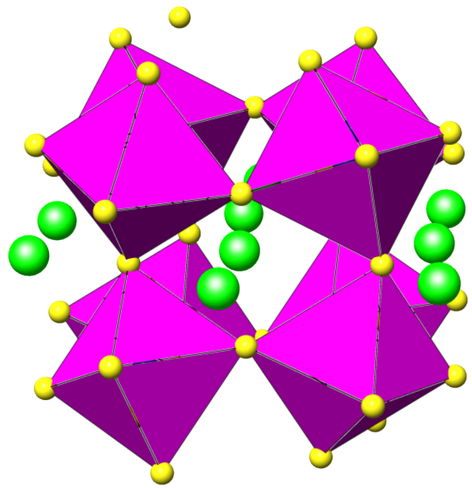
Pyrochlore ferromagnet





material	κ_{xy} (m W/Km)	$\lvert D/J \rvert$
$Lu_2V_2O_7$ (20K)	0.7	0.38
$Ho_2V_2O_7$ (20K)	0.4	0.07
$In_2Mn_2O_7$ (33K)	-0.5	0.02

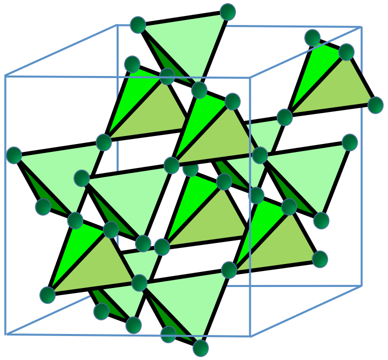
Perovskite ferromagnet

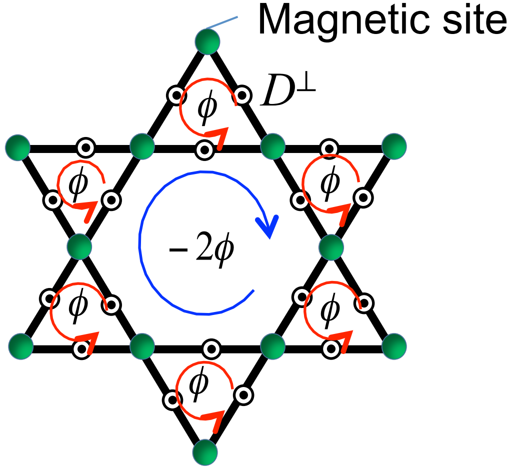


material	κ_{xy} (10^{-3} W/Km)
La_2NiMnO_6	indiscernible
$YTiO_3$	indiscernible
$BiMnO_3$ (31K)	-0.02~-0.04

Effect of lattice geometry on DM-induced magnon Hall effect

$Lu_2V_2O_7$
$Ho_2V_2O_7$
$In_2Mn_2O_7$

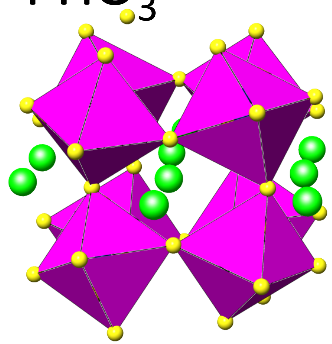




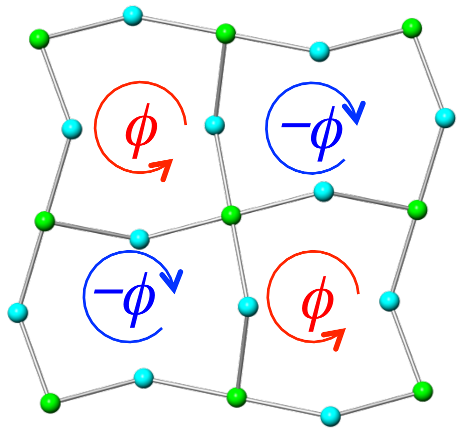
(111) plane

$$\kappa_{xy} \neq 0$$

La_2NiMnO_6
$YTiO_3$



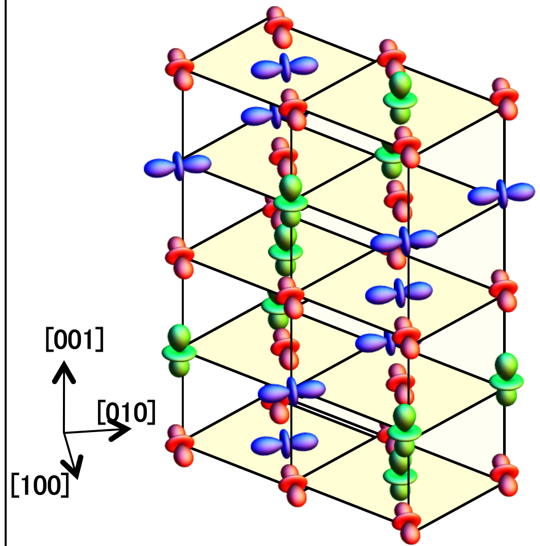
$GdFeO_3$-type
distorted perovskite



xz plane

$$\kappa_{xy} = 0$$

$BiMnO_3$

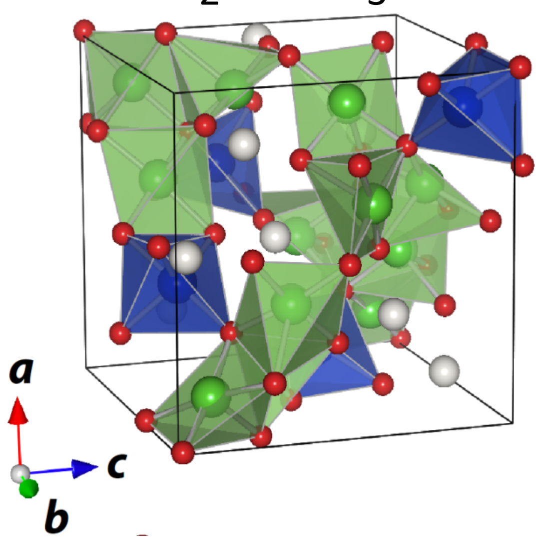


$$\kappa_{xy} \neq 0$$

Observation of magnetic excitations in skyrmion crystal

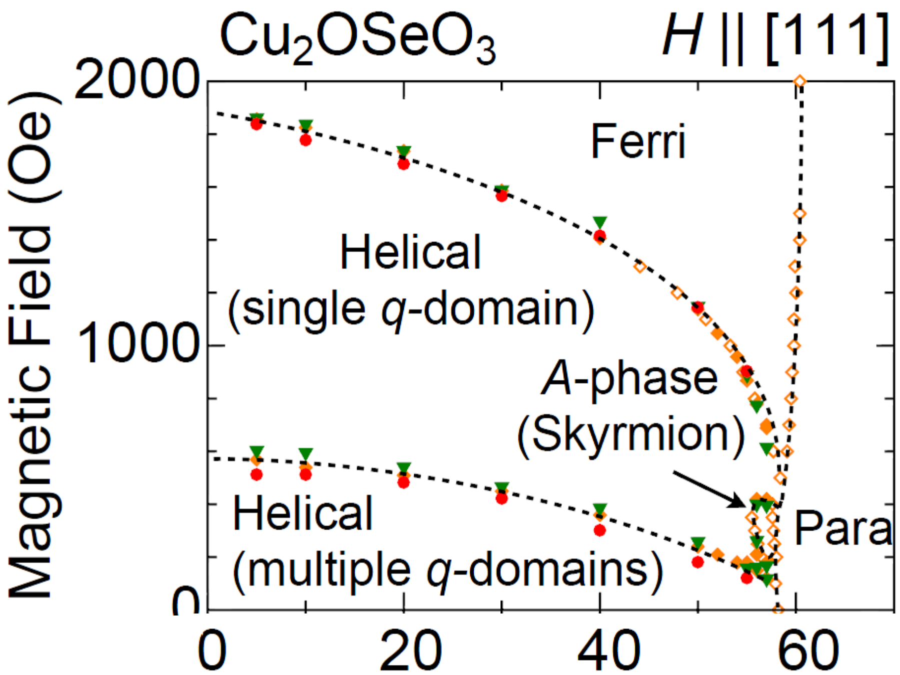
Skyrmion crystal in an insulating oxide Cu_2OSeO_3

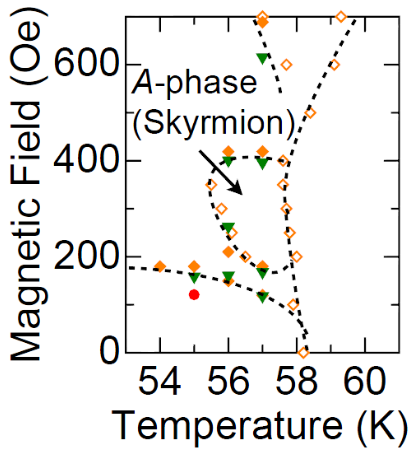
S. Seki *et al*. Science 2012



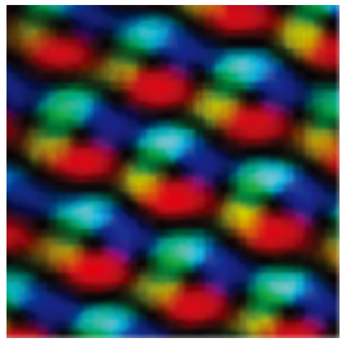
Space group: $P2_13$

Same as B20 compounds



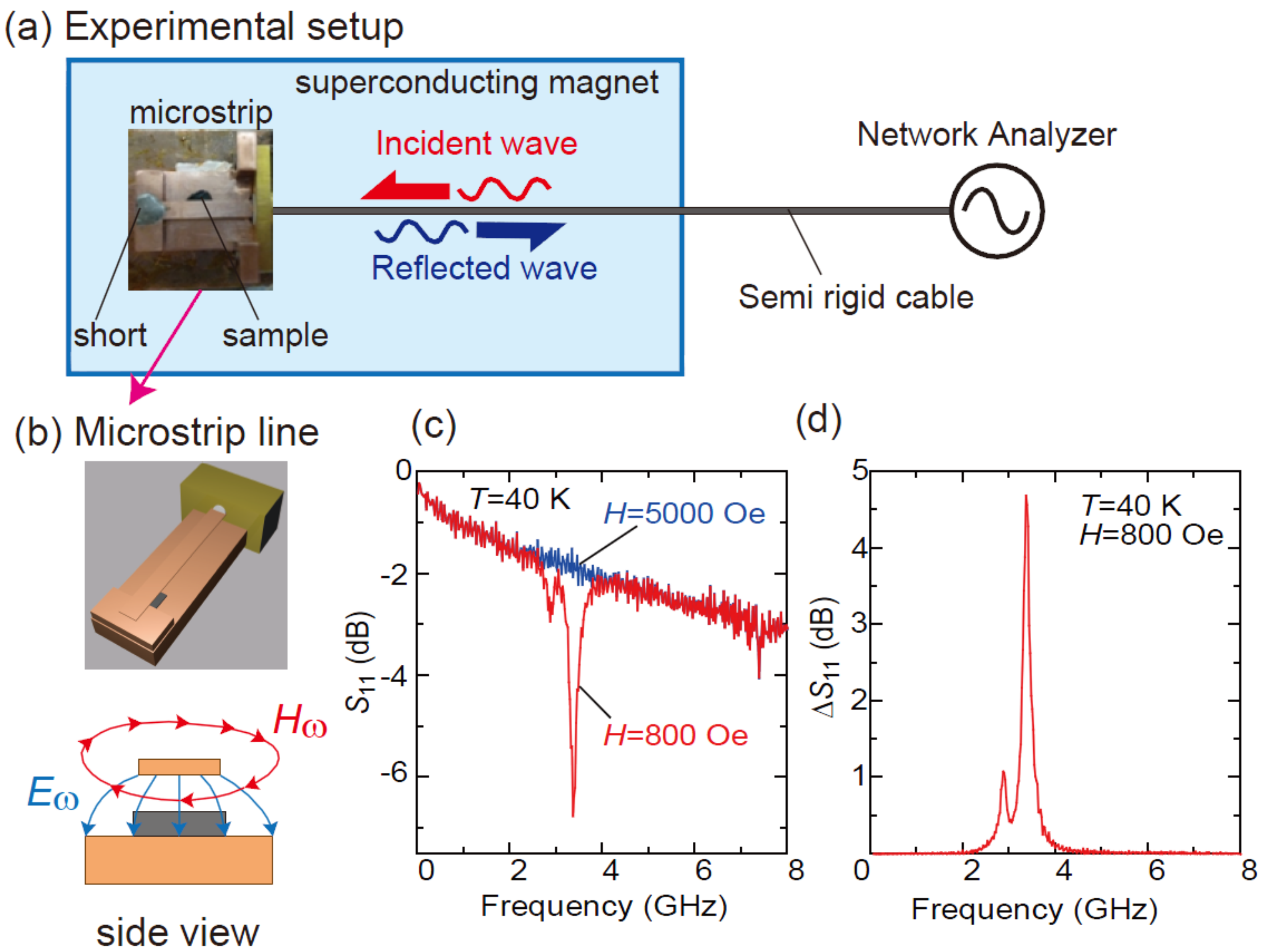


Lorentz TEM

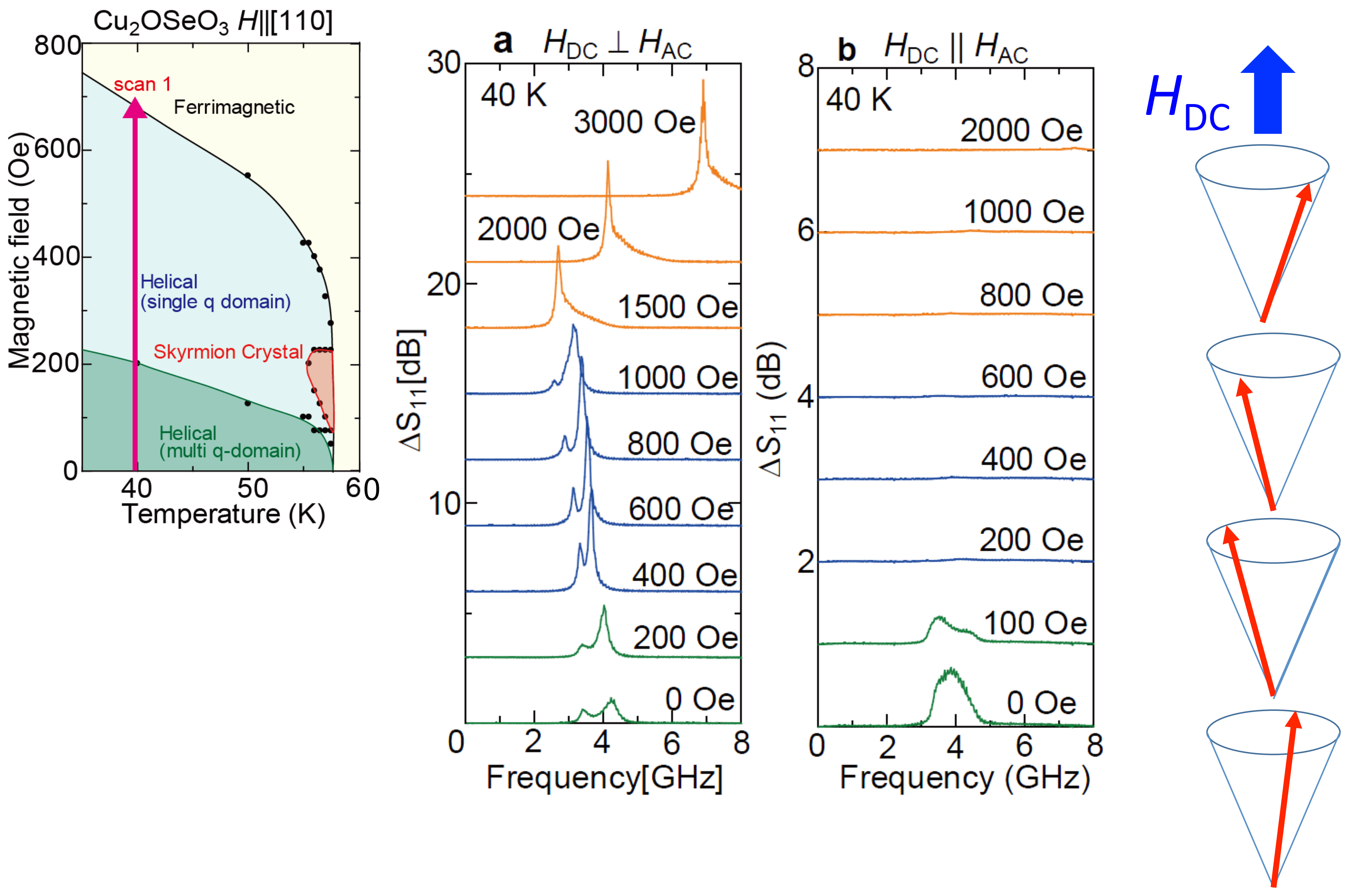


Microwave experiment

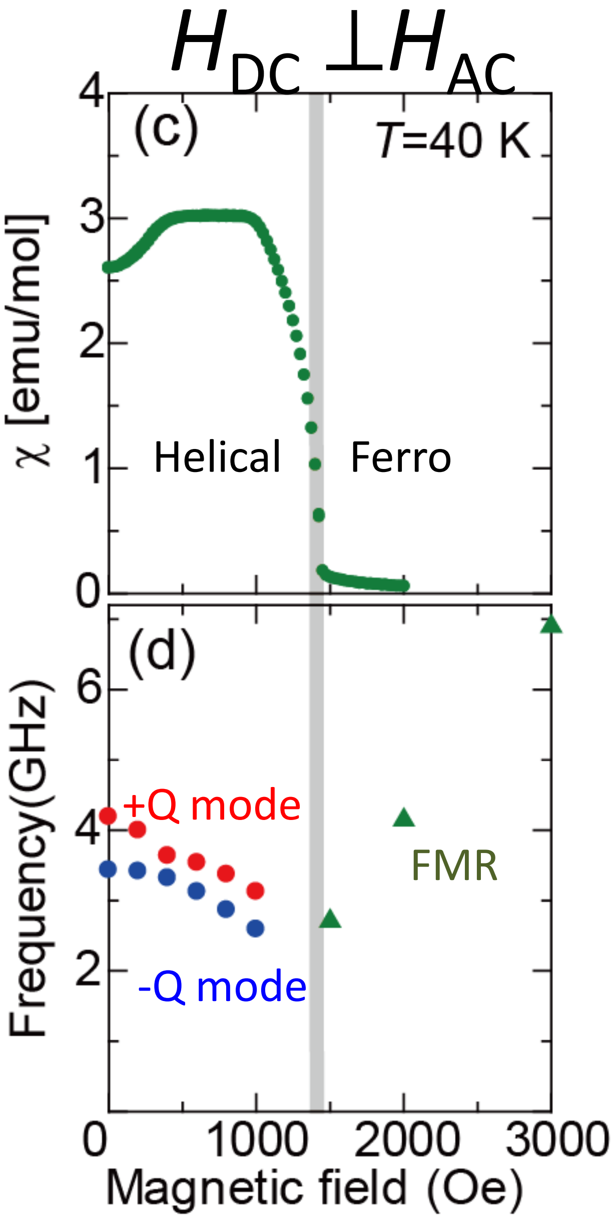
Broad band ESR

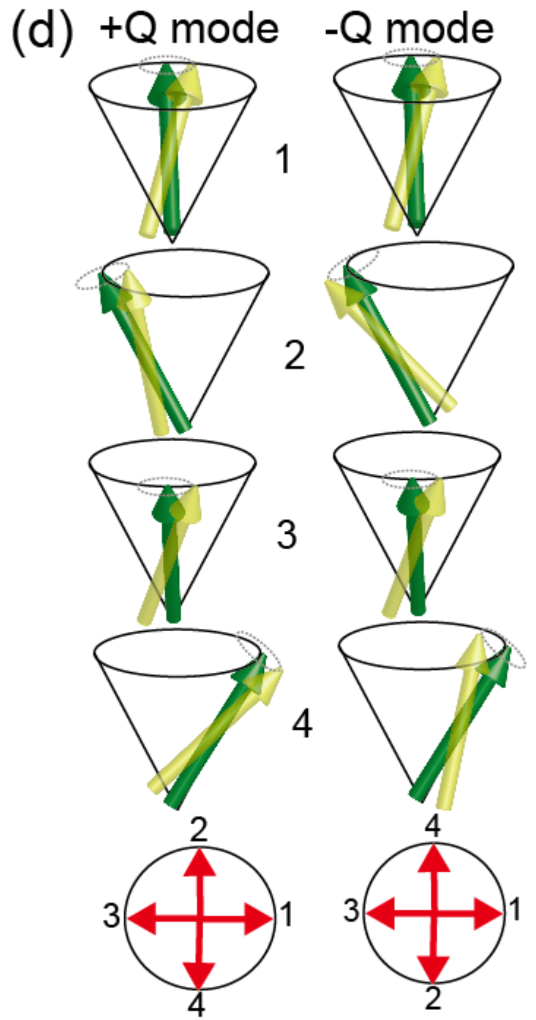


Microwave response in helical (conical) spin structure



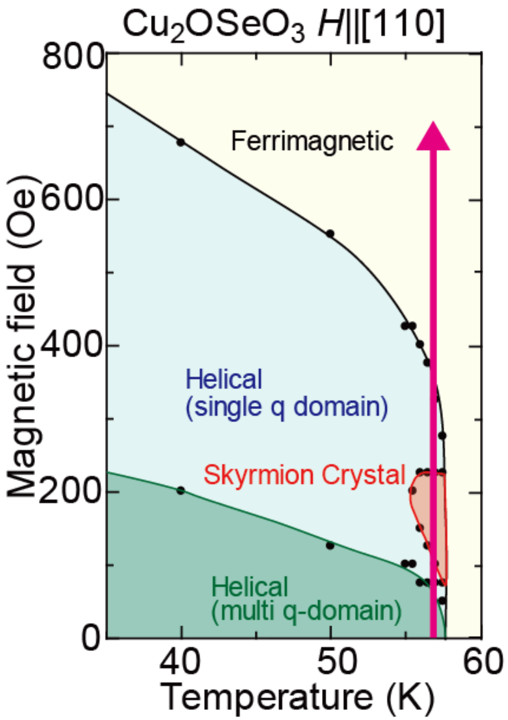
Magnetic oscillation modes in Helical spin state



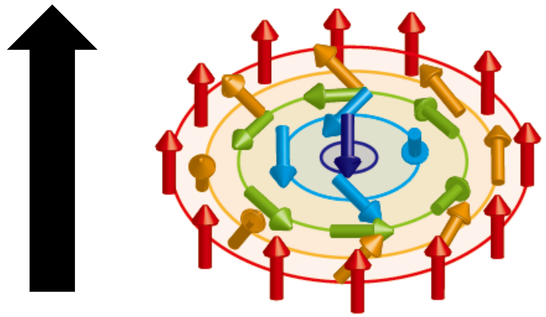


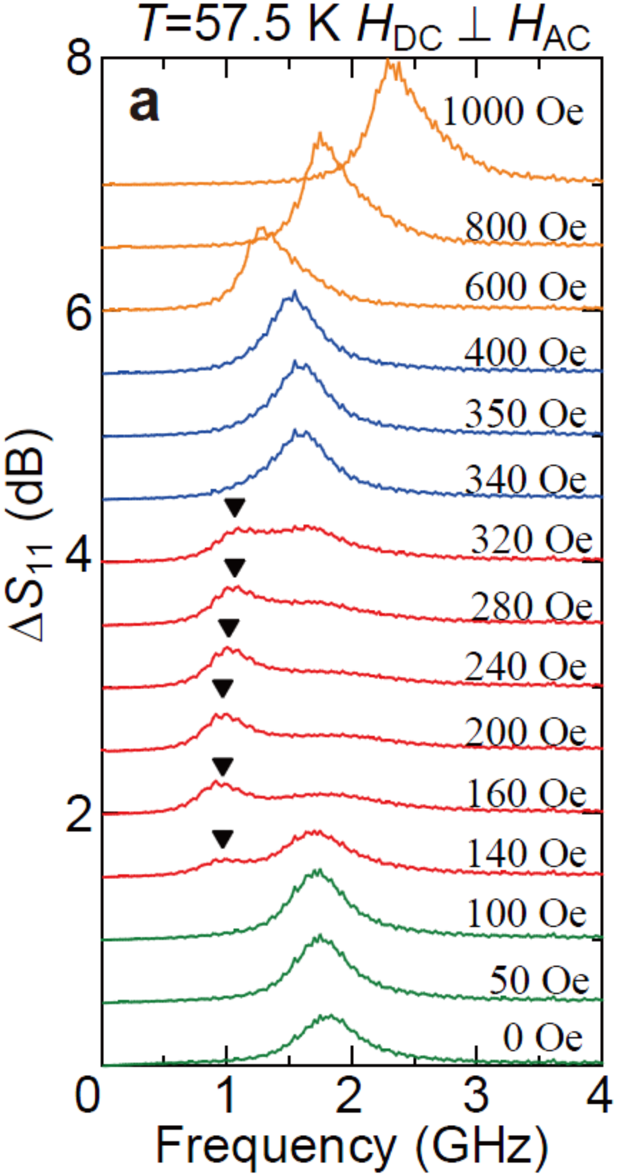
M. Kataoka JPSJ 1986
(Theory)

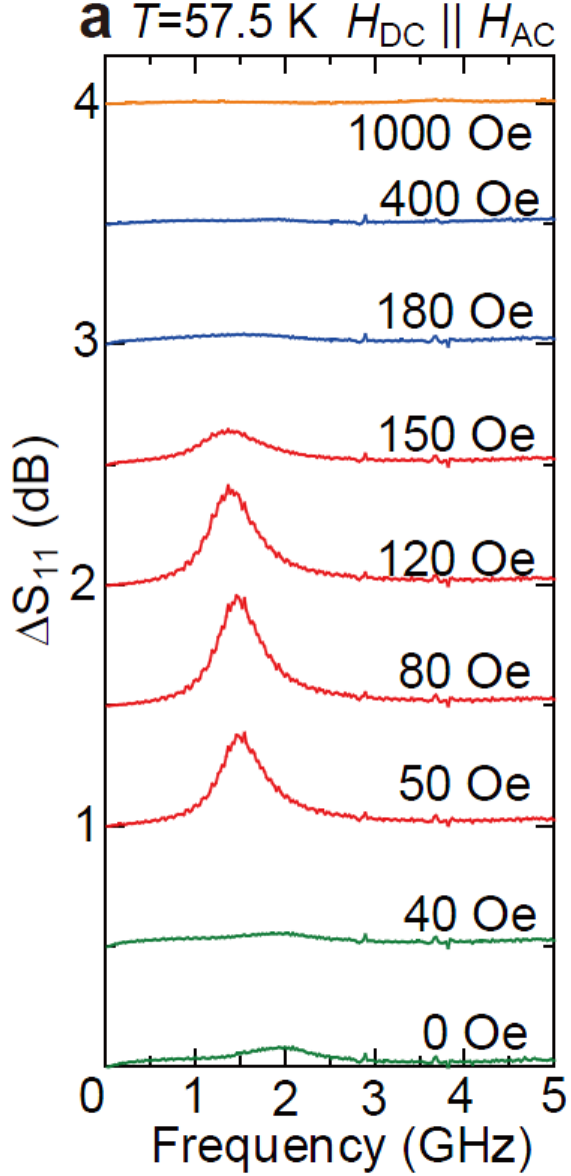
$H_{DC} \perp H_{AC}$ $\quad$ $H_{DC} \parallel H_{AC}$

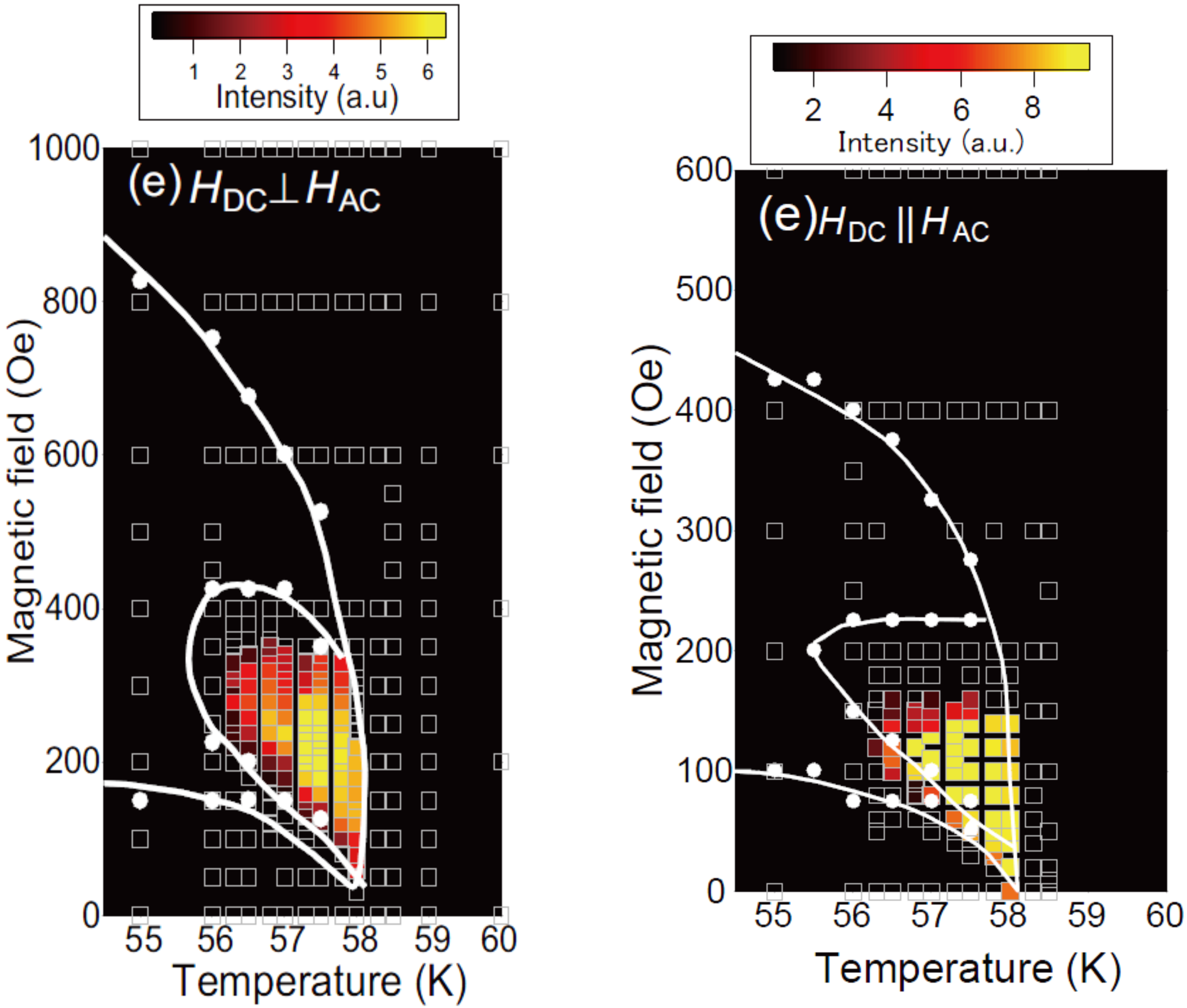


H_{DC}









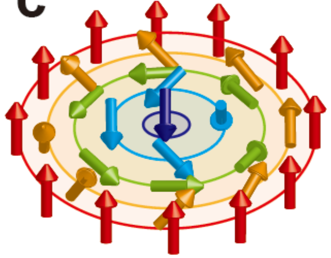
1 2 3 4 5 6
Intensity (a.u)
(e) $H_{DC} \perp H_{AC}$
Magnetic field (Oe)
0 200 400 600 800 1000
55 56 57 58 59 60
Temperature (K)
2 4 6 8
Intensity (a.u.)
(e) $H_{DC} \parallel H_{AC}$
Magnetic field (Oe)
0 100 200 300 400 500 600
55 56 57 58 59 60
Temperature (K)

Theoretical calculation of magnetic oscillation in skyrmion crystal

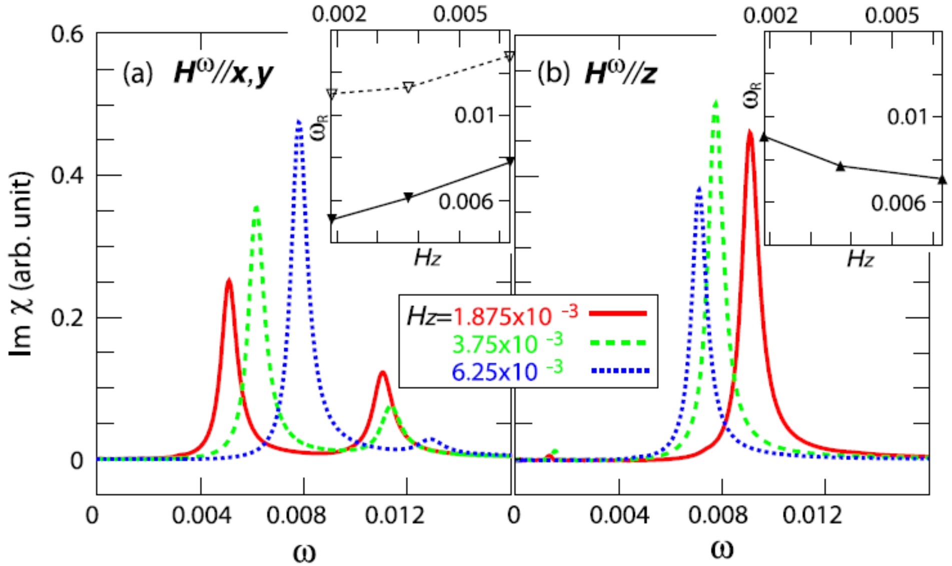
Mochizuki PRL

Skyrmion

c

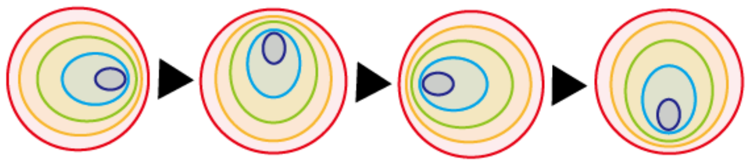


$H_{DC} \perp H_{AC}$ $\quad$ $H_{DC} \parallel H_{AC}$

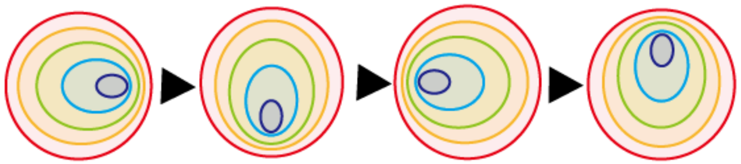


Numerical calculation
2D LLG equation

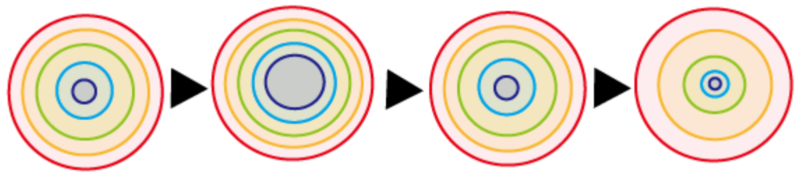
CCW rotation mode



CW rotation mode



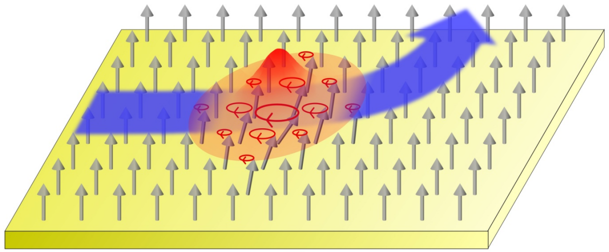
Breathing mode

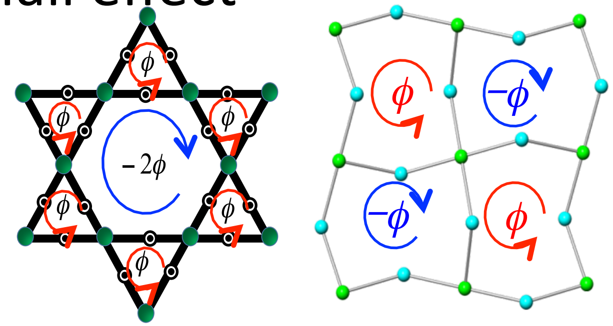


Summary

We have investigated topological phenomena related to magnetic excitations in magnetic materials .

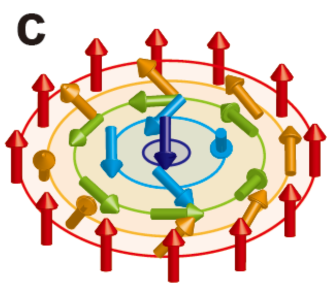
1, Observation of magnon Hall effect

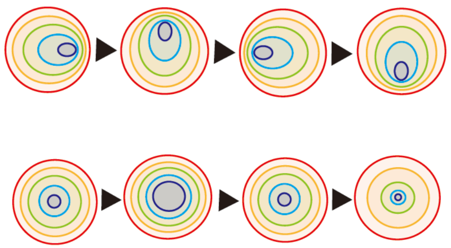




Effect of lattice geometry

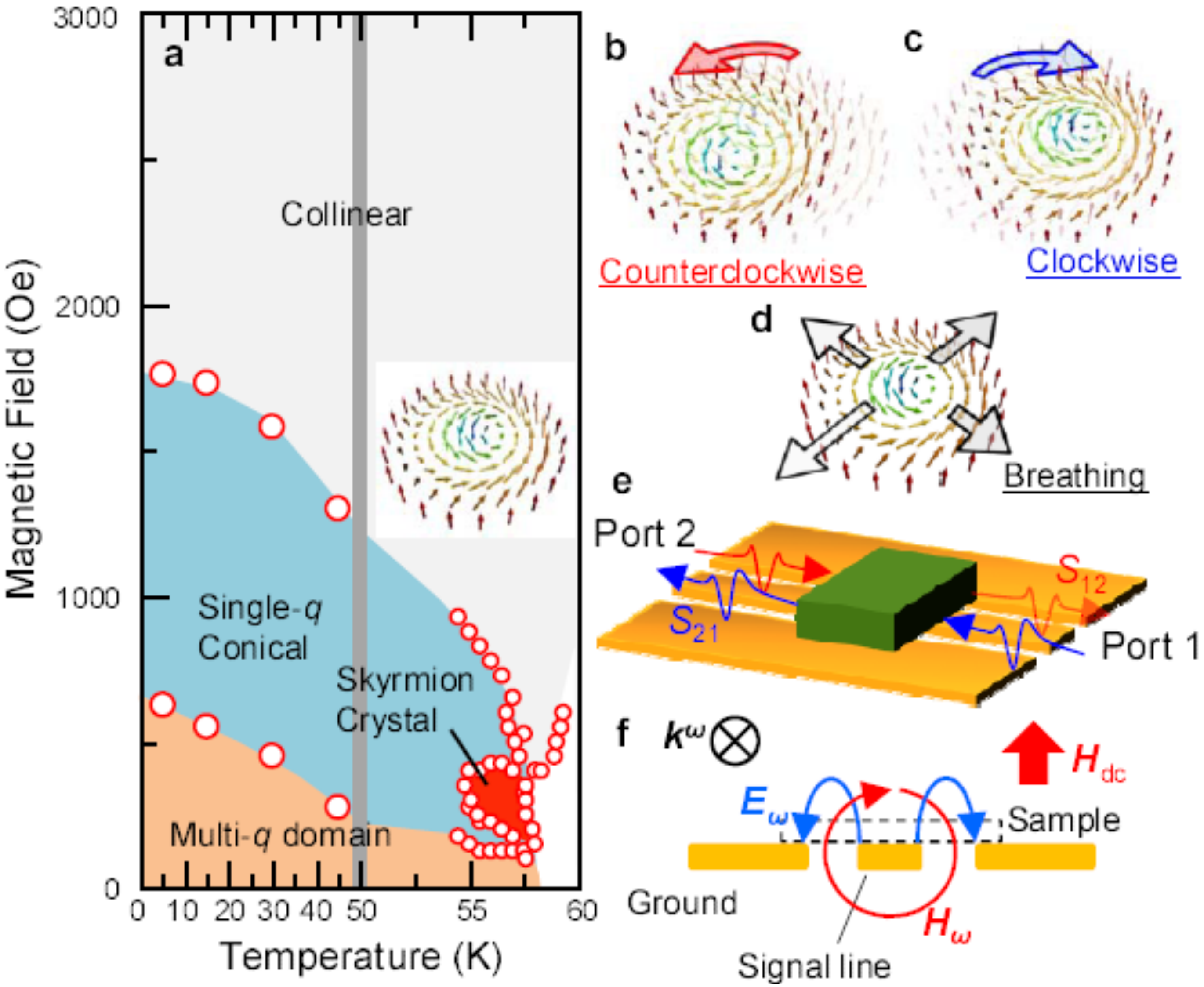
2, Magnetic excitations in Skyrmion crystal



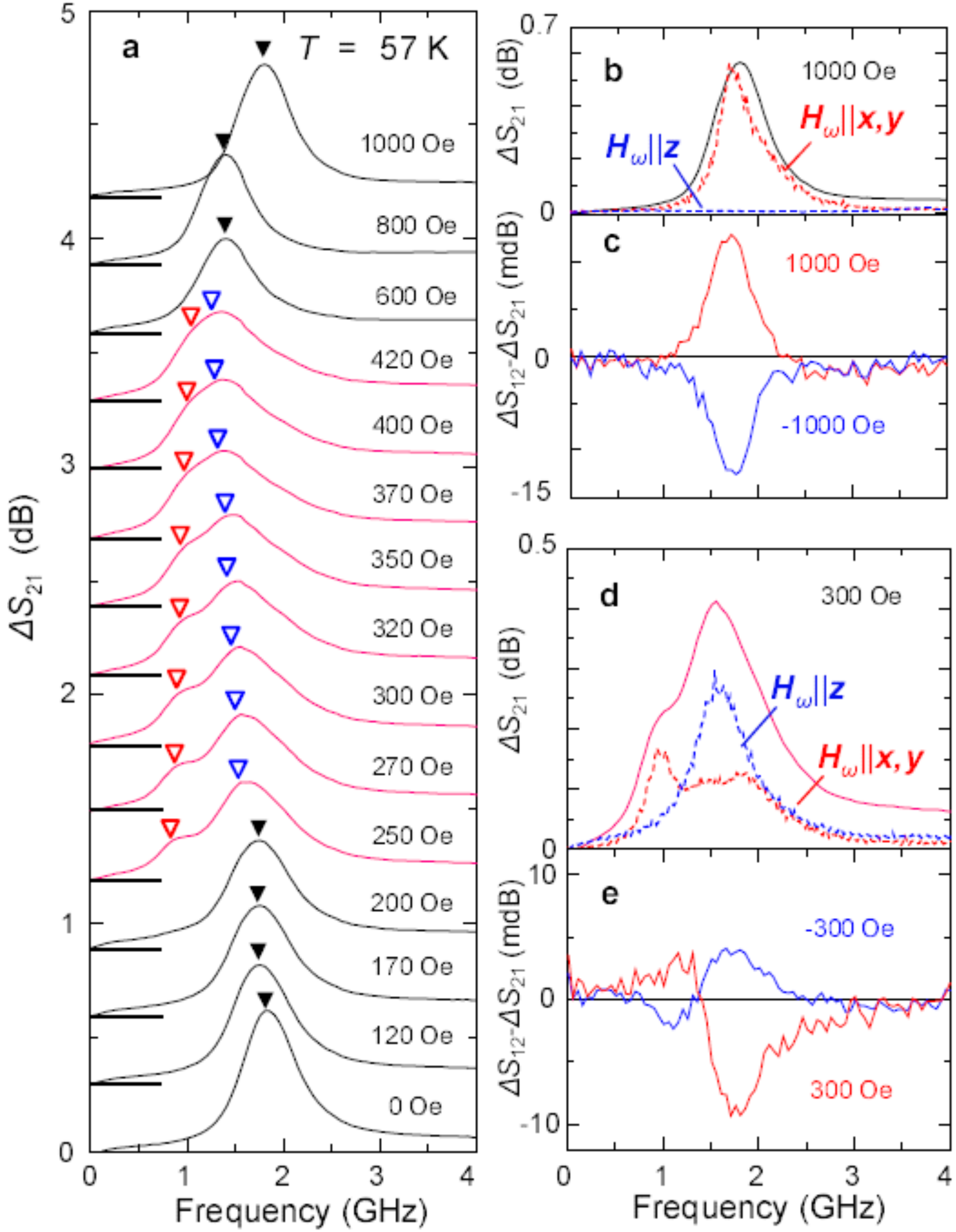


Skyrmion rotation mode

Skyrmion breathing mode

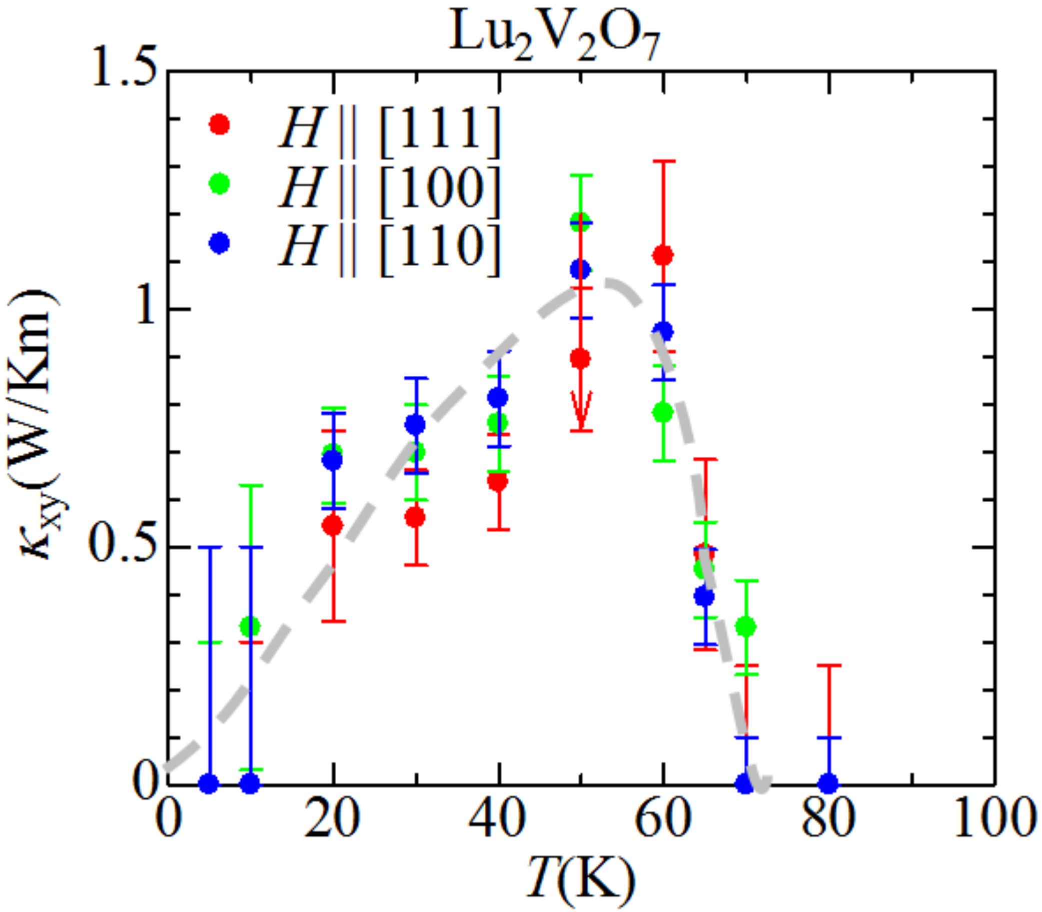


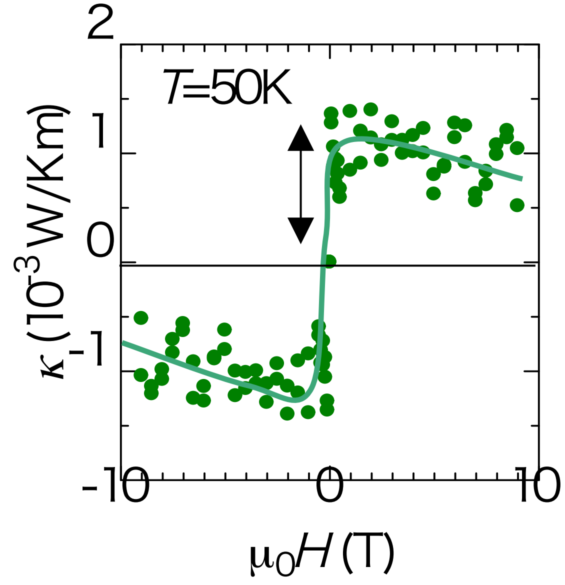
a
3000
2000
1000
0
Magnetic Field (Oe)
0 10 20 30 40 50 55 60
Temperature (K)
Collinear
Single-q
Conical
Skyrmion
Crystal
Multi-q domain
b
Counterclockwise
c
Clockwise
d
Breathing
e
Port 2
Port 1
S12
S21
f
kω
Hdc
Eω
Sample
Ground
Signal line
Hω



a
T = 57 K
1000 Oe
800 Oe
600 Oe
420 Oe
400 Oe
370 Oe
350 Oe
320 Oe
300 Oe
270 Oe
250 Oe
200 Oe
170 Oe
120 Oe
0 Oe
ΔS21 (dB)
Frequency (GHz)
b
1000 Oe
Hω||z
Hω||x,y
ΔS21 (dB)
c
1000 Oe
-1000 Oe
ΔS12-ΔS21 (mdB)
d
300 Oe
Hω||z
Hω||x,y
ΔS21 (dB)
e
-300 Oe
300 Oe
ΔS12-ΔS21 (mdB)
Frequency (GHz)

Temperature dependence, anisotropy





"spontaneous" component

✓Emergent at T_c

✓Almost isotropic