# Dynamical Responses from Magnetic Skyrmions and Monopoles

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Metastability of topolgically-protected skyrmions

Skrymion aggregation dynamics – glass transition and recrystalization

Nonreciprocal/nonlinear trasport via chiral spin fluctuation

Electrodynamics of skyrmion strings

Outcomes of dynamics of emergent magnetic monopoles

# collaborators

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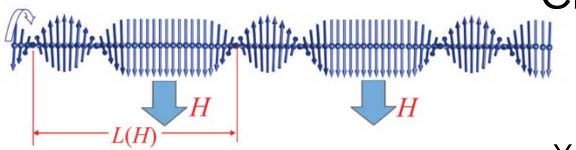
# Topological spin textures in chiral magnets

## 1D systems



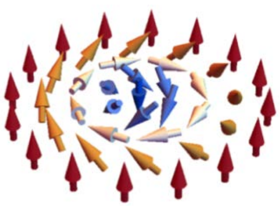

Chiral soliton lattice

- $CrNb_3S_6$
- $CsCuCl_3$

Y. Togawa *et al.*, PRL (2012).

## 2D systems

Skyrmion



Bloch-type

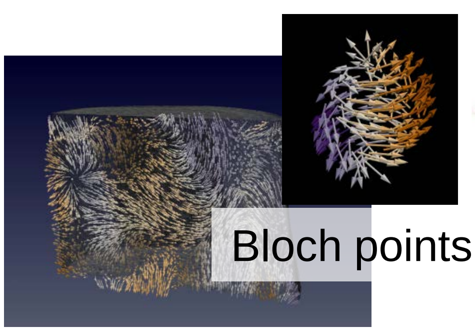
Néel-type

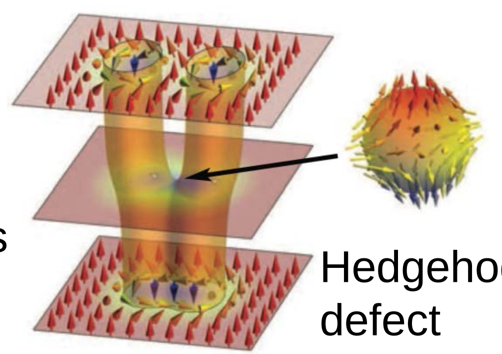
- B20 MnSi, FeGe
- $Cu_2OSeO_3$

- Fe/Ir interface
- $GaV_4S_8$

*e.g.*, Nagaosa & Tokura, Nat. Nanotech. (2013).

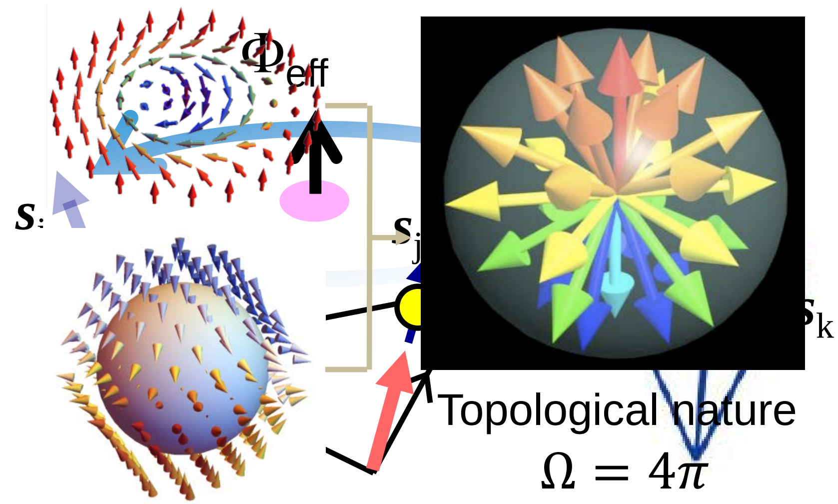
## 3D systems




C. Donnelly *et al.*, Nature (2017).   P. Milde *et al.*, Science (2013).

## Non-trivial topology in emergent electromagnetism




Topological nature
$\Omega = 4\pi$

Berry phase:

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

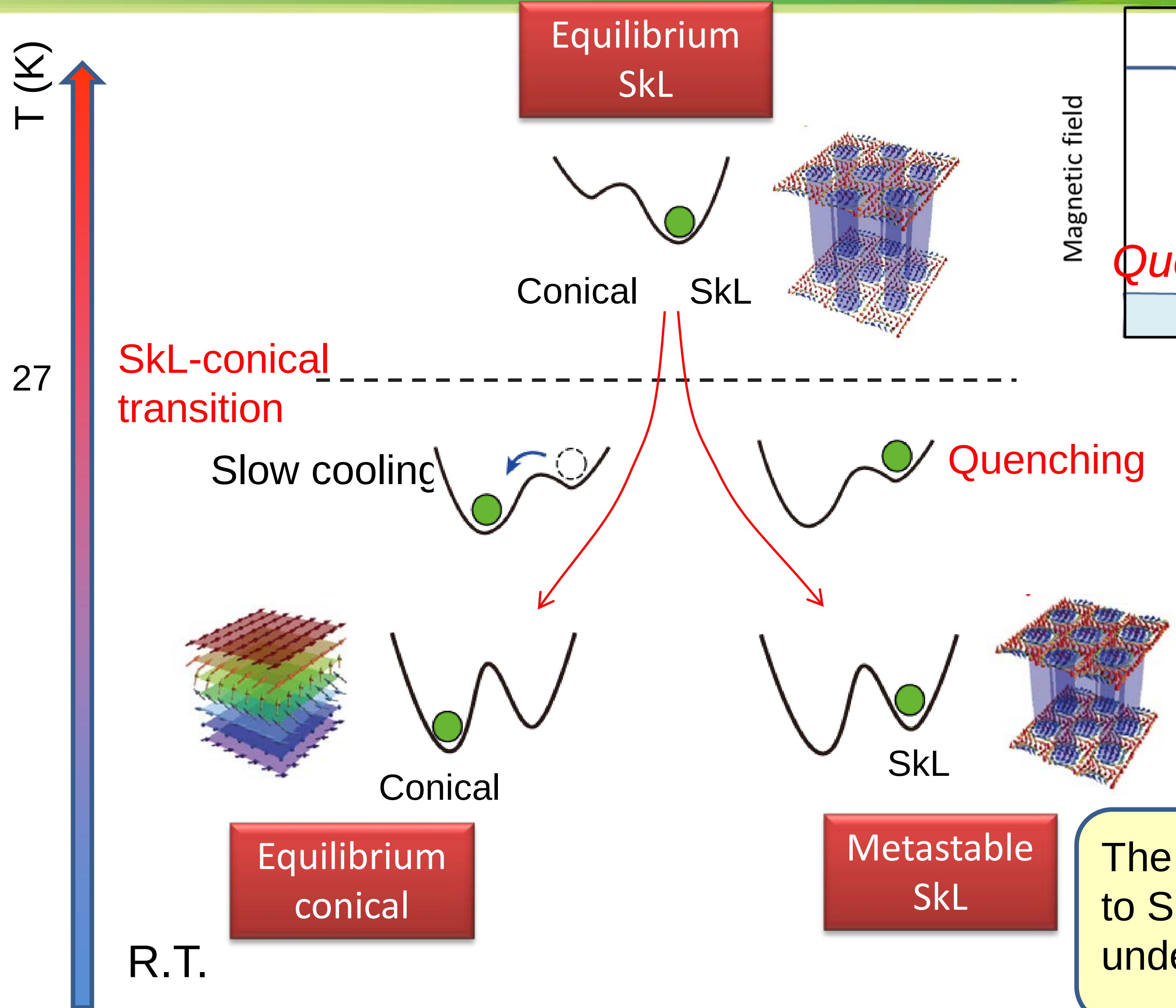
$$\pm 2\pi \leftrightarrow \pm\phi_0 = \pm\frac{h}{e}$$

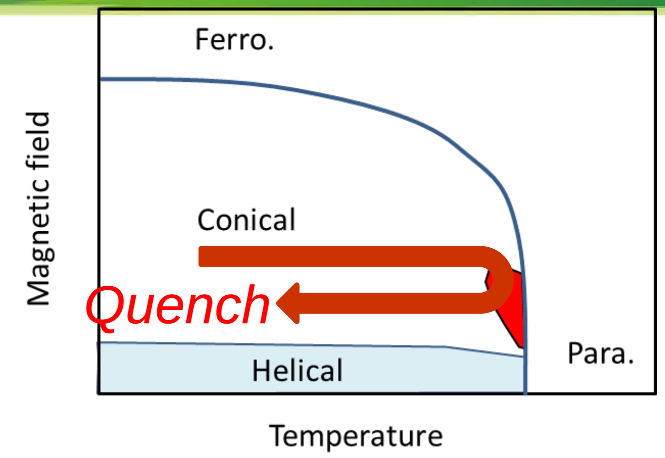
Equation of motion:

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

Topological Hall effe

# Creation of metastable skyrmions

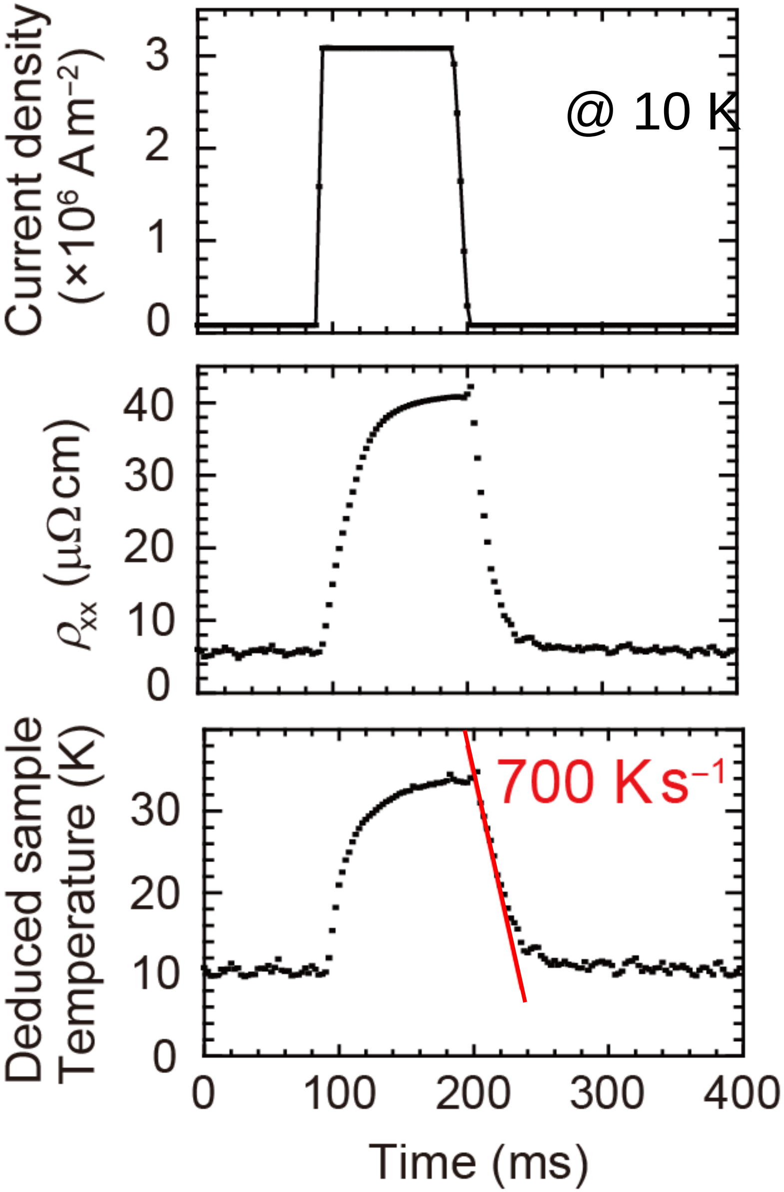



The transition from conical to SkL is kinetically voided under rapid cooling??

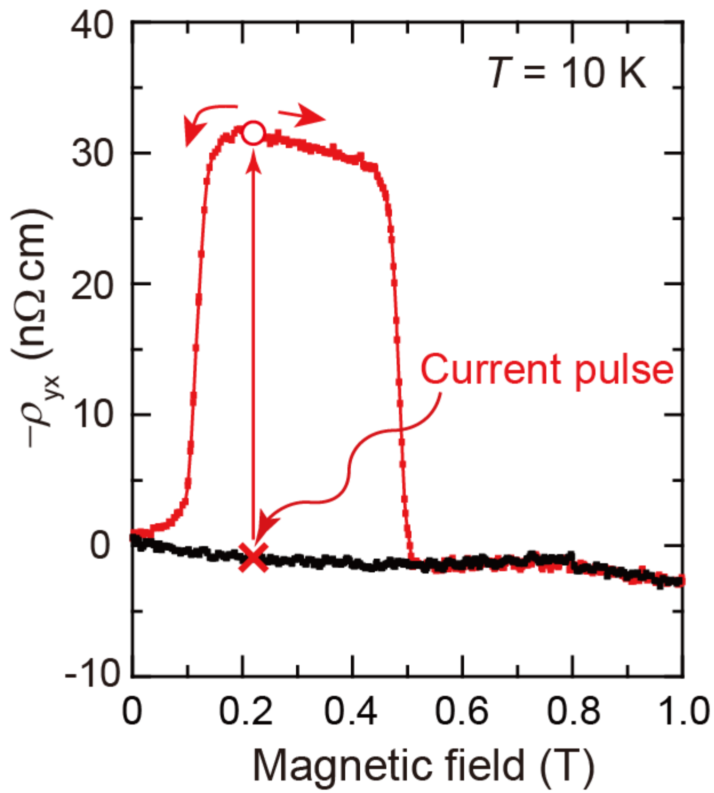
# How to achieve rapid cooling?

Application of electric heating to the sample




Lifetime >> 1 week @ 10 K

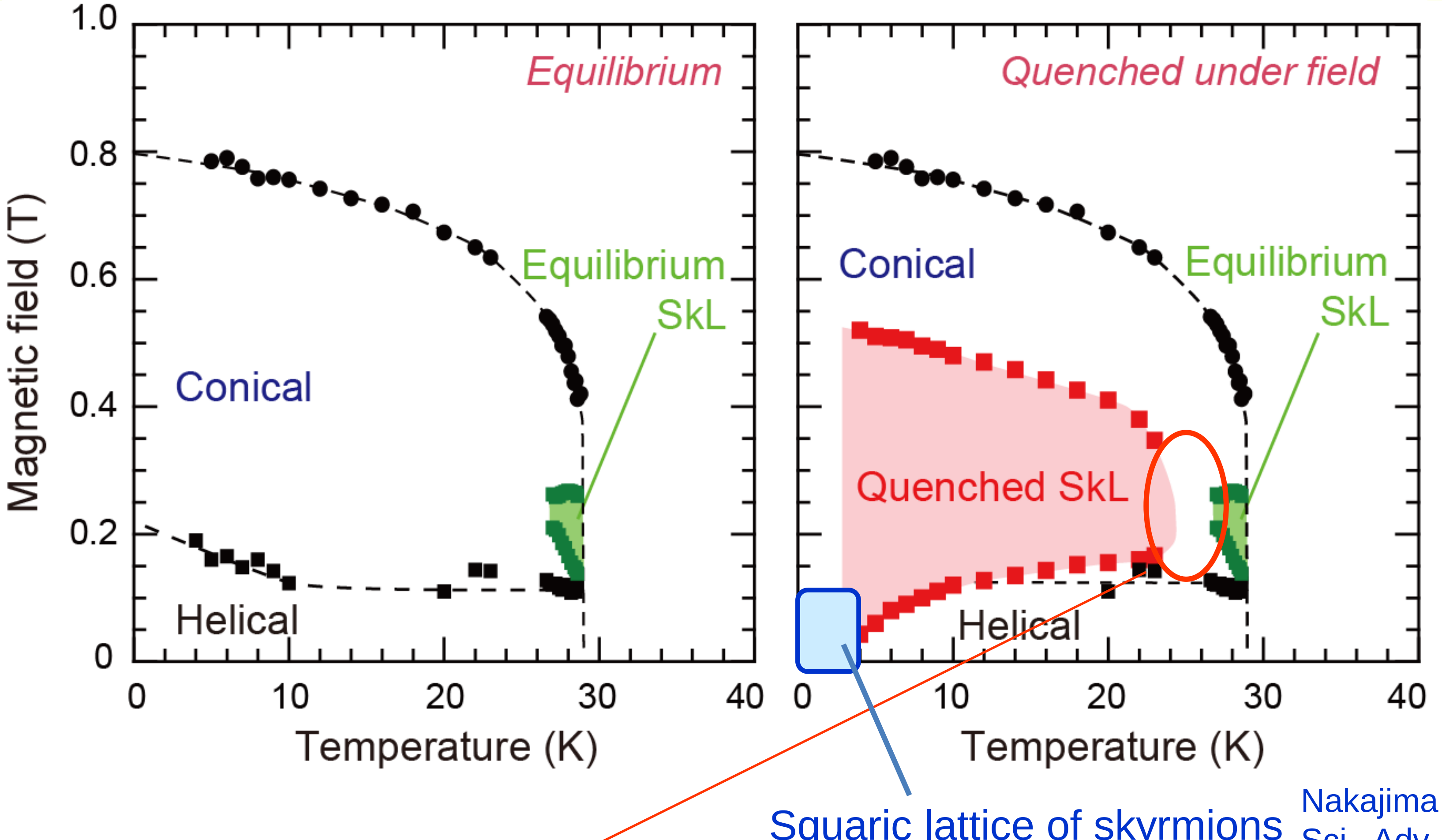
Topological Hall effect as a probe of Sk






Oike, Kagawa et al, Nature Phys. (2016)

# Phase diagram of equilibrium and quenched SkLs




Nakajima et al. Sci. Adv. (2017)

1. Quenched state is quite extended ⇨ Remarkable stability of metastable SkL

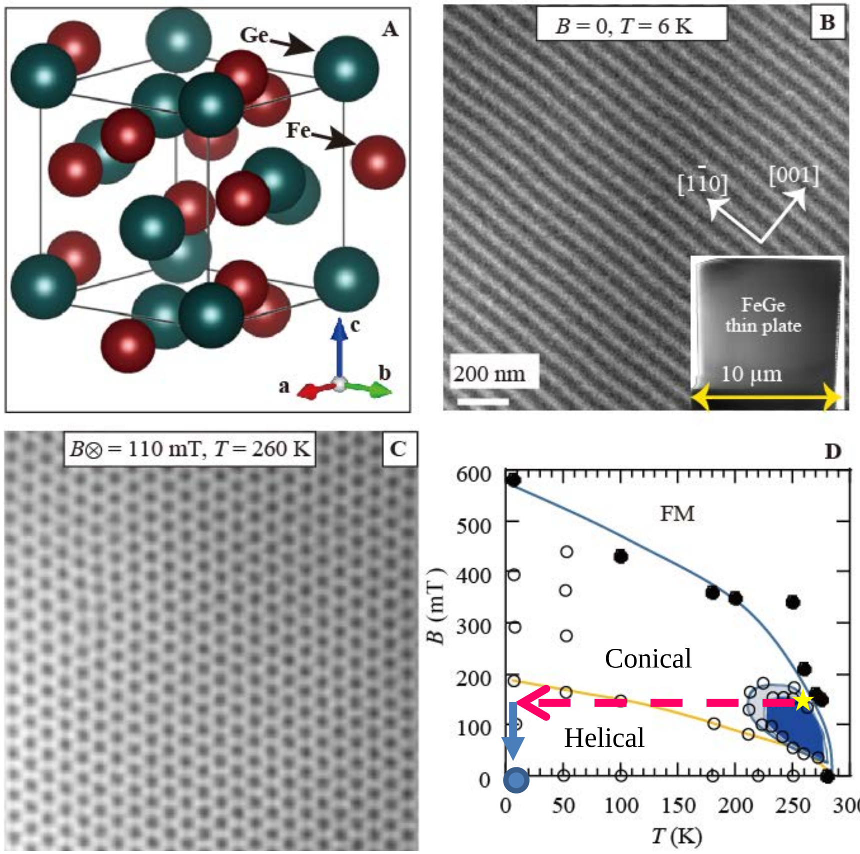
2. Appreciable gap between the quenched SkL and equilibrium SkL

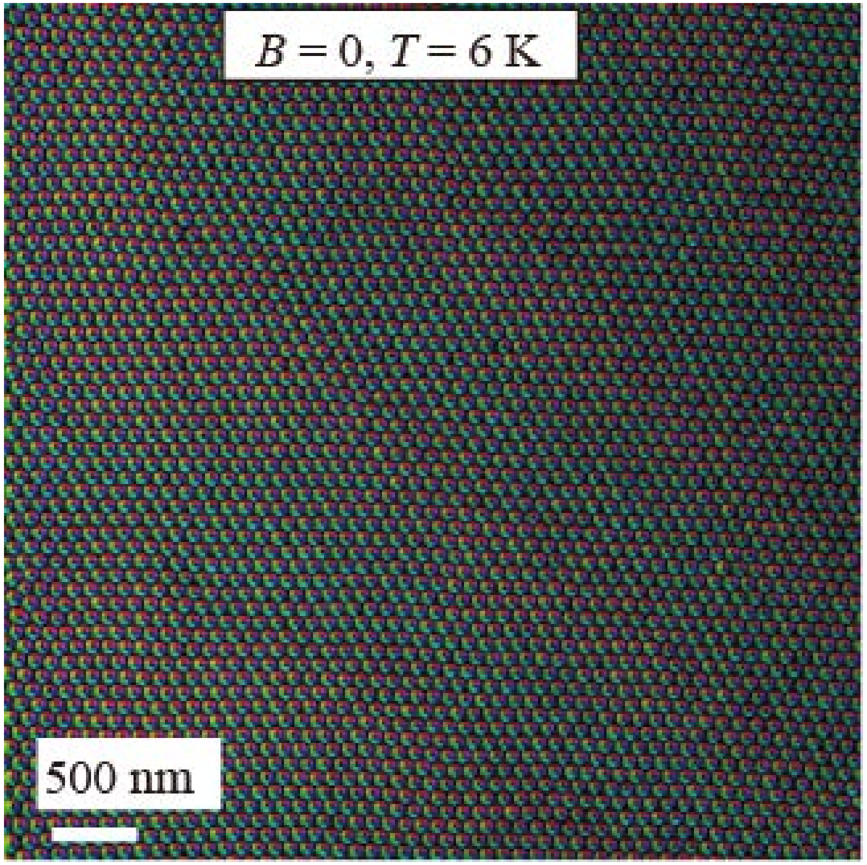
⇨ There, metastable SkL is short-lived

Oike, Kagawa et al, Nature Phys. (2016)

# Quenching of thermal-equilibrium SkX to low temperature and zero field

## FeGe thin plate



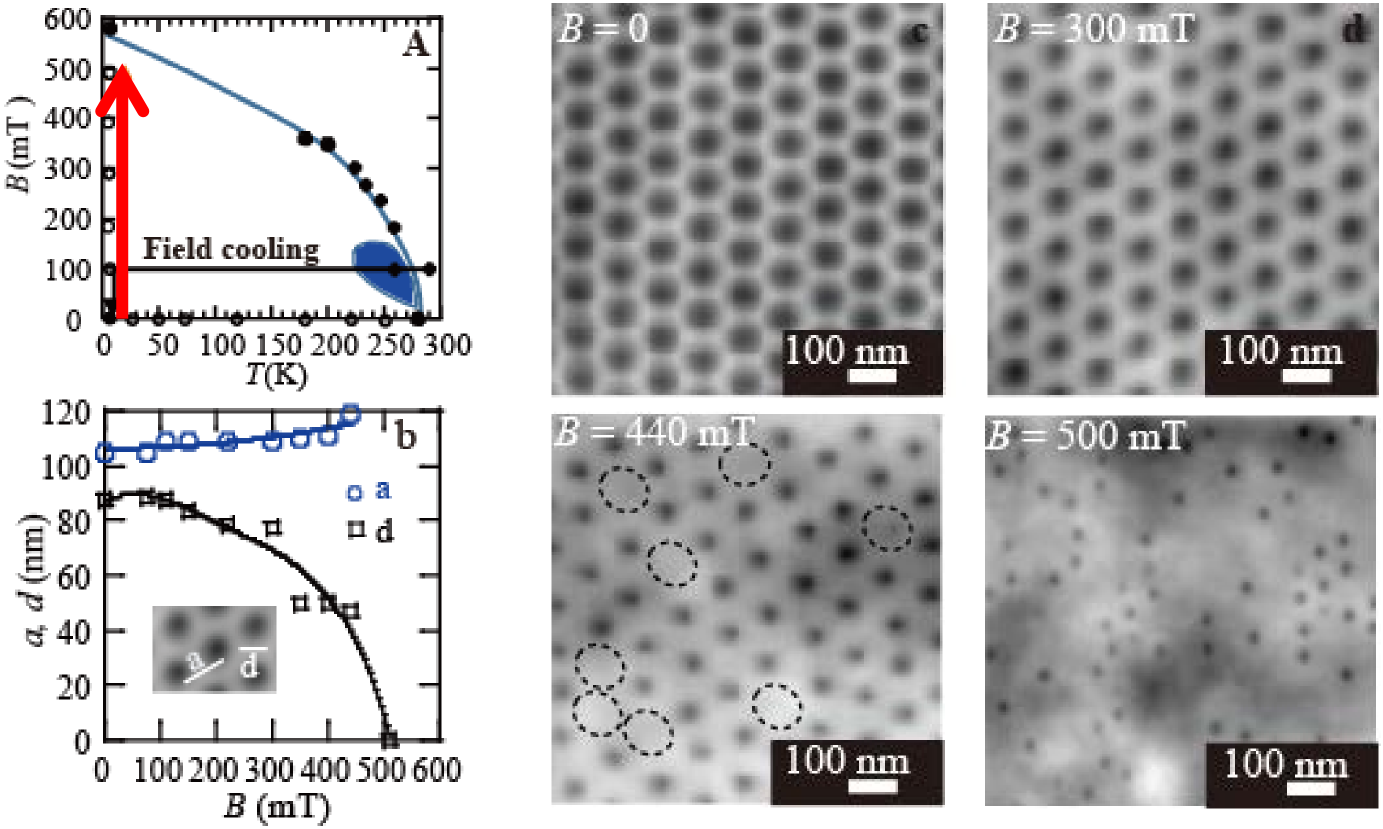




XZ Yu et al. (submitted)

# Shrink of skyrmions with an increase of the bias-field

shrinking of Sk size

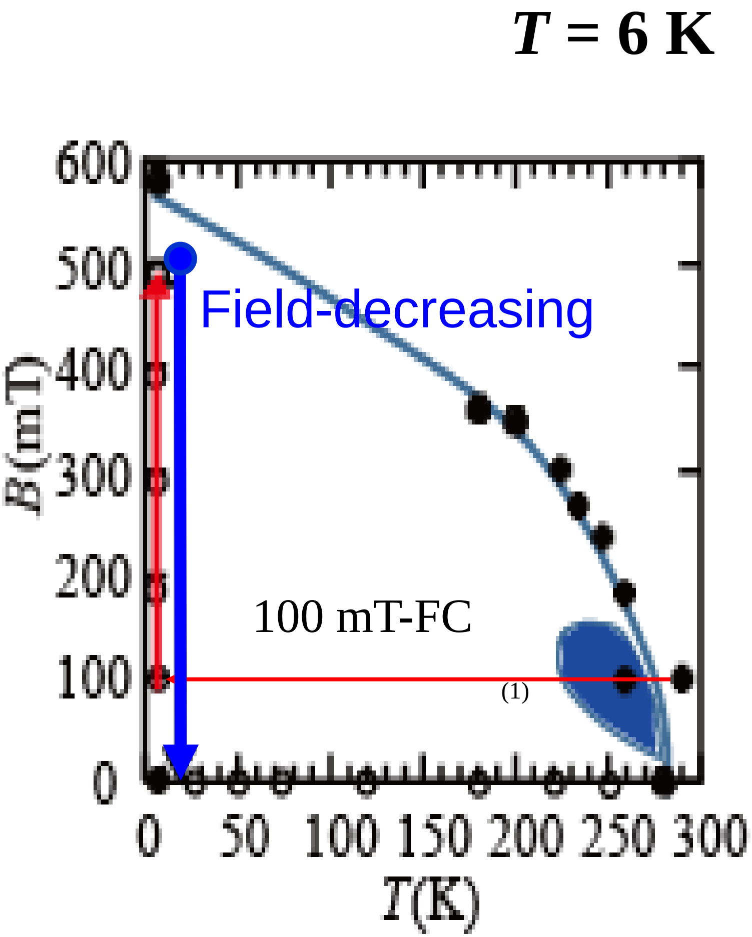
B//z

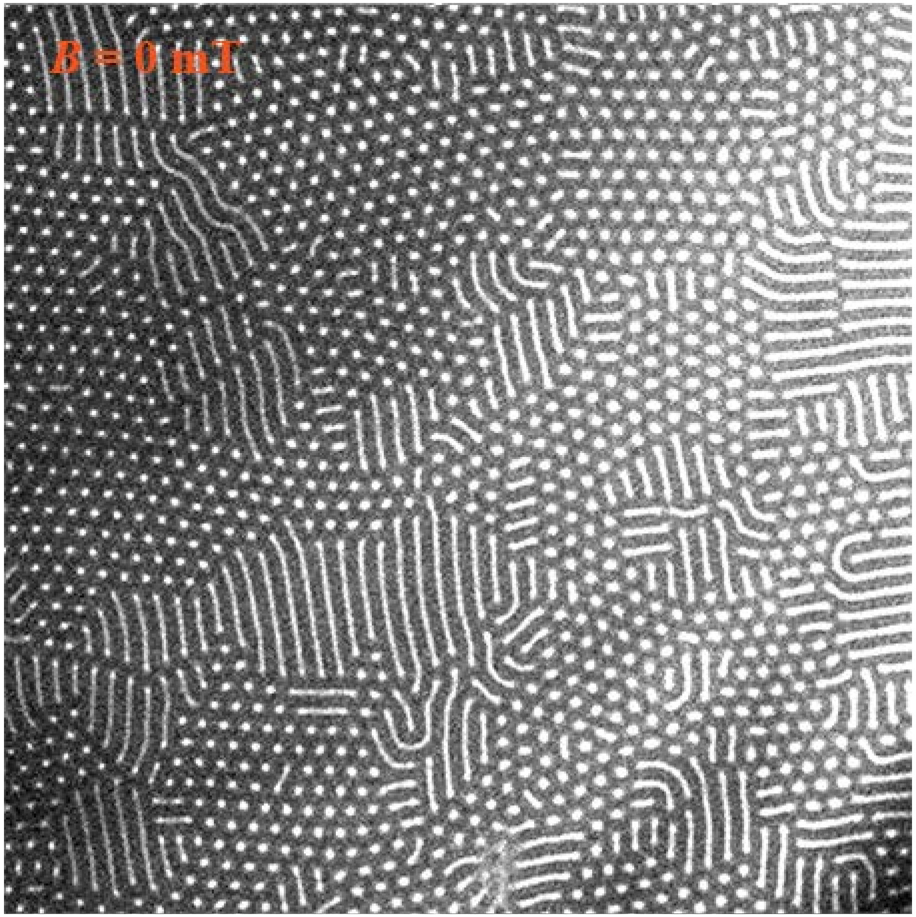



Sk vacancies in SkX

collapse of SkX

# Recrystalization of metastable skyrmions




⟹ Sk glass ⟹ recrystallization ⟹ SkX+ conical ⟹ SkX+helical/elongated Sks monopoles

# Nonreciprocal Responses of Noncentrosymmetric Matters

| Nonreciprocal Response | Linear Response | Nonlinear Response |
|---|---|---|
| Time-reversal Unbroken | Forbidden | Shift current<br>Nonlinear Hall effect<br>pn junction |
| Time-reversal Broken | Optical ME effect<br>Magnetochiral effect<br>Nonreciprocal magnon | Nonreciprocal nonlinear optical effect<br>Electric magnetochiral effect<br>Inverse Edelstein effect<br>Magnetochiral anisotropy |

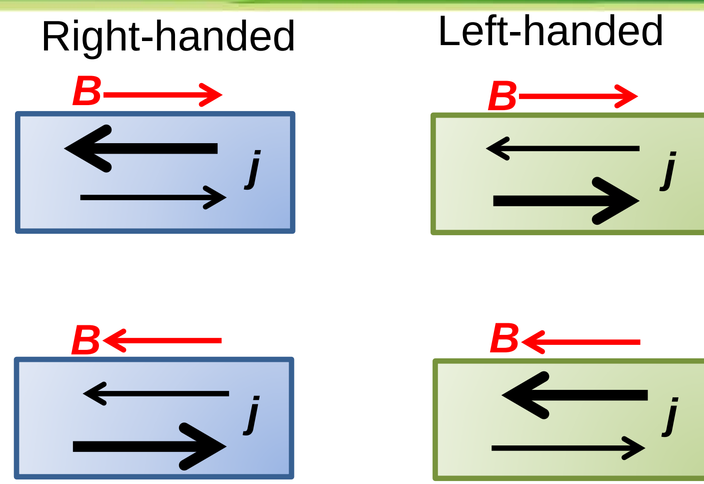
chiral magnet
skrymion

# Electrical magnetochiral effect (eMChE)

**eMChE**

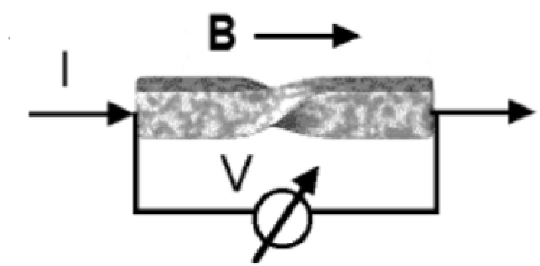
$$R^{\mathrm{D/L}} = R_0(1+\boxed{\gamma^{\mathrm{D/L}}\boldsymbol{B}\cdot\boldsymbol{I}}+\beta B^2)$$

- ✓ Resistivity depending on current direction
- ✓ Odd against magnetic field



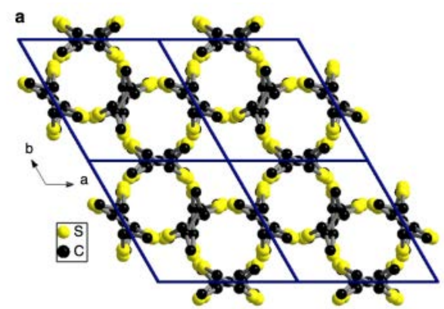

## Previous works

**Twisted Bismuth**




G. L. J. A. Rikken *et al.*, PRL **87**, 236602 (2001).

**Chiral molecular conductor**




F. Pop *et al.*, Nature Commun. (2014).

**Chiral magnets**

# eMChE in MnSi thin plate

Voltage is proportion to $I^2$

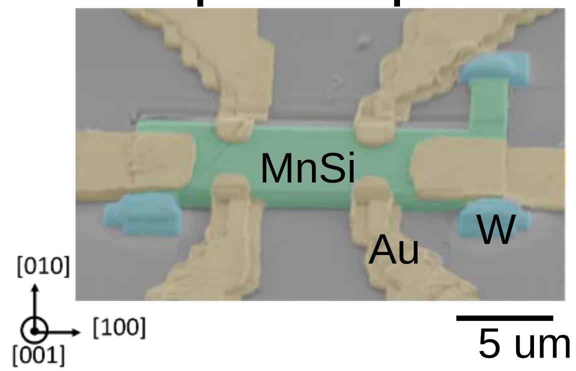
→ Detection of second harmonic signal

$$V_{\mathrm{eMChA}} \propto \gamma^{\mathrm{R/L}}(\boldsymbol{B}\cdot\boldsymbol{I})I$$

$I \propto \sin(2\pi f t)$

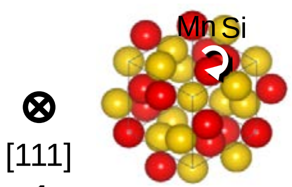
$V_{\mathrm{eMChA}} \propto \sin(2\pi \cdot 2ft)$

**Thin plate sample**

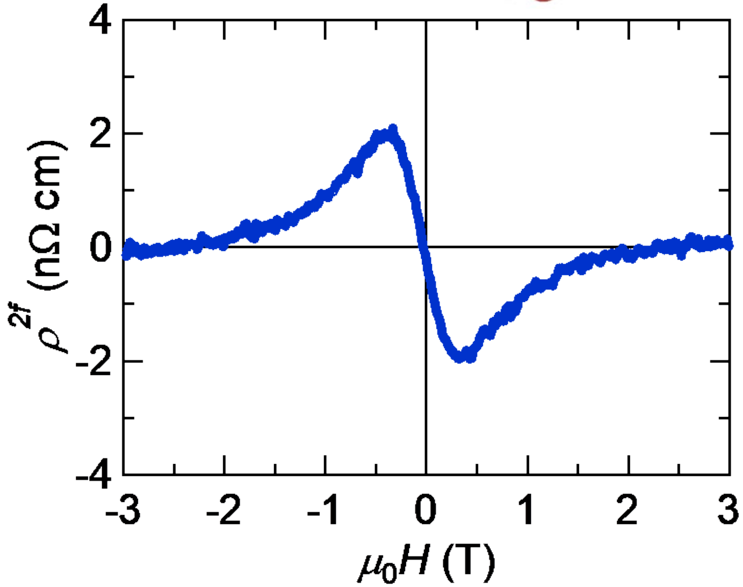


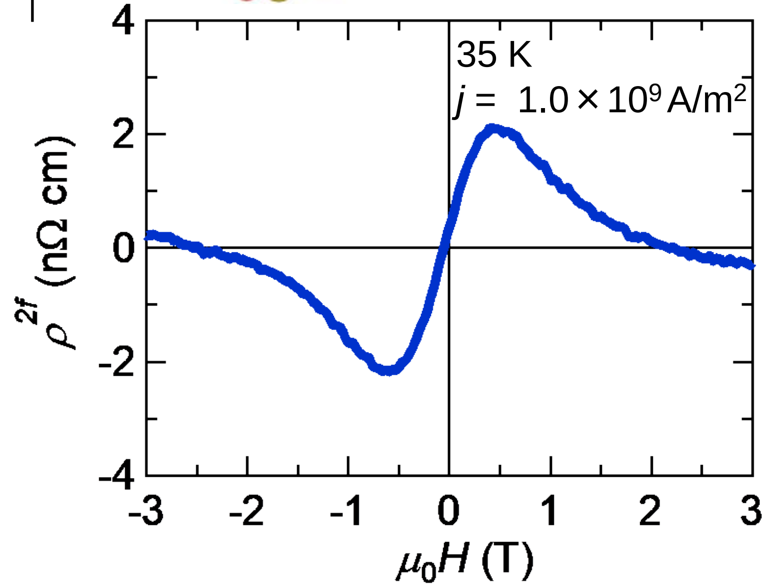


**Left-handed crystal**

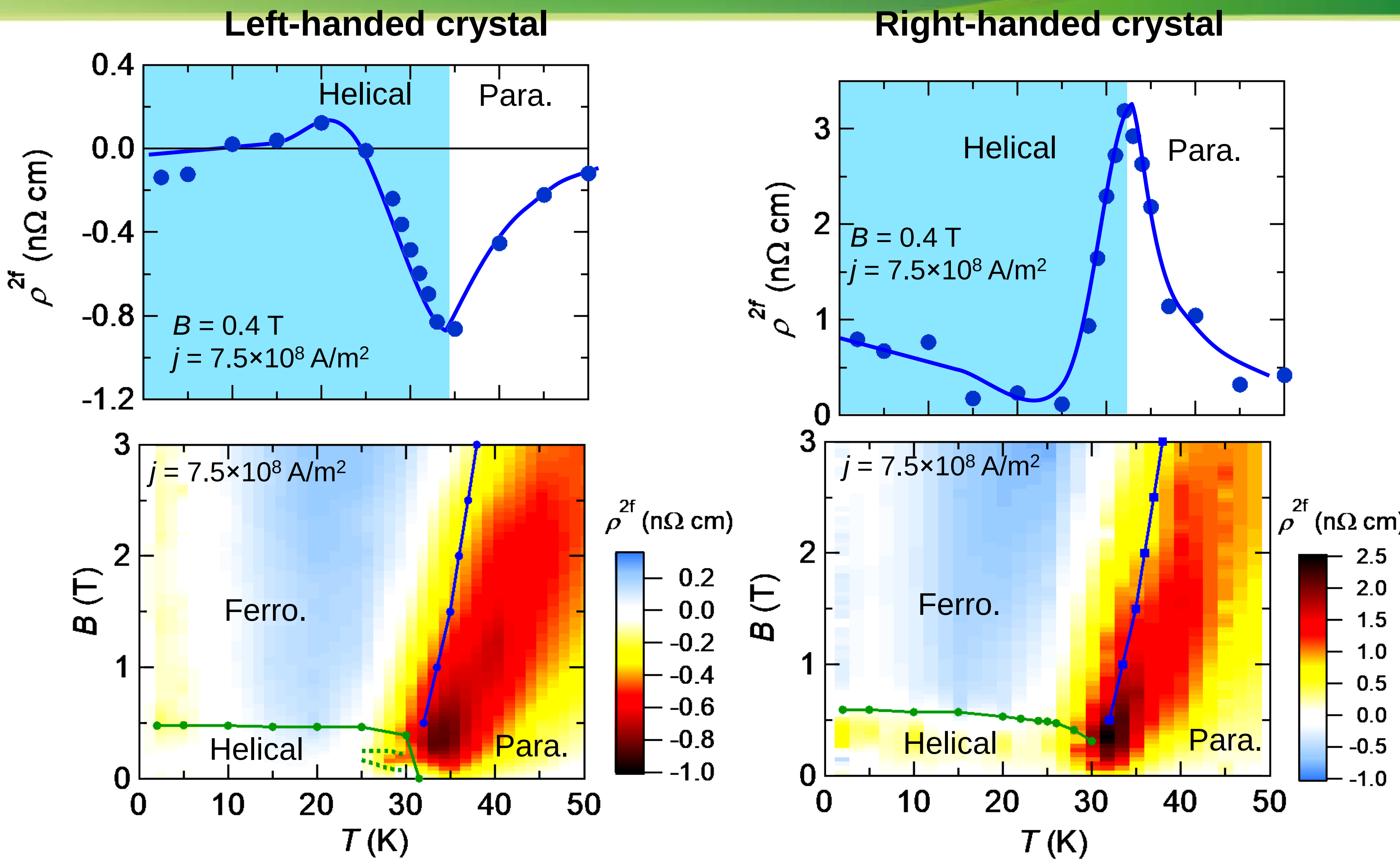



**Right-handed crystal**



# Field & temperature dependence of eMChE



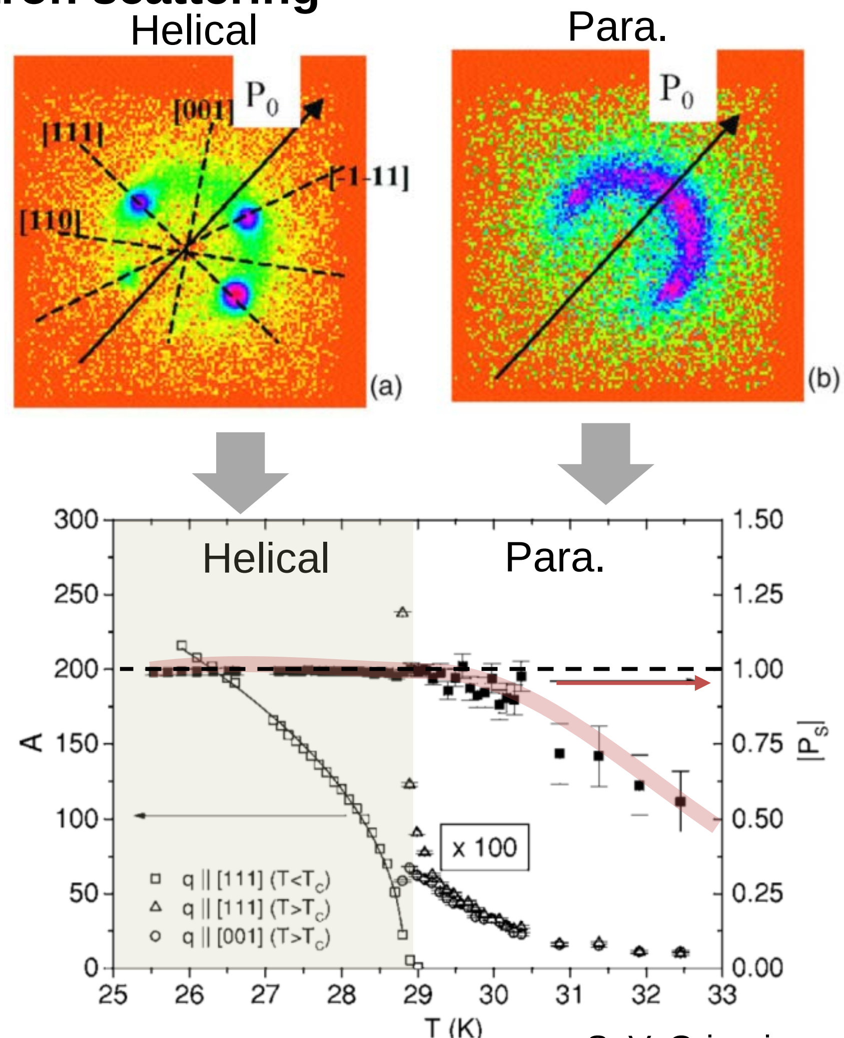

T. Yokouchi *et al.*, Nat. Commun. **8**, 866 (2017).



The magnitude of eMChE is largest just above the transition temperature.

# Chiral spin fluctuations in MnSi

**Polarized neutron scattering**




S. V. Grigoriev, *et al.*, PRB **72**, 134420 (2005).

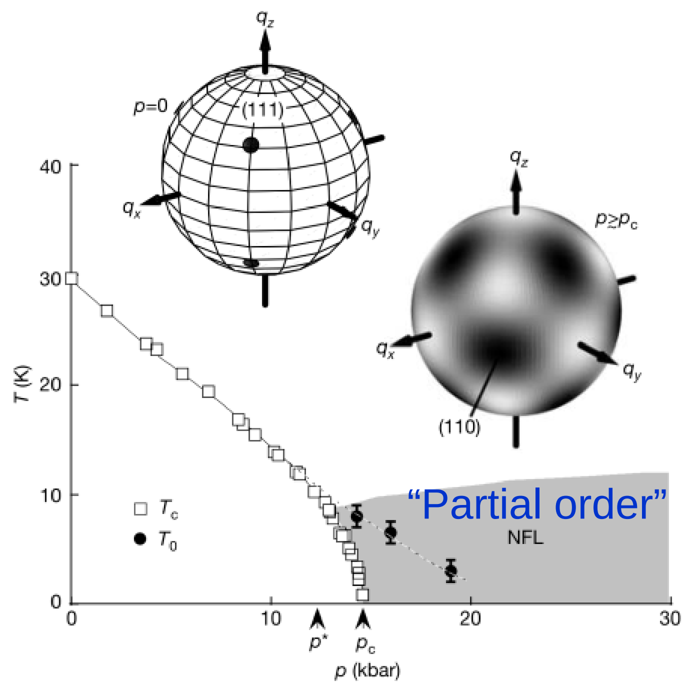
**Chiral spin fluctuations**

$$\left\langle \left(\boldsymbol{C}(t) - \langle \boldsymbol{C} \rangle\right)^2 \right\rangle$$

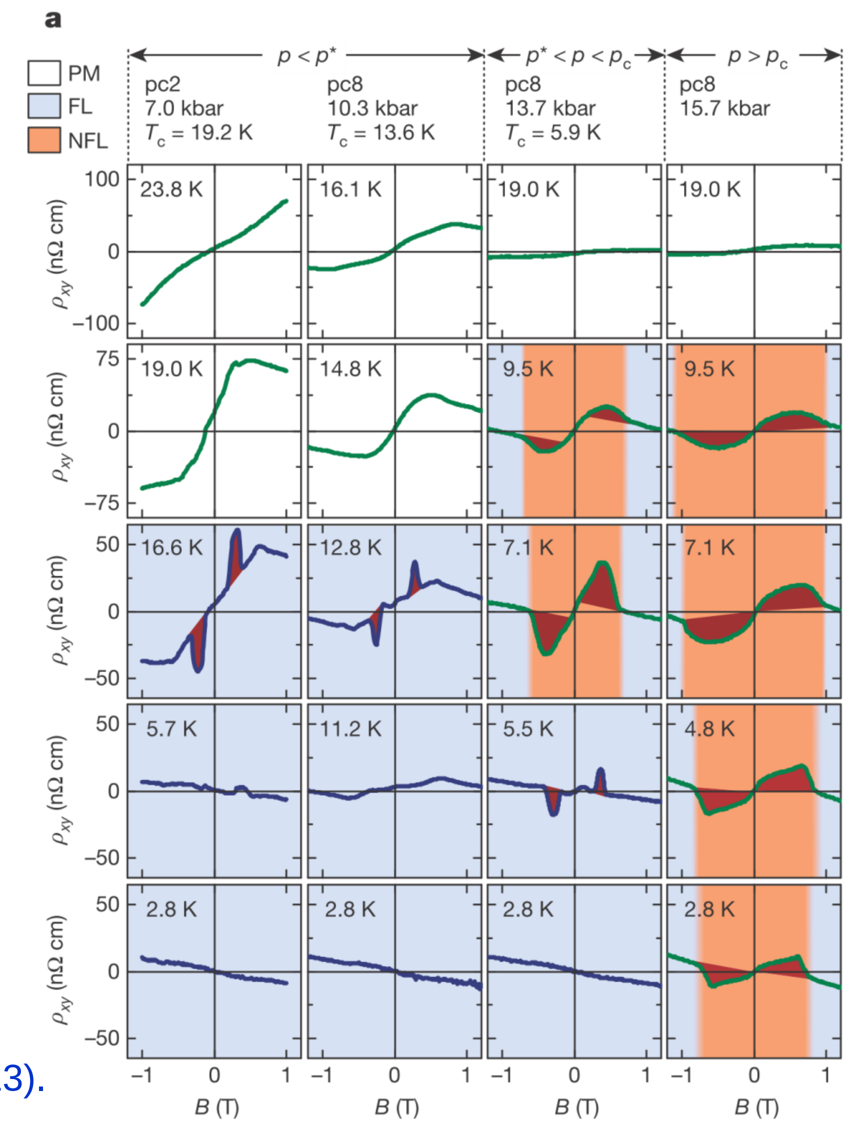
$$\boldsymbol{C} = \boldsymbol{S}_i \times \boldsymbol{S}_j$$

The chiral nature of spins still remains even in the paramagnetic phase.
Asymmetric electron scattering by the chiral spin fluctuations gives rise to eMChE.

# Pressure effect on eMChE




C. Pfleiderer, *et al*., Nature **427**, 227 (2004).

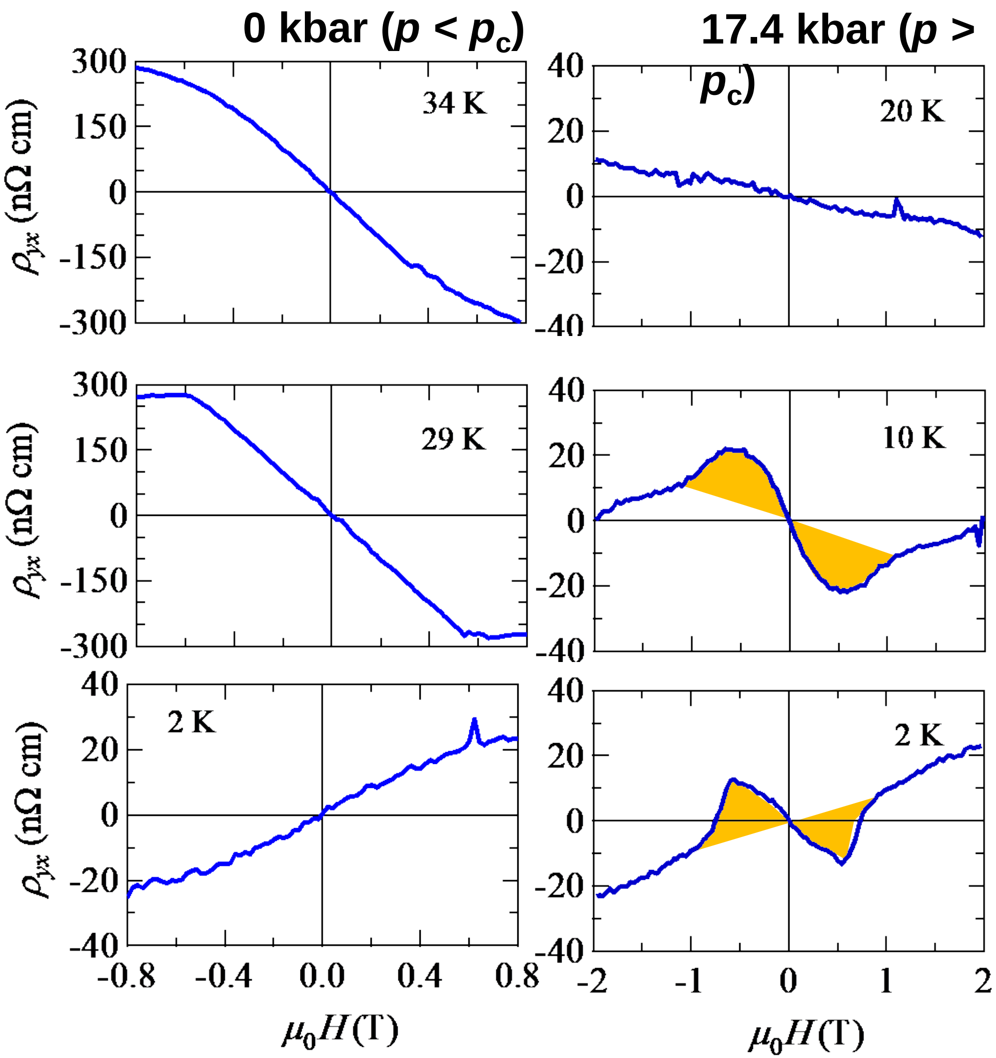


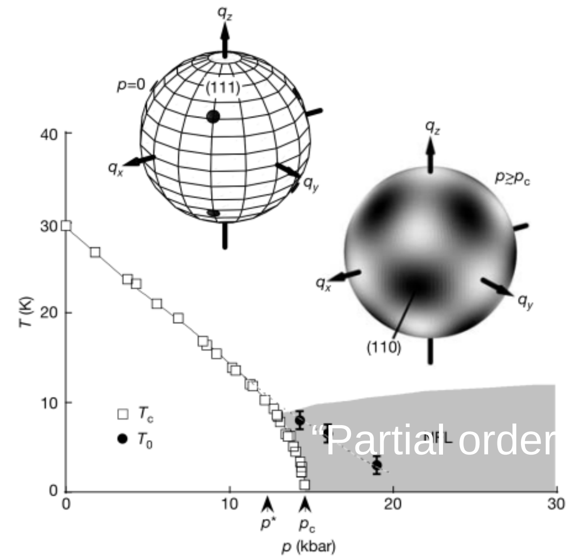

R.Ritz et al. Nature, 497, 231 (2013).

"Partial order"　Dynamical topological spin texture related to quantum phase transition.

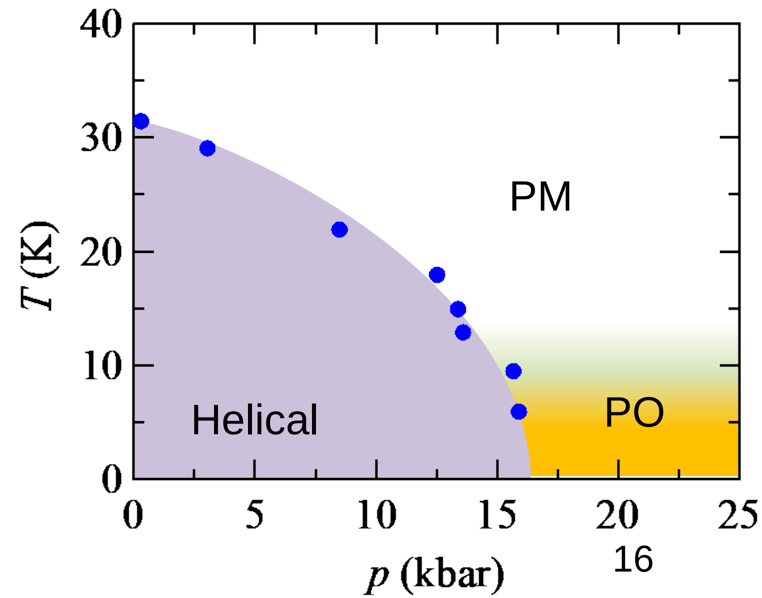
# Pressure effect on Hall resistivity

Topological Hall effect in PO



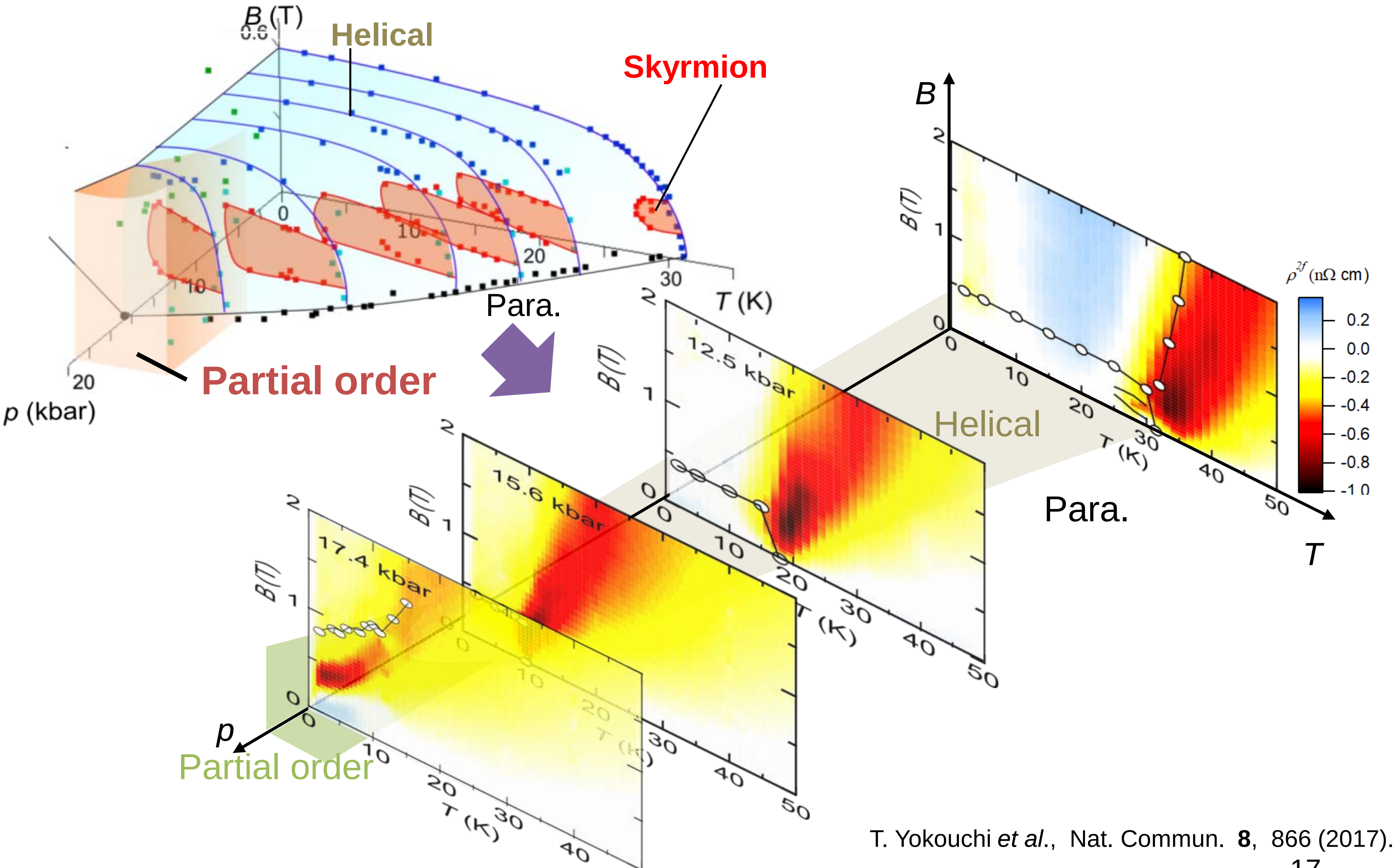




C. Pfleiderer, *et al.*, Nature **427**, 227 (2004).



# Electrical magnetochiral effect under pressure

**$p$-$T$-$B$ phase diagram of MnSi**




T. Yokouchi *et al.*, Nat. Commun. **8**, 866 (2017).

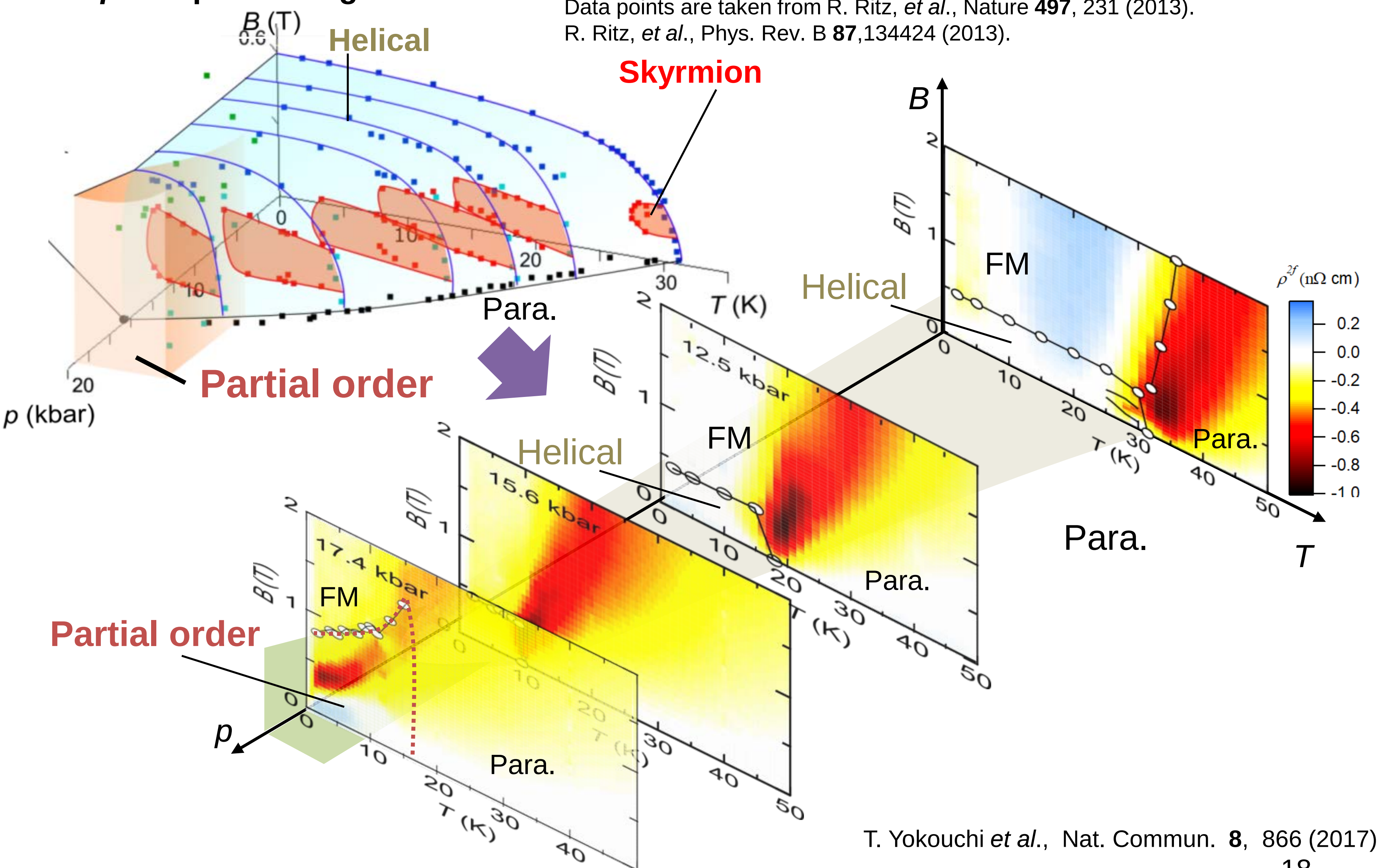


**The eMChE is also observed in partial order phase→Quantum chiral spin fluctuations**

# Electrical magnetochiral effect under pressure

***p*-*T*-*B* phase diagram of MnSi**

Data points are taken from R. Ritz, *et al.*, Nature **497**, 231 (2013).
R. Ritz, *et al.*, Phys. Rev. B **87**,134424 (2013).




T. Yokouchi *et al.*, Nat. Commun. **8**, 866 (2017).



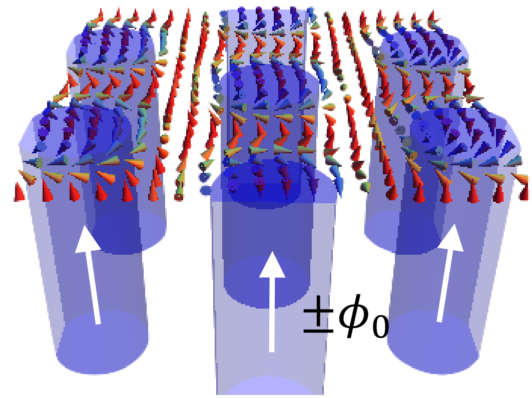
**The eMChE is also observed in partial order phase→Quantum chiral spin fluctuations**

# Hedgehogs and emergent monopoles

Skyrmions and anti-skyrmions

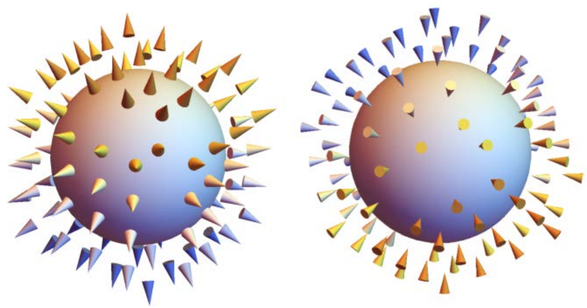
Bloch   Néel   Anti-skyrmion

etc…

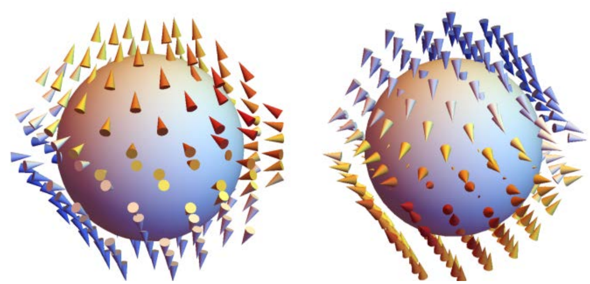



Flux-line distribution

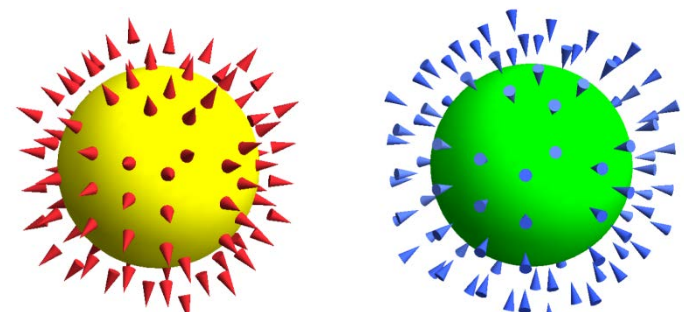
Hedgehogs and anti-hedgehogs



etc…



Pair of hedgehog and anti-hedgehog in MnGe



Monopole   Anti-monopole

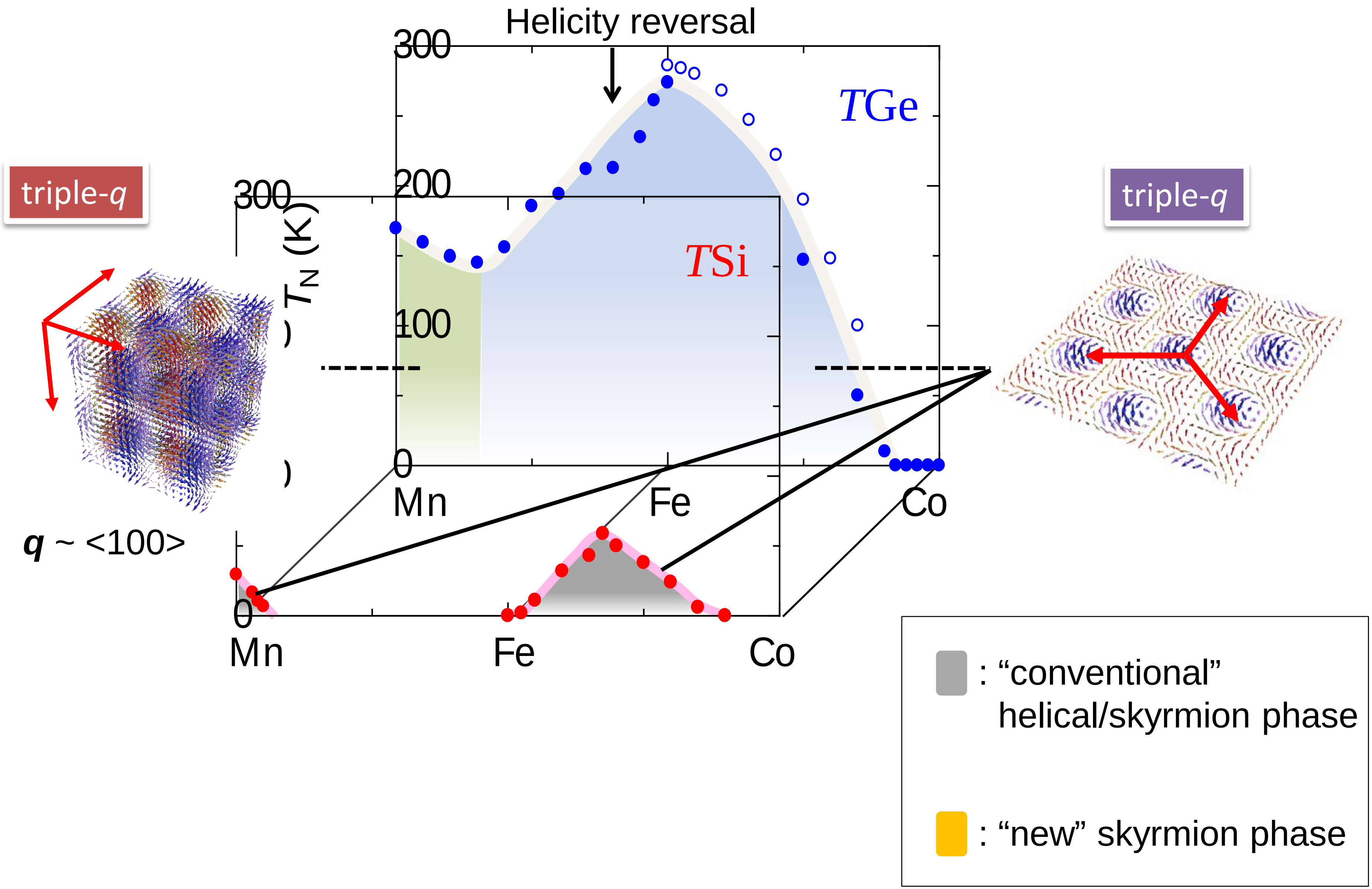
$$\nabla \cdot \boldsymbol{b} = 4\pi Q \delta(\boldsymbol{r})$$

$Q$: monopole charge

$$\frac{\mathrm{d}\boldsymbol{b}}{\mathrm{d}t} + \nabla \times \boldsymbol{e} = -\boldsymbol{J}_m$$

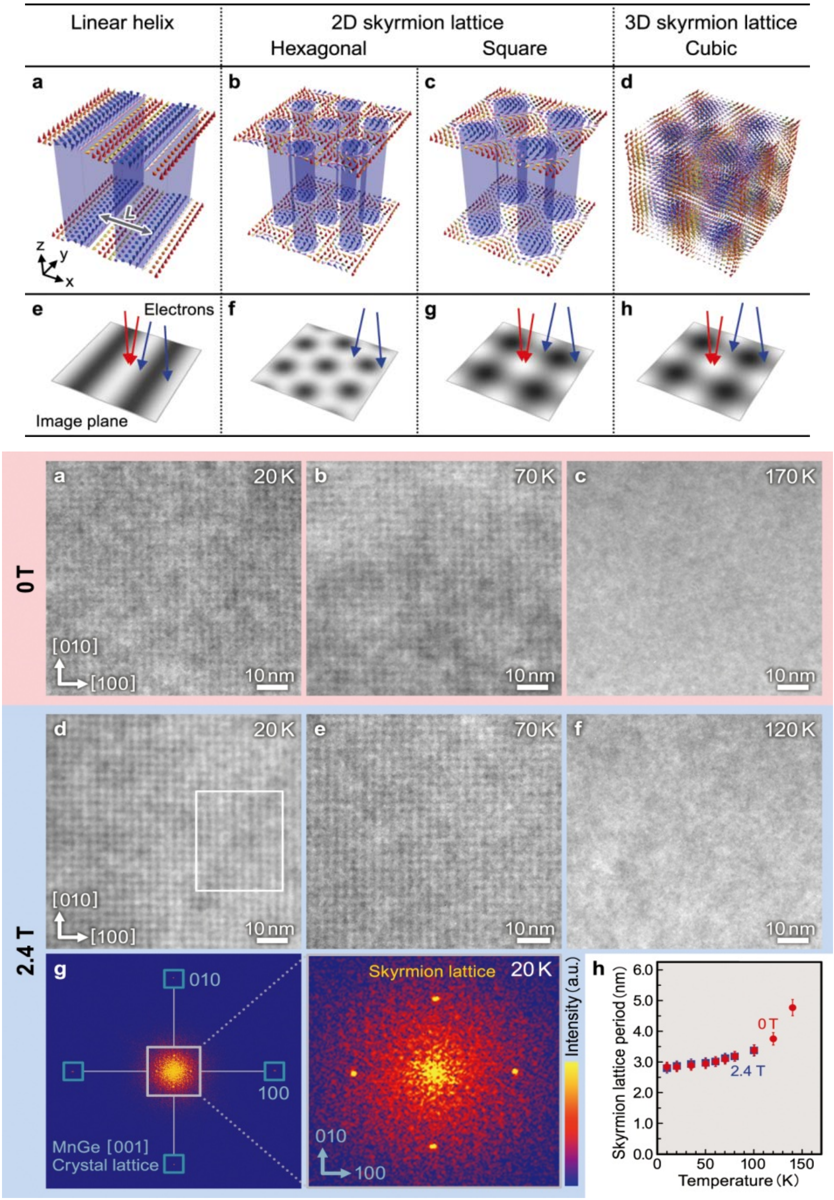
$\boldsymbol{J}_{\mathrm{m}}$: monopole current

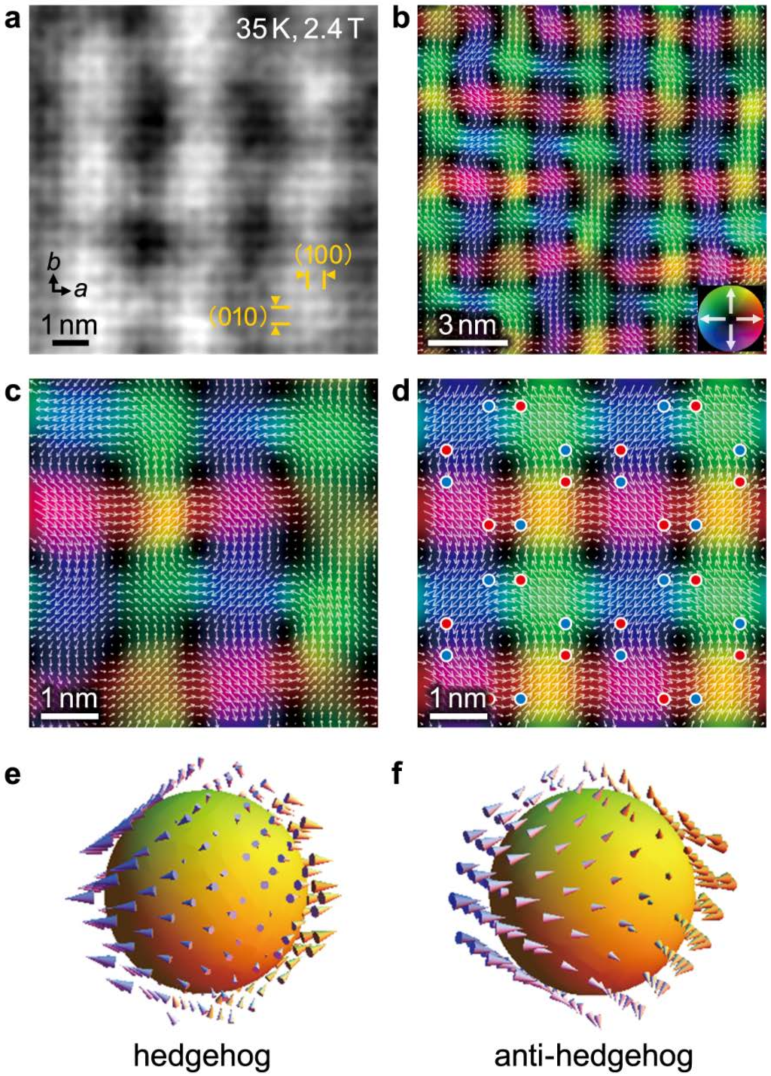
# Magnetic phase diagram in *B*20 compounds



# MnGe; short-period cubic lattice of skyrmion

T. Tanigaki et al. Nano Lett.(2016)



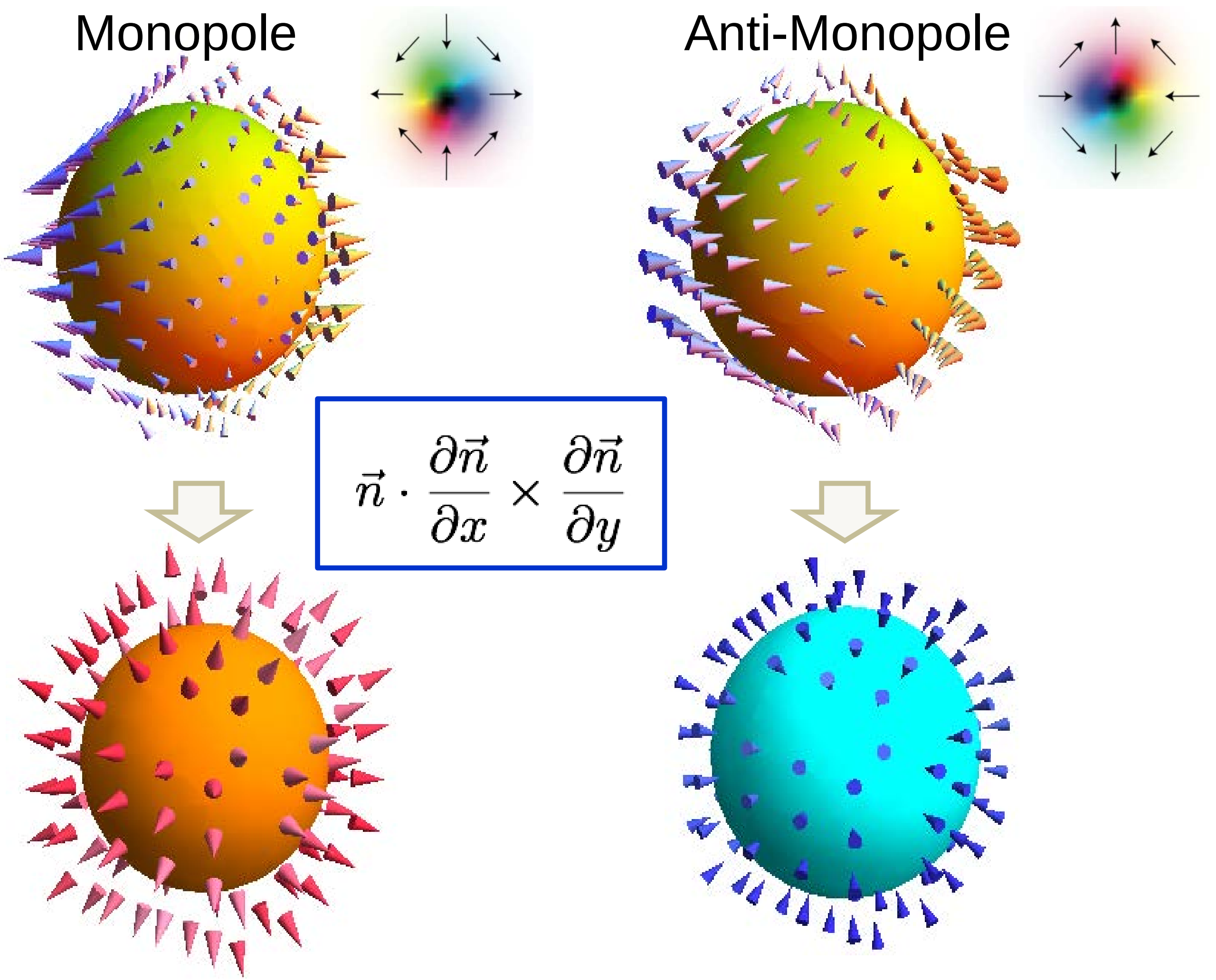



# Monopole and anti-monopole



Spin arrangement

Emergent *b*-field



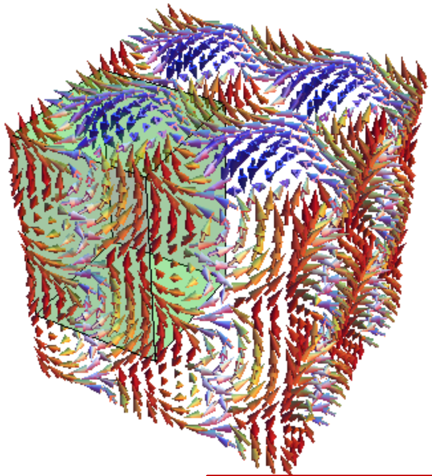

$$\vec{n} \cdot \frac{\partial \vec{n}}{\partial x} \times \frac{\partial \vec{n}}{\partial y}$$

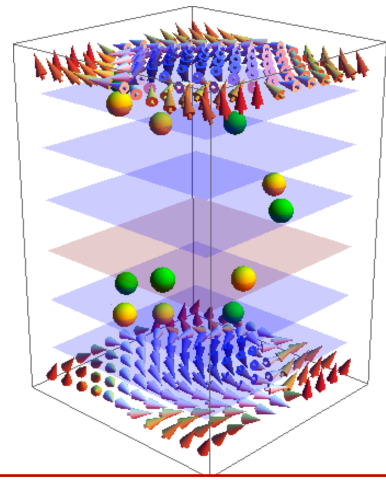
Monopole electronics??

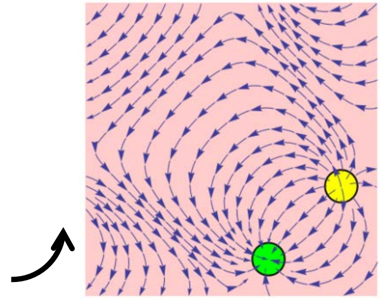
N. Kanazawa et al. Nature Commun. (2016)

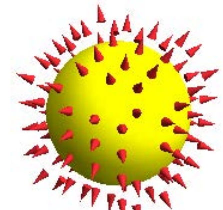
# Magnetic field dependence of emergent monopole-antimonopole crystal

N. Kanazawa et al. Nature Commun. (2016)

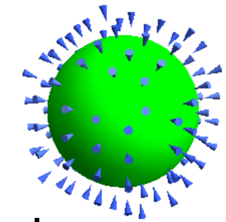








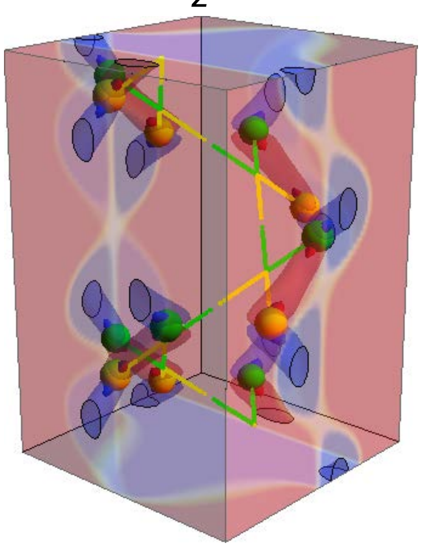
Monopole



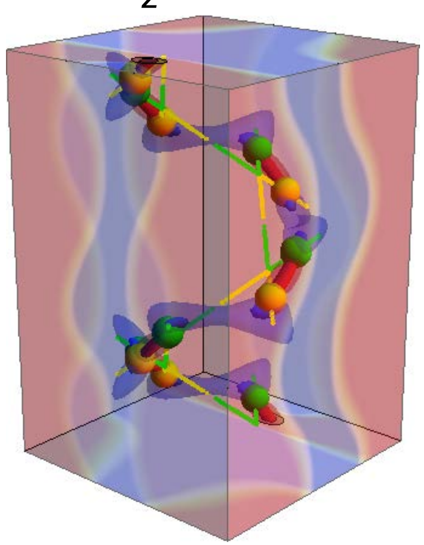
Anti-monopole

$$\text{polarization factor} \quad n_z \equiv \frac{1}{V_{\text{unit cell}}} \int_{\text{unit cell}} M_z(\mathbf{r})/|\mathbf{M}(\mathbf{r})|\, dV$$

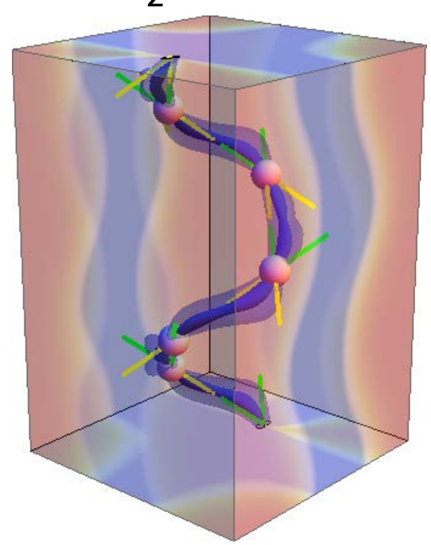
$n_z = 0$



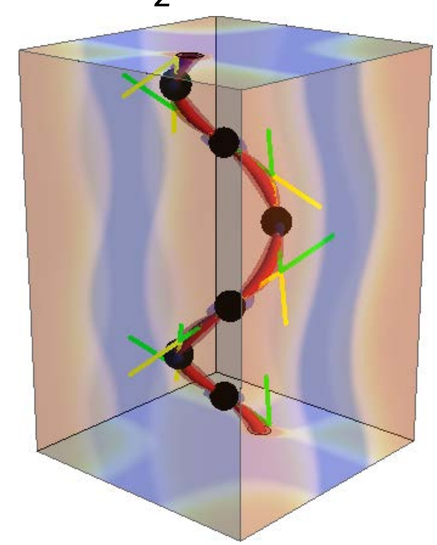
$n_z = 0.245$



$n_z = 0.457$

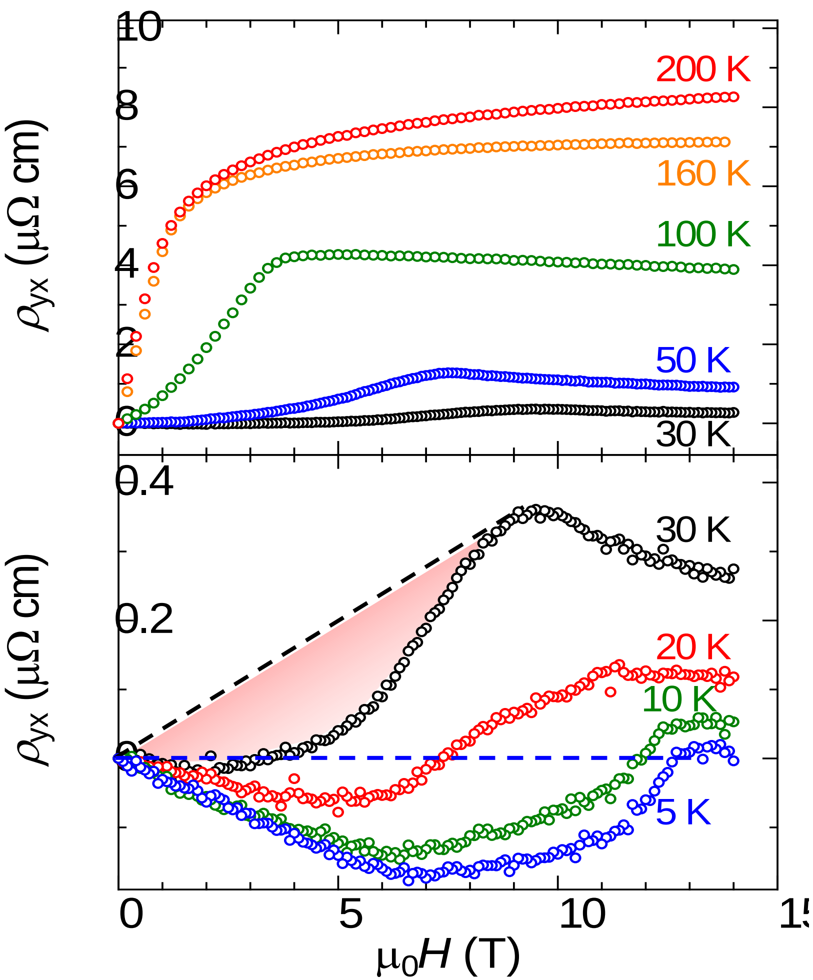


$n_z = 0.605$



# Topological Hall effect in MnGe






**Hall "resistivity"**

$$\rho_{yx} = R_0 B_z + S_H \rho_{xx}^2 M + P R_0 b_z(r)$$

**Do not obey AHE relation**

-Hall resistivity is not proportional to *M*

-Sign change of $\rho_{yx}$ below 30 K

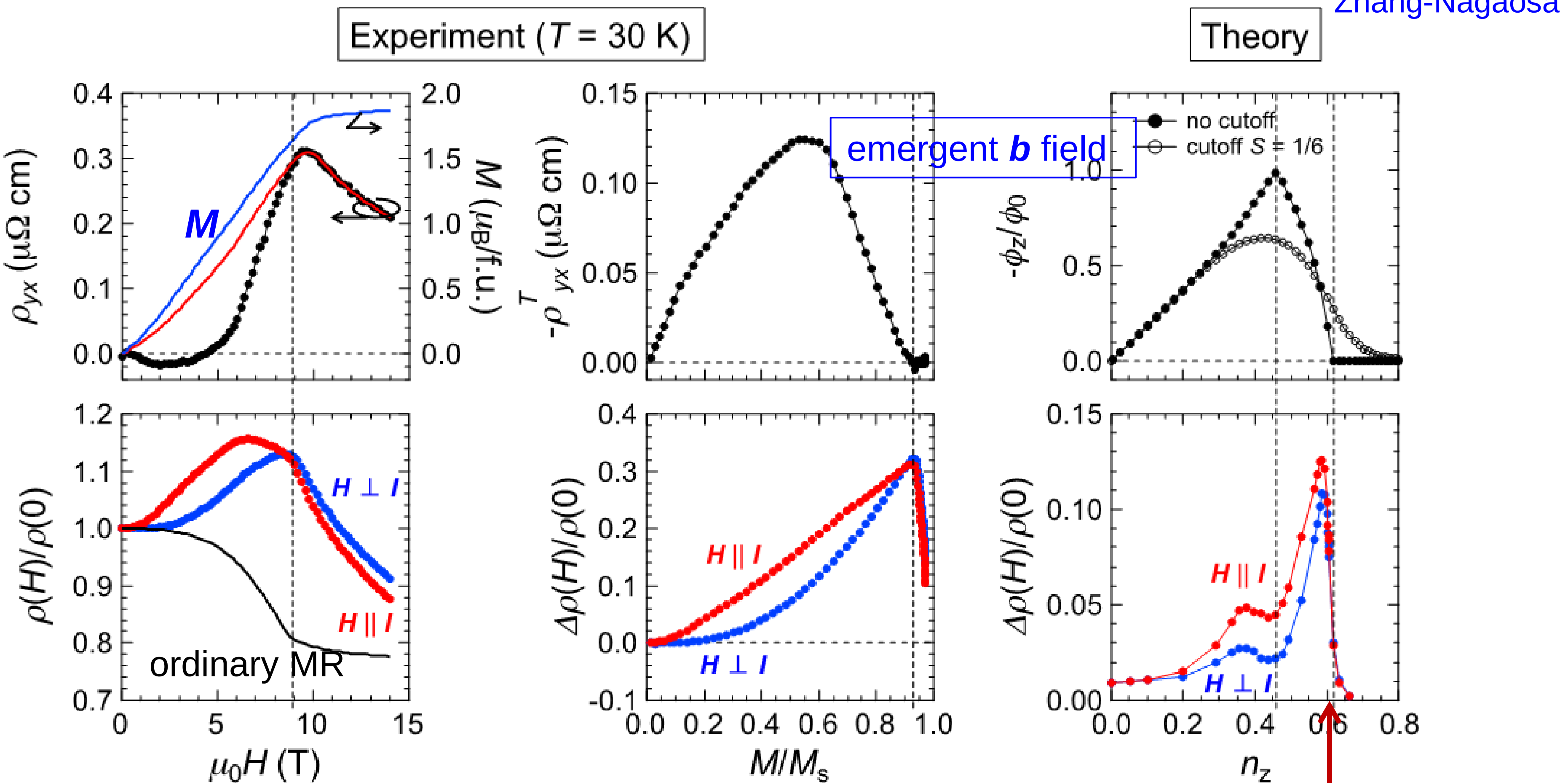
$H < H_C$

Topological Hall effect
due to a non-coplanar spin order (Skyrmion)

$\rho^T_{yx}$ ~ - 0.16 μΩ cm → $B_{eff}$ ~ -40 T

# Magnetic field dependence of emergent monopole-antimonopole crystal

N. Kanazawa et al. Nature Commun. (2016)




monopole pair annihilation

☑Topological Hall effect (emergent ***b*** filed) is maximized at mid H region.

☑Positive MR is maximized at the skyrmion-vanishing point.



Large scattering rate by the enhanced fluctuation at the annihilation point.

# Summary

particle nature of skrmions protected by topology

Skyrmion recrystalization
topological phase separation

skyrmion strings as quantum soft matter

Dynamical deformation of skyrmion strings
generate emergent ***e*** &***b*** fields.

Mangetic monopole fluctuations
as strong scatterer of conductin electrons

Large magnetoresistance and thermoelectricity
upon unwiding monopole-antimonople pairs