Magnetization dynamics of skyrmions lattice in chiral magnets

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Oscar Li

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Dennis Mettus
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Hans Hübl
TU Munich


Christian Back, Sina Mehboodi, Liquing Yang,
all members

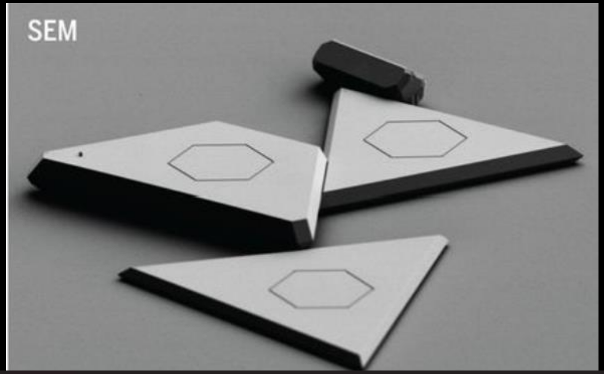
Functional Spin Systems
TU Munich

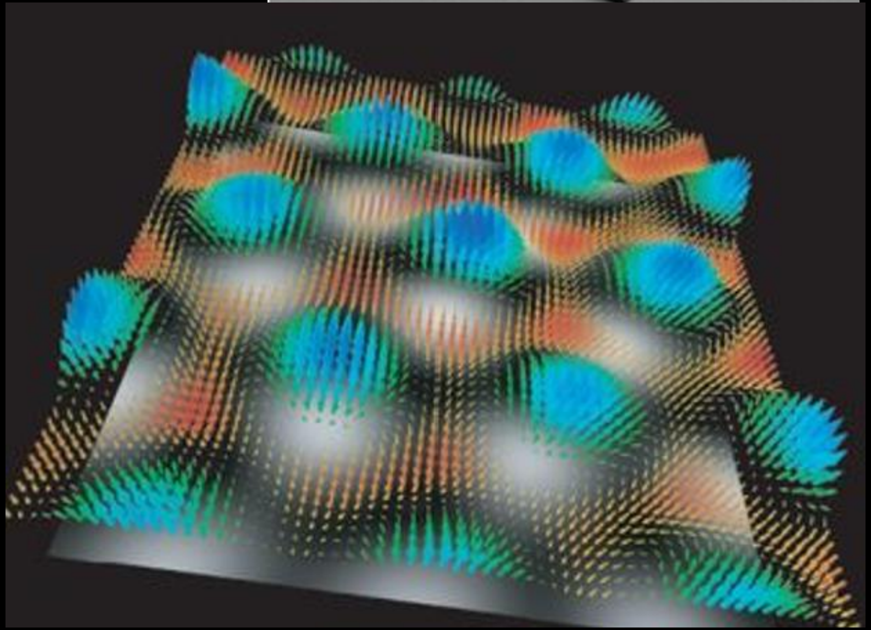
Skyrmions

Let’s see how the dynamics looks for skyrmions lattice
Considering prototype system

Optical

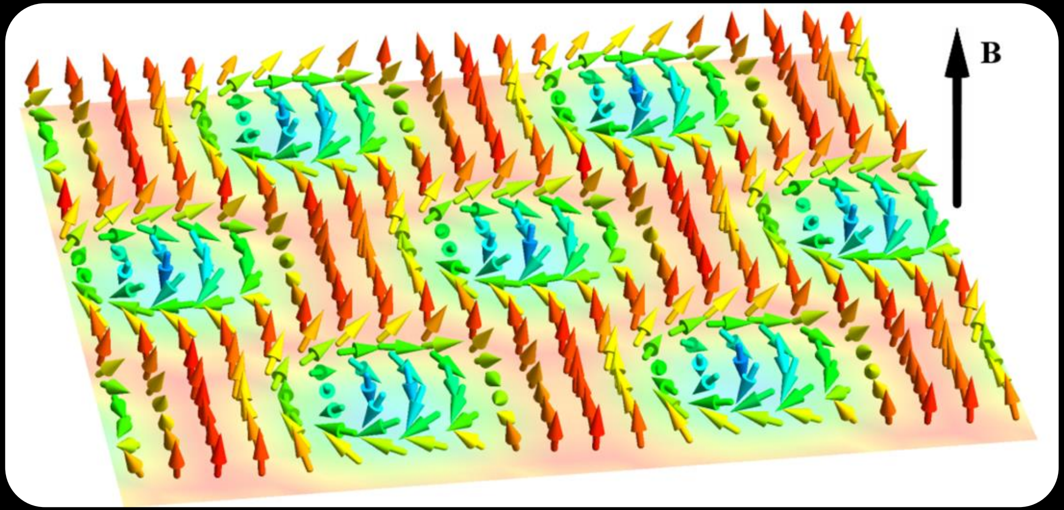
PEEM





Davis, et al, Science 368, (2020)

Magnetic



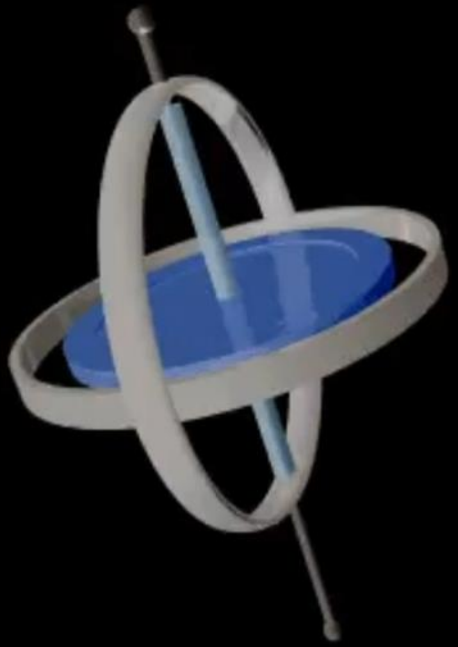
Everschor-sitte PhD thesis 2012

Outline

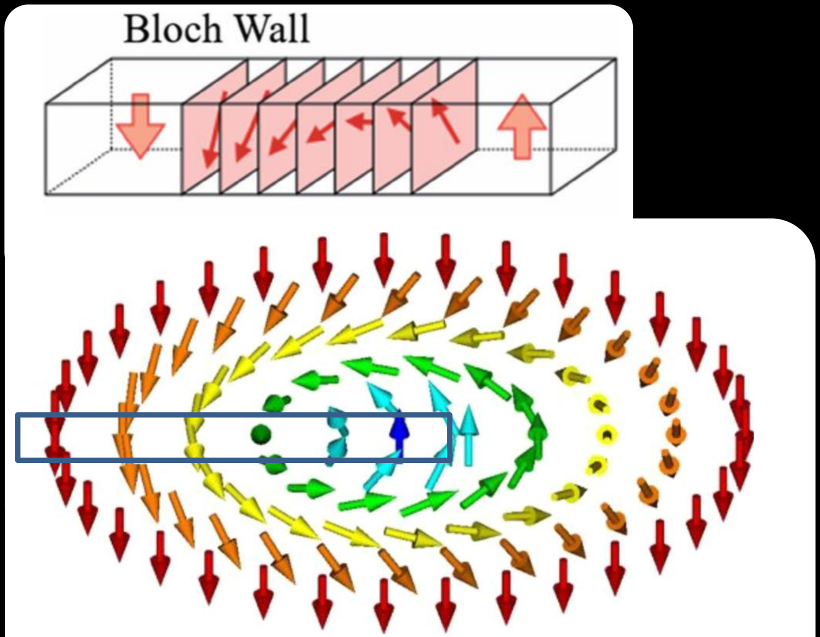
1. Introduction   -> Chiral magnet + Insulator

2. Static magnetization

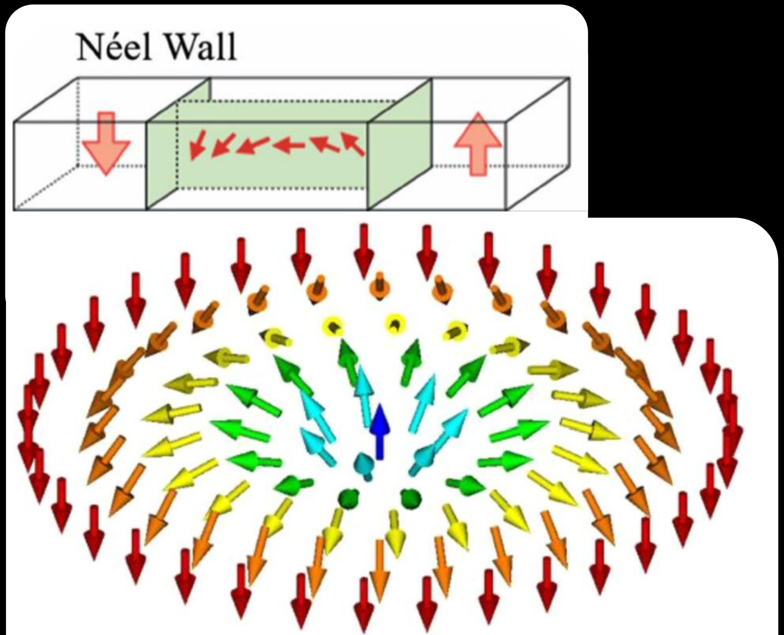
3. Magnetization dynamics



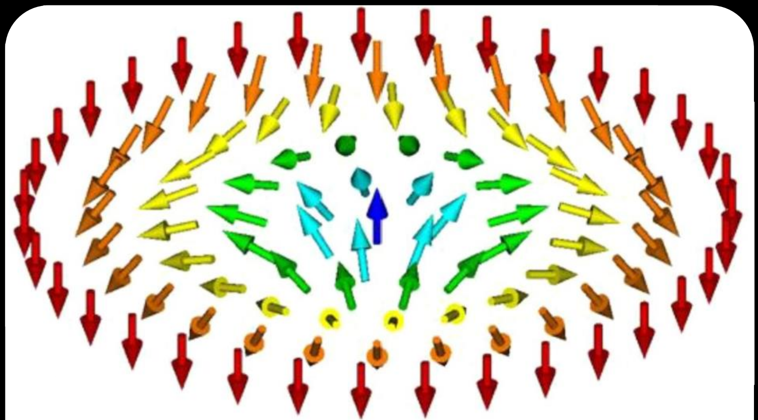
Magnetic Skyrmions



Bloch-type skyrmion



Néel-type skyrmion



Antiskyrmion

Cubic
e.g. MnSi, FeGe, Cu_2OSeO_3

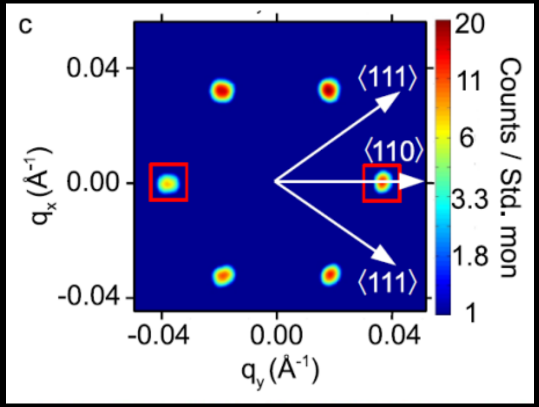
C_{2v} (Polar)
GaV_4S_8, GaV_4Se_8

D_{2d} (Polar)
$Mn_{1.4}$(Pt,Pd) Sn

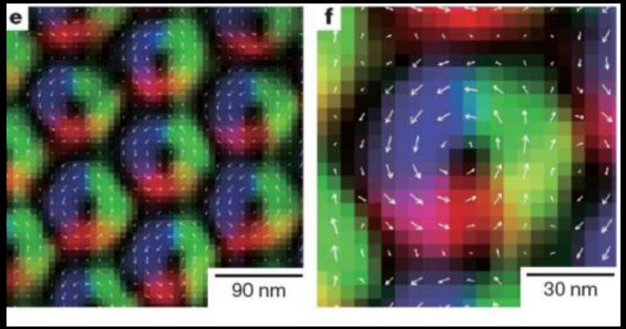
e.g. Back *et al J. Phys. D: Appl. Phys.* **53** 363001 (2020), Zhou et al., Adv. Mater. 2312935 (2024),
Leonov and Kézsmárki, Phys. Rev. B 96, 214413 (2017)
Li-cong *et al., Chinese Physics B*, 27(6): 066802 (2018)

Imaging of skyrmions in chiral magnets

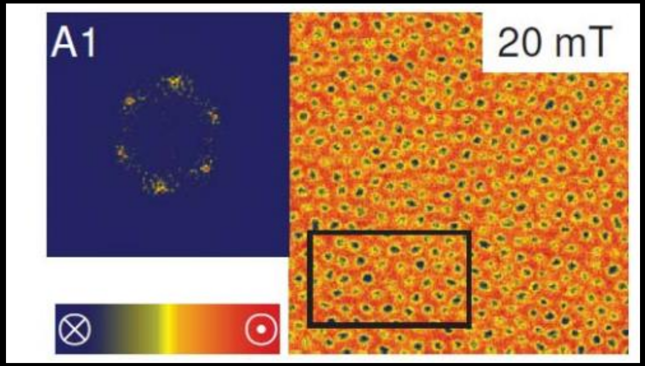
Neutron Scattering MnSi
Pfleiderer, Böni, et al., 2009-2012



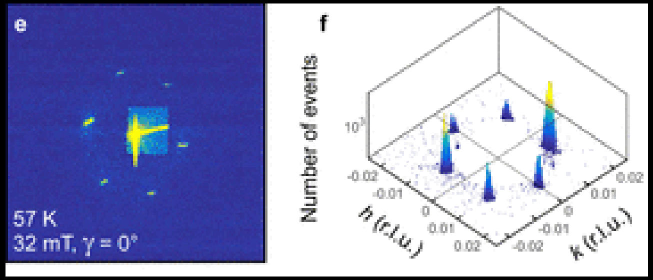
Lorentz transmission electron microscopy $Fe_{0.5}Co_{0.5}Si$ films
Tokura group, 2010



Magnetic force microscopy $Fe_{0.5}Co_{0.5}Si$ films
Milde, Köhler, ..Rosch 2013



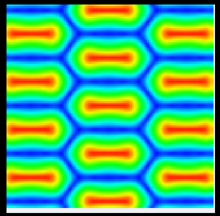
X-ray scattering Cu_2OSeO_3
Hesjedal, 2016



Poellath, Aqeel, *et al.*, (2019)
HZB Berlin

Ferromagnetic resonance at distinct positions in the reciprocal space

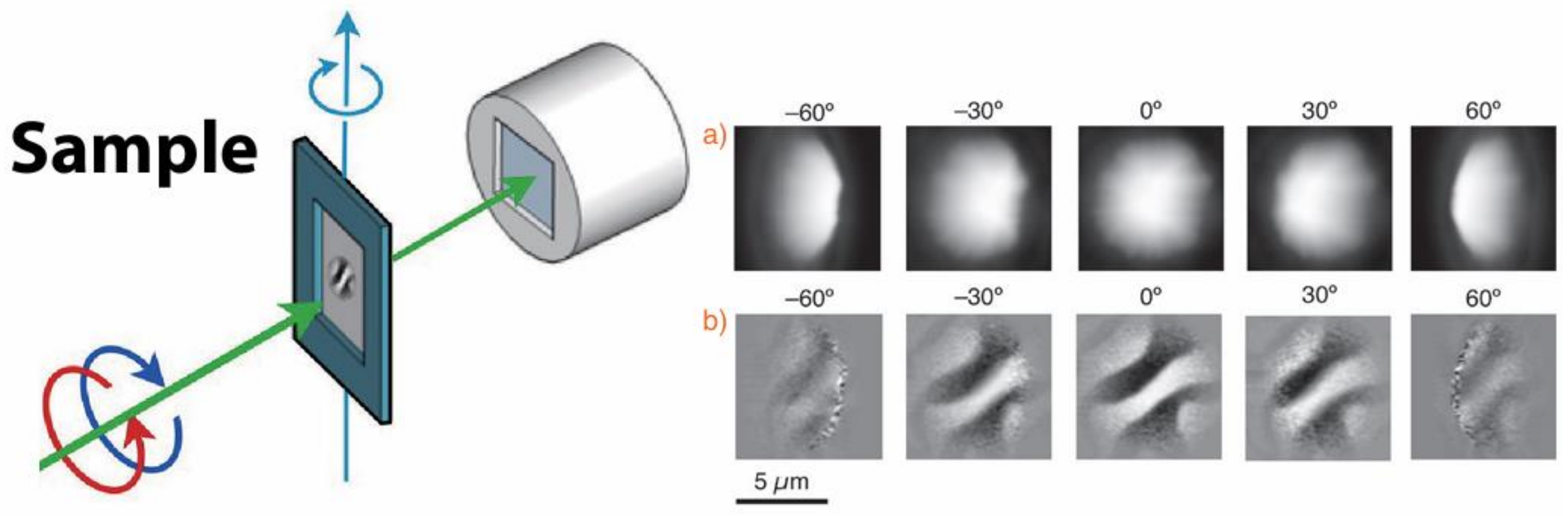
Aqeel, et al., (2021)
Ferromagnetic resonance



elongated SkL

Also magnetic STM and MOKE,…

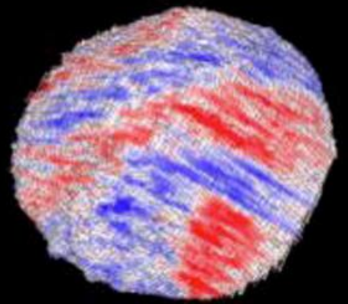
X-ray magnetic tomography



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

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

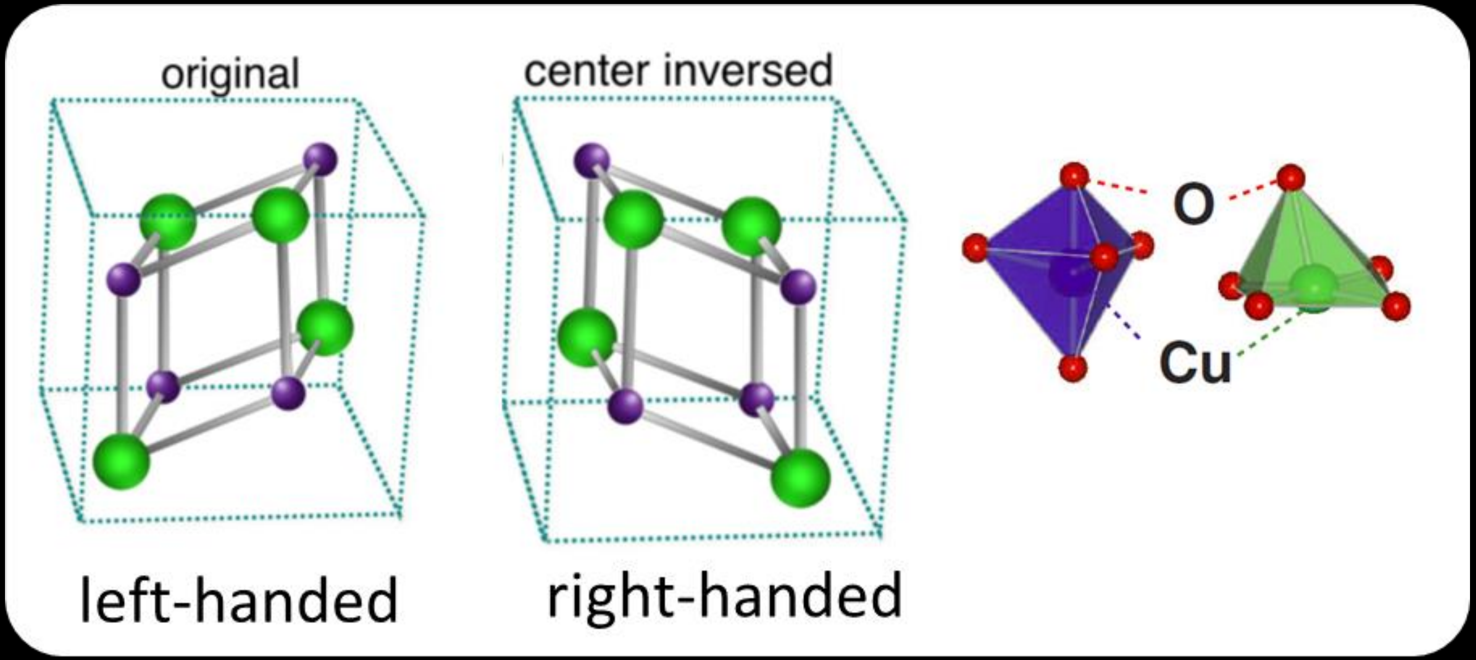
GdFeCo

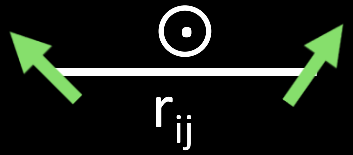


Chiral magnets

Cubic: MnSi, MnGe, FeGe, $Fe_xMn_{1-x}Si$, $Fe_xCo_{1-x}Si$, Cu_2OSeO_3

Broken inversion symmetry: $(x, y, z) \neq (-x, -y, -z)$

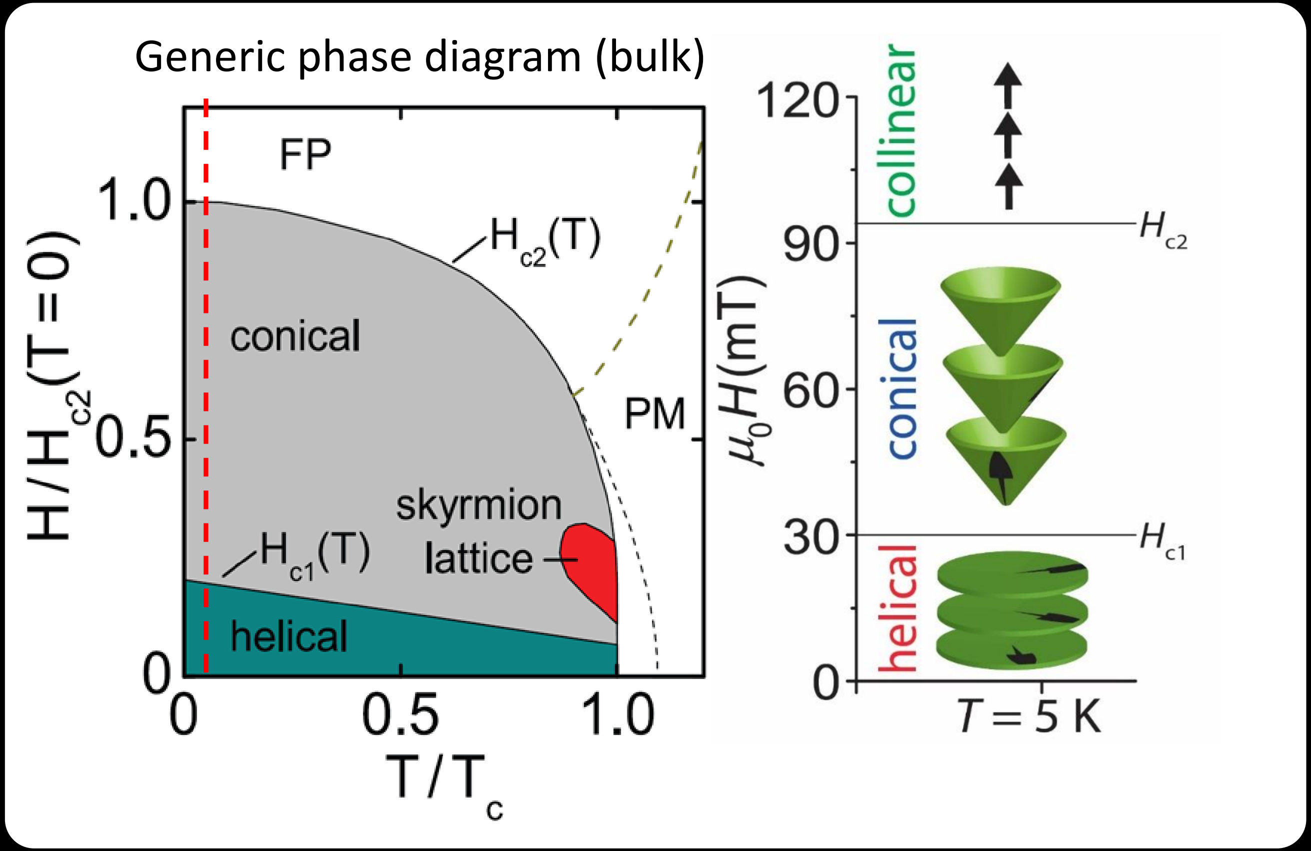


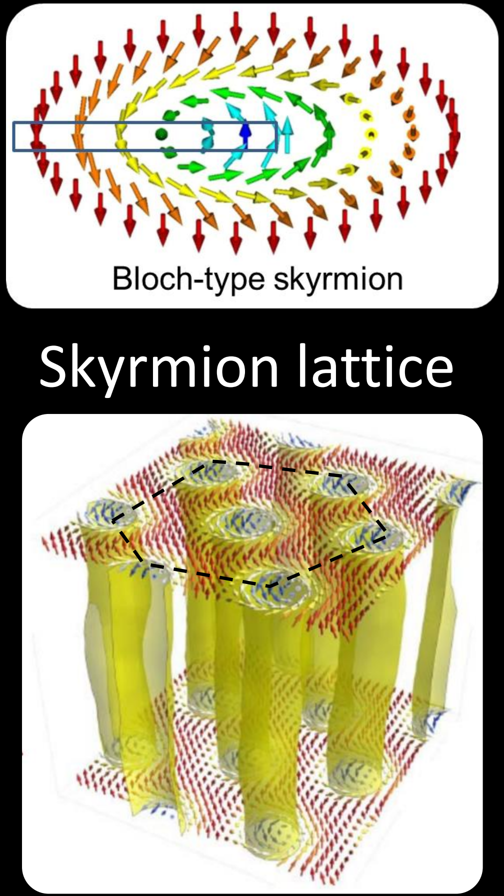


$$\sum_{i,j} D_{ij}\ S_i \times S_j$$

Bulk Dzyaloshinskii-Moriya Interaction (DMI)

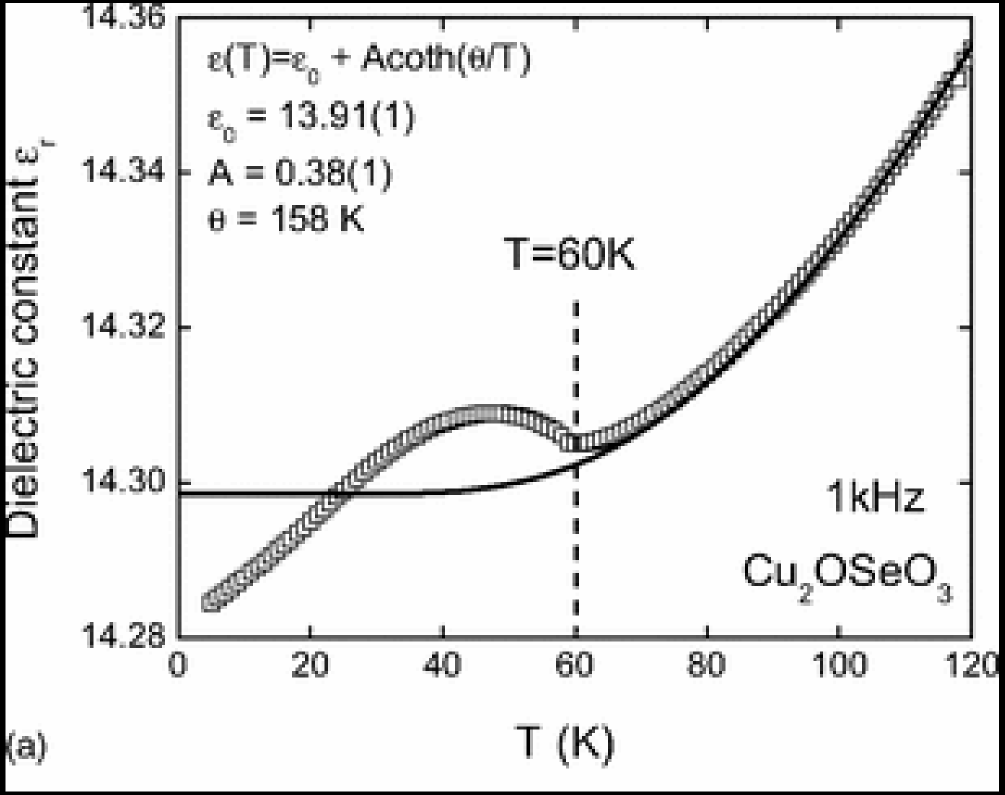
Cubic: MnSi, MnGe, FeGe, $Fe_xMn_{1-x}Si$, $Fe_xCo_{1-x}Si$, Cu_2OSeO_3





Skyrmion diameter: ≈ 60 nm

Cu_2OSeO_3 - Insulator



Dielectric – Piezoelectric

Magnetocapacitance developed

Magnetoelectric coupling

Bos, Claire V. Colin, and Thomas T. M. Palstra, Phys. Rev. B **78**, 094416 (2008)

Cu_2OSeO_3 - Insulator

Skyrmion Lattice in a Chiral Magnet

S. Mühlbauer,[1,2] B. Binz,[3] F. Jonietz,[1] C. Pfleiderer,[1]* A. Rosch,[3] A. Neubauer,[1] R. Georgii,[1,2] P. Böni[1]

MnSi

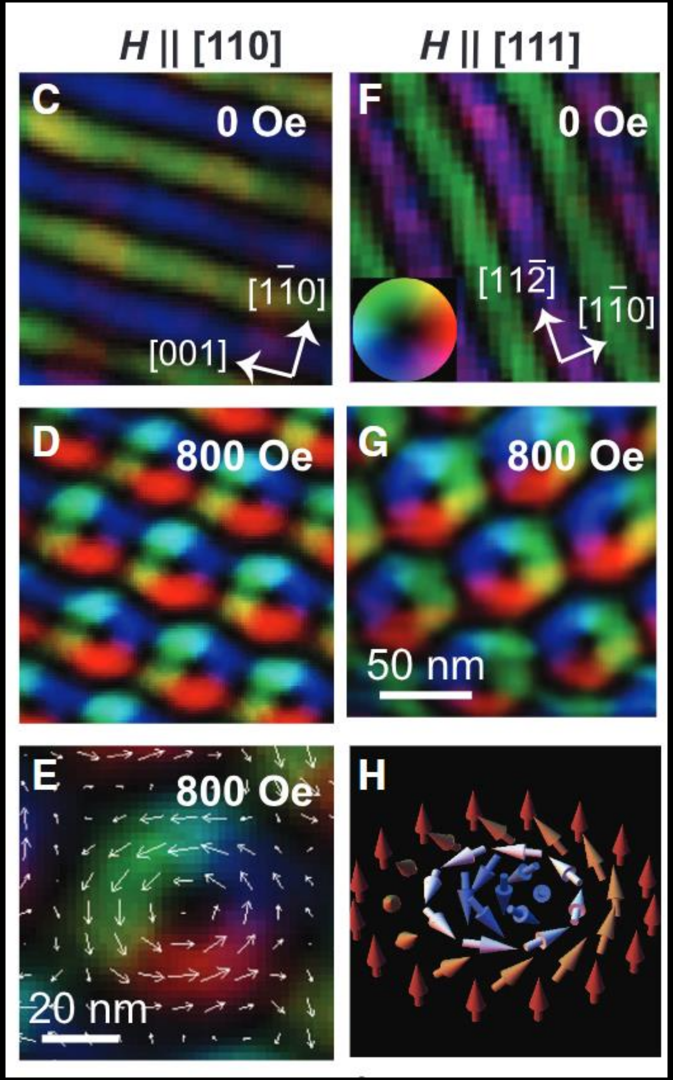
Science 323, 915-919 (2009)

Observation of Skyrmions in a Multiferroic Material

S. Seki,[1]* X. Z. Yu,[2] S. Ishiwata,[1] Y. Tokura[1,2,3]

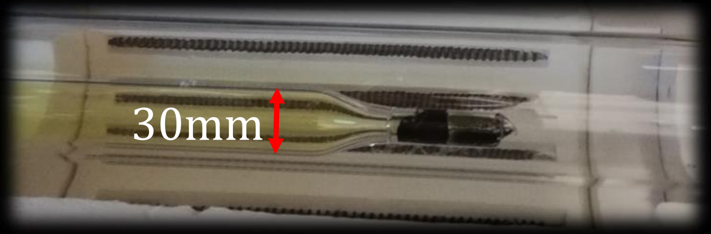
S. Seki et al., Science **336**, 198 (2012)

Lorentz TEM

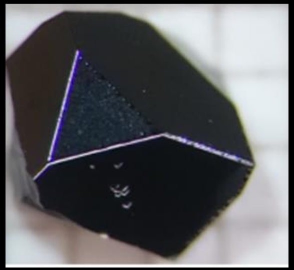


Cu_2OSeO_3 - Insulator

Furnace inner view



Cu_2OSeO_3



Aqeel, et al., Phys. Status Solidi B (2022)

- → Large sized ~ 1 cm
- → Both left/right handed crystals
- → No measurable twining
- → Anisotropic exchange change by doping

Large Faraday rotation $\sim 170 \text{ deg/mm}$

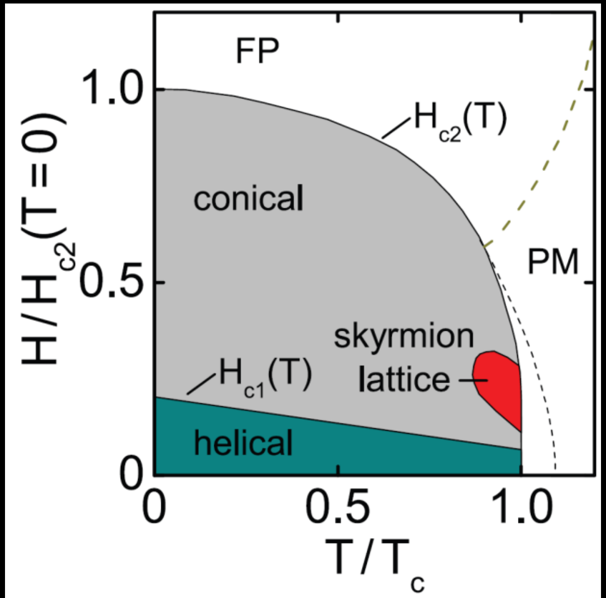
Large magneto-optical response quantified by magneto-optical susceptibility of $\upsilon\ (540\text{nm}) \sim 10^4 \text{ rad/T.m}$

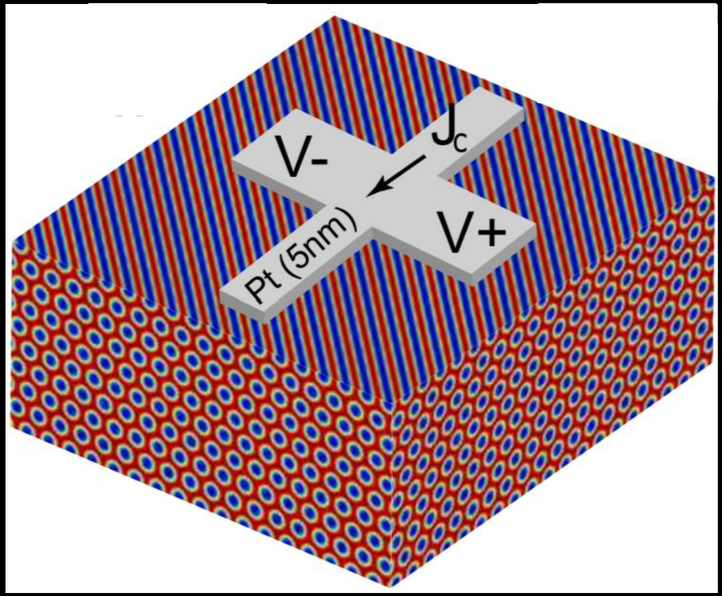
Versteeg *et al.*, Phys. Rev. B **94**, 094409 (2016)

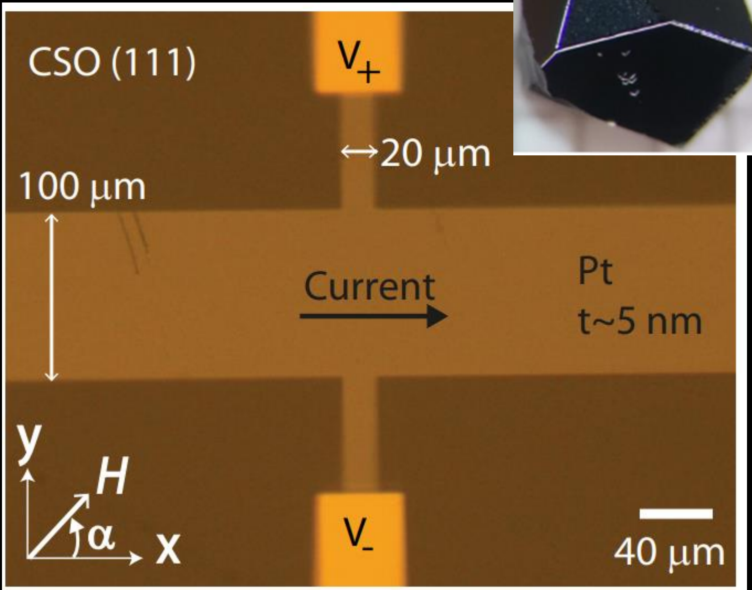
Spin-Hall magnetoresistance

Electric probe to detect magnetization of an insulator

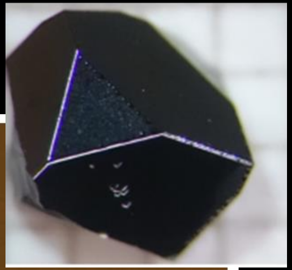
Transparent interface





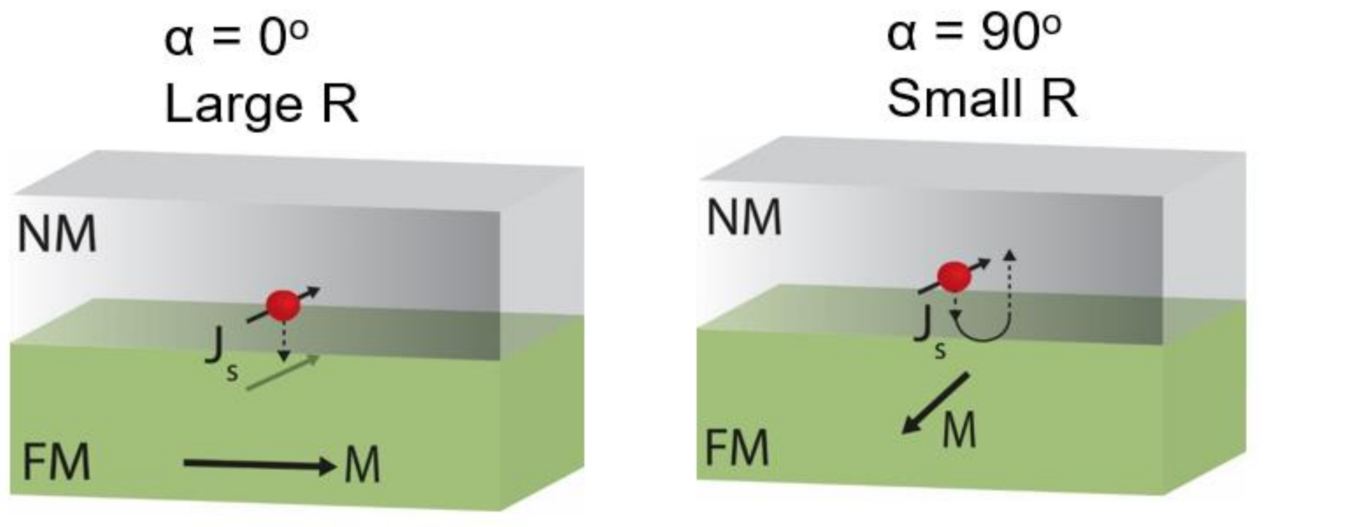


Cu_2OSeO_3



Spin-Hall magnetoresistance

Magnetization direction dependent

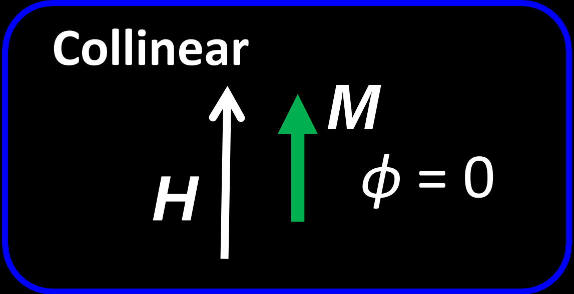


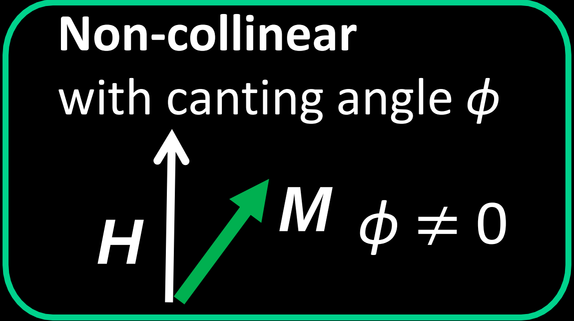
$\tau_{STT} \propto M \times (M \times s) \neq 0$

Large dissipation in NM

$\tau_{STT} = 0$

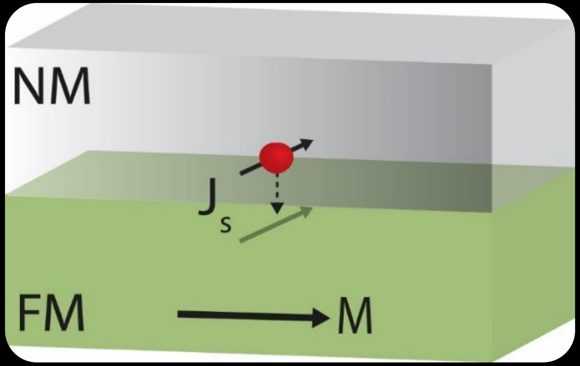
Reduced dissipation in NM

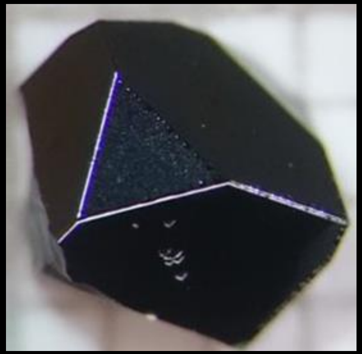




Spin-Hall magnetoresistance

Pt resistance directly indicates magnetization configuration

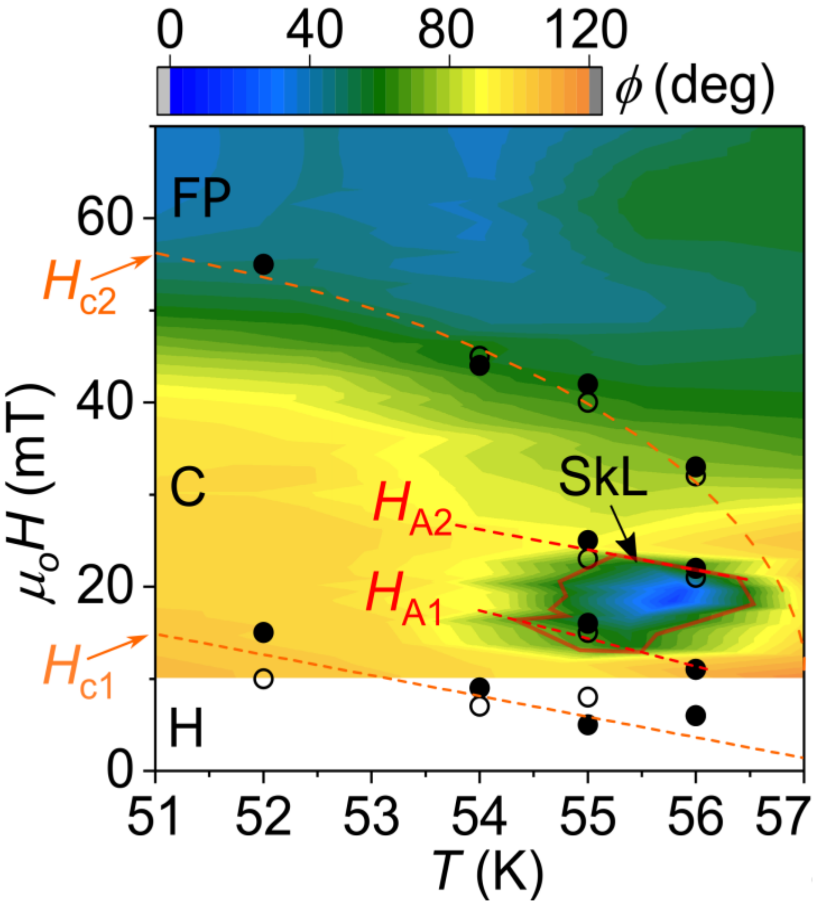




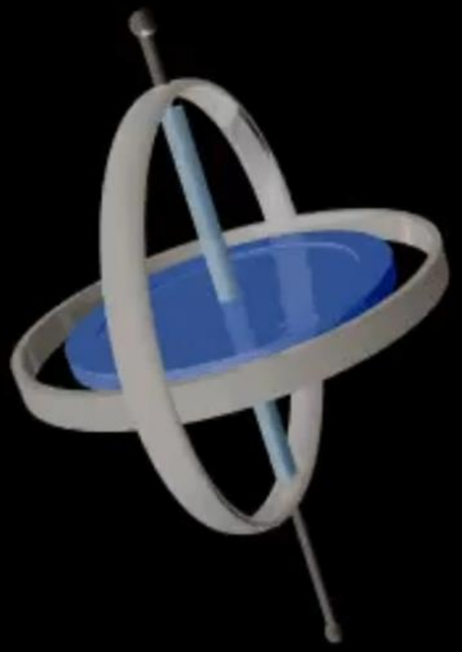
Aqeel, et al., PRB, 94, *134418.* (2016)
Aqeel, et al., J. Phys. D: Appl. Phys, 50, *174006* (2017)
Aqeel, et al., Phys. Rev. B **103**, L100410 (2021)

- **Developed theory** valid for other complex magnets
- **First experimental and theoretical** work for helimagnetic insulators

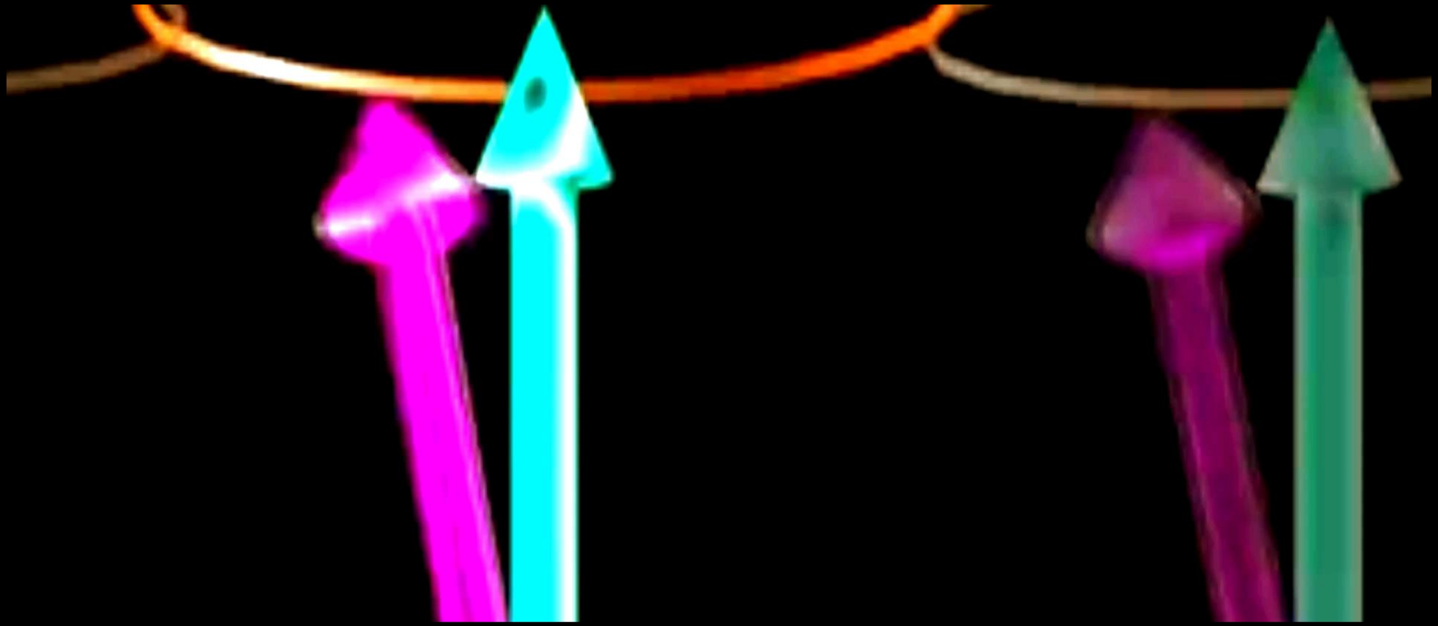
Magnetic phase diagram



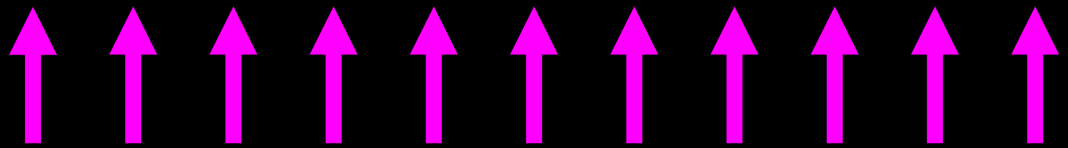
Magnetization dynamics



Magnetic insulator



Collective oscillations - Magnons



No free electrons – No charge current

Magnetostatic spin waves

- Dipolar interactions – long range and sample shape dependent (instead of size)
- Spin waves are mainly driven by magnetic dipole-dipole interaction
- Wave length of spin waves >> exchange interaction length

Dipole regime (GHz)

Exchange regime (THz)

Walker, Phys. Rev. 105, 390 (1957)
Röschmann and Dötsch, Phys. stat. sol. (b), 82: 11-57 (1977)

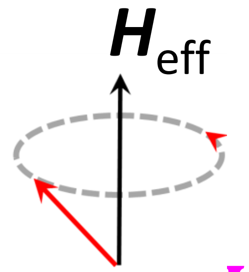
Magnetostatic spin waves

LL equation (no damping)
Linearize LL eq for spherical sample including Demag fields
Then the solution of linear equation under particular conditions - non linear driving field
(infinite solutions)

Uniform (Kittel)model dynamic component will map on sphere , it will look same at any point on the sphere.

Other modes will have dynamic component out of phase e.g. top and bottom side of the sphere.

The separation between modes is defined by M_s



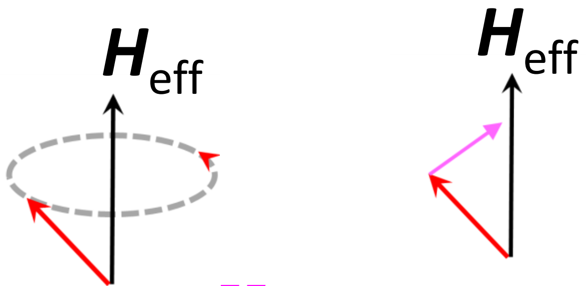
$$\frac{d\boldsymbol{m}}{dt} = -\gamma\mu_0 \boldsymbol{m} \times \boldsymbol{H}_{\mathrm{eff}}$$

precession

Walker, Phys. Rev. 105, 390 (1957)
Röschmann and Dötsch, Phys. stat. sol. (b), 82: 11-57 (1977)

Magnetization dynamics

Landau-Lifshitz-Gilbert equation:

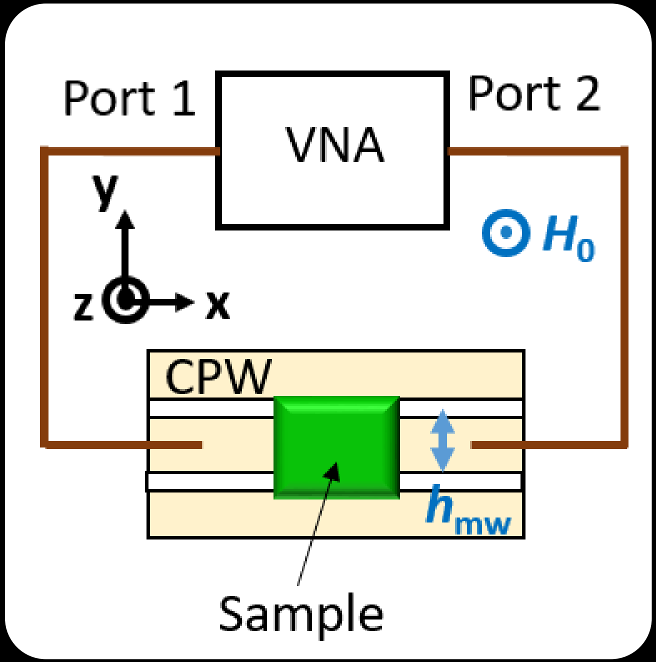


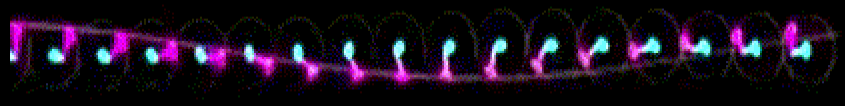
$$\frac{d\boldsymbol{m}}{dt} = -\gamma\mu_0 \boldsymbol{m} \times \boldsymbol{H}_{\text{eff}} + \alpha \boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t}$$

precession damping

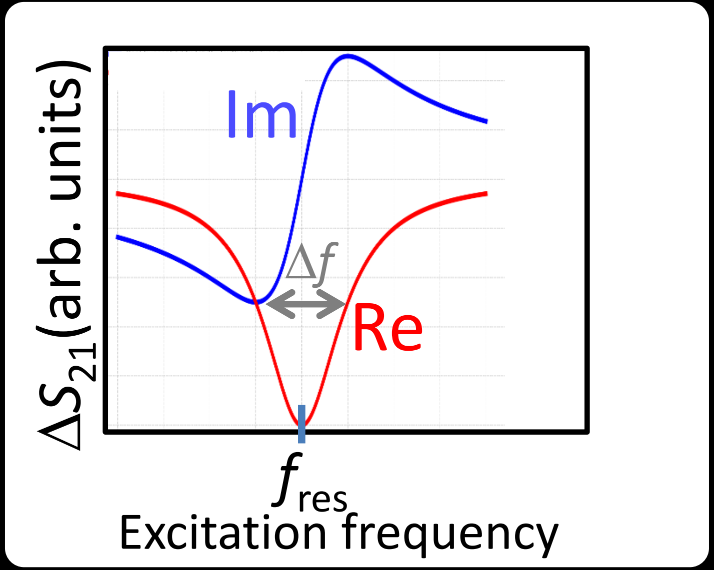
$$\boldsymbol{H}_{\text{eff}} = H_0 + H_{\text{aniso}} + h_{mw} \qquad \boldsymbol{m} = \frac{\boldsymbol{M}}{M_s}$$

At resonance Microwave power <P> is absorbed by the sample: $\langle P \rangle \propto \chi''(\mathrm{f}, \mathrm{H})$





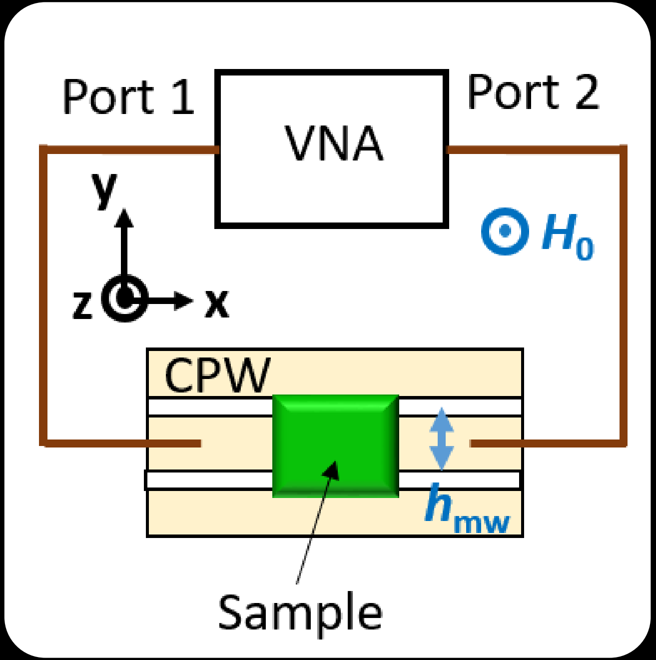
Experimental setup

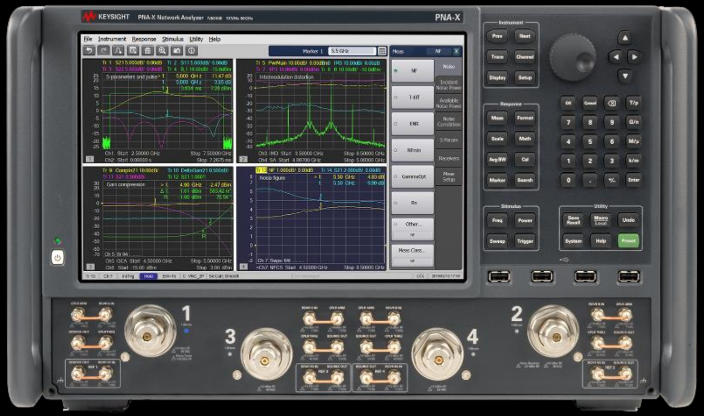


$$\Delta S_{21} = -\frac{i\omega\tilde{L}}{2Z_0}\chi$$

$$f_{\text{res}} = \frac{\gamma}{2\pi} H_{\text{eff}}$$

$$\alpha = \frac{\Delta f}{2 f_{\text{res}}}$$

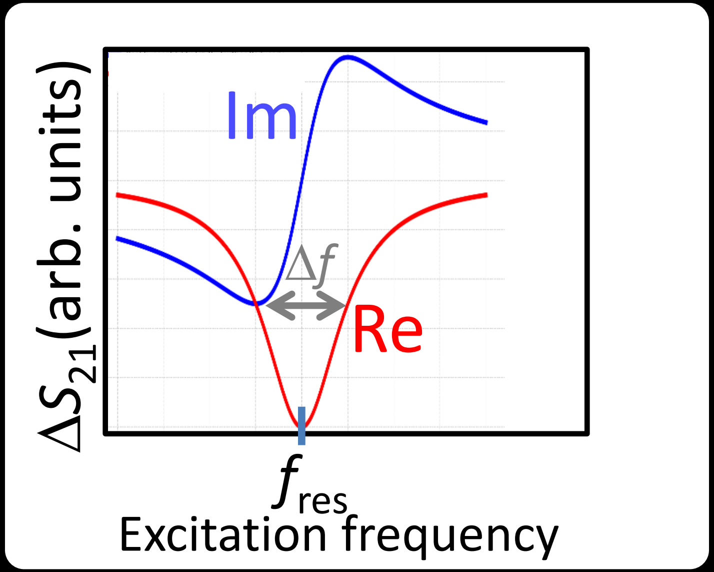


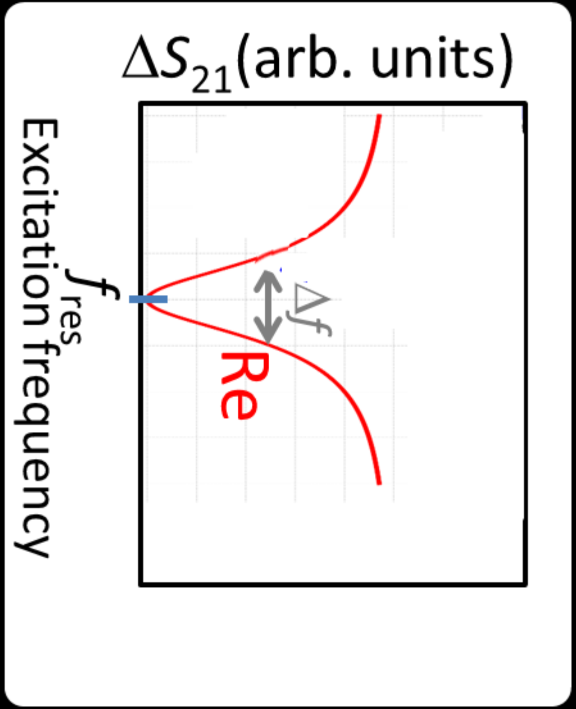


$$S_{21} = \frac{V_2}{V_1} = \frac{V_{ind}(H_0) + V_1 \Gamma}{V_1}$$

At resonance Microwave power absorbed by the sample:

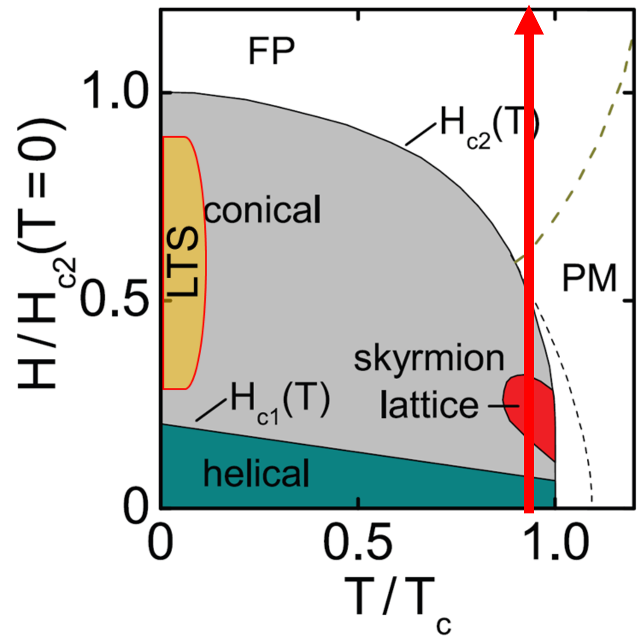
Experimental setup

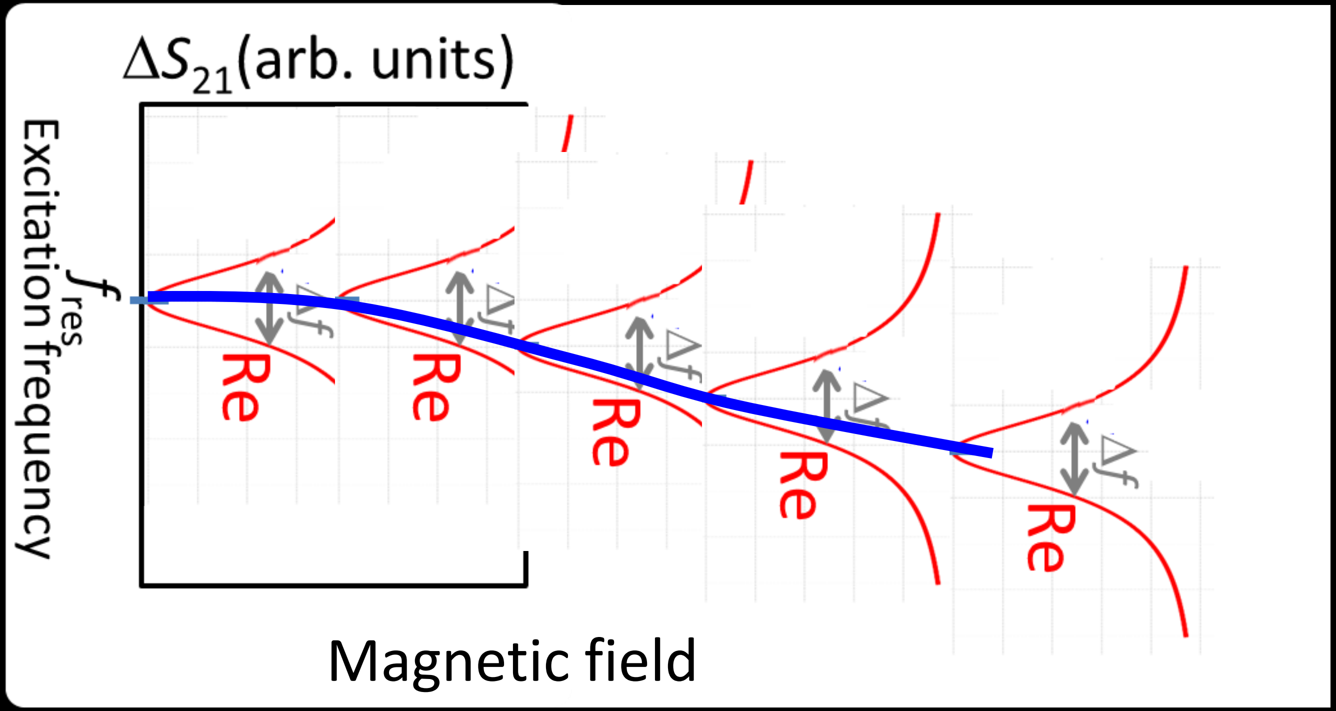




At resonance Microwave power <P> is absorbed by the sample: $\langle P \rangle \propto \chi''(f, H)$

Experimental setup

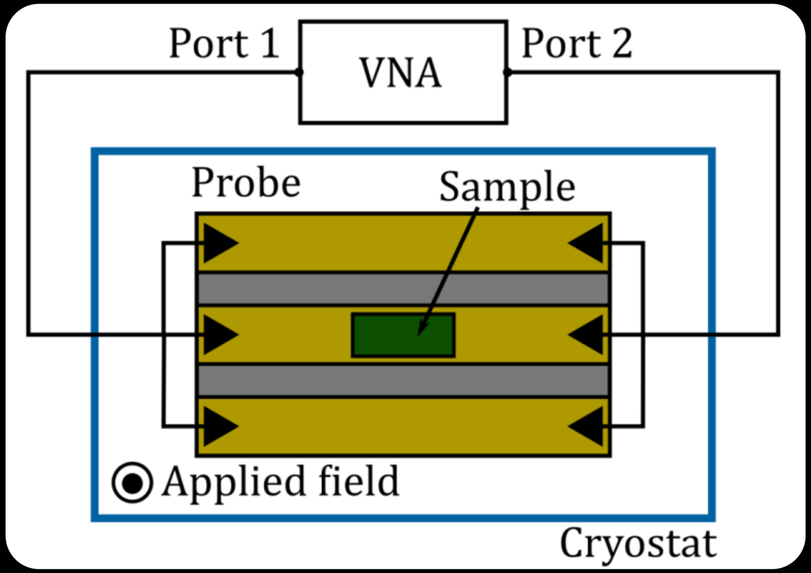




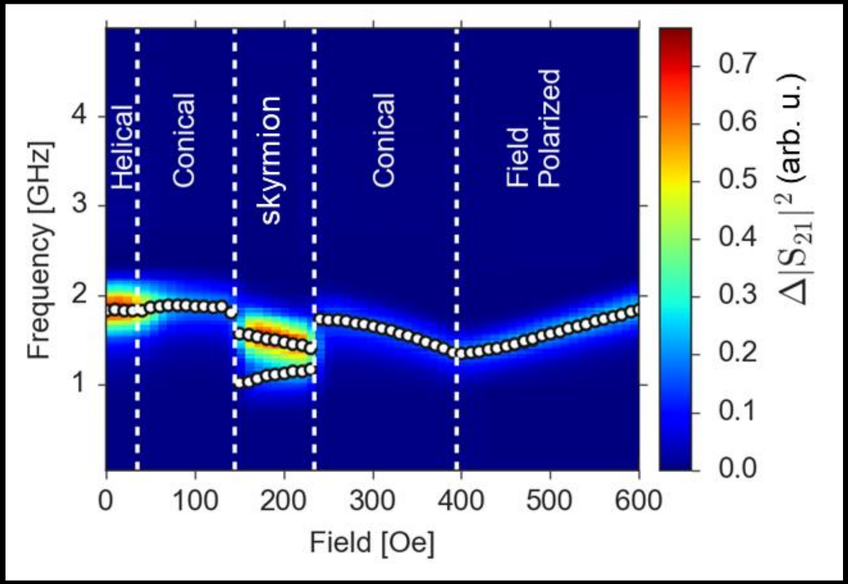
At resonance Microwave power <P> is absorbed by the sample:

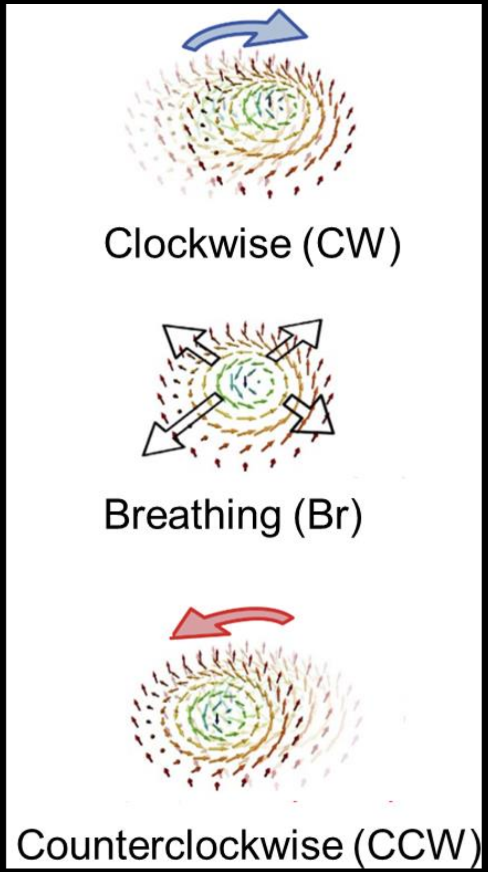
$$\langle P \rangle \propto \chi''(f, H)$$

Experiment

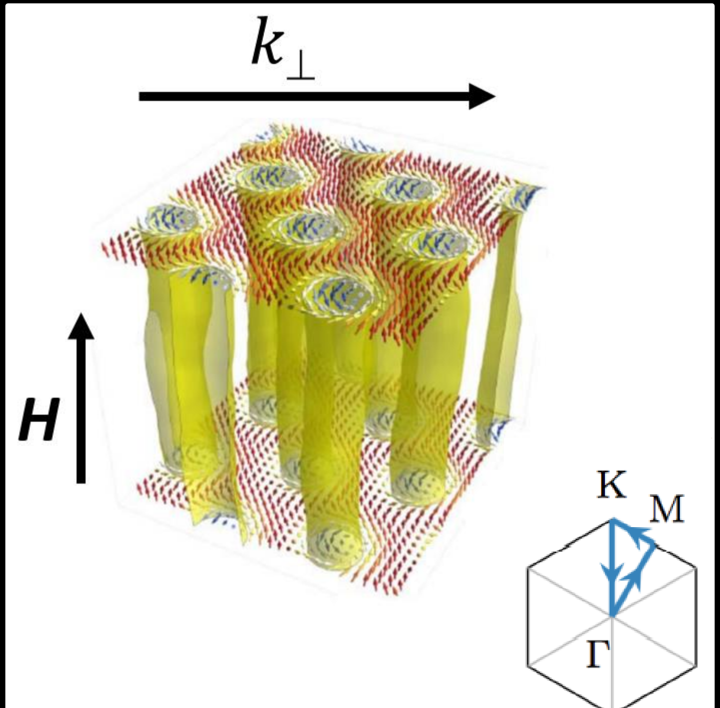


Spectra in high-temp. skyrmion phase



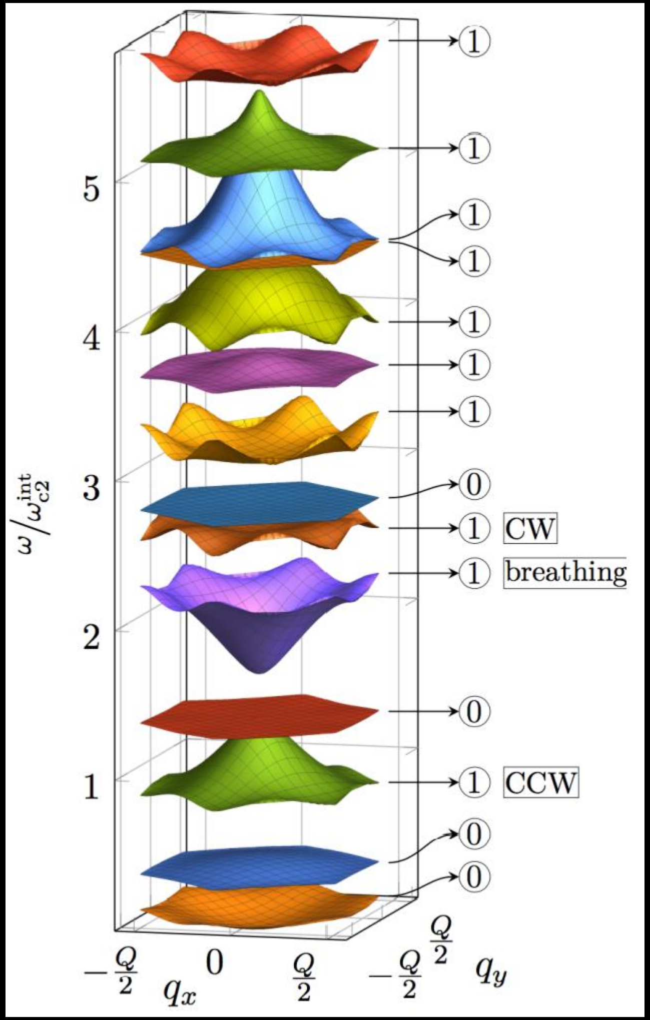


Magnetization dynamics



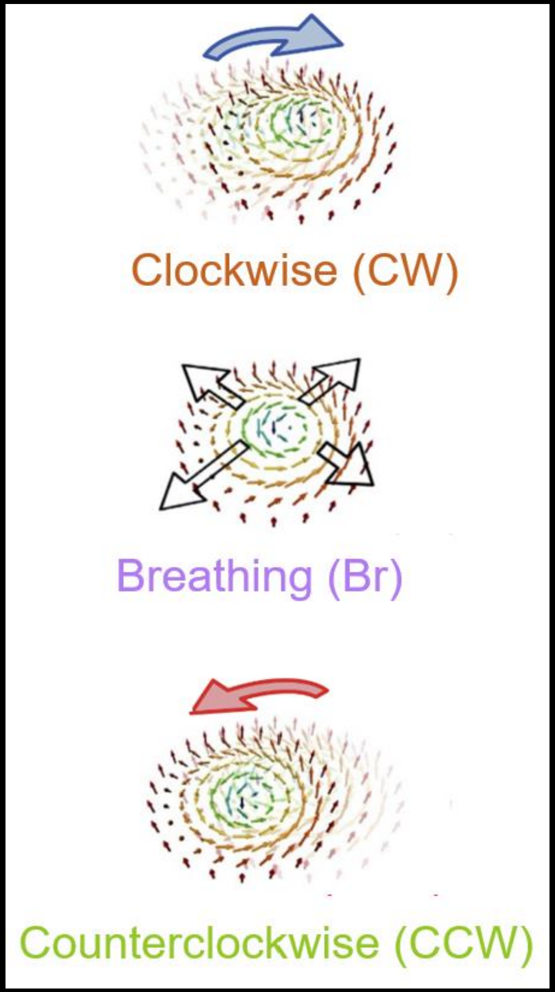
2D hexagonal Brillouin zone

Magnon band structure



Garst et al., J. Phys. D: Appl. Phys. **50** 293002 (2017)

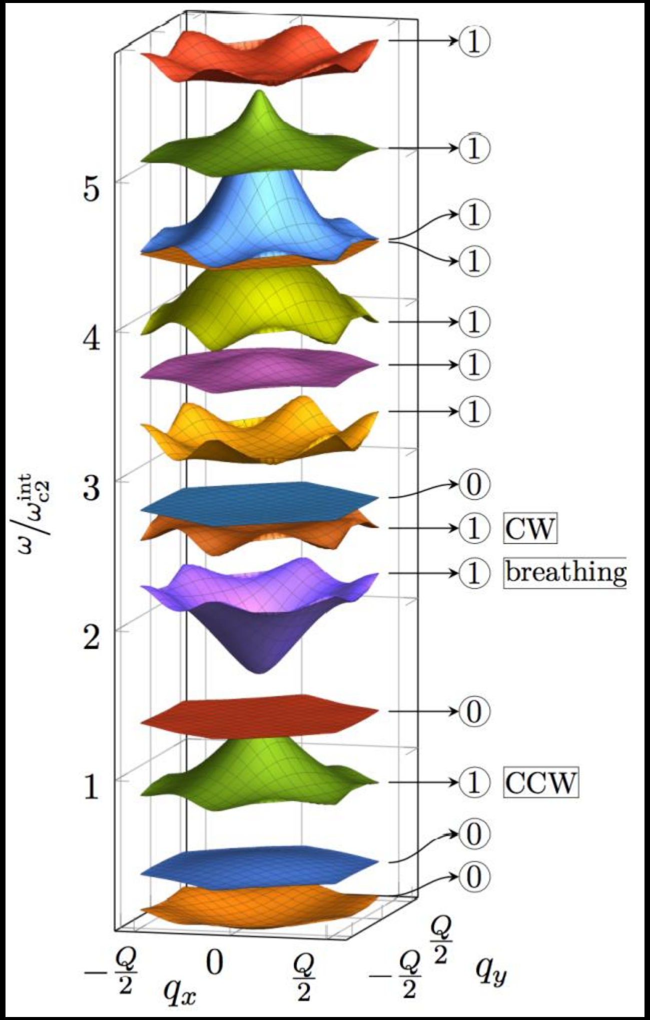
Magnetization dynamics



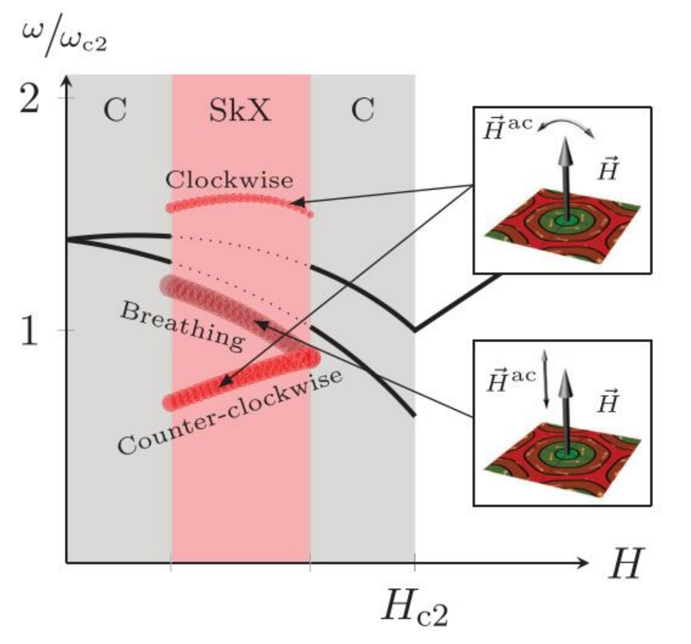
T. Schwarze et al., Nat. Mat. **14**, 478 (2015);
Y. Okamura et al., Nat. Com. **4**, 2391 (2013)

Garst et al., J. Phys. D: Appl. Phys. **50** 293002 (2017)

Magnon band structure

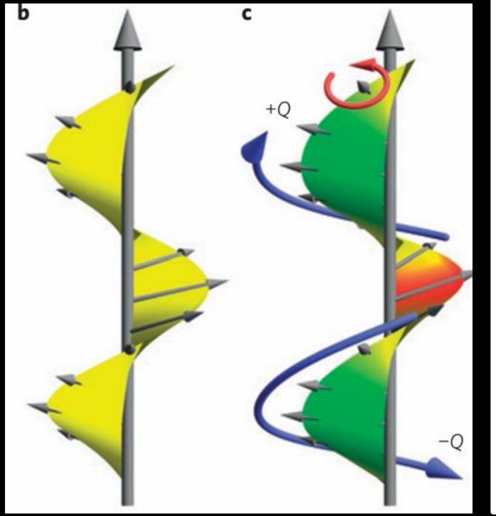


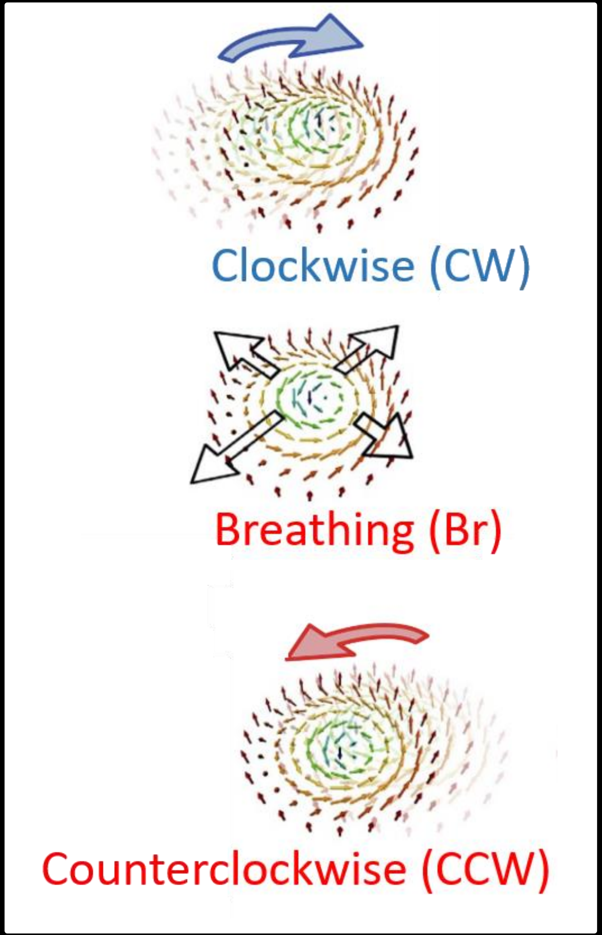
Magnetization dynamics



FP: uniform precessional mode
(field polarized state)

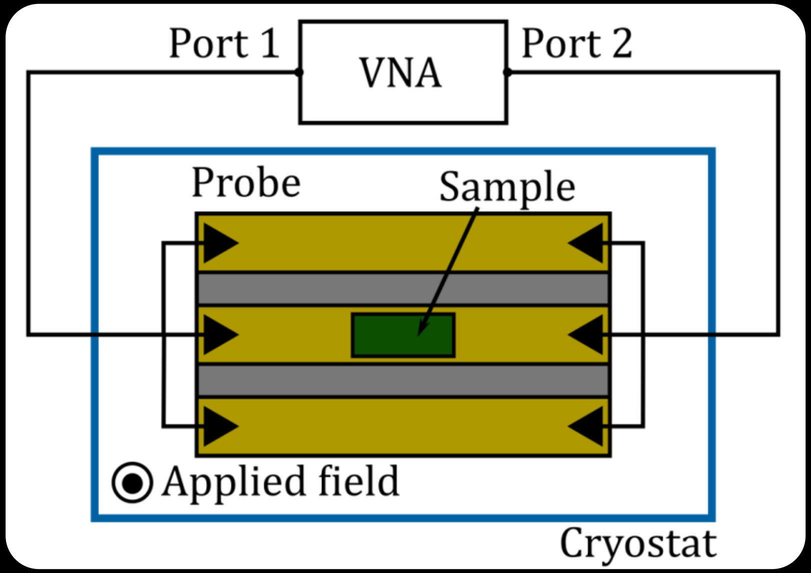
Conical C:
+Q, -Q, Eigenmodes of the spin helix



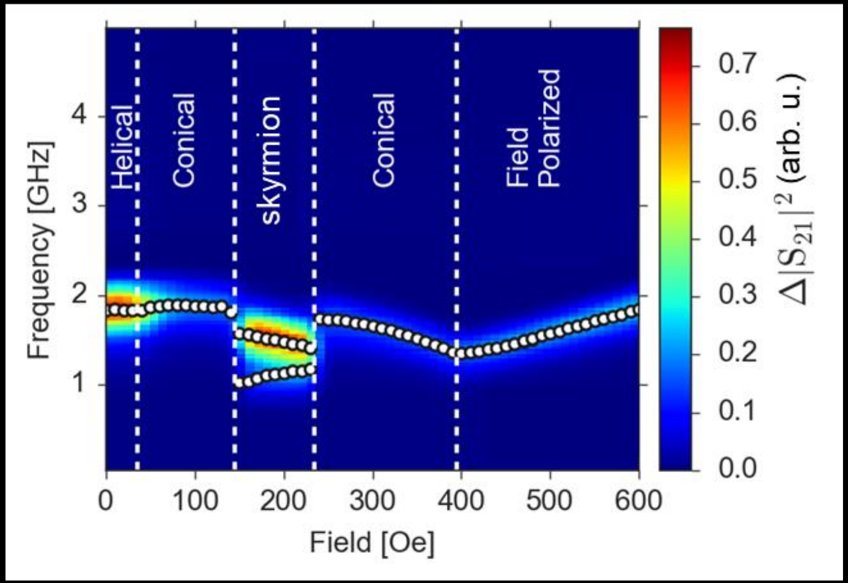


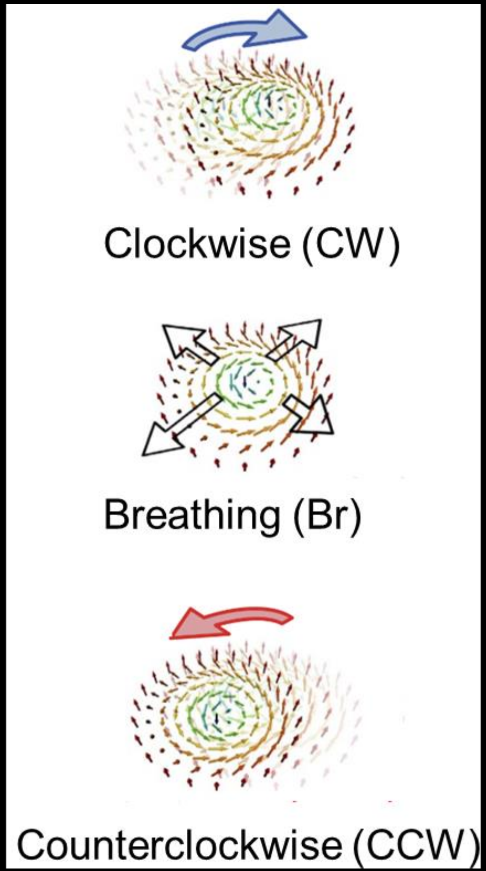
Y. Okamura et al., Nat. Com. **4**, 2391 (2013)
T. Schwarze et al., Nat. Mat. **14**, 478 (2015)
M. Garst et al., J. Phys. D: Appl. Phys.**50** 293002 (2017)

Experiment



Spectra in high-temp. skyrmion phase





Experiment at 55K, large damping

Magnetization dynamics

Low magnetic damping by decreasing T

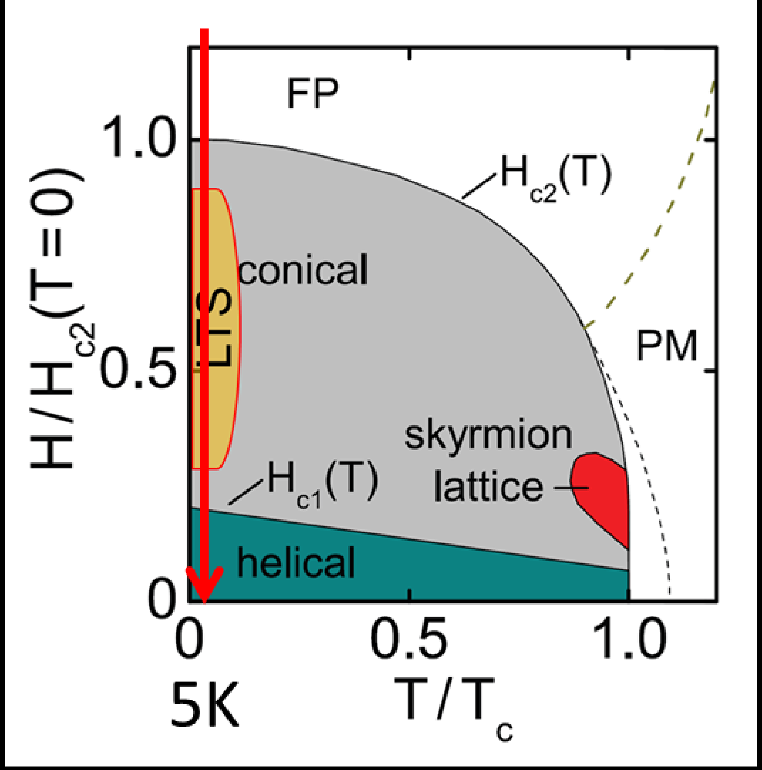
Skyrmions at low temperatures

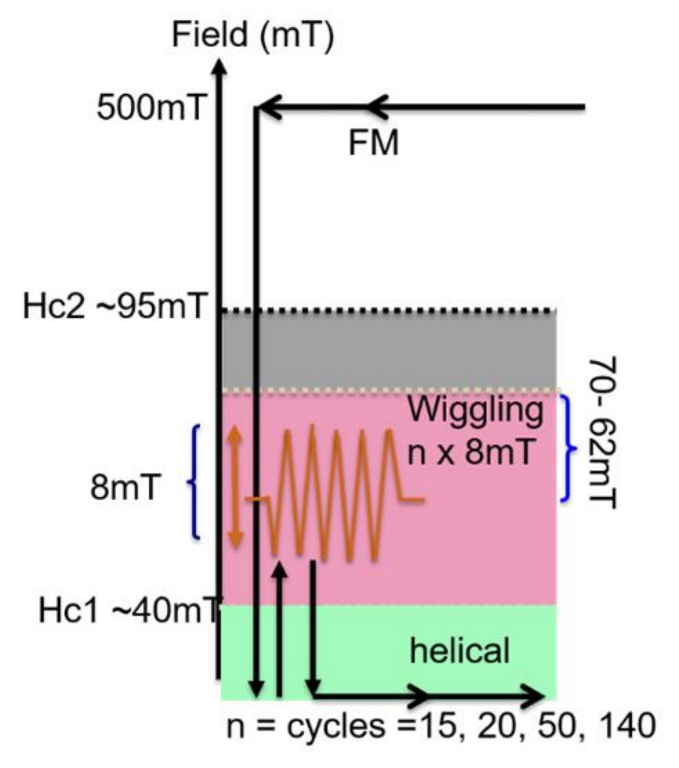
Observation of two independent skyrmion phases in a chiral magnetic material

A. Chacon[1*], L. Heinen[2], M. Halder[1], A. Bauer[1], W. Simeth[1], S. Mühlbauer[3], H. Berger[4], M. Garst[5], A. Rosch[2] and C. Pfleiderer[1*]

nature physics

Nat. Phys. **14**, 936 (2018)





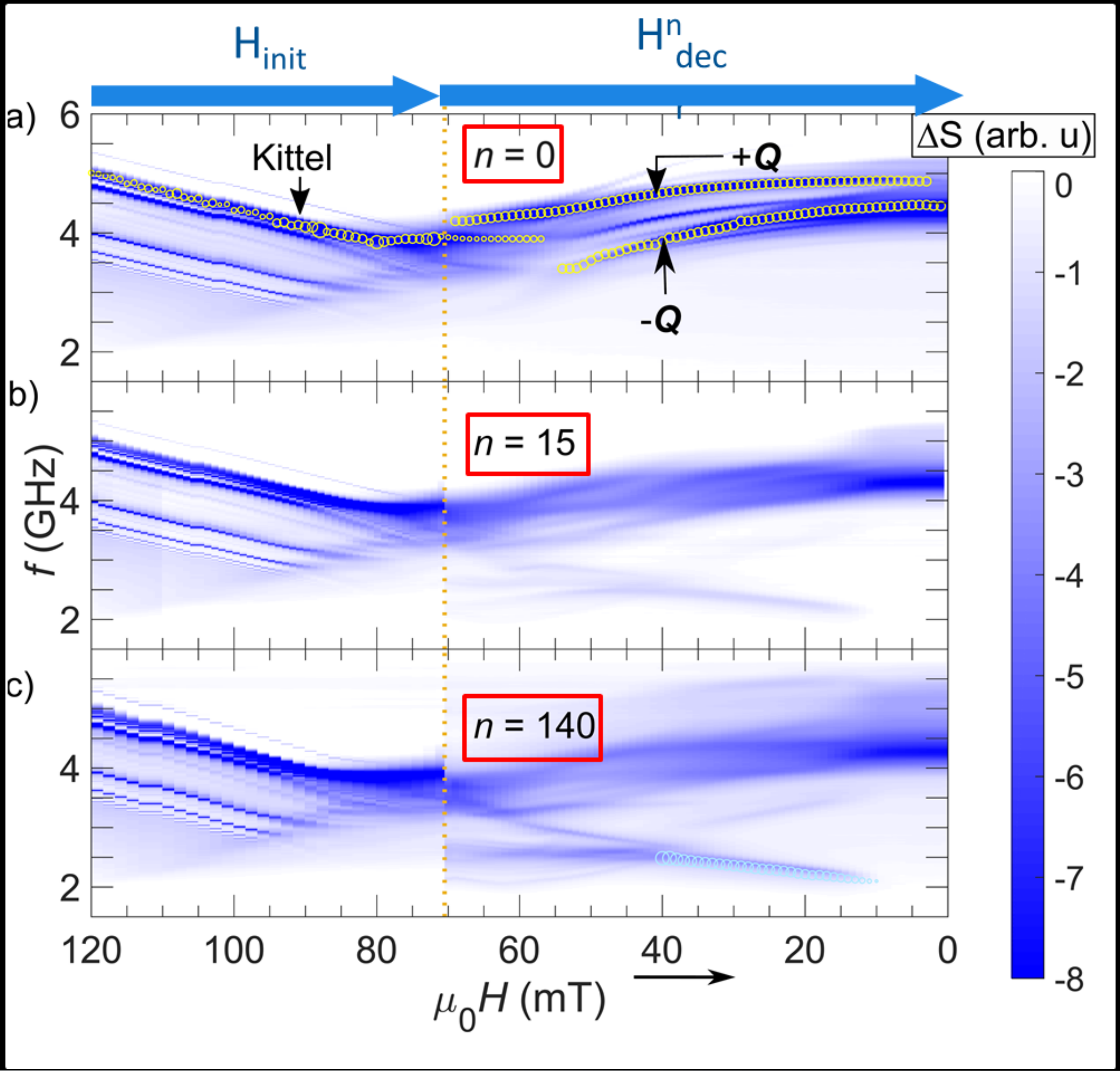
LTS: stabilized by crystalline anisotropy

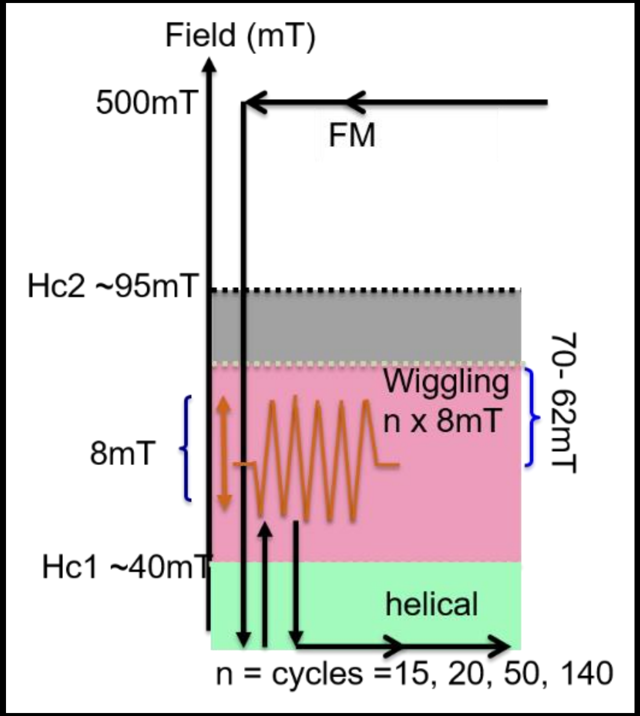
Complex

Interesting dynamics

Low damping

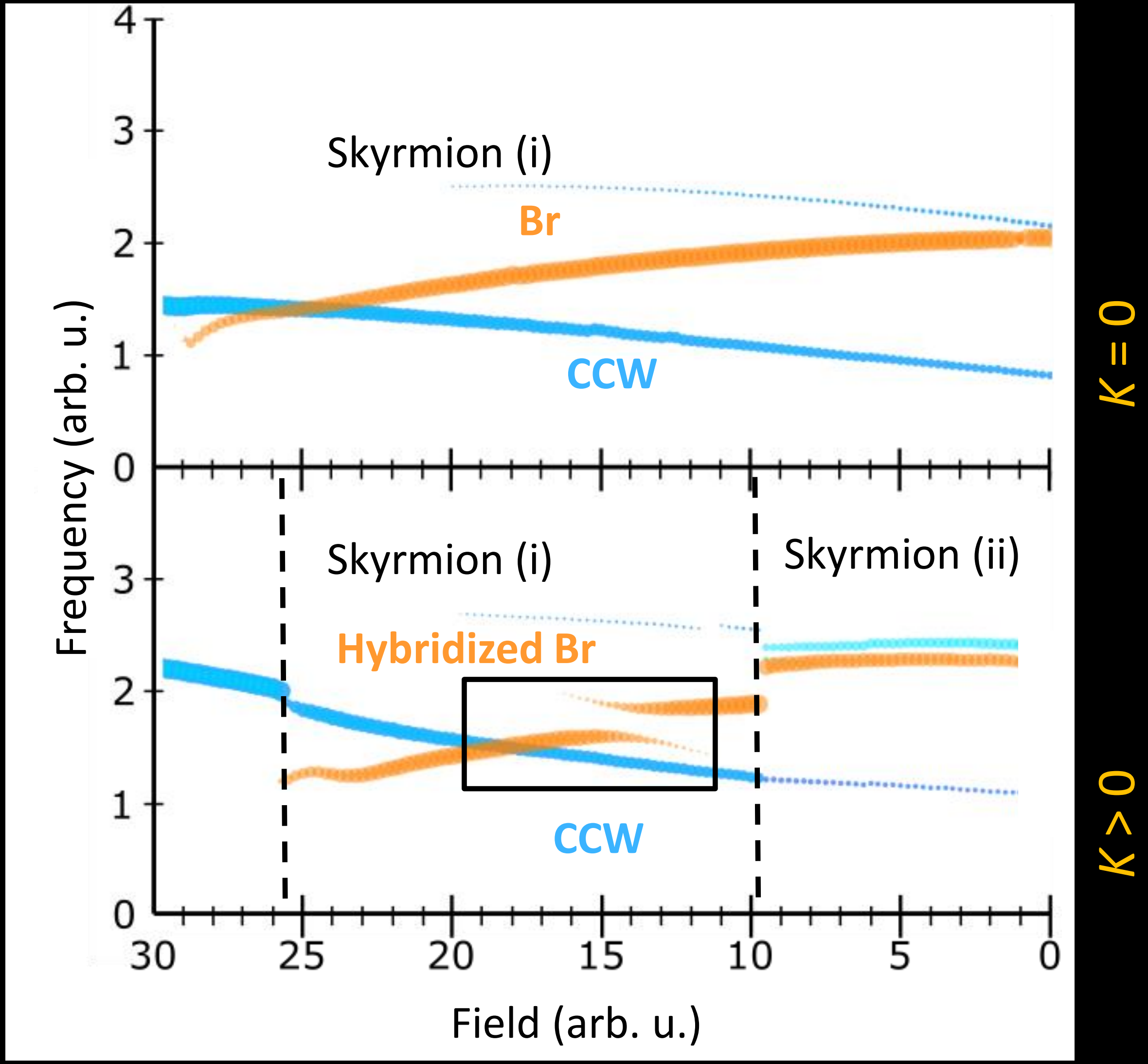
Skyrmions at low temperatures





Aqeel, Sahliger et al., PRL **126**, 017202 (2021)

Skyrmions at low temperatures



Ginzburg-Landau free energy functional

$$\mathrm{F} = \mathrm{F}_{\mathrm{Ex}} + \mathrm{F}_{\mathrm{DMI}} + \mathrm{F}_{\mathrm{Zee}} + \mathrm{F}_{\mathrm{Dip}} + \mathrm{F}_{\mathrm{Aniso}}$$

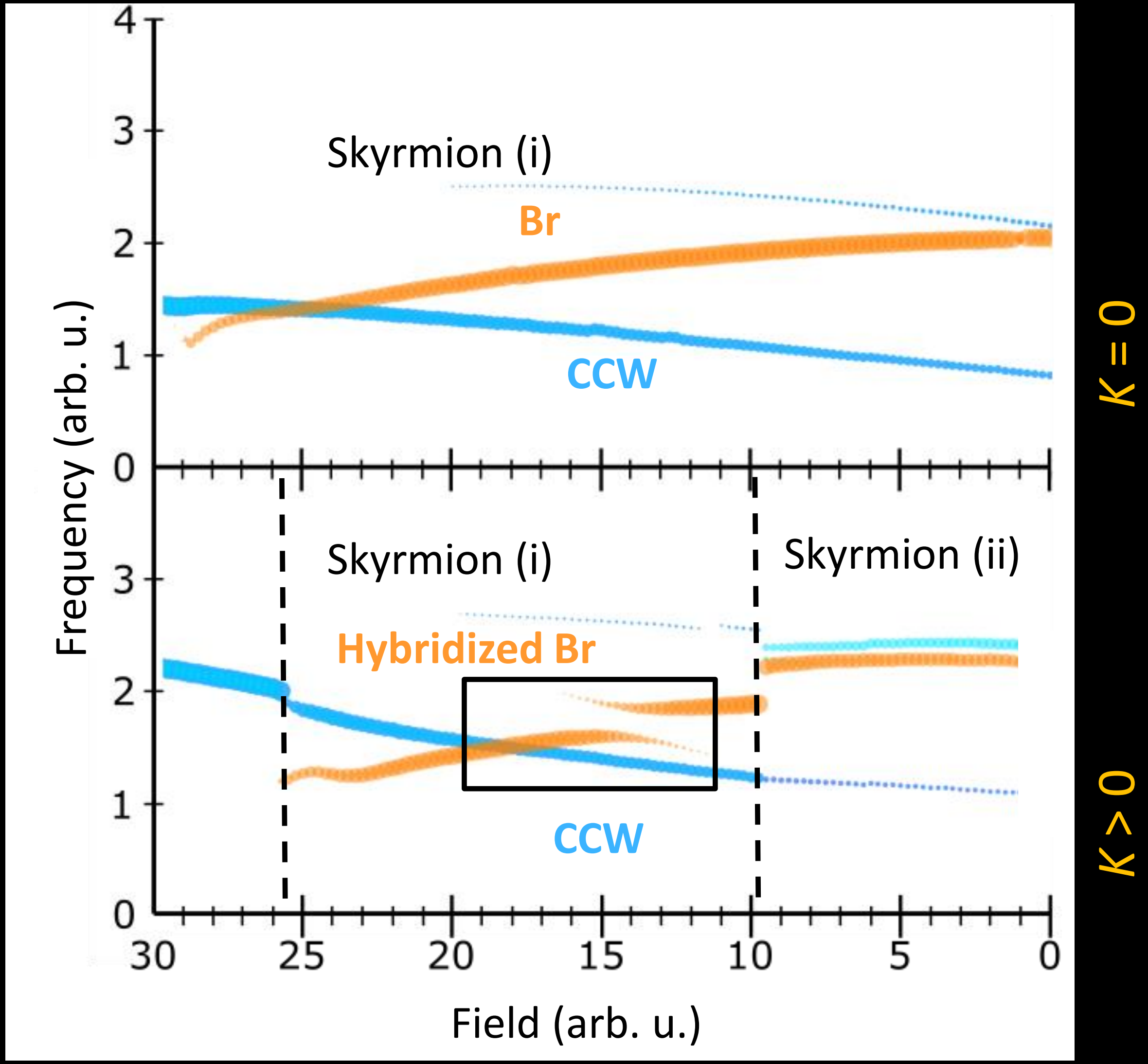
$$\mathrm{F}_{\mathrm{Aniso}} = -K \int d^3 r \left(M_x^4 + M_y^4 + M_z^4 \right)$$

Landau-Lifshitz equation

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff}$$

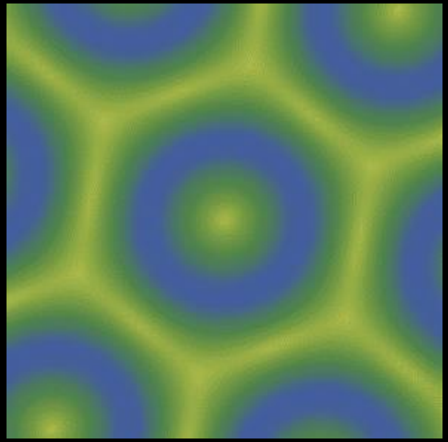
$$H_{eff} = -\frac{1}{M_s} \frac{\delta F}{\delta \vec{M}}$$

Skyrmions at low temperatures

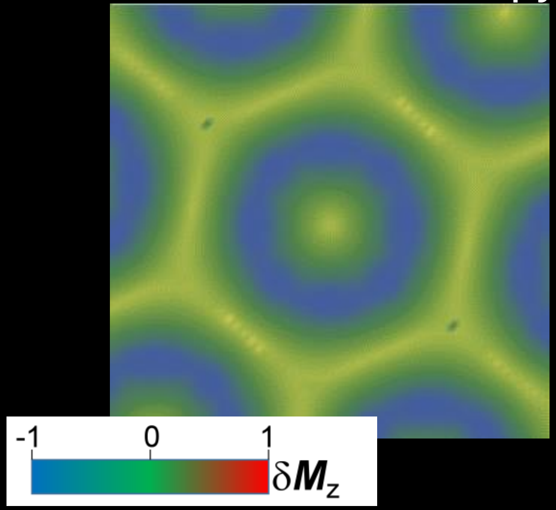


Real space images

Without cubic anisotropy

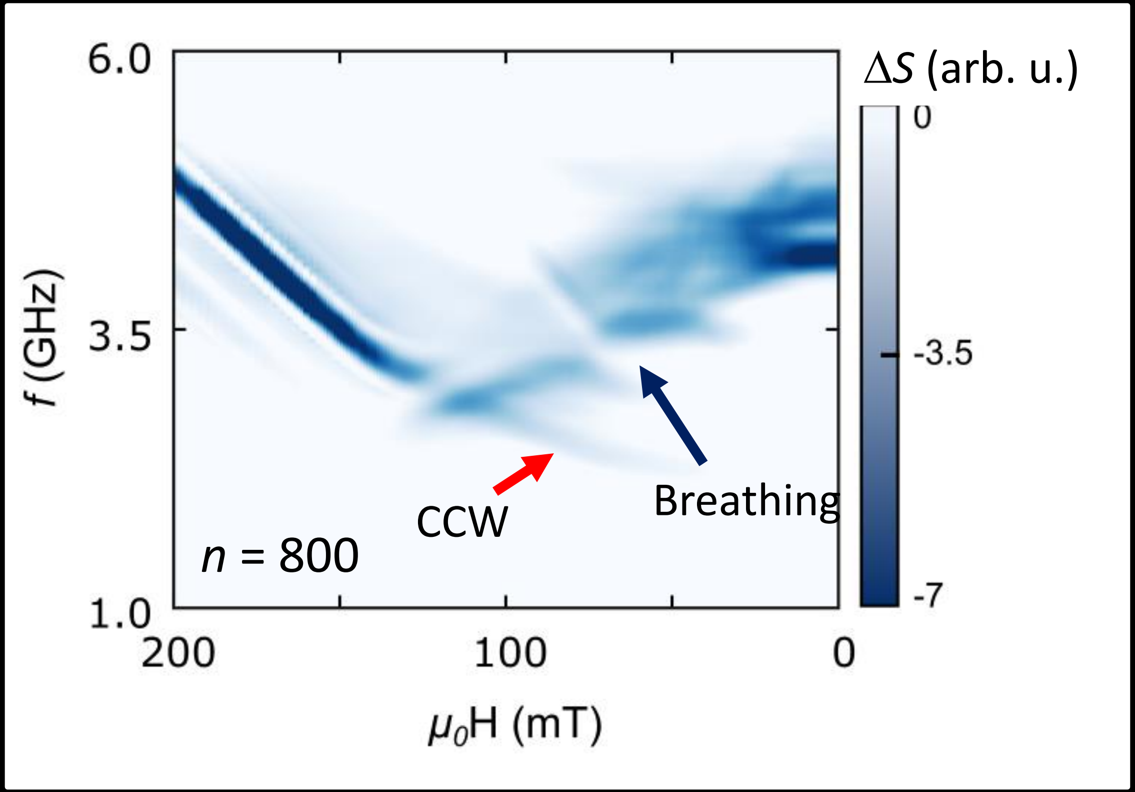


With cubic anisotropy



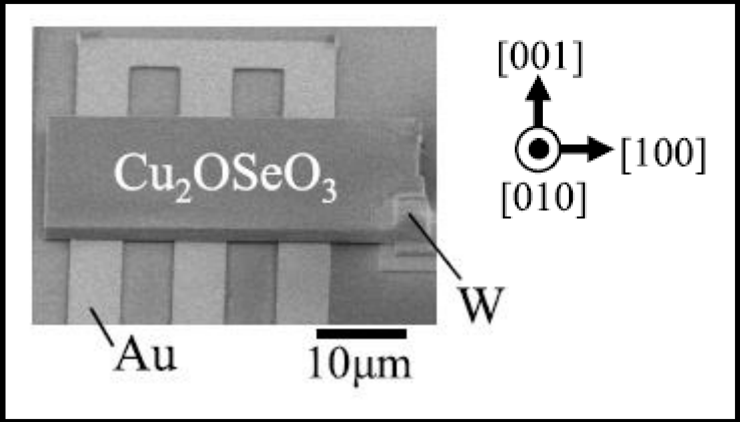
Skyrmions at low temperatures

Experiment



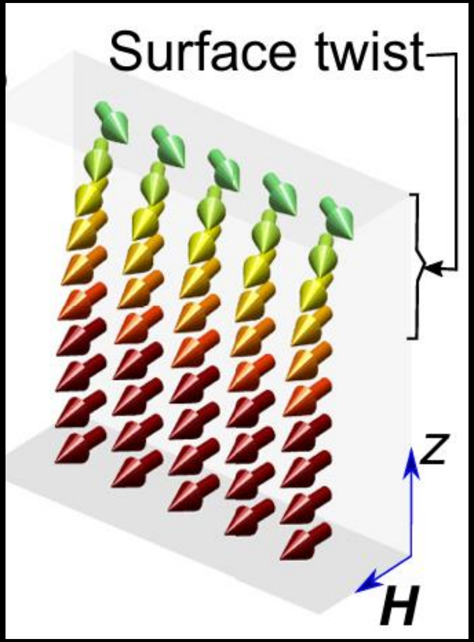
cuboid ~ 1.4 x 1.5 x 1.8 mm³
<001> direction out of plane
surface not polished

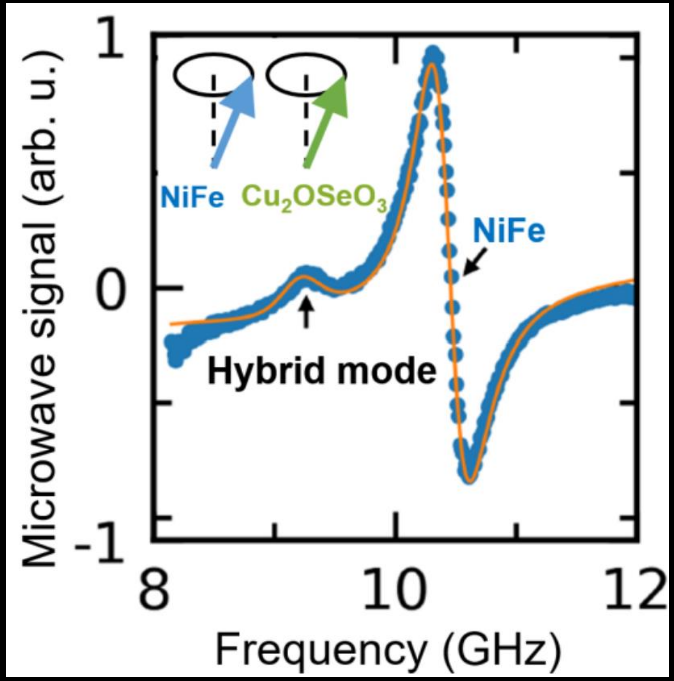
Aqeel, Sahliger, *et al.*, Phys. Rev. Lett. **126**, 017202 (2021)
Lee, JS, Aqeel *et al.*, *J. Phys.: Condens. Matter* **34** 095801 (2022)

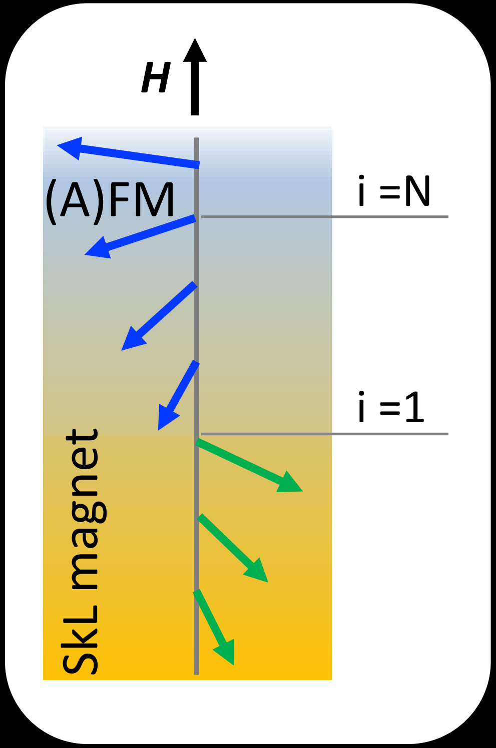


R. Takagi, *et al.*, Phys. Rev. B 104, 144410 (2021)

Surface of chiral magnet







Hybrid mode, CW and Py

Aqeel, **Azhar** et al., Phys. Rev. B **103**, L100410 (2021)

Surface twist -

Giant surface-type DMI

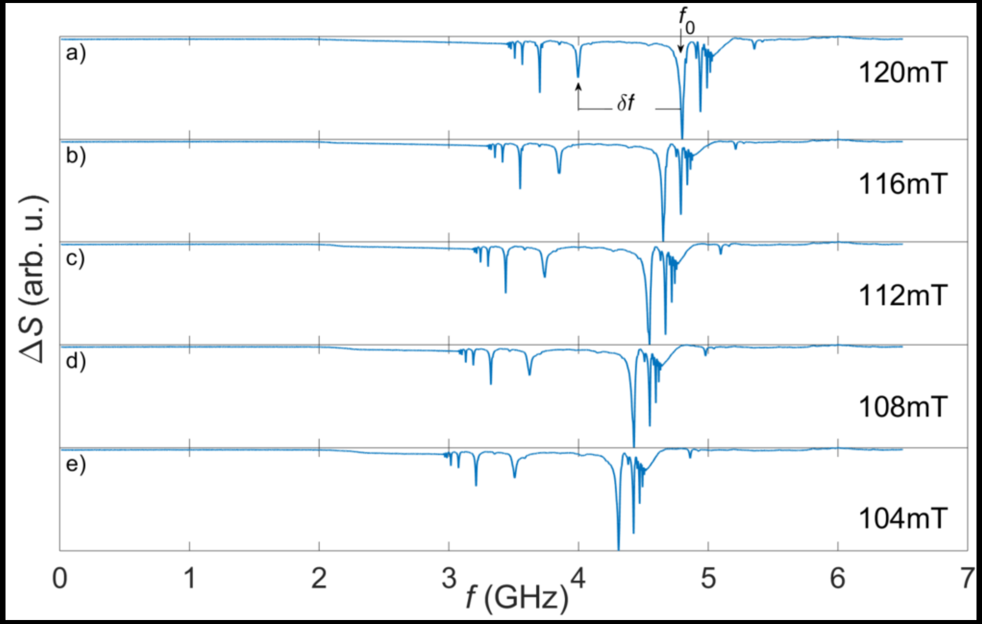
Tan et al., PRB, 109, L220402 (2024)

Low spin wave damping

At 4 K: very small magnetic damping $\alpha \cong 10^{-4}$

Yttrium Iron Garnet (YIG)

Ultra low damping ~10^{-5}



ADVANCED ELECTRONIC MATERIALS

Open Access

Research Article

Magnetic Properties and Growth-Induced Anisotropy in Yttrium Thulium Iron Garnet Thin Films

Ethan R. Rosenberg, Kai Litzius, Justin M. Shaw, Grant A. Riley, Geoffrey S. D. Beach, Hans T. Nembach, Caroline A. Ross

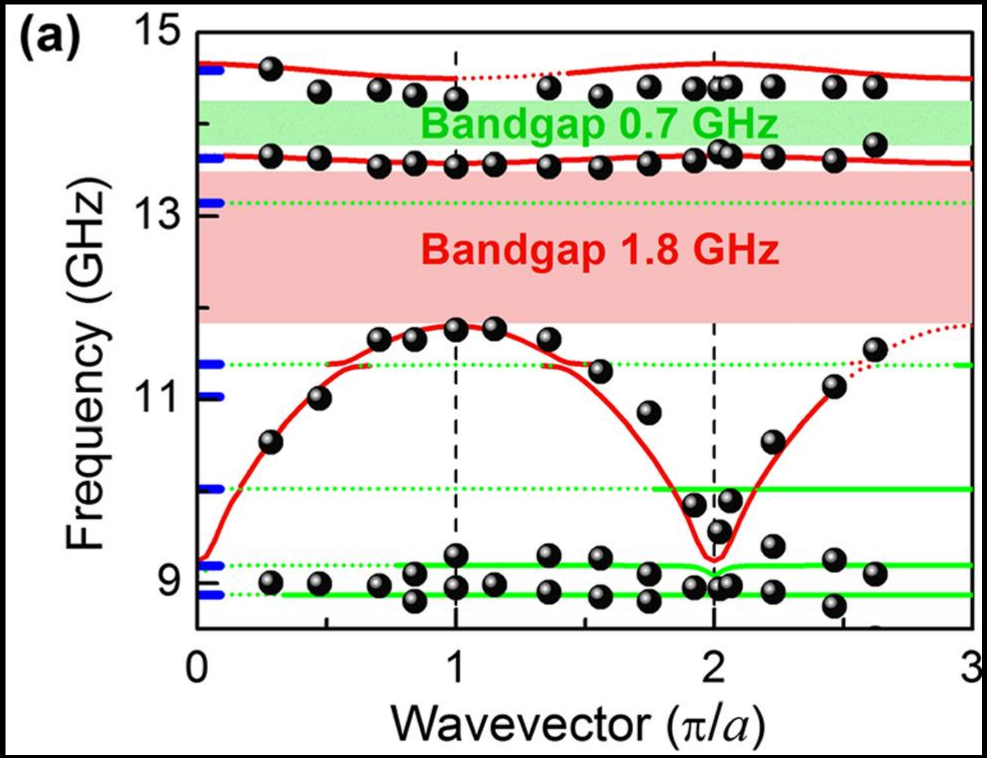
First published: 30 July 2021 | https://doi.org/10.1002/aelm.202100452 | Citations: 16

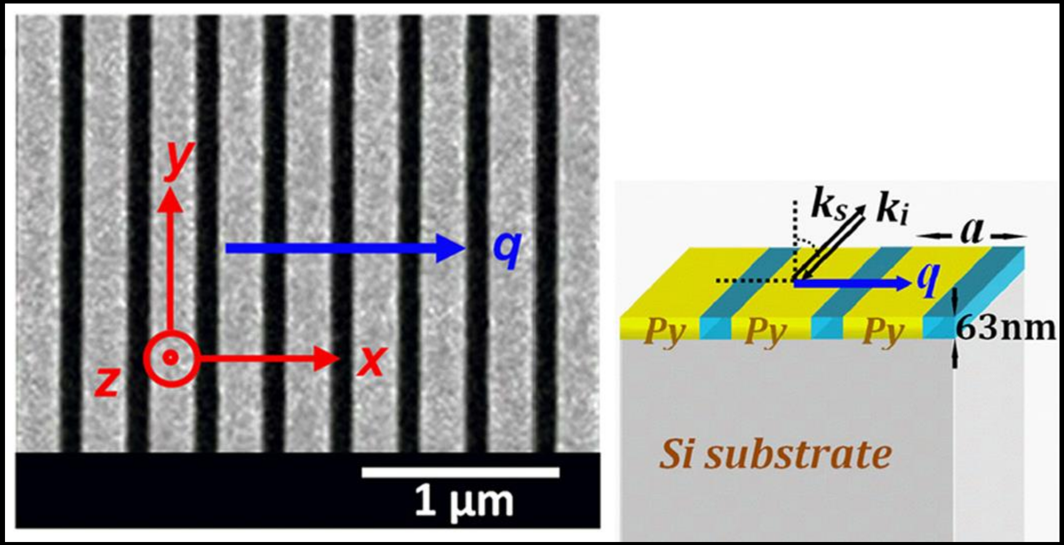
Magnetization dynamics

Chiral magnonic crystal

Periodically modulated magnetic materials

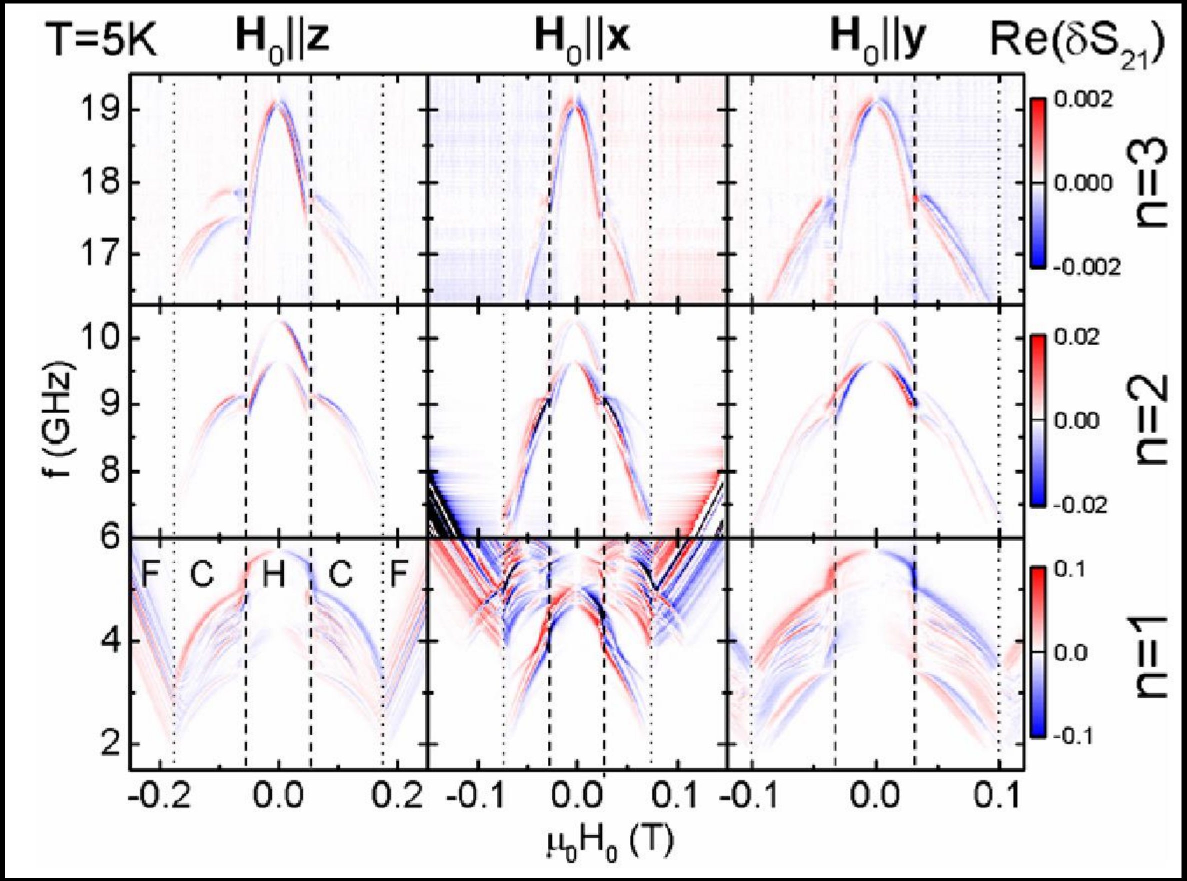
Multiple band structure in magnetostatic regime



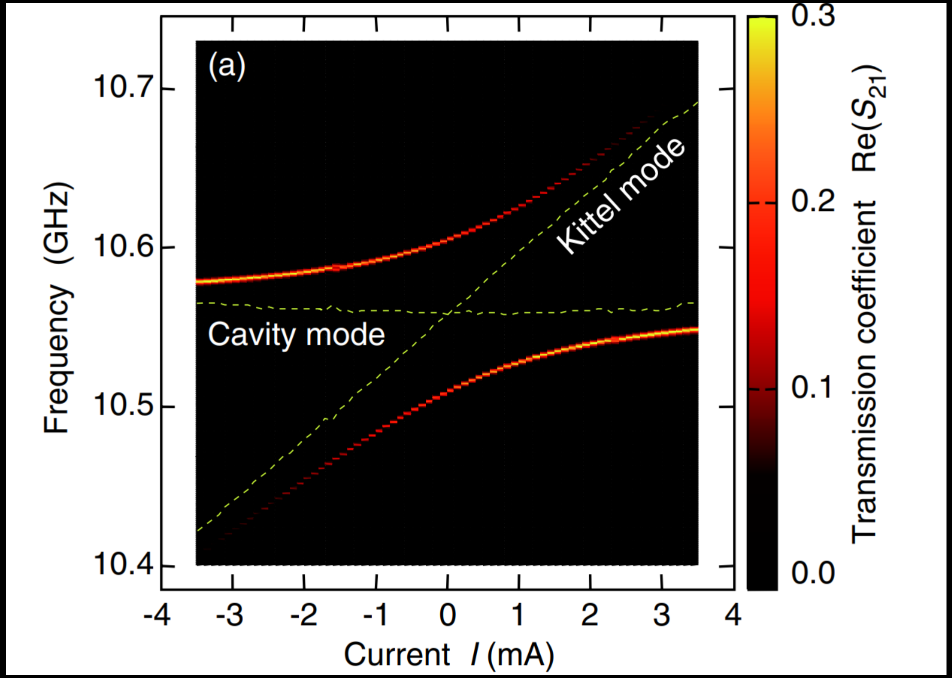


Pan et al. Nanoscale Research Letters 8:115 (2013)

Chiral magnonic crystal

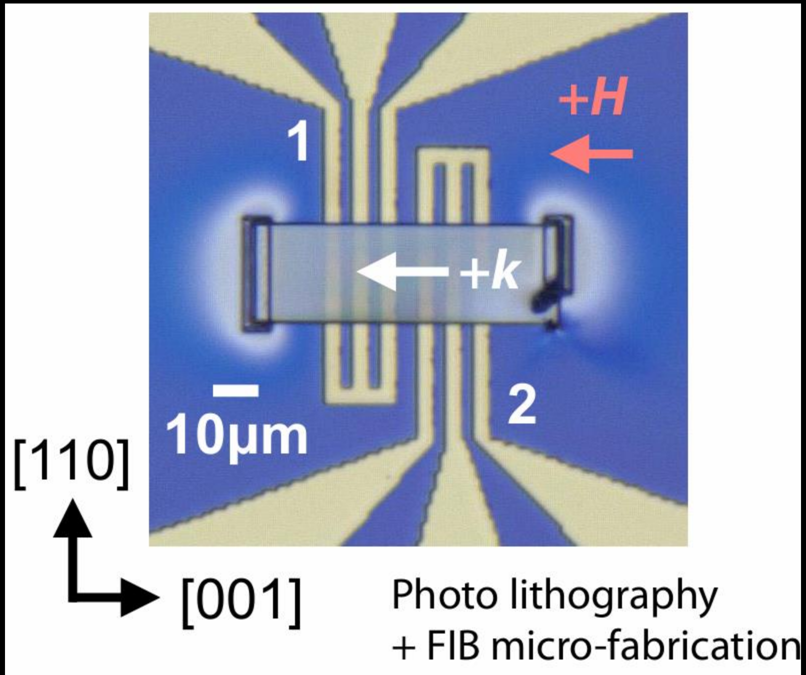


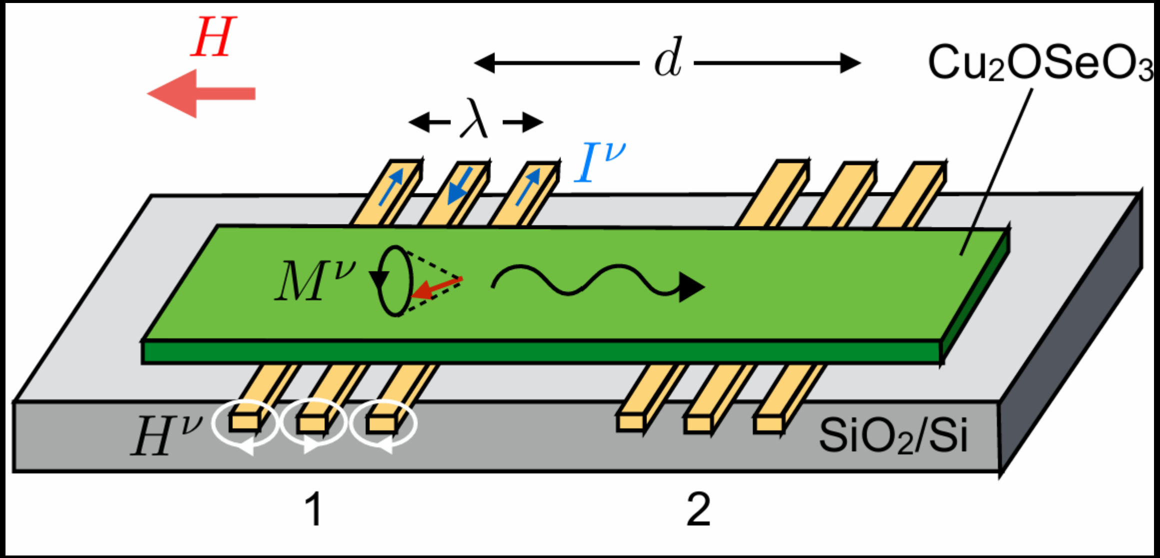
Weiler, Aqeel et al., Phys. Rev. Lett., 119, *237204* (2017)



Huebl *et al.*, Phys. Rev. Lett. **111**, 127003 (2013);
Tabuchi *et al.*, Phys. Rev. Lett. **113**, 083603 (2014)

Propagating Spin Wave Spectroscopy





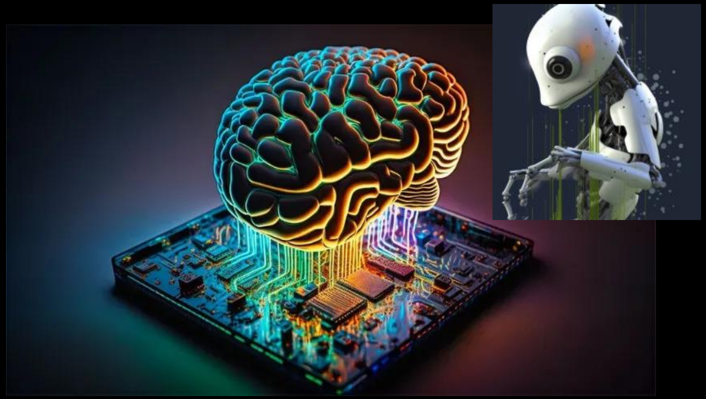
Wavelength : λ~12µm

Propagation gap : d ~ 20 µm

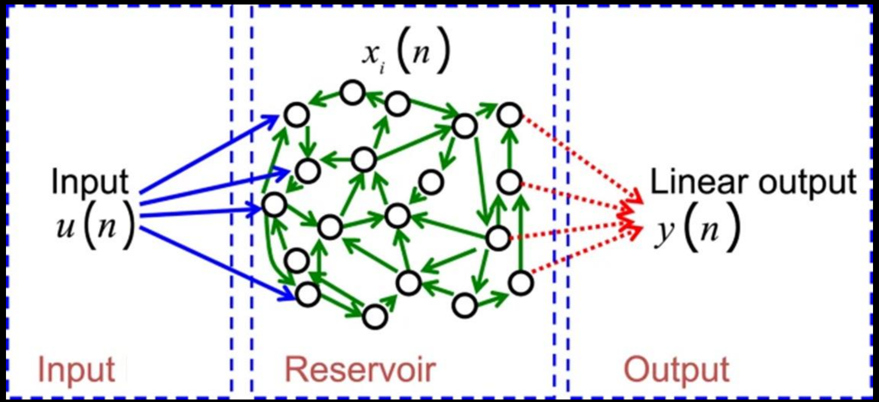
V. Vlaminck and M. Bailleul, Science 322, 410 (2008). Phys. Rev. B 81, 014425 (2010).

Neuromorphic computing

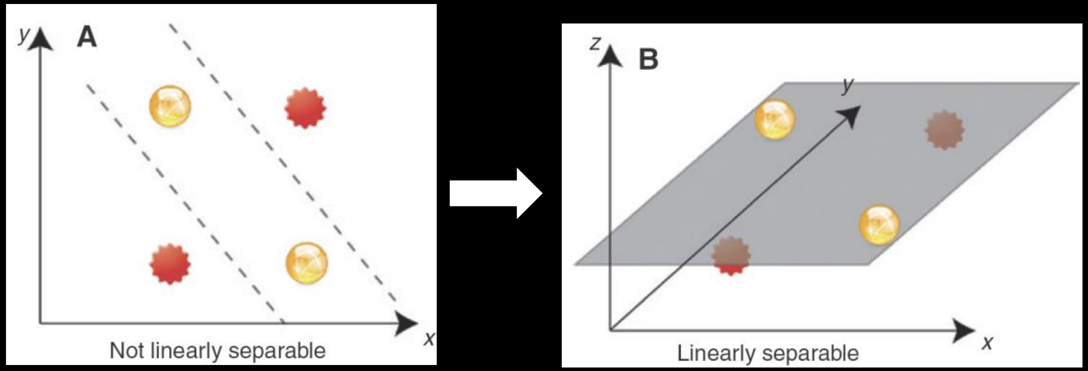
Neuromorphic computing Reservoir computing



Tasks:
Recognition
Prediction
…



Materials' properties needed:
Non-linearity
Memory capacity
Unique response to input (Echo state property)

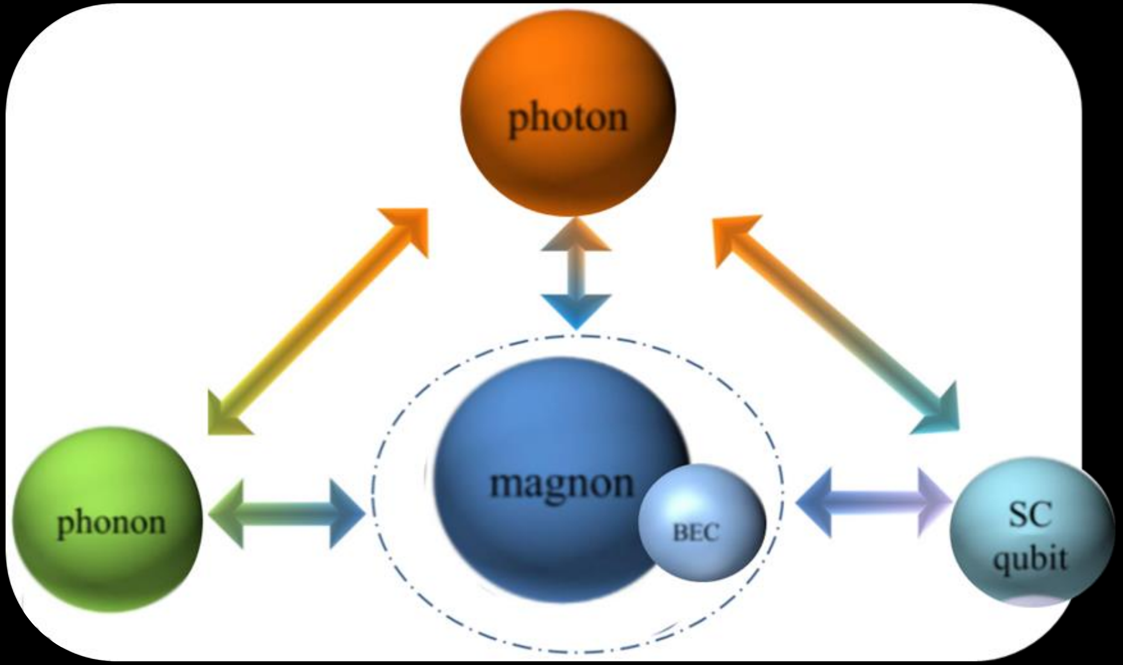


First experimental demonstration

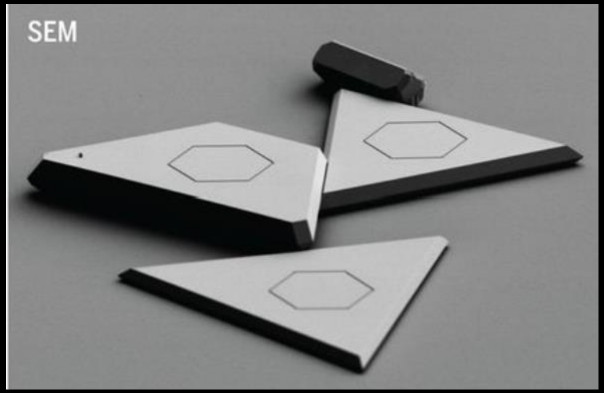
Task-adaptive nature of helimagnetic insulator – field tunability to perform different tasks

Lee,…Aqeel *et al.*, Nat. Mat. (2024)

Outlook : Coupling Skyrmions of different type



Yuan *et al*., Phys. Rep. **965**, 1 (2014)



Magnons or spin currents

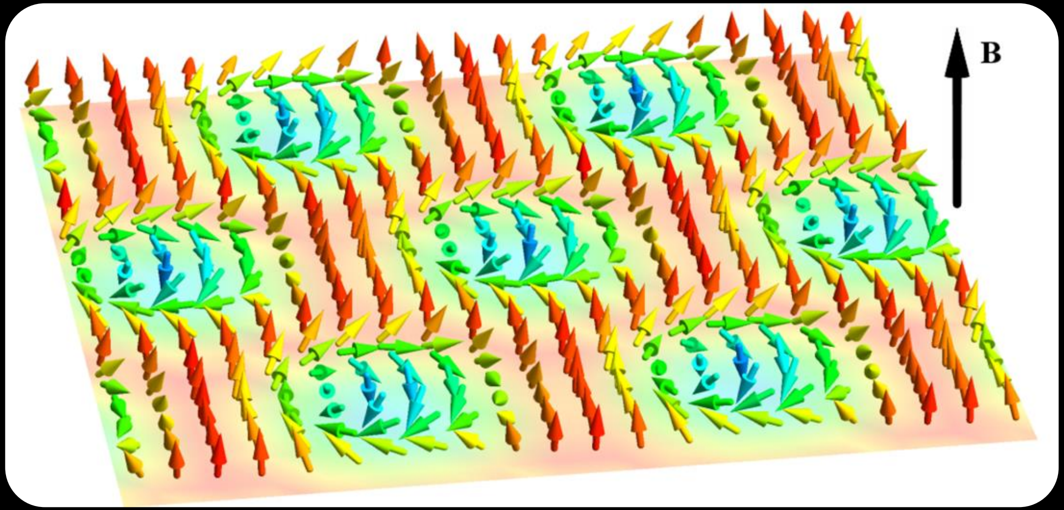
Tabuchi *et al*., Phys. Rev. Lett. **113**, 083603 (2014)

Summary

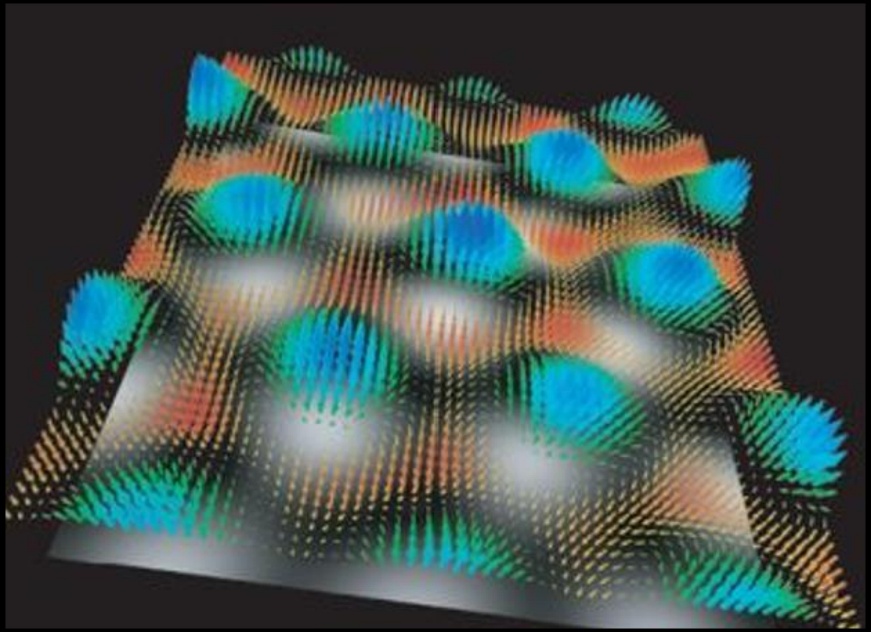
For magnetic skyrmions
needed in low loss systems

Control and Manipulate at the interface
Coupling to other quasi particles

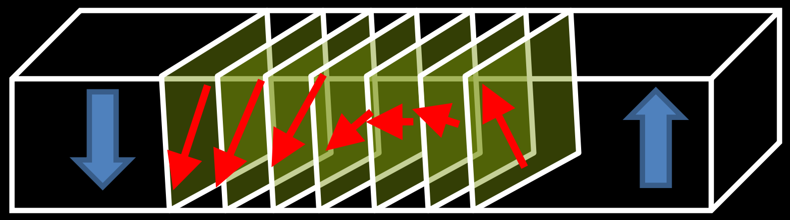
Magnetic



Everschor-sitte PhD thesis 2012



Davis, et al, Science 368, (2020)

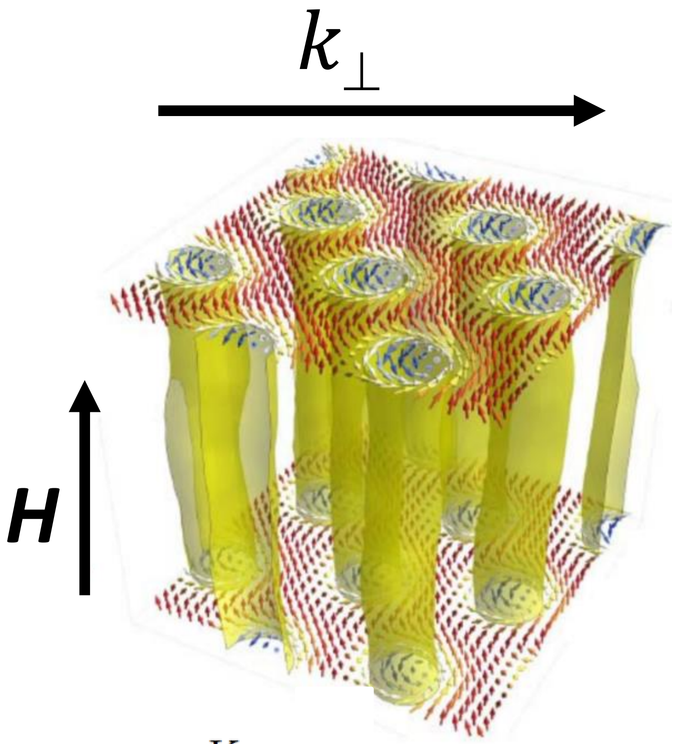


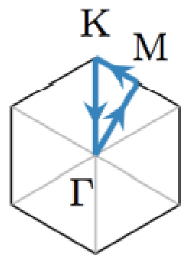
LTS: Low-temp skyrmion phase coexist with other magnetic phases

$$\mathrm{F} = \mathrm{F}_{\mathrm{Ex}} + \mathrm{F}_{\mathrm{DMI}} + \mathrm{F}_{\mathrm{Zee}} + \mathrm{F}_{\mathrm{Dip}} + \mathbf{F}_{\mathbf{Aniso}}$$

$$\mathrm{F}_{\mathrm{Aniso}} = -K \int d^3 r \left(M_x^4 + M_y^4 + M_z^4\right)$$

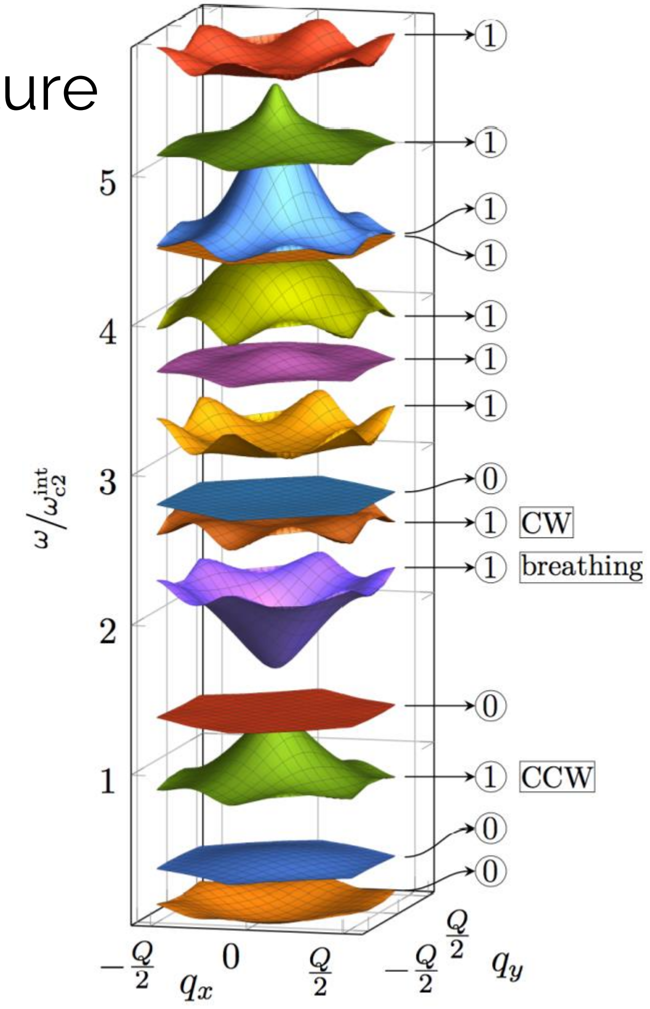
Magnetization dynamics





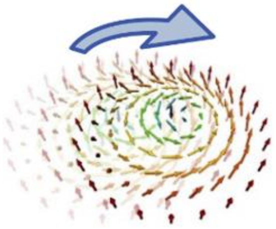
2D hexagonal Brillouin zone

Magnon band structure

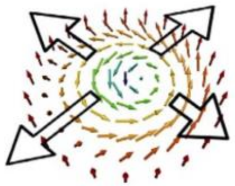


Garst et al., J. Phys. D: Appl. Phys. **50** 293002 (2017)

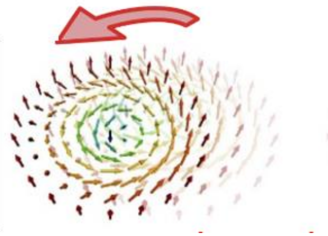
Magnetization dynamics



Clockwise (CW)

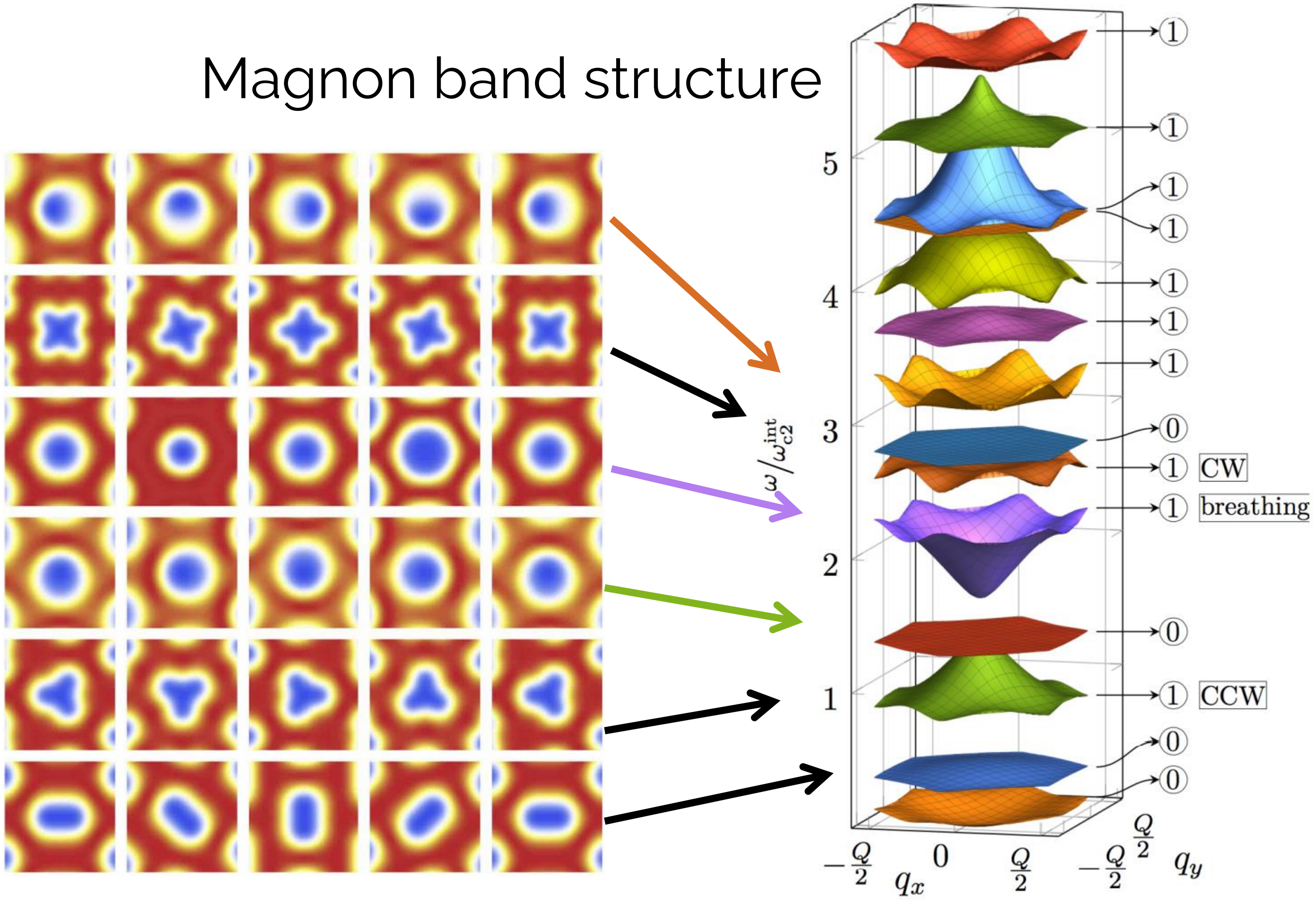


Breathing (Br)



Counterclockwise (CCW)

Magnon band structure



Garst et al., J. Phys. D: Appl. Phys. **50** 293002 (2017)

T. Schwarze et al., Nat. Mat. **14**, 478 (2015); Y. Okamura et al., Nat. Com. **4**, 2391 (2013)