Electrical detection & magnetization dynamics of skyrmions in chiral magnetic insulators

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Acknowledgements & New Group

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  - Christian Back
  - Christian Pfleiderer
  - Hans Hübl
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TU Munich

Emmy Noether Group (May 2024 – April 2030)

Focus and facilities

- AC/DC transport
- GHz magnetic resonance
- Crystal growth

1D
14T
1.5K
Cryo-free

PhD students

Mathew James

Ankita Nayak

MCQST   TUM   SPP2137 Skyrmionics   DFG   UNIA Universität Augsburg University   SpinLEGO

Research directions: finding magnetic materials with ultralow damping

- **Single crystal growth**

mainly magnetic insulators, oxides – chiral magnets including Cu_2OSeO_3 etc.
Recently frustrated magnets $CuSeO_3$, anitferromagnets Cu_3TeO_6.

Aqeel, et al., Phys. Status Solidi B (2022)
Ma et al., J. Mater. Chem. C 2024

Focus and facilities

- AC/DC transport
- GHz magnetic resonance
- Crystal growth

1D
14T
1.5K
Cryo-free

- **Resonance x-ray elastic scattering**

Mehboodi,…Aqeel ArXiv:2412.15882 2025
Simeth, et al., Phys. Rev. Lett. 2023

- **GHz microwave spectroscopy**

Single crystals & bilayers for coupled dynamics

Lee, ..Aqeel et al. *Nat. Mater*. 2024
Lüthi, Flacke, Aqeel, *et al*., APL 2023

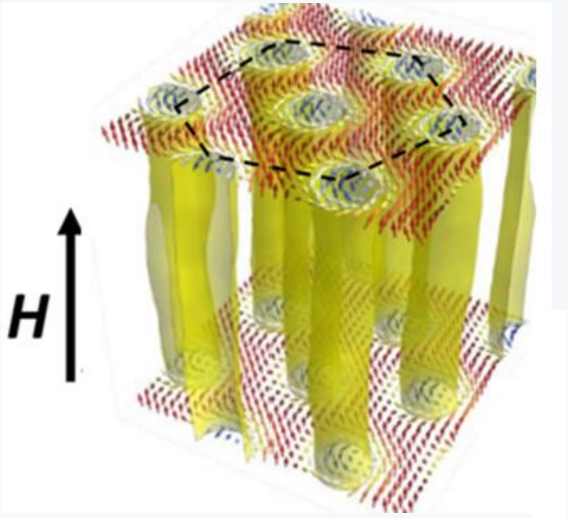
- **Spin transport experiments**

Spin Hall magnetoresistance,
Spin Seebeck effect

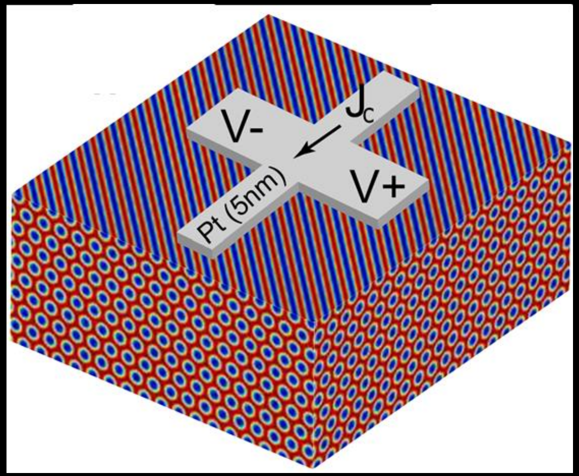
Aqeel, et al., Sci. Technol. Adv. Mate. 2025

Outline

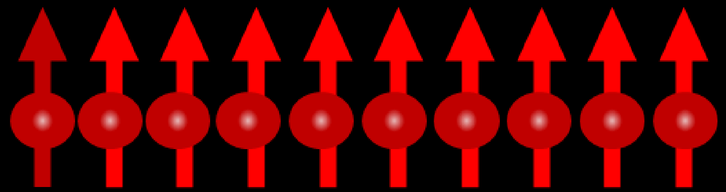
Part 1: Skyrmion dynamics
Cubic chiral magnets
Cu_2OSeO_3



Part 2: Electrical detection via
Spin Hall magnetoresistance (SMR)
Cu_2OSeO_3



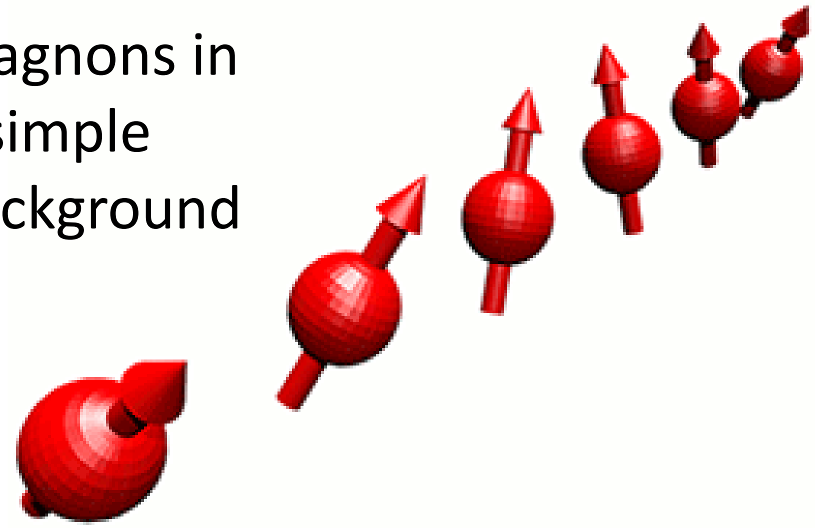
Magnons in Ferromagnetic vs. Skyrmion Backgrounds



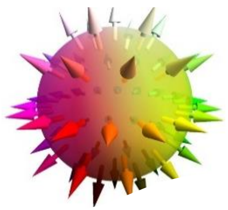
Collective oscillations of spins with a well-defined dispersion relation.

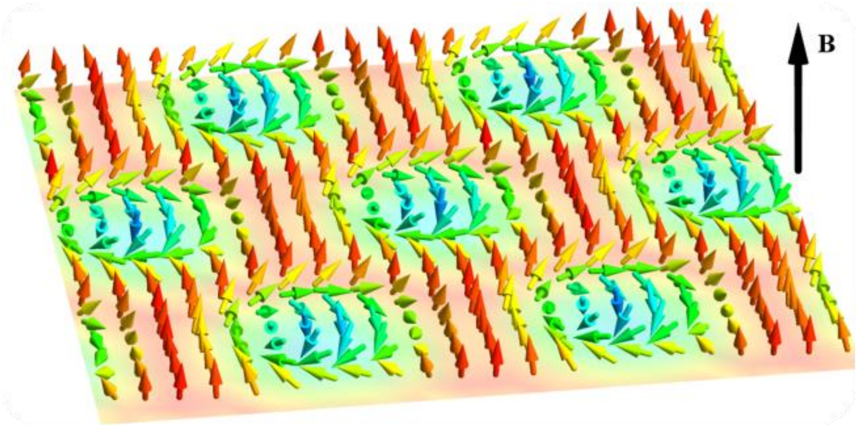
*Skyrmion Lattice = **Magnetic Superstructure***

Magnons in a simple background



Periodic, but **non-uniform**
Breaks symmetry of uniform magnet





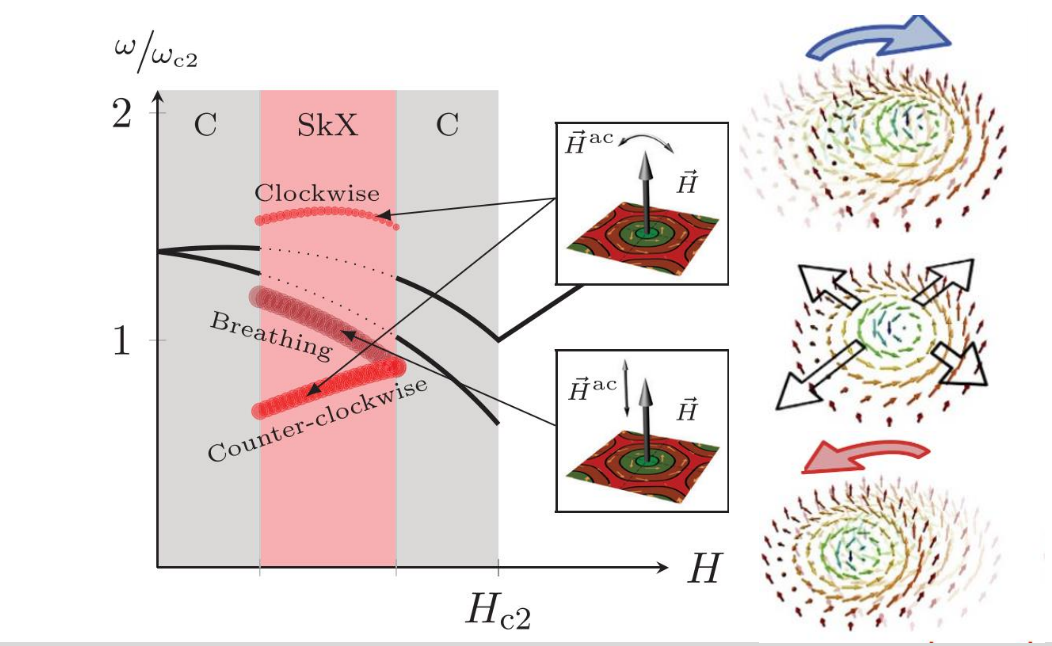
Chumak et al., Nat Phys (2015), Göbel et al., Physics Reports (2021)
Pradip, KIT 2016

Magnons in Ferromagnetic vs. Skyrmion Backgrounds

Magnons in spatially varying effective magnetic field background

- **Effective magnetic field** varies across space
- Results in **band structure with natural gaps** *(like electrons in solids!)*

*Skyrmion Lattice = **Magnetic Superstructure***



Clockwise (CW)

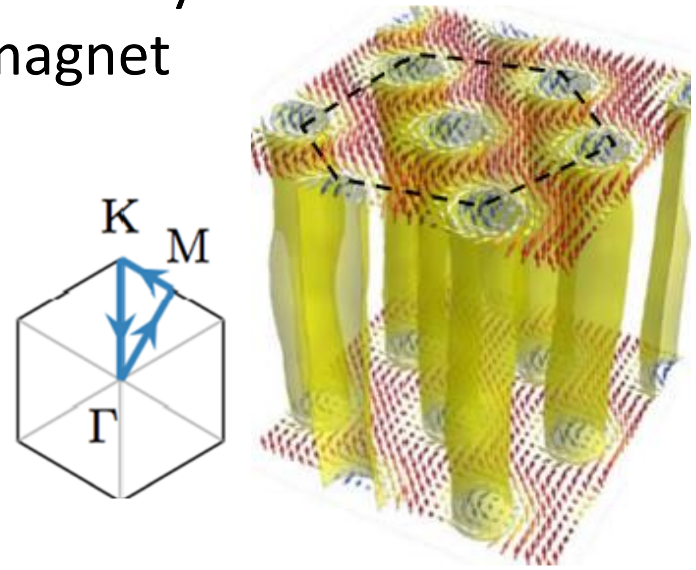
Breathing (Br)

Counterclockwise (CCW)

Periodic, but **non-uniform**

Breaks symmetry of uniform magnet

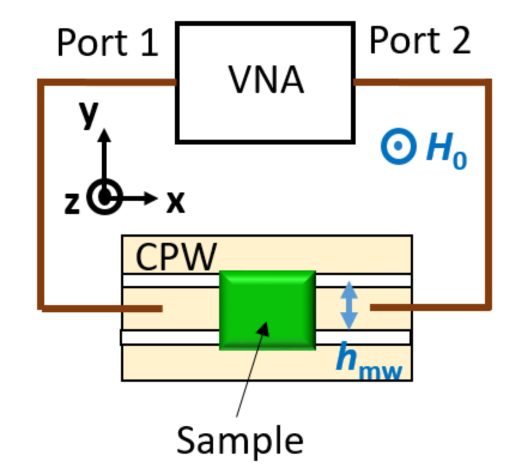
3D view

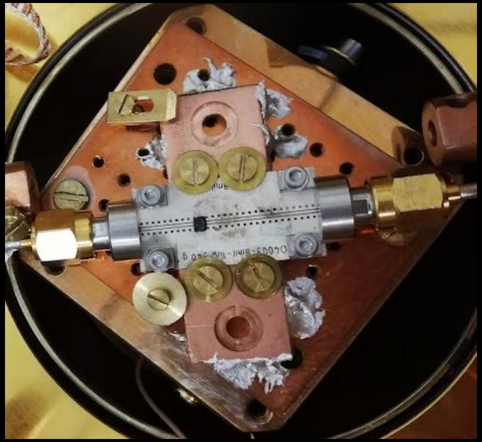


Chumak et al., Nat Phys (2015), Göbel et al., Physics Reports (2021)
Pradip, KIT 2016

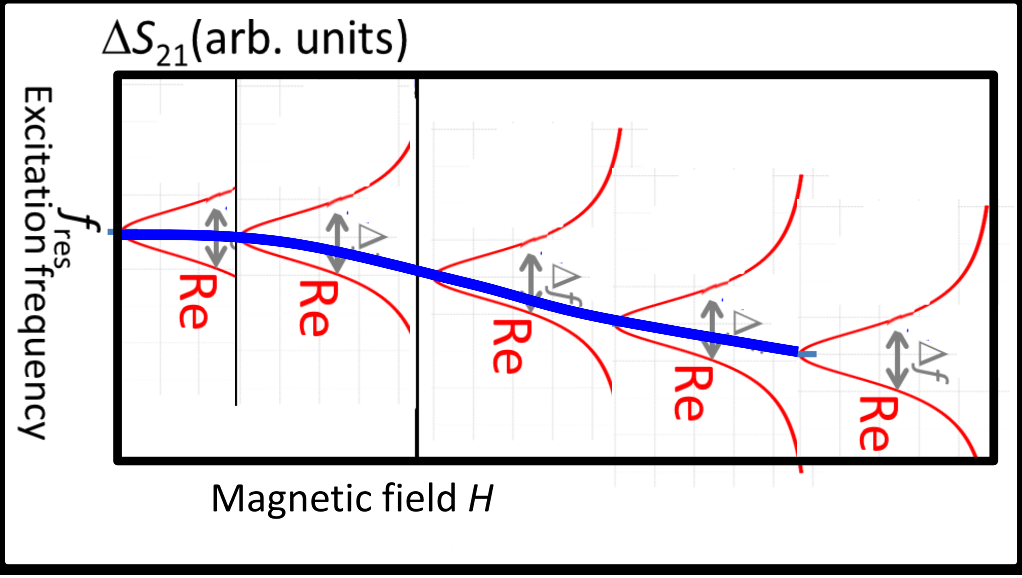
Experimental Detection – Our Approach

Microwave spectroscopy technique
GHz excitation & detection by
Vector Network Analyzer VNA
Resonance → Microwave power absorption





Tracking resonant frequency

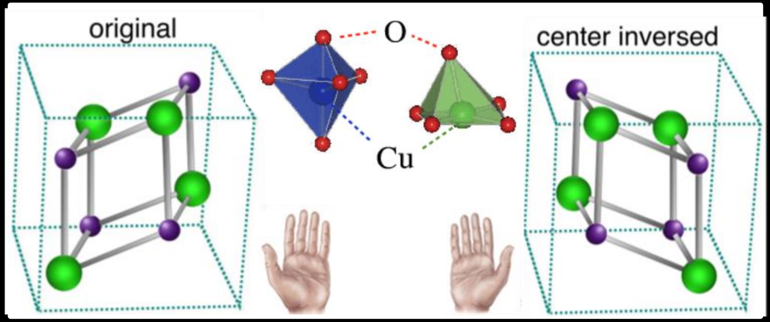


Weiler, Aqeel, et al. *PRL* 2017

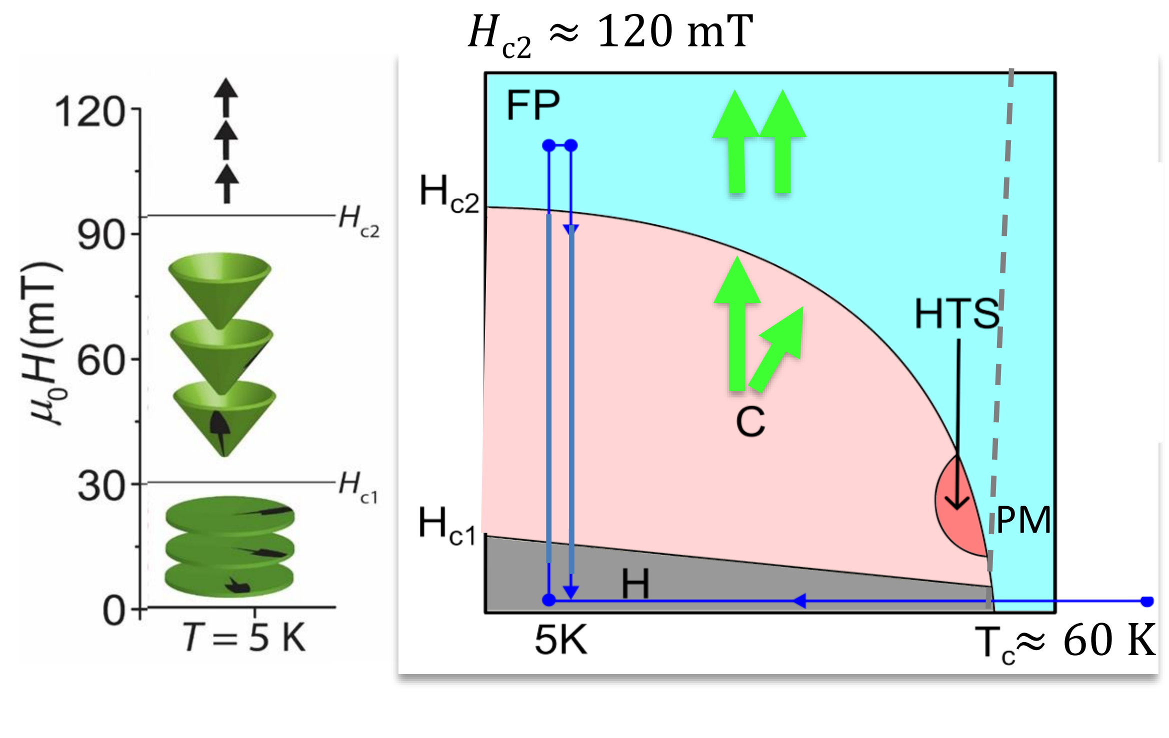
Okamura..., Nat. Com. **4**, 2391 (2013) Schwarze..., Nat. Mat. **14**, 478 (2015)

Experimental detection in Cu_2OSeO_3

- **Electrically Insulating**
- Inversion symmetry breaking → twisted spin textures through the Dzyaloshinskii–Moriya interaction (DMI)
- Magnetic texture pitch ~ **60 nm**



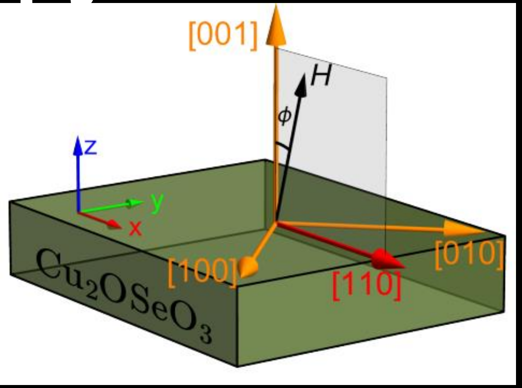
Magnetic phase diagram



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

Bos …, PRB **78** (2008)

Stabilizing LTS Skyrmions & Role of Anisotropy



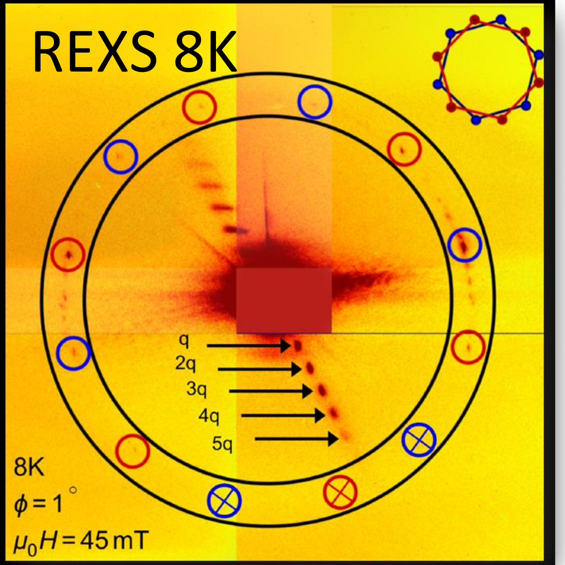
Two independent skyrmion pockets

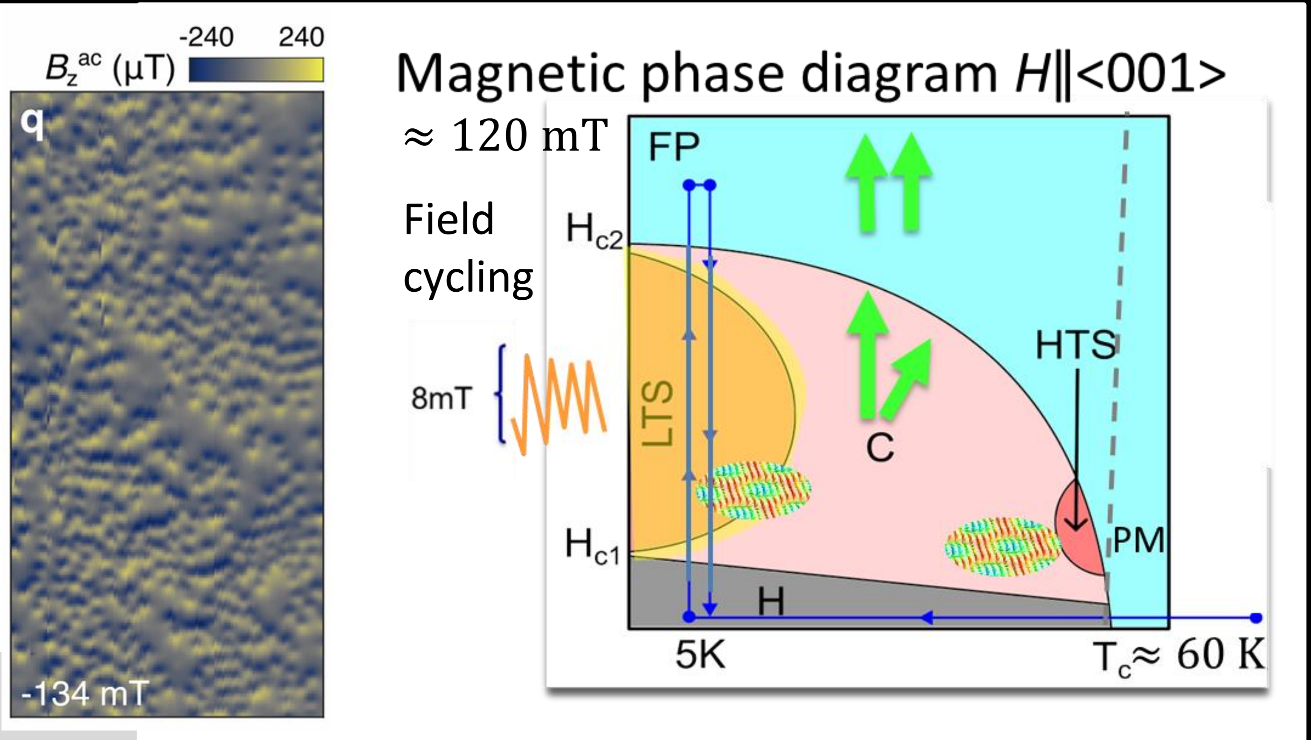
HTS: by DMI & thermal fluctuations

LTS: by DMI & cubic anisotropy, **coexists with spirals**

cycling removes metastable spirals, stabilizing skyrmions.

LTS by Resonant x-ray elastic scattering (REXS)



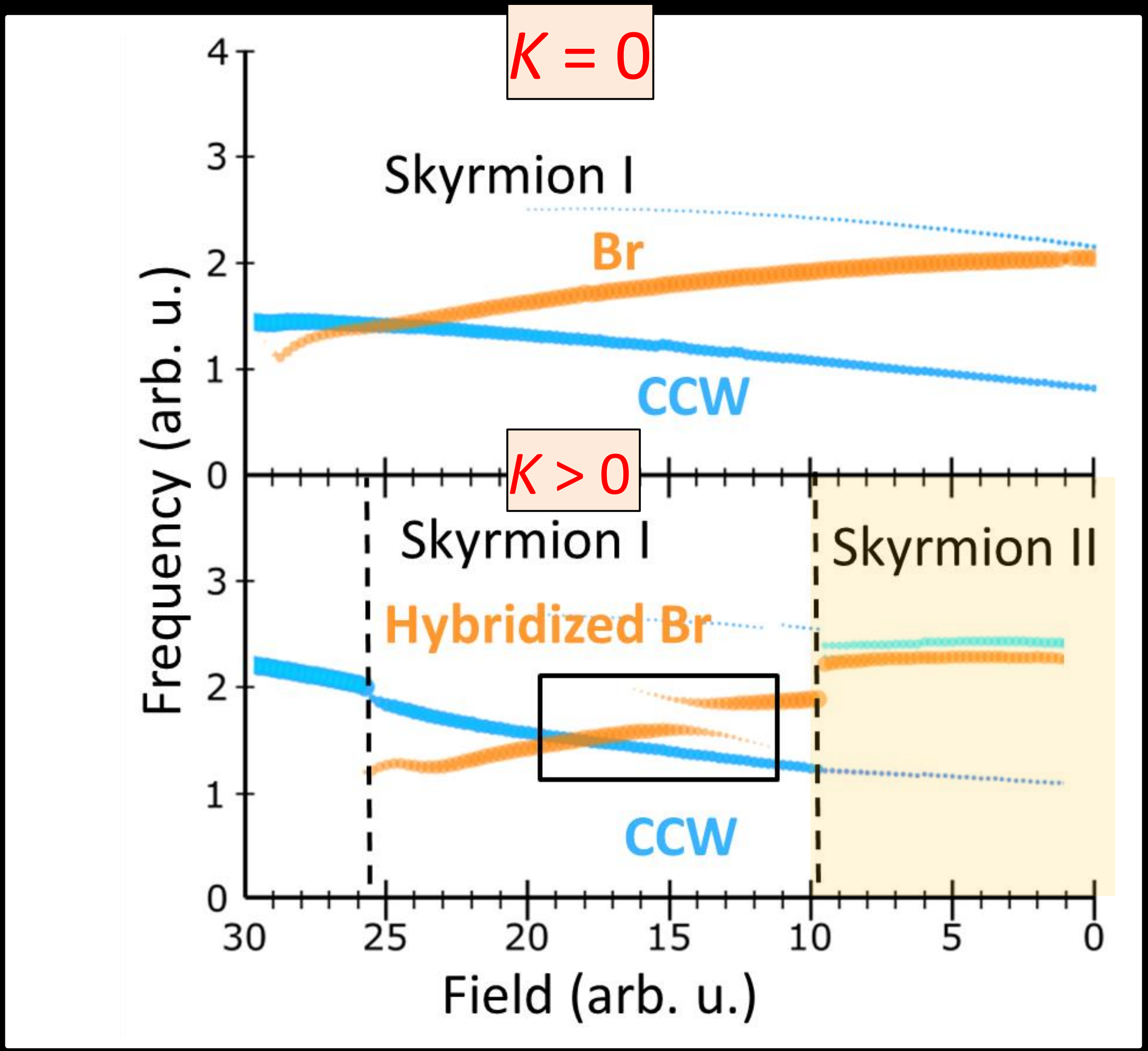


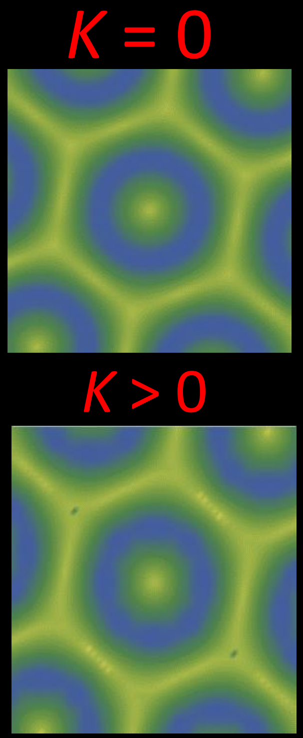
Mehboodi,…Aqeel ArXiv:2412.15882 2025

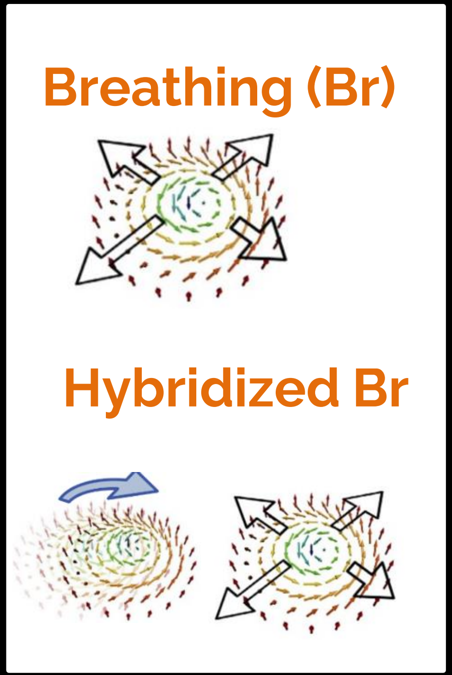
Chacon ..., Nat. Phys. (2018) Martino Poggio 2024

Effects of Cubic Anisotropy on Skyrmion Magnon Modes

Theoretically identified magnon modes with anisotropy K







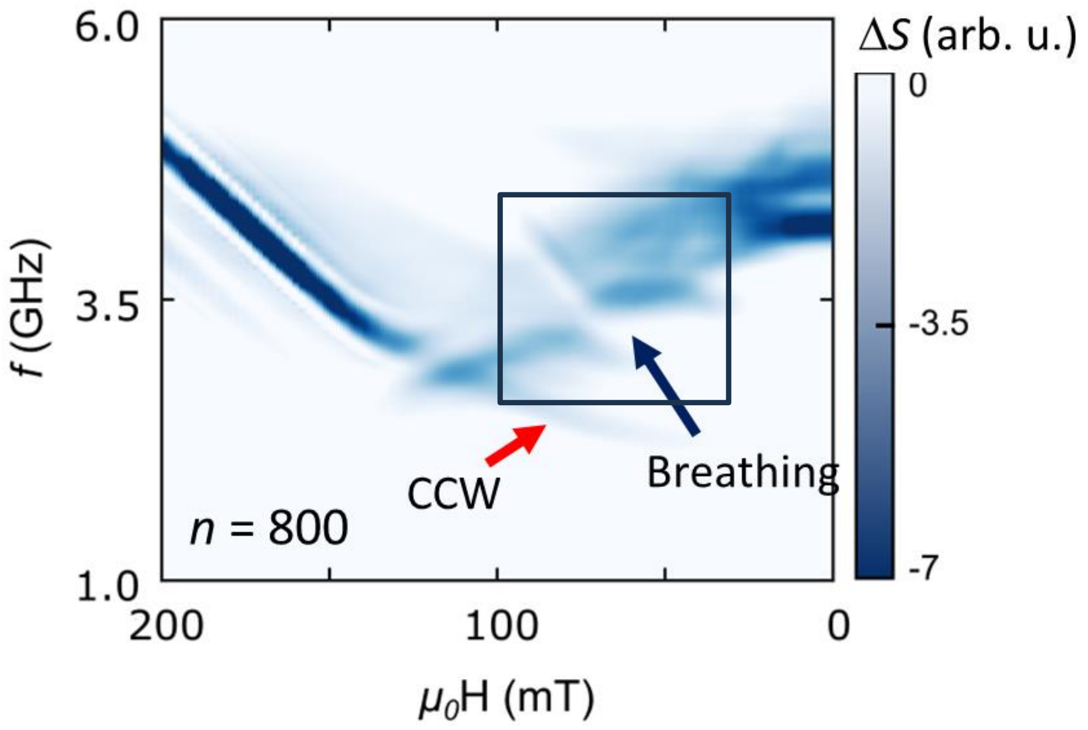
Hybridized mode → Breathing + 1 dark gyrational

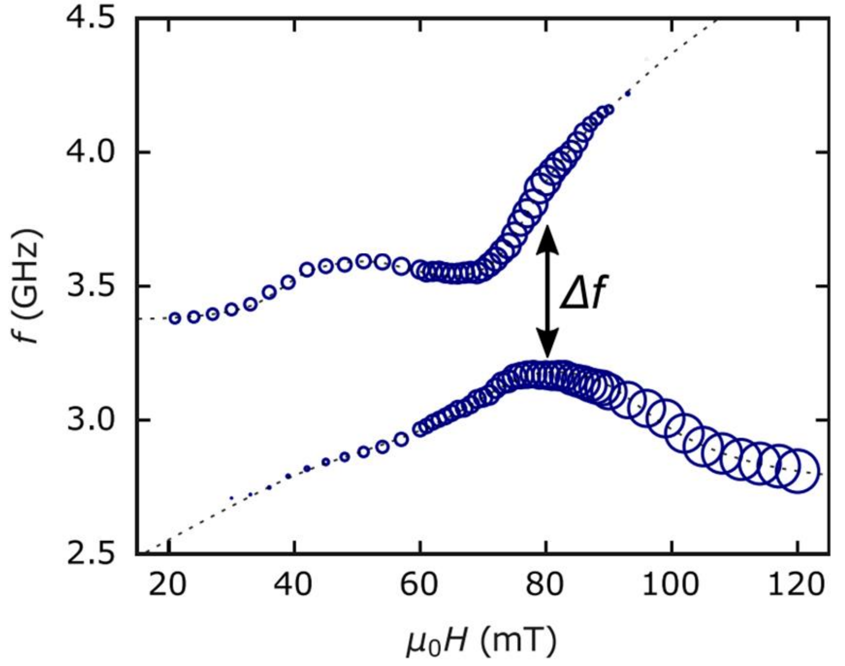
Hexagonal → elongated skyrmion lattice at low fields

Experimental Evidence for Mode Hybridization

Microwave spectroscopy reveals reveals mode hybridization *in skyrmion lattice*

Experiment at 4 K, *H*‖<001>





Lee, Sahliger, Aqeel et al., *JPCM* 2022
Aqeel, Sahliger, et al., *PRL* 2021

Experimental Evidence for Mode Hybridization

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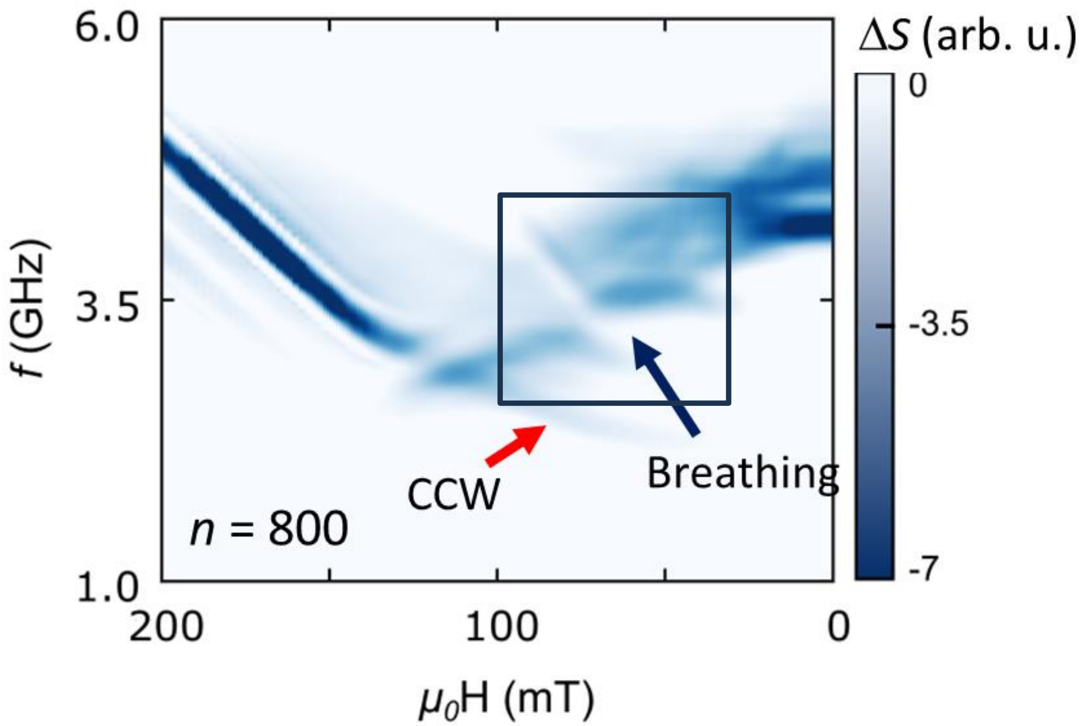
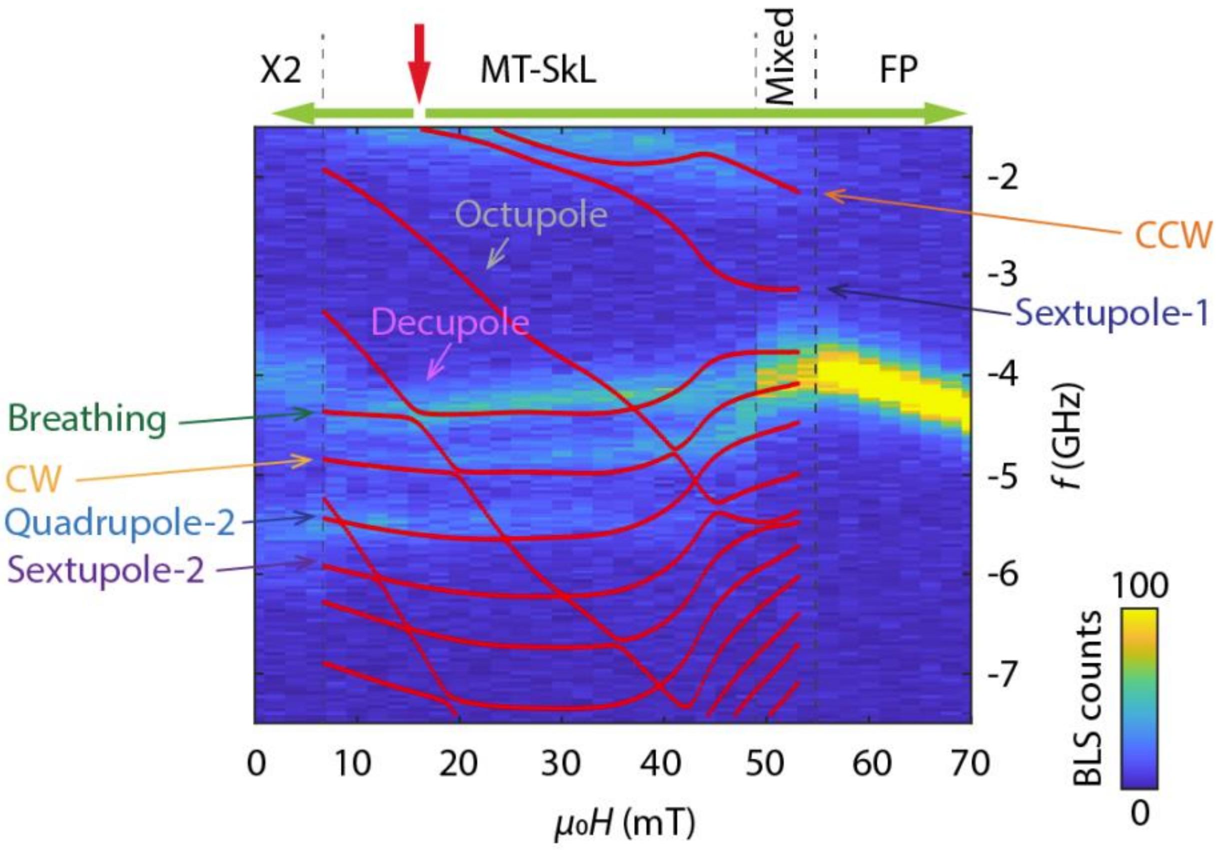


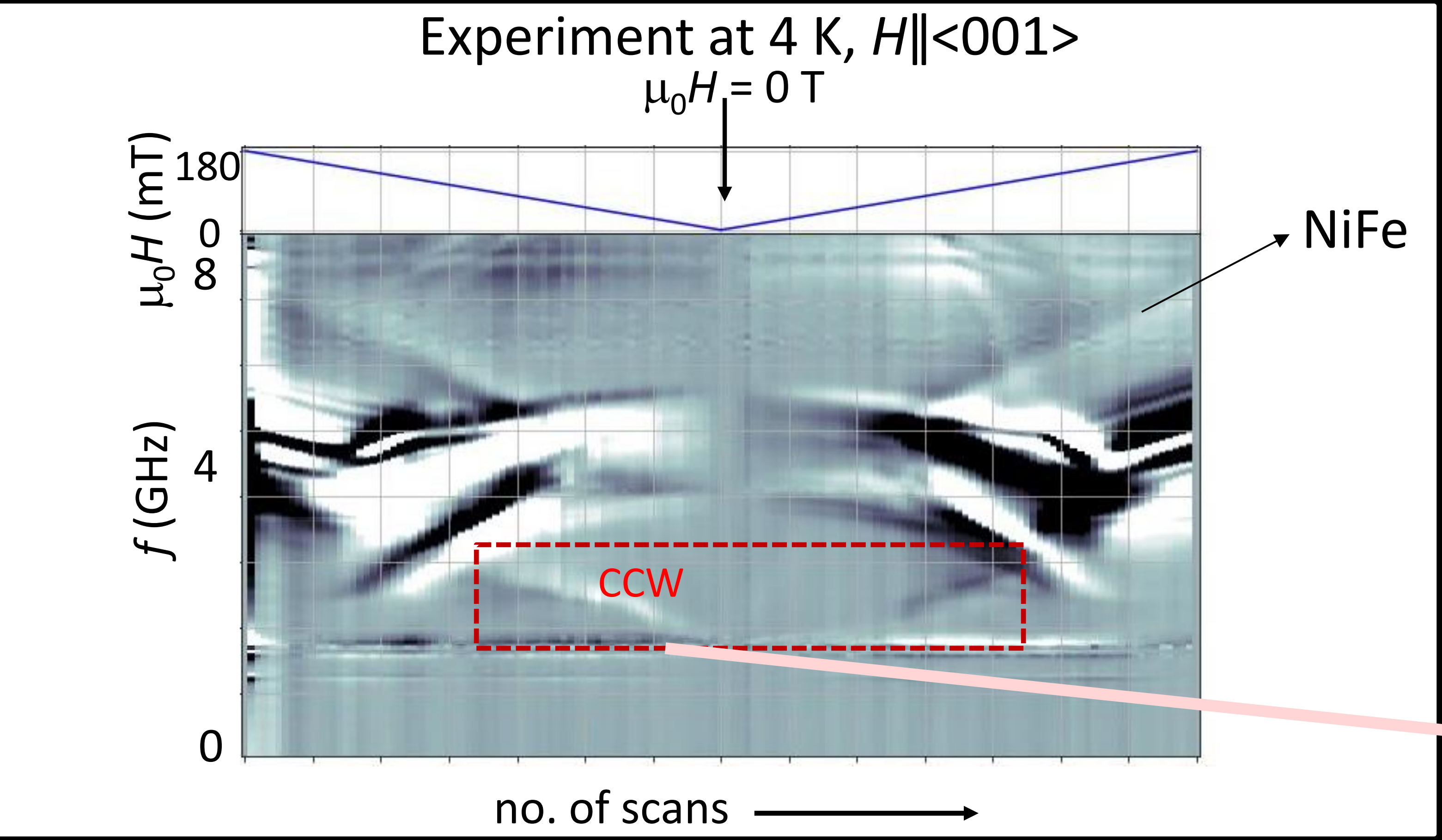


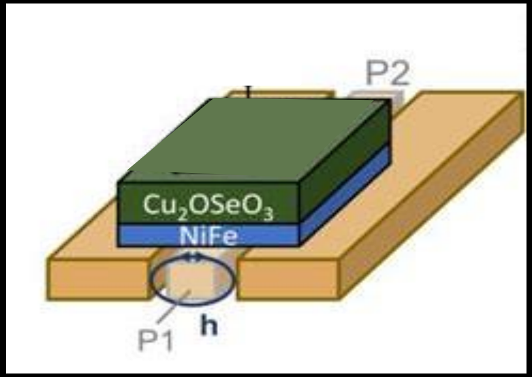
Che …, arXiv:2404.14314

Skyrmions at NiFe/Cu_2OSeO_3 interface

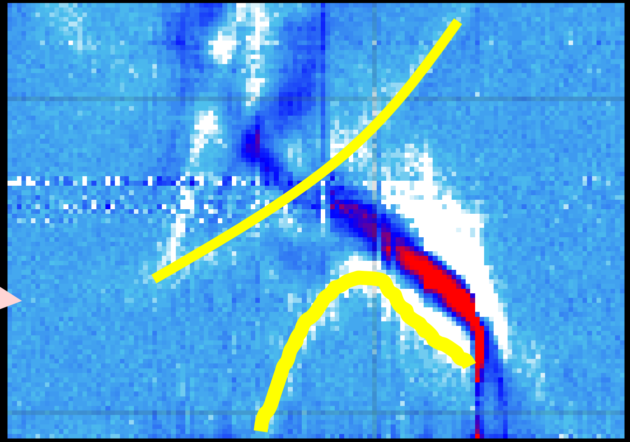
Surface-selective stabilization via interface engineering

NiFe (40 nm) layer stabilizes skyrmion lattice - no field cycling





Zoom-in: Hybridized mode near interface



Skyrmions for Magnonics: Challenges and Opportunities

- Magnons decay due to damping α better as we cool 🧊 😊

  At **60 K**, damping **$\alpha \approx 10^{-2}$**

  At **4 K**, damping **$\alpha \approx 10^{-4}$**

  → *longer-lived spin excitations at low T!*

- Cubic anisotropy reveals hidden modes in experiment

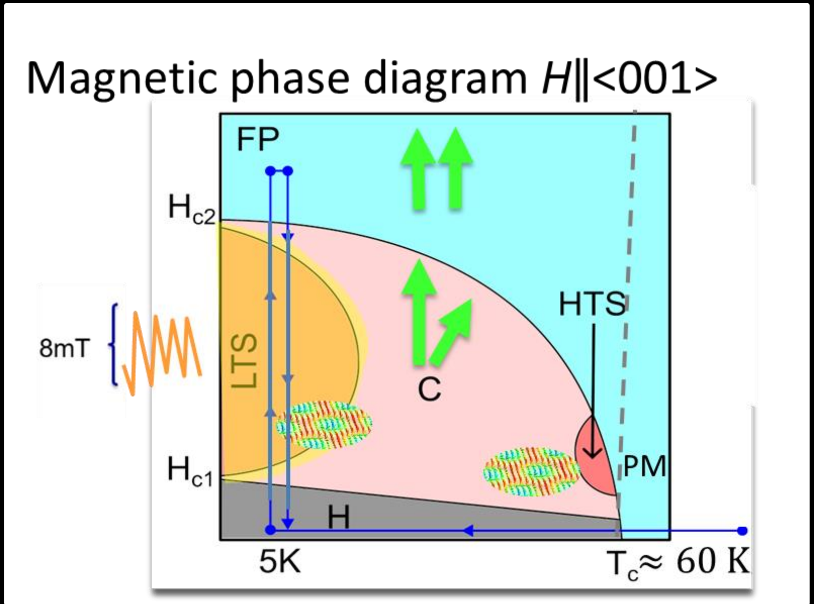
- Magnons in Cu_2OSeO_3 → functional hardware:

  Reservoir Computing 💡 🧠

Lee, ..Aqeel et al. *Nat. Mater*. 2024

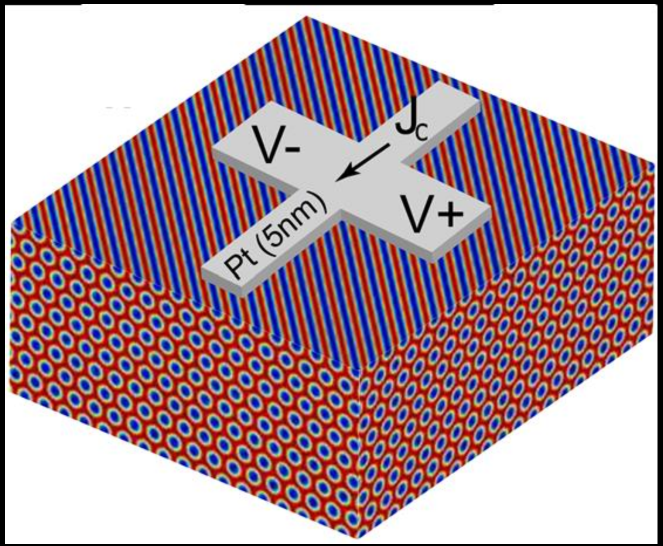
What we need: low damping + **smaller skyrmions**

Can we electrically detect skyrmions?



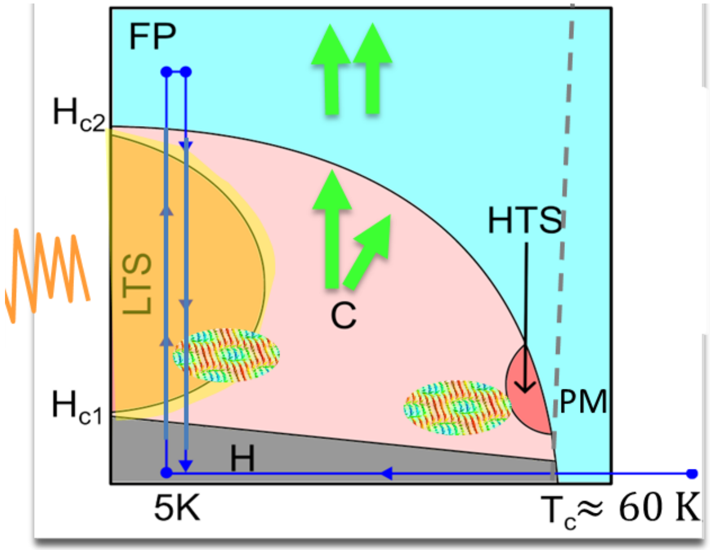
Part 2: Electrical detection via **Spin Hall magnetoresistance (SMR)**

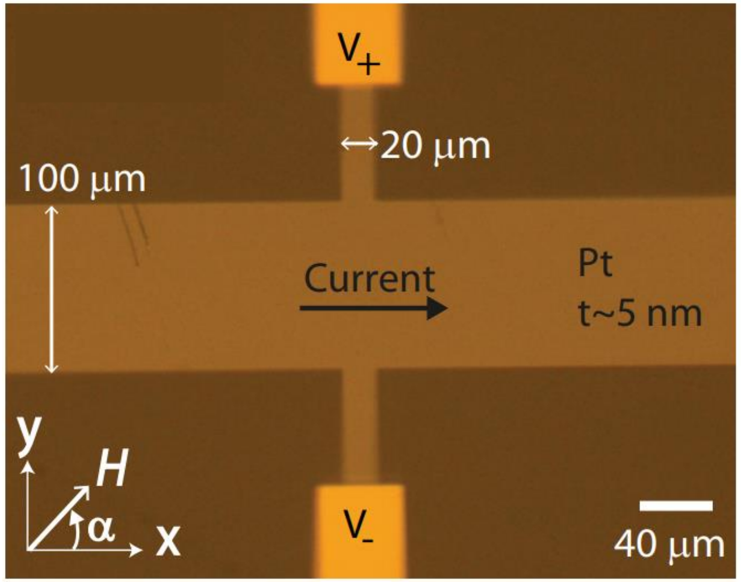
From GHz excitations to low-frequency resistance readout via SMR

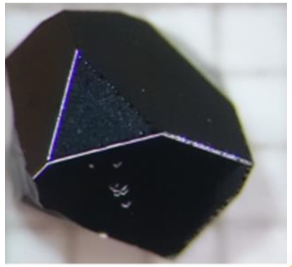


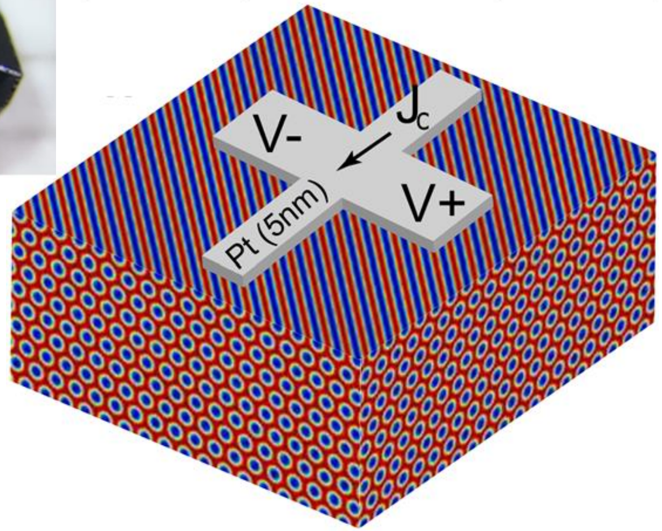
Detecting skyrmions with SMR: Our Experimental Setup

Low-frequency AC current ⟶ spin Hall effect ⟶ SMR readout





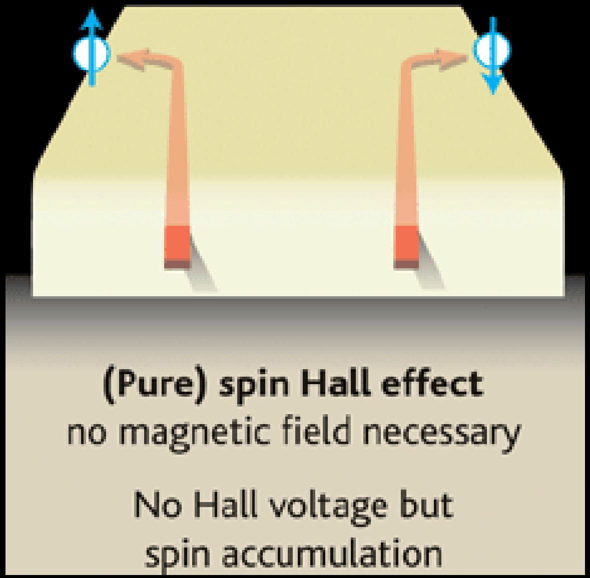




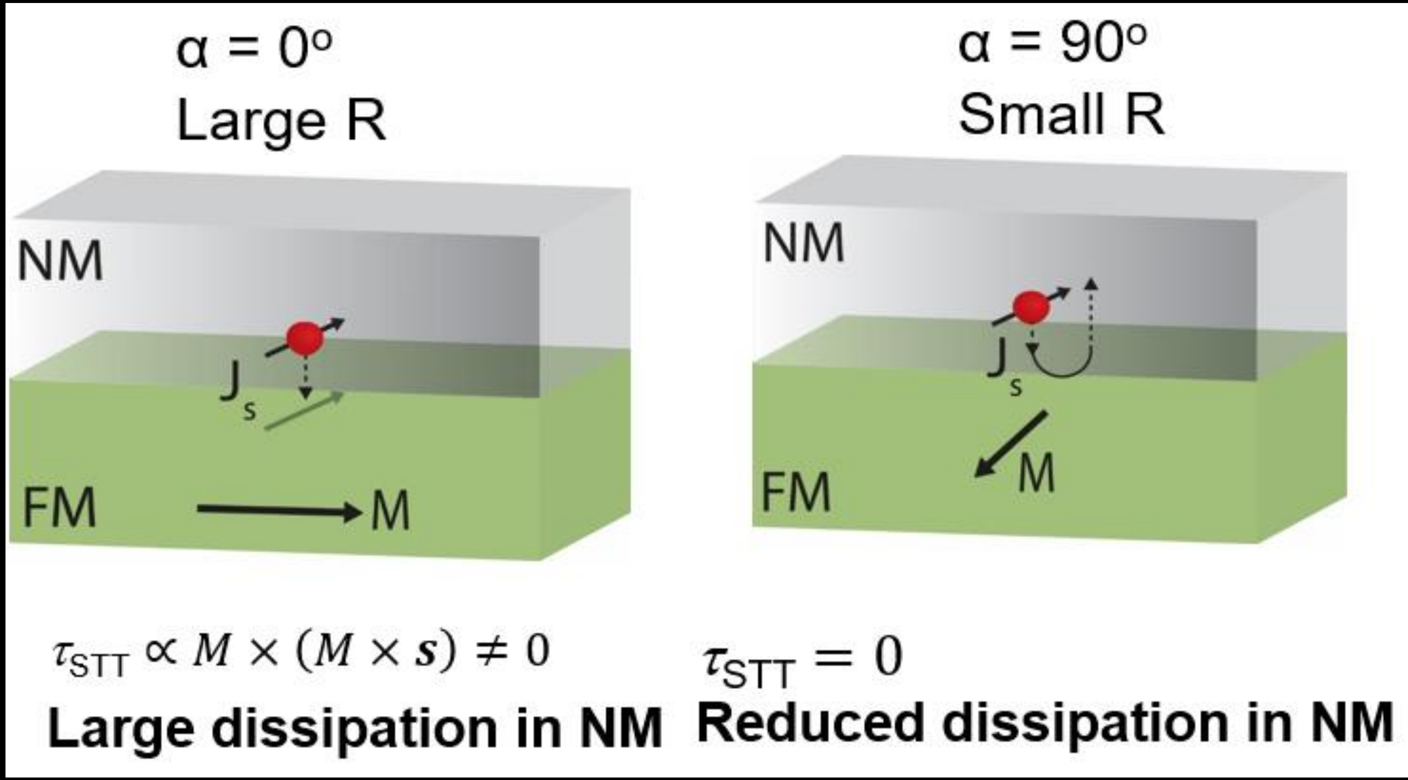
Aqeel, et al., Sci. Technol. Adv. Mate. 2025
Aqeel, et al., Phys. Rev. B 2016, 2021

SMR: Sensing magnetic order electrically

Spin currents generated/detected in heavy metals e.g. Pt, Ta..



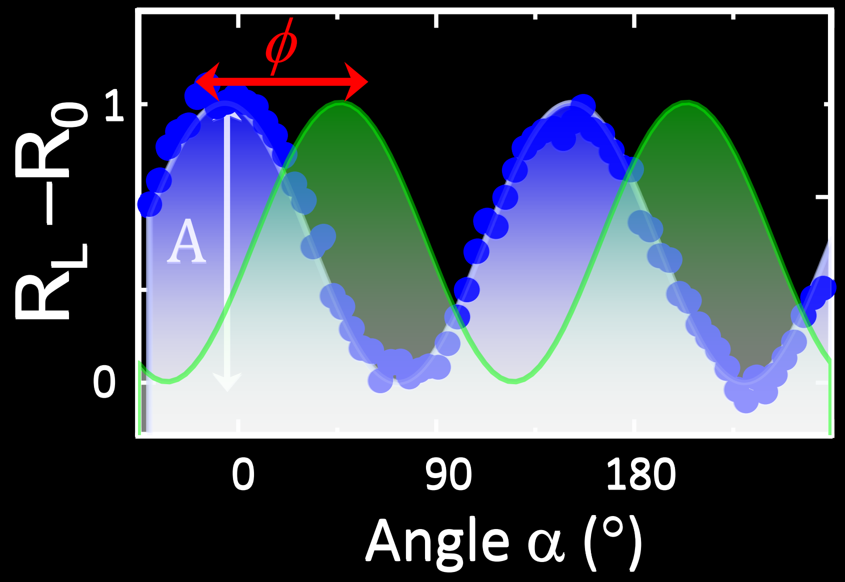
Spin Hall effect (SHE):
charge → spin current

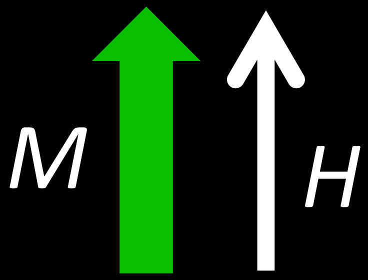


SMR = resistance modulation due to spin current reflection governed by **magnetization direction**

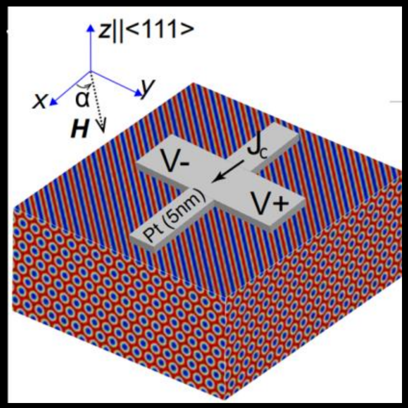
Sinova *et al*., RMP 87, 1213 (2015)
Theory (2013): Chen, *et al.*, PRB
Detection (2013) PRLs: Nakayama *et al*., & Vlietstra *et al*.,

SMR: Sensing magnetic order electrically

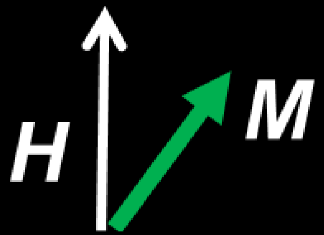




$\phi = 0$



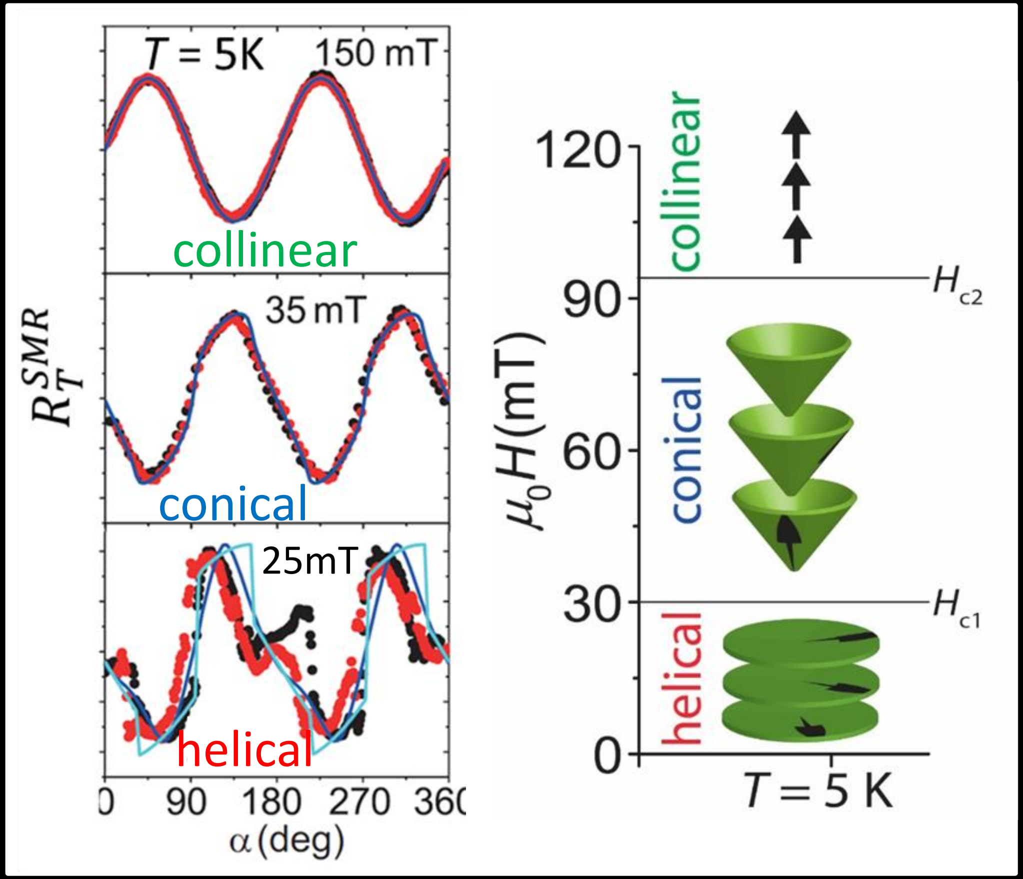
$$R_T^{SMR} = A \sin 2(\alpha - \phi)$$

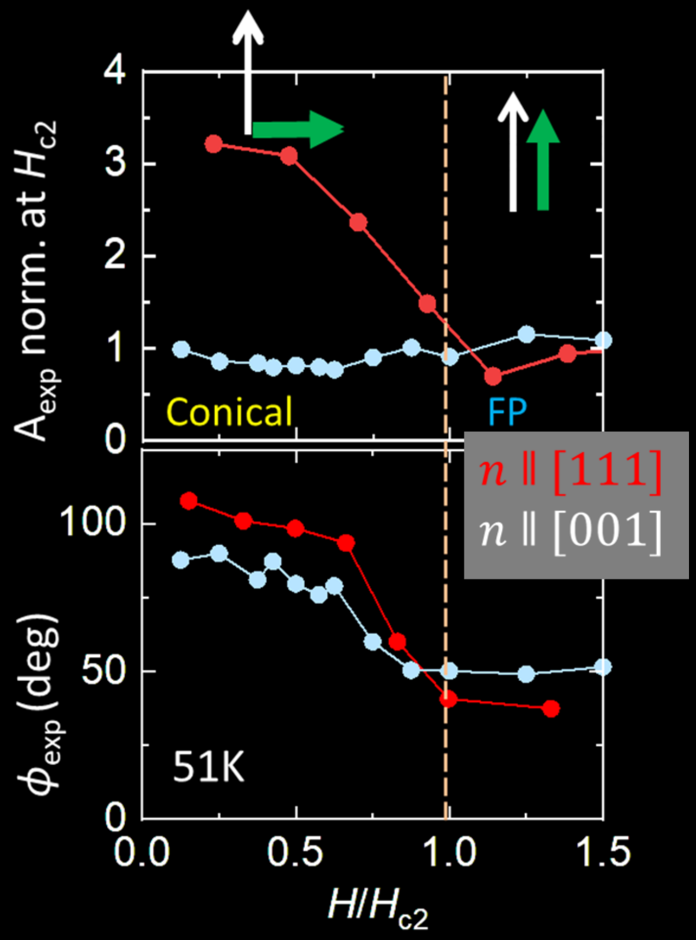


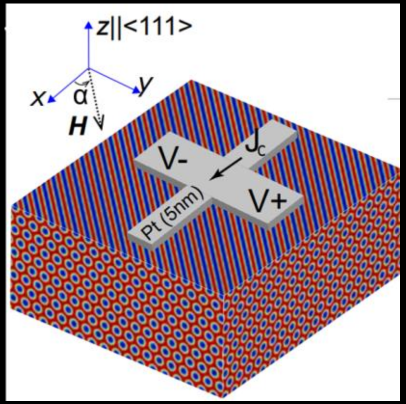
$\phi \neq 0$

Magnetization (*M*) is slightly **tilted** due to anisotropy/DMI

SMR in Pt/Cu_2OSeO_3 within {111} plane







$$R_T^{SMR} = A \sin 2(\alpha - \phi)$$

SMR sensitivity to **twisting of *M*** & **spatial textures**

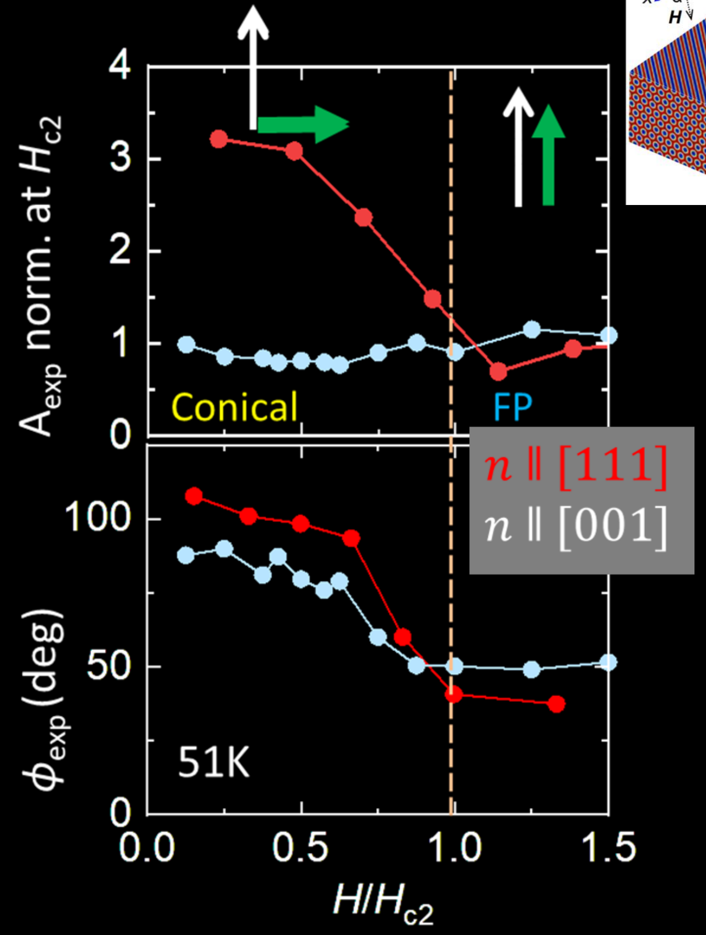
Comparison to theory of SMR

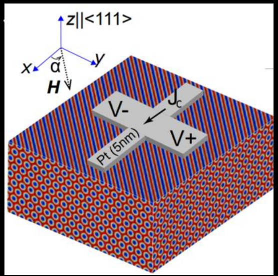
$$R_T^{SMR} = A \sin 2(\alpha - \phi)$$

$$R_T^{SMR} = \underbrace{a\, m_x m_y}_{1} + b\, (\underbrace{m_z \partial_y m_x - (\partial_y m_z) m_x}_{2})$$

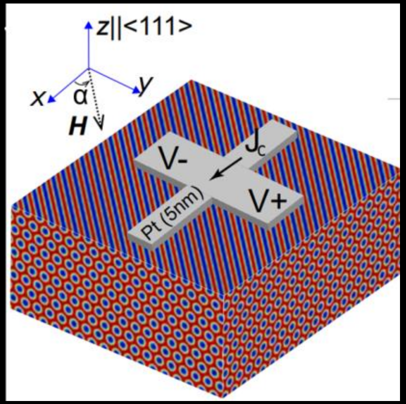
1. Sensitive to **uniform tilting,** largest SMR for ϕ = 0
2. detects **spatial variation** (e.g., tight spiral, skyrmions)

SMR sensitivity to **twisting of *M*** & **spatial textures**

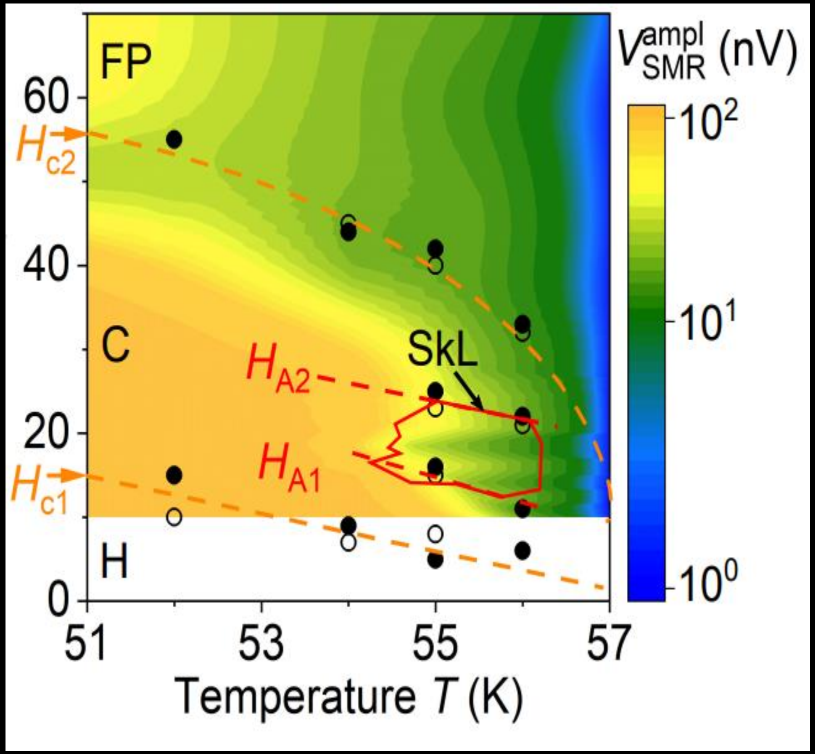


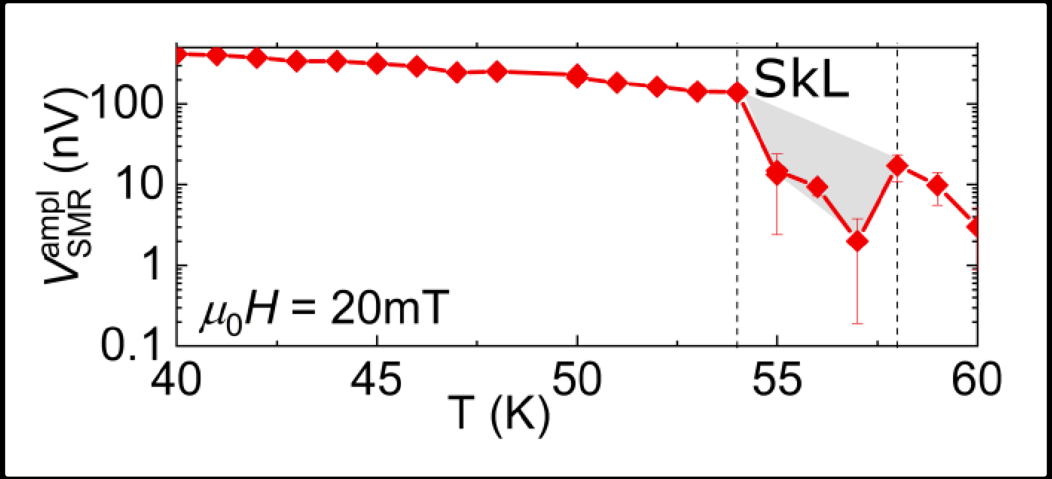


SMR in Pt/Cu_2OSeO_3 within {111} plane



Amplitude SMR





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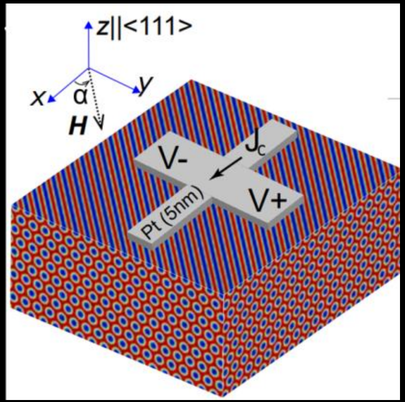

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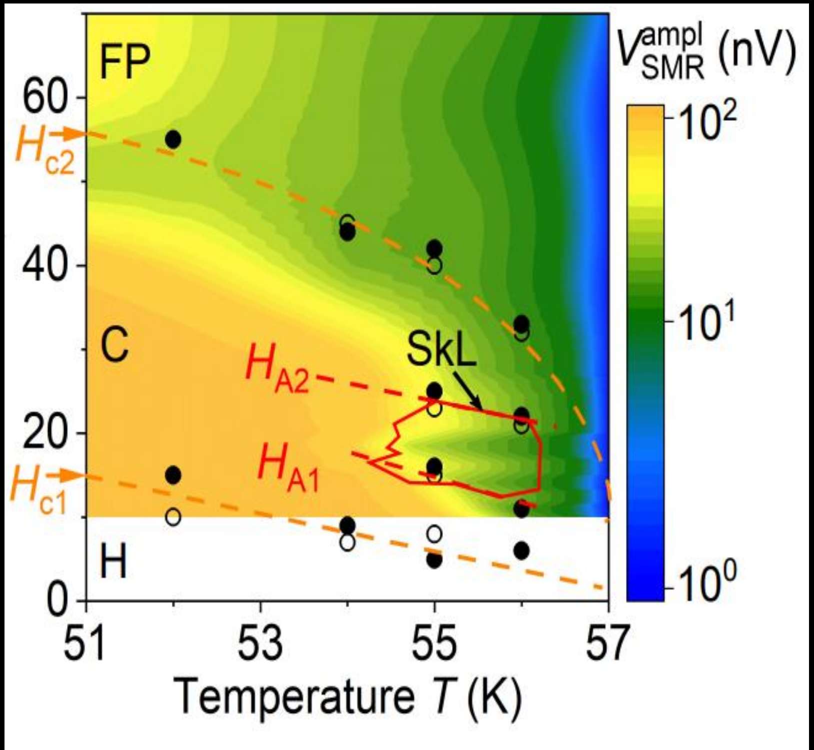
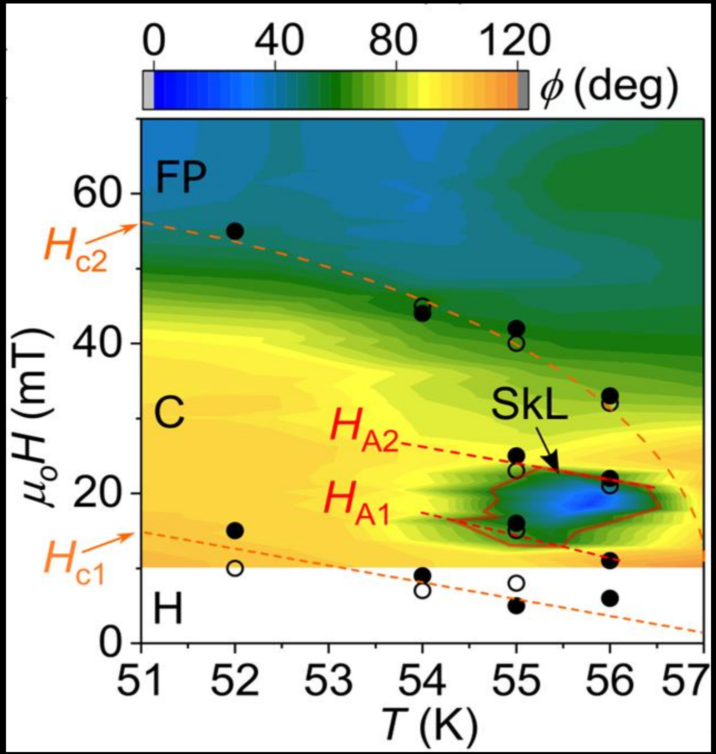
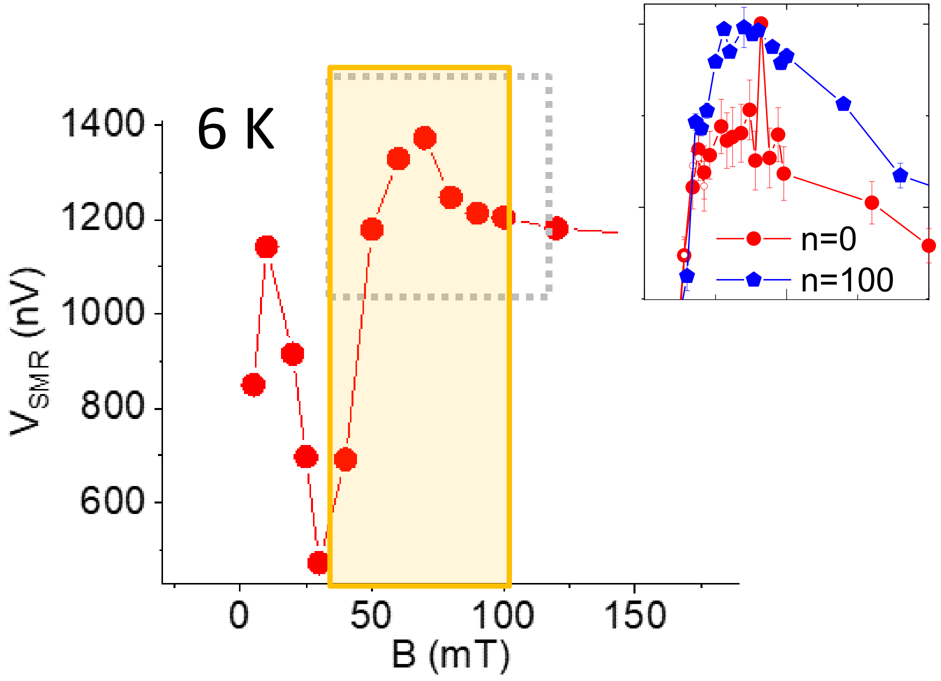
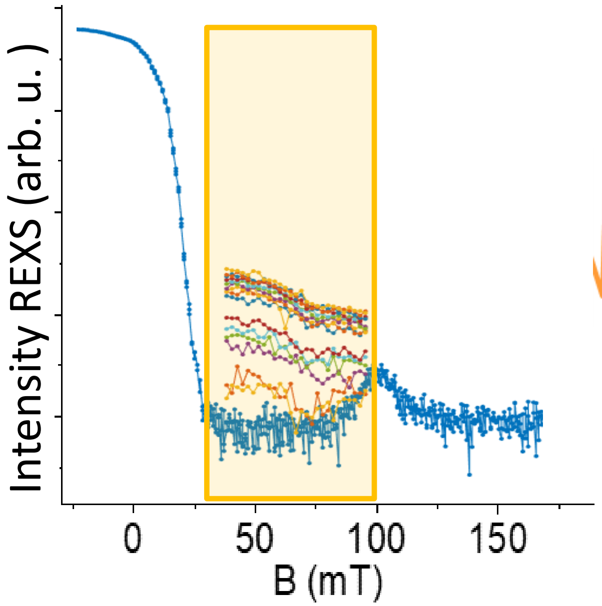


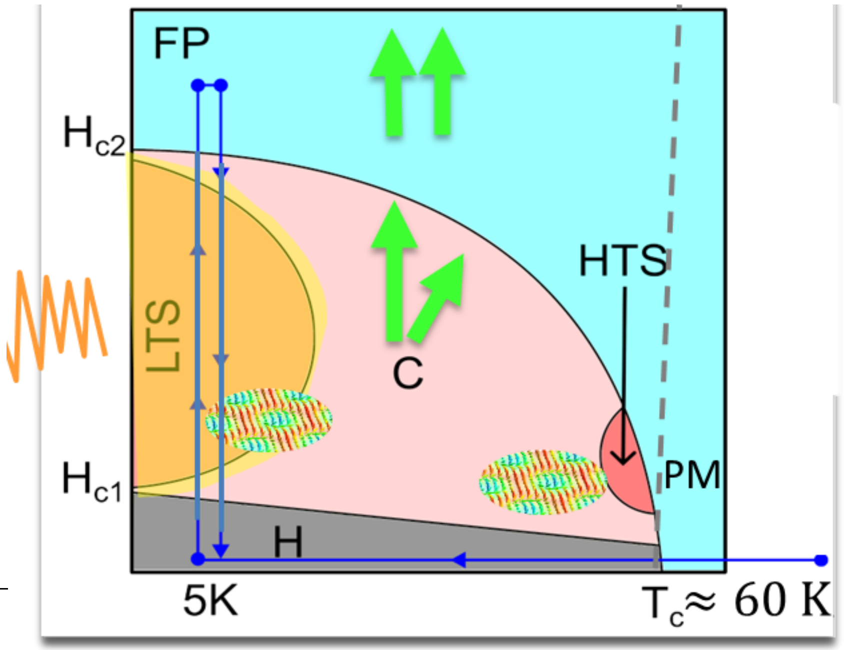
Phase SMR



SMR in Pt/Cu_2OSeO_3 within {001} plane







SMR Sensitivity and Compact Magnetic Structures

Perspective materials with strong SMR signals due to small spin structures

$$R_T^{SMR} = a\, m_x m_y + b\,(m_z \partial_y m_x - (\partial_y m_z) m_x)$$

Smaller spiral pitch → large SMR
Smaller damping → small spin scattering → large SMR

Lacunar Spinels – *GaV_4S_8* / *GaV_4Se_8*
→ Néel-type skyrmions (~10–20 nm)

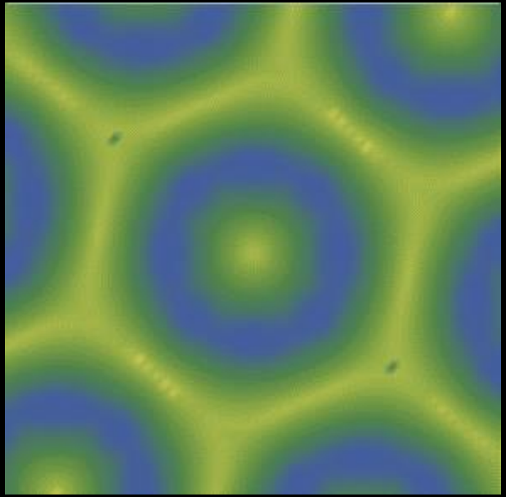
Delafossites – e.g., *$CuFeO_2$*
→ Short-period spiral magnetic order due to frustration

Kézsmárki et al., Nat. Mater. **14**, 1116 (2015)
Seki et al., Phys. Rev. Lett. **103**, 237601 (2009)

Summary

Skyrmion dynamics in LTS

Cu_2OSeO_3 $\alpha \approx 10^{-4}$, 4K



$K > 0$

Skyrmion detection by SMR