Resonant dynamics of skyrmion lattices in thin film multilayers: Localised modes and spin wave emission

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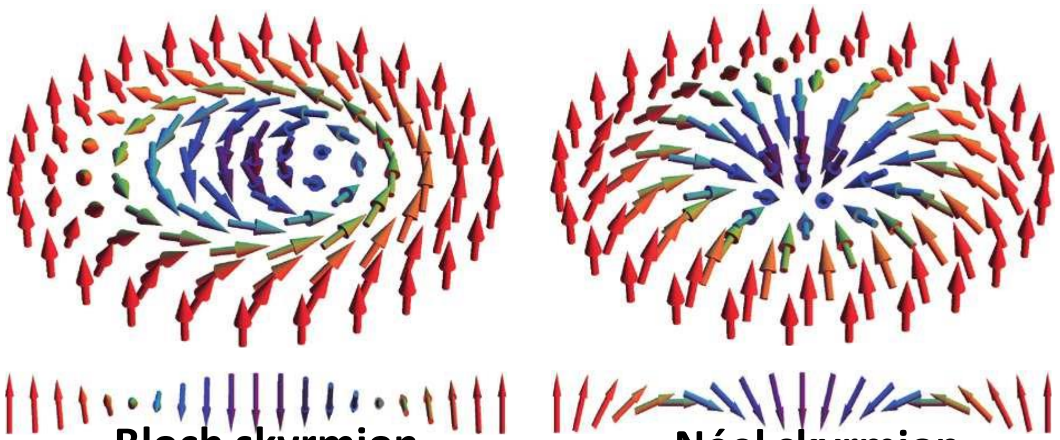
Introduction



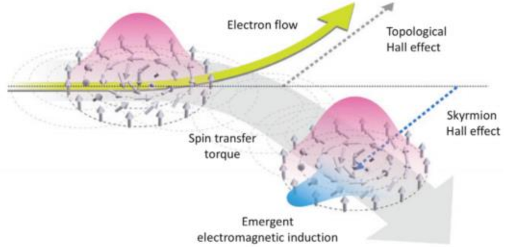
Bloch skyrmion
Bulk systems

Néel skyrmion
Thin-film systems

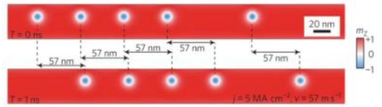
Topological charge $S = \frac{1}{4\pi}\int \vec{m}.\left(\frac{\partial \vec{m}}{\partial x} \times \frac{\partial \vec{m}}{\partial y}\right) \mathrm{dxdy} = 1$

Mainly stabilized by ***Dzyaloshinskii-Moriya interaction***

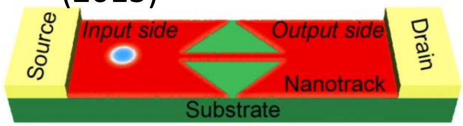
DC current driven dynamics ✓



Skyrmion racetrack memory
Fert *et al.*, Nat. Nanotech. **8**,152 (2013)



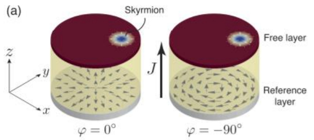
Logic gates
Zhang *et al.*, Sci. Rep. **5**,9400 (2015)



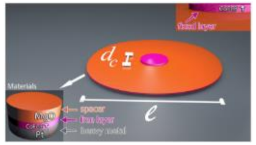
Microwave response ?

Skyrmion eigen modes

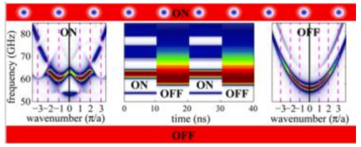
Spin-torque oscillator
Garcia-Sanchez *et al.*, N. J. P. **18**,075011 (2016)



Microwave detectors
Finocchio *et al.*, App. Phys. Lett. **107**,262401 (2015)

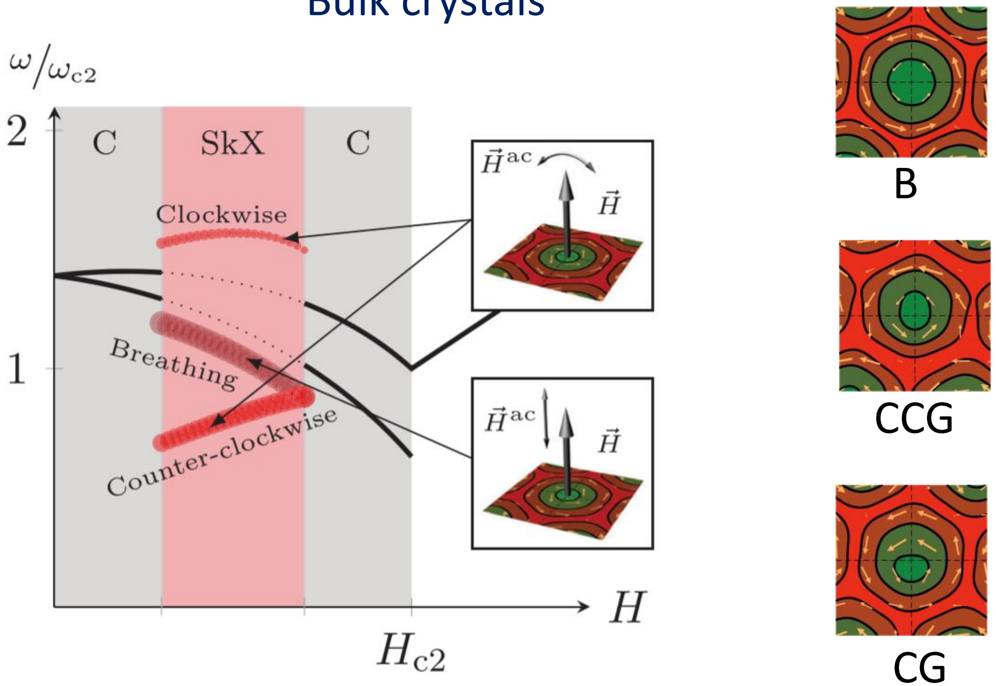


Dynamic magnonic crystal
Ma *et al.*, Nano Lett. **15**,4029 (2015)



Theoretical studies

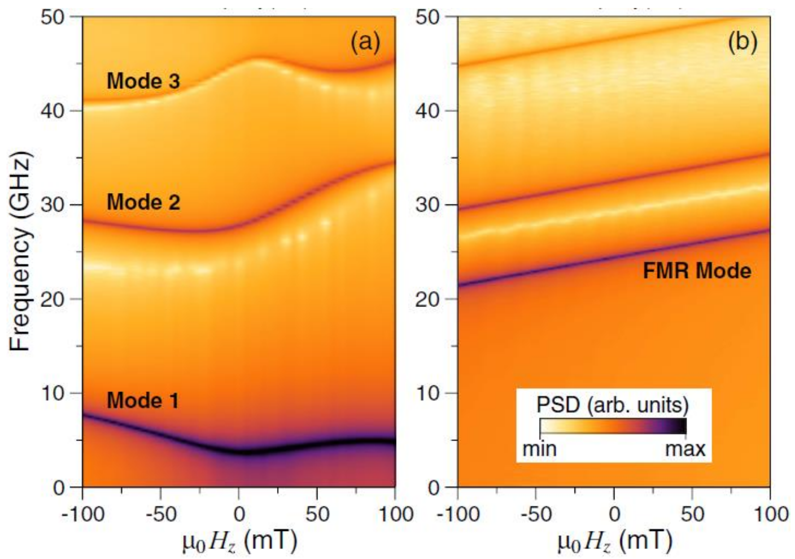
Bulk crystals



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

- Example: B20 cystals
- Bulk DMI
- Bloch skyrmion lattice
- No geometrical confinement

Thin film system

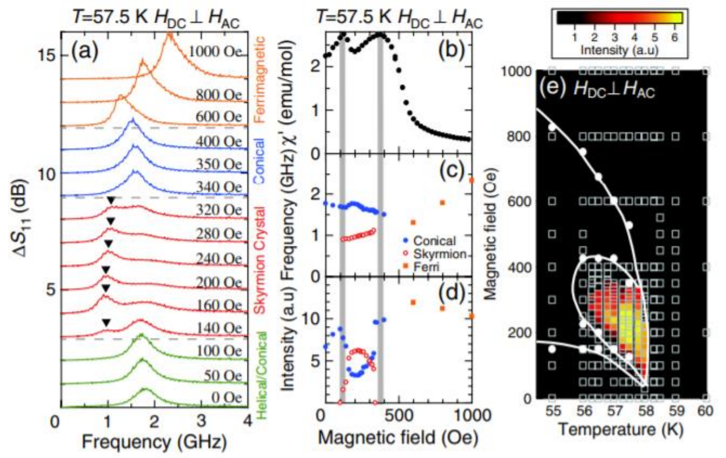


J-V. Kim *et al.* PRB **90**, 064410 (2014)

- Example Heavy metal/Ferromagnet/Non magnet
- Interfacial DMI
- Single Neel skyrmions
- In confined geometries

Experimental observations

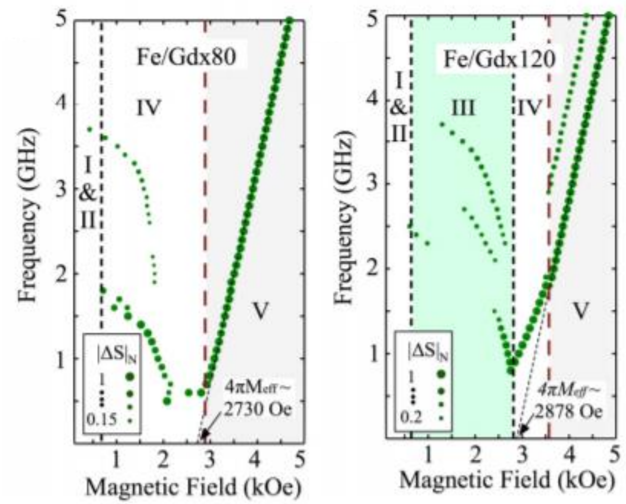
bulk DMI, low temp, Bloch skyrmions



Cu_2OSeO_3

Onose *et al.* PRL **109**, 037603 (2012)

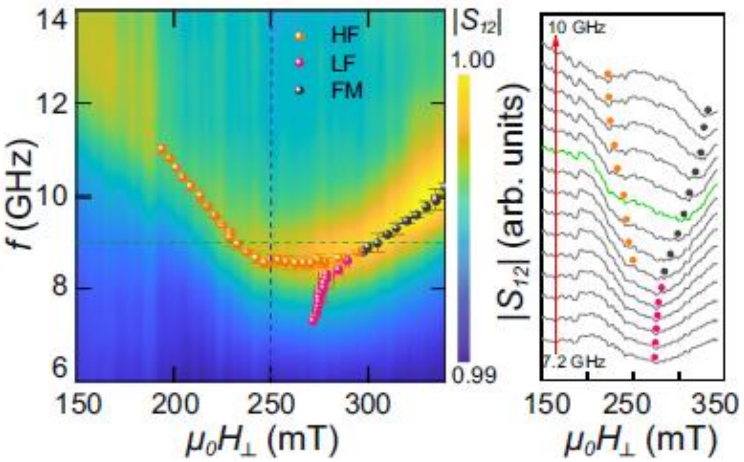
no DMI, low temp, 'dipole skyrmions'



$[Fe/Gd]_{120}$

S. A. Montoya *et al.* PRB **95**, 224405 (2017)

iDMI, Néel skyrmions, high damping



$[Ir/Fe/Co/Pt]_{20}$

B. Satywali *et al.* Nat. Commun. **12** (2021),

- Experimental demonstrations of skyrmion modes in B20 systems at low temperatures.
- Very few experiments in the case of thin film multilayers.
- Difficult to observe in thin film multilayers with iDMI due to high damping.

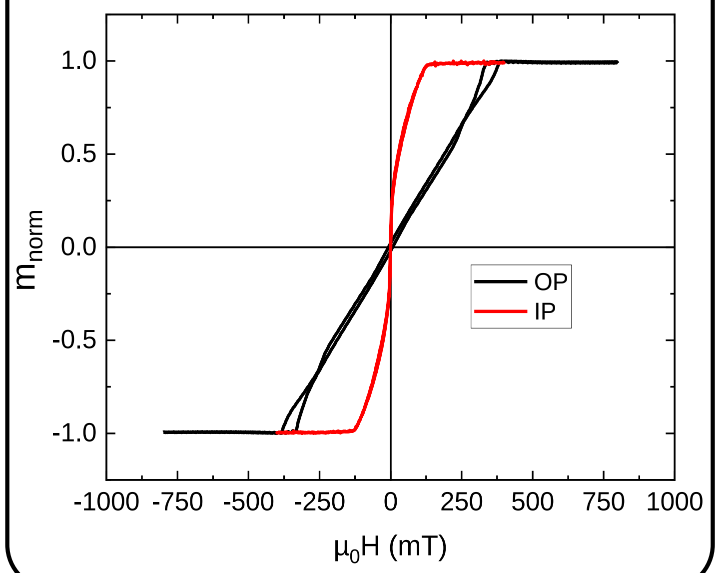
To study the skyrmion eigen modes in thin film systems : sufficient iDMI + reduced damping

Outline

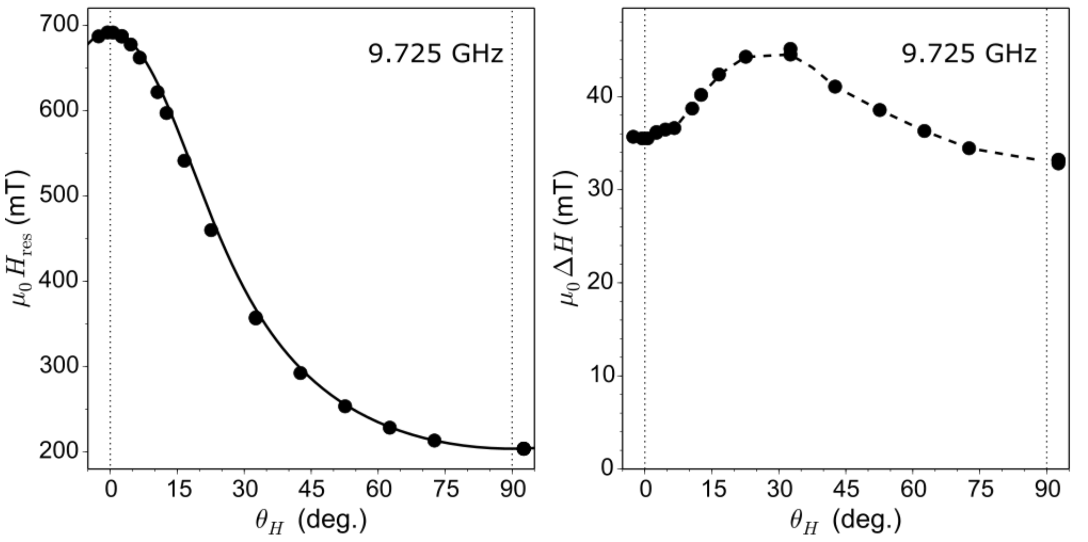
- Sample
- Static Properties : MFM
- Dynamic Properties : VNA-FMR
- Micromagnetic Simulations using μmax3

Sample and its characteristics

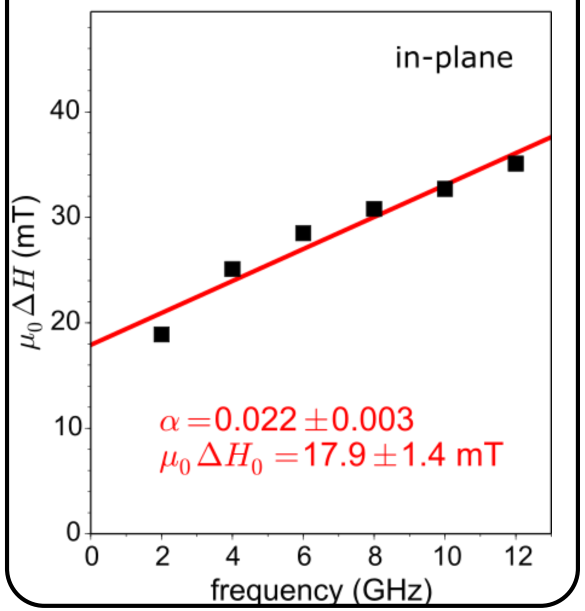
AGFM/SQUID: Hysteresis

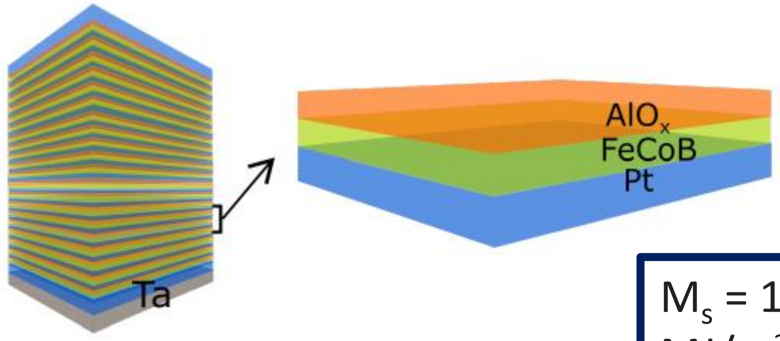


Cavity FMR



Broadband FMR

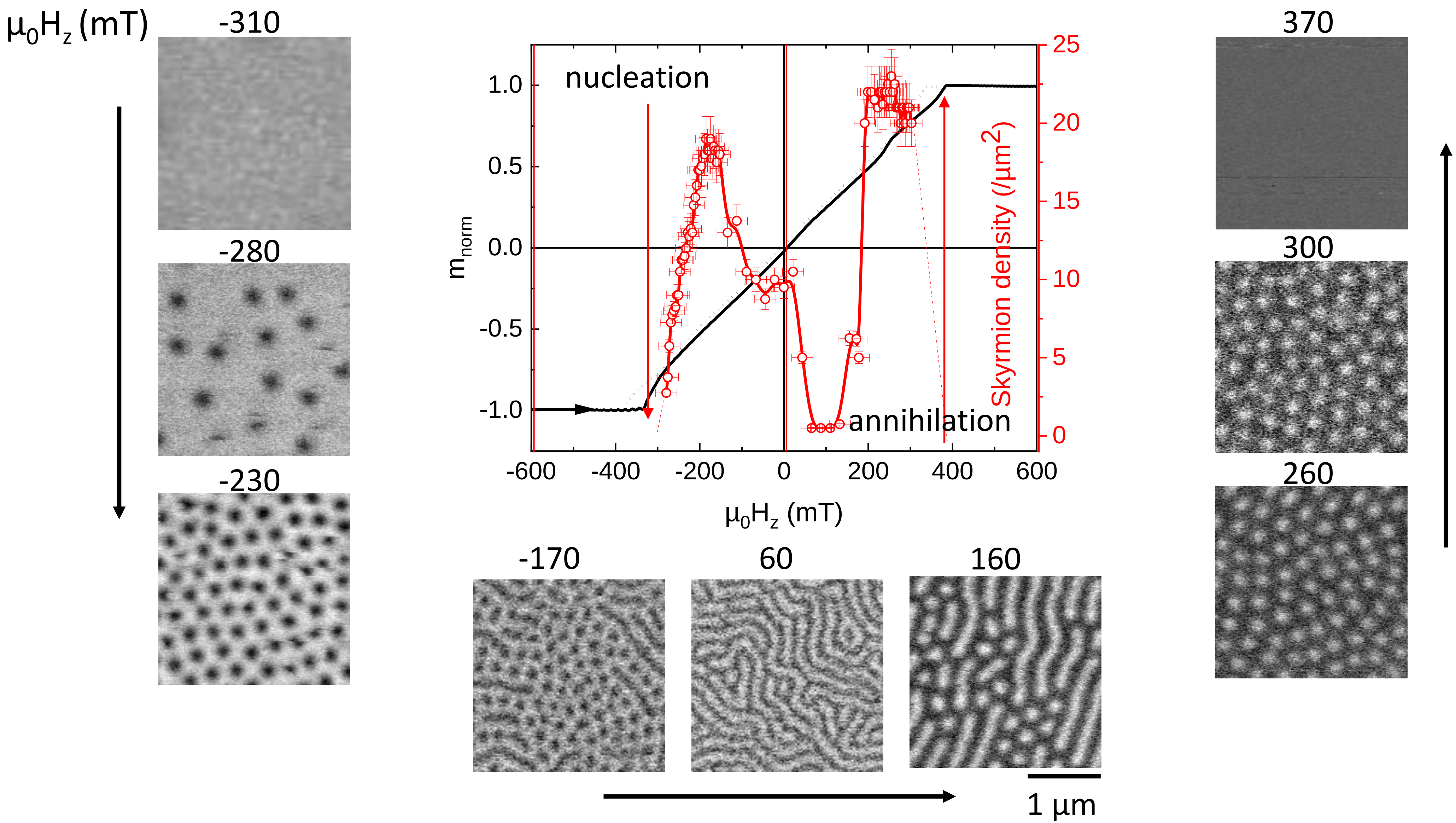




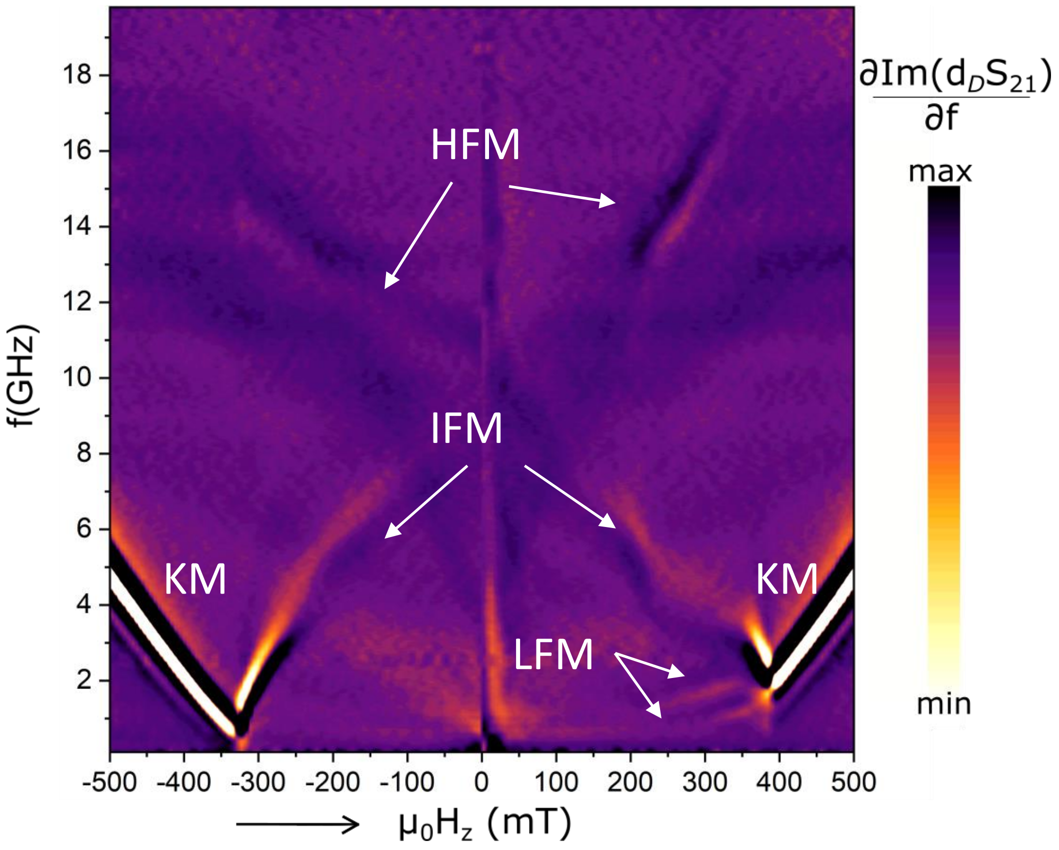
M_s = 1.2 MA/m, $\gamma_0/2\pi$=28.74 GHz/T, K_u = 0.7 MJ/m^3, α =0.02, D = 1.2 mJ/m^2, A = 15 pJ/m

- Optimisation: tuning of Pt and FeCoB thicknesses, no. of repetitions
- low damping, large magnetic volume → high signal-to-noise (SNR) ratio expected

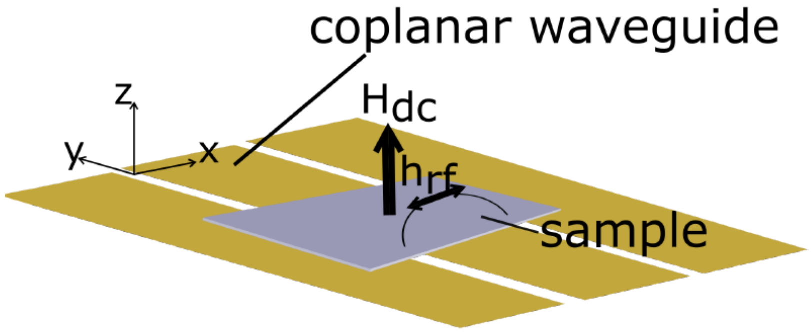
Quasi-static magnetic properties: MFM



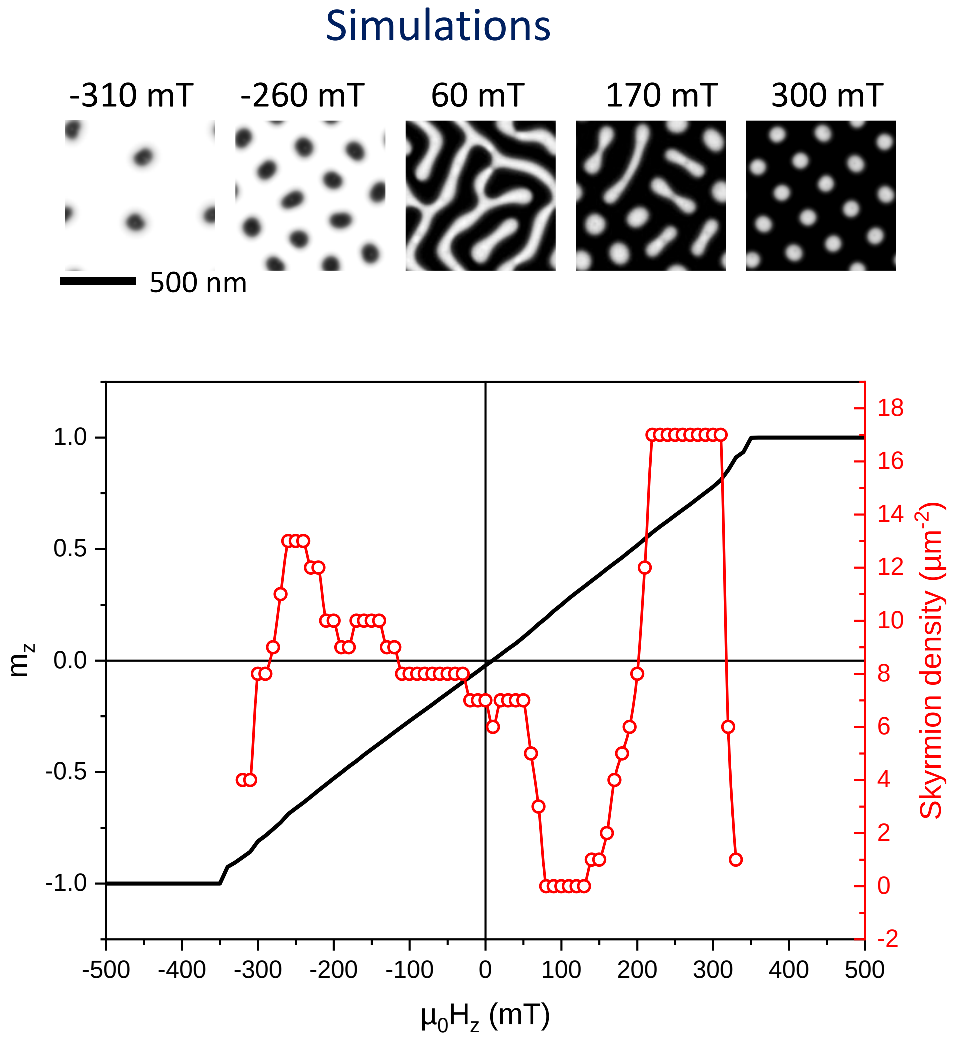
Dynamic properties: VNA-FMR

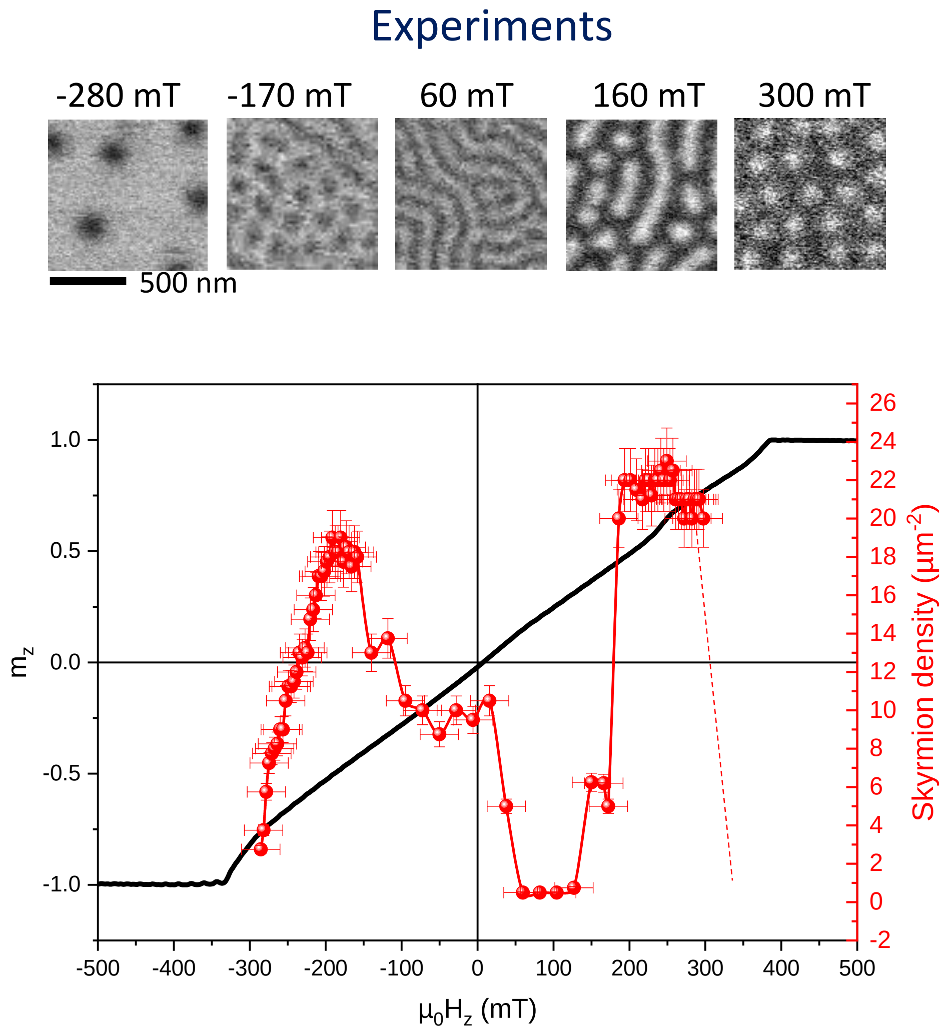


- Kittel (uniform) mode above saturation:
  $f = \frac{\mu_0 \gamma}{2\pi}(H - H_{eff})$
- **Distinct spectral response** at both **high and low frequencies** in the **non saturated state**
- Left and the right branches slightly asymmetric



Micromagnetic simulations: Static properties

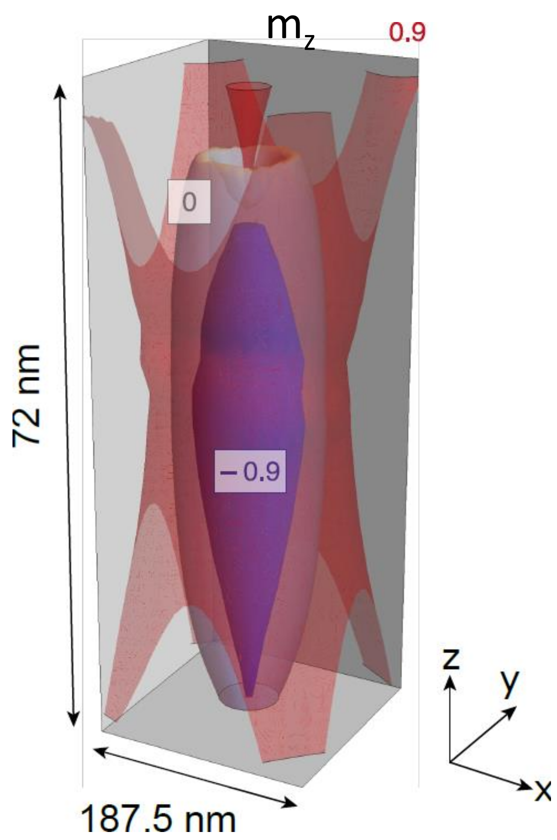


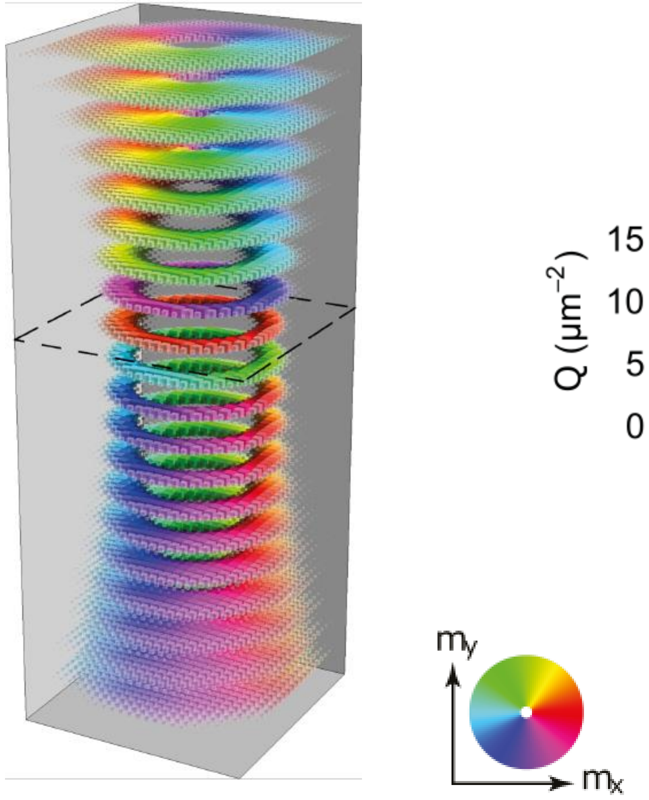


- The entire 20 layer repetition is modeled and periodic boundary condition used in the x and y direction used to mimic an extended film
- Good correlation between the simulated and experimental data

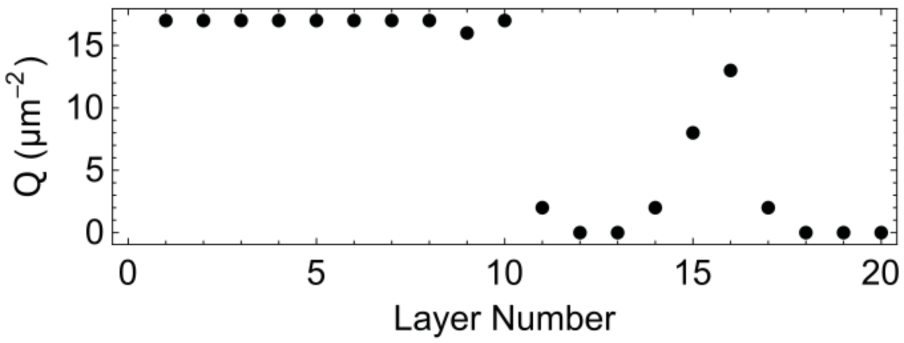
Micromagnetic simulations: 3D structure of skyrmions

$\mu_0 H_z$= 250 mT





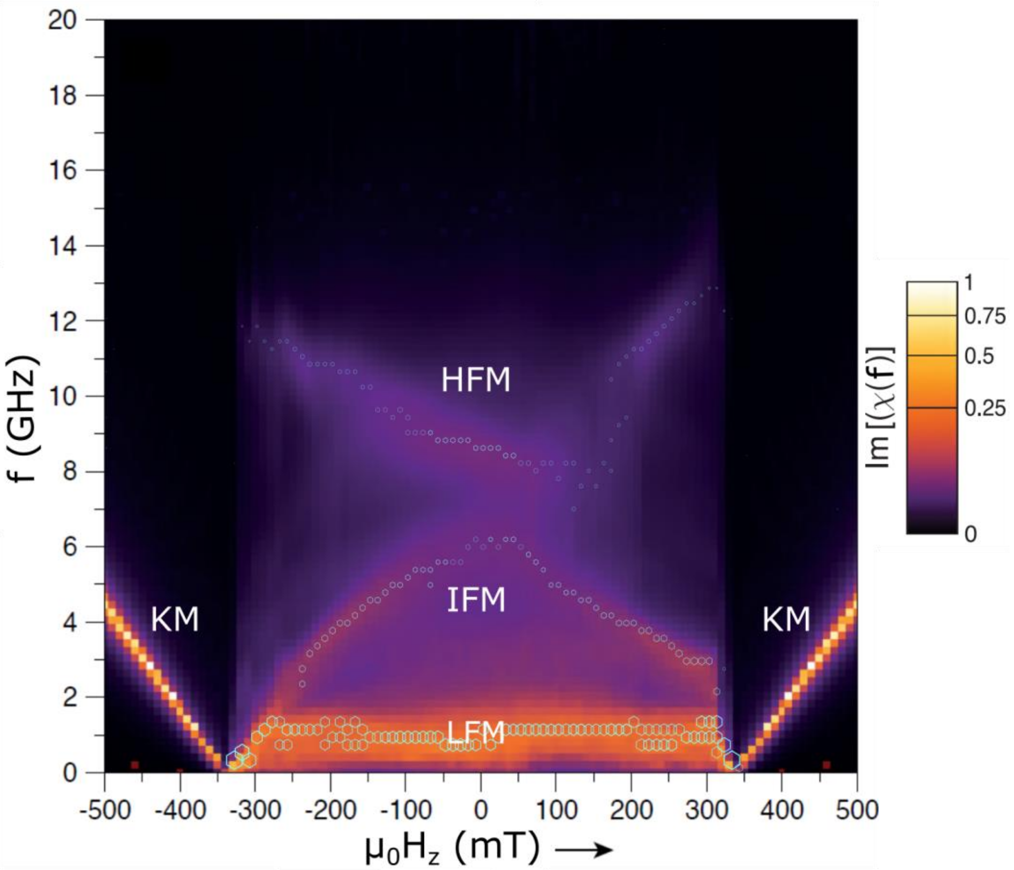
Surface topological charge density



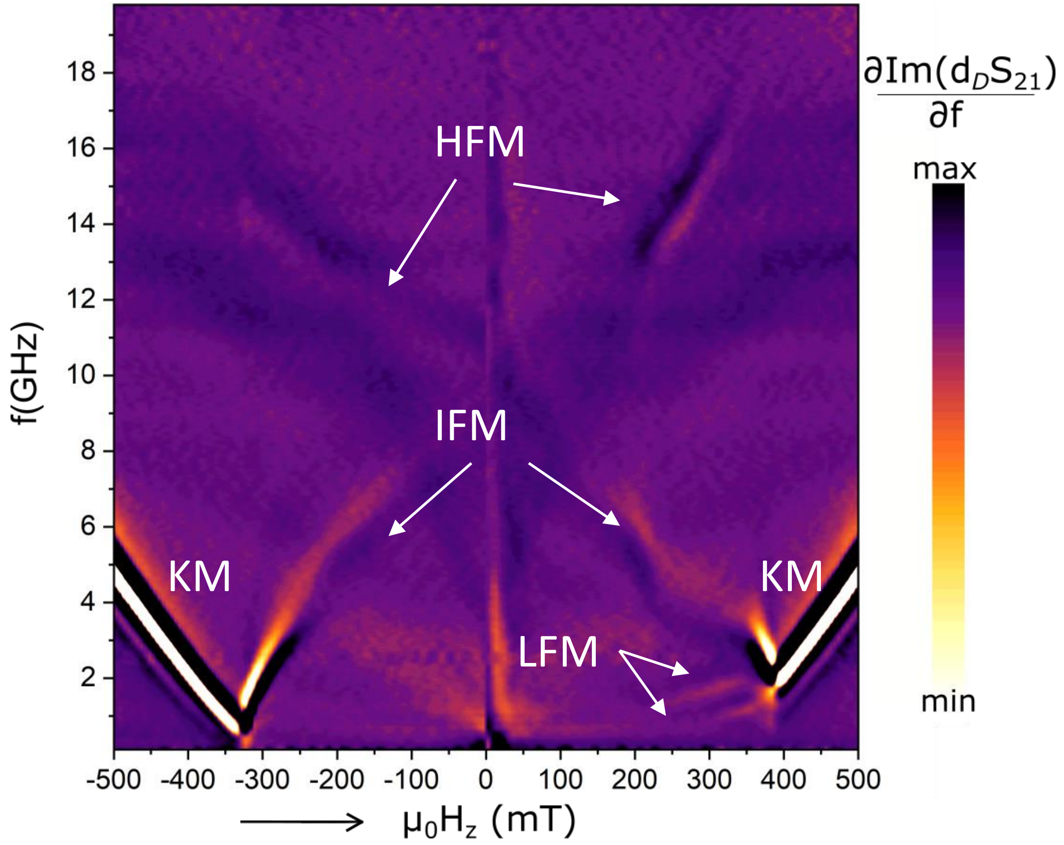
- Dipolar interactions maintain an alignment of the core centre but too weak to promote a coherent magnetization profile.

Micromagnetic Simulations: Dynamics

Simulations

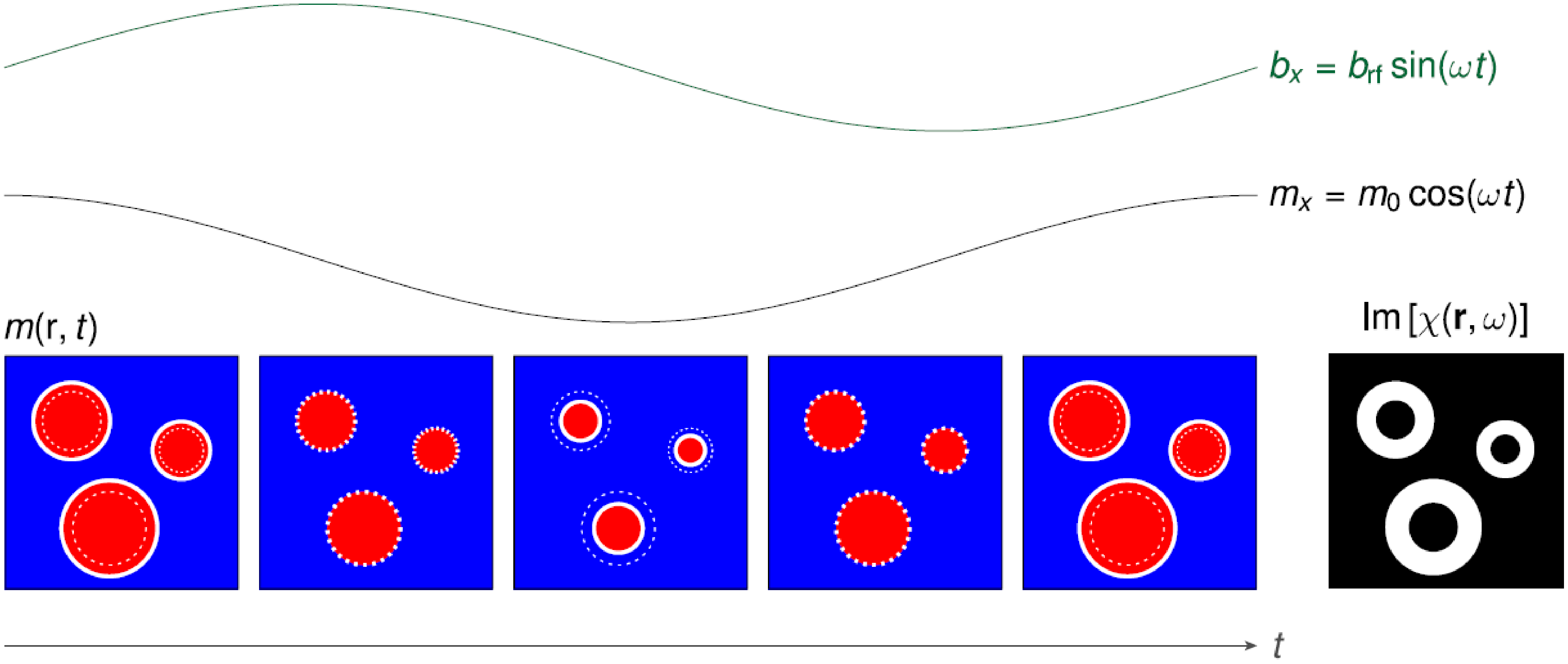


Experiments



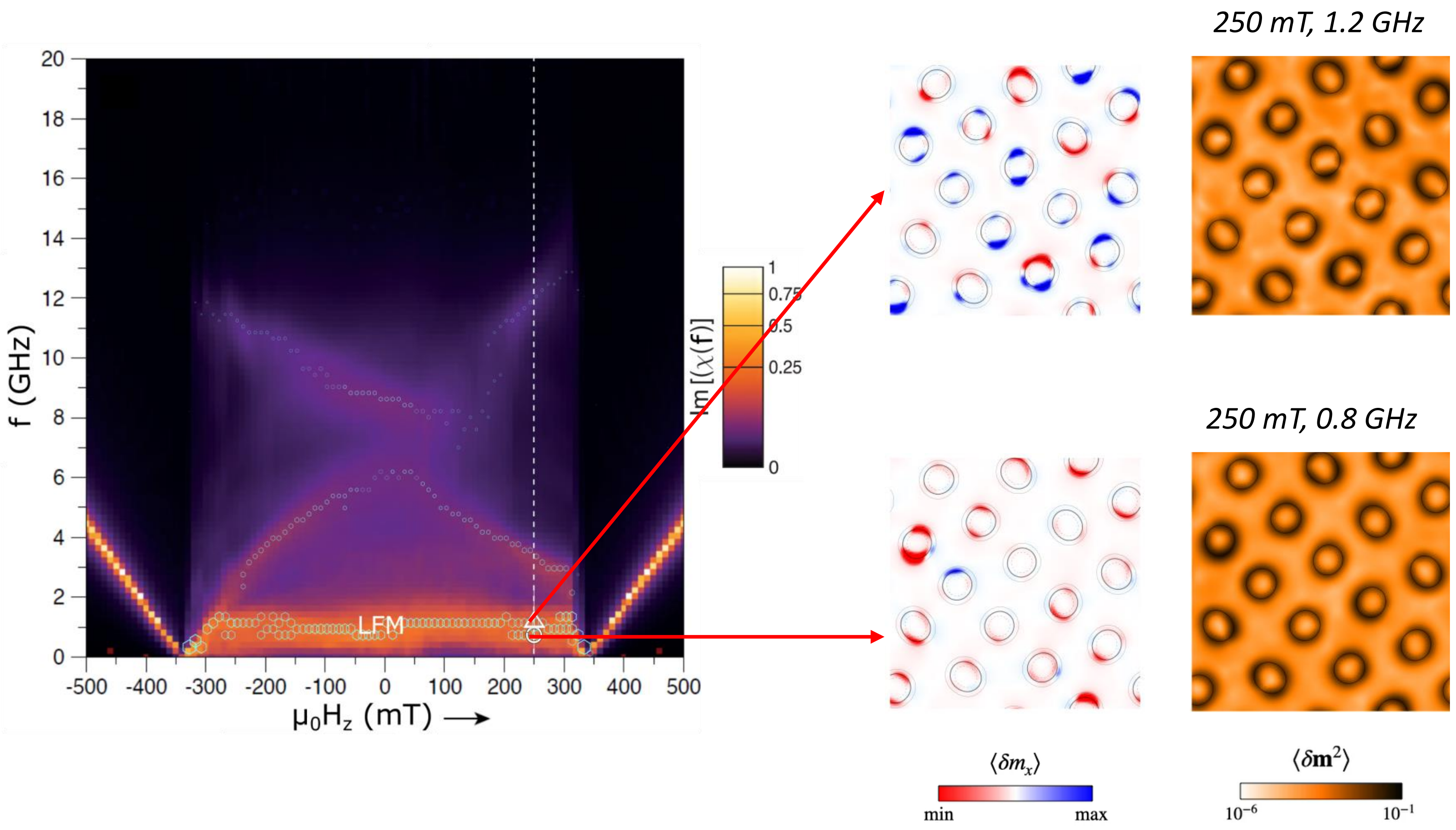
- Resonant excitation
- For each field value a simulated static magnetization profile is excited with a sinusoidal field over a range of frequencies and magnetization is recorded.
- Simulation results coherent with the experiments

Micromagnetic Simulations: Mode profile estimation



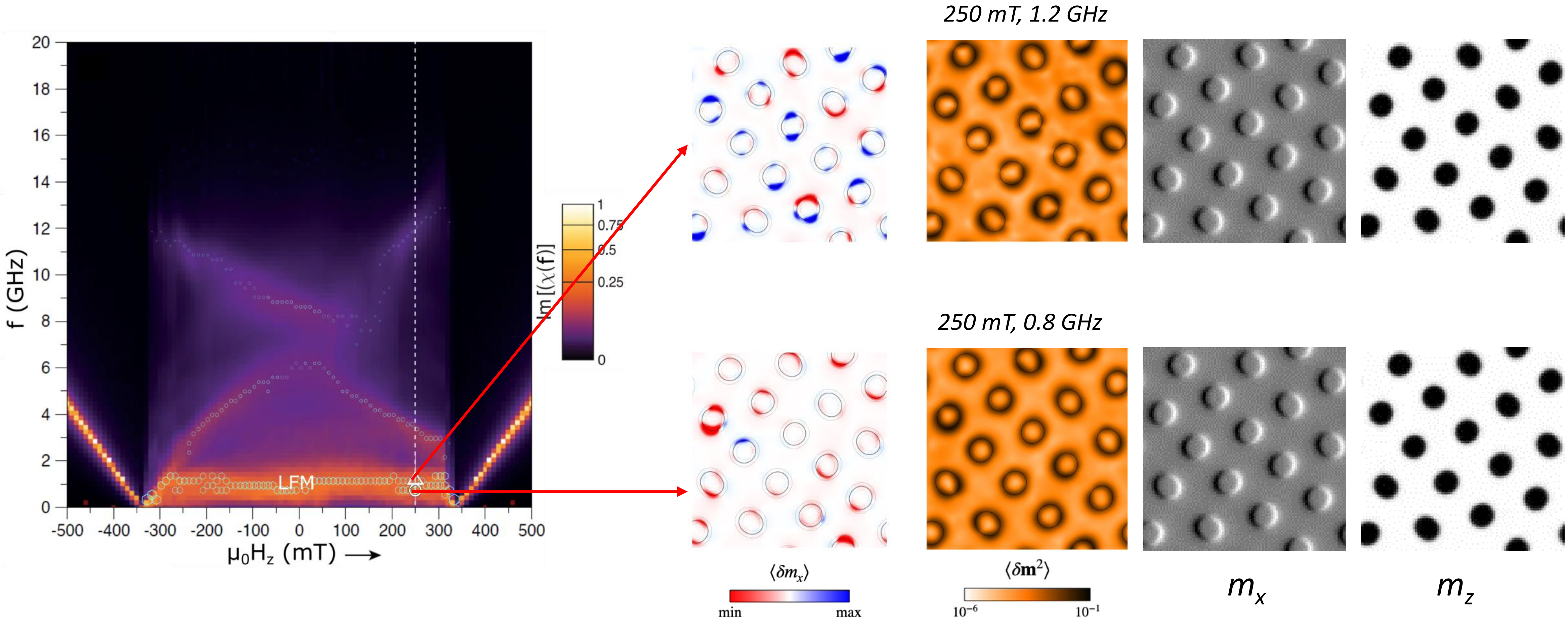
Estimate mode profile at given (resonance) frequency (f) by driving at that frequency (f) and recording cell by cell the components of magnetization *m* stroboscopically.

Micromagnetic Simulations: Mode profile estimation



- Low frequency mode (< 2 GHz) features localized skyrmion edge modes : 1.2 GHz subsequent azimuthal harmonics of the one at 0.8 GHz

Micromagnetic Simulations: Mode profile estimation



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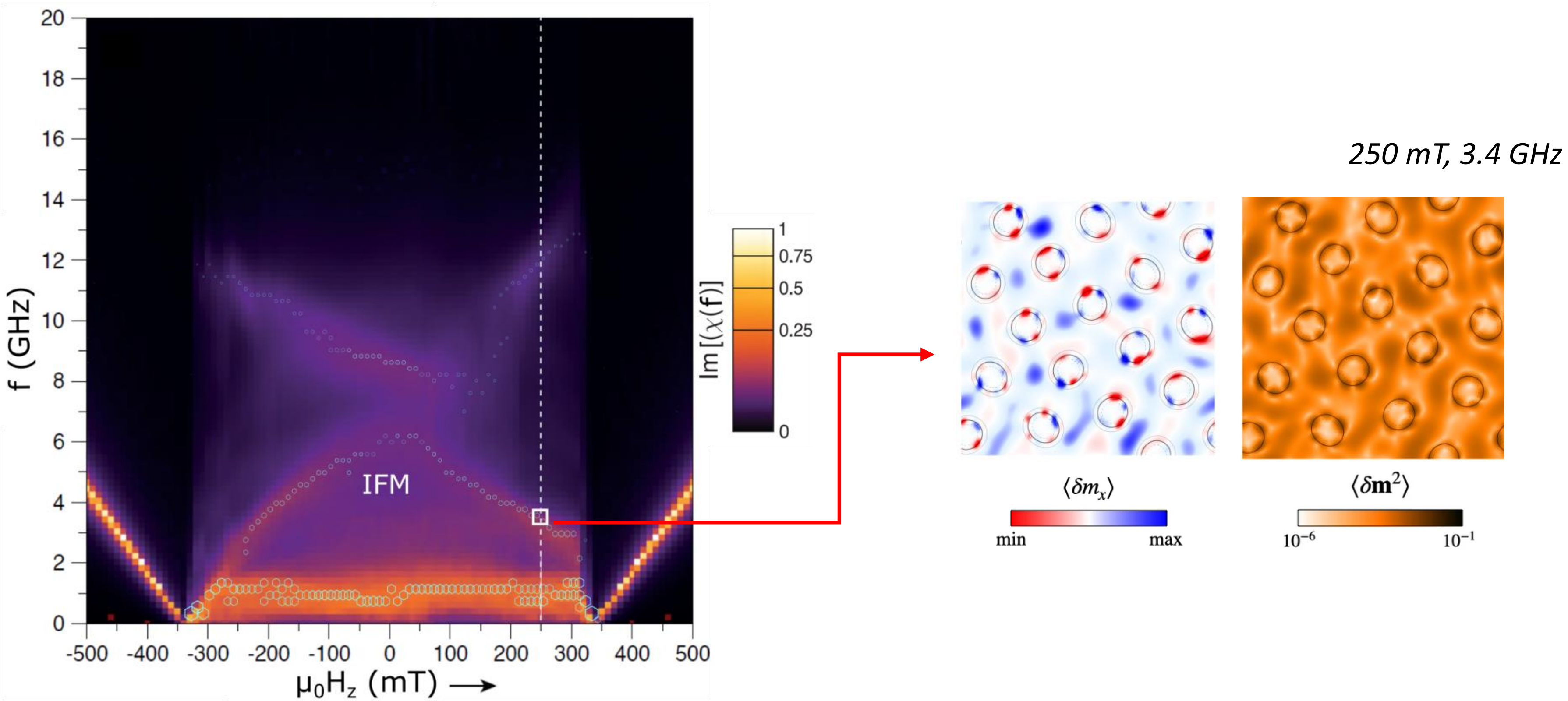
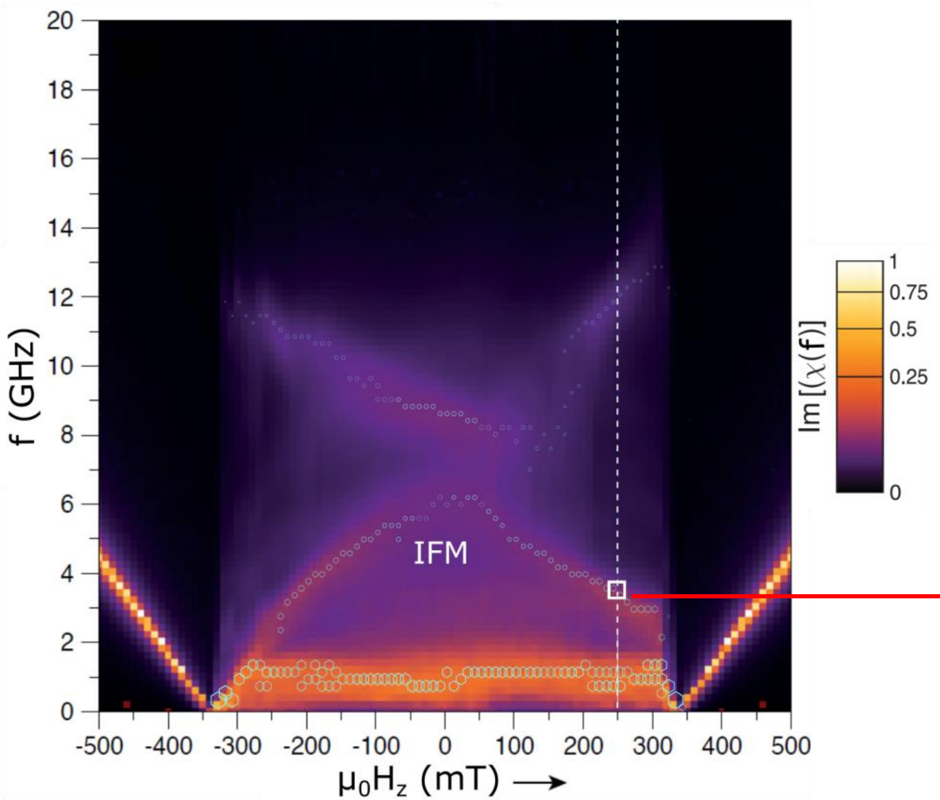
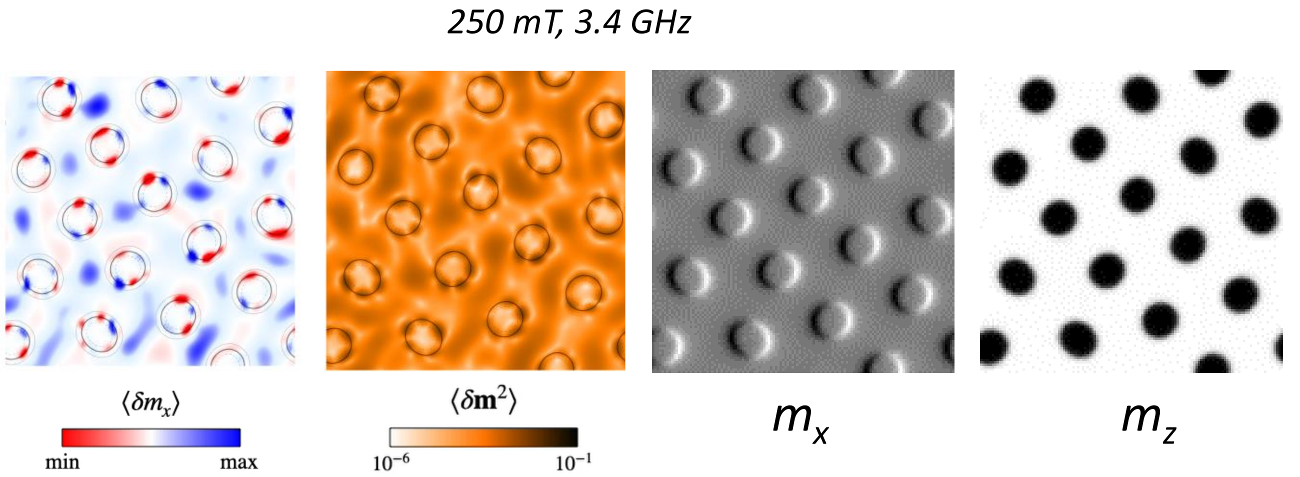


- Middle frequency mode (< 6 GHz) features background domain resonances (parallel to applied field) and (domain wall) channelled spin wave modes.

Micromagnetic Simulations: Mode profile estimation





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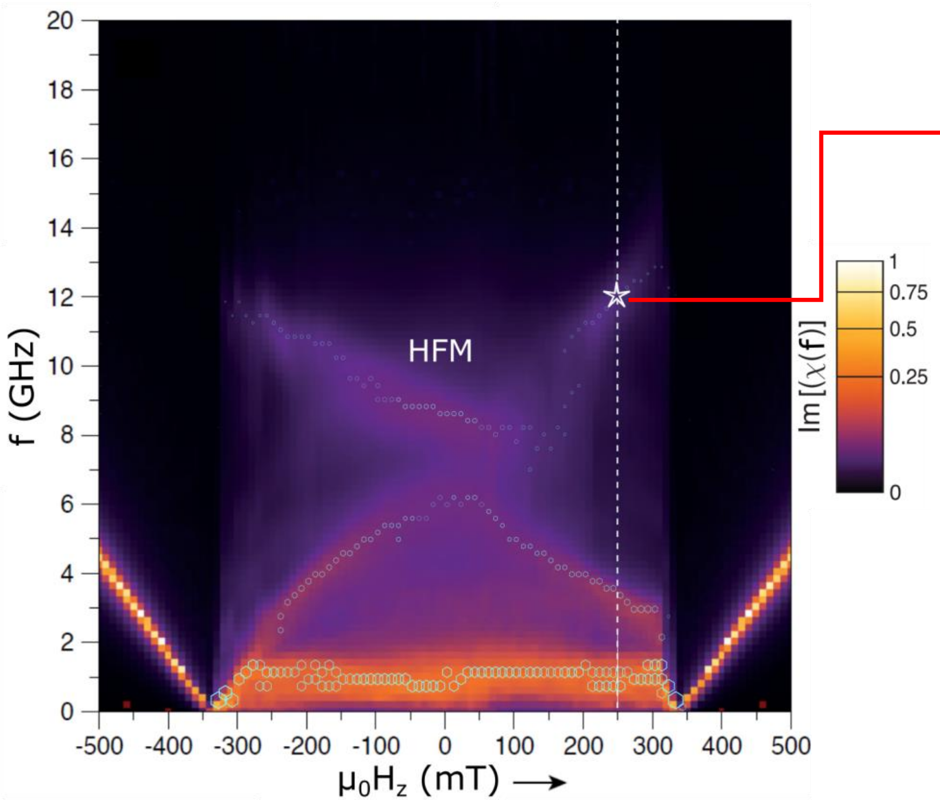
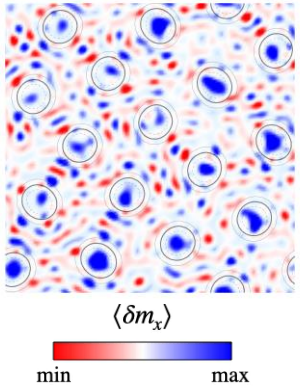
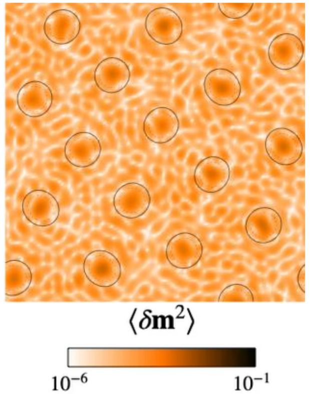
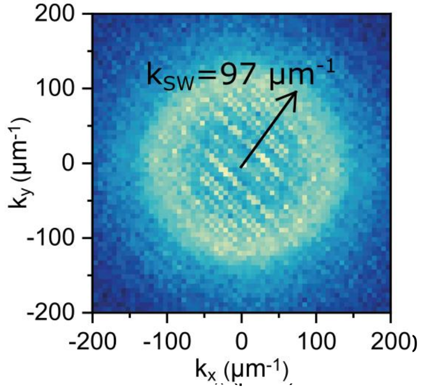
Micromagnetic Simulations: Mode profile estimation

250 mT, 12 GHz

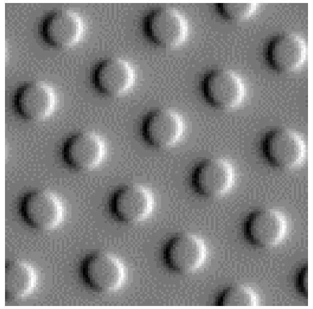




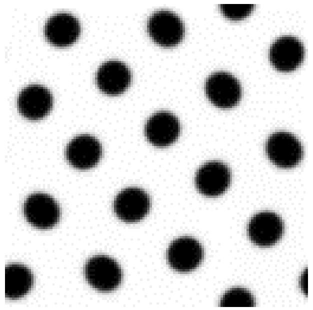




Layout averaged spatial FFT



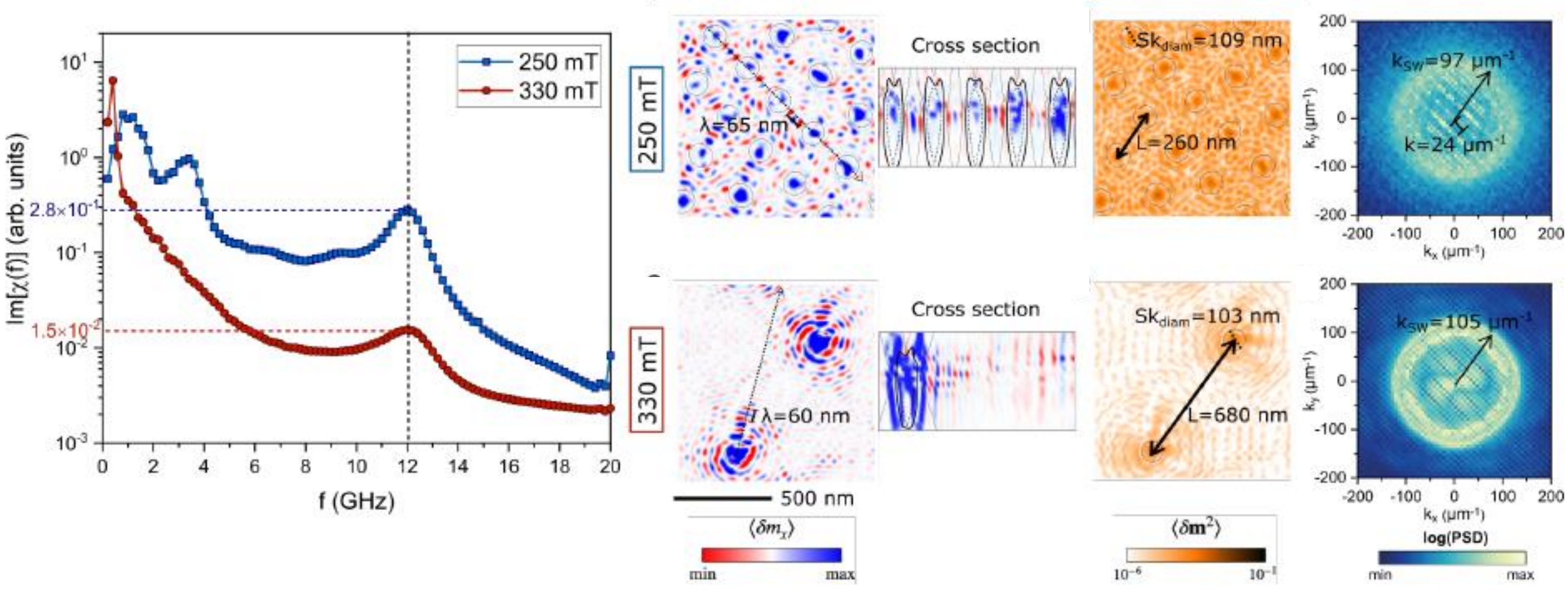
m_x



m_z

- High frequency mode (> 10 GHz) corresponds to the in phase precession of the reversed magnetisation localised within the skyrmion cores, whose typical size lies in the 100 nm range.
- Emission of spin waves into the surrounding uniformly magnetised background. SWs in the exchange dominated regime of wavelength : 50 nm
- Skyrmions act as SW transducers

Isolated skyrmions vs Skyrmion lattice

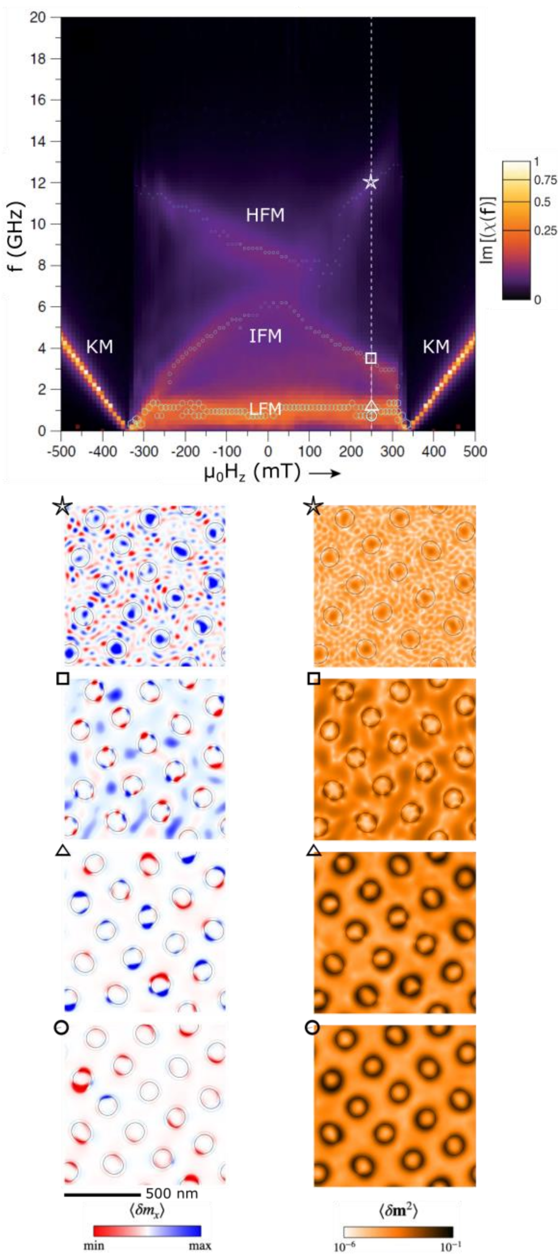


- In the two cases, resonance comes from the in-phase precession of the skyrmion cores. It is a fundamental mode
- In the case of skyrmion lattice, the spin waves emitted by the precessing skyrmions can lead to constructive/destructive interferences

Summary

- Optimized Pt/FeCoB/AlOx multilayers with iDMI and **low damping**
- **Complete quasi-static magnetization profile study** using MFM
- VNA-FMR measurements reveal:
  - Kittel modes in the saturated region
  - **Distinct spectral response at low and high frequencies in the skyrmion lattice zone**
- Simulations reproduce well the static and the dynamic properties
- Three orders of resonances identified in the skyrmion lattice state: LFM, IFM and HFM
- LFM: skyrmion edge mode, IFM: background resonance + spin wave channelling
- HFM : skyrmion core precession accompanied by omnidirectional ultra-short wavelength spin wave emission. Skyrmions behave as transducers
- Interference of SWs in skyrmion lattices

For more information: T. Srivastava *et al.* arXiv:2111.11797



Thank you

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