Exploring spin waves and complex magnetic textures with scanning NV microscopy

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Team Solid-State Quantum Technologies (S2QT)

CNRS and Université de Montpellier, Montpellier, France

SQLM Workshop, September 24th, Kaiserslautern

slides available at `https://magimag.eu`

The team

https://solidstatequantumtech-l2c.fr/

SOLID STATE Quantum technologies

Quantum sensing

Isabelle Robert-Philip
Vincent Jacques

Scanning NV

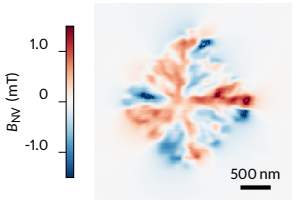
Elias Sfeir
Carolin Schrader
Roméo Beignon
Elijah Wane

V_B^- in hBN

Tristan Clua-Provost
Jessica Tournaud

Outline

Whirling magnetic textures



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A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

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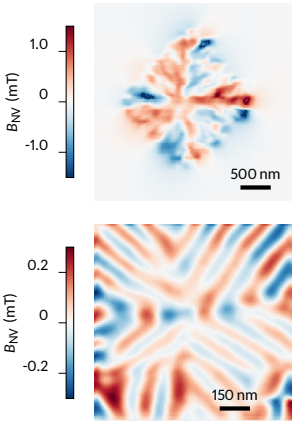

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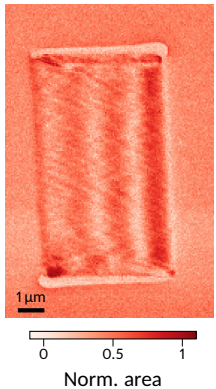
Imaging of spin waves



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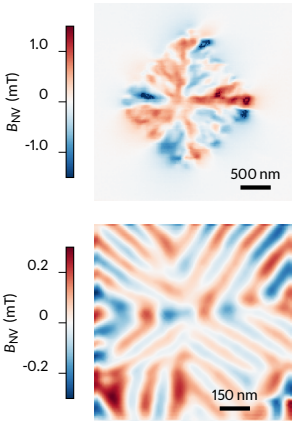

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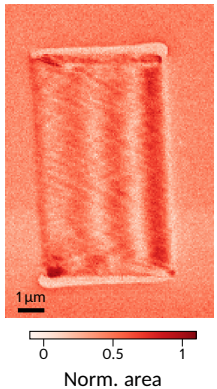

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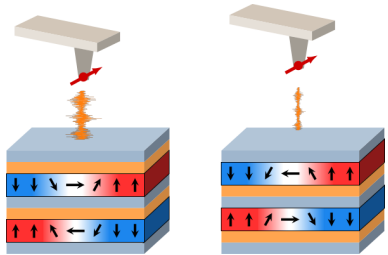
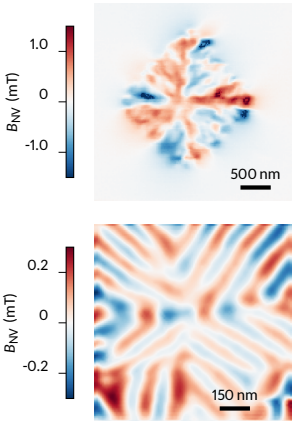
Spin wave noise to probe magnetic handedness



A. Finco *et al.* *arXiv:2502.03166* (2025)

Outline

Whirling magnetic textures



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Effect of confinement in Fe_5GeTe_2?

11.8 nm-thick film grown by MBE with 3 nm-thick Al capping

M. Ribeiro *et al.* *npj 2D Mater. Appl.* 6 (2022), 10

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SPIN IN ELECTRONICS

Jules Courtin, Céline Vergnaud
Matthieu Jamet, Frédéric Bonell

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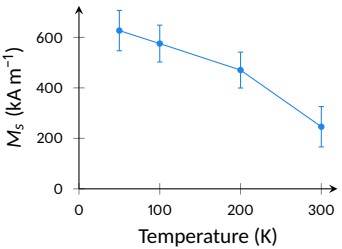
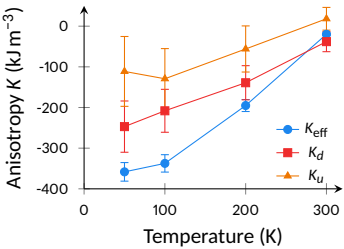
Macroscopic characterization





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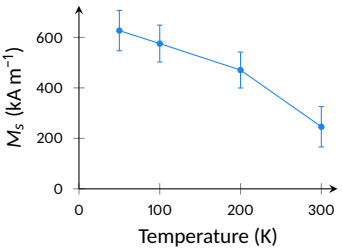
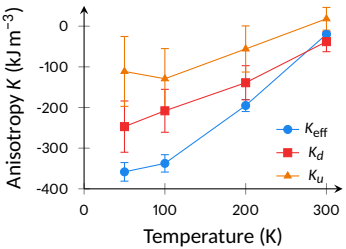
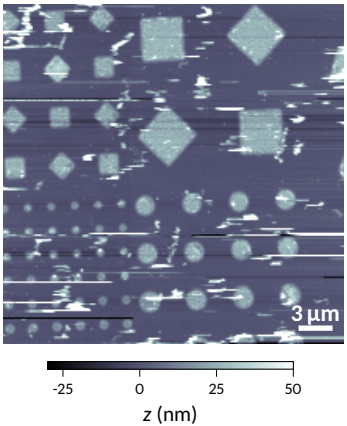
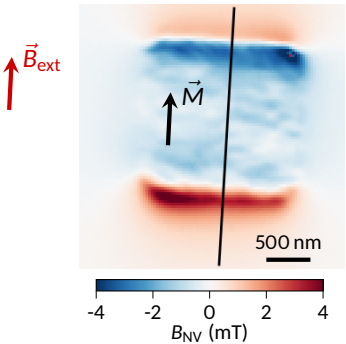


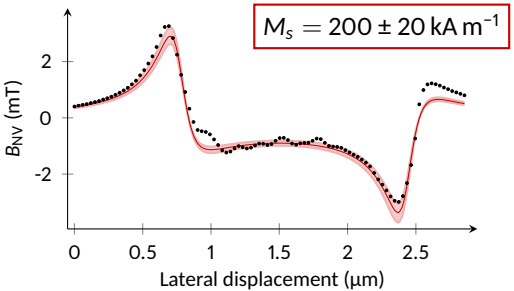


AFM scan



Measurement of the saturation magnetization





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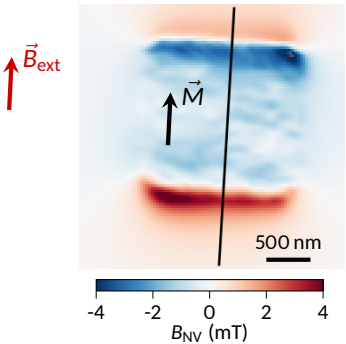
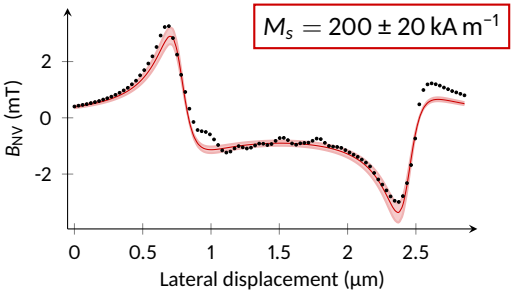
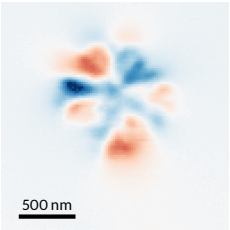


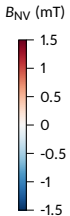


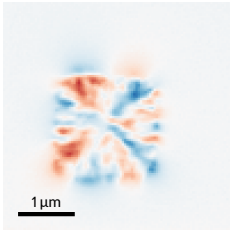
No effect of confinement on M_s → no change of T_C

E. Sfeir *et al.* *arXiv:2507.03454* (2025)

Vortices in micro-squares







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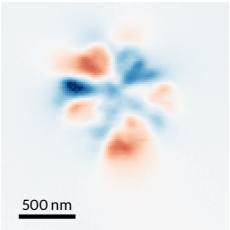
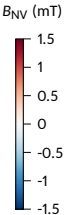
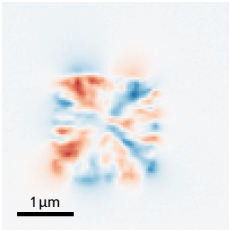
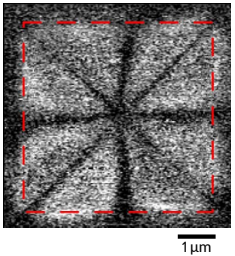






Early NV data on vortices in Py



L. Rondin *et al.* *Nat. Commun.* 4 (2013), 2279

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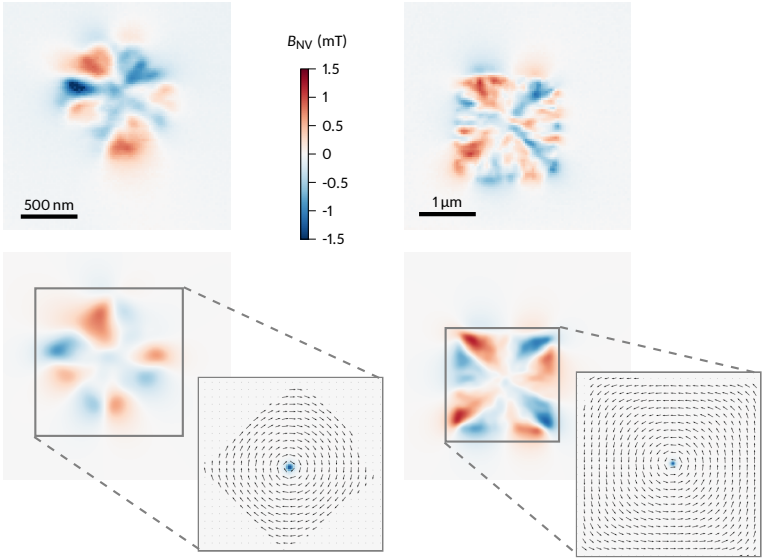

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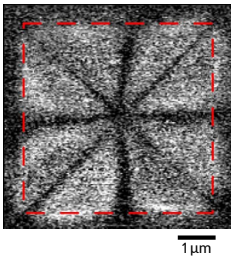

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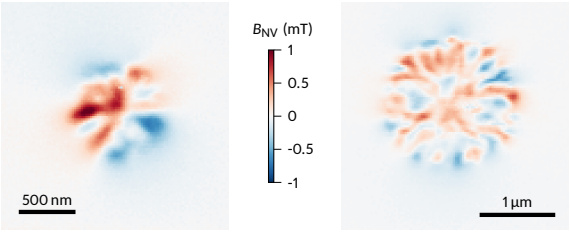
Micromagnetic simulations including M_s disorder

What about discs?



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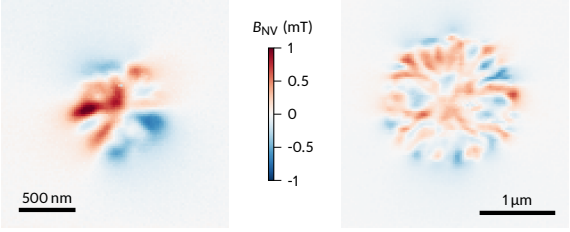
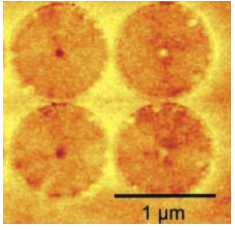


MFM data on vortices in Py



T. Shinjo *et al.* *Science* 289 (2000), 930

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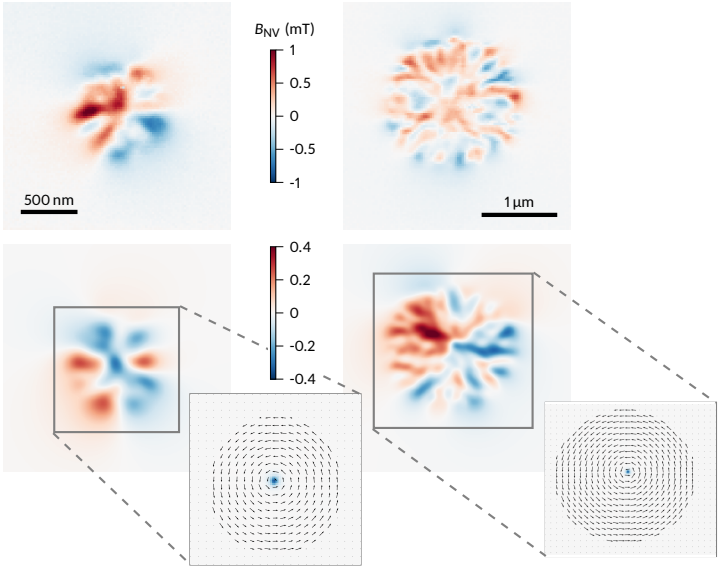

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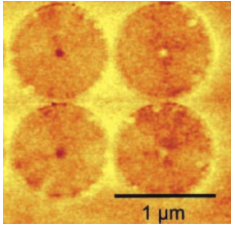

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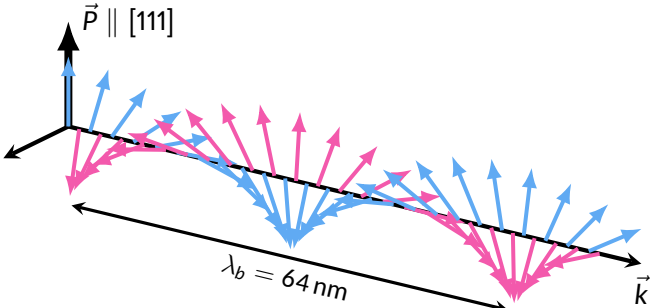
Micromagnetic simulations including M_s disorder

The room-temperature multiferroic $BiFeO_3$



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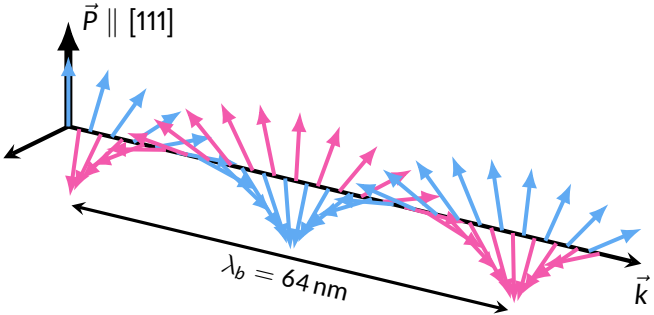

Fully compensated cycloid

→ **No stray field!**

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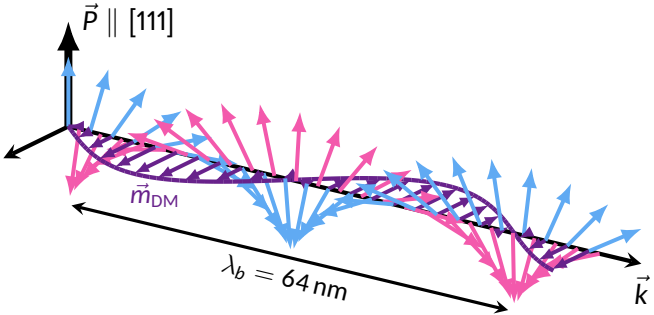
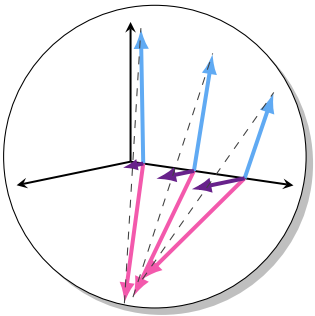
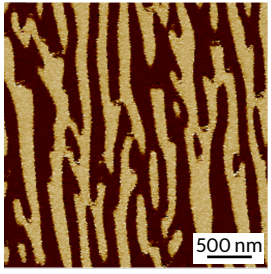




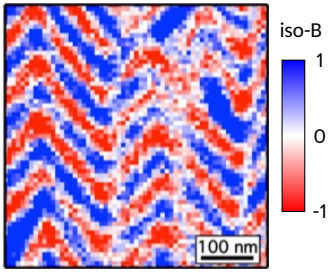
Spin density wave
Weak uncompensated moment
→ **Small stray field**

M. Ramazanoglu *et al*. *Phys. Rev. Lett*. 107 (2011), 207206

Imaging antiferromagnetic $BiFeO_3$ thin films



PFM, FE domains



NV, cycloid

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J. Fischer

I. Gross *et al.* *Nature* 549 (2017), 252

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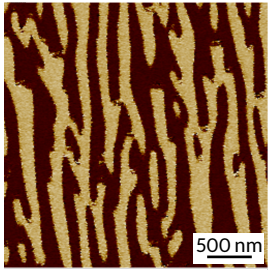

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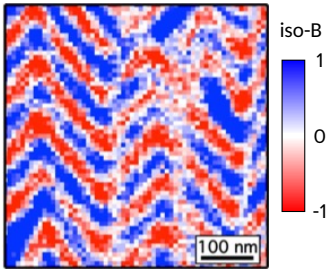

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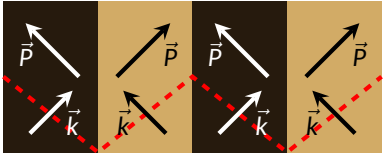

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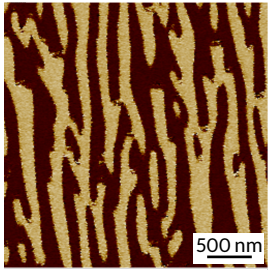
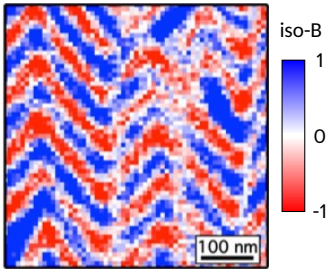
Imaging antiferromagnetic $BiFeO_3$ thin films

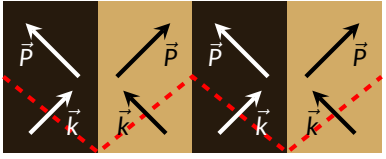
Substrate $DyScO_3$, strain -0.35%



PFM, FE domains



NV, cycloid



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K. Bouzehouane
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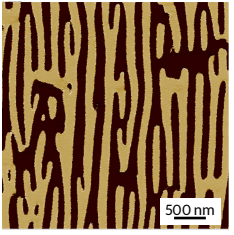
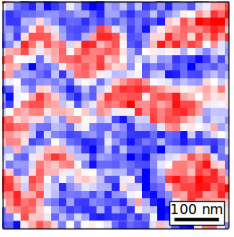
Substrate $SmScO_3$, strain +0.5%

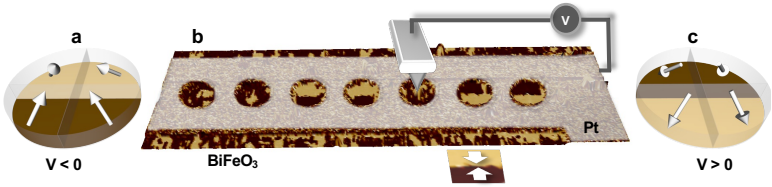




I. Gross *et al.* *Nature* 549 (2017), 252

A. Haykal *et al.* *Nat. Comm.* 11 (2020), 1704

Towards topological textures



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A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

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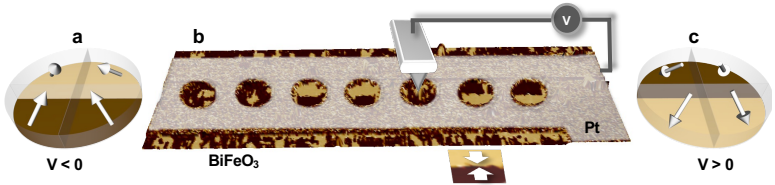

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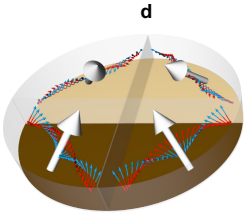

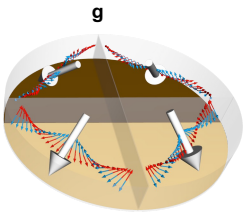

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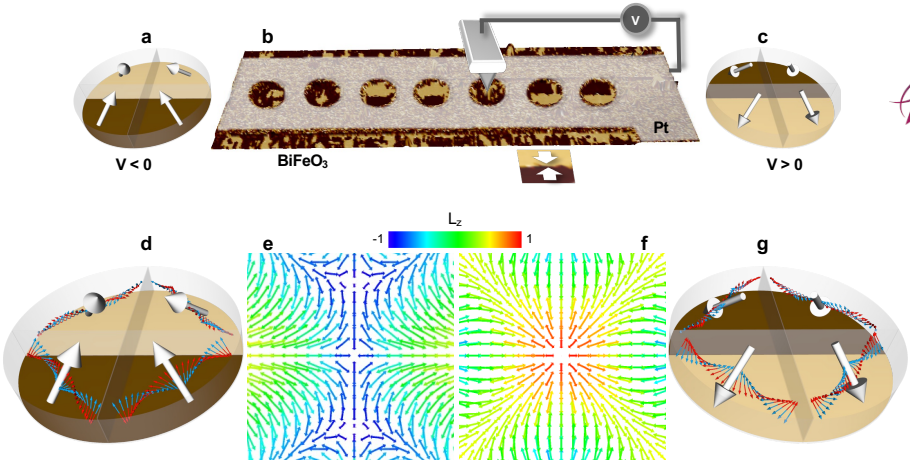

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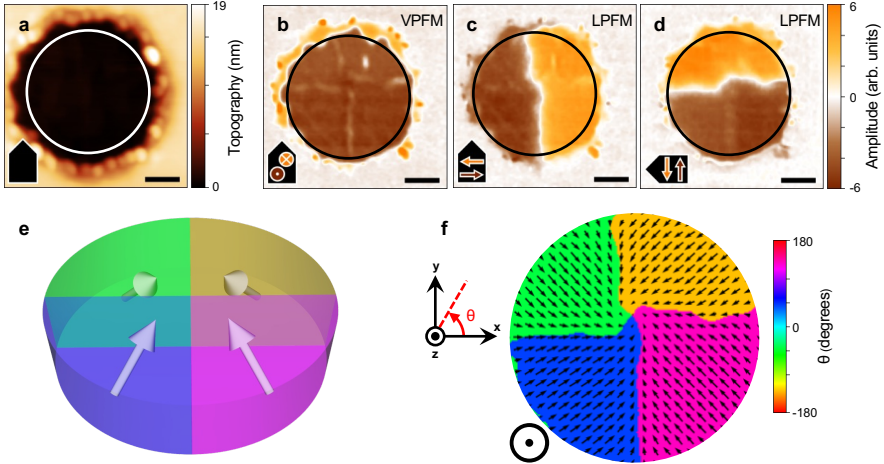
A. Chaudron

spec

J-Y. Chauleau
M. Viret
Li Zixin

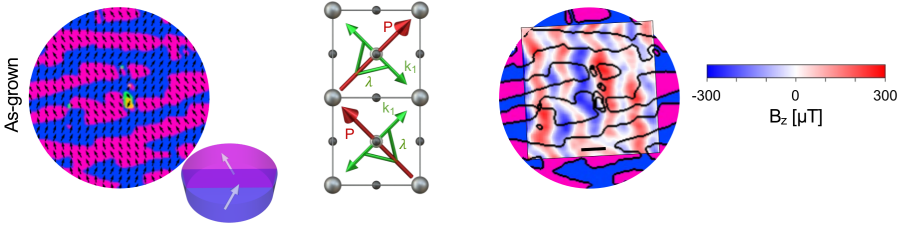
A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

Center ferroelectric domains imaged with PFM



A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

Flux closure of spin cycloids (low strain)



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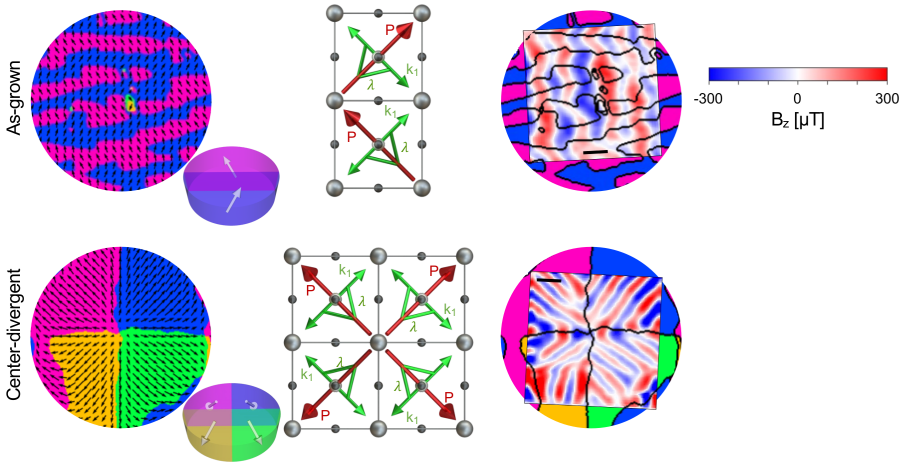

A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

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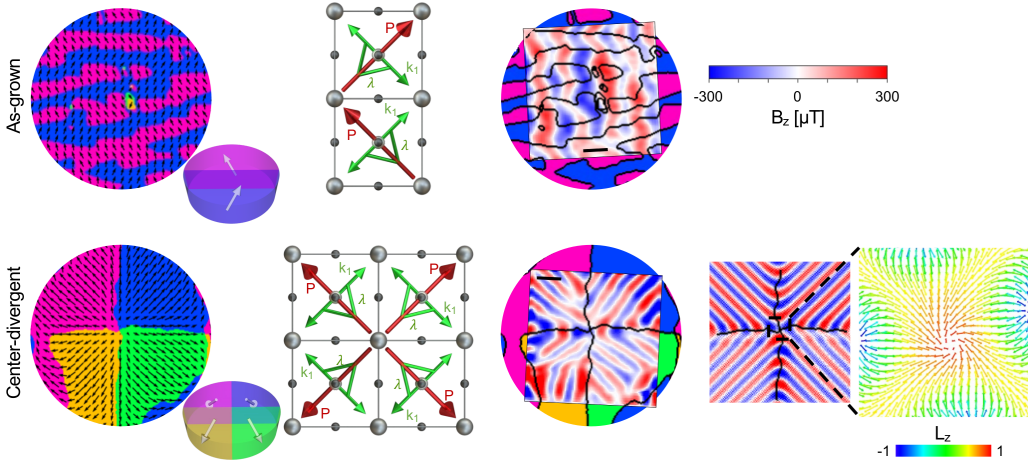
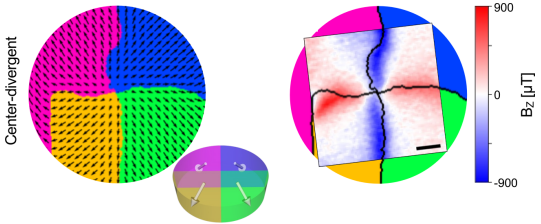
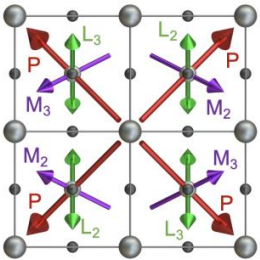
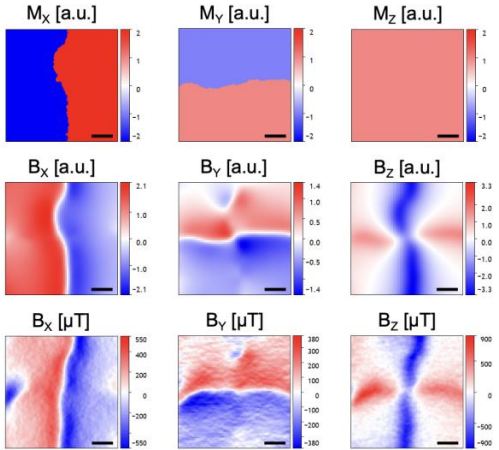


A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

Antiferromagnetic quadrants







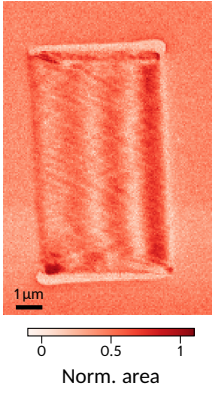
A. Chaudron *et al*. *Nat. Mater.* 23 (2024), 905

Outline

Whirling magnetic textures

E. Sfeir *et al.* *arXiv:2507.03454* (2025)
A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

Imaging of spin waves



R. Beignon *et al.* *in preparation* (2025)

Spin wave noise to probe magnetic handedness

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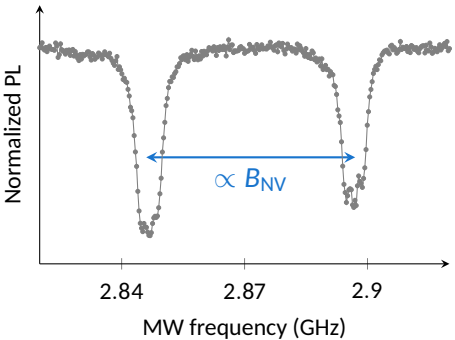
Imaging of spin waves with NV microscopy

The stray field from **resonant** spin waves can drive the NV spin transition



Shift ➔ Static stray field

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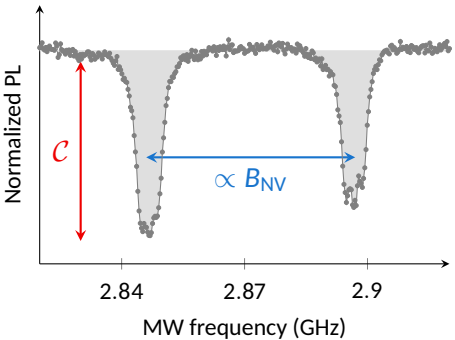

Shift ➔ Static stray field

Contrast $\mathcal{C}$ or area ➔ MW power

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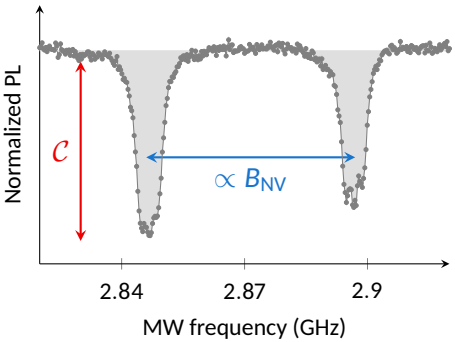
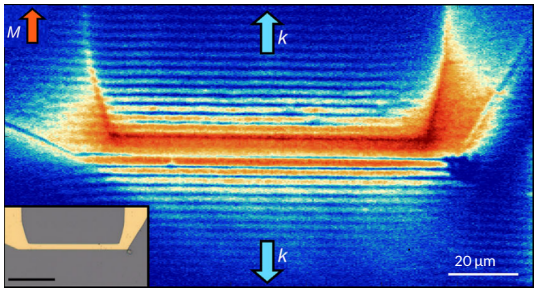


Pioneering work: van der Sar lab (TU Delft)



I. Bertelli *et al.* *Adv. Qu. Tech.* 4 (2021), 2100094

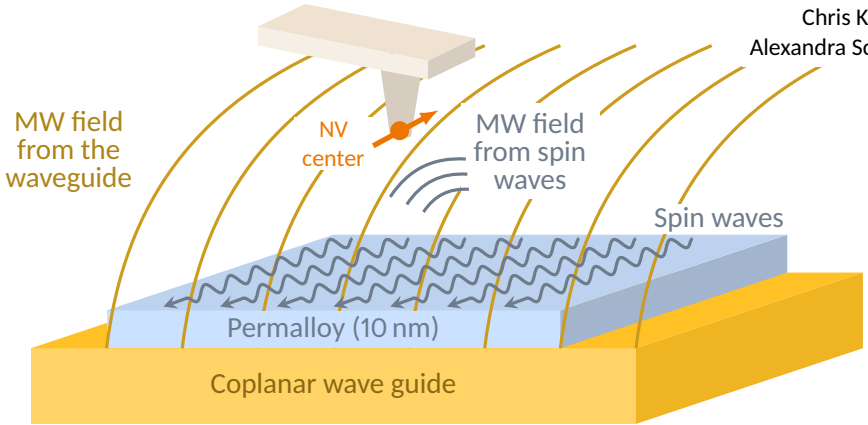
Shift ➔ Static stray field

Contrast $\mathcal{C}$ or area ➔ MW power

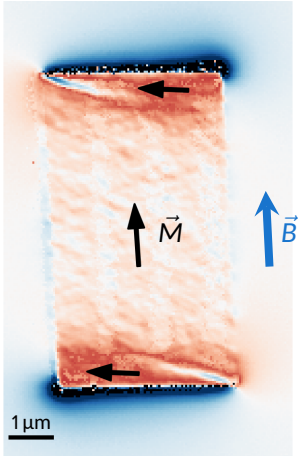
Experiments on Py microstructures

Interference between the microwave field from the antenna and the microwave field from the excited spin waves

Martin-Luther-Universität Halle-Wittenberg
Chris Körner, Rouven Dreyer
Alexandra Schrader, Georg Woltersdorf

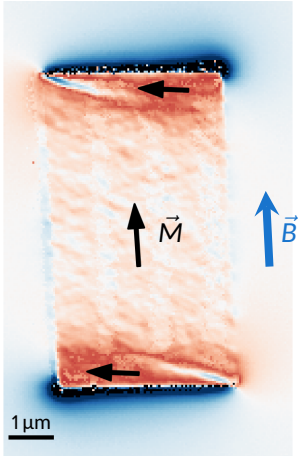


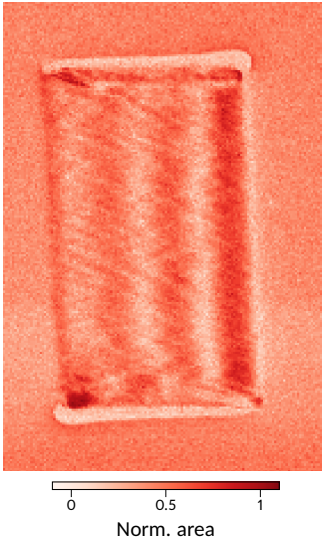
Imaging propagating spin waves



Excitation at 2.87 GHz
$B = 1.4$ mT

Imaging propagating spin waves





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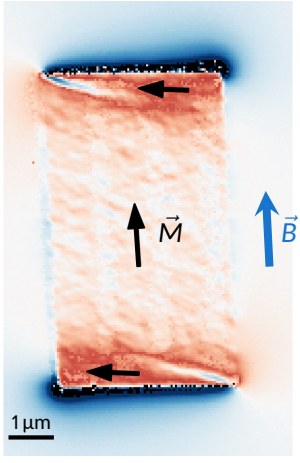

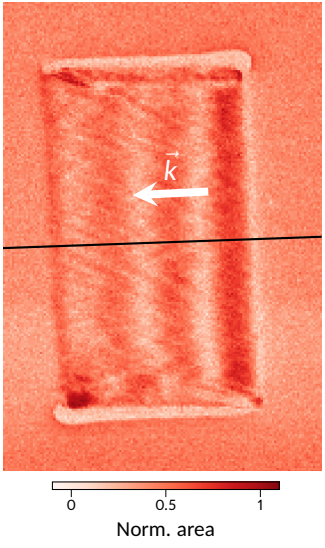

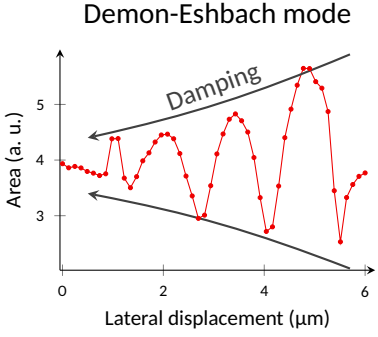

Excitation at 2.87 GHz

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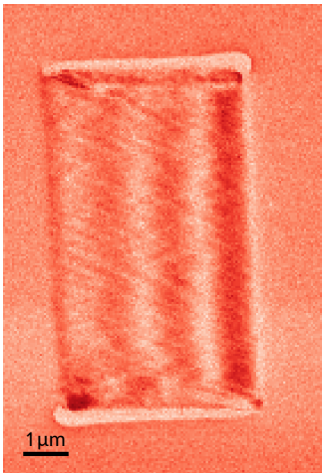
Is this really noise?



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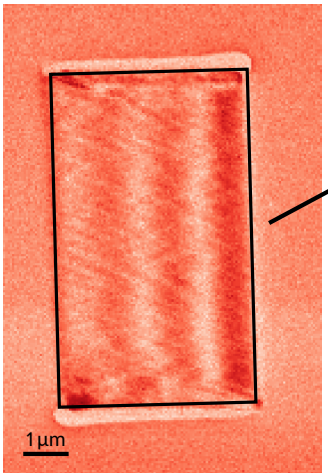

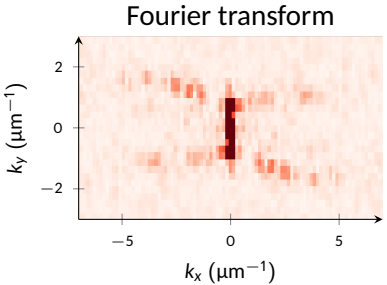

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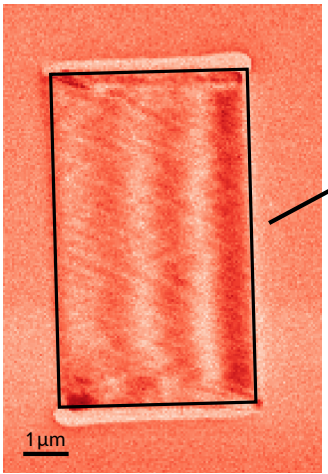

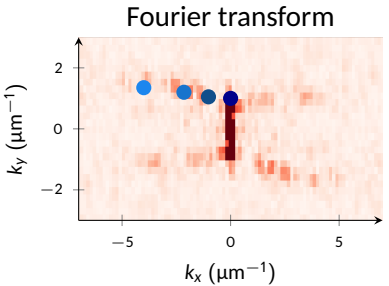

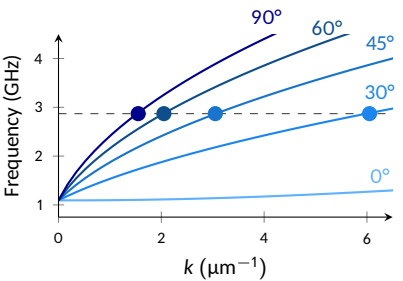

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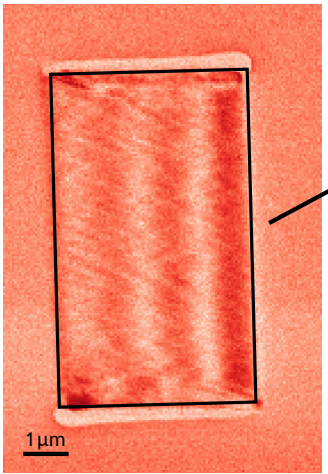
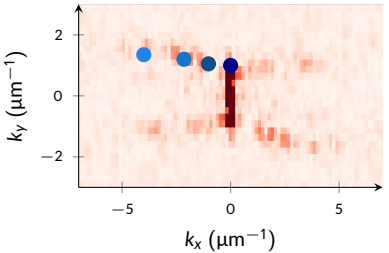
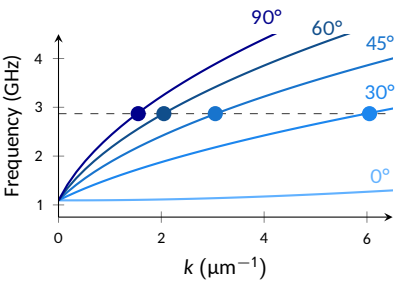
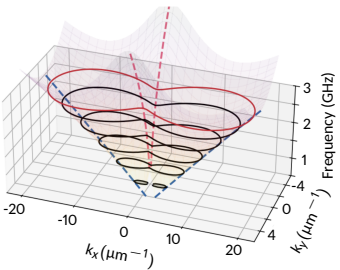


Fourier transform

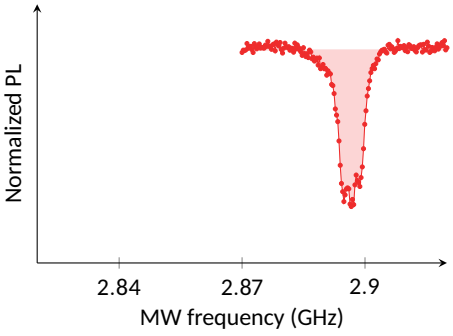


Iso-frequency curve





Selection of the propagation direction



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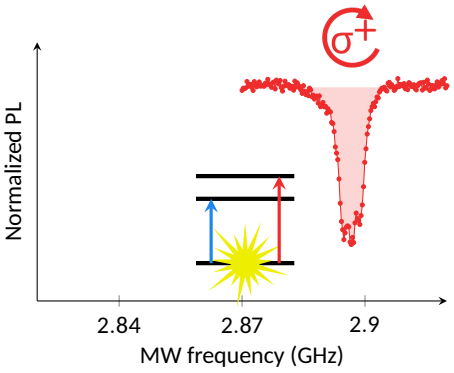

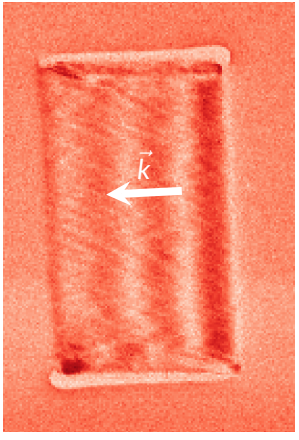

I. Bertelli *et al.* *Sci. Adv.* 6 (2020), eabd3556

R. Beignon *et al.* *in preparation* (2025)

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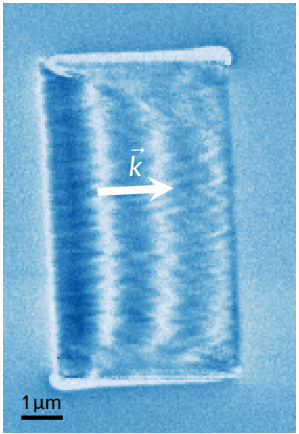

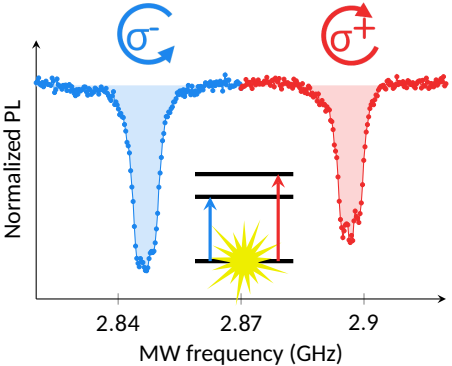

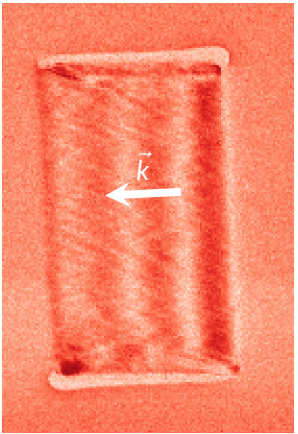

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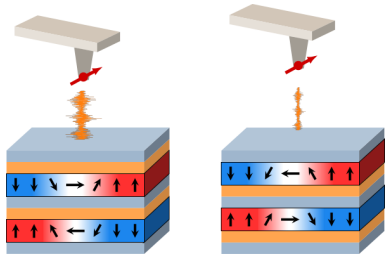

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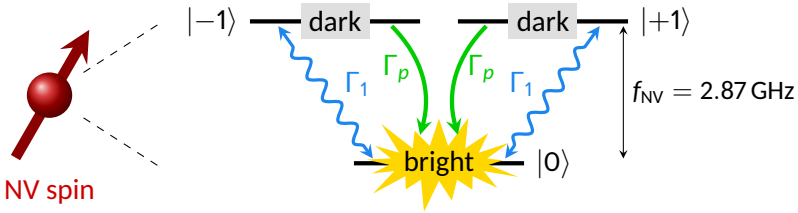
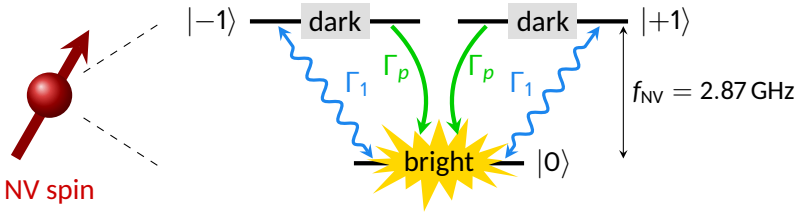
Effect of magnetic noise on the photoluminescence



Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}

M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

Effect of magnetic noise on the photoluminescence



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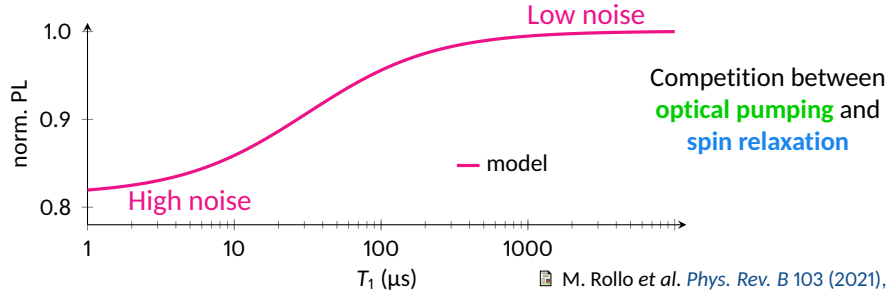

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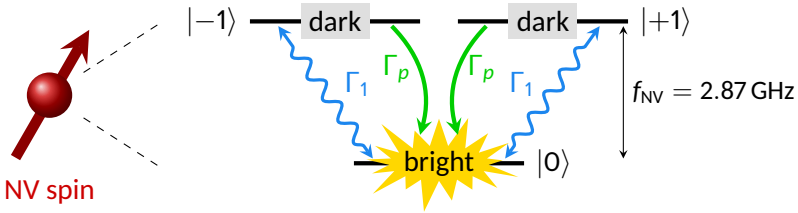

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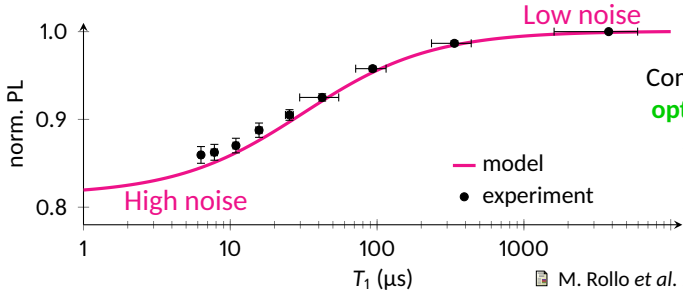
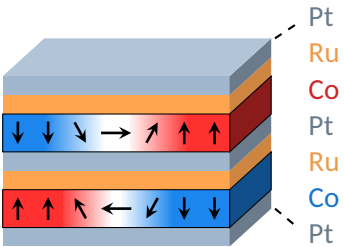


Competition between **optical pumping** and **spin relaxation**

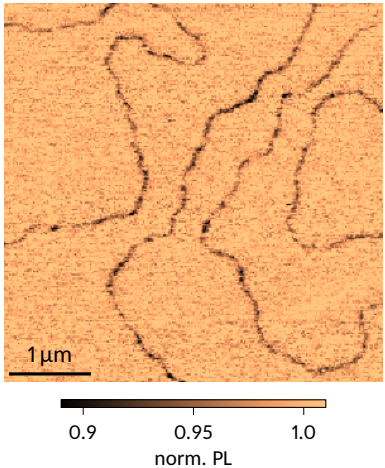
M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

Antiferromagnetic domain walls probed with noise



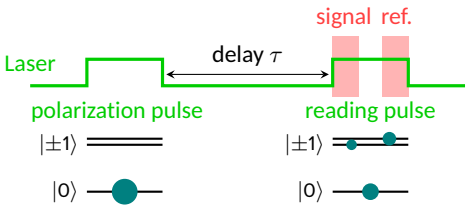
W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34

V. T. Pham *et al.* *Science* 384 (2024), 307



A. Finco *et al.* *Nat. Commun.* 12 (2021), 767

Local variation of the relaxation time



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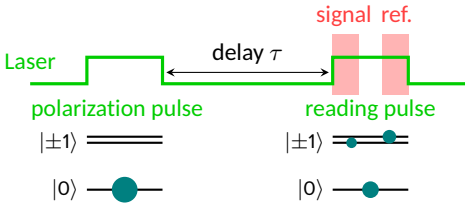

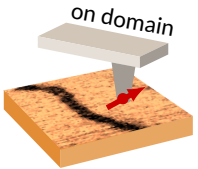

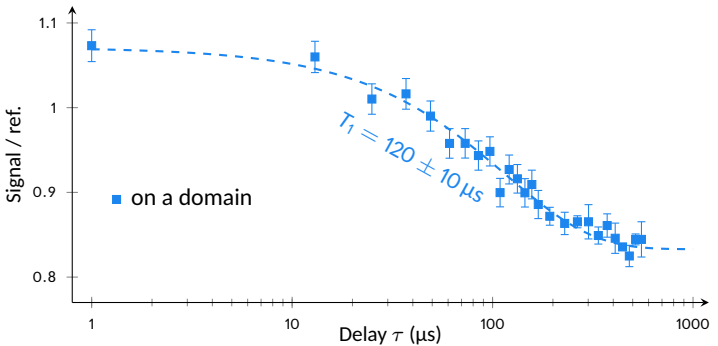

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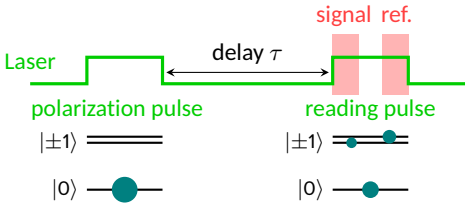
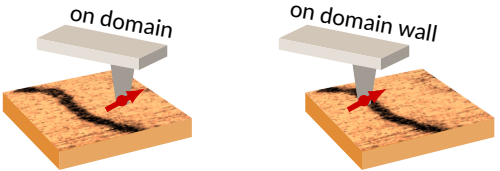
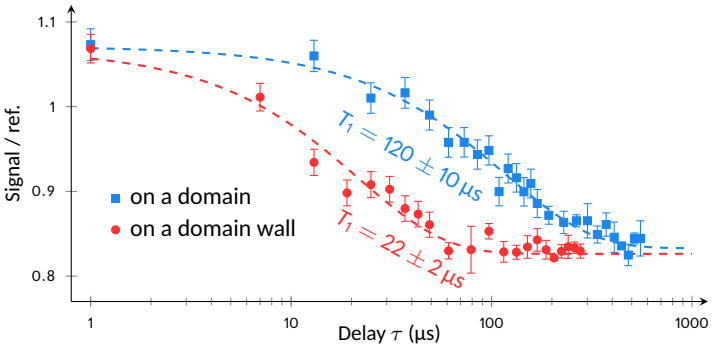


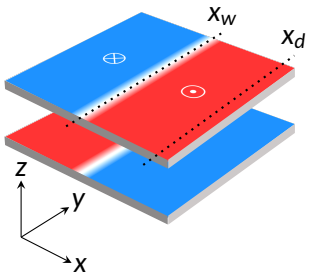


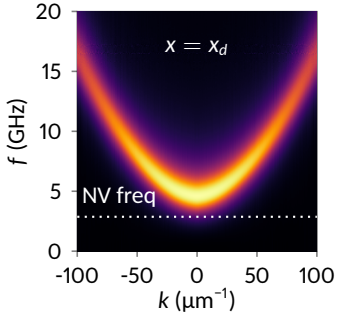
→ **Enhancement of the spin relaxation at walls**

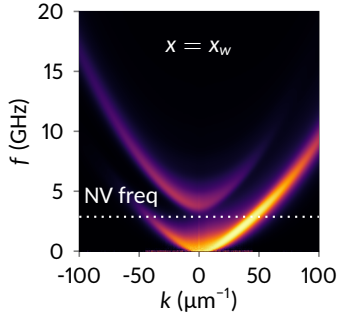


Origin of the noise: spin waves

Jean-Paul Adam, Joo-Von Kim





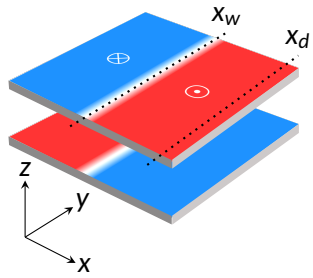


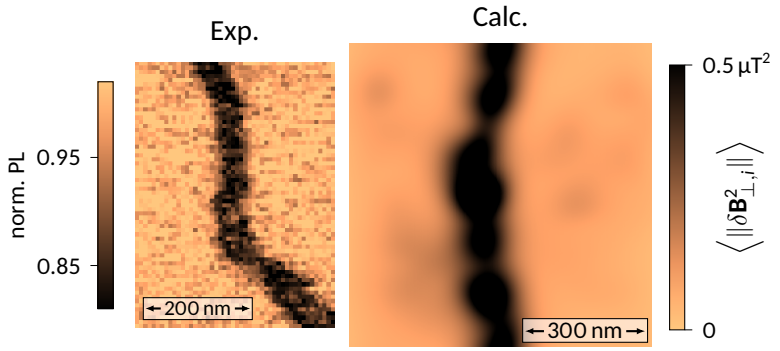
In-plane magnetized region + no spin wave gap in the domain walls

→ Modes in the walls generating stray field at the NV frequency

Origin of the noise: spin waves

Jean-Paul Adam, Joo-Von Kim

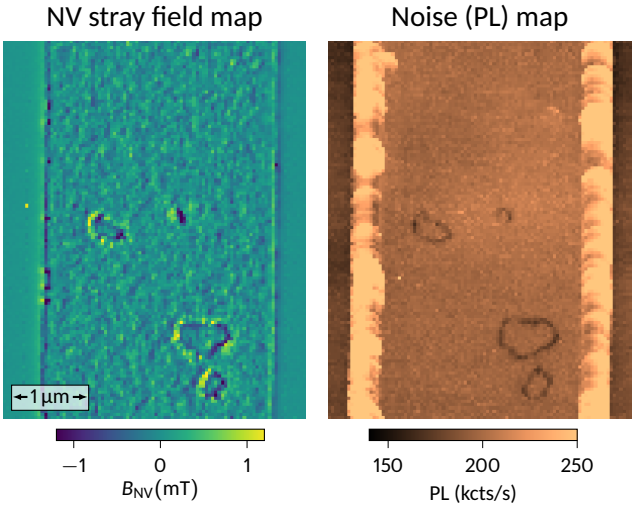




In-plane magnetized region + no spin wave gap in the domain walls

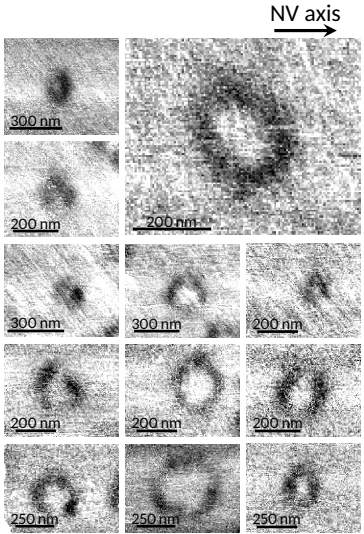
→ Modes in the walls generating stray field at the NV frequency

After applying magnetic field

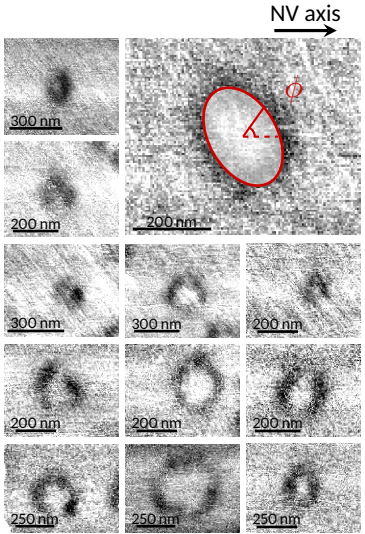


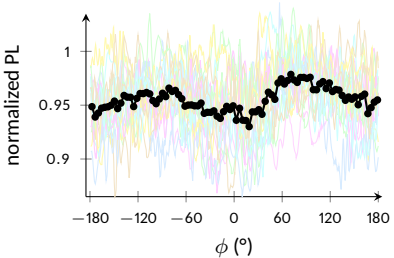
- Oop field of about 150 mT applied for nucleation
- Skyrmions and big bubbles pinned

Statistics on Néel left (CCW) skyrmions

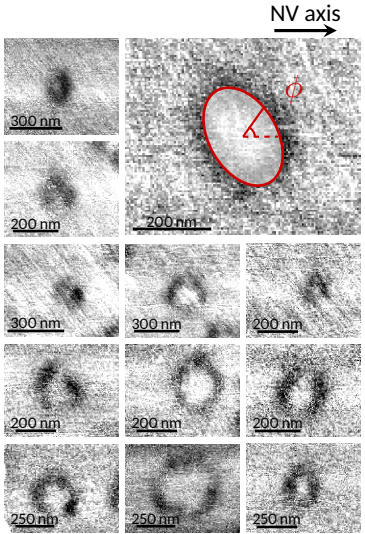


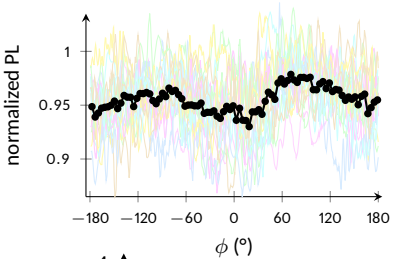
Statistics on Néel left (CCW) skyrmions

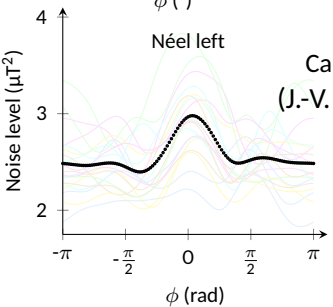




Statistics on Néel left (CCW) skyrmions



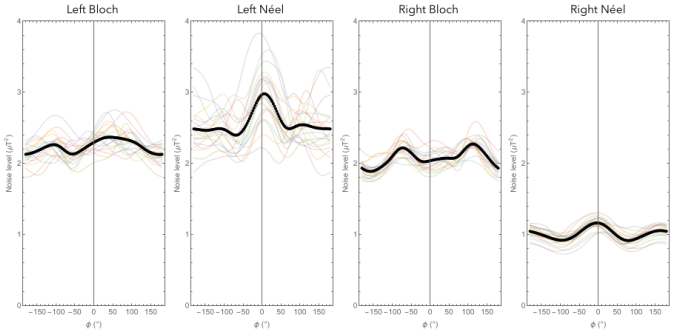




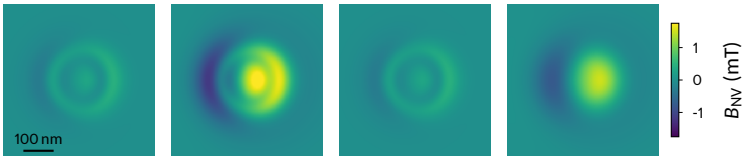
Calculation
(J.-V. Kim, C2N)

Expected pattern on other skyrmion types

Simulated noise distribution along the contour



Simulated stray field maps

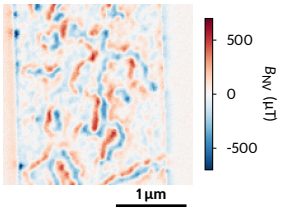


- The pattern allows us to identify Néel skyrmions
- Strong difference in noise amplitude expected between Néel left and Néel right skyrmions…
- … while the stray field maps are very similar!

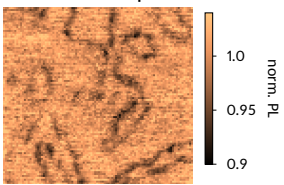
Experiment: looking at both sides of the film

Initial stack: Néel left

Magnetic field map



Noise map



spintec
SPIN IN ELECTRONICS

Samples: J. Urrestarazu, R. Guedas, O. Boulle

A. Finco *et al.* *arXiv:2502.03166* (2025)

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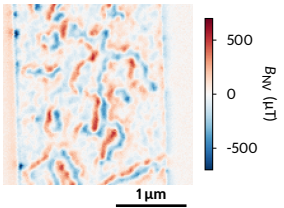
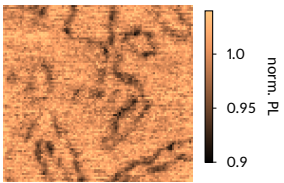
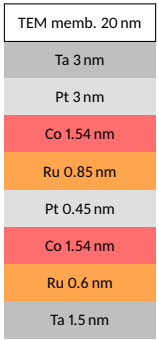


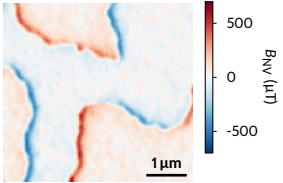
Noise map



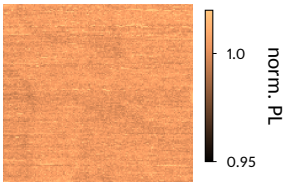
Inverted stack: Néel right



Magnetic field map



Noise map



spintec
SPIN IN ELECTRONICS

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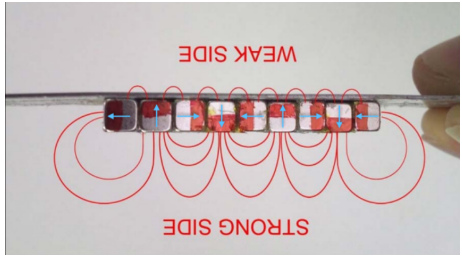
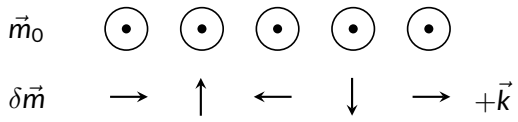
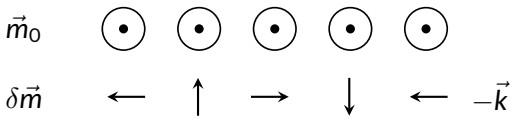
A. Finco *et al.* *arXiv:2502.03166* (2025)

1st ingredient : Spin waves = fridge magnets

Halbach arrays





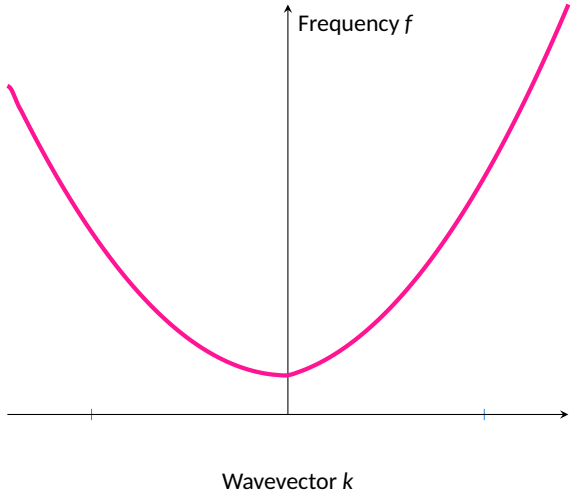


J. Mallinson. *IEEE Trans. on Mag.* 9 (1973), 678

T. Devolder. *Phys. Rev. Appl.* 20 (2023), 054057

2nd ingredient: Dzyaloshinkii-Moriya interaction

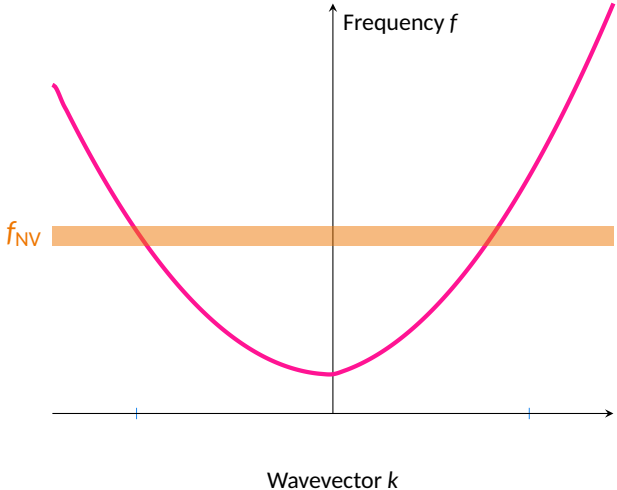
1. DMI induces non-reciprocity in the SW dispersion



2nd ingredient: Dzyaloshinkii-Moriya interaction

1. DMI induces non-reciprocity in the SW dispersion

2. The NV probe is filtering SW at f_{NV}



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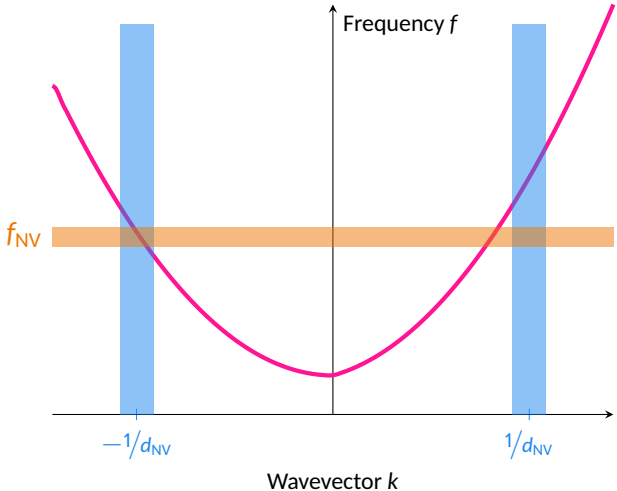
3. The NV probe is filtering SW at $\pm 1/d_{NV}$



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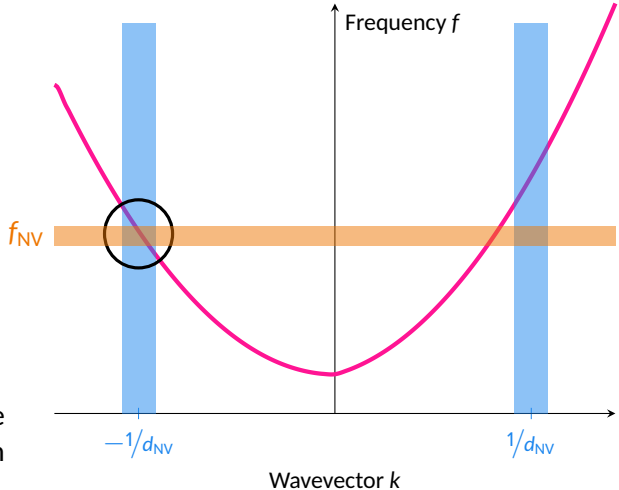
1. DMI induces non-reciprocity in the SW dispersion

2. The NV probe is filtering SW at f_{NV}

3. The NV probe is filtering SW at $\pm 1/d_{NV}$

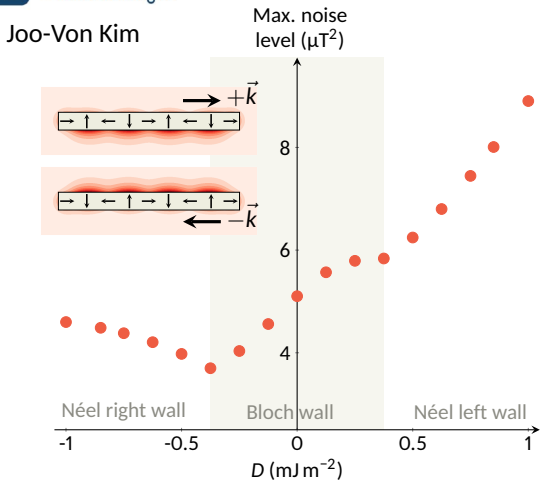
→ The NV center is more sensitive to a *k* direction than the other



In a single ferromagnetic layer

Centre DE Nanosciences & DE Nanotechnologies

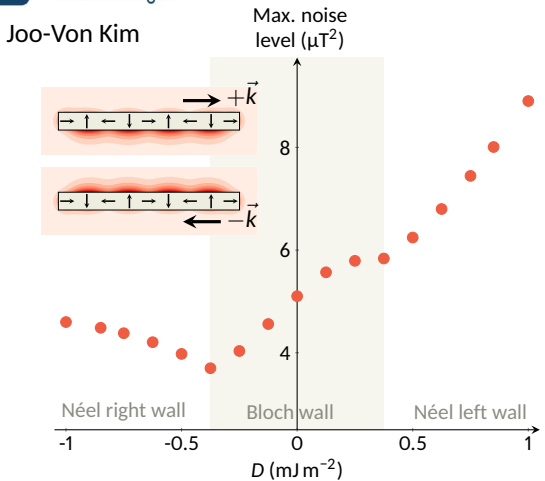
Joo-Von Kim

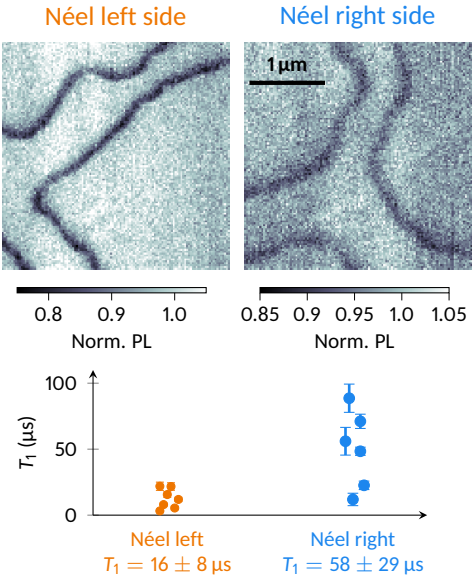


In a single ferromagnetic layer

Centre de Nanosciences & de Nanotechnologies

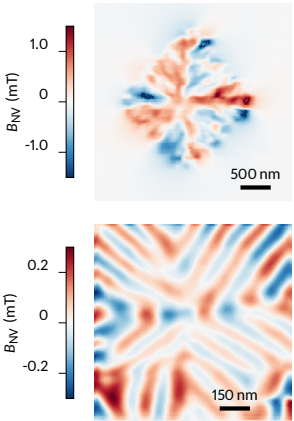
Joo-Von Kim





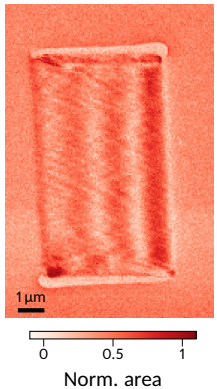
Summary

Whirling magnetic textures



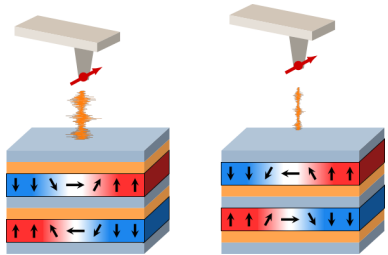
E. Sfeir *et al.* *arXiv:2507.03454* (2025)
A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

Imaging of spin waves



R. Beignon *et al.* *in preparation* (2025)

Spin wave noise to probe magnetic handedness



A. Finco *et al.* *arXiv:2502.03166* (2025)

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Olivier Boulle

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