Spin waves, domain walls, skyrmions and vortices probed with scanning NV microscopy

Aurore Finco

Laboratoire Charles Coulomb
Team Solid-State Quantum Technologies (S2QT)

CNRS and Université de Montpellier, Montpellier, France

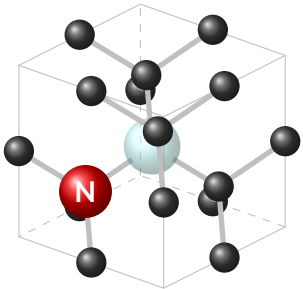
E-MRS Fall meeting 2025, Symposium O, September 17th, Warsaw

slides available at https://magimag.eu

Scanning NV center microscopy

Integration of a quantum sensor into a scanning probe microscope

B. M. Chernobrod and G. P. Berman. *J. Appl. Phys.* 97 (2004), 014903



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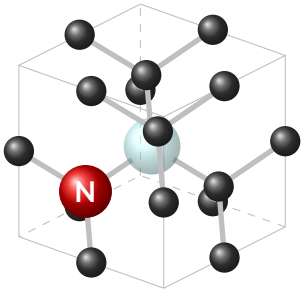

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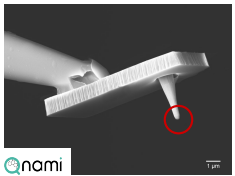

P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

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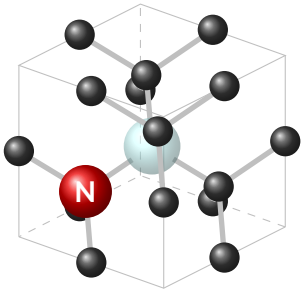

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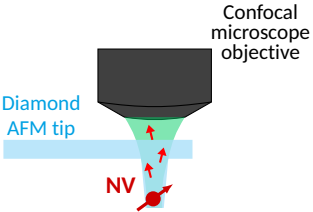

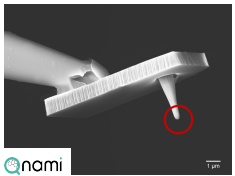

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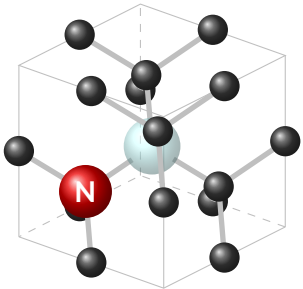

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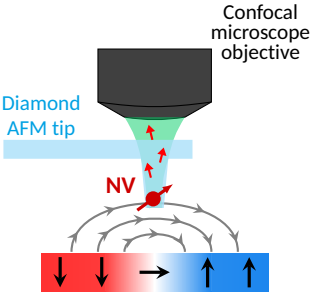

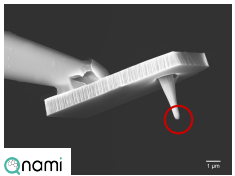

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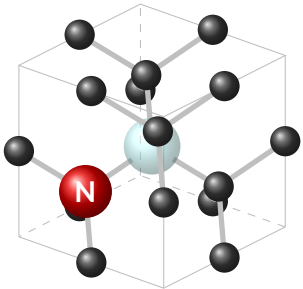

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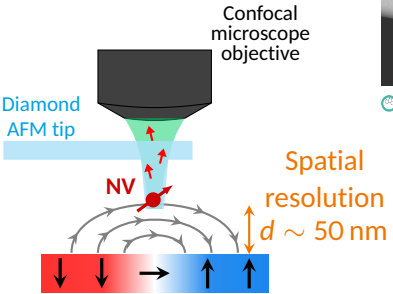

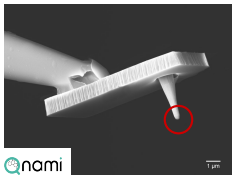

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Why is NV microscopy spreading so fast?

➔ Because it is sensitive, versatile (i.e. great) and commercially available

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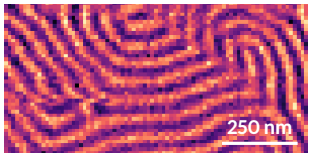
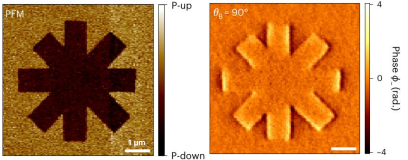
Antiferromagnets ($BiFeO_3$)



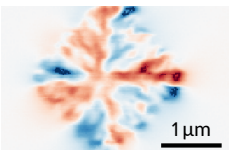
A. Finco and V. Jacques. *APL Mater.* 11 (2023), 100901

Ferroelectrics



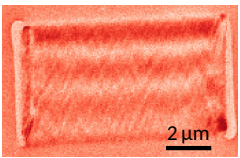
W. S. Huxter *et al.* *Nat. Phys.* 19 (2023), 644

2D magnets (Fe_5GeTe_2)



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

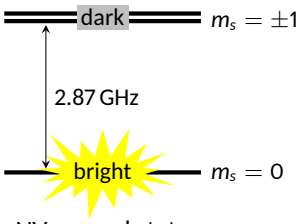
Spin waves



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

Measuring magnetic field with a NV center

Spin-dependent fluorescence



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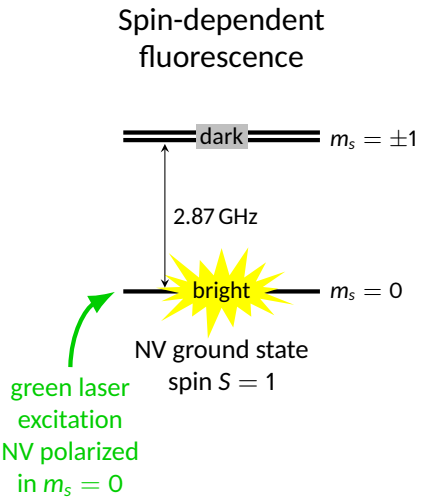

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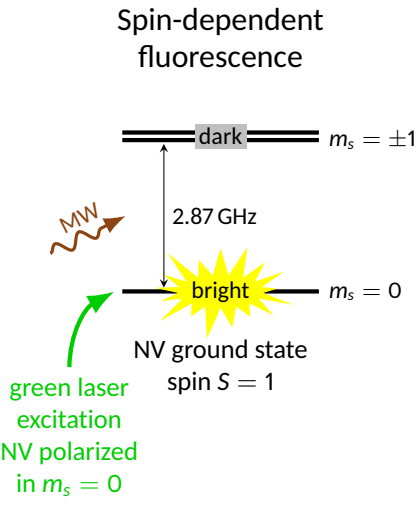

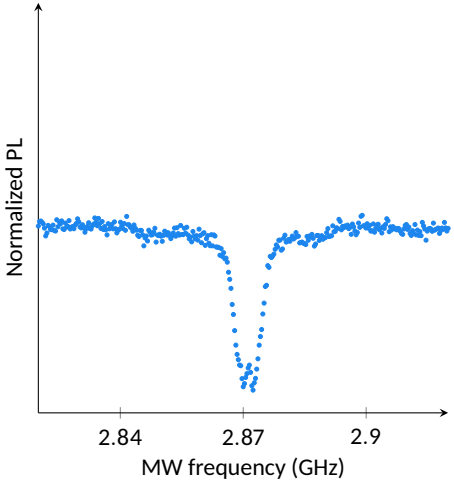

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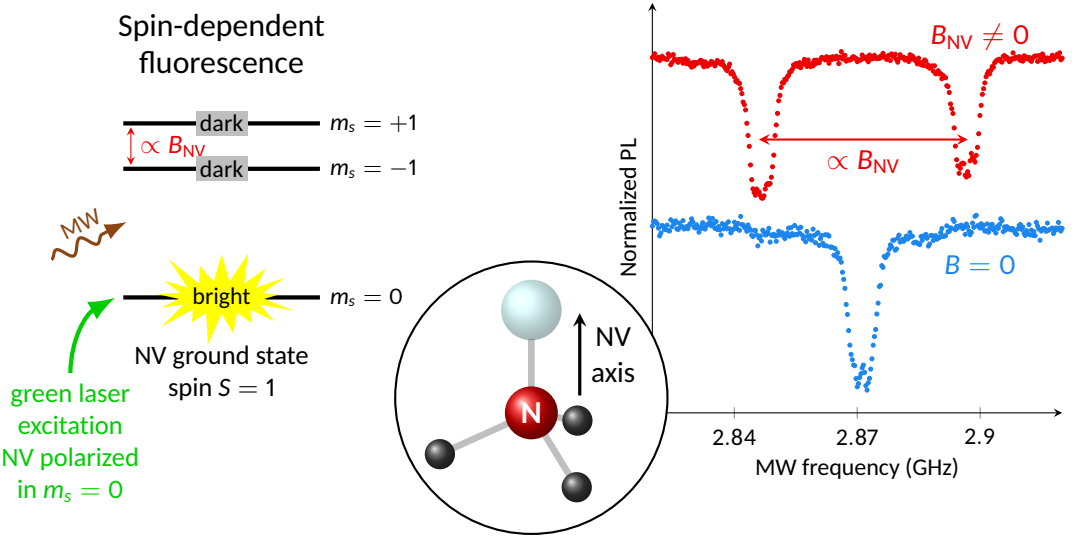
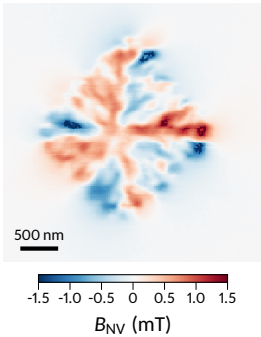


Outline

Room temperature vortices in a 2D ferromagnet

Elias Sfeir, Carolin Schrader



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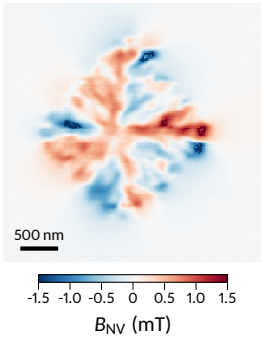

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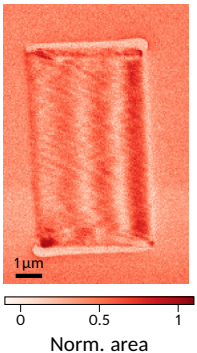

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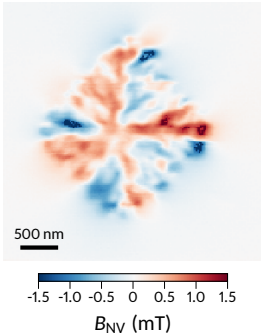

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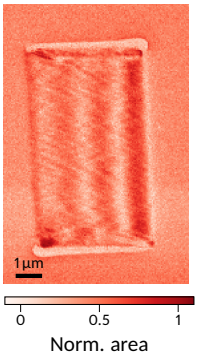

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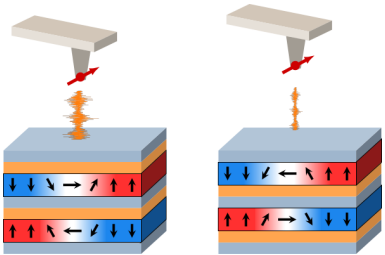
Spin wave noise to probe magnetic handedness



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

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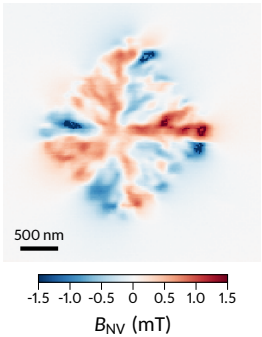

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Effect of confinement in Fe_5GeTe_2?

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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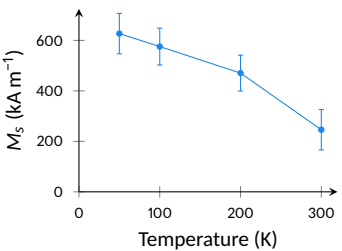
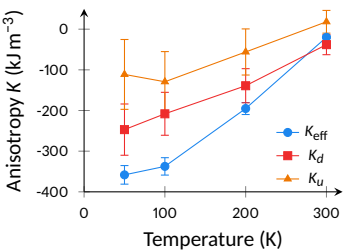
Macroscopic characterization





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SPIN IN ELECTRONICS

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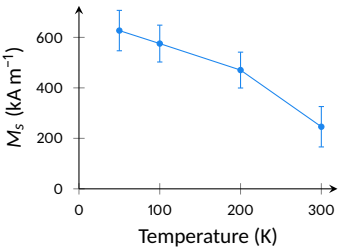
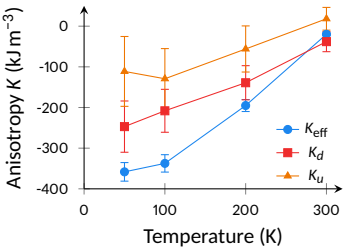
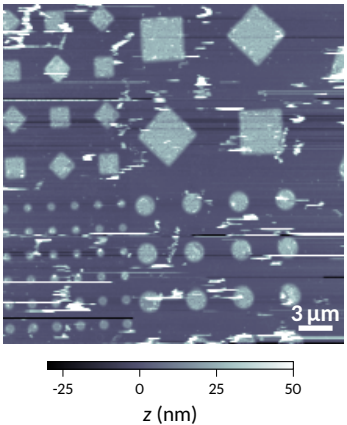
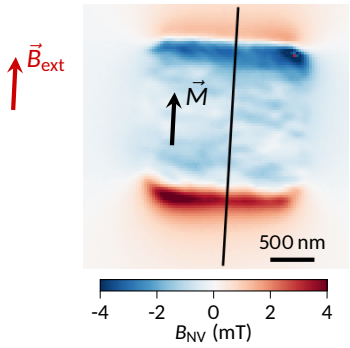


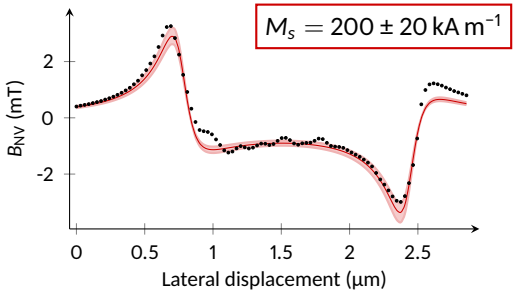


AFM scan



Measurement of the saturation magnetization





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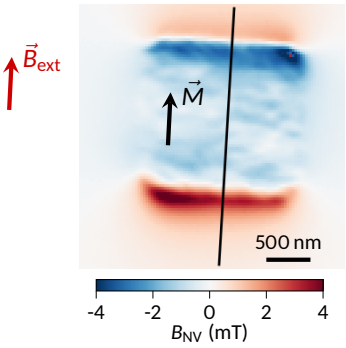

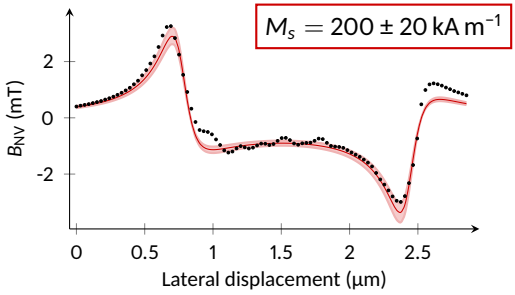

No effect of confinement on M_s → no change of T_C

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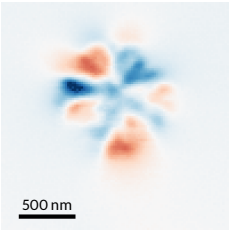
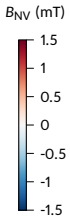
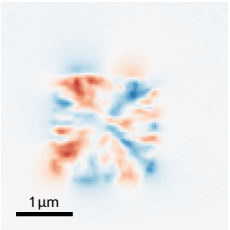
Vortices in micro-squares







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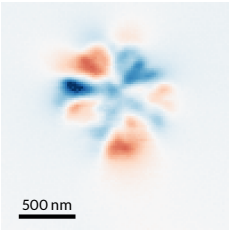
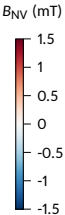
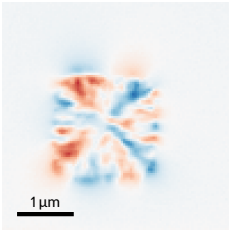
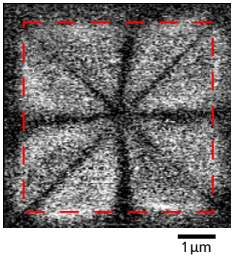




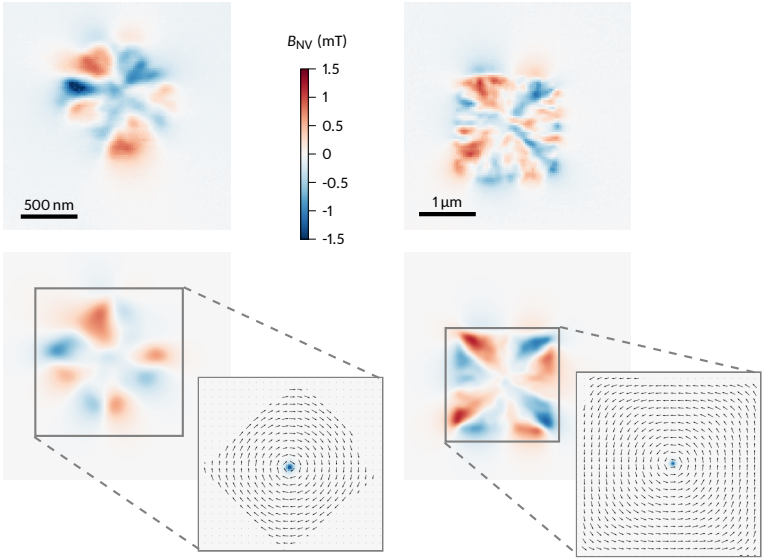


Early NV data on vortices in Py



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

Vortices in micro-squares



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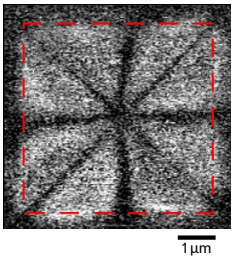

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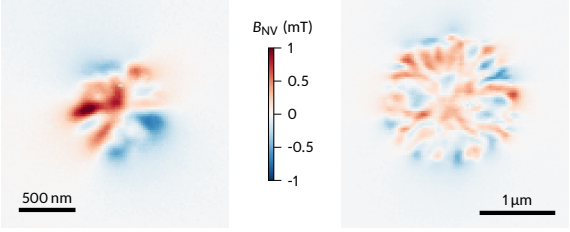
Micromagnetic simulations including M_s disorder

What about discs?



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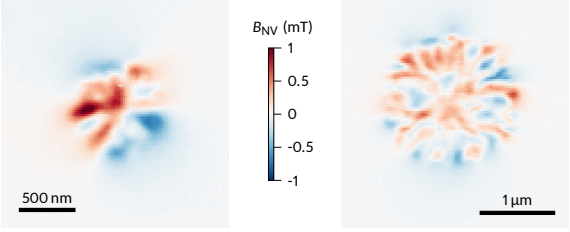
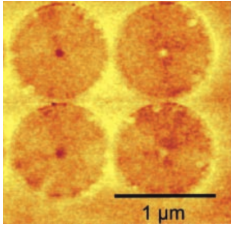
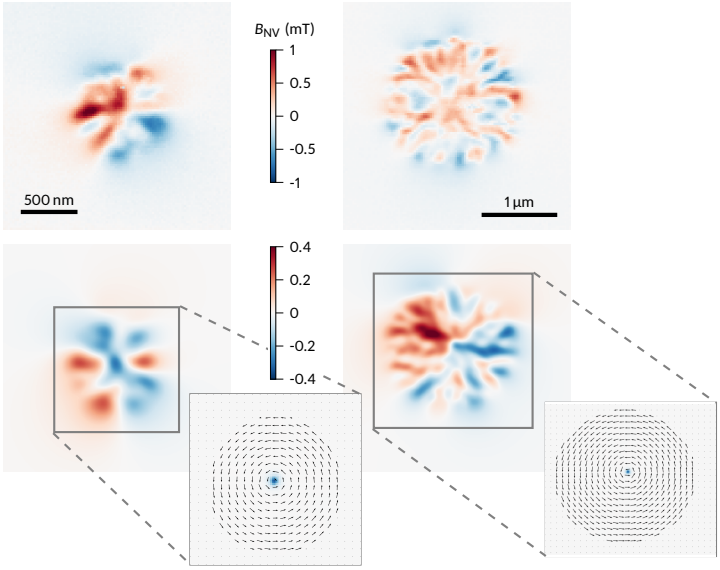


MFM data on vortices in Py

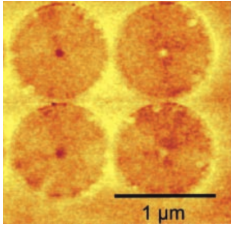


T. Shinjo *et al.* *Science* 289 (2000), 930

What about discs?



MFM data on vortices in Py



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

Micromagnetic simulations including M_s disorder

Outline

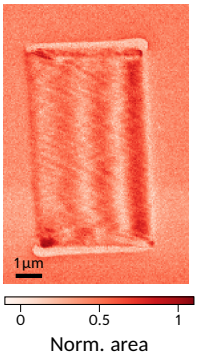
Room temperature vortices in a 2D ferromagnet

Elias Sfeir, Carolin Schrader

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

Imaging of spin waves

Roméo Beignon



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

Spin wave noise to probe magnetic handedness

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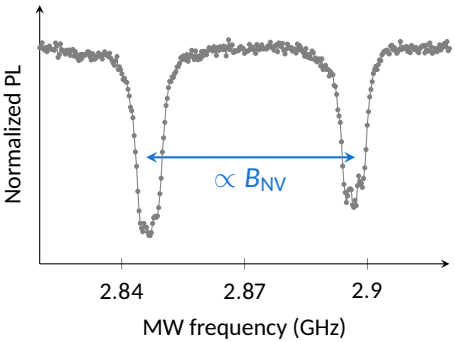
Imaging of spin waves with NV microscopy

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



Shift ➔ Static stray field

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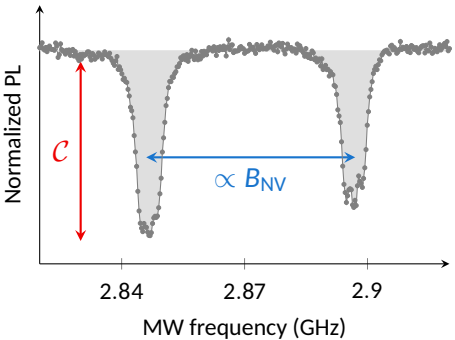

Shift ➔ Static stray field

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

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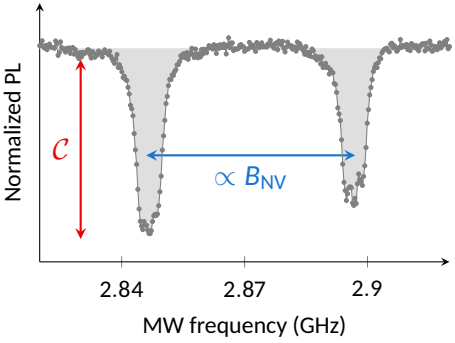
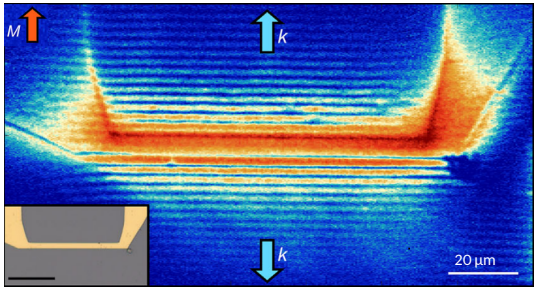


Pioneering work: van der Sar lab (TU Delft)



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

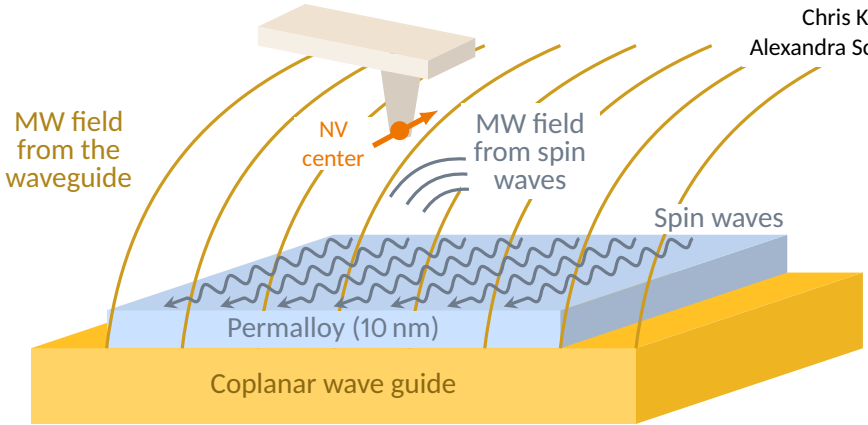
Shift ➔ Static stray field

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

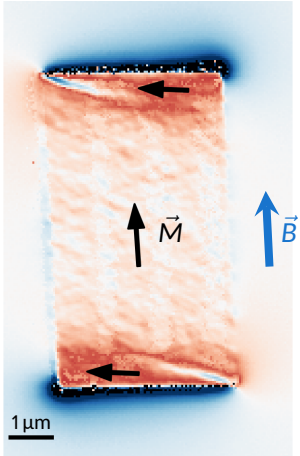
Experiments on Py microstructures

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



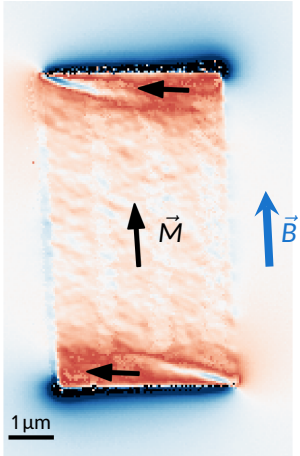
Imaging propagating spin waves

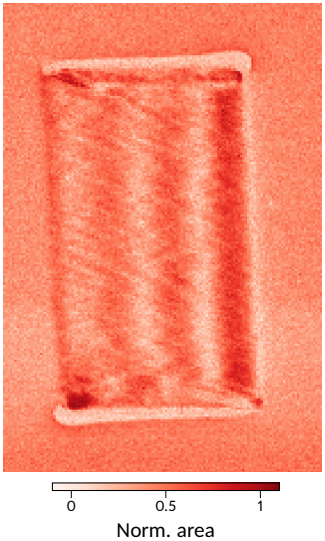


Excitation at 2.87 GHz

$B = 1.4$ mT

Imaging propagating spin waves





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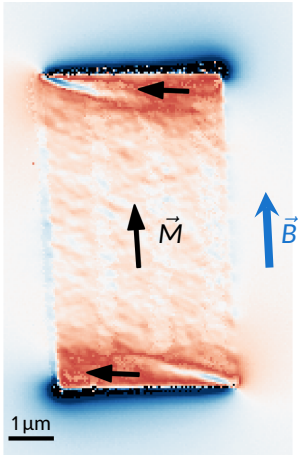

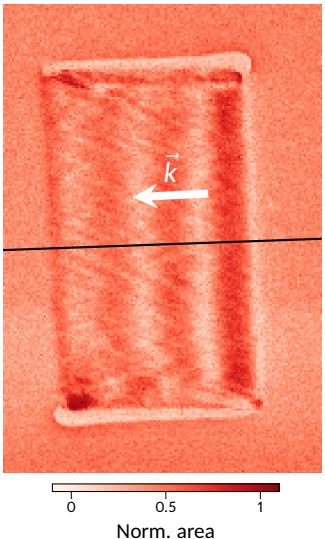

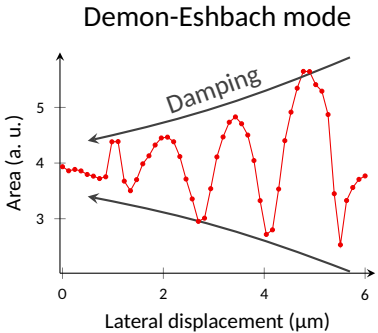

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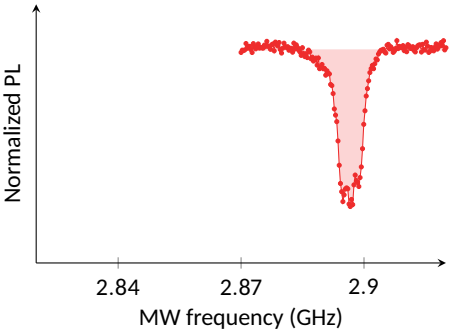
Why do we see a single direction of $\vec{k}$?



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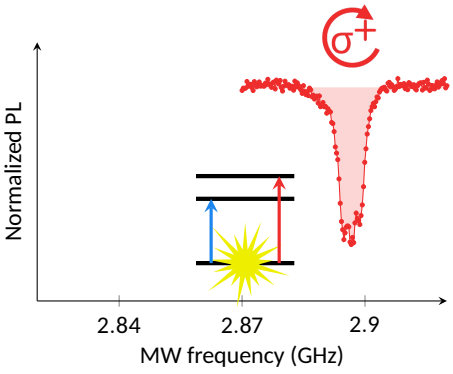

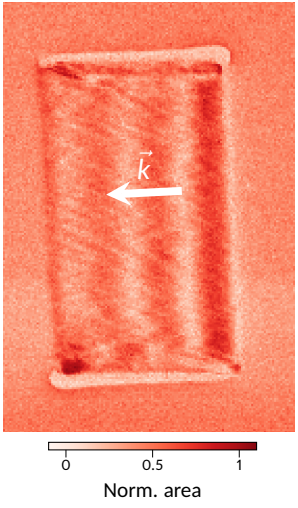

I. Bertelli *et al.* *Sci. Adv.* 6 (2020), eabd3556

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

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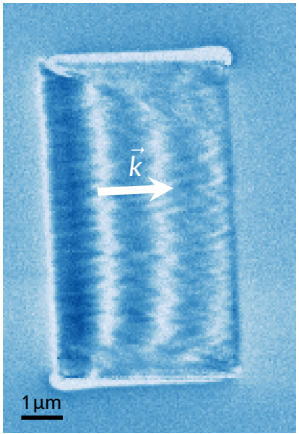

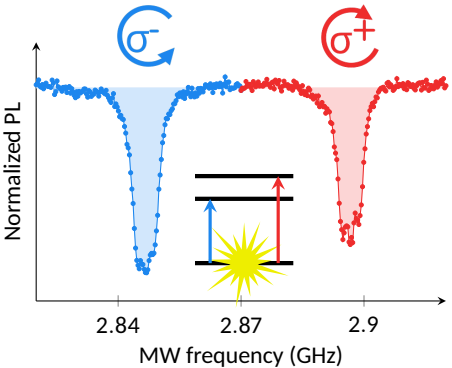

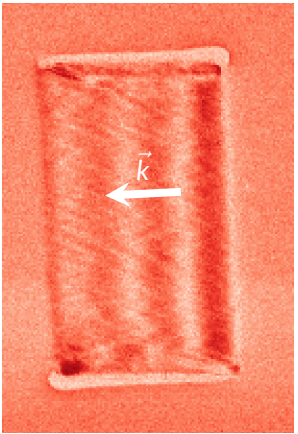

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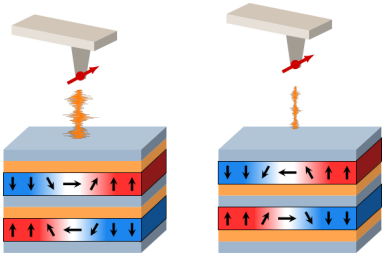
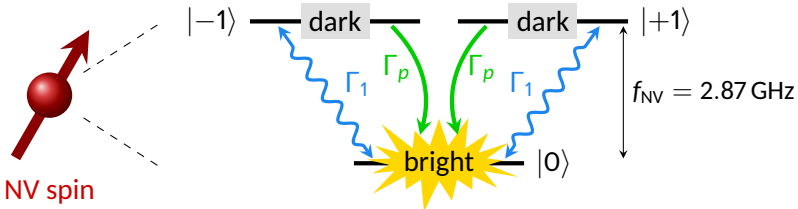


A. Finco *et al.* *arXiv:2502.03166* (2025)

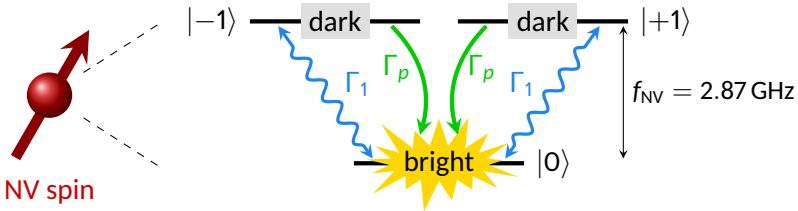
Effect of magnetic noise on the photoluminescence



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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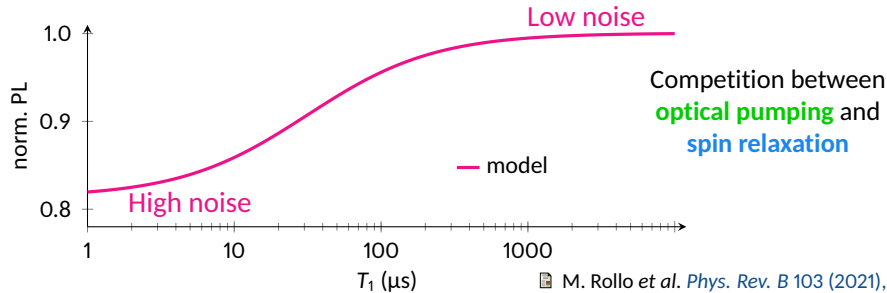

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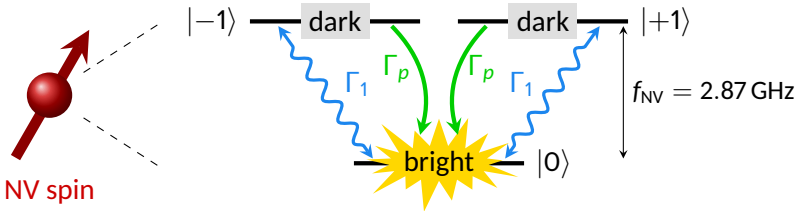

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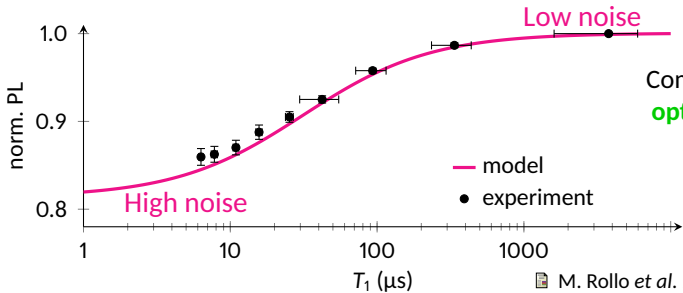
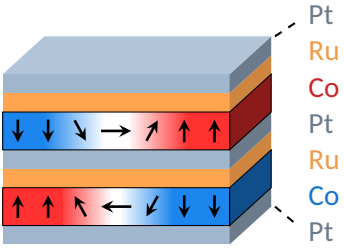


Competition between **optical pumping** and **spin relaxation**

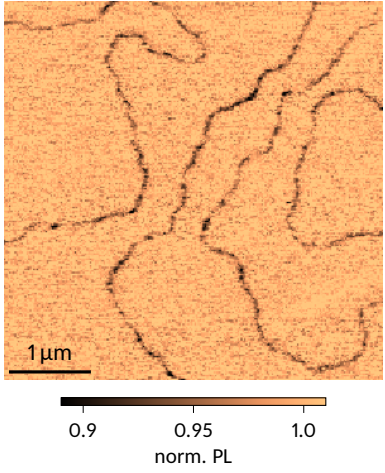
M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

Antiferromagnetic domain walls probed with noise



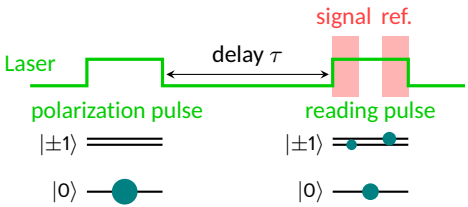
W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34

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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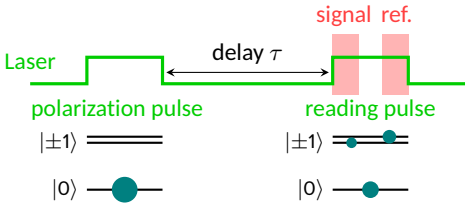

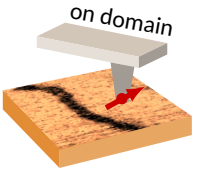

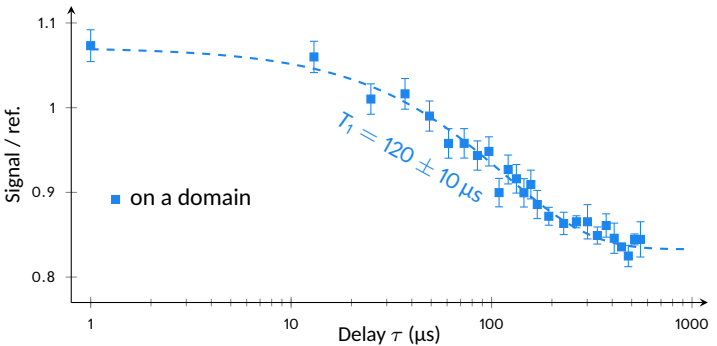

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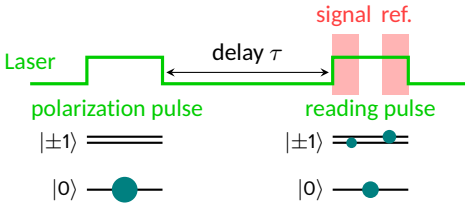
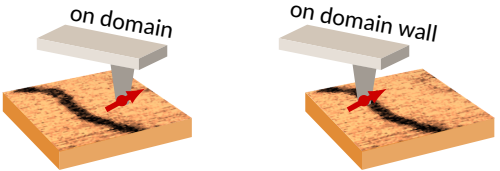
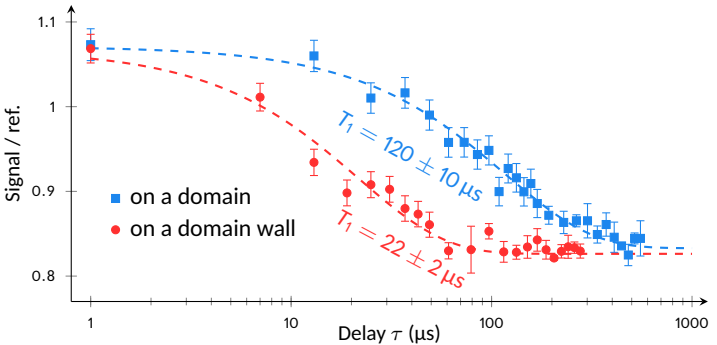


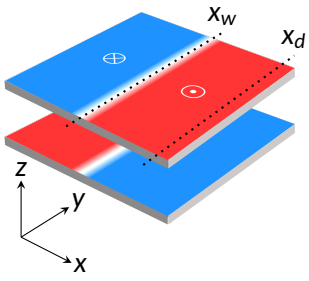


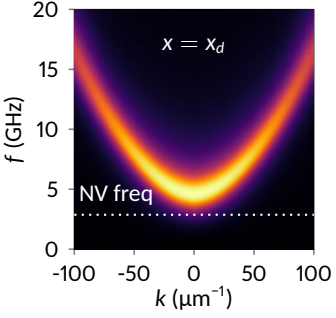
→ **Enhancement of the spin relaxation at walls**

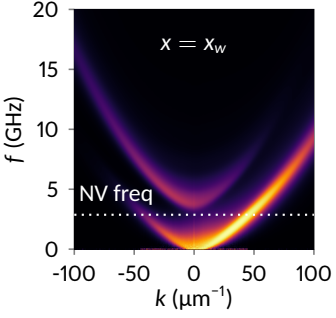


Origin of the noise: spin waves

Jean-Paul Adam, Joo-Von Kim





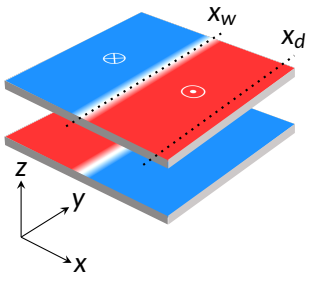


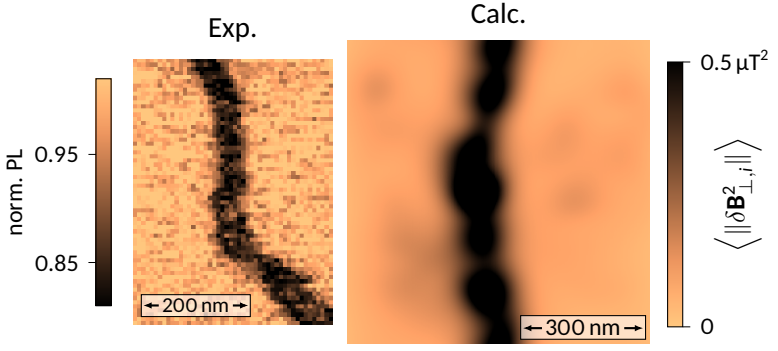
In-plane magnetized region + no spin wave gap in the domain walls

→ Presence of modes in the walls generating stray field at the NV frequency

Origin of the noise: spin waves

Centre de Nanosciences & de Nanotechnologies
Jean-Paul Adam, Joo-Von Kim





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What is happening on the other side?

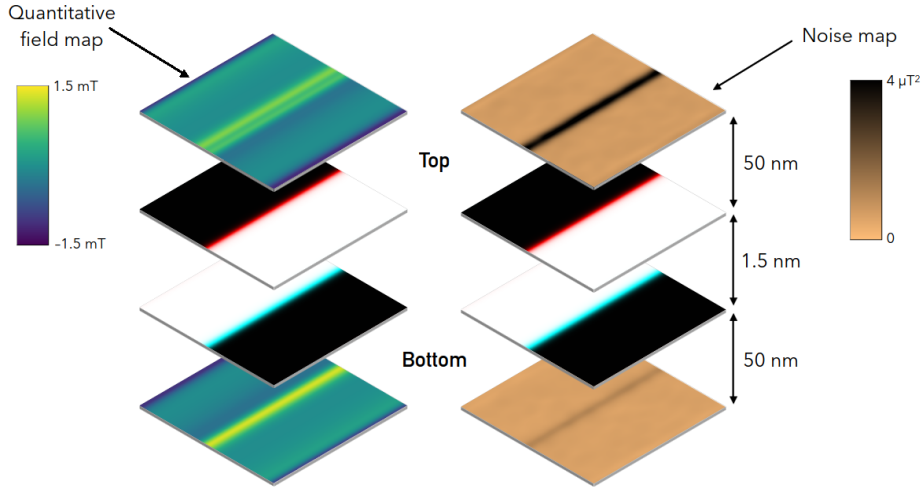
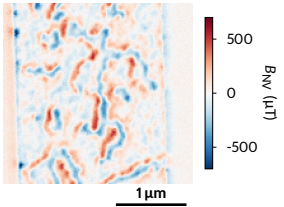


Figure by Joo-Von Kim

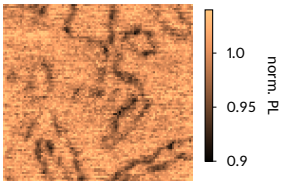
Experiment: looking at both sides of the film

Initial stack: Néel left

Magnetic field map



Noise map



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

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

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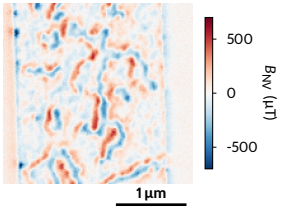

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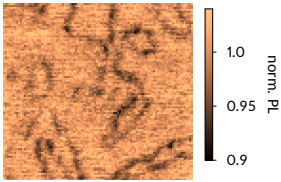
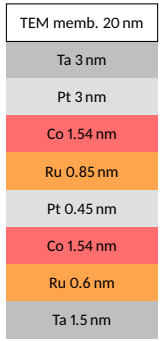


Inverted stack: Néel right



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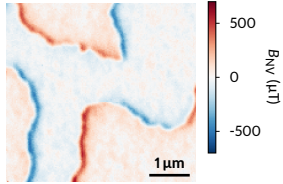

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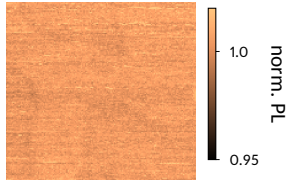


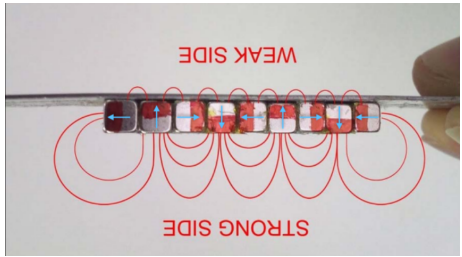
spintec
SPIN IN ELECTRONICS

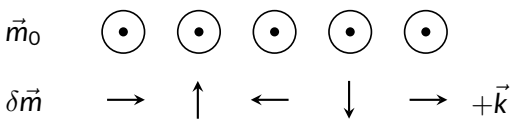
Samples: J. Urrestarazu, R. Guedas, O. Boulle

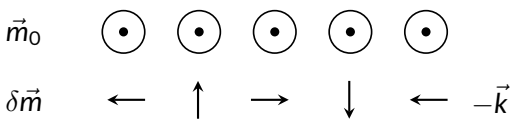
A. Finco *et al.* *arXiv:2502.03166* (2025)

1st ingredient : Spin waves = fridge magnets

Halbach arrays





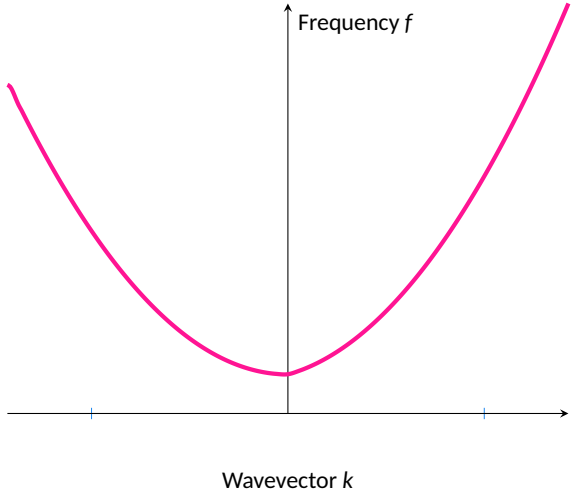


J. Mallinson. *IEEE Trans. on Mag.* 9 (1973), 678

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

2nd ingredient: Dzyaloshinkii-Moriya interaction

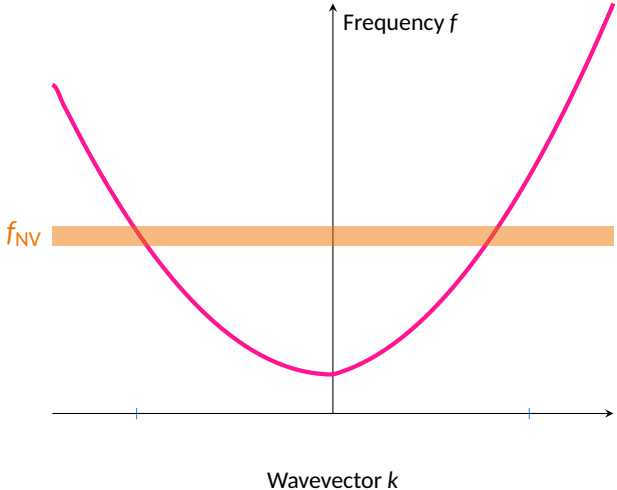
1. DMI induces non-reciprocity in the SW dispersion



2nd ingredient: Dzyaloshinkii-Moriya interaction

1. DMI induces non-reciprocity in the SW dispersion

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



2nd ingredient: Dzyaloshinkii-Moriya interaction

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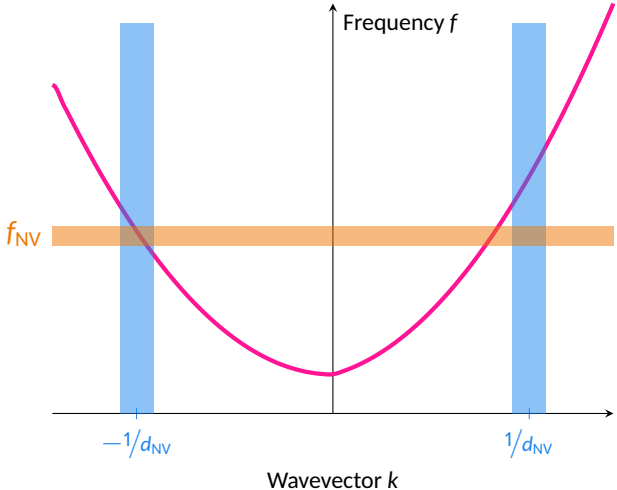

2nd ingredient: Dzyaloshinkii-Moriya interaction

1. DMI induces non-reciprocity in the SW dispersion

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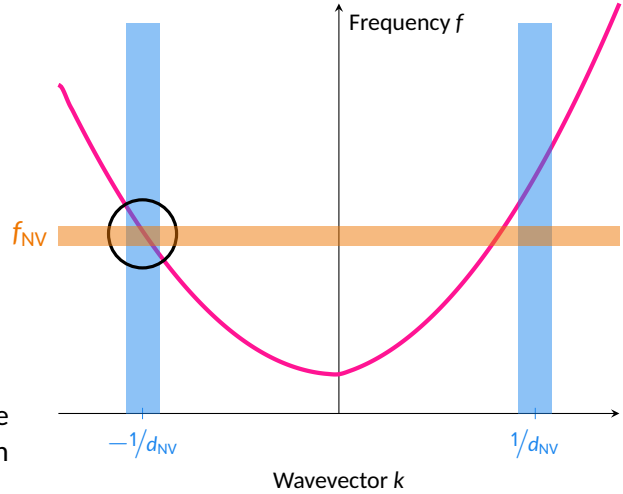
3. The NV probe is filtering SW at $\pm 1/d_{NV}$

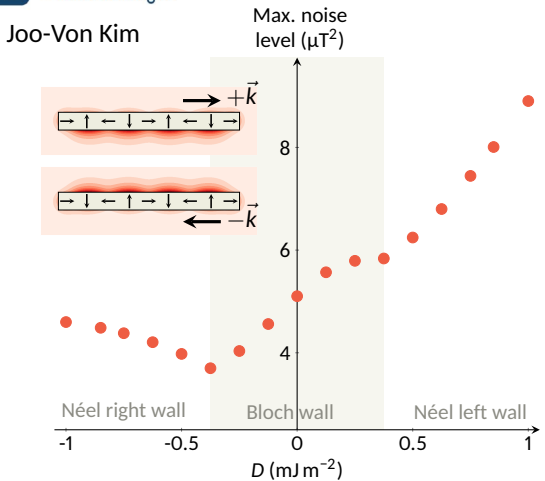
→ The NV center is more sensitive to a *k* direction than the other



In a single ferromagnetic layer

Centre DE Nanosciences & DE Nanotechnologies

Joo-Von Kim



In a single ferromagnetic layer

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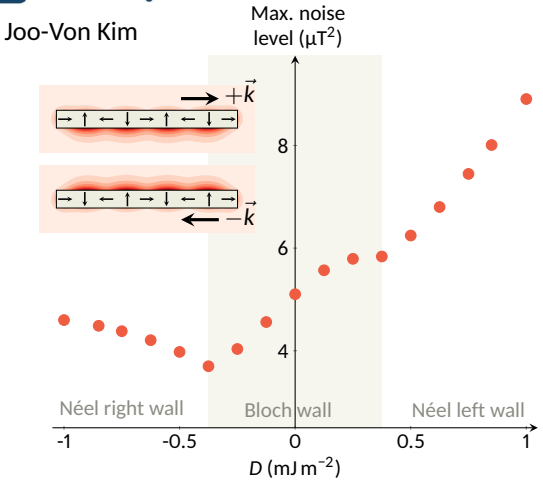
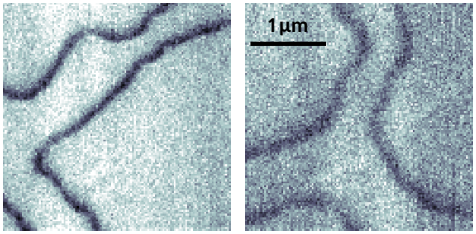
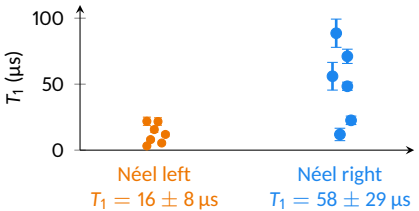


Néel left side

Néel right side

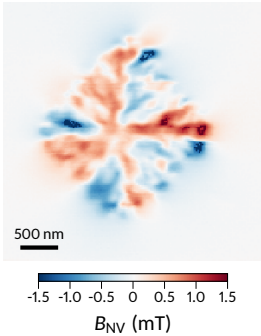




Summary

Room temperature vortices in a 2D ferromagnet

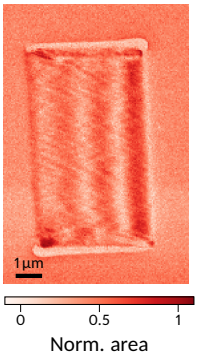
Elias Sfeir, Carolin Schrader



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

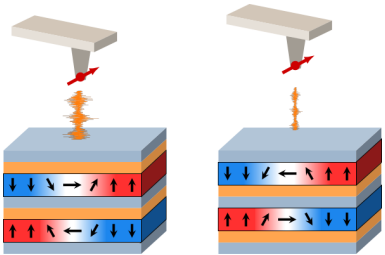
Imaging of spin waves

Roméo Beignon



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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