# AF-01 Statics and dynamics of complex magnetic states in microstructures

Aurore Finco

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

*CNRS and Université de Montpellier, Montpellier, France*



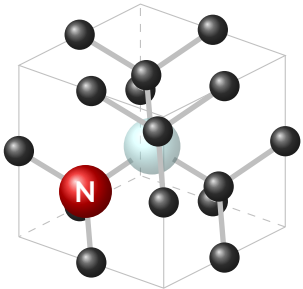

Intermag, April 14th 2026, Manchester

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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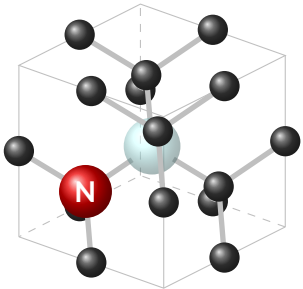


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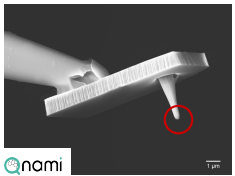


P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

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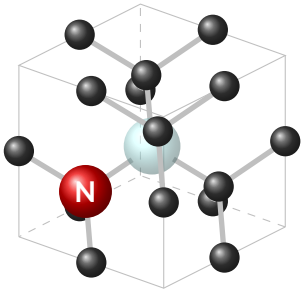


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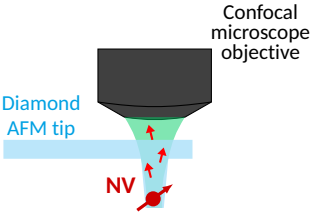


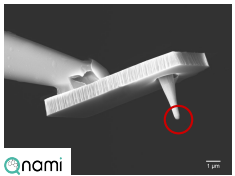


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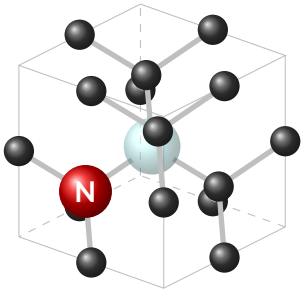


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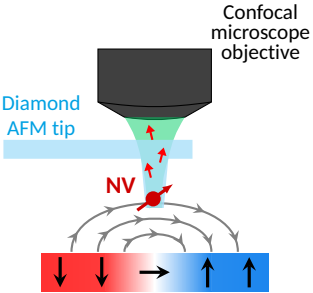


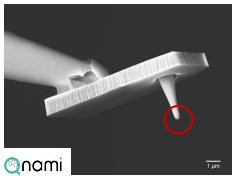


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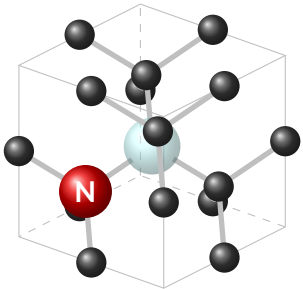


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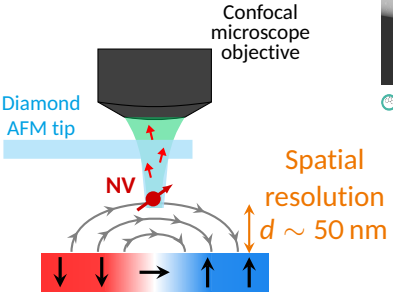


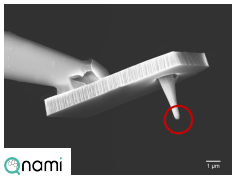


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# Why is NV microscopy spreading so fast?

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

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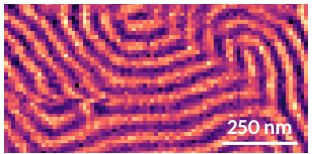
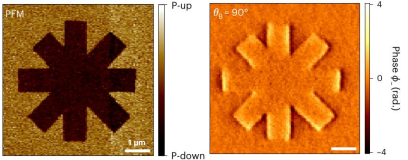
## Antiferromagnets ($BiFeO_3$)



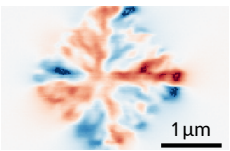

A. Finco and V. Jacques. *APL Mater.* 11 (2023), 100901

## Ferroelectrics



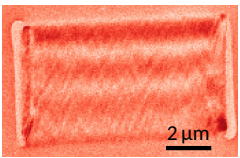

W. S. Huxter *et al.* *Nat. Phys.* 19 (2023), 644

## 2D magnets ($Fe_5GeTe_2$)




E. Sfeir *et al.* *Phys. Rev. Mater.* 9 (2025), 114003

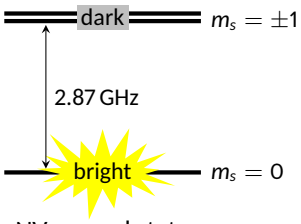
## Spin waves




R. Beignon *et al.* *in preparation* (2026)

# Measuring magnetic field with a NV center

Spin-dependent fluorescence



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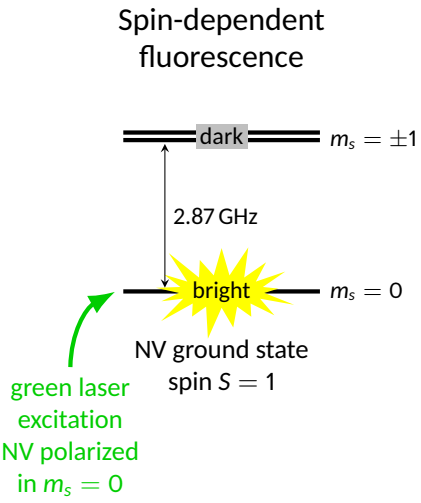

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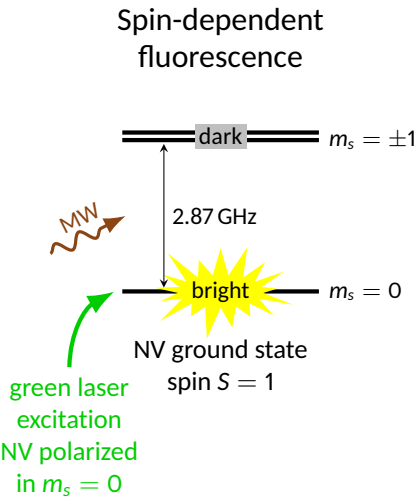


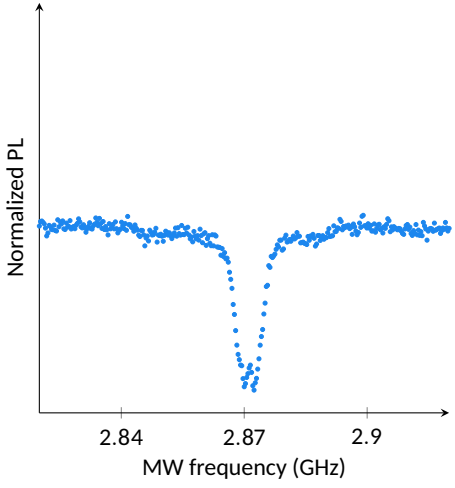

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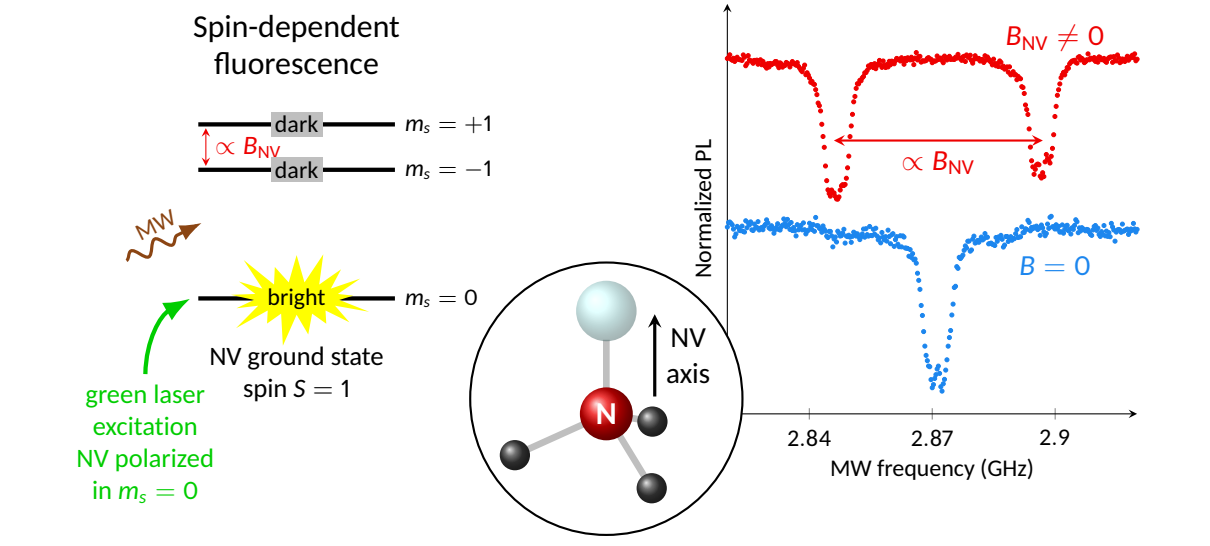
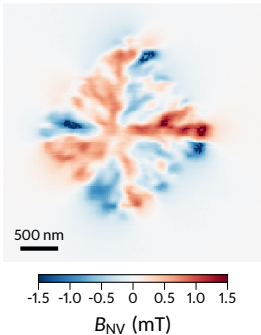


# Outline

**Room temperature vortices in a 2D ferromagnet**

Elias Sfeir, Carolin Schrader

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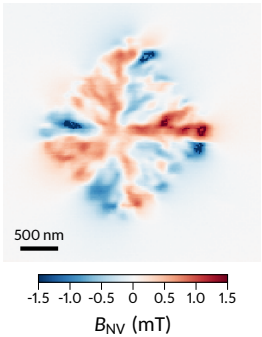


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**Imaging of spin waves**

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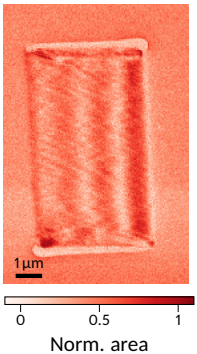


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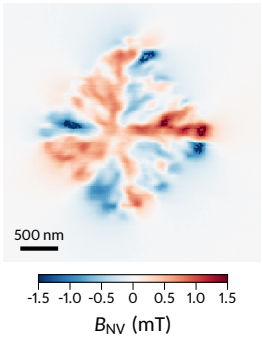


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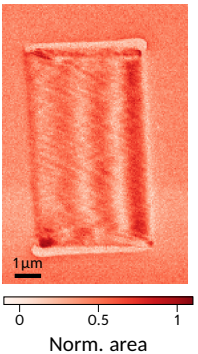


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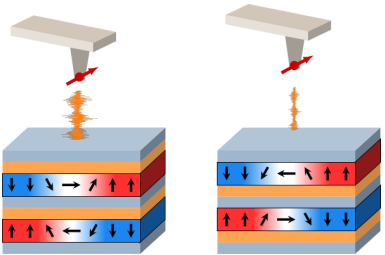

A. Finco *et al.* *Physical Review Letters* 135 (2025), 136703

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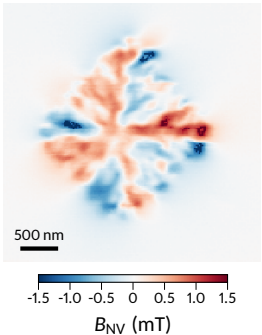


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Spin wave noise to probe magnetic handedness



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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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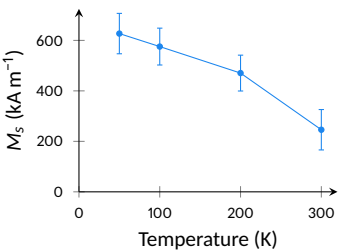


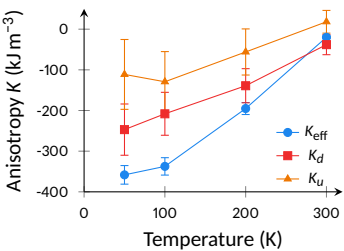

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SPIN IN ELECTRONICS

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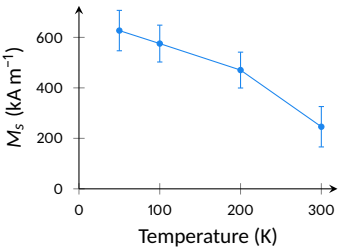
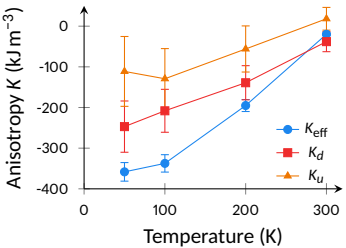
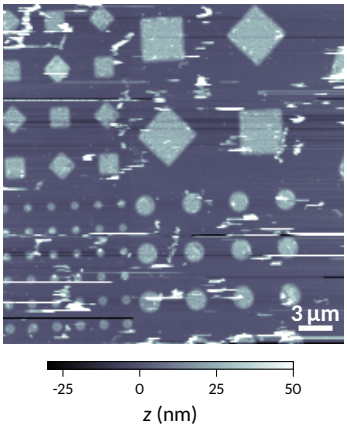
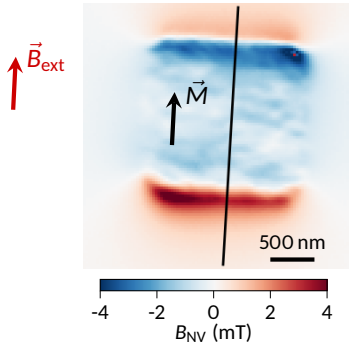


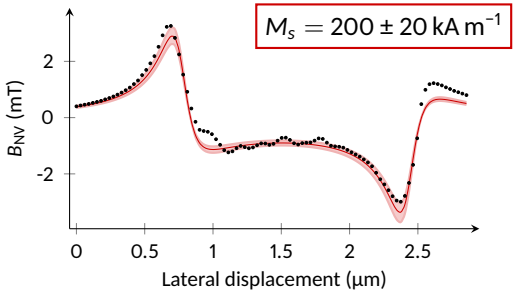




## AFM scan



# Measurement of the saturation magnetization

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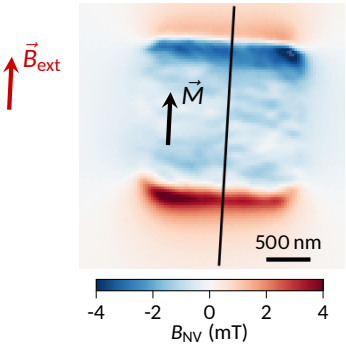


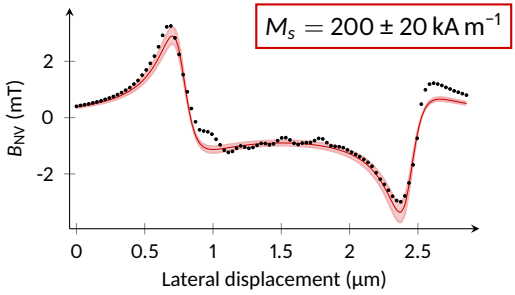


**No effect of confinement on $M_s$ → no change of $T_C$**

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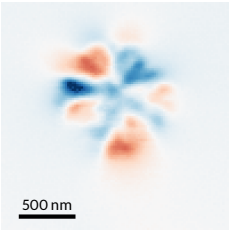
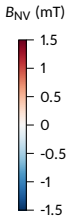
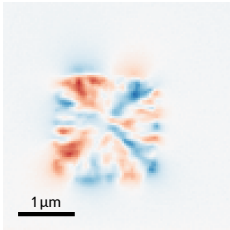
# Vortices in micro-squares



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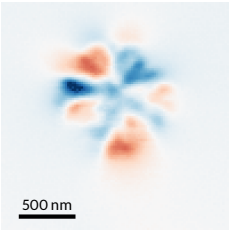
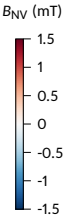
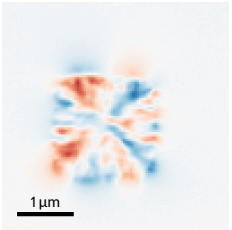
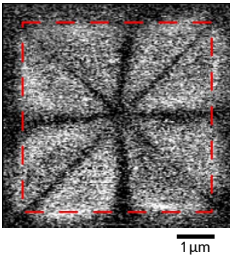



Early NV data on vortices in Py




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

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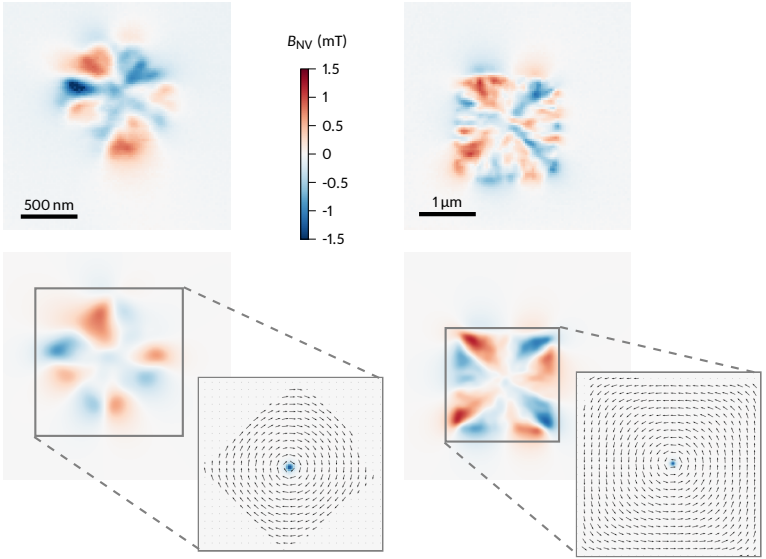


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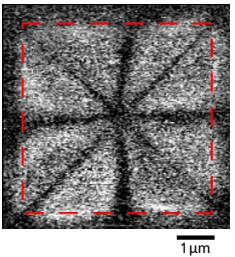


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Micromagnetic simulations including $M_s$ disorder

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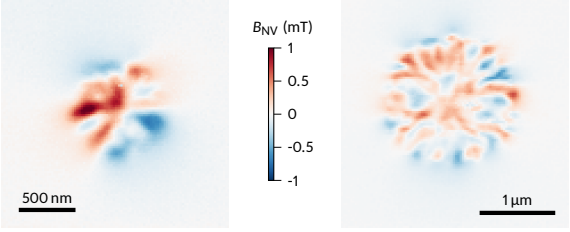

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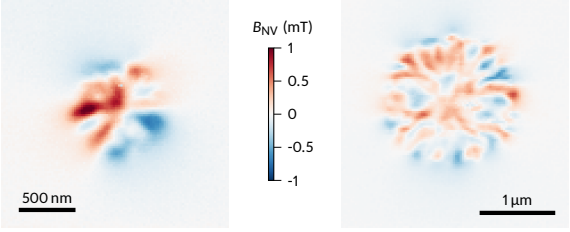


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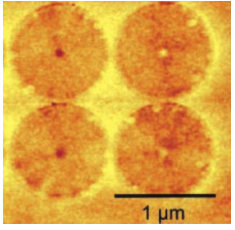


T. Shinjo *et al.* *Science* 289 (2000), 930

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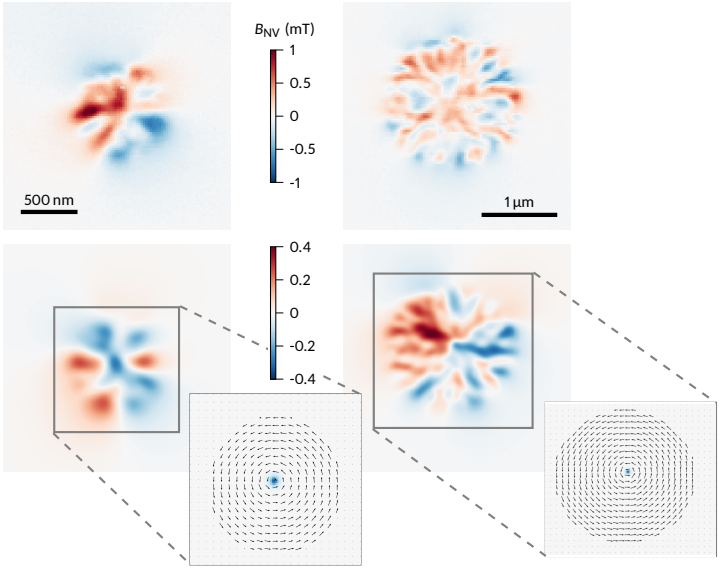
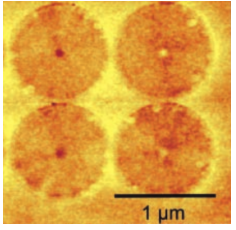



MFM data on vortices in Py




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

Micromagnetic simulations including $M_s$ disorder

# Outline

Room temperature vortices in a 2D ferromagnet

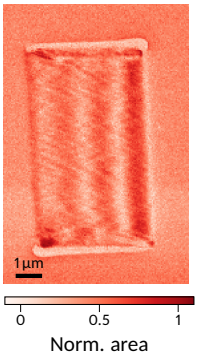
Elias Sfeir, Carolin Schrader




E. Sfeir *et al. Phys. Rev. Mater.* 9 (2025), 114003

**Imaging of spin waves**

Roméo Beignon




R. Beignon *et al. in preparation* (2026)

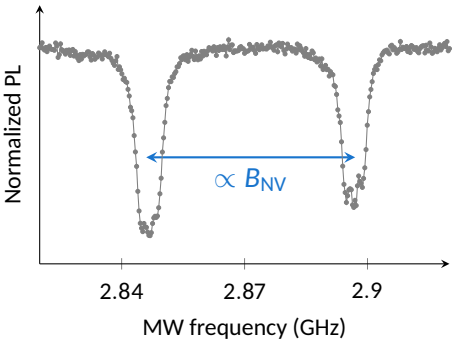
Spin wave noise to probe magnetic handedness



A. Finco *et al. Physical Review Letters* 135 (2025), 136703

# Imaging of spin waves with NV microscopy

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




Shift ➔ Static stray field

# Imaging of spin waves with NV microscopy

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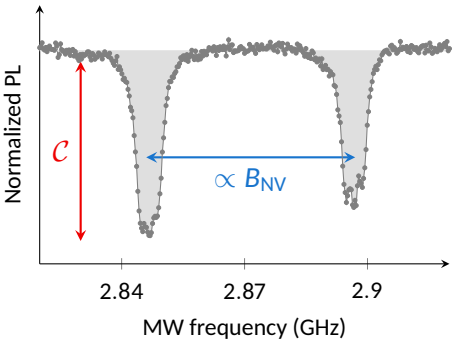
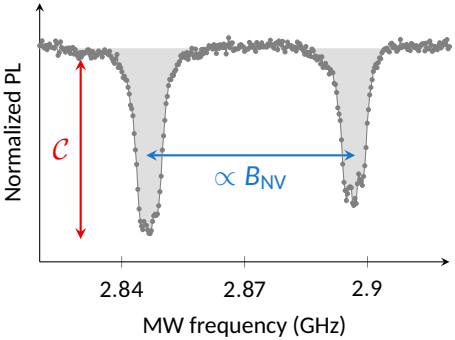



Shift ➔ Static stray field

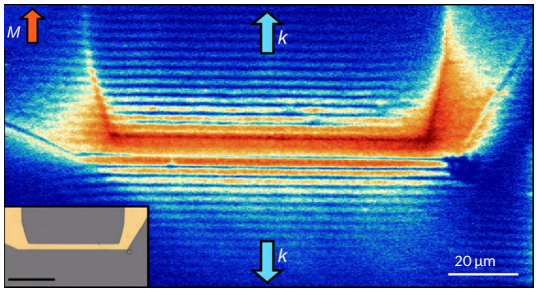
Contrast $\mathcal{C}$ or area ➔ MW power

# Imaging of spin waves with NV microscopy

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




Pioneering work: van der Sar lab (TU Delft)




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

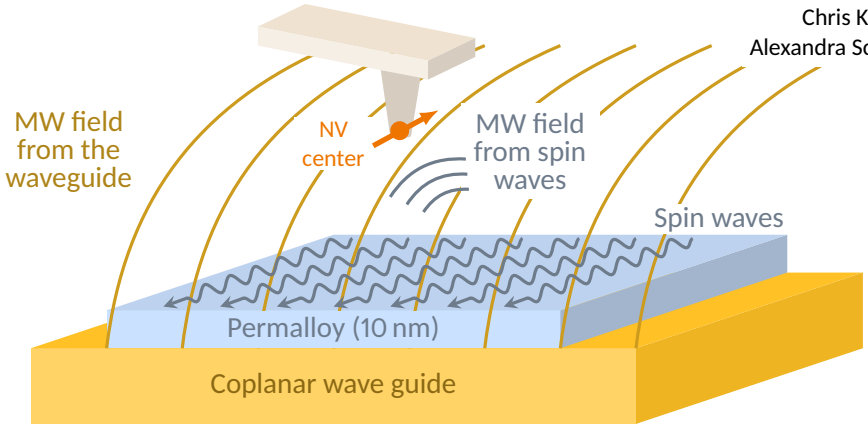
Shift ➔ Static stray field

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

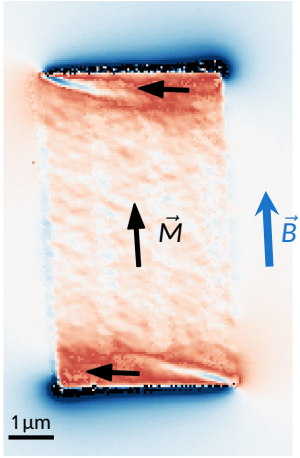
# Experiments on Py microstructures

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



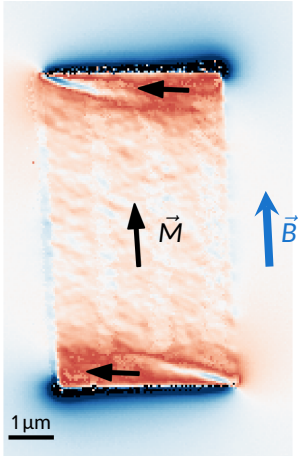
# Imaging propagating spin waves

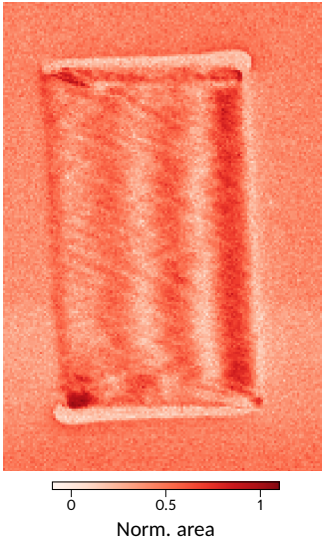



Excitation at 2.87 GHz

$B = 1.4$ mT

# Imaging propagating spin waves

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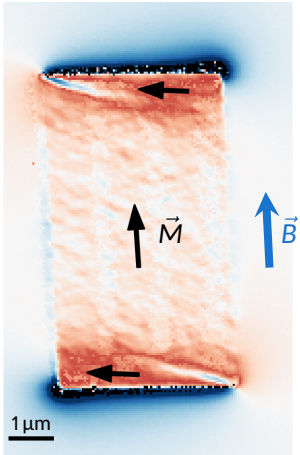


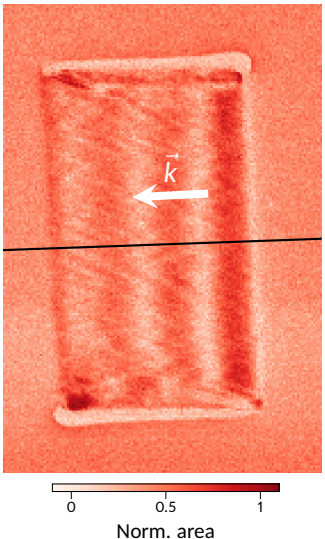


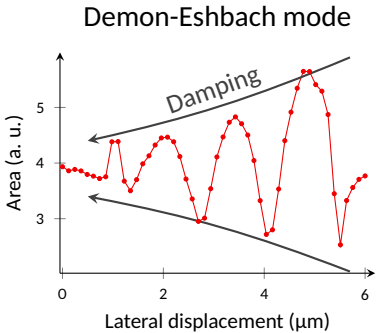


Excitation at 2.87 GHz

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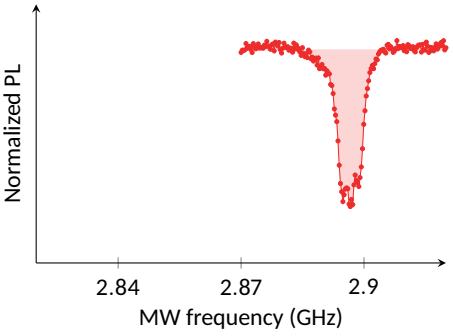
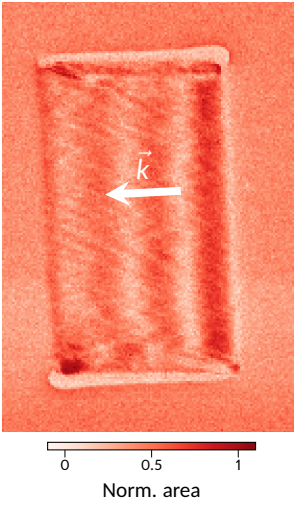
# Why do we see a single direction of $\vec{k}$?



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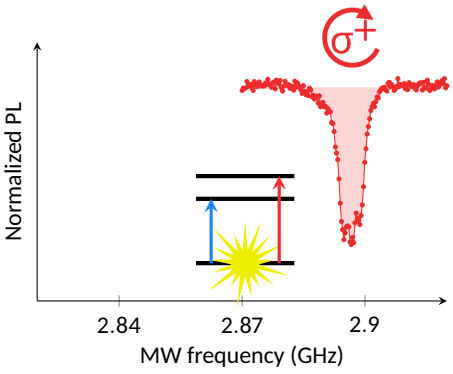
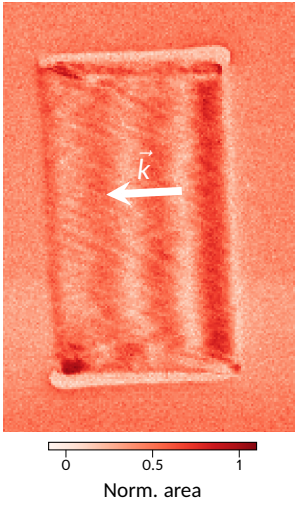
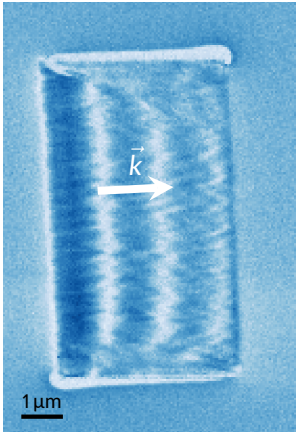


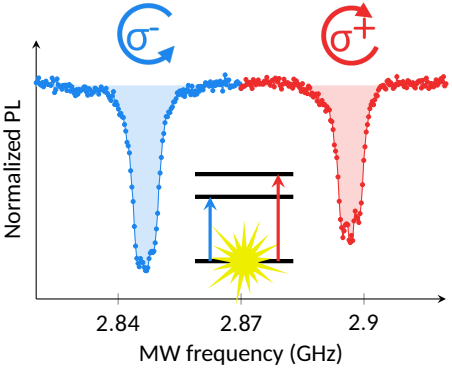

I. Bertelli *et al.* *Sci. Adv.* 6 (2020), eabd3556

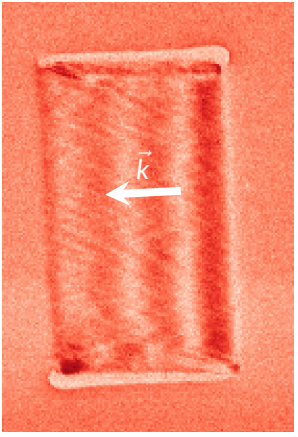
R. Beignon *et al.* *in preparation* (2026)

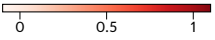
# Why do we see a single direction of $\vec{k}$?





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E. Sfeir *et al. Phys. Rev. Mater.* 9 (2025), 114003

Imaging of spin waves

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R. Beignon *et al. in preparation* (2026)

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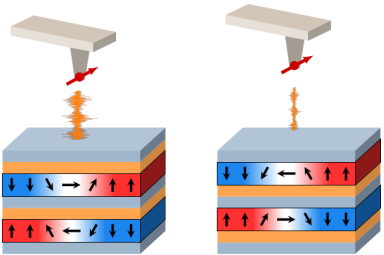
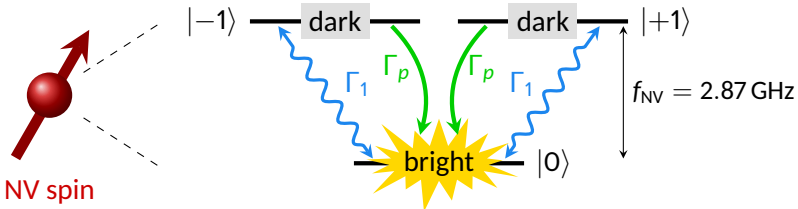


A. Finco *et al. Physical Review Letters* 135 (2025), 136703

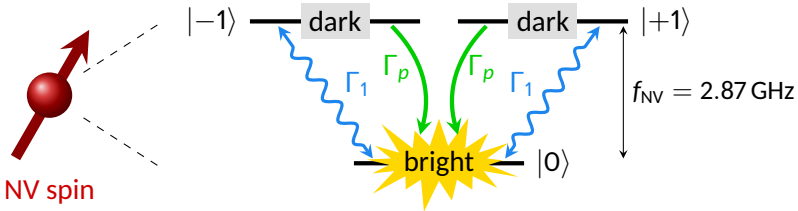
# Effect of magnetic noise on the photoluminescence




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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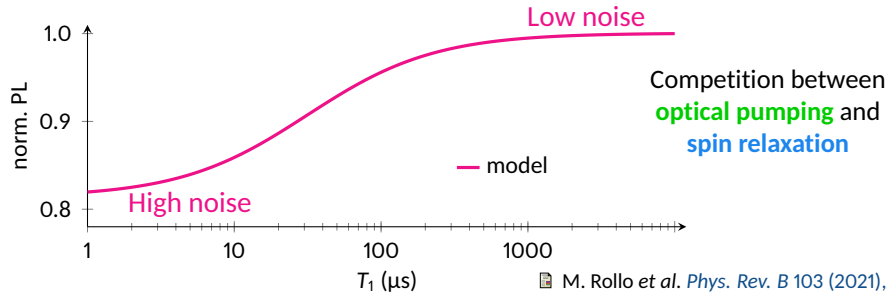


M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

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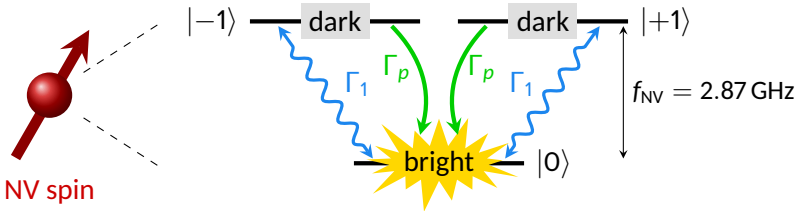


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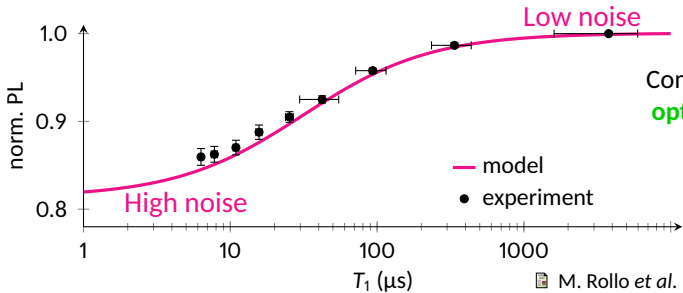
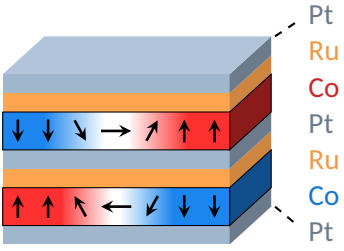



Competition between **optical pumping** and **spin relaxation**

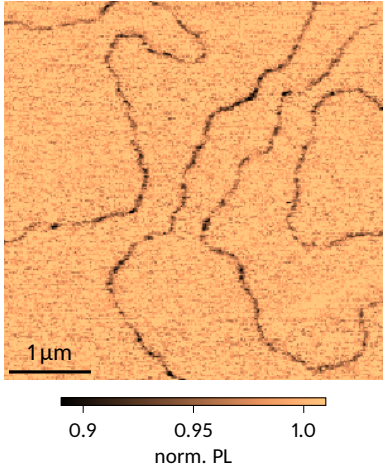
M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

# Antiferromagnetic domain walls probed with noise



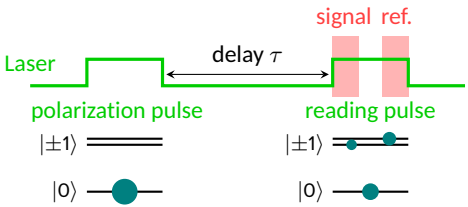

W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34

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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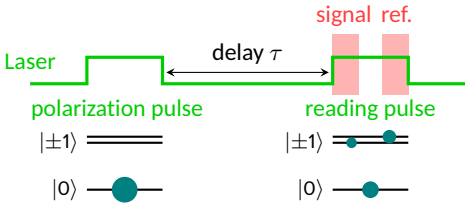


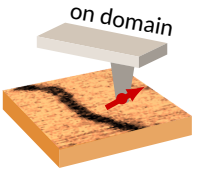


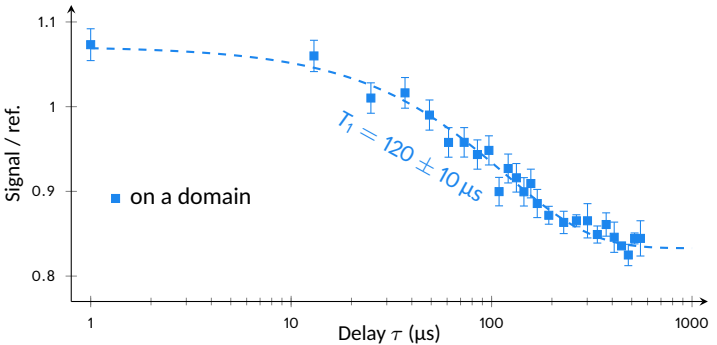

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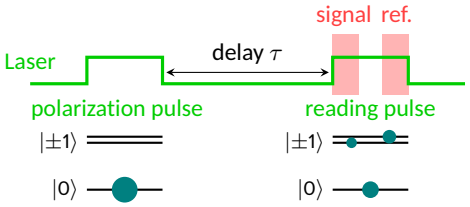
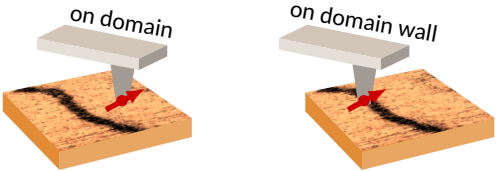
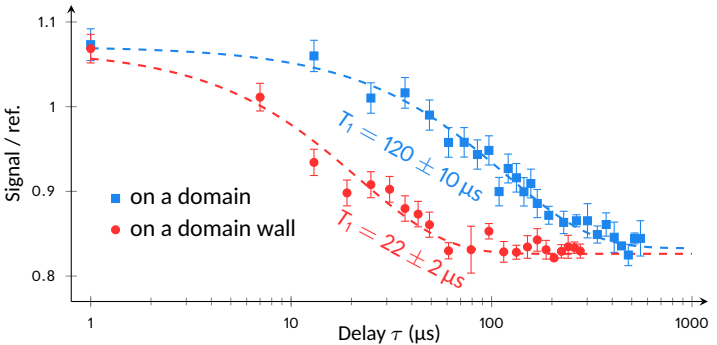


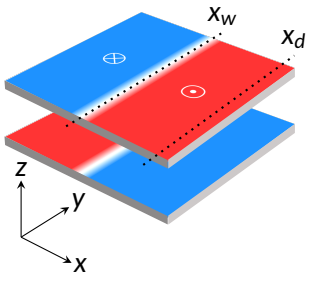



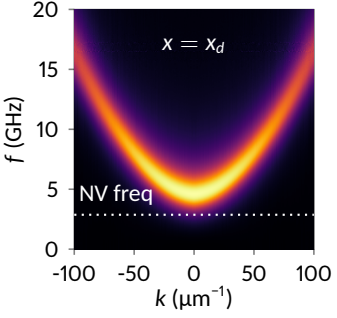

→ **Enhancement of the spin relaxation at walls**

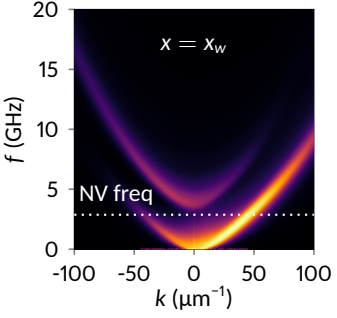


# Origin of the noise: spin waves

Jean-Paul Adam, Joo-Von Kim



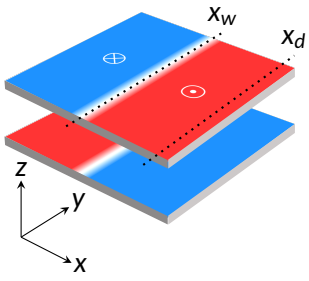



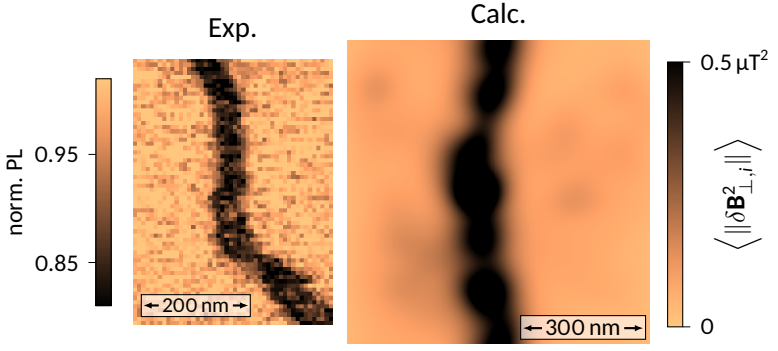

In-plane magnetized region + no spin wave gap in the domain walls

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

# Origin of the noise: spin waves

Centre de Nanosciences & de Nanotechnologies
C2N
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**

# What is happening on the other side?

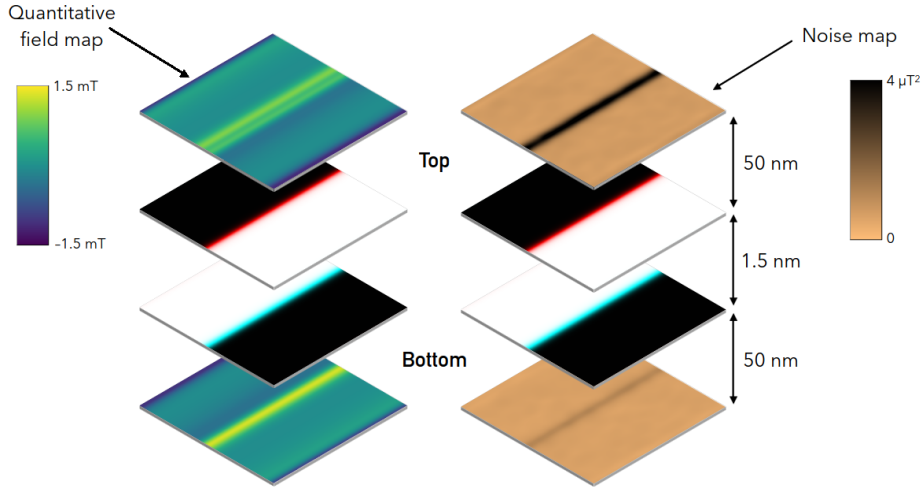
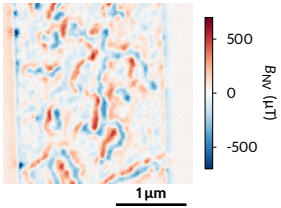



Figure by Joo-Von Kim

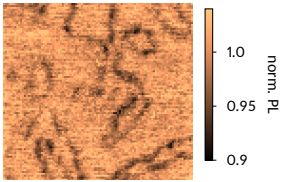
# Experiment: looking at both sides of the film

**Initial stack: Néel left**


Magnetic field map




Noise map




spintec
SPIN IN ELECTRONICS

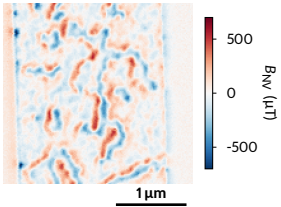
Samples: J. Urrestarazu, R. Guedas, O. Boulle

A. Finco *et al.* *Physical Review Letters* 135 (2025), 136703

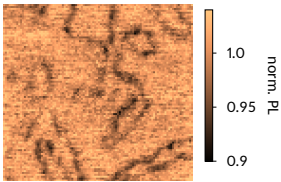
# Experiment: looking at both sides of the film

## Initial stack: Néel left

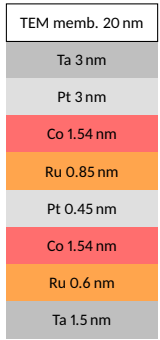

Magnetic field map



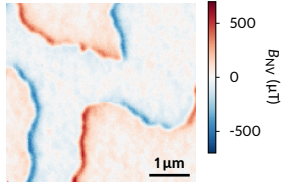

Noise map



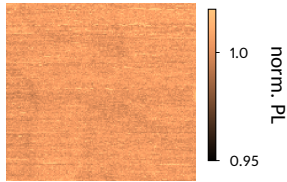

## Inverted stack: Néel right




Magnetic field map




Noise map



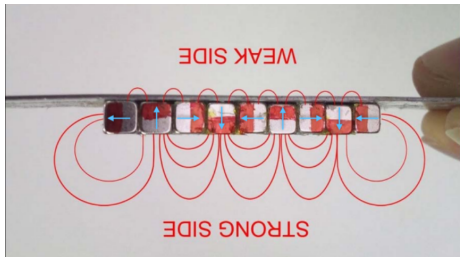

spintec
SPIN IN ELECTRONICS

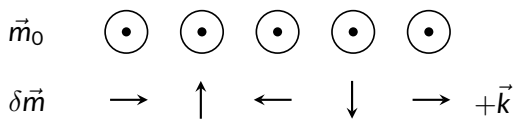
Samples: J. Urrestarazu, R. Guedas, O. Boulle

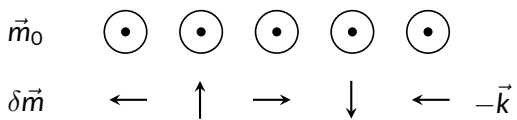
A. Finco *et al.* *Physical Review Letters* 135 (2025), 136703

# 1st ingredient : Spin waves = fridge magnets

## Halbach arrays

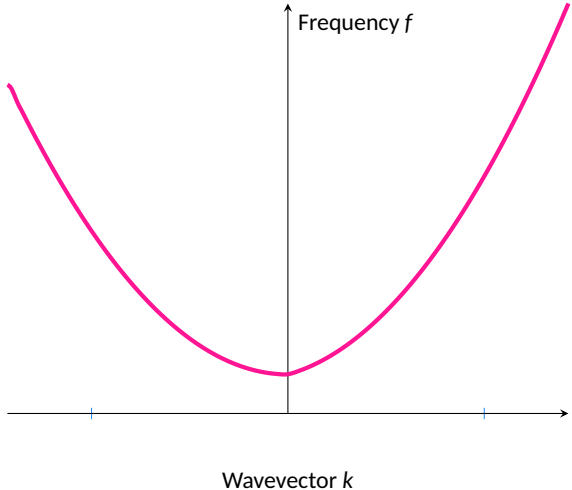




J. Mallinson. *IEEE Trans. on Mag.* 9 (1973), 678

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

# 2nd ingredient: Dzyaloshinkii-Moriya interaction

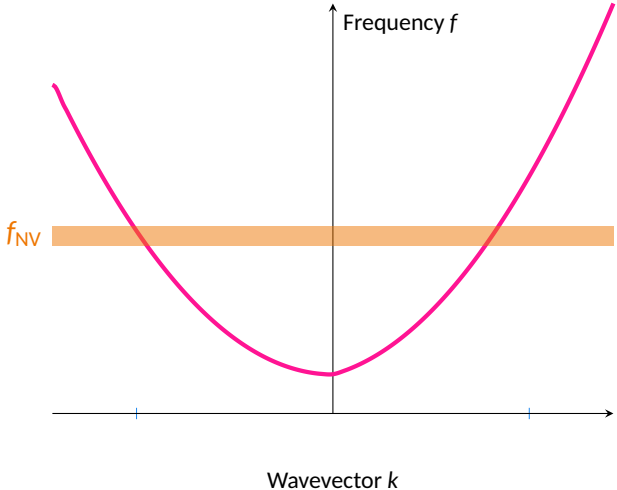
1. DMI induces non-reciprocity in the SW dispersion



# 2nd ingredient: Dzyaloshinkii-Moriya interaction

1. DMI induces non-reciprocity in the SW dispersion

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

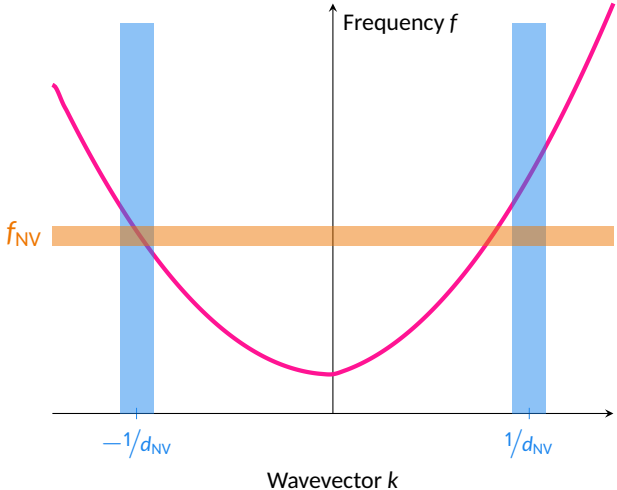


# 2nd ingredient: Dzyaloshinkii-Moriya interaction

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 $\pm 1/d_{NV}$



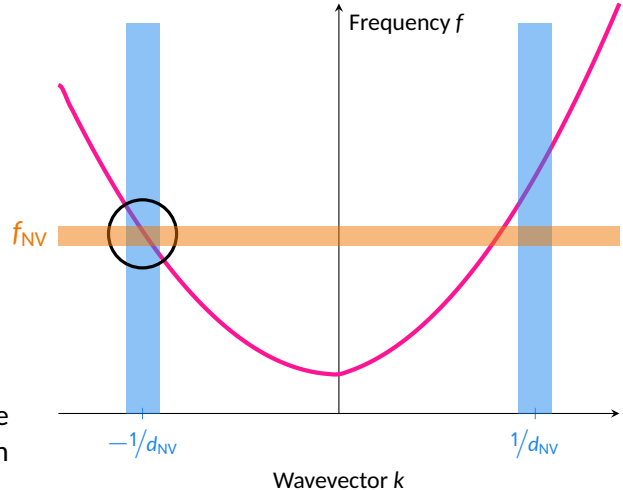
# 2nd ingredient: Dzyaloshinkii-Moriya interaction

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 $\pm 1/d_{NV}$

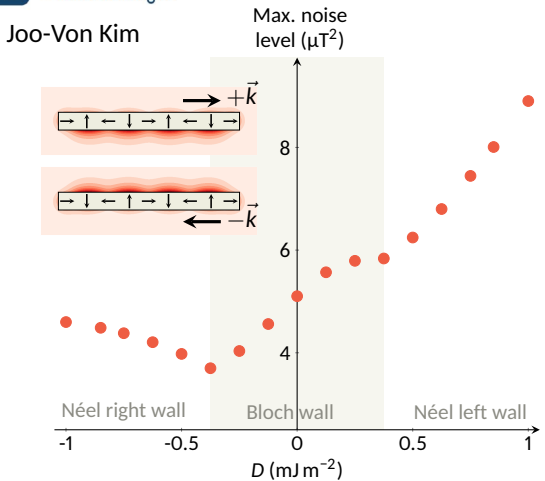
→ The NV center is more sensitive to a $k$ direction than the other



# In a single ferromagnetic layer

Centre DE Nanosciences & DE Nanotechnologies

Joo-Von Kim



# In a single ferromagnetic layer

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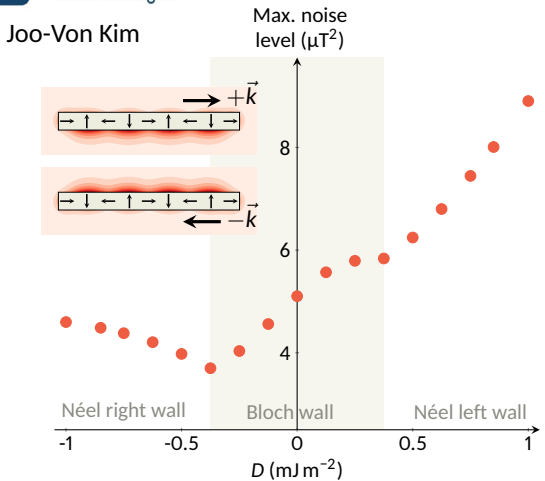
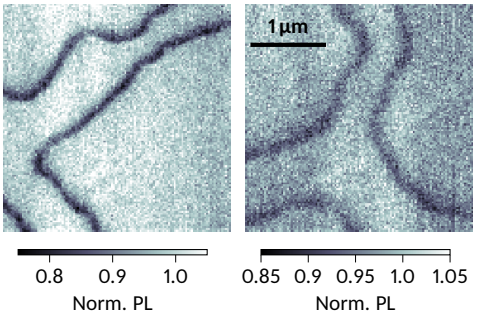
Joo-Von Kim




Néel left side

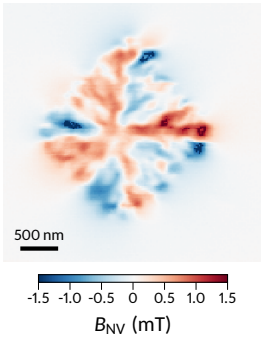
Néel right side



# Summary

## Room temperature vortices in a 2D ferromagnet

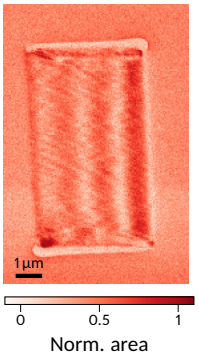
Elias Sfeir, Carolin Schrader




E. Sfeir *et al.* *Phys. Rev. Mater.* 9 (2025), 114003

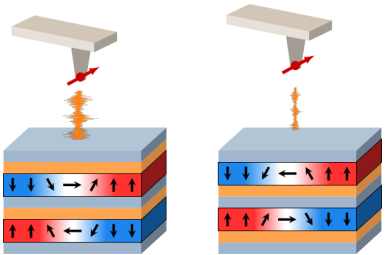
## Imaging of spin waves

Roméo Beignon




R. Beignon *et al.* *in preparation* (2026)

## Spin wave noise to probe magnetic handedness



A. Finco *et al.* *Physical Review Letters* 135 (2025), 136703

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