

Thermal and driven spin waves investigated with a scanning NV microscope

Aurore Finco

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

CNRS and Université de Montpellier, Montpellier, France



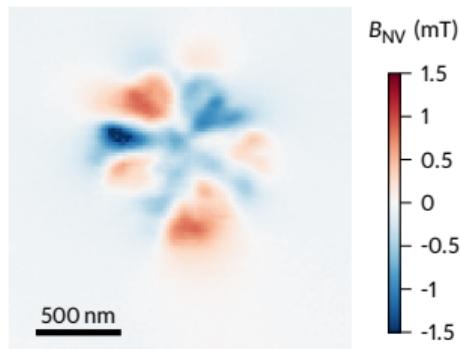
Chimera in the Alps, February 25th 2026, Les Houches

slides available at <https://magimag.eu>

NV centers can probe...

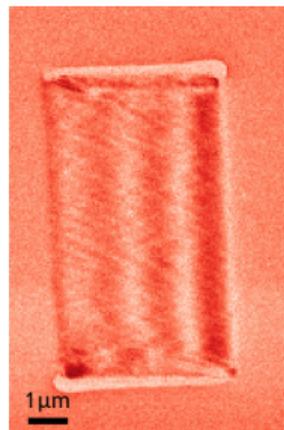
Static B field

Magnetic vortex in a 2D magnet



Microwave field

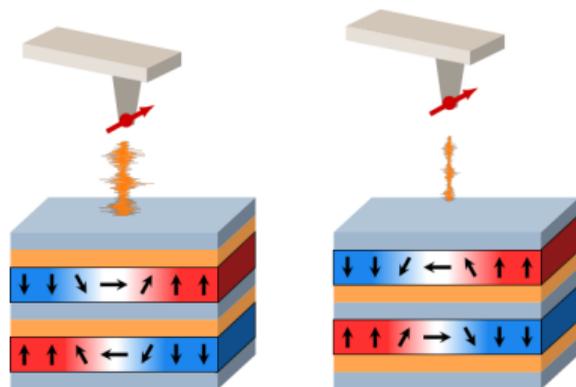
Driven spin waves



Norm. area

Magnetic noise

Thermal spin waves

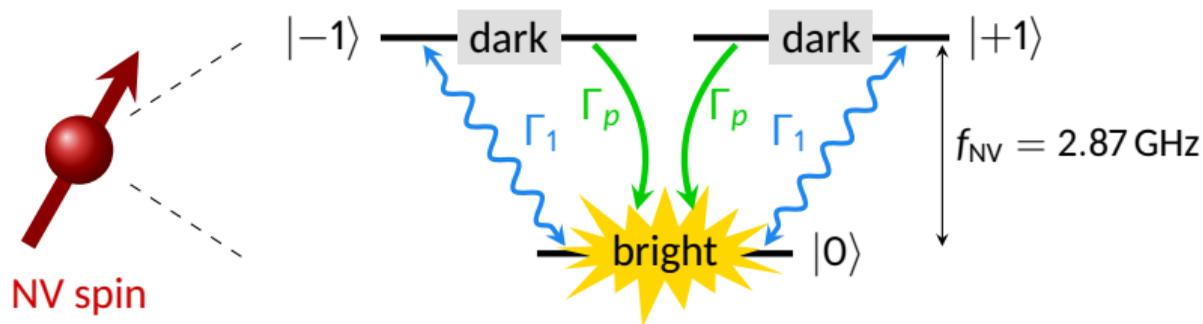


E. Sfeir et al. *Phys. Rev. Mater.* 9 (2025), 114003

A. Finco et al. *Phys. Rev. Lett.* 135 (2025), 136703

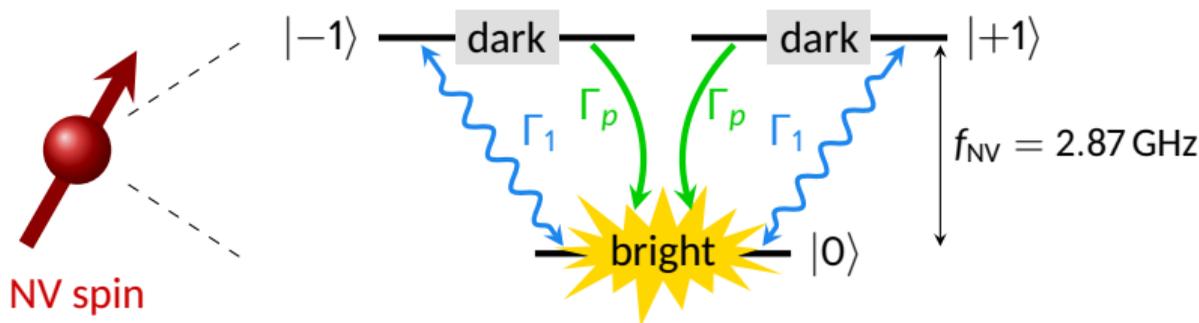
and also temperature, electric field, pressure, ...

Effect of magnetic noise on the photoluminescence

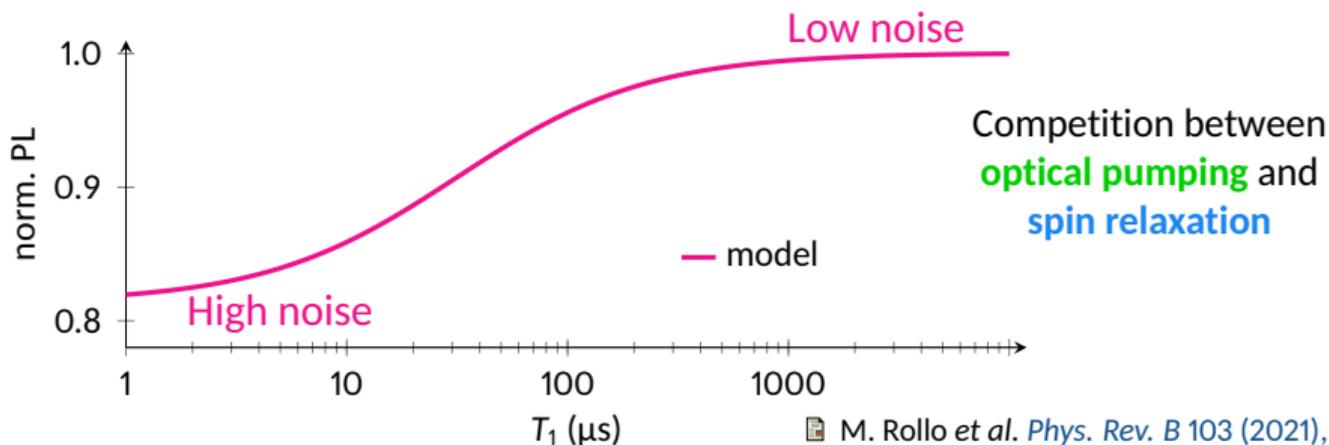


Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}

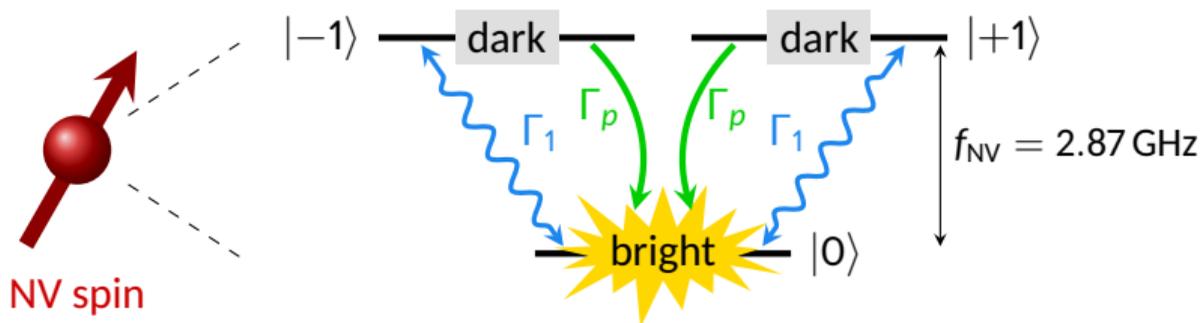
Effect of magnetic noise on the photoluminescence



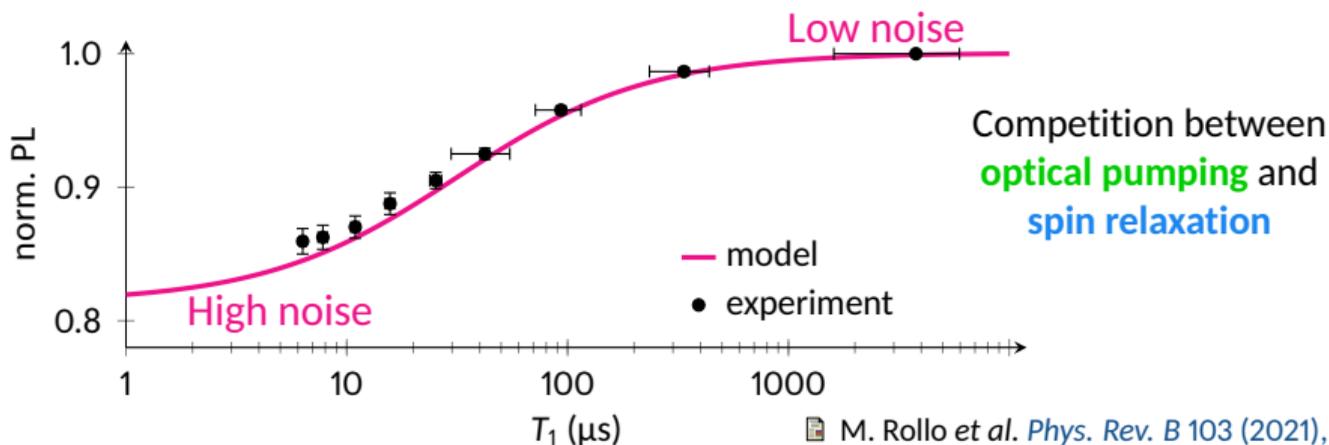
Relaxation rate $\Gamma_1 \propto S_{B_{\perp}}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}



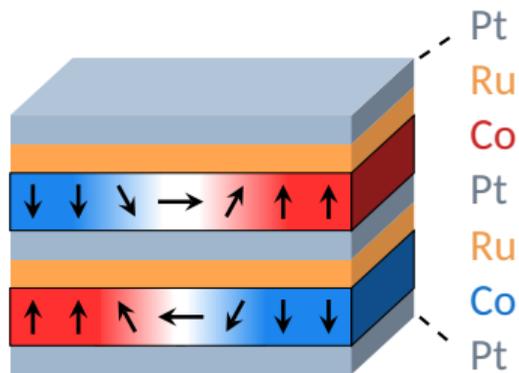
Effect of magnetic noise on the photoluminescence



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

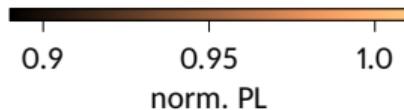
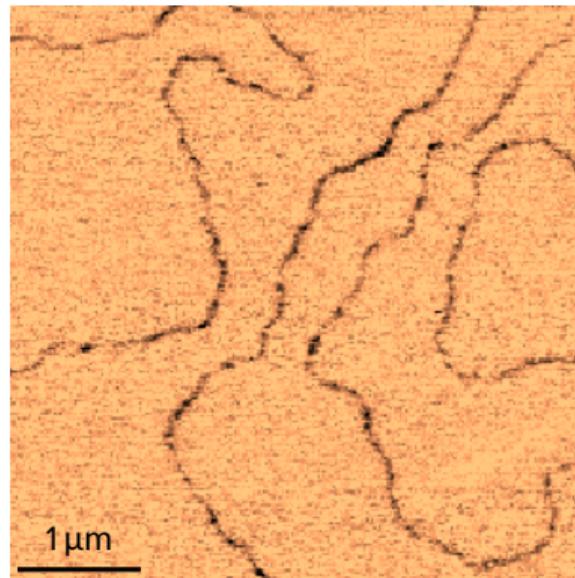


Antiferromagnetic domain walls probed with noise



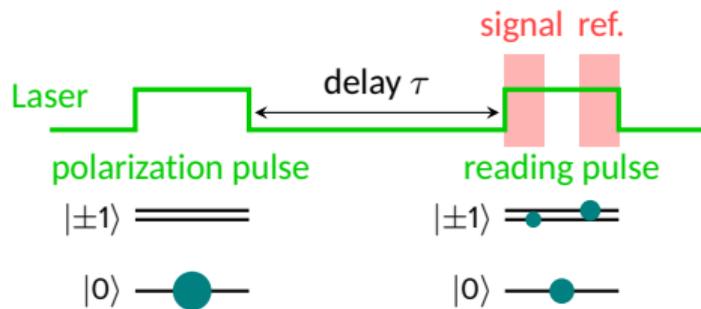
W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34–42

V. T. Pham *et al.* *Science* 384 (2024), 307–312

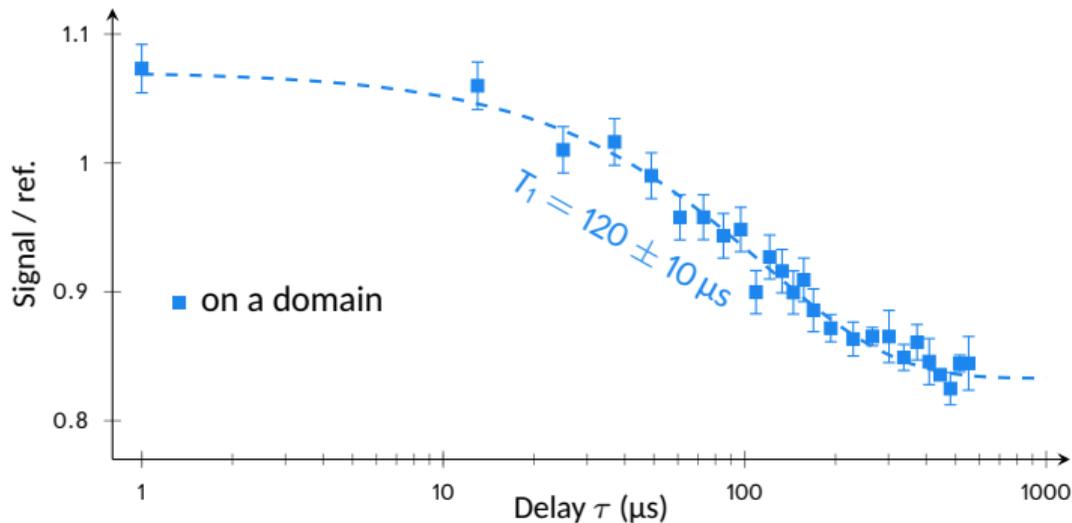
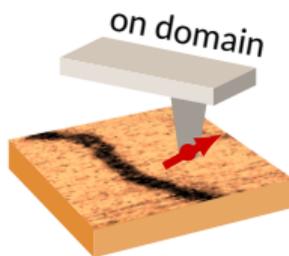
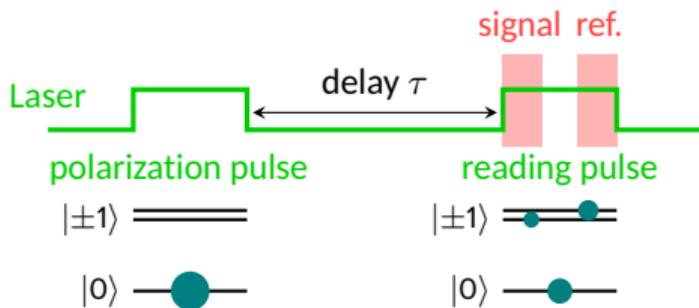


A. Finco *et al.* *Nat. Commun.* 12 (1 2021), 767

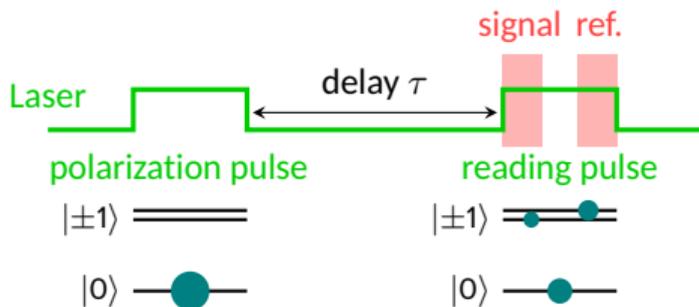
Local variation of the relaxation time



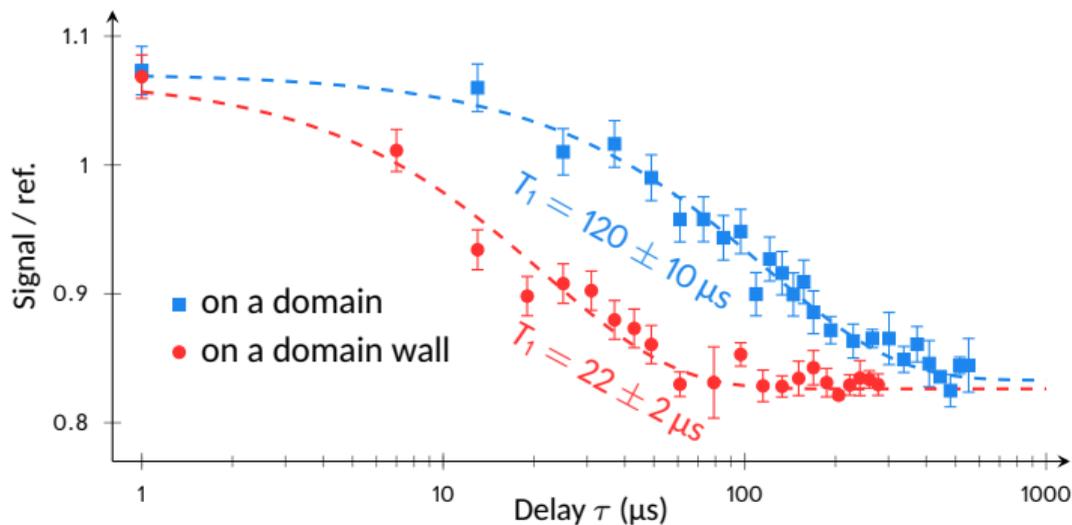
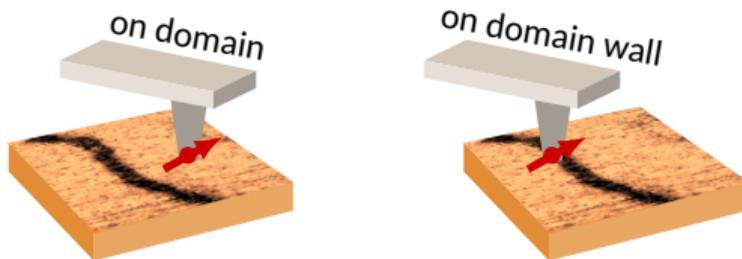
Local variation of the relaxation time



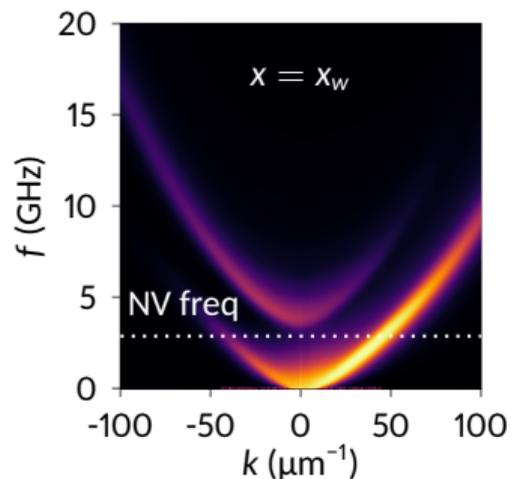
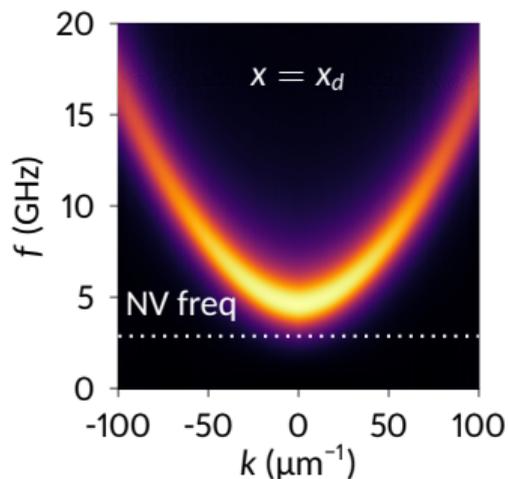
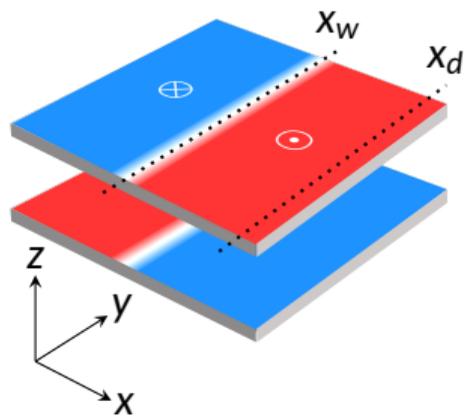
Local variation of the relaxation time



→ Enhancement of the spin relaxation at walls



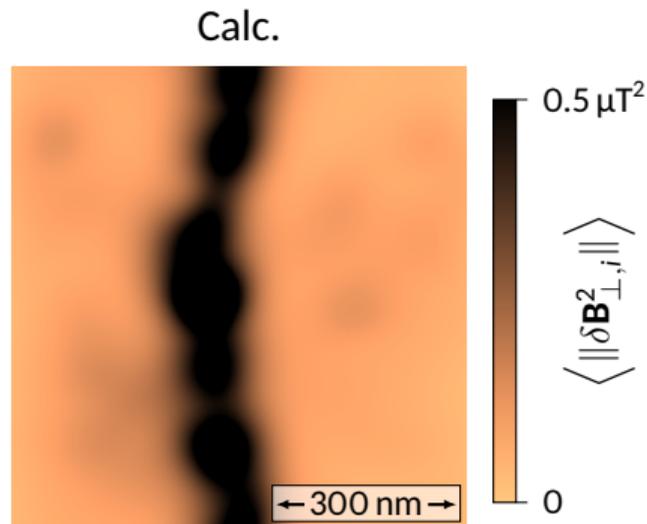
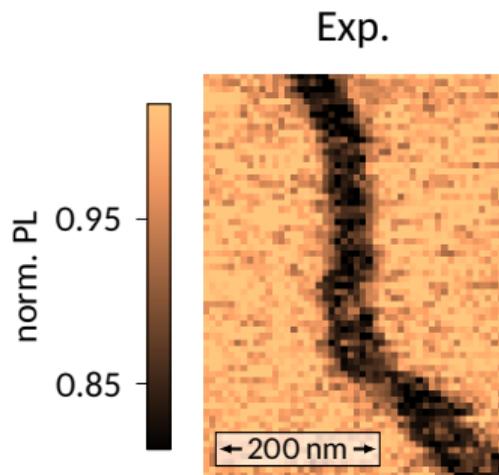
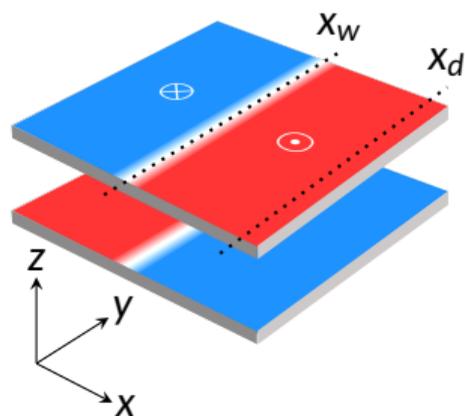
Origin of the noise: spin waves



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

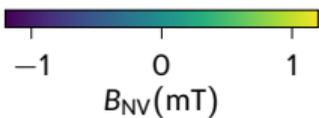
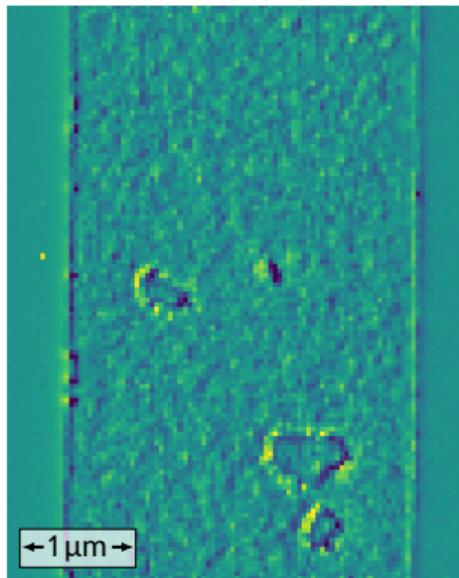


In-plane magnetized region + no spin wave gap in the domain walls

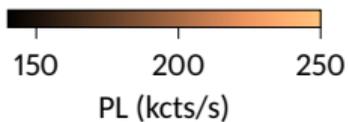
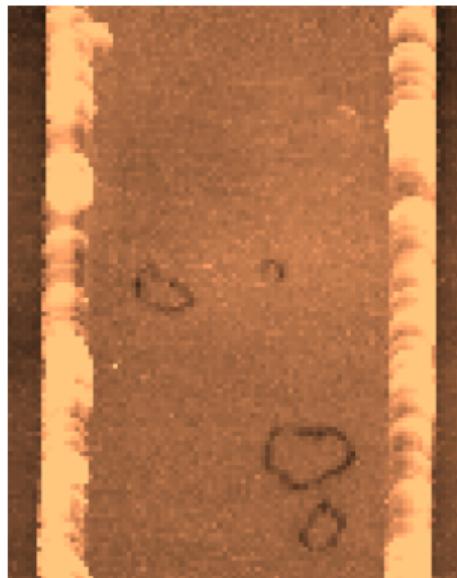
→ Presence of modes in the walls generating stray field at the NV frequency

After applying magnetic field

NV stray field map

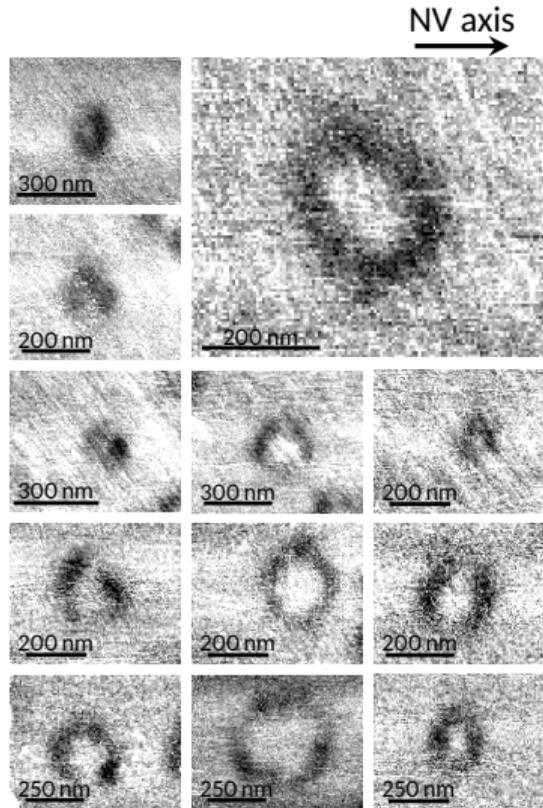


Noise (PL) map

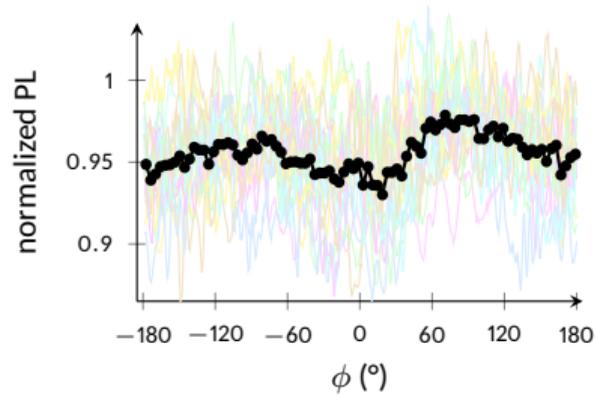
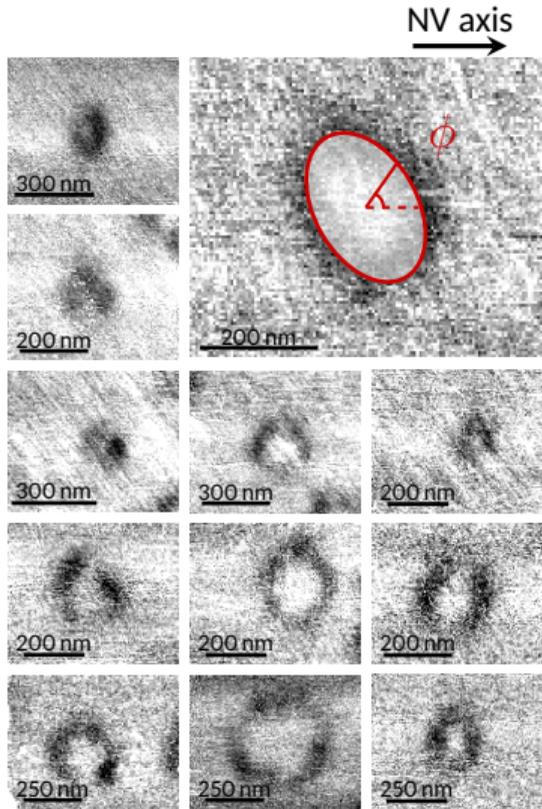


- Oop field of about 150 mT applied for nucleation
- Skyrmions and big bubbles pinned

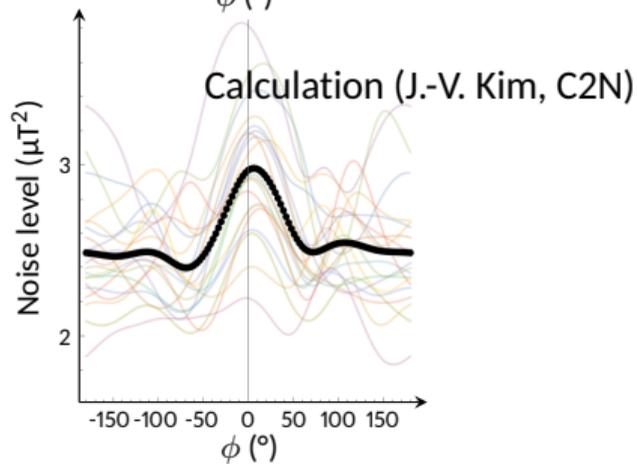
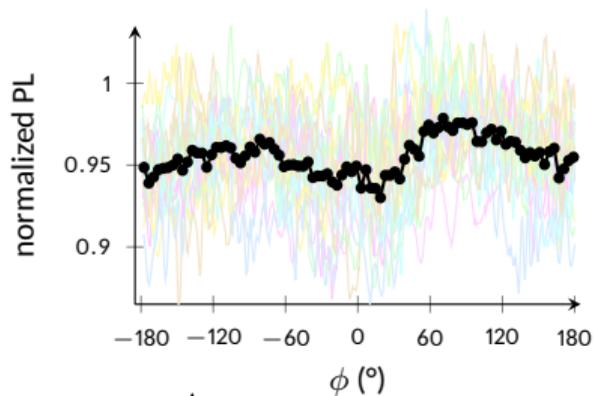
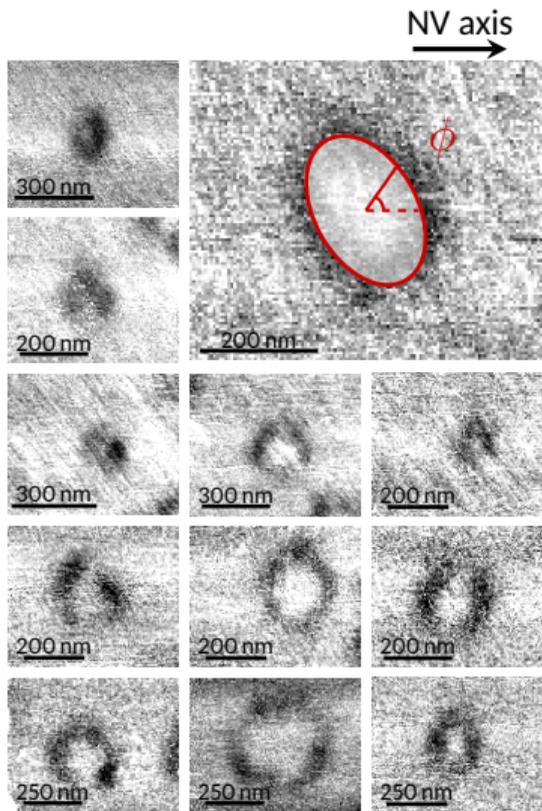
Statistics on Néel left (CCW) skyrmions



Statistics on Néel left (CCW) skyrmions

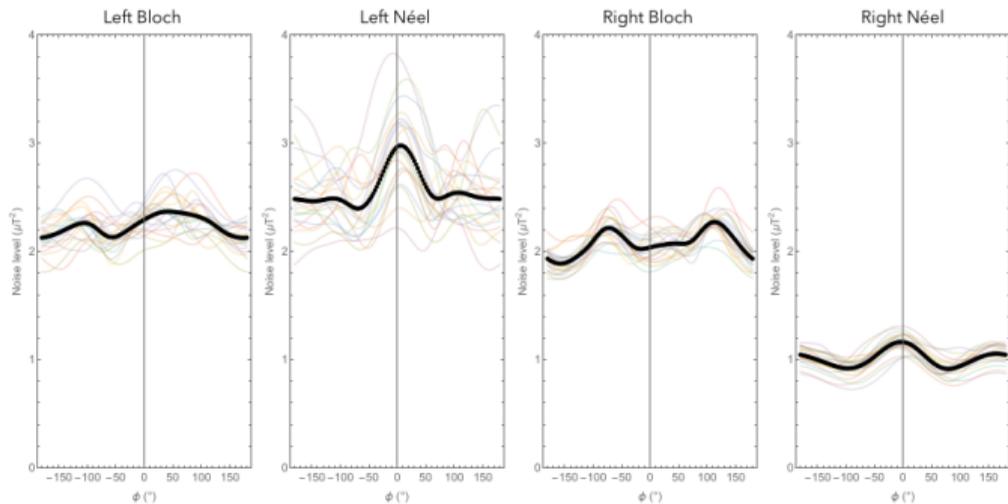


Statistics on Néel left (CCW) skyrmions

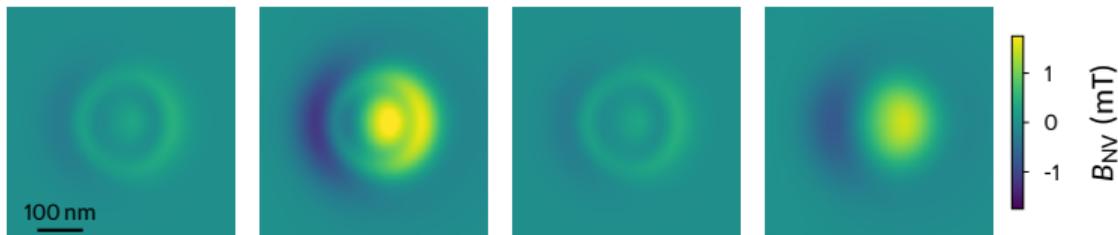


Expected pattern on other skyrmion types

Simulated noise distribution along the contour



Simulated stray field maps



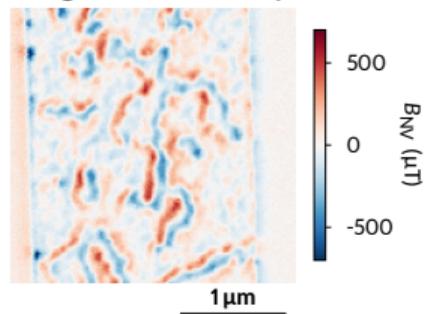
- The pattern allows us to identify Néel skyrmions
- Strong difference in noise amplitude expected between Néel left and Néel right skyrmions...
- ... while the stray field maps are very similar!

Experiment: looking at both sides of the film

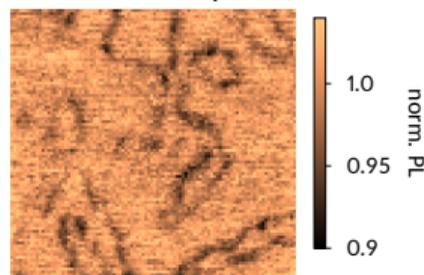
Initial stack: Néel left

TaOx 3 nm
Ru 0.6 nm
Co 1.5 nm
Pt 0.5 nm
Ru 0.8 nm
Co 1.5 nm
Pt 3 nm
Ta

Magnetic field map



Noise map

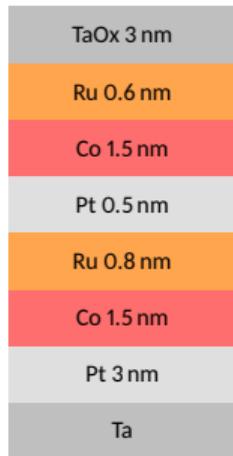


Samples: J. Urrestarazu,
R. Guedas, O. Boulle

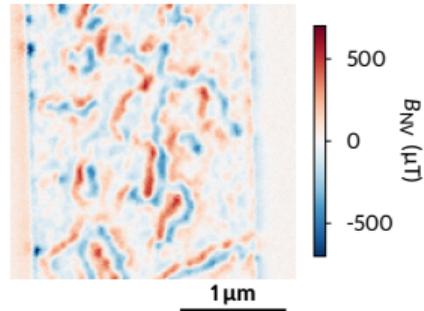
Experiment: looking at both sides of the film

Initial stack: Néel left

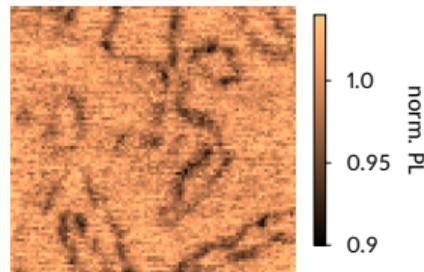
Inverted stack: Néel right



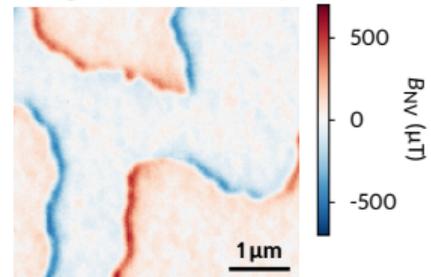
Magnetic field map



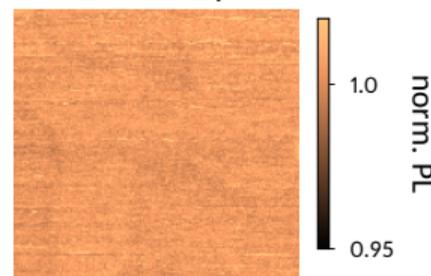
Noise map



Magnetic field map



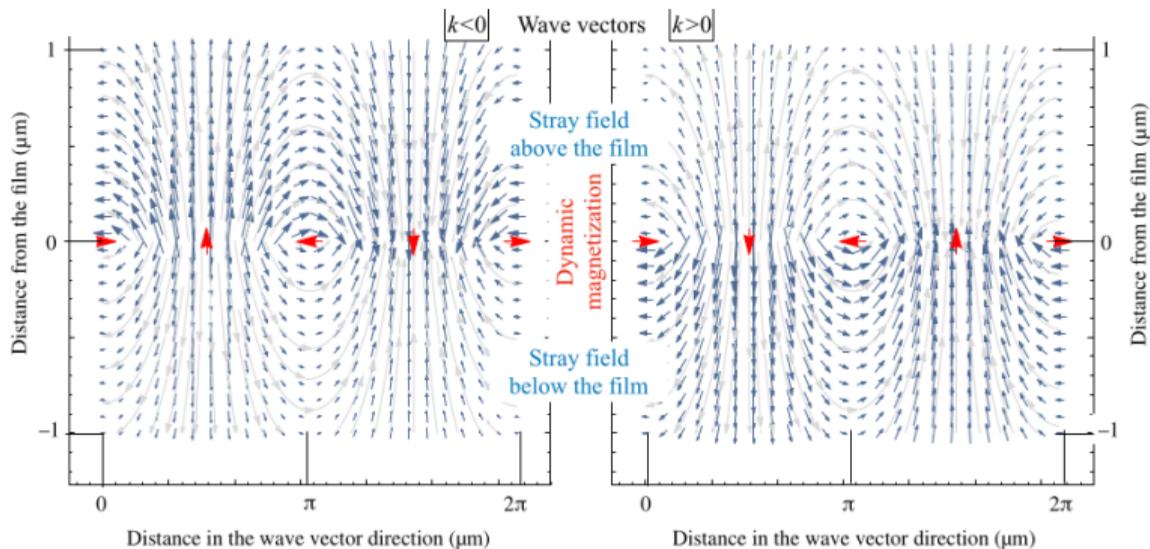
Noise map



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

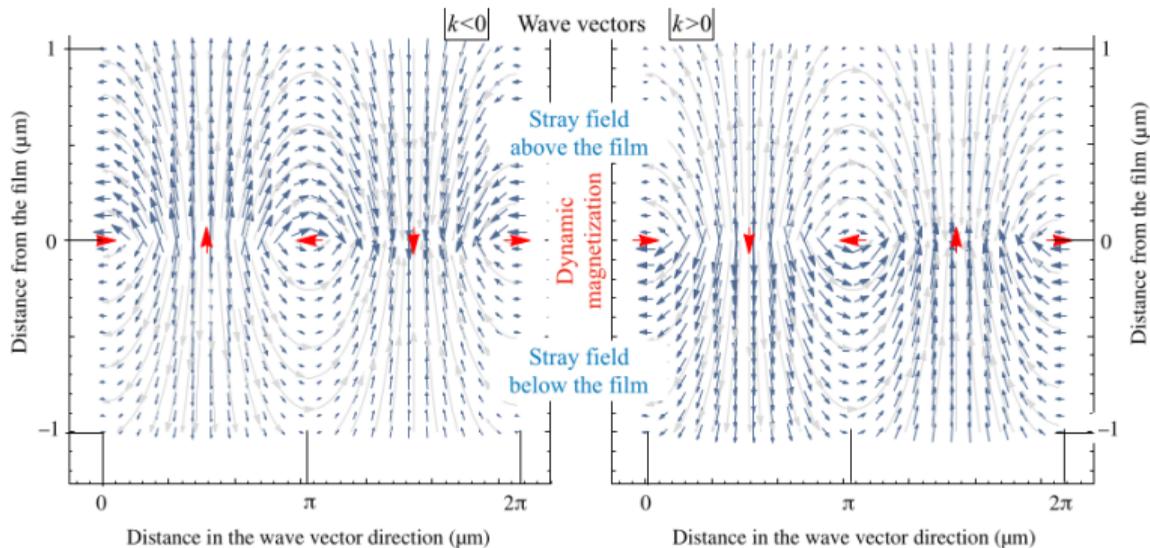
A. Finco et al. *Phys. Rev. Lett.* 135 (2025), 136703

Stray field from a propagating spin wave



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

Stray field from a propagating spin wave



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

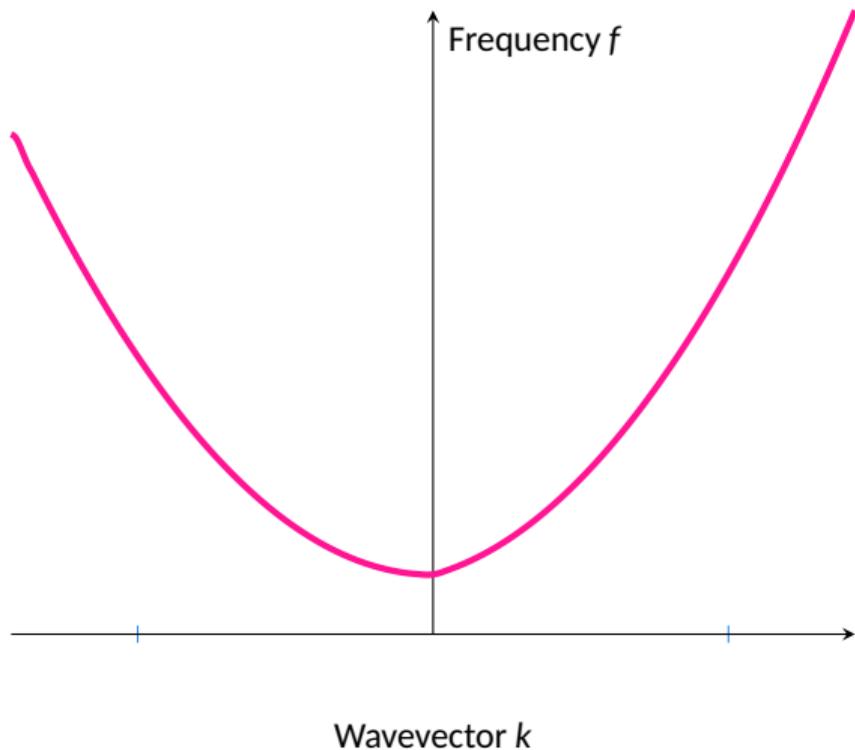
Above the film, for an in-plane propagating spin wave:

$$B_z^{SW}(\vec{k}) = \frac{\mu_0}{2} e^{-kz-i\omega t} (1 - e^{-kd}) \left(M_z(\vec{k}) - i \frac{k_y}{k} M_y(\vec{k}) \right) \text{ and } B_y^{SW}(\vec{k}) = -i \text{sign}(k_y) B_z^{SW}(\vec{k})$$

→ Vanishing stray field on a side of the film + polarization-momentum locking

The role of the Dzyaloshinskii-Moriya interaction

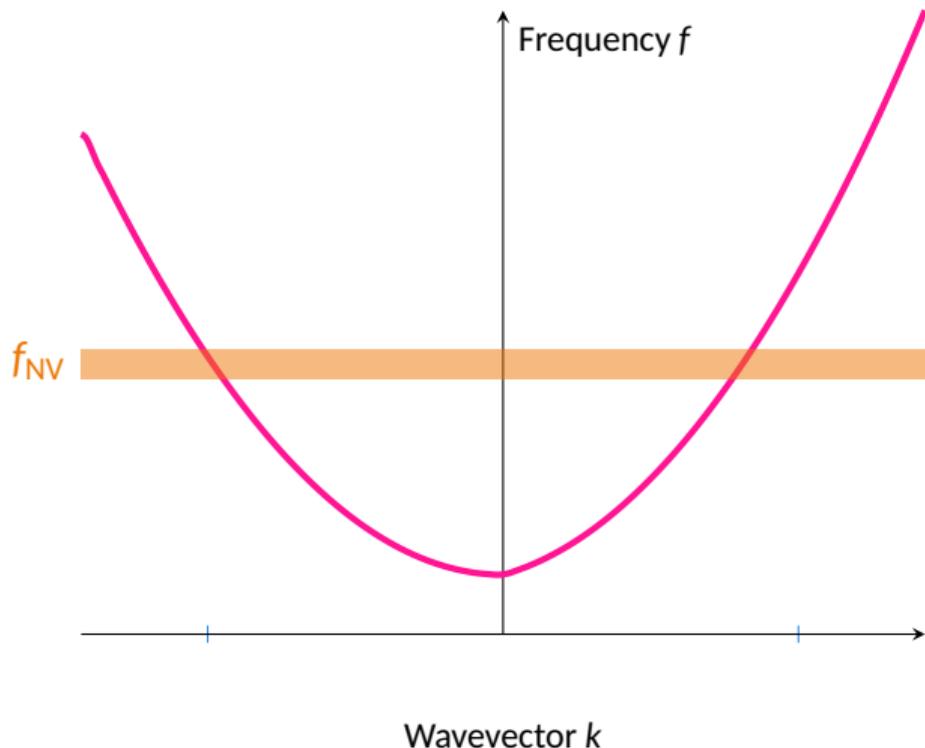
1. DMI induces non-reciprocity in the SW dispersion



The role of the Dzyaloshinskii-Moriya interaction

1. DMI induces non-reciprocity in the SW dispersion

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

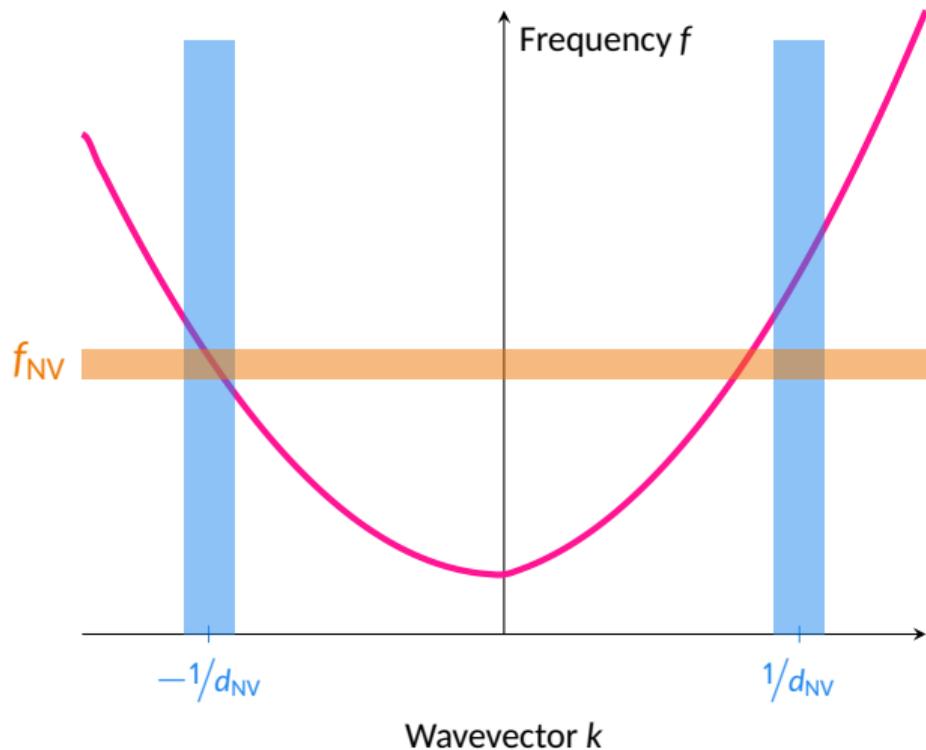


The role of the Dzyaloshinskii-Moriya interaction

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 $\pm 1/d_{\text{NV}}$



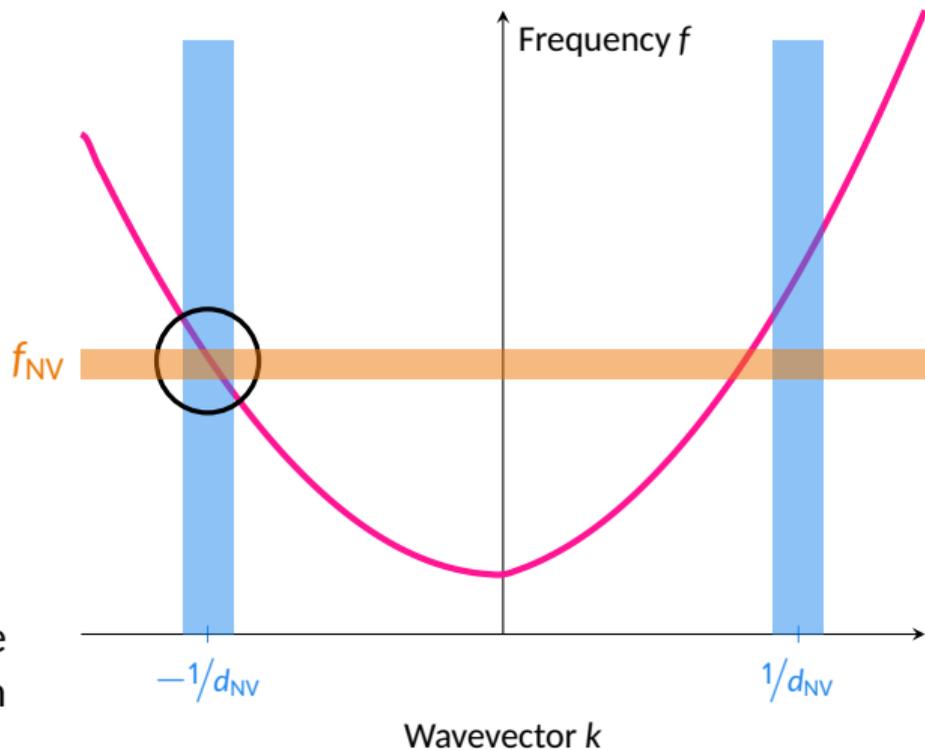
The role of the Dzyaloshinskii-Moriya interaction

1. DMI induces non-reciprocity in the SW dispersion

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

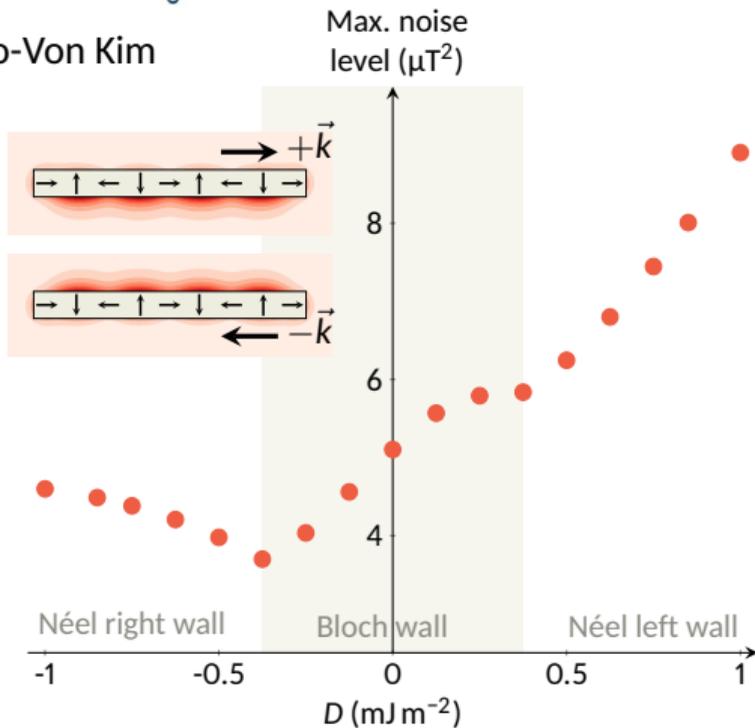
3. The NV probe is filtering SW at $\pm 1/d_{\text{NV}}$

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



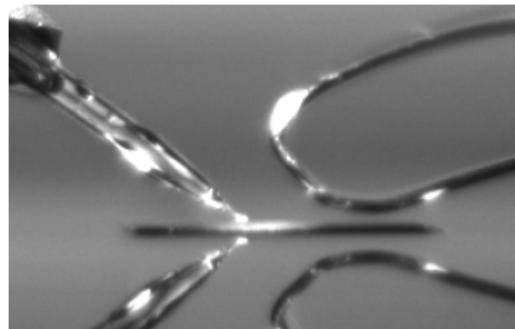
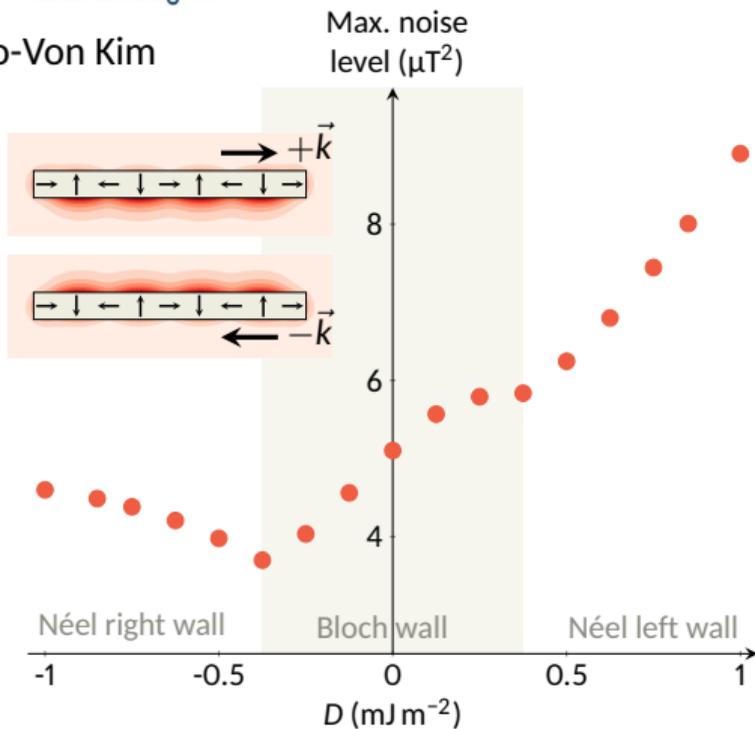
In a single ferromagnetic layer

Joo-Von Kim



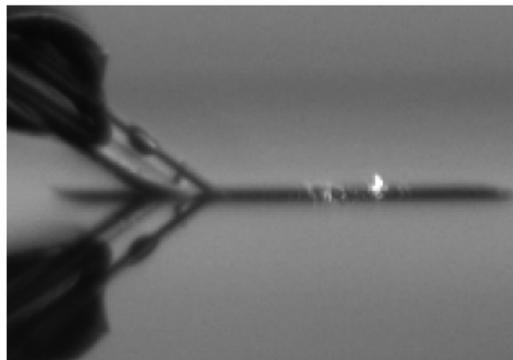
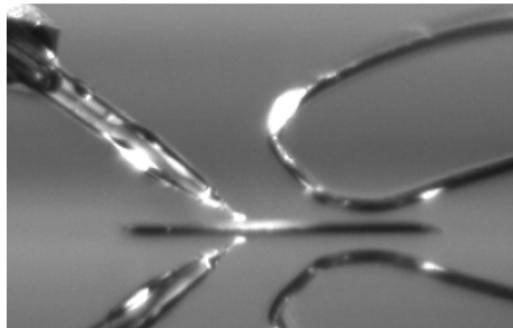
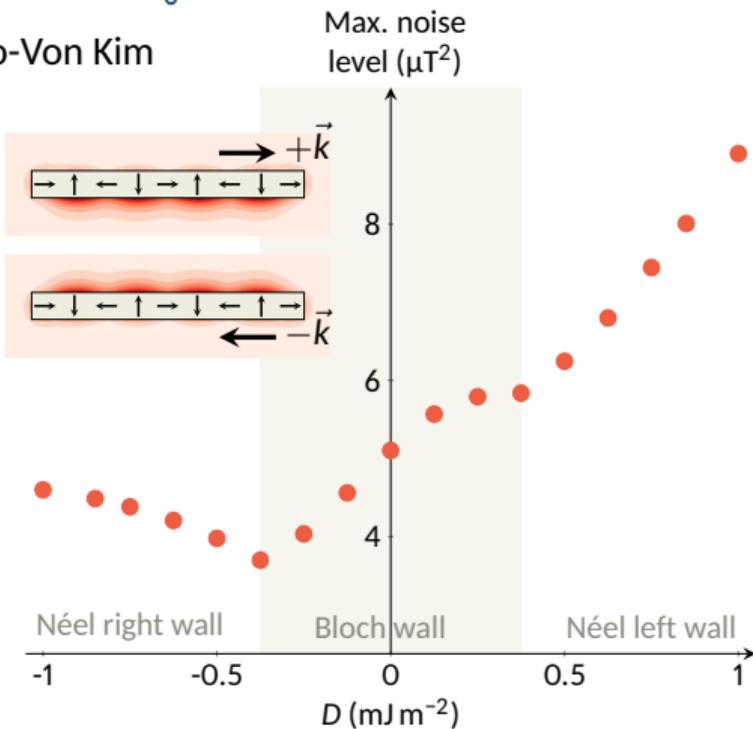
In a single ferromagnetic layer

Joo-Von Kim



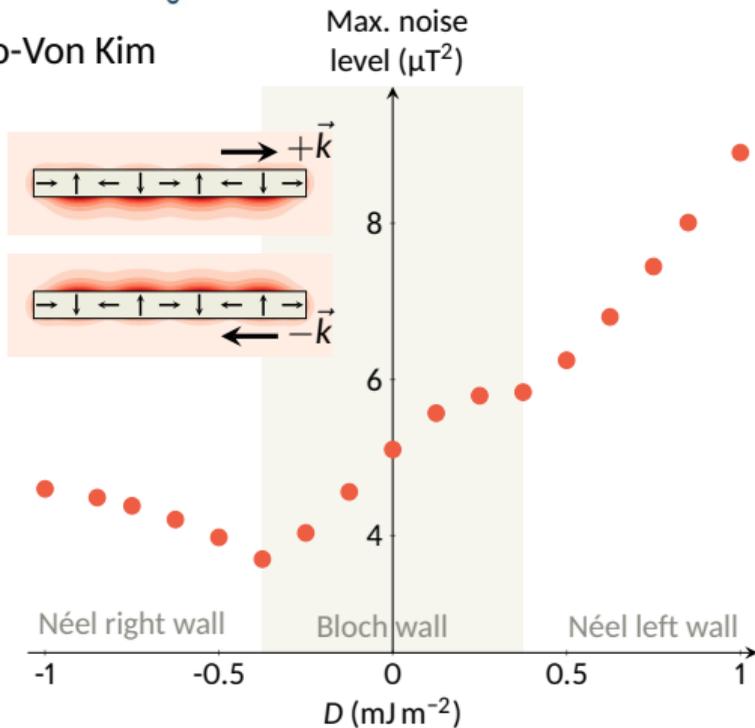
In a single ferromagnetic layer

Joo-Von Kim

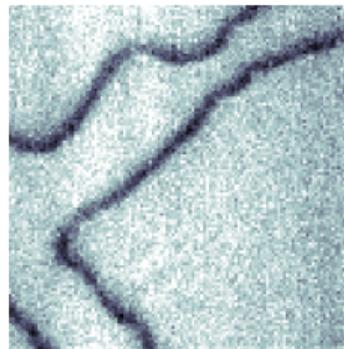


In a single ferromagnetic layer

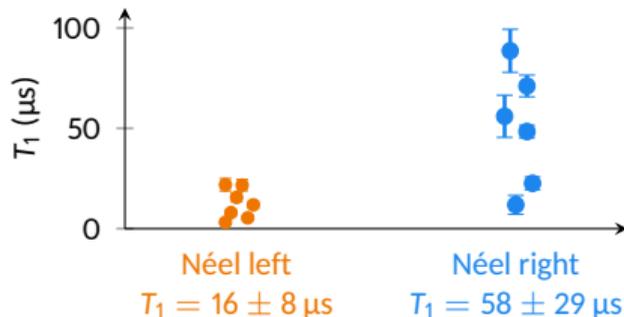
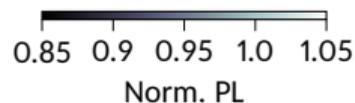
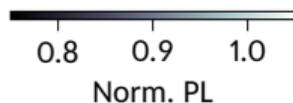
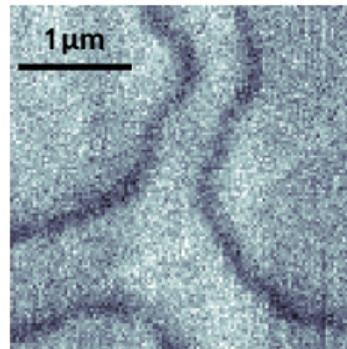
Joo-Von Kim



Néel left side



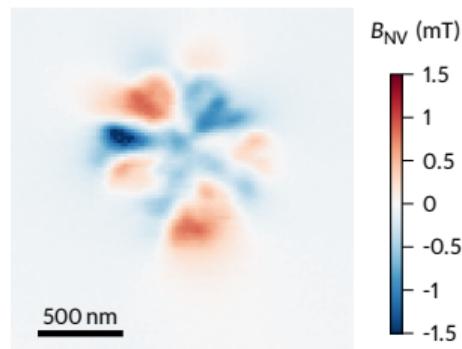
Néel right side



NV centers can probe...

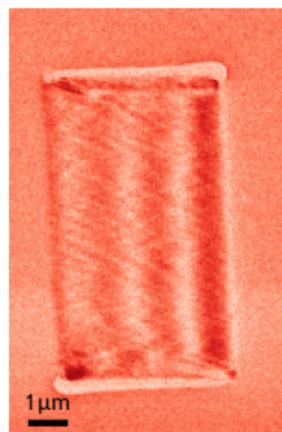
Static B field

Magnetic vortex in a 2D magnet



Microwave field

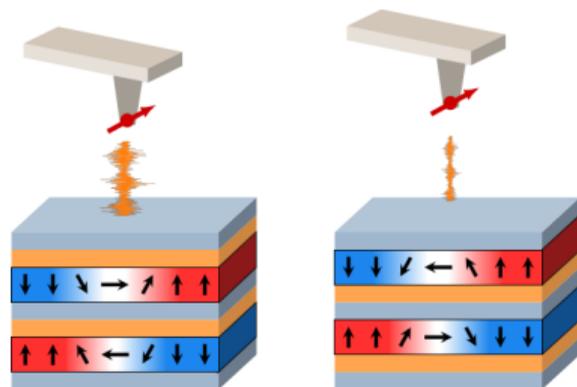
Driven spin waves



Norm. area

Magnetic noise

Thermal spin waves



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

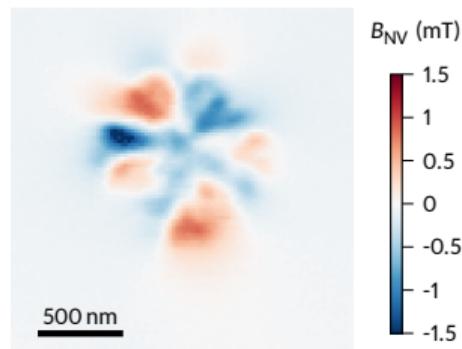
A. Finco et al. *Phys. Rev. Lett.* 135 (2025), 136703

and also temperature, electric field, pressure, ...

NV centers can probe...

Static B field

Magnetic vortex in a 2D magnet



Microwave field

Driven spin waves



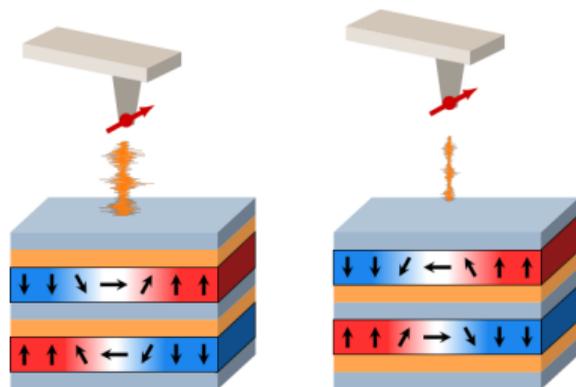
Roméo Beignon



Norm. area

Magnetic noise

Thermal spin waves



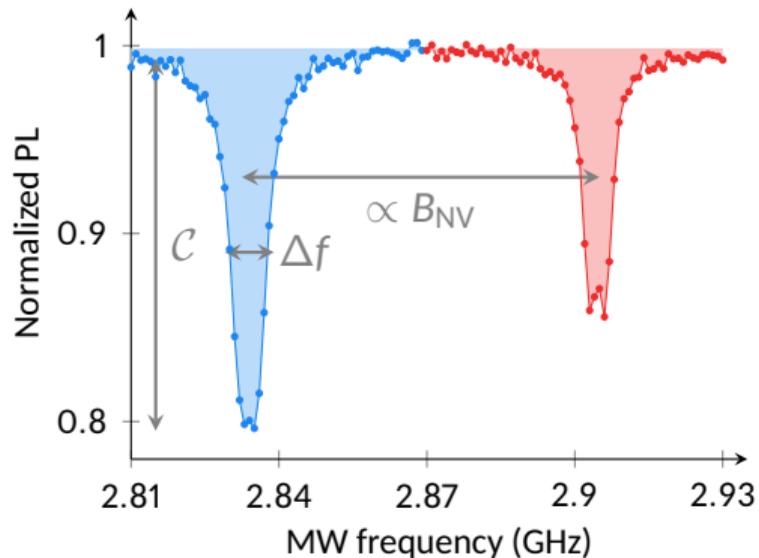
E. Sfeir et al. *Phys. Rev. Mater.* 9 (2025), 114003

A. Finco et al. *Phys. Rev. Lett.* 135 (2025), 136703

and also temperature, electric field, pressure, ...

Using the integral of the resonance

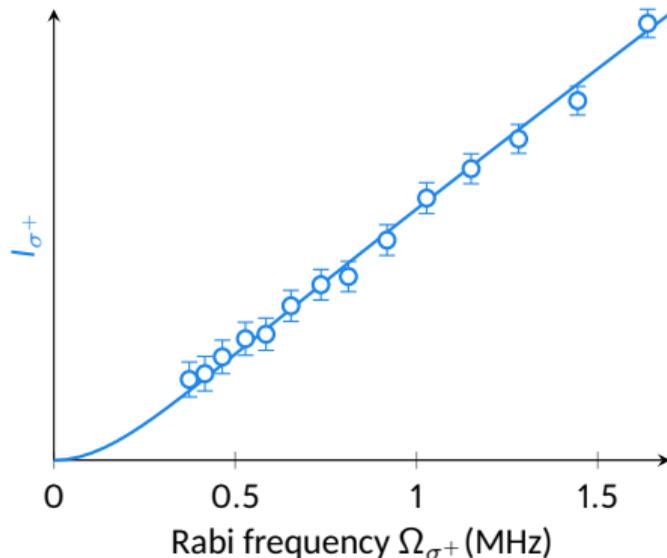
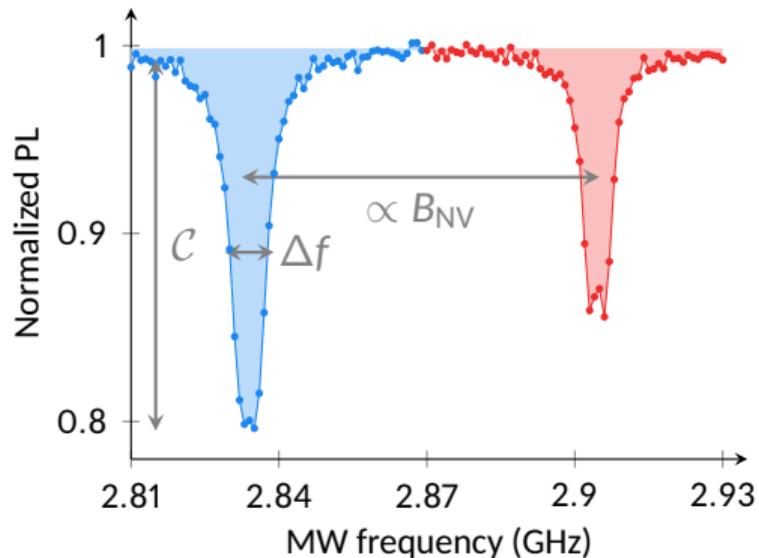
Increasing the MW power broadens and deepens the resonances \rightarrow we map the integral



 A. Dréau et al. *Phys. Rev. B* 84 (2011), 195204

Using the integral of the resonance

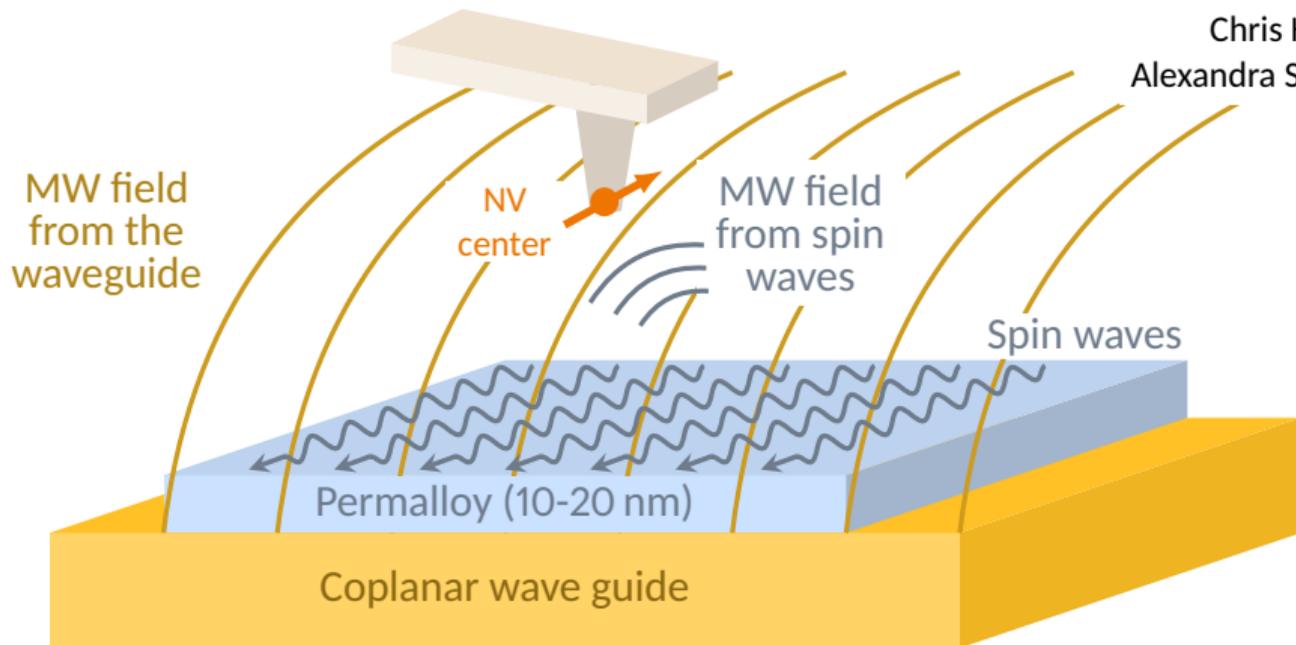
Increasing the MW power broadens and deepens the resonances \rightarrow we map the integral



A. Dréau et al. *Phys. Rev. B* 84 (2011), 195204

Experiments on Py microstructures

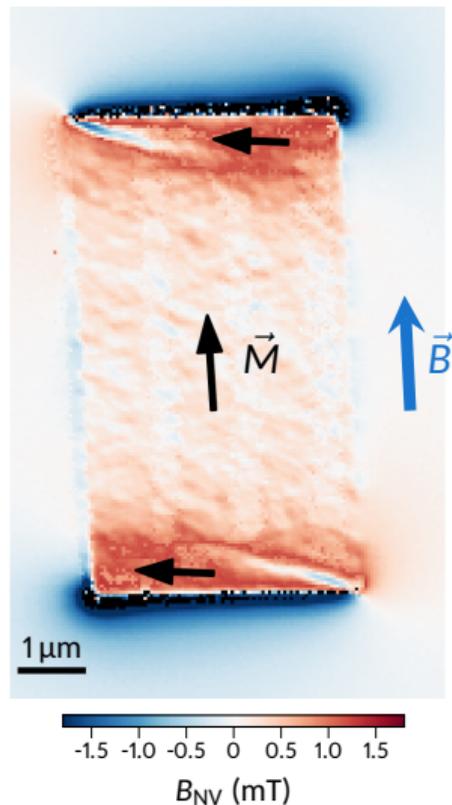
Interference between the microwave field from the antenna and the microwave field from the excited spin waves



**Martin-Luther-Universität
Halle-Wittenberg**

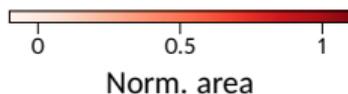
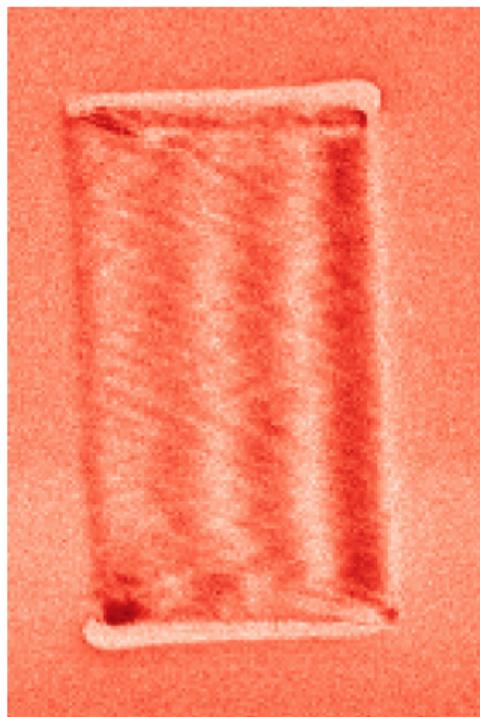
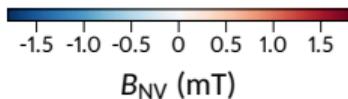
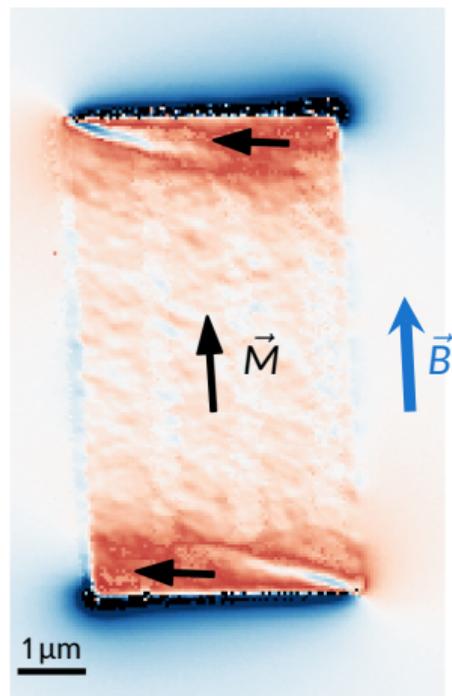
Chris Körner, Rouven Dreyer
Alexandra Schrader, Georg Woltersdorf

Imaging propagating spin waves



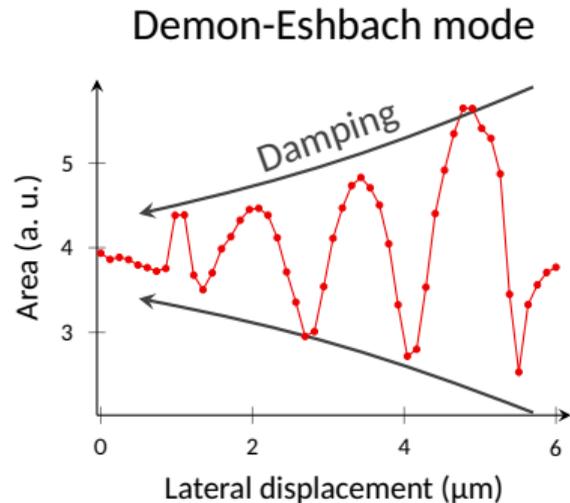
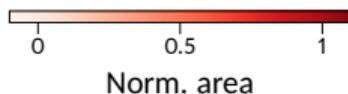
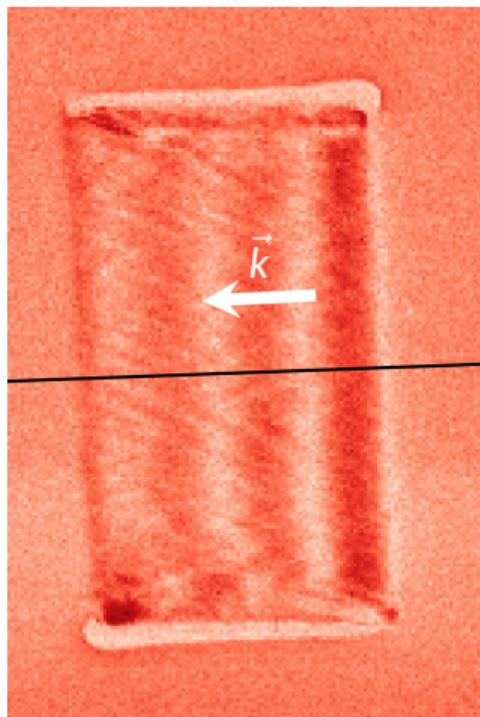
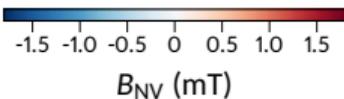
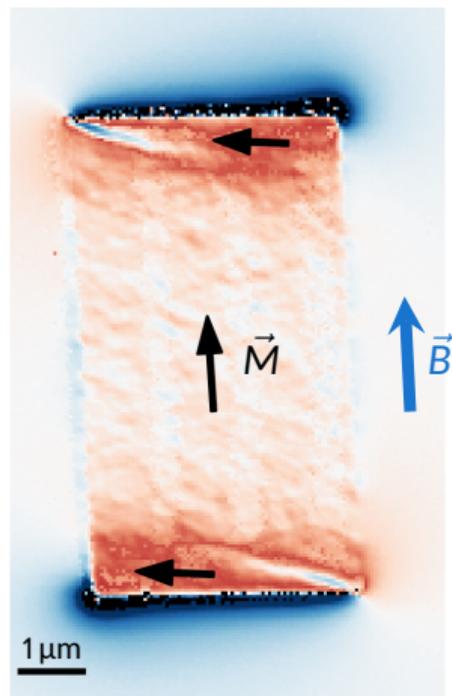
Excitation at 2.87 GHz
 $B = 1.4\ \text{mT}$

Imaging propagating spin waves



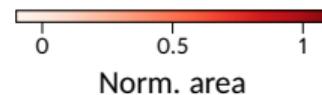
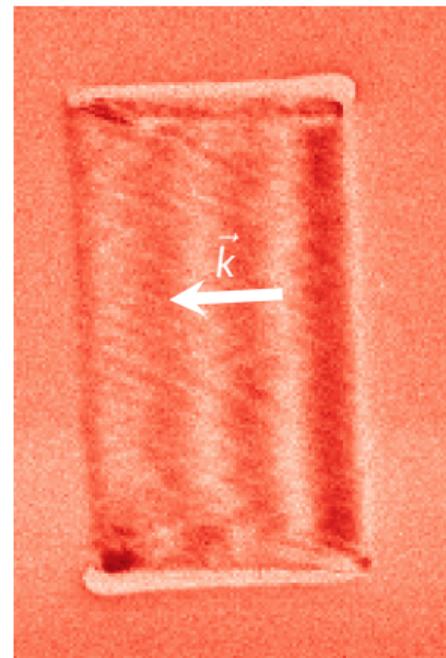
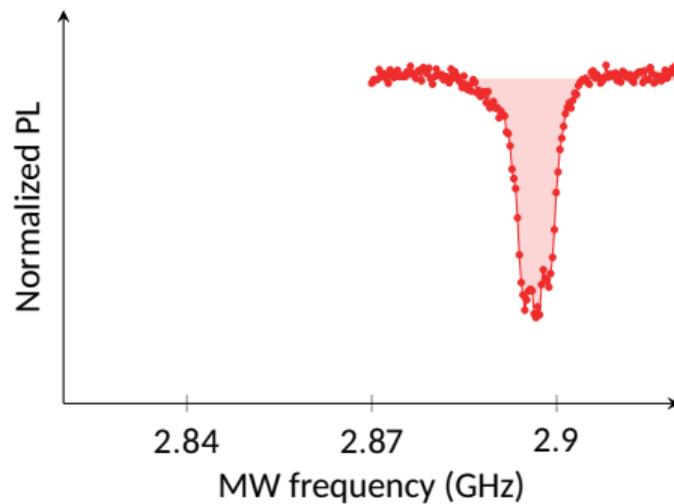
Excitation at 2.87 GHz
 $B = 1.4\ \text{mT}$

Imaging propagating spin waves

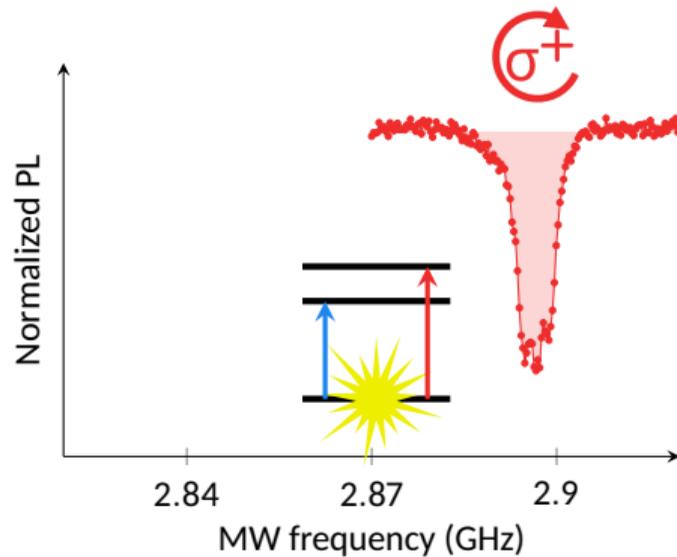


Excitation at 2.87 GHz
 $B = 1.4\ \text{mT}$

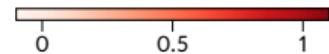
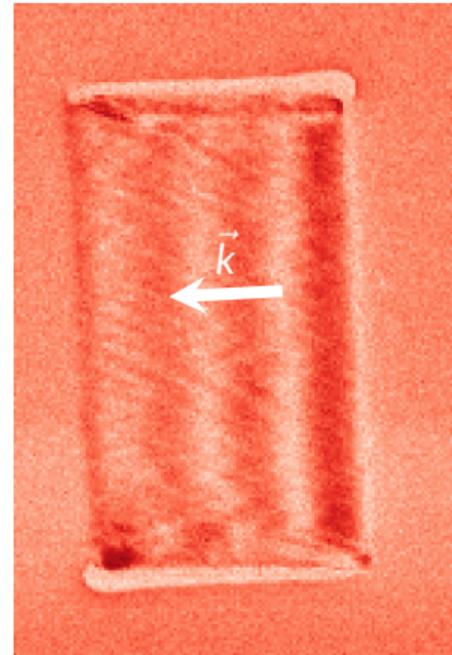
Where is the opposite \vec{k} ?



Where is the opposite \vec{k} ?

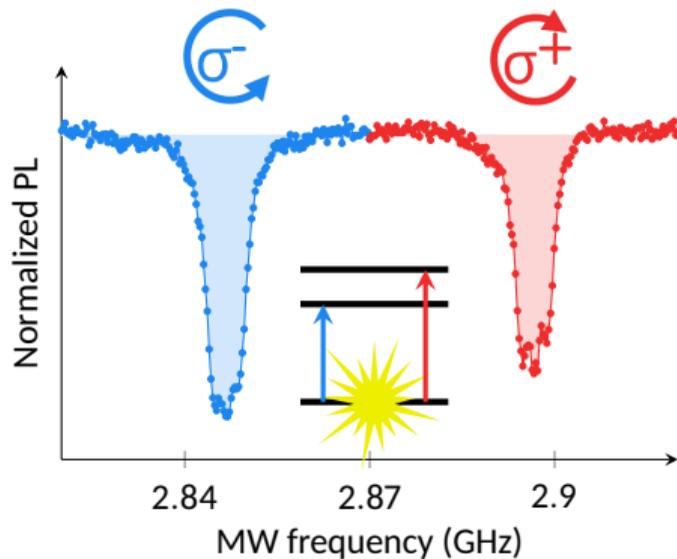
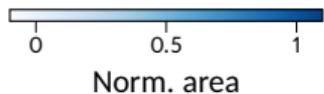
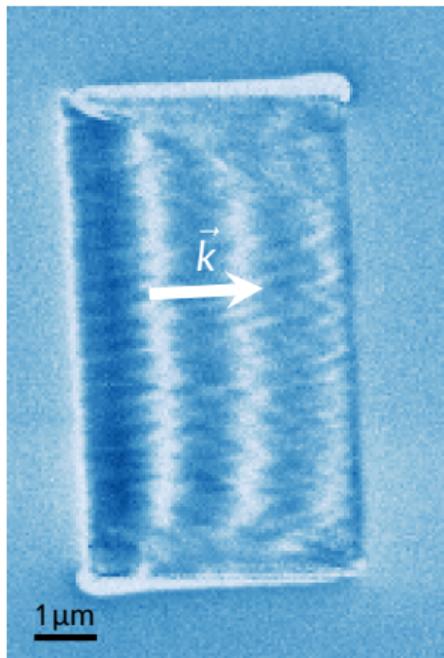


R. Beignon et al. *in preparation* (2026)

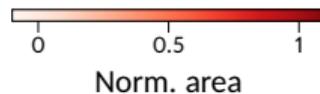
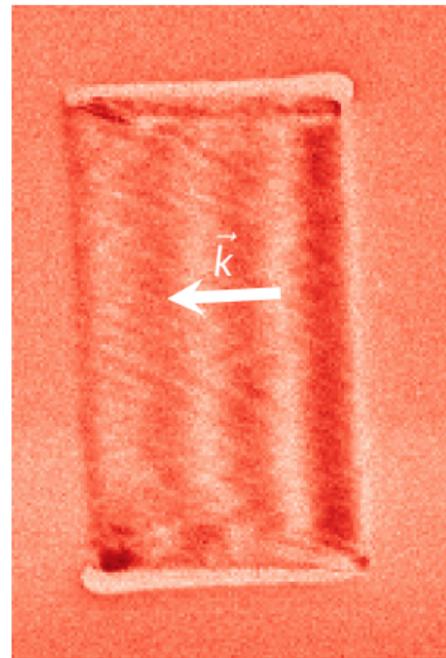


Norm. area

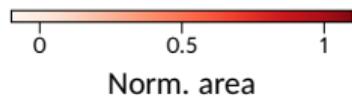
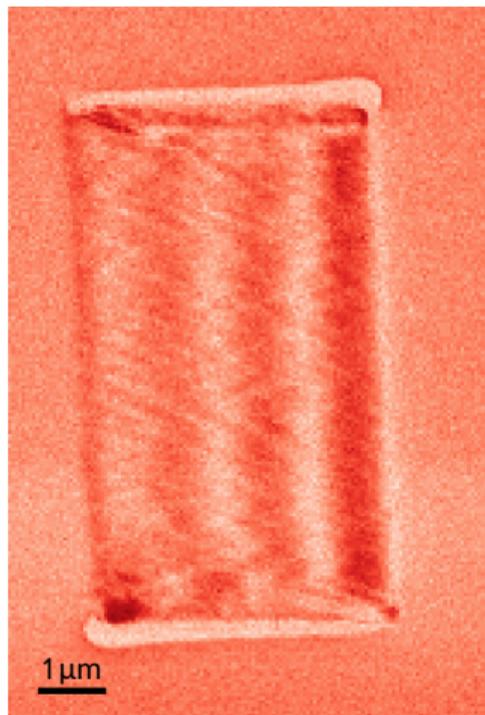
Where is the opposite \vec{k} ?



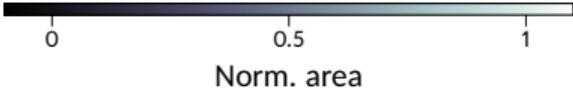
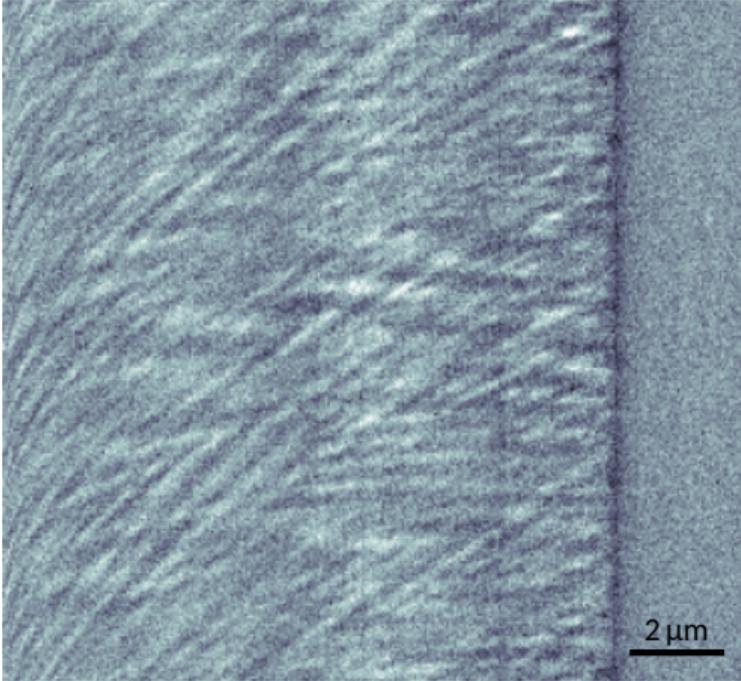
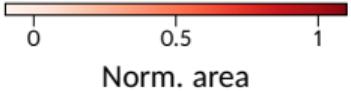
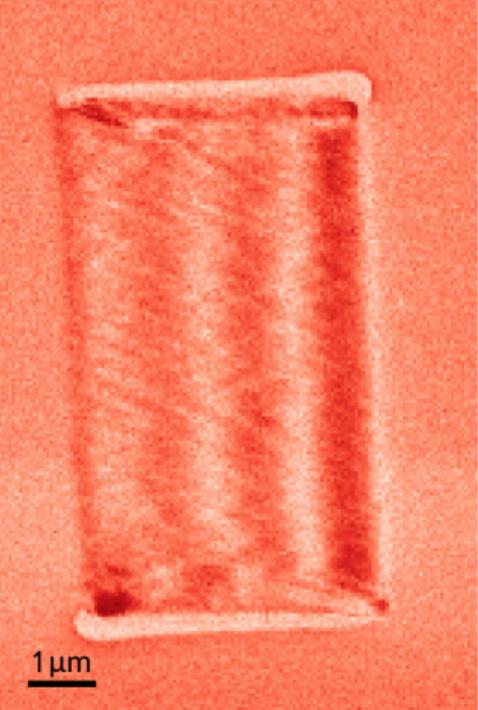
 R. Beignon *et al.* *in preparation* (2026)



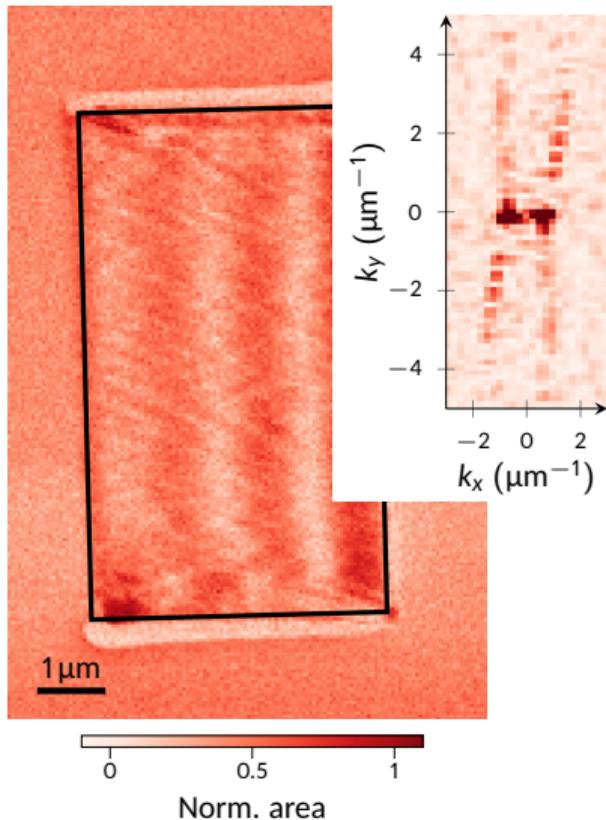
Have a closer look at the data



Have a closer look at the data

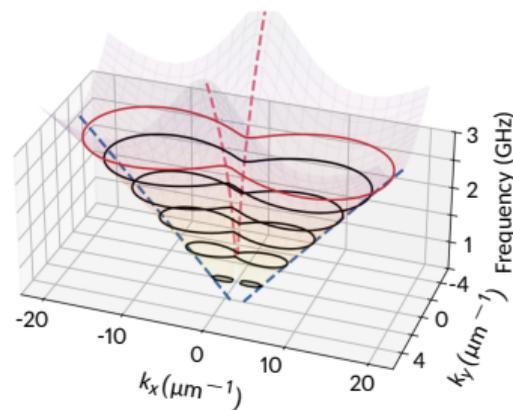
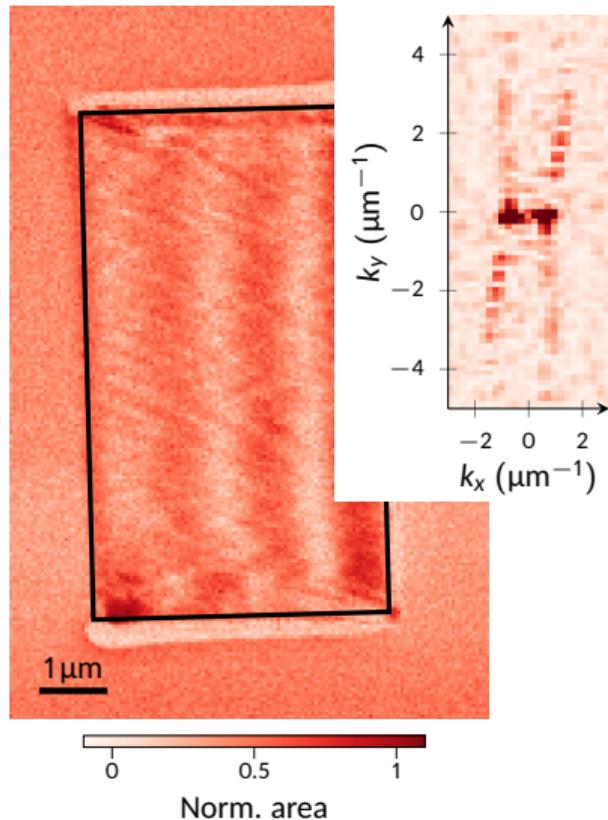


We have access to the dispersion relation!



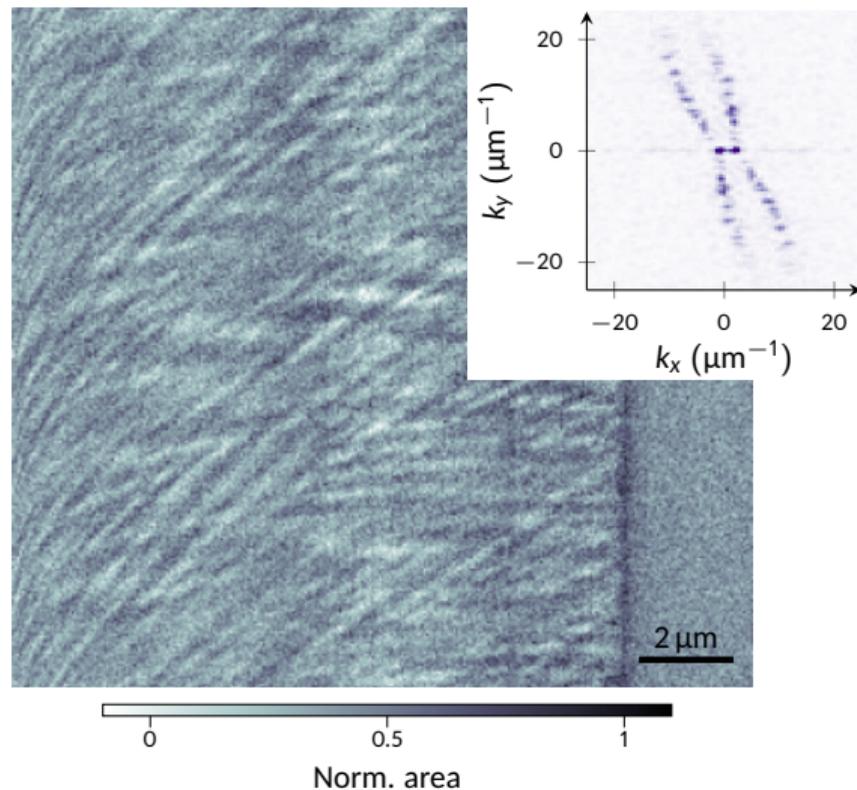
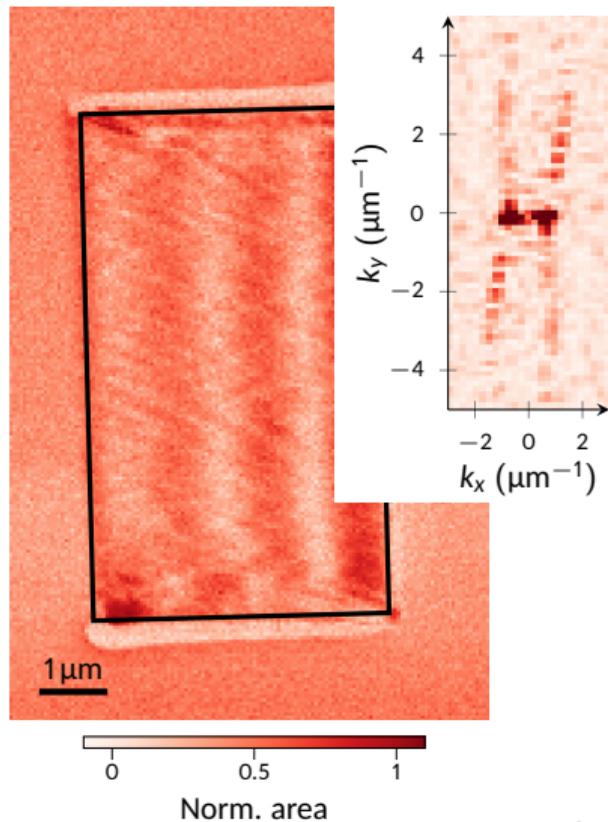
Looks similar to  B. G. Simon *et al.* *Nano Lett.* 22 (22 2022), 9198–9204

We have access to the dispersion relation!



Looks similar to  B. G. Simon et al. *Nano Lett.* 22 (22 2022), 9198–9204

We have access to the dispersion relation!

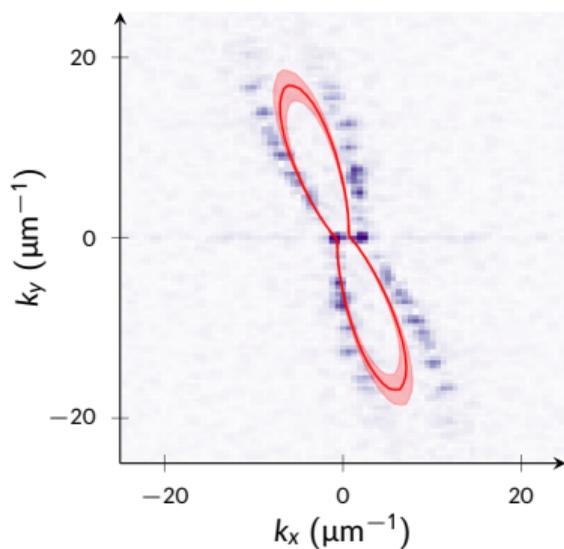


Looks similar to  B. G. Simon et al. *Nano Lett.* 22 (22 2022), 9198-9204

How can we fit this dispersion relation?

Permalloy film, 20 nm-thick, $B_{\text{ext}} = 1.4$ mT

Expected spin wave
dispersion

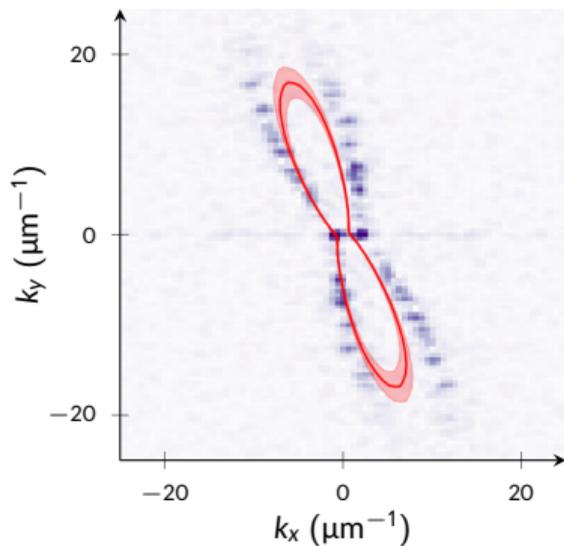


$\pm 10\%$ error related to the calibration of the scanners

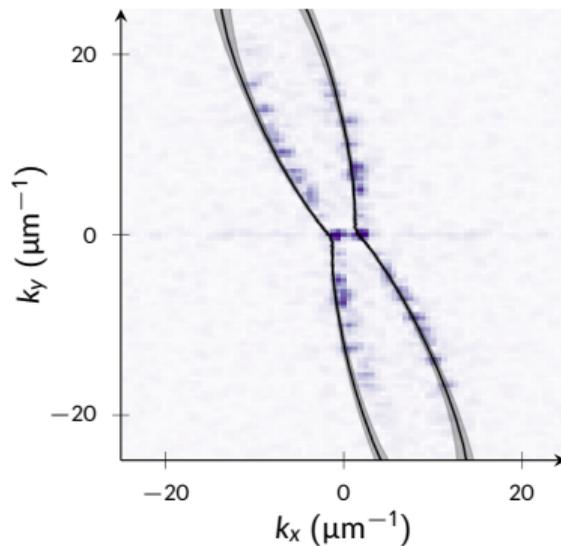
How can we fit this dispersion relation?

Permalloy film, 20 nm-thick, $B_{\text{ext}} = 1.4$ mT

Expected spin wave dispersion



Expected dispersion $\times 2$

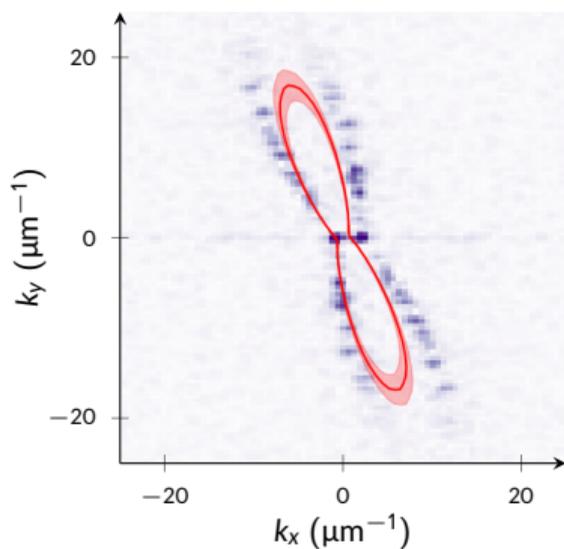


$\pm 10\%$ error related to the calibration of the scanners

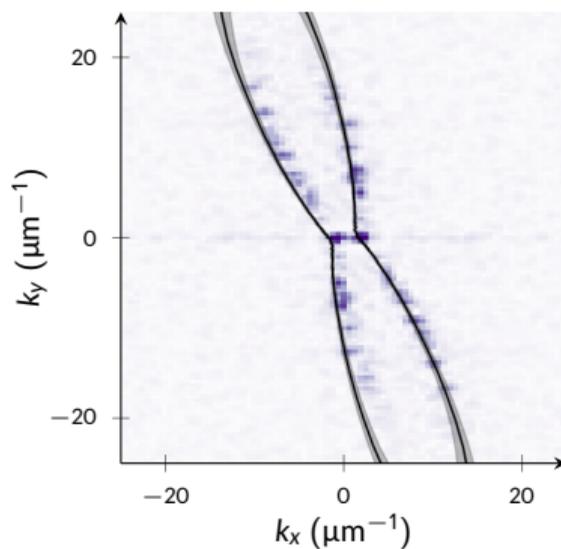
How can we fit this dispersion relation?

Permalloy film, 20 nm-thick, $B_{\text{ext}} = 1.4$ mT

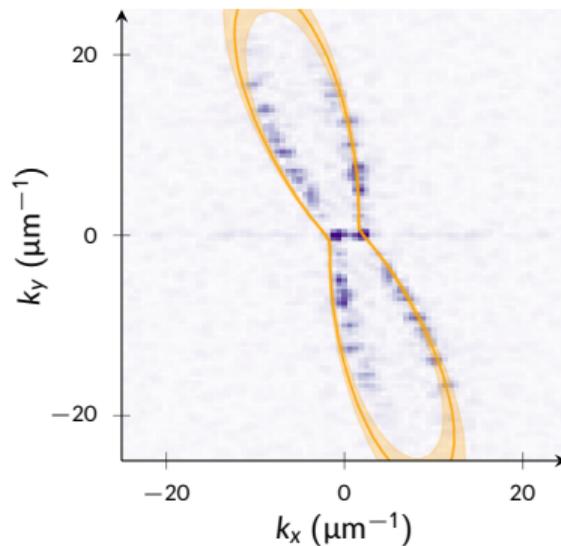
Expected spin wave dispersion



Expected dispersion $\times 2$



Expected dispersion at $3/2 f_{\text{NV}}$



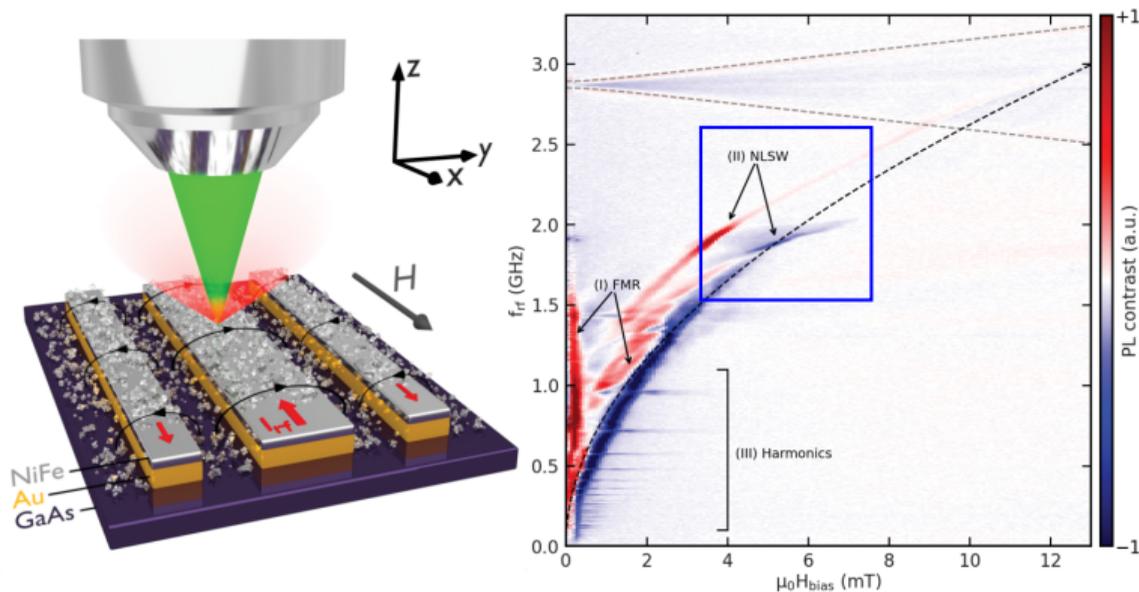
$\pm 10\%$ error related to the calibration of the scanners

Spin waves at $3/2 f_{\text{exc}}$

Predicted in  H. G. Bauer *et al.* *Nat. Commun.* 6 (2015), 8274

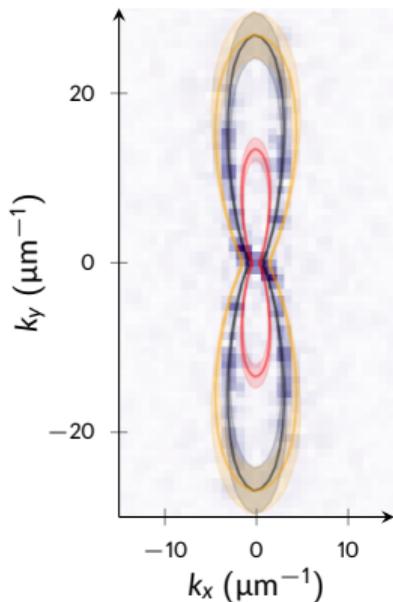
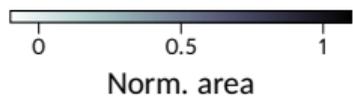
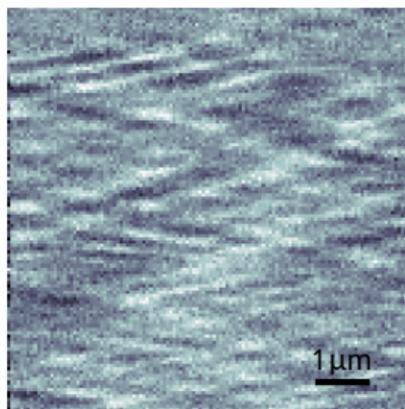
Observed experimentally in  R. Dreyer *et al.* *Nat. Commun.* 13 (2022), 4939

Detected with NV in the same samples as ours in  C. Koerner *et al.* *Science* 375 (2022), 1165–1169



Applying magnetic field

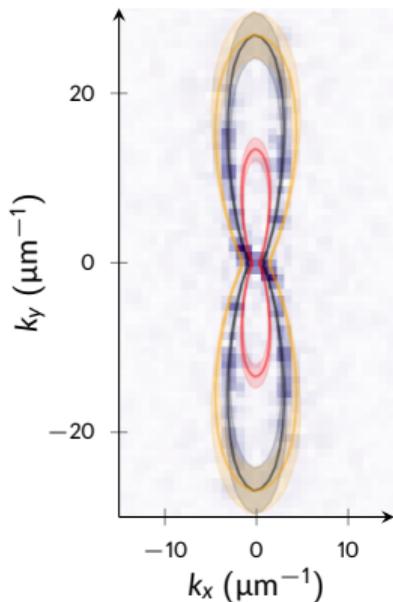
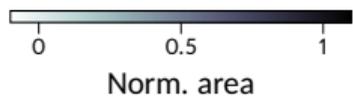
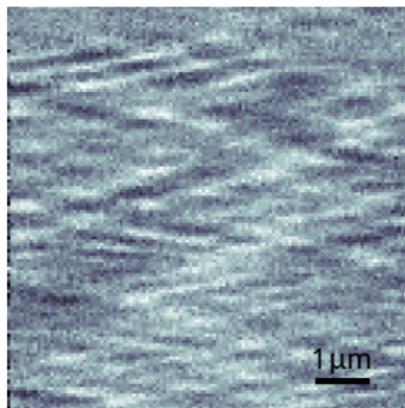
At 5.4 mT, $f_{NV} = 2.86$ GHz



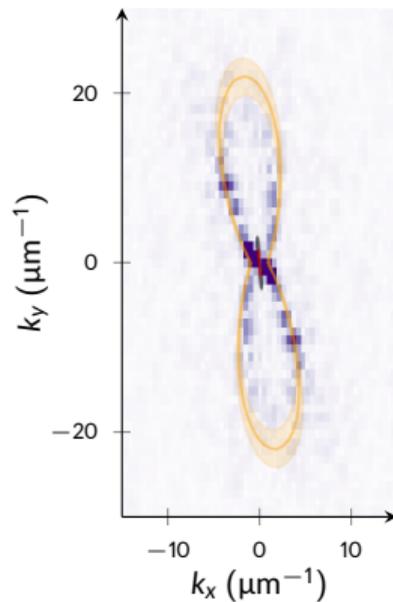
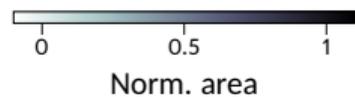
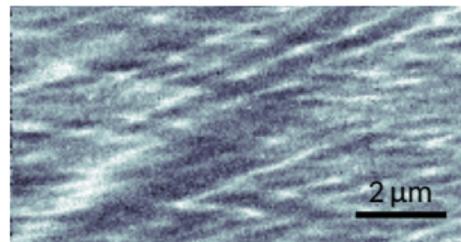
Expected dispersion at f_{NV} , multiplied by 2, at $3/2 f_{NV}$

Applying magnetic field

At 5.4 mT, $f_{NV} = 2.86$ GHz



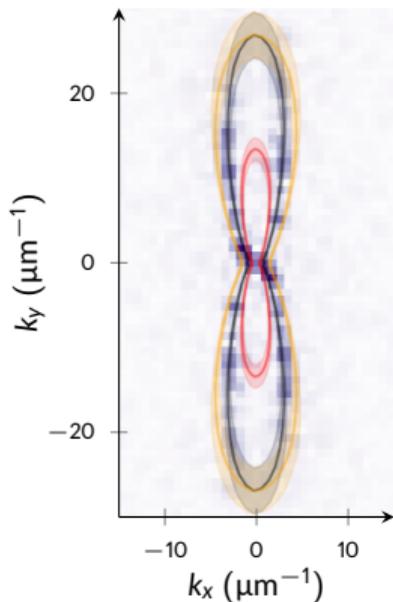
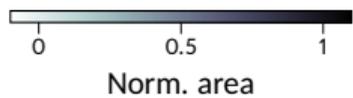
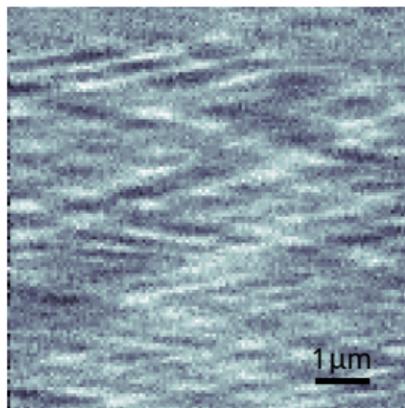
At 9 mT, $f_{NV} = 2.72$ GHz



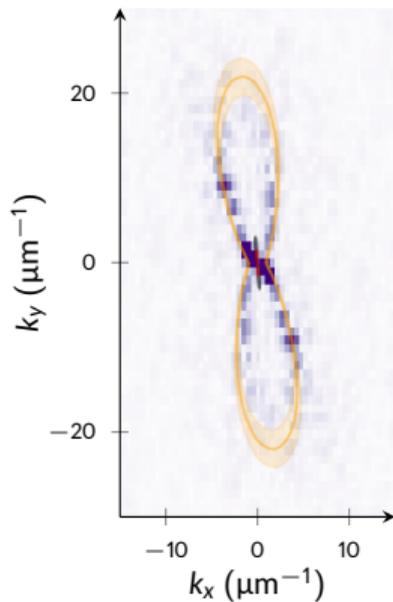
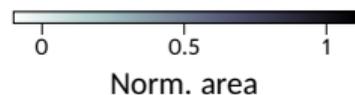
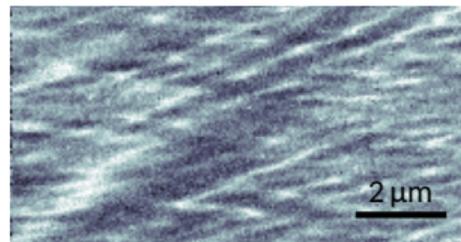
Expected dispersion at f_{NV} , multiplied by 2, at $3/2 f_{NV}$

Applying magnetic field

At 5.4 mT, $f_{NV} = 2.86$ GHz



At 9 mT, $f_{NV} = 2.72$ GHz

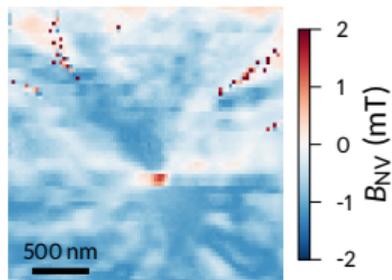
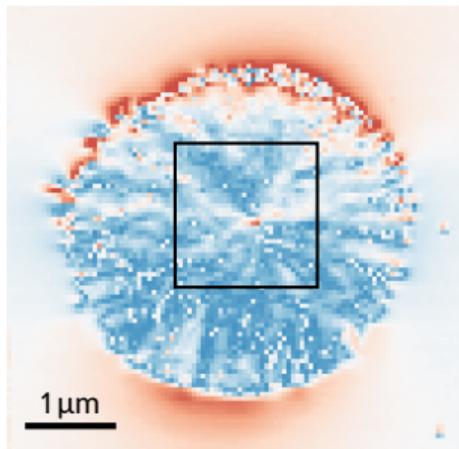


Expected dispersion at f_{NV} , multiplied by 2, at $3/2 f_{NV}$

Why do we see the modes at $3/2 f_{NV}$???

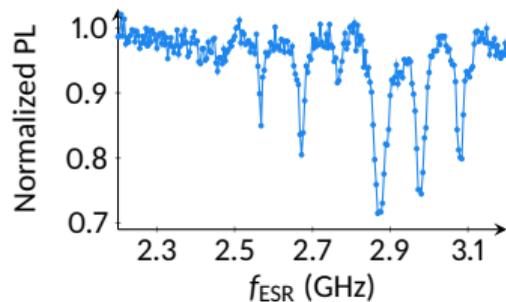
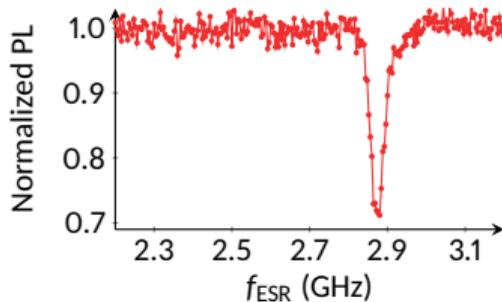
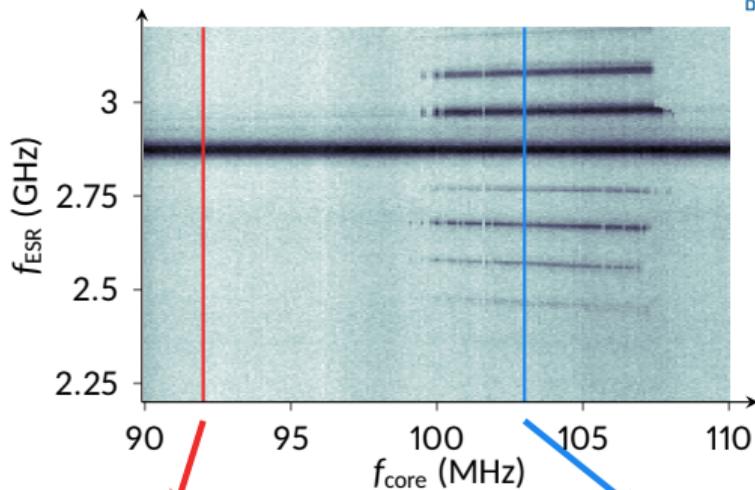
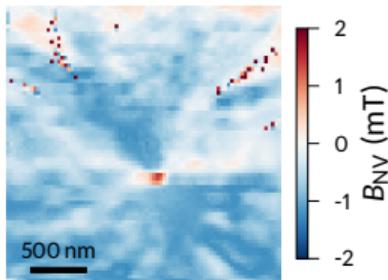
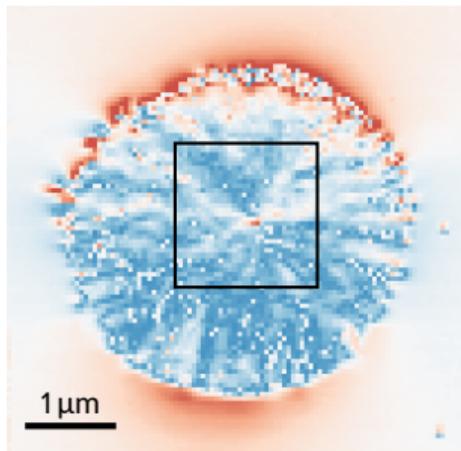
NVs can also see Floquet modes!

Sample from HZDR 
HELMHOLTZ ZENTRUM
DRESDEN ROSENDRORF



NVs can also see Floquet modes!

Sample from HZDR
HELMHOLTZ ZENTRUM
DRESDEN ROSENDRORF



C. Heins et al. *Science* 391 (2026), 190–194

Acknowledgments



Roméo Beignon
Florie Mesple
Pawan Kumar, Maxime Rollo
Vincent Jacques



Joo-Von Kim



Zeling Xiong, Christopher Heins
Katrin and Helmut Schultheiss



**Martin-Luther-Universität
Halle-Wittenberg**

Chris Körner, Rouven Dreyer
Alexandra Schrader, Georg Woltersdorf



Joseba Urrestarazu
Rodrigo Guedas
Olivier Boule