Detection of DMI-induced magnetic chirality from spin wave noise

Aurore Finco

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

CNRS and Université de Montpellier, Montpellier, France

Ferroics workshop, August 29th 2024, Le Mans

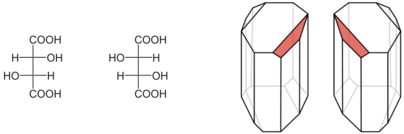
slides available at https://magimag.eu

Chirality

The aspect of a structure or property that renders it distinguishable from its mirror image.
Term introduced by Kelvin in 1904.

V. Simonet *et al*. *Euro. Phys. Journal Special Topics* 213 (2012), 5

Pasteur (1848): chirality in chemistry



A. Sevin. *Bibnum. Textes fondateurs de la science* (2012)

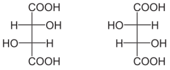
Crucial in chemistry and biology.
Life is **homochiral**.

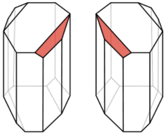
Chirality

The aspect of a structure or property that renders it distinguishable from its mirror image.
Term introduced by Kelvin in 1904.

V. Simonet *et al.* *Euro. Phys. Journal Special Topics* 213 (2012), 5

Pasteur (1848): chirality in chemistry





A. Sevin. *Bibnum. Textes fondateurs de la science* (2012)

Crucial in chemistry and biology.
Life is **homochiral**.

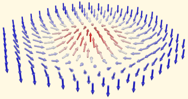
Magnetic chirality

Quantity that should indicate the sense of spin rotation when moving along oriented loops or lines

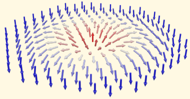
CCW

CW

CCW

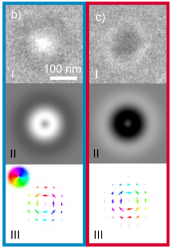


CW



How can we probe magnetic chirality?

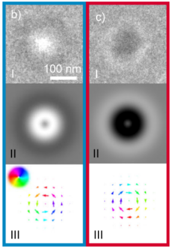
Measure the **direction of the magnetization**
(LTEM, PEEM, SP-STM, ...)



M. Heigl *et al.* *Nat. Commun.* 12 (2021), 2611

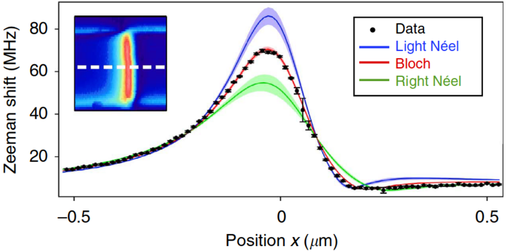
How can we probe magnetic chirality?

Measure the **direction of the magnetization**
(LTEM, PEEM, SP-STM, ...)



M. Heigl *et al.* Nat. Commun. 12 (2021), 2611

Measure quantitatively the **stray field**
produced by the texture

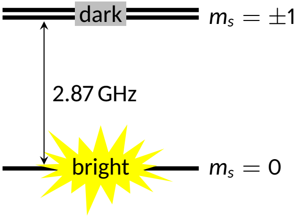


J.-P. Tetienne *et al.* Nat. Commun. 6 (2015), 6733

→ Scanning NV magnetometry

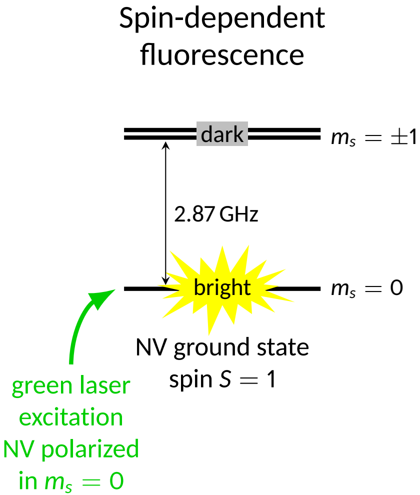
Measuring magnetic field with NV centers

Spin-dependent fluorescence

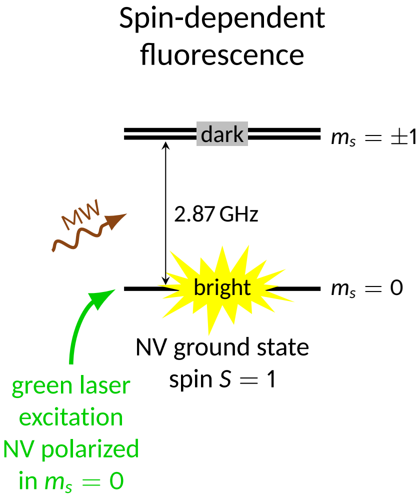


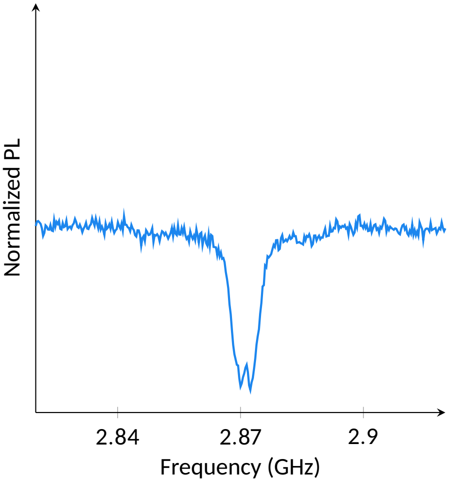
NV ground state
spin $S = 1$

Measuring magnetic field with NV centers

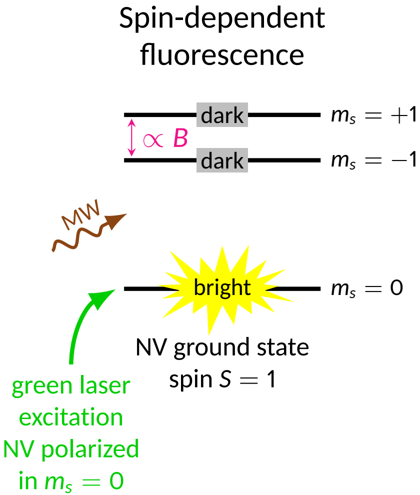


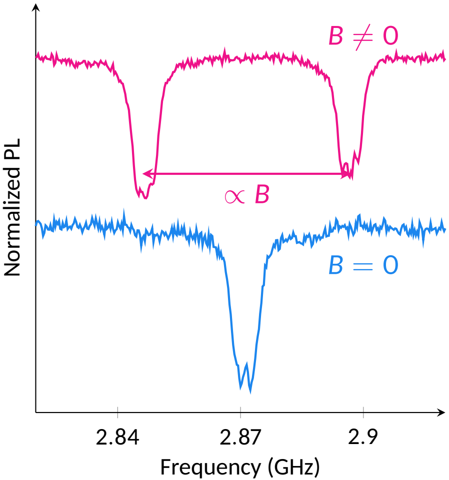
Measuring magnetic field with NV centers



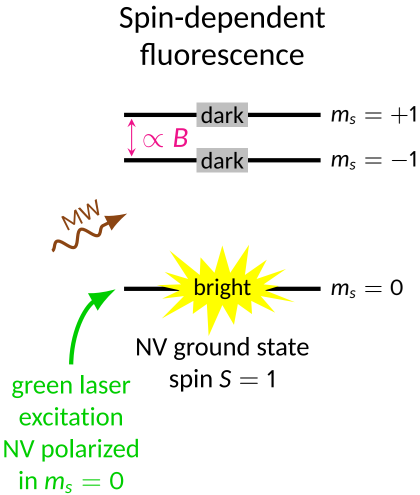


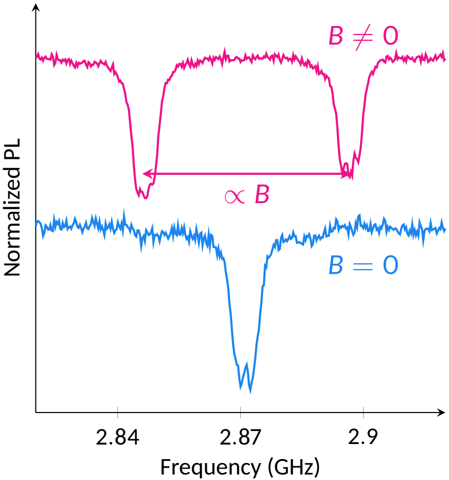
Measuring magnetic field with NV centers





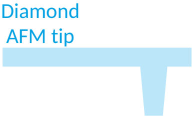
Measuring magnetic field with NV centers

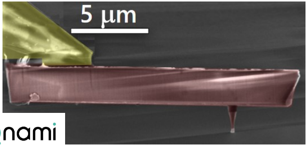




It is also possible to measure electric field: W. S. Huxter *et al.* *Nat. Phys* 19 (2023), 644

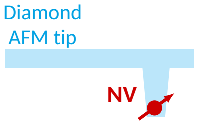
Integration of the defect in a scanning probe microscope

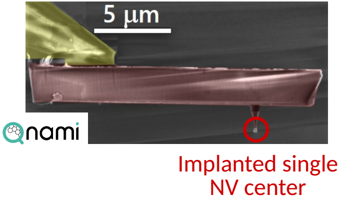




P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

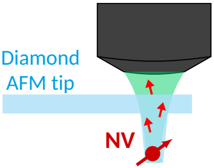
Integration of the defect in a scanning probe microscope

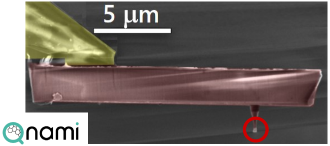




P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

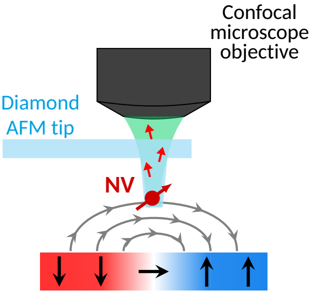
Integration of the defect in a scanning probe microscope

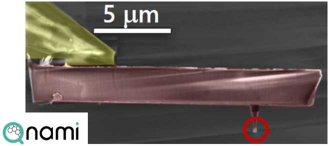




P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

Integration of the defect in a scanning probe microscope

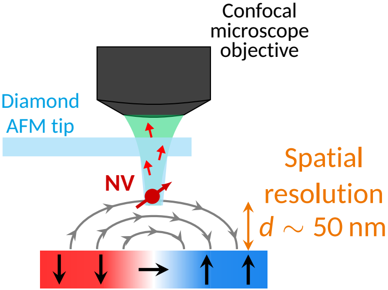


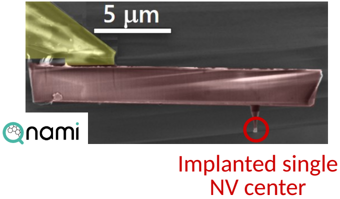


Implanted single
NV center

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

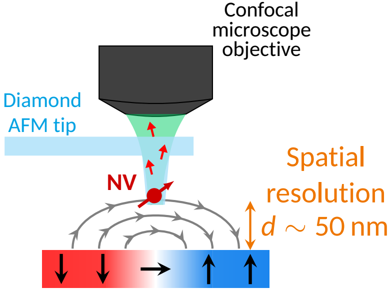
Integration of the defect in a scanning probe microscope

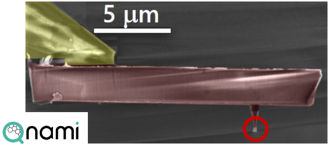




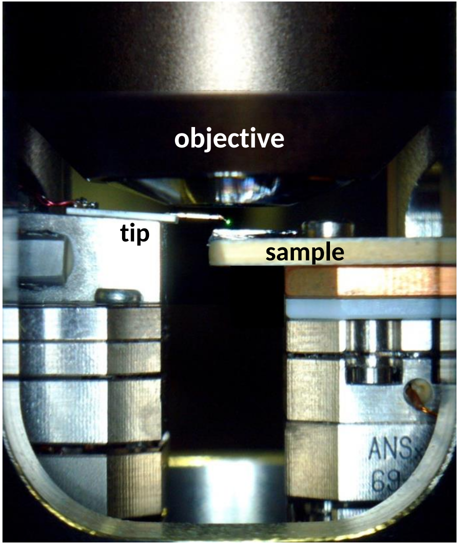
P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

Integration of the defect in a scanning probe microscope



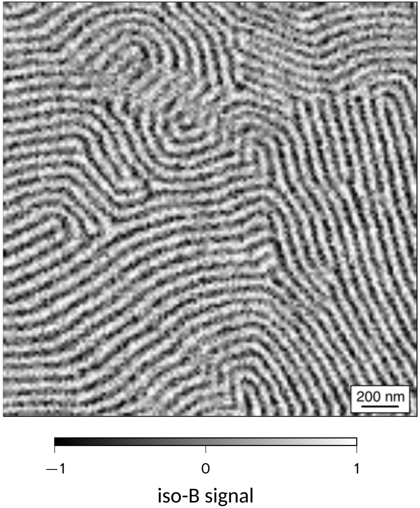


Implanted single NV center



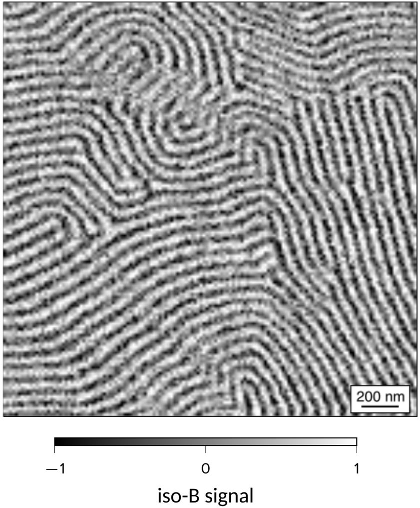
P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

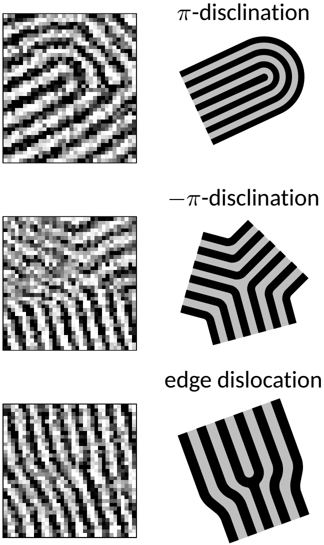
Example: Topological defects at the surface of bulk $BiFeO_3$ crystals



A. Finco *et al.* *PRL* 128 (2022), 187201

Example: Topological defects at the surface of bulk $BiFeO_3$ crystals





A. Finco *et al.* *PRL* 128 (2022), 187201

Detection of magnetic noise rather than stray field

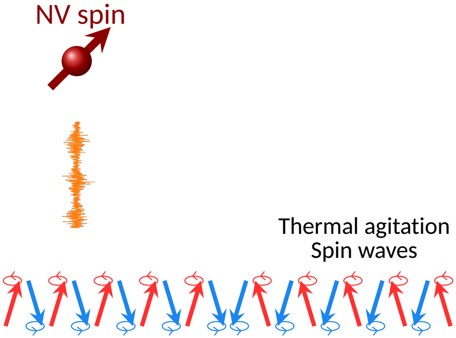
B. Flebus *et al.* *Phys. Rev. B* 98 (2018), 180409

- Completely compensated antiferromagnets = **no static stray field** to probe
- But NV centers are also sensitive to **magnetic noise**!
- Use the different noise properties above domains and domain walls for imaging

Detection of magnetic noise rather than stray field

B. Flebus *et al.* *Phys. Rev. B* 98 (2018), 180409

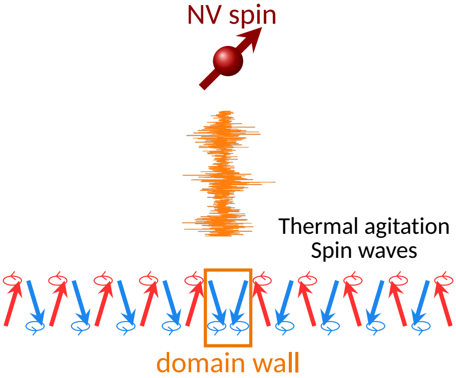
- Completely compensated antiferromagnets = **no static stray field** to probe
- But NV centers are also sensitive to **magnetic noise**!
- Use the different noise properties above domains and domain walls for imaging



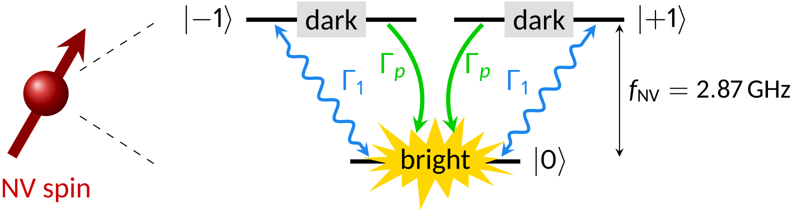
Detection of magnetic noise rather than stray field

B. Flebus *et al.* *Phys. Rev. B* 98 (2018), 180409

- Completely compensated antiferromagnets = **no static stray field** to probe
- But NV centers are also sensitive to **magnetic noise**!
- Use the different noise properties above domains and domain walls for imaging



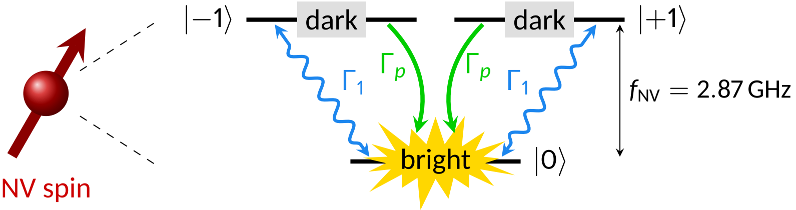
Effect of magnetic noise on the emitted photoluminescence



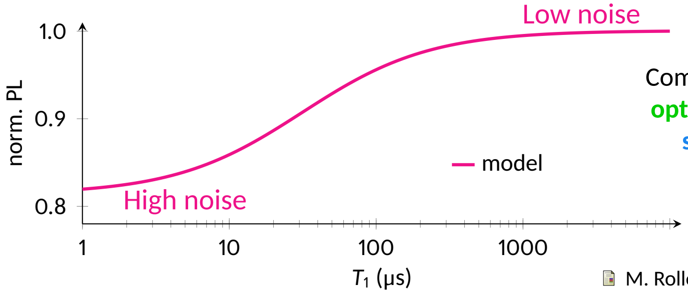
Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}

M. Rollo *et al.* *PRB* 103 (2021), 235418

Effect of magnetic noise on the emitted photoluminescence



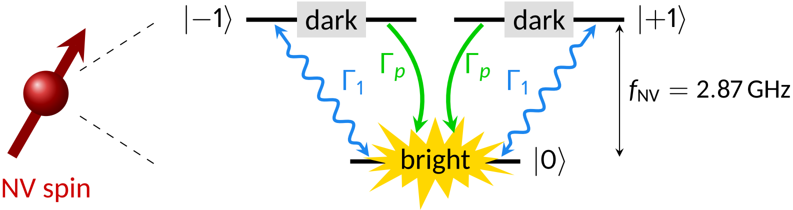
Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}



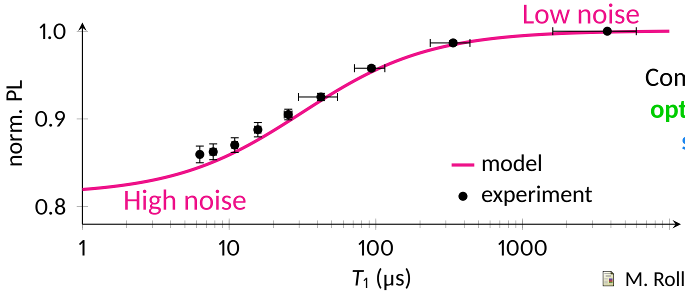
Competition between **optical pumping** and **spin relaxation**

M. Rollo *et al.* *PRB* 103 (2021), 235418

Effect of magnetic noise on the emitted photoluminescence



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



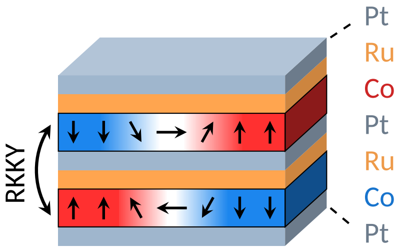
Competition between **optical pumping** and **spin relaxation**

M. Rollo *et al.* *PRB* 103 (2021), 235418

Synthetic antiferromagnets

Samples: LAF, Palaiseau (W. Legrand, K. Bouzehouane, N. Reyren, V. Cros)
Spintec, Grenoble (V.-T. Pham, J. Urrestarazu, R. Guedas, O. Boulle)

Two **ferromagnetic** layers coupled **antiferromagnetically**



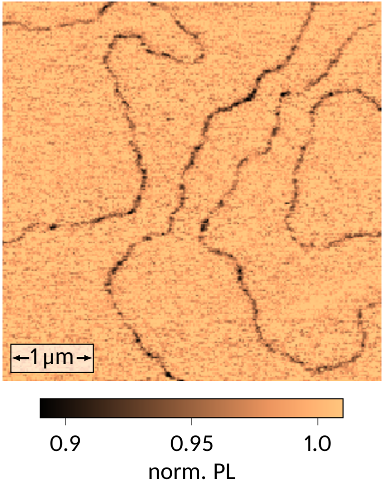
- No net magnetic moment
- Small stray field (vertical shift)
- Highly tunable properties
- Spin wave frequencies in the few GHz range

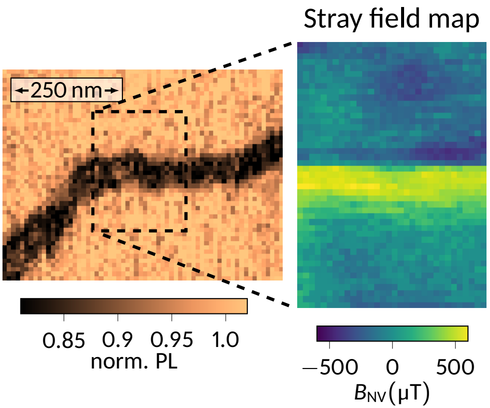
→ Perfect test system for noise imaging!

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

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

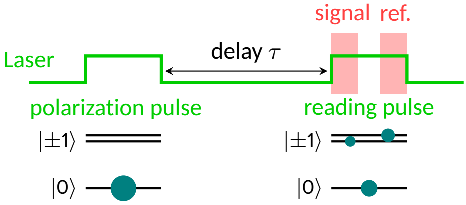
Detection of domain walls by relaxometry



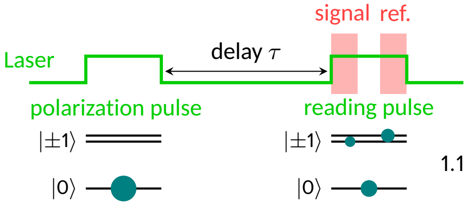


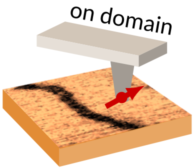
A. Finco *et al.* Nat. Commun. 12 (2021), 767

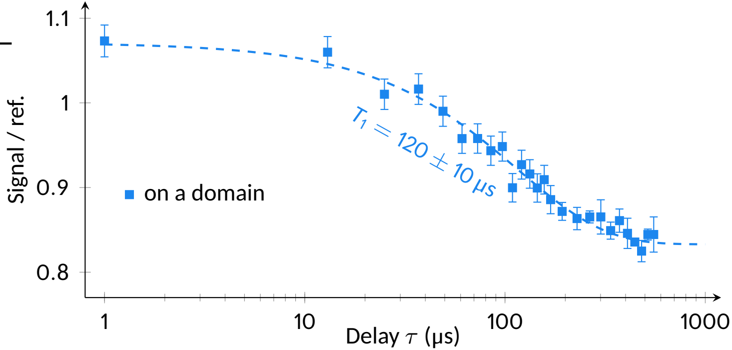
Local variation of the relaxation time



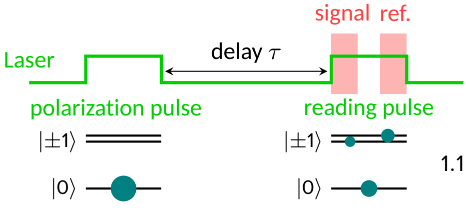
Local variation of the relaxation time

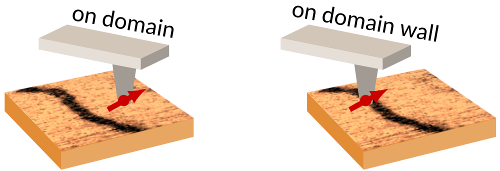


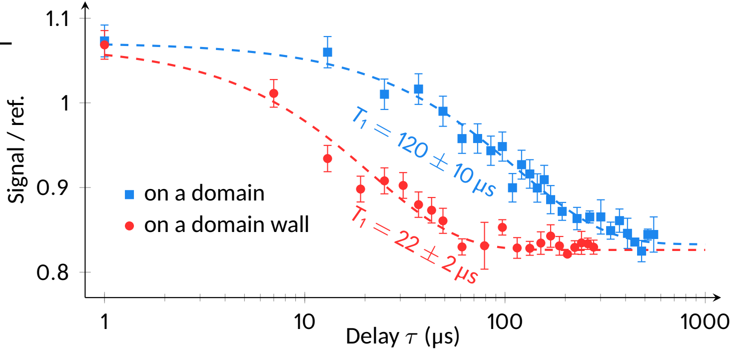




Local variation of the relaxation time





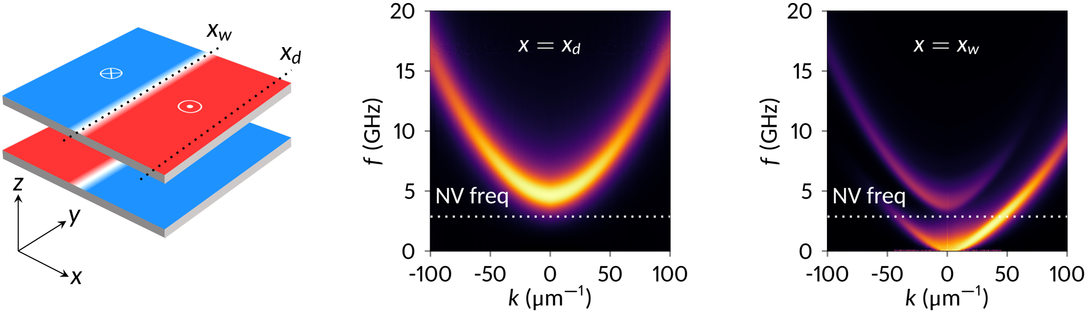


Clear diminution of T_1

→ **Enhancement of the spin relaxation**

Origin of the noise: spin waves

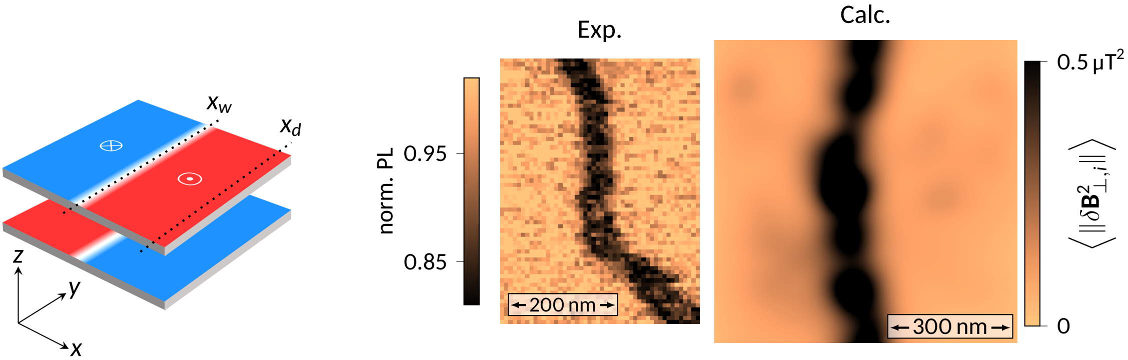
Collaboration: C2N, Palaiseau (J.-P. Adam, J.-V. Kim)



No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

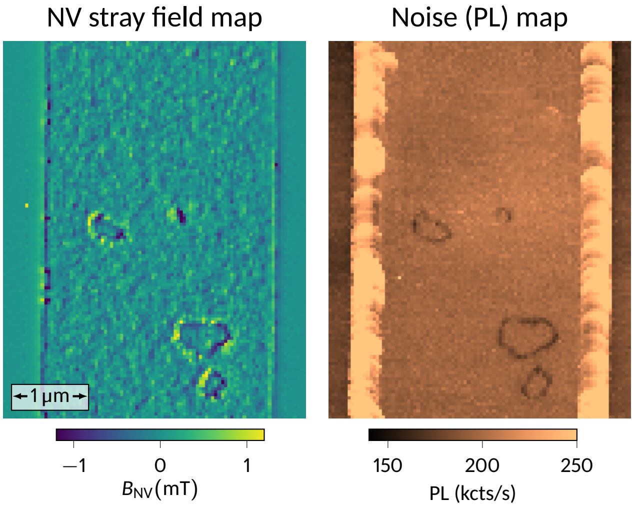
Origin of the noise: spin waves

Collaboration: C2N, Palaiseau (J.-P. Adam, J.-V. Kim)



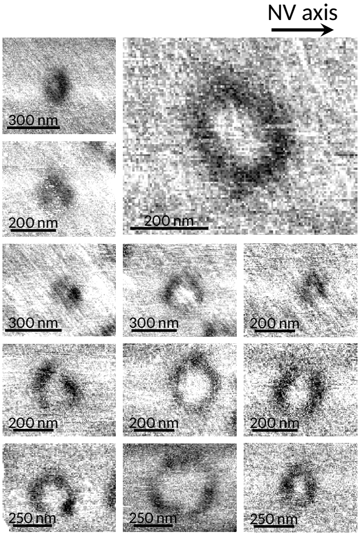
No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

After applying magnetic field

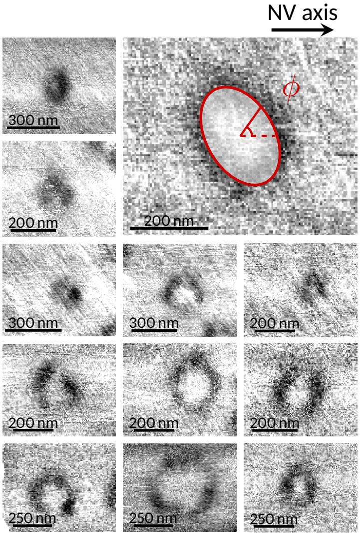


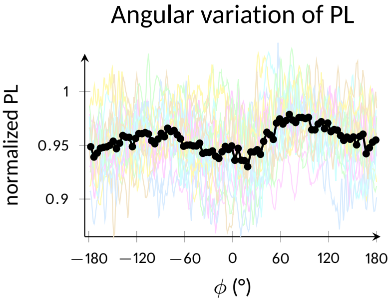
- Oop field of about 150 mT applied for nucleation
- Skyrmions and big bubbles pinned

Statistics on Néel left (CCW) skyrmions

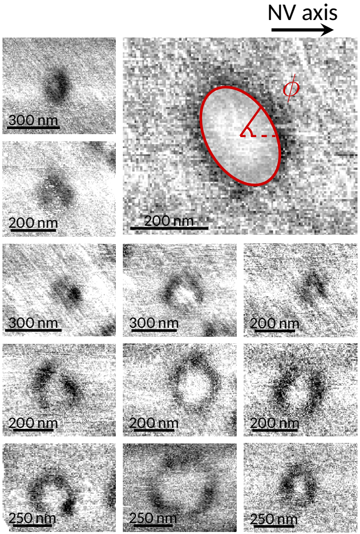


Statistics on Néel left (CCW) skyrmions

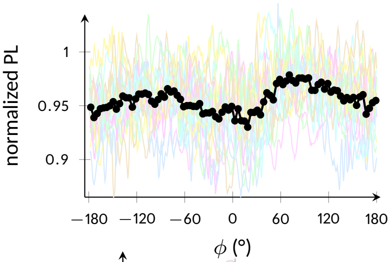


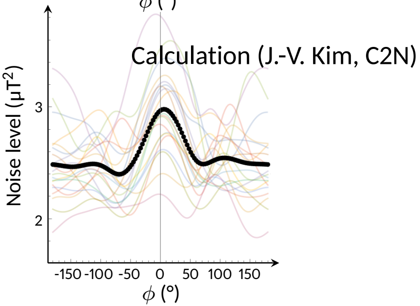


Statistics on Néel left (CCW) skyrmions



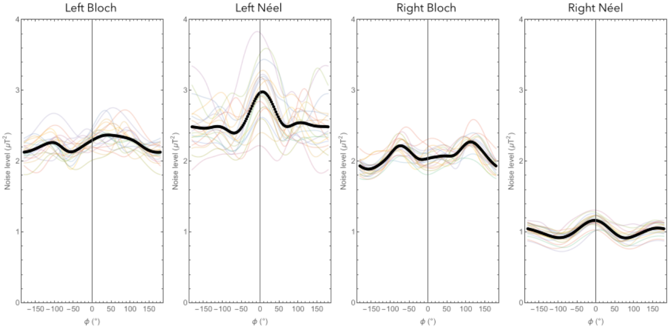
Angular variation of PL



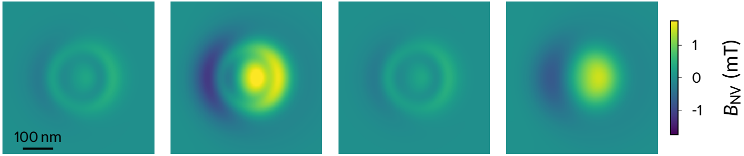


Expected pattern on other skyrmion types

Simulated noise distribution along the contour



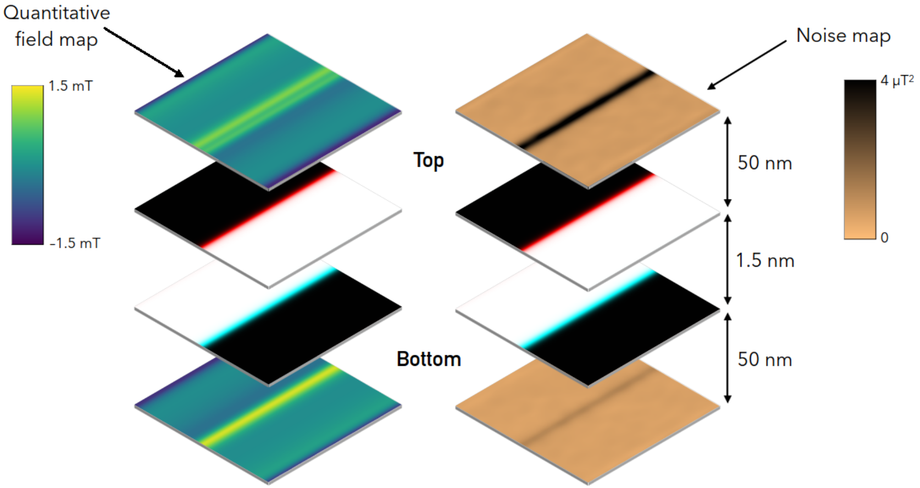
Simulated stray field maps



- 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!

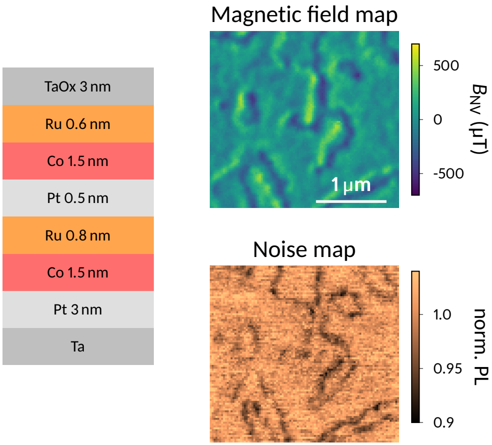
Do we also expect this for domain walls? Yes!

Calculation: C2N, Palaiseau (J.-V. Kim)



Experiment: looking at both sides of the film

Initial stack: Néel left

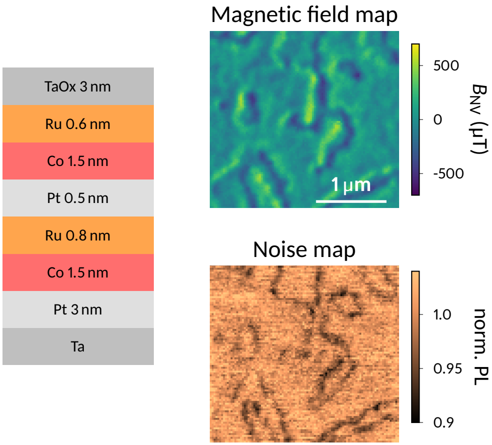


A. Finco *et al.* *in preparation* (2024)

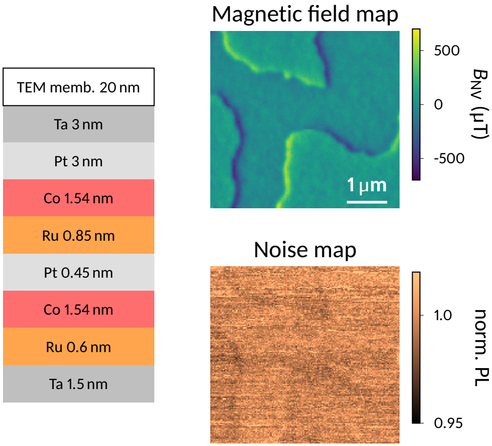
Samples: J. Urrestarazu, R. Guedas, Spintec, Grenoble

Experiment: looking at both sides of the film

Initial stack: Néel left



Inverted stack: Néel right

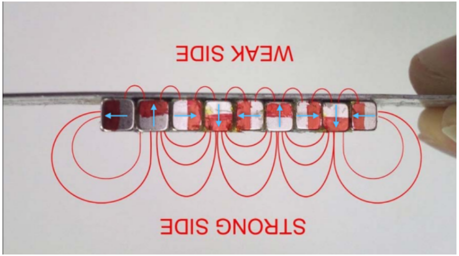


A. Finco *et al.* *in preparation* (2024)

Samples: J. Urrestarazu, R. Guedas, Spintec, Grenoble

Origin of this effect, 1st ingredient : Spin waves = fridge magnets

Halbach arrays



$\vec{m}_0 \quad \odot \quad \odot \quad \odot \quad \odot \quad \odot$

$\delta\vec{m} \quad \rightarrow \quad \uparrow \quad \leftarrow \quad \downarrow \quad \rightarrow \quad +\vec{k}$

$\vec{m}_0 \quad \odot \quad \odot \quad \odot \quad \odot \quad \odot$

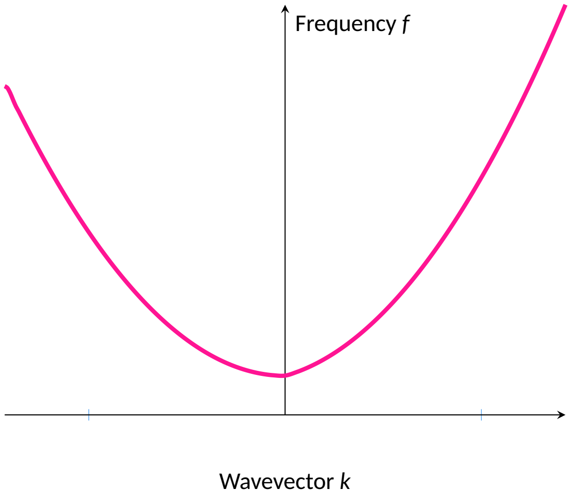
$\delta\vec{m} \quad \leftarrow \quad \uparrow \quad \rightarrow \quad \downarrow \quad \leftarrow \quad -\vec{k}$

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

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

Origin of this effect, 2nd ingredient: DMI

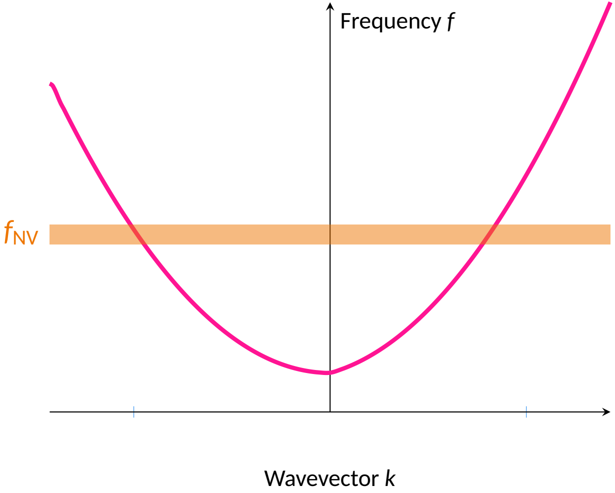
1. DMI induces non-reciprocity in the SW dispersion



Origin of this effect, 2nd ingredient: DMI

1. DMI induces non-reciprocity in the SW dispersion

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

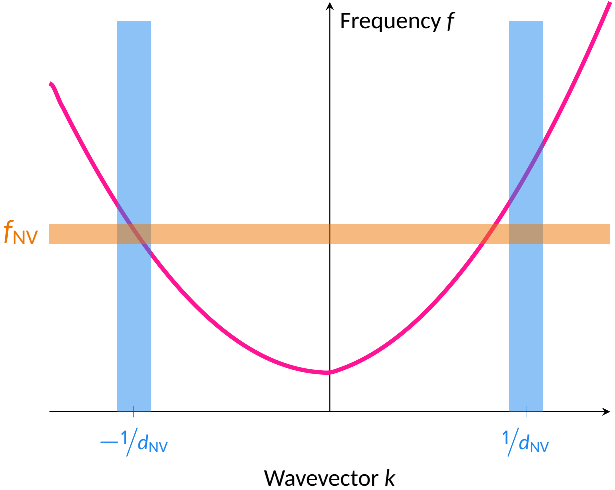


Origin of this effect, 2nd ingredient: DMI

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 $\pm 1/d_{NV}$



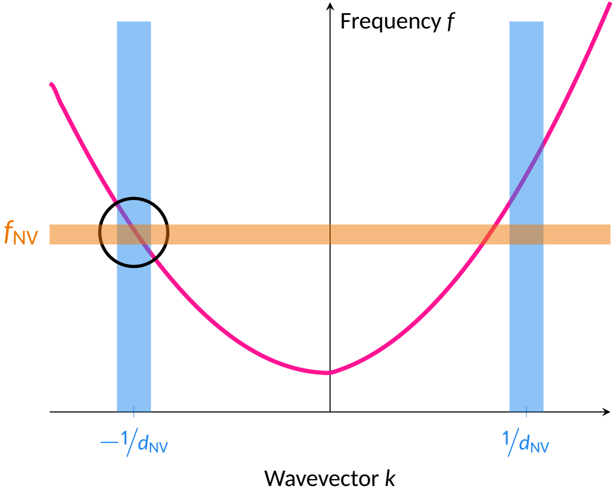
Origin of this effect, 2nd ingredient: DMI

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 $\pm 1/d_{NV}$

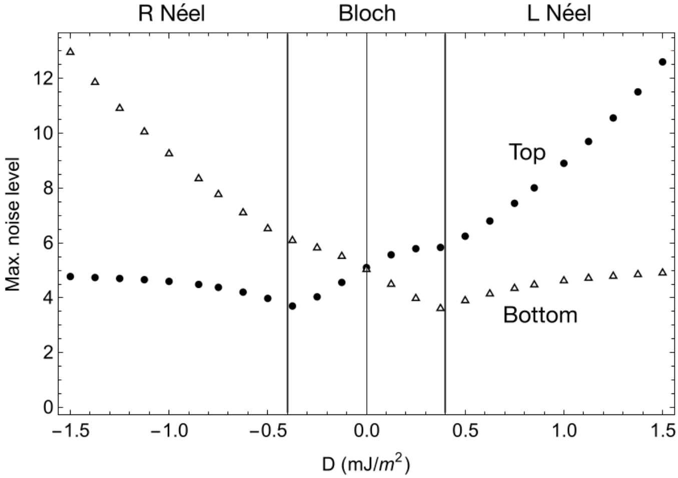
➔ The NV center is more sensitive to a k direction than the other



Expected noise level vs DMI

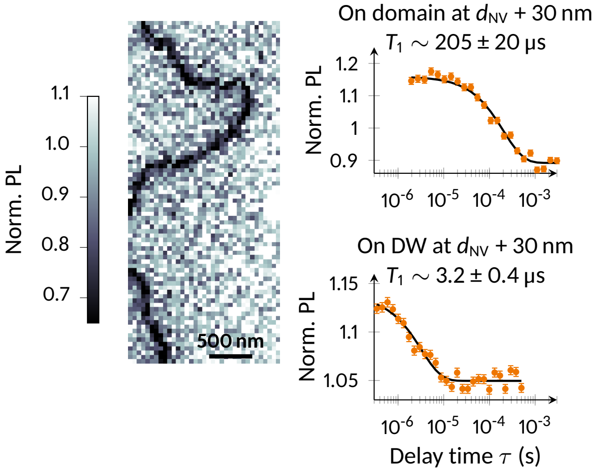
Calculation: J.-V. Kim, C2N, Palaiseau

For a **single** ferromagnetic layer

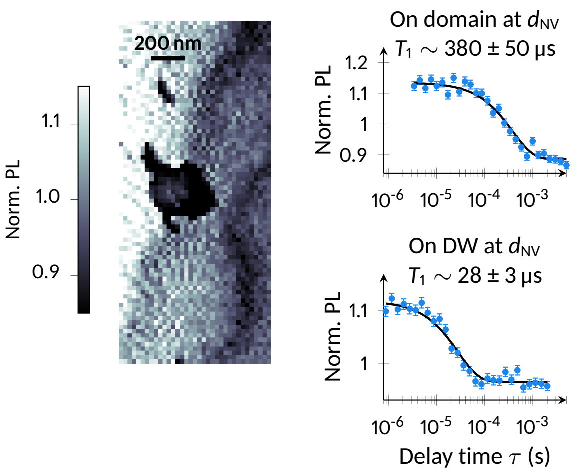


Data measured on a single FM layer grown on a membrane

Néel left side of the membrane (top)

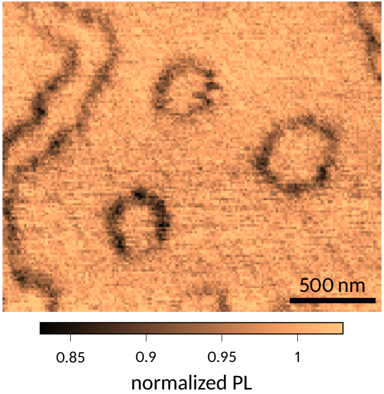


Néel right side of the membrane (bottom)

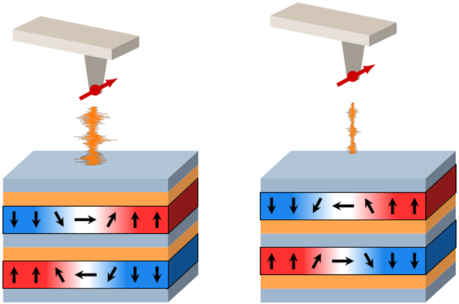


Summary

Localization and characterization of magnetic textures from thermal spin wave noise using scanning NV center microscopy



Method to get insight about sign and strength of DMI



M. Rollo *et al.* PRB 103 (2021), 235418

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

A. Finco *et al.* *in preparation* (2024)

Acknowledgments

L2C, Montpellier
Pawan Kumar, Maxime Rollo, Florentin Fabre, Angela Haykal, Rana Tanos, Saddem Chouaieb, Waseem Akhtar, Isabelle Philip, Vincent Jacques

Laboratoire Albert Fert, Palaiseau
William Legrand, Fernando Ajejas, Karim Bouzehouane, Nicolas Reyren, Vincent Cros

C2N, Palaiseau
Jean-Paul Adam, Thibaut Devolder, Joo-Von Kim

Spintec, Grenoble
Van-Tuong Pham, Joseba Urrestarazu-Larrañaga, Rodrigo Guedas Garcia, Naveen Sisodia, Kaushik Bairagi, Johan Pelloux-Prayer, Liliana Buda-Prejbeanu, Gilles Gaudin, Olivier Boulle

erc
European Research Council
Established by the European Commission

EXAFONIS

anr agence nationale de la recherche

TATOO

TSAR