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

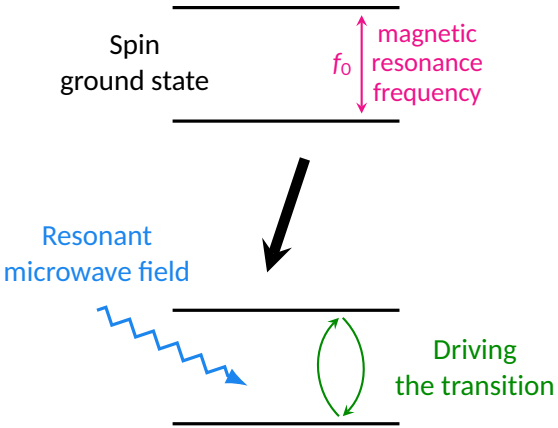
ICM 2024, July 2nd 2024, Bologna

slides available at https://magimag.eu

How can we use a quantum system to probe condensed matter?

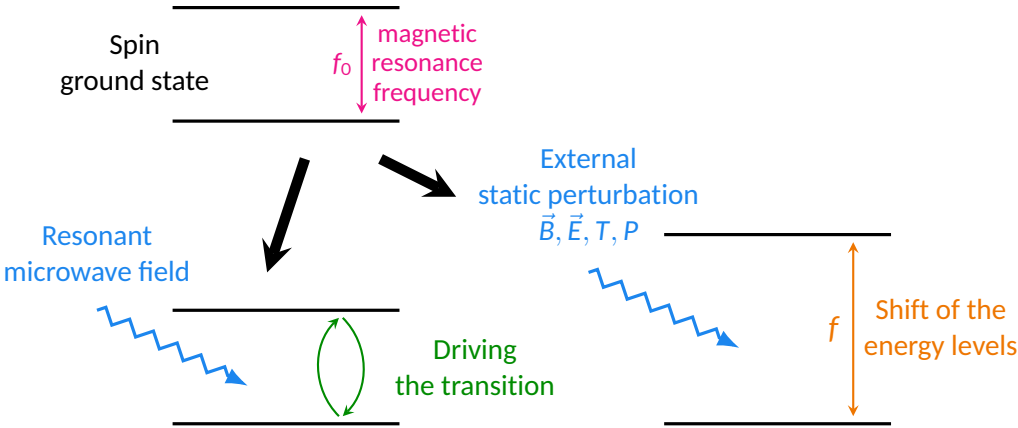
C. L. Degen *et al*. *Rev. Mod. Phys*. 89 (2017), 035002
F. Casola *et al*. *Nat. Rev. Mater.* 3 (2018), 17088

How can we use a quantum system to probe condensed matter?



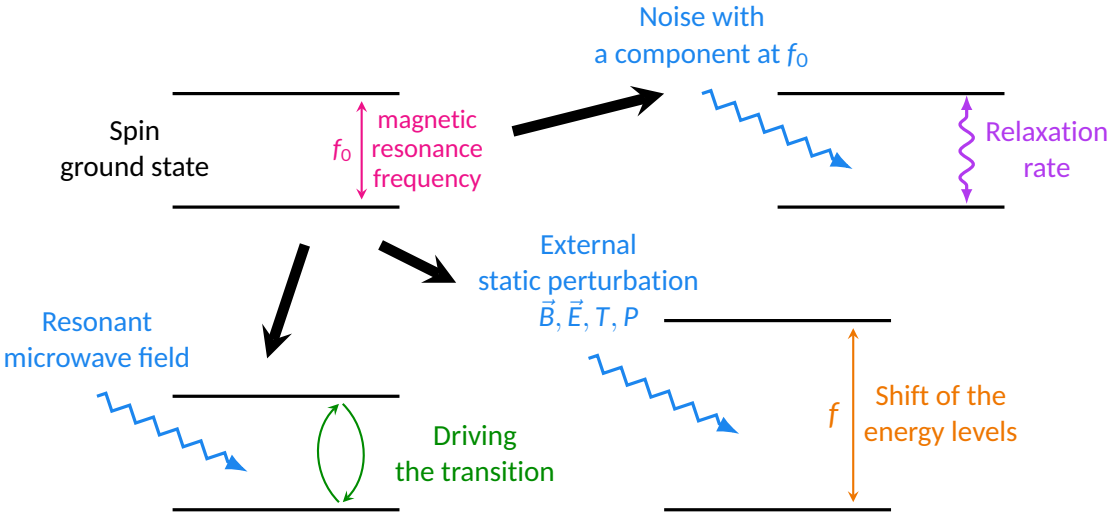
C. L. Degen *et al.* *Rev. Mod. Phys.* 89 (2017), 035002
F. Casola *et al.* *Nat. Rev. Mater.* 3 (2018), 17088

How can we use a quantum system to probe condensed matter?



C. L. Degen *et al.* *Rev. Mod. Phys.* 89 (2017), 035002
F. Casola *et al.* *Nat. Rev. Mater.* 3 (2018), 17088

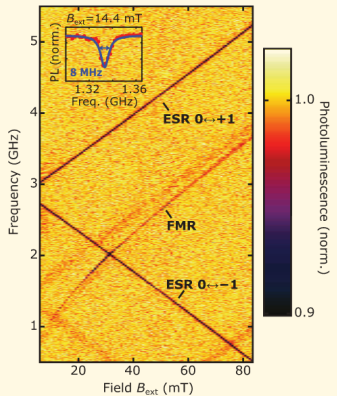
How can we use a quantum system to probe condensed matter?



C. L. Degen *et al.* *Rev. Mod. Phys.* 89 (2017), 035002
F. Casola *et al.* *Nat. Rev. Mater.* 3 (2018), 17088

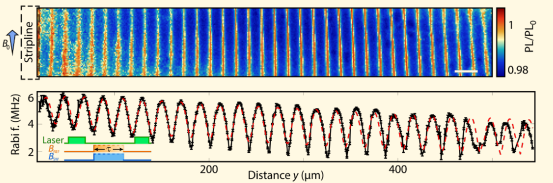
Quantum sensing for magnonics (a few examples)

Measurement of spin chemical potential

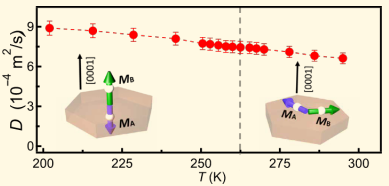


C. Du *et al.* *Science* 357 (2017), 195–198

Imaging of propagating spin waves



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



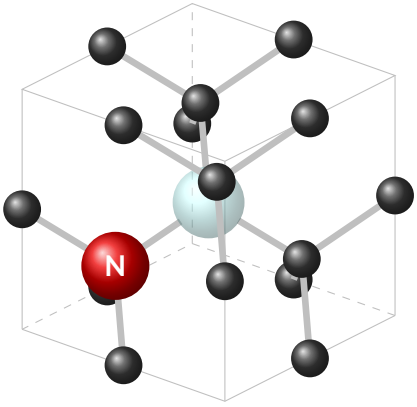
Measurement of the spin diffusion constant

H. Wang *et al.* *Sci. Adv.* 8 (2022), eabg8562

➔ The 2024 Magnonics Roadmap

B. Flebus *et al.* *J. Phys.: Condens. Matter* 36 (2024), 363501

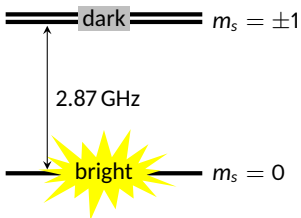
Our quantum sensor: the NV center in diamond



- Artificial atom: energy levels in the diamond bandgap
- Photostable defect
- Spin S=1
- Individual defects can be isolated/implanted
- Ambient conditions

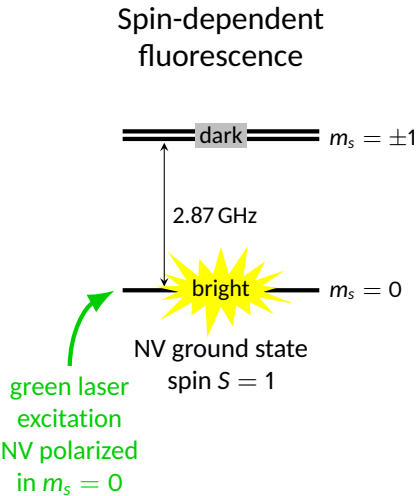
Principle of static magnetic field measurement

Spin-dependent fluorescence

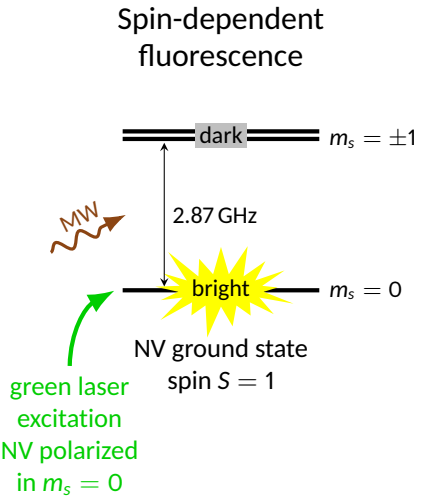


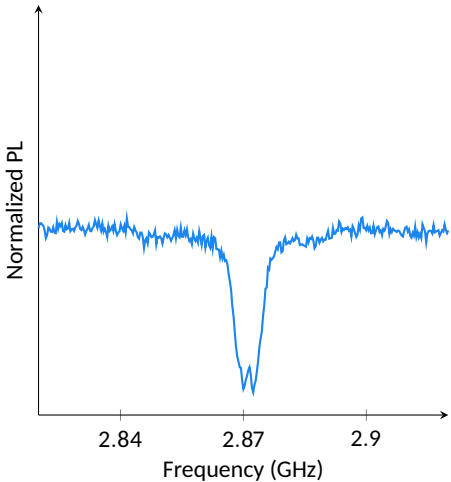
NV ground state
spin $S = 1$

Principle of static magnetic field measurement

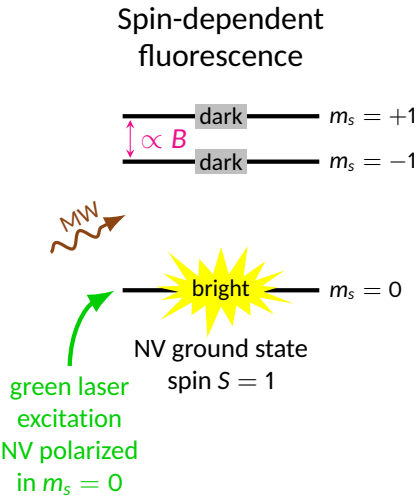


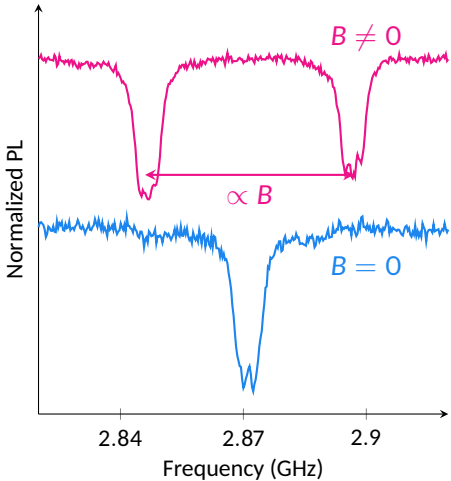
Principle of static magnetic field measurement



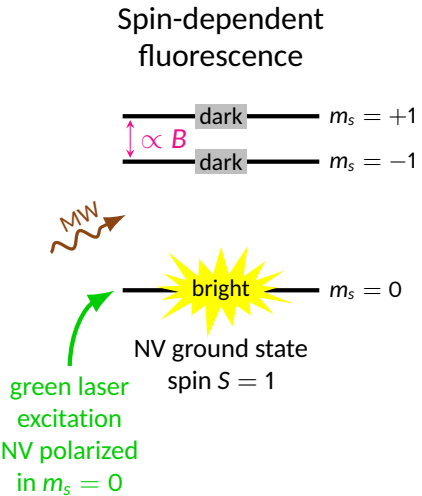


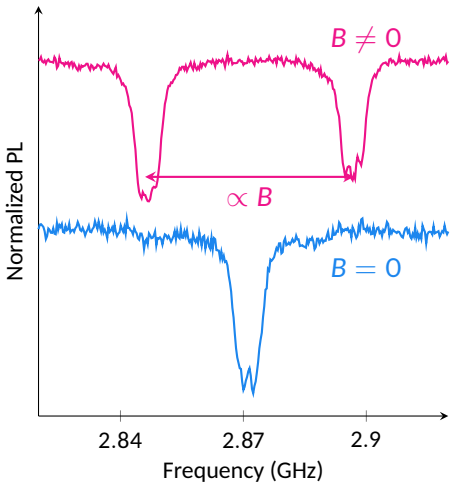
Principle of static magnetic field measurement





Principle of static magnetic field measurement

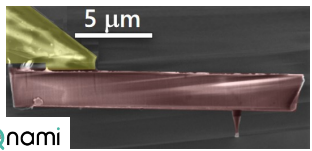




Sensitivity: a few $\mu T/\sqrt{Hz}$

Integration of the defect in a scanning probe microscope

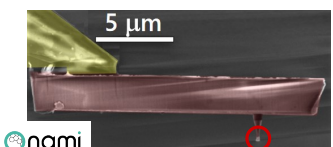
Diamond
AFM tip



Qnami

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

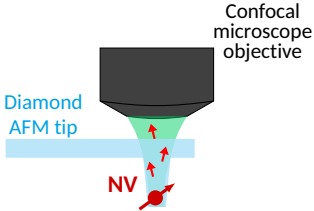
Integration of the defect in a scanning probe microscope

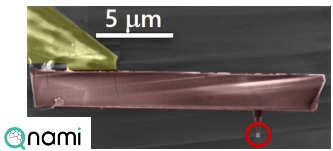


Implanted single
NV center

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

Integration of the defect in a scanning probe microscope

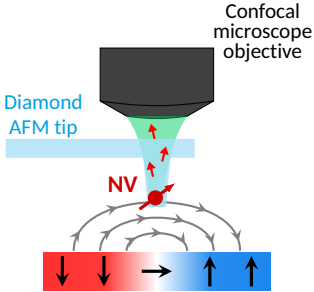




Implanted single
NV center

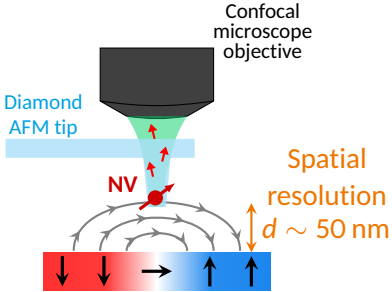
P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

Integration of the defect in a scanning probe microscope



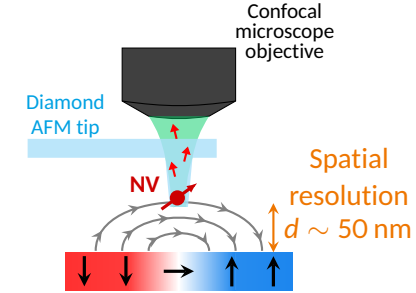
P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

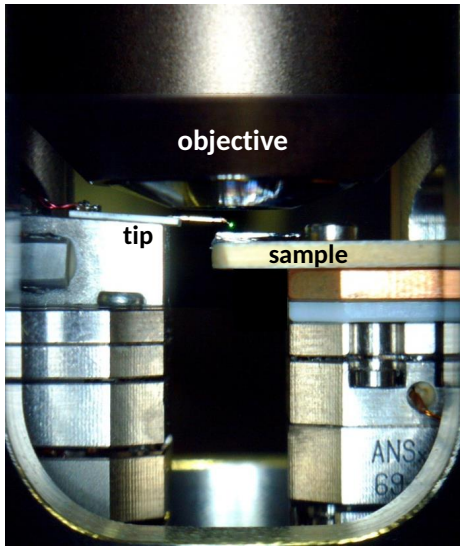
Integration of the defect in a scanning probe microscope



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

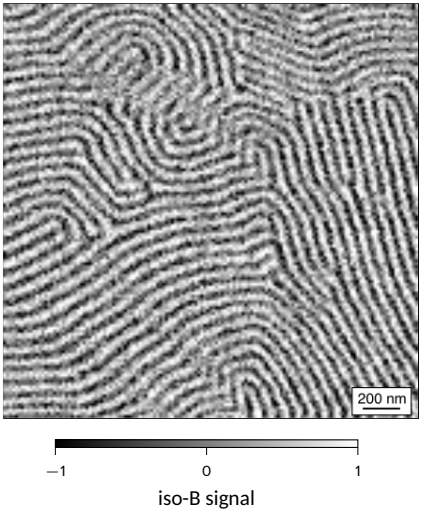
Integration of the defect in a scanning probe microscope





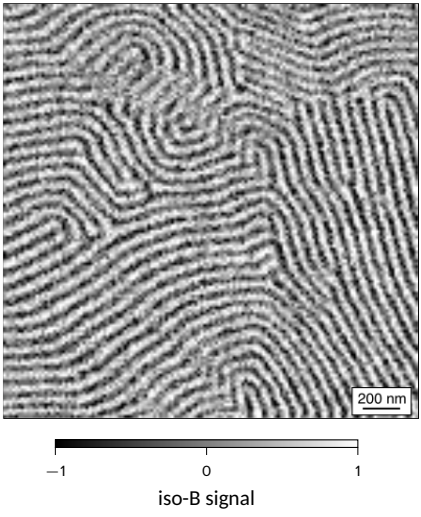
P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

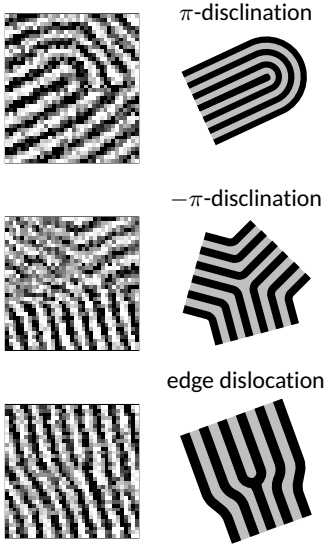
Example: Topological defects at the surface of bulk $BiFeO_3$ crystals



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

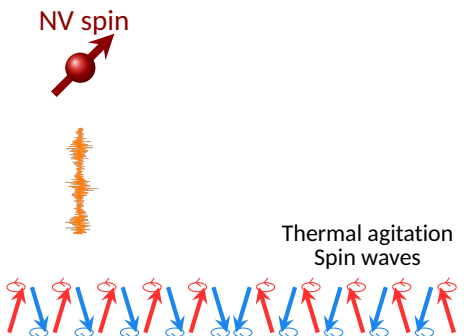
B. Flebus *et al.* *Phys. Rev. B* 98 (2018), 180409

- 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

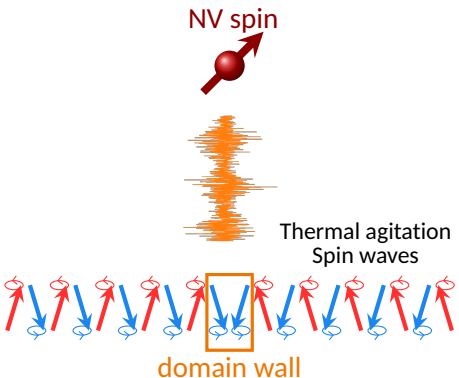
- Completely compensated antiferromagnets = **no static stray field** to probe
- But NV centers are also sensitive to **magnetic noise**!
- Use the different noise properties above domains and domain walls for imaging



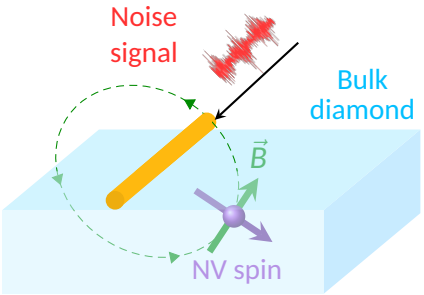
Detection of magnetic noise rather than stray field

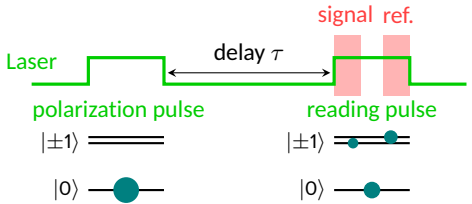
B. Flebus *et al.* *Phys. Rev. B* 98 (2018), 180409

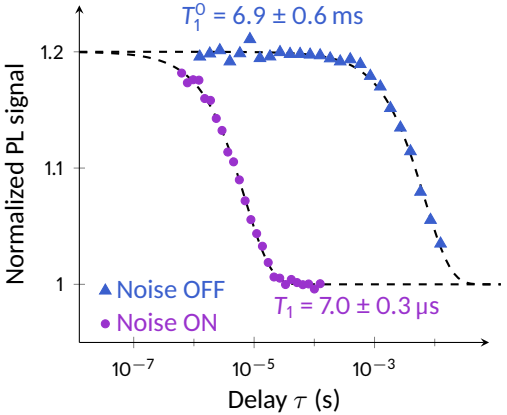
- Completely compensated antiferromagnets = **no static stray field** to probe
- But NV centers are also sensitive to **magnetic noise**!
- Use the different noise properties above domains and domain walls for imaging



Acceleration of the relaxation with noise



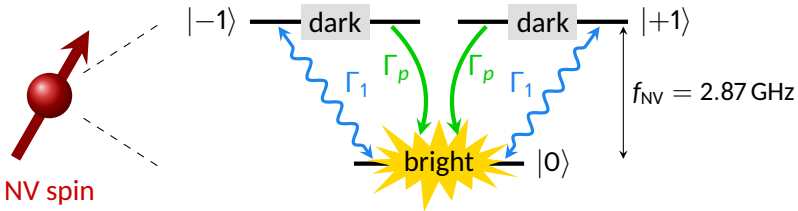




Noise spectrum centered
at the NV transition frequency

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

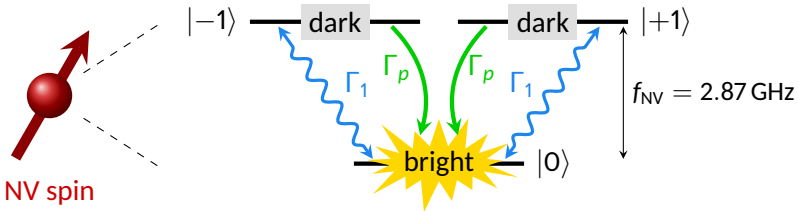
Effect of magnetic noise on the emitted photoluminescence



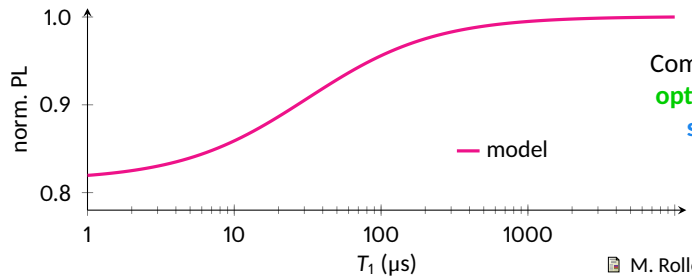
Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}

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

Effect of magnetic noise on the emitted photoluminescence



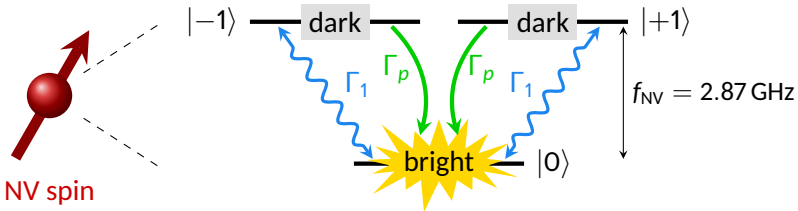
Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}



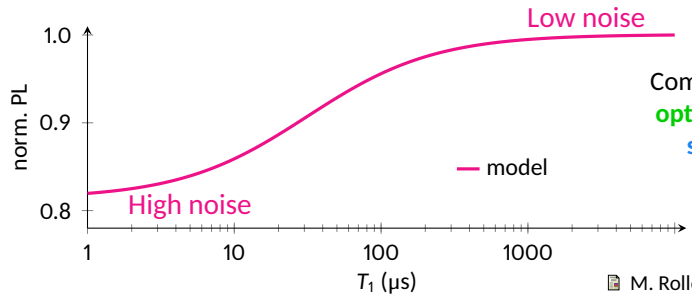
Competition between **optical pumping** and **spin relaxation**

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

Effect of magnetic noise on the emitted photoluminescence



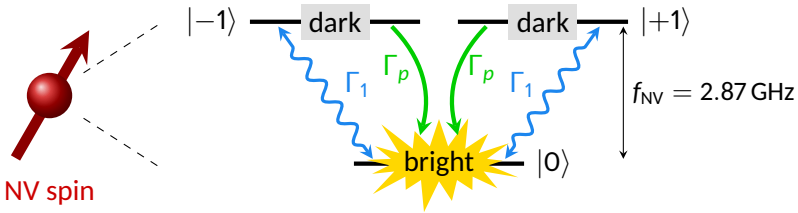
Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}



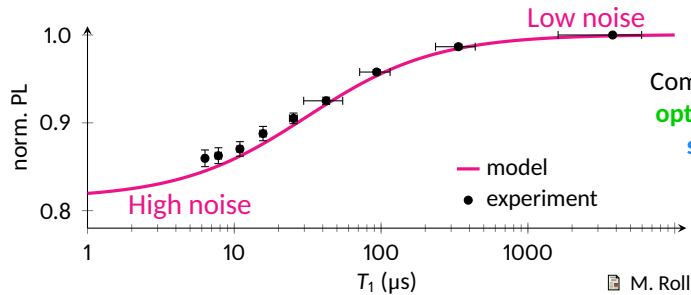
Competition between **optical pumping** and **spin relaxation**

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

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}



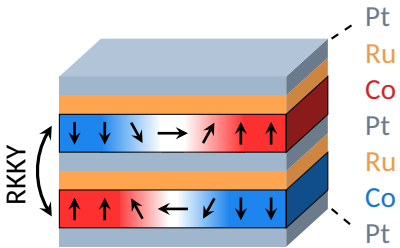
Competition between **optical pumping** and **spin relaxation**

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**

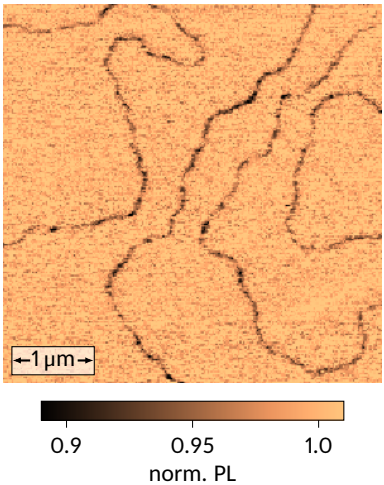


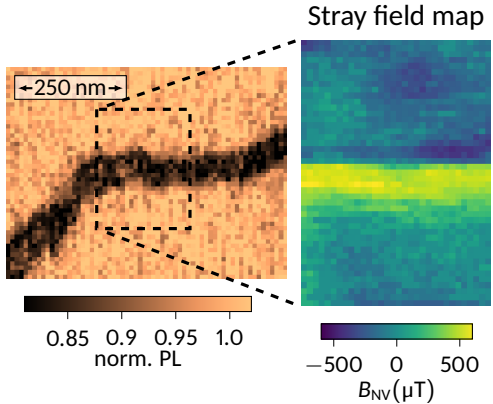
- W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34
- V. T. Pham *et al.* *Science* 384 (2024), 307

- 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!

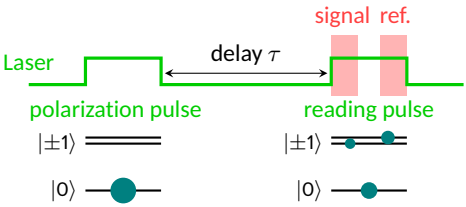
Detection of domain walls by relaxometry



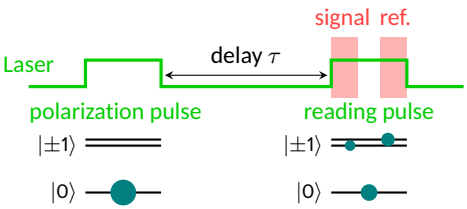


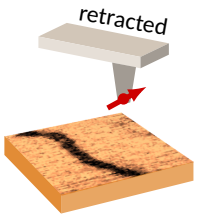
A. Finco *et al.* *Nat. Commun.* 12 (2021), 767

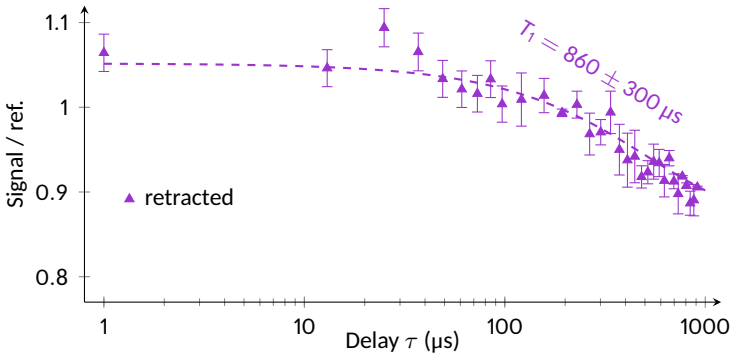
Local variation of the relaxation time



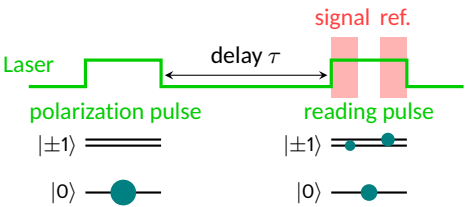
Local variation of the relaxation time

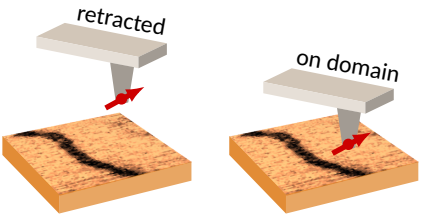






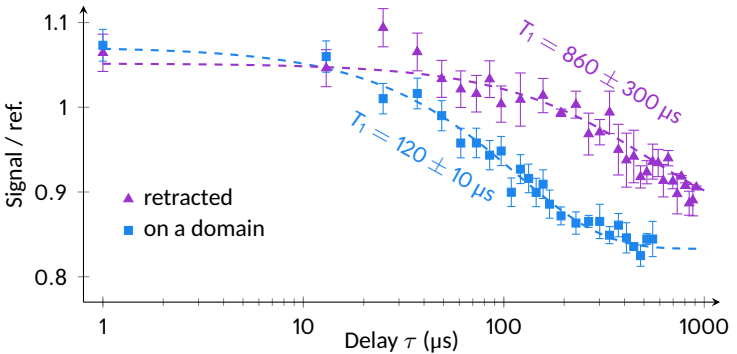
Local variation of the relaxation time



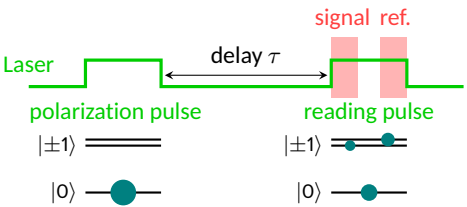


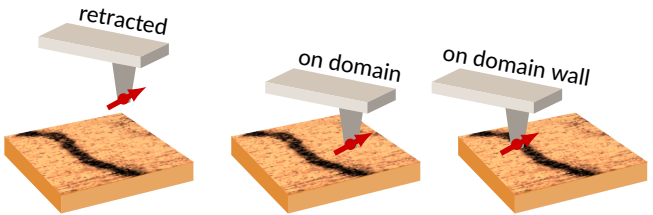
Clear diminution of T_1

→ **Enhancement of the spin relaxation**



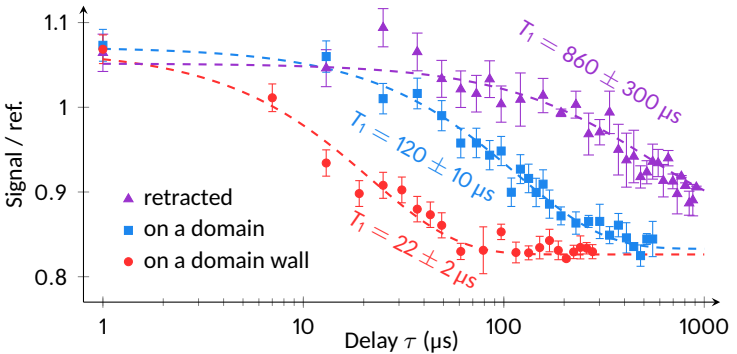
Local variation of the relaxation time





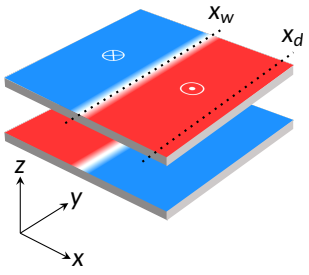
Clear diminution of T_1

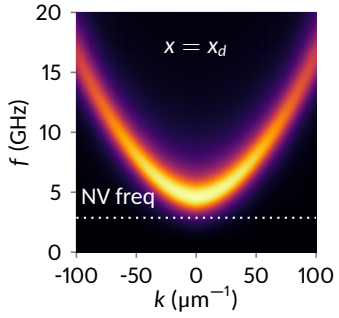
→ **Enhancement of the spin relaxation**

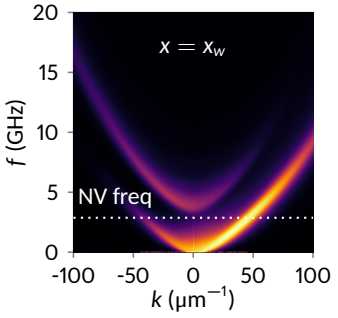


Origin of the noise: spin waves

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



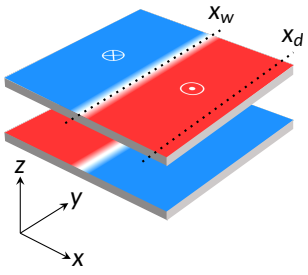


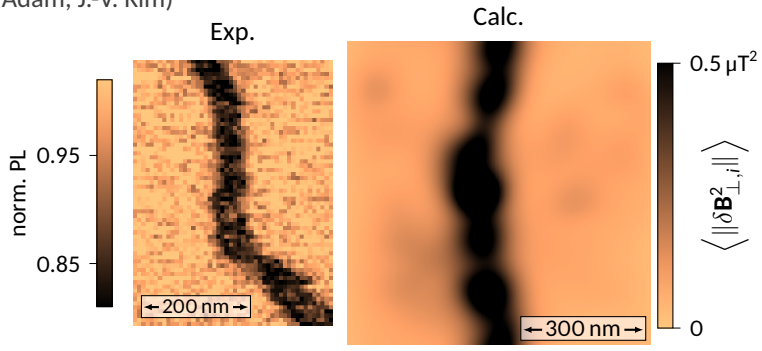


- NV frequency slightly below the gap, in the tail of power spectral density, which is the reason why we detect some noise when approaching the tip.
- No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

Origin of the noise: spin waves

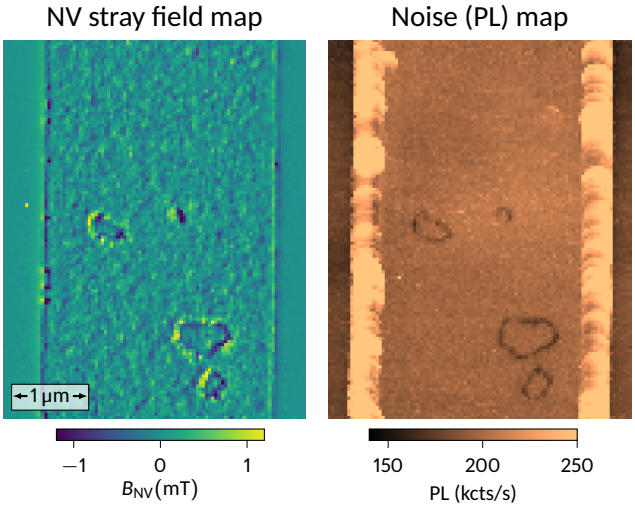
Collaboration: C2N, Palaiseau (J.-P. Adam, J.-V. Kim)





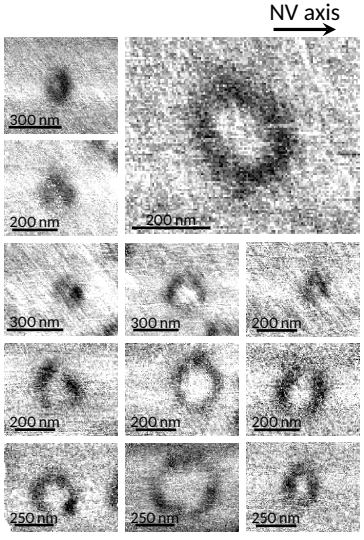
- NV frequency slightly below the gap, in the tail of power spectral density, which is the reason why we detect some noise when approaching the tip.
- No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

After applying magnetic field

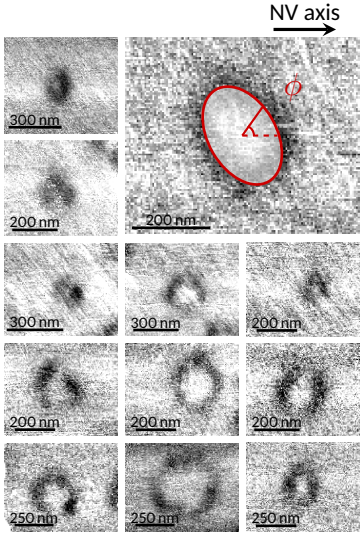


- Oop field of about 150 mT applied for nucleation
- Skyrmions and big bubbles pinned

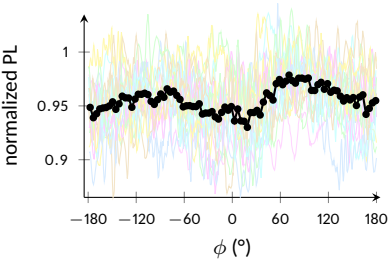
Statistics on Néel left (CCW) skyrmions



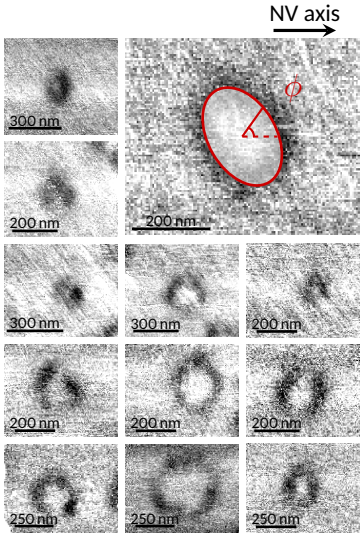
Statistics on Néel left (CCW) skyrmions



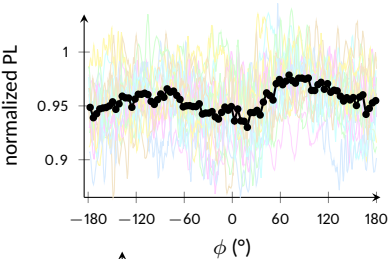
Angular variation of PL



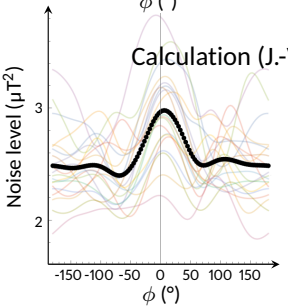
Statistics on Néel left (CCW) skyrmions



Angular variation of PL

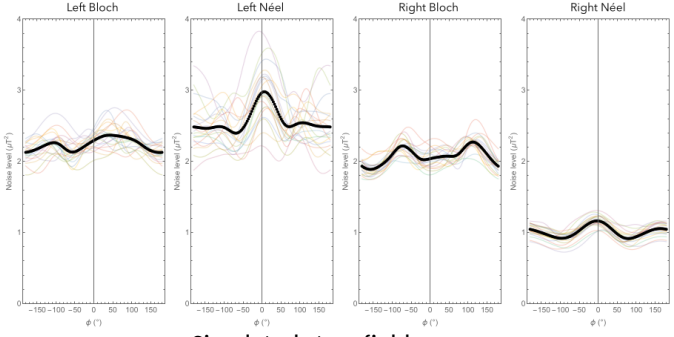


Calculation (J.-V. Kim, C2N)

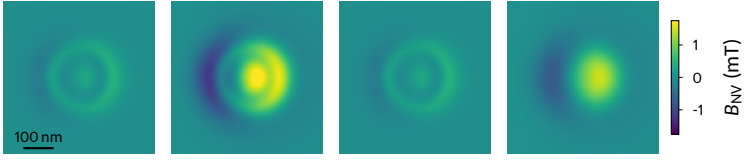


Expected pattern on other skyrmion types

Simulated noise distribution along the contour



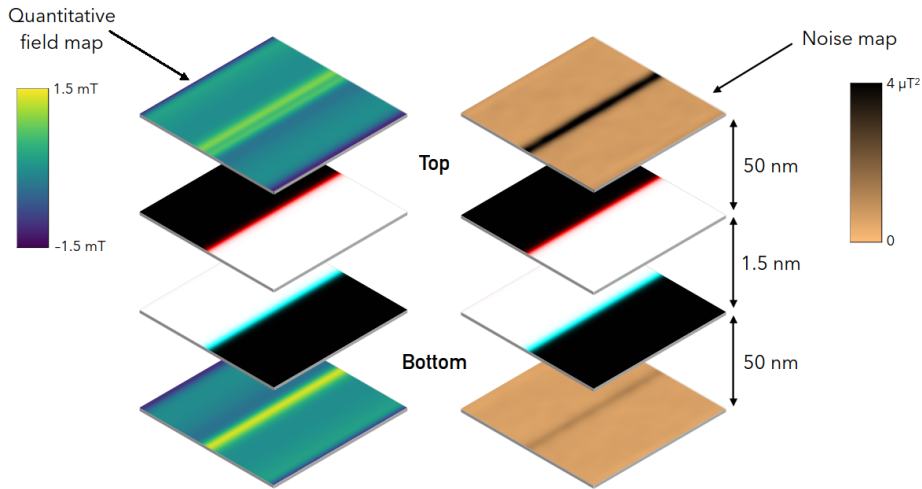
Simulated stray field maps



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

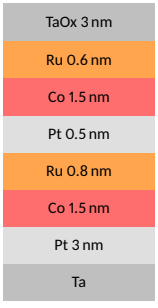
Do we also expect this for domain walls? Yes!

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

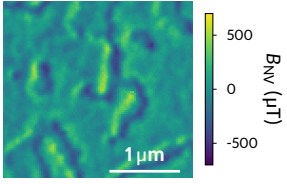


Experiment: looking at both sides of the film

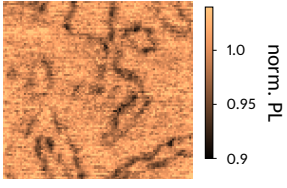
Initial stack: Néel left



Magnetic field map



Noise map



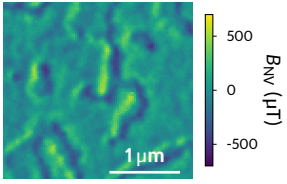
A. Finco *et al.* *in preparation* (2024)

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

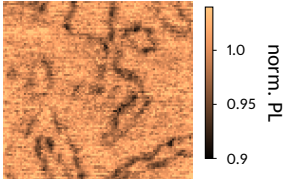
Experiment: looking at both sides of the film

Initial stack: Néel left

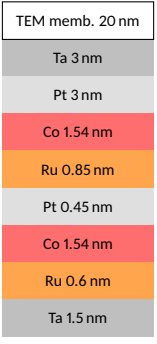
Magnetic field map



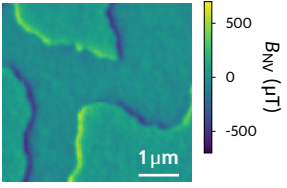
Noise map



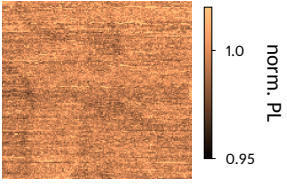
Inverted stack: Néel right



Magnetic field map



Noise map

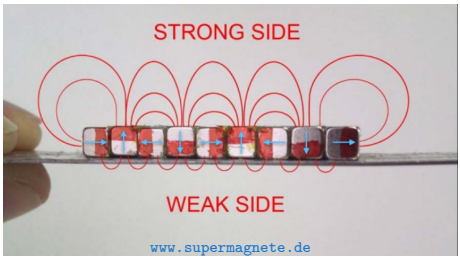


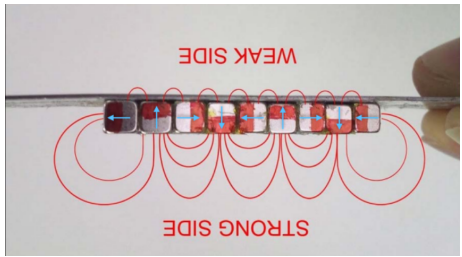
A. Finco *et al.* *in preparation* (2024)

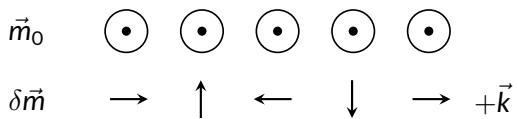
Samples: J. Urrestarazu, R. Guedas, Spintec, Grenoble

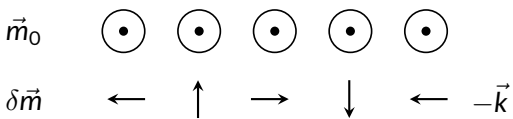
Origin of this effect, 1st ingredient : Spin waves = fridge magnets

Halbach arrays







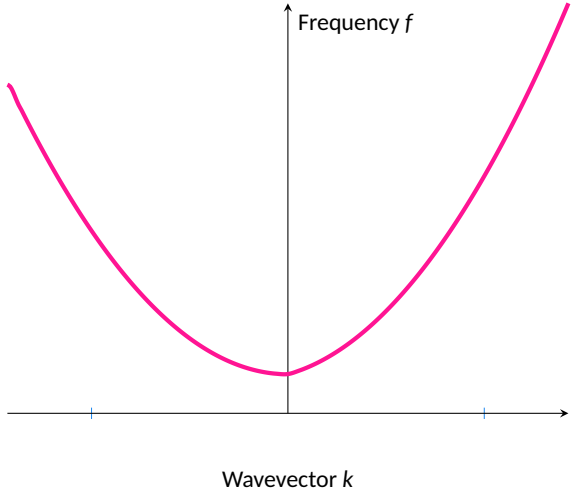


J. Mallinson. *IEEE Trans. on Mag.* 9 (1973), 678

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

Origin of this effect, 2nd ingredient: DMI

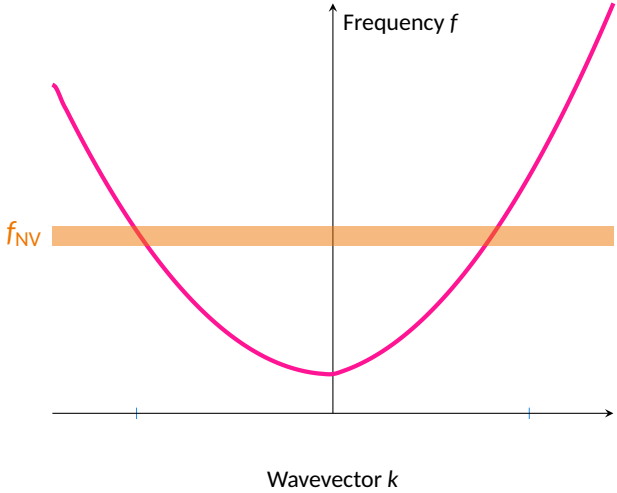
1. DMI induces non-reciprocity in the SW dispersion



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}

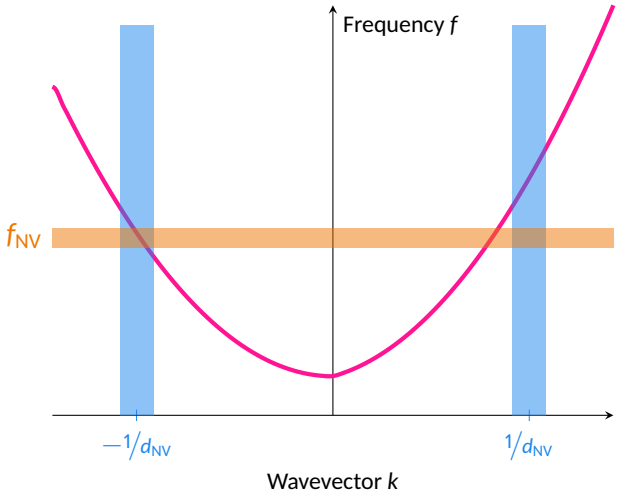


Origin of this effect, 2nd ingredient: DMI

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 $\pm 1/d_{NV}$



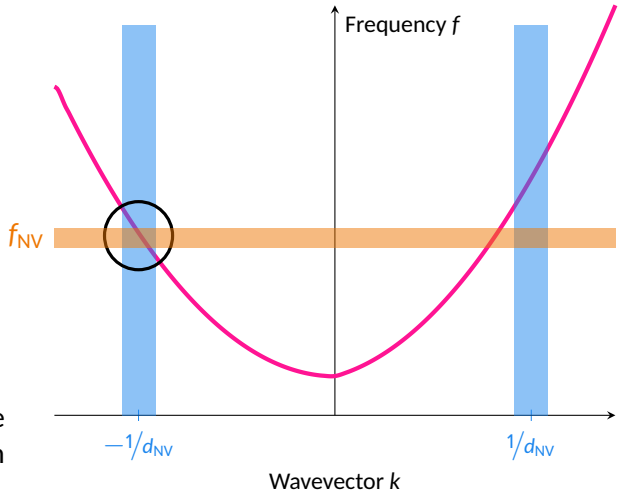
Origin of this effect, 2nd ingredient: DMI

1. DMI induces non-reciprocity in the SW dispersion

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

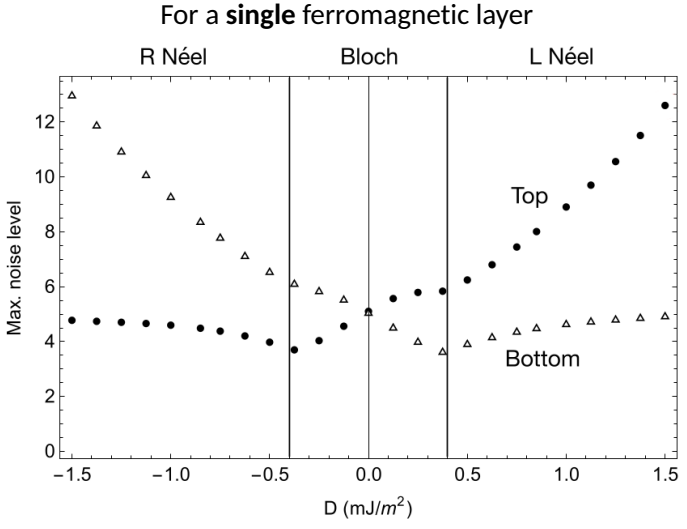
3. The NV probe is filtering SW at $\pm 1/d_{NV}$

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



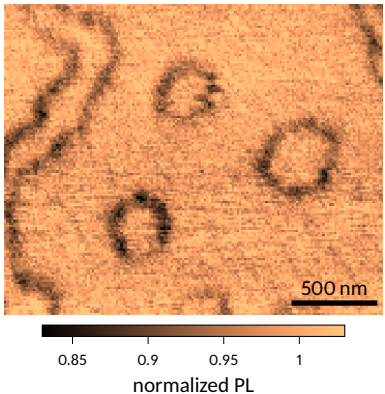
Expected noise level vs DMI

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

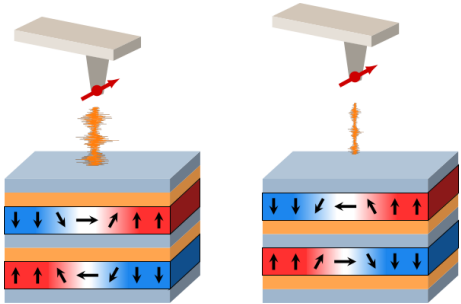


Summary

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

UMR CNRS/Thales, 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

European Research Council
Established by the European Commission

EXAFONIS

anr agence nationale de la recherche

TATOO

TSAR