Detection of DMI-induced magnetic chirality from spin wave noise

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Team Solid-State Quantum Technologies (S2QT)

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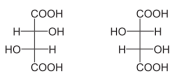
slides available at https://magimag.eu

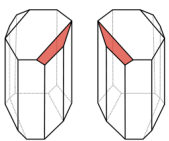
Chirality

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*. *Eur. Phys. J. 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**.

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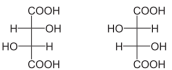

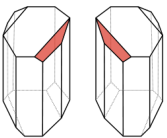

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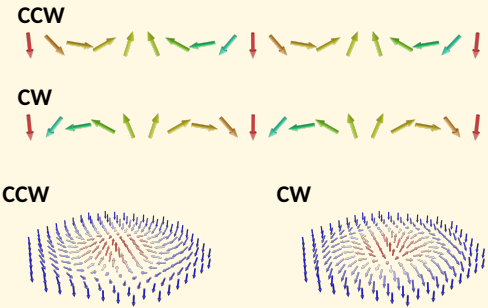
Magnetic chirality

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



What can we learn from magnetic chirality?

Insight about the magnetic interactions inside the sample: are the structures stabilized by dipolar effects, by Dzyaloshinkii-Moriya interaction (DMI), what is the sign of the DMI, etc?

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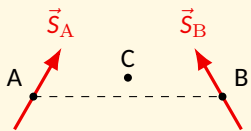
Dzyaloshinkii-Moriya interaction

Antisymmetric exchange interaction, requires spatial inversion symmetry breaking

$$\mathcal{E}_{\mathrm{DM}} = \vec{D} \cdot (\vec{S}_A \times \vec{S}_B)$$



I. E. Dzyaloshinskii. *Sov. Phys. JETP* 5 (1957), 1259

T. Moriya. *Physical Review* 120 (1960), 91

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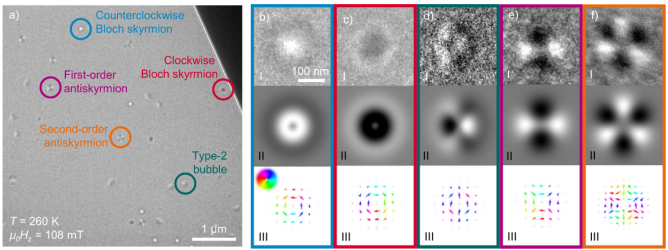
Objects stabilized by dipolar couplings
➔ no fixed chirality



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

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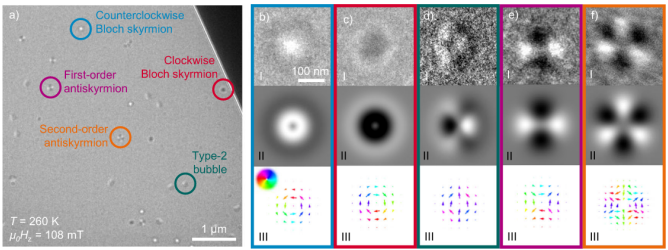
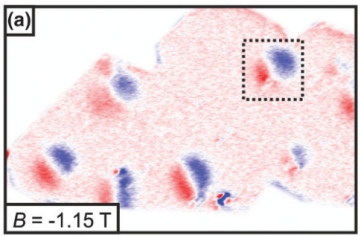


M. Heigl *et al.* *Nat. Commun.* 12 (2021), 2611

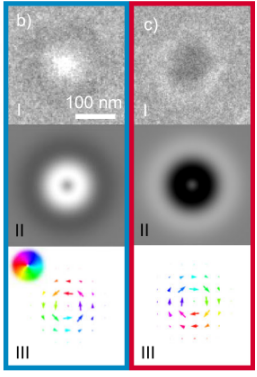
Objects stabilized by DMI
➔ single chirality/rotational sense



N. Romming *et al.* *PRL* 114 (2015), 177203

How can we probe magnetic chirality?

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



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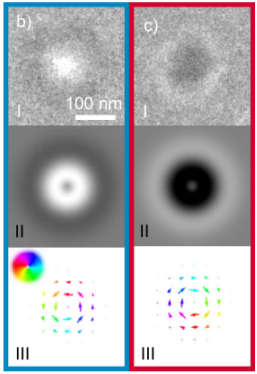
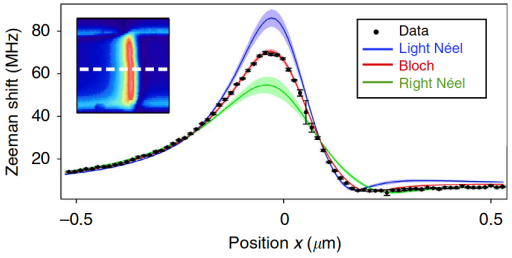


M. Heigl *et al.* *Nat. Commun.* 12 (2021), 2611

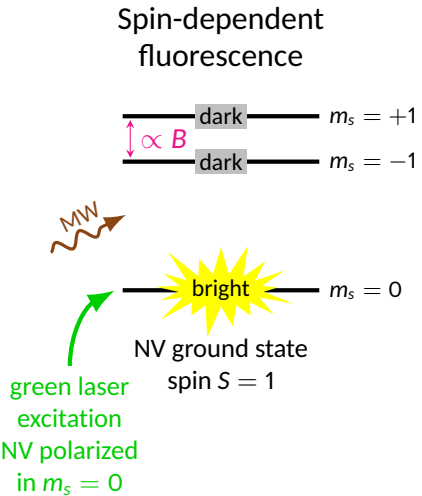
Measure quantitatively the **stray field**
produced by the texture

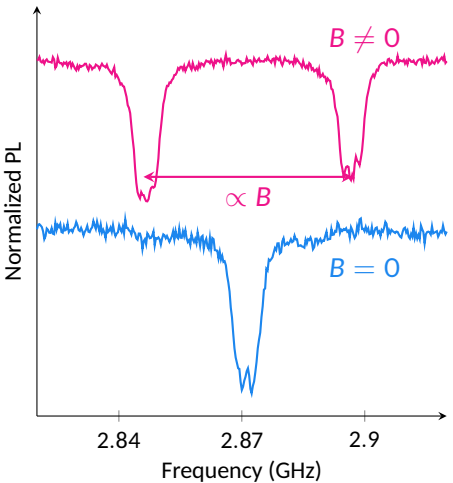


J.-P. Tetienne *et al.* *Nat. Commun.* 6 (2015), 6733

➔ Scanning NV magnetometry

Principle of static magnetic field measurement with an NV center

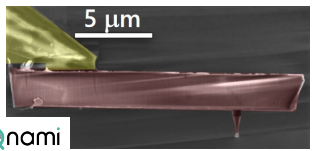




Sensitivity: a few $\mu T/\sqrt{Hz}$

Integration of the NV defect in a scanning probe microscope

Diamond
AFM tip



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

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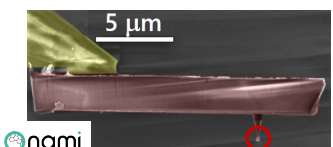

Implanted single
NV center

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

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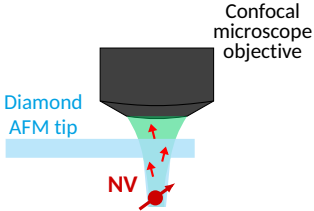

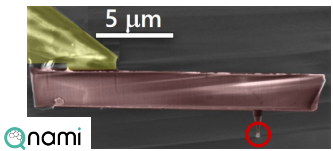

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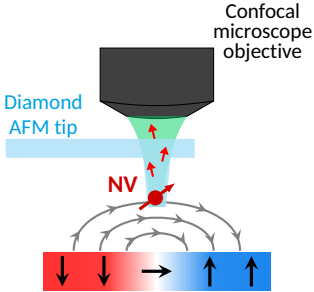

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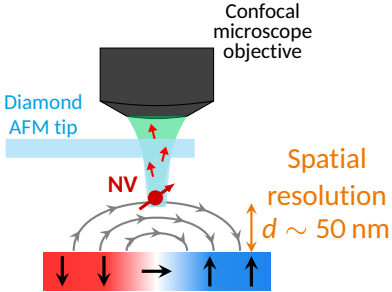

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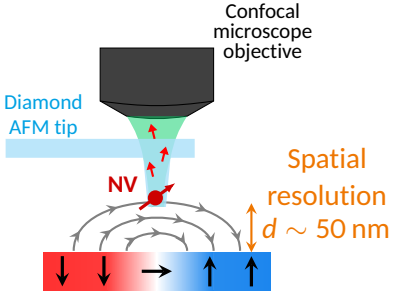

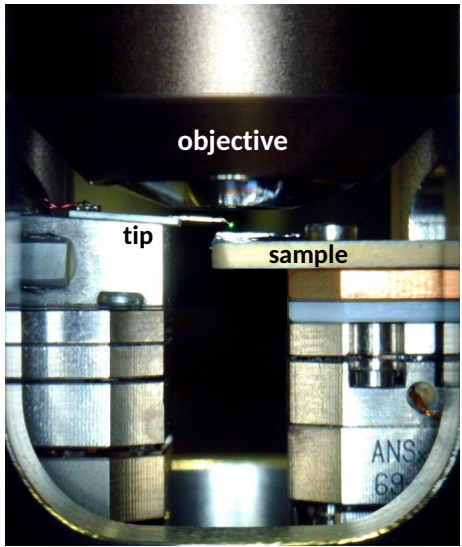

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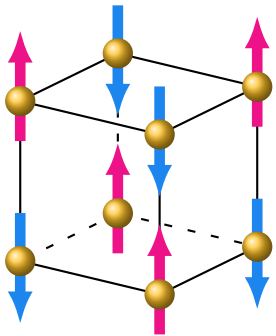
A powerful tool to image antiferromagnets

Example: Bismuth ferrite

G-type antiferromagnet



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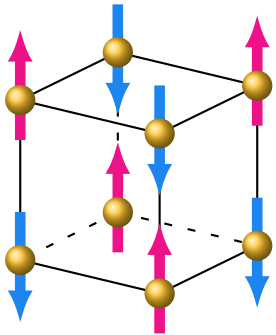

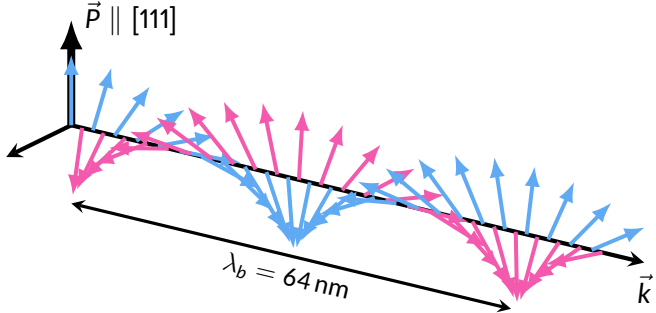

Fully compensated cycloid
$\rightarrow$ **No stray field!**

M. Ramazanoglu *et al.* *Phys. Rev. Lett.* 107 (2011), 207206

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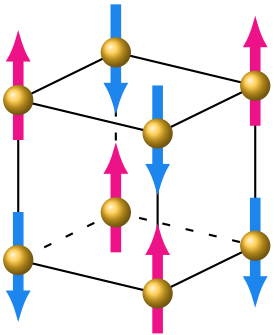
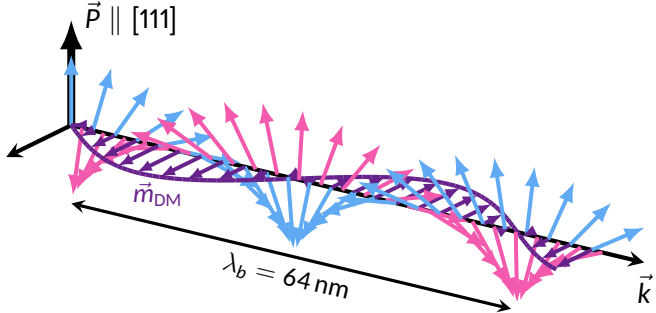
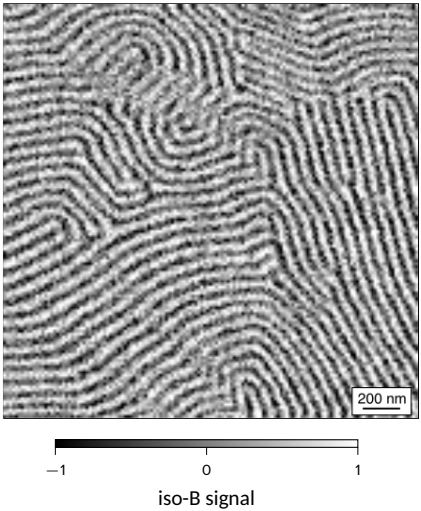




Spin density wave
Weak uncompensated moment
$\rightarrow$ **Small stray field**

M. Ramazanoglu *et al.* *Phys. Rev. Lett.* 107 (2011), 207206

Topological defects at the surface of bulk $BiFeO_3$ crystals



A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

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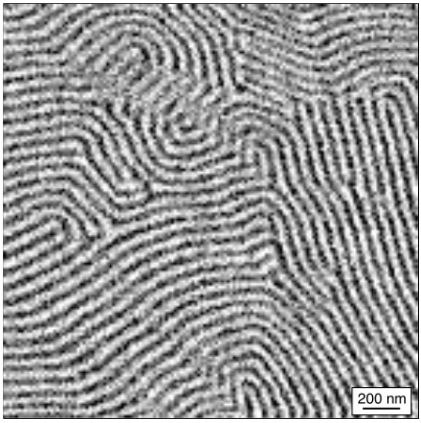
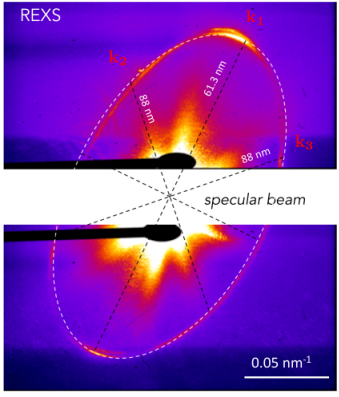


Resonant X-ray scattering



SOLEIL SYNCHROTRON

N. Jaouen

A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

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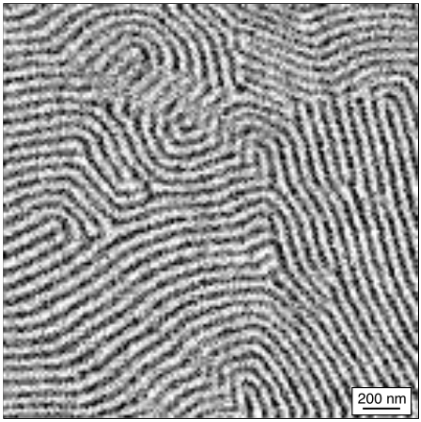

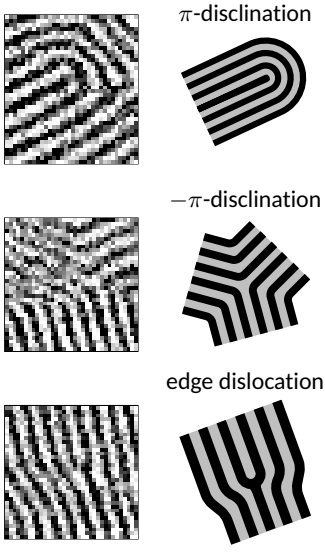

A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

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

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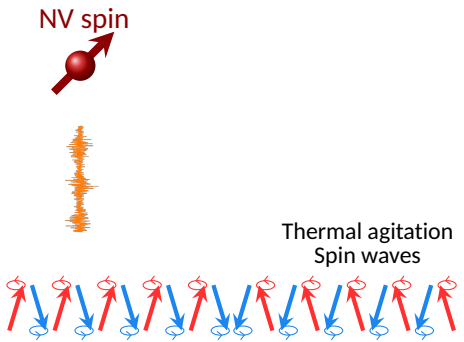

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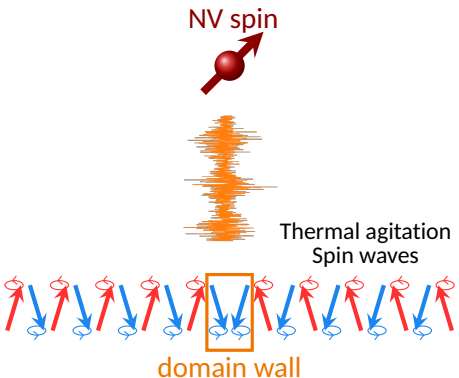
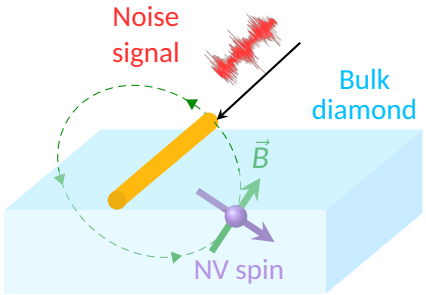
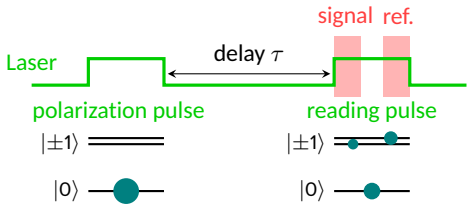
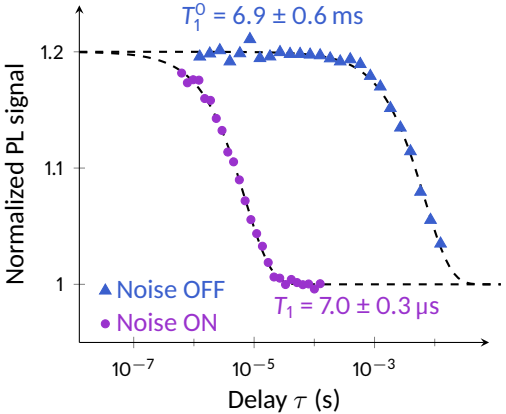


Acceleration of the relaxation with noise



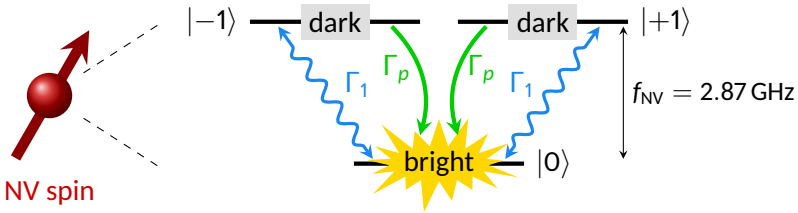




Noise spectrum centered
at the NV transition frequency

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}

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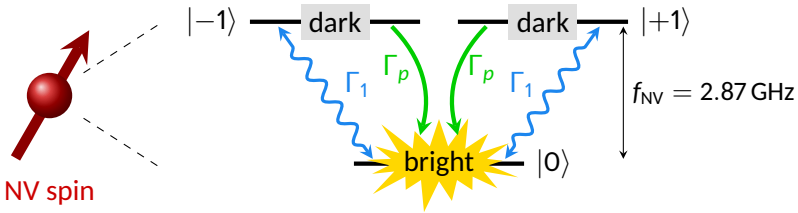

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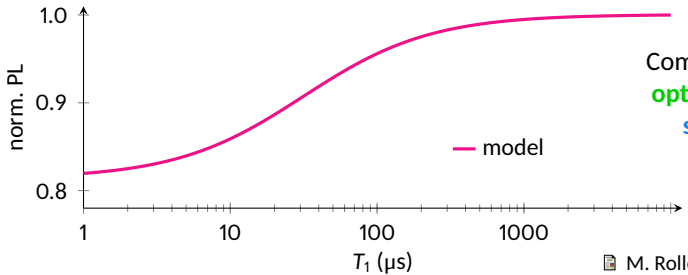

Competition between **optical pumping** and **spin relaxation**

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

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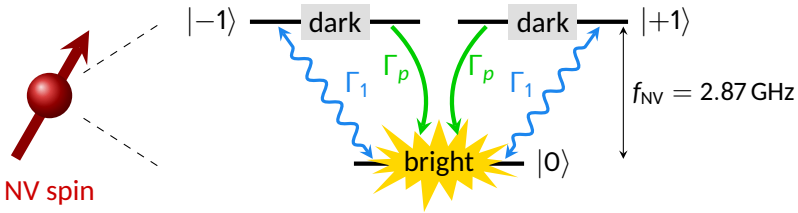

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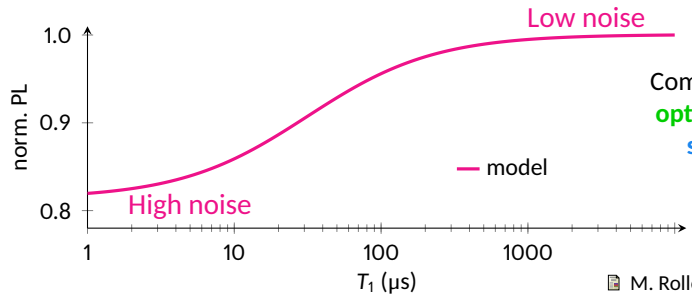

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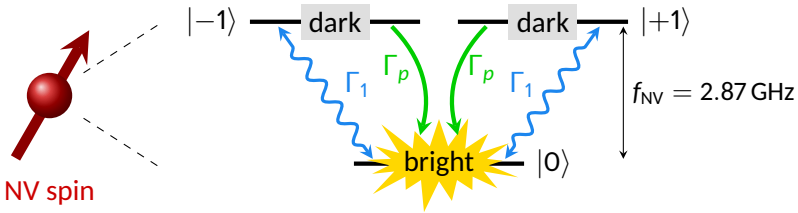

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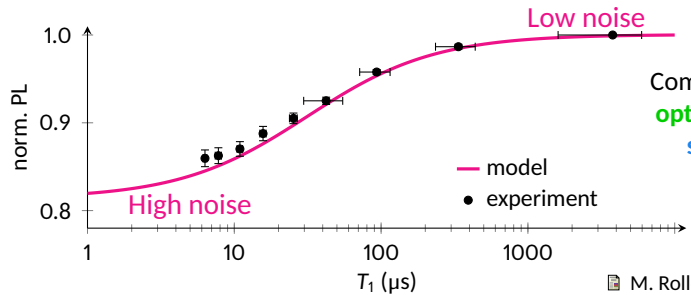


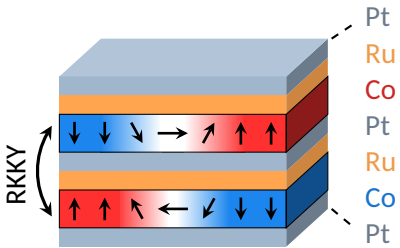
Competition between **optical pumping** and **spin relaxation**

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**

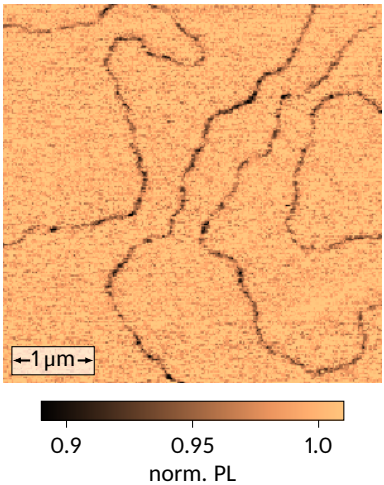


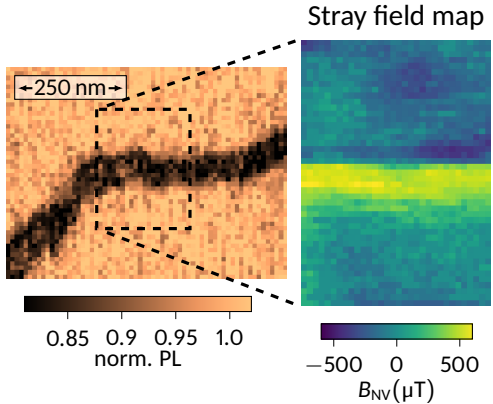
- W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34
- V. T. Pham *et al.* *Science* 384 (2024), 307

- 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!

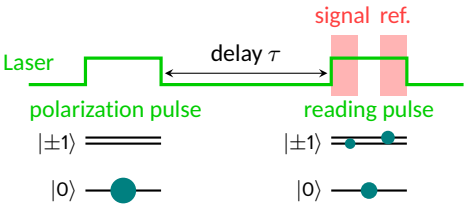
Detection of domain walls by relaxometry



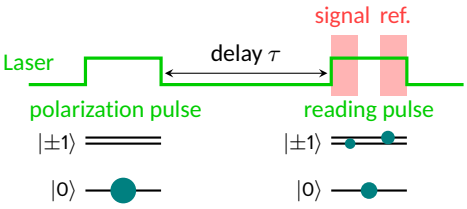


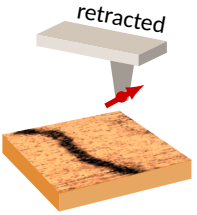
A. Finco *et al.* *Nat. Commun.* 12 (2021), 767

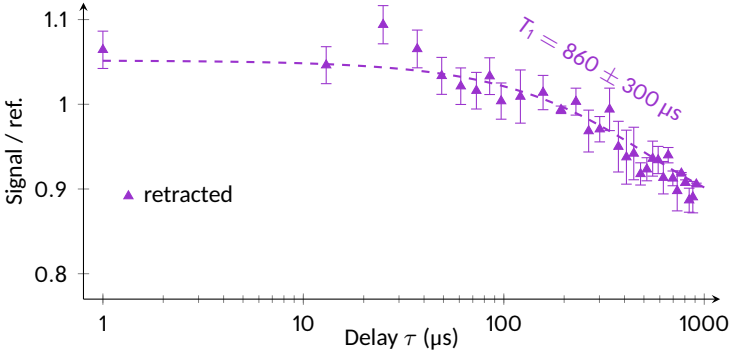
Local variation of the relaxation time



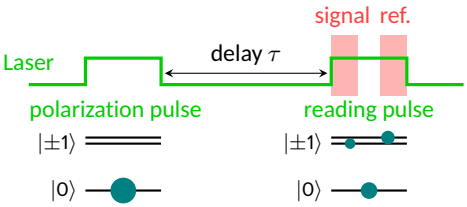
Local variation of the relaxation time

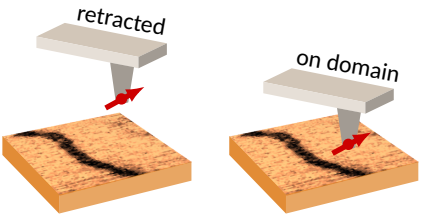






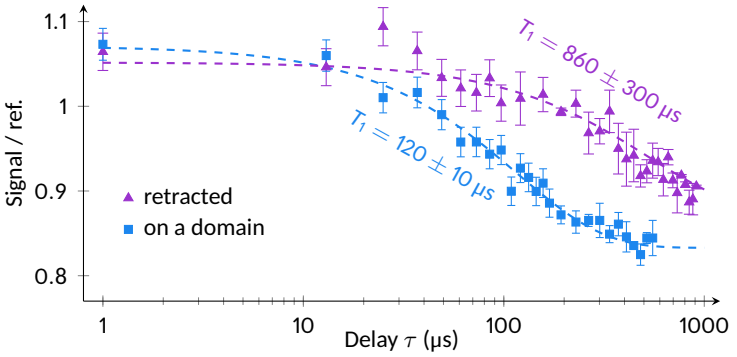
Local variation of the relaxation time



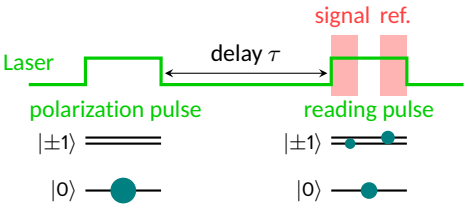


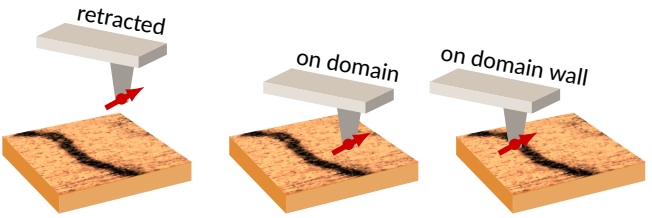
Clear diminution of T_1

→ **Enhancement of the spin relaxation**



Local variation of the relaxation time





Clear diminution of T_1

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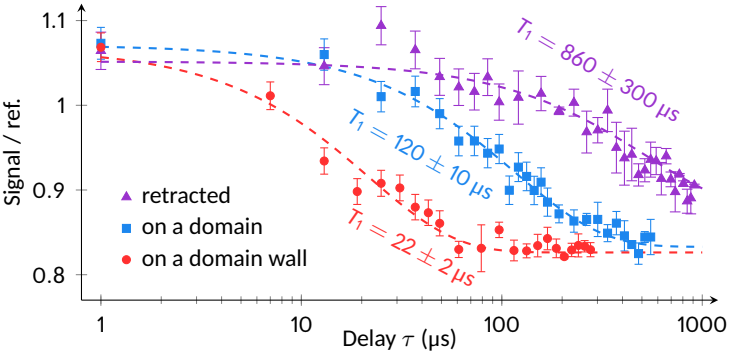
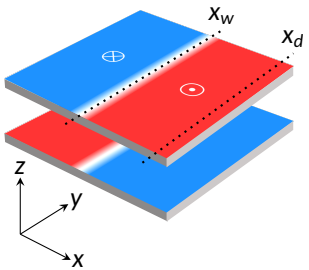
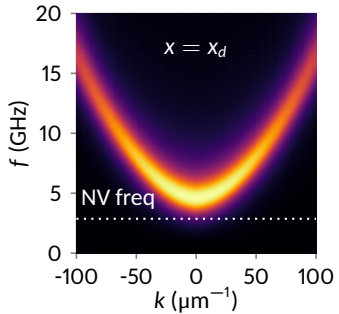
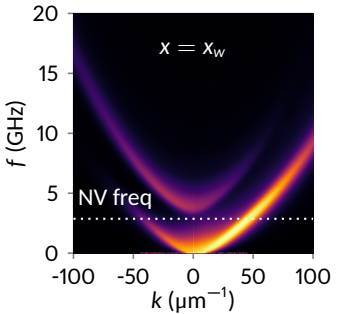


Origin of the noise: spin waves

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



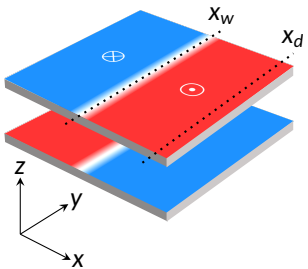


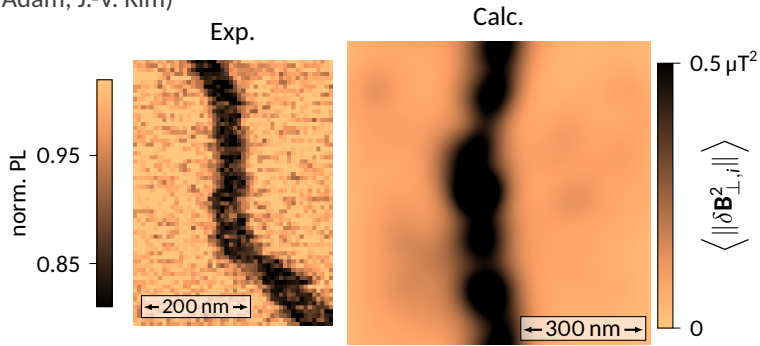


- NV frequency slightly below the gap, in the tail of power spectral density, which is the reason why we detect some noise when approaching the tip.
- No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

Origin of the noise: spin waves

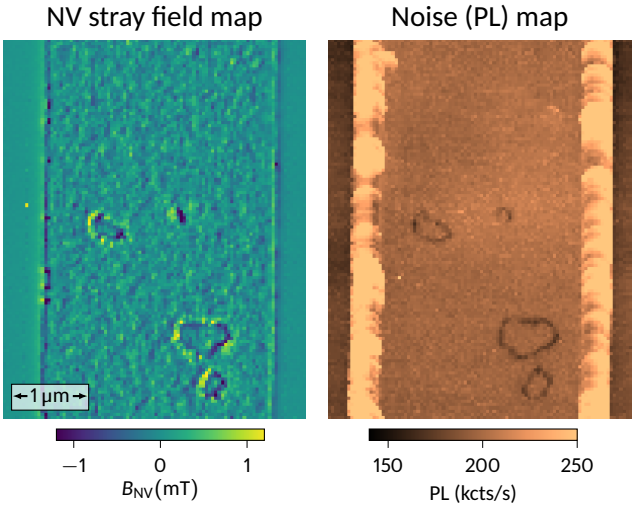
Collaboration: C2N, Palaiseau (J.-P. Adam, J.-V. Kim)





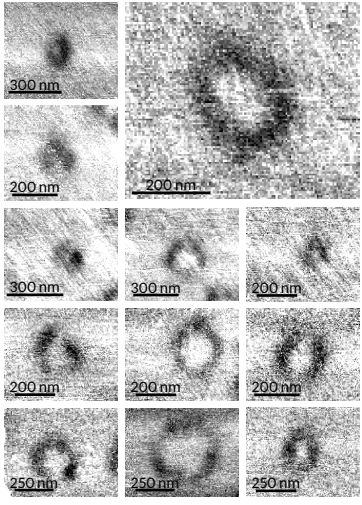
- NV frequency slightly below the gap, in the tail of power spectral density, which is the reason why we detect some noise when approaching the tip.
- No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

After applying magnetic field

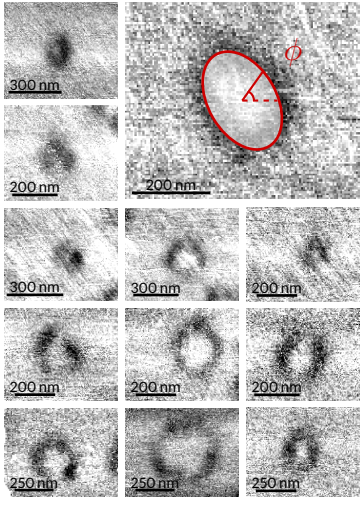


- Oop field of about 150 mT applied for nucleation
- Skyrmions and big bubbles pinned

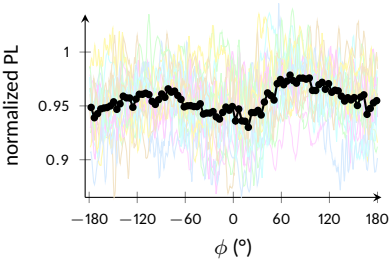
Statistics on Néel left (CCW) skyrmions



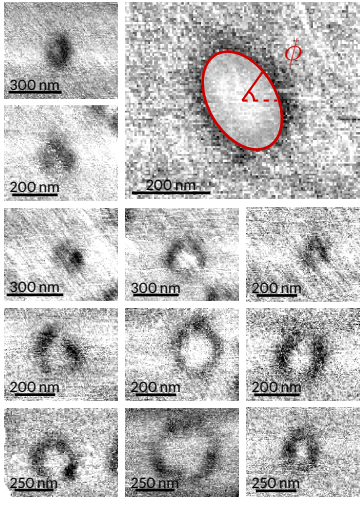
Statistics on Néel left (CCW) skyrmions



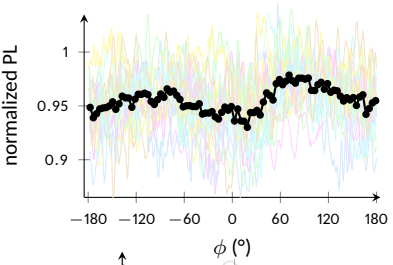
Angular variation of PL



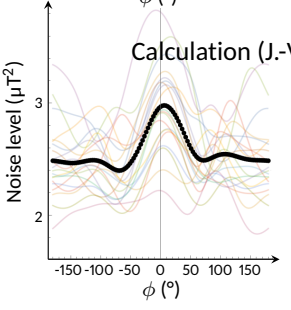
Statistics on Néel left (CCW) skyrmions



Angular variation of PL

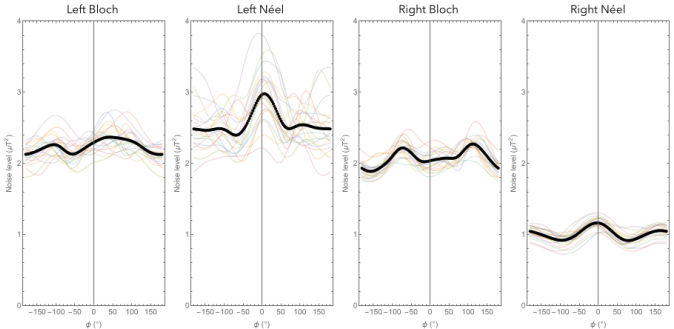


Calculation (J.-V. Kim, C2N)

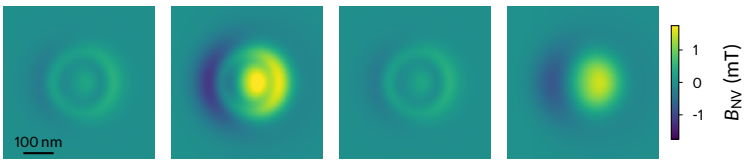


Expected pattern on other skyrmion types

Simulated noise distribution along the contour



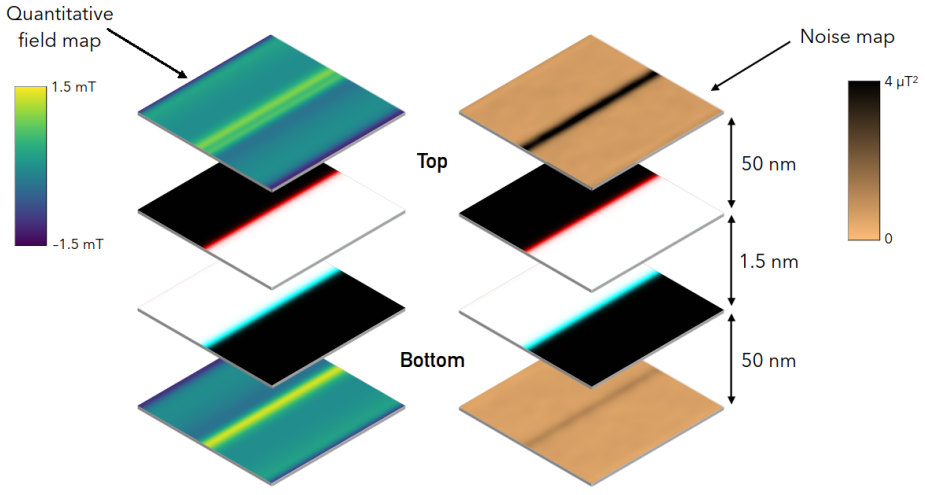
Simulated stray field maps



- 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!

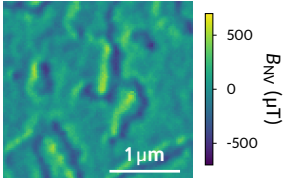
Calculation: C2N, Palaiseau (J.-V. Kim)



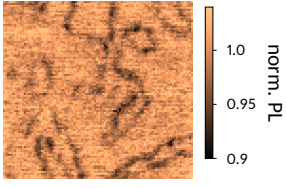
Experiment: looking at both sides of the film

Initial stack: Néel left

Magnetic field map



Noise map



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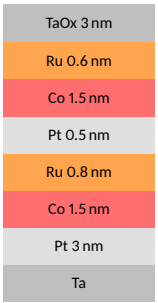
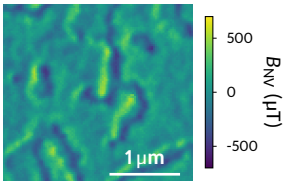
Samples: J. Urrestarazu, R. Guedas, Spintec, Grenoble

Experiment: looking at both sides of the film

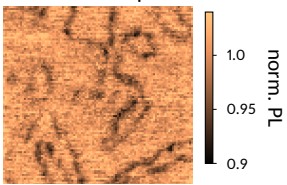
Initial stack: Néel left



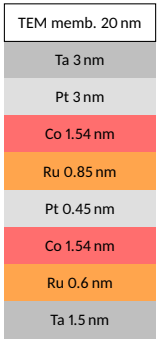
Magnetic field map



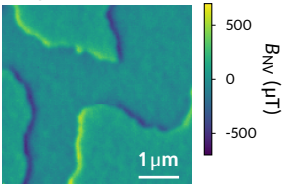
Noise map



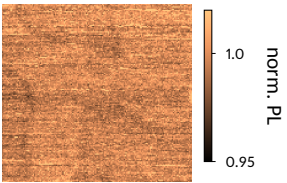
Inverted stack: Néel right



Magnetic field map



Noise map



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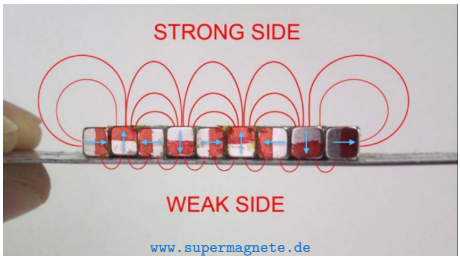
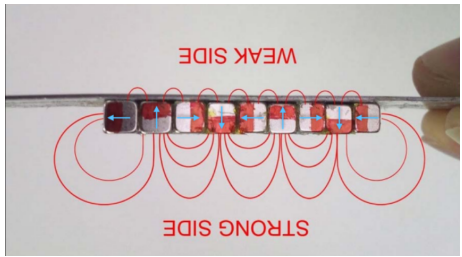
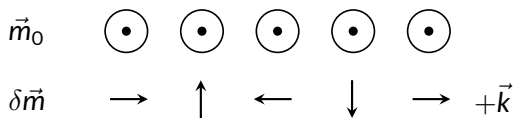
Samples: J. Urrestarazu, R. Guedas, Spintec, Grenoble

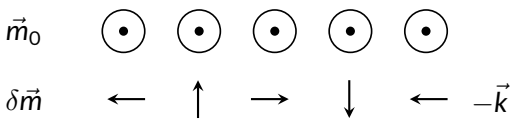
Origin of this effect, 1st ingredient : Spin waves = fridge magnets

Halbach arrays









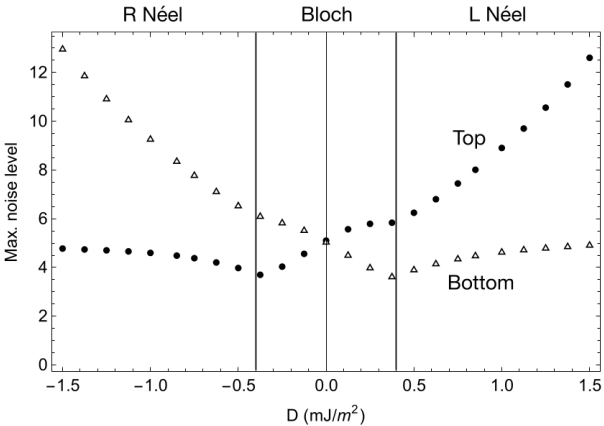
J. Mallinson. *IEEE Trans. on Mag.* 9 (1973), 678

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

Origin of this effect, 2nd ingredient: DMI

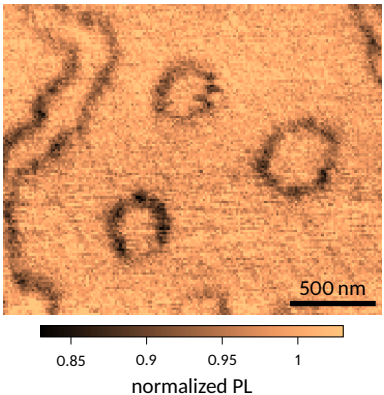
Calculation: C2N, Palaiseau (J.-V. Kim)

Calculation made for a **single** ferromagnetic layer

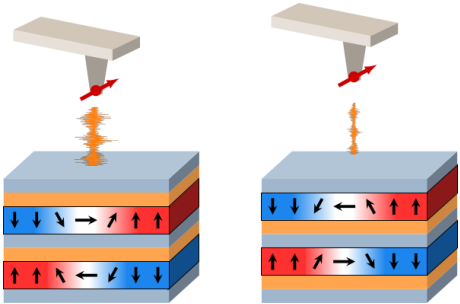


- DMI induces non-reciprocity in the spin wave dispersion
- This results in the selection of a propagation direction for the modes producing the detected noise
- These modes create noise only on one side of the film!

Summary



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



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

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

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

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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

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