Probing magnetic chiral textures through spin waves with a quantum sensor

Aurore Finco

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

CNRS and Université de Montpellier, Montpellier, France

E-MRS Fall meeting, September 19th 2023, Warsaw

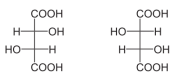
slides available at https://magimag.eu

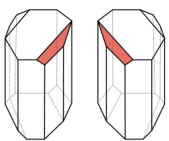
Chirality

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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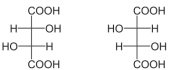

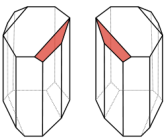

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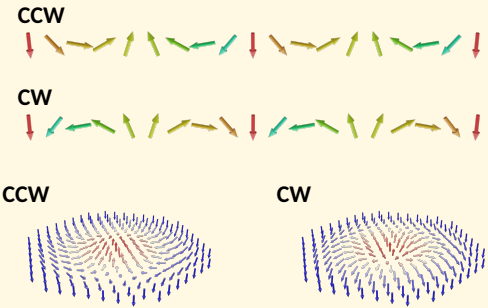
Magnetic chirality

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, what is the sign of the DMI, etc?

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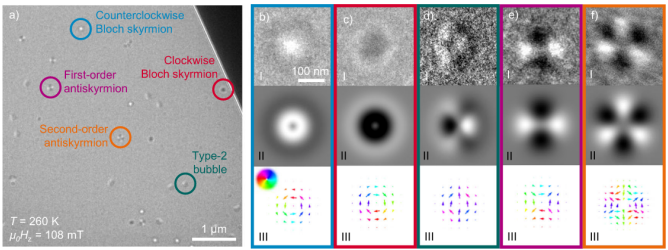
Objects stabilized by dipolar couplings
➔ no fixed chirality



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

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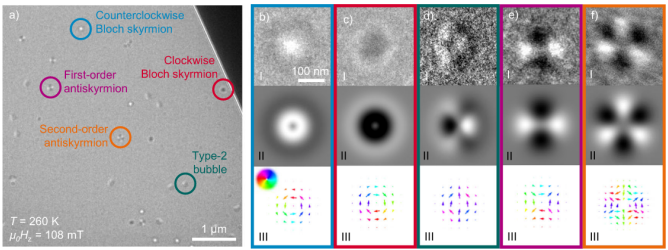
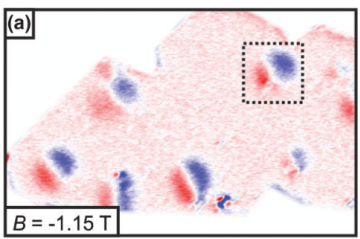


M. Heigl *et al.* *Nat. Commun.* 12 (2021), 2611

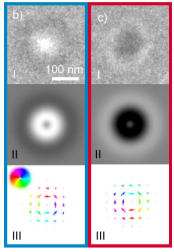
Objects stabilized by DMI
➔ single chirality/rotational sense



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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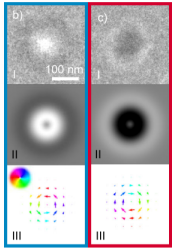
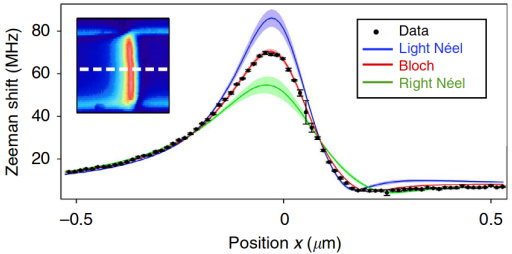


M. Heigl *et al.* *Nat. Commun.* 12 (2021), 2611

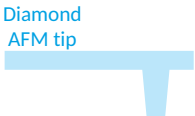
Measure quantitatively the **stray field**
produced by the texture

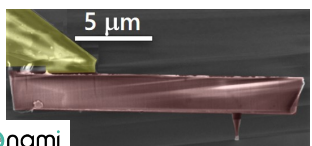


J.-P. Tetienne *et al.* *Nat. Commun.* 6 (2015), 6733

→ Scanning NV magnetometry

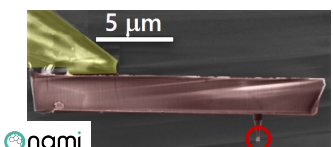
Scanning NV center microscopy to probe stray fields





P. Maletinsky *et al.* *Nature Nano.* 7 (2012), 320–324

Scanning NV center microscopy to probe stray fields



Implanted single
NV center

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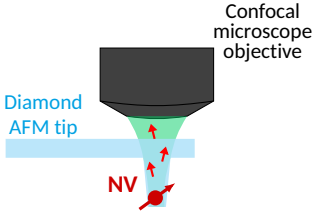

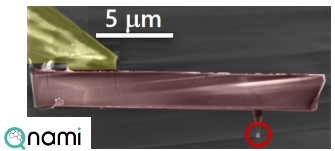

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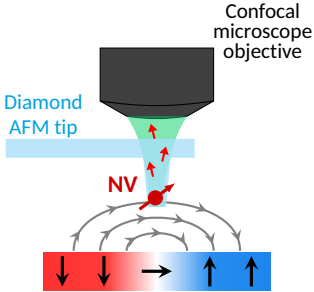

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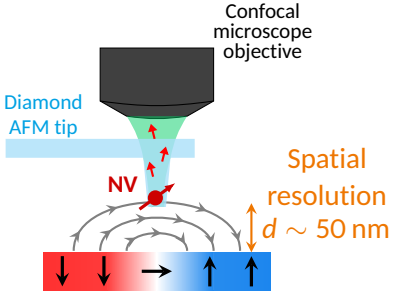

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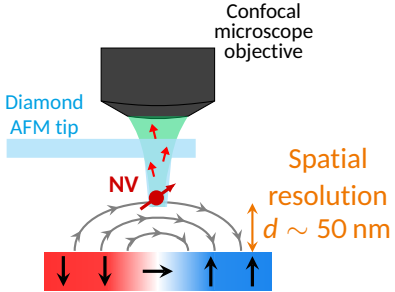

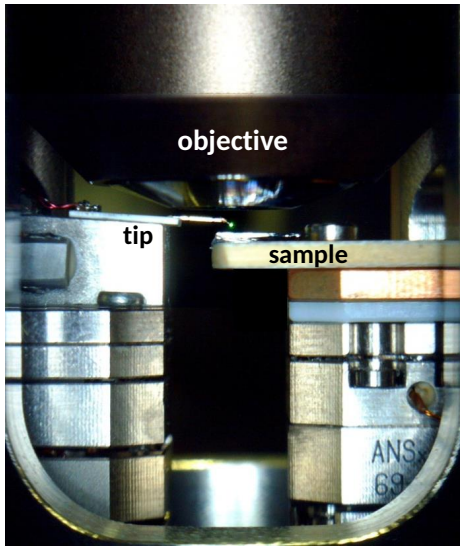

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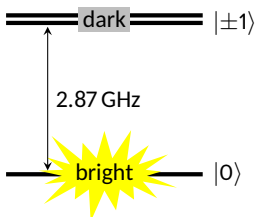
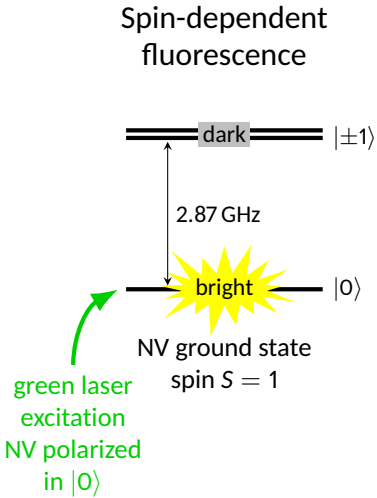
Magnetometry with NV centers

Spin-dependent fluorescence



NV ground state
spin $S = 1$

Magnetometry with NV centers



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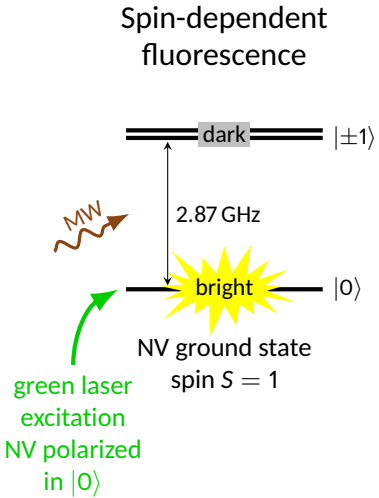

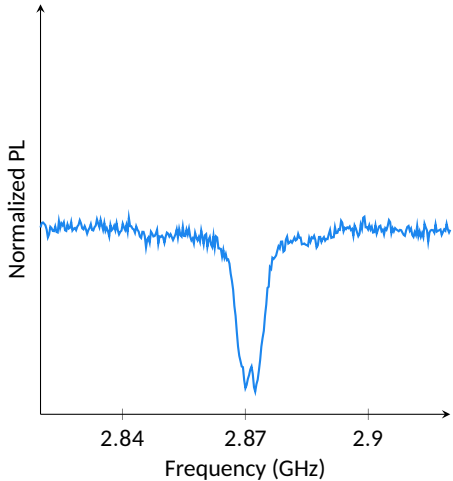

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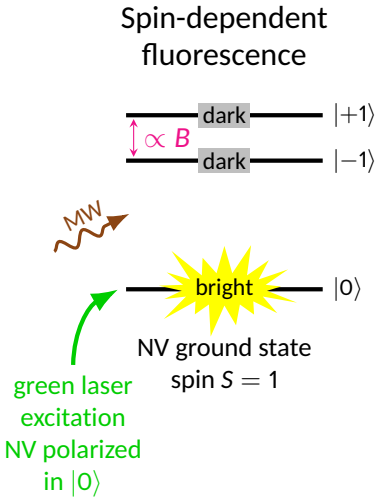

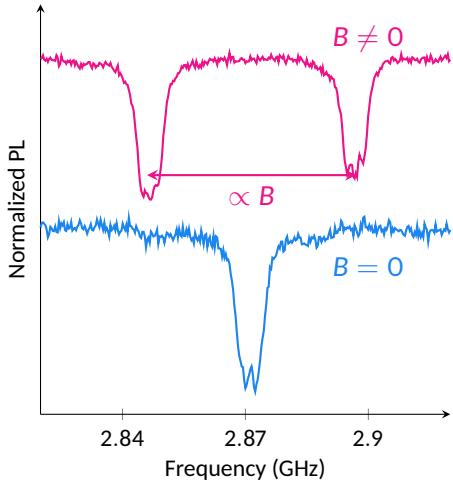

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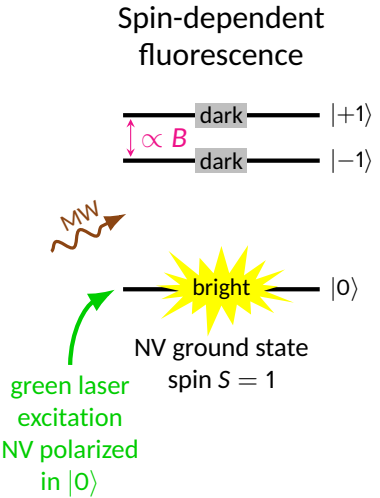
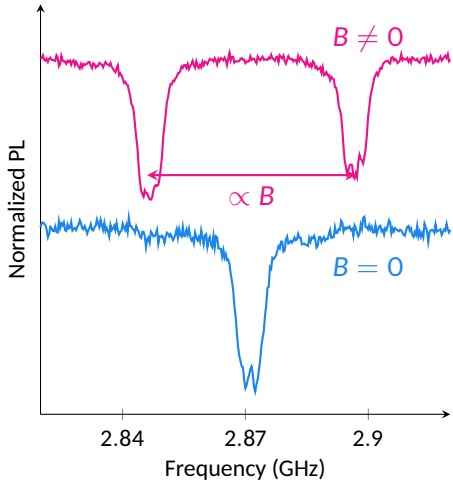
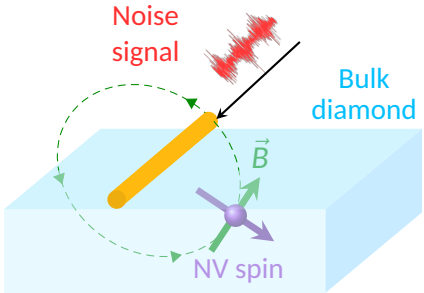




Sensitivity: a few $\mu T/\sqrt{Hz}$

Another approach: relaxometry



Collaboration C2N: T. Devolder

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

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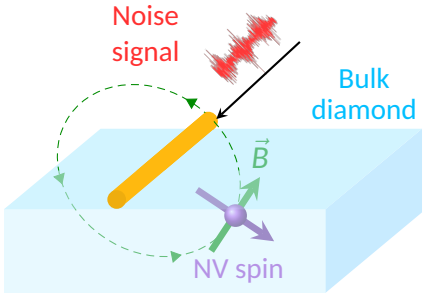

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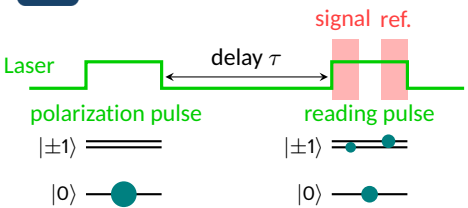

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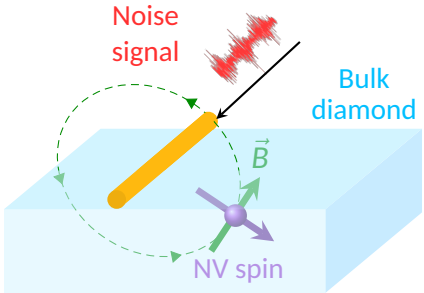

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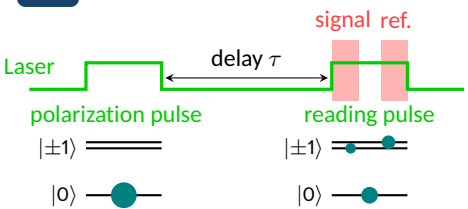

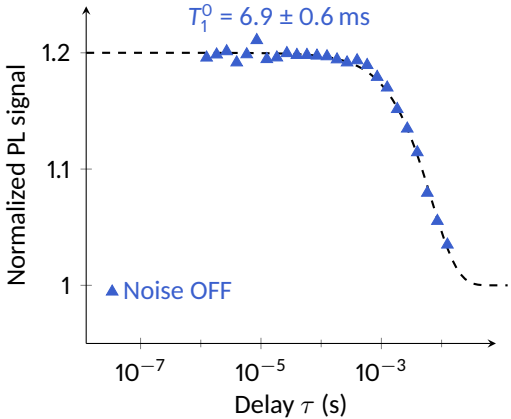

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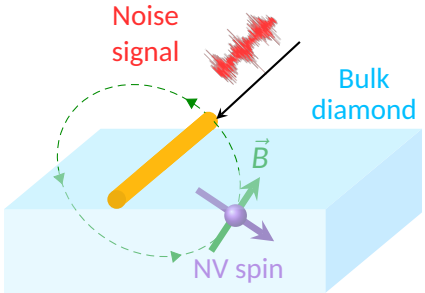

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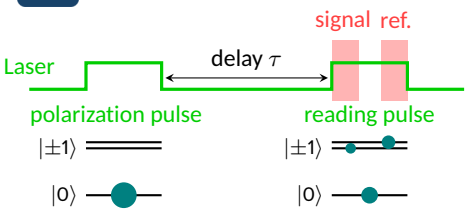
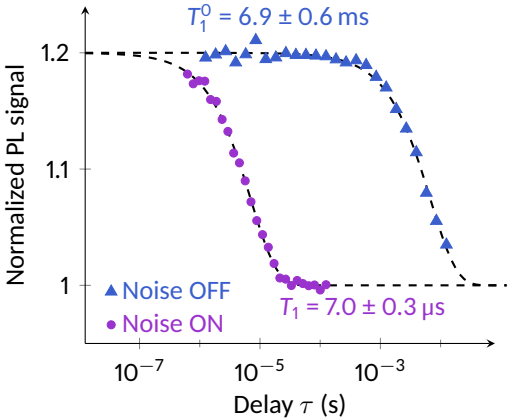
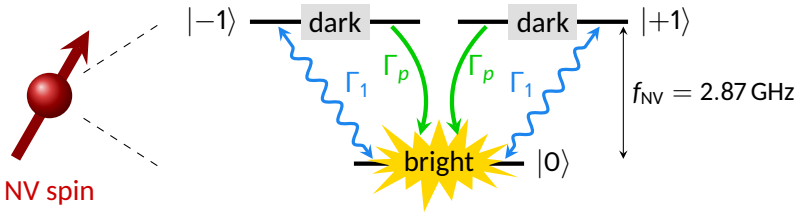




Noise spectrum centered
at the NV transition frequency

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

Effect of magnetic noise on the emitted signal



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

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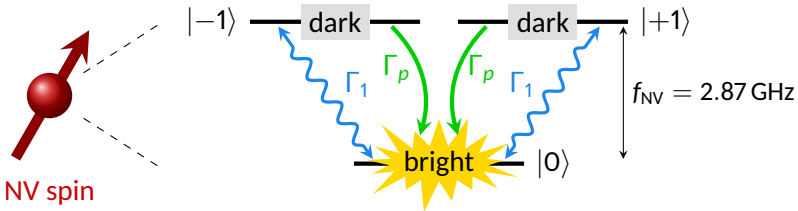

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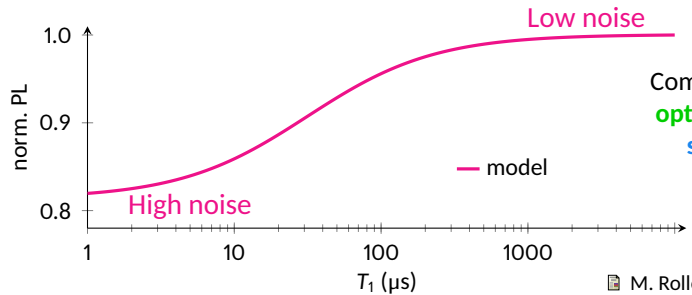

Competition between **optical pumping** and **spin relaxation**

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

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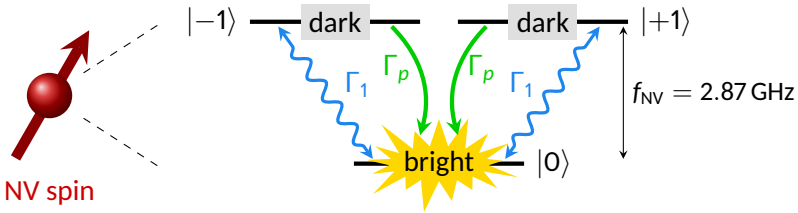

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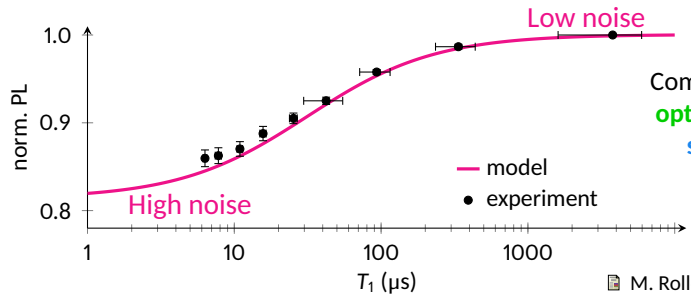

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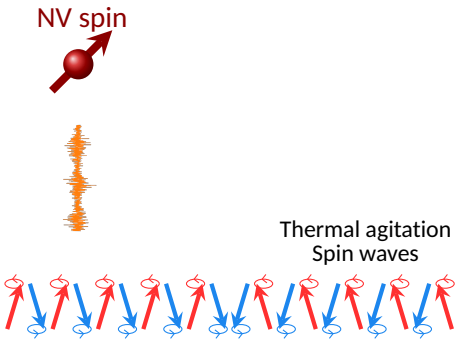
Noise-based imaging mode

Principle: localize magnetic textures via spin wave noise



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

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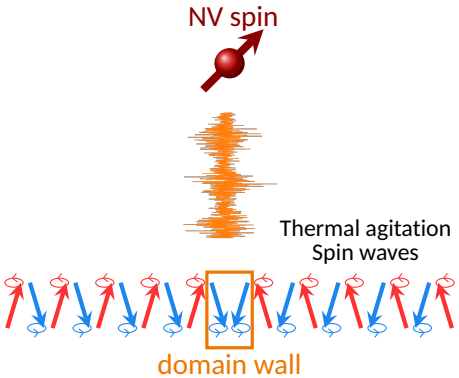
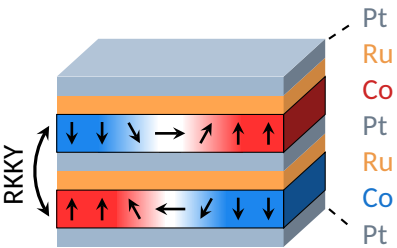


B. Flebus *et al.* *Phys. Rev. B* 98 (2018), 180409

Synthetic antiferromagnets

Collaboration UMR CNRS/Thales: William Legrand, Fernando Ajejas, Karim Bouzehouane, Nicolas Reyren, Vincent Cros

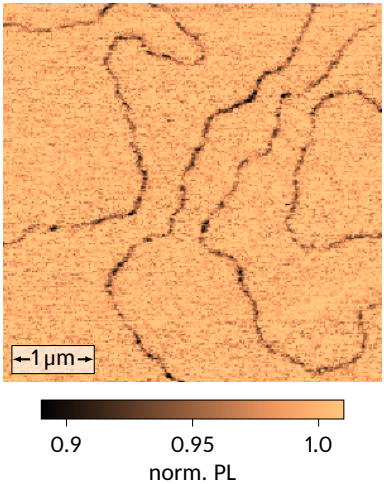
Two **ferromagnetic** layers coupled **antiferromagnetically**

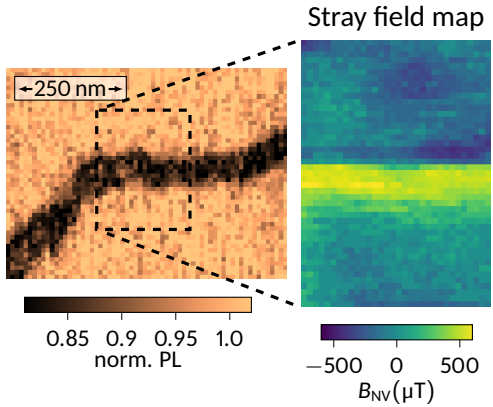


W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34

- No net magnetic moment
- Compensation of dipolar effects
- Small stray field due to vertical spacing
  → test system for noise imaging

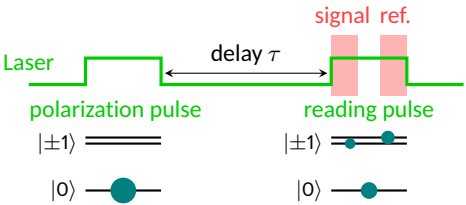
Domain wall in a SAF





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

Measurement of the relaxation time T_1



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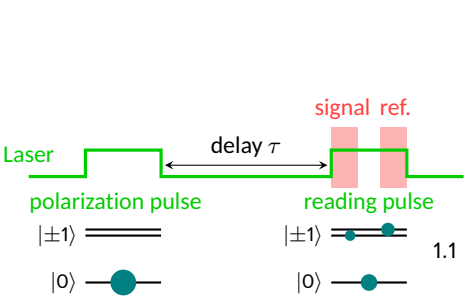
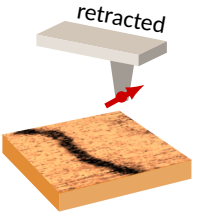
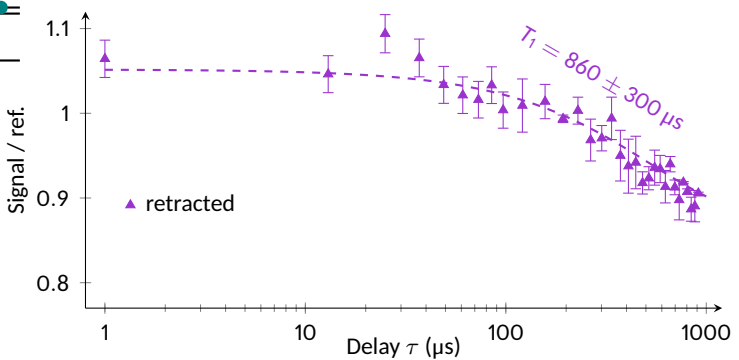
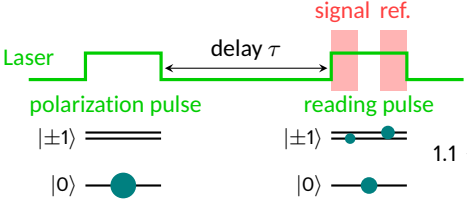
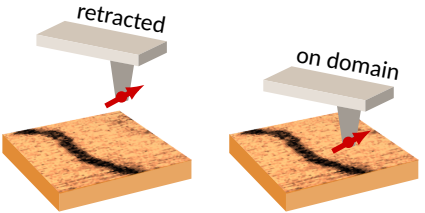


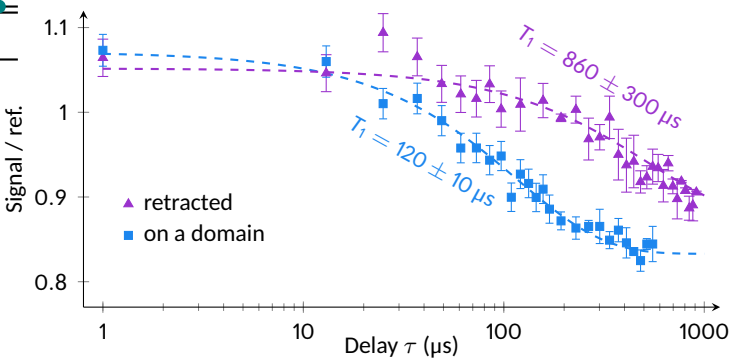




Measurement of the relaxation time T_1







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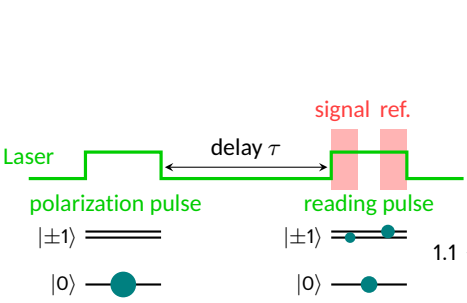
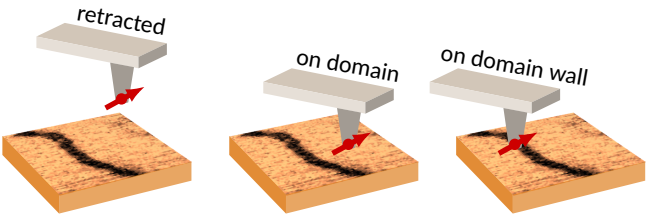
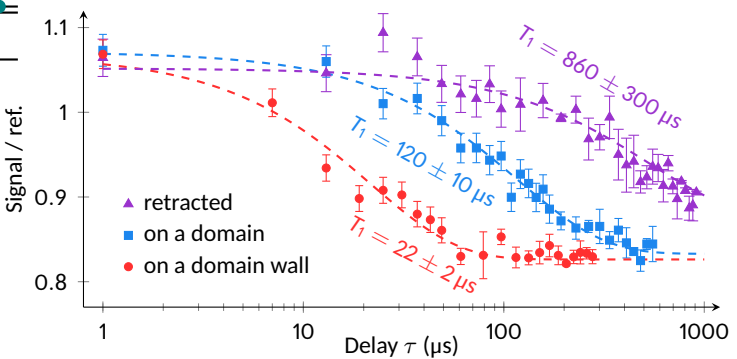
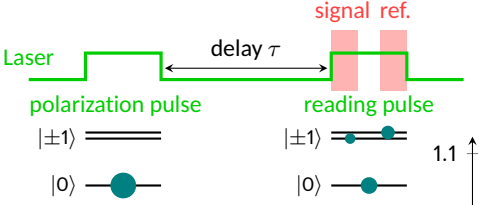
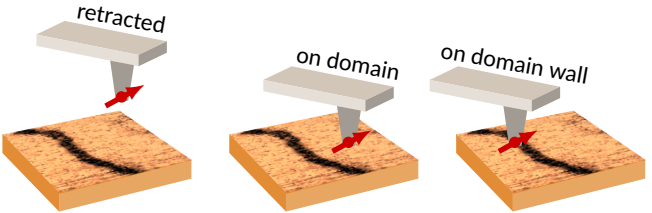




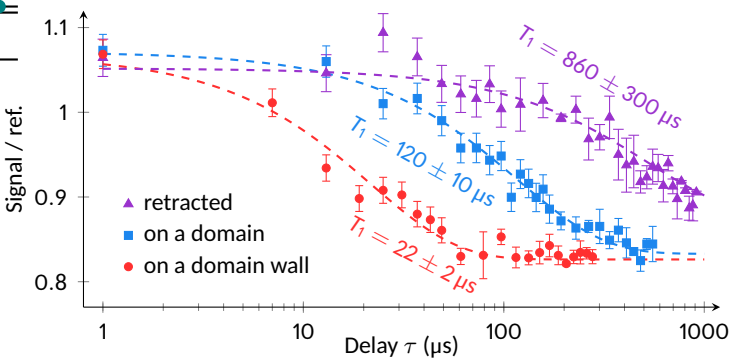


Measurement of the relaxation time T_1



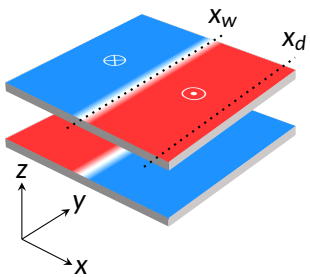


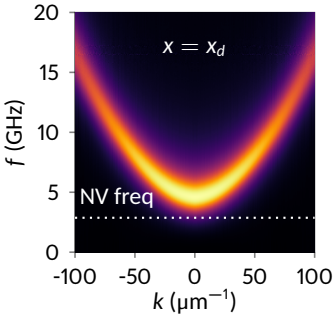
Enhancement of the spin relaxation
→ Magnetic noise!

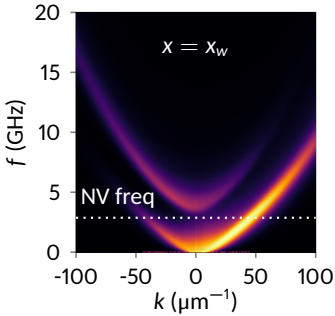


Origin of the noise contrast : spin waves!

Collaboration C2N: Jean-Paul Adam, Joo-Von Kim

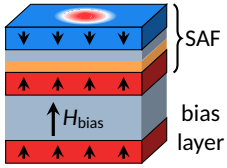




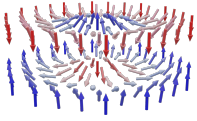


- NV frequency slightly below the gap, in the tail of power spectral density, which is the reason why we detect some noise when approaching the tip.
- No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

Stabilization and observation of magnetic skyrmions



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



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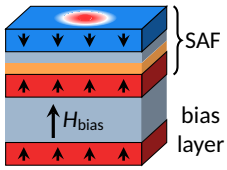
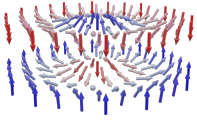
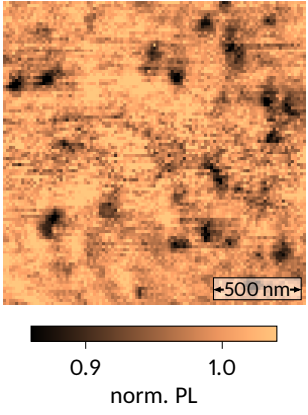
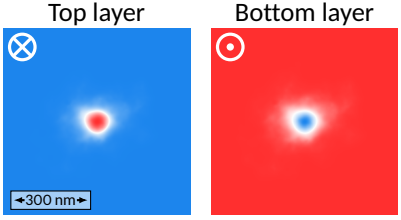
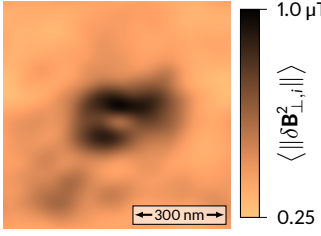


W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34





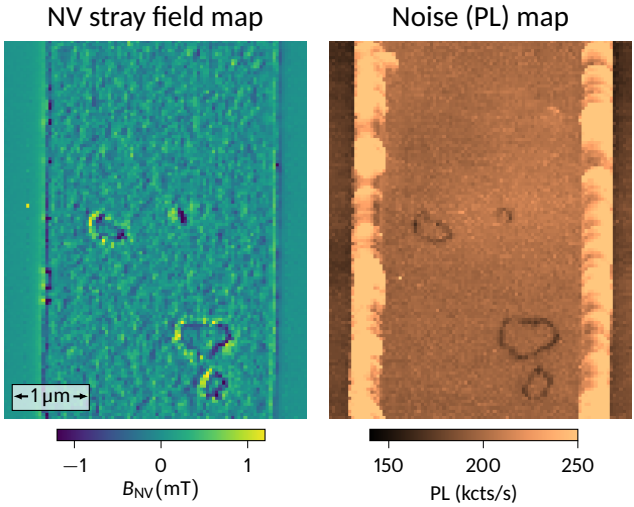




We are not probing the internal modes but the scattering of spin waves on the skyrmions

Pinned large skyrmions

Collaboration Spintec: Van-Tuong Pham, Olivier Boulle



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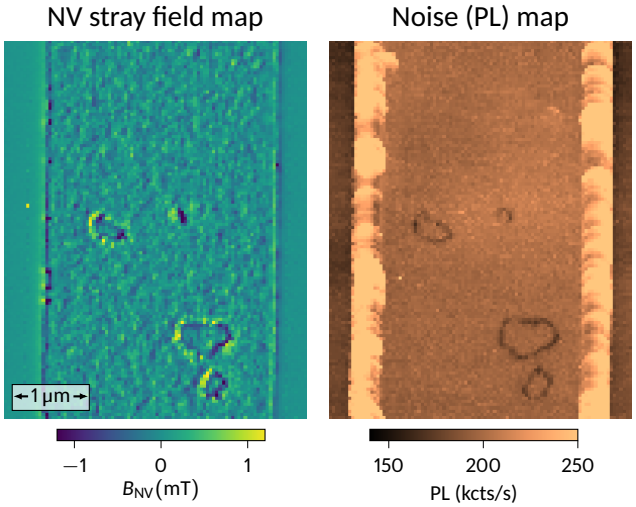
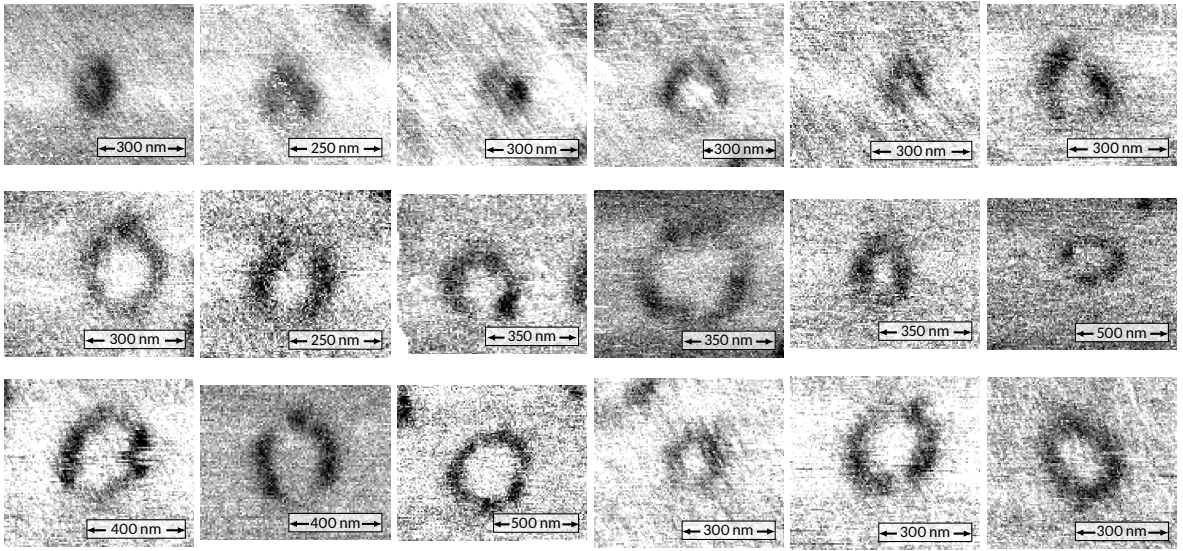
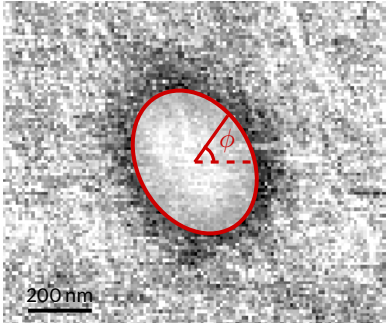


Various skyrmion noise maps

The PL drop is not uniform around the skyrmions, is this only related to their irregular shape?



Extracting the signal around the skyrmion



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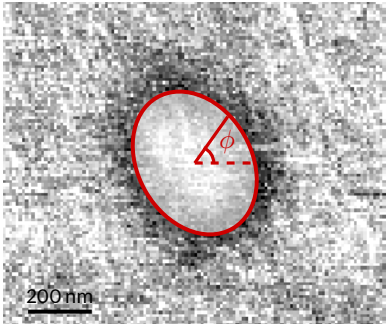

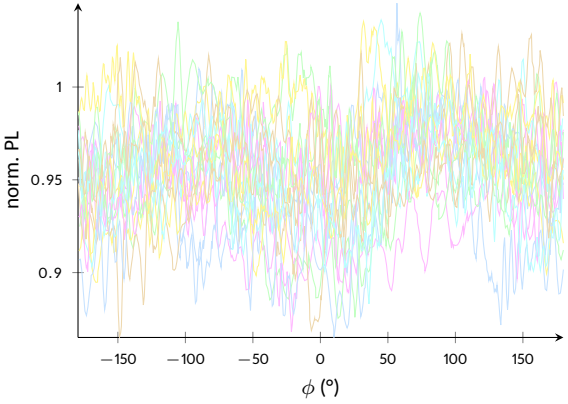

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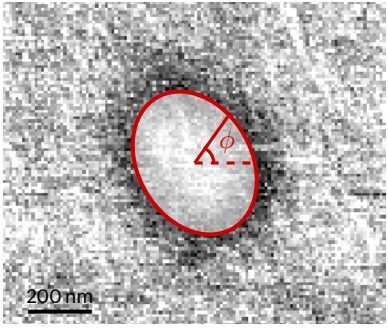
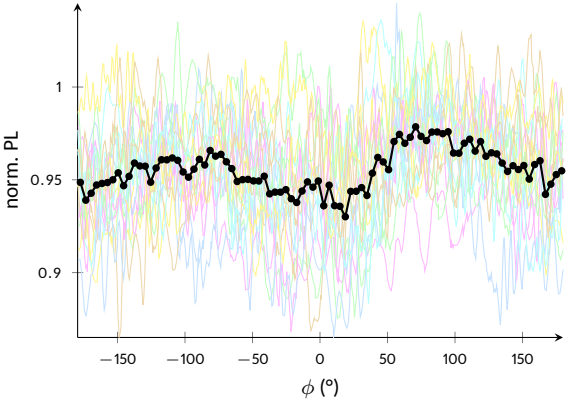
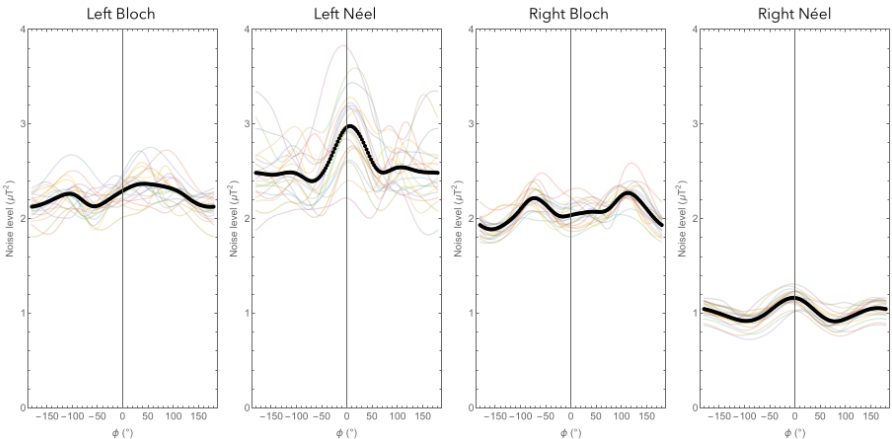




Expected noise profile for other skyrmion types

Collaboration C2N: Joo-Von Kim



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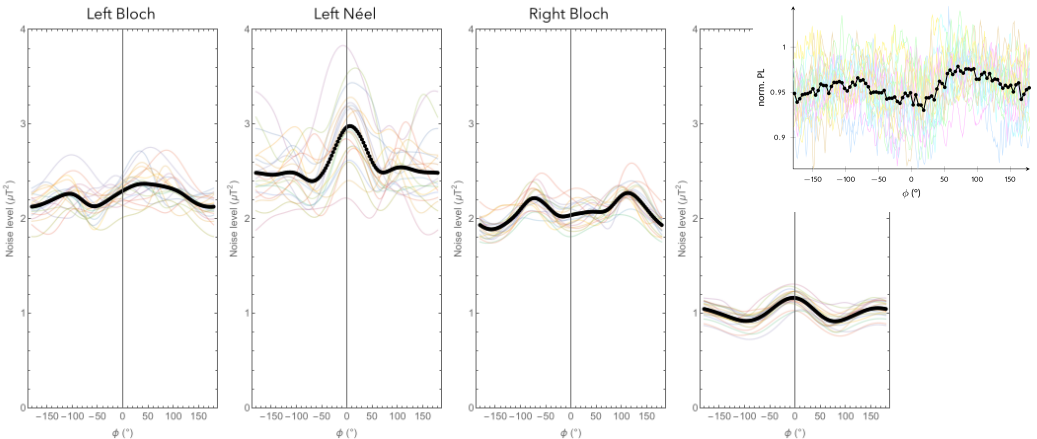
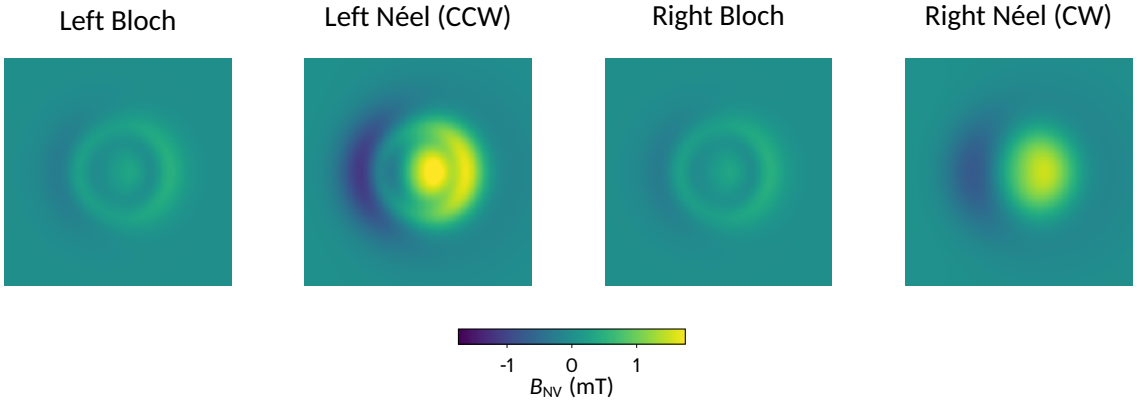


What about stray field maps?

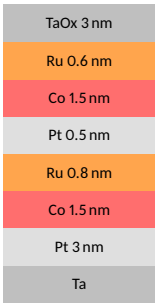


➔ Difficult to distinguish CCW and CW, especially if there is disorder in the sample.

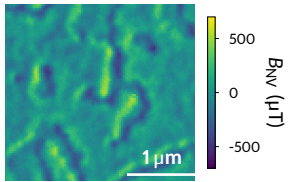
➔ Rather use noise ?

Is the detected noise really lower for CW Néel textures ?

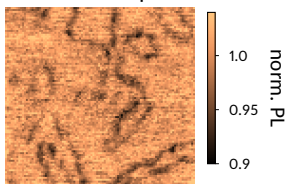
Initial stack



Magnetic field map



Noise map



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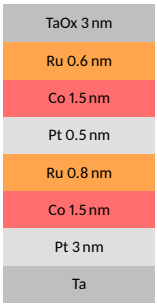
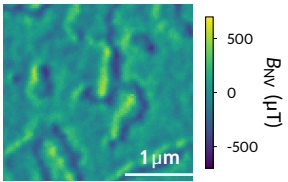
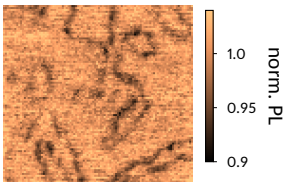


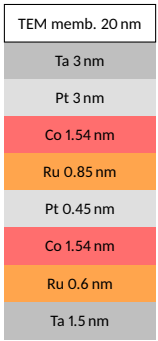
Magnetic field map



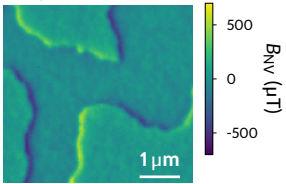
Noise map



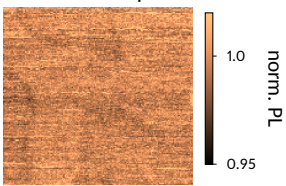
Inverted stack



Magnetic field map



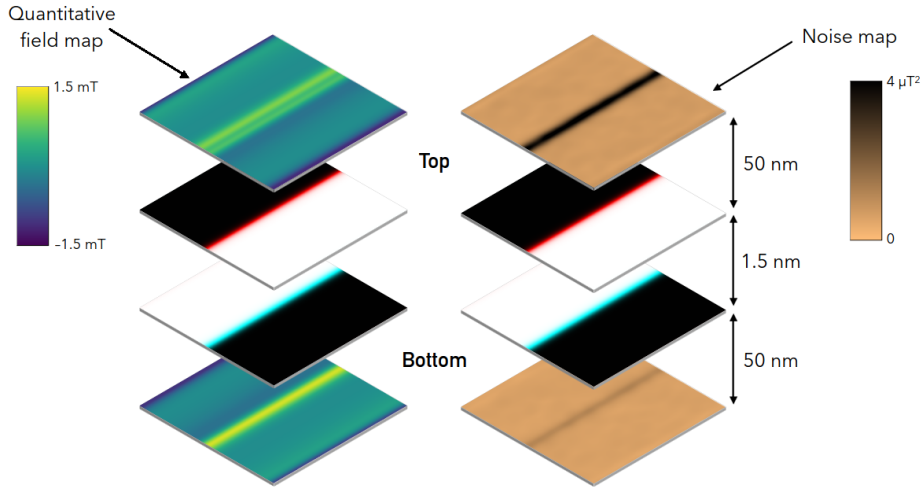
Noise map



Sample: J. Urrestarazu, Spintec, Grenoble

Expected noise level for each domain wall chirality

Collaboration C2N: Joo-Von Kim



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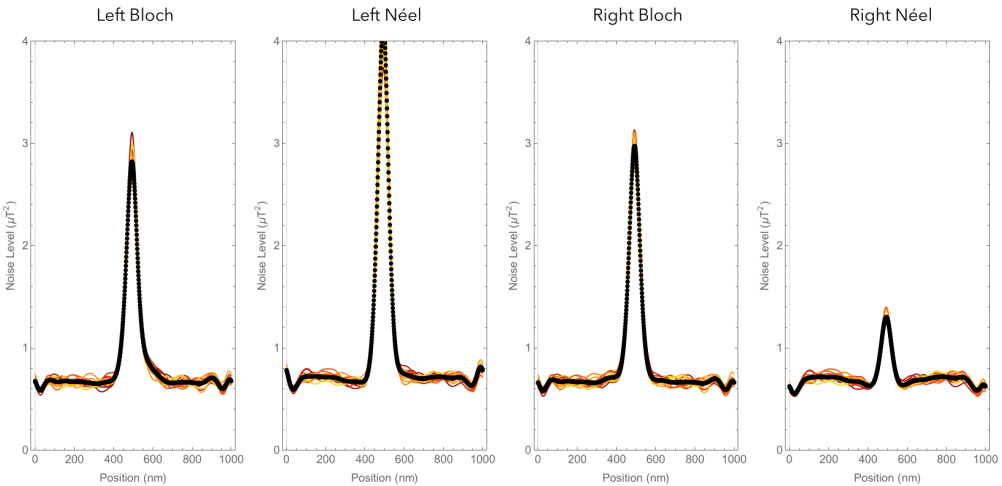

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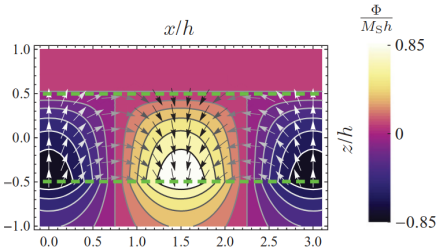
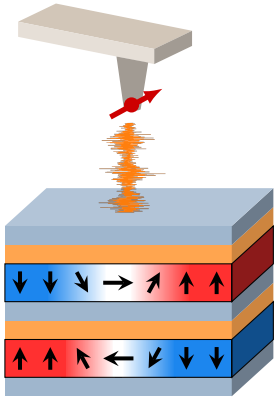
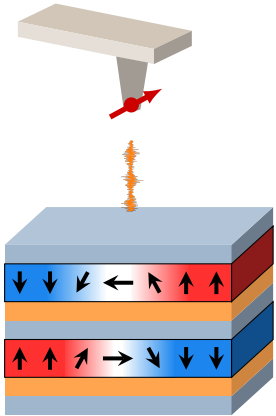
3. Something similar to this effect?



N. Mikuszeit *et al.* *PRB* 84 (2011), 054404

Summary





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

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

A. Finco *et al.* *in preparation* (2023)

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

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

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