Imaging of multiferroic solitons and investigation of DMI with a quantum sensor

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International conference on skyrmionics, September 2nd 2024, Seeon

slides available at `https://magimag.eu`

Outline

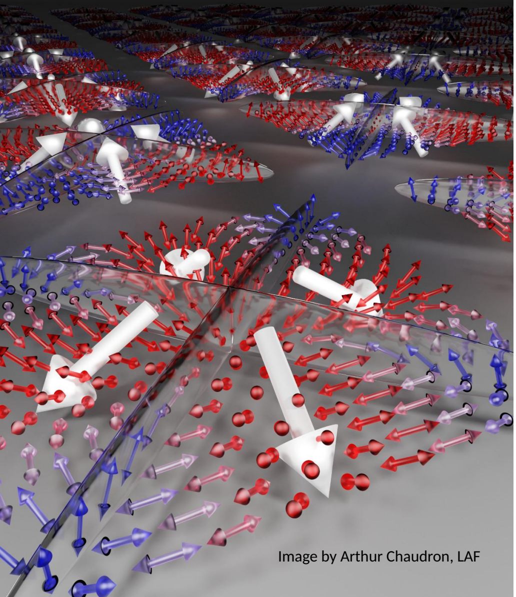

Image by Arthur Chaudron, LAF

1. Observation of multiferroic solitons in $BiFeO_3$ microstructures

   A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

2. Characterization of DMI with the help of spin wave magnetic noise

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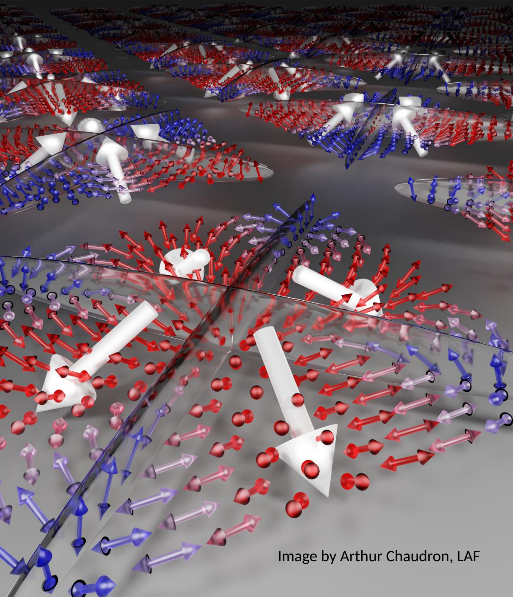

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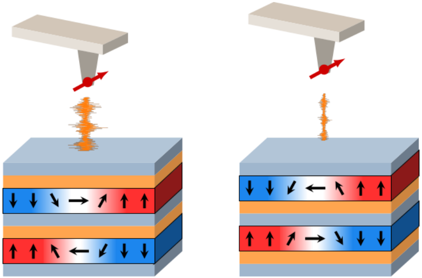
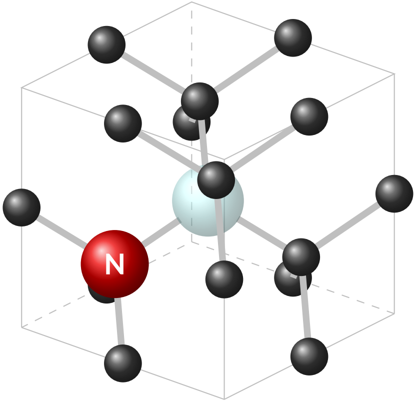


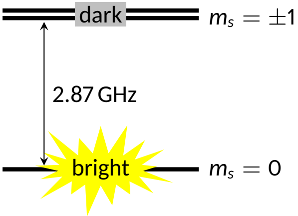
Our quantum sensor: the NV center in diamond



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

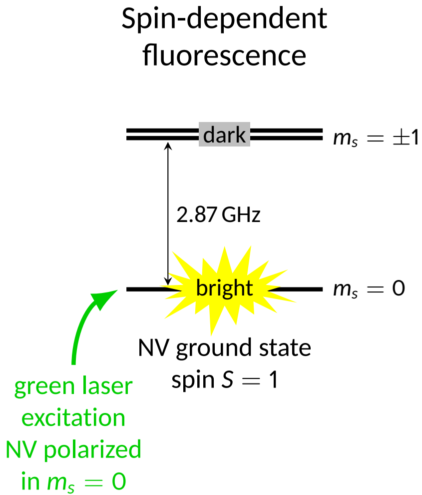
Measuring magnetic field with NV centers

Spin-dependent fluorescence



NV ground state
spin $S = 1$

Measuring magnetic field with NV centers



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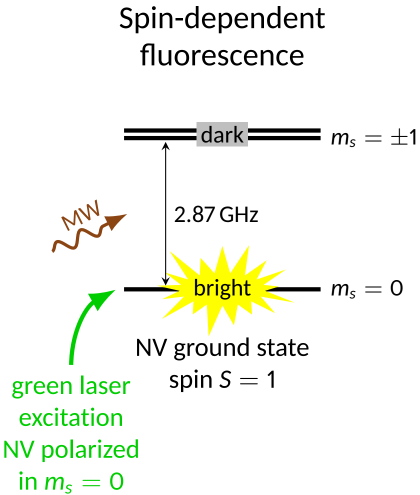

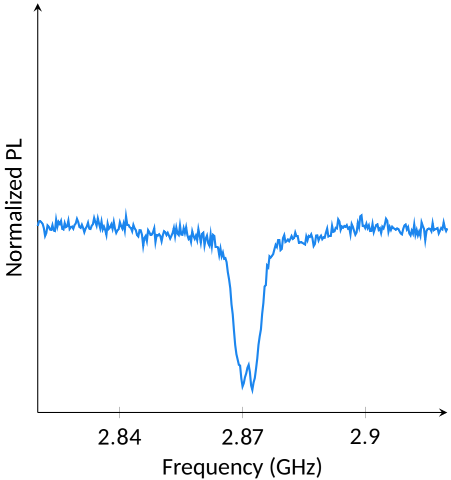

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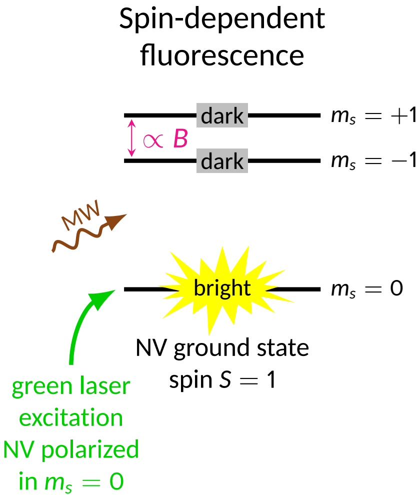

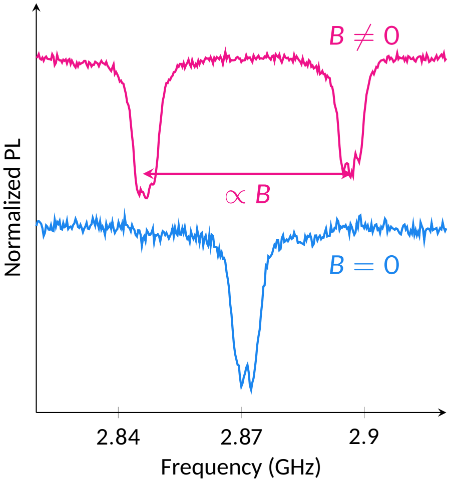

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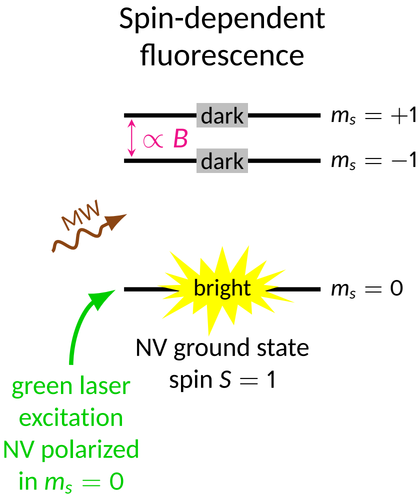
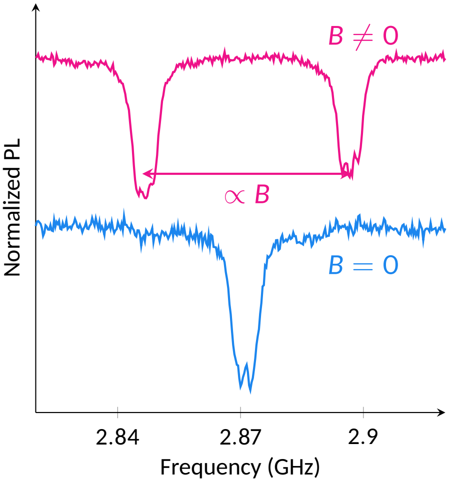
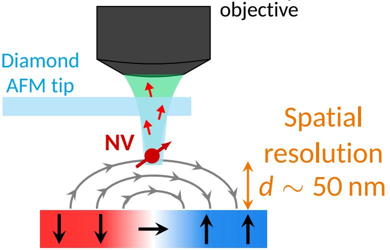
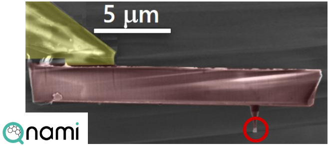


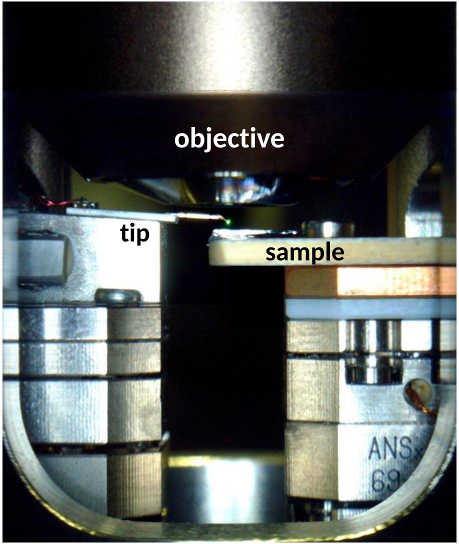


Sensitivity: a few $\mu T/\sqrt{Hz}$

Integration of the defect in a scanning probe microscope







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

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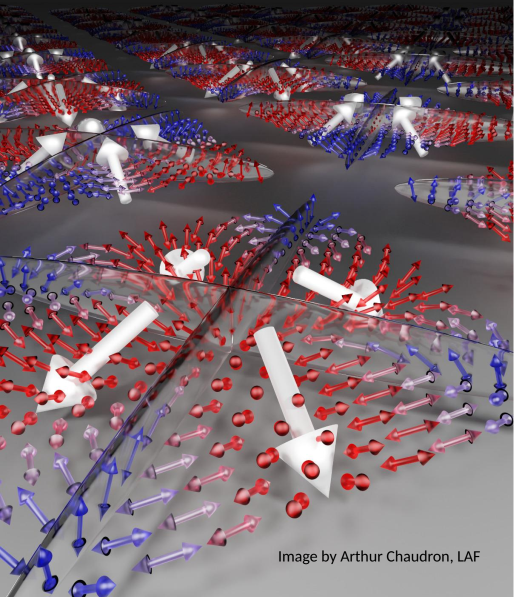

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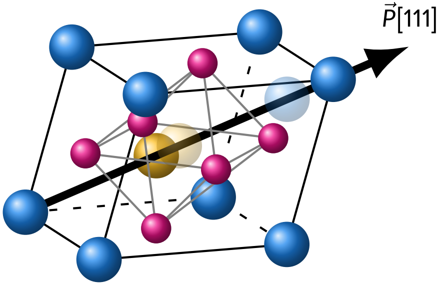
Bismuth ferrite, a room-temperature multiferroic

Electric polarization



Ferroelectric phase (T<1100 K)

G. Catalan *et al*. *Adv. Mater.* 21 (2009), 2463–2485

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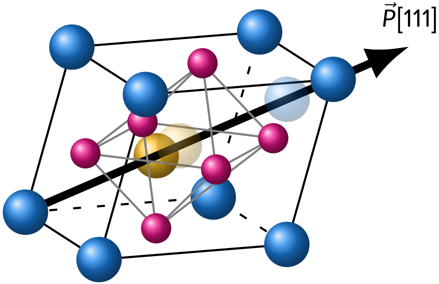
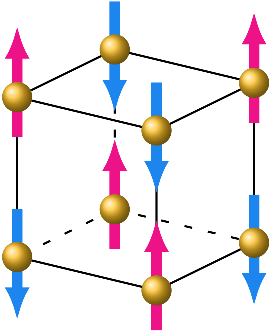


Ferroelectric phase (T<1100 K)

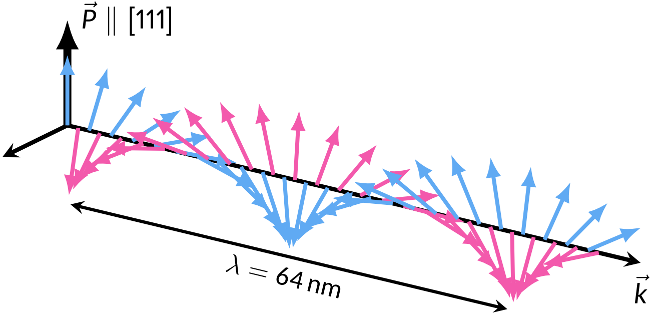
Magnetism



G-type antiferromagnetic phase ($T_N = 643\,K$)

G. Catalan *et al.* *Adv. Mater.* 21 (2009), 2463–2485

The effects of magnetoelectric coupling in $BiFeO_3$



Fully compensated cycloid

$\rightarrow$ **No stray field!**

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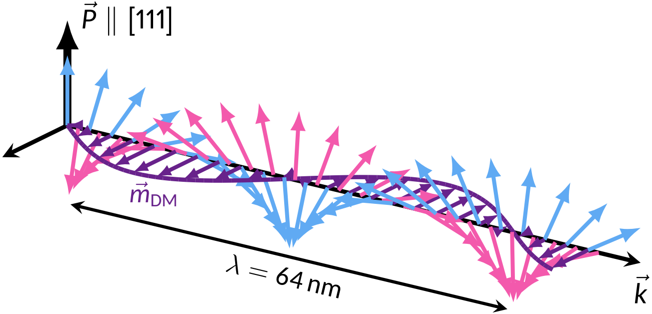

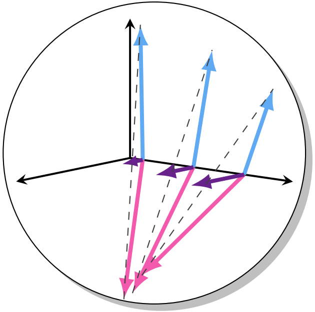

Spin density wave
Weak uncompensated moment
$\rightarrow$ **Small stray field**

M. Ramazanoglu *et al.* *PRL* 107 (2011), 207206

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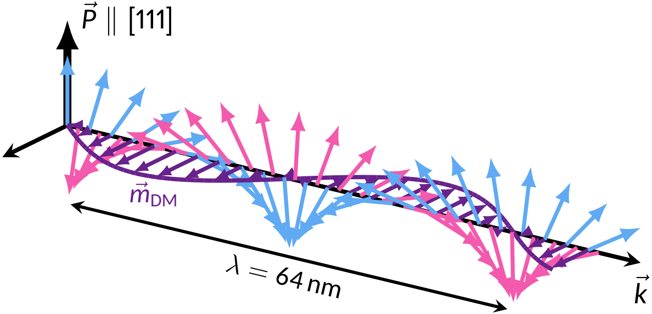

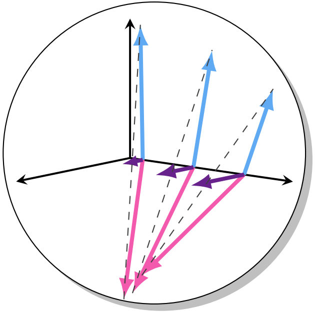

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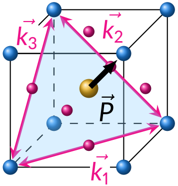
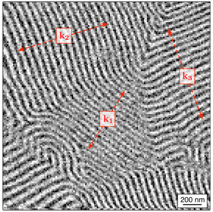
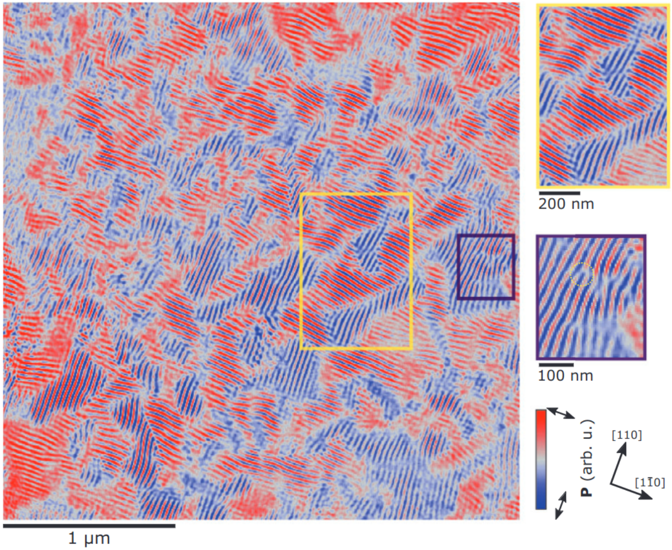




M. Ramazanoglu *et al.* *PRL* 107 (2011), 207206

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

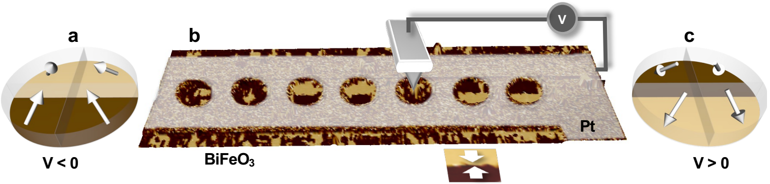
Soft X-ray ptychography now also sees the cycloid!



T. A. Butcher *et al.* Adv. Mater. (2024), 2311157

Towards topological textures

Objective: use the magnetoelectric coupling to stabilize an antiferromagnetic topological state



A. Chaudron, S. Fusil, V. Garcia

A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

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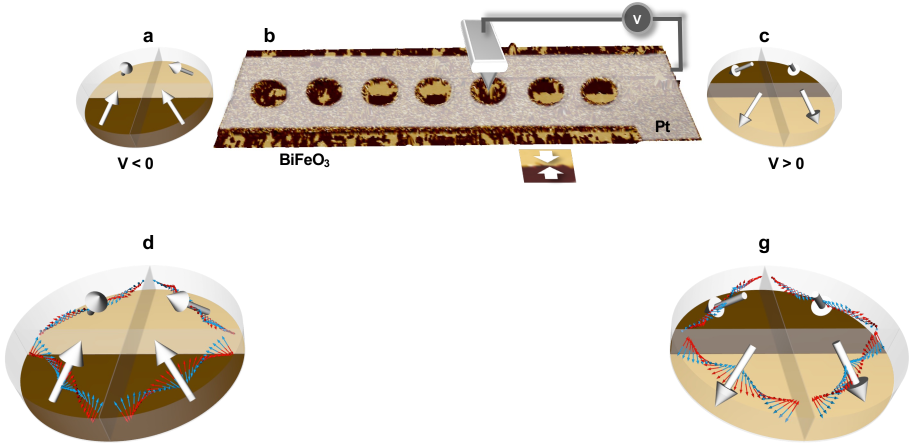

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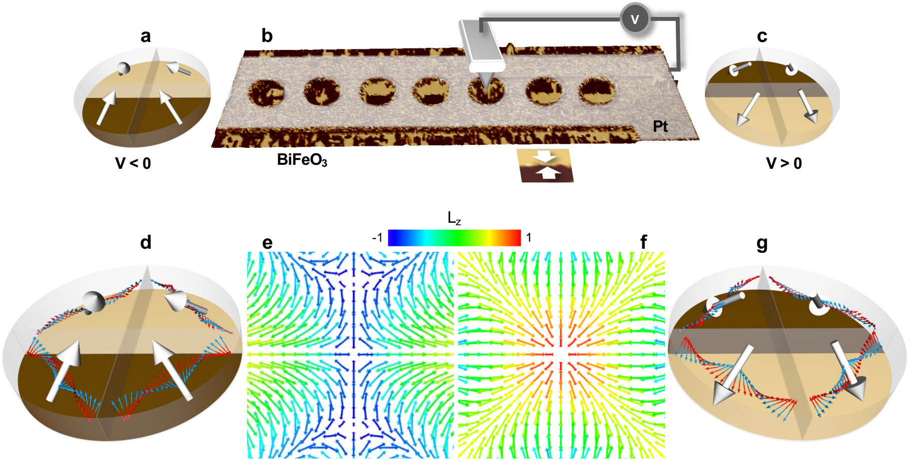
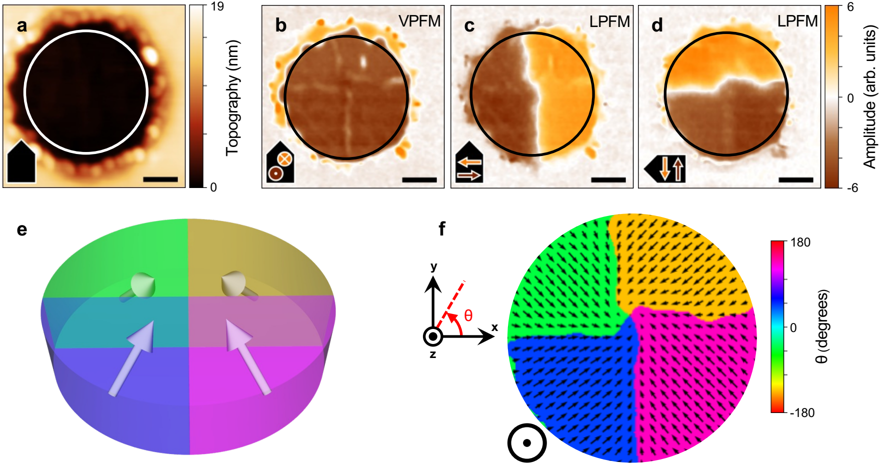


Z. Li, J.-Y. Chauleau, M. Viret

A. Chaudron *et al.* *Nat. Mater.* 23 (2024), 905

Center ferroelectric domains imaged with PFM



laboratoire Albert Fert A. Chaudron, S. Fusil, V. Garcia

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Discs hosting the cycloidal state

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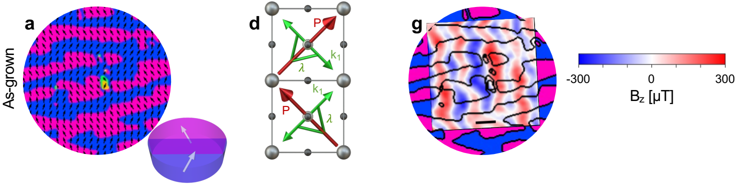

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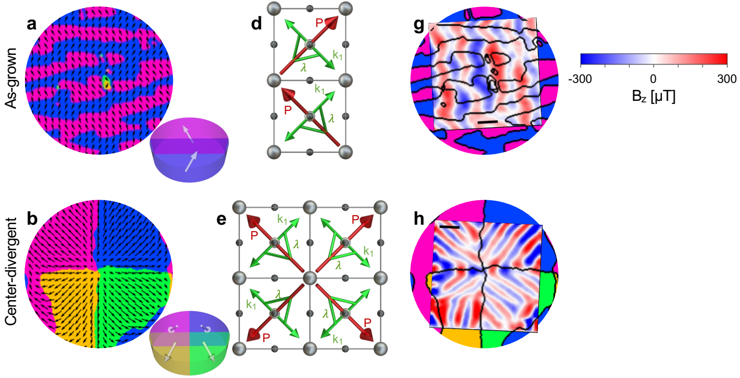

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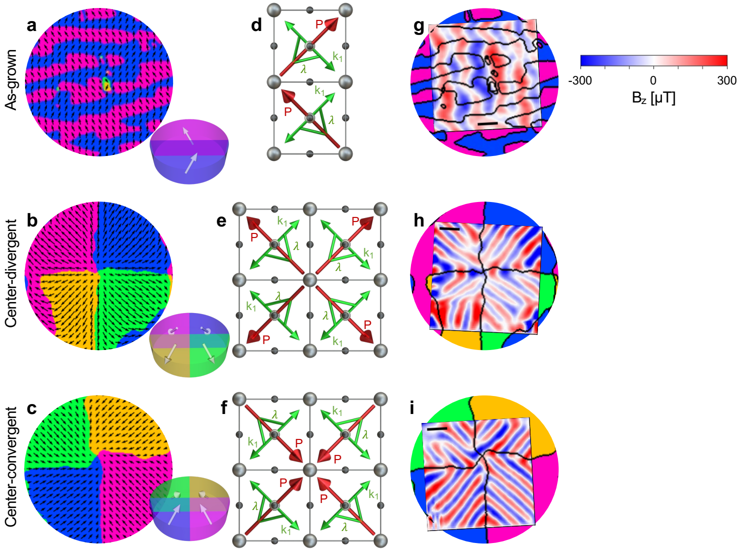

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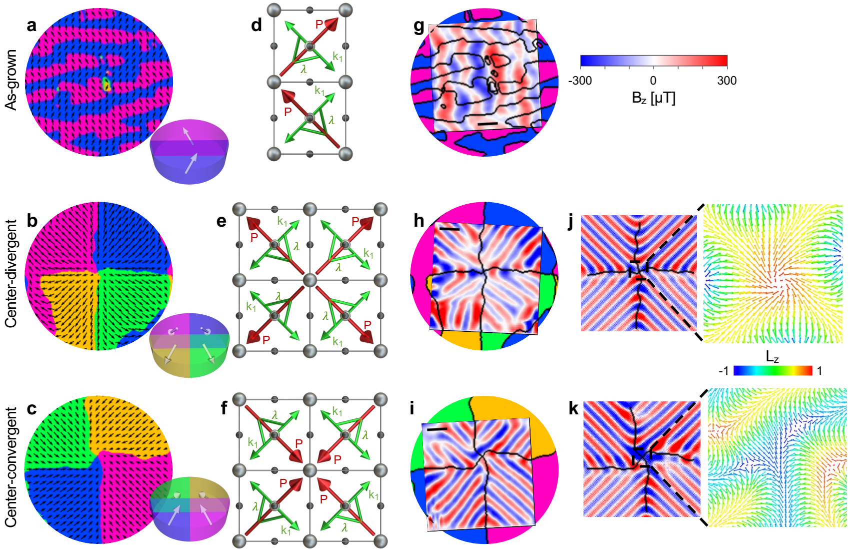

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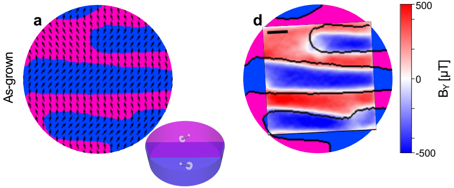
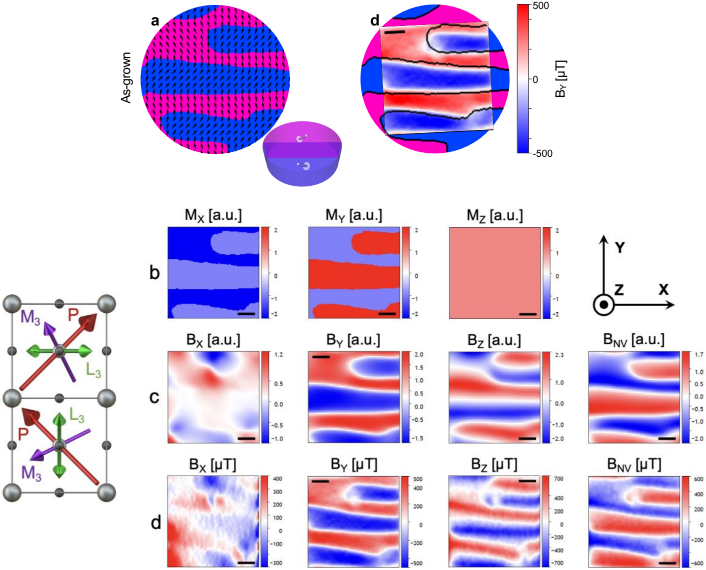
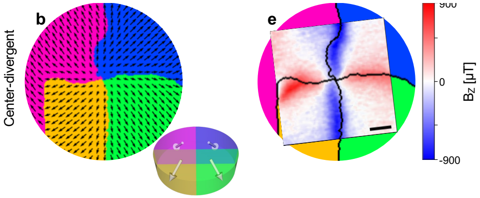
Discs hosting the AFM state – FE stripes



Discs hosting the AFM state – FE stripes



Discs hosting the AFM state – divergent FE state



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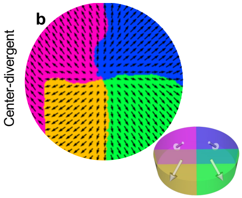

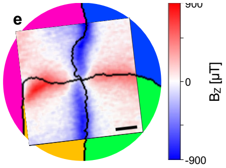

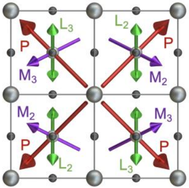

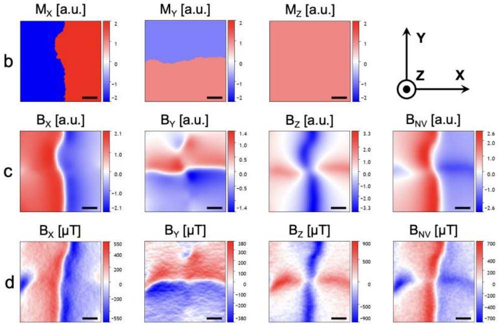

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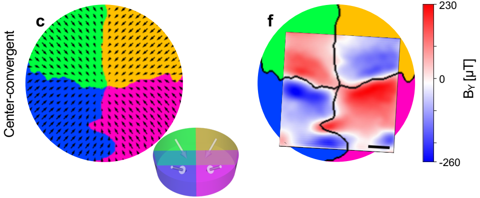

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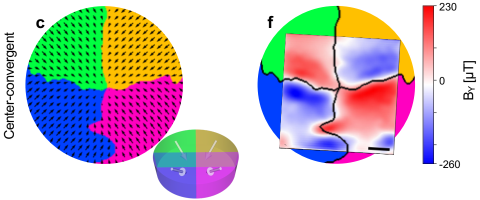

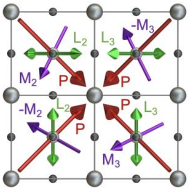

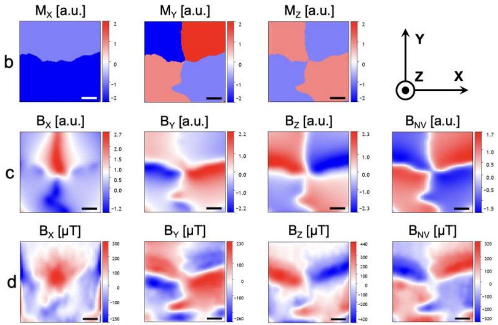

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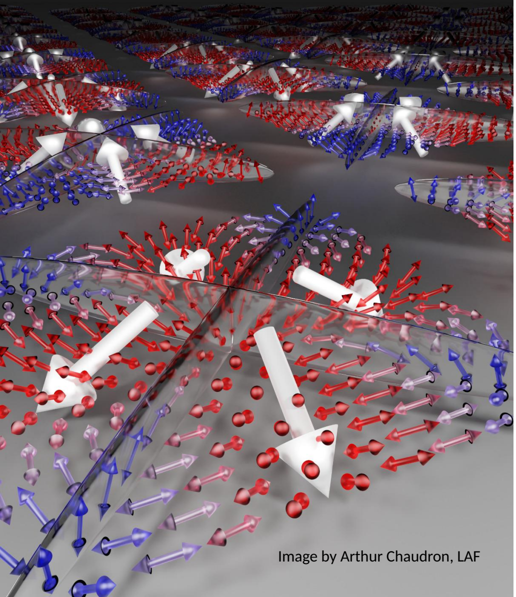

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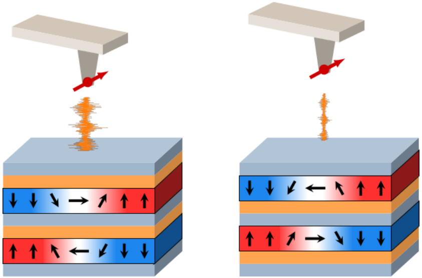

Detection of magnetic noise rather than stray field

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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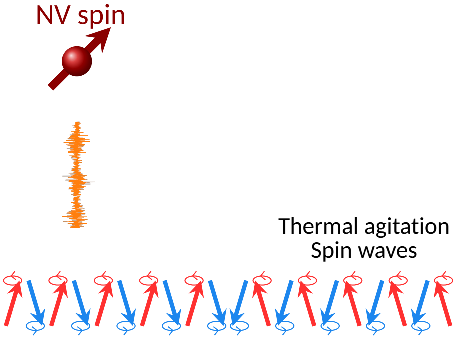

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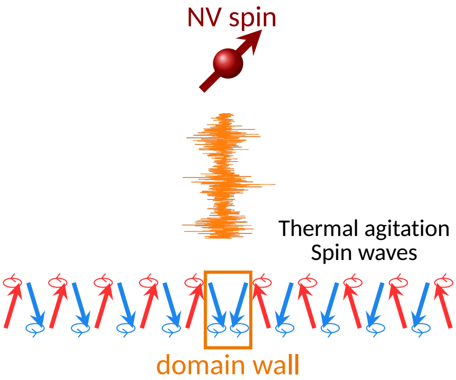
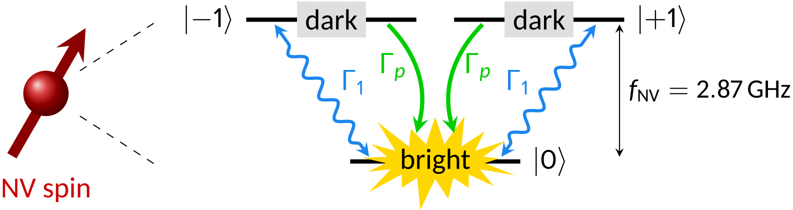


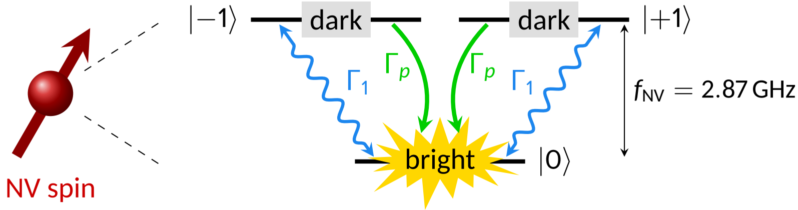
Effect of magnetic noise on the emitted photoluminescence



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



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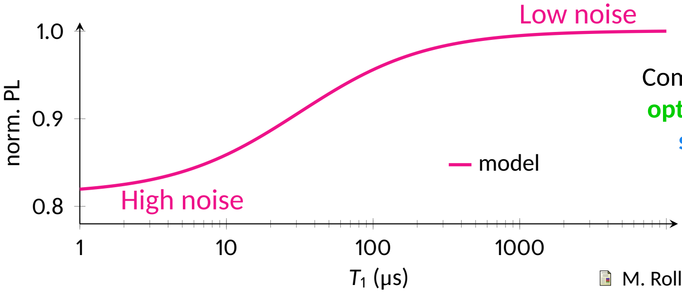

Competition between **optical pumping** and **spin relaxation**

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

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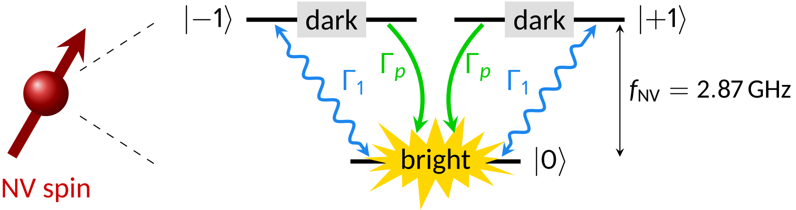

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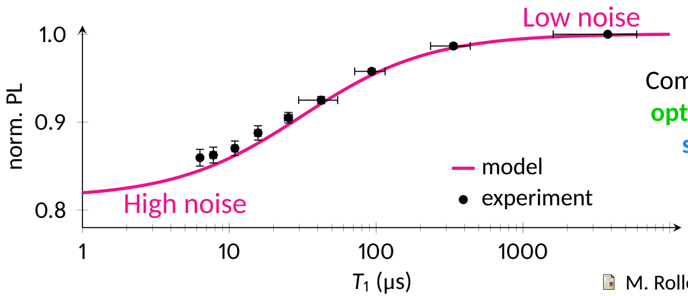

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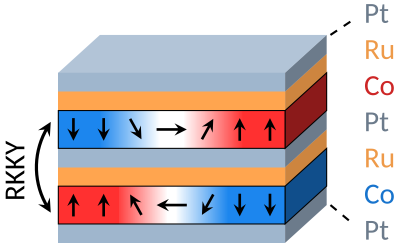
M. Rollo *et al.* *PRB* 103 (2021), 235418

Synthetic antiferromagnets

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

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



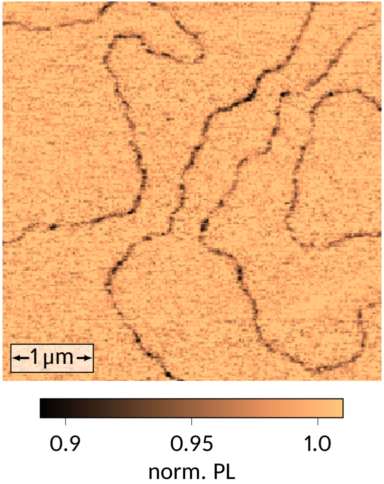
- No net magnetic moment
- Small stray field (vertical shift)
- Highly tunable properties
- Spin wave frequencies in the few GHz range

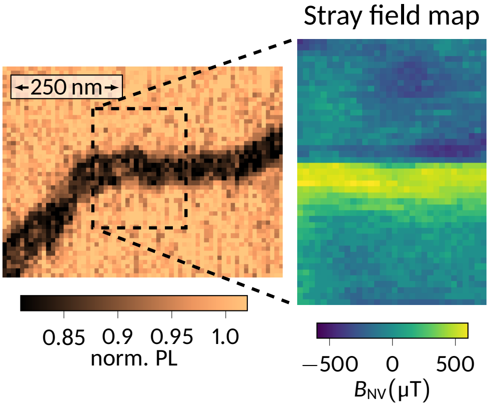
→ Perfect test system for noise imaging!

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

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

Detection of domain walls by relaxometry





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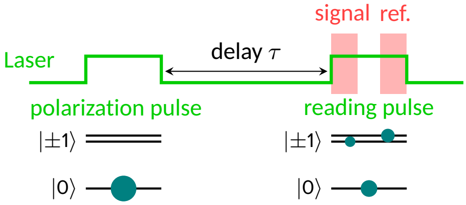
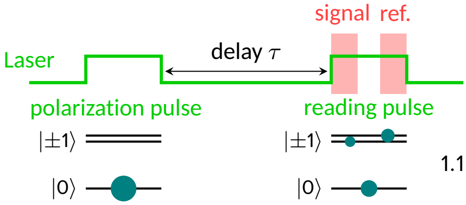
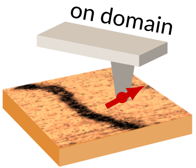
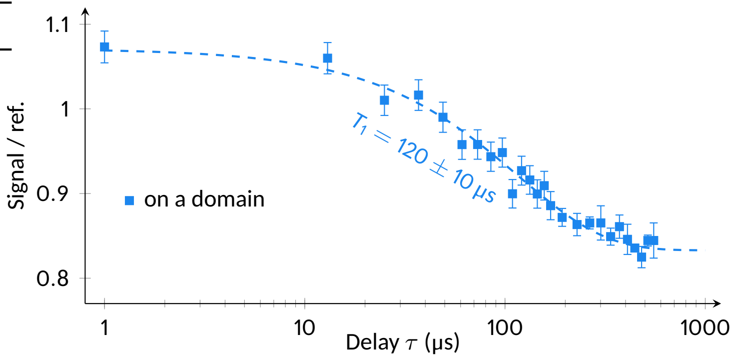
Local variation of the relaxation time



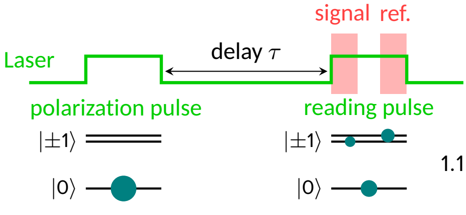
Local variation of the relaxation time

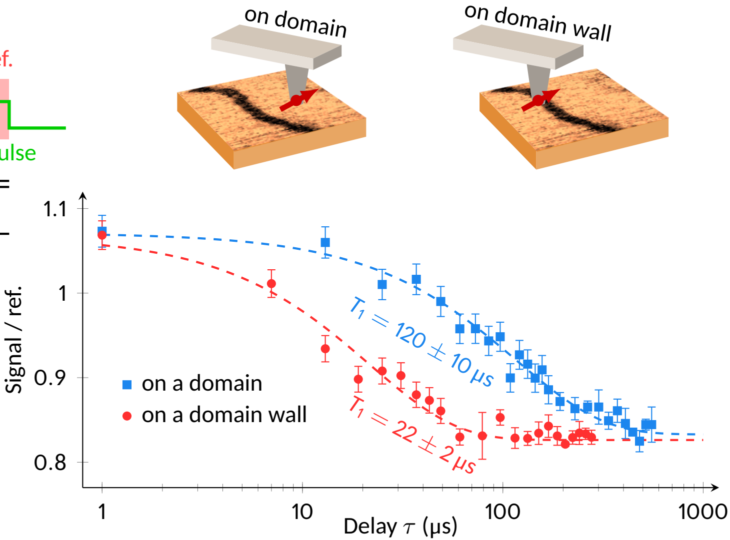






Local variation of the relaxation time



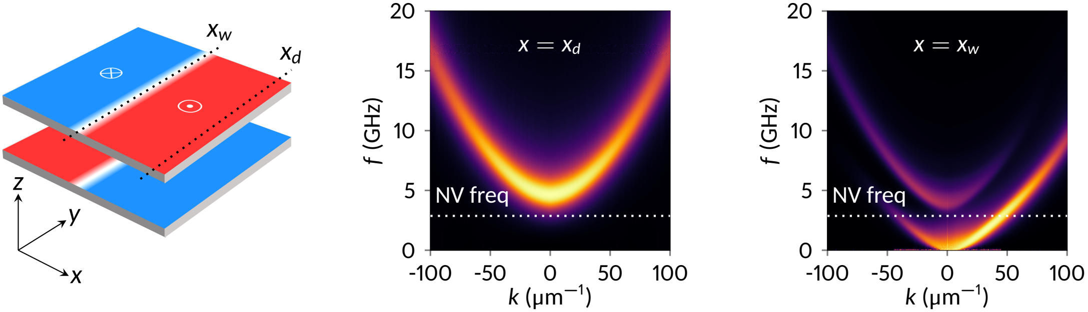


Clear diminution of T_1

→ **Enhancement of the spin relaxation**

Origin of the noise: spin waves

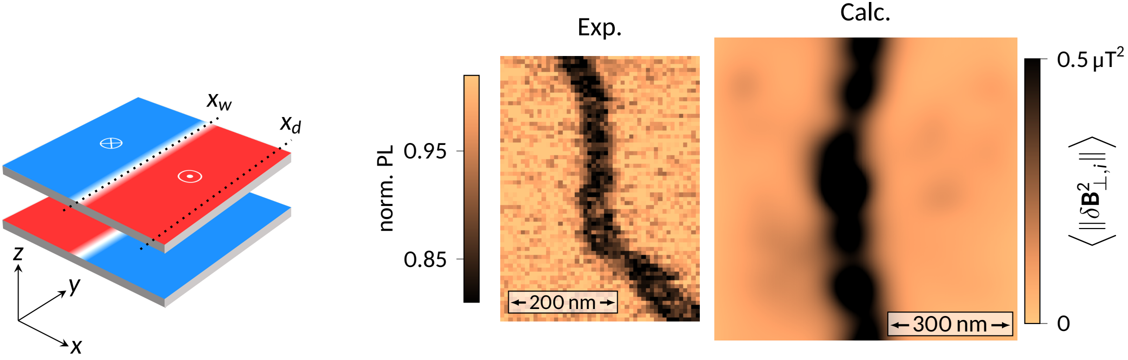
Collaboration: C2N, Palaiseau (J.-P. Adam, J.-V. Kim)



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

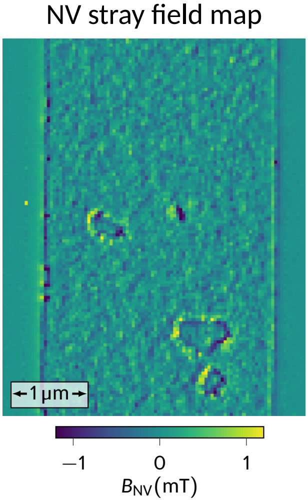
Origin of the noise: spin waves

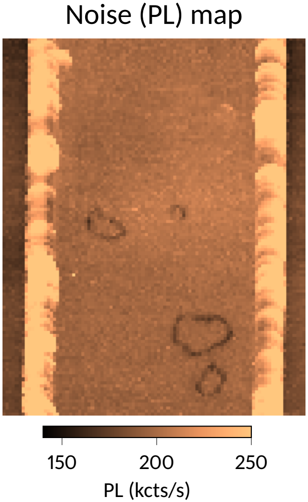
Collaboration: C2N, Palaiseau (J.-P. Adam, J.-V. Kim)



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

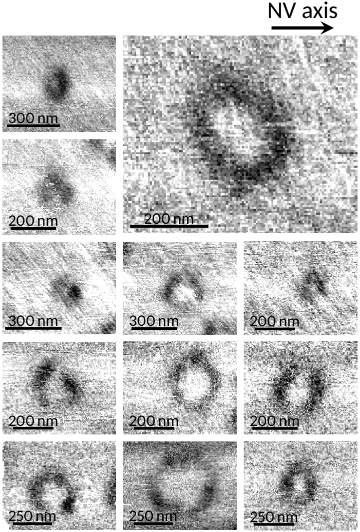
After applying magnetic field



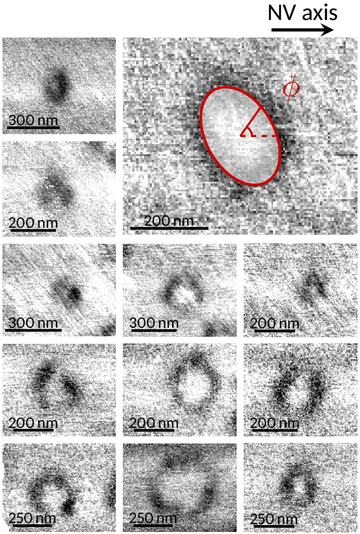


- Oop field of about 150 mT applied for nucleation
- Skyrmions and big bubbles pinned

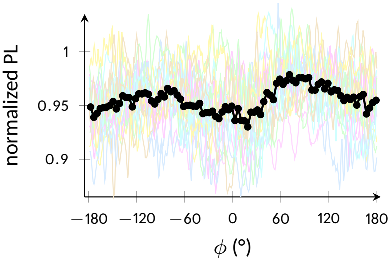
Statistics on Néel left (CCW) skyrmions



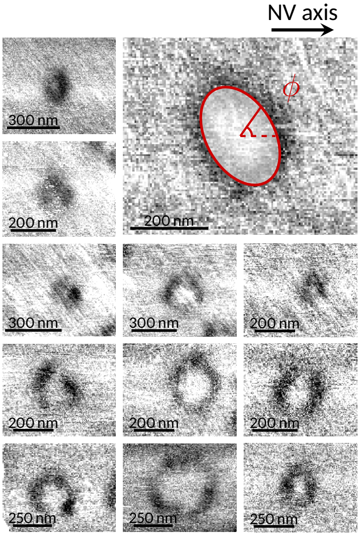
Statistics on Néel left (CCW) skyrmions



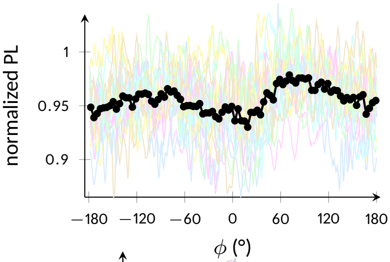
Angular variation of PL



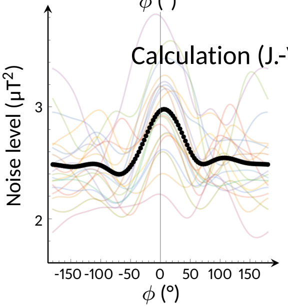
Statistics on Néel left (CCW) skyrmions



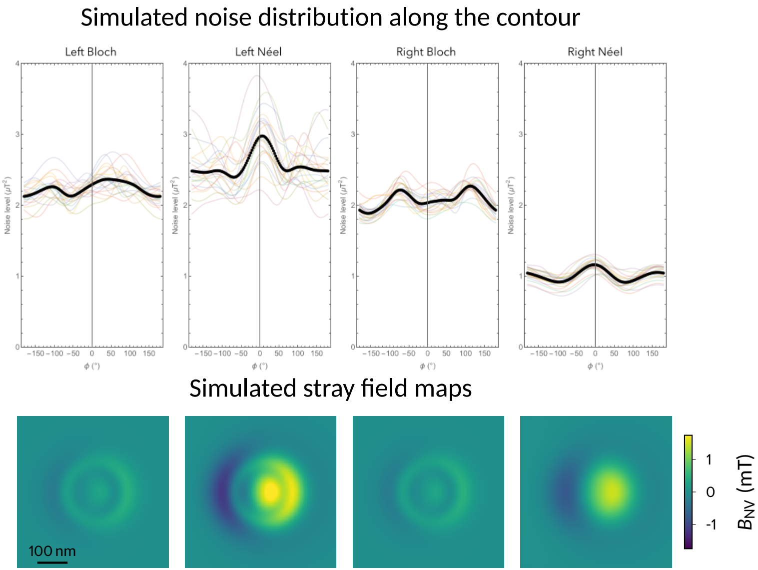
Angular variation of PL



Calculation (J.-V. Kim, C2N)



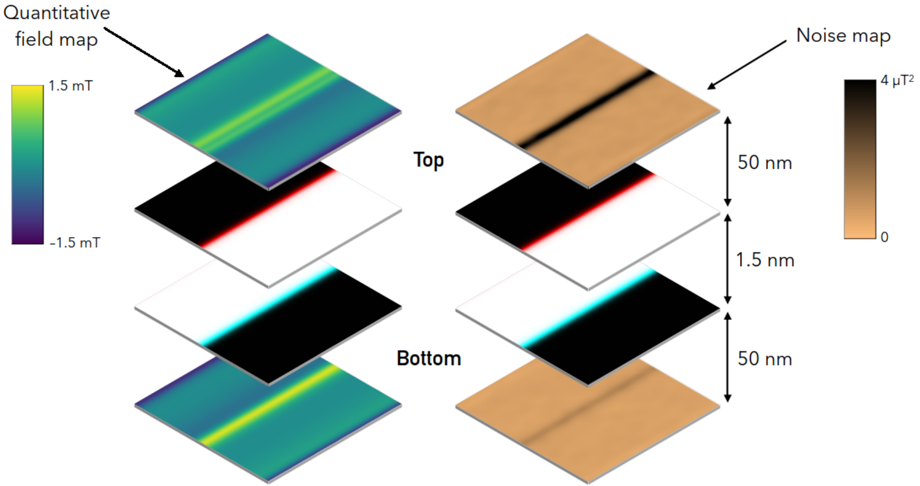
Expected pattern on other skyrmion types



- 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!

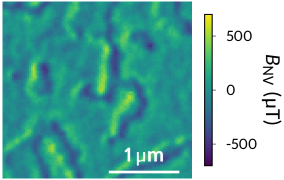
Calculation: C2N, Palaiseau (J.-V. Kim)



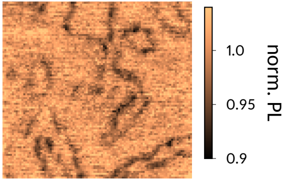
Experiment: looking at both sides of the film

Initial stack: Néel left

Magnetic field map



Noise map

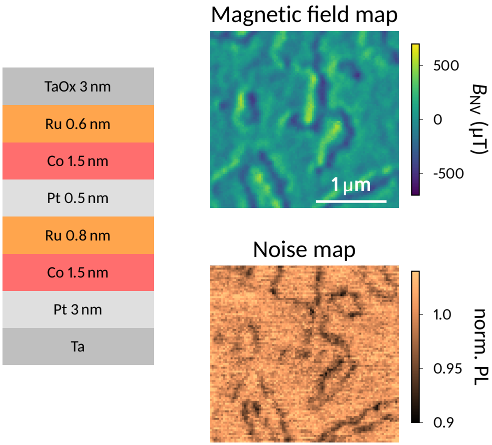


A. Finco *et al.* *in preparation* (2024)

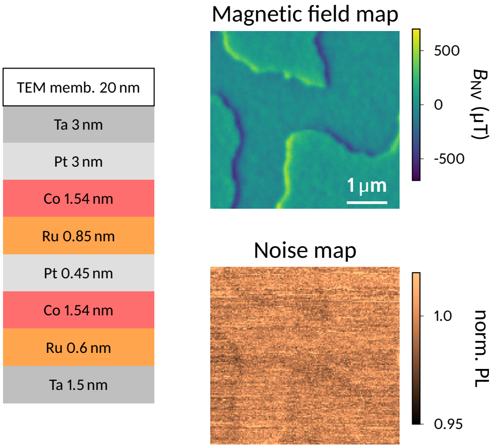
Samples: J. Urrestarazu, R. Guedas, Spintec, Grenoble

Experiment: looking at both sides of the film

Initial stack: Néel left



Inverted stack: Néel right

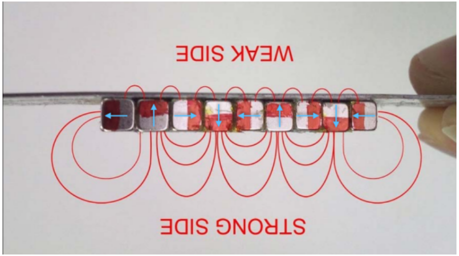


A. Finco *et al.* *in preparation* (2024)

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

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

Halbach arrays



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

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

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

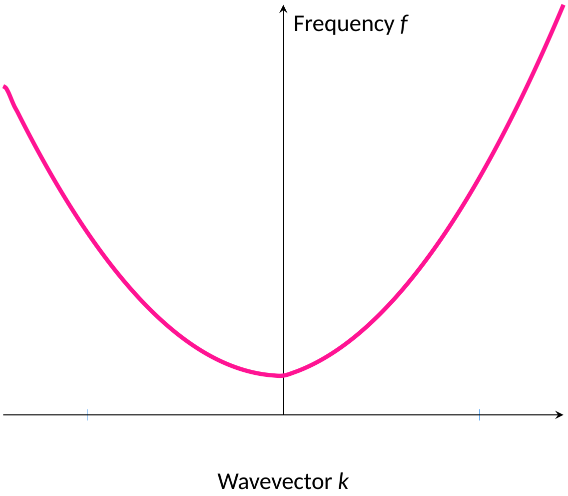
$\delta\vec{m} \quad \leftarrow \quad \uparrow \quad \rightarrow \quad \downarrow \quad \leftarrow \quad -\vec{k}$

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

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

Origin of this effect, 2nd ingredient: DMI

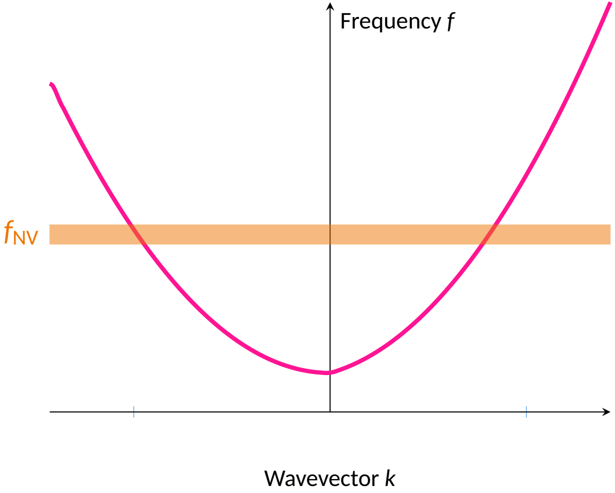
1. DMI induces non-reciprocity in the SW dispersion



Origin of this effect, 2nd ingredient: DMI

1. DMI induces non-reciprocity in the SW dispersion

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

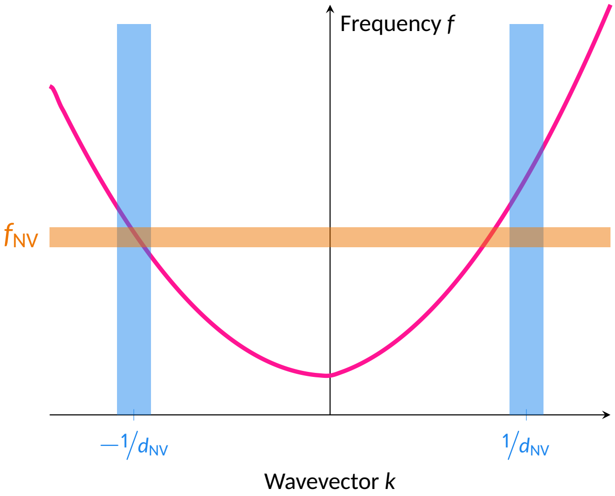


Origin of this effect, 2nd ingredient: DMI

1. DMI induces non-reciprocity in the SW dispersion

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

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



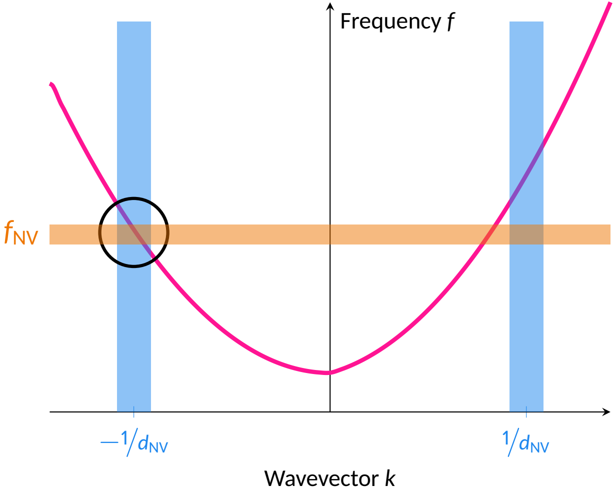
Origin of this effect, 2nd ingredient: DMI

1. DMI induces non-reciprocity in the SW dispersion

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

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

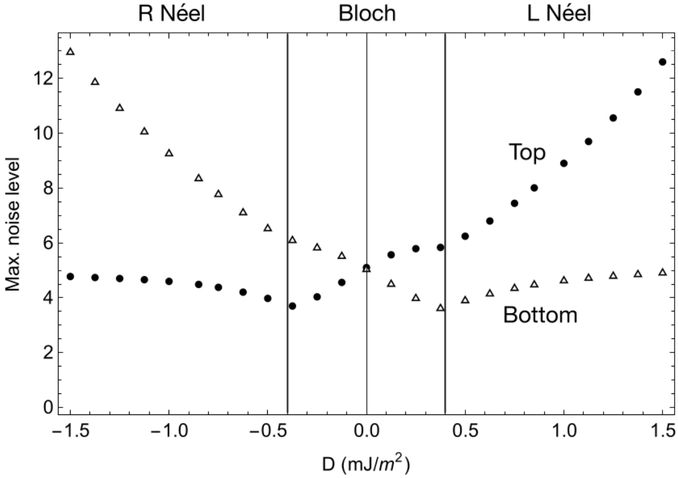
➔ The NV center is more sensitive to a k direction than the other



Expected noise level vs DMI

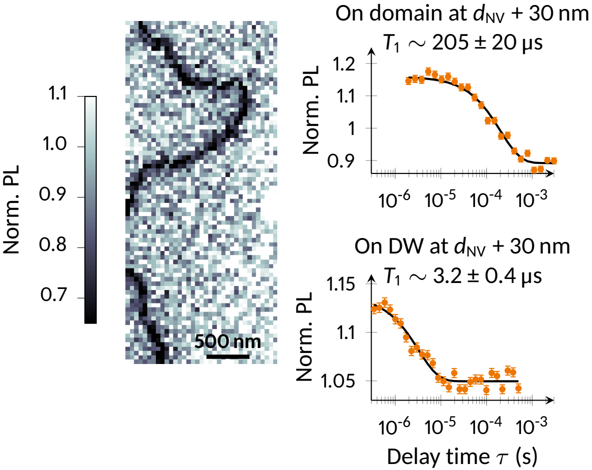
Calculation: J.-V. Kim, C2N, Palaiseau

For a **single** ferromagnetic layer

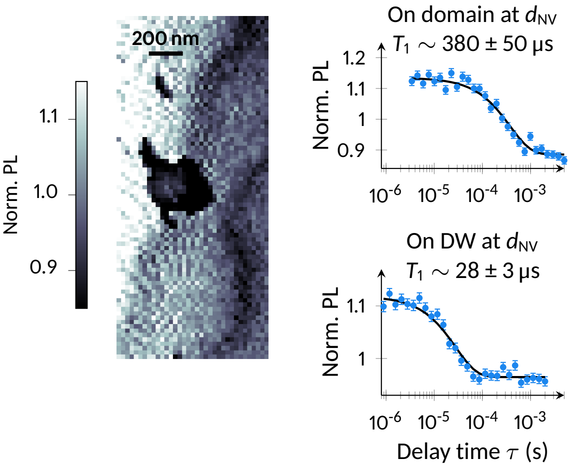


Data measured on a single FM layer grown on a membrane

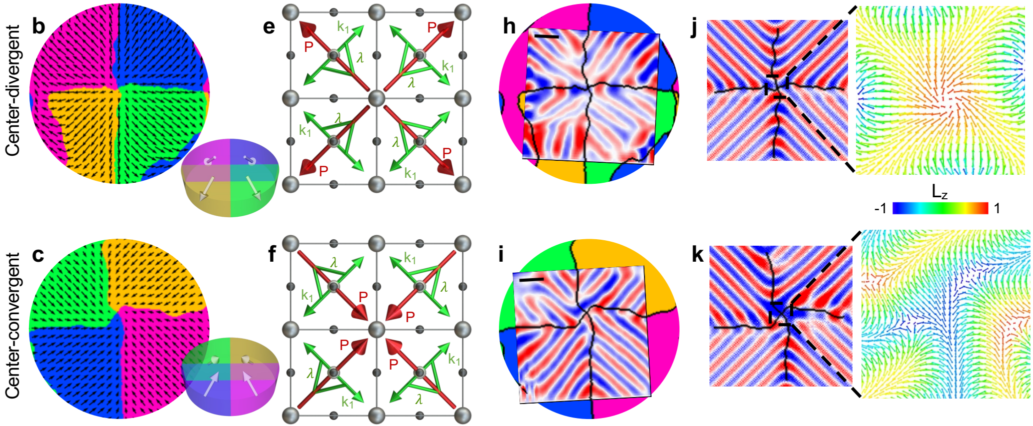
Néel left side of the membrane (top)



Néel right side of the membrane (bottom)



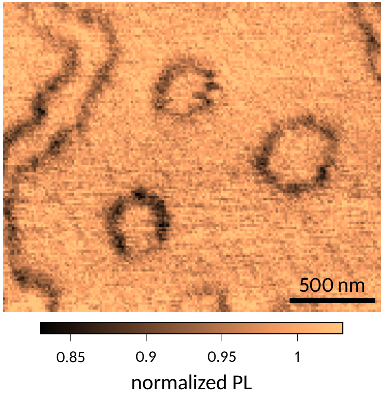
Summary: multiferroic solitons in BFO discs



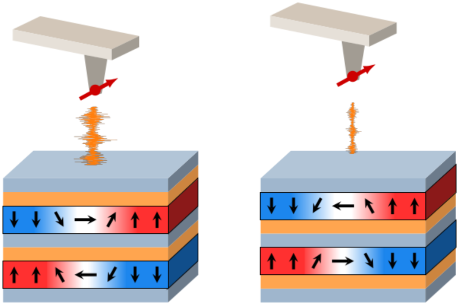
A. Chaudron *et al.* Nat. Mater. 23 (2024), 905

Summary: DMI probing from noise

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)

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Spintec, Grenoble
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