NV-center microscopy
a versatile tool to study magnetism

Aurore Finco

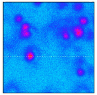
Laboratoire Charles Coulomb
Team Solid-State Quantum Technologies (S2QT)

CNRS and Université de Montpellier, Montpellier, France

ITN-SPEAR, FTS5: Skyrmions, February 28th 2024, Hamburg

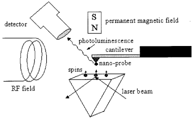
slides available at `https://magimag.eu`

A very short history



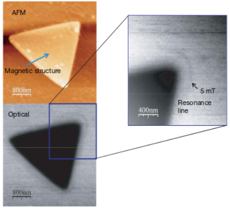
1997: First detection of single NV centers

A. Gruber *et al.* *Science* 276 (1997), 2012



2004: Proposal of the scanning NV center magnetometer

B. M. Chernobrod and G. P. Berman. *J. Appl. Phys.* 97 (2004), 014903

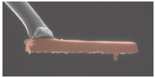


2008: First demonstration of scanning NV imaging

G. Balasubramanian *et al.* *Nature* 455 (2008), 648–651

2012: All-diamond probes

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



2020: Commercial scanning NV microscopes available

Further reading

Reviews about NV center magnetometry:

- S. Hong *et al.* *MRS Bulletin* 38 (2013), 155–161
- L. Rondin *et al.* *Reports on Progress in Physics* 77 (2014), 056503
- F. Casola *et al.* *Nature Reviews Materials* 3 (2018), 17088
- A. Laraoui and K. Ambal. *Applied Physics Letters* 121 (2022), 060502
- Y. Xu *et al.* *Photonics Research* 11 (2023), 393–412
- A. Finco and V. Jacques. *APL Materials* 11 (2023), 100901

Outline

1. The NV center in diamond as a quantum sensor
2. Dismantling the scanning NV microscope
3. Quantitative ODMR experiments
   - Principle of the measurement
   - The need for a proper calibration
   - Example 1: analyzing domain walls
   - Example 2: the spin cycloid in bismuth ferrite
   - Example 3: van der Waals magnets
4. Taking a step back: PL quenching effects
   - Strong off-axis magnetic fields
   - Magnetic noise!
5. Relaxometry: sensing via the relaxation time
6. Coherent control of the NV center using spin waves
7. Going further: other sensors and sensing methods

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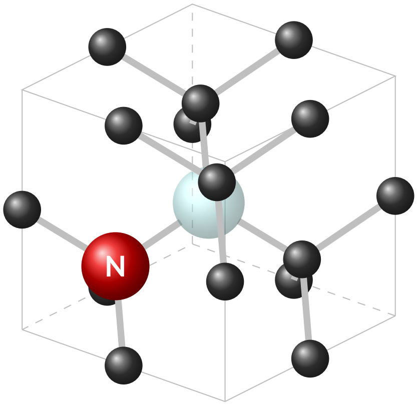
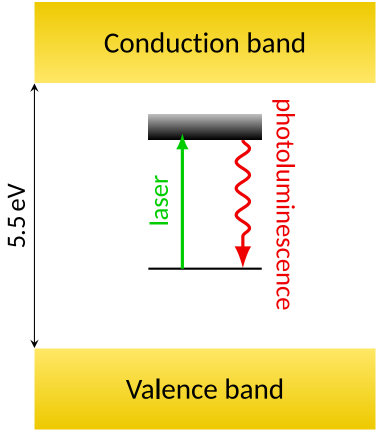
The NV center in diamond



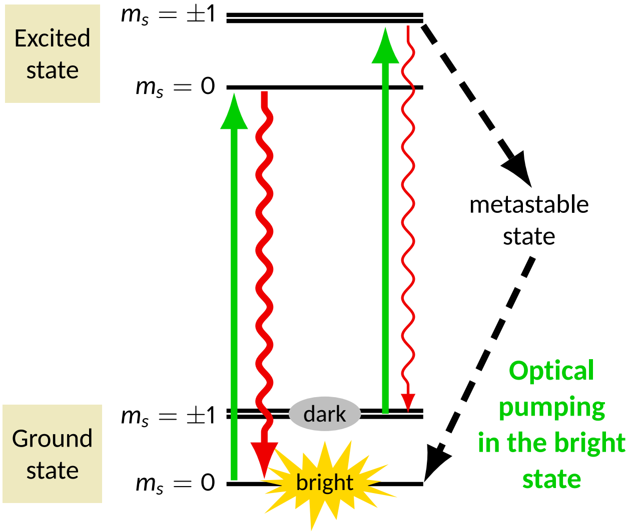
- Artificial atom: energy levels in the diamond bandgap
- Photostable defect
- Spin S=1
- Individual defects can be isolated/implanted
- Ambient conditions

Optical properties

Artificial atom
in the diamond band gap

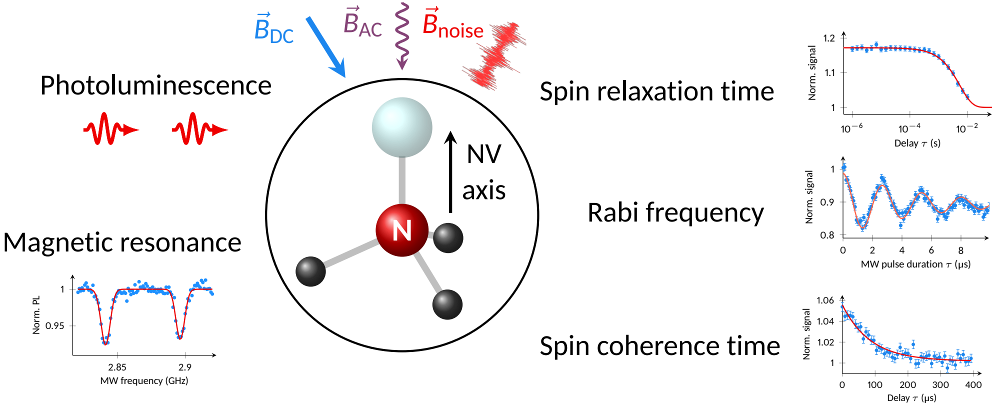


Spin dependent photoluminescence



The NV center as a quantum sensor

$$\mathcal{H}_{\mathrm{gs}} = h\left[D_{\mathrm{NV}}\hat{S}_z^2 + \gamma_{\mathrm{NV}}\hat{\vec{S}}\cdot\vec{B}\right] \quad \text{with} \quad \begin{cases} D_{\mathrm{NV}} \simeq 2.87\,\mathrm{GHz} \\ \gamma_{\mathrm{NV}} \simeq 28\,\mathrm{GHz\,T^{-1}} \end{cases}$$



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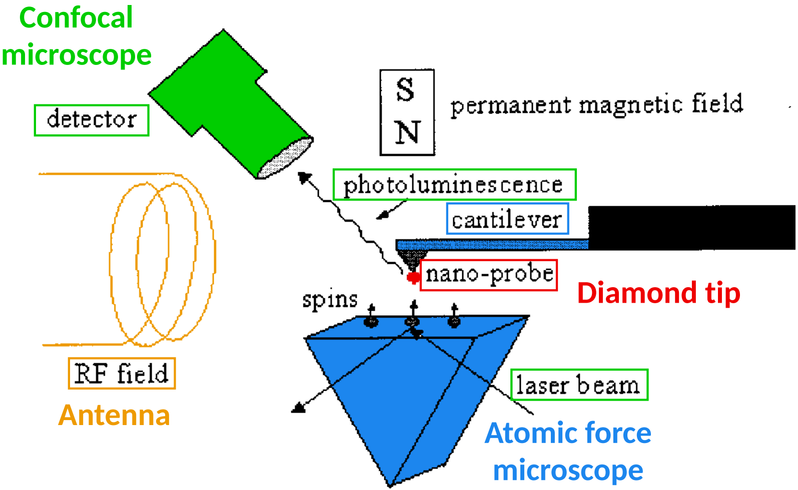
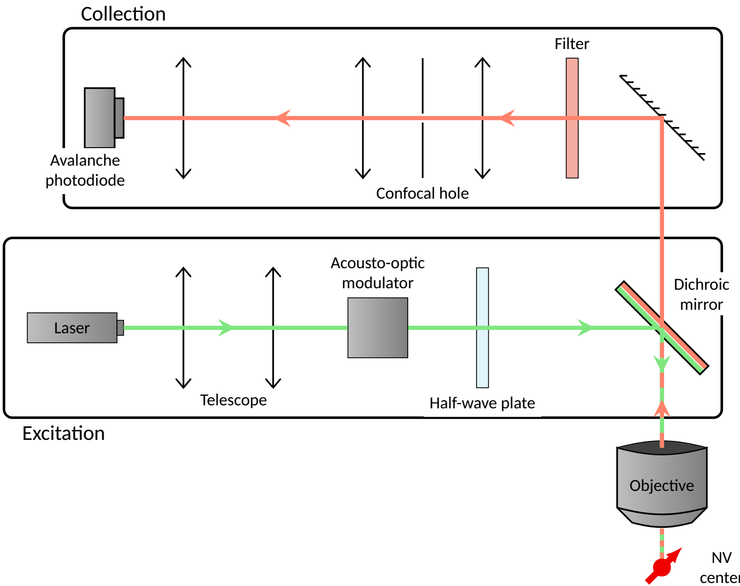
Dismantling the scanning NV microscope



B. M. Chernobrod and G. P. Berman. *J. Appl. Phys.* 97 (2004), 014903

The confocal microscope



The atomic force microscope

Akiyama probes

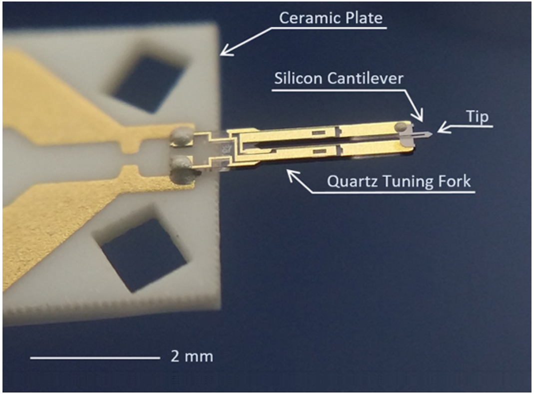


Image from www.akiyamaprobe.com

- The quartz tuning fork oscillates at about 32 kHz.
- The tip and cantilever are removed and the diamond tip glued on one of the arms.
- Excitation and reading of the mechanical resonance with piezo elements.
- Feedback loop onto the frequency or the amplitude of the mechanical resonance.

The diamond probes

All-diamond probes developed in 2012

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

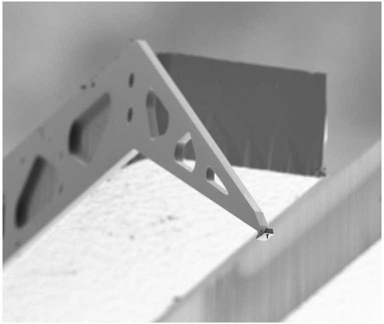


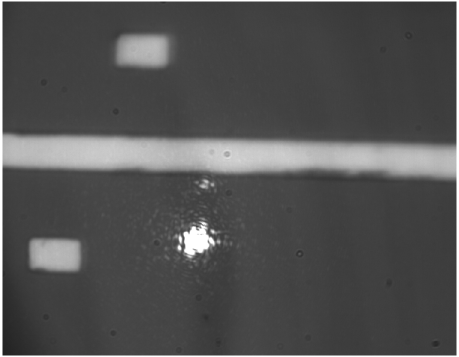
Image from www.qzabre.com

- High-purity diamond
  → Good coherence properties
- Hosting single NV centers at 50-100 nm from the sample surface
  → Spatial resolution of the microscope
- Usually made from (001) diamond
  → Tilted NV axis
- Diamond pillar as guide for the emitted light
  → Optimized signal collection

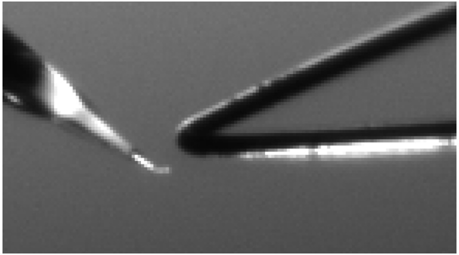
The microwave antenna

We need to deliver a microwave signal very close to the NV center. Several options:

Patterned gold line on the sample

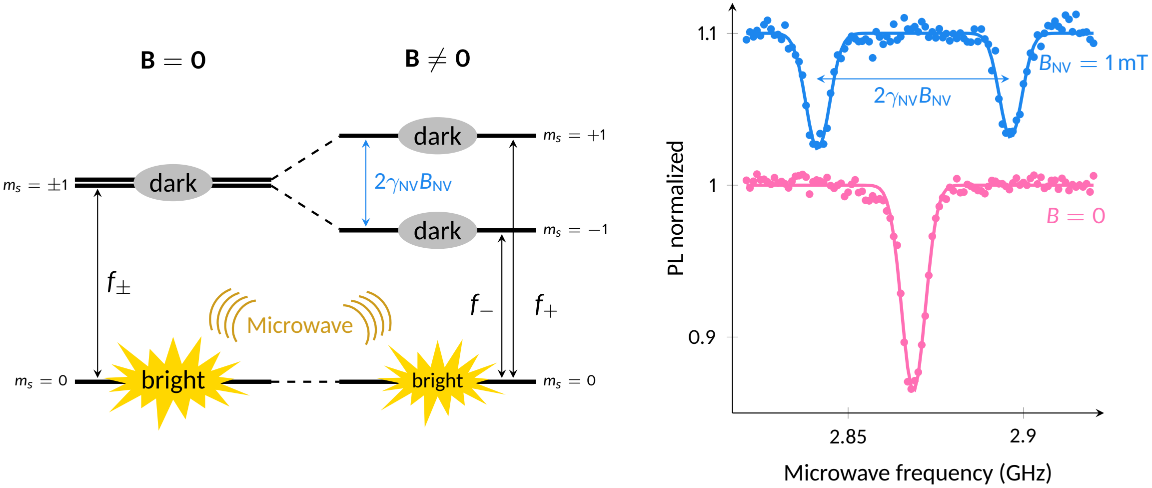


Use a wire, close to the tip



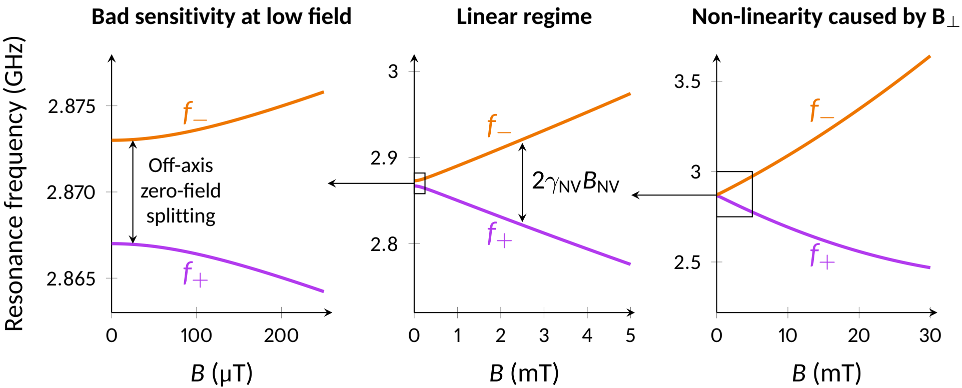
Outline

Optically detected magnetic resonance (ODMR)



The different regimes

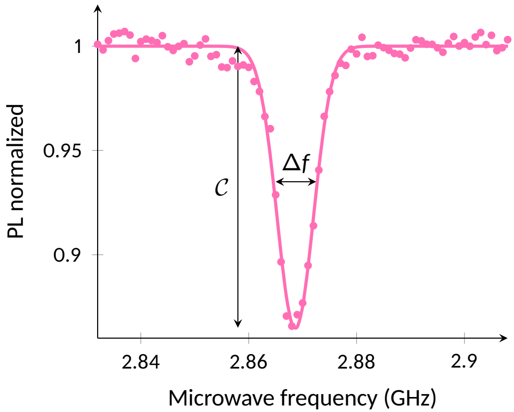
Calculation of f_- and f_+, with a 45° angle between $\vec{B}$ and the NV axis



→ We apply a bias field roughly aligned with the NV axis (also to extract the sign of B_{NV})

→ Quantitative measurements of very strong fields impossible

Magnetic field sensitivity



$$\eta_B = \frac{4}{3\sqrt{3}\,\gamma_{\mathrm{NV}}} \frac{\Delta f}{\mathcal{C}\sqrt{\mathcal{R}}}$$

- Linewidth Δf: tunable with the microwave power
- Contrast $\mathcal{C}$: tunable with the laser and the microwave power
- Off-resonance count rate $\mathcal{R}$: tunable with the laser power

→ Optimal $(P_{\mathrm{laser}}, P_{\mathrm{MW}})$ values
→ Sensitivity: a few $\mu\mathrm{T}/\sqrt{\mathrm{Hz}}$

A. Dréau *et al.* *Physical Review B* 84 (2011), 195204

Understanding stray field maps

$$\vec{B} = \mu_0 \vec{\nabla} \phi$$

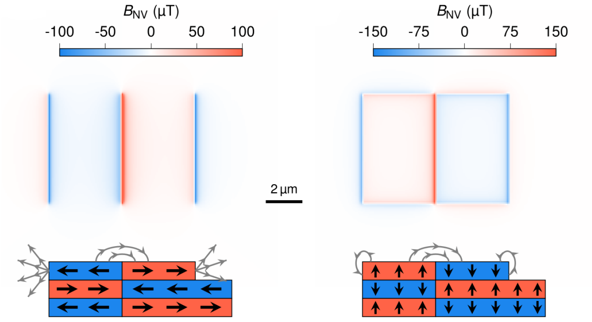
where ϕ is a scalar potential which verifies the Poisson equation:

$$\Delta \phi = \vec{\nabla} \cdot \vec{M}$$

Same equation as for the electrostatic potential V

$$\Delta V = -\frac{\rho}{\varepsilon_0}$$

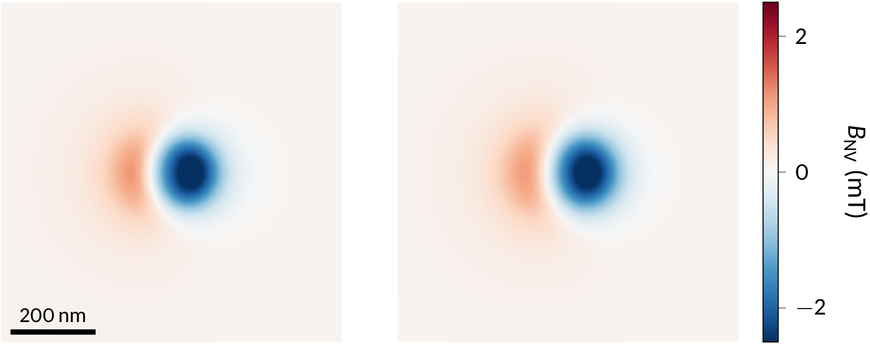
$\Rightarrow \vec{\nabla} \cdot \vec{M}$ can be seen as the magnetic field source



Field sources: edges, domain walls, skyrmions, etc.

We need to calibrate the NV flying distance!

Simulated stray field maps from skyrmions of diameter 150 nm in a 0.5 nm thick film with $M_s = 1\,\mathrm{MA\,m^{-1}}$



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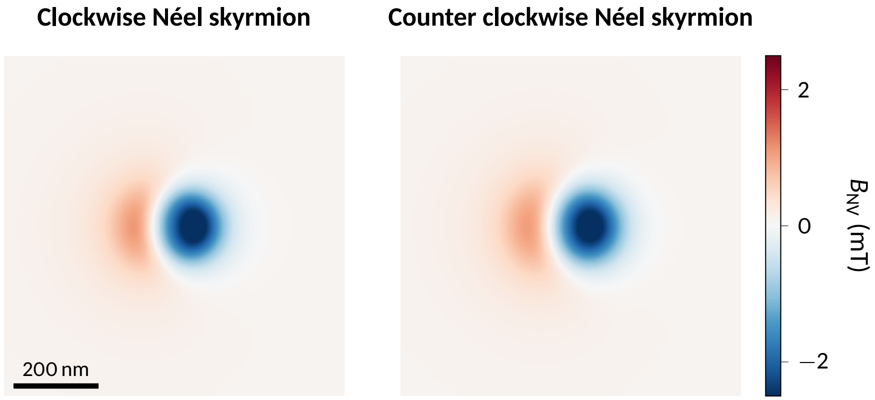
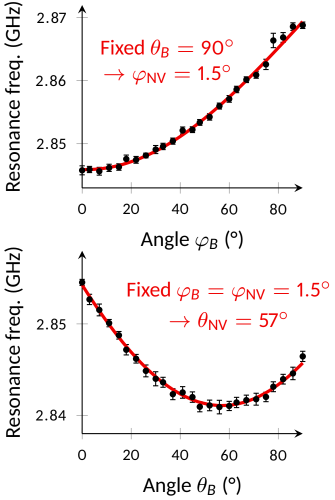


NV height: $d_{\mathrm{NV}} = 50\,\mathrm{nm}$
DW width: $w = 15\,\mathrm{nm}$

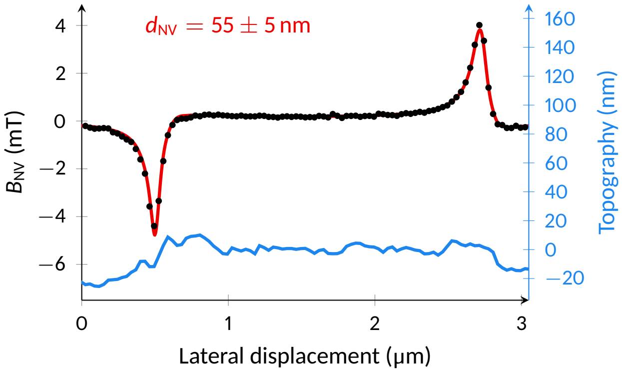
NV height: $d_{\mathrm{NV}} = 80\,\mathrm{nm}$
DW width: $w = 30\,\mathrm{nm}$

The calibration procedure

1. Find the NV axis orientation



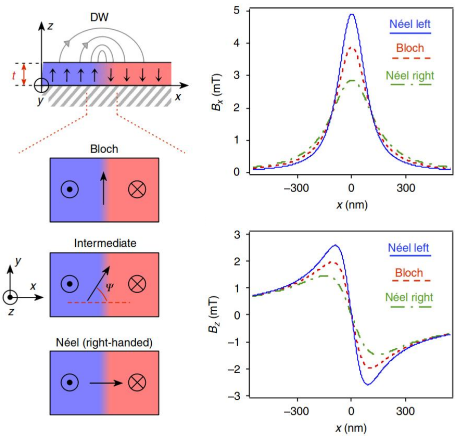
2. Find the NV height d_{NV} with a well-known ferromagnetic stripe



T. Hingant *et al.* *Phys. Rev. Appl.* 4 (2015), 014003

Example 1: analysis of domain walls

Analytical expression of the stray field



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

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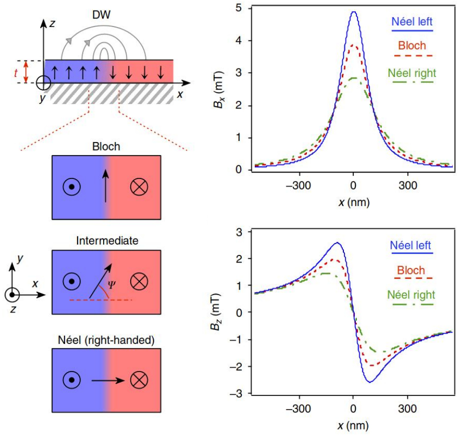
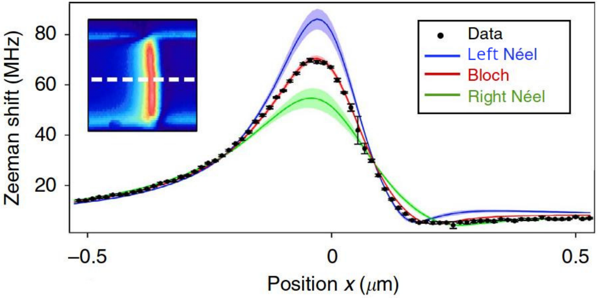


Ta/CoFeB/MgO stripe

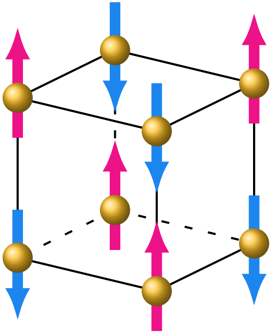


→ With a precise calibration, we can determine the internal texture of the domain wall

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

Example 2: the cycloid in bismuth ferrite

G-type antiferromagnet



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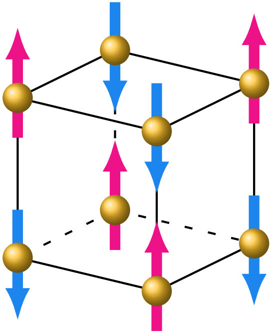

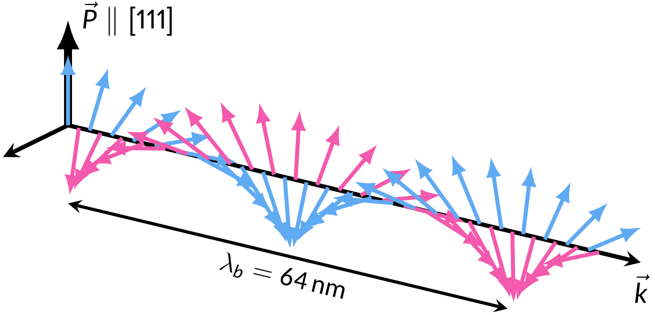

Fully compensated cycloid
$\rightarrow$ **No stray field!**

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

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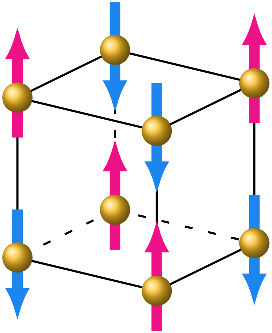
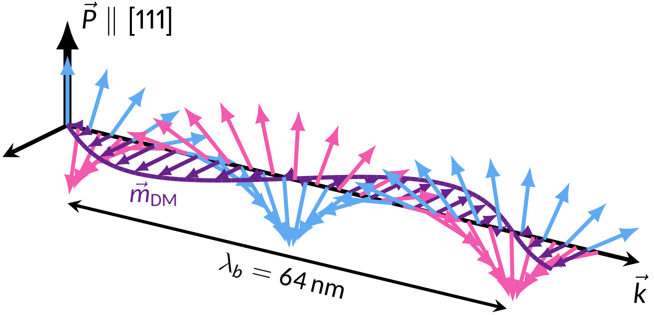
G-type antiferromagnet



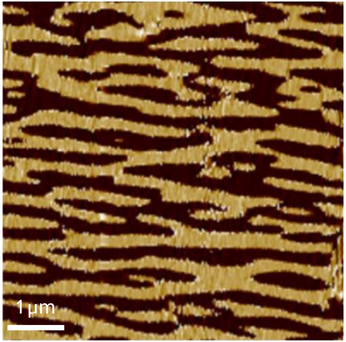


Spin density wave
Weak uncompensated moment
$\rightarrow$ **Small stray field**

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

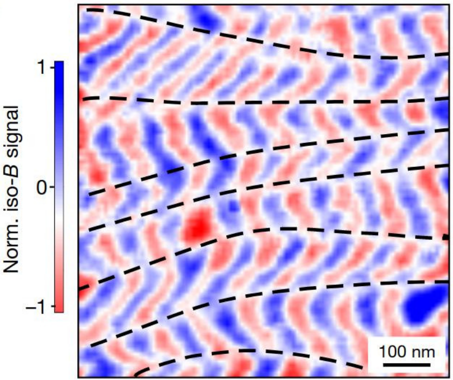
First real-space images of the cycloid

Piezoresponse force microscopy image
Ferroelectric domains



Reminder: The wavevector $\vec{k}$ of the cycloid is always perpendicular to $\vec{P}$

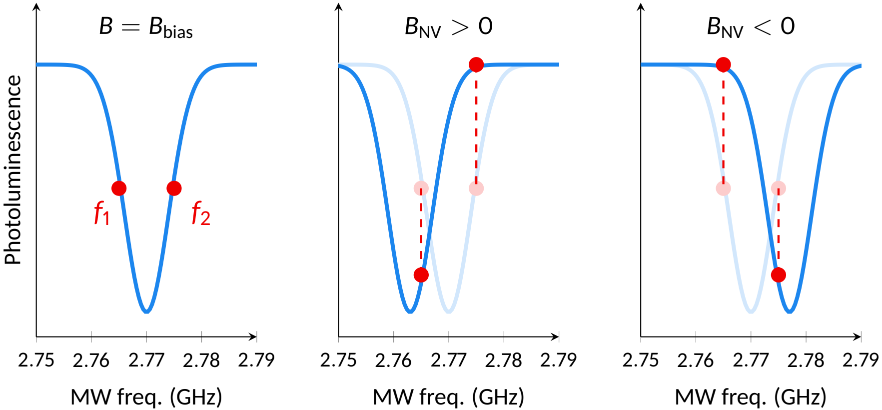
NV image
Field from the spin density wave



I. Gross *et al.* *Nature* 549 (2017), 252–256

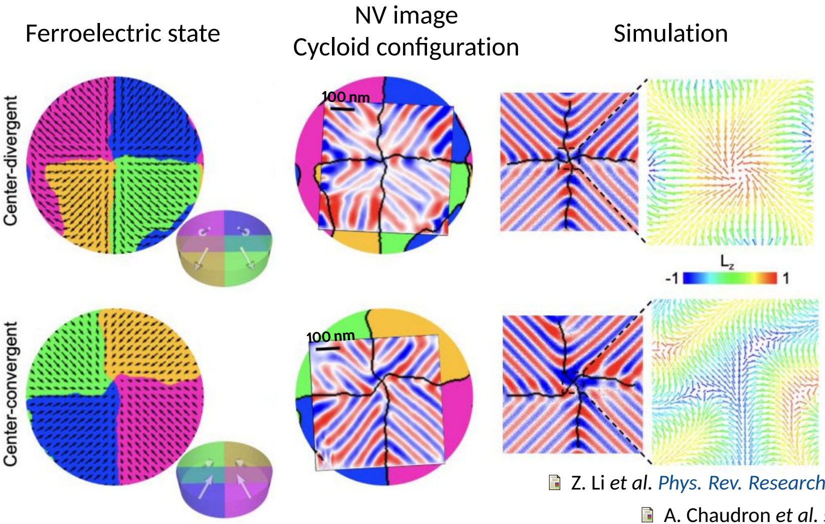
Note: the iso-B mode

$$\Delta\mathrm{PL} = \mathrm{PL}(f_2) - \mathrm{PL}(f_1)$$



Creating "topological" multiferroic states in $BiFeO_3$

Collaboration: Lab. A. Fert, Paris (A. Chaudron, K. Bouzehouane, S. Fusil, V. Garcia)

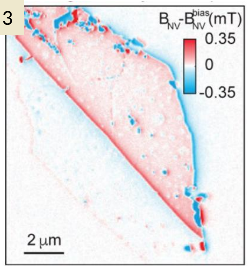


Z. Li *et al.* *Phys. Rev. Research* 5 (2023), 043109

A. Chaudron *et al.* *submitted* (2024)

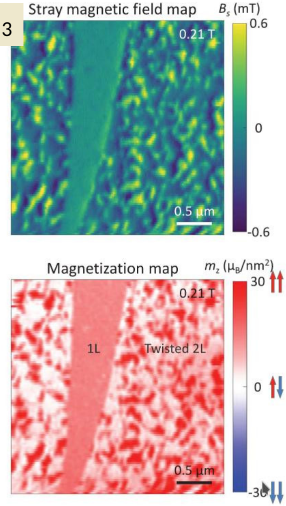
Example 3: van der Waals magnets

CrI_3



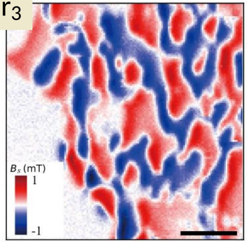
L. Thiel *et al.* *Science* 364 (2019), 973–976

CrI_3



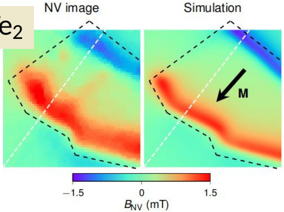
T. Song *et al.* *Science* 374 (2021), 1140

$CrBr_3$



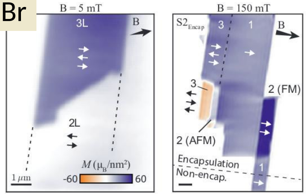
Q.-C. Sun *et al.* *Nat. Commun.* 12 (2021), 1989

$CrTe_2$



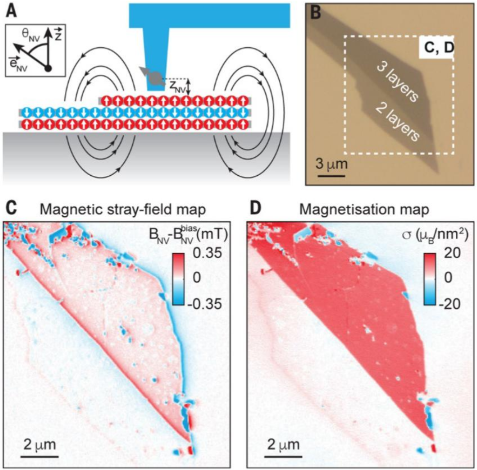
F. Fabre *et al.* *Phys. Rev. Mater.* 5 (2021), 034008

CrSBr



M. A. Tschudin *et al.* *arXiv* 2312.09279 (2023)

Reverse propagation to compute M maps



- Reconstruction of ferromagnetic magnetization density maps
- Fourier space calculation
- $\vec{M}$ needs to be aligned along a single direction (α, β)
- Mostly reliable for out-of-plane magnetized samples

$$\begin{pmatrix} \tilde{B}_x \\ \tilde{B}_y \\ \tilde{B}_z \end{pmatrix} = \frac{-\mu_0}{2\, e^{q\, z_{NV}}} \begin{pmatrix} \frac{q_x^2}{q} & \frac{q_x q_y}{q} & iq_x \\ \frac{q_x q_y}{q} & \frac{q_y^2}{q} & iq_y \\ iq_x & iq_y & -q \end{pmatrix} \begin{pmatrix} \sin\alpha\cos\beta\tilde{M}(q_x, q_y) \\ \sin\alpha\sin\beta\tilde{M}(q_x, q_y) \\ \cos\alpha\tilde{M}(q_x, q_y) \end{pmatrix}$$

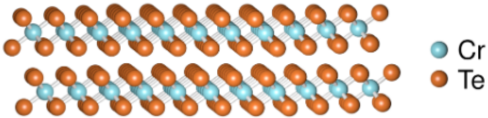
L. Thiel *et al.* *Science* 364 (2019), 973–976

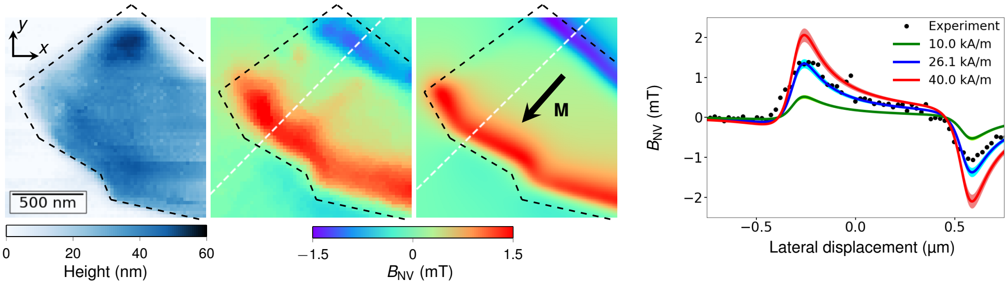
D. Broadway *et al.* *Phys. Rev. Appl.* 14 (2020), 024076

Working with a model

Collaboration: Institut Néel, Grenoble (A. Purbawati, J. Coraux, N. Rougemaille)

2D ferromagnet at room temperature with in-plane magnetization



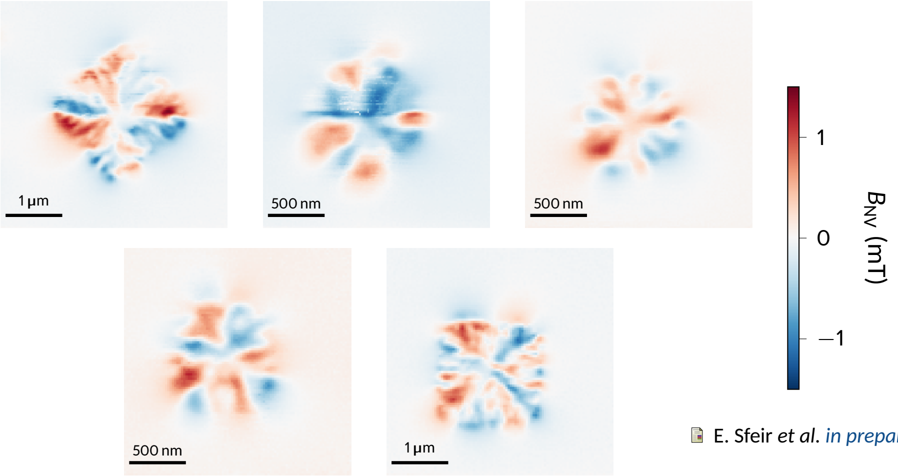


F. Fabre *et al.* *Phys. Rev. Mater.* 5 (2021), 034008

Vortices!

Collaboration: Spintec, Grenoble (F. Bonnell, M. Jamet)

At zero field, we observe vortices in microstructured Fe_5GeTe_2 (also an in-plane RT magnet):



E. Sfeir *et al.* *in preparation* (2024)

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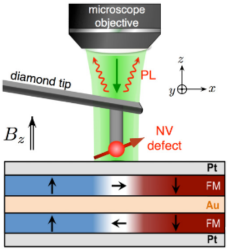
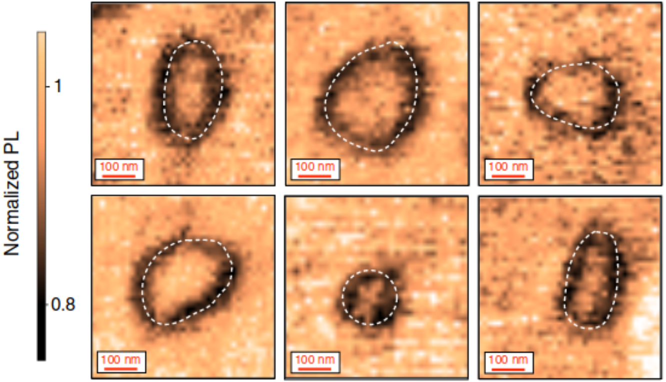
Simpler, faster but qualitative: measure the PL

Photoluminescence maps, under $B_z = 3\,\text{mT}$





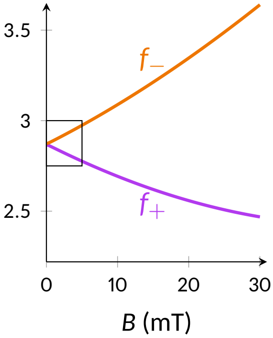
I. Gross *et al.* *Phys. Rev. Mater.* 2 (2018), 024406

The effect of perpendicular magnetic field

"Strong" field not oriented along the NV axis

➔ Mixing of the states $m_s = 0, \pm 1$, which are not eigenstates anymore

Non-linearity caused by $B_\perp$



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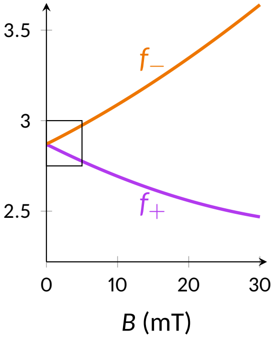
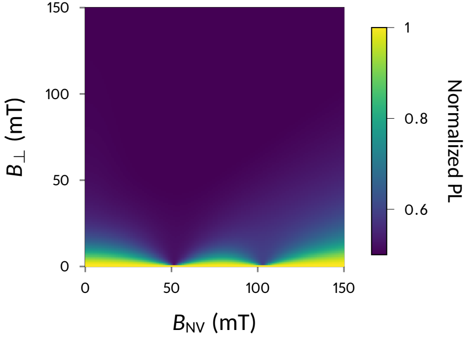
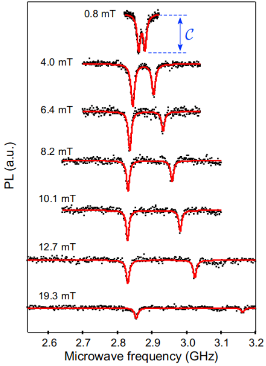
→ Mixing of the states $m_s = 0, \pm 1$, which are not eigenstates anymore

Non-linearity caused by $B_\perp$

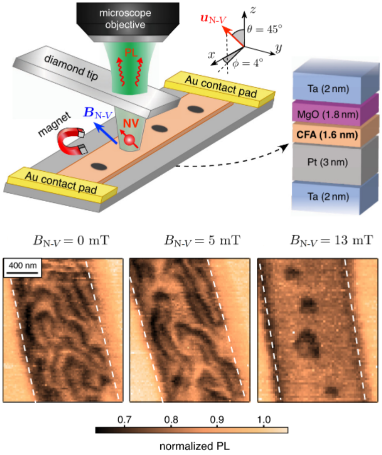






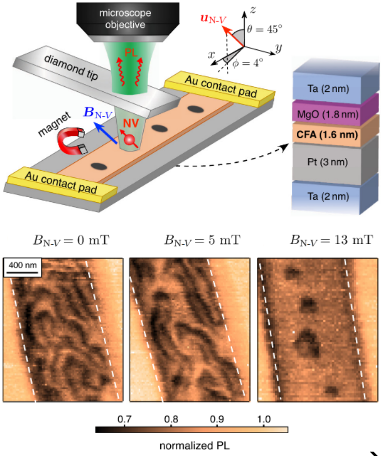
J.-P. Tetienne *et al.* *New J. Phys.* 14 (2012), 103033

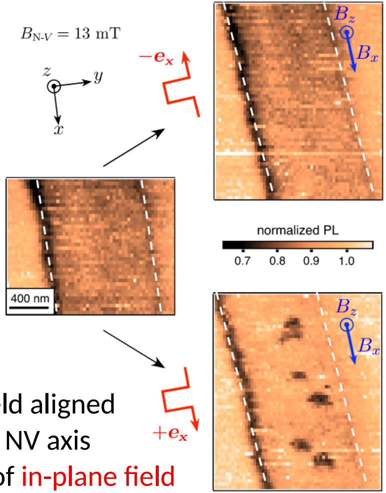
Skyrmion nucleation in PL quenching mode



W. Akhtar *et al*. *Phys. Rev. Appl.* 11 (2019), 034066

Skyrmion nucleation in PL quenching mode



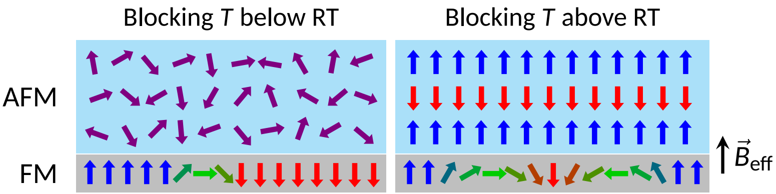


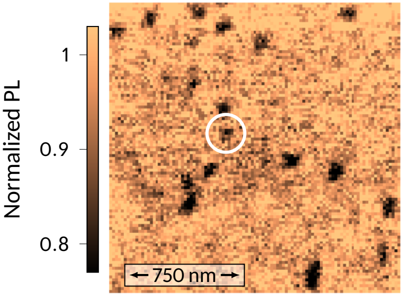
Applied field aligned with the NV axis

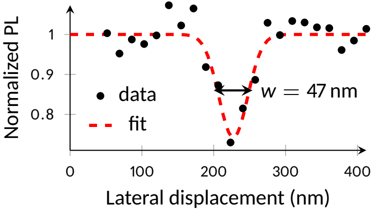
→ Observation of in-plane field assisted nucleation

W. Akhtar *et al.* *Phys. Rev. Appl.* 11 (2019), 034066

Skyrmions stabilized by exchange-bias

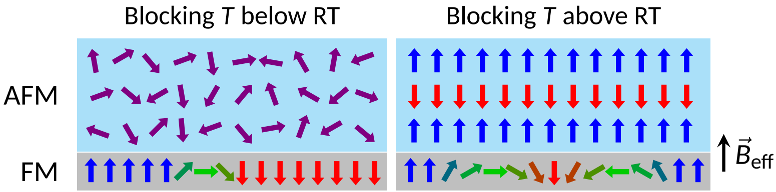


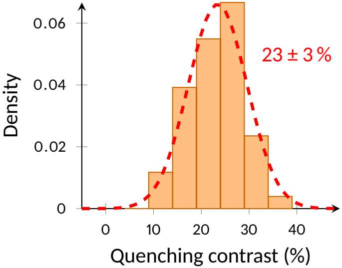


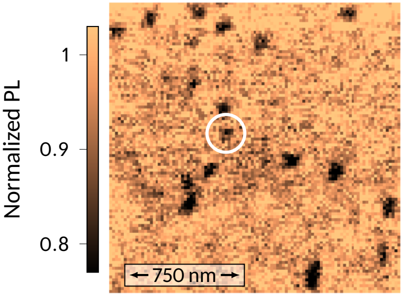


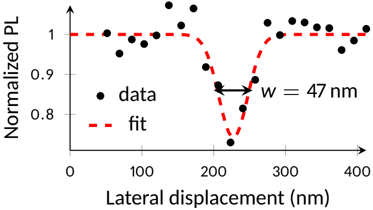
K. G. Rana *et al.* *Phys. Rev. Appl.* 13 (2020), 044079

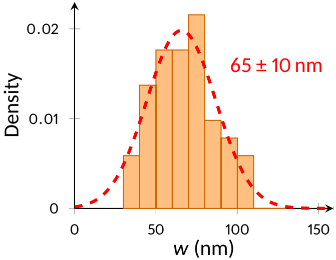
Skyrmions stabilized by exchange-bias





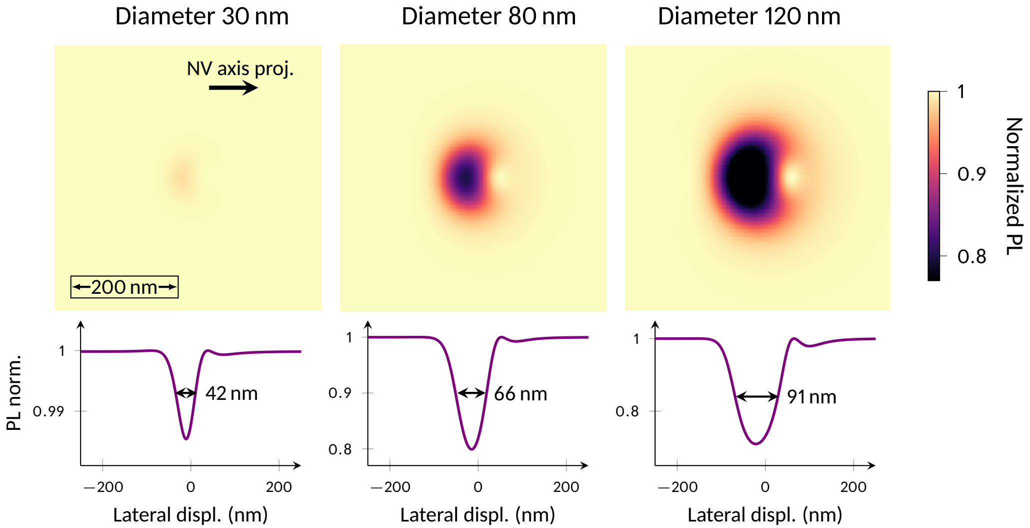






K. G. Rana *et al.* *Phys. Rev. Appl.* 13 (2020), 044079

Trying to extract quantitative information

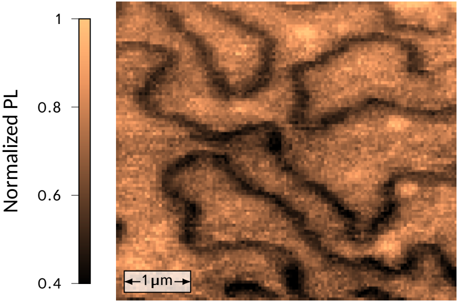


K. G. Rana *et al.* *Phys. Rev. Appl.* 13 (2020), 044079

Noise: another source of PL quenching

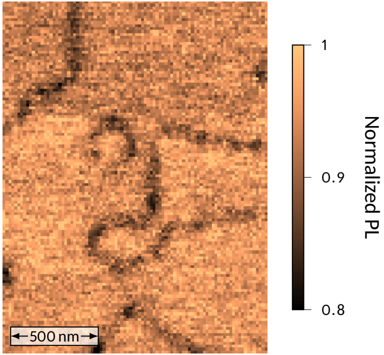
Thick ferromagnet

[Pt / Co (0.65 nm)]$_4$



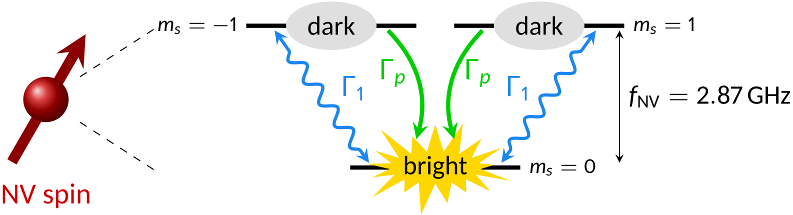
Synthetic antiferromagnet

Pt / Co (0.65 nm) / Ru / Pt / Co (0.65 nm) / Ru



Outline

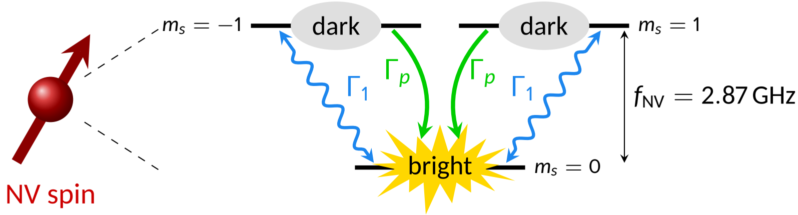
Effect of magnetic noise on the NV center



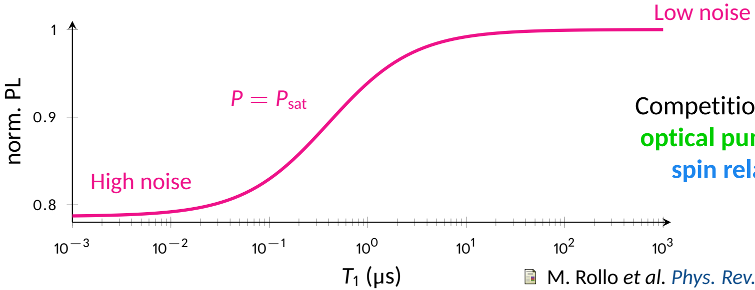
Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}

M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

Effect of magnetic noise on the NV center



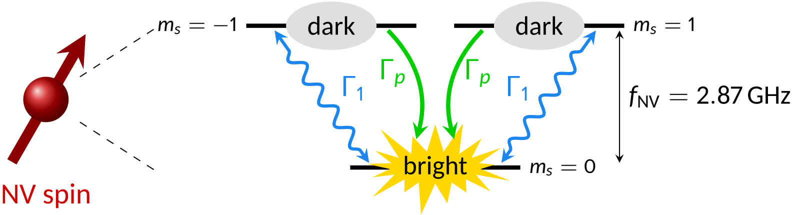
Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}



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

M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

Effect of magnetic noise on the NV center



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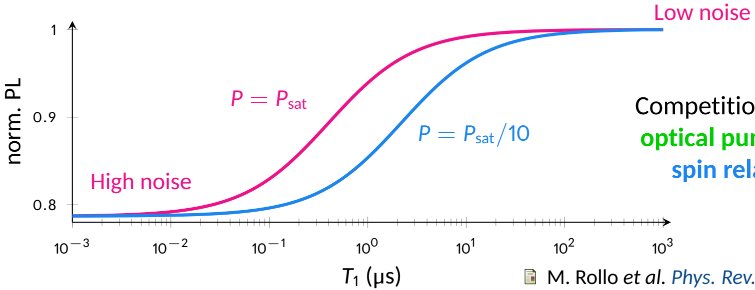
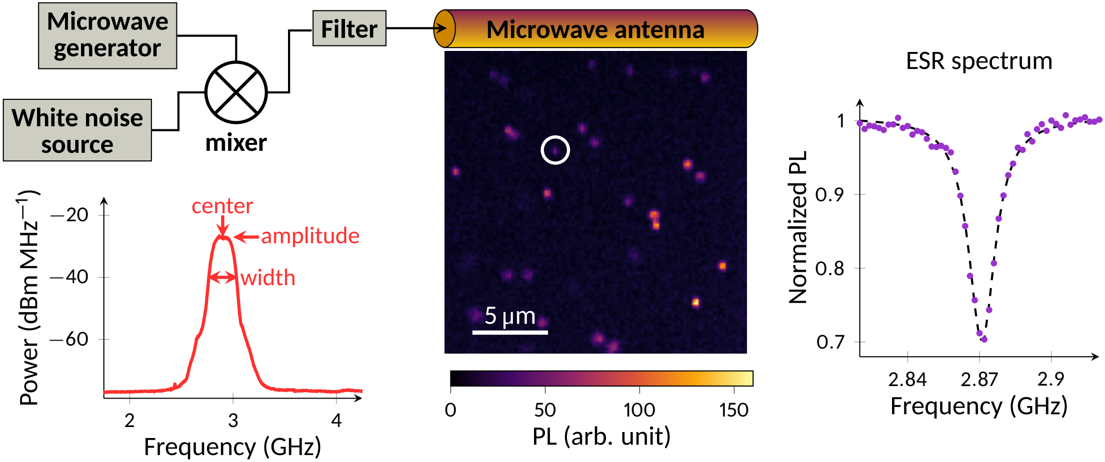


Competition between **optical pumping** and **spin relaxation**

M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

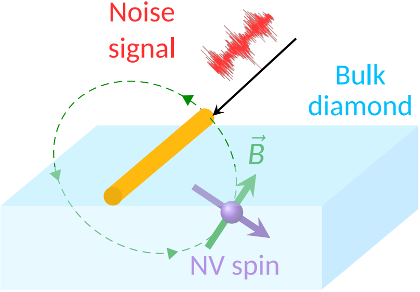
Experimental investigation

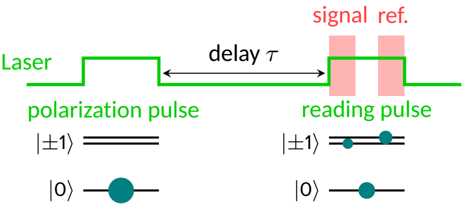
Collaboration: C2N, Palaiseau (Thibaut Devolder)

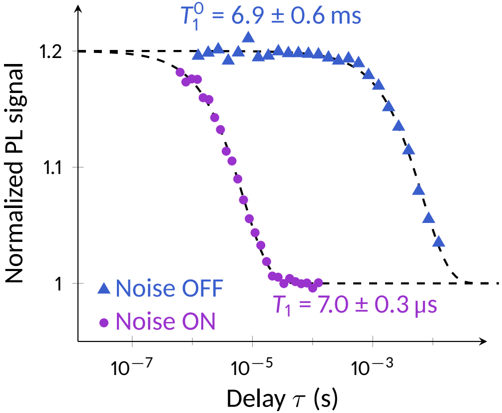


M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

Acceleration of the relaxation with noise



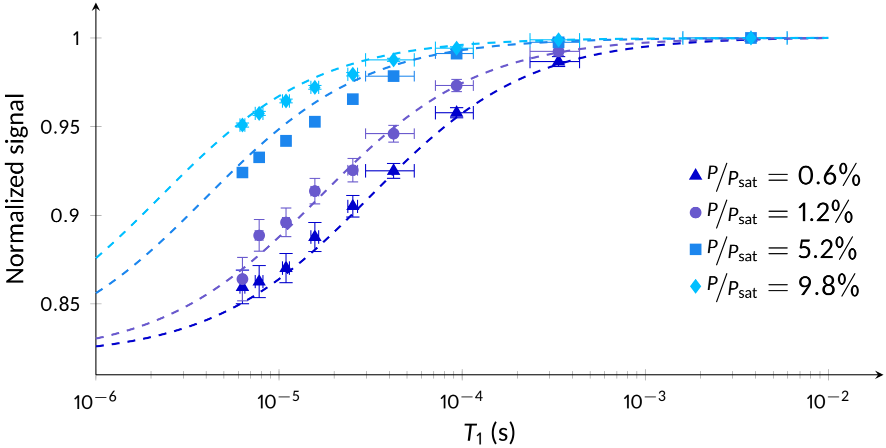




Noise spectrum centered
at the NV transition frequency

M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

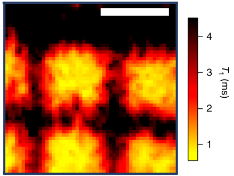
Evolution of the PL with noise



M. Rollo *et al.* *Phys. Rev. B* 103 (2021), 235418

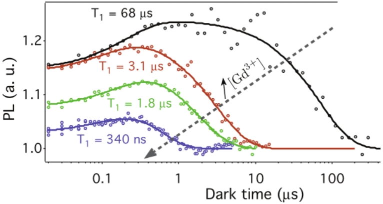
Applications of NV relaxometry

Measurement of Johnson noise: conductivity



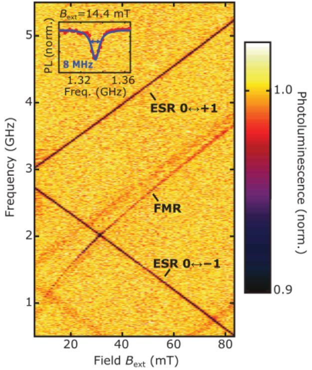
A. Ariyaratne *et al.* *Nat. Commun.* 9 (2018), 2406

Detection of fluctuating magnetic particles



J.-P. Tetienne *et al.* *Phys. Rev. B* 87 (2013), 235436

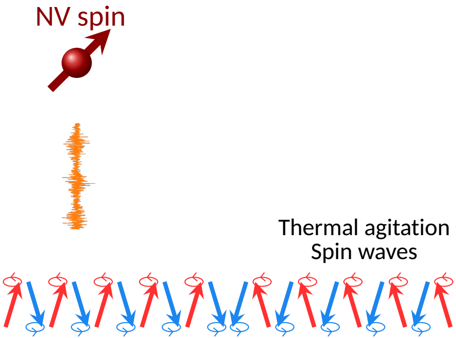
Investigation of spin waves



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

Relaxometry to image antiferromagnets

Principle: spin waves have different frequencies when they are confined inside domain walls



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

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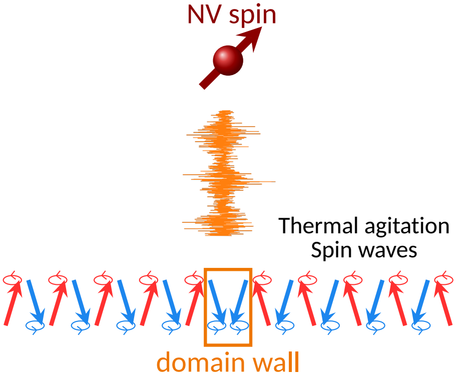
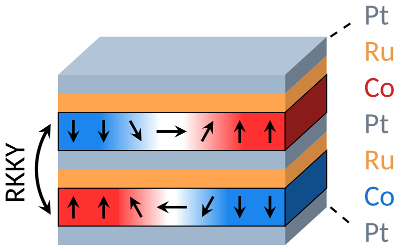


B. Flebus *et al.* *Phys. Rev. B* 98 (2018), 180409

Synthetic antiferromagnets

Collaboration: LAF, Palaiseau (W. Legrand, K. Bouzehouane, N. Reyren, V. Cros)

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

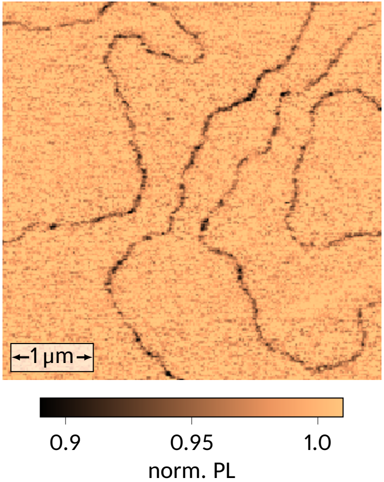


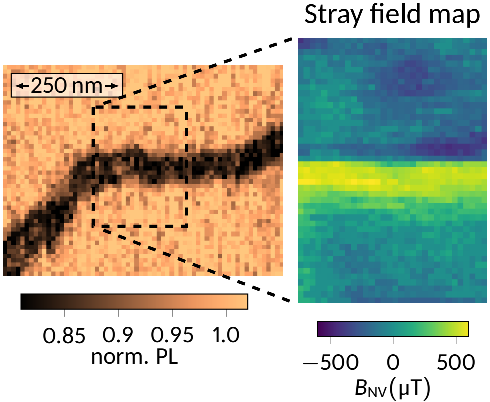
W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34

- 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!

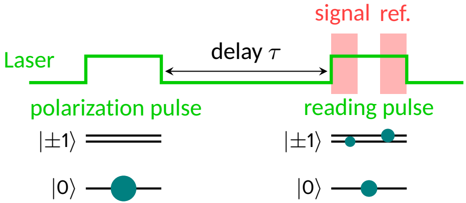
Detection of domain walls by relaxometry



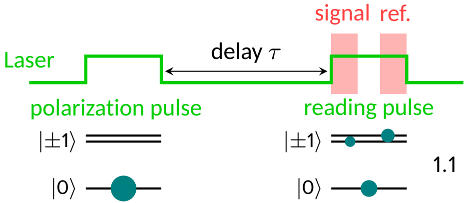


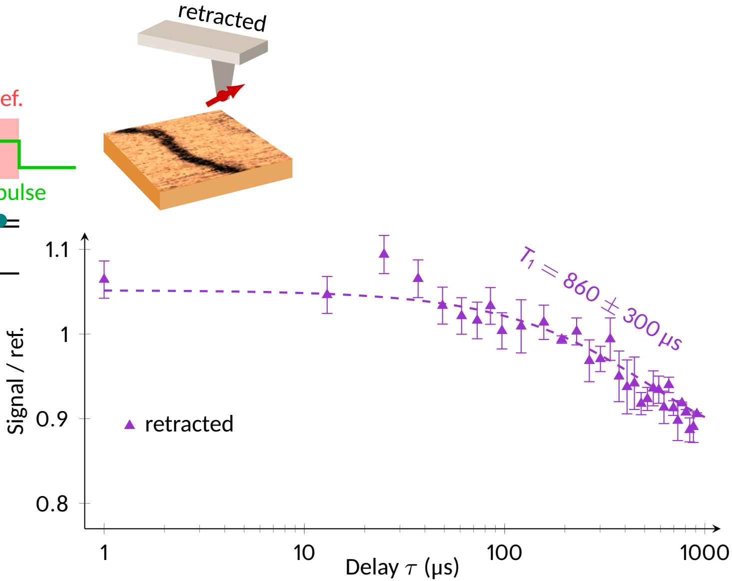
A. Finco *et al.* *Nat. Commun.* 12 (2021), 767

Local variation of the relaxation time

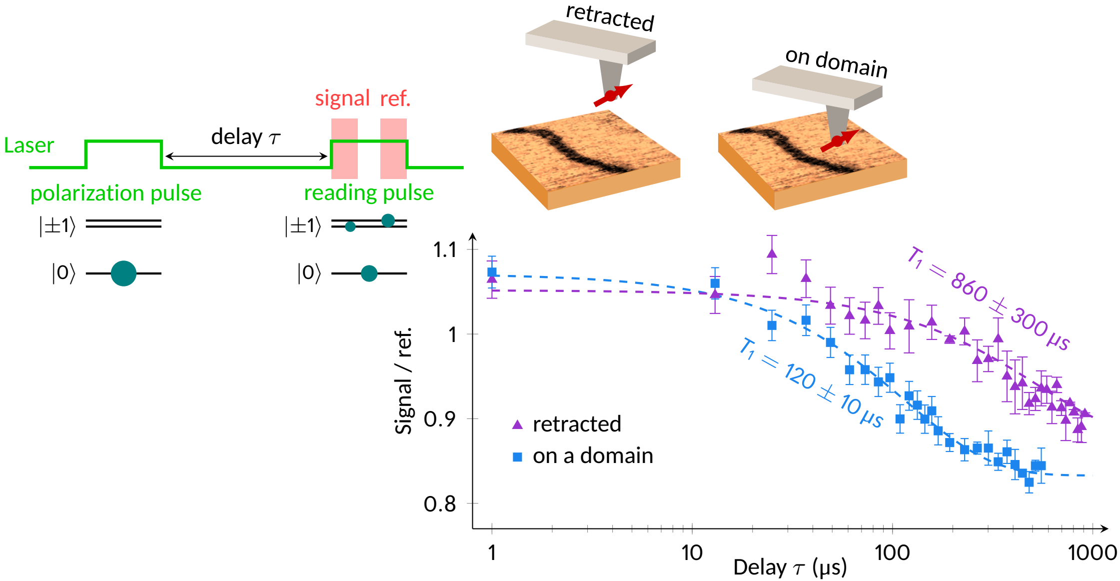


Local variation of the relaxation time

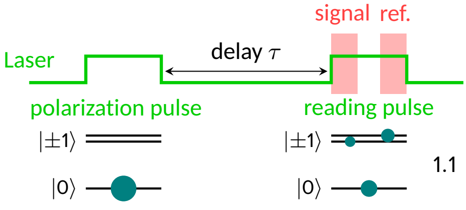


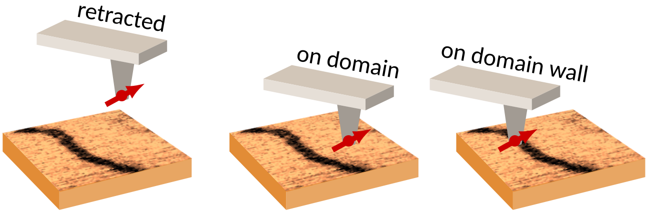


Local variation of the relaxation time



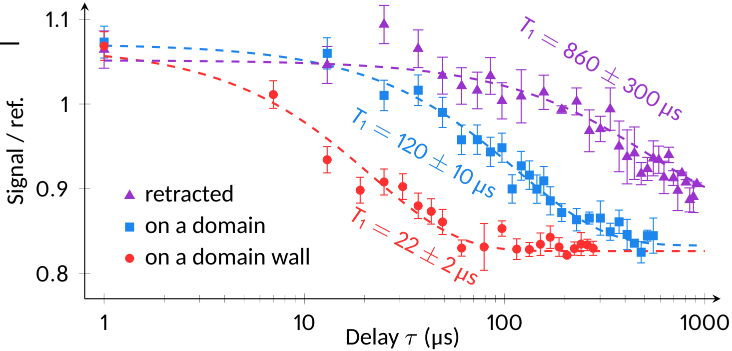
Local variation of the relaxation time





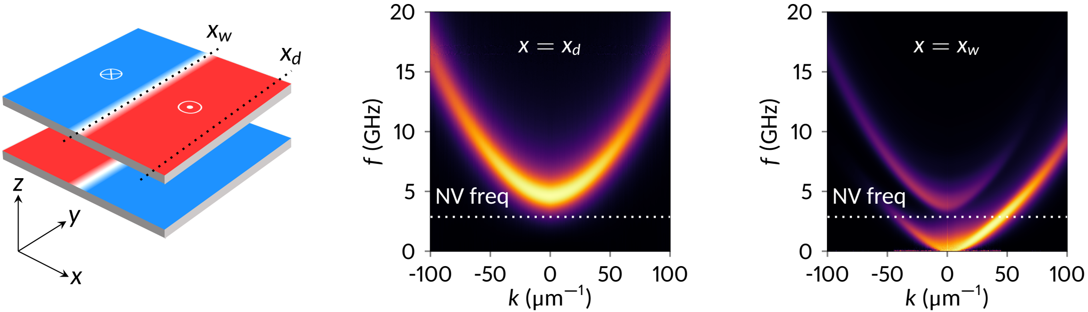
Clear diminution of T_1

→ **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

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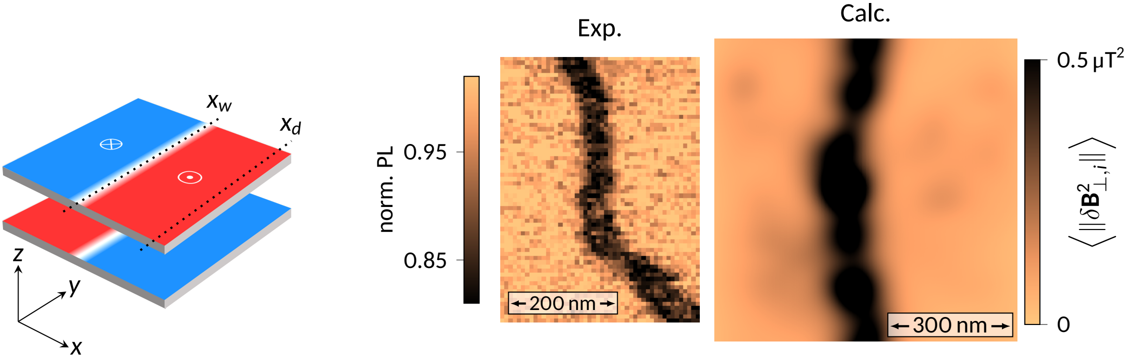

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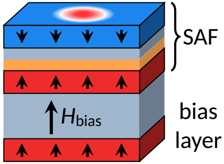
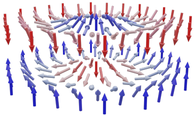
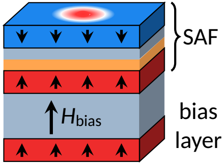
Skyrmions stabilized by a bias layer



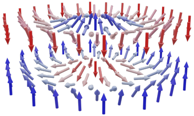
W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34

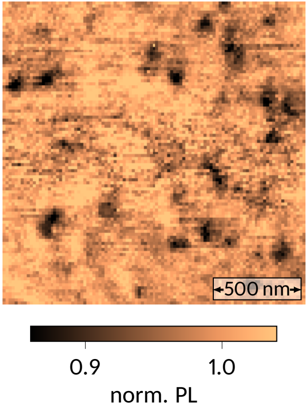


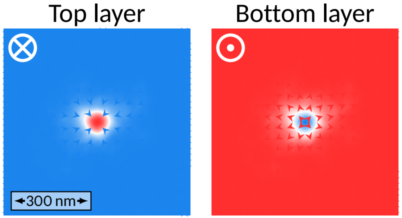
Skyrmions stabilized by a bias layer

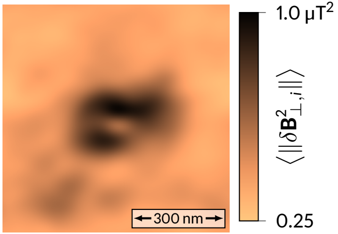


W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34





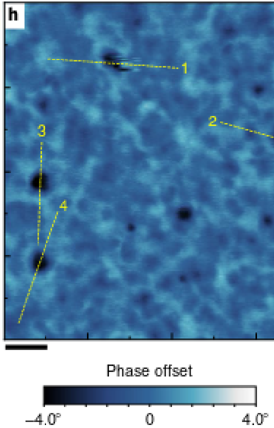




We are not probing the internal modes but the scattering of spin waves on the skyrmions

Are these really skyrmions?

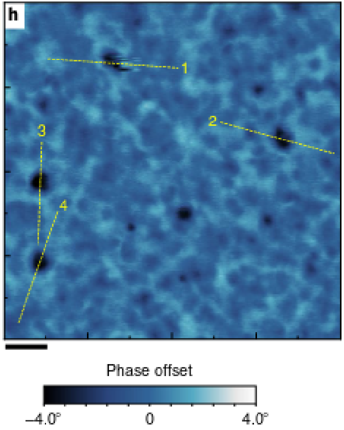
MFM under oop field 110 mT



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

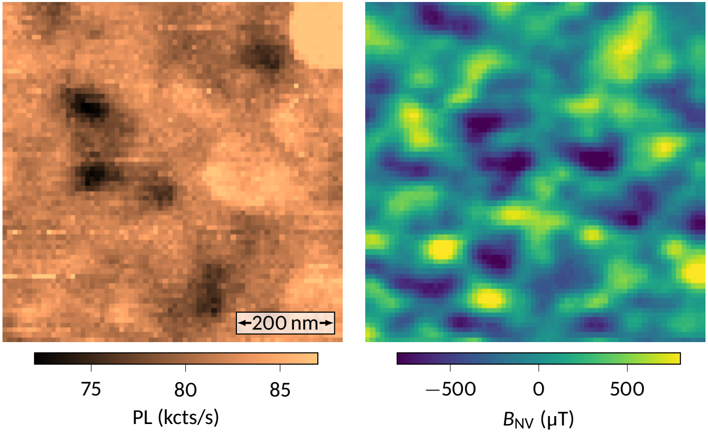
Are these really skyrmions?

MFM under oop field 110 mT



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

NV images (zero field)

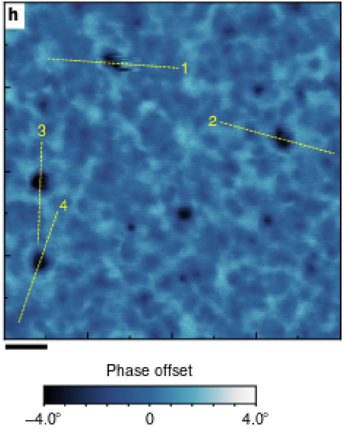


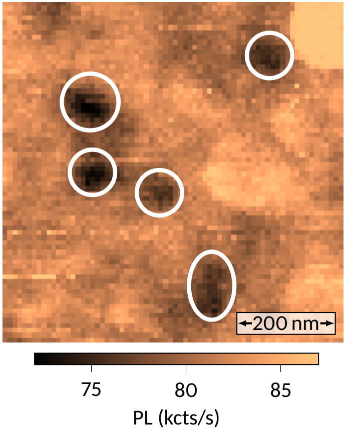
Large background fluctuations (roughness of the film)

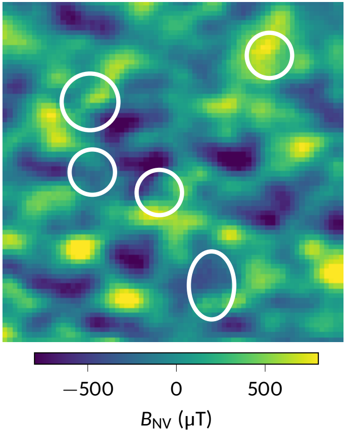
Are these really skyrmions?

MFM under oop field 110 mT

NV images (zero field)





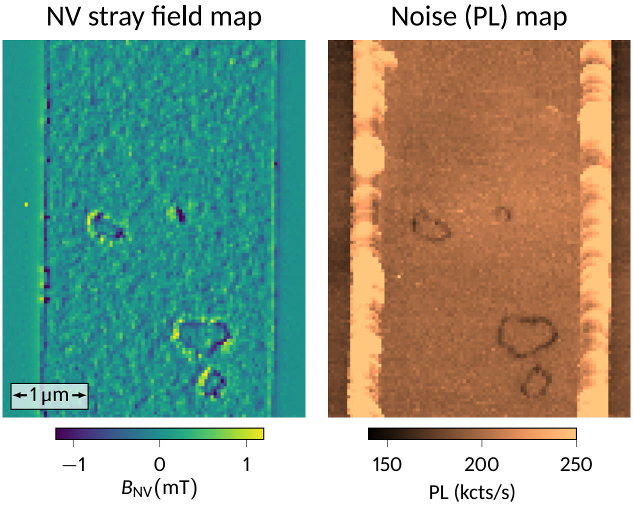


W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34

Large background fluctuations (roughness of the film)

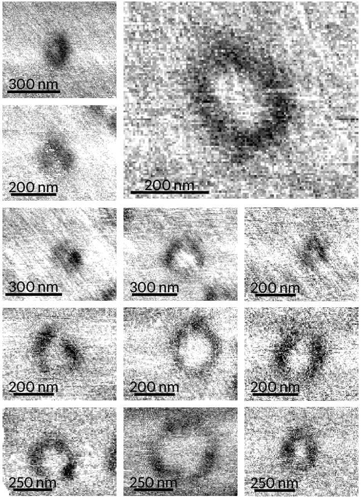
Other samples without bias layer

Collaboration: Spintec, Grenoble (V.-T. Pham, J. Urrestarazu, O. Boulle)

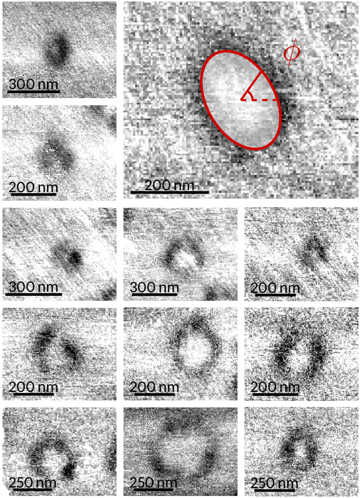


- Oop field of about 150 mT applied for nucleation
- Less background fluctuations

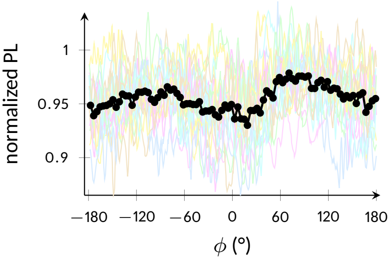
Statistics on Néel left skyrmions



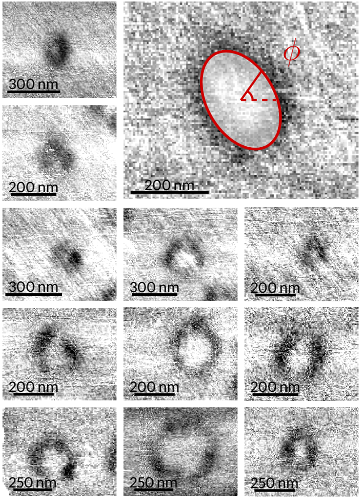
Statistics on Néel left skyrmions



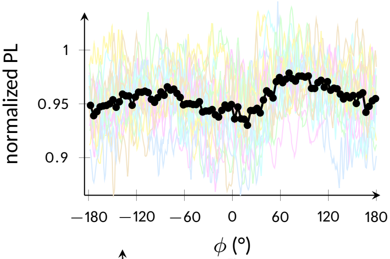
Angular variation of PL

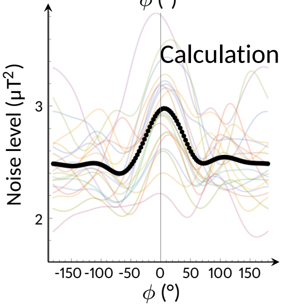


Statistics on Néel left skyrmions



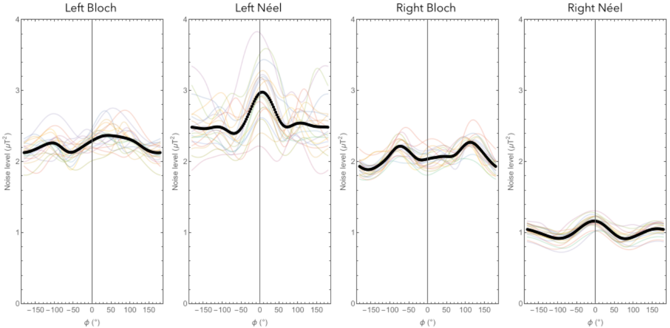
Angular variation of PL



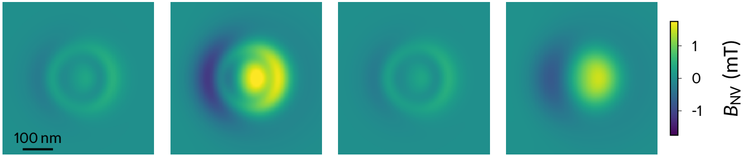


Expected pattern on other skyrmion types

Simulated noise distribution along the contour

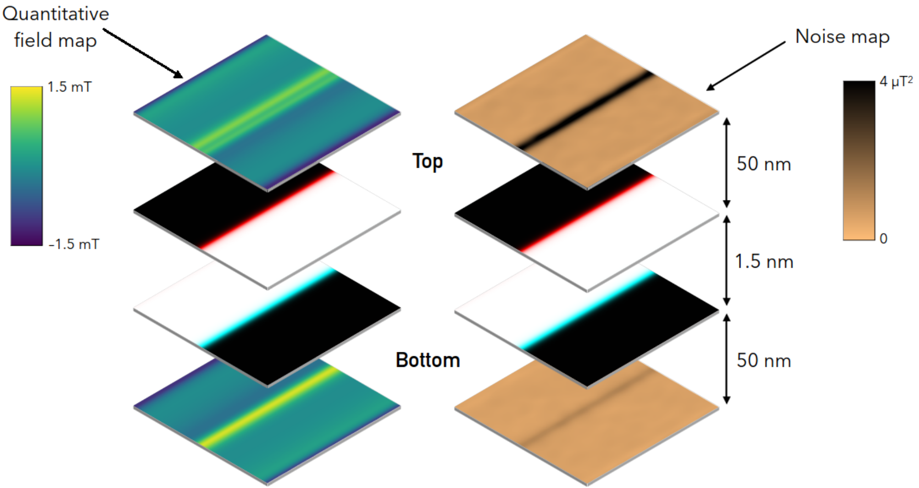


Simulated stray field maps



Expected noise level for each domain wall chirality

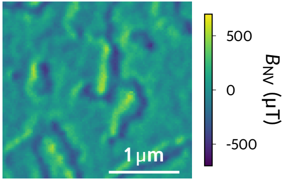
Calculation: C2N, Palaiseau (J.-V. Kim)



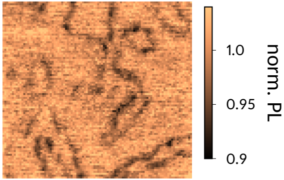
Experiment: looking at both sides of the film

Initial stack: Néel left

Magnetic field map



Noise map



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

Samples: J. Urrestarazu, Spintec, Grenoble

Experiment: looking at both sides of the film

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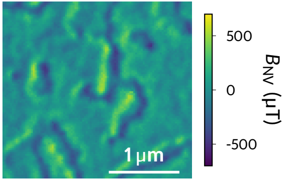
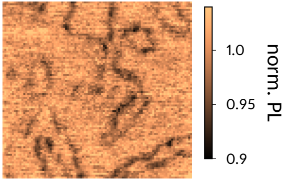
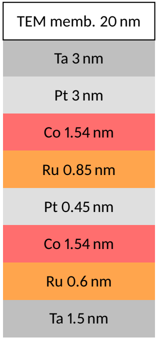
Magnetic field map



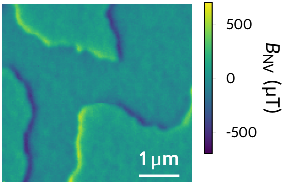
Noise map



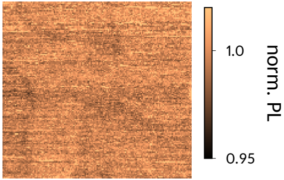
Inverted stack: Néel right



Magnetic field map



Noise map



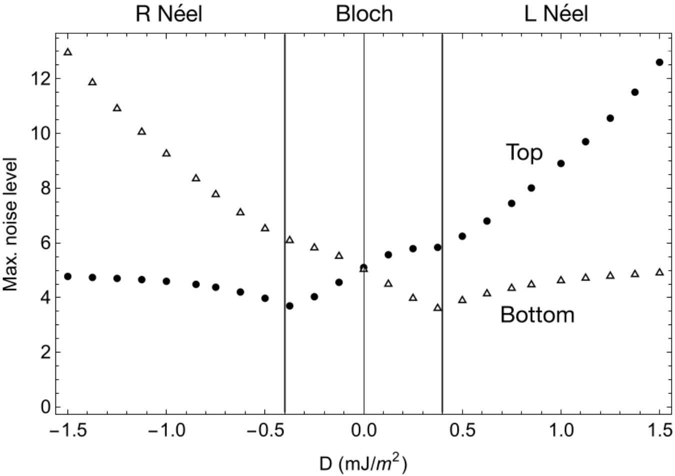
A. Finco *et al.* *in preparation* (2024)

Samples: J. Urrestarazu, Spintec, Grenoble

A DMI-related effect

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

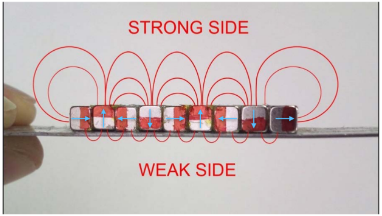
Calculation made for a **single** ferromagnetic layer

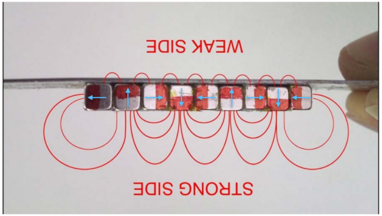


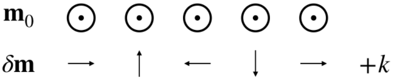
Spin waves are like fridge magnets!

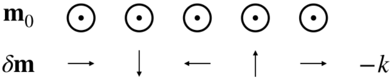
©*Thibaut Devolder, C2N, Palaiseau*

… and the DMI is selecting a propagation direction!





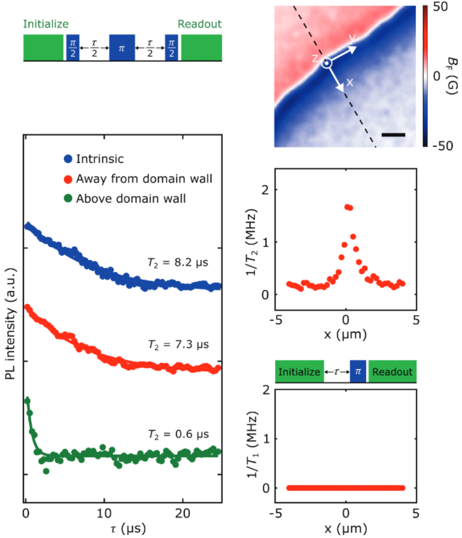




J. Mallinson. *IEEE Trans. on Mag.* 9 (1973), 678

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

Decrease of T_2 at ferromagnetic domain walls



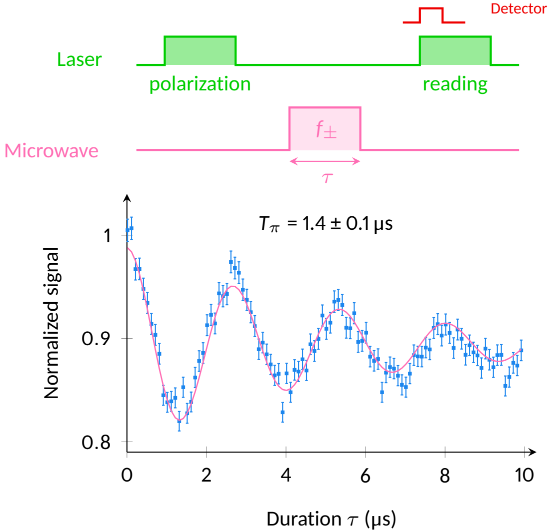
- Co/Ni/Co/Ni ferromagnetic layer
- Coherence time T_2 of the NV center decreased above the domain wall
- Here T_1 is not modified!
- Effect attributed to the gapless magnetic excitation of the wall

N. J. McLaughlin *et al.* *ACS Nano* 17 (2023), 25689

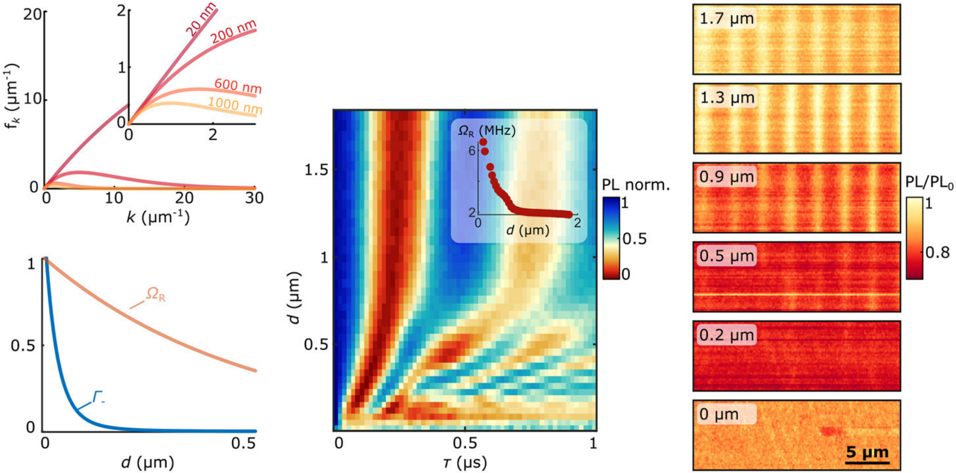
Outline

1. The NV center in diamond as a quantum sensor
2. Dismantling the scanning NV microscope
3. Quantitative ODMR experiments
    - Principle of the measurement
    - The need for a proper calibration
    - Example 1: analyzing domain walls
    - Example 2: the spin cycloid in bismuth ferrite
    - Example 3: van der Waals magnets
4. Taking a step back: PL quenching effects
    - Strong off-axis magnetic fields
    - Magnetic noise!
5. Relaxometry: sensing via the relaxation time
6. **Coherent control of the NV center using spin waves**
7. Going further: other sensors and sensing methods

Measurement of a Rabi oscillation



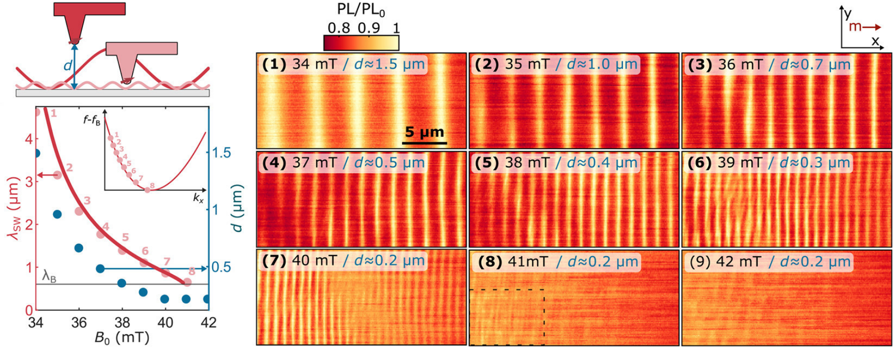
Rabi oscillation driven by a spin wave



B. G. Simon *et al.* *Nano Letters* 22 (2022), 9198

Wavelength filter with d_{NV}

- Spin waves excited in YIG with a microwave stripline
- The wavelength of the spin wave at $f_{\pm}$ is tuned with magnetic field
- The flying distance d_{NV} is optimized to observe it in the ODMR contrast map



B. G. Simon *et al.* *Nano Letters* 22 (2022), 9198

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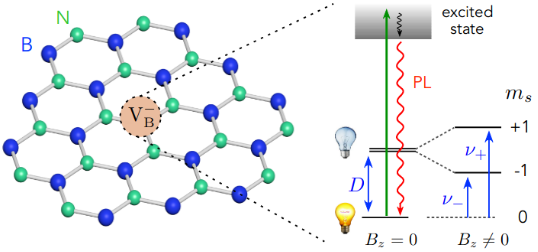
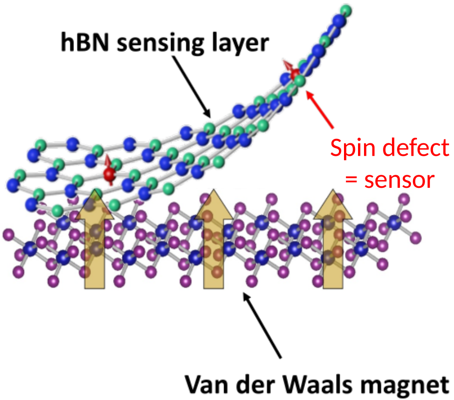
Boron vacancies in h-BN

Optically-active spin defect in h-BN found in 2020

A. Gottscholl *et al.* *Nat. Mater.* 19 (2020), 540

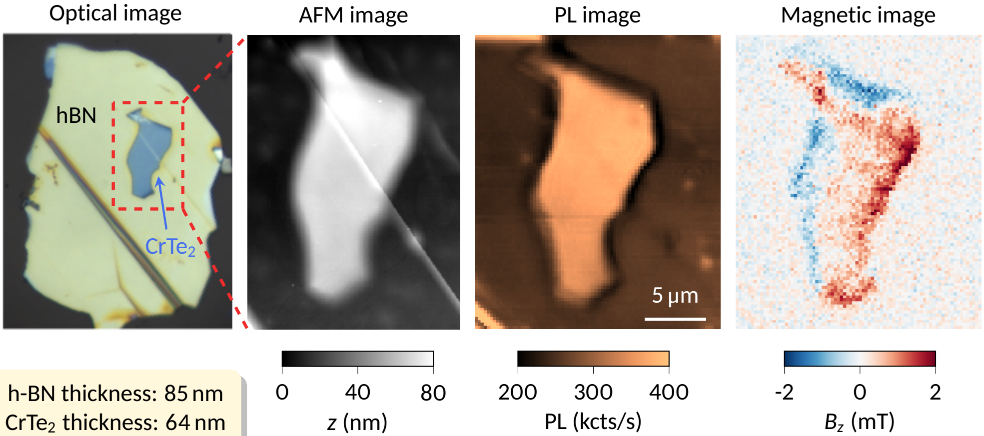


P. Kumar *et al.* *Phys. Rev. Appl.* 18 (2022), L061002



Imaging with boron vacancies

Collaboration: Institut Néel, Grenoble and LPCNO, Toulouse

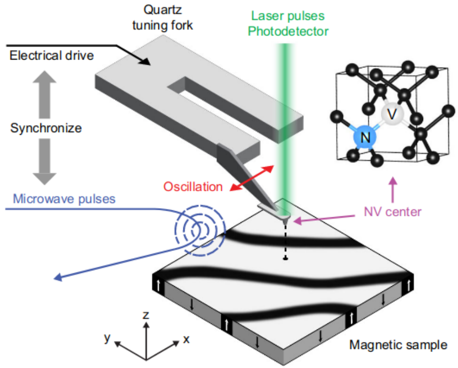


h-BN thickness: 85 nm
$CrTe_2$ thickness: 64 nm

P. Kumar *et al.* *Phys. Rev. Appl.* 18 (2022), L061002
M. Huang *et al.* *Nat. Commun.* 13 (2022), 5369
A. J. Healey *et al.* *Nat. Phys.* 19 (2023), 87

Advanced mode: gradiometry

Use a spin echo sequence to improve the magnetic sensitivity



W. S. Huxter *et al.* Nat. Commun. 13 (2022), 3761

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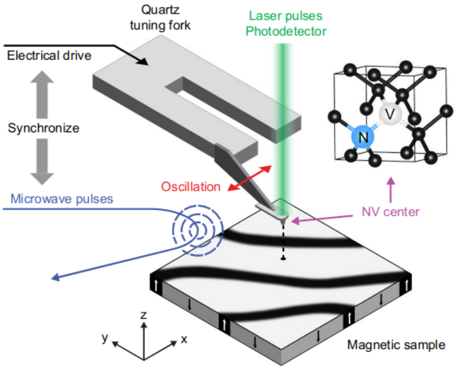
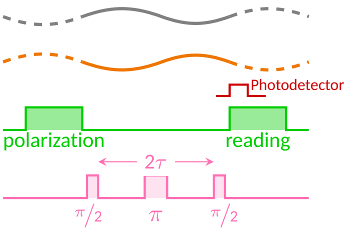
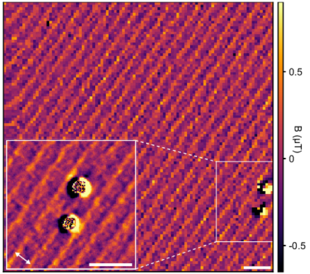






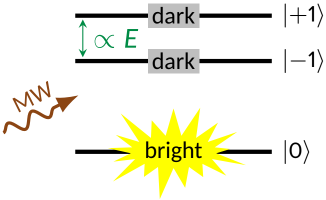
Stray field from atomic steps visible in the A-type antiferromagnet Cr_2O_3

W. S. Huxter *et al.* *Nat. Commun.* 13 (2022), 3761

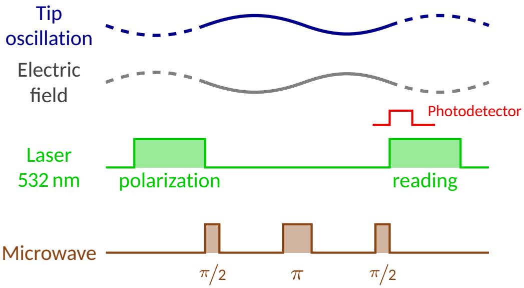
Electric field sensing

To investigate ferroelectrics!

Stark shift



- Need to apply off-axis field to avoid that Zeeman effect dominates
- Electric susceptibilities rather small
  → spin echo sequences



W. S. Huxter *et al.* *Nat. Phys.* 19 (2023), 644

Z. Qiu *et al.* *npj Quantum Info.* 8 (2022), 107

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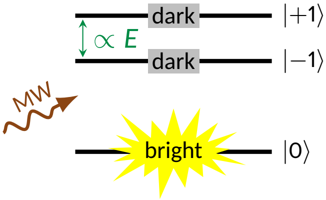
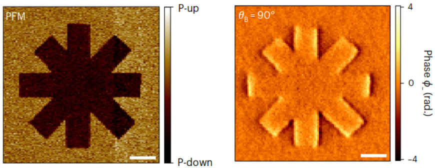


$Pb[Zr_{0.2}Ti_{0.8}]O_3$



W. S. Huxter *et al.* *Nat. Phys.* 19 (2023), 644

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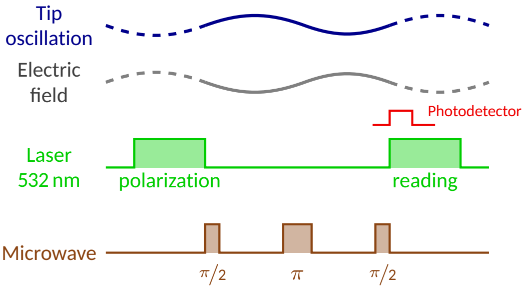
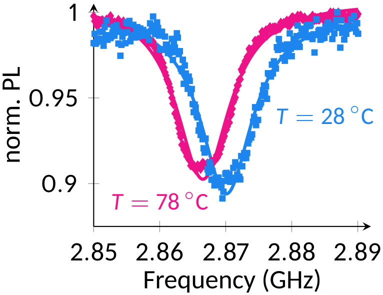


Z. Qiu *et al.* *npj Quantum Info.* 8 (2022), 107

Temperature sensing

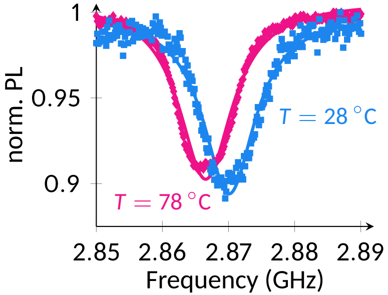
Crystal dilatation ➔ Shift of the zero-field splitting



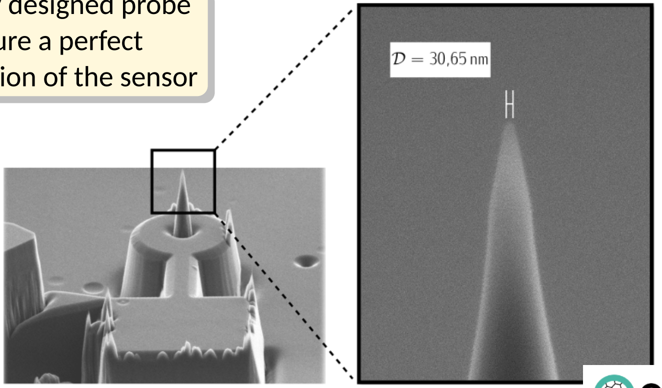
Temperature sensing

Crystal dilatation ➔ Shift of the zero-field splitting

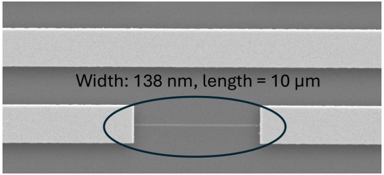
Specifically designed probe to ensure a perfect thermalization of the sensor



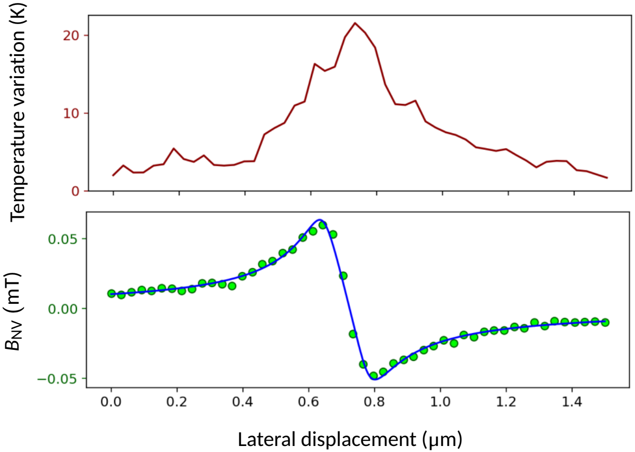
Sensitivity $\sim 1\,\mathrm{K}/\sqrt{\mathrm{Hz}}$



First results on thermometry



Nanowire of doped Si from CEA Grenoble
$I = 60\,\mu A$



E. Sfeir *et al.* *in preparation* (2024)

A versatile microscope to probe condensed matter

Magnetic field

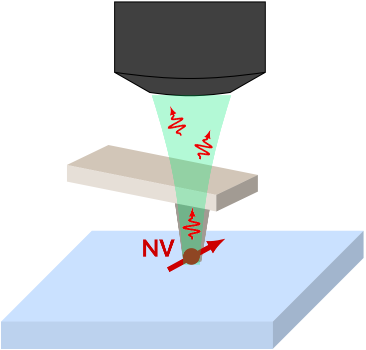
(Anti)ferromagnetic textures

Currents

Magnetic noise

Spin waves

Conductivity



Electric field

Ferroelectric textures

Temperature

Localized hot spots

Interested in NV microscopy?
Join us!

https://solidstatequantumtech-l2c.fr/