Mapping nanomagnetism (mostly with scanning NV center microscopy)

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CarMaSchool, July 7th 2026, Autrans

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

Outline

1. A brief introduction to nanomagnetism
2. Routes for imaging nanoscale magnetic textures
3. The NV center in diamond as a magnetic field sensor
4. Scanning NV center microscopy
5. How to obtain quantitative information from the data?
6. What about the dynamics?
7. What to remember

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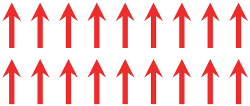
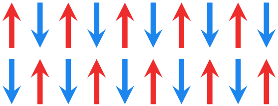
Ordered magnetic materials

Ferromagnet

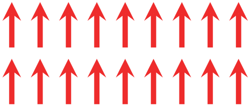


Antiferromagnet



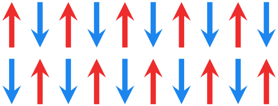
Ordered magnetic materials

Ferromagnet



$J < 0$

Antiferromagnet



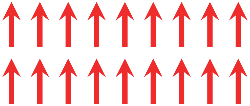
$J > 0$

Exchange interaction

$$\mathcal{H} = J \; \vec{S}_i \cdot \vec{S}_j$$

Ordered magnetic materials

Ferromagnet



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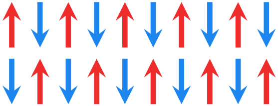

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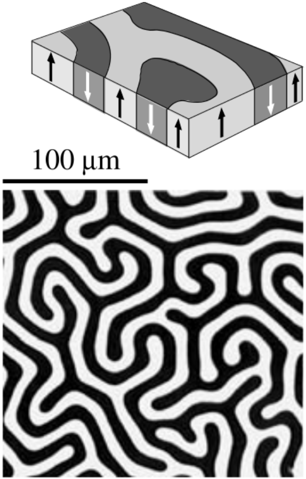
Exchange interaction

$$\mathcal{H} = J\ \vec{S}_i \cdot \vec{S}_j$$

→ Not nano yet!

Formation of magnetic domains

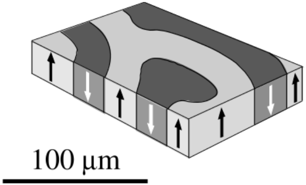


A. Hubert and R. Schäfer. Springer, 1998

Shape anisotropy (dipolar interaction)

- Formation of flux closure patterns
- Creating domain walls costs some exchange energy
- **The magnetic state is fixed by the competition between the different contributions**

Formation of magnetic domains



A. Hubert and R. Schäfer. Springer, 1998

Shape anisotropy (dipolar interaction)

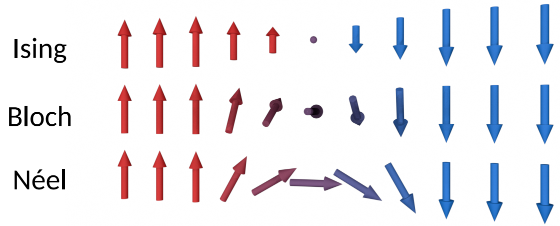
- Formation of flux closure patterns
- Creating domain walls costs some exchange energy
- **The magnetic state is fixed by the competition between the different contributions**

Crystalline anisotropy

- Constrains the direction of the magnetization
- Adds some cost to the formation of domain walls
- Large anisotropy ➔ large domains

Magnetic domain walls

Internal texture



S. Parkin and S.-H. Yang. *Nat. Nano.* 10 (2015), 195

Magnetic domain walls

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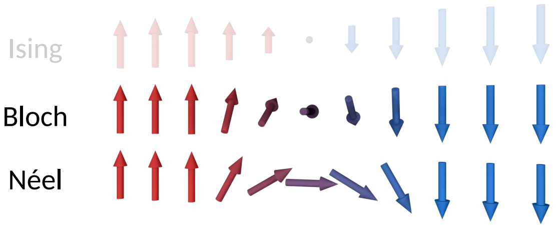

The norm of $\vec{m}$ stays constant!

The way $\vec{m}$ rotates gives information about the magnetic interactions.

S. Parkin and S.-H. Yang. *Nat. Nano.* 10 (2015), 195

Magnetic domain walls

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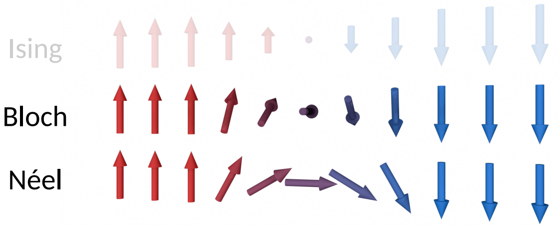

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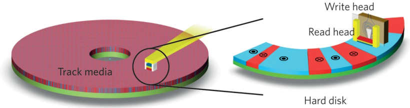
Proposed application Racetrack memory



S. Parkin and S.-H. Yang. *Nat. Nano.* 10 (2015), 195

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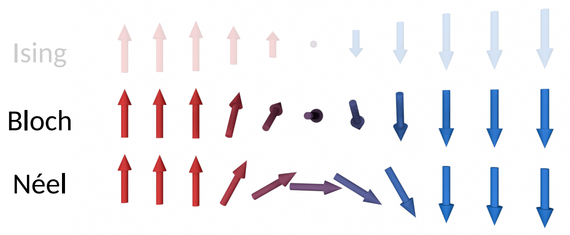

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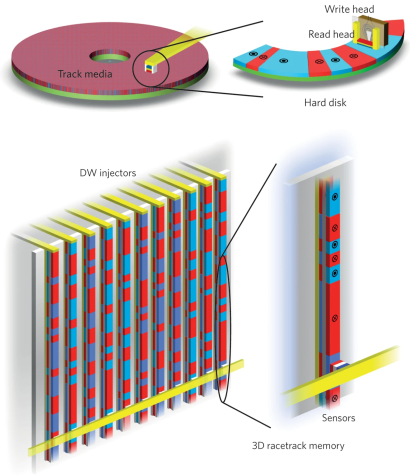
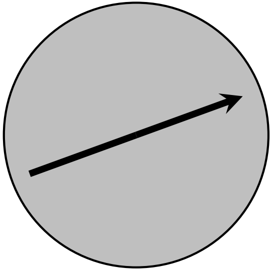
Proposed application
Racetrack memory



S. Parkin and S.-H. Yang. *Nat. Nano.* 10 (2015), 195

Low anisotropy + confinement = vortex

In-plane magnetized disk
no in-plane anisotropy



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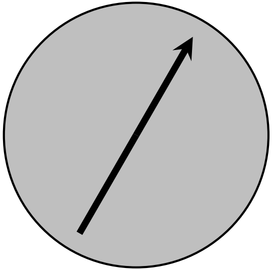

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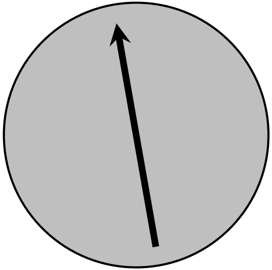

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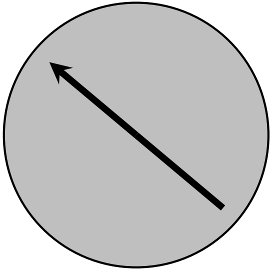

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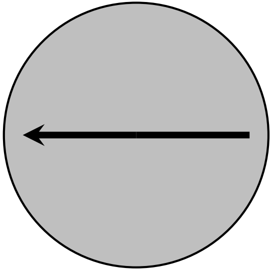

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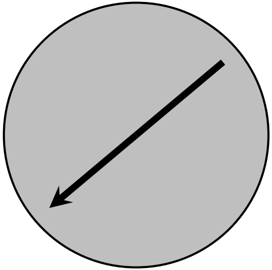

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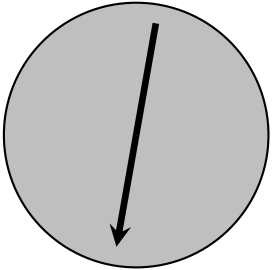

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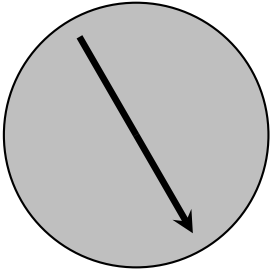

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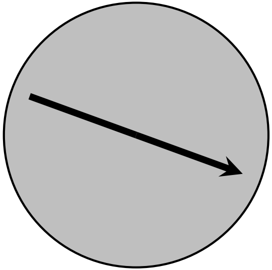

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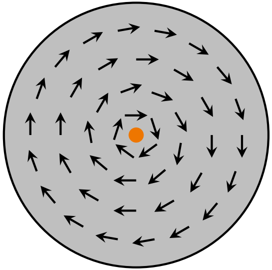

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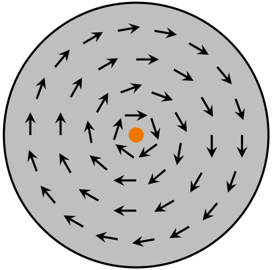
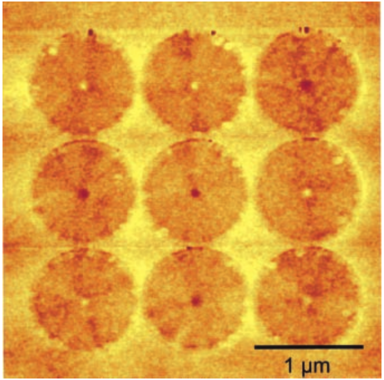


Magnetic vortex

MFM image



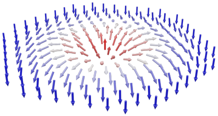
T. Shinjo *et al.* *Science* 289 (2000), 930

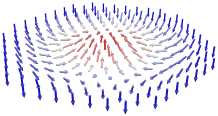
DMI + magnetic field = skyrmions

Dzyaloshinkii-Moriya interaction

$$\mathcal{H}_{\mathrm{DM}} = \vec{D} \cdot (\vec{S}_i \times \vec{S}_j)$$

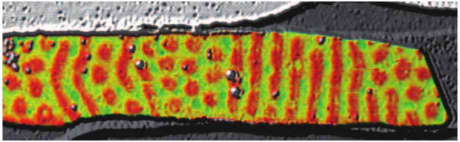
Favors a rotation of the magnetic moments
Requires inversion symmetry breaking





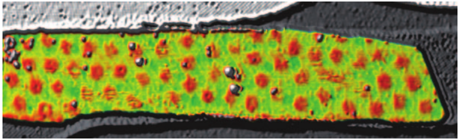
SP-STM images
PdFe/Ir(111)

$B_z = 1\,\mathrm{T}$



$B_z = 1.4\,\mathrm{T}$

25 nm



N. Romming *et al.* *Science* 341 (2013), 636

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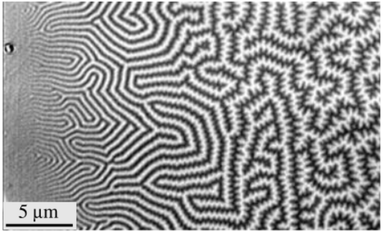
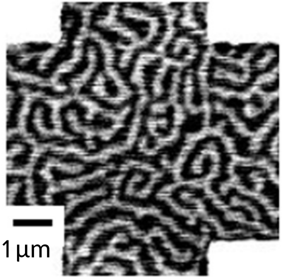
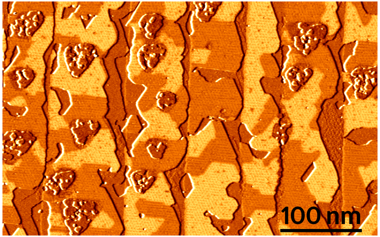
Mapping the magnetization

Probe the direction of the magnetization, which is often what we are interested in anyway ➔ MOKE, XMCD, SP-STM, …







A. Hubert and R. Schäfer. Springer, 1998

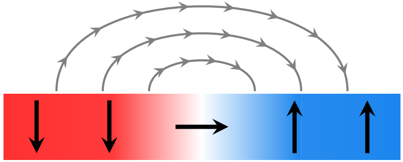
T.-E. Park *et al.* *PRB* 103 (2021), 104410

A. Finco *et al.* *PRB* 98 (2018), 174435

Limitation: usually does not give the amplitude of the magnetization

Mapping the stray field

Probe the magnetic stray field which is produced by the magnetization
➔ MFM, NV magnetometry, …



- Requires to work on the inverse problem $\vec{B} \rightarrow \vec{M}$
- MFM probe the **magnetostatic force** between the magnetized tip and the sample
- NV magnetometry measures the **stray field** at the position of the tip

Sources of magnetic field

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

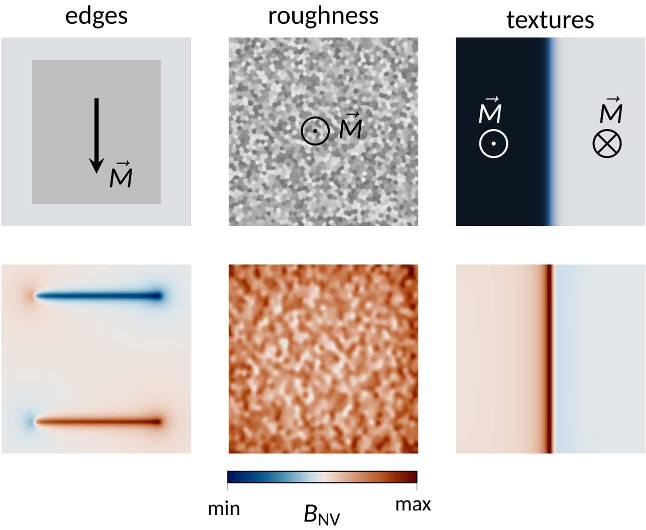
where ϕ is a scalar potential which verifies the Poisson equation:

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

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



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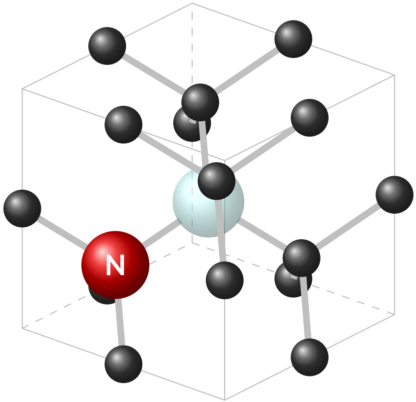
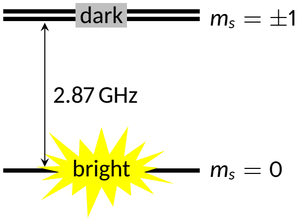
Our sensor: the NV center in diamond



- High magnetic field sensitivity
- Non perturbative sensor
- Quantitative measurements
- Operates from 4 K to 300 K
- Versatility ($\vec{B}$, $\vec{E}$, T, P)
- Nanoscale spatial resolution

Optically detected magnetic resonance

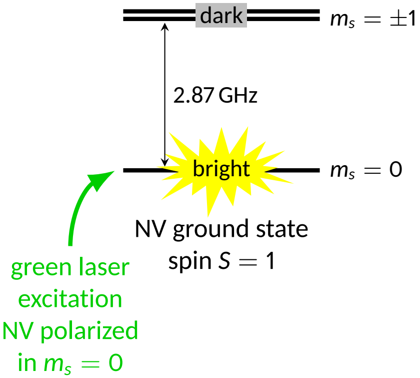
Spin-dependent fluorescence



NV ground state
spin $S = 1$

Optically detected magnetic resonance

Spin-dependent fluorescence



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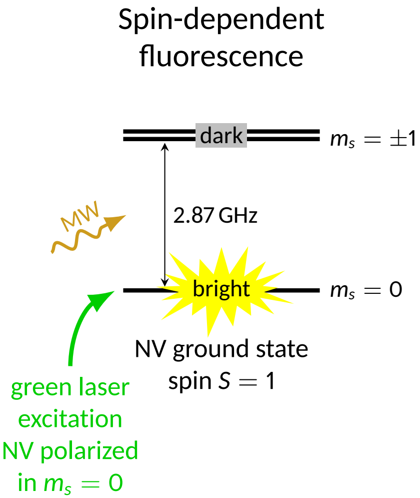

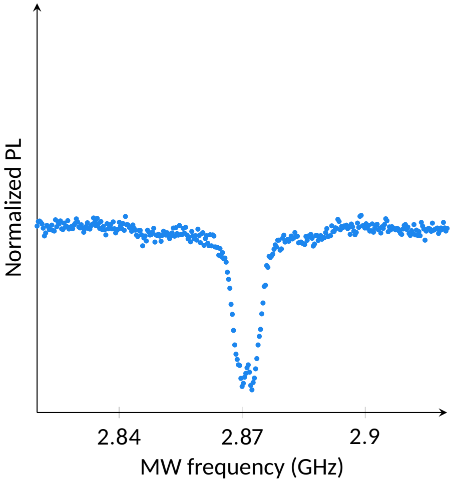

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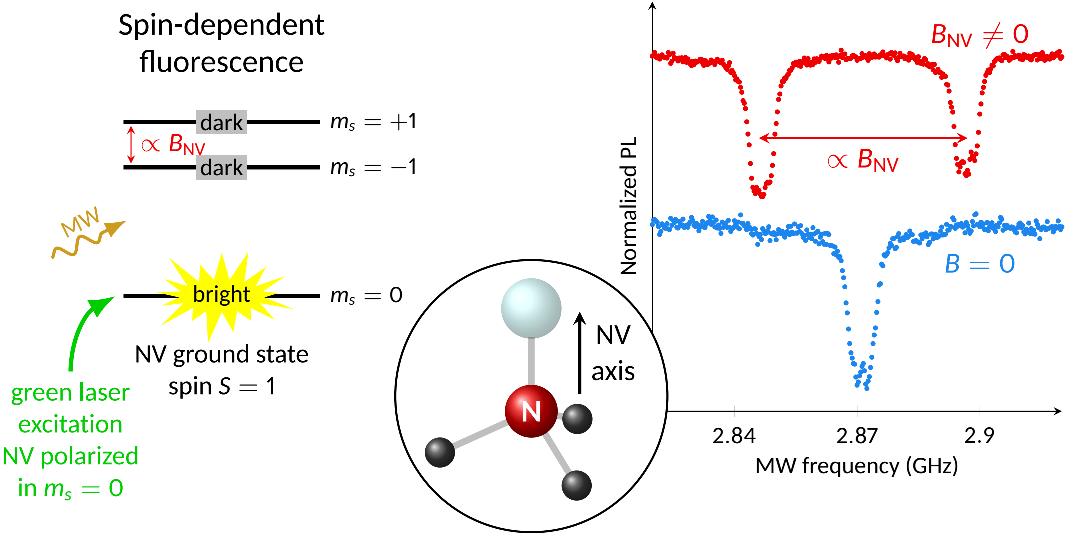
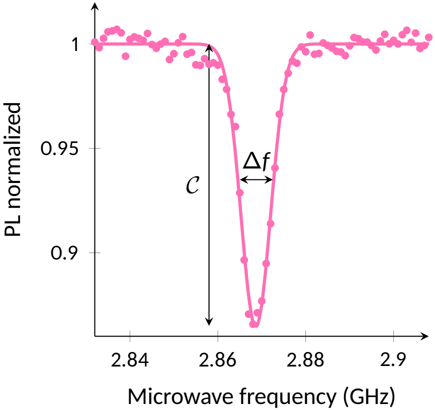


Sensitivity to magnetic field



$$\eta_B = \frac{4}{3\sqrt{3}\,\gamma_{\mathrm{NV}}} \frac{\Delta f}{\mathcal{C}\sqrt{\mathcal{R}}} \simeq 2 - 10\,\mu\mathrm{T}/\sqrt{\mathrm{Hz}}$$

- Linewidth Δf: increase with P_{MW}
- Contrast $\mathcal{C}$: decrease with P_{laser} and increase with P_{MW}
- Off-resonance count rate $\mathcal{R}$: increase with P_{laser}

A. Dréau *et al.* *PRB* 84 (2011), 195204

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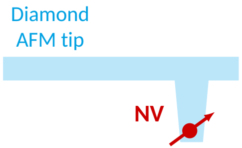

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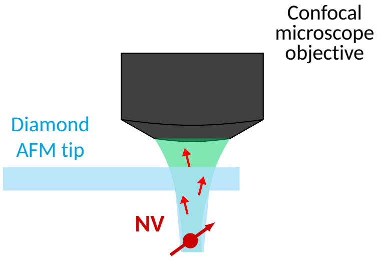

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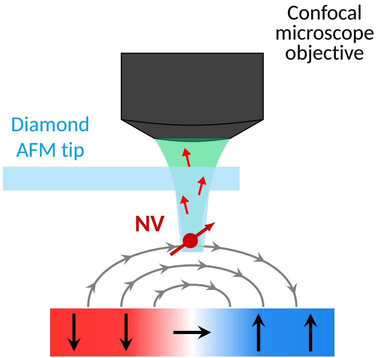

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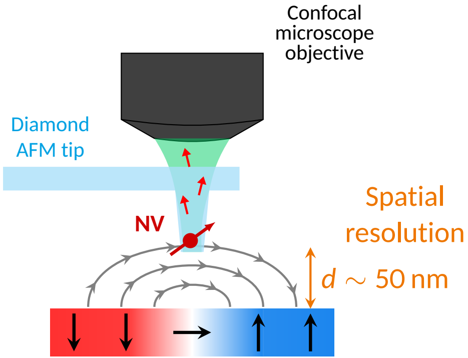

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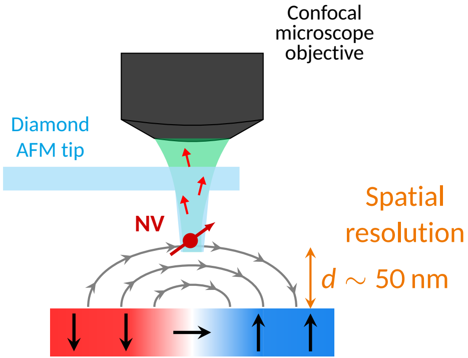
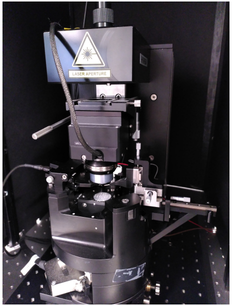


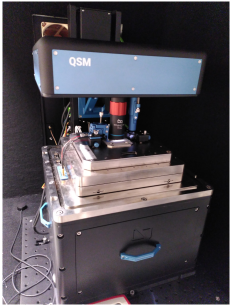
Examples of commercial setups

ProteusQ
Qnami



Room temperature
Easy to use, good AFM

QSM
Qzabre



Room temperature
80 mT vectorial $\vec{B}$ field

The diamond probes

All-diamond probes developed in 2012, constantly improved since

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

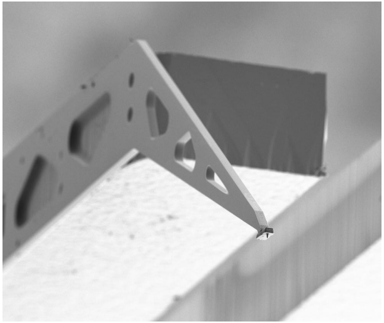


Image from www.qzabre.com

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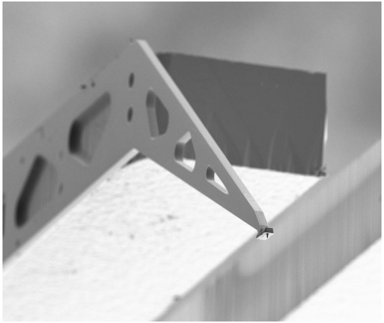

Image from www.qzabre.com

- High-purity diamond
- Hosting single NV centers at 50-100 nm from the sample surface
- Usually made from (001) diamond
- Diamond pillar as guide for the emitted light

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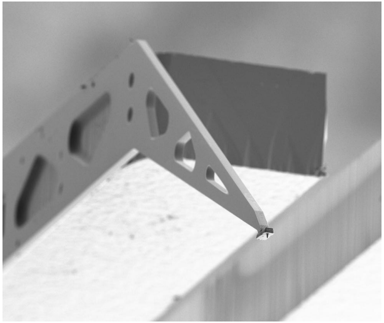

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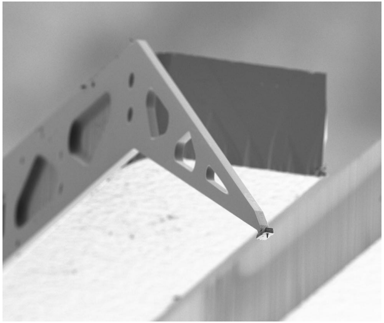

Image from www.qzabre.com

- High-purity diamond
  → Good quantum coherence properties
- Hosting single NV centers at 50-100 nm from the sample surface
  → Spatial resolution of the microscope
- Usually made from (001) diamond
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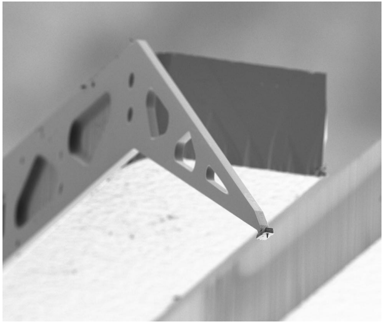
P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320–324



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- 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

The diamond probes

All-diamond probes developed in 2012, constantly improved since

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

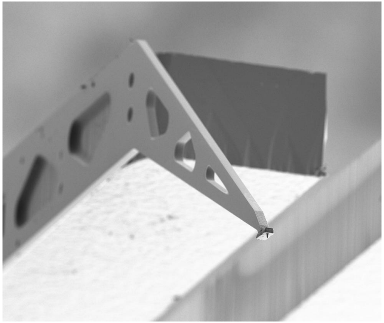

Image from www.qzabre.com

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- Hosting single NV centers at 50-100 nm from the sample surface
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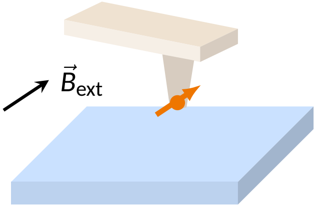
- Diamond pillar as guide for the emitted light
  → Optimized signal collection

Experimental conditions

Typical setup
300 K, in air
with $\vec{B}_{\text{ext}} \parallel$ NV axis



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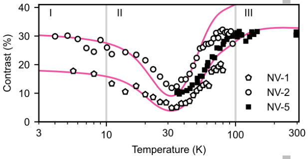

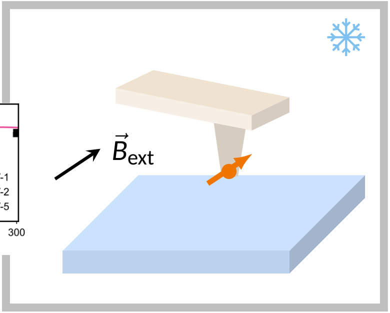

In a cryostat

→ Reduced performance (lower PL and contrast)

J. Happacher *et al.* *PRL* 131 (2023), 086904 , S. Ernst *et al.* *PRL* 131 (2023), 086903

→ Charge instability at low T and UHV

J. N. Neethirajan *et al.* *Nano Lett.* 23 (2023), 2563–2569

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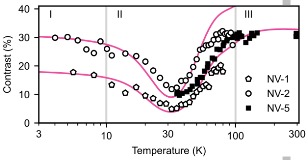

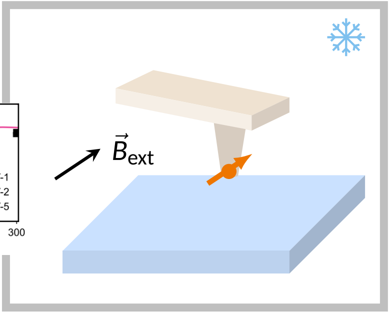

4 K

📄 M. Pelliccione *et al.* *Nat. Nano.* 11 (2016), 700

4 K and UHV

📄 E. Schaefer-Nolte *et al.* *RSI* 85 (2014), 013701

350 mK

📄 P. J. Scheidegger *et al.* *APL* 120 (2022), 224001

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📄 J. Happacher *et al.* *PRL* 131 (2023), 086904 , 📄 S. Ernst *et al.* *PRL* 131 (2023), 086903

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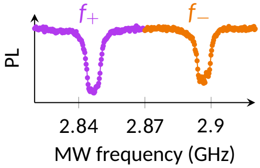
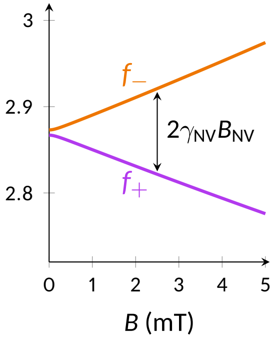
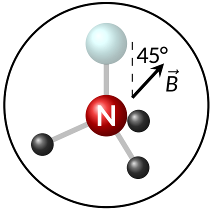
The different measurement regimes



Linear regime





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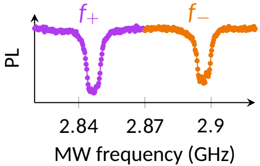
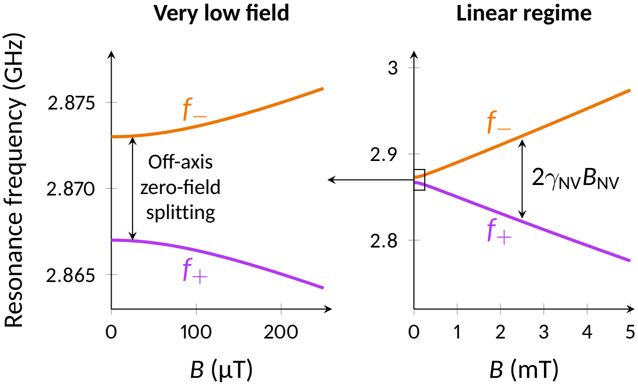
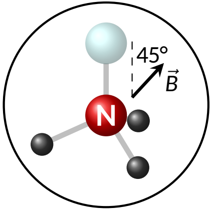


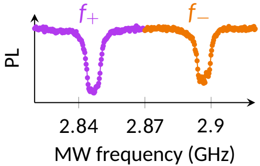


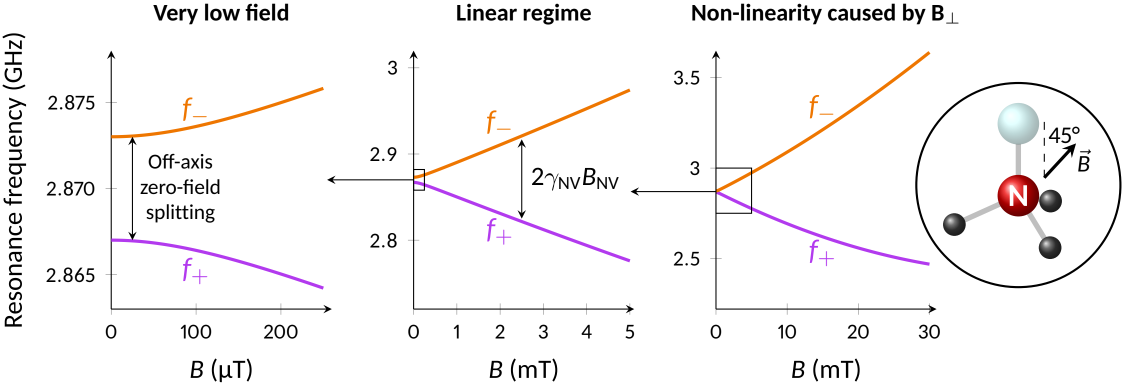


Related to internal
electric field in the diamond

T. Mittiga *et al.* *PRL* 121 (2018), 246402

The different measurement regimes





Related to internal
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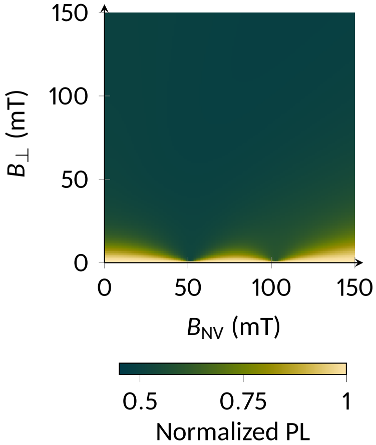
T. Mittiga *et al.* *PRL* 121 (2018), 246402

Mixing of the spin states

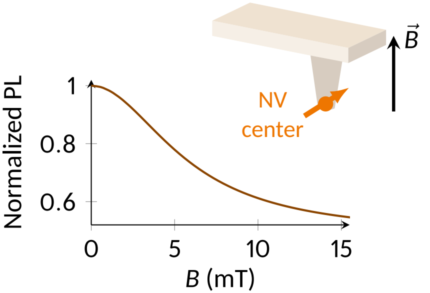
J.-P. Tetienne *et al.* *New J. Phys.* 14 (2012), 103033

Strong field regime, photoluminescence extinction



A strong $B_\perp$ mixes the bright and the dark states

The photoluminescence can drop from 40%



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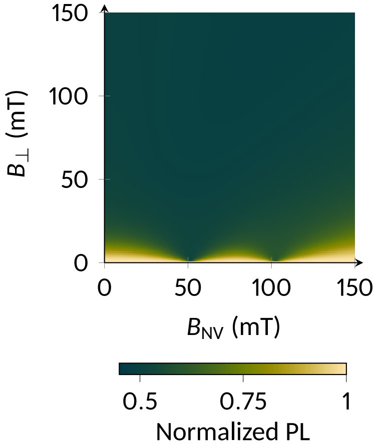

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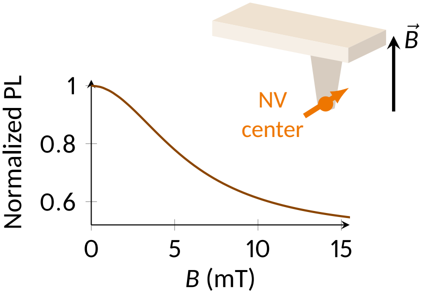
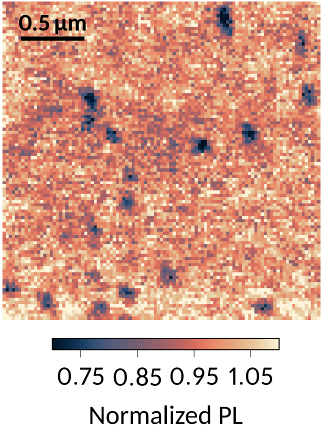


J.-P. Tetienne *et al.* *New J. Phys.* 14 (2012), 103033

→ Qualitative imaging mode for thick ferromagnets!

Example: skyrmions!

NiFe/Co bilayer



- Localization of skyrmions
- Upper boundary on their size
- ~~Determination of their internal structure~~

This method is purely qualitative.

The PL variation often does not come only from the stray field, and we cannot disentangle the different effects.

K. G. Rana *et al.* *PRAppl.* 13 (2020), 044079

Linear regime, quantitative mode

1. Apply a small field (few mT range), if possible along the NV axis
2. Measure a reference ODMR spectrum
3. Bring the diamond tip close to the sample, and measure an ODMR at each pixel
4. Extract the field map from the 3D dataset and the reference spectrum
5. It often takes a few hours . . .

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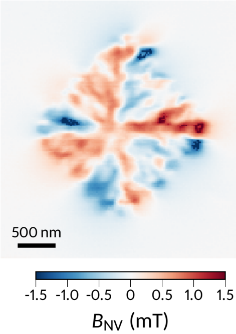
Example
Magnetic vortices in Fe_5GeTe_2

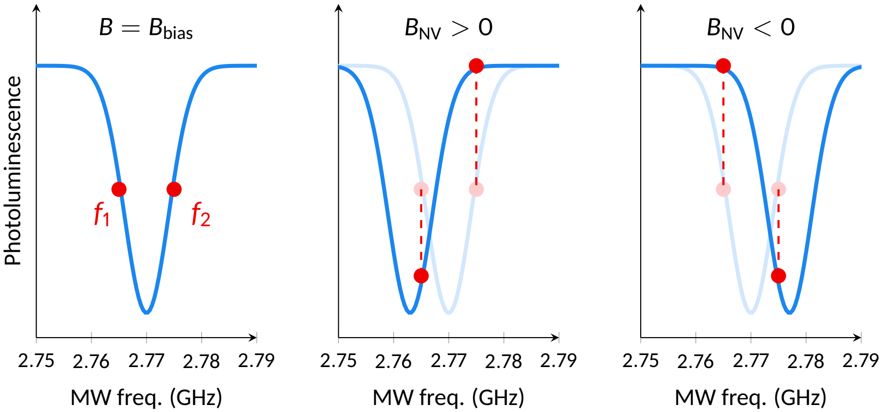


E. Sfeir *et al.* *PRMaterials* 9 (2025), 114003

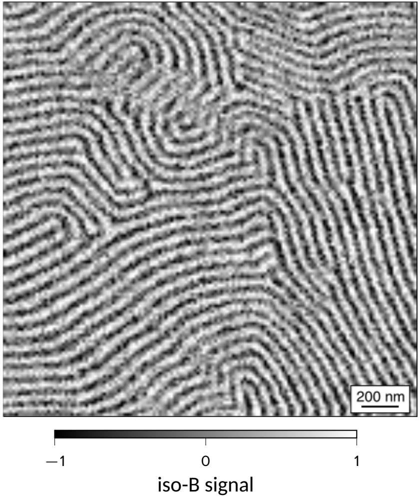
Linear regime, iso-B mode

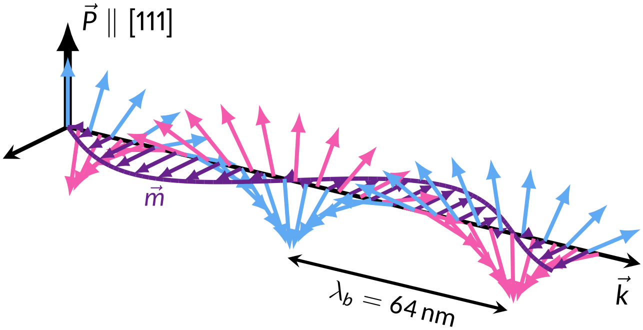
Quick and qualitative mode for samples producing low field

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



Antiferromagnetic topological defects in iso-B





Spin density wave
Weak uncompensated moment
→ **Small stray field**

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

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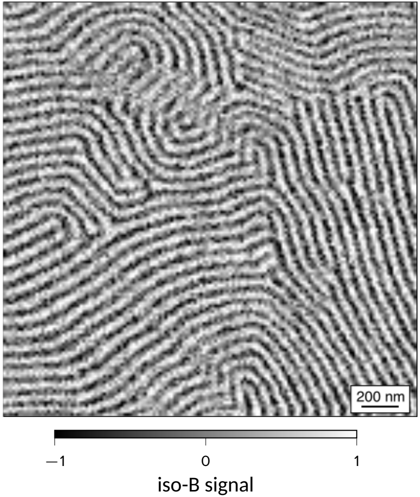
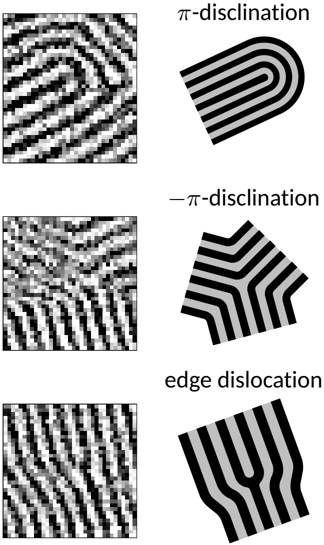




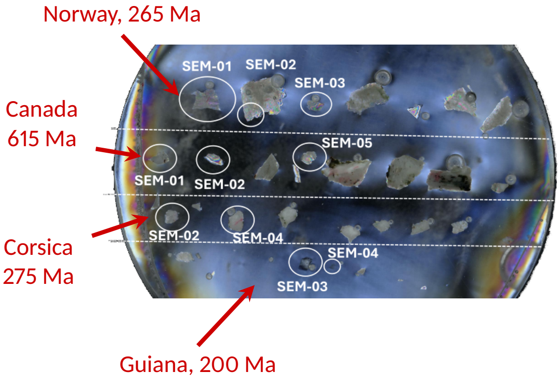
A. Finco *et al.* *PRL* 128 (2022), 187201

Iso-B for paleomagnetism

- Study the history of the earth's magnetic field (intensity, reversals, etc.)
- Volcanic rocks with "fast" cool down
  ➔ Info about the earth's field is imprinted in the magnetic minerals embedded in the rock

Paul Antonio

Géosciences Montpellier



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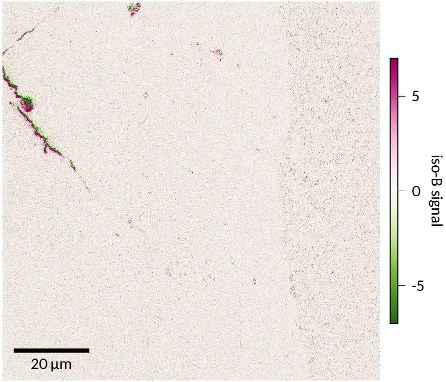
Corsica sample



Léa Houzelle
Carolin Schrader

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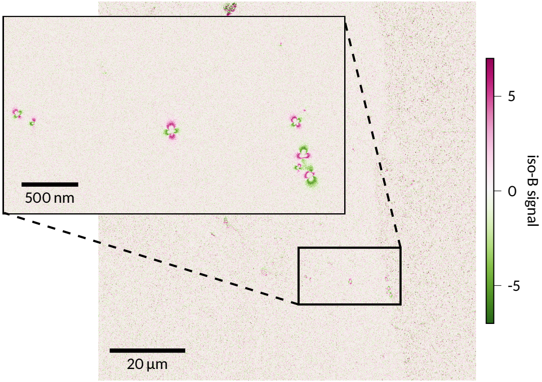

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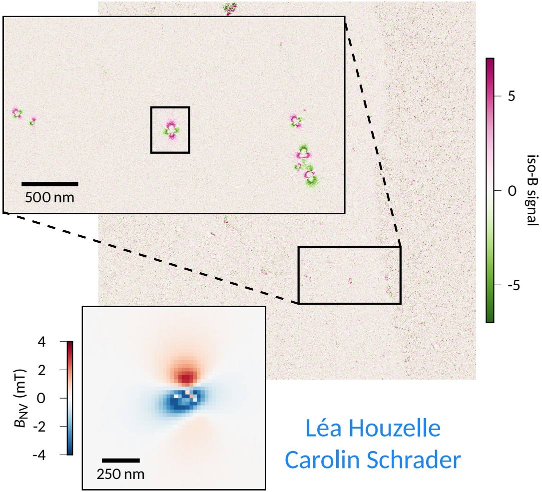


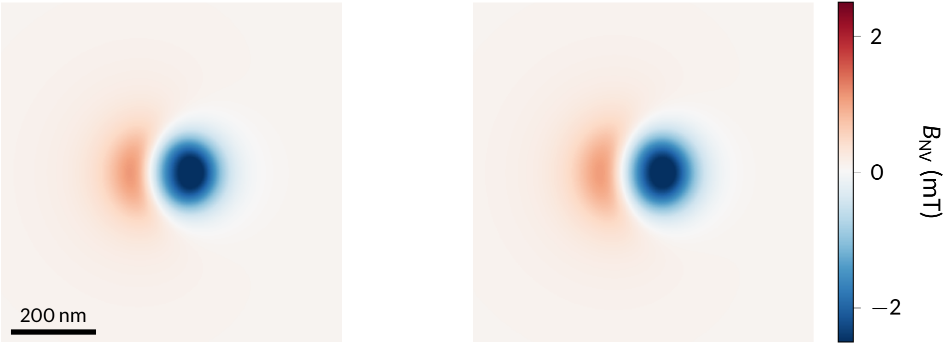
Léa Houzelle
Carolin Schrader

Outline

1. A brief introduction to nanomagnetism
2. Routes for imaging nanoscale magnetic textures
3. The NV center in diamond as a magnetic field sensor
4. Scanning NV center microscopy
5. How to obtain quantitative information from the data?
6. What about the dynamics?
7. What to remember

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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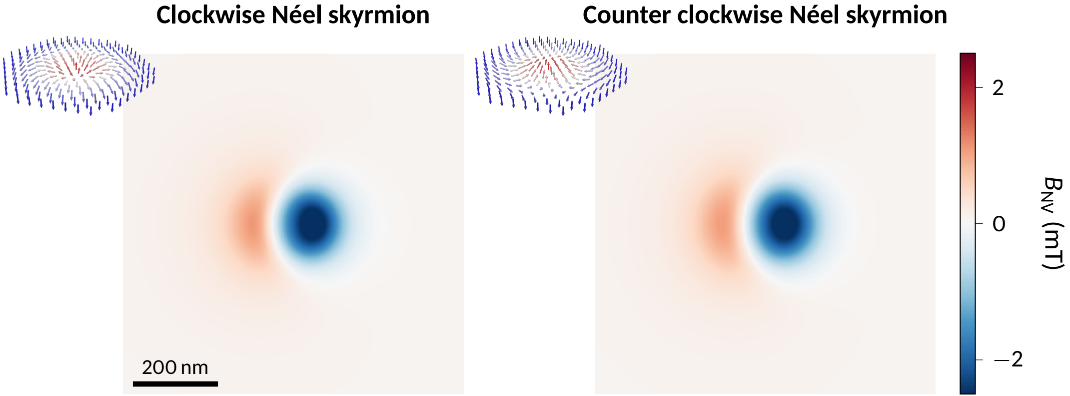
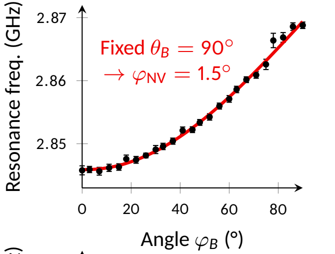


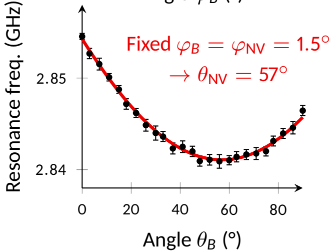
NV height: $d_{NV} = 50$ nm
DW width: $w = 15$ nm

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

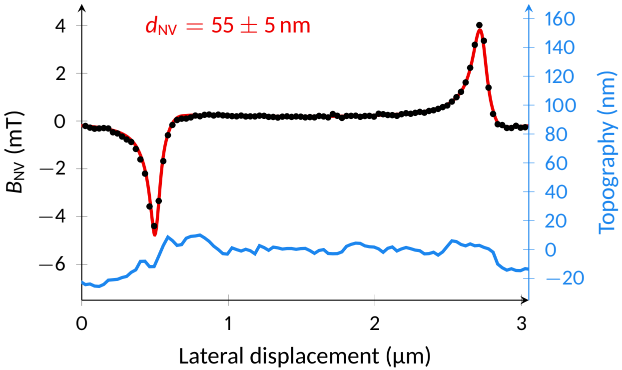
The calibration procedure

1. Find the NV axis orientation





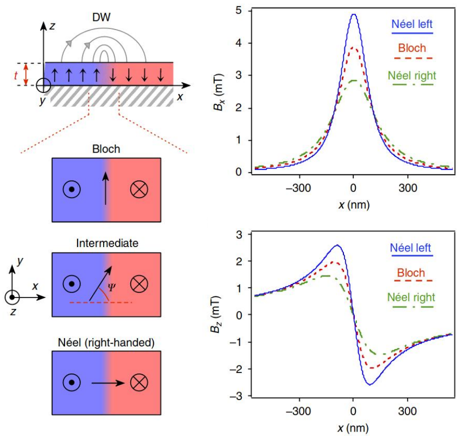
2. Find the NV height d_{NV} with a well-known ferromagnetic stripe



T. Hingant *et al.* *PRAppl.* 4 (2015), 014003

Comparing with a model: domain walls

Analytical expression of the stray field



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

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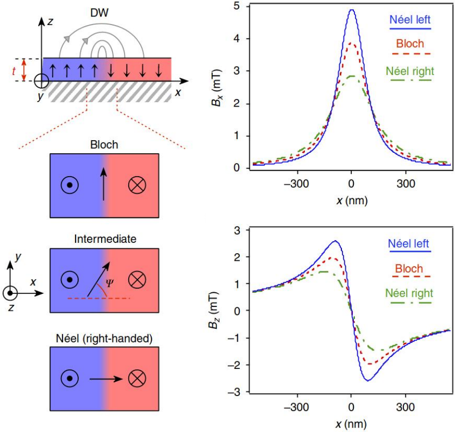
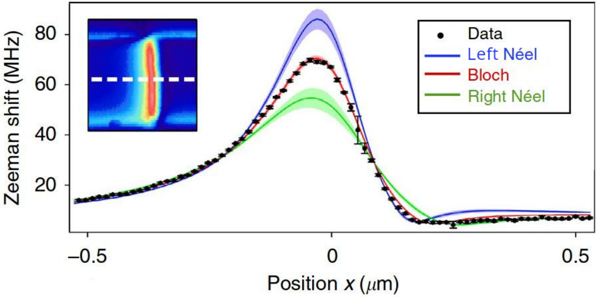


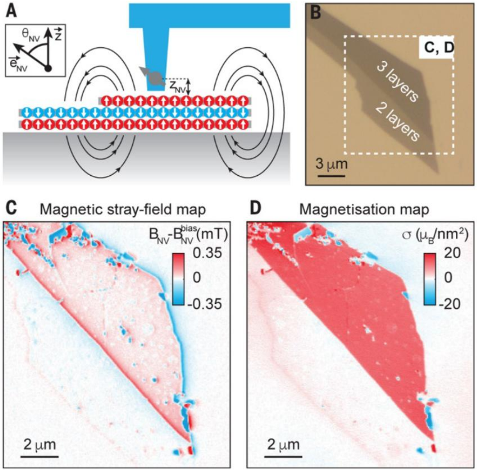
Ta/CoFeB/MgO stripe



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

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

Reverse propagation to compute M maps



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

- 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

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

D. Broadway *et al.* *PRAppl.* 14 (2020), 024076

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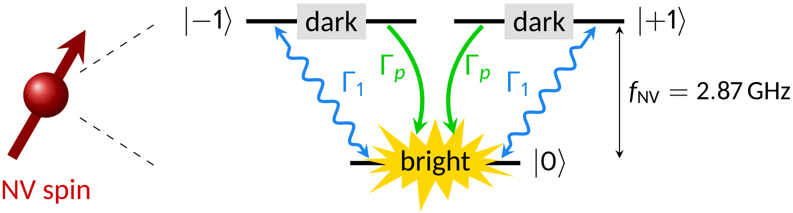
Incoherent dynamics probed with relaxometry



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

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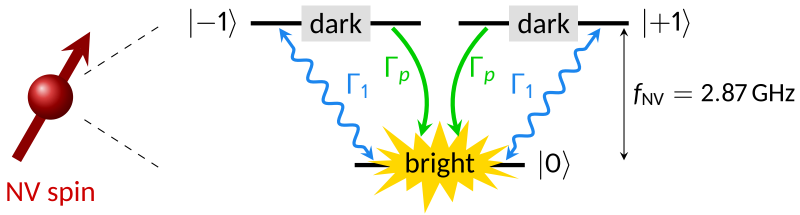

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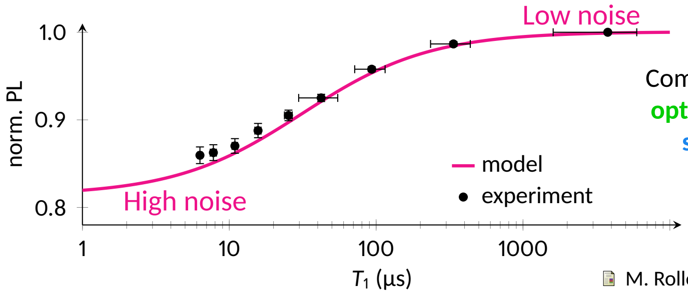
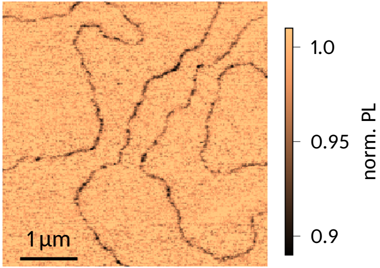


Competition between **optical pumping** and **spin relaxation**

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

Relaxometry on domain walls



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

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

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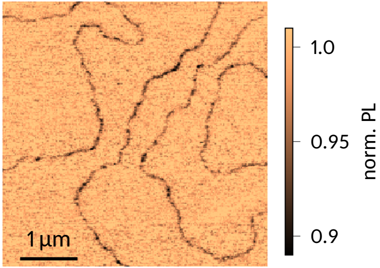

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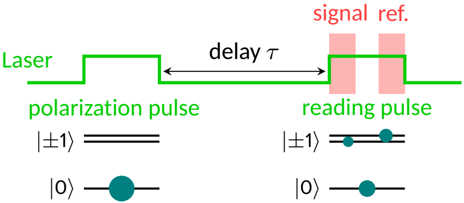

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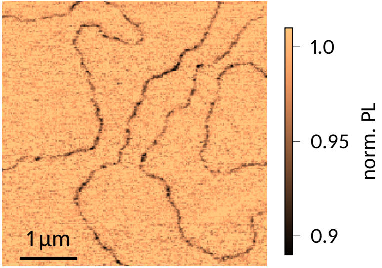

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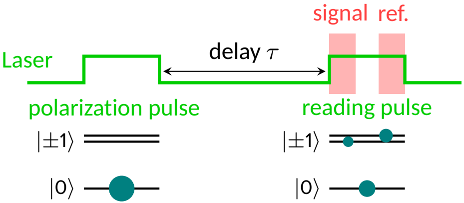

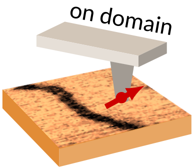

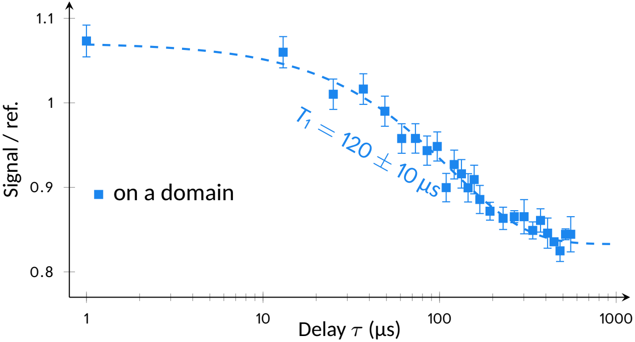

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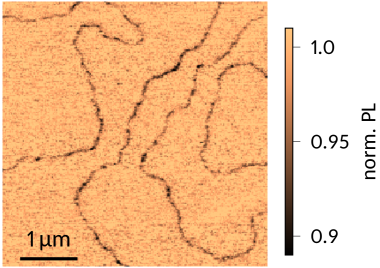

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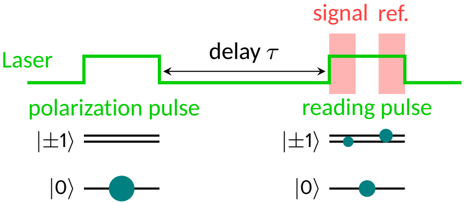
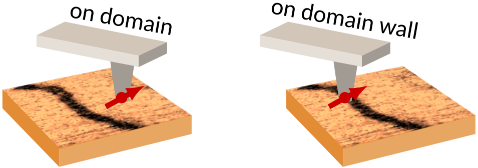
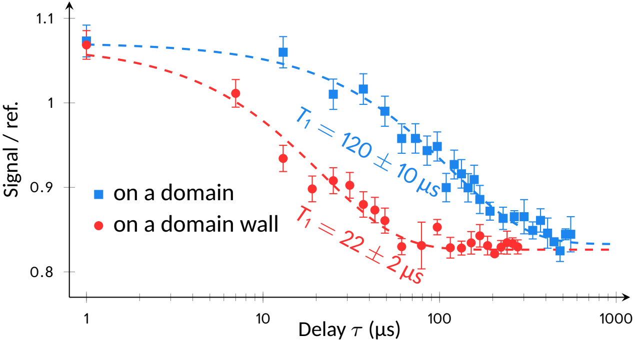
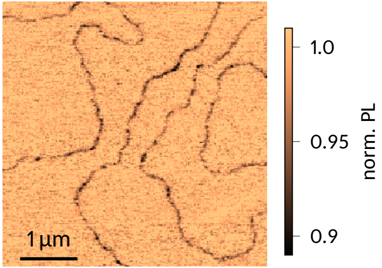
A. Finco *et al.* *Nat. Commun.* 12 (2021), 767





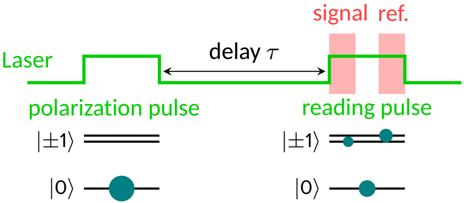


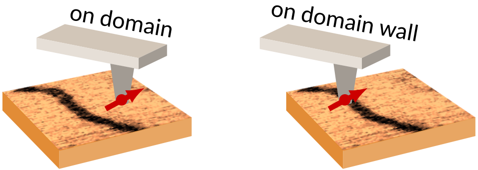
Relaxometry on domain walls

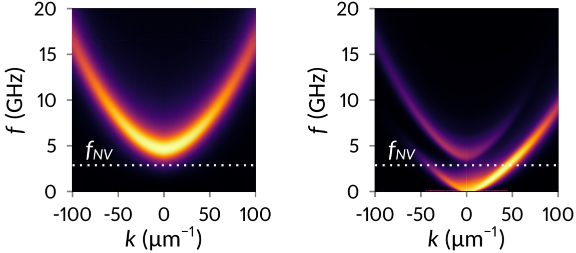


W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34

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

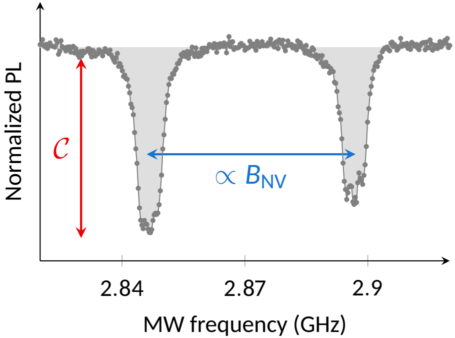






Detection of coherent microwave stray field

The stray field from **resonant** spin waves can drive the NV spin transition

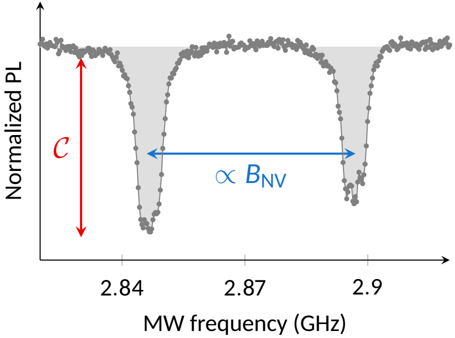


Shift → Static stray field

Contrast $\mathcal{C}$ or area → MW field

Detection of coherent microwave stray field

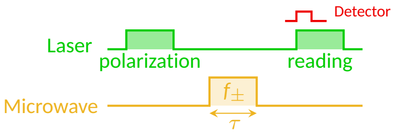
The stray field from **resonant** spin waves can drive the NV spin transition

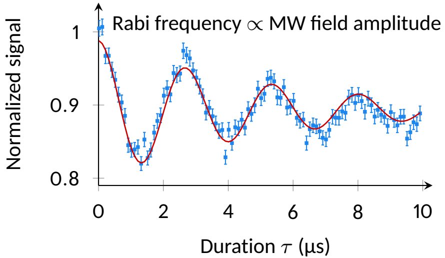


Shift → Static stray field

Contrast $\mathcal{C}$ or area → MW field

Rabi oscillations





Detection of coherent microwave stray field

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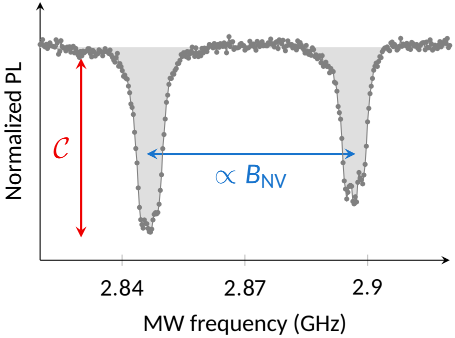
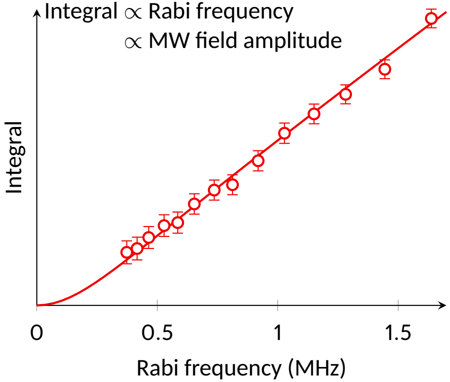


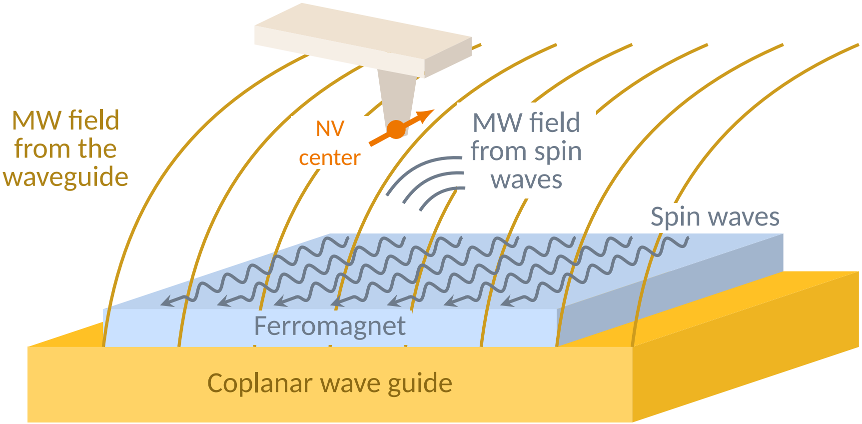
Shift → Static stray field

Contrast $\mathcal{C}$ or area → MW field

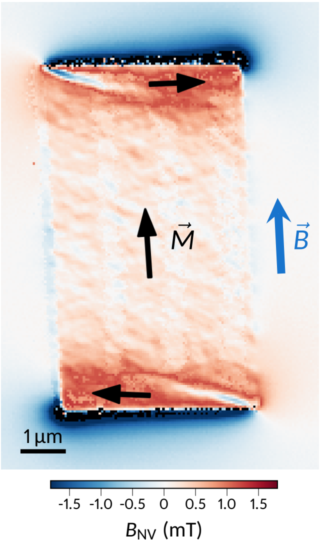


Mapping driven spin waves

Interference between the microwave field from the antenna and the microwave field from the excited spin waves



Imaging spin waves



Roméo Beignon

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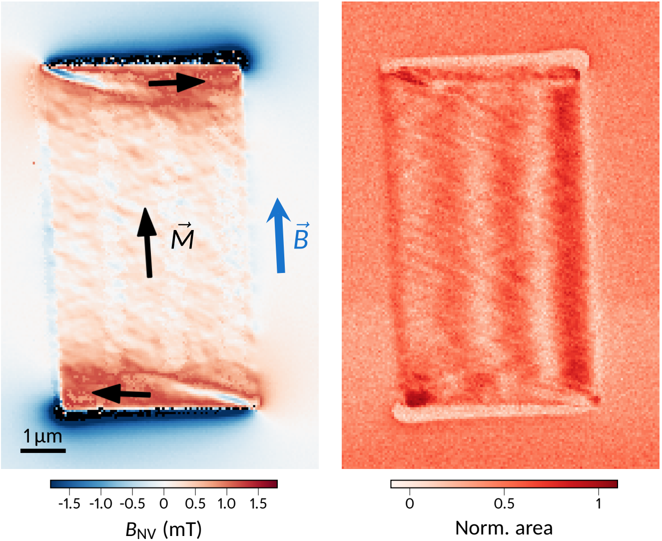
Imaging spin waves



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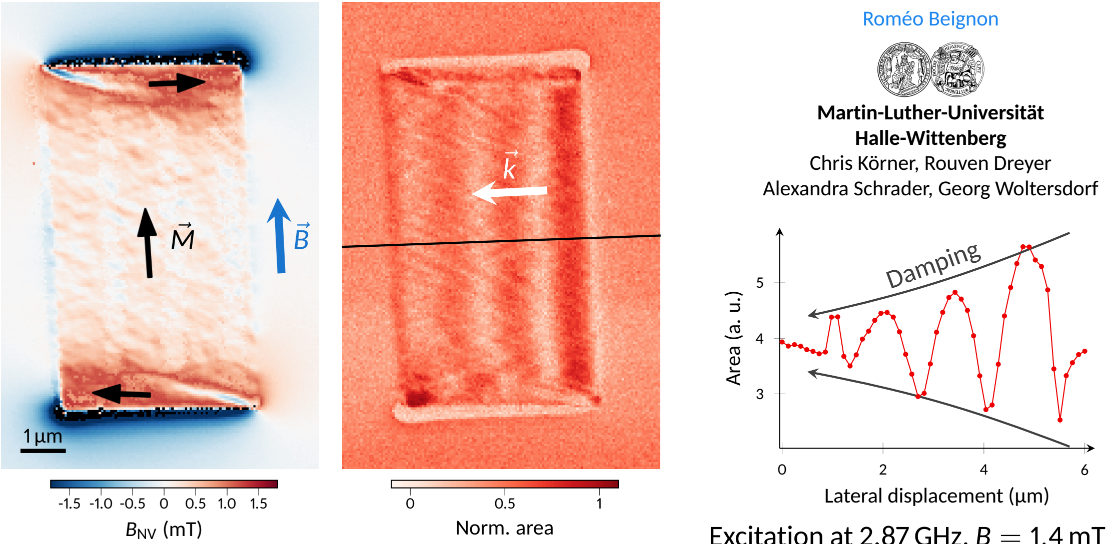

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Excitation at 2.87 GHz, $B = 1.4\,\mathrm{mT}$

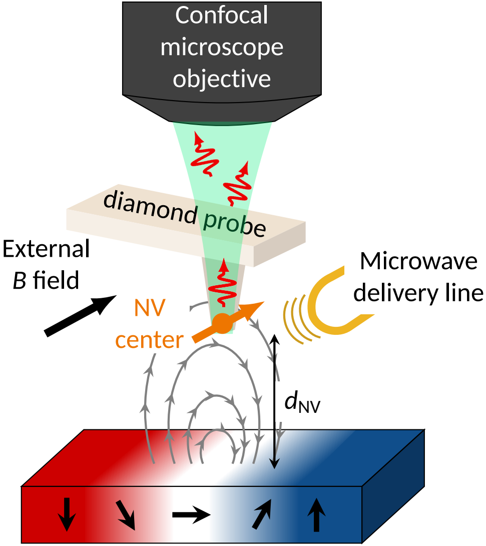
Outline

1. A brief introduction to nanomagnetism
2. Routes for imaging nanoscale magnetic textures
3. The NV center in diamond as a magnetic field sensor
4. Scanning NV center microscopy
5. How to obtain quantitative information from the data?
6. What about the dynamics?
7. What to remember

How to decide which technique to use?

	Scanning NV magnetometry	MOKE microscopy	MFM
Measured quantitity	Stray field	Magnetization direction	Magnetostatic force
Measurement properties	quantitative non-perturbative	– not too perturbative	hard to make quantitative often perturbative
Spatial resolution	$\sim$ 50 nm	$\sim$ 500 nm	$\sim$ 10 nm
Sample type	ferro- or antiferromagnet	ferromagnet	ferromagnet
Applied external field	few tens of mT along the NV axis	up to several T	up to several T
Cryogenic operation	rather difficult	quite common	not easy

What to remember about scanning NV



- Quantitative and non-perturbative
- Spatial resolution about 50 nm
- Magnetic sensitivity a few $\mu T/\sqrt{Hz}$
- Especially well-suited to antiferromagnets
- Versatile: magnetic textures, spin waves, paleomagnetism, etc.

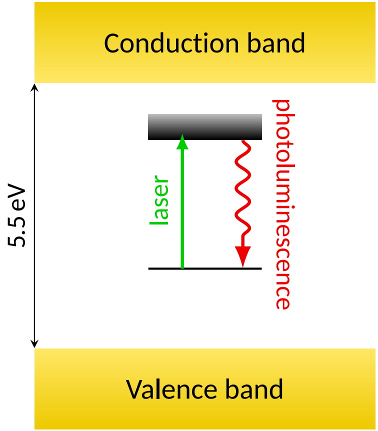
Some reading:

- A. Finco. *Techniques de l'Ingénieur* (2024), R 6 803
- V. Jacques *et al.* *Reflets de la physique* (2025), 17–22
- A. Finco and V. Jacques. *APL Materials* 11 (2023), 100901
- L. Rondin *et al.* *Reports on Progress in Physics* 77 (2014), 056503
- F. Casola *et al.* *Nature Reviews Materials* 3 (2018), 17088

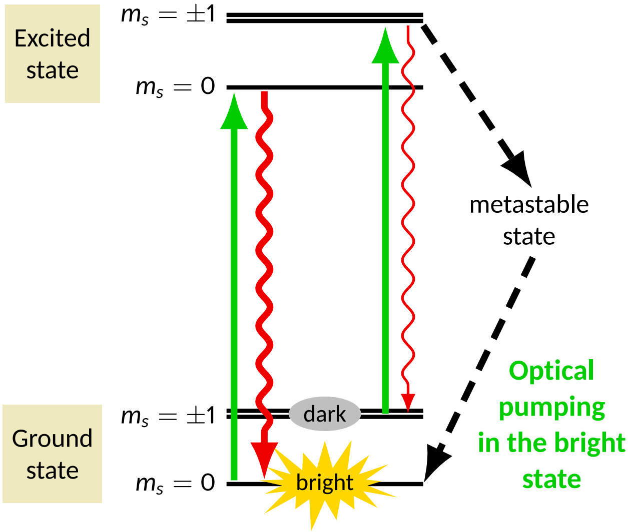
Additional slides

Optical properties

Artificial atom
in the diamond band gap



Spin dependent photoluminescence



Retrieve B_x, B_y, B_z from B_{NV}

Maxwell-Ampère equation

$$\vec{\nabla} \times \vec{B} = 0$$

In cartesian coordinates

$$\begin{cases} \dfrac{\partial B_z}{\partial y} - \dfrac{\partial B_y}{\partial z} = 0 \\ \dfrac{\partial B_z}{\partial x} - \dfrac{\partial B_x}{\partial z} = 0 \\ \dfrac{\partial B_x}{\partial y} - \dfrac{\partial B_y}{\partial x} = 0 \end{cases}$$

2D Fourier transform

$$\begin{cases} \tilde{B}_x(q_x, q_y, z) = \dfrac{-iq_x}{q} \tilde{B}_z(q_x, q_y, z) \\ \tilde{B}_y(q_x, q_y, z) = \dfrac{-iq_y}{q} \tilde{B}_z(q_x, q_y, z) \end{cases}$$

If we know the orientation of the NV axis (not in-plane)

$$\begin{cases} \tilde{B}_x(q_x, q_y, z) = \dfrac{-iq_x \tilde{B}_{NV}(q_x, q_y, z)}{q \cos\theta_{NV} - i \sin\theta_{NV}(q_x \cos\varphi_{NV} + q_y \sin\varphi_{NV})} \\ \tilde{B}_y(q_x, q_y, z) = \dfrac{-iq_y \tilde{B}_{NV}(q_x, q_y, z)}{q \cos\theta_{NV} - i \sin\theta_{NV}(q_x \cos\varphi_{NV} + q_y \sin\varphi_{NV})} \\ \tilde{B}_z(q_x, q_y, z) = \dfrac{\tilde{B}_{NV}(q_x, q_y, z)}{\cos\theta_{NV} - \frac{i \sin\theta_{NV}}{q}(q_x \cos\varphi_{NV} + q_y \sin\varphi_{NV})} \end{cases}$$

E. A. Lima and B. P. Weiss. *J. Geophys. Res. Solid Earth* 114 (2009)

Conservation of angular momentum