Mapping nanomagnetism with scanning NV center microscopy

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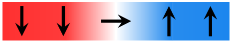
Forum des microscopies à sonde locale, June 9th 2026, Saint-Rémy-lès-Chevreuse

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

Two approaches to map nanomagnetism

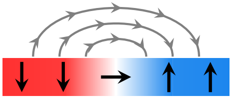
Probe the magnetization



→ STM lecture by Marie this morning

This is usually the information we are interested in, but it might be difficult to probe it directly.

Probe the stray field



→ This lecture about NV magnetometry

Since we are interested in the magnetization, we will need a way to solve the inverse problem ($\vec{B} \rightarrow \vec{M}$).

What are the sources of magnetic field?

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

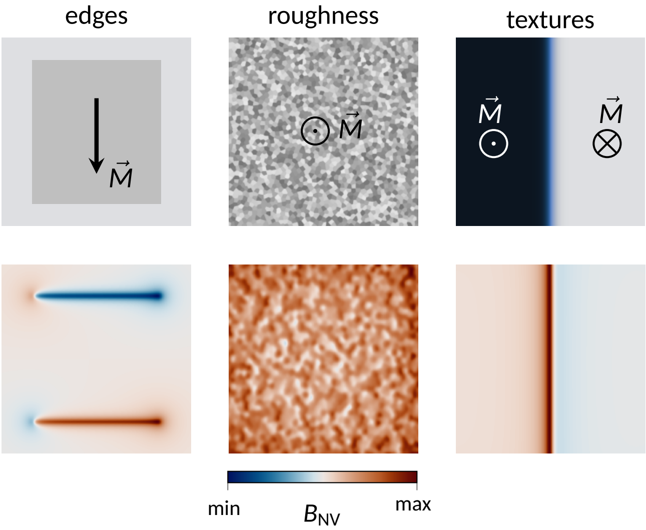
where ϕ is a scalar potential which verifies the Poisson equation:

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

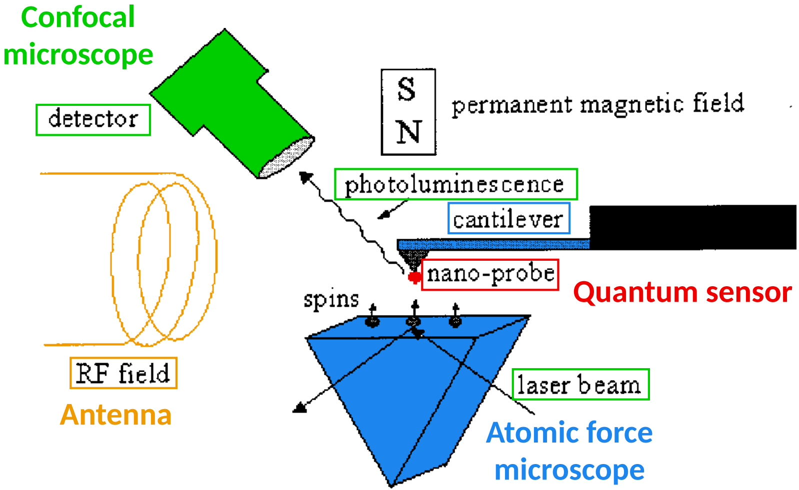
Same equation as for the electrostatic potential V

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

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



The original idea



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

Outline

1. The NV center in diamond as a magnetic field sensor
2. Scanning NV center microscopy
   Experimental details
   Standard measurement modes
3. How to obtain quantitative information from the data?
4. What about the dynamics?
5. Advanced modes
6. What to remember

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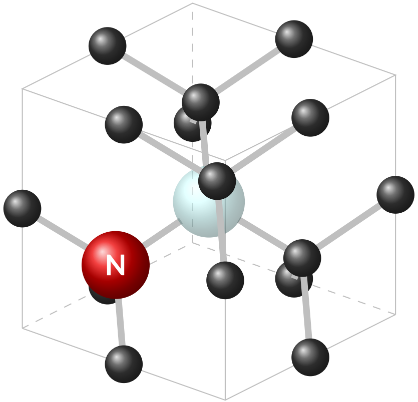
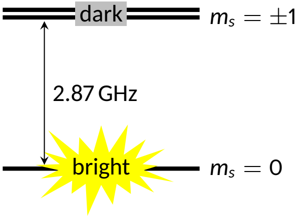
Our sensor: the NV center in diamond



- 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

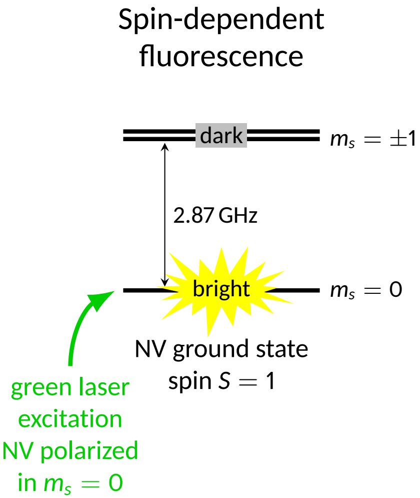
Optically detected magnetic resonance

Spin-dependent
fluorescence



NV ground state
spin $S = 1$

Optically detected magnetic resonance



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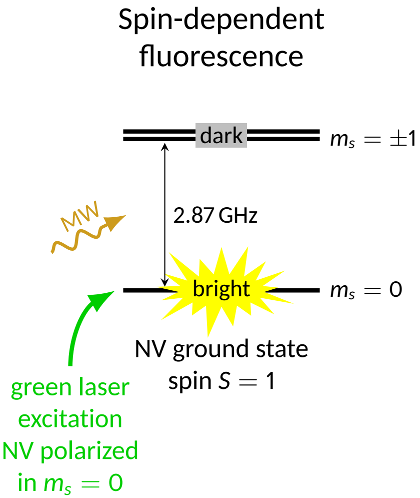

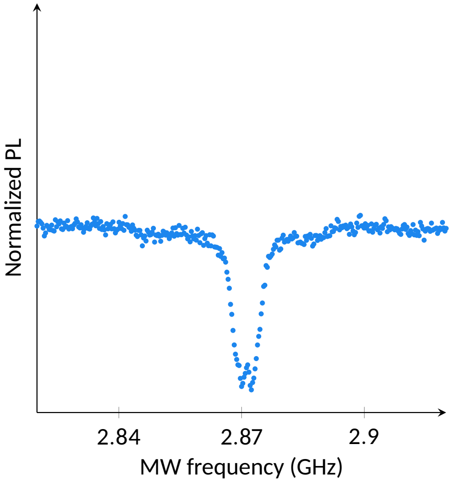

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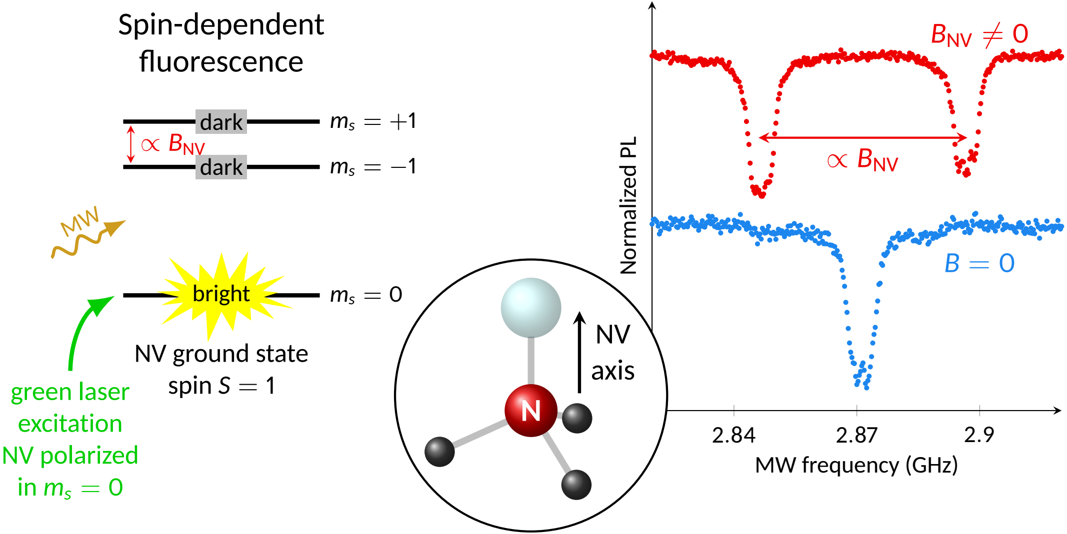
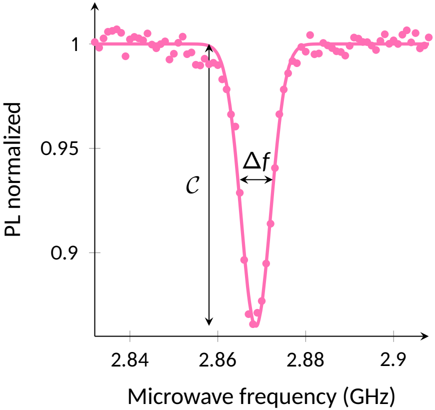


Sensitivity to magnetic field



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

- 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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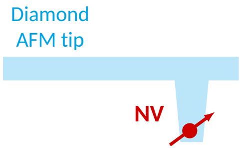
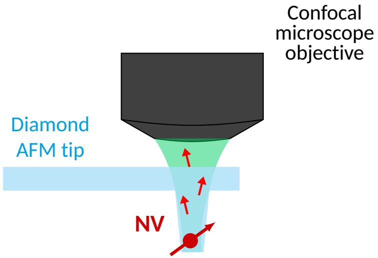
Scanning NV center microscopy



Scanning NV center microscopy



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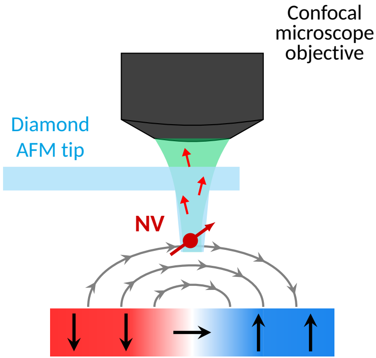

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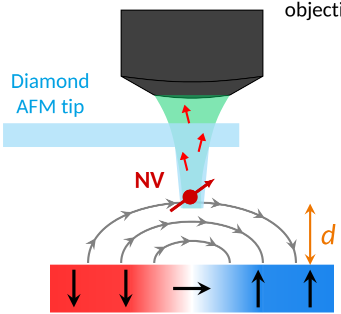

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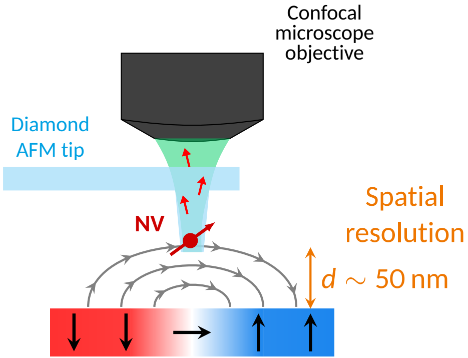
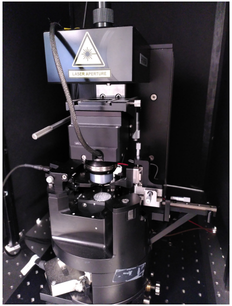


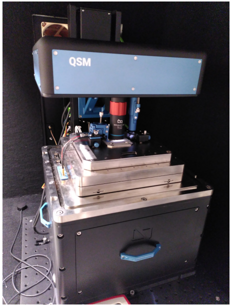
Examples of commercial setups

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

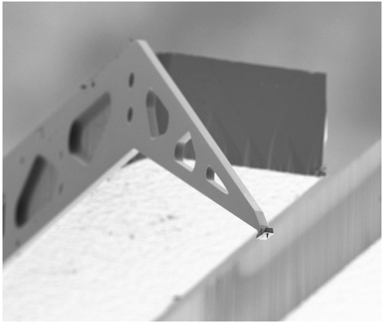


Image from www.qzabre.com

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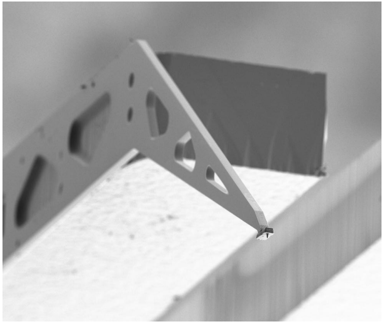

Image from `www.qzabre.com`

- 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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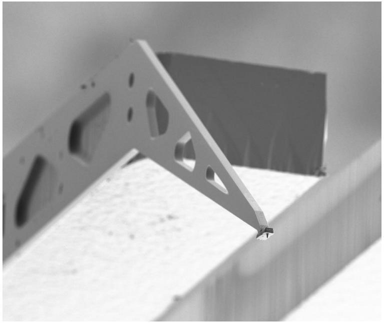

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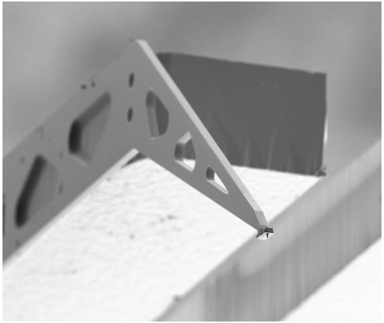

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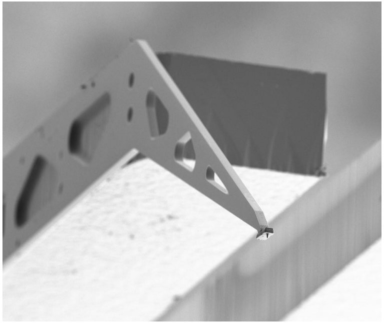

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  → Tilted NV axis
- Diamond pillar as guide for the emitted light

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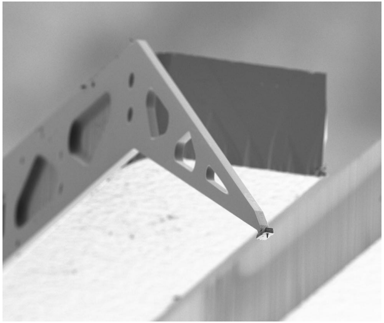

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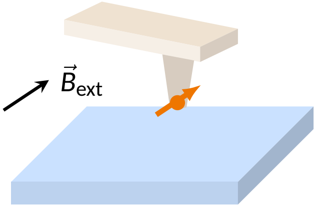
- Hosting single NV centers at 50-100 nm from the sample surface
  ➔ Spatial resolution of the microscope
- Usually made from (001) diamond
  ➔ Tilted NV axis
- Diamond pillar as guide for the emitted light
  ➔ Optimized signal collection

Experimental conditions

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



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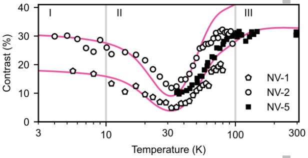

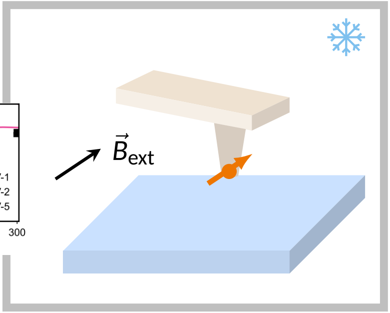

In a cryostat

→ 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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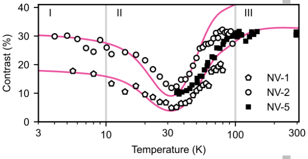

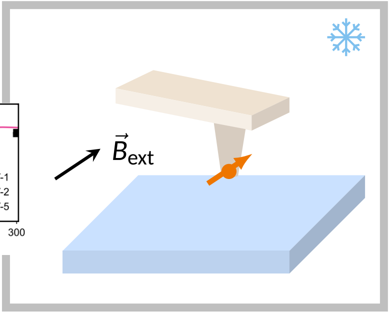

4 K

📄 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

In a cryostat

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

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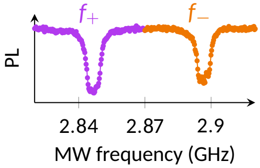
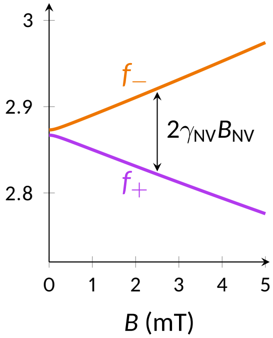
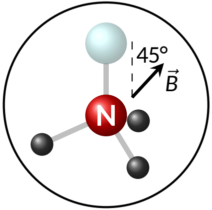
The different measurement regimes



Linear regime





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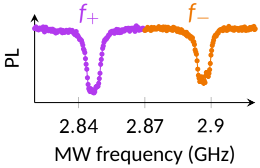
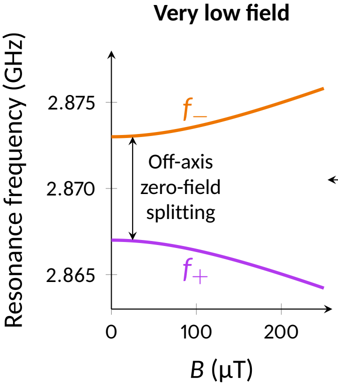
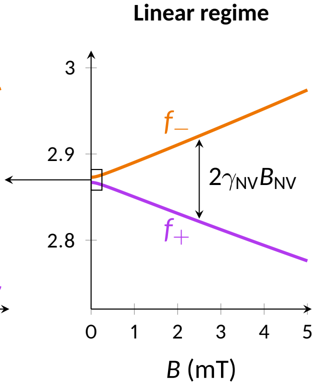
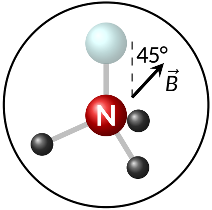




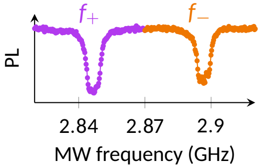




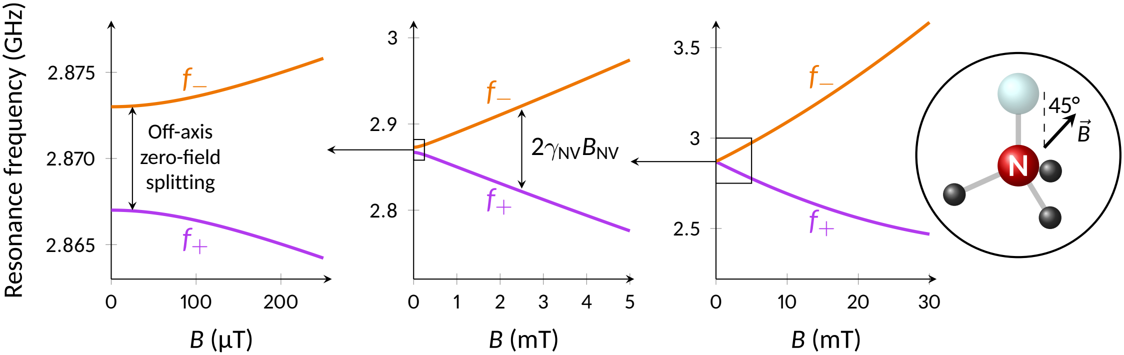
Related to internal
electric field in the diamond

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

The different measurement regimes



Very low field | **Linear regime** | **Non-linearity caused by $B_\perp$**



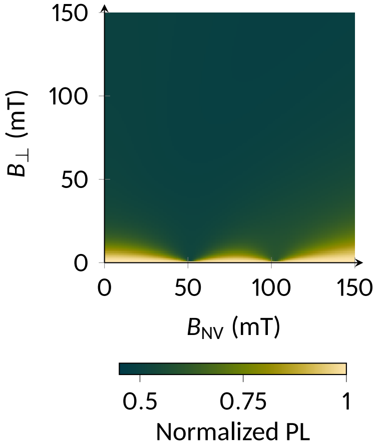
Related to internal electric field in the diamond

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

Mixing of the spin states

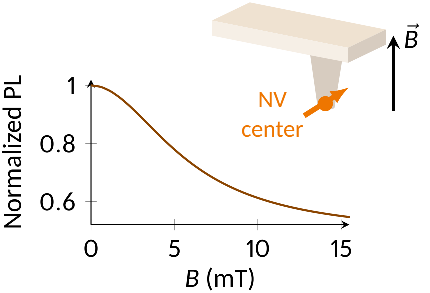
J.-P. Tetienne *et al.* *New J. Phys.* 14 (2012), 103033

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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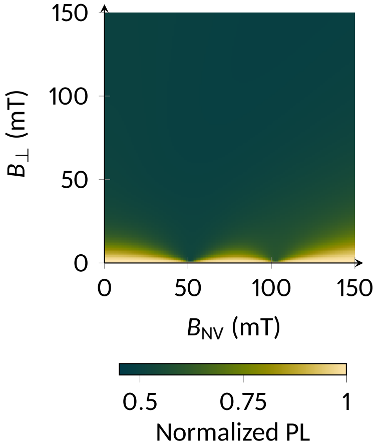

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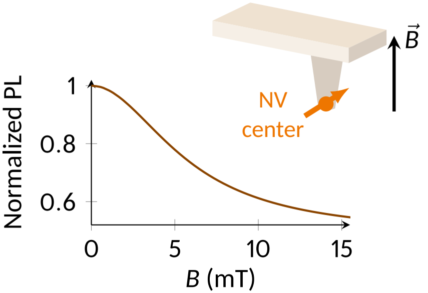
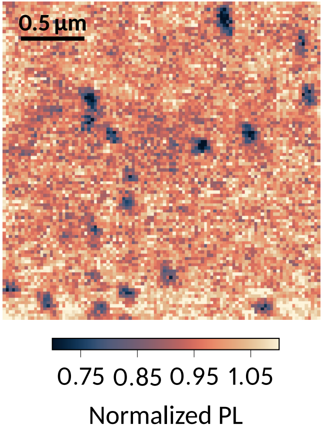


J.-P. Tetienne *et al.* *New J. Phys.* 14 (2012), 103033

→ 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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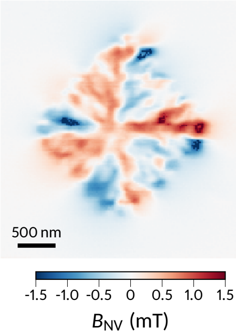
Example
Magnetic vortices in Fe_5GeTe_2

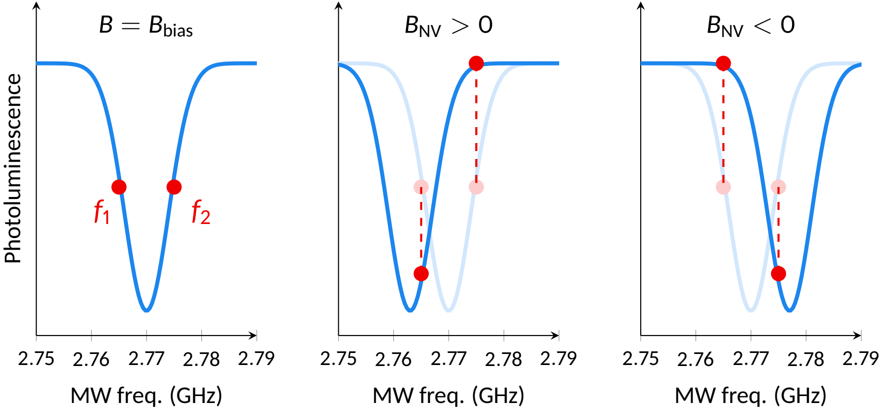


E. Sfeir *et al.* *PRMaterials* 9 (2025), 114003

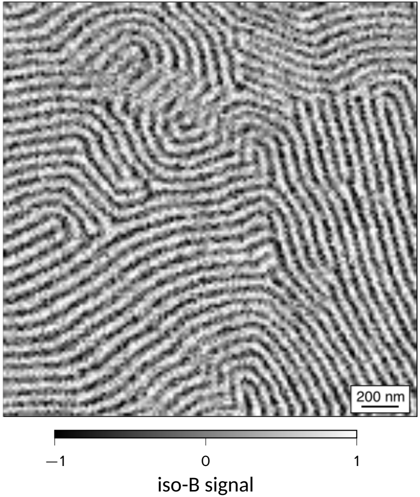
Linear regime, iso-B mode

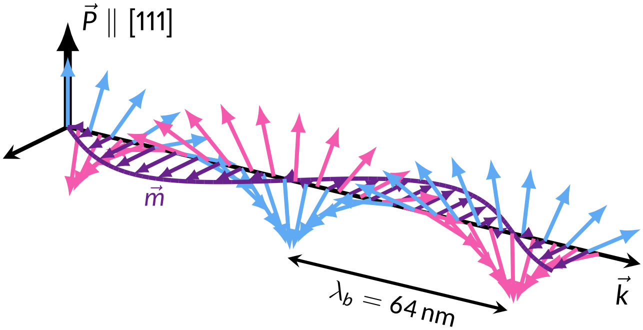
Quick and qualitative mode for samples producing low field

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



Antiferromagnetic topological defects in iso-B





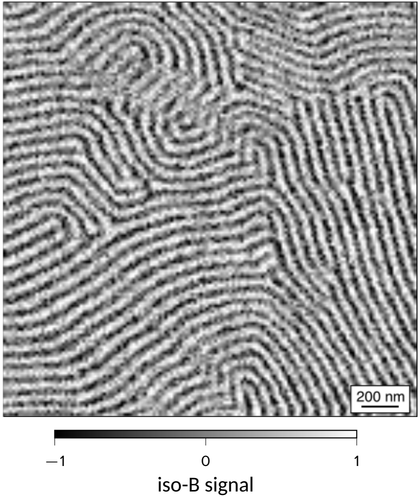
Spin density wave

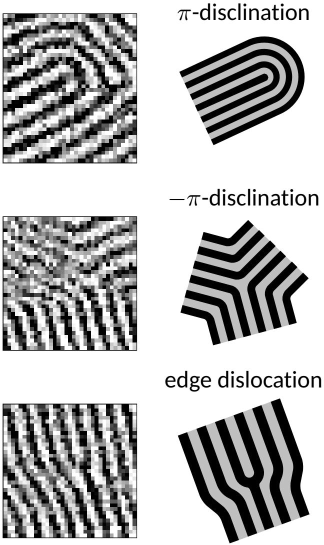
Weak uncompensated moment

→ **Small stray field**

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

Antiferromagnetic topological defects in iso-B

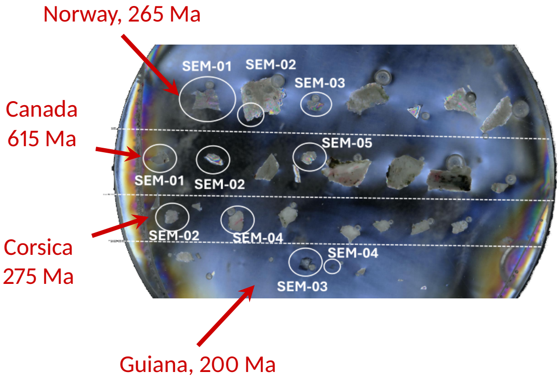




A. Finco *et al*. *PRL* 128 (2022), 187201

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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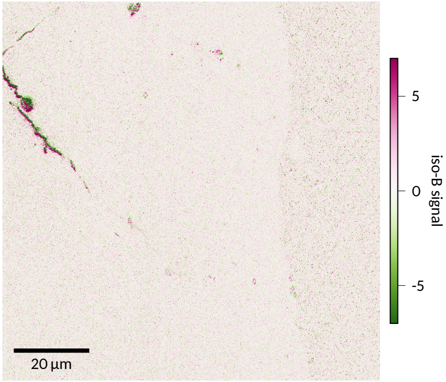
Corsica sample



Léa Houzelle
Carolin Schrader

Iso-B for paleomagnetism

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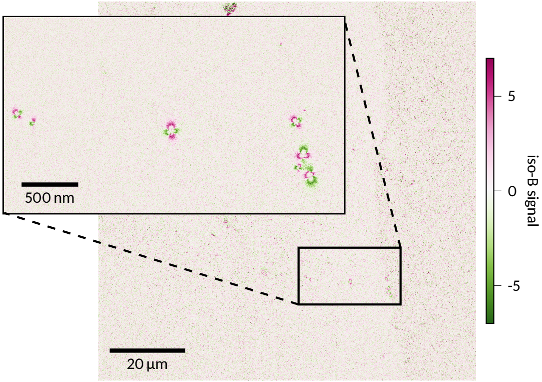
- Volcanic rocks with "fast" cool down

  ➔ Info about the earth's field is imprinted in the magnetic minerals embedded in the rock

Paul Antonio

Géosciences Montpellier

Corsica sample



Léa Houzelle
Carolin Schrader

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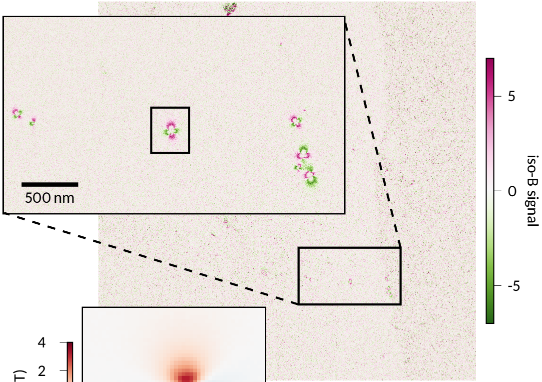

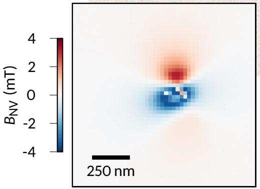

Léa Houzelle
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Outline

1. The NV center in diamond as a magnetic field sensor
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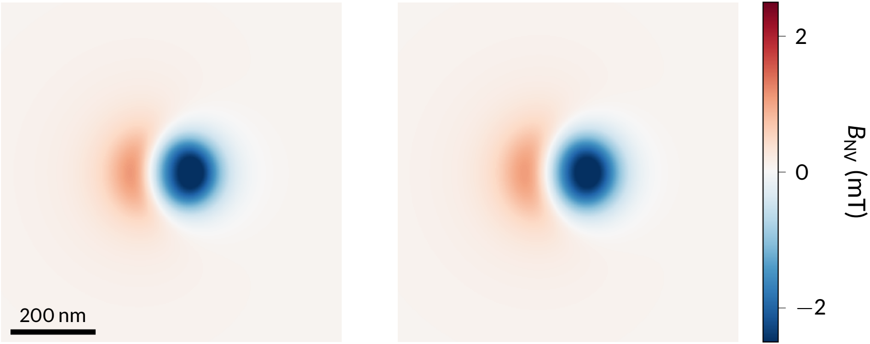
We need to calibrate the NV flying distance!

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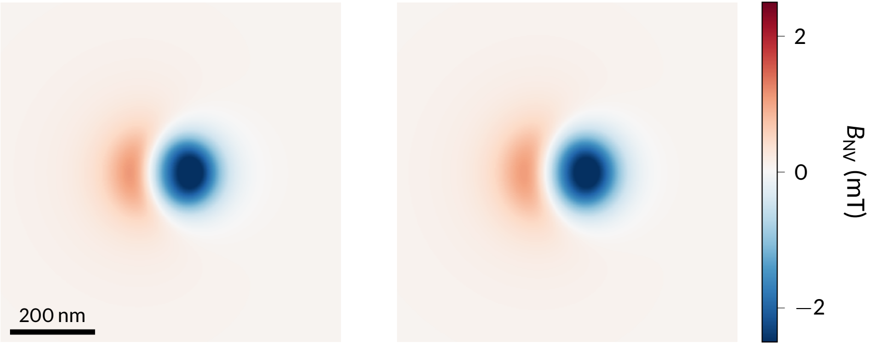
Simulated stray field maps from skyrmions of diameter 150 nm in a 0.5 nm thick film with $M_s = 1\,\mathrm{MA\,m^{-1}}$

Clockwise Néel skyrmion **Counter clockwise Néel skyrmion**

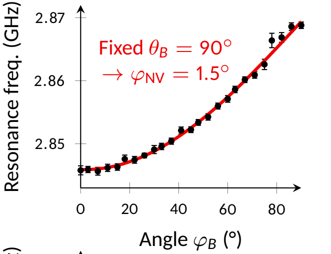


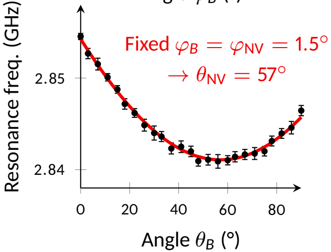
NV height: $d_{\mathrm{NV}} = 50\,\mathrm{nm}$
DW width: $w = 15\,\mathrm{nm}$

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

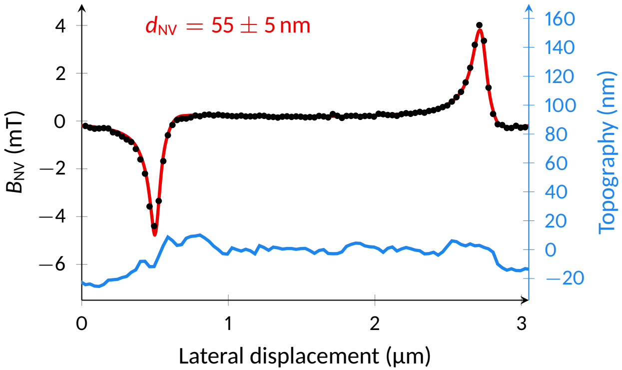
The calibration procedure

1. Find the NV axis orientation





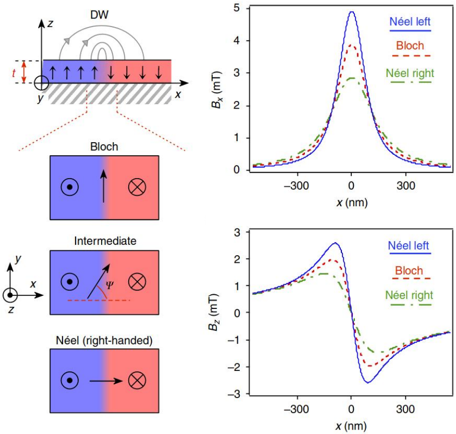
2. Find the NV height d_{NV} with a well-known ferromagnetic stripe



T. Hingant *et al.* *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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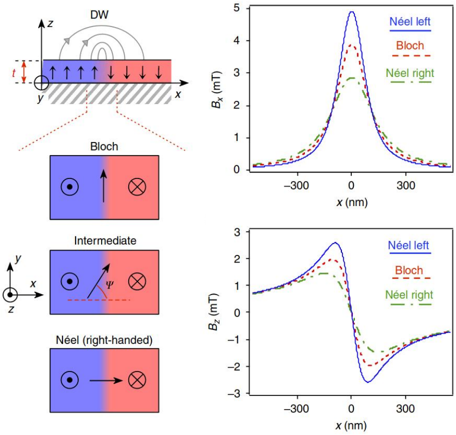
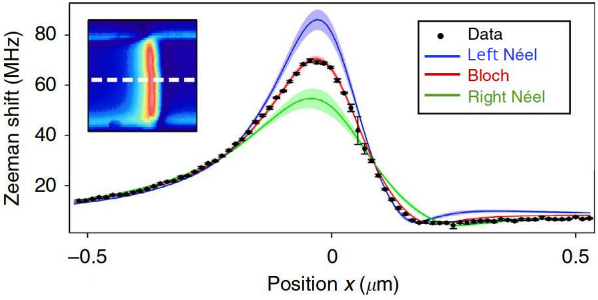


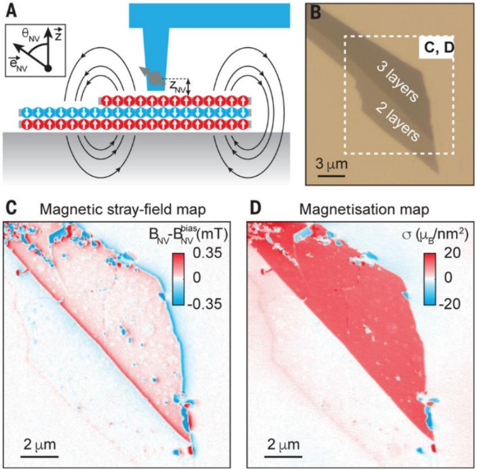
Ta/CoFeB/MgO stripe



→ 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

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

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

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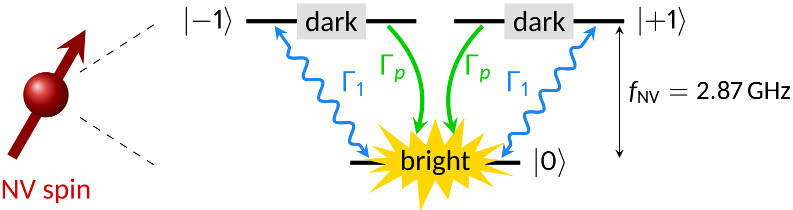
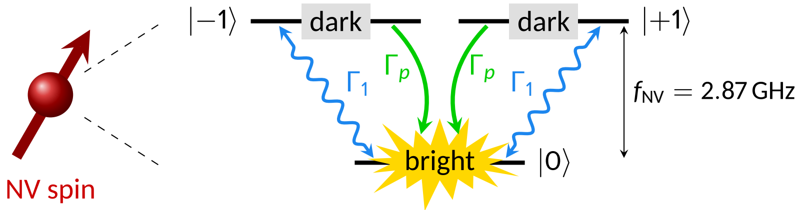
Incoherent dynamics probed with relaxometry



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

Incoherent dynamics probed with relaxometry



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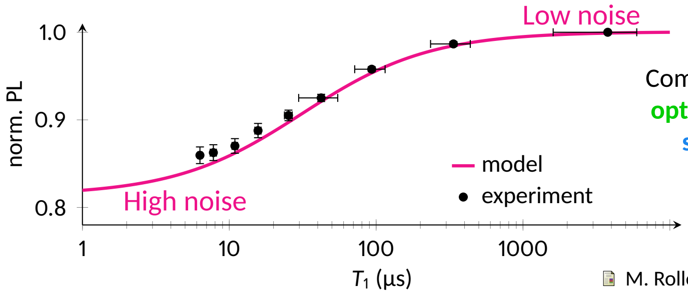
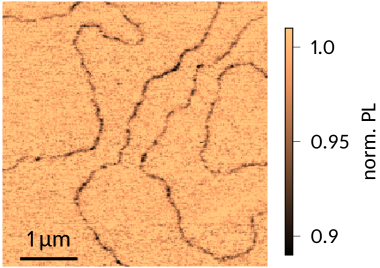


Competition between **optical pumping** and **spin relaxation**

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

Relaxometry on domain walls



- W. Legrand *et al.* *Nat. Mater.* 19 (2020), 34
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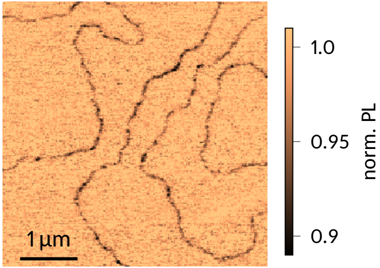
Relaxometry on domain walls



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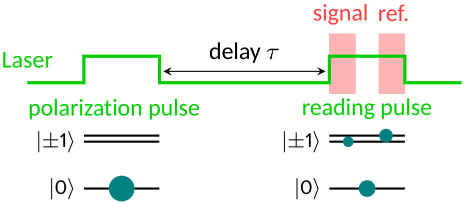

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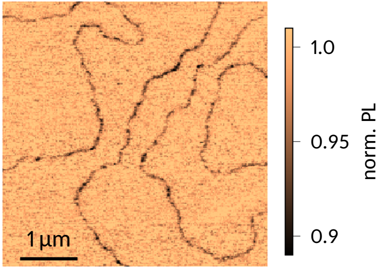

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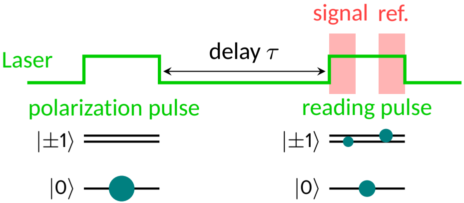

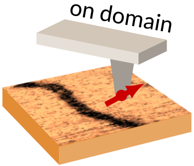

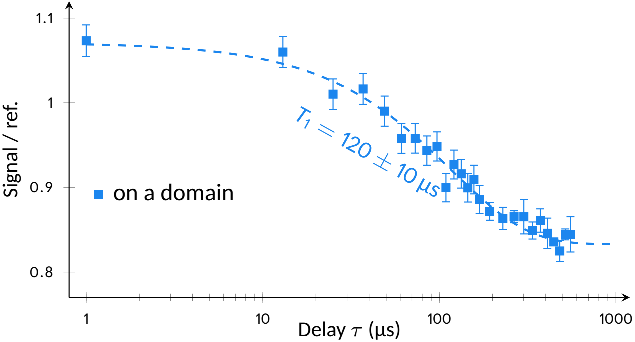

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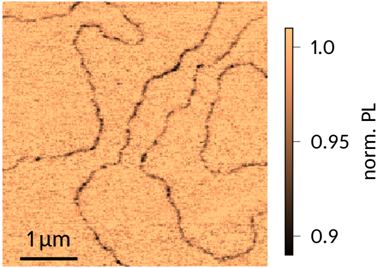

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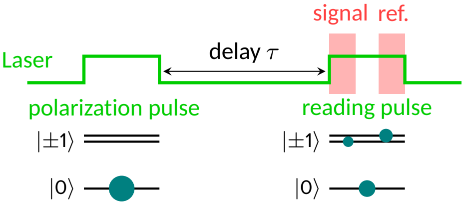

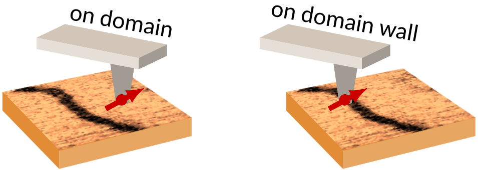

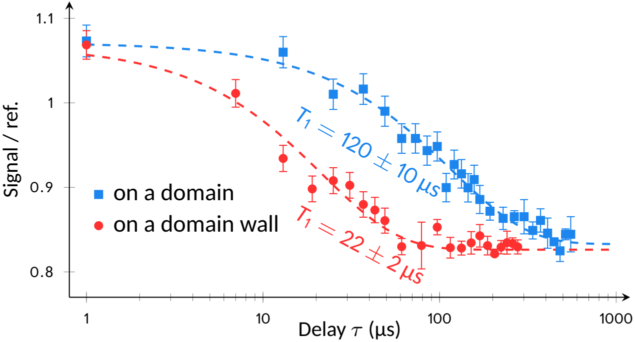

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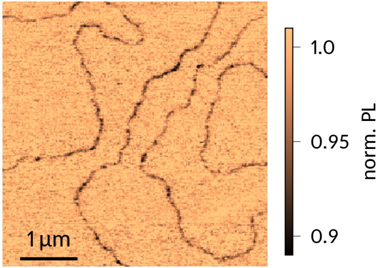

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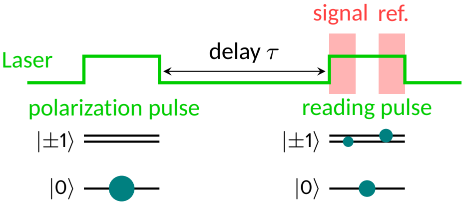
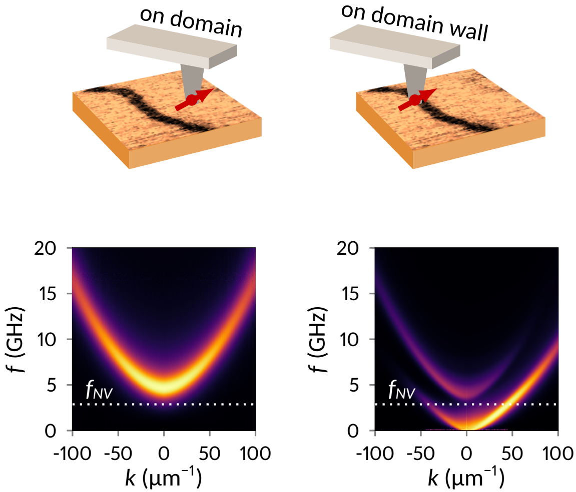
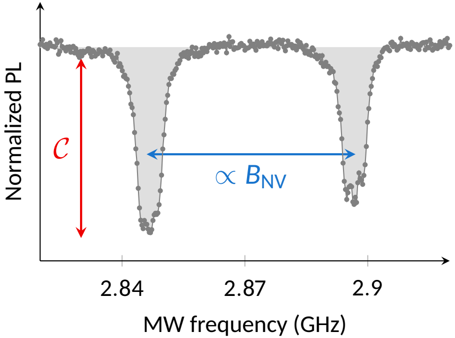




Detection of coherent microwave stray field

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



Shift → Static stray field

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

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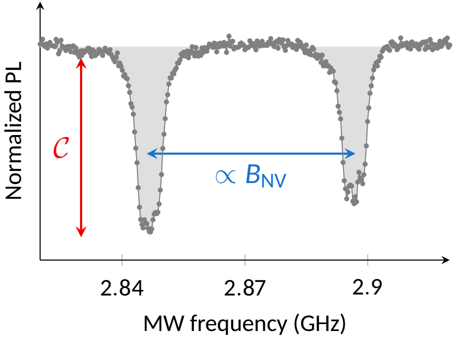

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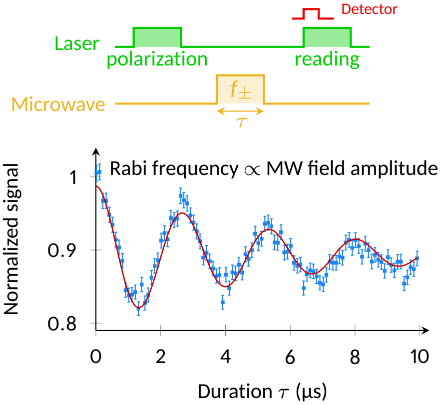
Rabi oscillations



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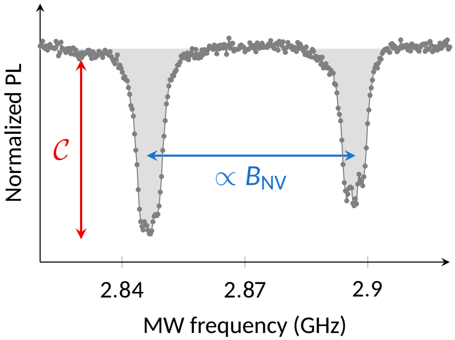

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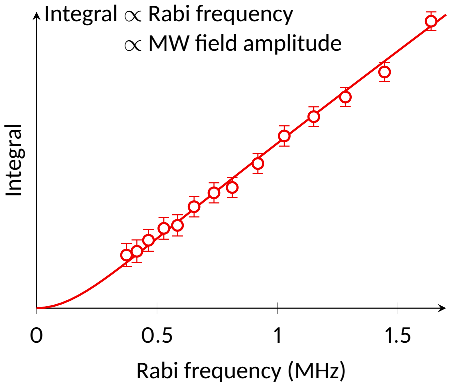
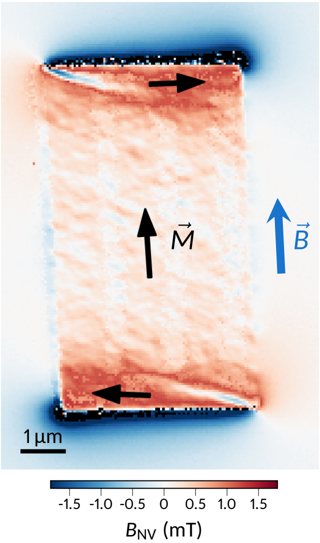


Imaging spin waves



Roméo Beignon

Martin-Luther-Universität Halle-Wittenberg
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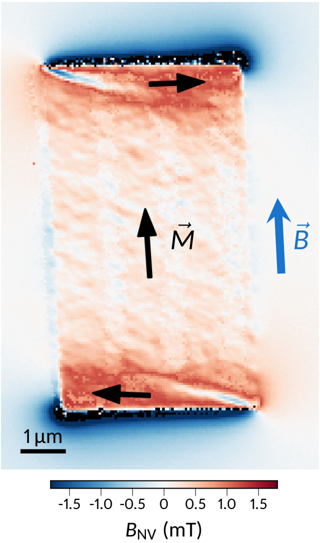

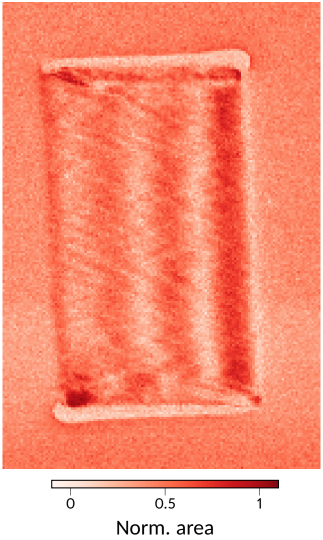

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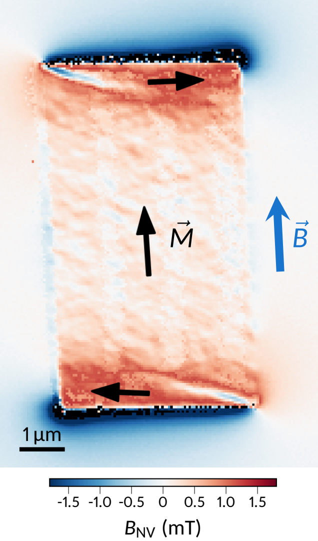

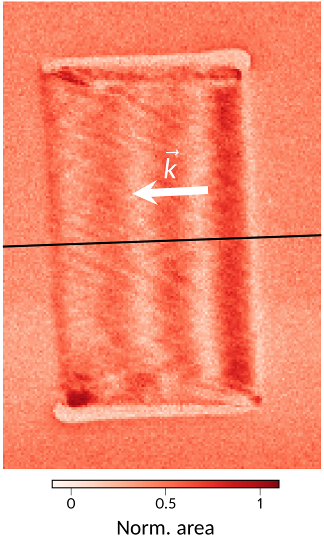

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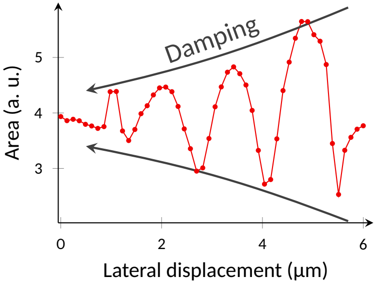

Excitation at 2.87 GHz, $B = 1.4$ mT

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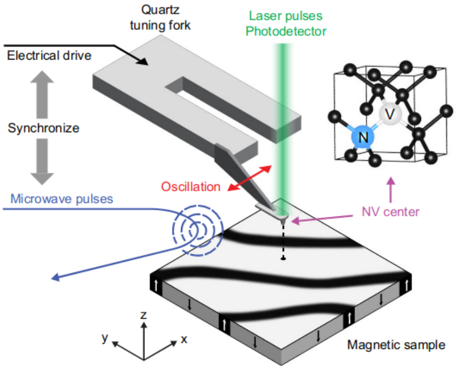
Advanced mode: gradiometry

Use a spin echo sequence to improve the magnetic sensitivity



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

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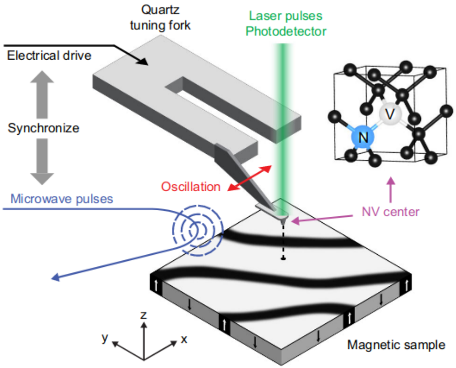
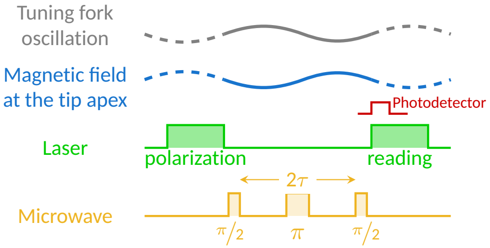
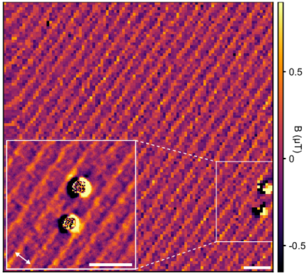






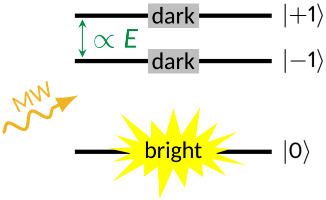
Stray field from atomic steps visible in the layered antiferromagnet Cr_2O_3

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

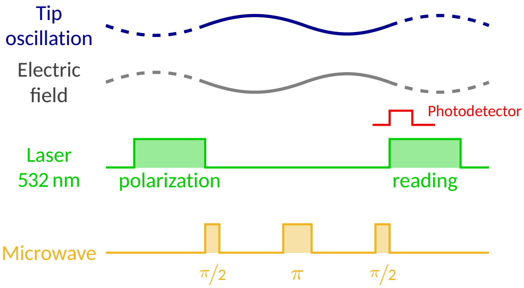
Electric field sensing

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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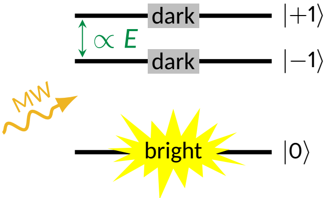
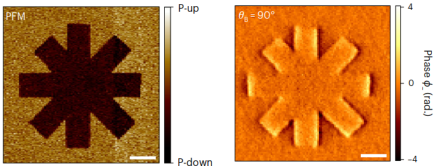


$Pb[Zr_{0.2}Ti_{0.8}]O_3$



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

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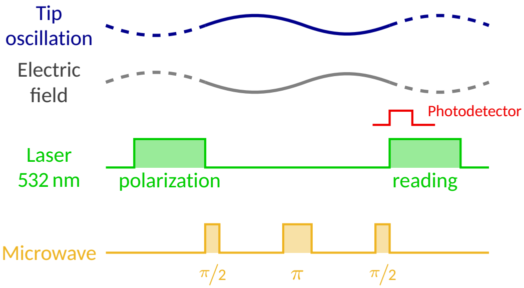

Z. Qiu *et al.* *npj Quantum Info.* 8 (2022), 107

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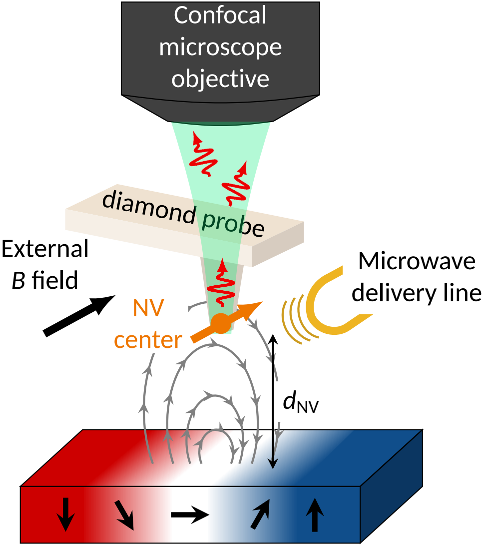


- Quantitative and non-perturbative
- Spatial resolution about 50 nm
- Magnetic sensitivity a few $\mu T/\sqrt{Hz}$
- Especially well-suited to antiferromagnets
- Versatile: magnetic textures, spin waves, paleomagnetism, etc.

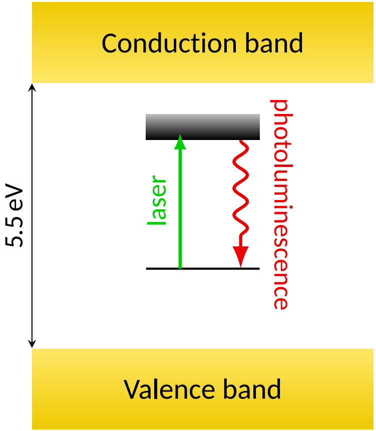
Some reading:

- 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

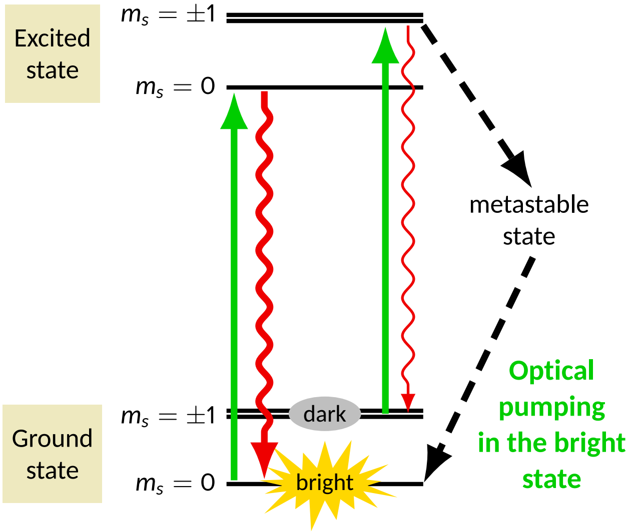
Additional slides

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)

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

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Conservation of angular momentum