Scanning NV center microscopy for nanoscale magnetic characterization

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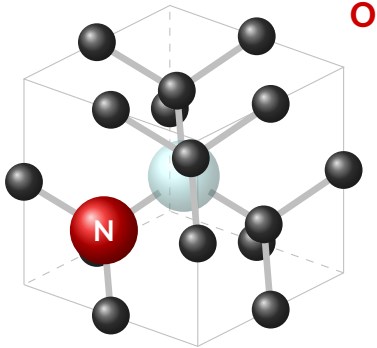
SpinCharac days, January 28th 2025, Lyon

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

Scanning NV center microscopy

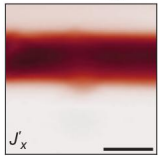
Principle: Integration of a quantum sensor in a scanning probe microscope

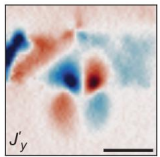


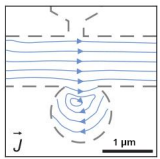
Our sensor: the Nitrogen-Vacancy center

- High sensitivity
- Nanoscale spatial resolution
- Non perturbative
- Quantitative
- Versatility

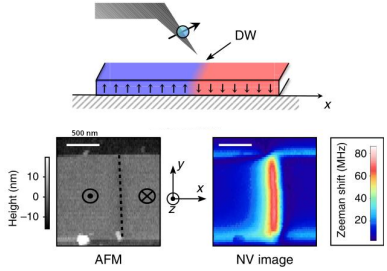
Sensing magnetic stray field, but not only







M. L. Palm *et al.* *Science* 384 (2024), 465



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

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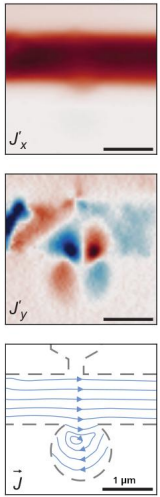
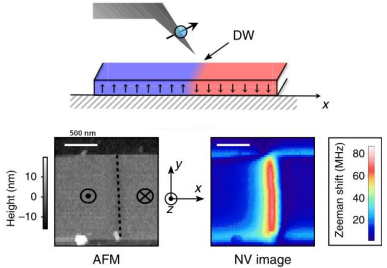
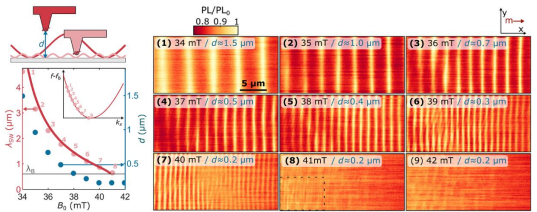


M. L. Palm *et al.* *Science* 384 (2024), 465

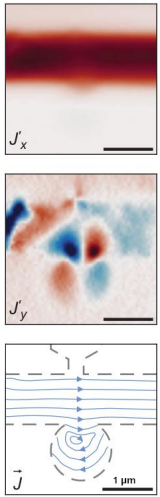


J.-P. Tetienne *et al.* *Nat. Commun.* 6 (2015), 6733



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

Sensing magnetic stray field, but not only



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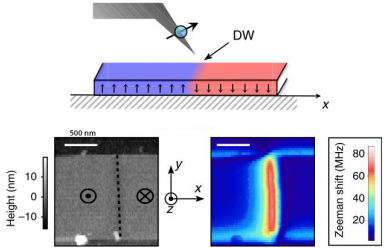
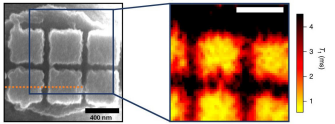
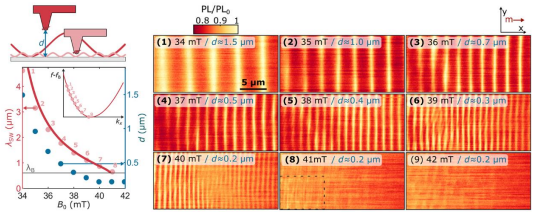


J.-P. Tetienne *et al.* *Nat. Commun.* 6 (2015), 6733

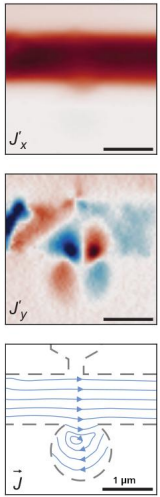


A. Ariyaratne *et al.* *Nat. Commun.* 9 (2018), 2406



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

Sensing magnetic stray field, but not only



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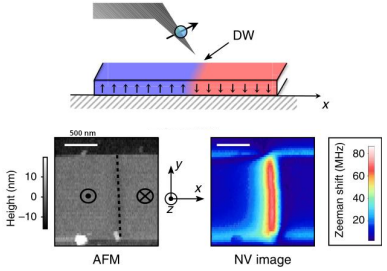
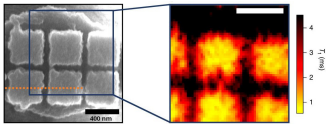
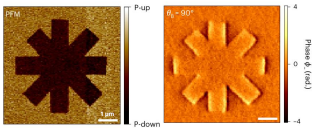


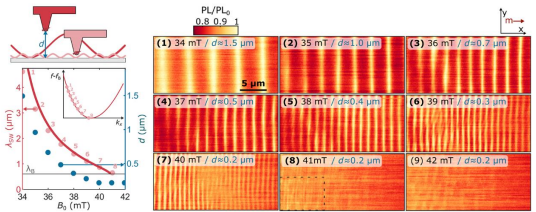
J.-P. Tetienne *et al.* *Nat. Commun.* 6 (2015), 6733



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



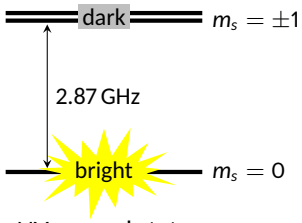
W. S. Huxter *et al.* *Nat. Phys.* 19 (2023), 644



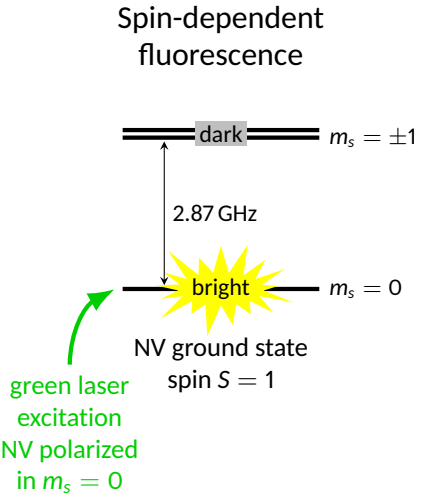
B. G. Simon *et al.* *Nano Letters* 22 (2022), 9198

Principle of static magnetic field measurements

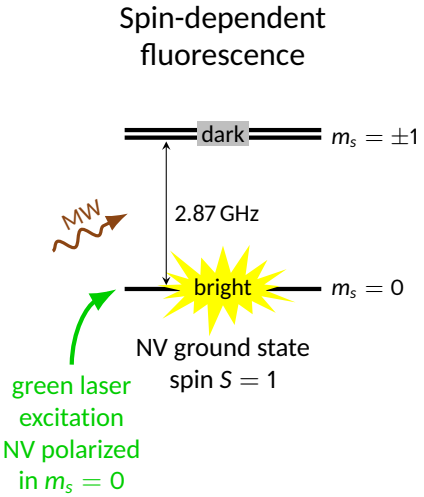
Spin-dependent fluorescence

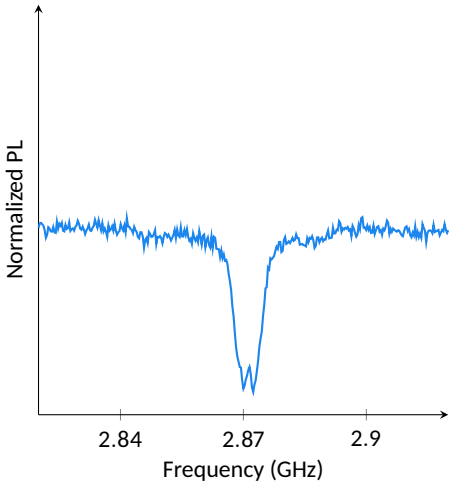


Principle of static magnetic field measurements

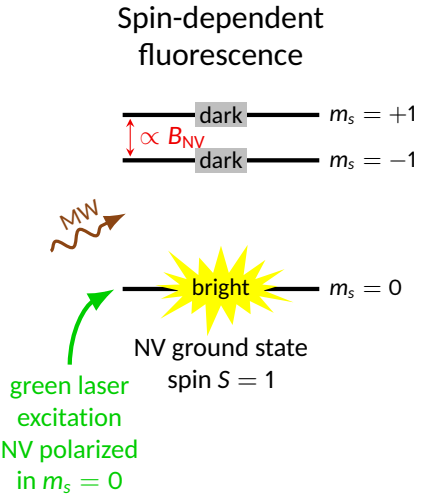


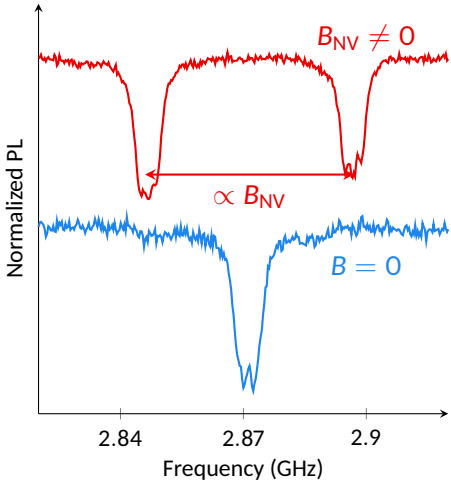
Principle of static magnetic field measurements



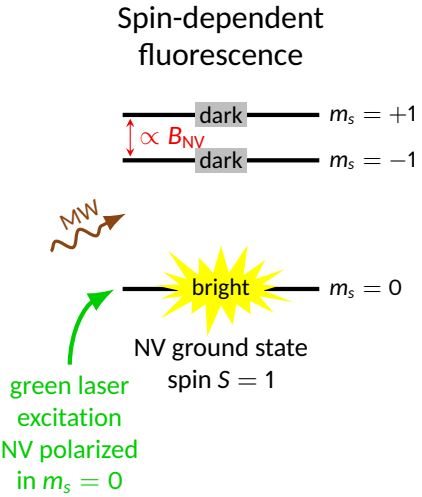


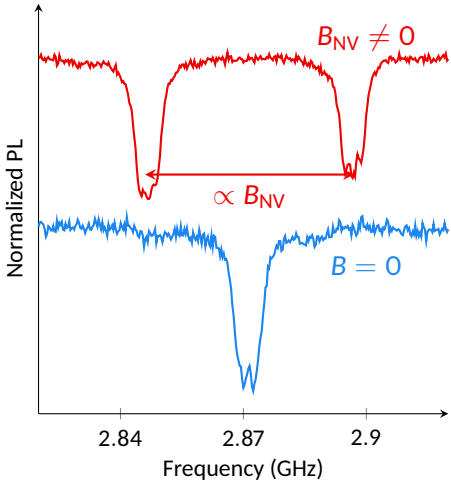
Principle of static magnetic field measurements





Principle of static magnetic field measurements





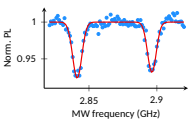
Sensitivity: a few $\mu T/\sqrt{Hz}$

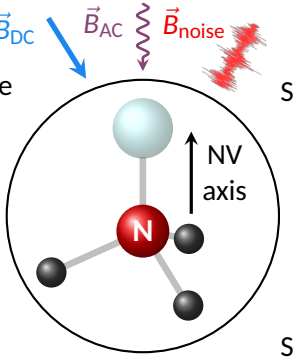
Quantum sensing with a NV center

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

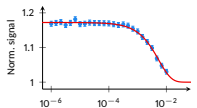
Photoluminescence

Magnetic resonance

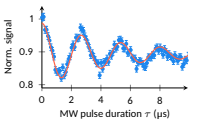




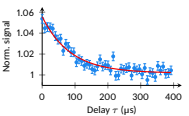
Spin relaxation time



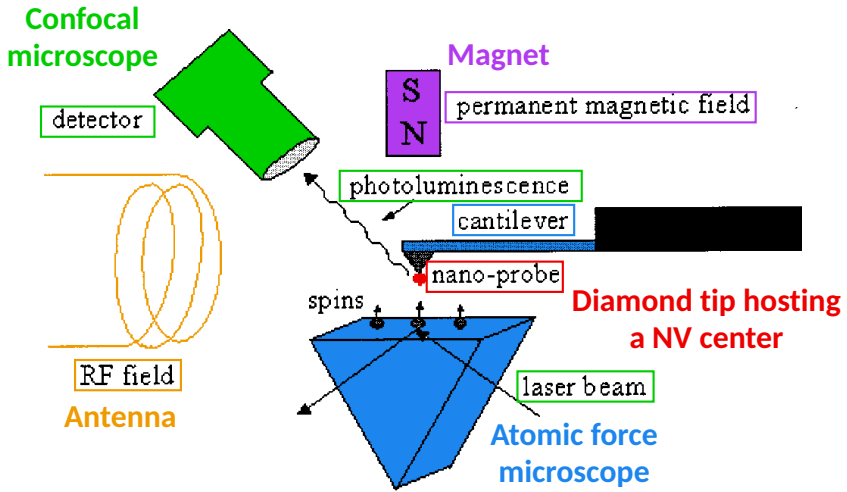
Rabi frequency



Spin coherence time



The ingredients of a scanning NV microscope

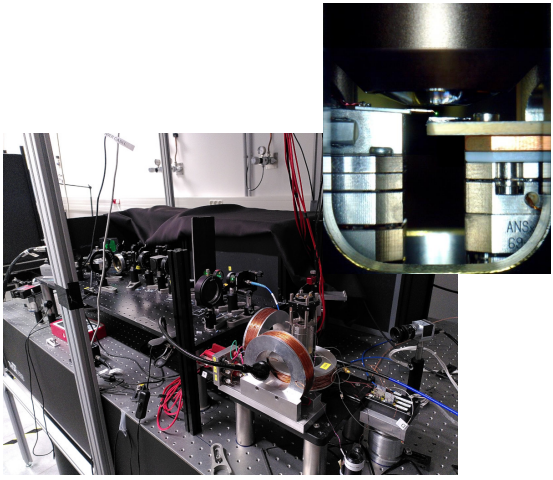


B. M. Chernobrod and G. P. Berman. *J. Appl. Phys.* 97 (2004), 014903

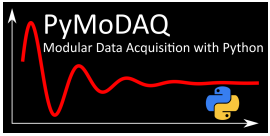
Setups@L2C: Balbuzard

Home made scanning NV microscope at RT

Roméo Beignon



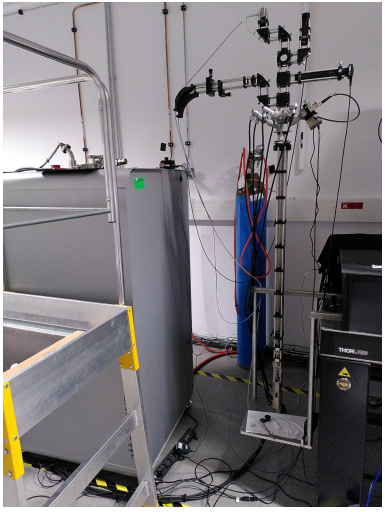
- Attocube AFM
- Home-made confocal microscope
- Coils to go up to 1 mT in any direction
- Controlled with custom Pymodaq plugins



Setups@L2C: Goéland

Home made scanning NV microscope at 4 K

Carolin Schrader

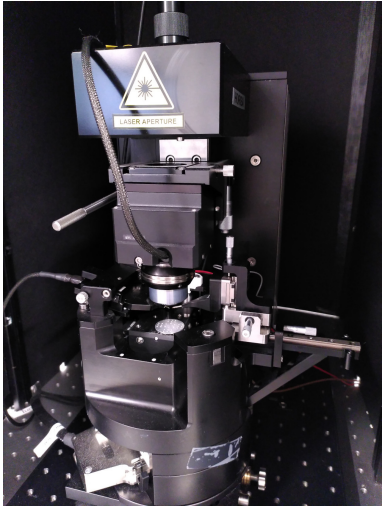


- Attocube AFM
- Home-made confocal microscope
- Operation at 4 K (or RT)
- Superconducting vector magnet up to 0.5 T in any direction
- Compatible with probes with integrated antenna from Qzabre

Setups@L2C: Kamichi

Commercial ProteusQ from Qnami, RT

Elias Sfeir

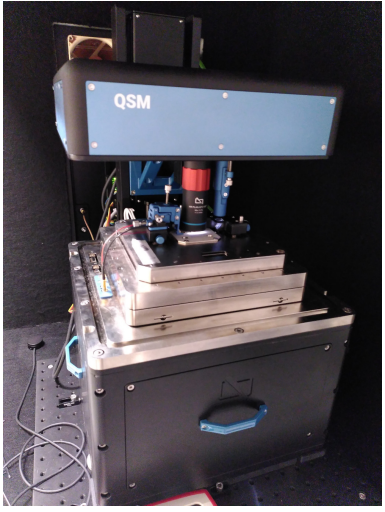


- Commercial microscope from Qnami
- Good AFM from Horiba
- Operation at room temperature
- Magnetic field applied roughly out-of-plane by a permanent magnet around the objective (a few mT)

Setups@L2C: Oréophase

Commercial QSM from Qzabre, RT

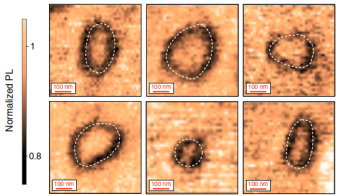
Elijah Wane



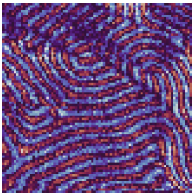
- Commercial microscope from Qzabre
- Operation at room temperature
- Vector electromagnet, field up to 80 mT in any direction
- Advanced spin manipulation protocols included

Some examples

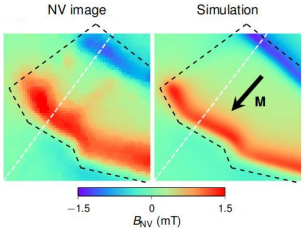
Strong field regime



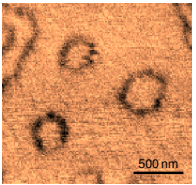
Imaging of antiferromagnetic textures



Magnetization in 2D flakes

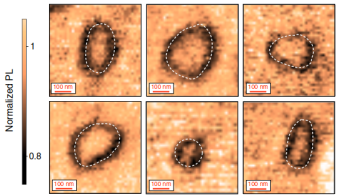


Detection of spin waves

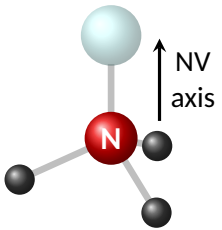


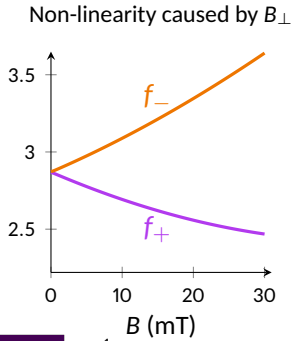
Some examples

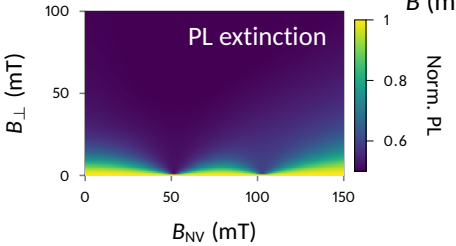
Strong field regime



Photoluminescence extinction at ferromagnetic textures



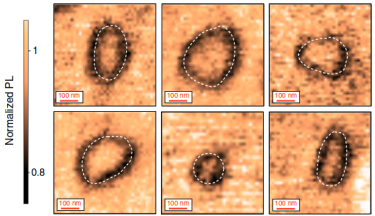




In a strong off-axis field, we lose:

- the linearity
- the photoluminescence
- the ODMR contrast

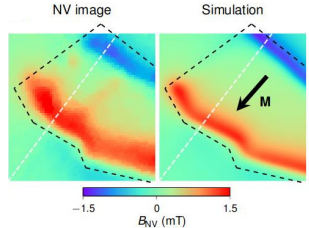
But we can use this to image ferromagnets which produce strong fields!



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

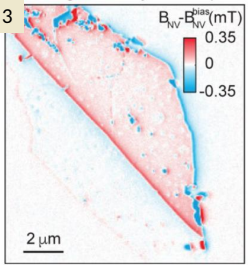
Some examples

Magnetization in 2D flakes



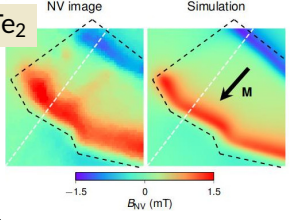
Magnetic imaging of 2D magnets flakes

CrI_3



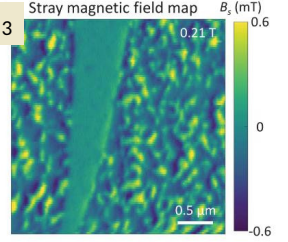
L. Thiel *et al.* *Science* 364 (2019), 973–976

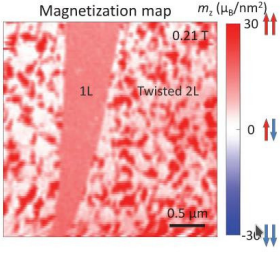
$CrTe_2$



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

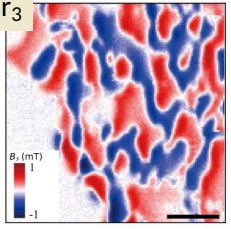
CrI_3





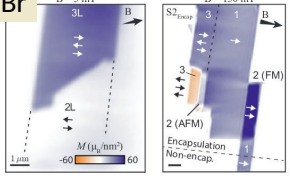
T. Song *et al.* *Science* 374 (2021), 1140

$CrBr_3$



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

CrSBr



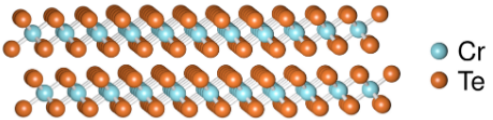
M. A. Tschudin *et al.* *Nat. Commun* (2024), 6005

Ask Carolin about this!

Extracting the magnetization locally

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

Extracting the magnetization locally

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

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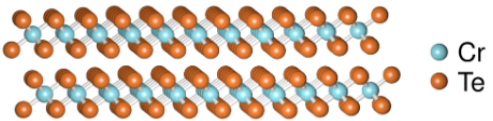

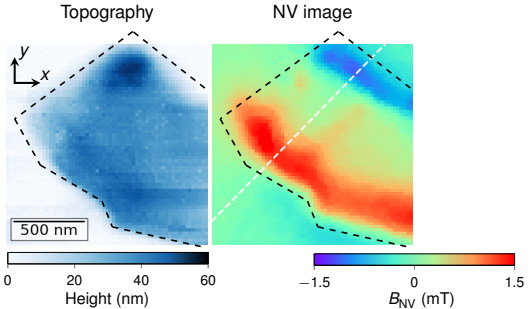

F. Fabre *et al.* *Phys. Rev. Mater.* 5 (2021), 034008

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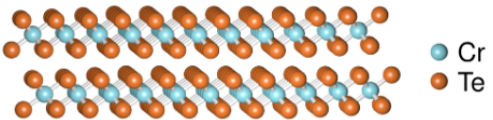

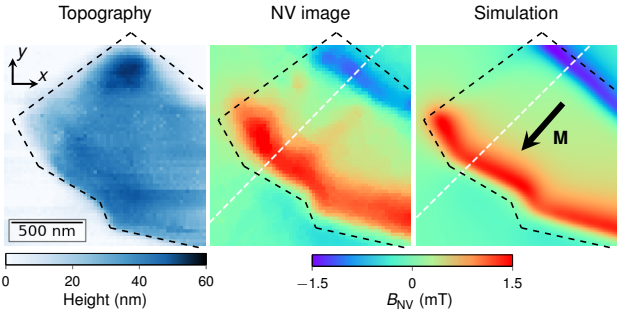

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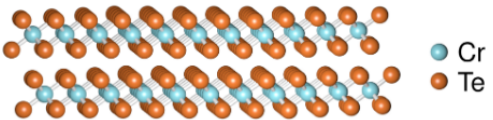
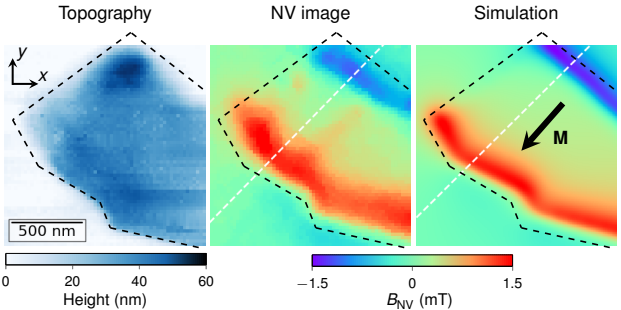
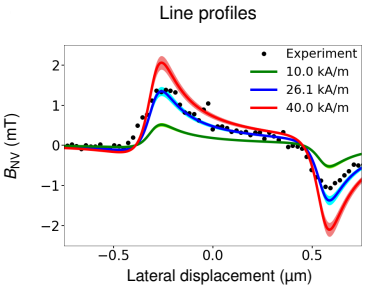


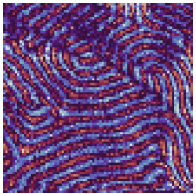




F. Fabre *et al.* *Phys. Rev. Mater.* 5 (2021), 034008

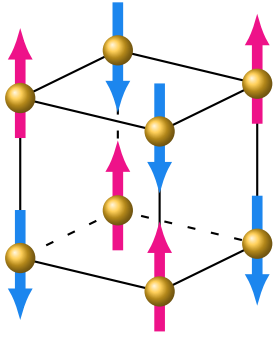
Some examples

Imaging of antiferromagnetic textures



The complex antiferromagnetic state of $BiFeO_3$

G-type antiferromagnet



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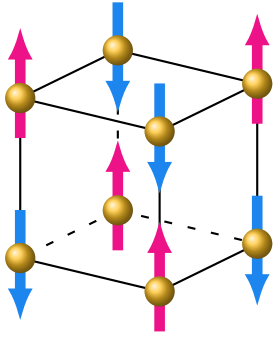

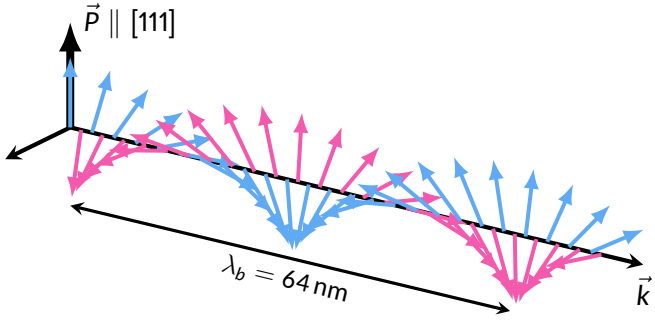

Fully compensated cycloid
$\rightarrow$ **No stray field!**

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

The complex antiferromagnetic state of $BiFeO_3$

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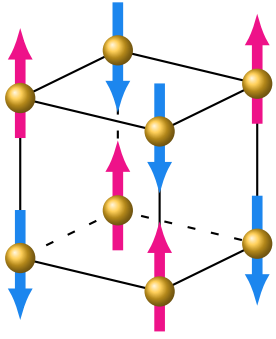
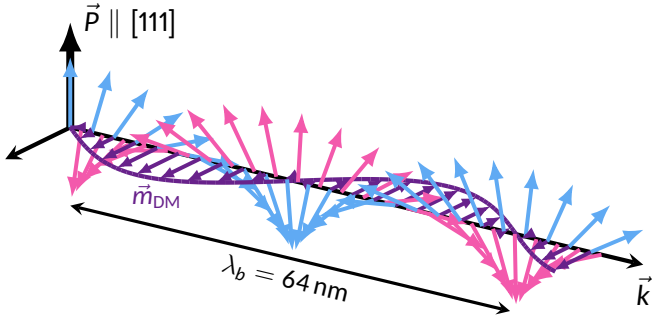


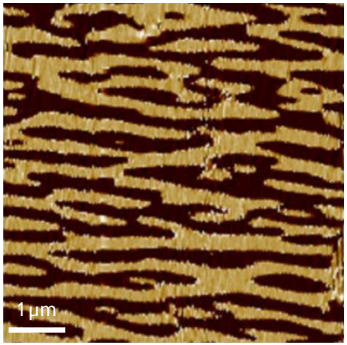


Spin density wave
Weak uncompensated moment
$\rightarrow$ **Small stray field**

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

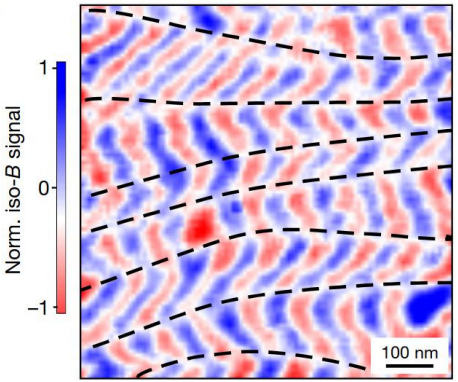
Imaging the cycloid in ultrathin $BiFeO_3$ films

Piezoresponse force microscopy image
Ferroelectric domains



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

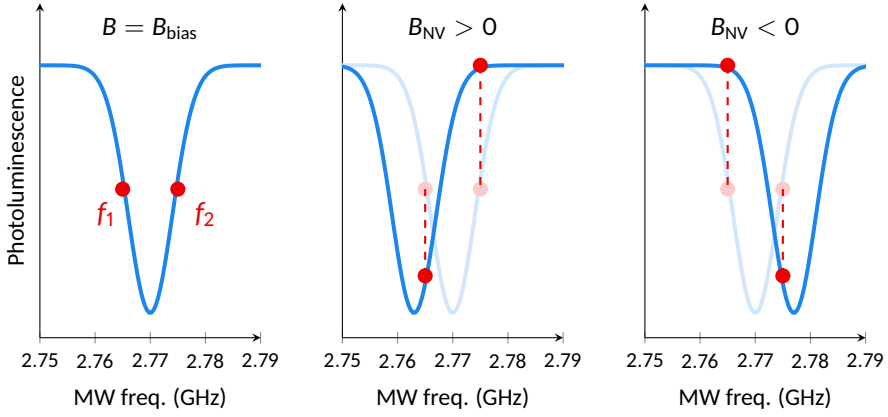
NV image
Field from the spin density wave



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

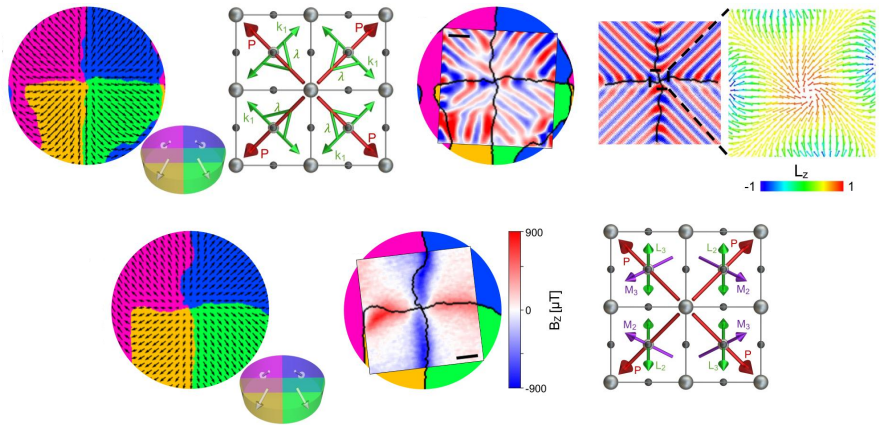
Note: the iso-B mode

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



Design of multiferroic solitons

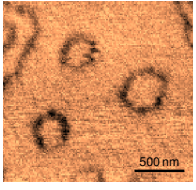
Collaboration: LAF, Palaiseau (A. Chaudron, K. Bouzehouane, S. Fusil, V. Garcia)
SPEC, Saclay (Z. Li, J.-Y. Chauleau, M. Viret)



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

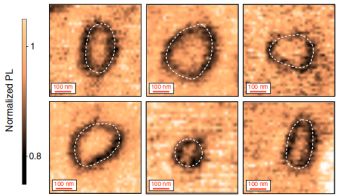
Some examples

Detection of spin waves

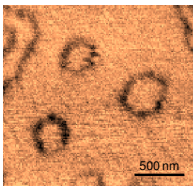


Some examples

Strong field regime



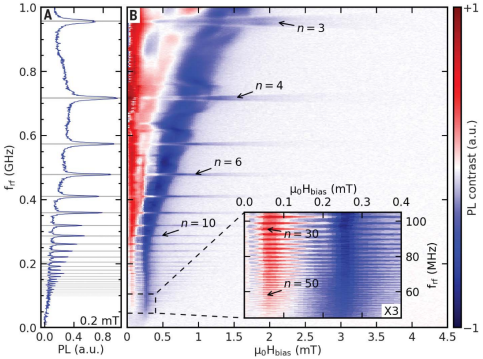
Detection of spin waves



Detecting the stray field from spin waves

First approach

Use the microwave stray field of the spin wave to drive the NV center magnetic transition



C. Koerner *et al*. *Science* 375 (2022), 1165

Ask Roméo about this!

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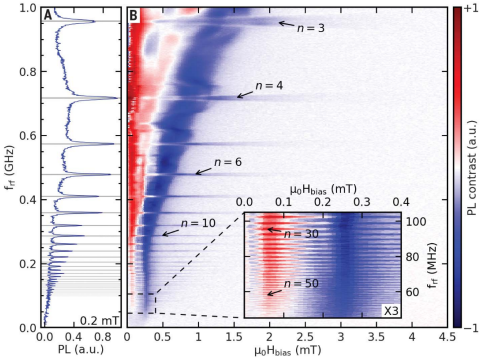
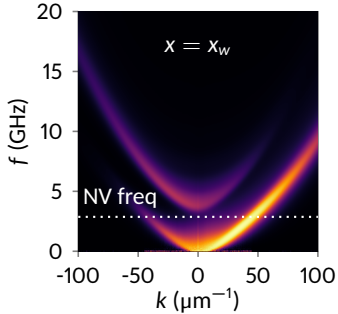


C. Koerner *et al.* *Science* 375 (2022), 1165

Ask Roméo about this!

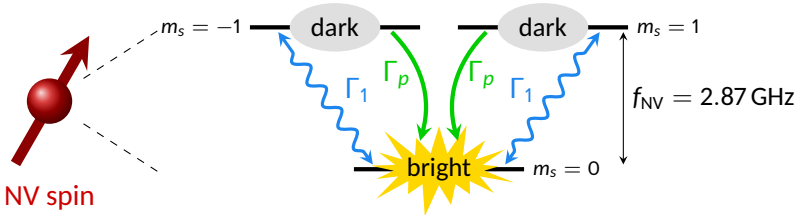
Second approach

Detect the magnetic noise from thermal spin waves



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

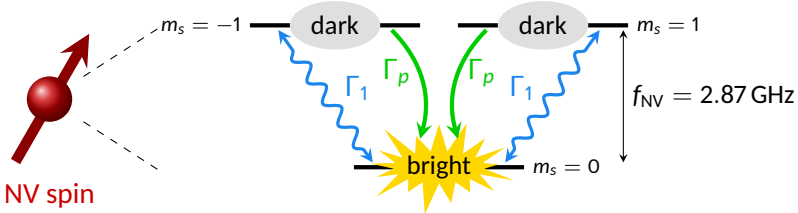
Measuring magnetic noise with NV relaxometry



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

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

Measuring magnetic noise with NV relaxometry



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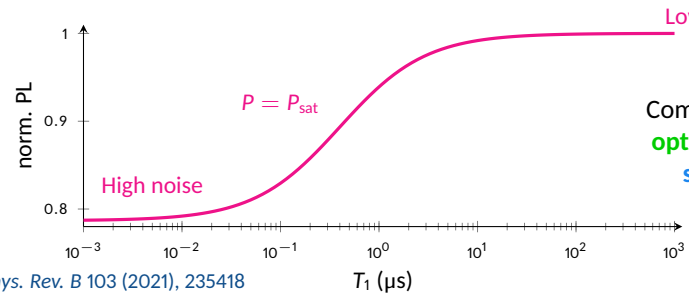

Competition between **optical pumping** and **spin relaxation**

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

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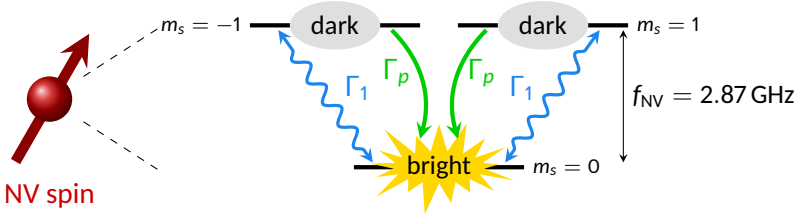

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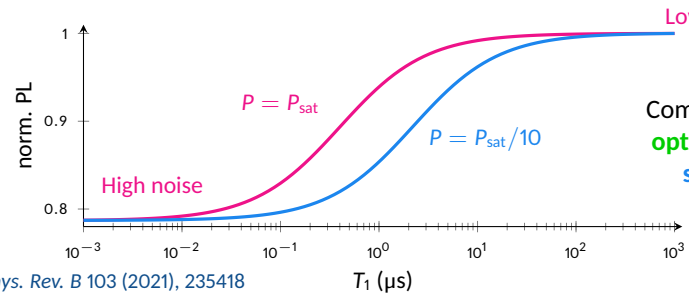
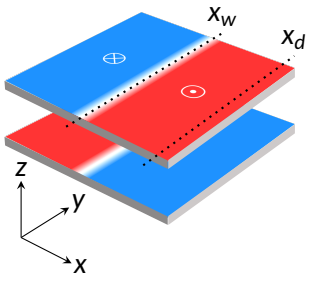
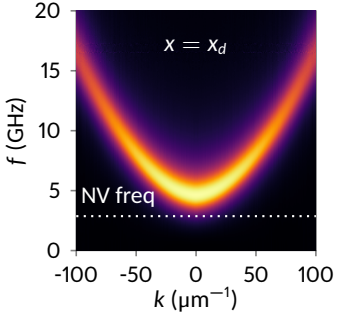


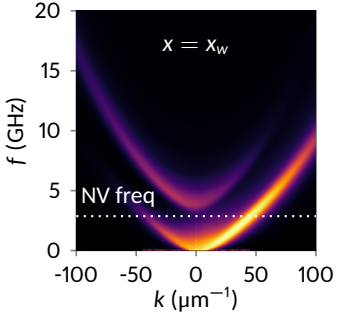
Competition between **optical pumping** and **spin relaxation**

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

Thermal spin waves confined in domain walls







- 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!**

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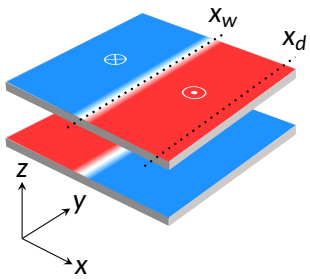

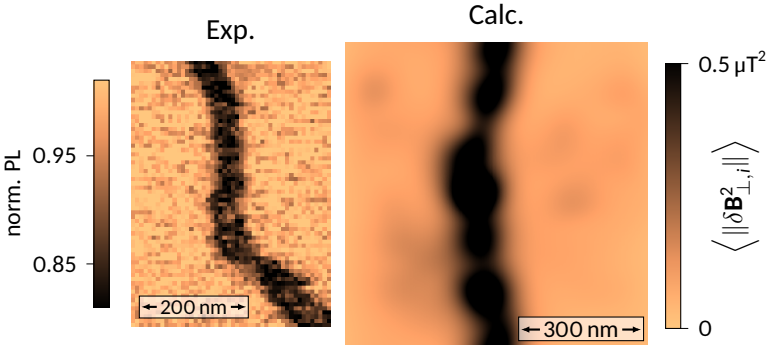

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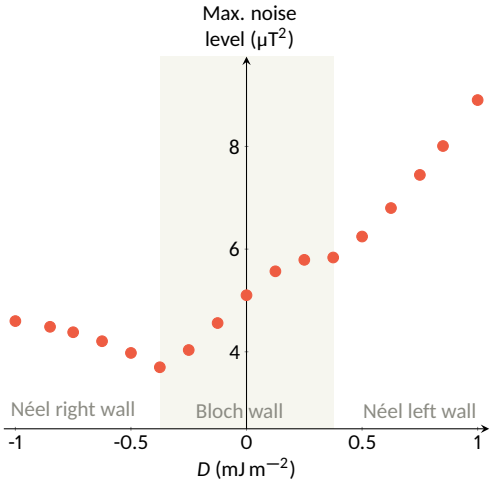
Magnetic handedness dependent noise level



A. Finco *et al.* *very soon on arXiv* (2025)

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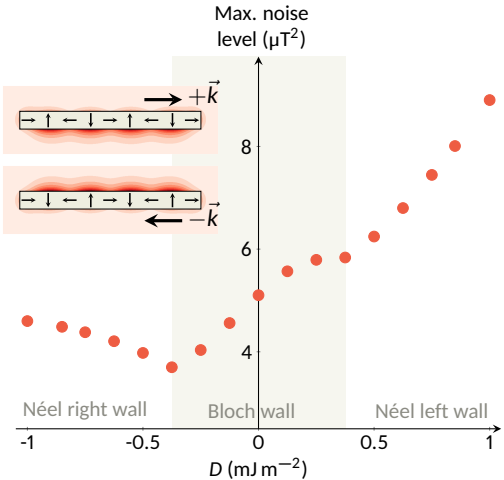

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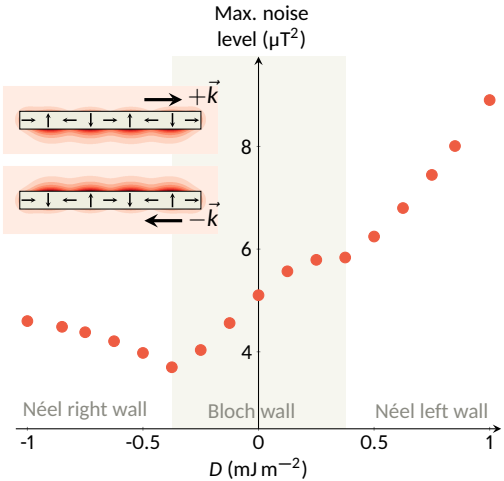

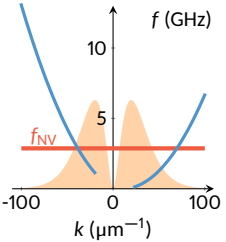

A. Finco *et al.* *very soon on arXiv* (2025)

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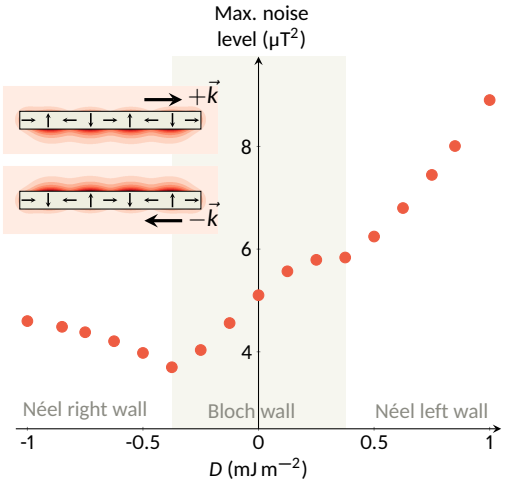

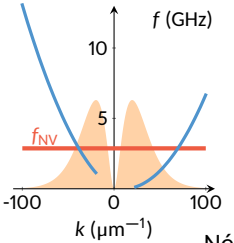

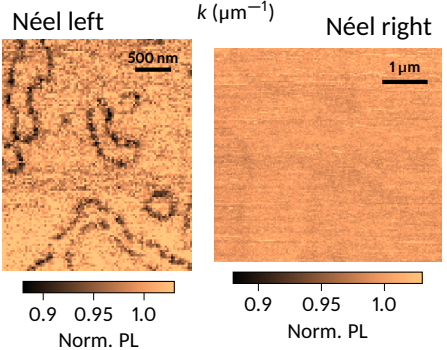

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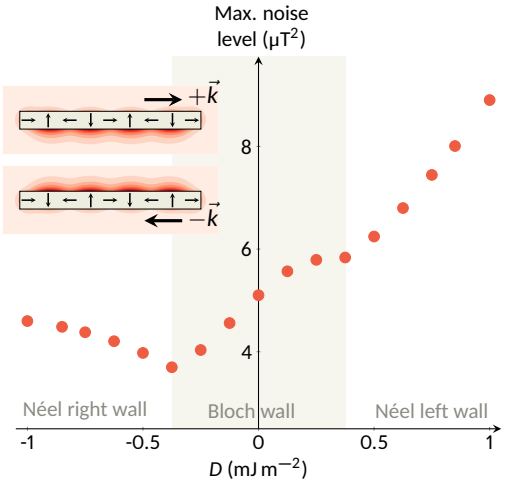
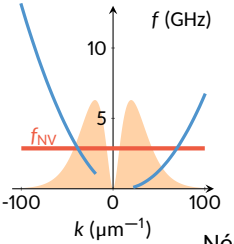
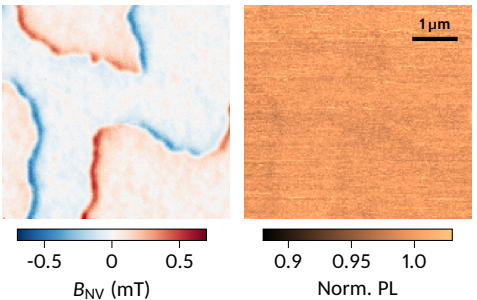




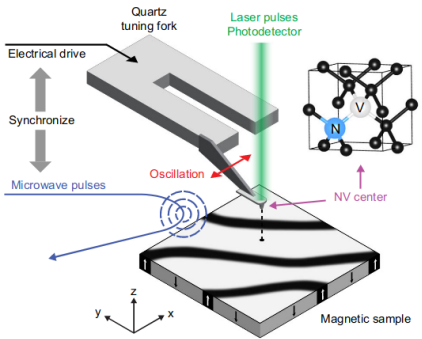
Néel right



A. Finco *et al.* *very soon on arXiv* (2025)

Gradiometry and electrometry

Gradiometry: use a spin echo sequence to improve the magnetic sensitivity



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

Gradiometry and electrometry

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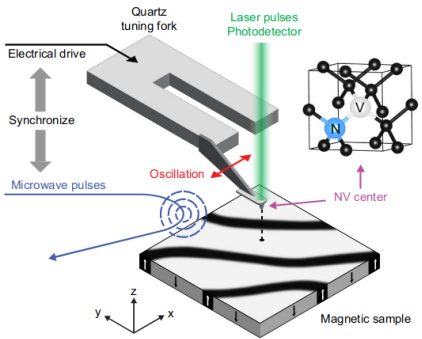
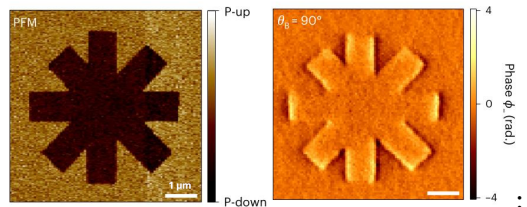


W. S. Huxter *et al.* *Nat. Commun.* 13 (2022), 3761

This approach can be followed to detect Stark shift, much weaker, and therefore electric field!

Ferroelectric domain in PZT

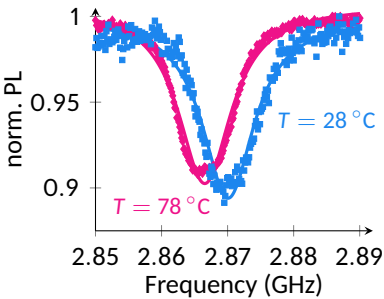


W. S. Huxter *et al.* *Nat. Phys.* 19 (2023), 644

Ask Elijah about this!

Thermometry

Crystal dilatation leads to
a shift of the resonance



Ask Elias about this!

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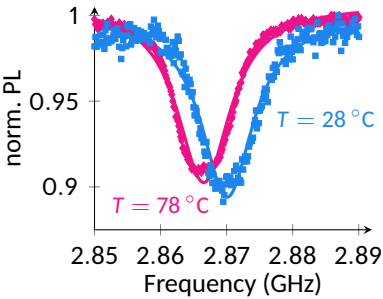

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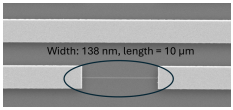
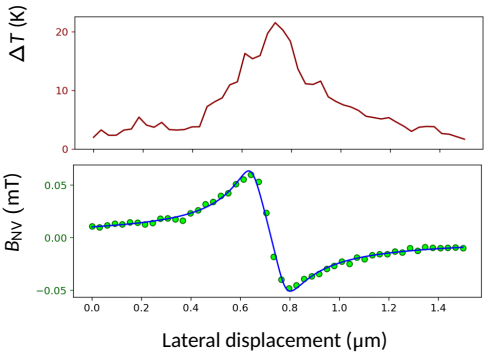


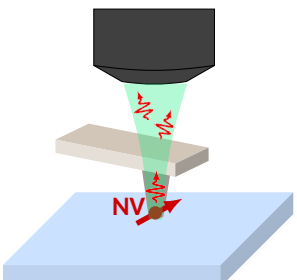
Nanowire of doped Si from CEA Grenoble
$I = 60\ \mu A$



E. Sfeir *et al.* *in preparation* (2025)

Summary and further reading

Scanning NV center microscopy is a powerful and versatile imaging tool for nanoscale magnetic phenomena and more!



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