Probing nanoscale magnetism with quantum sensors: from antiferromagnets to 2D materials

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slides available at https://magimag.eu

How can we use a quantum system to probe nanomagnetism?

C. L. Degen *et al.* *Rev. Mod. Phys.* 89 (2017), 035002

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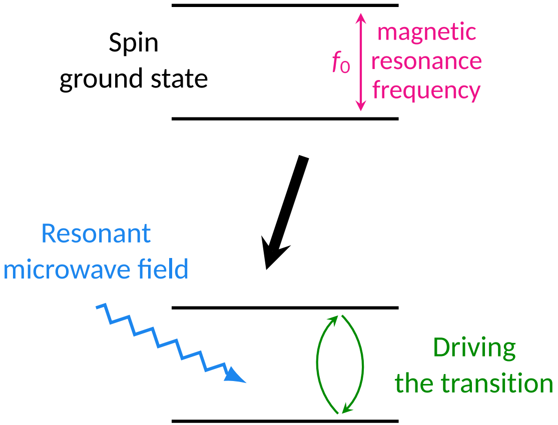

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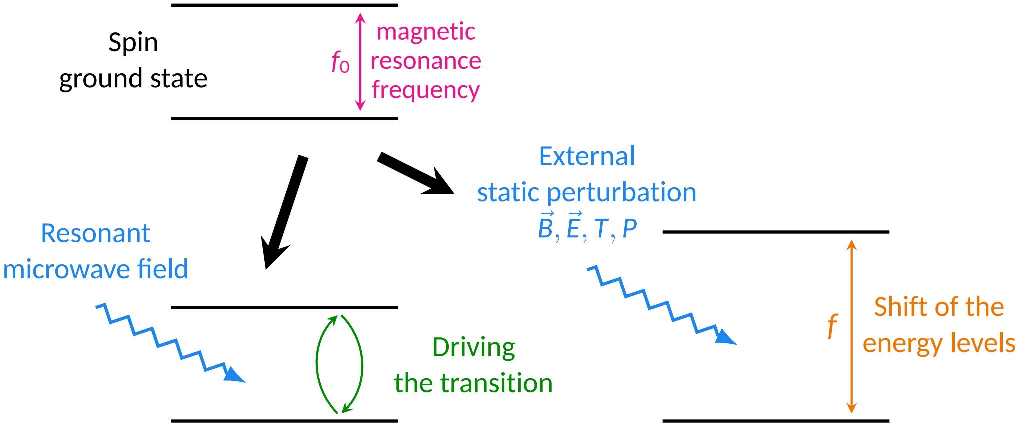

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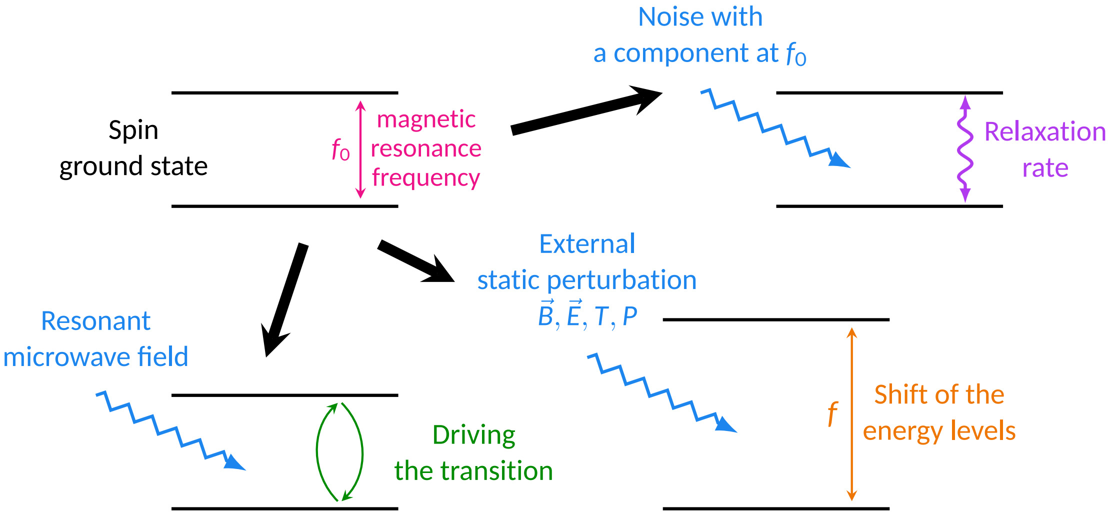

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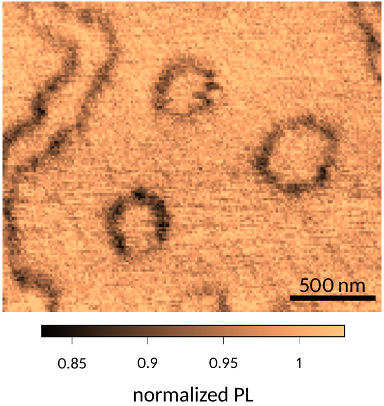
Outline

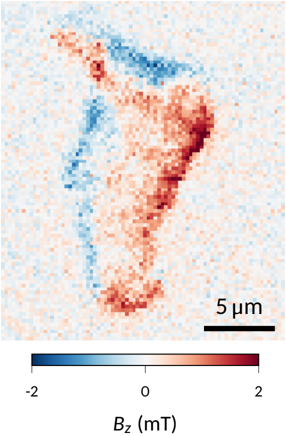
NV centers in diamond

Probe magnetic textures using spin wave noise



Boron vacancies in h-BN

Integrate the sensor in a van der Waals heterostructure



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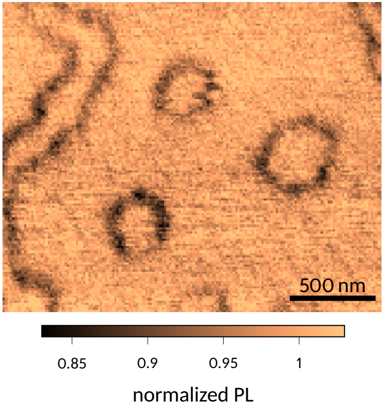

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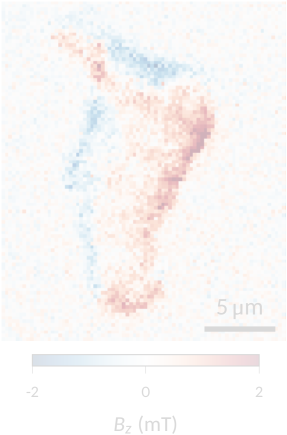
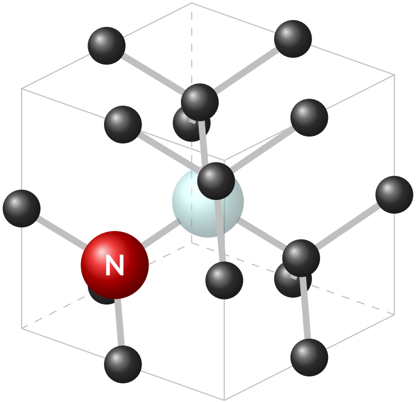


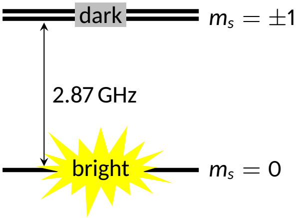
The NV center in diamond



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

Principle of static magnetic field measurement

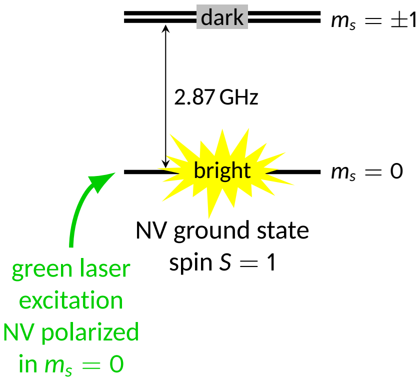
Spin-dependent fluorescence



NV ground state
spin $S = 1$

Principle of static magnetic field measurement

Spin-dependent fluorescence



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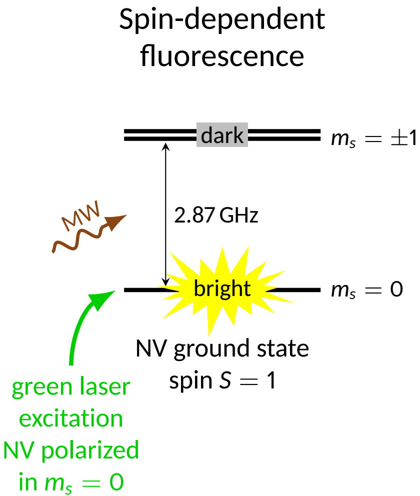

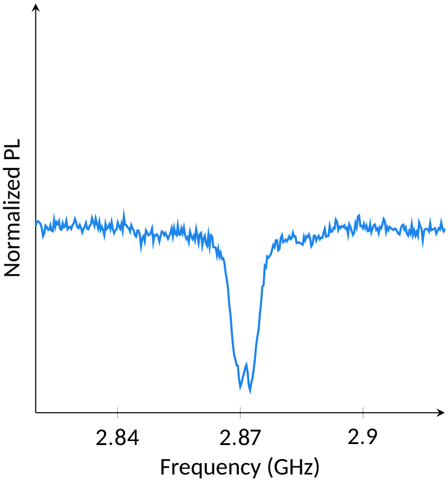

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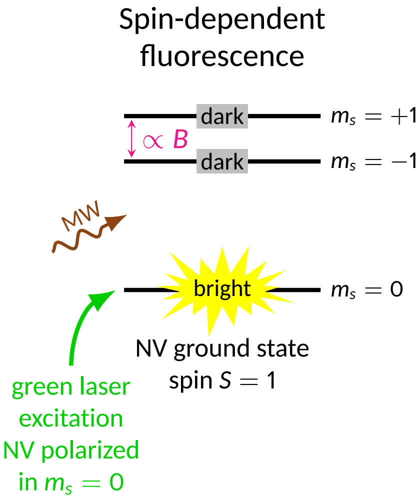

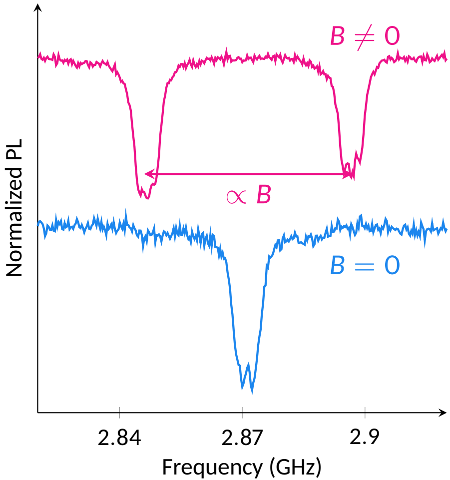

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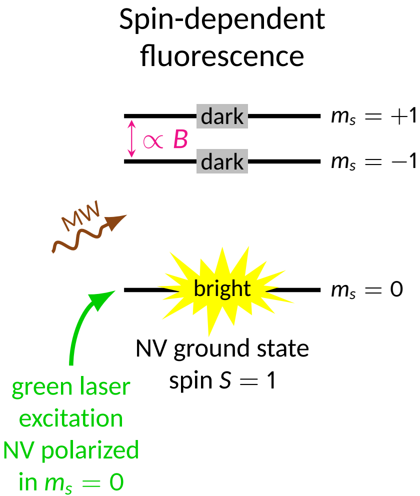
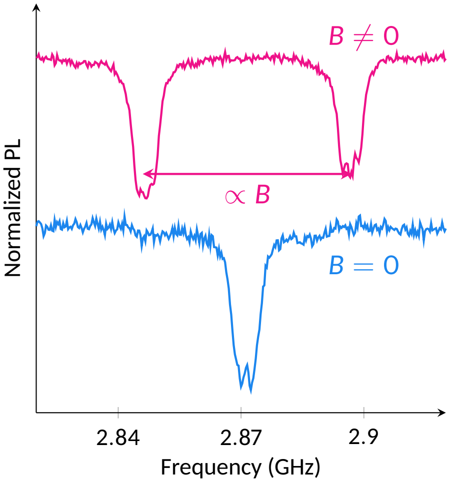
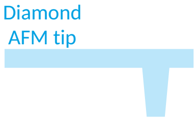
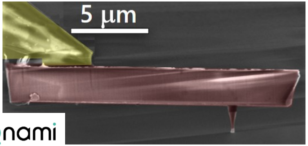




Sensitivity: a few $\mu T/\sqrt{Hz}$

Integration of the defect in a scanning probe microscope





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

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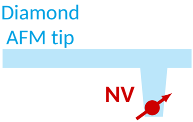

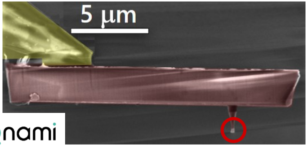

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Implanted single
NV center

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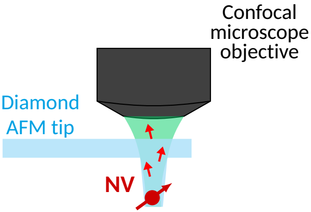

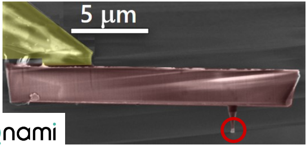

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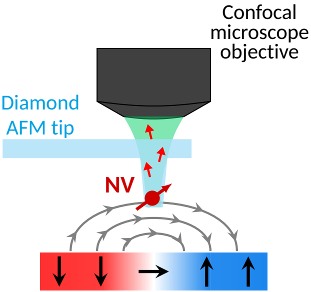

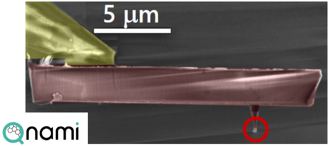

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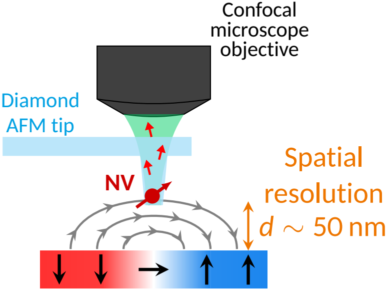

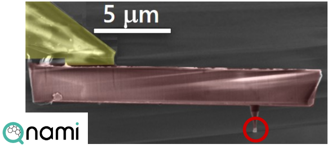

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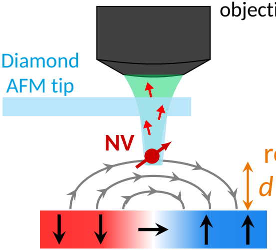

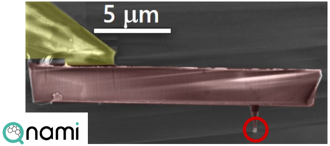

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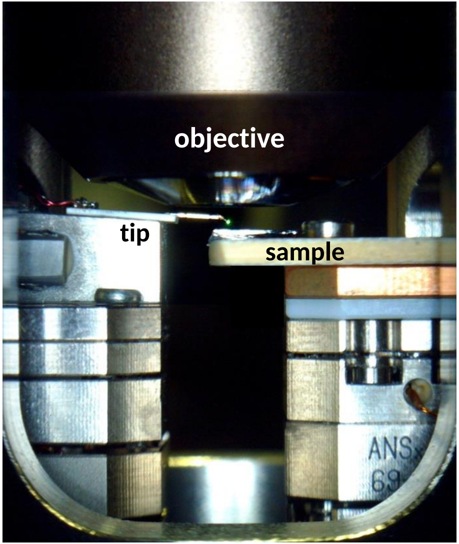

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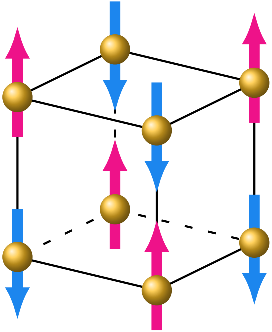
A powerful tool to image antiferromagnets

Example: Bismuth ferrite

G-type antiferromagnet



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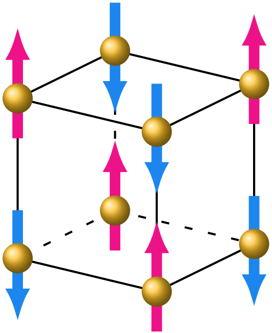

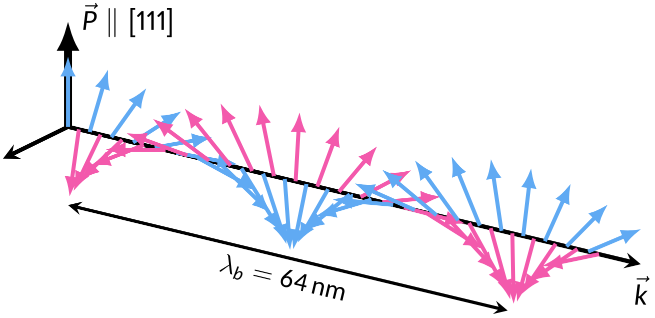

Fully compensated cycloid
$\rightarrow$ **No stray field!**

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

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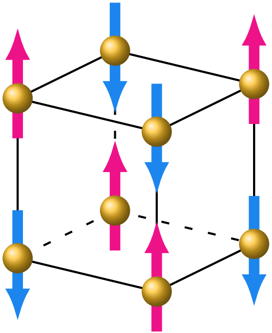
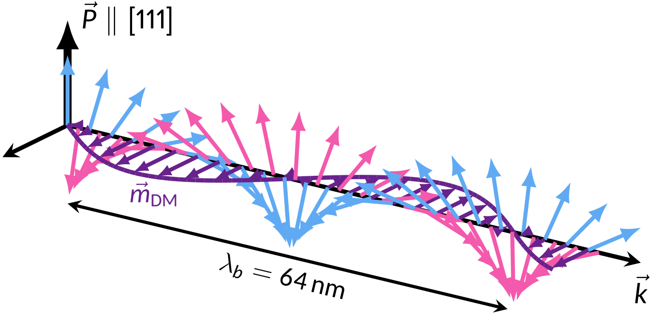
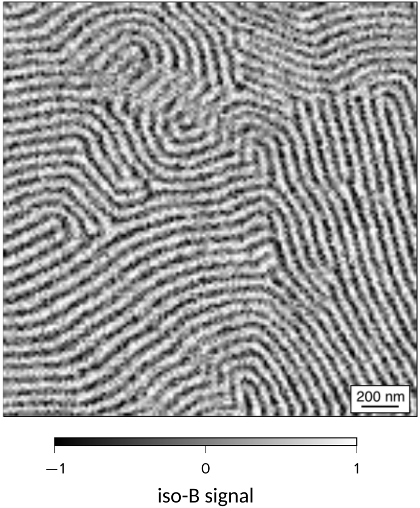




Spin density wave
Weak uncompensated moment
$\rightarrow$ **Small stray field**

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

Topological defects at the surface of bulk $BiFeO_3$ crystals



A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

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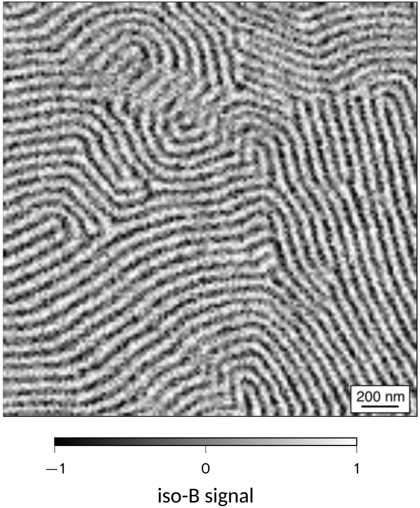

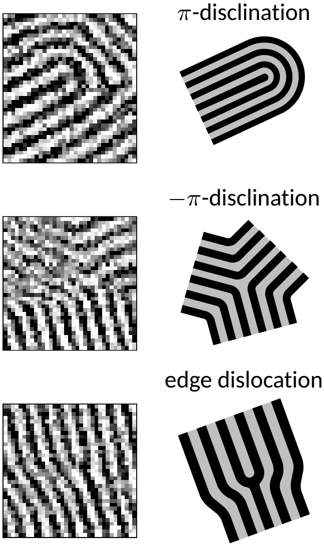

A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

Detection of magnetic noise rather than stray field

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

- Completely compensated antiferromagnets = **no static stray field** to probe
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- Use the different noise properties above domains and domain walls for imaging

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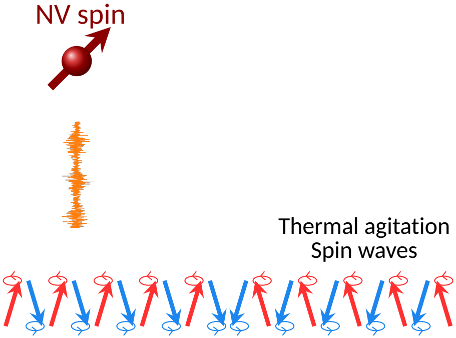

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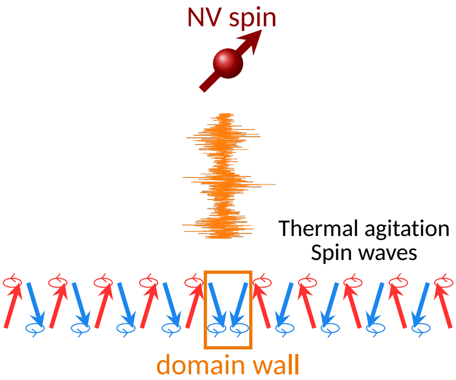
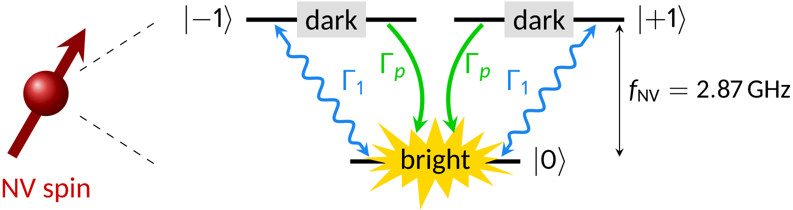


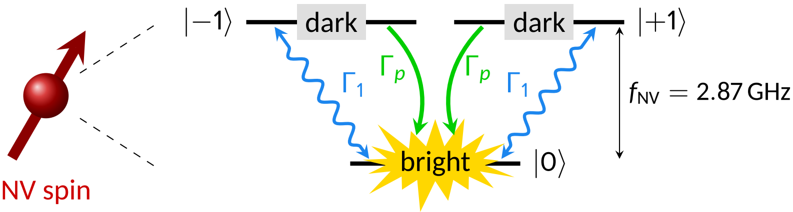
Effect of magnetic noise on the emitted photoluminescence



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

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

Effect of magnetic noise on the emitted photoluminescence



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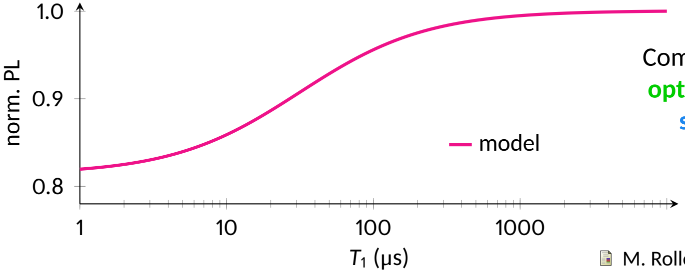

Competition between **optical pumping** and **spin relaxation**

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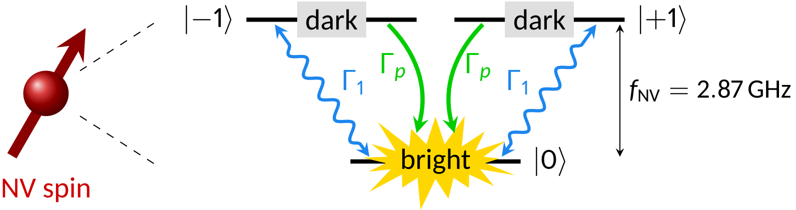

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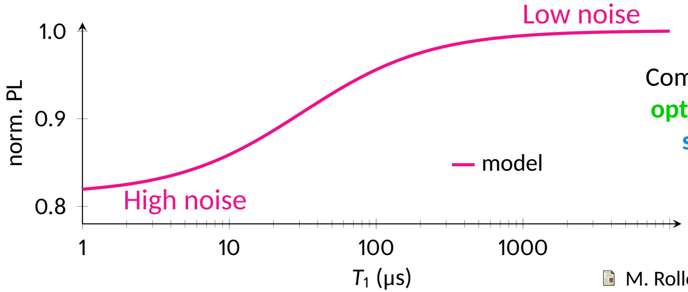

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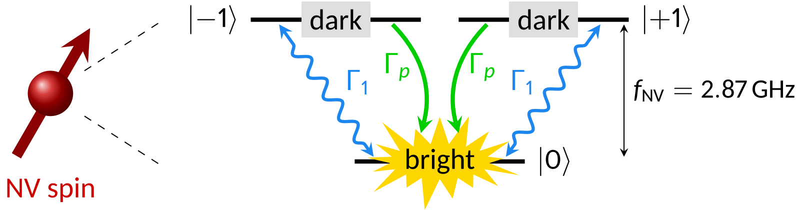

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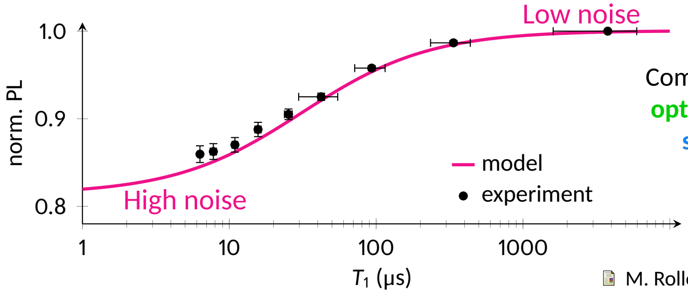


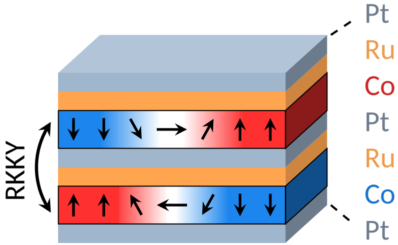
Competition between **optical pumping** and **spin relaxation**

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

Synthetic antiferromagnets

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

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



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

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

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

➔ Perfect test system
for noise imaging!

Which magnetic state do we expect in this stack?

Large magnetic domains with **Néel left** (counter-clockwise) domain walls.

Perpendicular magnetic anisotropy

➔ The magnetization is pointing out-of-plane

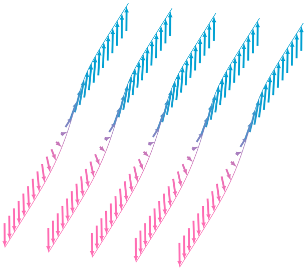
➔ Tuned by the Co thickness

Dzyaloshinkii-Moriya interaction

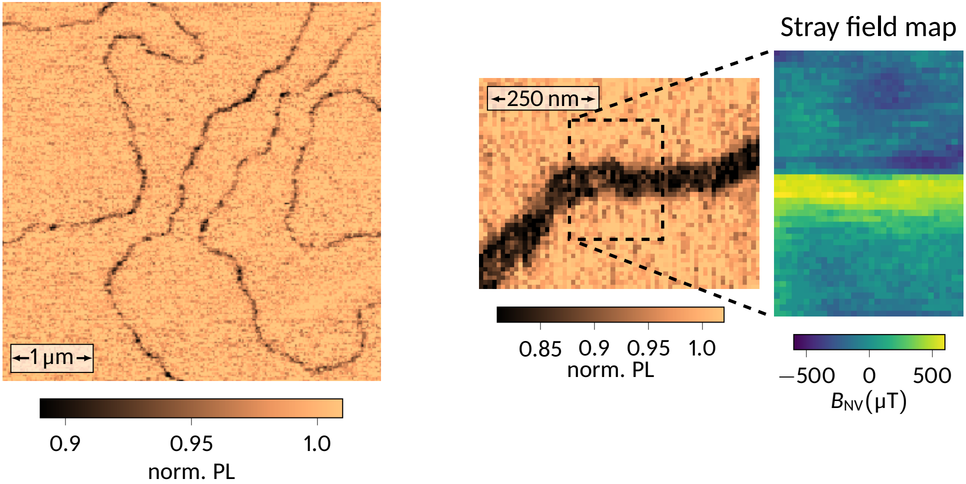
➔ $H_{\mathrm{DMI}} = \vec{D} \cdot (\vec{S_i} \times \vec{S_j})$

➔ Strong at the Pt/Co interface

➔ Favors Néel walls with a fixed chirality

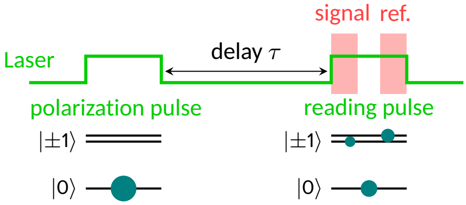


Detection of domain walls by relaxometry



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

Local variation of the relaxation time



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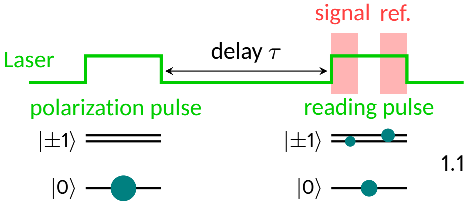

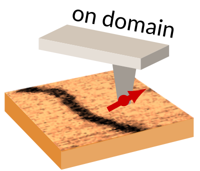

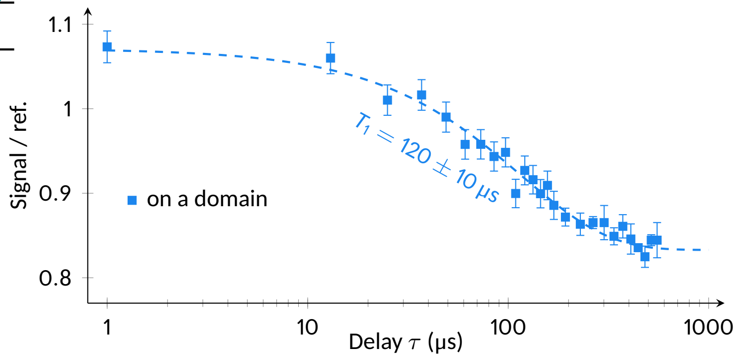

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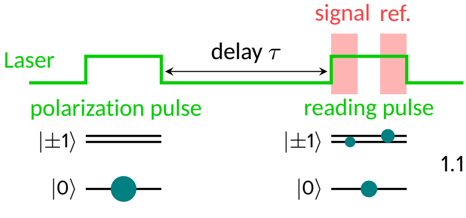
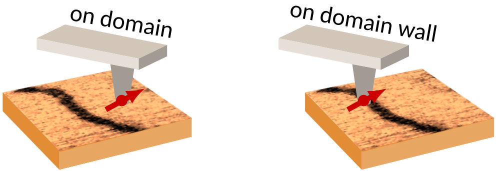
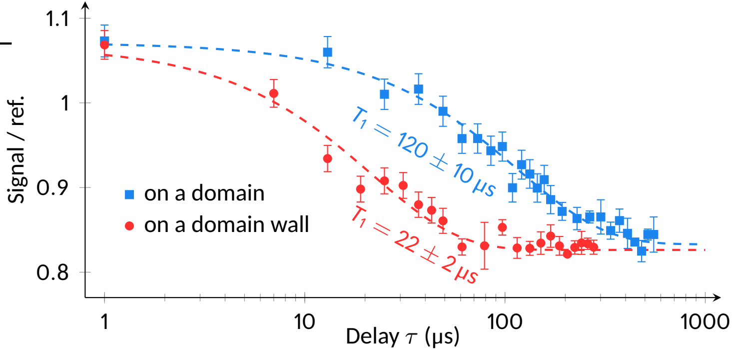


Clear diminution of T_1

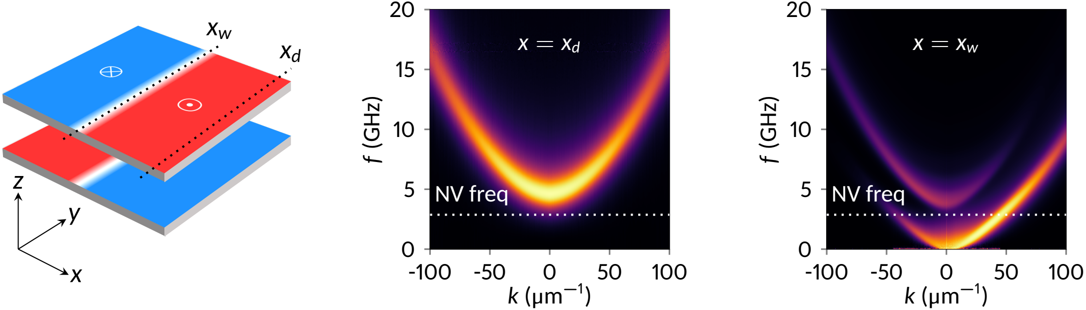
→ **Enhancement of the spin relaxation**





Origin of the noise: spin waves

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



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

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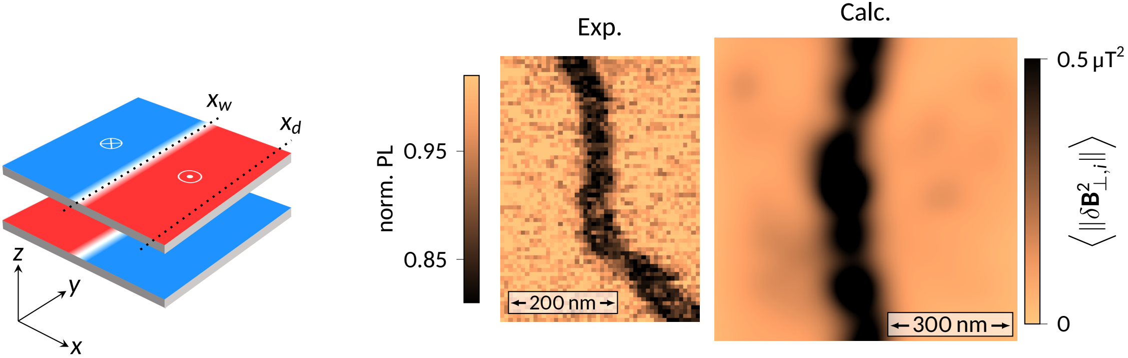

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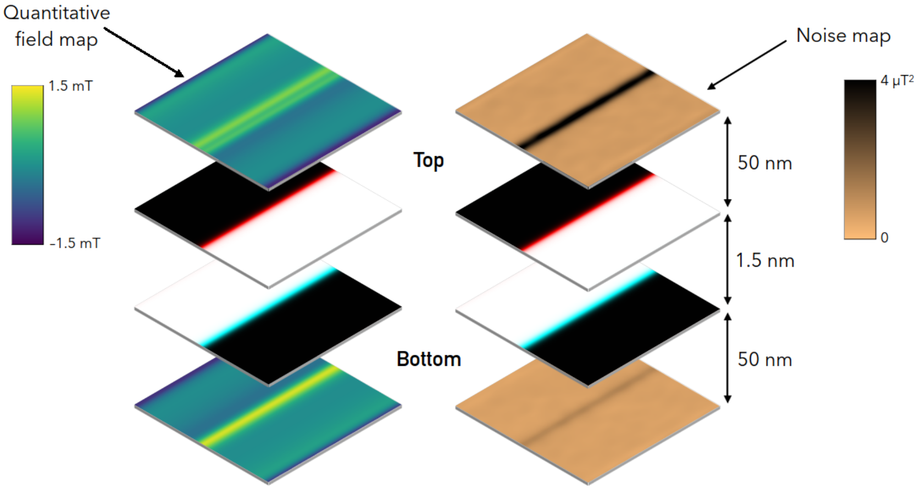
Could we get more insight about the nature of the domain walls? Yes!

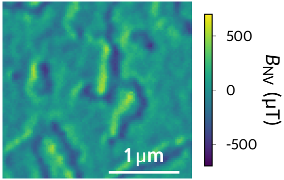
Calculation: C2N, Palaiseau (J.-V. Kim)



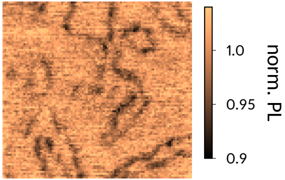
Experiment: looking at both sides of the film

Initial stack: Néel left

Magnetic field map



Noise map



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

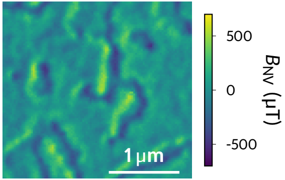
Samples: J. Urrestarazu, R. Guedas, O. Boulle
Spintec, Grenoble

Experiment: looking at both sides of the film

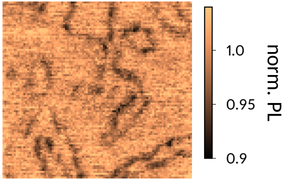
Initial stack: Néel left

- TaOx 3 nm
- Ru 0.6 nm
- Co 1.5 nm
- Pt 0.5 nm
- Ru 0.8 nm
- Co 1.5 nm
- Pt 3 nm
- Ta

Magnetic field map



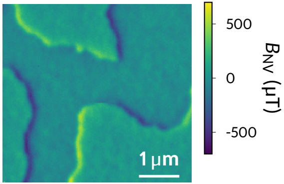
Noise map



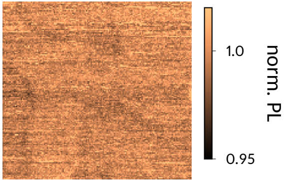
Inverted stack: Néel right

- TEM memb. 20 nm
- Ta 3 nm
- Pt 3 nm
- Co 1.54 nm
- Ru 0.85 nm
- Pt 0.45 nm
- Co 1.54 nm
- Ru 0.6 nm
- Ta 1.5 nm

Magnetic field map



Noise map

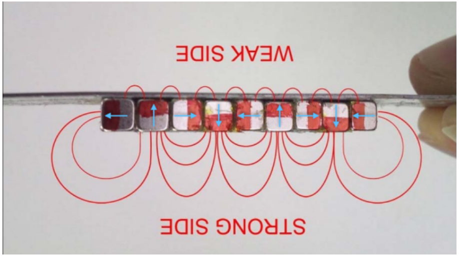


A. Finco *et al.* *in preparation* (2024)

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

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

Halbach arrays



$\vec{m}_0$	$\odot$	$\odot$	$\odot$	$\odot$	$\odot$	
$\delta\vec{m}$	$\rightarrow$	$\uparrow$	$\leftarrow$	$\downarrow$	$\rightarrow$	$+\vec{k}$

$\vec{m}_0$	$\odot$	$\odot$	$\odot$	$\odot$	$\odot$	
$\delta\vec{m}$	$\leftarrow$	$\uparrow$	$\rightarrow$	$\downarrow$	$\leftarrow$	$-\vec{k}$

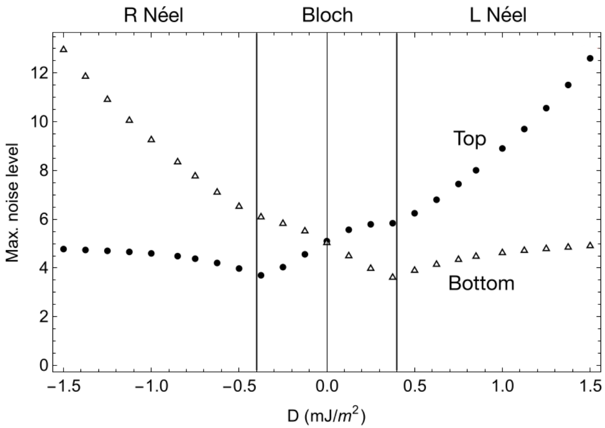
J. Mallinson. *IEEE Trans. on Mag.* 9 (1973), 678

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

Origin of this effect, 2nd ingredient: DMI

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

Calculation made for a **single** ferromagnetic layer

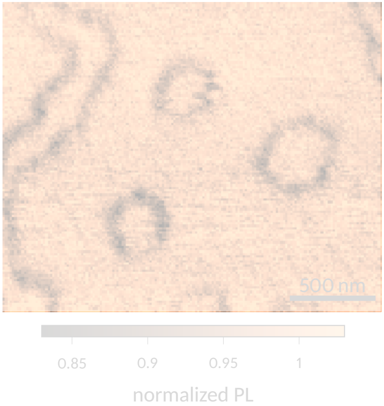


- DMI induces non-reciprocity in the spin wave dispersion
- This results in the selection of a propagation direction for the modes producing the detected noise
- These modes create noise only on one side of the film!

Outline

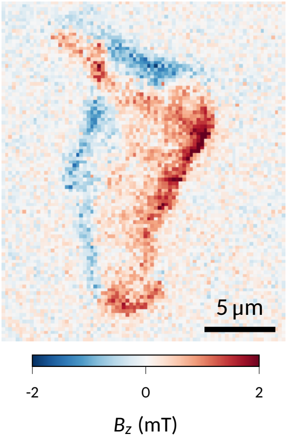
NV centers in diamond

Probe magnetic textures using spin wave noise



Boron vacancies in h-BN

Integrate the sensor in a van der Waals heterostructure

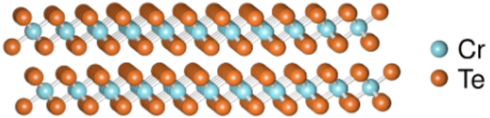


Imaging magnetic van der Waals materials

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

Scanning NV center magnetometry on $CrTe_2$

2D ferromagnet at room temperature with in-plane magnetization



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

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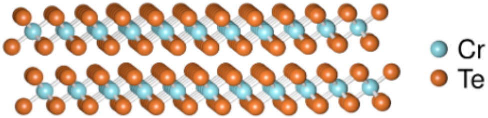

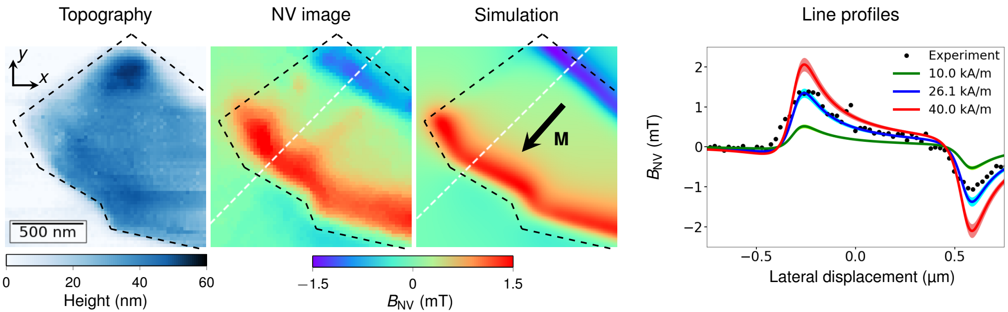

F. Fabre *et al.* *Phys. Rev. Mater.* 5 (2021), 034008

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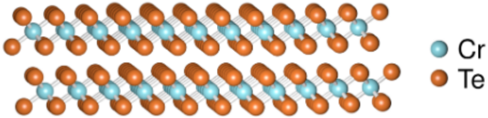
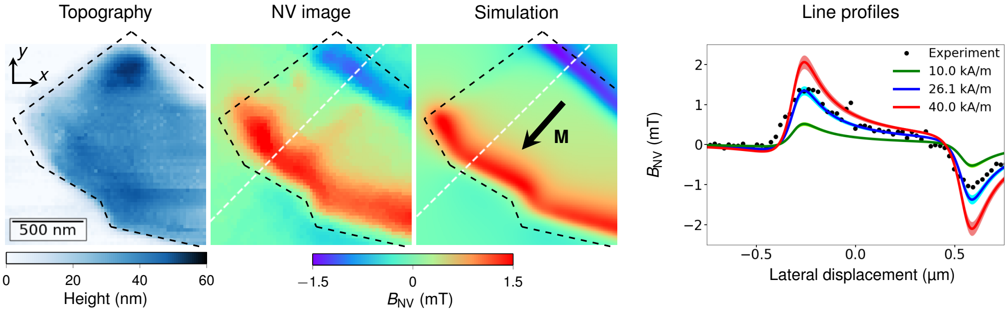




F. Fabre *et al.* *Phys. Rev. Mater.* 5 (2021), 034008

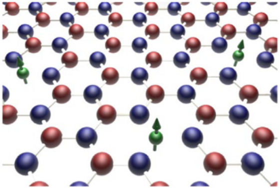
$CrTe_2$ is not stable in air → encapsulation with h-BN

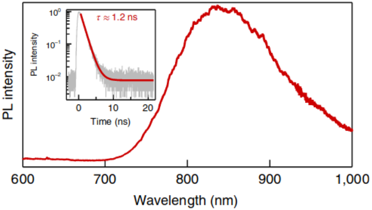
Defects in h-BN

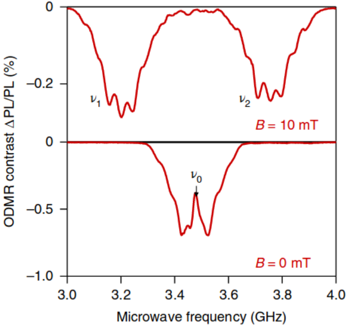
- h-BN is a wide bandgap material (about 6 eV)
- Single photon emitters were known in h-BN

T. T. Tran *et al.* Nature Nanotechnology 11 (2016), 37

- A **spin defect** was identified in 2020

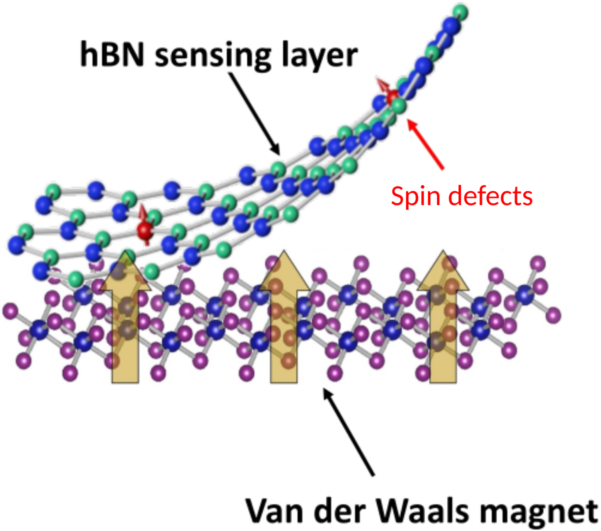






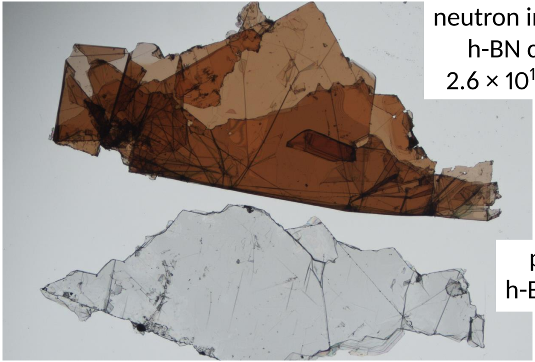
A. Gottscholl *et al.* Nat. Mater. 19 (2020), 540

Objective: a quantum sensing foil integrated in the van der Waals heterostructure



Creating ensembles of boron vacancies in h-BN

Collaboration: Kansas State University (J. Li, J. Edgar)



S. Liu *et al*. *Chem. of Mater.* 30 (2018), 6222

Creating ensembles of boron vacancies in h-BN

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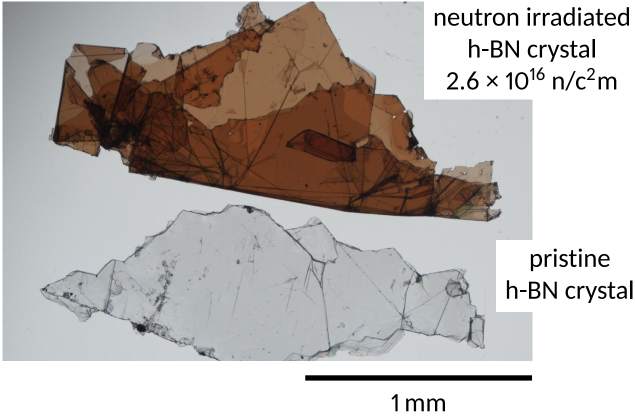
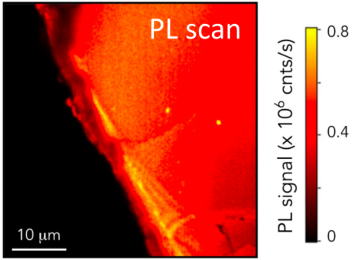


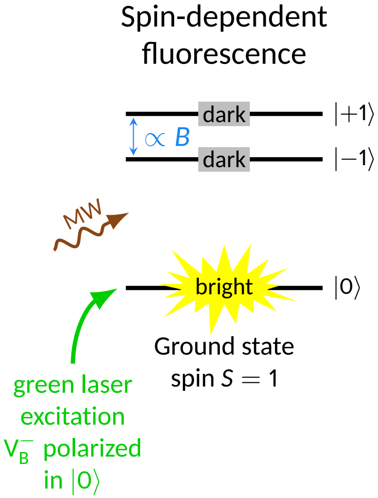
S. Liu *et al.* *Chem. of Mater.* 30 (2018), 6222

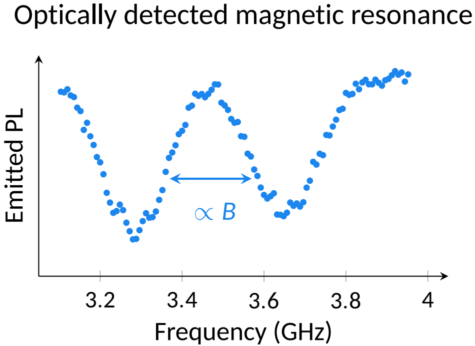
- Excitation at 532 nm
- Ambient conditions



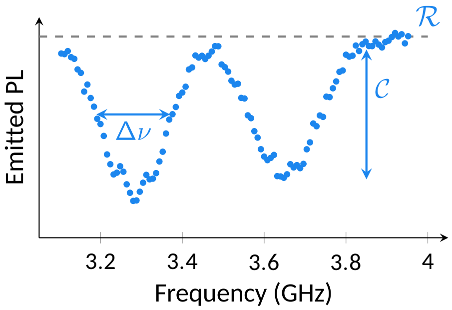
A. Haykal *et al.* *Nat. Commun.* 13 (2022), 4347

Measuring magnetic fields with V_B^-

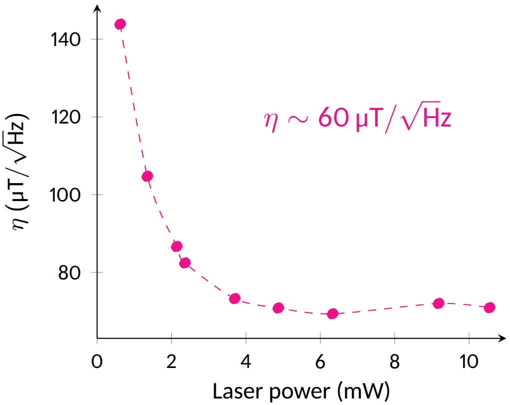




Magnetic field sensitivity



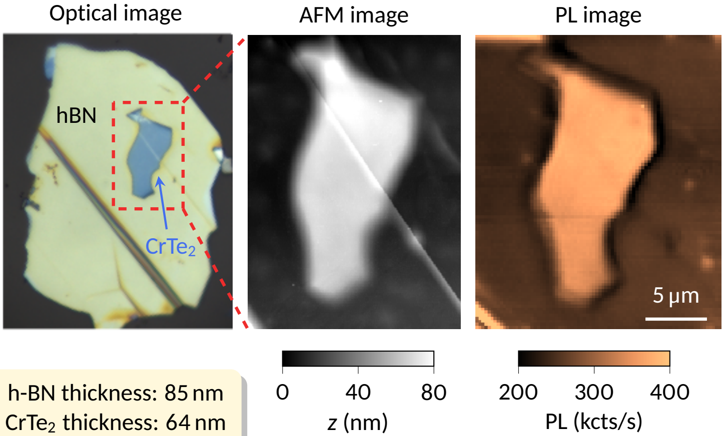
$$\eta \sim 0.7\,\frac{1}{\gamma_e}\,\frac{\Delta\nu}{\mathcal{C}\sqrt{\mathcal{R}}}$$



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

Imaging a $CrTe_2$ flake

Collaboration: Institut Néel, Grenoble and LPCNO, Toulouse



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

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

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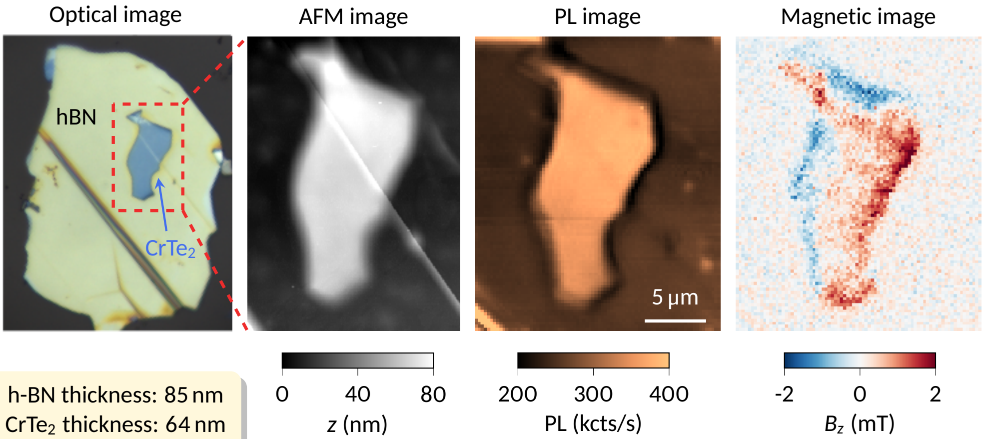


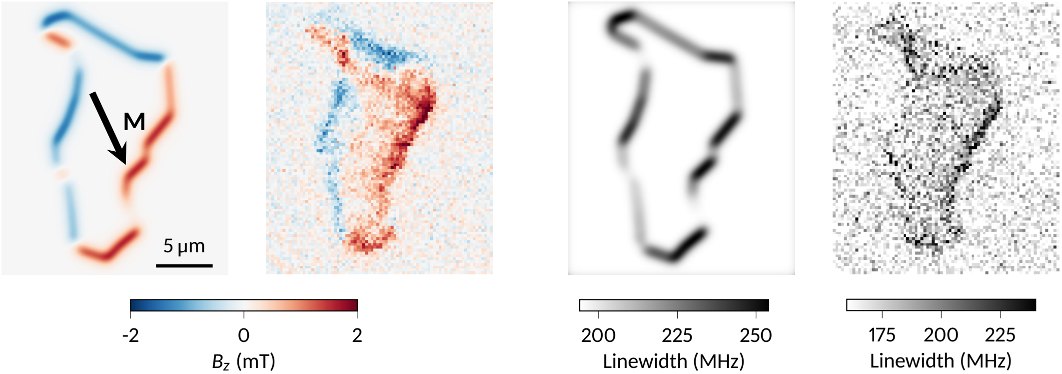
h-BN thickness: 85 nm
$CrTe_2$ thickness: 64 nm

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

Comparison with simulations

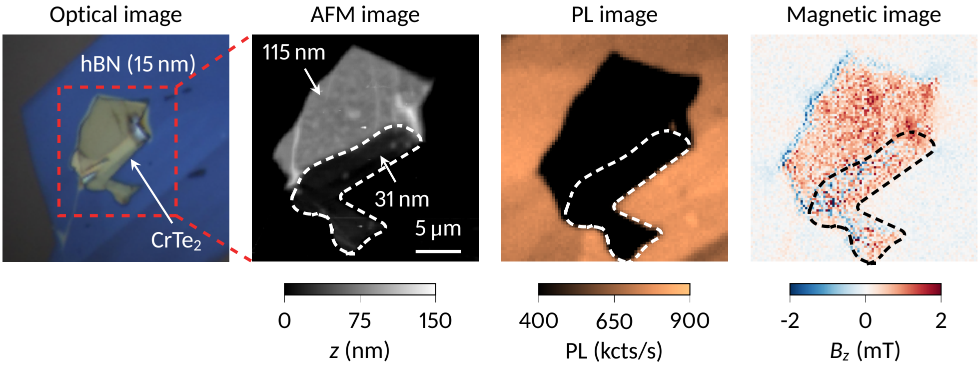
Two averaging procedures are necessary:

- Vertically, over the h-BN film thickness
- Laterally, over the gaussian profile of the laser beam



→ **Being really quantitative is difficult, using thinner flakes would help!**

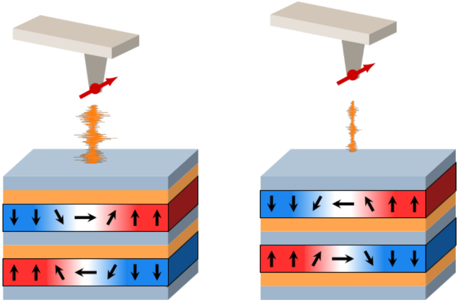
Using thinner flakes



- PL quenching effect at the metallic surface of $CrTe_2$
- Need for larger laser excitation power
- Heating of the magnetic material, crossing T_C

Summary

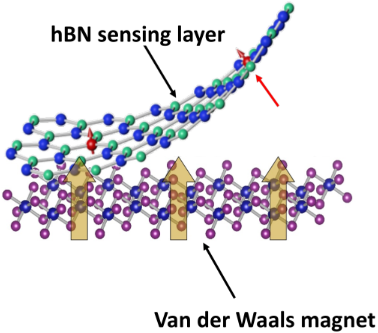
Localization and characterization of magnetic textures for thermal spin wave noise using scanning NV center microscopy



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

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

Imaging van der Waals magnets with boron vacancies in hBN, integrating the sensor inside the heterostructure



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

A. J. Healey *et al.* *Nat. Phys.* 19 (2023), 87

M. Huang *et al.* *Nat. Commun.* 13 (2022), 5369

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C2N, Palaiseau

Thibaut Devolder, Jean-Paul Adam, Joo-Von Kim

Spintec, Grenoble

Van-Tuong Pham, Joseba Urrestarazu Larranaga, Rodrigo Guedas Garcia, Olivier Boulle

Kansas State University

Jiahan Li, James Edgar

Institut Néel, Grenoble

Johann Coraux, Nicolas Rougemaille

LPCNO, Toulouse

Jules Fraunié, Pierre Renucci, Xavier Marie, Cédric Robert

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