Antiferromagnetic textures imaged by probing thermally excited spin waves

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LABORATOIRE CHARLES COULOMB MONTPELLIER

UNIVERSITÉ DE MONTPELLIER

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CHIRON workshop, April 27th 2022

slides available at https://magimag.eu

S2QT team at L2C in Montpellier

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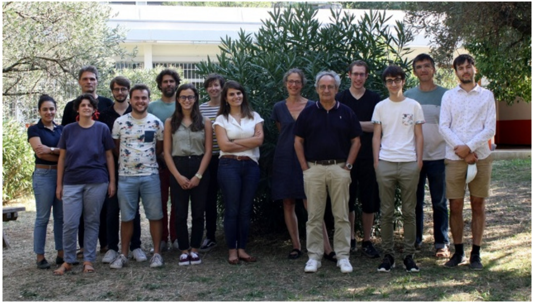
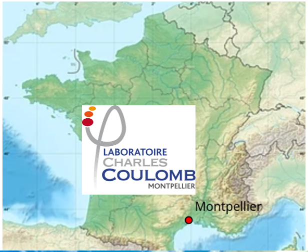


→ Ultrawide bandgap semiconductors
→ Point defects in semiconductors
→ Quantum sensing



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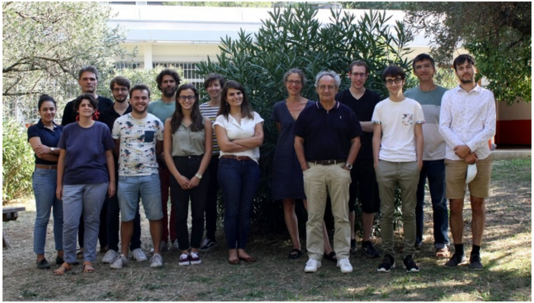

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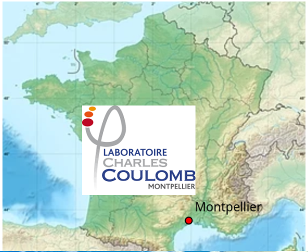
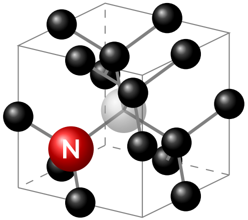
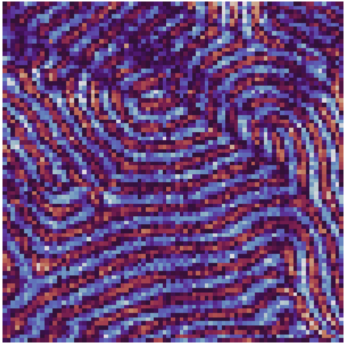


Outline

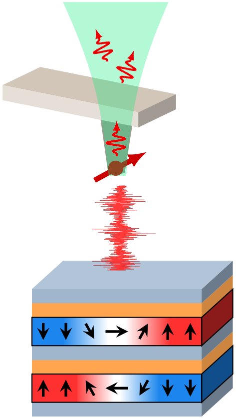
Spin waves detection with NV centers in diamond



Scanning-NV magnetometry applied to antiferromagnets



Imaging of antiferromagnetic textures by probing thermally excited spin waves



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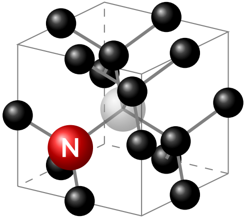

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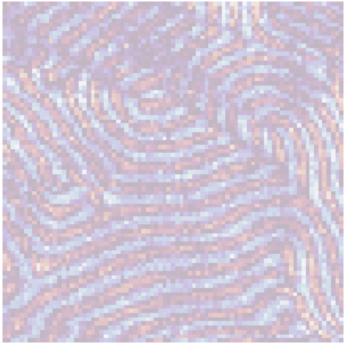

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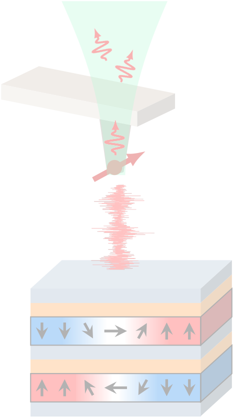
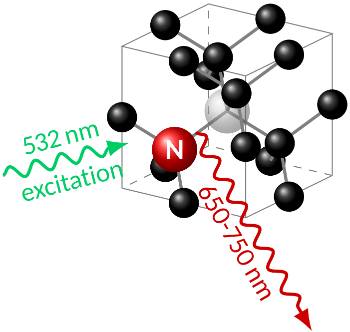
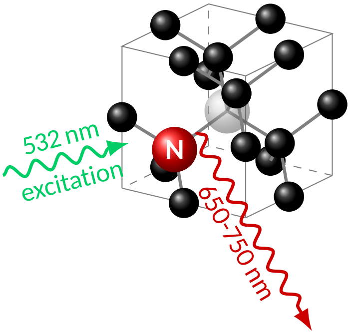


Quantum sensing with NV centers in diamond



Nitrogen-Vacancy defect
in diamond

Quantum sensing with NV centers in diamond



Nitrogen-Vacancy defect
in diamond

$\vec{B}$ Magnetic field

T Temperature

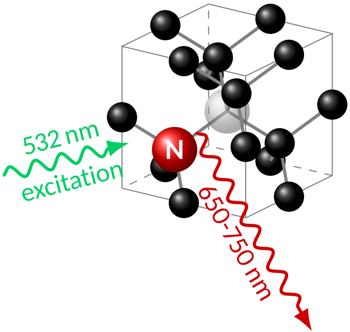
$\vec{E}$ Electric field

Electronic spin S=1
energy levels
dynamics

$\langle \vec{B} \rangle$ Magnetic noise

σ Strain

Quantum sensing with NV centers in diamond



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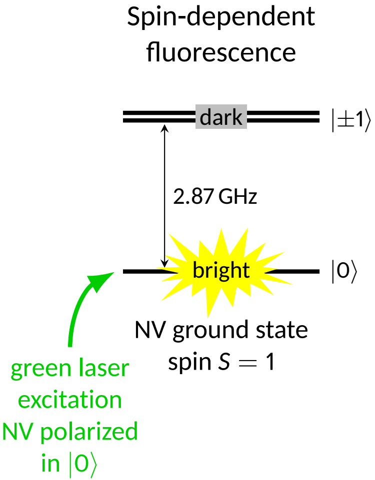
How do we measure magnetic field?



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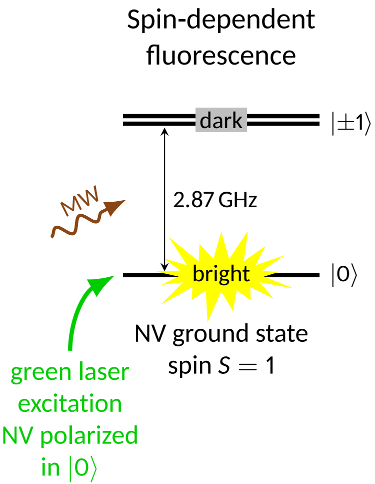

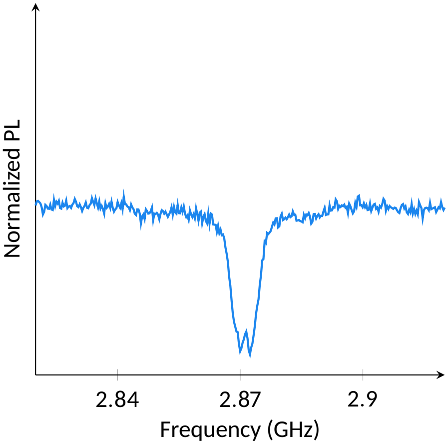

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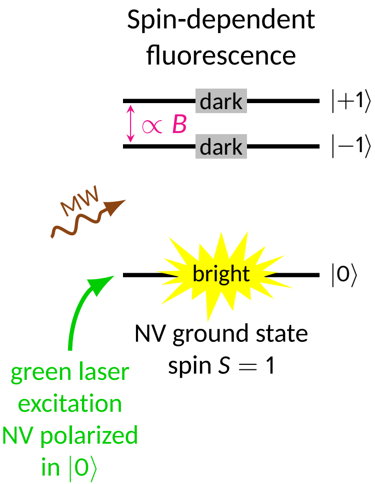
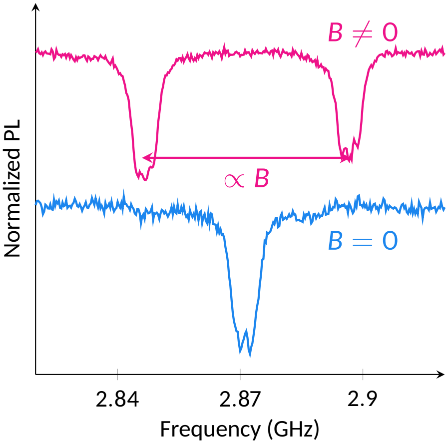
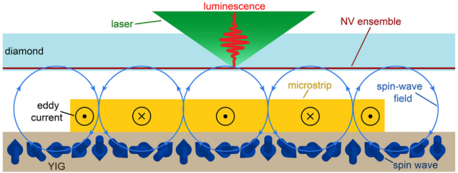




- Stronger MW signal → larger contrast
- Sensibility: a few $\mu T/\sqrt{Hz}$

Application to the detection of resonant spin waves

T. van der Sar group
Delft



I. Bertelli *et al.* *Adv. Qu. Tech.* 4 (2021), 2100094

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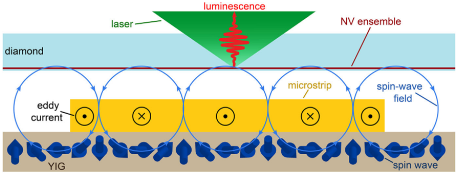

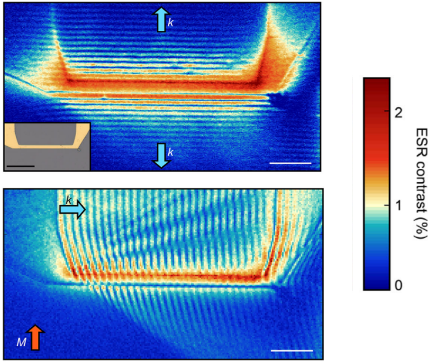

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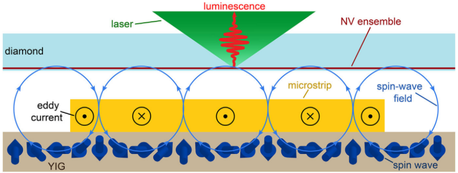

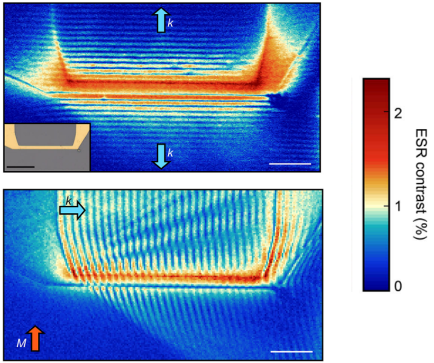

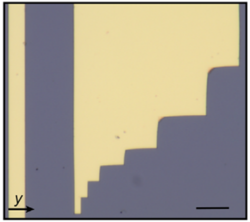

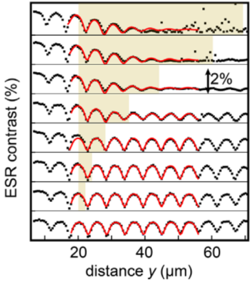

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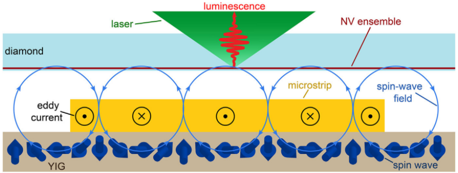
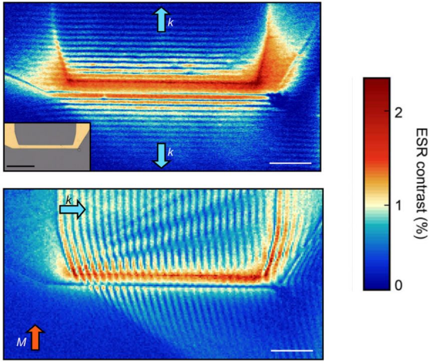
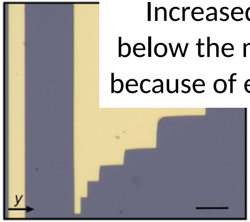
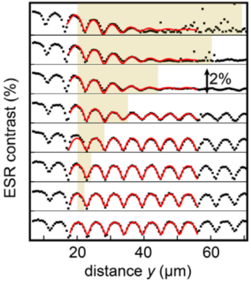






Increased damping below the metallic layer because of eddy currents



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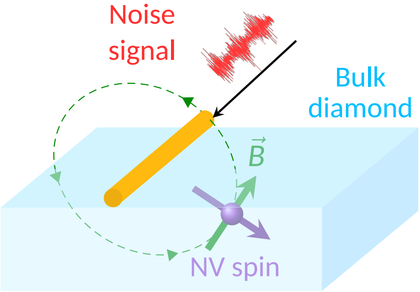
Other approach: relaxometry to probe magnetic noise



Collaboration C2N: T. Devolder

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

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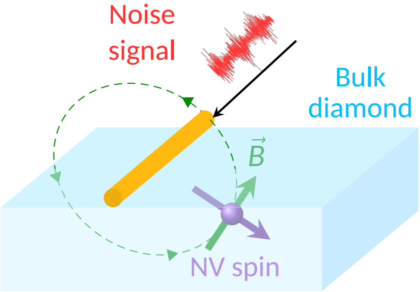

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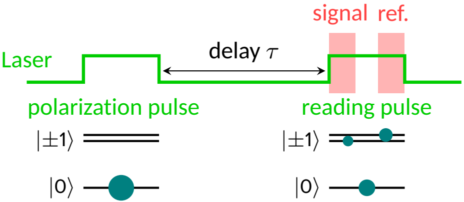

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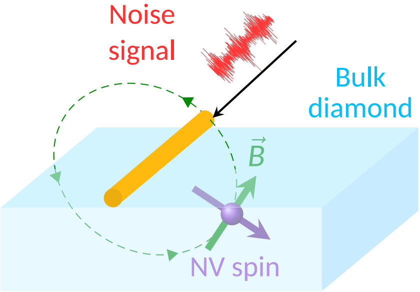

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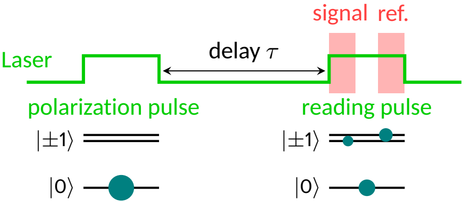

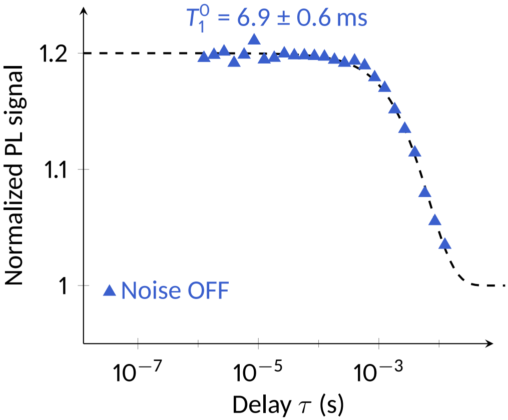

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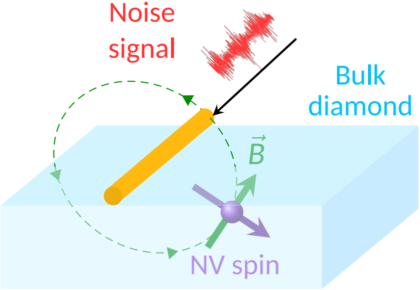

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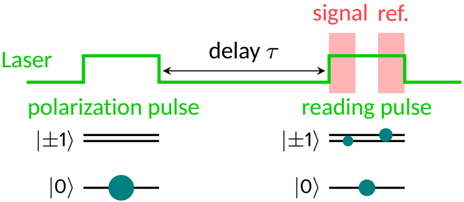

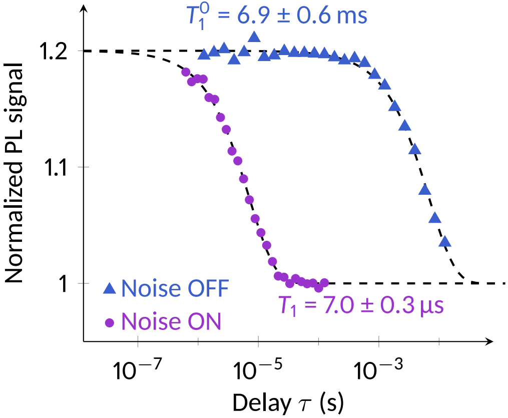

Noise spectrum centered
at the NV transition frequency

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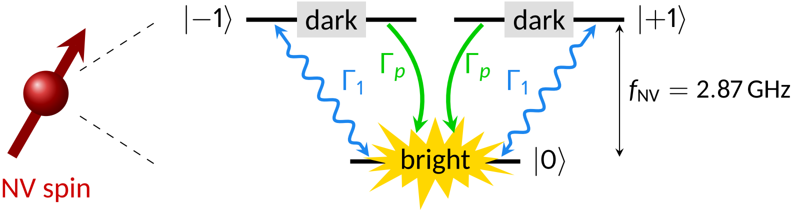
Effect on the emitted photoluminescence



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

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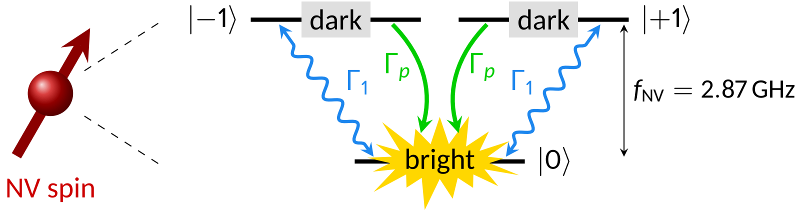

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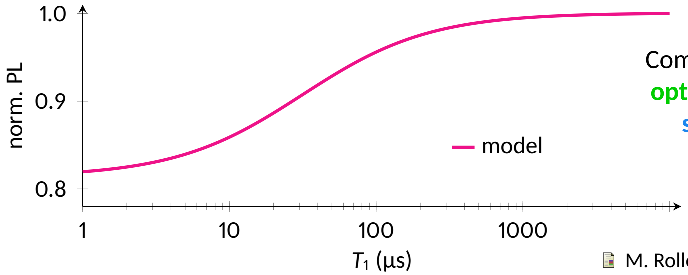

Competition between **optical pumping** and **spin relaxation**

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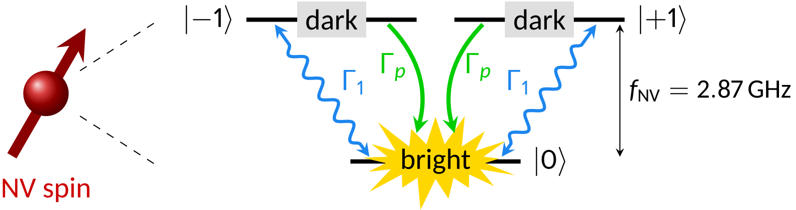

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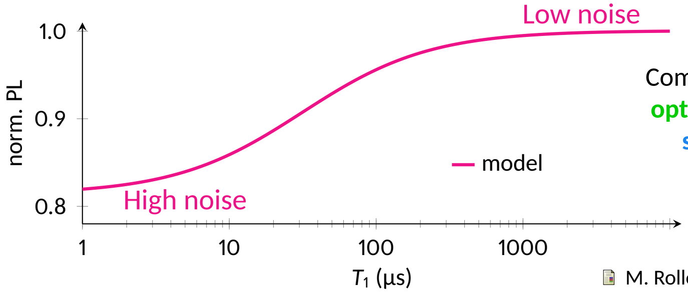

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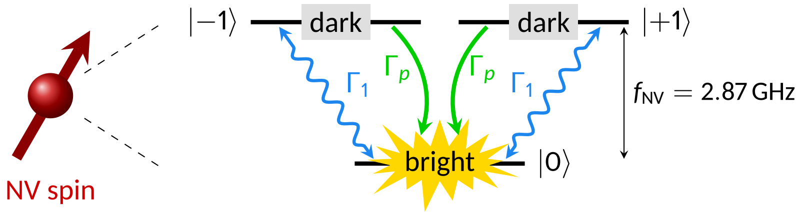

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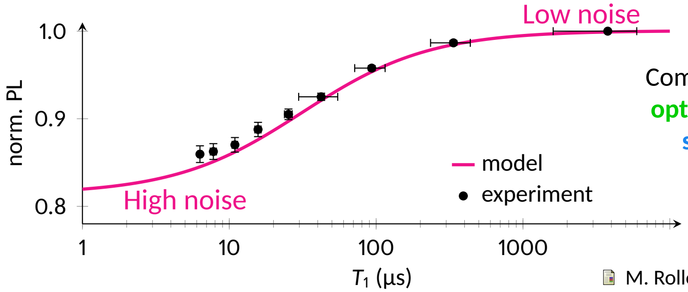

Competition between **optical pumping** and **spin relaxation**

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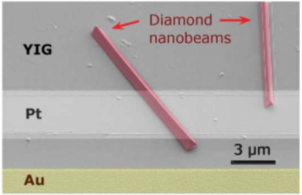
Example in YIG



A. Yacoby
group
Boston

C. Du *et al.* *Science* 357 (2017), 195–198

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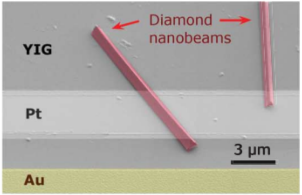

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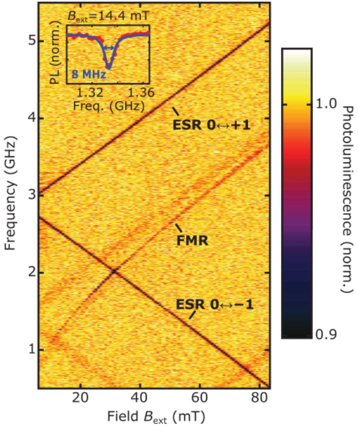

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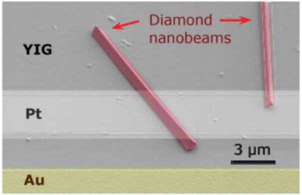

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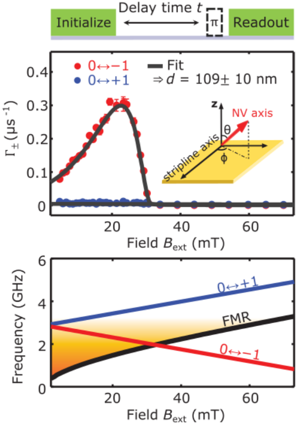

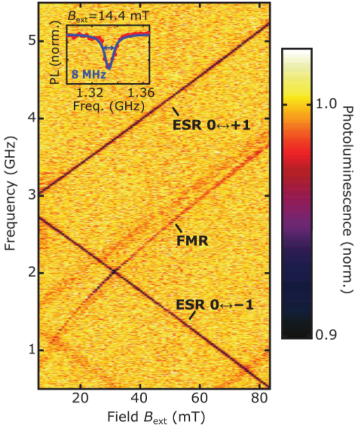

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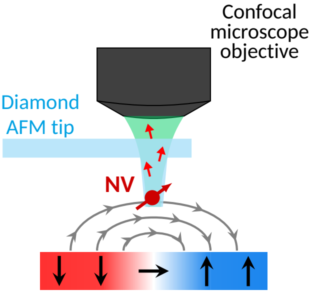
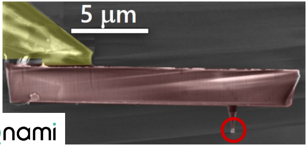
Our scanning-NV microscopes





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

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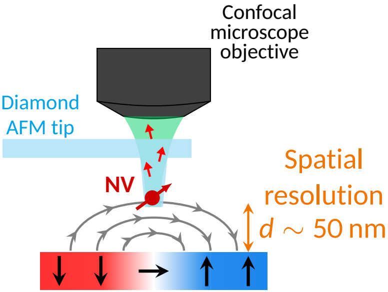

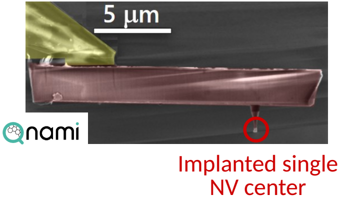

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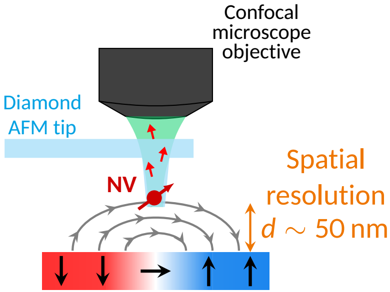
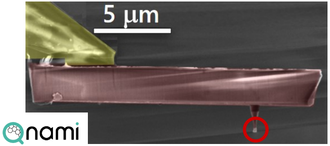
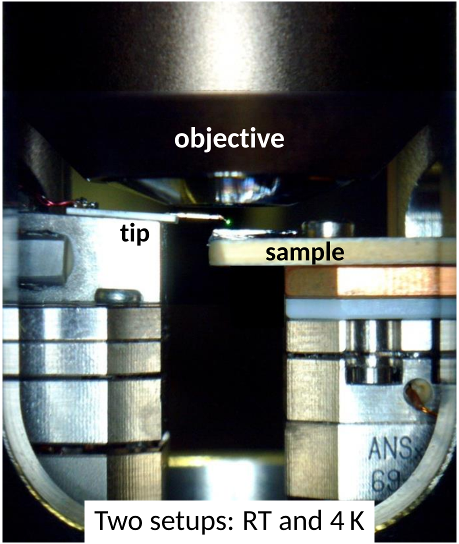




Implanted single NV center



Two setups: RT and 4 K

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

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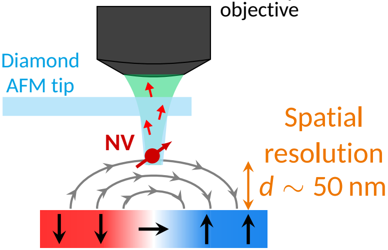

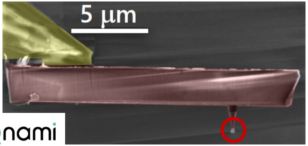

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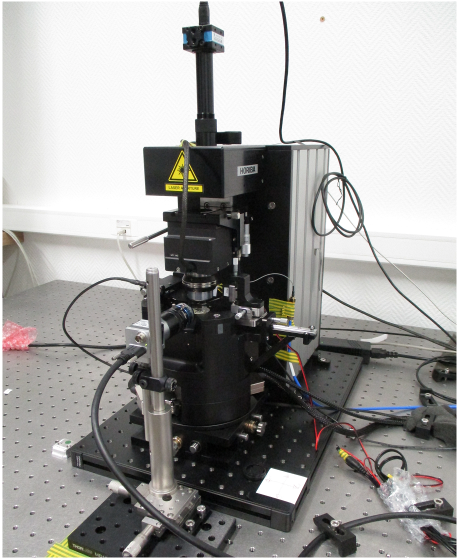

Commercial microscope from Qnami

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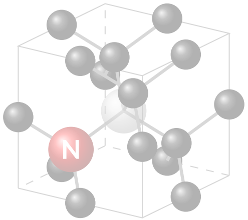
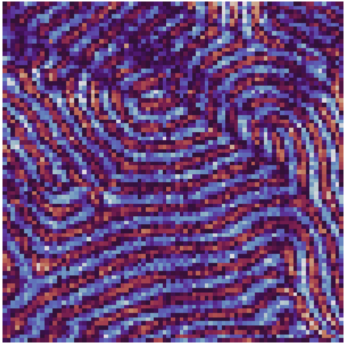
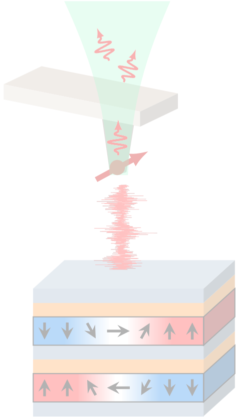


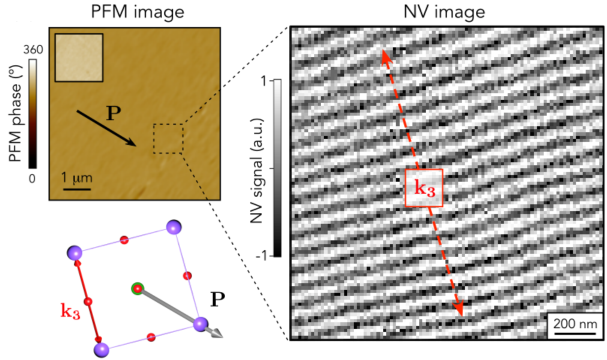
Scanning-NV magnetometry applied to antiferromagnets



Imaging of antiferromagnetic textures by probing thermally excited spin waves



Imaging the antiferromagnetic cycloid in bulk $BiFeO_3$



Collaboration SPEC: J.-Y. Chauleau, M. Viret

A. Finco *et al.* *arXiv:2202.02243* (2022)

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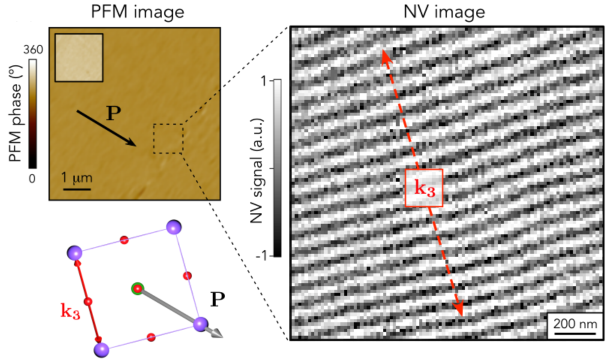

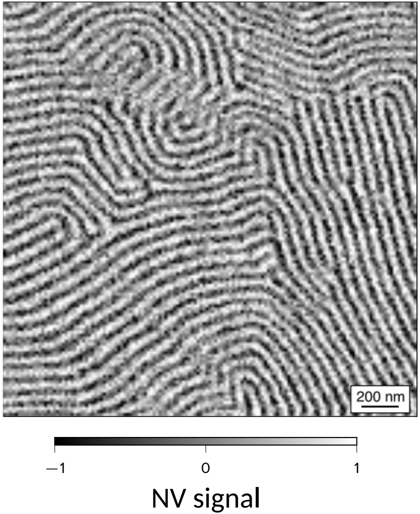

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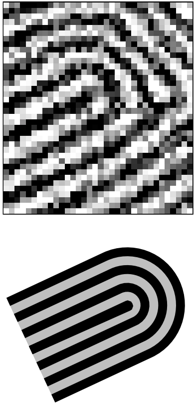
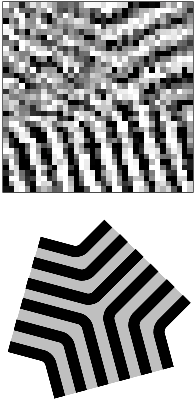
Topological defects in the antiferromagnetic cycloidal order

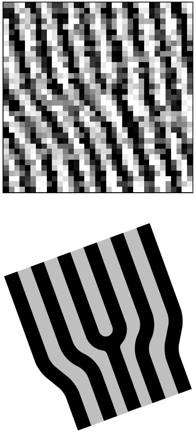
π-disclination



$-\pi$-disclination



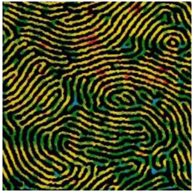
Edge dislocation



Advantages in $BiFeO_3$: i) robustness of antiferromagnetic textures
ii) energy-efficient electrical control

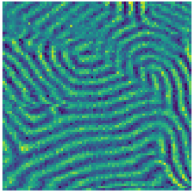
Overview of various lamellar systems: universal patterns!

Block copolymer
Period 40 nm



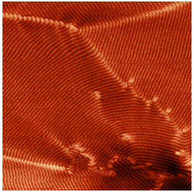
T. A. Witten. *Phys. Today* 43 (1990), 21

$BiFeO_3$ magnetic cycloid
Period 64 nm



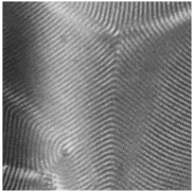
A. Finco *et al.* *arXiv:2202.02243* (2022)

FeGe magnetic helix
Period 70 nm



P. Schoenherr *et al.* *Nat. Phys.* 14 (2018), 465

Liquid crystals
Period 800 nm

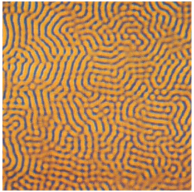


Y. Bouligand. *Dislocations in solids* (1983), Chap. 23

Ferrimagnetic garnet
Period 8 µm

M. Seul *et al.* *Phys. Rev. A* 46 (1992), 7519

Fluid diffusion
Period 250 µm



Q. Ouyang *et al.* *Chaos* 1 (1991), 411

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
- But NV centers are also sensitive to **magnetic noise**!
- Use the different noise properties above domains and domain walls for imaging

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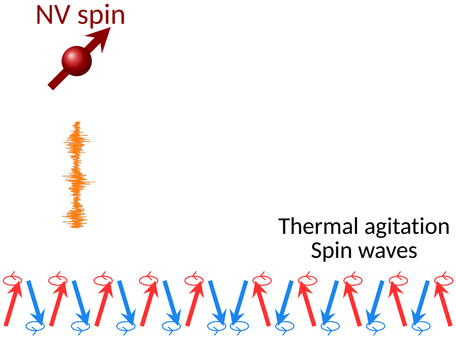

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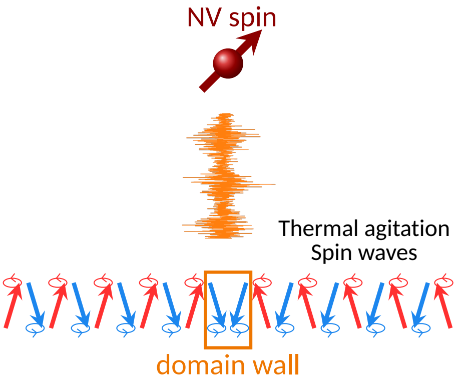
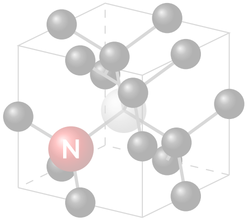
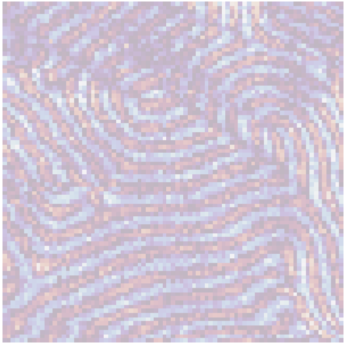


Outline

Spin waves detection with NV centers in diamond



Scanning-NV magnetometry applied to antiferromagnets



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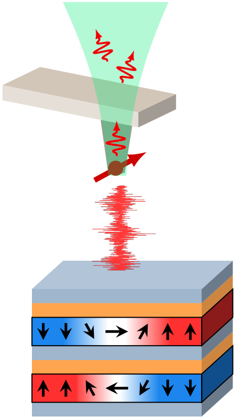
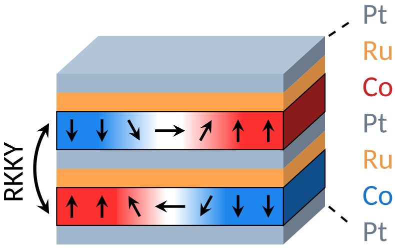


Imaging of synthetic antiferromagnets

Collaboration UMR CNRS/Thales: William Legrand, Fernando Ajejas, Karim Bouzehouane, Nicolas Reyren, Vincent Cros

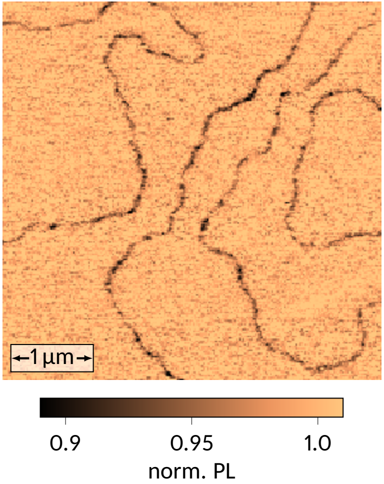
Two **ferromagnetic** layers coupled **antiferromagnetically**

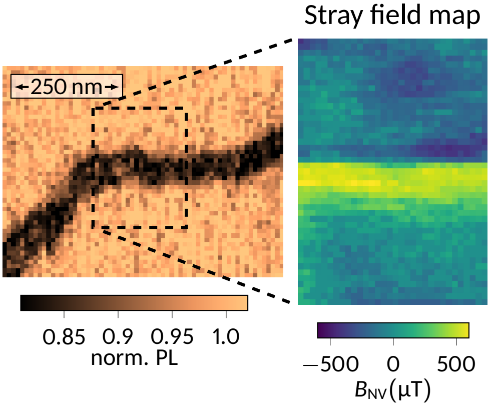


W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34

- No net magnetic moment
- Compensation of dipolar effects
  → small skyrmions
- No skyrmion Hall effect
- Small stray field due to vertical spacing
  → test system for noise imaging

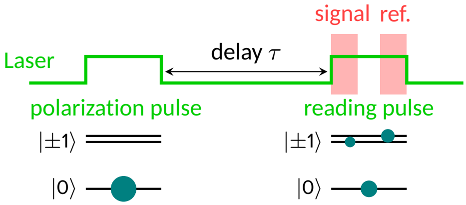
Detection of domain walls by relaxometry





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

Local variation of the relaxation time



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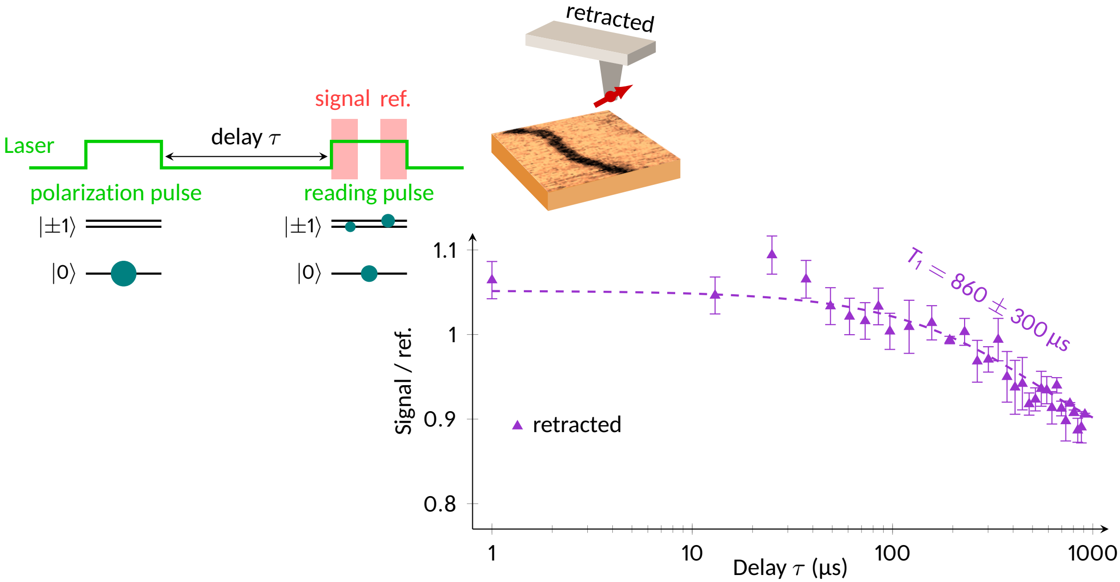

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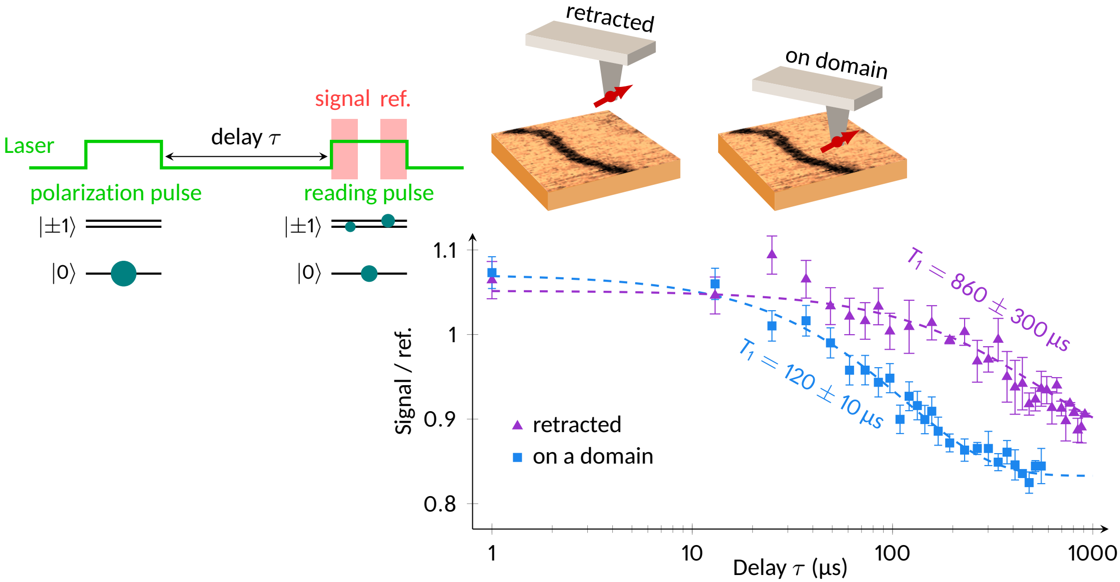

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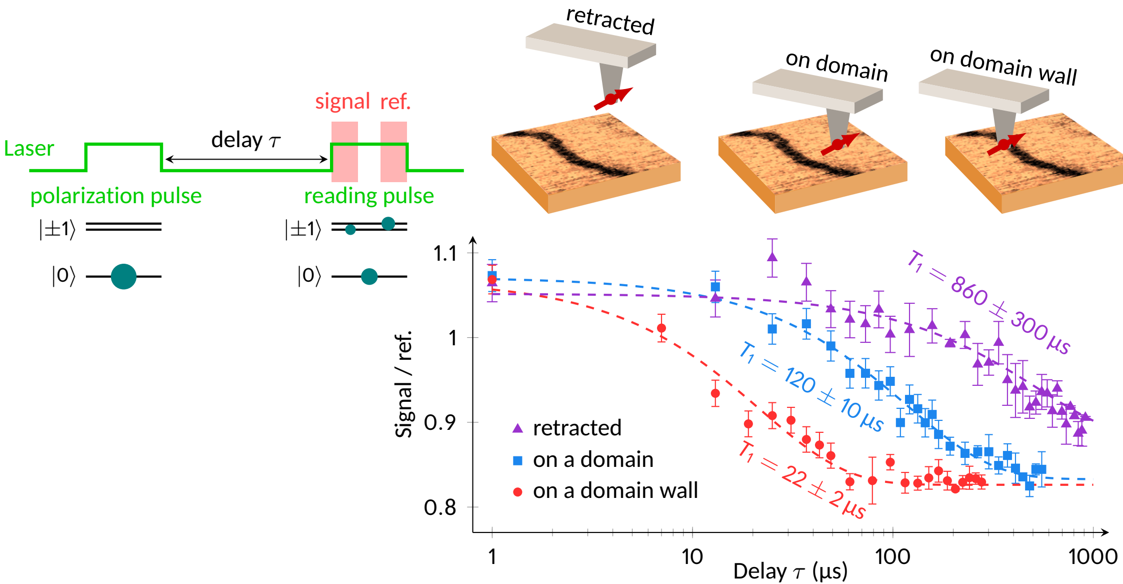

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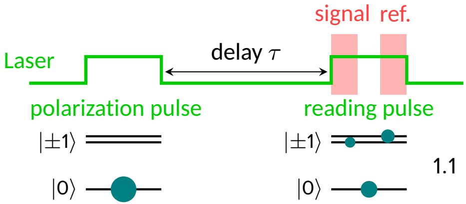
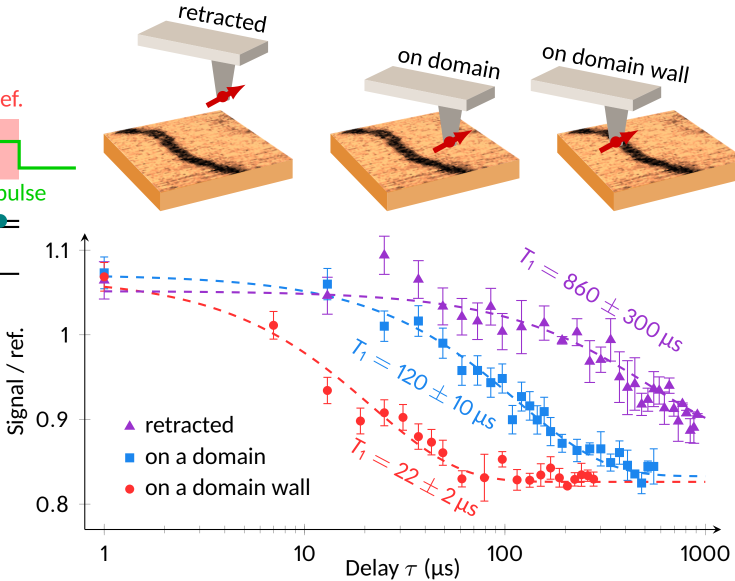


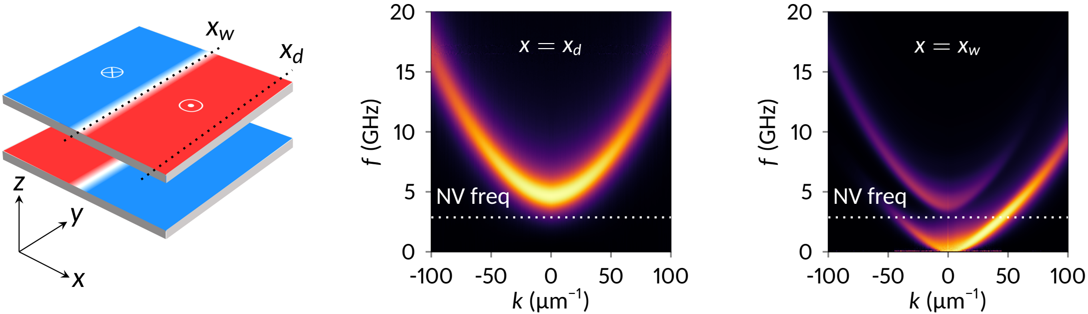
Clear diminution of T_1

→ **Enhancement of the spin relaxation**



Origin of the noise: spin waves

Collaboration C2N: Jean-Paul Adam, Joo-Von Kim



- NV frequency slightly below the gap, in the tail of power spectral density, which is the reason why we detect some noise when approaching the tip.
- No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

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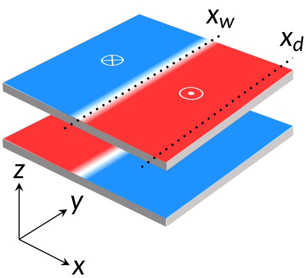

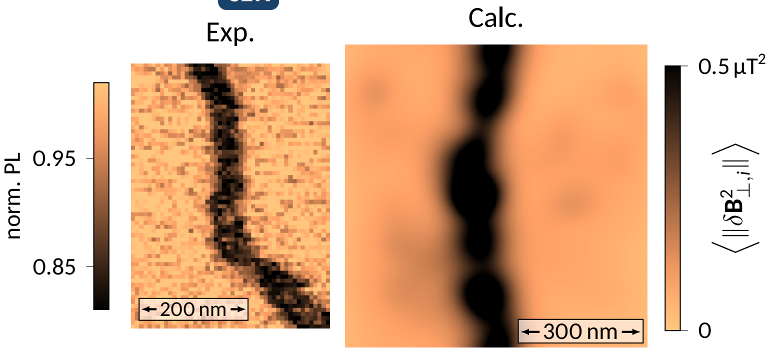

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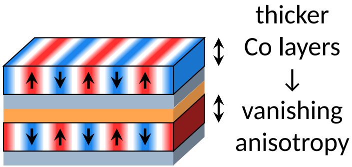
Imaging a spin spiral



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

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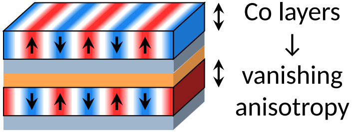

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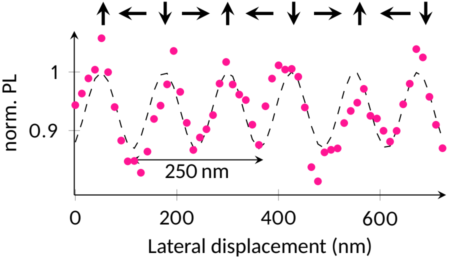
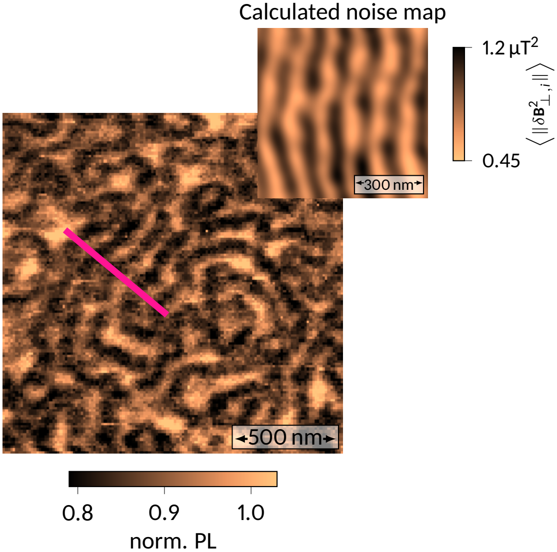
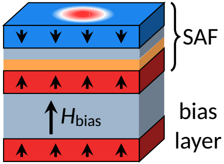




and antiferromagnetic skyrmions!



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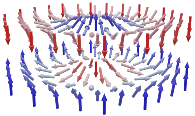

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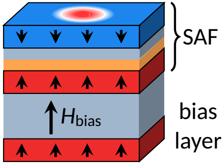

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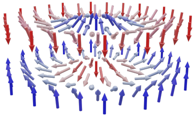
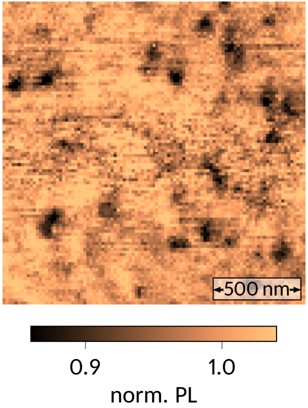
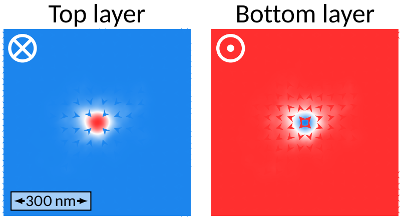
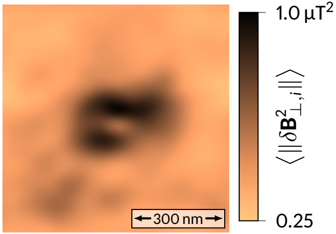


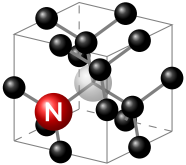






We are not probing the internal modes but the scattering of spin waves on the skyrmions

To conclude



- NV centers are **quantum sensors** with the ability to probe spin waves in the GHz range, resonant or not.
- **Two magnons processes** can also be detected, e.g. in **antiferromagnets** where the spin wave frequencies are out of reach.

Example in Fe_2O_3 (C. Du group): H. Wang *et al.* *Science Adv.* 8 (2022), eabg8562

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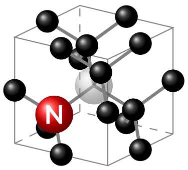

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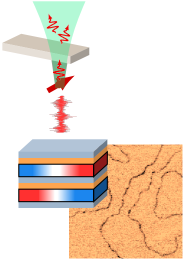

- Measurements in a scanning-NV microscope
  → **spatial resolution 50 nm** + combination with **magnetic imaging**.
- Easy fully optical detection of spin waves through **magnetic noise**.

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

- Allows the study of **spin waves confined in textures** like domain walls.

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

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William Legrand, Fernando Ajejas, Karim Bouzehouane, Nicolas Reyren, Vincent Cros

C2N, Palaiseau
Jean-Paul Adam, Thibaut Devolder, Joo-Von Kim

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