

Antiferromagnetic textures imaged by probing thermally excited spin waves

Aurore Finco

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<https://solidstatequantumtech-l2c.fr/>

CNRS and Université de Montpellier, Montpellier, France

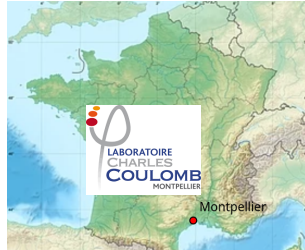
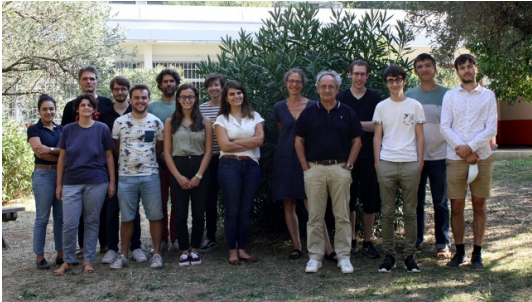


CHIRON workshop, April 27th 2022

slides available at <https://magimag.eu>

S2QT team at L2C in Montpellier

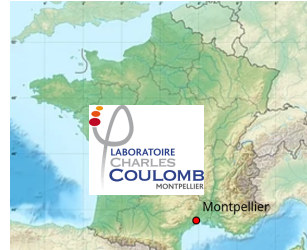
Laboratoire Charles Coulomb
Team Solid-State Quantum Technologies



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

S2QT team at L2C in Montpellier

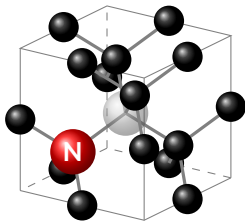
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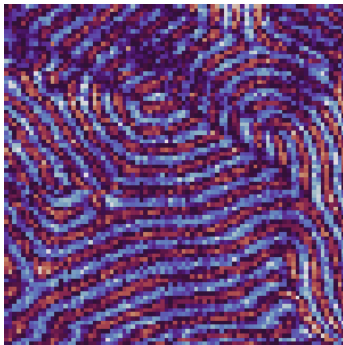
- Ultrawide bandgap semiconductors
- Point defects in semiconductors
- Quantum sensing

Outline

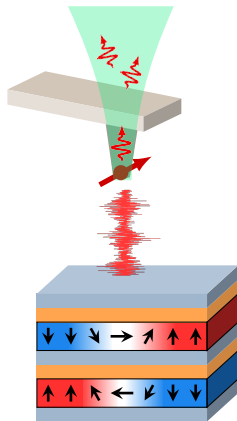
Spin waves detection with NV centers in diamond



Scanning-NV magnetometry applied to antiferromagnets

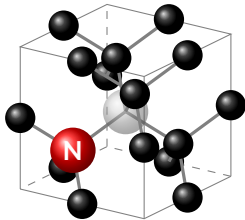


Imaging of antiferromagnetic textures by probing thermally excited spin waves

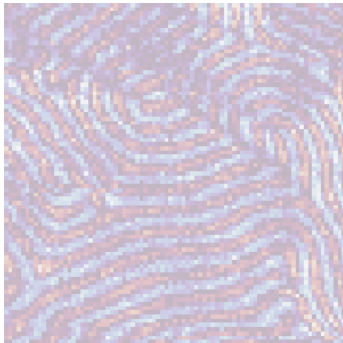


Outline

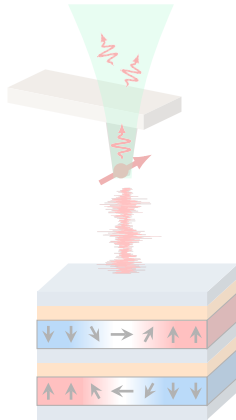
Spin waves detection with NV centers in diamond



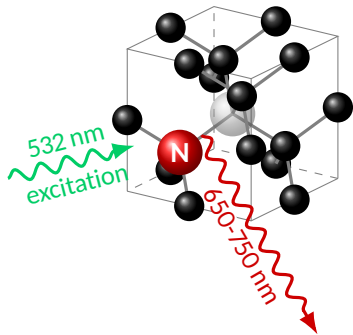
Scanning-NV magnetometry applied to antiferromagnets



Imaging of antiferromagnetic textures by probing thermally excited spin waves

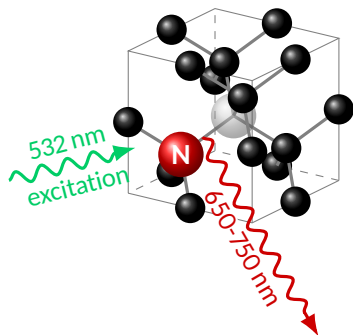


Quantum sensing with NV centers in diamond



Nitrogen-Vacancy defect
in diamond

Quantum sensing with NV centers in diamond



Nitrogen-Vacancy defect
in diamond

$\vec{B}$ Magnetic
field

T Temperature

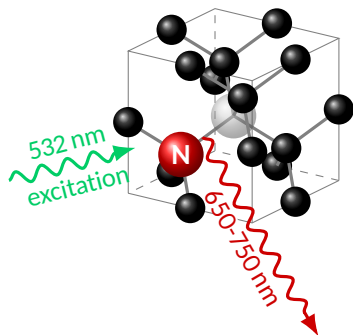
$\vec{E}$ Electric
field

Electronic spin $S=1$
energy levels
dynamics

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

σ Strain

Quantum sensing with NV centers in diamond



Nitrogen-Vacancy defect
in diamond

$\vec{B}$ Magnetic
field

T Temperature

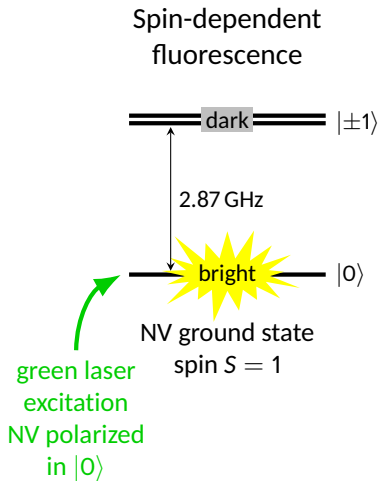
$\vec{E}$ Electric
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Electronic spin $S=1$
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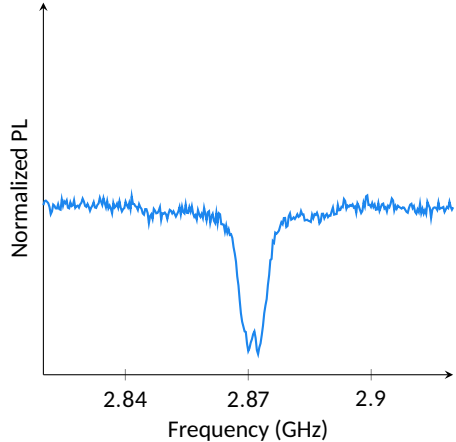
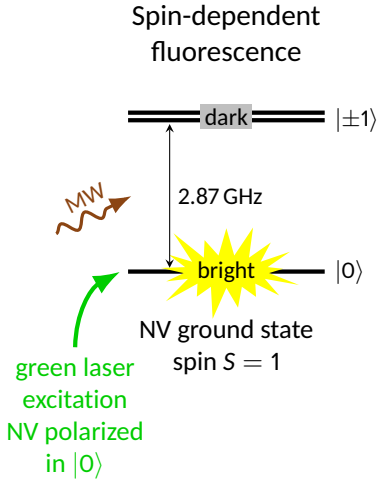
$\langle \vec{B} \rangle$ Magnetic
noise

σ Strain

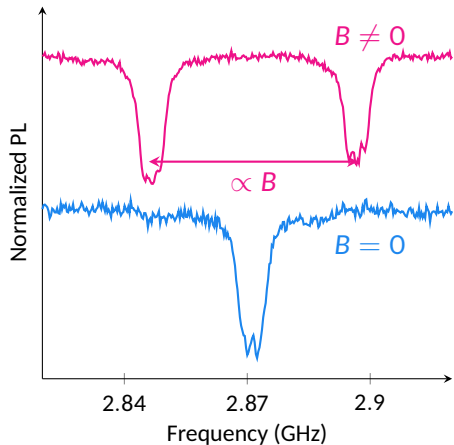
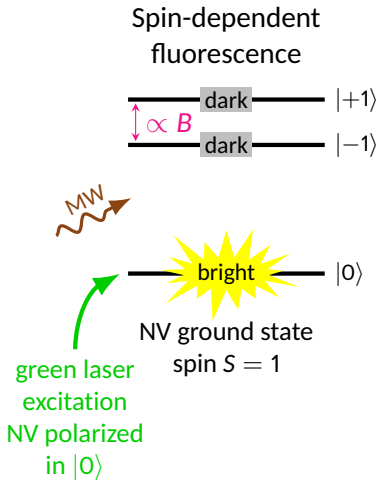
How do we measure magnetic field?



How do we measure magnetic field?



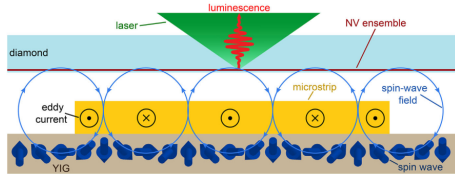
How do we measure magnetic field?



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

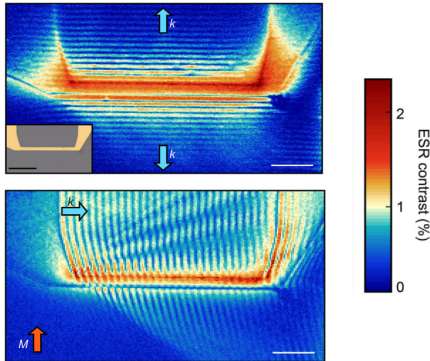
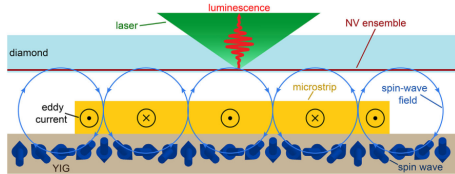
Application to the detection of resonant spin waves

T. van der Sar
group
Delft



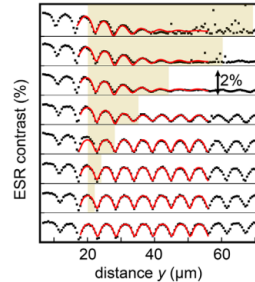
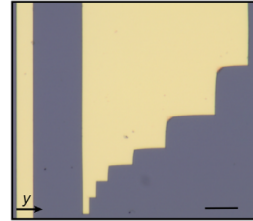
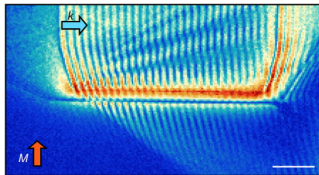
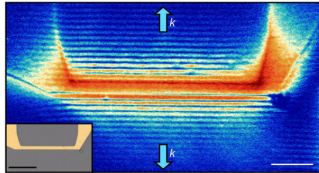
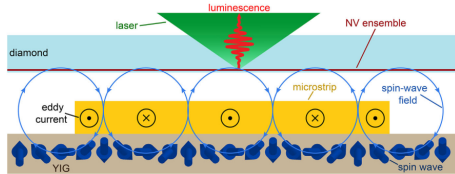
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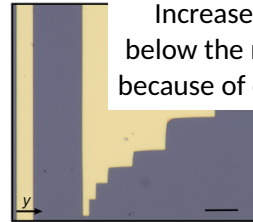
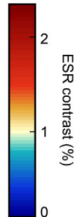
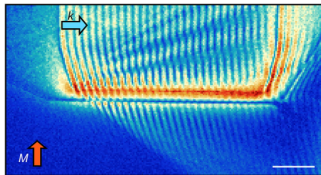
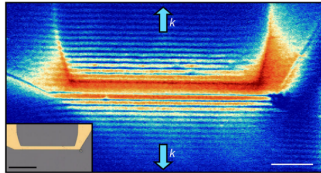
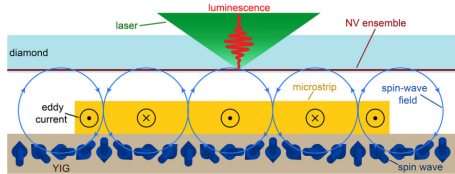
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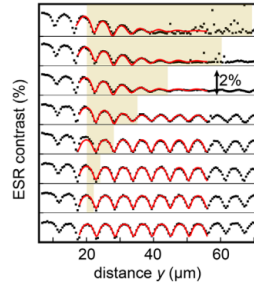


Application to the detection of resonant spin waves

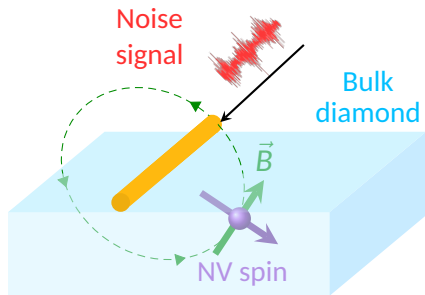
T. van der Sar
group
Delft



Increased damping
below the metallic layer
because of eddy currents

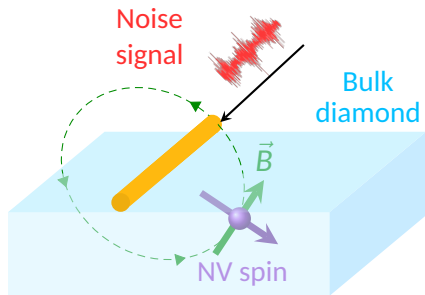


Other approach: relaxometry to probe magnetic noise

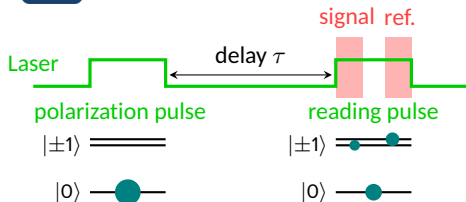


Collaboration C2N: T. Devolder

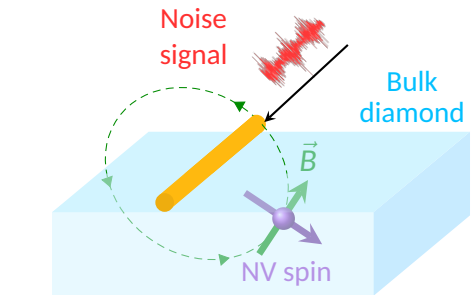
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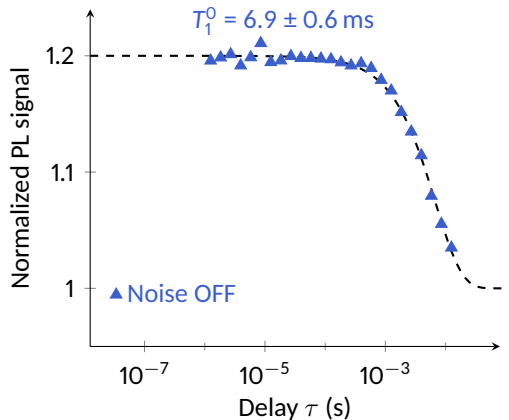
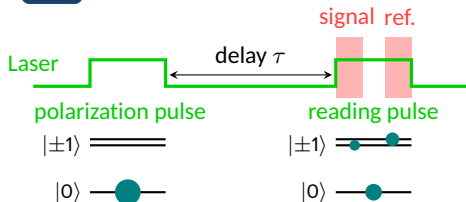
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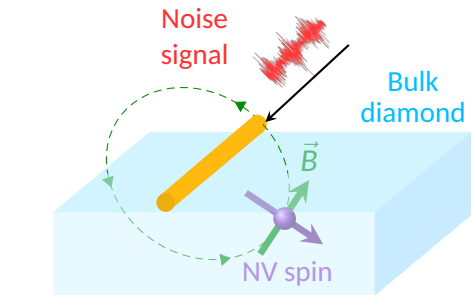
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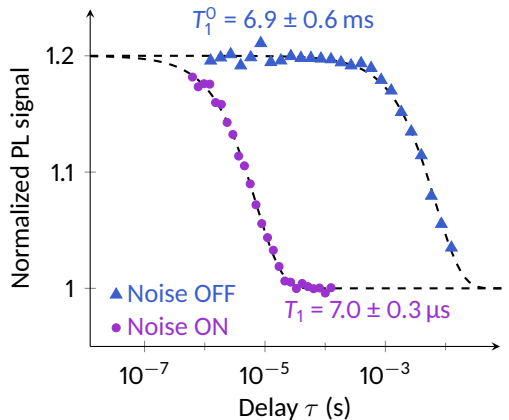
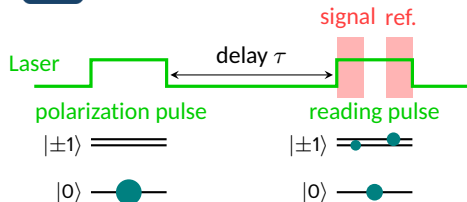
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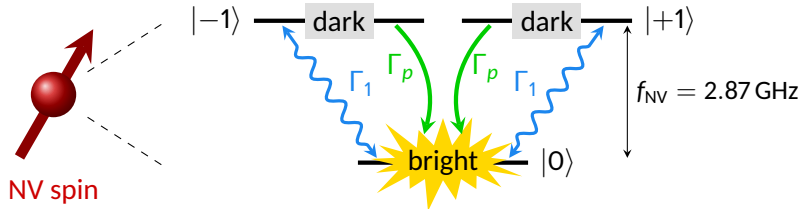


Collaboration C2N: T. Devolder



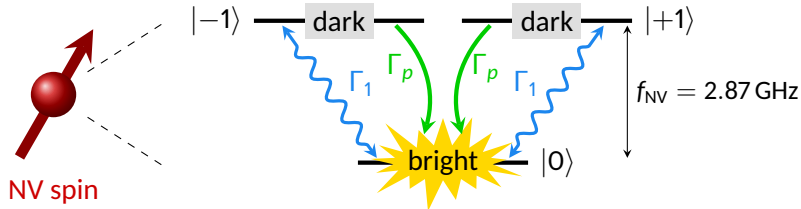
Noise spectrum centered
at the NV transition frequency

Effect on the emitted photoluminescence

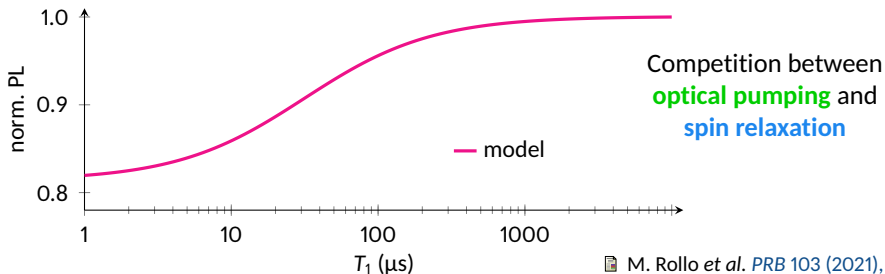


Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{\text{NV}})$ magnetic field spectral density at the resonance frequency f_{NV}

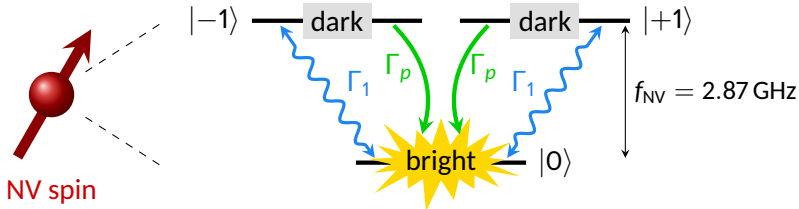
Effect on the emitted photoluminescence



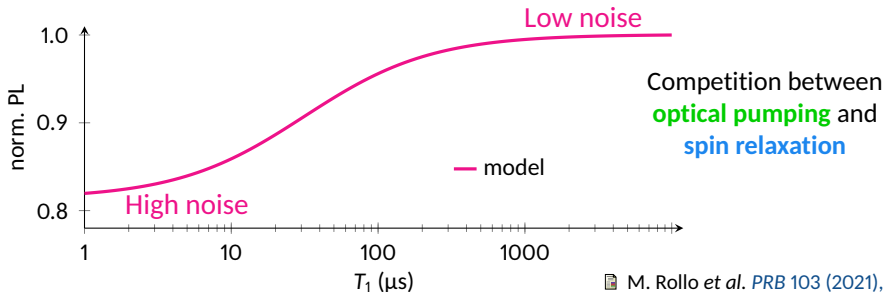
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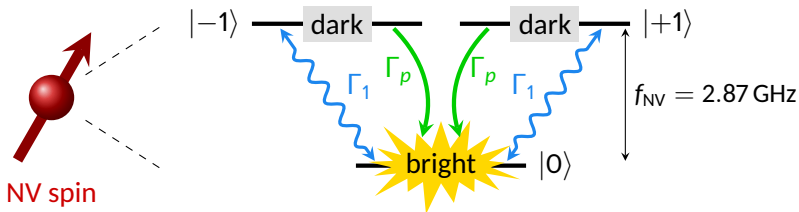
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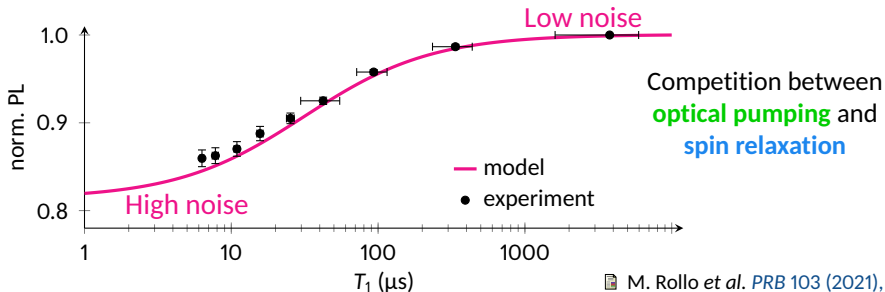
Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{\text{NV}})$ magnetic field spectral density at the resonance frequency f_{NV}



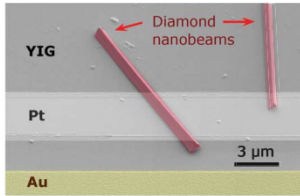
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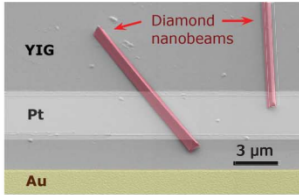
Example in YIG



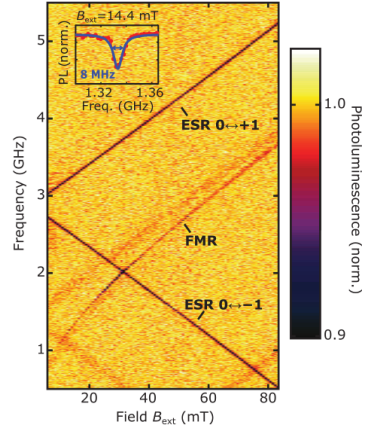
A. Yacoby
group
Boston

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

Example in YIG

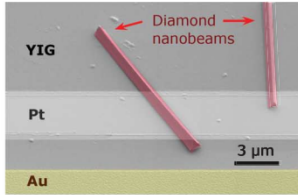


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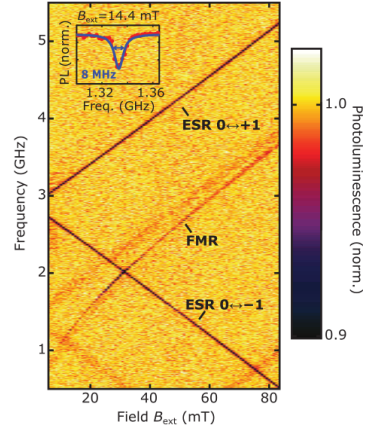
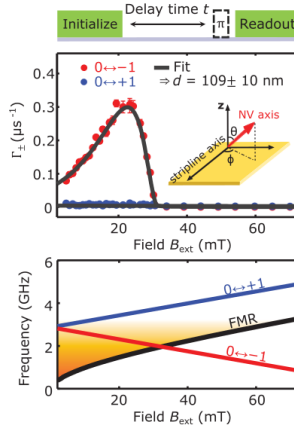


 C. Du *et al.* *Science* 357 (2017), 195–198

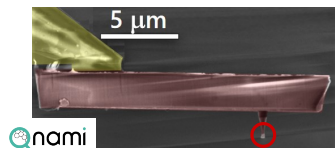
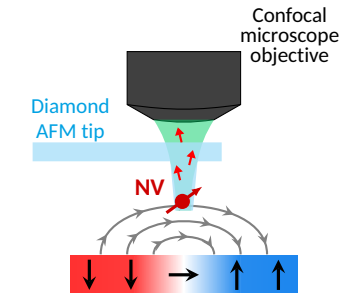
Example in YIG



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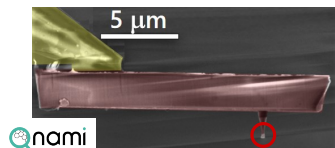
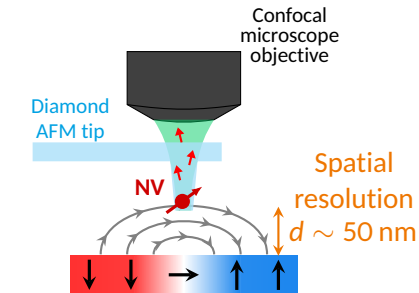


Our scanning-NV microscopes



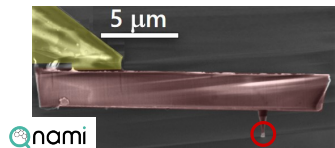
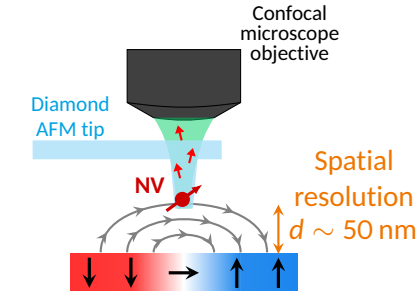
Implanted single
NV center

Our scanning-NV microscopes

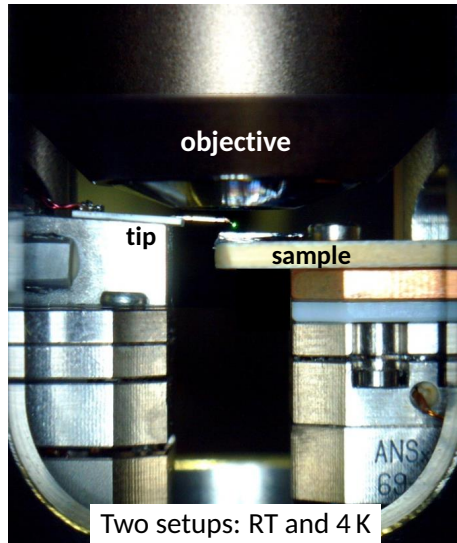


Implanted single
NV center

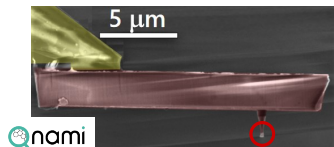
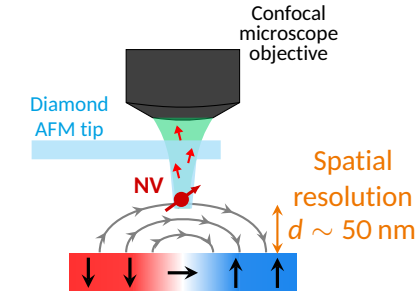
Our scanning-NV microscopes



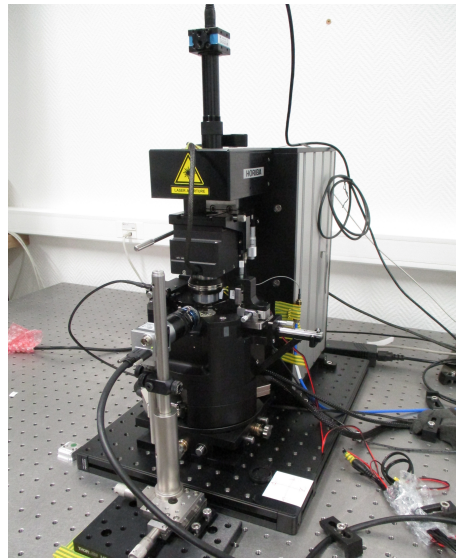
Implanted single
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Our scanning-NV microscopes



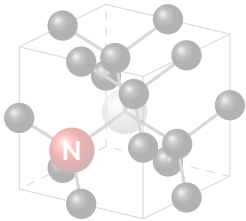
Implanted single NV center



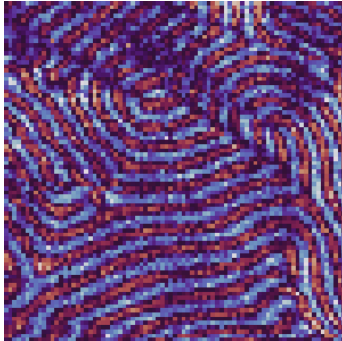
Commercial microscope from Qnami

Outline

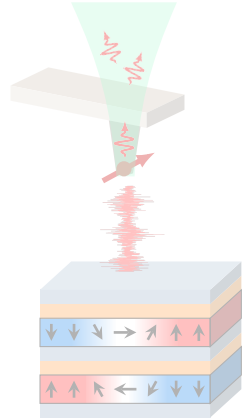
Spin waves detection with NV centers in diamond



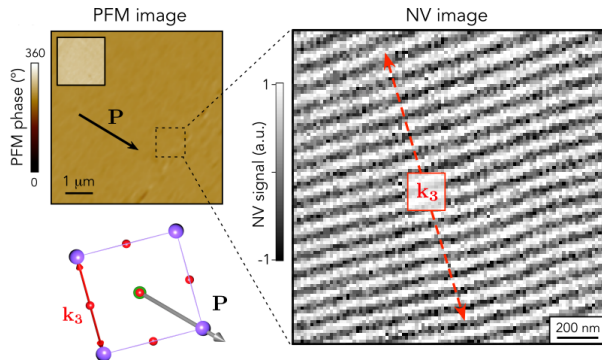
Scanning-NV magnetometry applied to antiferromagnets



Imaging of antiferromagnetic textures by probing thermally excited spin waves

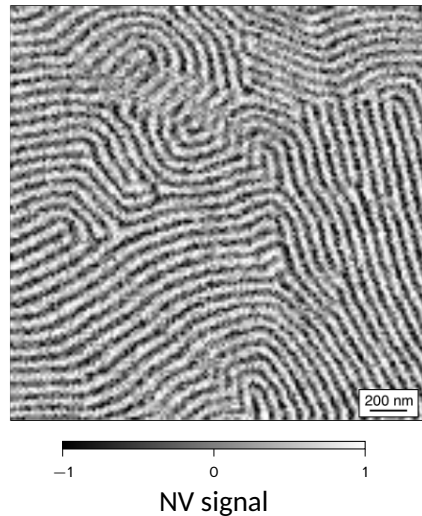
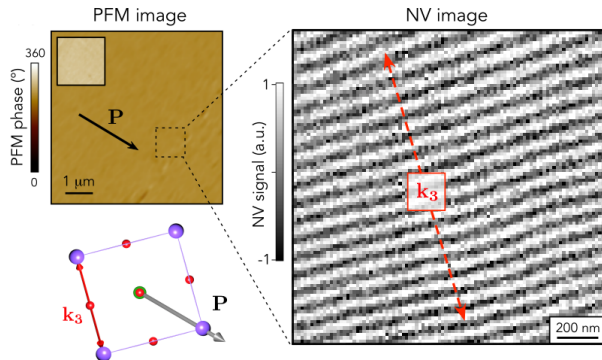


Imaging the antiferromagnetic cycloid in bulk BiFeO_3



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

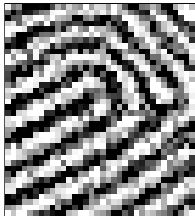
Imaging the antiferromagnetic cycloid in bulk BiFeO_3



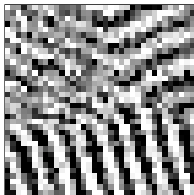
 Collaboration SPEC: J.-Y. Chauleau, M. Viret

Topological defects in the antiferromagnetic cycloidal order

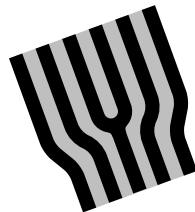
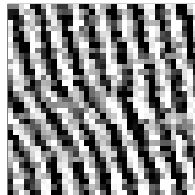
π -disclination



$-\pi$ -disclination



Edge dislocation

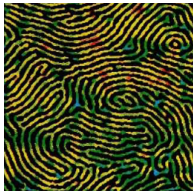


Advantages in BiFeO₃: i) robustness of antiferromagnetic textures
ii) energy-efficient electrical control

Overview of various lamellar systems: universal patterns!

Block copolymer

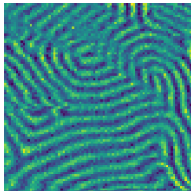
Period 40 nm



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

BiFeO₃ magnetic cycloid

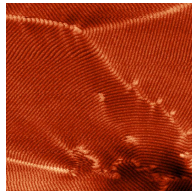
Period 64 nm



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

FeGe magnetic helix

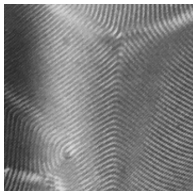
Period 70 nm



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

Liquid crystals

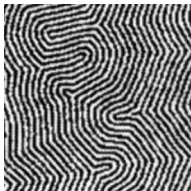
Period 800 nm



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

Ferrimagnetic garnet

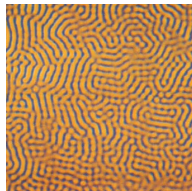
Period 8 μm



 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

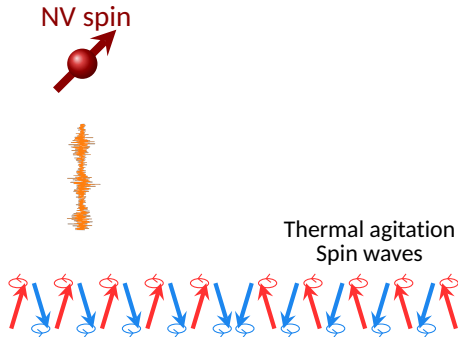
 B. Flebus *et al.* [Phys. Rev. B 98 \(2018\), 180409](#)

- 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

Detection of magnetic noise rather than stray field

📄 B. Flebus *et al.* [Phys. Rev. B 98 \(2018\), 180409](#)

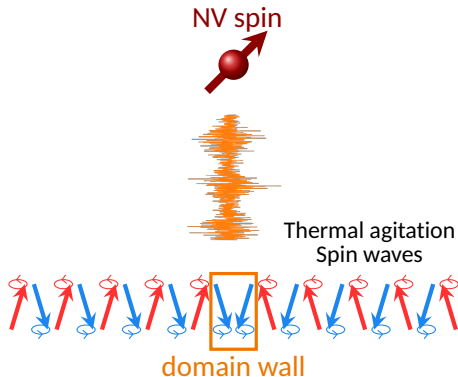
- Completely compensated antiferromagnets = **no static stray field** to probe
- But NV centers are also sensitive to **magnetic noise**!
- Use the different noise properties above domains and domain walls for imaging



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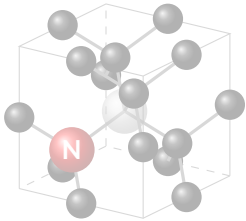
 B. Flebus et al. *Phys. Rev. B* 98 (2018), 180409

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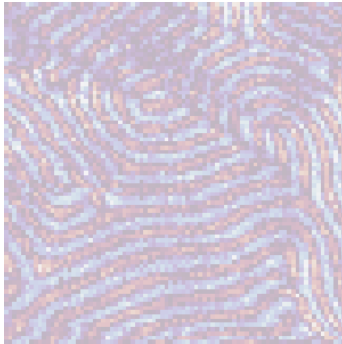


Outline

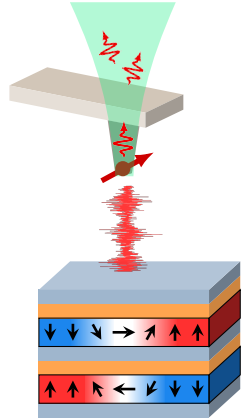
Spin waves detection with NV centers in diamond



Scanning-NV magnetometry applied to antiferromagnets



Imaging of antiferromagnetic textures by probing thermally excited spin waves

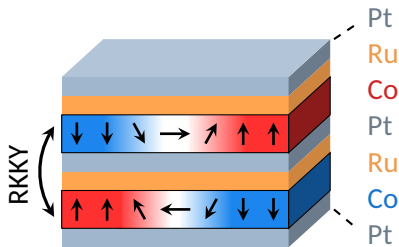


Imaging of synthetic antiferromagnets

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



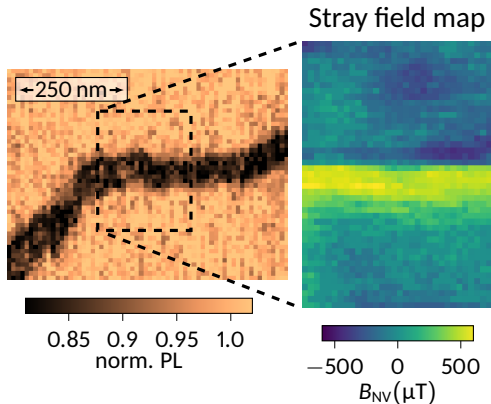
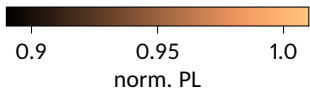
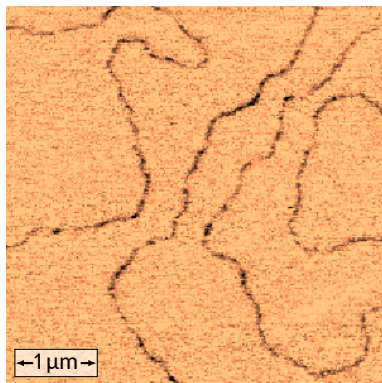
Two **ferromagnetic** layers coupled **antiferromagnetically**



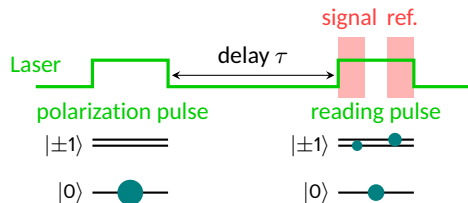
- No net magnetic moment
- Compensation of dipolar effects
→ small skyrmions
- No skyrmion Hall effect
- Small stray field due to vertical spacing
→ test system for noise imaging

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

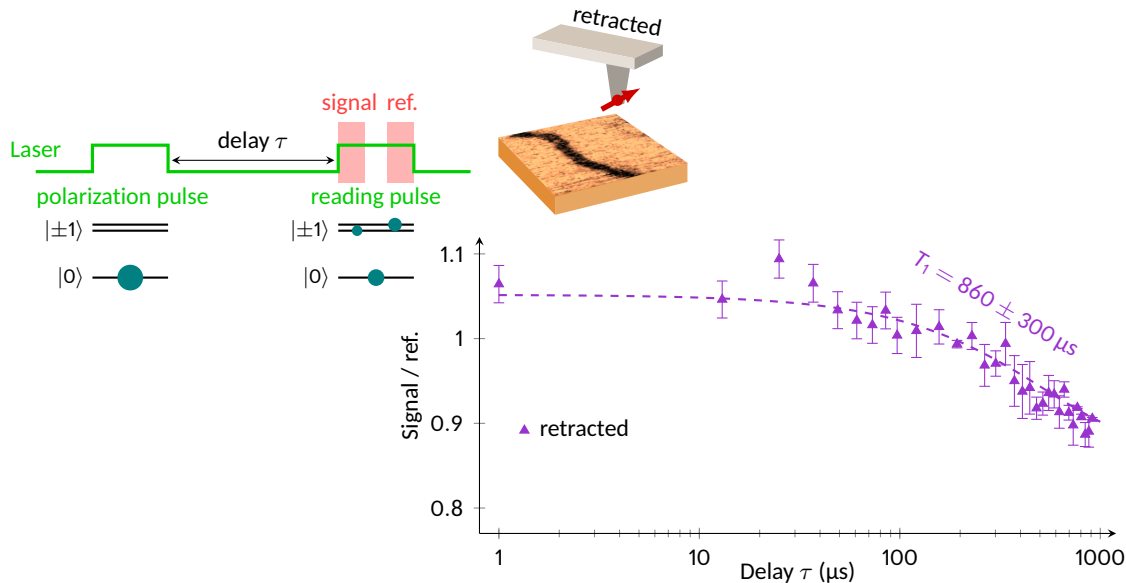
Detection of domain walls by relaxometry



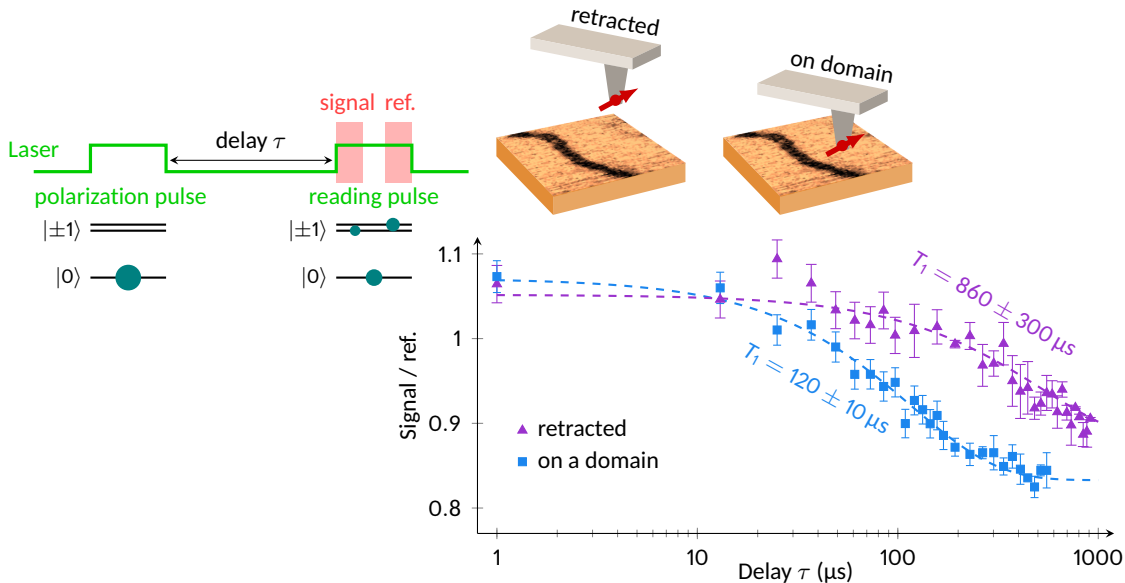
Local variation of the relaxation time



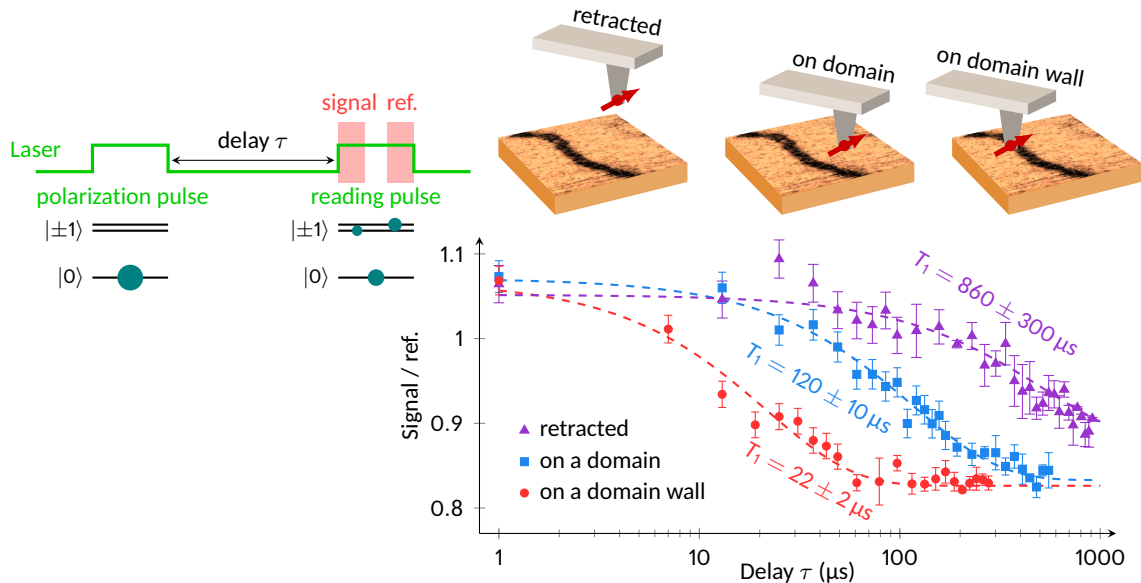
Local variation of the relaxation time



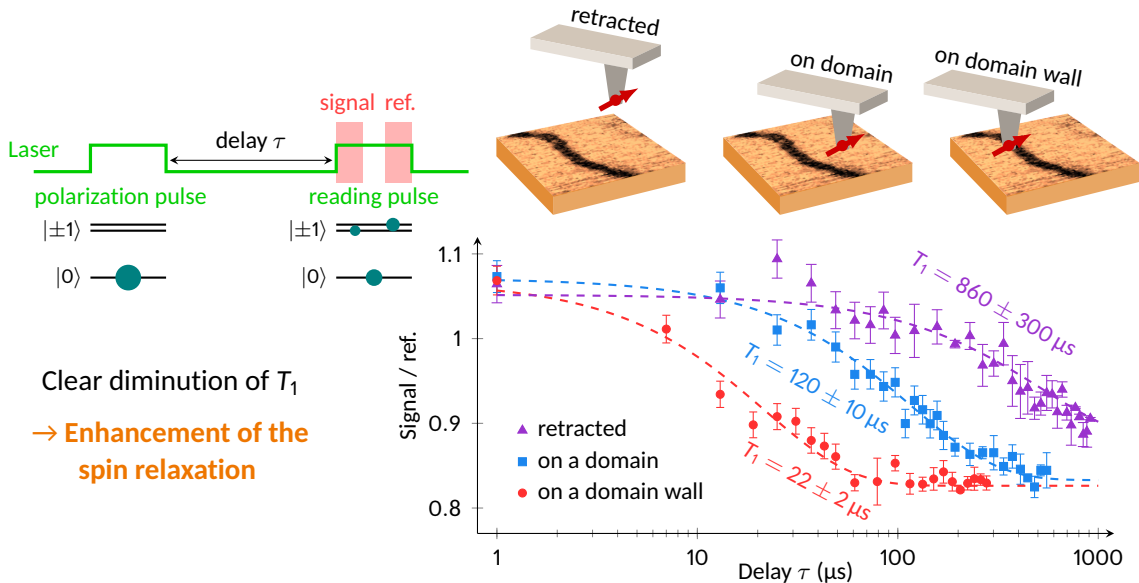
Local variation of the relaxation time



Local variation of the relaxation time

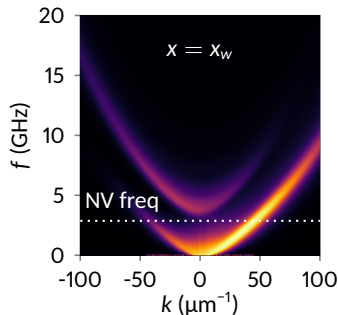
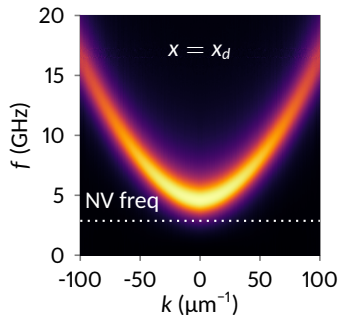
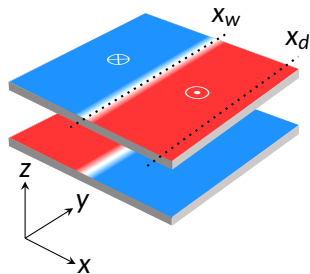


Local variation of the relaxation time



Origin of the noise: spin waves

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



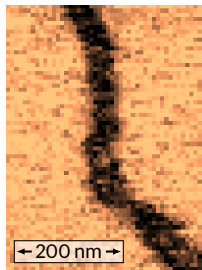
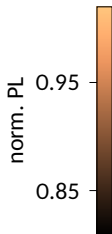
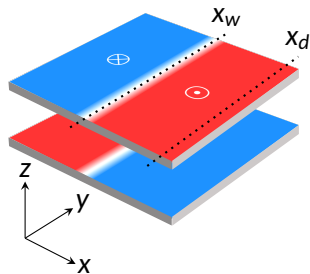
- NV frequency slightly below the gap, in the tail of power spectral density, which is the reason why we detect some noise when approaching the tip.
- No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

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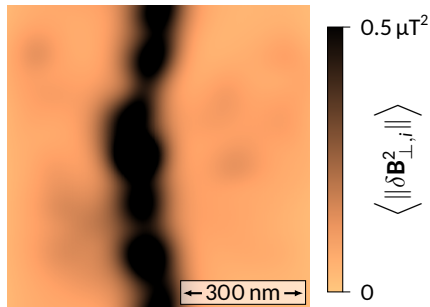
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Exp.

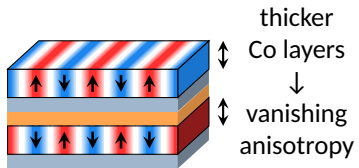


Calc.



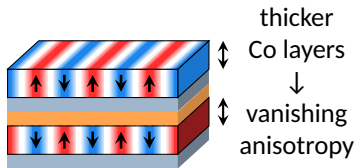
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Imaging a spin spiral

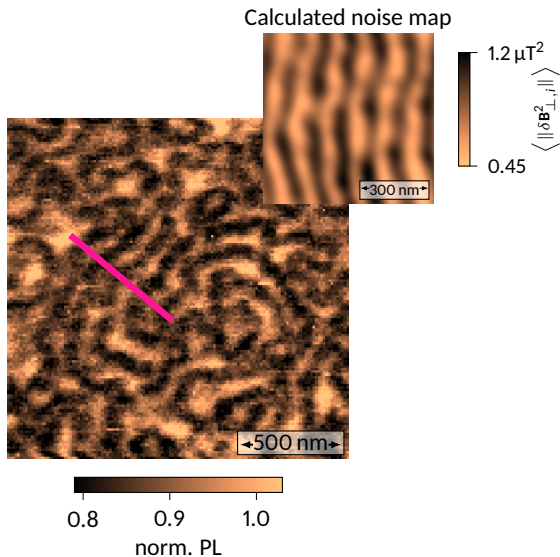
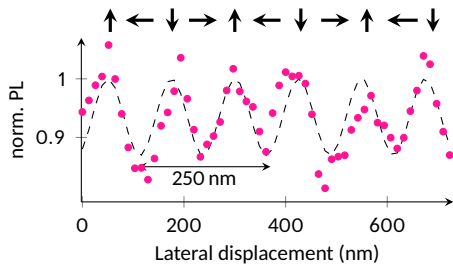


 W. Legrand et al. *Nat. Mat.* 19 (2020), 34

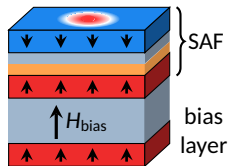
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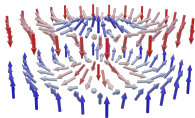
W. Legrand et al. *Nat. Mat.* 19 (2020), 34



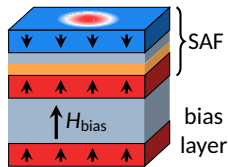
and antiferromagnetic skyrmions!



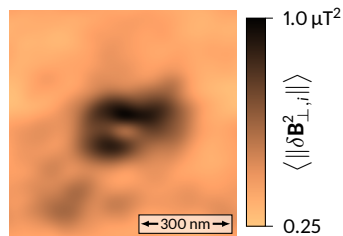
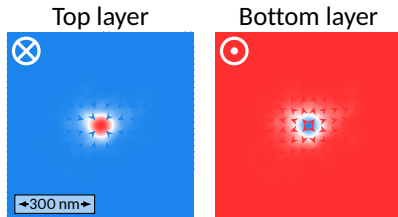
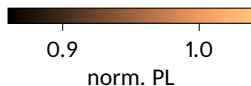
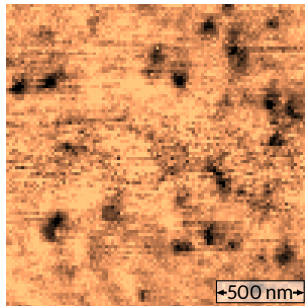
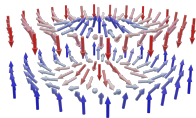
 W. Legrand et al. *Nat. Mat.* 19 (2020), 34



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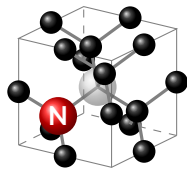


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We are not probing the internal modes but the scattering of spin waves on the skyrmions

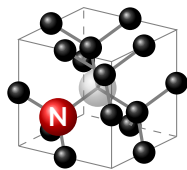
To conclude



- 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.

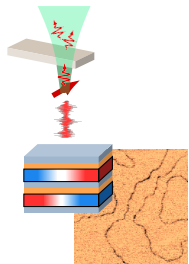
Example in Fe_2O_3 (C. Du group): 📄 H. Wang et al. [Science Adv. 8 \(2022\), eabg8562](#)

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- Measurements in a scanning-NV microscope
→ **spatial resolution 50 nm** + combination with **magnetic imaging**.
- Easy fully optical detection of spin waves through **magnetic noise**.
- Allows the study of **spin waves confined in textures** like domain walls.

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

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

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C2N, Palaiseau

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

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Nicolas Jaouen



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