Magnetic imaging via single spin relaxometry

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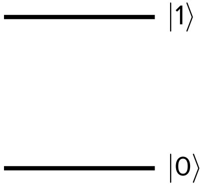
Journée Spins et Défauts, December 10th 2020

slides available at https://magimag.eu

Relaxometry

→ Quantum sensing



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

Relaxometry

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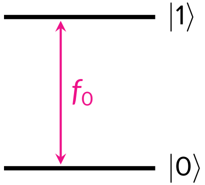

transition frequency

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Relaxometry

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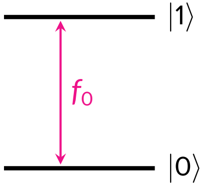

transition frequency

$\vec{B} \rightarrow$ *Zeeman shift*
$\vec{E} \rightarrow$ *Stark shift*
$\dots$

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Relaxometry

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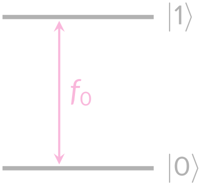
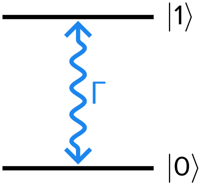


transition frequency

$\vec{B}$ → Zeeman shift
$\vec{E}$ → Stark shift
…



relaxation rate

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

Relaxometry

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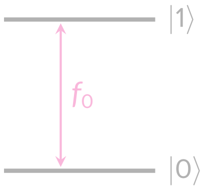

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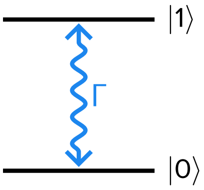


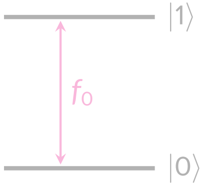
relaxation rate

Specifically sensitive to noise at the transition frequency f_0

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

Relaxometry

→ Quantum sensing



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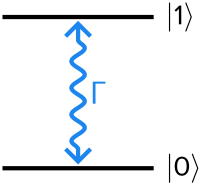


relaxation rate

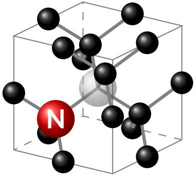
Specifically sensitive to noise at the transition frequency f_0

Γ directly proportional to the spectral field density

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

Applications of NV center relaxometry...

NV spin
$S = 1$



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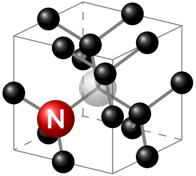

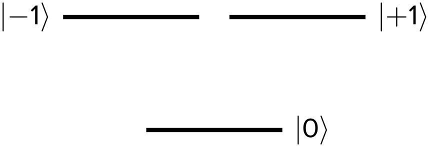

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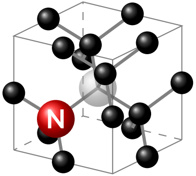

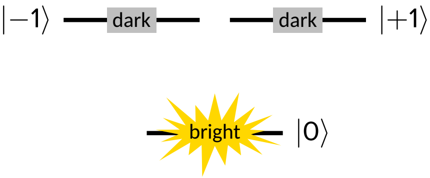

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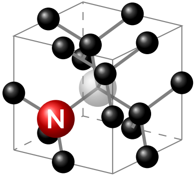

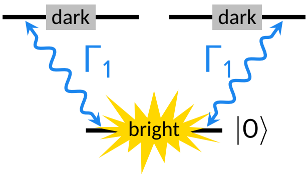

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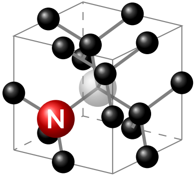

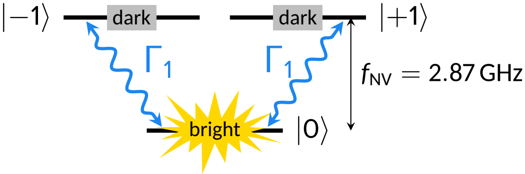

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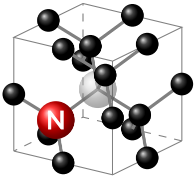
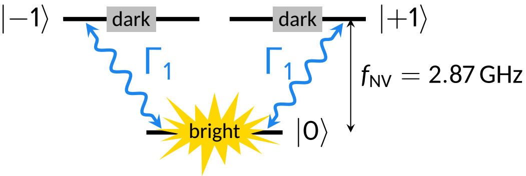
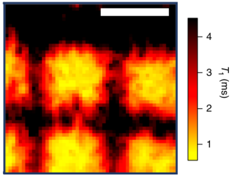


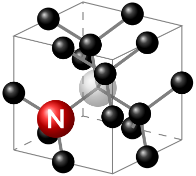


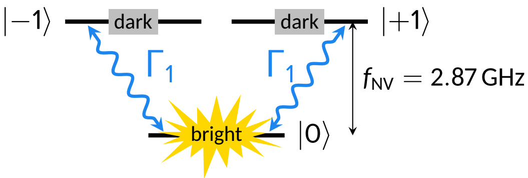
Measurement of Johnson noise
(conductivity maps)



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

Applications of NV center relaxometry...





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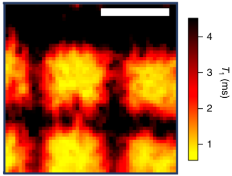
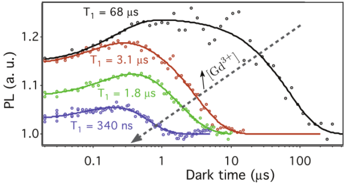


Detection of fluctuating magnetic particles



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J.-P. Tetienne *et al.* *Phys. Rev. B* 87 (2013), 235436

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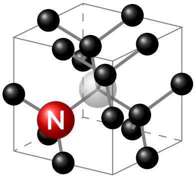

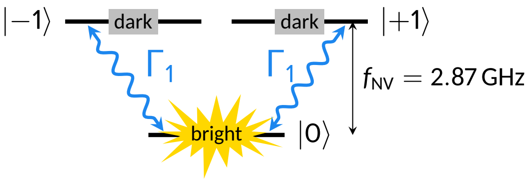

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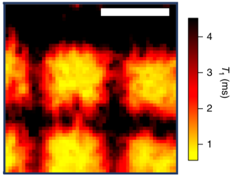

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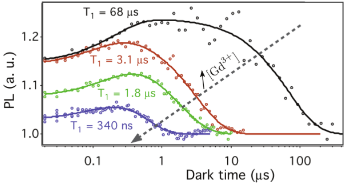
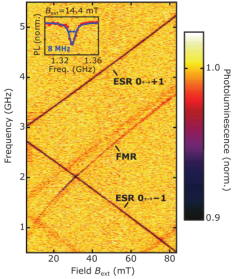


J.-P. Tetienne *et al.* *Phys. Rev. B* 87 (2013), 235436

Investigation of spin waves



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

... in a scanning microscope?

→ Perform a measurement of the relaxation time $T_1 = \dfrac{1}{\Gamma_1}$ at each pixel?

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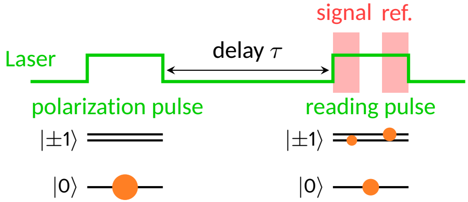

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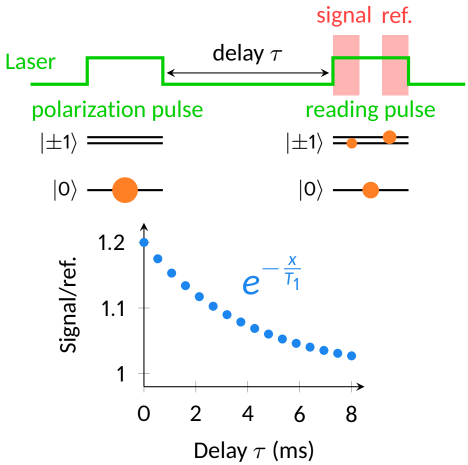

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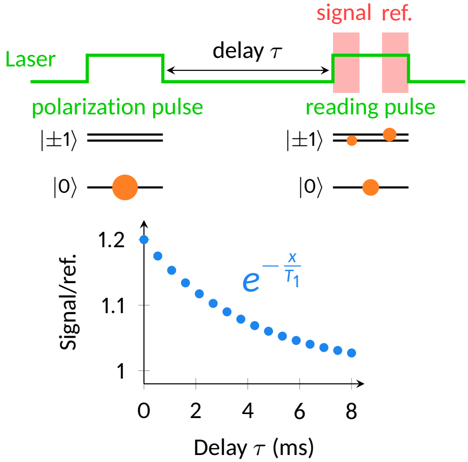

Measurement on the **hour** timescale!

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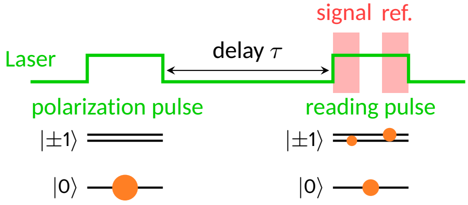
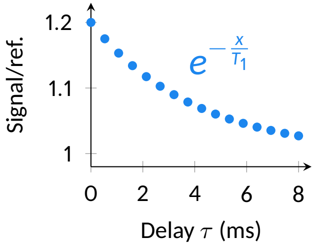
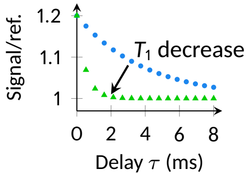




Measurement on the **hour** timescale!

Solutions:

- Single-τ measurements



D. Schmid-Lorch *et al.* *Nano Lett.* 15 (2015), 4942

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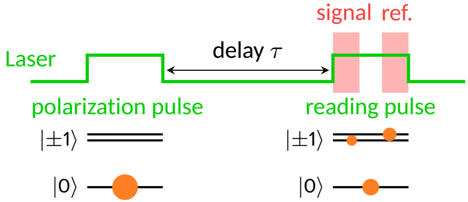

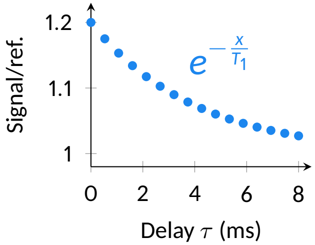

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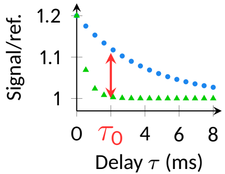

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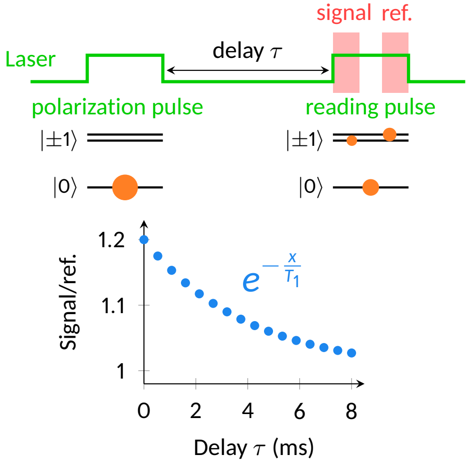

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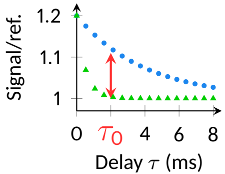

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- Complicated spin-to-charge readout sequences

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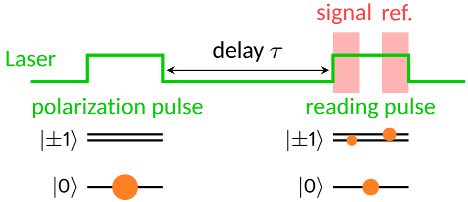

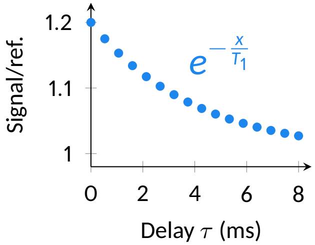

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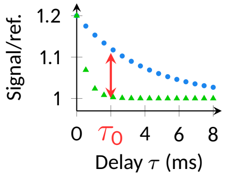

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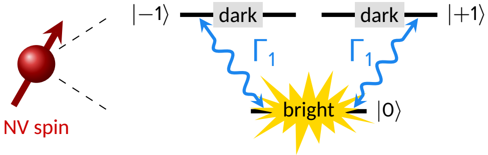
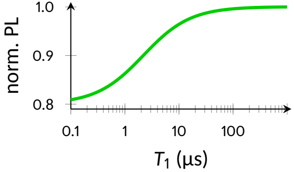
- **Detect ΔT_1 through ΔPL**

Outline

1. Experimental investigation of the NV center response to magnetic noise





A. Finco *et al.* *arXiv:2006.13130 [cond-mat]* (2020)

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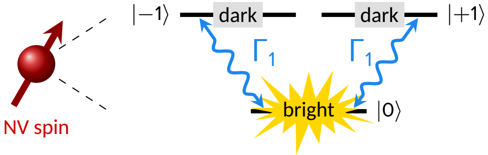
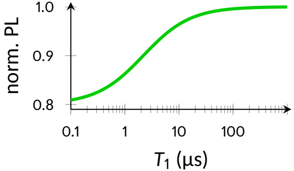
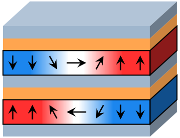
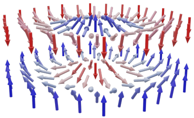




2. Application to the imaging of complex magnetic textures in synthetic antiferromagnets





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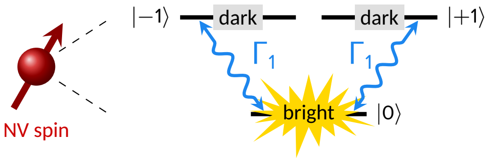

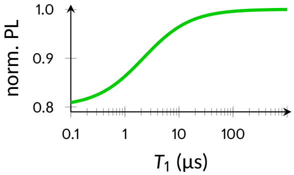

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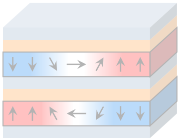

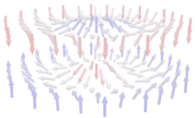

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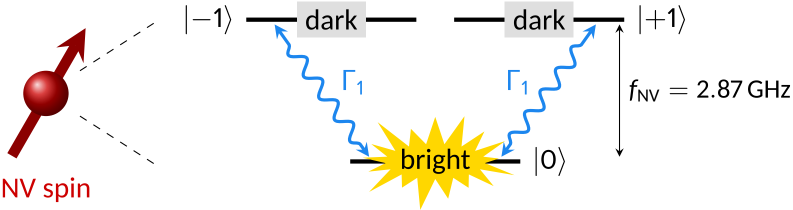
Detecting magnetic noise from the emitted PL



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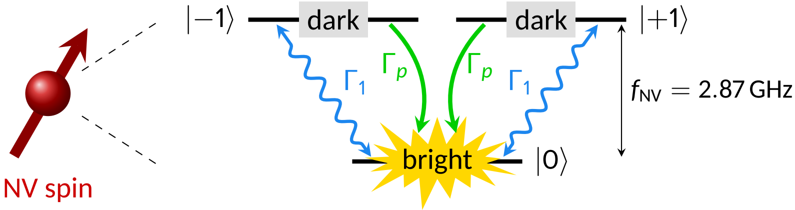

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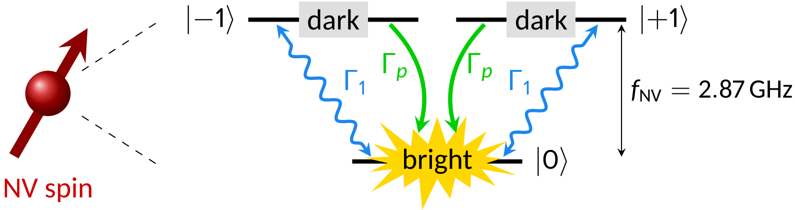

Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{\mathrm{NV}})$ magnetic field spectral density at the resonance frequency f_{NV}

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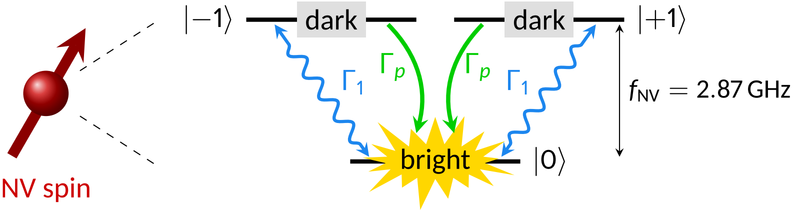

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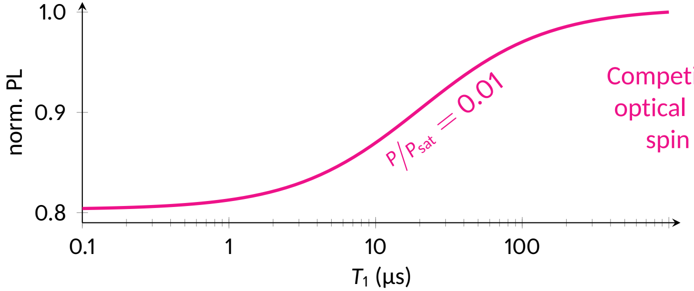
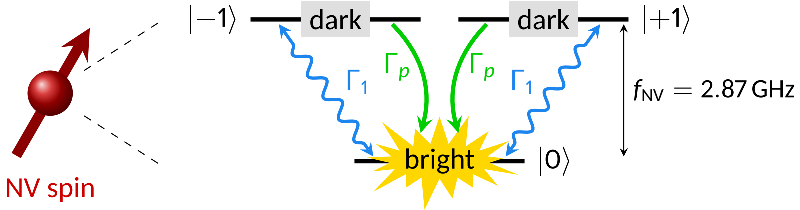
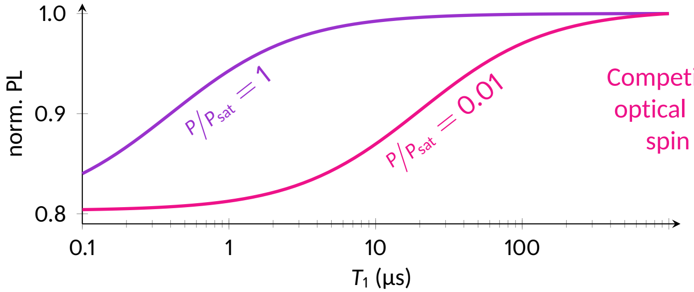


Competition between optical pumping and spin relaxation

Detecting magnetic noise from the emitted PL



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

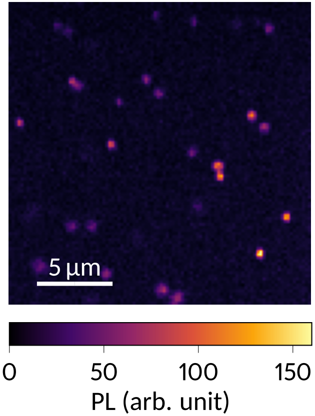


Competition between optical pumping and spin relaxation

Experimental investigation of the effect of magnetic noise

Collaboration C2N: Thibaut Devolder

Bulk diamond sample



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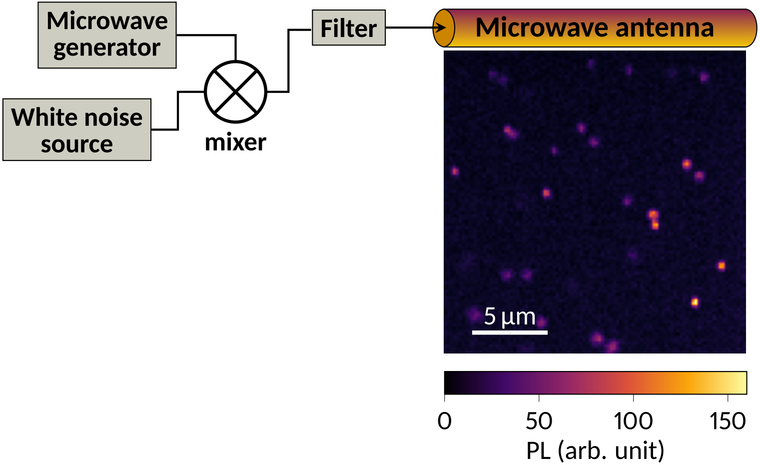

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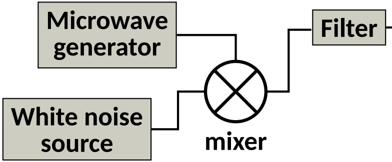

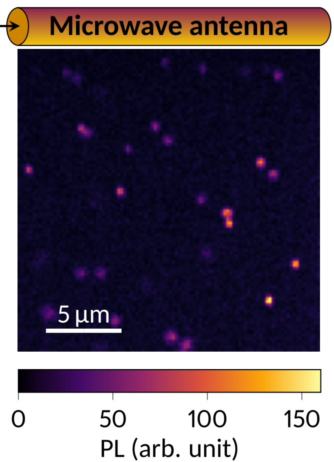

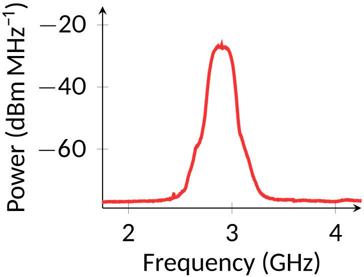

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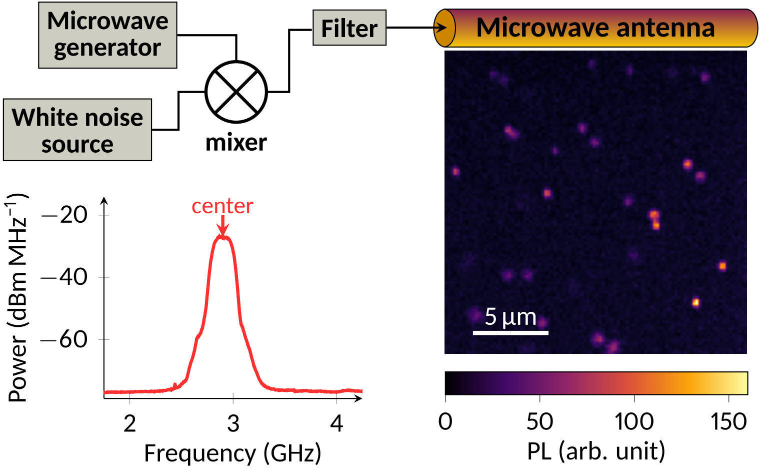

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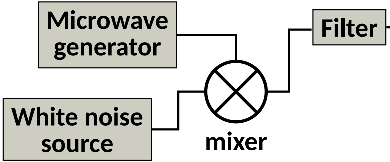

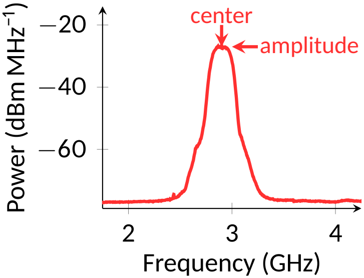

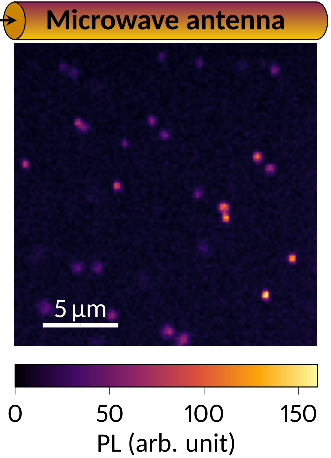

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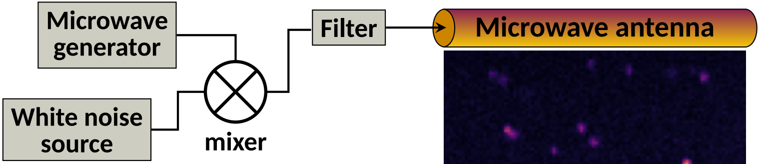

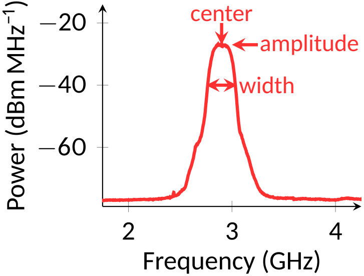

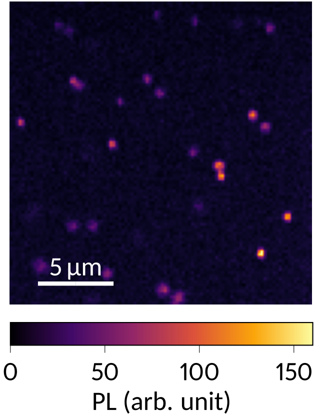

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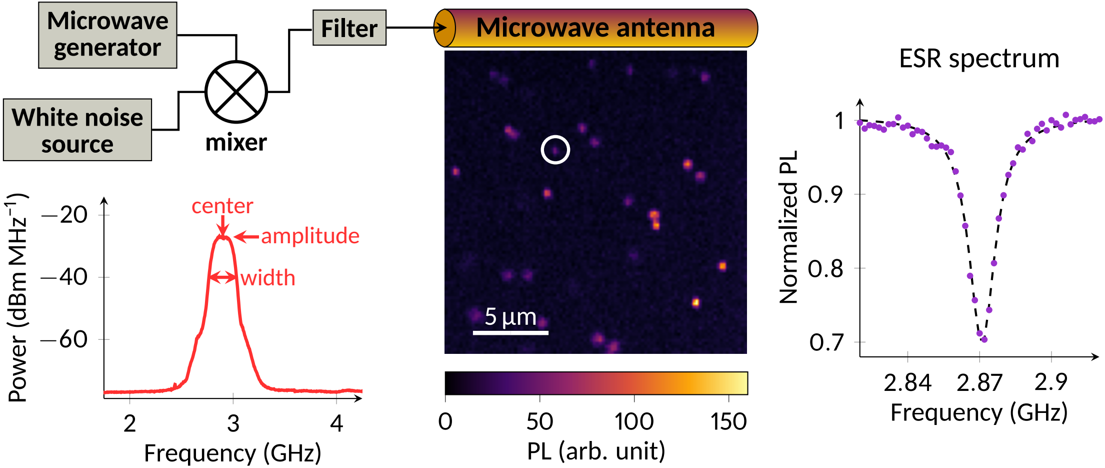
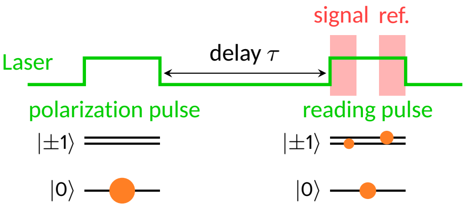


Acceleration of the longitudinal spin relaxation



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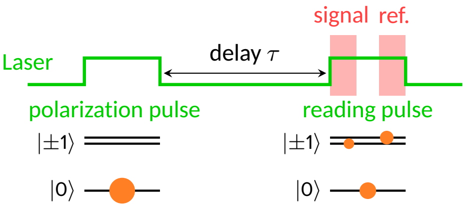

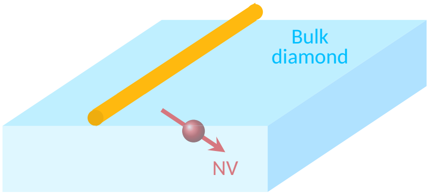

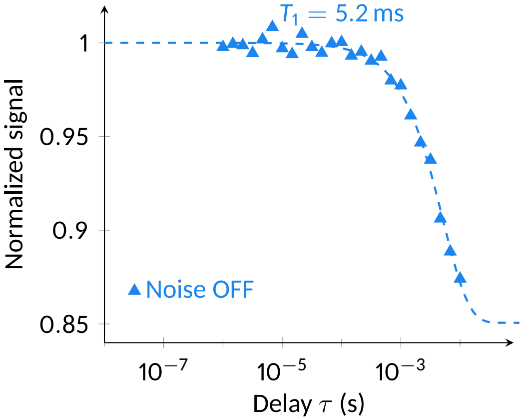

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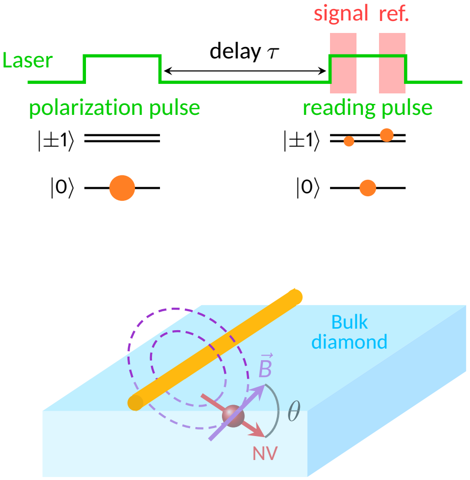

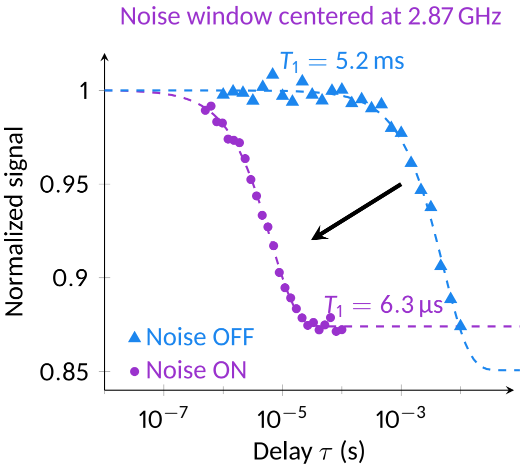

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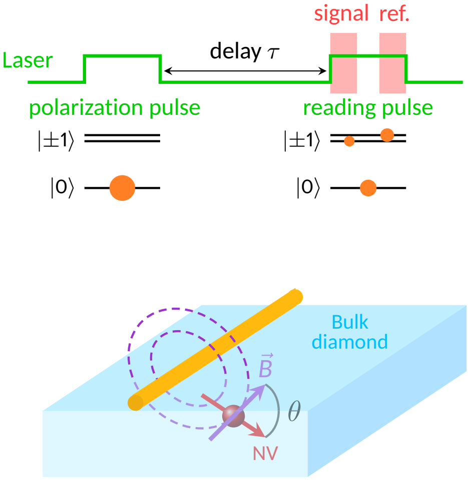

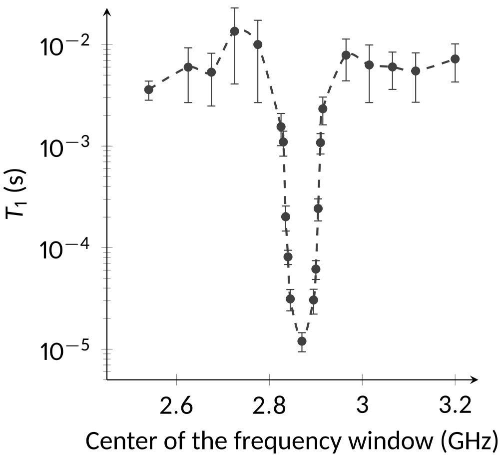

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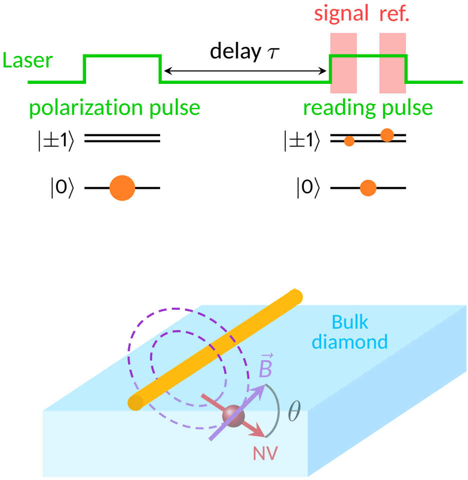
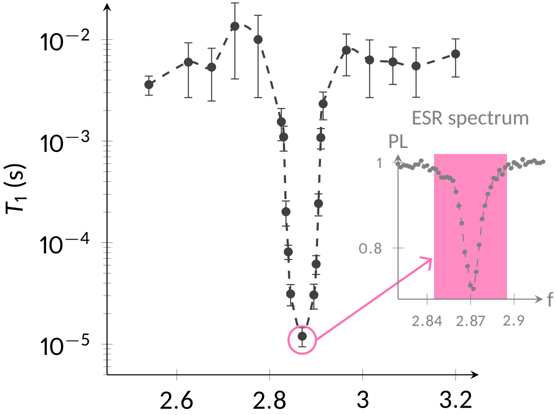


Shifting the noise window



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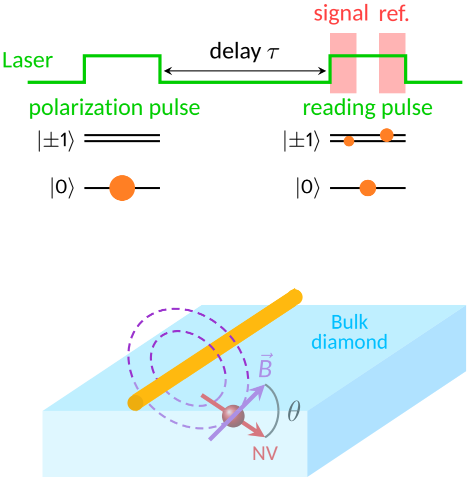

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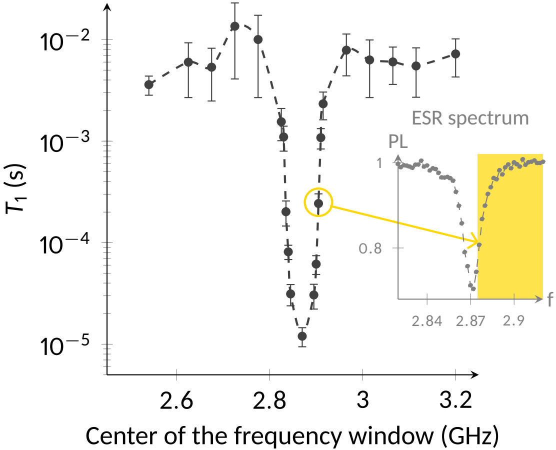

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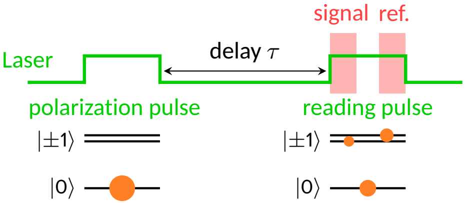

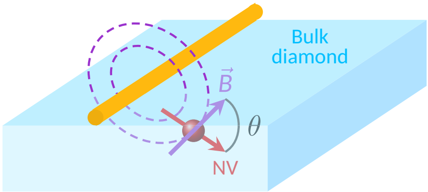

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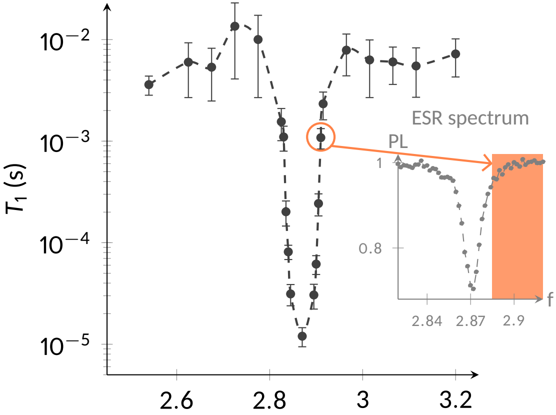

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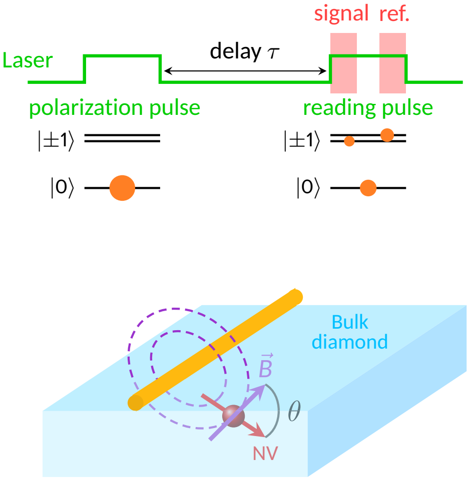
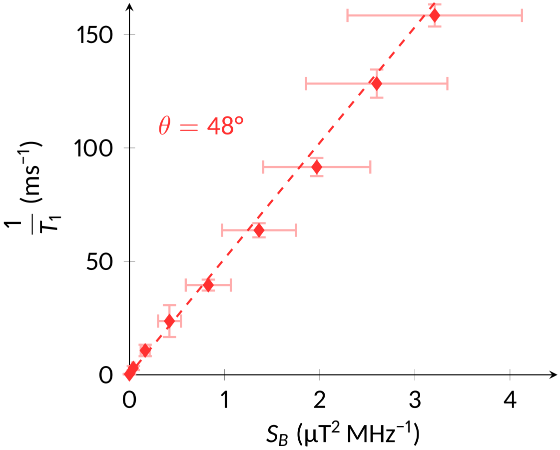


Variation with the noise power



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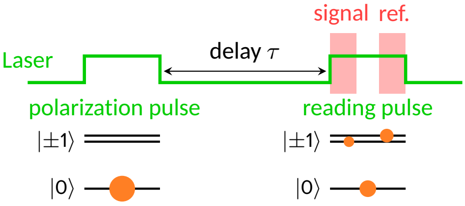

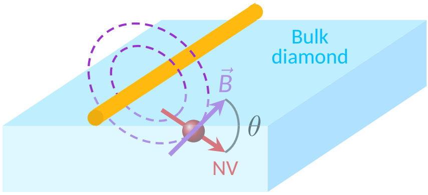

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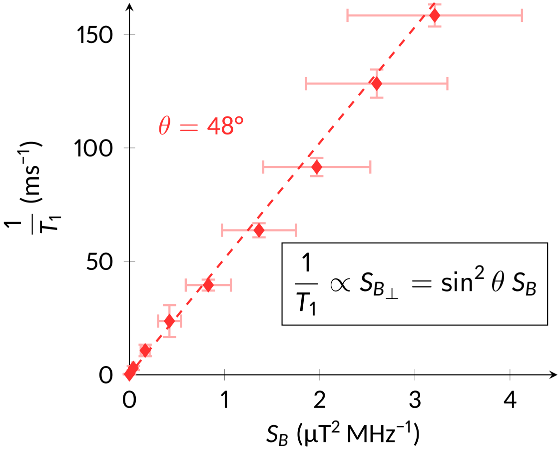
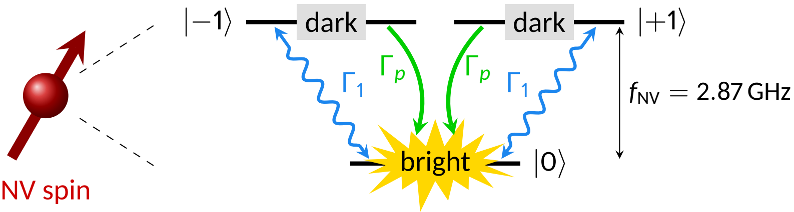
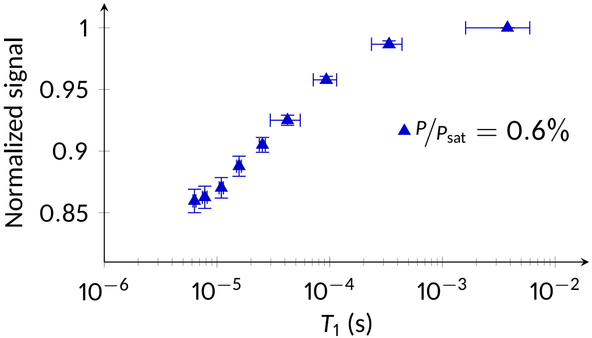


Effect on the emitted photoluminescence





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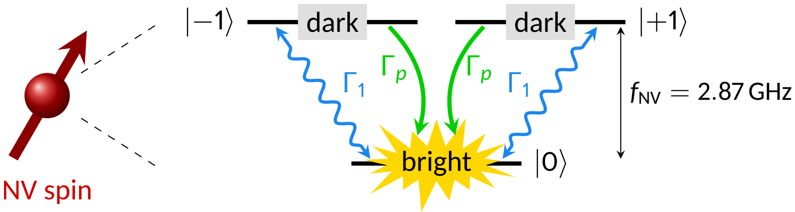

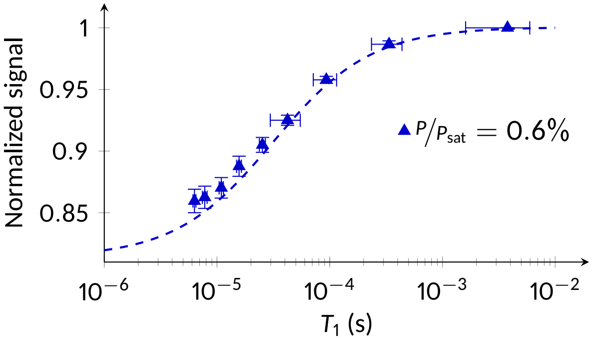

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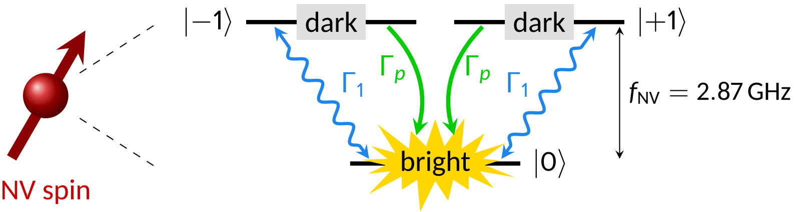

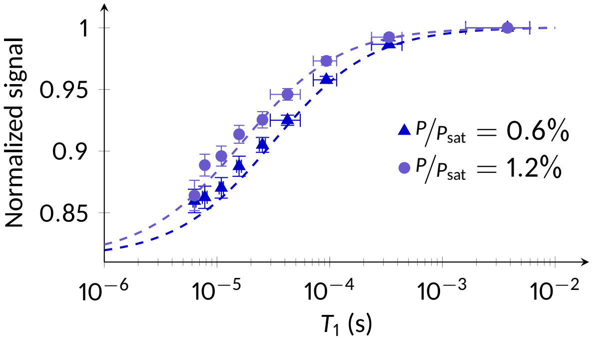

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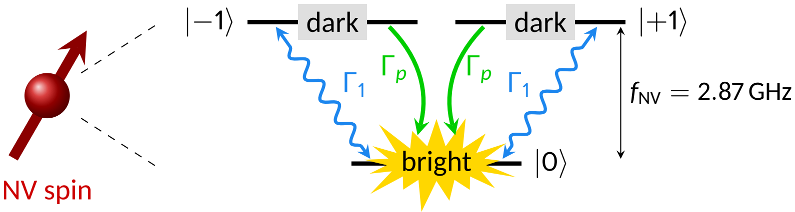

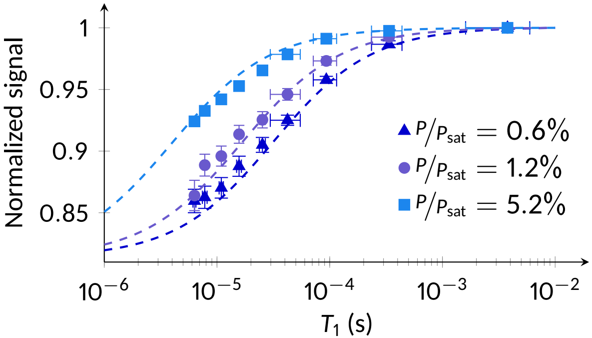

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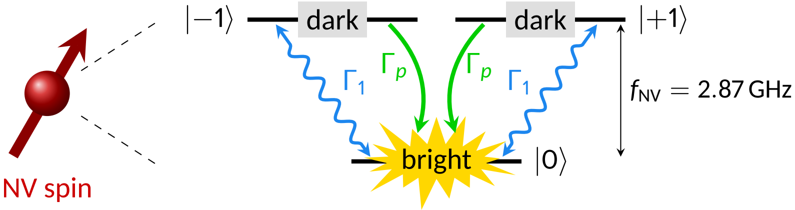

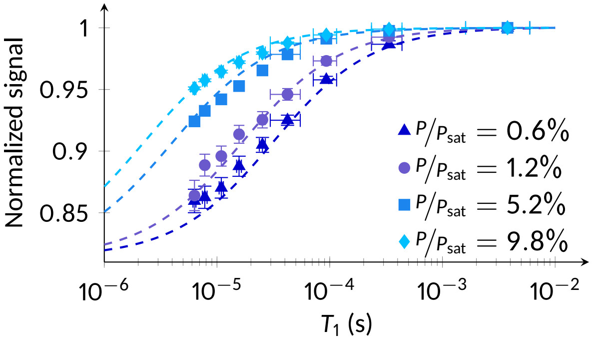

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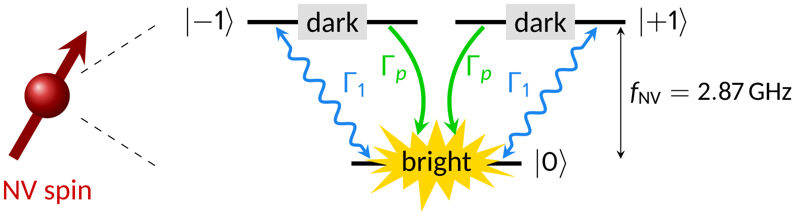

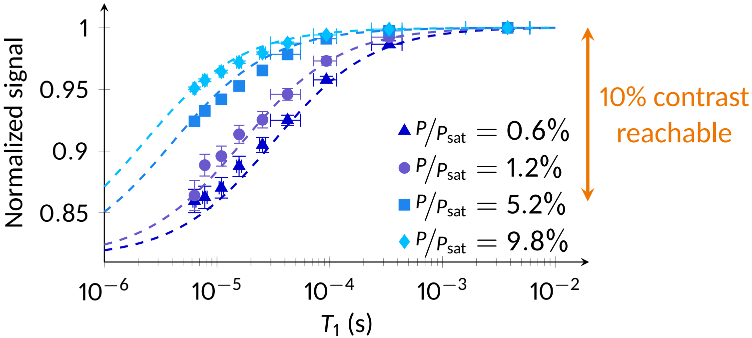

Sensitivity of the measurement

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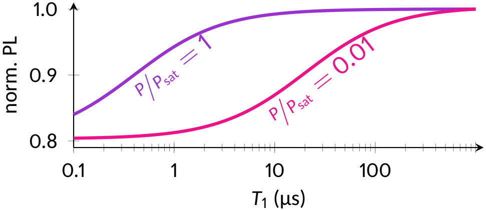

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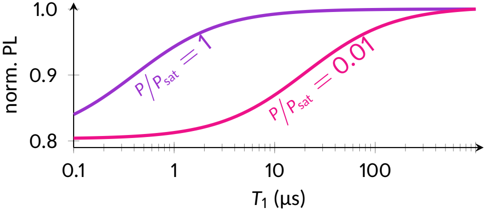

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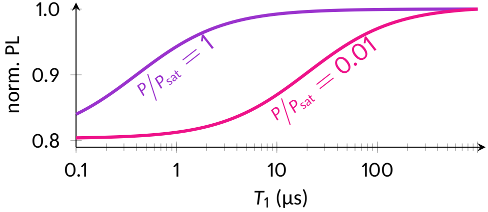

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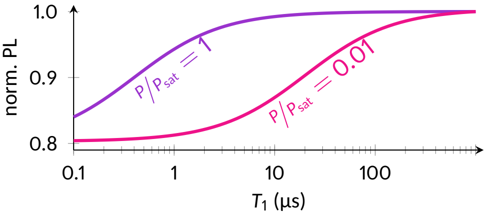
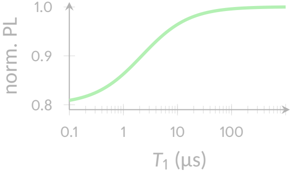


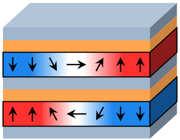
- **Equivalent to a single-τ measurement**

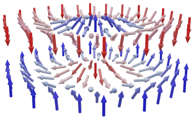
Outline

1. Experimental investigation of the NV center response to magnetic noise



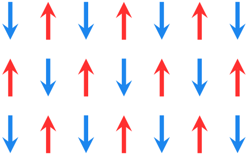
2. Application to the imaging of complex magnetic textures in synthetic antiferromagnets





A. Finco *et al.* *arXiv:2006.13130 [cond-mat]* (2020)

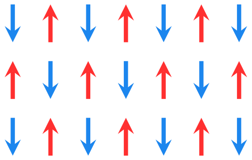
Imaging antiferromagnets…



Alternating magnetic moments

→ Weak signals

Imaging antiferromagnets...



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Promising materials for spintronics

→ **Need for efficient imaging techniques**

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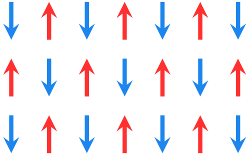

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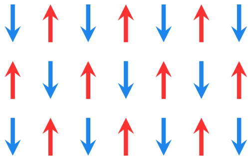

Alternating magnetic moments

→ Weak signals

Promising materials for spintronics

→ **Need for efficient imaging techniques**

Existing options:

- measure the magnetization direction
  (SHG, XMLD-PEEM, SP-STM)
  limited spatial resolution or demanding experimental conditions
- measure the stray field
  (usual NV magnetometry)
  need a small uncompensated moment

… with relaxometry!

- Completely compensated antiferromagnets = **no static stray field** to probe

… with relaxometry!

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

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

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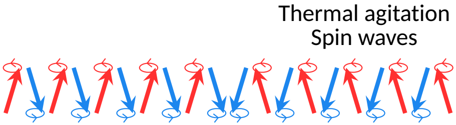

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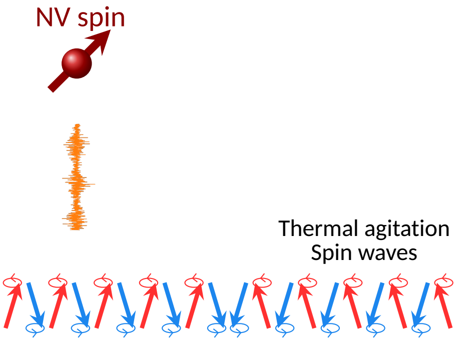

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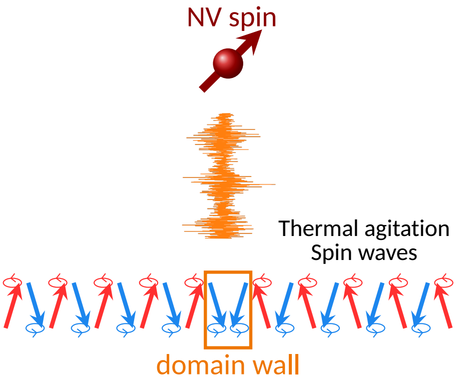
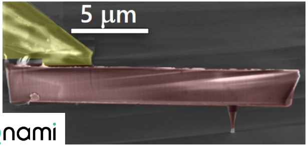


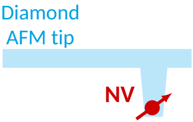
Our scanning NV microscope

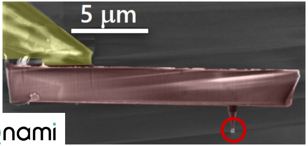
Diamond
AFM tip



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

Our scanning NV microscope





Implanted single NV center

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

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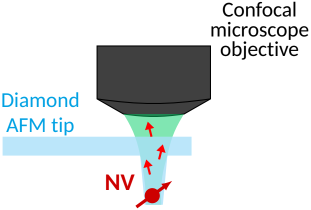

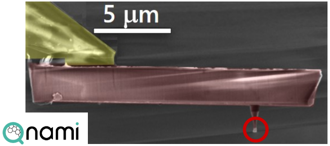

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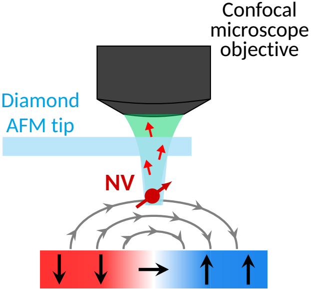

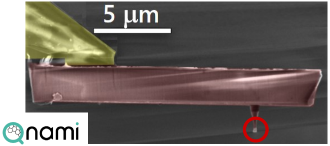

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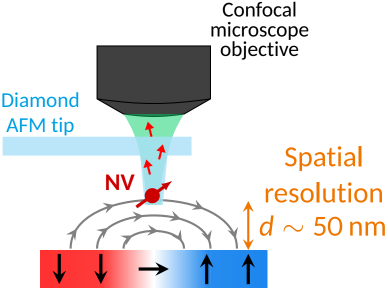

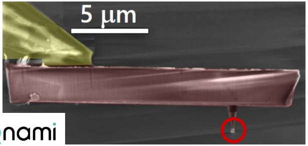

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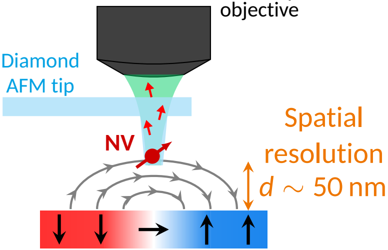

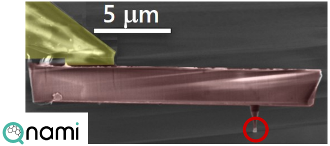

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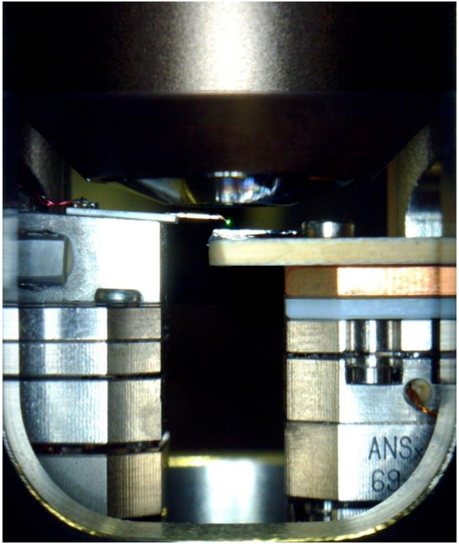

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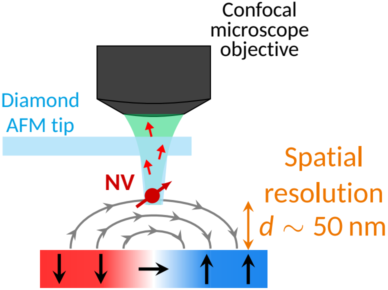

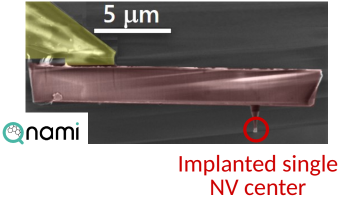

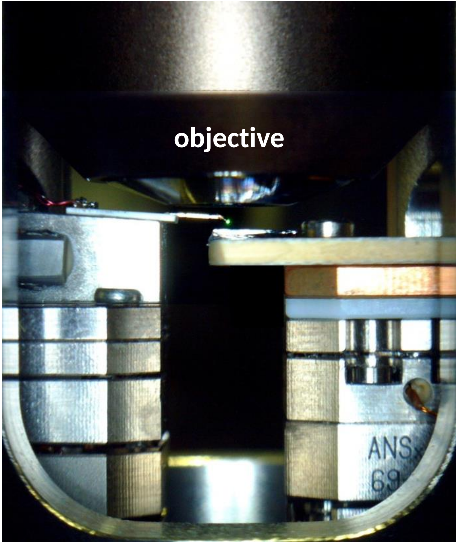

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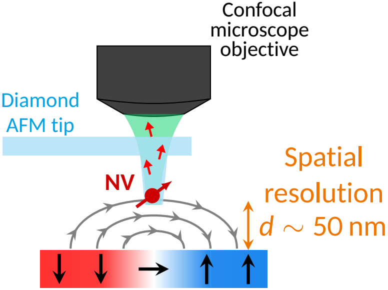

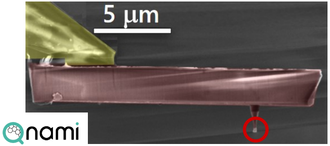

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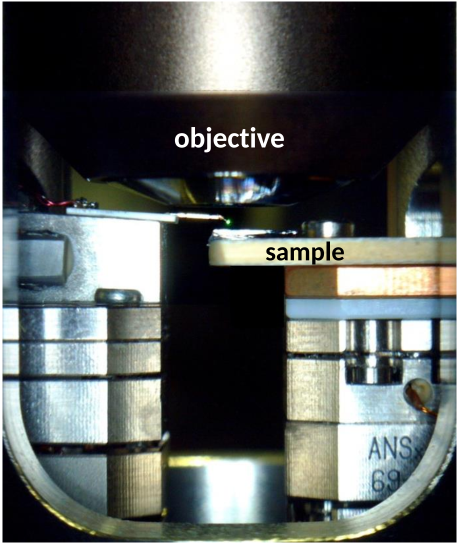

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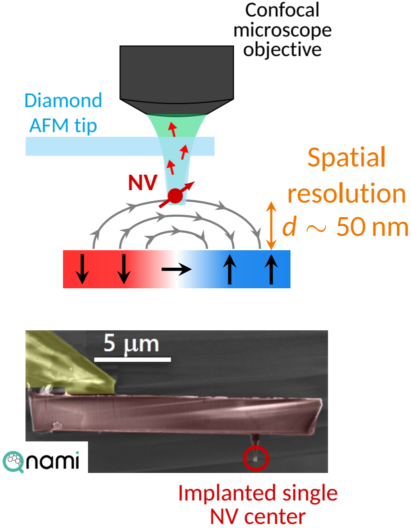

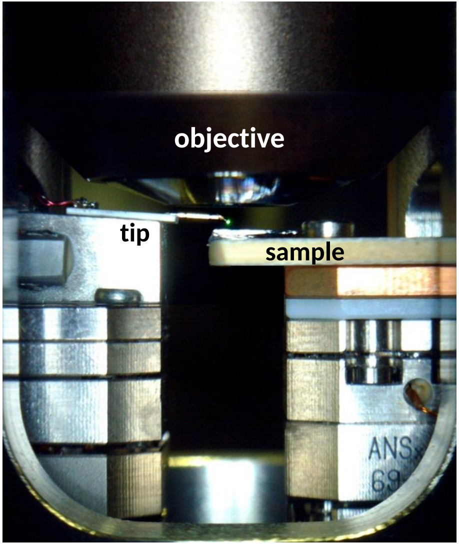

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Synthetic antiferromagnets

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

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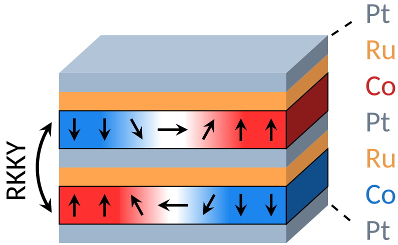

W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34

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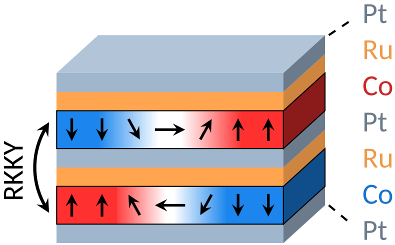

- No net magnetic moment
- Small stray field (vertical shift)
- Highly tunable properties

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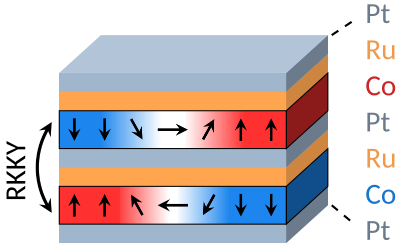

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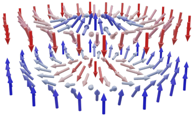
First observation of "antiferromagnetic" skyrmions



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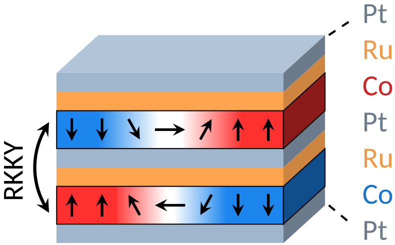

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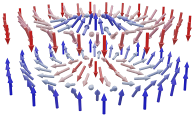

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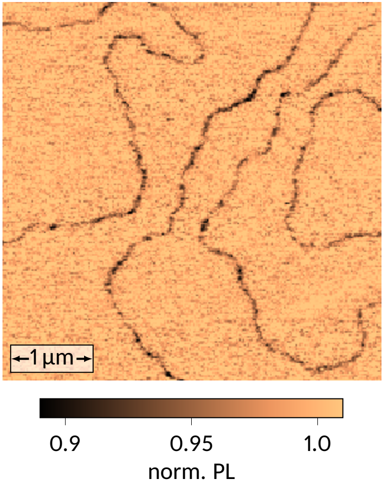
Perfect test system for noise imaging!

Domain wall imaging by relaxometry



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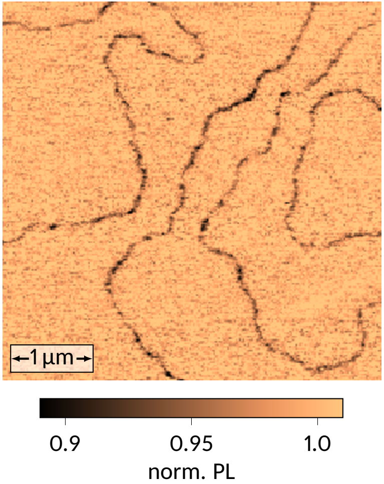

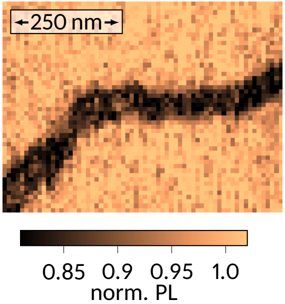

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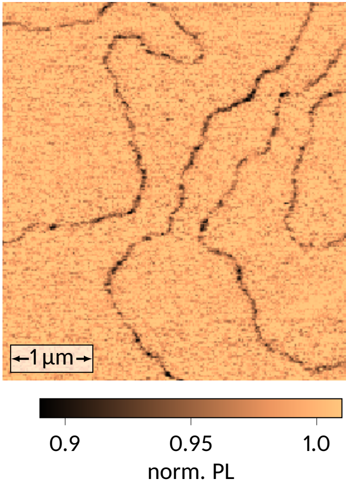

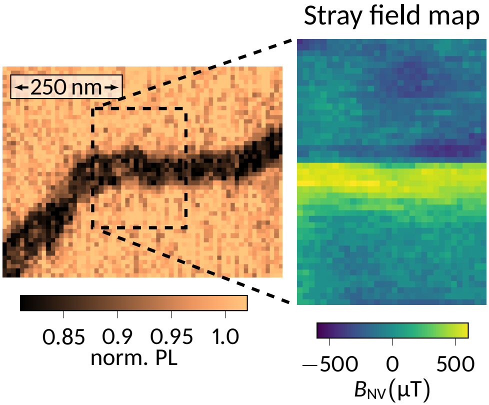

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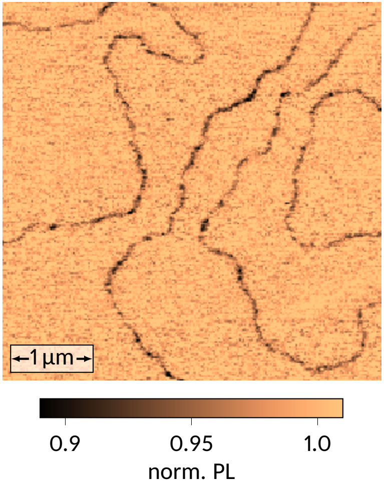
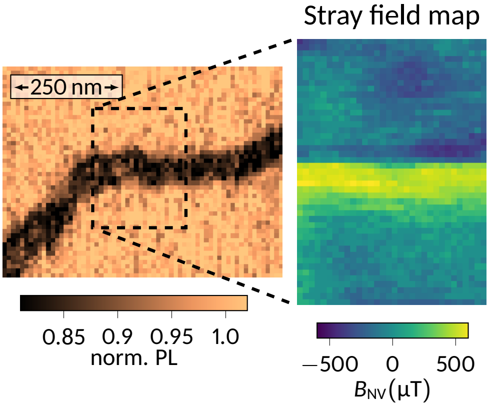
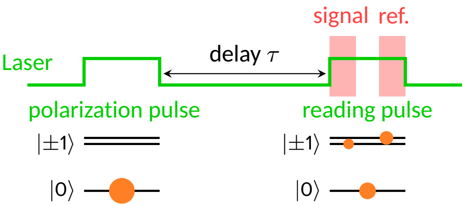




Not an off-axis field induced PL quenching!

Local variation of the relaxation time



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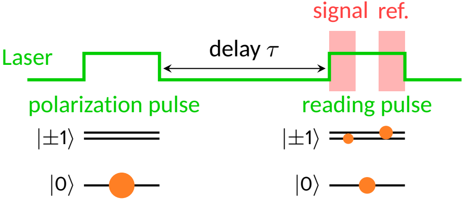

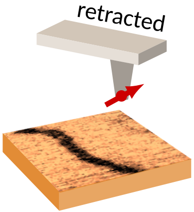

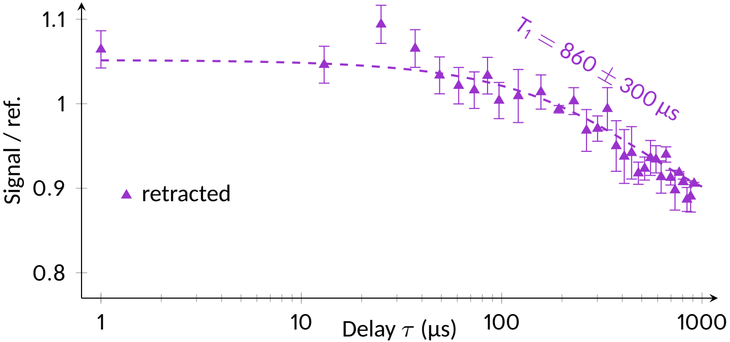

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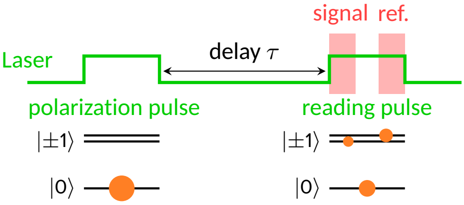

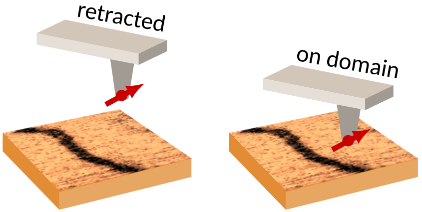

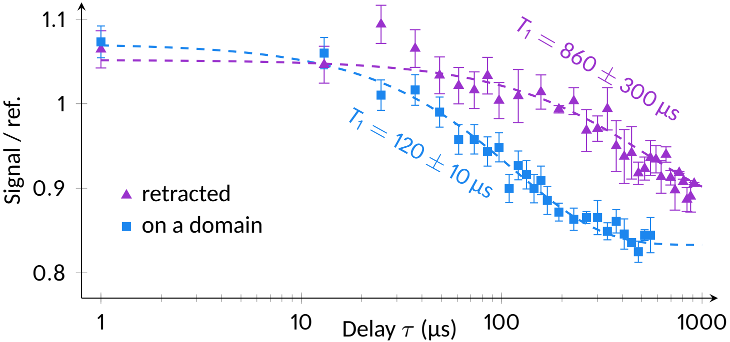

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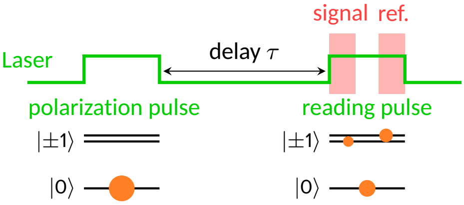

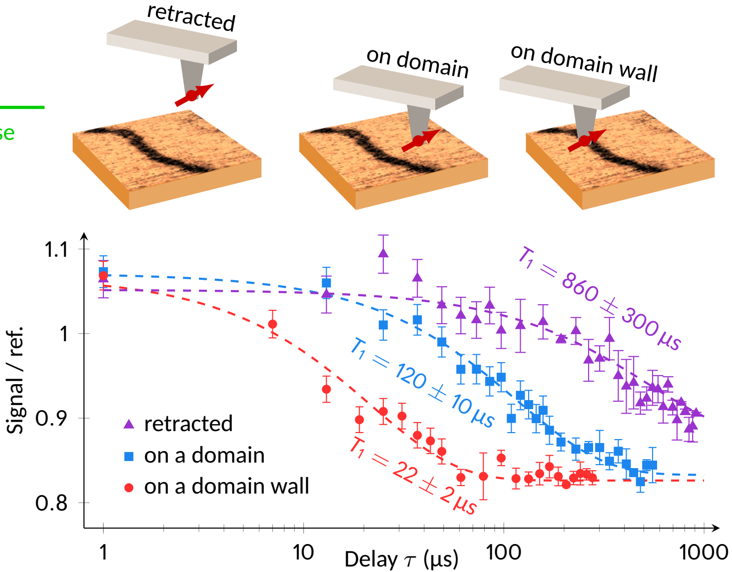

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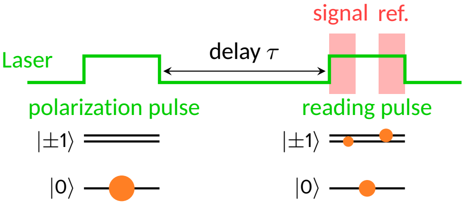
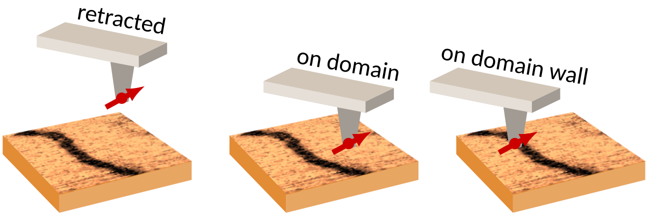
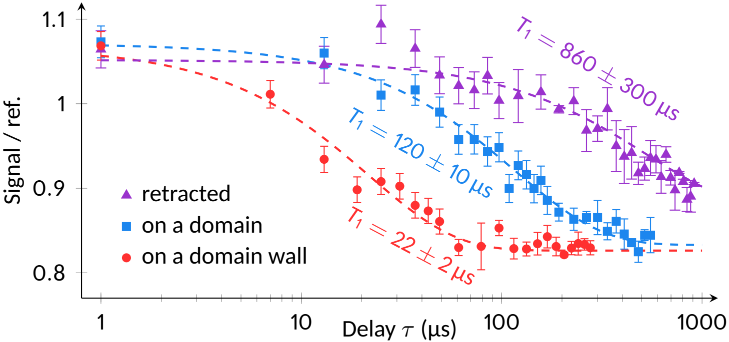




Clear diminution of T_1
above the domain wall



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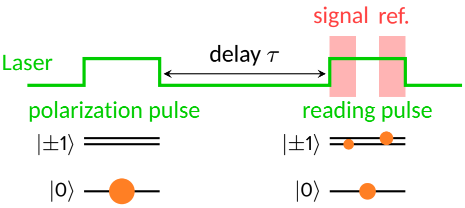
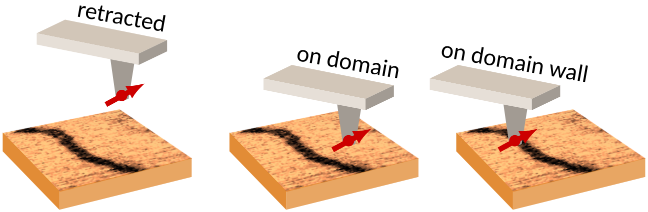
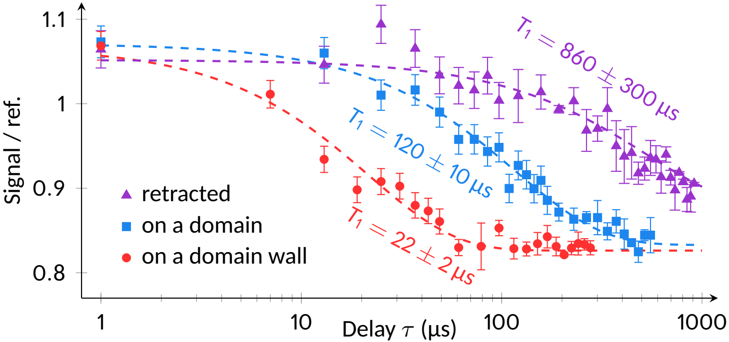


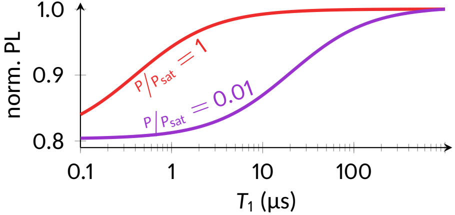




Clear diminution of T_1 above the domain wall

→ Enhancement of the spin relaxation

Dependence on the optical power



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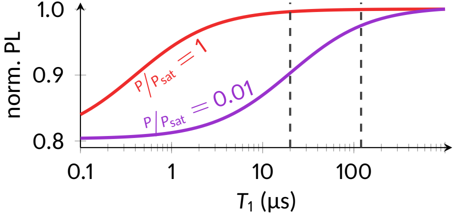

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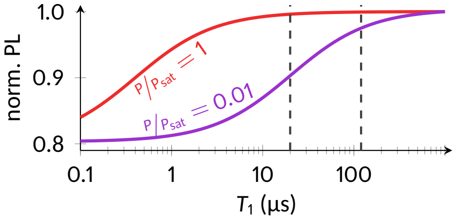

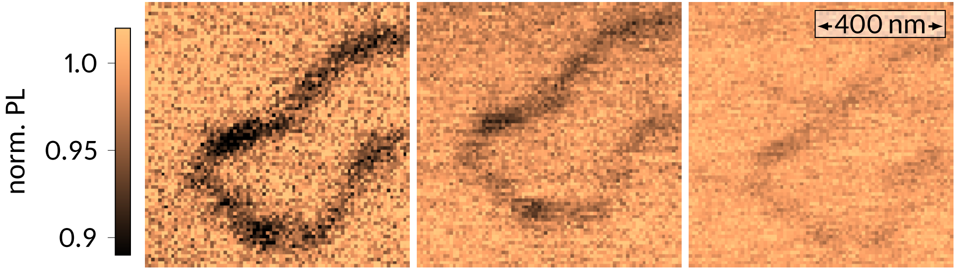

$P/P_{sat} = 0.05$ $P/P_{sat} = 0.48$ $P/P_{sat} = 1.65$

Origin of the noise: spin waves

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

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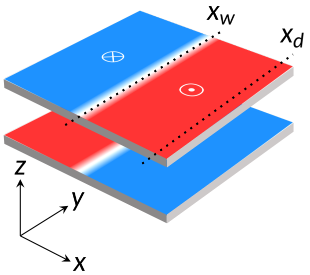

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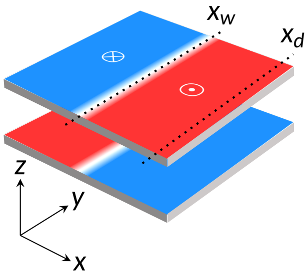

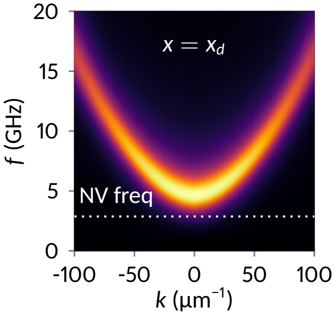

- NV frequency in the tail of the dispersion relation, almost below the gap: we are only sensitive to a few modes in the domains

Origin of the noise: spin waves

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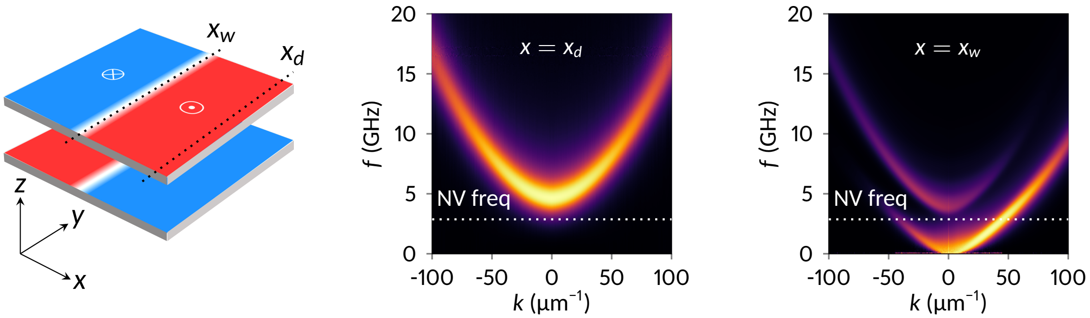

- NV frequency in the tail of the dispersion relation, almost below the gap: we are only sensitive to a few modes in the domains
- No gap in the domain walls, presence of modes at the NV frequency: **we are much more sensitive to the noise from the walls!**

Map of the detectable noise

Simulation of the expected noise map
above a domain wall
(at 2.87 GHz and at 80 nm from the surface)

Map of the detectable noise

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- Disorder in the static magnetic configuration (anisotropy variations)

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Simulation of the expected noise map above a domain wall

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- Disorder in the static magnetic configuration (anisotropy variations)
- Driving field at 2.87 GHz with random spatial variations

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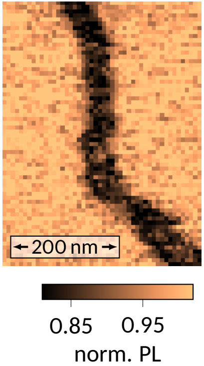
Exp.



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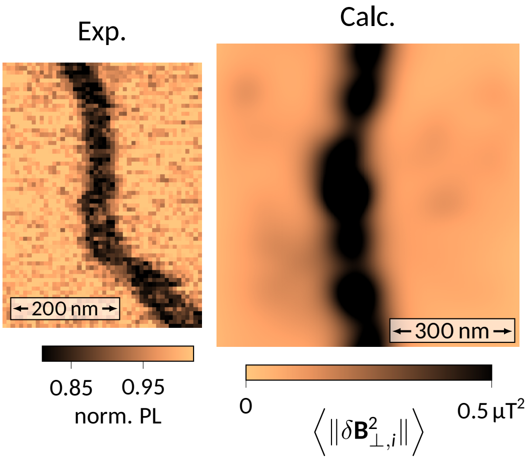
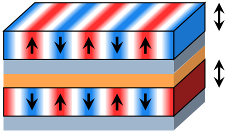


Going to spin spirals and skyrmions



thicker
Co layers
↓
vanishing
anisotropy

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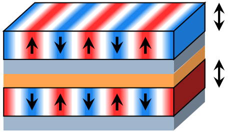
Going to spin spirals and skyrmions



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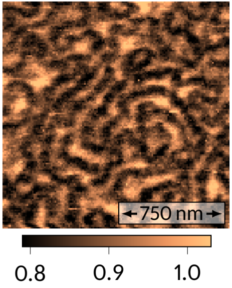
Experiment



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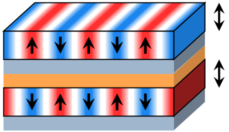

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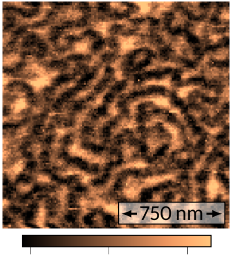
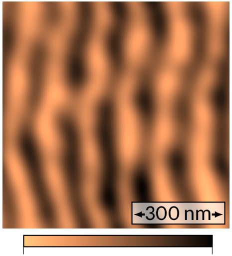
W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34

Experiment



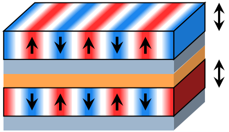
0.8 0.9 1.0
norm. PL

Calculation



0.45 $\langle \|\delta \mathbf{B}^2_{\perp,i}\| \rangle$ 1.2 μT^2

Going to spin spirals and skyrmions



thicker
Co layers
↓
vanishing
anisotropy

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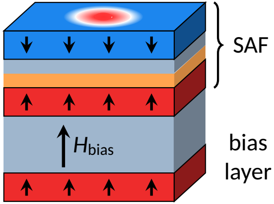

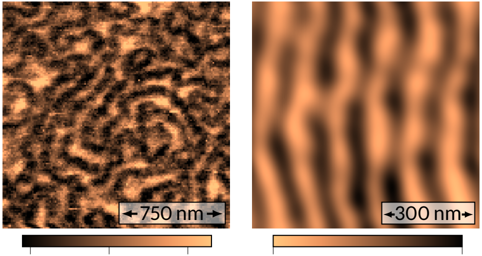

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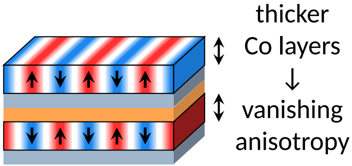

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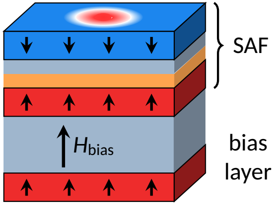
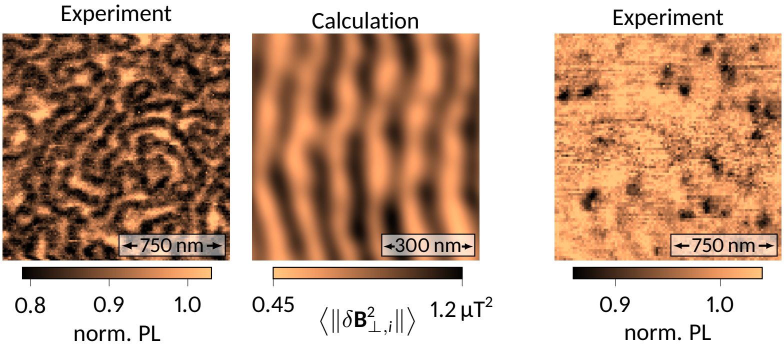
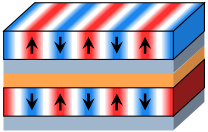




Going to spin spirals and skyrmions



thicker
Co layers
↓
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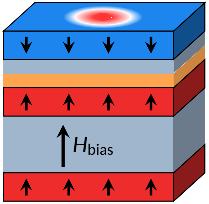
anisotropy

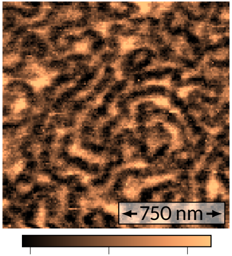
W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34



SAF

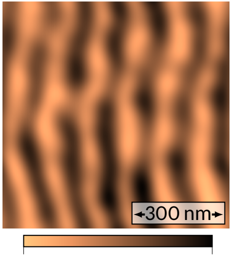
bias
layer

Experiment



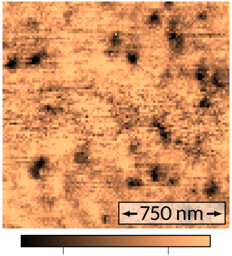
0.8 0.9 1.0
norm. PL

Calculation



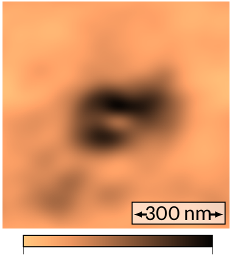
0.45 $\langle \| \delta \mathbf{B}^2_{\perp,i} \| \rangle$ 1.2 μT^2

Experiment



0.9 1.0
norm. PL

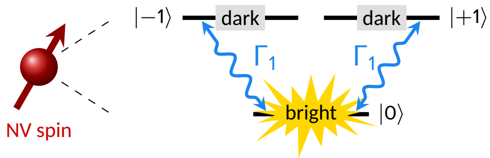
Calculation

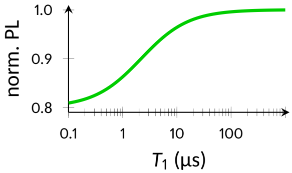


0.25 $\langle \| \delta \mathbf{B}^2_{\perp,i} \| \rangle$ 1.0 μT^2

Summary

→ All optical detection of magnetic noise with NV centers

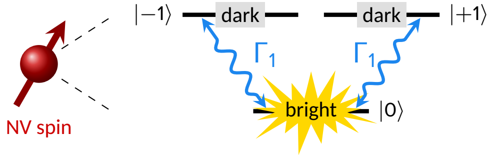


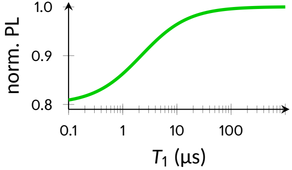


A. Finco *et al.* *arXiv:2006.13130 [cond-mat]* (2020)

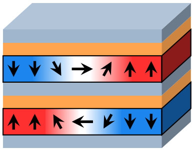
Summary

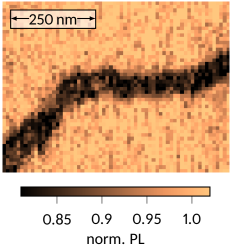
→ All optical detection of magnetic noise with NV centers

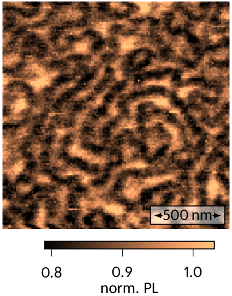


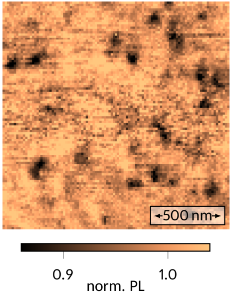


→ Application to the imaging of magnetic textures in synthetic antiferromagnets









A. Finco *et al.* *arXiv:2006.13130 [cond-mat]* (2020)

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