

Imaging non-collinear textures in antiferromagnets with NV-centers

Aurore Finco

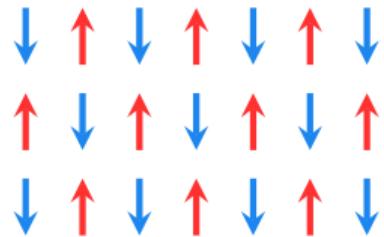
Laboratoire Charles Coulomb, Université de Montpellier and CNRS, Montpellier, France



03/09/2020

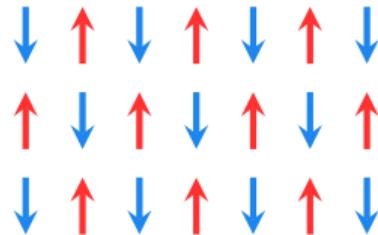
slides available at <https://magimag.eu>

Why is it interesting to look at antiferromagnets?



Alternating magnetic moments

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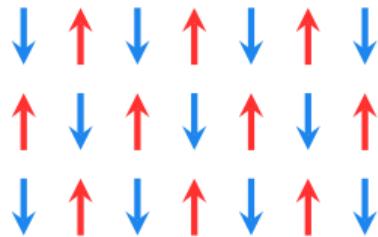
► **Spintronics:** robust, fast, efficient

■ T. Jungwirth *et al.* *Nat. Nano.* 11 (2016), 231

■ V. Baltz *et al.* *Rev. Mod. Phys.* 90 (2018)

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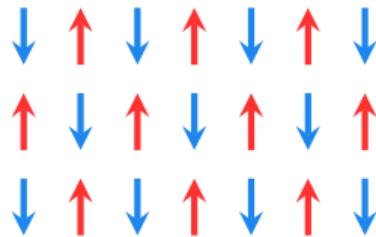
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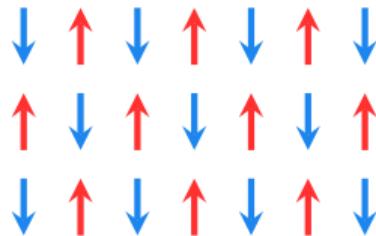
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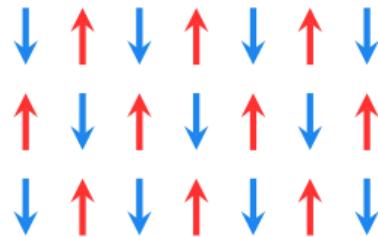


No net magnetization

Weak signals

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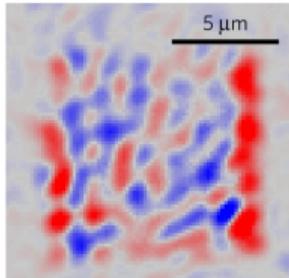
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→ Antiferromagnetic structures are difficult to image!

▣ S.-W. Cheong *et al.* *npj Quant. Mat.* 5 (2020), 1

How to look at antiferromagnetic states?

SHG



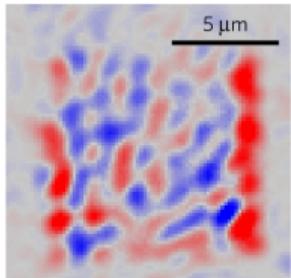
■ J.-Y. Chauleau *et al.* *Nat. Mat.* 16 (2017), 803



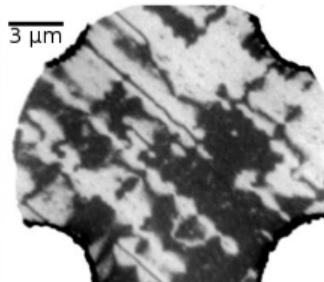
Spatial
resolution

How to look at antiferromagnetic states?

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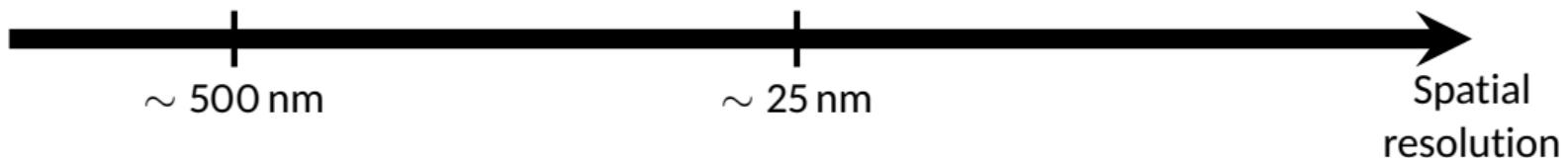


XMLD-PEEM



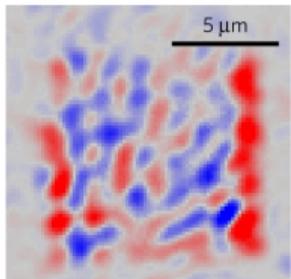
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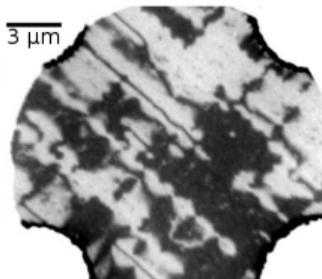


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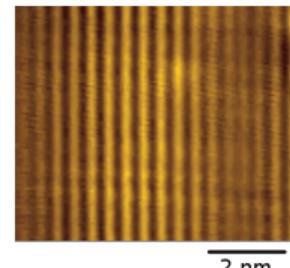
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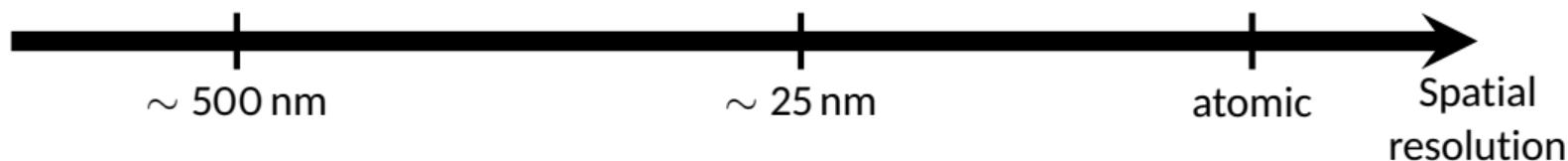
SP-STM



■ J.-Y. Chauleau *et al.* *Nat. Mat.* 16 (2017), 803

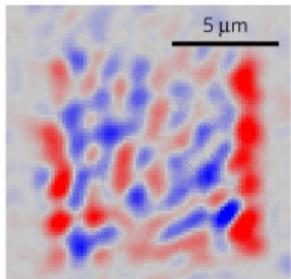
■ P. Wadley *et al.* *Nat. Nano.* 13 (2018), 362

■ M. Bode *et al.* *Nature* 447 (2007), 190

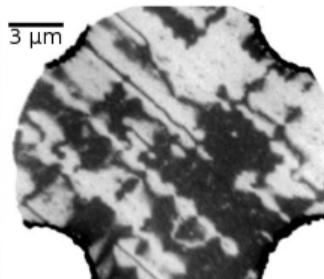


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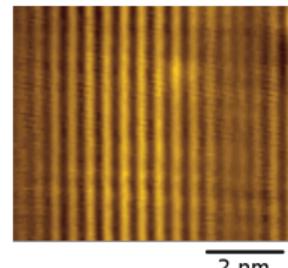
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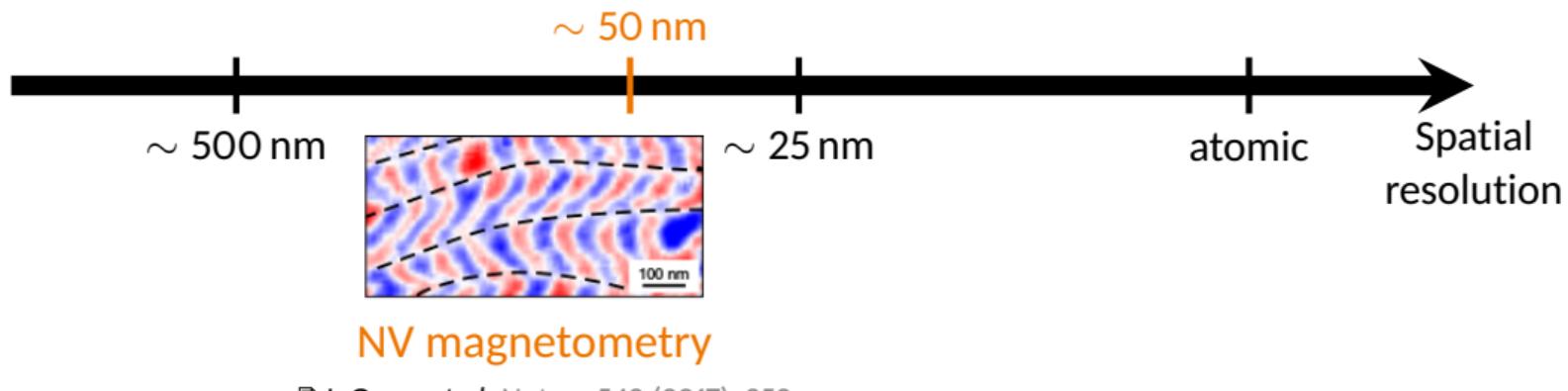
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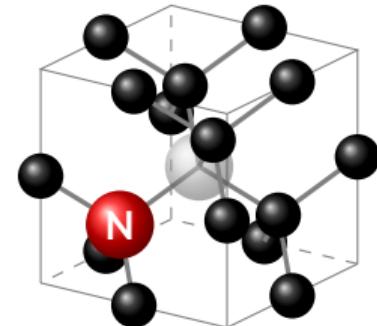
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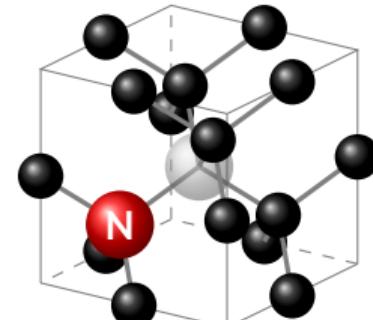
■ I. Gross et al. *Nature* 549 (2017), 252

NV centers as quantum sensors for SPM



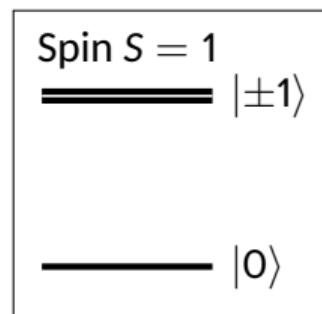
Defect in diamond

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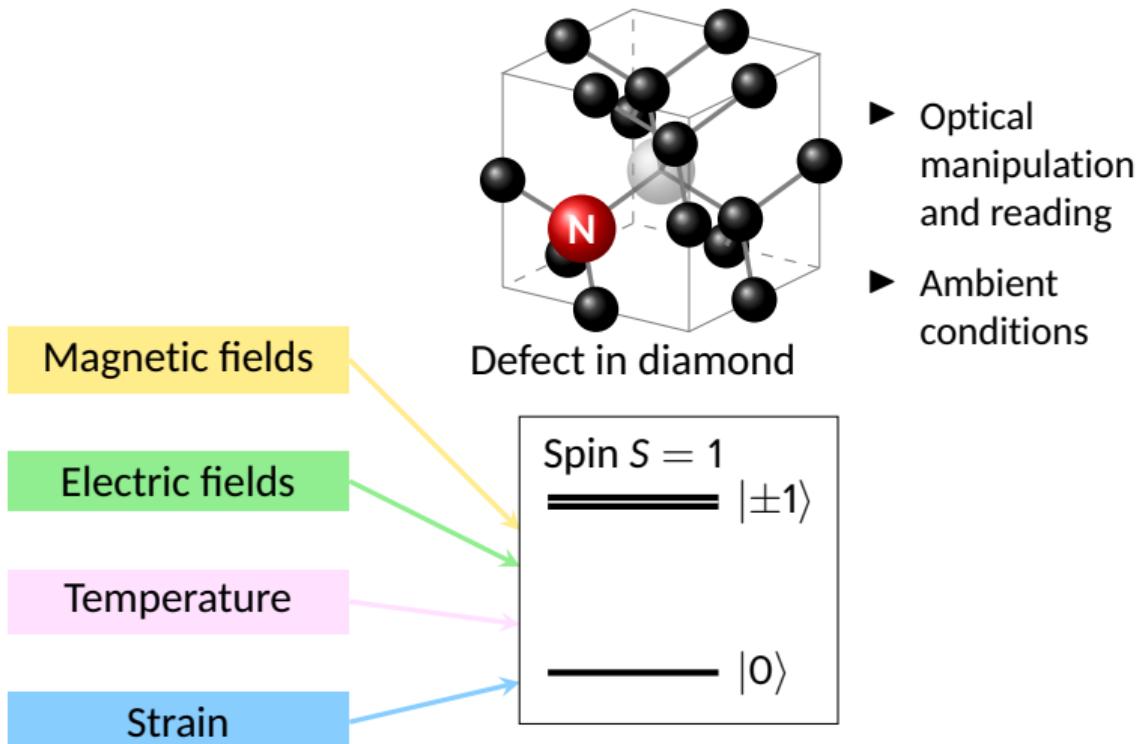


Defect in diamond

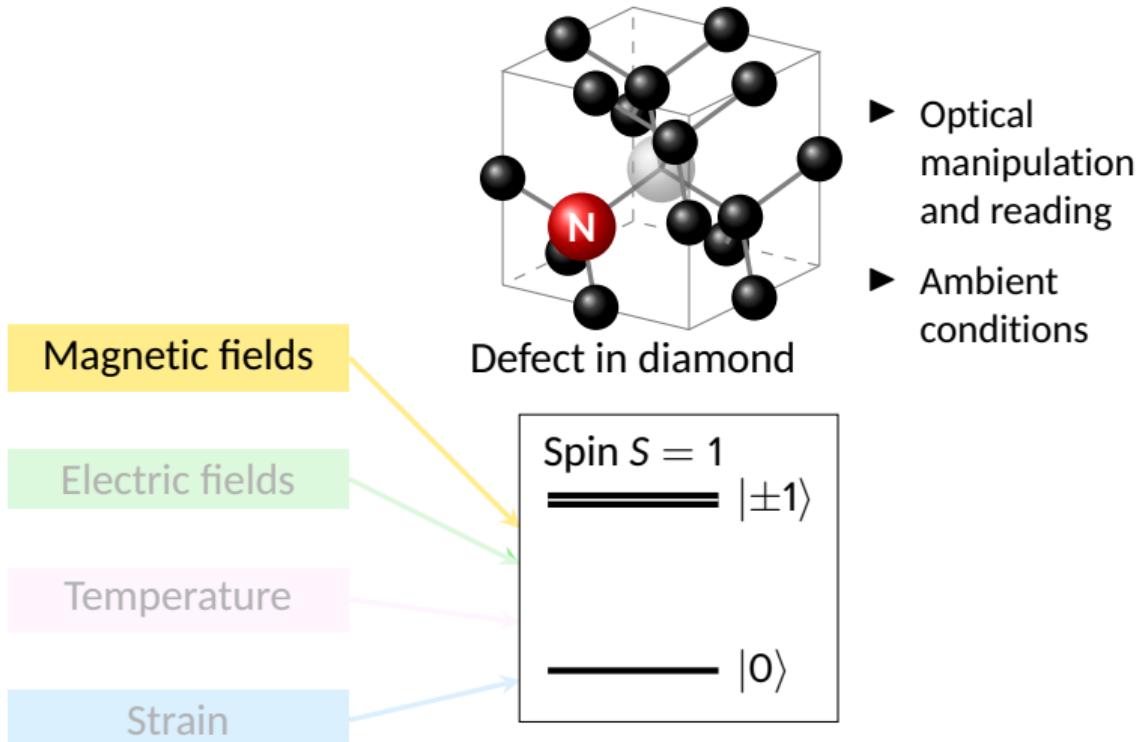
- ▶ Optical manipulation and reading
- ▶ Ambient conditions



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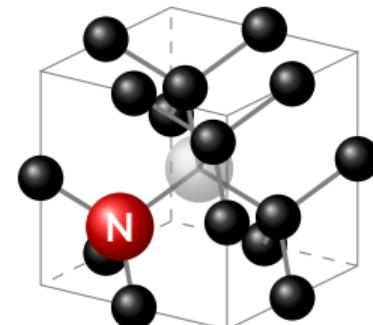


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Magnetic fields



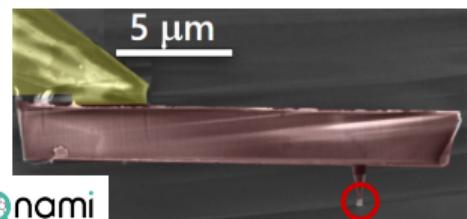
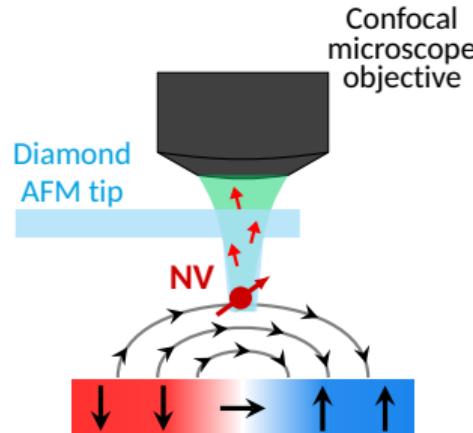
Electric fields

Temperature

Strain

$$\begin{array}{c} \text{Spin } S = 1 \\ \hline \hline | \pm 1 \rangle \\ \hline \hline | 0 \rangle \end{array}$$

- ▶ Optical manipulation and reading
- ▶ Ambient conditions



Implanted single NV center

■ L. Rondin et al. *Rep. Prog. Phys.* 77 (2014), 056503

■ F. Casola et al. *Nat. Rev. Mat.* 3 (2018), 17088

Outline

Measuring weak magnetic fields

Antiferromagnets with small uncompensated moments (BiFeO_3 , ...)

Collaborations: UMR CNRS/Thales, SPEC (CEA), SOLEIL

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Probing magnetic noise

Characterization of the effect of magnetic on the NV spin relaxation

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Detecting magnetic textures via noise

Synthetic antiferromagnets

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

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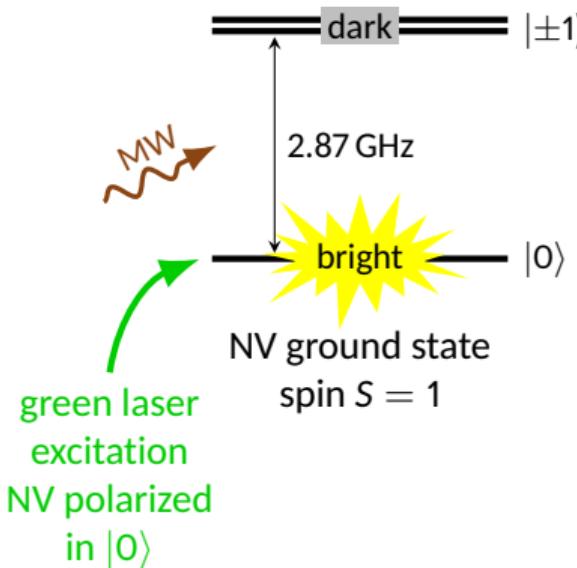
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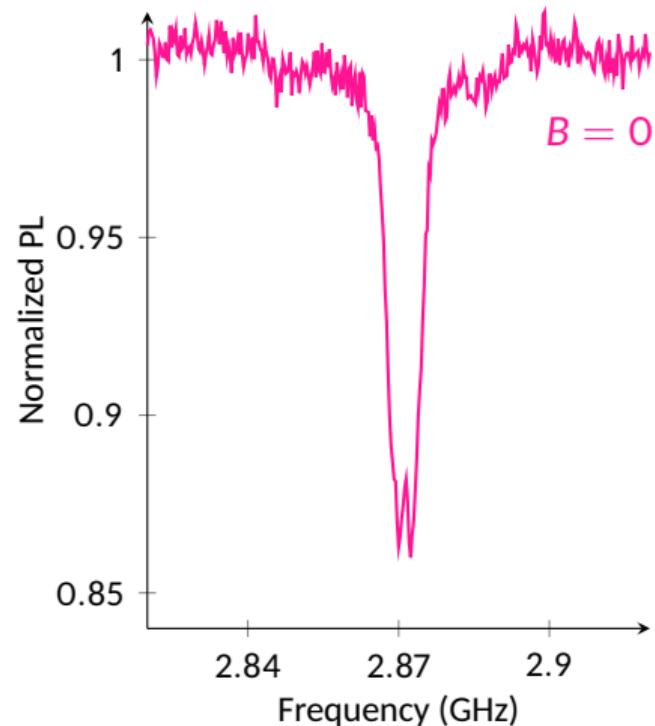
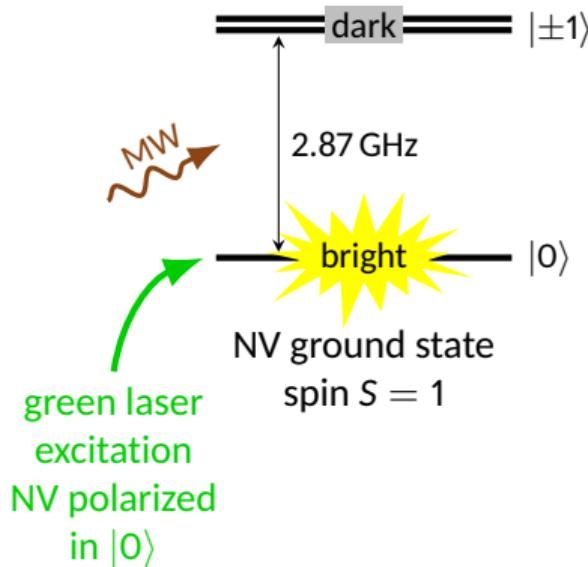
Measuring small magnetic fields with NV centers

Spin-dependent fluorescence



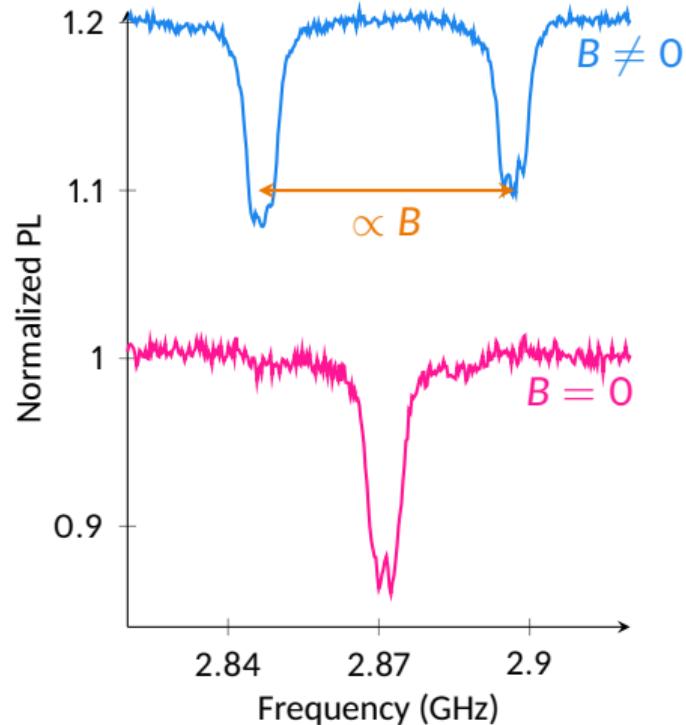
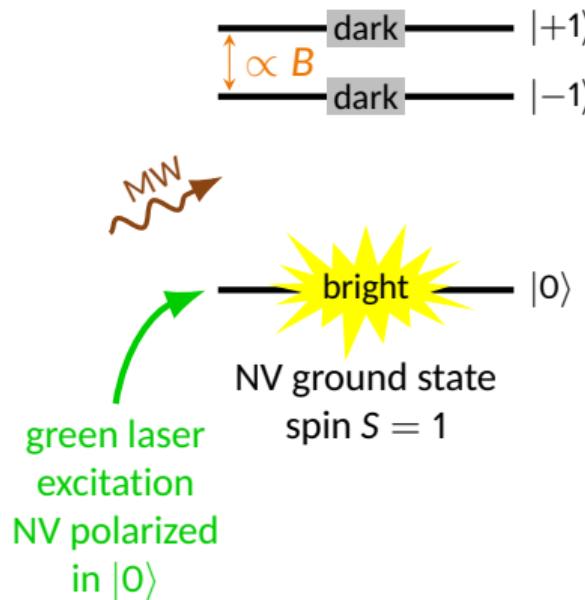
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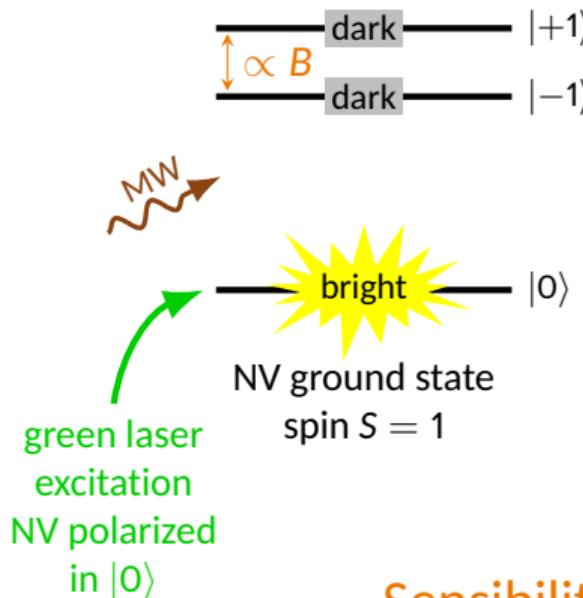
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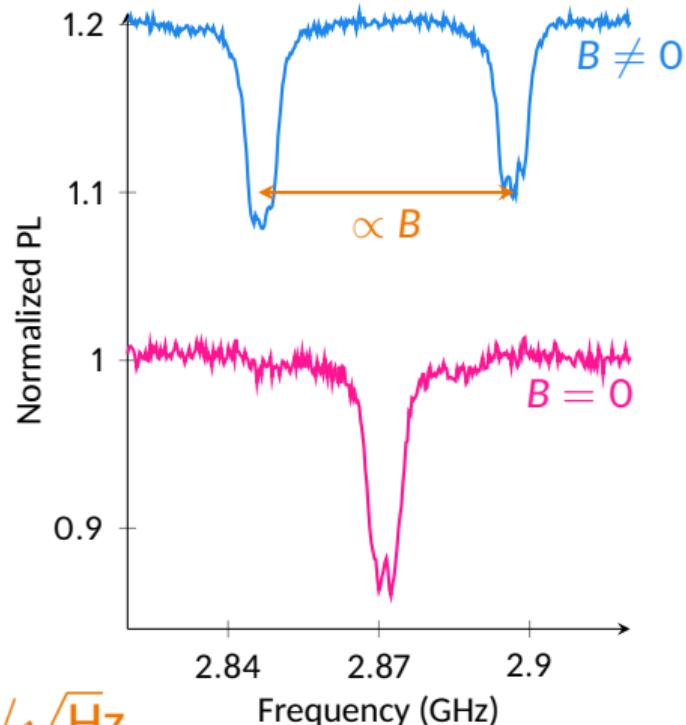


Measuring small magnetic fields with NV centers

Spin-dependent fluorescence



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

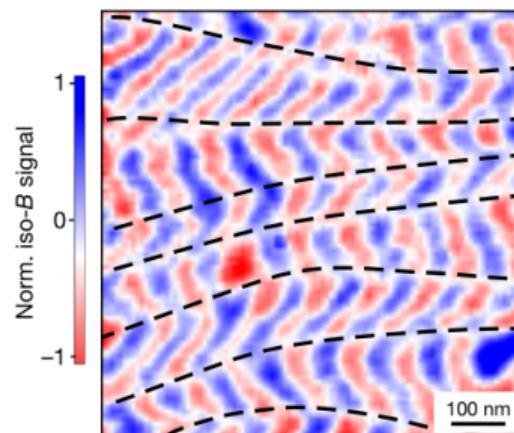
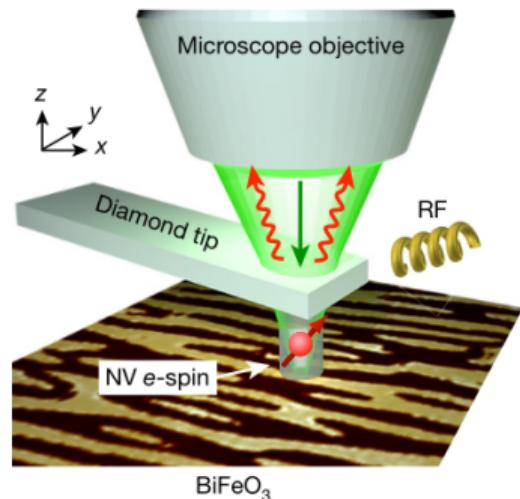


Application to the multiferroic BiFeO₃

Multiferroic = coexistence of ferroelectric and (anti-)ferromagnetic orders

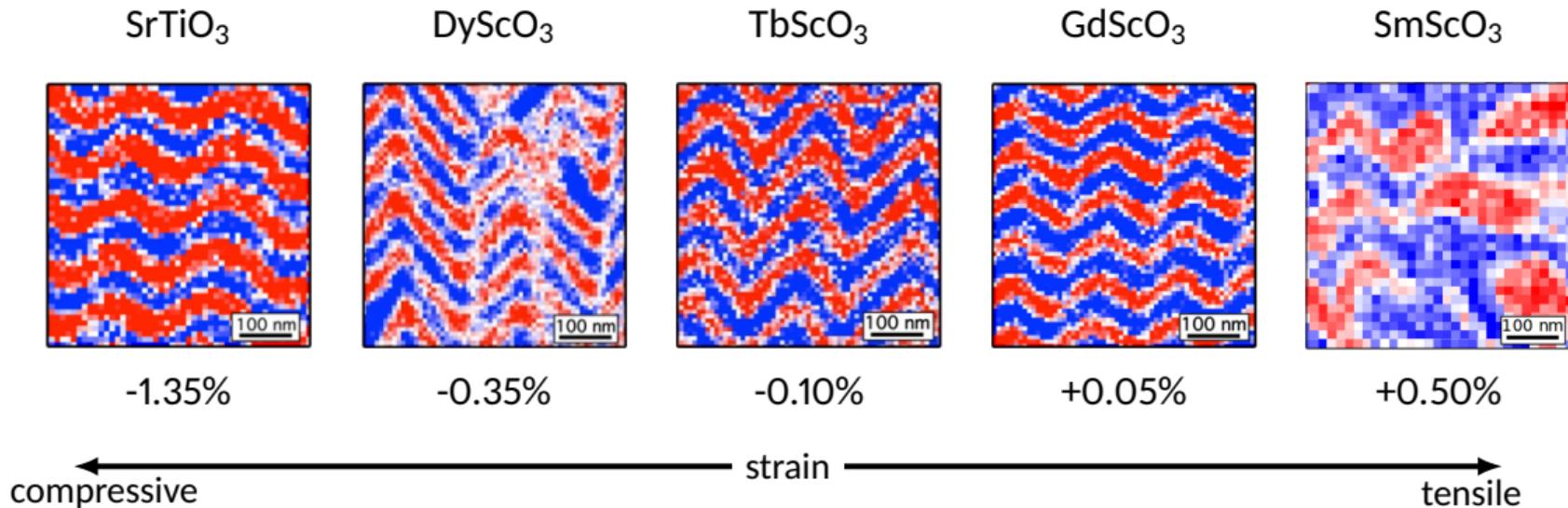
BiFeO₃: most studied, multiferroic at room temperature

- ▶ Large electric polarization
- ▶ G-type antiferromagnet with a cycloidal modulation ($\lambda = 64$ nm)

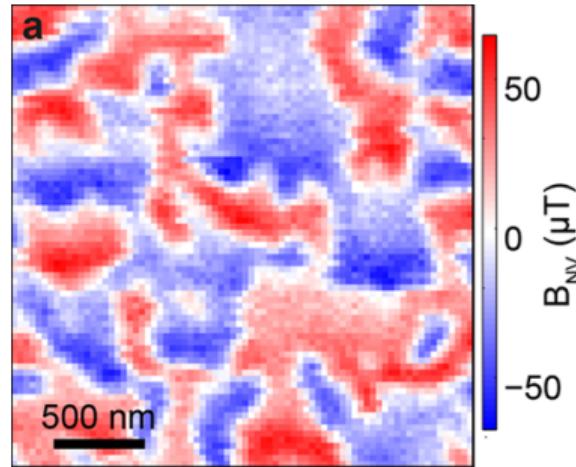
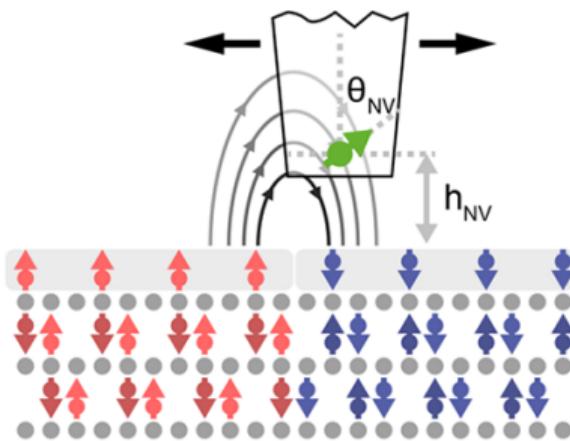


Effect of epitaxial strain on the ferromagnetic order

Collaborations: UMR CNRS/Thales: Johanna Fischer, Stéphane Fusil, Vincent Garcia
SPEC (CEA): Théophile Chirac, Jean-Yves Chauleau, Michel Viret
Synchrotron SOLEIL: Nicolas Jaouen



Another example: Cr₂O₃, a layered antiferromagnet



■ P. Appel et al. *Nano Lett.* 19 (2019), 1682–1687

→ NV magnetometry is a powerful tool to study antiferromagnets with small uncompensated moments

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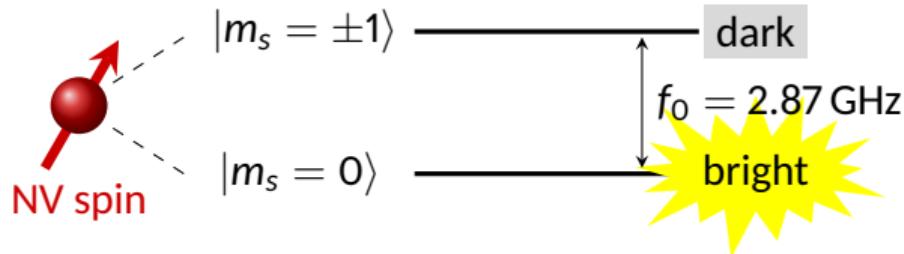
Detecting magnetic textures via noise

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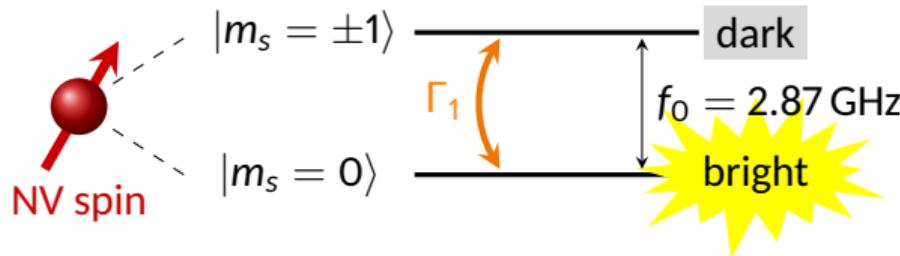
Detecting magnetic noise originating from spin textures



→ Static \vec{B} field

Zeeman shift of the
magnetic resonance

Detecting magnetic noise originating from spin textures



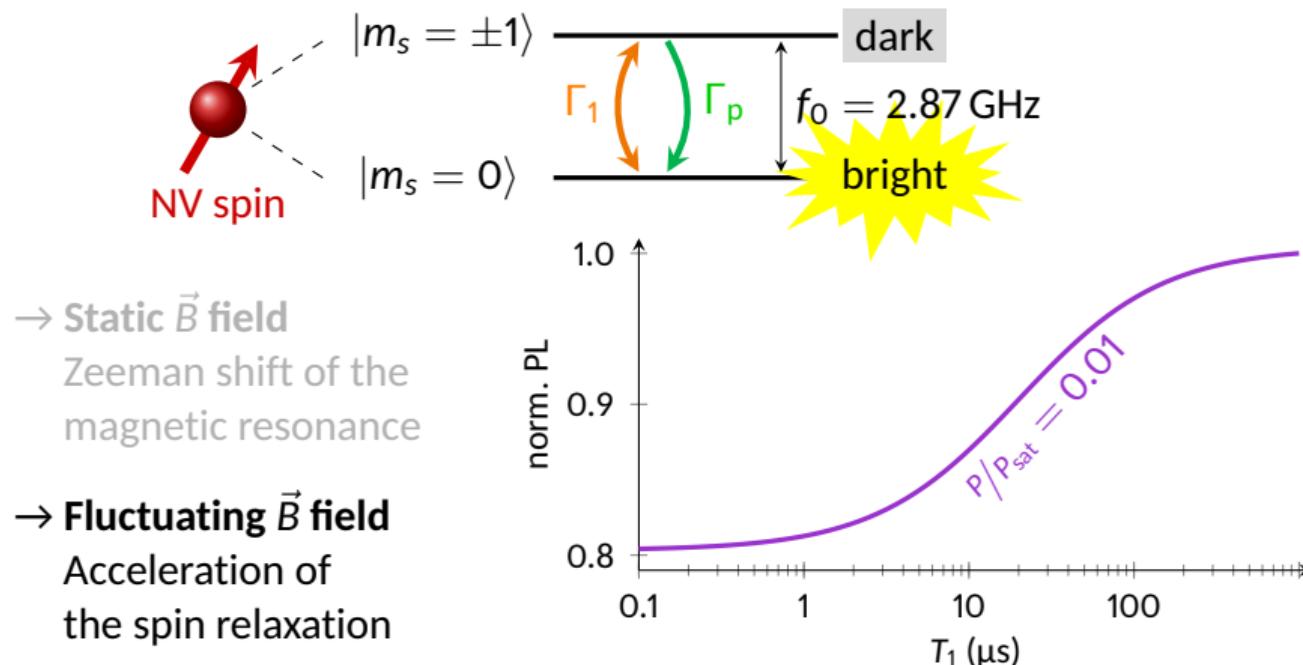
→ Static \vec{B} field

Zeeman shift of the
magnetic resonance

→ Fluctuating \vec{B} field

Acceleration of
the spin relaxation

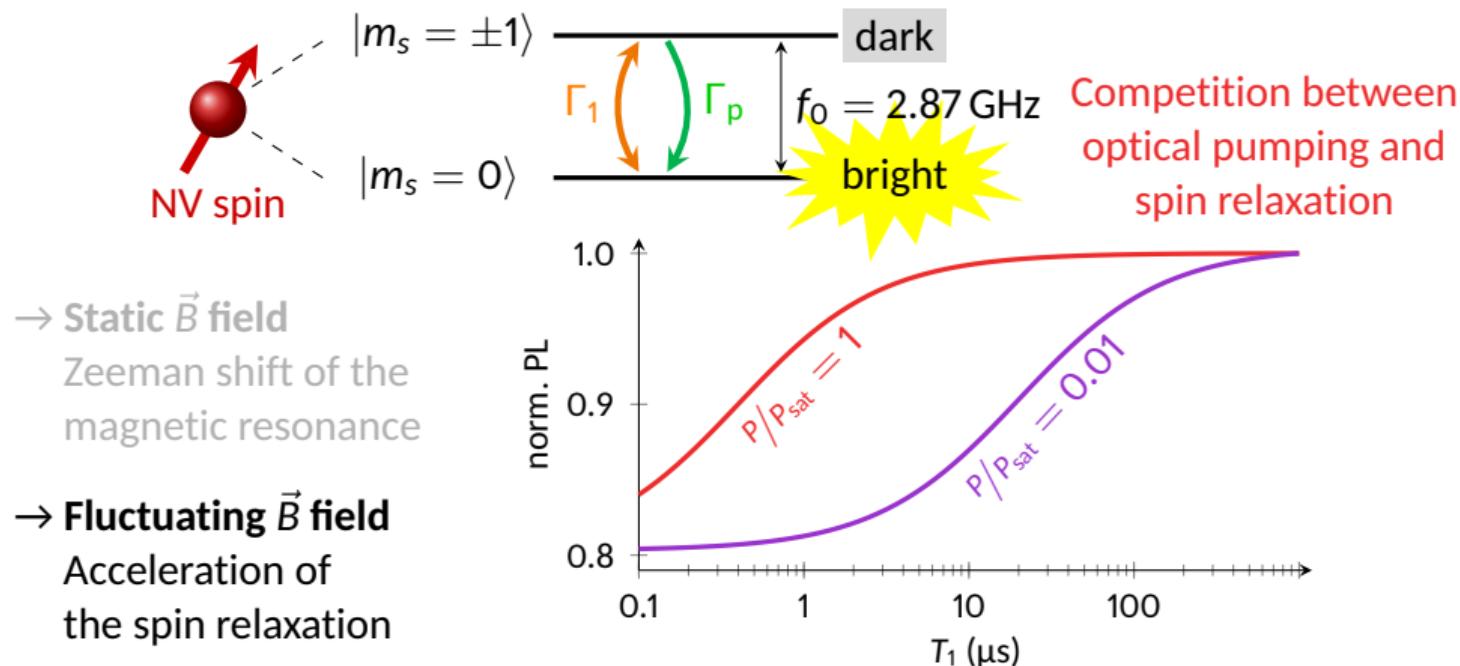
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Relaxation rate $\Gamma_1 \propto S_B(f_0)$ field spectral density at the resonance frequency f_0

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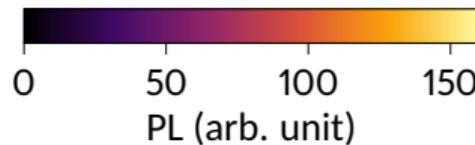
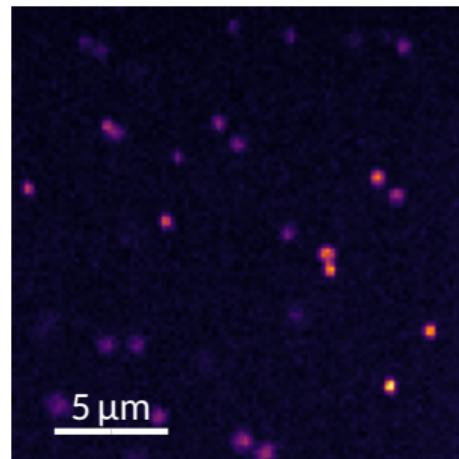
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Experimental investigation of the effect of magnetic noise

Collaboration C2N: Thibaut Devolder



Bulk diamond sample

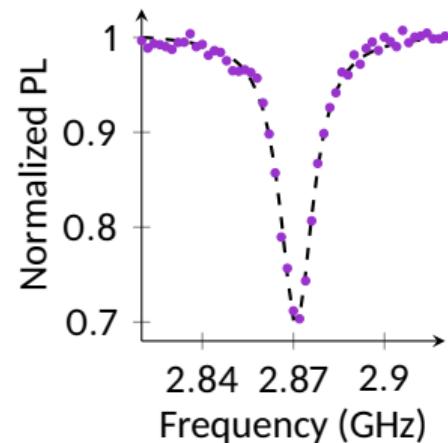
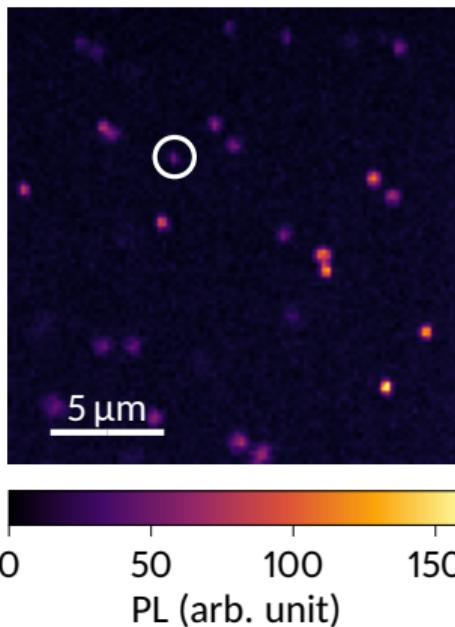


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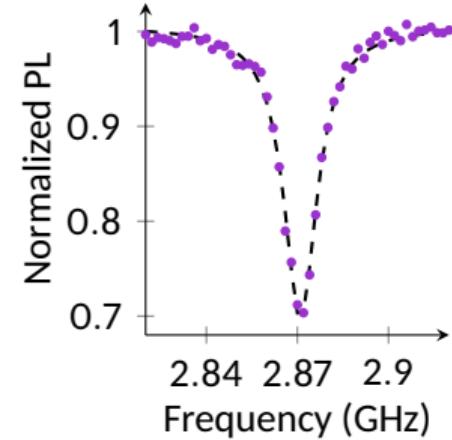
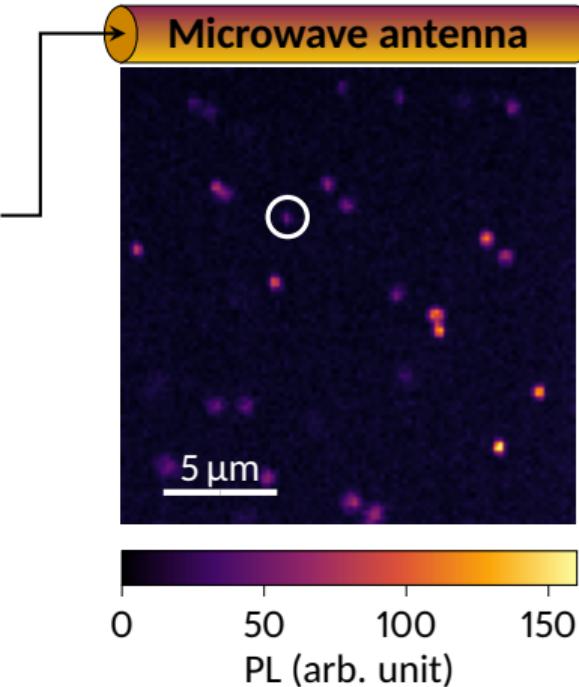
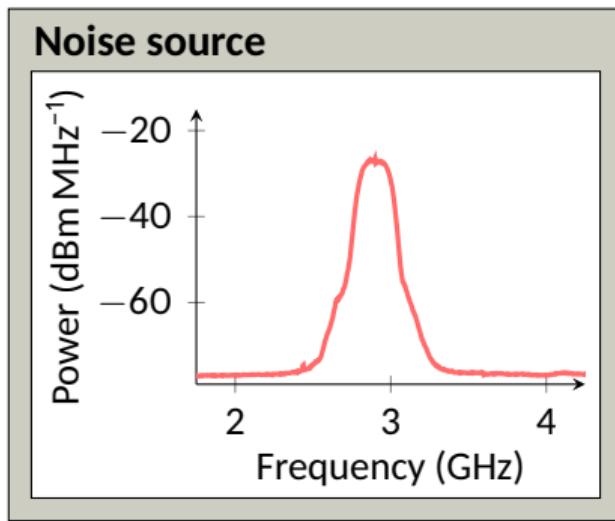


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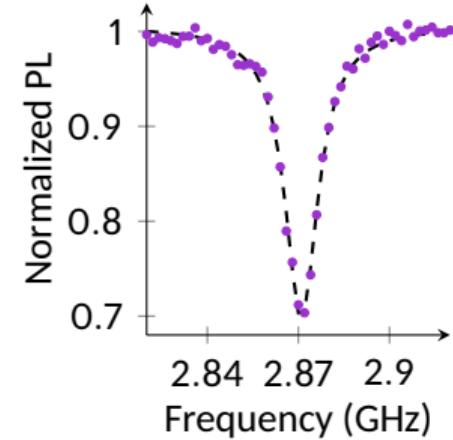
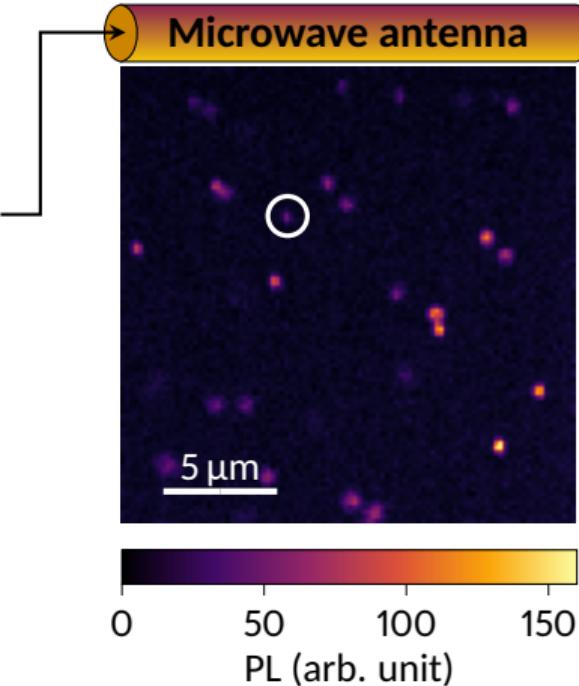
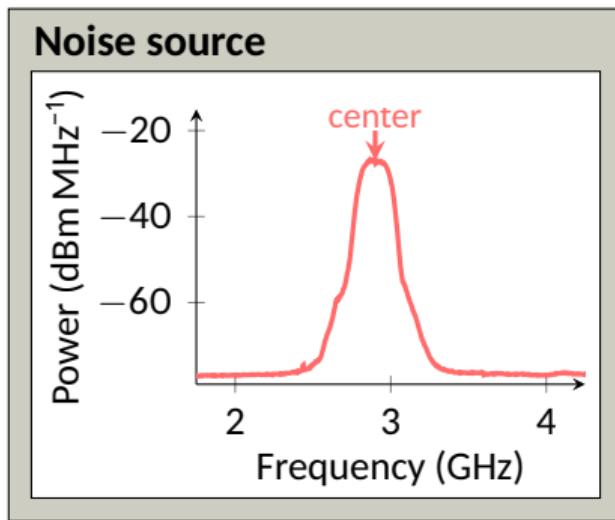
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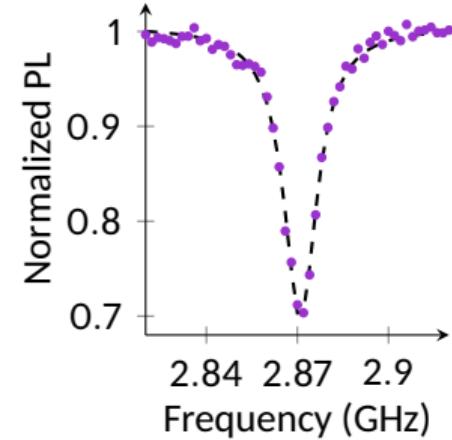
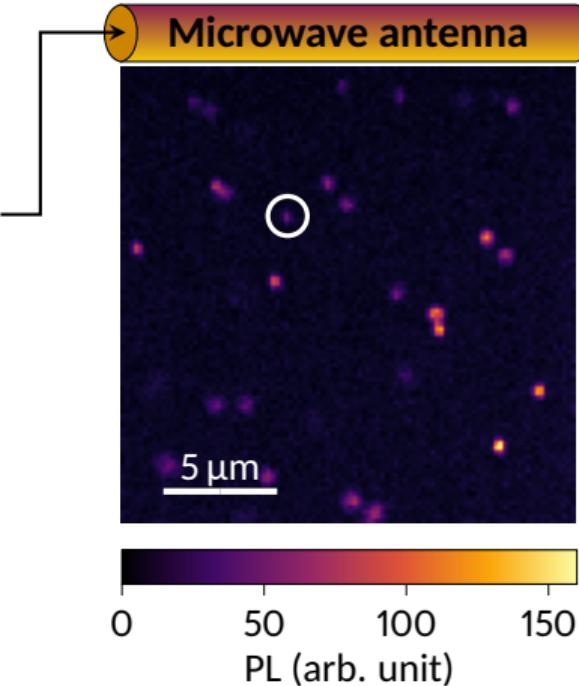
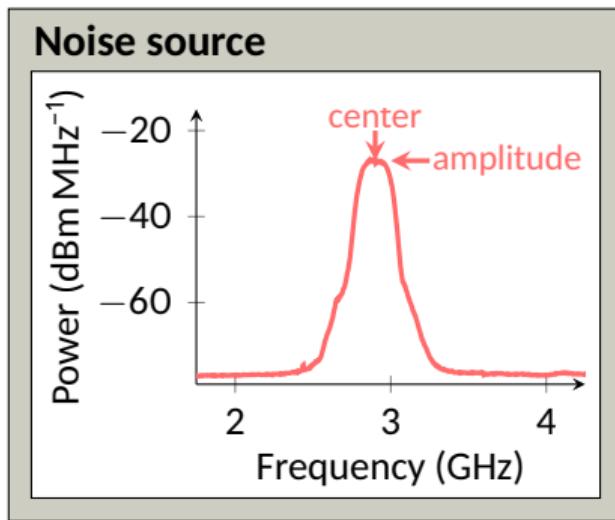
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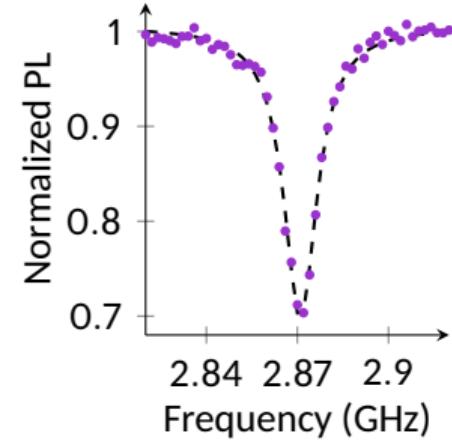
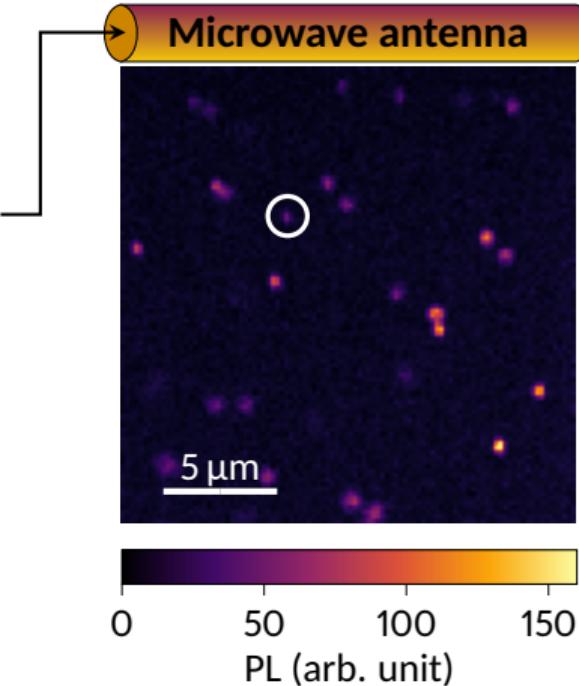
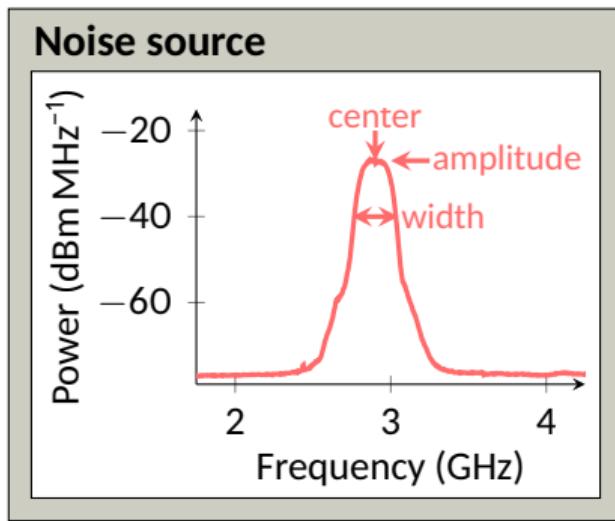
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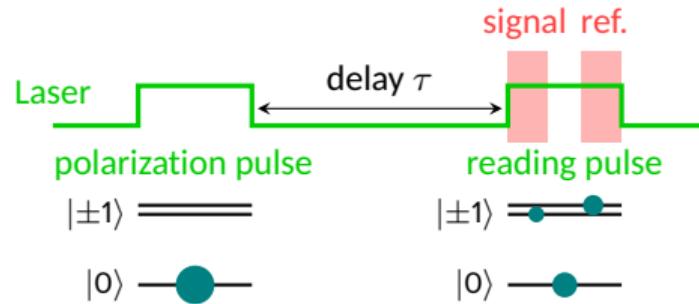


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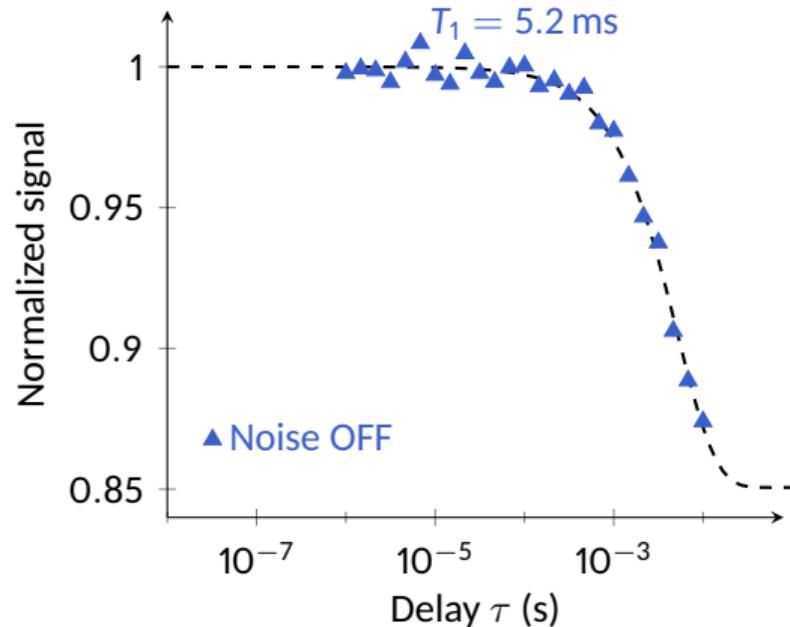
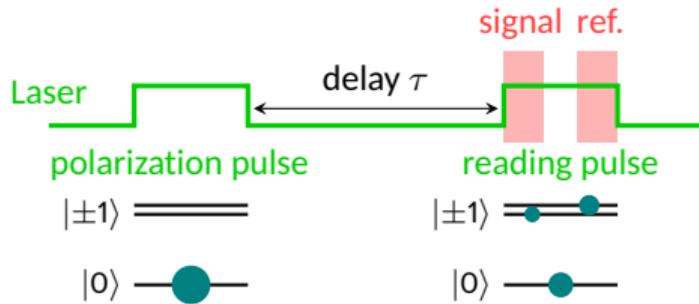
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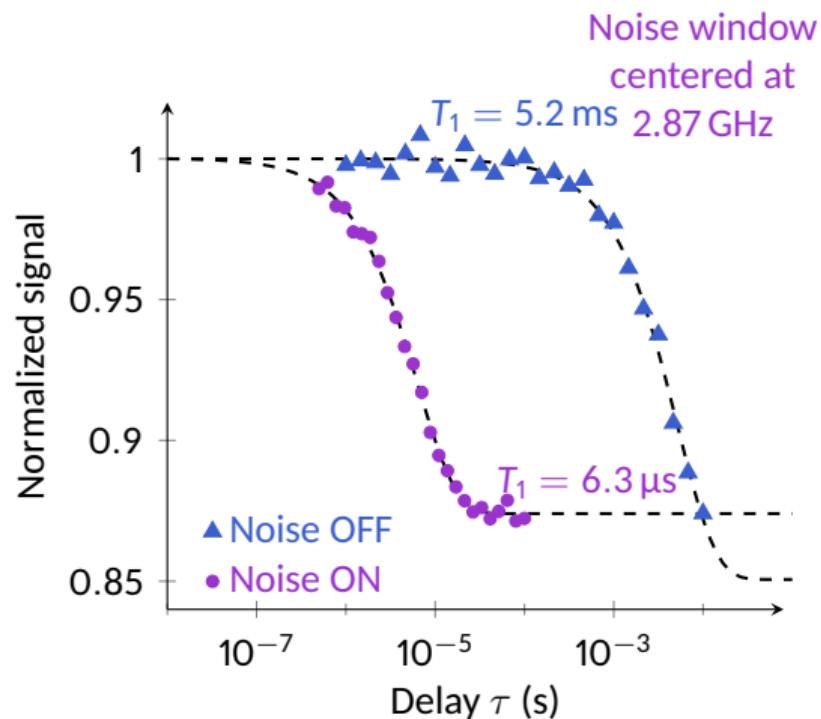
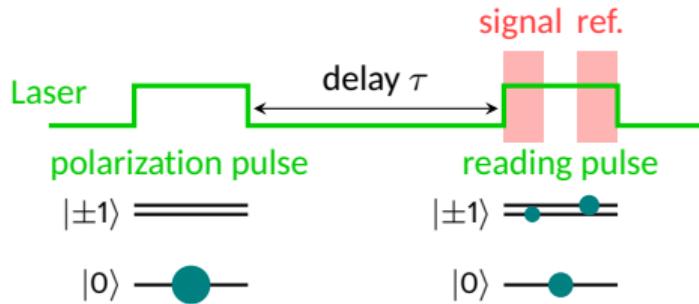
Acceleration of the longitudinal spin relaxation



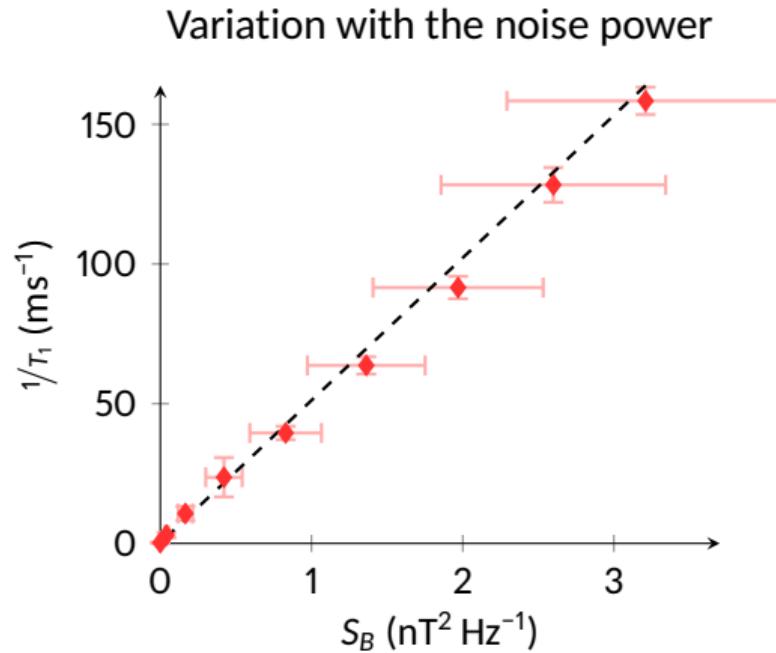
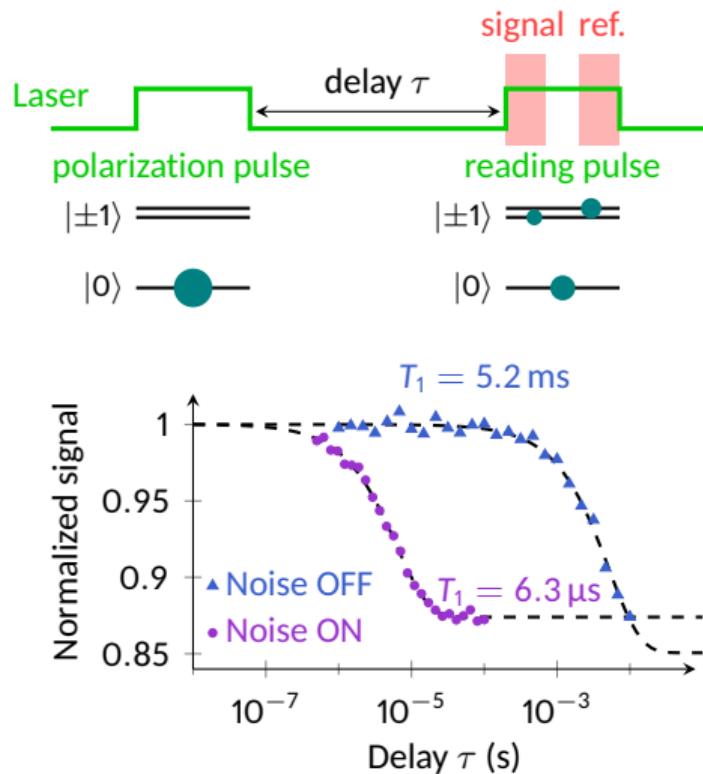
Acceleration of the longitudinal spin relaxation



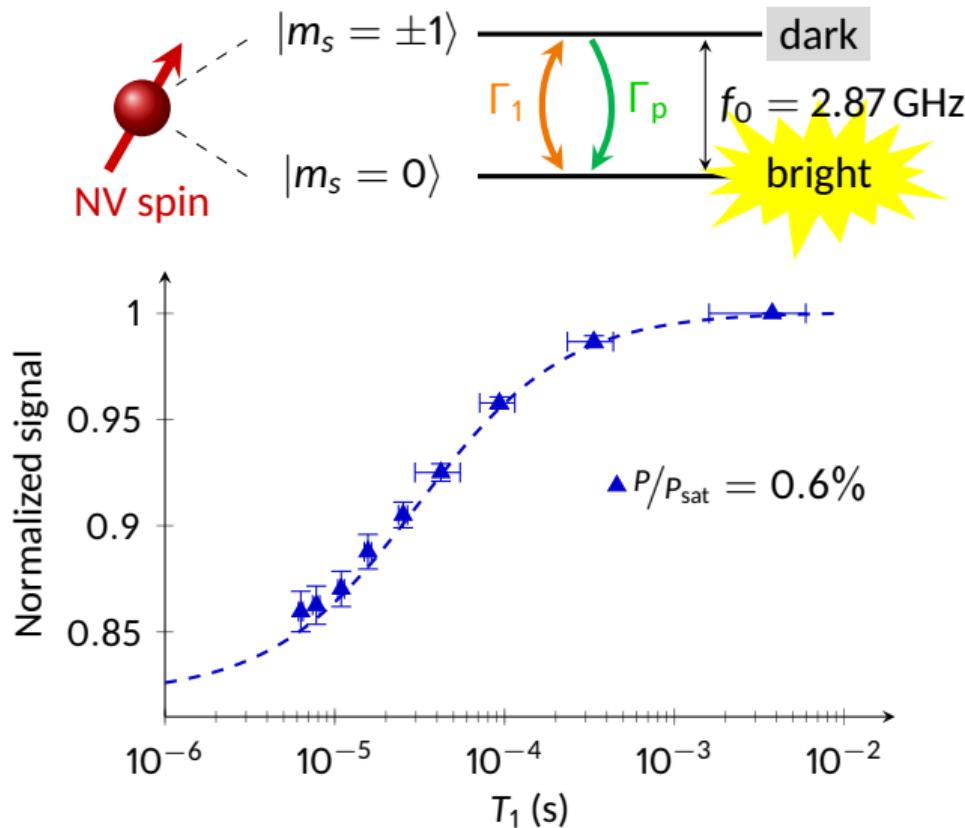
Acceleration of the longitudinal spin relaxation



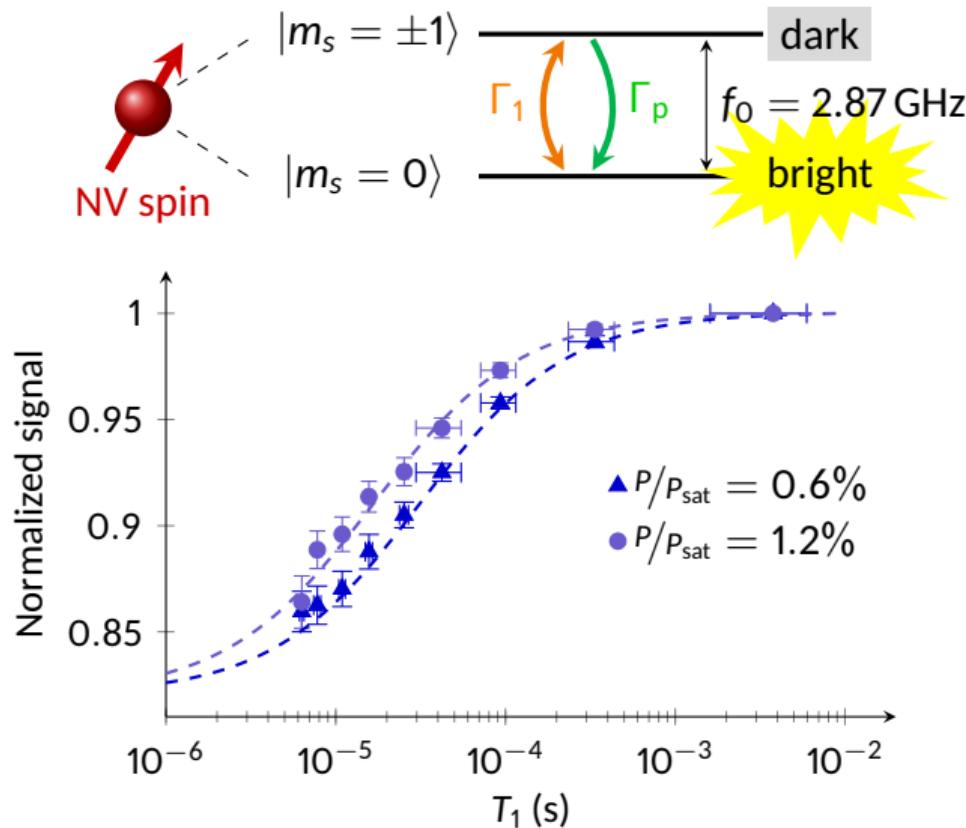
Acceleration of the longitudinal spin relaxation



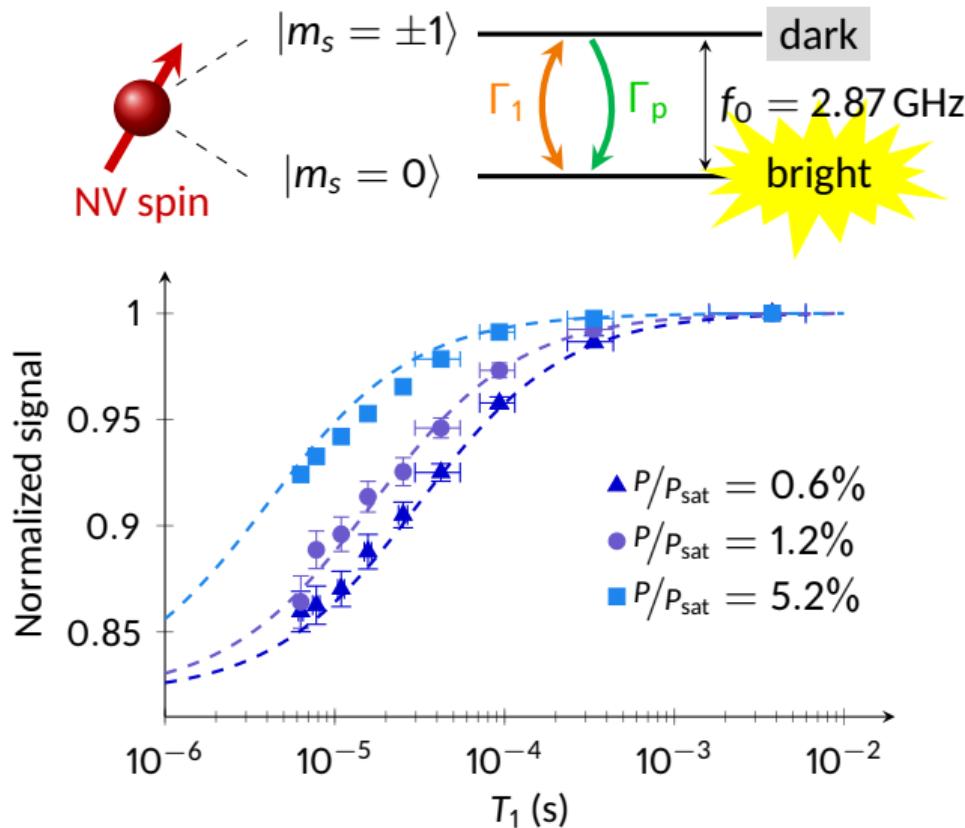
Effect on the emitted photoluminescence



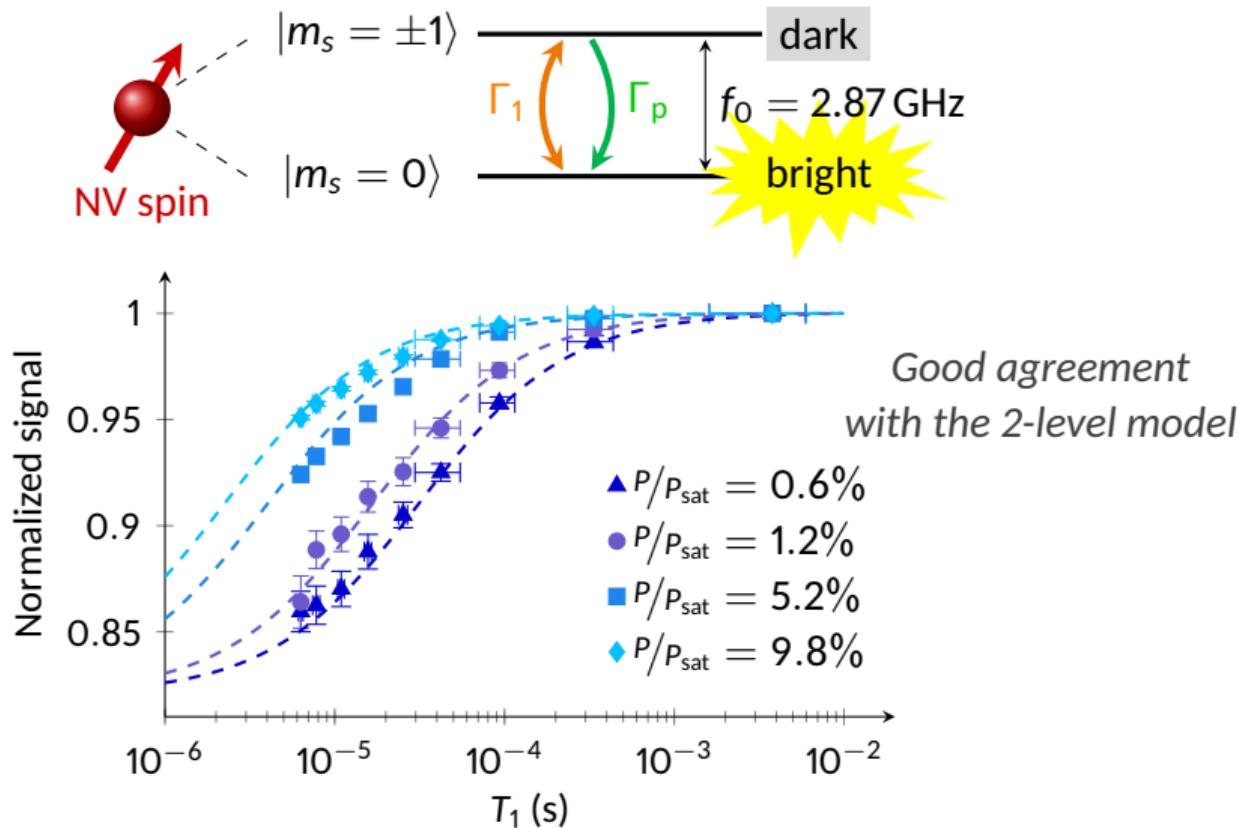
Effect on the emitted photoluminescence



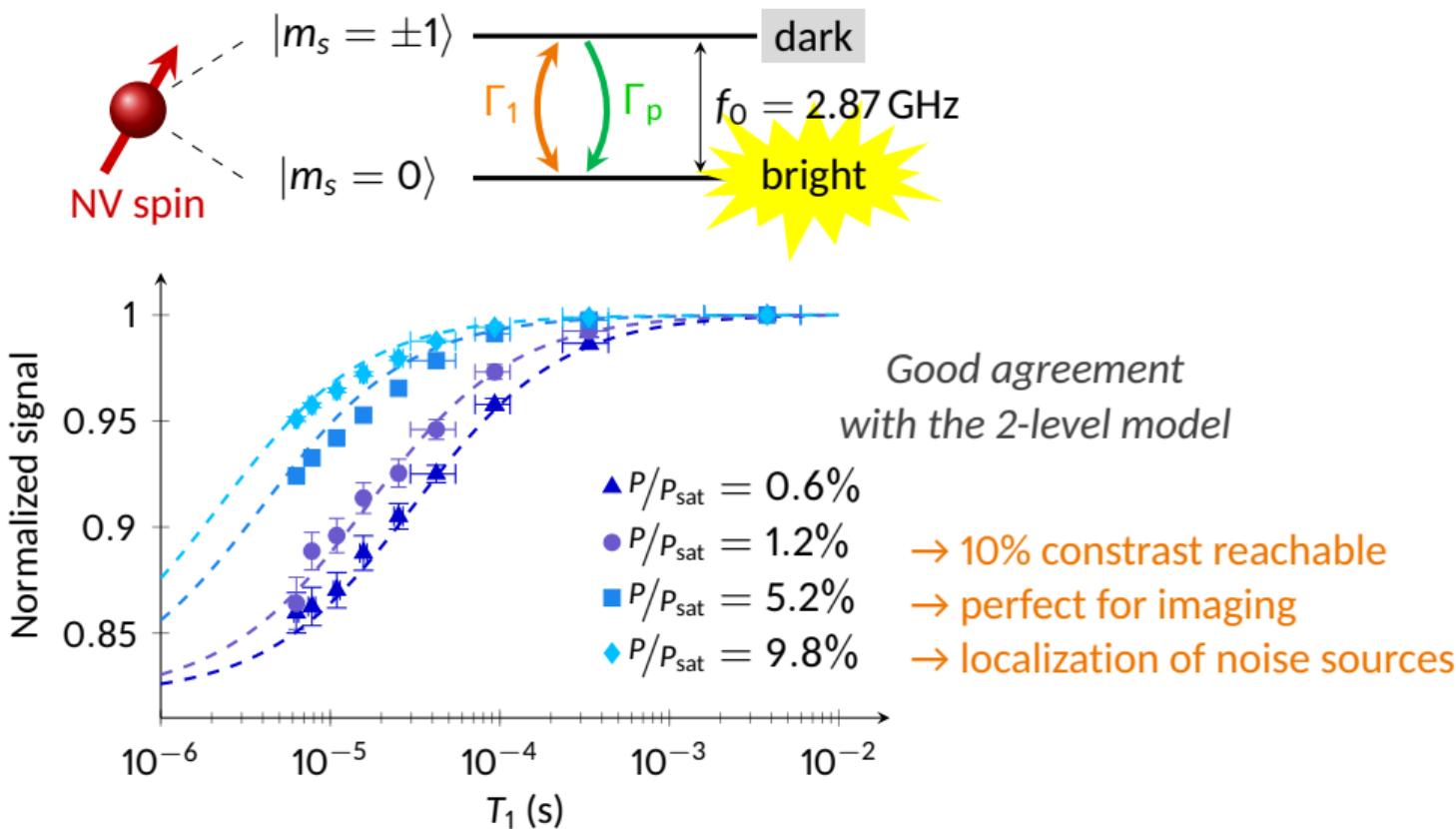
Effect on the emitted photoluminescence



Effect on the emitted photoluminescence



Effect on the emitted photoluminescence



Outline

Measuring weak magnetic fields

Antiferromagnets with small uncompensated moments (BiFeO_3 , ...)

Collaborations: UMR CNRS/Thales, SPEC (CEA), SOLEIL

■ A. Haykal *et al.* *Nat. Comm.* 11 (2020), 1704

■ J.-Y. Chauleau *et al.* *Nat. Mat.* 19 (2020), 386

Probing magnetic noise

Characterization of the effect of magnetic on the NV spin relaxation

Collaboration: C2N

Detecting magnetic textures via noise

Synthetic antiferromagnets

Collaborations: UMR CNRS/Thales, C2N

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

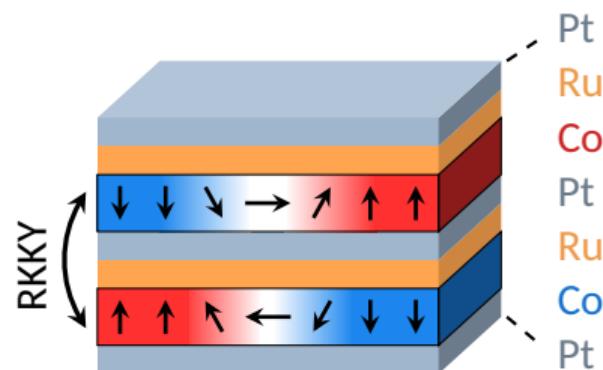
Synthetic antiferromagnets

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



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

- ▶ No net magnetic moment
- ▶ Small stray field (vertical shift)



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

Synthetic antiferromagnets

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Two ferromagnetic layers coupled antiferromagnetically

- ▶ No net magnetic moment
- ▶ Small stray field (vertical shift)
- ▶ Compensation of the dipolar fields

- Fast domain wall movement

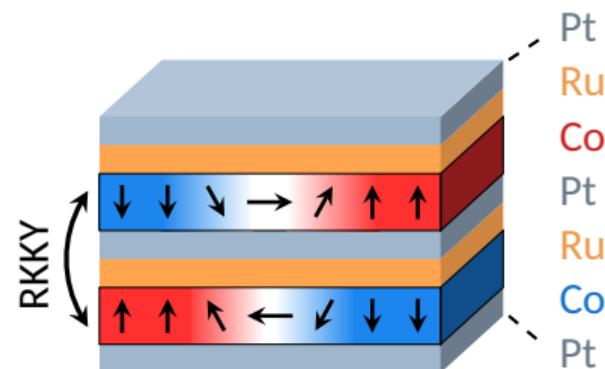
✉ S.-H. Yang *et al.* *Nat. Nano.* 10 (2015), 221

- Small skyrmions

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

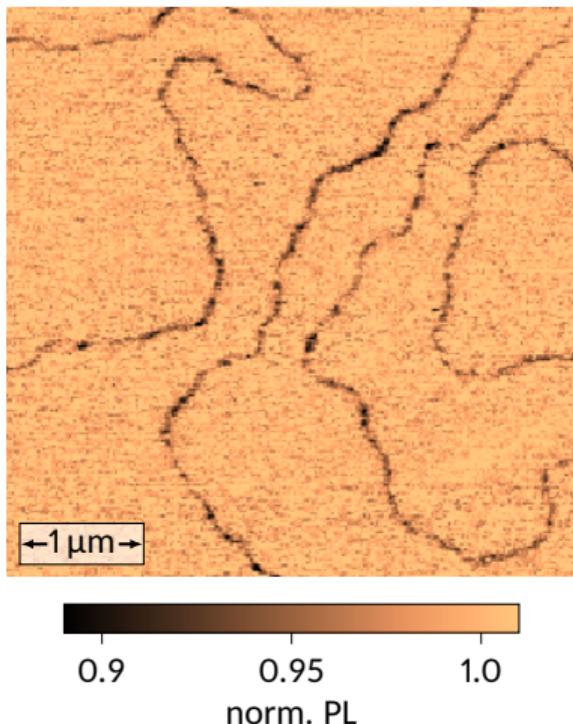
- ▶ No skyrmion Hall effect

✉ T. Dohi *et al.* *Nat. Comm.* 10 (2019), 5153

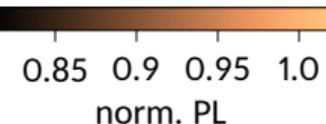
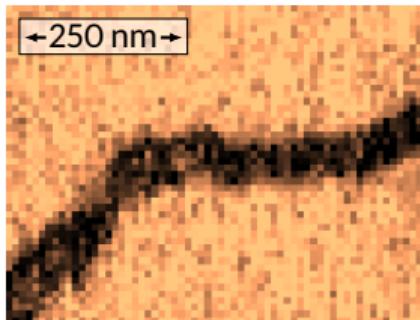
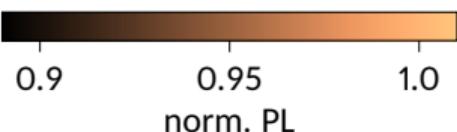
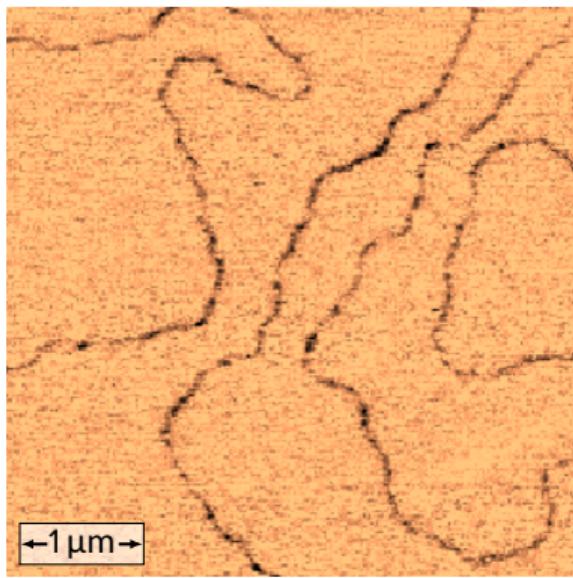


✉ W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34

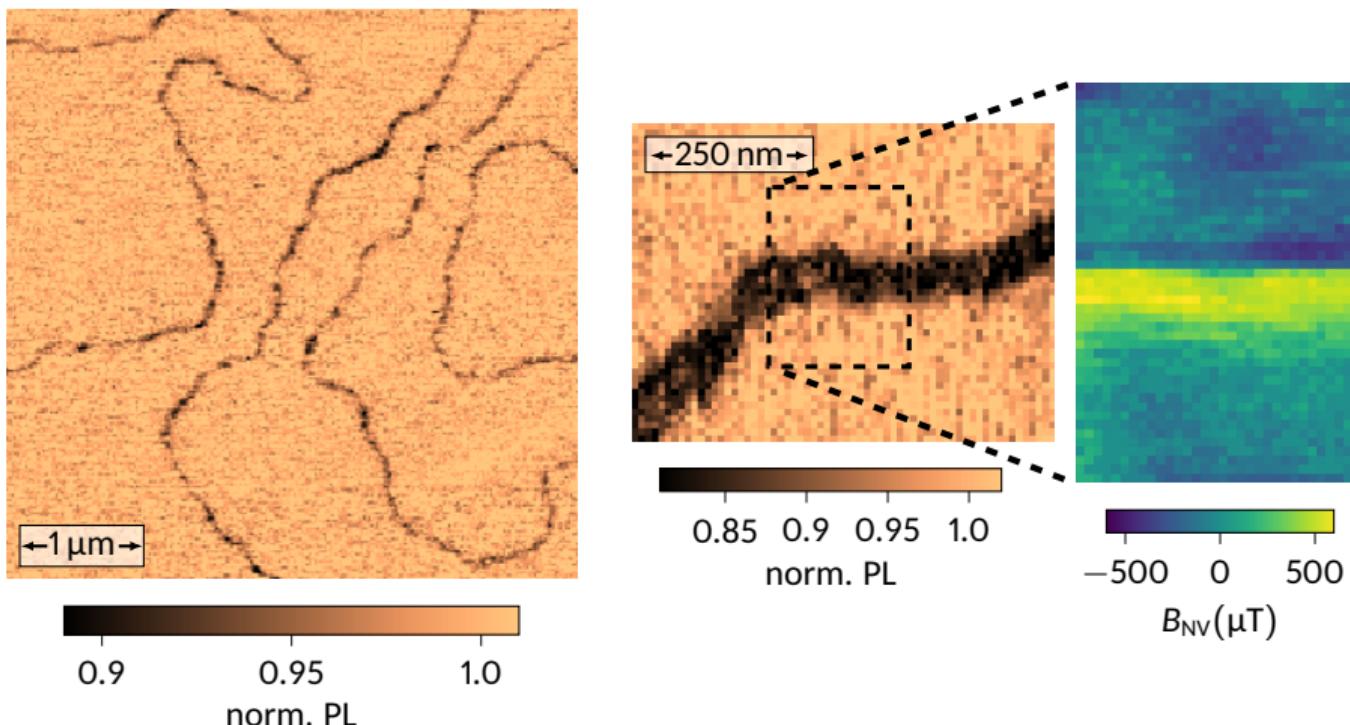
Detection of domain walls by single spin relaxometry



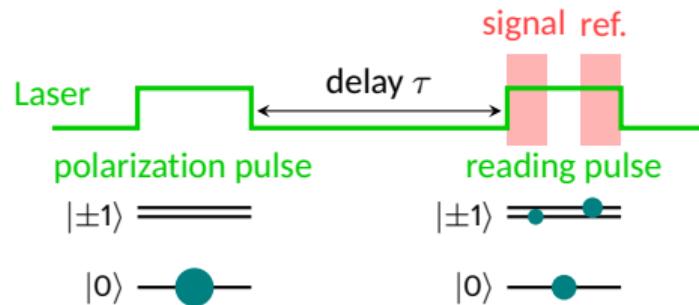
Detection of domain walls by single spin relaxometry



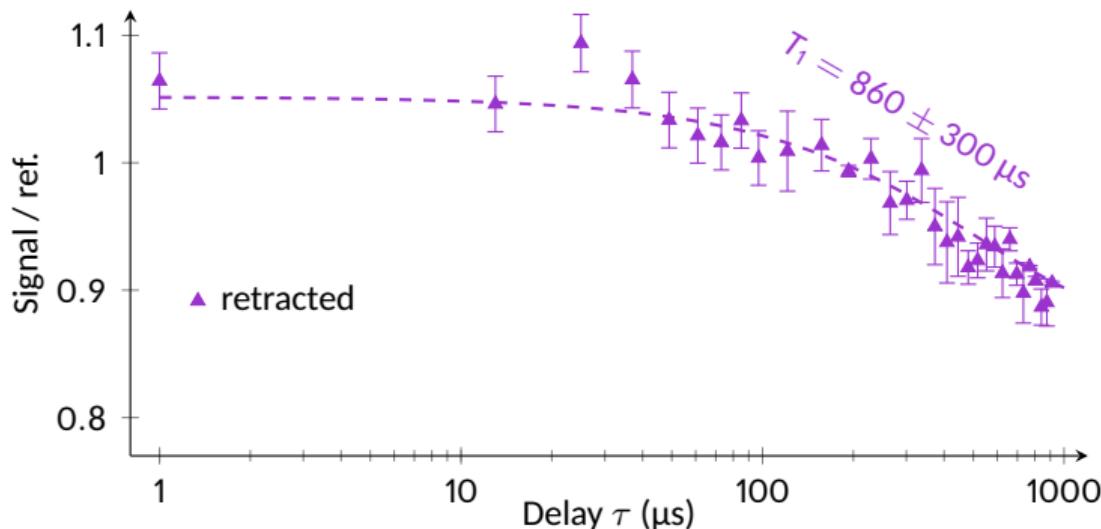
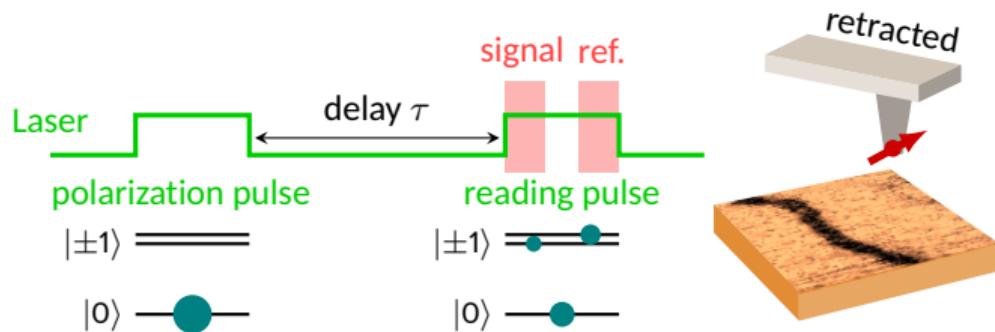
Detection of domain walls by single spin relaxometry



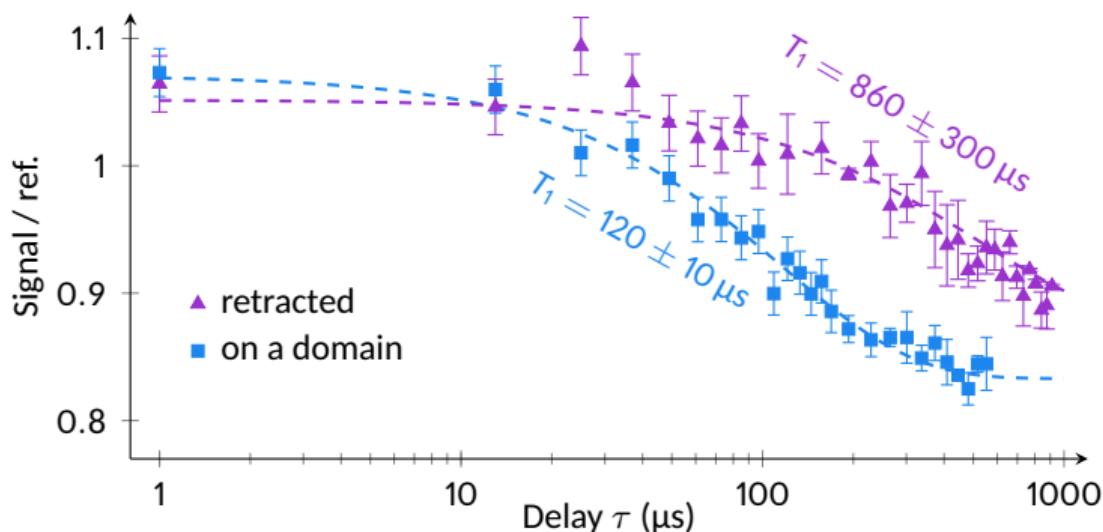
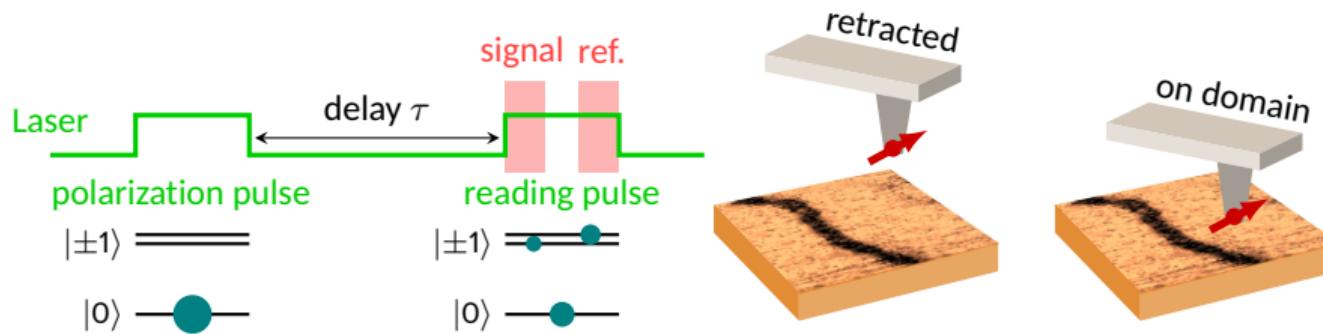
Measurements of the spin relaxation time



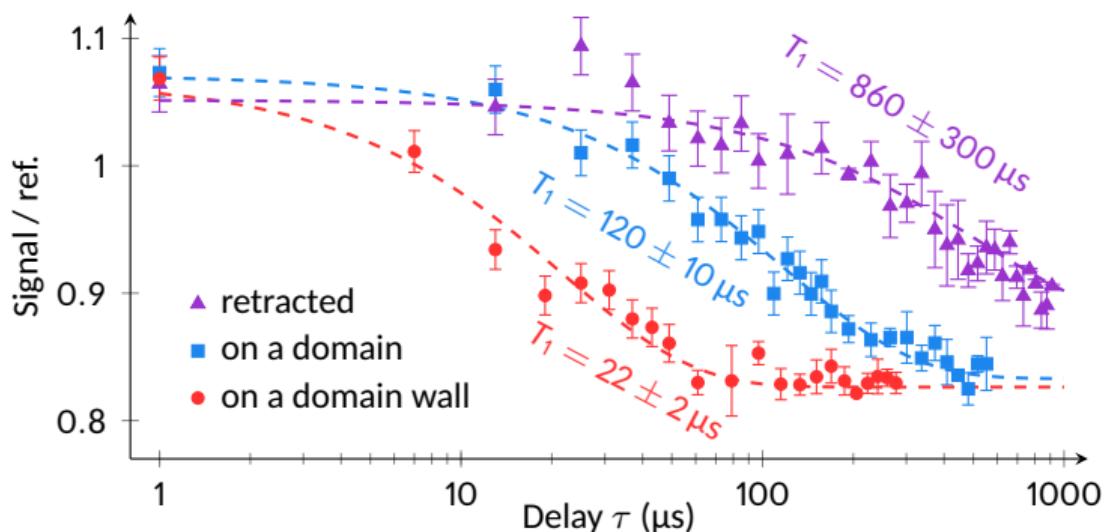
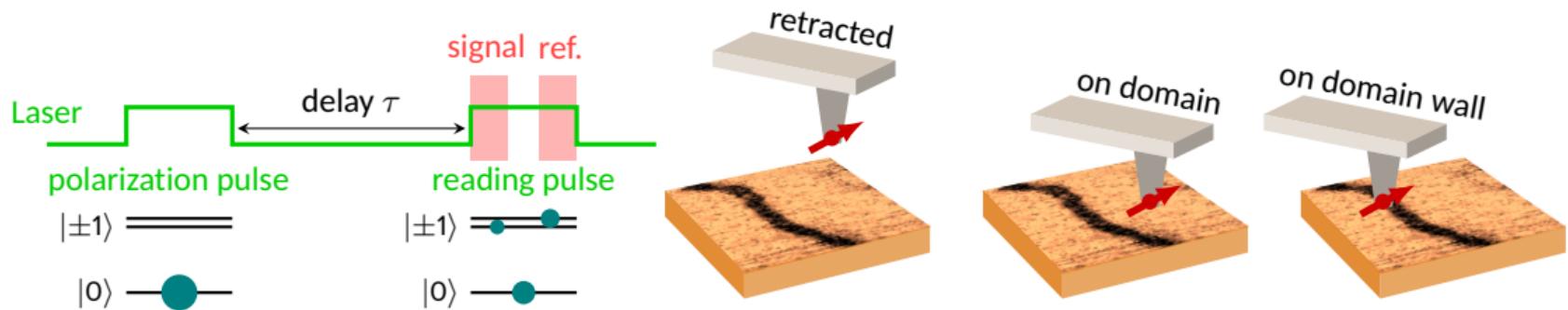
Measurements of the spin relaxation time



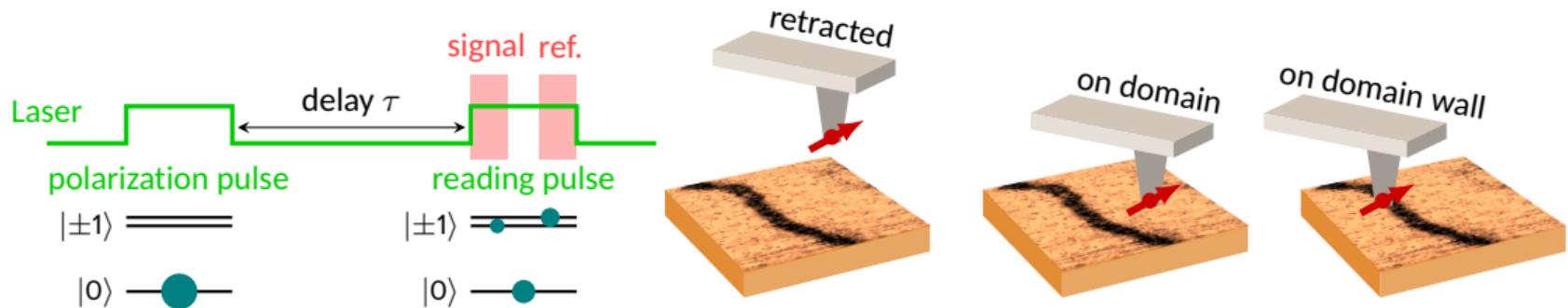
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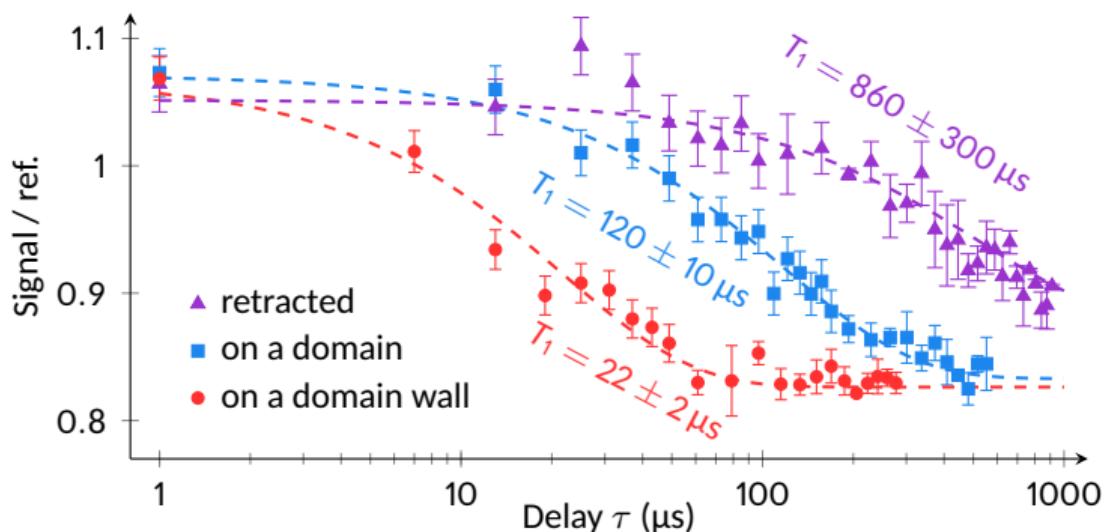


Measurements of the spin relaxation time

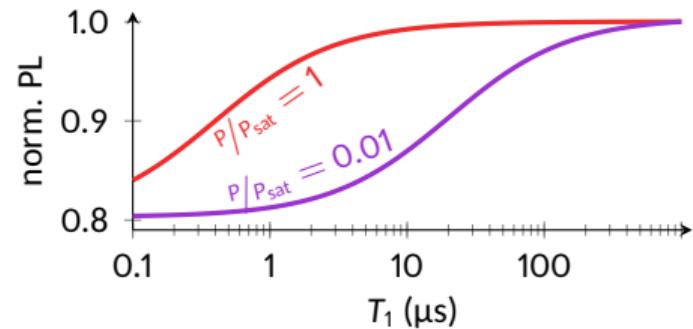


Clear diminution of T_1 above the domain wall

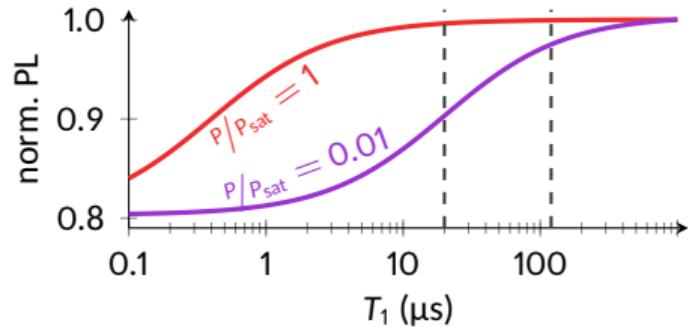
→ Enhancement of the spin relaxation by magnetic noise



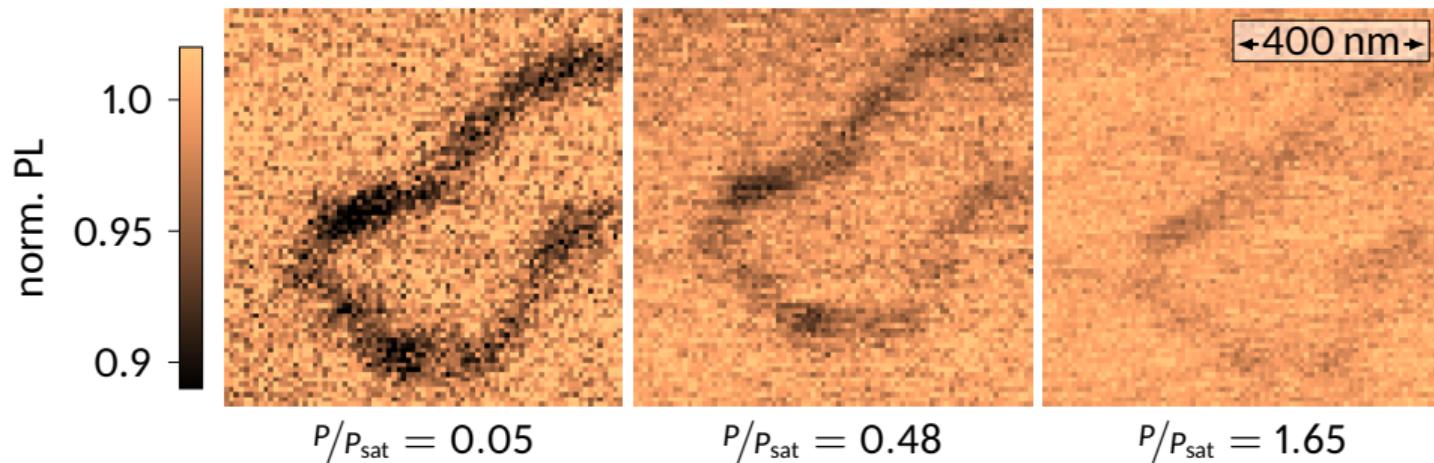
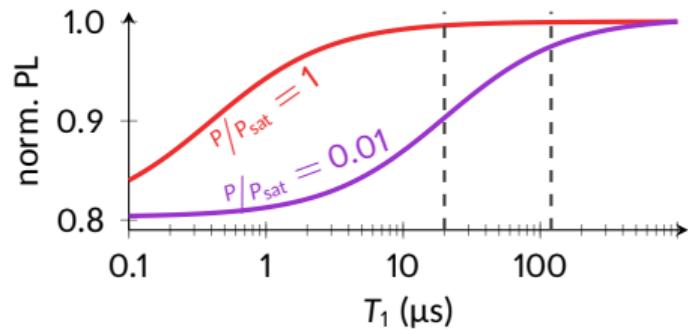
Dependence on optical excitation power



Dependence on optical excitation power

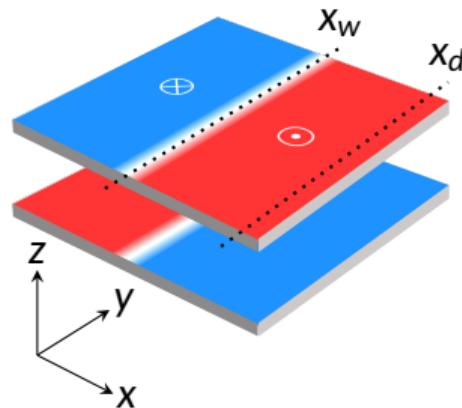


Dependence on optical excitation power



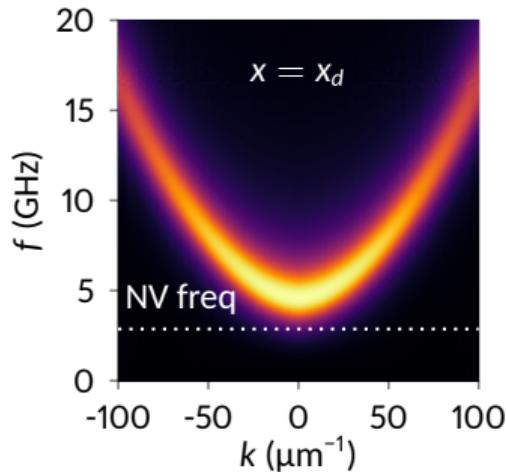
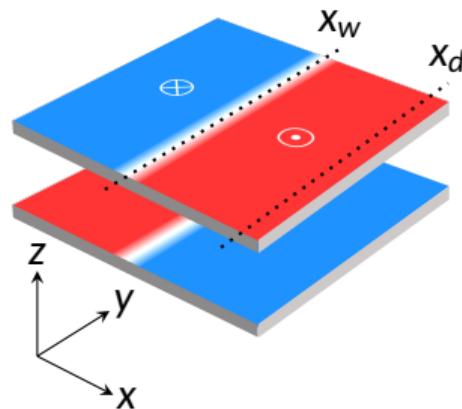
Dispersion of the spin waves inside the domain and the domain wall

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



Dispersion of the spin waves inside the domain and the domain wall

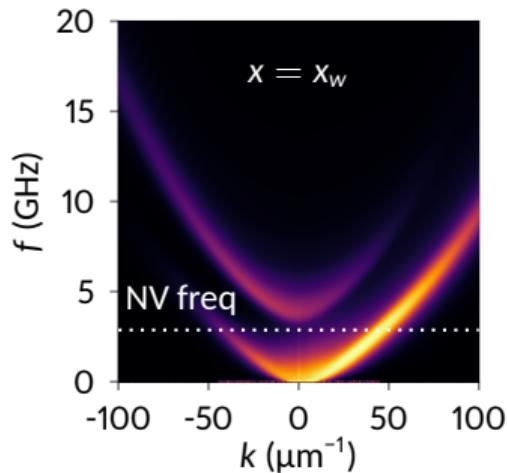
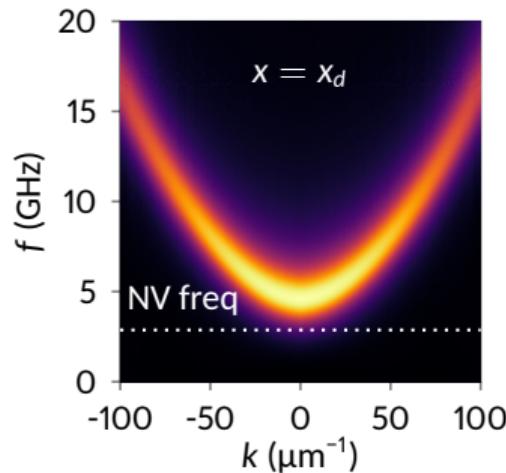
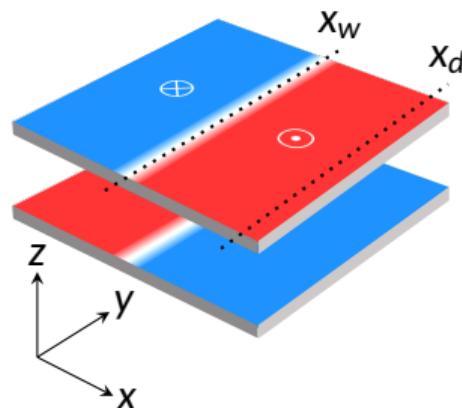
Collaboration C2N: Jean-Paul Adam, Joo-Von Kim



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

Dispersion of the spin waves inside the domain and the domain wall

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

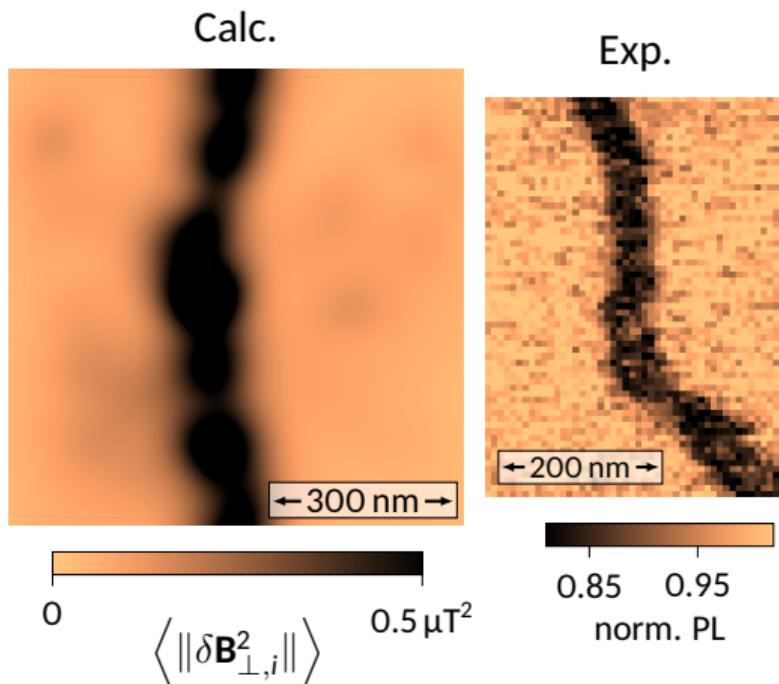


- ▶ NV frequency in the tail of the dispersion relation, almost below the gap: we are only sensitive to a few modes in the domains
- ▶ No gap in the domain walls, presence of modes at the NV frequency: **we are much more sensitive to the noise from the walls!**

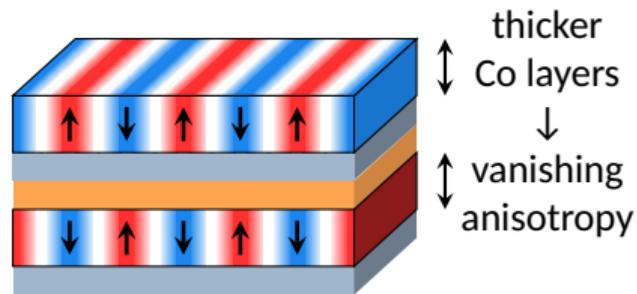
Noise map over a domain wall

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

- Disorder in the static magnetic configuration (anisotropy variations)
- Driving field at 2.87 GHz with random spatial variations
- Map obtained by averaging the resulting stray field for 500 realizations

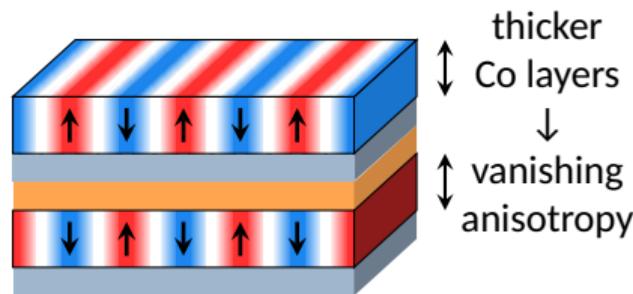


Going further: spin spirals ...

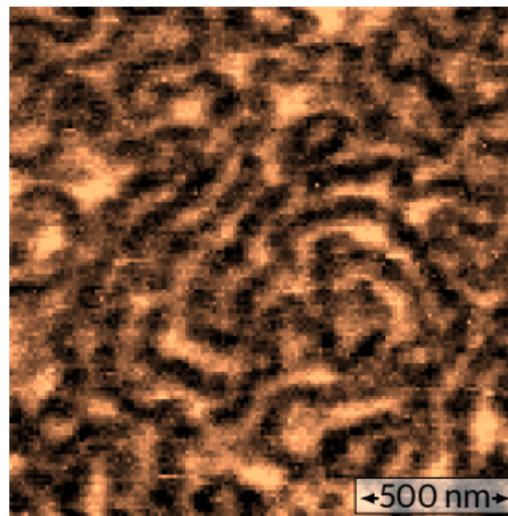


W. Legrand et al. *Nat. Mat.* 19 (2020), 34

Going further: spin spirals ...



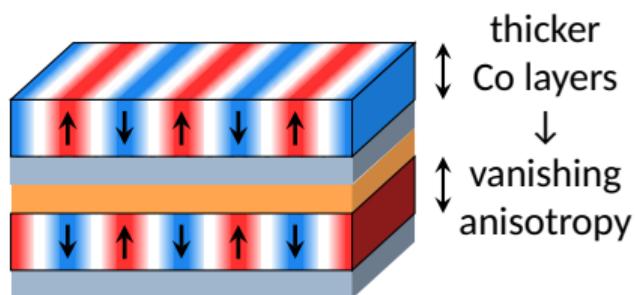
Experiment



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

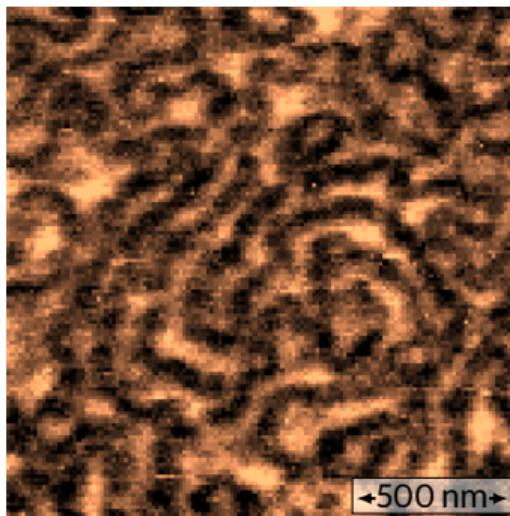
0.8 0.9 1.0
norm. PL

Going further: spin spirals ...

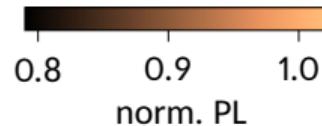
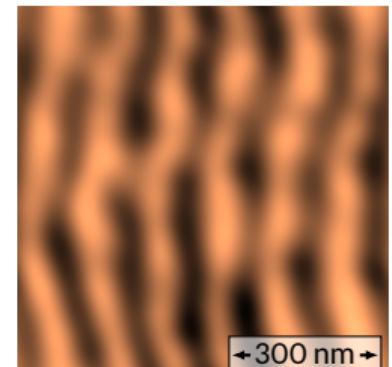


■ W. Legrand et al. *Nat. Mat.* 19 (2020), 34

Experiment

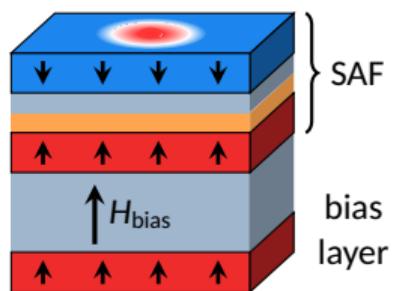


Calculation

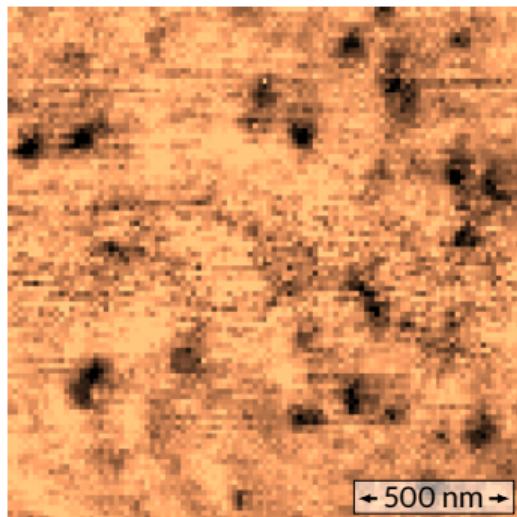


$$0.45 \langle \|\delta\mathbf{B}_{\perp,i}^2\| \rangle^{1.2} \mu\text{T}^2$$

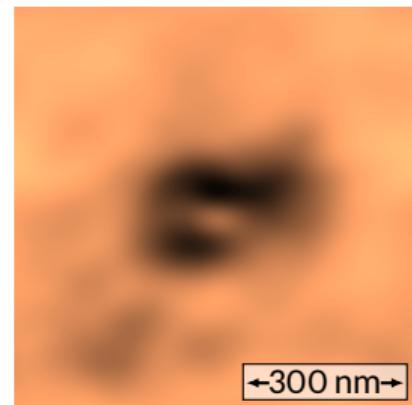
...and antiferromagnetic skyrmions



Experiment



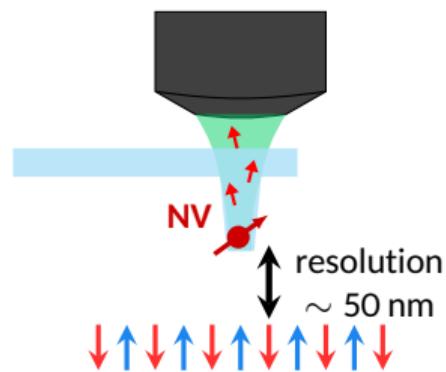
Calculation



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



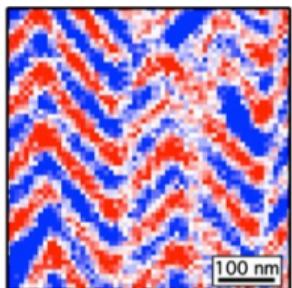
Summary: NV microscopy for antiferromagnets



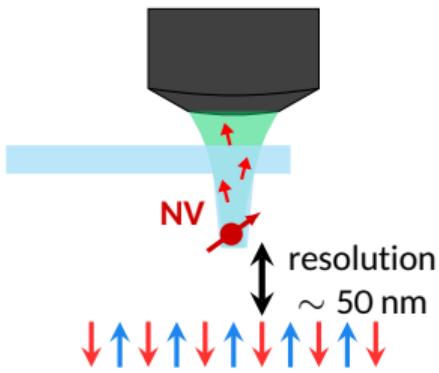
Summary: NV microscopy for antiferromagnets

Quantitative magnetometry

*Measurement of small
stray fields from
uncompensated moments*



Ex: BiFeO_3

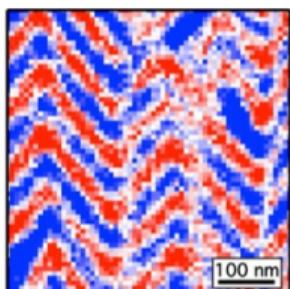


- A. Haykal *et al.* *Nat. Comm.* 11 (2020), 1704
- J.-Y. Chauleau *et al.* *Nat. Mat.* 19 (2020), 386

Summary: NV microscopy for antiferromagnets

Quantitative magnetometry

Measurement of small stray fields from uncompensated moments

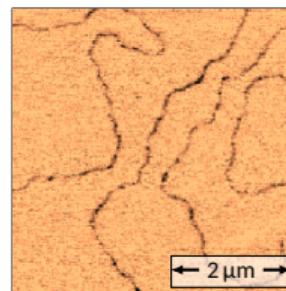
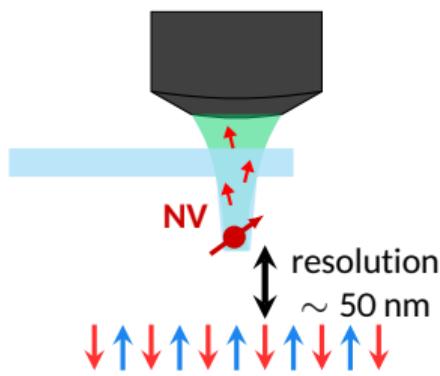


Ex: BiFeO₃

- A. Haykal *et al.* *Nat. Comm.* 11 (2020), 1704
- J.-Y. Chauleau *et al.* *Nat. Mat.* 19 (2020), 386

All-optical relaxometry

Detection of magnetic noise from noncollinear antiferromagnetic textures



Ex: Synthetic antiferromagnets

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

Acknowledgments

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Joo-Von Kim

SPEC, CEA, Gif-sur-Yvette

Théophile Chirac

Jean-Yves Chauleau

Michel Viret



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