Imaging skyrmions in synthetic antiferromagnets by single spin relaxometry

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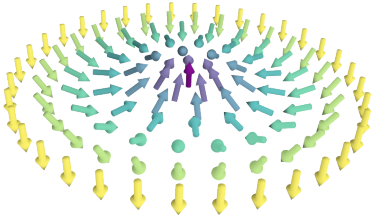
DPG Spring Meeting online, September 28th 2021

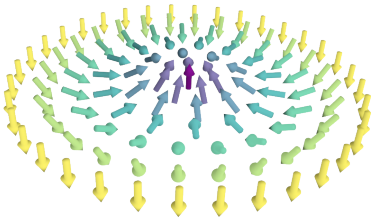
slides available at https://magimag.eu

Magnetic skyrmions



- Localized magnetic object
- Topological charge: the magnetization direction covers a sphere
- Nanoscale size
- Moves with current

Magnetic skyrmions



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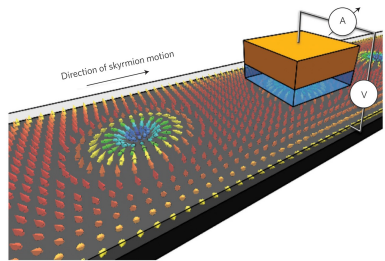
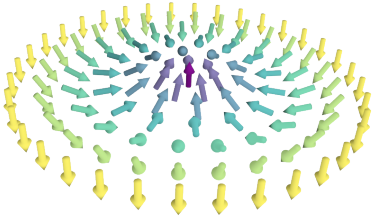
Skyrmion racetrack memory



T. L. Monchesky. *Nat. Nano.* 10 (2015), 1008

Challenges: size, pinning, efficient movement, …

Magnetic skyrmions



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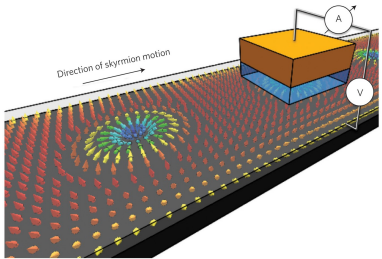

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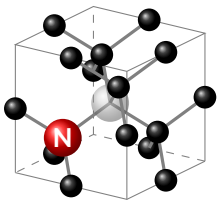
Challenges: size, pinning, efficient movement, …

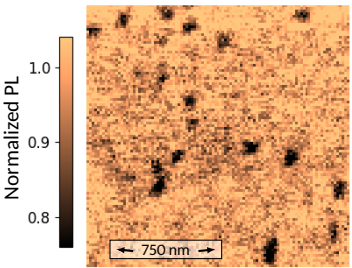
→ Efficient and non-perturbative imaging technique under ambient conditions?

Outline

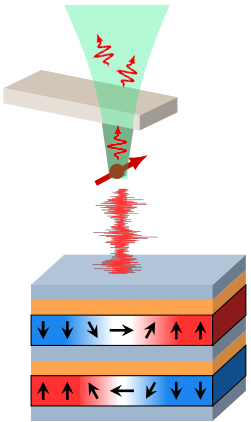
Scanning NV microscopy



Skyrmions in ferromagnets



Noise based imaging in synthetic antiferromagnets



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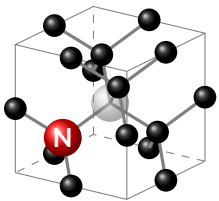

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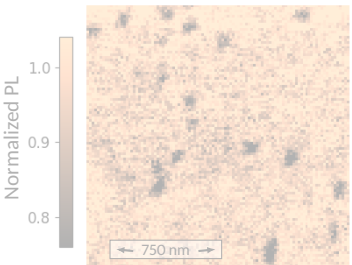

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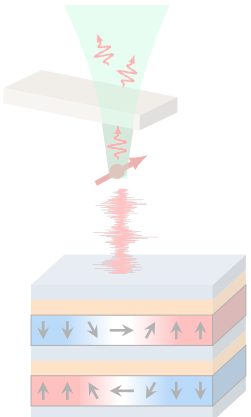
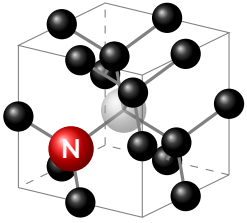


Principle of magnetic field sensing with NV centers



Defect in diamond

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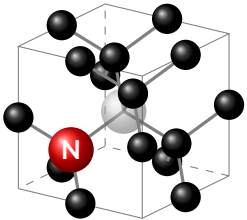

Defect in diamond

- Optical manipulation and reading
- Ambient conditions

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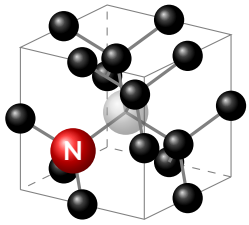

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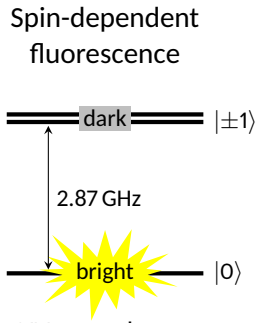

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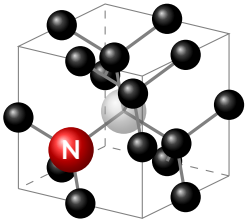

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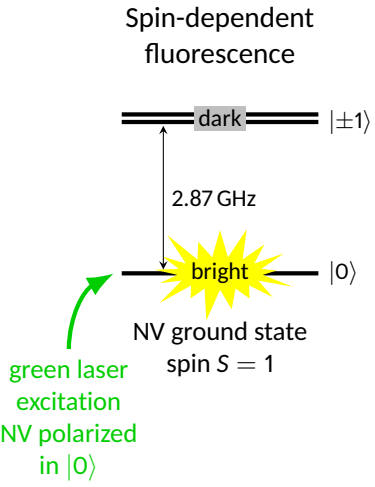

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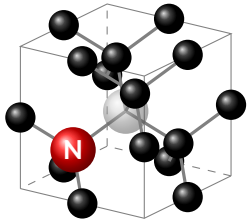

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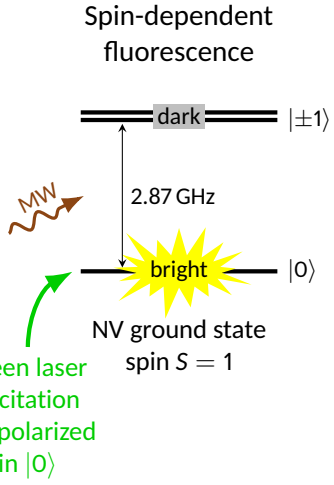

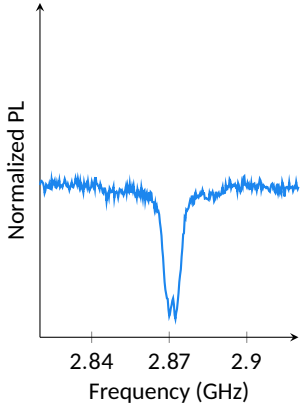

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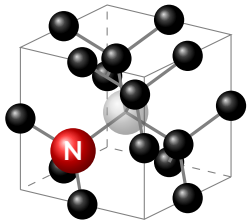

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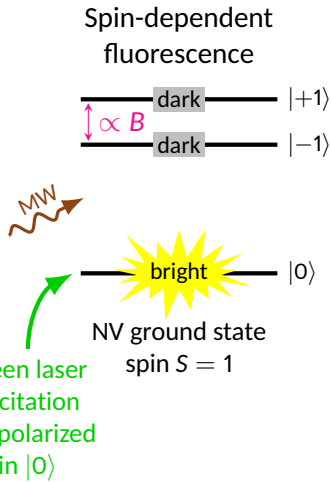

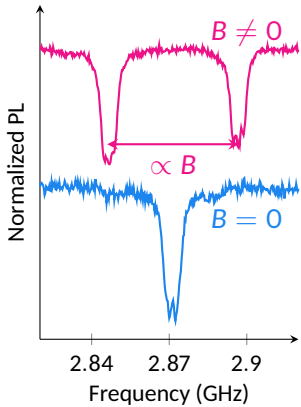

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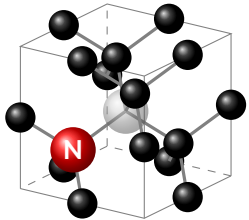

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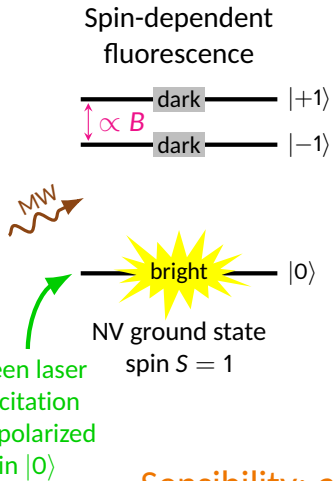
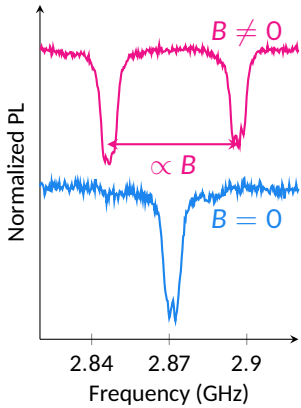
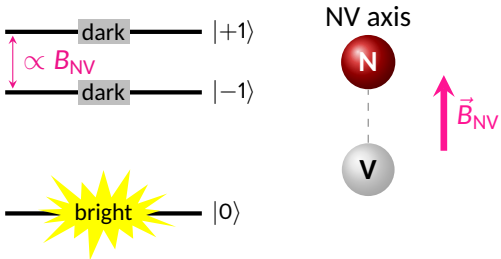




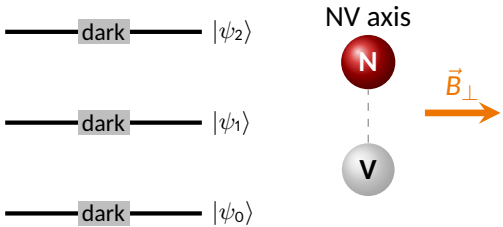
Sensibility: a few $\mu T/\sqrt{Hz}$

Strong field regime



Strong field regime

Mixing of the spin states



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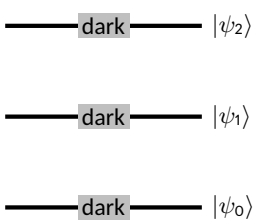

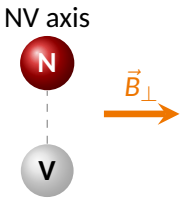

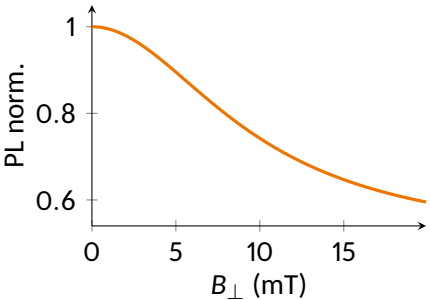

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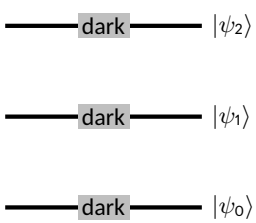
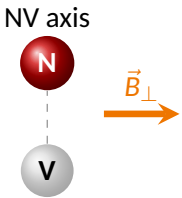
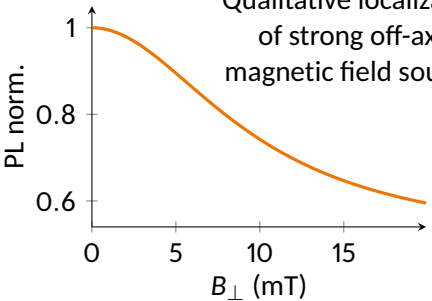


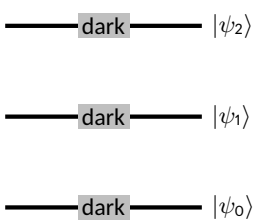


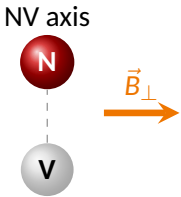


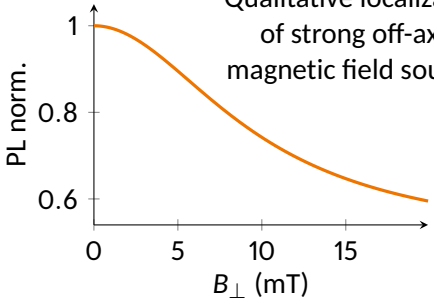
Qualitative localization of strong off-axis magnetic field sources

Strong field regime

Mixing of the spin states





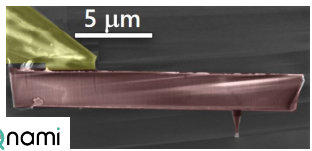


To summarize:

1. Quantitative imaging mode: for small fields, tracking the spin resonance
2. Qualitative imaging mode: for large fields ($>$ 10 mT), monitoring photoluminescence

Our scanning NV microscope

Diamond
AFM tip



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

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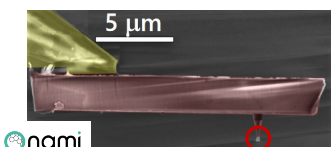

Implanted single
NV center

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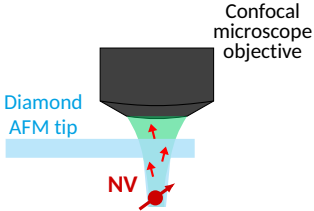

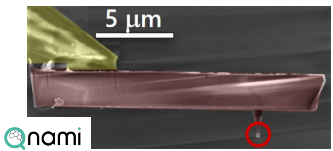

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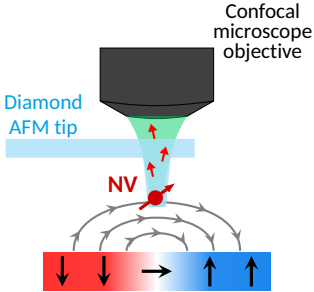

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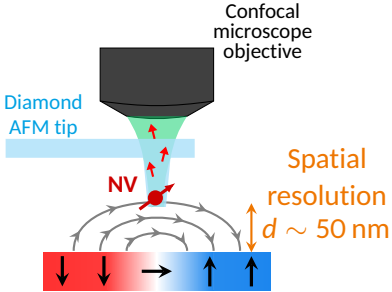

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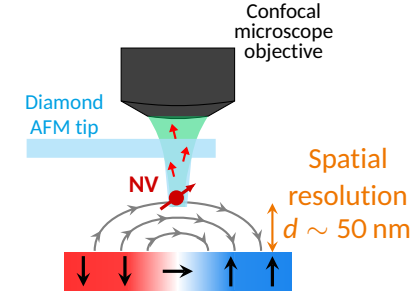

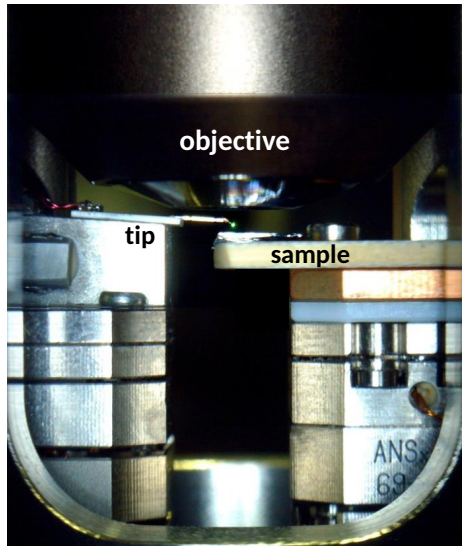

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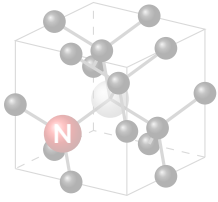

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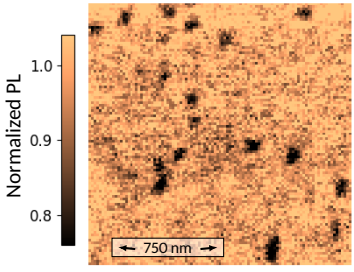

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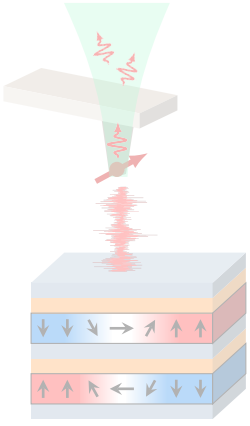
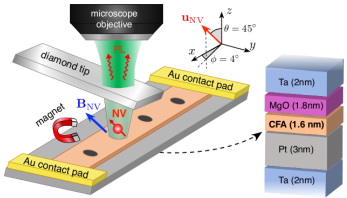


Nucleation by current in tilted magnetic field

Collaborations: LPS Orsay, LSPM Villetaneuse, TU Cluj-Napoca, Uni Basel



W. Akhtar *et al.* *Phys. Rev. Applied* 11 (2019), 034066

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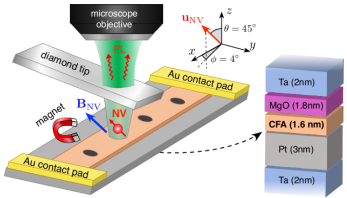

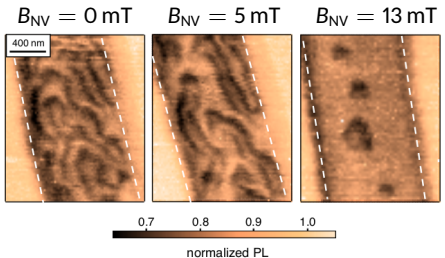

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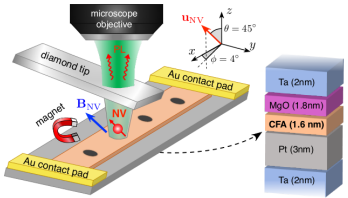

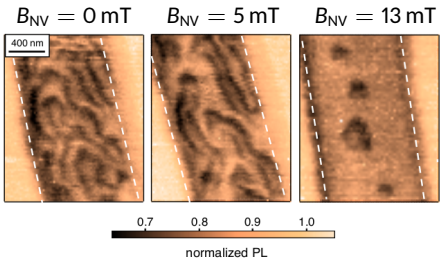

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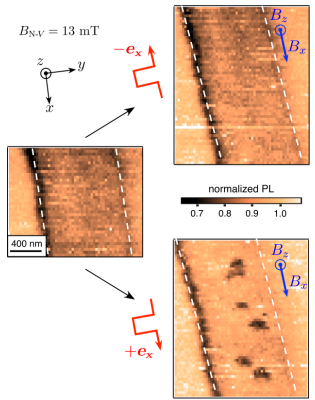
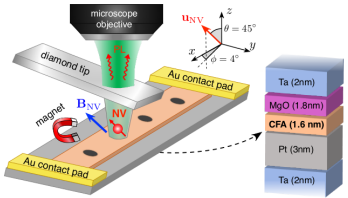
Nucleation with current pulses

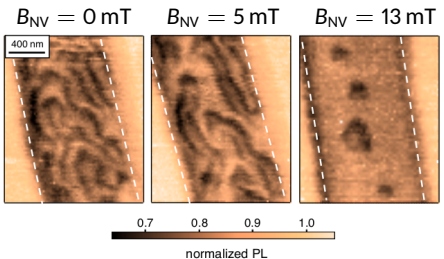


Directionality: m_x leads to an effective SHE field perpendicular to the surface

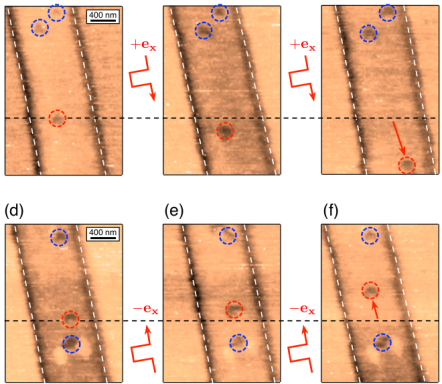
Nucleation by current in tilted magnetic field

Collaborations: LPS Orsay, LSPM Villetaneuse, TU Cluj-Napoca, Uni Basel





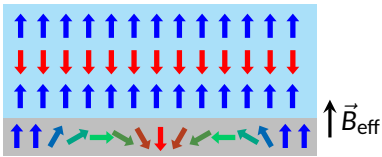
Movement with current pulses



W. Akhtar *et al.* *Phys. Rev. Applied* 11 (2019), 034066

Zero field skyrmions stabilized by exchange bias

Collaborations: Spintec Grenoble, Institut Néel Grenoble, LSPM Villetaneuse, FZ Jülich



K. G. Rana *et al*. *Phys. Rev. Applied* 13 (2020), 044079

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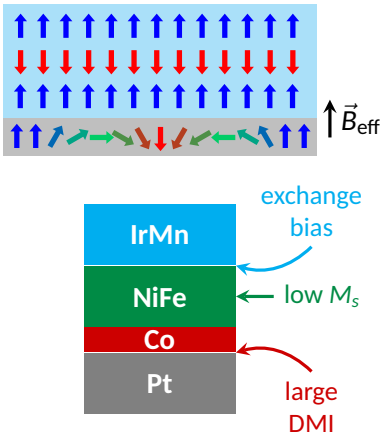

K. G. Rana *et al*. *Phys. Rev. Applied* 13 (2020), 044079

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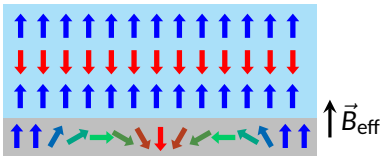
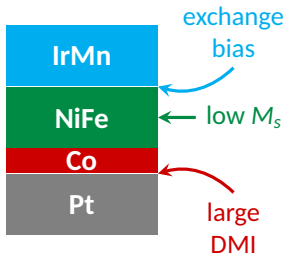
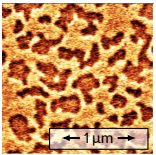


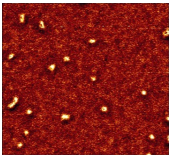


MFM images

$t_{IrMn} = 4.02$ nm



$t_{IrMn} = 4.19$ nm



K. G. Rana *et al*. *Phys. Rev. Applied* 13 (2020), 044079

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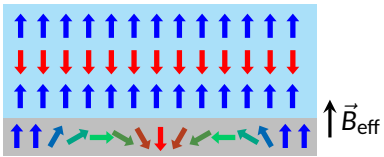

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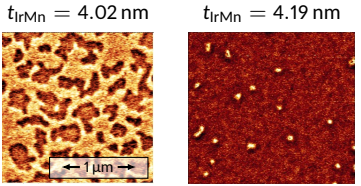
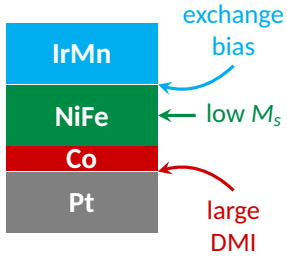
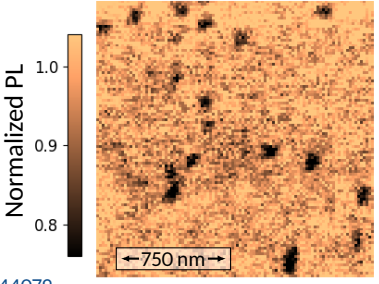
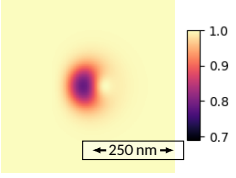






PL simulation

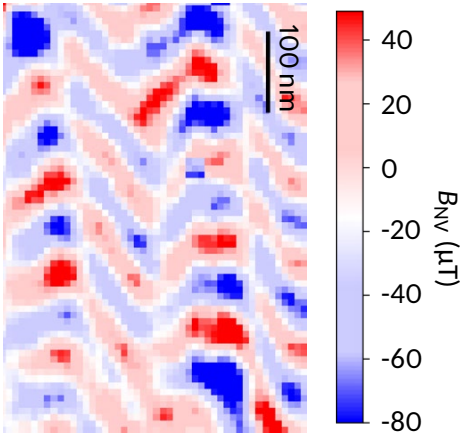


diameter 60 nm

K. G. Rana *et al*. *Phys. Rev. Applied* 13 (2020), 044079

A perfect tool to study antiferromagnets

Collaborations: UMR CNRS/Thales, Palaiseau, SPEC CEA Saclay, Synchrotron Soleil



$BiFeO_3$

- Room temperature multiferroic
- Cycloidal modulation of the antiferromagnetic order
- Study of magnetoelectric couplings, strain effects, etc.

See SYNV 1.3, V. Jacques

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

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

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

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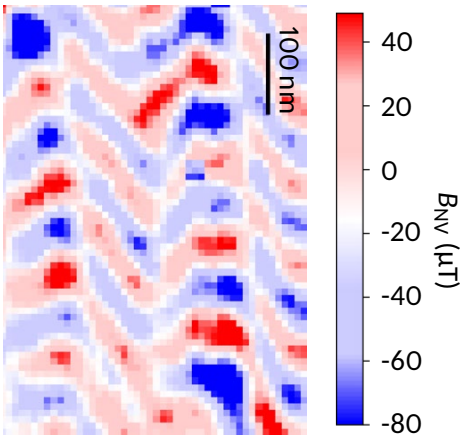

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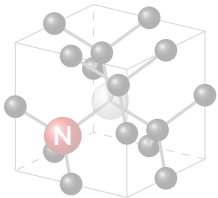
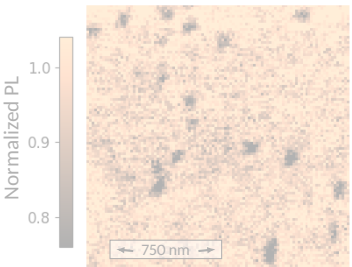
What if there are no uncompensated moments at all?

Outline

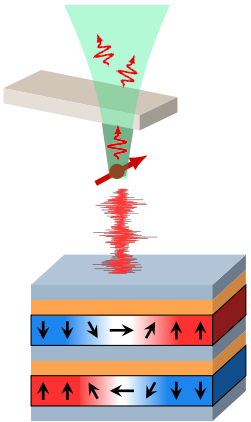
Scanning NV microscopy



Skyrmions in ferromagnets



Noise based imaging in synthetic antiferromagnets



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

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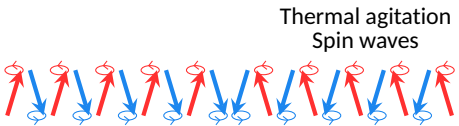

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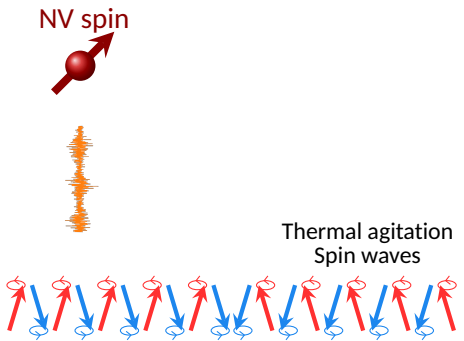

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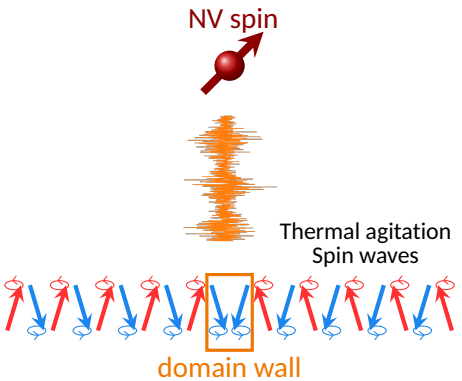
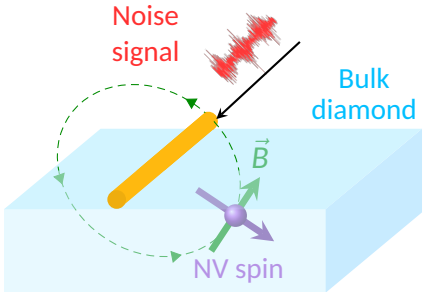


Acceleration of the NV spin relaxation with magnetic noise



Collaboration C2N: T. Devolder

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

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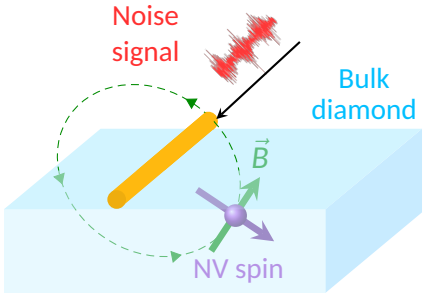

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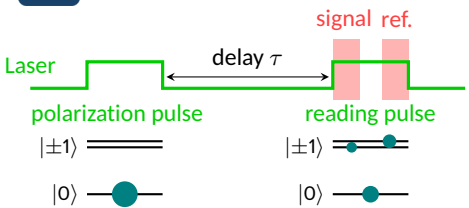

M. Rollo *et al.* *PRB* 103 (2021), 235418

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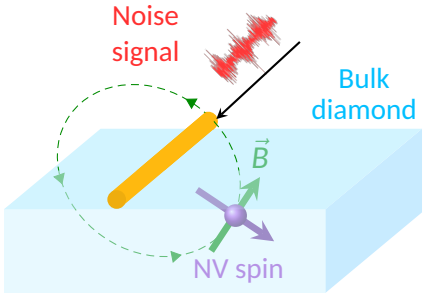

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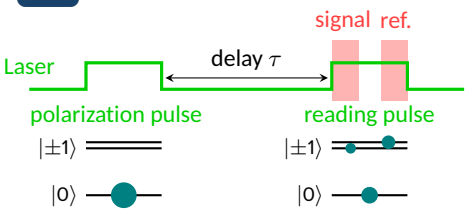

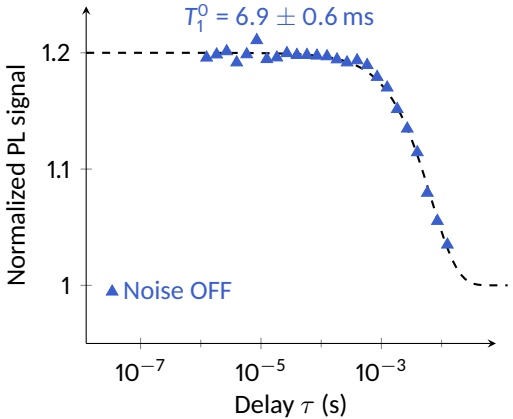

M. Rollo *et al.* *PRB* 103 (2021), 235418

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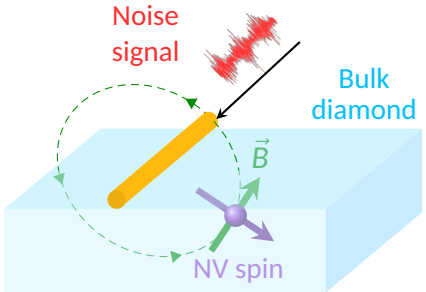
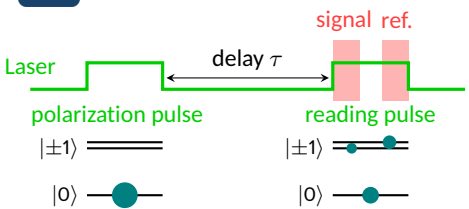
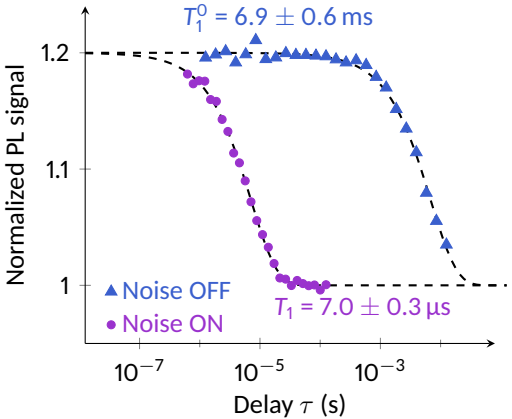


C2N *Collaboration C2N: T. Devolder*

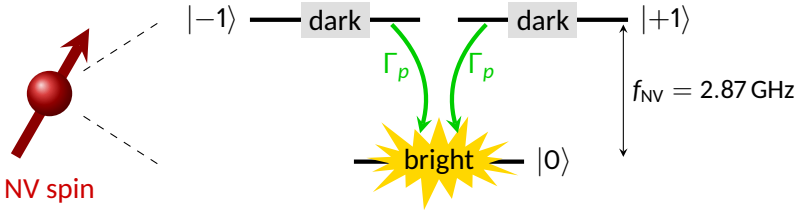




Noise spectrum centered
at the NV transition frequency

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

Effect on the emitted photoluminescence



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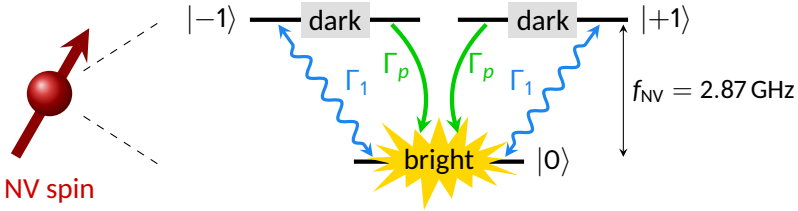

Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{NV})$ magnetic field spectral density at the resonance frequency f_{NV}

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

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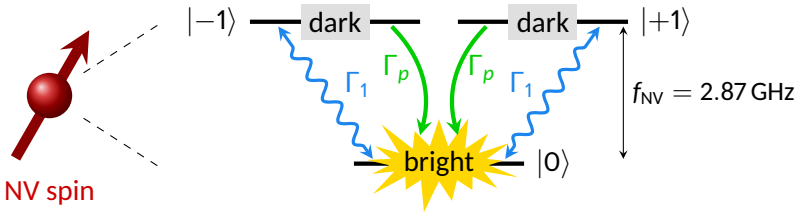

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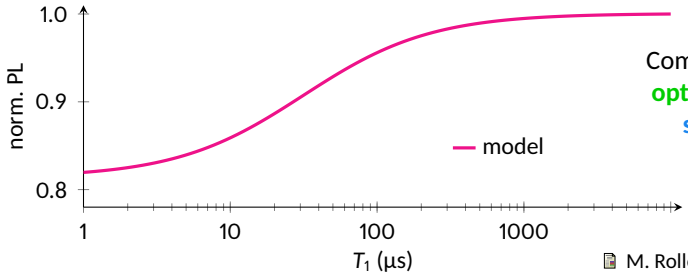

Competition between **optical pumping** and **spin relaxation**

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

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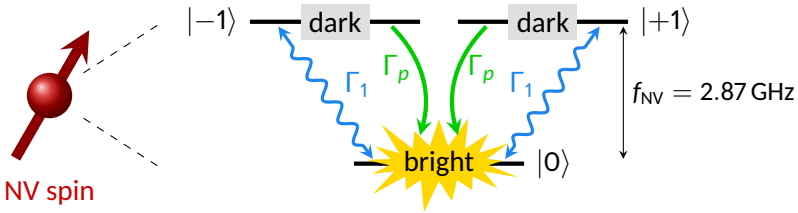

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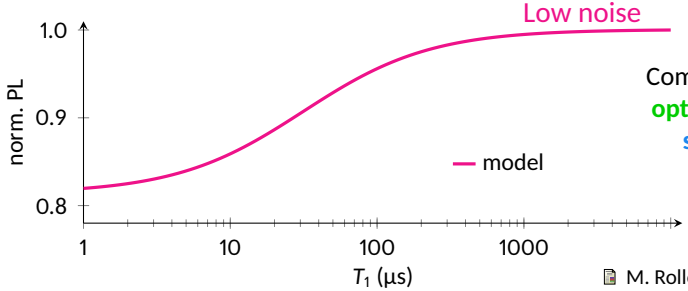

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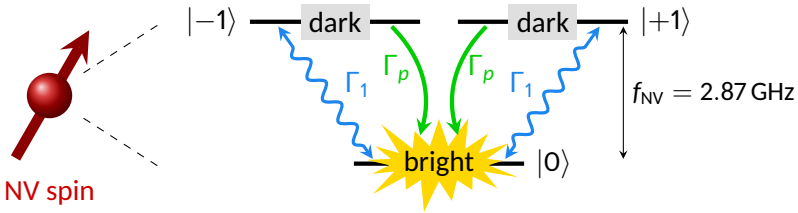

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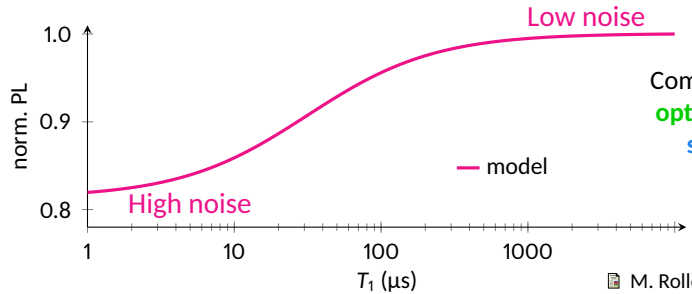

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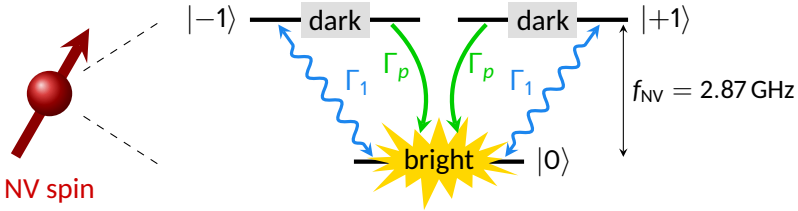

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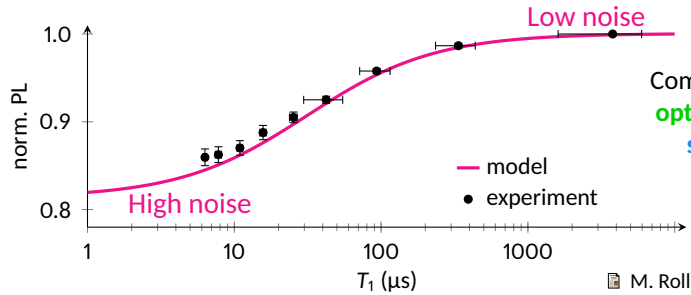

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Application to the imaging of synthetic antiferromagnets

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

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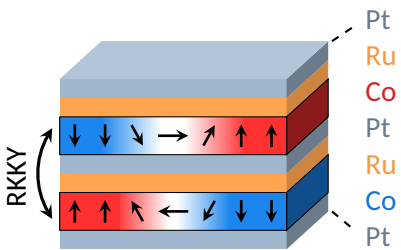

W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34

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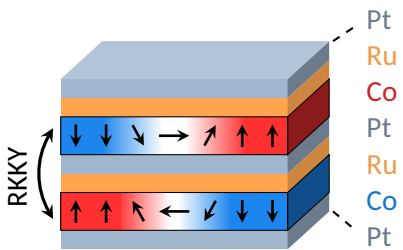
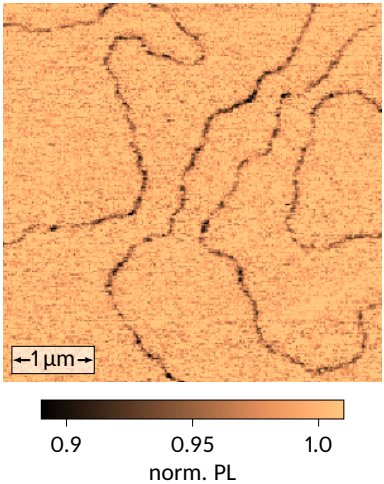


W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34

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

Detection of domain walls by relaxometry



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

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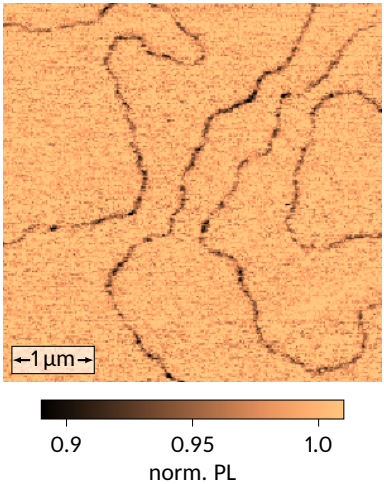
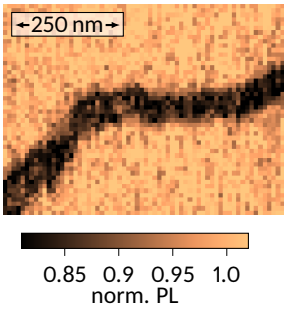
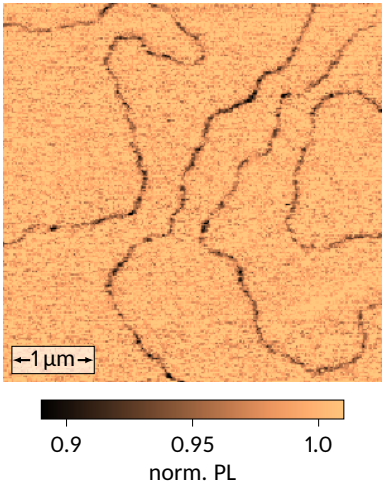
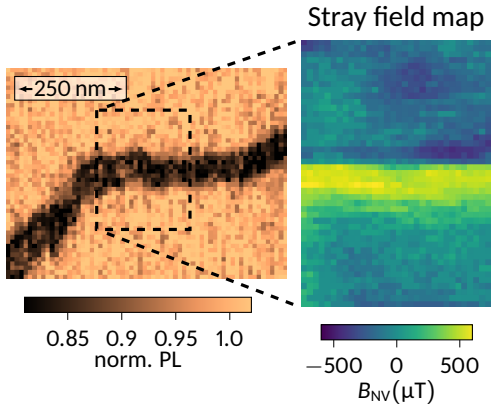




A. Finco *et al.* *Nat. Commun.* 12 (2021), 767

Detection of domain walls by relaxometry





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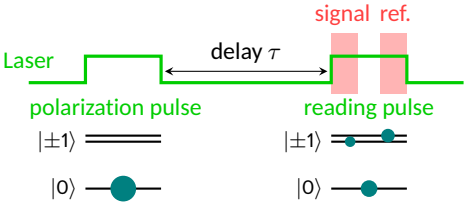
Local variation of the relaxation time



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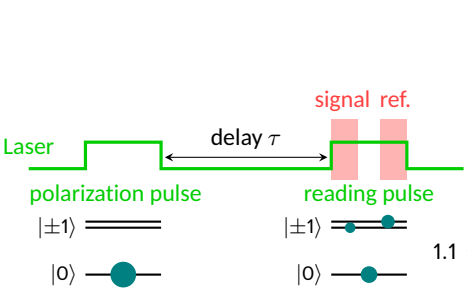

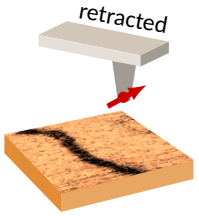

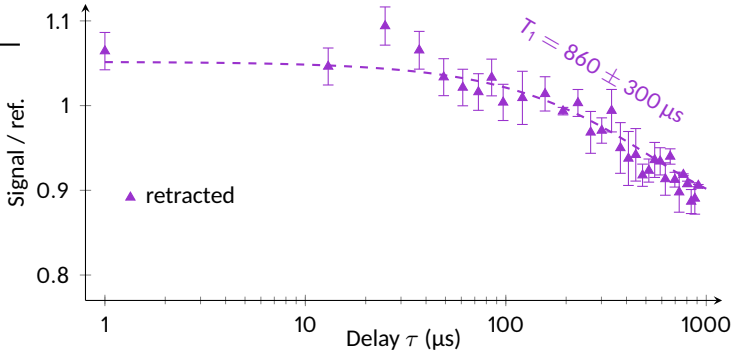

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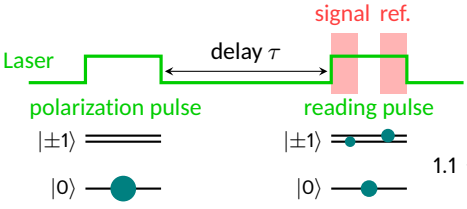

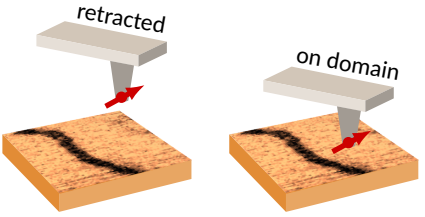

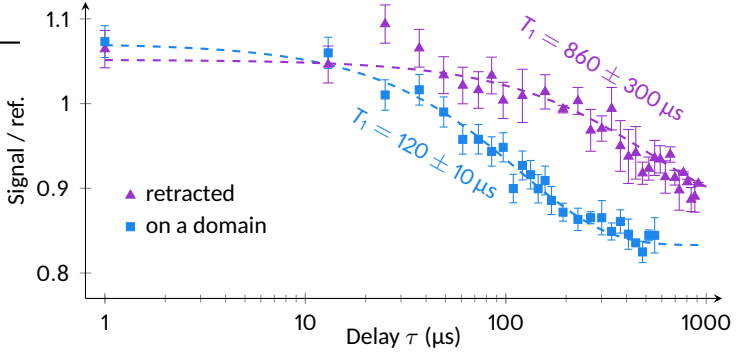

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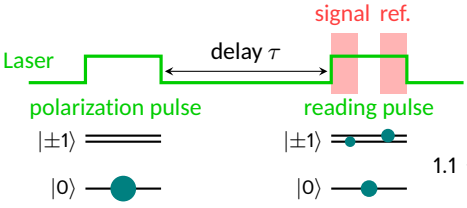

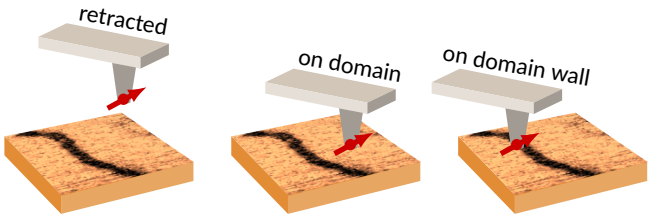

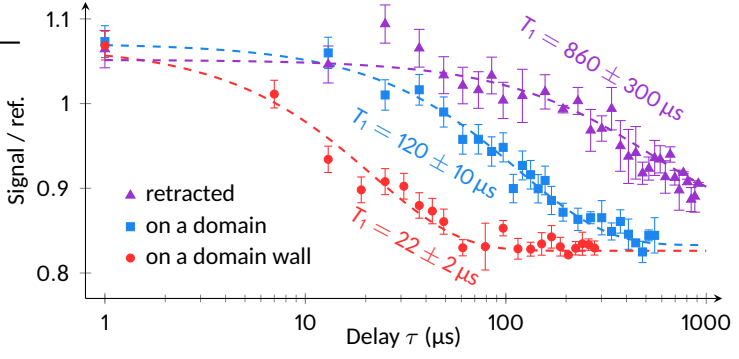

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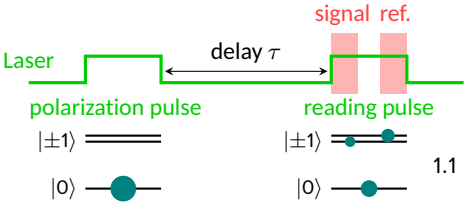
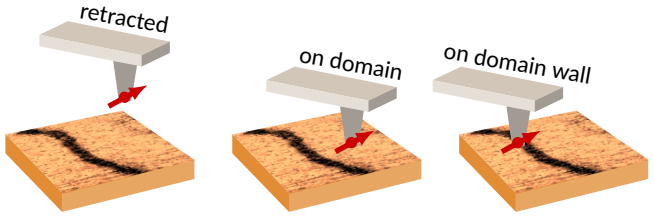
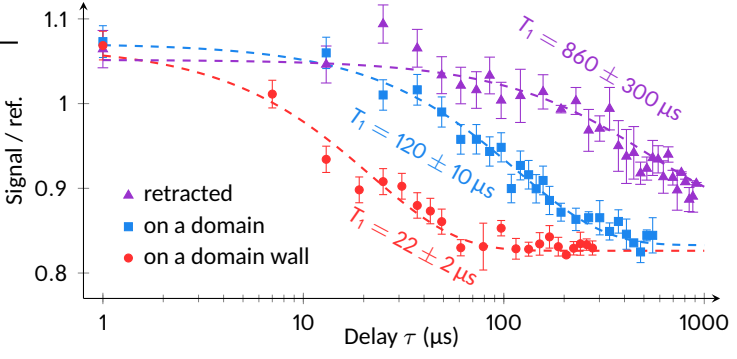




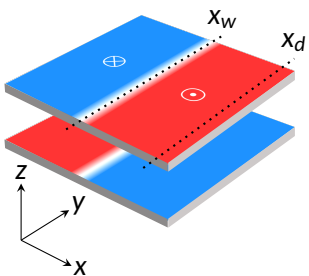
Clear diminution of T_1

→ **Enhancement of the spin relaxation**



Origin of the noise: spin waves

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



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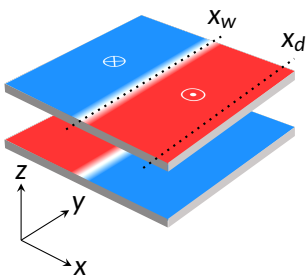

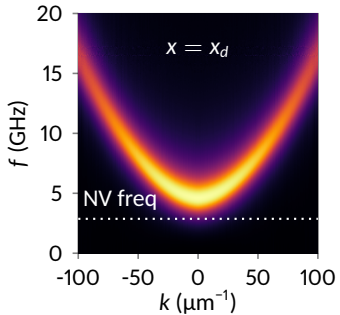

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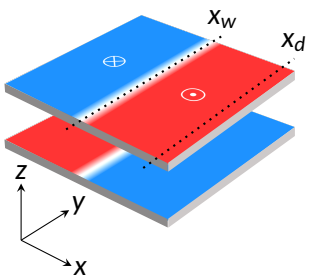

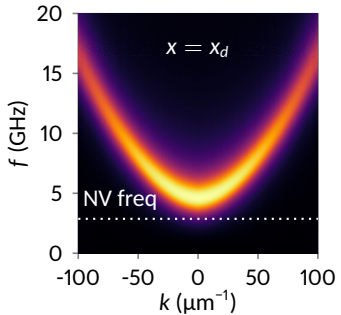

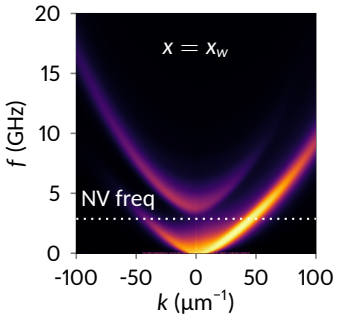

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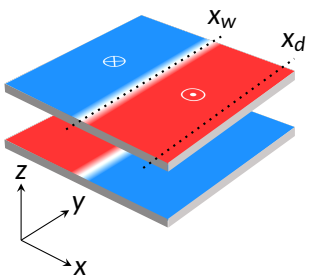

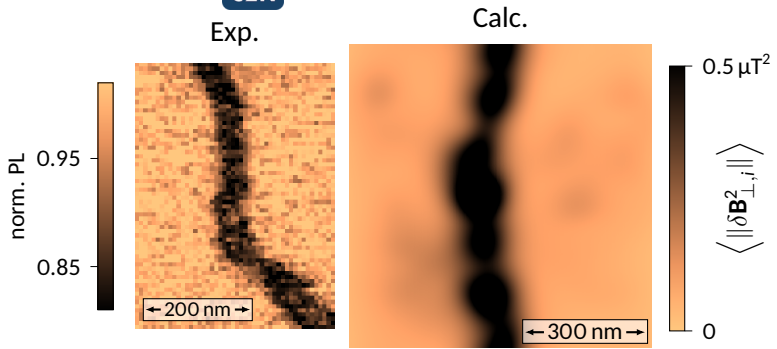

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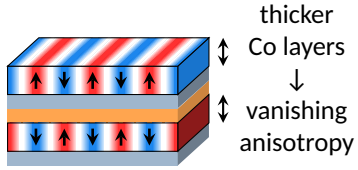
Imaging a spin spiral



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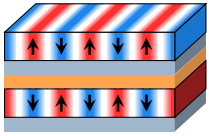
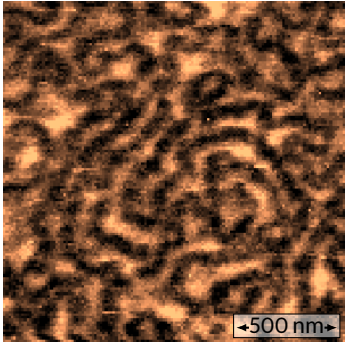


thicker
Co layers
↓
vanishing
anisotropy

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



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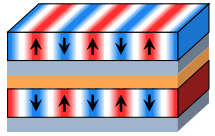

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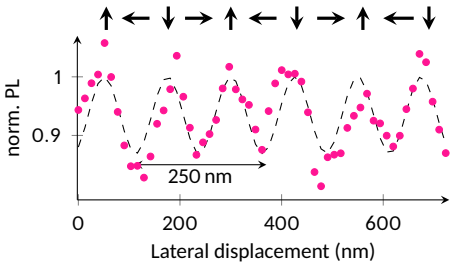
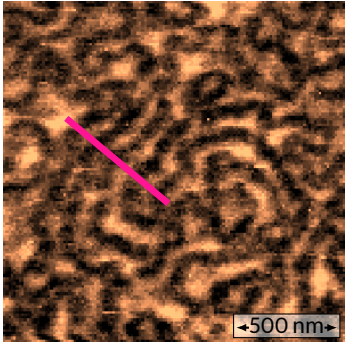
W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34





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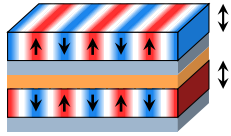

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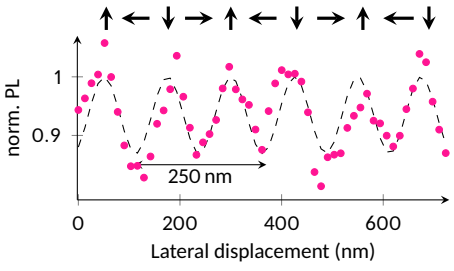
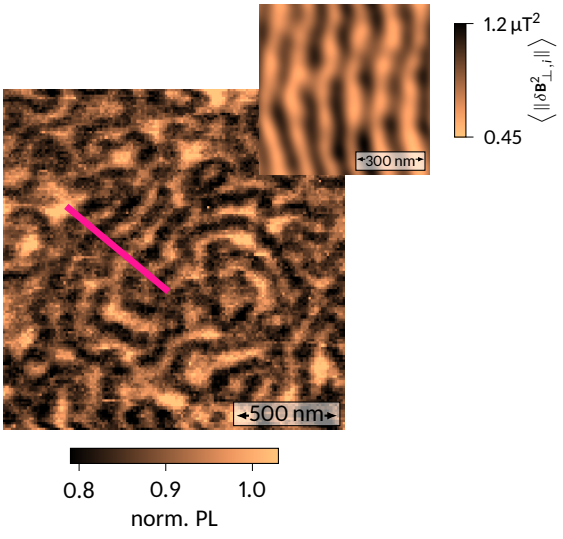
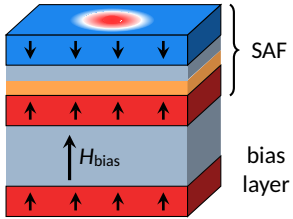


Calculated noise map



Synthetic antiferromagnetic skyrmions



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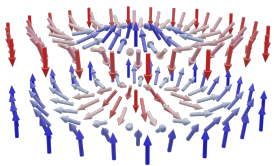

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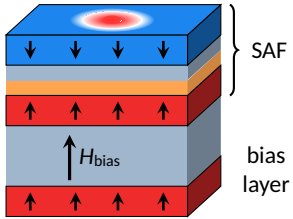

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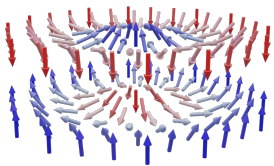
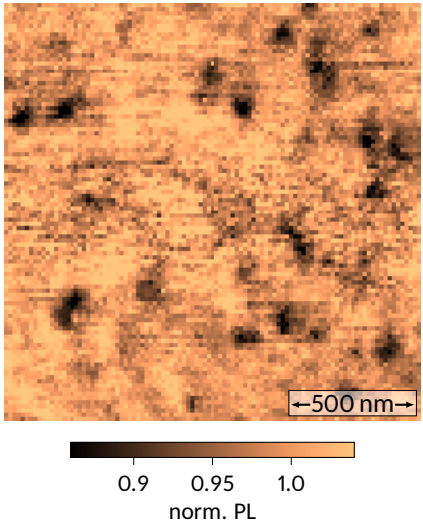


Experimental noise map



Origin of the contrast in the skyrmion case

- No internal skyrmion excitation at 2.87 GHz
- Scattering of the spin waves on the skyrmions

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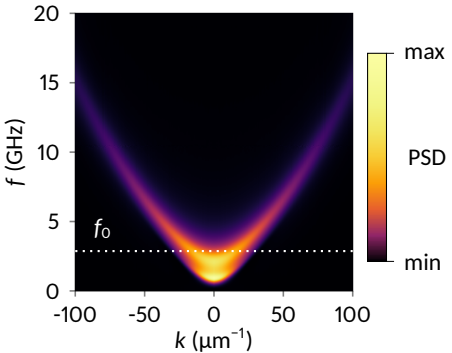

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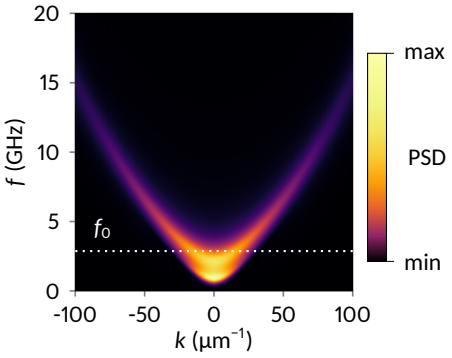
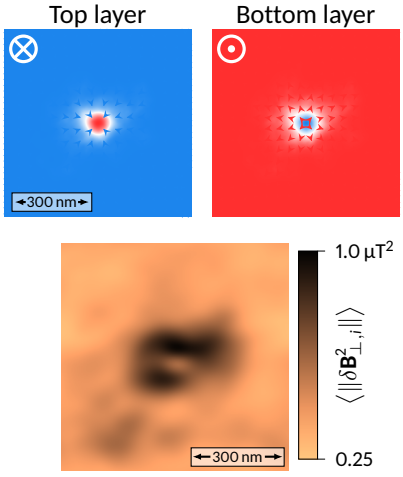
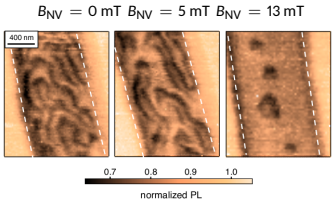




Summary

→ Imaging of skyrmions in ferromagnets



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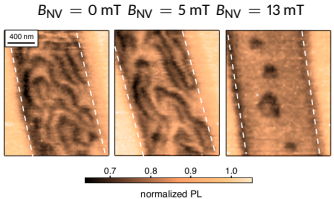
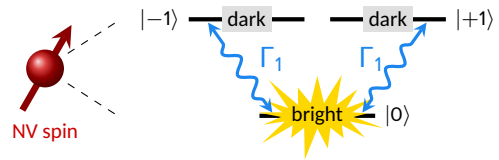


→ All optical noise detection with NV centers



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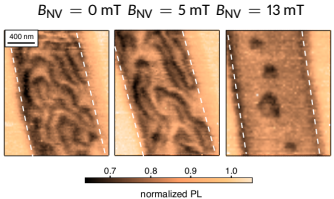

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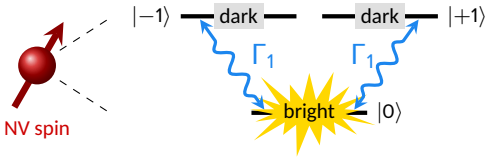

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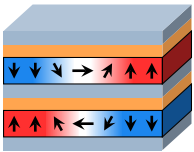
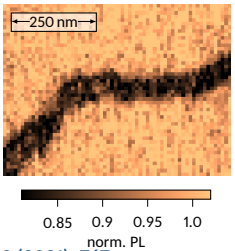
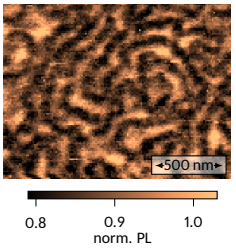
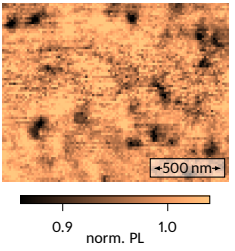
→ Application to the imaging of magnetic textures in synthetic antiferromagnets









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Acknowledgments

L2C, Montpellier

Angela Haykal
Rana Tanos
Maxime Rollo
Saddem Chouaieb
Florentin Fabre
Waseem Akhtar
Isabelle Robert-Philip
Vincent Jacques

UMR CNRS/Thales, Palaiseau

William Legrand
Fernando Ajejas
Karim Bouzehouane
Nicolas Reyren
Vincent Cros

C2N, Palaiseau

Jean-Paul Adam
Thibaut Devolder
Joo-Von Kim

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