

NM 04.04.01

Imaging skyrmions in ferromagnets and antiferromagnets with scanning NV microscopy

Aurore Finco

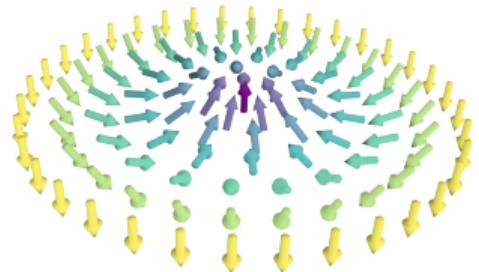
Université de Montpellier and CNRS, Montpellier, France



MRS Spring Meeting online, April 21 2021

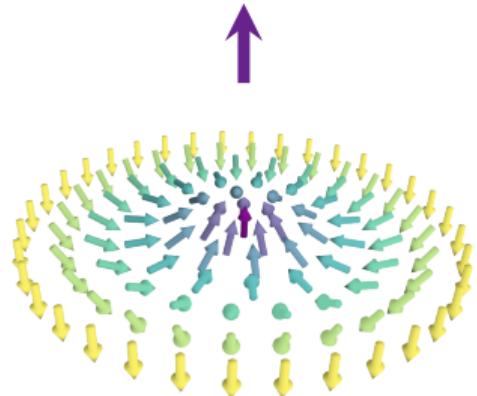
slides available at <https://magimag.eu>

Imaging magnetic skyrmions



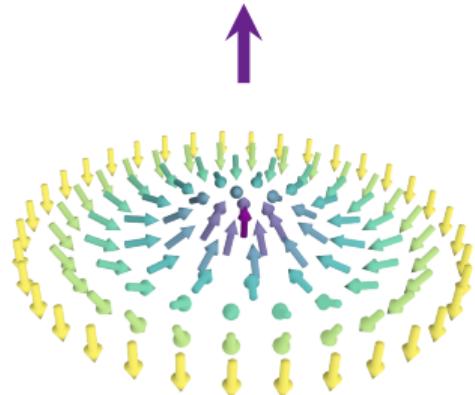
Imaging magnetic skyrmions

Measure directly
the magnetization rotation



Imaging magnetic skyrmions

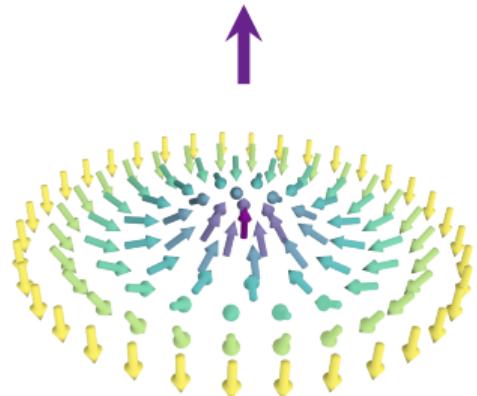
Measure directly
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Measure the magnetic
stray field produced

Imaging magnetic skyrmions

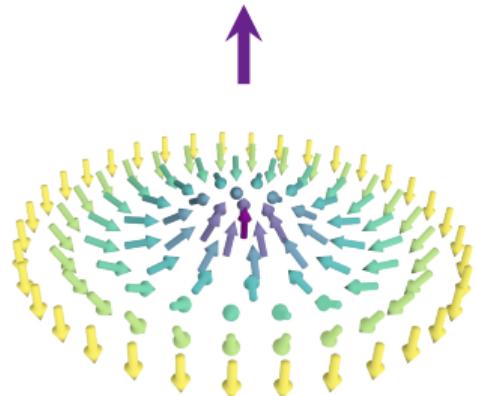
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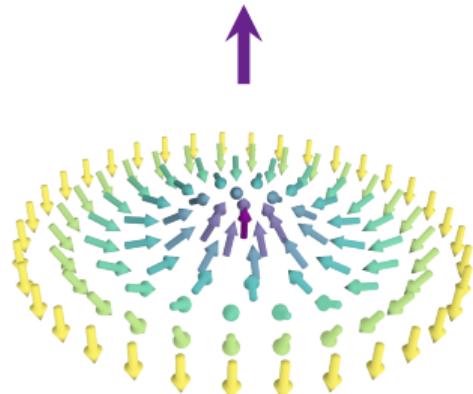
Measure the magnetic
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Magnetic stray field sensor requirements

- Nanometric spatial resolution
- Non-perturbative
- High sensibility
- Working under ambient conditions

Imaging magnetic skyrmions

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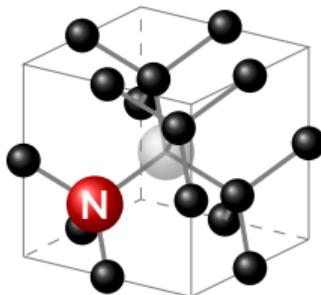
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Magnetic stray field sensor requirements

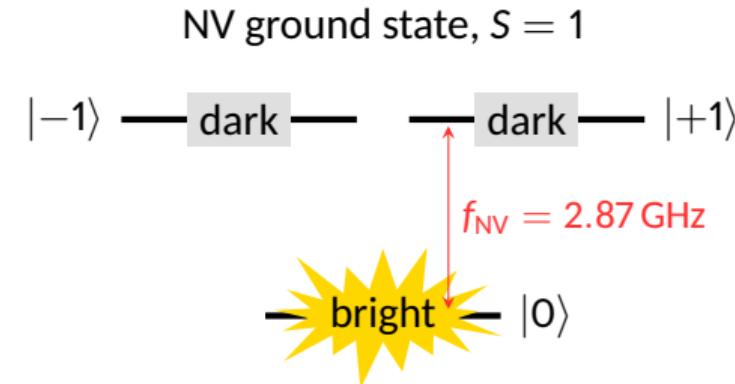
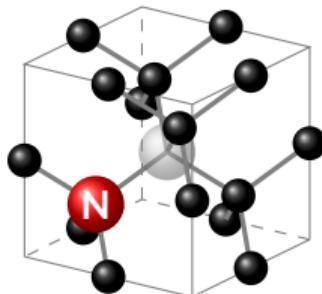
- Nanometric spatial resolution
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Use NV centers in diamond

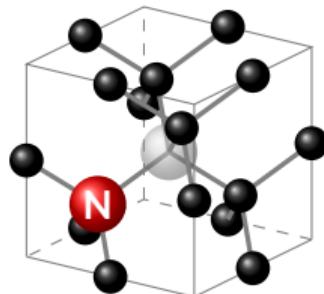
NV centers as quantum sensors for magnetic field



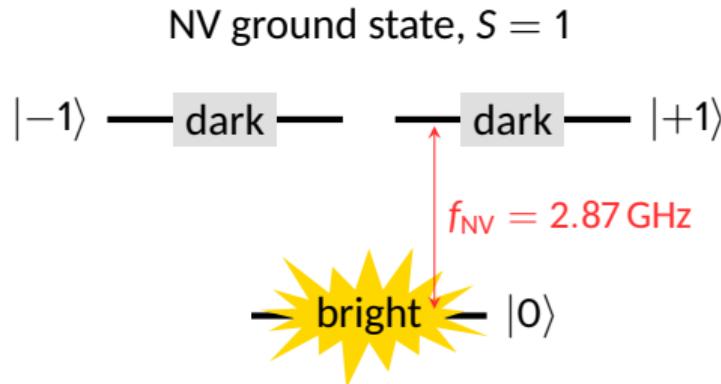
NV centers as quantum sensors for magnetic field



NV centers as quantum sensors for magnetic field



NV ground state, $S = 1$



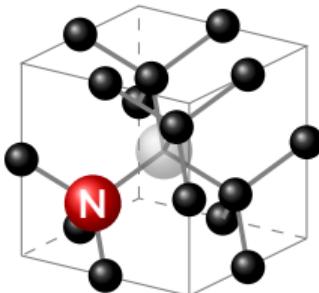
i) Low stray field

Quantitative stray field
measurement

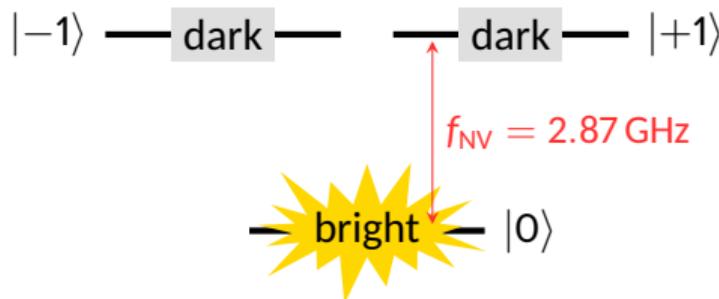
*Optical tracking of
the Zeeman shift*

→ Antiferromagnets

NV centers as quantum sensors for magnetic field



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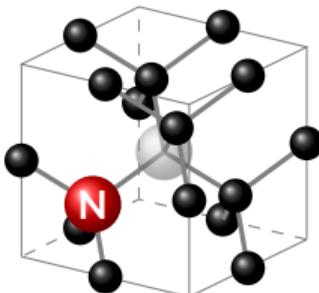
ii) Large stray field

Qualitative stray field
sources detection

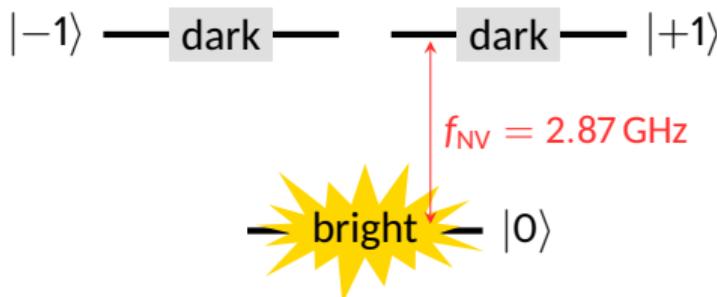
*Monitoring of the emitted
photoluminescence*

→ Ferromagnets

NV centers as quantum sensors for magnetic field



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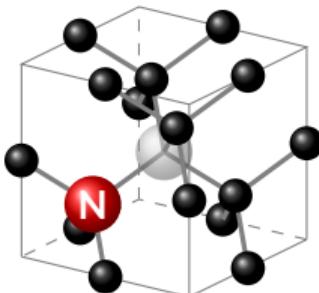
iii) Magnetic noise

Qualitative noise
sources detection

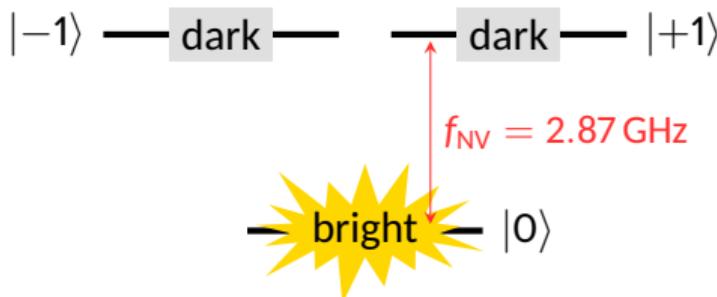
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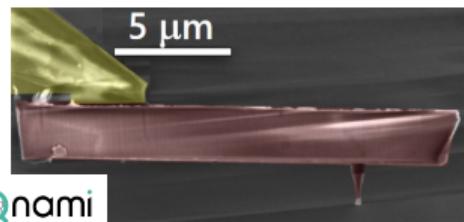
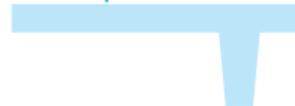
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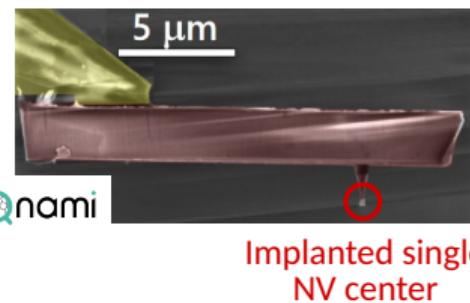
→ Antiferromagnets

Our scanning NV microscope

Diamond
AFM tip

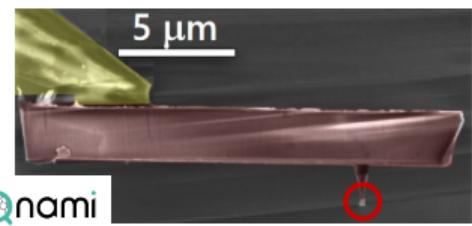
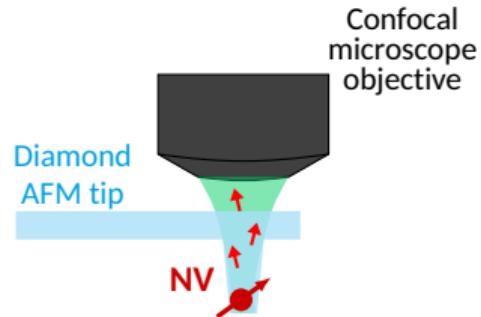


Our scanning NV microscope



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

Our scanning NV microscope

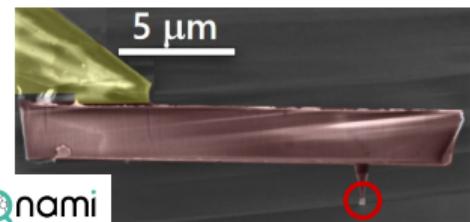
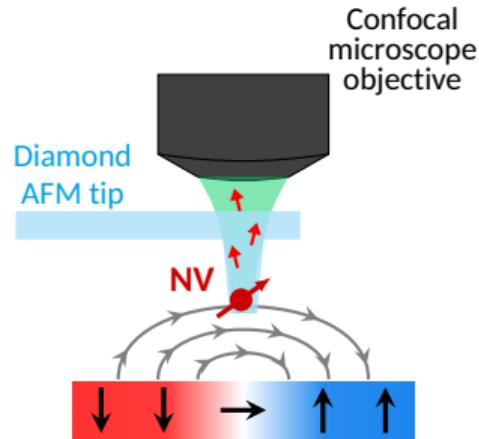


Implanted single
NV center



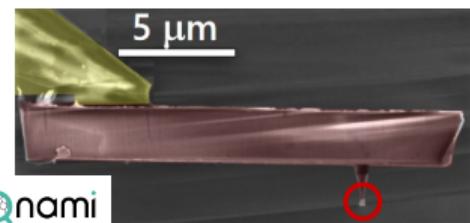
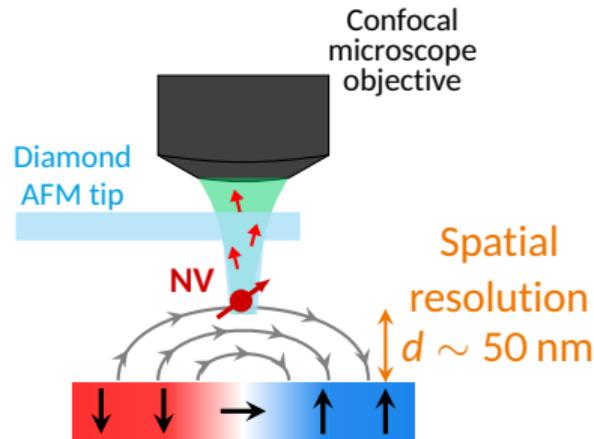
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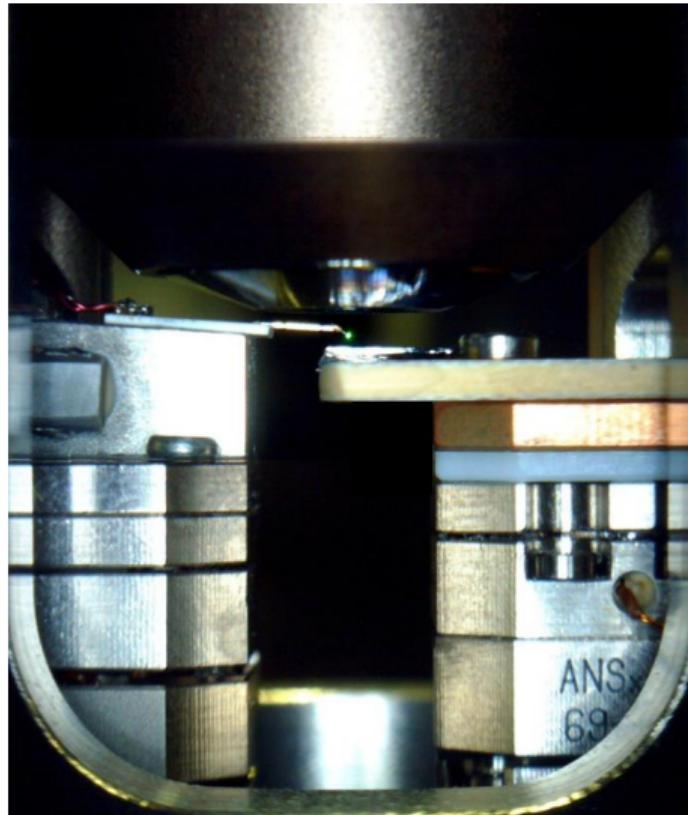
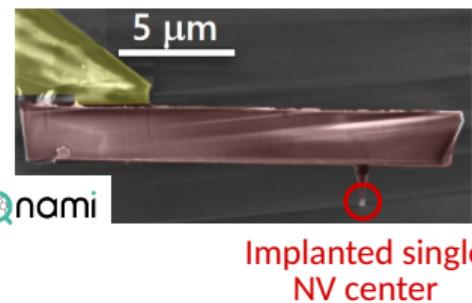
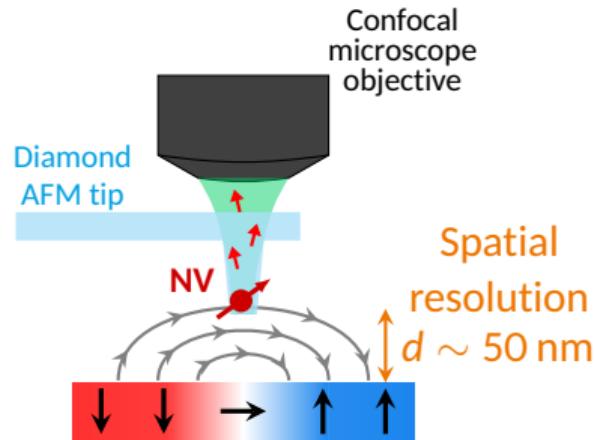
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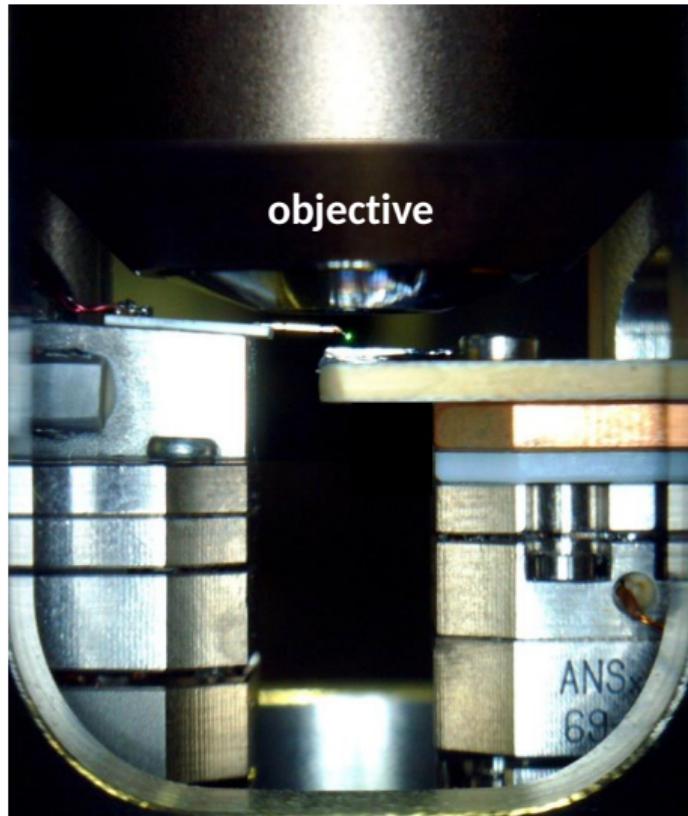
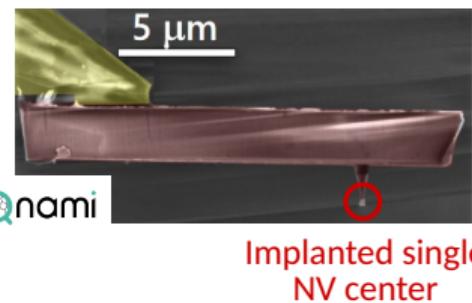
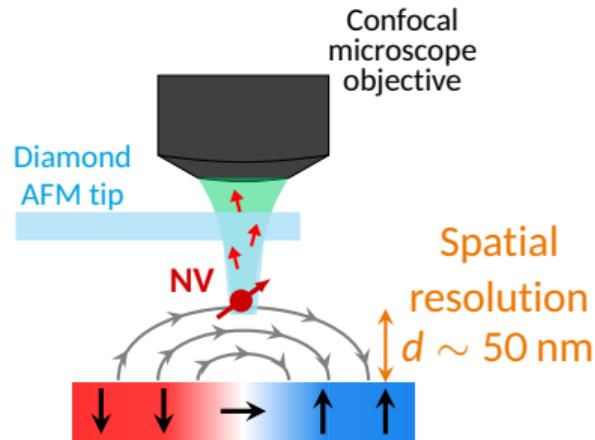


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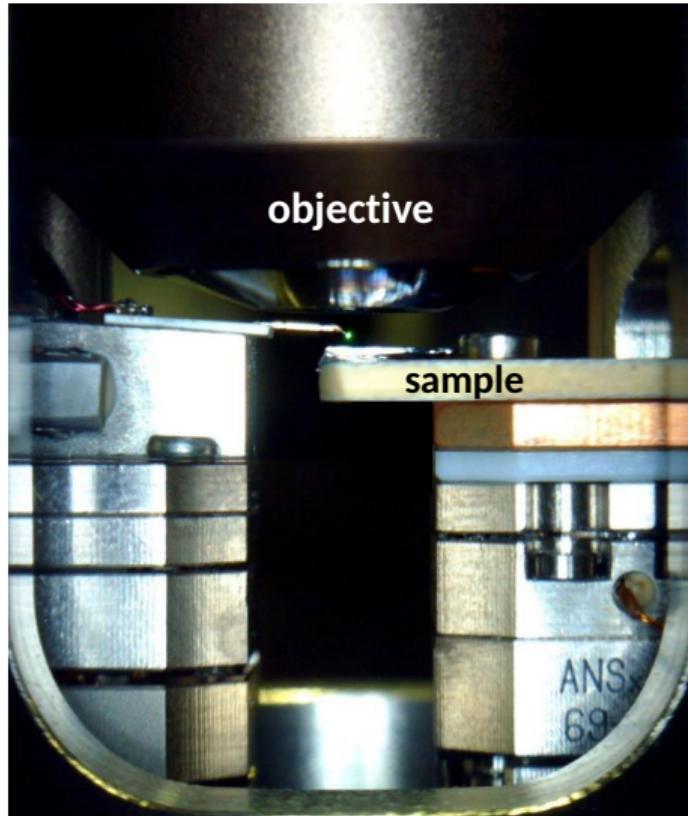
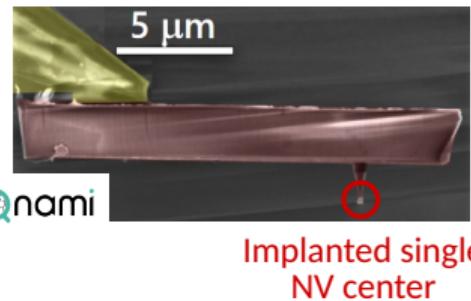
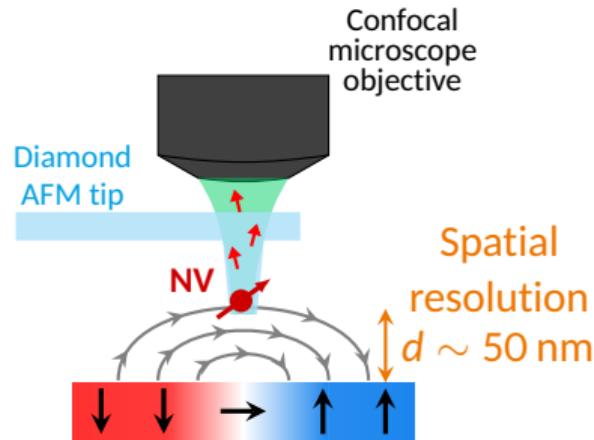


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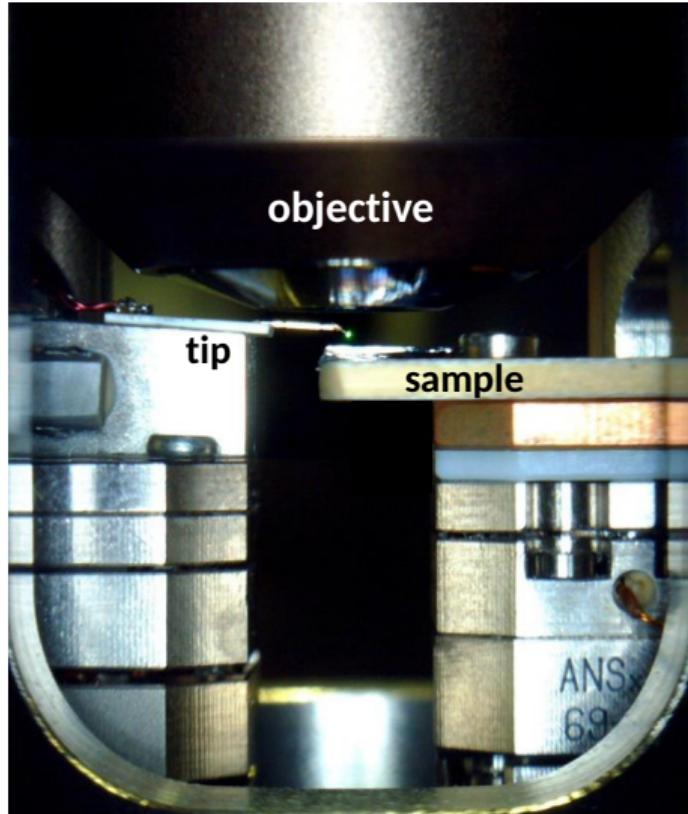
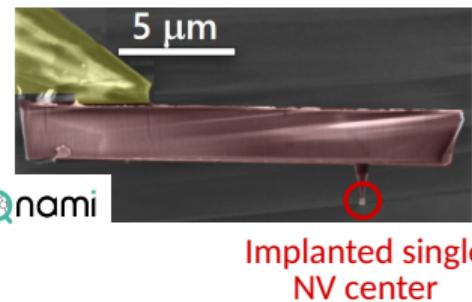
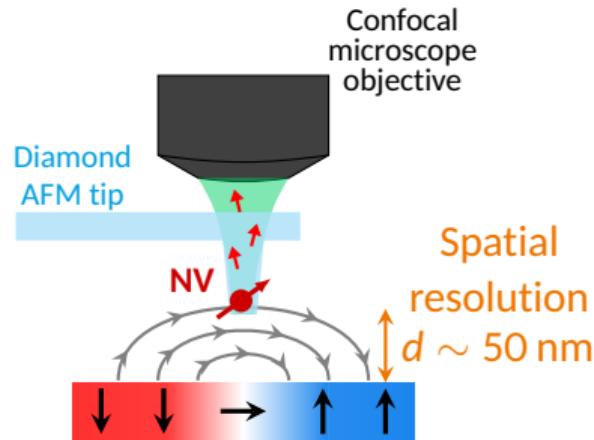
■ P. Maletinsky et al. *Nat. Nano.* 7 (2012), 320

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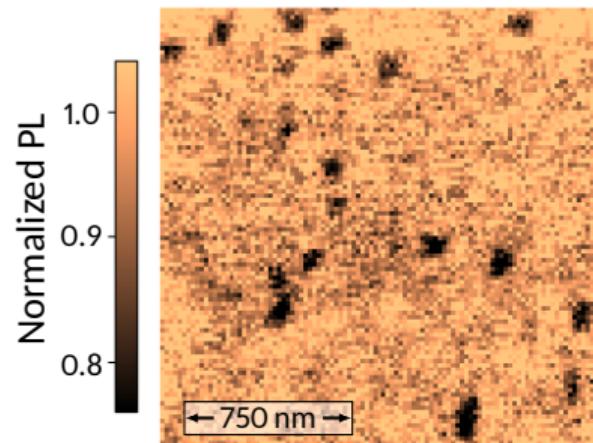
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Our scanning NV microscope



Outline

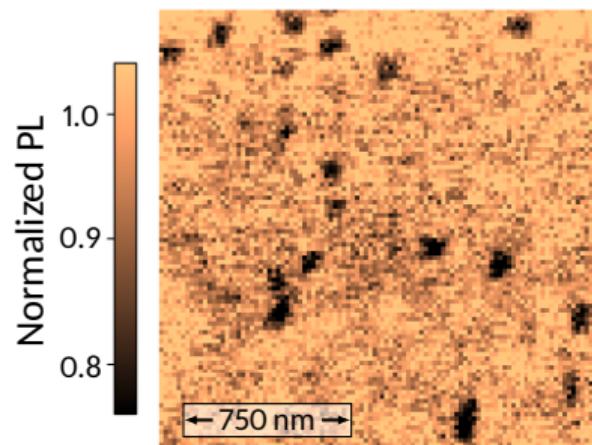
Zero-field skyrmions
in a **ferromagnet**
stabilized by exchange-bias



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

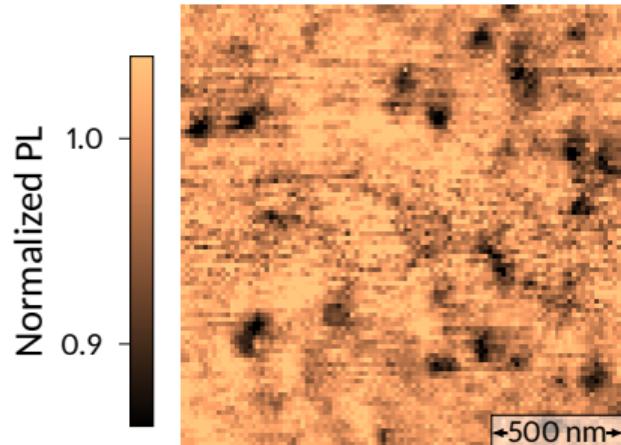
Outline

Zero-field skyrmions in a **ferromagnet** stabilized by exchange-bias



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

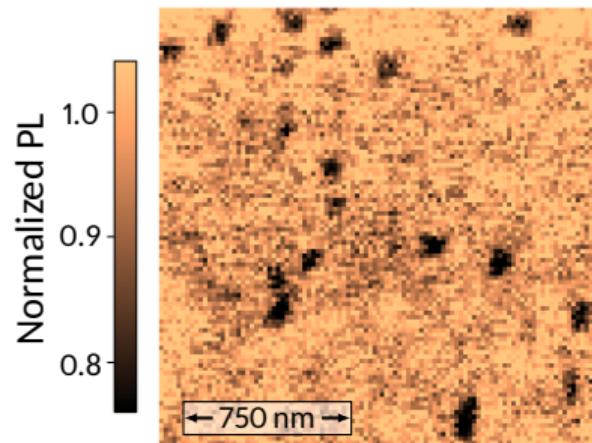
Noise-based imaging of skyrmions in a **synthetic antiferromagnet**



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

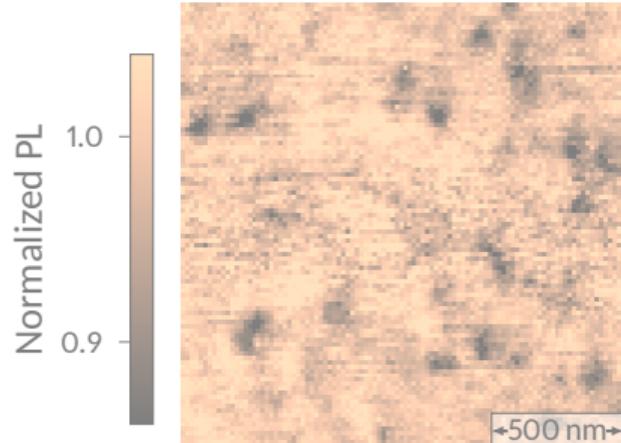
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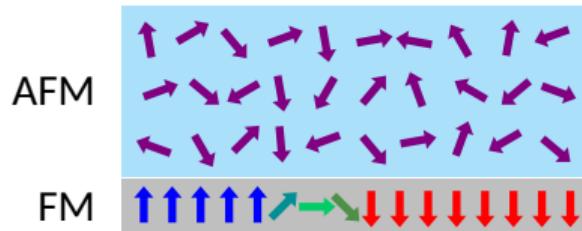


■ A. Finco et al. *Nat. Commun.* 12 (2021), 767

Use exchange bias as an effective field

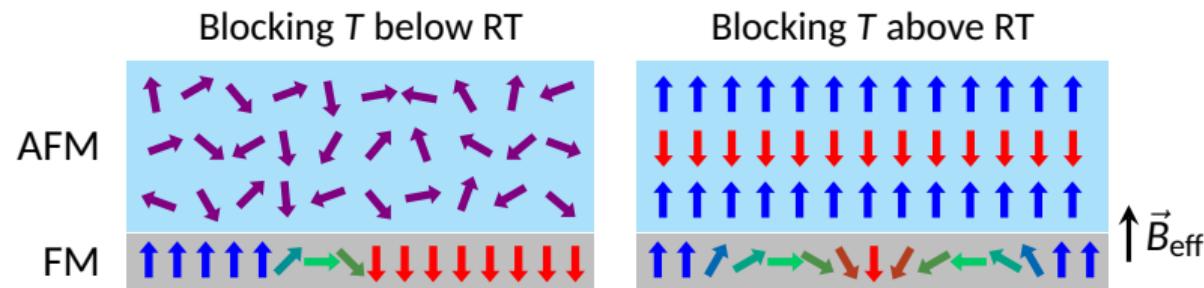
Goal: stable zero-field skyrmions at room temperature without confinement

Blocking T below RT



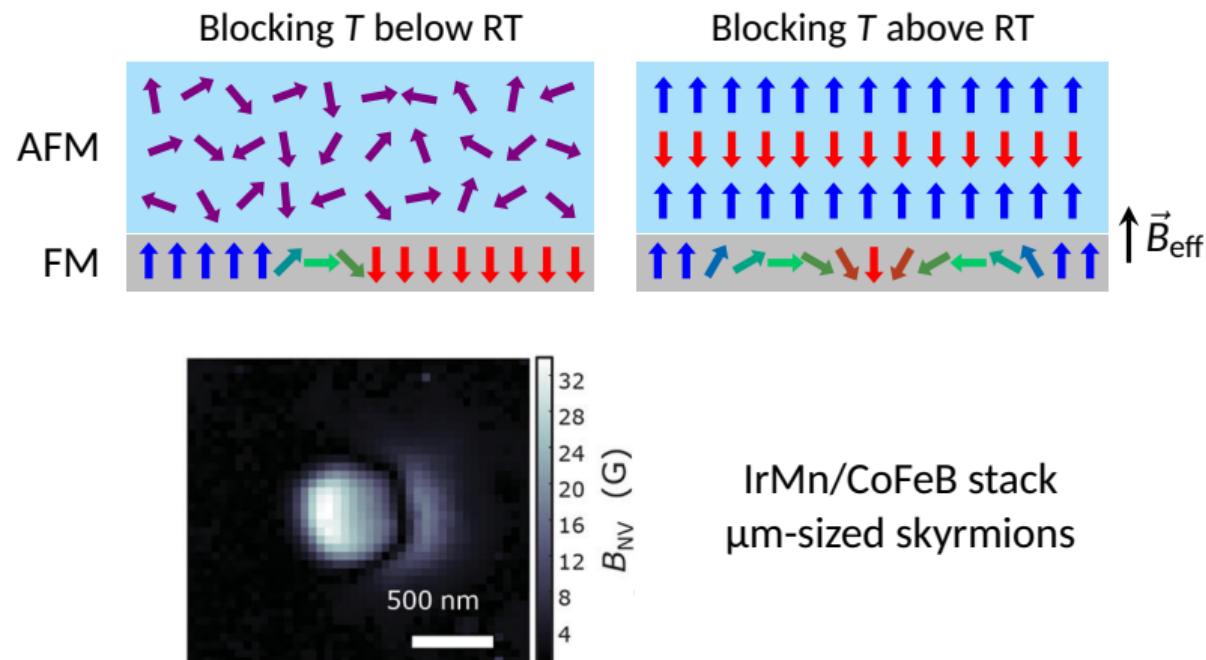
Use exchange bias as an effective field

Goal: stable zero-field skyrmions at room temperature without confinement



Use exchange bias as an effective field

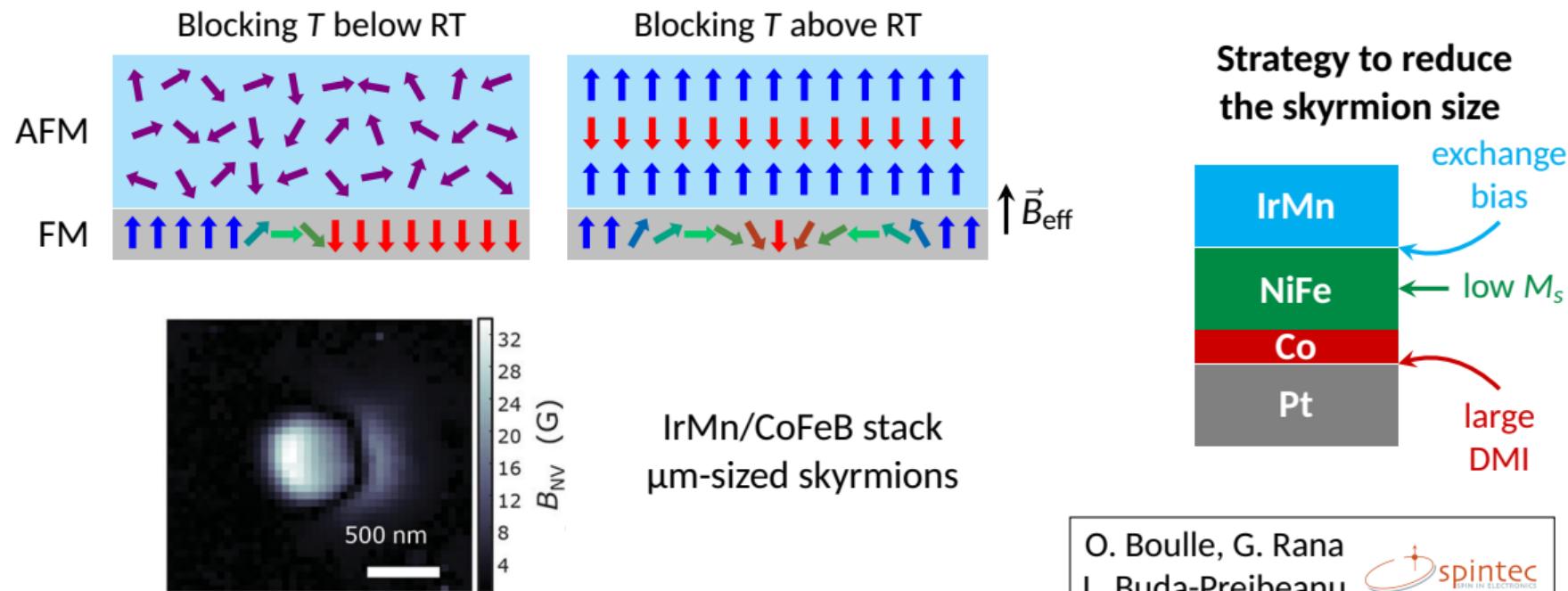
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G. Yu et al. *Nano Letters* 18 (2018), 980–986

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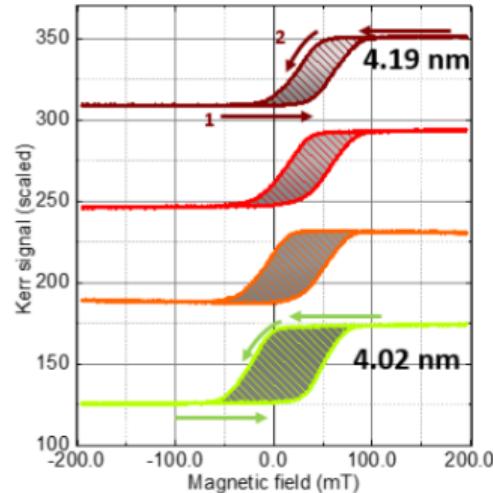
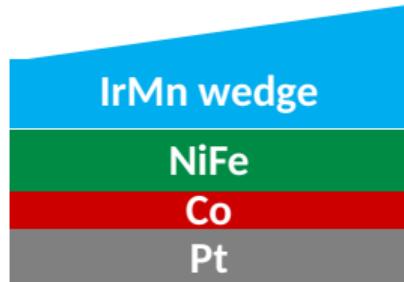


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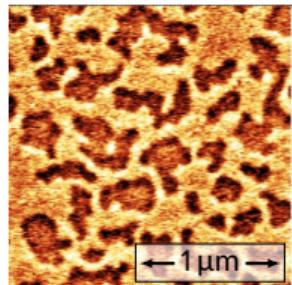
O. Boulle, G. Rana
L. Buda-Prejbeanu



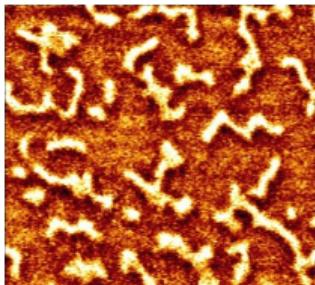
Optimization of the sample parameters



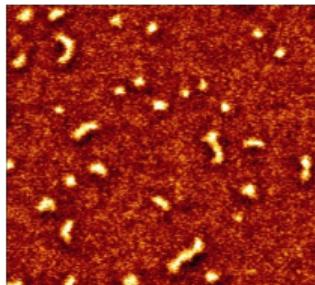
$$t_{\text{IrMn}} = 4.02 \text{ nm}$$



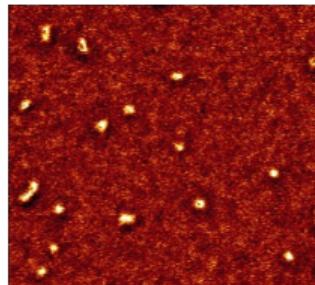
$$t_{\text{IrMn}} = 4.11 \text{ nm}$$



$$t_{\text{IrMn}} = 4.15 \text{ nm}$$

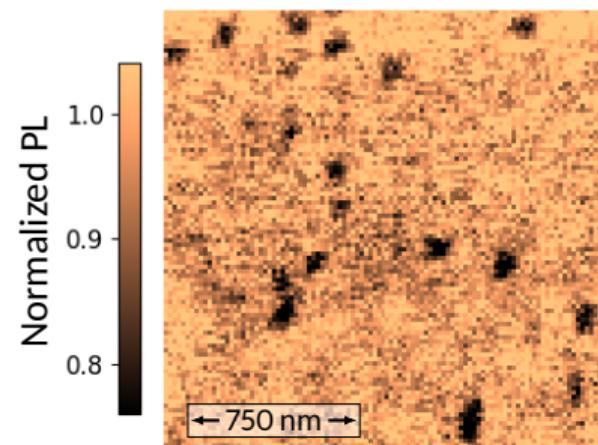


$$t_{\text{IrMn}} = 4.19 \text{ nm}$$



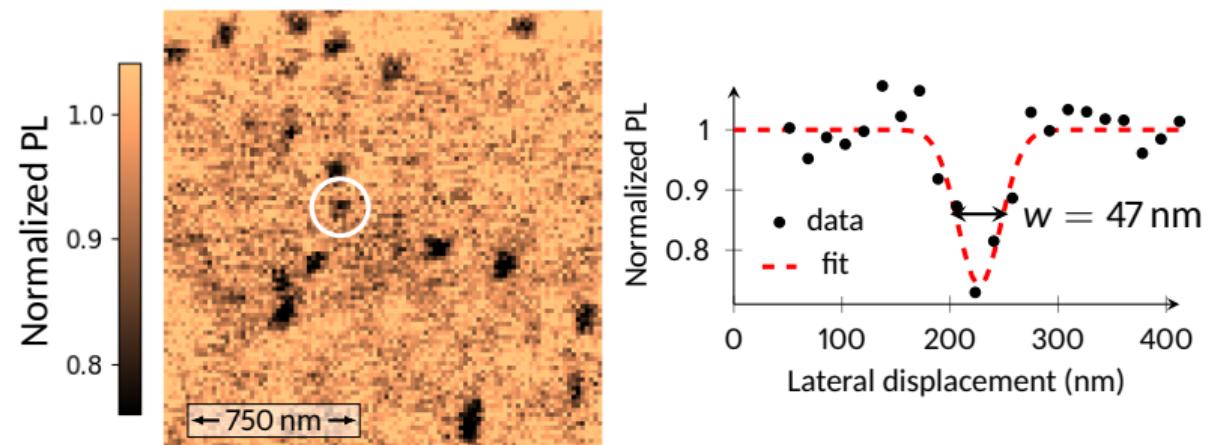
MFM
images

Magnetic skyrmions in qualitative high field mode



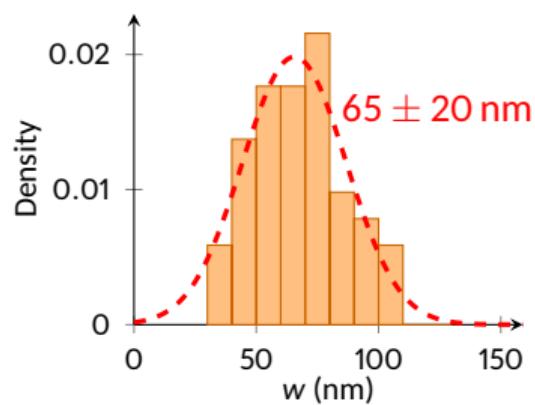
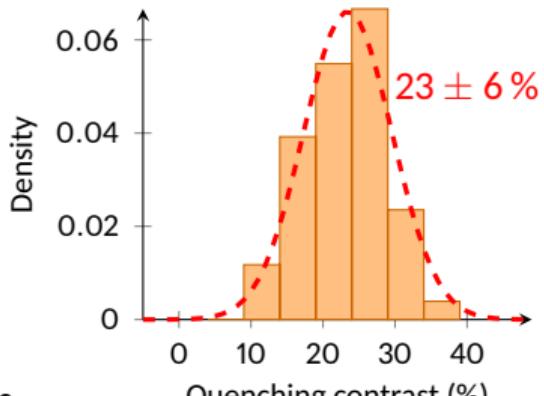
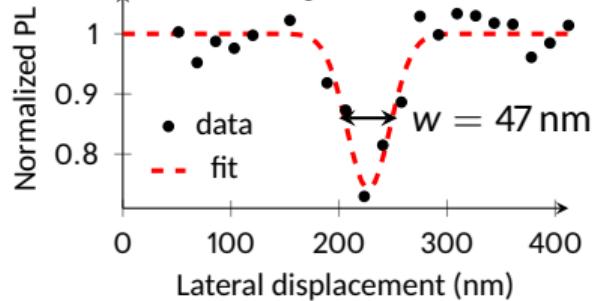
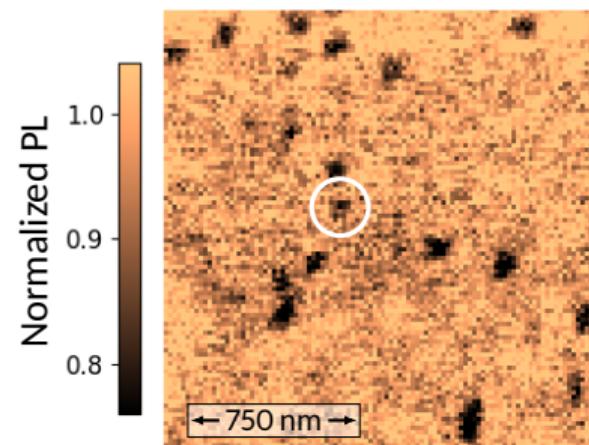
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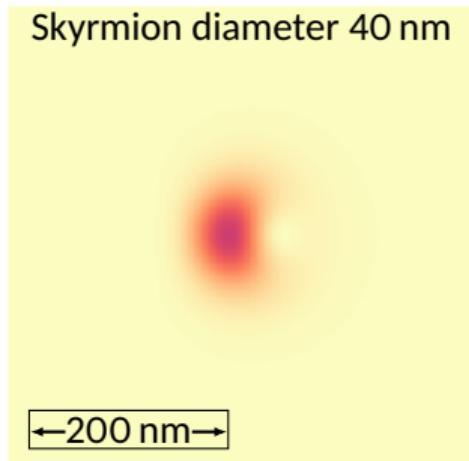
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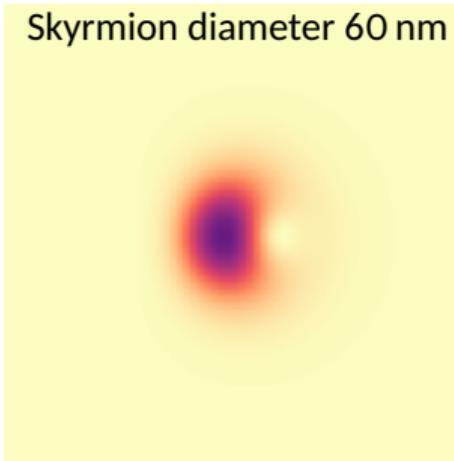
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Comparison with simulations

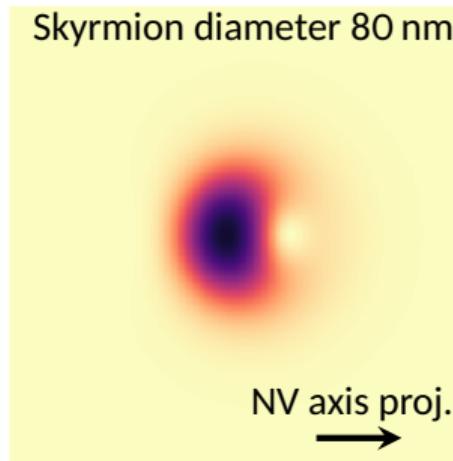
Skyrmion diameter 40 nm



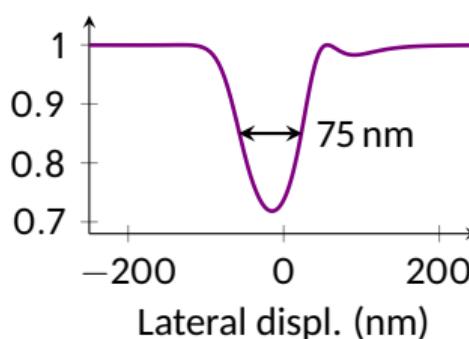
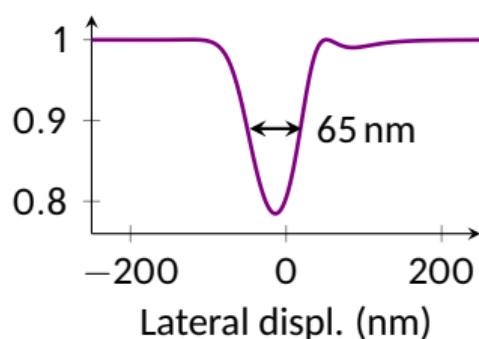
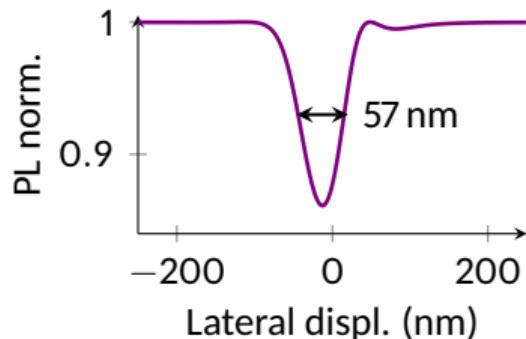
Skyrmion diameter 60 nm



Skyrmion diameter 80 nm

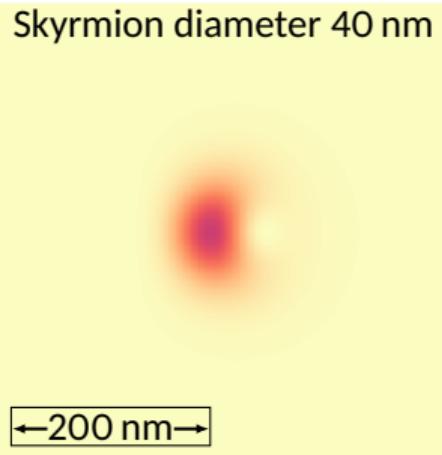


PL norm.
1.0
0.9
0.8
0.7



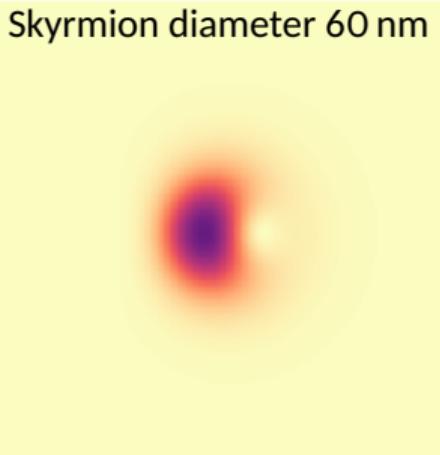
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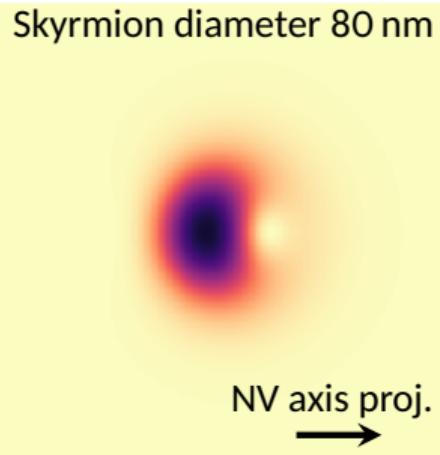


←200 nm→

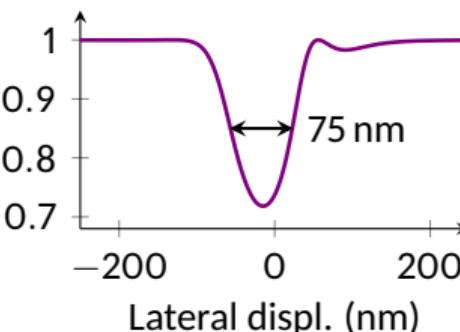
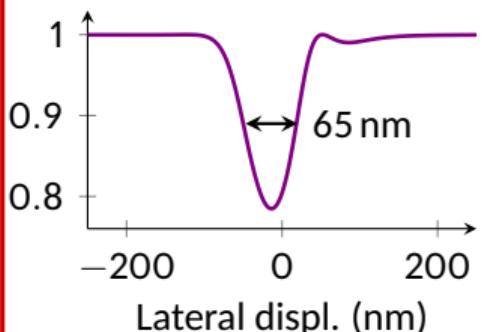
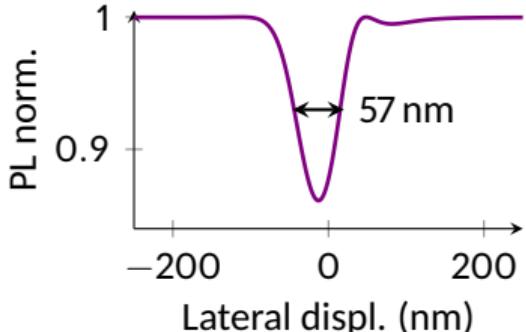
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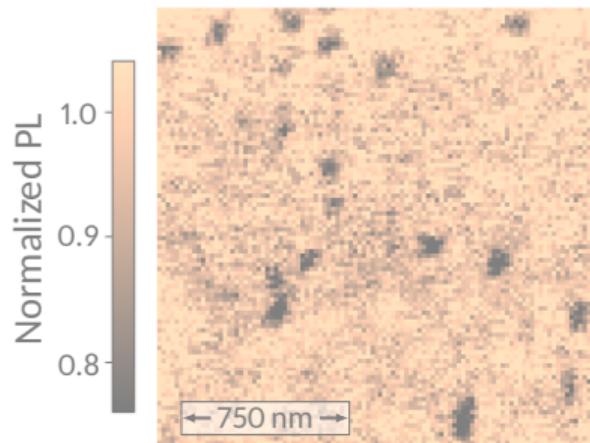


PL norm.
1.0
0.9
0.8
0.7



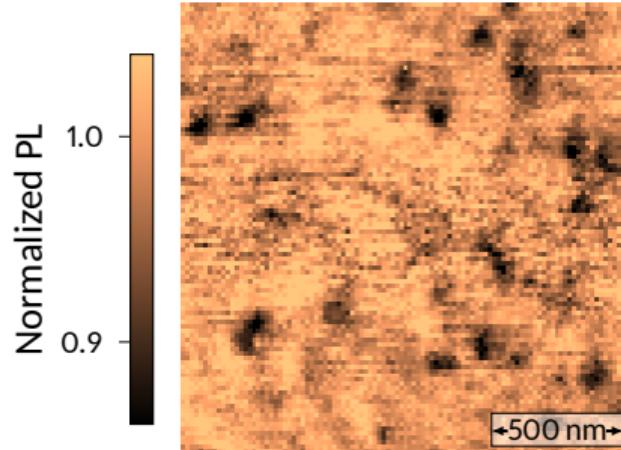
Outline

Zero-field skyrmions
in a **ferromagnet**
stabilized by exchange-bias



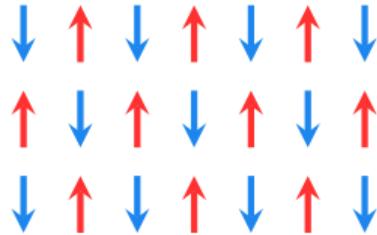
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Antiferromagnets

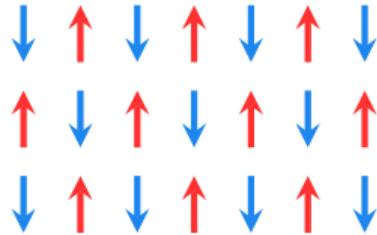


- No parasitic fields
- Robust textures
- Fast dynamics (THz range)
- Energy efficient switching

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

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

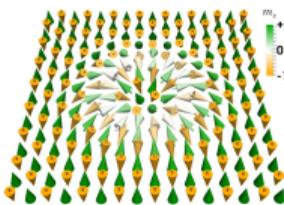
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- No parasitic fields
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- Fast dynamics (THz range)
- Energy efficient switching

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

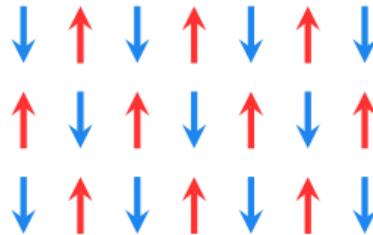
■ V. Baltz et al. *Rev. Mod. Phys.* 90 (2018)



No deflection
by skyrmion
Hall effect

■ X. Zhang et al. *Sci. Rep.* 6 (2016), 24795

Antiferromagnets



→ There is no stray field to probe!

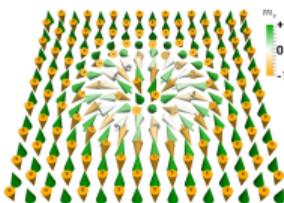
Solution: Detect **magnetic noise** from thermal fluctuations

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

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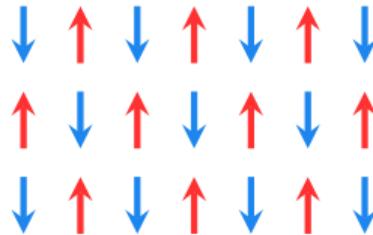
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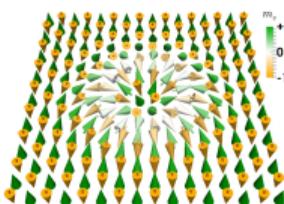
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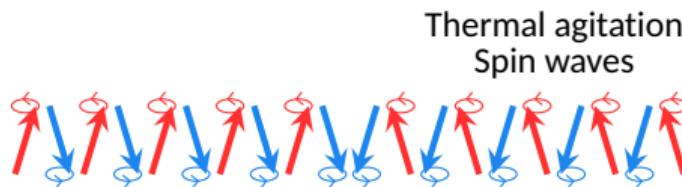
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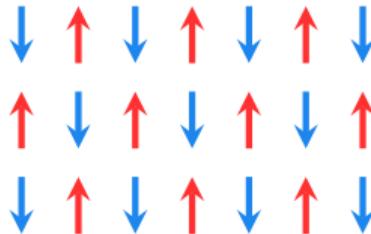
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■ X. Zhang et al. *Sci. Rep.* 6 (2016), 24795

Thermal agitation
Spin waves

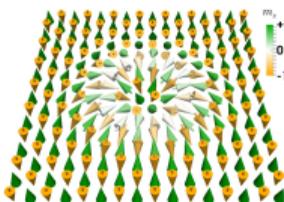
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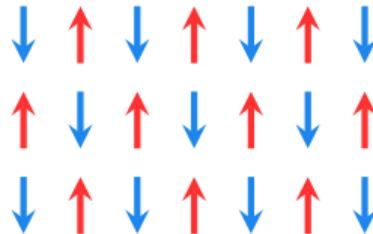
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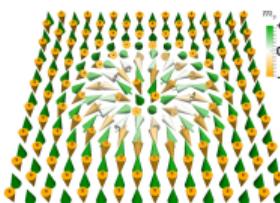
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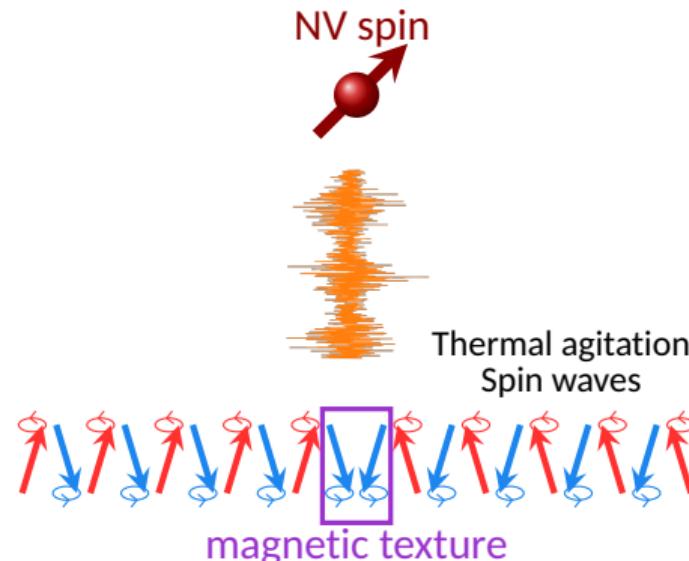
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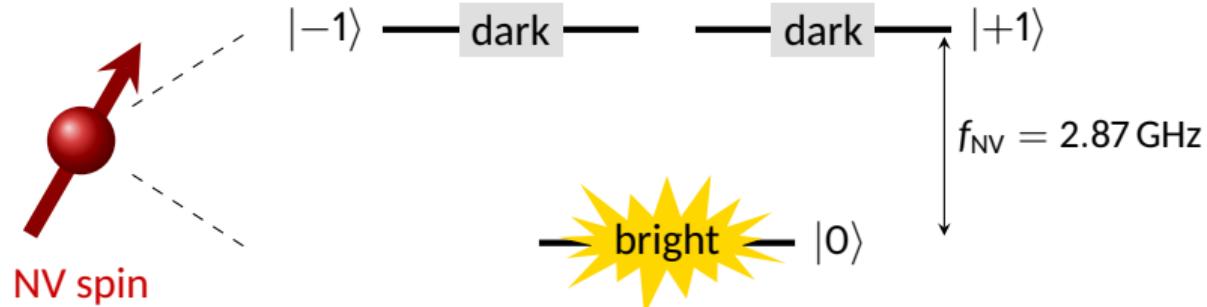
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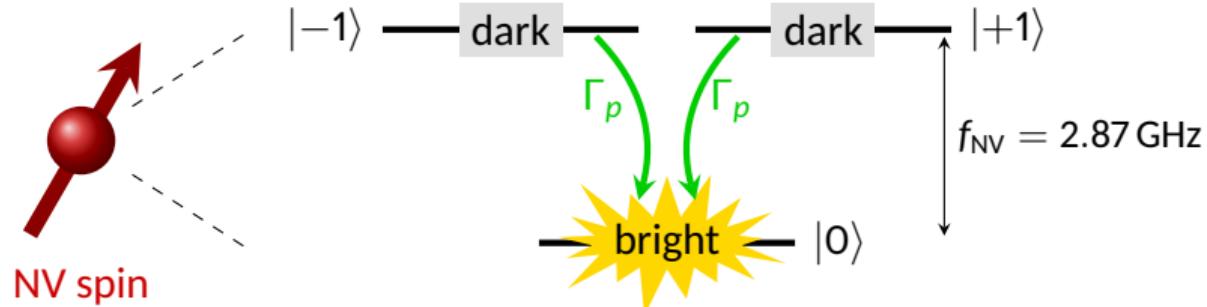
■ B. Flebus et al. *Phys. Rev. B* 98 (2018), 180409



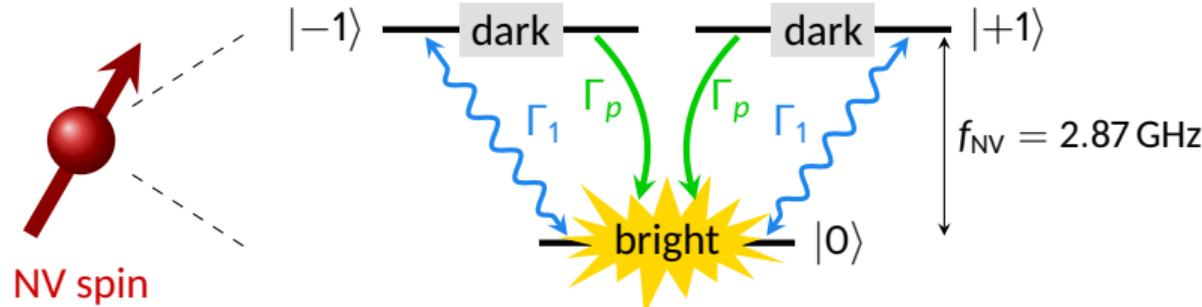
Effect of magnetic noise on the emitted PL



Effect of magnetic noise on the emitted PL

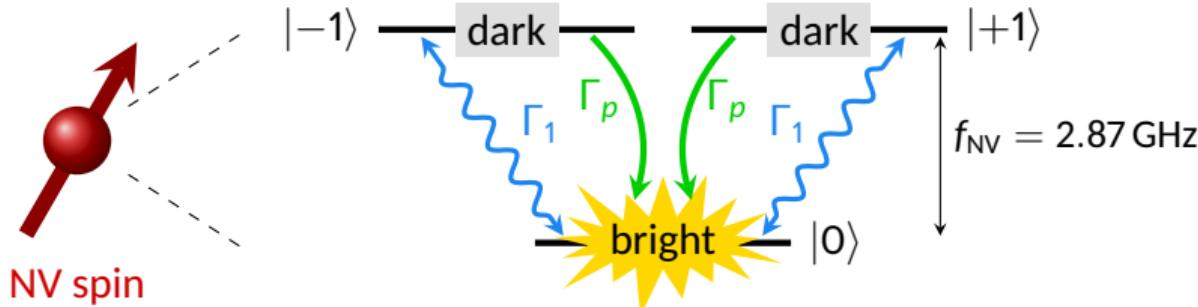


Effect of magnetic noise on the emitted PL

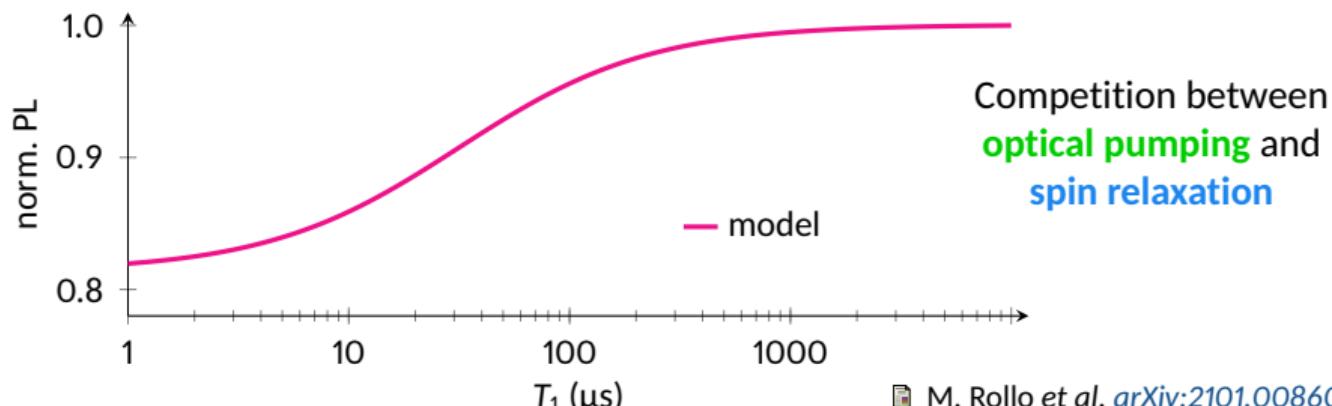


Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{\text{NV}})$ magnetic field spectral density at the resonance frequency f_{NV}

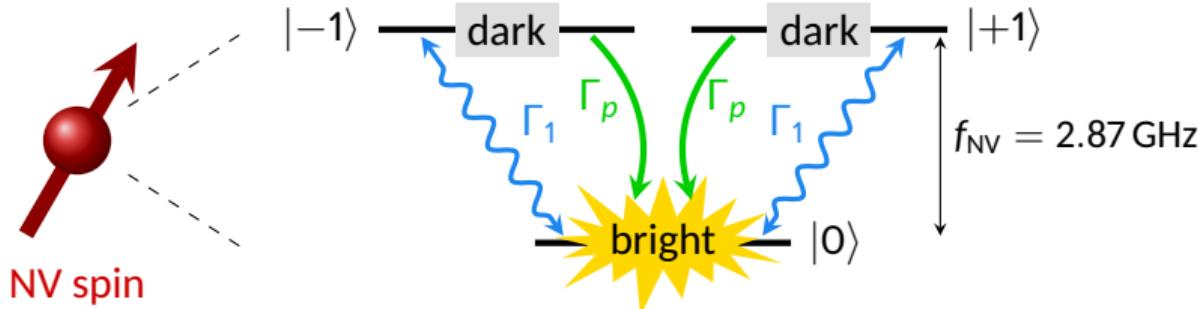
Effect of magnetic noise on the emitted PL



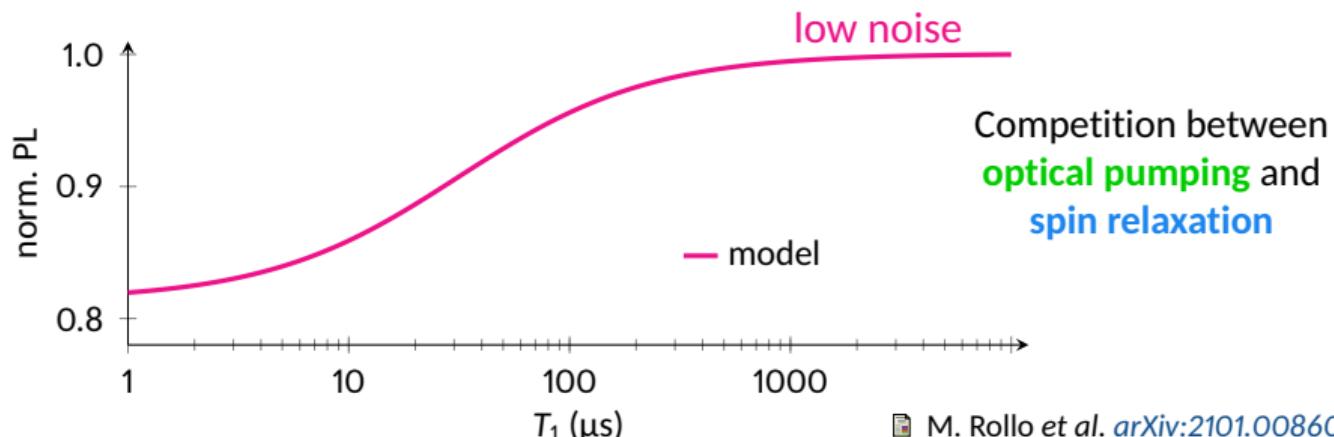
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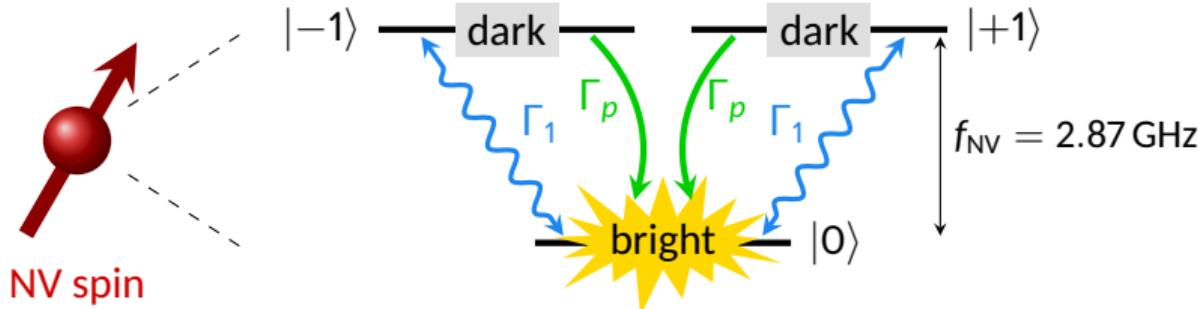
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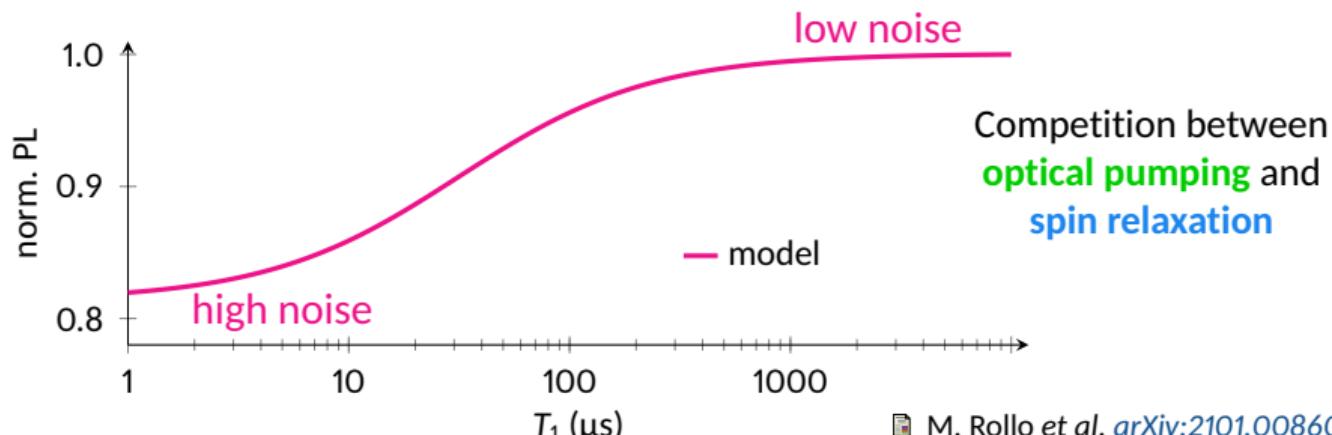
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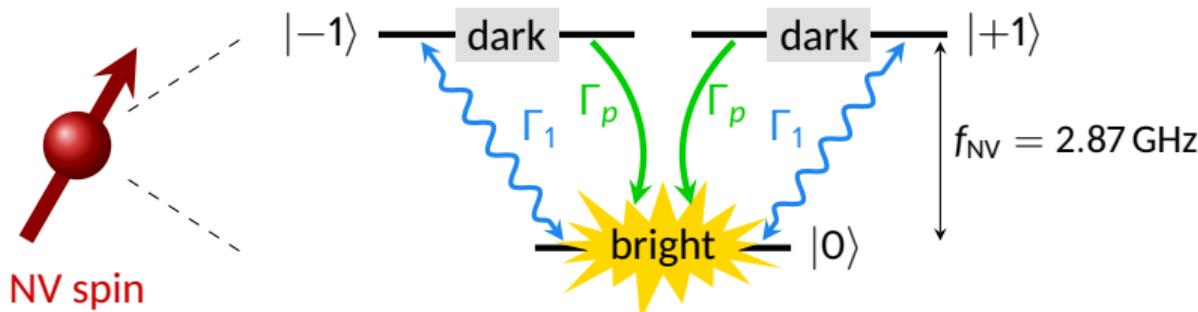
Effect of magnetic noise on the emitted PL



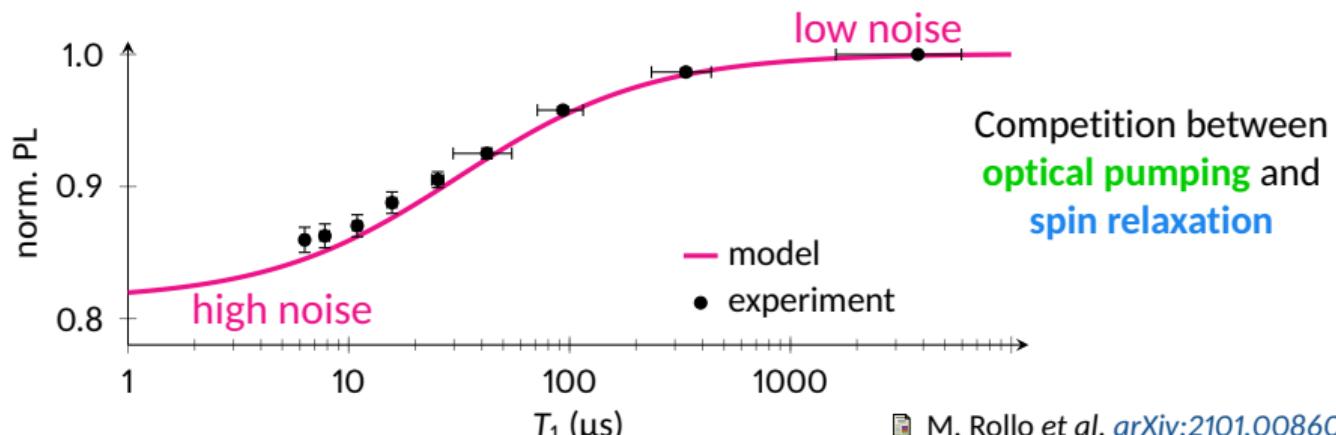
Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{\text{NV}})$ magnetic field spectral density at the resonance frequency f_{NV}



Effect of magnetic noise on the emitted PL



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



Synthetic antiferromagnets

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



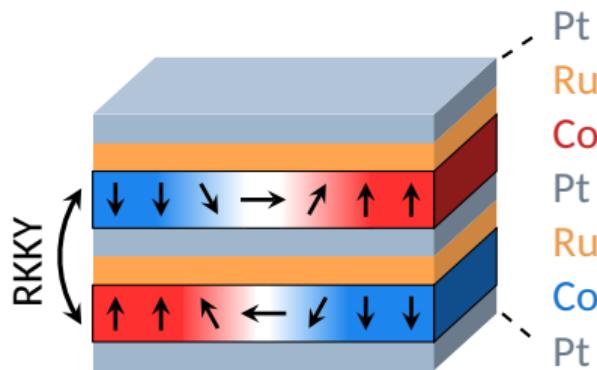
Two **ferromagnetic** layers coupled **antiferromagnetically**

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



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

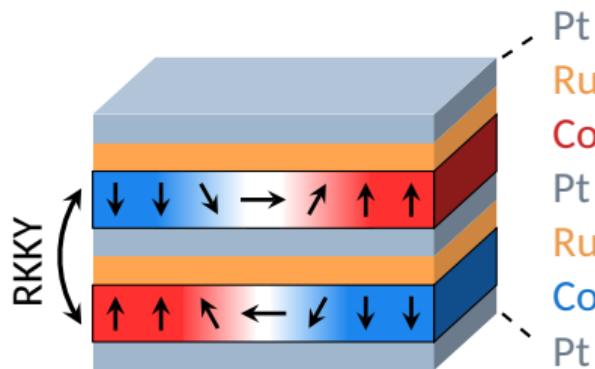
■ A. Finco et al. *Nat. Commun.* 12 (2021), 767

Synthetic antiferromagnets

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

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

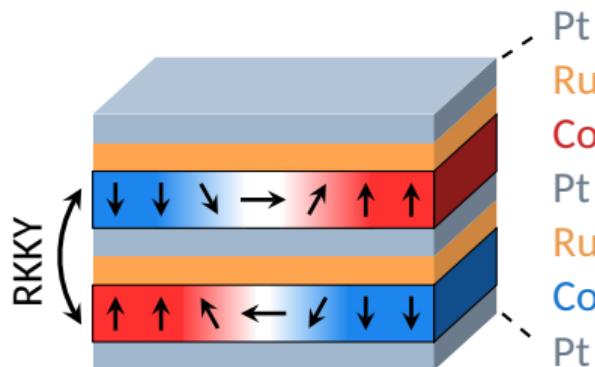
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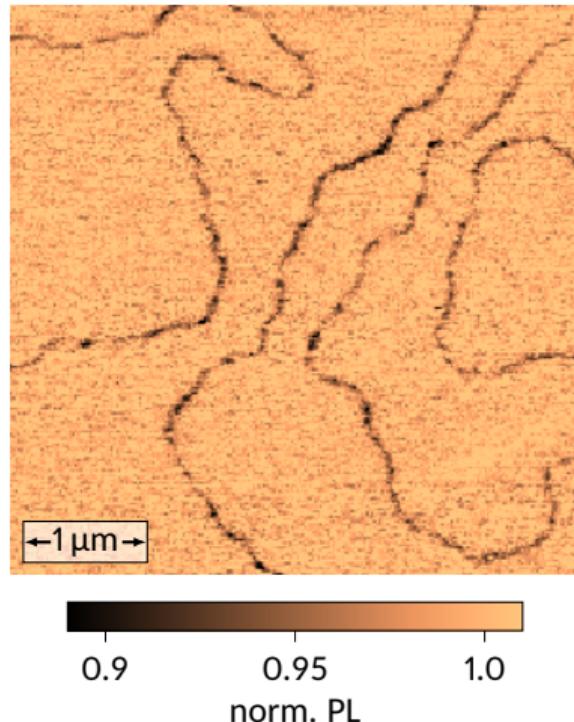
- No net magnetic moment
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Perfect **test system** for noise imaging!

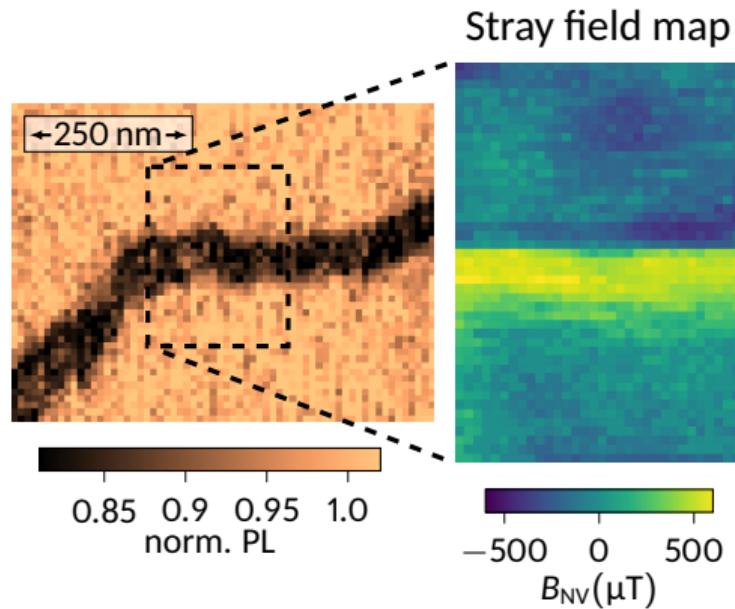
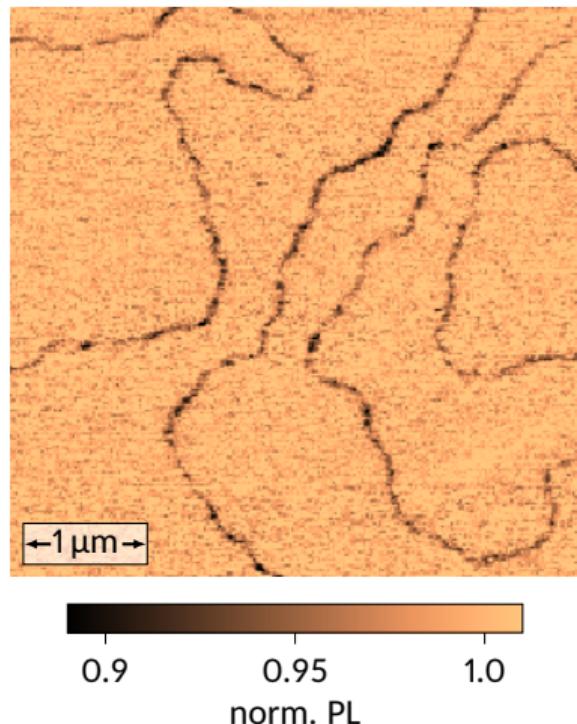
✉ W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34

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

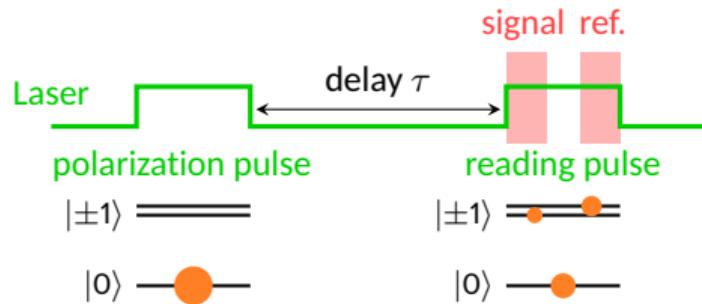
Detection of domain walls by relaxometry



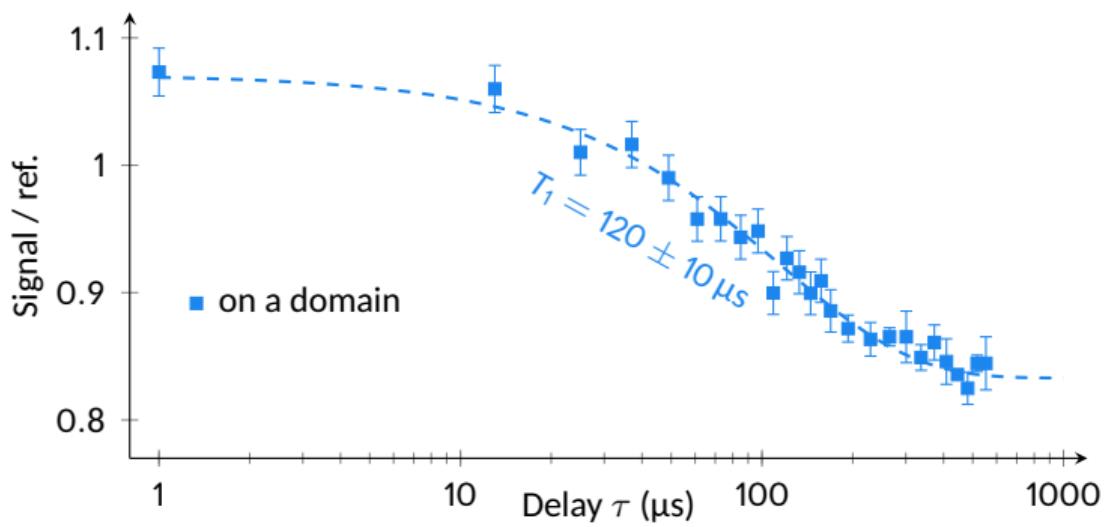
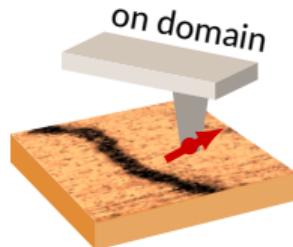
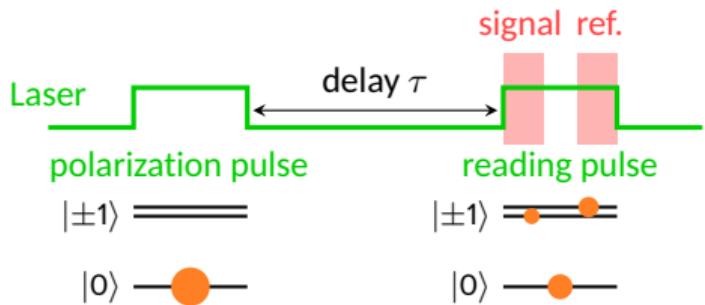
Detection of domain walls by relaxometry



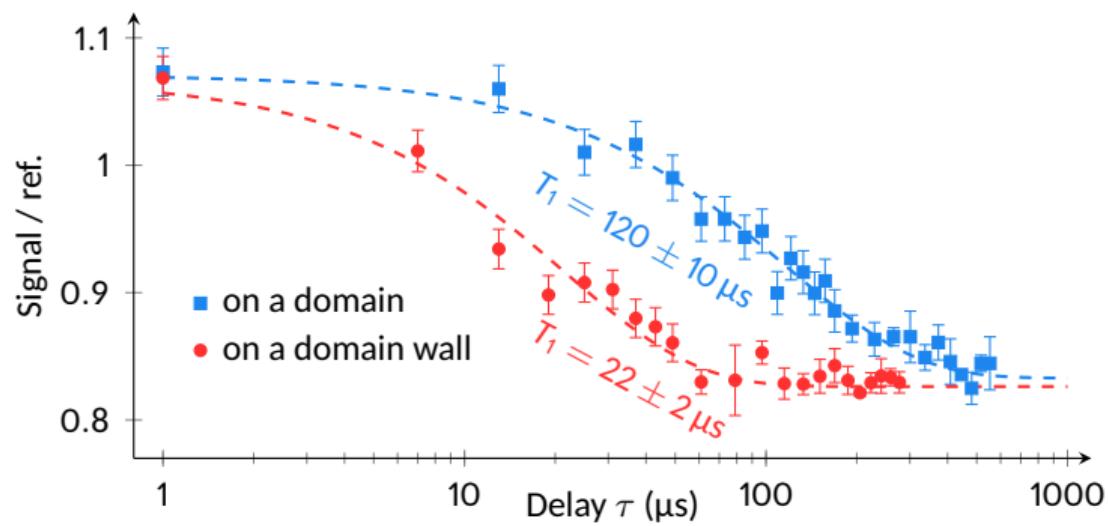
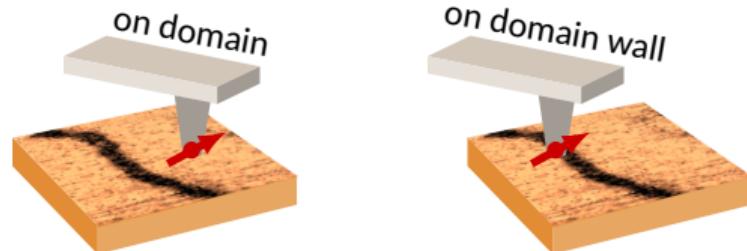
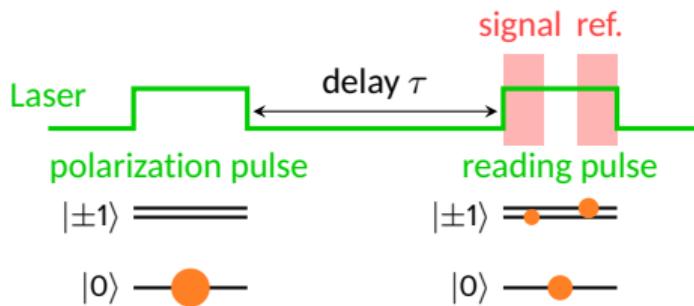
Acceleration of the NV spin relaxation on the walls



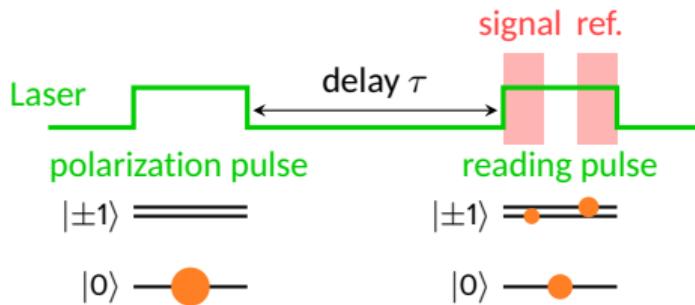
Acceleration of the NV spin relaxation on the walls



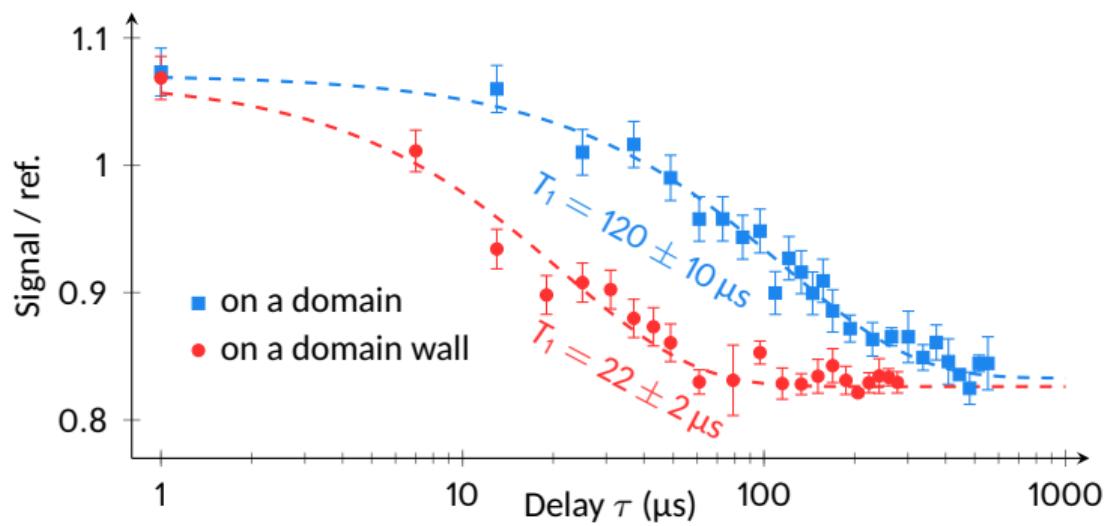
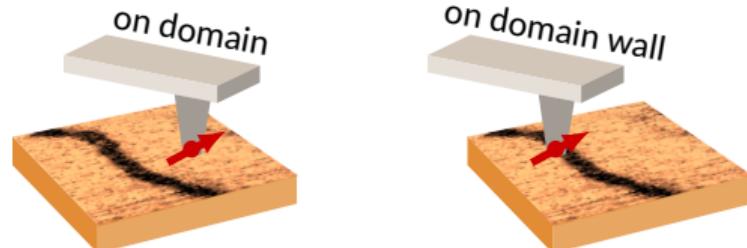
Acceleration of the NV spin relaxation on the walls



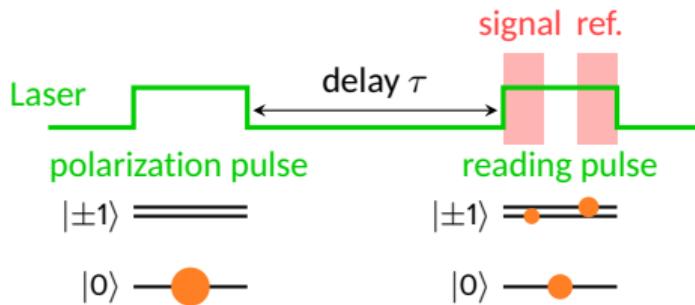
Acceleration of the NV spin relaxation on the walls



Clear diminution of T_1
above the domain wall

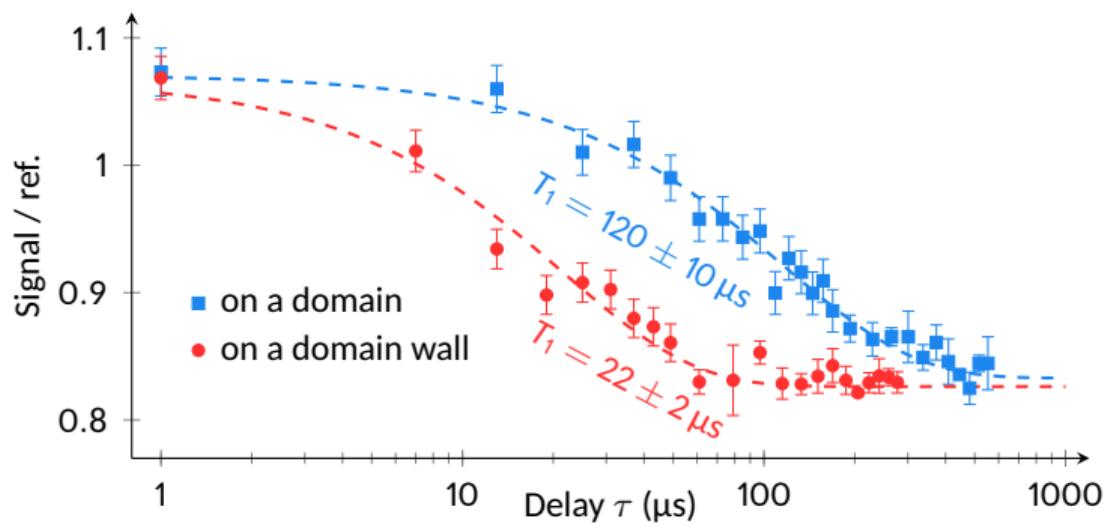
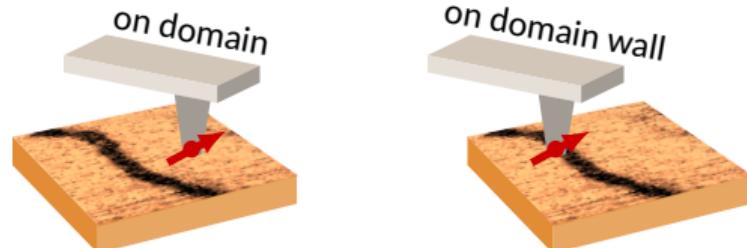


Acceleration of the NV spin relaxation on the walls



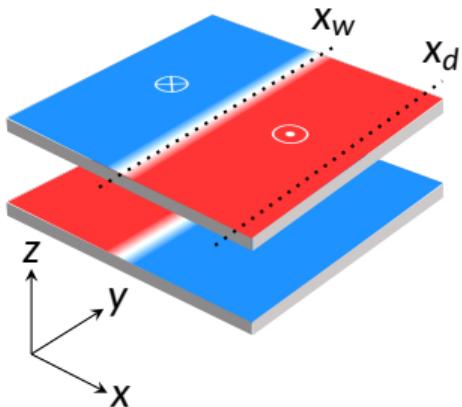
Clear diminution of T_1 above the domain wall

→ Enhancement of the spin relaxation



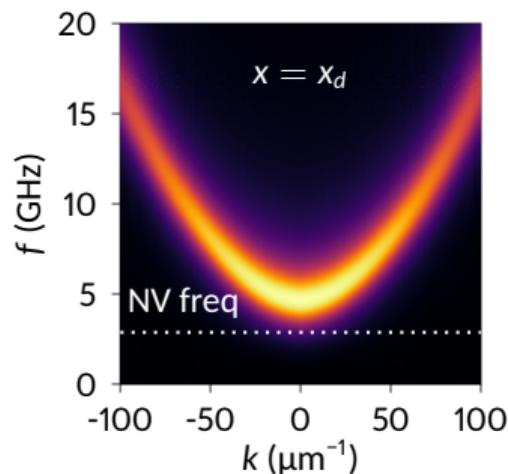
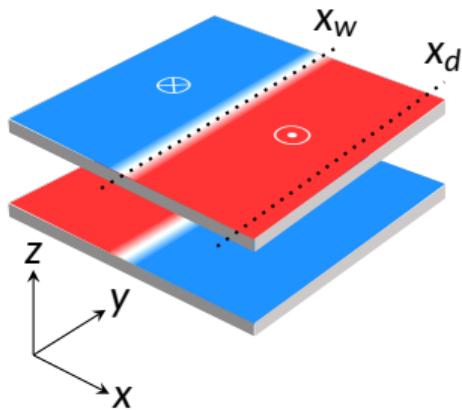
Origin of the noise: spin waves

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



Origin of the noise: spin waves

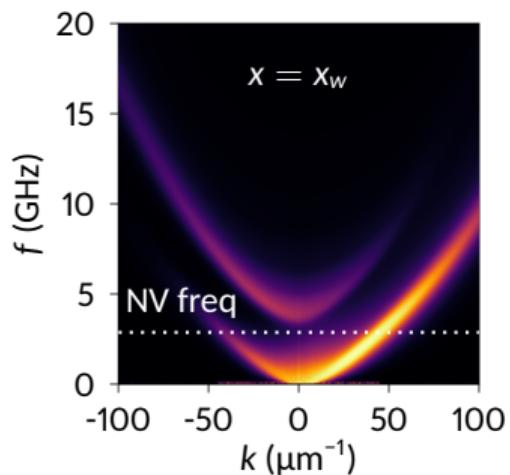
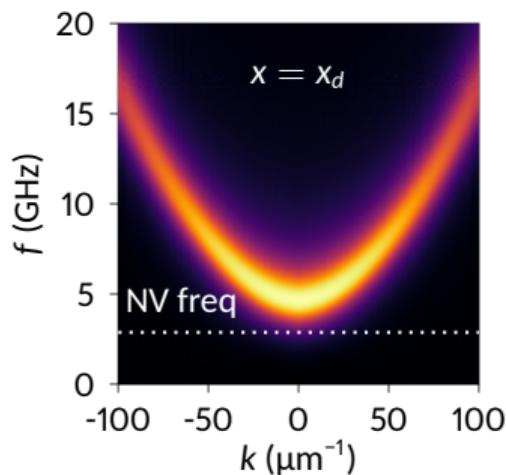
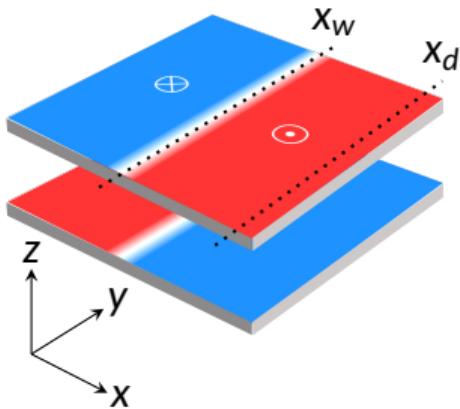
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- NV frequency below the gap: we are not sensitive to the spin waves in the domains.

Origin of the noise: spin waves

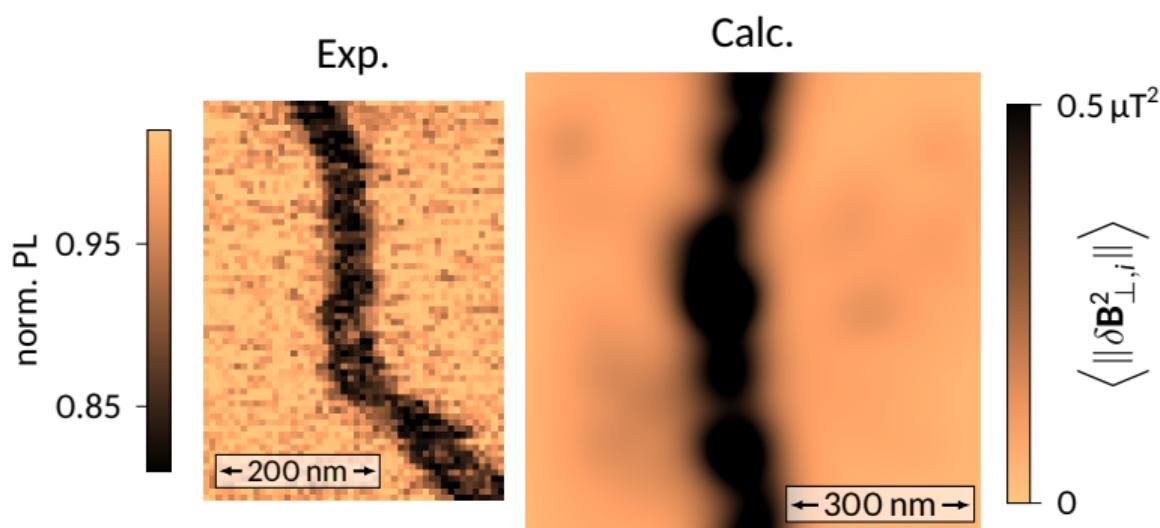
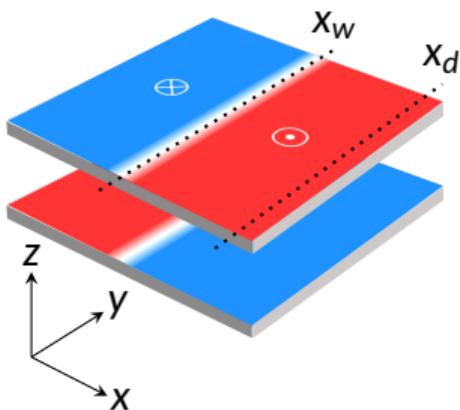
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- NV frequency below the gap: we are not sensitive to the spin waves in the domains.
- No gap in the domain walls, presence of modes at the NV frequency: **we are much more sensitive to the noise from the walls!**

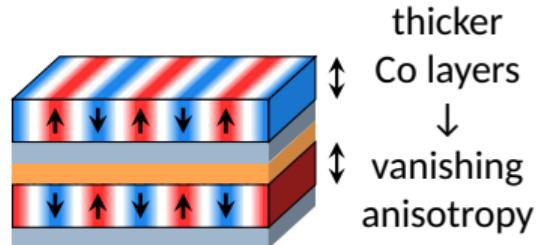
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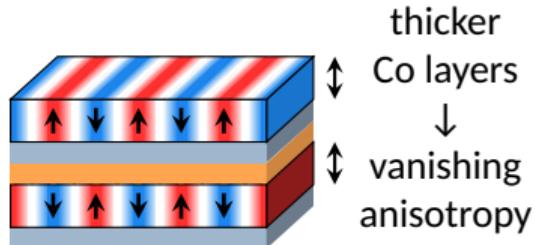
- NV frequency below the gap: we are not sensitive to the spin waves in the domains.
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Imaging a spin spiral

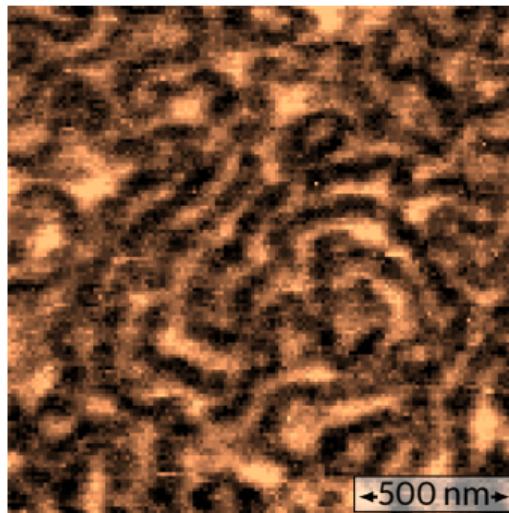


W. Legrand et al. *Nat. Mat.* 19 (2020), 34

Imaging a spin spiral

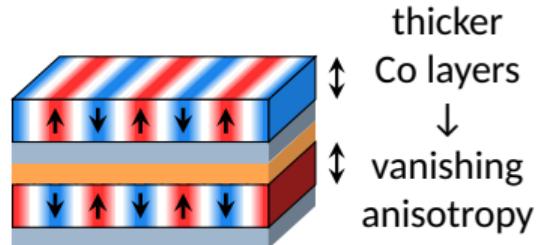


W. Legrand et al. *Nat. Mat.* 19 (2020), 34

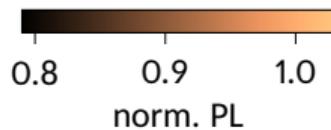
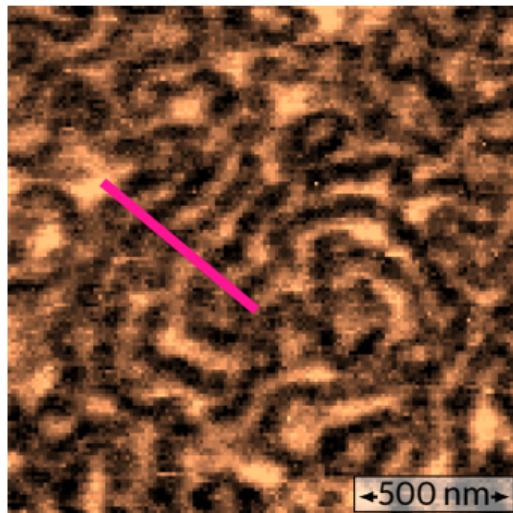
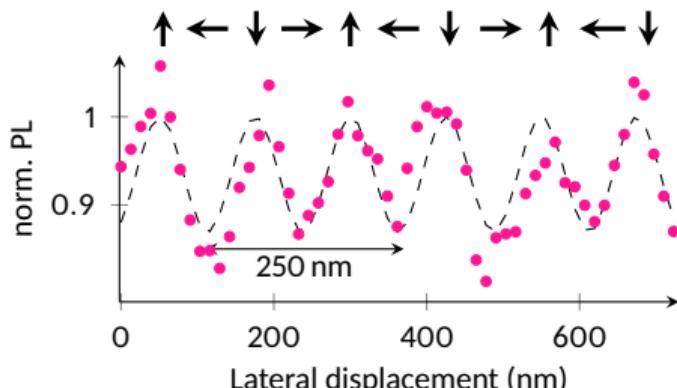


0.8 0.9 1.0
norm. PL

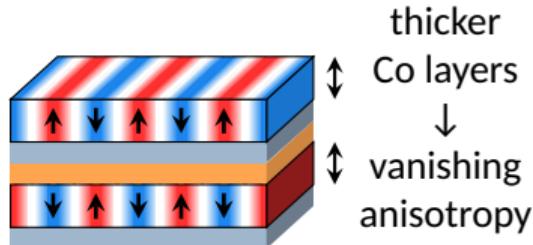
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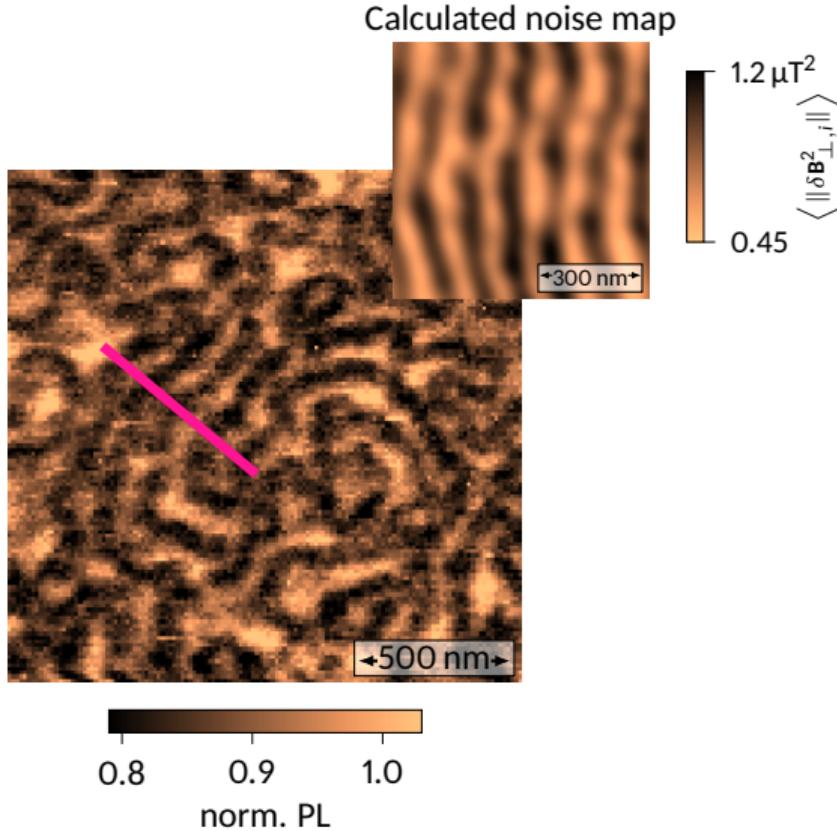
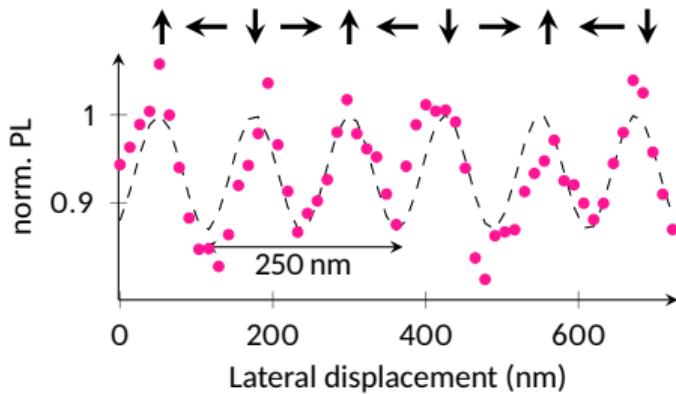
W. Legrand et al. *Nat. Mat.* 19 (2020), 34



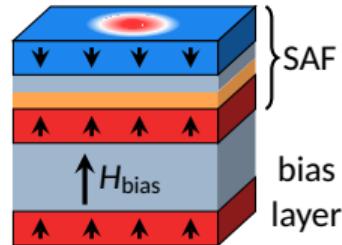
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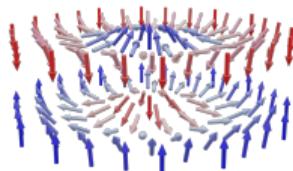
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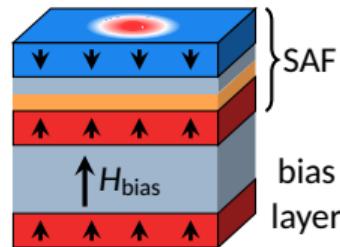
and antiferromagnetic skyrmions!



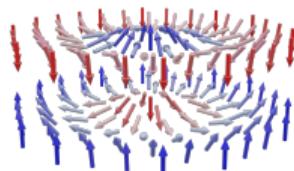
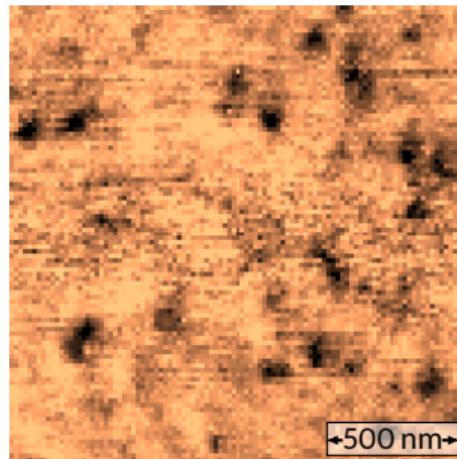
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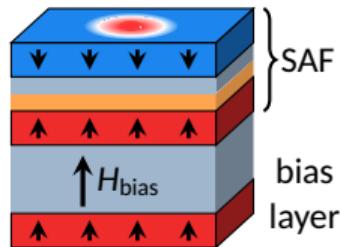
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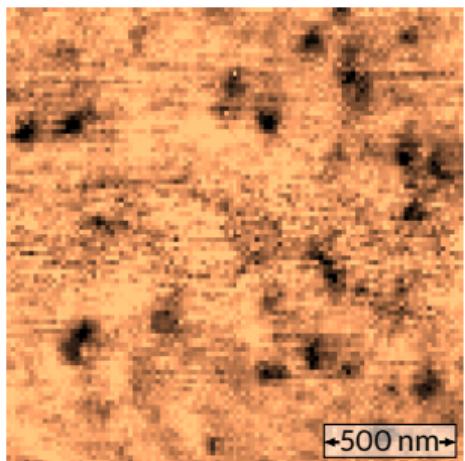
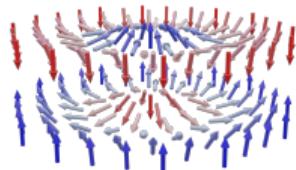
0.9 1.0

norm. PL

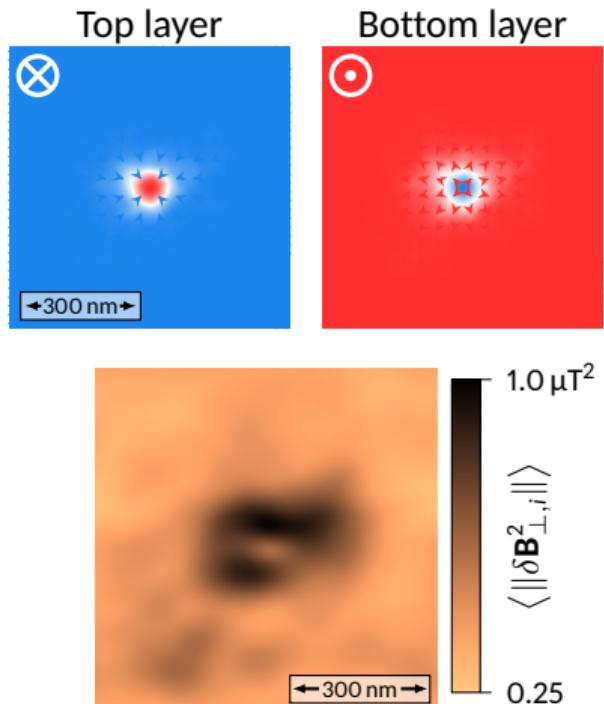
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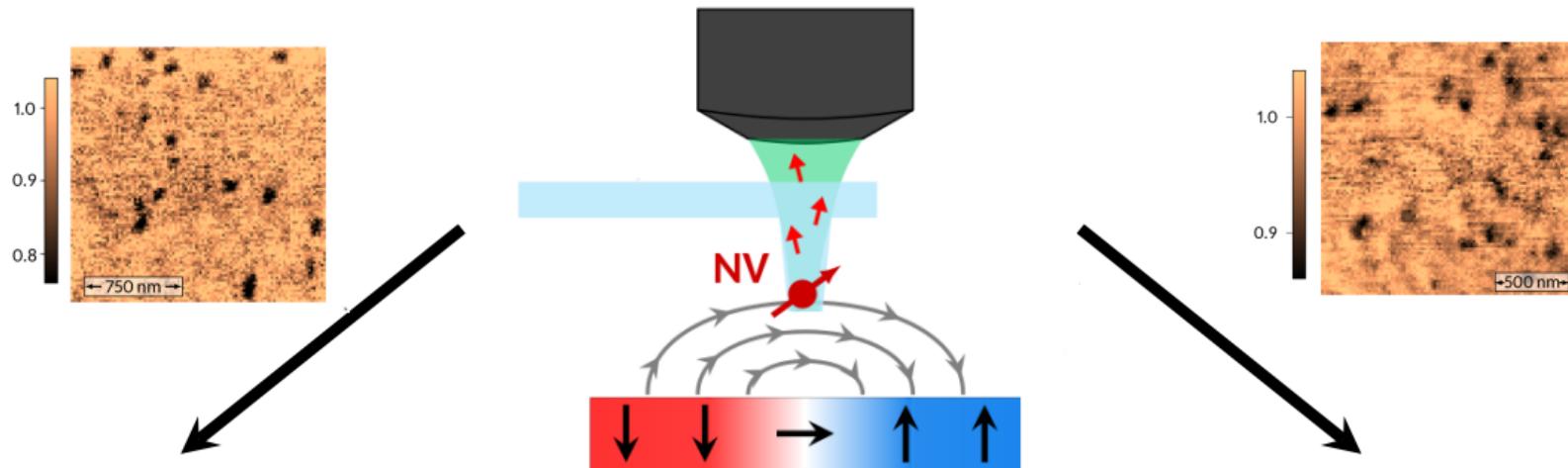
■ W. Legrand et al. *Nat. Mat.* 19 (2020), 34



0.9
1.0
norm. PL



Summary



**Non-perturbative measurements
of skyrmions in a ferromagnet**

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

**Noise detection of skyrmions
in a synthetic antiferromagnet**

M. Rollo *et al.* [arXiv:2101.00860](https://arxiv.org/abs/2101.00860) (2021)

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

Acknowledgments

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Vincent Cros
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Jean-Paul Adam
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Joo-Von Kim

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