

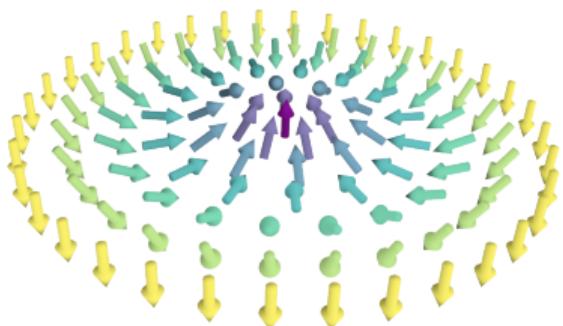
All-optical imaging of zero-field skyrmions with a scanning-NV magnetometer



K. Gaurav Rana, **A. Finco**, F. Fabre, S. Chouaieb, A. Haykal, L. D. Buda-Prejbeanu,
O. Fruchart, S. Le Denmat, P. David, M. Belmeguenai, T. Denneulin,
R. E. Dunin-Borkowski, G. Gaudin, V. Jacques, and O. Boulle

AIM 2021 virtual meeting, June 14th 2021
Slides available at magimag.eu

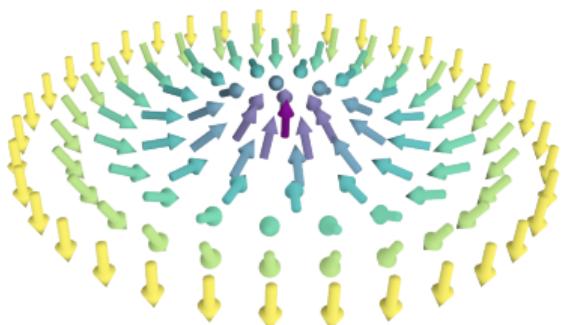
Magnetic skyrmions for spintronics



- Localized magnetic texture
- No continuous deformation towards the ferromagnetic state → **topological structure**
- Small size (down to 5 nm)
- Stability

 A. Fert et al. *Nat. Rev. Mater.* 2 (2017)

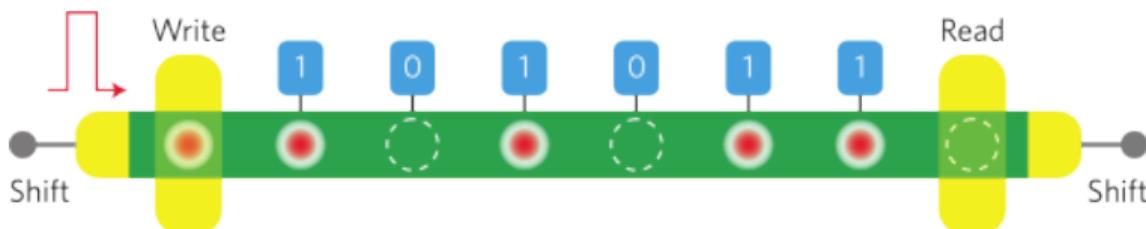
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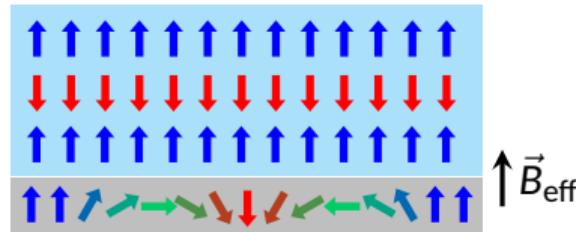
Example of application: racetrack memory



S. Krause et al. *Nat. Mater.* 15 (2016), 493

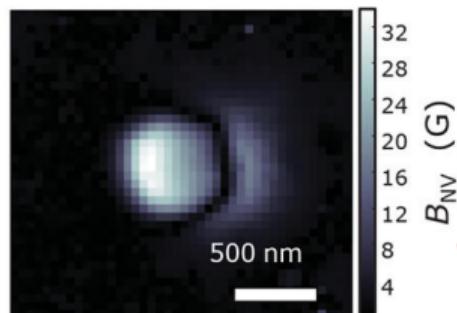
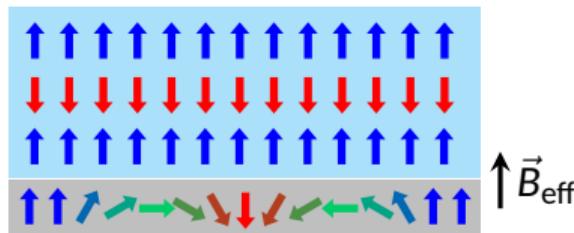
Stabilization of skyrmions with exchange bias

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



Stabilization of skyrmions with exchange bias

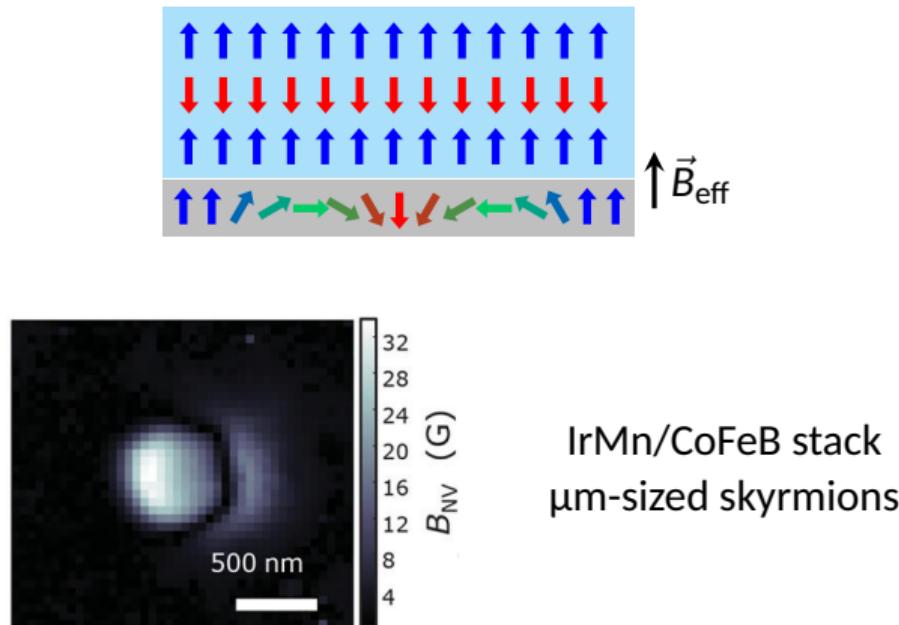
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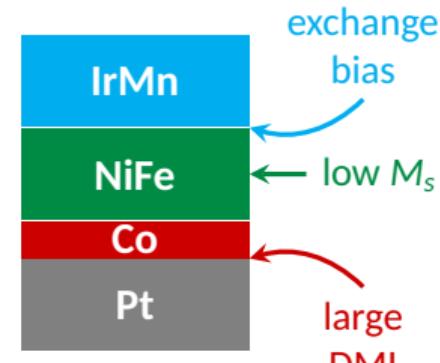
G. Yu *et al.* *Nano Lett.* 18 (2018), 980

Stabilization of skyrmions with exchange bias

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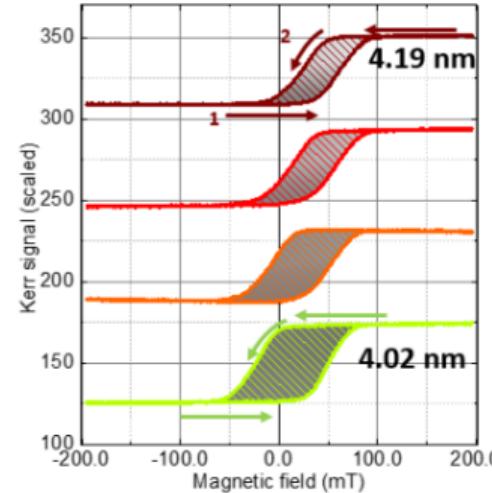
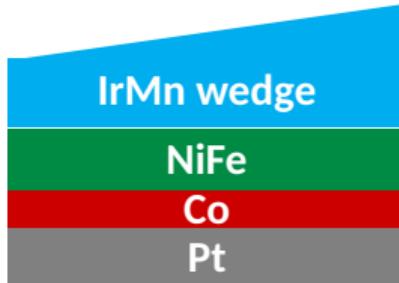
Strategy to reduce
the skyrmion size



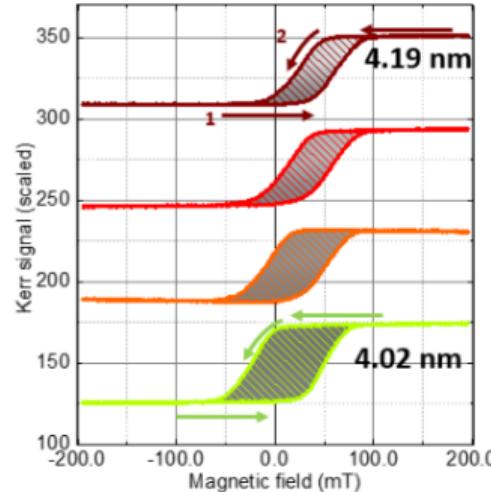
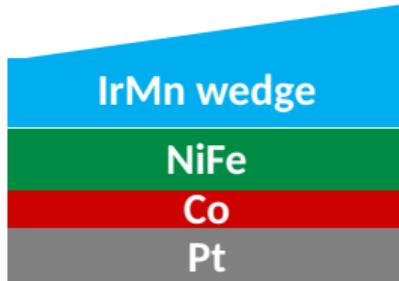
O. Boulle, G. Rana
L. Buda-Prejbeanu



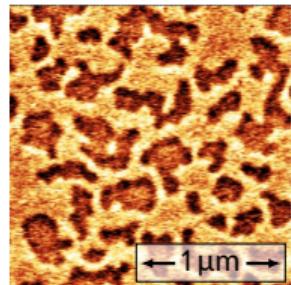
Optimization of the IrMn thickness



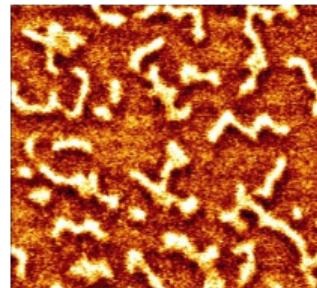
Optimization of the IrMn thickness



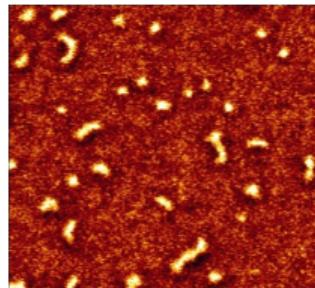
$$t_{\text{IrMn}} = 4.02 \text{ nm}$$



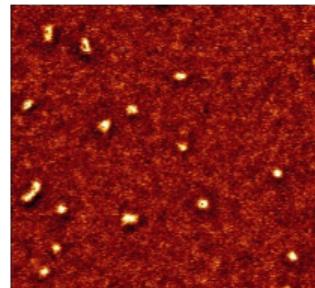
$$t_{\text{IrMn}} = 4.11 \text{ nm}$$



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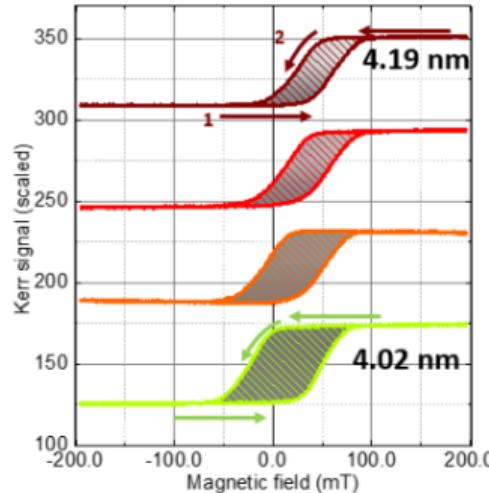
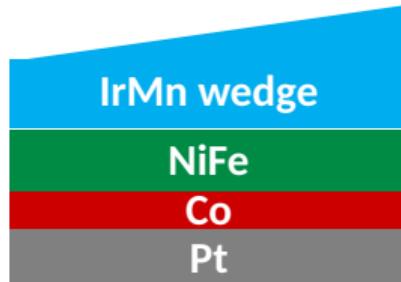


$$t_{\text{IrMn}} = 4.19 \text{ nm}$$

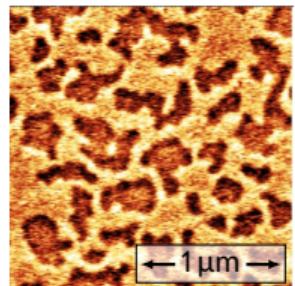


MFM
images

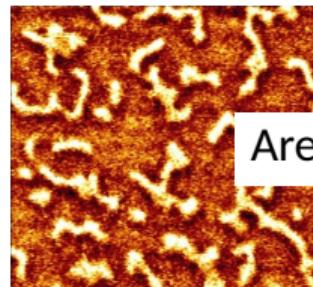
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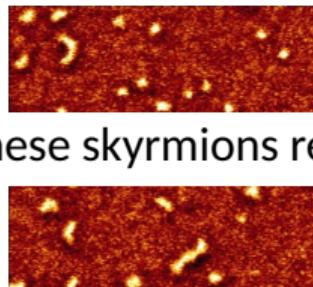
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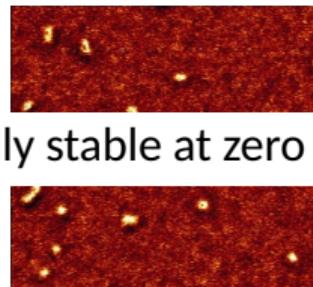
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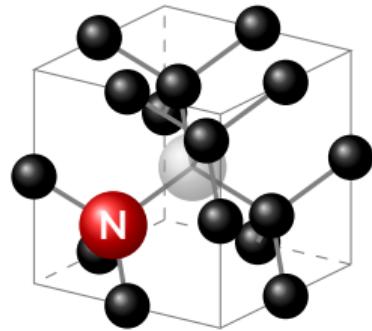
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MFM
images

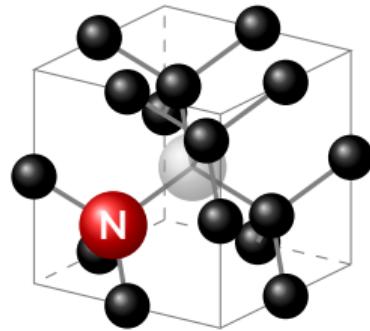
Are these skyrmions really stable at zero field?

NV centers as magnetic field quantum sensors



Defect in diamond

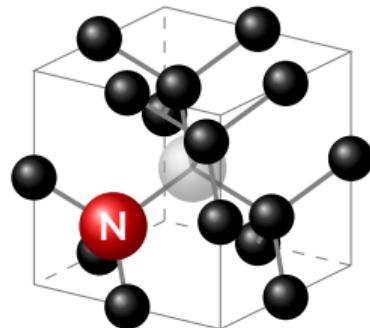
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Defect in diamond

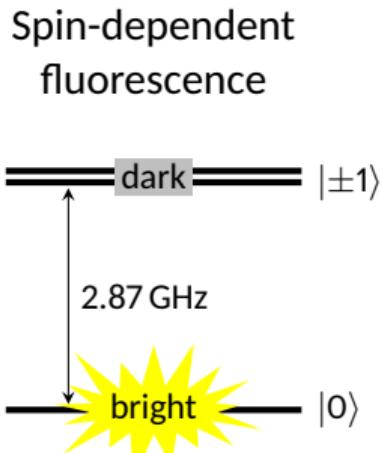
- Optical manipulation and reading
- Ambient conditions

NV centers as magnetic field quantum sensors



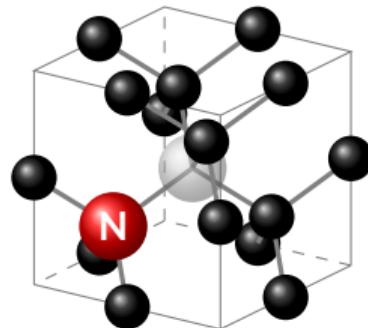
Defect in diamond

- Optical manipulation and reading
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NV ground state
spin $S = 1$

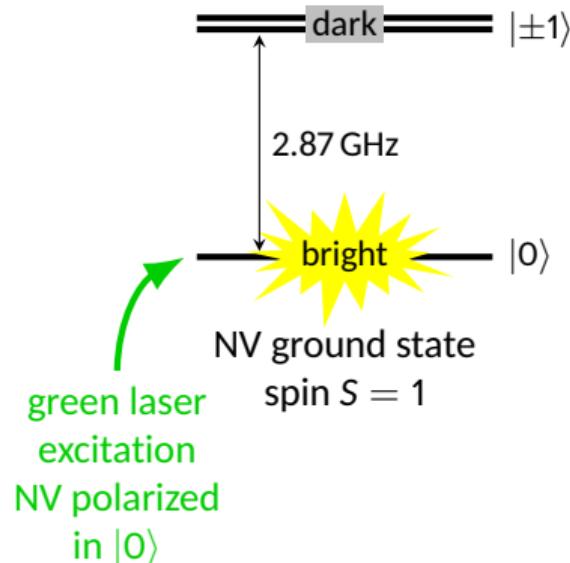
NV centers as magnetic field quantum sensors



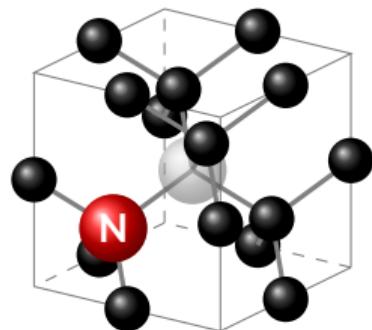
Defect in diamond

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Spin-dependent fluorescence

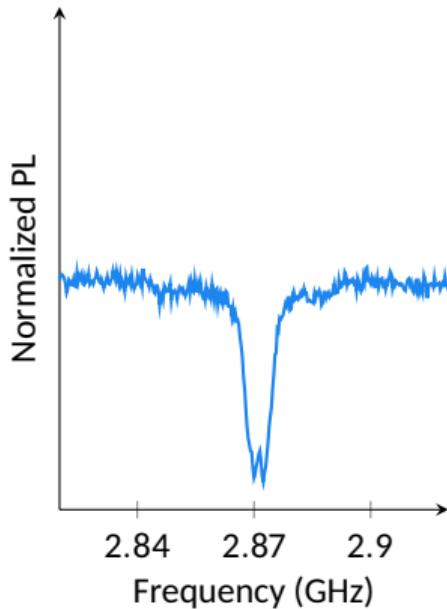
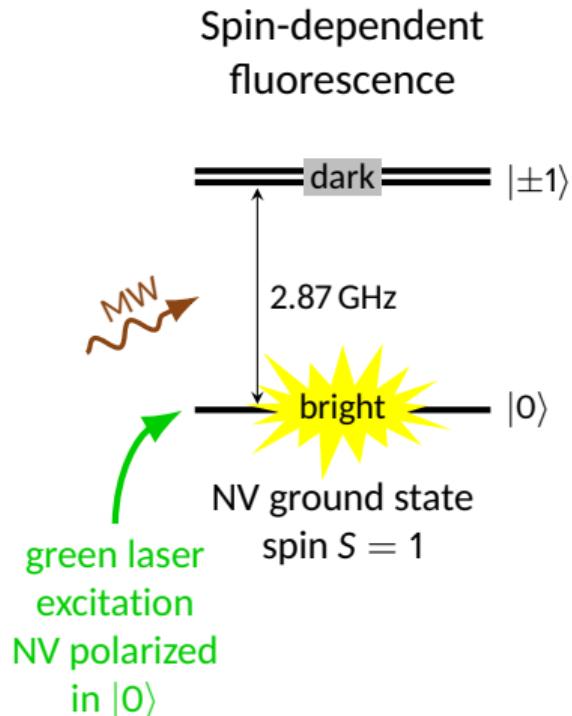


NV centers as magnetic field quantum sensors

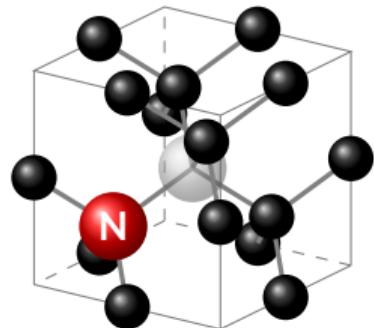


Defect in diamond

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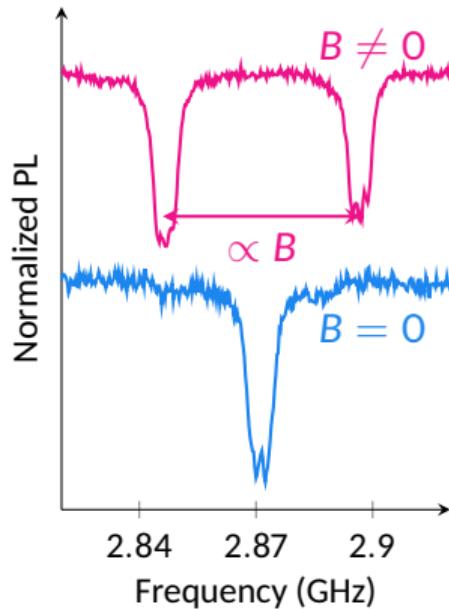
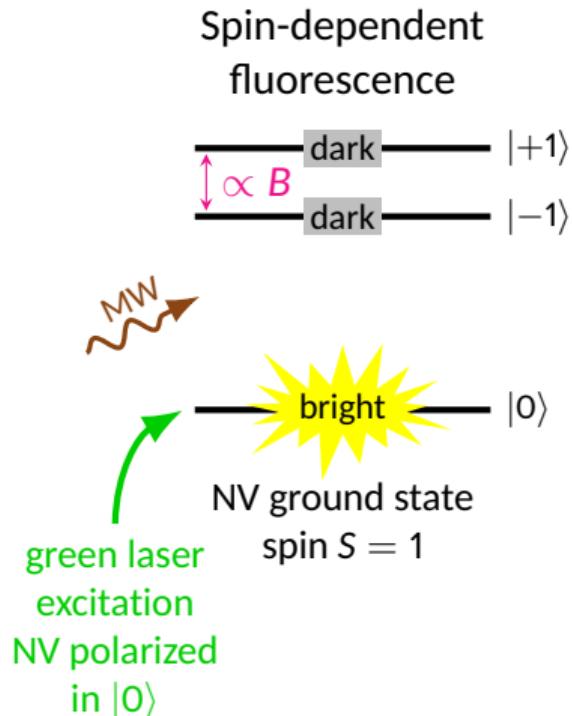


NV centers as magnetic field quantum sensors

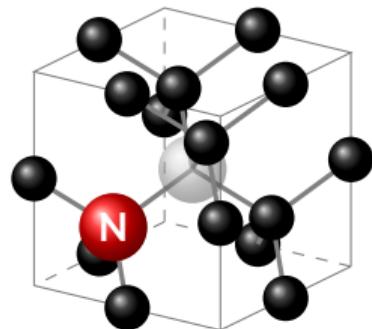


Defect in diamond

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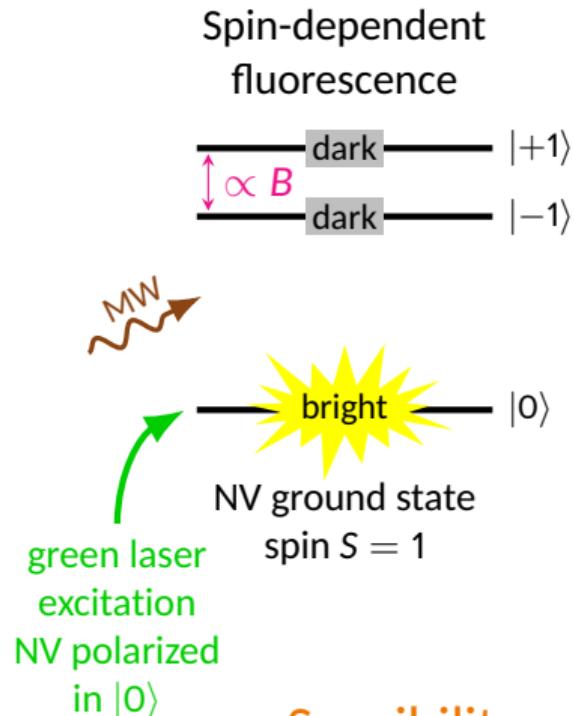


NV centers as magnetic field quantum sensors

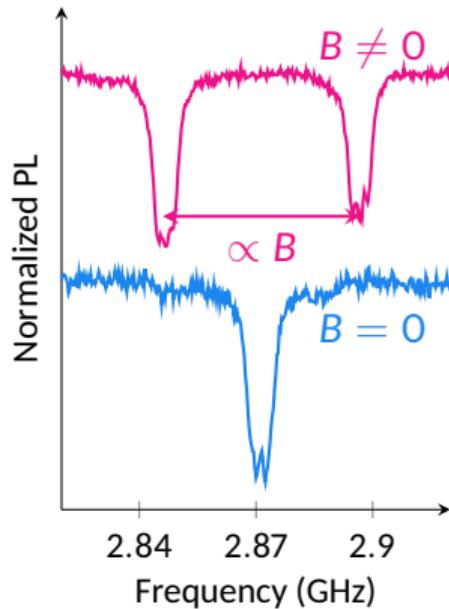


Defect in diamond

- Optical manipulation and reading
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Sensibility: a few $\mu\text{T}/\sqrt{\text{Hz}}$



Qualitative measurement in the high field regime



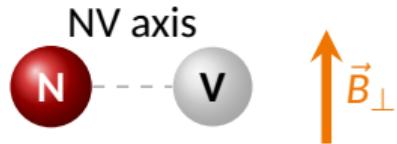
Qualitative measurement in the high field regime

Mixing of the spin states

— dark — $|\psi_2\rangle$

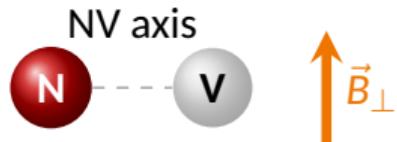
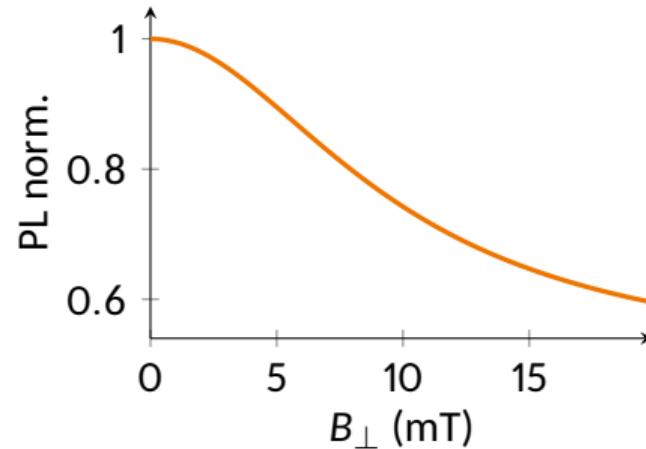
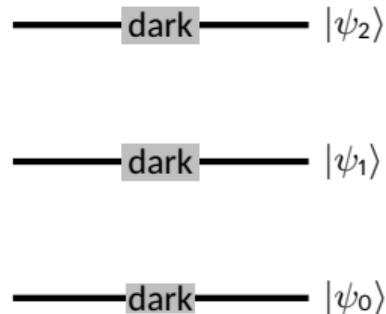
— dark — $|\psi_1\rangle$

— dark — $|\psi_0\rangle$



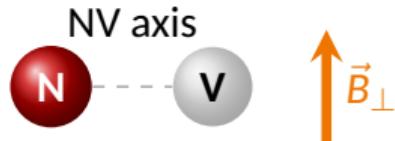
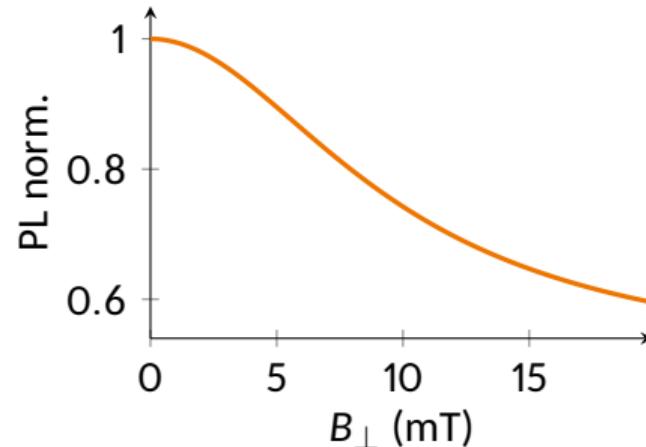
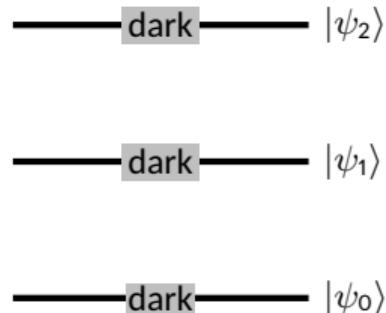
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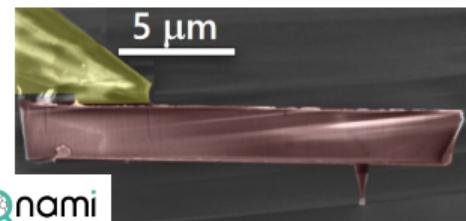
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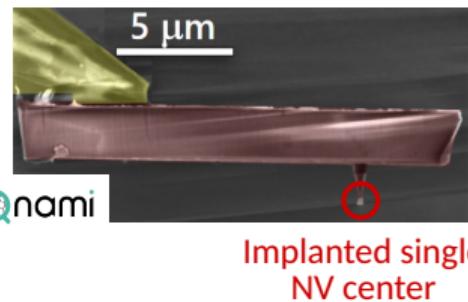
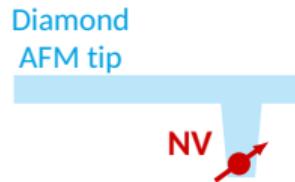
Qualitative localization of
strong magnetic field sources

Our scanning NV microscope



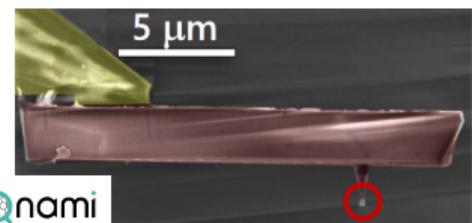
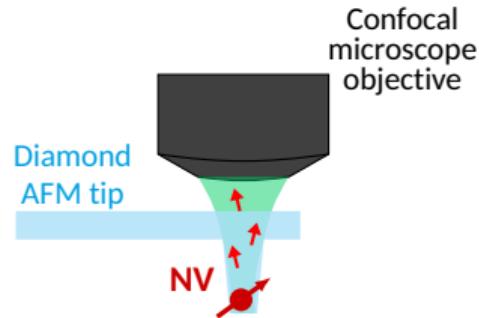
 P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

Our scanning NV microscope



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

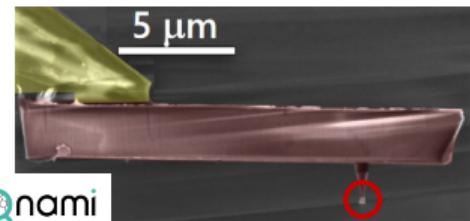
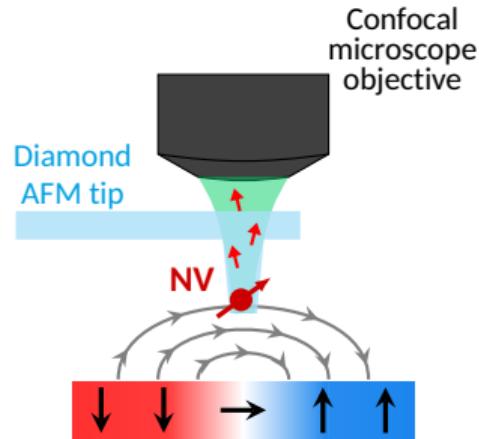
Our scanning NV microscope



Implanted single
NV center

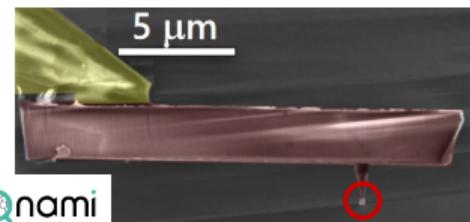
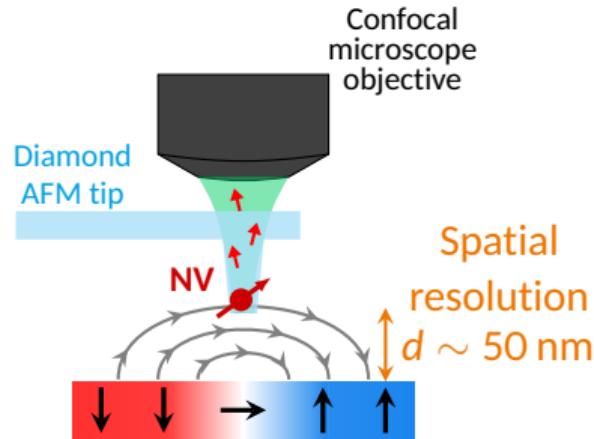
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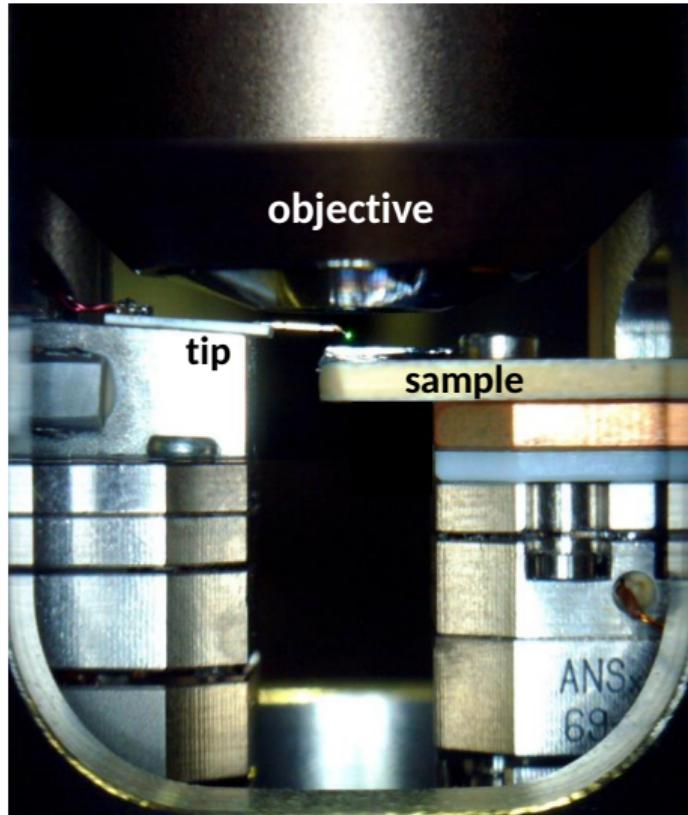
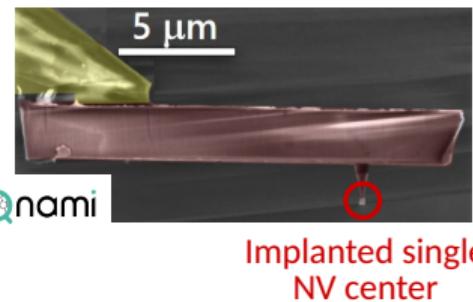
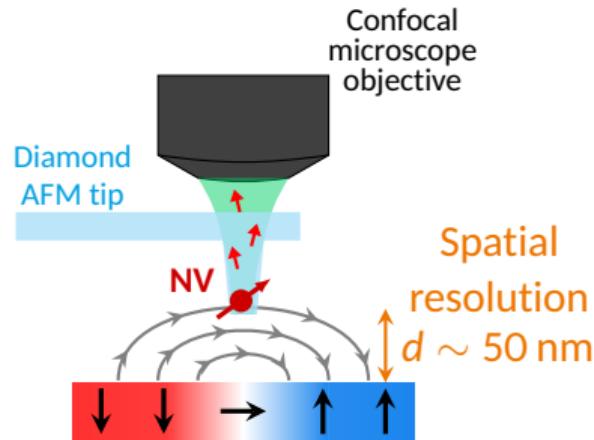
Implanted single
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Our scanning NV microscope



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

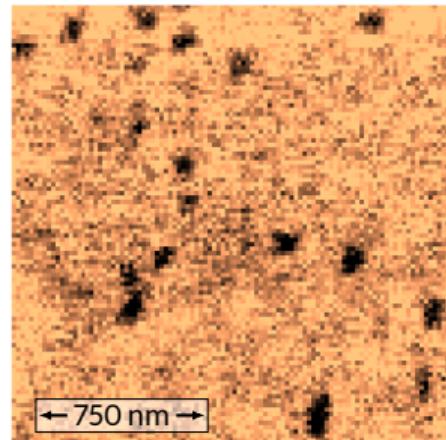
Our scanning NV microscope



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

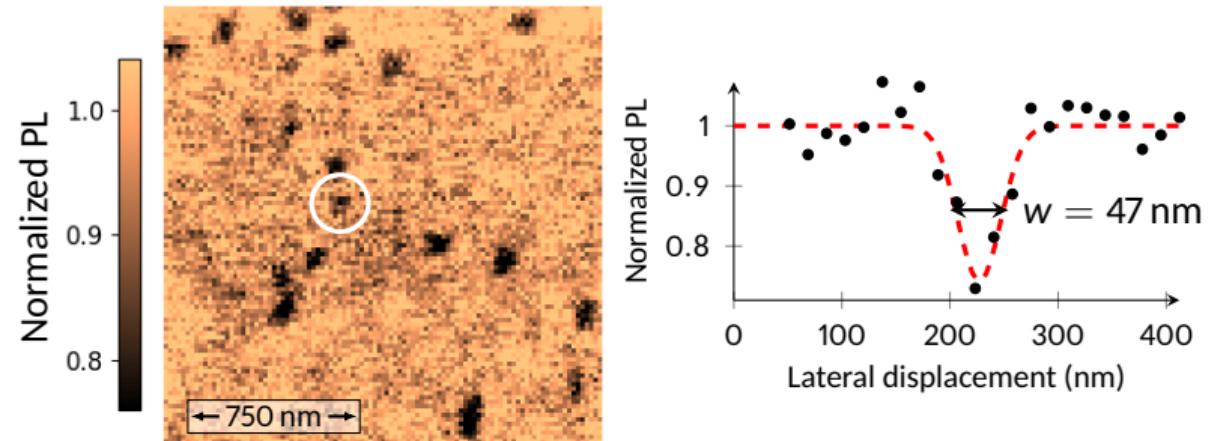
Imaging of zero-field skyrmions

Normalized PL



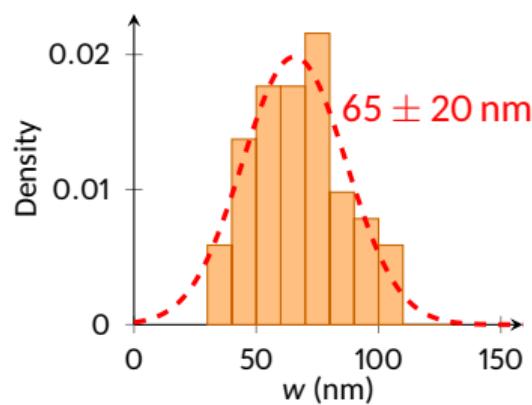
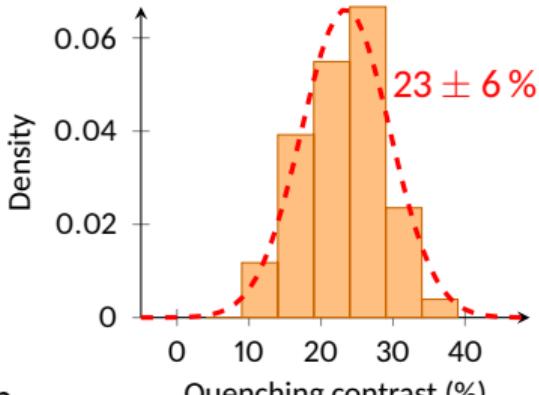
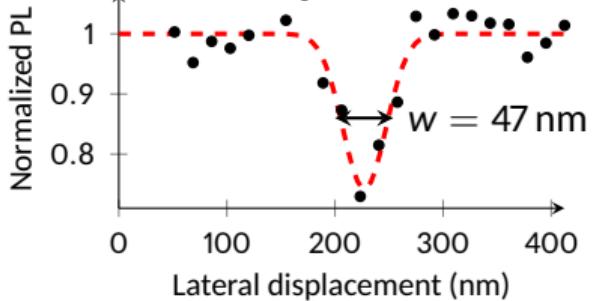
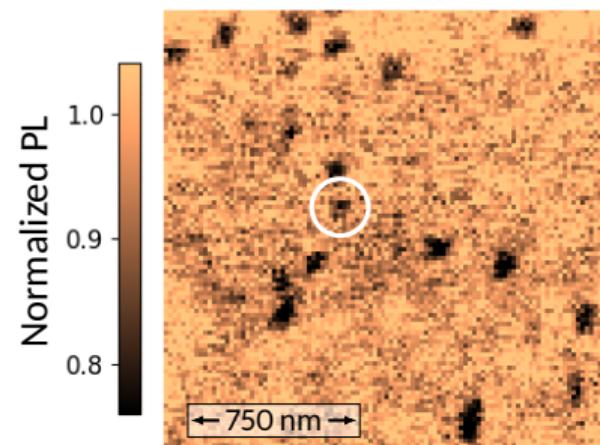
K. G. Rana et al. *Phys. Rev. Applied* 13 (2020), 044079

Imaging of zero-field skyrmions



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

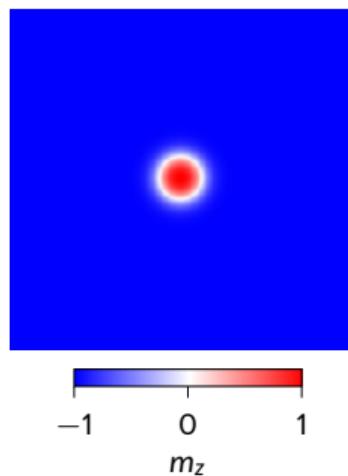
Imaging of zero-field skyrmions



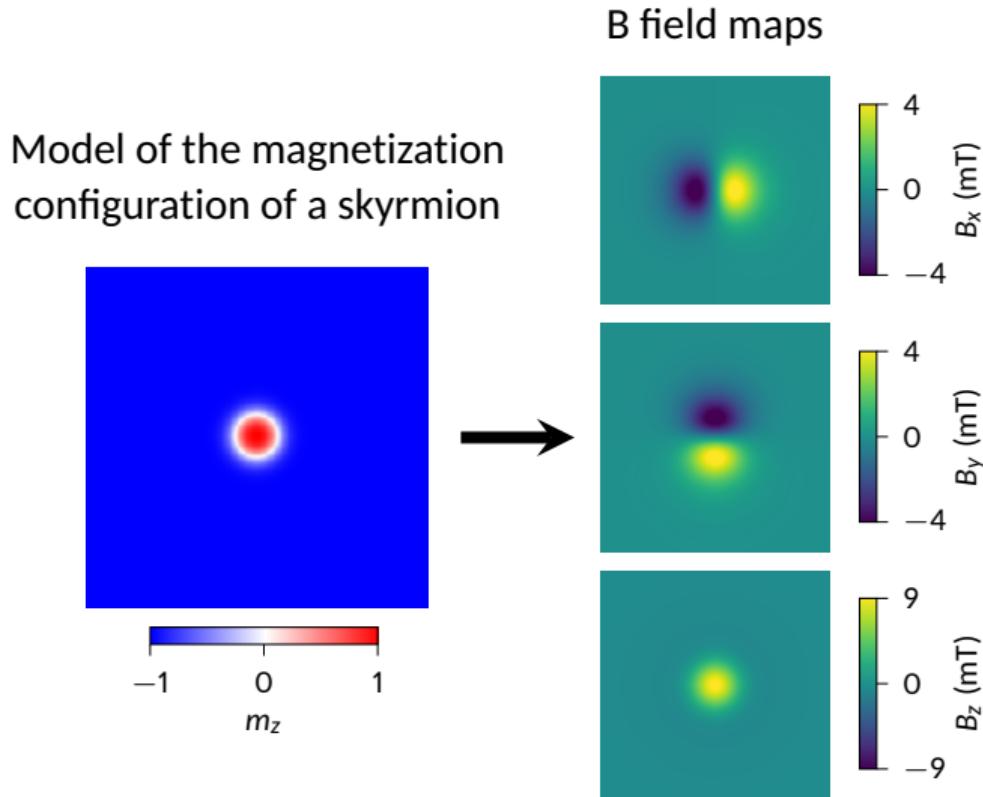
K. G. Rana et al. Phys. Rev. Applied 13 (2020), 044079

Simulation of the expected signal

Model of the magnetization configuration of a skyrmion

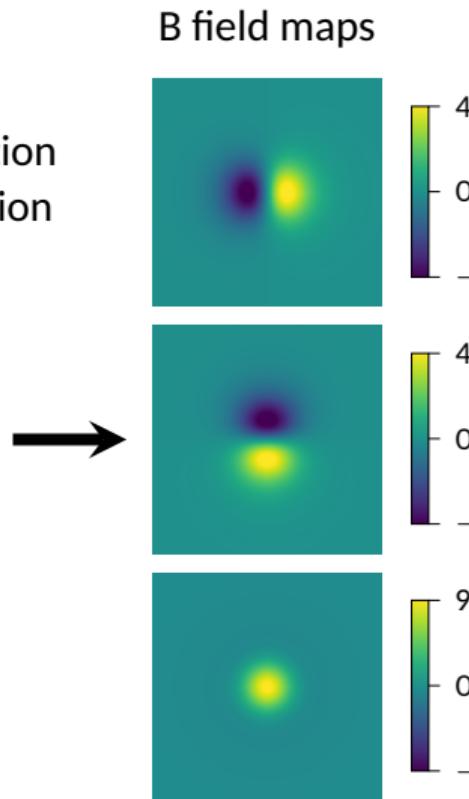
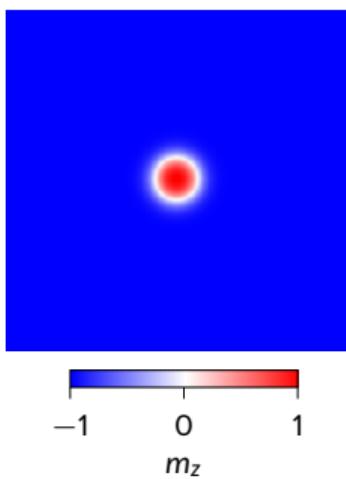


Simulation of the expected signal



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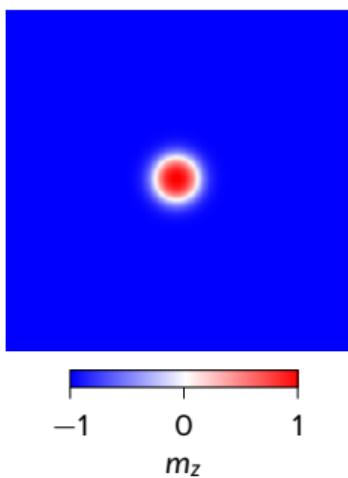
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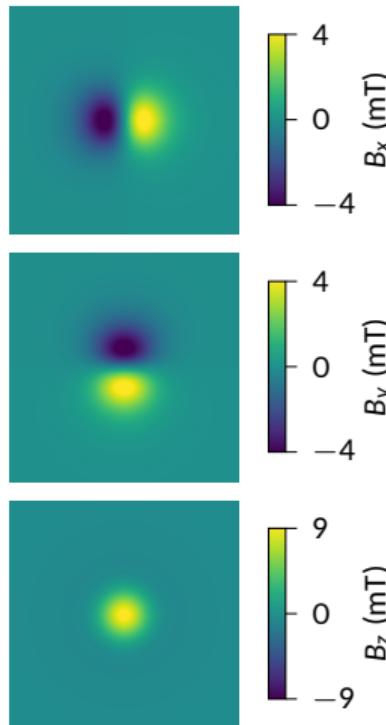
Calculation of the expected NV PL from a 7-levels model of the NV photophysics

Simulation of the expected signal

Model of the magnetization configuration of a skyrmion



B field maps

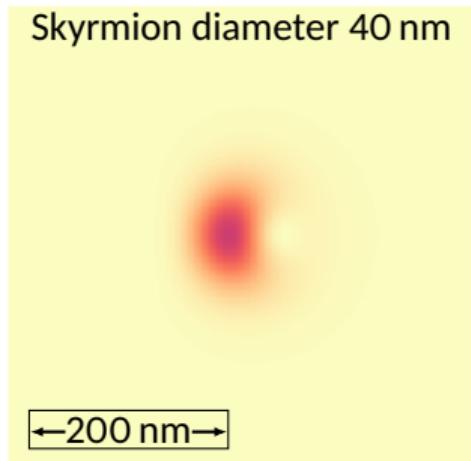


Calculation of the expected NV PL from a 7-levels model of the NV photophysics

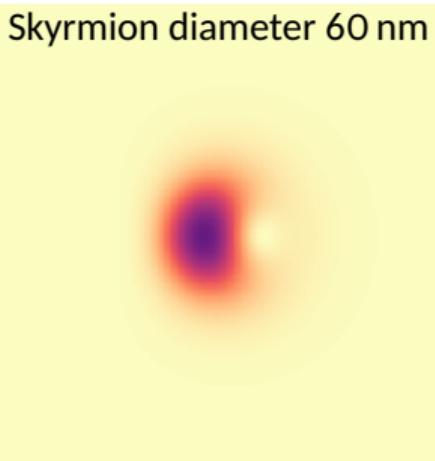
Comparison with the experiment

Comparison with simulations

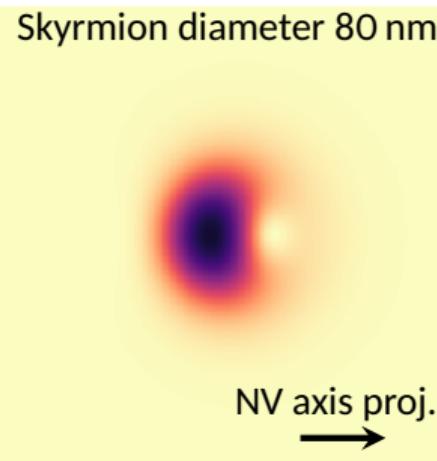
Skyrmion diameter 40 nm



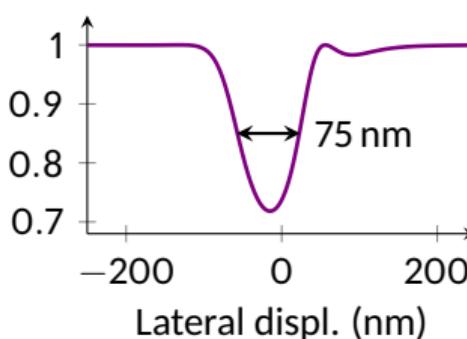
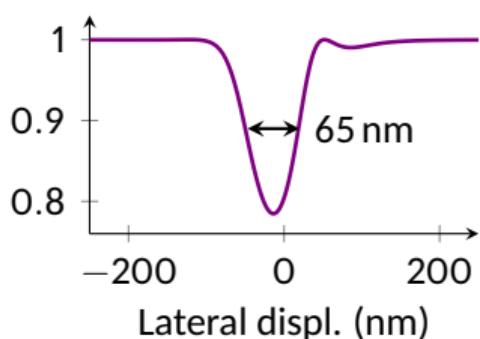
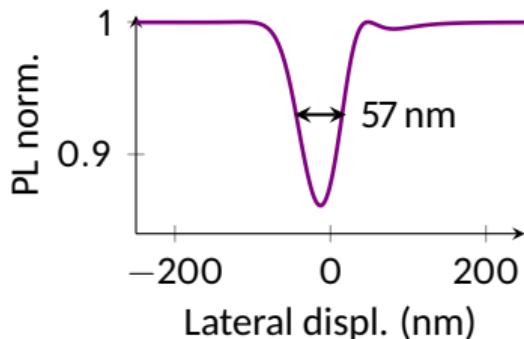
Skyrmion diameter 60 nm



Skyrmion diameter 80 nm

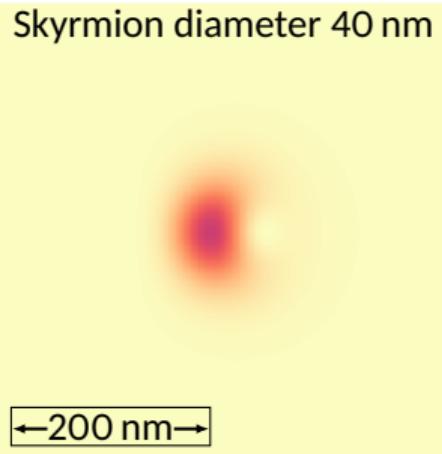


PL norm.
1.0
0.9
0.8
0.7



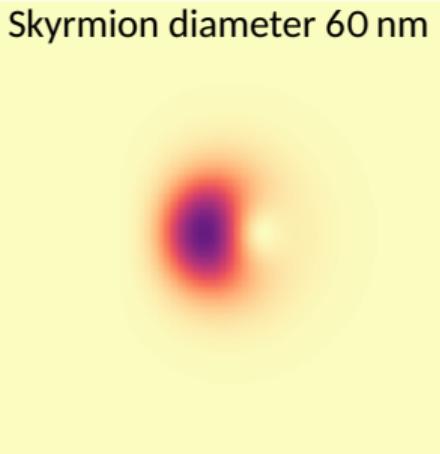
Comparison with simulations

Skyrmion diameter 40 nm

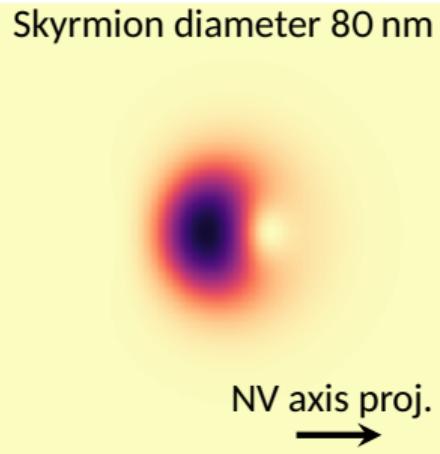


←200 nm→

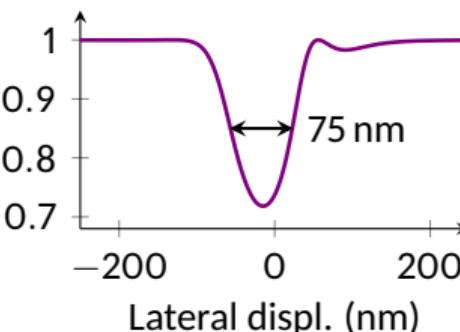
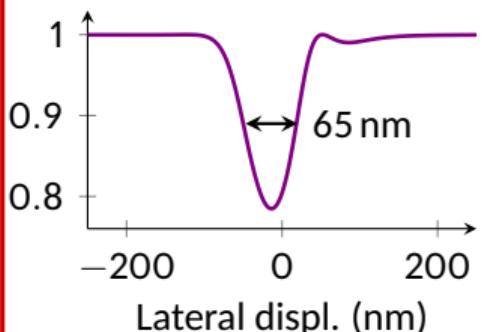
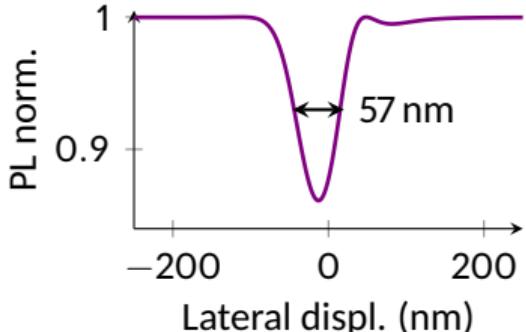
Skyrmion diameter 60 nm



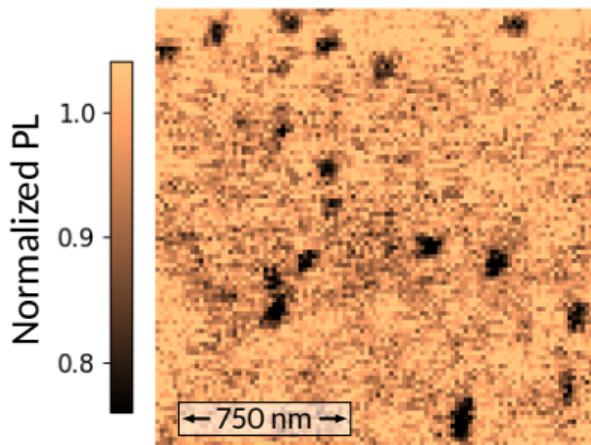
Skyrmion diameter 80 nm



PL norm.
1.0
0.9
0.8
0.7



Summary



- Demonstration of the stabilisation of **zero-field skyrmions** using a **non perturbative measurement technique**
- Qualitative imaging of **sub-100 nm skyrmions**
- Extraction of additional information from a comparison with simulations

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