

# Magnetic imaging via single spin relaxometry

A. Finco, A. Haykal, R. Tanos, M. Rollo, F. Fabre, S. Chouaieb, W. Akhtar,  
I. Robert-Philip, V. Jacques

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

W. Legrand, F. Ajejas, K. Bouzehouane, N. Reyren, V. Cros

*Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, Palaiseau, France*

T. Devolder, J.-P. Adam, J.-V. Kim

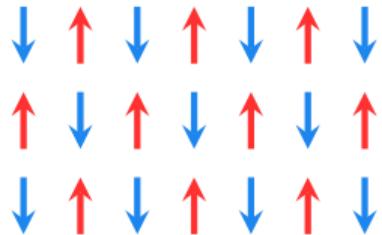
*Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, Palaiseau, France*



736. WE-Heraeus-Seminar, *Magnetism at the Nanoscale*, January 7<sup>th</sup> 2021

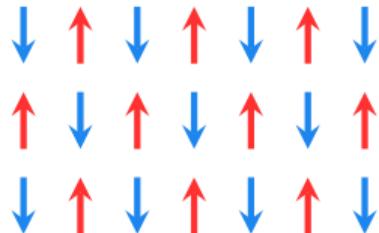
slides available at <https://magimag.eu>

# Why are we interested in antiferromagnets?



Alternating magnetic moments

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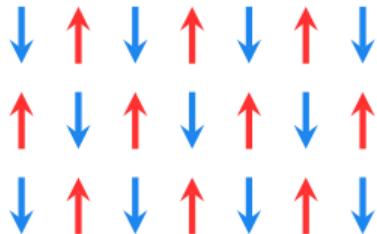
Alternating magnetic moments

- **Spintronics:** robust, fast, efficient

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

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

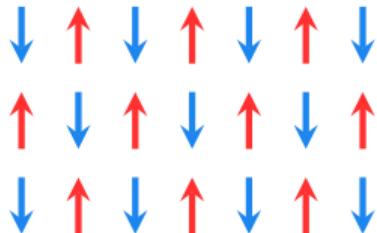
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- **Multiferroics:** coexistence of several orders, majority of compounds are AFM
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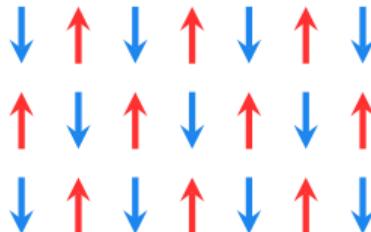
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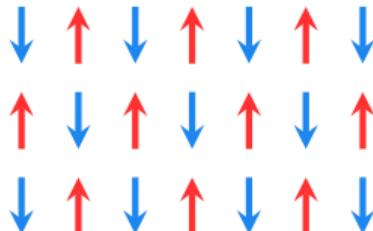


Alternating magnetic moments

No net magnetization  
Weak signals

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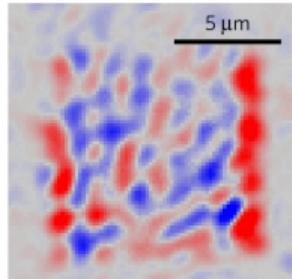
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→ Antiferromagnetic structures are difficult to image!

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

# Techniques to image antiferromagnets

SHG



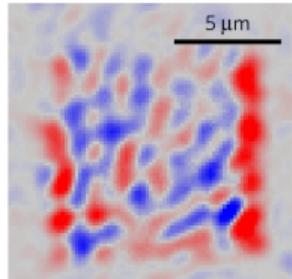
■ J.-Y. Chauleau et al. *Nat. Mat.* 16 (2017), 803



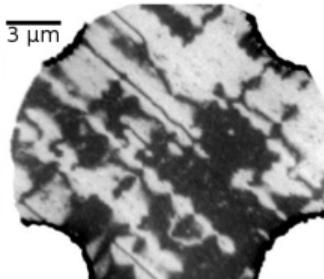
Spatial  
resolution

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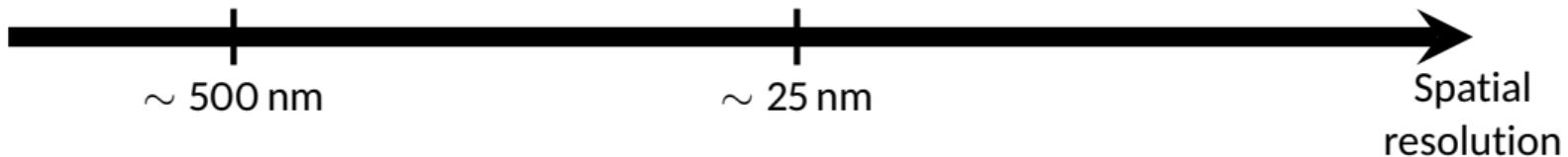


XMLD-PEEM



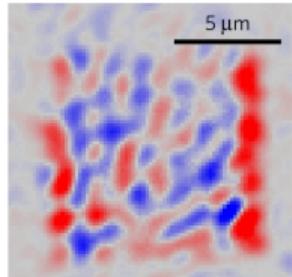
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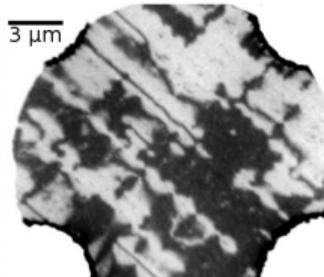


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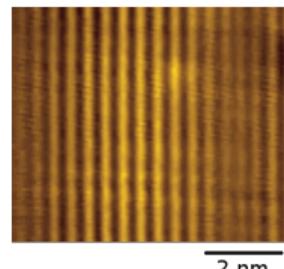
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XMLD-PEEM



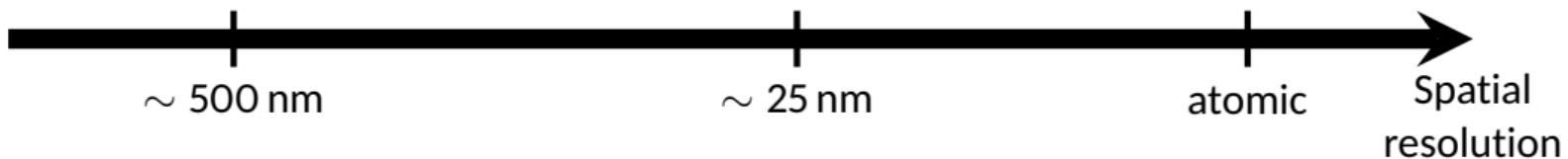
SP-STM



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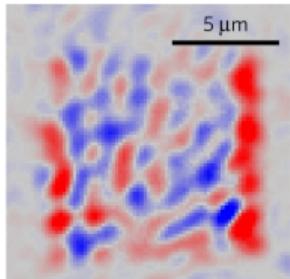
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■ M. Bode et al. *Nature* 447 (2007), 190

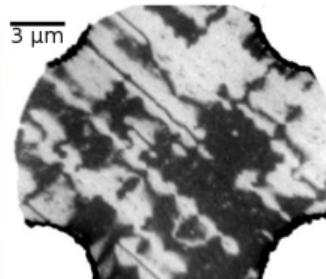


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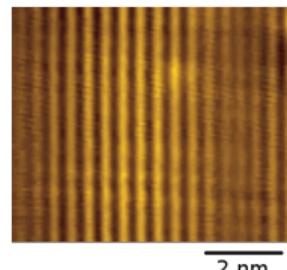
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XMLD-PEEM



SP-STM

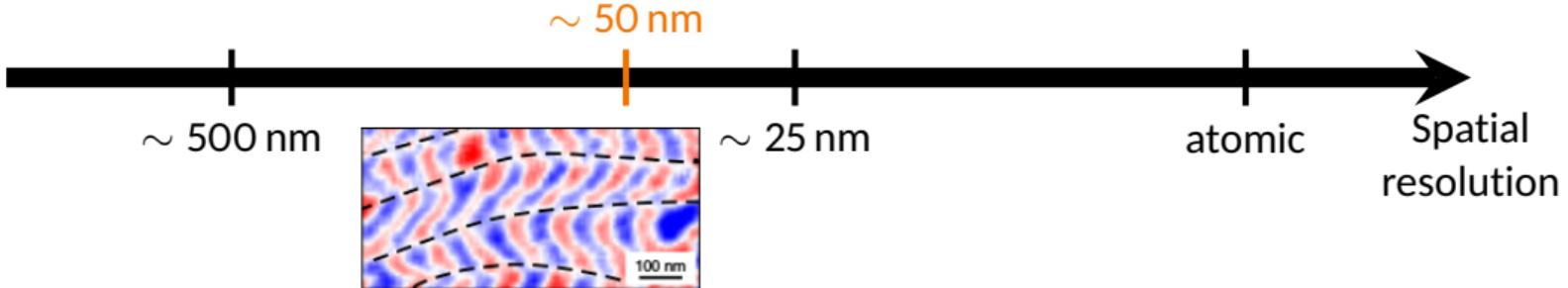


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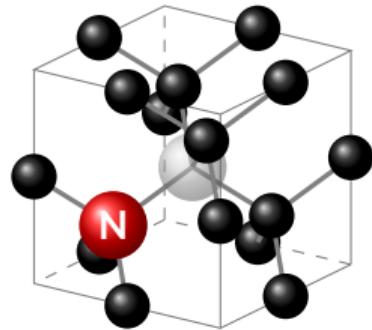
~ 50 nm



NV magnetometry

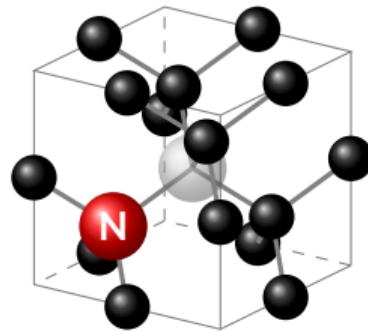
■ I. Gross et al. *Nature* 549 (2017), 252

# NV centers to measure magnetic fields



Defect in diamond

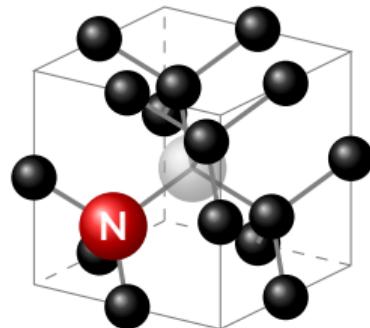
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Defect in diamond

- Optical manipulation and reading
- Ambient conditions

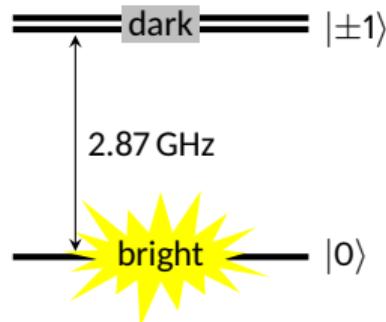
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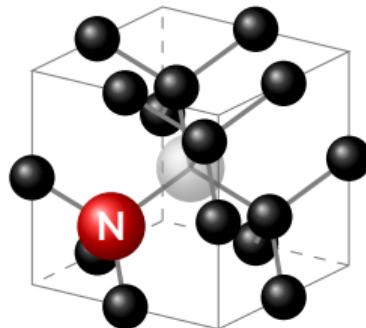
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Spin-dependent  
fluorescence



NV ground state  
spin  $S = 1$

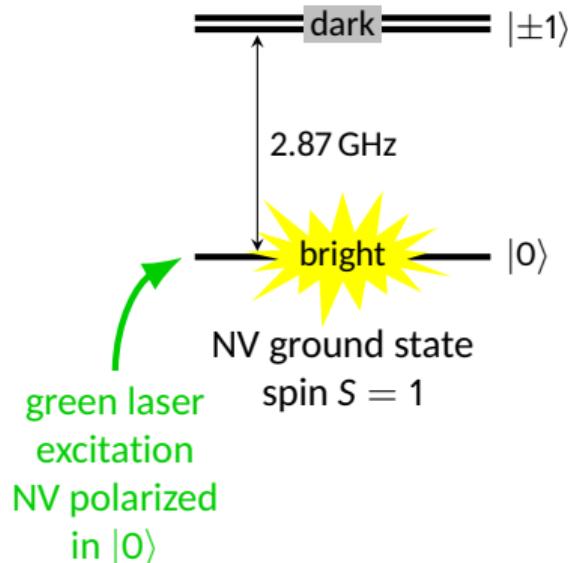
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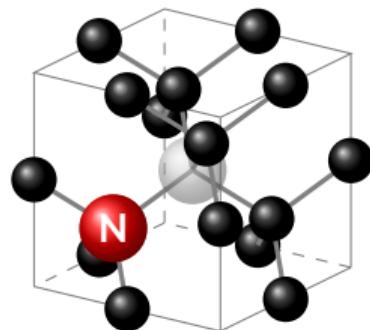
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Spin-dependent fluorescence

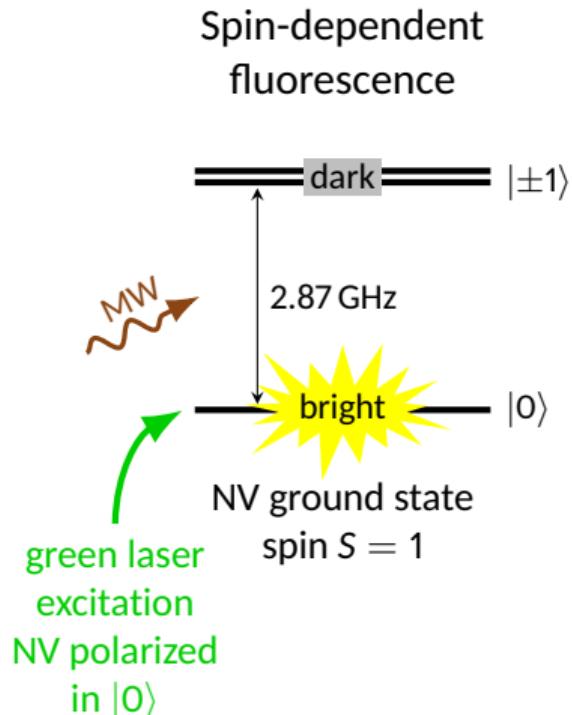


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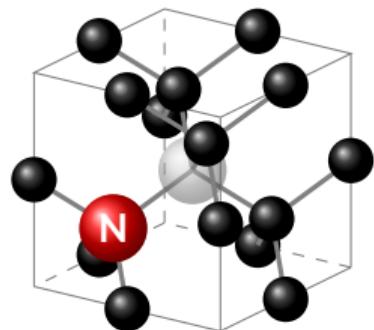


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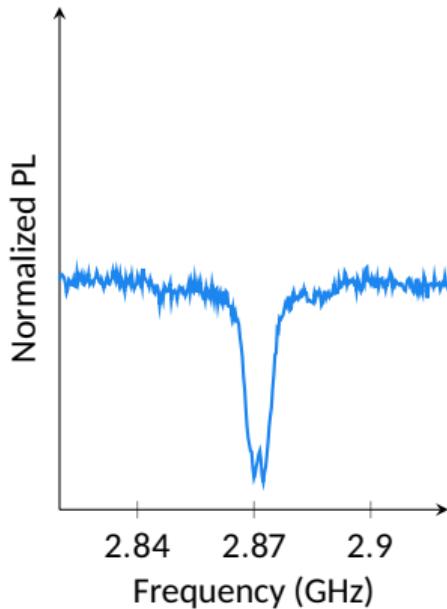
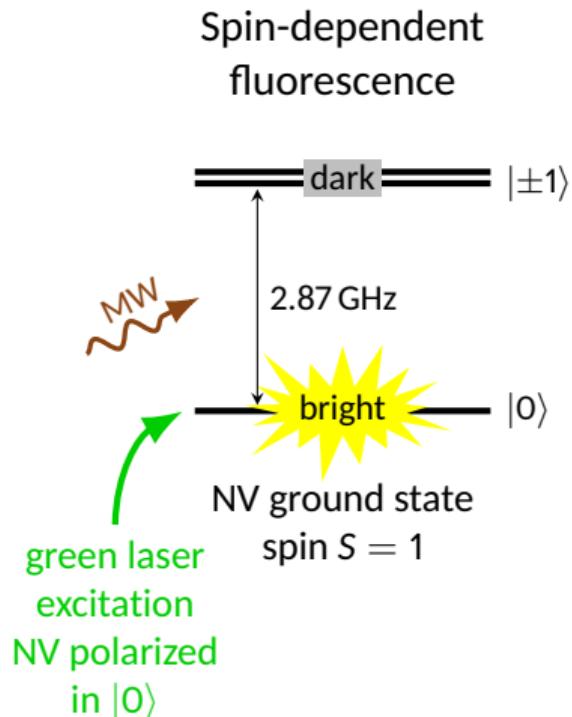


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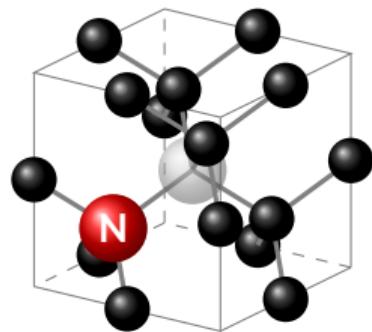


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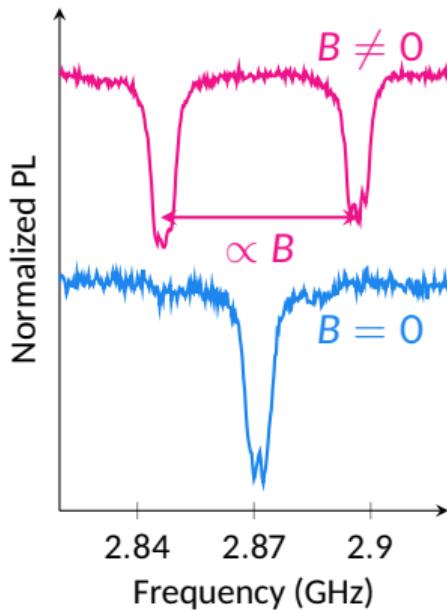
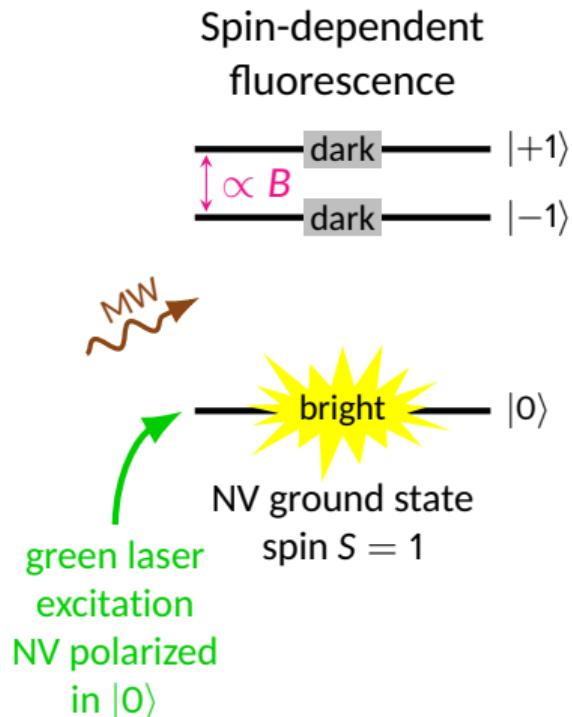


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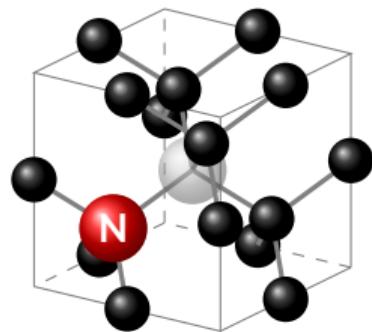


Defect in diamond

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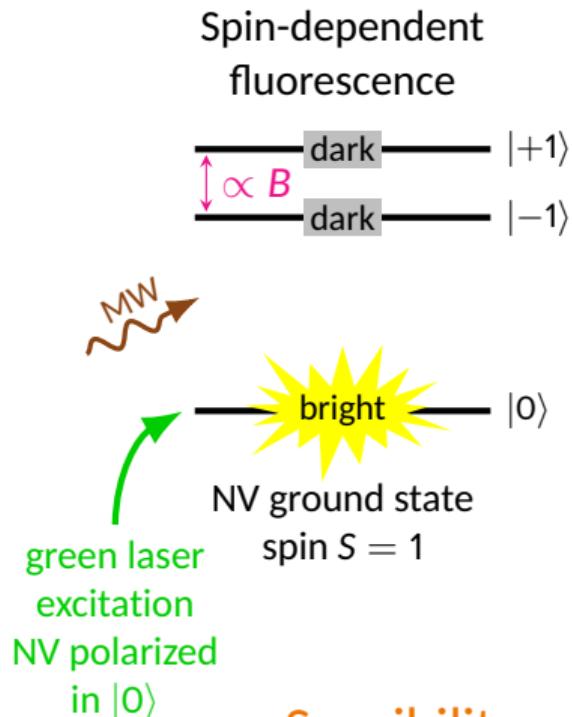


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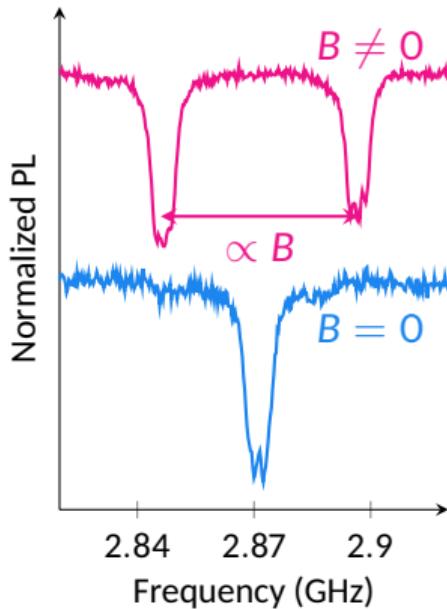


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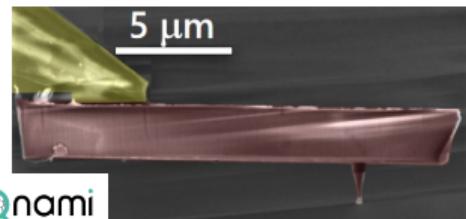


Sensibility: a few  $\mu\text{T}/\sqrt{\text{Hz}}$

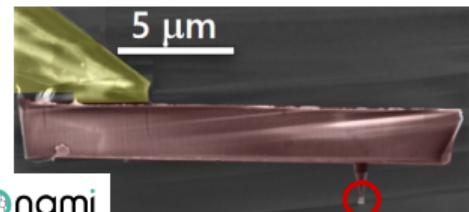


# Quantitative scanning NV magnetometry on antiferromagnets

Diamond  
AFM tip

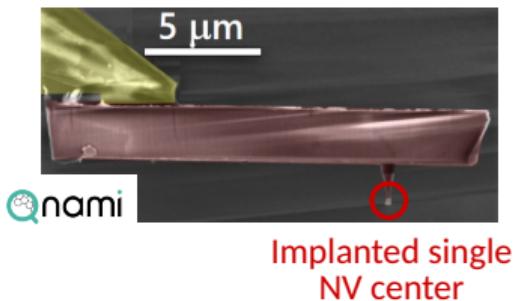
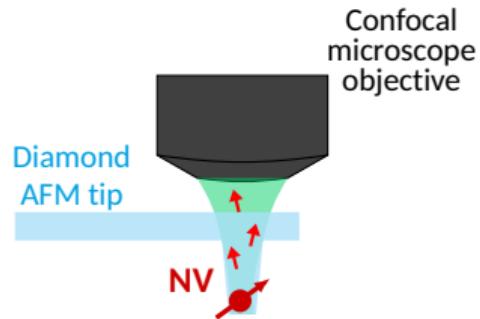


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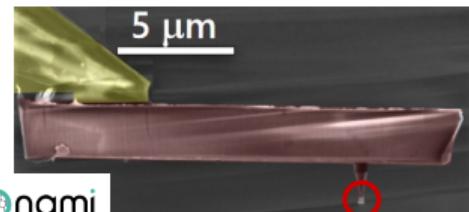
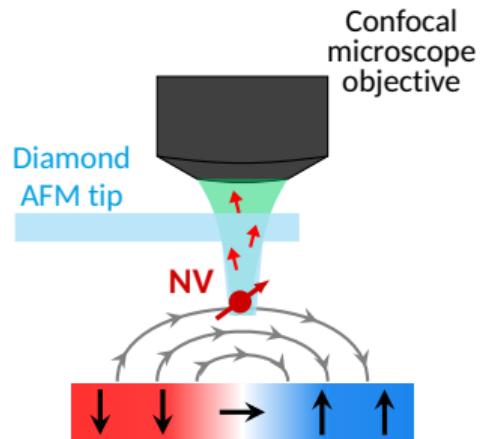


Implanted single  
NV center

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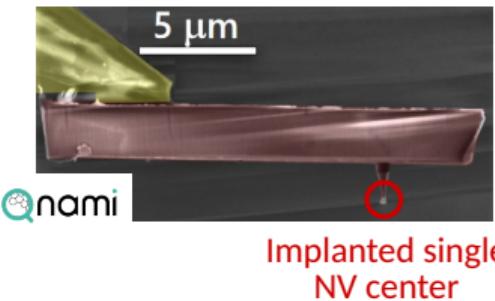
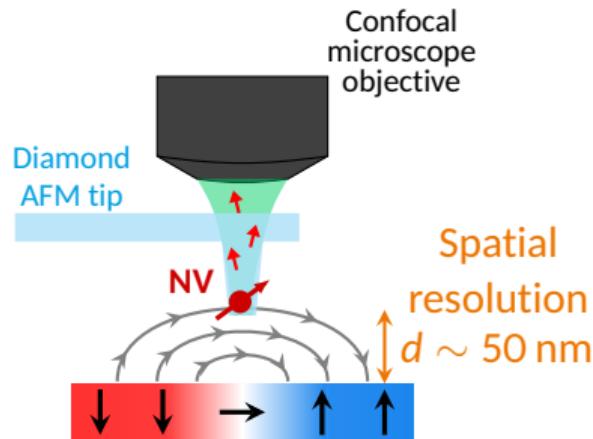


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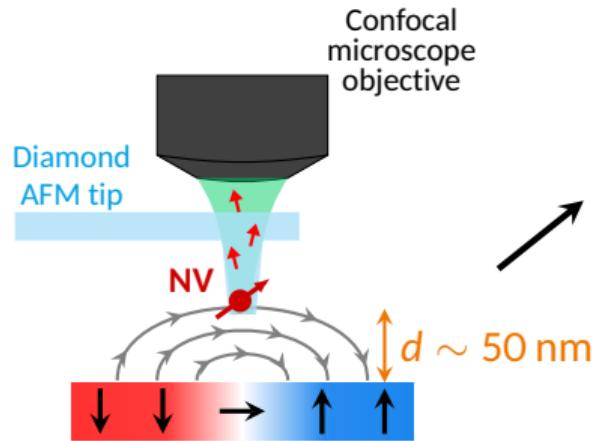


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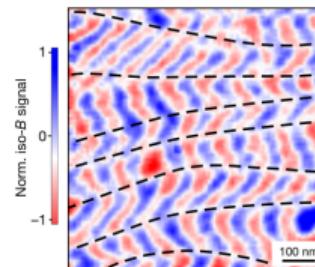
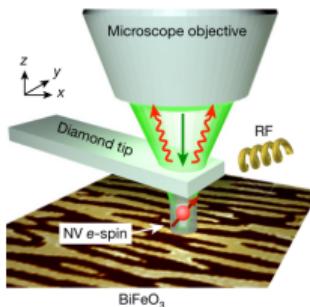
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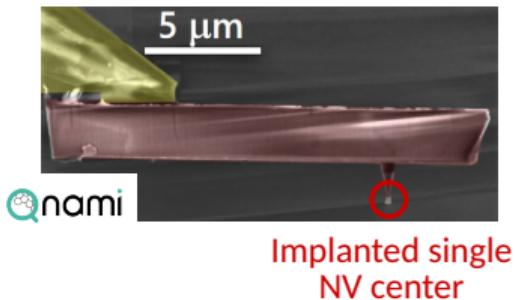


**BiFeO<sub>3</sub>:** a room-temperature multiferroic

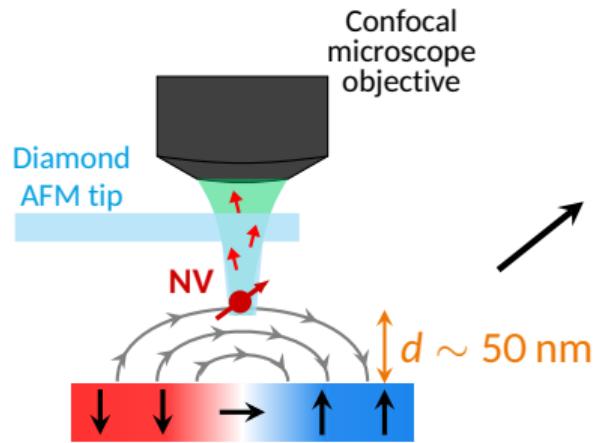


I. Gross et al. *Nature* 549 (2017), 252

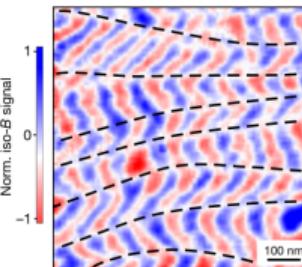
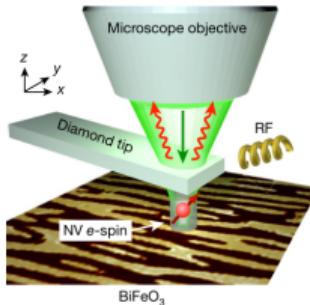
A. Haykal et al. *Nat. Comm.* 11 (2020), 1704



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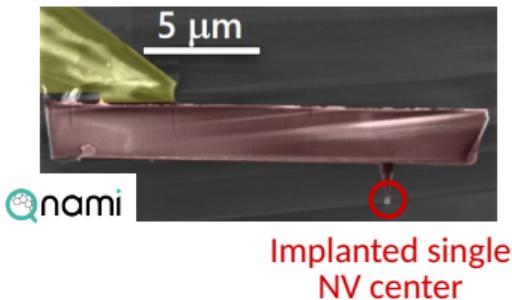


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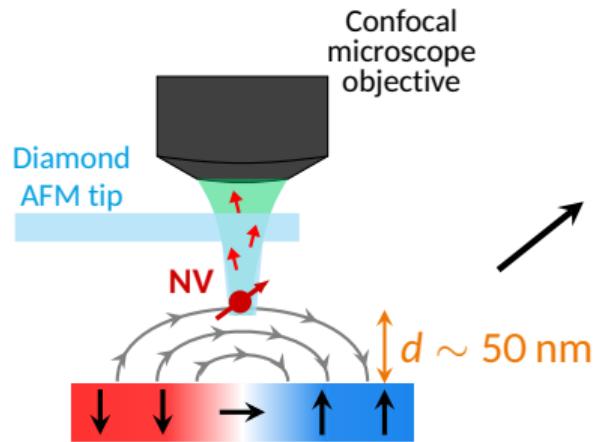


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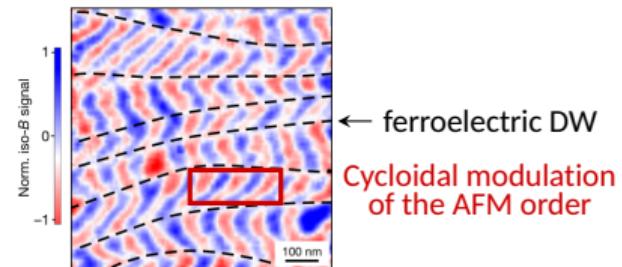
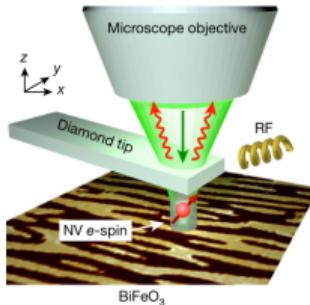
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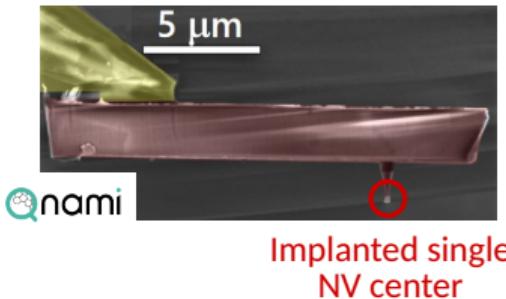


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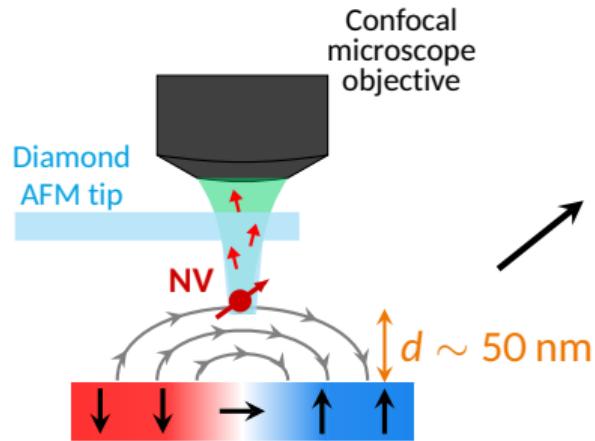


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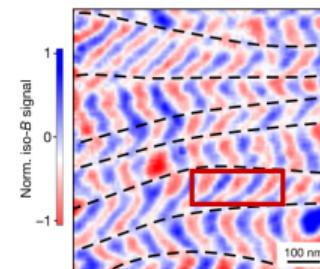
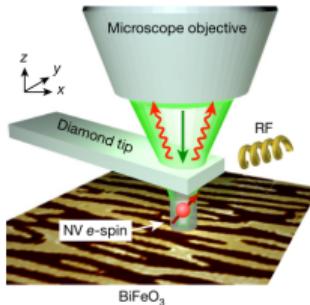
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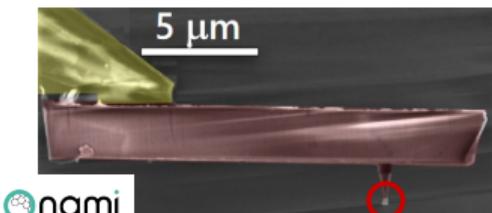
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ferroelectric DW  
Cycloidal modulation of the AFM order

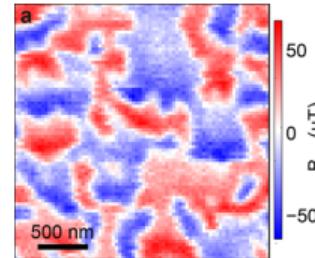
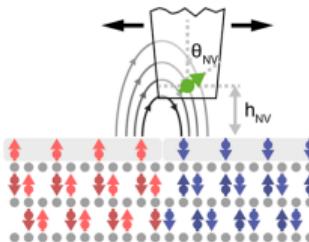
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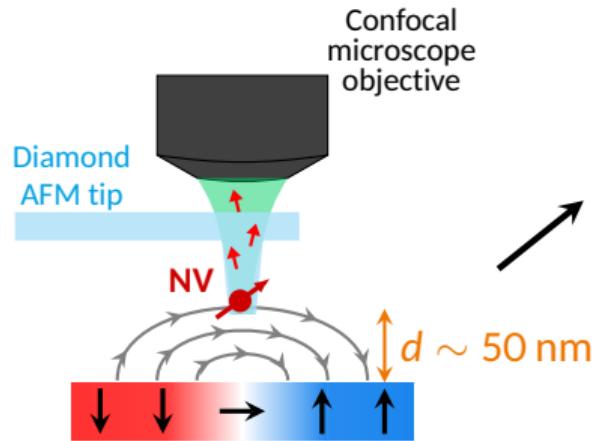
Implanted single NV center

**Cr<sub>2</sub>O<sub>3</sub>:** a layered antiferromagnet

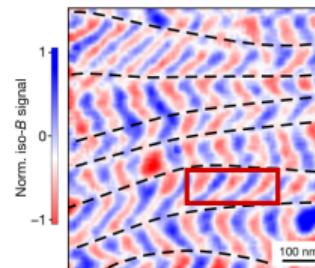
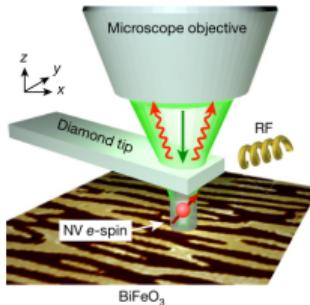


P. Appel et al. *Nano Lett.* 19 (2019), 1682

# Quantitative scanning NV magnetometry on antiferromagnets



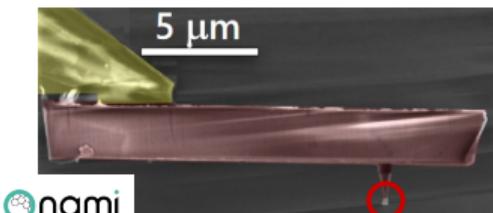
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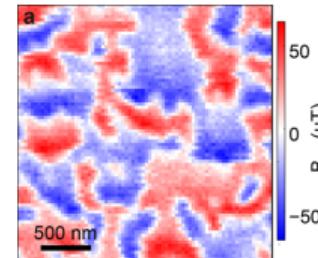
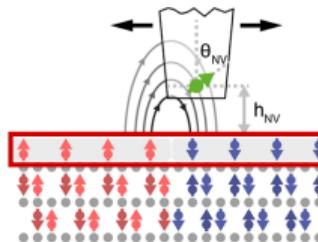
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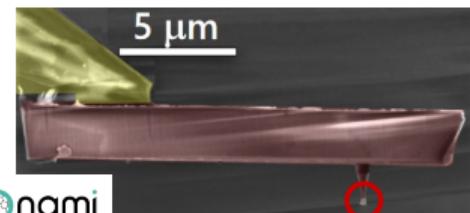
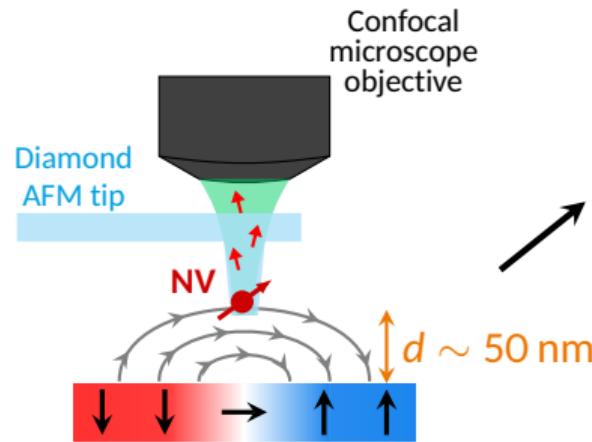
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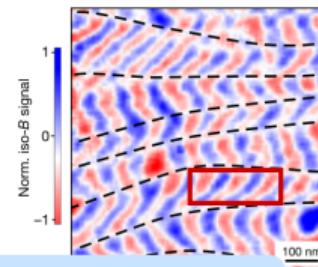
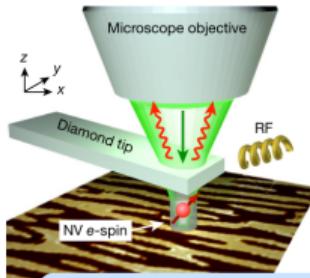
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# Quantitative scanning NV magnetometry on antiferromagnets



Implanted single NV center

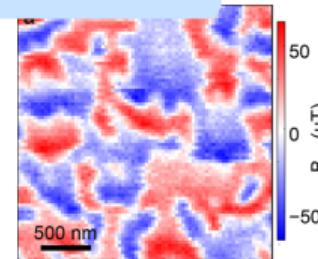
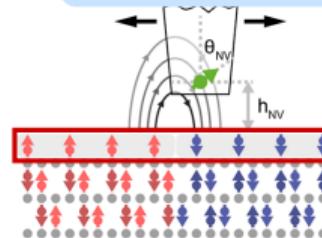
**BiFeO<sub>3</sub>: a room-temperature multiferroic**



Nature 549 (2017), 252  
Comm. 11 (2020), 1704

Antiferromagnets with small uncompensated moments

**What if this is not the case?**



P. Appel et al. Nano Lett. 19 (2019), 1682

# Use magnetic noise instead of stray field!

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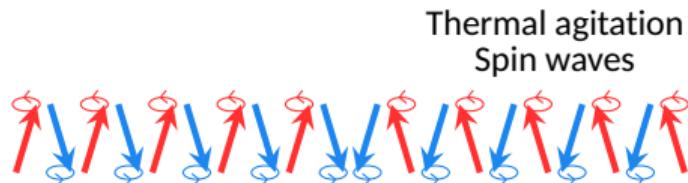
 B. Flebus *et al.* *Phys. Rev. B* 98 (2018), 180409

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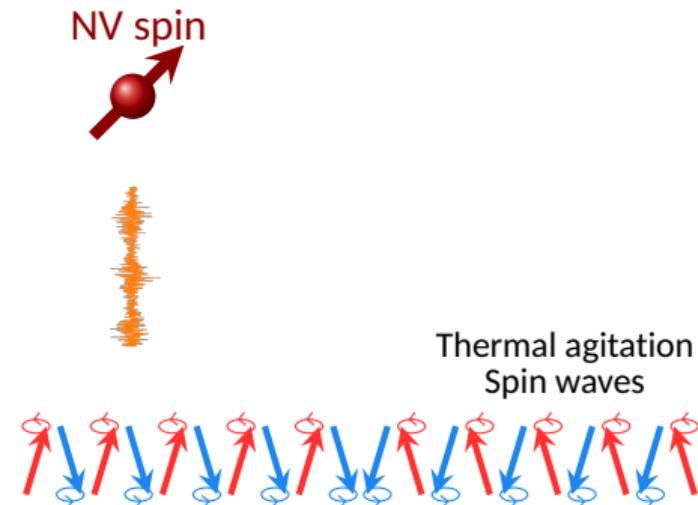
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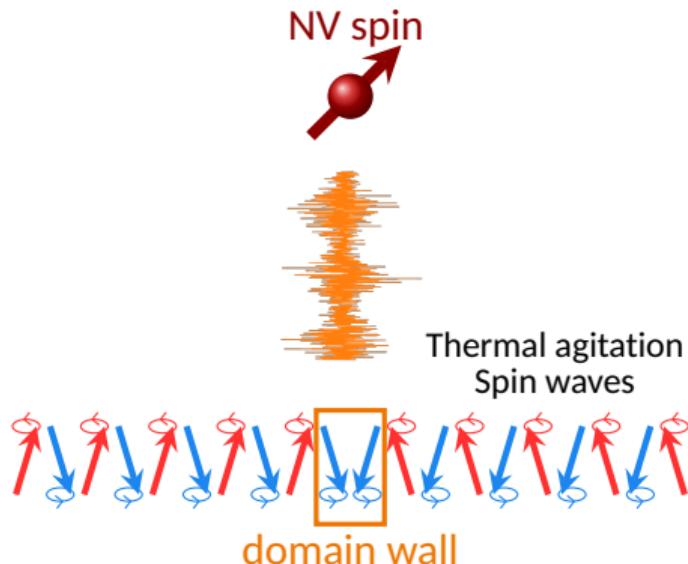
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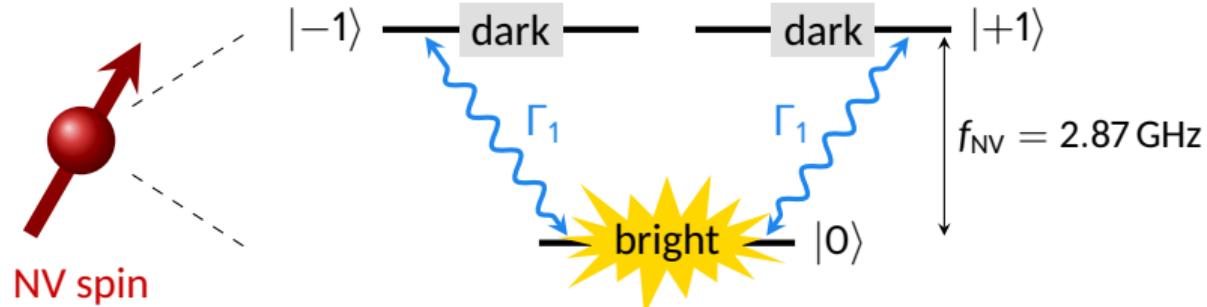
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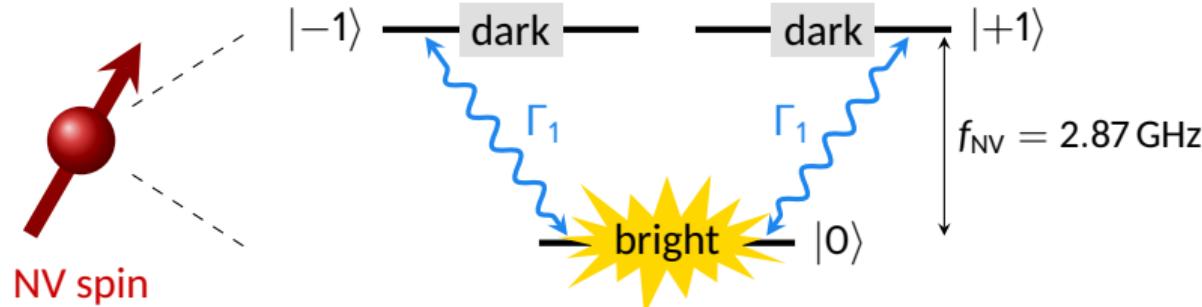
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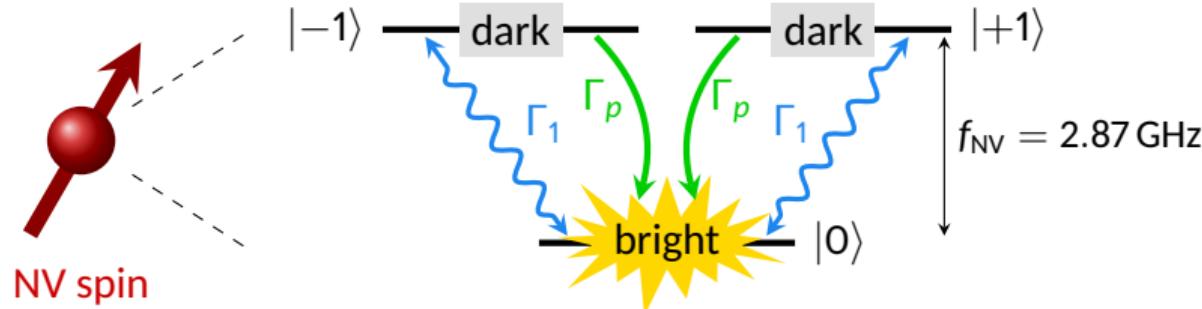


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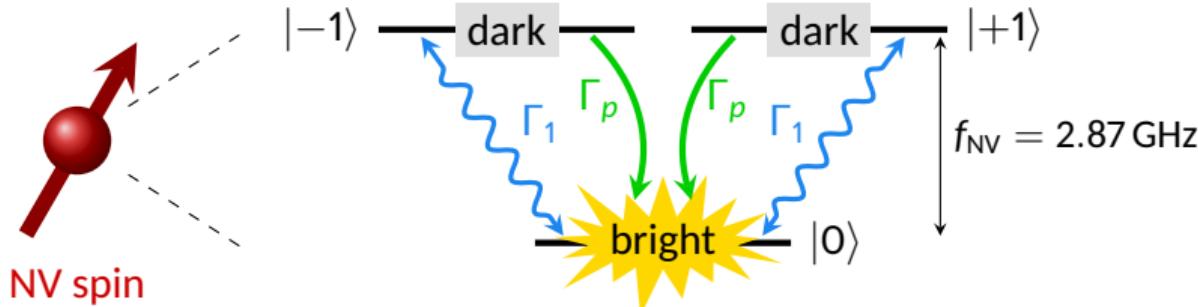
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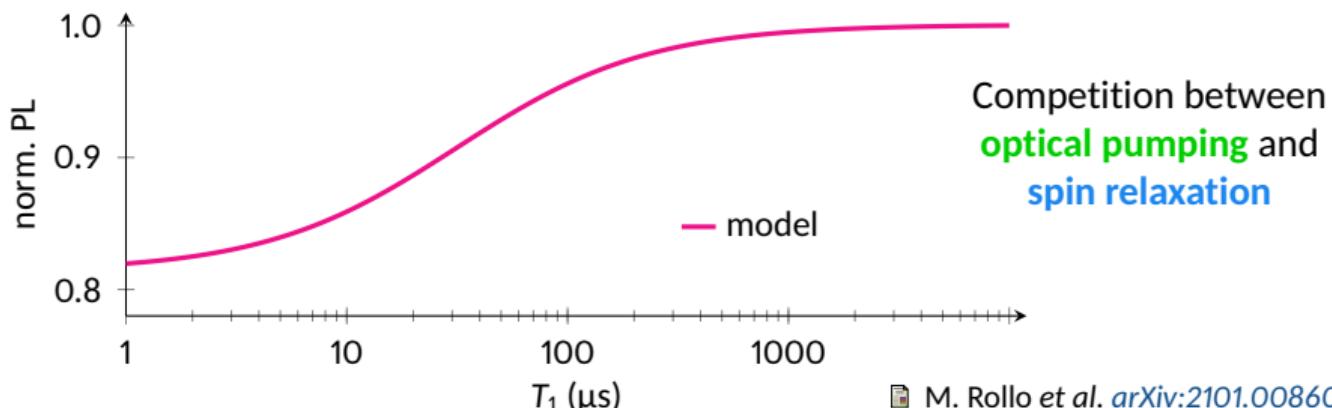


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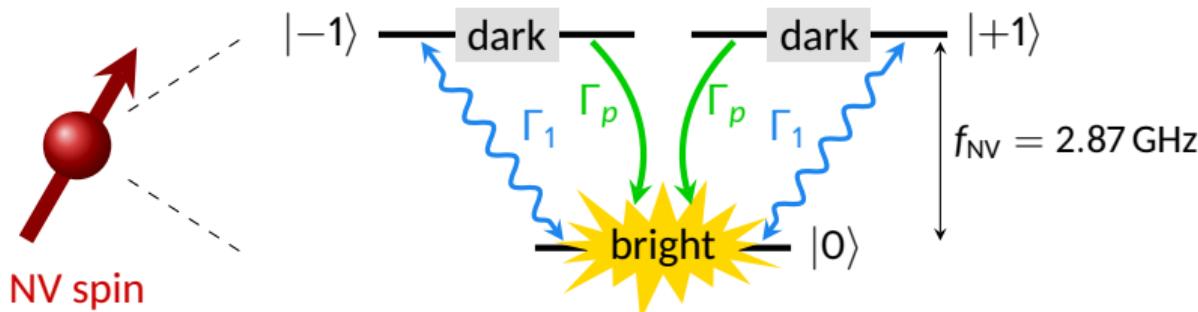
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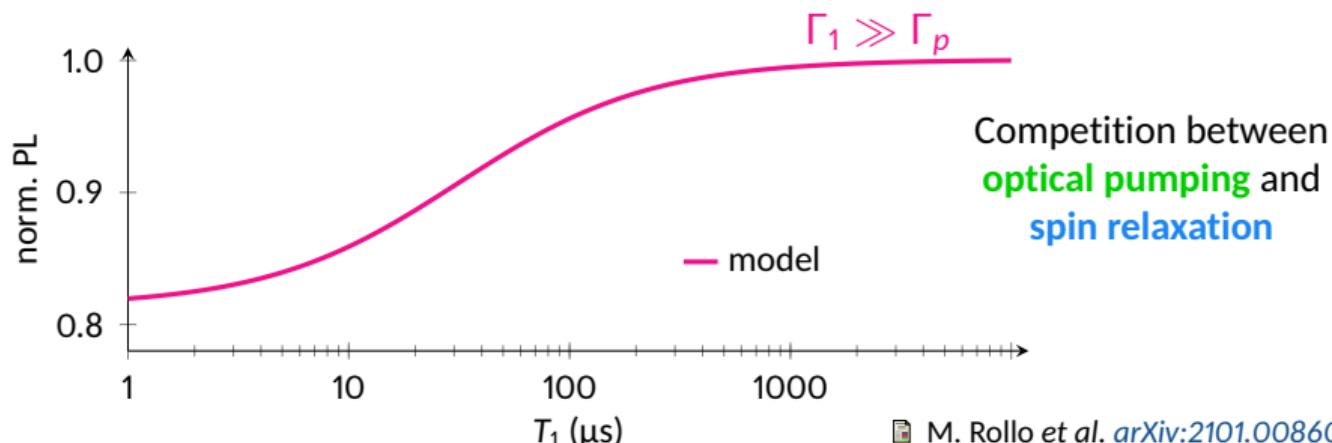
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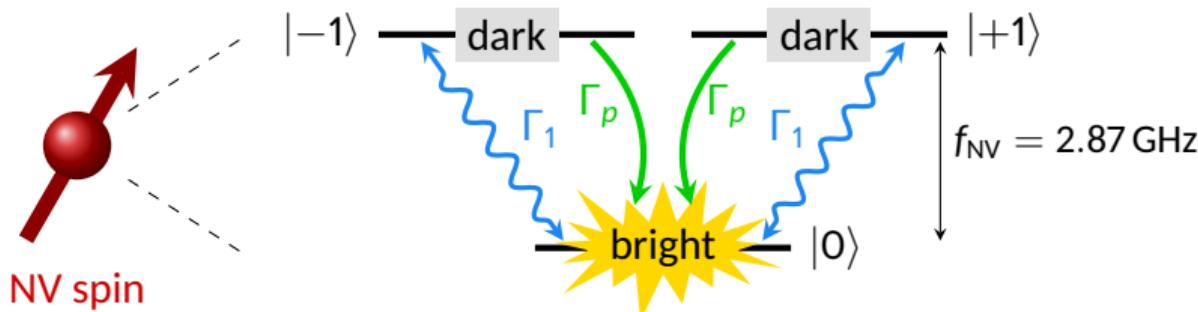
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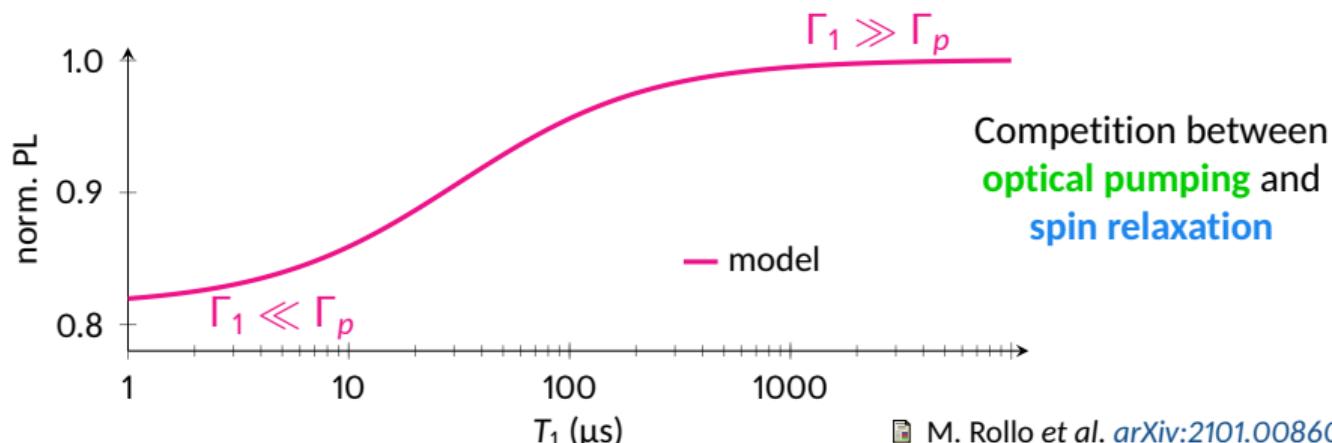
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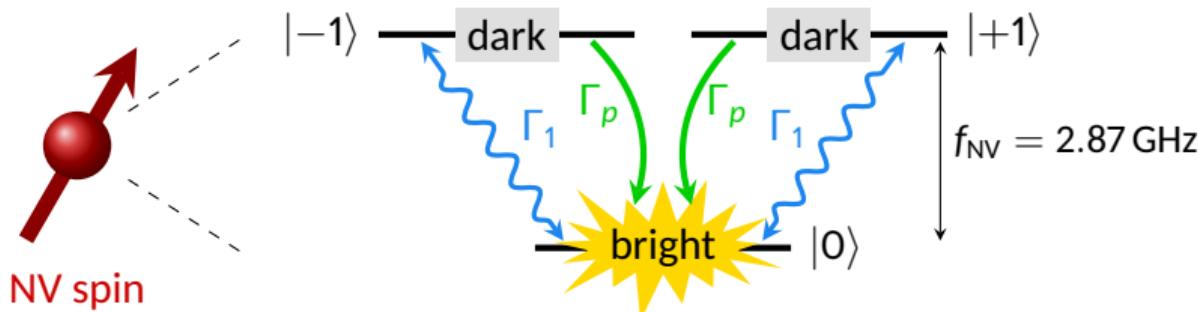
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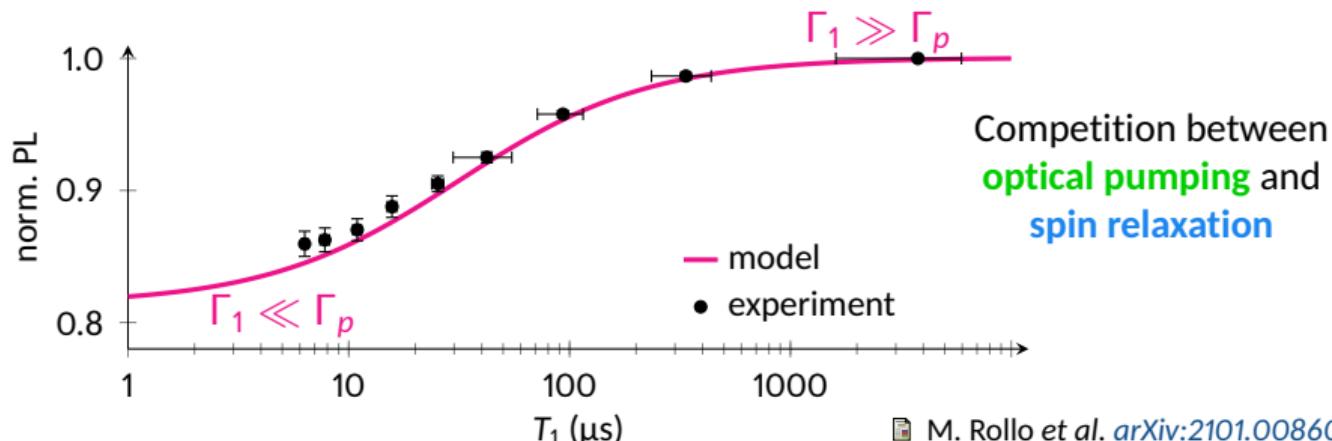
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Collaboration UMR CNRS/Thales: William Legrand, Fernando Ajejas, Karim Bouzehouane,  
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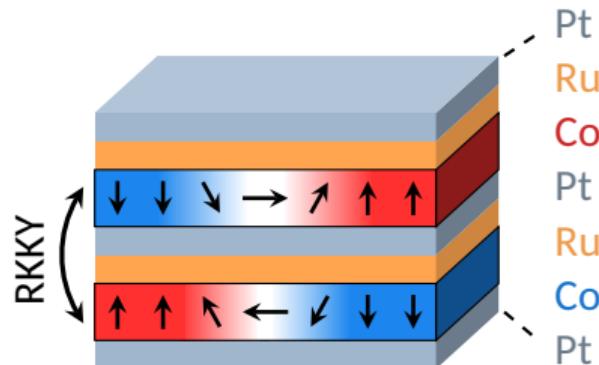
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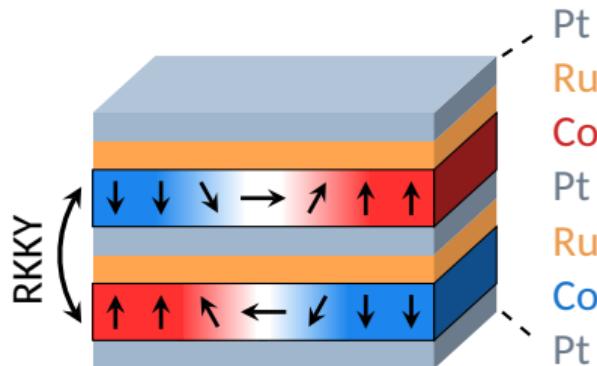
W. Legrand et al. *Nat. Mat.* 19 (2020), 34

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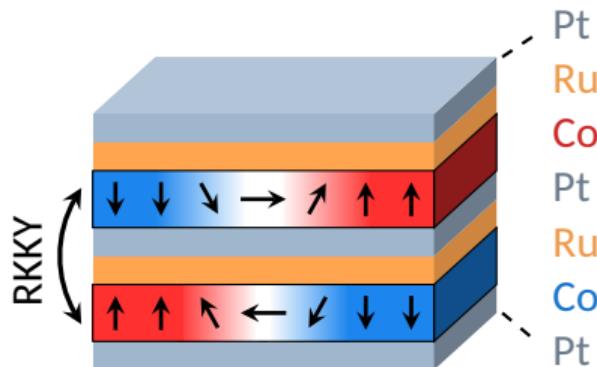
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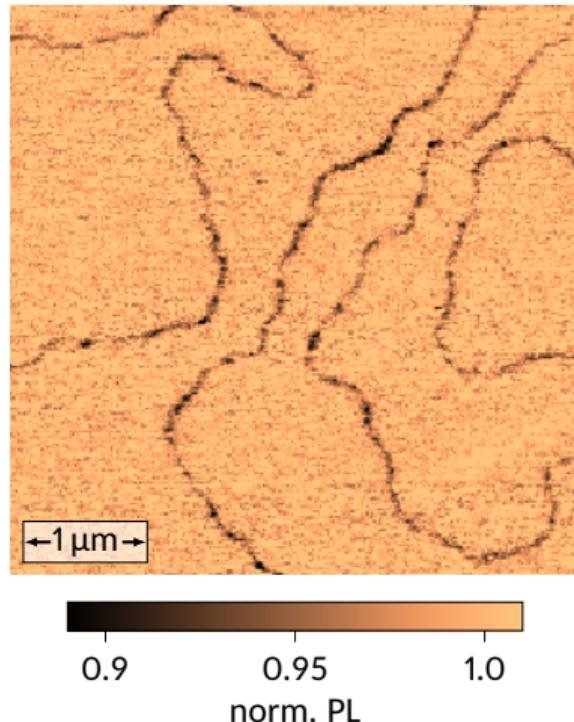


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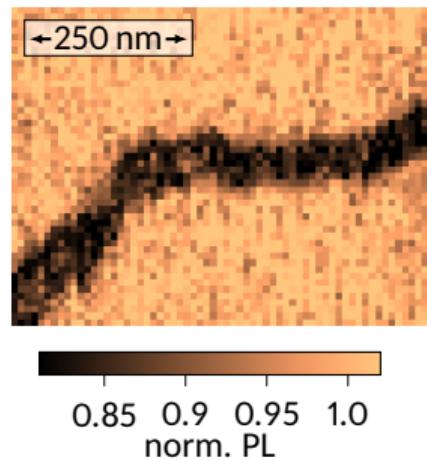
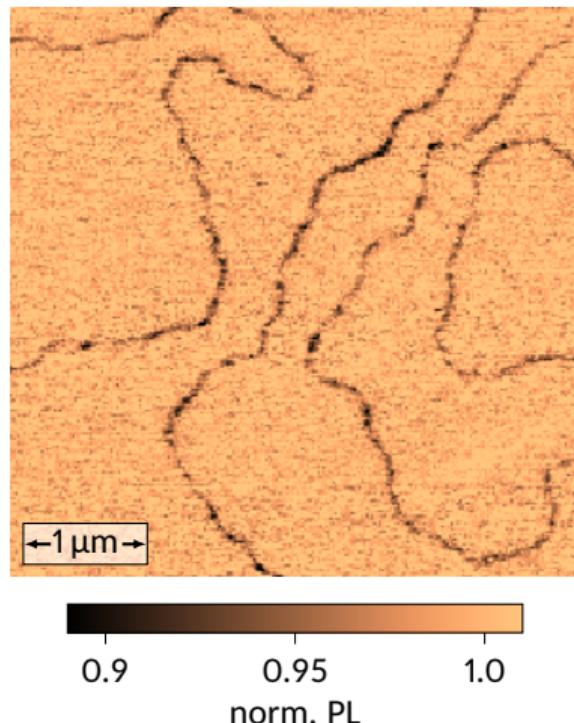
Perfect **test system** for noise imaging!

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

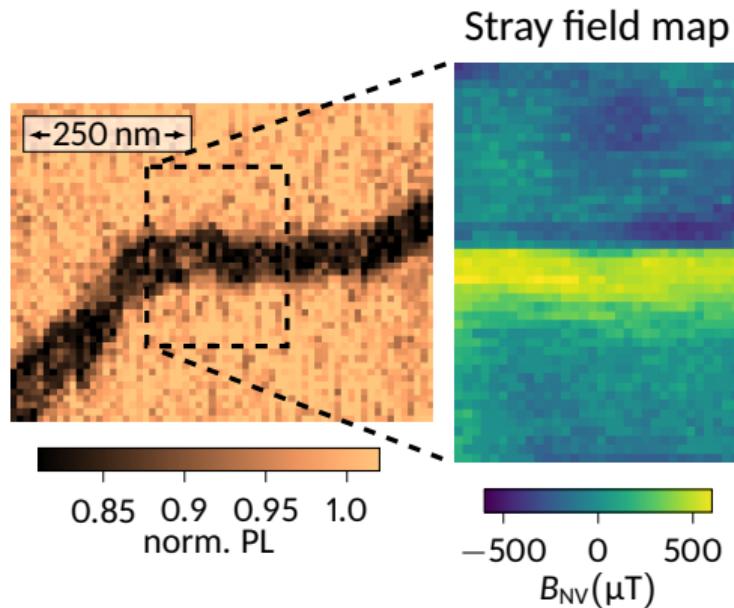
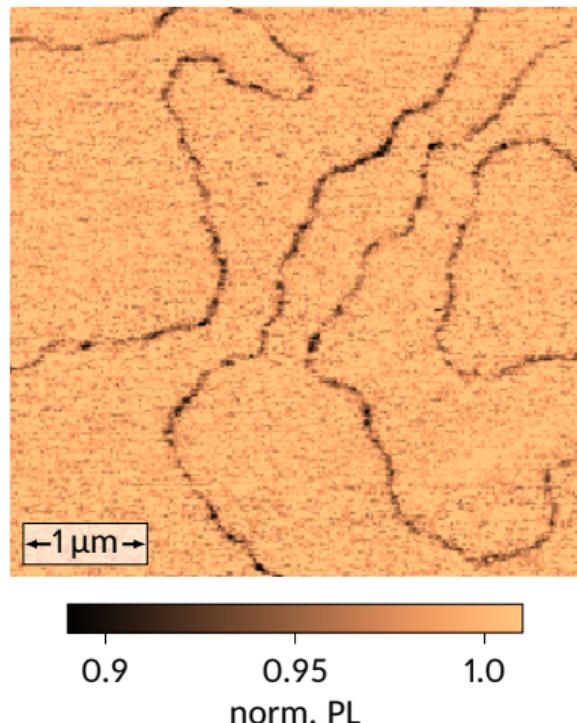
# Detection of domain walls by relaxometry



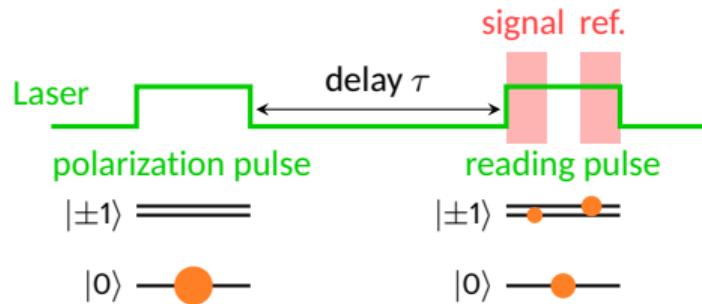
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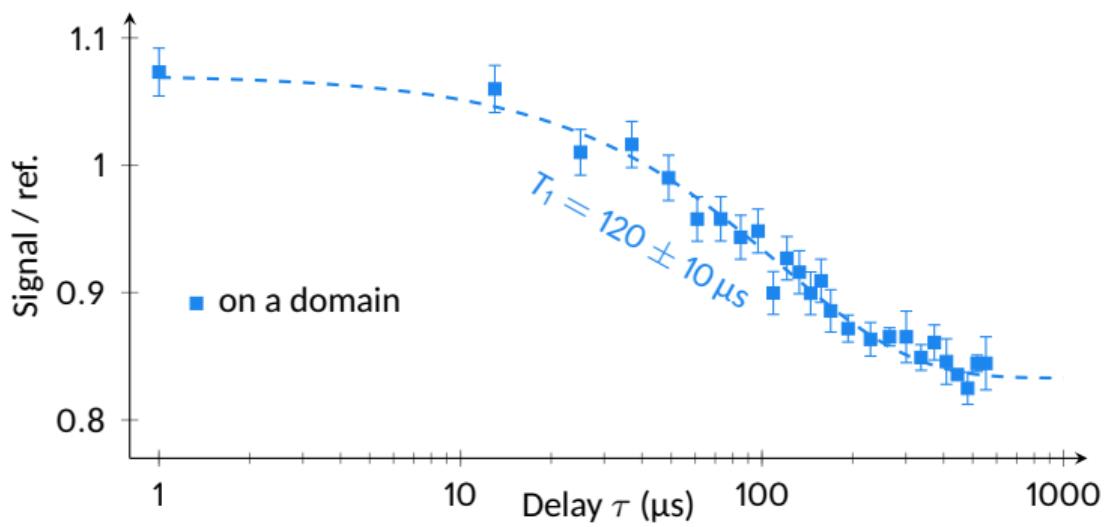
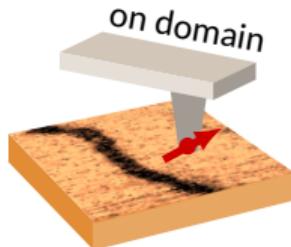
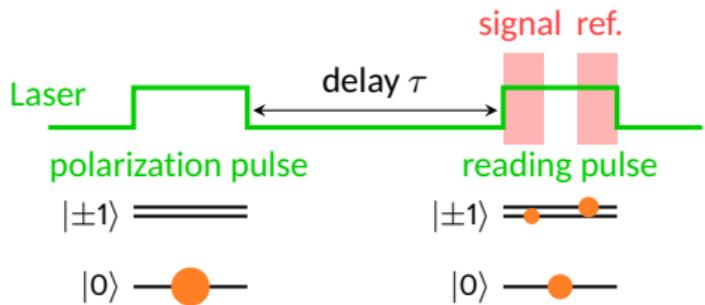
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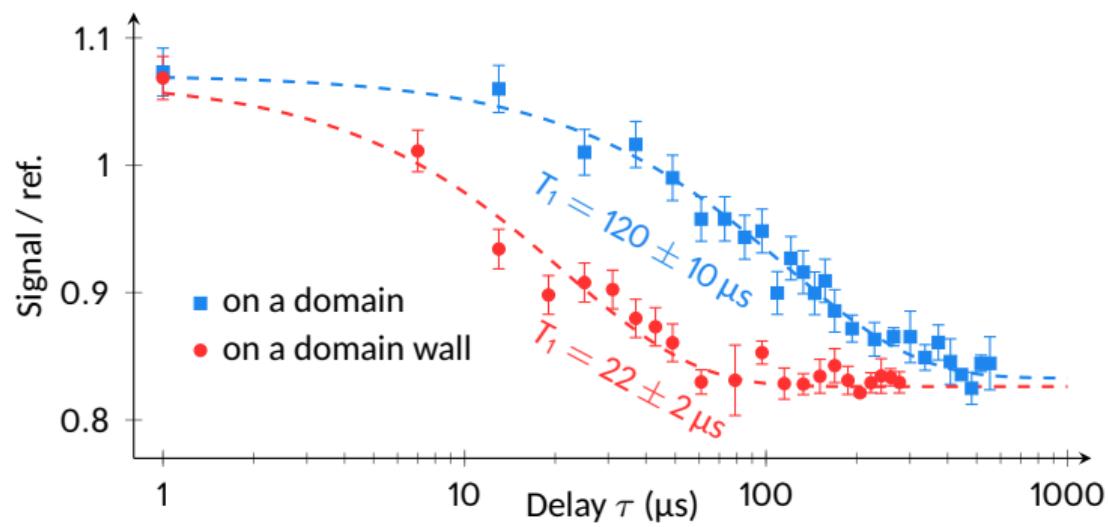
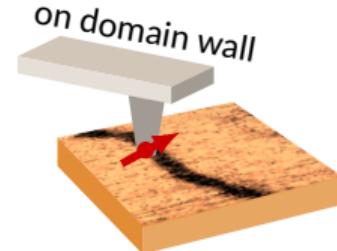
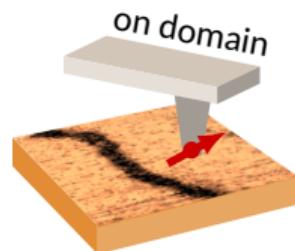
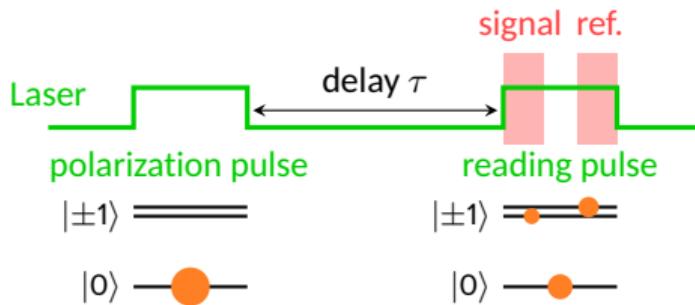
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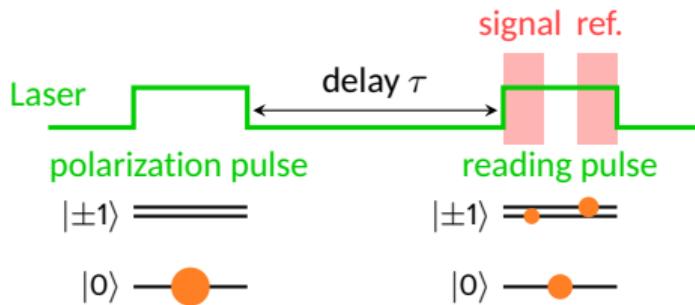
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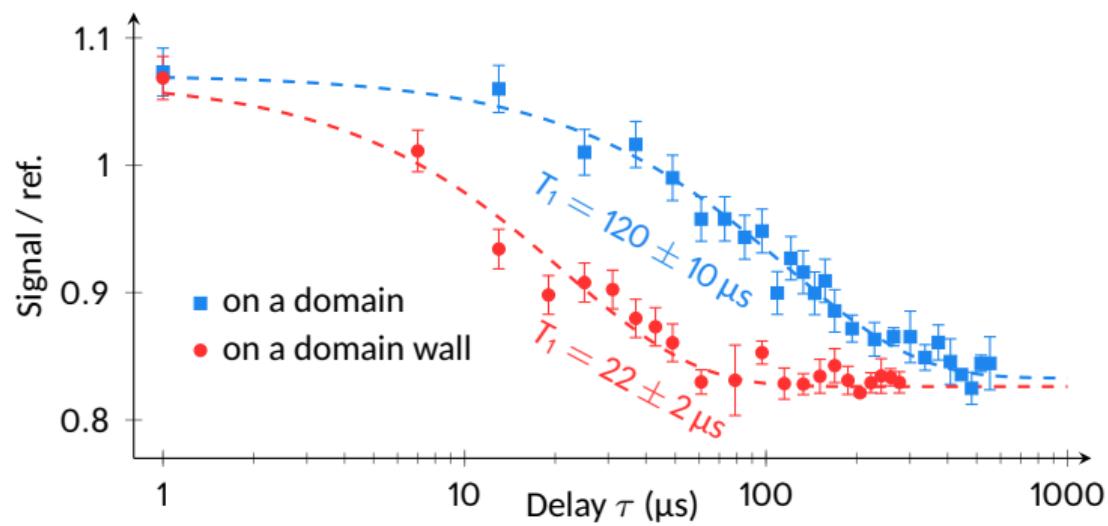
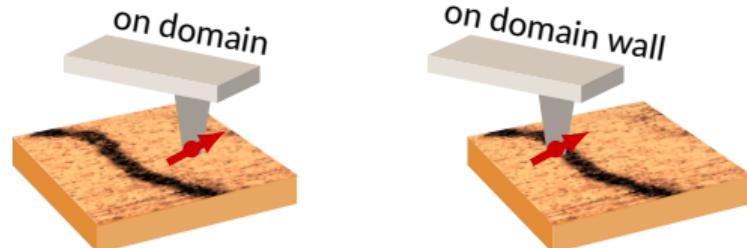
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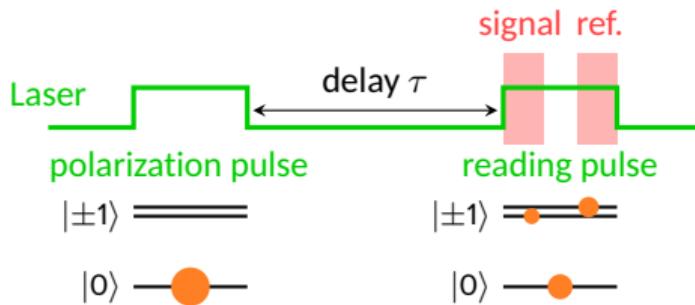
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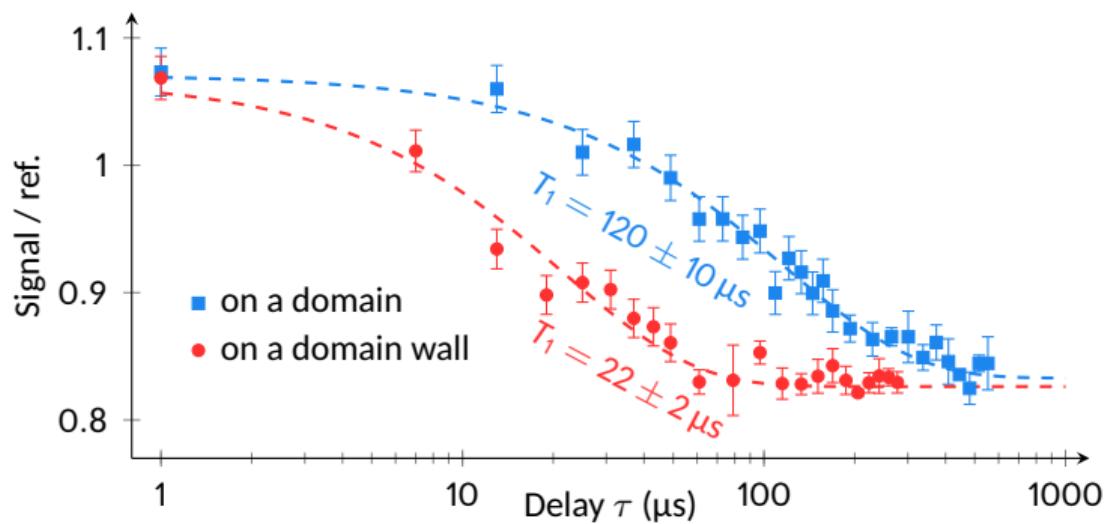
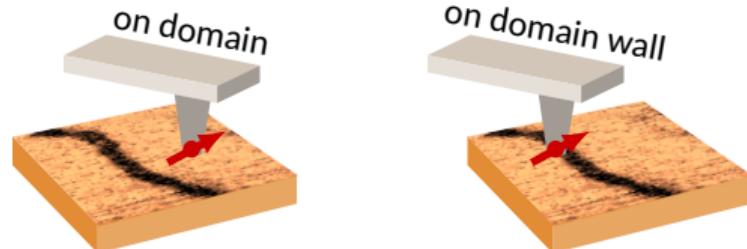


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→ Enhancement of the  
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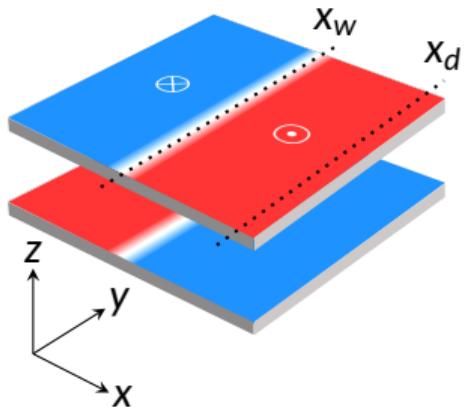
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Collaboration C2N: Jean-Paul Adam, Joo-Von Kim



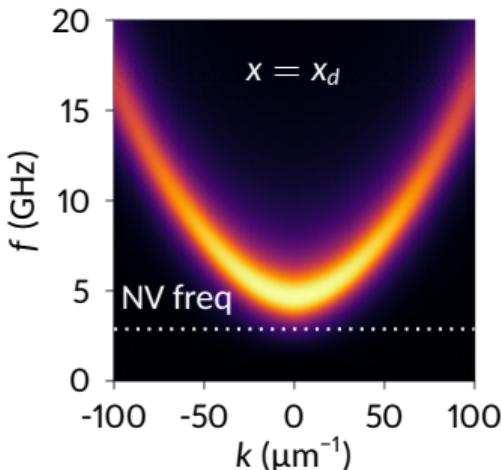
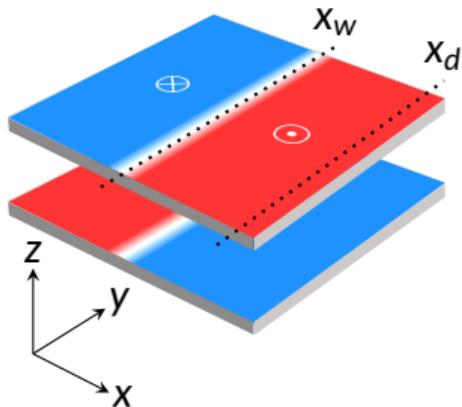
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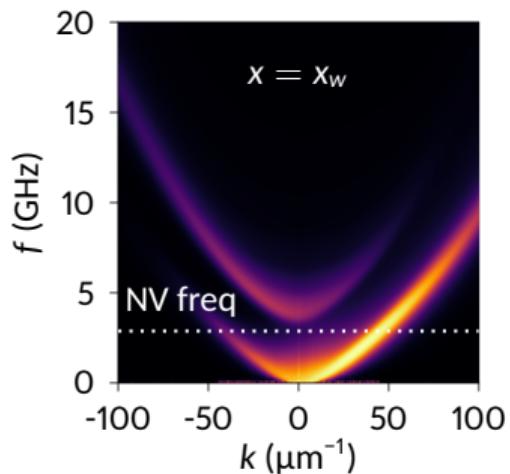
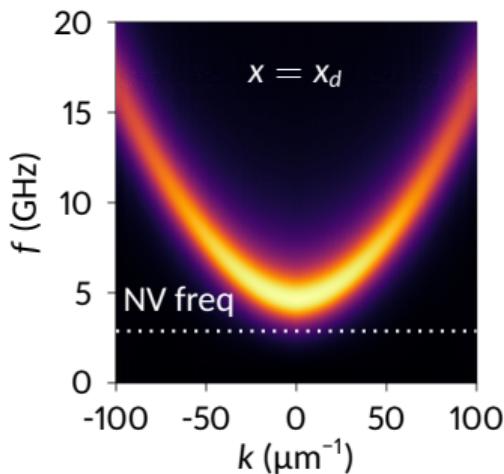
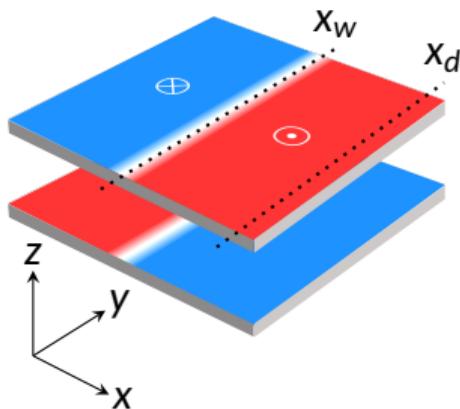
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- NV frequency below the gap: we are not sensitive to the spin waves in the domains.
- No gap in the domain walls, presence of modes at the NV frequency: **we are much more sensitive to the noise from the walls!**

# Calculated noise map

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

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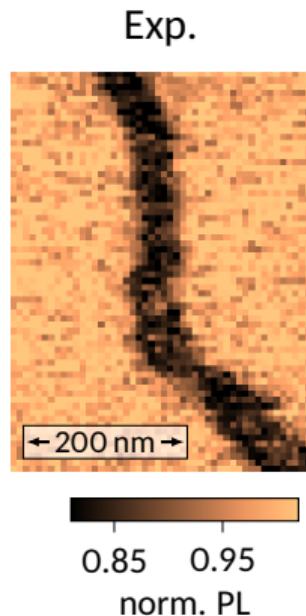
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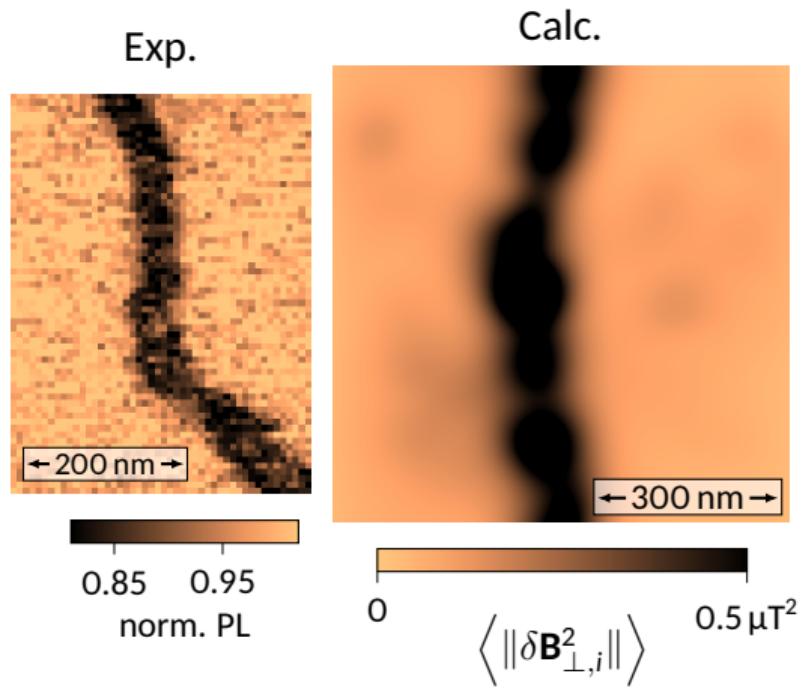
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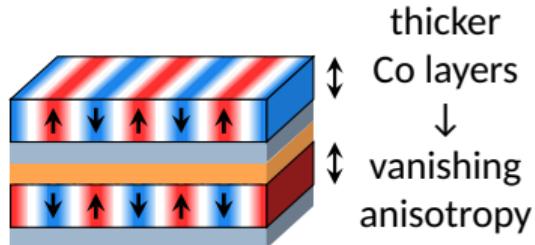
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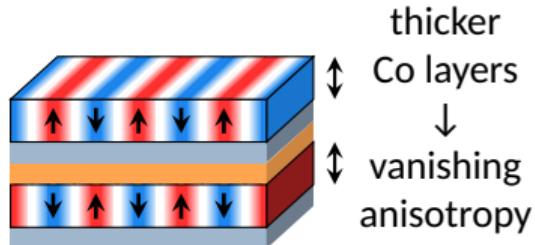


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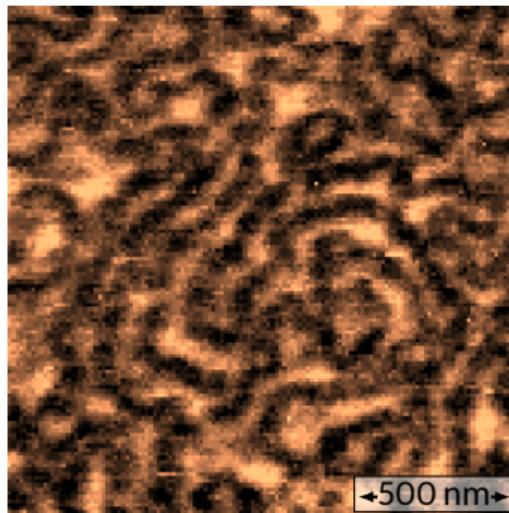


W. Legrand et al. *Nat. Mat.* 19 (2020), 34

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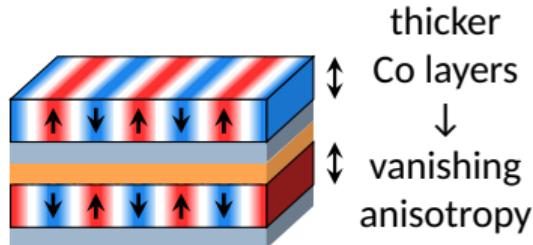


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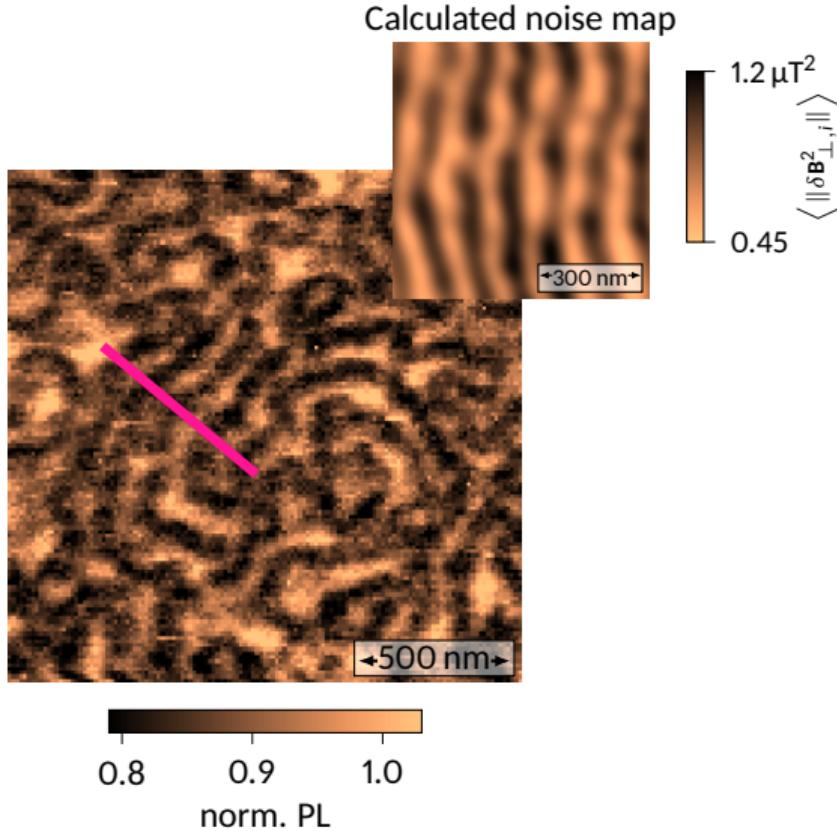
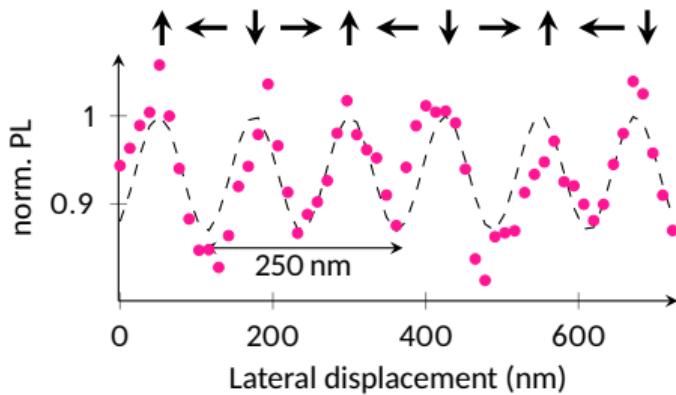


0.8    0.9    1.0  
norm. PL

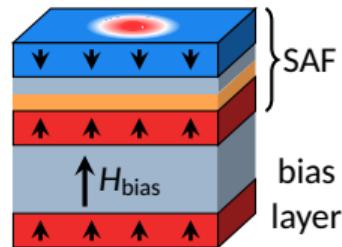
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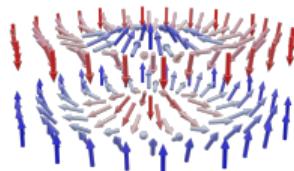
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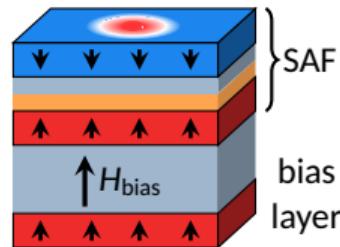
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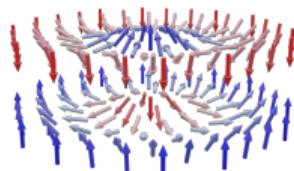
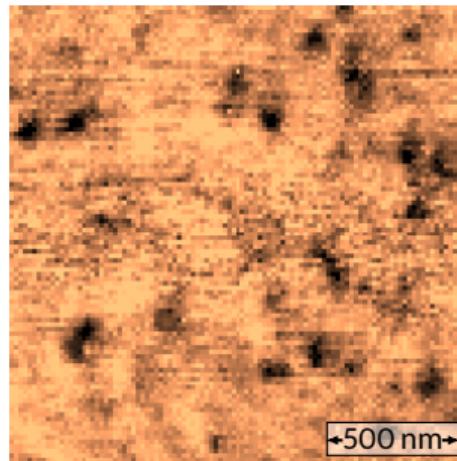
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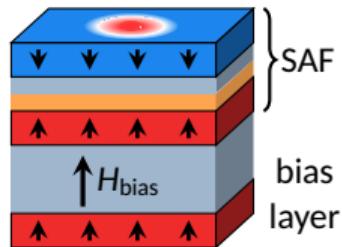
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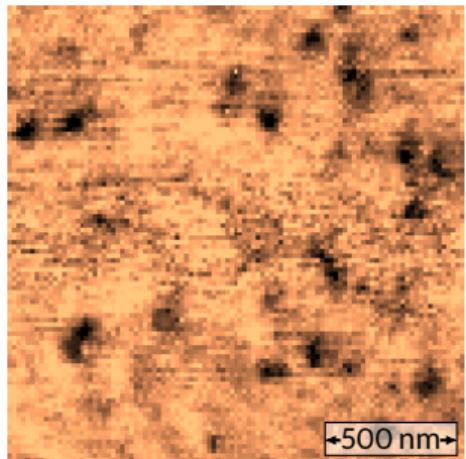
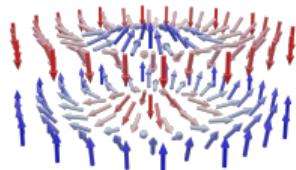
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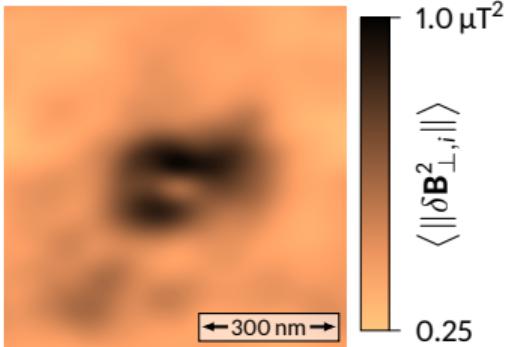
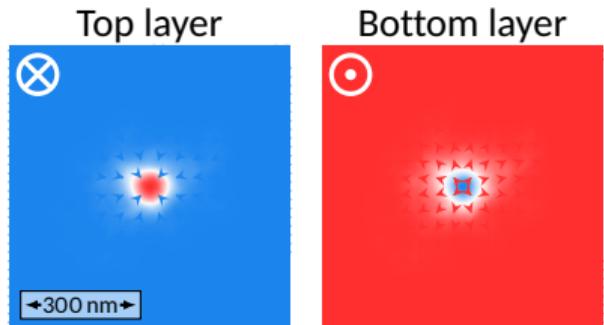
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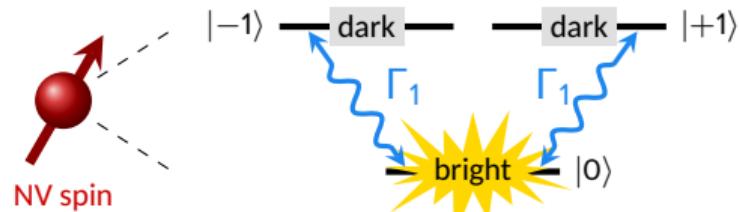


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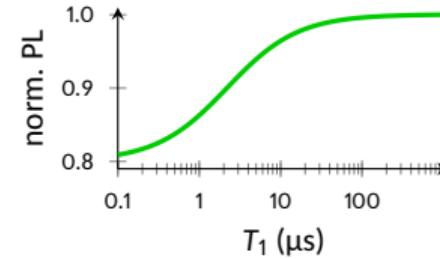


# Summary

→ All optical detection of magnetic noise with NV centers

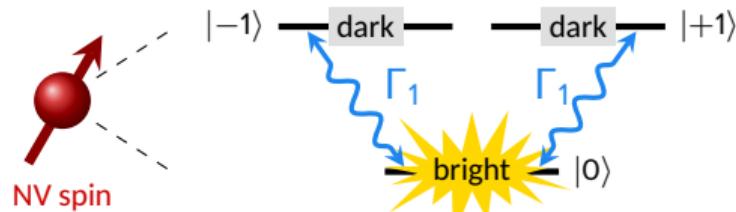


■ M. Rollo et al. [arXiv:2101.00860](https://arxiv.org/abs/2101.00860) (2021)

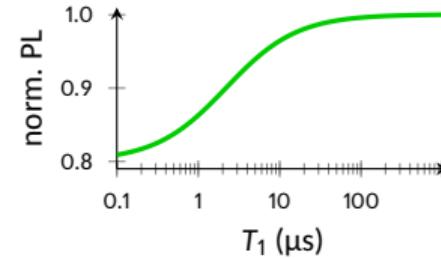


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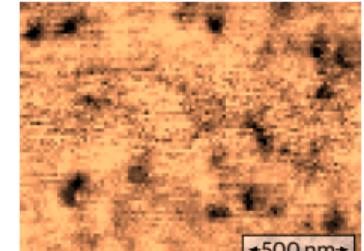
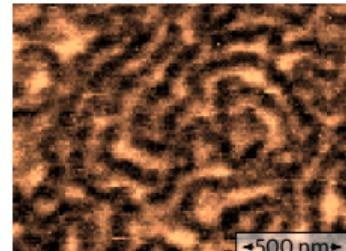
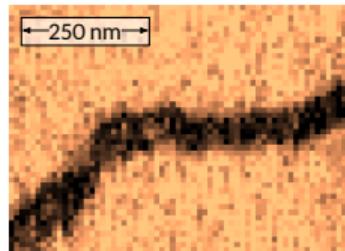
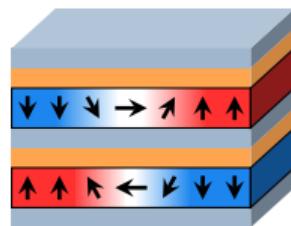
→ All optical detection of magnetic noise with NV centers



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



→ Application to the imaging of magnetic textures in synthetic antiferromagnets



■ A. Finco et al. [arXiv:2006.13130](https://arxiv.org/abs/2006.13130) (2020), accepted in Nat. Comm.

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Vincent Cros

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Jean-Paul Adam

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Joo-Von Kim



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