GDR PHYSIQUE QUANTIQUE MESOSCOPIQUE - SESSION PLENIERE 2016

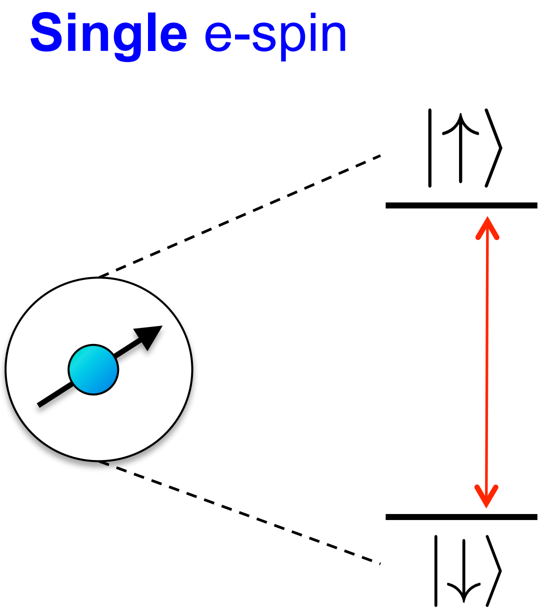
5-8 déc. 2016 Aussois (France)

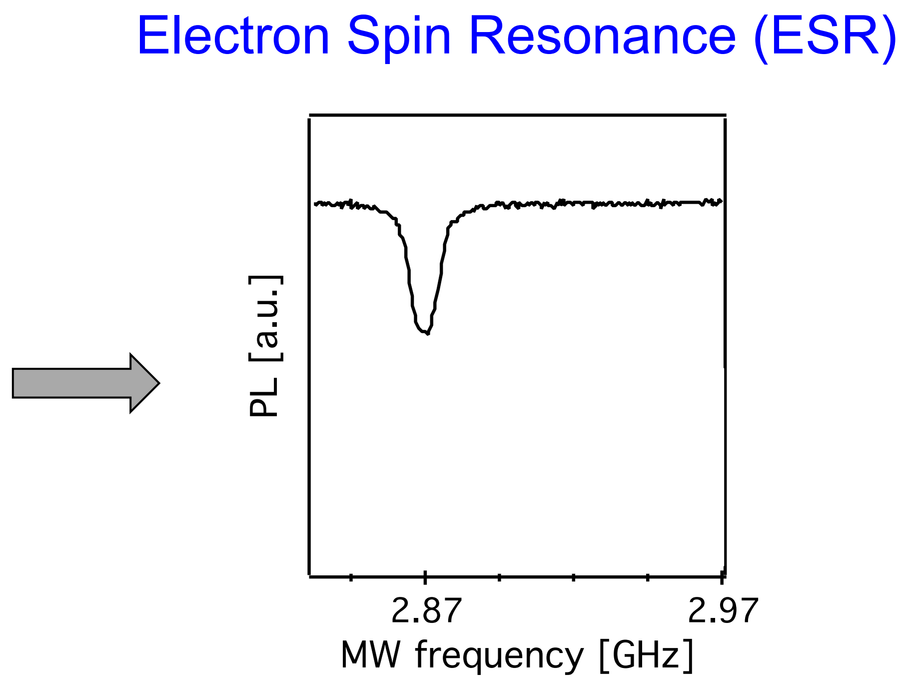
Imaging magnetism at the nanoscale with a single spin microscope

Vincent JACQUES

Laboratoire Charles Coulomb UMR 5221, Université Montpellier, and CNRS

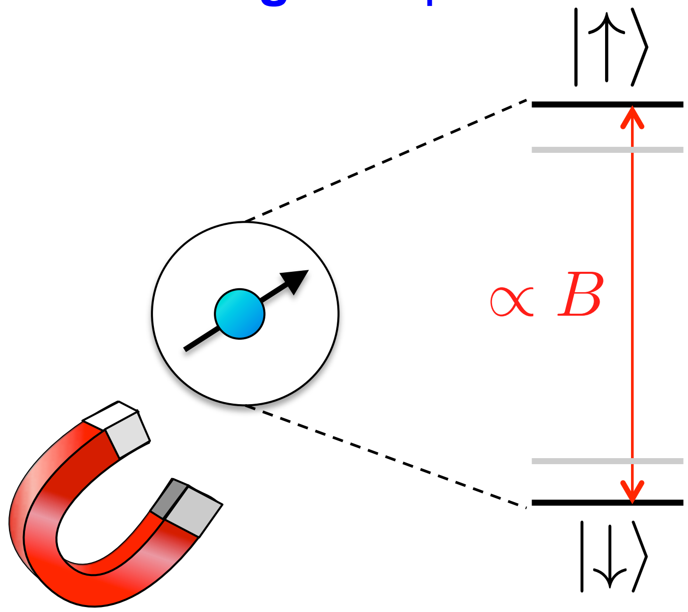
Magnetic field sensing with a single spin



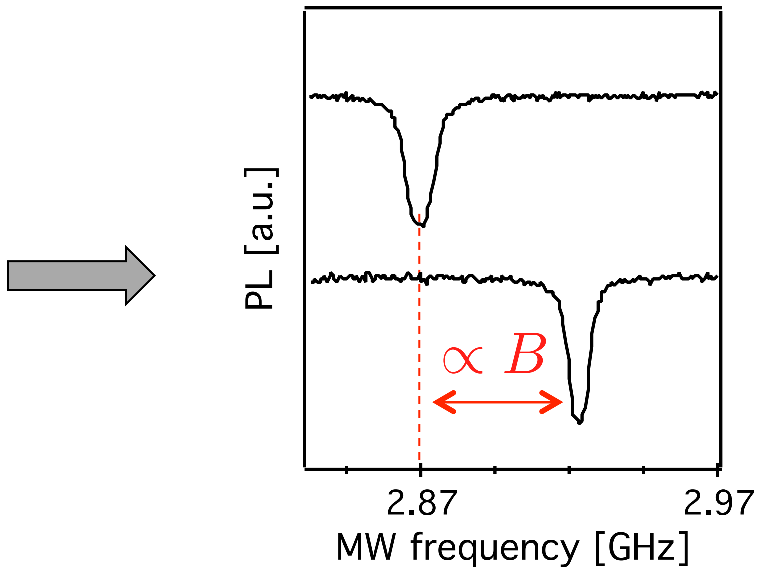


Magnetic field sensing with a single spin

Single e-spin



Electron Spin Resonance (ESR)



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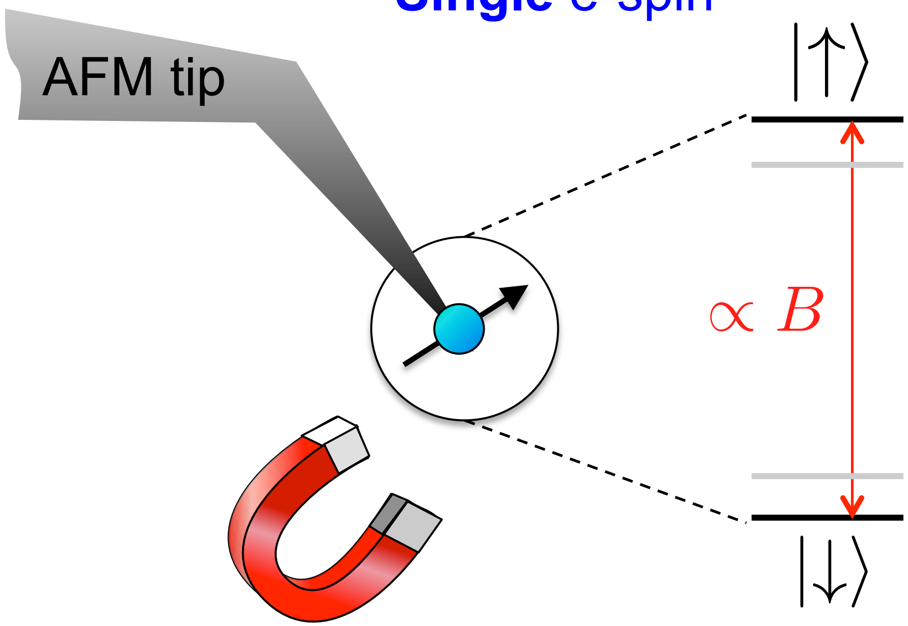
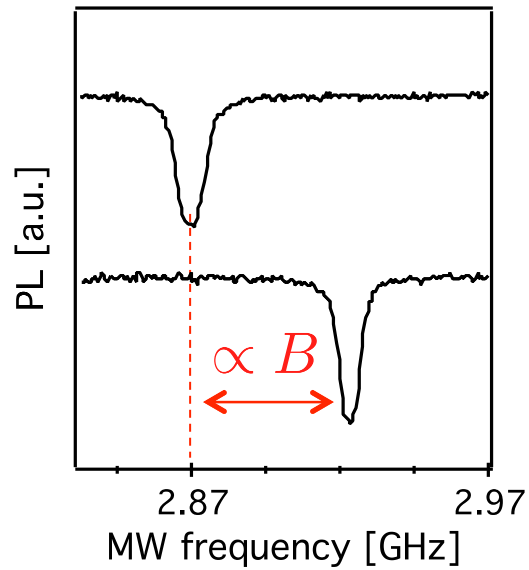


Chernobrod *et al., J. Appl. Phys*. **97**, 014903 (2005)

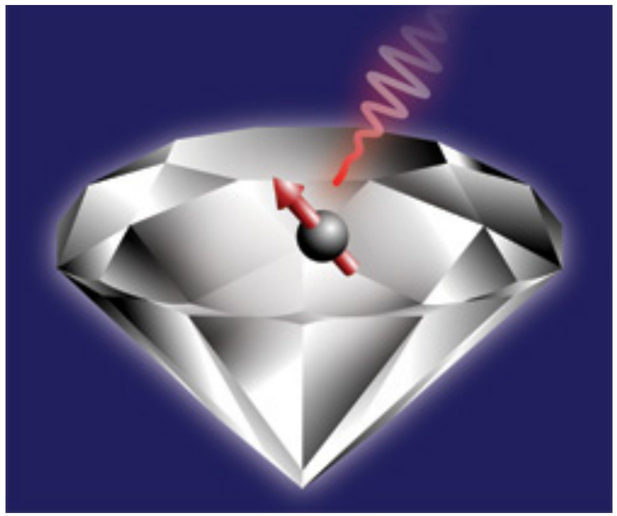
Electron Spin Resonance (ESR)



Quantitative B field measurement within an atomic-size detection volume

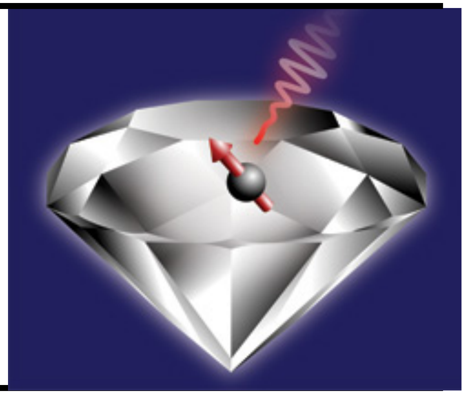
↓

Can be realized with the e-spin of a **single NV defect in diamond**



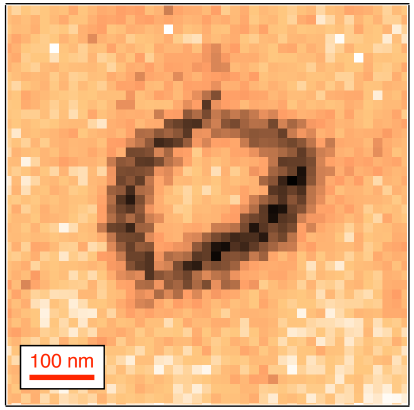
Outline of the talk

1. The NV defect in diamond as an atomic-sized magnetic field sensor

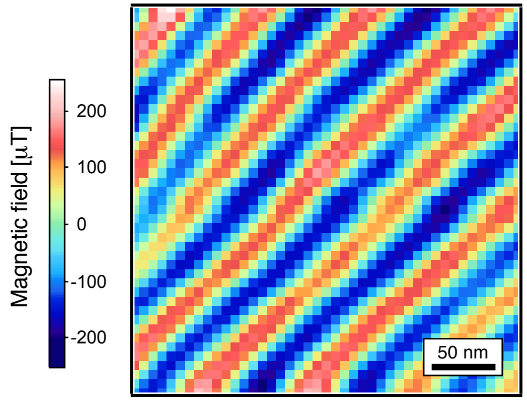


2. Applications in nanomagnetism

From dowain walls to skyrmions in ultrathin ferromagnets



Imaging antiferromagnetic order in multiferroics



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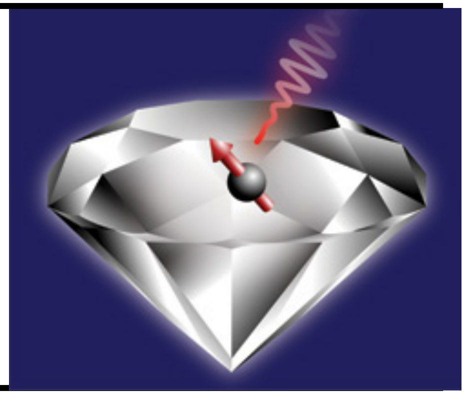


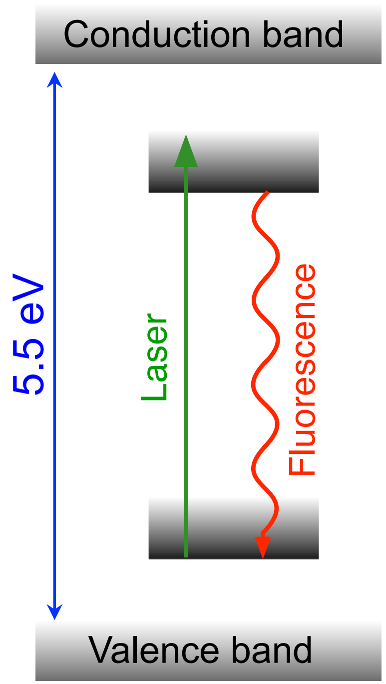
2. Applications in nanomagnetism

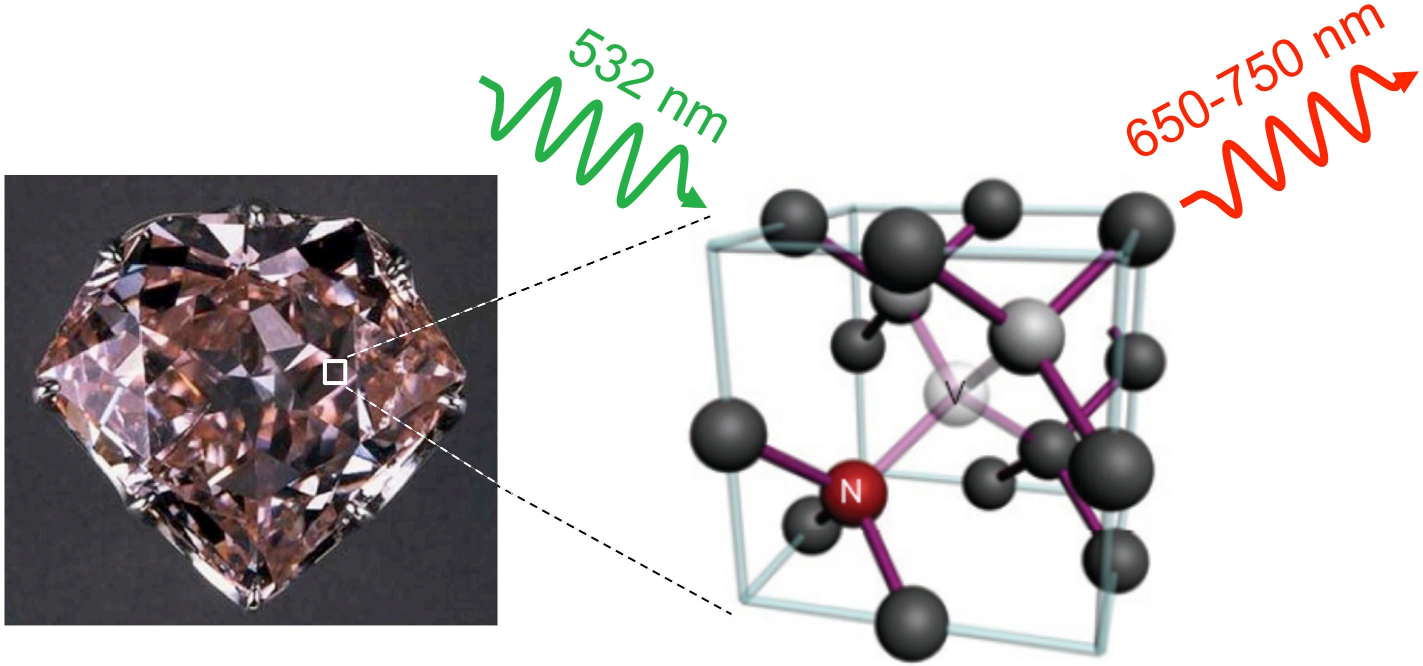
From dowain walls to skyrmions in ultrathin ferromagnets

Imaging antiferromagnetic order in multiferroics

Nitrogen-Vacancy (NV) defect in diamond

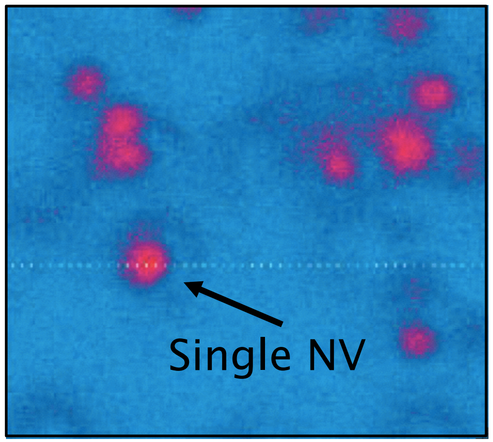
- An artificial atom « trapped » in the diamond lattice





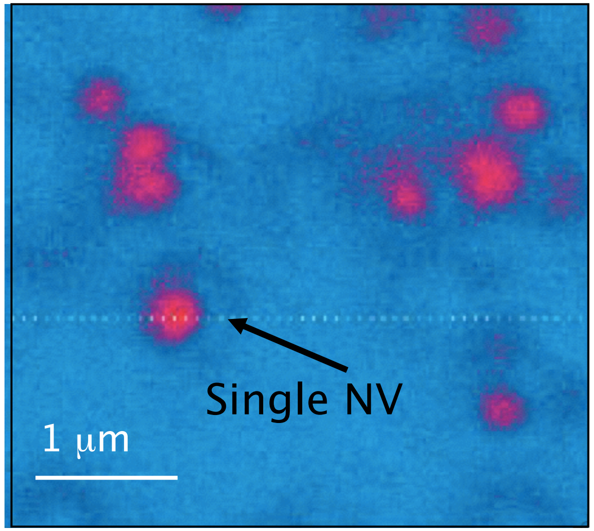
- Detection at the single emitter level **at room T –** *perfect photostability*

Gruber *et al.*, *Science* **276**, 2012 (1997)

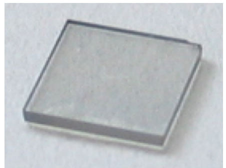


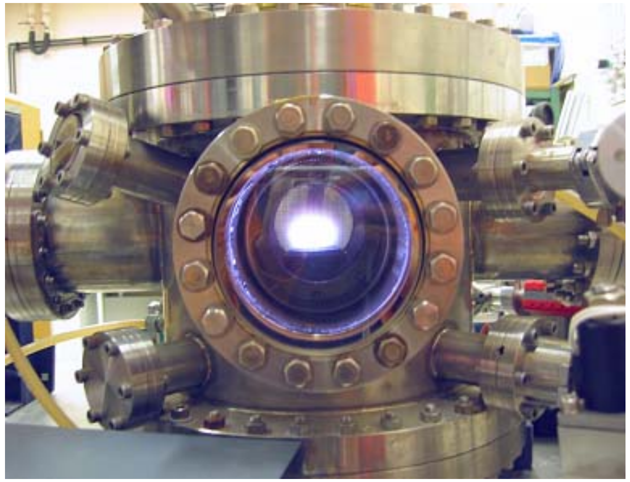
Engineering NV defect in diamond

1997



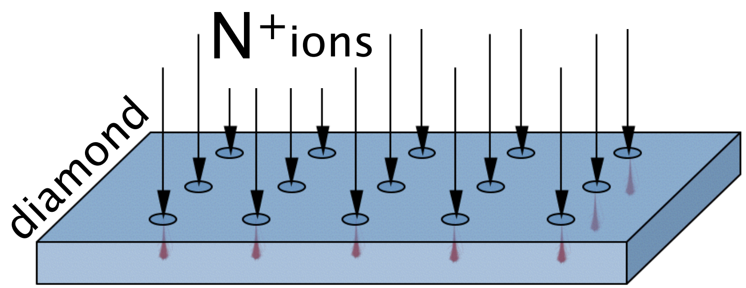
High purity diamond using **CVD growth**





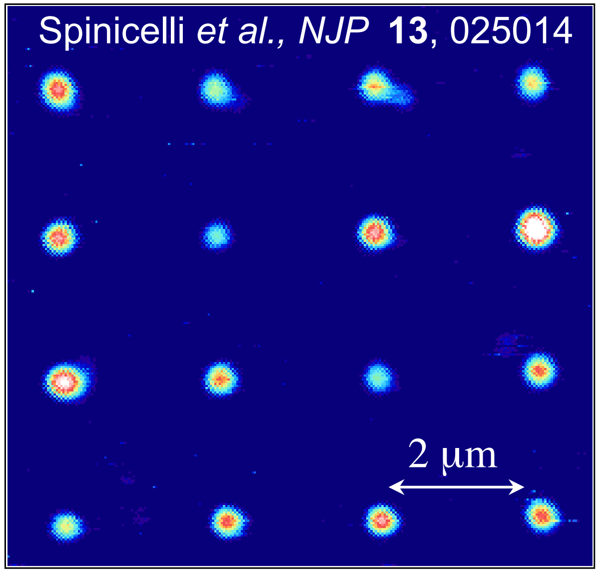
Gicquel and Achard group (Villetaneuse)

NV defect engineering through **nanoscale ion implantation**



Meijer group (Leipzig)

2012



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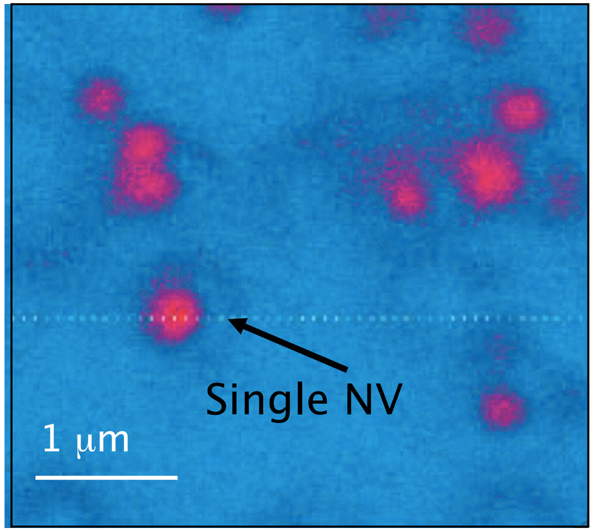

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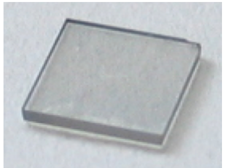

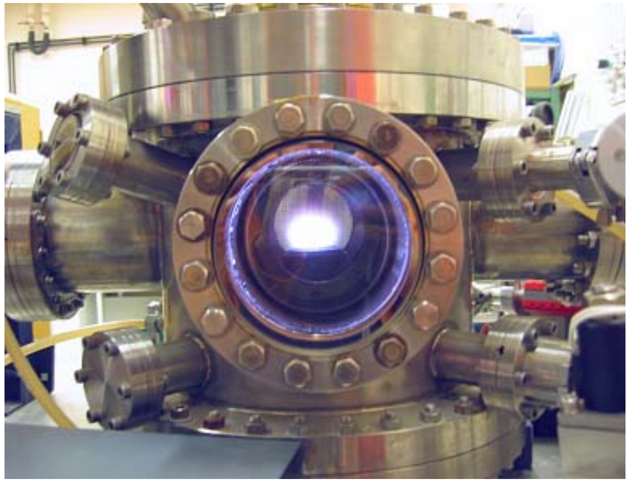

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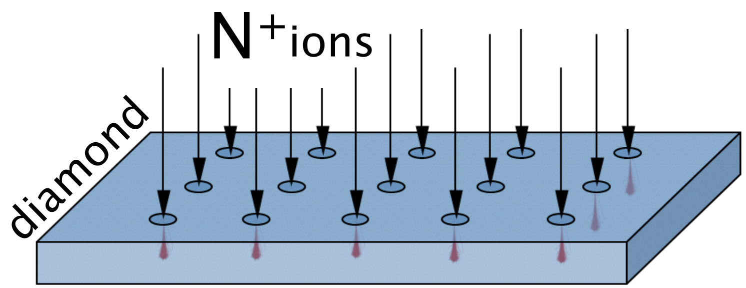

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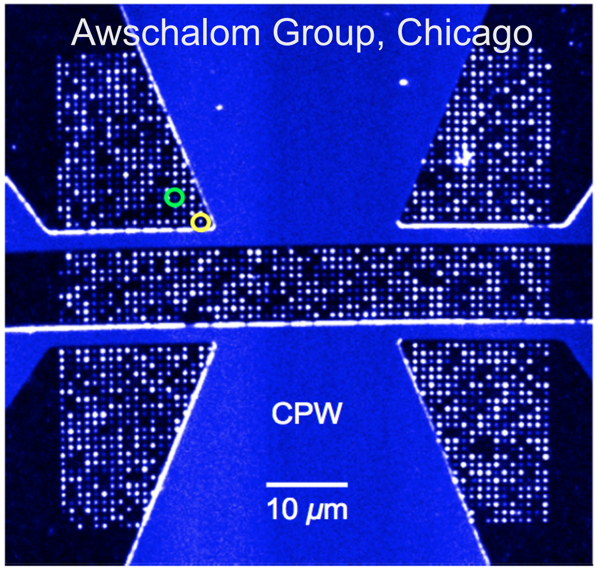
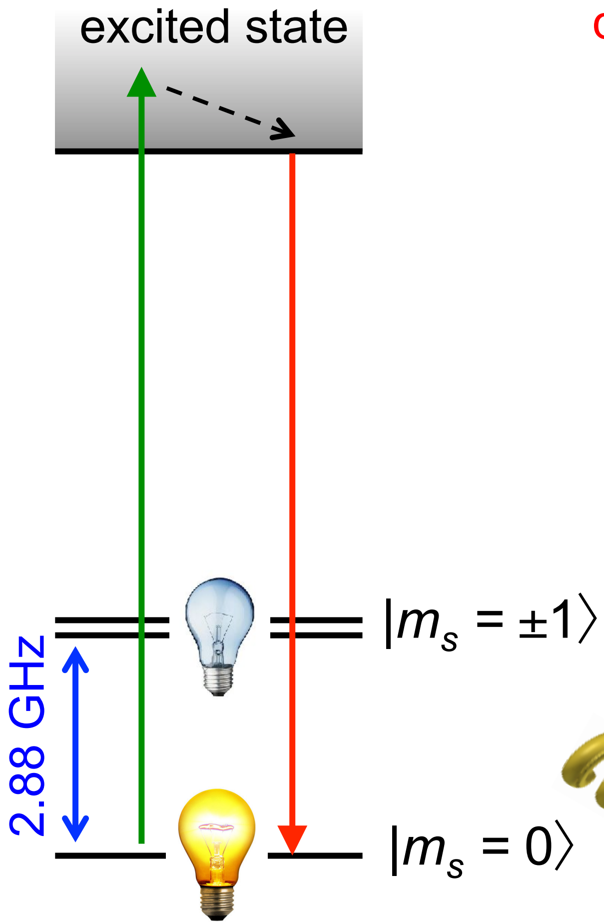
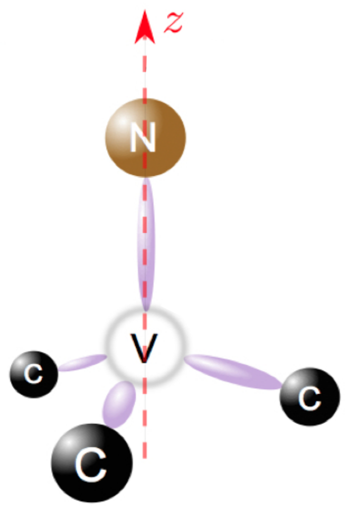
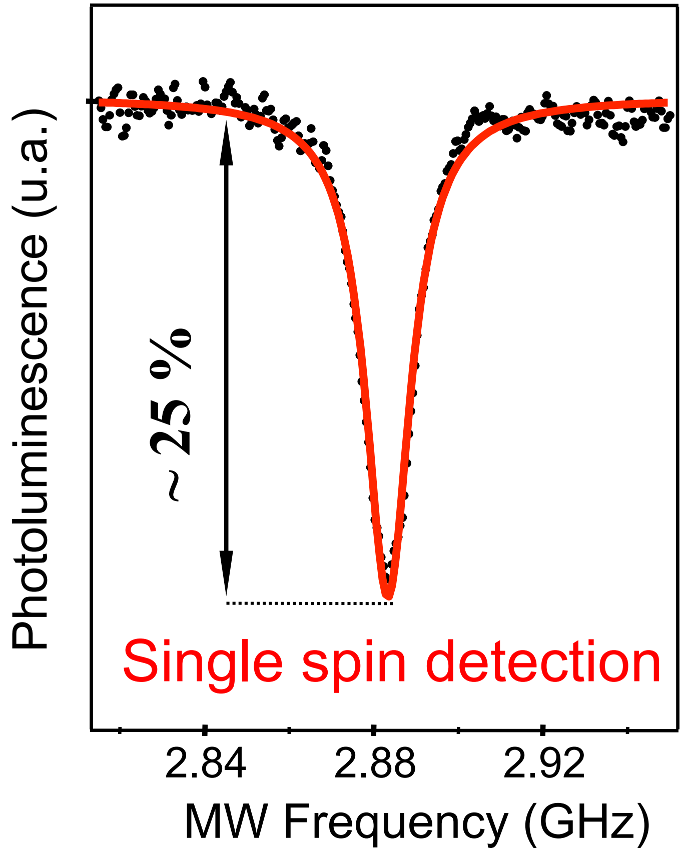


Optical detection of the electron spin resonance

- The ground state is a spin triplet (S=1)







NV = e-spin qubit

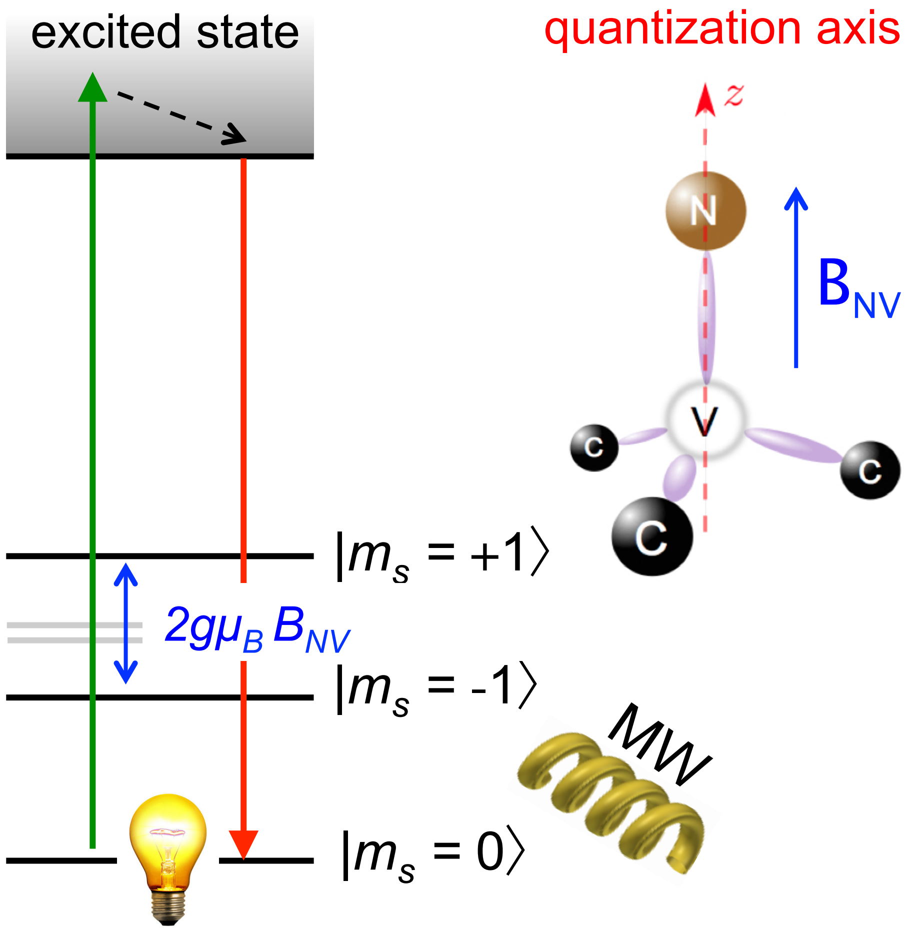
Coherence time T_2 ~ms @ room T

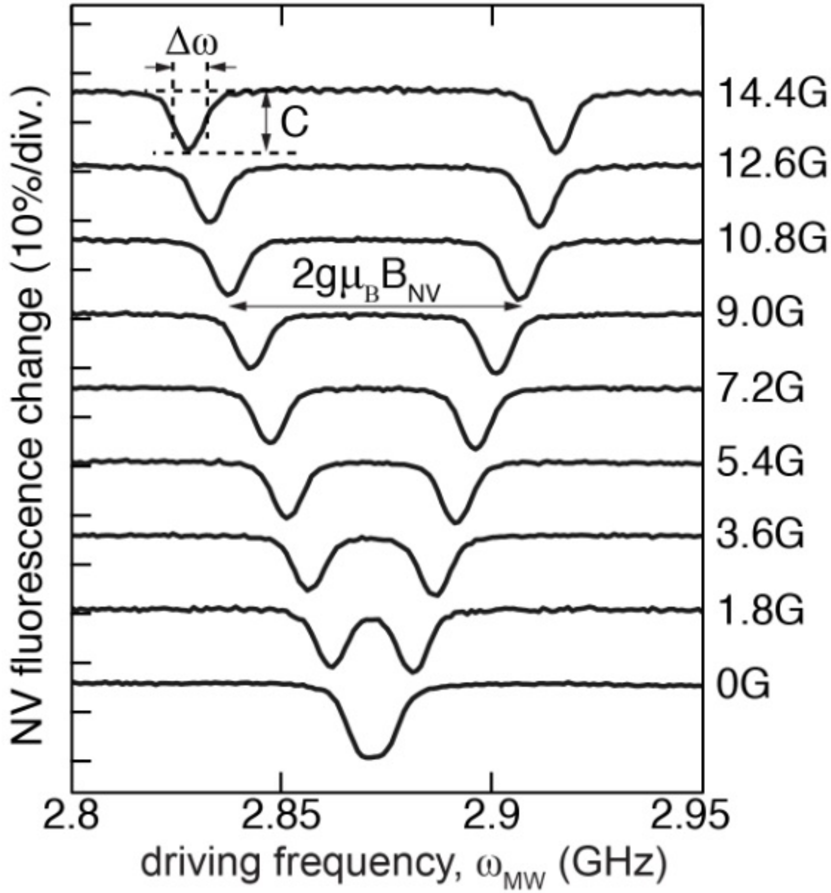
- Optical polarization into $m_s = 0$
- **Spin-dependent fluorescence**

Optical detection of the electron spin resonance

➤ The ground state is a spin triplet (S=1)

Rondin, *Rep. Prog. Phys.* **77**, 056503 (2014)





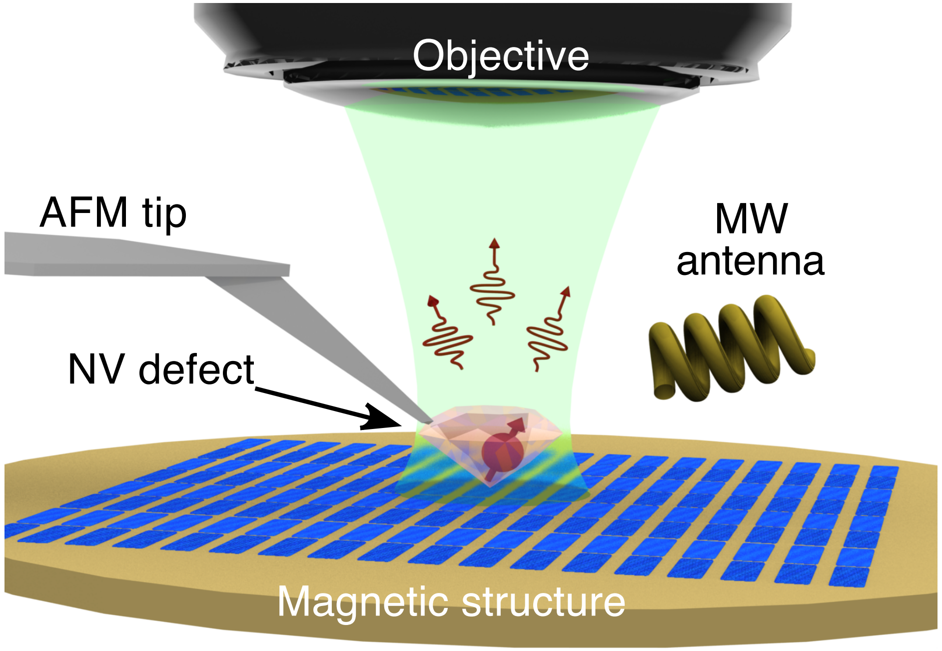
- Optical polarization into $m_s = 0$
- **Spin-dependent fluorescence**

NV defect
= magnetometer

Scanning-NV magnetometry

➢ Principle

Balasubramanian *et al.*, *Nature* **455**, 648 (2008)



- ⋆ Atomic-sized detection volume
- ⋆ Quantitative and vectorial
- ⋆ No magnetic back-action

Scanning-NV magnetometry

➢ Principle

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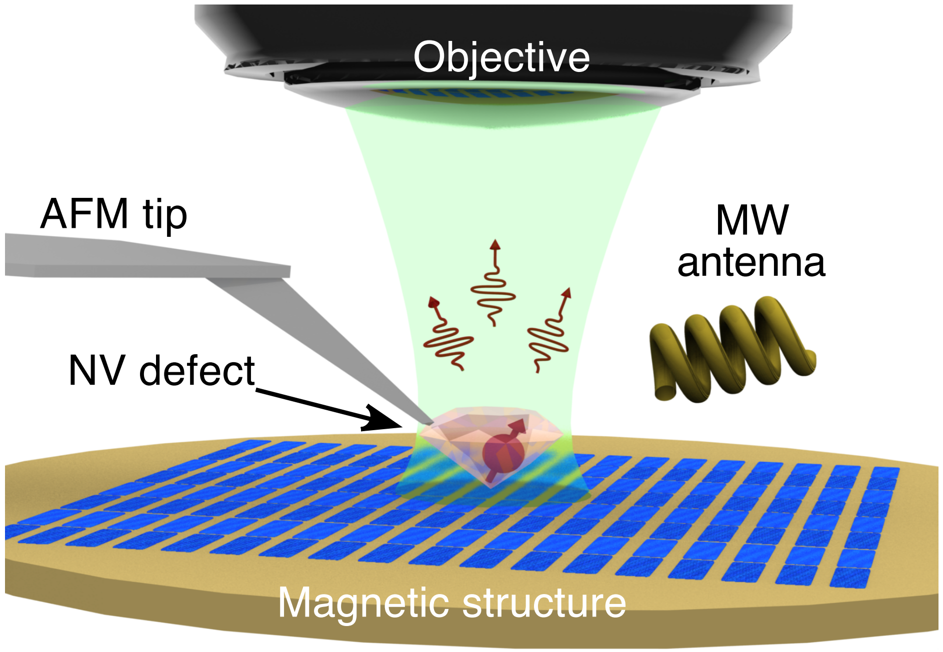
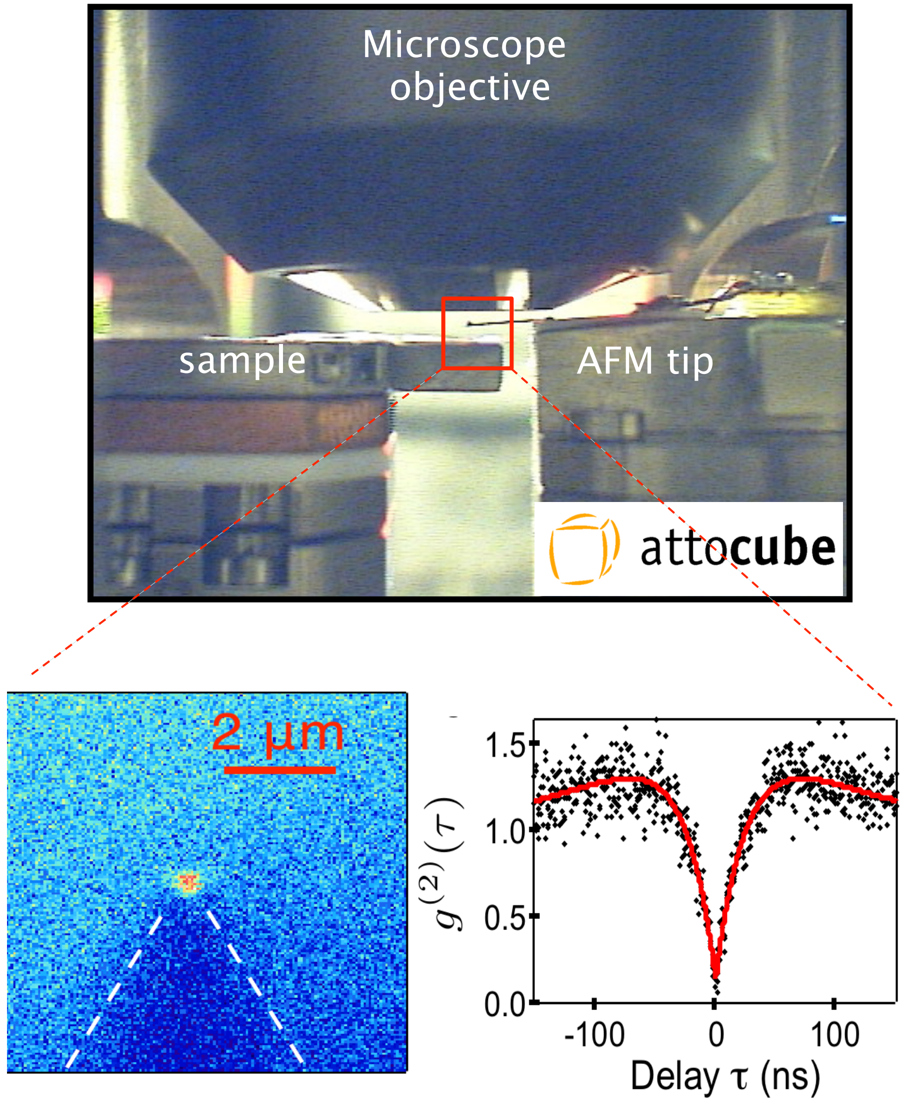
Nature **455**, 648 (2008)



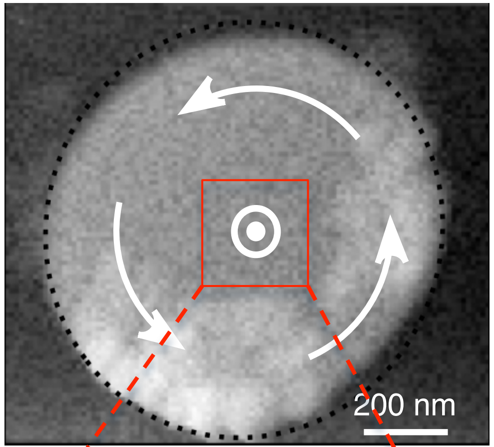
- ★ Atomic-sized detection volume
- ★ Quantitative and vectorial
- ★ No magnetic back-action

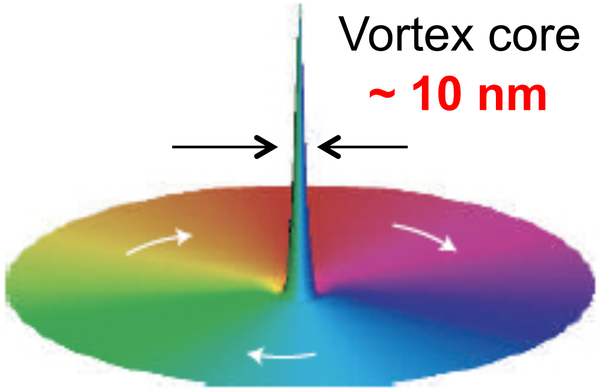
➢ Experiment

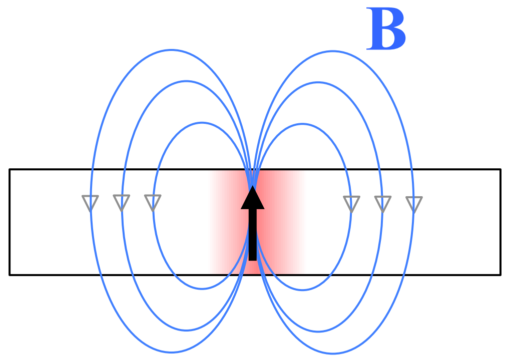


Imaging the core of a magnetic vortex

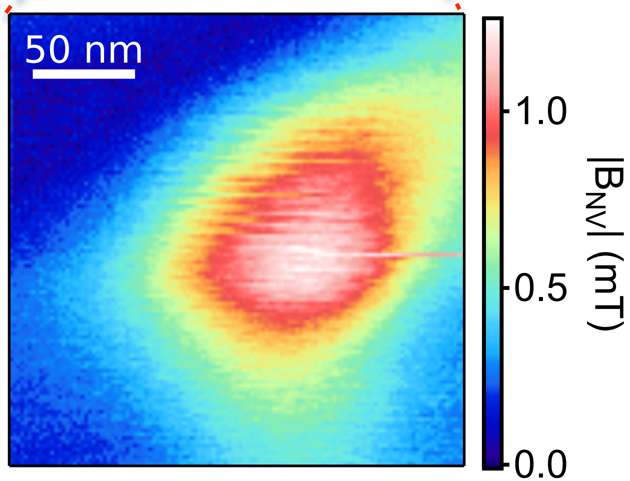
AFM image







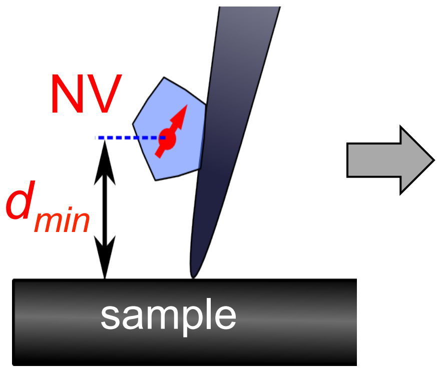
NV image

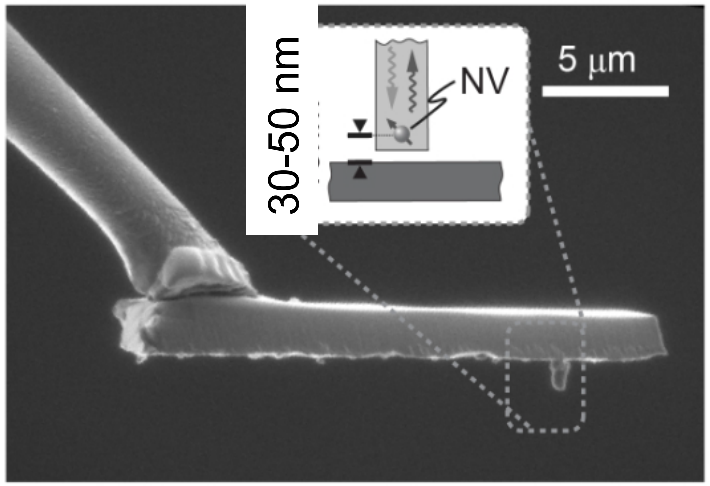


Rondin, *Nat. Com.* **4**, 2279 (2013)

- **Resolving power ~ 100 nm**

Limited by the probe-to-sample distance d_{min}





Maletinsky group (Basel)

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2. Applications in nanomagnetism

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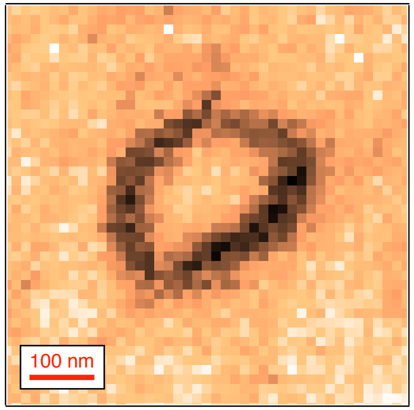
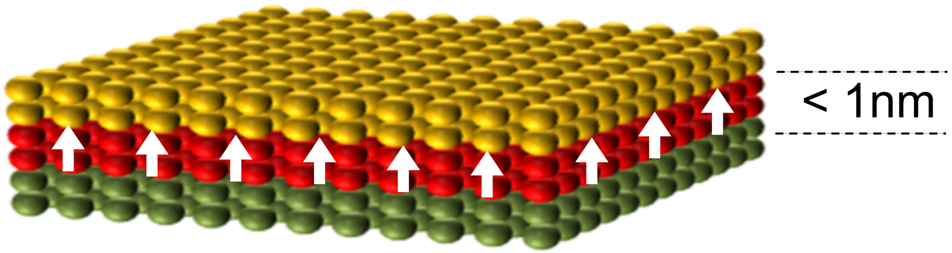


Imaging antiferromagnetic order in multiferroics

Ferromagnets “shrink” to few atomic layers…

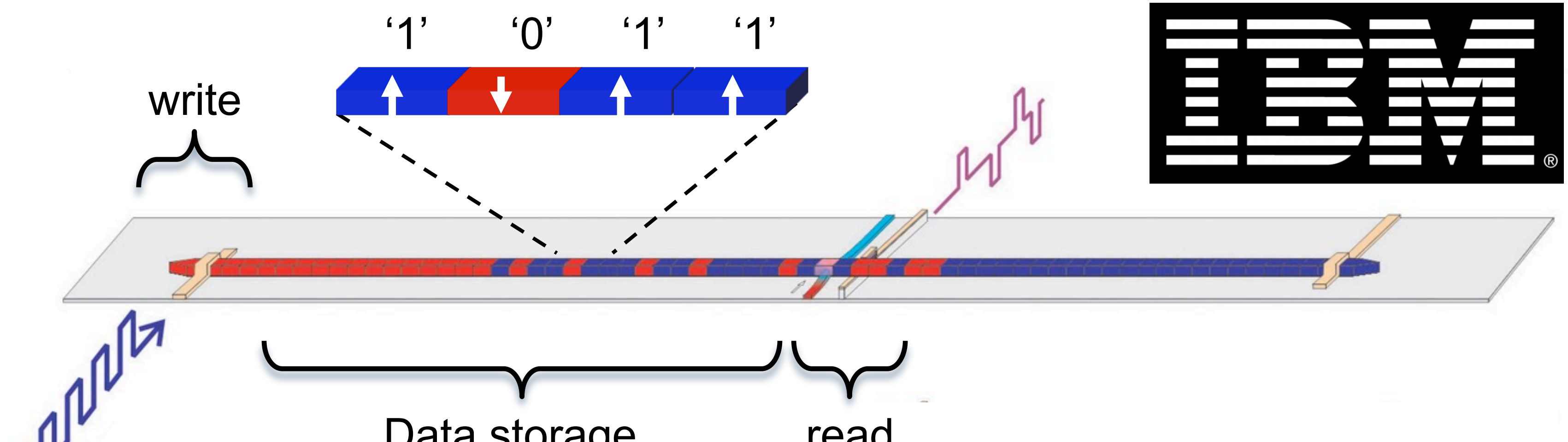


Surface energy ≈ Volume energy

Interface interactions — Anisotropy, exchange…

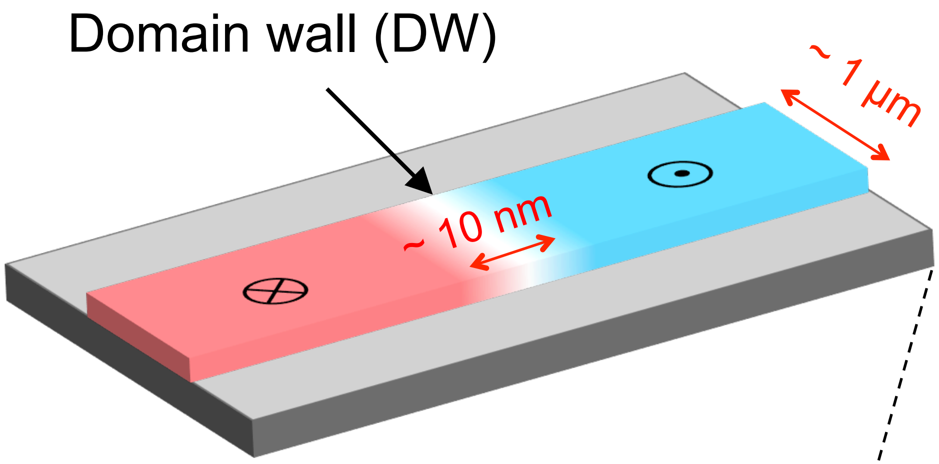
- ★ **Technological interest** (spintronic devices with low power consumption)
- ★ **Rich new physics** mediated by the interface

e. g. *:* the domain wall (DW) “racetrack memory”



Parkin et al., Science 320, 190 (2008)

Domain walls in ultrathin ferromagnets

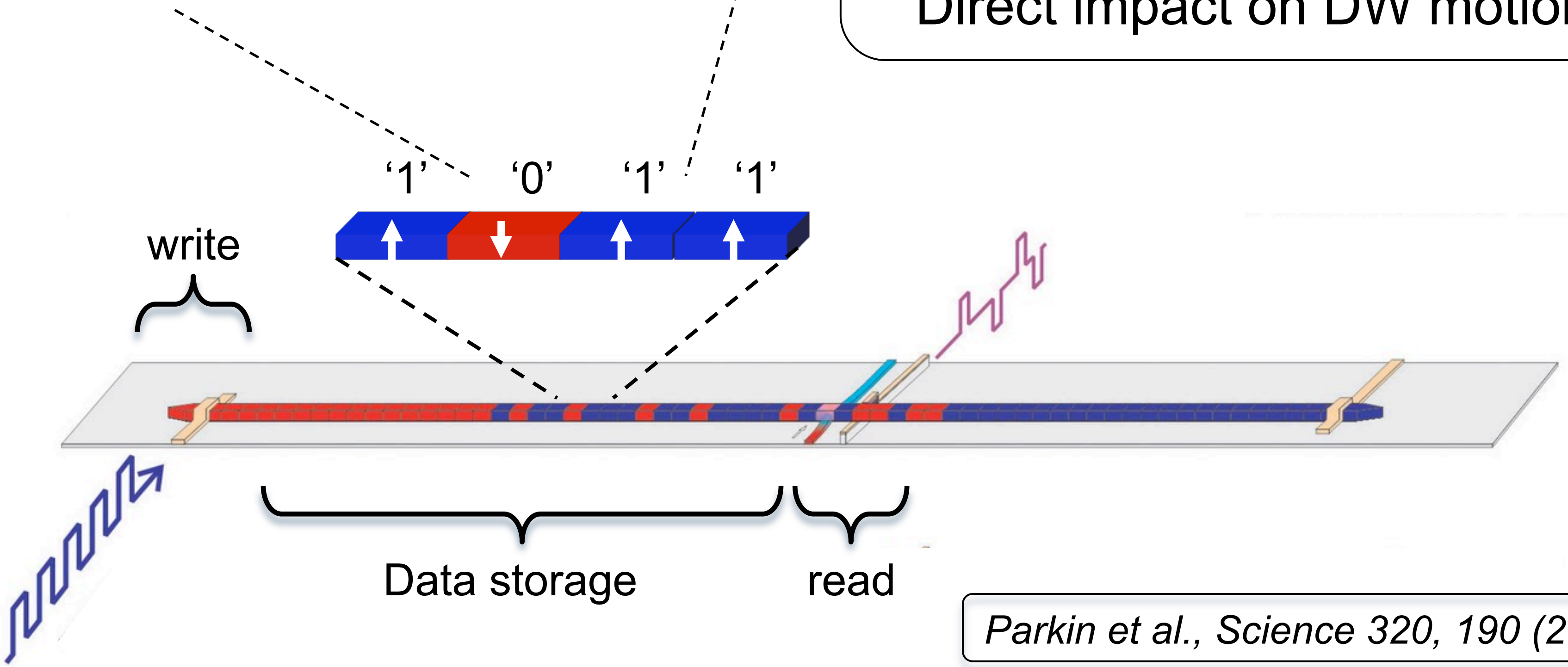


One important issue

What is the effect of the interface on the DW structure ?

↓

Direct impact on DW motion



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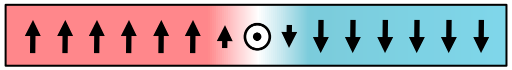
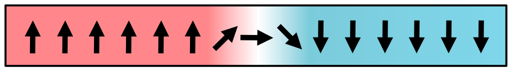
Inner structure of a domain wall

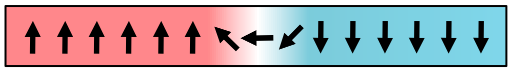
Bloch wall



Néel wall (right)



Néel wall (left)



- Bloch walls are predicted by elementary magnetostatic theory

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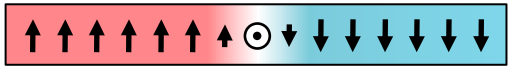

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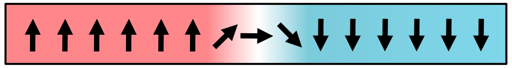

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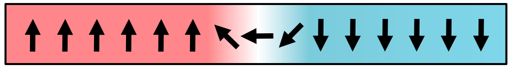
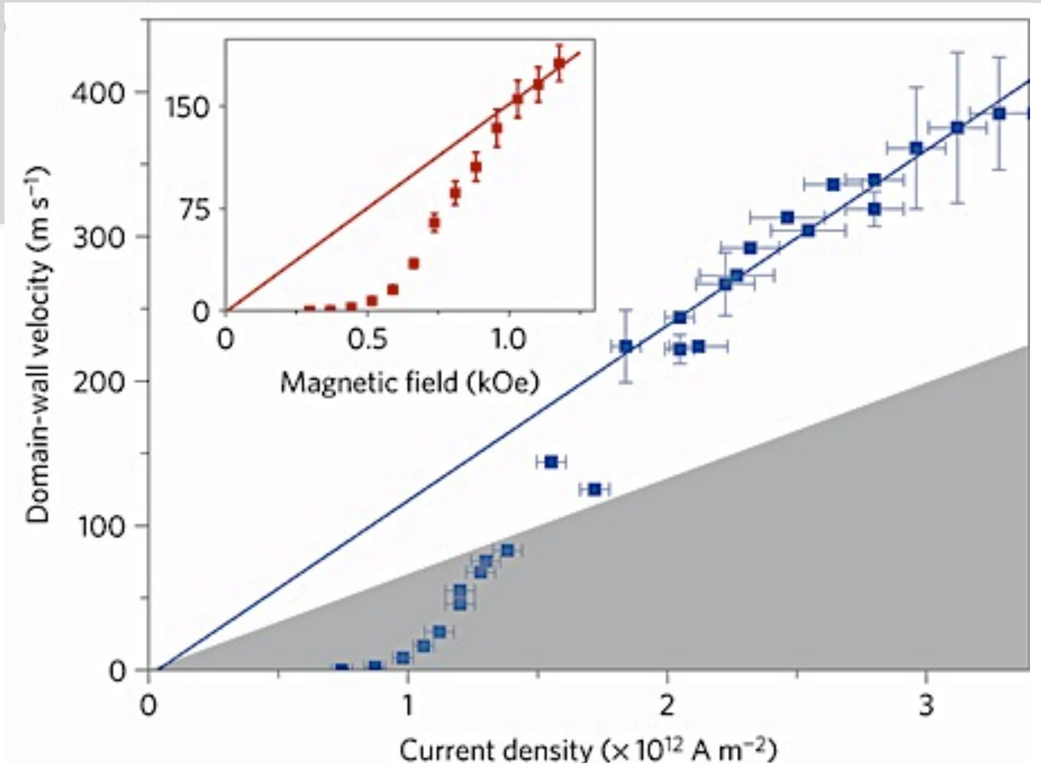


- Bloch walls are predicted by elementary magnetostatic theory
- But inconsistencies in recent current-induced domain wall motion experiments

Miron et al., Nat. Mater. 10, 419 (2011)
Ryu et al., Nat. Nano. 8, 527 (2013)



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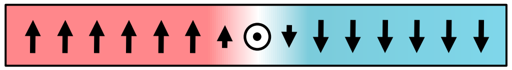

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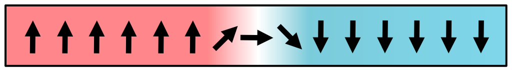

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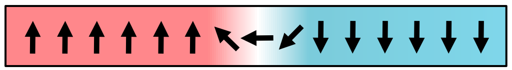


Fert *et al. Nat. Nano.* **8**, 152 (2013)

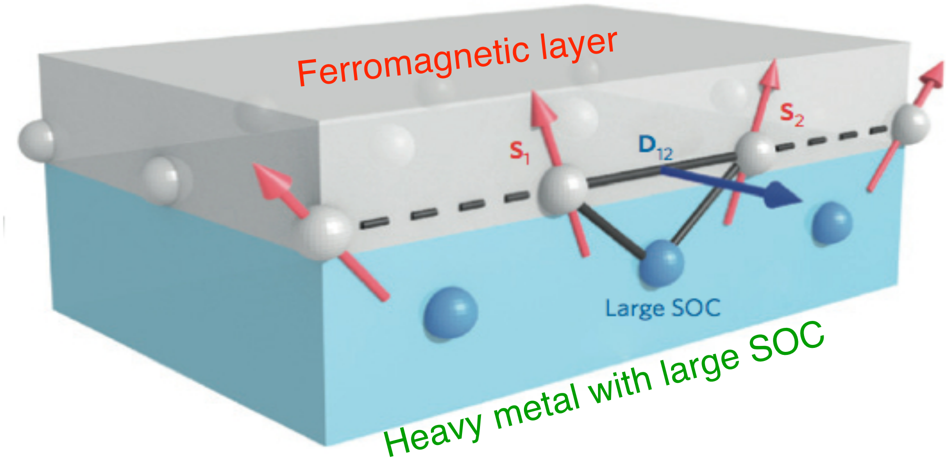
- Bloch walls are predicted by elementary magnetostatic theory

- But inconsistencies in recent current-induced domain wall motion experiments

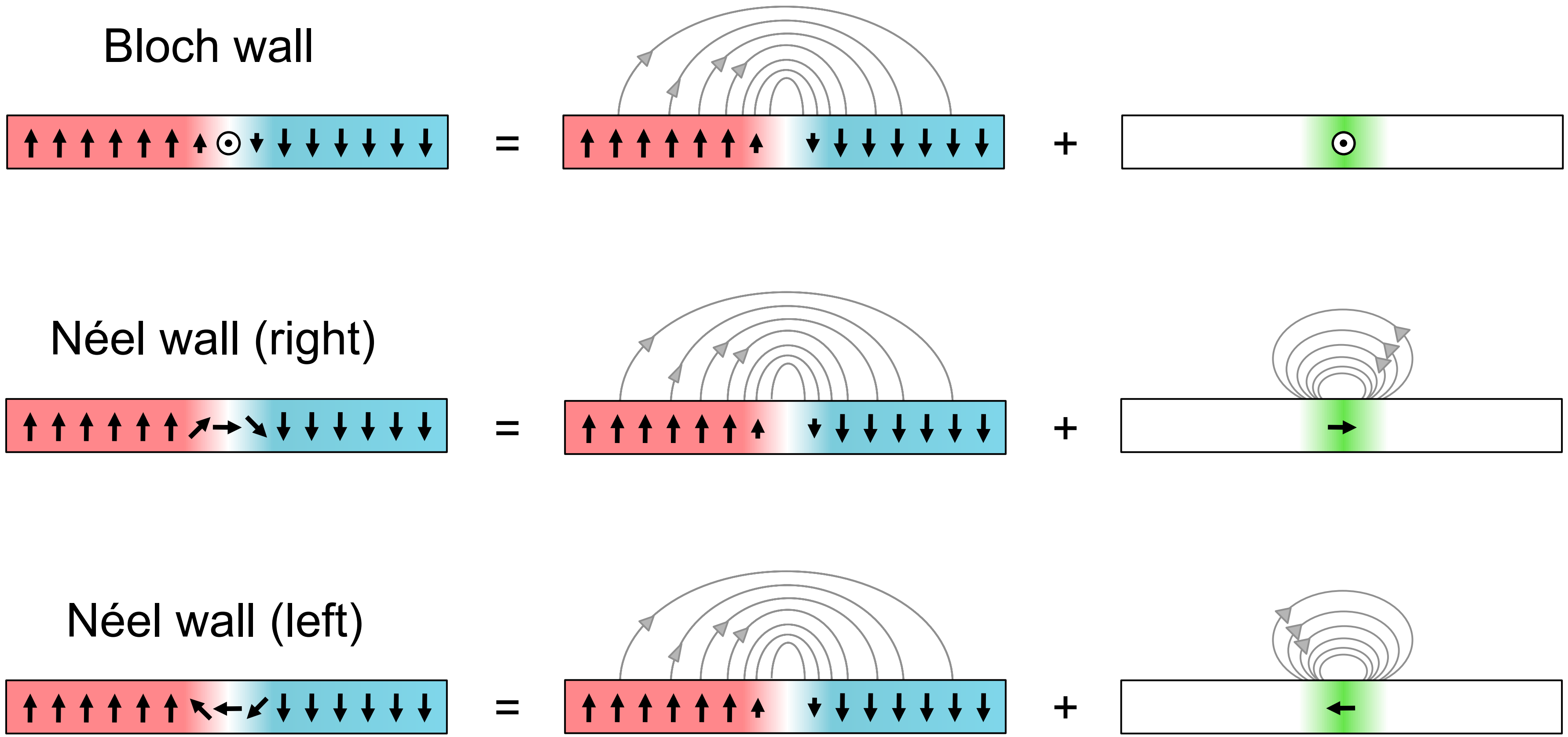
  Miron et al., Nat. Mater. 10, 419 (2011)
  Ryu et al., Nat. Nano. 8, 527 (2013)

- Interfacial Dzyaloshinskii-Moriya interaction proposed as a way to stabilize Néel walls

  Thiaville et al., EJP 100, 57002 (2012)



Determining the structure of the DW



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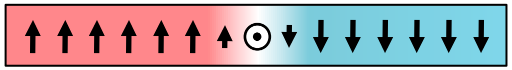

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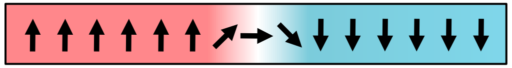

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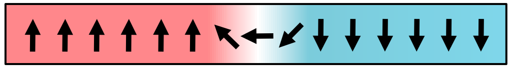
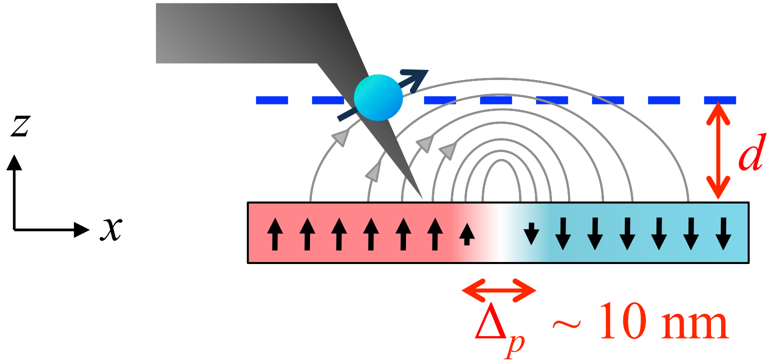
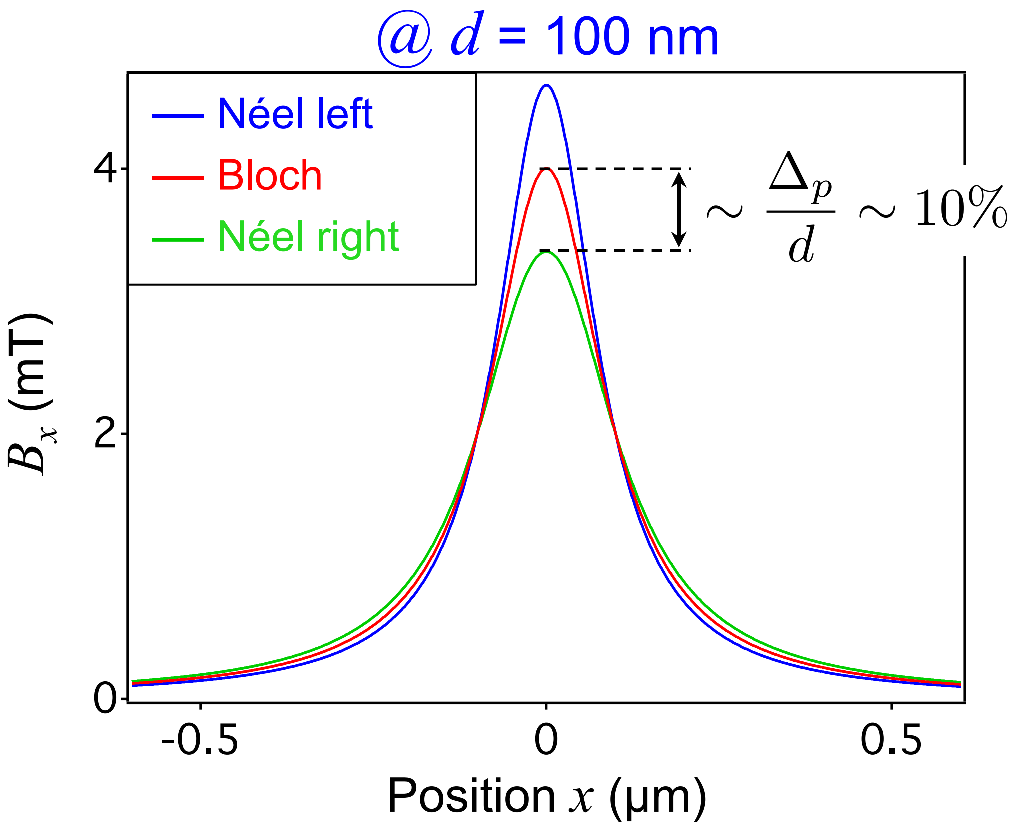


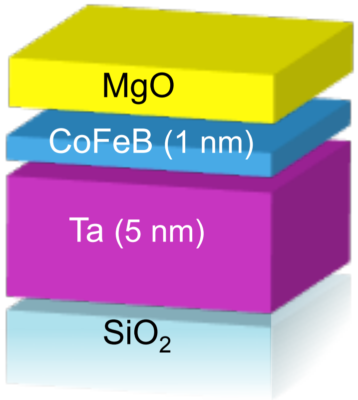


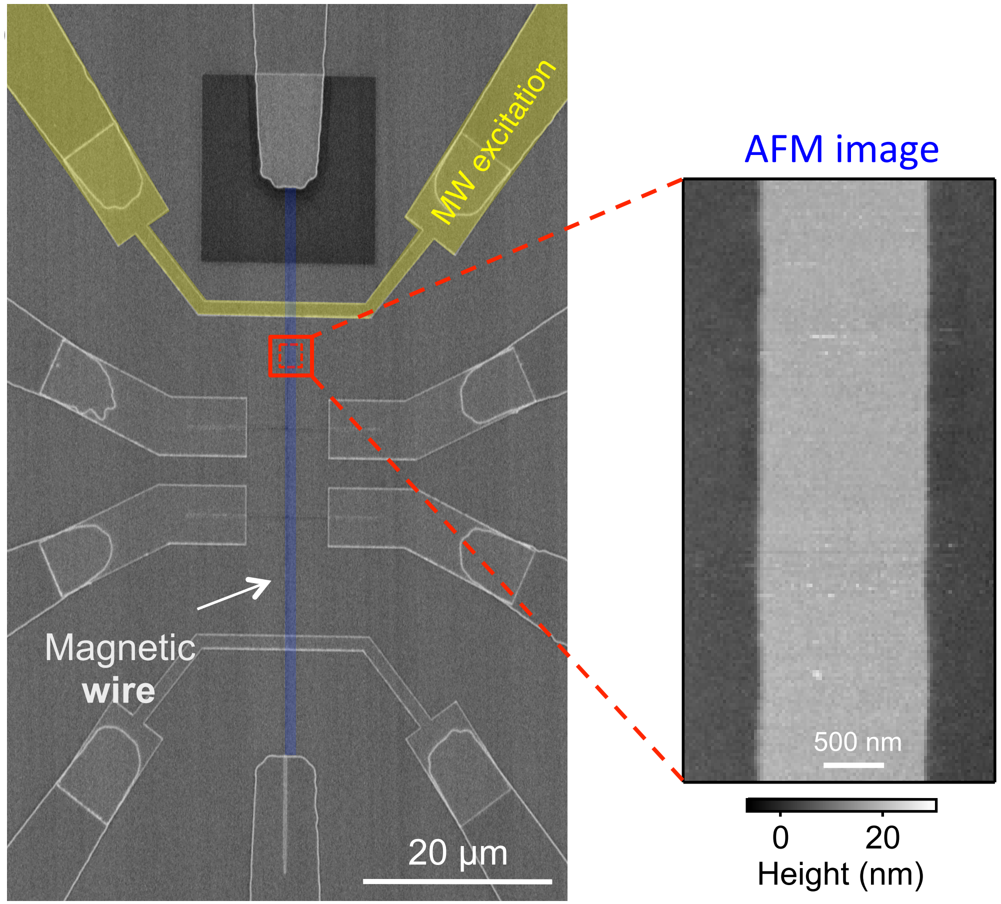


DW imaging with a scanning NV magnetometer

Magnetic wire

Ta / $Co_{40}Fe_{40}B_{20}$(1 nm) / MgO





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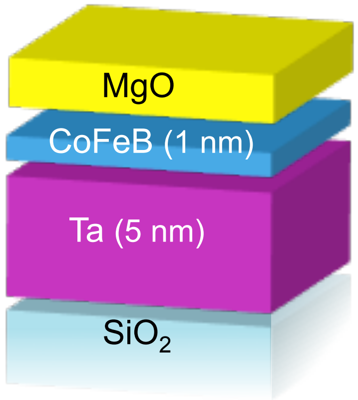
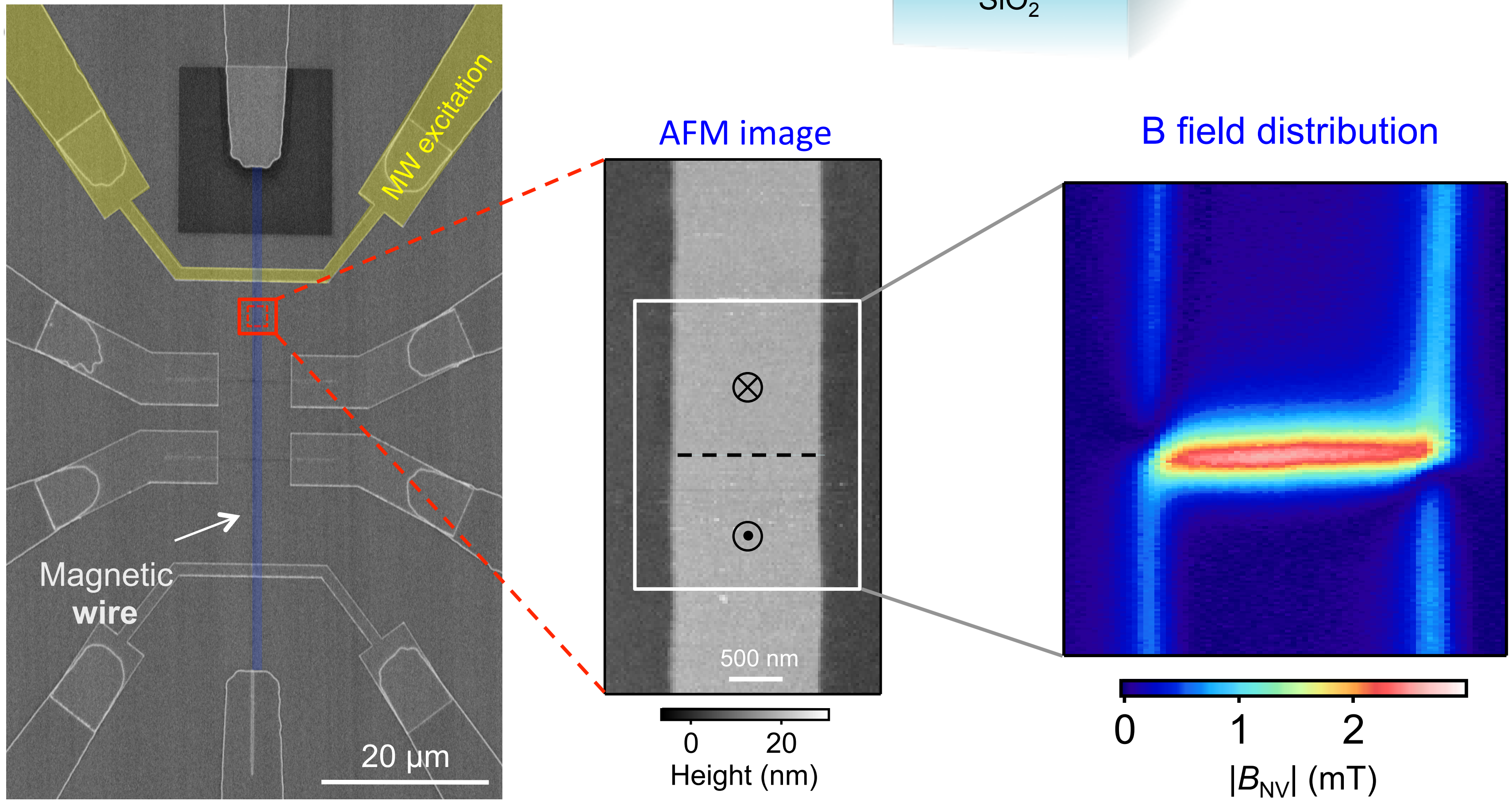
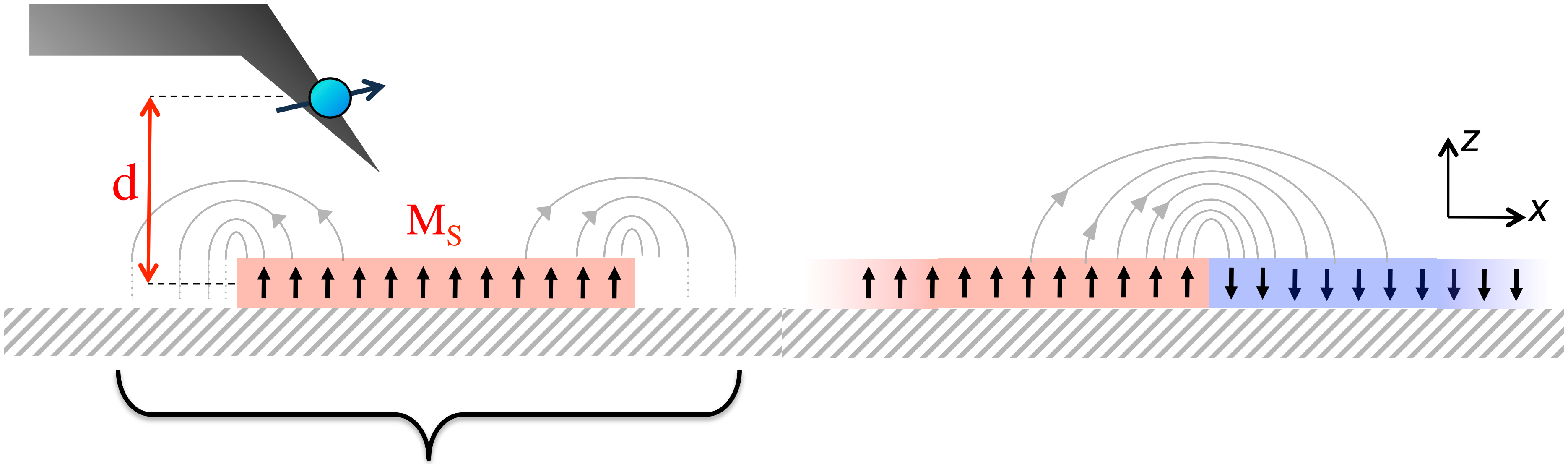
Ta / $Co_{40}Fe_{40}B_{20}$(1 nm) / MgO





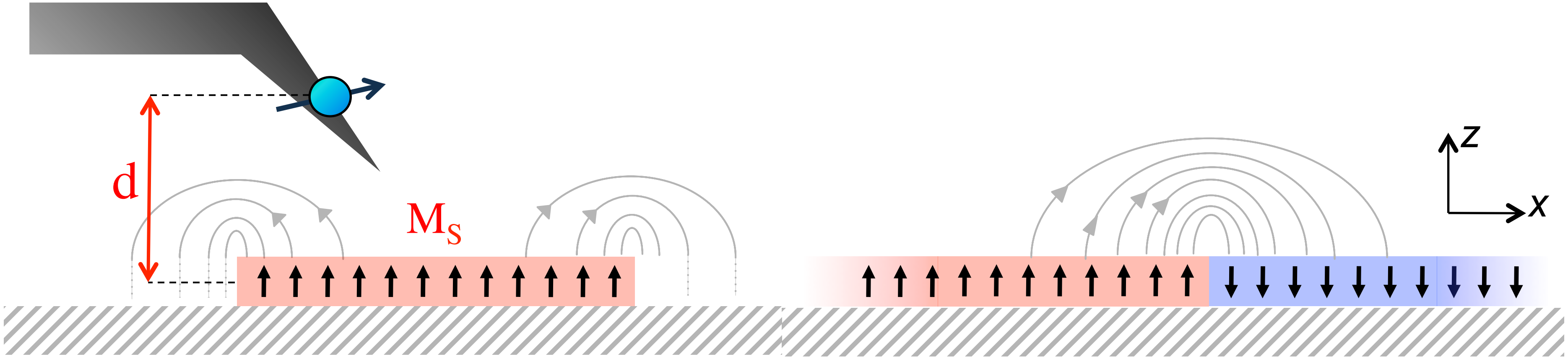
Calibration of the experiment : M_s, d ?

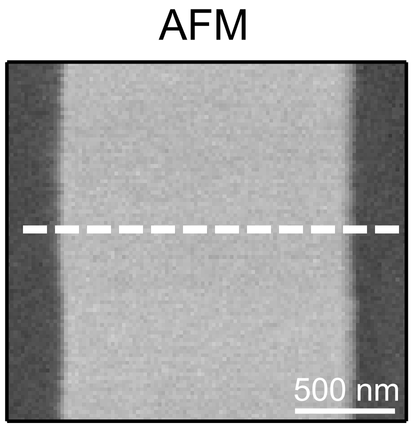


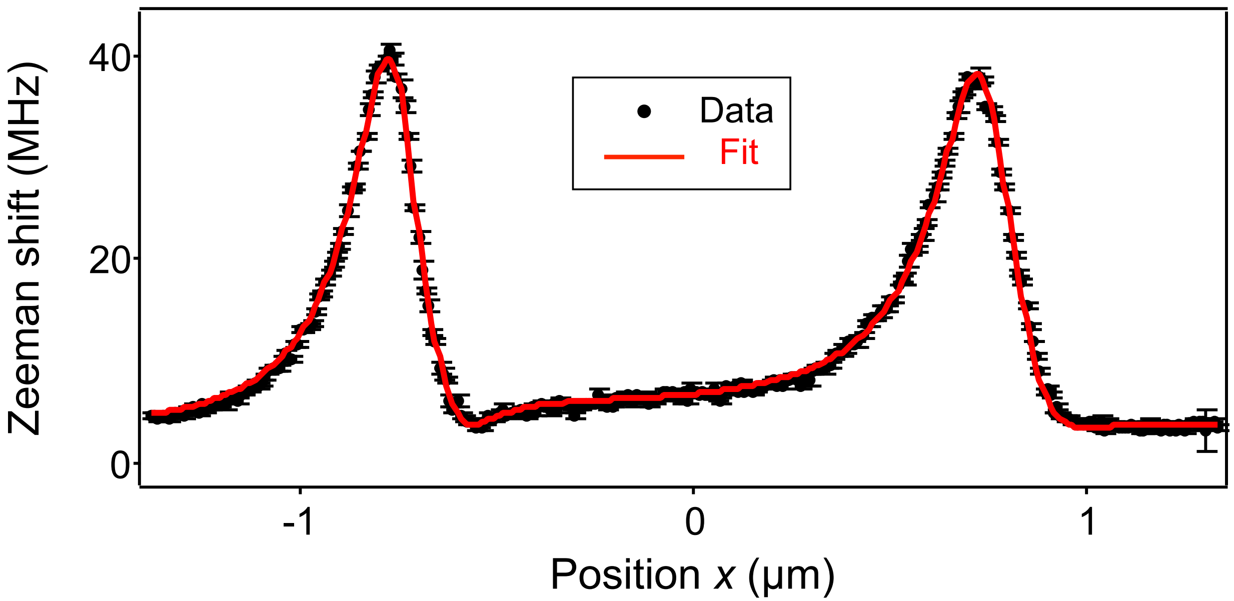
(1) Calibration

determine M_s and d

Calibration of the experiment : M_s, d ?



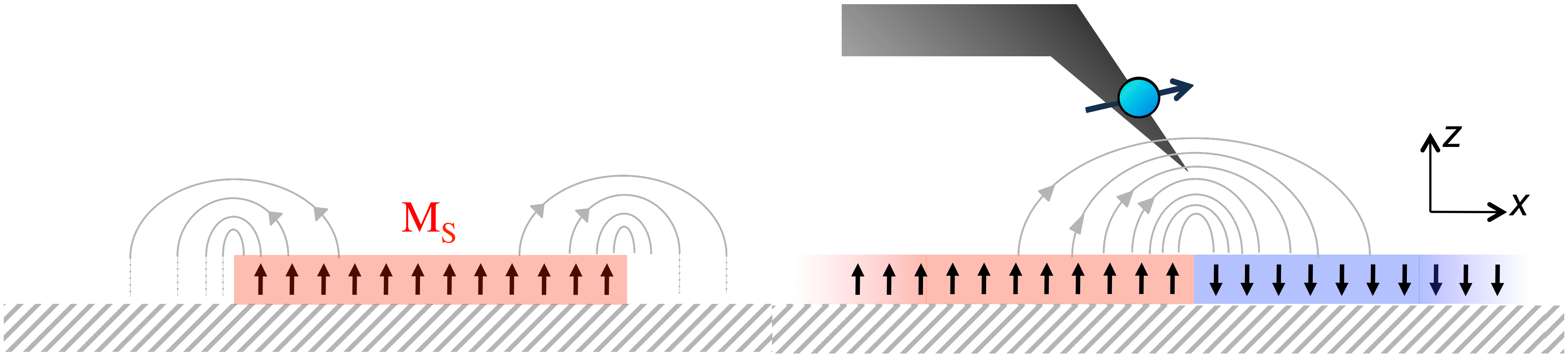


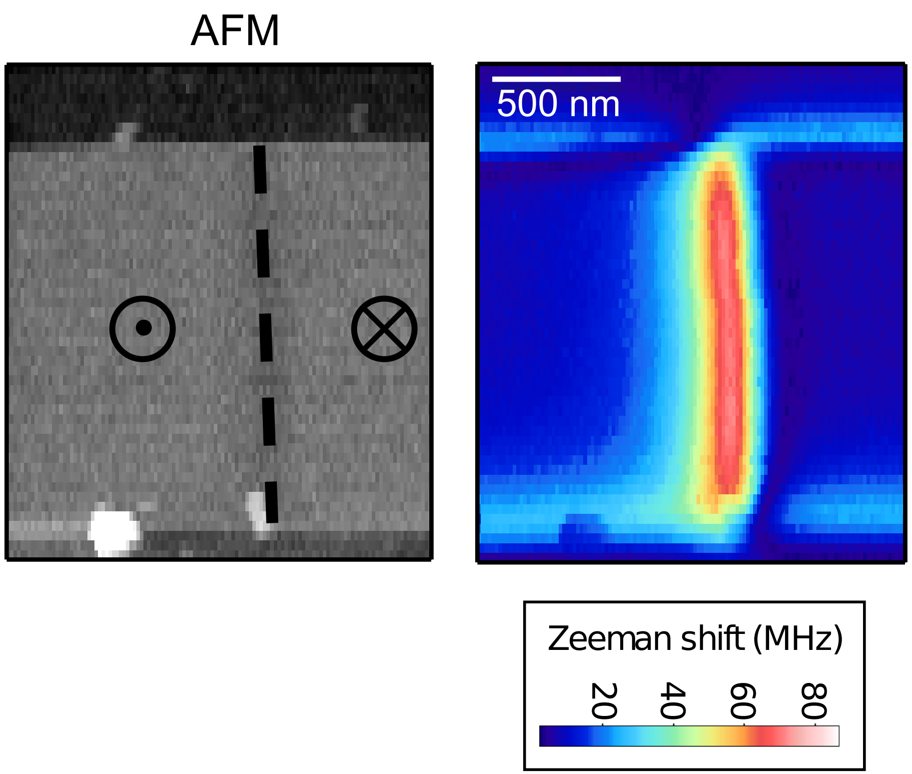


M_s = 0.93 ± 0.03 MA/m
d = 123 ± 3 nm

Hingant *et al.*, *Phys. Rev. Applied* **4**, 014003 (2015)

Extracting the structure of the domain wall





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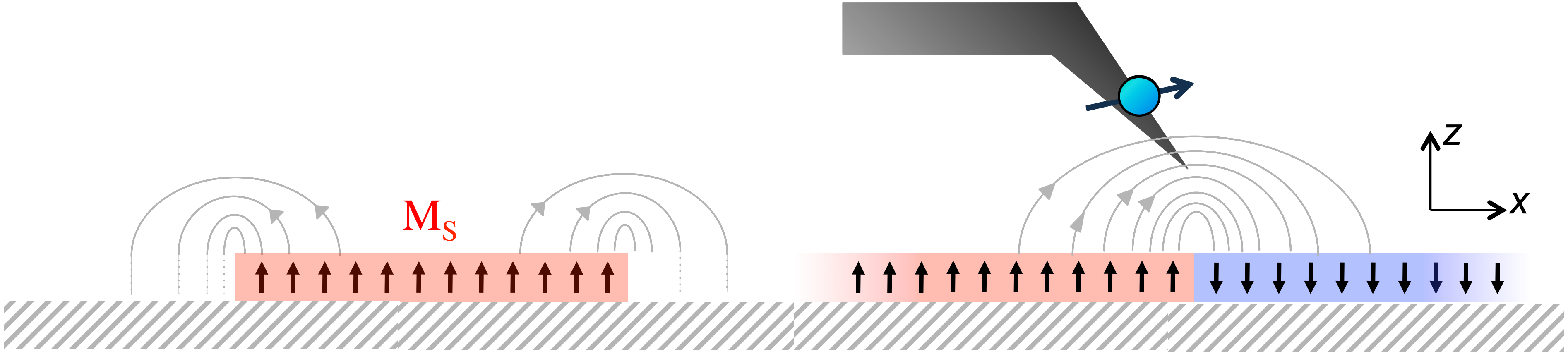
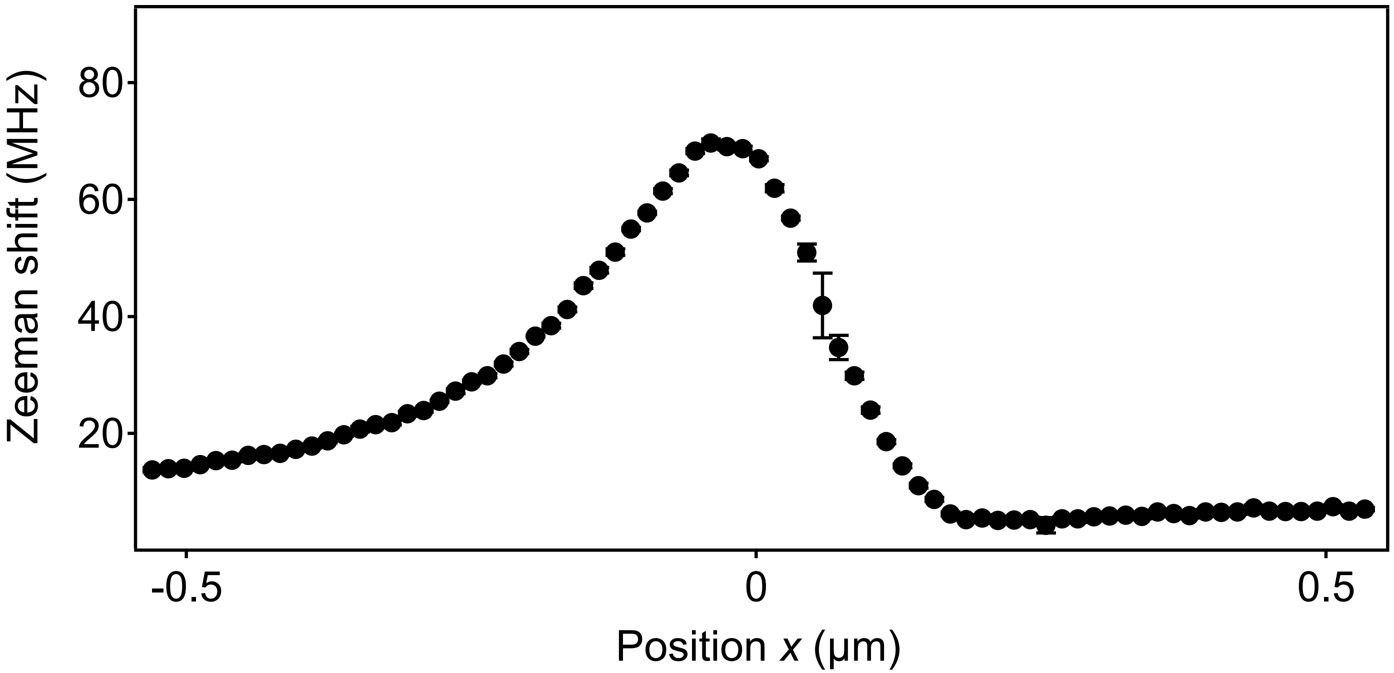
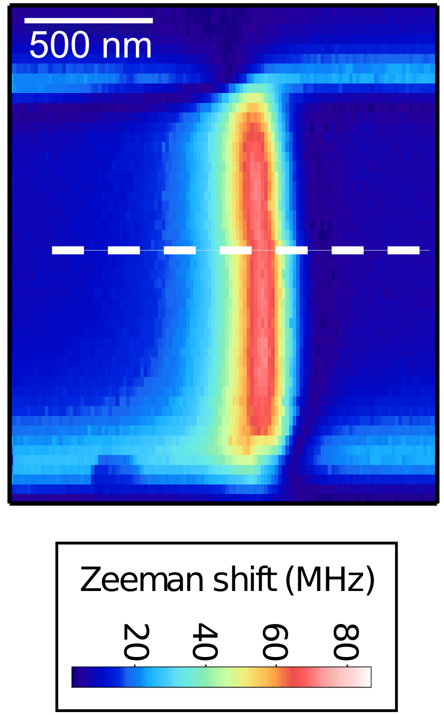
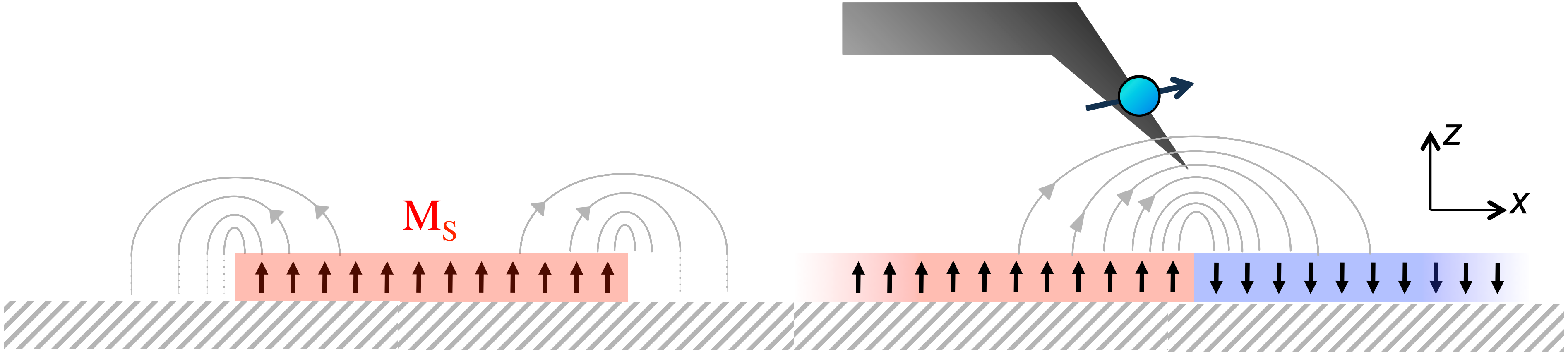
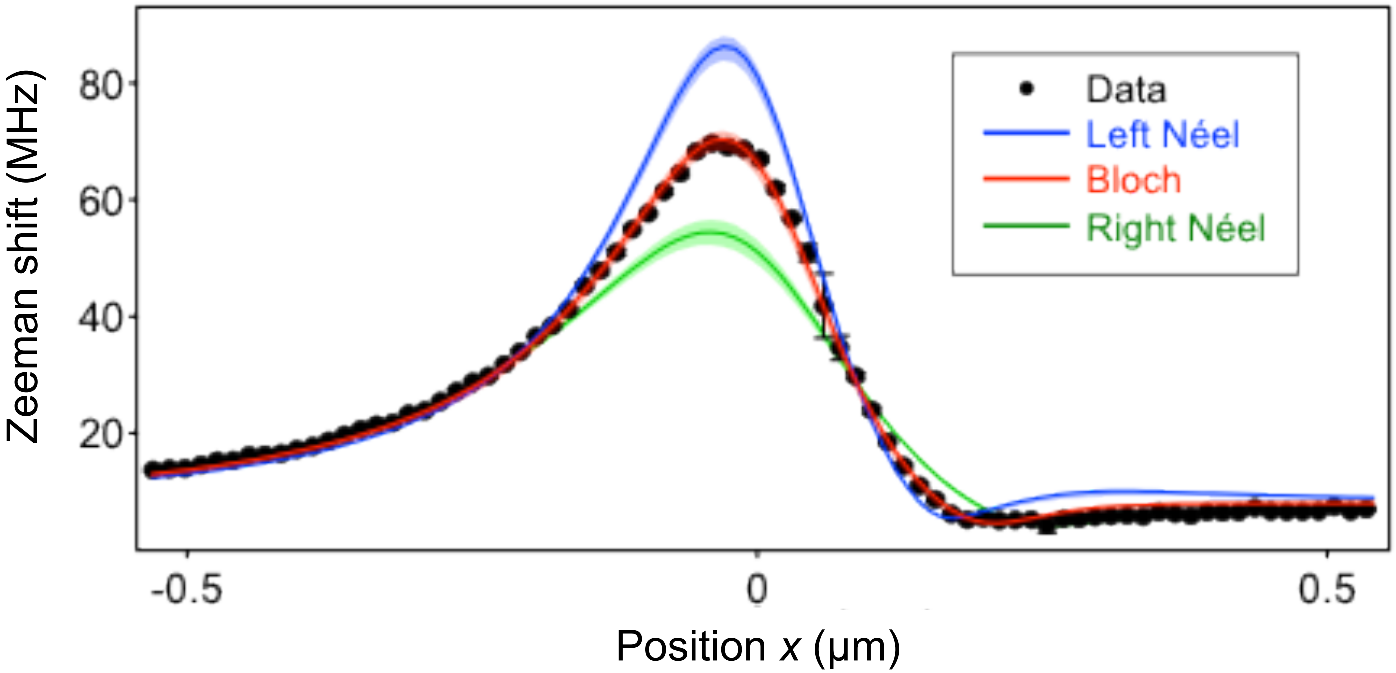


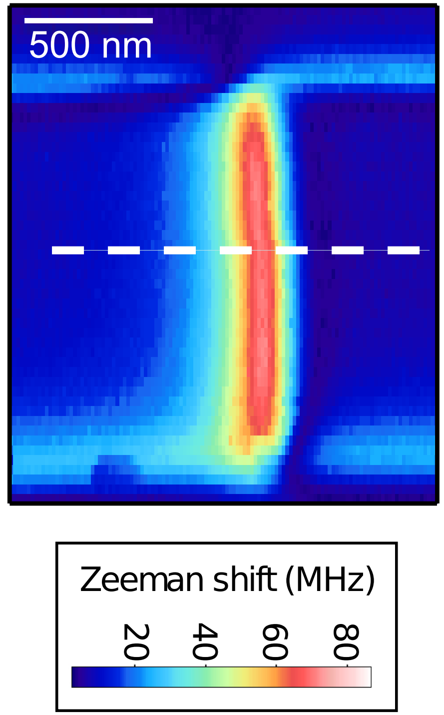




Extracting the structure of the domain wall

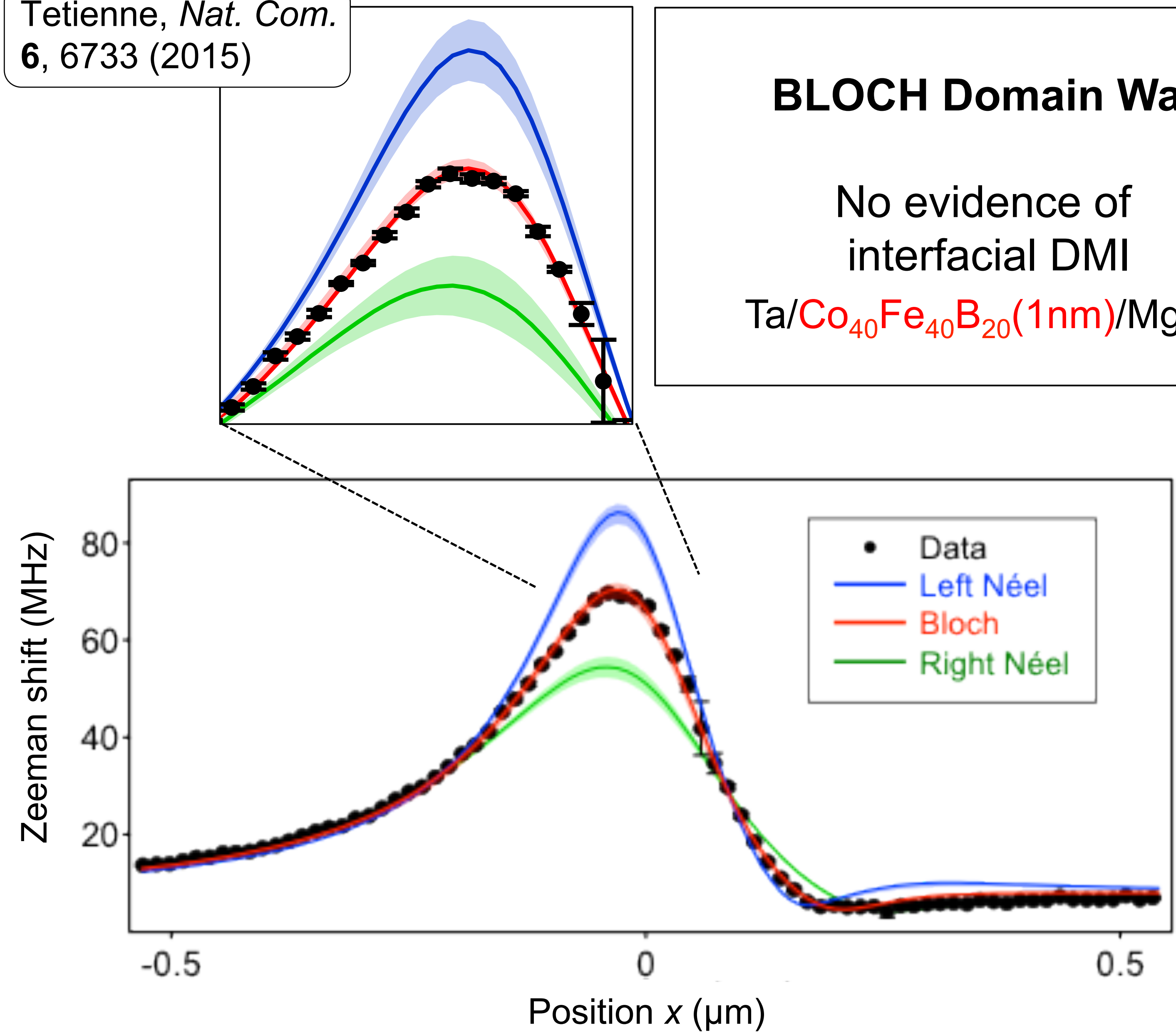






Extracting the structure of the domain wall

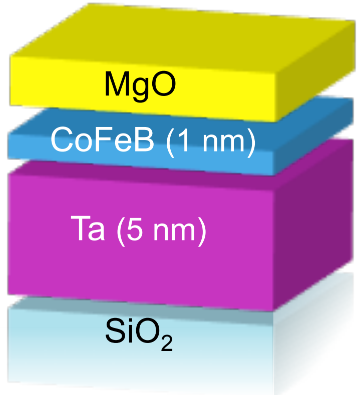
Tetienne, *Nat. Com.* **6**, 6733 (2015)

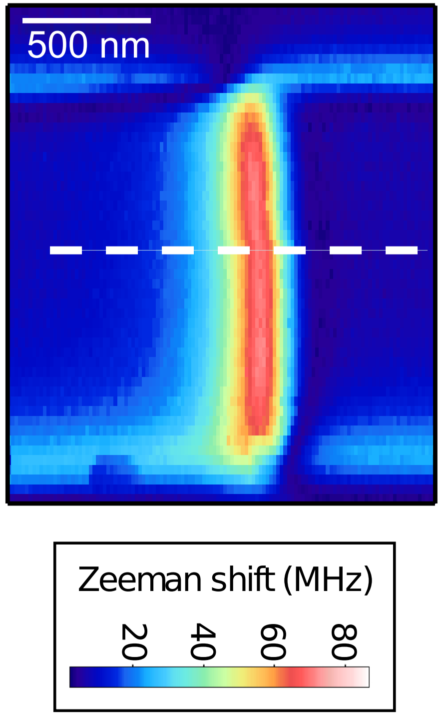


BLOCH Domain Wall

No evidence of interfacial DMI

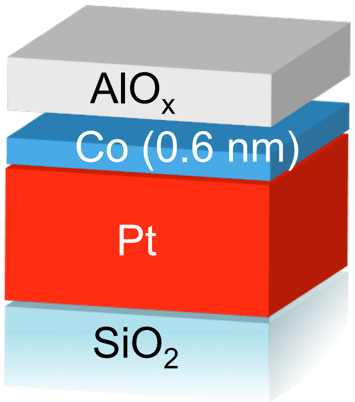
Ta/$Co_{40}Fe_{40}B_{20}$(1nm)/MgO



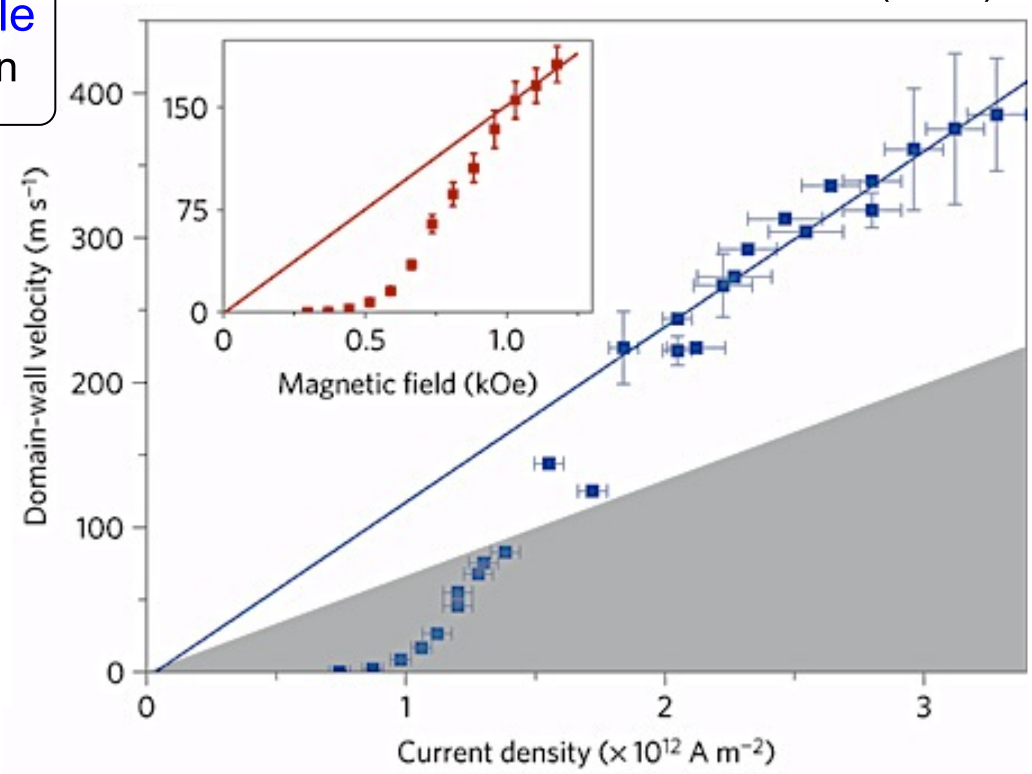


What about Pt/Co(0.6nm)/AlOx ?

SPINTEC Grenoble
G. Gaudin, M. Miron



I. M. Miron *et al., Nat. Mater.* 10, 419 (2011)



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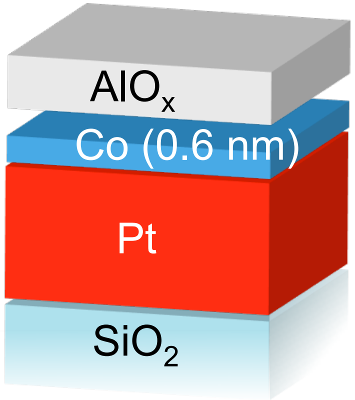

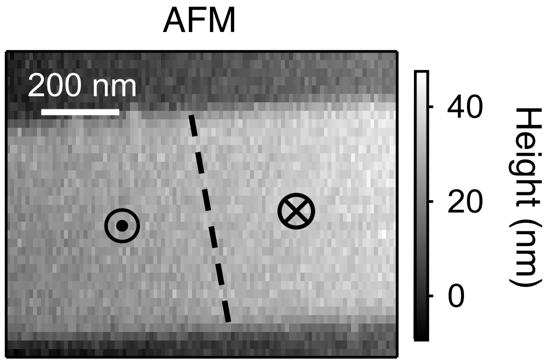

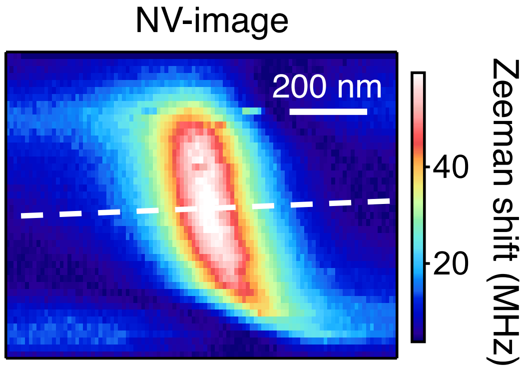

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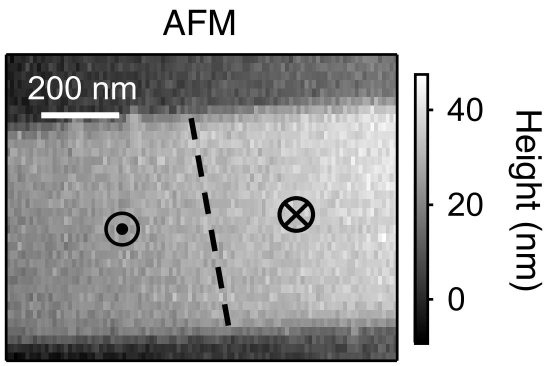
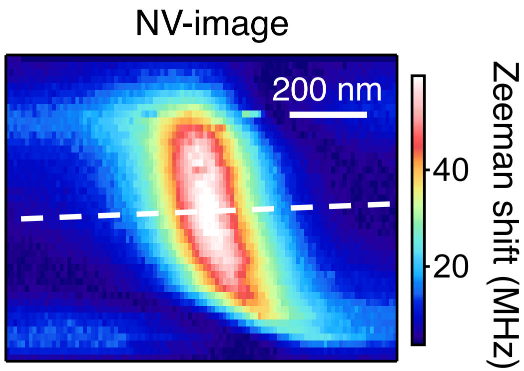
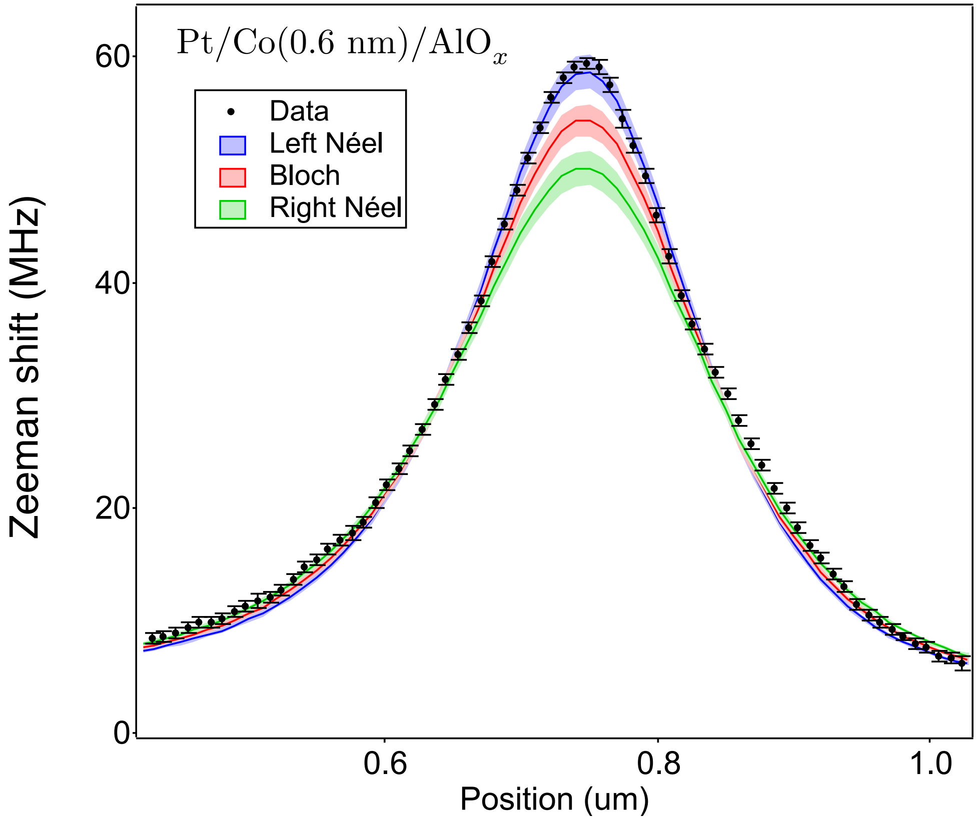
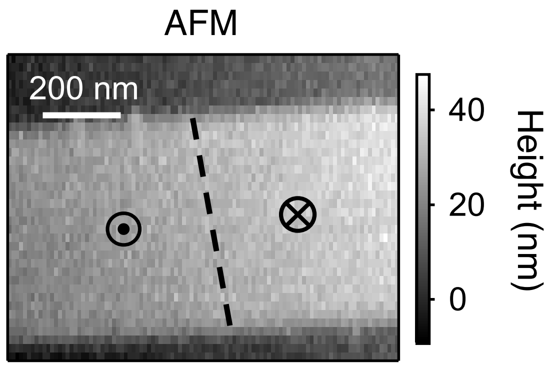


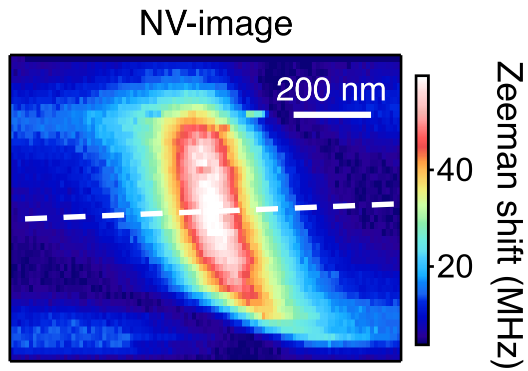


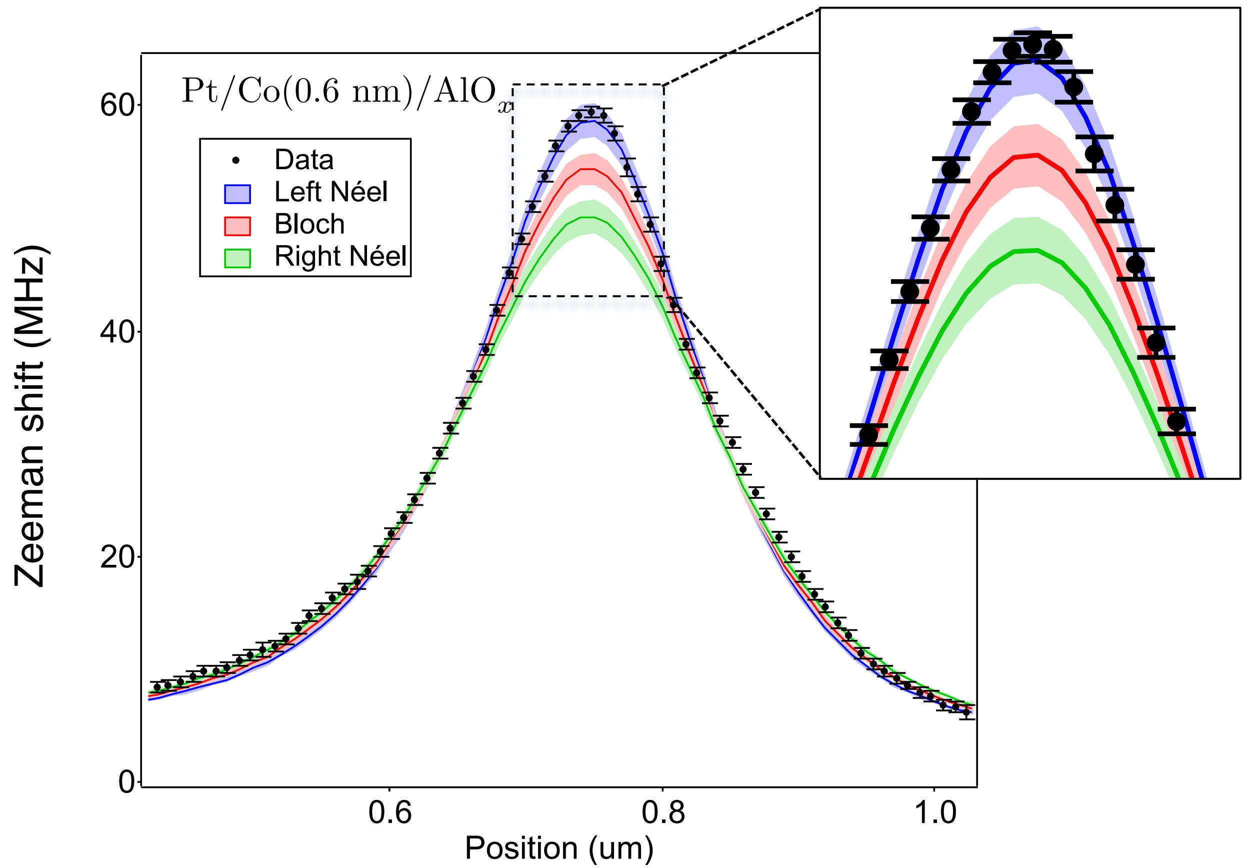


What about Pt/Co(0.6nm)/AlOx ?

SPINTEC Grenoble
G. Gaudin, M. Miron



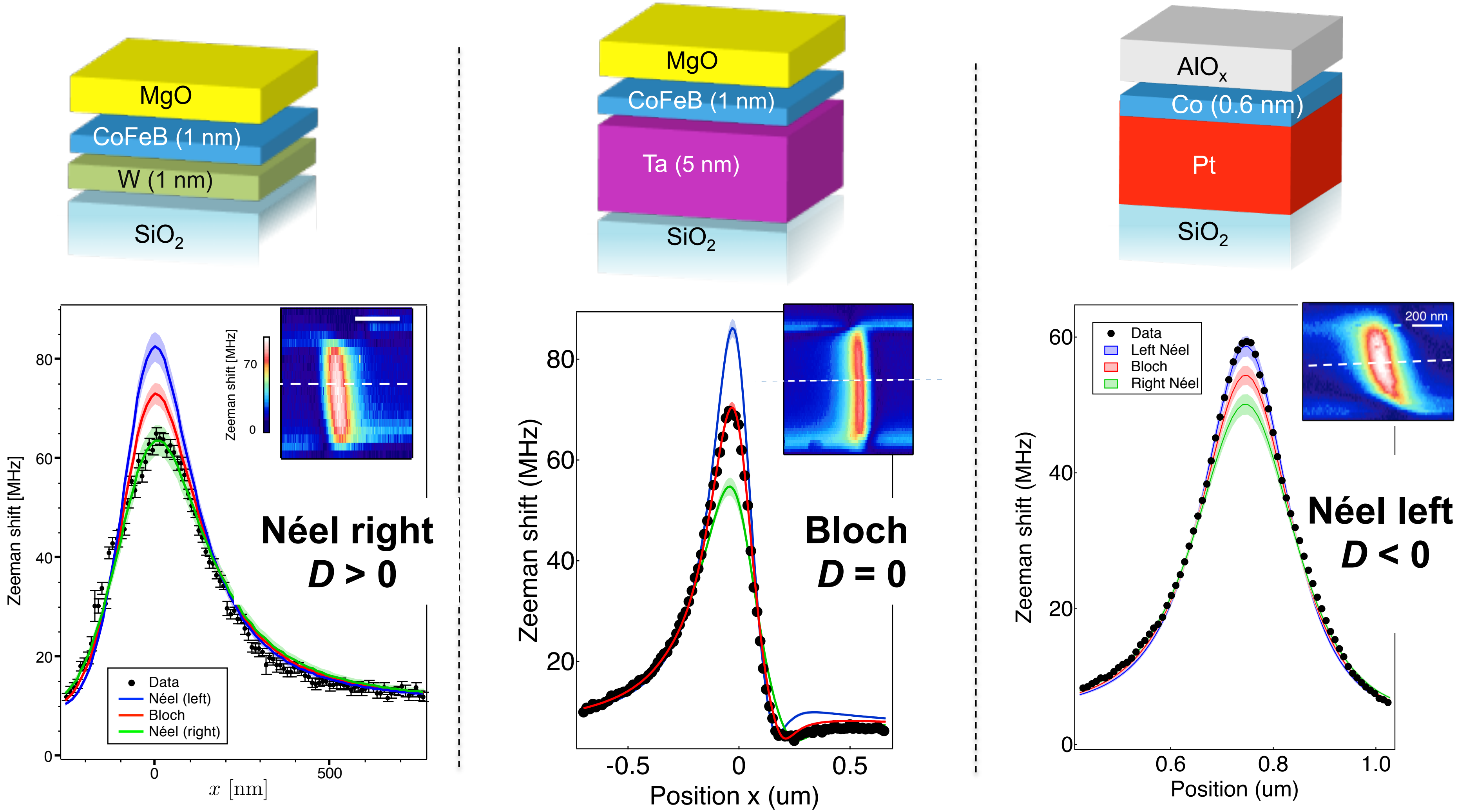




Néel left DW

Direct evidence of a sizable interfacial DMI at the Pt/Co interface

Playing with the interface

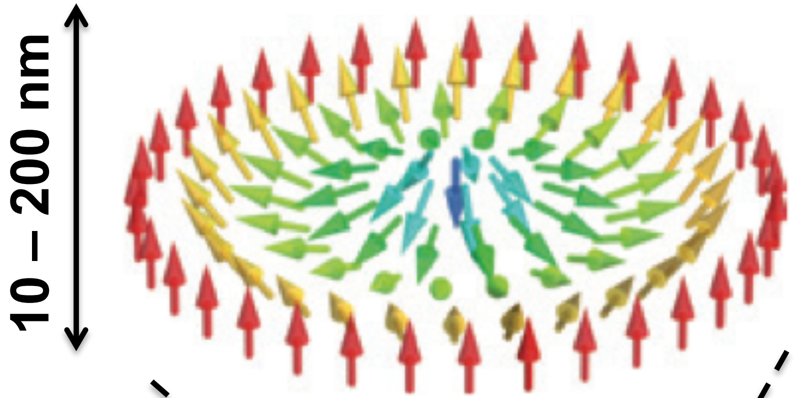


Unique tool to probe interfacial DMI in thin films

Tetienne, *Nat. Com.* **6**, 6733 (2015)
Gross, *Phys. Rev. B* **94**, 064413 (2016)

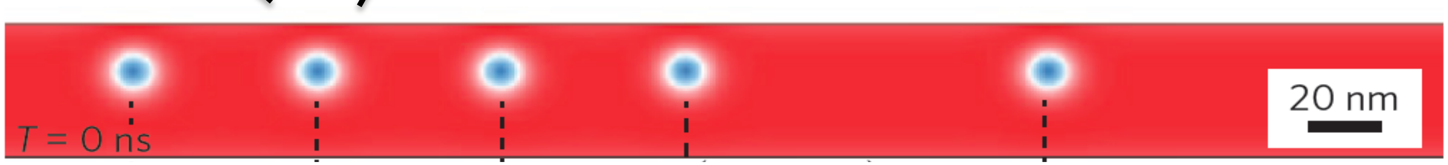
Exploiting large interfacial DMI…

From DW to magnetic skyrmions…



- ★ Topologically protected spin texture
- ★ Efficent motion at low current densities
- ★ Ultrahigh information-storage density

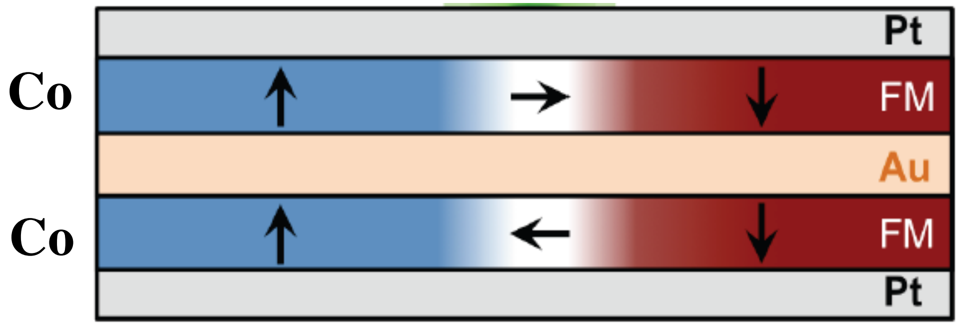
« Skyrmionics »



Fert *et al. Nat. Nano.* **8**, 152 (2013)

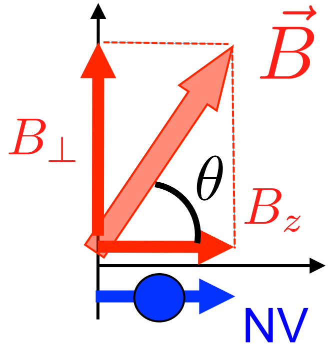
The sample – symmeric bilayer Pt/Co(1nm)/Au

A.Thiaville
S. Rohart
A. Hrabec



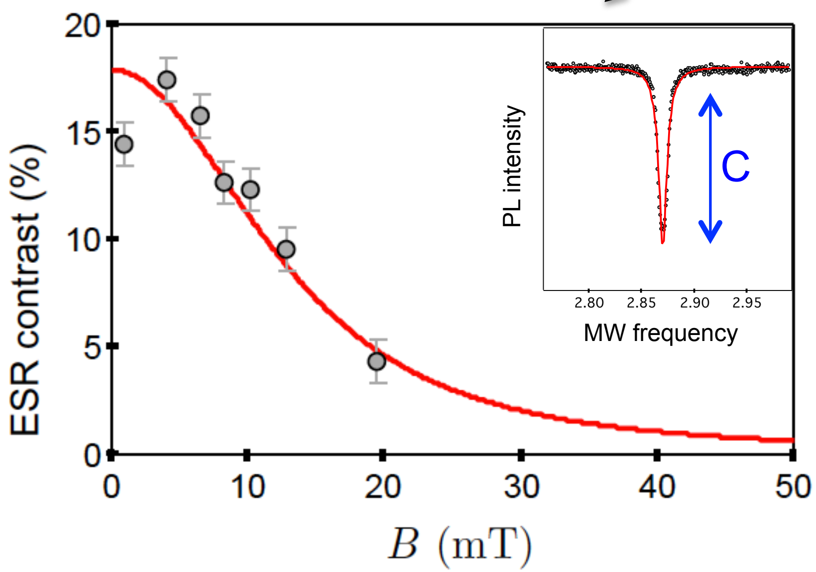
Hrabec et al., arXiv:1611.00647

B>20 mT
@ 50 nm



Regime of strong *off-axis* magnetic field

Tetienne *et al., NJP* **14**, 103033 (2012)



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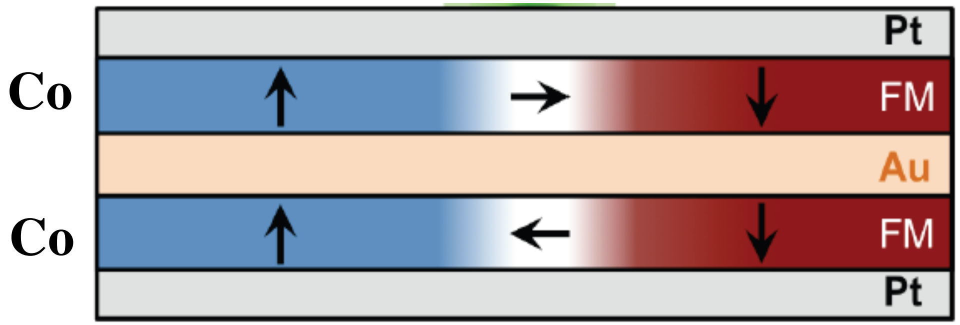

Hrabec et al., arXiv:1611.00647

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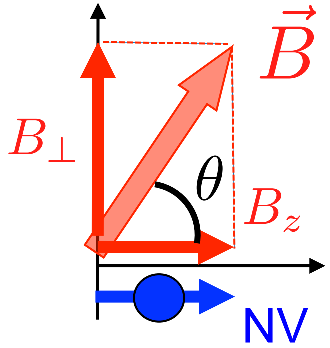

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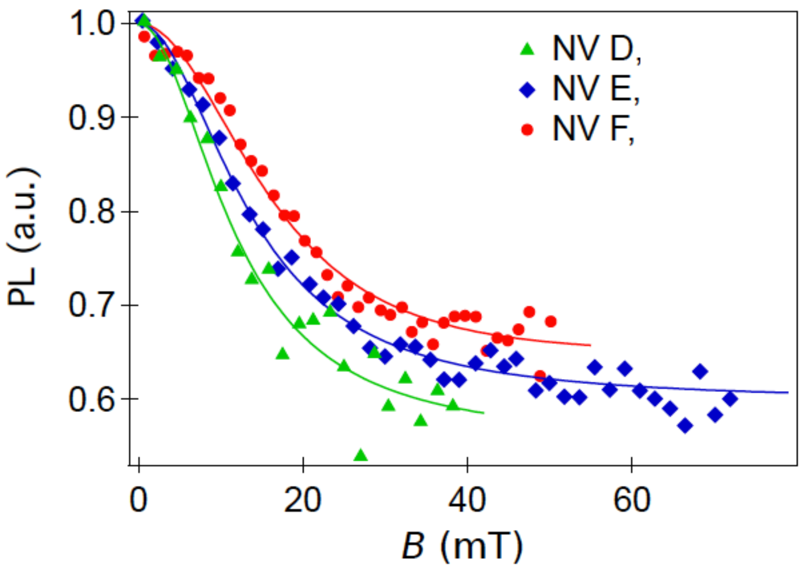
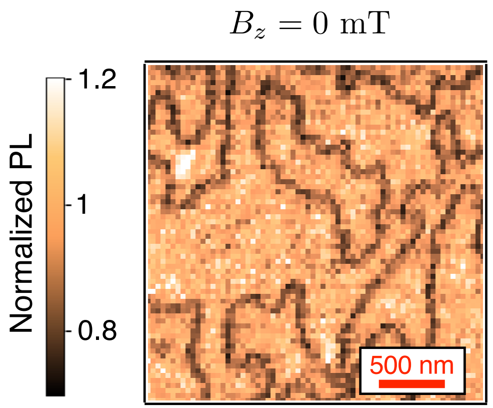
Tetienne *et al., NJP* **14**, 103033 (2012)

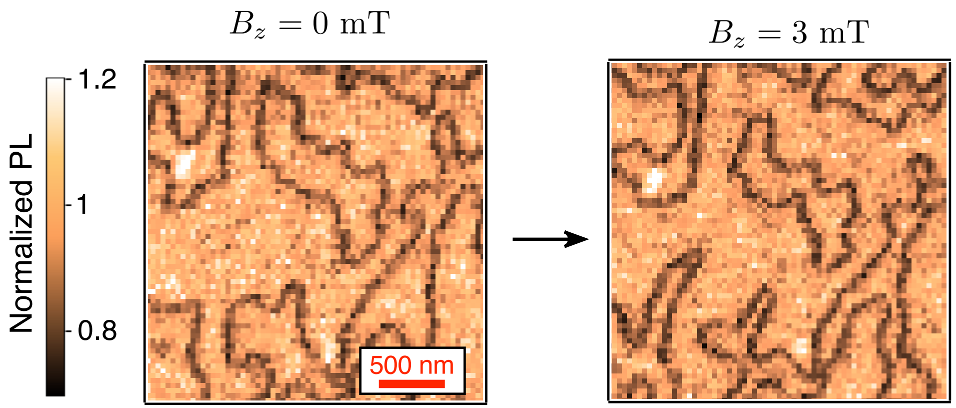


Can be exploited for
all-optical magnetic imaging
(MW free)

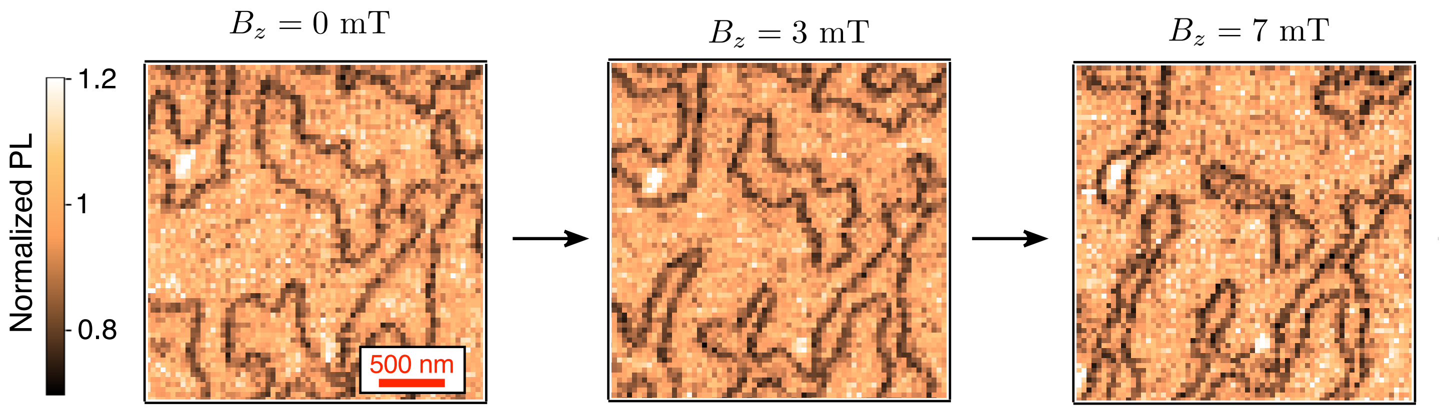
All-optical imaging of individual skyrmions



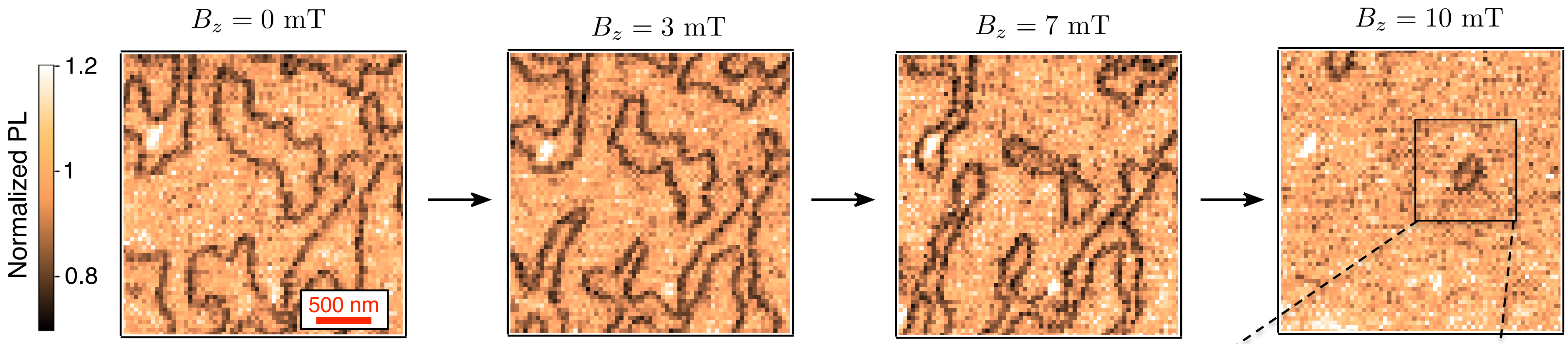
All-optical imaging of individual skyrmions



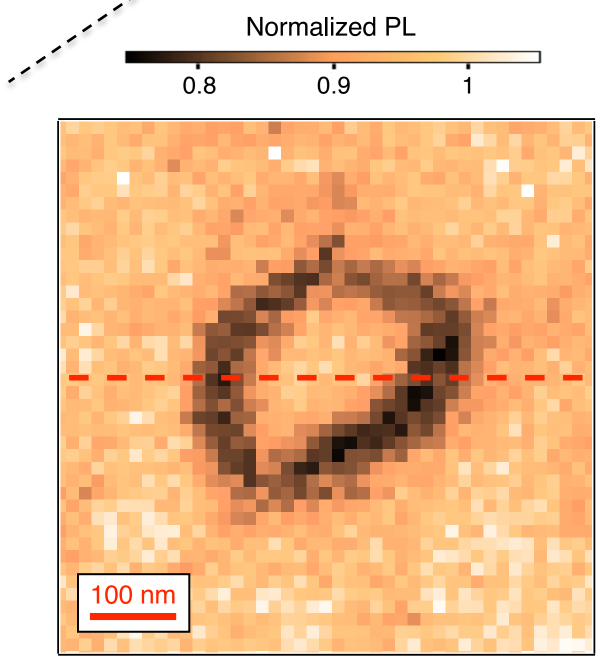
All-optical imaging of individual skyrmions



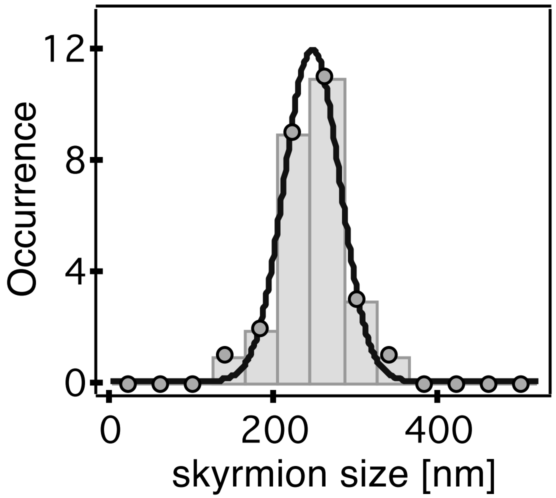
All-optical imaging of individual skyrmions



related work from A. Yacoby group
arXiv:1611.00673



In progress



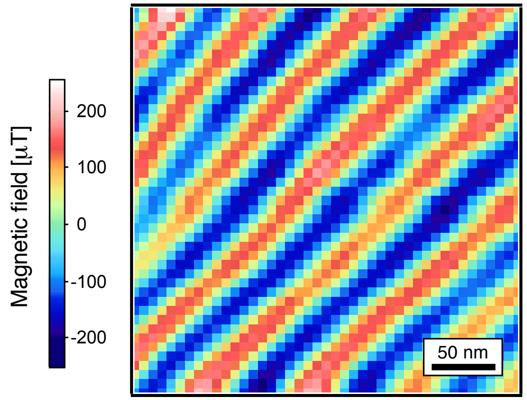
Outline of the talk

1. The NV defect in diamond as an atomic-sized magnetic field sensor

2. Applications in nanomagnetism

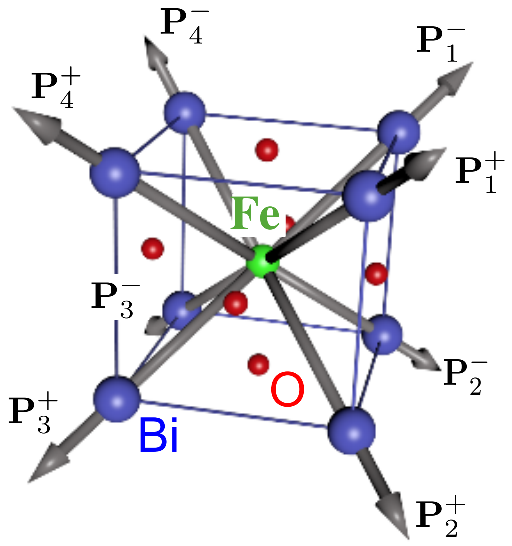
From dowain walls to skyrmions in ultrathin ferromagnets

Imaging antiferromagnetic order in multiferroics



Antiferromagnetic order in multiferroics

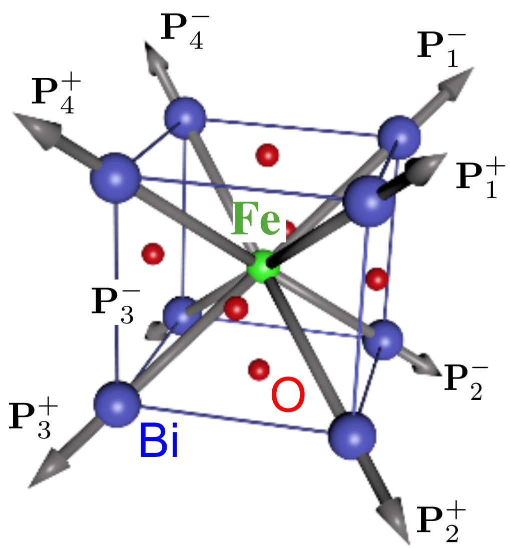
BiFeO$_3$: ferroelectricity….

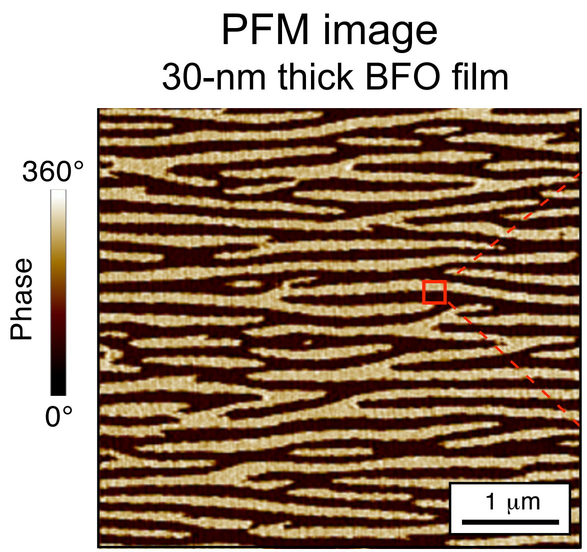


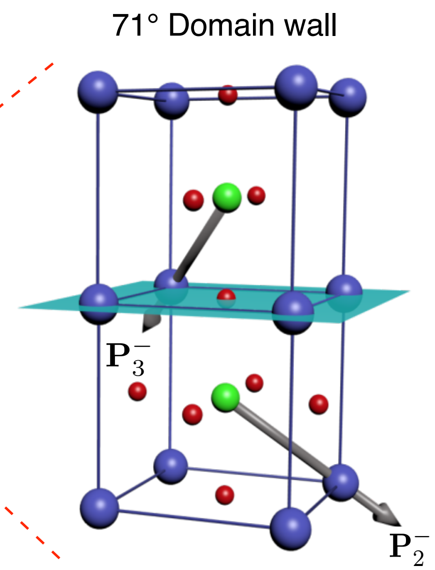
Antiferromagnetic order in multiferroics

$BiFeO_3$: ferroelectricity….

THALES
RESEARCH & TECHNOLOGY
S. Fusil, V. Garcia, M. Bibes



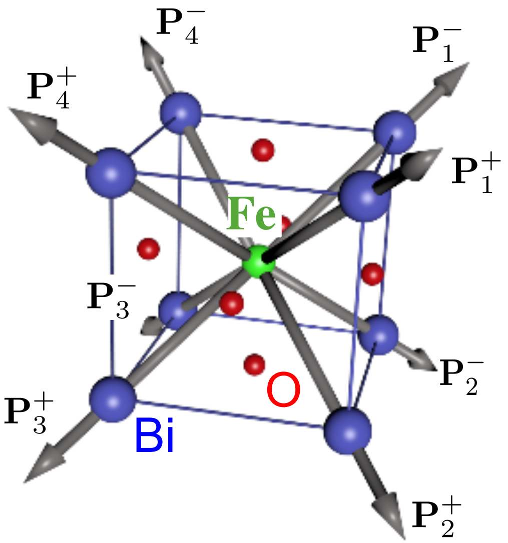


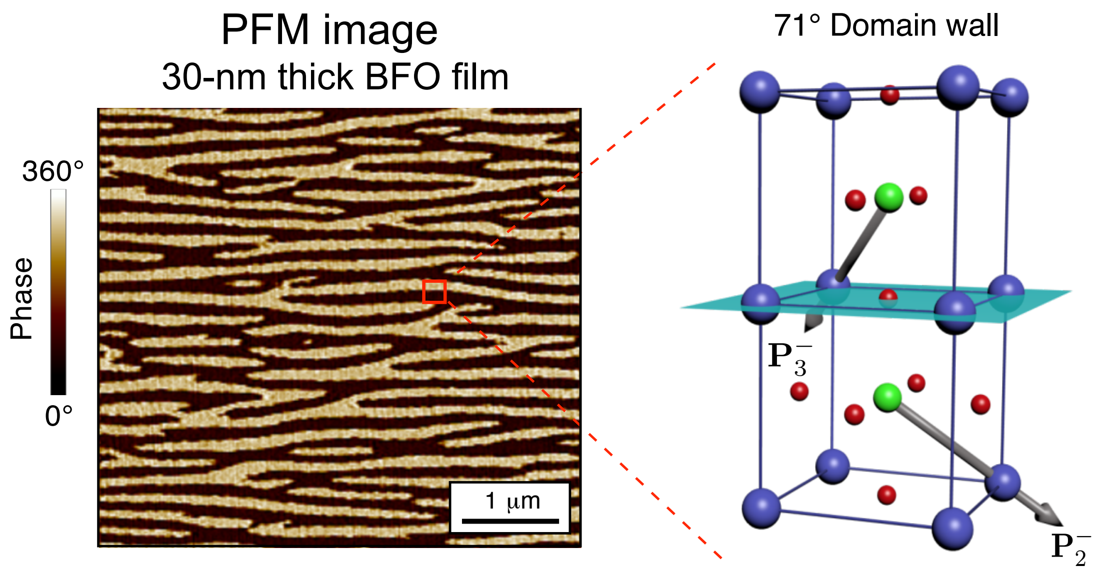


Antiferromagnetic order in multiferroics

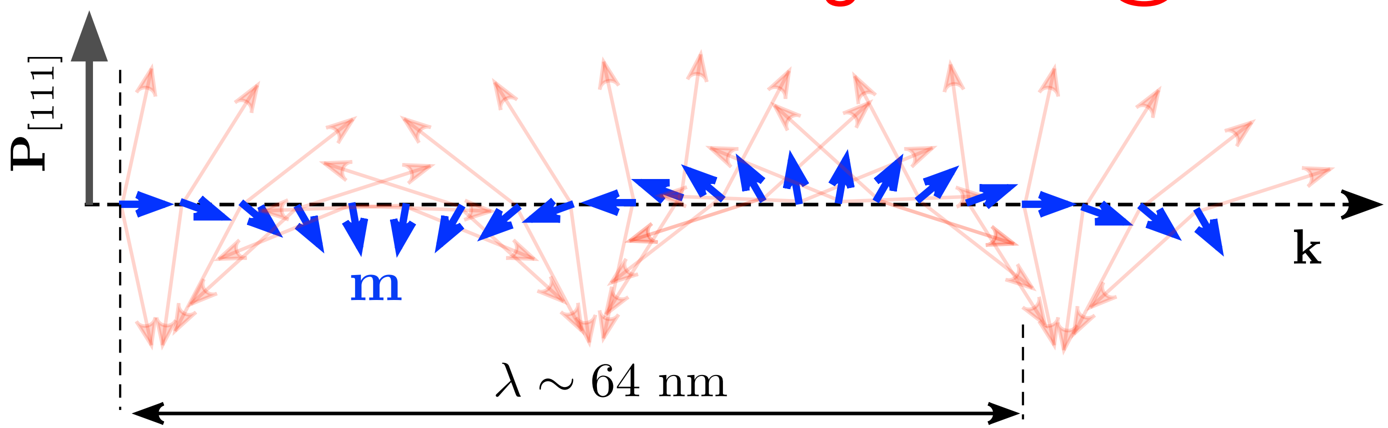
BiFeO$_3$: ferroelectricity….

THALES
S. Fusil, V. Garcia, M. Bibes

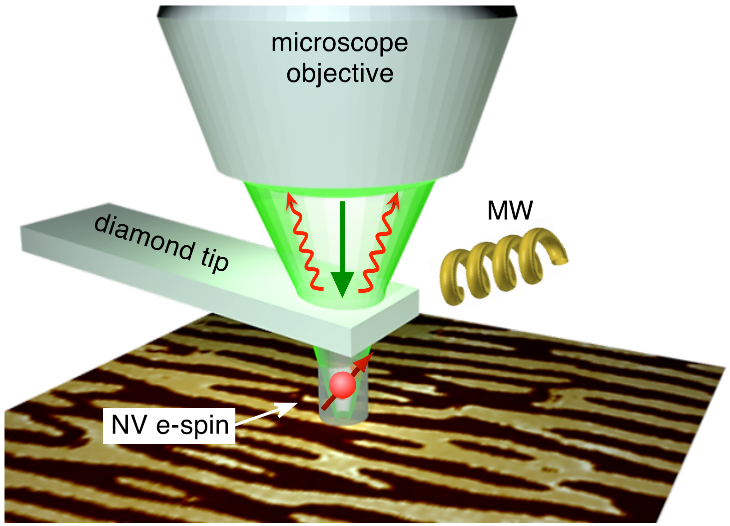




…+ antiferromagnetism @ 300 K

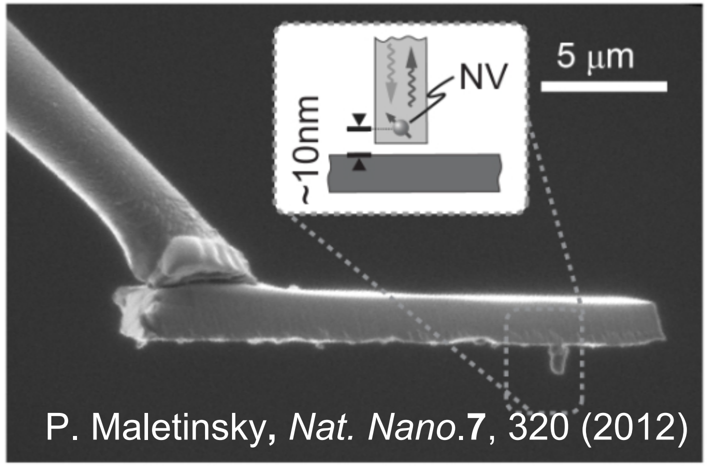


Imaging antiferromagnetic order in BFO

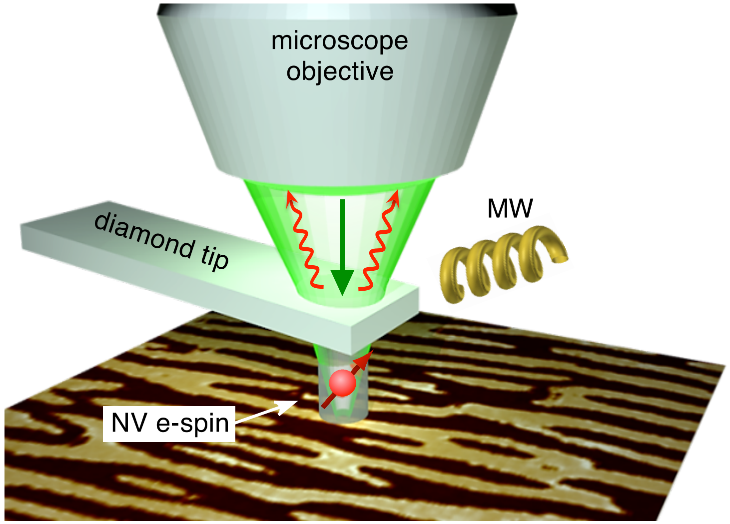


30 nm thick (001)-$BiFeO_3$

Diamond tip - **P. Maletinsky (Basel)**



Imaging antiferromagnetic order in BFO



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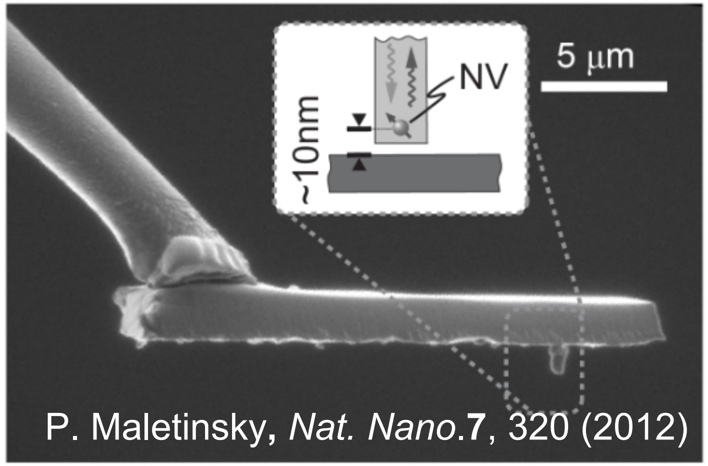
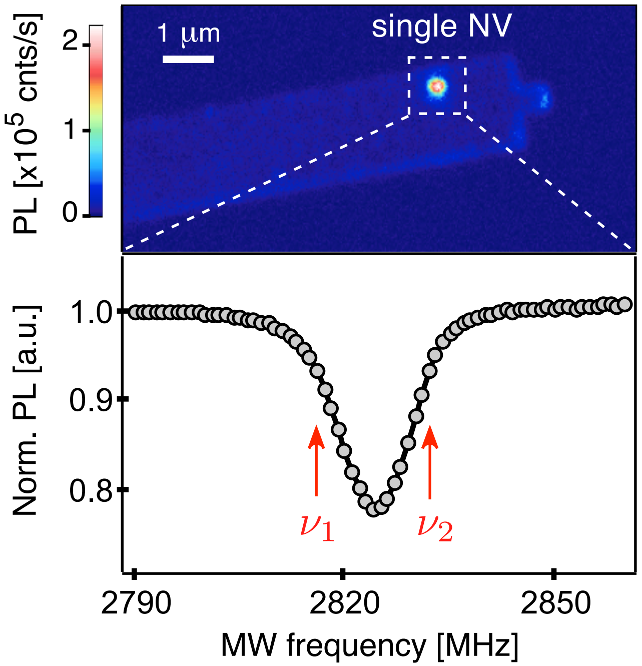
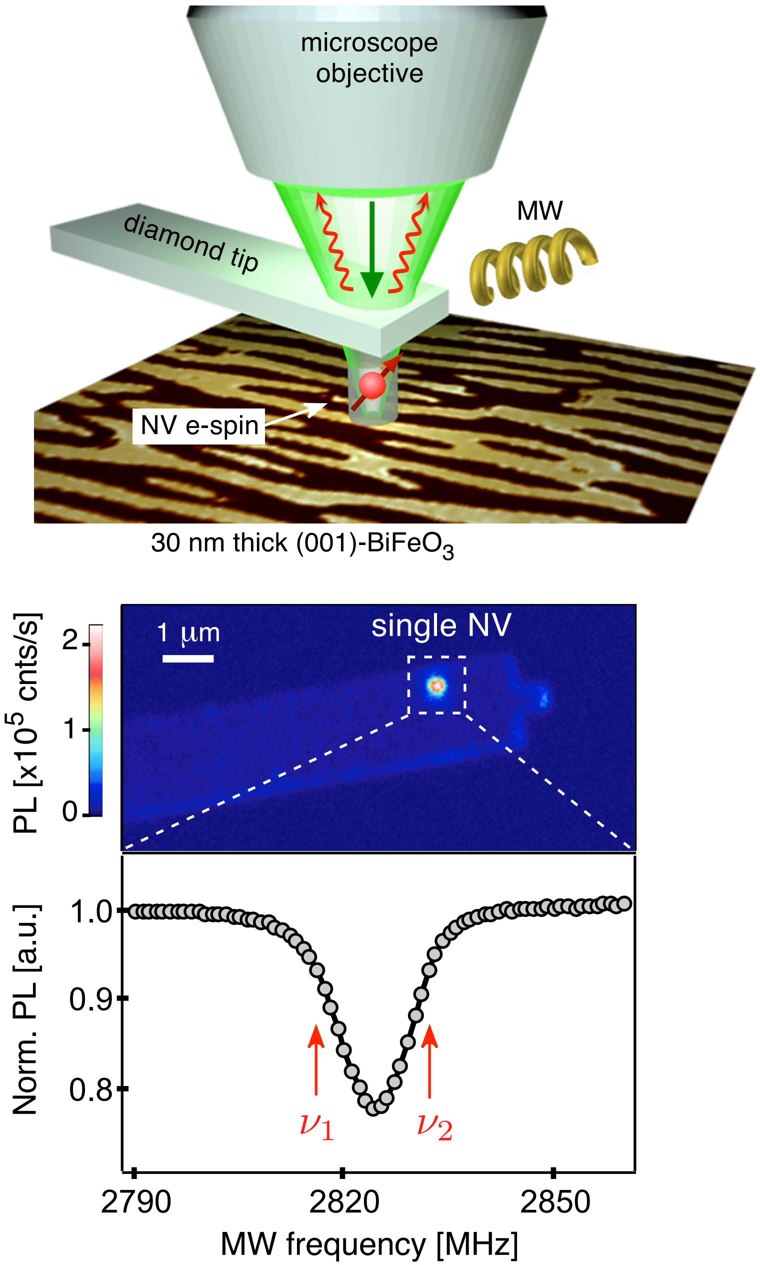
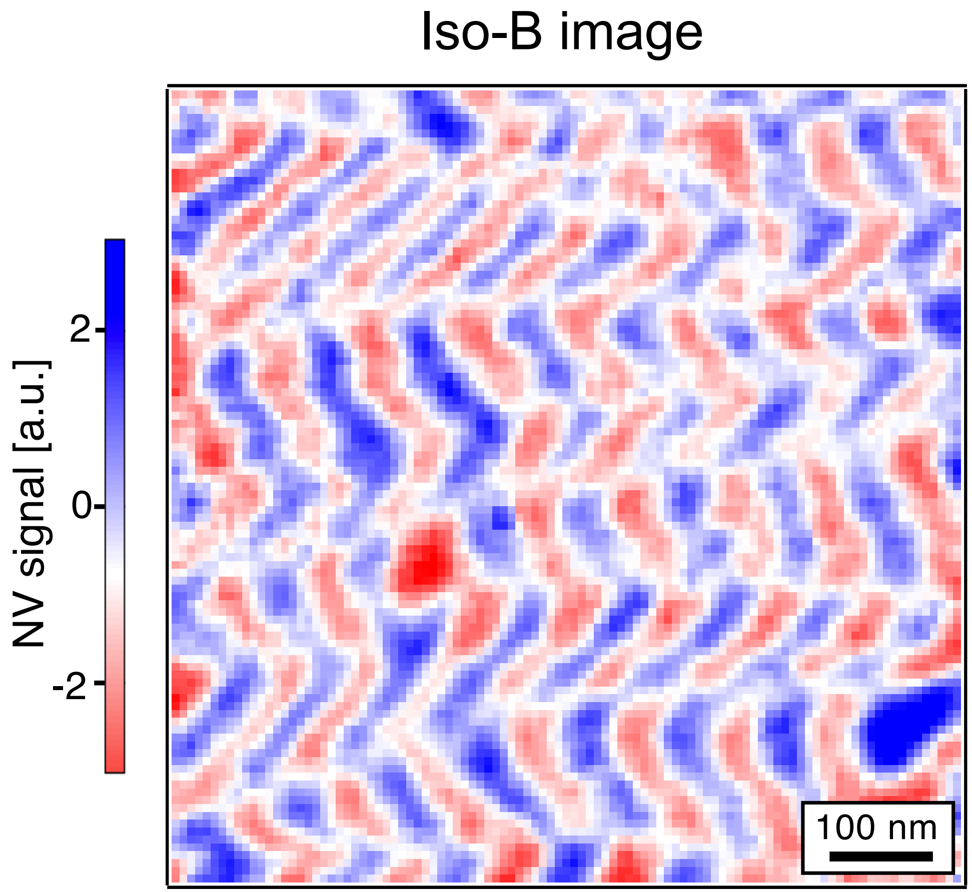




Imaging antiferromagnetic order in BFO





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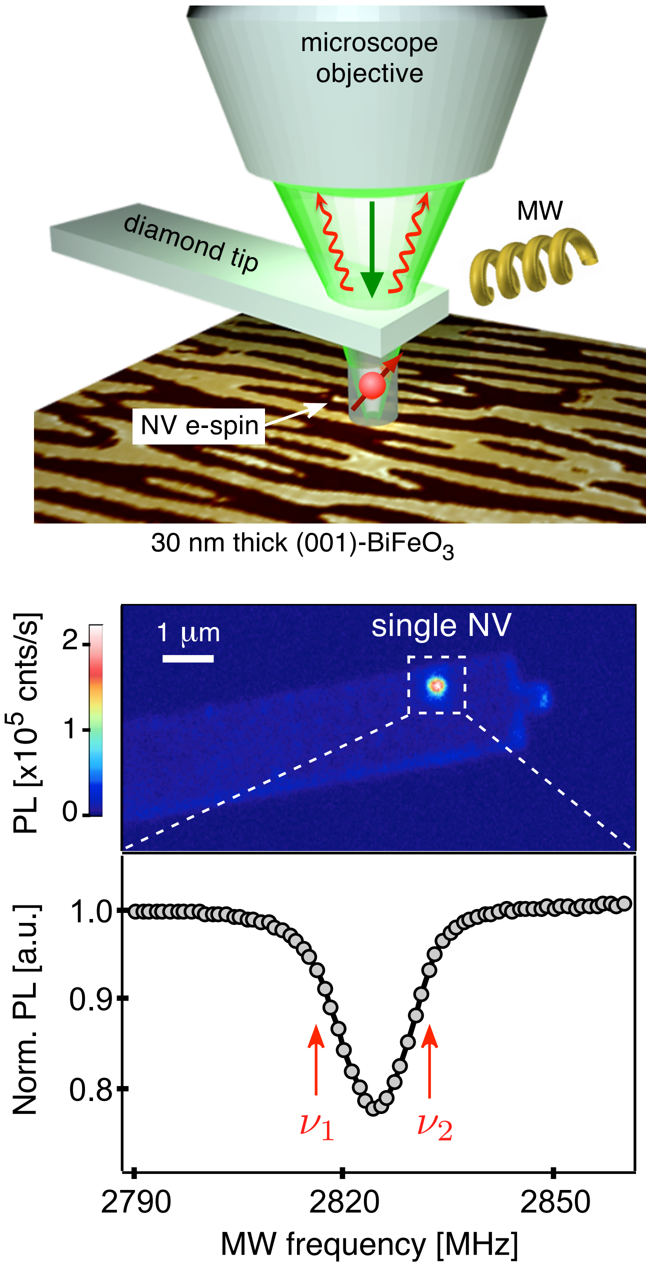
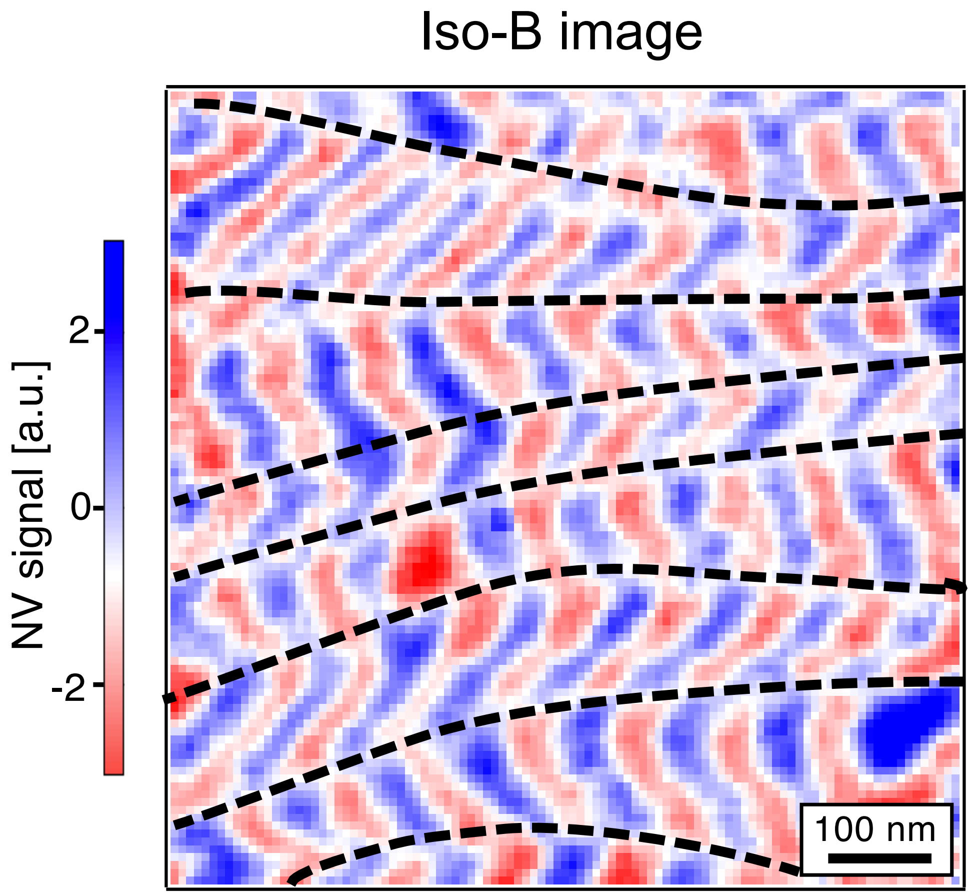
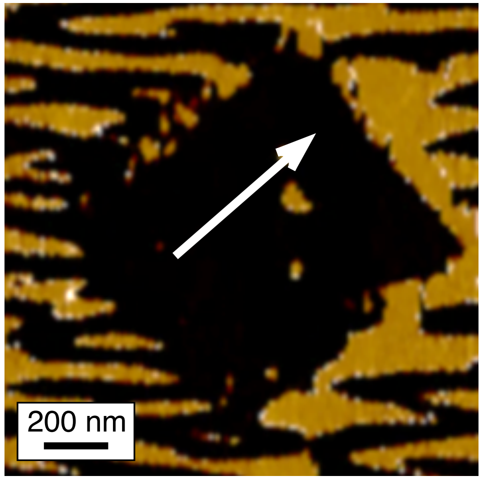


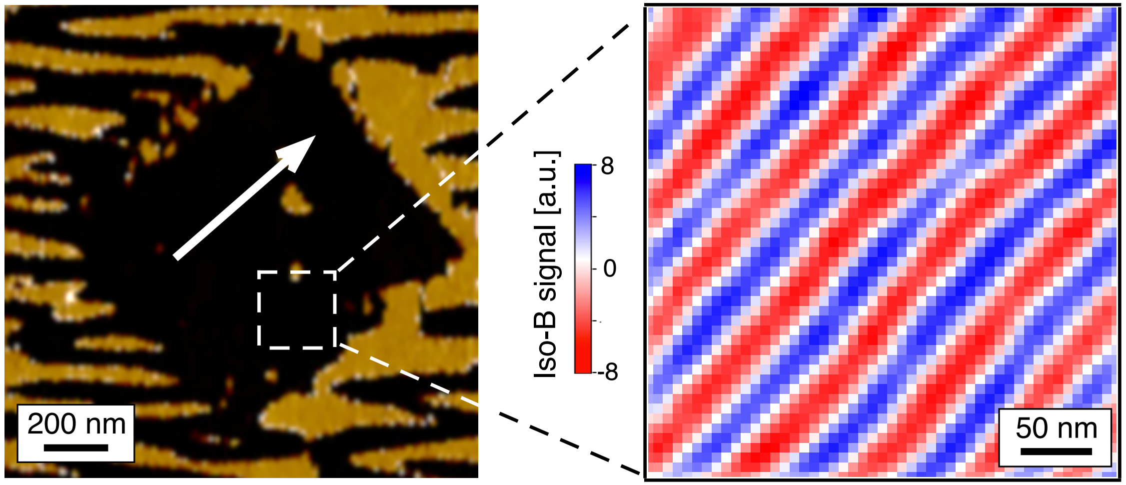


Controlling the spin spiral in BFO



PFM images

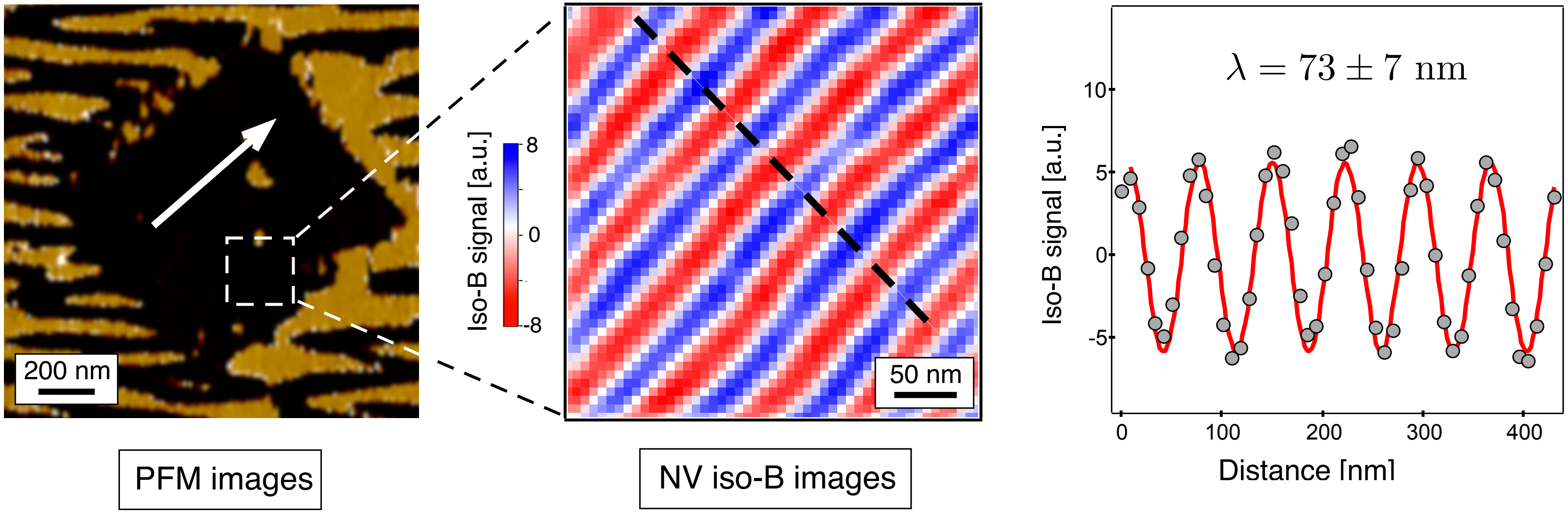
Controlling the spin spiral in BFO



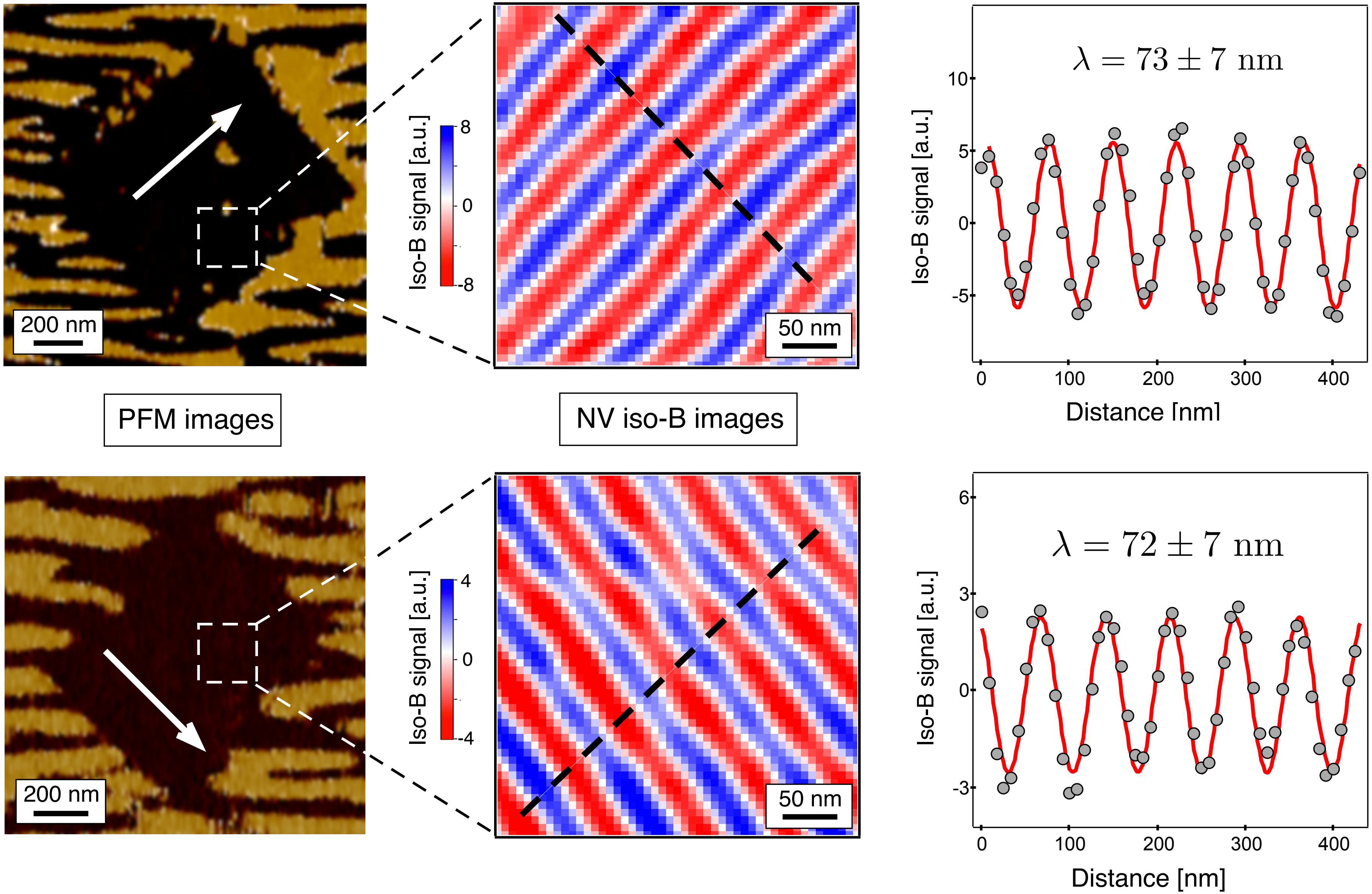
PFM images

NV iso-B images

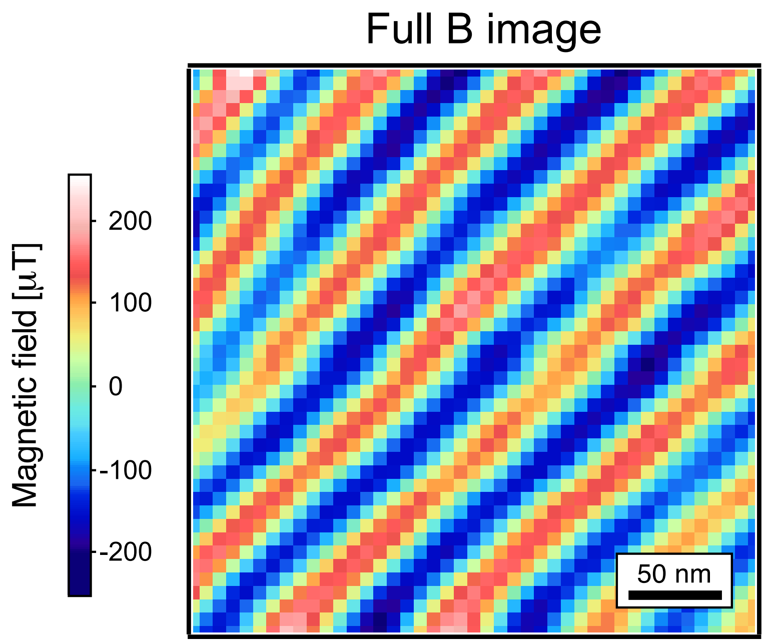
Controlling the spin spiral in BFO



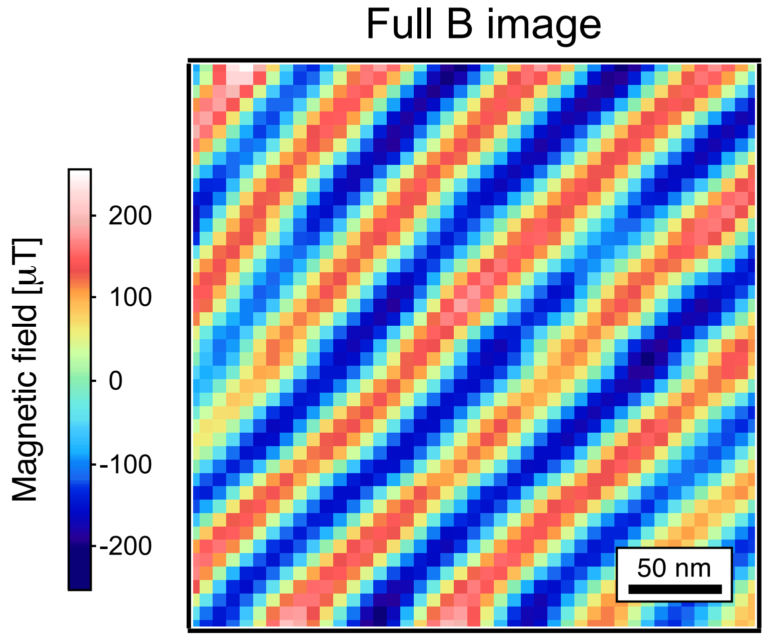
Controlling the spin spiral in BFO

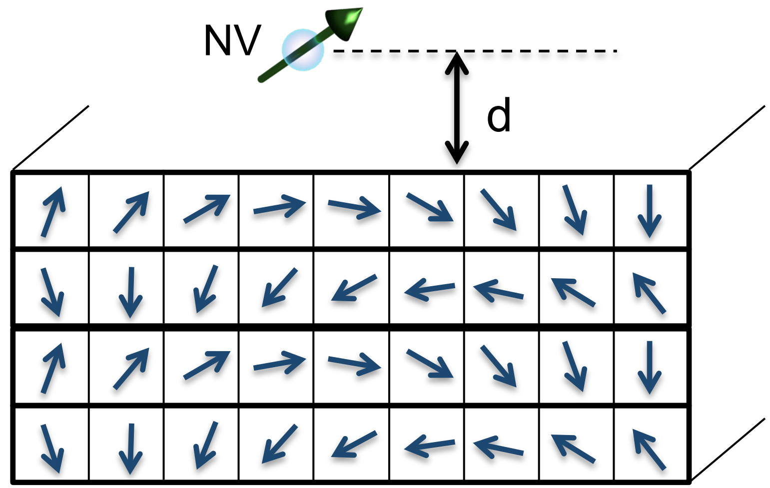


Quantitative analysis…



Quantitative analysis…

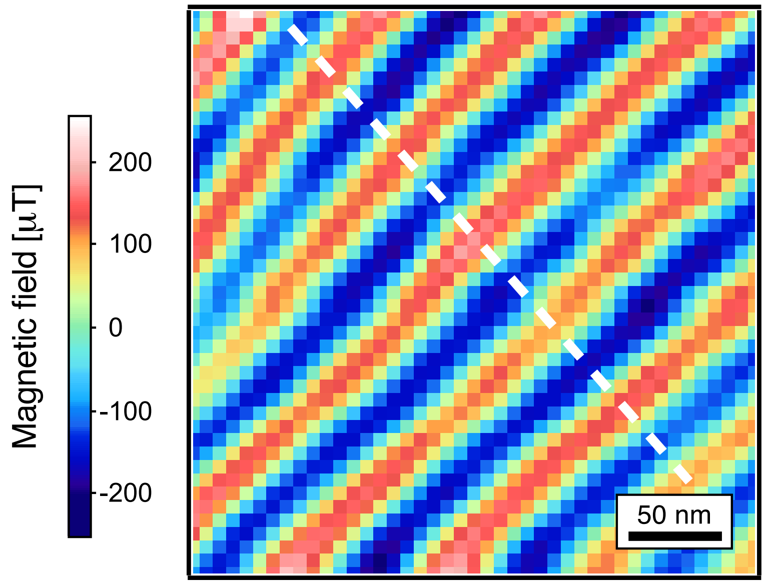


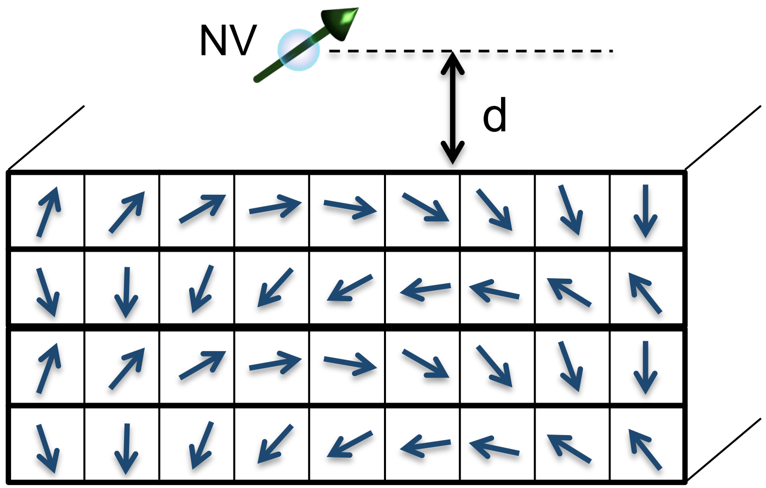


- 5 μ_B/Fe atom
- d=51±5 nm
- Cycloid periodicity λ = 70 nm

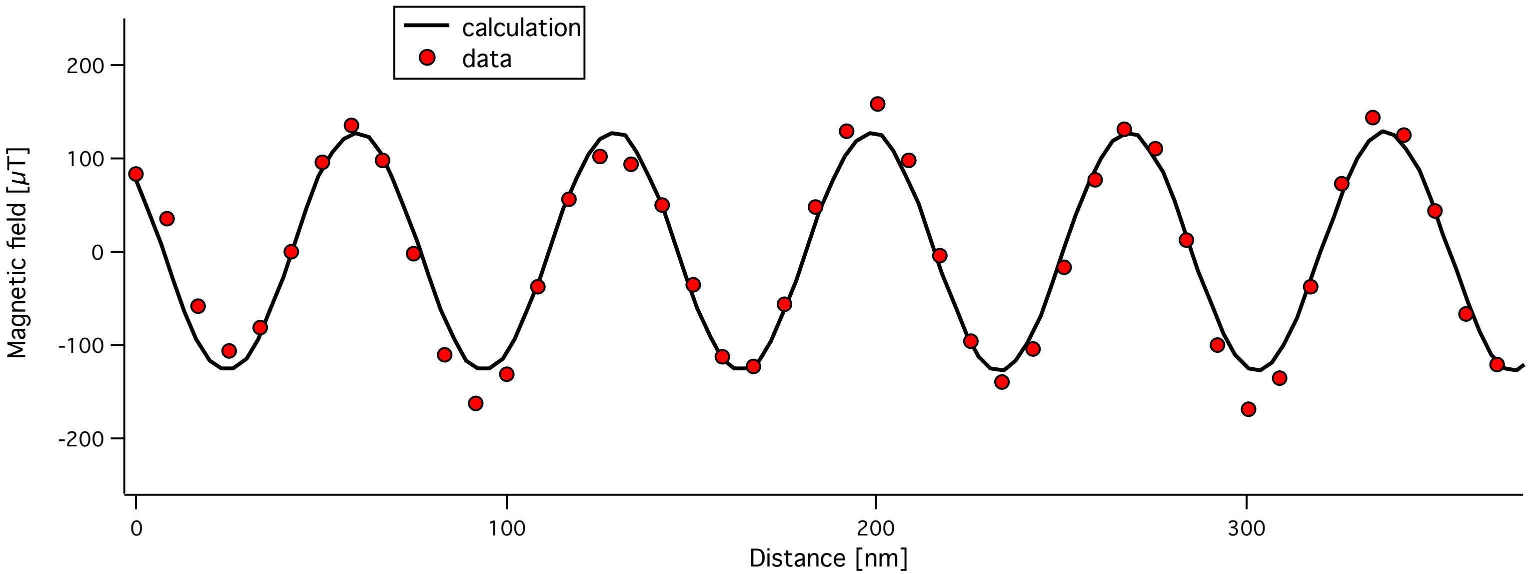
Quantitative analysis…

Full B image

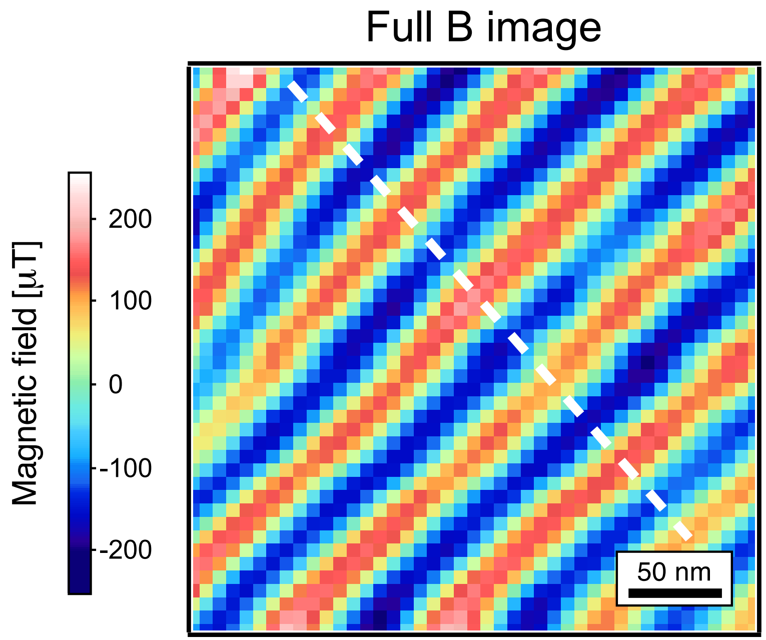


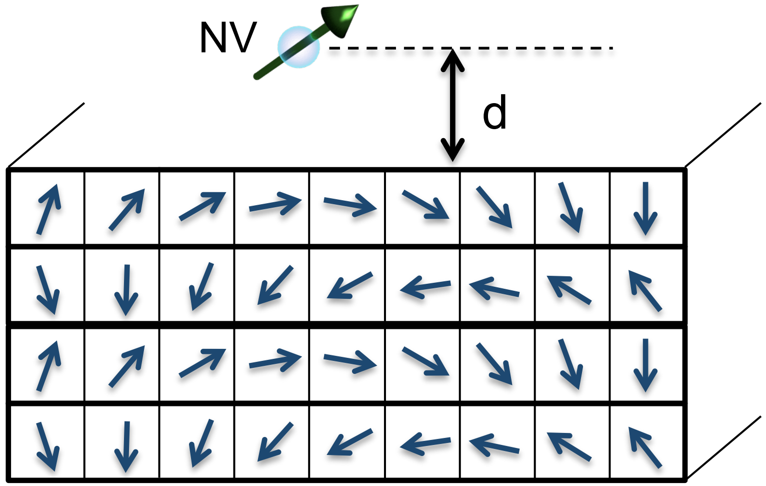


- 5 μ_B/Fe atom
- d=51±5 nm
- Cycloid periodicity λ = 70 nm



Quantitative analysis…





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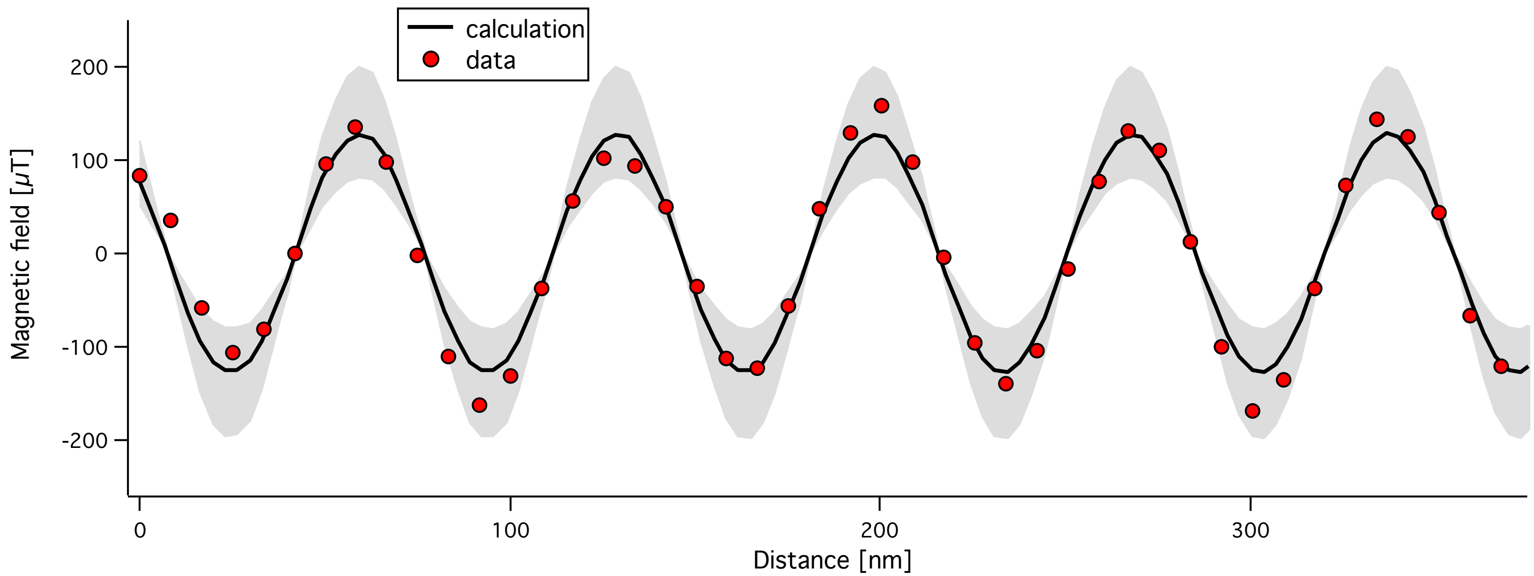
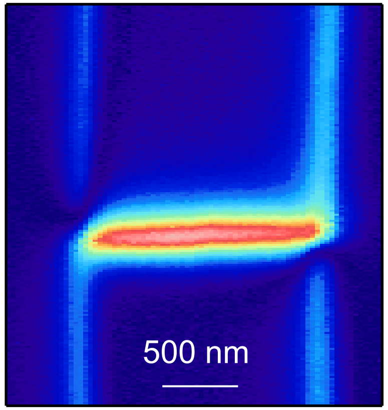
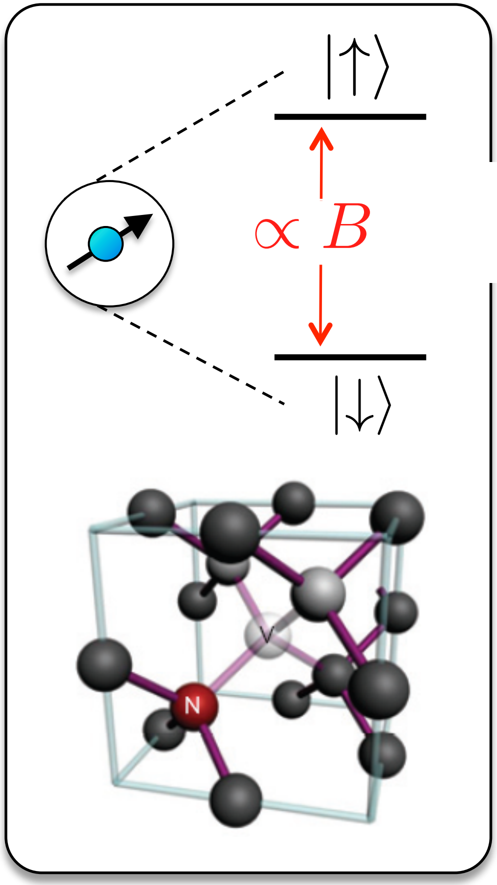


Conclusion

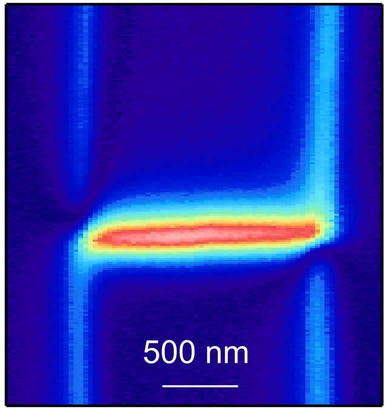
Magnetometry

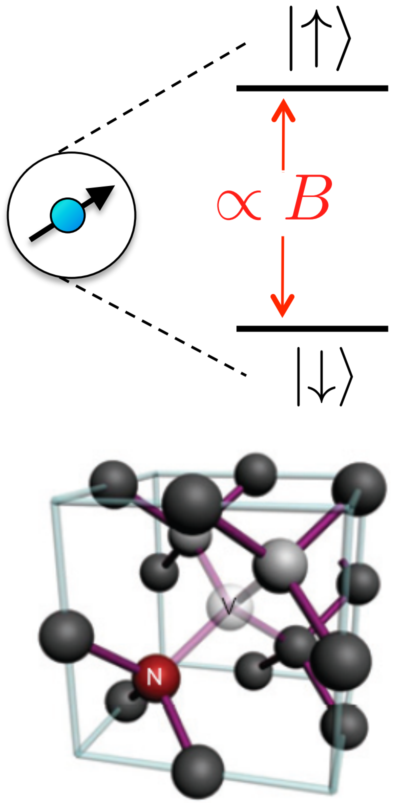




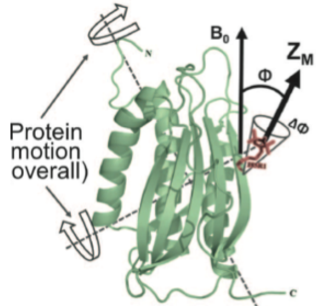
Conclusion

Magnetometry





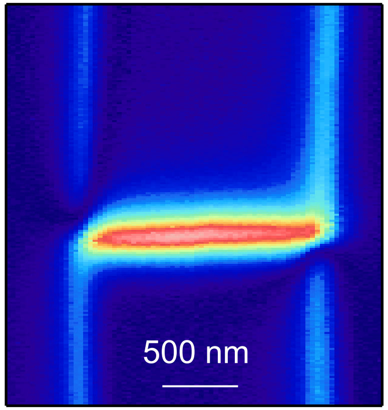
nanoMRI
Protein imaging

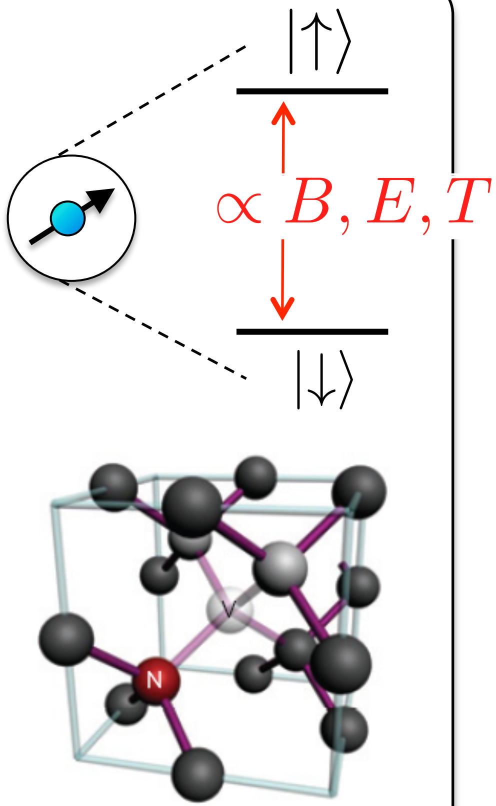


Shi *et al.*, *Science* (2015)
Sushkov *et al.*, *PRL* (2014)

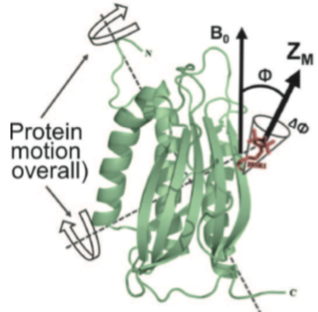
Conclusion

Magnetometry



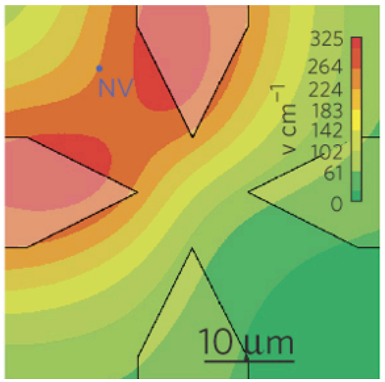


nanoMRI
Protein imaging



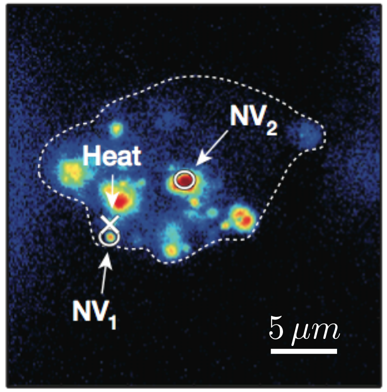
Shi *et al., Science* (2015)
Sushkov *et al., PRL* (2014)

Electrometry



Dolde et al., *Nat. Phys.* **7**, 459 (2011)

Thermometry



Kucsko *et al., Nature* **500**, 54 (2013)

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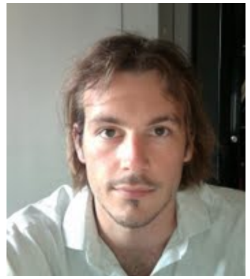

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(early DW experiments)

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