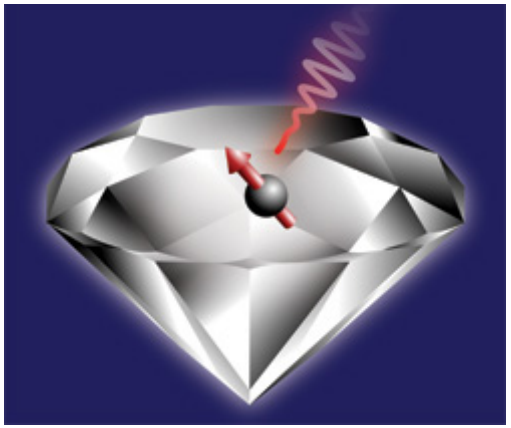
18ème Forum des microscopies à sonde locale

18 Mars 2015

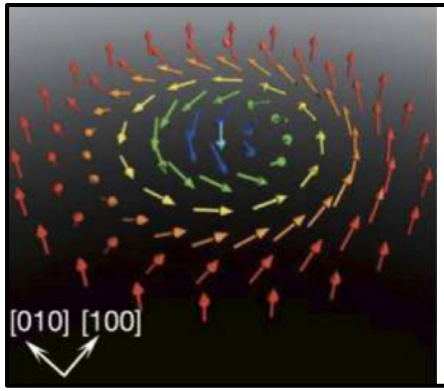
Imagerie magnétique à l'échelle nanométrique à l'aide d'un spin électronique individuel dans le diamant

Vincent JACQUES

Ecole Normale Supérieure de Cachan,
Université Paris-Sud, and CNRS



Spintronic, Nanomagnetism



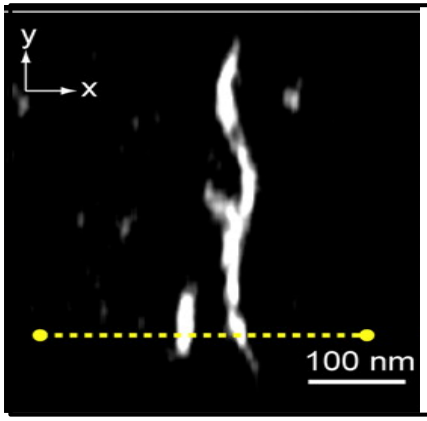
- Domain walls
- Skyrmions
- Spin transport

Quantum information

- Single spin detection

Nanoscale magnetometry

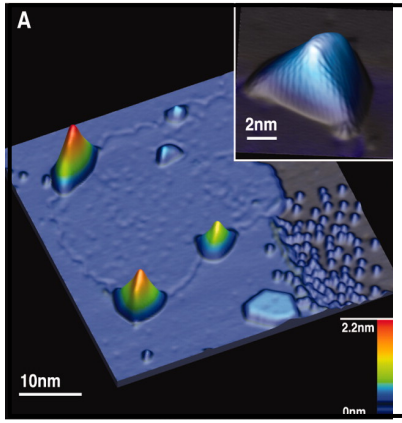
Nano-MRI



Spin density of a tobocco mosaic virus imaged by MRFM

Degen C. et al. *PNAS* 106, 1313 (2009)

Meso. Physics



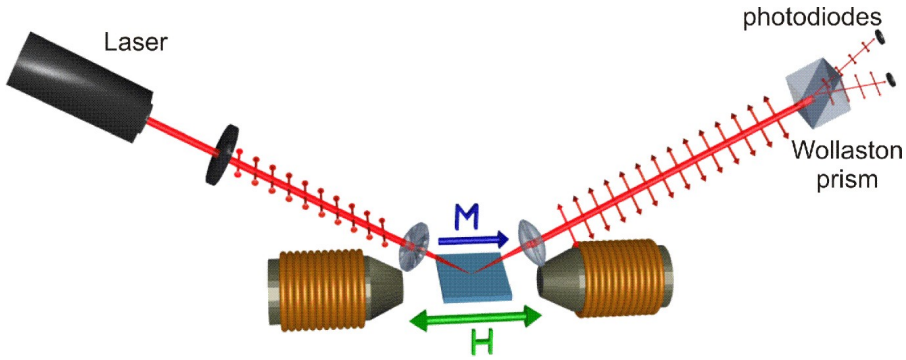
- Magnetism of graphene
- Superconduc-ting materials

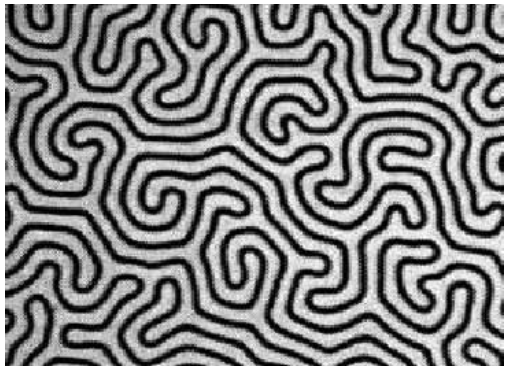
Imaging the sample magnetization

M

Magnetization-dependent interaction with test particles

Magneto-Optical Kerr effect (MOKE)

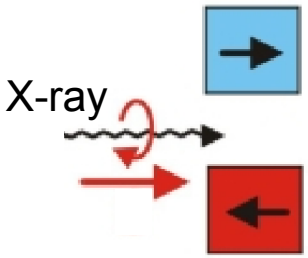


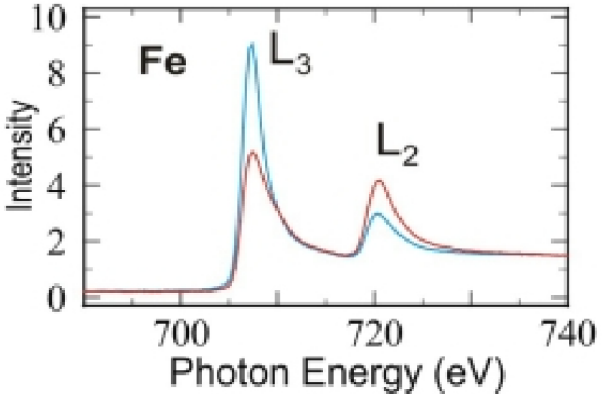


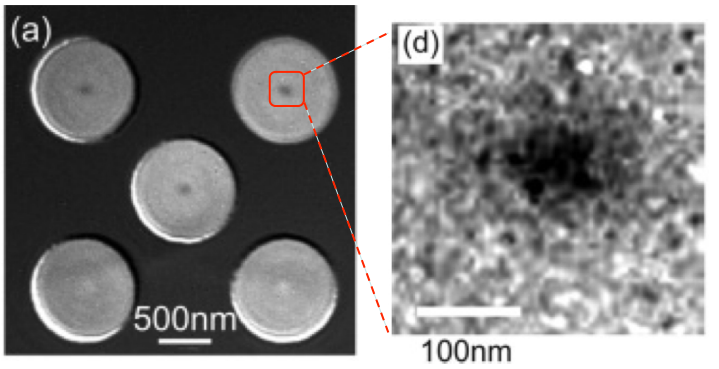
diffraction-limited resolution (~200 nm)

X-ray magnetic circular dichroism (XMCD)

Fischer et al. *PRB* **83**, 212402 (2011)







Resolution ~ 20 nm

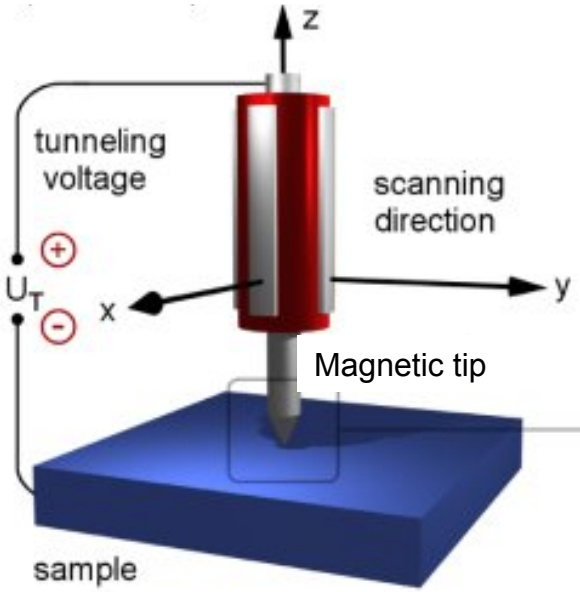
Imaging the sample magnetization

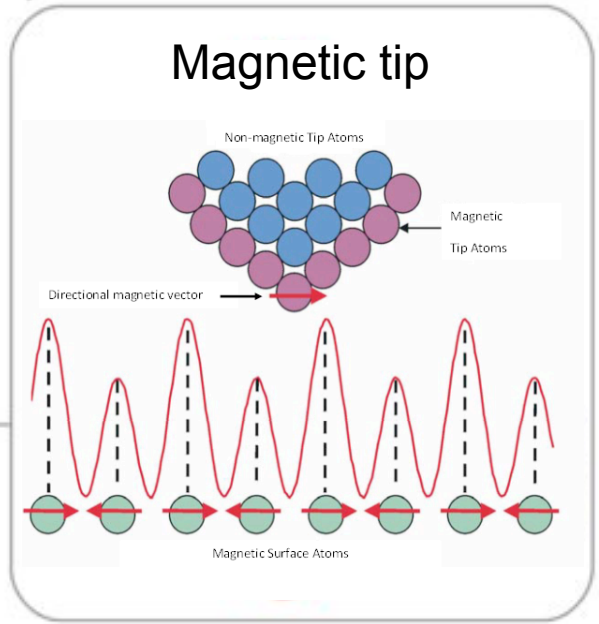
M

Magnetization-dependent interaction with test particles

Spin-Polarized Scanning Tunneling Microscopy (SP-STM)

Cf. Vincent Repain, Jeudi 19 mars, 14h

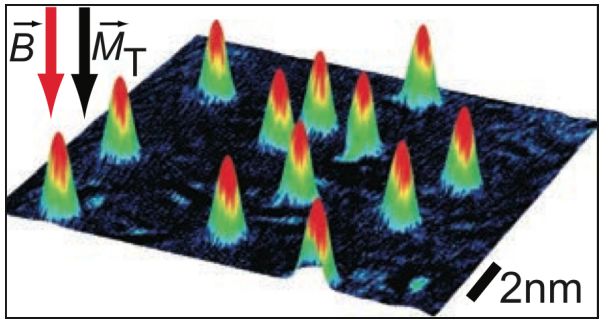




Spin-dependent tunnel current

Atomic scale resolution

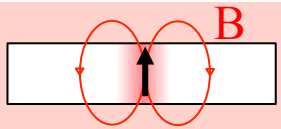
Single Co atoms on Pt



Meier et al. *Science* **82**, 320 (2008)

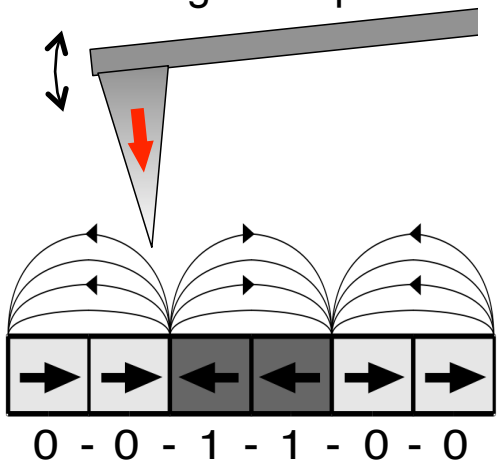
☹ Limited to « model » magnetic samples (ultrahigh vacuum)

Imaging the stray magnetic field



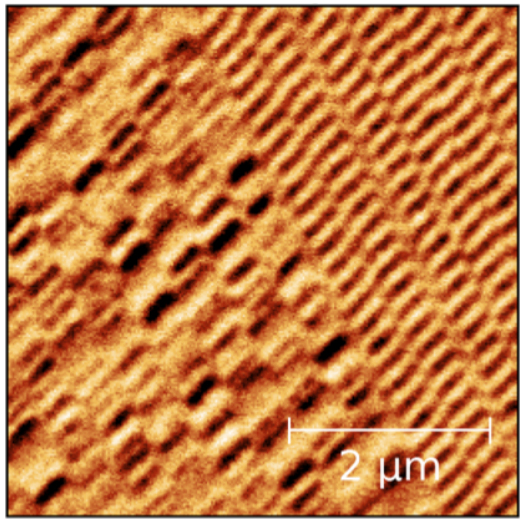
Magnetic Force Microscopy (MFM)

Magnetic tip

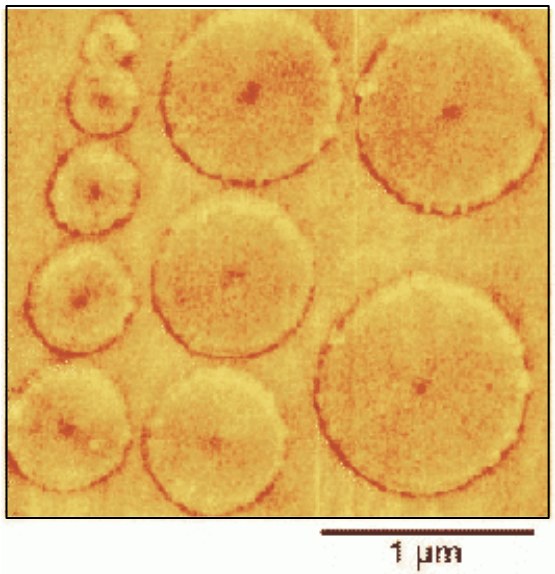


Martin and Wickramasinghe,
Appl. Phys. Lett. **50**, 1455 (1987)

Magnetic Hard disk



Magnetic vortex
in ferromagnetic dot

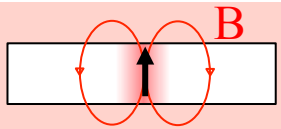


Shinjo et al. *Science* **289**, 930 (2000)

☺ **Resolution ~ 20 nm** under ambient conditions

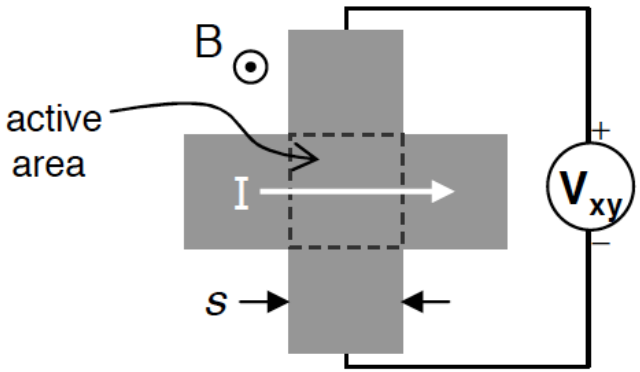
☹ Hardly quantitative, Magnetic back-action

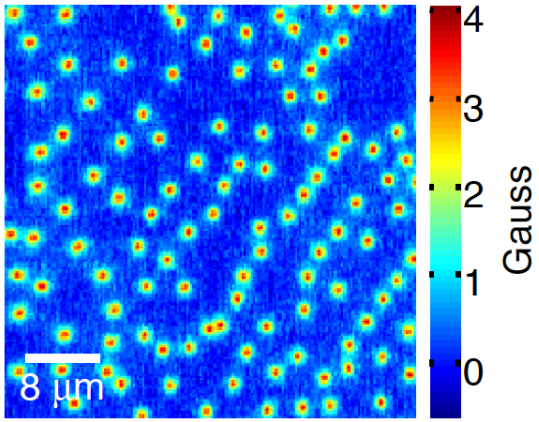
Imaging the stray magnetic field



Scanning Hall probes

Chang *et al. APL* **61**, 1974 (1992)

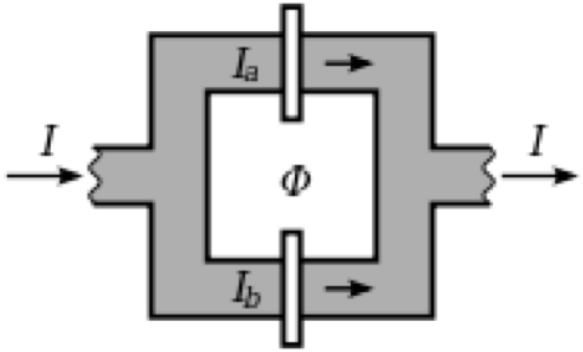


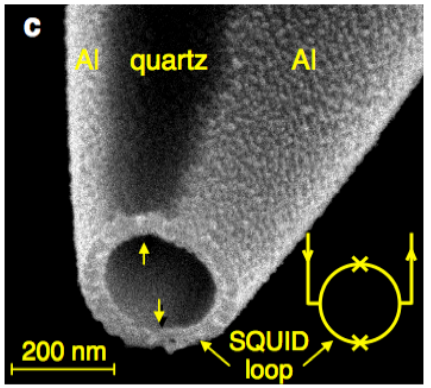


Guikema, *PRB* **77**, 104515 (2008)
(Superconducting vortices imaged with a 500 nm Hall probe)

Scanning SQUID

Superconducting loop
with Josephson junctions



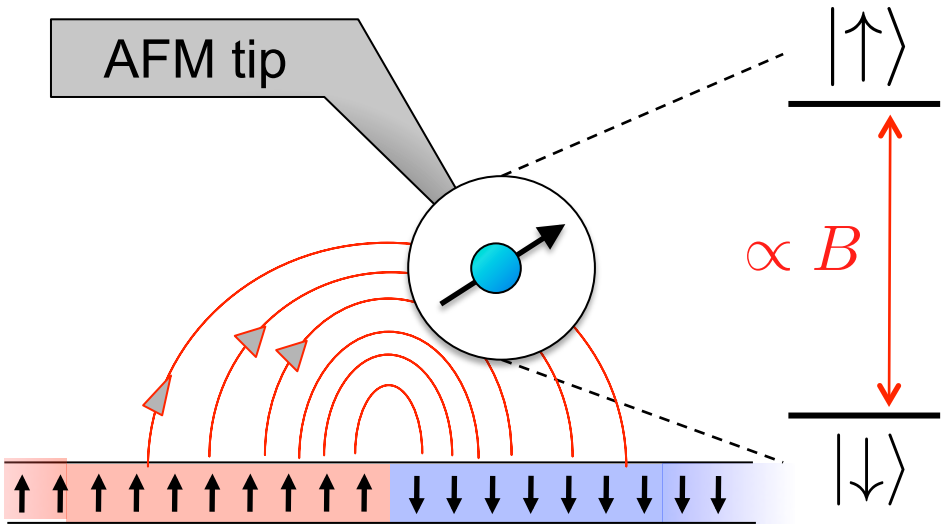


Finkler *et al., Nano Lett.*
10, 1046 (2010)

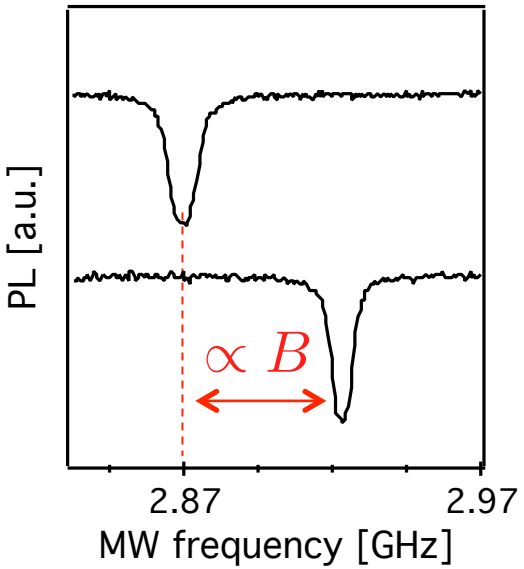
Spatial resolution ultimately limited by the size of the magnetic sensor

Imaging magnetic fields with a single spin

Single e-spin

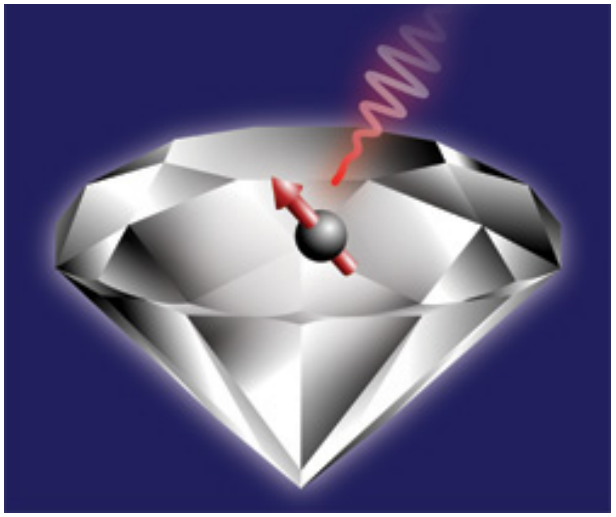


Electron Spin Resonance (ESR)



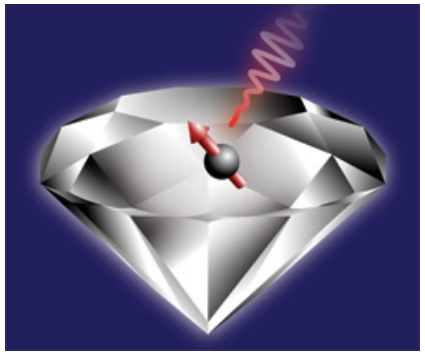
Quantitative B field measurement within an atomic-size detection volume

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



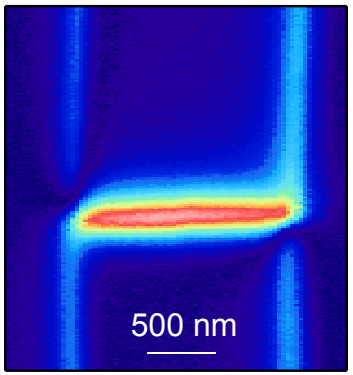
Outline of the talk

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



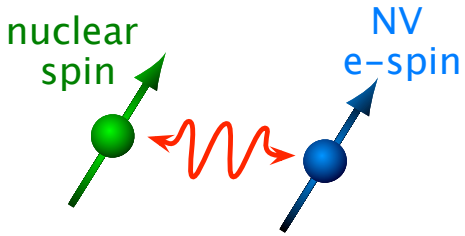
2. Applications in fundamental nanomagnetism

Imaging dowain walls in ultrathin magnetic wires



3. Other Applications

Biology, Quantum information science…



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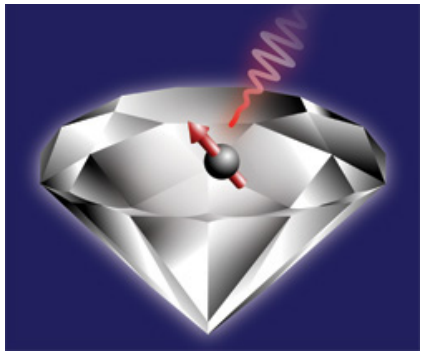
1. The NV defect in diamond as an atomic-sized magnetic field sensor

   See recent review

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



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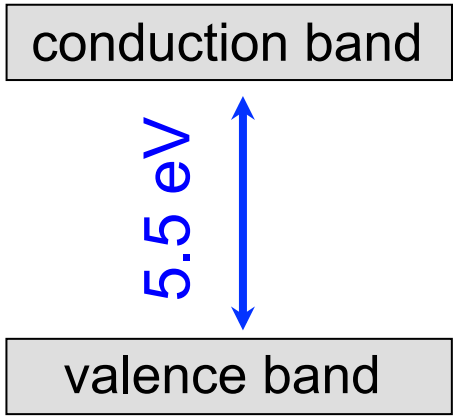
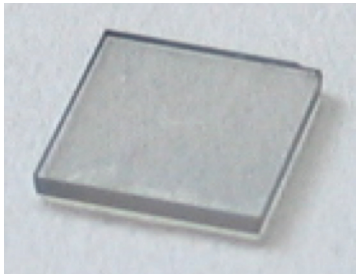
Defects in diamond, a real zoology…



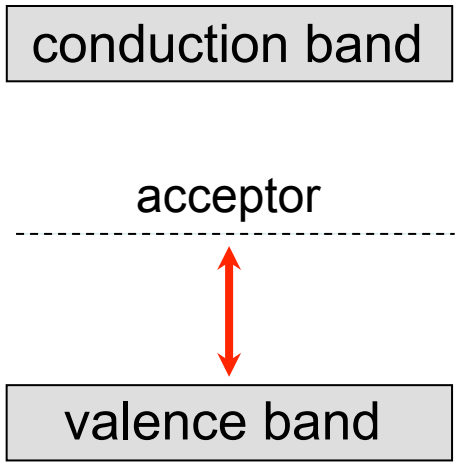
A perfect diamond would not absorb visible light…



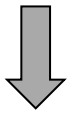
…but many defects are optically active

→ Color centers

e.g. Boron (B) impurities



Red absorption

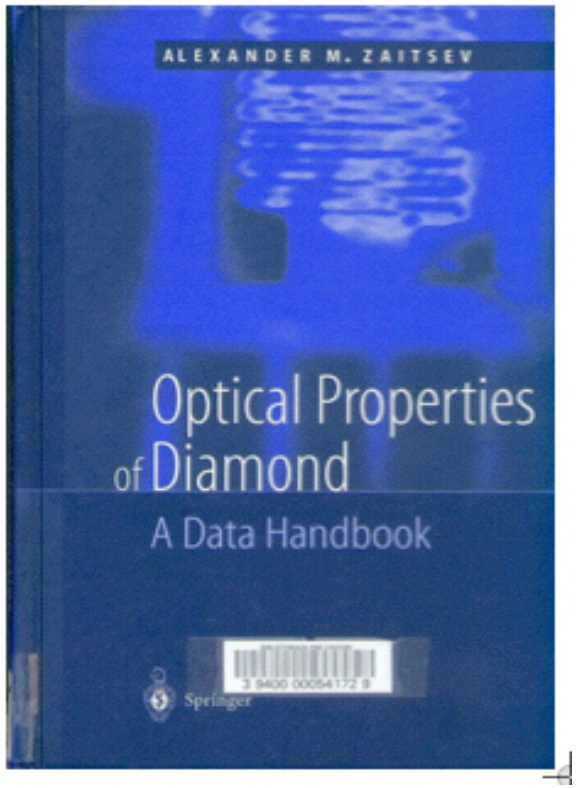


Blue color

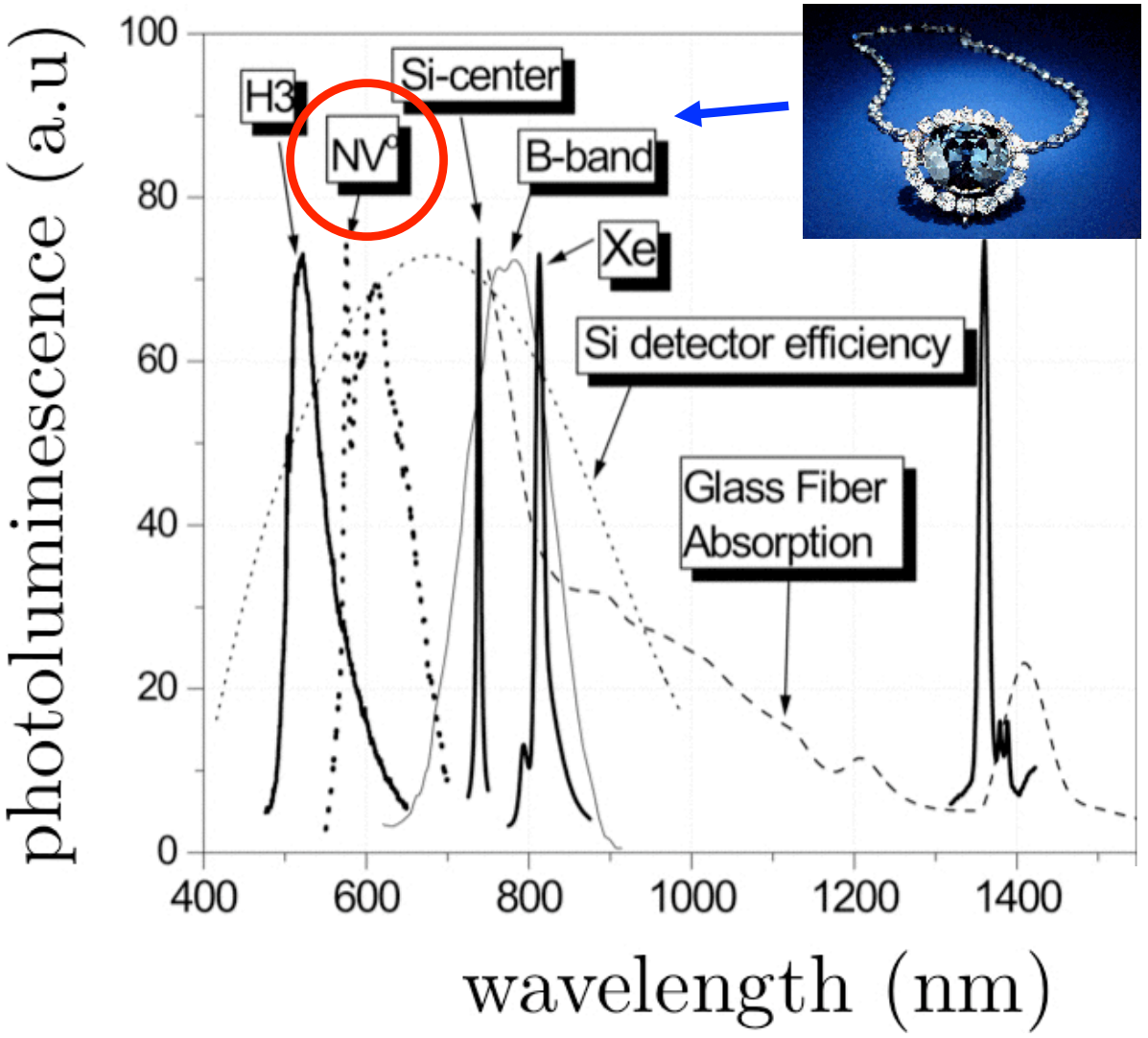
The « Hope » diamond

Defects in diamond, a real zoology…

more than 500 optically-active defects are known in diamond



– A. M. Zaitsev –



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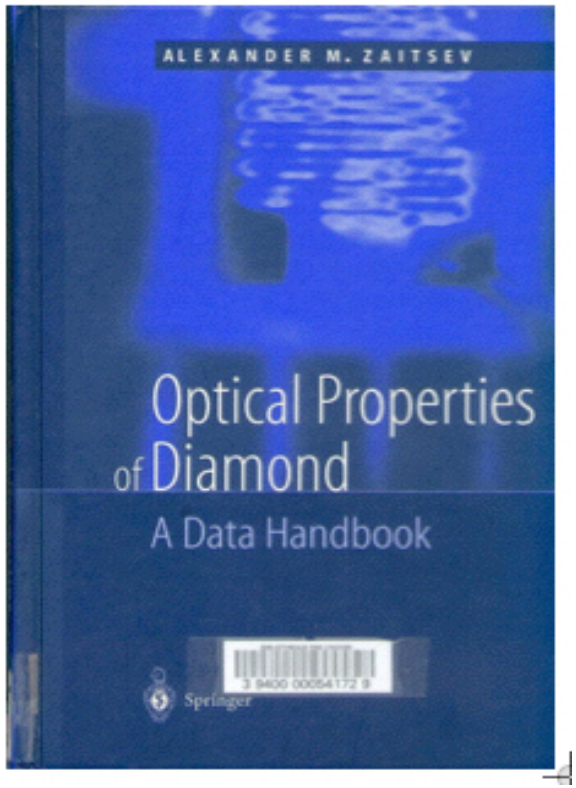
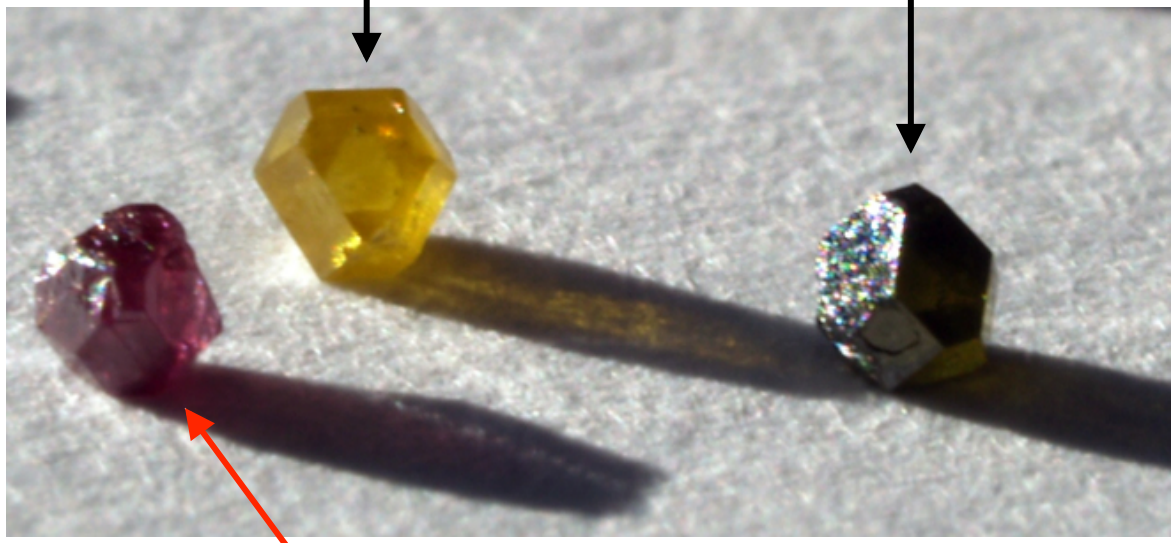


– A. M. Zaitsev –

Nitrogen doped (N) *yellow*

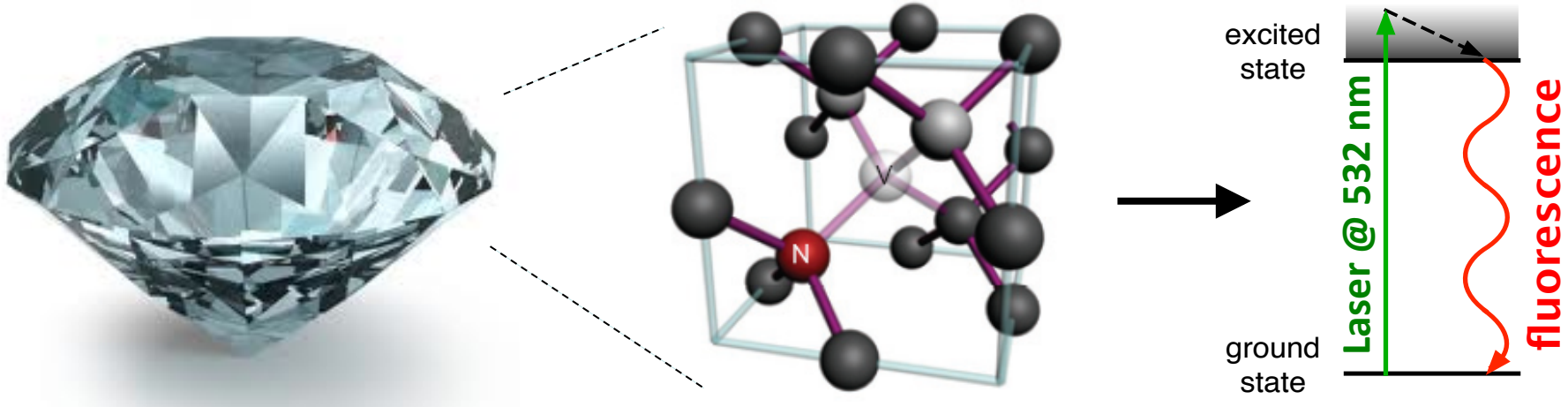
Vacancy doped (V) *green*



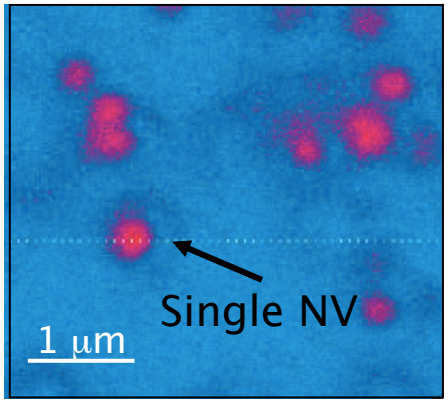
Nitrogen-Vacancy (NV) doped – *pink*

Nitrogen-Vacancy (NV) defect in diamond

- Artificial atom « trapped » in the diamond lattice

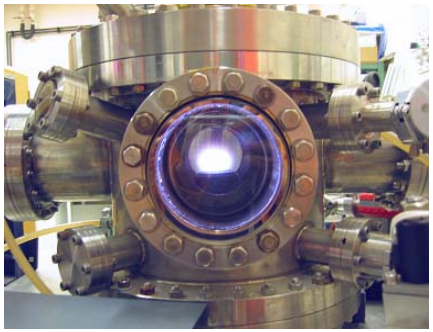


- Detection at the single emitter level at room T



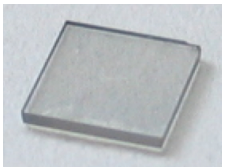
Gruber *et al.*, *Science* **276**, 2012 (1997)

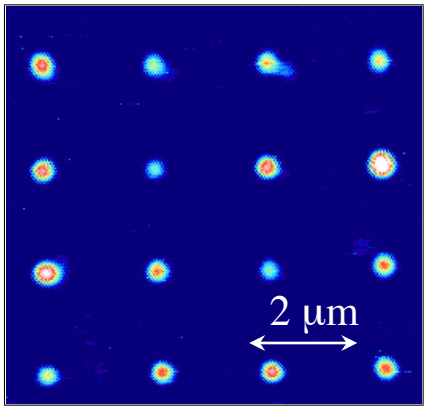
High purity diamond with CVD growth



Gicquel and Achard group (Villetaneuse)

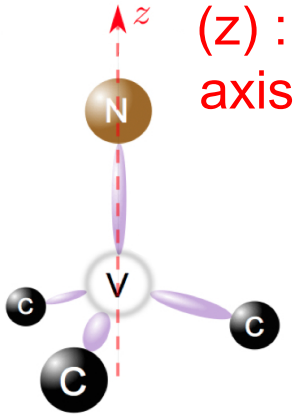
NV defect engineering with nanoscale ion implantation





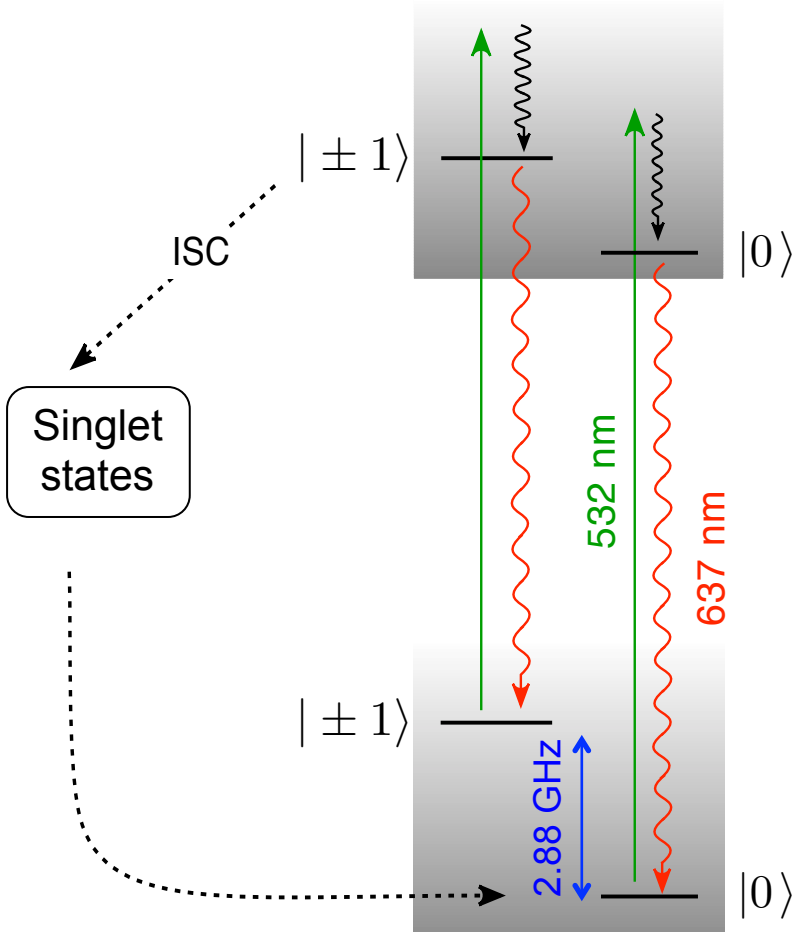
Spinicelli *et al.*, *NJP* **13**, 025014 (2011)

Spin properties



(z) : quantization axis of the defect

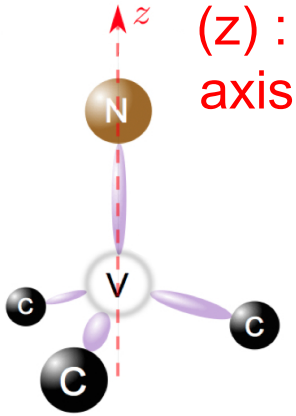
spin triplet (S=1) ground state



Important properties

- Spin-conserving optical transition $\Delta m_s=0$.
- Spin-dependent ISC to singlet states.

Spin properties



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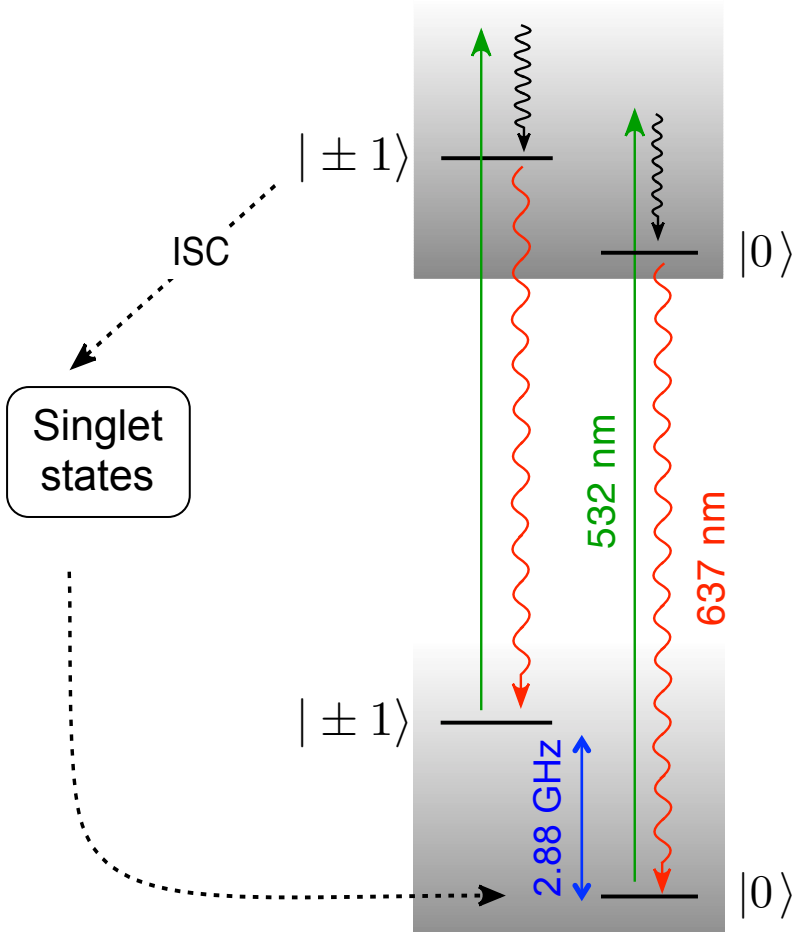

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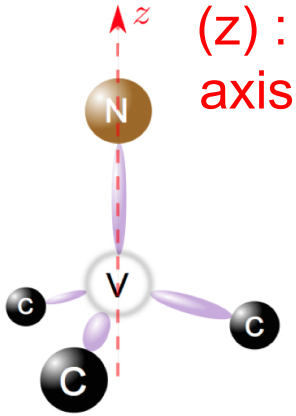

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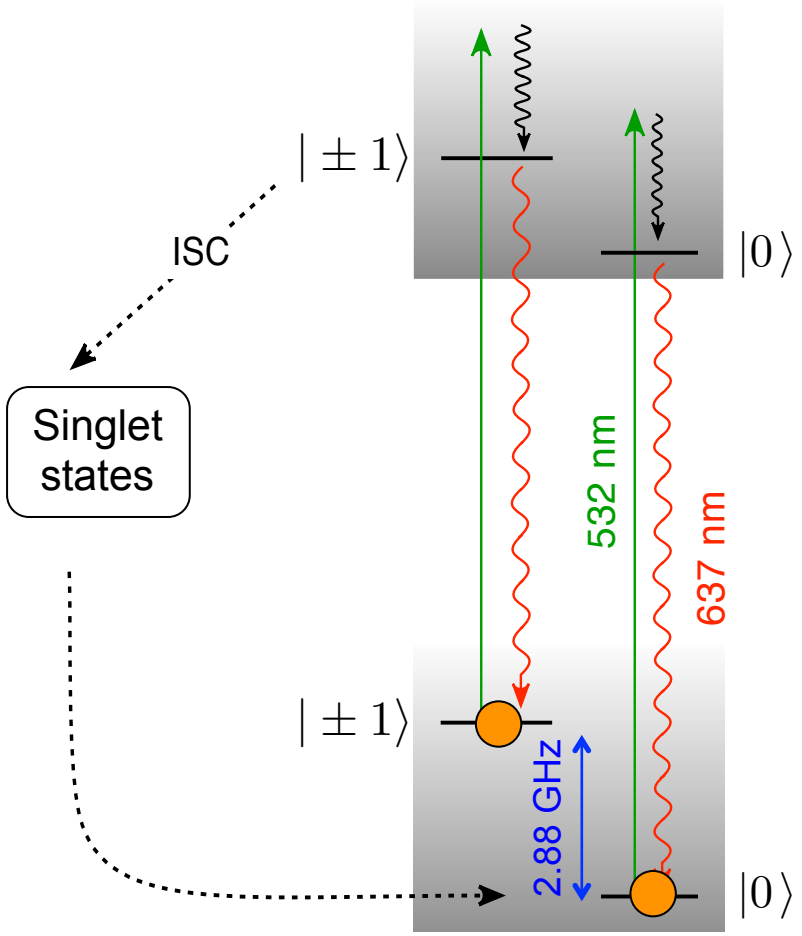

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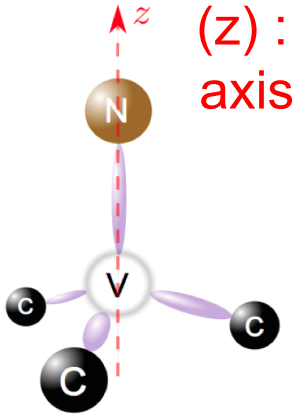

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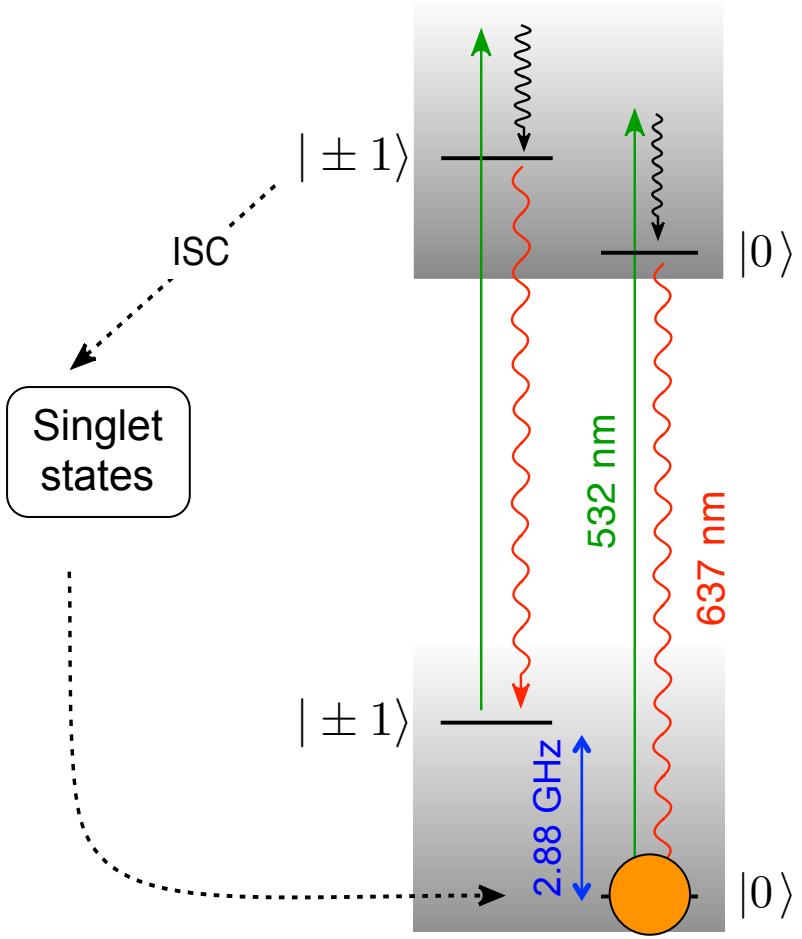


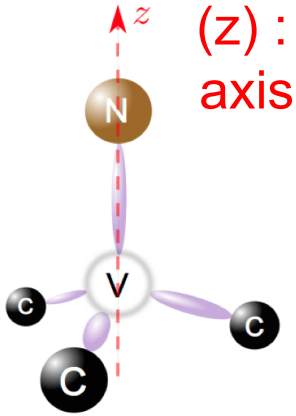
Important properties

- Spin-conserving optical transition $\Delta m_s=0$.
- Spin-dependent ISC to singlet states.

Consequences

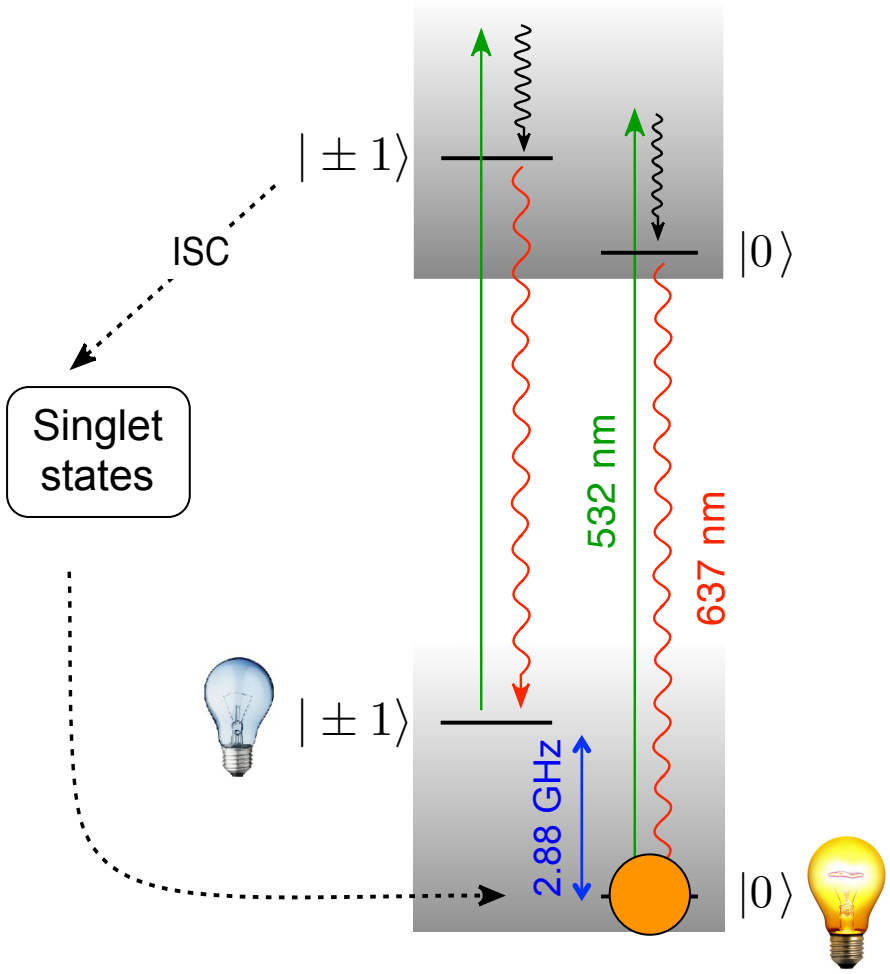
- Polarization in $m_s=0$ by optical pumping.

Spin properties



(z) : quantization axis of the defect

spin triplet (S=1) ground state



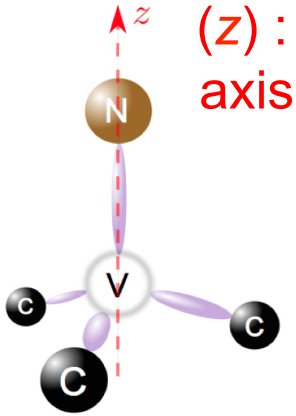
Important properties

- Spin-conserving optical transition $\Delta m_s=0$.
- Spin-dependent ISC to singlet states.

Consequences

- Polarization in $m_s=0$ by optical pumping.
- Spin-dependent fluorescence.

Spin properties



(*z*) : quantization axis of the defect

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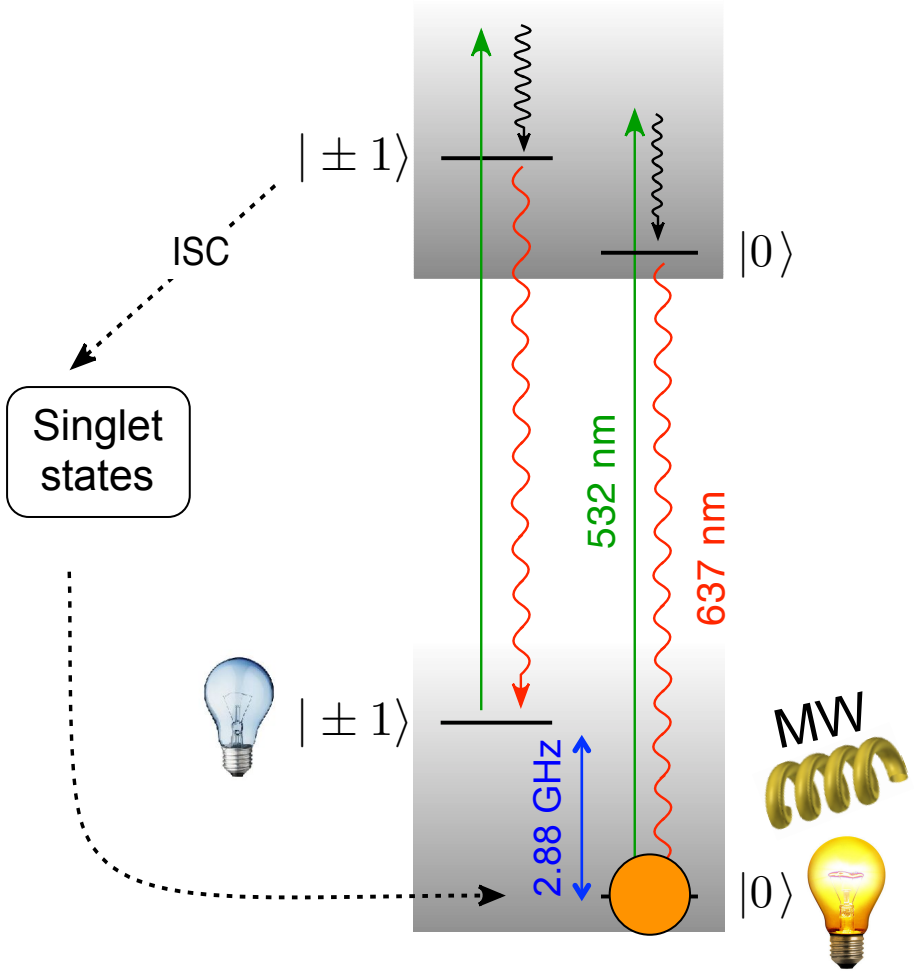
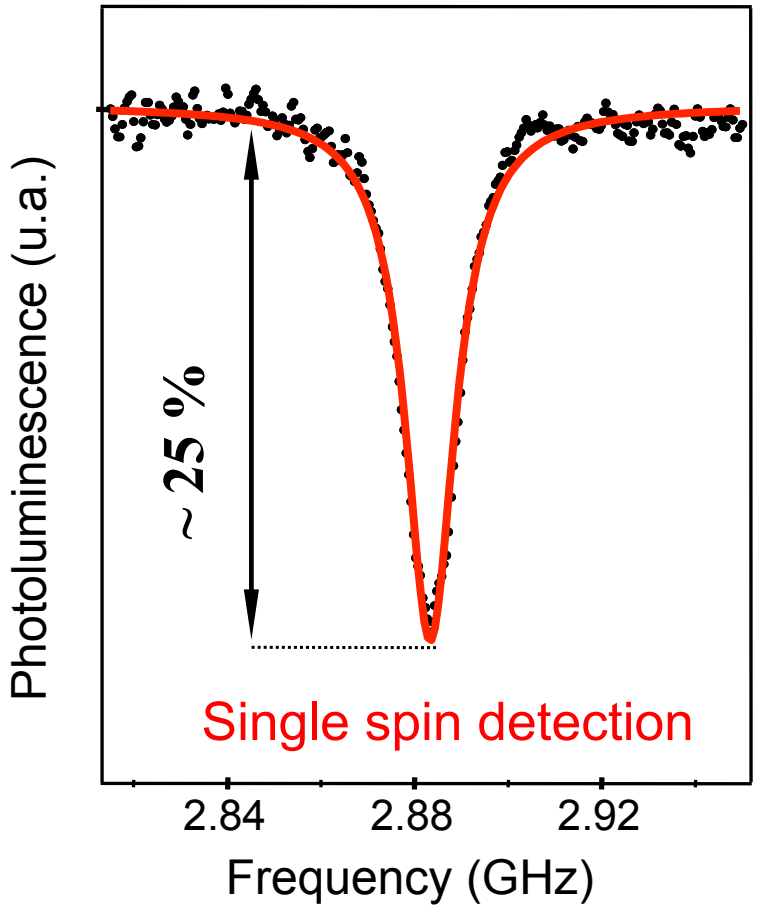
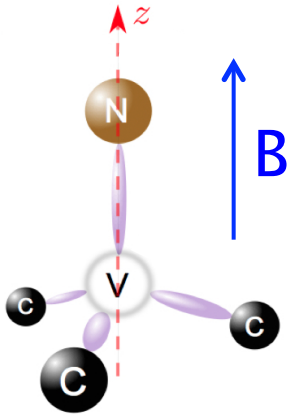


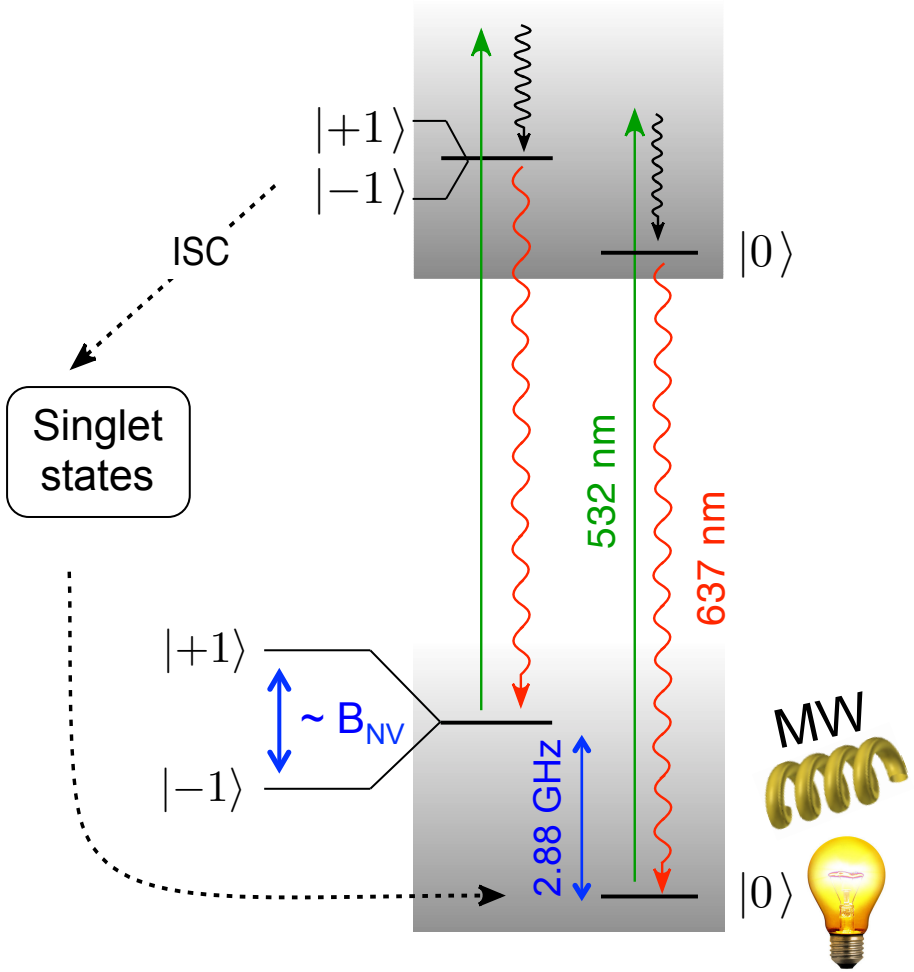


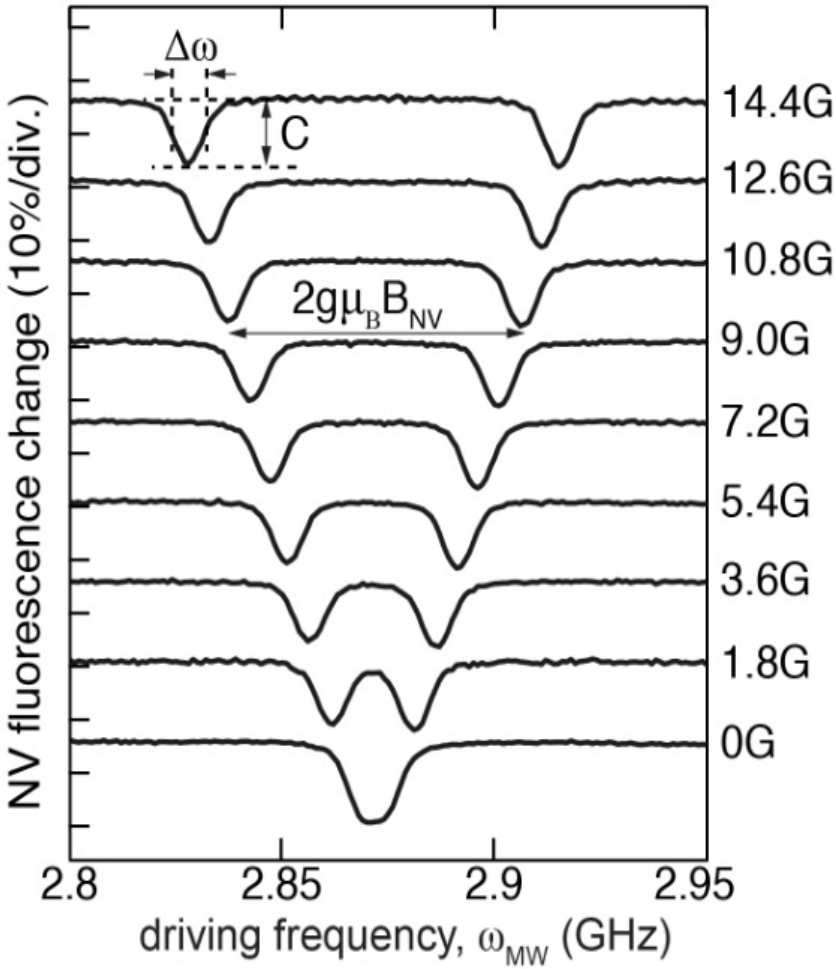
NV defect
= e-spin qubit

Spin properties

spin triplet (S=1)
ground state







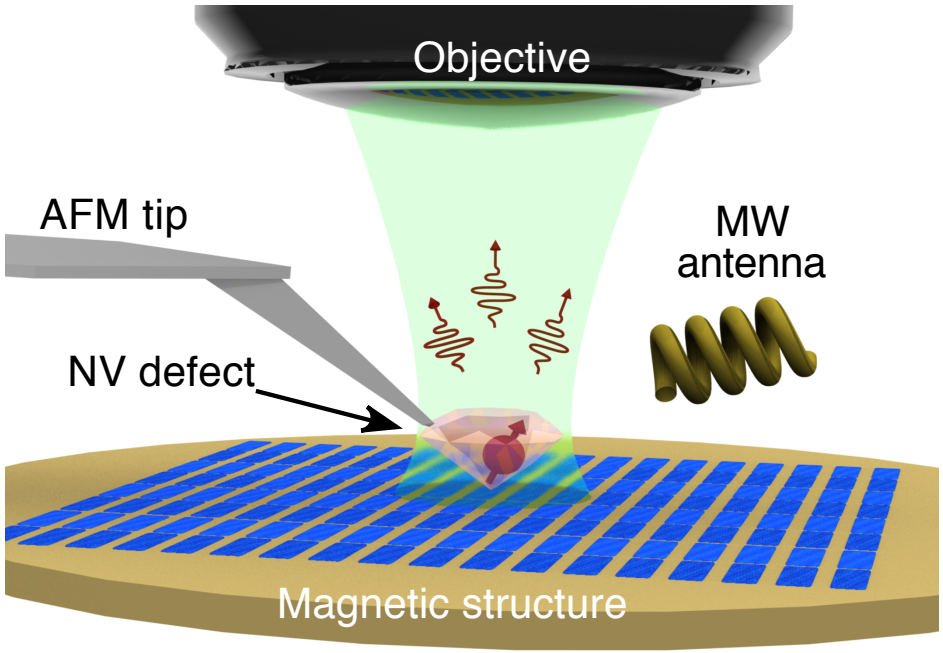
NV defect
= magnetometer

Maze et al. *Nature* **455**, 644 (2008)

Scanning-NV magnetometry

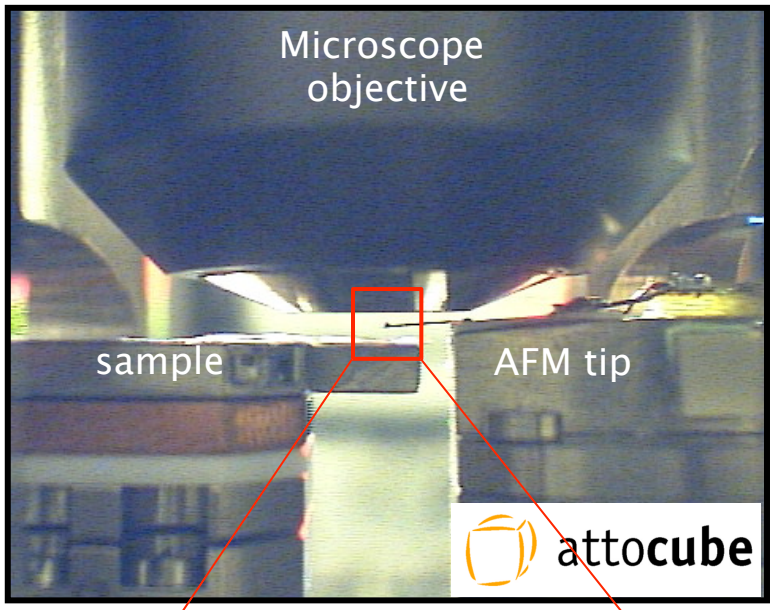
➢ Principle

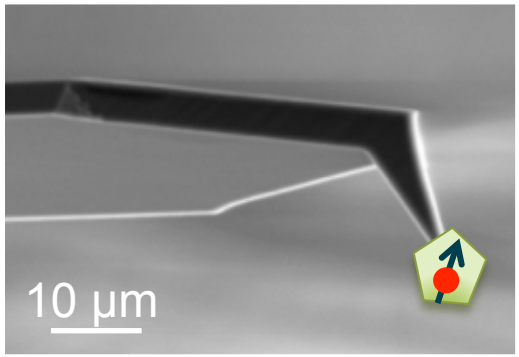
Balasubramanian *et al.*,
Nature **455**, 648 (2008)



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

➢ Experiment

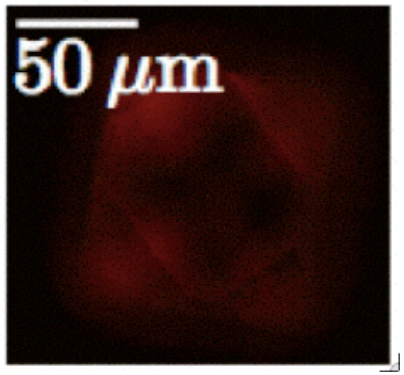




Diamond nanoparticle
hosting a single NV defect

Engineering NV defects in nanodiamonds

Diamond with a **high**
N content (>100 ppm)

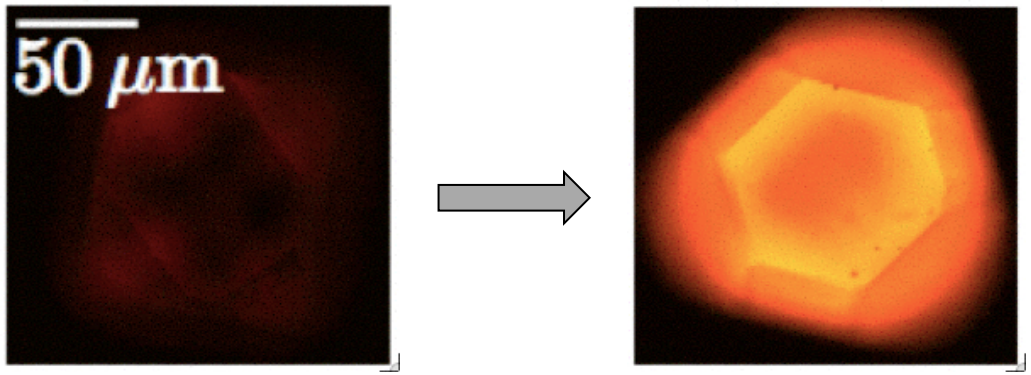


Photoluminescence of a diamond microcrystal

Engineering NV defects in nanodiamonds

Diamond with a **high N content (>100 ppm)**

Irradiation (e,H^+,…) to **create vacancies**



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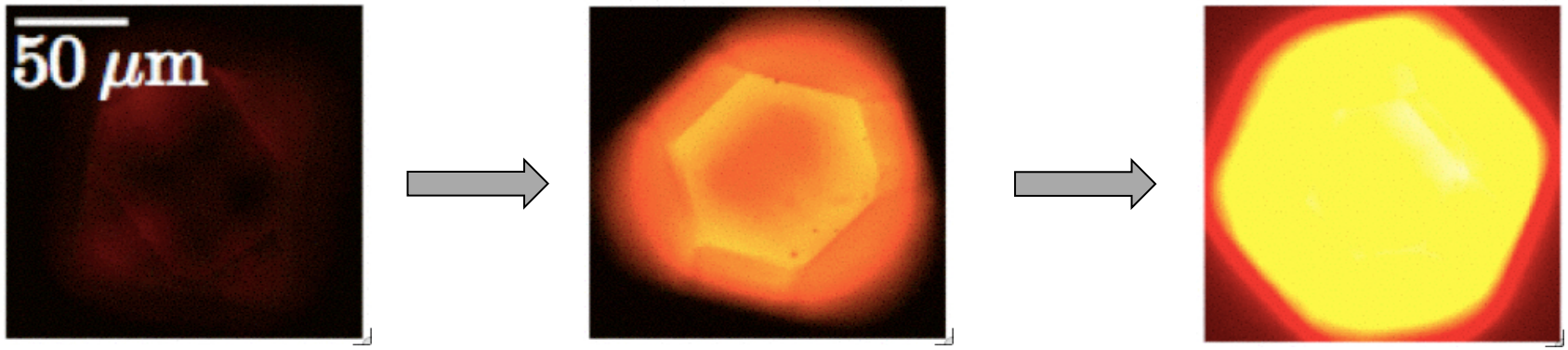
Annealing @ 800°C to **stabilize NV defects**



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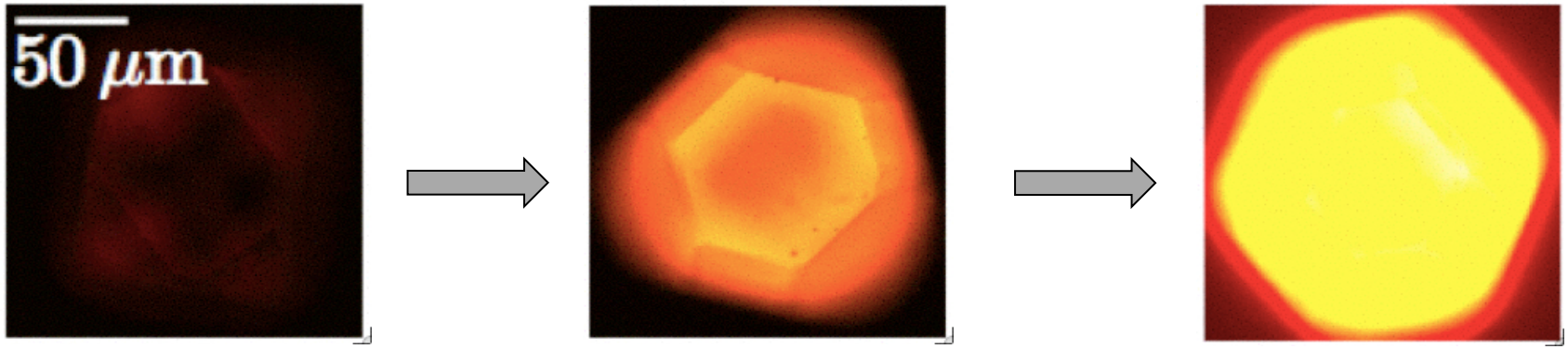


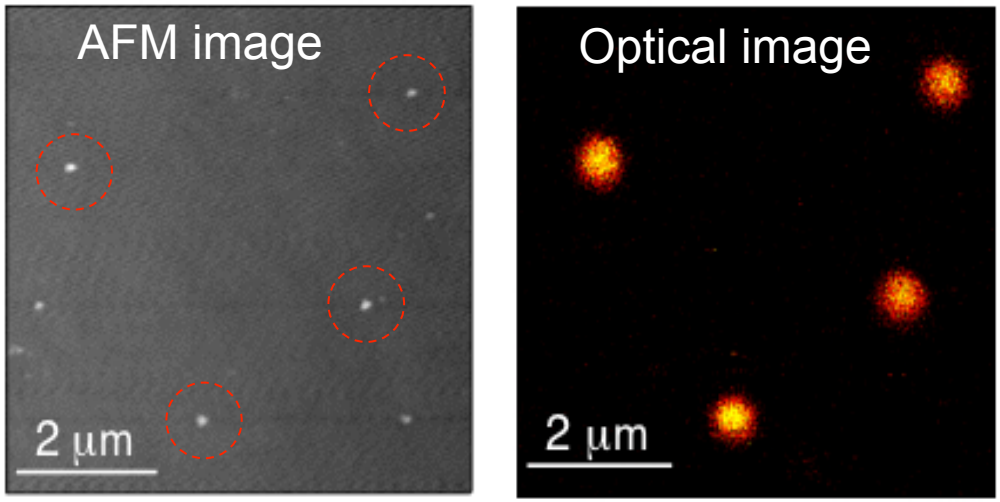
Photoluminescence of a diamond microcrystal

- Also works for diamond nanocrystals…

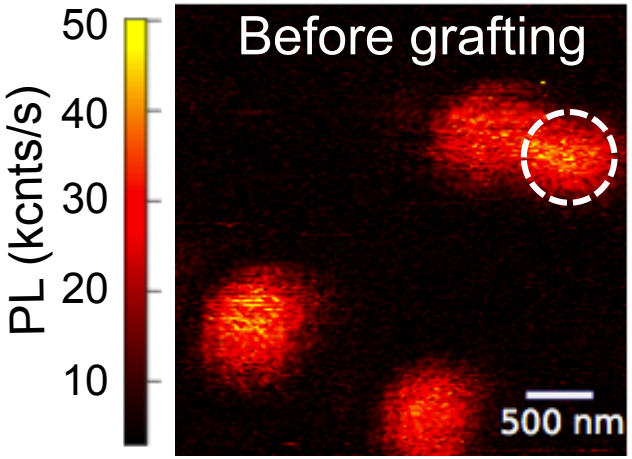
Collab with G. Dantelle (LPMC, Polytechnique)

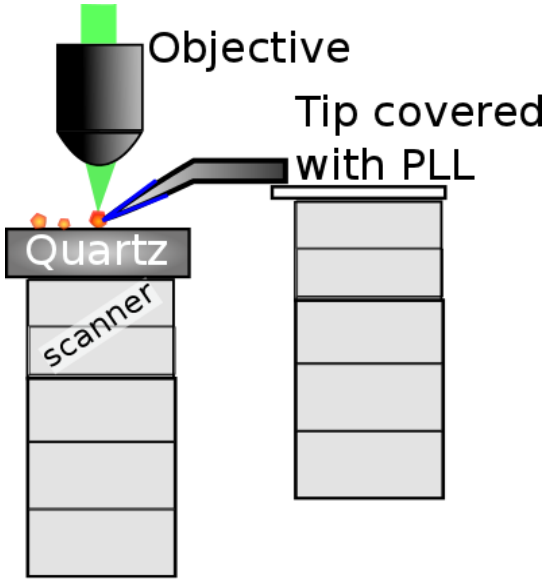
10-20 nm diamond nanocrystals hosting single NV defects…

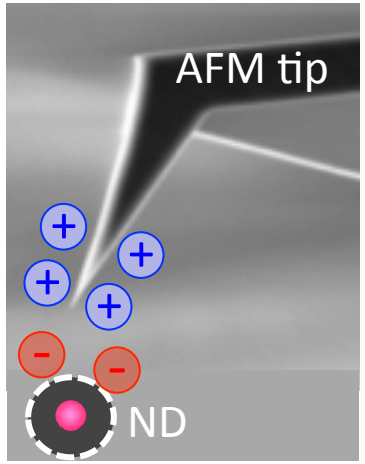
Rondin et al., *PRB* **82**, 115449 (2010)



Grafting a nanodiamond to an AFM tip



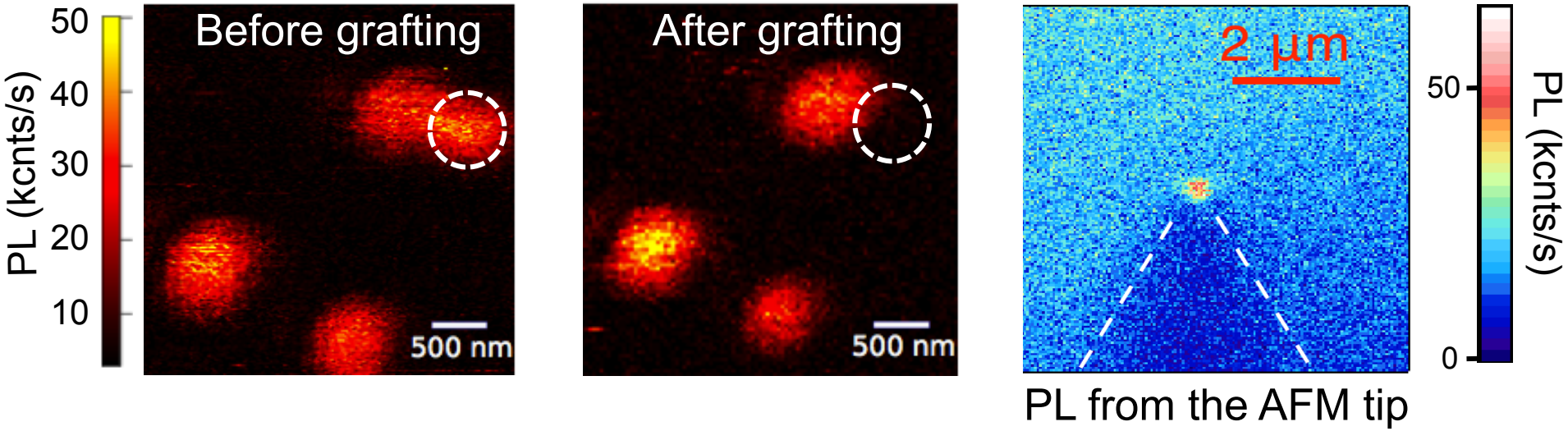


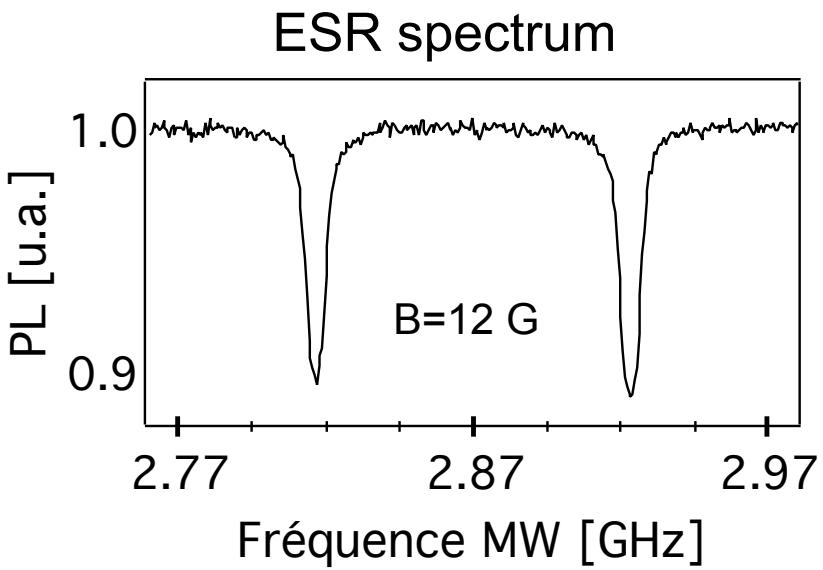


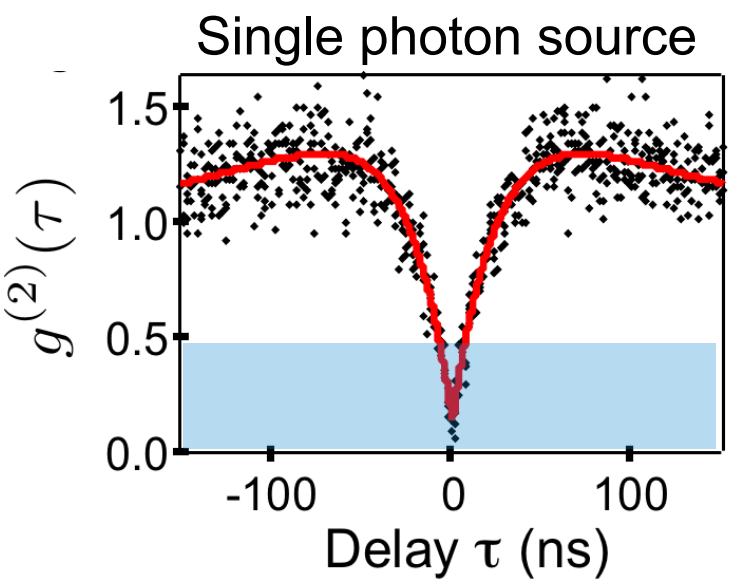
Grafting by electrostatic interaction

A. Cuche et al., *Opt. Exp.* 17, 19969 (2009)
S. Khün et al., *J. Microsc.,* 202, 2 (2001)

Grafting a nanodiamond to an AFM tip



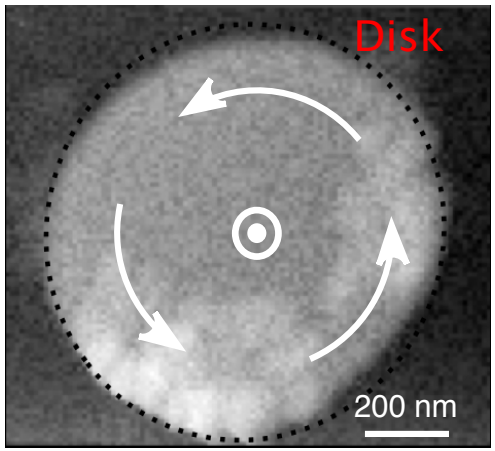


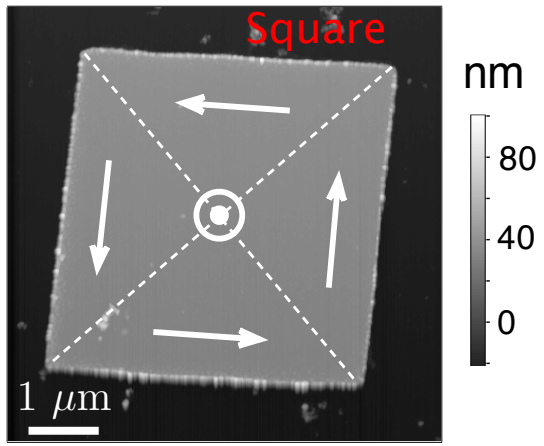


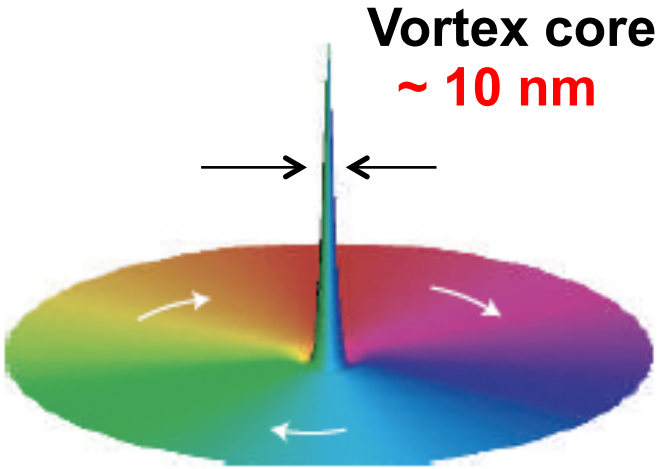
Proof-of-principle experiment

Magnetic vortices in thin ferromagnetic dots

Typical AFM images

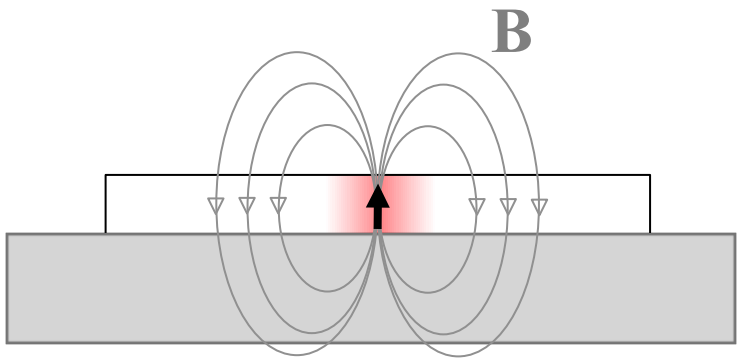




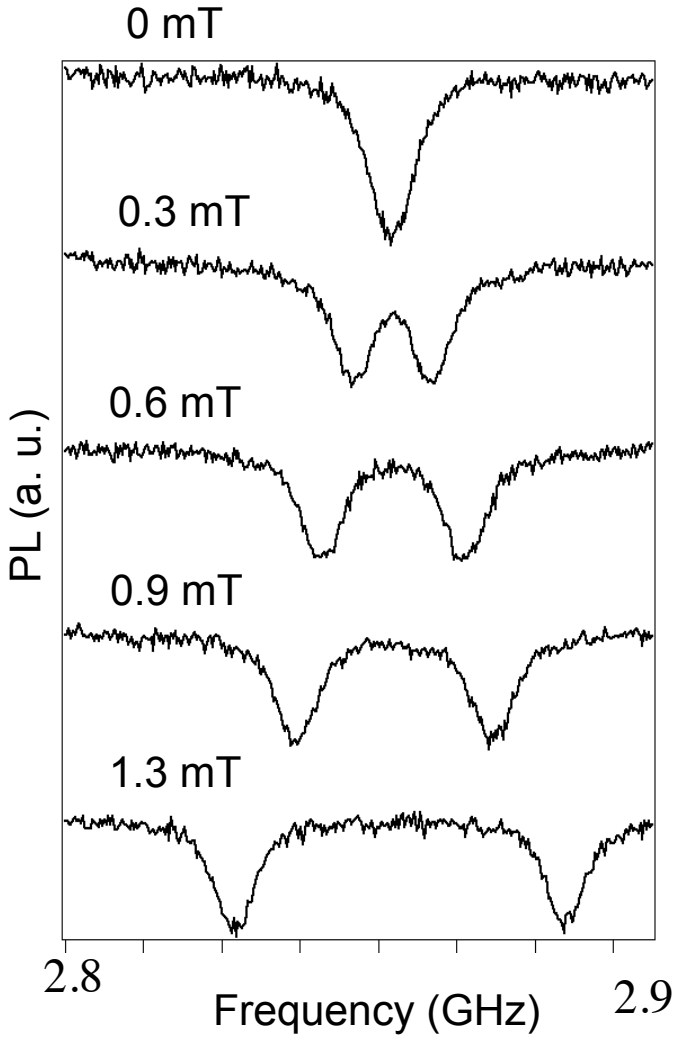


Ideal « point-like » magnetic object to characterize the performances of scanning-NV magnetometry

Rondin *et al*. Nat. Commun. **4**, 2279 (2013)



Imaging methods



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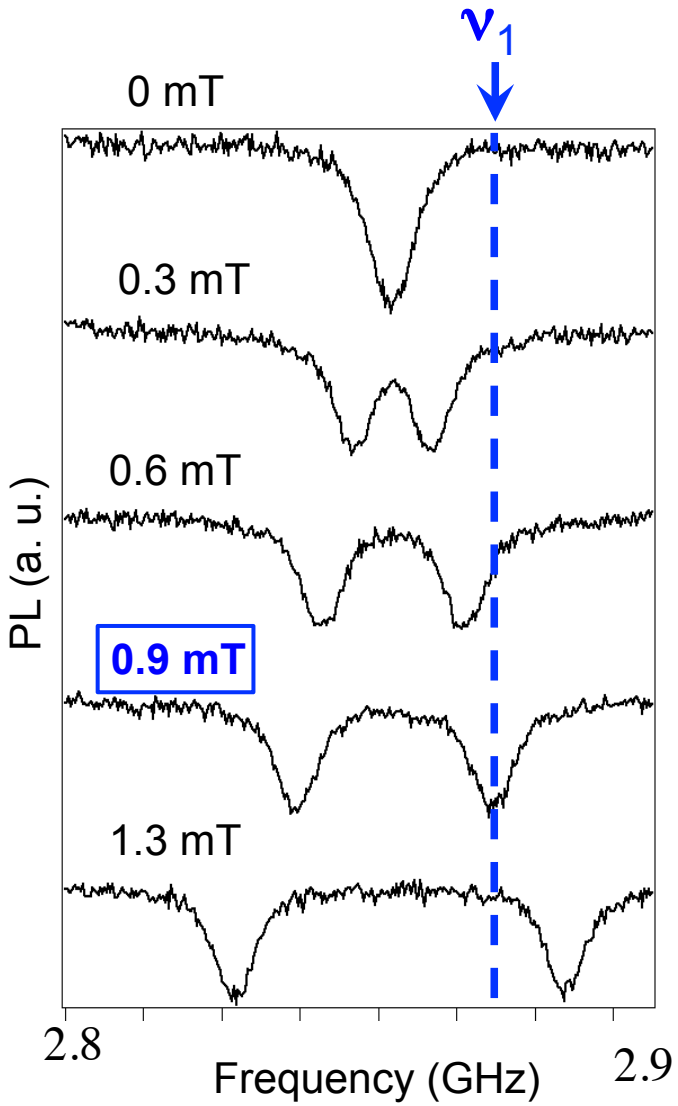
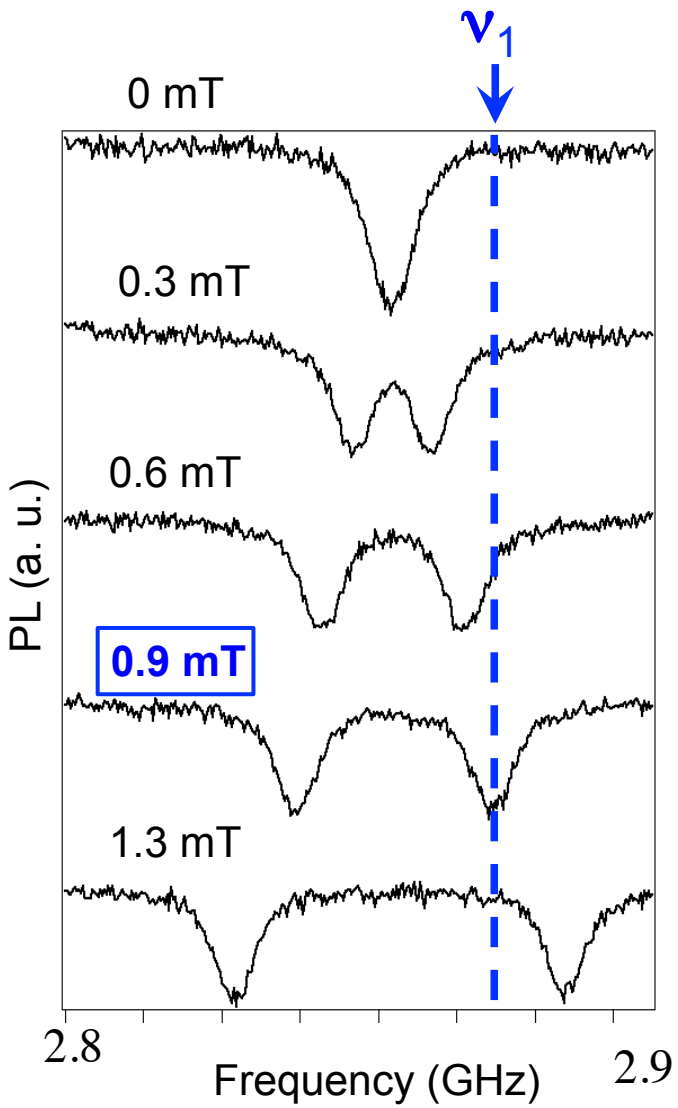
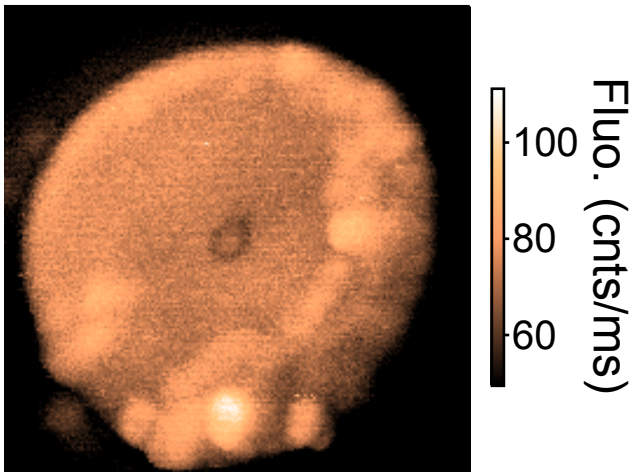


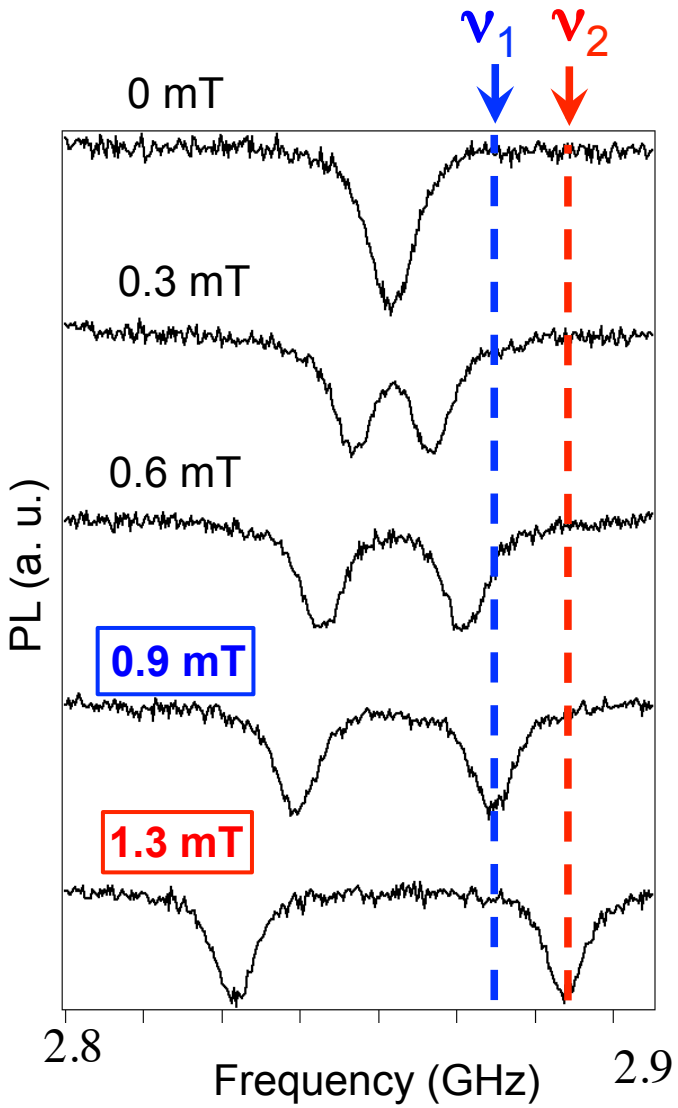
Imaging methods

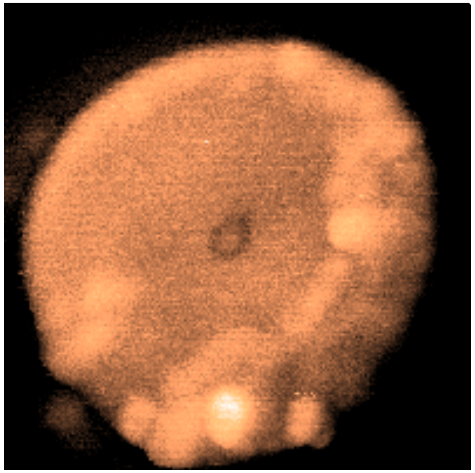


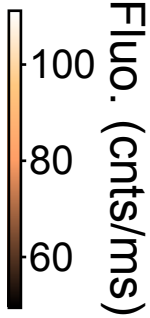


Iso-B @ ± 0.9 mT

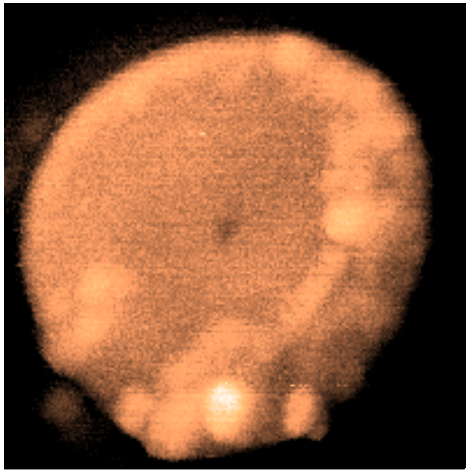
Imaging methods





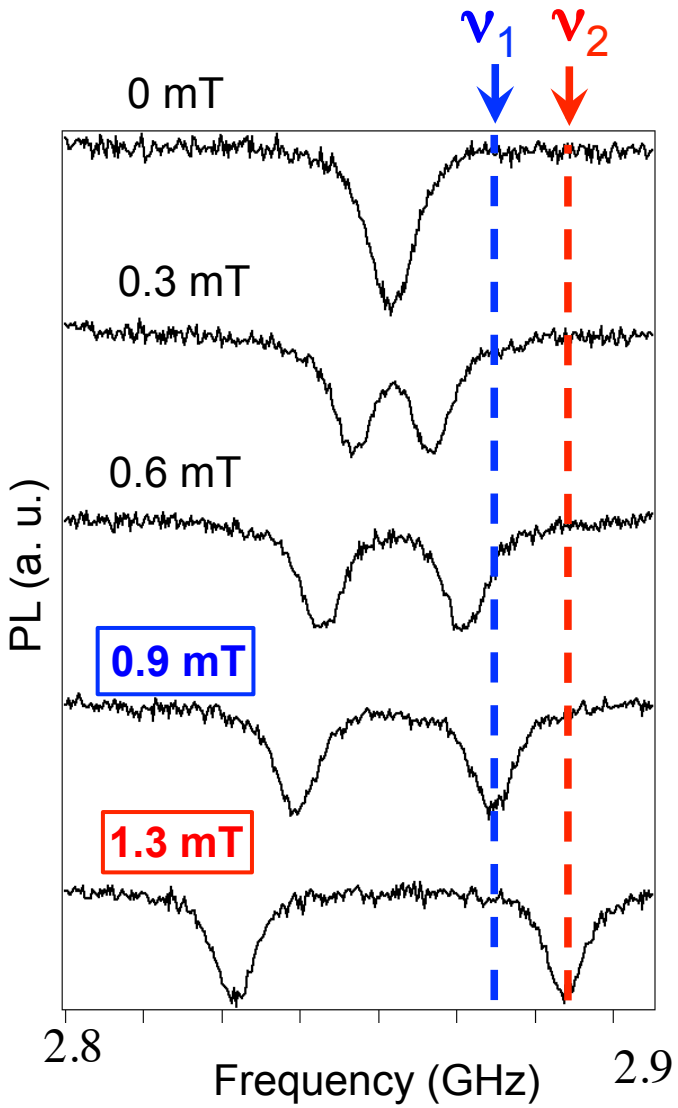


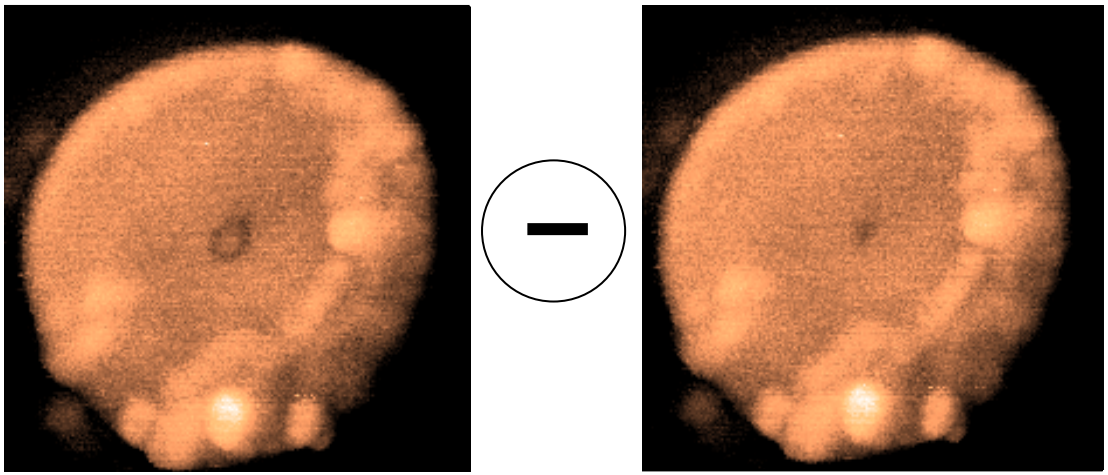
Iso-B @ ± 0.9 mT



Iso-B @ ± 1.3 mT

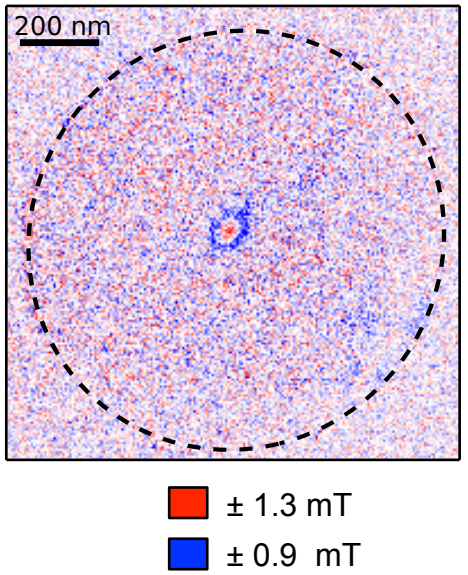
Imaging methods



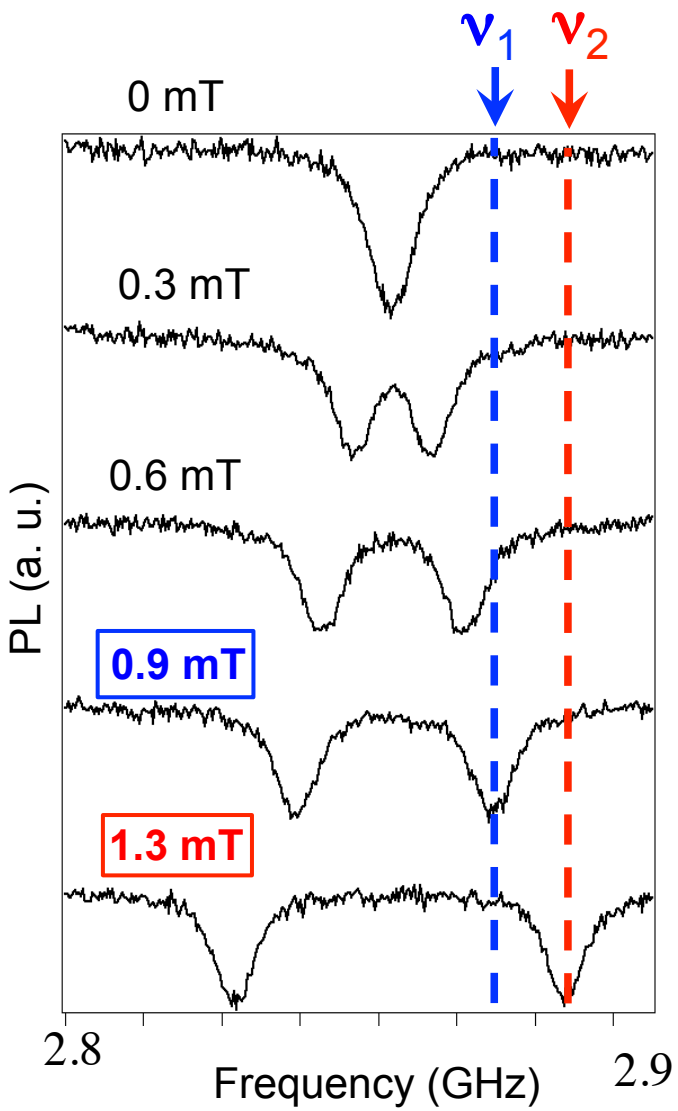


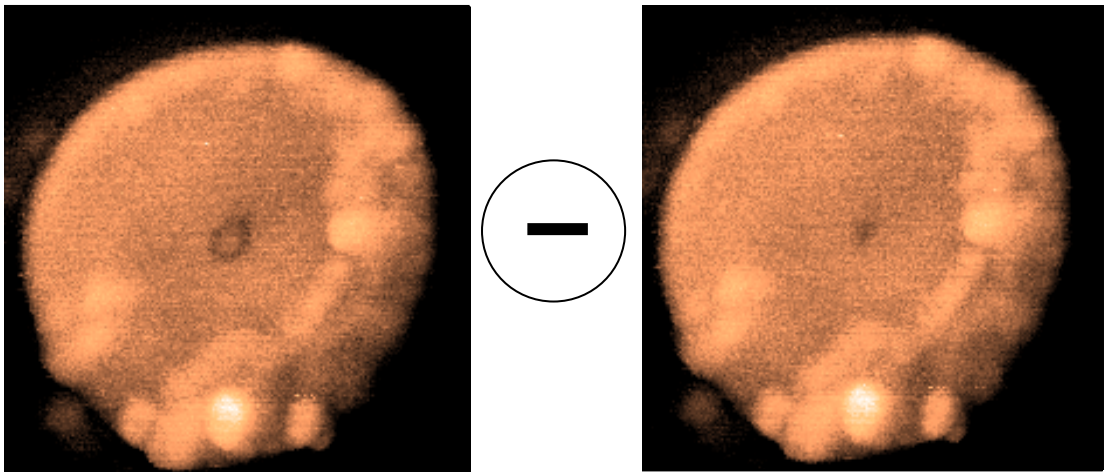
Iso-B @ ± 0.9 mT

Iso-B @ ± 1.3 mT



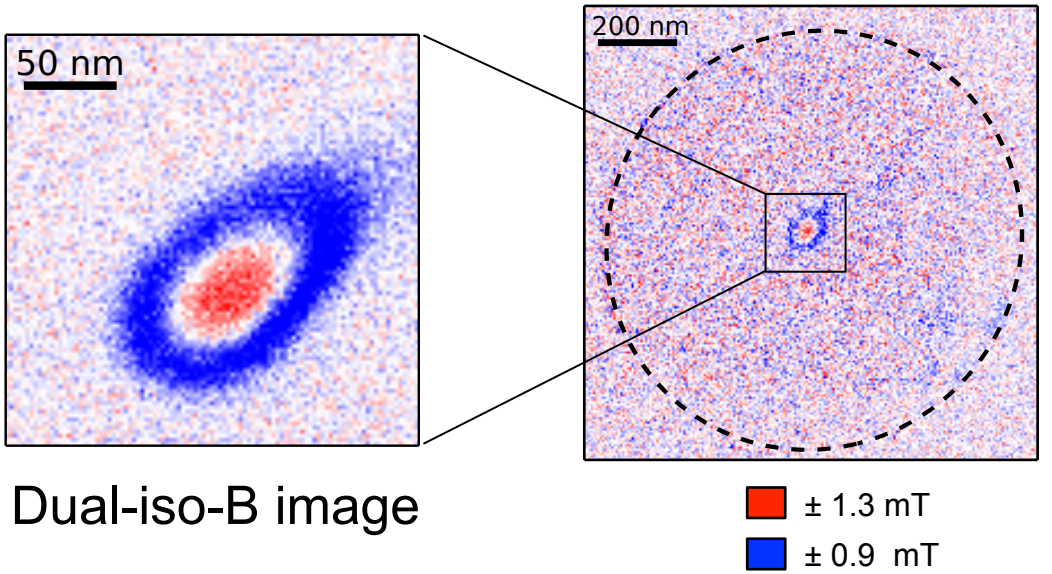
Imaging methods





Iso-B @ ± 0.9 mT

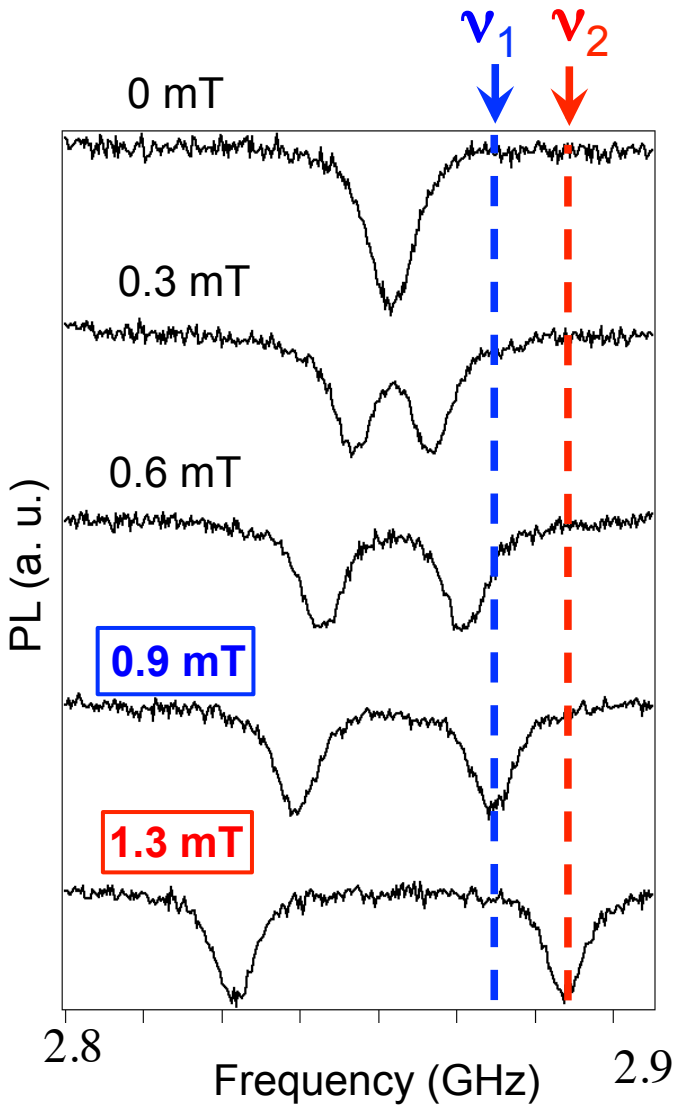
Iso-B @ ± 1.3 mT

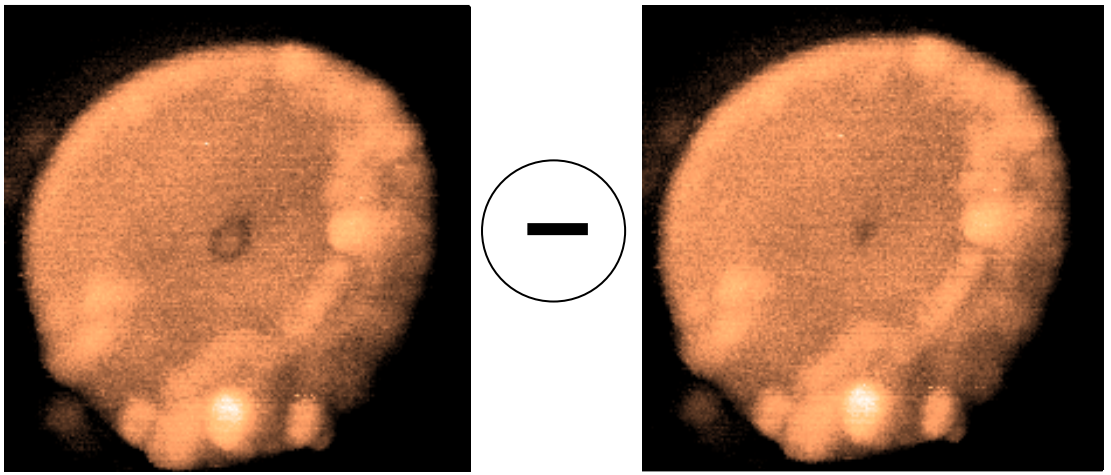


Dual-iso-B image

Rondin *et al*. Nat. Commun. **4**, 2279 (2013)

Imaging methods





Iso-B @ ± 0.9 mT

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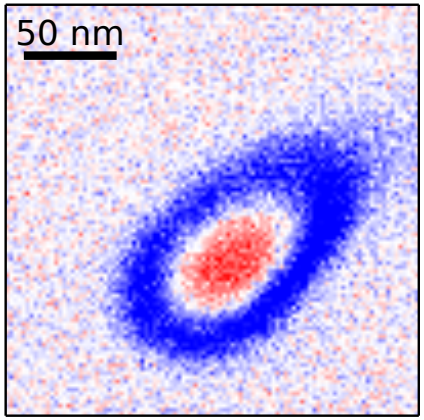
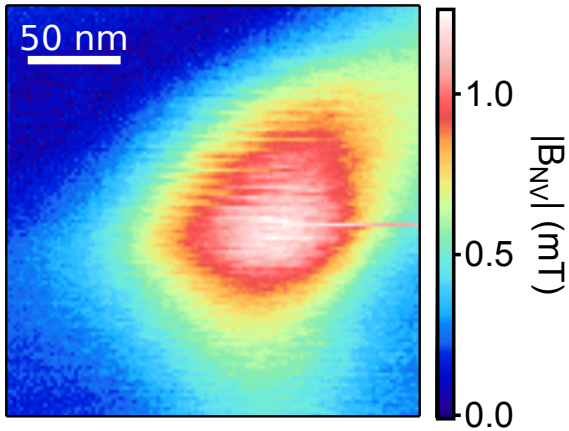


Dual-iso-B image

40 ms per pixel

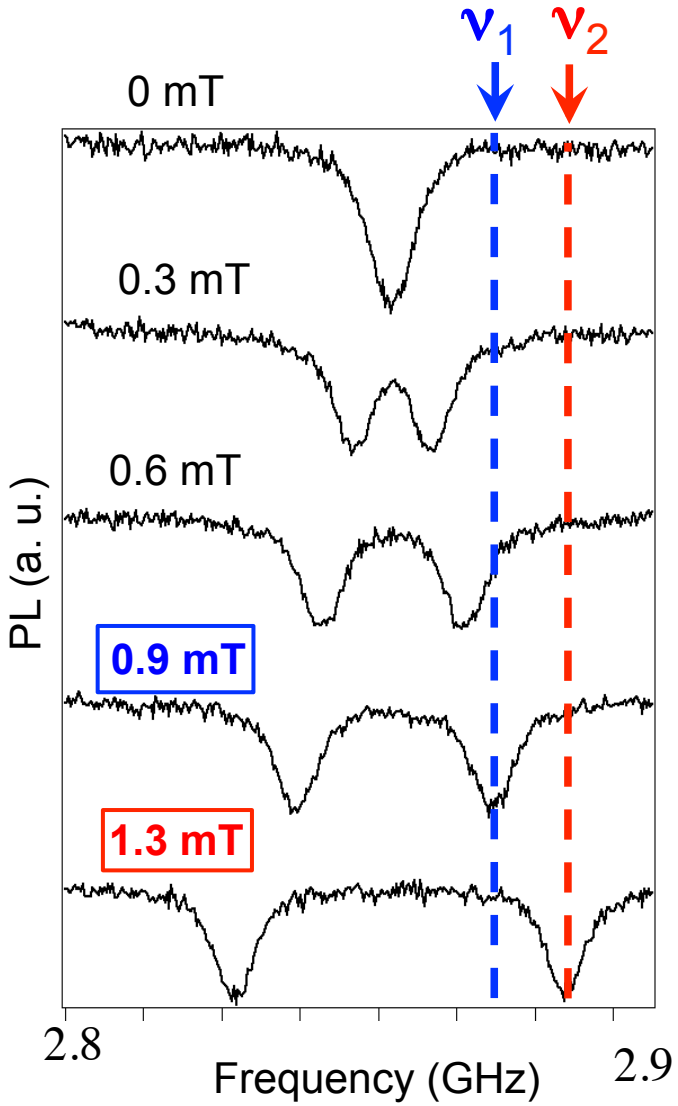


Full-B image

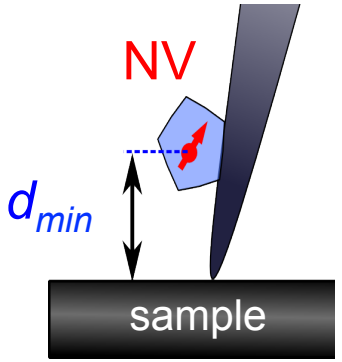
400 ms per pixel

Rondin *et al*. Nat. Commun. **4**, 2279 (2013)

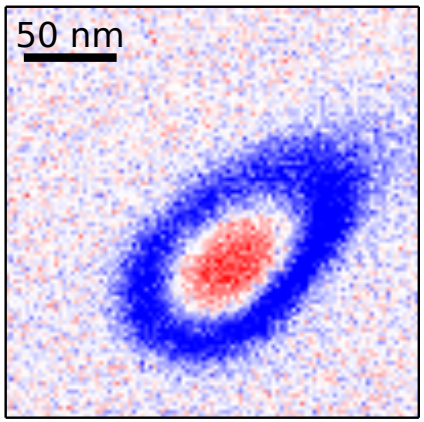
Imaging methods



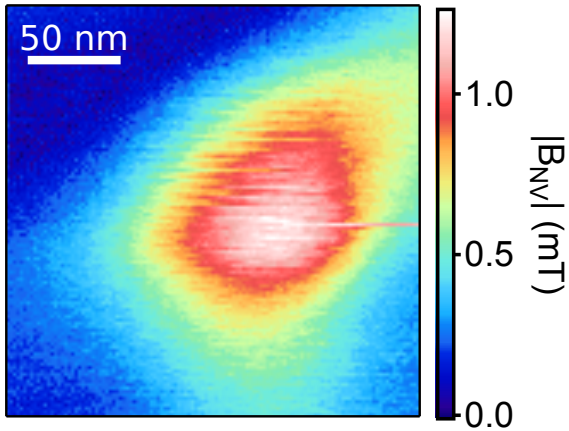
- Resolving power ~ 80 nm
  Limited by the probe-to-sample distance d_{min}



- B field distribution still recorded with nanoscale resolution



Dual-iso-B image
40 ms per pixel



Full-B image
400 ms per pixel

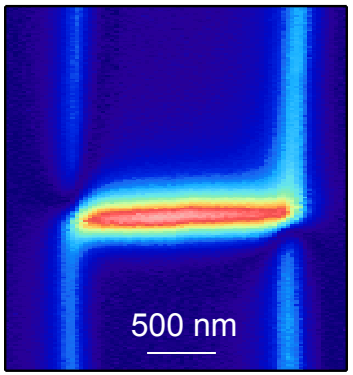
Rondin *et al*. Nat. Commun. **4**, 2279 (2013)

Outline of the talk

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

2. Applications in fundamental nanomagnetism

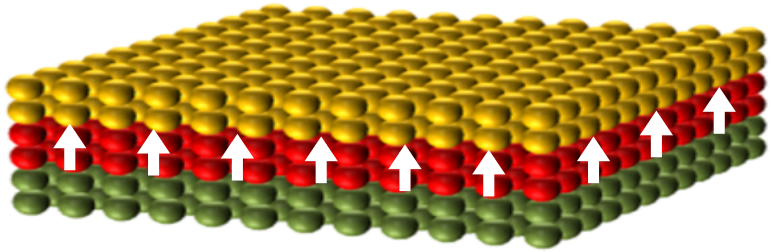
Imaging dowain walls in ultrathin magnetic wires



3. Other Applications

Biology, Quantum information science…

Ferromagnets “shrink” to few atomic layers…



Surface energy ≈ Volume energy

Interface interactions

Anisotropy, exchange…

★ **Rich new physics** mediated by the interface

★ **Technological interest** (spintronic devices)

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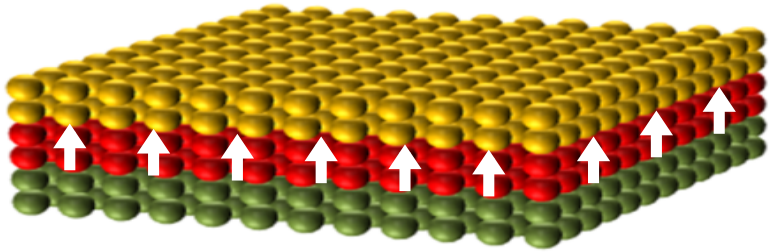

Surface energy ≈ Volume energy

Interface interactions

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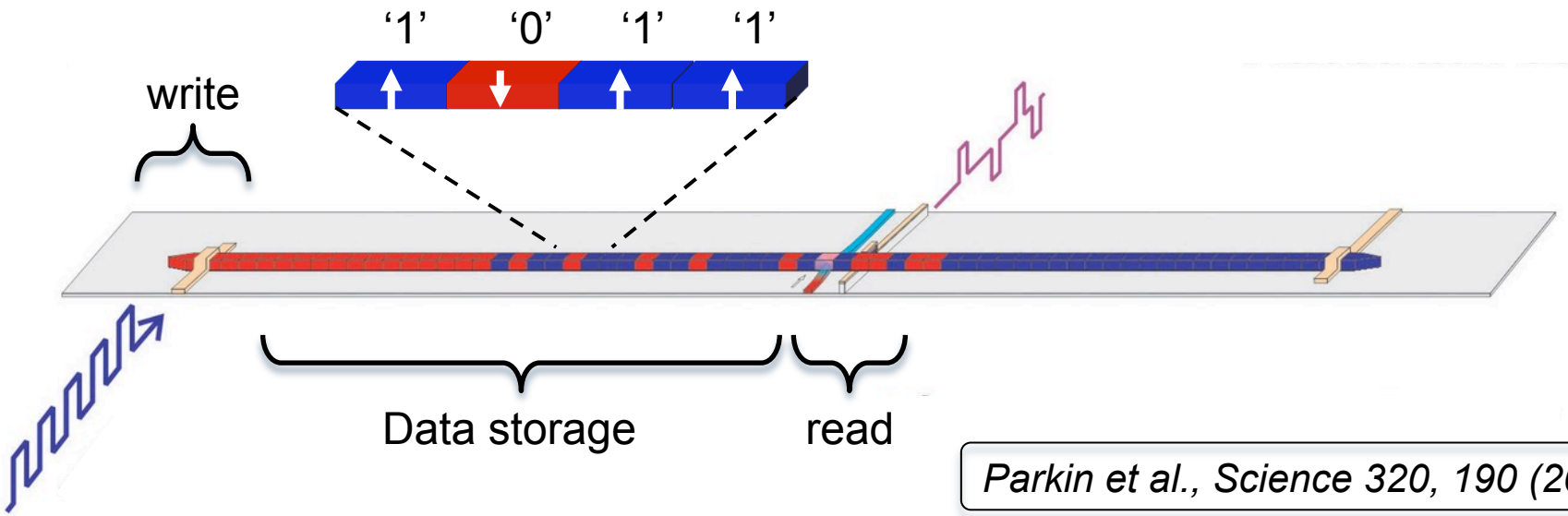
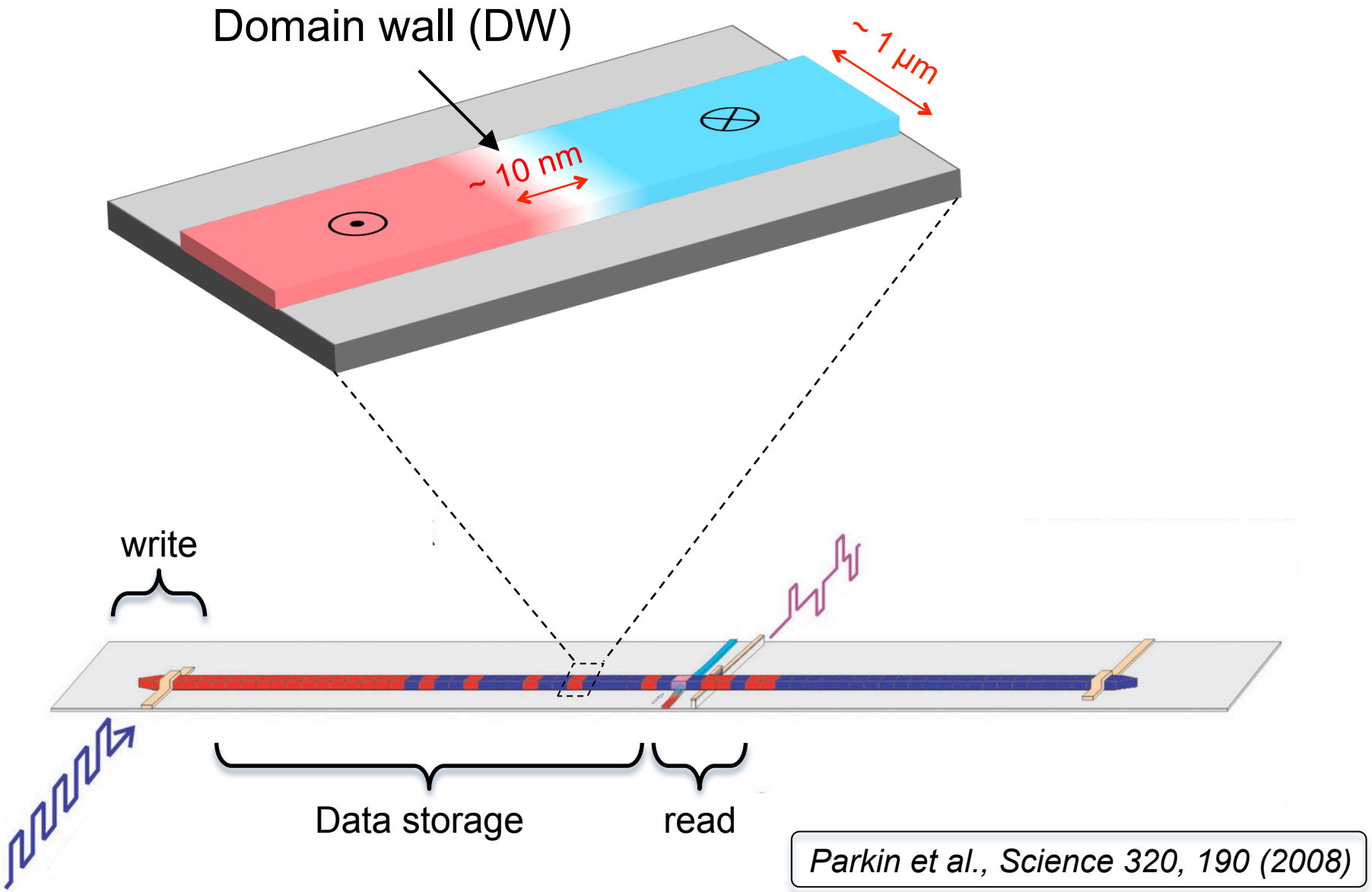
★ **Technological interest** (spintronic devices)

One example *:* the domain wall (DW) “racetrack memory” protocol



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

Domain walls in ultrathin ferromagnets



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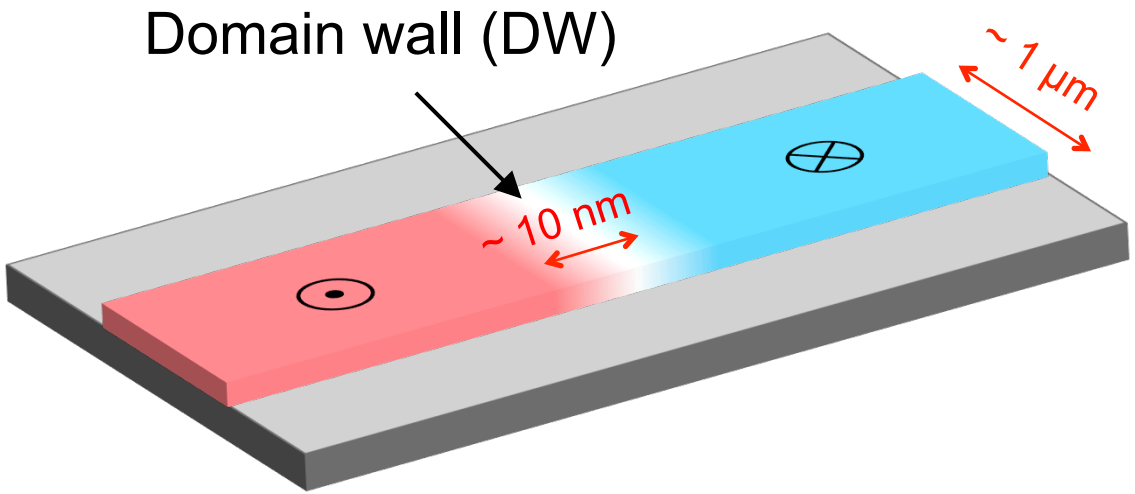

Some important issues to address…

- Characterize DW pinning at the nanoscale
- Determine the inner structure (Bloch *vs* Néel) of the DW

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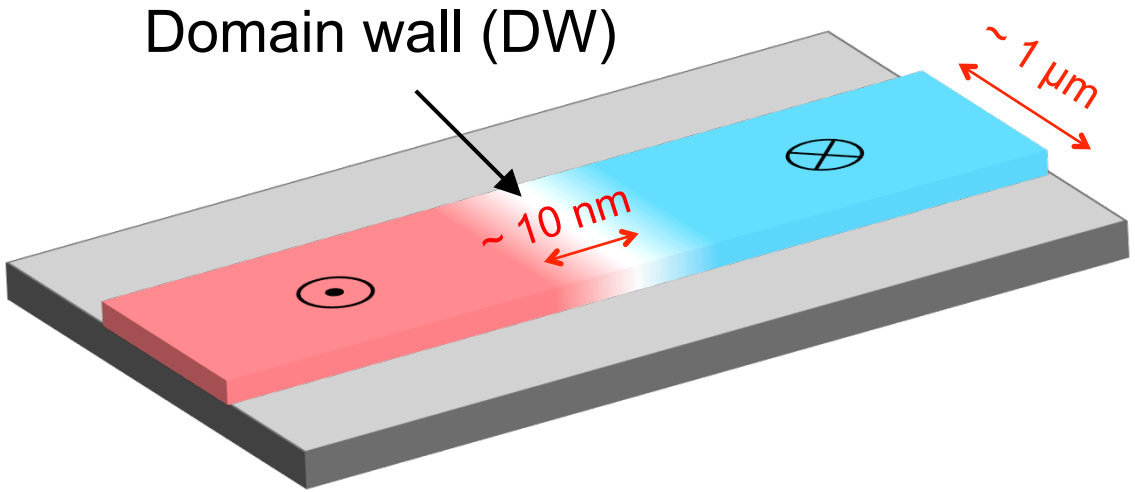


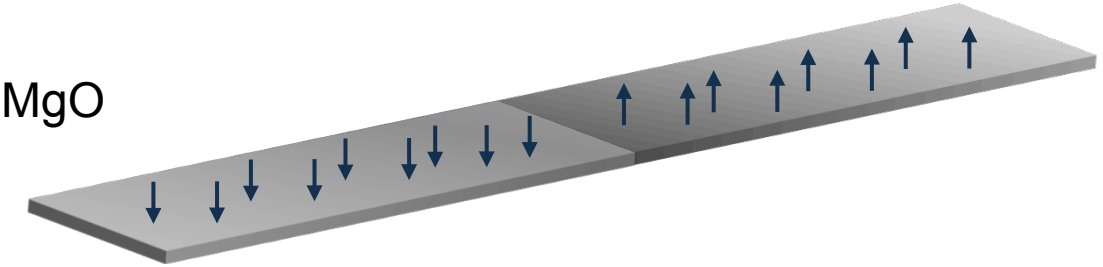
Some important issues to address…

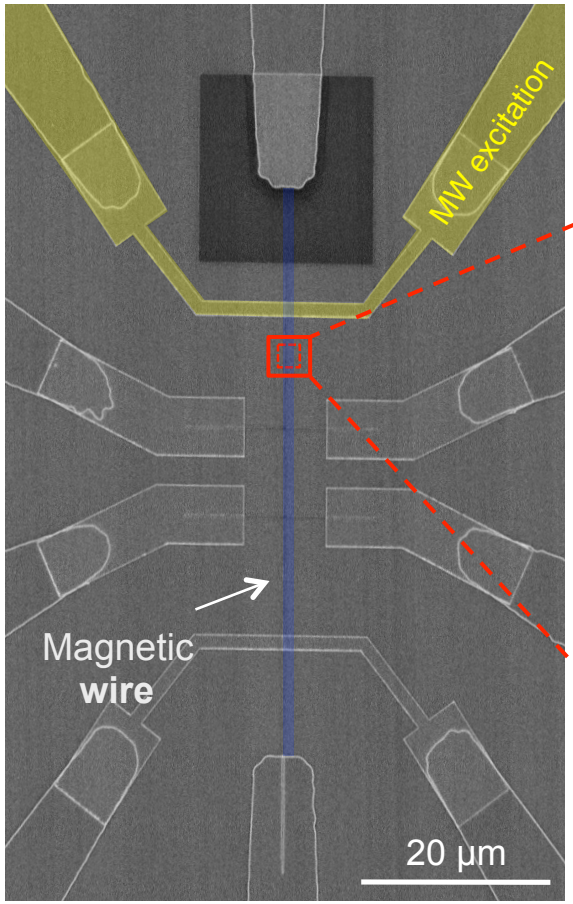
- **Characterize DW pinning at the nanoscale**
- Determine the inner structure (Bloch *vs* Néel) of the DW

DW imaging with a scanning NV magnetometer

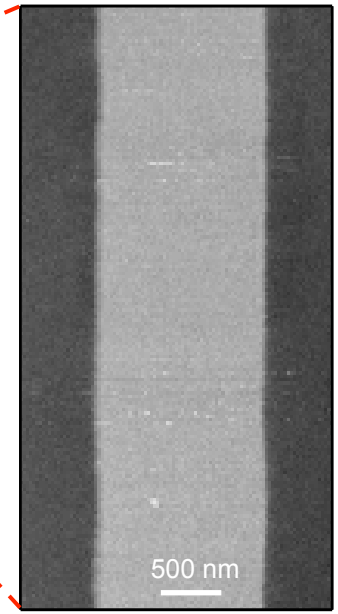
Magnetic wire

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



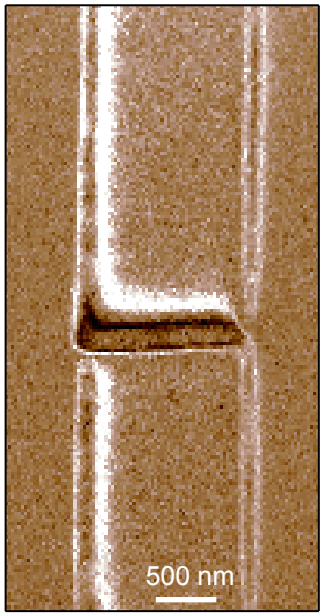


AFM



0 20
Height (nm)

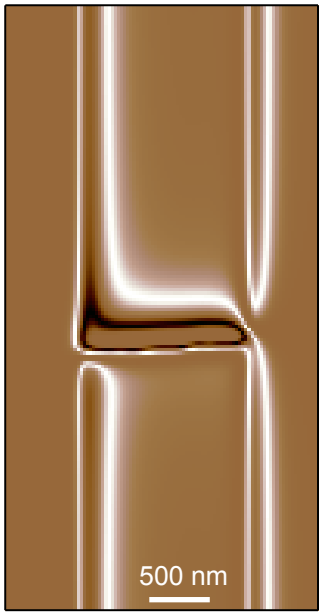
NV



iso-B image

± 1.5 mT
± 0.7 mT

Fit



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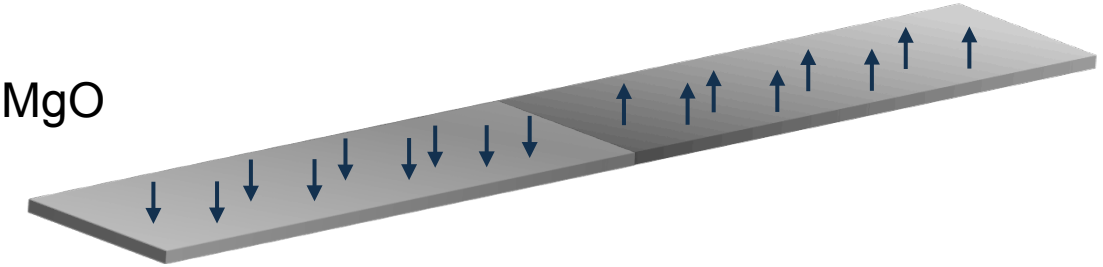
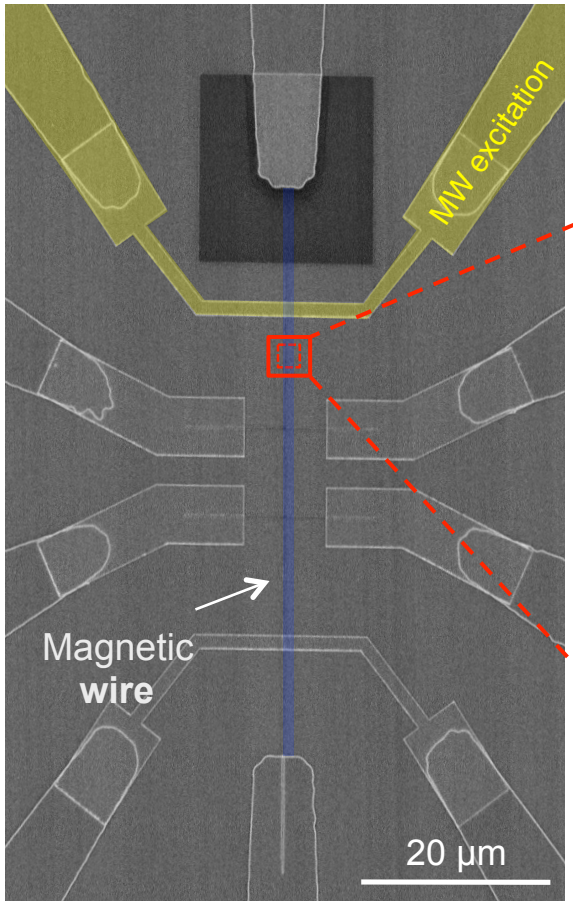
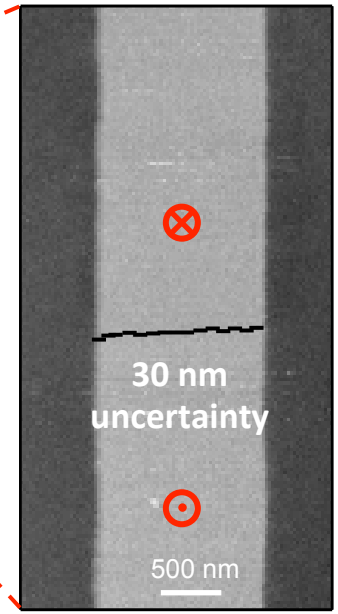
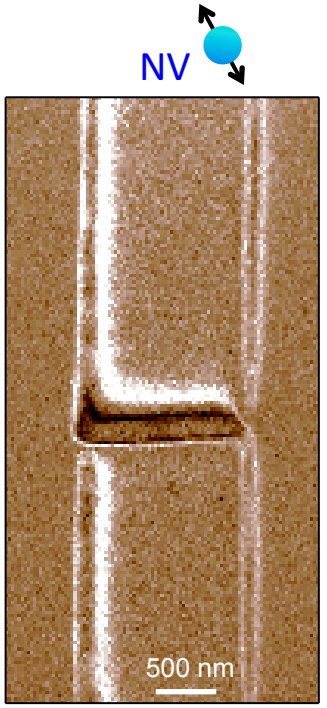
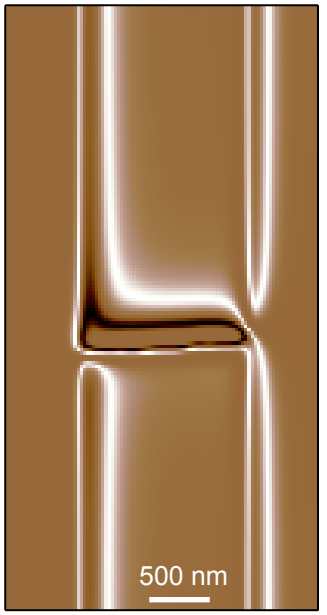


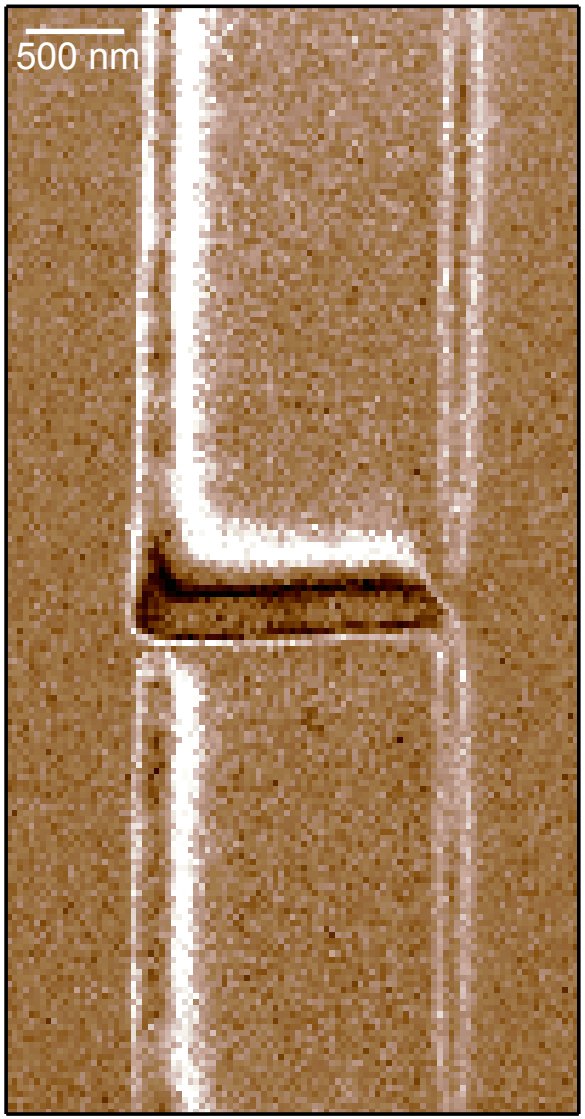






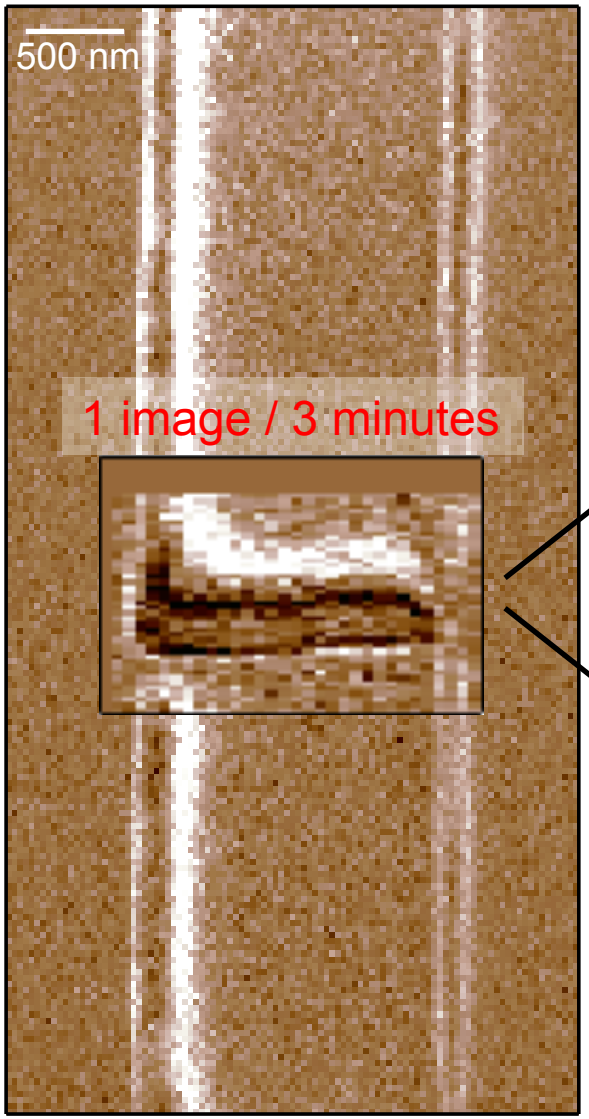


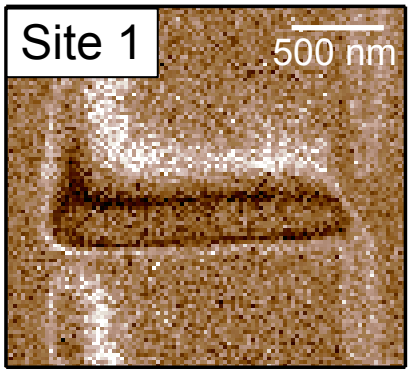
Observation of domain wall hopping

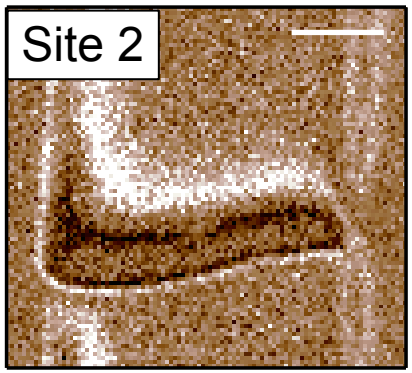


■ B_{NV} = 1.5 mT □ B_{NV} = 0.7 mT

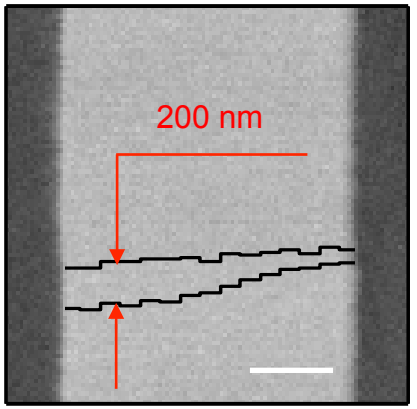
Observation of domain wall hopping







AFM image



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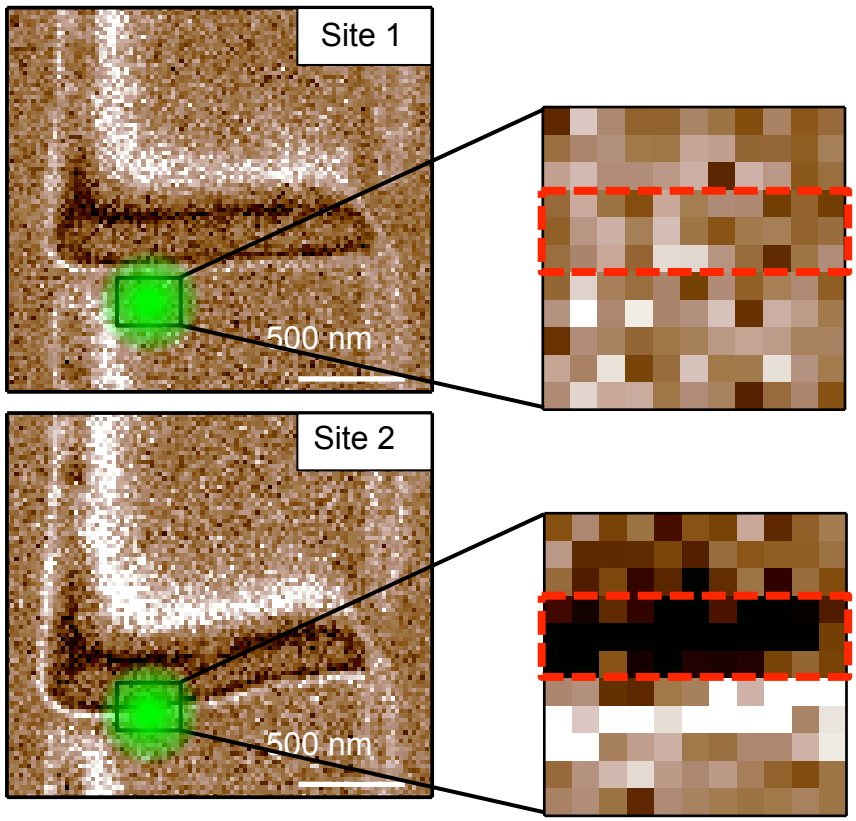
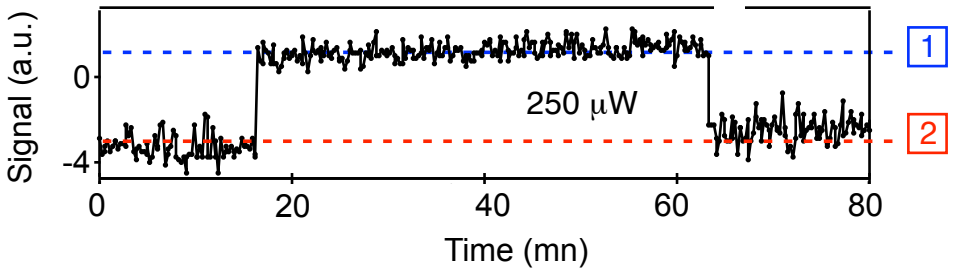
Thermally-activated DW hopping

Barkhausen jumps

Observation of domain wall hopping





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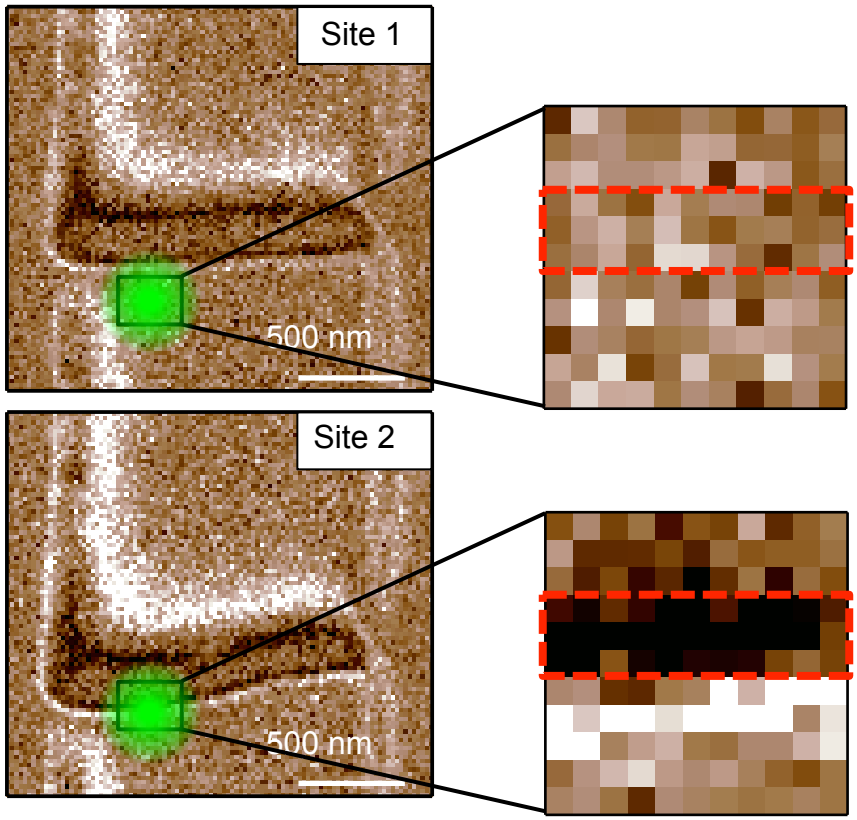
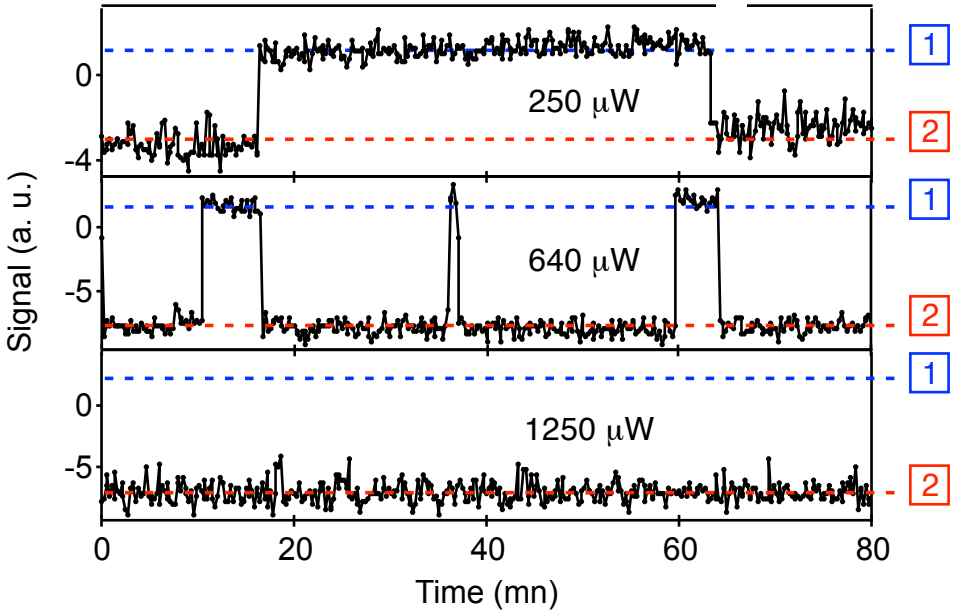
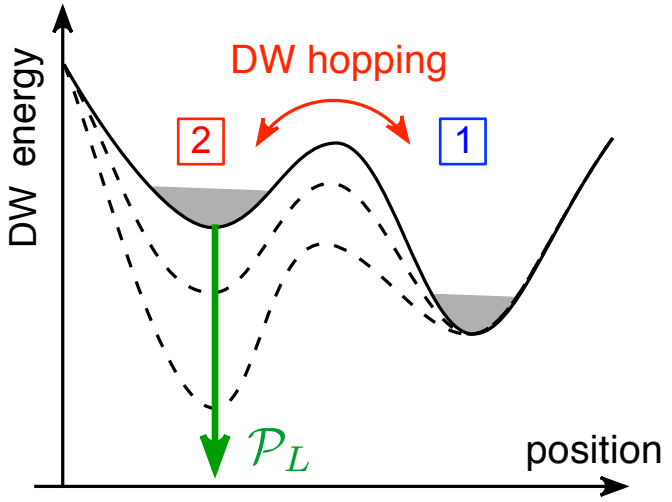




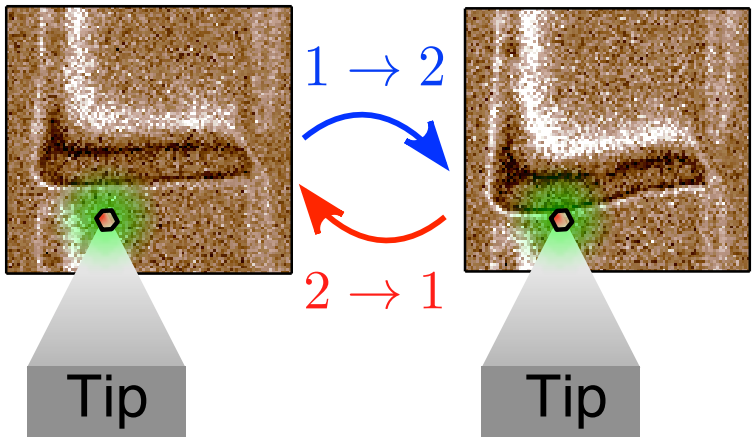
The laser tends to pin the DW in site 2

Modification of the DW energy through the decrease in saturation magnetization and anisotropy **with increasing temperature**

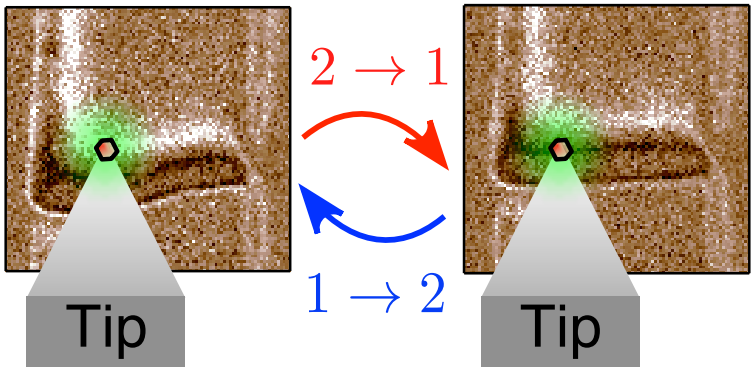


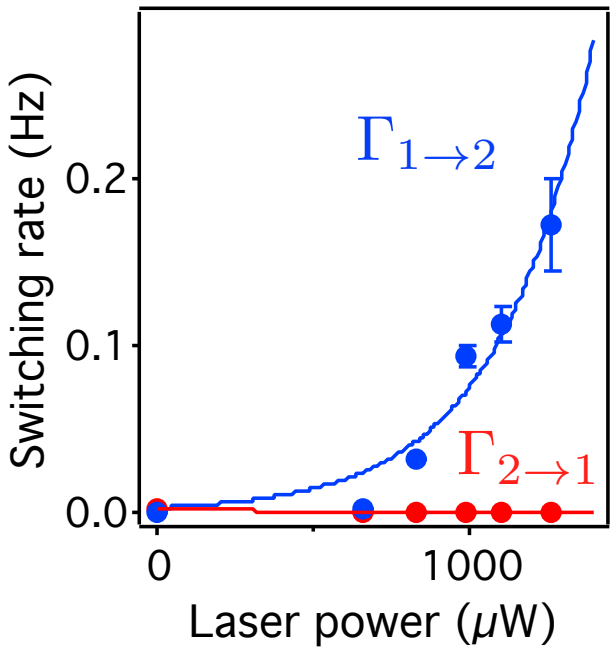
Laser-induced domain wall pinning

Tip on site 2

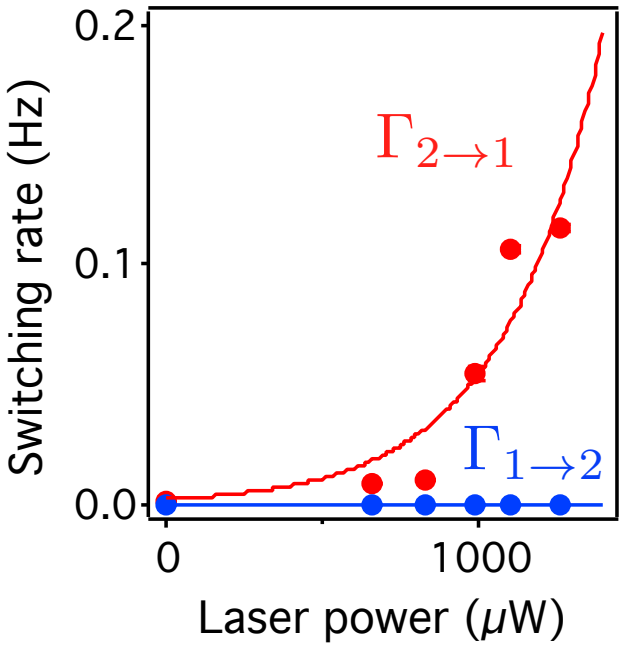


Tip on site 1



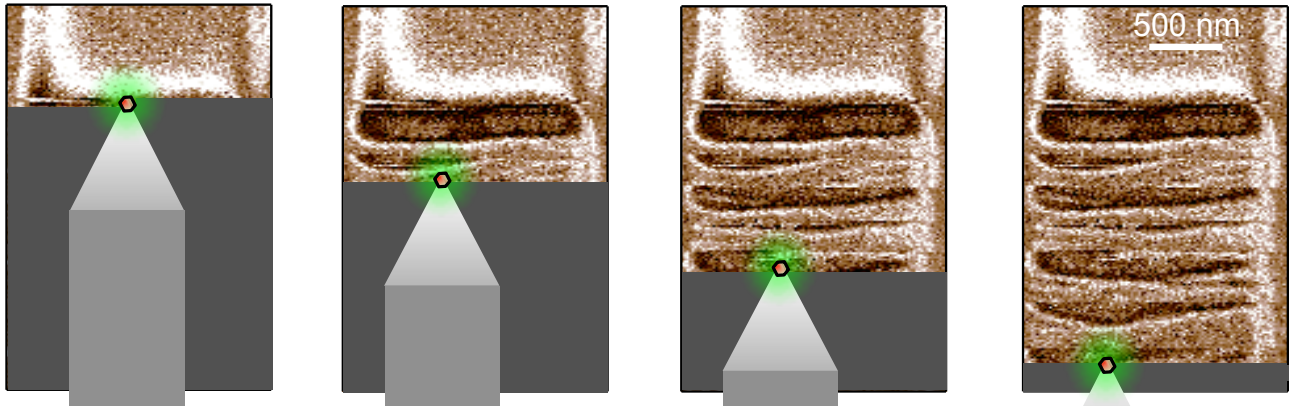


Modeled by
J. V. Kim

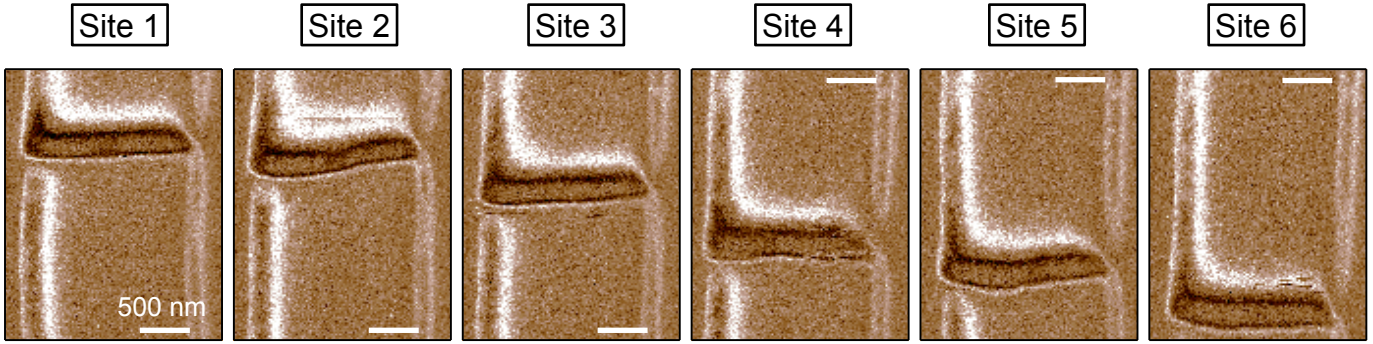


Exploiting the effect…

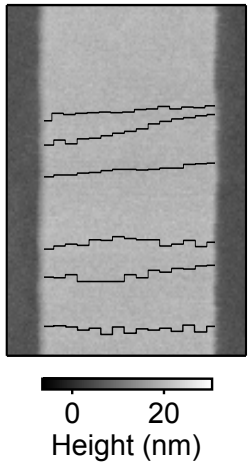
(1)- Dragging the DW at high laser power



(2)- Imaging the DW at low laser power

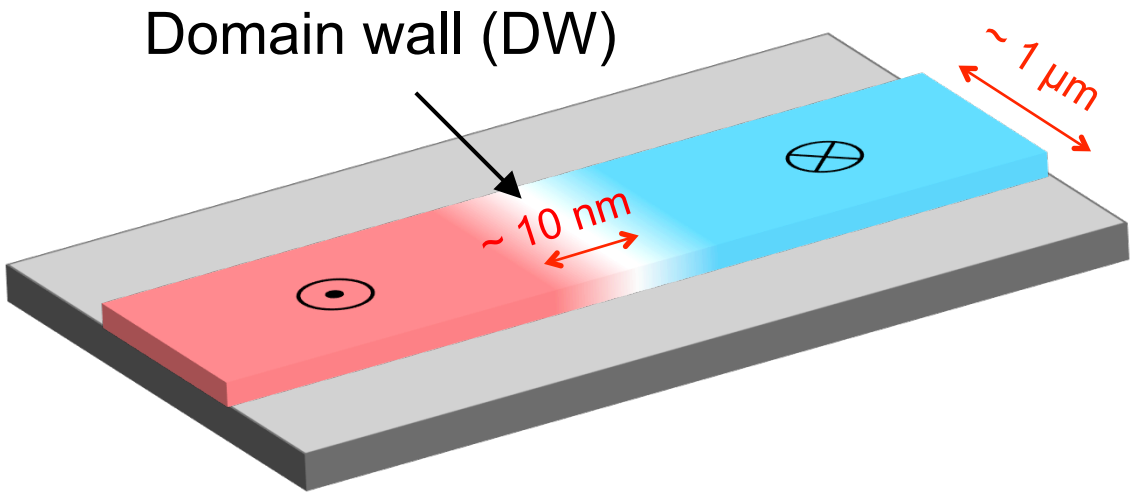


(3)- Pinning sites map



Tetienne *et al.*, *Science* **344**, 1366 (2014)

Domain walls in ultrathin ferromagnets



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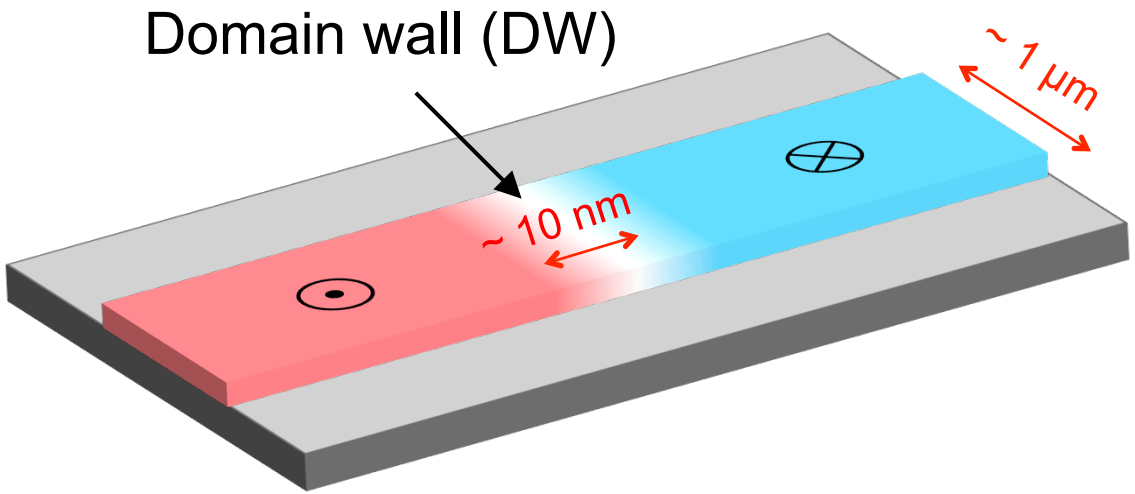

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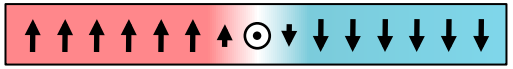
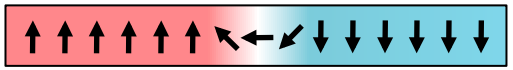
Inner structure of a domain wall

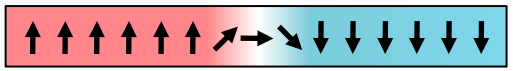
Bloch wall



Néel wall (left)



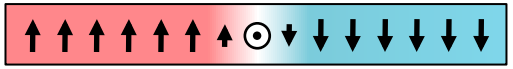
Néel wall (right)



- Bloch walls are predicted by elementary magnetostatic theory

Inner structure of a domain wall

Bloch wall



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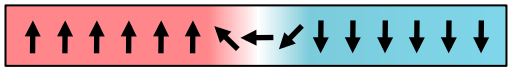
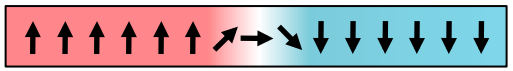


Néel wall (right)



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

Ryu et al., Nat. Nano. 8, 527 (2013)
Emori et al., Nat. Mater. 12, 611 (2013)

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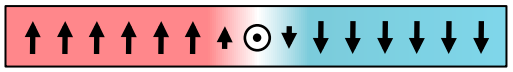

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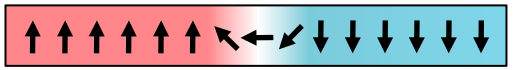
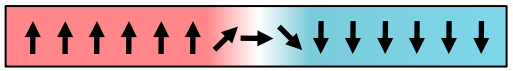


Néel wall (right)



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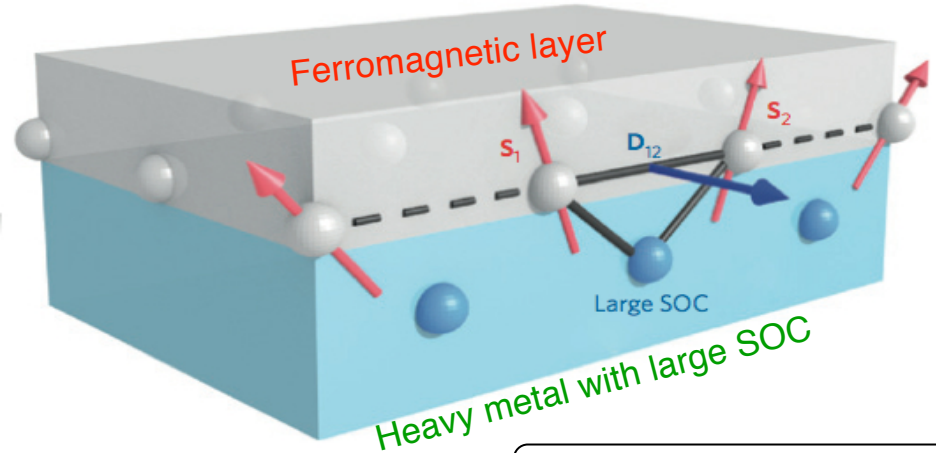
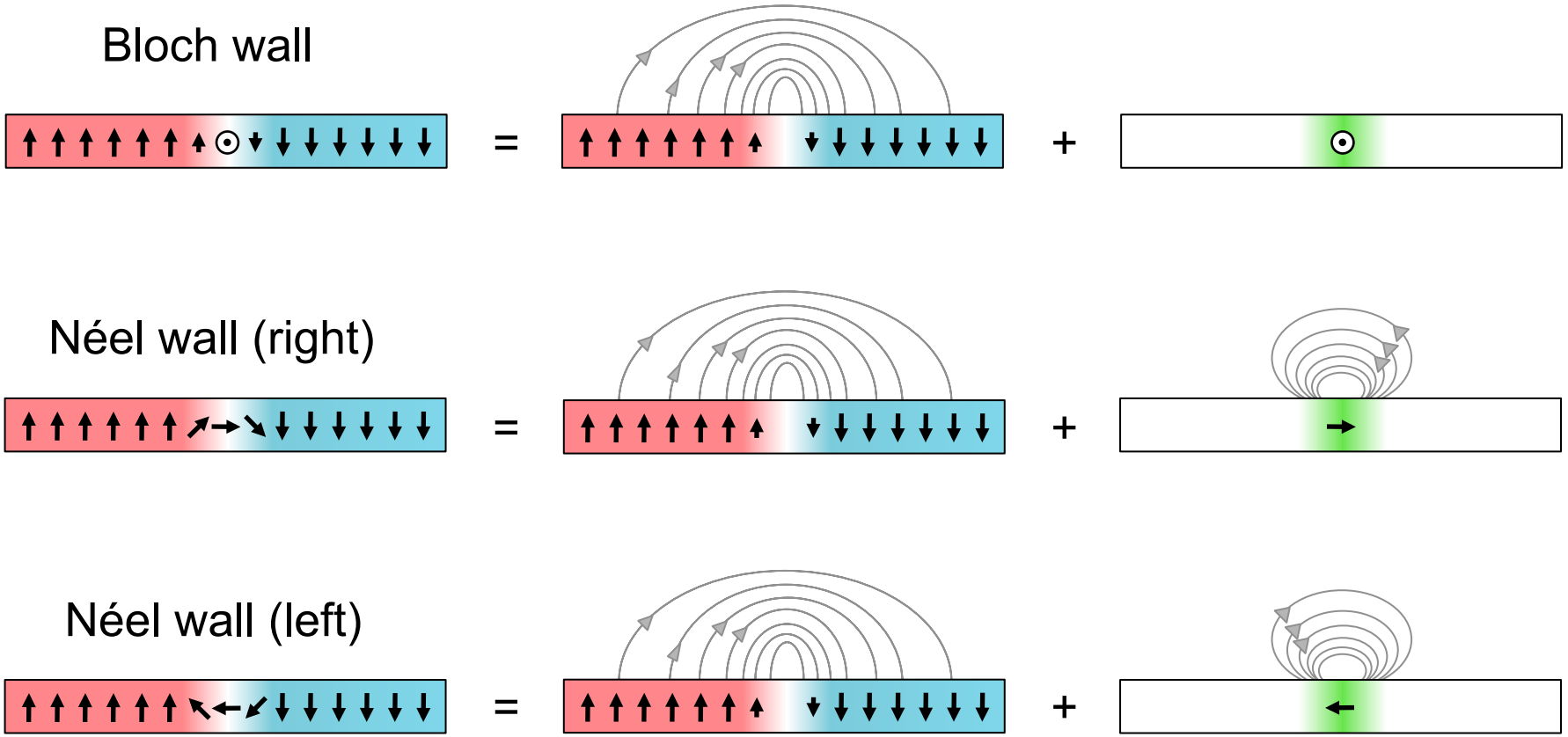
- Interfacial Dzyaloshinskii-Moriya interaction proposed as a way to stabilize Néel walls

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



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

Determining the structure of the DW



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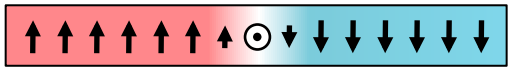
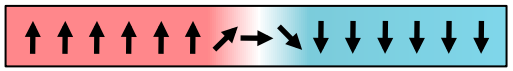
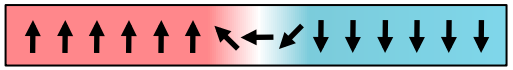
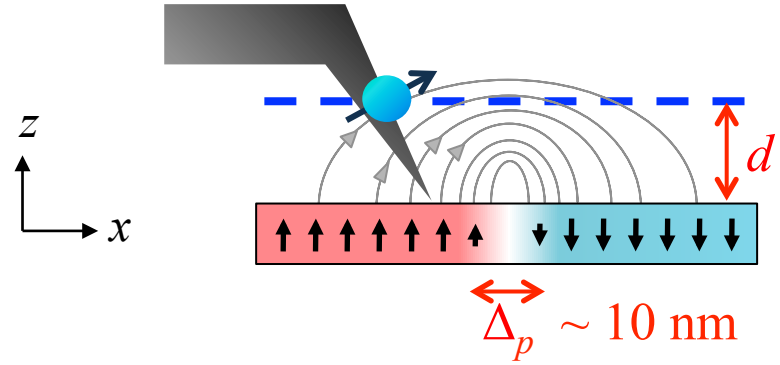


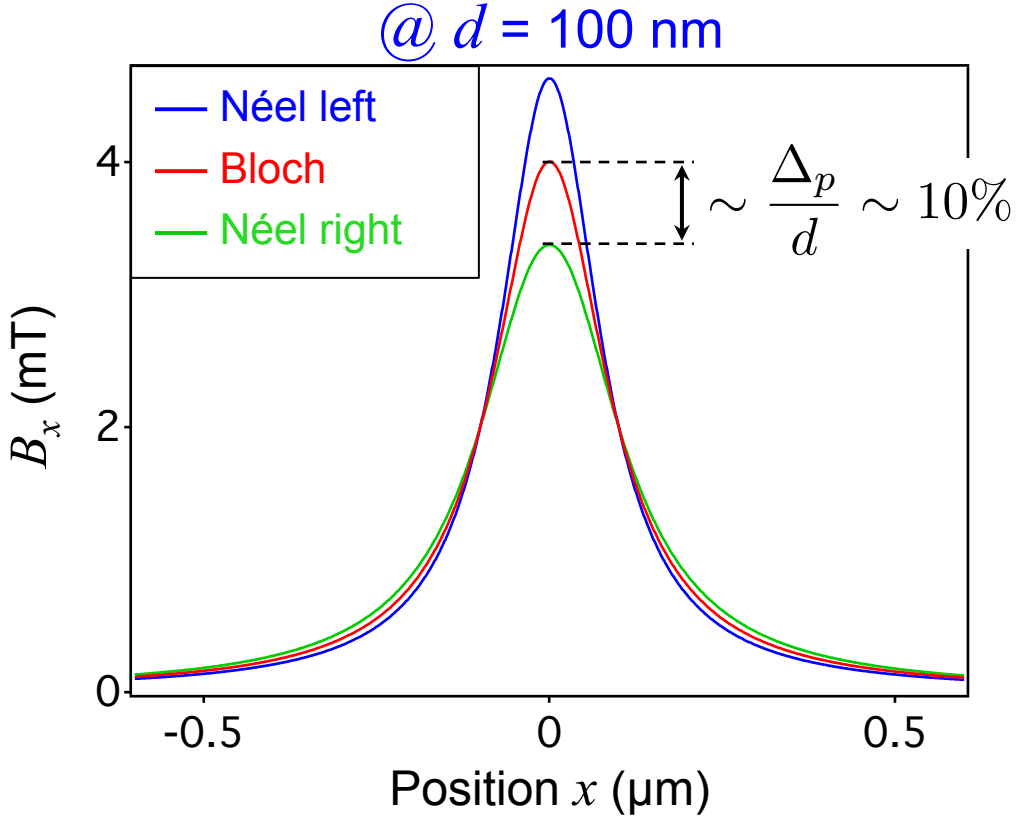
Néel wall (right)



Néel wall (left)



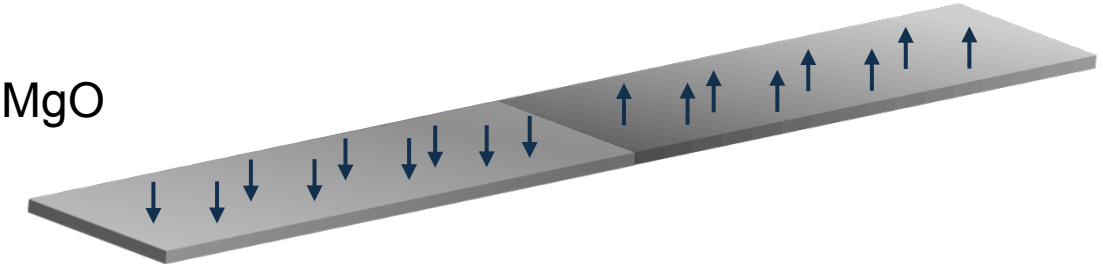


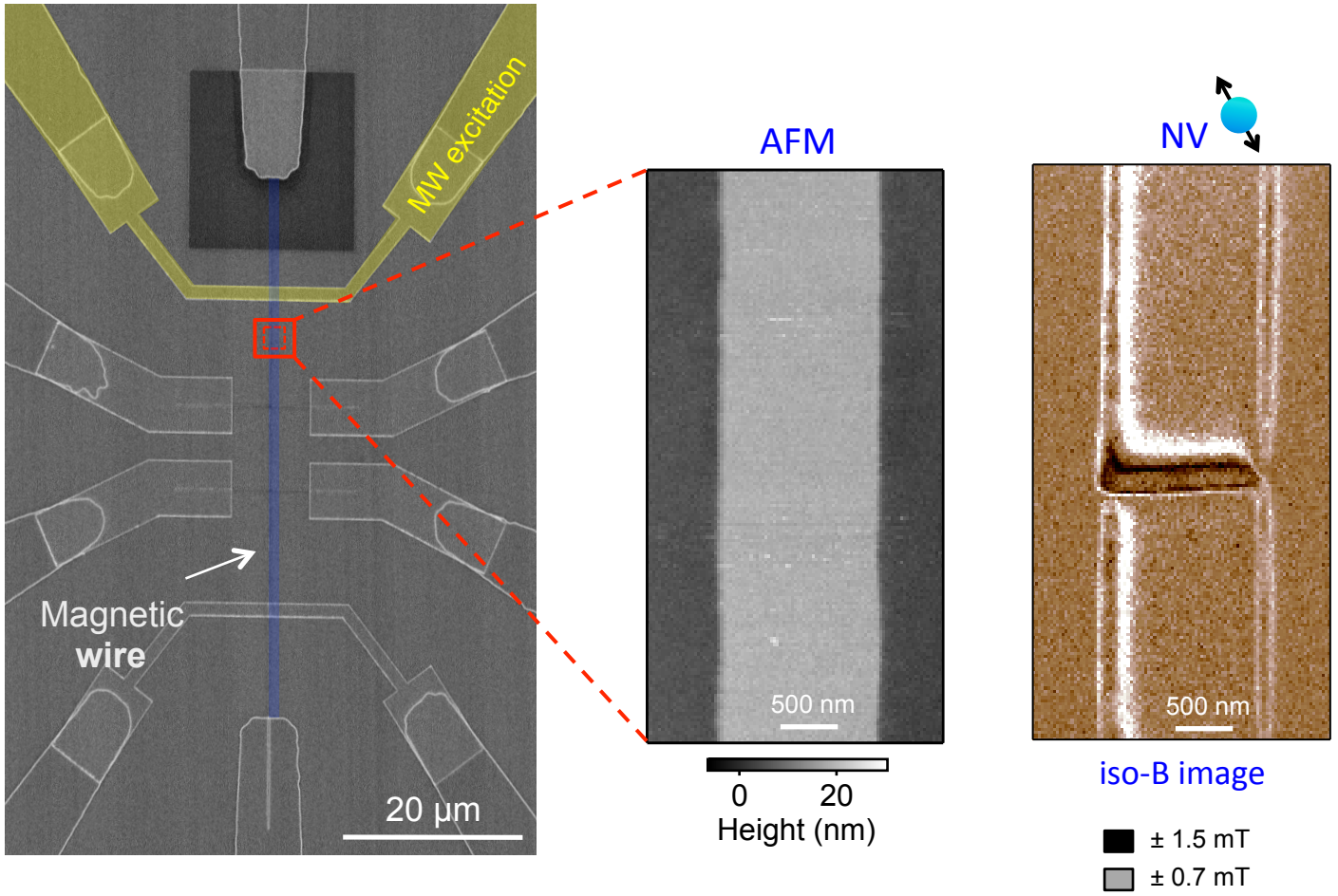


DW imaging with a scanning NV magnetometer

Magnetic wire

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





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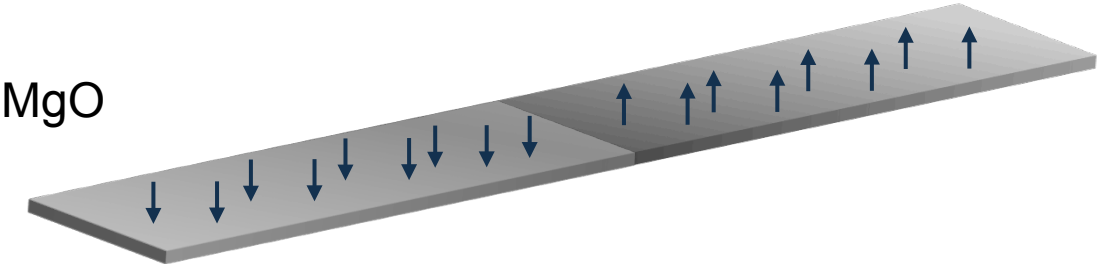
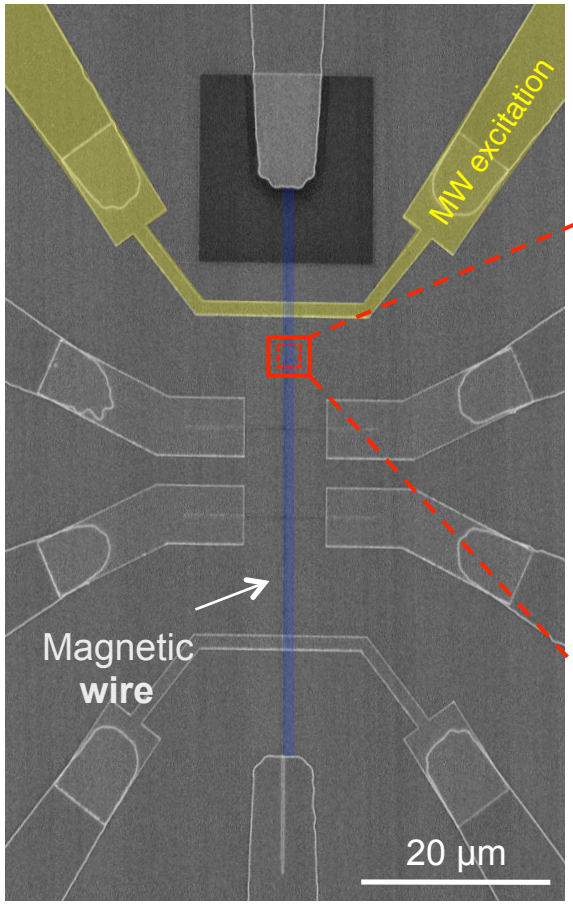
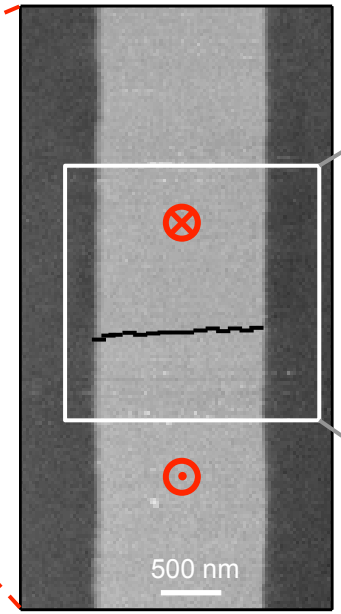
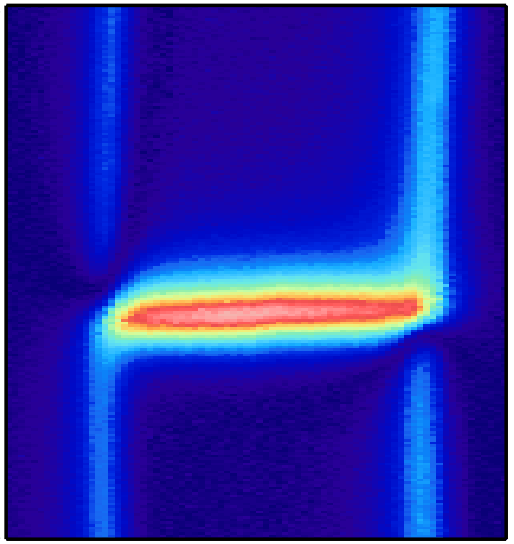




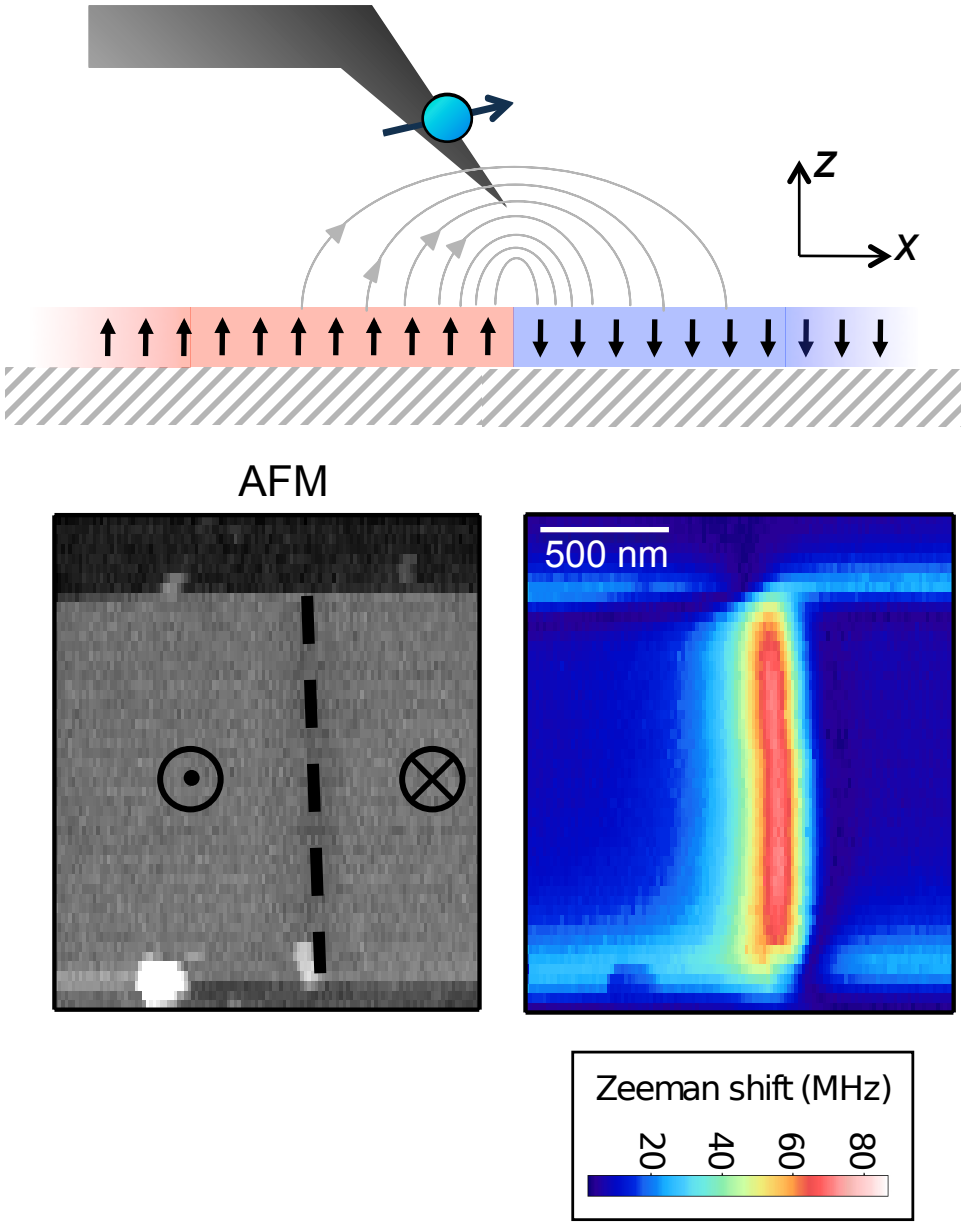
AFM



Full B field distribution



Extracting the nature of the domain wall



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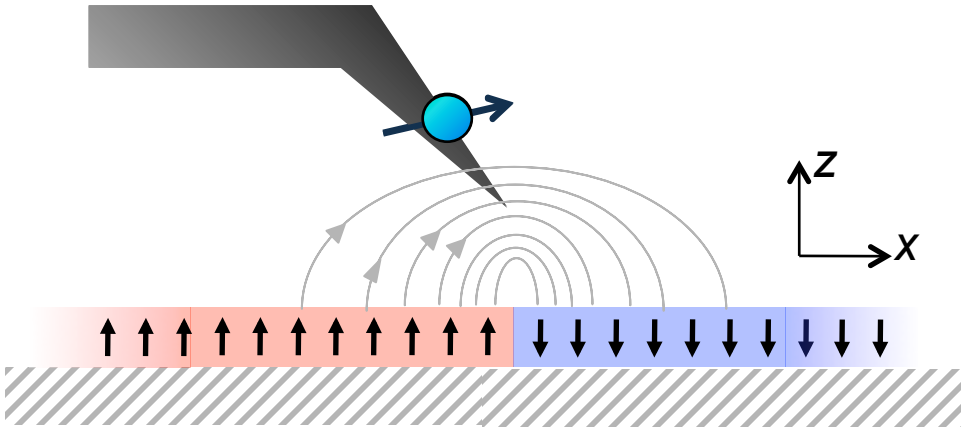
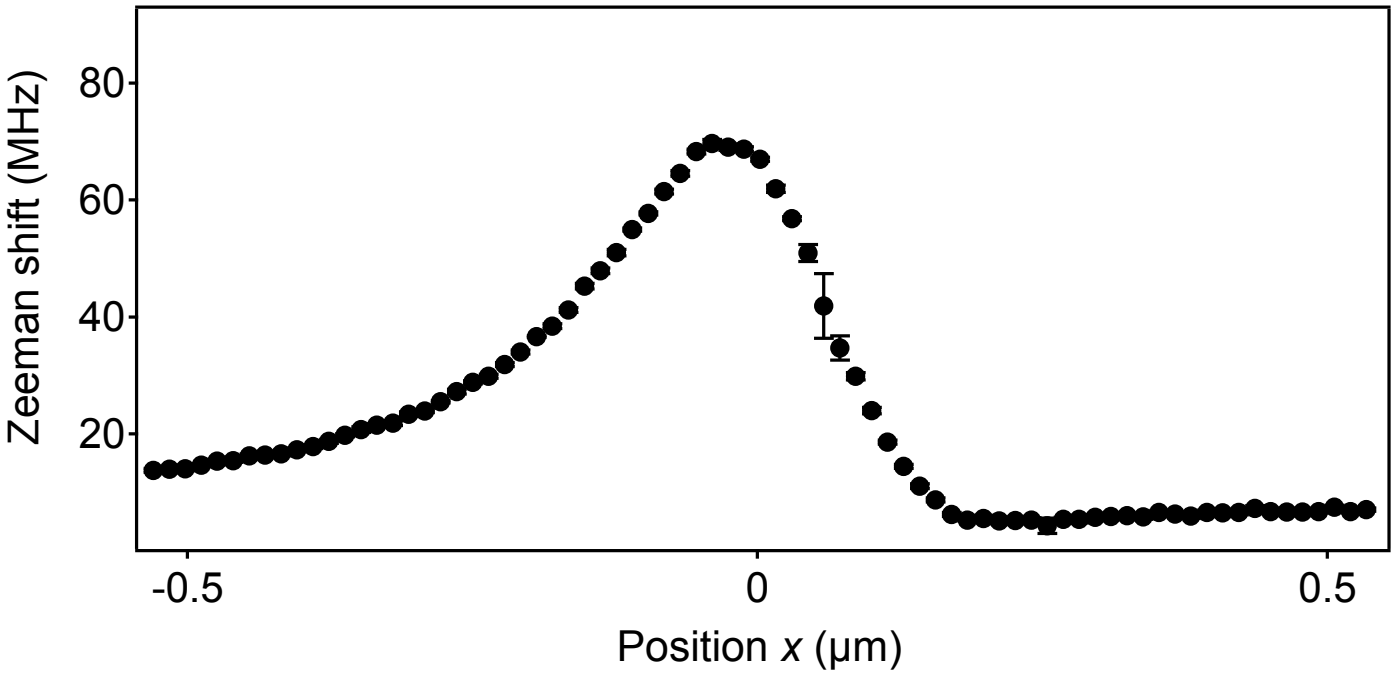
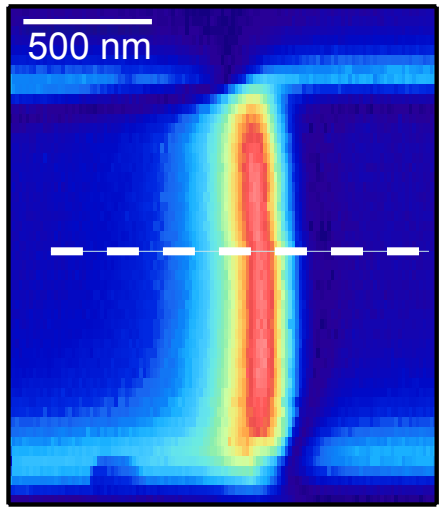
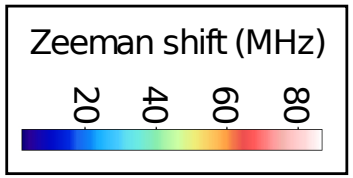
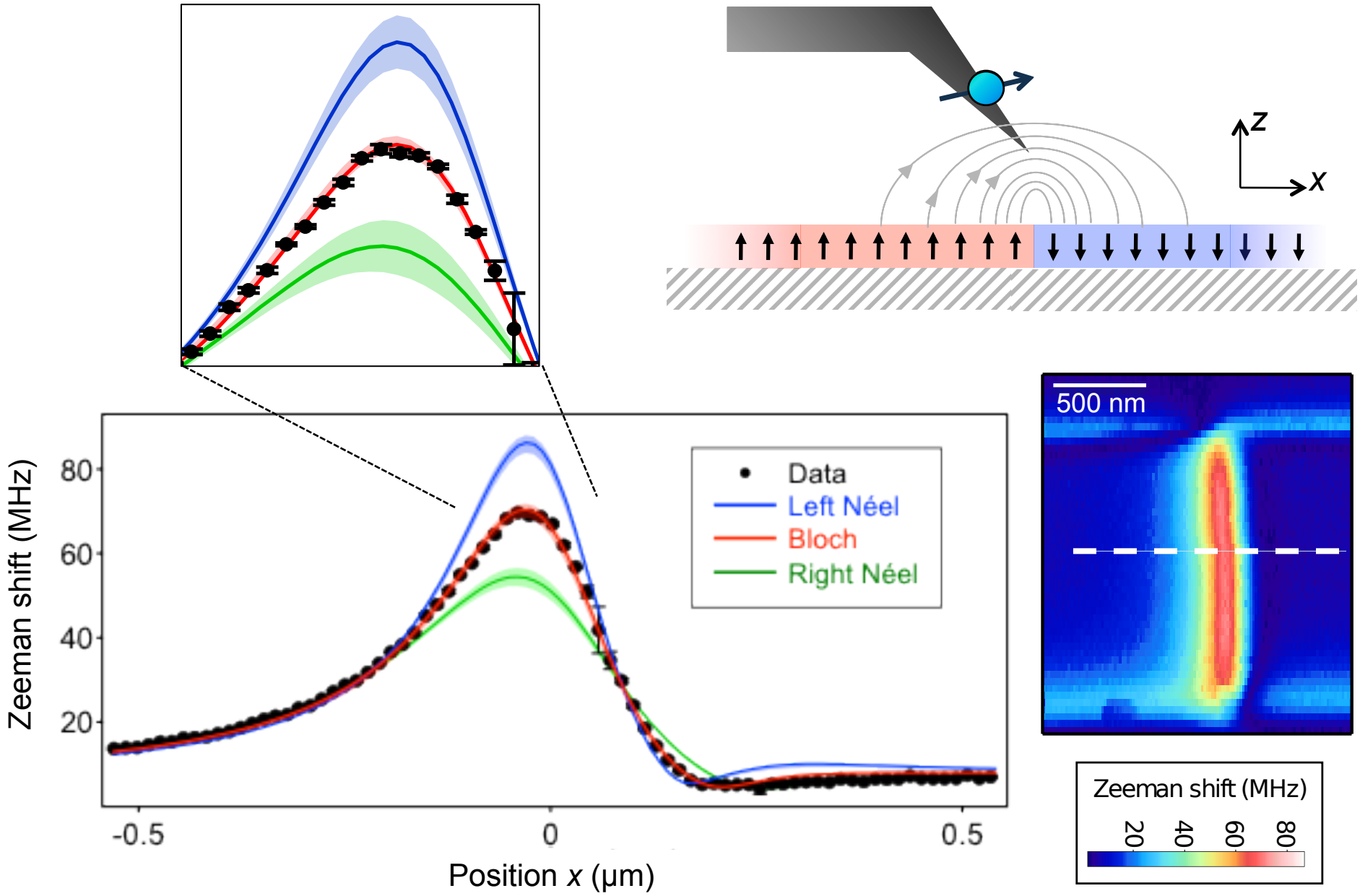




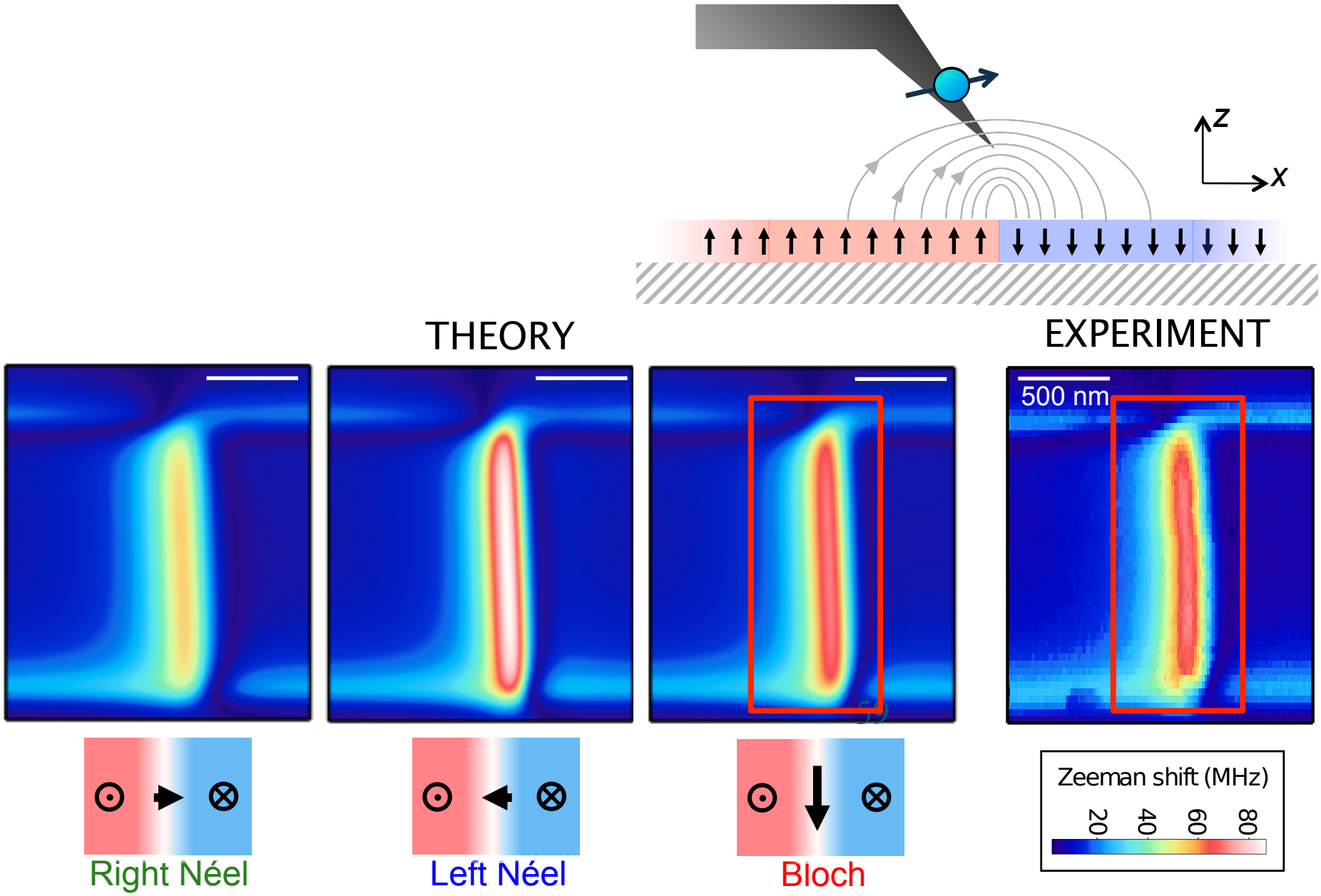




Extracting the nature of the domain wall



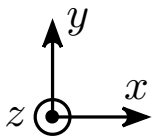
Extracting the nature of the domain wall

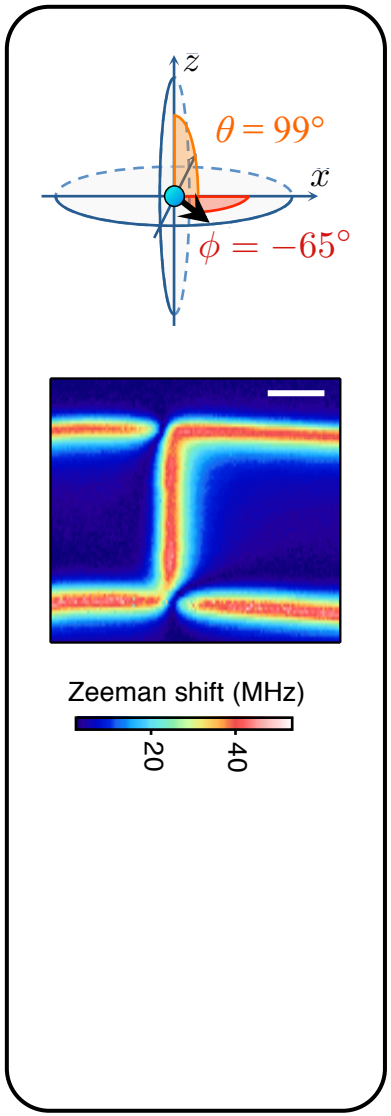


Vectorial magnetic imaging

NV axis

Data

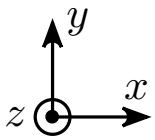


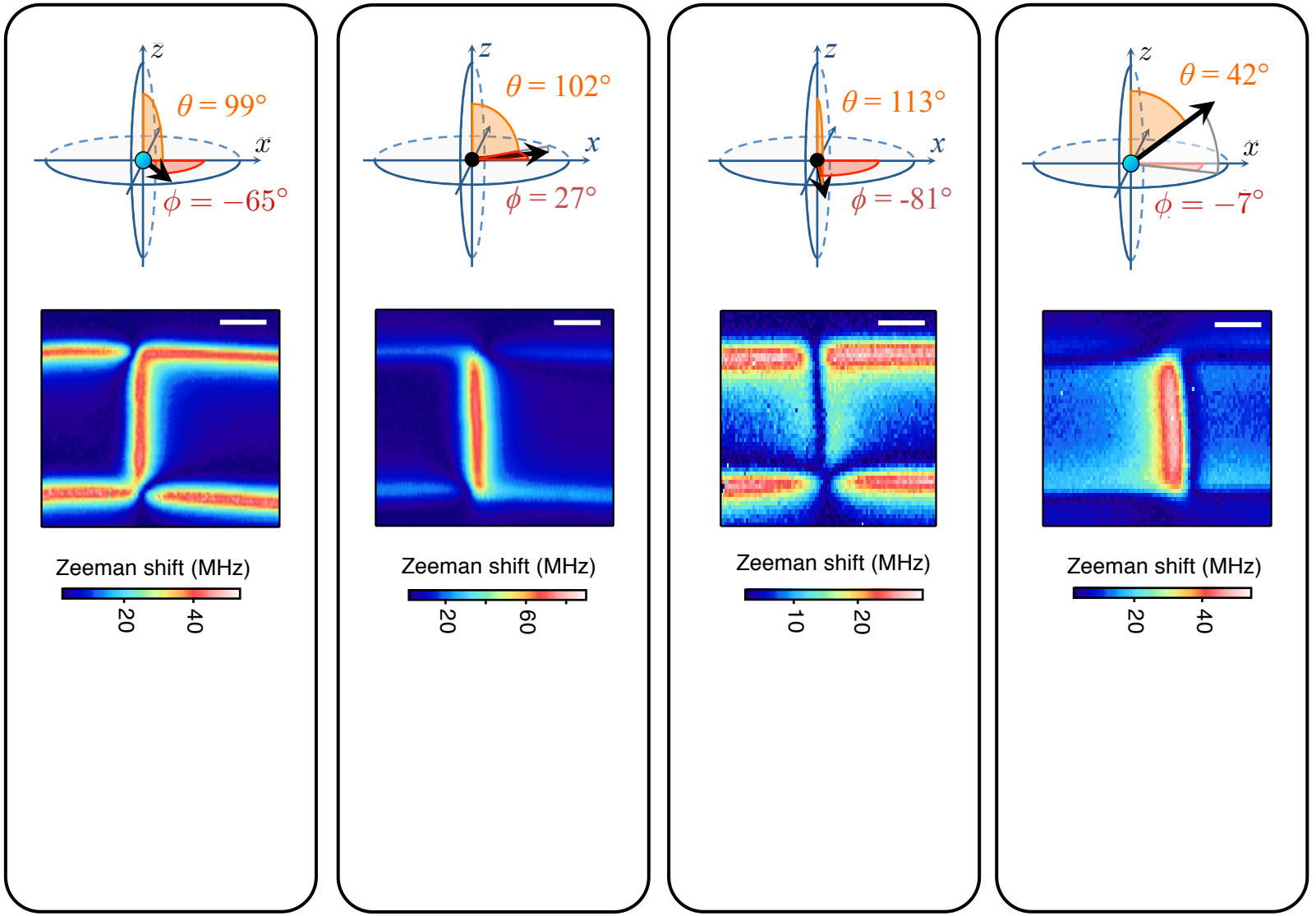


Vectorial magnetic imaging

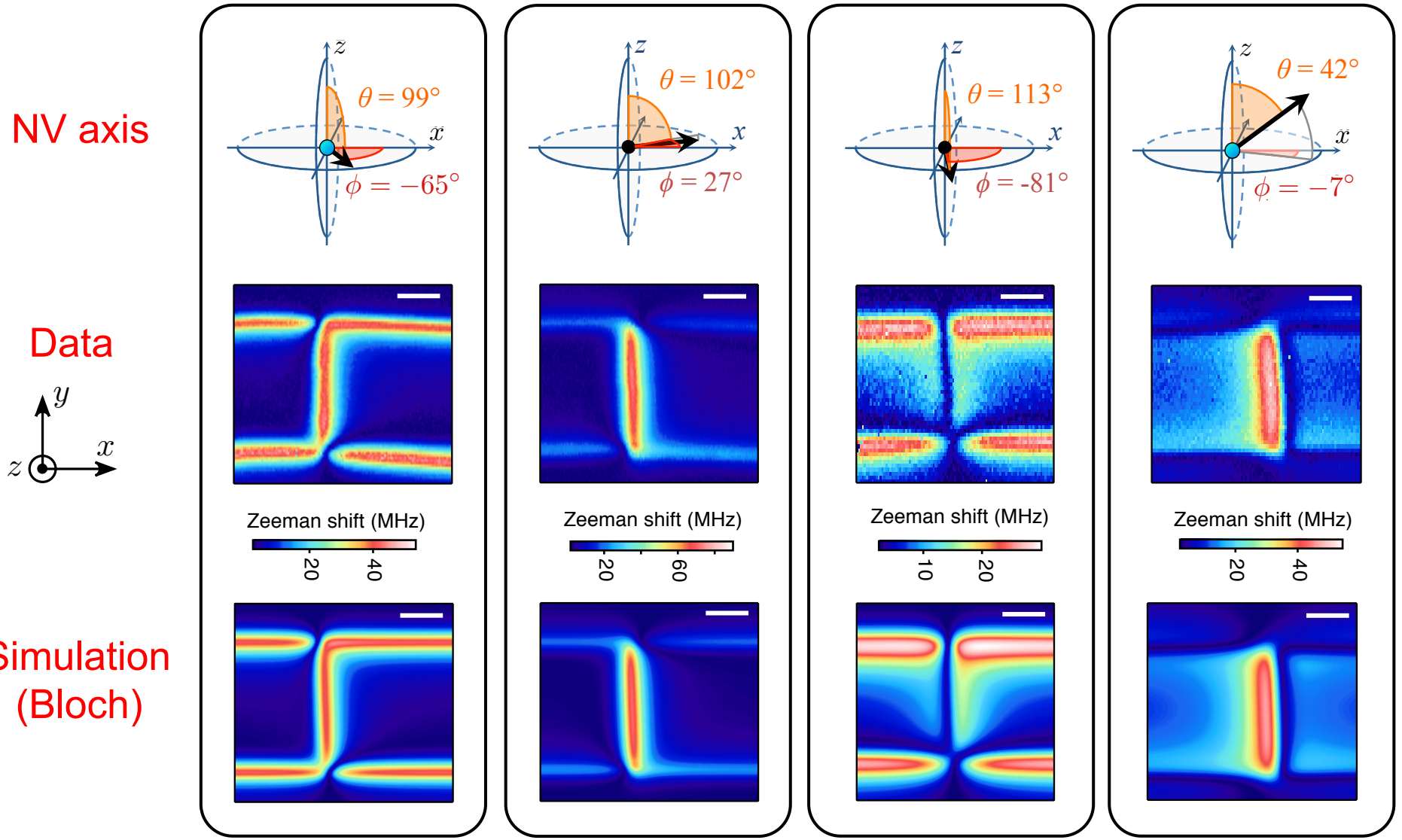
NV axis

Data

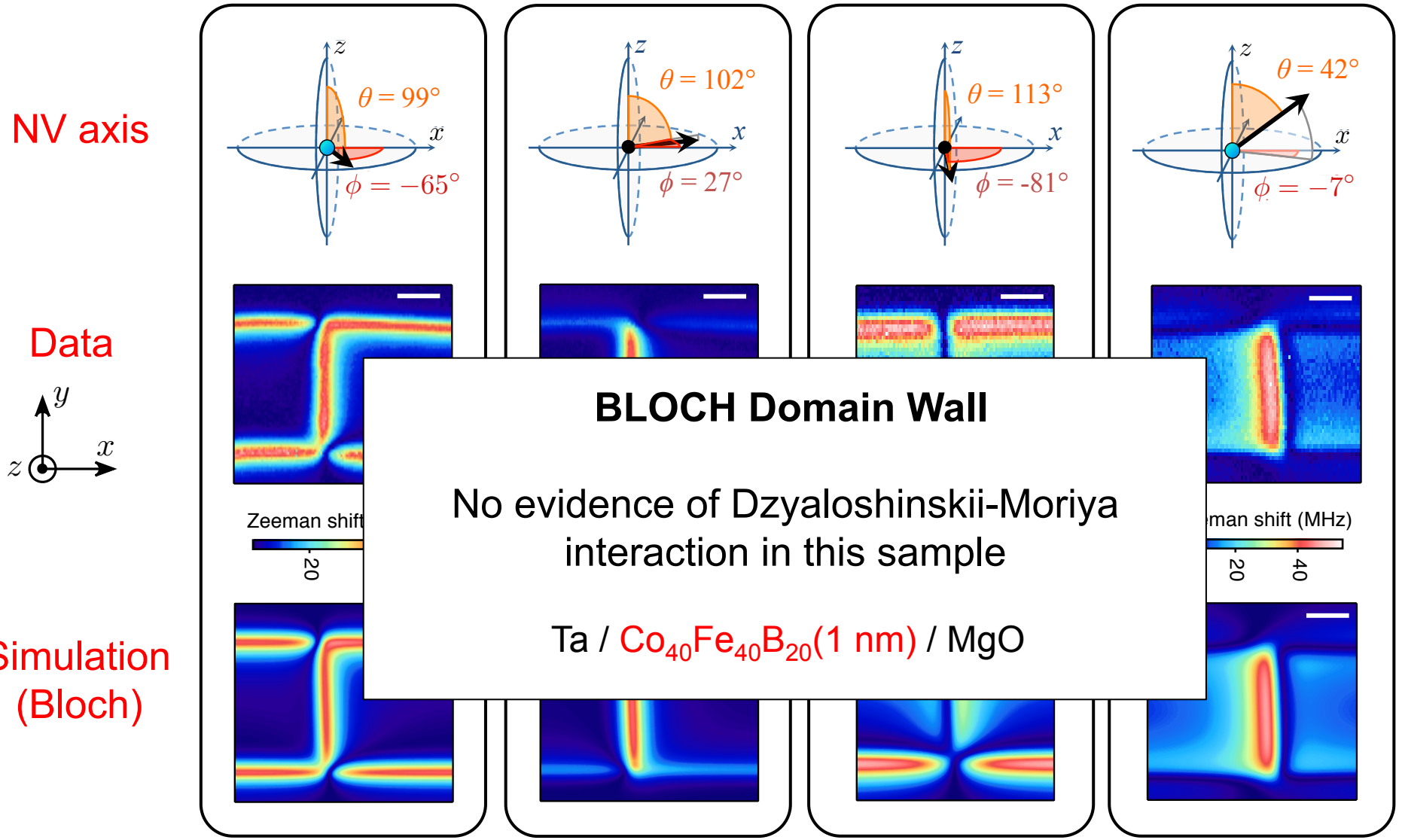




Vectorial magnetic imaging

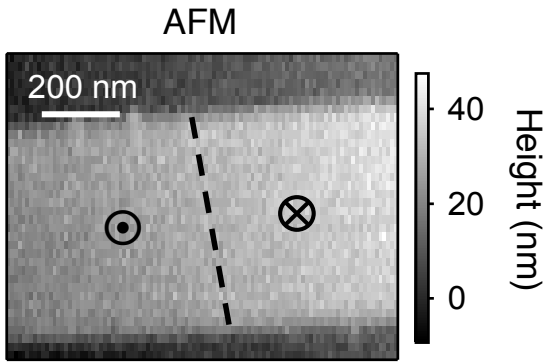


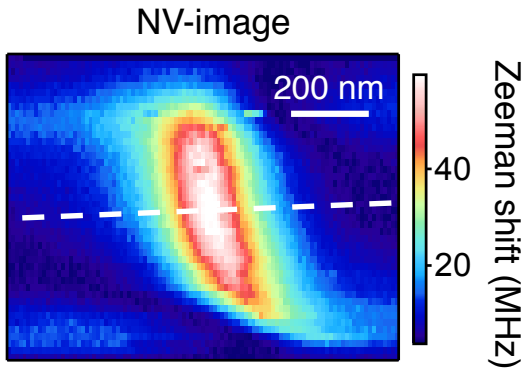
Vectorial magnetic imaging



Another type of sample…Pt/Co(0.6nm)/AlOx

SPINTEC Grenoble
G. Gaudin
M. Miron





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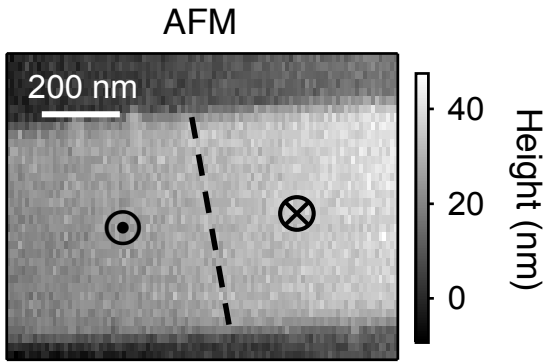
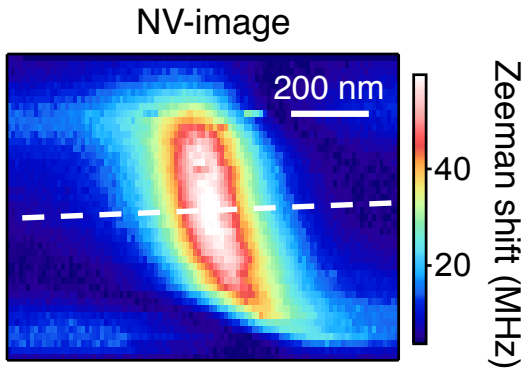
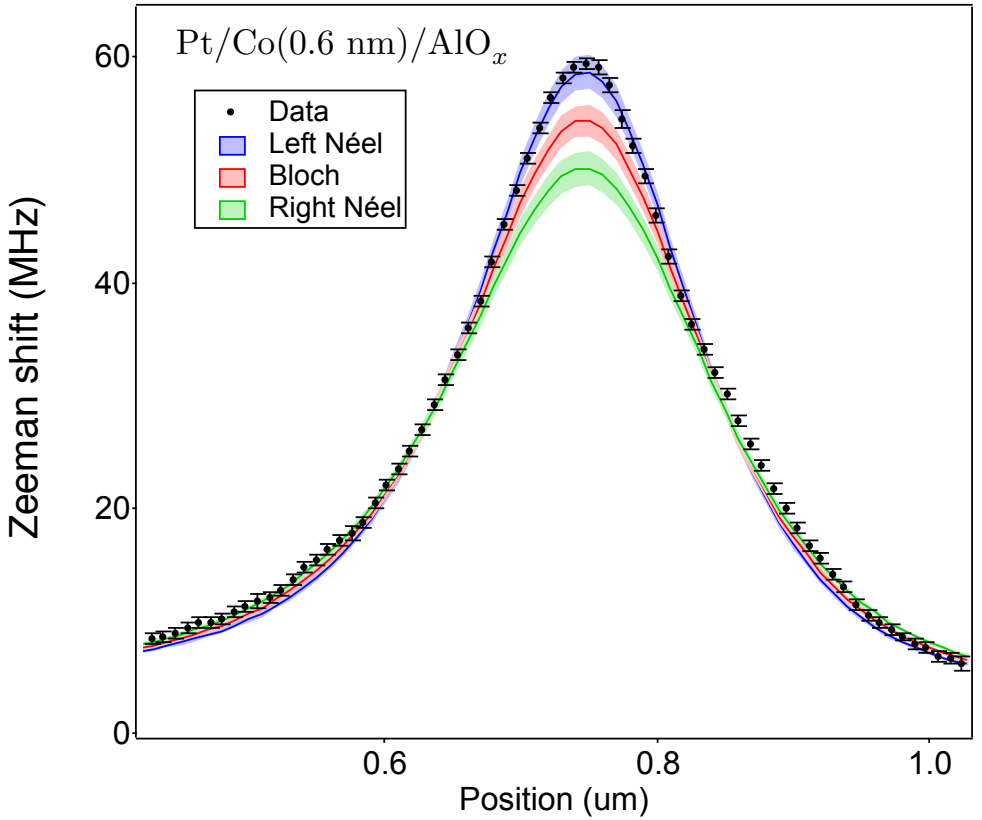




Néel DW !!!!

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

Tetienne *et al., preprint arXiv:*1410.1313
to appear in Nat. Commun.



Outline of the talk

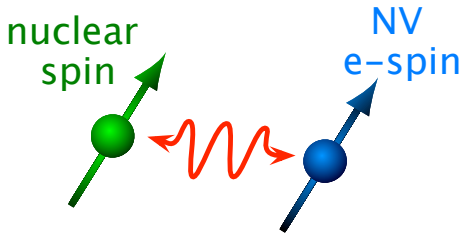
1. The NV defect in diamond as an atomic-sized magnetic field sensor

2. Applications in fundamental nanomagnetism

Imaging dowain walls in ultrathin magnetic wires

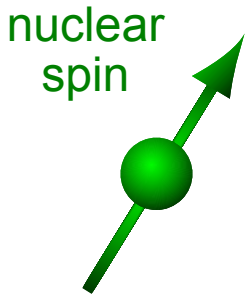
3. Other Applications

Biology, Quantum information science…



Quantum information science – Spin physics

An ideal qubit : a single nuclear spin

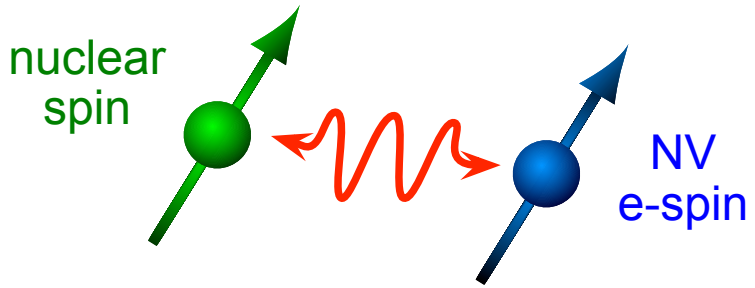


High isolation from the environment

- long coherence times
- hard to detect and control single nuclear spin

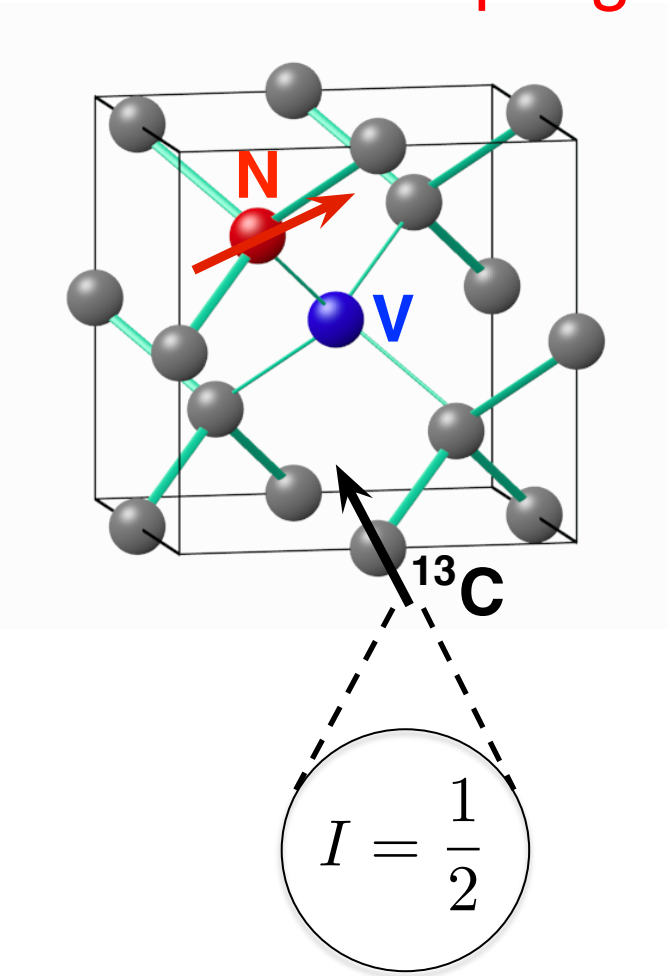
One strategy : use an ancillary electronic spin as a detector

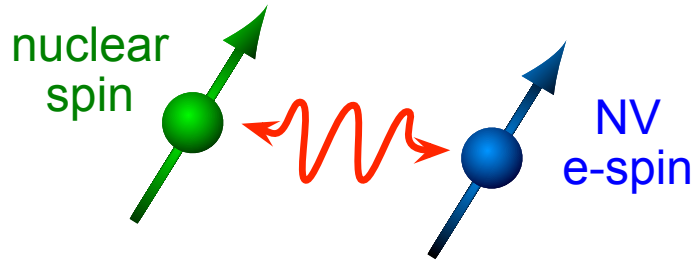
Steger *et al*. *Science* **336**, 1280 (2012)
Neumann *et al*. *Science* **320**, 1326 (2008)



Quantum information science – Spin physics

Coupling with nearby nuclear spins…

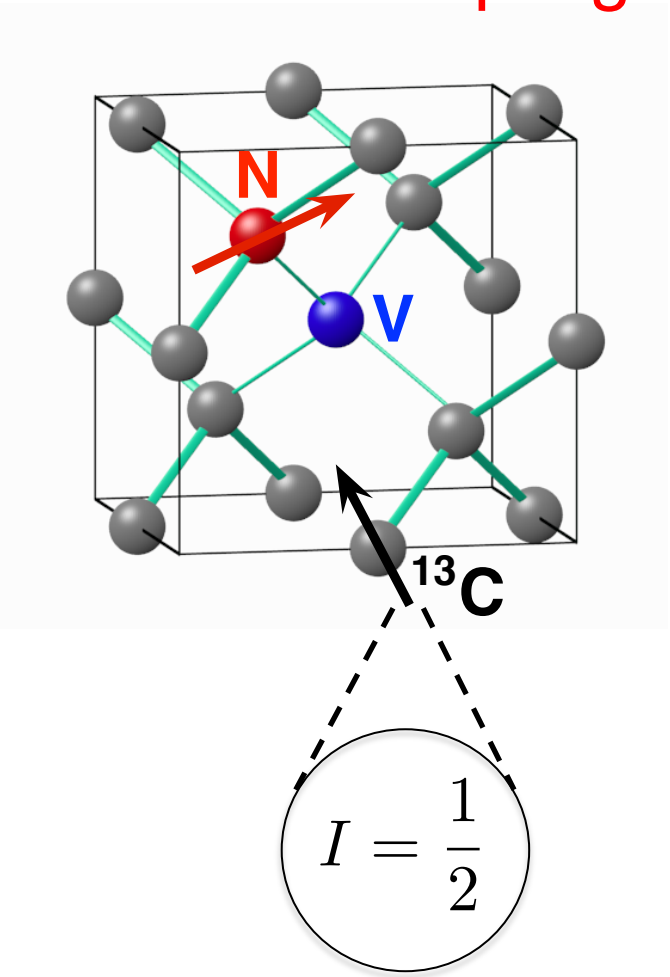


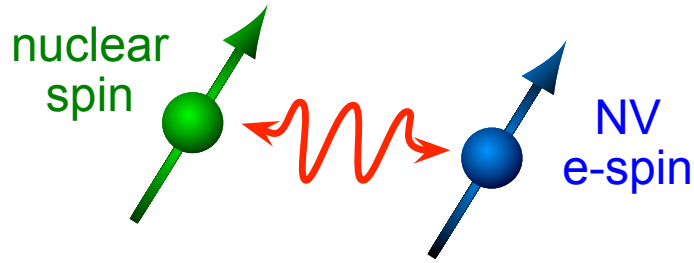


hyperfine interaction → $\mathcal{H}_{hi} \simeq \mathcal{A}^{hs}\, \hat{S} \cdot \hat{I}$

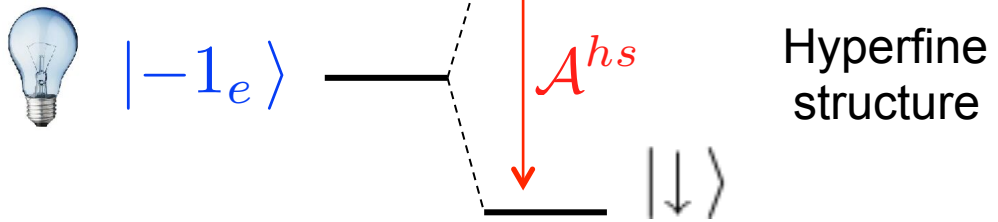
Quantum information science – Spin physics

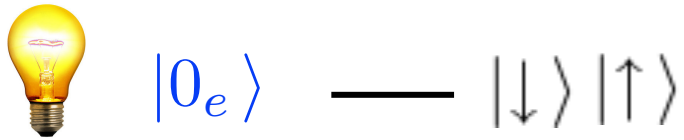
Coupling with nearby nuclear spins…





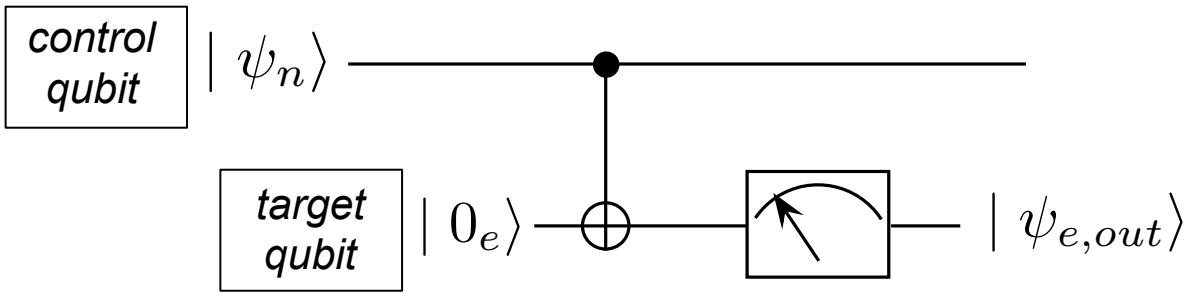
hyperfine interaction ⟹ $\mathcal{H}_{hi} \simeq \mathcal{A}^{hs}\, \hat{S} \cdot \hat{I}$



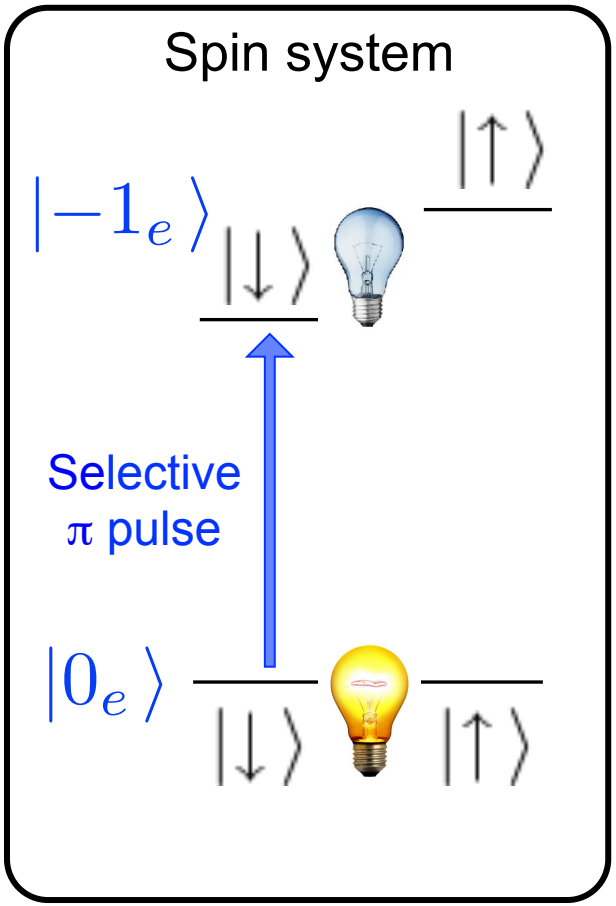


Quantum information science – Spin physics

Single-shot readout of a single nuclear spin



$\|\psi_n\rangle$	$\|\psi_{e,out}\rangle$	PL signal
$\|\downarrow\rangle$	$\|-1_e\rangle$	**low**
$\|\uparrow\rangle$	$\|0_e\rangle$	**high**

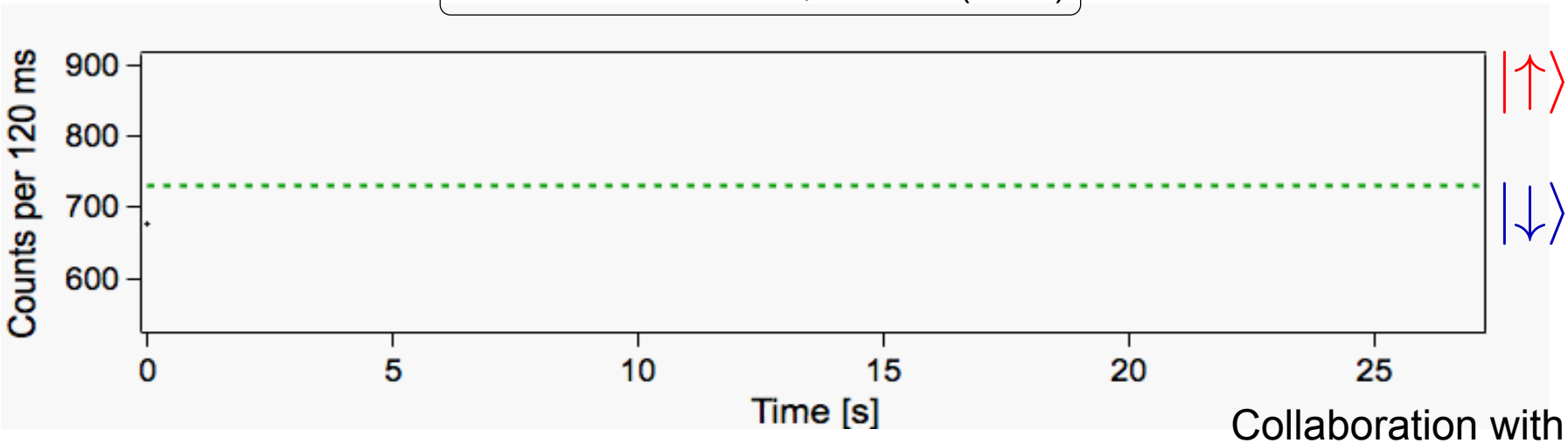


Neumann *et al., Science* **329**, 542 (2010)

Quantum information science – Spin physics

Single-shot readout of a single nuclear spin

Dréau *et al*. *PRL* **110**, 060502 (2013)

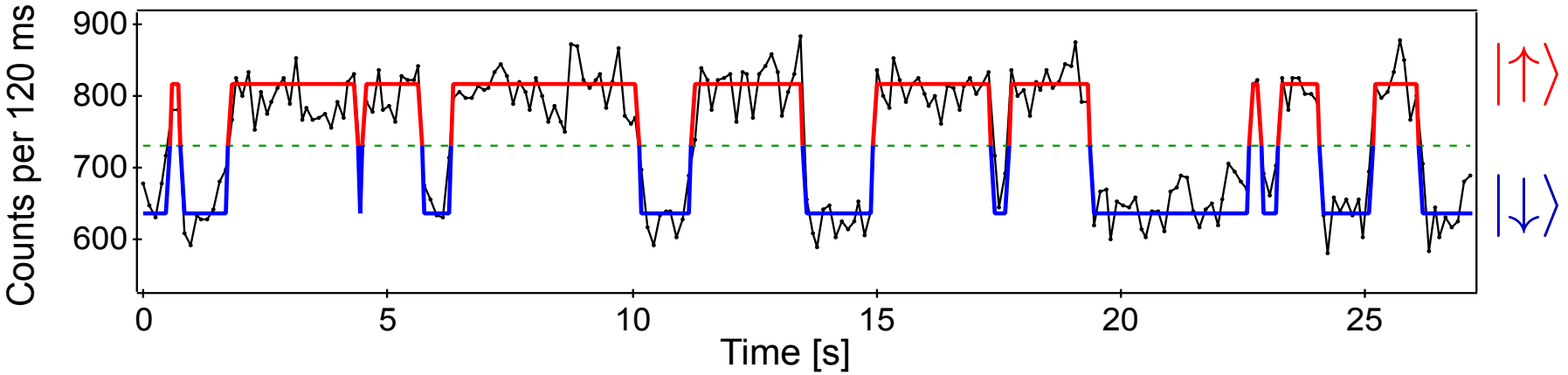


Collaboration with
J. Maze (Santiago)

Quantum information science – Spin physics

Single-shot readout of a single nuclear spin

Dréau *et al*. *PRL* **110**, 060502 (2013)



Recently used…

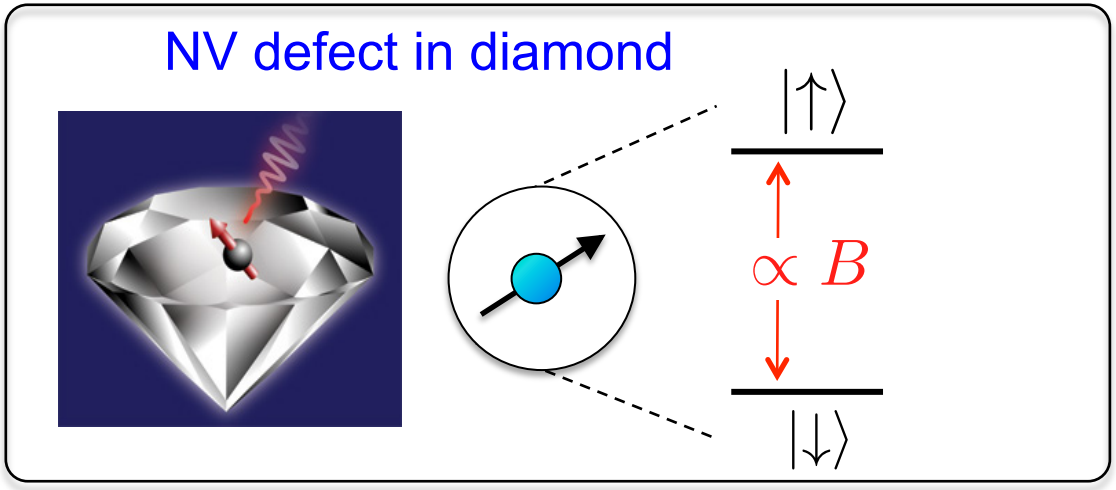
- to investigate in real-time the dynamics of a nuclear-spin bath

Dréau *et al*. *PRL* **113**, 137601 (2014)

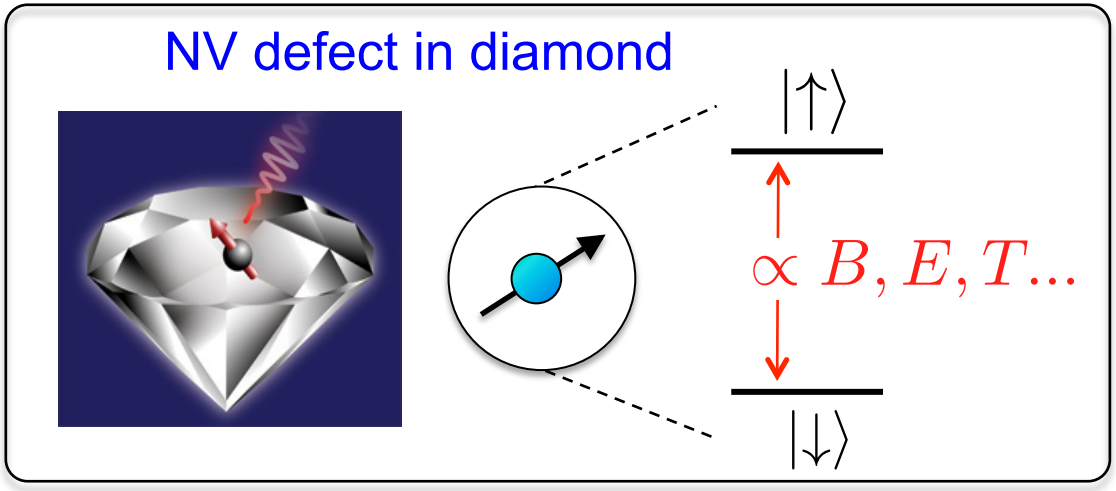
- to perform quantum error correction

Walderr *et al. Nature* **506**, 204 (2014) Stuttgart group

Sensing at the nanoscale

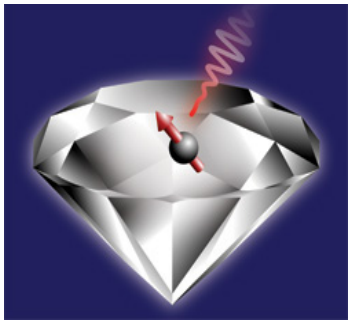


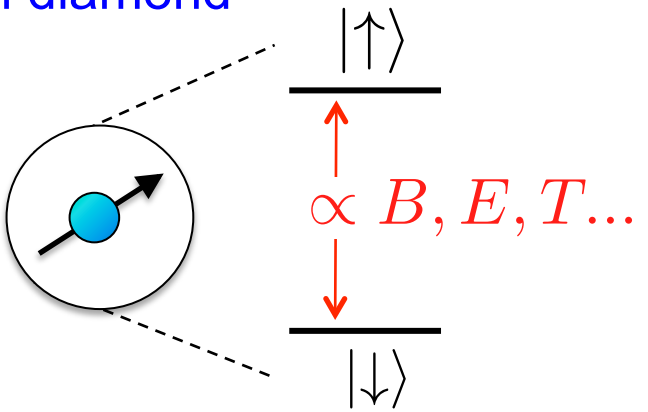
Sensing at the nanoscale



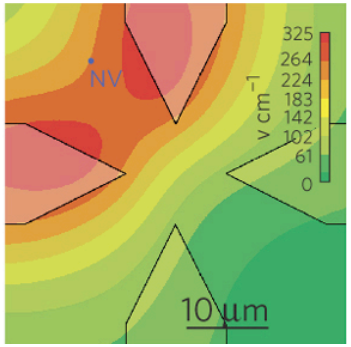
Sensing at the nanoscale

NV defect in diamond



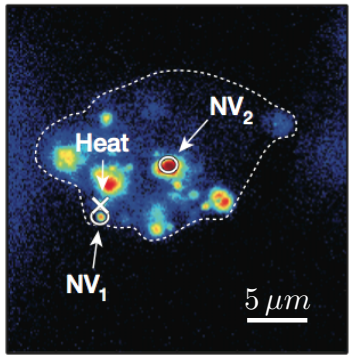


Electric field



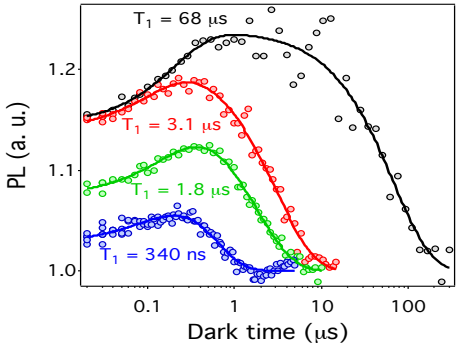
Dolde *et al., Nat. Phys.* ***7****, 459 (2011)*
Stuttgart

Temperature



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

Magnetic noise

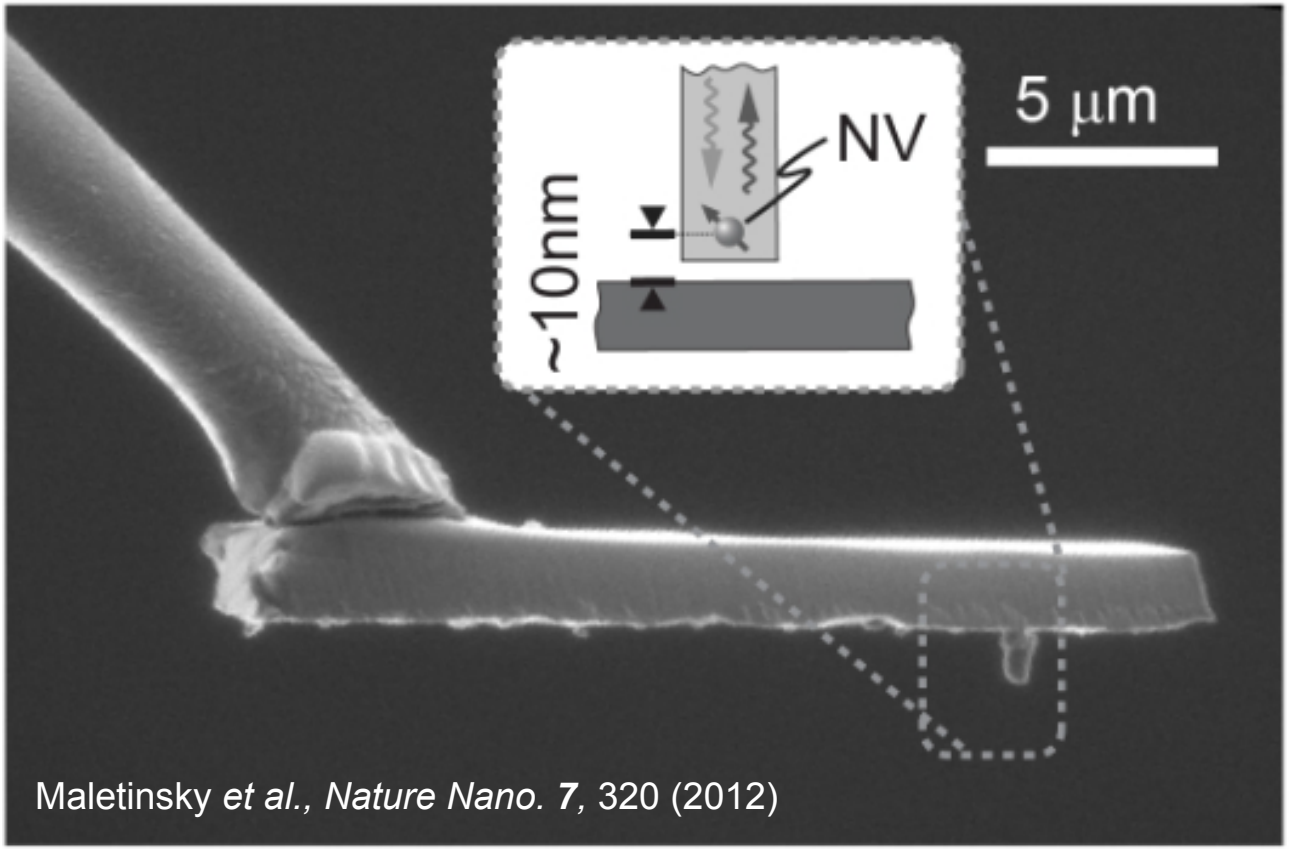


Tetienne *et al., PRB 87, 235436 (2013)*
Cachan

Engineering the magnetic sensor

All diamond tip

P. Maletinsky, Basel University

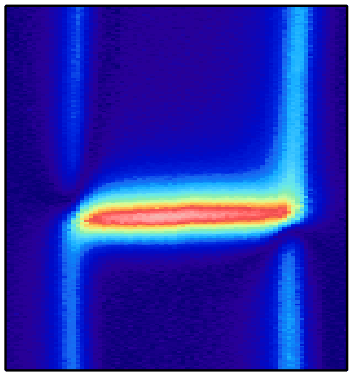


Quantum information, Spin physics

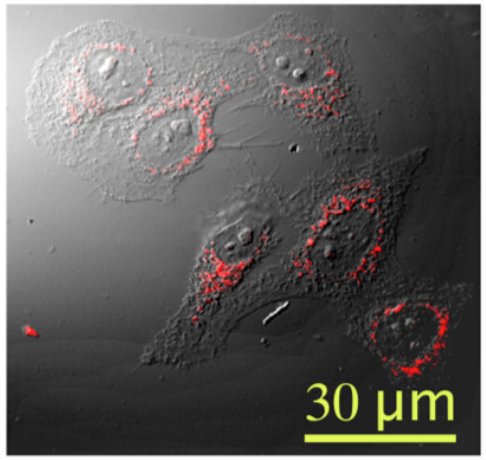
nuclear spin

NV e-spin

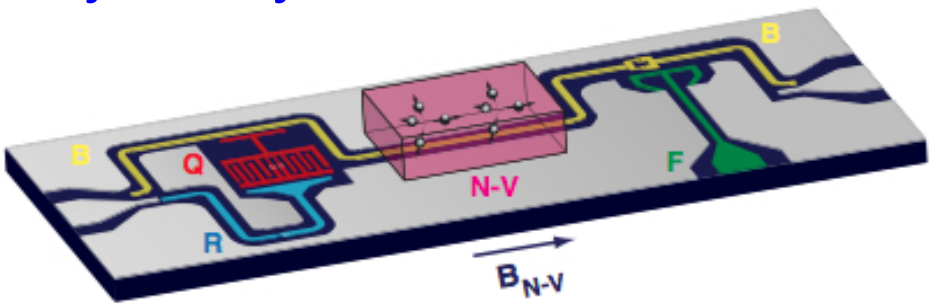
Nanoscale sensing



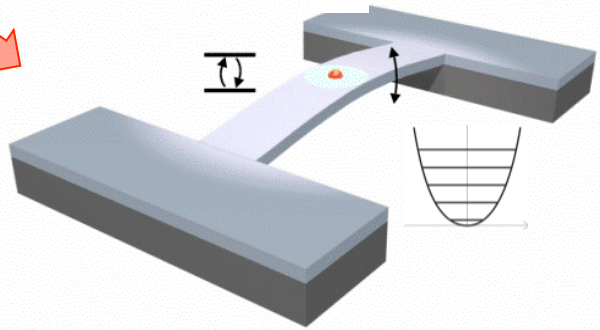
Fluorescent label in Biology



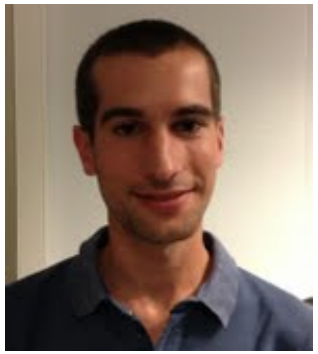
Hybrid systems



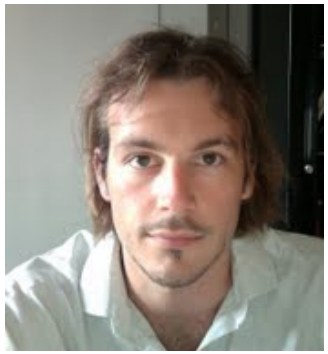
Kubo *et al., Phys. Rev. Lett.* **107**, 220501 (2011)



Arcizet *et al., Nat. Phys.* **7**, 879 (2011)



J.-P. Tetienne



T. Hingant

L. J. Martinez

I. Gross

M. Lesik, J.-F. Roch

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Thank you for your attention

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