Nanoscale magnetic imaging with quantum sensors

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slides available at https://magimag.eu

Solid-state quantum technologies team in Montpellier

→ Defects in semiconductors, and their use as quantum sensors
→ Ultrawide bandgap semiconductors for deep-UV electronics

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Can we use a quantum system to probe nanomagnetism?

C. Degen *et al*. *Rev. of Mod. Phys.* 89 (2017), 035002

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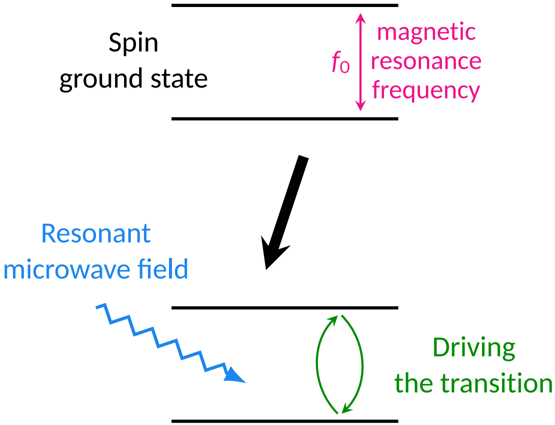

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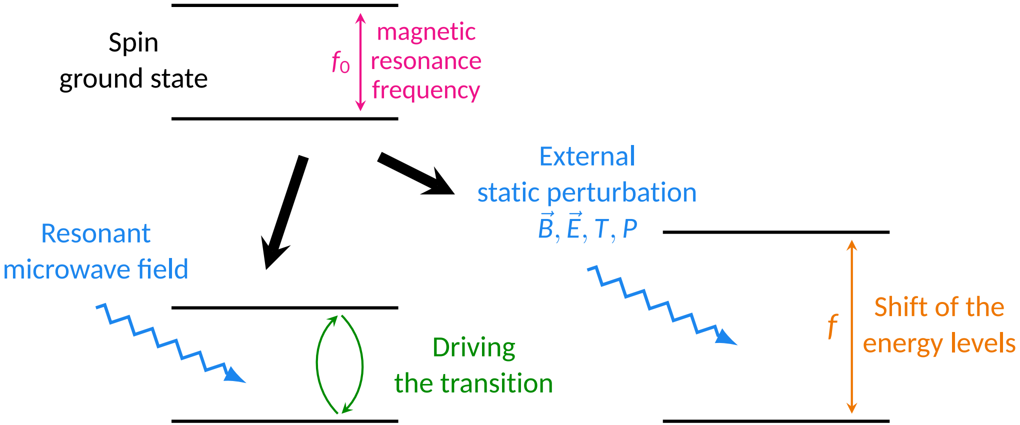

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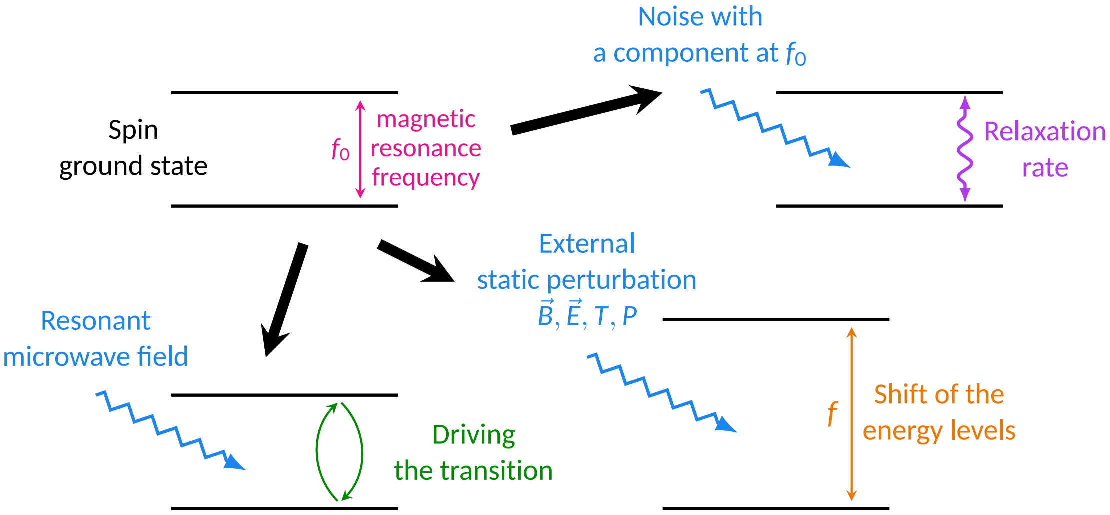
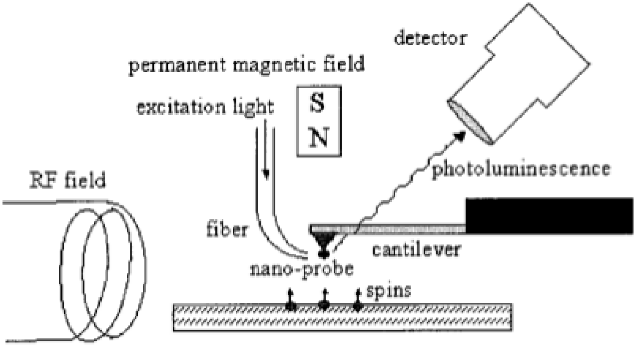


C. Degen *et al.* *Rev. of Mod. Phys.* 89 (2017), 035002

The proposal of Chernobrod and Berman



B. M. Chernobrod *et al.* *J. Appl. Phys.* 97 (2004), 014903

- Atomic force microcope for spatial resolution
- High sensitivity to perturbations of the quantum system
- Sensor: point defect in a semiconductor

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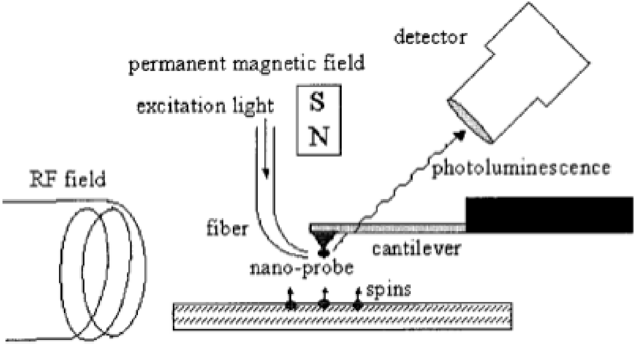

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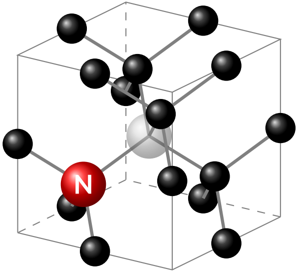
NV center in diamond

The NV center in diamond



Nitrogen-Vacancy defect

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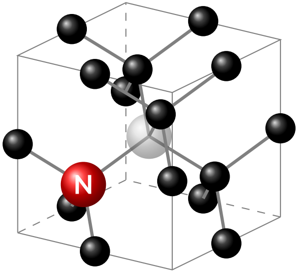

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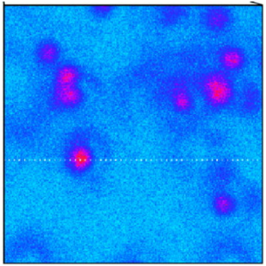
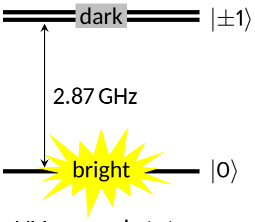


- Photostable defect
- Spin S=1
- Individual defects can be isolated/implanted
- Ambient conditions

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

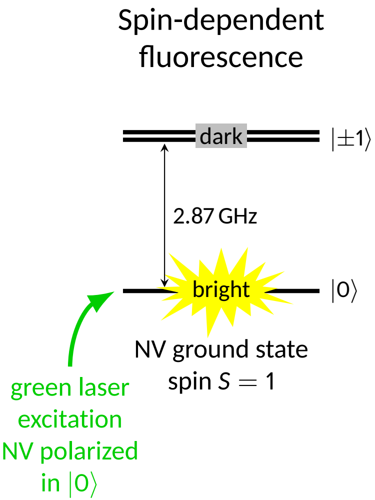
Principle of static magnetic field measurement

Spin-dependent fluorescence



NV ground state
spin $S = 1$

Principle of static magnetic field measurement



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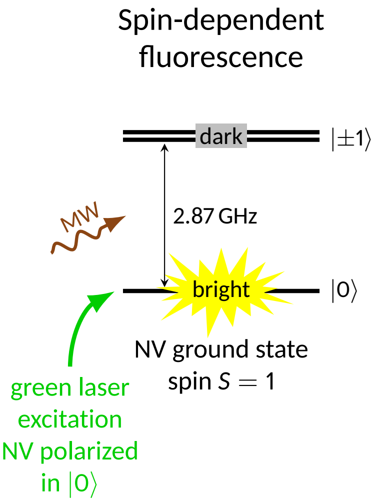

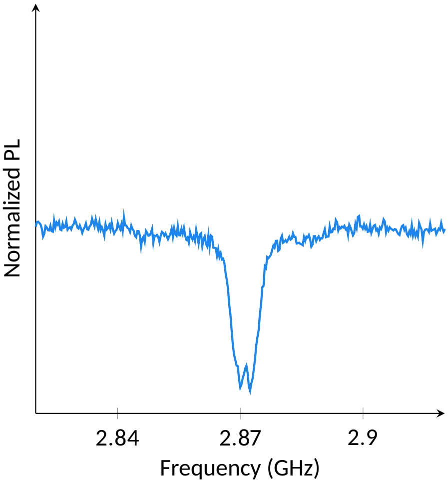

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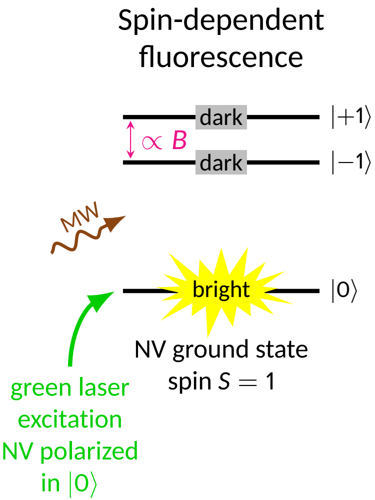

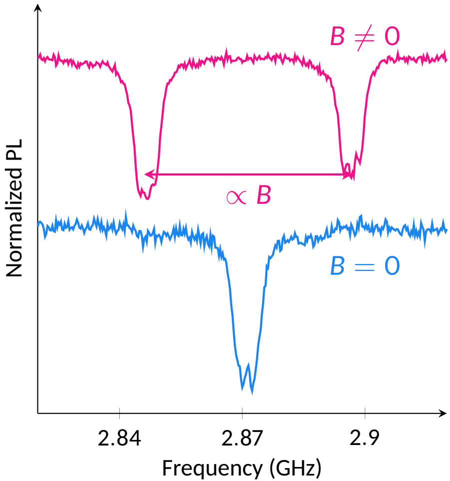

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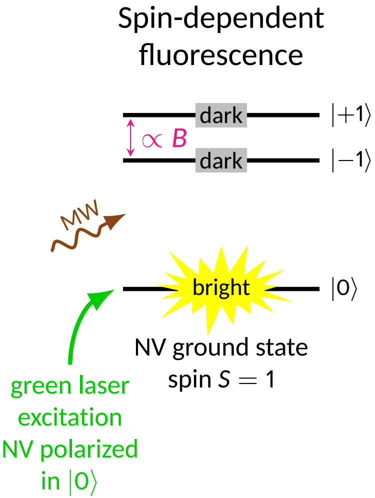
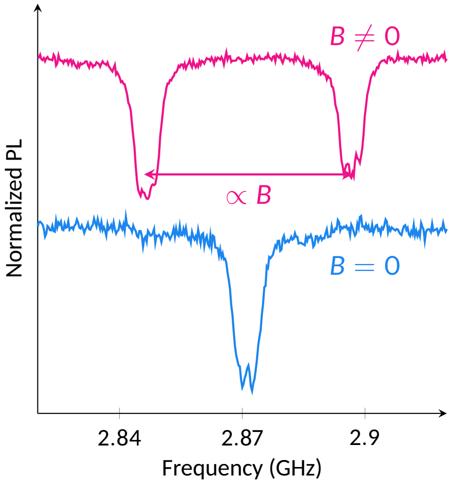
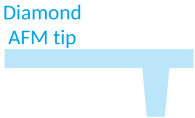
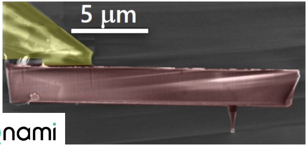




Sensibility: a few $\mu T/\sqrt{Hz}$

Integration of the defect in a scanning probe microscope





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

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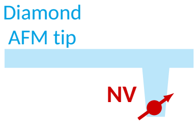

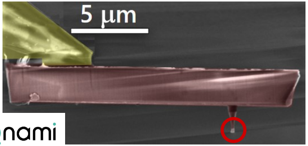

Implanted single
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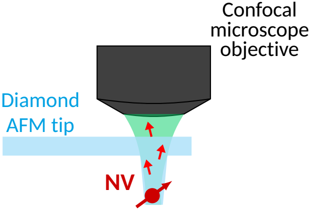

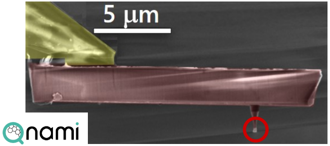

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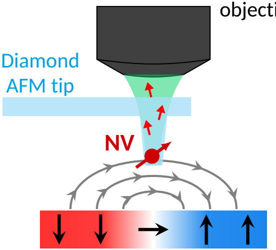

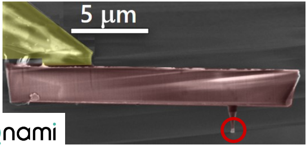

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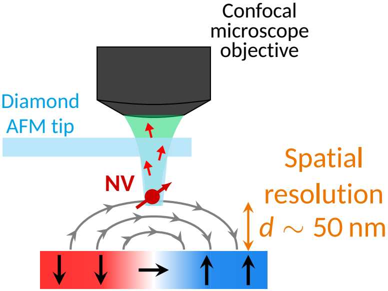

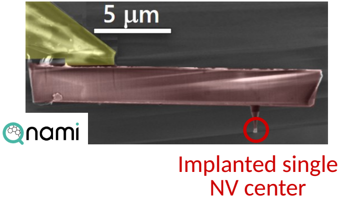

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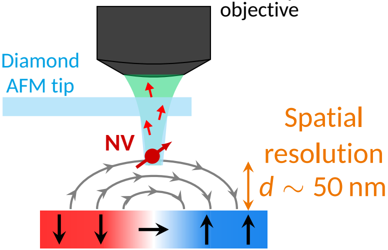

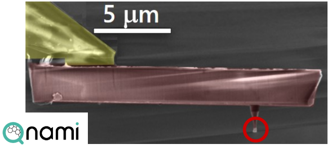

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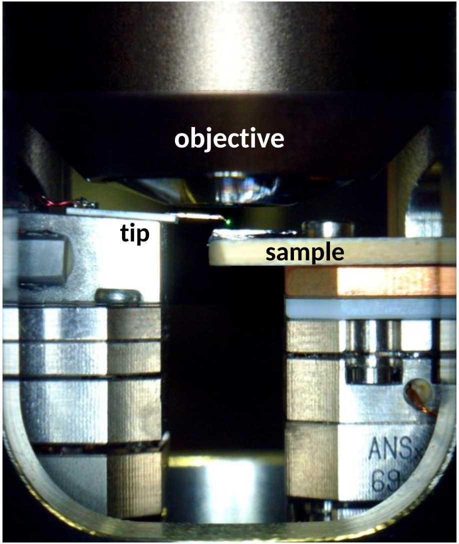

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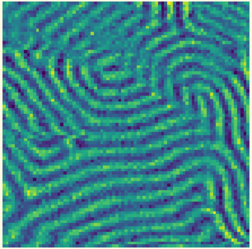
Outline



Imaging topological defects
in a multiferroic antiferromagnet

A. Finco *et al*. *Phys. Rev. Lett.* 128 (2022), 187201

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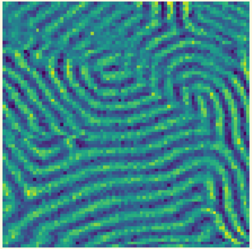

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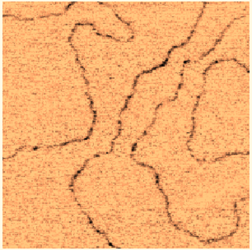

Detection of magnetic textures
through channelled spin waves

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

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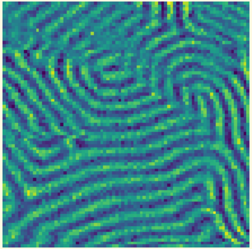

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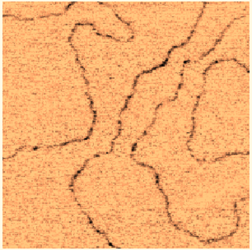

Detection of magnetic textures
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A. Finco *et al.* *Nat. Commun.* 12 (2021), 767

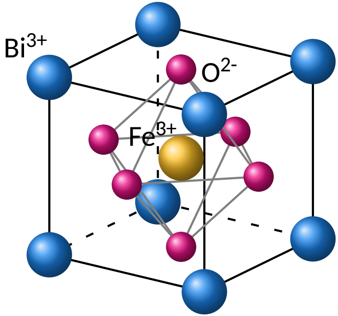
Outlook: further sensing possibilities

- Sensing electric field or temperature
- Other defects: boron vacancies in h-BN

P. Kumar *et al.* *Phys. Rev. Appl.* 18 (2022), L061002

Bismuth ferrite, a room temperature multiferroic

Electric polarization



Paraelectric phase (T>1100 K)

G. Catalan *et al*. *Adv. Mater.* 21 (2009), 2463–2485

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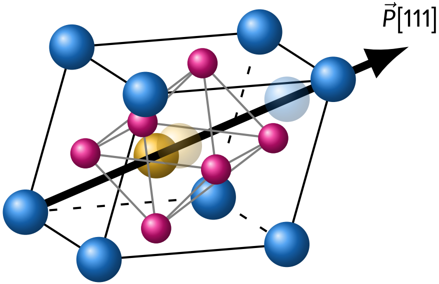

Ferroelectric phase (T<1100 K)

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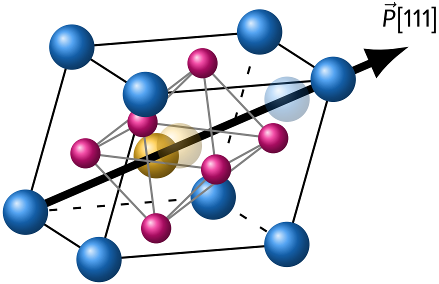
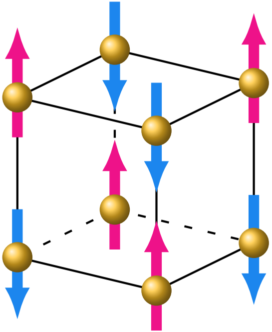


Magnetism

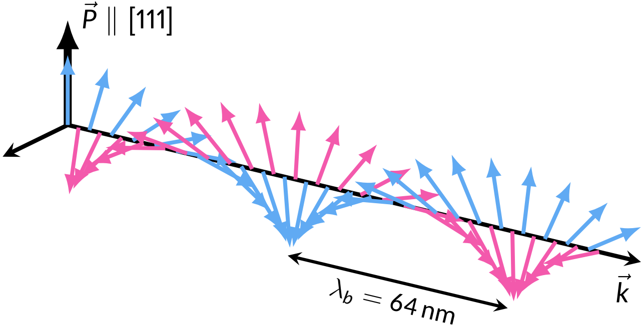


Ferroelectric phase (T<1100 K)

G-type antiferromagnetic phase ($T_N = 643$ K)

G. Catalan *et al*. *Adv. Mater.* 21 (2009), 2463–2485

The effects of magnetoelectric coupling in $BiFeO_3$



Fully compensated cycloid
→ **No stray field!**

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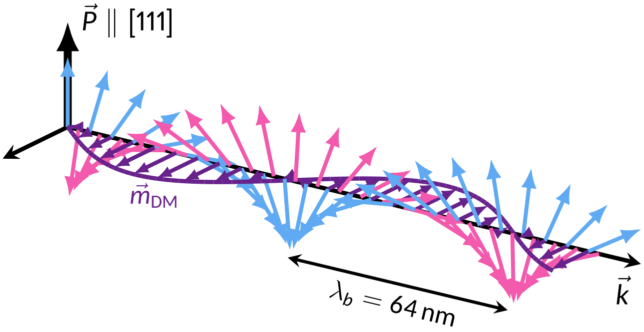

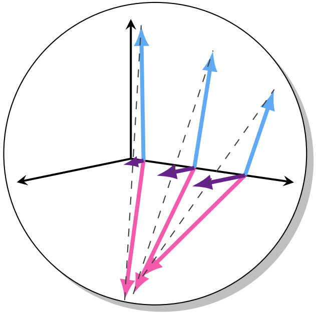

Spin density wave

Weak uncompensated moment

→ **Small stray field**

M. Ramazanoglu *et al.* *Phys. Rev. Lett.* 107 (2011), 207206

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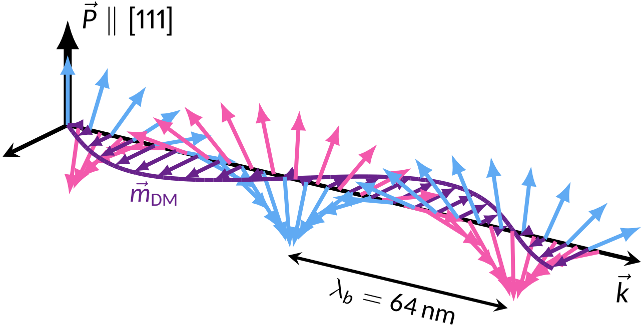

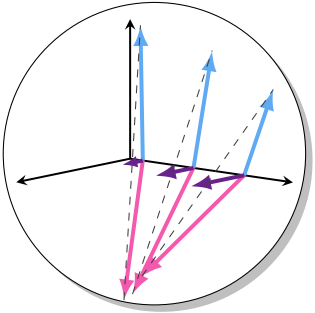

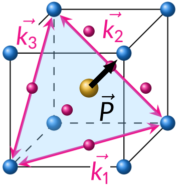

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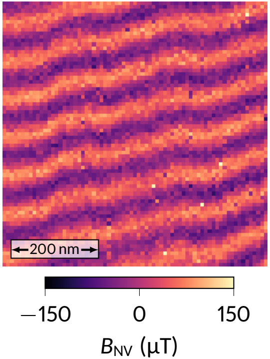
Quantitative analysis of the cycloid in bulk single crystals

Collaborations: UMR CNRS/Thales, Palaiseau (V. Garcia, S. Fusil)
CEA SPEC, Gif-sur-Yvette (J.-Y. Chauleau, M. Viret)



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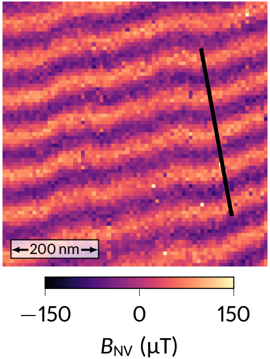

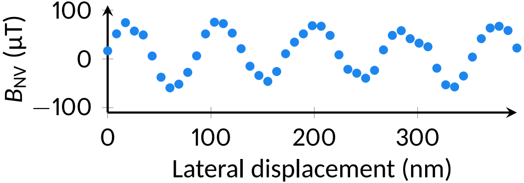

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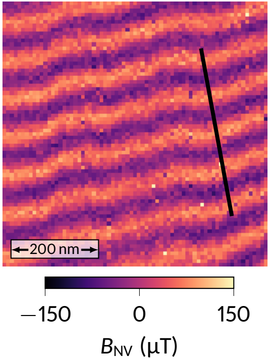

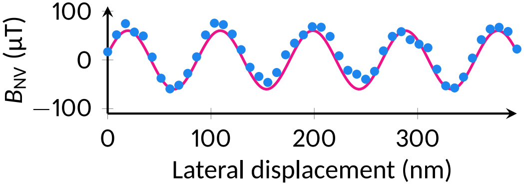

$$\begin{cases} B_x = 0 \\ B_y = -\frac{A}{\sqrt{2}}\left(\mathrm{Re}\{S\} - \mathrm{Im}\{S\}\right) \\ B_z = \sqrt{2}\,A\,\mathrm{Re}\{S\} \end{cases} \quad \text{with} \quad \begin{cases} A = \frac{\mu_0 m_{DM}}{\sqrt{3}\,a^3}\sinh\left(\frac{ka}{2\sqrt{2}}\right) \\ S = e^{-kz/\sqrt{2}} e^{ik(y-z)/\sqrt{2}} \frac{1 - e^{-kt(1+i)/\sqrt{2}}}{1 - e^{-ka(1+i)/\sqrt{2}}} \end{cases}$$

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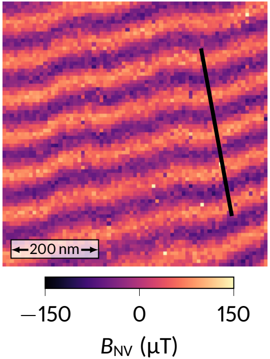

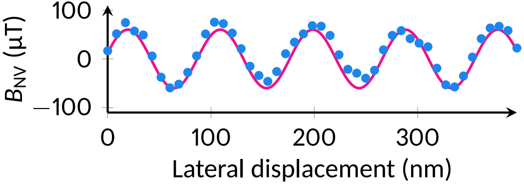

$$m_{DM} = 0.09 \pm 0.03\ \mu_B$$

M. Ramazanoglu *et al.* *Phys. Rev. Lett.* 107 (2011), 207206

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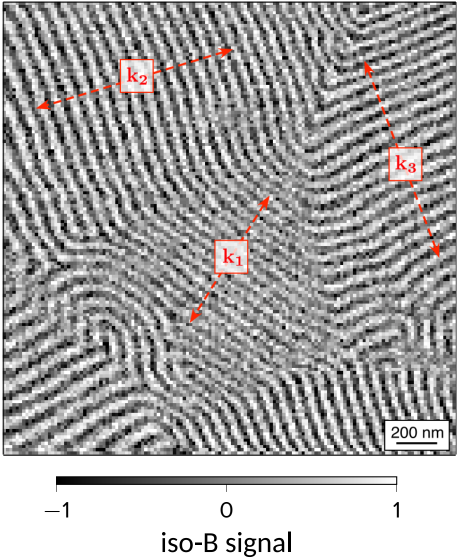
Rotation of the cycloid propagation direction measured in real space…



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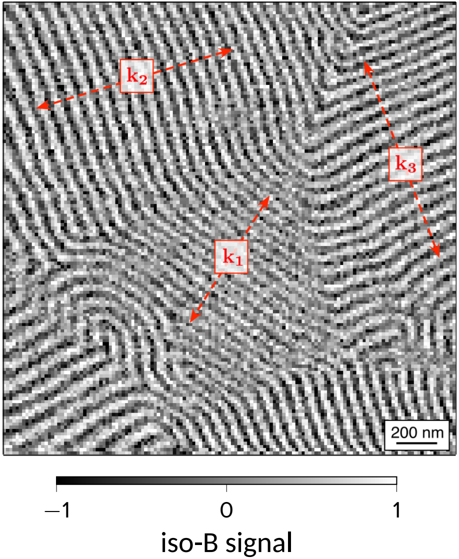
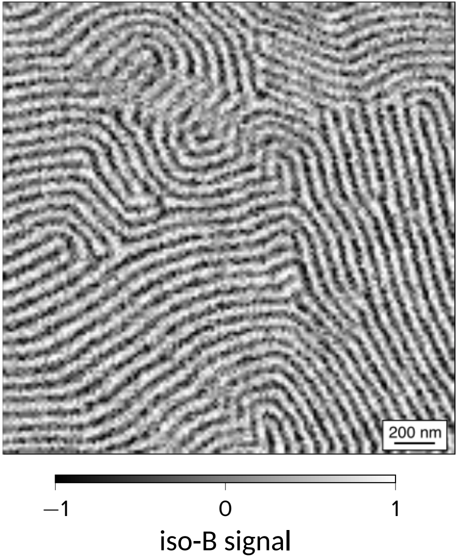
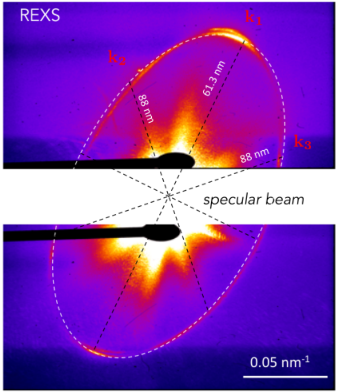




… and in reciprocal space

Resonant X-ray scattering



N. Jaouen

… and in reciprocal space

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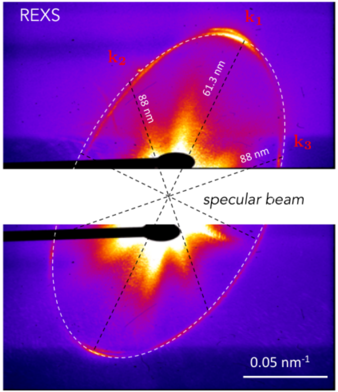
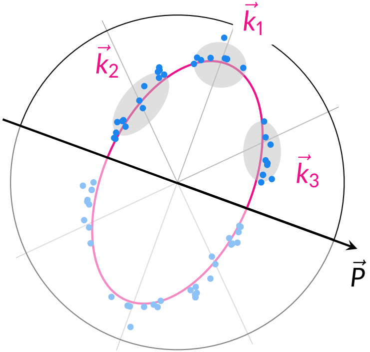
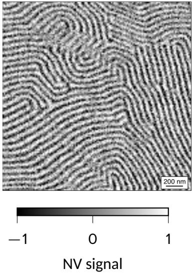


SOLEIL SYNCHROTRON
N. Jaouen

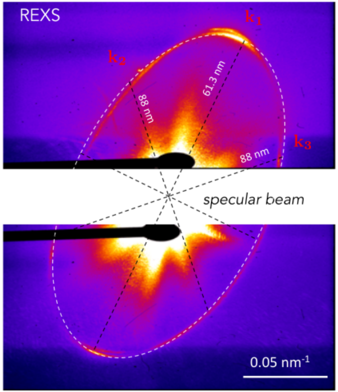
Polar plot of $\frac{2\pi}{\lambda}$ vs $\vec{k}$ direction





… and in reciprocal space

Resonant X-ray scattering



SOLEIL SYNCHROTRON
N. Jaouen

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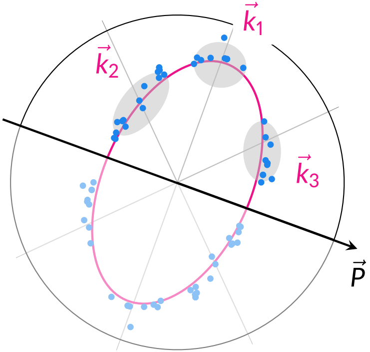

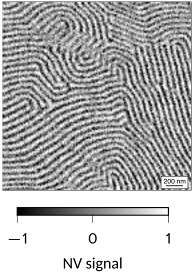

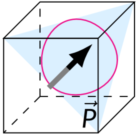

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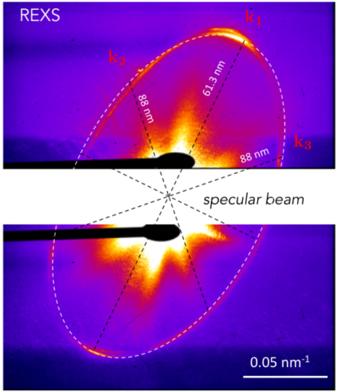

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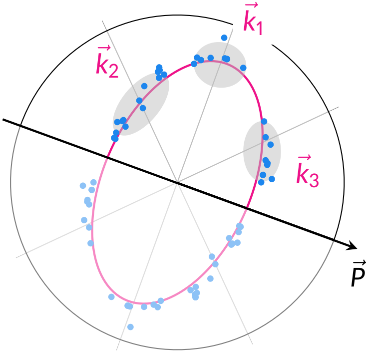
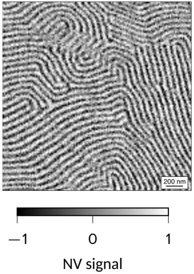
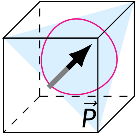






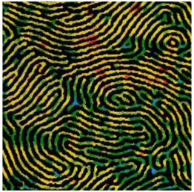
SOLEIL SYNCHROTRON
N. Jaouen

Surface effect? Only $\vec{k}_1$ seen by neutrons

D. Lebeugle *et al.* *Phys. Rev. Lett.* 100 (2008), 227602

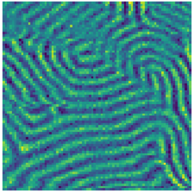
Universal patterns in lamellar systems

Block copolymer
Period 40 nm



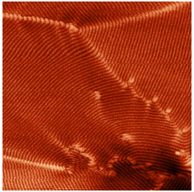
T. A. Witten. *Phys. Today* 43 (1990), 21

$BiFeO_3$ magnetic cycloid
Period 64 nm



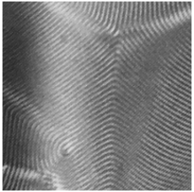
A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

FeGe magnetic helix
Period 70 nm



P. Schönherr *et al.* *Nat. Phys.* 14 (2018), 465

Liquid crystals
Period 800 nm

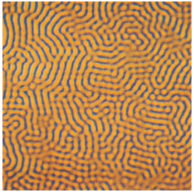


Y. Bouligand. *Dislocations in solids* (1983), Chap. 23

Ferrimagnetic garnet
Period 8 µm

M. Seul *et al.* *Phys. Rev. A* 46 (1992), 7519

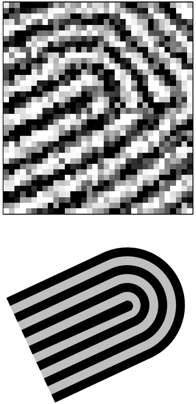
Fluid diffusion
Period 250 µm



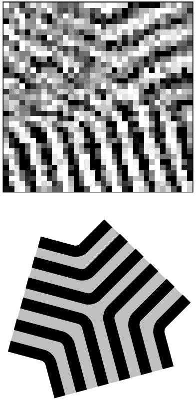
Q. Ouyang *et al.* *Chaos* 1 (1991), 411

Identification of these topological defects in $BiFeO_3$

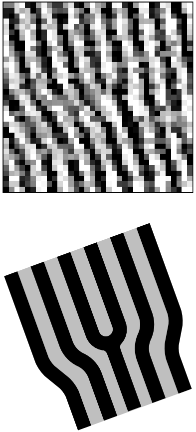
$+\pi$-disclination



$-\pi$-disclination



Edge dislocation



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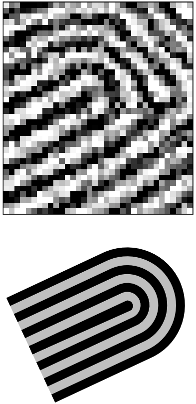

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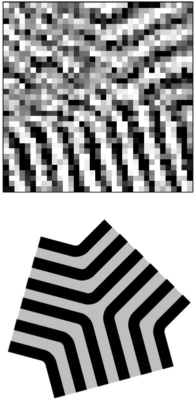

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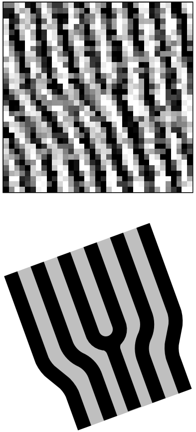
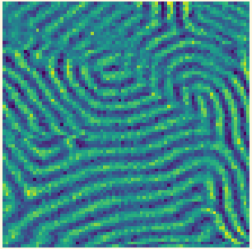


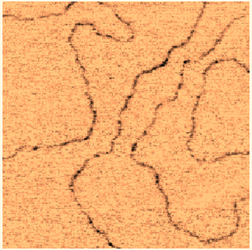
Perspective: electrical control?

Outline



Imaging topological defects
in a multiferroic antiferromagnet

A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201



Detection of magnetic textures
through channelled spin waves

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

Outlook: further sensing possibilities

- Sensing electric field or temperature
- Other defects: boron vacancies in h-BN

P. Kumar *et al.* *Phys. Rev. Appl.* 18 (2022), L061002

Detection of magnetic noise rather than stray field

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

- Completely compensated antiferromagnets = **no static stray field** to probe
- But NV centers are also sensitive to **magnetic noise**!
- Use the different noise properties above domains and domain walls for imaging

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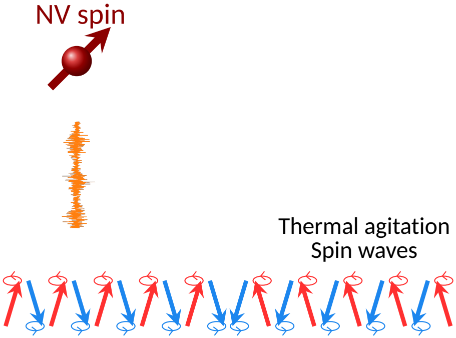

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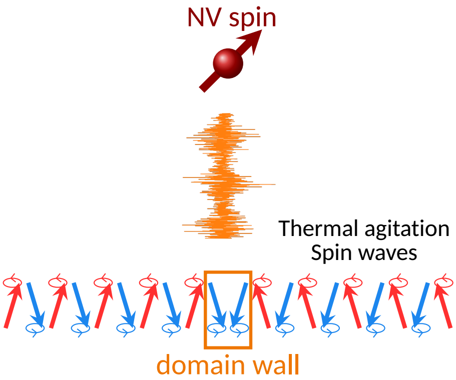
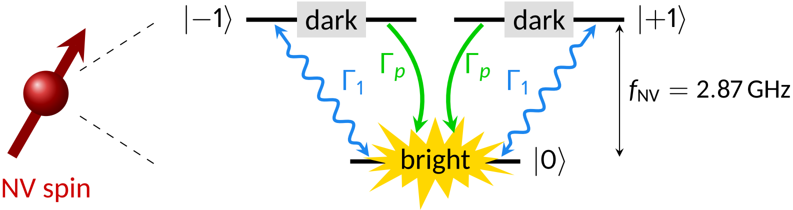


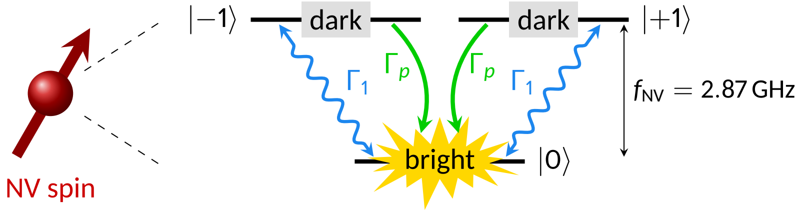
Effect of magnetic noise on the emitted photoluminescence



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

M. Rollo *et al.* *PRB* 103 (2021), 235418

Effect of magnetic noise on the emitted photoluminescence



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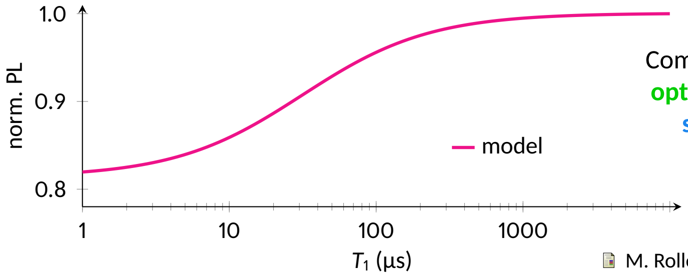

Competition between **optical pumping** and **spin relaxation**

M. Rollo *et al.* *PRB* 103 (2021), 235418

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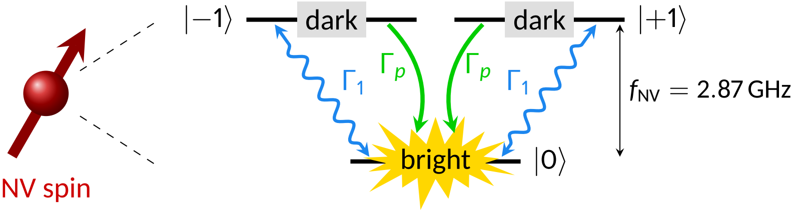

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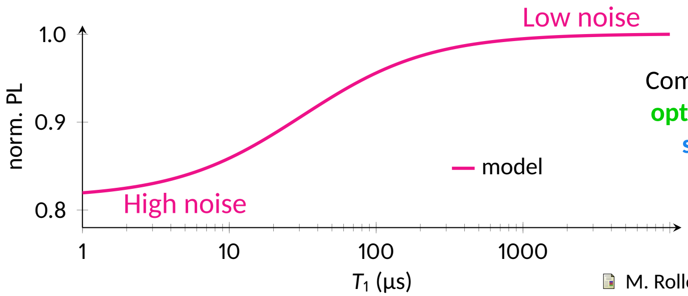

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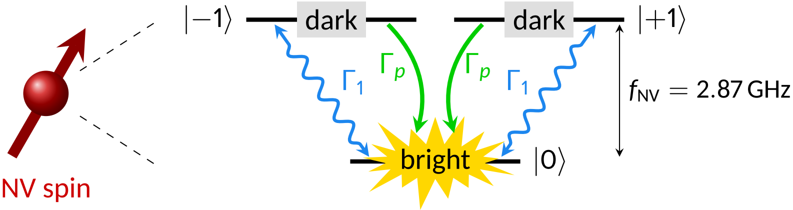

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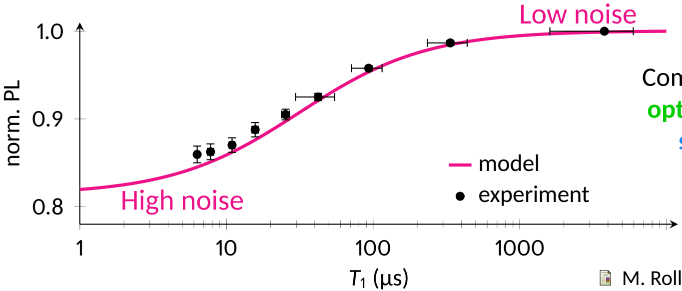


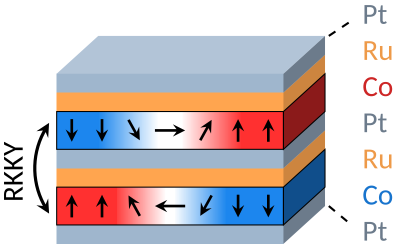
Competition between **optical pumping** and **spin relaxation**

M. Rollo *et al.* *PRB* 103 (2021), 235418

Imaging of synthetic antiferromagnets

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

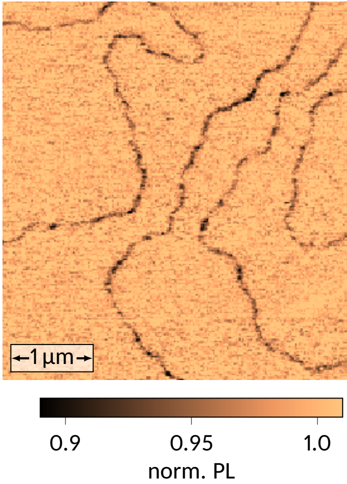
Two **ferromagnetic** layers coupled **antiferromagnetically**

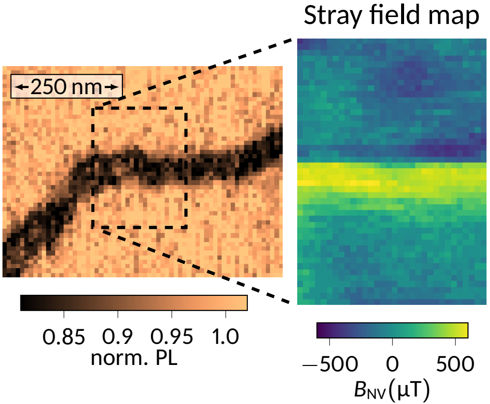


W. Legrand *et al*. *Nat. Mat.* 19 (2020), 34

- No net magnetic moment
- Compensation of dipolar effects
  → small skyrmions
- Small stray field due to vertical spacing
  → test system for noise imaging

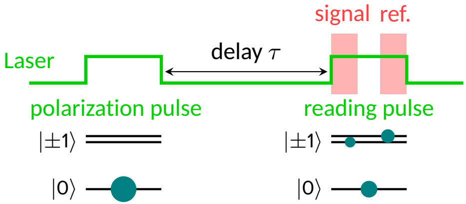
Detection of domain walls by relaxometry





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

Local variation of the relaxation time



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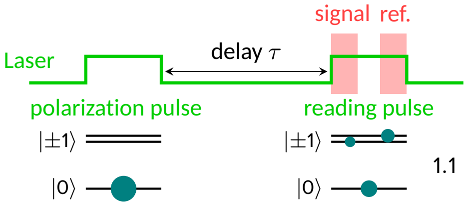

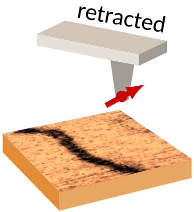

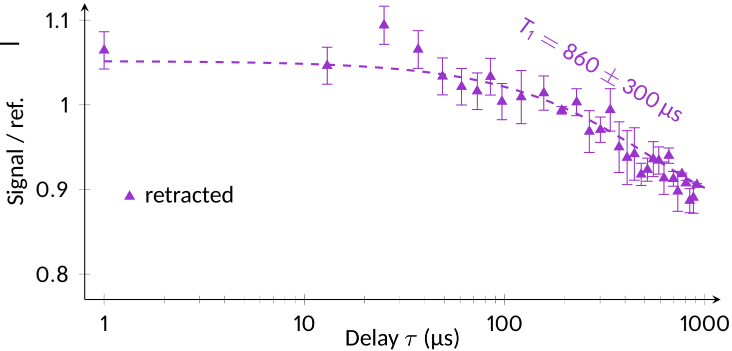

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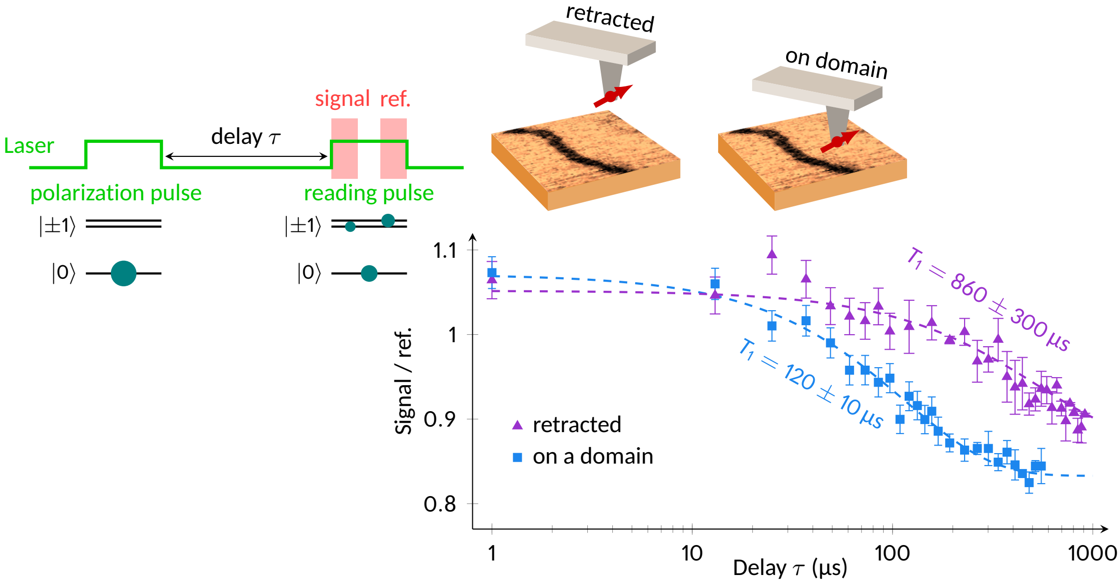

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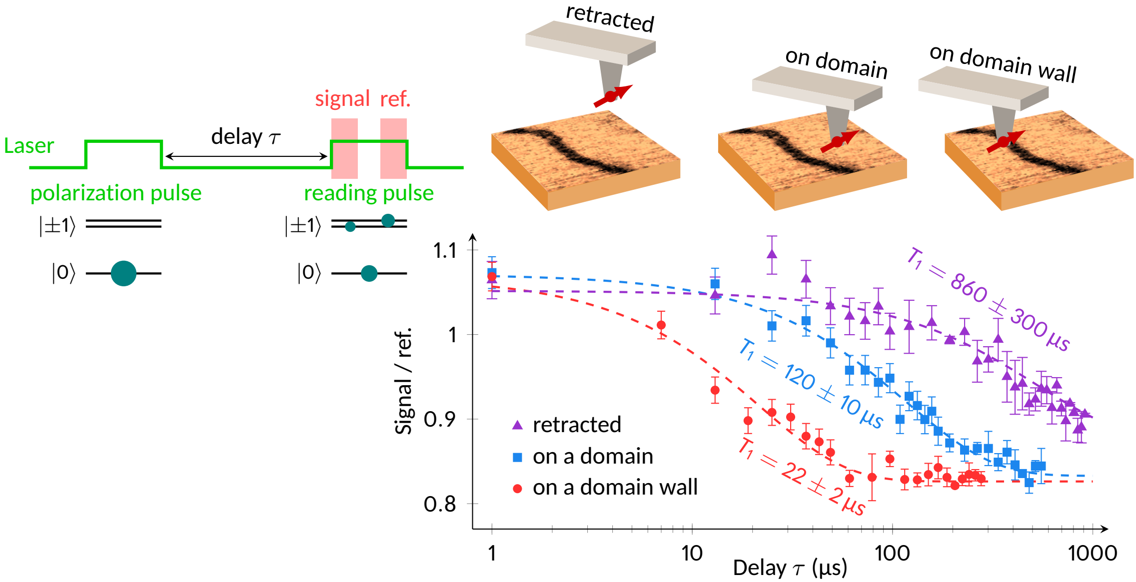

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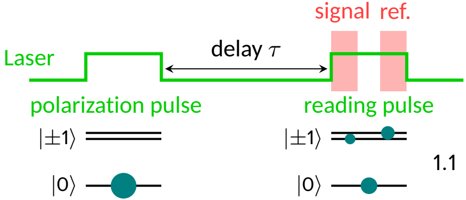
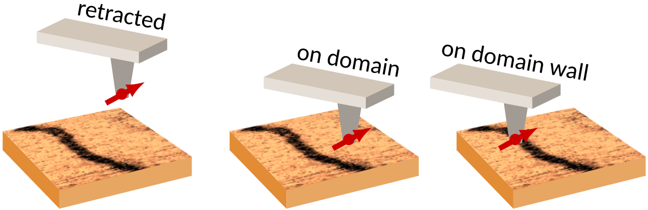
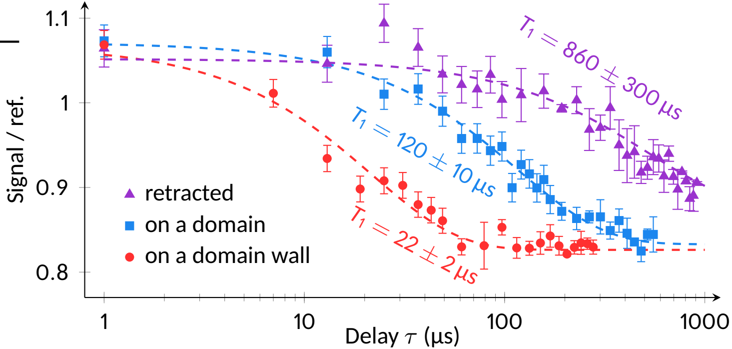




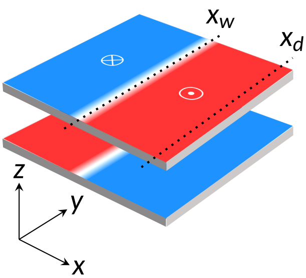


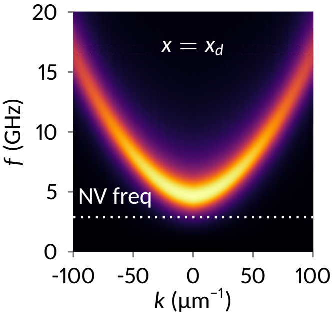
Clear diminution of T_1

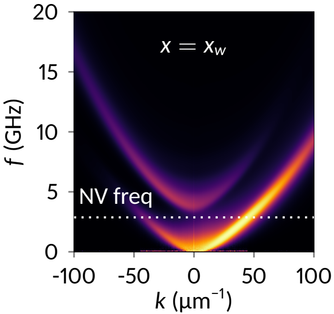
→ Presence of magnetic noise

Origin of the noise: spin waves

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







- NV frequency slightly below the gap, in the tail of power spectral density, which is the reason why we detect some noise when approaching the tip.
- No gap in the domain walls, presence of modes at the NV frequency: **the NV center is more sensitive to the noise from the walls!**

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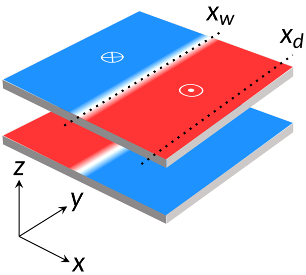

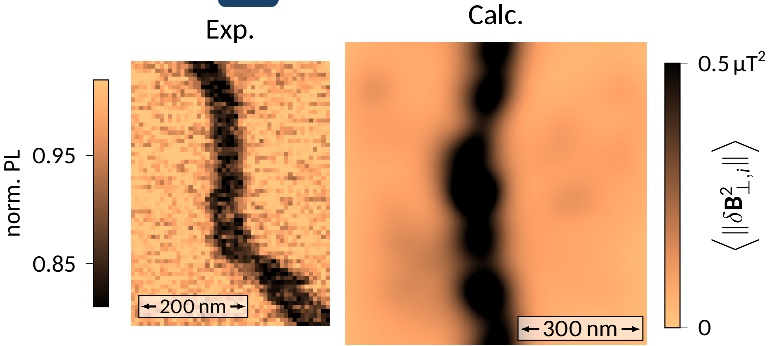

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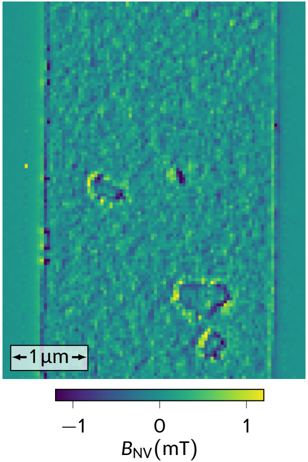
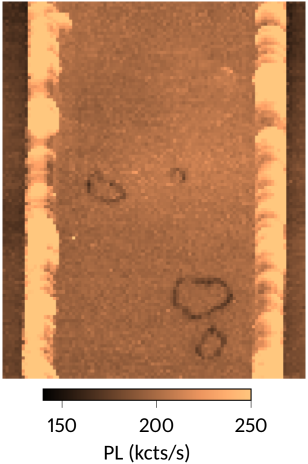
Skyrmions stabilized by pinning

Collaboration Spintec: Van-Tuong Pham, Olivier Boulle

NV stray field map

Noise (PL) map





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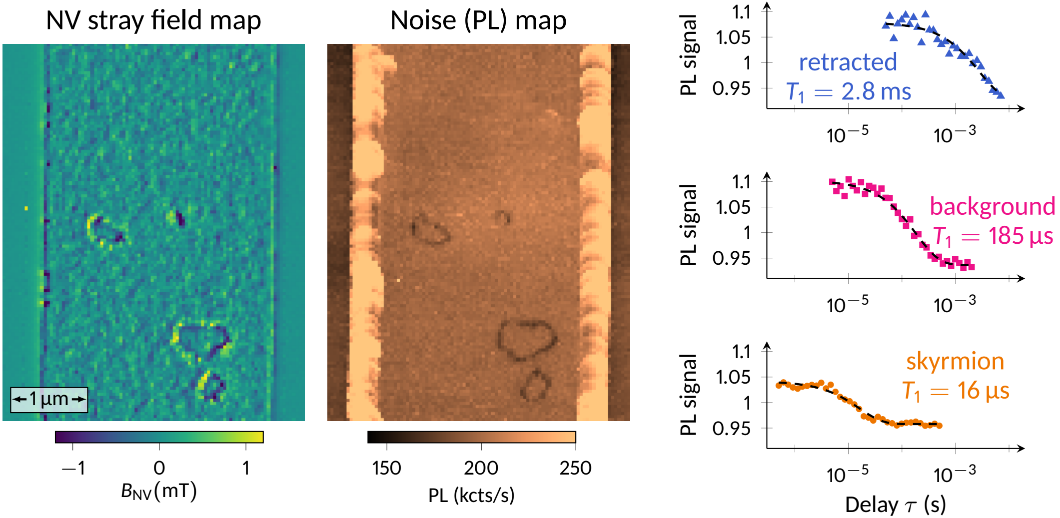
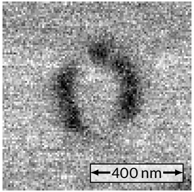


Insight about the internal structure of the skyrmions

Collaboration C2N: Joo-Von Kim



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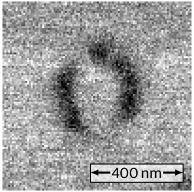
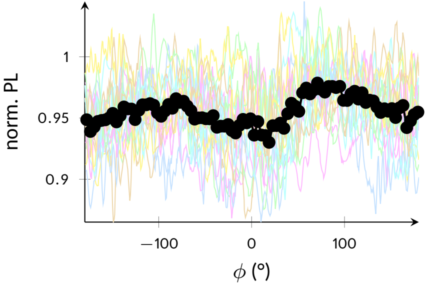


Analysis of the PL signal along the skyrmion contour



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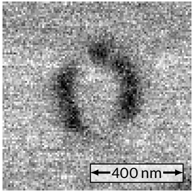

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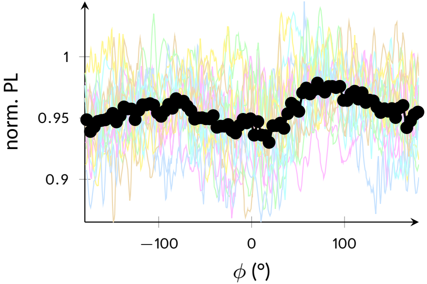

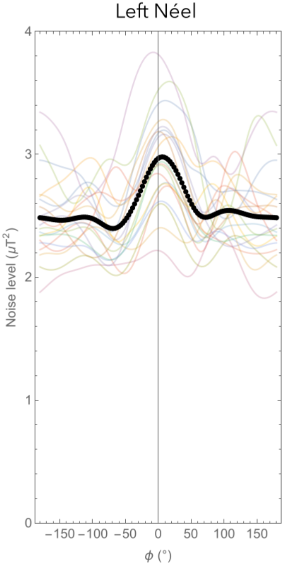

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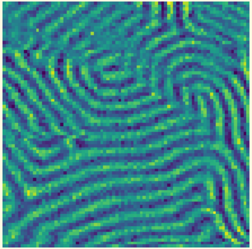

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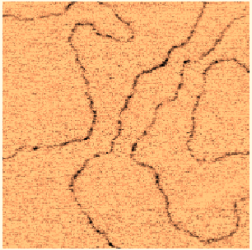
A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201



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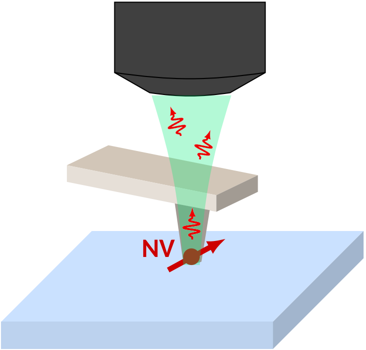
P. Kumar *et al.* *Phys. Rev. Appl.* 18 (2022), L061002

NV centers as multifunctional sensors

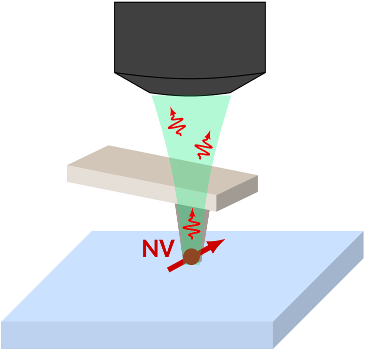


NV centers as multifunctional sensors

Magnetic field

(Anti)ferromagnetic textures

Currents



NV centers as multifunctional sensors

Magnetic field

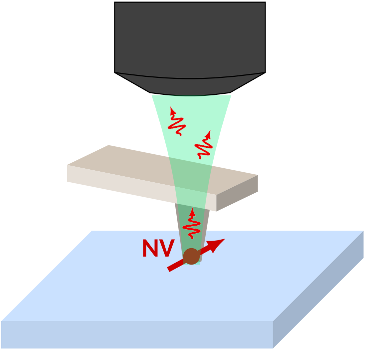
(Anti)ferromagnetic textures

Currents

Magnetic noise

Spin waves

Conductivity



NV centers as multifunctional sensors

Magnetic field

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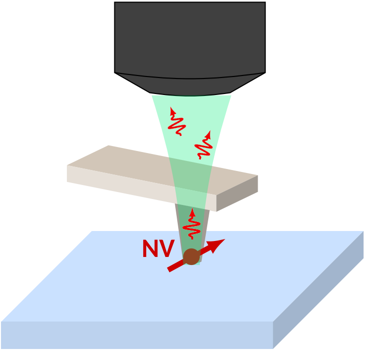


Electric field

Ferroelectric textures

NV centers as multifunctional sensors

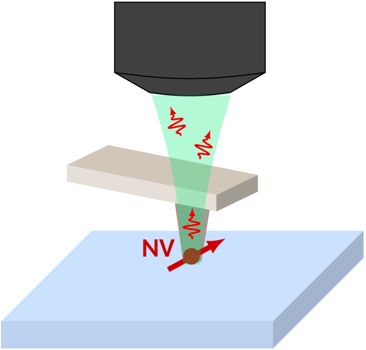
Magnetic field

(Anti)ferromagnetic textures

Currents

Electric field

Ferroelectric textures



Magnetic noise

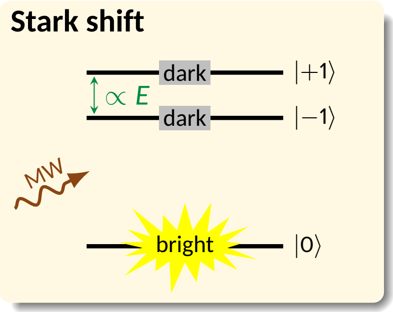
Spin waves

Conductivity

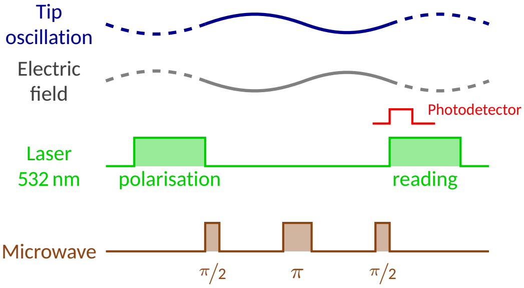
Temperature

Localized hot spots

Electric field sensing



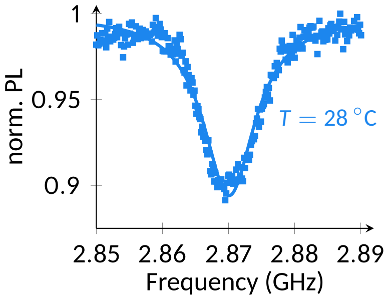
- Need to apply off-axis field to avoid that Zeeman effect dominates
- Electric susceptibilities rather small
  → spin echo sequences



Z. Qiu *et al.* *npj Quantum Information* 8 (2022)
W. S. Huxter *et al.* *Nature Physics* (2023)

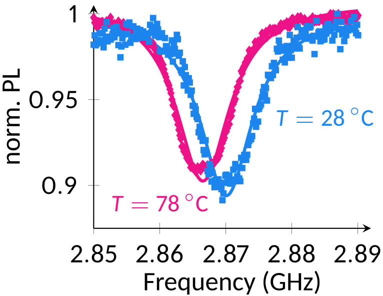
Temperature sensing

Crystal dilatation → Shift of the zero-field splitting



Temperature sensing

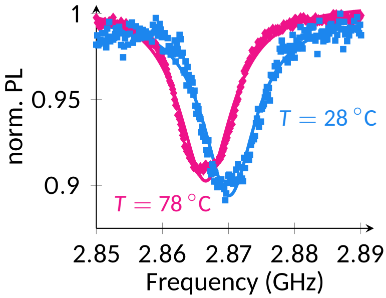
Crystal dilatation → Shift of the zero-field splitting

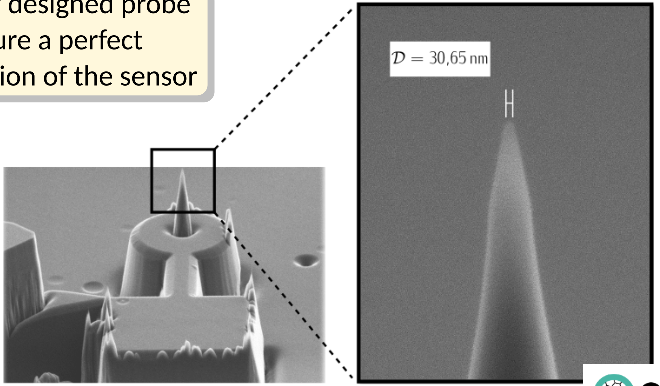


Temperature sensing

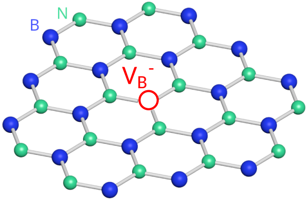
Crystal dilatation → Shift of the zero-field splitting

Specifically designed probe to ensure a perfect thermalization of the sensor

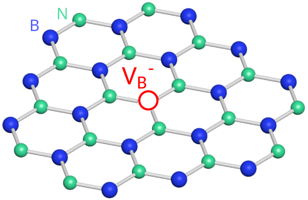


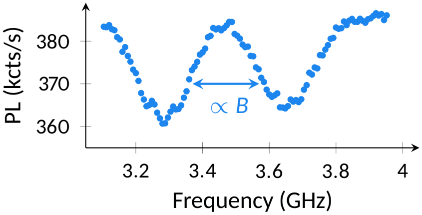


Magnetic field sensing with boron vacancies in h-BN

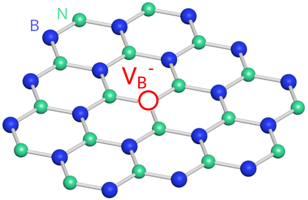


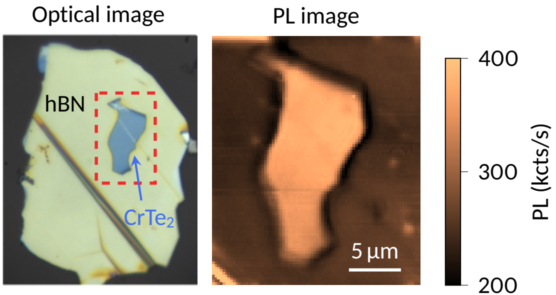
Magnetic field sensing with boron vacancies in h-BN

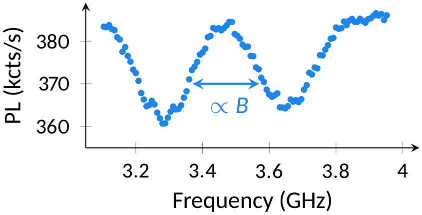




Magnetic field sensing with boron vacancies in h-BN

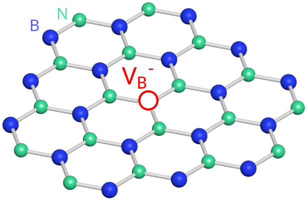


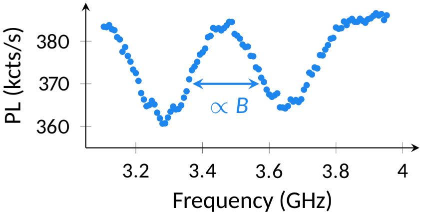


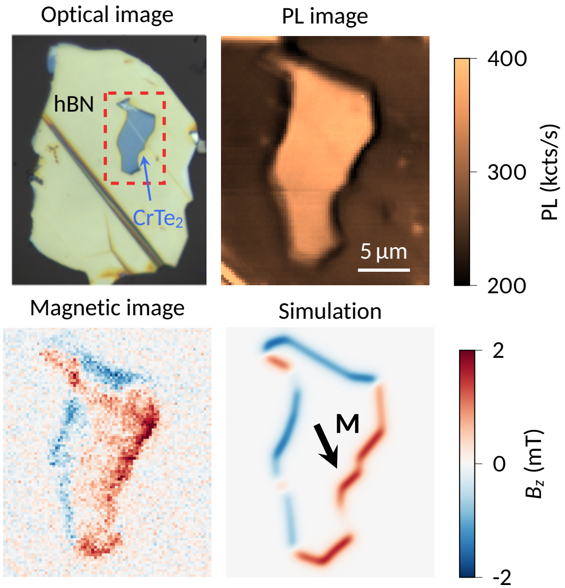


P. Kumar *et al.* *Phys. Rev. Appl.* 18 (2022), L061002

Magnetic field sensing with boron vacancies in h-BN

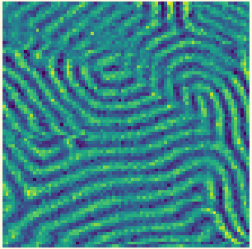






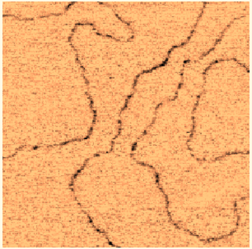
P. Kumar *et al.* *Phys. Rev. Appl.* 18 (2022), L061002

Summary



Imaging topological defects
in a multiferroic antiferromagnet

A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201



Detection of magnetic textures
through channelled spin waves

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

Further sensing possibilities

- Sensing electric field or temperature
- Other defects: boron vacancies in h-BN

P. Kumar *et al.* *Phys. Rev. Appl.* 18 (2022), L061002

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