Imaging magnetic textures with a quantum microscope

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Team Solid-State Quantum Technologies (S2QT)

CNRS and Université de Montpellier, Montpellier, France

WOLTE 15, June 6th 2022

slides available at https://magimag.eu

Nanoscale magnetic textures…

Domain wall

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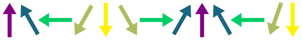
Spin spiral



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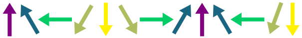
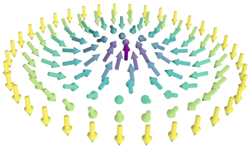


Skyrmion



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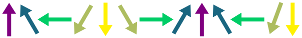

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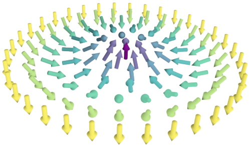
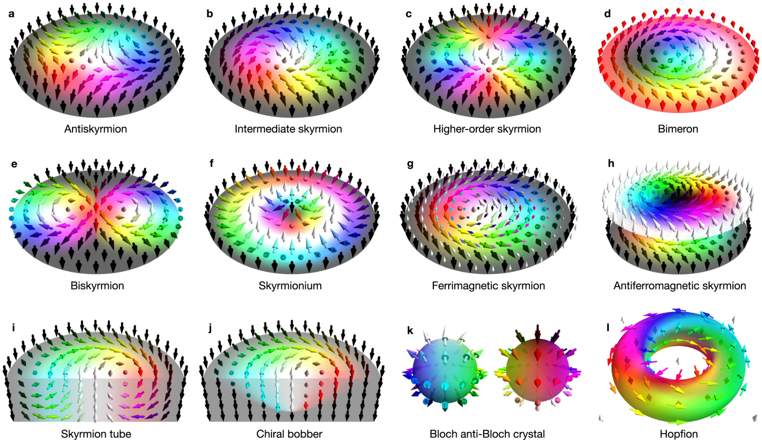
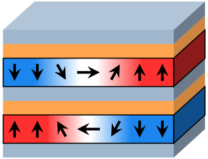




B. Göbel *et al.* *Phys. Rep.* 895 (2021)

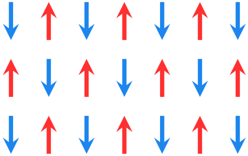
… in various hosting materials

Metallic multilayers



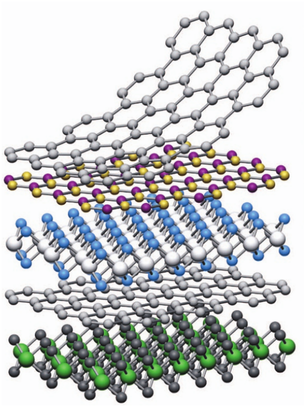
Well-controlled sputter growth
High tunability

Antiferromagnets



Robustness
Large switching speed

van der Waals heterostructures



Stacking of magnetic and non-magnetic layers with different properties

Multiferroics

Electric control of the magnetic state

$$\vec{P} \longleftrightarrow \vec{M}$$

The need for advanced magnetic microscopy tools

To study these magnetic objects and materials, we need **imaging techniques**.

Challenges:

- Nanoscale objects
- Low net magnetic moment
- Lack of stability under ambient conditions

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Techniques available:

- Magnetic force microscopy
- Scanning transmission X-ray microscopy
- Lorentz transmission electron microscopy
- Spin polarized scanning tunneling microscopy
- Scanning NV-center microscopy
- …

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Techniques available:

- Magnetic force microscopy → *not sensitive enough for antiferromagnets*
- Scanning transmission X-ray microscopy → *synchrotron, samples on membranes*
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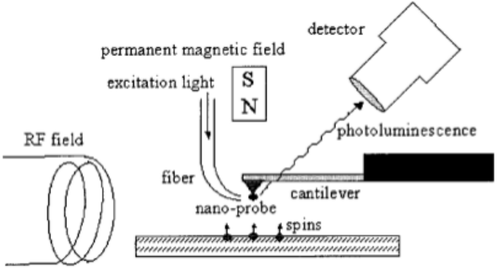
Scanning NV center microscopy

Principle: Combine a scanning probe microscope with a tiny quantum sensor



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

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

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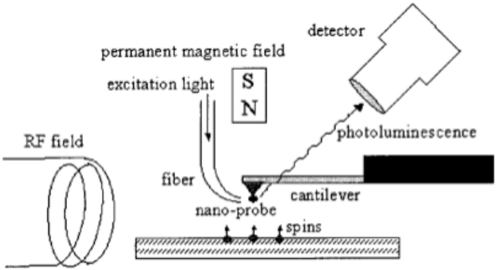

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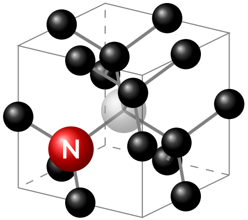
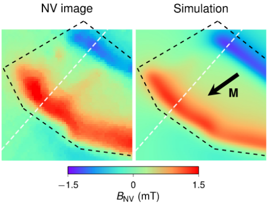
NV center in diamond

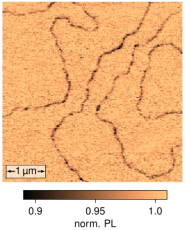
Outline

Principle of scanning NV microscopy

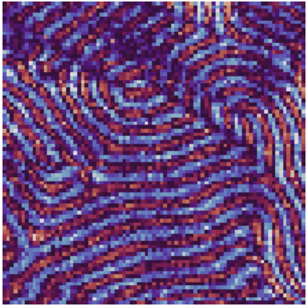


Some examples





Topological defects in a multiferroic



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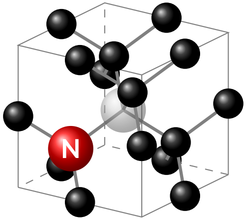

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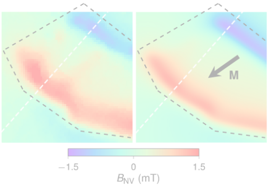

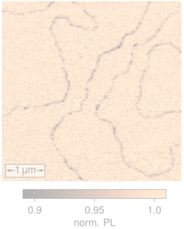

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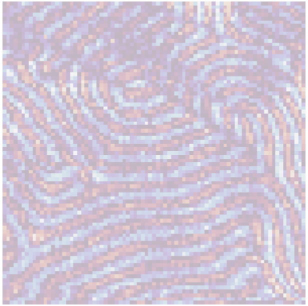
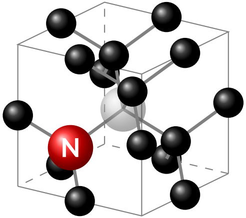


Quantum sensing of static magnetic fields



Nitrogen-Vacancy defect
in diamond

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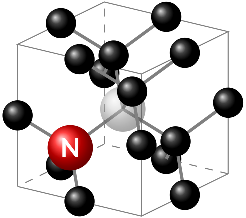

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- Ambient conditions

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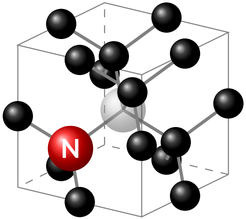

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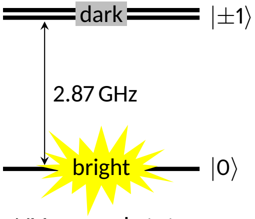

NV ground state
spin $S = 1$

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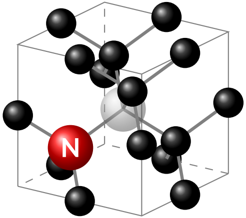

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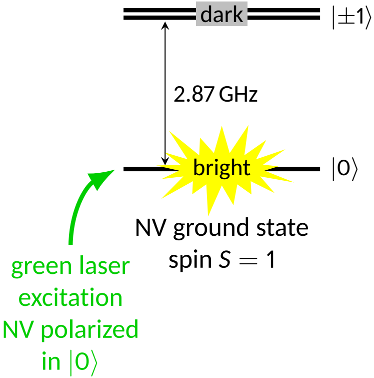

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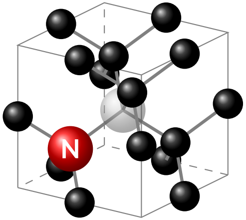

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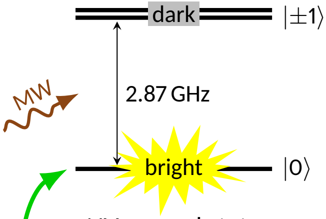

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green laser
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NV polarized
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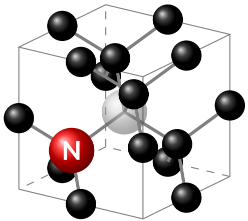

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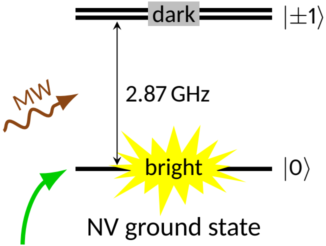

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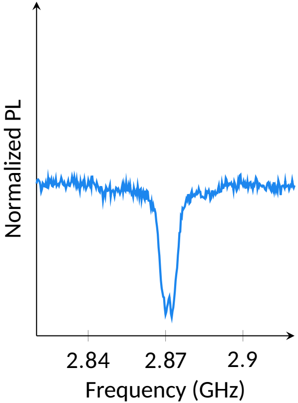

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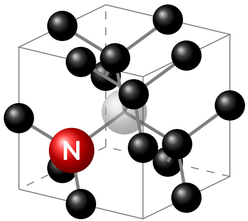

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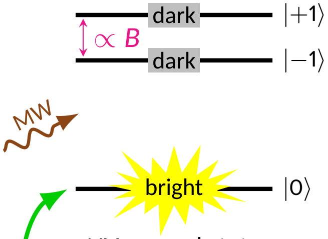

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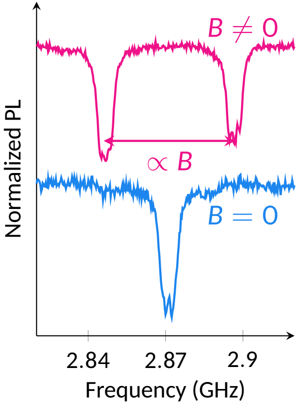

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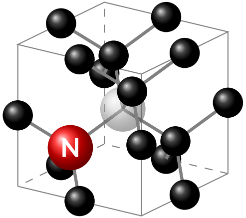

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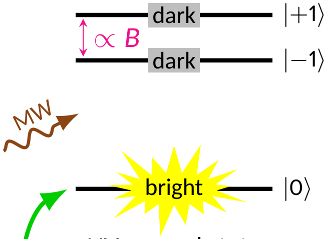

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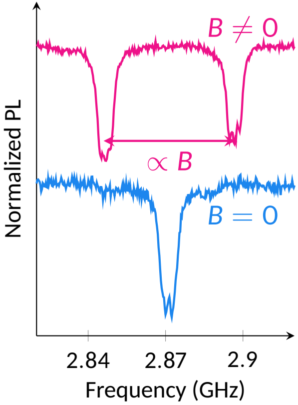
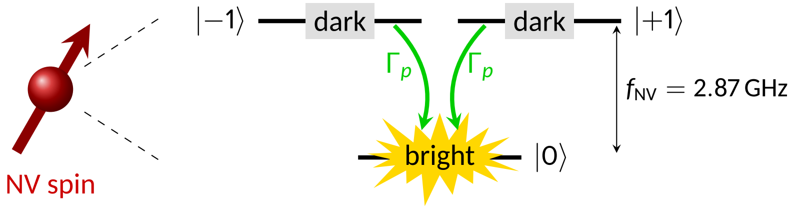


Non invasive technique

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

Detection of magnetic noise via relaxometry

Collaboration: C2N, Palaiseau (T. Devolder)



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

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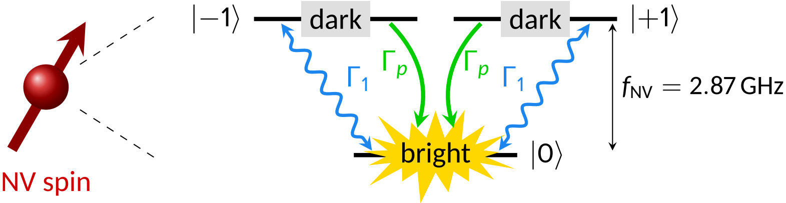

Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{\mathrm{NV}})$ magnetic field spectral density at the resonance frequency f_{NV}

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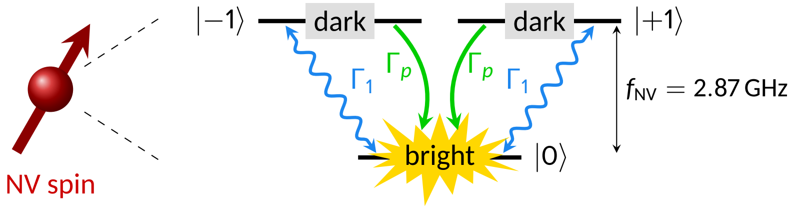

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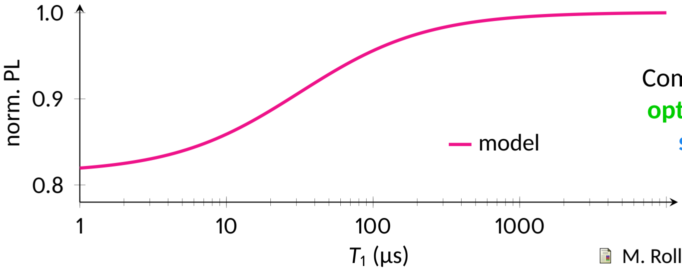

Competition between **optical pumping** and **spin relaxation**

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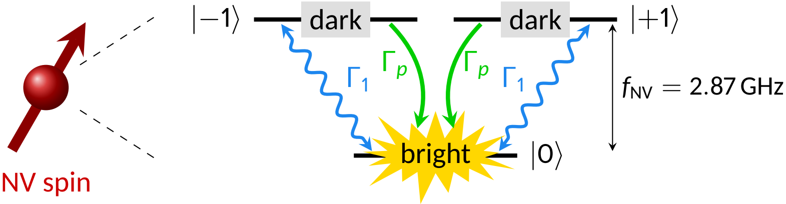

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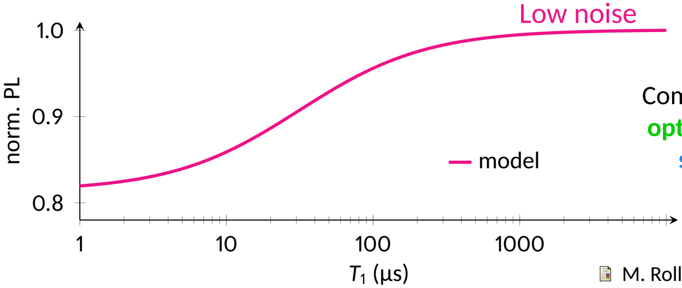

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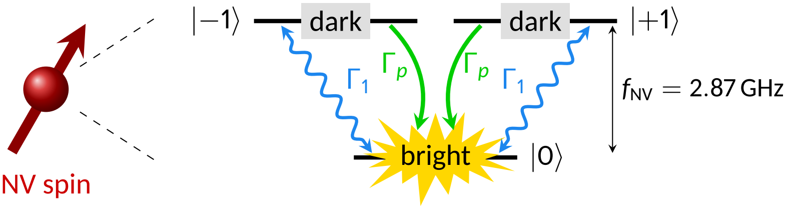

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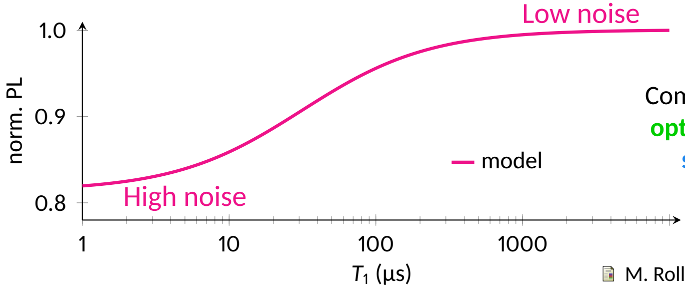

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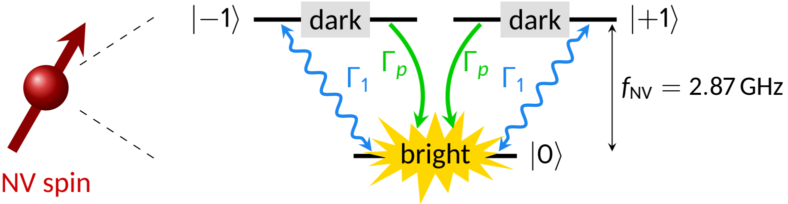

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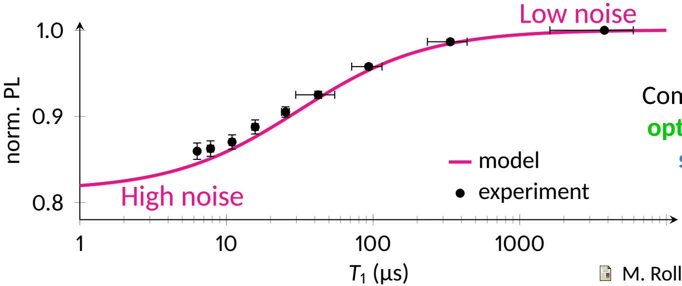

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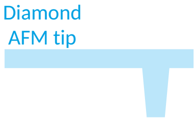
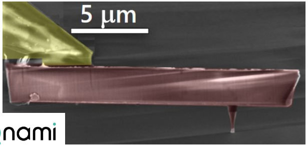
The scanning NV microscope setup





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

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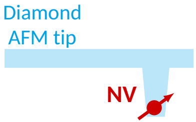

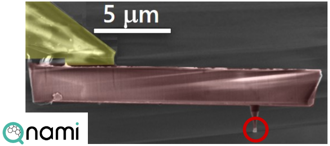

Implanted single
NV center

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

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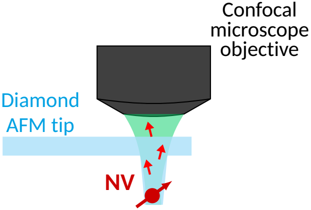

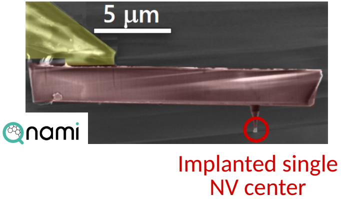

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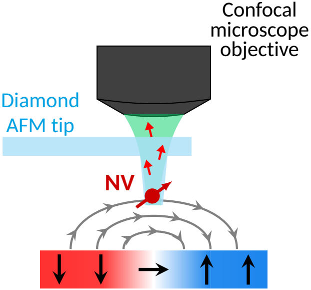

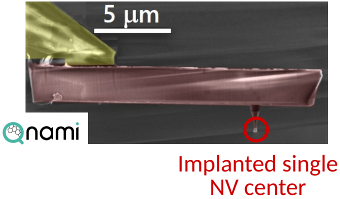

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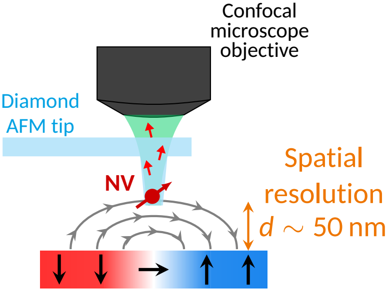

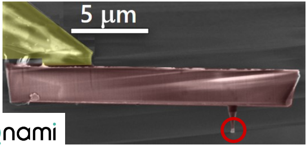

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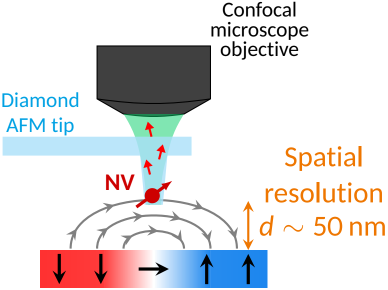
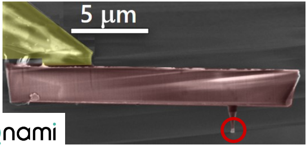
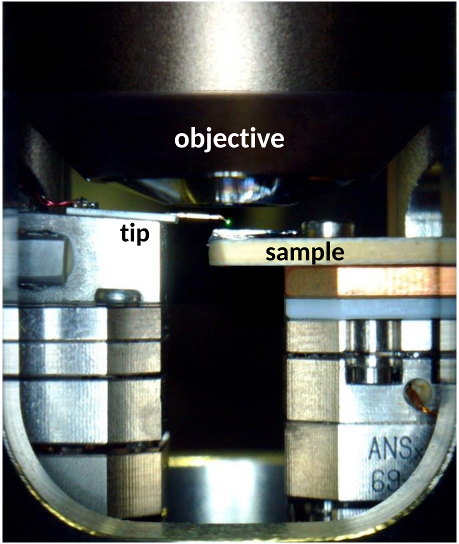




nami

Implanted single
NV center



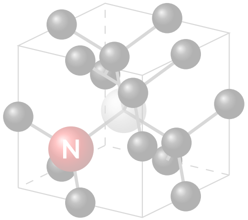
P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

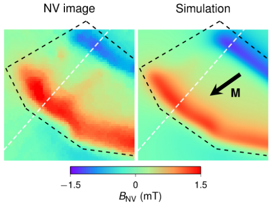
Outline

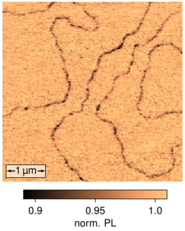
Principle of scanning NV microscopy

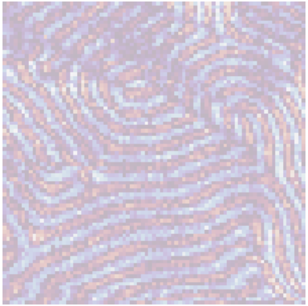
Some examples

Topological defects in a multiferroic









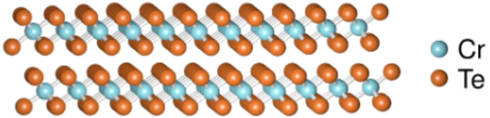
Measurement of the magnetization in flakes of a 2D ferromagnet

Collaboration: Institut Néel, Grenoble (A. Purbawati, J. Coraux, N. Rougemaille)

$CrTe_2$

2D ferromagnet at room temperature

with in-plane magnetization



F. Fabre *et al*. *Phys. Rev. Mat.* 5 (2021), 034008

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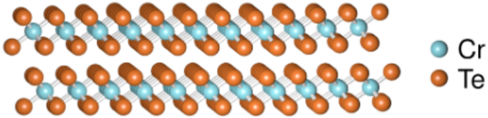

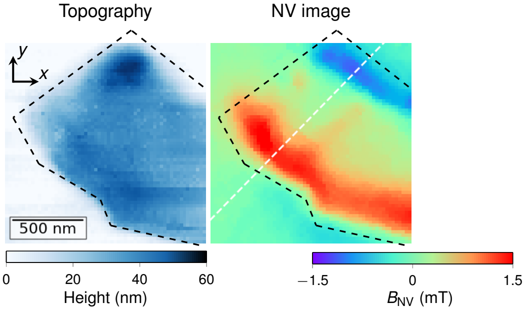

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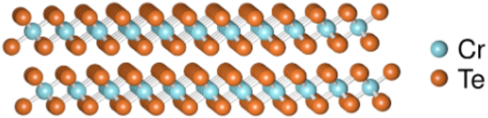

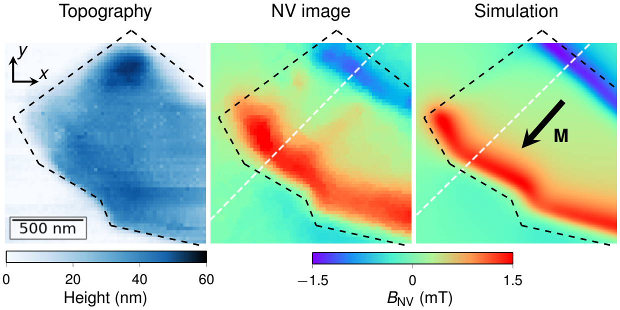

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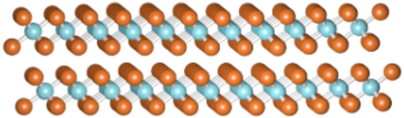
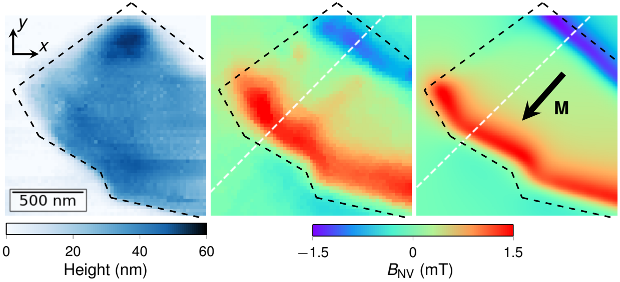
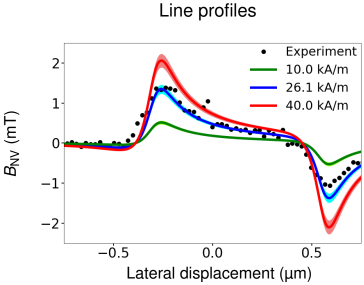


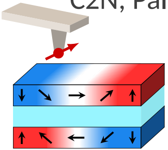




F. Fabre *et al.* *Phys. Rev. Mat.* 5 (2021), 034008

Detection of spin waves confined in domain walls

Collaborations: UMR CNRS/Thales, Palaiseau (W. Legrand, K.Bouzehouane, N. Reyren, V. Cros)
C2N, Palaiseau (J.-P. Adam, J.-V. Kim)



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

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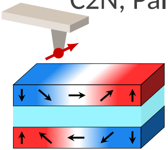
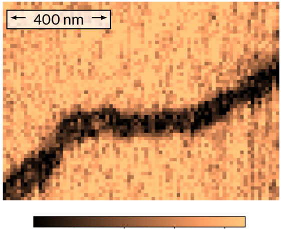


W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34

Domain wall



PL norm.

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

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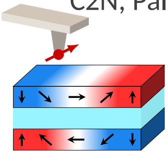
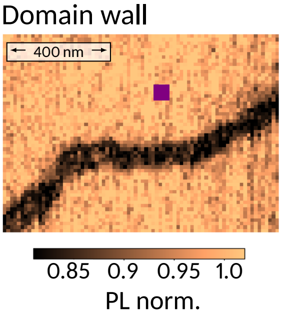
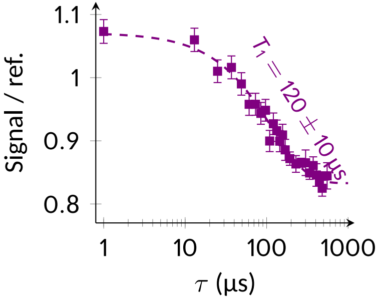


W. Legrand *et al.* *Nat. Mat.* 19 (2020), 34





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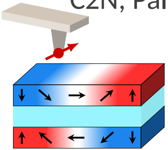

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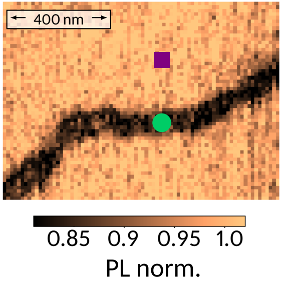

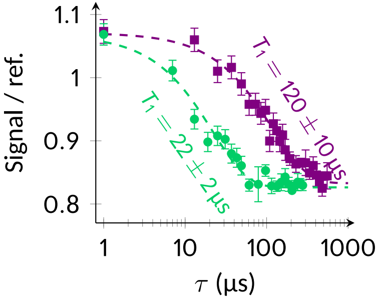

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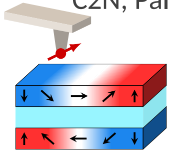

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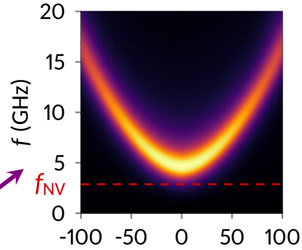
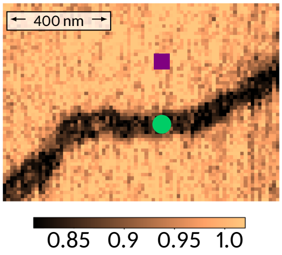
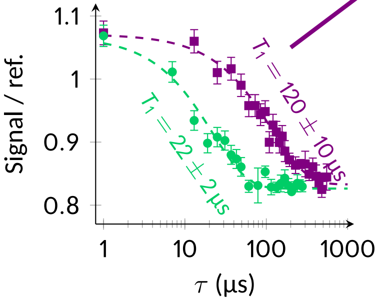
Domain wall detection through the enhancement of the NV spin relaxation by confined spin waves



Domain wall





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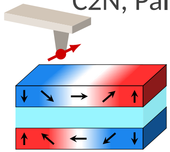

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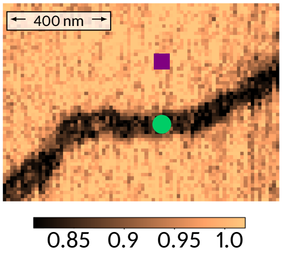
Domain wall



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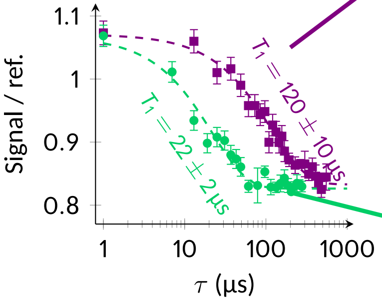
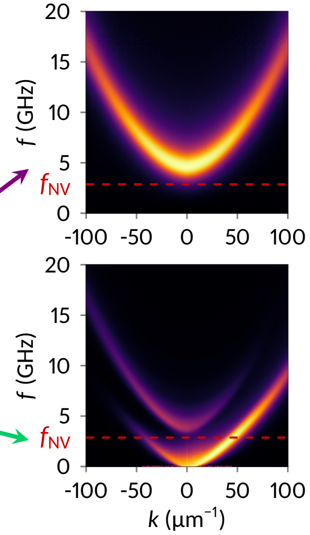
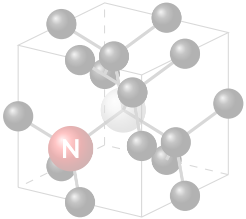




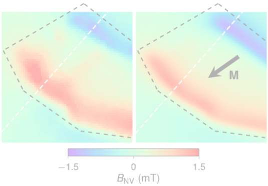
A. Finco *et al.* *Nat. Commun.* 12 (2021), 767

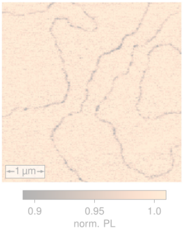
Outline

Principle of scanning NV microscopy

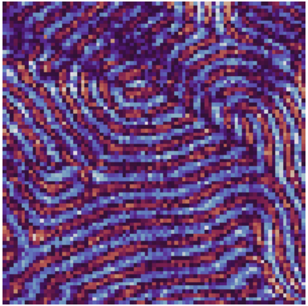


Some examples



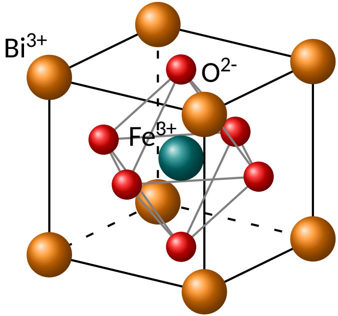


Topological defects in a multiferroic



Bismuth ferrite, a room-temperature multiferroic

Electric polarization



Paraelectric phase (T>1100 K)

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

Bismuth ferrite, a room-temperature multiferroic

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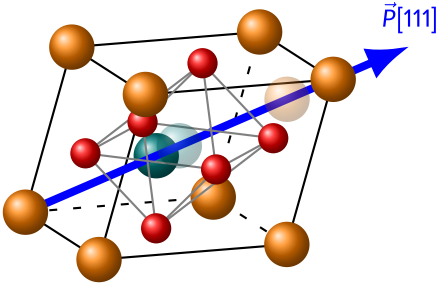

Ferroelectric phase (T<1100 K)

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

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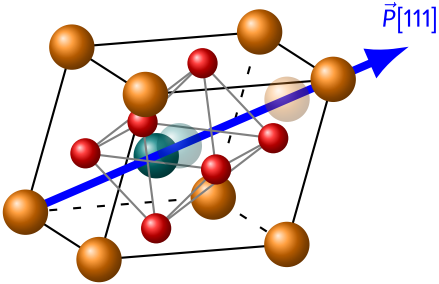

Ferroelectric phase (T<1100 K)

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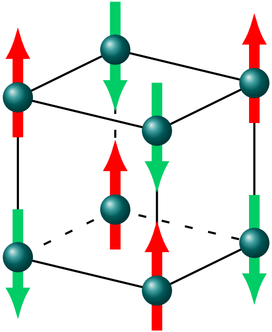
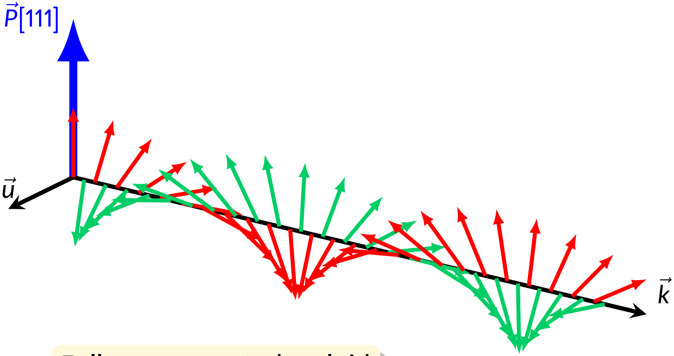
Magnetism



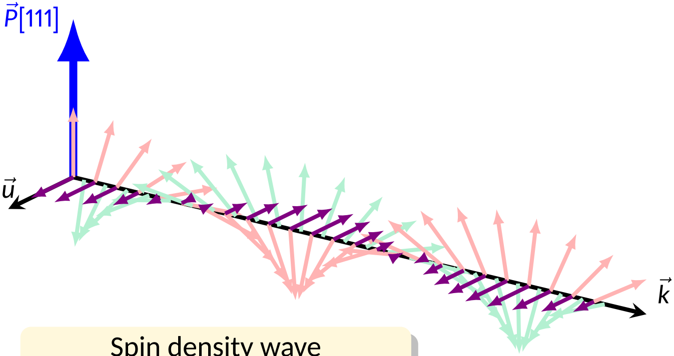
G-type antiferromagnetic phase ($T_N = 643\,K$)

The effects of magnetoelectric coupling in $BiFeO_3$



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

The effects of magnetoelectric coupling in $BiFeO_3$



Spin density wave
Weak uncompensated moment
→ **Small stray field**

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

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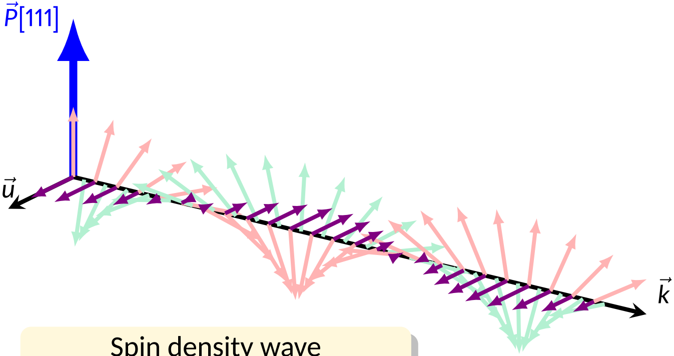

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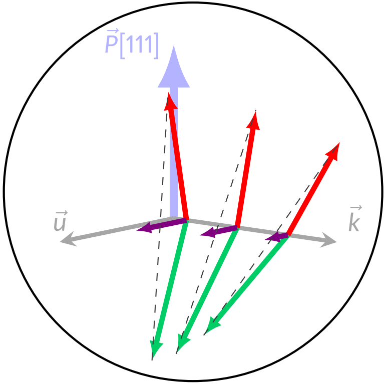
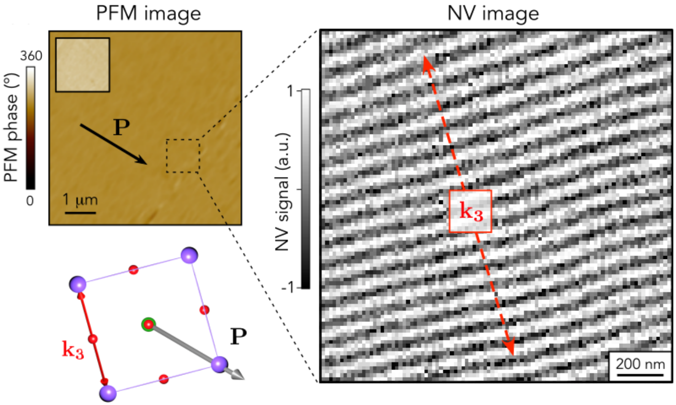


M. Ramazanoglu *et al.* *Phys. Rev. Lett.* 107 (2011), 207206

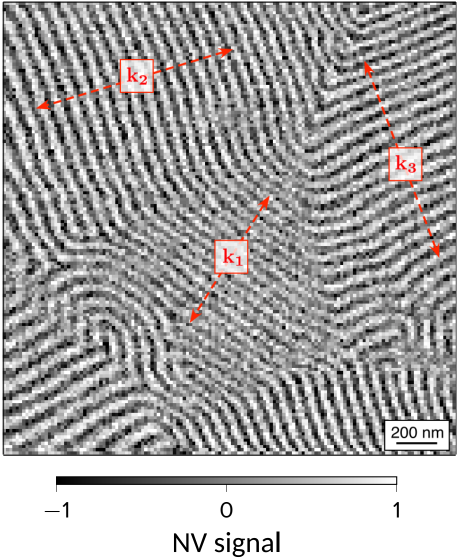
Imaging the cycloidal modulation in a bulk $BiFeO_3$ crystal

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



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

Rotation of the cycloid propagation direction measured in real space…



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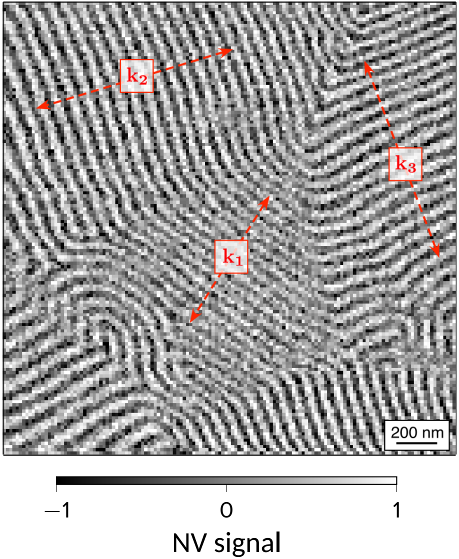
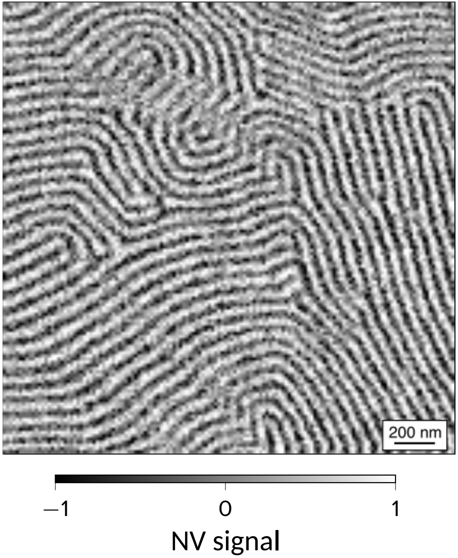
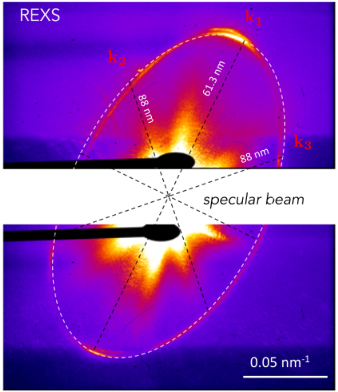




… and in reciprocal space

Resonant X-ray scattering



SOLEIL SYNCHROTRON
N. Jaouen

… and in reciprocal space

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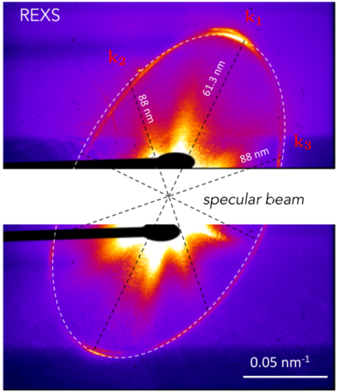
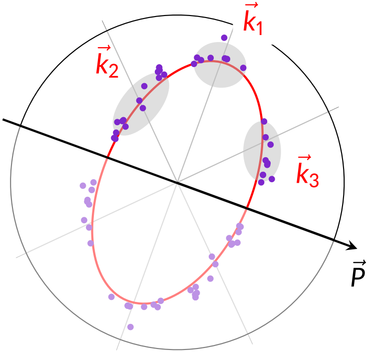


Polar plot of $\frac{2\pi}{\lambda}$ vs $\vec{k}$ direction



SOLEIL SYNCHROTRON
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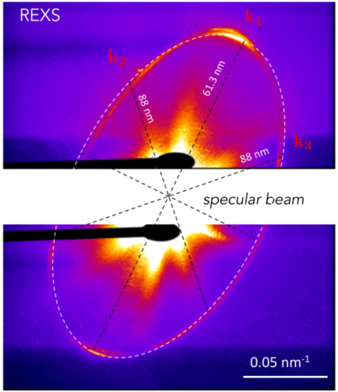

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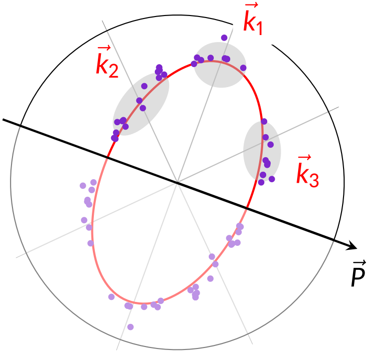

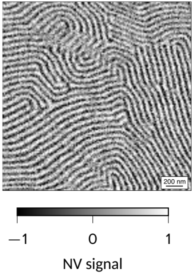

N. Jaouen

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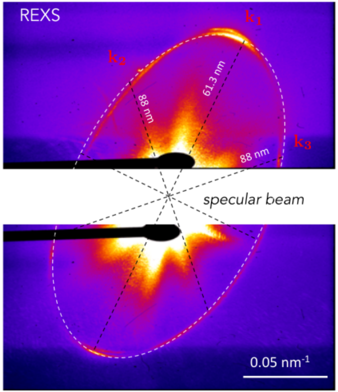

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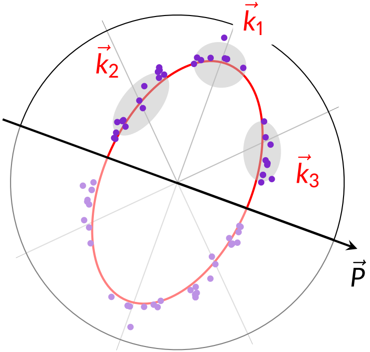

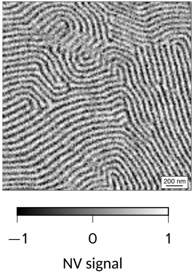

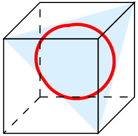

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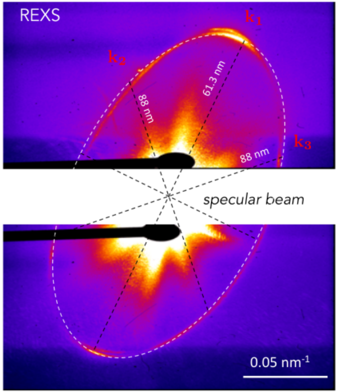
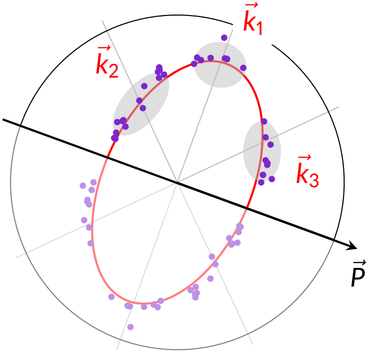
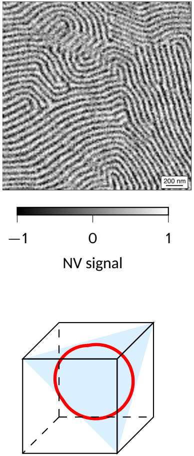


Polar plot of $\frac{2\pi}{\lambda}$ vs $\vec{k}$ direction





SOLEIL SYNCHROTRON
N. Jaouen

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

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

Topological defects in lamellar systems

General ordered medium

Order parameter

non-uniform, smoothly varying in space

N. D. Mermin. *Rev. Mod. Phys.* 51 (1979), 591

Topological defects in lamellar systems

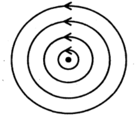
General ordered medium		Lamellar system
Order parameter	→	Wavevector $\vec{k}$ of the periodic modulation
non-uniform, smoothly varying in space	→	with a rotating direction

N. D. Mermin. *Rev. Mod. Phys.* 51 (1979), 591

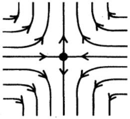
Topological defects in lamellar systems

General ordered medium		Lamellar system
Order parameter	→	Wavevector $\vec{k}$ of the periodic modulation
non-uniform, smoothly varying in space	→	with a rotating direction

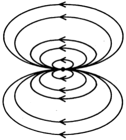
except at singular regions of lower dimensionality → **topological defects**



disclination
winding number = 1



disclination
winding number = -1

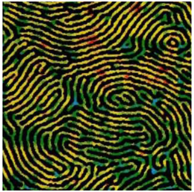


disclination
winding number = 2

N. D. Mermin. *Rev. Mod. Phys.* 51 (1979), 591

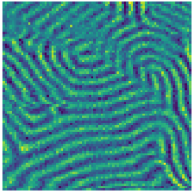
Universal patterns in lamellar systems

Block copolymer
Period 40 nm



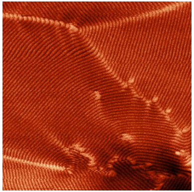
T. A. Witten. *Phys. Today* 43 (1990), 21

$BiFeO_3$ magnetic cycloid
Period 64 nm



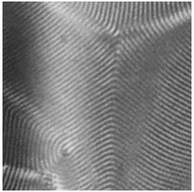
A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

FeGe magnetic helix
Period 70 nm



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

Liquid crystals
Period 800 nm

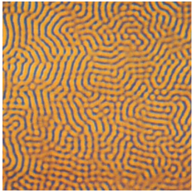


Y. Bouligand. *Dislocations in solids* (1983), Chap. 23

Ferrimagnetic garnet
Period 8 μm

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

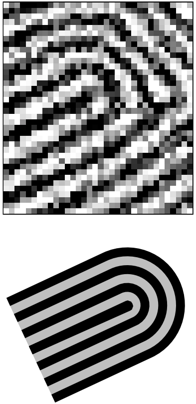
Fluid diffusion
Period 250 μm



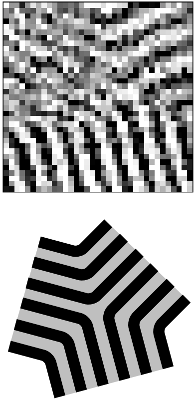
Q. Ouyang *et al.* *Chaos* 1 (1991), 411

Identification of these topological defects in $BiFeO_3$

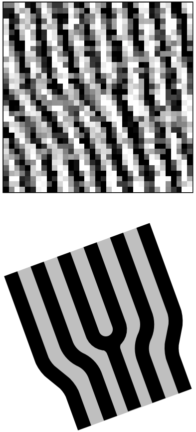
$+\pi$-disclination



$-\pi$-disclination



Edge dislocation



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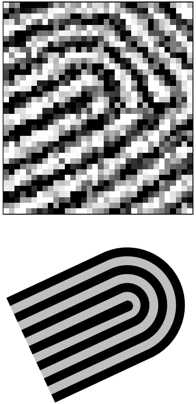
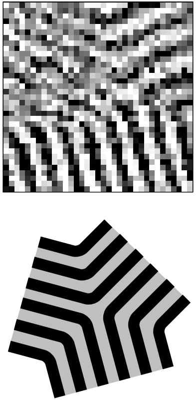
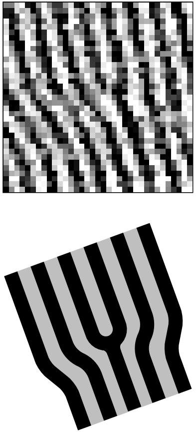


$-\pi$-disclination



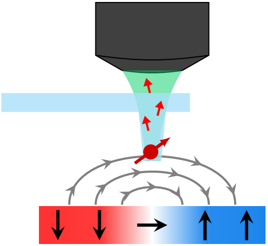
Edge dislocation



Perspective: electrical control?

Summary

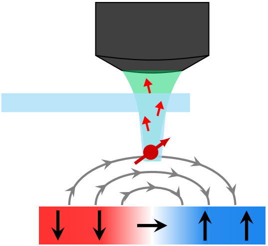
NV center magnetometry

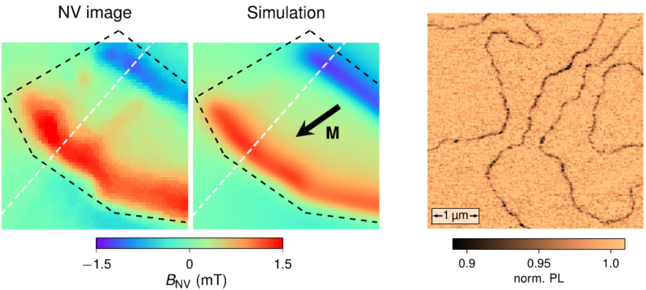


- highly sensitive
- nanoscale
- quantitative
- non-perturbative
- versatile

Summary

NV center magnetometry





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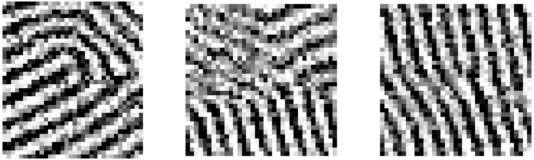

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