MA 11.1: Imaging topological defects in a non-collinear antiferromagnet

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DPG SKM 2023, March 27th 2023, Dresden

slides available at https://magimag.eu

Acknowledgments

L2C, Montpellier
Angela Haykal, Pawan Kumar, Vincent Jacques

UMR CNRS/Thales, Palaiseau
Pauline Dufour, Vincent Garcia, Stéphane Fusil

SPEC, CEA Gif-sur-Yvette
Anne Forget, Dorothée Colson, Jean-Yves Chauleau, Michel Viret

Synchrotron Soleil
Nicolas Jaouen

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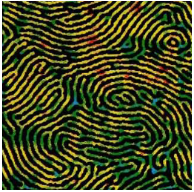
anr agence nationale de la recherche

TSAR

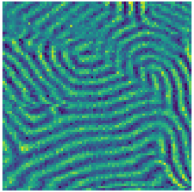
Universal patterns in lamellar systems

Block copolymer
Period 40 nm



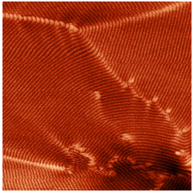
T. A. Witten. *Phys. Today* 43 (1990), 21

$BiFeO_3$ magnetic cycloid
Period 64 nm



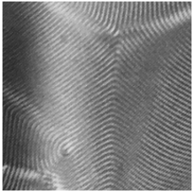
A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

FeGe magnetic helix
Period 70 nm



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

Liquid crystals
Period 800 nm

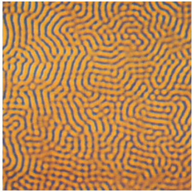


Y. Bouligand. *Dislocations in solids* (1983), Chap. 23

Ferrimagnetic garnet
Period 8 μm

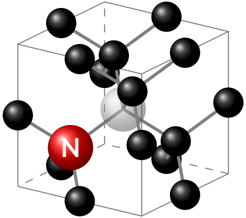
M. Seul *et al.* *Phys. Rev. A* 46 (1992), 7519

Fluid diffusion
Period 250 μm



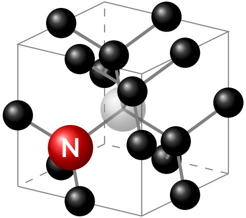
Q. Ouyang *et al.* *Chaos* 1 (1991), 411

NV centers for magnetic imaging



Defect in diamond

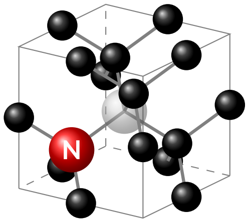
NV centers for magnetic imaging



Defect in diamond

- Optical manipulation and reading
- Ambient conditions

NV centers for magnetic imaging



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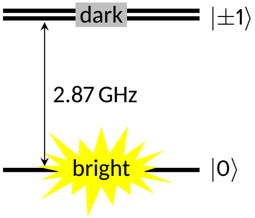
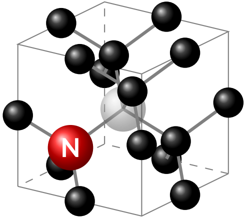
Spin-dependent fluorescence



NV ground state spin $S = 1$

NV centers for magnetic imaging



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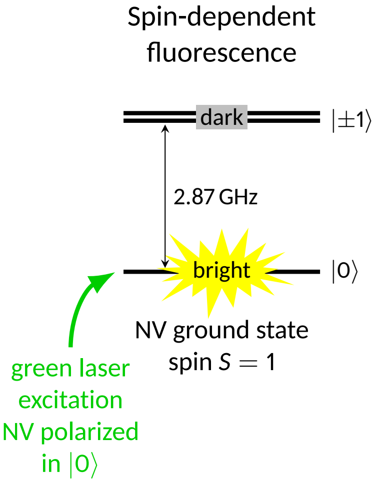

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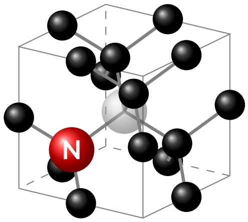

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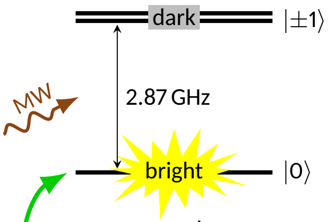
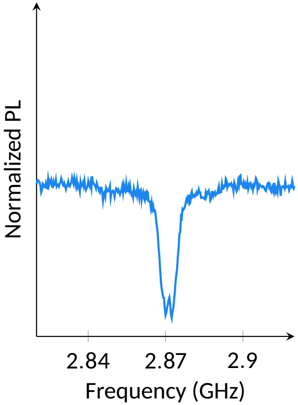


green laser excitation
NV polarized in $|0\rangle$

NV ground state
spin $S = 1$



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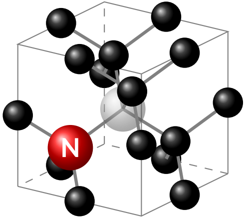

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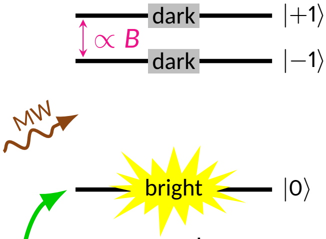

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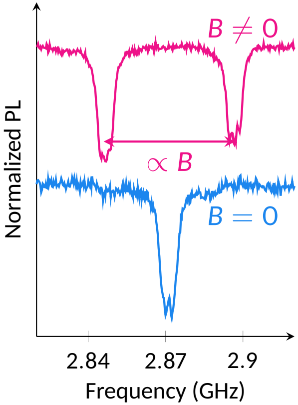

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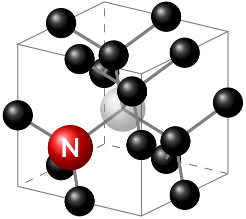

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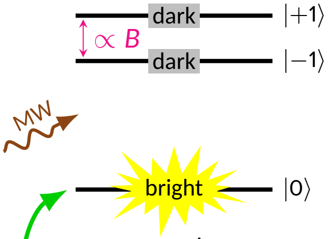

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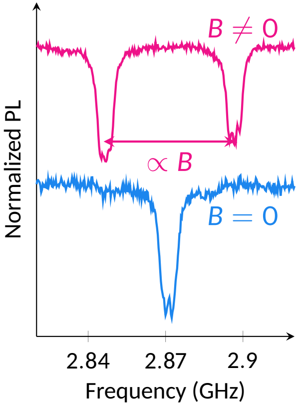
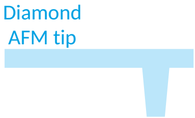
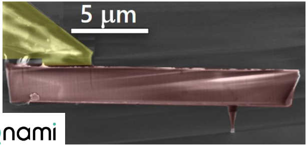


Sensibility: a few $\mu T/\sqrt{Hz}$

The scanning NV microscope setup





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

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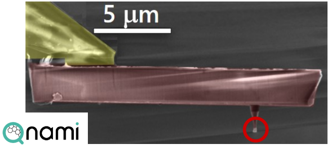

P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320

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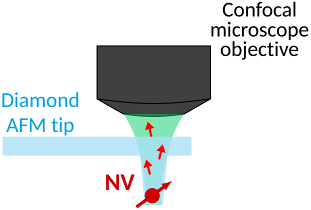

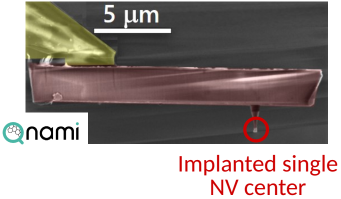

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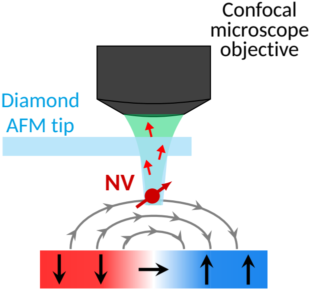

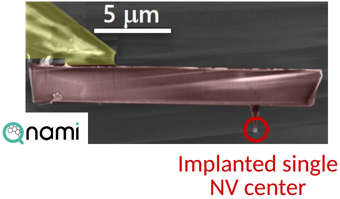

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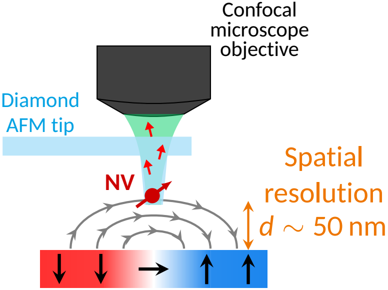

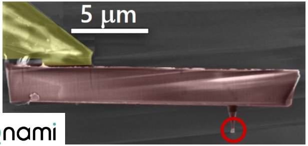

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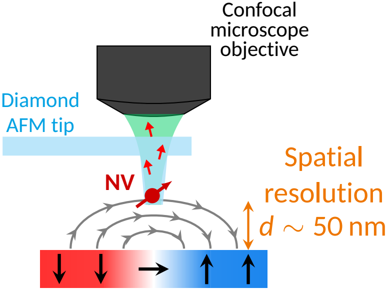
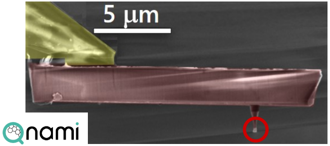
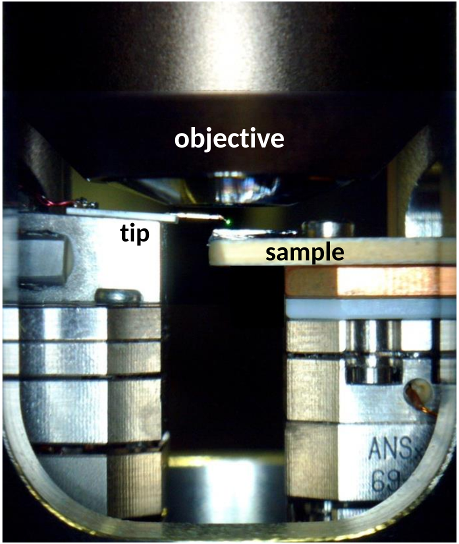




Implanted single
NV center



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

Application to nanoscale magnetic texture imaging

Quantitative

Non-perturbative

Highly sensitive

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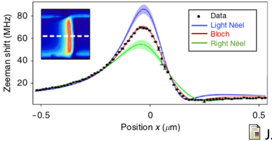
Determination of domain wall chirality



J.-P. Tetienne *et al.* *Nat Commun.* 6 (2015), 6733

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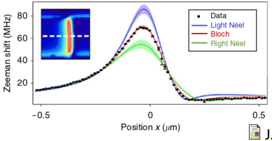

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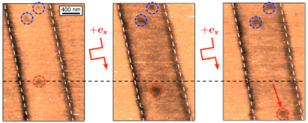
Imaging of current-induced skyrmion movement



W. Akhtar *et al.* *Phys. Rev. Appl.* 11 (2019), 034066

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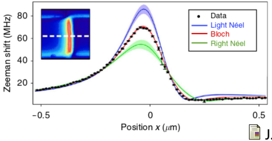

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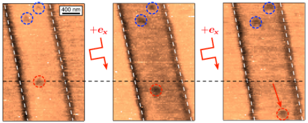

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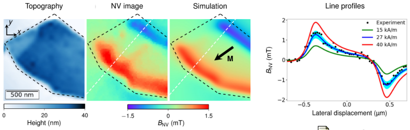
Quantitative characterization of 2D ferromagnets



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

Application to nanoscale magnetic texture imaging

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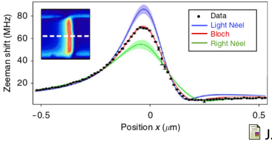
Highly sensitive

Great tool to image antiferromagnets!

Determination of domain wall chirality



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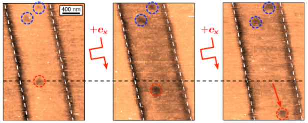

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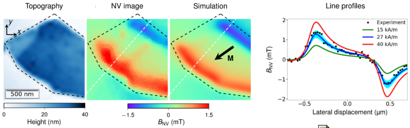

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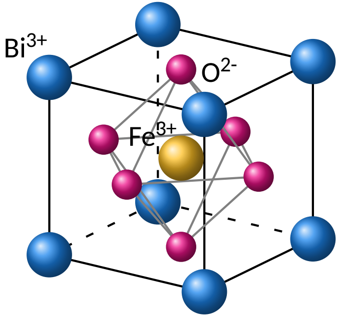
Bismuth ferrite, a room-temperature multiferroic

Electric polarization



Paraelectric phase (T>1100 K)

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

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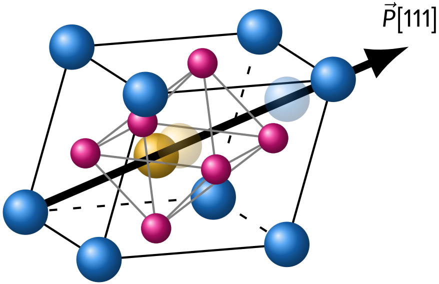

Ferroelectric phase (T<1100 K)

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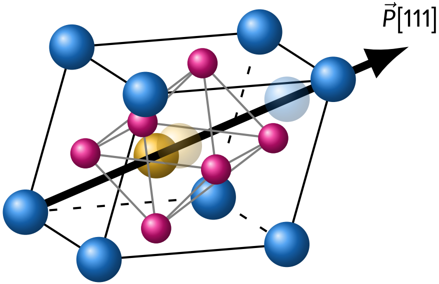
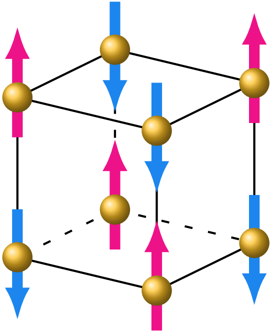


Ferroelectric phase (T<1100 K)

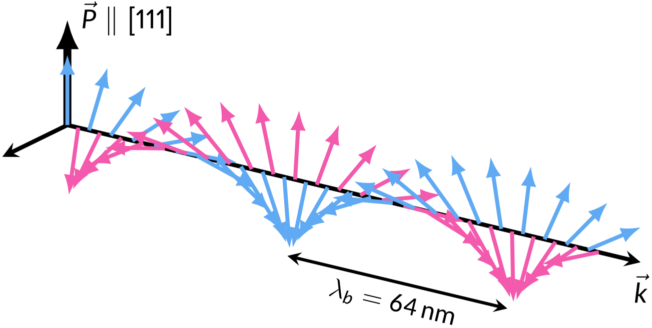
Magnetism



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

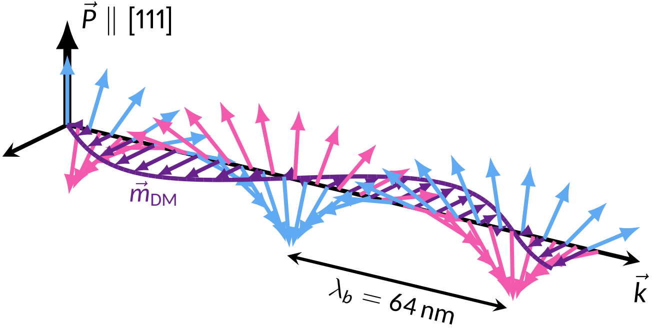
G. Catalan *et al*. *Adv. Mater.* 21 (2009), 2463–2485

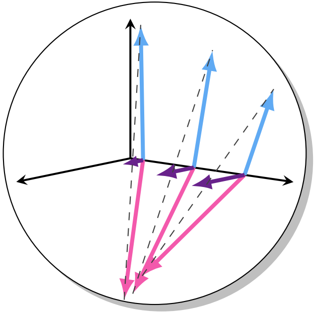
The effects of magnetoelectric coupling in $BiFeO_3$



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

The effects of magnetoelectric coupling in $BiFeO_3$

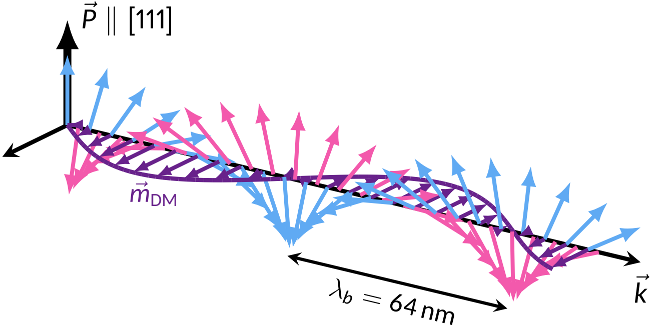


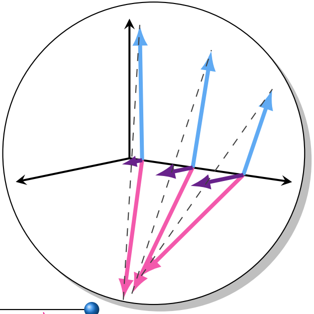


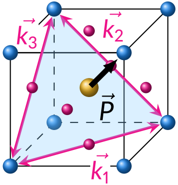
Spin density wave
Weak uncompensated moment
→ **Small stray field**

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

The effects of magnetoelectric coupling in $BiFeO_3$







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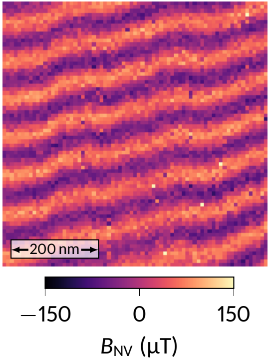
M. Ramazanoglu *et al.* *Phys. Rev. Lett.* 107 (2011), 207206

Quantitative analysis of the cycloid in bulk single crystal

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



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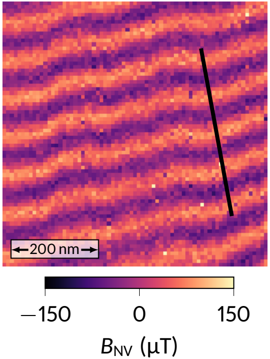

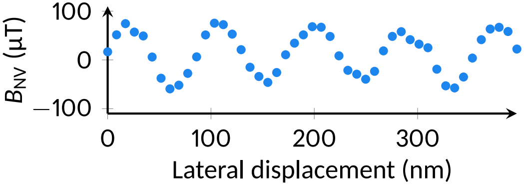

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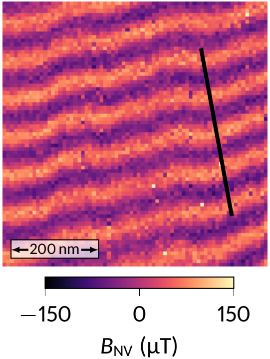

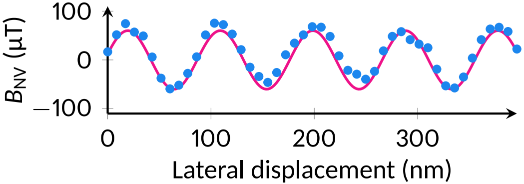

$$\begin{cases} B_x = 0 \\ B_y = -\dfrac{A}{\sqrt{2}}\left(\mathrm{Re}\{S\} - \mathrm{Im}\{S\}\right) \\ B_z = \sqrt{2}\, A\, \mathrm{Re}\{S\} \end{cases} \quad \text{with} \quad \begin{cases} \mathrm{A} = \dfrac{\mu_0 m_{\mathrm{DM}}}{\sqrt{3}\, a^3} \sinh\left(\dfrac{ka}{2\sqrt{2}}\right) \\ \mathrm{S}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

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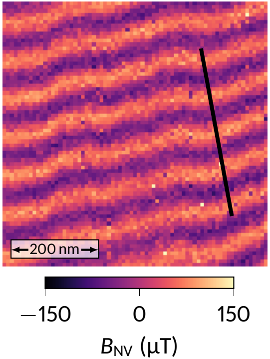
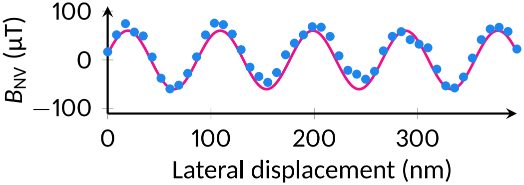
CEA SPEC, Gif-sur-Yvette (J.-Y. Chauleau, M. Viret)



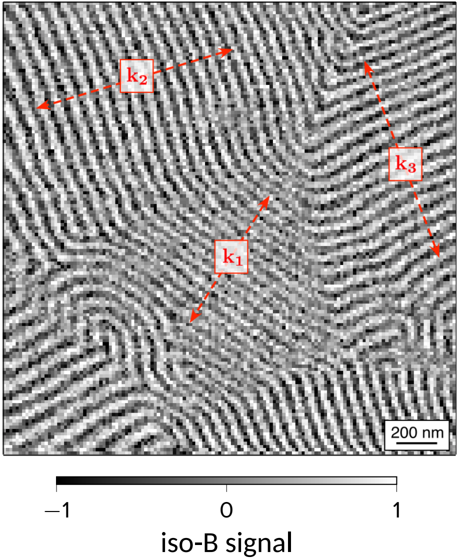


$$m_{DM} = 0.09 \pm 0.03\ \mu_B$$

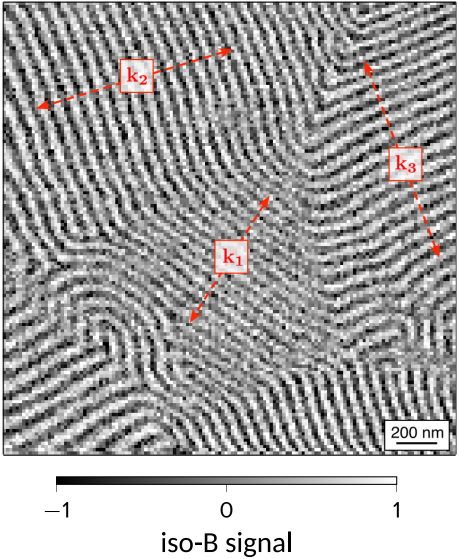
M. Ramazanoglu *et al.* *Phys. Rev. Lett.* 107 (2011), 207206

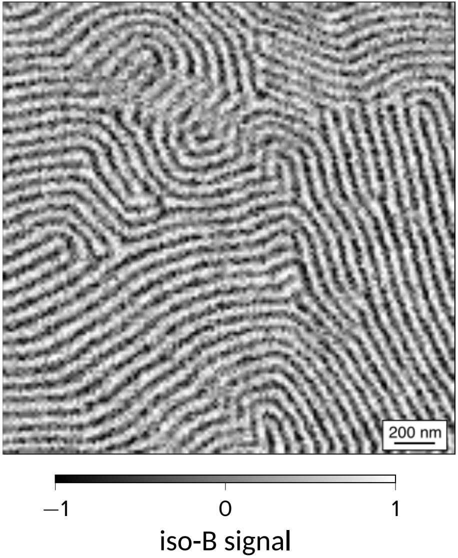
$$\begin{cases} B_x = 0 \\ B_y = -\dfrac{A}{\sqrt{2}}\left(\mathrm{Re}\{S\} - \mathrm{Im}\{S\}\right) \\ B_z = \sqrt{2}\,A\,\mathrm{Re}\{S\} \end{cases} \quad \text{with} \quad \begin{cases} A = \dfrac{\mu_0 m_{DM}}{\sqrt{3}\,a^3}\sinh\left(\dfrac{ka}{2\sqrt{2}}\right) \\ S = e^{-kz/\sqrt{2}} e^{ik(y-z)/\sqrt{2}}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

Rotation of the cycloid propagation direction measured in real space...



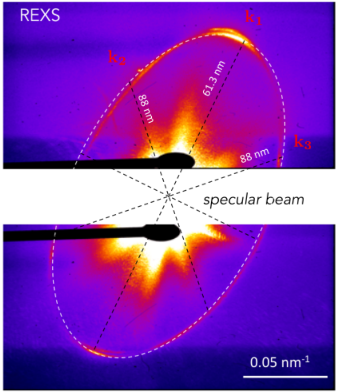
Rotation of the cycloid propagation direction measured in real space...





… and in reciprocal space

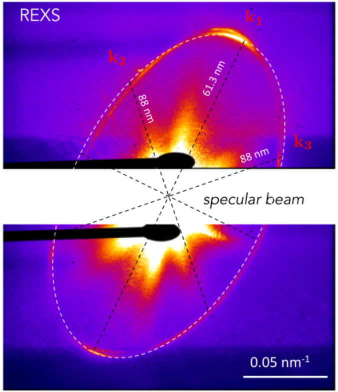
Resonant X-ray scattering



SOLEIL SYNCHROTRON
N. Jaouen

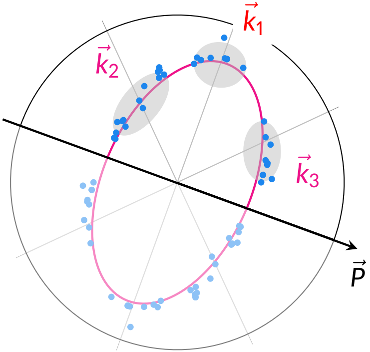
... and in reciprocal space

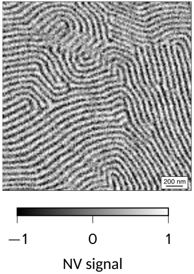
Resonant X-ray scattering



SOLEIL SYNCHROTRON
N. Jaouen

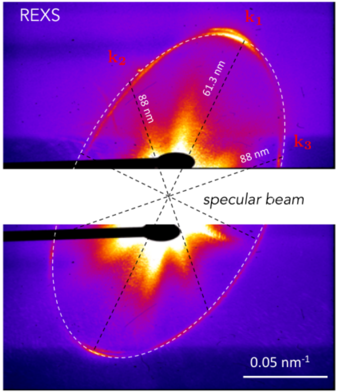
Polar plot of $\frac{2\pi}{\lambda}$ vs $\vec{k}$ direction





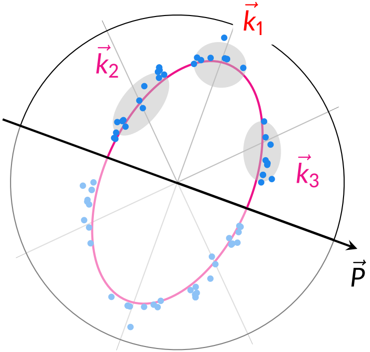
… and in reciprocal space

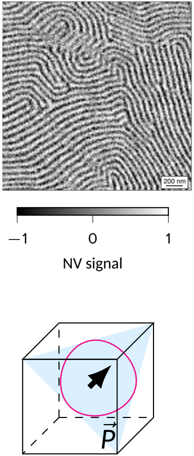
Resonant X-ray scattering



SOLEIL SYNCHROTRON
N. Jaouen

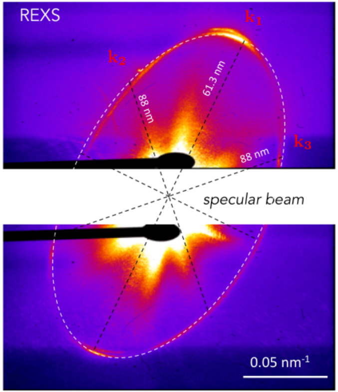
Polar plot of $\frac{2\pi}{\lambda}$ vs $\vec{k}$ direction



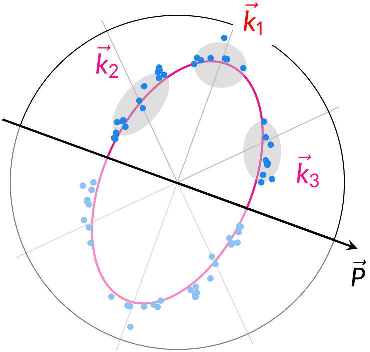


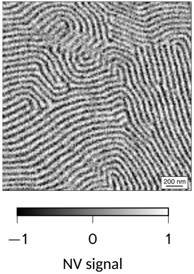
… and in reciprocal space

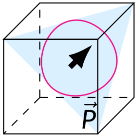
Resonant X-ray scattering



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







SOLEIL SYNCHROTRON

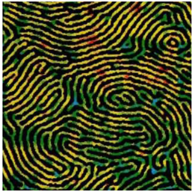
N. Jaouen

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

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

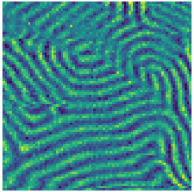
Universal patterns in lamellar systems

Block copolymer
Period 40 nm



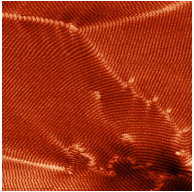
T. A. Witten. *Phys. Today* 43 (1990), 21

$BiFeO_3$ magnetic cycloid
Period 64 nm



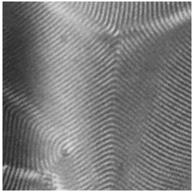
A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

FeGe magnetic helix
Period 70 nm



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

Liquid crystals
Period 800 nm

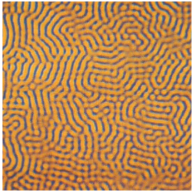


Y. Bouligand. *Dislocations in solids* (1983), Chap. 23

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

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

Order parameter

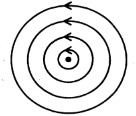
non-uniform, smoothly varying in space

Lamellar system

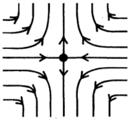
Wavevector $\vec{k}$ of the periodic modulation

with a rotating direction

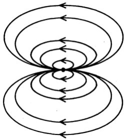
except at singular regions of lower dimensionality → **topological defects**



disclination
winding number = 1



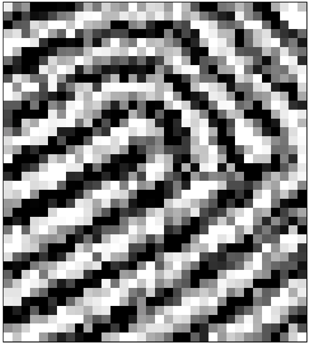
disclination
winding number = -1

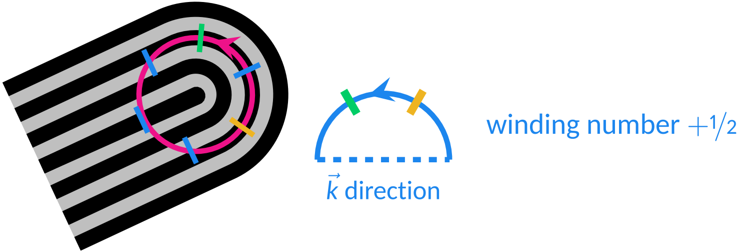


disclination
winding number = 2

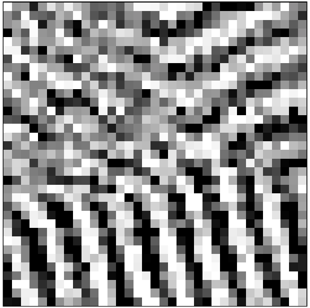
N. D. Mermin. *Rev. Mod. Phys.* 51 (1979), 591

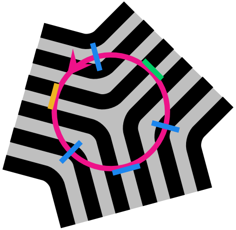
$+\pi$-disclination

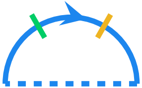




$-\pi$-disclination



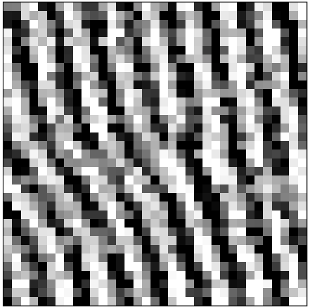


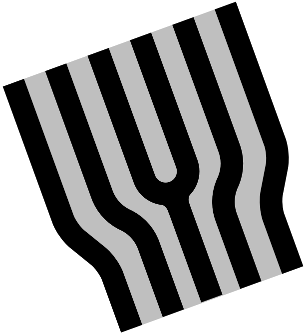


$\vec{k}$ direction

winding number $-1/2$

Edge dislocation



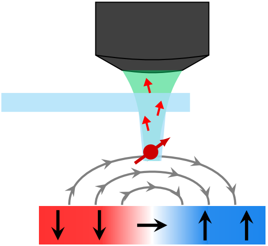


Combination of
$+\pi$- and $-\pi$-disclinations

winding number 0

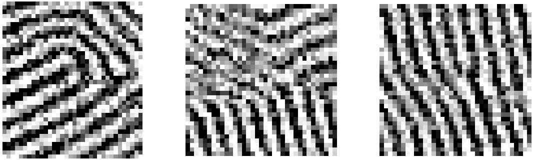
Summary

NV center magnetometry



- highly sensitive
- nanoscale
- quantitative
- non-perturbative

Topological defects in multiferroic $BiFeO_3$



Towards electric control?

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

The team S2QT in Montpellier

We are looking for students and postdocs!