# Imaging topological defects in a non-collinear antiferromagnet

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MMM 2022, Minneapolis

slides available at https://magimag.eu

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“They are extremely interesting from the theoretical viewpoint, but do not seem to have any applications.”

Louis Néel, *Nobel lecture* (1970)

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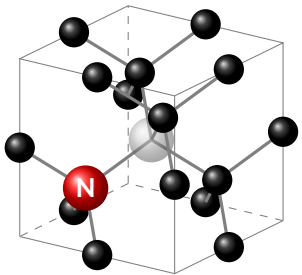
**Imaging antiferromagnets remains complicated!**

- S.-W. Cheong *et al.* *npj Quantum Materials* 5 (2020)

# Our magnetic field sensor: the NV center in diamond




Nitrogen-Vacancy defect

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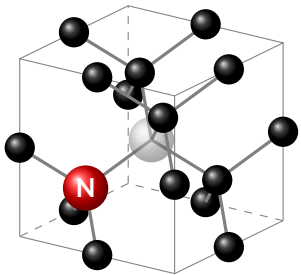


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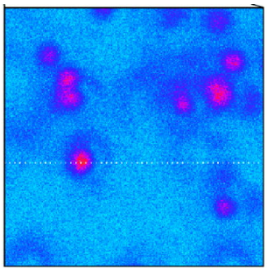
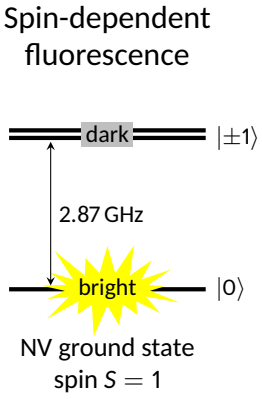


- Photostable defect
- Spin S=1
- Individual defects can be isolated/implanted
- Ambient conditions

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

# Principle of the magnetic field measurement



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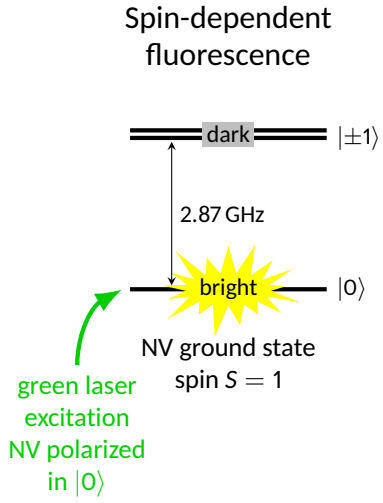

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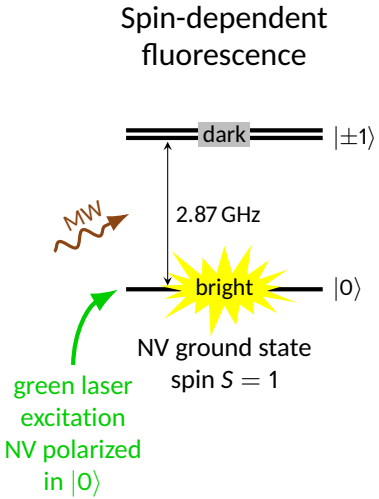


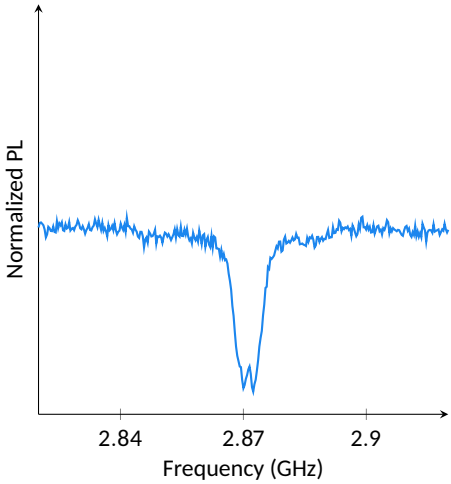

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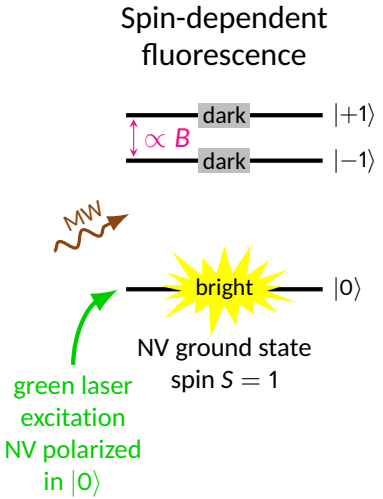


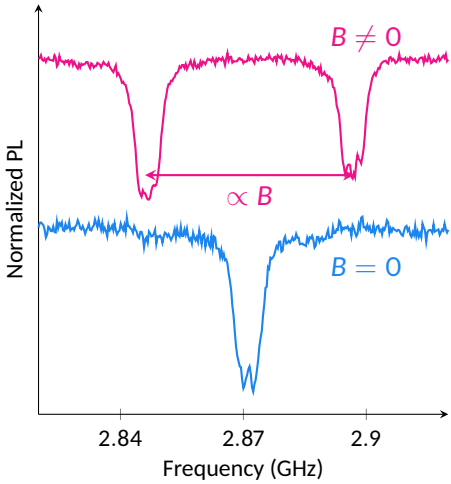

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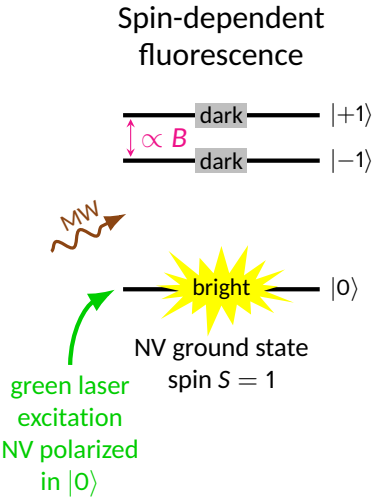
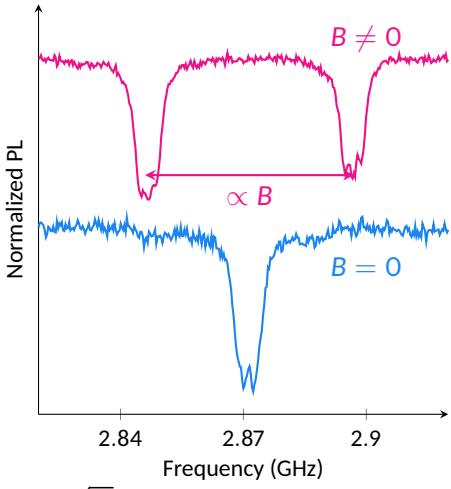
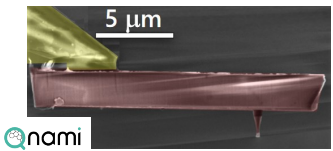



Sensibility: a few $\mu T/\sqrt{Hz}$

# The scanning NV microscope setup

Diamond
AFM tip




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

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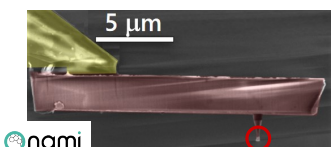


Implanted single
NV center

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

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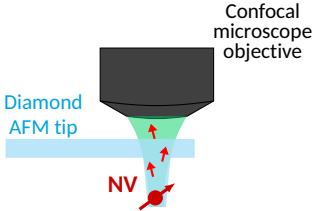


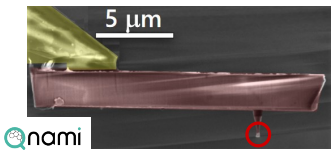


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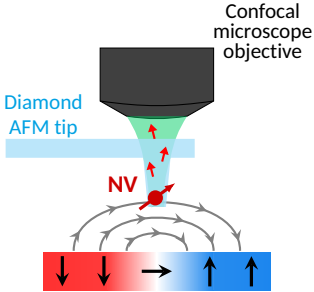


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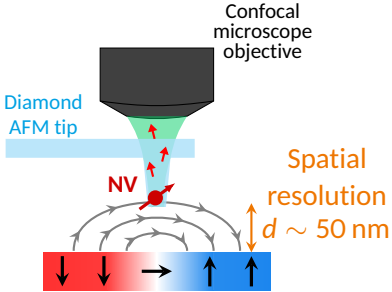


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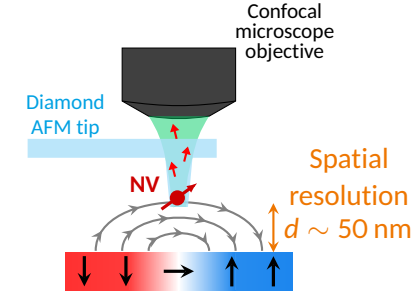


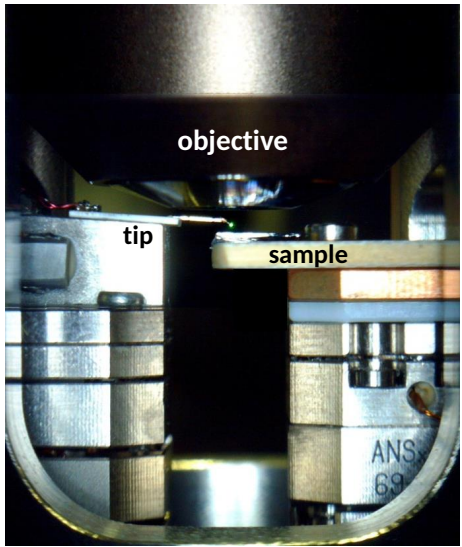


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# Application to nanoscale magnetic texture imaging

Quantitative

Non-perturbative

Highly sensitive

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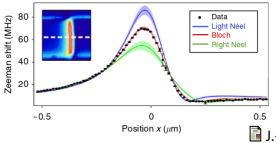
**Determination of domain wall chirality**




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

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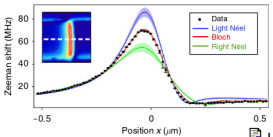


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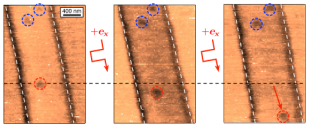
**Imaging of current-induced skyrmion movement**




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

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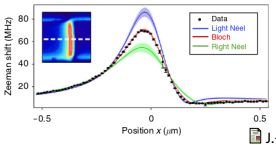


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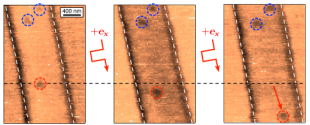
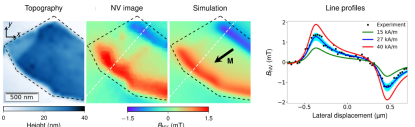



W. Akhtar *et al.* *Phys. Rev. Appl.* 11 (2019), 034066

## Quantitative characterization of 2D ferromagnets

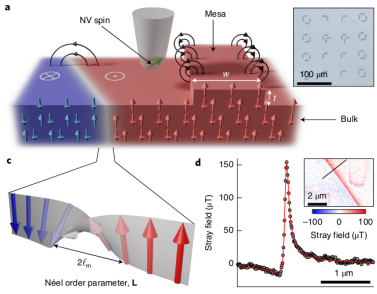



F. Fabre *et al.* *Phys. Rev. Mat.* 5 (2021), 034008

# What about antiferromagnets?

Small stray field measurements

$Cr_2O_3$




N. Hedrich *et al.* *Nat. Phys.* 17 (2021), 574

See talk by K. Wagner SC-O5/CA-04

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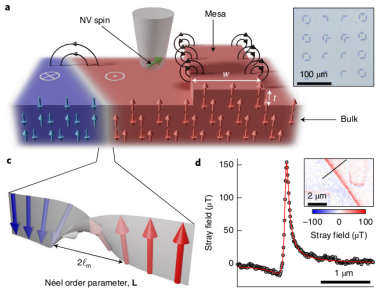


N. Hedrich *et al.* *Nat. Phys.* 17 (2021), 574

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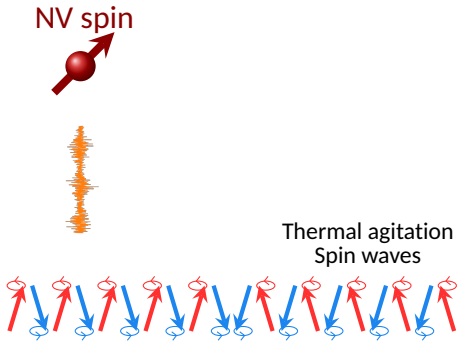
## Magnetic noise detection




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

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

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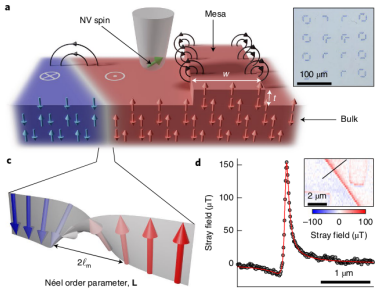


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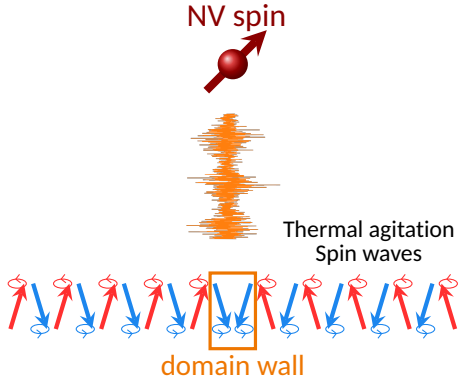


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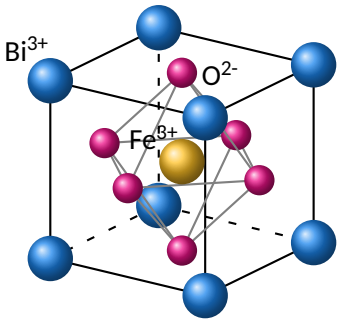
# Bismuth ferrite, a room-temperature multiferroic

Electric polarization




**Paraelectric phase (T>1100 K)**

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

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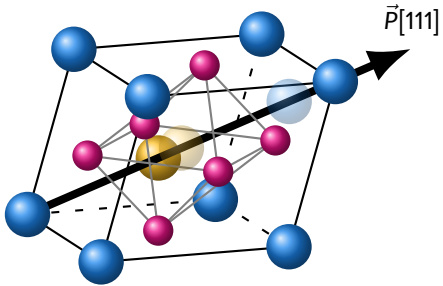


## Ferroelectric phase (T<1100 K)

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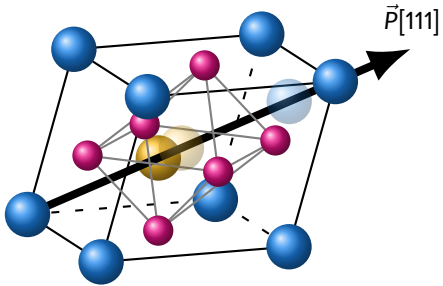
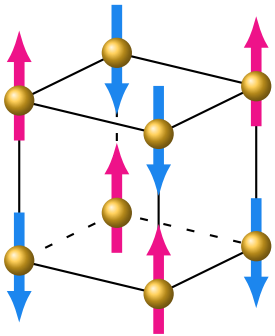



**Ferroelectric phase (T<1100 K)**

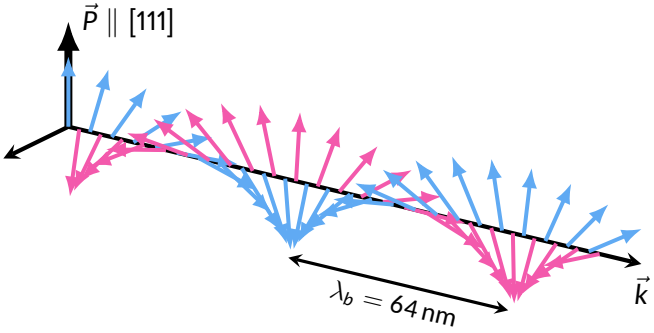
Magnetism



**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!**

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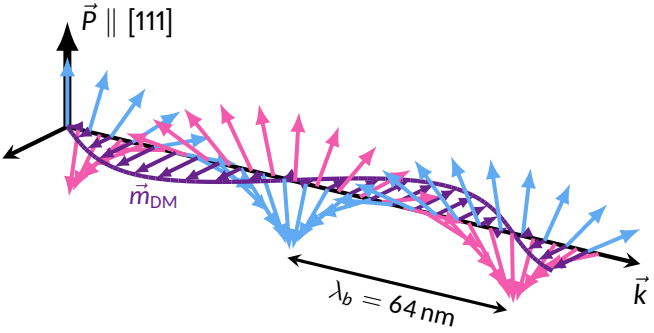


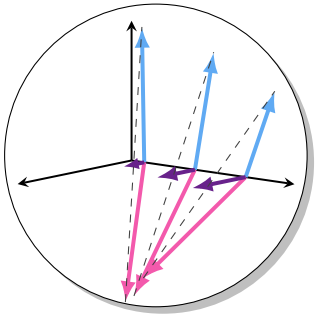

Spin density wave
Weak uncompensated moment
→ **Small stray field**

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

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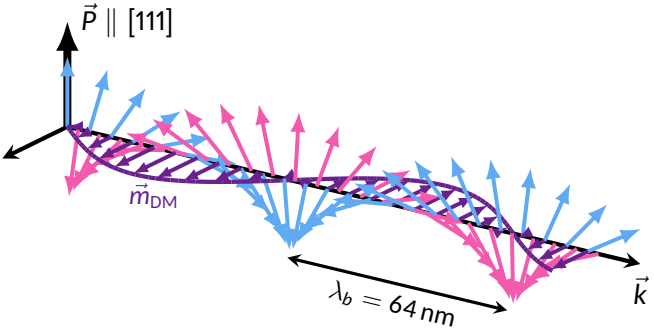


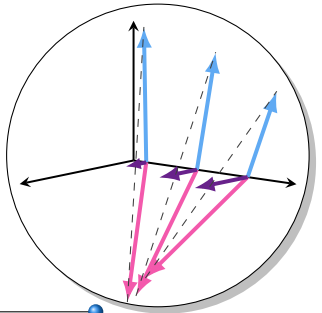


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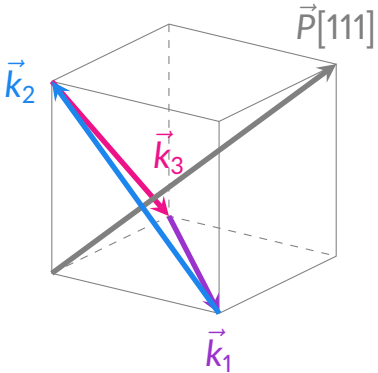
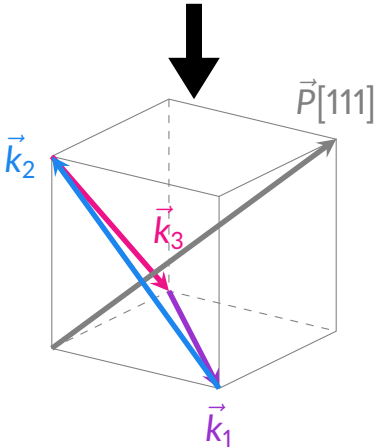
M. Ramazanoglu *et al*. *Phys. Rev. Lett.* 107 (2011), 207206

# The bulk-like cycloid




$\vec{k}_1 \parallel [1\bar{1}0]$
$\vec{k}_2 \parallel [\bar{1}01]$
$\vec{k}_3 \parallel [01\bar{1}]$

# The bulk-like cycloid




$\vec{k}_1 \parallel [1\bar{1}0]$
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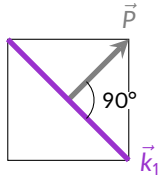
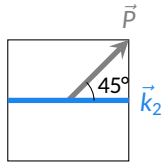
$\vec{k}_3 \parallel [01\bar{1}]$

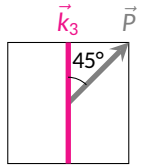
Top view




$\lambda_{IP} = \lambda_b$
64 nm



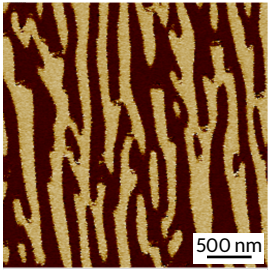

$\lambda_{IP} = \sqrt{2}\lambda_b$
90 nm



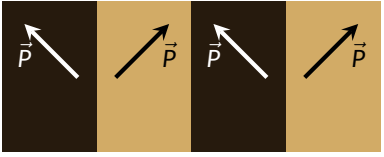

$\lambda_{IP} = \sqrt{2}\lambda_b$
90 nm

# The cycloid in a low strained $BiFeO_3$ thin film

*Collaborations:* UMR CNRS/Thales, Palaiseau (V. Garcia, S. Fusil)

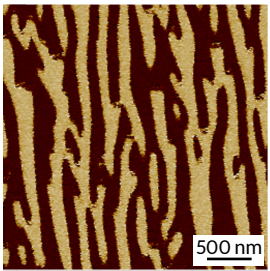



PFM image
ferroelectric domains

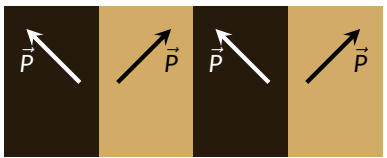


# The cycloid in a low strained $BiFeO_3$ thin film

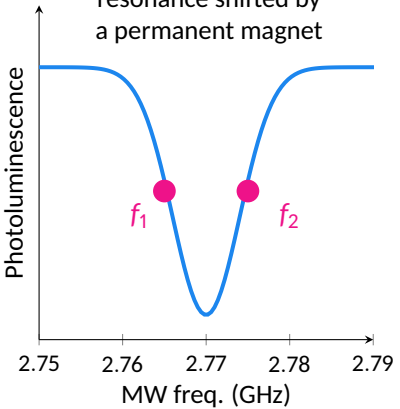
*Collaborations:* UMR CNRS/Thales, Palaiseau (V. Garcia, S. Fusil)




PFM image
ferroelectric domains



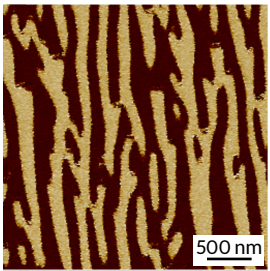

**Reference spectrum**
resonance shifted by
a permanent magnet



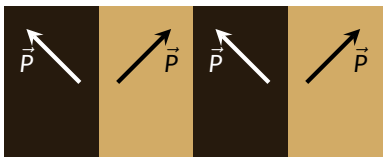

$$\Delta PL = PL(f_2) - PL(f_1)$$

# The cycloid in a low strained $BiFeO_3$ thin film

*Collaborations:* UMR CNRS/Thales, Palaiseau (V. Garcia, S. Fusil)

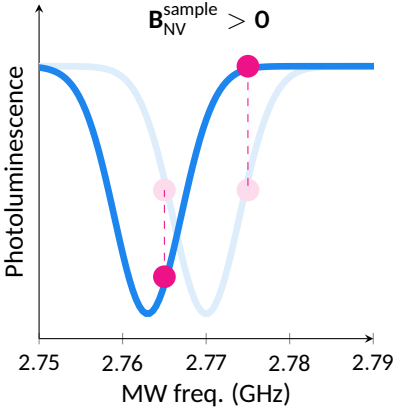



PFM image
ferroelectric domains




**Spectrum for**

$B_{NV}^{sample} > 0$

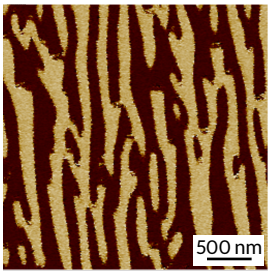



$$\Delta PL = PL(f_2) - PL(f_1)$$

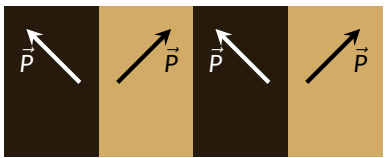
$$\Delta PL > 0$$

# The cycloid in a low strained $BiFeO_3$ thin film

*Collaborations:* UMR CNRS/Thales, Palaiseau (V. Garcia, S. Fusil)

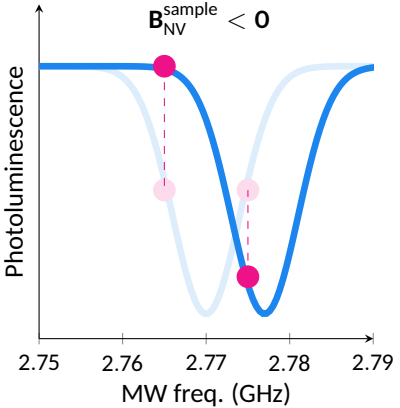



PFM image
ferroelectric domains




**Spectrum for**

$B_{NV}^{sample} < 0$

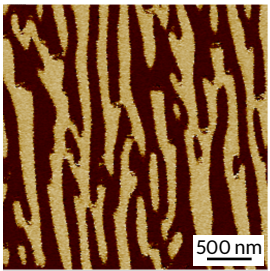



$$\Delta PL = PL(f_2) - PL(f_1)$$

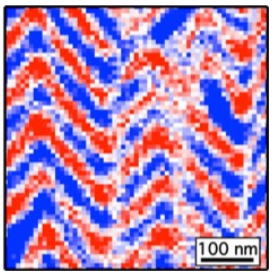
$$\Delta PL < 0$$

# The cycloid in a low strained $BiFeO_3$ thin film

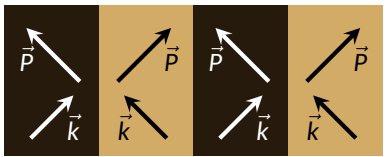
*Collaborations:* UMR CNRS/Thales, Palaiseau (V. Garcia, S. Fusil)




PFM image
ferroelectric domains



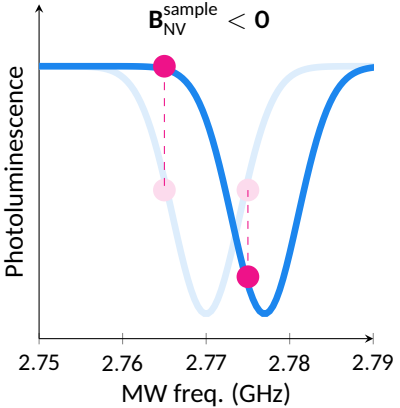

NV image
cycloid


$\vec{k}_1$ wavevector

**Spectrum for**

$B_{NV}^{sample} < 0$

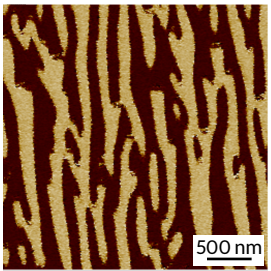



$\Delta PL = PL(f_2) - PL(f_1)$

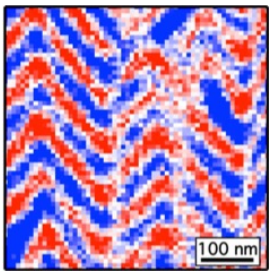
$\Delta PL < 0$

# The cycloid in a low strained $BiFeO_3$ thin film

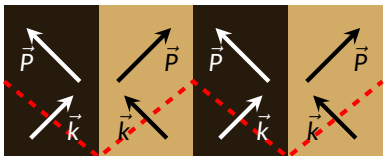
*Collaborations:* UMR CNRS/Thales, Palaiseau (V. Garcia, S. Fusil)




PFM image
ferroelectric domains



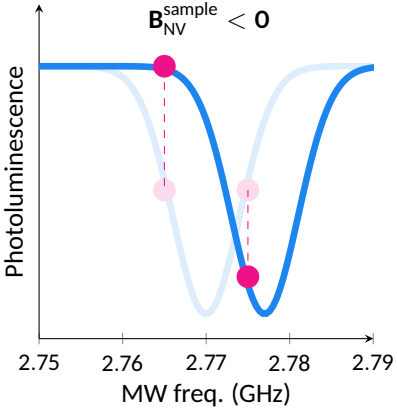

NV image
cycloid


$\vec{k}_1$ wavevector

**Spectrum for**

$B_{NV}^{sample} < 0$

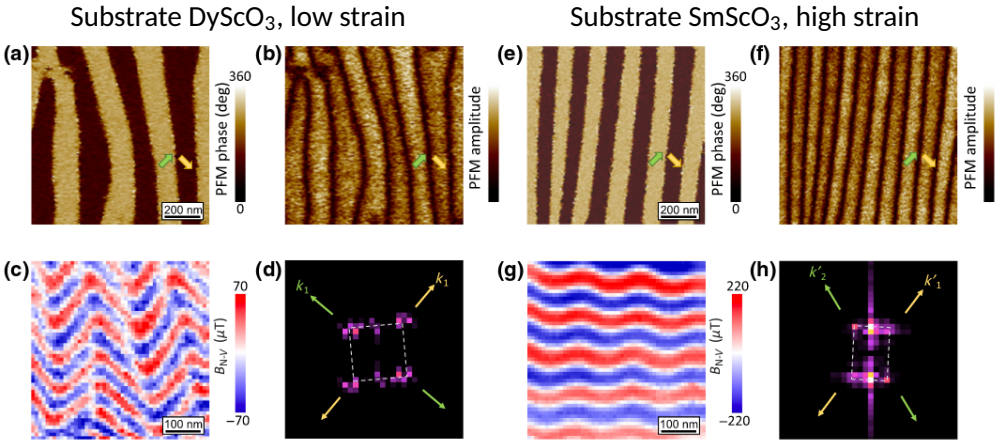



$\Delta PL = PL(f_2) - PL(f_1)$

$\Delta PL < 0$

# Stabilizing an exotic cycloid type with strain

*Collaborations:* UMR CNRS/Thales, Palaiseau (V. Garcia, S. Fusil), Qnami, Basel (H. Zhong)

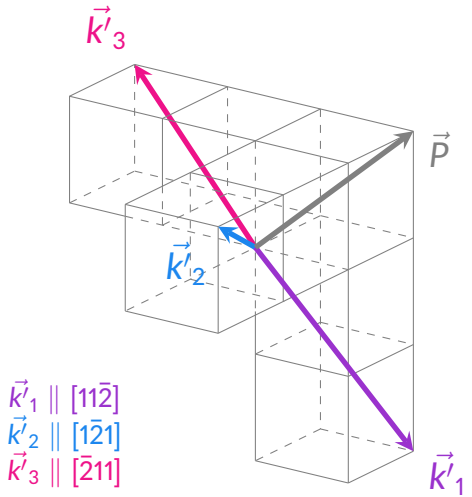




H. Zhong *et al.* *Phys. Rev. Appl.* 17 (2022), 044051

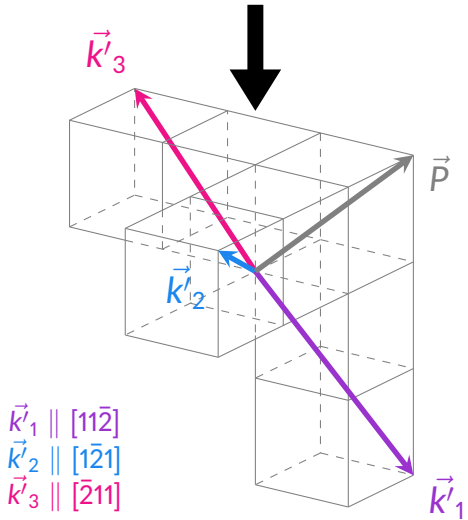
A. Haykal *et al.* *Nat. Commun.* 11 (2020), 1704

# The type II cycloid

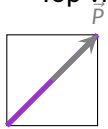



D. Sando *et al.* *Nat. Mater.* 12 (2013), 641

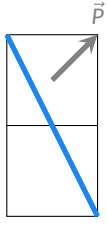
# The type II cycloid



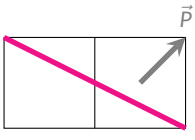

Top view




$\lambda_{IP} = \sqrt{3}\lambda_b$
111 nm



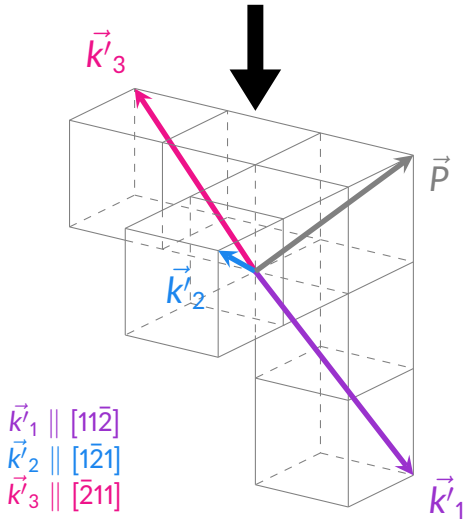

$\lambda_{IP} = \sqrt{\frac{6}{5}}\lambda_b$
70 nm

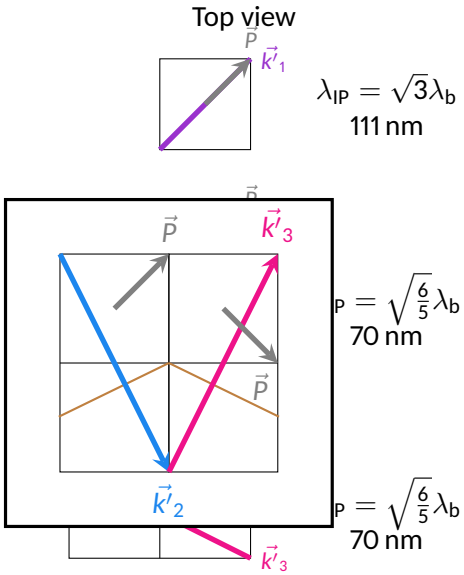



$\lambda_{IP} = \sqrt{\frac{6}{5}}\lambda_b$
70 nm

D. Sando *et al.* *Nat. Mater.* 12 (2013), 641

# The type II cycloid

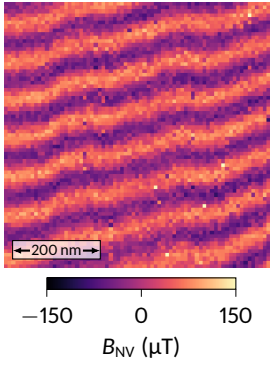



D. Sando *et al.* *Nat. Mater.* 12 (2013), 641

# 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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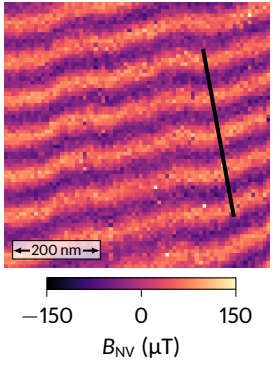


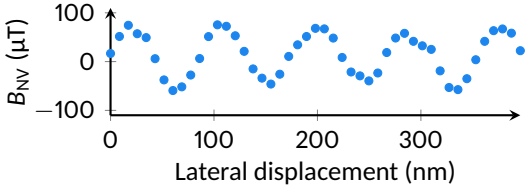

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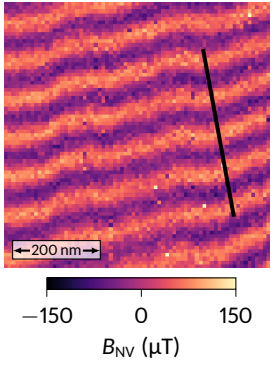
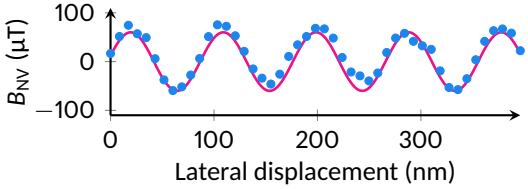
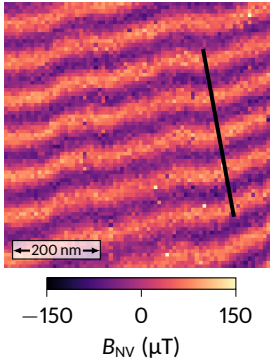


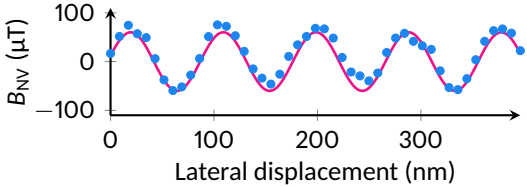




$$\begin{cases} B_x = 0 \\ B_y = -\dfrac{A}{\sqrt{2}}\left(\mathrm{Re}\{S\} - \mathrm{Im}\{S\}\right) \\ B_z = \sqrt{2}\,A\,\mathrm{Re}\{S\} \end{cases} \quad \text{with} \quad \begin{cases} A = \dfrac{\mu_0 m_{DM}}{\sqrt{3}\,a^3}\sinh\left(\dfrac{ka}{2\sqrt{2}}\right) \\ S = e^{-kz/\sqrt{2}} e^{ik(y-z)/\sqrt{2}}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

# 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)



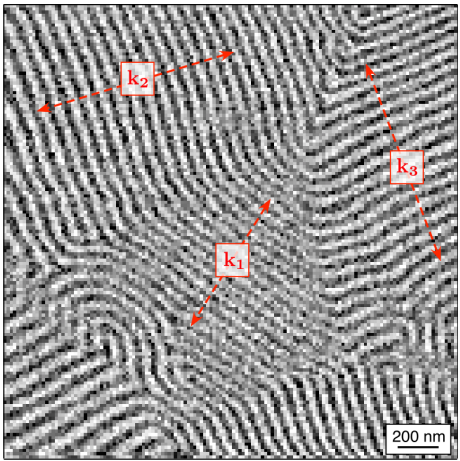




$$m_{DM} = 0.09 \pm 0.03\ \mu_B$$

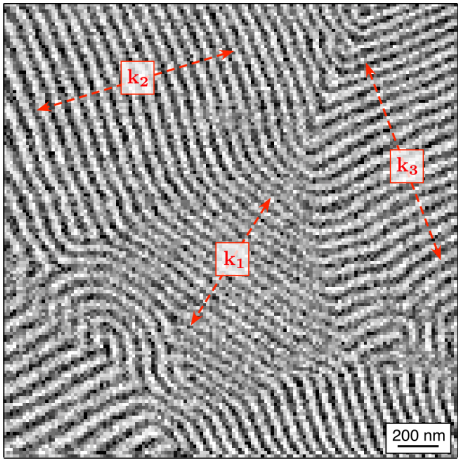
M. Ramazanoglu *et al.* *Phys. Rev. Lett.* 107 (2011), 207206

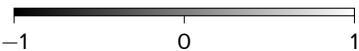
$$\begin{cases} B_x = 0 \\ B_y = -\dfrac{A}{\sqrt{2}}\left(\mathrm{Re}\{S\} - \mathrm{Im}\{S\}\right) \\ B_z = \sqrt{2}\,A\,\mathrm{Re}\{S\} \end{cases} \quad \text{with} \quad \begin{cases} A = \dfrac{\mu_0 m_{DM}}{\sqrt{3}\,a^3}\sinh\left(\dfrac{ka}{2\sqrt{2}}\right) \\ S = e^{-kz/\sqrt{2}} e^{ik(y-z)/\sqrt{2}}\,\dfrac{1-e^{-kt(1+i)/\sqrt{2}}}{1-e^{-ka(1+i)/\s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

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

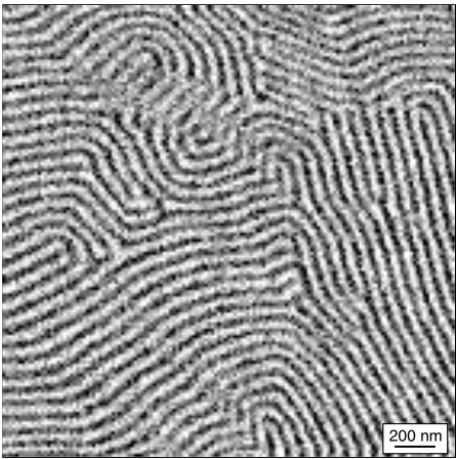


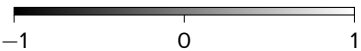
# Rotation of the cycloid propagation direction measured in real space...




iso-B signal

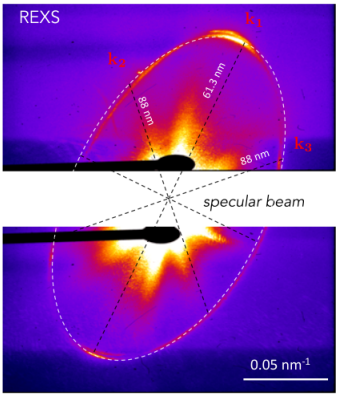



iso-B signal

# … and in reciprocal space

Resonant X-ray scattering

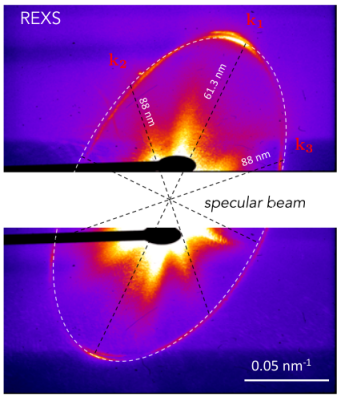



SOLEIL SYNCHROTRON

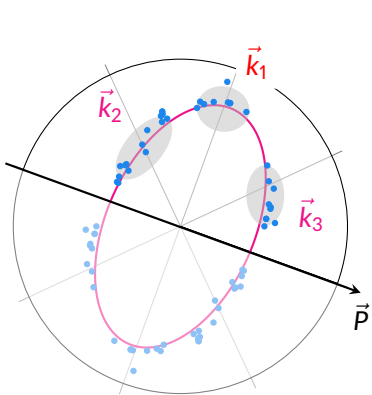
*N. Jaouen*

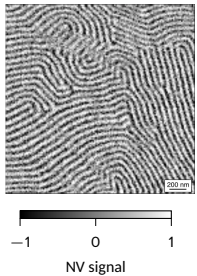
# … and in reciprocal space

Resonant X-ray scattering




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



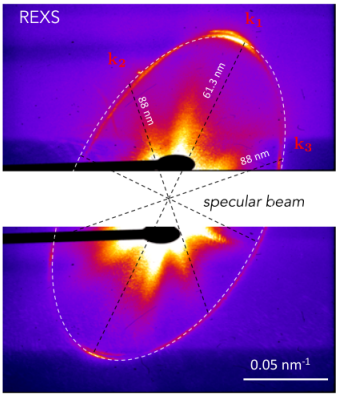




SOLEIL SYNCHROTRON

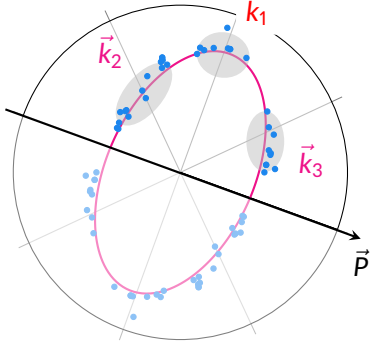
*N. Jaouen*

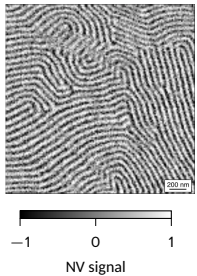
# … and in reciprocal space

Resonant X-ray scattering




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



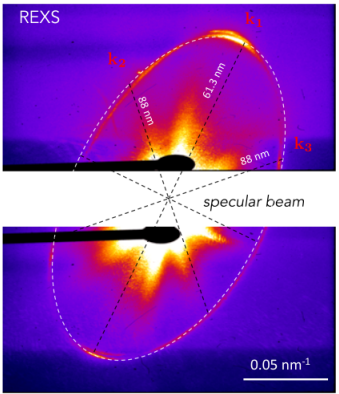




SOLEIL SYNCHROTRON

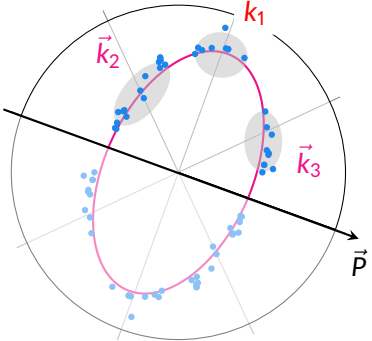
*N. Jaouen*

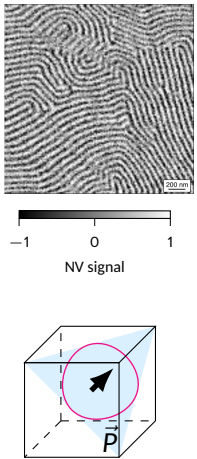
# … and in reciprocal space

Resonant X-ray scattering




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



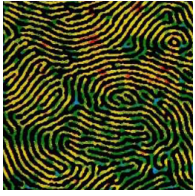

Surface effect? Only $\vec{k}_1$ seen by neutrons

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

SOLEIL SYNCHROTRON
*N. Jaouen*

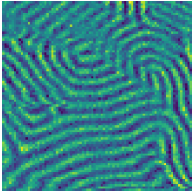
# Universal patterns in lamellar systems

**Block copolymer**
Period 40 nm



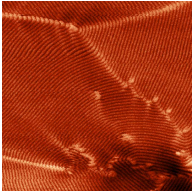
T. A. Witten. *Phys. Today* 43 (1990), 21

**$BiFeO_3$ magnetic cycloid**
Period 64 nm



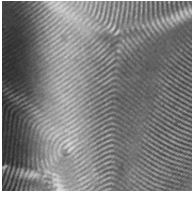
A. Finco *et al.* *Phys. Rev. Lett.* 128 (2022), 187201

**FeGe magnetic helix**
Period 70 nm



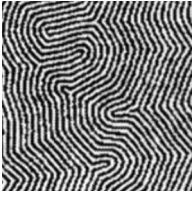
P. Schönherr *et al.* *Nat. Phys.* 14 (2018), 465

**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

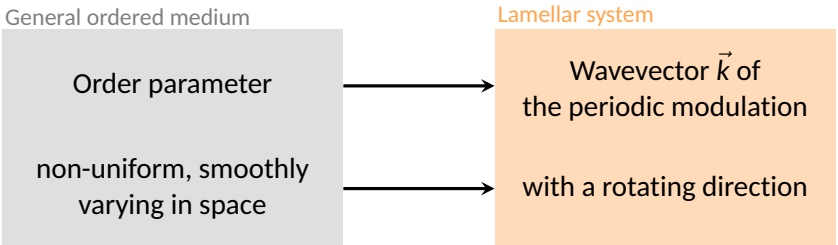
General ordered medium

Order parameter

non-uniform, smoothly varying in space

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

# Topological defects in lamellar systems




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

# Topological defects in lamellar systems

General ordered medium

Order parameter

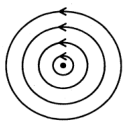
non-uniform, smoothly varying in space

Lamellar system

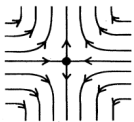
Wavevector $\vec{k}$ of the periodic modulation

with a rotating direction

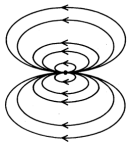
except at singular regions of lower dimensionality → **topological defects**



disclination
winding number = 1



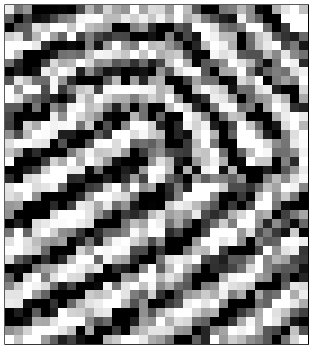
disclination
winding number = -1

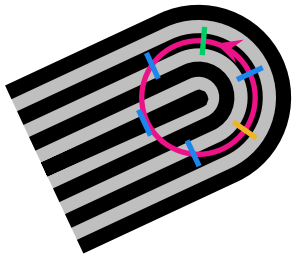


disclination
winding number = 2

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

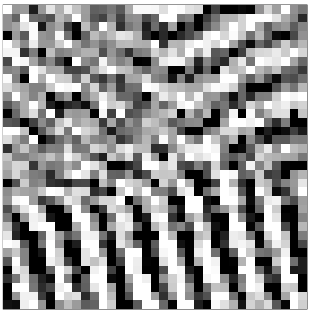
# $+\pi$-disclination

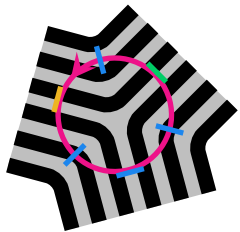


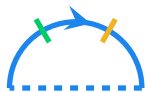



winding number $+1/2$

# $-\pi$-disclination

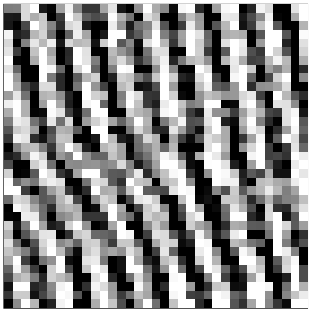


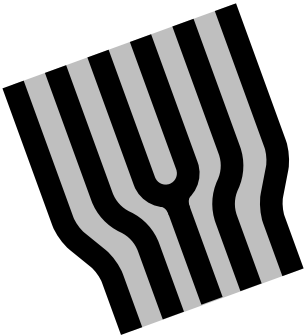





winding number $-1/2$

# Edge dislocation



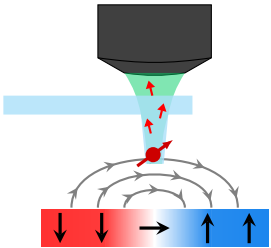


Combination of
$+\pi$- and $-\pi$-disclinations

winding number 0

## Summary

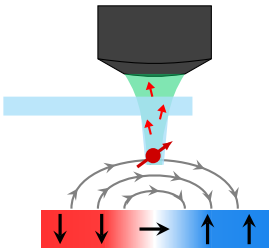
NV center magnetometry



- highly sensitive
- nanoscale
- quantitative
- non-perturbative

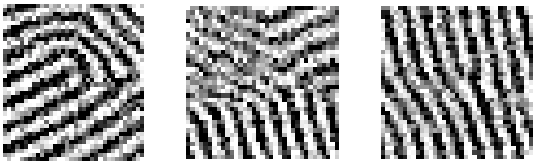
# Summary

## 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

# Acknowledgments

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Nicolas Jaouen

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