Imaging antiferromagnetic states with scanning NV magnetometry

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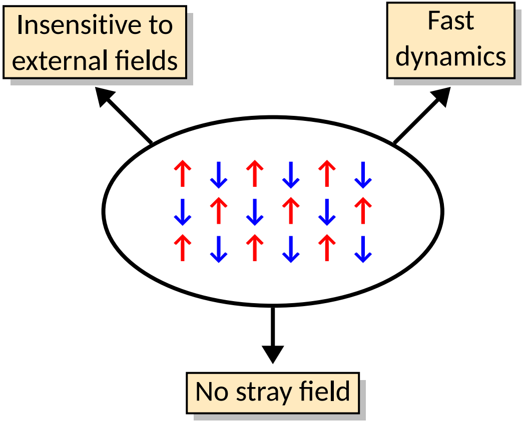
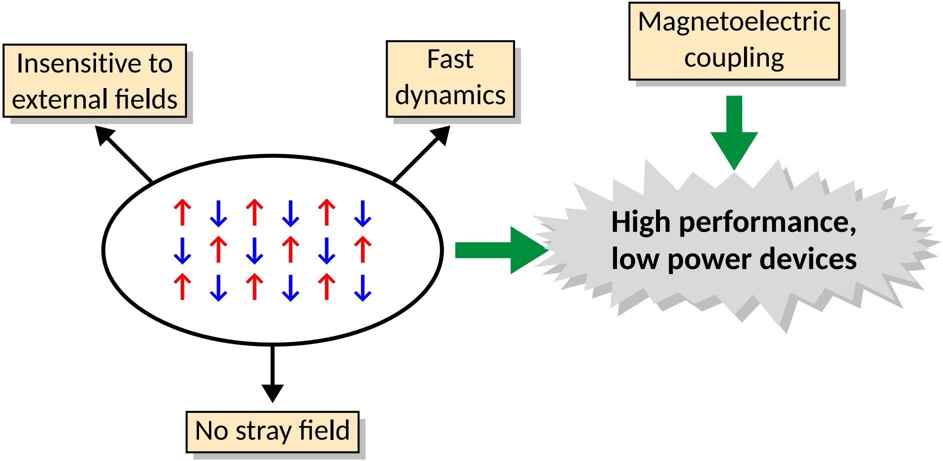
SPEC, CEA, CNRS, Université Paris-Saclay, Gif-sur-Yvette, France

IMAGINE

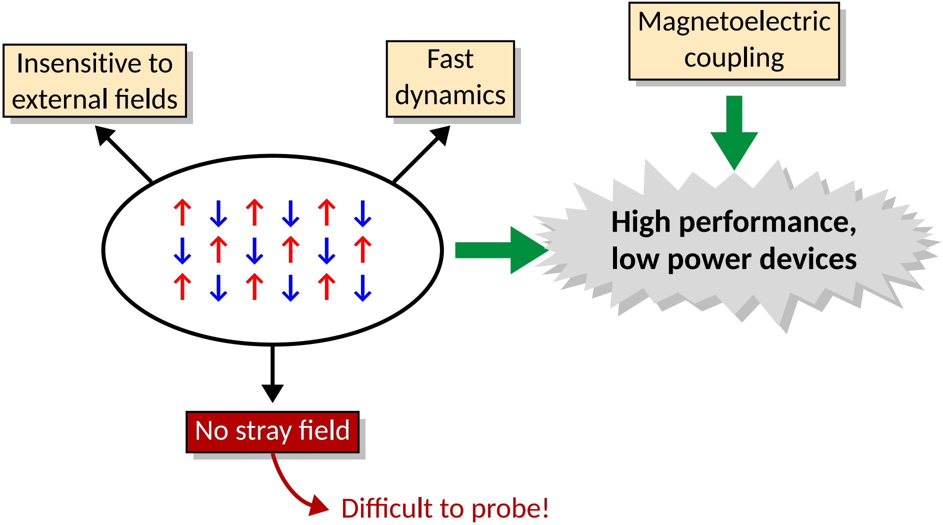
Antiferromagnets



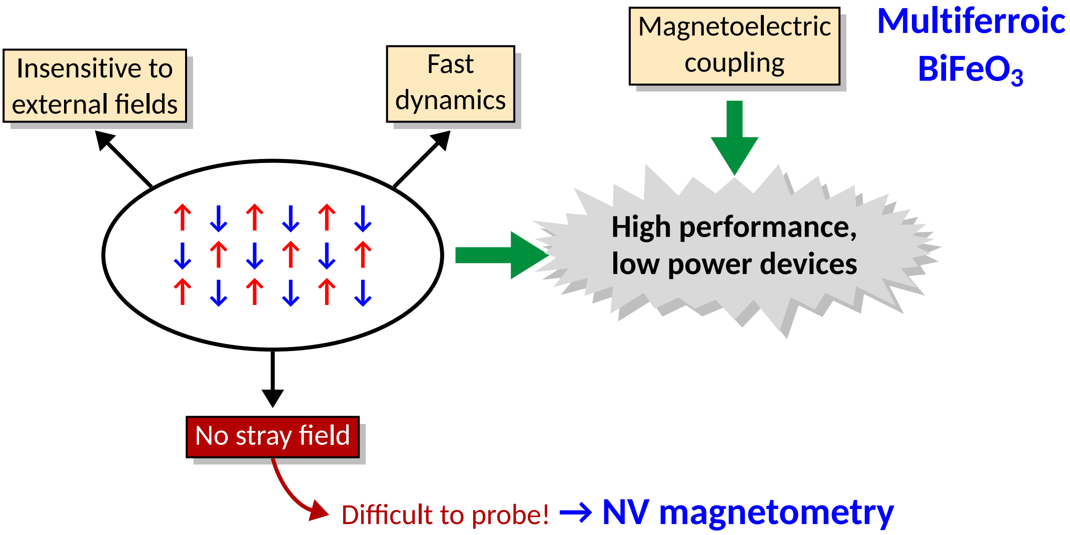
Antiferromagnets



Antiferromagnets

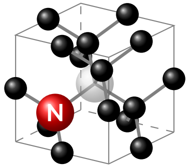


Antiferromagnets

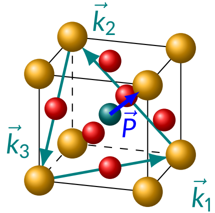


Outline

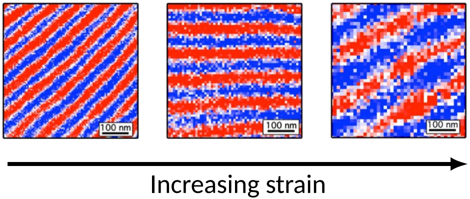
NV center magnetometry



$BiFeO_3$, a room temperature multiferroic

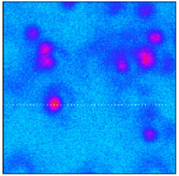


Effect of epitaxial strain on the cycloid in $BiFeO_3$ thin films

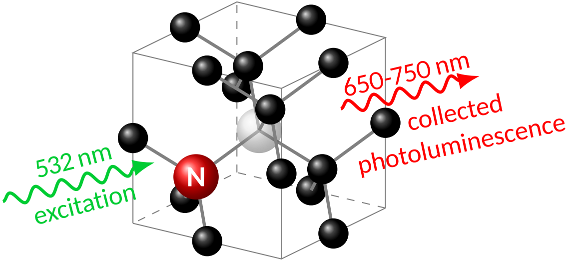


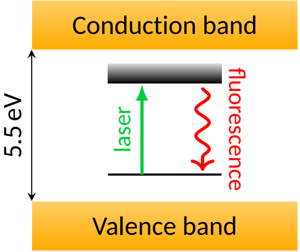
The Nitrogen Vacancy (NV) center in diamond

- Defect consisting of a N atom and a vacancy inside the C lattice
- Equivalent to an artificial atom with levels inside the diamond gap
- Detection of the photoluminescence of **single emitters** at room temperature



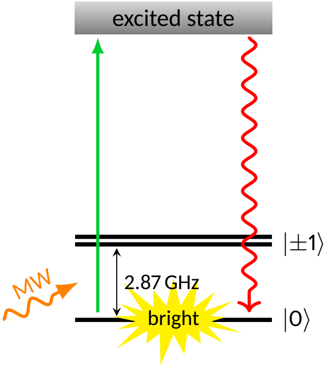
A. Gruber *et al.* *Science* 276 (1997), 2012–2014





Atomic-size magnetic field sensors

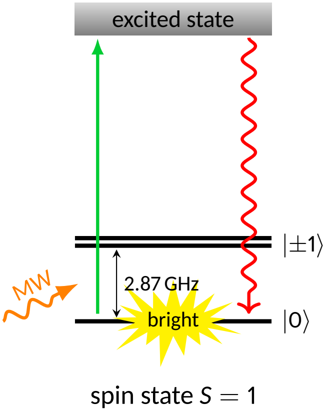
Spin-dependent fluorescence



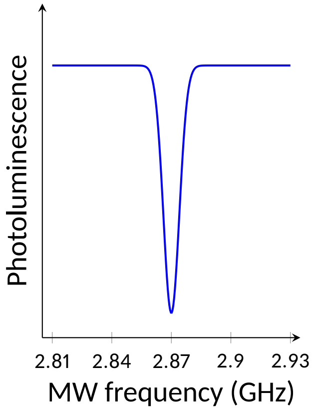
spin state $S = 1$

Atomic-size magnetic field sensors

Spin-dependent fluorescence

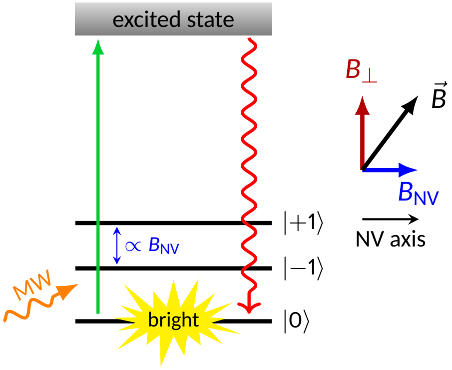


Optically Detected Magnetic Resonance



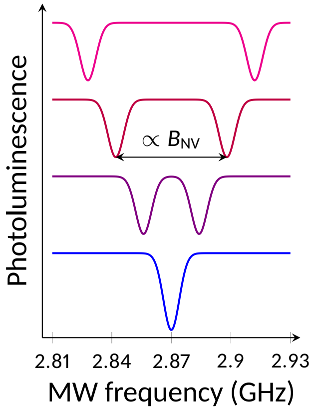
Atomic-size magnetic field sensors

Spin-dependent fluorescence

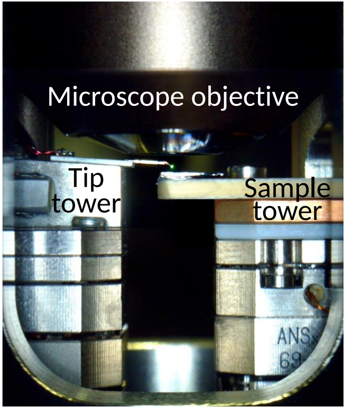


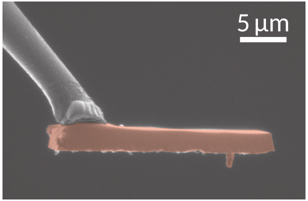
spin state $S = 1$

Optically Detected Magnetic Resonance

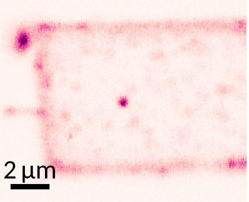


Experimental setup

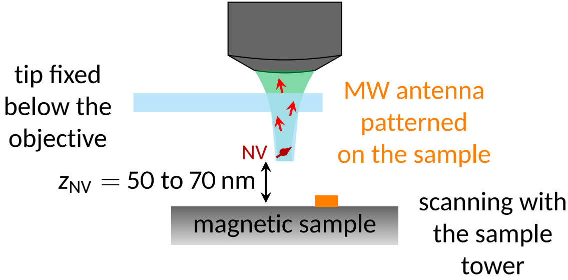




PL scan, top view

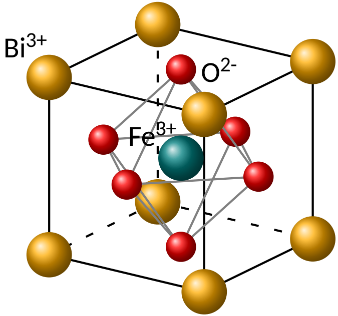


P. Maletinsky *et al.* *Nat. Nano.* 7 (2012), 320–324



$BiFeO_3$, a room temperature multiferroic

Electric polarization

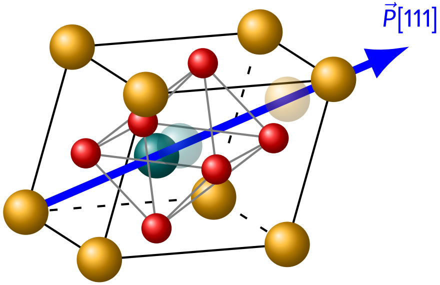


Paraelectric phase (T>1100 K)

G. Catalan *et al*. *Advanced Materials* 21 (2009), 2463–2485

$BiFeO_3$, a room temperature multiferroic

Electric polarization

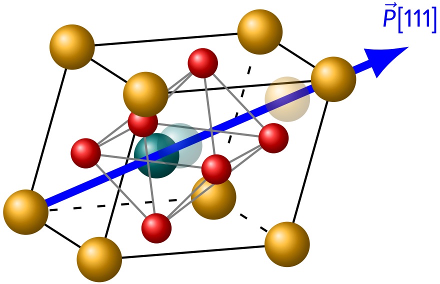


Ferroelectric phase (T<1100 K)

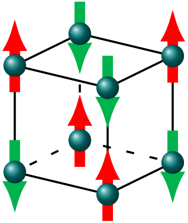
G. Catalan *et al.* *Advanced Materials* 21 (2009), 2463–2485

$BiFeO_3$, a room temperature multiferroic

Electric polarization



Magnetism



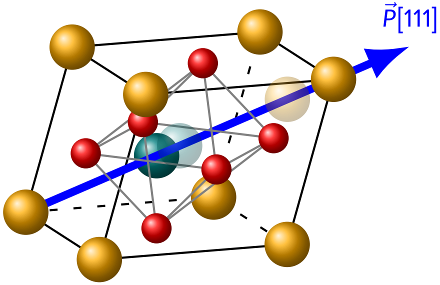
G-type
antiferromagnet

Ferroelectric phase (T<1100 K)

G. Catalan *et al.* *Advanced Materials* 21 (2009), 2463–2485

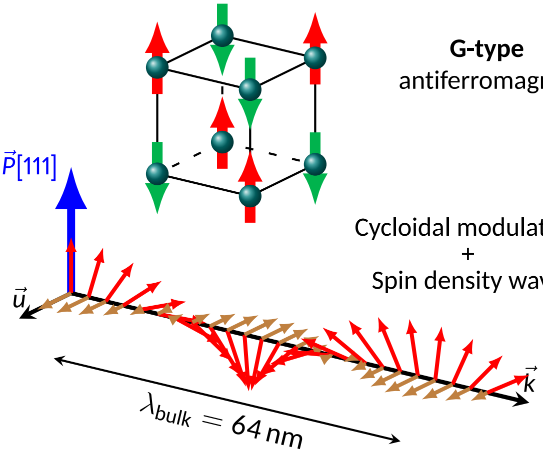
$BiFeO_3$, a room temperature multiferroic

Electric polarization



Ferroelectric phase (T<1100 K)

Magnetism

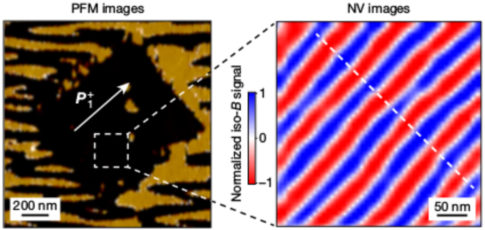


G-type
antiferromagnet

Cycloidal modulation
+
Spin density wave

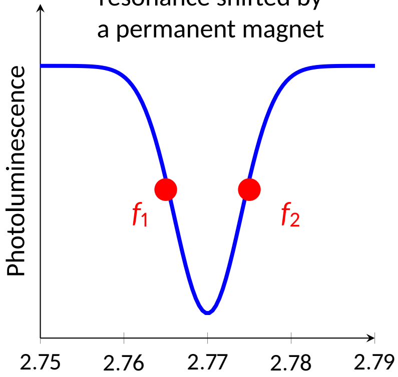
G. Catalan *et al.* *Advanced Materials* 21 (2009), 2463–2485

NV imaging of the cycloid, iso-B mode



Reference spectrum

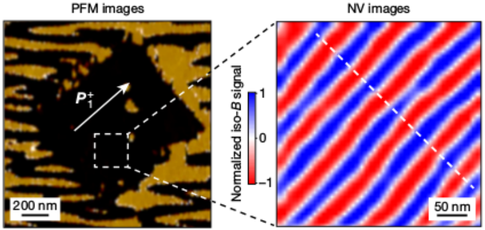
resonance shifted by
a permanent magnet



$$\Delta\mathrm{PL} = \mathrm{PL}(f_2) - \mathrm{PL}(f_1)$$

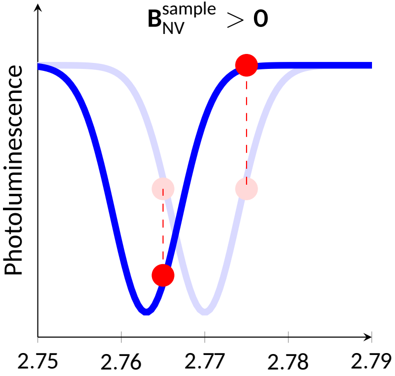
I. Gross *et al.* *Nature* 549 (2017), 252–256

NV imaging of the cycloid, iso-B mode



Spectrum for

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

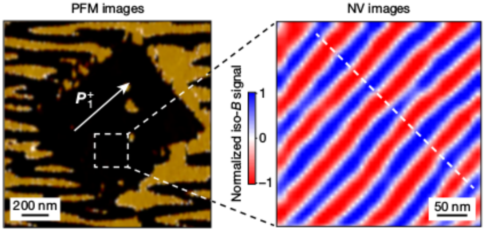


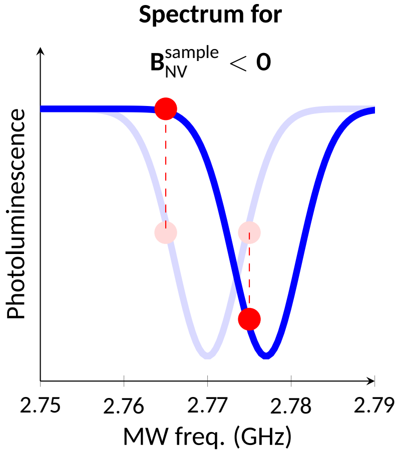
$$\Delta PL = PL(f_2) - PL(f_1)$$

$$\Delta PL > 0$$

I. Gross *et al.* *Nature* 549 (2017), 252–256

NV imaging of the cycloid, iso-B mode



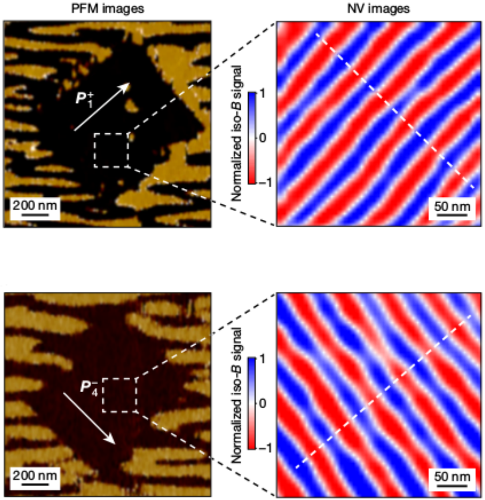


$$\Delta PL = PL(f_2) - PL(f_1)$$

$$\Delta PL < 0$$

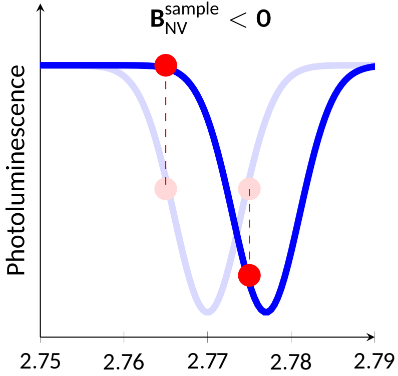
I. Gross *et al.* *Nature* 549 (2017), 252–256

NV imaging of the cycloid, iso-B mode



Spectrum for

$\mathbf{B}_{\mathrm{NV}}^{\mathrm{sample}} < 0$



$$\Delta\mathrm{PL} = \mathrm{PL}(f_2) - \mathrm{PL}(f_1)$$

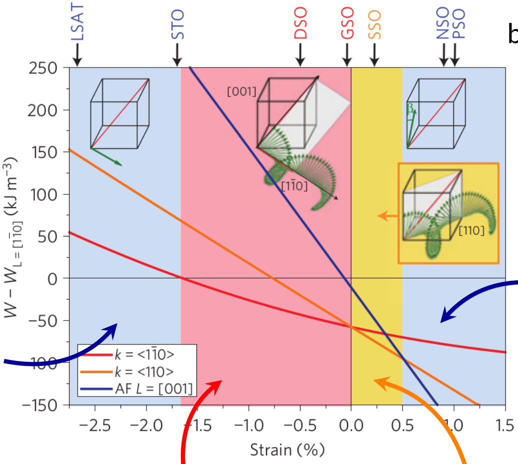
$$\Delta\mathrm{PL} < 0$$

I. Gross *et al.* *Nature* 549 (2017), 252–256

Known effect of epitaxial strain on the cycloid

Phase diagram obtained from spectroscopic measurements

Epitaxial strain tuned by changing the substrate



Large tensile strain antiferromagnetic order

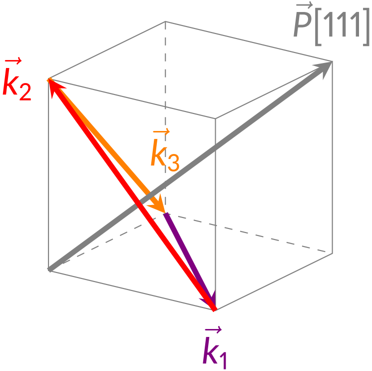
Large compressive strain antiferromagnetic order

Small compressive strain cycloid type I

Small tensile strain cycloid type II

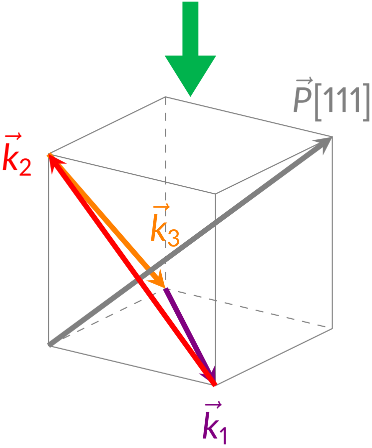
D. Sando *et al.* *Nature Materials* 12 (2013), 641–646

The type I cycloid



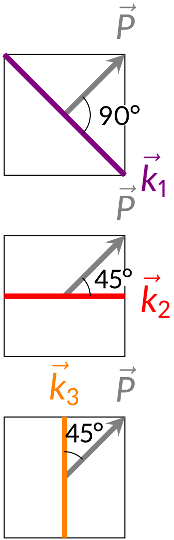
$\vec{k}_1 \parallel [1\bar{1}0]$
$\vec{k}_2 \parallel [\bar{1}01]$
$\vec{k}_3 \parallel [01\bar{1}]$

The type I cycloid



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

Top view

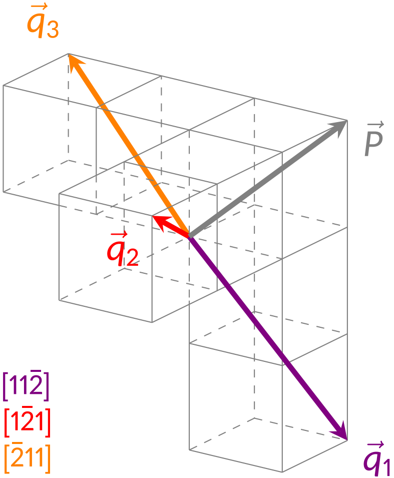


$$\lambda_{\text{IP}} = \lambda_{\text{bulk}}$$
64 nm

$$\lambda_{\text{IP}} = \sqrt{2}\lambda_{\text{bulk}}$$
90 nm

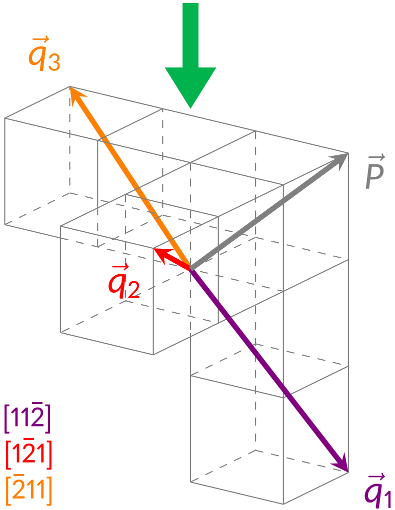
$$\lambda_{\text{IP}} = \sqrt{2}\lambda_{\text{bulk}}$$
90 nm

The type II cycloid



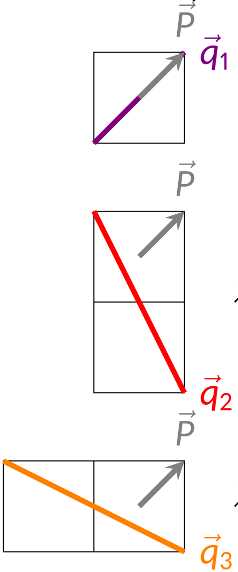
$\vec{q}_1 \parallel [11\bar{2}]$
$\vec{q}_2 \parallel [1\bar{2}1]$
$\vec{q}_3 \parallel [\bar{2}11]$

The type II cycloid



$\vec{q}_1 \parallel [11\bar{2}]$
$\vec{q}_2 \parallel [1\bar{2}1]$
$\vec{q}_3 \parallel [\bar{2}11]$

Top view



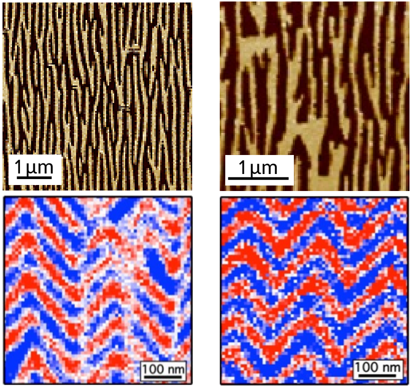
$\lambda_{\mathrm{IP}} = \sqrt{3}\lambda_{\mathrm{bulk}}$
111 nm

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

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

Virgin state of the films

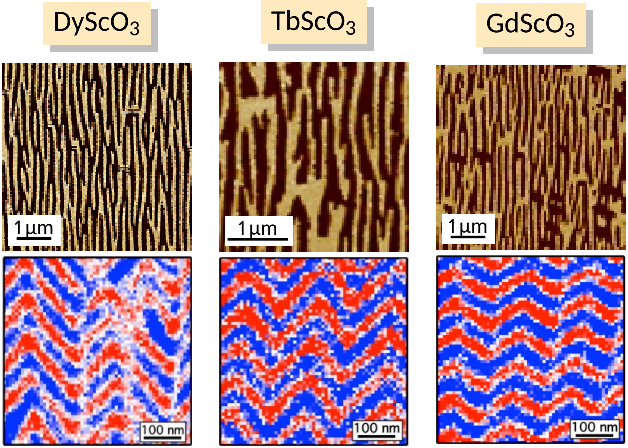
$DyScO_3$	$TbScO_3$



compressive ← strain → tensile

$DyScO_3$	$TbScO_3$
type I cycloid $\vec{k}_1$	type I cycloid $\vec{k}_1$

Virgin state of the films



compressive ← strain → tensile

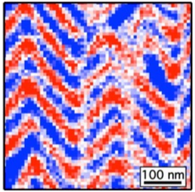
type I cycloid	type I cycloid	type II cycloid
$\vec{k}_1$	$\vec{k}_1$	$\vec{q}_2, \vec{q}_3$

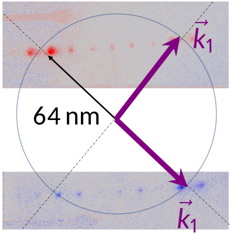
X-ray diffraction

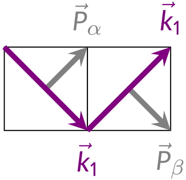
$DyScO_3$

type I cycloid

$\vec{k}_1$







$\lambda_{\text{IP}} = \lambda_{\text{bulk}}$

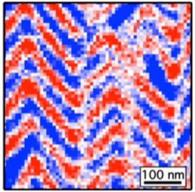
64 nm

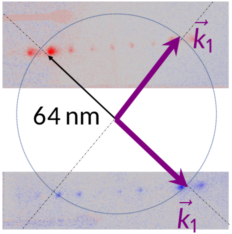
X-ray diffraction

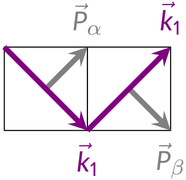
$DyScO_3$

type I cycloid

$\vec{k}_1$







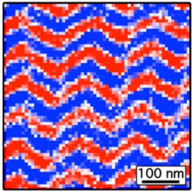
$\lambda_{IP} = \lambda_{bulk}$

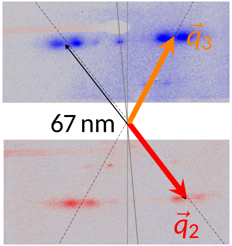
64 nm

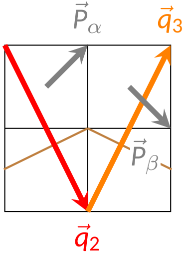
$GdScO_3$

type II cycloid

$\vec{q}_2, \vec{q}_3$



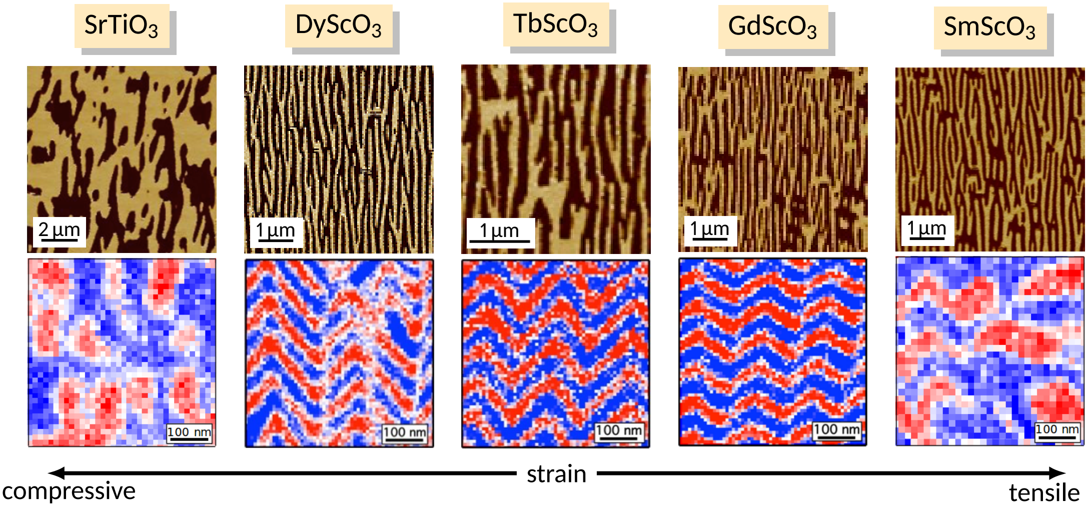




$\lambda_{IP} = \sqrt{\frac{6}{5}}\lambda_{bulk}$

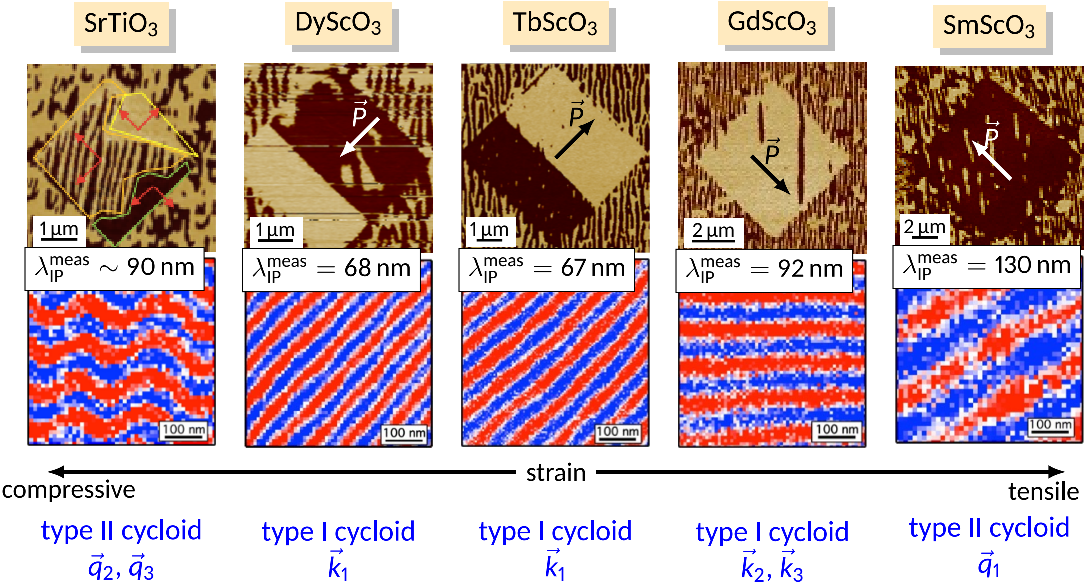
70 nm

Virgin state of the films



antiferromagnetic domains | type I cycloid $\vec{k}_1$ | type I cycloid $\vec{k}_1$ | type II cycloid $\vec{q}_2, \vec{q}_3$ | antiferromagnetic domains

Written domains



Summary

- NV magnetometry is the right tool to probe the small uncompensated magnetic moments in $BiFeO_3$
- New exploration of the phase diagram of $BiFeO_3$ thin films using **real-space imaging**
- Demonstration of the ability to manipulate **electrically** the magnetic cycloid