

Electric-field-induced multiferroic topological solitons

Aurore Finco

Laboratoire Charles Coulomb
Team Solid-State Quantum Technologies (S2QT)

CNRS and Université de Montpellier, Montpellier, France



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slides available at <https://magimag.eu>

Collaborators

L2C, Montpellier

Pawan Kumar, Angela Haykal, Waseem Akhtar, Isabelle Philip, Vincent Jacques

Laboratoire Albert Fert, Palaiseau

Arthur Chaudron, Pauline Dufour, Amr Abdelsamie, Johanna Fischer, Sophie Collin, Karim Bouzehouane, Stéphane Fusil, Vincent Garcia,

CEA SPEC, Gif-sur-Yvette

Zixin Li, Jean-Yves Chauleau, Michel Viret

Institute of Physics, Czech Academy of Sciences, Prague

Pavel Marton, Jirka Hlinka

SPMS, CentraleSupélec, Gif-sur-Yvette

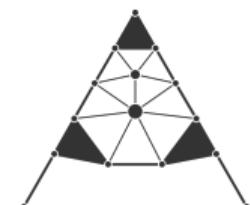
Brahim Dkhil

Synchrotron Soleil

Nicolas Jaouen



TATOO



TSAR

Outline

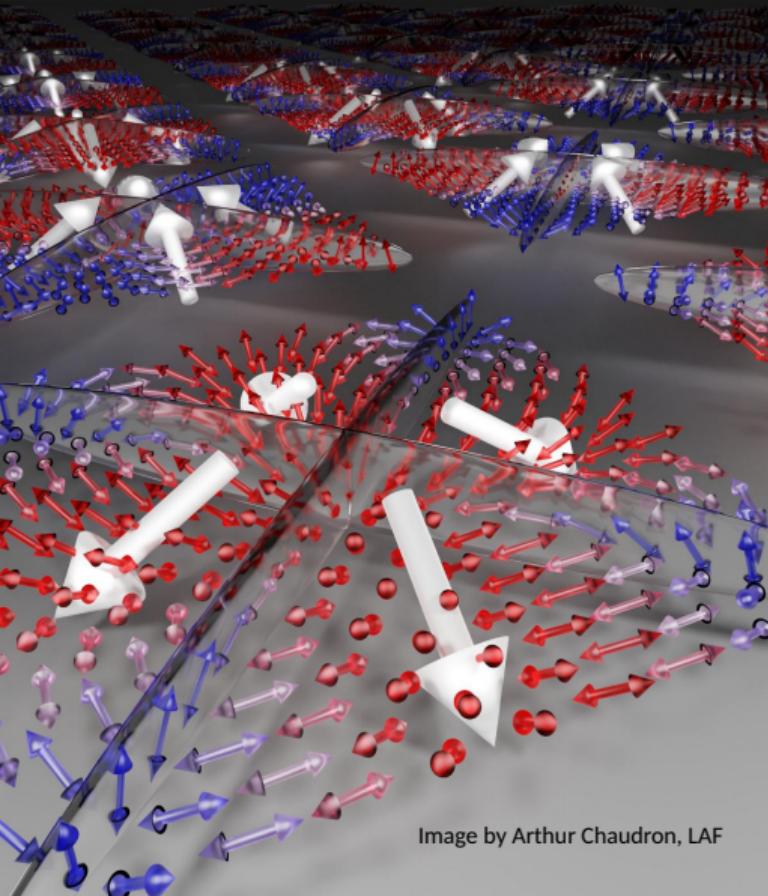


Image by Arthur Chaudron, LAF

1. Ferroic whirling textures
2. Bismuth ferrite, a room temperature multiferroic
3. Scanning NV center magnetometry
4. Antiferromagnetic topological defects in bulk BiFeO_3
5. Creation of multiferroic solitons in BiFeO_3 microstructures

 A. Finco et al. *PRL* 128 (2022), 187201

 A. Chaudron et al. *Nat. Mater.* 23 (2024), 905

Outline

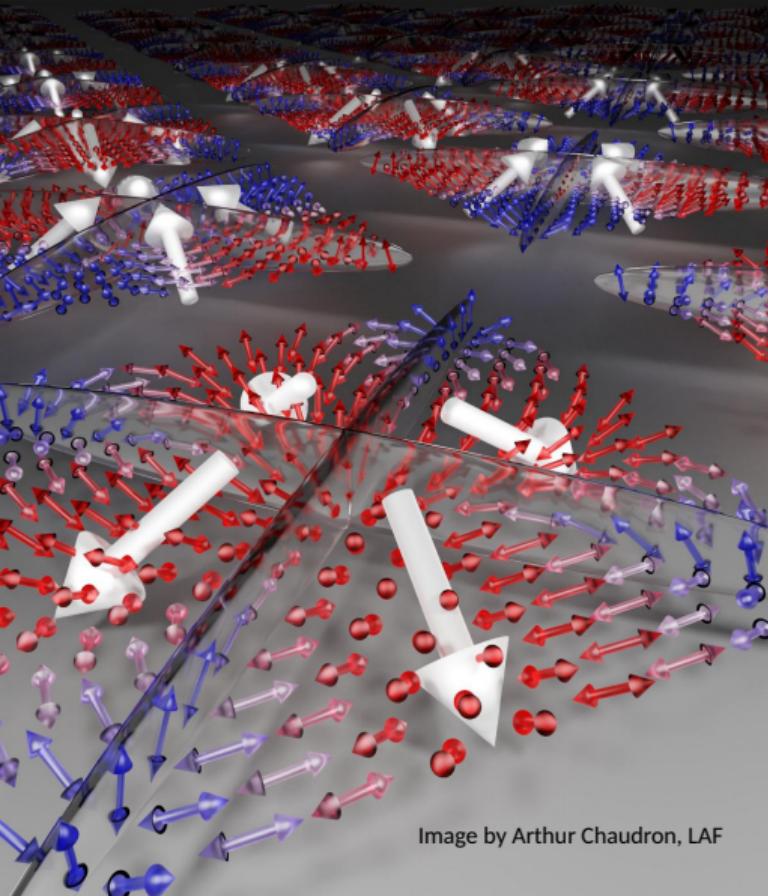


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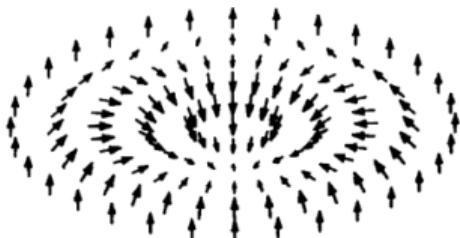
 A. Chaudron et al. *Nat. Mater.* 23 (2024), 905

Magnetic skyrmions

Spatially localized magnetic objects in which the magnetization whirls, with its direction covering a whole sphere. They are said **topologically protected** as they cannot be continuously deformed to reach a ferromagnetic state.

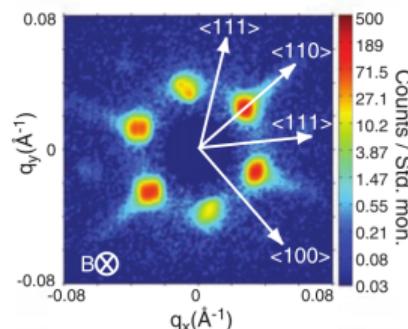
They are often stabilized by antisymmetric exchange (Dzyaloshinskii-Moriya interaction).

Predicted in the late 80's



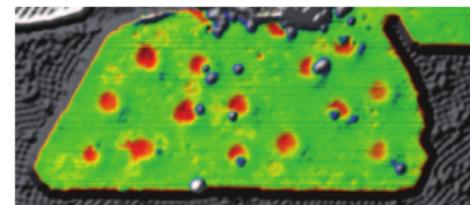
 A. Bogdanov et al. *pss (b)* 186 (1994), 527

Experimentally discovered
in 2009 in MnSi



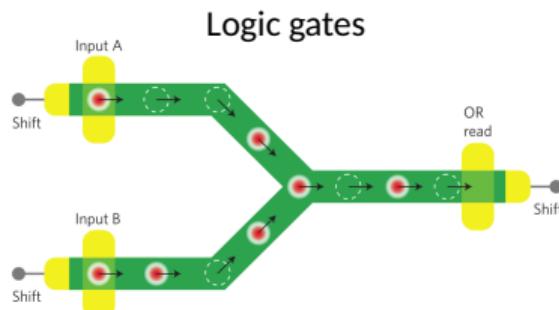
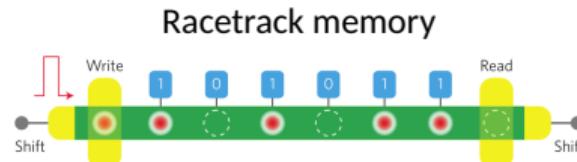
 S. Mühlbauer et al. *Science* 323 (2009), 915

Stabilized in ultrathin
films in 2013

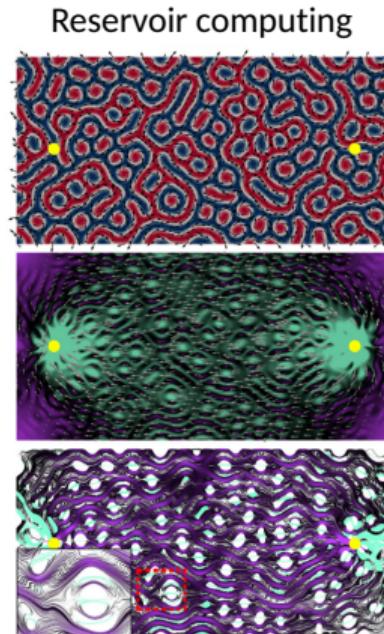


 N. Romming et al. *Science* 341 (2013), 636

Proposed applications of magnetic skyrmions

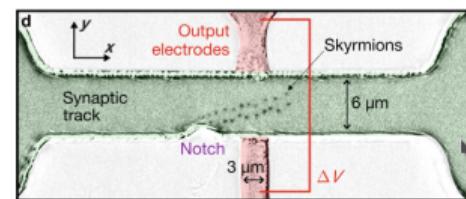
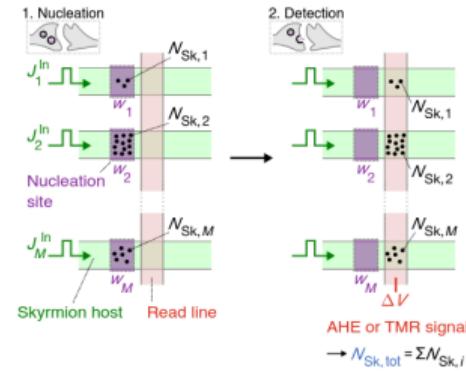


S. Krause et al. *Nat. Mater.* 15 (2016), 493



G. Bourianoff et al. *AIP Adv.* 8 (2018), 055602

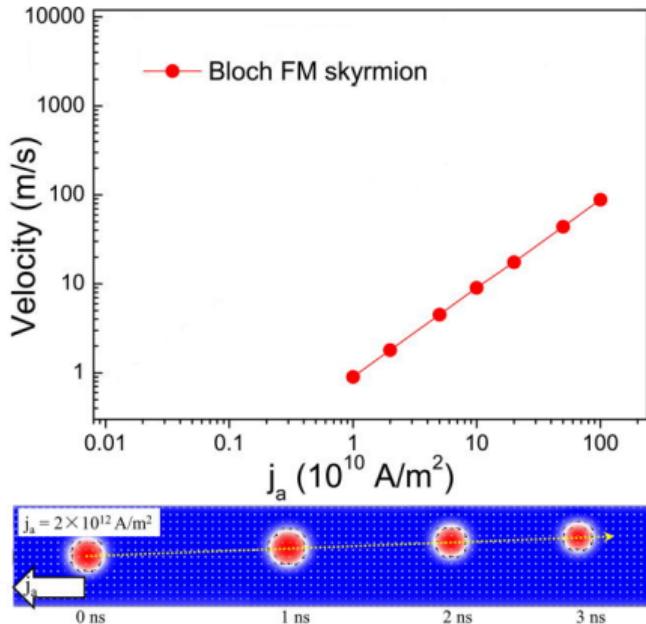
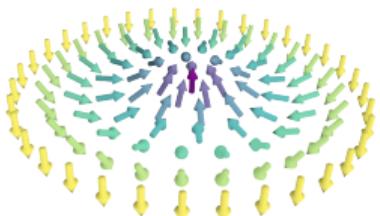
Neural networks (weighted sum)



T. Gomes et al. *arXiv:2310.16909* (2023)

Limitations in ferromagnets

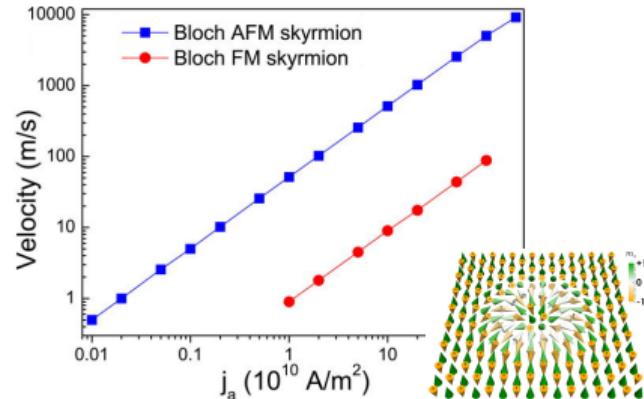
- Limited speed to about 100 m s^{-1}
- “Skyrmion Hall effect”: they do not move straight along the current and get pushed towards the edges of tracks
- The power consumption to displace them is rather large



C. Jin et al. *APL* 109 (2016), 182404

Other approaches

Antiferromagnets



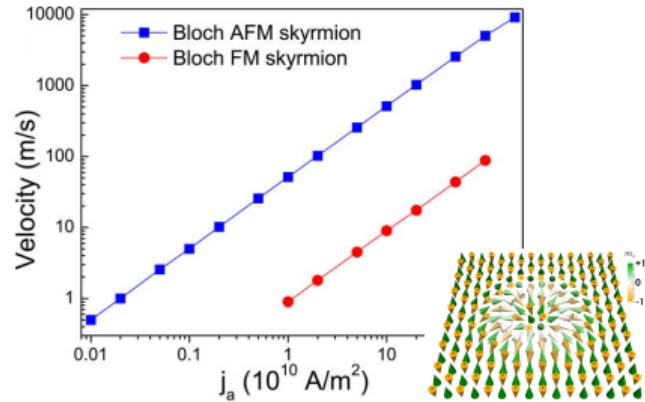
C. Jin et al. *APL* 109 (2016), 182404

X. Zhang et al. *Sci. Rep.* 6 (2016), 24795

→ Faster, lower current needed

Other approaches

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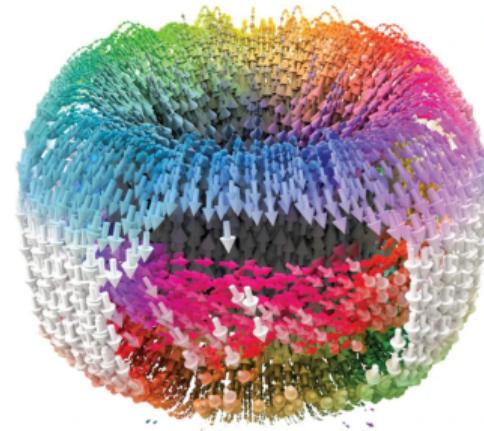


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Ferroelectrics

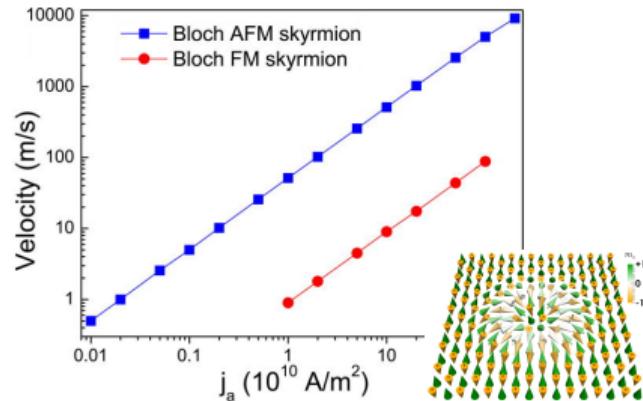


■ S. Das et al. *Nature* 568 (2019), 368–372

→ Electric control, smaller sizes

Other approaches

Antiferromagnets

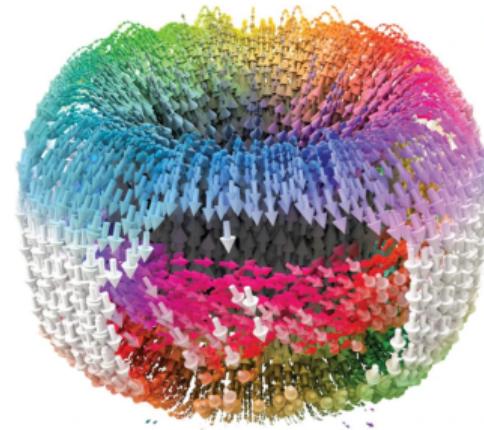


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→ Faster, lower current needed

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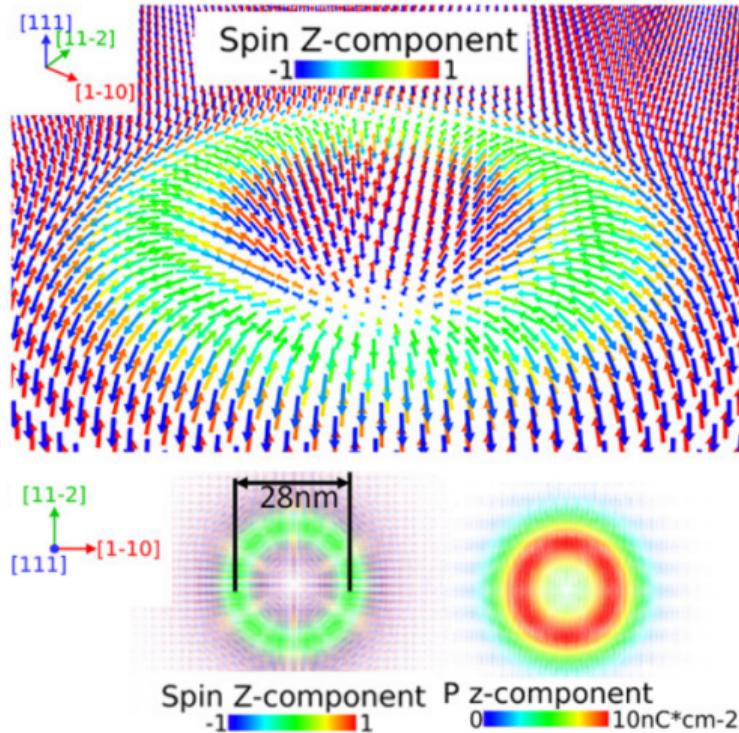


S. Das et al. *Nature* 568 (2019), 368–372

→ Electric control, smaller sizes

Combine these two directions? Multiferroics!

Simulated multiferroic skyrmion in BiFeO₃



One can nucleate and stabilize
multiferroic skyrmions in BiFeO_3
by tuning the magnetic
anisotropy in calculations.
Can we do this experimentally?

Outline

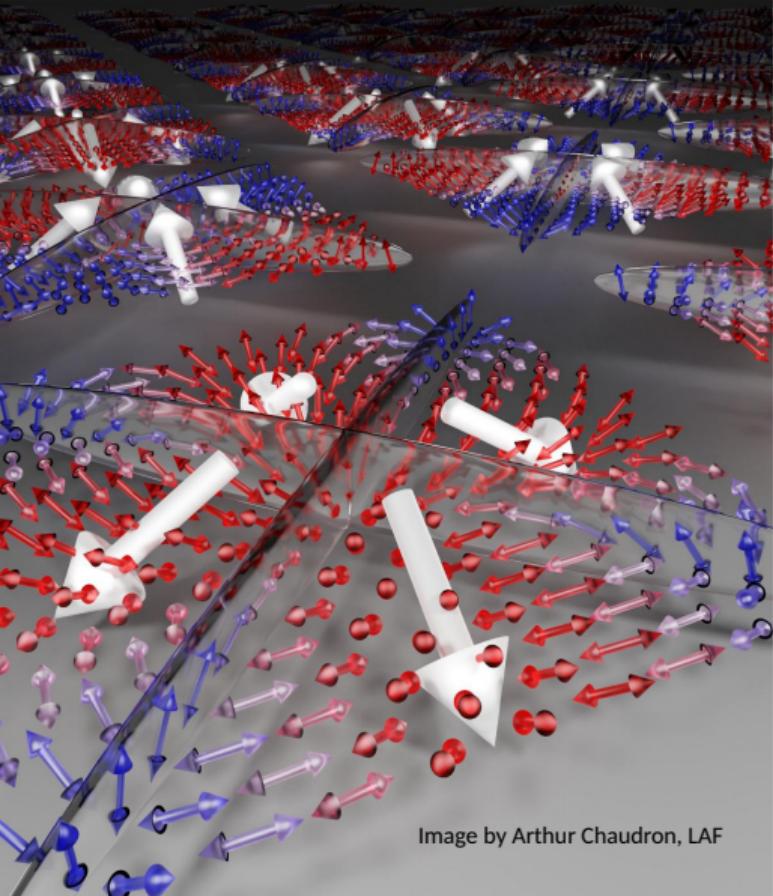


Image by Arthur Chaudron, LAF

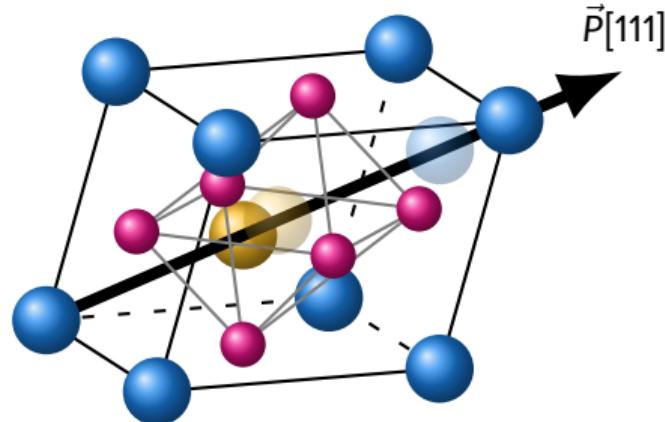
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Introduction to bismuth ferrite

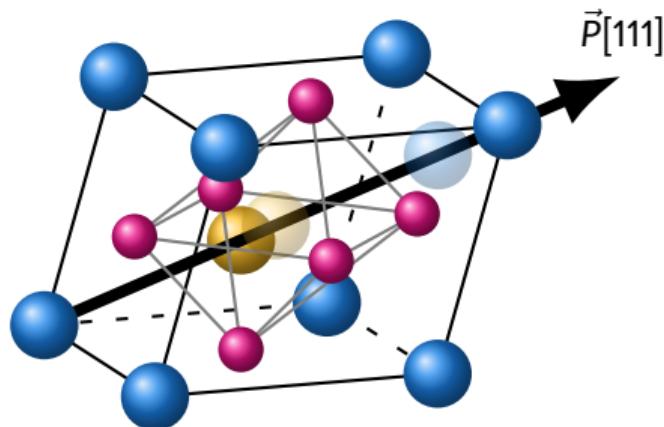
Electric polarization



Ferroelectric phase ($T < 1100$ K)

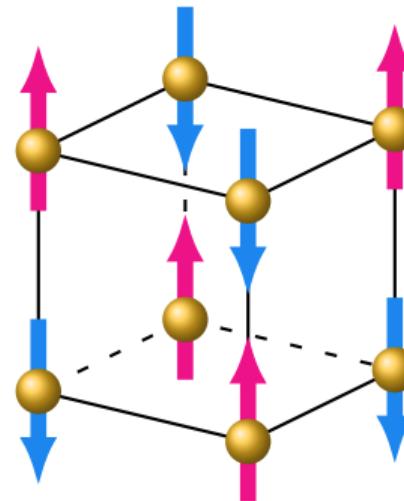
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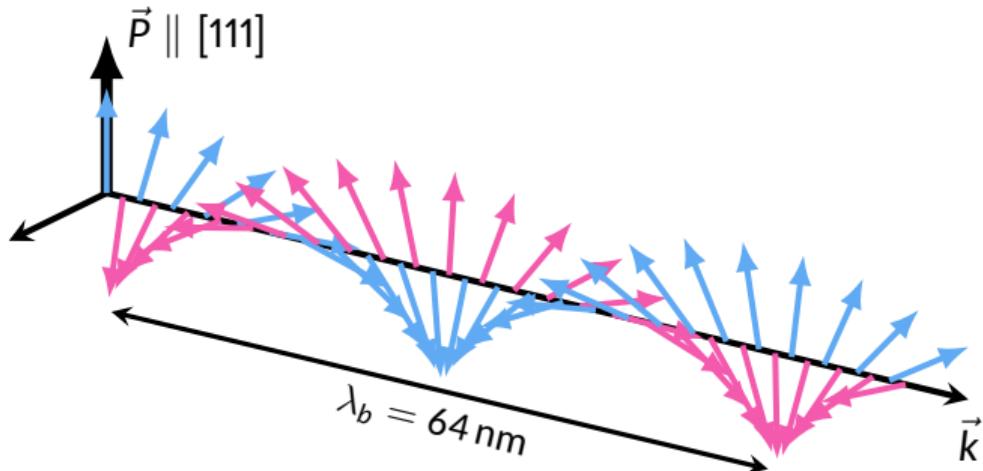
Ferroelectric phase ($T < 1100 \text{ K}$)

Magnetism



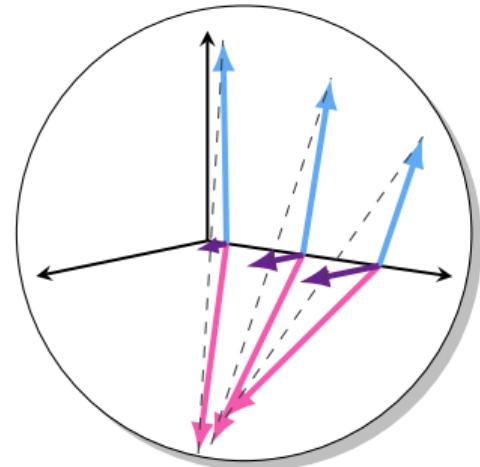
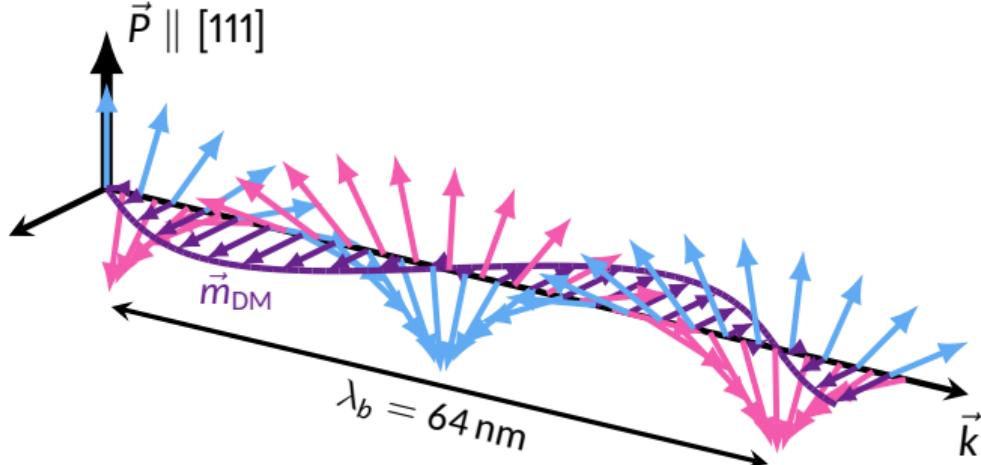
G-type antiferromagnetic
phase ($T_N = 643 \text{ K}$)

The effects of magnetoelectric coupling in BiFeO₃



Fully compensated cycloid
→ No stray field!

The effects of magnetoelectric coupling in BiFeO₃

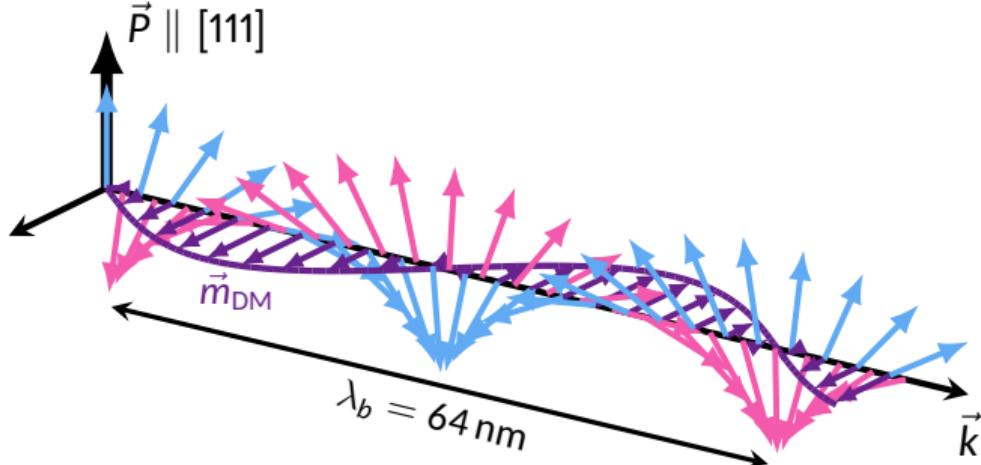


Spin density wave

Weak uncompensated moment

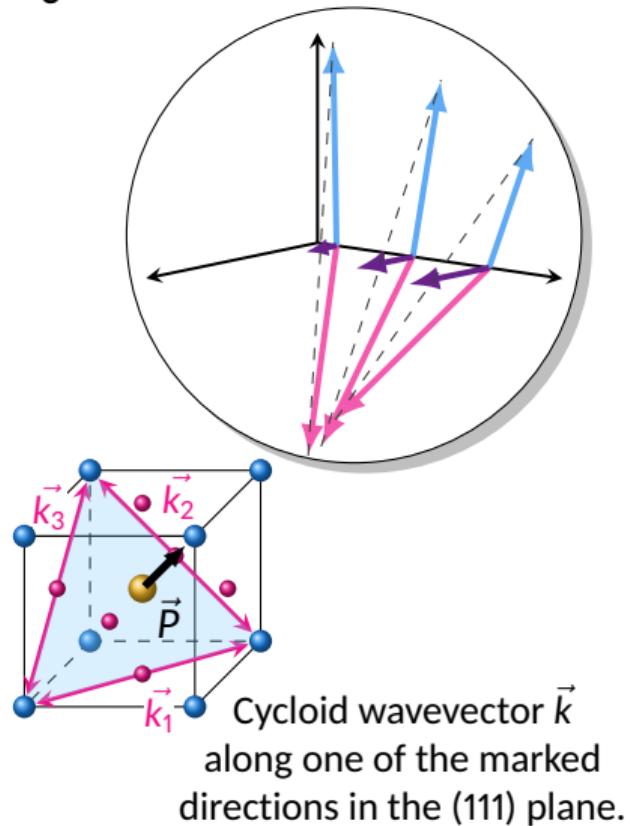
→ **Small stray field**

The effects of magnetoelectric coupling in BiFeO₃

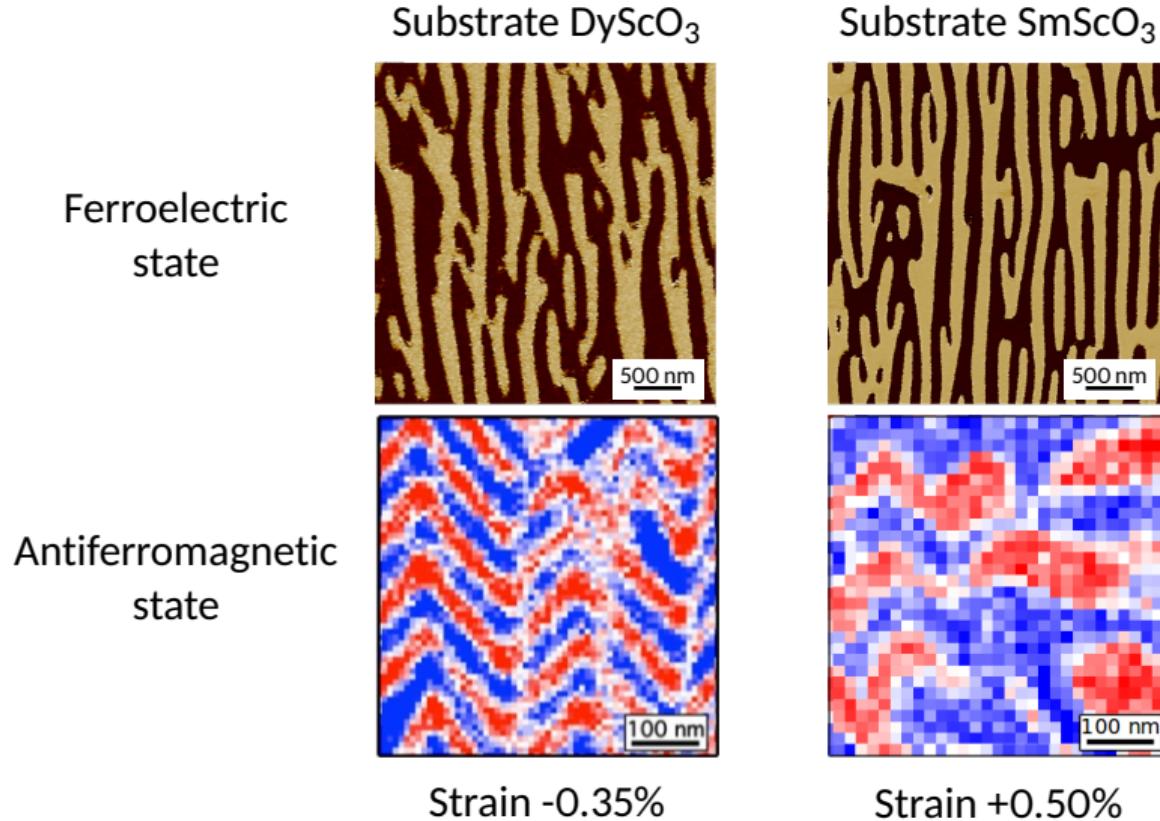


Spin density wave

Weak uncompensated moment
→ Small stray field



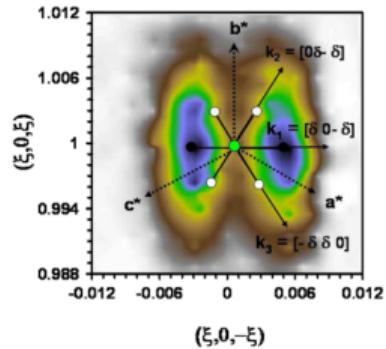
Strained BiFeO₃ films



The cycloid can be destabilized by strain.
We can control this with
the growth substrate
in thin films.

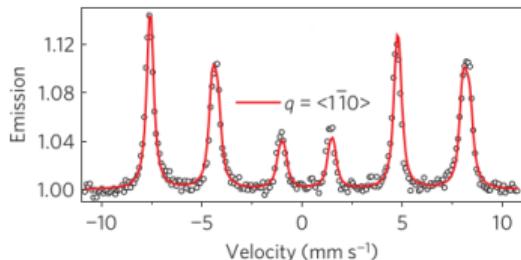
How to detect the magnetic state of BiFeO₃?

Neutron diffraction



D. Lebeugle et al. *PRL* 100 (2008), 227602

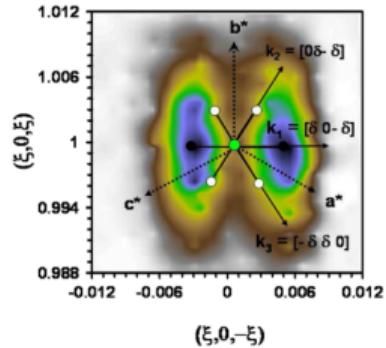
Spectroscopy (here Mössbauer)



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

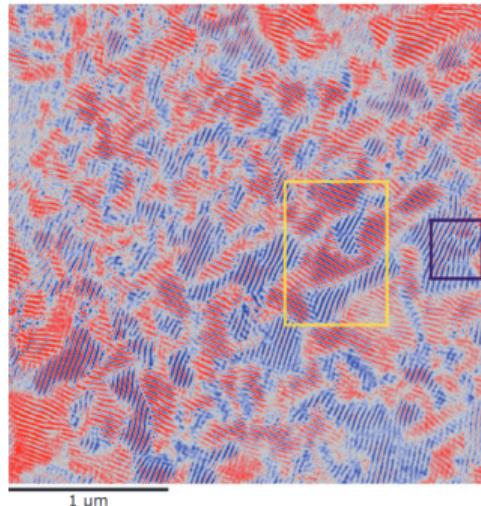
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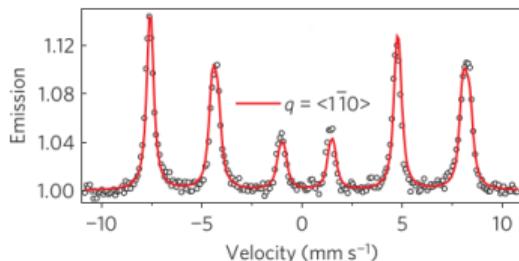
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X-ray ptychography



T. A. Butcher et al. *Adv. Mater.* (2024), 2311157

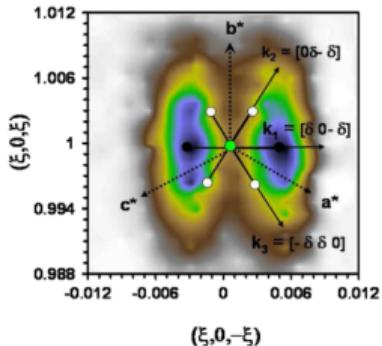
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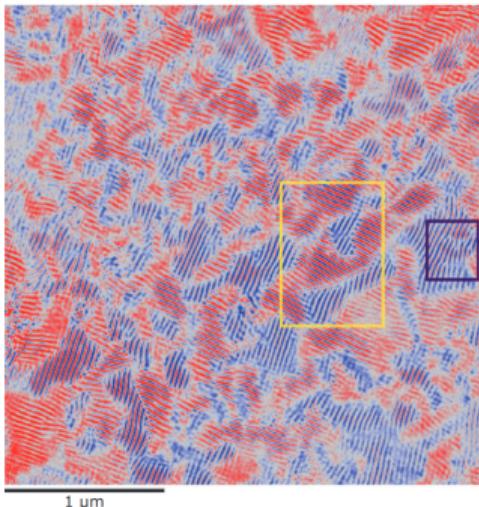
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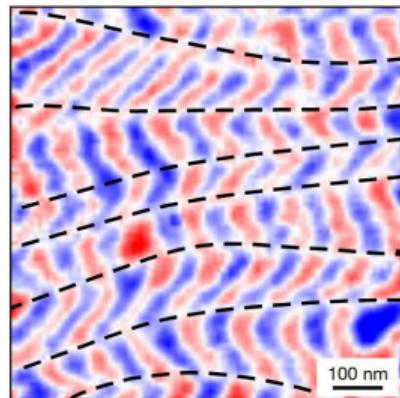
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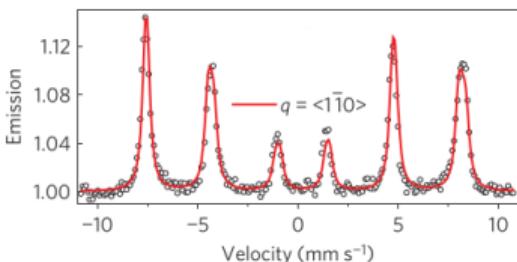
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Scanning NV center magnetometry



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

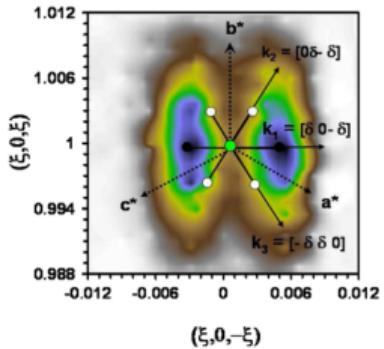
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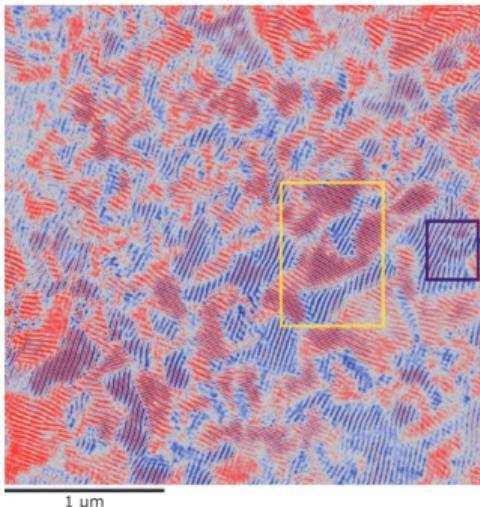
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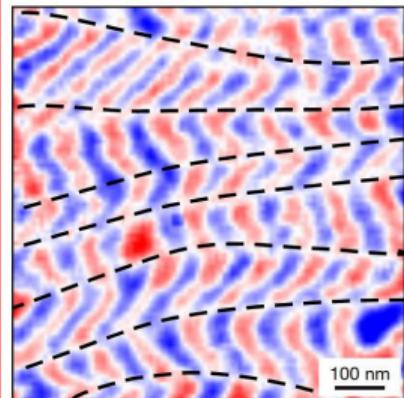
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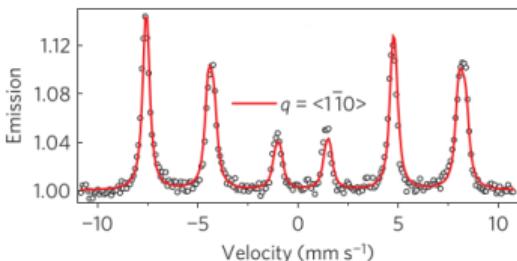
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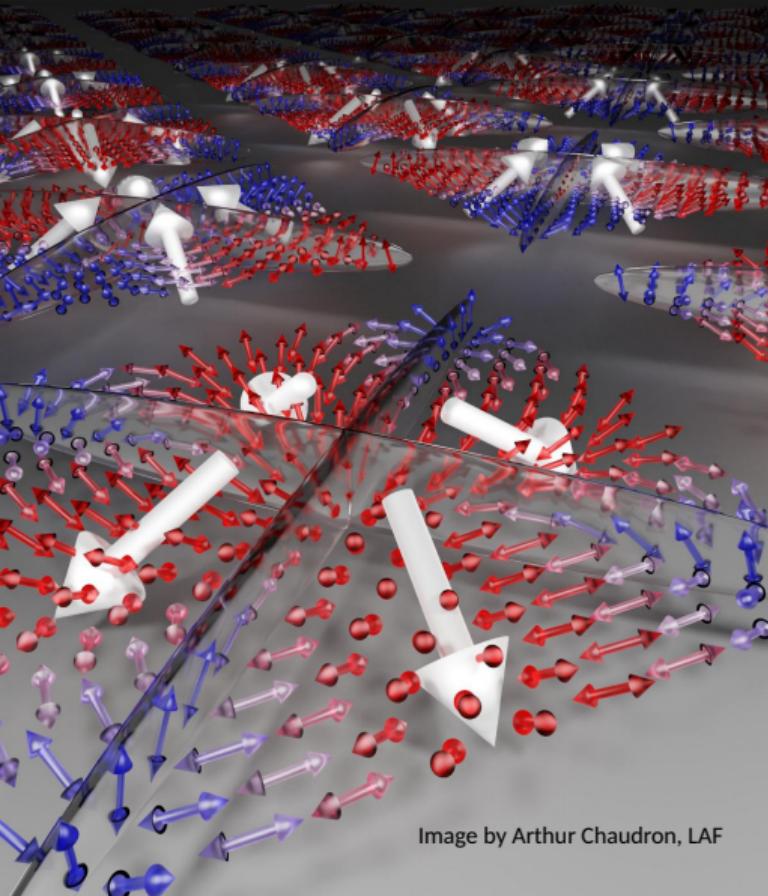


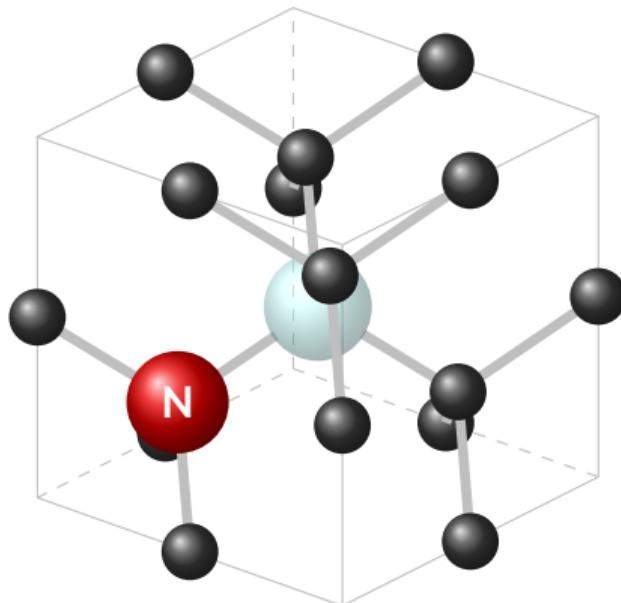
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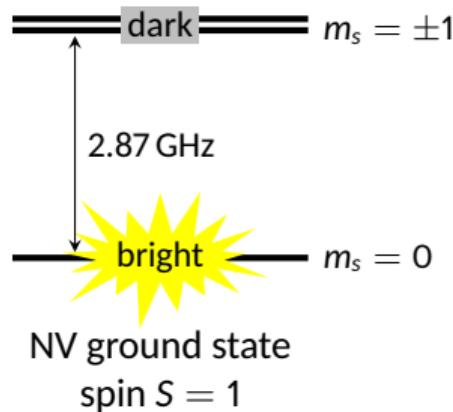
The NV center in diamond



- Artificial atom: energy levels in the diamond bandgap
- Photostable defect
- Spin $S=1$
- Individual defects can be isolated/implanted
- Ambient conditions

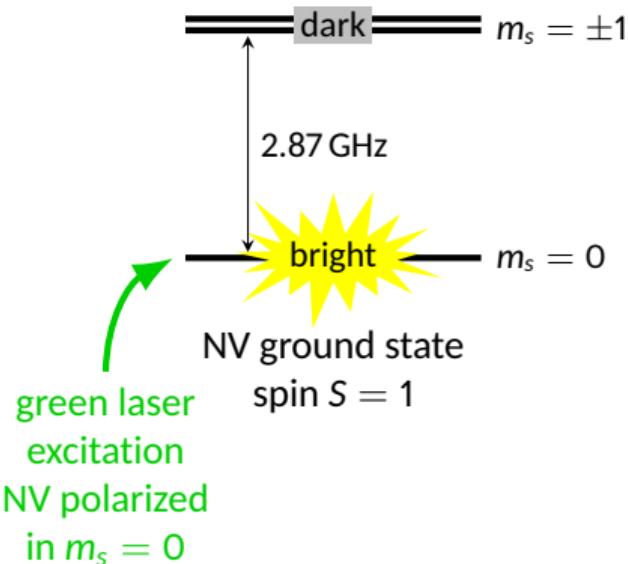
Principle of static magnetic field measurement

Spin-dependent
fluorescence

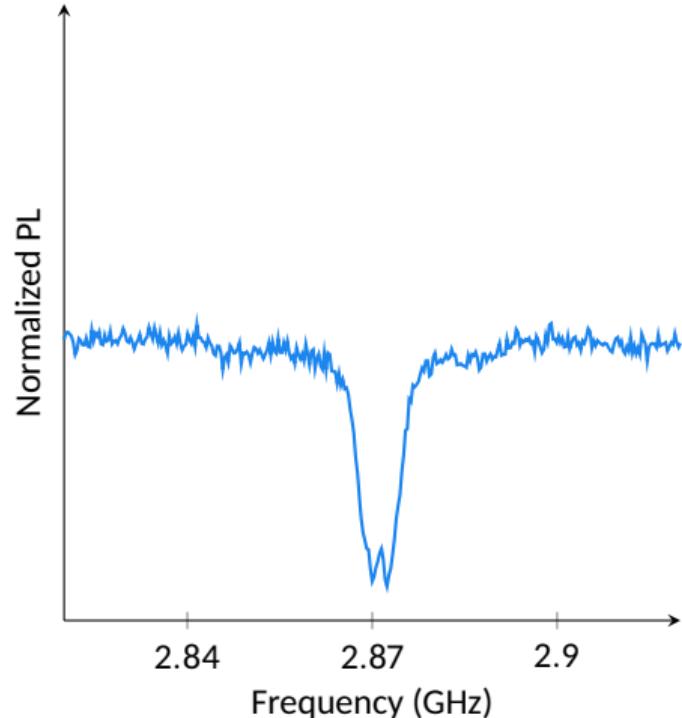
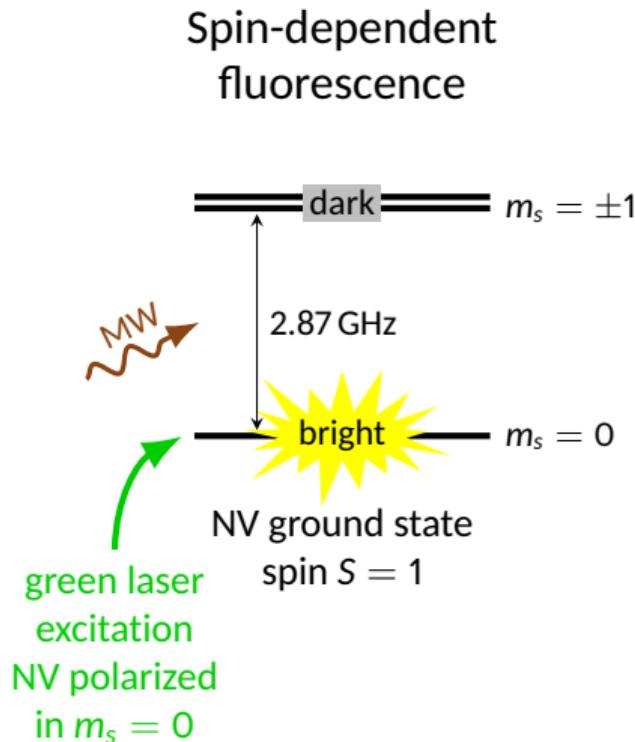


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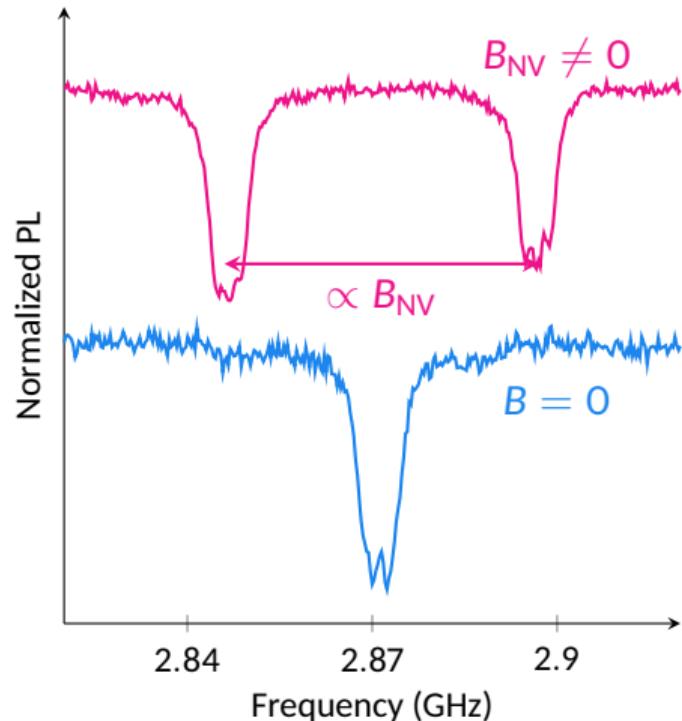
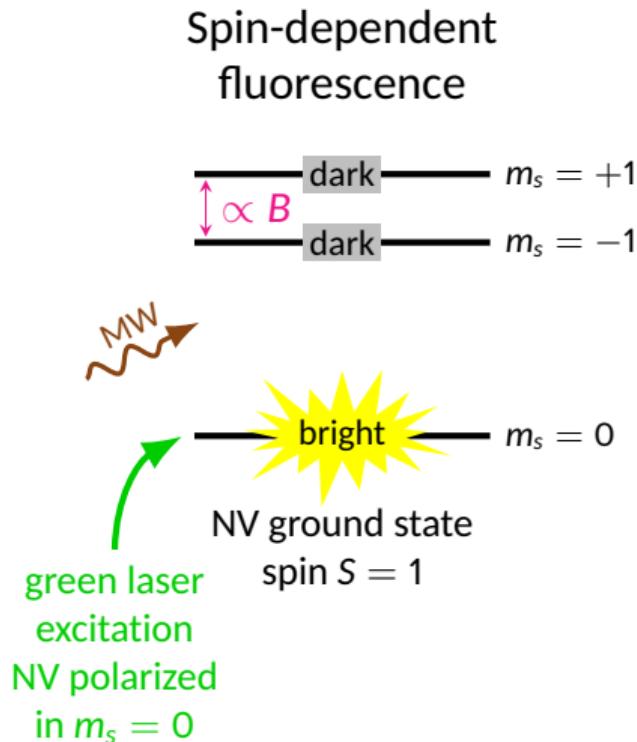
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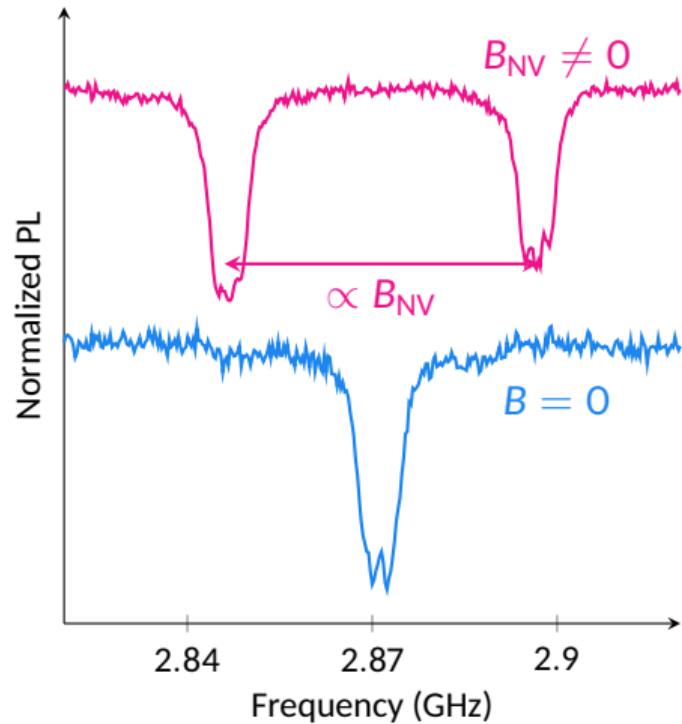
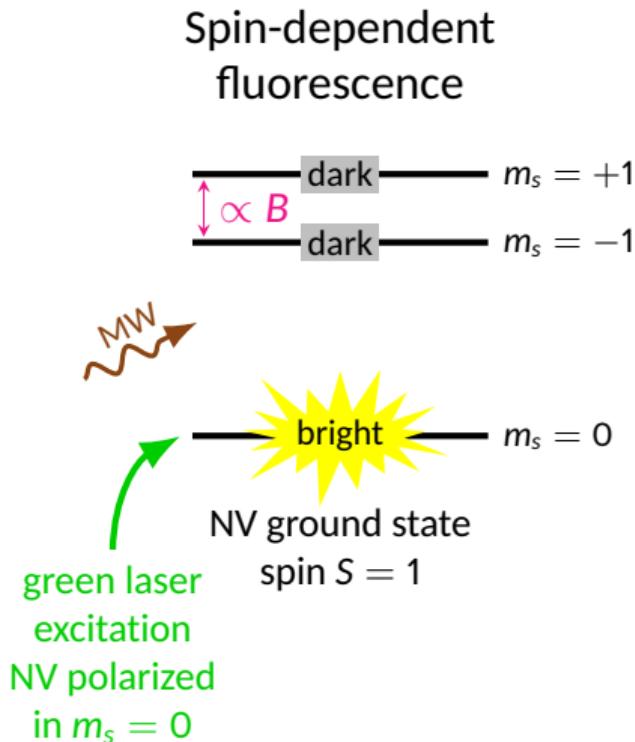
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Principle of static magnetic field measurement



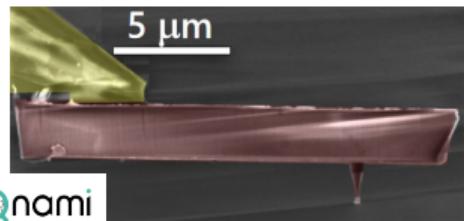
Principle of static magnetic field measurement



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

Integration of the defect in a scanning probe microscope

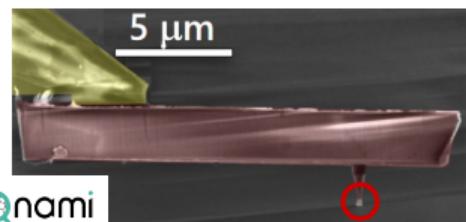
Diamond
AFM tip



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

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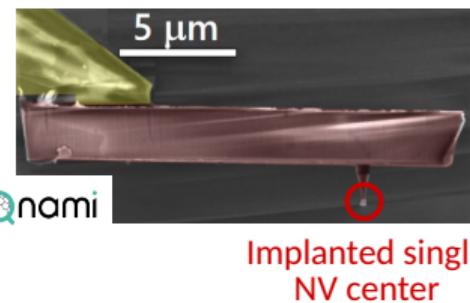
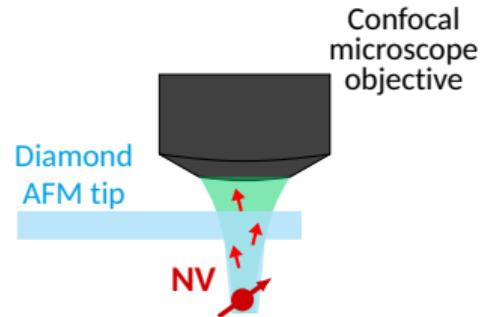
Diamond
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Implanted single
NV center

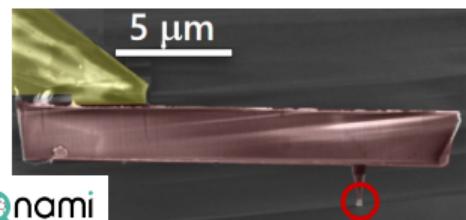
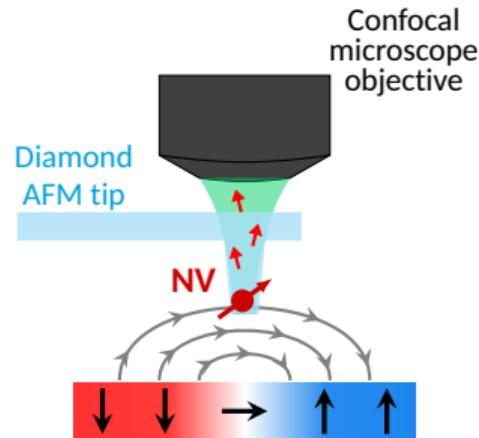
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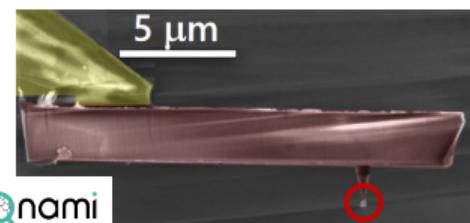
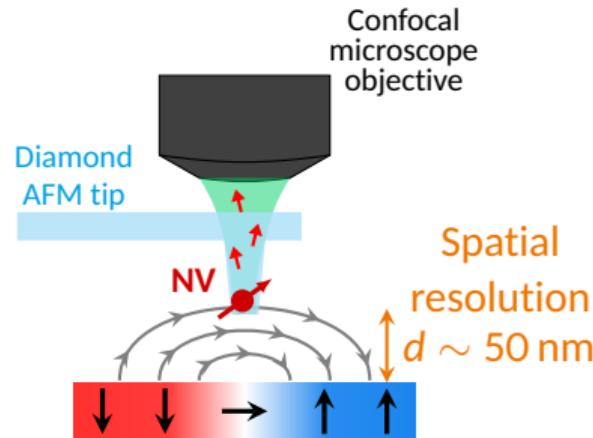
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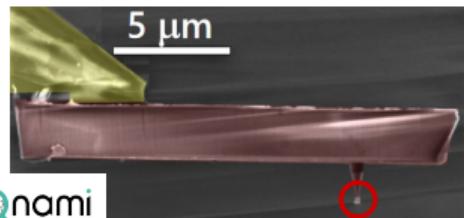
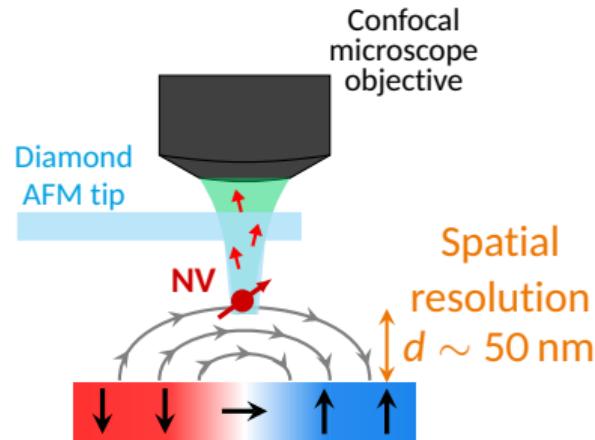
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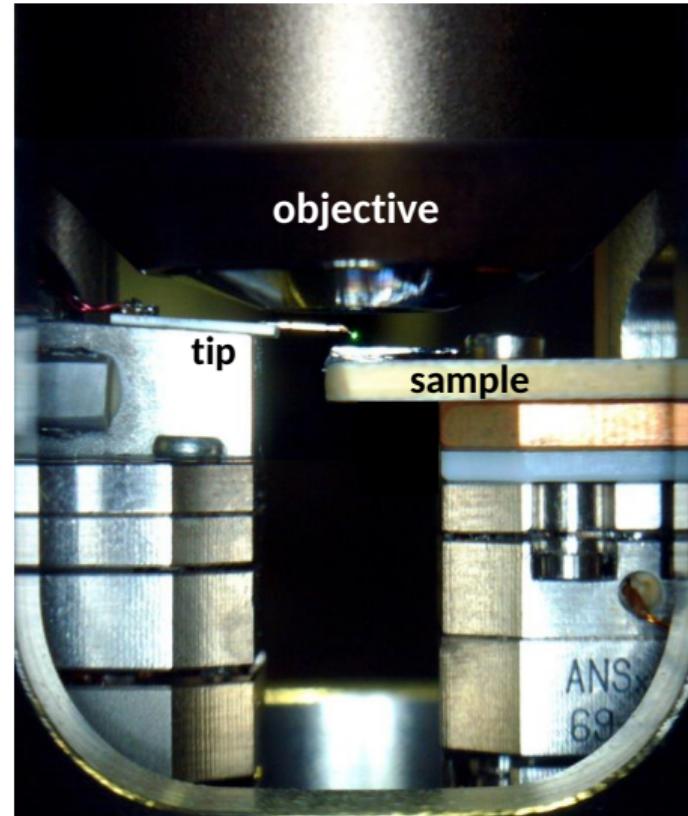
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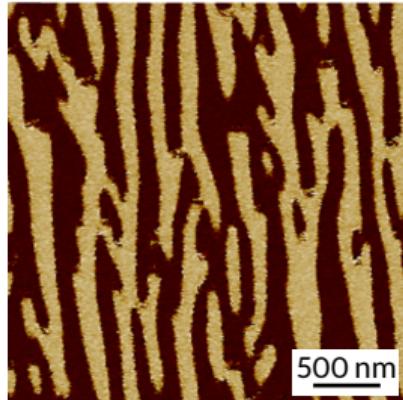


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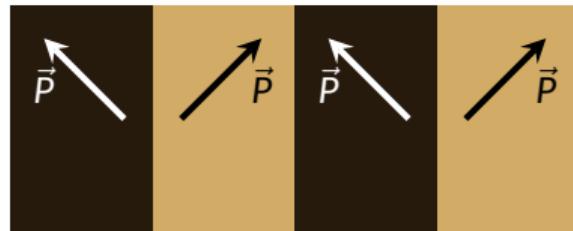


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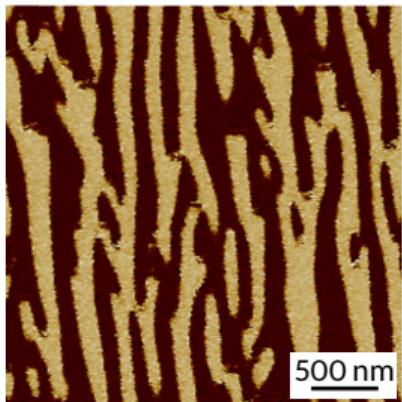
Imaging the cycloid in a low strained BiFeO₃ thin film



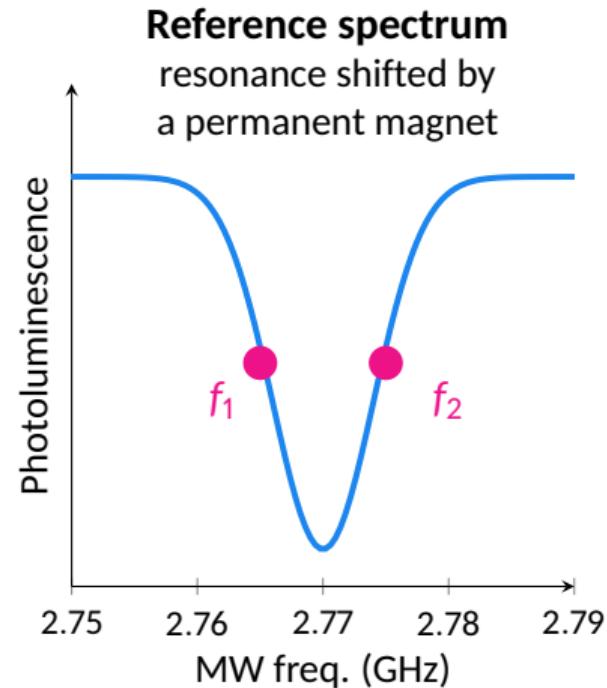
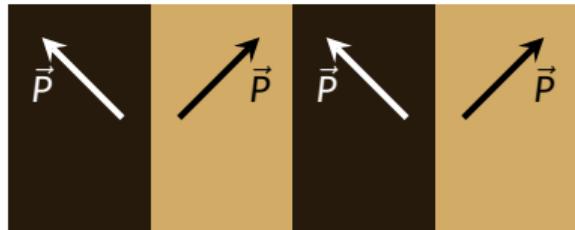
PFM image
ferroelectric domains



Imaging the cycloid in a low strained BiFeO₃ thin film

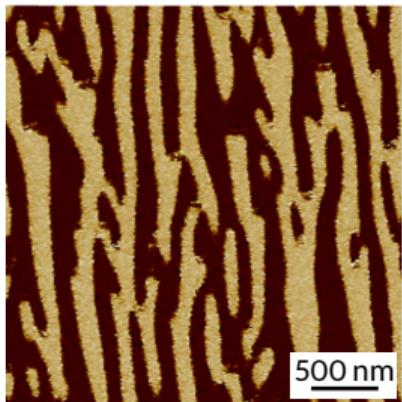


PFM image
ferroelectric domains

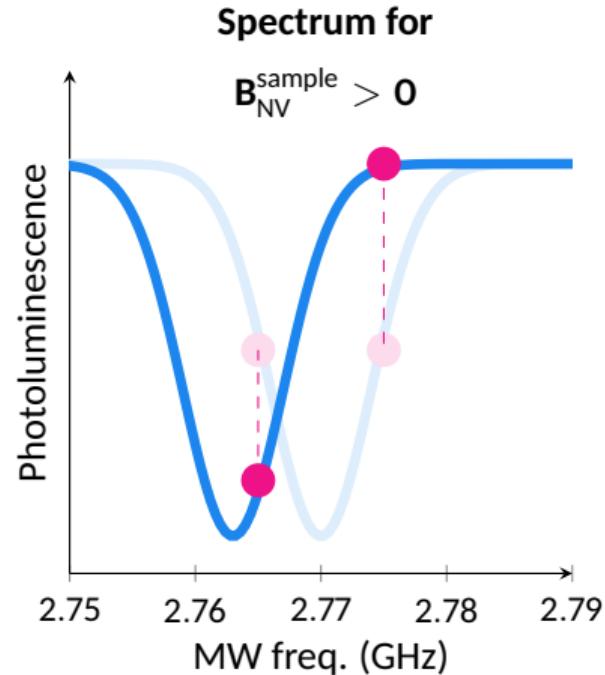
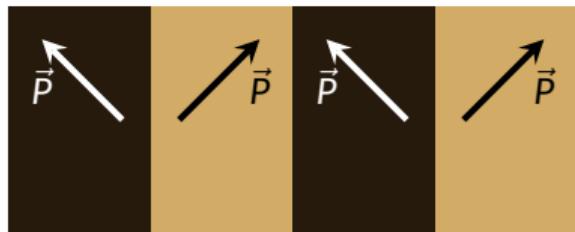


$$\Delta PL = PL(f_2) - PL(f_1)$$

Imaging the cycloid in a low strained BiFeO₃ thin film

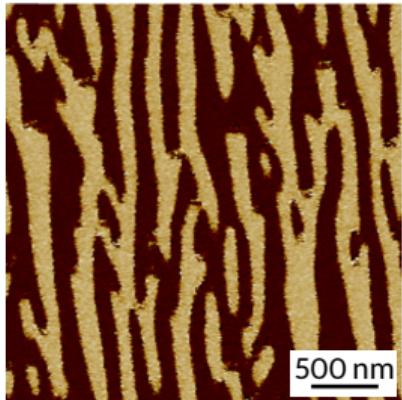


PFM image
ferroelectric domains

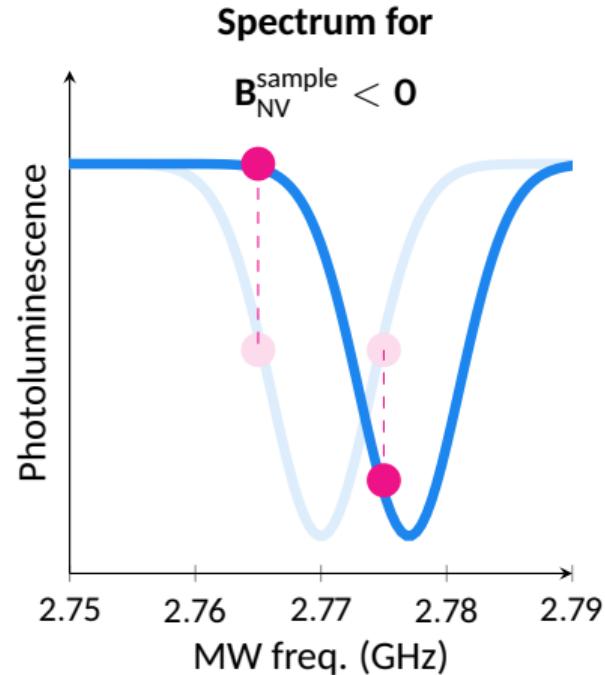
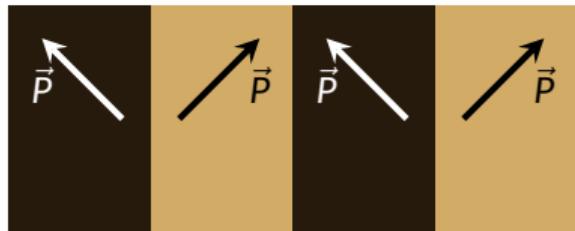


$$\Delta \text{PL} = \text{PL}(f_2) - \text{PL}(f_1)$$
$$\Delta \text{PL} > 0$$

Imaging the cycloid in a low strained BiFeO₃ thin film



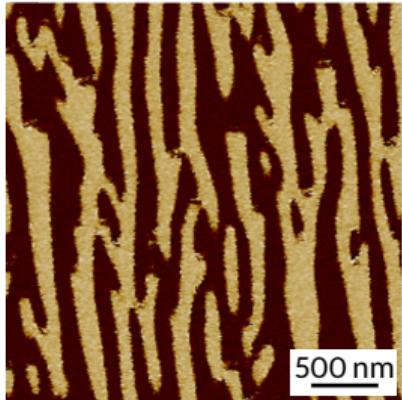
PFM image
ferroelectric domains



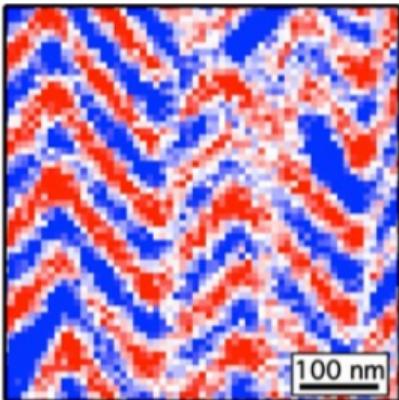
$$\Delta \text{PL} = \text{PL}(f_2) - \text{PL}(f_1)$$

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

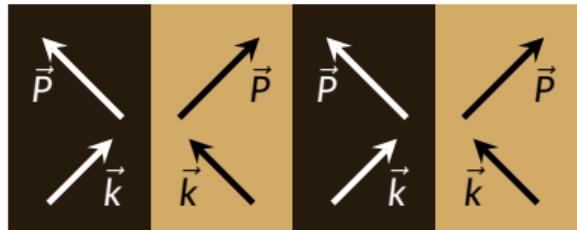
Imaging the cycloid in a low strained BiFeO₃ thin film



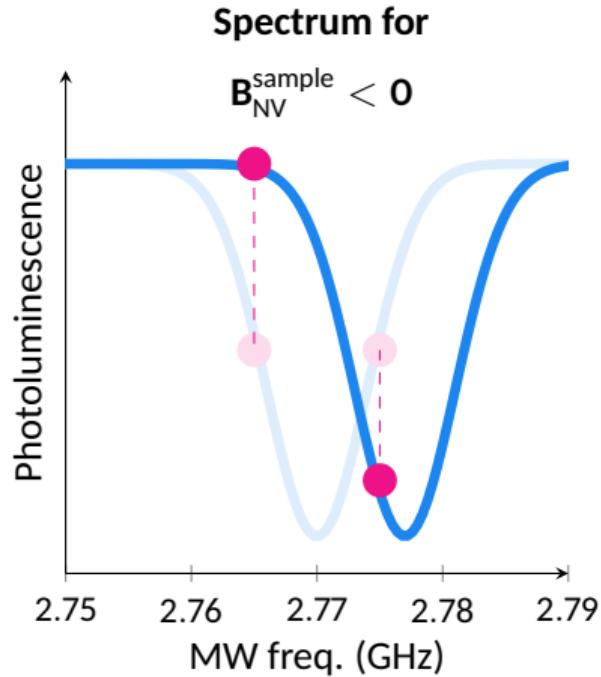
PFM image
ferroelectric domains



NV image
cycloid

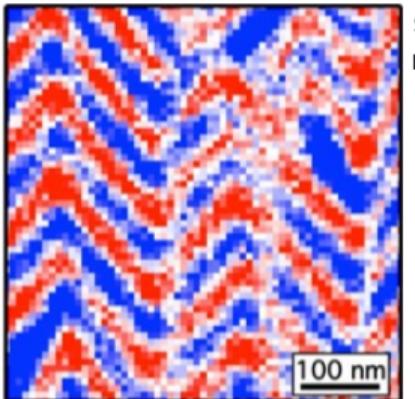
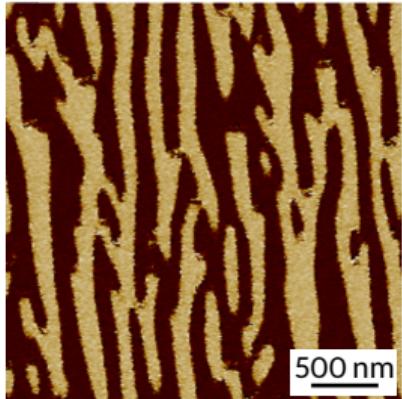


\vec{k}_1 wavevector

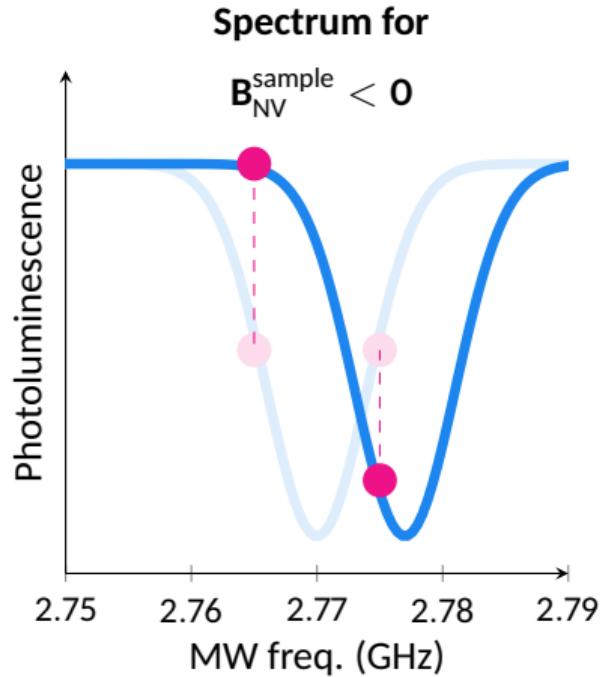
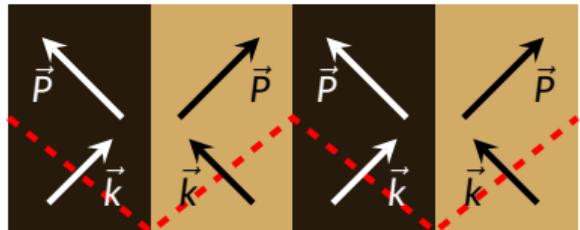


I. Gross et al. *Nature* 549 (2017), 252

Imaging the cycloid in a low strained BiFeO₃ thin film



\vec{k}_1 wavevector



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

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

Outline

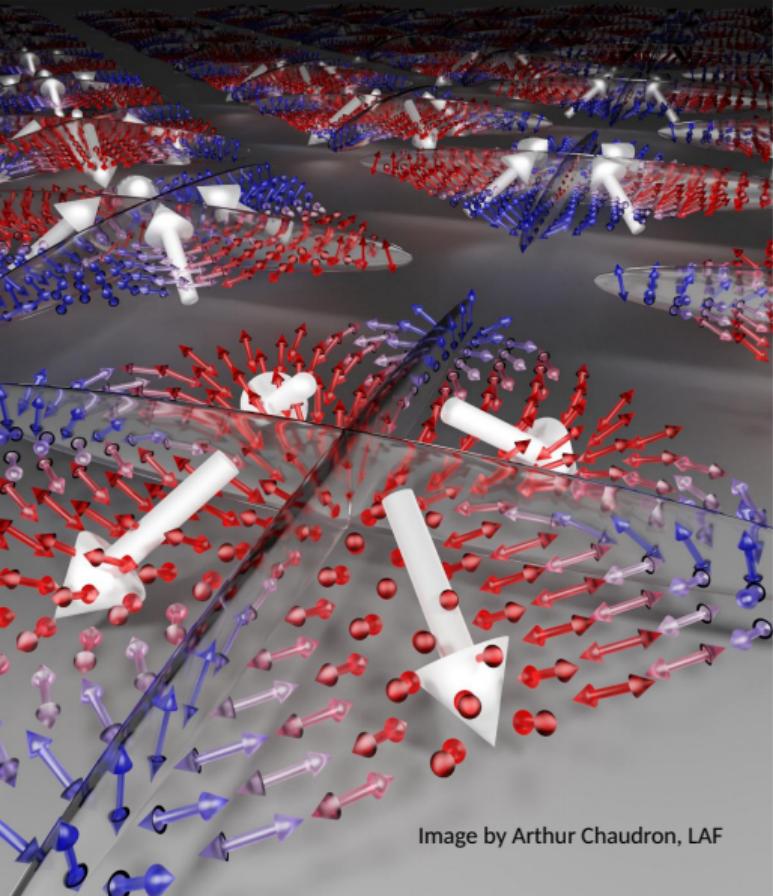
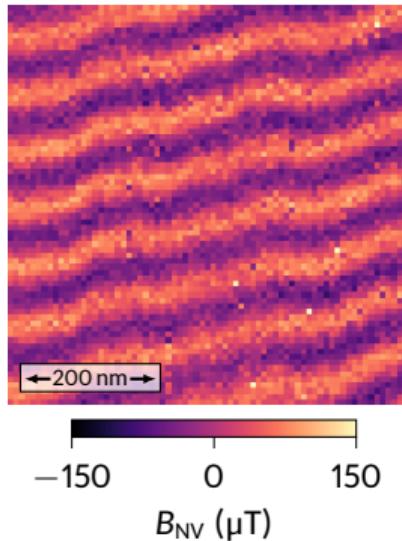


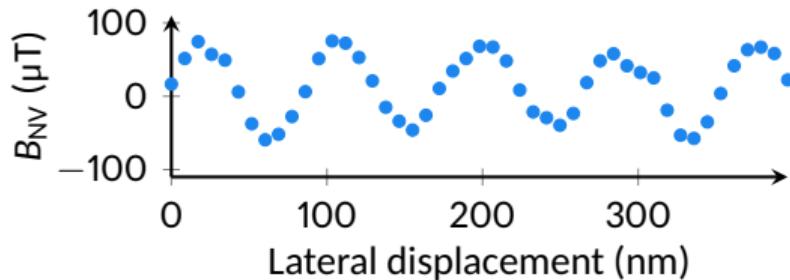
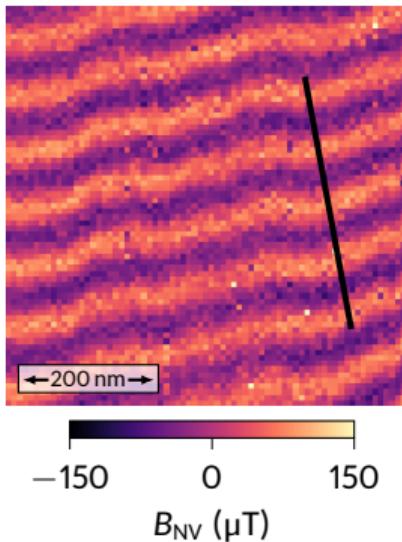
Image by Arthur Chaudron, LAF

1. Ferroic whirling textures
2. Bismuth ferrite, a room temperature multiferroic
3. Scanning NV center magnetometry
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 A. Finco et al. *PRL* 128 (2022), 187201
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 A. Chaudron et al. *Nat. Mater.* 23 (2024), 905

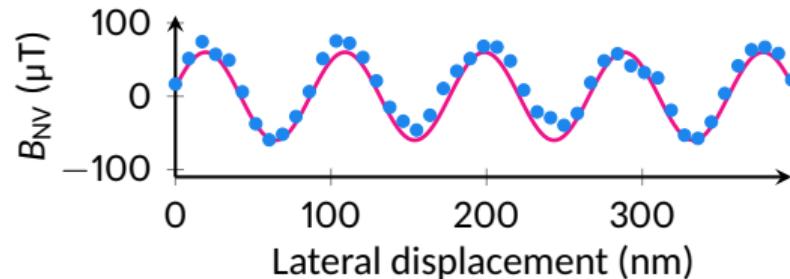
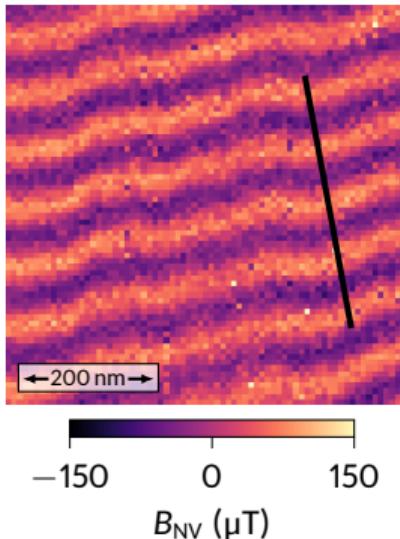
Quantitative analysis of the cycloid in bulk single crystal



Quantitative analysis of the cycloid in bulk single crystal



Quantitative analysis of the cycloid in bulk single crystal

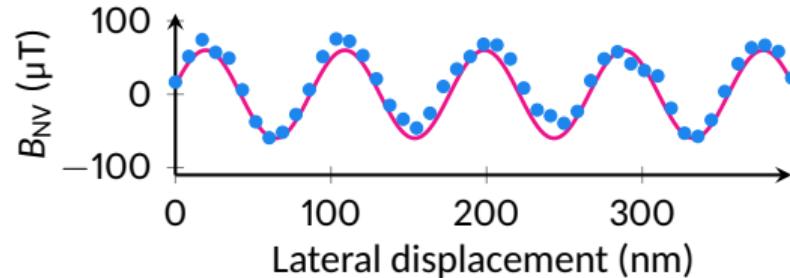
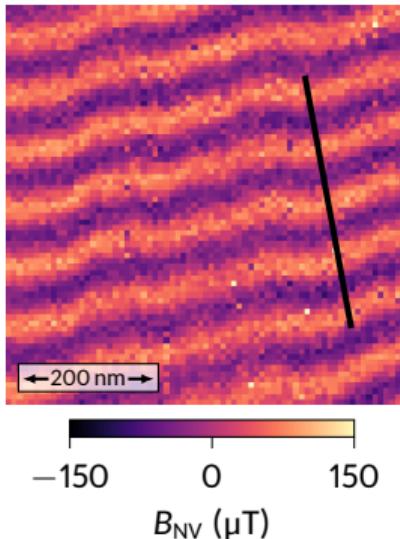


$$\begin{cases} B_x = 0 \\ B_y = -\frac{A}{\sqrt{2}} (\text{Re}\{S\} - \text{Im}\{S\}) \\ B_z = \sqrt{2} A \text{Re}\{S\} \end{cases}$$

with

$$\begin{cases} A = \frac{\mu_0 m_{\text{DM}}}{\sqrt{3} a^3} \sinh\left(\frac{ka}{2\sqrt{2}}\right) \\ S = e^{-kz/\sqrt{2}} e^{ik(y-z)/\sqrt{2}} \frac{1 - e^{-kt(1+i)/\sqrt{2}}}{1 - e^{-ka(1+i)/\sqrt{2}}} \end{cases}$$

Quantitative analysis of the cycloid in bulk single crystal



$$m_{\text{DM}} = 0.09 \pm 0.03 \mu\text{B}$$

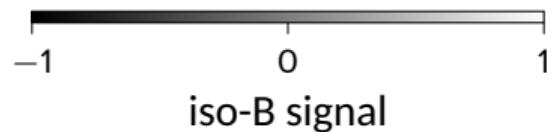
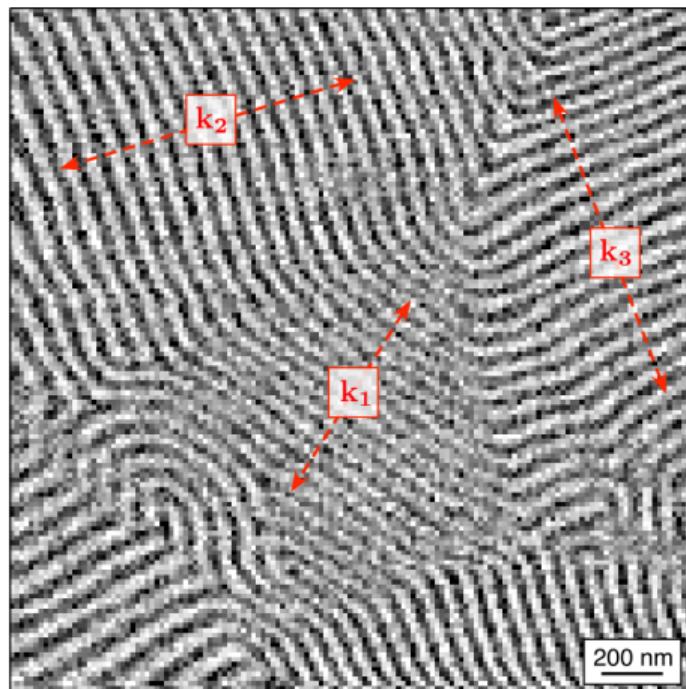
M. Ramazanoglu et al. PRL 107 (2011), 207206

$$\begin{cases} B_x = 0 \\ B_y = -\frac{A}{\sqrt{2}} (\text{Re}\{S\} - \text{Im}\{S\}) \\ B_z = \sqrt{2} A \text{Re}\{S\} \end{cases}$$

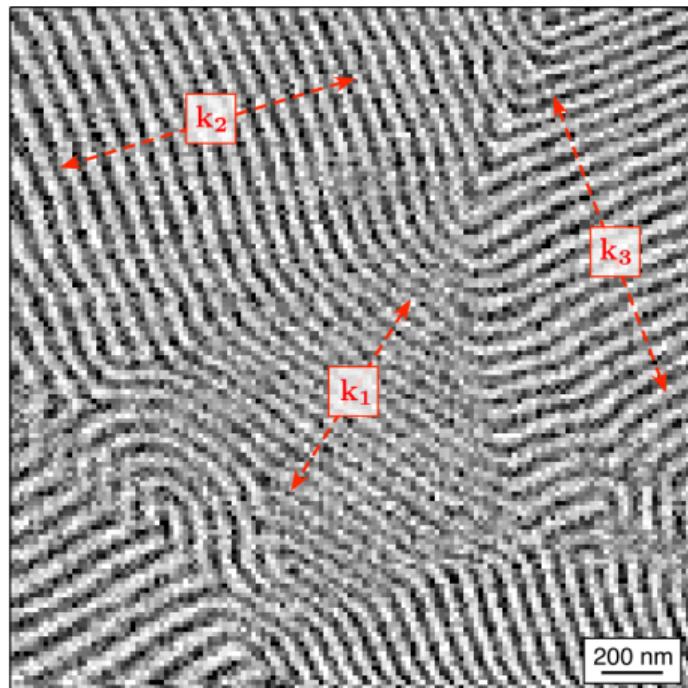
with

$$\begin{cases} A = \frac{\mu_0 m_{\text{DM}}}{\sqrt{3} a^3} \sinh\left(\frac{ka}{2\sqrt{2}}\right) \\ S = e^{-kz/\sqrt{2}} e^{ik(y-z)/\sqrt{2}} \frac{1 - e^{-kt(1+i)/\sqrt{2}}}{1 - e^{-ka(1+i)/\sqrt{2}}} \end{cases}$$

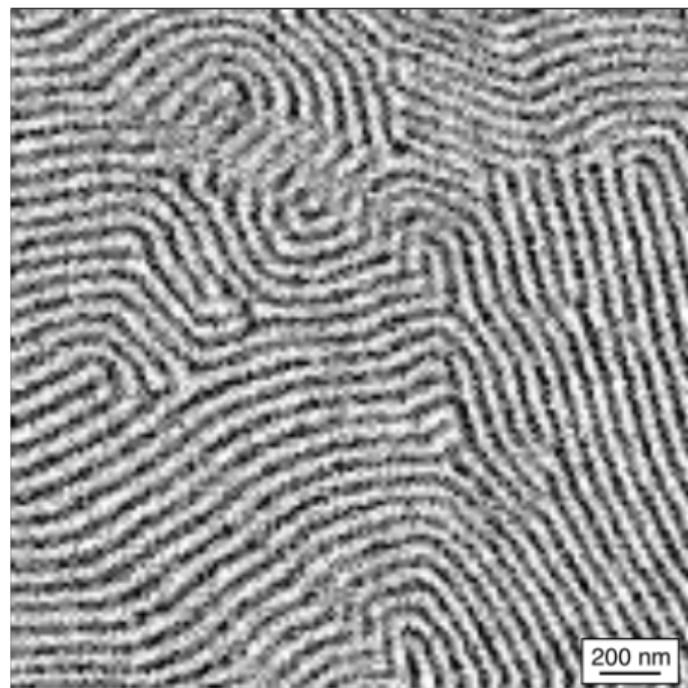
Rotation of the cycloid propagation direction measured in real space...



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



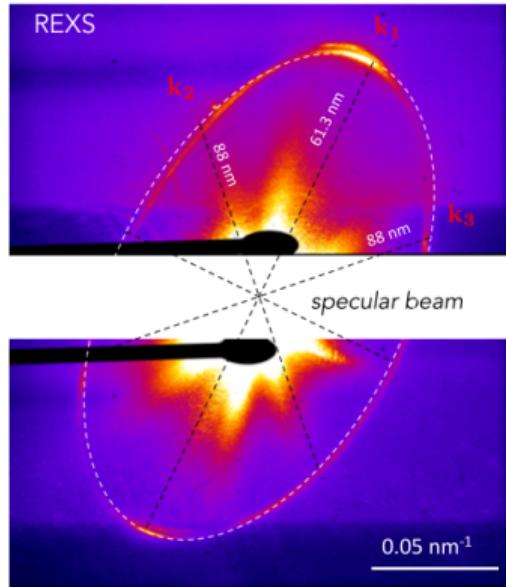
iso-B signal



iso-B signal

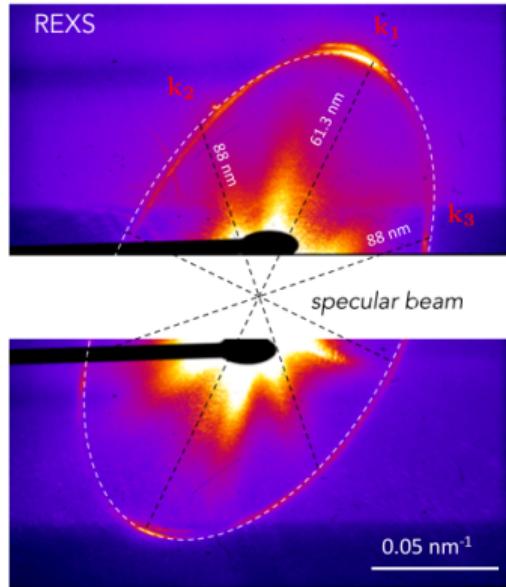
... and in reciprocal space

Resonant X-ray scattering

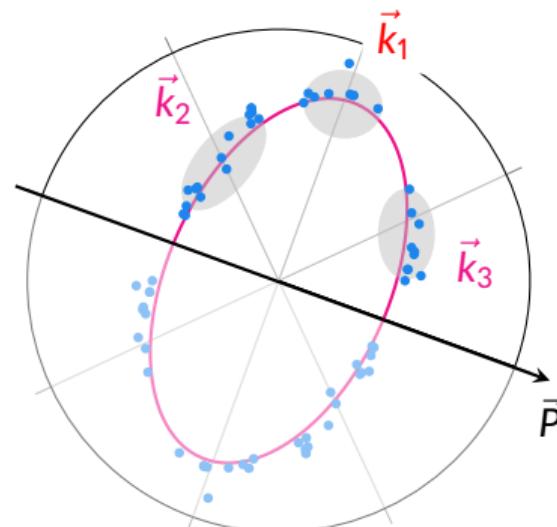


... and in reciprocal space

Resonant X-ray scattering

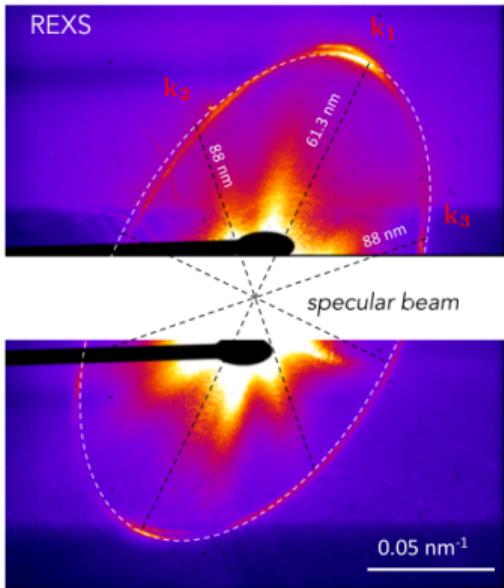


Polar plot of $\frac{2\pi}{\lambda}$ vs \vec{k} direction

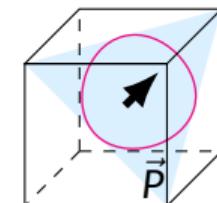
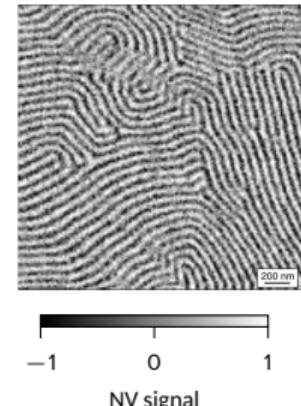
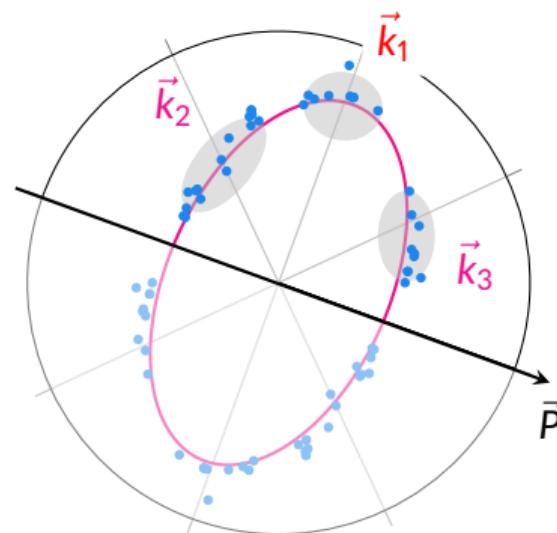


... and in reciprocal space

Resonant X-ray scattering

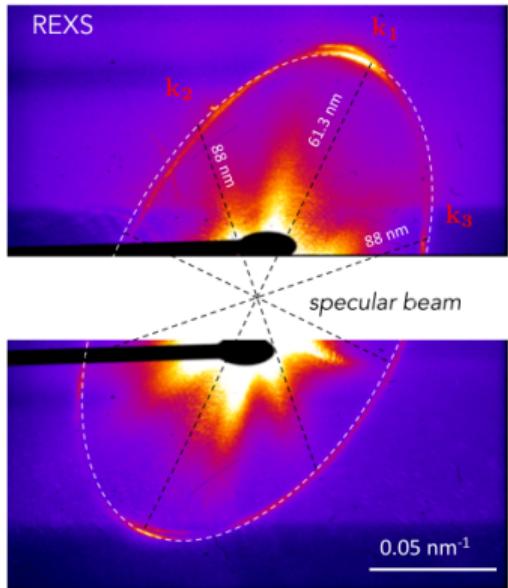


Polar plot of $\frac{2\pi}{\lambda}$ vs \vec{k} direction

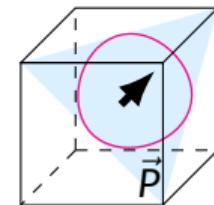
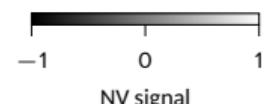
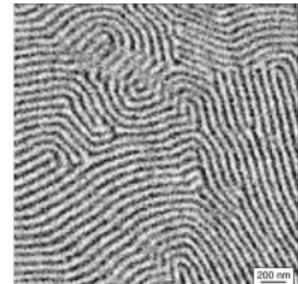
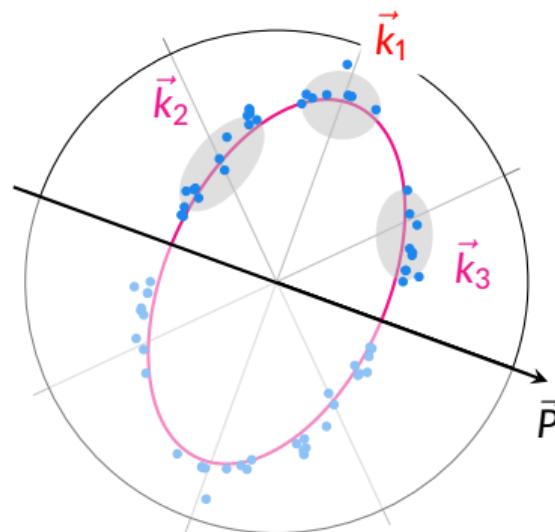


... and in reciprocal space

Resonant X-ray scattering



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



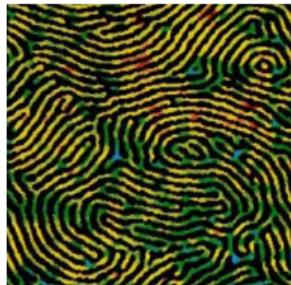
Surface effect? Only \vec{k}_1 seen by neutrons

D. Lebeugle et al. PRL 100 (2008), 227602

Universal patterns in lamellar systems

Block copolymer

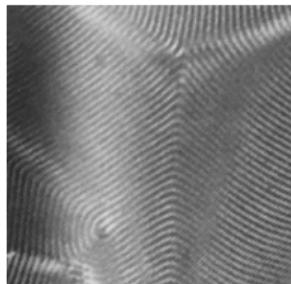
Period 40 nm



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

Liquid crystals

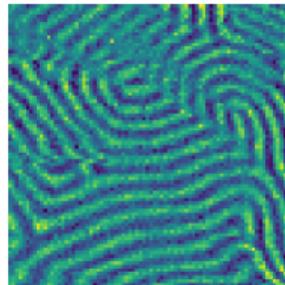
Period 800 nm



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

BiFeO₃ magnetic cycloid

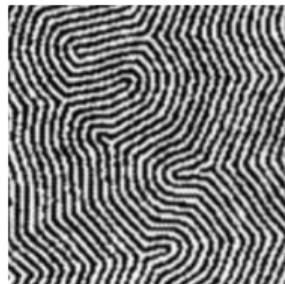
Period 64 nm



A. Finco et al. *PRL* 128 (2022), 187201

Ferrimagnetic garnet

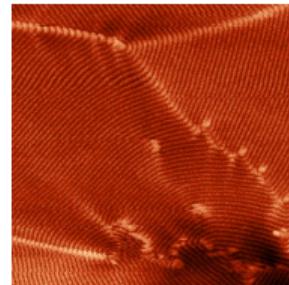
Period 8 μm



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

FeGe magnetic helix

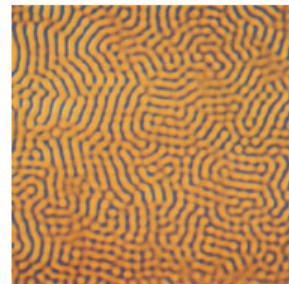
Period 70 nm



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

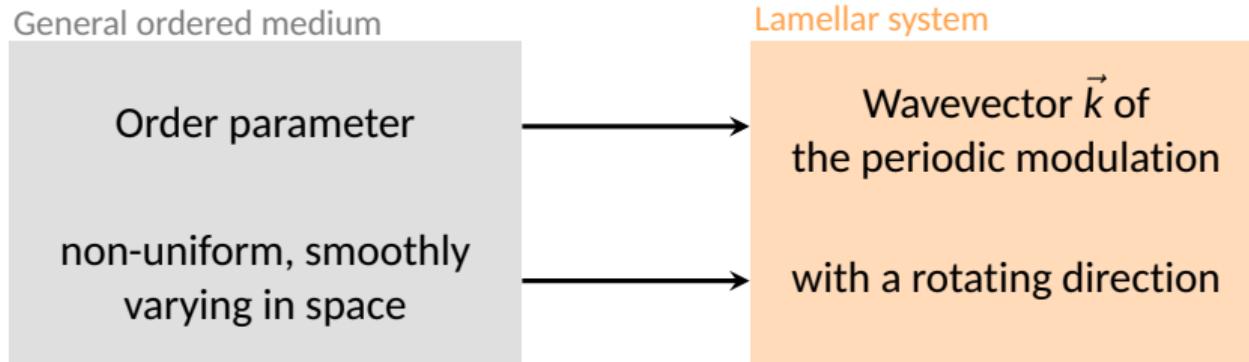
Fluid diffusion

Period 250 μm

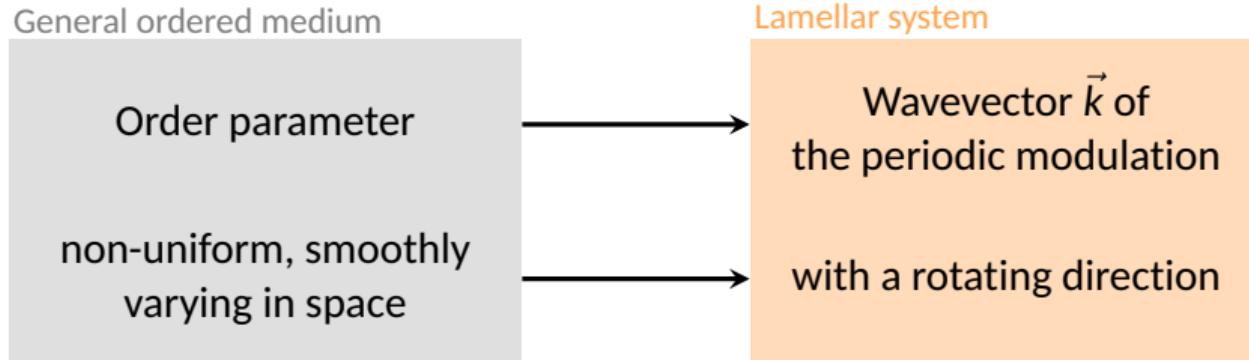


Q. Ouyang et al. *Chaos* 1 (1991), 411

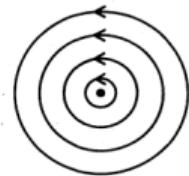
Topological defects in lamellar systems



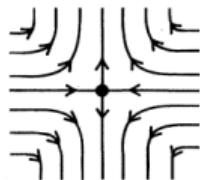
Topological defects in lamellar systems



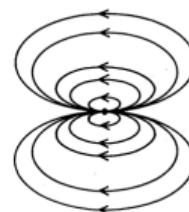
except at **singular regions of lower dimensionality** → **topological defects**



disclination
winding number = 1

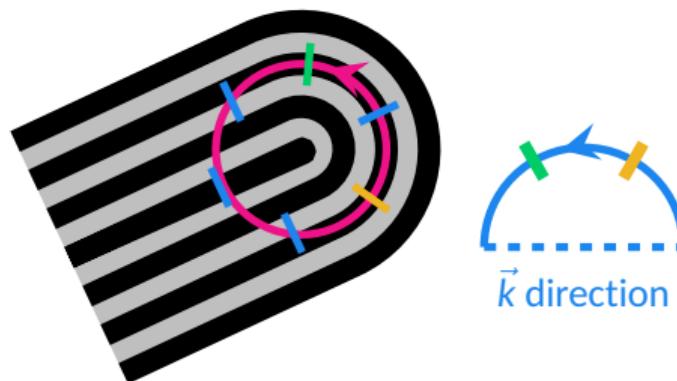
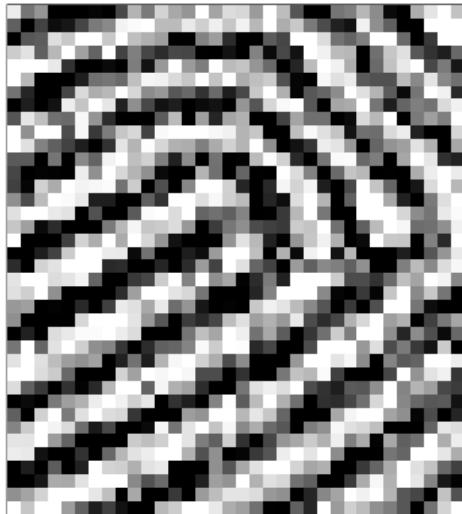


disclination
winding number = -1



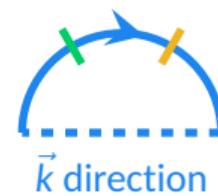
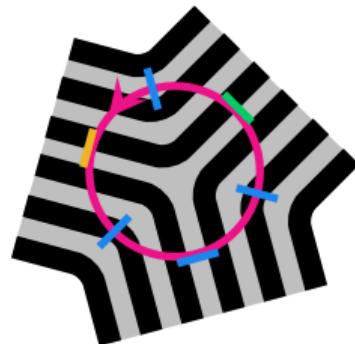
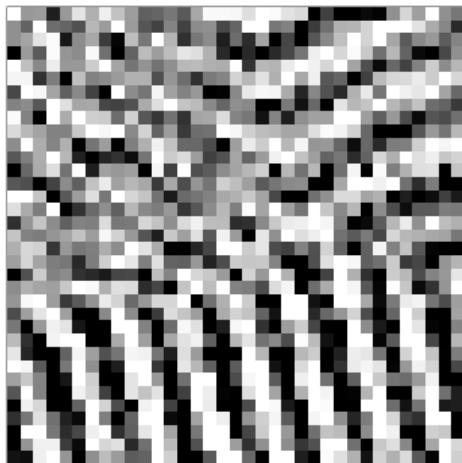
disclination
winding number = 2

$+\pi$ -disclination



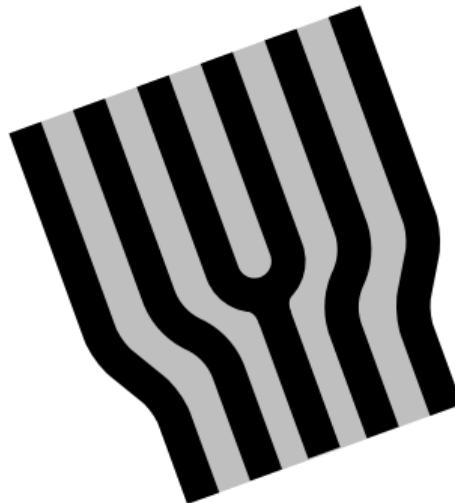
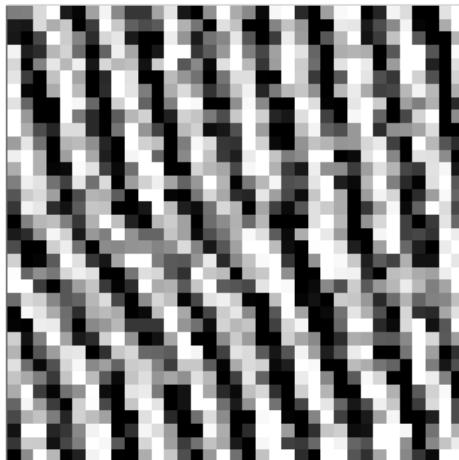
winding number $+1/2$

$-\pi$ -disclination



winding number $-1/2$

Edge dislocation



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

winding number 0

Outline

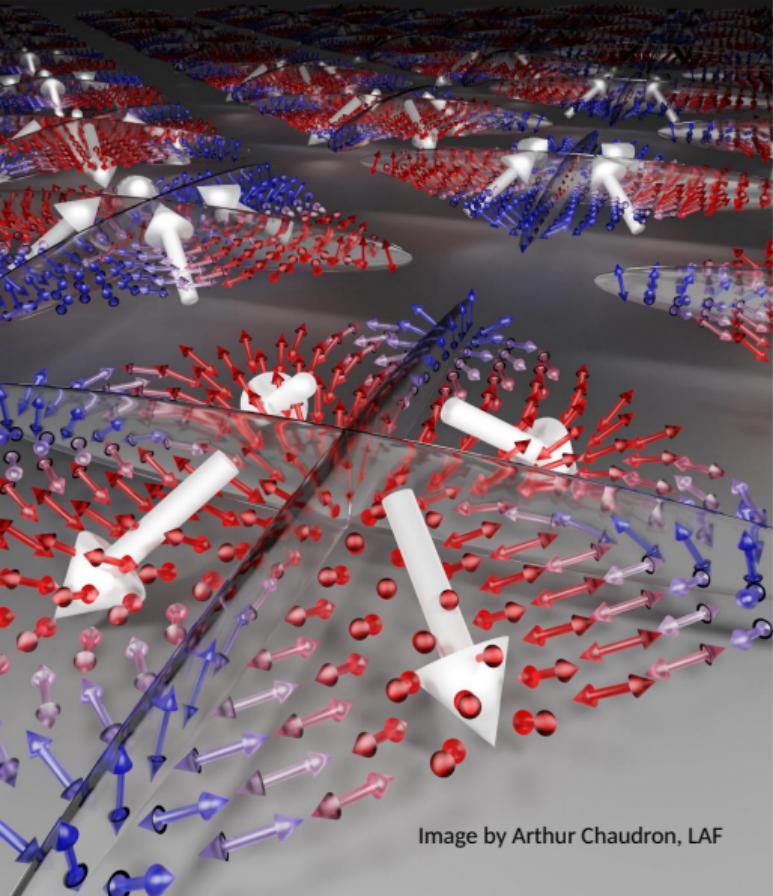


Image by Arthur Chaudron, LAF

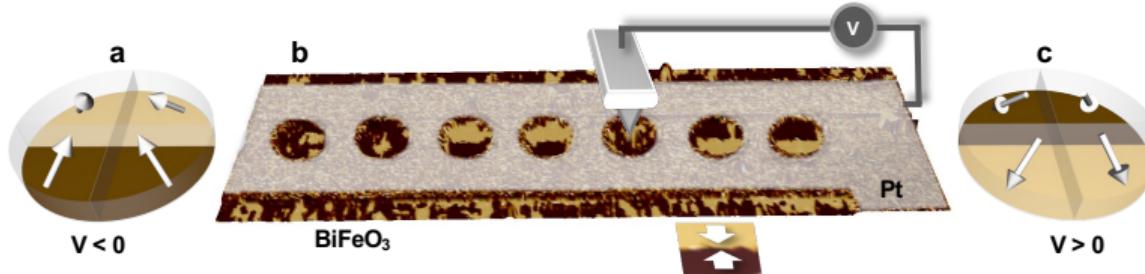
1. Ferroic whirling textures
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3. Scanning NV center magnetometry
4. Antiferromagnetic topological defects in bulk BiFeO_3
5. Creation of multiferroic solitons in BiFeO_3 microstructures

 A. Finco et al. *PRL* 128 (2022), 187201

 A. Chaudron et al. *Nat. Mater.* 23 (2024), 905

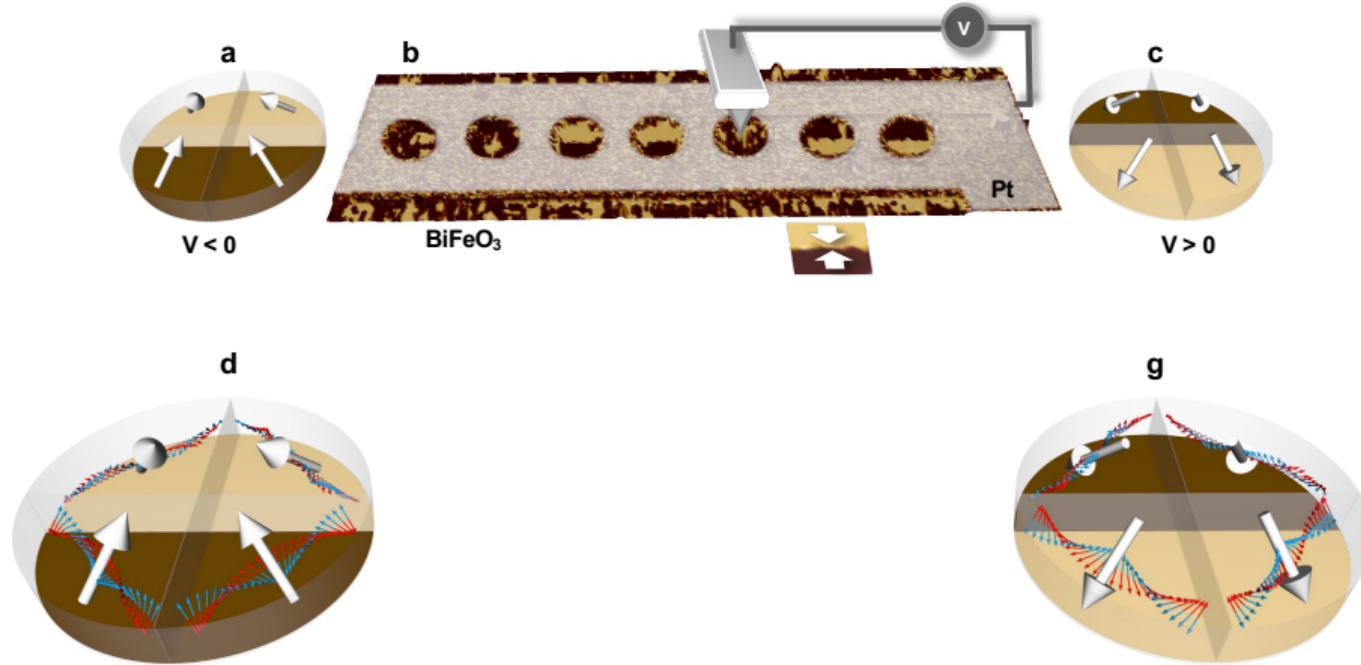
Towards topological textures

Objective: use the magnetoelectric coupling to stabilize an antiferromagnetic topological state



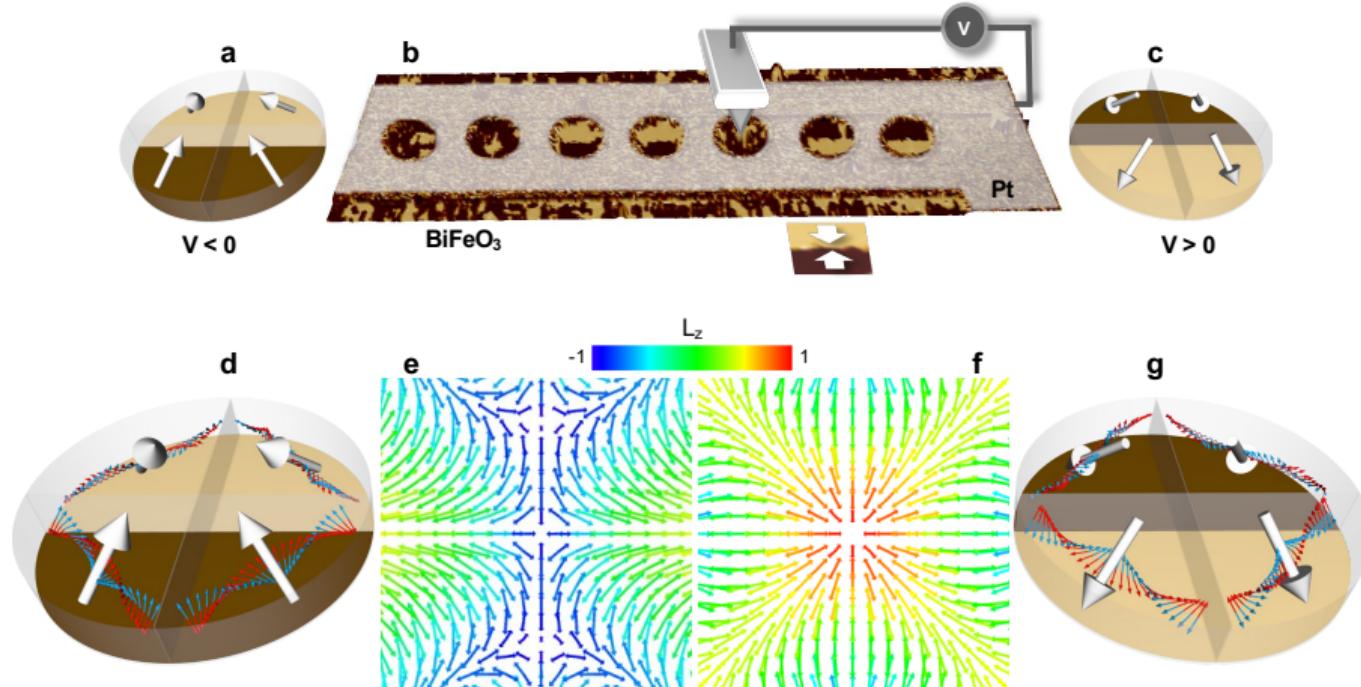
Towards topological textures

Objective: use the magnetoelectric coupling to stabilize an antiferromagnetic topological state

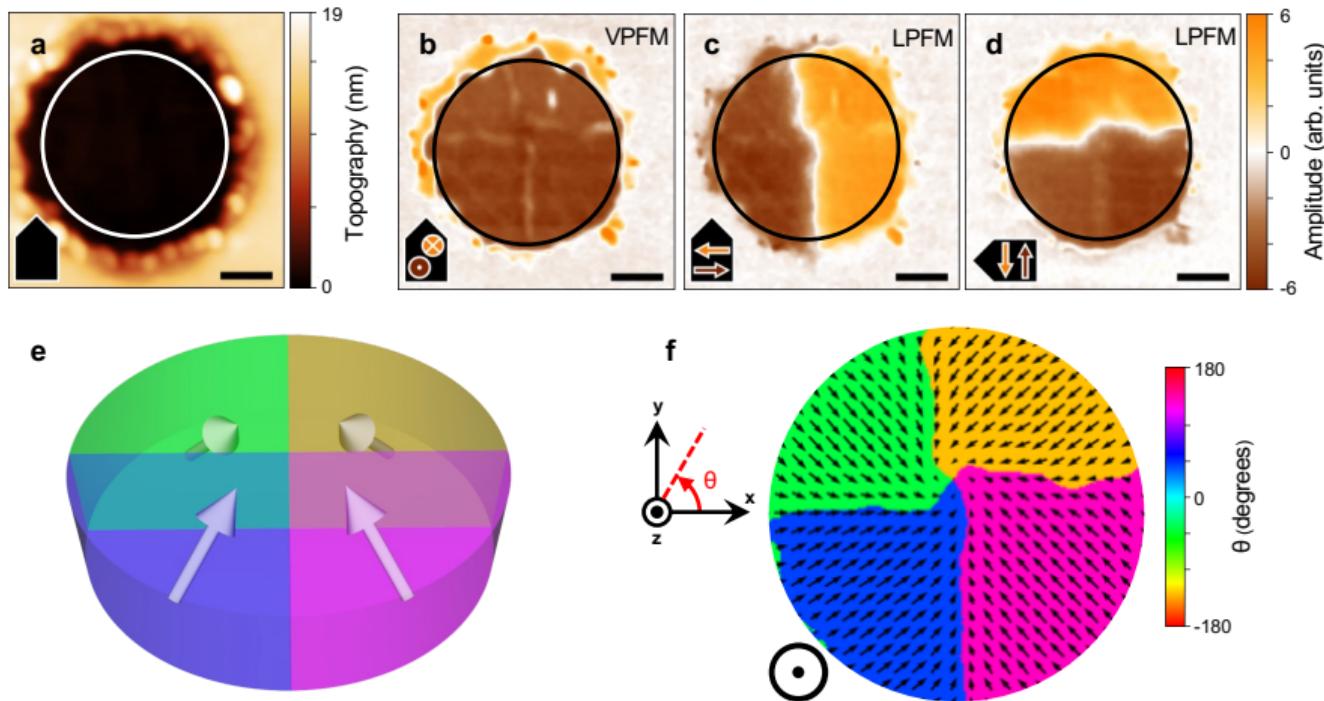


Towards topological textures

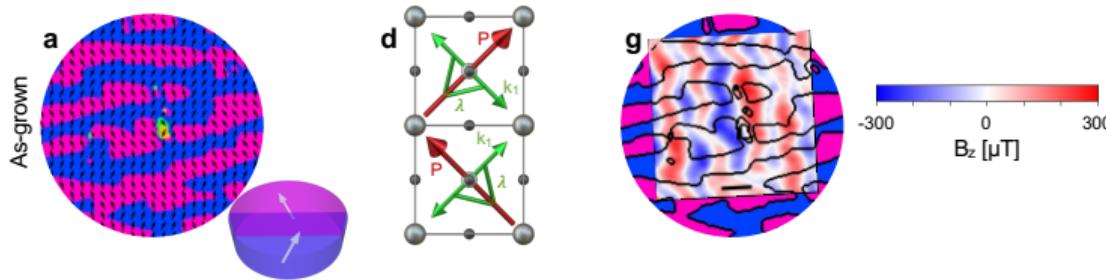
Objective: use the magnetoelectric coupling to stabilize an antiferromagnetic topological state



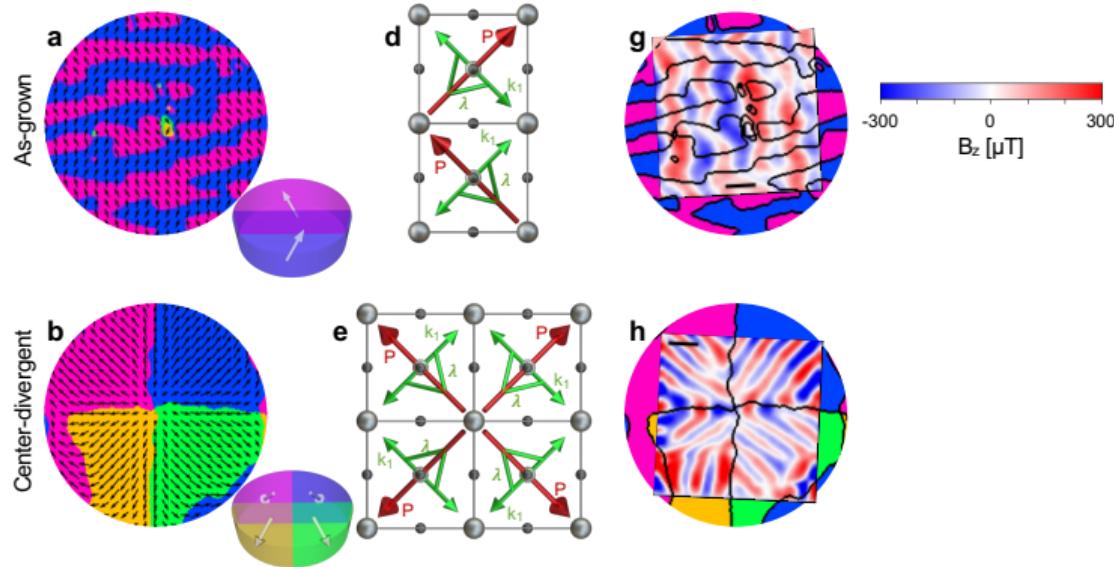
Center ferroelectric domains imaged with PFM



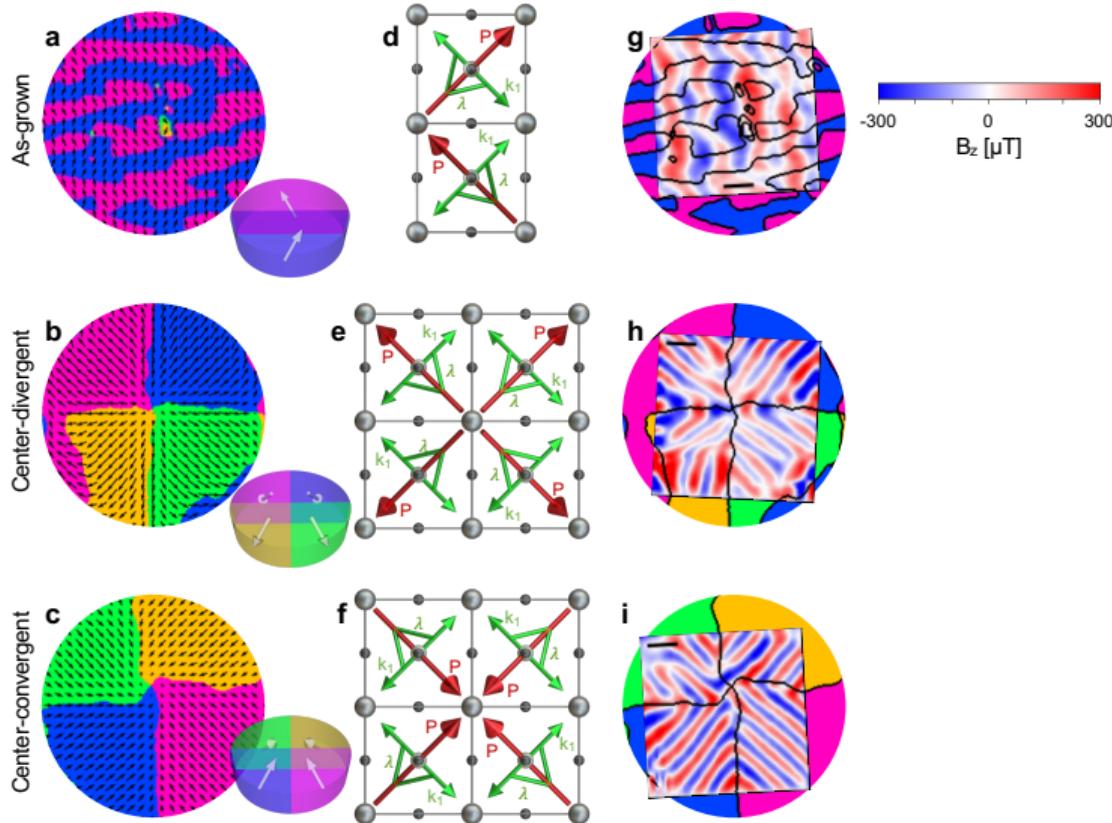
Flux closure of spin cycloids (low strain)



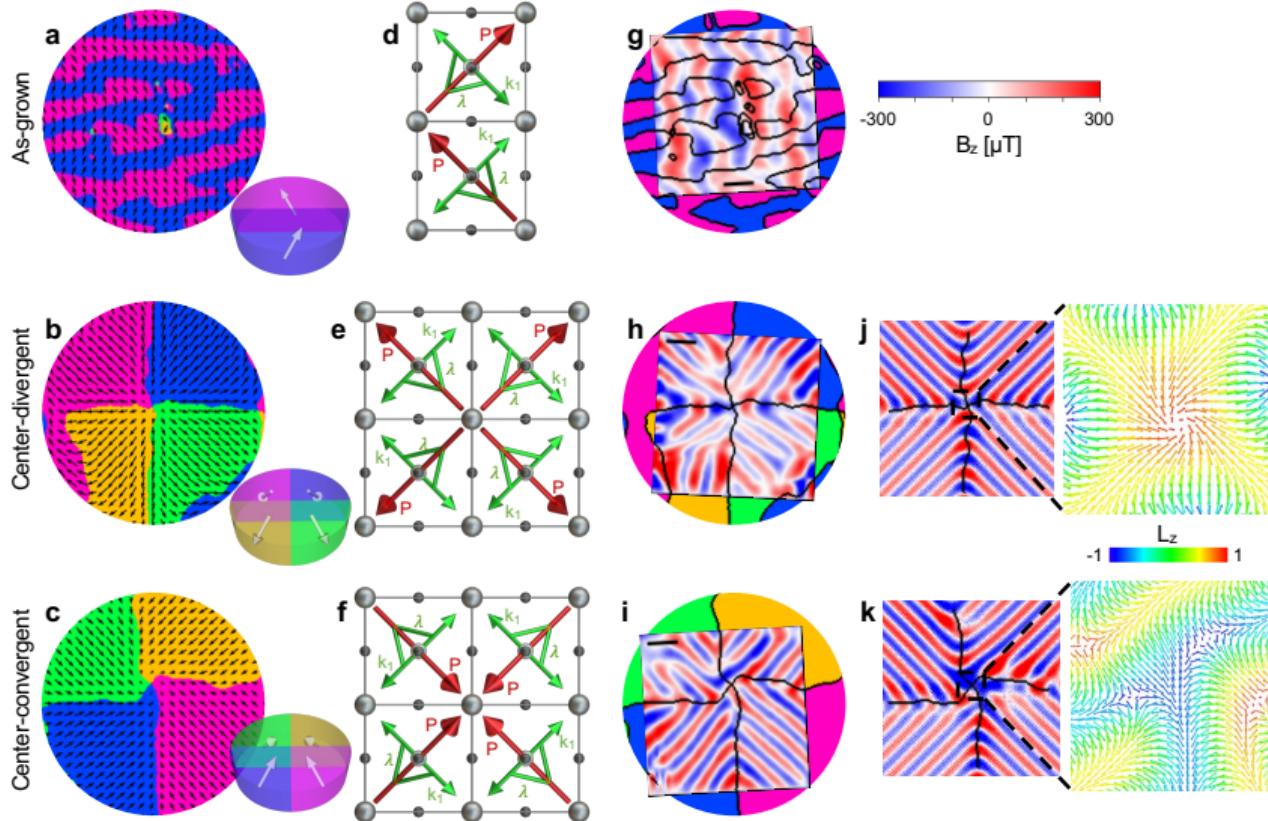
Flux closure of spin cycloids (low strain)



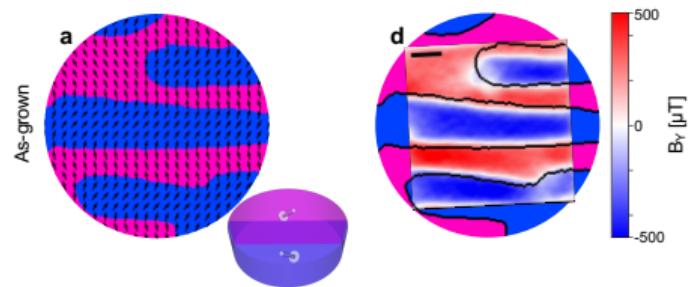
Flux closure of spin cycloids (low strain)



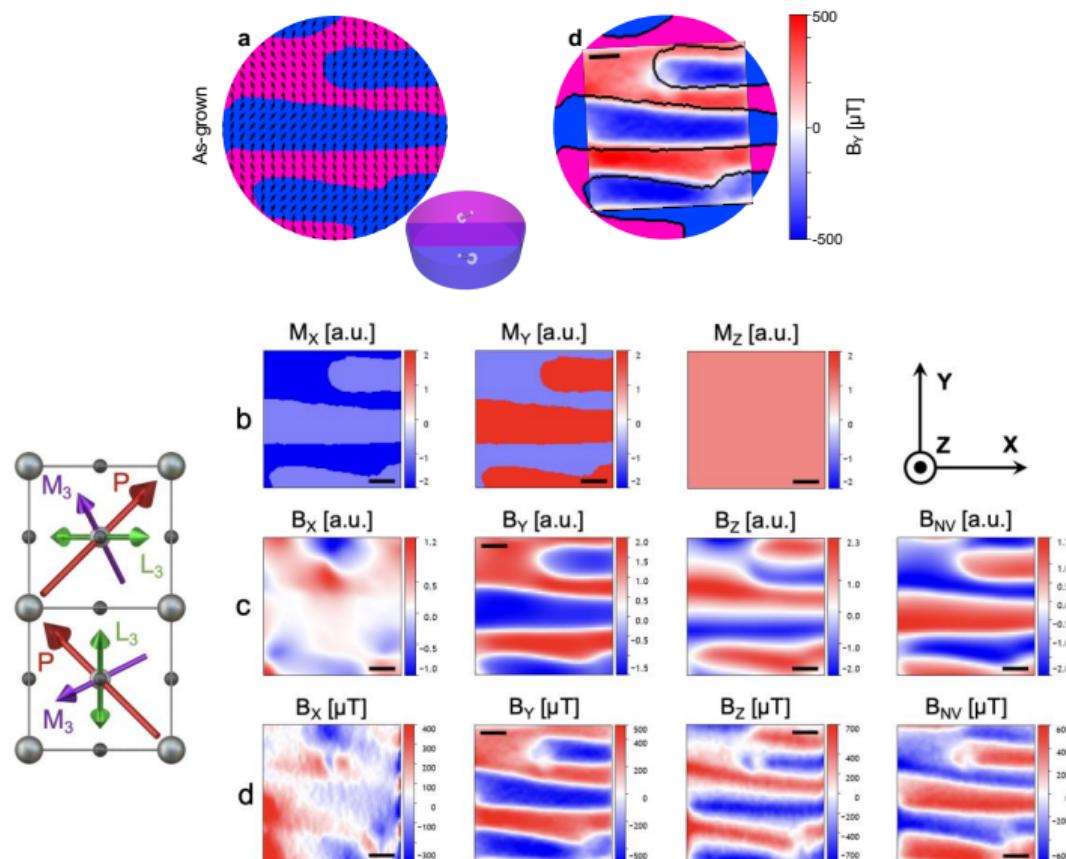
Flux closure of spin cycloids (low strain)



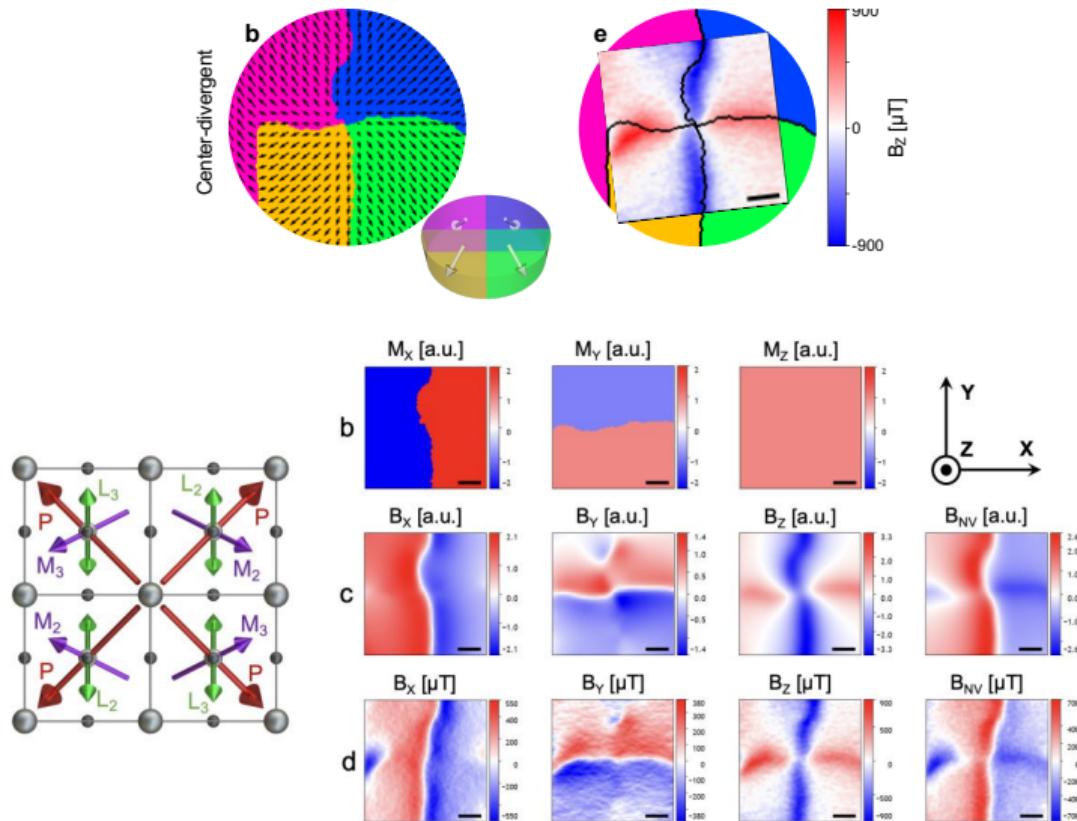
Antiferromagnetic/ferroelectric domains (high strain)



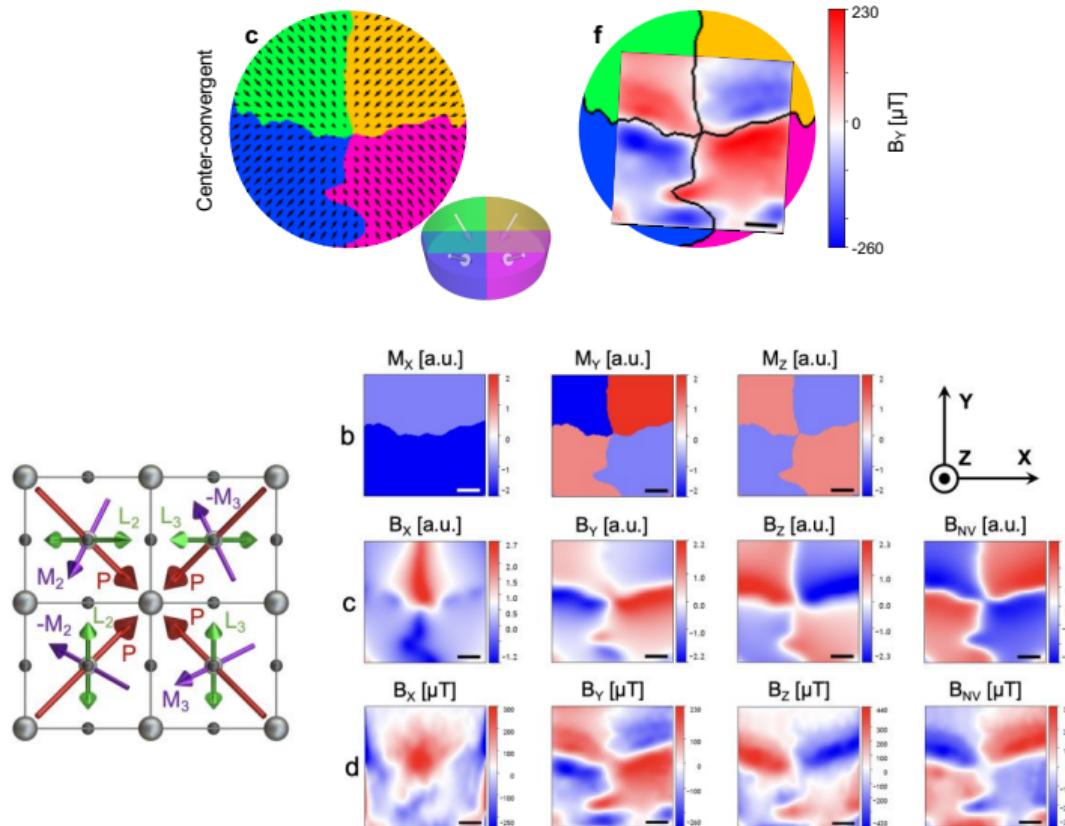
Antiferromagnetic/ferroelectric domains (high strain)



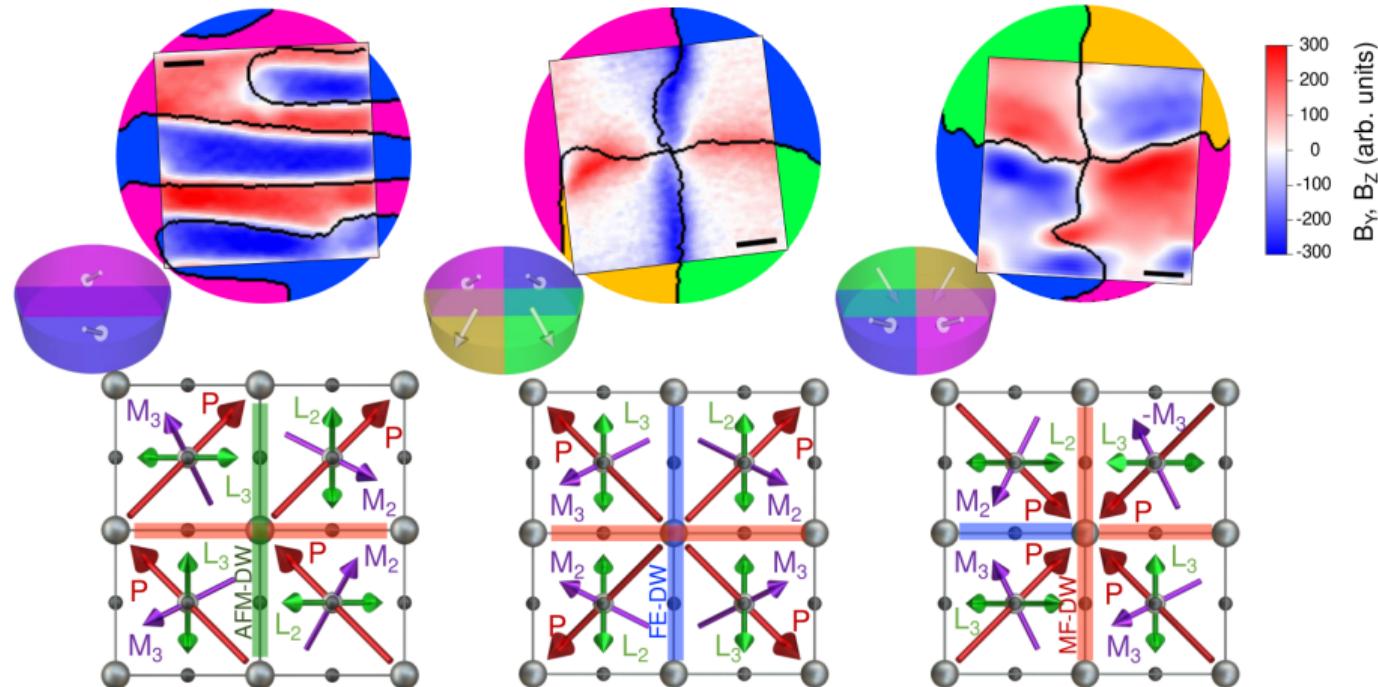
Antiferromagnetic quadrants in a divergent ferroelectric state



Antiferromagnetic quadrants in a convergent ferroelectric state



Identification of types of domain boundaries



Summary

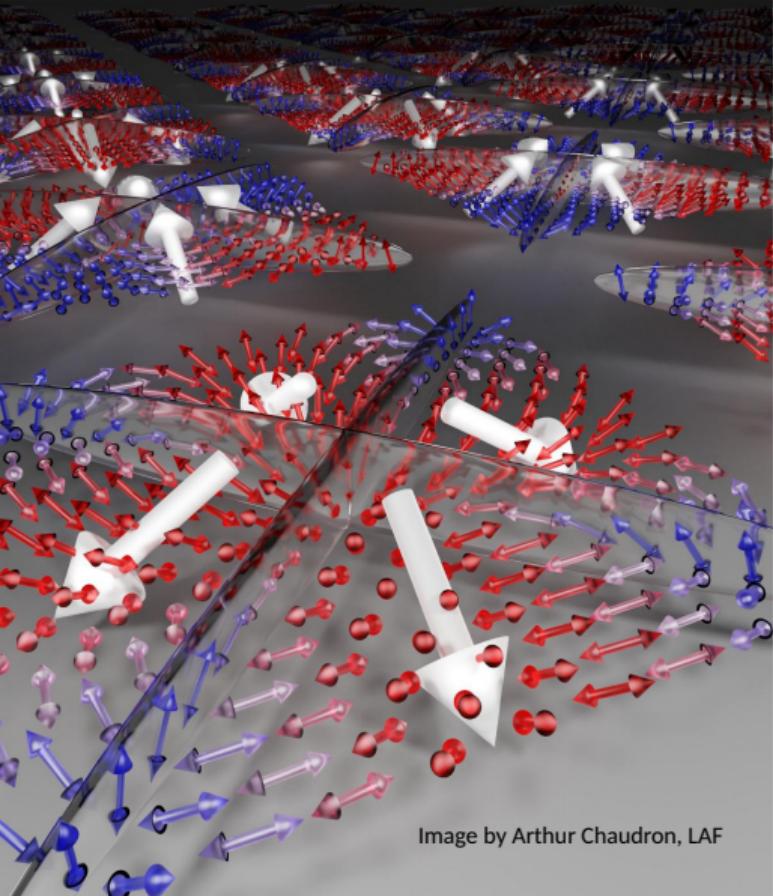


Image by Arthur Chaudron, LAF

Topological ferroic textures in BiFeO_3

- Scanning NV center magnetometry is a great tool to image antiferromagnets at the nanoscale
- Observation of antiferromagnetic topological defects in bulk BiFeO_3
A. Finco et al. *PRL* 128 (2022), 187201
- Creation of multiferroic solitons in BiFeO_3 microstructures using electric field
A. Chaudron et al. *Nat. Mater.* 23 (2024), 905

Acknowledgments

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Sophie Collin, Karim Bouzehouane, Stéphane Fusil, Vincent Garcia,

CEA SPEC, Gif-sur-Yvette

Zixin Li, Jean-Yves Chauleau, Michel Viret

Institute of Physics, Czech Academy of Sciences, Prague

Pavel Marton, Jirka Hlinka

SPMS, CentraleSupélec, Gif-sur-Yvette

Brahim Dkhil

Synchrotron Soleil

Nicolas Jaouen

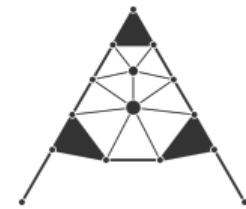


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