Spintronics, Multiferroics and magnetic chirality

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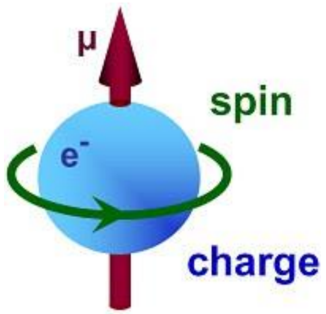
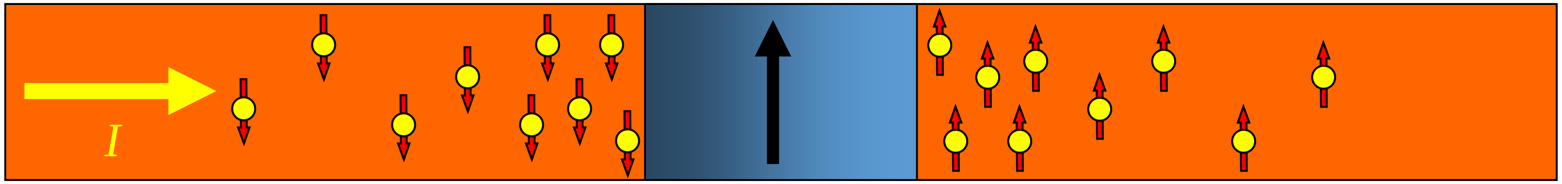
Spintronics

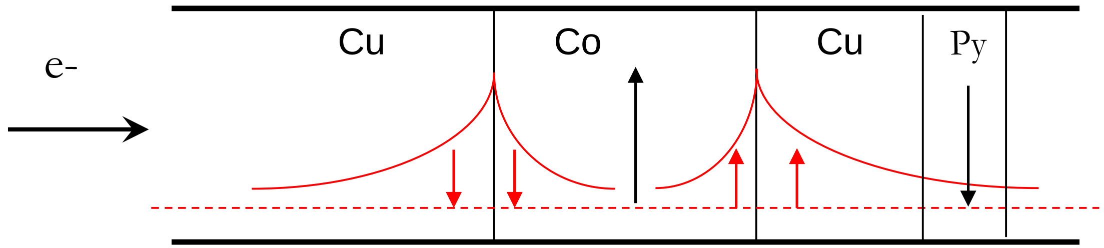
« Classical electronics has forgotten the spin of the electron »

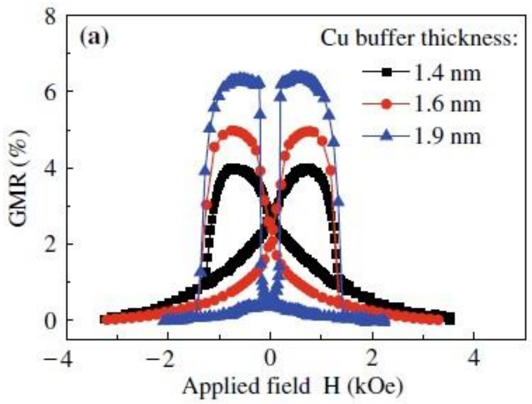
→ SPINTRONICS



Based on spin effects and born with the spin valve (A. Fert, P. Grunberg, late 80's)







→ Magneto-resistance in multilayers

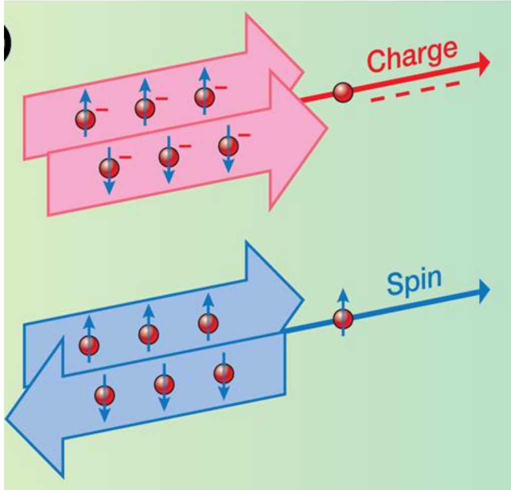
From discovery to applications in record time: Computer read head, MRAMs

Present issues

Major present problem: **dissipation**…!

Do we really need moving charges?

→ ***Pure spin currents***
→ ***Electric field control of magnetism***



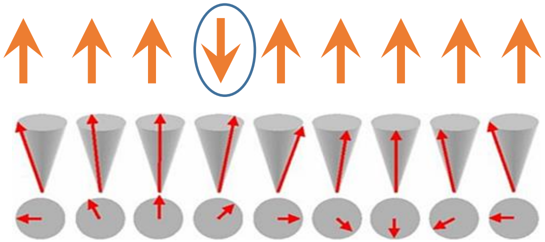
Elements needed to design devices:

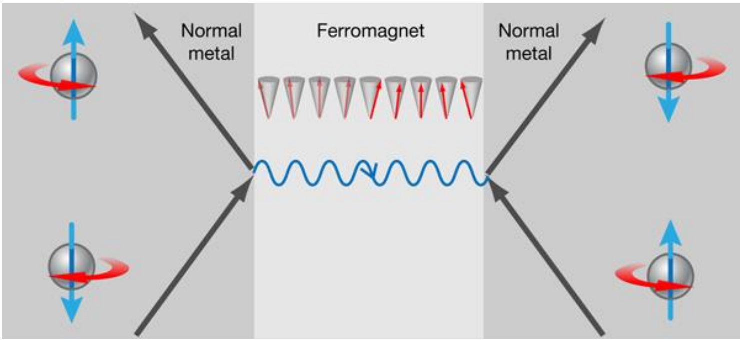
- Spin sources → generate spins
- Spin conductors → propagate spins
- Spin sensors → transform spin into voltage/current

Fundamental research on pure spin transport, spin/charge conversion, multiferroics

Introduce insulators in spintronics ex:

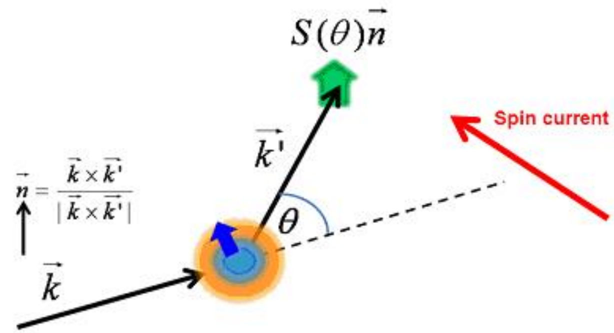
Propagating spins using the elementary magnetic excitations: the magnons



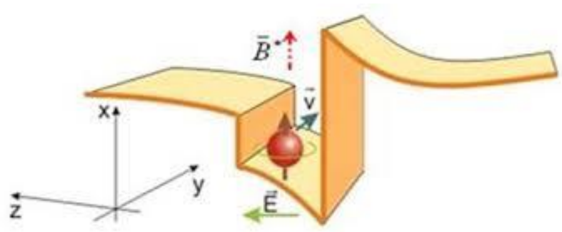


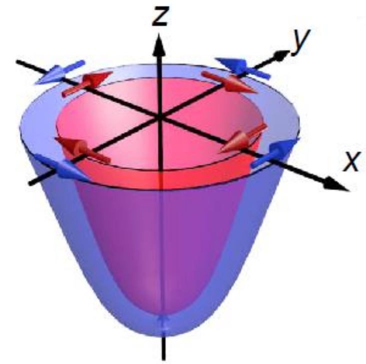
Spin orbitronics

Spin-orbit effects converting spin and charge



Rashba-Edelstein Effect :





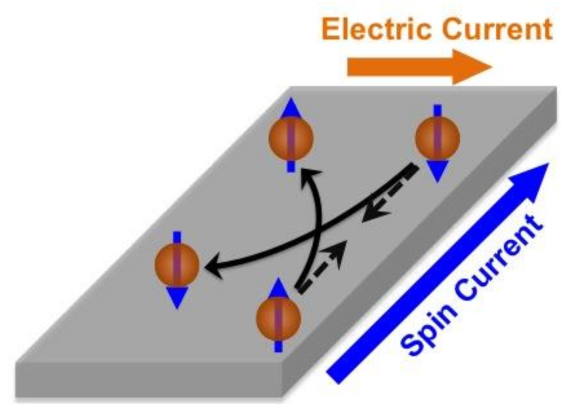
Built-in electric field at interfaces couples to the spin

$$H = \frac{\mathbf{p}^2}{2m} - \mathbf{b} \cdot \boldsymbol{\sigma}$$

Rashba internal field: Spin

$$\mathbf{b} = \alpha \mathbf{e}_z \times \mathbf{p}$$

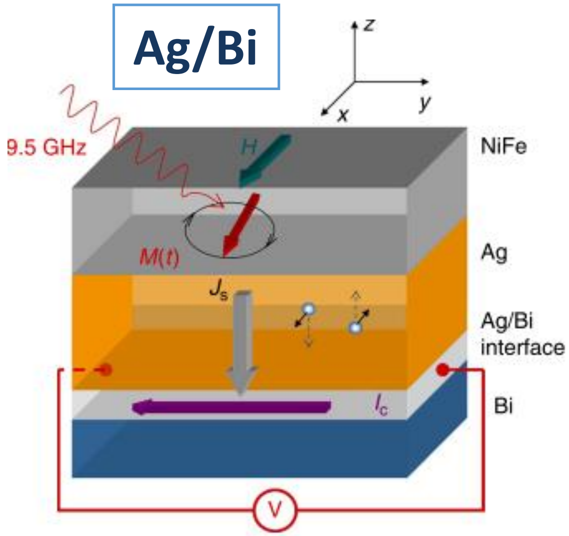
Spin Hall Effect :



→ *Spin current generation and measurement*

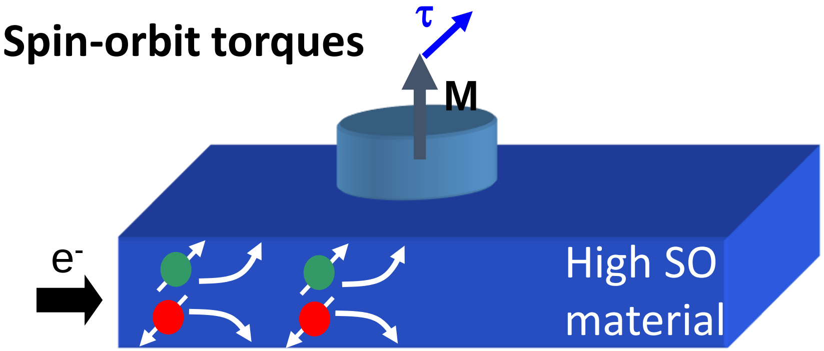
Spin Orbitronics

Giant spin-to-charge conversion at Rashba interfaces:



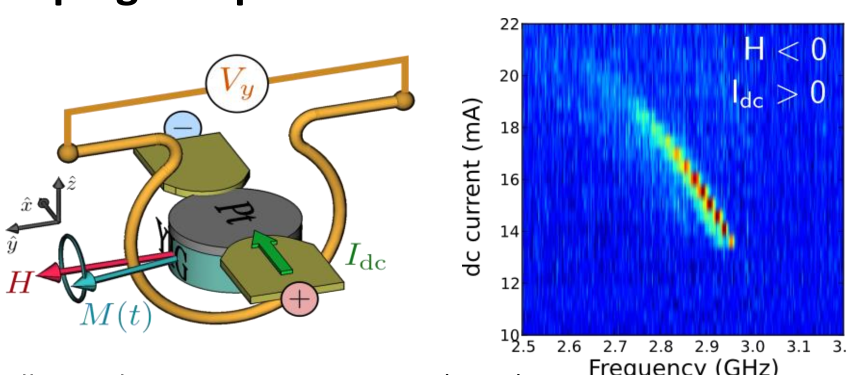
J.C. Rojas Sanchez et al, Nat. Comm. 4, 2944 (2013)
S. Sangiao et al., Appl. Phys. Lett. **106**, 172403 (2015).

Spin-orbit torques



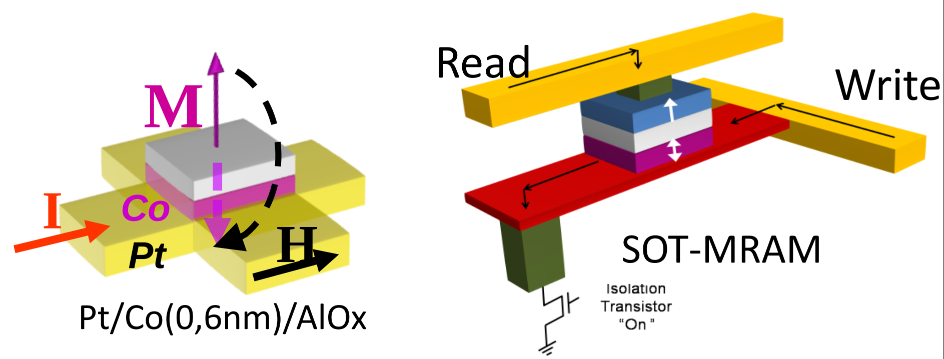
source of angular momentum to manipulate magnetization

Damping compensation in a FM insulator



M. Collet et al. Nat. Comm. **7**, 103777 (2016)

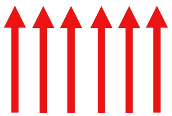
Magnetization switching



I. M. Miron *et al.*, Nat. Mat. **9**, 230 (2010)
I. M. Miron *et. al.*, Nature **189**, 156601 (2011)
K. Garello *et al.*, Nat. Nano, **105**, 212402 (2014)

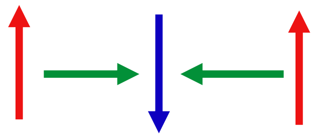
Magnetic Skyrmions

Exchange interaction



$$E_{ex} = -J\overrightarrow{S_1}.\overrightarrow{S_2}$$

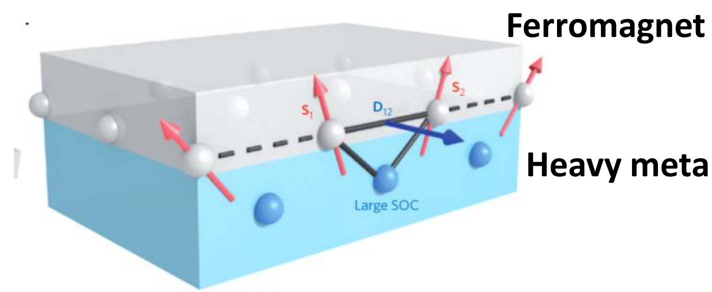
Chiral interaction



$$E_{Ch} = -\vec{D}.\overrightarrow{S_1} \times \overrightarrow{S_2}$$

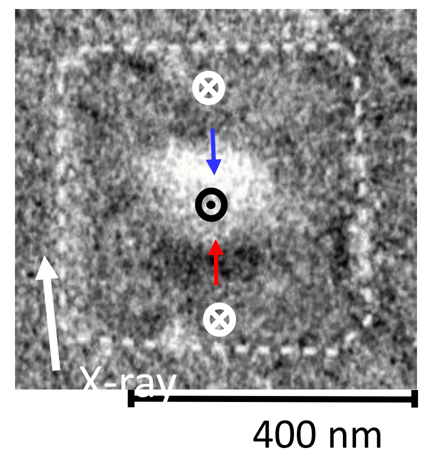
- Large spin-orbit coupling
- Structural inversion asymmetry

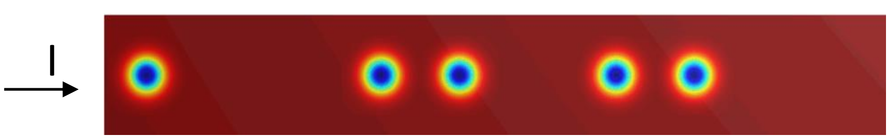
=



- **Magnetic Skyrmions**

- Nanometer size
- Homochiral, topologically protected
- Can be moved by small in-plane current
- → Logic and memory applications





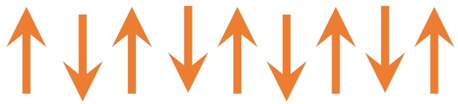
→ Room temperature skyrmions at zero field in Pt/Co/MgO nanostructrures

Boulle *et al.*, Nat. Nano, **11**, 449 (2016)

But: so far quite slow motion + ‘directional’ problems

Future directions: Antiferromagnets

Antiferromagnetic Spintronics



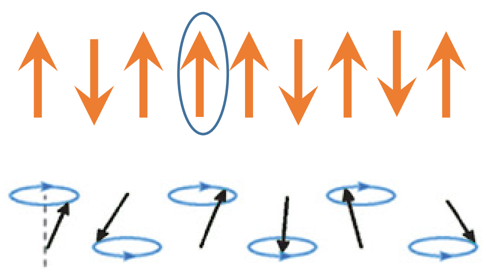
Antiferromagnetic materials could represent the future of spintronics

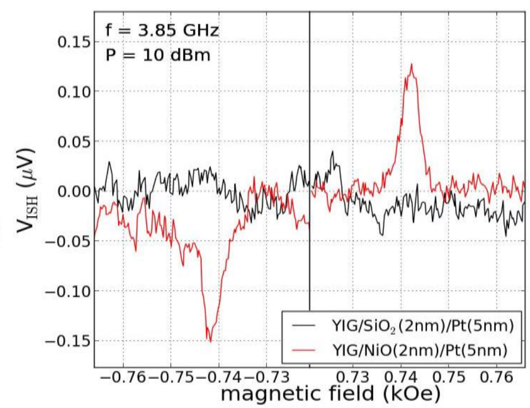
- immune to magnetic fields: no more unwanted data erasure
- produce no parasitic stray fields: secure 'invisible' data
- large magneto-transport effects: write/read with a spin current
- ultrafast TeraHertz dynamics: picosecond writing vs nanosecond today.

Addressing using:

- Spin currents
- Electrical polarization in Multiferroics

Spin conduction in insulating AntiferroMagnets





Elementary excitation:
Antiferromagnon

Transfer of angular momentum = spin conduction

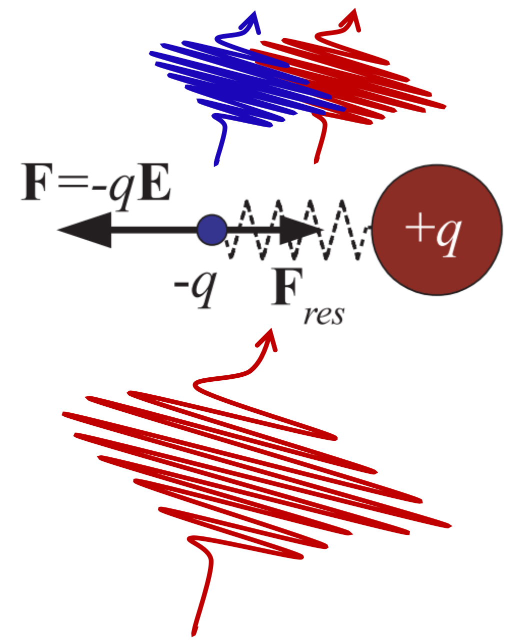
C. Hahn et al., EPL 108, 57005 (2014)

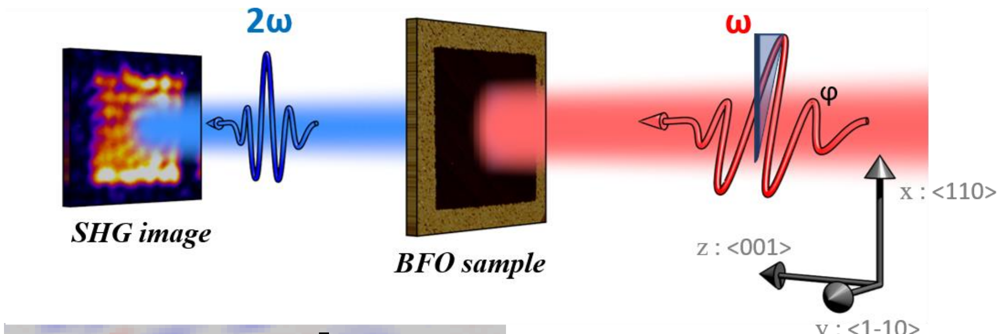
Imaging the Antiferromagnetic order

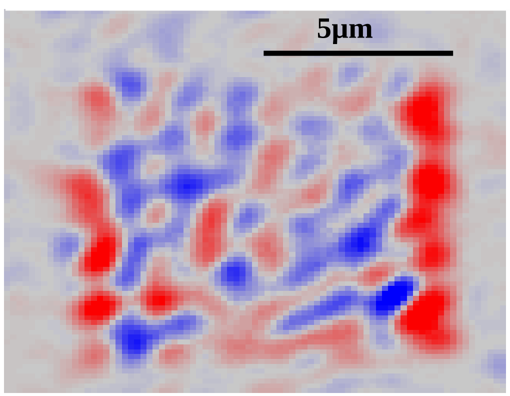
<u>*Second harmonic generation induced by :*</u>

Fiebig, Pavlov & Pisarev J. Opt. Soc. Am. B **22** 96 (2005)

- Spatial centro-symmetry breaking (ferroelectricity)
- Time-inversion symmetry breaking ((anti)-ferromagnetism)

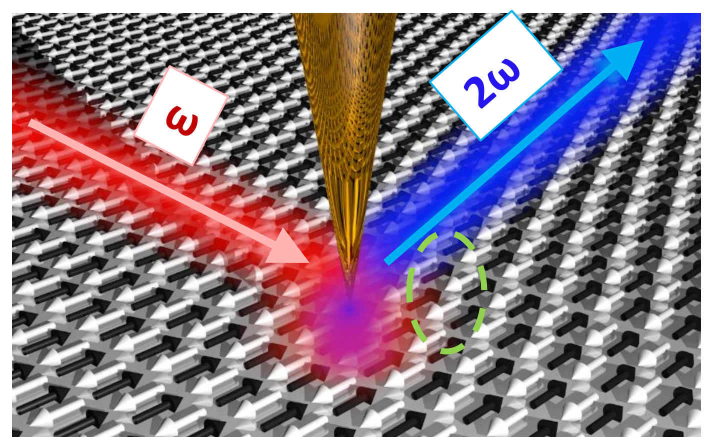






AF domains in BFO by second harmonic generation
J.-Y Chauleau et al., Nat. Mat. **16**, 803 (2017)

Project:



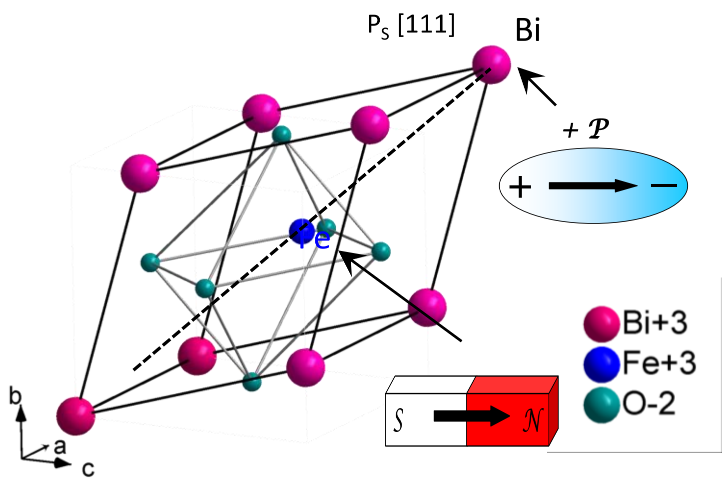
Tip-enhanced near-field light

AF multiferroics

$BiFeO_3$: ferroelectric, ferroelelastic and anti-ferromagnetic at 300K

Ferroelectric properties (T_C ~ 1090 K)

- Cubic perovskite structure $\rightarrow$ pseudo-cubic : rhombohedral distortion
- P_S due to Bi^{3+} and Fe^{3+} displacements along [111]



Kubel et al., Acta Cryst. B, 46 , 698 (1990)

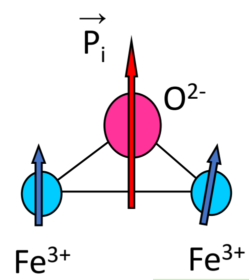
Large atomic displacements $\rightarrow$ large P_S

Magnetic properties: G type AF + magnetoelectric coupling

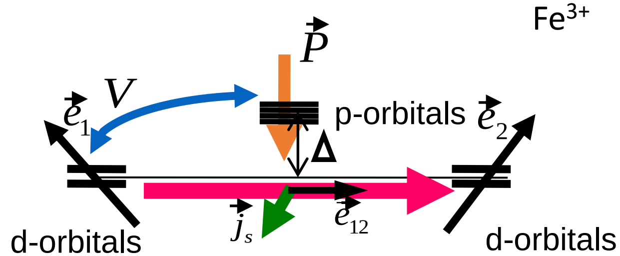
Magneto-electric coupling

In a solid with non-collinear magnetism (generalised Dzyaloshinski-Moriya interactions):

Typically oxydes with distorted crystallographic cells :



$E_{DM} = \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$



$$\vec{P} \propto \vec{e}_{12} \times \vec{j}_s$$

j_s = spin current

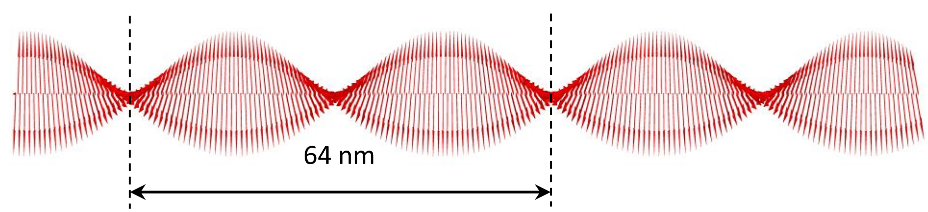
- P_S due to the magnetic structure

Katsura-Balatsky-Nagaosa PRL07

$$E_{ME} = \gamma_{ME} \sum \vec{P} \cdot \left(\vec{R}_{ij} \times (\vec{S}_i \times \vec{S}_j) \right)$$

with γ_{ME} the inhomogeneous ME coupling constant

Leads to an AF cycloidal ordering :



AF skyrmions?

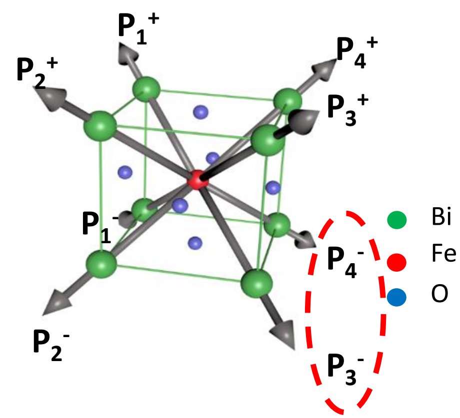
Dream: generate AF skyrmions in $BiFeO_3$!
Would be fast, move in straight lines, addressable with an electric field…

But: very difficult to generate without the magnetic field 'knob'

Idea: Use the frustration induced by a large density of FE domain walls

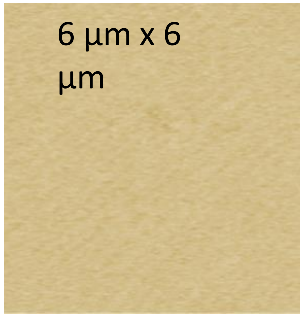
Sample : DSO/SRO/$BiFeO_3$ (001) (≈ 110 nm)

Ferroelectric configuration in thin epitaxial layers:

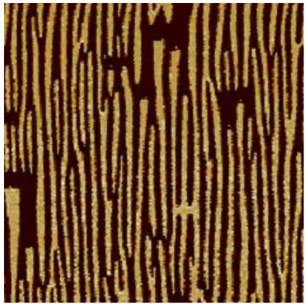


FE stripe domains

PFM images



<u>Out of plane P</u>

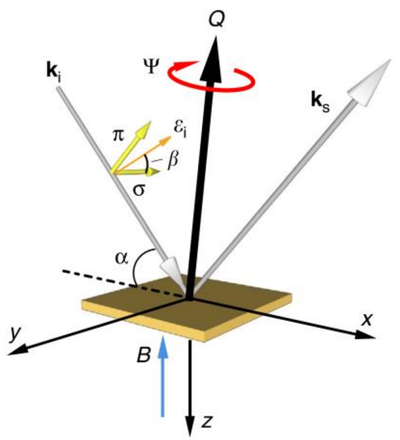


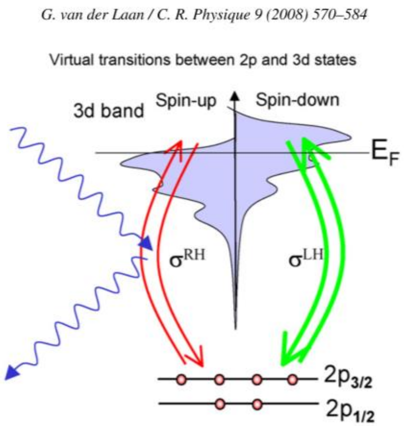
<u>In-plane P</u>

AF cycloids in Ferroelectric stripe pattern : XRMS

X-ray resonant magnetic diffraction:

Direct access to magnetic chirality:





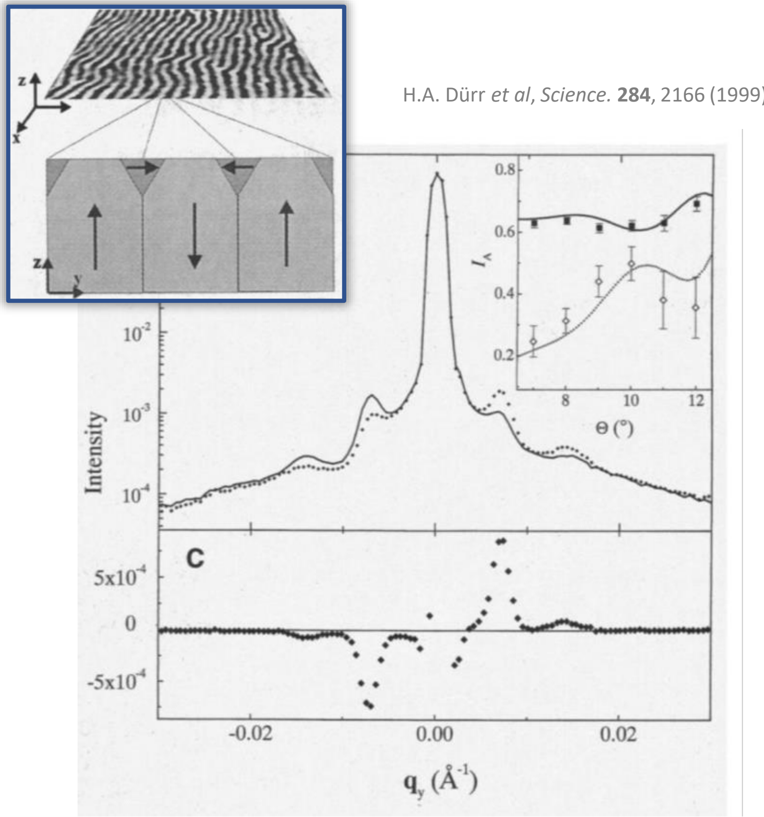


Table 1
Extensions to X-ray scattering possible with synchrotron radiation

Extensions to X-ray scattering	Allows one to probe
Tunable X-rays at resonance	Element, site and valence specificity
Polarized X-rays	Magnetic orbital and spin profile
Soft X-rays	Nanoscale sensitivity (down to 1 nm)
Coherent radiation	Local configuration
Pulsed radiation	Dynamics

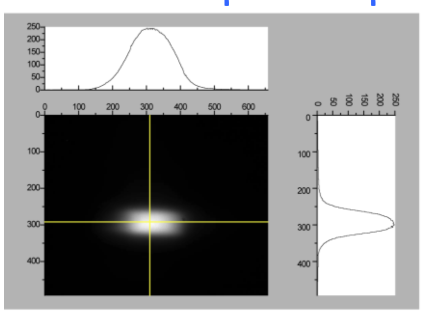
AF cycloids in Ferroelectric stripe pattern : XRMS

SOLEIL SYNCHROTRON

sextants
Soft x-ray EXperimenT resonANT Scattering

XRMS + Open Port

h-slit = 40µm / v-slit 10µm
Calculated @2.2m from M8
18µm * 7µm FMHM
Measured @ 2.2m from M8
17.3µm * 7.4µm



- **Energy range** : **50-1700 eV** (optimized 70-1000 eV)
- **High flux** : **>5 10^{12} ph/s** on the sample,
- **Resolving power** **$E/\Delta E \geq 10000$**

Variable polarization: linear and circular:

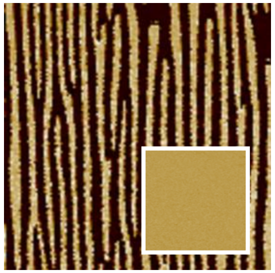
2 Apple-II undulators HU80 + HU44

=> the whole energy range in first harmonic

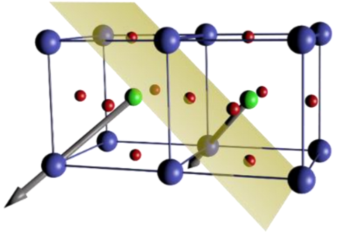
Resonant elastic scattering
Resonant inelastic scattering
Holography

XRMS in reflectivity

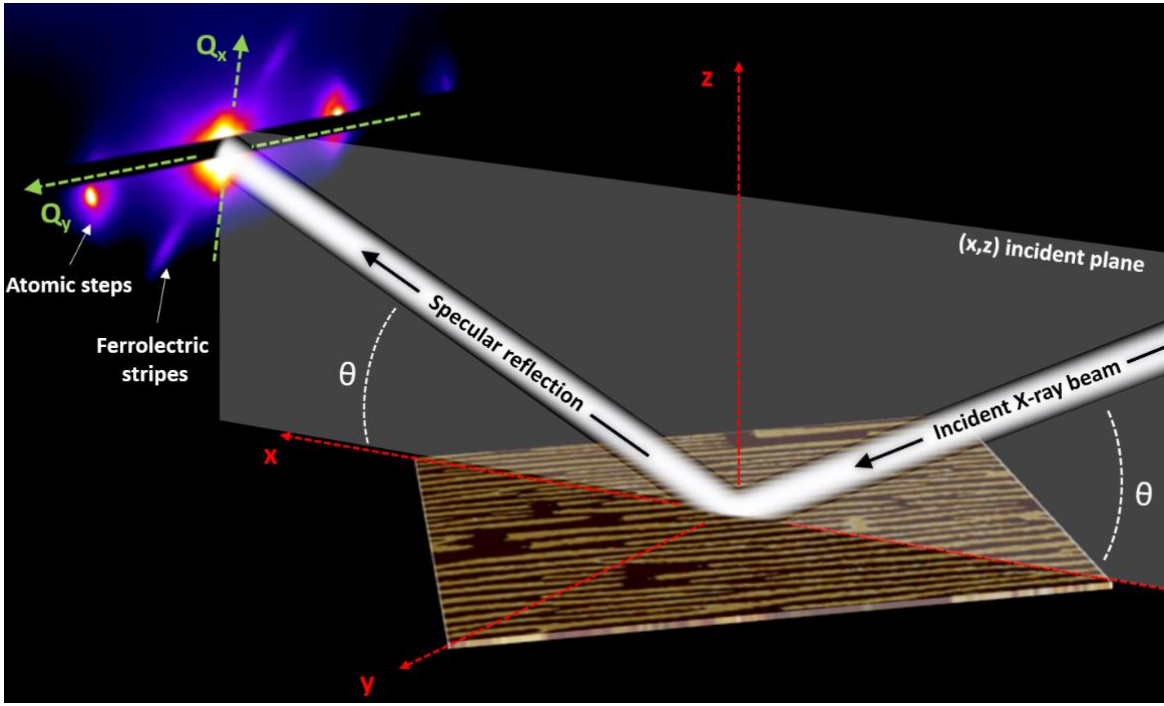
$BiFeO_3$ / $SrRuO_3$ // $DyScO_3$
71° walls



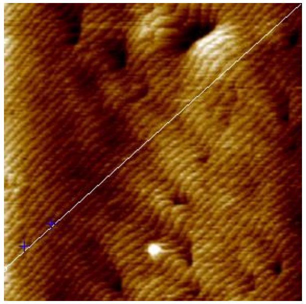
4 × 4 µm^2 in-plane PFM
+ out of plane in inset



XRMS experiment in reflectivity configuration at O K edge

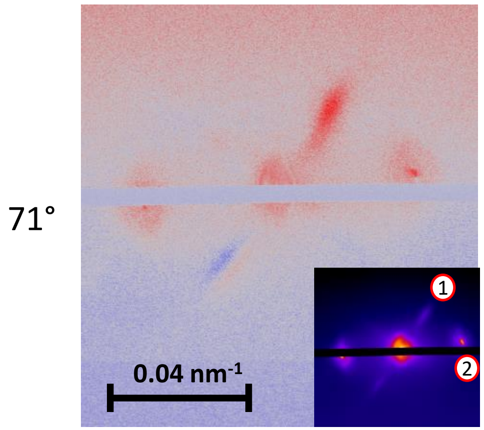


AFM image:

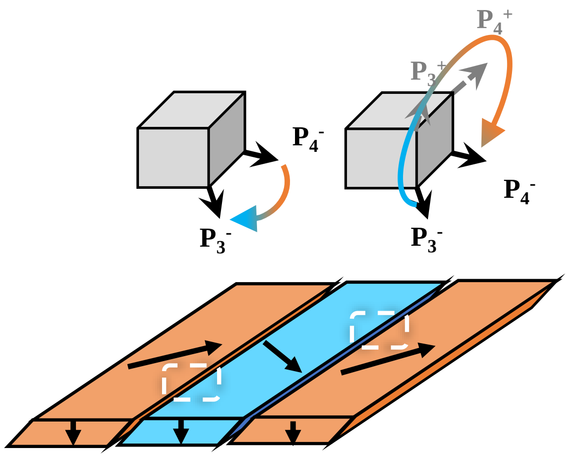


Chiral electrical polarization

Dichroism at the Oxygen K edge !



Chiral FE structures

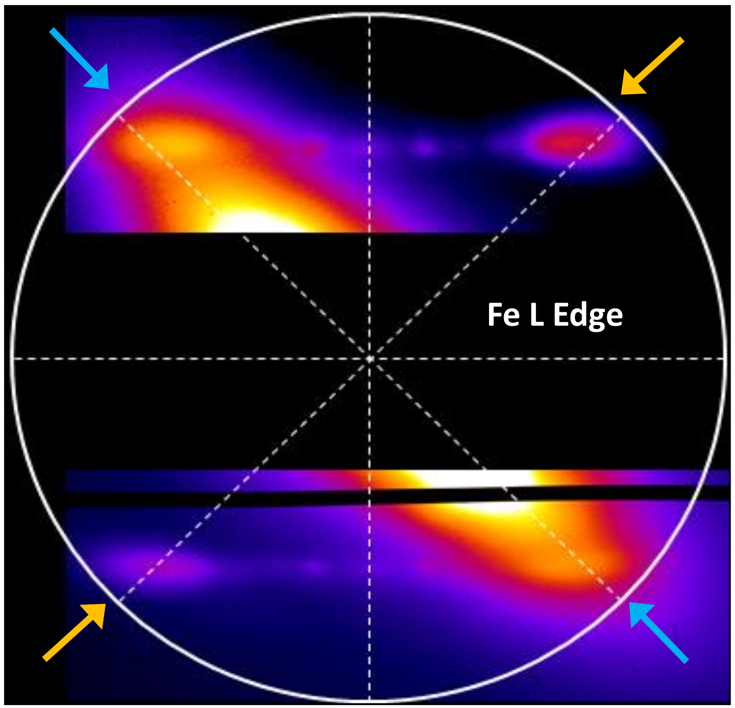


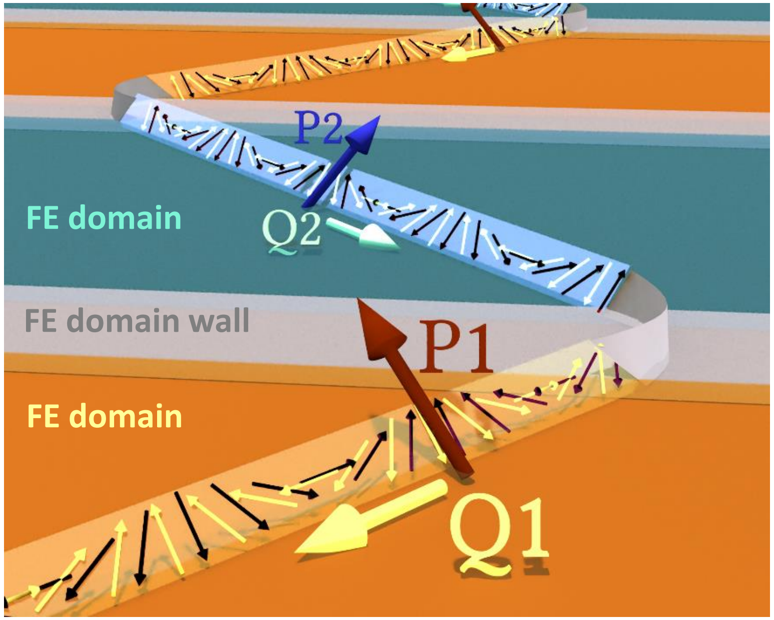
Very surprising because this is not the lowest energy state…

AF cycloids

<u>What about the magnetic textures?</u>
<u>→ Fe L edge</u>

Cycloids 80 ± 8 nm





scattering amplitude:

$$f_n^{\mathrm{res}} = f_0(\hat{\epsilon}\cdot\hat{\epsilon}') - i\, f_1(\hat{\epsilon}\times\hat{\epsilon}')\cdot \boldsymbol{m}_n + f_2(\hat{\epsilon}'\cdot\boldsymbol{m}_n)(\hat{\epsilon}\cdot\boldsymbol{m}_n)$$

$\hat{\epsilon}$ and $\hat{\epsilon}'$: polarization states of incident and diffracted beams

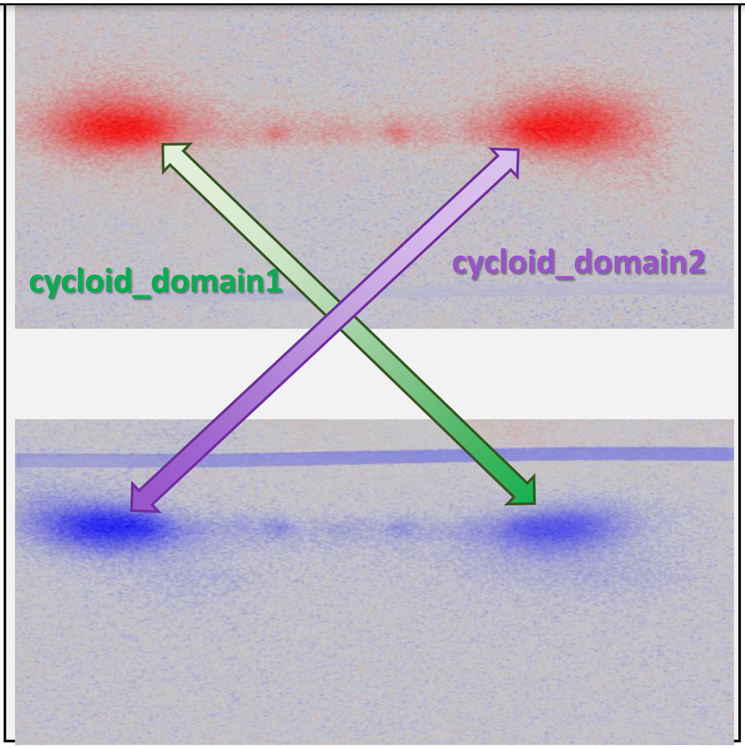
$\mathbf{m}_n$: local magnetization vector

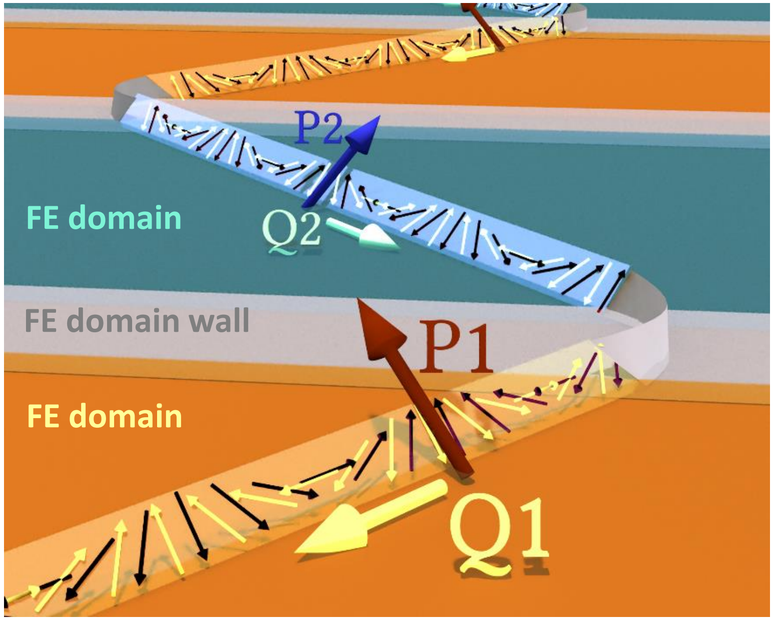
f_0, f_1, f_2 resonance factors for, the monopole, magnetic dipole and quadrupole parts of the scattering amplitude.

AF cycloids

<u>What about the magnetic textures?</u>
<u>→ Fe L edge</u>

Normalized circular dichroism : chiral structures

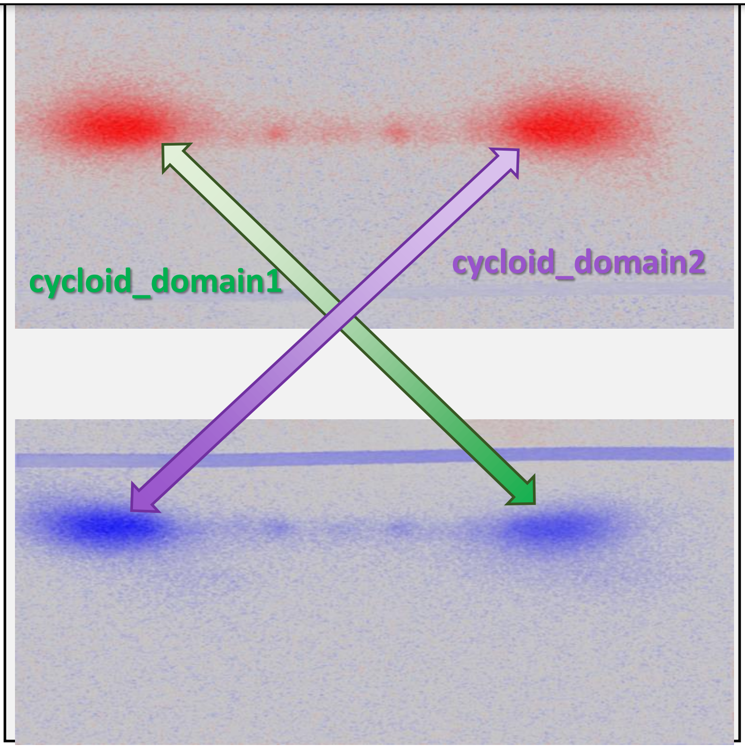


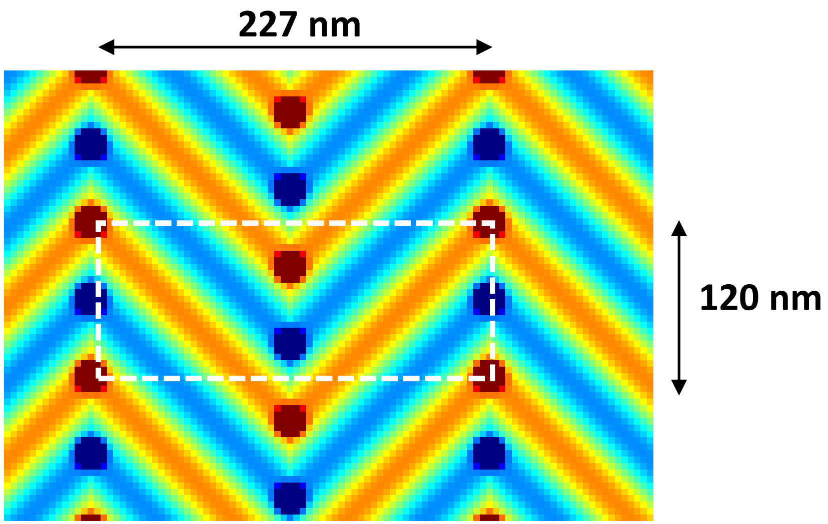


AF cycloids

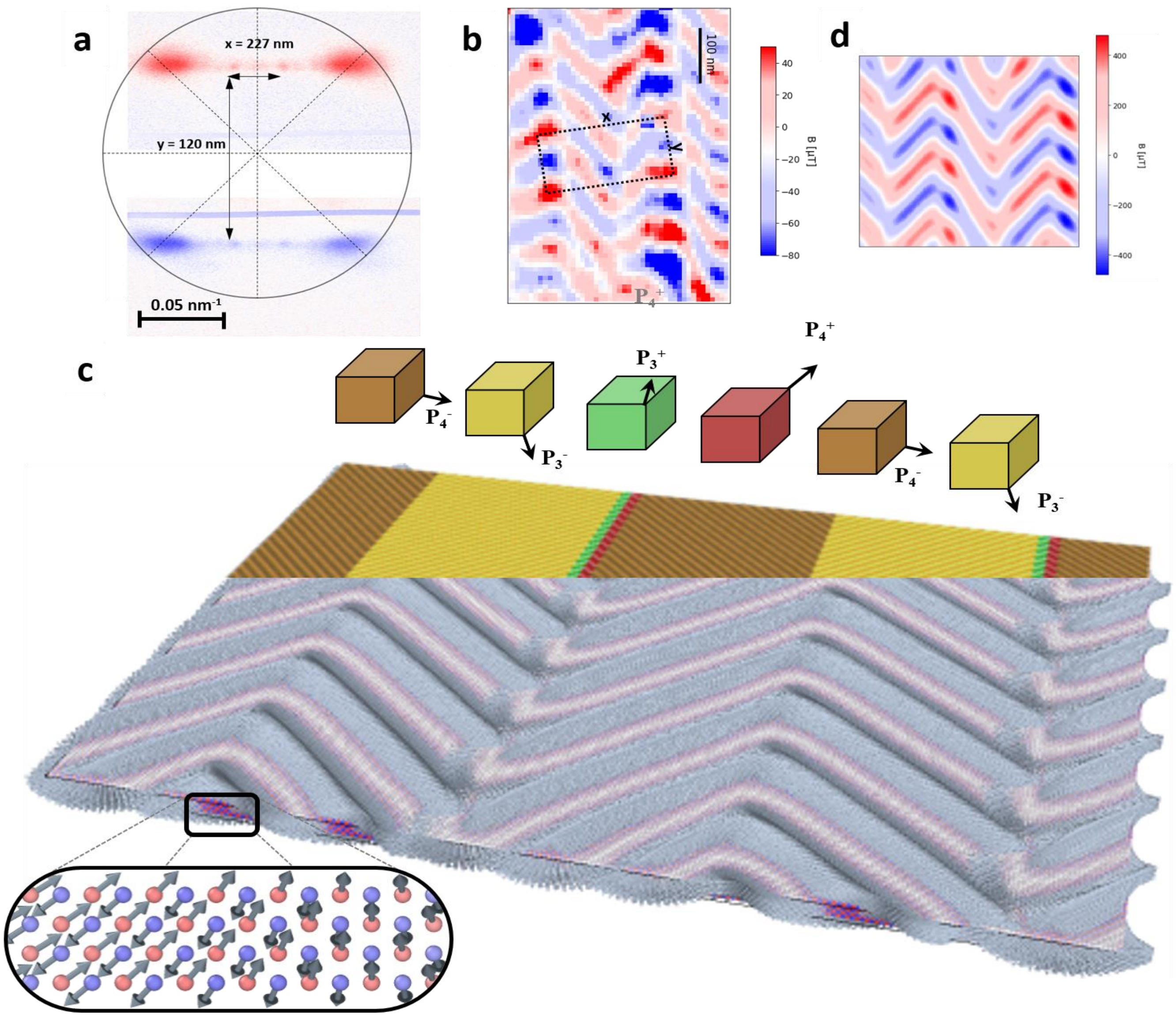
What about the magnetic textures?
→ Fe L edge

Normalized circular dichroism : chiral structures





Magnetic simulations



Conclusions / Perspectives

Present issues in ***information technologies***:

Dissipation → replace charge by spin

Size → reduce stray fields (Antiferromagnets),
use topological protection (skyrmions)

Speed → Reduce friction and size (skyrmions),
Change magnetic interaction:
Antiferromagnets (THz)