Seeing or listening: magnetoelastic effects in antiferromagnetic textures

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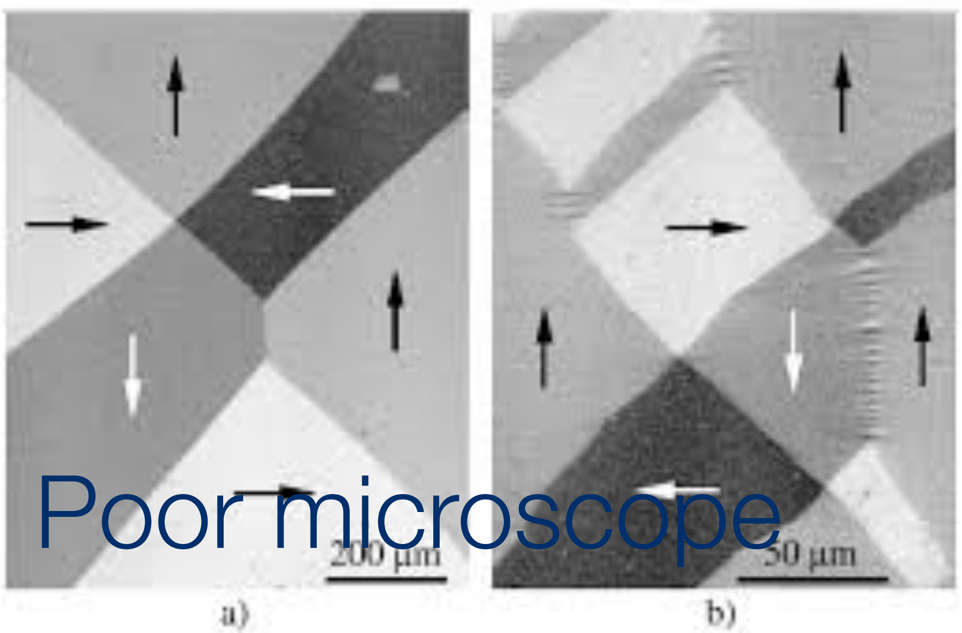
Johannes Gutenberg Universität Mainz

Februar, 17, 2021
SPICE Seminar

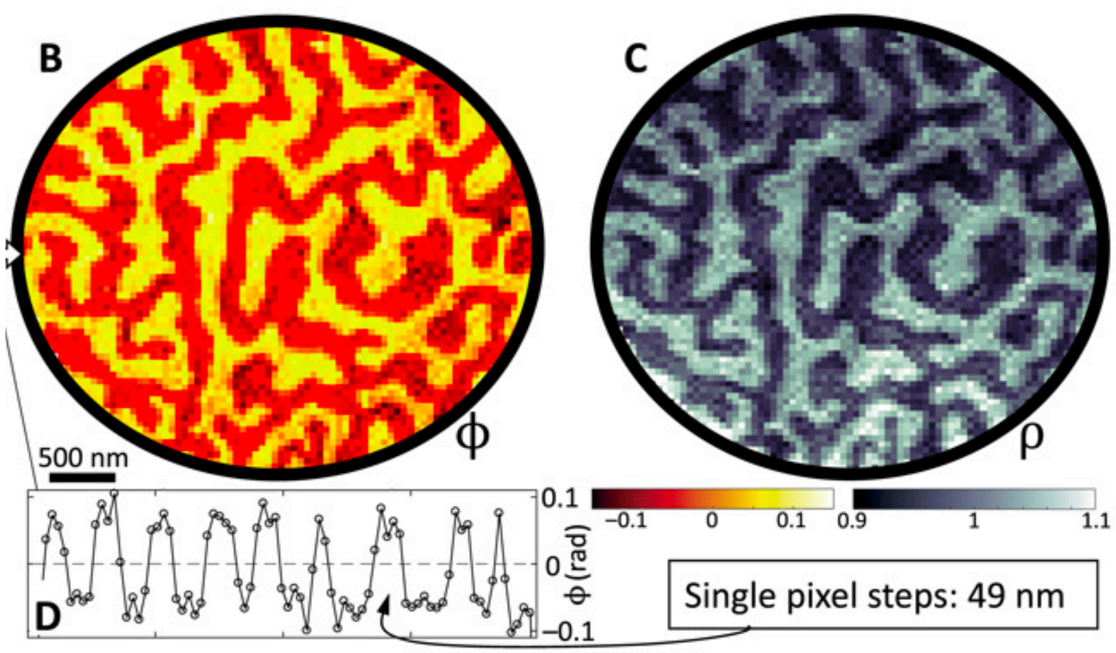
Ashe Wednesday: the end of having fun

Motivation

Visualization of
ferromagnetic domains

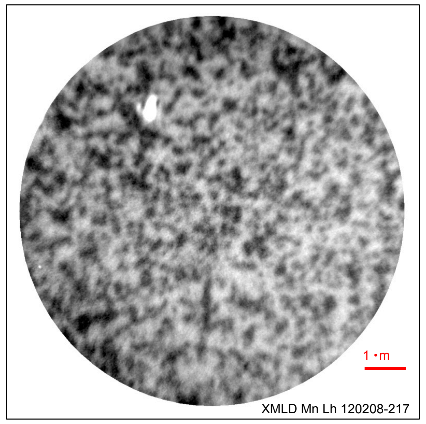


Poor microscope



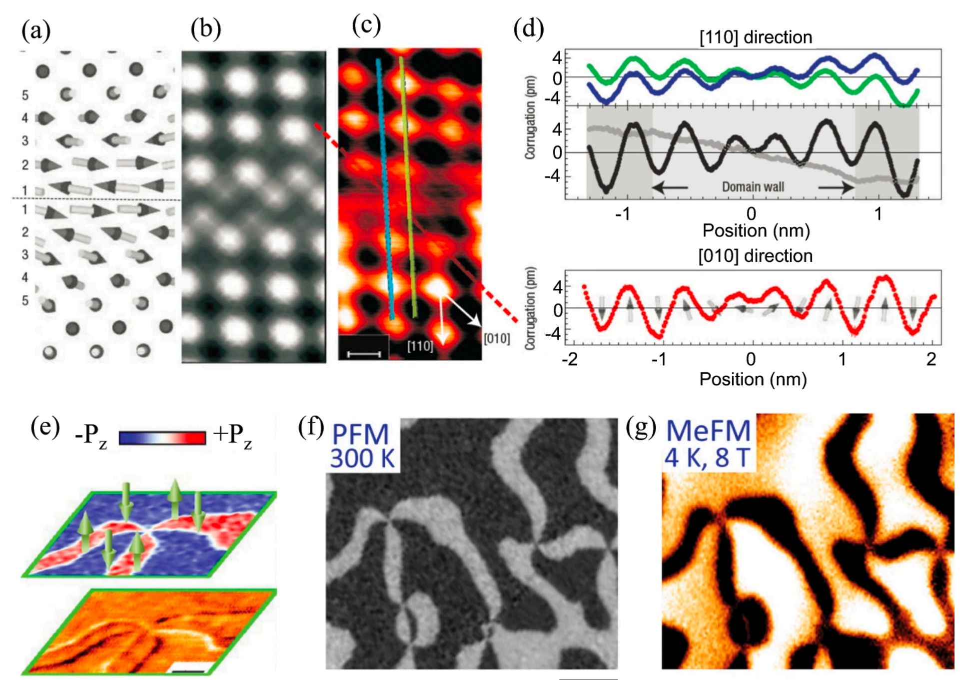
Good microscope

Visualization of
antiferromagnetic domains



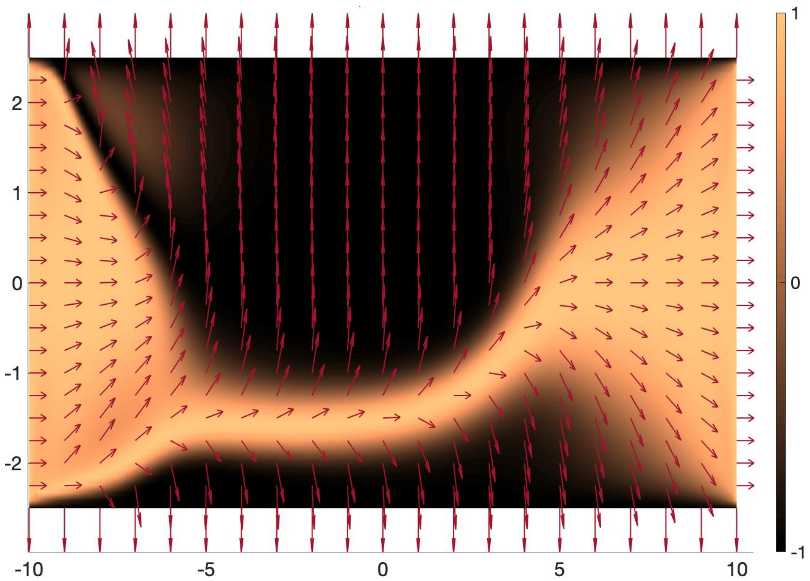
XMLD

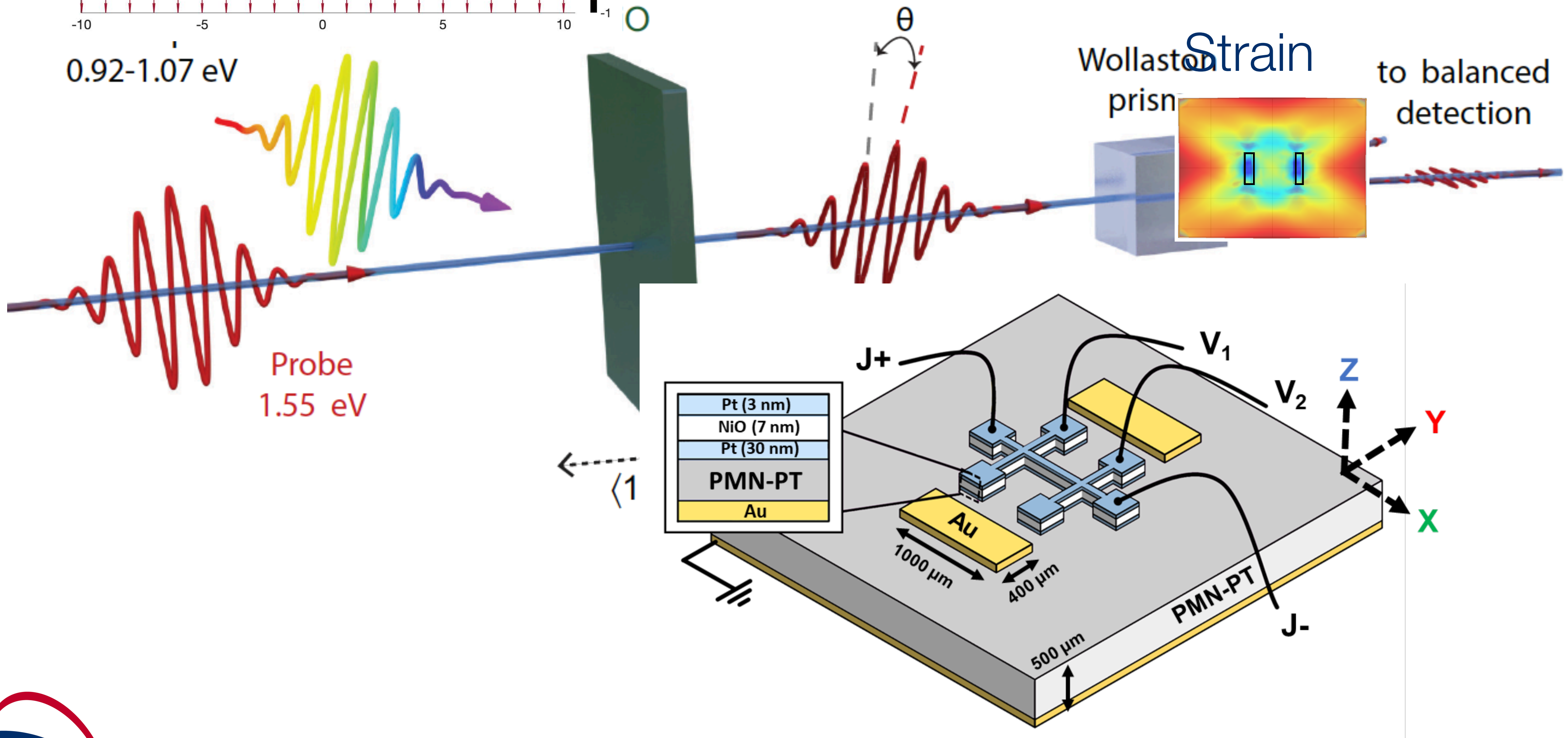
SP-STM



S.W. Cheong et al, Quantum Mat. (2020)

Seeing or listening?

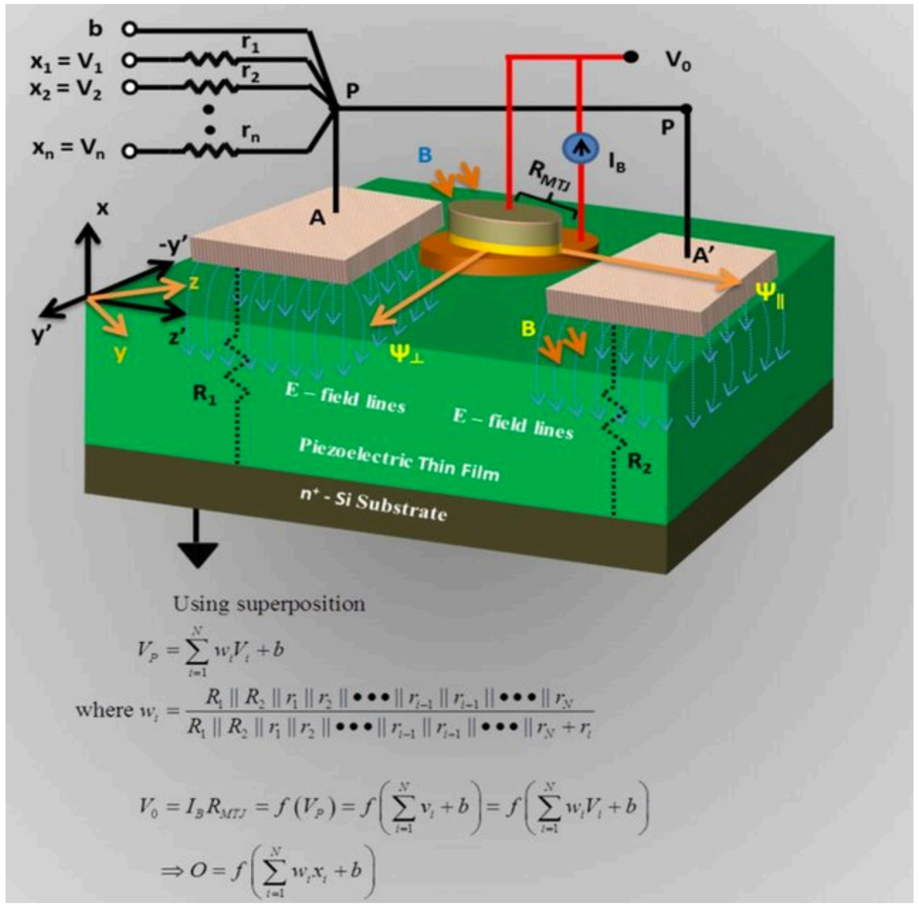




Motivation

Supriyo Bandyopadhyay

Straintronics and neuromorphic computing



DOI: 10.1109/OJNANO.2020.3011637

F. P. Chmiel et al, Nature Mat. (2018)

Take-home message

- **Strains** affect morphology and dynamics of **antiferromagnetic** textures
- **Antiferromagnets** can be effectively manipulated by **strains**

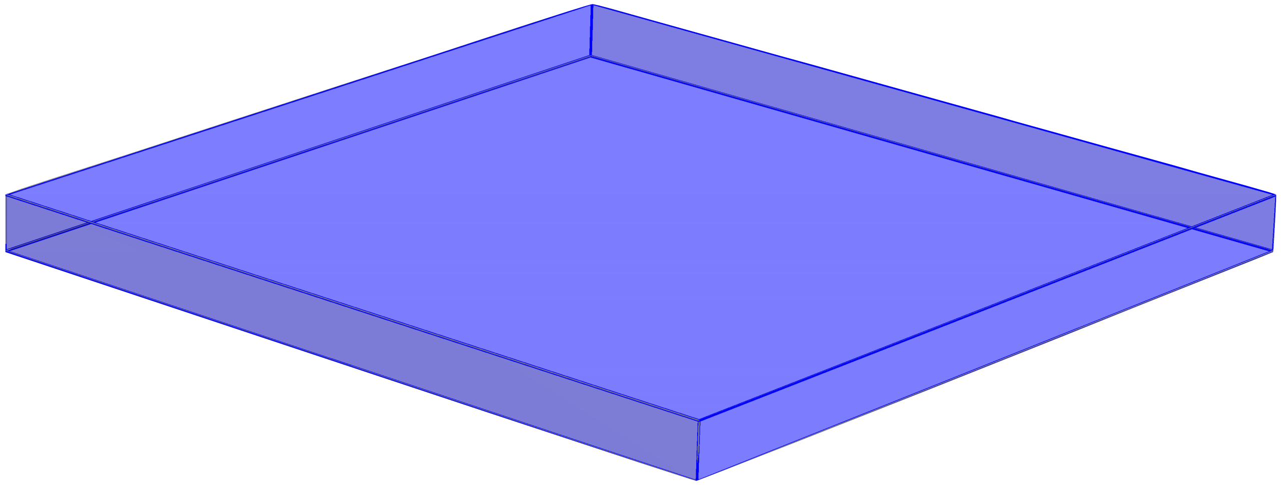
Outline

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

- Magnetoelasticity: frozen spontaneous strains and domain walls
- Incompatibility of strains
- Nonequilibrium strains: switching
- Equilibrium domain structure: Micr-*a*-magnetics
- Conclusions

SP/CE

Paramagnetic state



$$\hat{u}^{\text{spon}} \propto H_{\text{m-e}} \mathbf{n} \otimes \mathbf{n}$$

$$\hat{\sigma} \equiv -\frac{\partial}{\partial \hat{u}}\left(w_{\text{elas}} + w_{\text{me}}\right) = 0$$

"Frozen" lattice

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

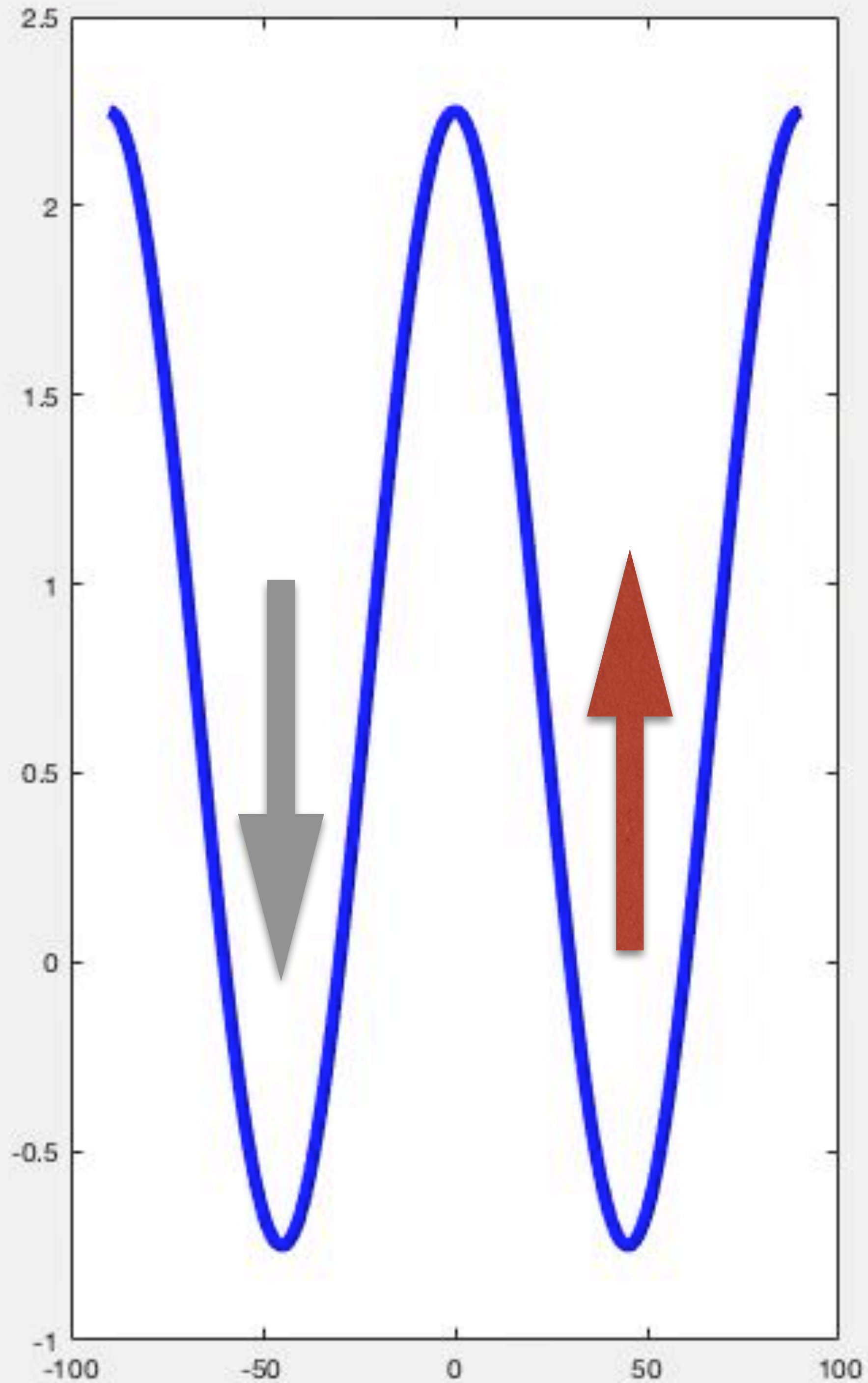
$$\tau_{\text{elas}} \propto L/v_{\text{sound}} \geq 10^{-9}\,\text{s}^{-1} \qquad \tau_{\text{mag}} \propto 1/\nu_{\text{AFMR}} \propto 10^{-12}\,\text{s}^{-1}$$

Frozen spontaneous strains

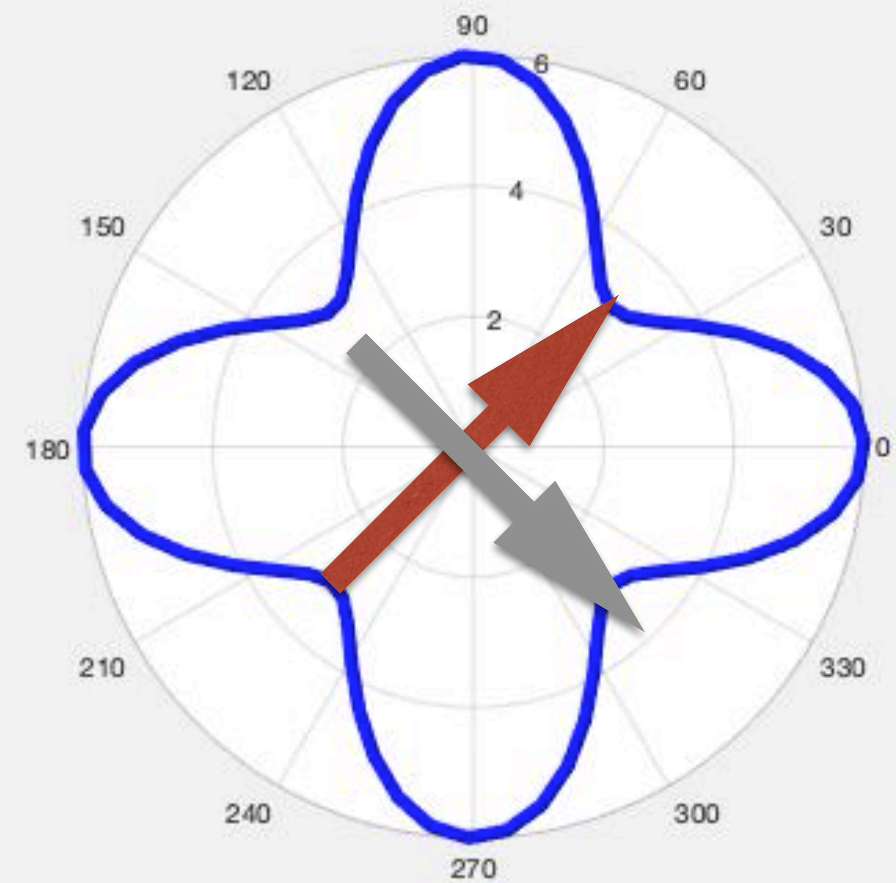
$$\varepsilon^{\text{spon}} = -\frac{H_{\text{me}} M_s}{\mu}(n_x^2 - n_y^2)\,|_0$$

$$w_{\text{me}} = H_{\text{me}} M_s \varepsilon^{\text{spon}} (n_x^2 - n_y^2)$$

Modification of the potential energy

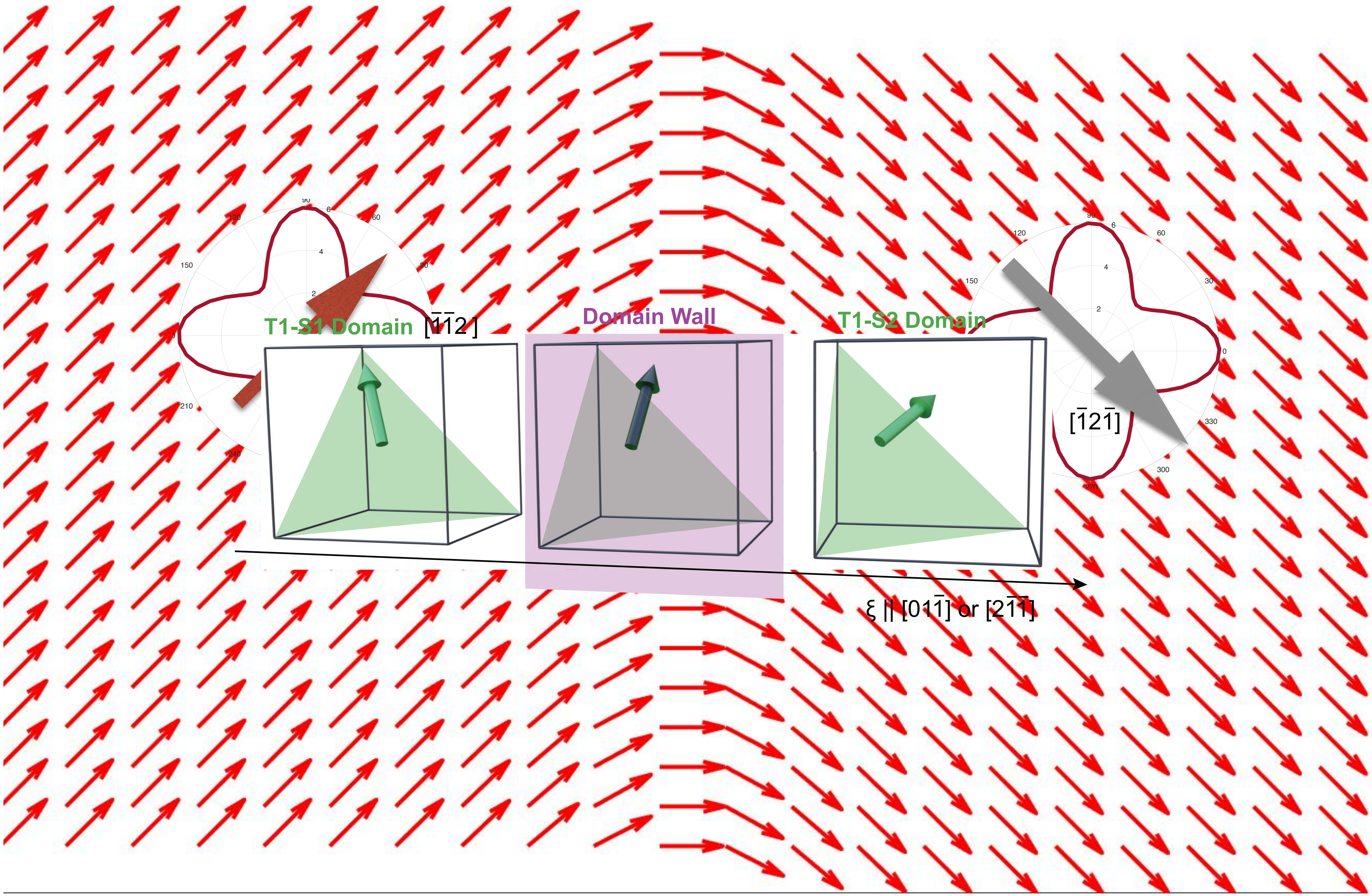


A Borovik-Romanov, 1965
V. Ozhogin, 1980



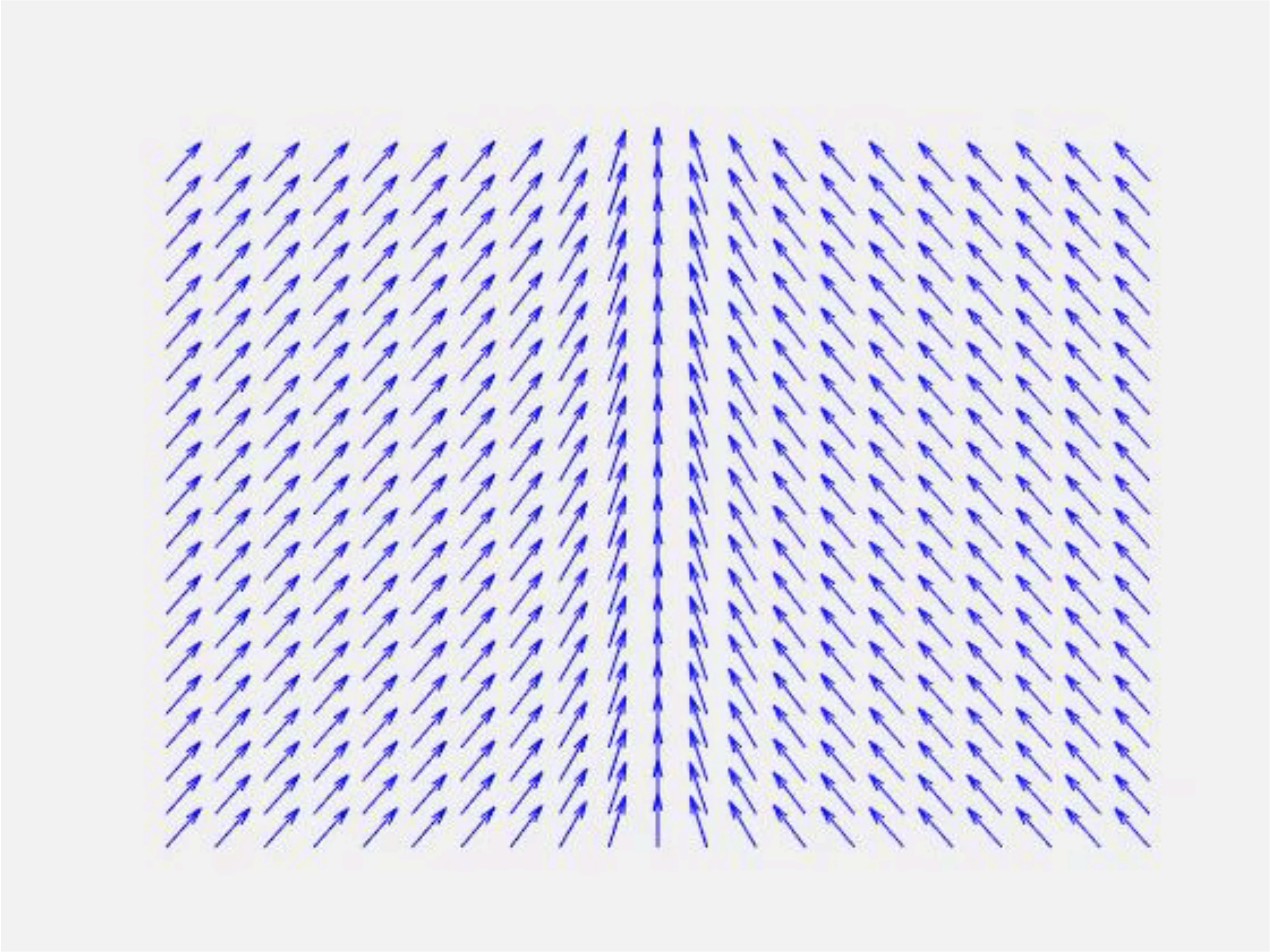
$$\omega_{\mathrm{AFMR}} \propto \sqrt{H_{\mathrm{an}} + H_{\mathrm{me}}\varepsilon^{\mathrm{spon}}}$$

Magnetic domain wall



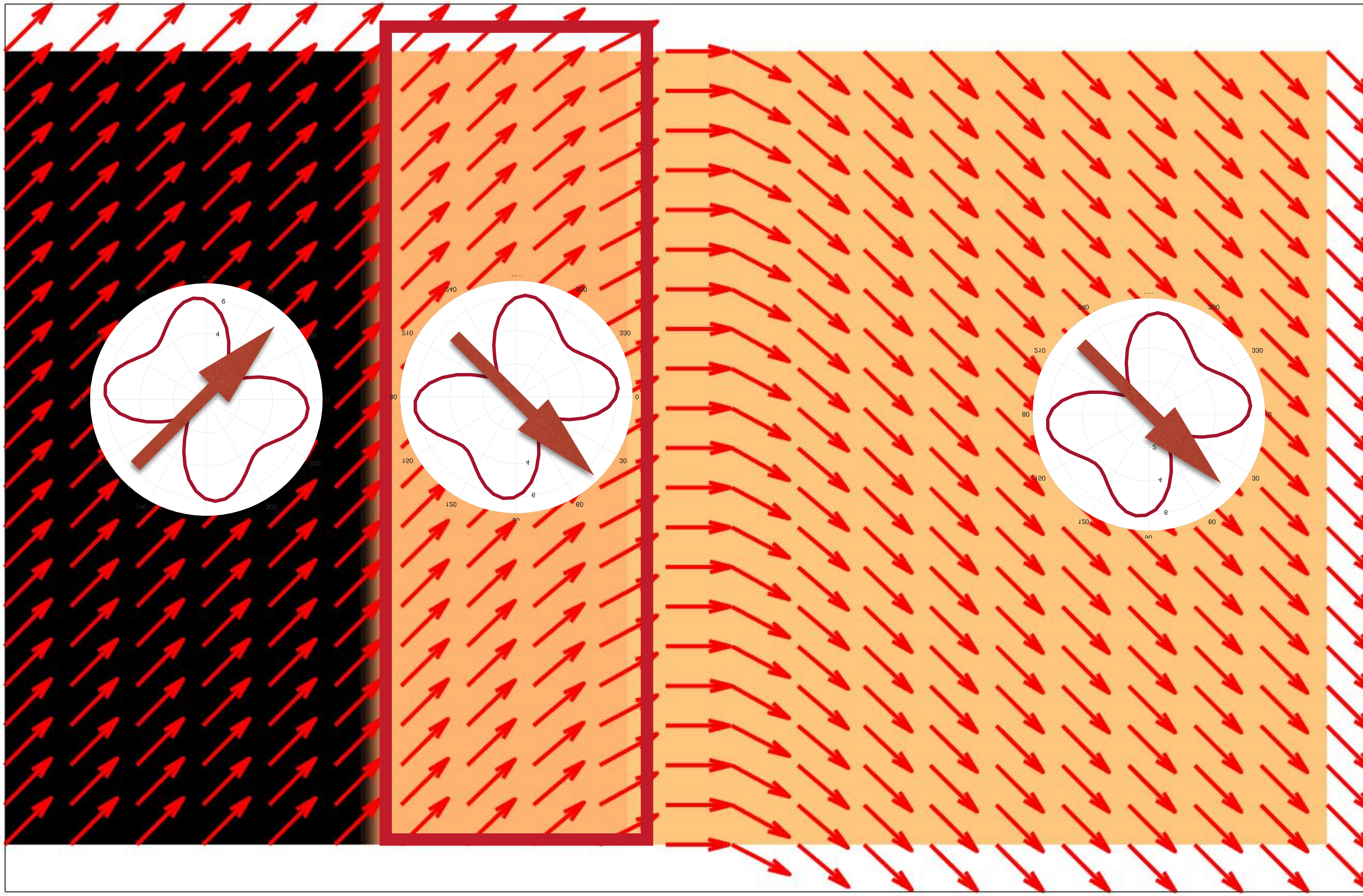
Free magnetic domain wall motion

$$\mathbf{n}\times\left(\ddot{\mathbf{n}} - c^2\Delta\mathbf{n} + \gamma^2 H_{\mathrm{ex}}\mathbf{H}_{\mathrm{an}}\right) = 0$$



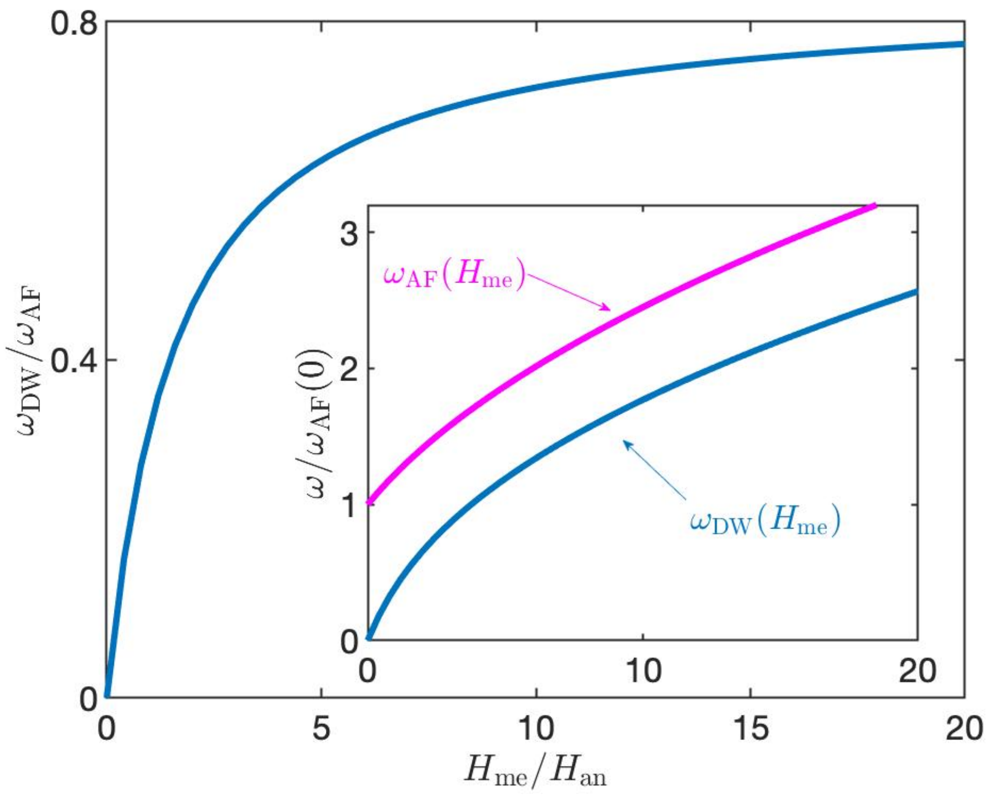
$$\omega_{\mathrm{DW}} = 0$$

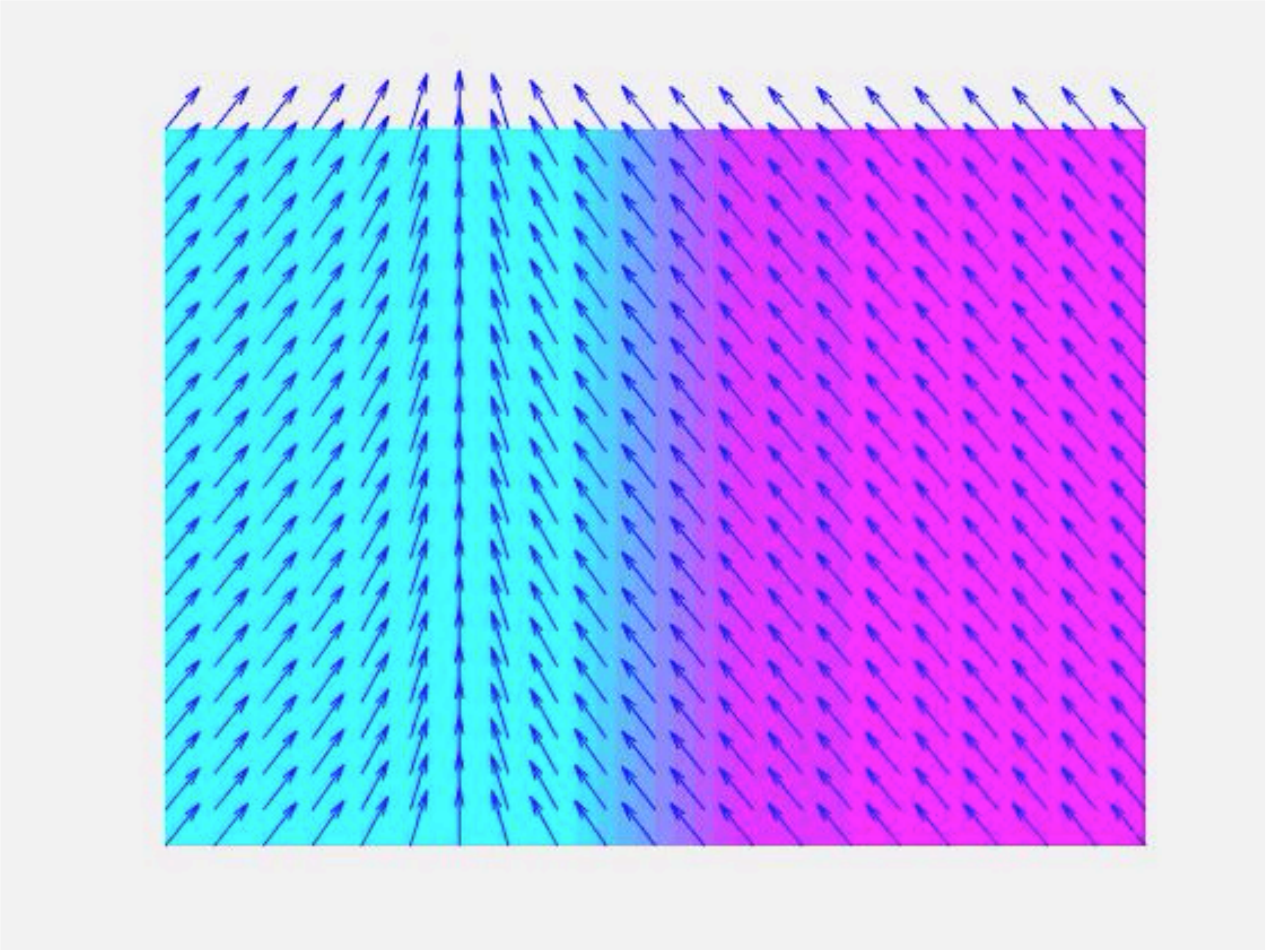
Magnetoelastic domain wall



Pinned domain wall

$$\mathbf{n}\times\left(\ddot{\mathbf{n}} - c^2\Delta\mathbf{n} + \gamma^2 H_{\mathrm{ex}}\mathbf{H}_{\mathrm{an}}(\xi)\right) = 0$$

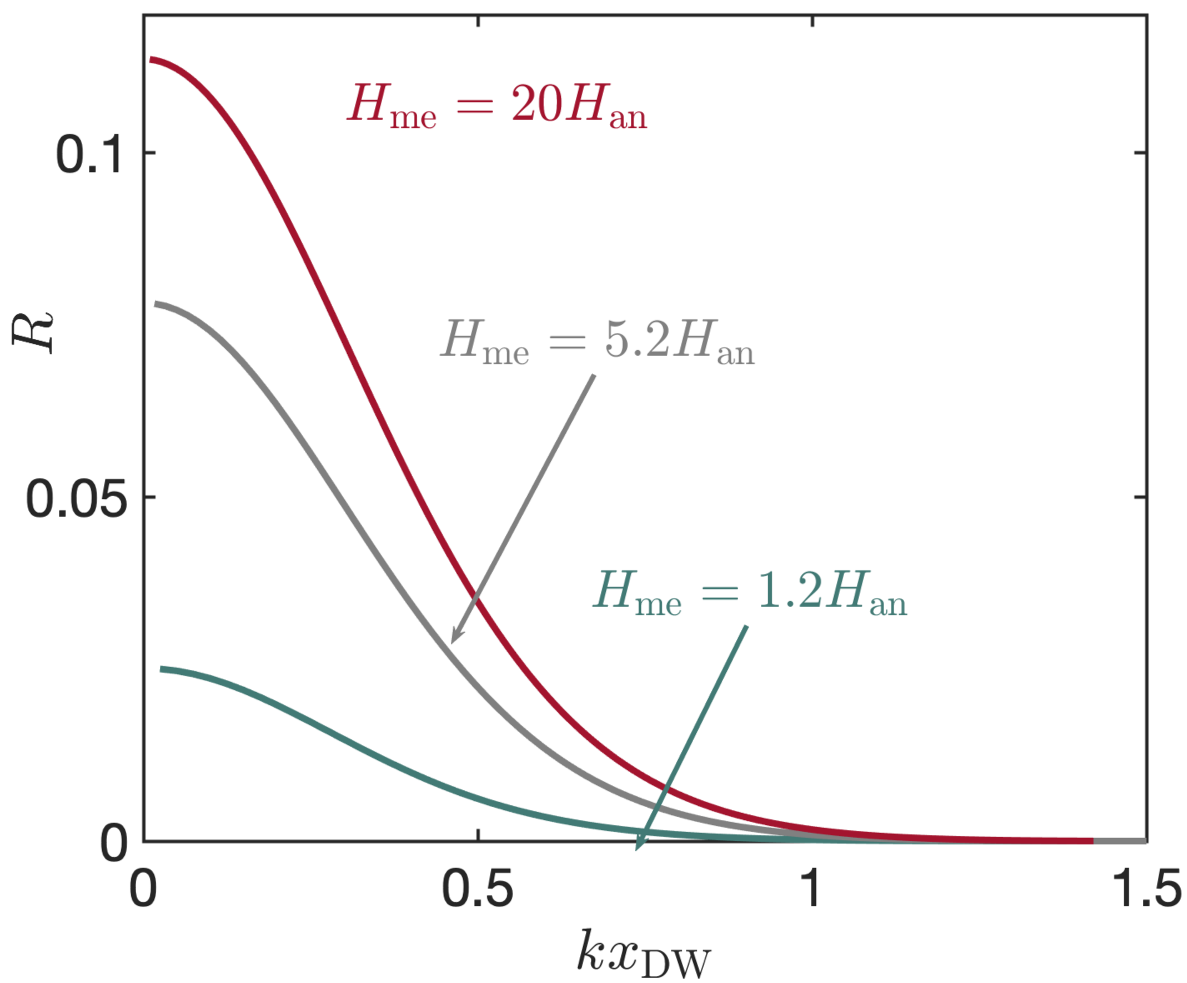




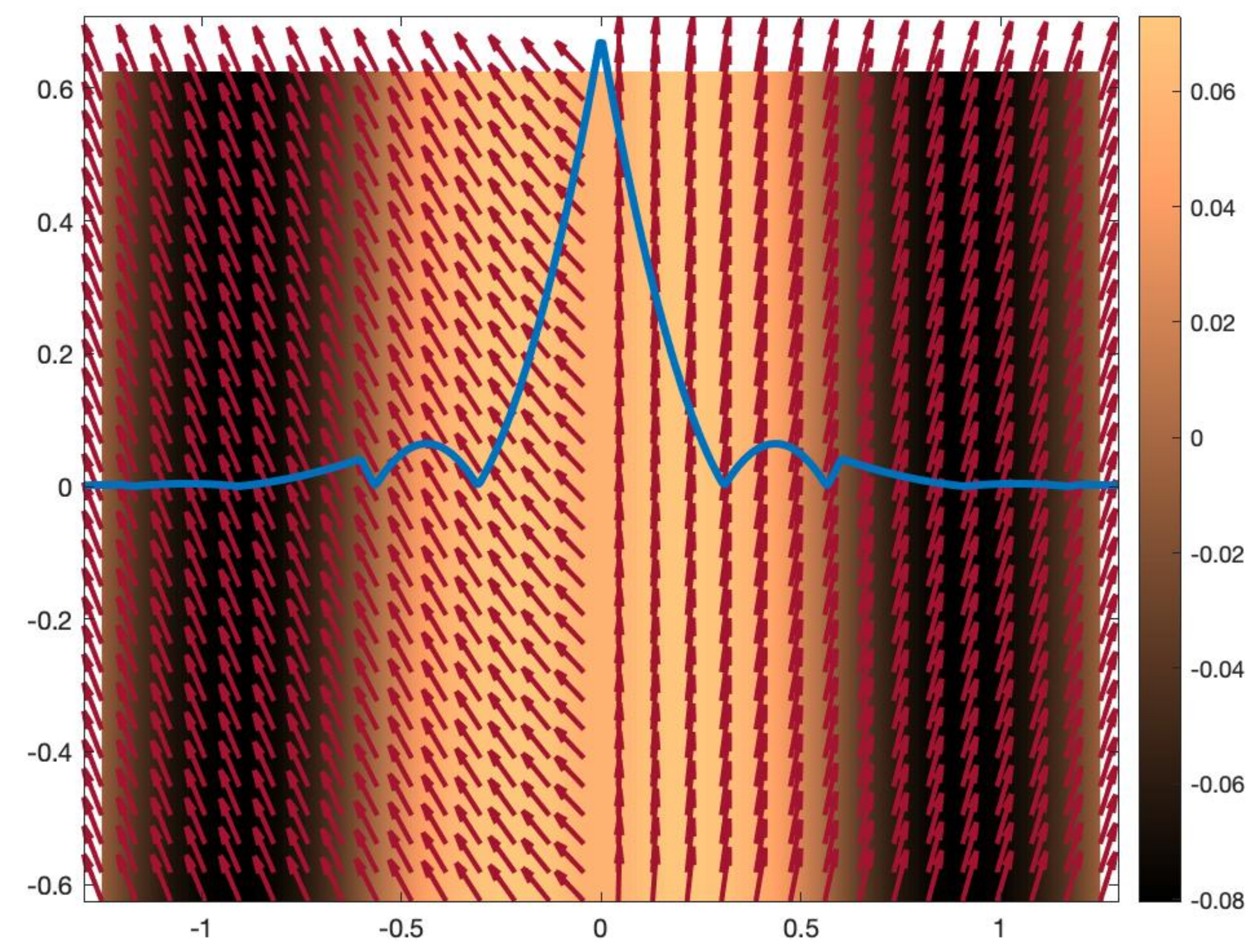
$$\omega_{\mathrm{DW}} \propto \sqrt{H_{\mathrm{me}}}$$

Pinned domain wall

$$\mathbf{n}\times\left(\ddot{\mathbf{n}} - c^2\Delta\mathbf{n} + \gamma^2 H_{\mathrm{ex}}\mathbf{H}_{\mathrm{an}}(\xi)\right) = 0$$

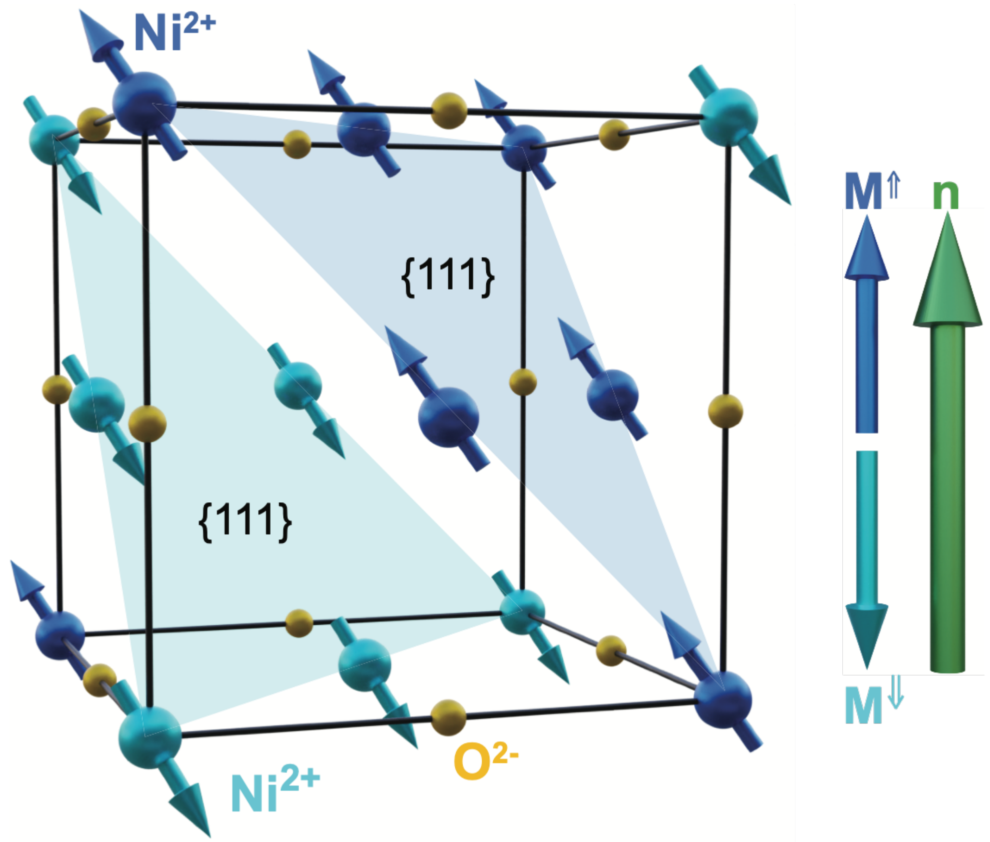


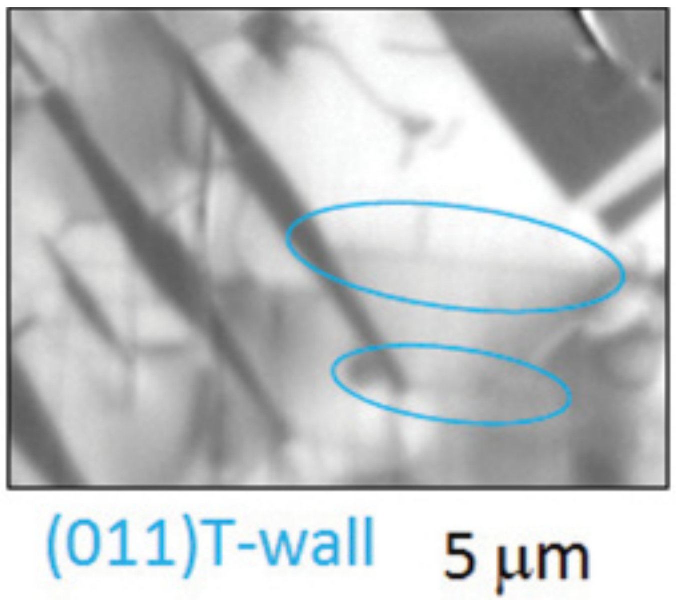
Reflection of magnons



Localised mode

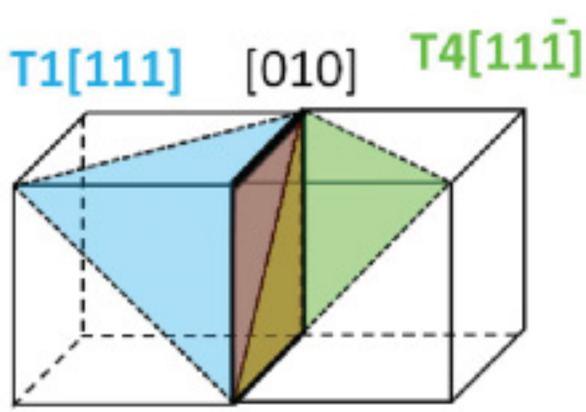
NiO and domain structure



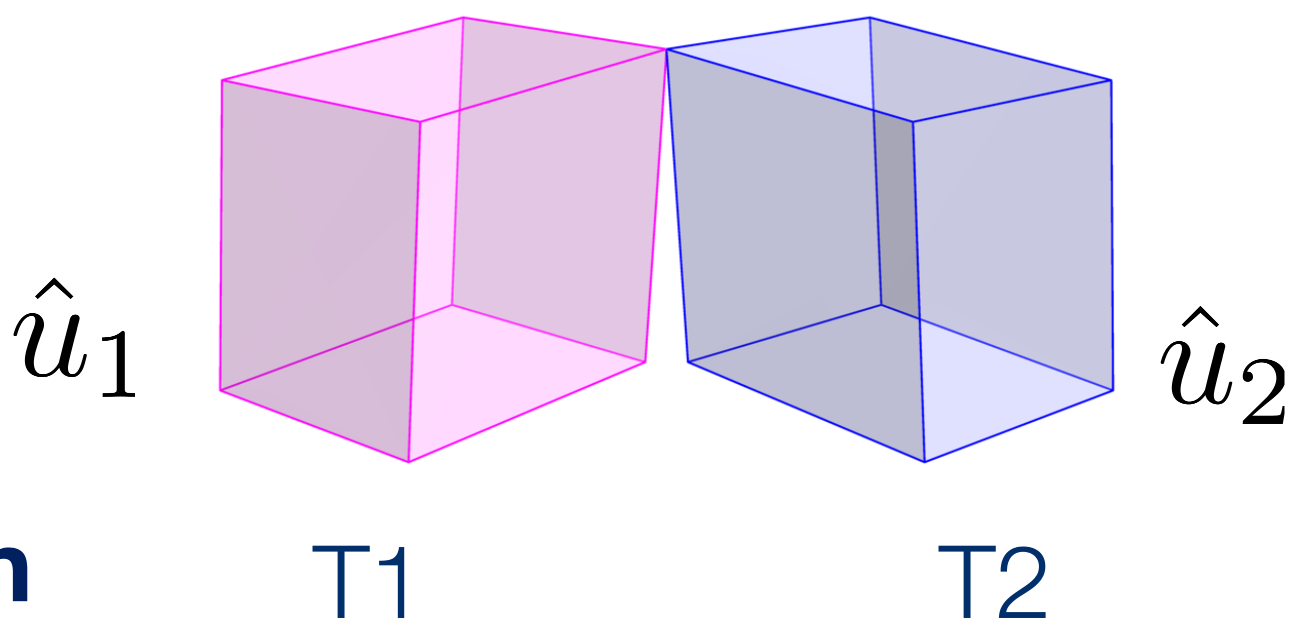


K. Arai et al, PRB, 85, 104418 (2012)

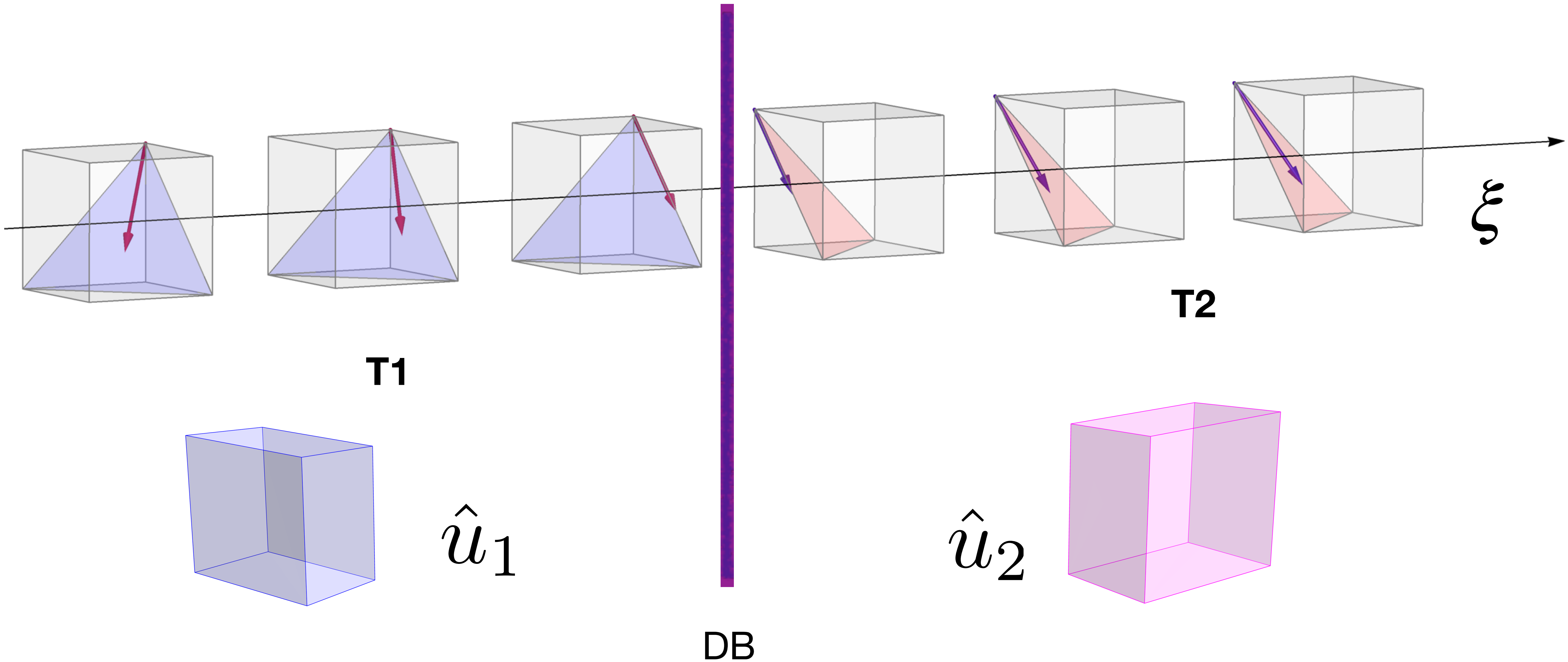
Distortion



Exchange striction

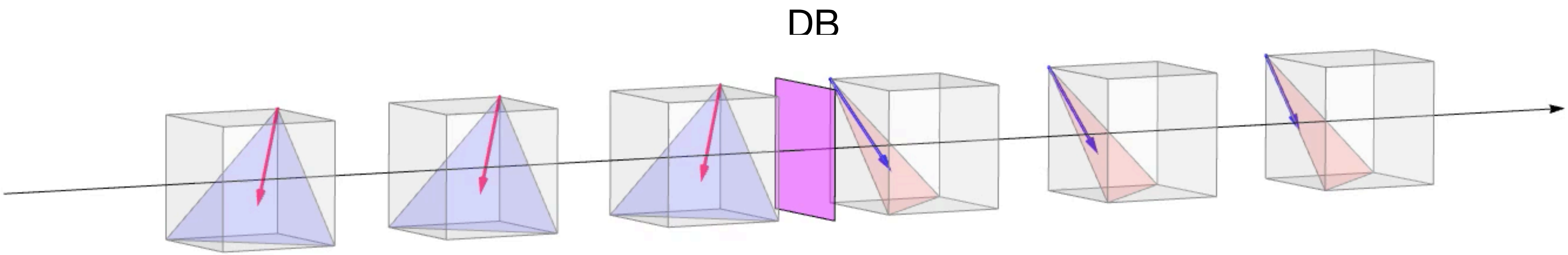


T domain wall



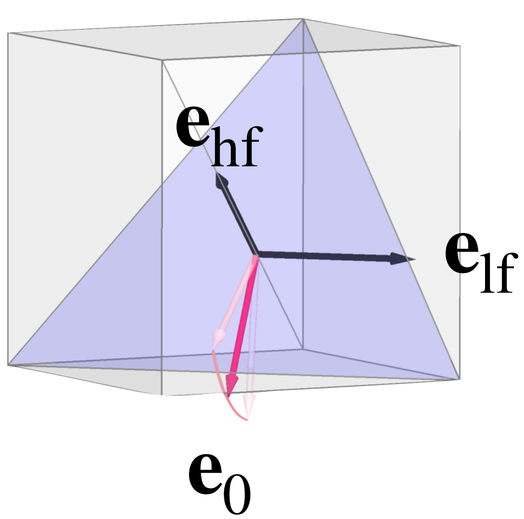
$$w_{\mathrm{an}}(\xi) = w_{\mathrm{mag}} + \boxed{\begin{cases} M_s H_{\mathrm{me}} \mathbf{n} \cdot \hat{u}_1 \cdot \mathbf{n}, & \xi < 0, \\ M_s H_{\mathrm{me}} \mathbf{n} \cdot \hat{u}_2 \cdot \mathbf{n}, & \xi > 0 \end{cases}}$$

Polarization of eigen modes



T1

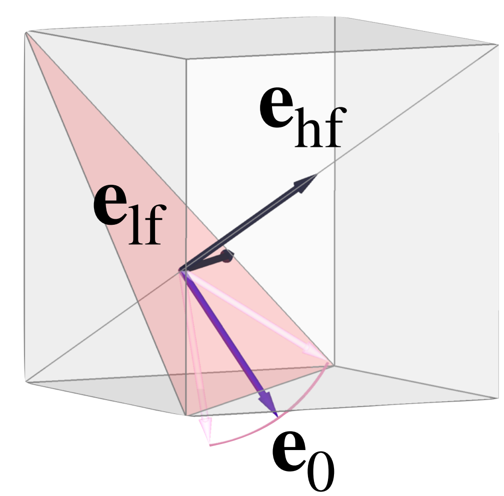
$[111]$



HF

T2

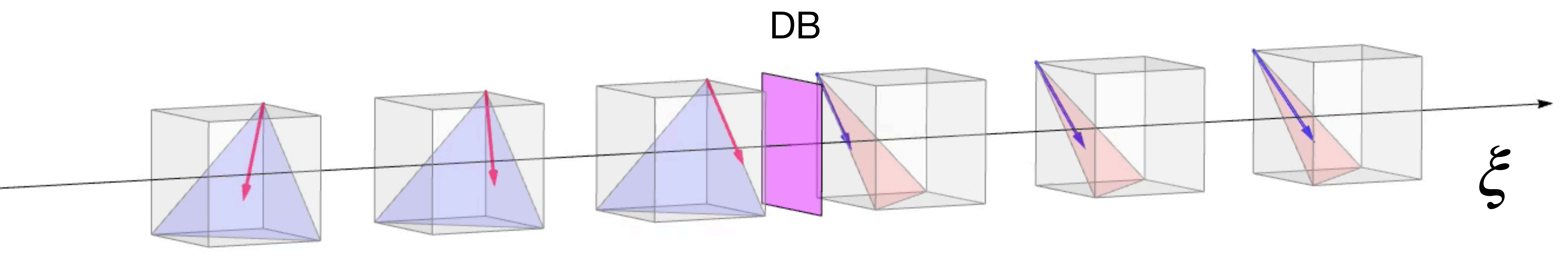
$[\bar{1}11]$

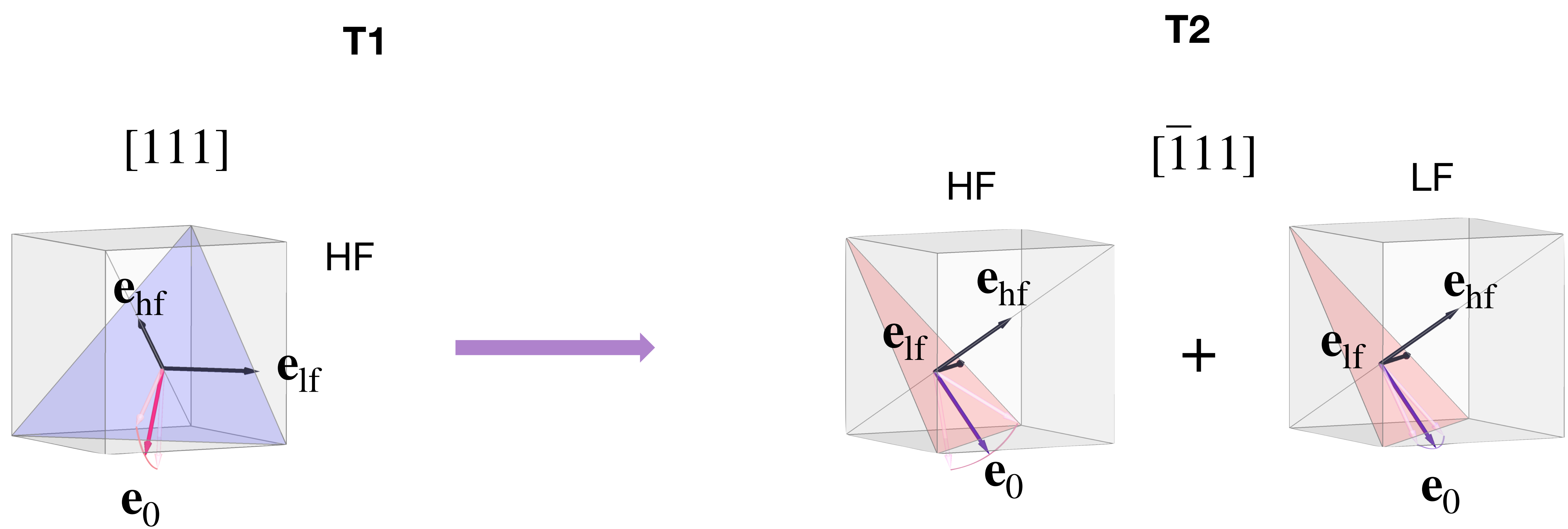


HF

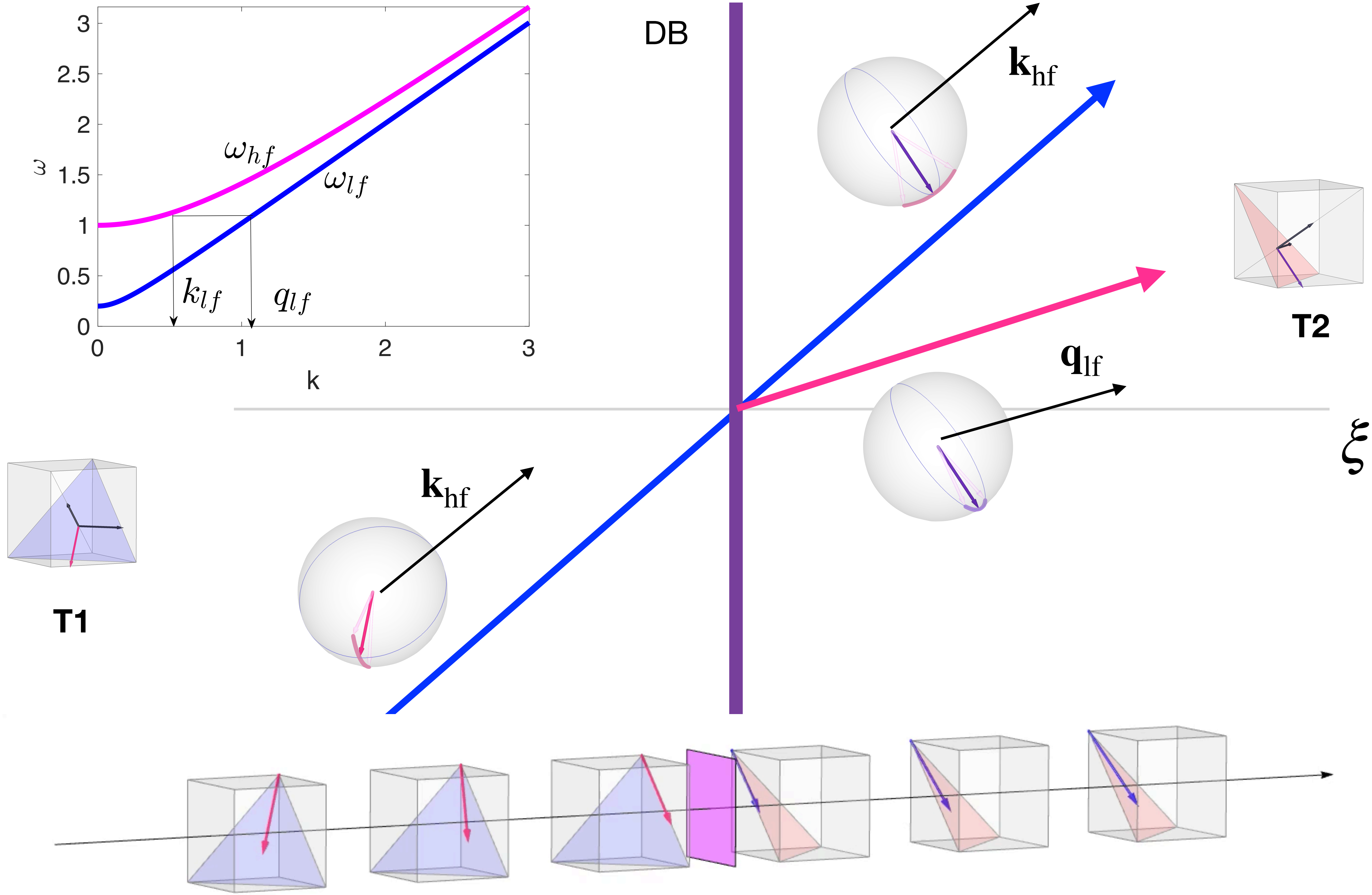
$$\mathbf{e}_{\mathrm{hf}}(\xi) = \frac{1}{\sqrt{3}} \begin{cases} [111] & \xi < 0, \\ [\bar{1}11] & \xi > 0, \end{cases} \qquad \mathbf{e}_0(\xi) = \frac{1}{\sqrt{6}} \begin{cases} [\bar{1}\bar{1}2] & \xi < 0, \\ [1\bar{1}2] & \xi > 0, \end{cases}$$

Polarization of eigen modes

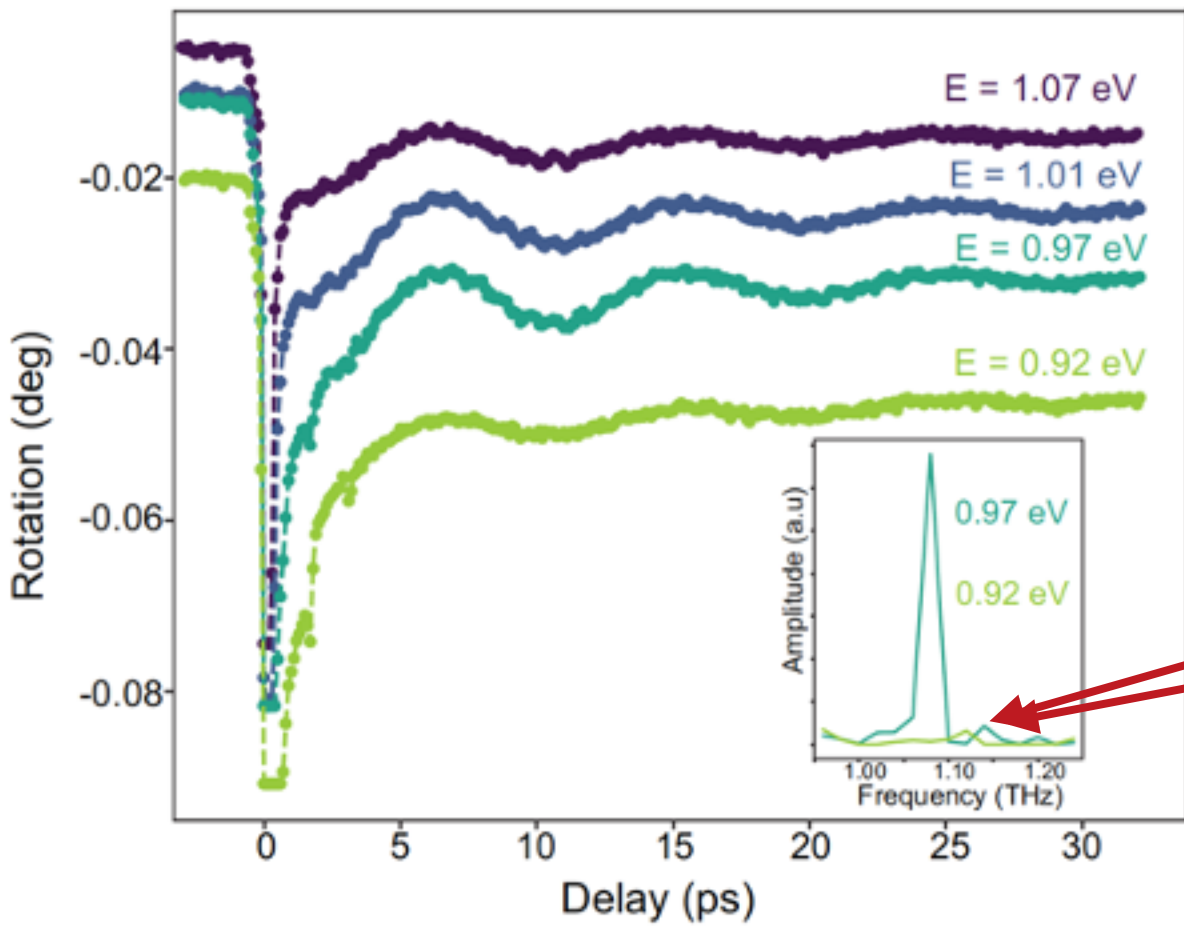


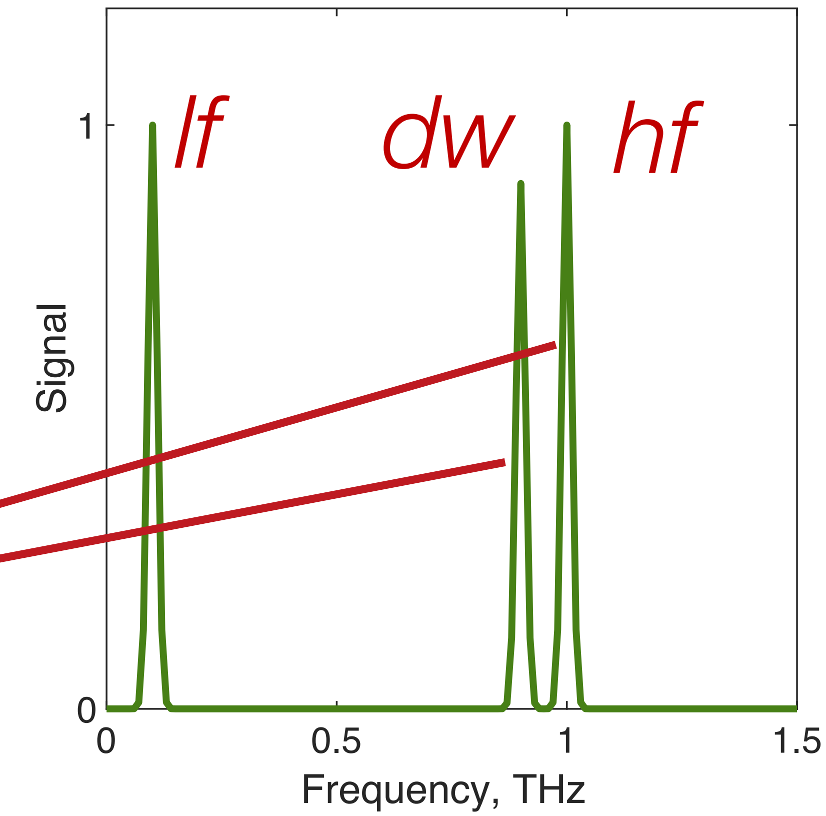


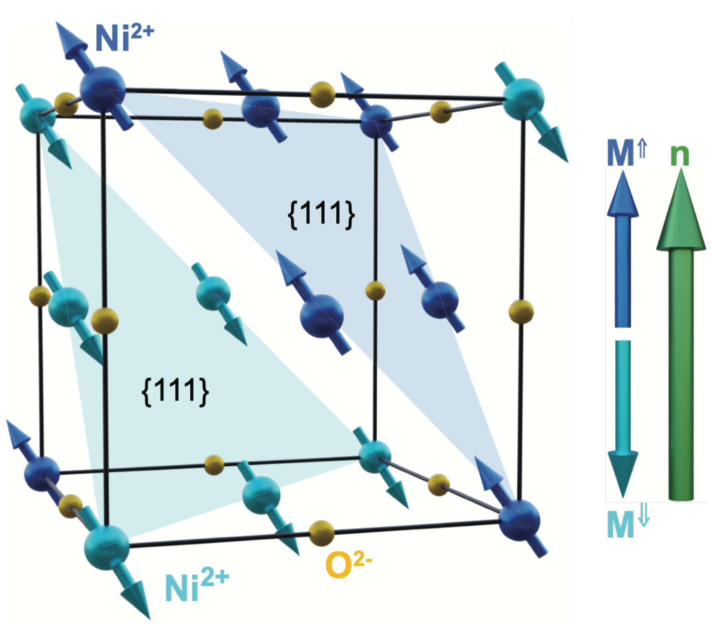
Magnon birefringence

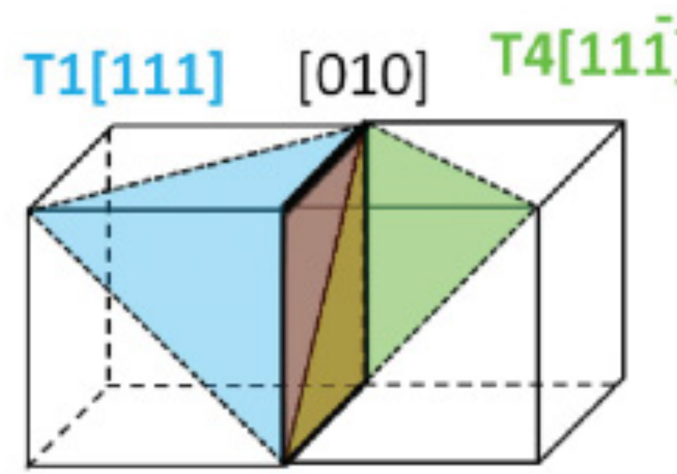


Parametric downconversion, NiO









Bossini, O.G, et, submitted to PRL

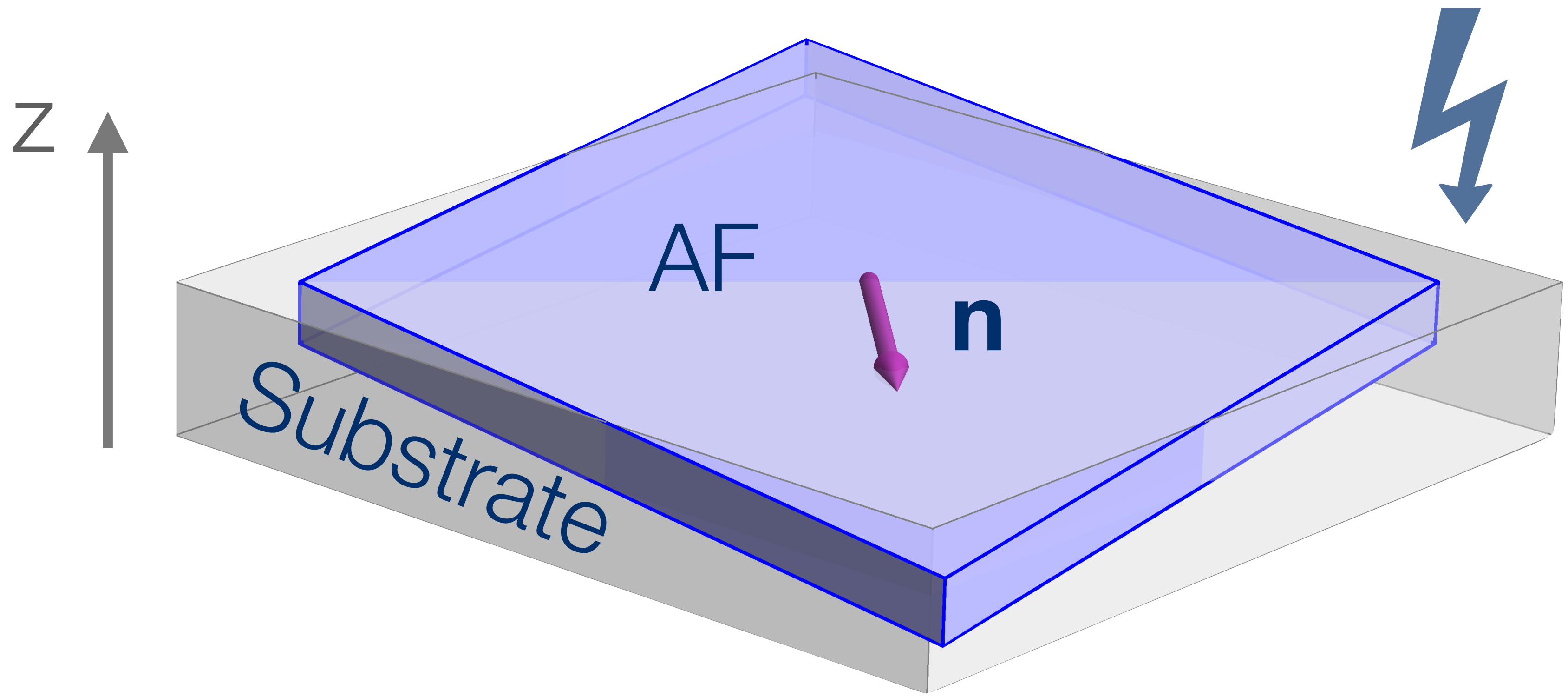
Outline

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

- Magnetoelasticity: frozen spontaneous strains and domain walls
- **Incompatibility of strains**
- Nonequilibrium strains: switching
- Equilibrium domain structure: Micr-*a*-magnetics
- Conclusions

Example I: AF + substrate

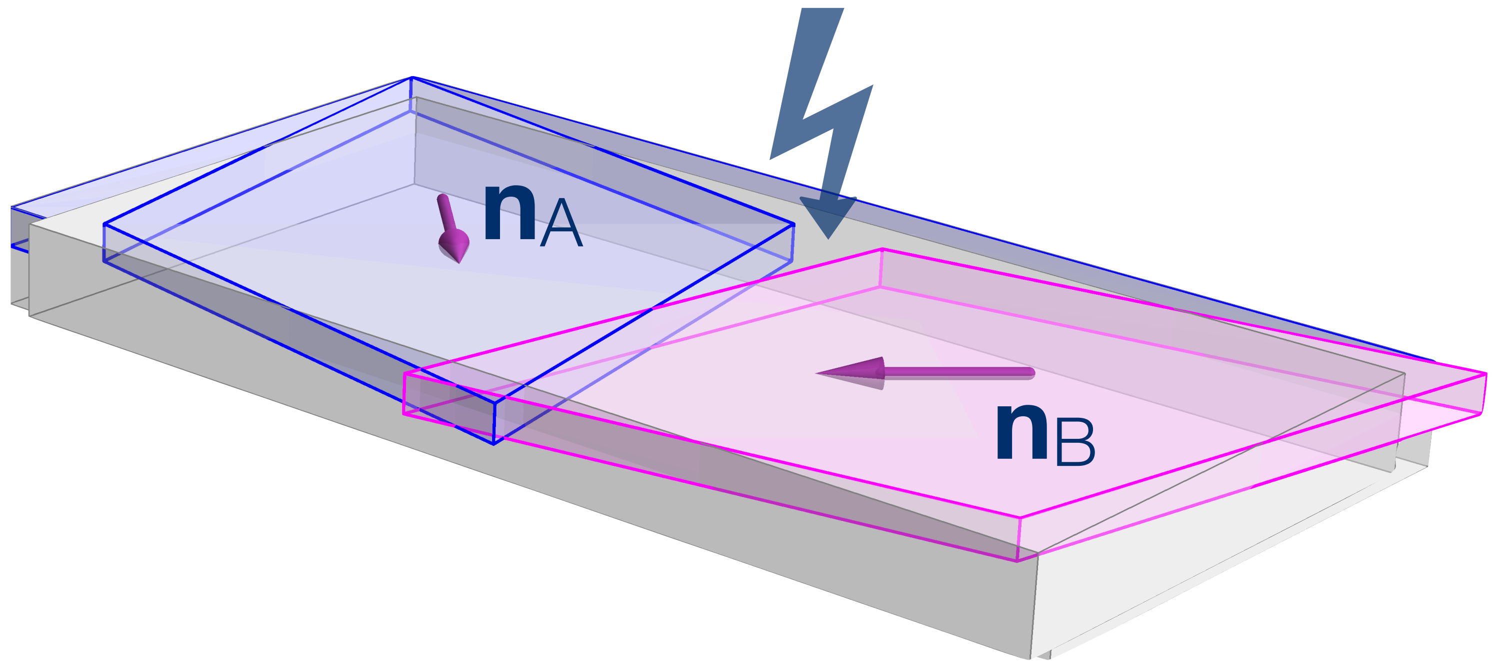
$$\hat{\eta} \propto \hat{u}^{\text{spon}} - \hat{u}^{\text{sub}}$$



Incompatibility at the interface

Example II: domain A + domain B

$$\hat{\eta} \propto \hat{u}_A^{\mathrm{spon}} - \hat{u}_B^{\mathrm{spon}}$$



Incompatibility between deformed regions

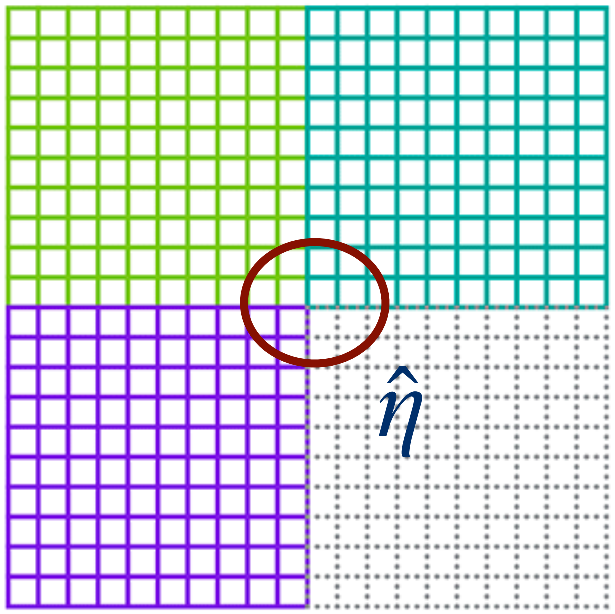
Elasticity problem

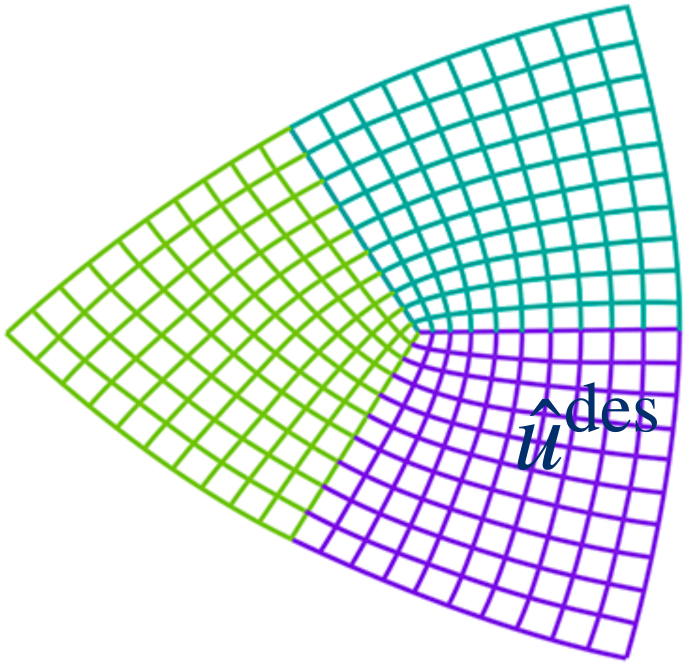
$$\nabla \times \hat{u}^{\mathrm{des}}(\mathbf{r}) \times \nabla = -\hat{\eta}$$

$$\hat{\eta} = \nabla \times \hat{u}^{\mathrm{spon}}(\mathbf{r}) \times \nabla$$

$$\hat{u} = \underbrace{\hat{u}^{\mathrm{spon}}(\mathbf{r})}_{\text{dislocations}} + \underbrace{\hat{u}^{\mathrm{des}}(\mathbf{r})}_{\text{plastic}}$$

$$\hat{u}^{\mathrm{spon}} \propto \mathbf{n} \otimes \mathbf{n}$$





Outline

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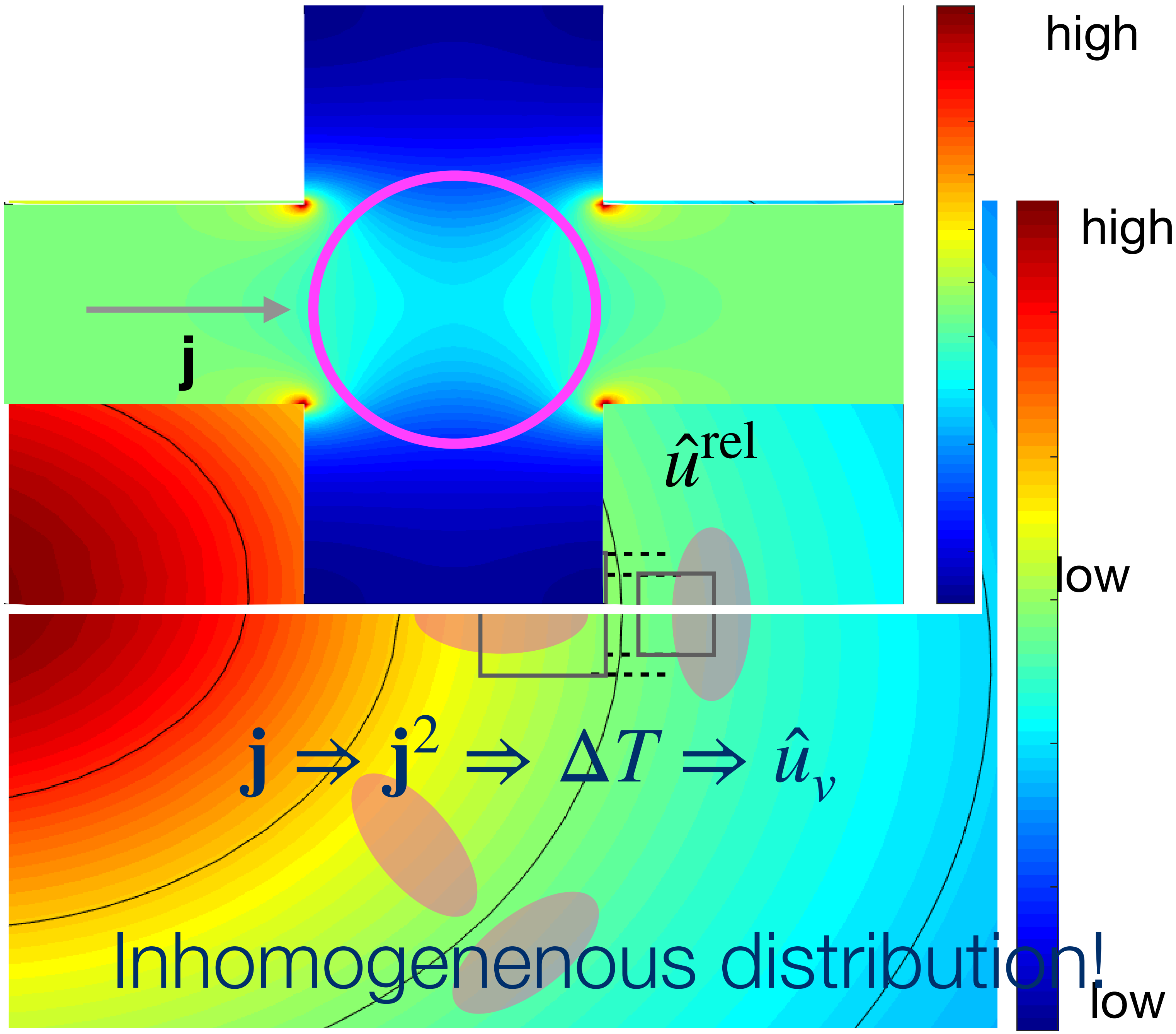
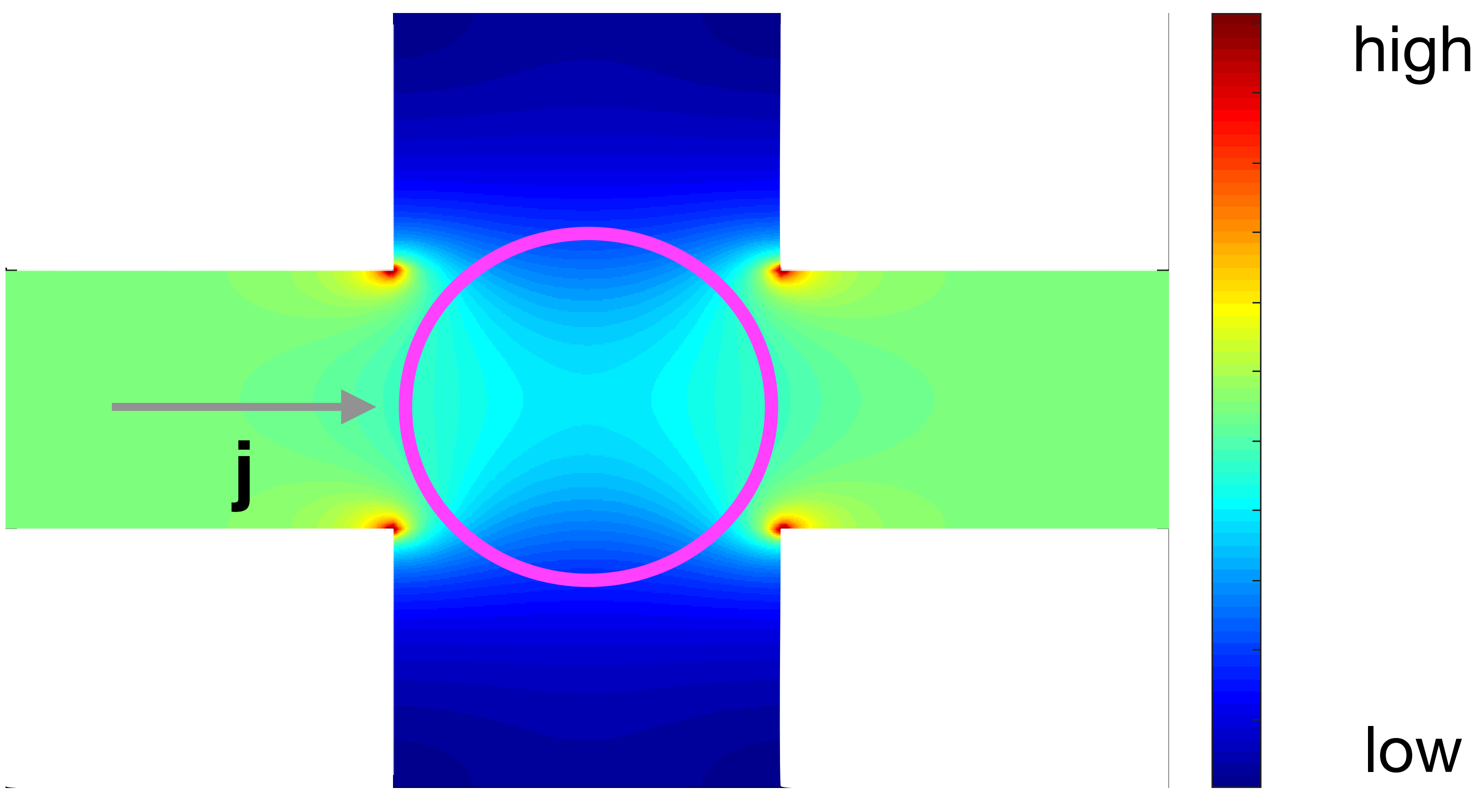
Thermo-magneto-elastic effect

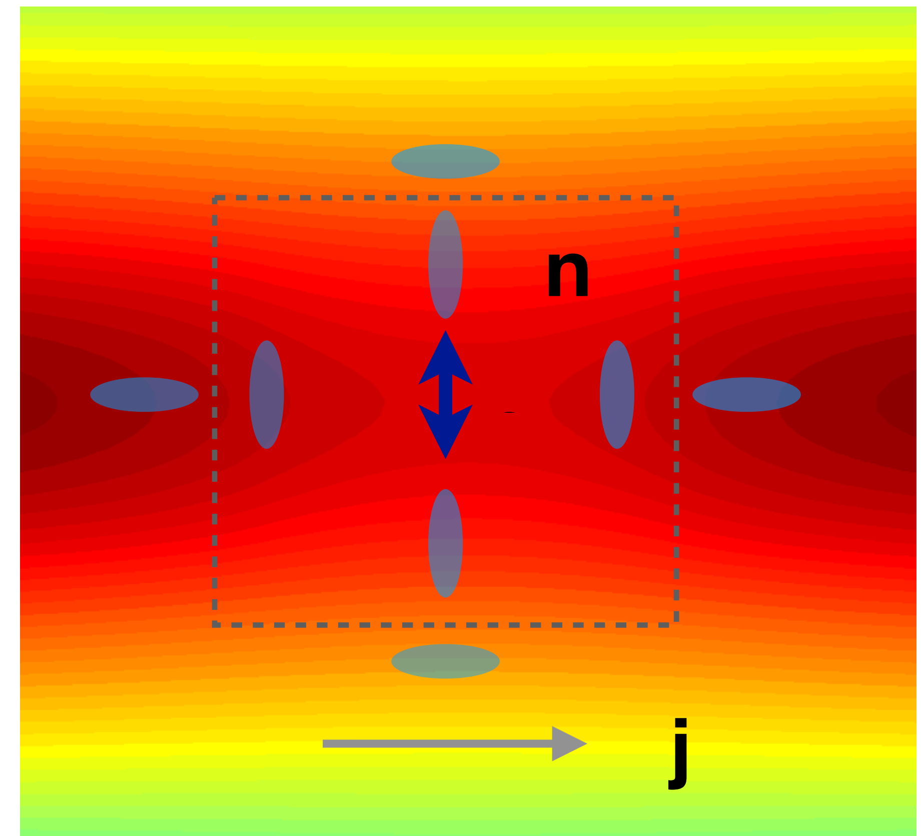


$$\mathbf{j} \Rightarrow \mathbf{j}^2 \Rightarrow \Delta T \Rightarrow \hat{u}_v$$

Inhomogenenous distribution!

Thermo-magneto-elastic effect





$$U_{\text{ext}} \propto \lambda(\mathbf{j}\cdot\mathbf{n})^2$$

Zhang et al Phys. Rev. Lett. 123, 247206 (2019)

Baldrati, OG, et al. Phys. Rev. Lett. 125, 77201 (2020)

Current, field and stress

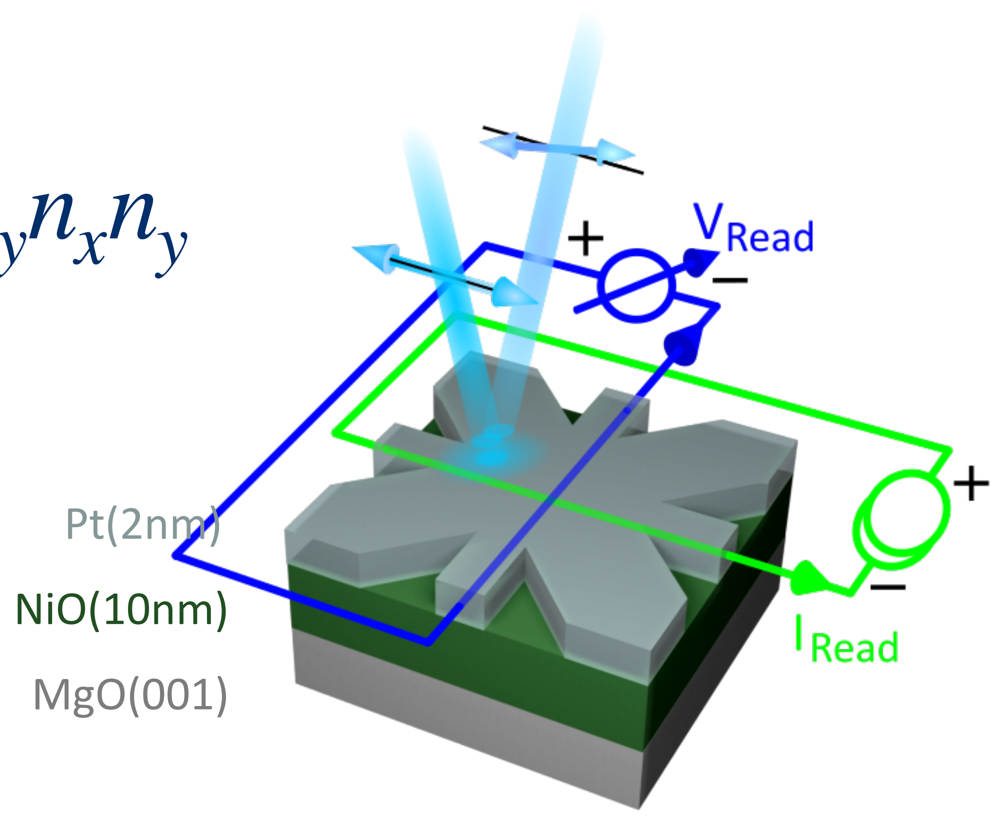
INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

Zeeman energy

$$U_{\text{ext}} \propto \left(H_x^2 - H_y^2\right)\left(n_x^2 - n_y^2\right) + 4H_xH_yn_xn_y = (\mathbf{H}\cdot\mathbf{n})^2$$

Magnetoelastic energy, external strains

$$U_{\text{ext}} \propto \left(u_{xx} - u_{yy}\right)\left(n_x^2 - n_y^2\right) + 2u_{xy}n_xn_y$$

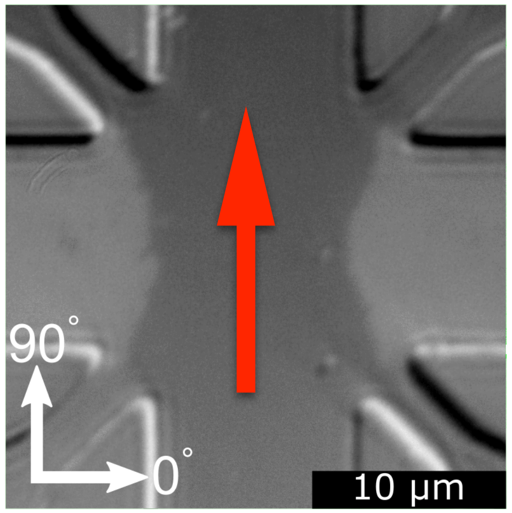


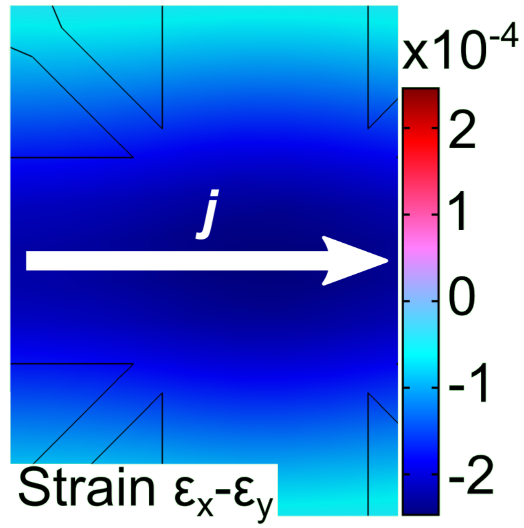
Courtesy F. Schreiber

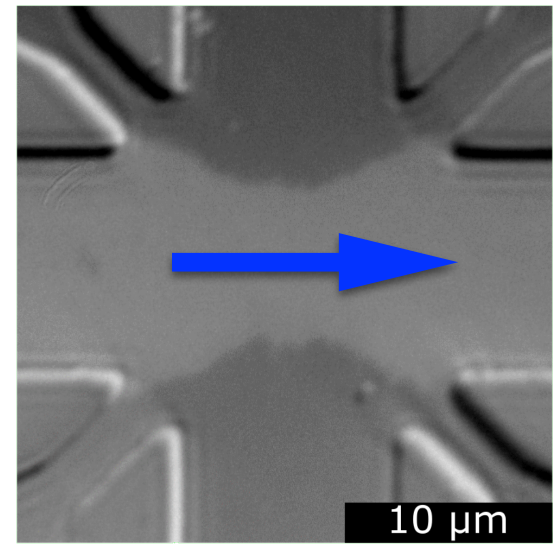
Thermo-magneto-elastic effect, NiO

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

From SMR



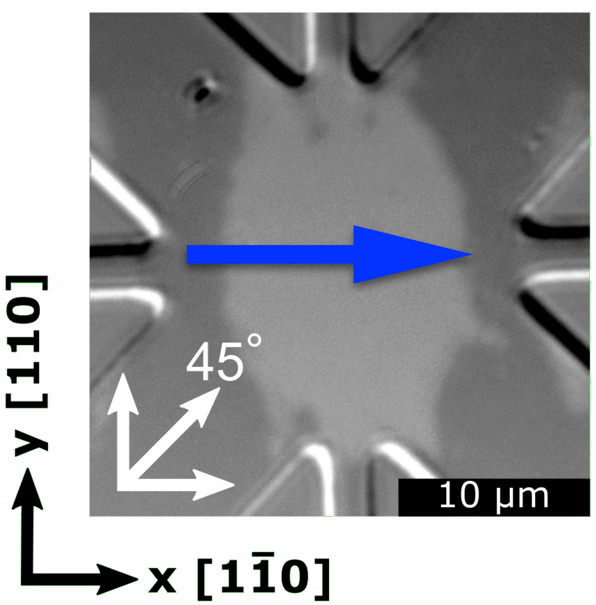


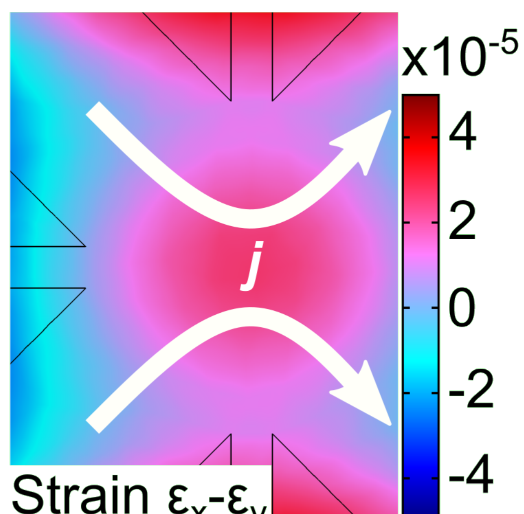


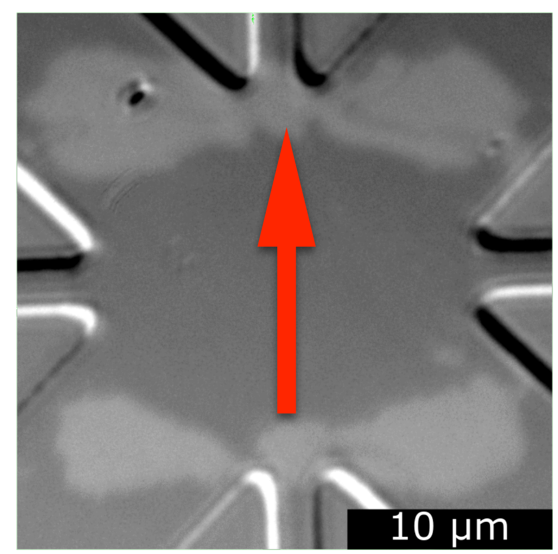
$\mathbf{j} \| \mathbf{n}$

Initial state

Final state



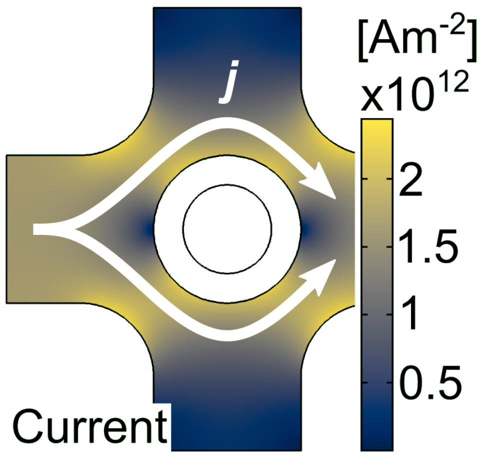


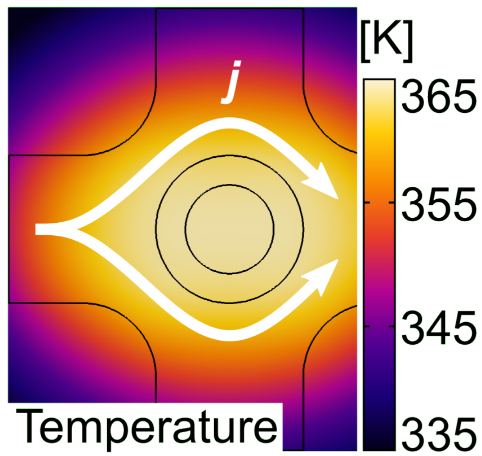


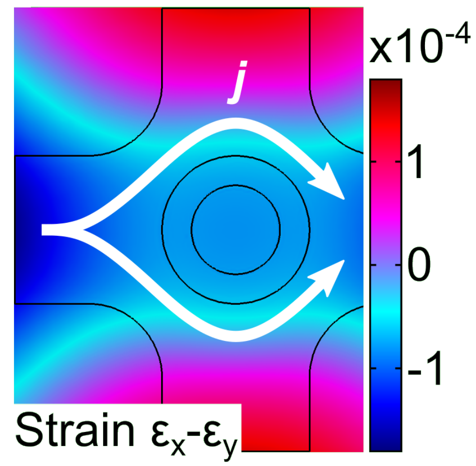
$\mathbf{j} \perp \mathbf{n}$

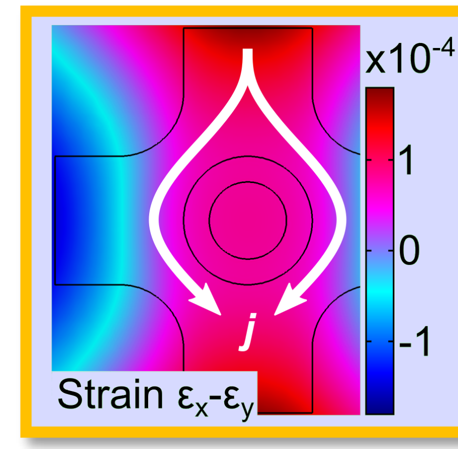
Courtesy H. Meer

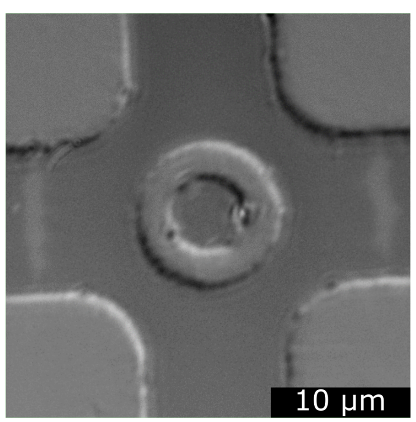
Thermo-magneto-elastic effect, NiO

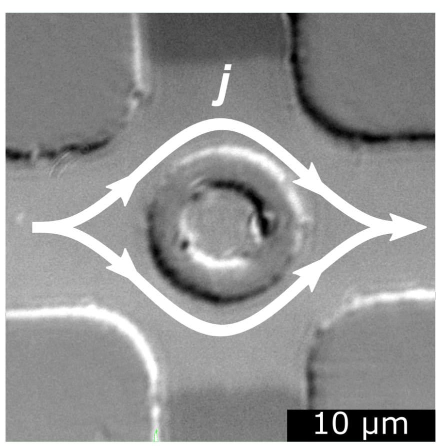


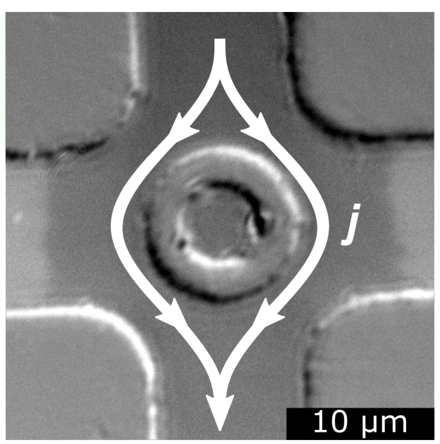








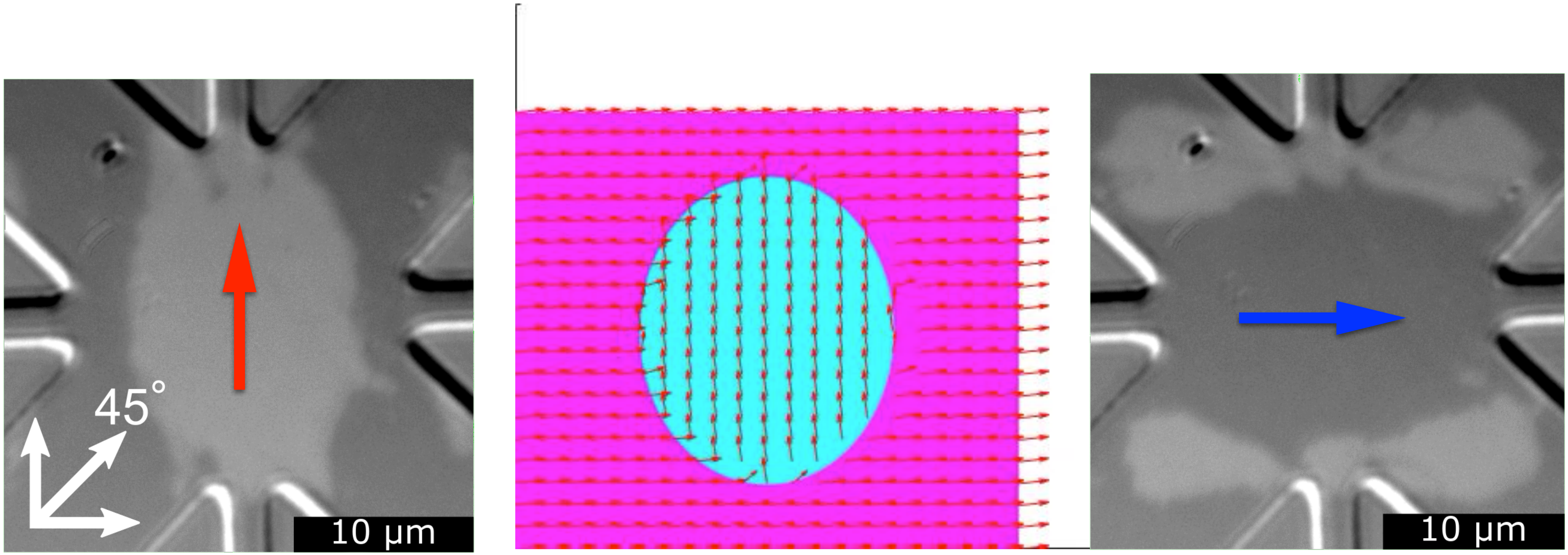




Meer, OG, et al. , Nano Lett. 21, 114 (2020)

Courtesy H. Meer

Dynamics of the domain switching



Courtesy F. Schreiber

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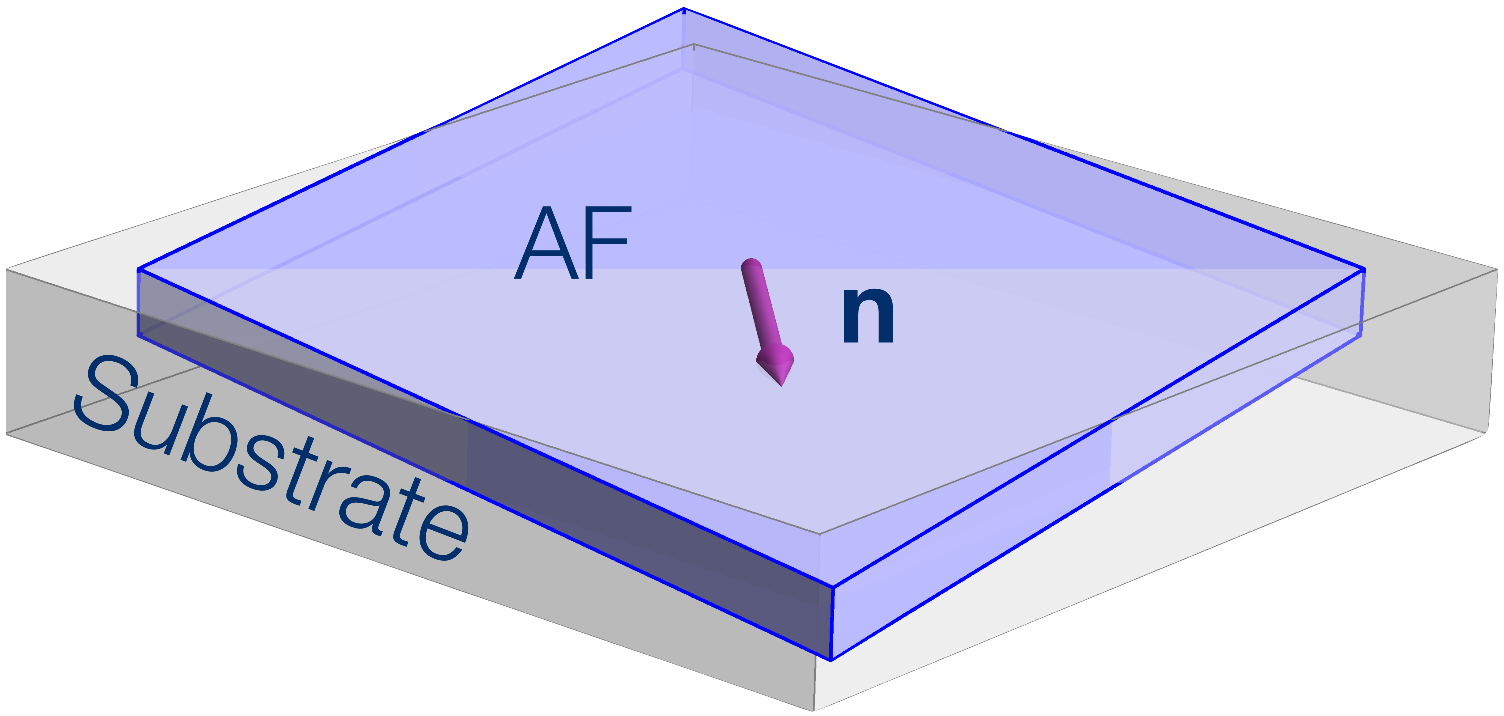
Magneto-elastostatics

Elastostatic	Magnetostatics
$\hat{\eta} = \nabla \times \hat{u}^{\text{spon}}(\mathbf{r}) \times \nabla$	$\rho_m = \text{div}\mathbf{M}$
$\nabla \times \hat{u}^{\text{des}}(\mathbf{r}) \times \nabla = -\hat{\eta}$	$\nabla \cdot \nabla\psi = -\rho_m$
$\hat{I}(\mathbf{r}) \propto \nabla_j \nabla_k \lvert\mathbf{r}\rvert \propto \frac{1}{\lvert\mathbf{r}\rvert}$	$G(\mathbf{r}) \propto \nabla \cdot \nabla \lvert\mathbf{r}\rvert = \frac{1}{\lvert\mathbf{r}\rvert}$
$\hat{u}^{\text{spon}} \propto \mathbf{n} \otimes \mathbf{n}$	$\mathbf{M} \propto \mathbf{M}$

$$\hat{u} = \underbrace{\hat{u}^{\text{spon}}(\mathbf{r})}_{\text{dislocations}} + \underbrace{\hat{u}^{\text{des}}(\mathbf{r})}_{\text{plastic}}$$

Destressing from the substrate

Demagnetising —> destressing



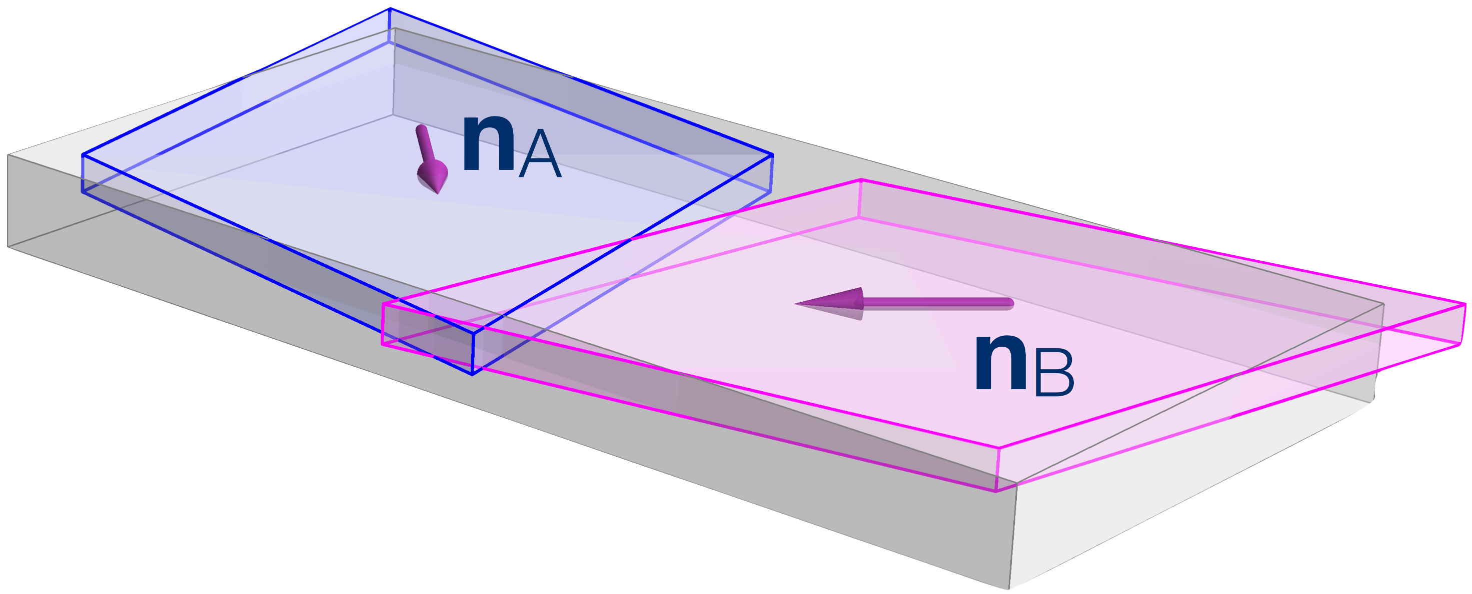
$$E_{\mathrm{des}} = \langle \mathbf{n} \otimes \mathbf{n} \rangle \hat{N} \langle \mathbf{n} \otimes \mathbf{n} \rangle V$$

$$\hat{N} = \int_V \hat{K}(\mathbf{r}_1 - \mathbf{r}_2) d\mathbf{r}_2$$

Gomonay, Loktev, 2002

Destressing at the domain boundary

Bloch type DW —> Nye type DW



Flat domain wall

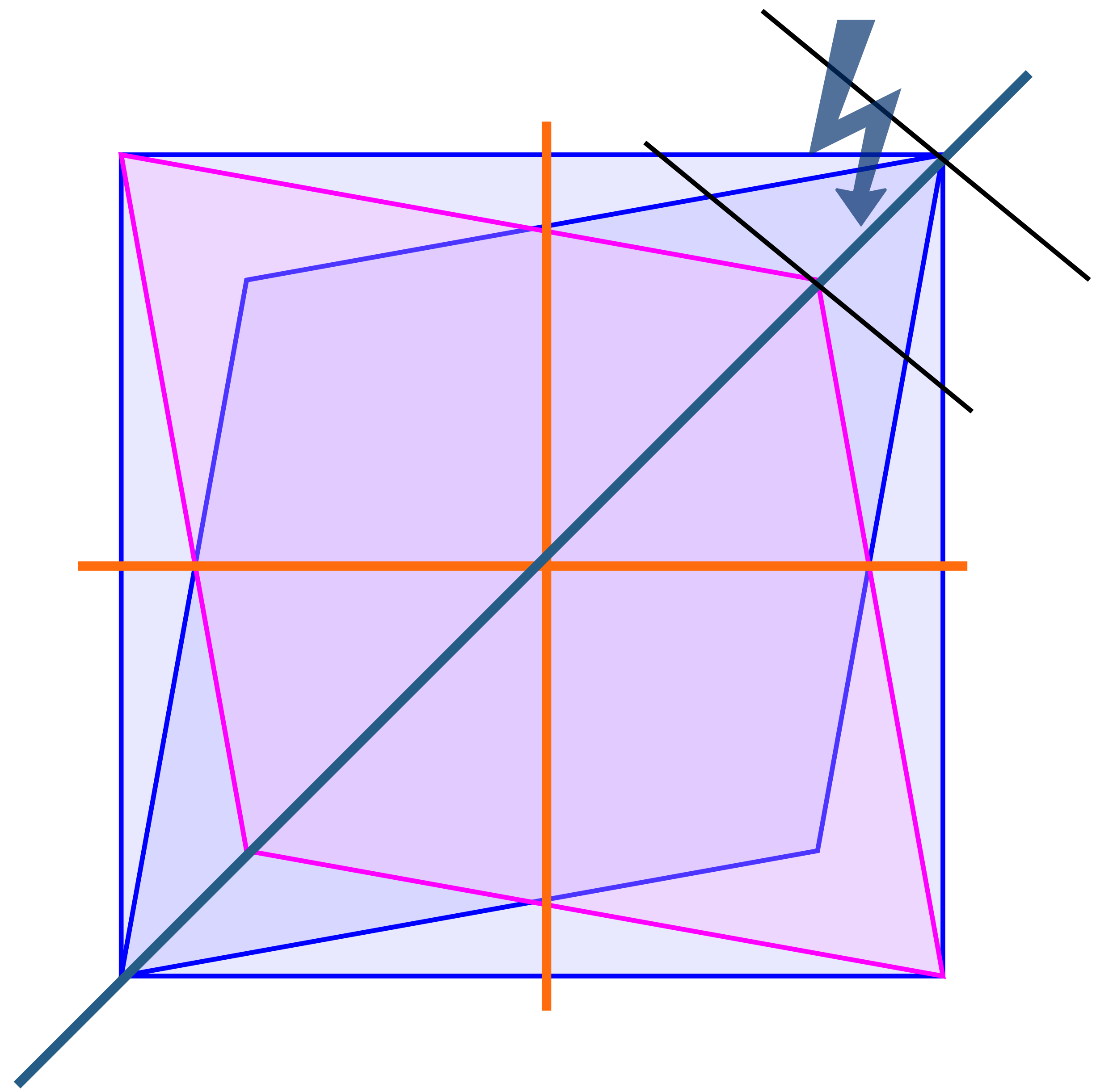
$$\hat{u}^{\mathrm{des}}(\mathbf{r}) = \mathbf{N} \times \left[\hat{u}_A^{\mathrm{spon}} - \hat{u}_B^{\mathrm{spon}}\right] \times \mathbf{N} \int \nabla \hat{I}(\mathbf{r} - \mathbf{r}_{\mathrm{DW}}) d\mathbf{r}_{\mathrm{DW}}$$

$$E_{\mathrm{des}} \propto V$$

Kleman, Miltat, 1972, for FM

Nye domain wall

$$\hat{\eta} \propto \mathbf{N} \times (\hat{u}_A^{\text{spon}} - \hat{u}_B^{\text{spon}}) \times \mathbf{N}$$

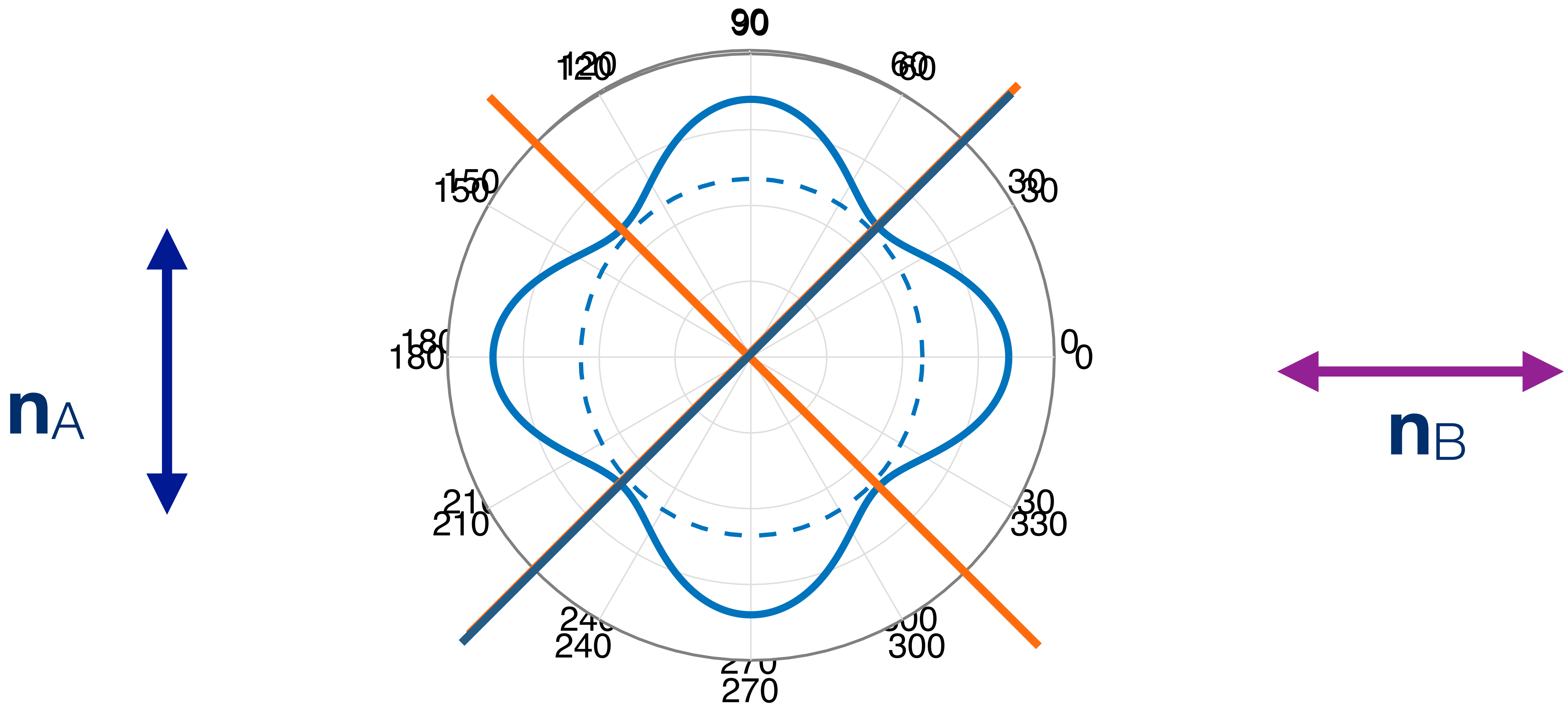


$$\hat{\eta}(\varphi) \neq 0$$

Domain wall energy

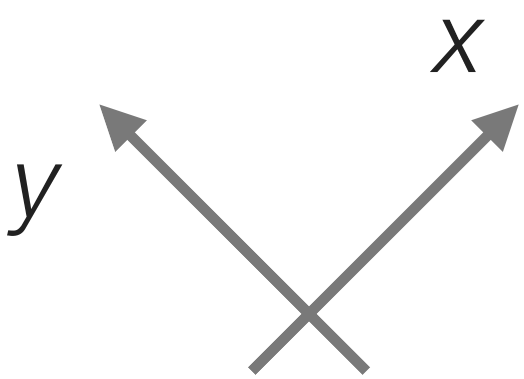
$$E_{\text{mag}} = \sqrt{A H_{\text{an}} M_s}$$

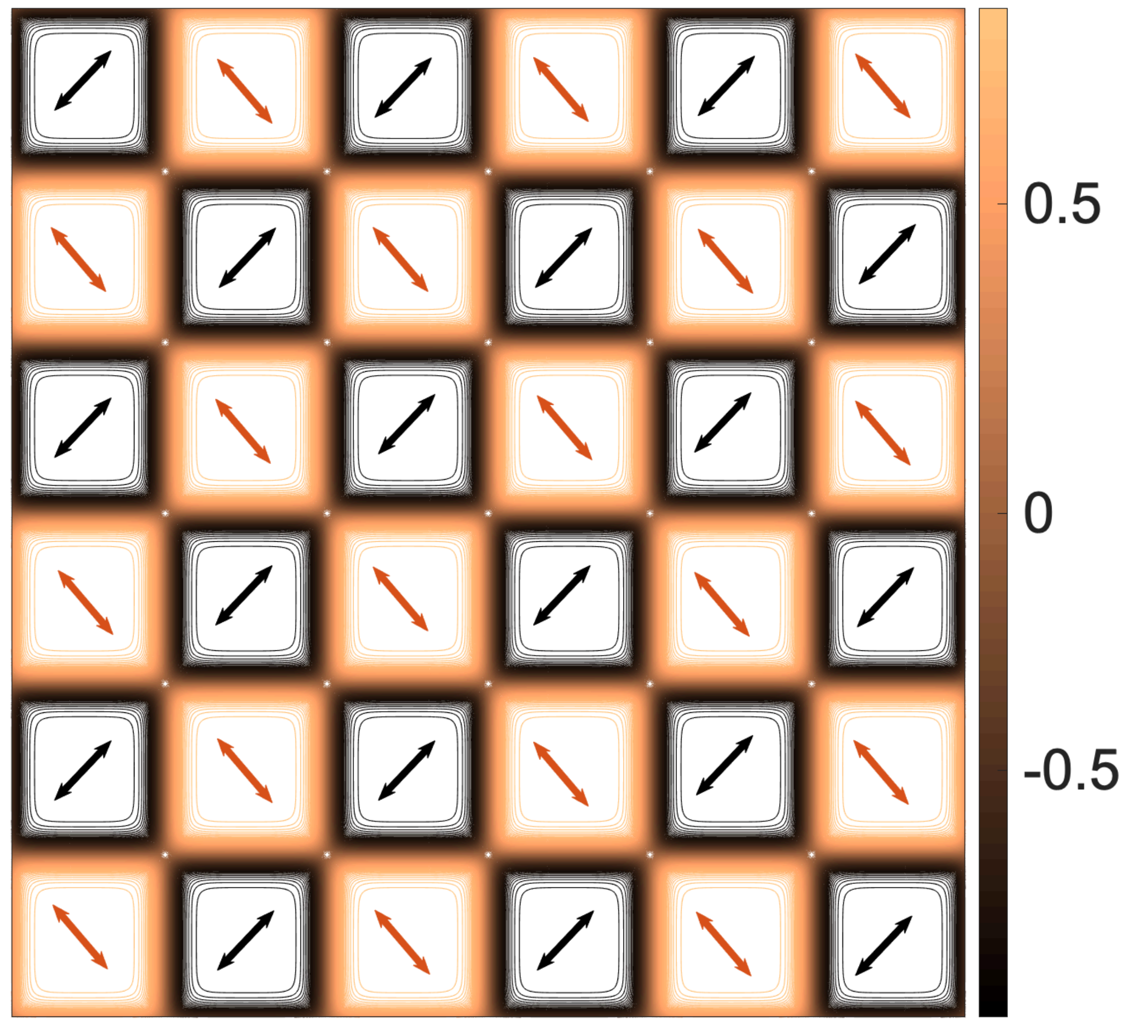
$$E_{\text{m-el}} \propto C u_{\text{spon}}^2 \cos^2(2\theta)$$



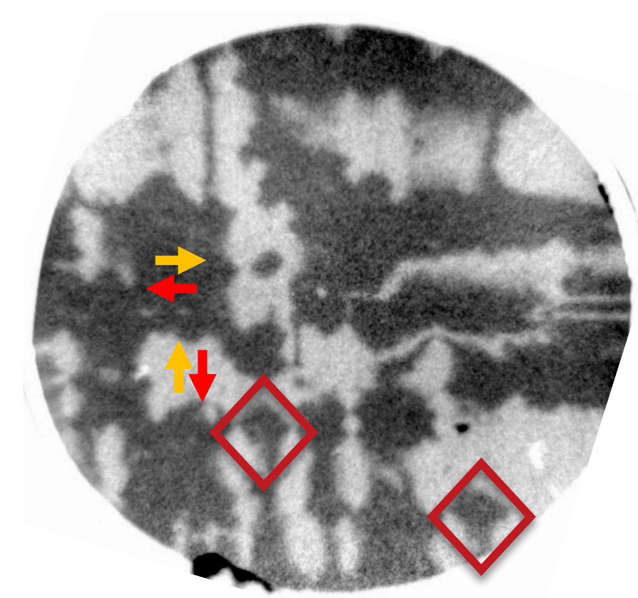
$$E_{\text{DW}} = E_{\text{mag}} + E_{\text{m-el}}$$

Domain structure in the blanket film





$$n_y^2 - n_x^2$$



Wadley, Reimers, et al, Nature Nanotechnology

Micr-*a*-magnetics

Elastic degrees of freedom => integrated out

$$\hat{u}^{\mathrm{des}}(\mathbf{r}) = \int d\mathbf{r}' \hat{I}(\mathbf{r} - \mathbf{r}')\hat{\eta}(\mathbf{r}')$$

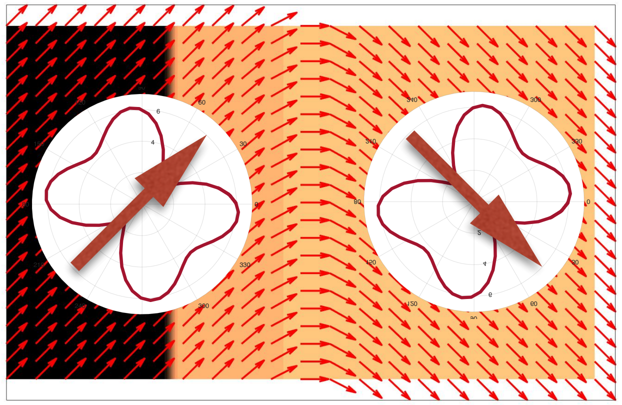
Destressing energy

$$E_{\mathrm{des}} = \int\int d\mathbf{r}_1 d\mathbf{r}_2 \mathbf{n}_1 \otimes \mathbf{n}_1 \hat{K}(\mathbf{r}_1 - \mathbf{r}_2)\mathbf{n}_2 \otimes \mathbf{n}_2$$

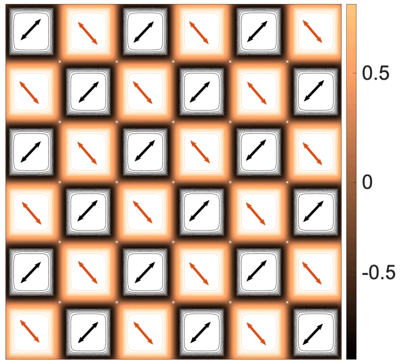
Kernel => dipole

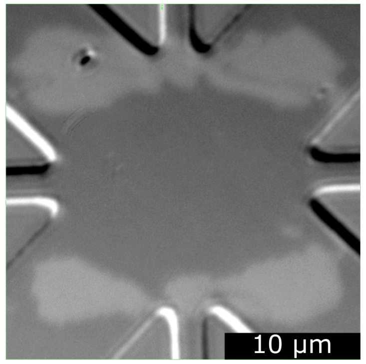
$$\hat{K}(\mathbf{r}) \propto \nabla_j \nabla_k \nabla_l \nabla_m |\mathbf{r}| \propto \frac{1}{|\mathbf{r}|^3}$$

Conclusions

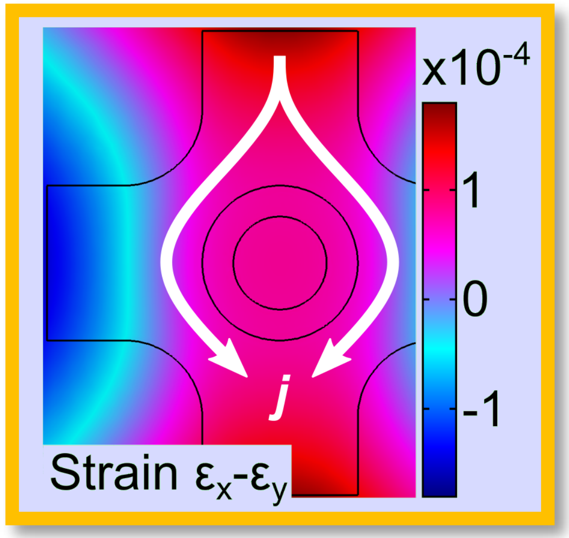


Domain wall dynamics





Domain structure



Domain switching

Collaborators

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

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Kevin Edmonds

Sonka Reimers

University of Nottinghem

Universität Konstanz

David Bossini

Mathias Kläui group, JGU

Stefano Bonetti

Stockholm University

THANK YOU!

General approach

Magneto+elastic:

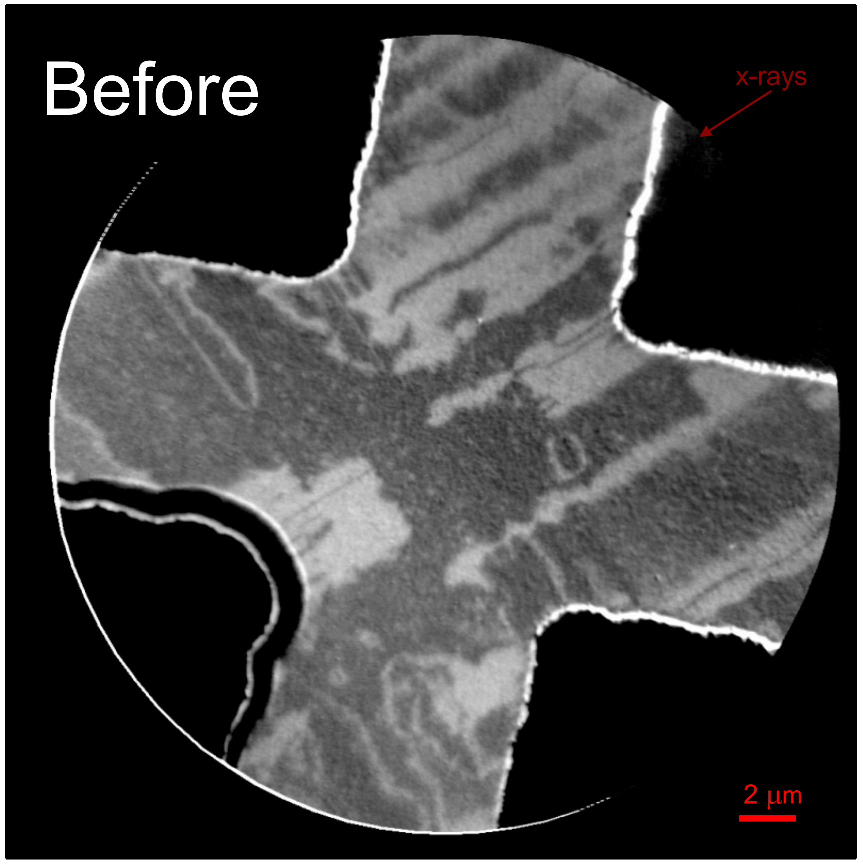
$$A\Delta\mathbf{n} + \mathbf{H}_{\mathbf{n}} = -H_{\mathrm{me}}\hat{u}\mathbf{n}$$

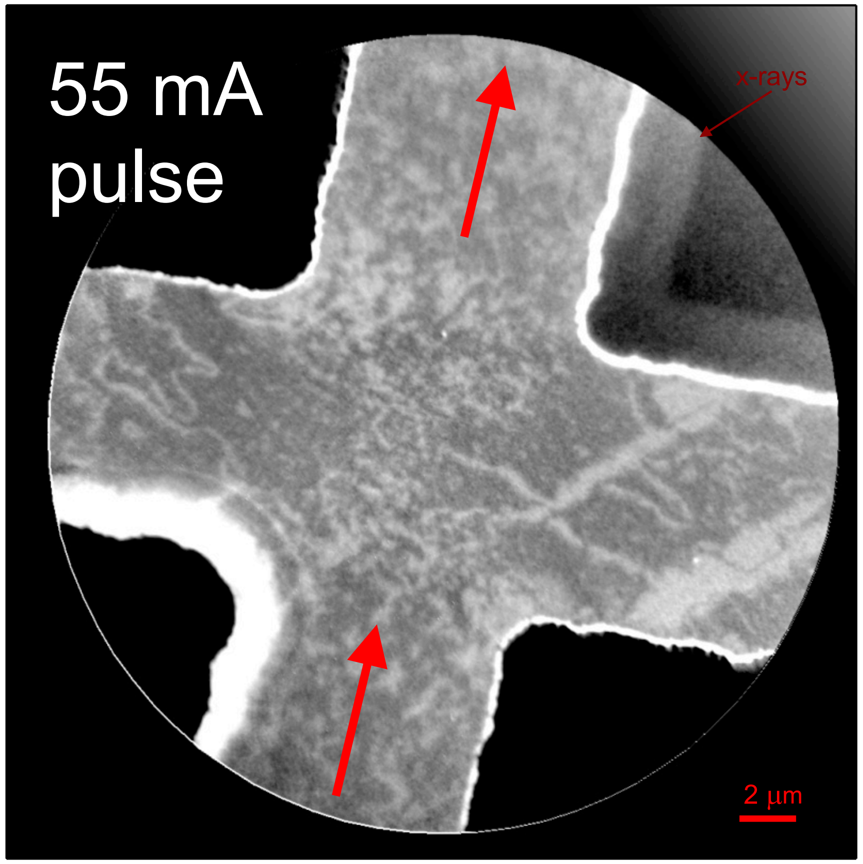
$$\nabla\left(\hat{c}\hat{u}\right) = -H_{\mathrm{me}}\nabla\left(\mathbf{n}\otimes\mathbf{n}\right)$$

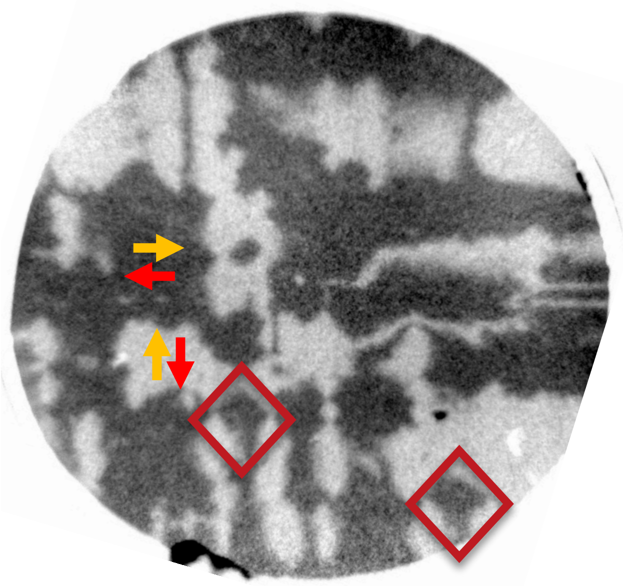
Magnetic plasticity (Kleman, Miltat, 1972)

$$\hat{u} = \underbrace{\hat{u}^{\mathrm{spon}}(\mathbf{r})}_{\text{dislocations}} + \underbrace{\hat{u}^{\mathrm{des}}(\mathbf{r})}_{\text{plastic}}$$

Experiment



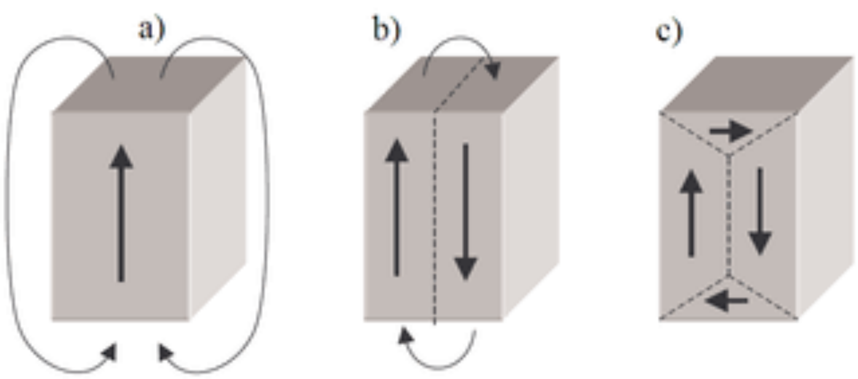




Wadley, Reimers, et al, Nature Nanotechnology,

Domain structure in FM

$$E_{\text{demag}} = \int\int d\mathbf{r}_1 d\mathbf{r}_2 \frac{\nabla \cdot \mathbf{M}(\mathbf{r}_1)\,\nabla \cdot \mathbf{M}(\mathbf{r}_2)}{|\mathbf{r}_1 - \mathbf{r}_2|}$$



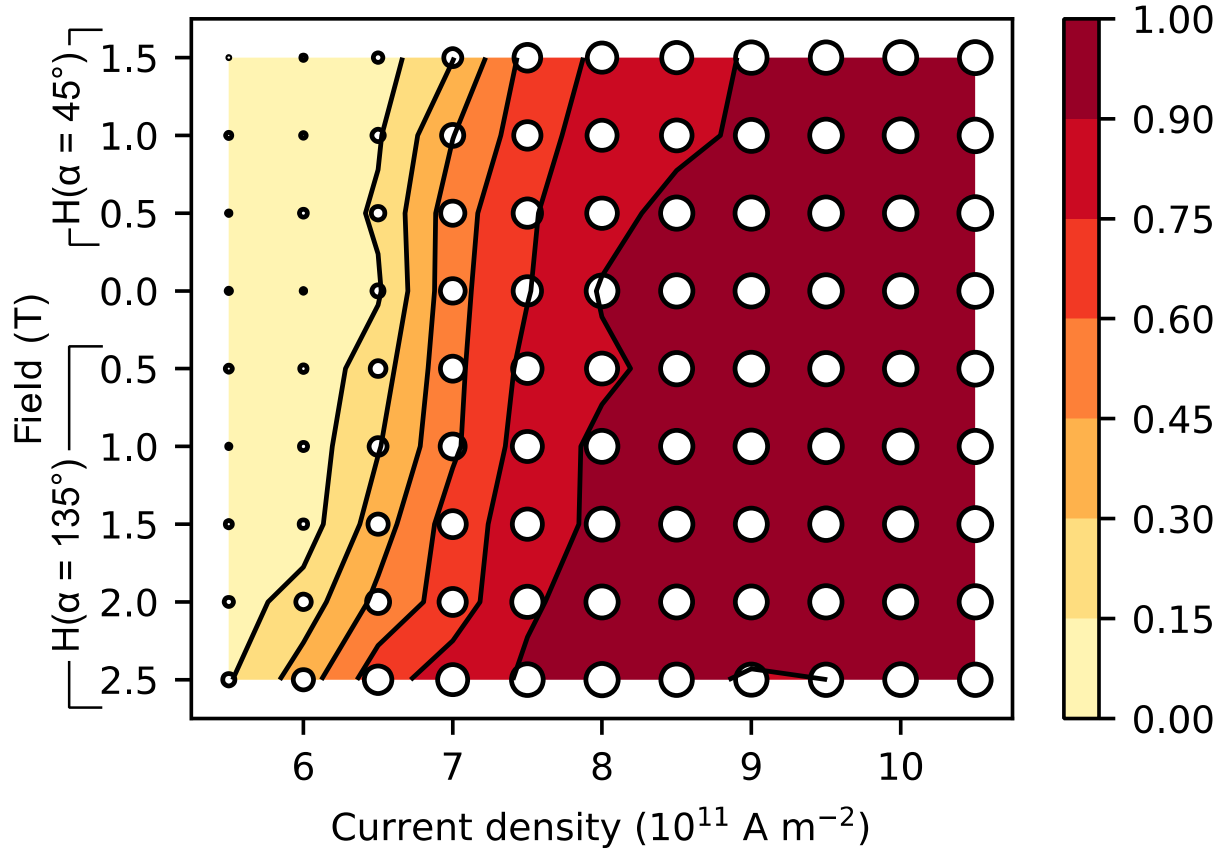
Problem

	FM	AF
Order parameter	**M**	**N**
Conjugated field	**H**	–
“Charge”	div **M**	–
Long range field	$\mathbf{H}_{\mathrm{dip}}$	–

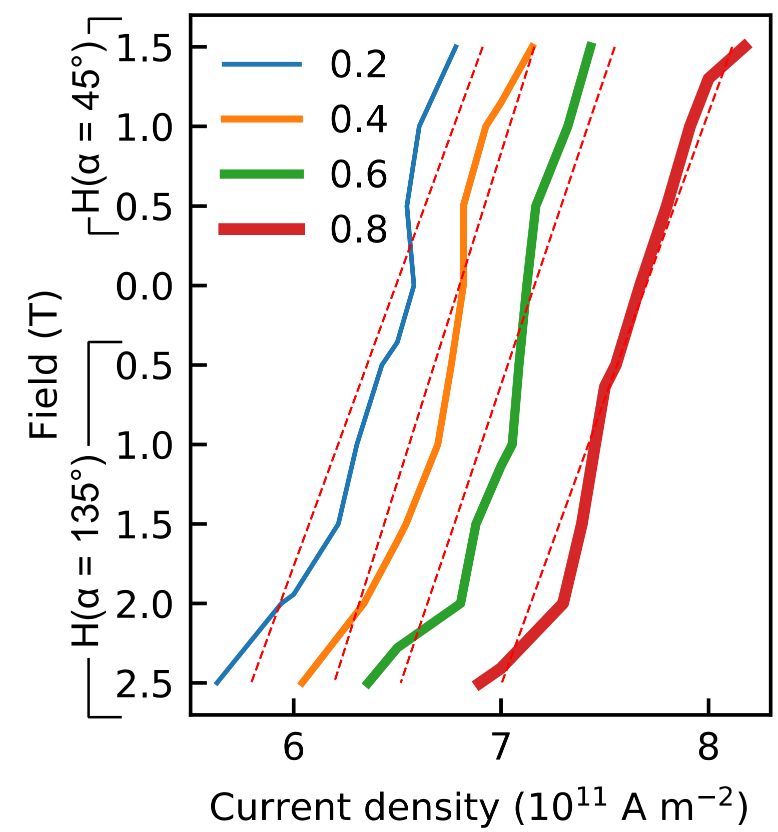
Possible solution

	FM	AF+ ME
Order parameter	**M**	$\mathbf{N} \otimes \mathbf{N} \propto \hat{u}^{\mathrm{spon}}$
Conjugated field	**H**	$\hat{\sigma}$
“Charge”	div **M**	inc $\hat{u}^{\mathrm{spon}}$
Long range field	$\mathbf{H}_{\mathrm{dip}}$	$\hat{\sigma}^{\mathrm{destr}}$

Field-current equivalence in CoO



$$U_{\text{ext}} \propto (\mathbf{H}\cdot\mathbf{n})^2$$

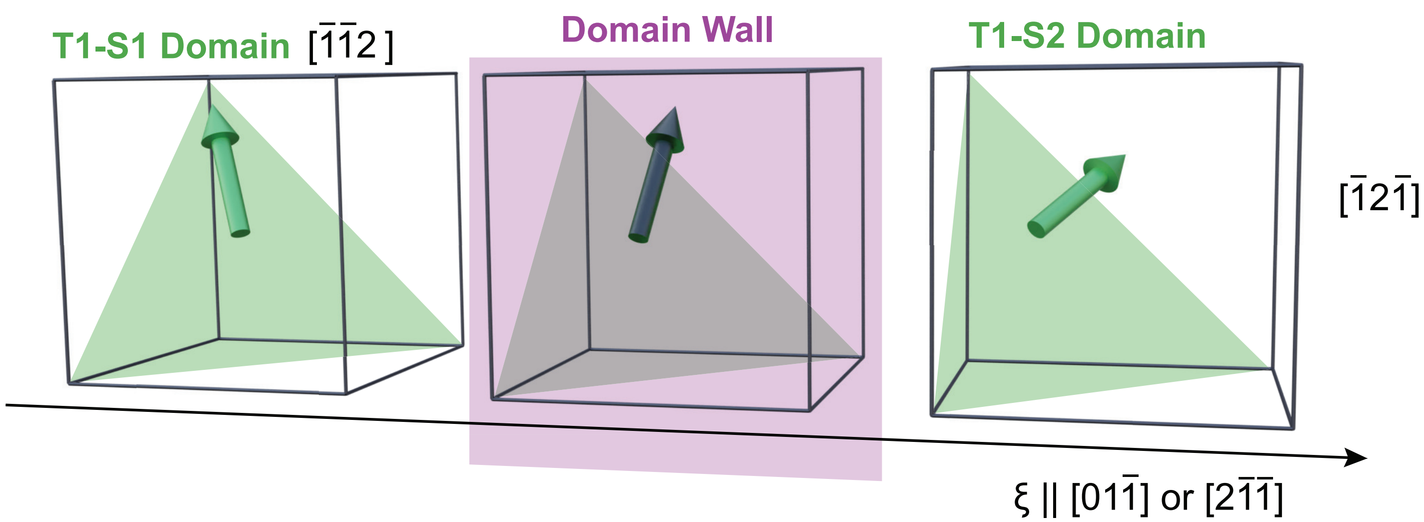


$$U_{\text{ext}} \propto \lambda(\mathbf{j}\cdot\mathbf{n})^2$$

Baldrati, OG, et al. Phys. Rev. Lett. 125, 77201 (2020)

Pinned domain wall

$$\mathbf{n}\times\left(\ddot{\mathbf{n}} - c^2\Delta\mathbf{n} + \gamma^2 H_{\mathrm{ex}}\mathbf{H}_{\mathrm{an}}(\xi)\right) = 0$$

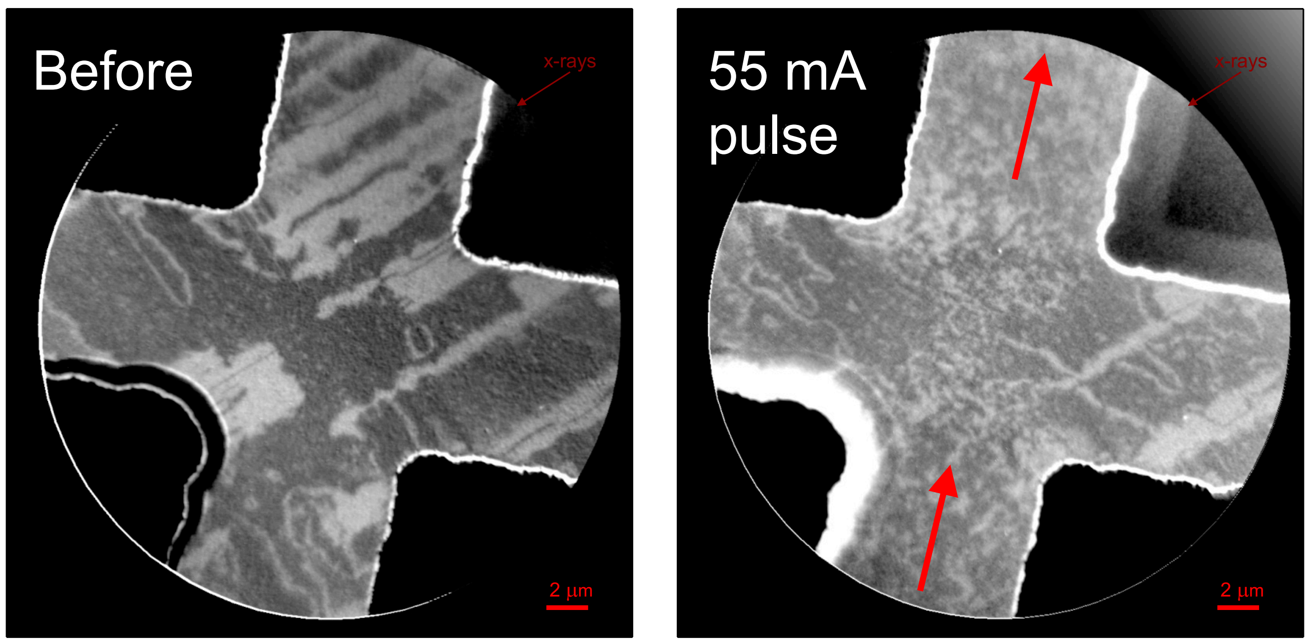


$$\omega_{\mathrm{DW}} \propto \sqrt{H_{\mathrm{me}}}$$

Current-induced switching

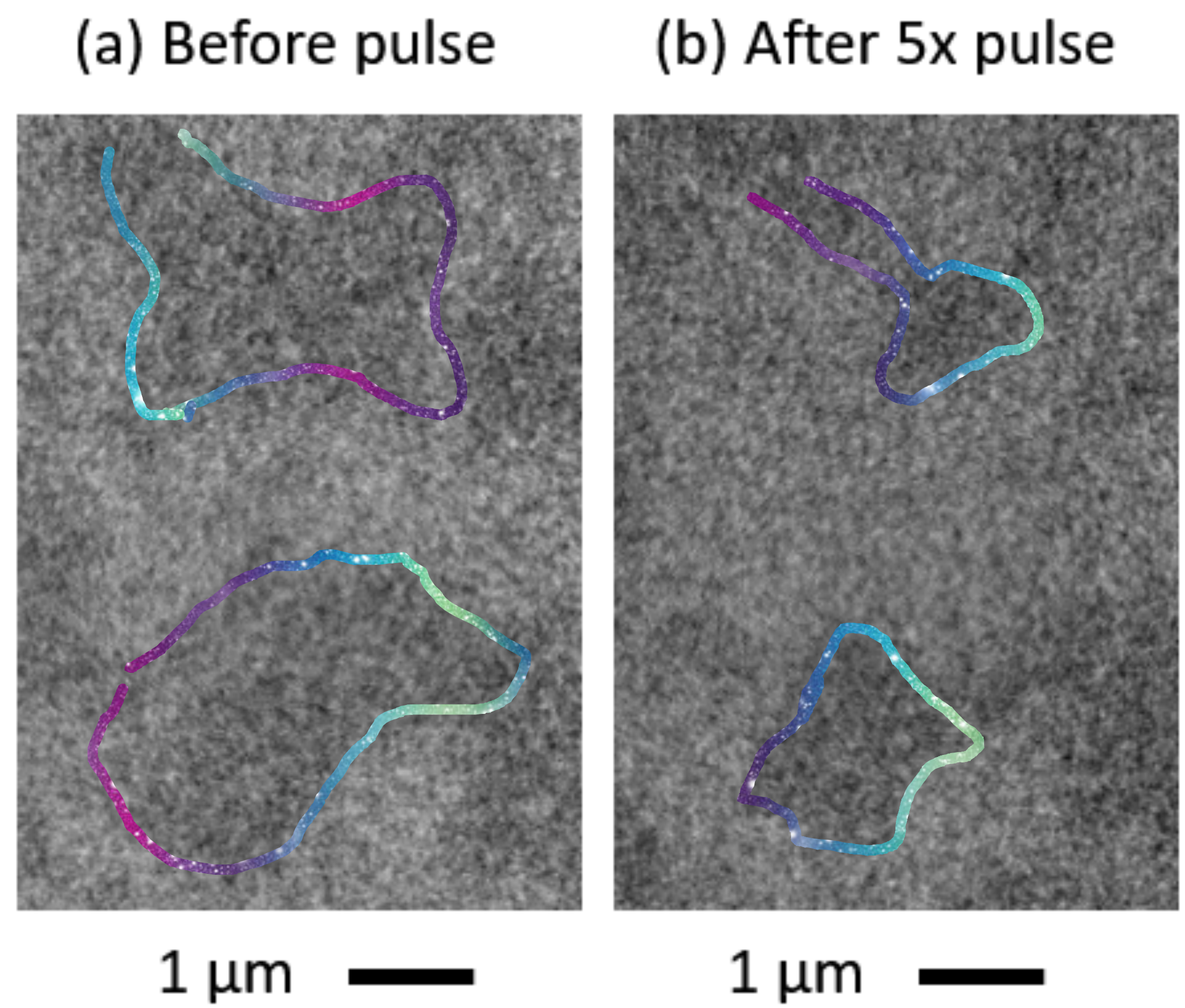
INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

CuMnAs



Wadley, Reimers et al *Nat. Nanotech.* 18
Wadley, Reimers, et al

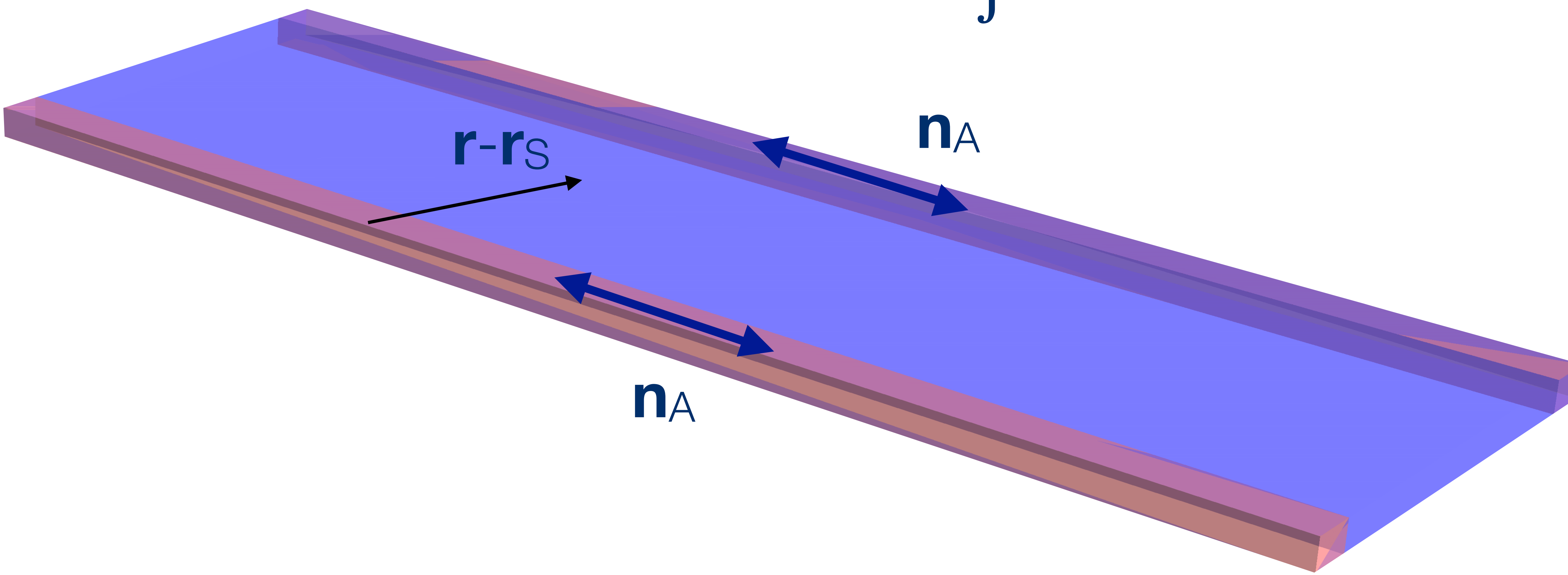
NiO



Baldrati, OG et al *PRL* 19

Surface effects

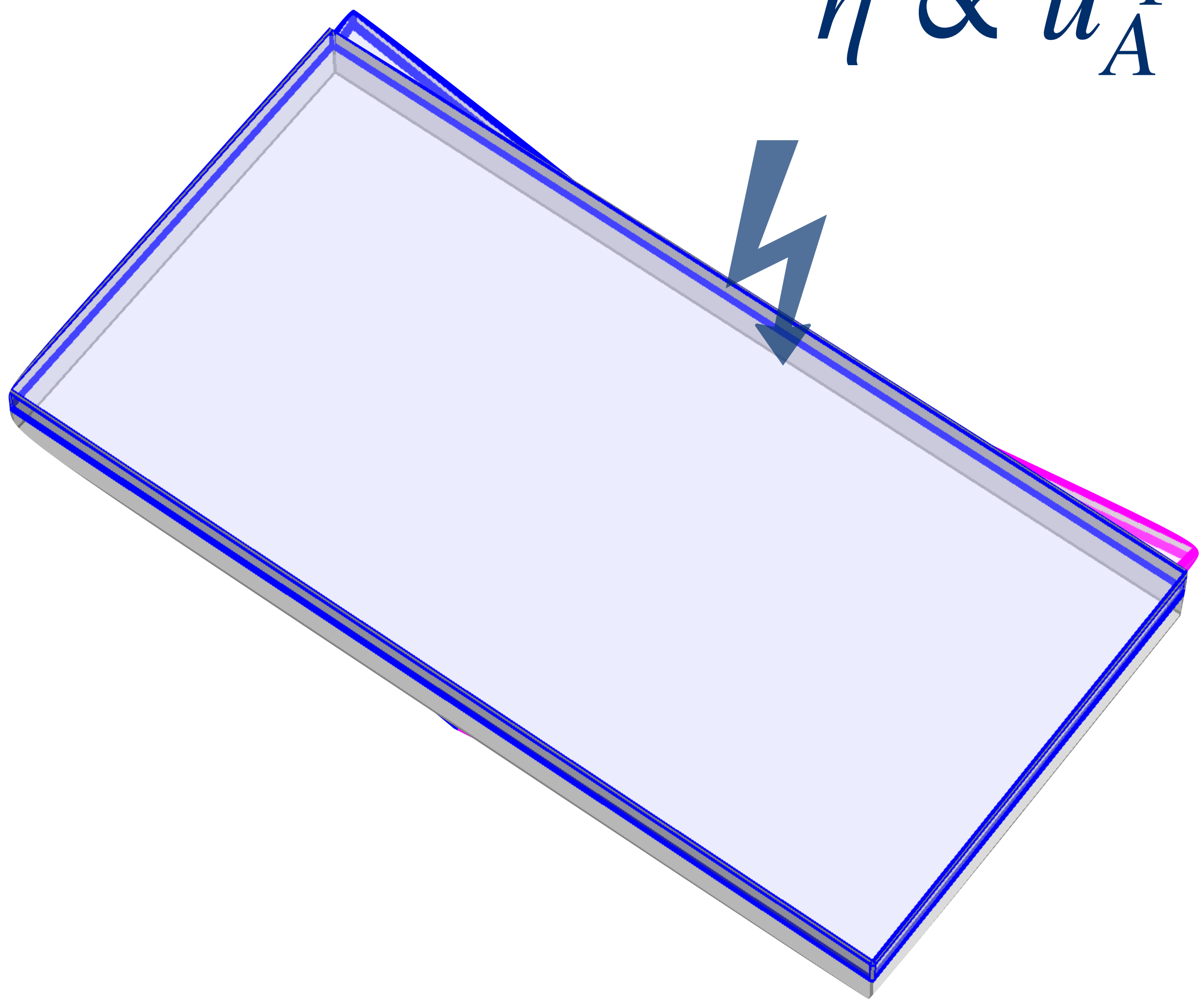
$$W_{\mathrm{surf}} = K_S \oint dS(\mathbf{n}\cdot\mathbf{e})^2$$



$$E_{\mathrm{surf}} = \int_V (\mathbf{n}\otimes\mathbf{n})(\mathbf{e}\cdot\nabla)\int_S \hat{I}(\mathbf{r}-\mathbf{r}_S)\mathbf{n}_S\otimes\mathbf{n}_S d\mathbf{r}_S$$

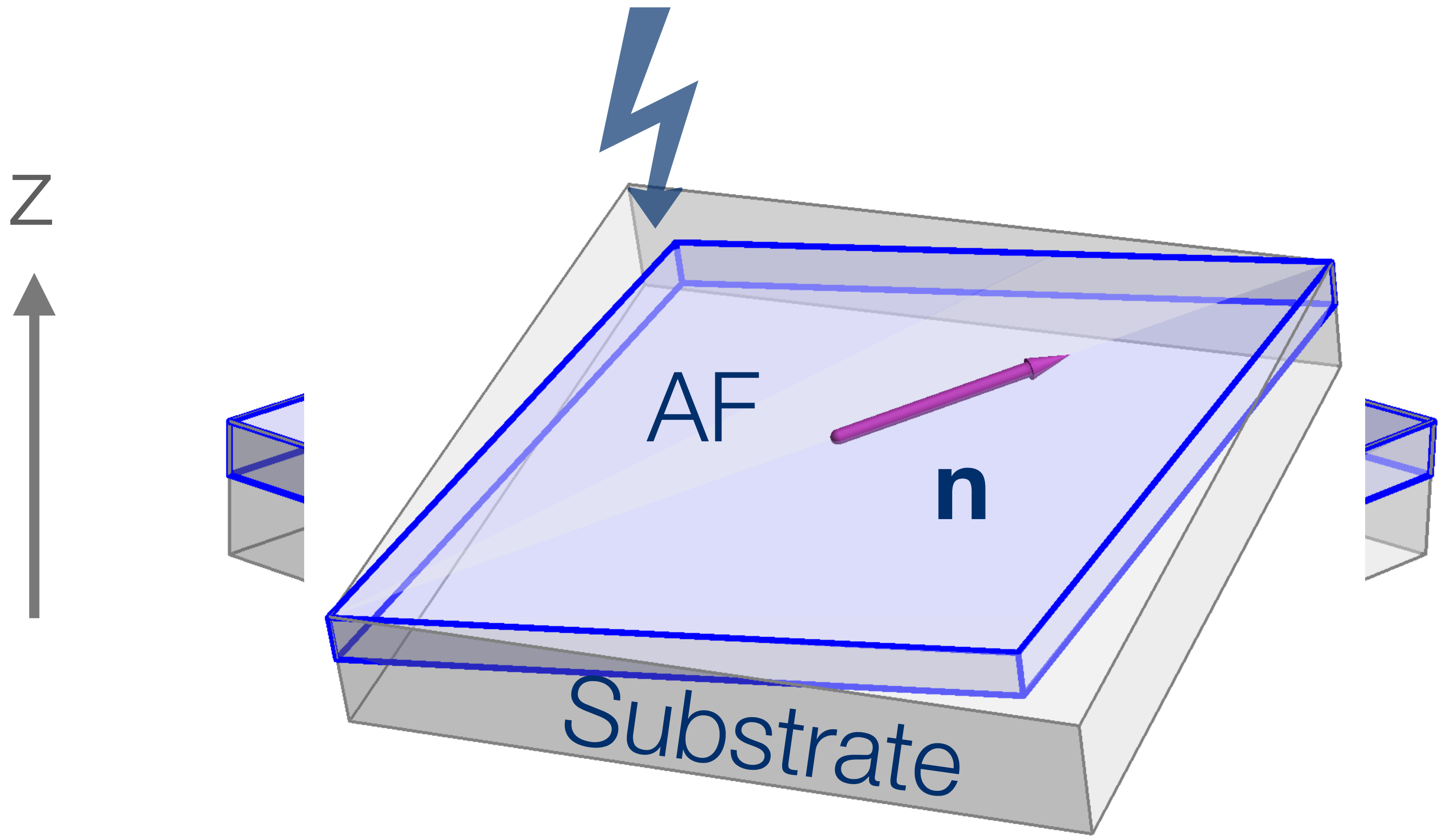
Dipole-dipole interaction

$$\hat{\eta} \propto \hat{u}_A^{\text{spon}} - \hat{u}_B^{\text{spon}}$$



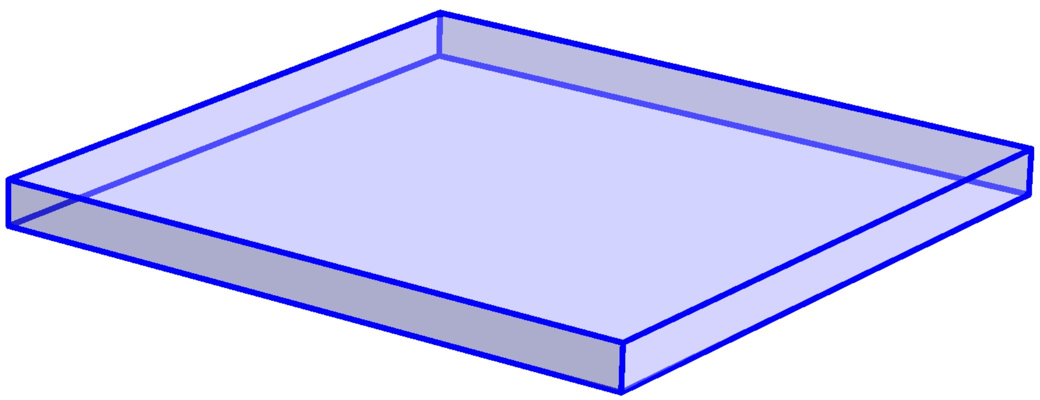
Incompatibility AF-substrate

$$\hat{\eta} \propto \hat{u}^{\rm spon}\delta'(z)$$

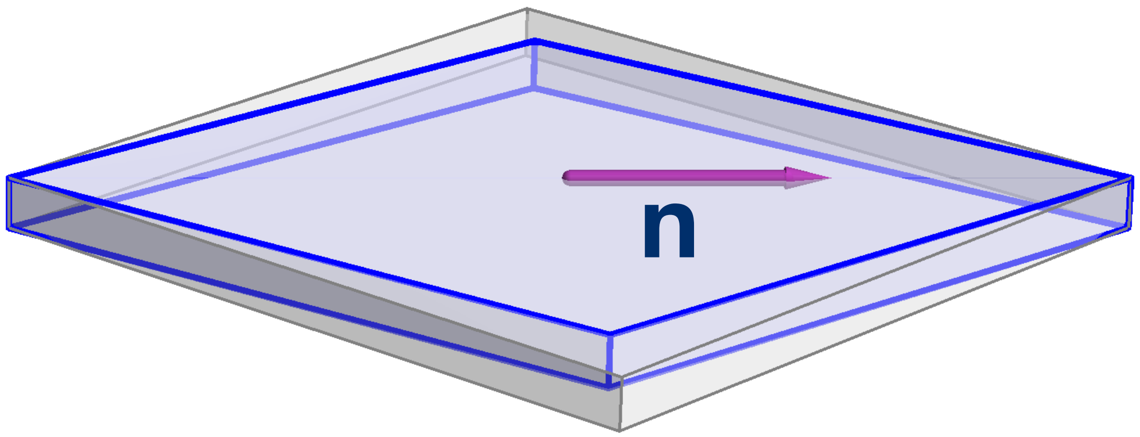


Magnetoelasticity

Paramagnetic state



AF state



$$\hat{u}^{\mathrm{spon}} \propto H_{\mathrm{m-e}}\mathbf{n} \otimes \mathbf{n}$$

Incompatibility charges

Elastostatic in terms of incompatibility

$$\nabla \times \hat{u}^{\mathrm{des}}(\mathbf{r}) \times \nabla = -\hat{\eta}$$

$$\hat{\eta}(\mathbf{r}) = \nabla \times \hat{u}^{\mathrm{spon}}(\mathbf{r}) \times \nabla$$

$$\hat{I}(\mathbf{r}) \propto \nabla_j \nabla_k |\mathbf{r}| \propto \frac{1}{|\mathbf{r}|}$$

$$\hat{u}^{\mathrm{spon}} \propto H_{\mathrm{m-e}} \mathbf{n} \otimes \mathbf{n}$$

Incompatibility of strains

$$\hat{u}^{\mathrm{des}} = \int d\mathbf{r}' \hat{I}(\mathbf{r} - \mathbf{r}')\hat{\eta}(\mathbf{r}')$$

$$\hat{\eta}(\mathbf{r}) = \nabla \times \hat{u}^{\mathrm{spon}}(\mathbf{r}) \times \nabla$$

$$\hat{I}(\mathbf{r}) \propto \nabla_j \nabla_k |\mathbf{r}| \propto \frac{1}{|\mathbf{r}|}$$

$$\hat{u}^{\mathrm{spon}} \propto H_{\mathrm{m-e}} \mathbf{n} \otimes \mathbf{n}$$

Magnetoelasticity

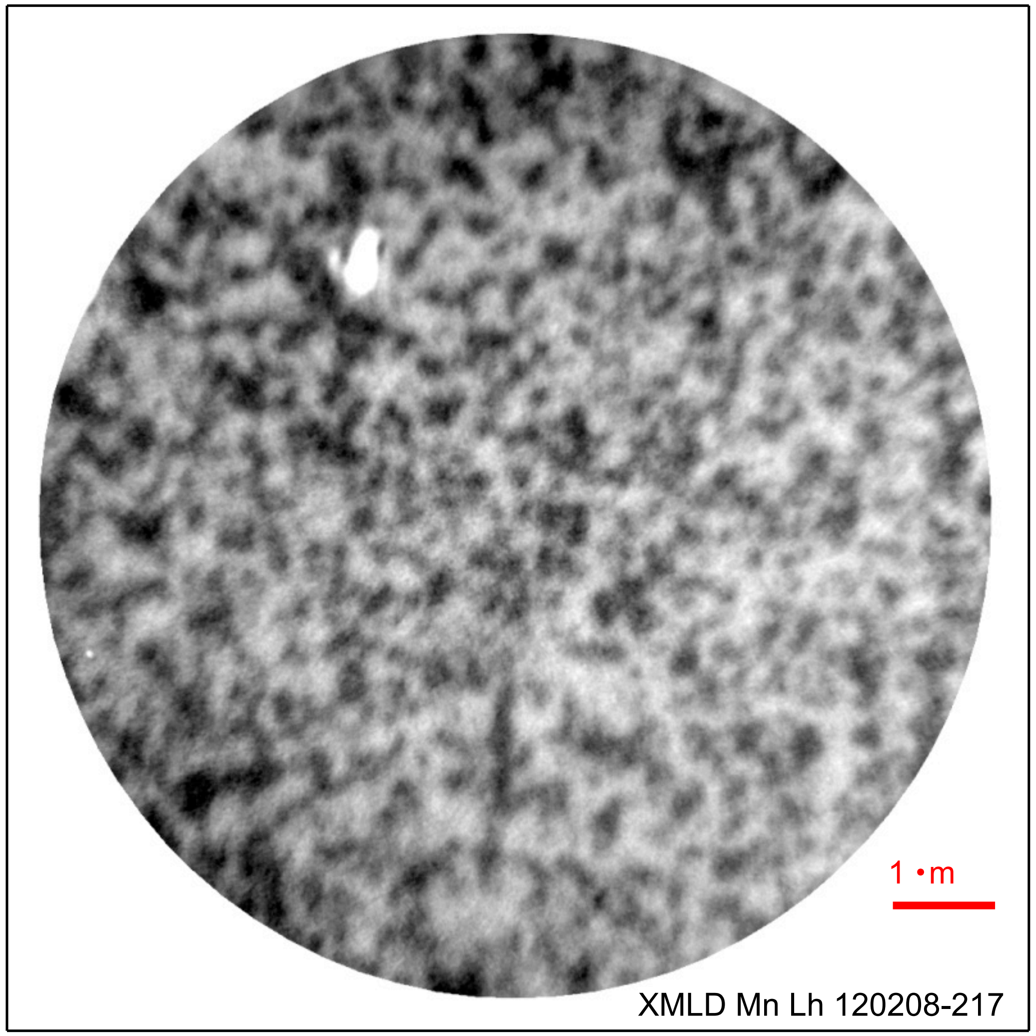
$$w_{\mathrm{me}} = H_{\mathrm{me}} M_s \left[(u_{xx} - u_{yy})(n_x^2 - n_y^2) + 2u_{xy} n_x n_y \right]$$

Frozen spontaneous strains

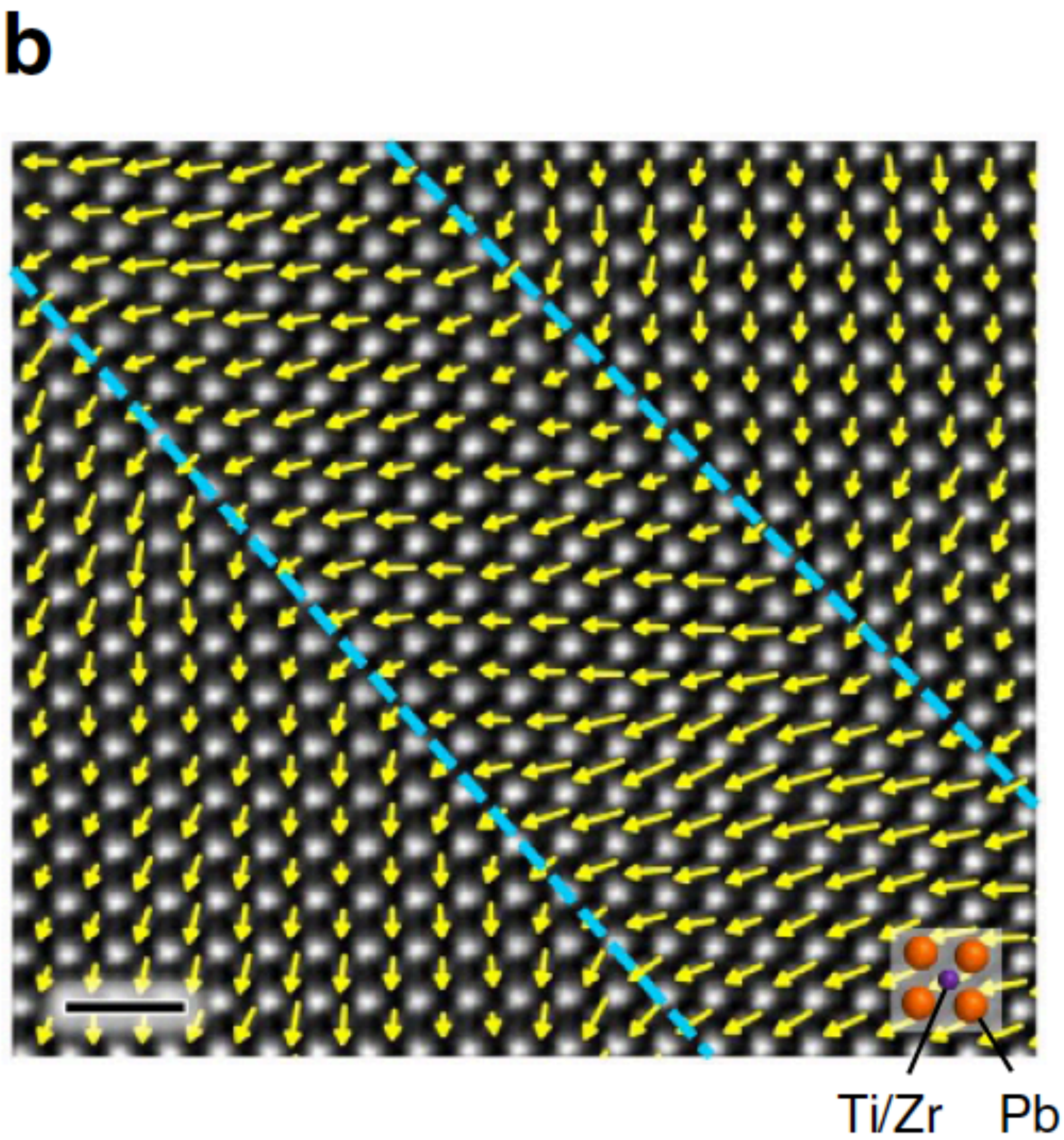
$$\varepsilon^{\mathrm{spon}} = -\frac{H_{\mathrm{me}} M_s}{\mu}(n_x^2 - n_y^2)\,|_0$$

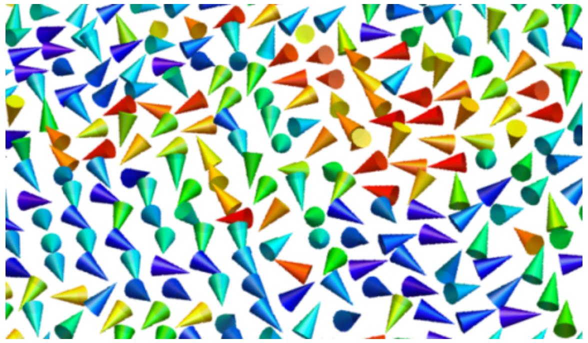
$$w_{\mathrm{me}} = H_{\mathrm{me}} M_s \varepsilon^{\mathrm{spon}} (n_x^2 - n_y^2)$$

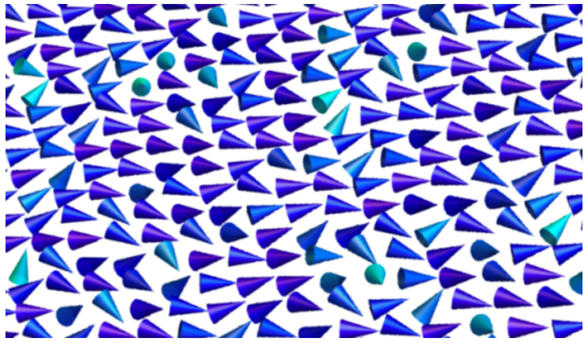
Motivation

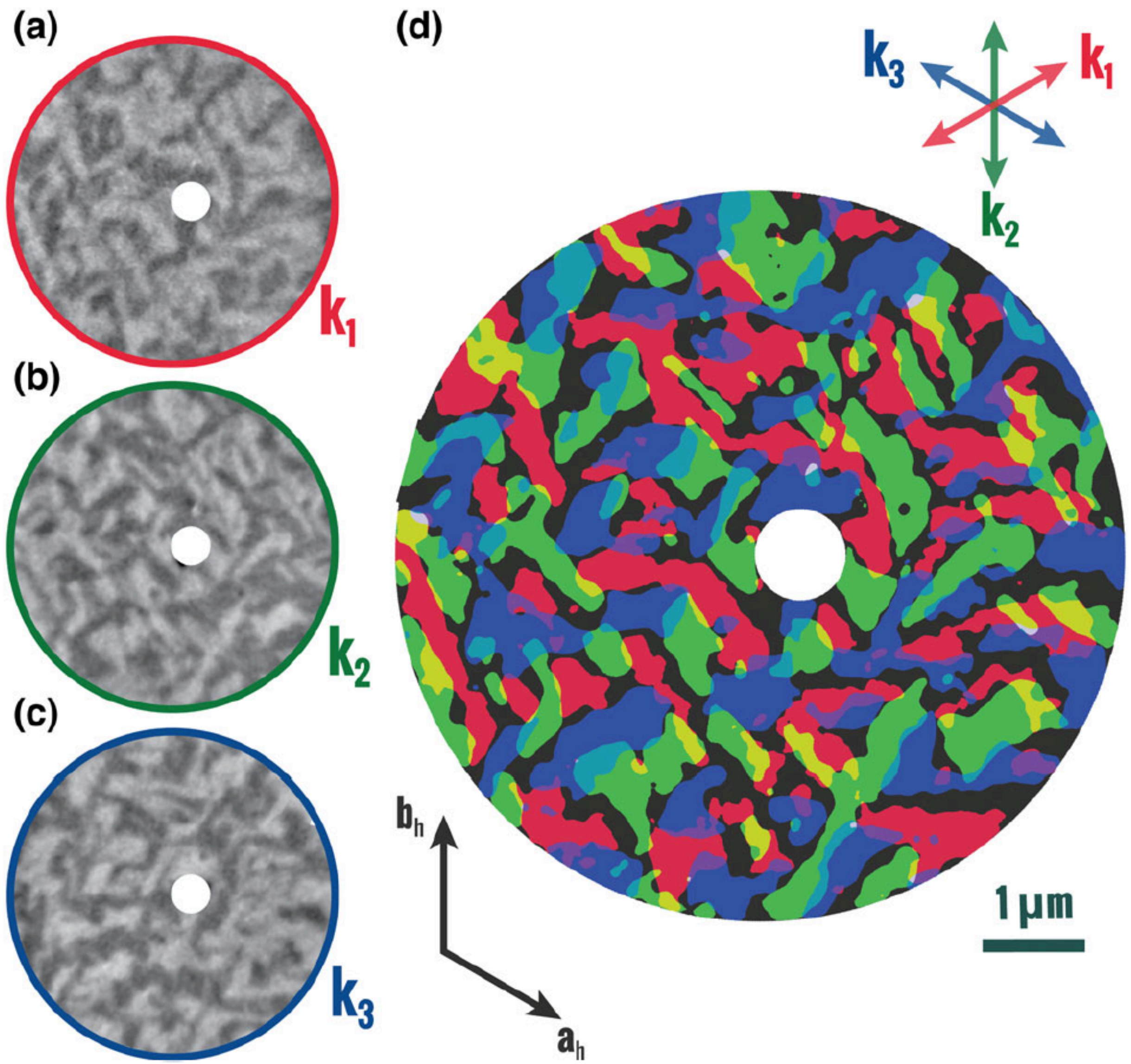


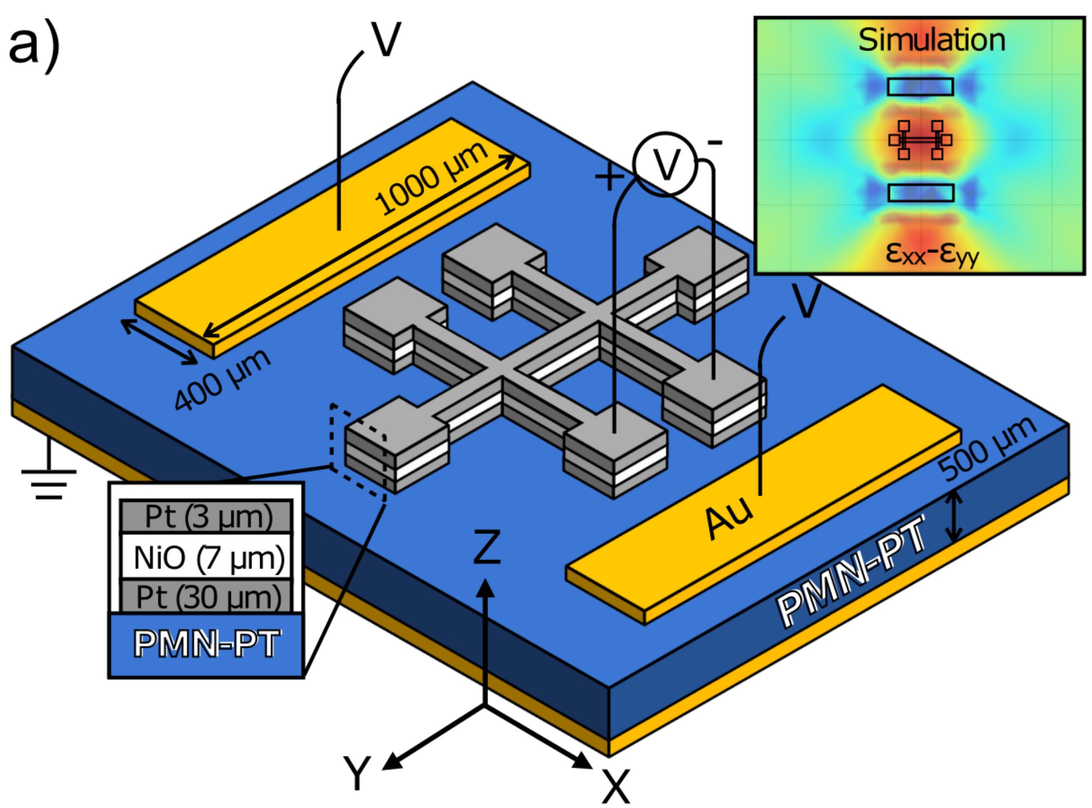
15 μm field view


b
Ti/Zr
Pb






(a)
k1
(b)
k2
(c)
k3
(d)
k3
k1
k2
bh
ah
1 μm


a)
V
Simulation
εxx-εyy
1000 μm
400 μm
+
V
-
V
500 μm
Au
PMN-PT
Pt (3 μm)
NiO (7 μm)
Pt (30 μm)
PMN-PT
Z
Y
X