Elastic manipulation of antiferromagnetic domain structure

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Take-home message

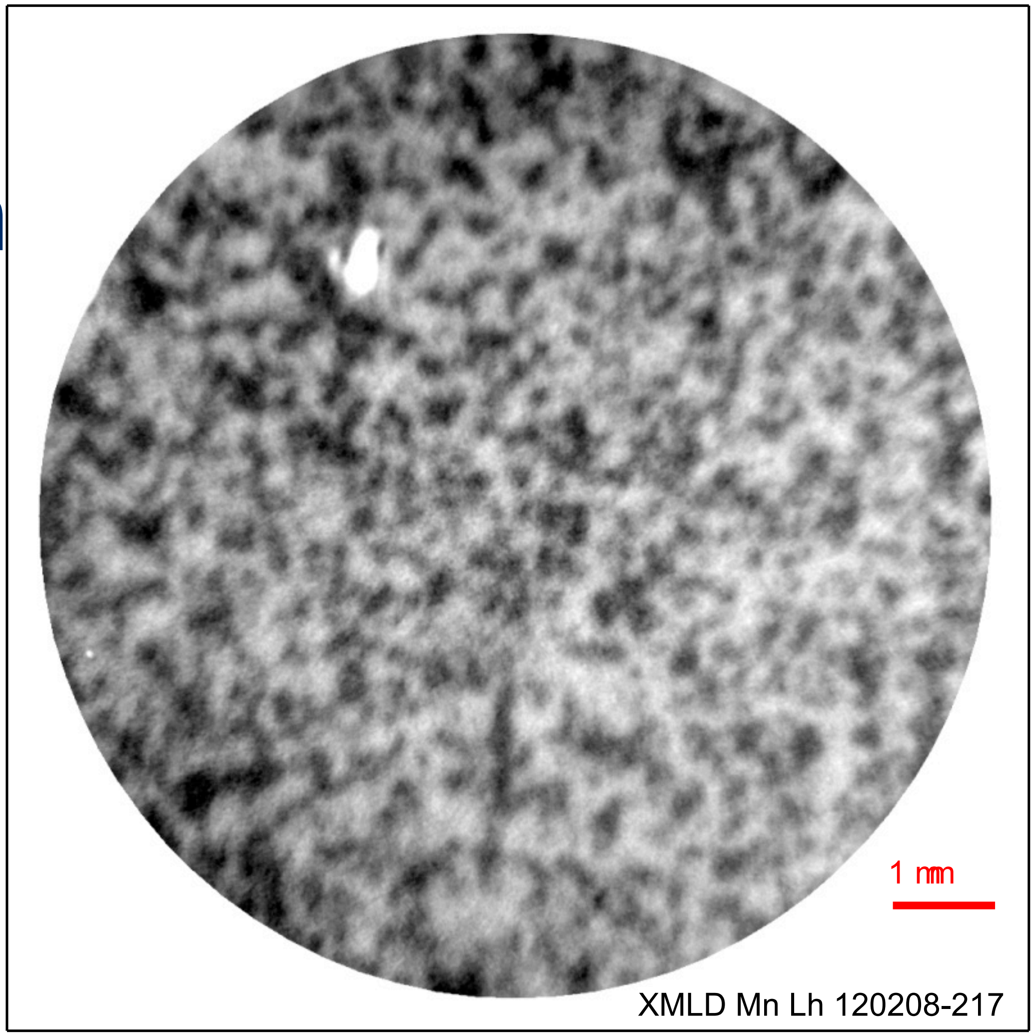
- Magnetoelasticity => long-range fields and shape effects in antiferromagnets
- Possible micr-***a-***magnetics => magneto elastic coupling

Outline

- Magnetoelasticity and elastic dipoles
- Incompatibility of strains
- Micr-*a*-magnetics
- Destressing energy and energy of the domain wall
- Equilibrium domain pattern in blanket films and stripes
- Conclusions

Motivation

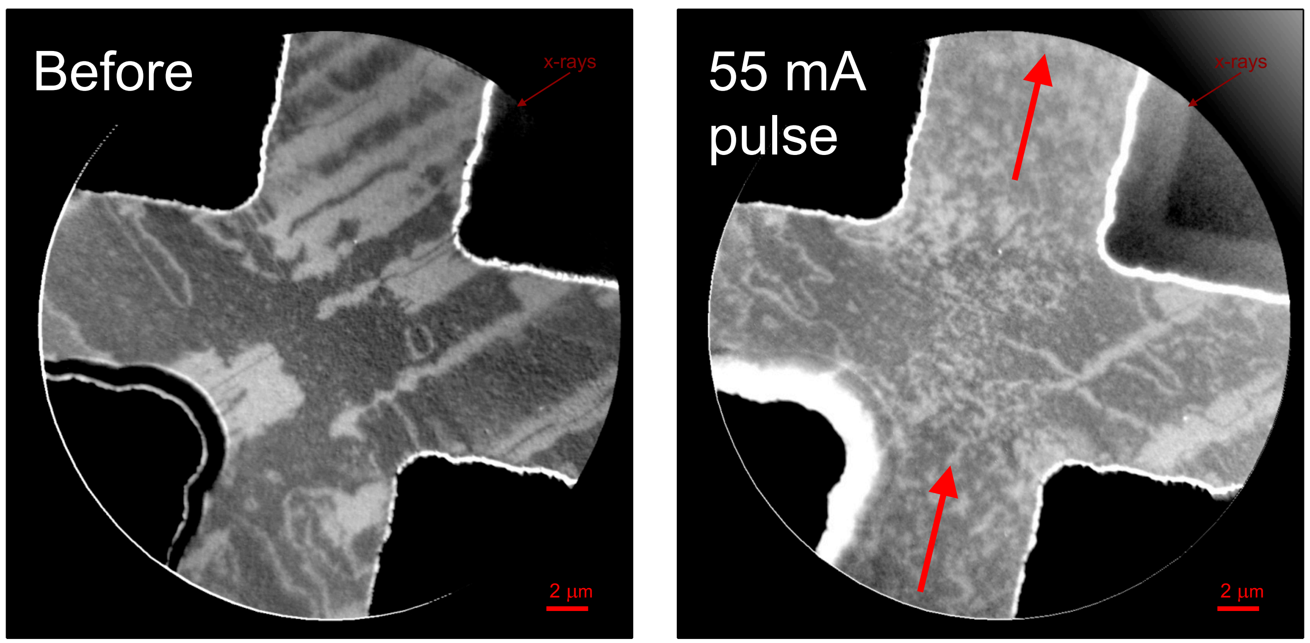
- Antiferromagnets => memory elements
- Samples are multidomain
- Switching => redistribution of th



15 μm field view

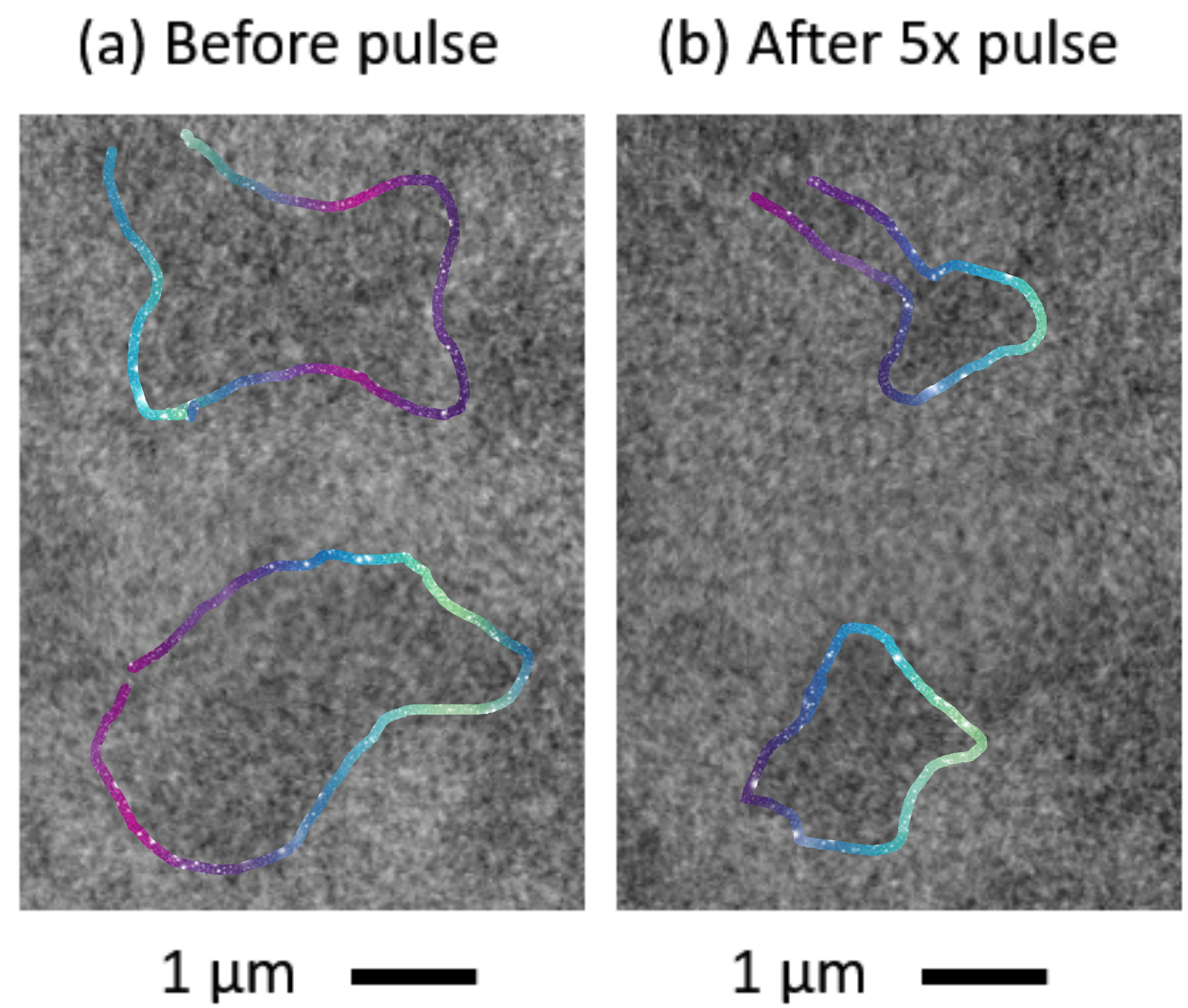
Current-induced switching

CuMnAs



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

NiO



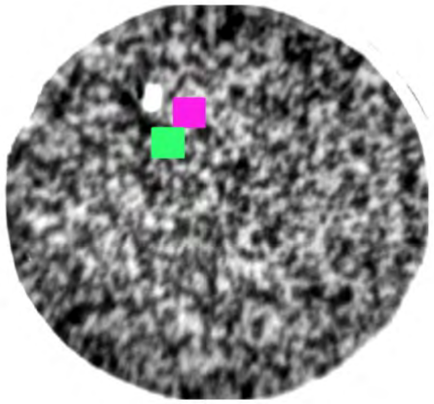
Baldrati, OG et al *PRL* 19

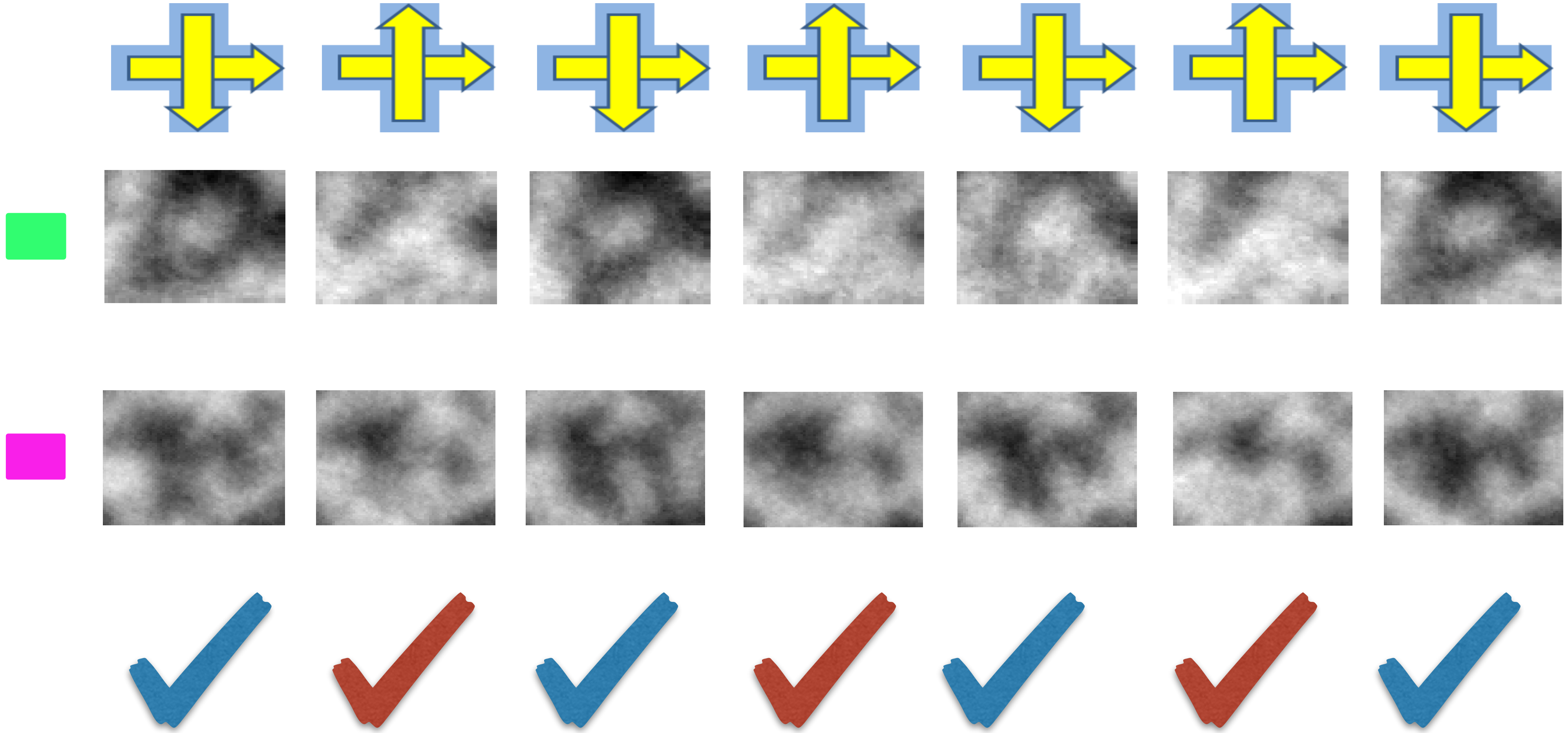
Motivation

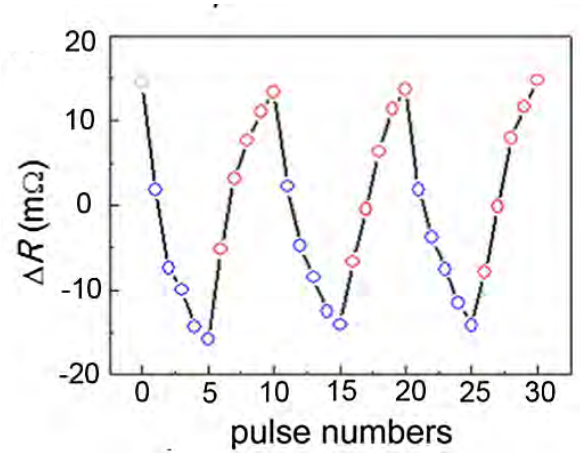
- Antiferromagnets => memory elements
- Samples are multidomain
- Switching => redistribution of the domains
- Domain structure => reversible

Reproducibility

500nm x 500nm regions:







Grzybowski, Wadley, Edmonds et al. PRL 17

Domain structure in FM

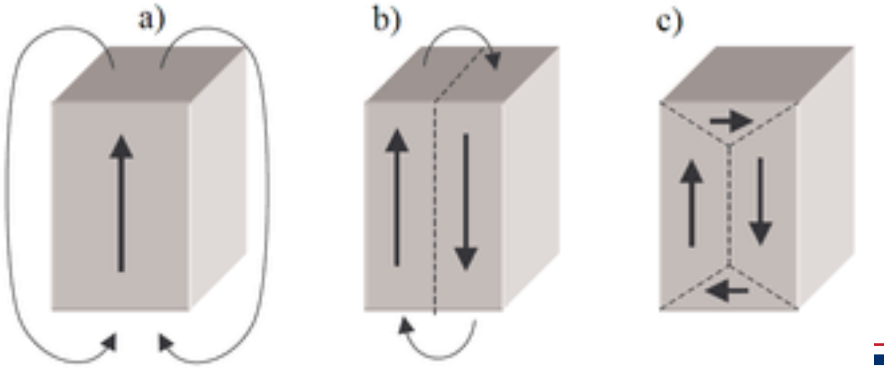
Long-range demagnetising fields:

$$\Delta\psi = -\,\mathrm{div}\mathbf{M},\ \mathbf{H}_{\mathrm{dip}} = -\,\nabla\psi$$

Boundary conditions: $\mathbf{M}\cdot\mathbf{N} = 0$

Demagnetising energy:

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



Problem

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

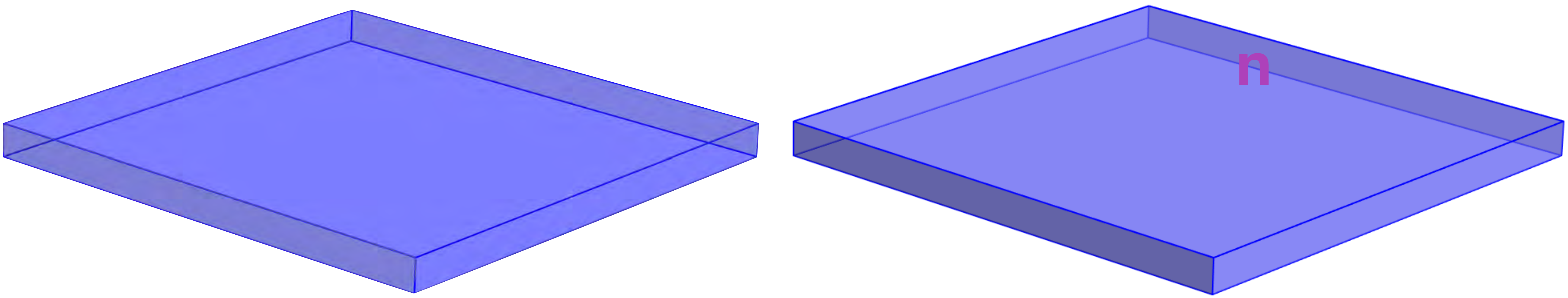
Possible solution

	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	$\mathbf{H}_{\mathrm{dip}}$	$\hat{\sigma}^{\mathrm{destr}}$

Magnetostriction and spontaneous strain

Paramagnetic state

AF state

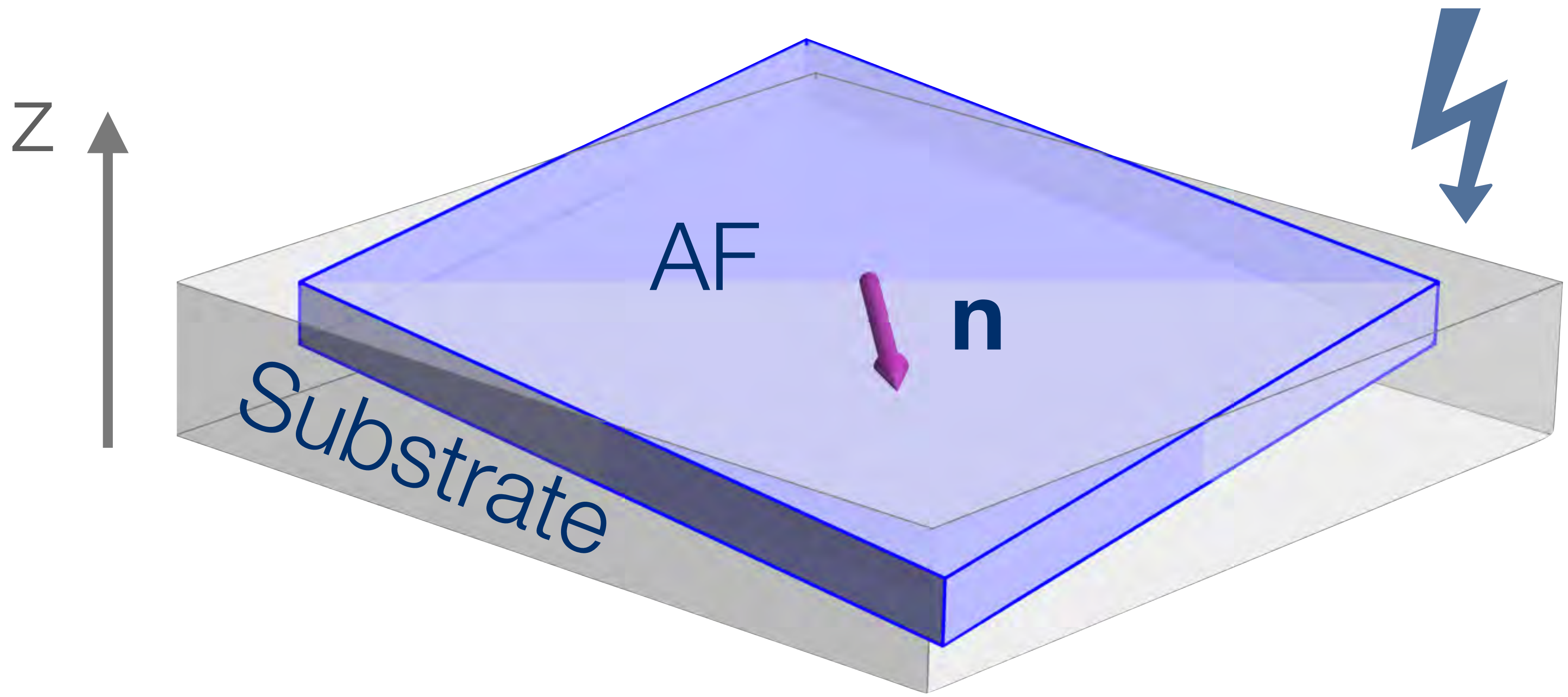


$$\hat{u}^{\mathrm{spon}} \propto H_{\mathrm{m-e}} \mathbf{n} \otimes \mathbf{n}$$

$$\hat{\sigma} \equiv -\frac{\partial}{\partial \hat{u}} \left(E_{\mathrm{elas}} + E_{\mathrm{m-e}} \right) = 0$$

Problem I: AF + substrate

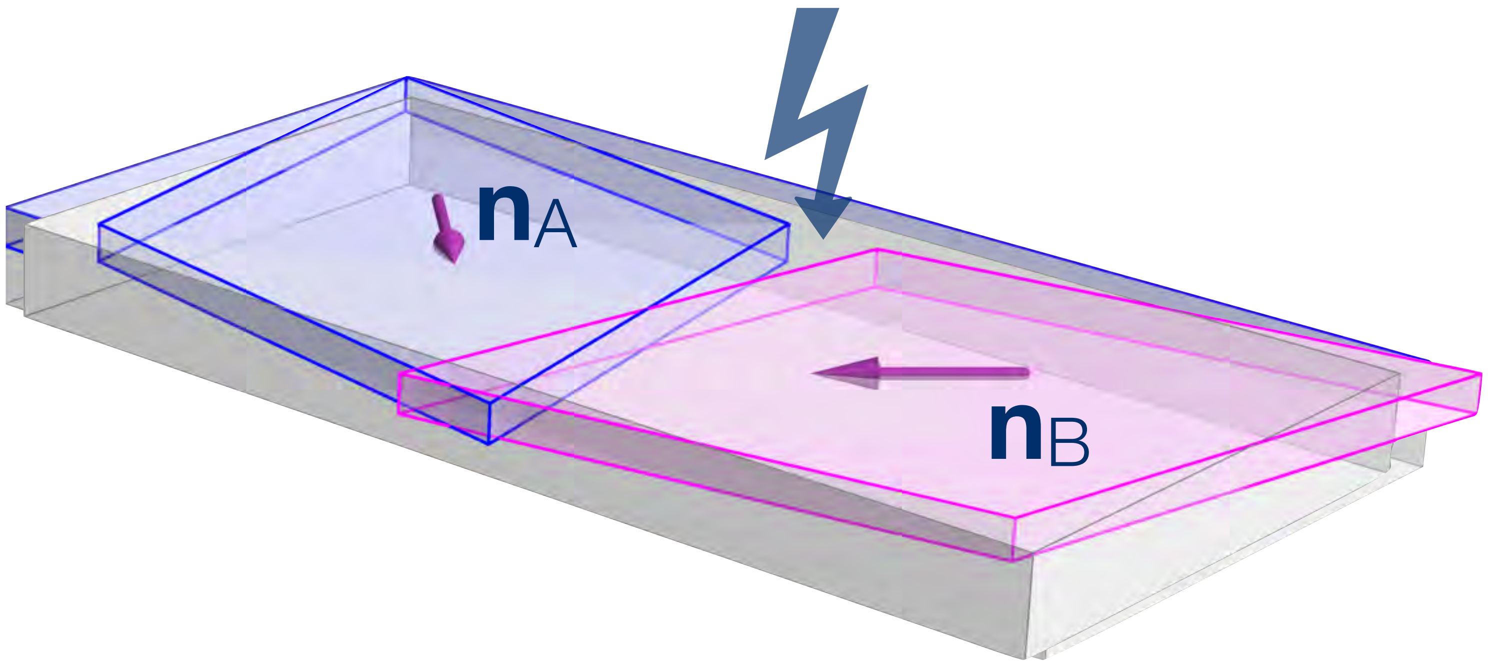
$$\hat{\eta} \propto \hat{u}^{\text{spon}} - \hat{u}^{\text{sub}}$$



Incompatibility at the interface

Problem II: domain A + domain B

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



Incompatibility between deformed regions

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)

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

Magneto-elastostatics

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

Micr-*a*-magnetics

Elastic degrees of freedom => integrated out

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

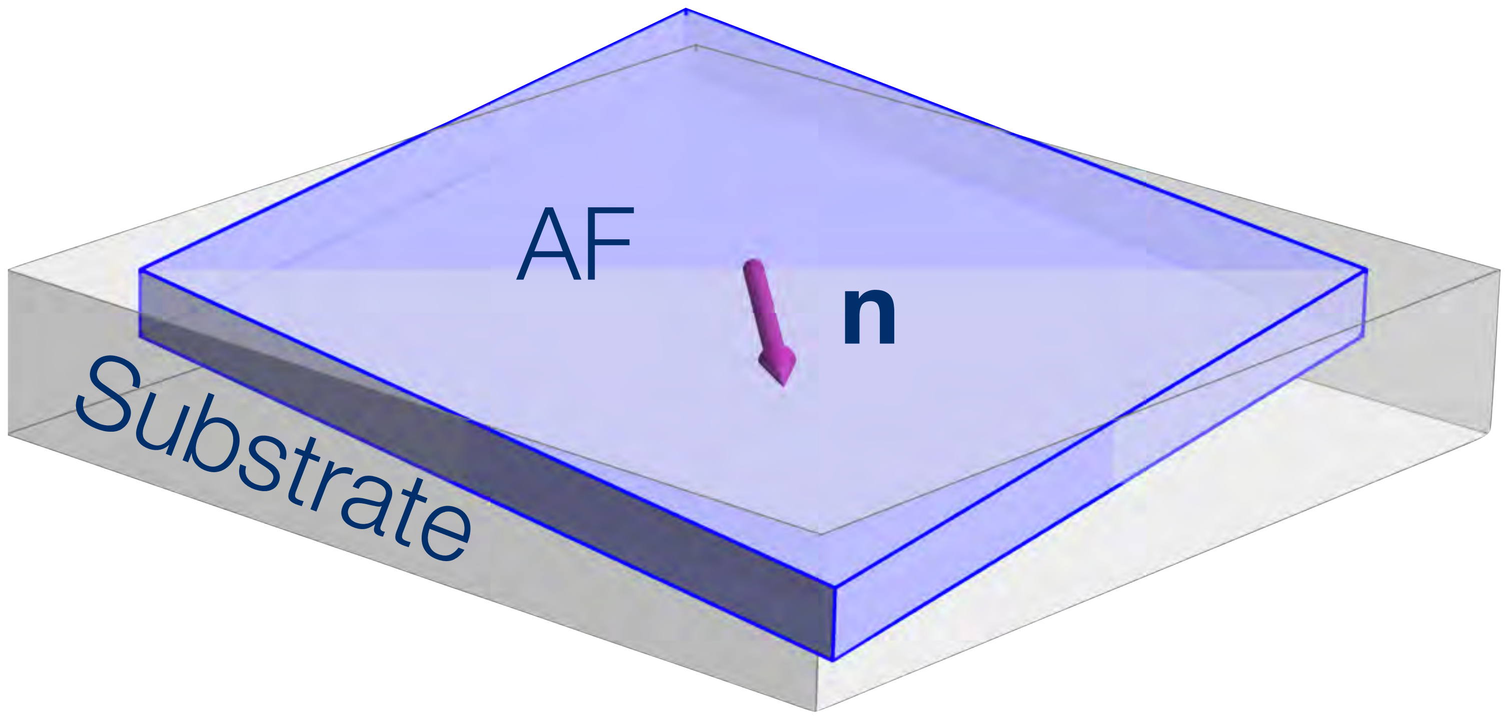
Destressing energy

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

Kernel => dipole

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

Destressing from the substrate

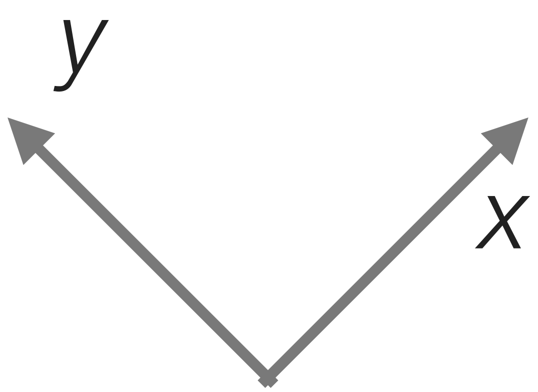


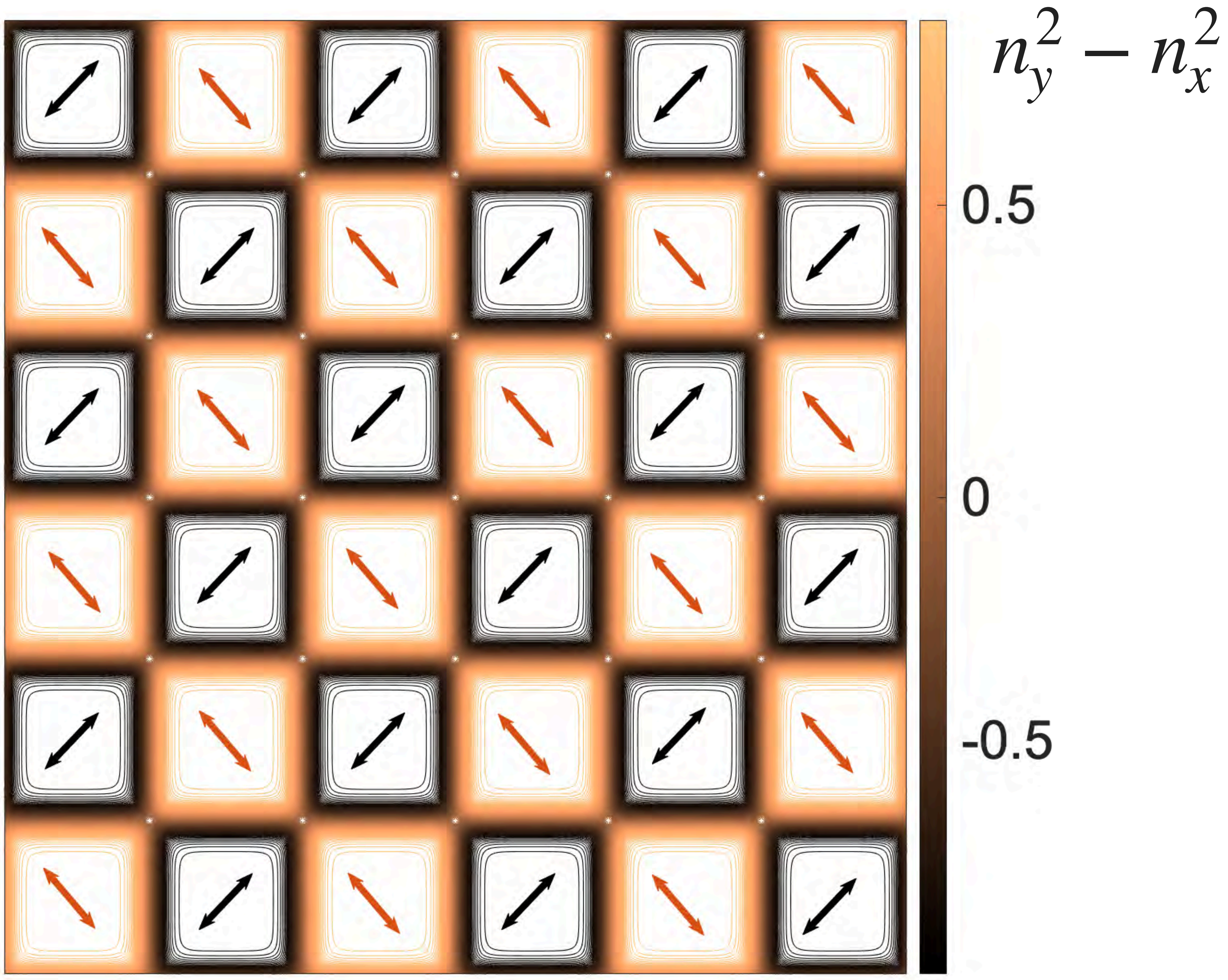
$$E_{\mathrm{des}} = \langle \mathbf{n} \otimes \mathbf{n} \rangle \hat{N} \langle \mathbf{n} \otimes \mathbf{n} \rangle V$$

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

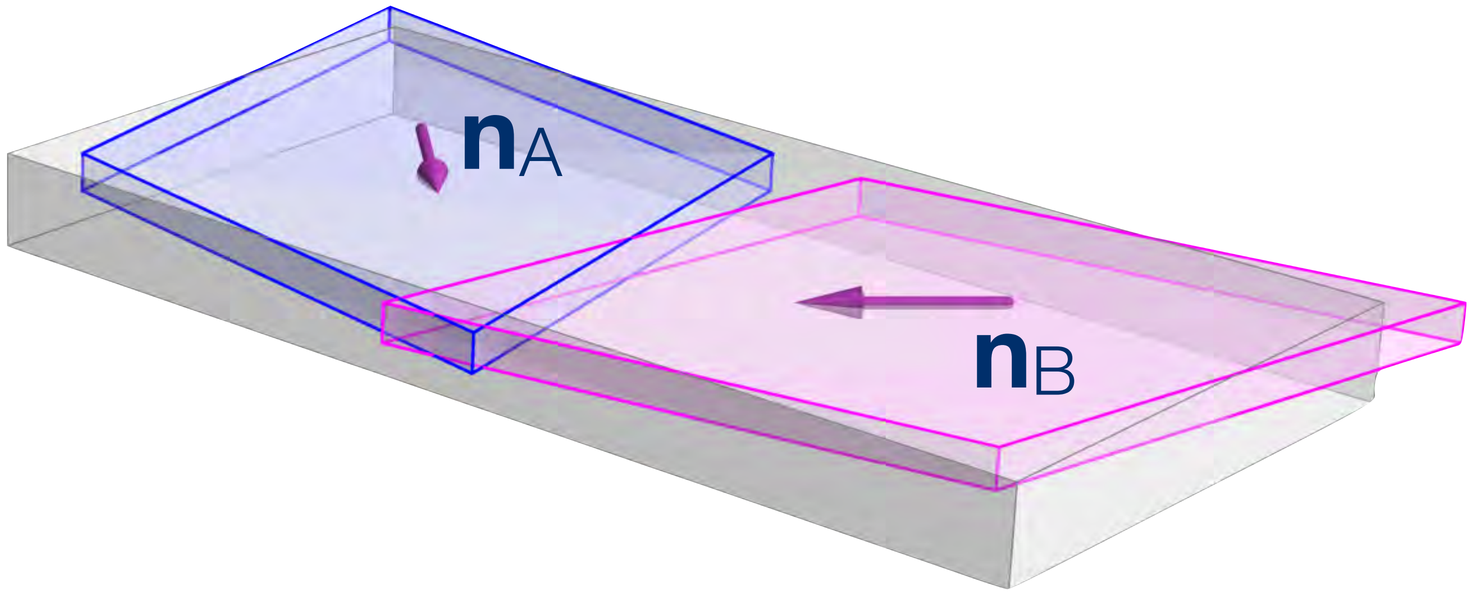
Gomonay, Loktev, 2002

Domain structure in the blanket film





Destressing at the domain boundary



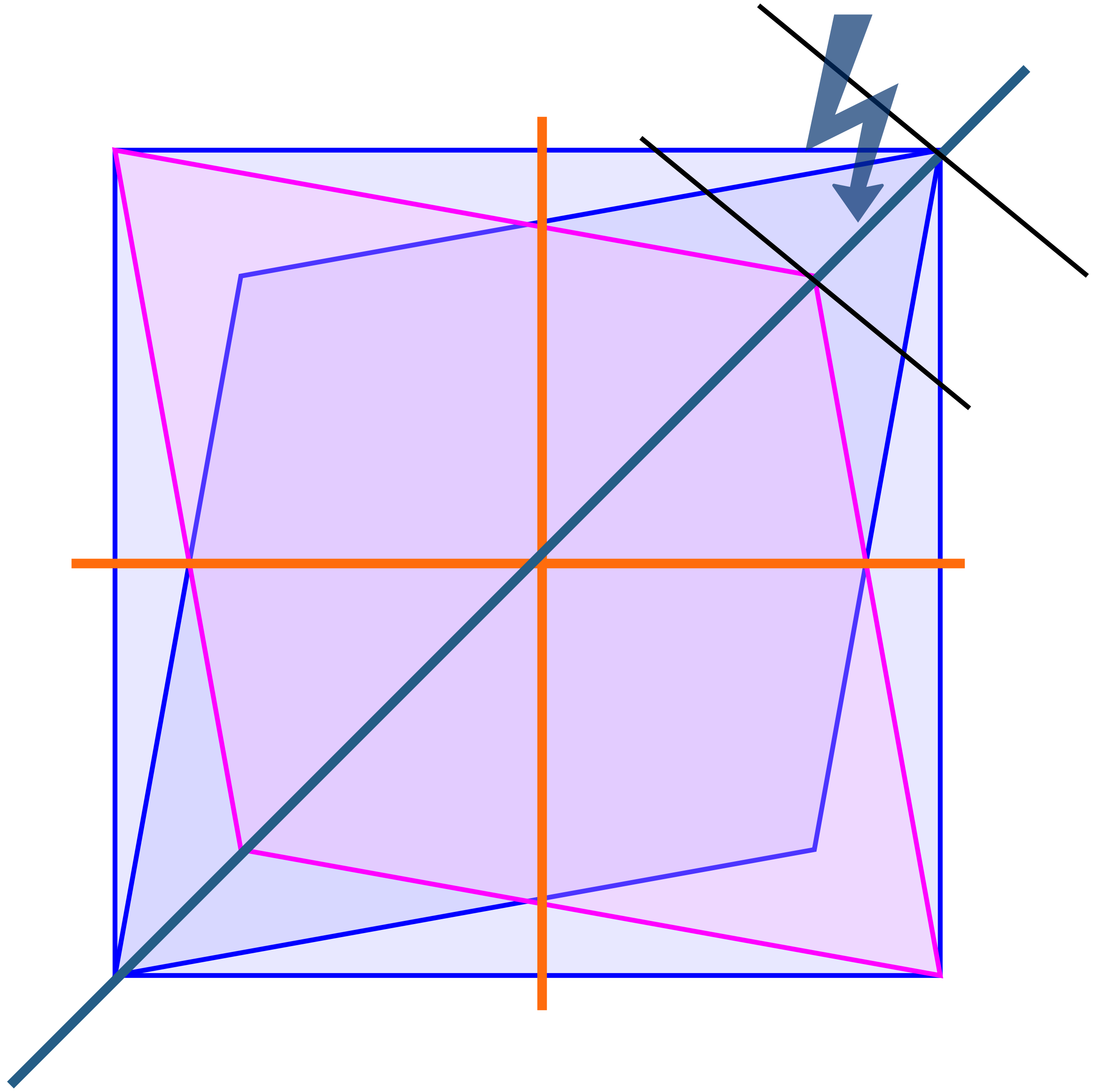
Flat domain wall

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

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

Domain boundary

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



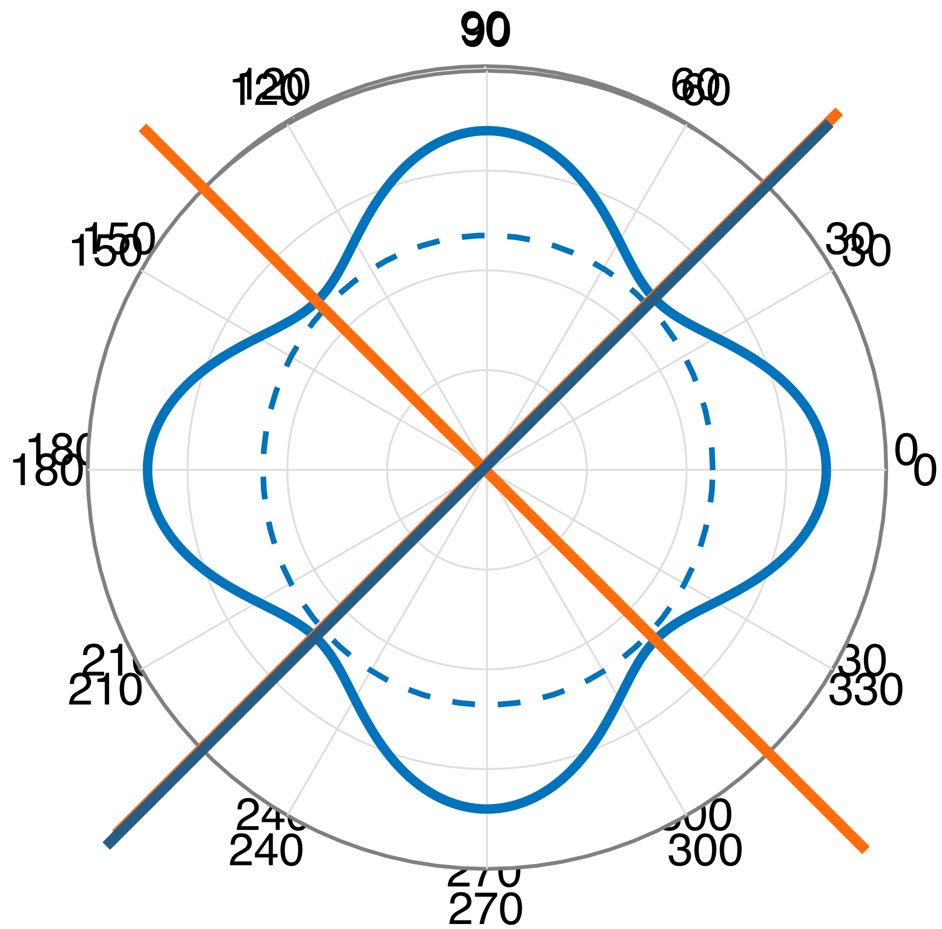
$$\hat{\eta}(\varphi) \neq 0$$

Domain wall energy

$$E_{\mathrm{mag}} = \sqrt{AH_{\mathrm{an}}M_s}$$

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

$\mathbf{n}_{\mathrm{A}}$

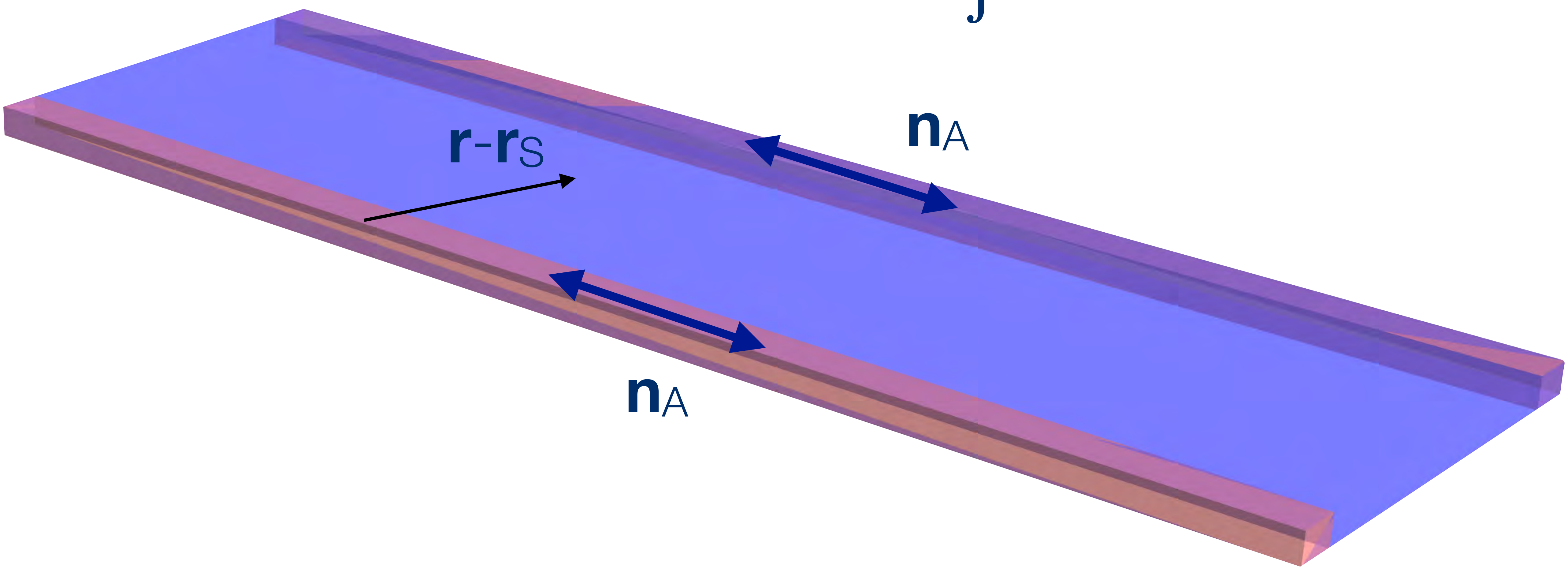


$\mathbf{n}_{\mathrm{B}}$

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

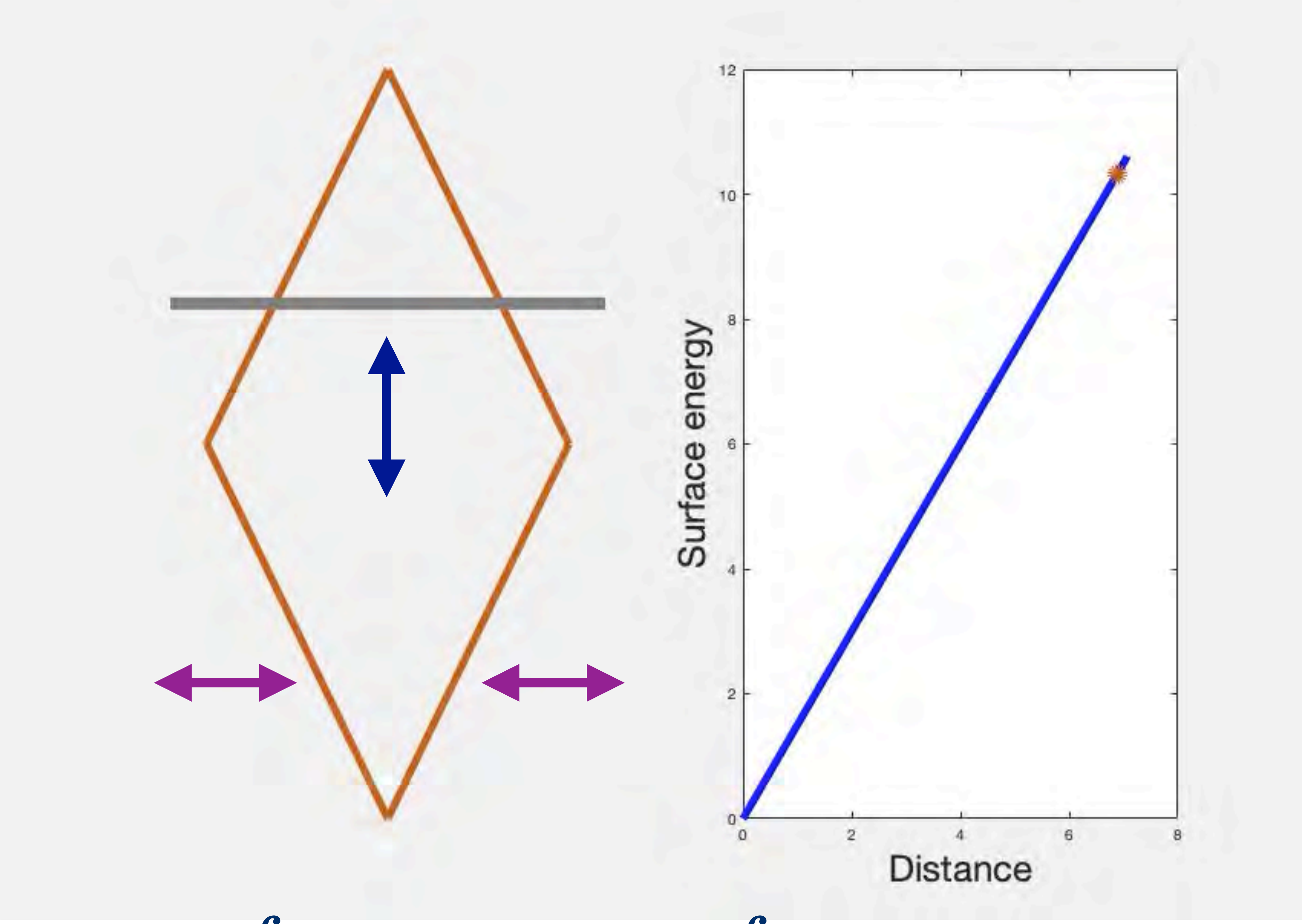
Surface effects

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



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

Surface energy



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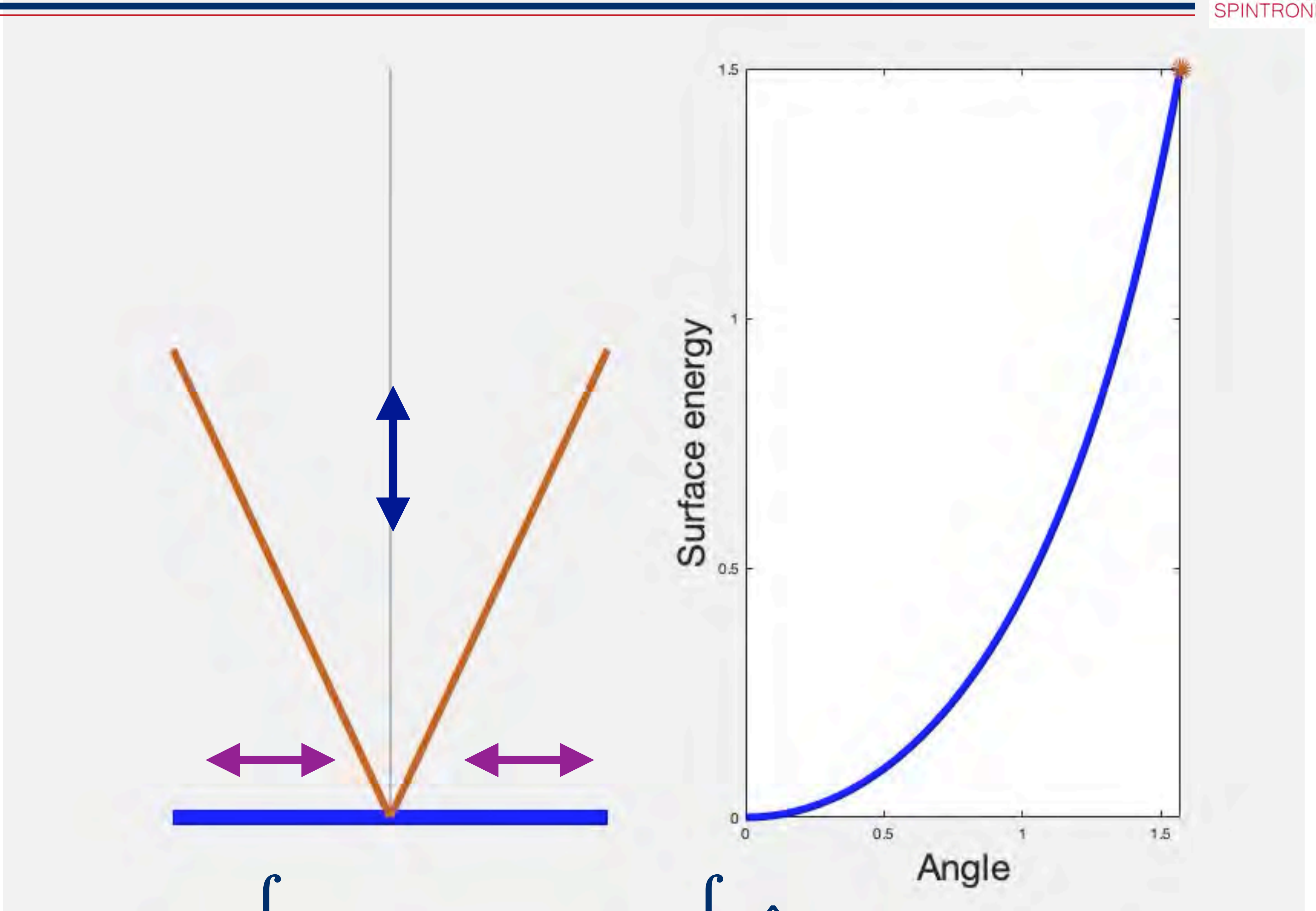
Surface energy



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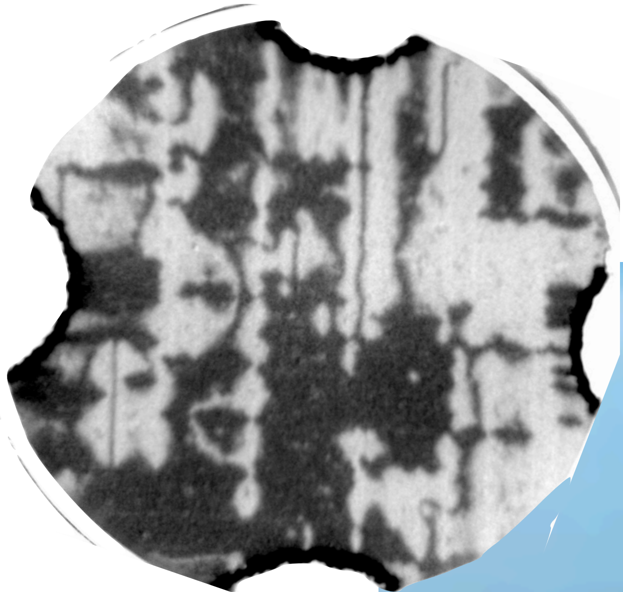
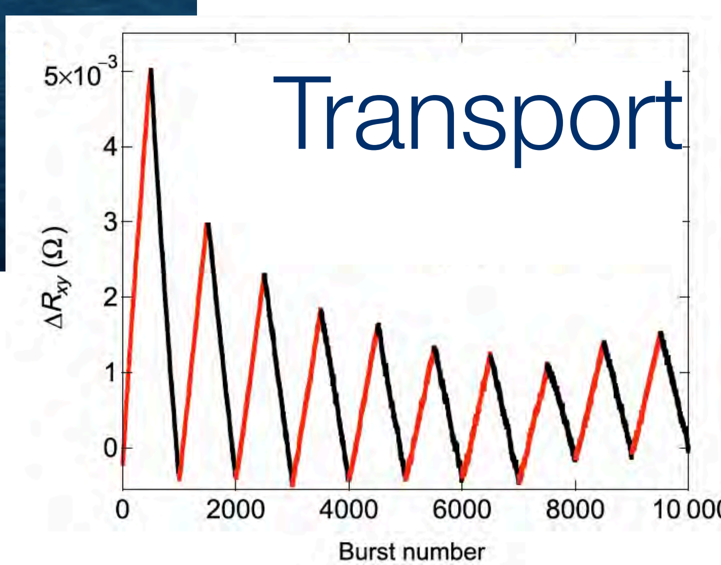
Conclusions



Micr-***a***-magnetics

Elasticity

AF



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THANK YOU!