

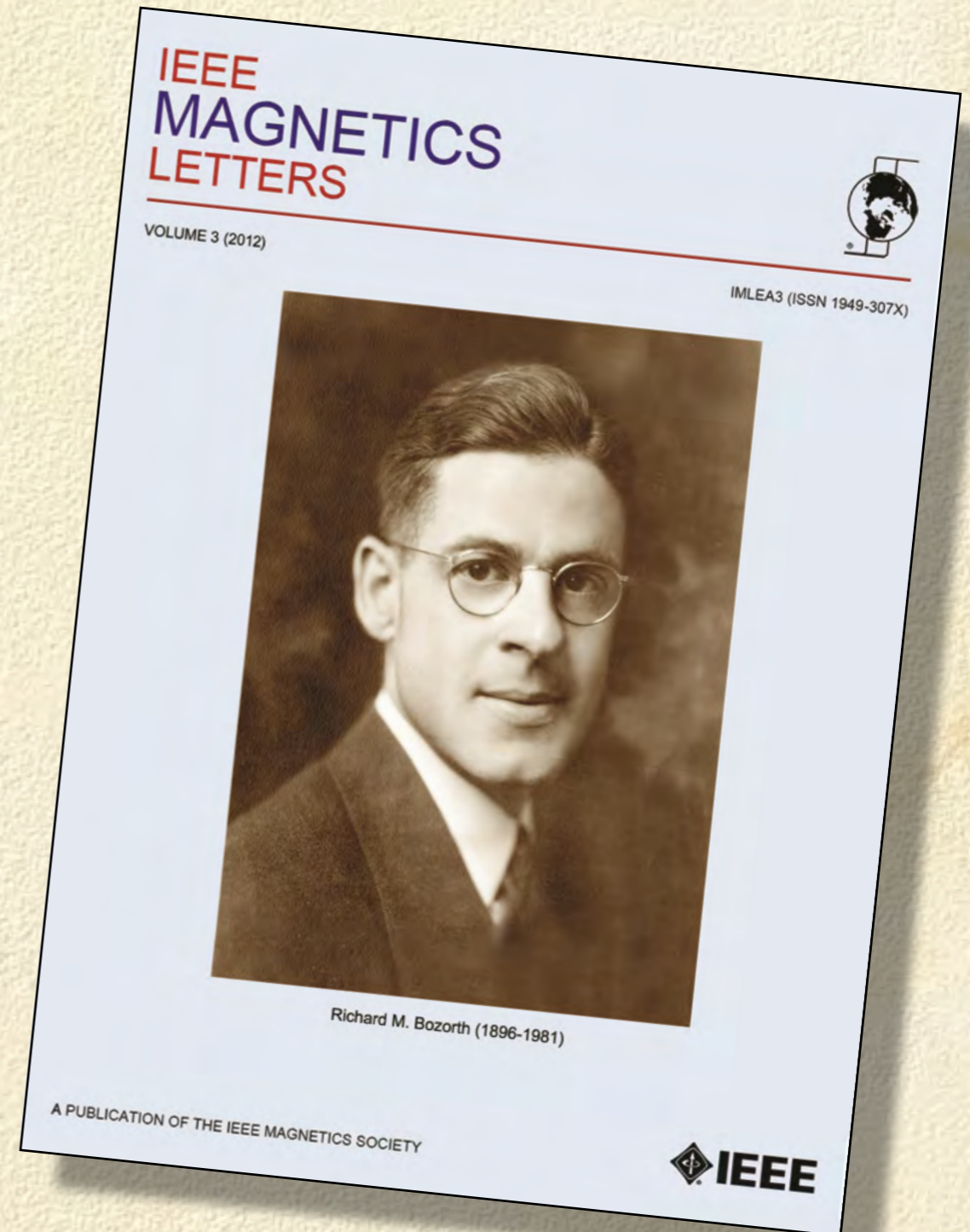


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Magneto-optical Analysis of Magnetic Microstructures*

R. Schäfer,

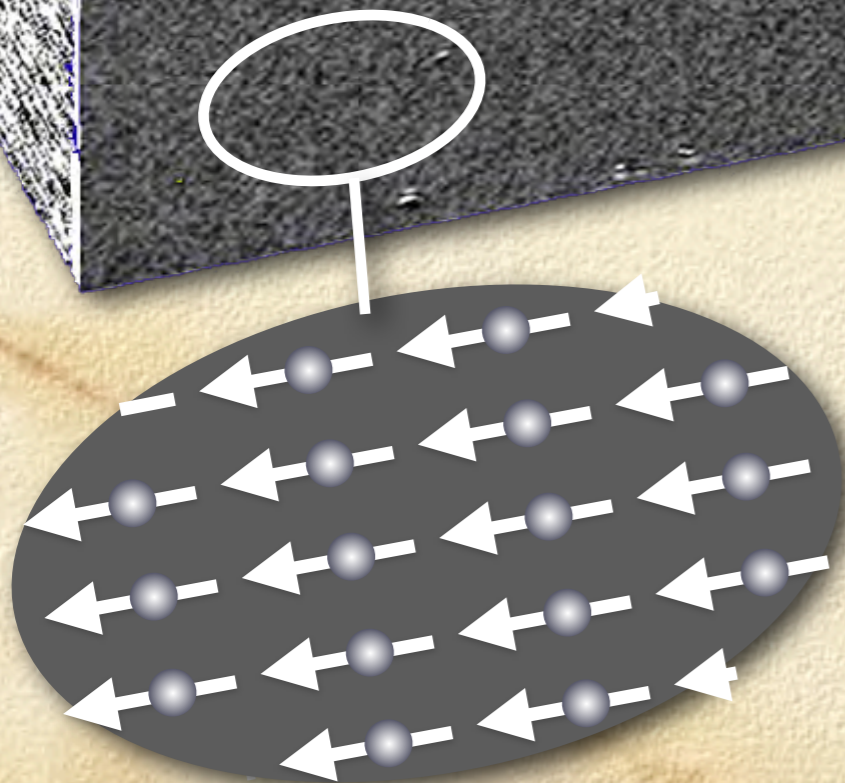
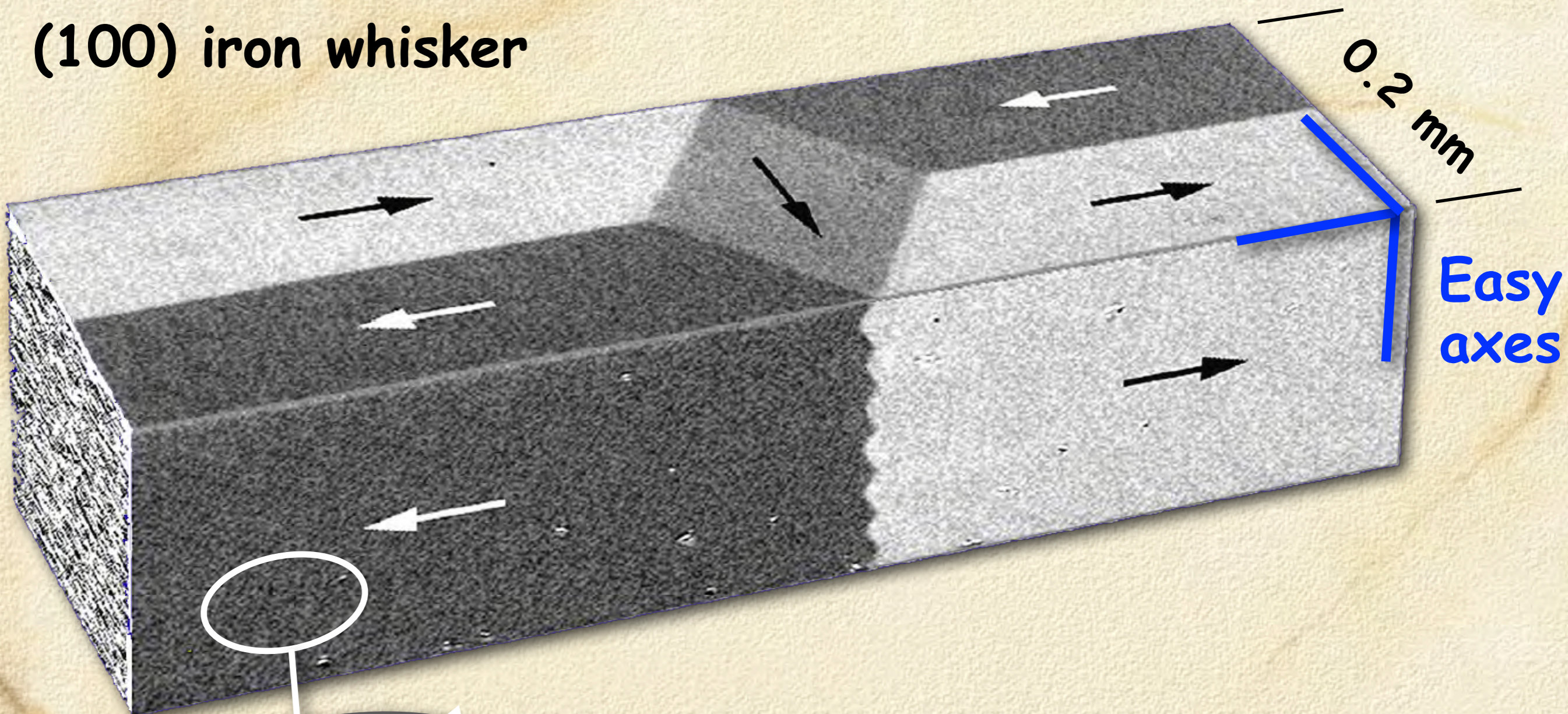
Leibniz Inst. for Solid State and Materials
Research (IFW) Dresden, Germany

*Review of Magnetic Domains,
studied (mostly) by Kerr microscopy

What are magnetic domains ?

What are magnetic domains ?

(100) iron whisker



**Magnetic domains:
uniformly magnetized regions
in a magnetic material**

What are magnetic domains?

CoPt multilayer (7 nm thick),
sample courtesy Tom Moore and Alex Bellew, Leeds

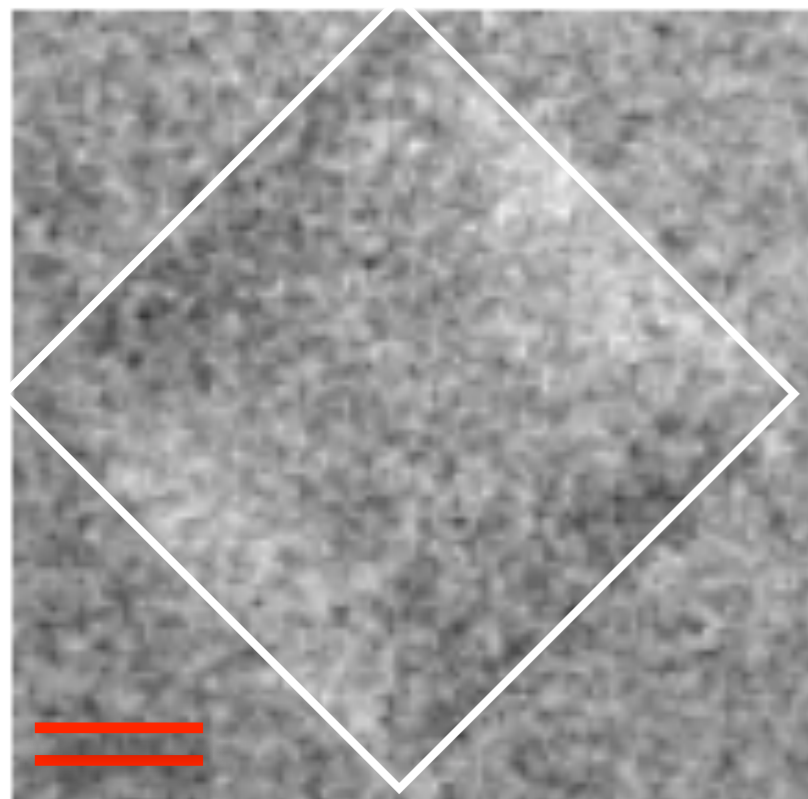
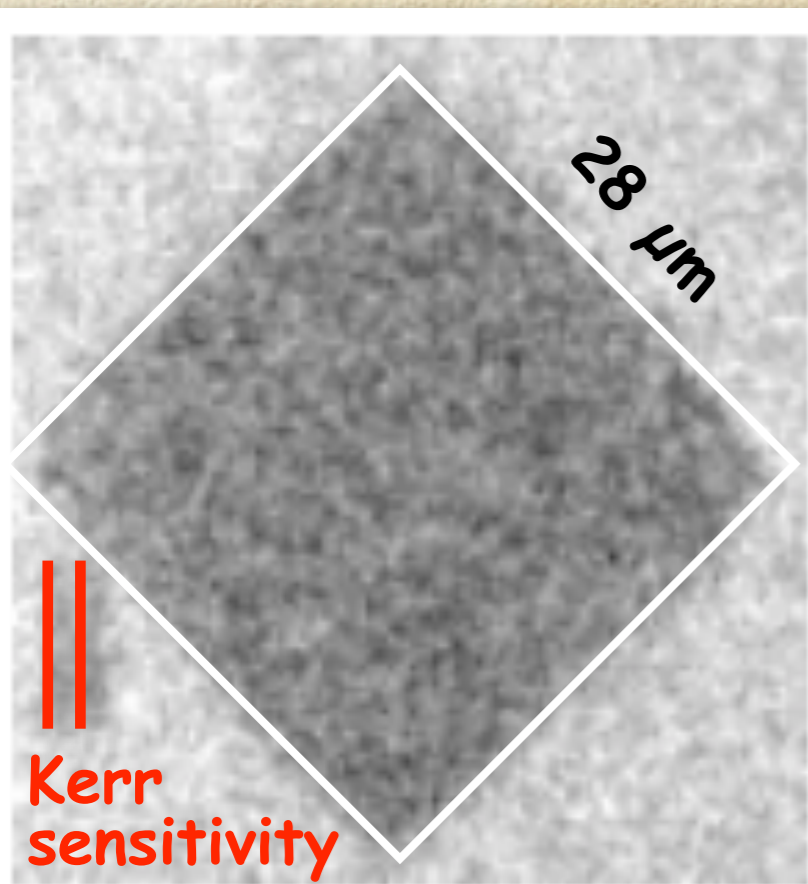


Magnetic field

**Magnetic Domains:
are dynamic if excited by
magnetic field**

What are magnetic domains?

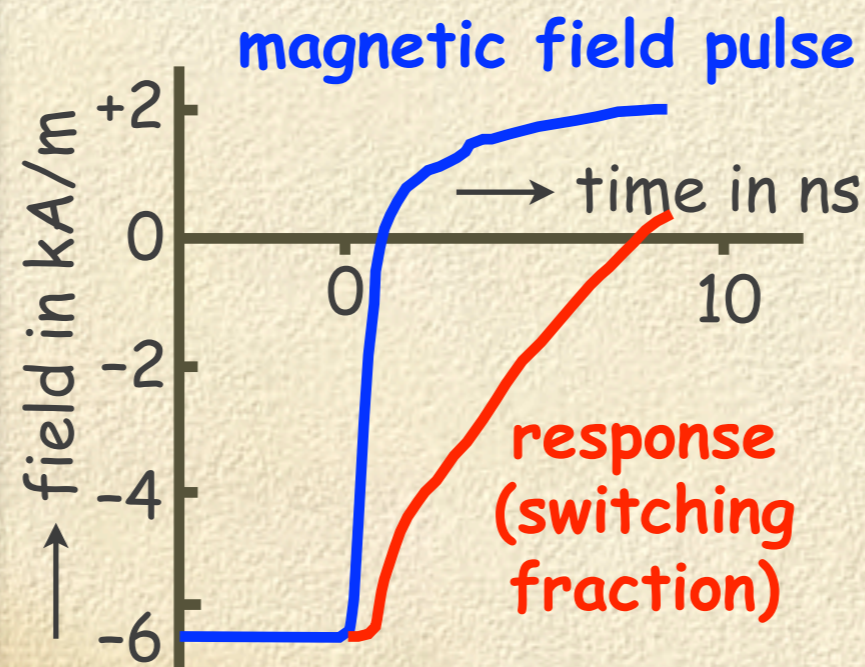
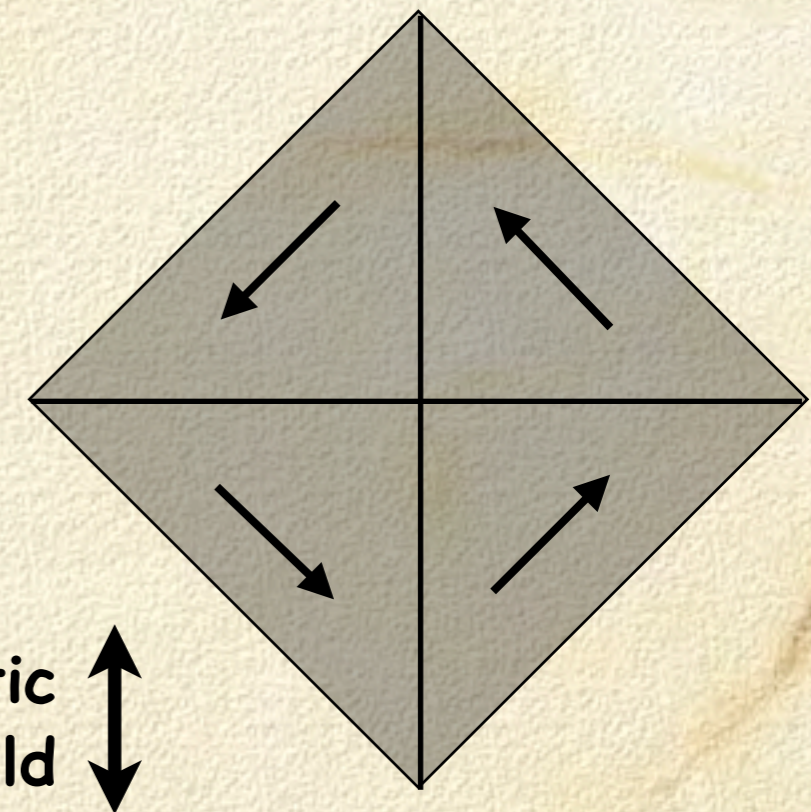
Pulse-field excitation



Quasistatic excitation



Permalloy (NiFe) film

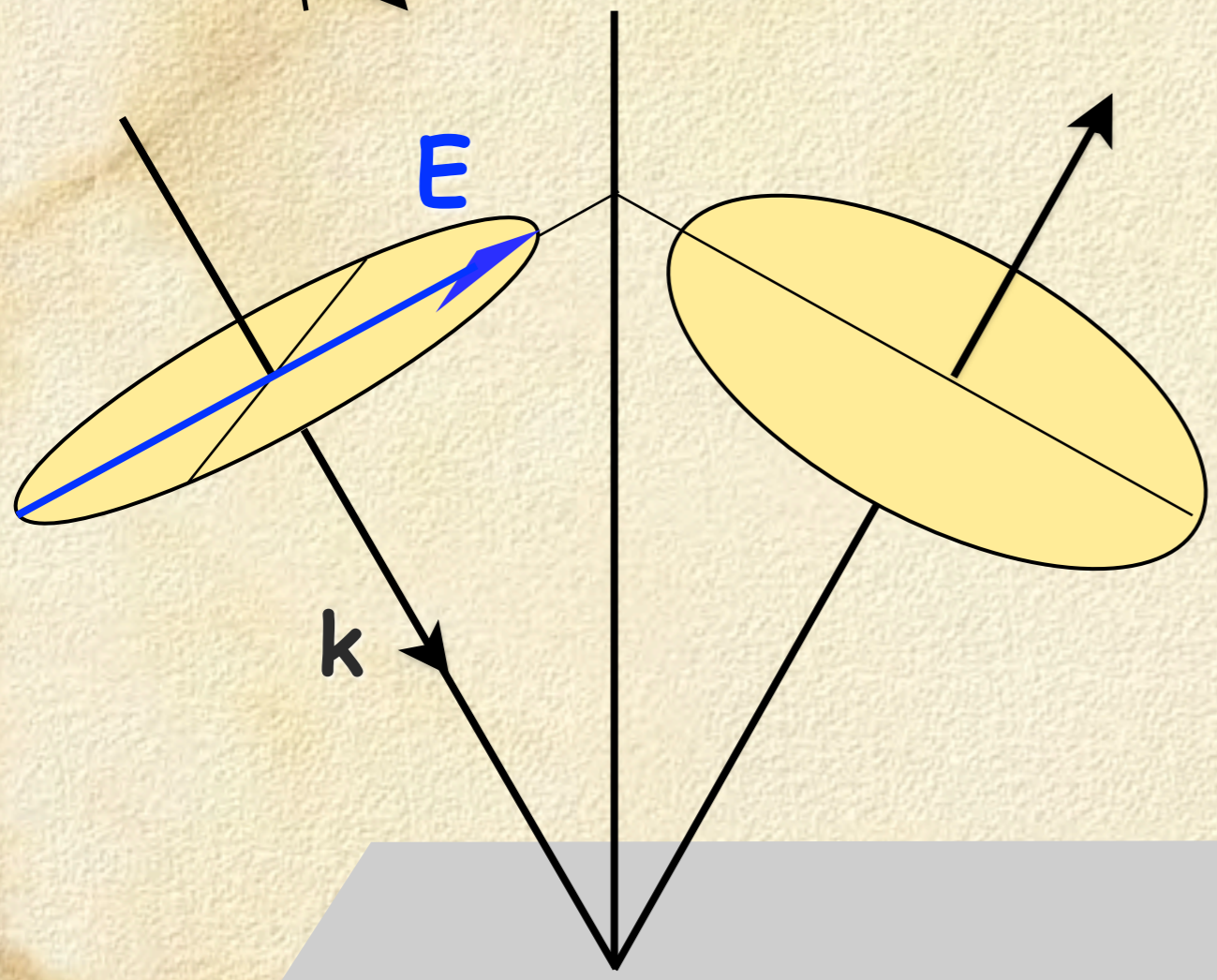
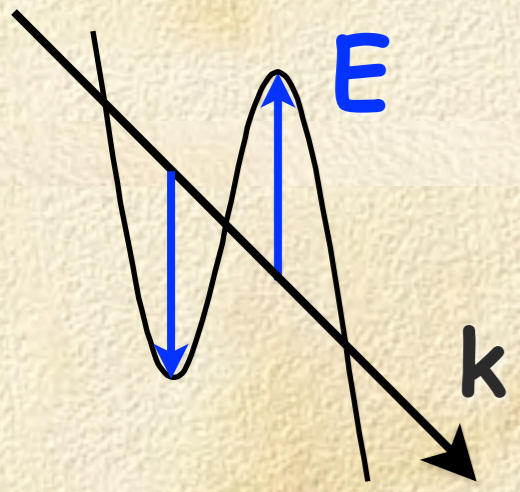


D. Chumakov et al.,
PRB 71, 014410 (2005)

Domain dynamics
depends on
excitation speed

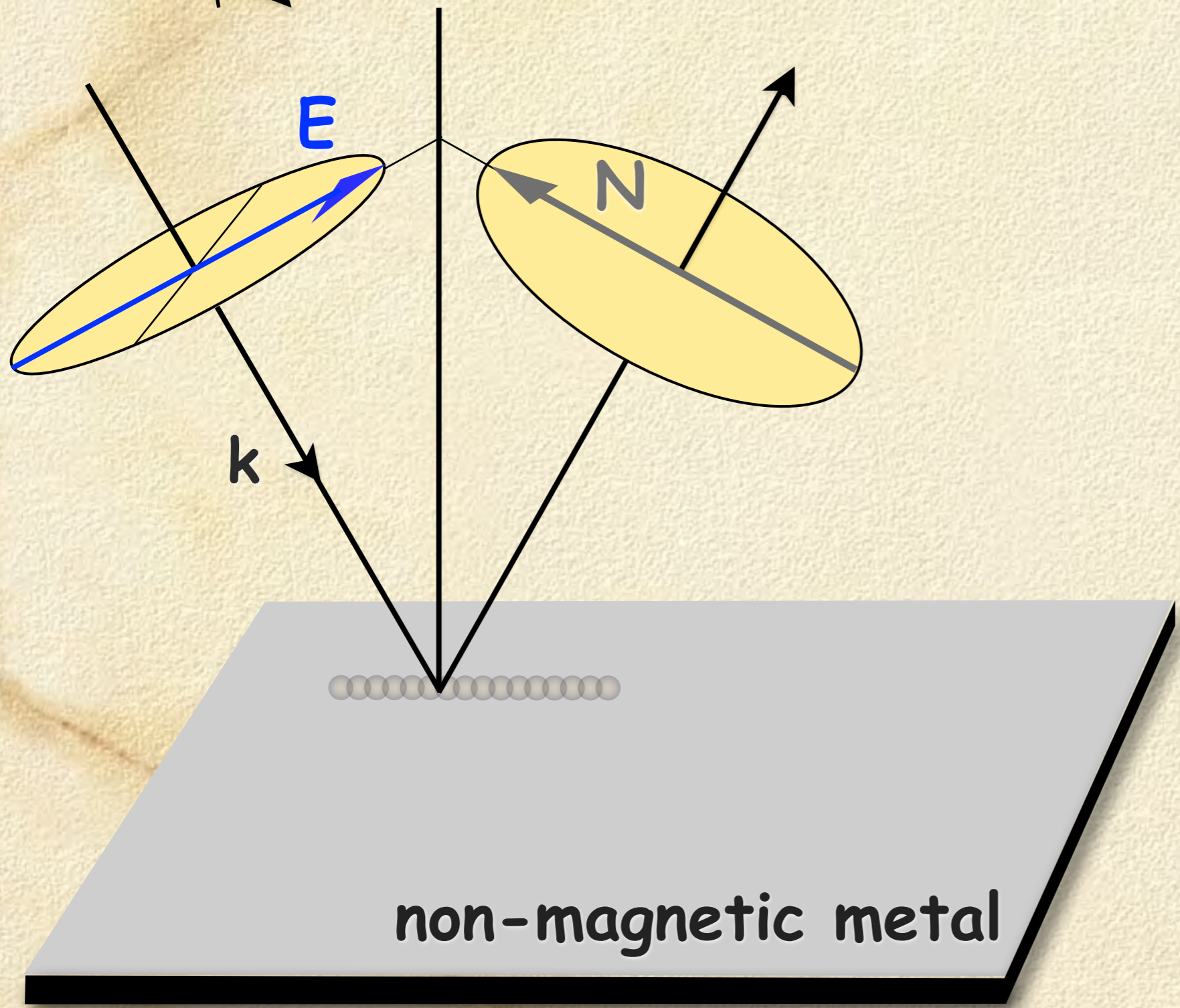
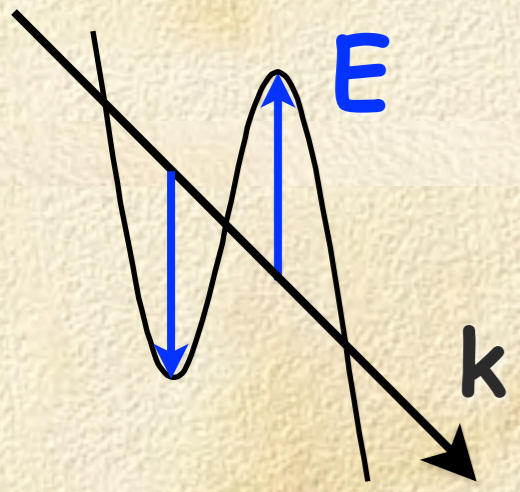
Magneto-optical Kerr microscopy

Kerr effect



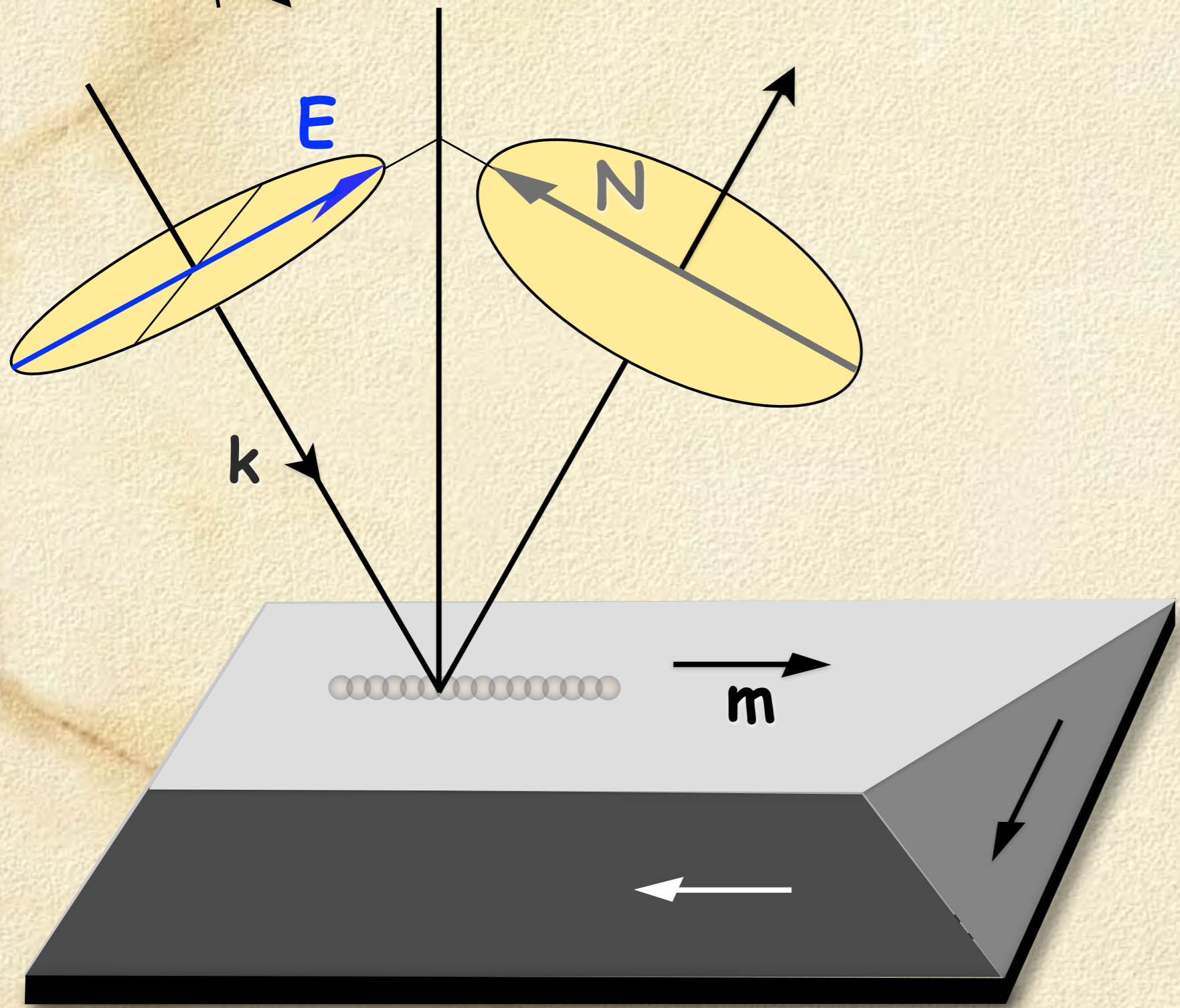
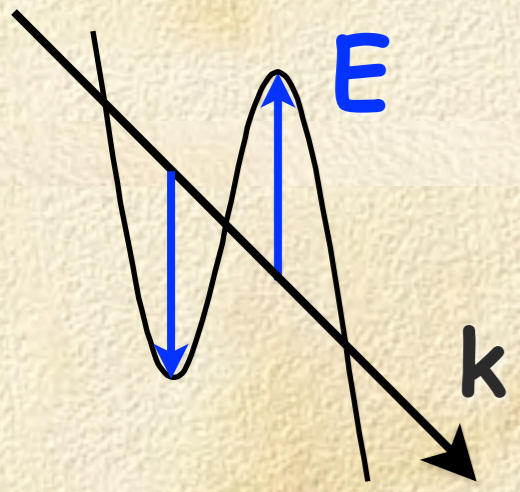
non-magnetic metal

Kerr effect

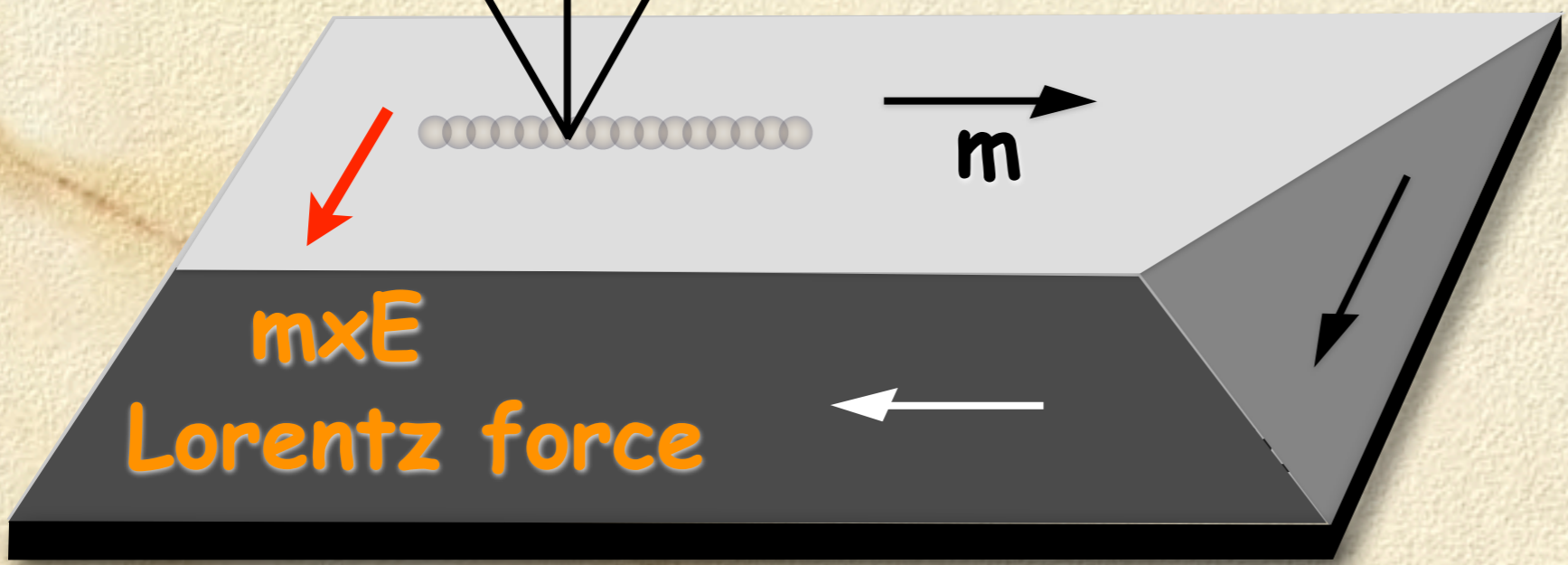
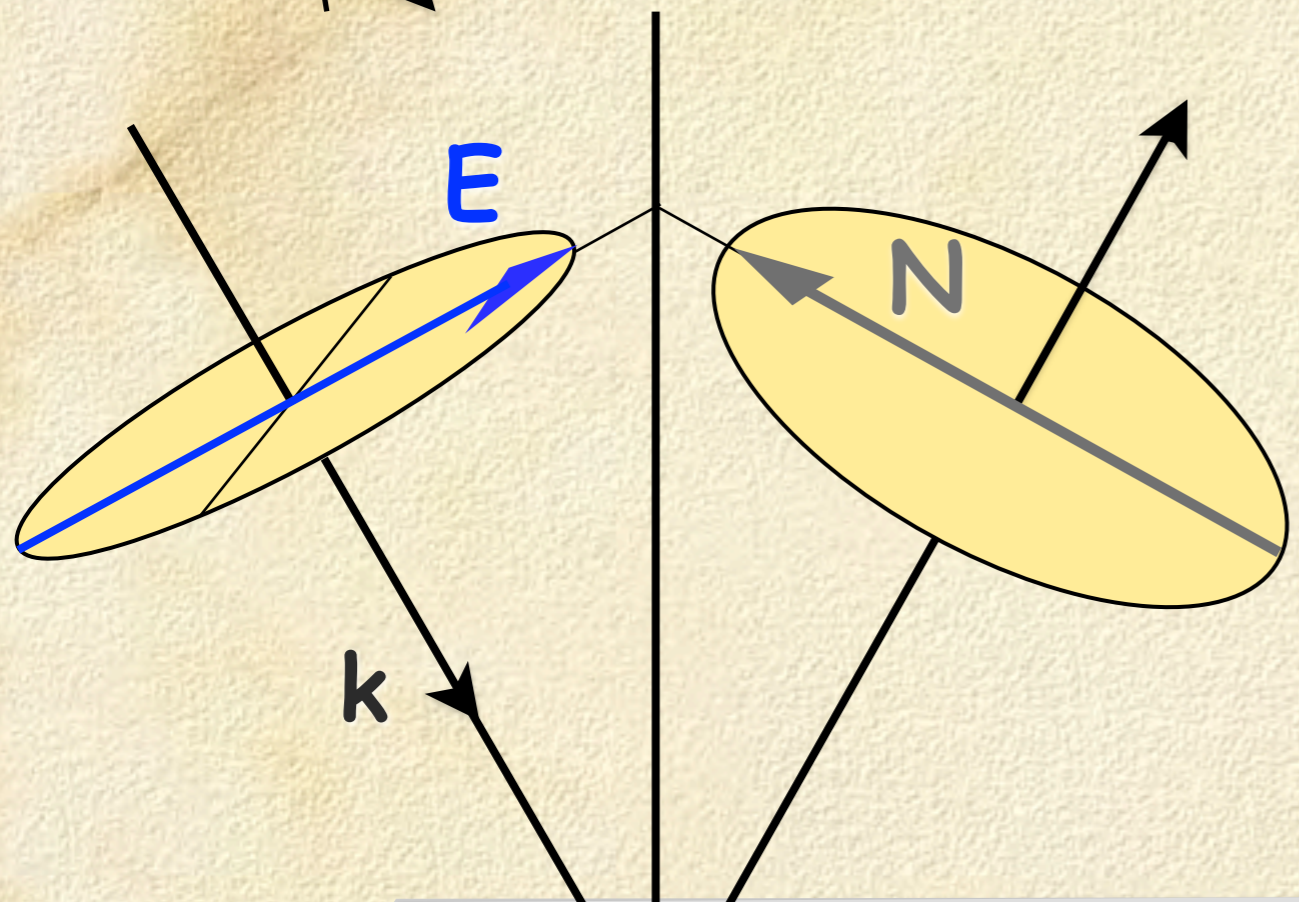
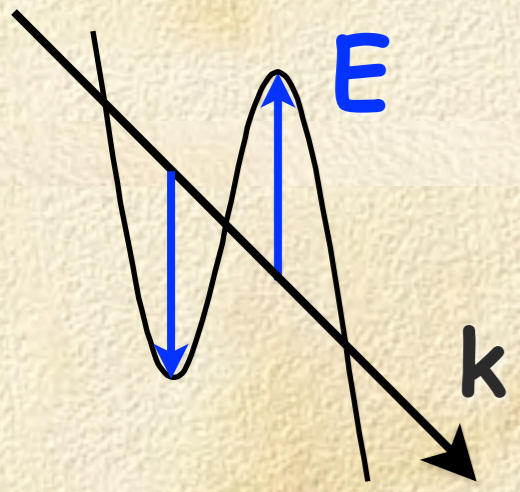


non-magnetic metal

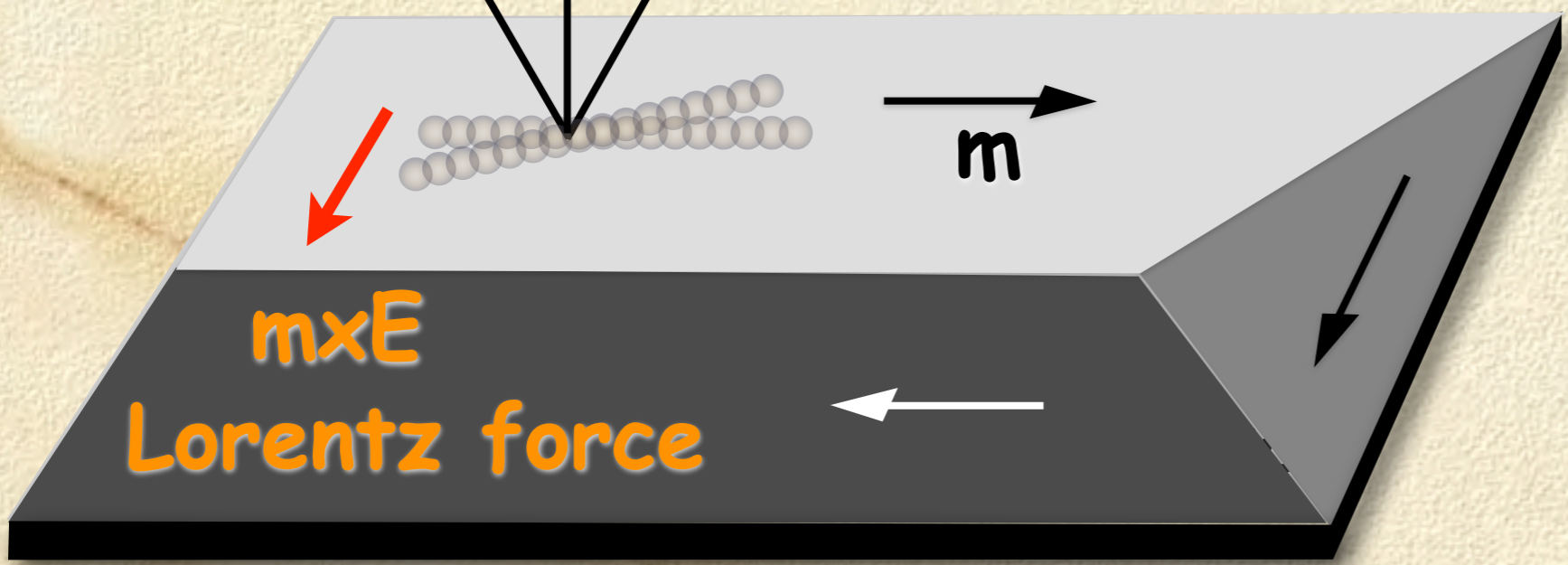
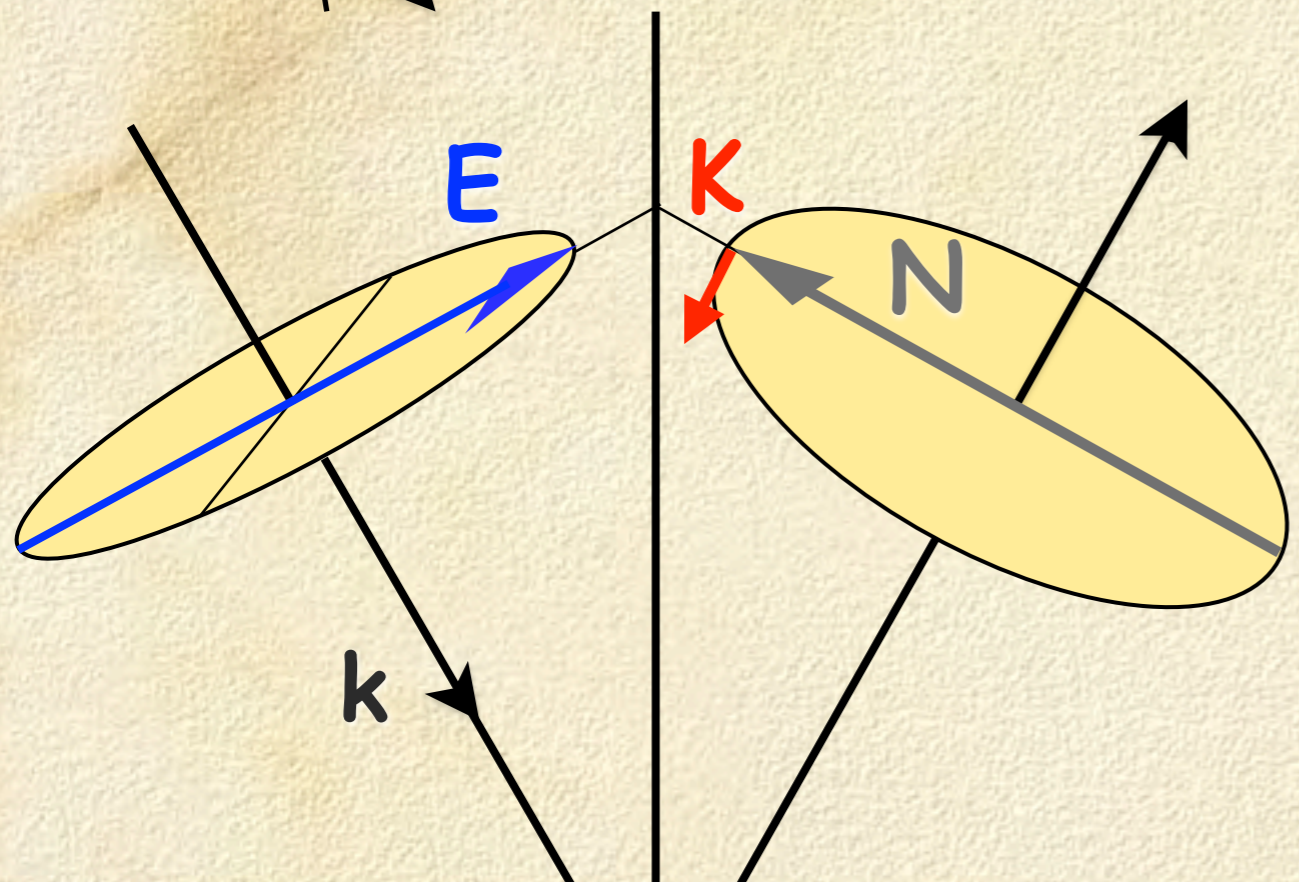
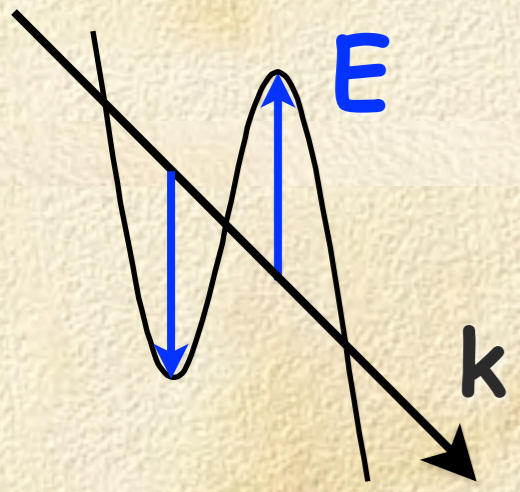
Kerr effect



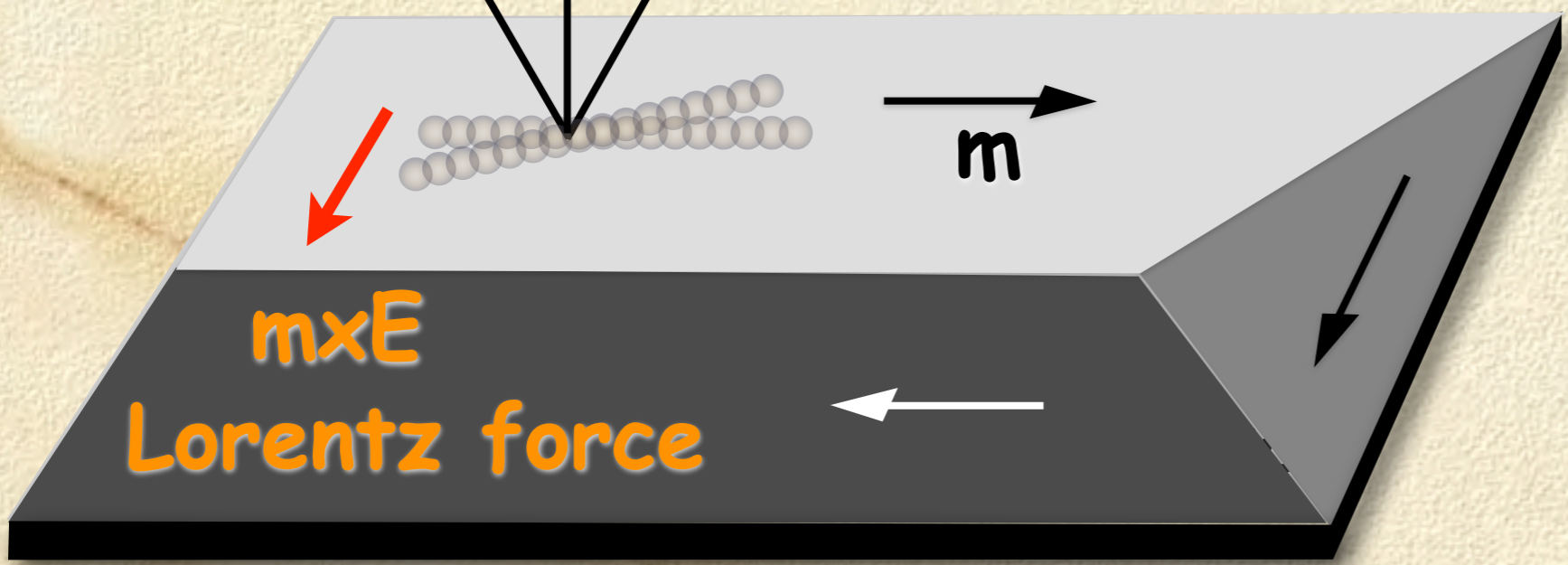
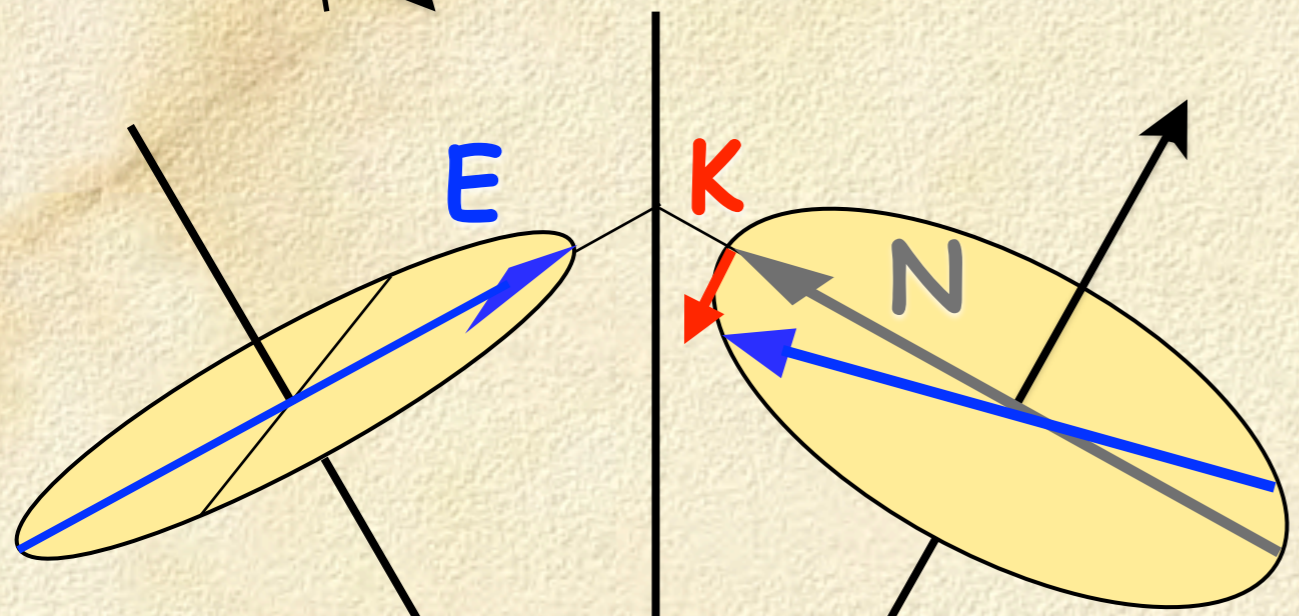
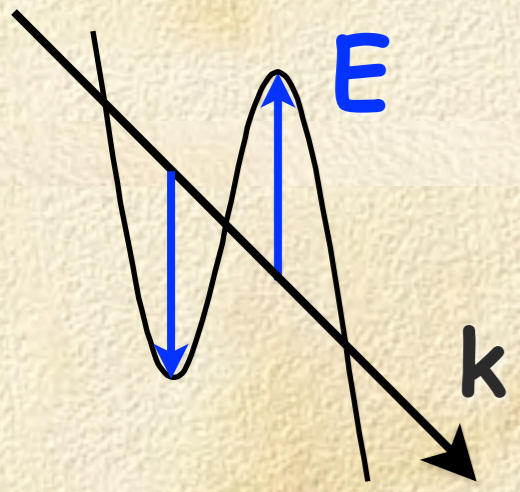
Kerr effect



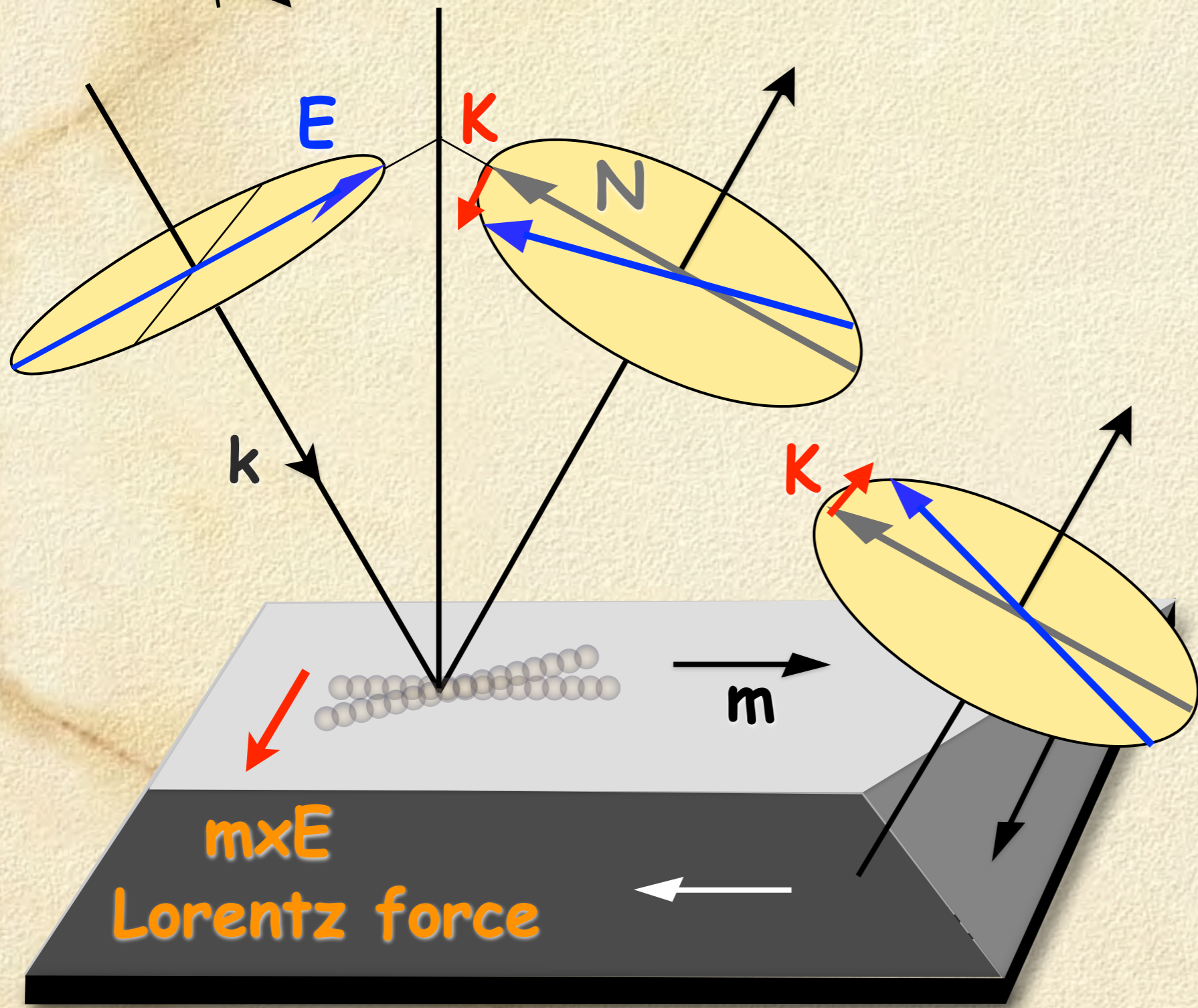
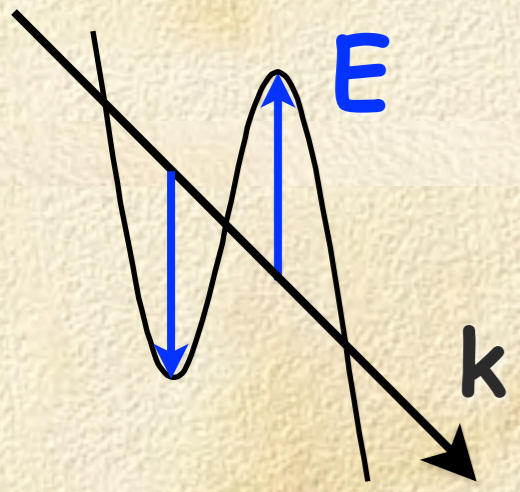
Kerr effect

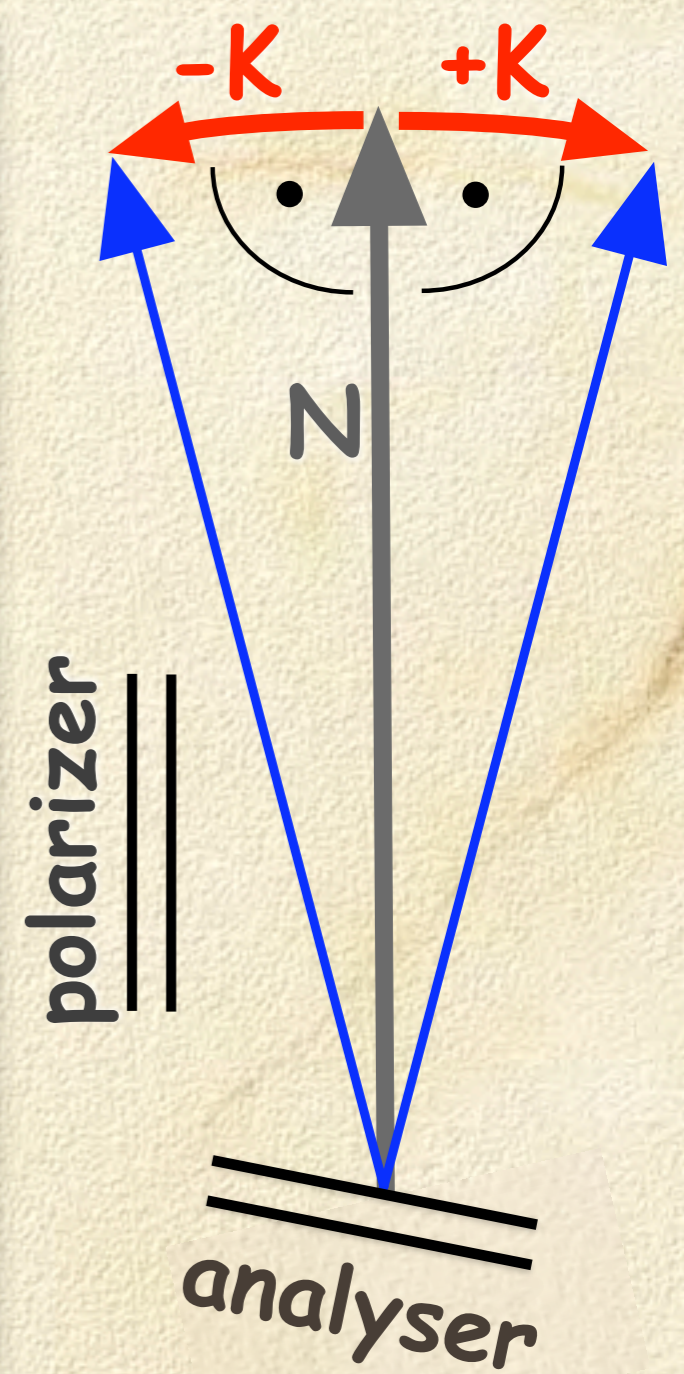
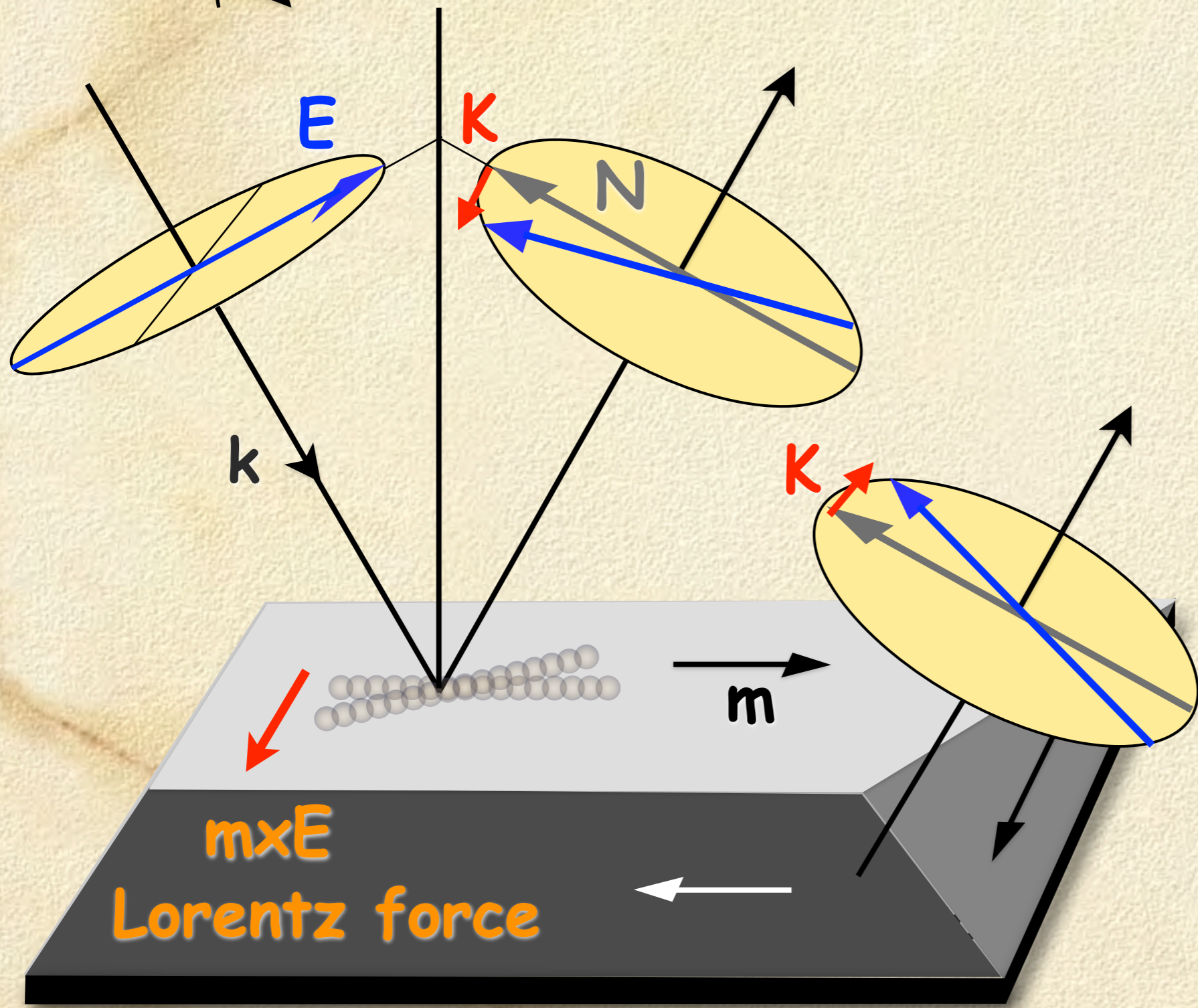
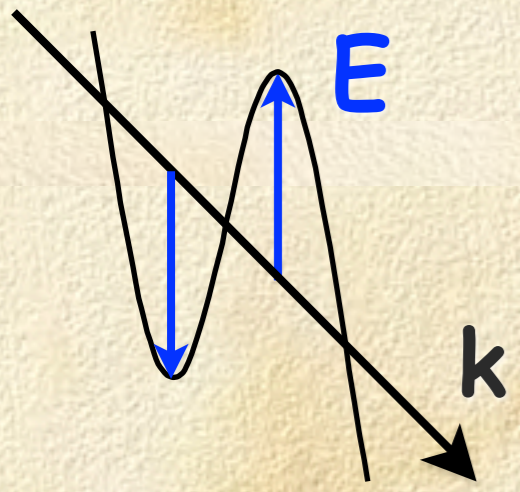


Kerr effect



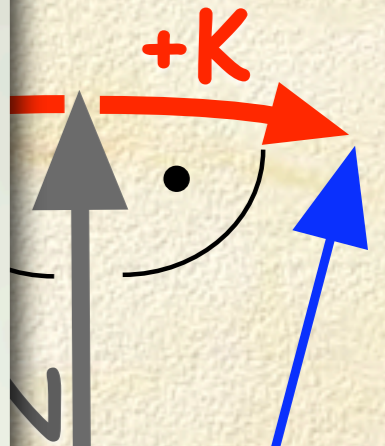
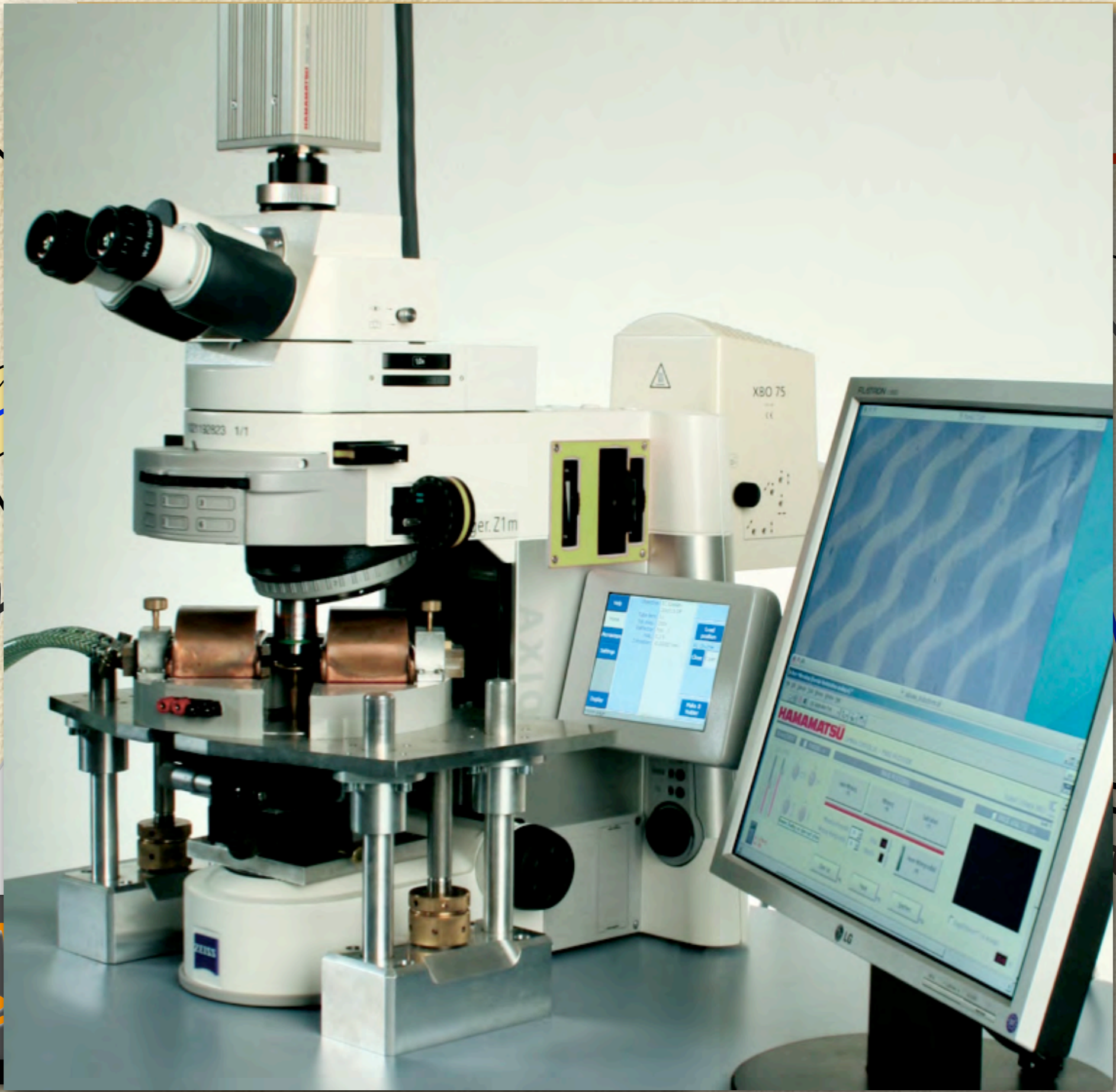
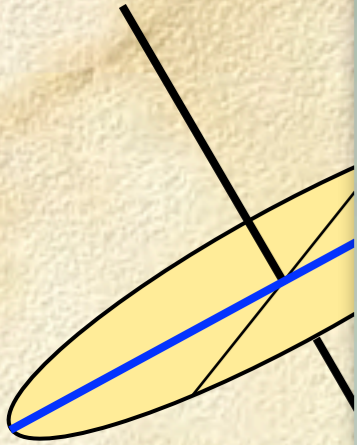
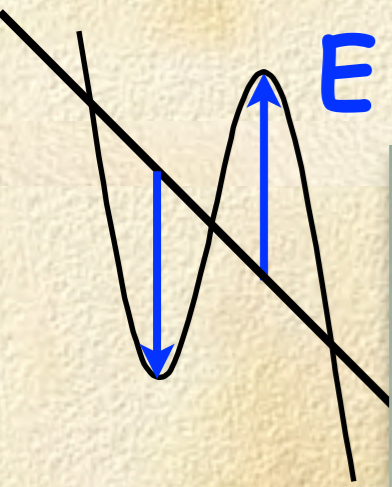
Kerr effect





Kerr rotation
= K/N

Kerr microscope



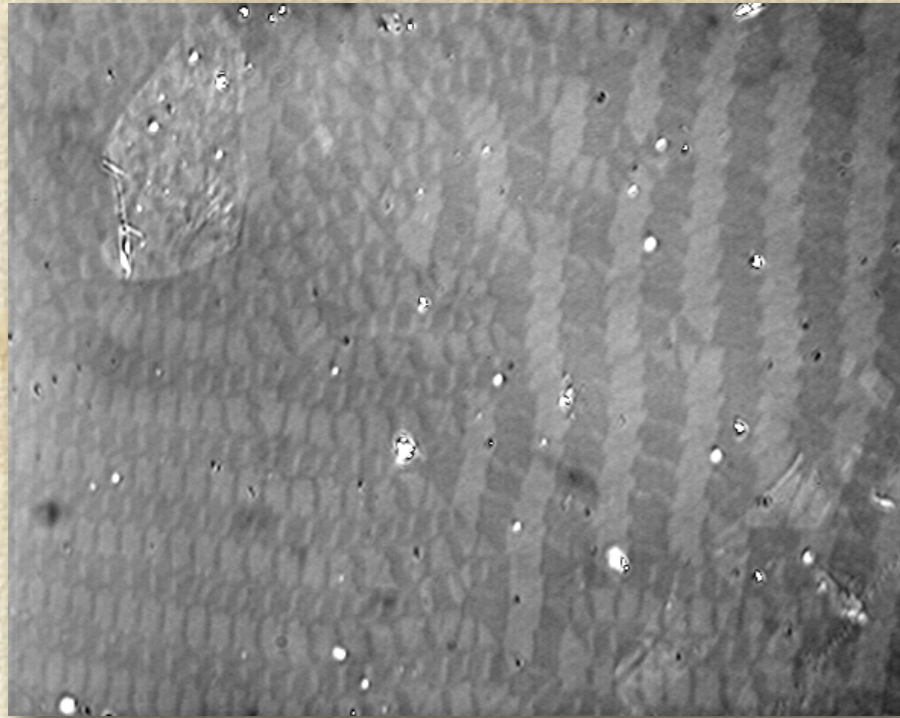
analyser

rotation
K/N

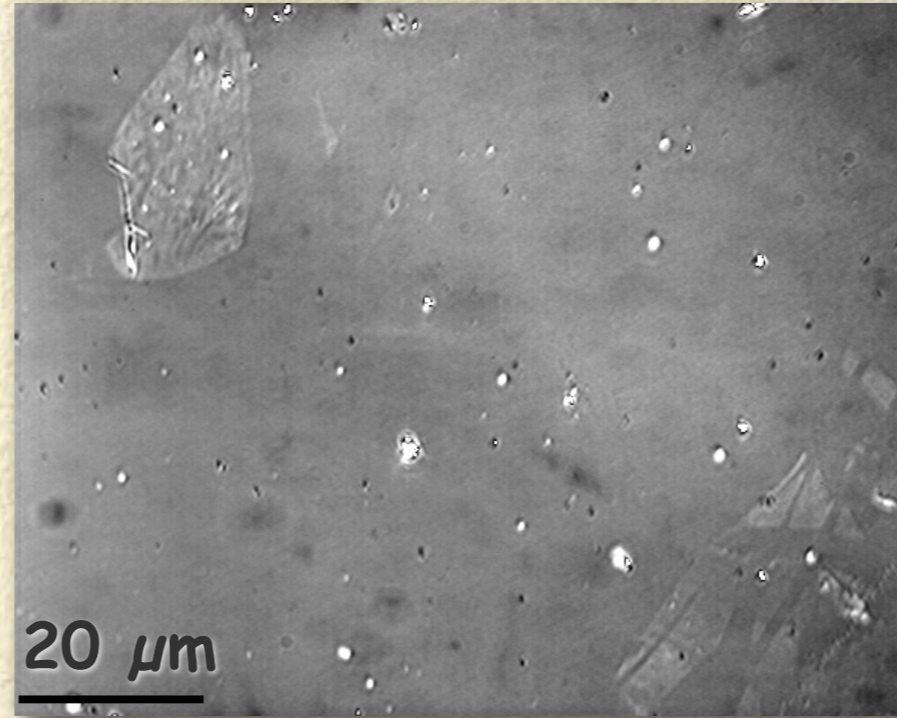
m
Lore

Kerr microscope

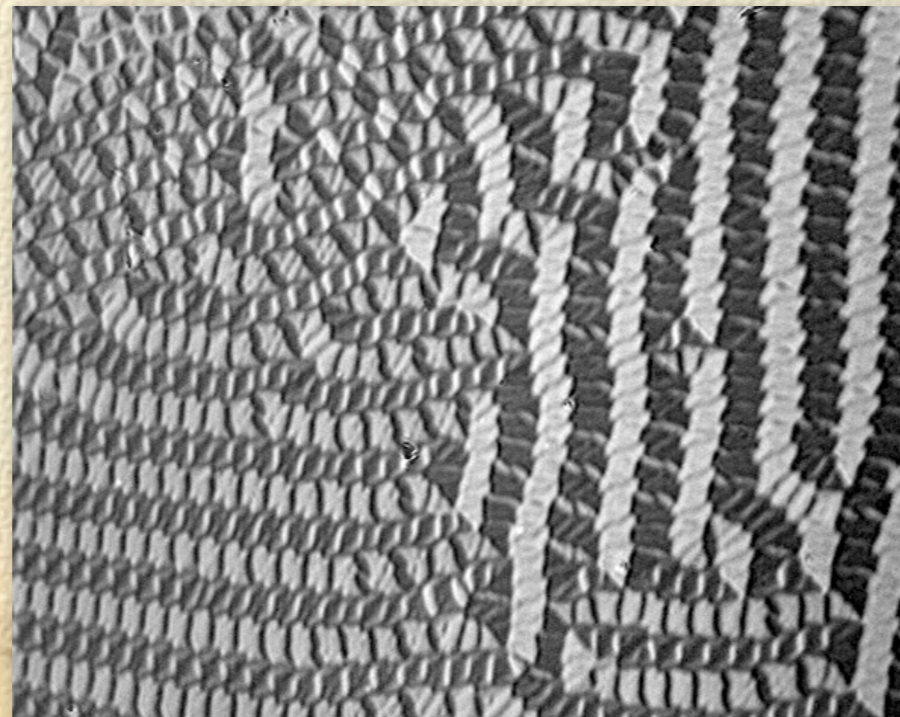
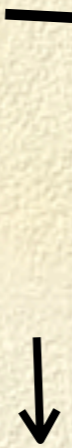
Digital contrast enhancement (difference image technique)



Original image

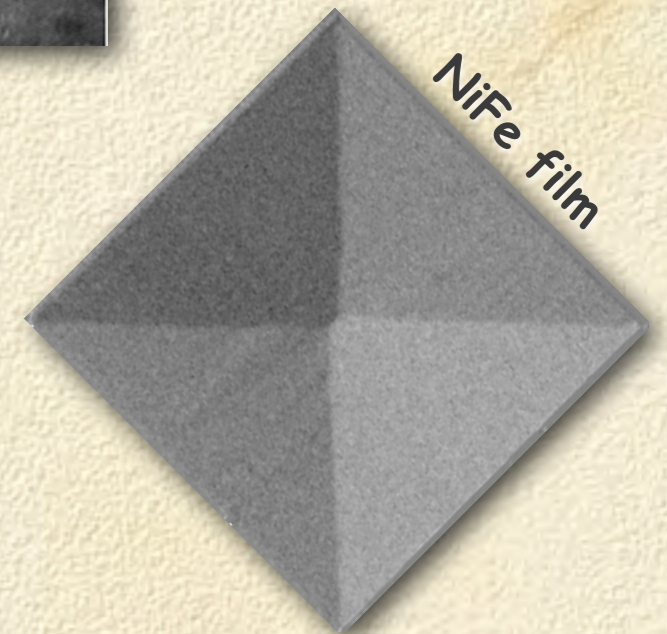


Reference image



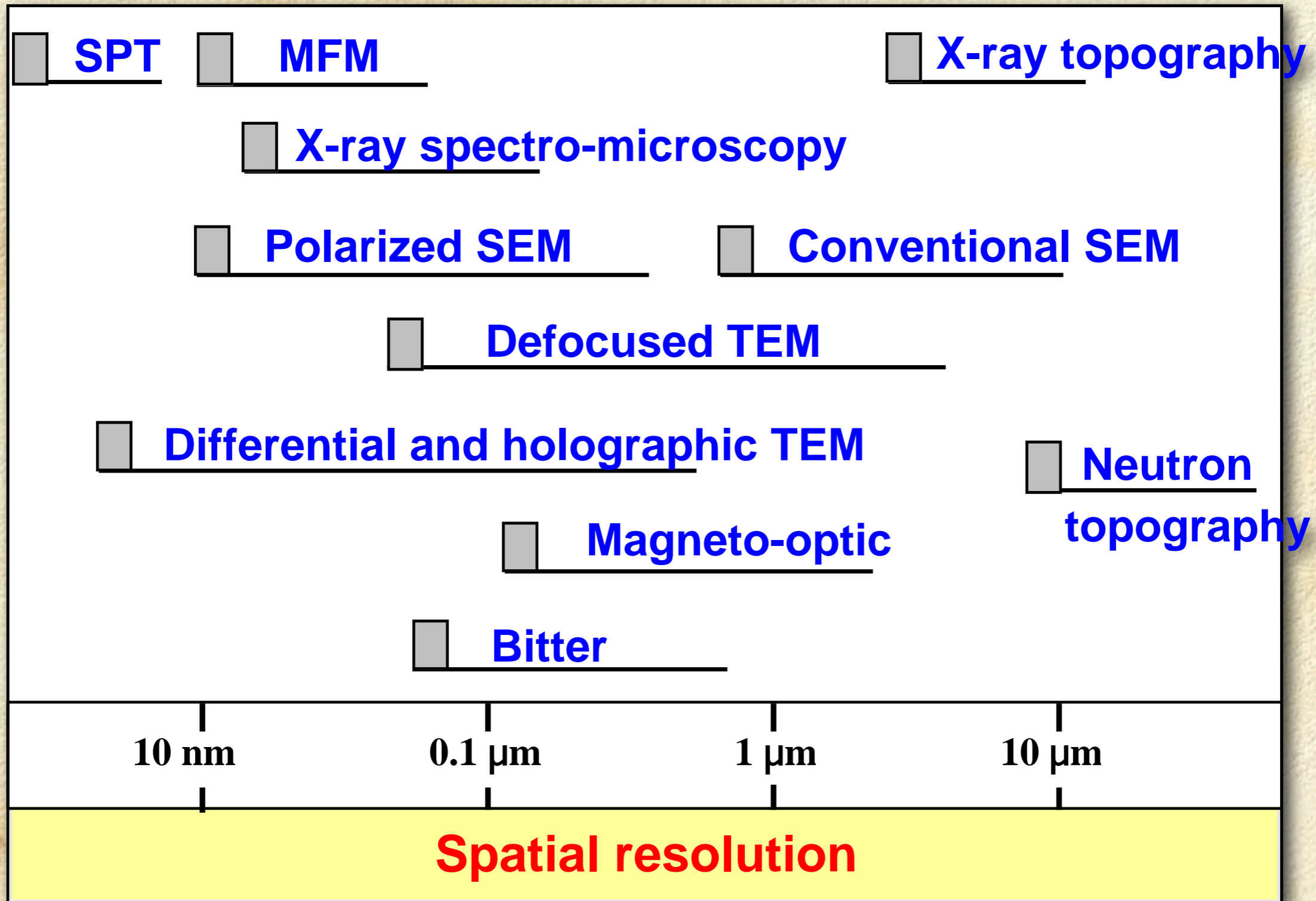
Difference image

amorphous
ribbon



Important:
Difference Imaging
in real time !

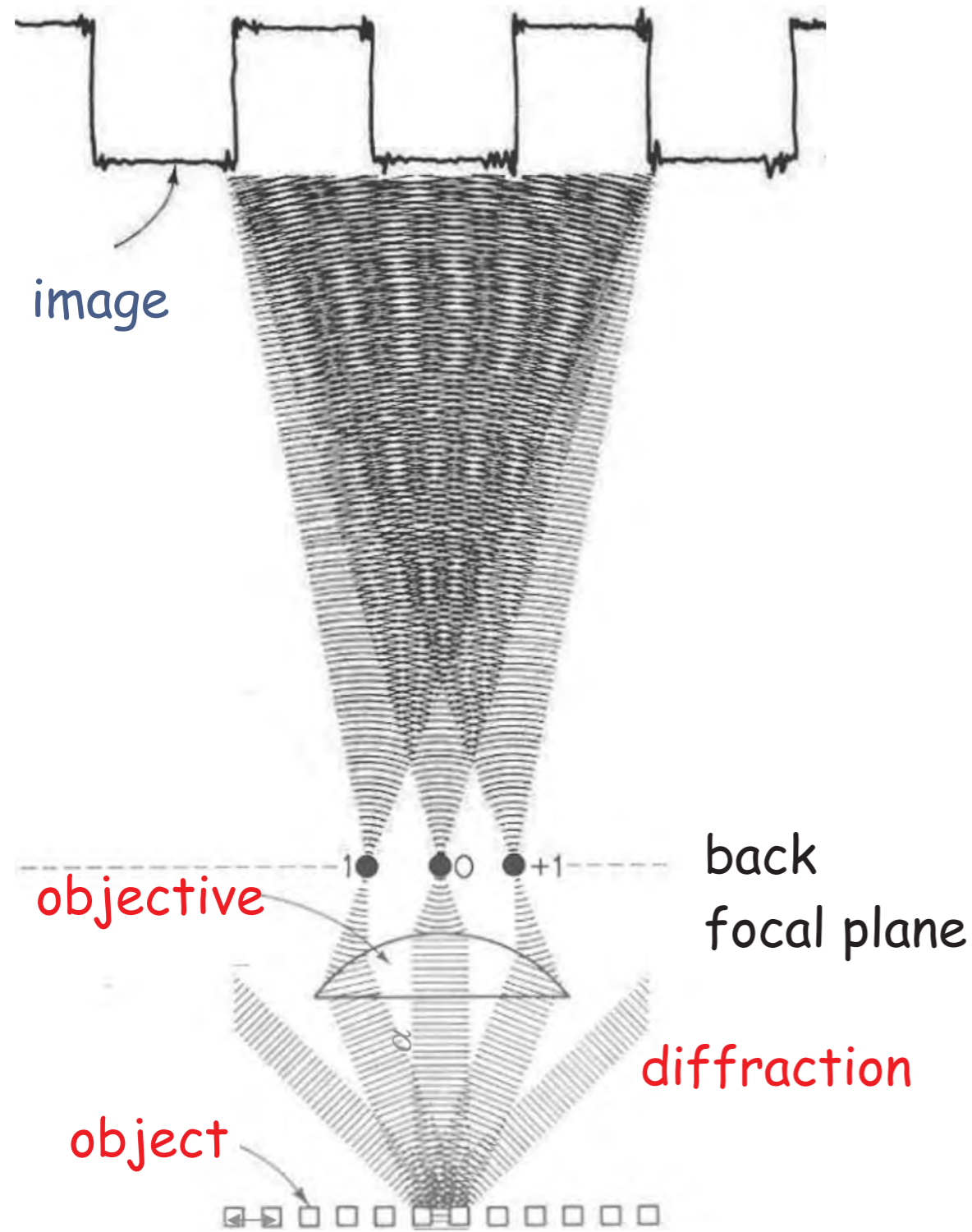
Comparison of Domain Observation Techniques



MFM: Magnetic Force Microscopy
SPT: Spin-Polarized Tunneling

SEM: Scanning (reflection) Electron Microscopy
TEM: Transmission Electron Microscopy

Resolution of Kerr microscopy



Resolution determined by
constructive interference

Diffraction-limited image formation

Rayleigh equation: $d = \frac{0.5 \lambda}{NA}$

d = separation between particles,
still allowing to see them

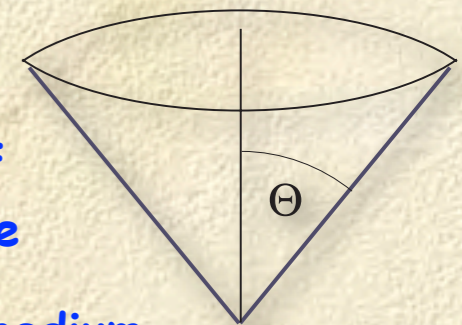
λ = wavelength

NA = numerical aperture of objective

$NA = n \sin\theta$

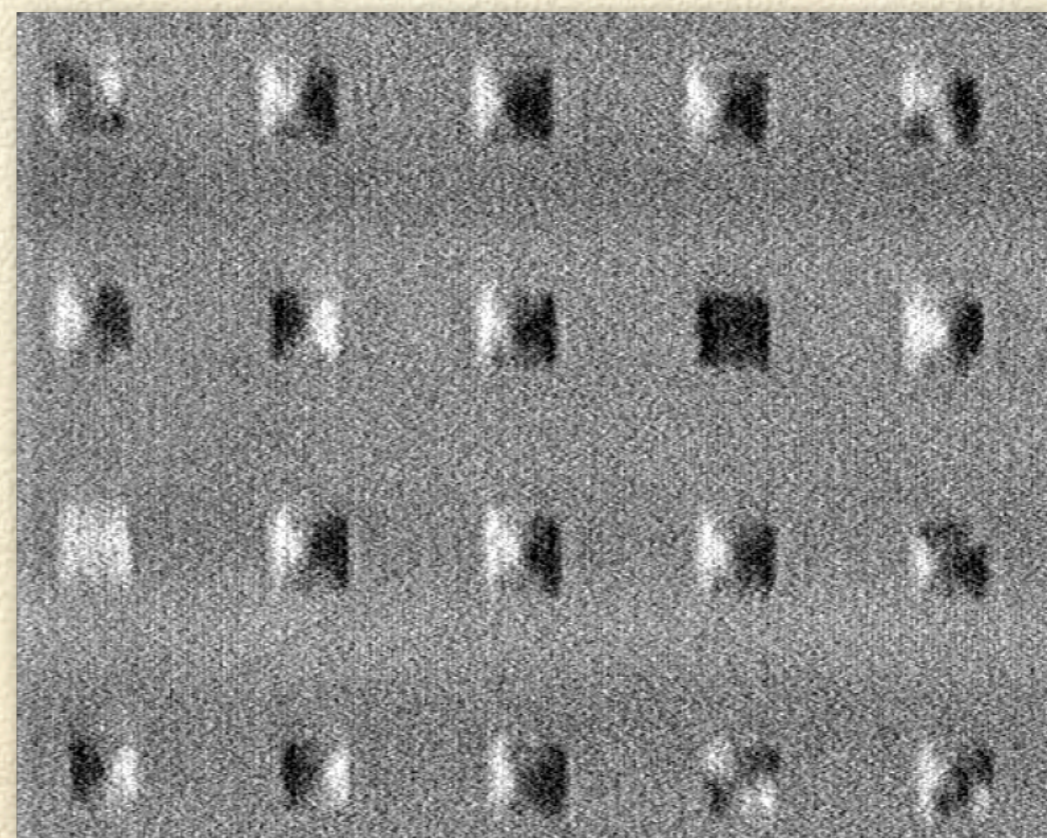
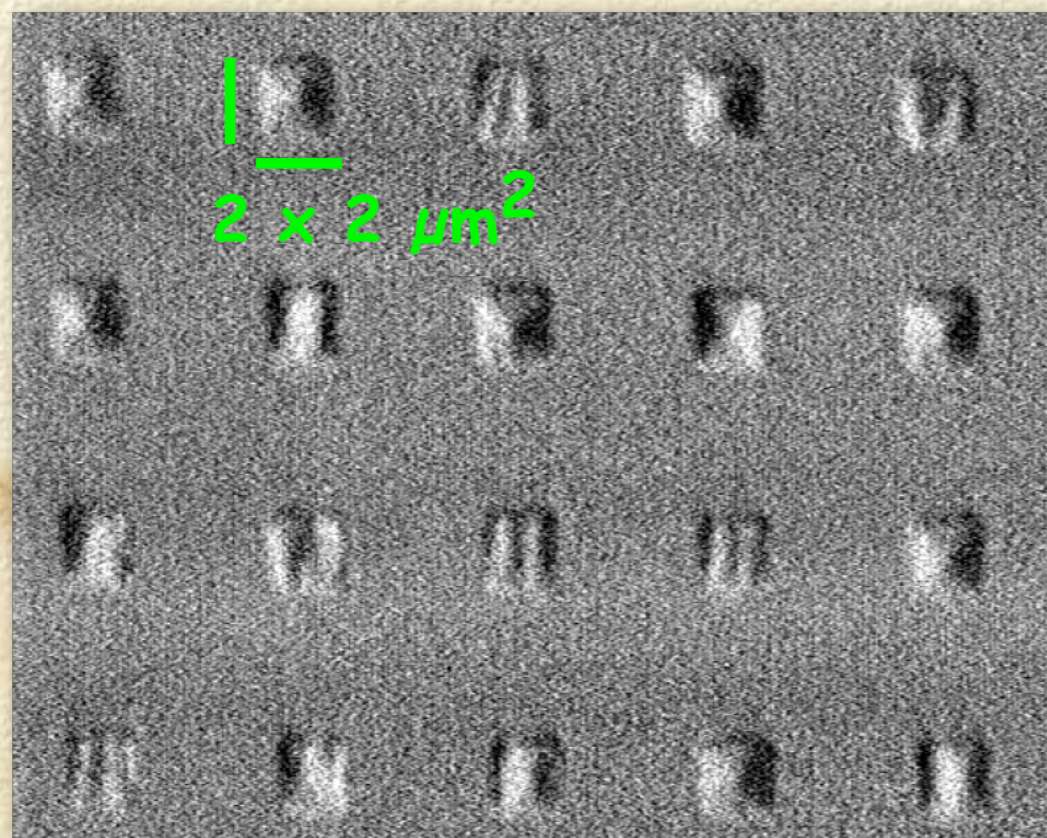
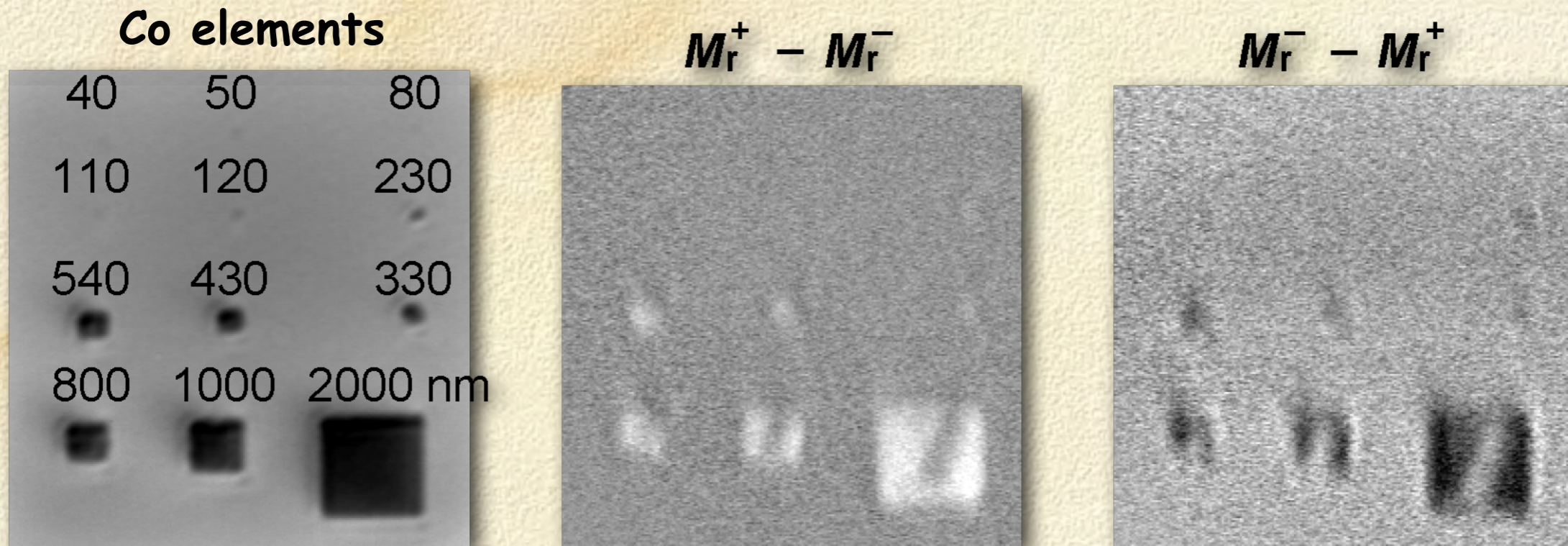
θ = half the cone angle of
light accepted by objective

n = refraction index of medium
between sample and objective



Best around 200-300 nm

Resolution of Kerr microscopy



H_{demag}

H_{demag}

(sample: Axel Carl, Duisburg)

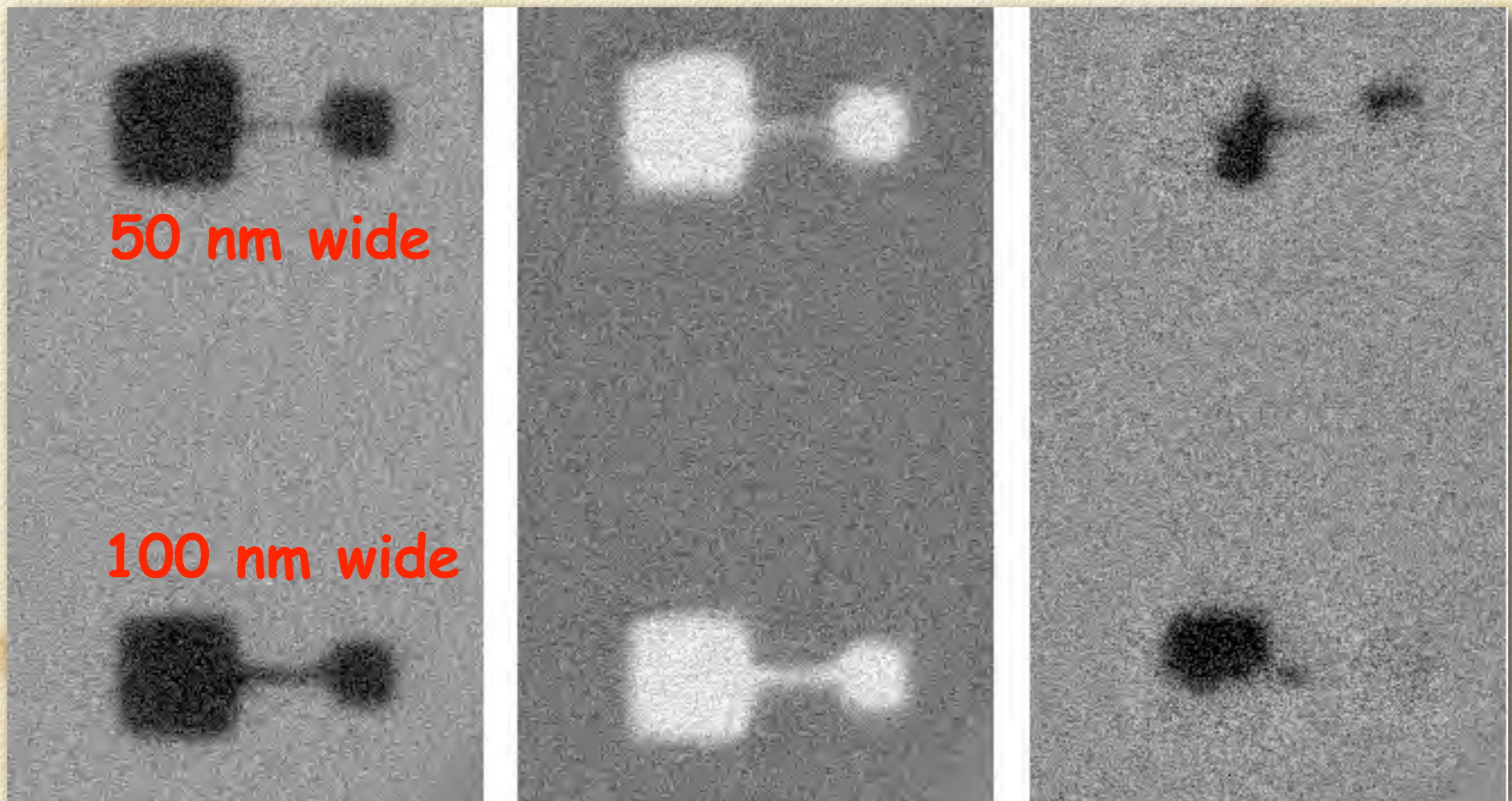
Resolution of Kerr microscopy

Nanowires (2 μm long) of magnetic film system with perpendicular anisotropy

Positive remanence

Negative remanence

Demagnetized



sample courtesy

Jimmy Zhu and Matt Moneck, Carnegie Mellon University, Pittsburgh

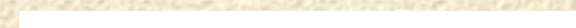
Ultra-high-resolution Kerr microscopy

FePt layer (16 nm thick),
sample courtesy P. He and S.M. Zhou, Fudan



Magnetic field

10 μm



Ultra-high-resolution Kerr microscopy

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Magnetic field

10 μm



Ultra-high-resolution Kerr microscopy

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1 μm

Ultra-high-resolution Kerr microscopy

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sample courtesy P. He and S.M. Zhou, Fudan

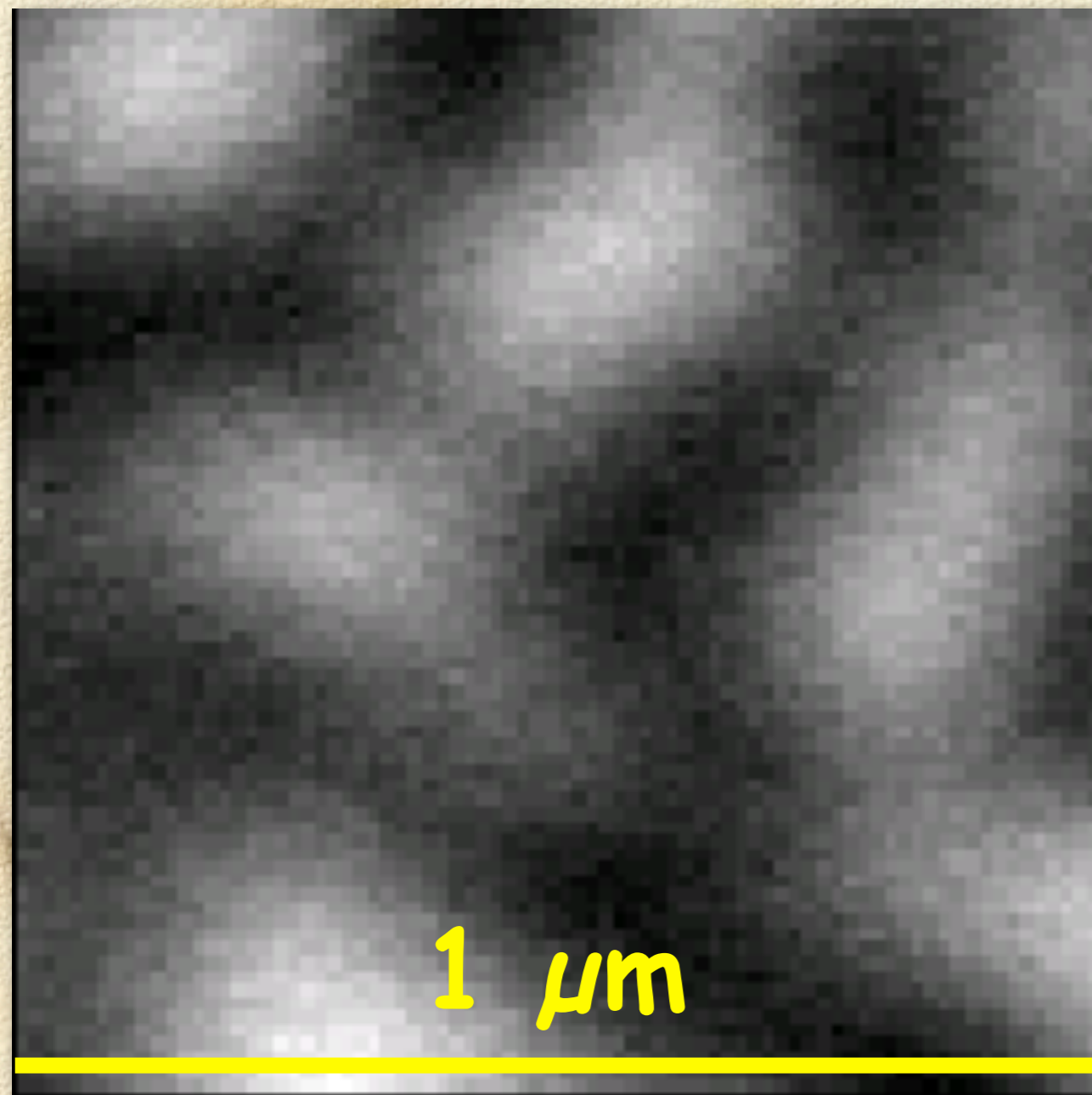


Image is folded by point-spread-function of microscope
→ loss of information
→ recovery of lost information by mathematical deconvolution
→ enhancement of resolution down to 50 nm regime

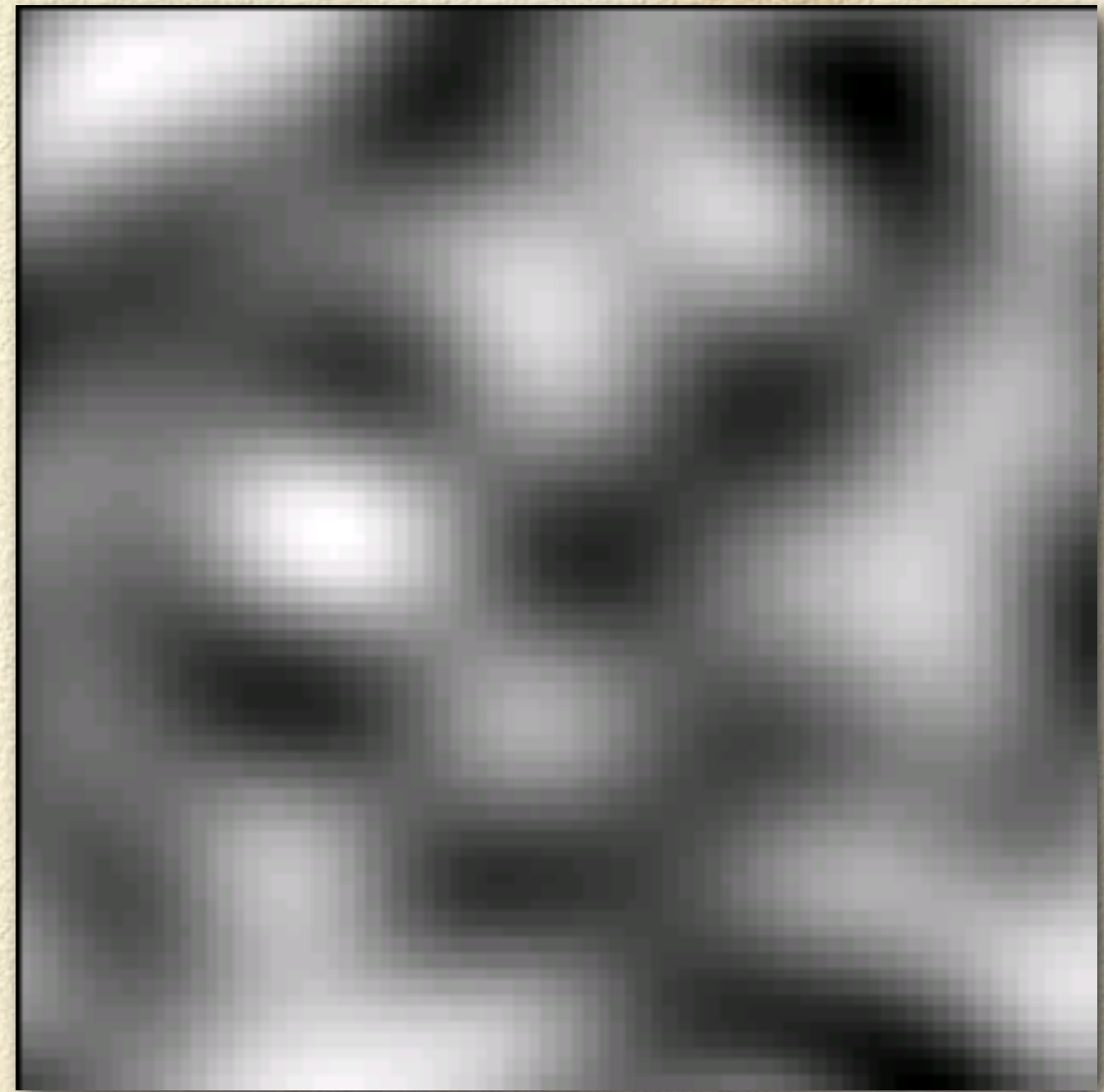
together with
N.Gorn & D.Berkov, Innovent Jena
(under development)

Ultra-high-resolution Kerr microscopy

FePt layer (16 nm thick),
sample courtesy P. He and S.M. Zhou, Fudan



1 μm



together with
N.Gorn & D.Berkov, Innovent Jena
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Ultra-high-resolution Kerr microscopy

Sample courtesy M. Shibihan and S.M. Zhou,
Tongji University (Shanghai)

FePd (15 nm)

FePt (20 nm)



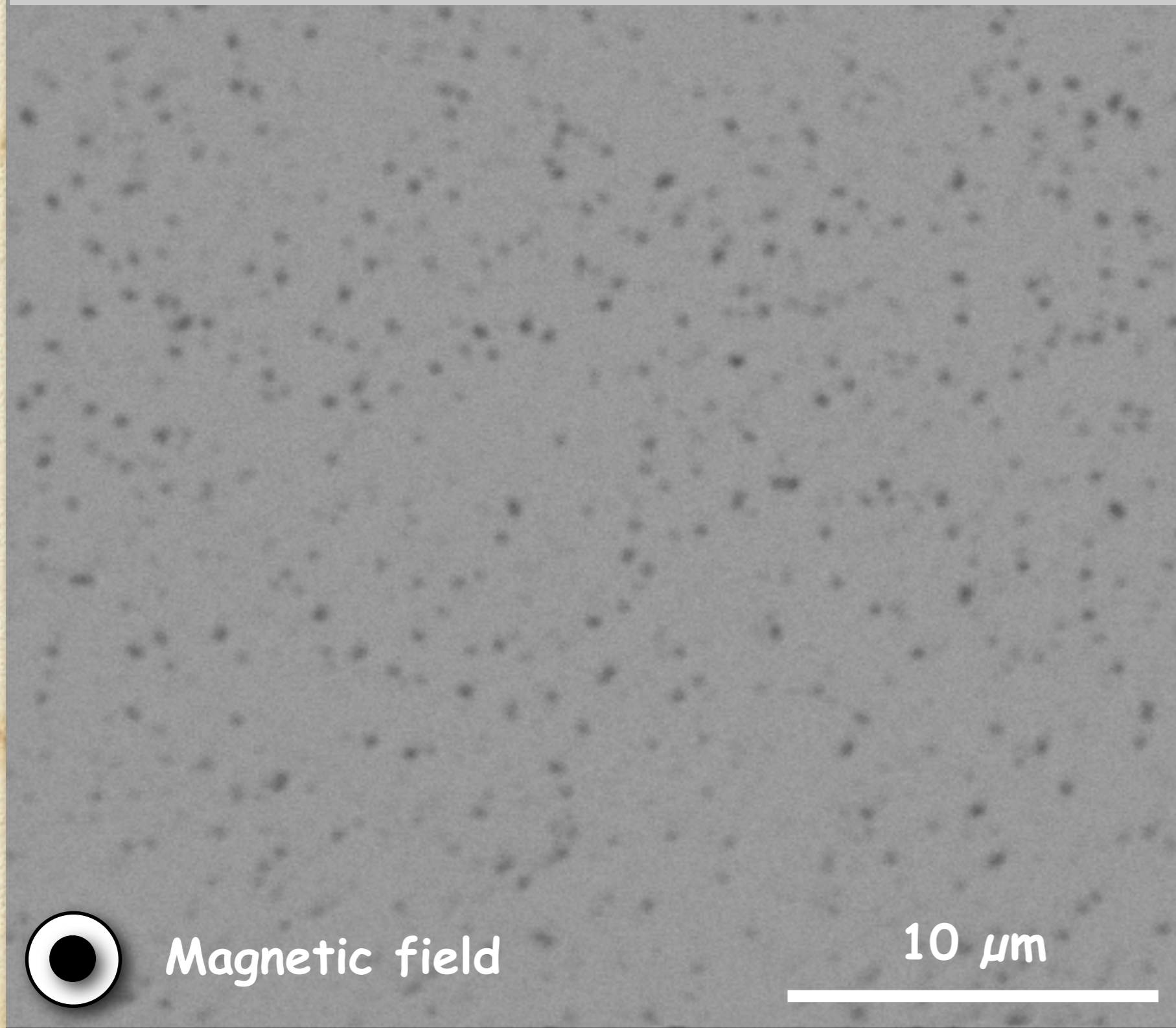
Magnetic field

10 μm



Ultra-high-resolution Kerr microscopy

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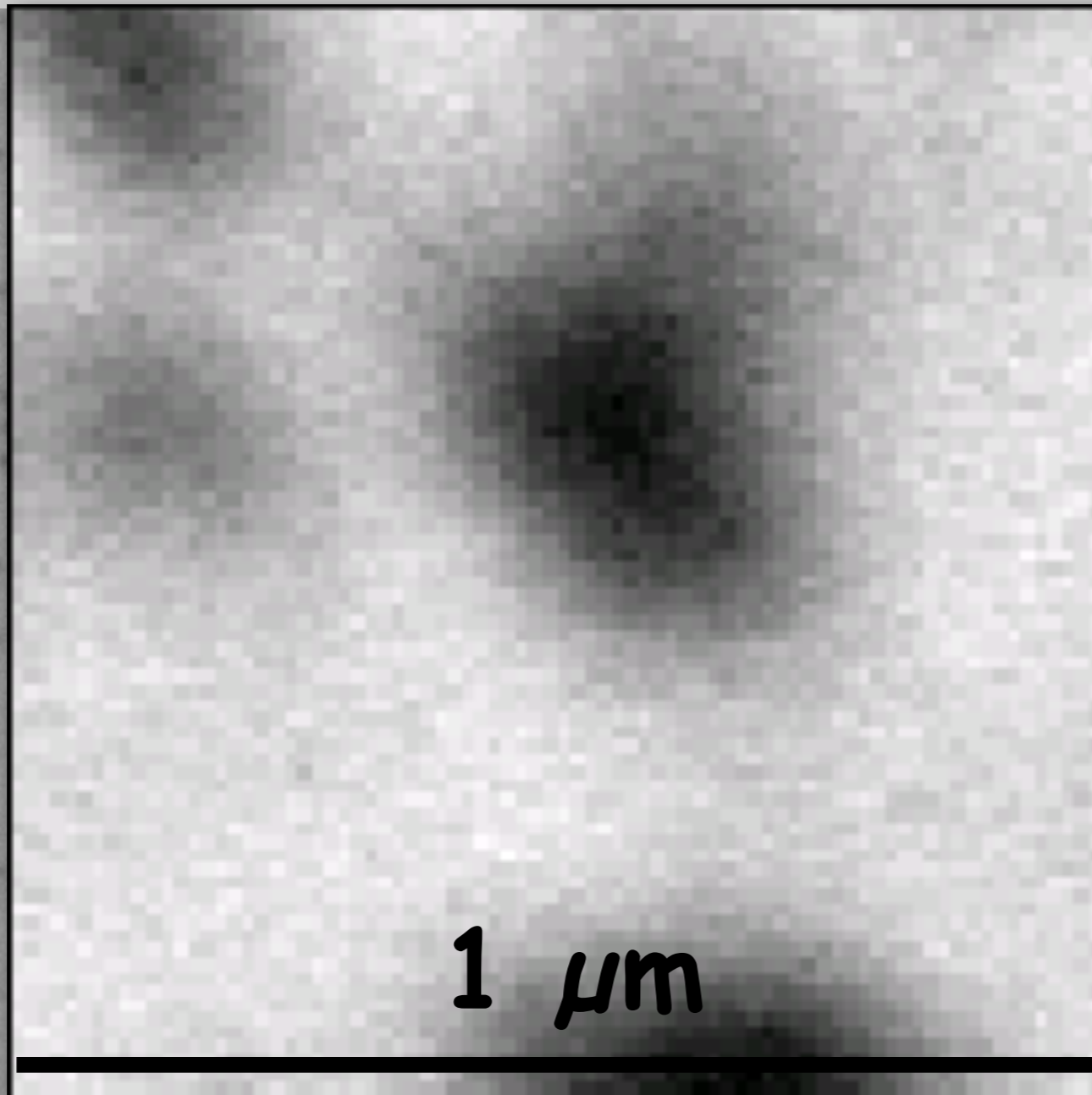


Magnetic field

10 μm

Ultra-high-resolution Kerr microscopy

Sample courtesy M. Shibihan and S.M. Zhou,
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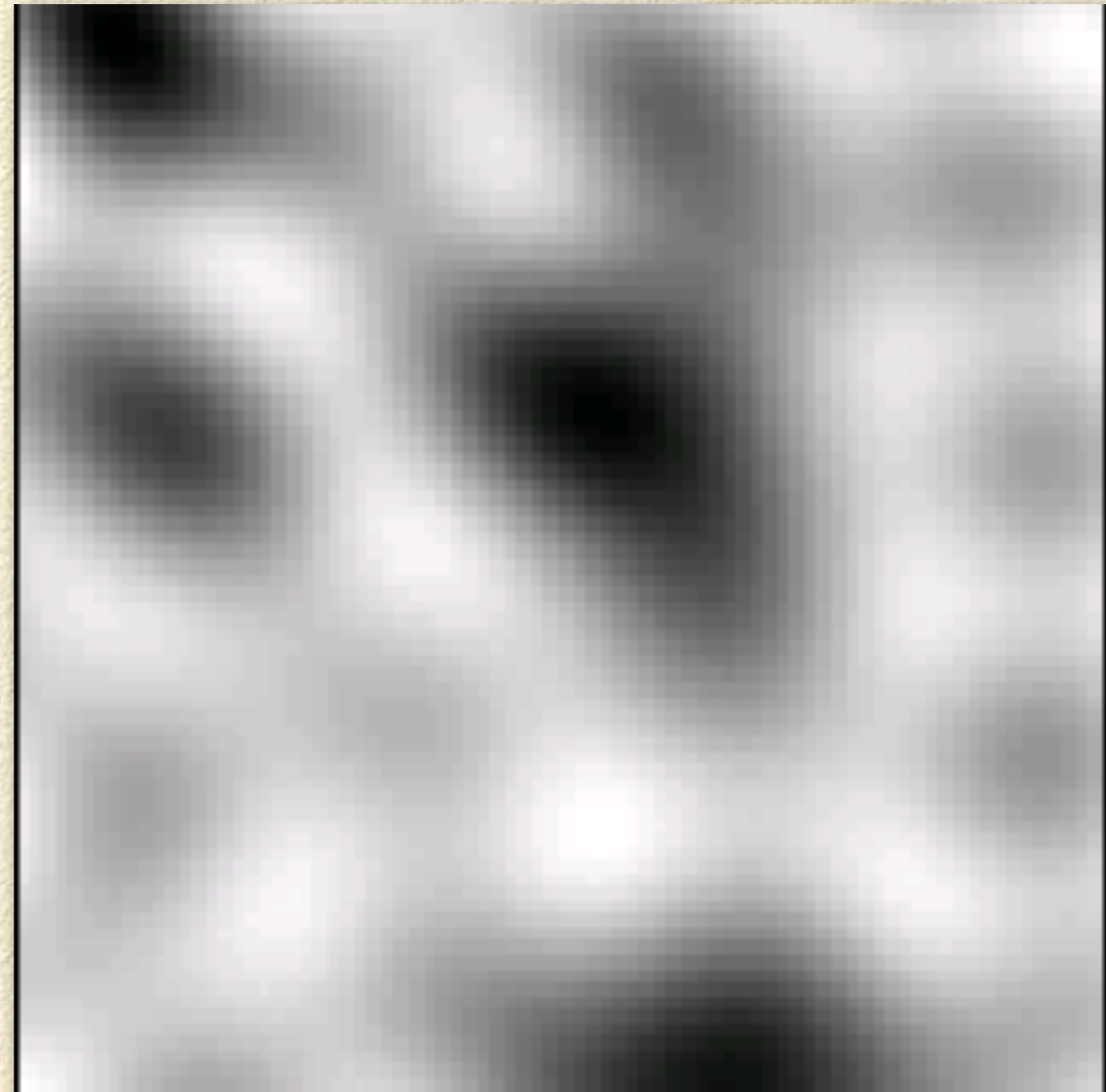
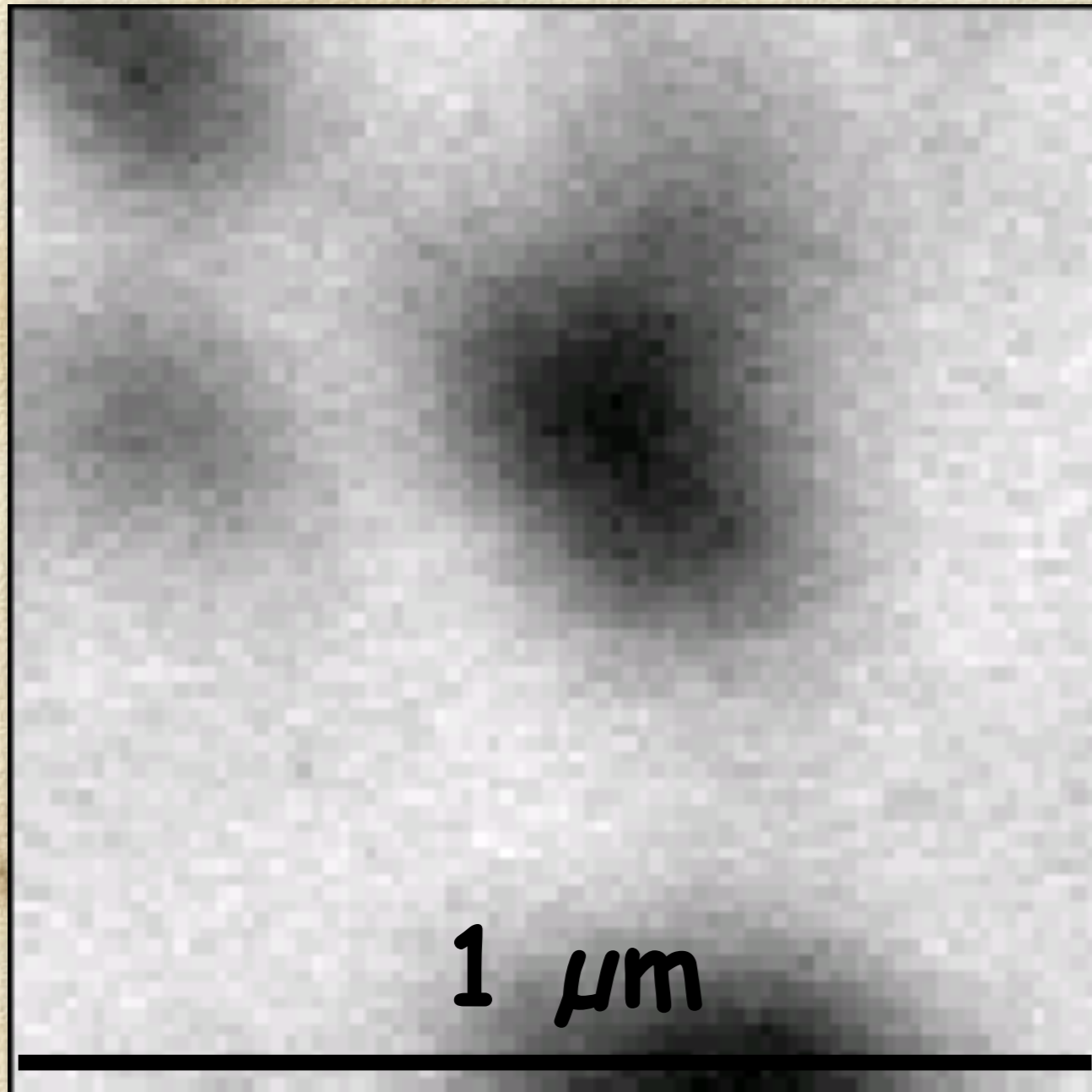
Magnetic field

10 μm



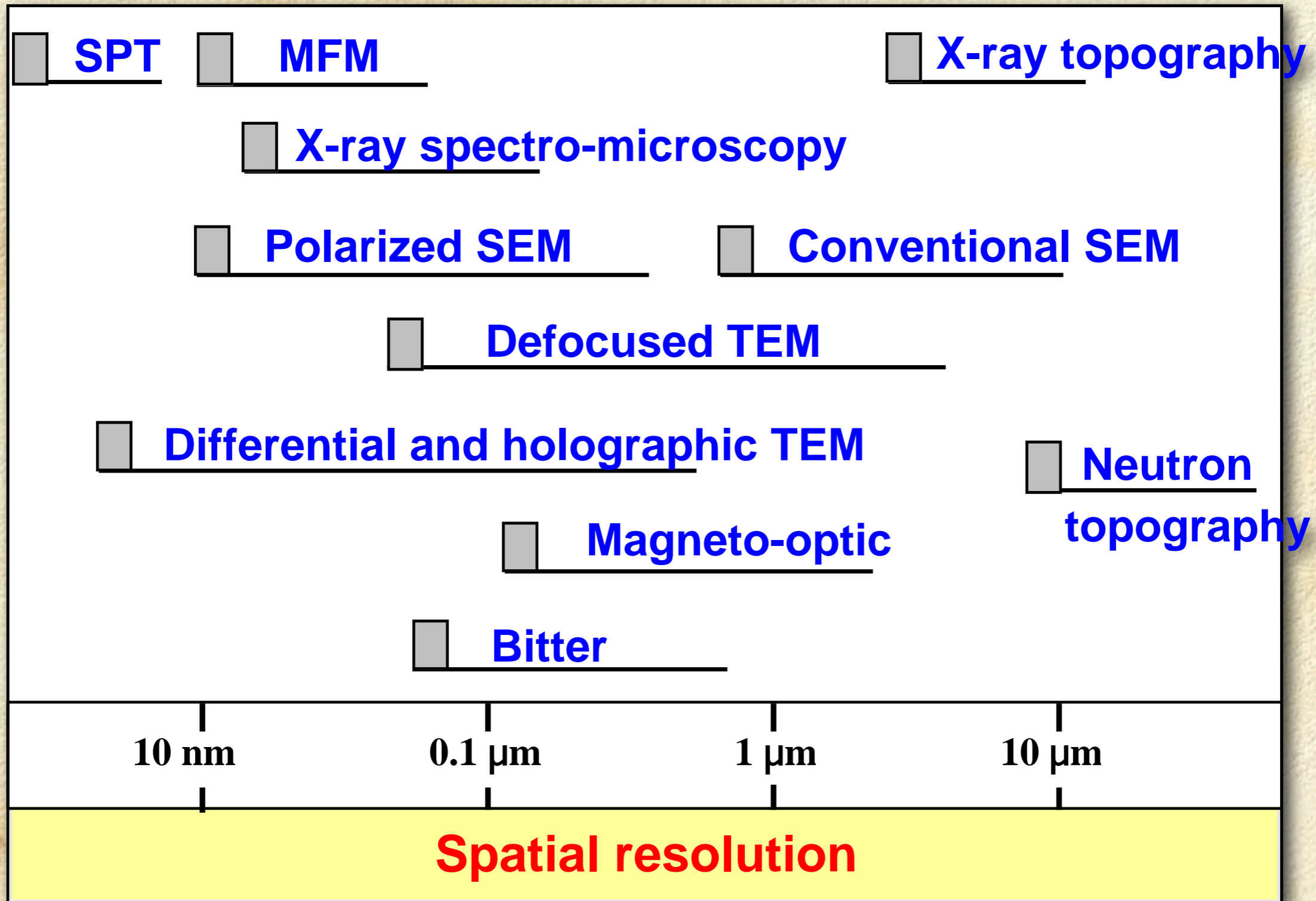
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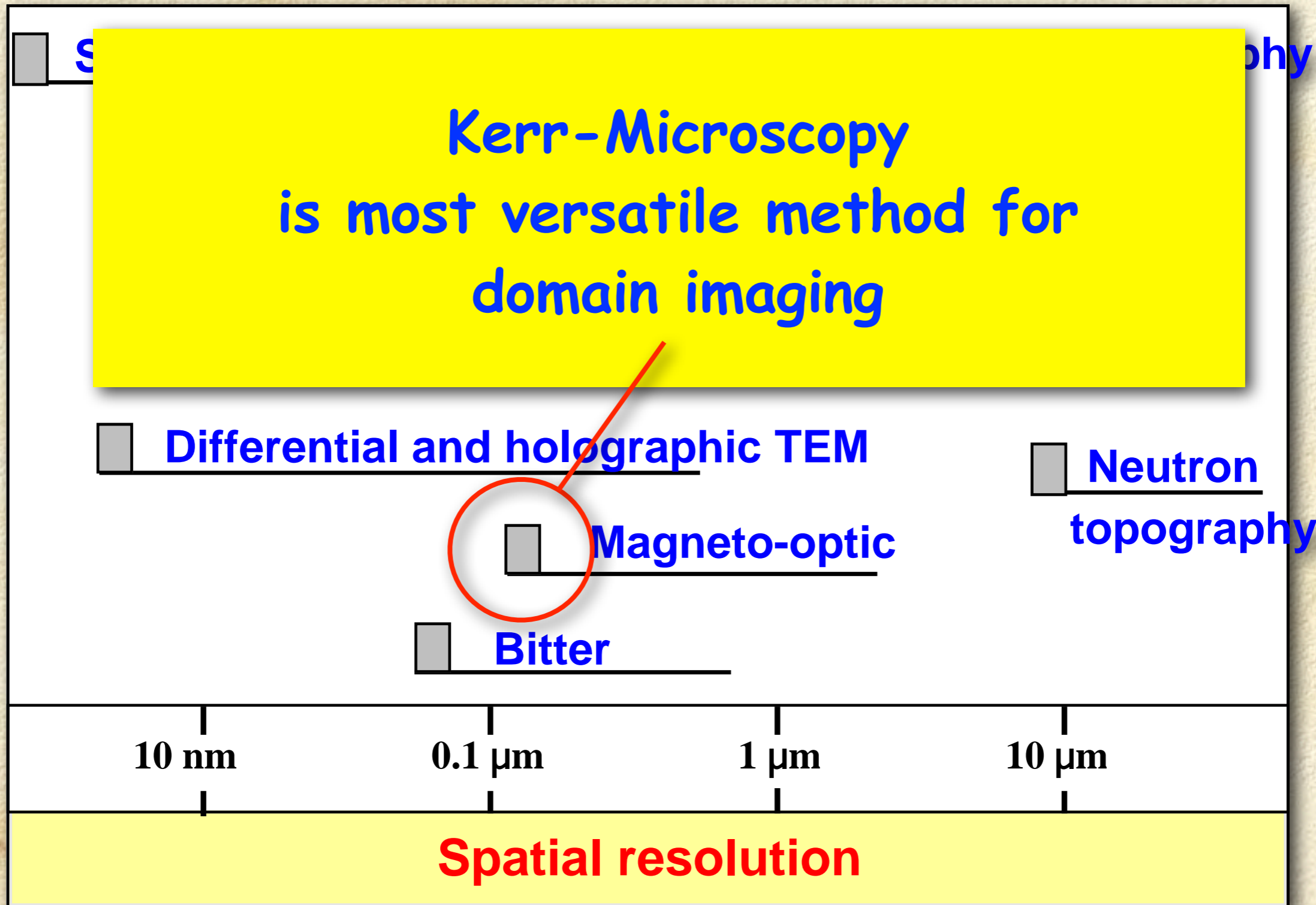
Comparison of Domain Observation Techniques



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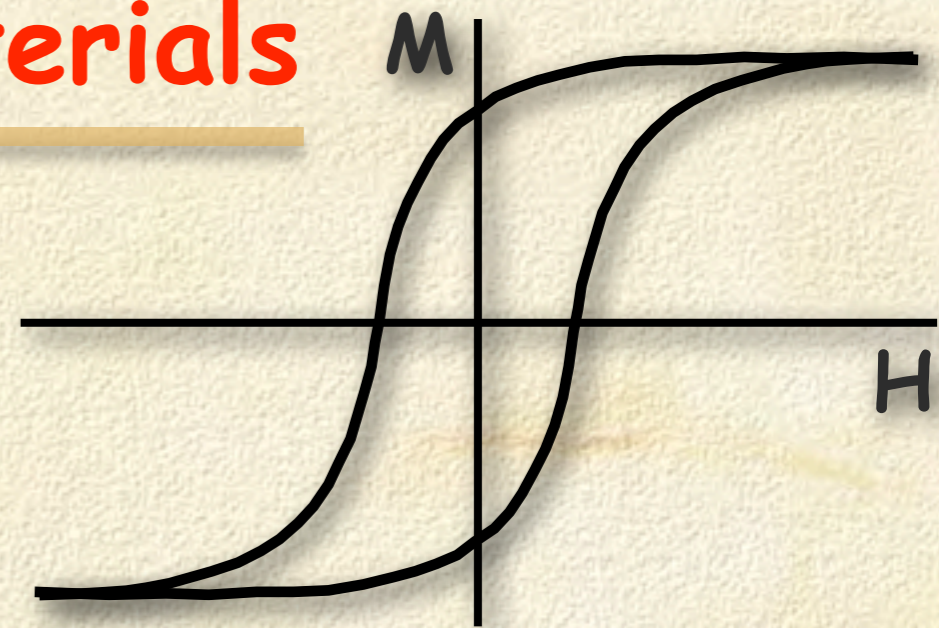


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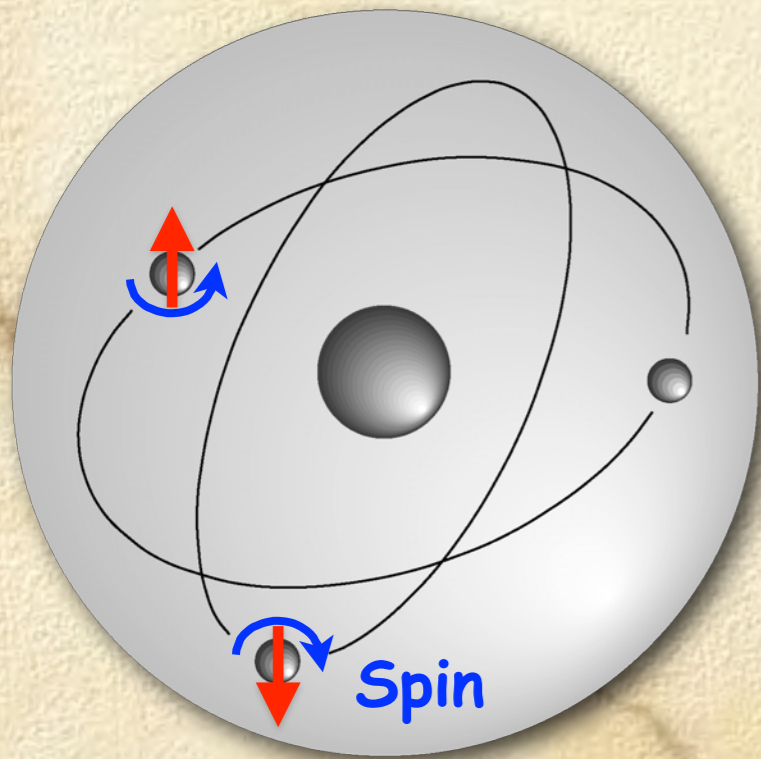
SEM: Scanning (reflection) Electron Microscopy
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**Why
magnetic microstructure
analysis?**

Descriptive levels of magn. materials

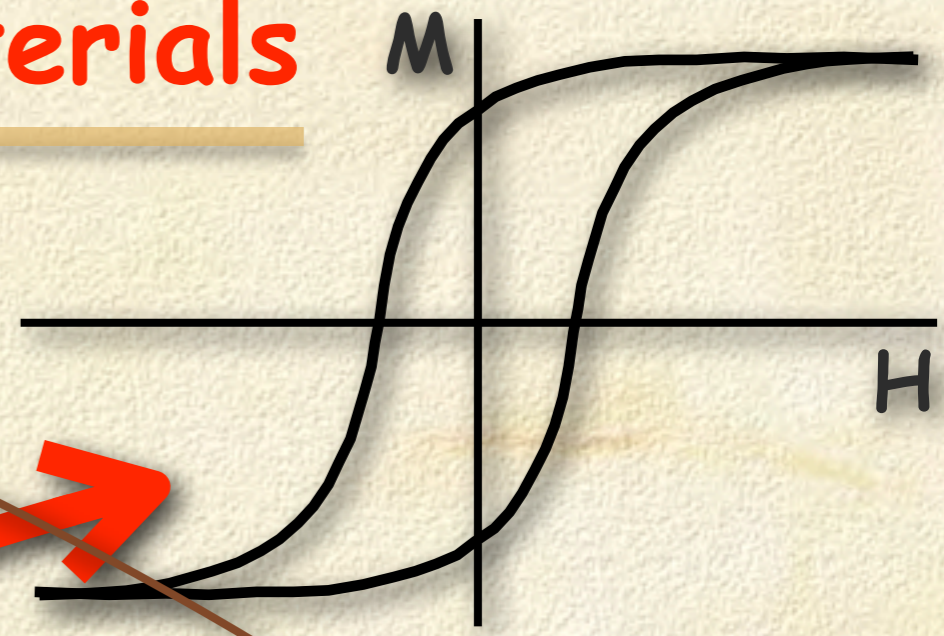


5. Magnetization curve



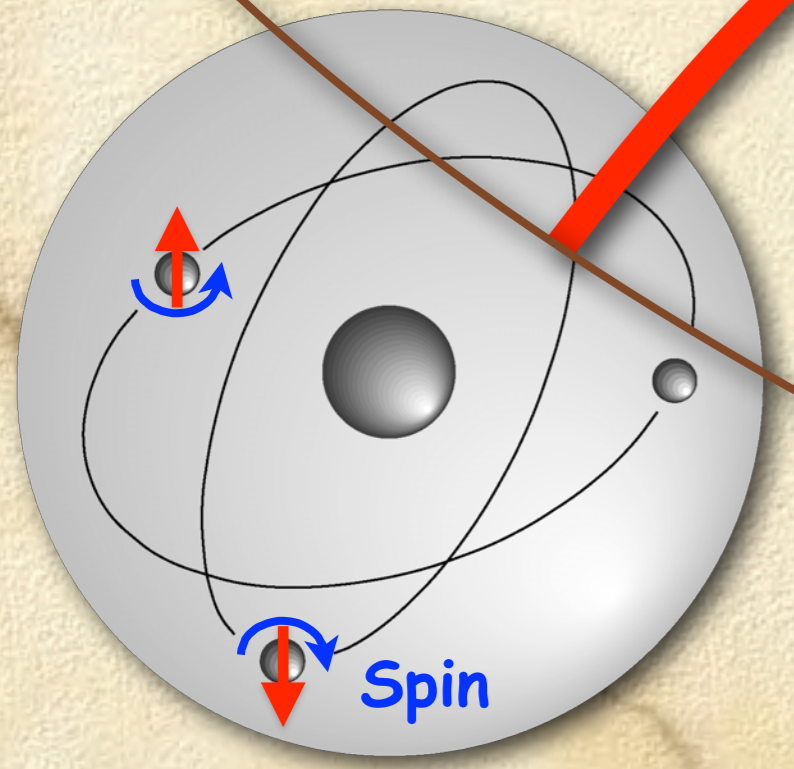
1. Atomic Level Theory

Descriptive levels of magn. materials



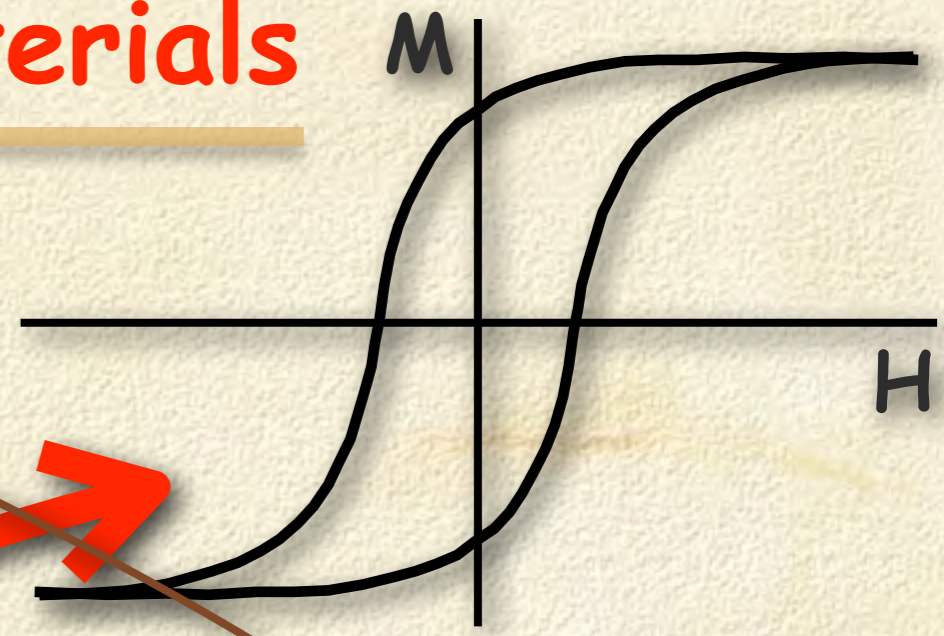
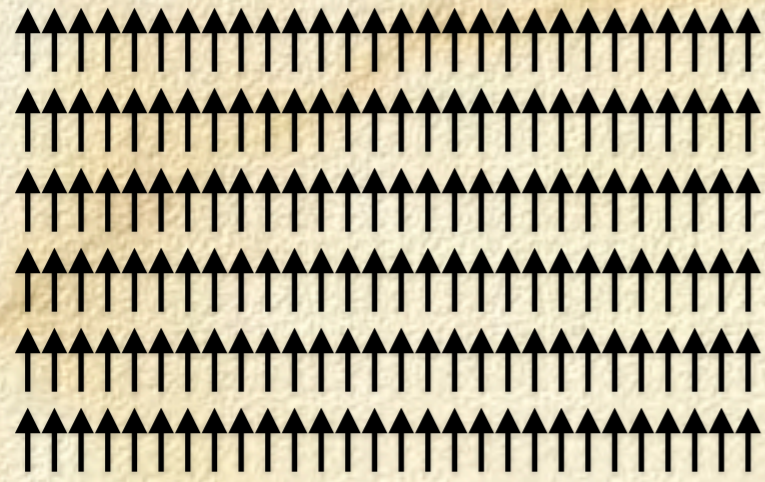
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Magnetic Microstructure Analysis



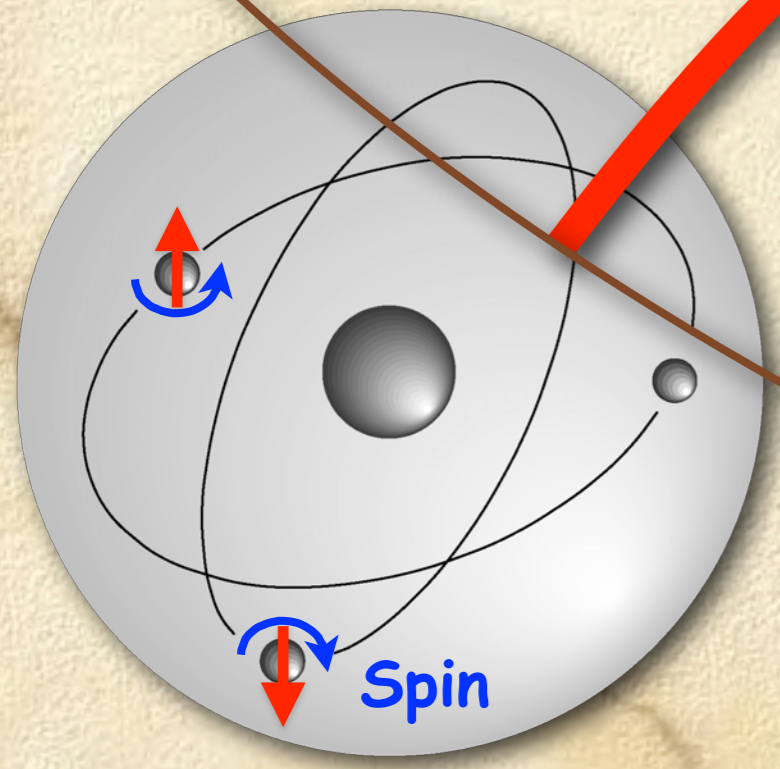
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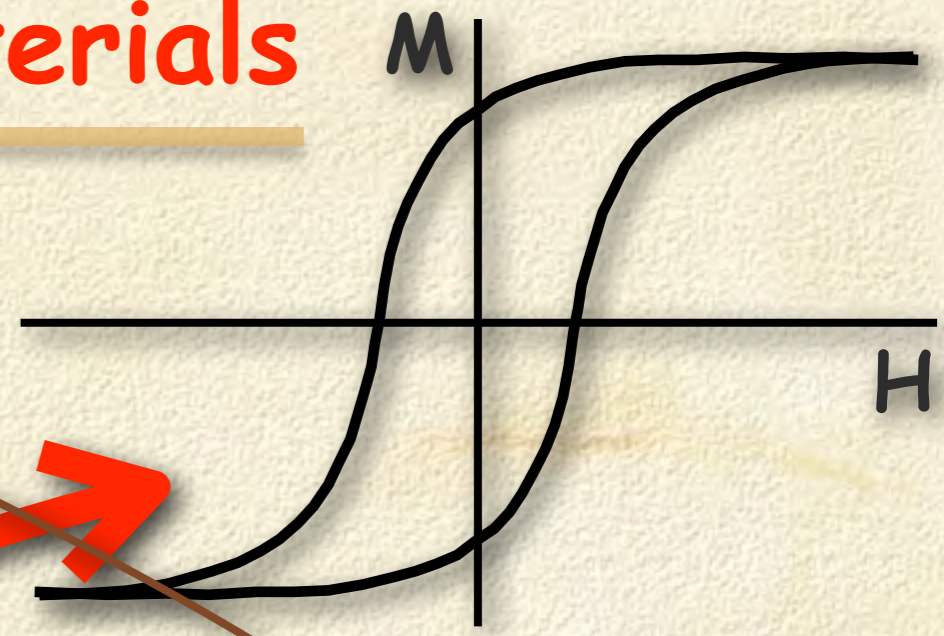
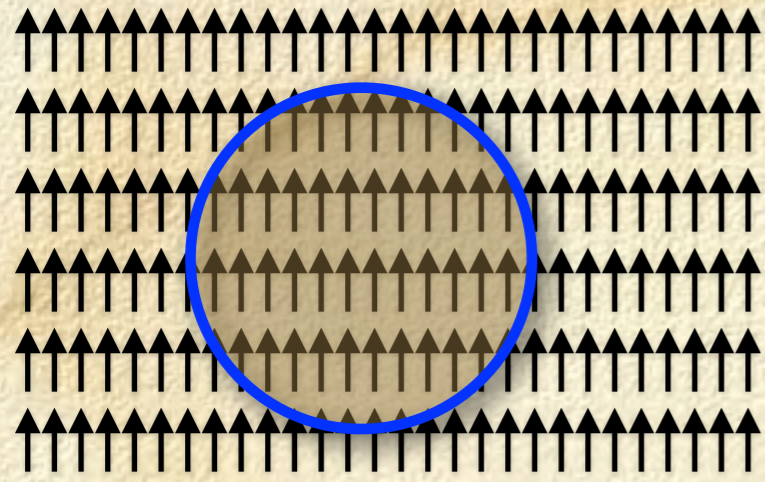
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Magnetic Microstructure Analysis



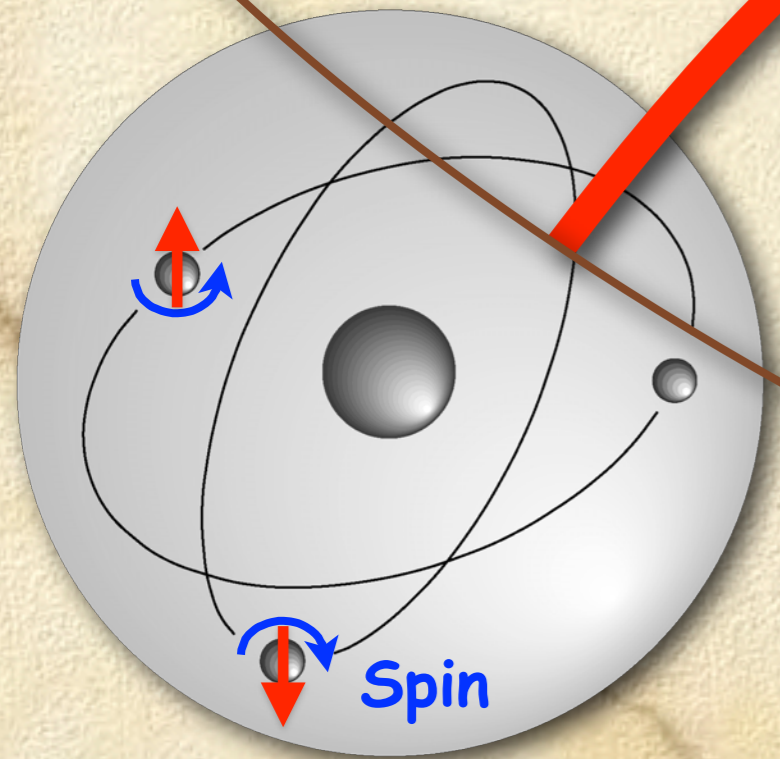
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Descriptive levels of magn. materials



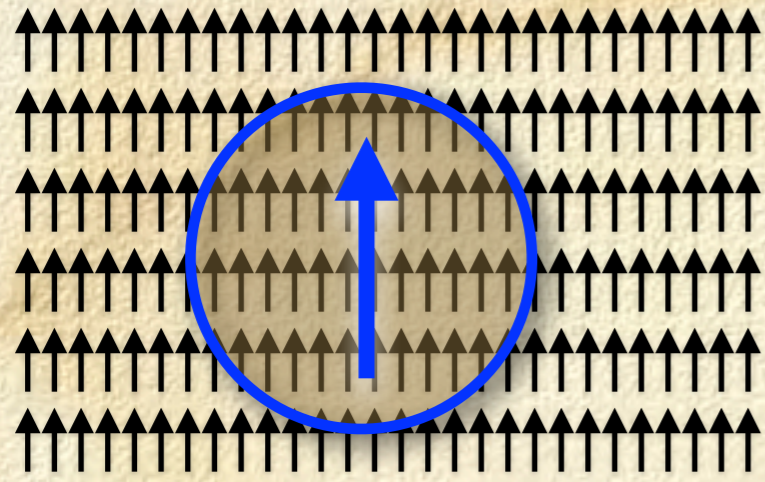
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Magnetic Microstructure Analysis

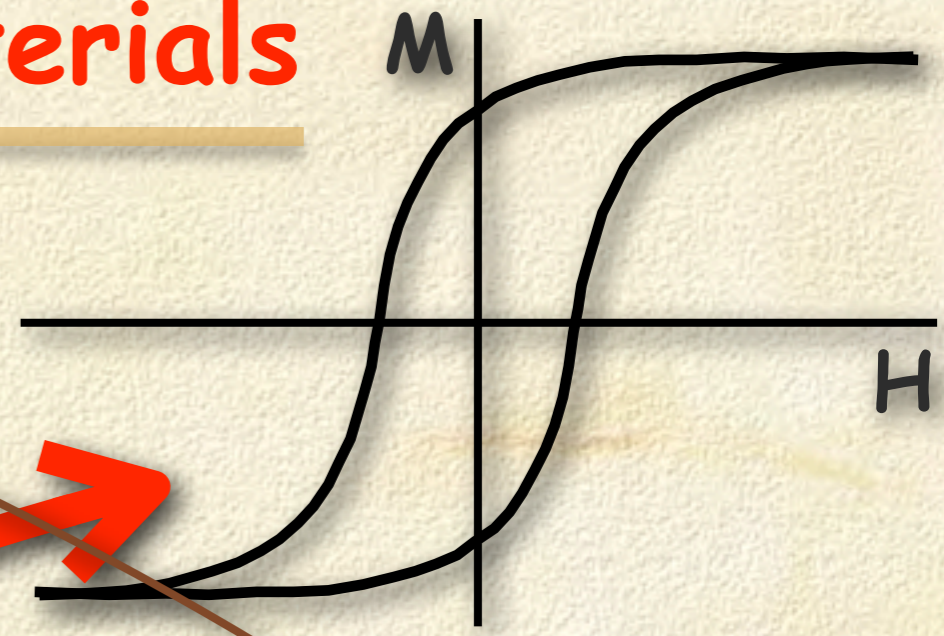


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Descriptive levels of magn. materials

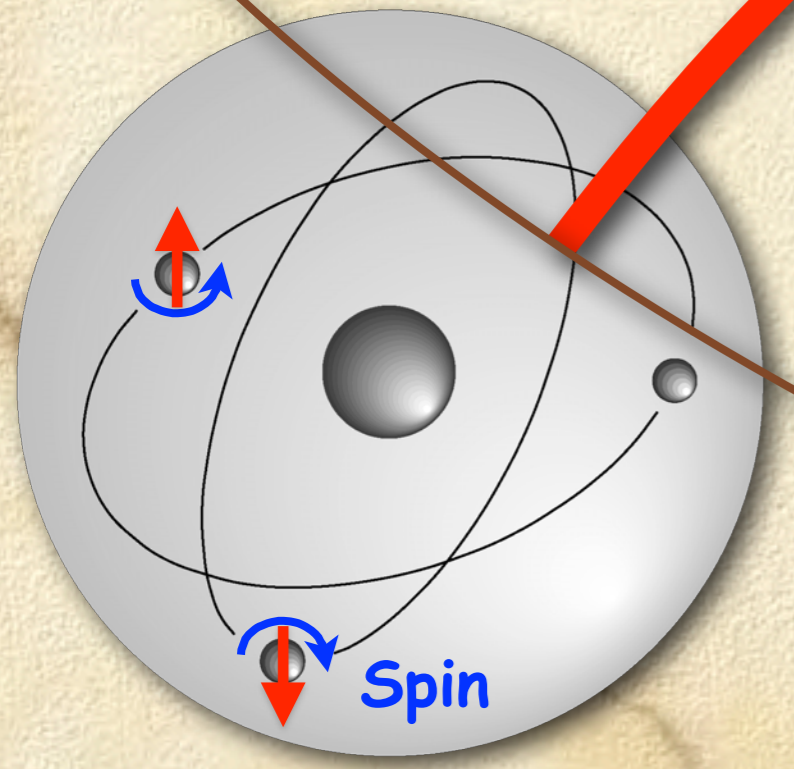


$$m = M/M_s$$



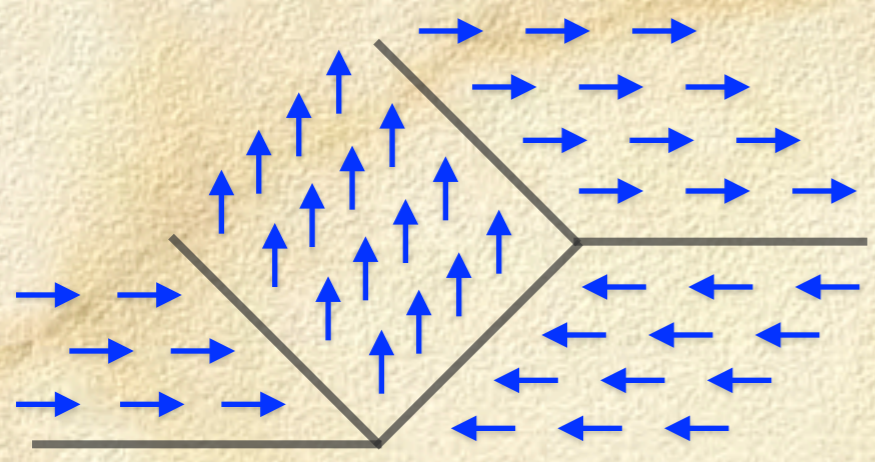
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Magnetic Microstructure Analysis

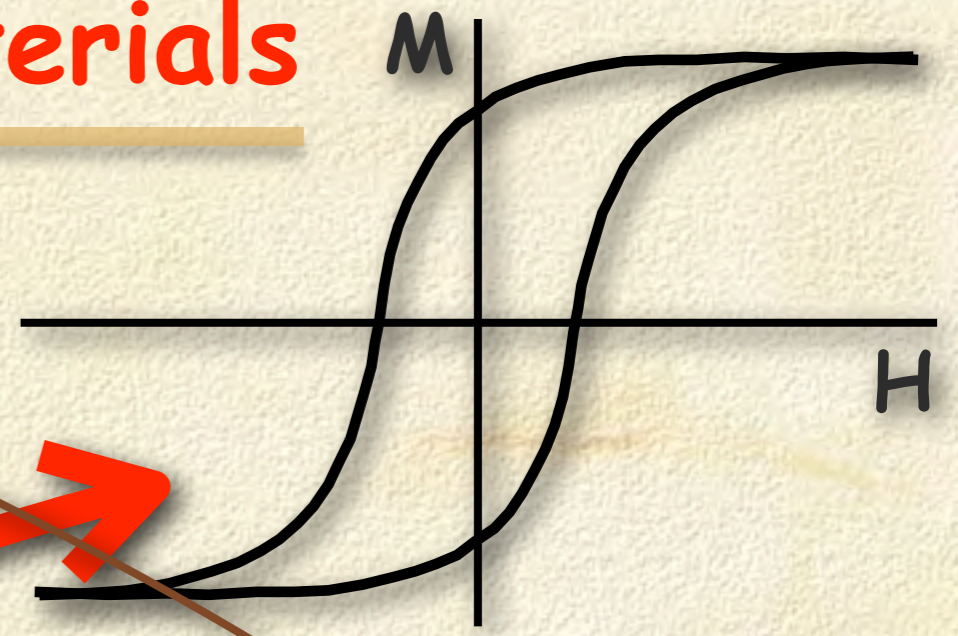


1. Atomic Level Theory

Descriptive levels of magn. materials

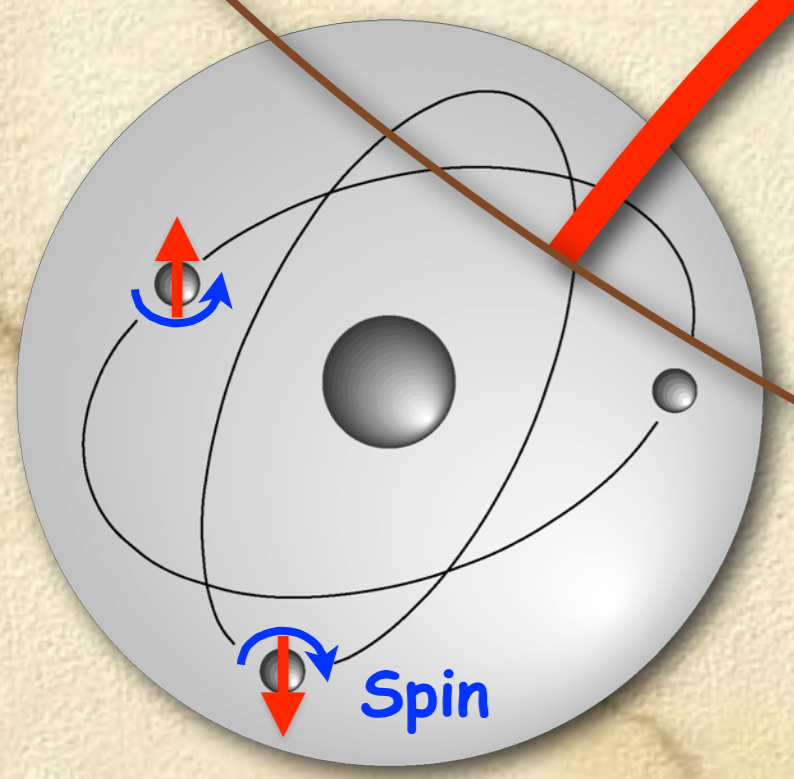


$m(r), m^2 = 1$



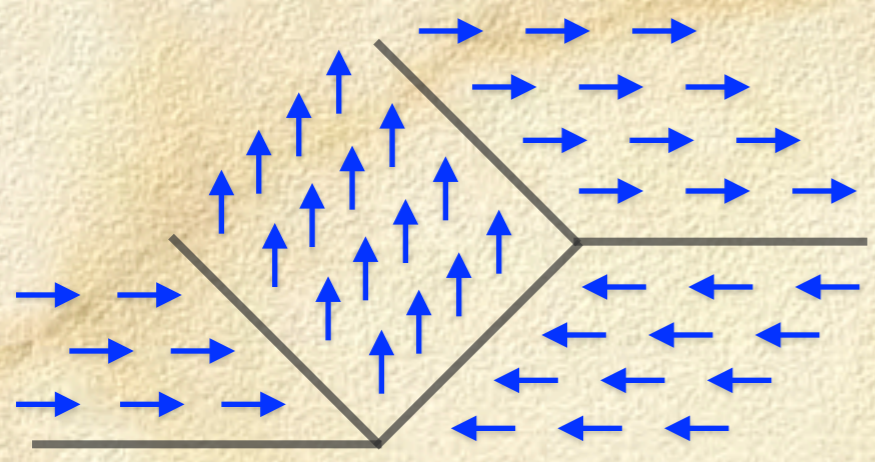
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Magnetic Microstructure Analysis

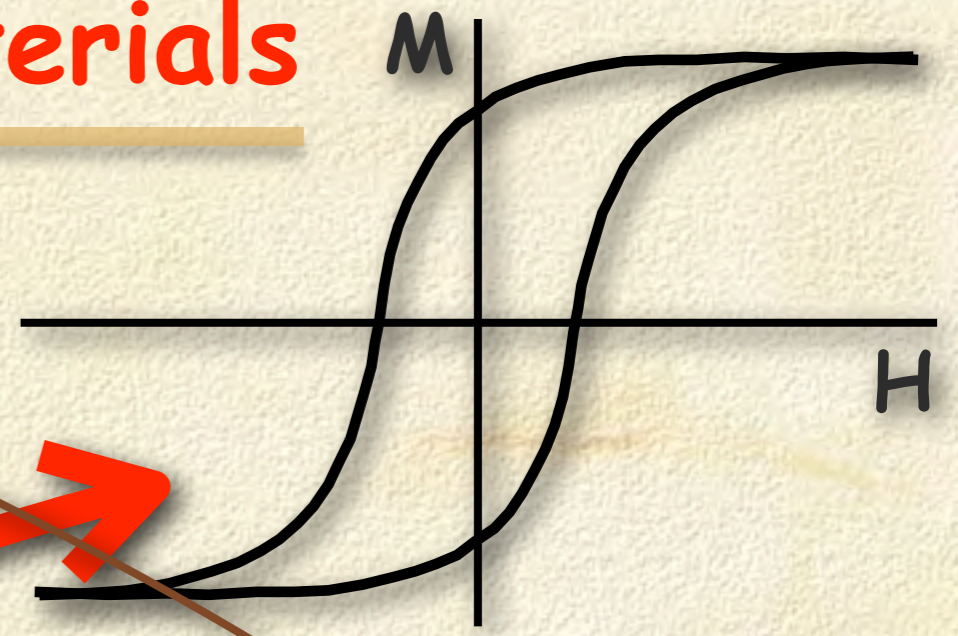


1. Atomic Level Theory

Descriptive levels of magn. materials

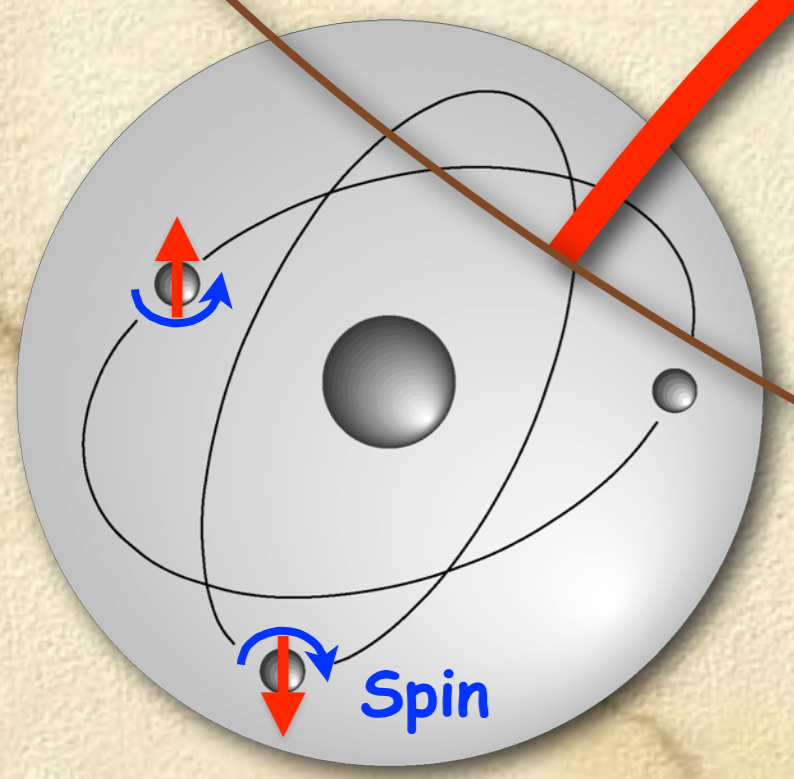


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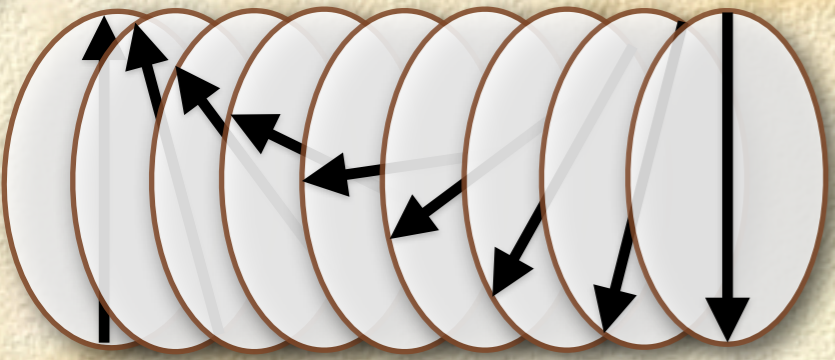
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Magnetic Microstructure Analysis

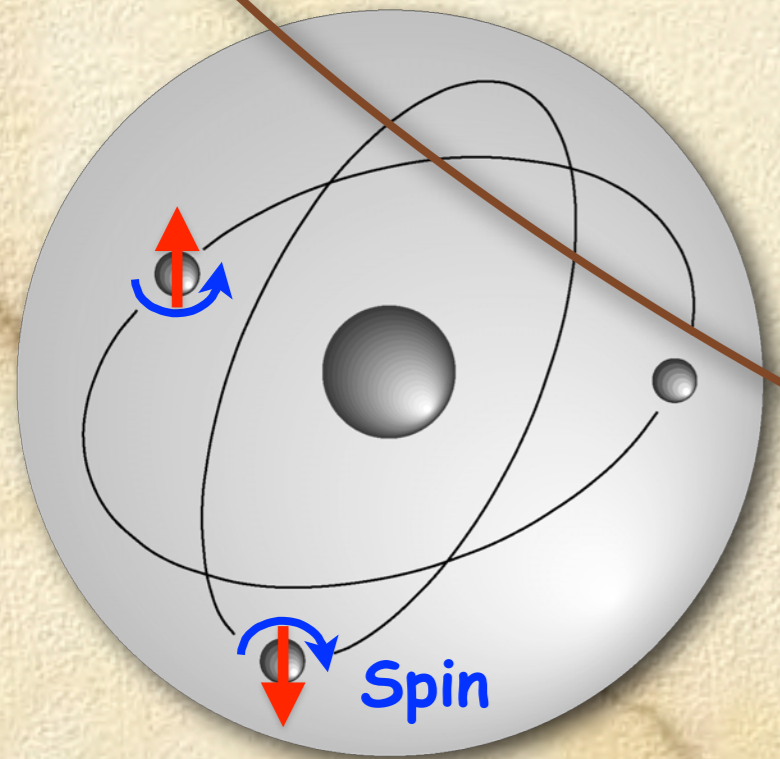


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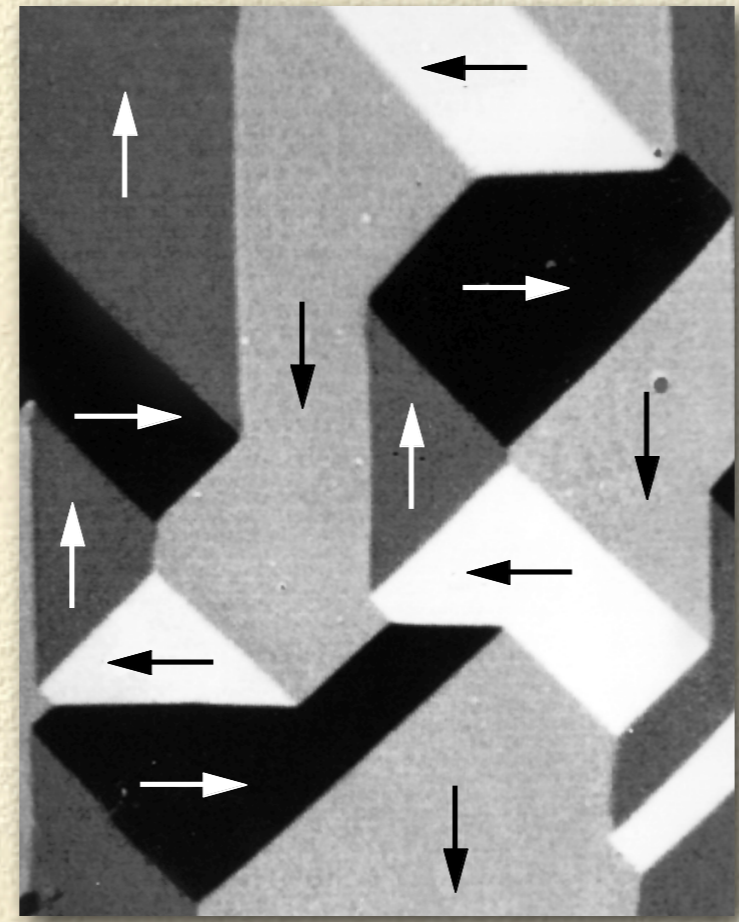
Descriptive levels of magn. materials



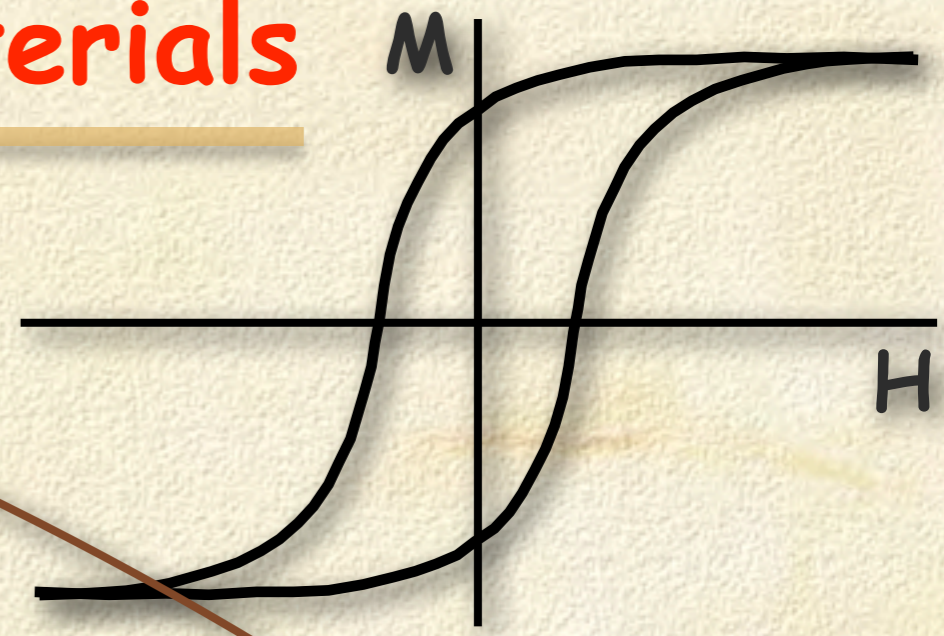
2. Micromagnetic Analysis



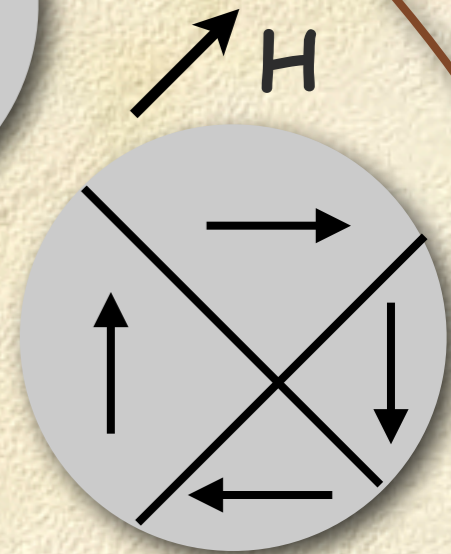
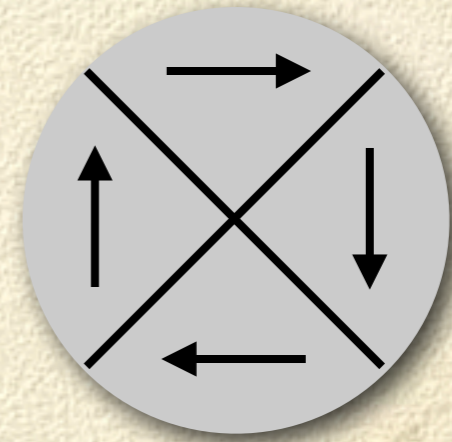
1. Atomic Level Theory



3. Domain Analysis

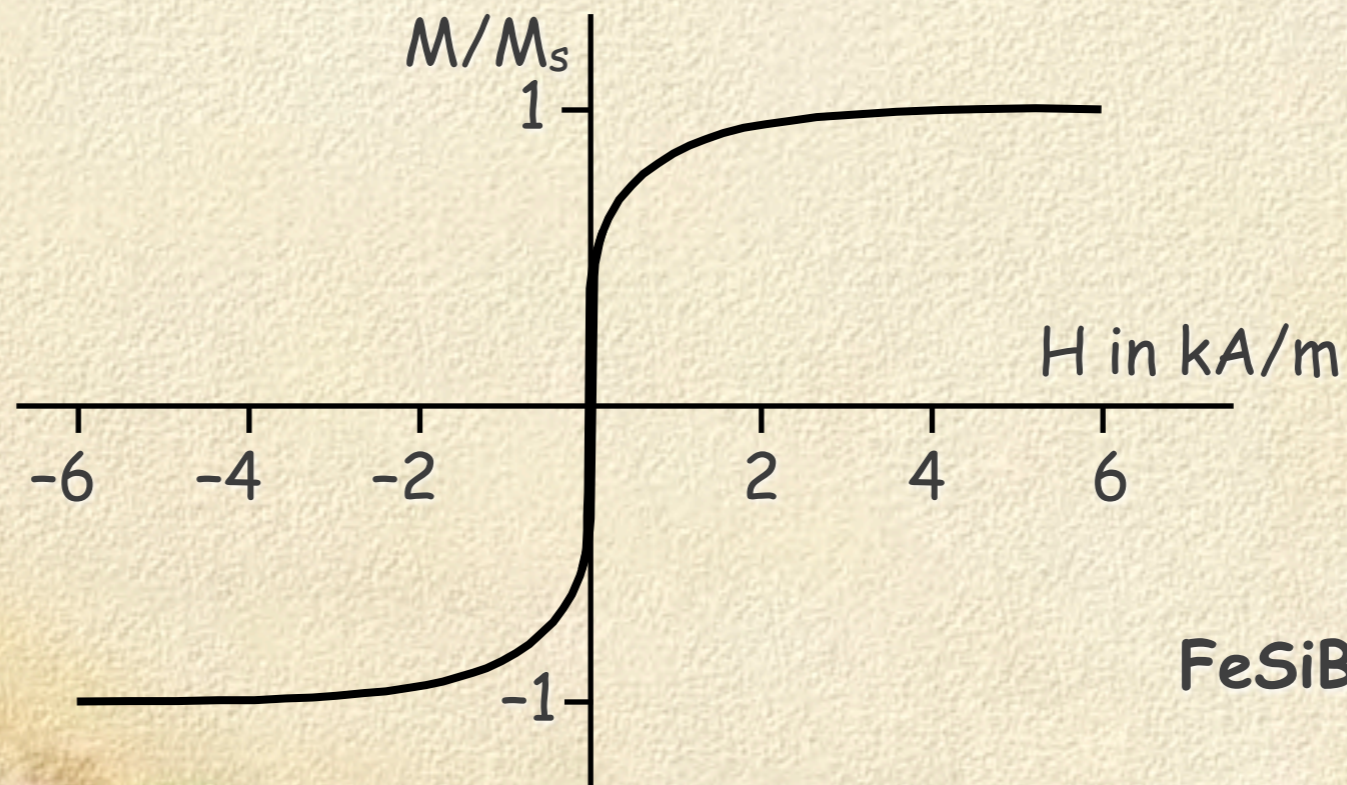
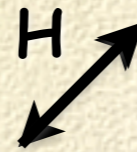
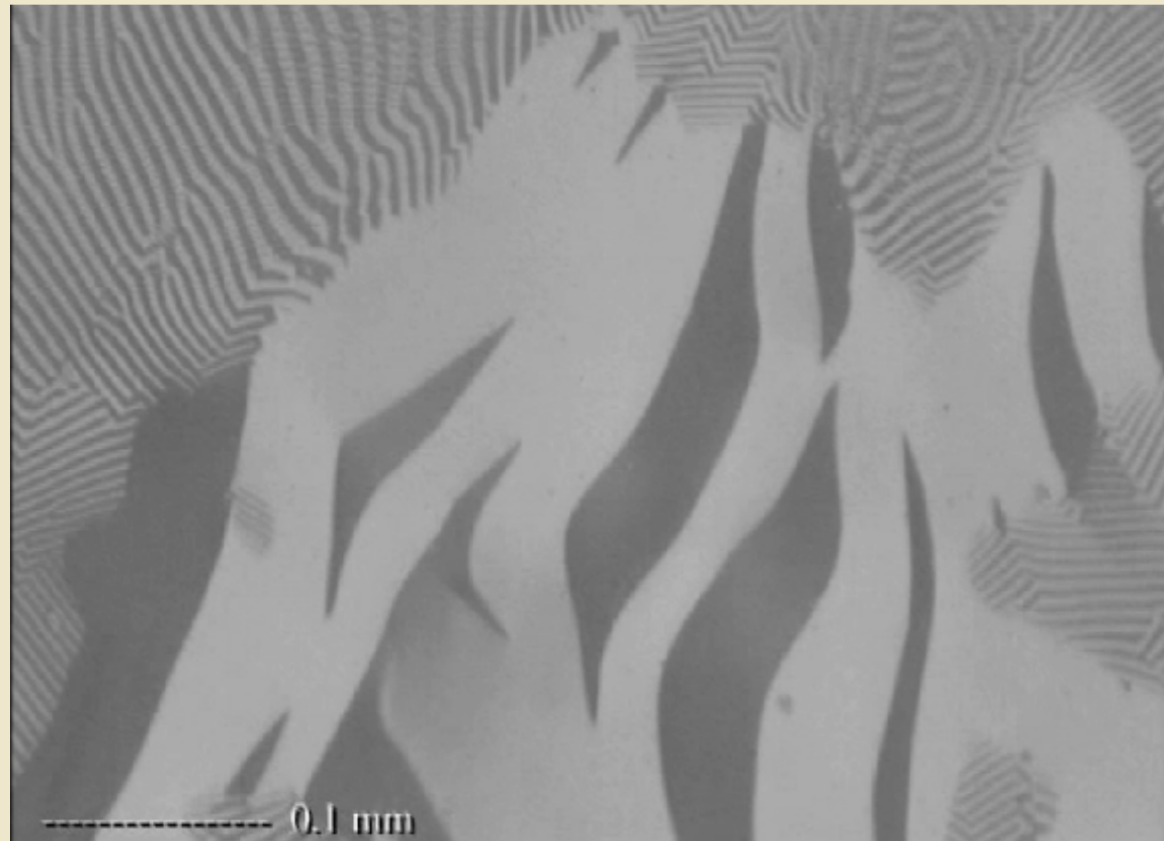


5. Magnetization curve



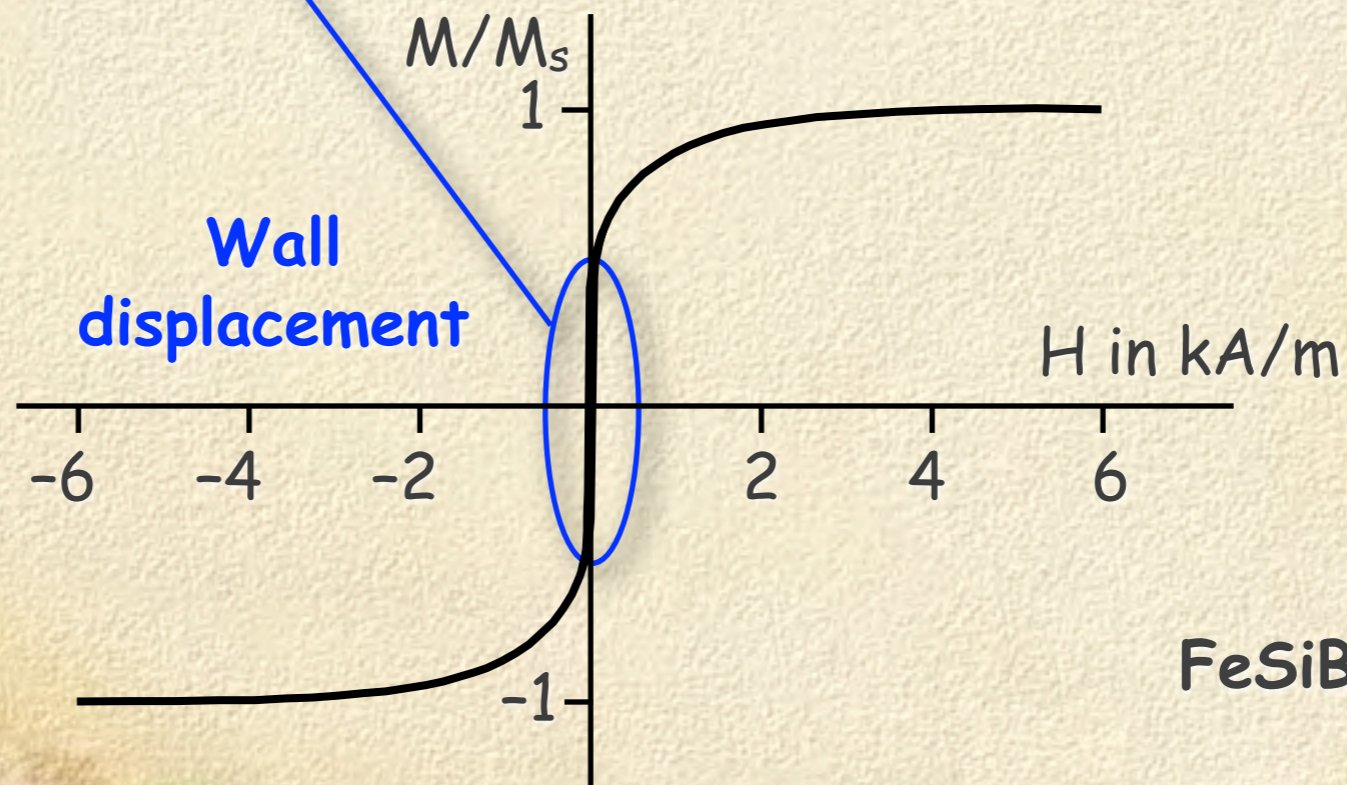
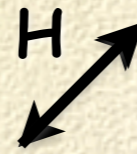
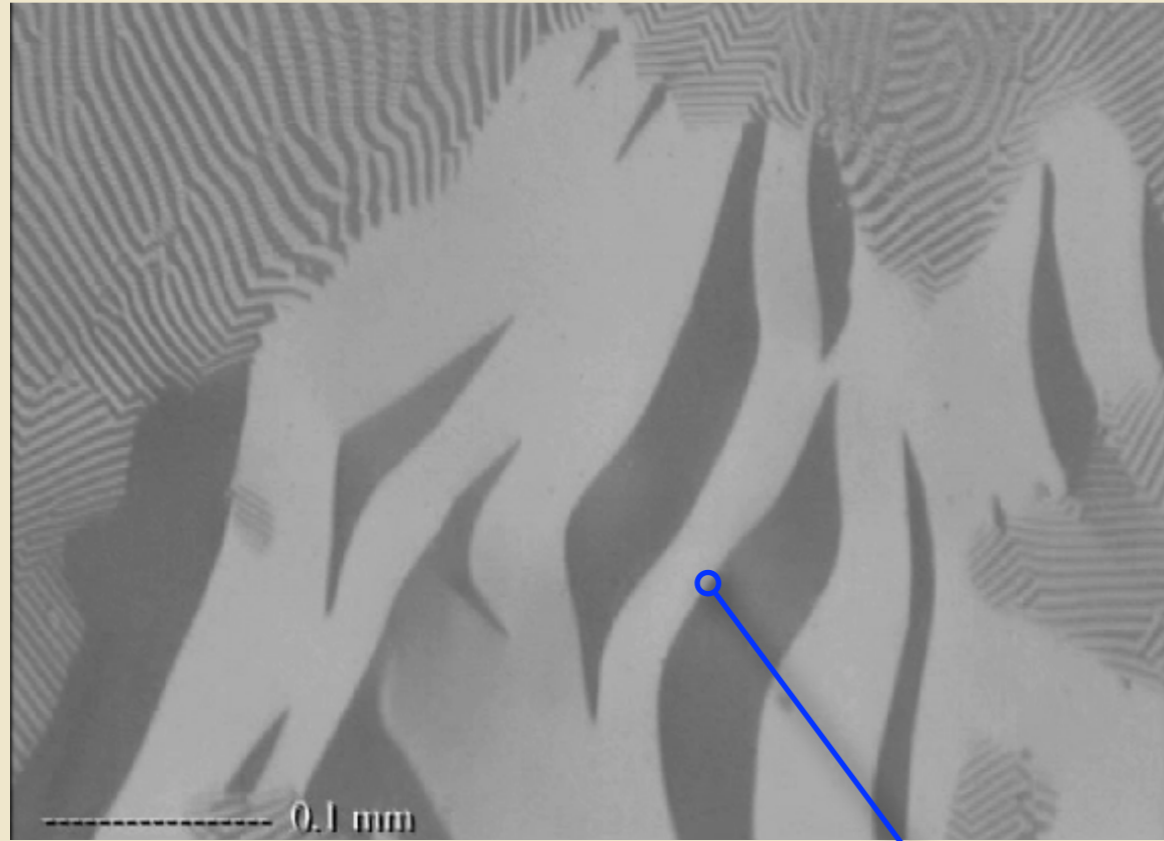
4. Phase Analysis

M(H) loop and domains



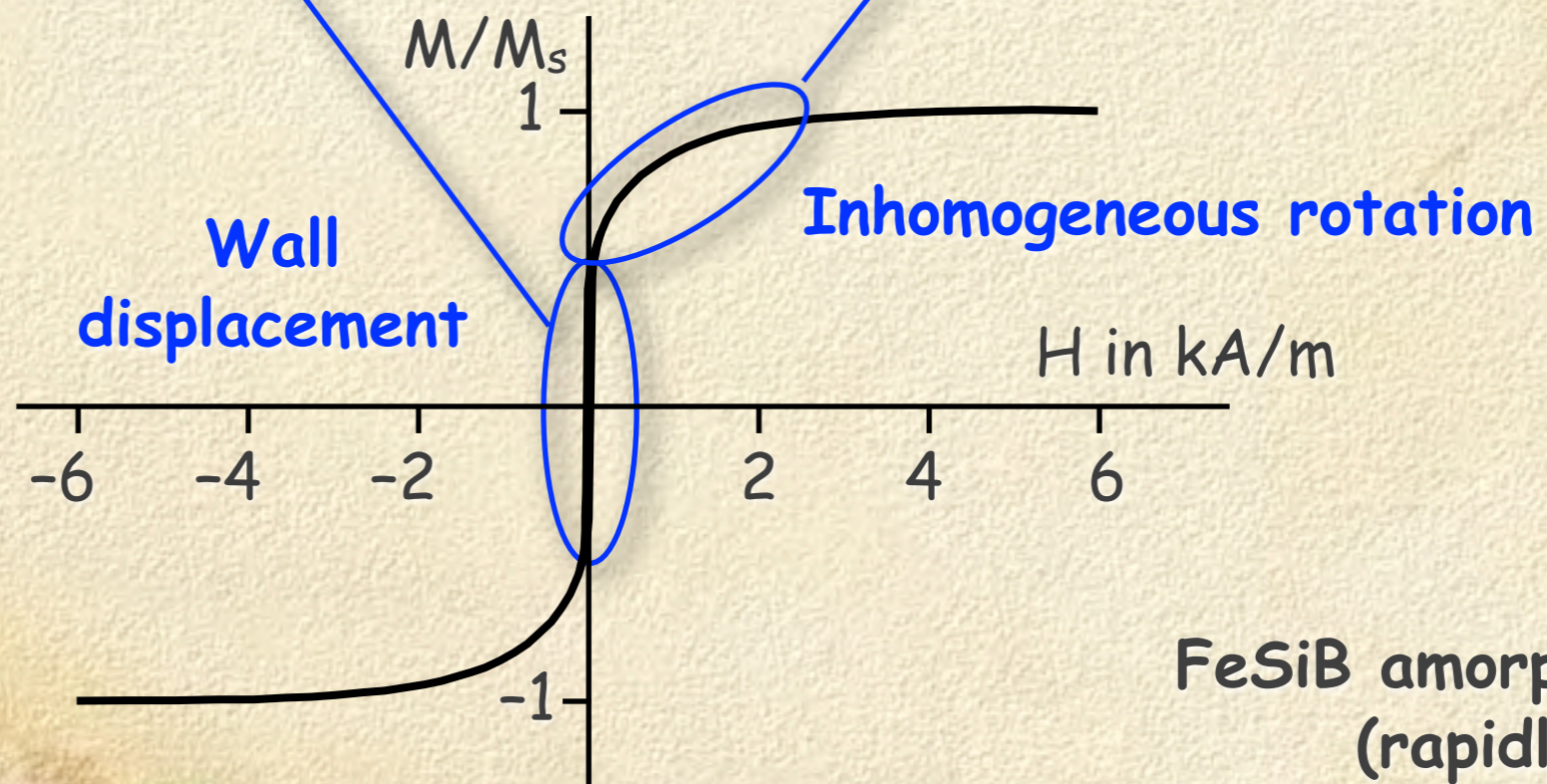
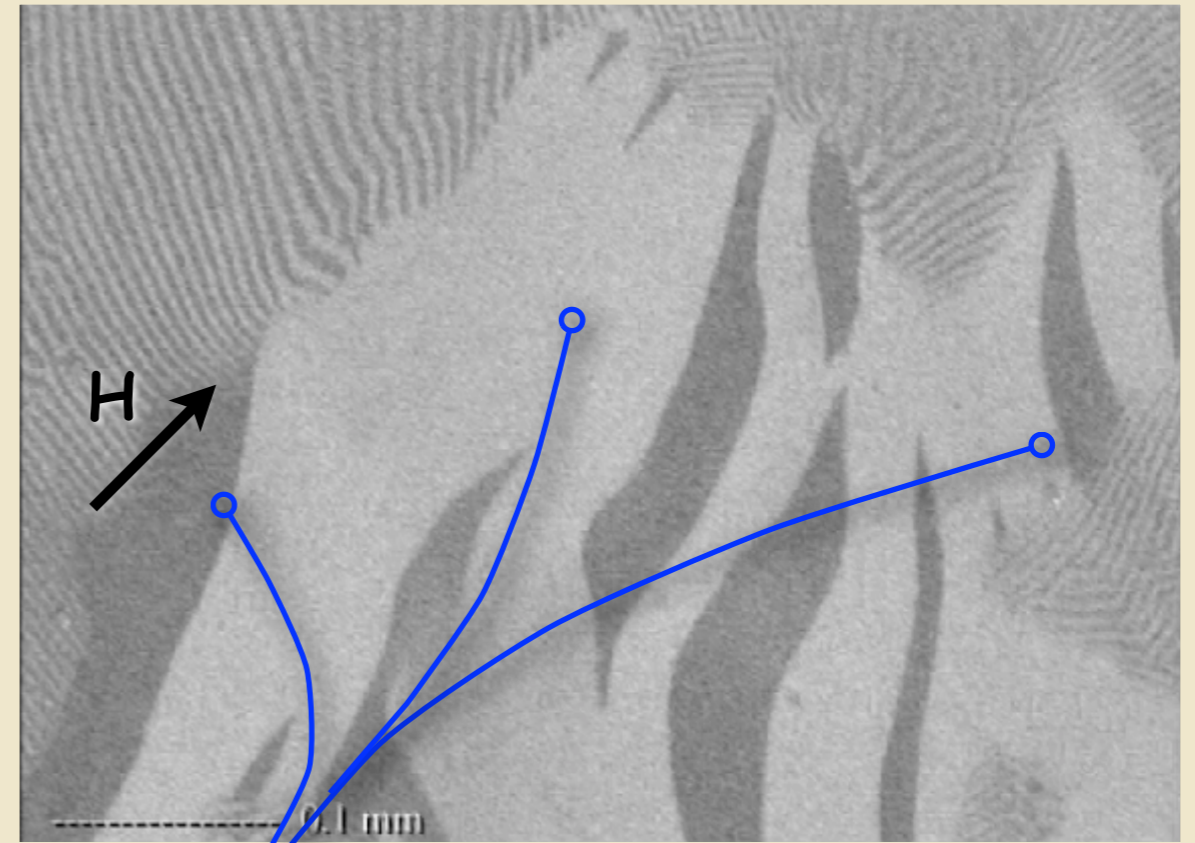
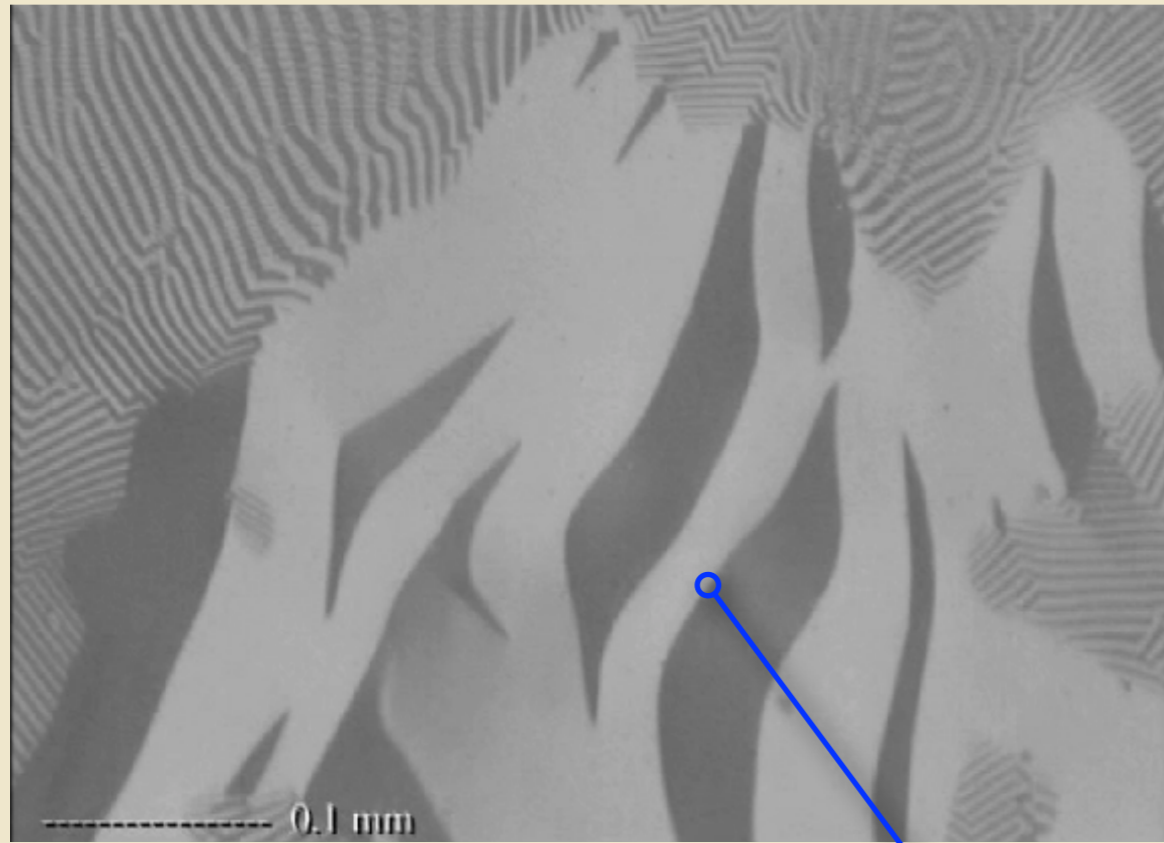
FeSiB amorphous ribbon
(rapidly quenched)

M(H) loop and domains



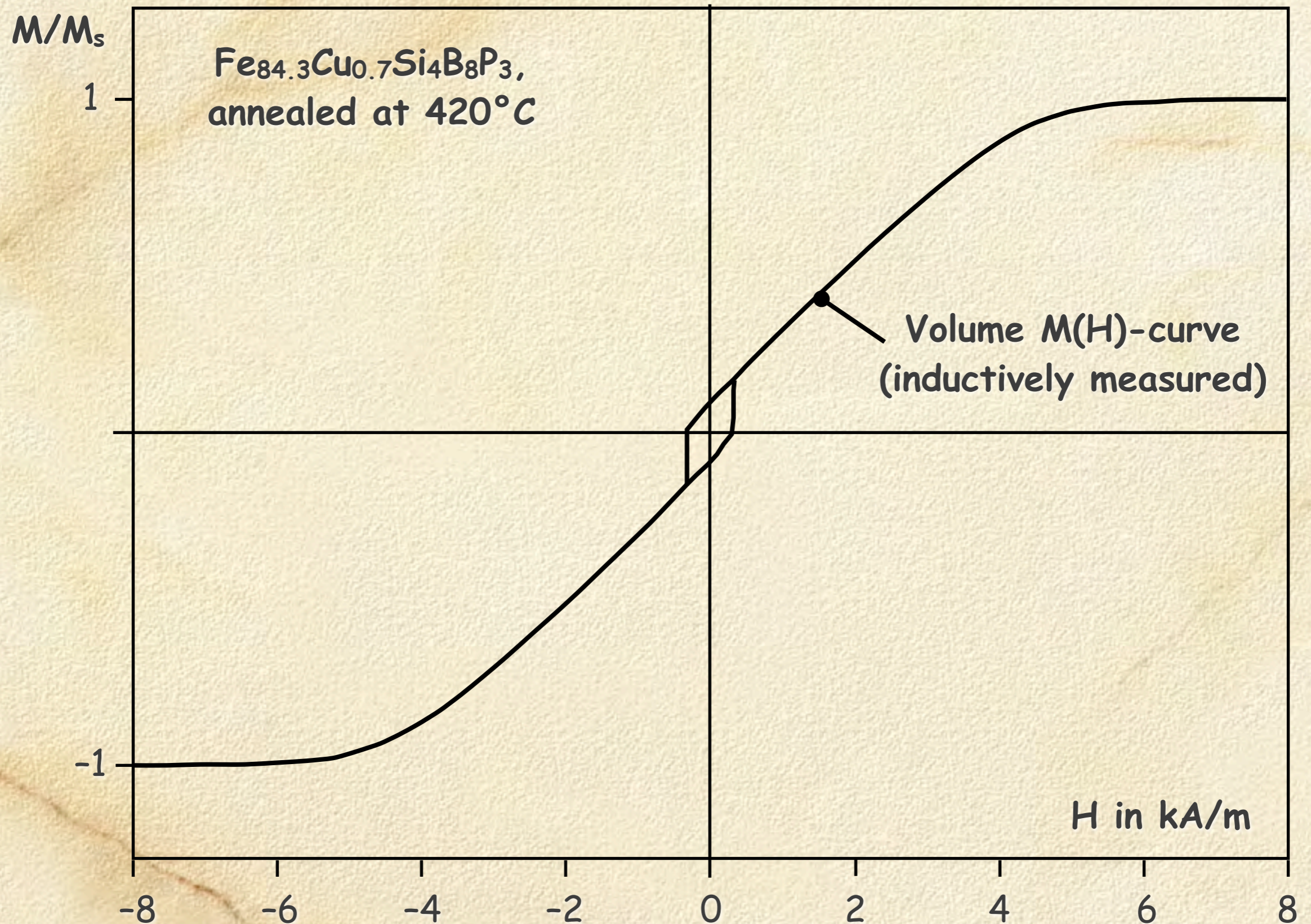
FeSiB amorphous ribbon
(rapidly quenched)

M(H) loop and domains



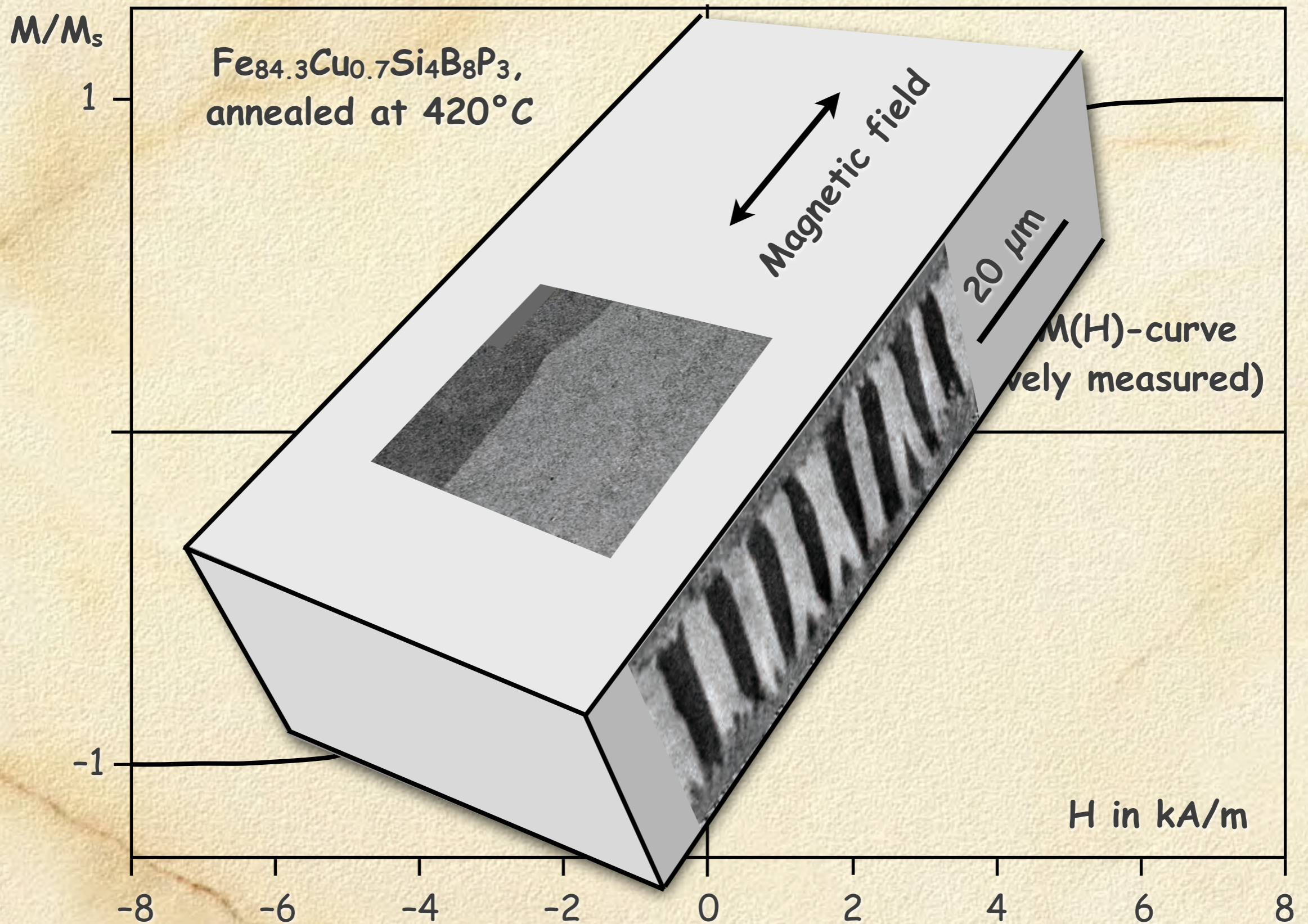
FeSiB amorphous ribbon
(rapidly quenched)

Amorphous ribbon



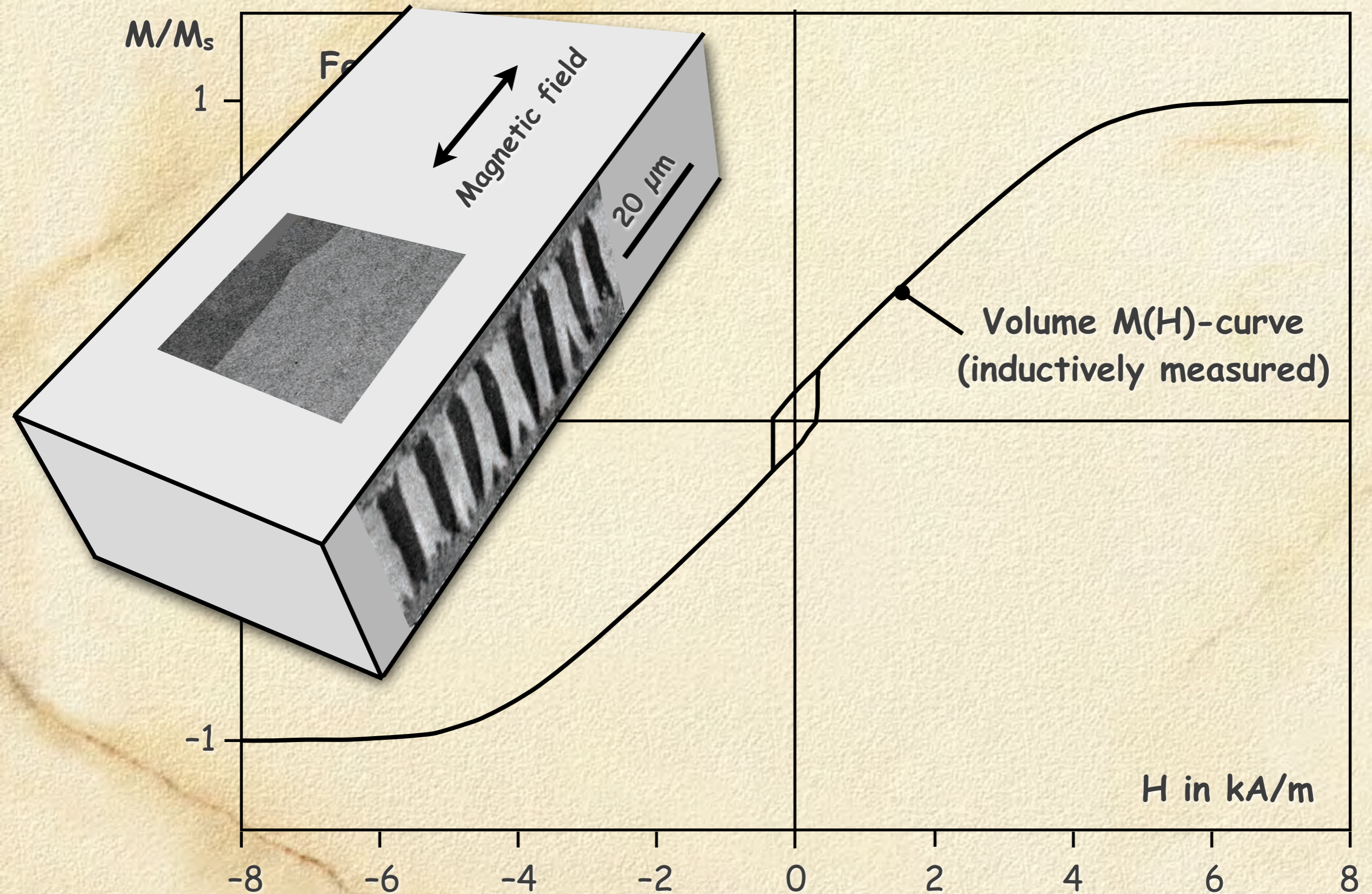
Together with E: Lopatina (IFW) and G. Herzer (VAC Hanau), unpublished

Amorphous ribbon



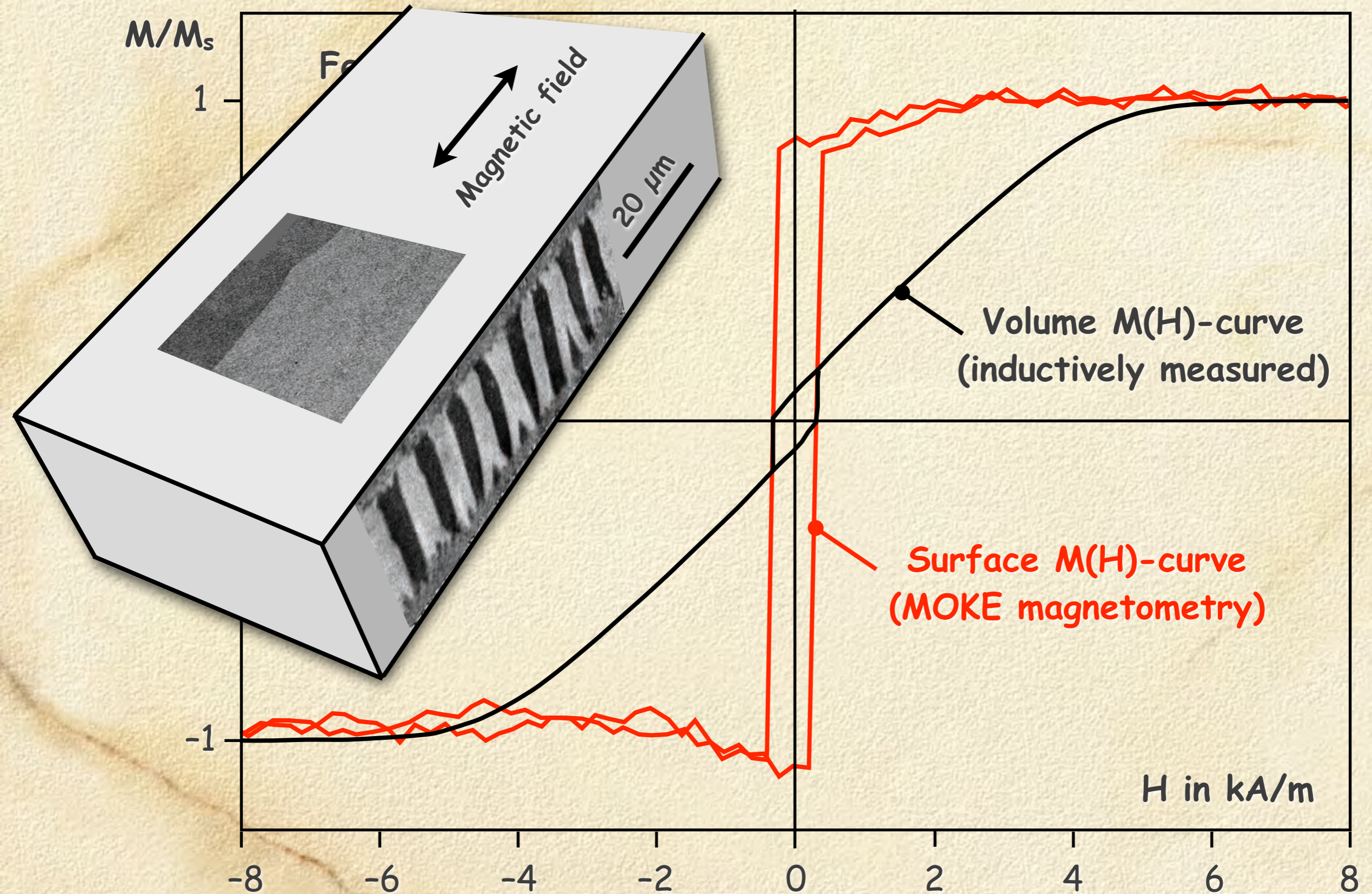
Together with E: Lopatina (IFW) and G. Herzer (VAC Hanau), unpublished

Amorphous ribbon



Together with E: Lopatina (IFW) and G. Herzer (VAC Hanau), unpublished

Amorphous ribbon



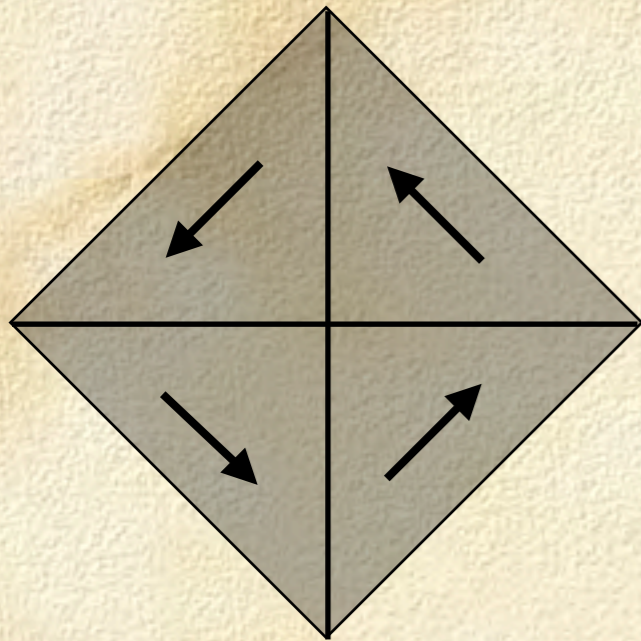
Together with E: Lopatina (IFW) and G. Herzer (VAC Hanau), unpublished

M(H) loop and domains

Permalloy (NiFe) film
207 nm thick

57 μm

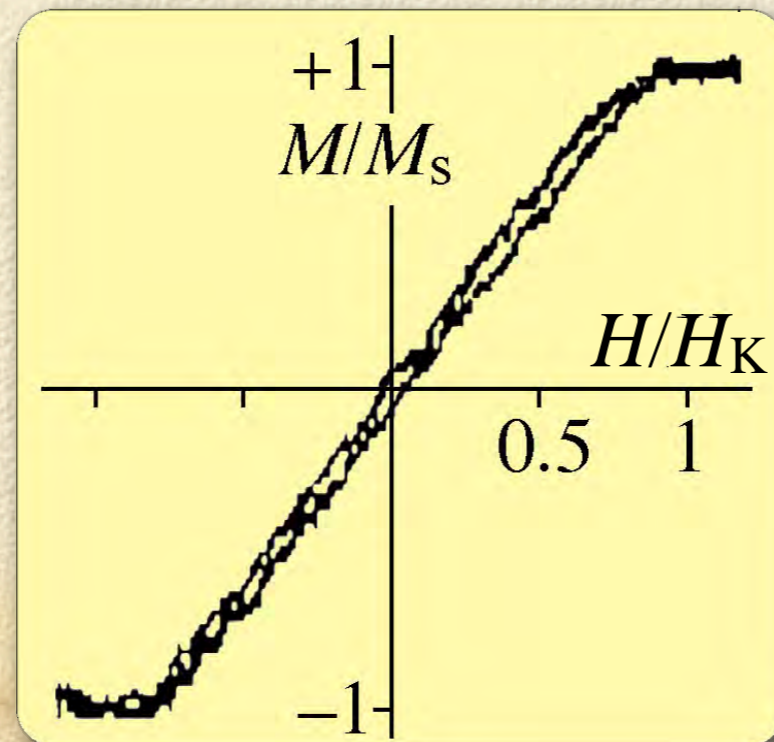
Concertina



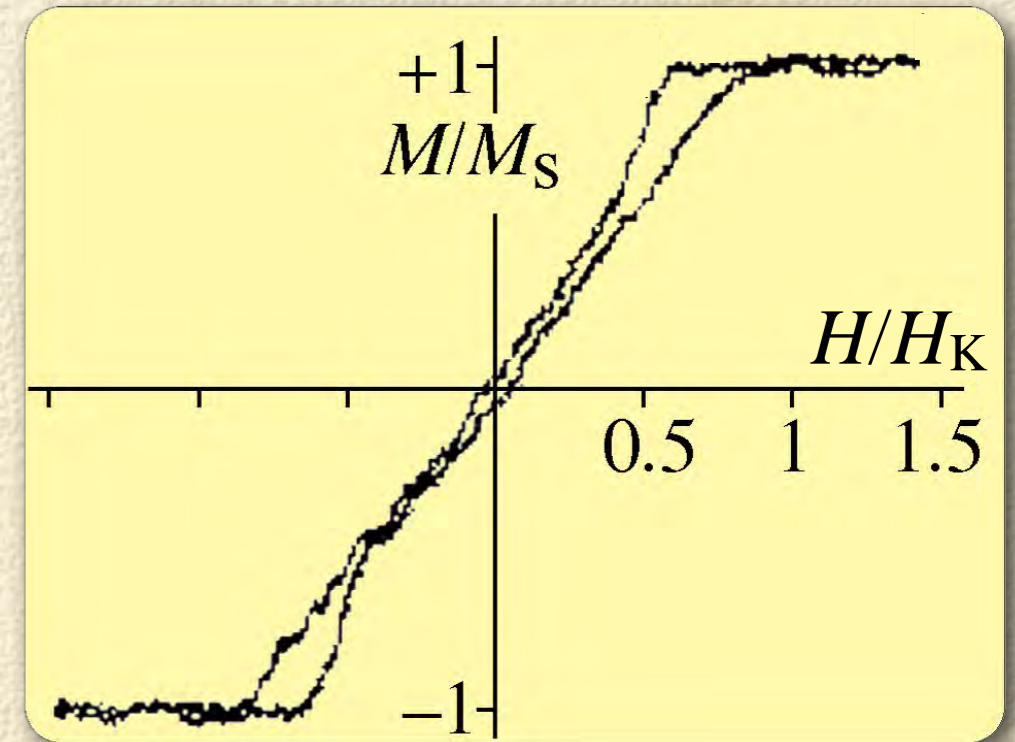
Magnetic field H



$H_{\text{max}} = H_K$

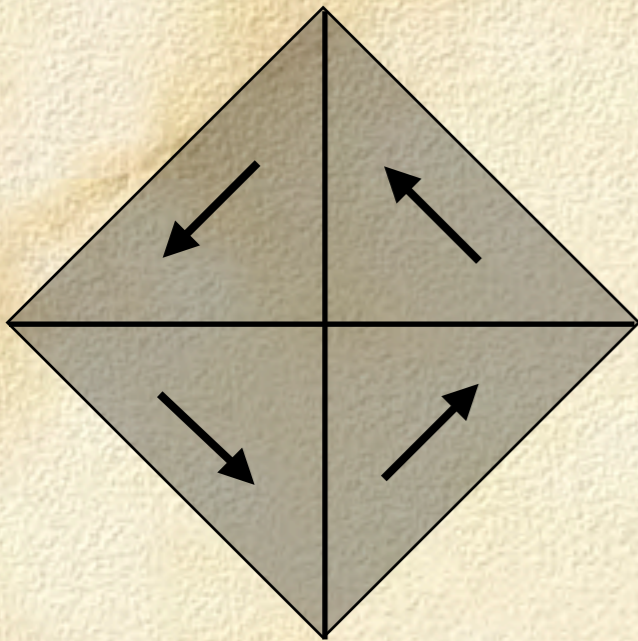


$H_{\text{max}} > H_K$

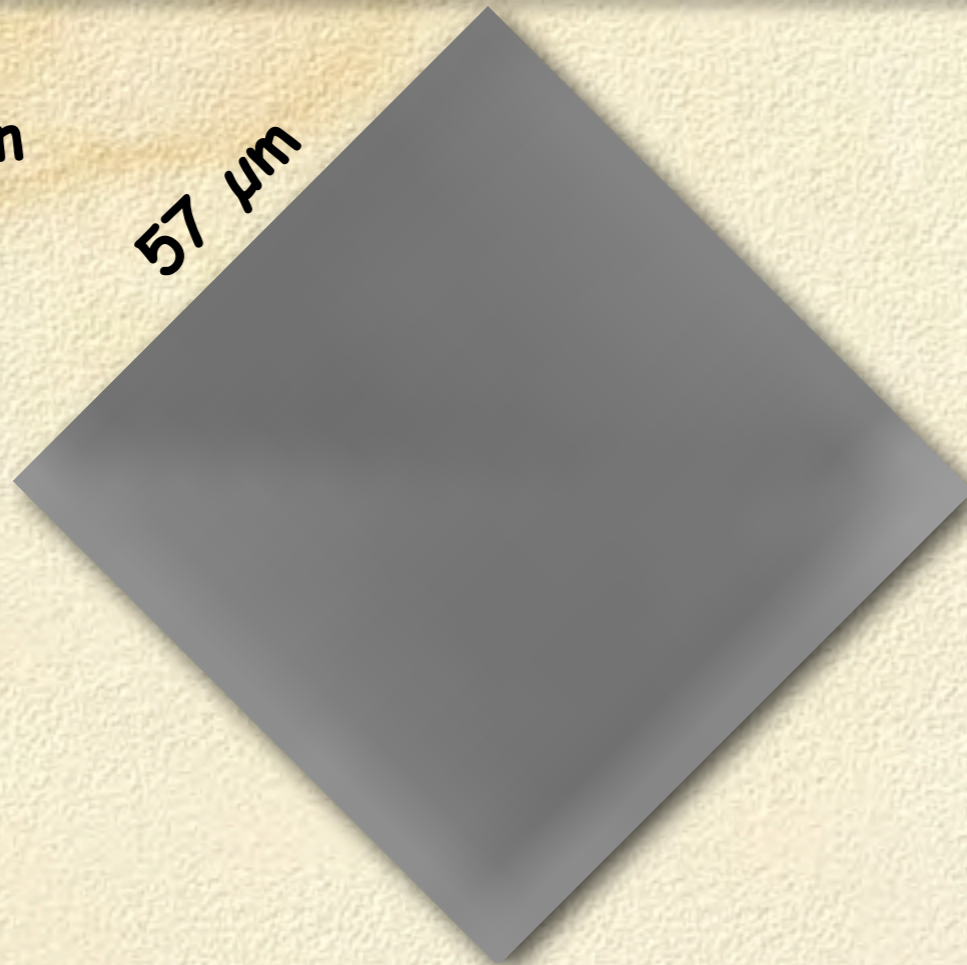


M(H) loop and domains

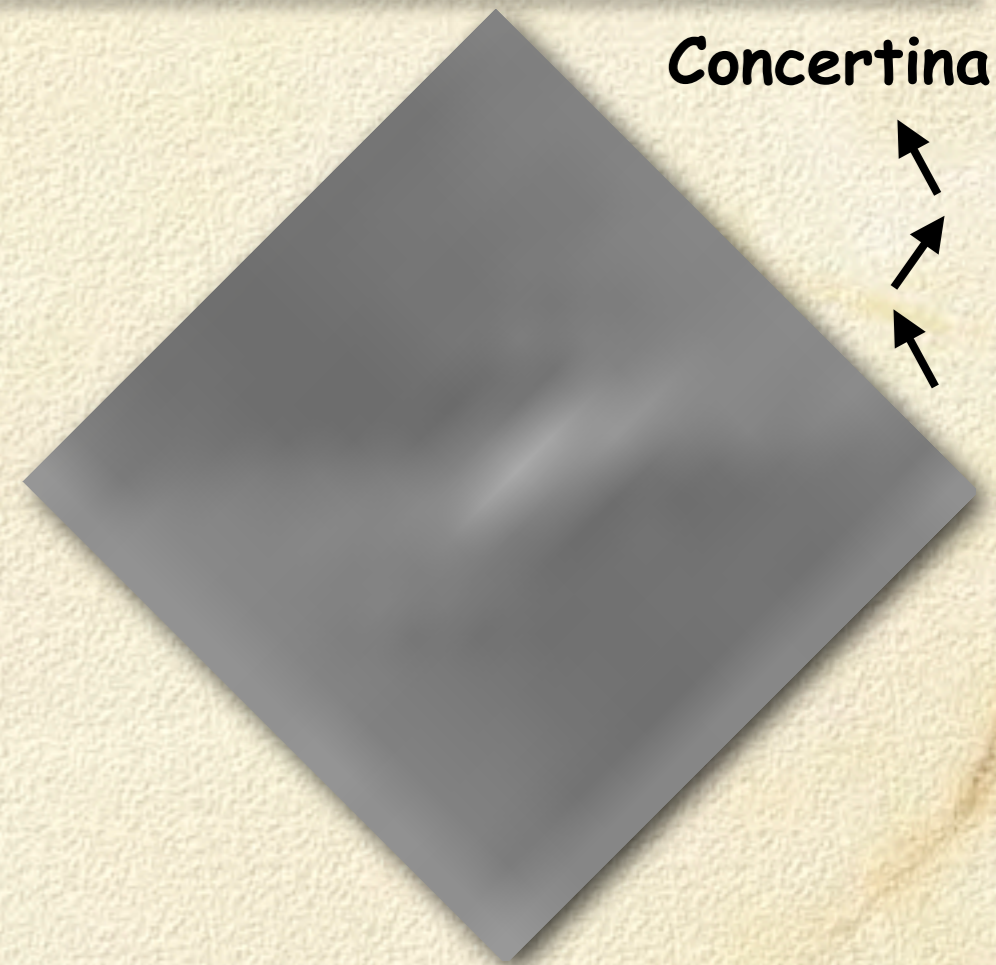
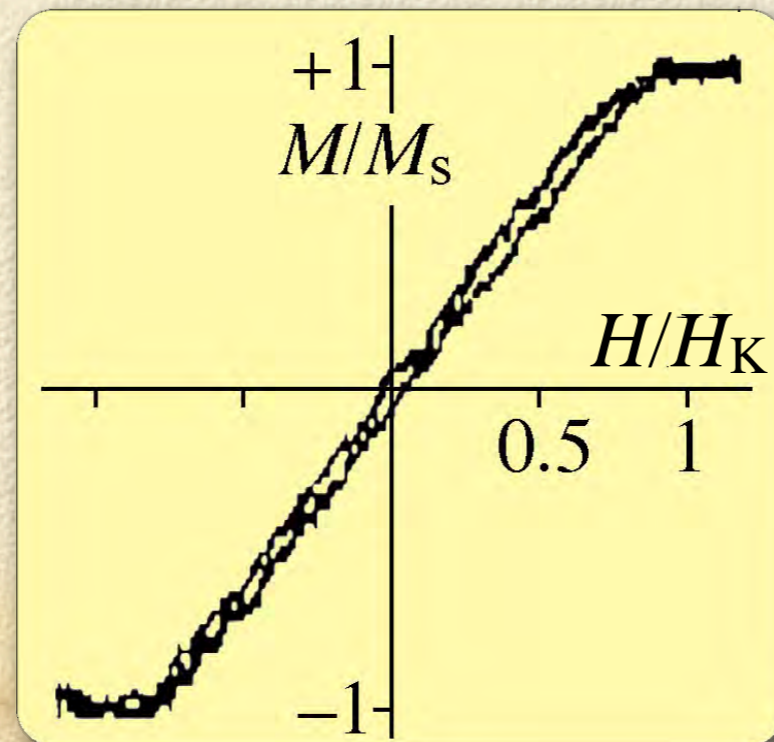
Permalloy (NiFe) film
207 nm thick



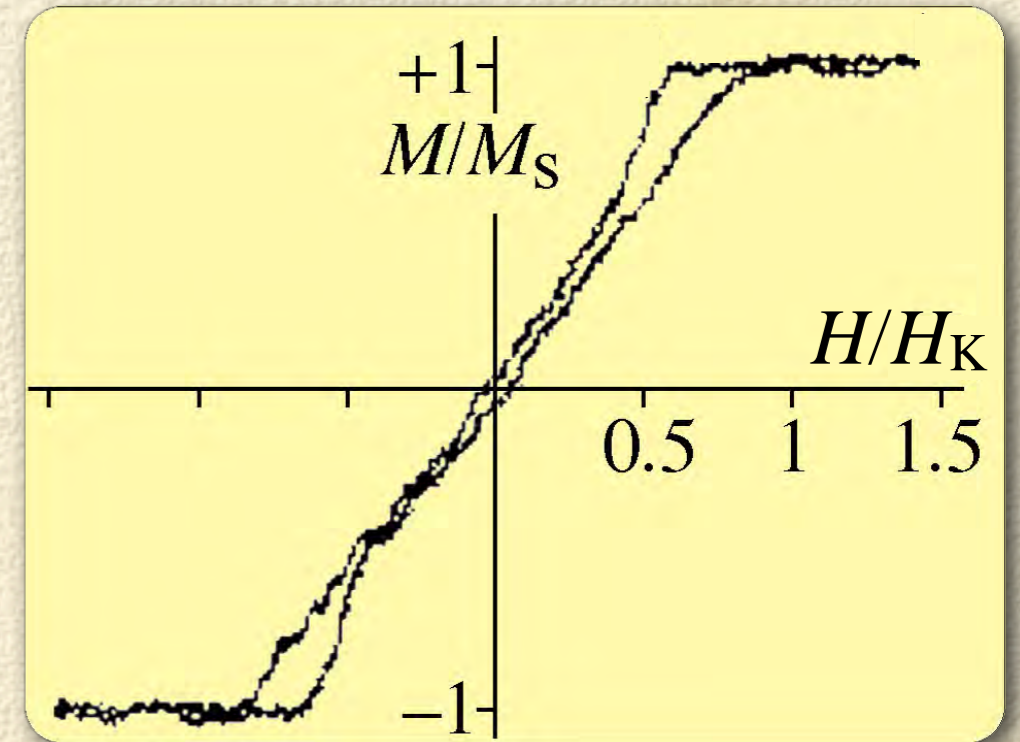
Magnetic field H



$H_{\max} = H_K$

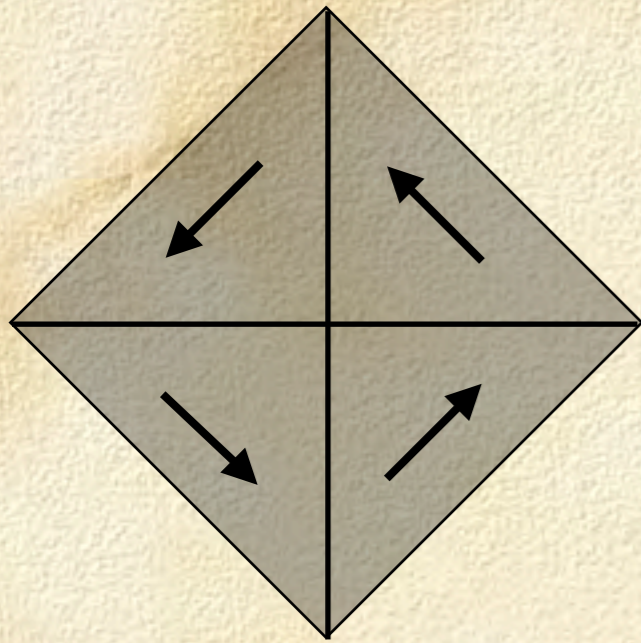


$H_{\max} > H_K$



M(H) loop and domains

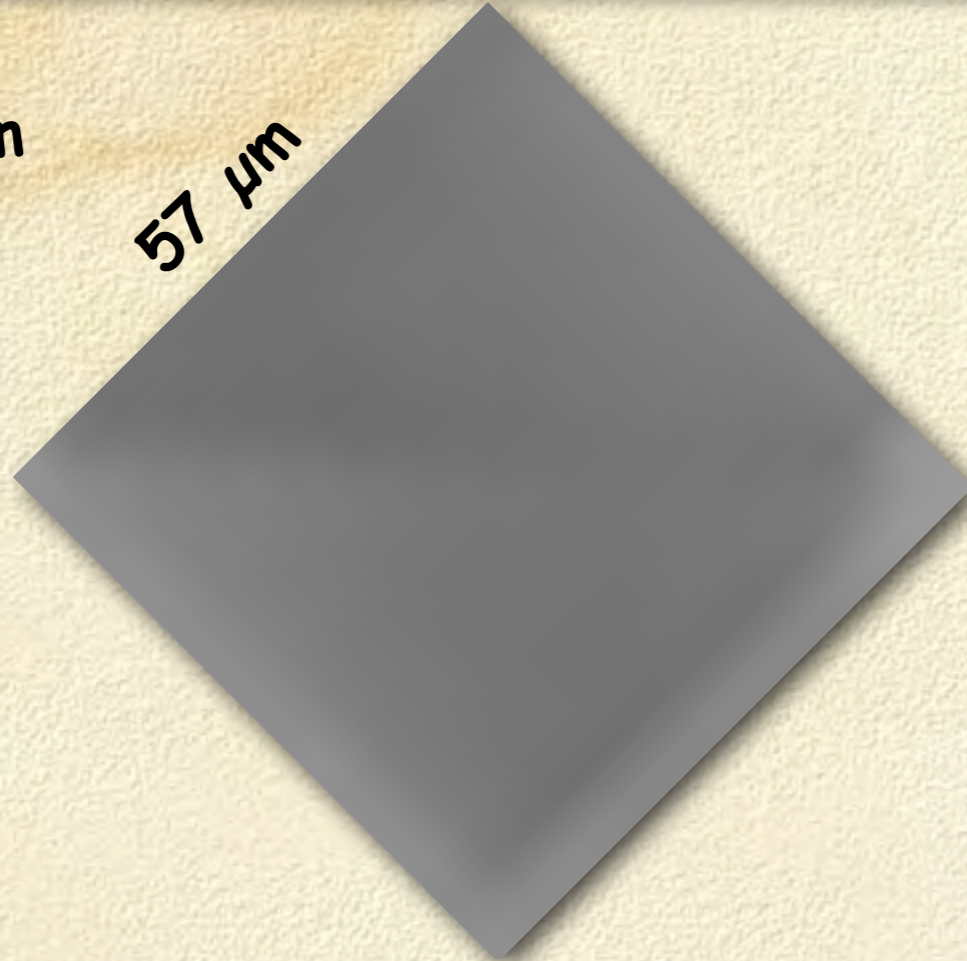
Permalloy (NiFe) film
207 nm thick



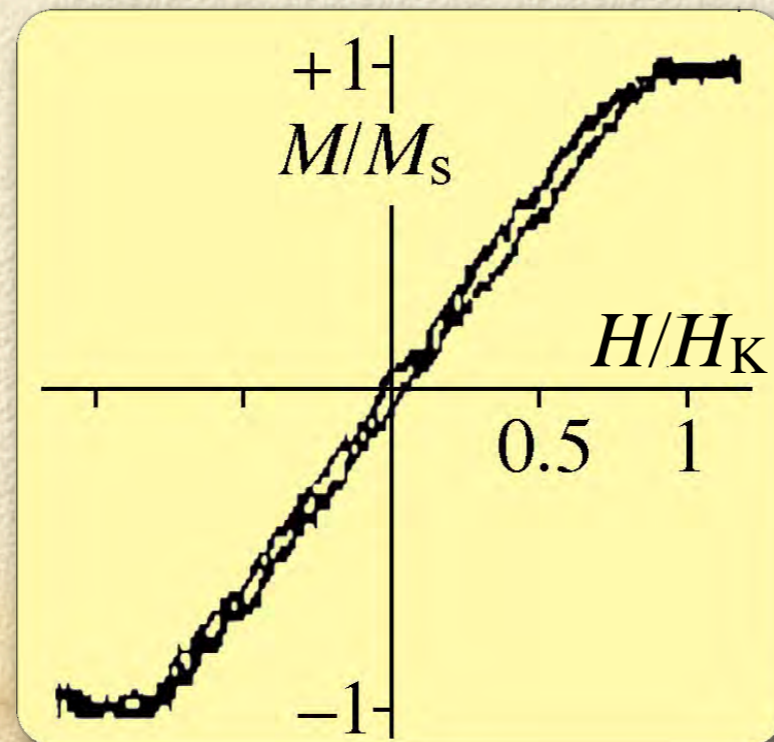
Magnetic field H



57 μm



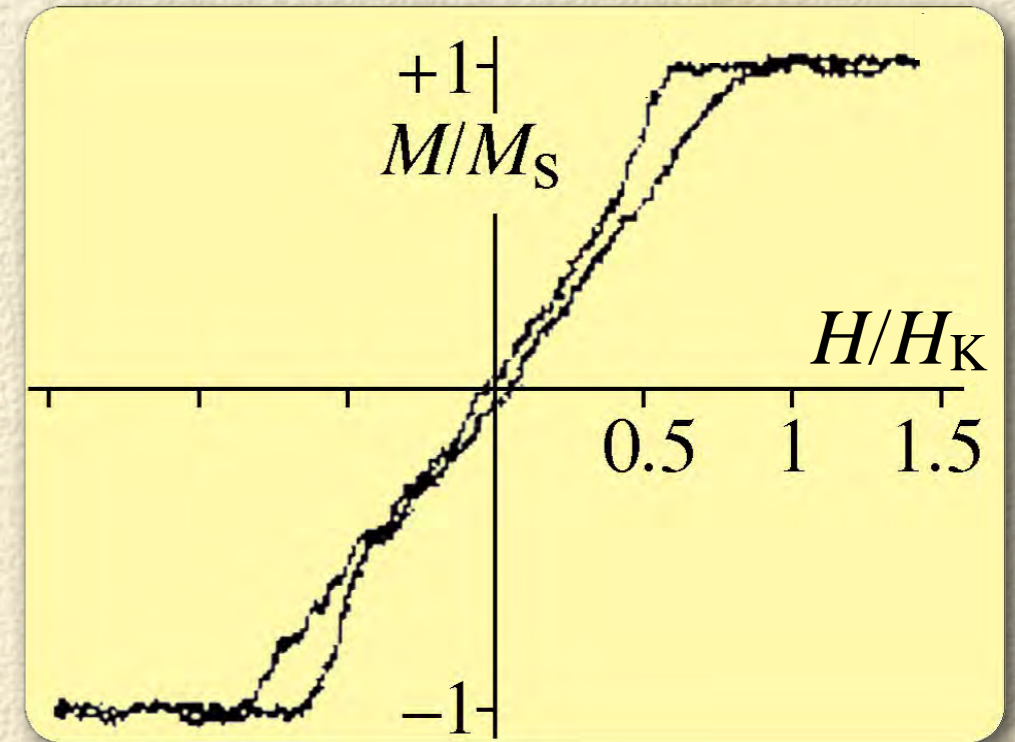
$H_{\text{max}} = H_K$



Concertina

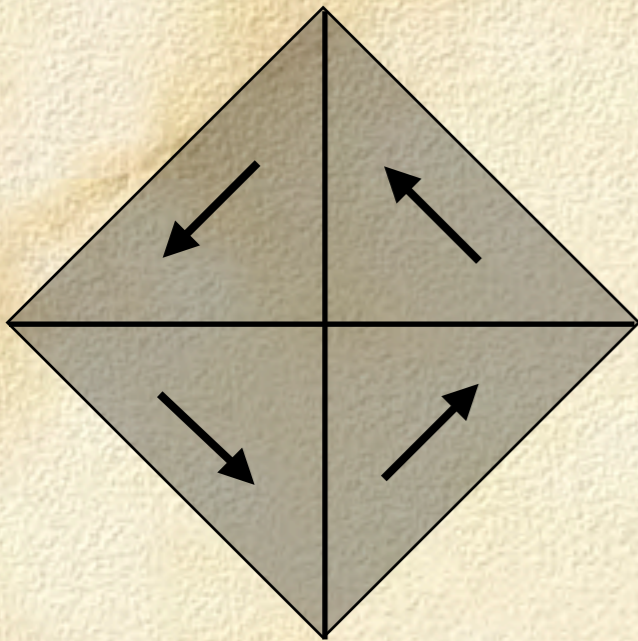


$H_{\text{max}} > H_K$



M(H) loop and domains

Permalloy (NiFe) film
207 nm thick

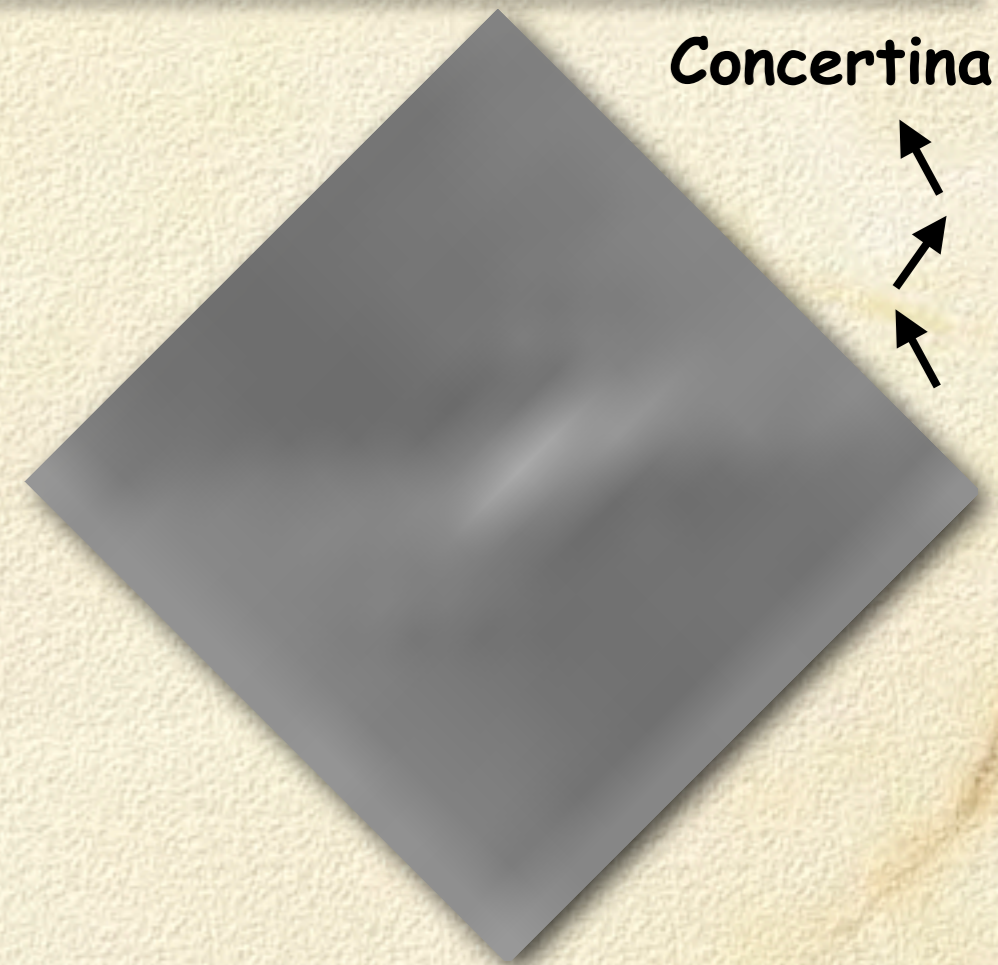
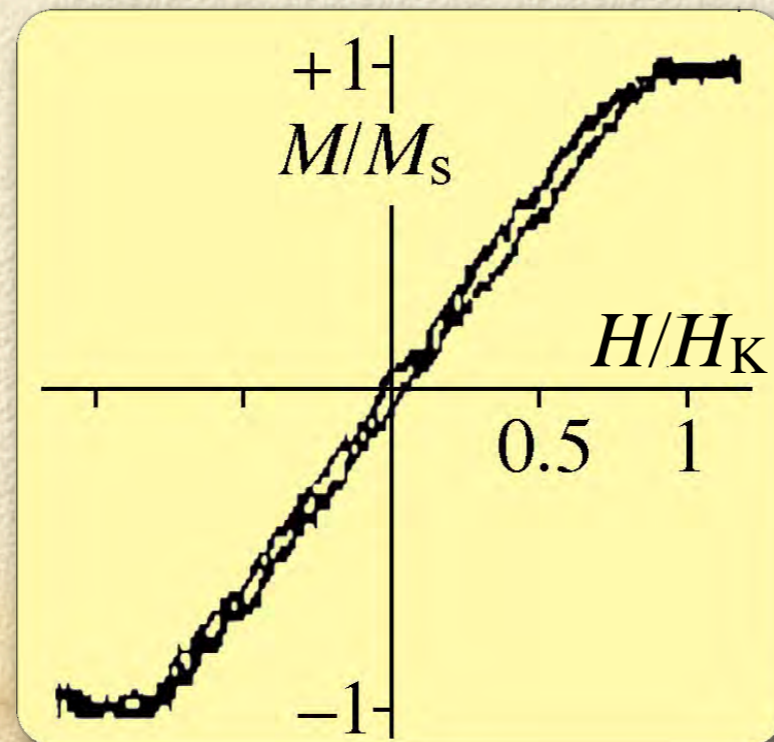


Magnetic field H



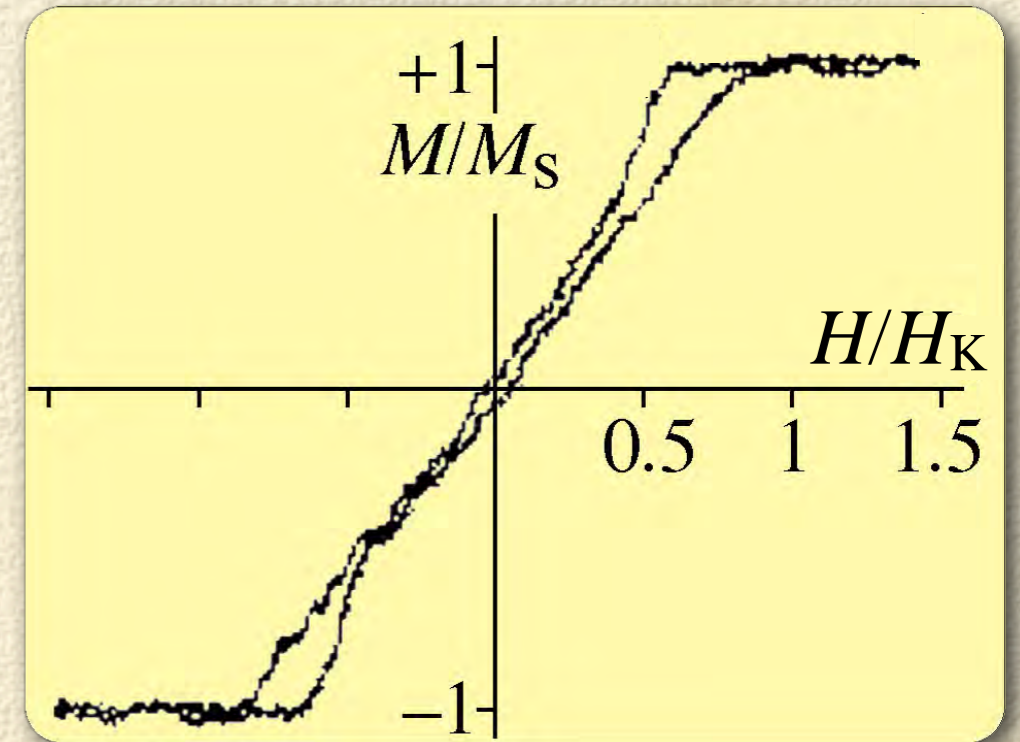
57 μm

$H_{\text{max}} = H_K$



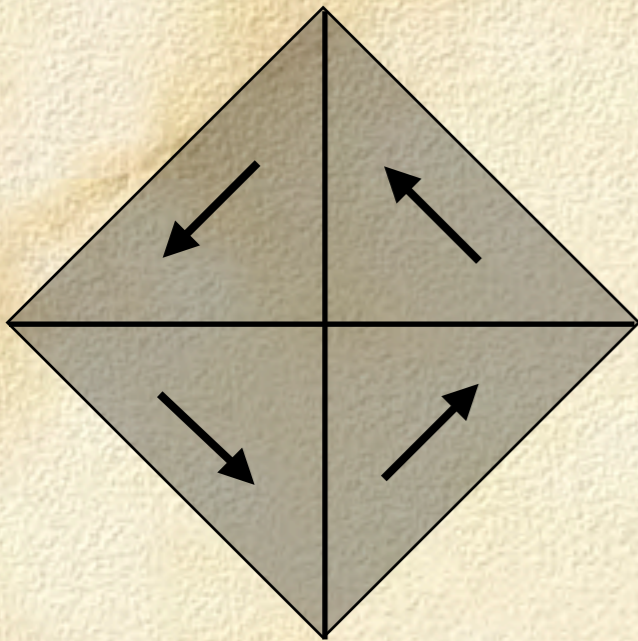
Concertina

$H_{\text{max}} > H_K$



M(H) loop and domains

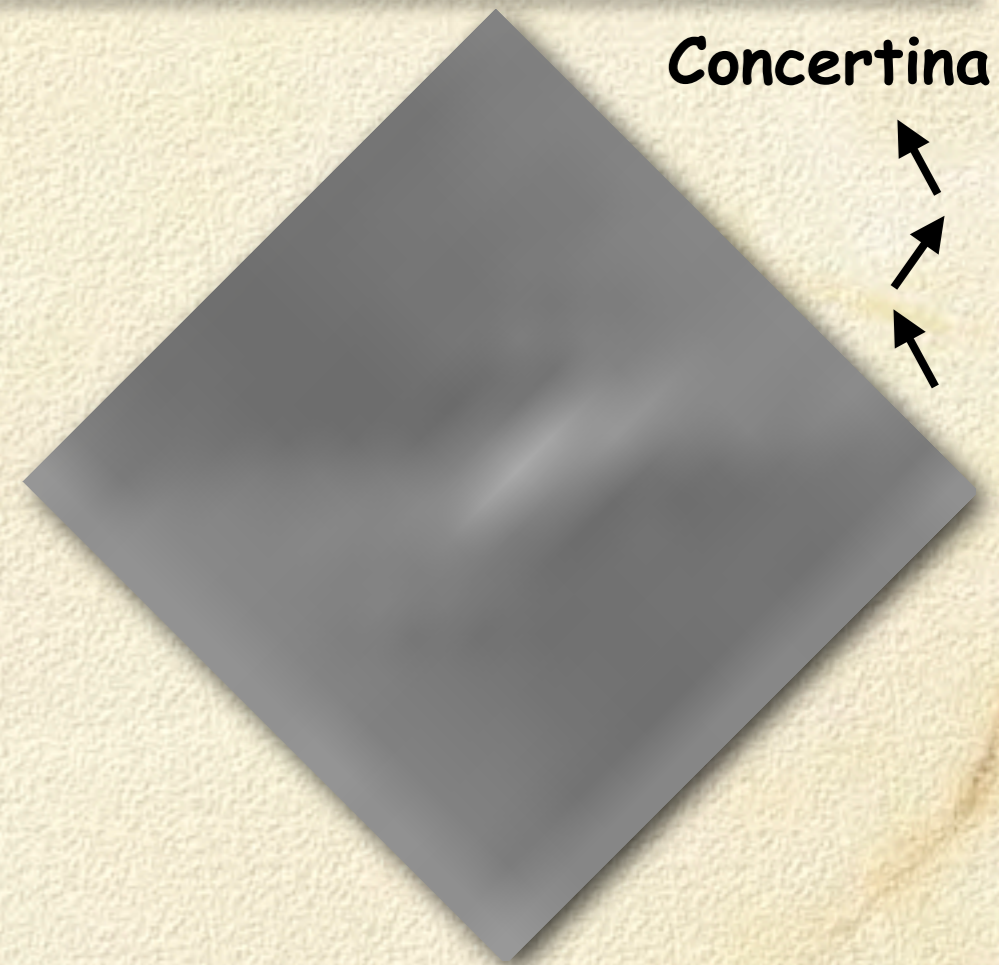
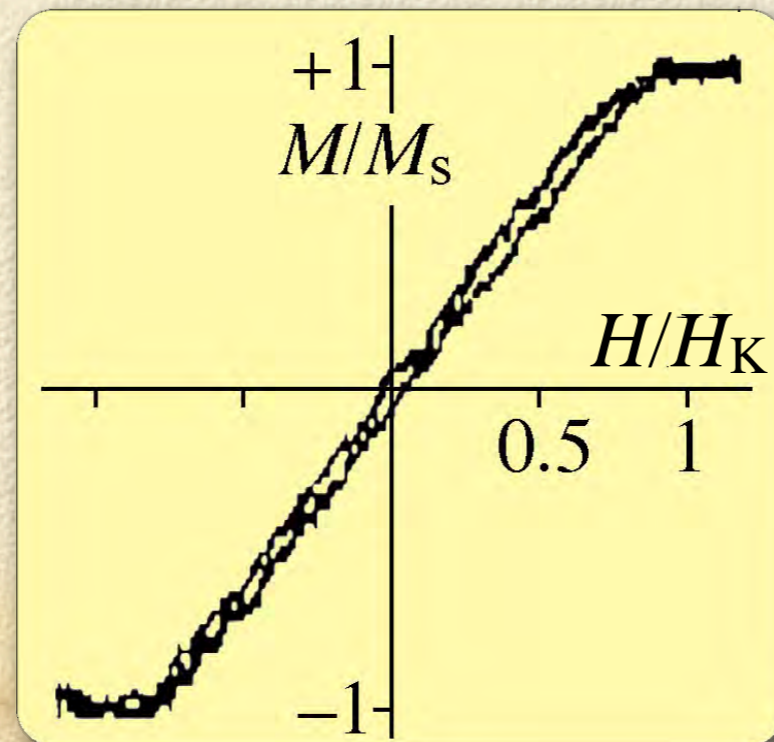
Permalloy (NiFe) film
207 nm thick



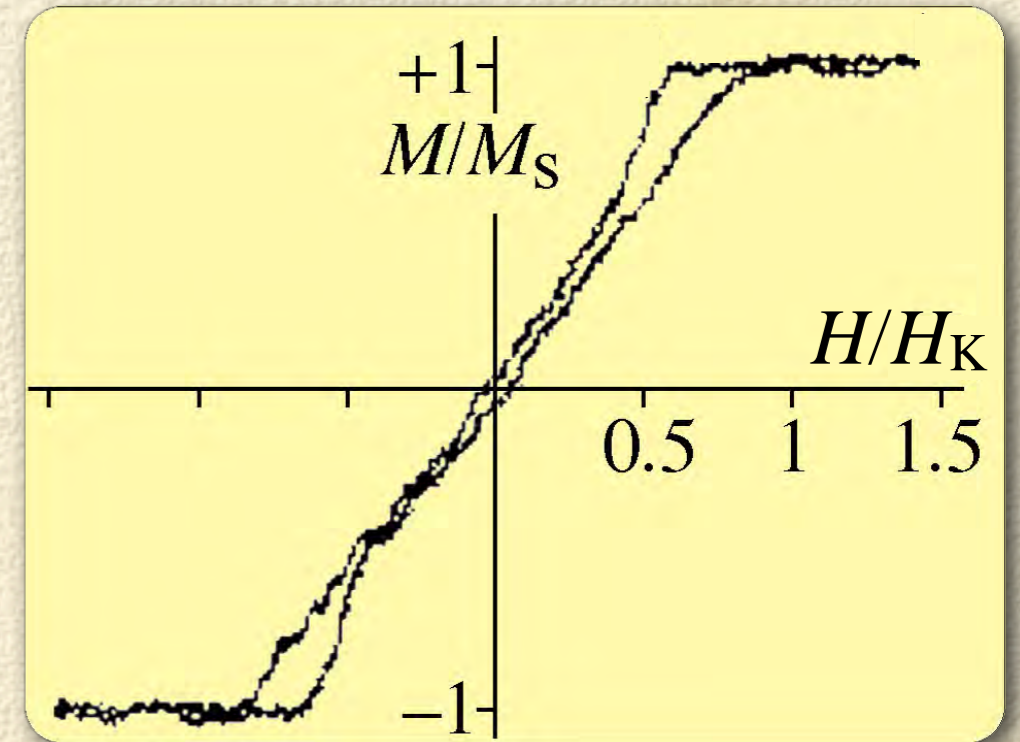
Magnetic field H



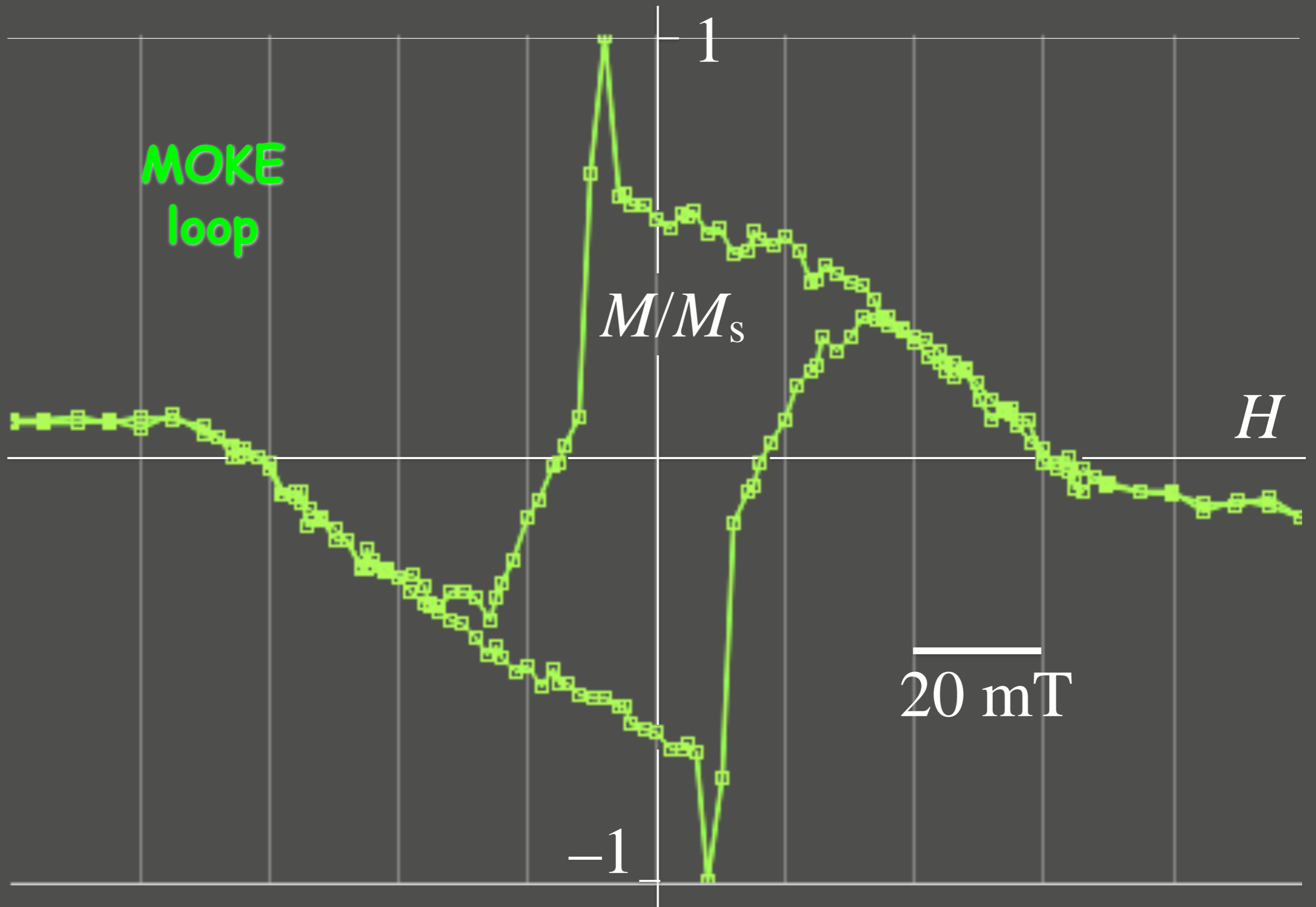
$H_{\max} = H_K$



$H_{\max} > H_K$

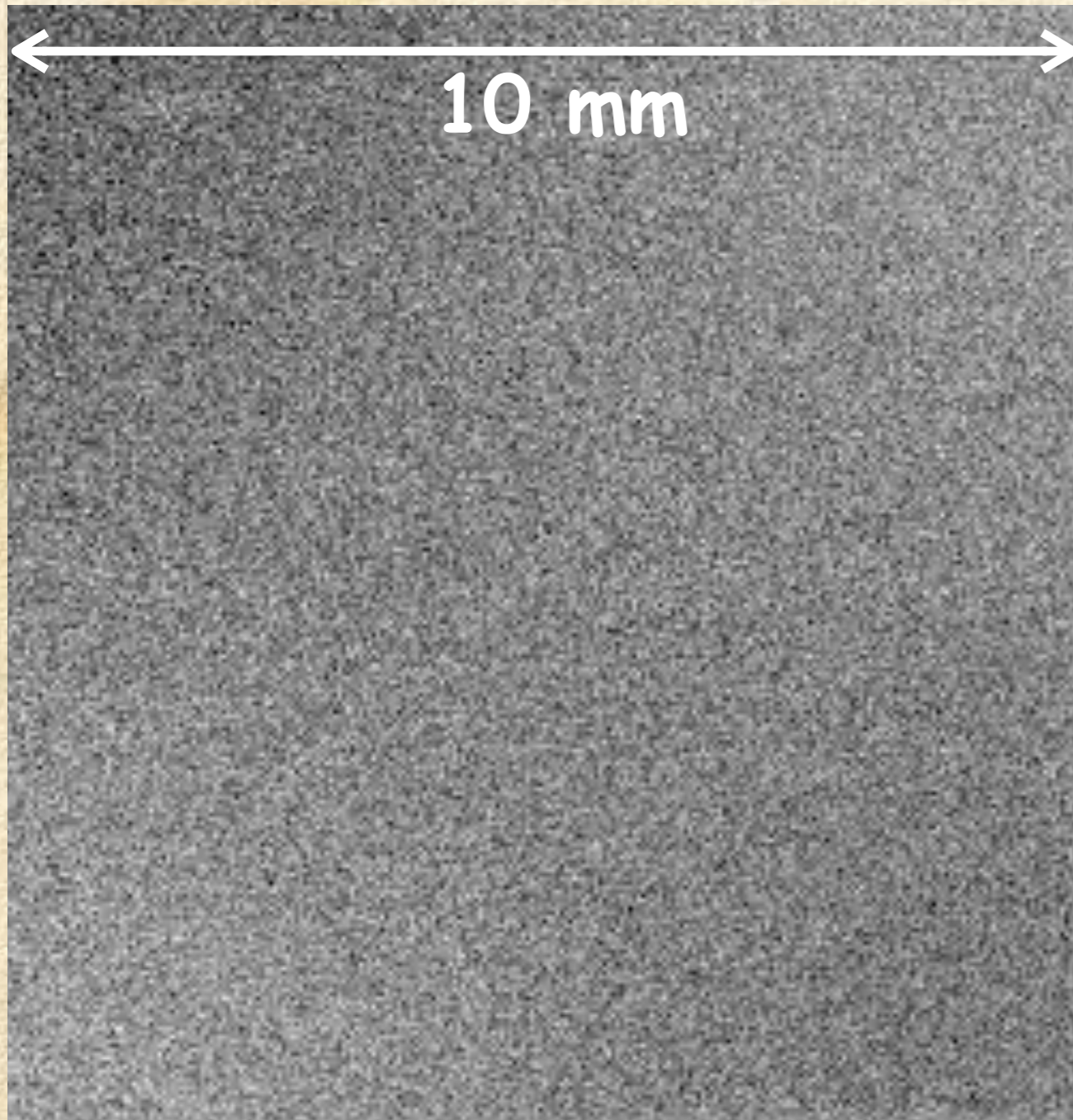


$M(H)$ loop and domains

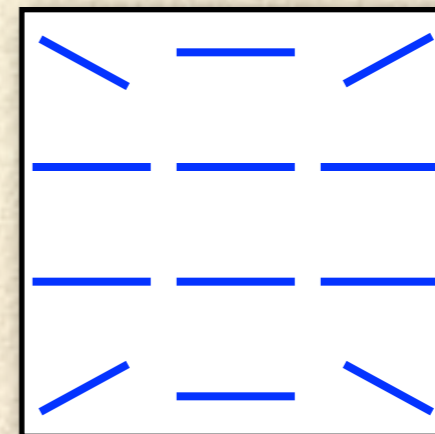
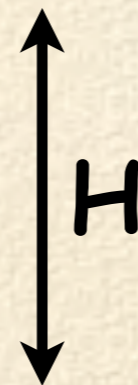
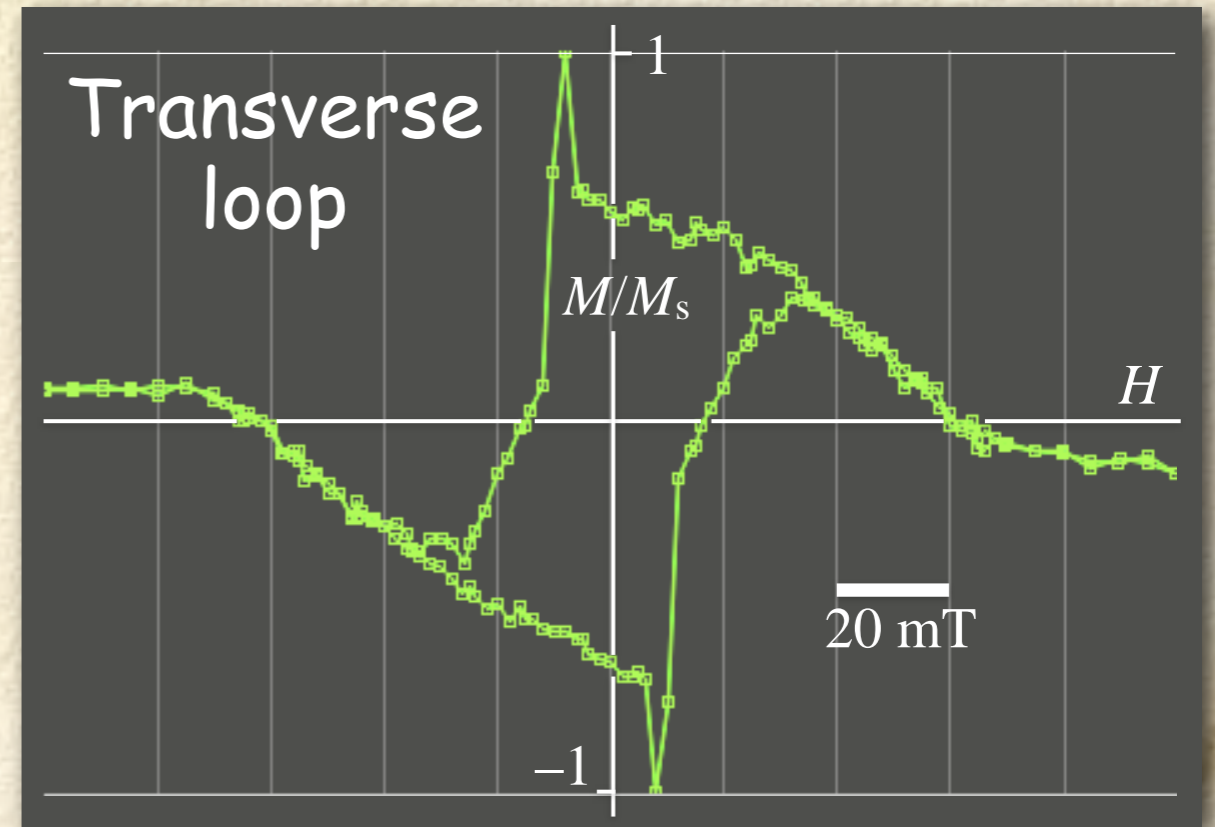


M(H) loop and domains

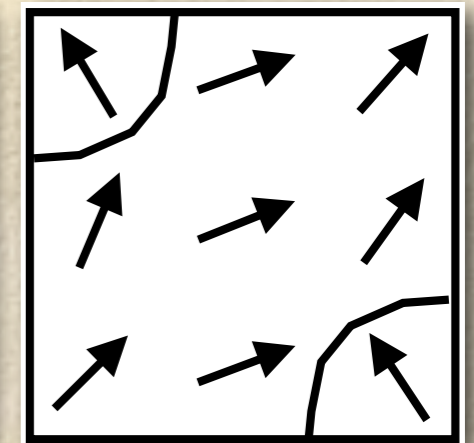
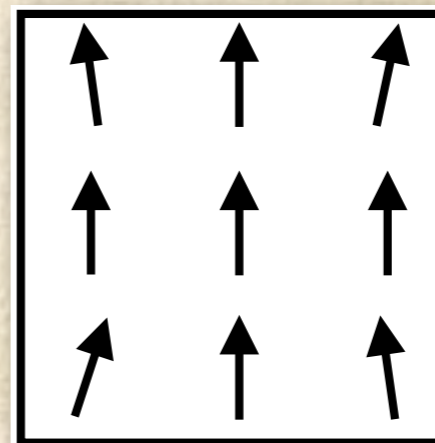
Co₂₇Sm₇₃ amorphous film
(thickness 200 nm)



Sample: F. Magnus and B. Hjörvarsson,
Uppsala University (unpublished)



Anisotropy

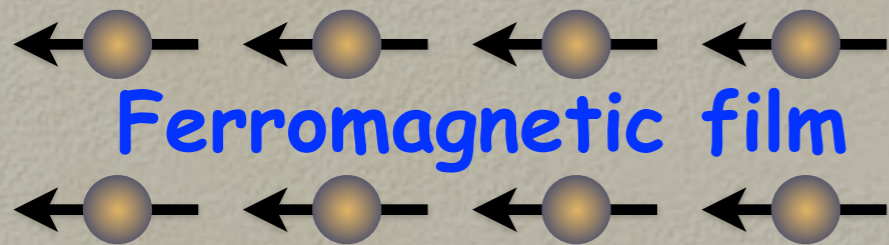
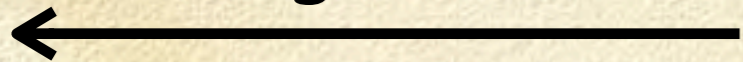


M(H) loop and domains

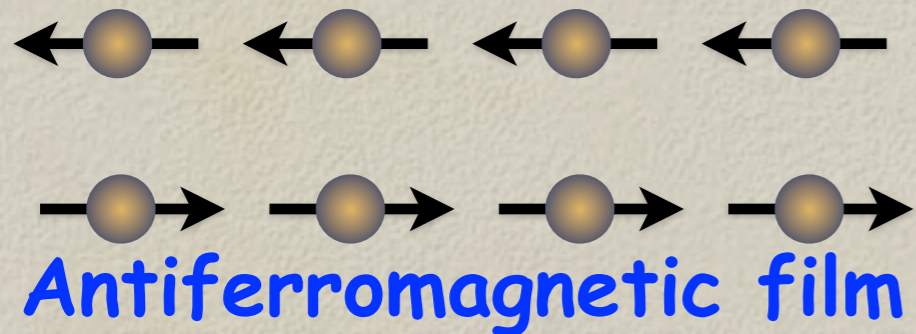
Reversal of Ni₈₁Fe₁₉ (30 nm) / NiO (30 nm)

Exchange bias

Pinning direction

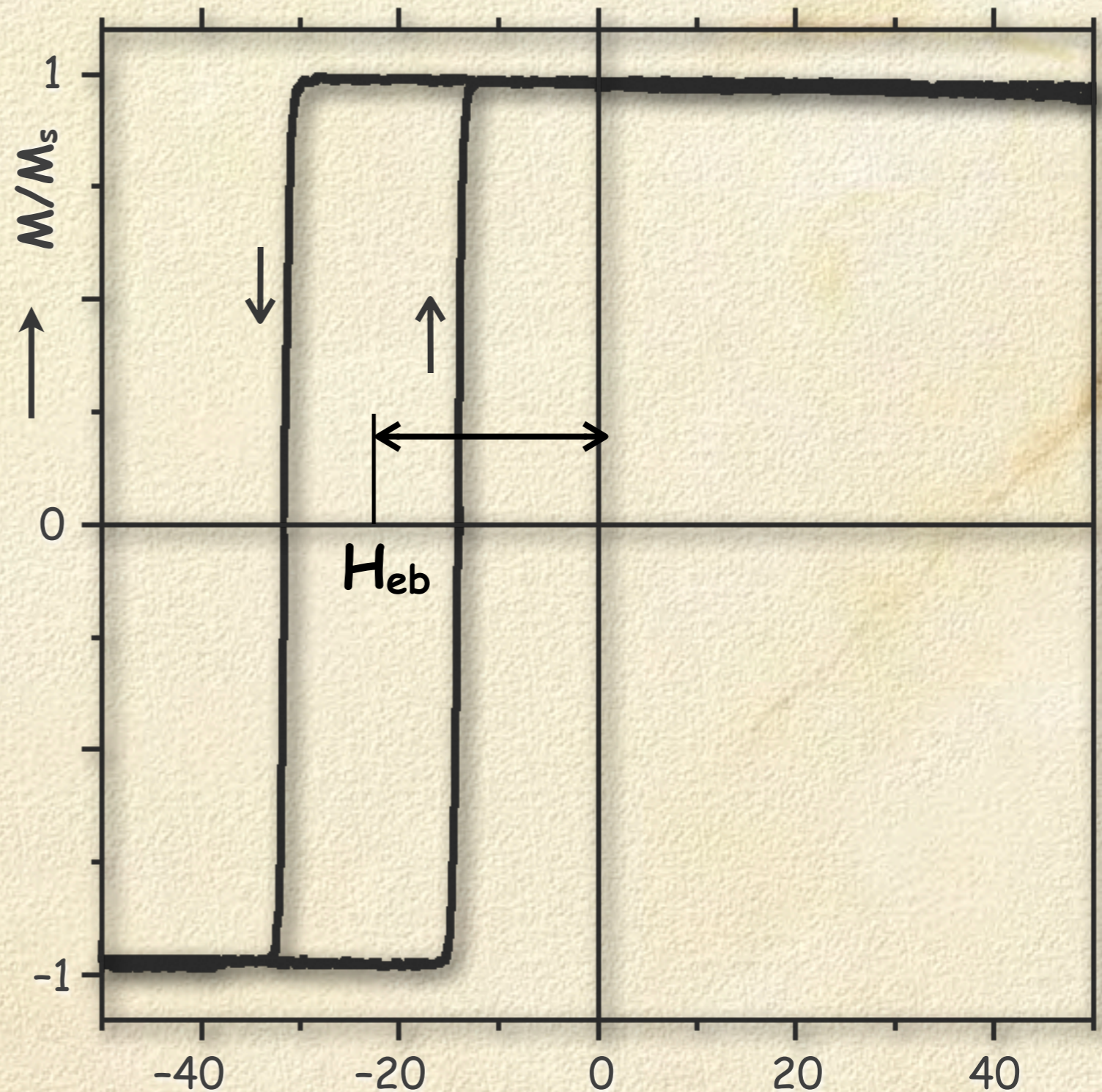


Ferromagnetic film



Antiferromagnetic film

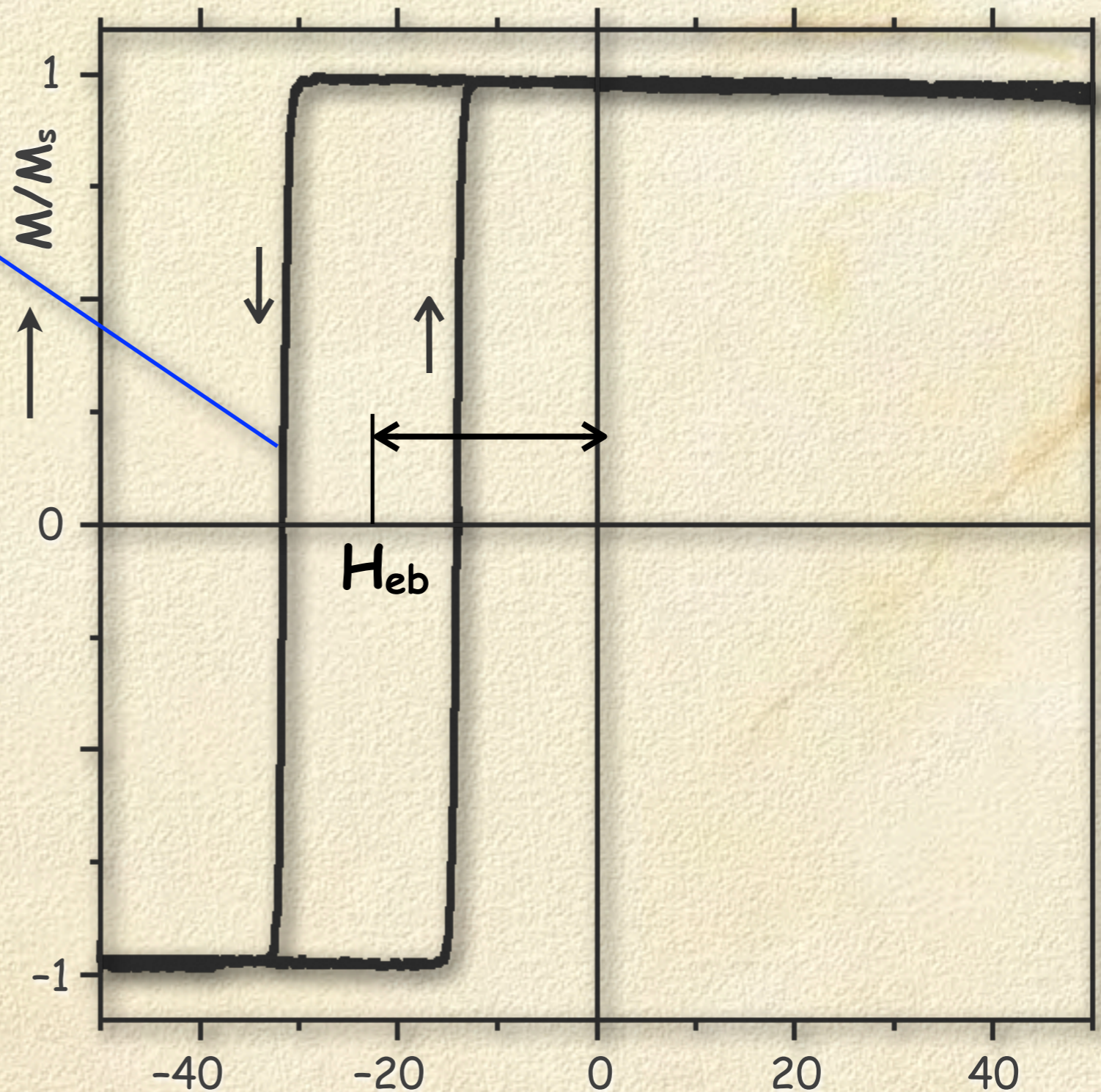
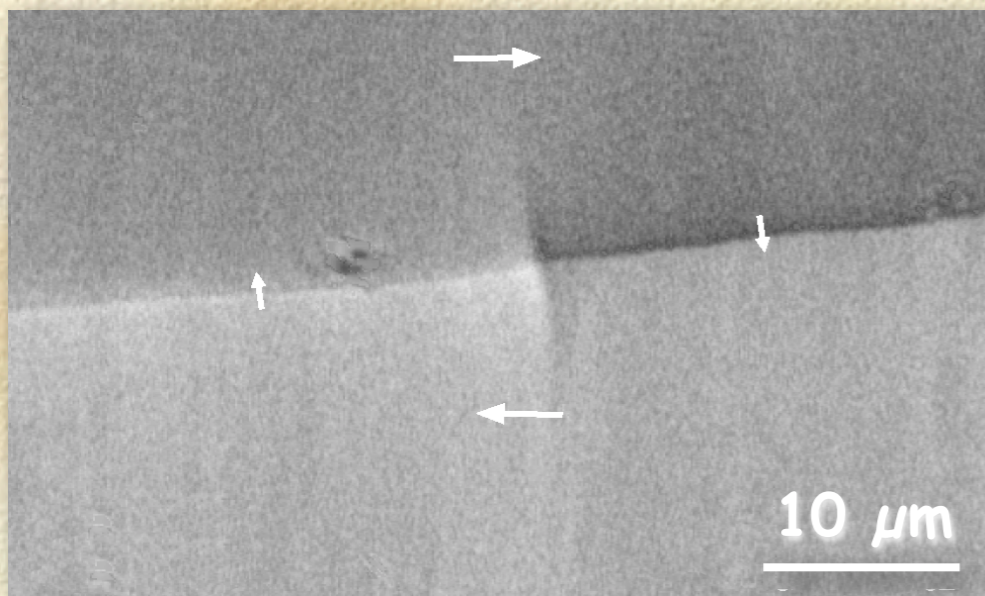
Unidirectional anisotropy



external field in Oe

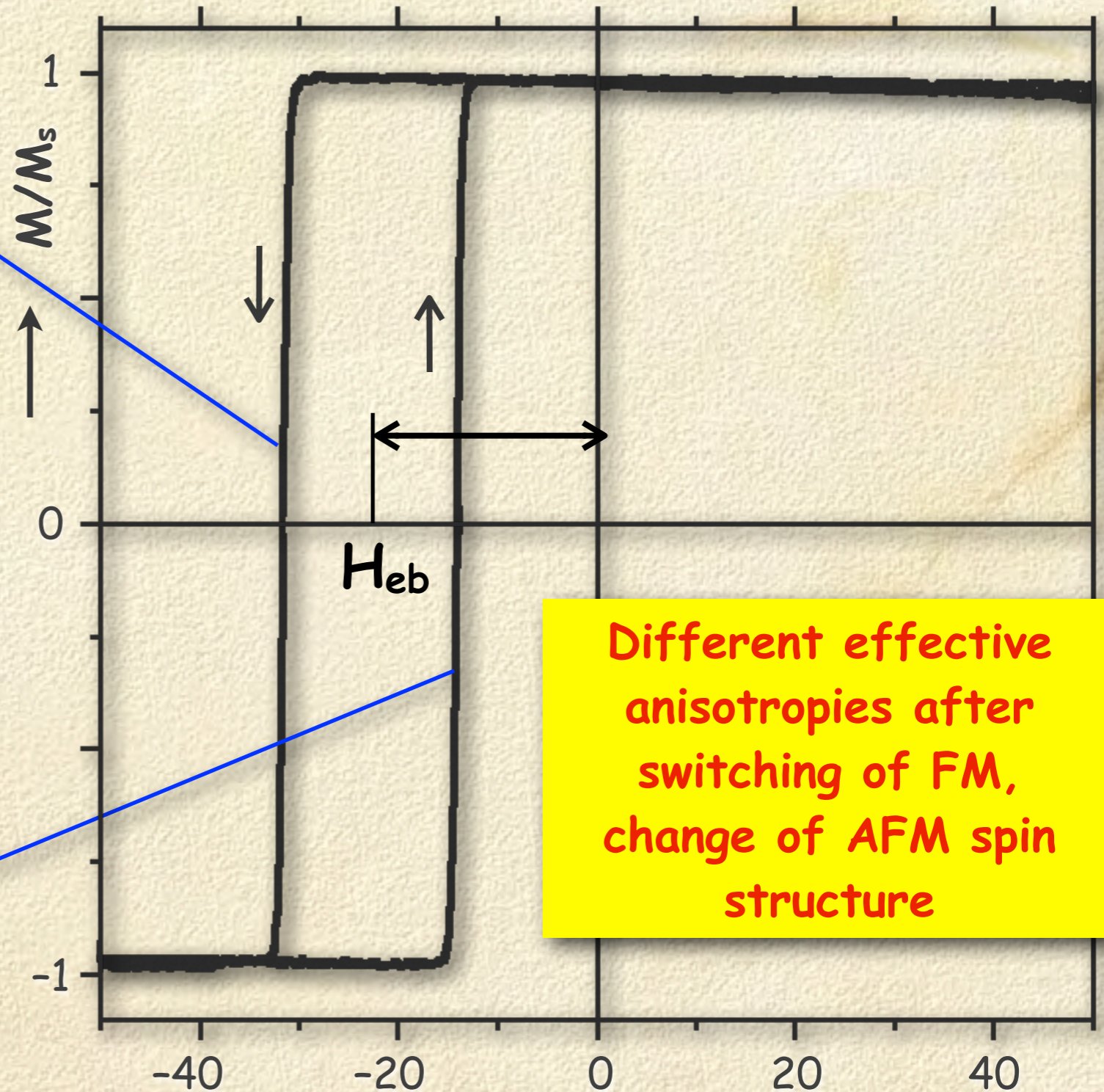
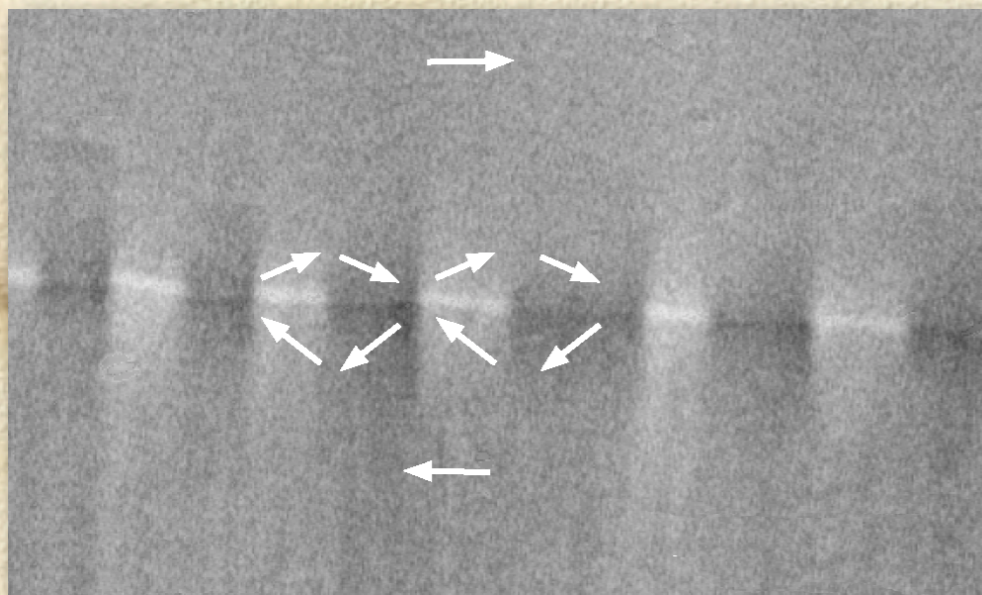
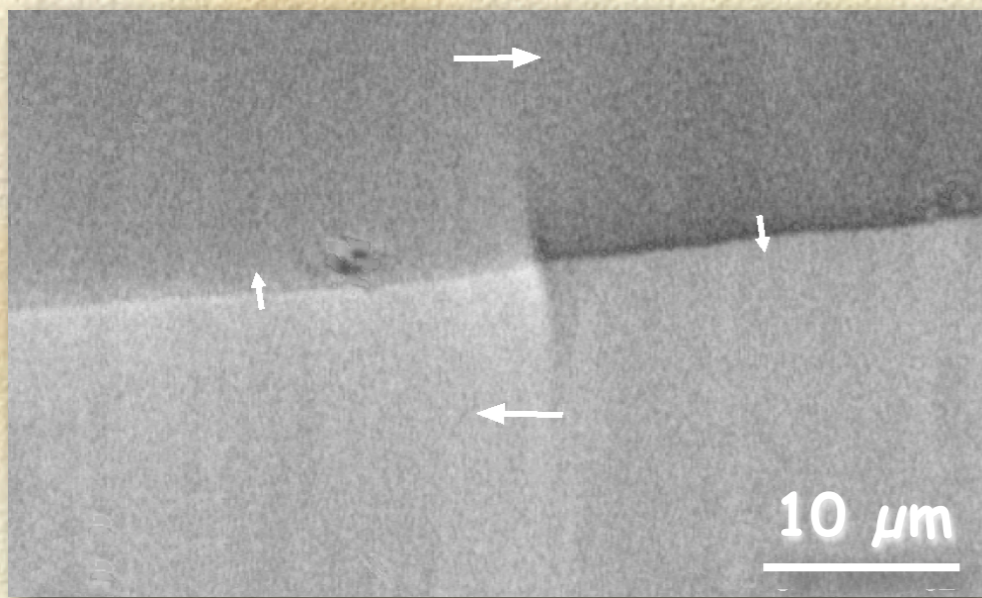
M(H) loop and domains

Reversal of Ni₈₁Fe₁₉ (30 nm) / NiO (30 nm)



M(H) loop and domains

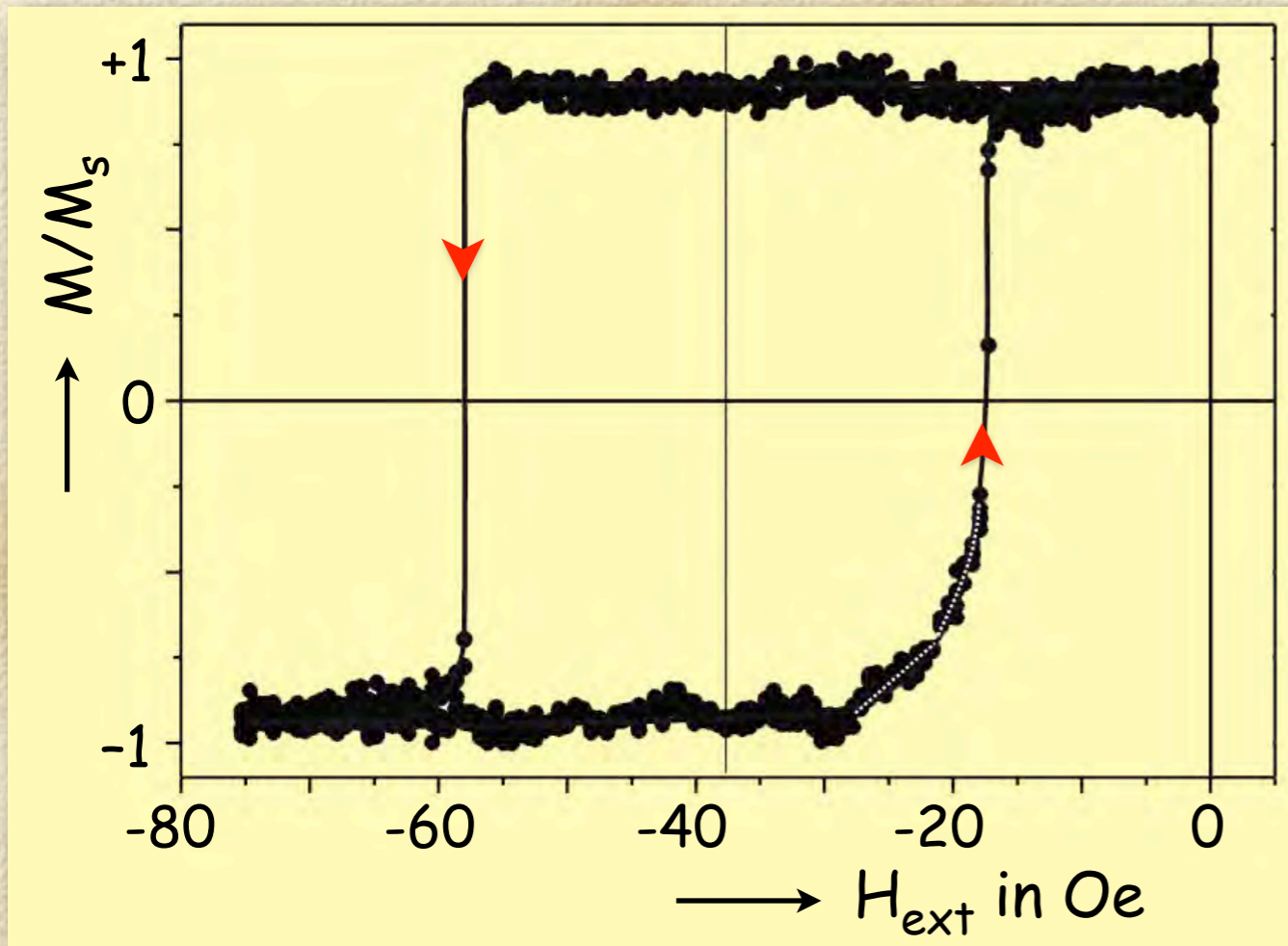
Reversal of Ni₈₁Fe₁₉ (30 nm) / NiO (30 nm)



Different effective anisotropies after switching of FM, change of AFM spin structure

$M(H)$ loop and domains

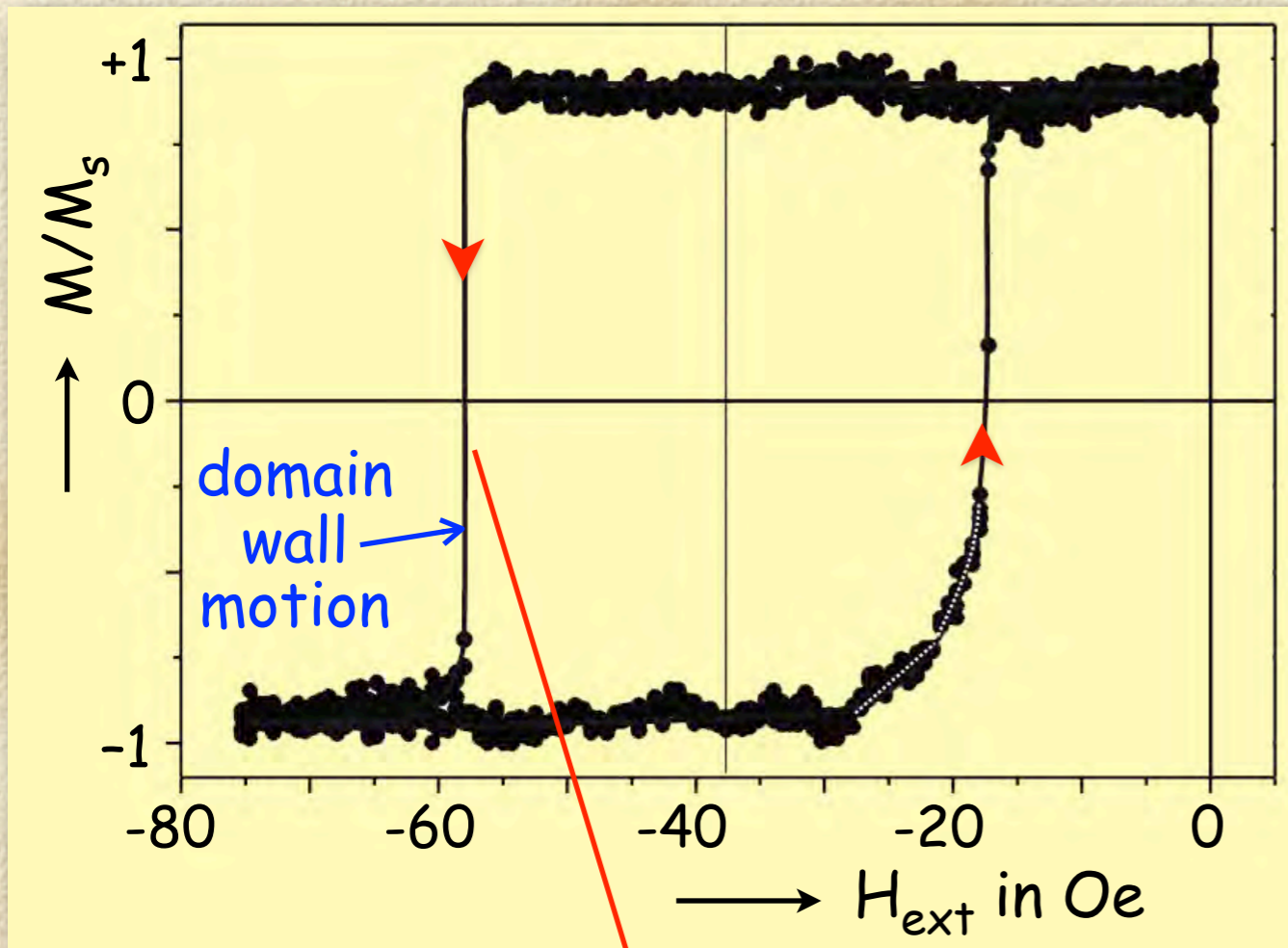
M(H) loop and domains



$Co_{90}Fe_{10}$ (20 nm)

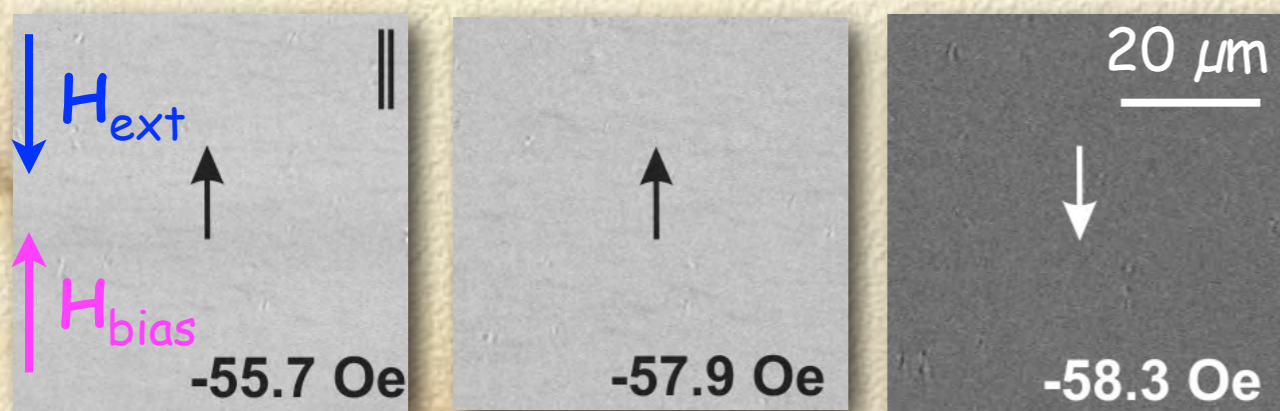
$Ir_{23}Mn_{77}$ (10 nm)

M(H) loop and domains



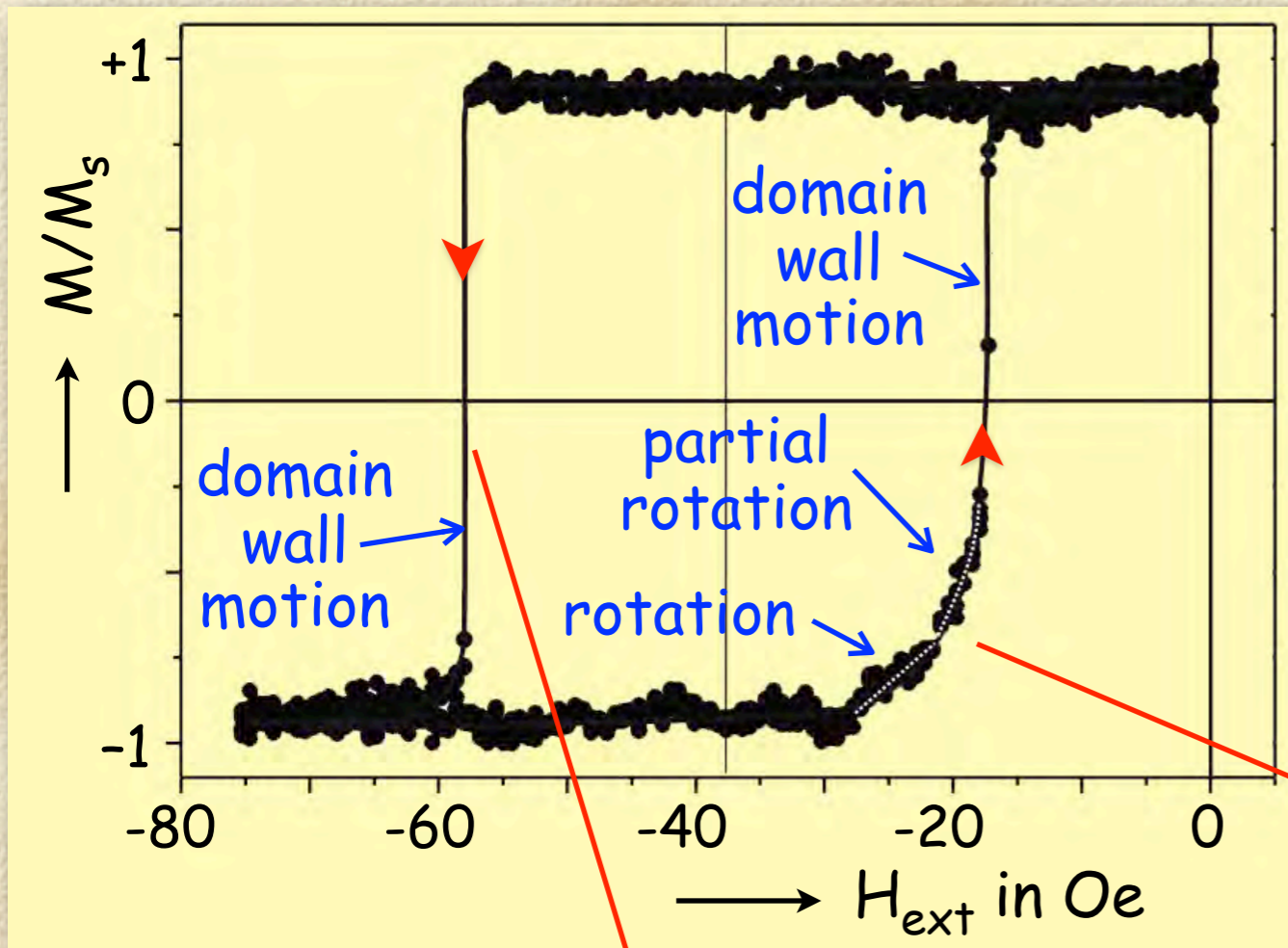
$Co_{90}Fe_{10}$ (20 nm)

$Ir_{23}Mn_{77}$ (10 nm)

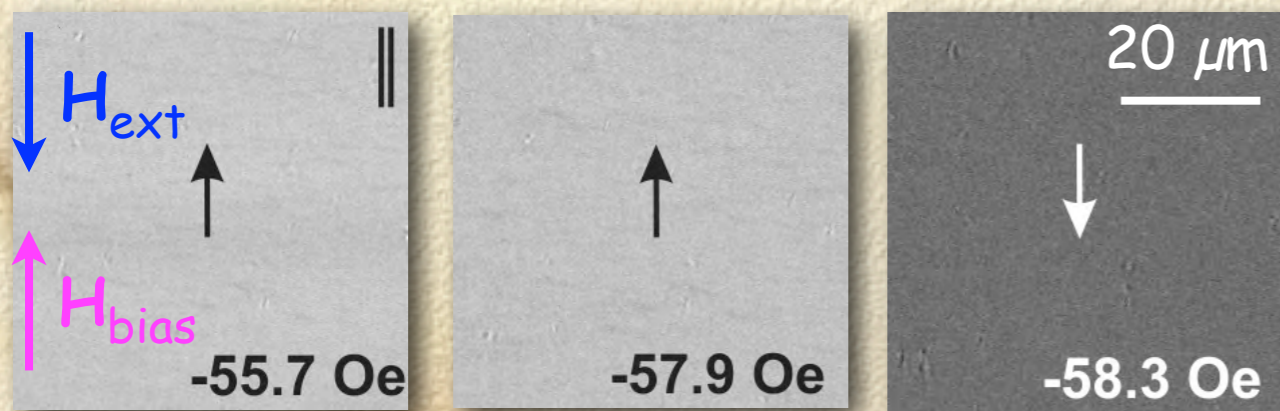
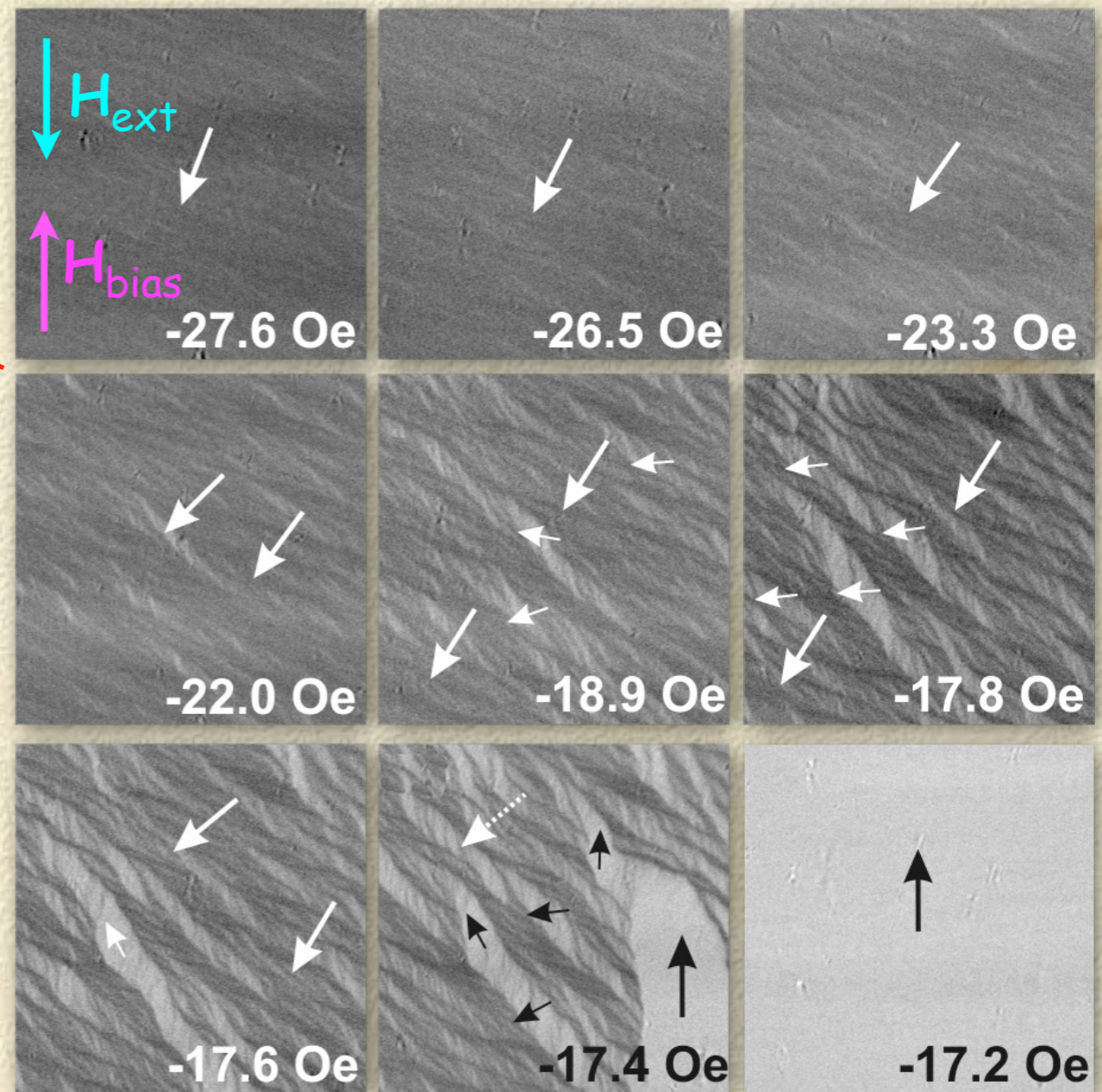


J. McCord, R.S., R. Mattheis, K.-U. Barholz:
J. Appl. Phys. 93, 5491 (2003)

M(H) loop and domains



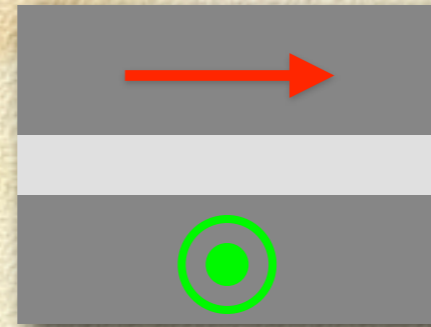
Co₉₀Fe₁₀ (20 nm)
Ir₂₃Mn₇₇ (10 nm)



J. McCord, R.S., R. Mattheis, K.-U. Barholz:
 J. Appl. Phys. 93, 5491 (2003)

indication of strong anisotropy dispersion

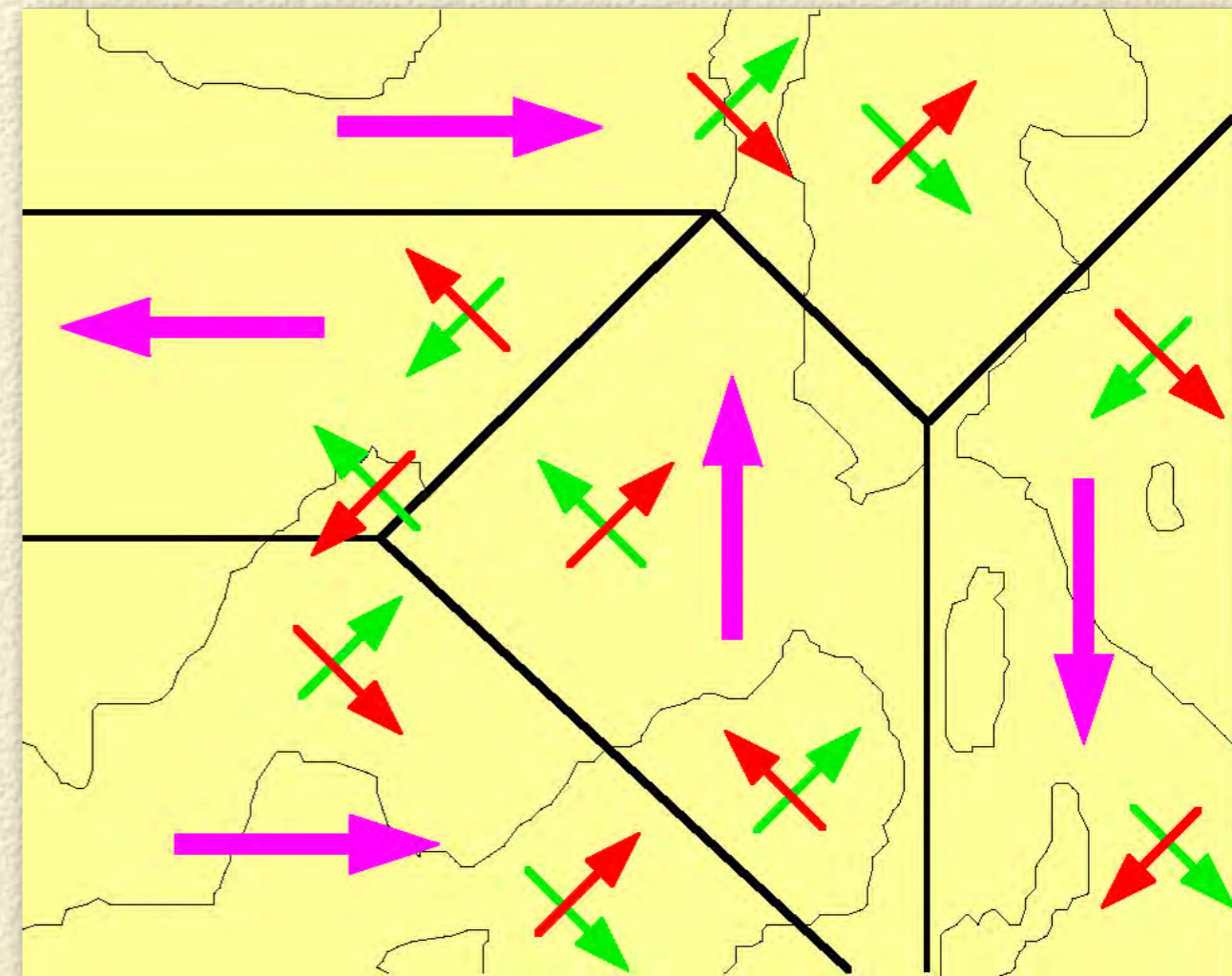
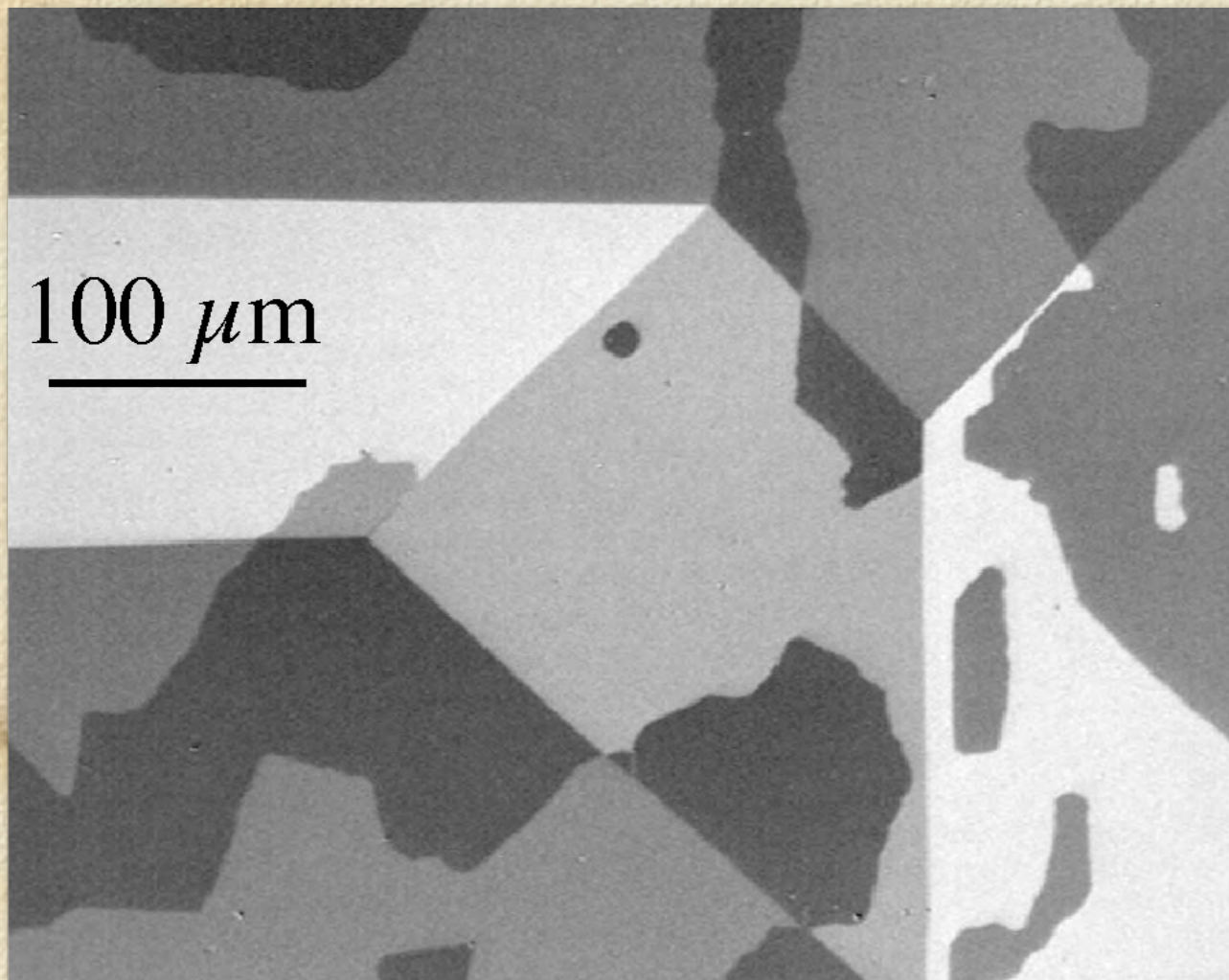
Biquadratic coupling in multilayers



Fe (30 nm)

Cr (1.6 nm)

Fe (30 nm)



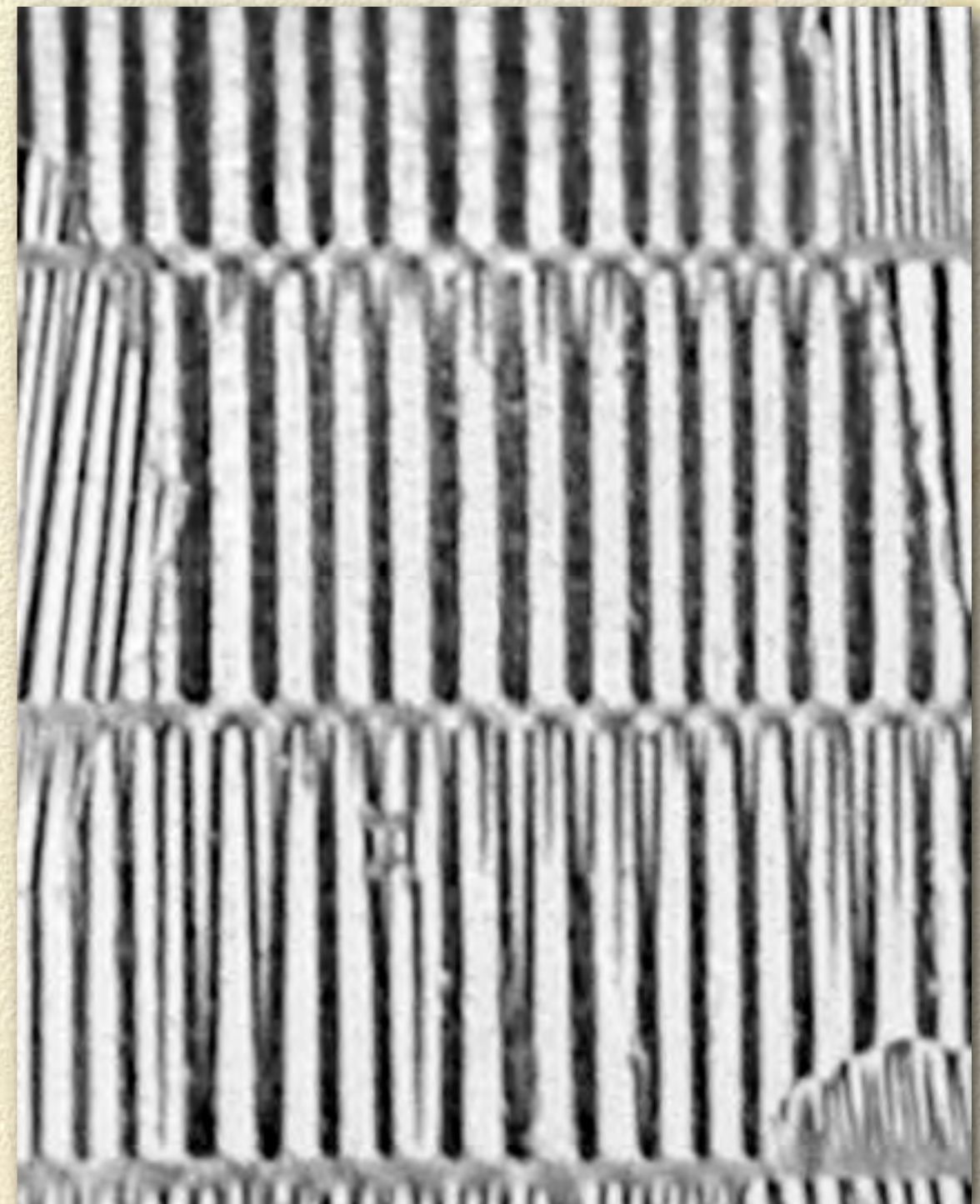
Loss control by domain control

Grain-oriented FeSi transformer material

Without artificial domain refinement



After laser scribing

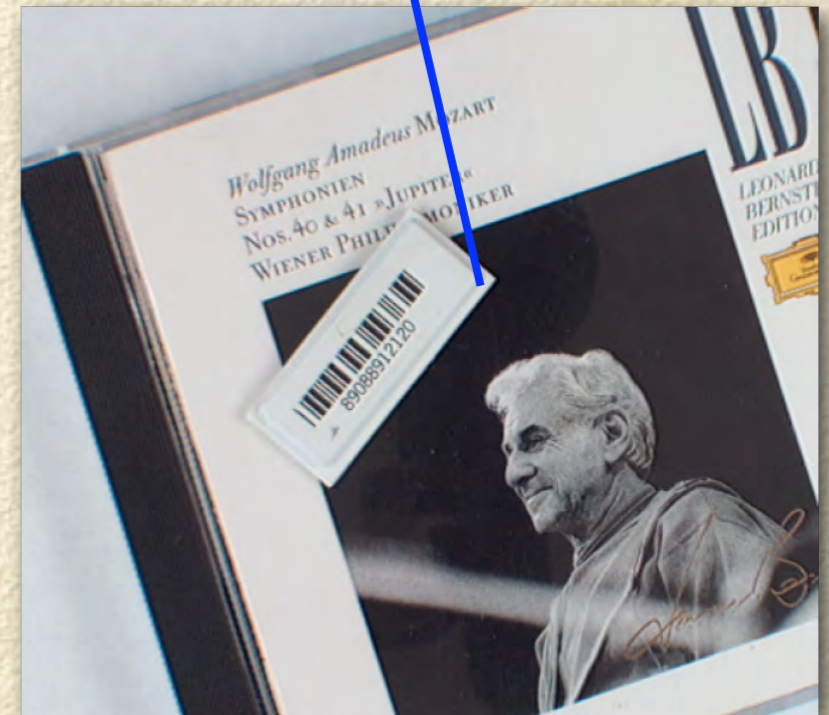
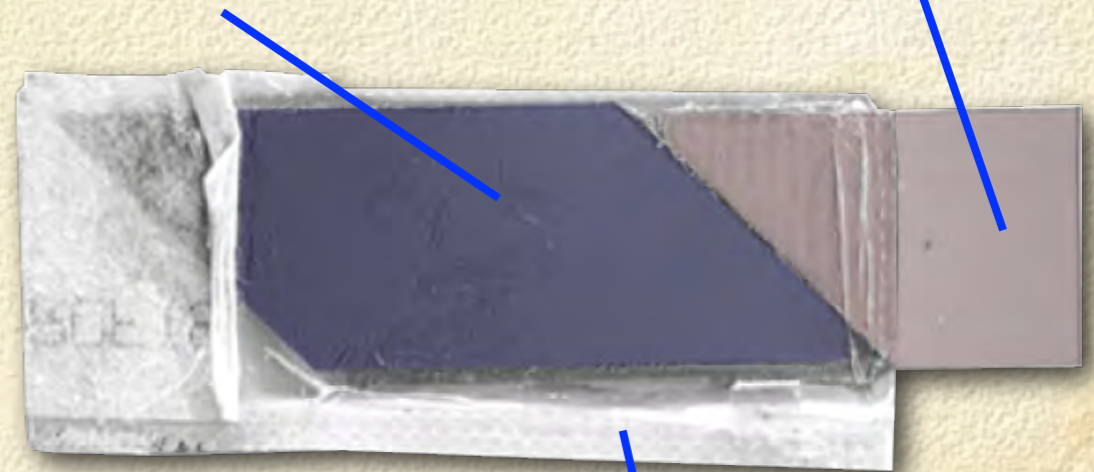


Magneto-acoustic Article Surveillance



semihard metall
(on-/off-switch)

amorphous ribbon
(sensor)



Magneto-acoustic Article Surveillance

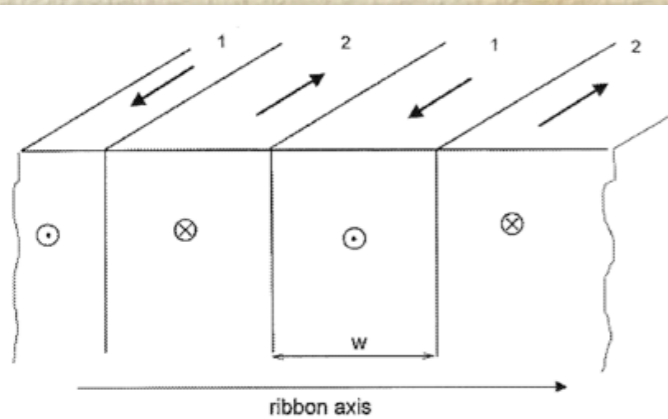


Fig. 1a (Prior Art)

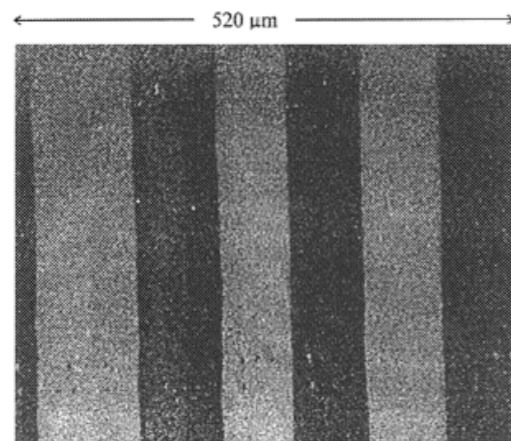


Fig. 1b (Prior Art)

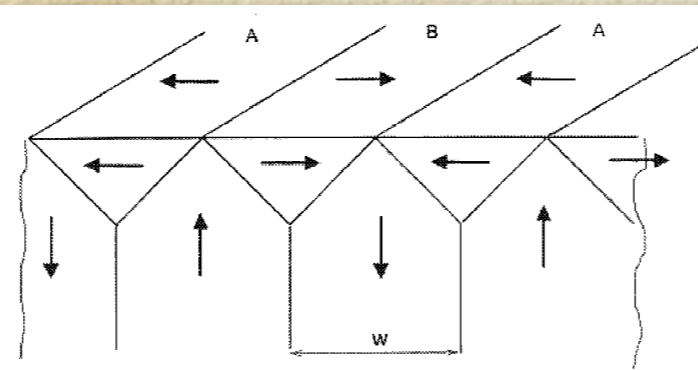


Fig. 2a (Prior Art)

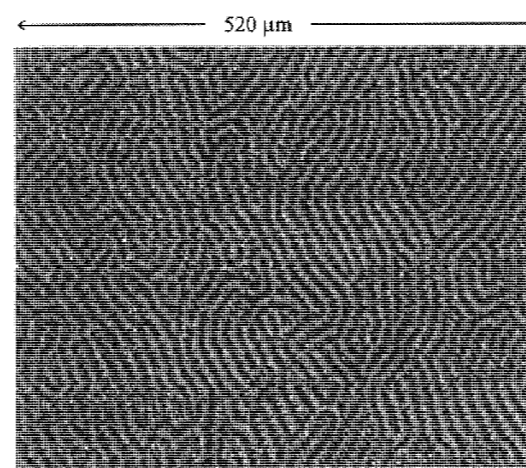


Fig. 2b

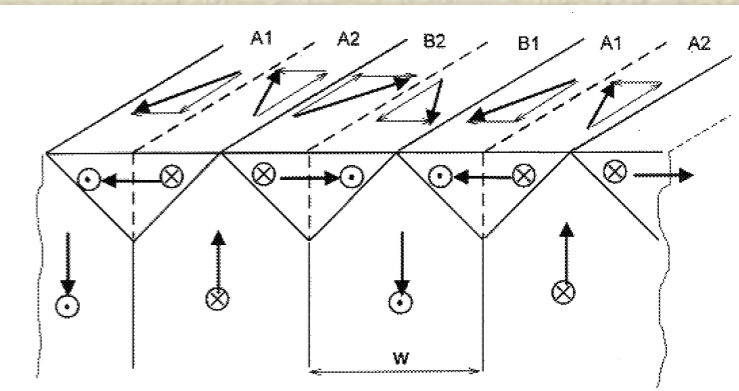


Fig. 8a

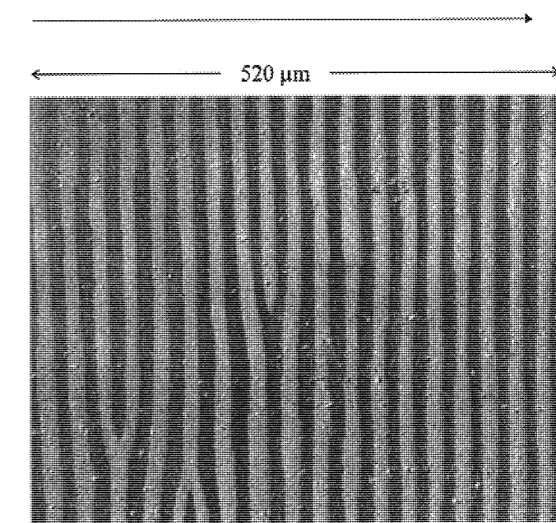


Fig. 8b

United States Patent [19]

Herzer

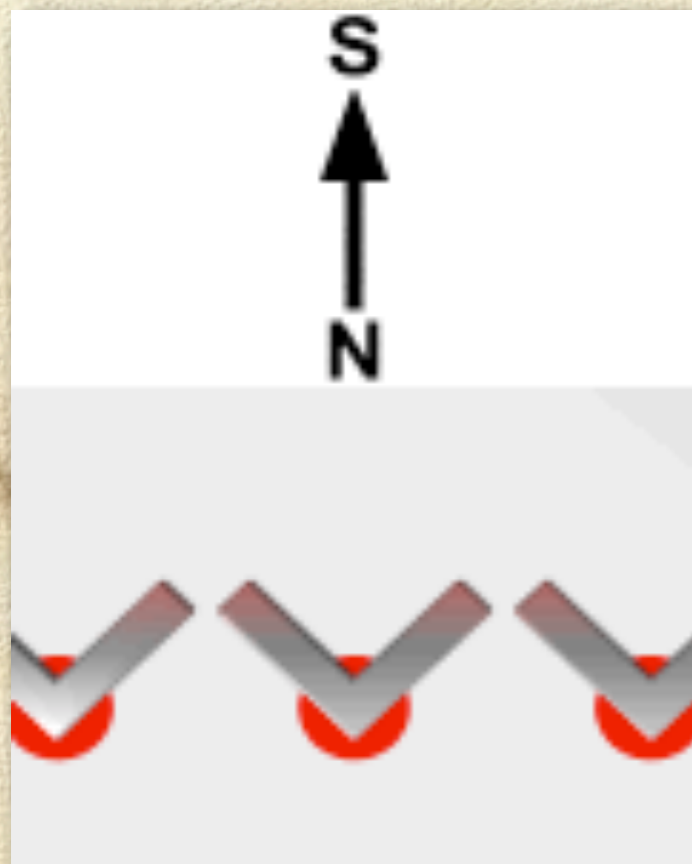
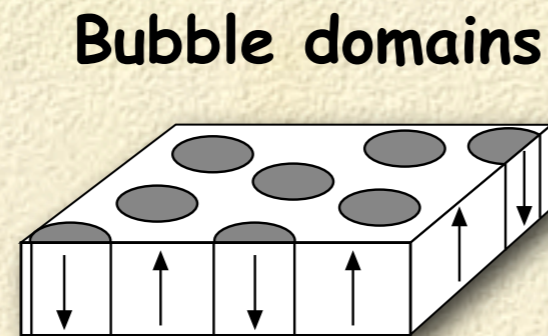
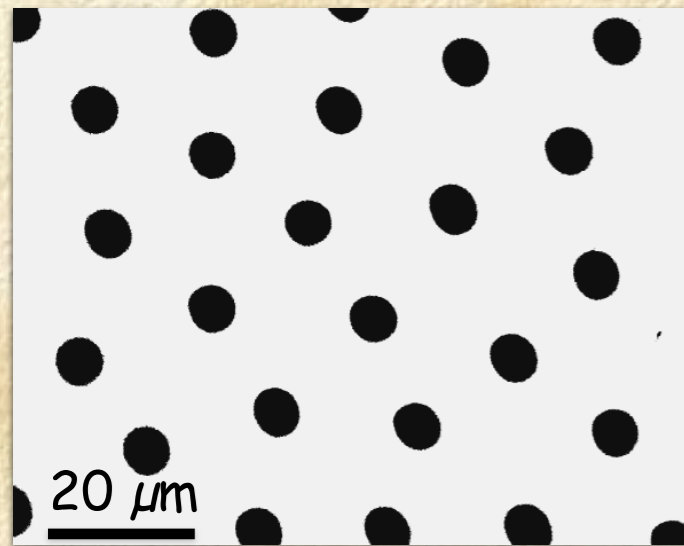
[54] METHOD OF ANNEALING AMORPHOUS RIBBONS AND MARKER FOR ELECTRONIC ARTICLE SURVEILLANCE

[75] Inventor: Giselher Herzer, Bruchkoebel, Germany

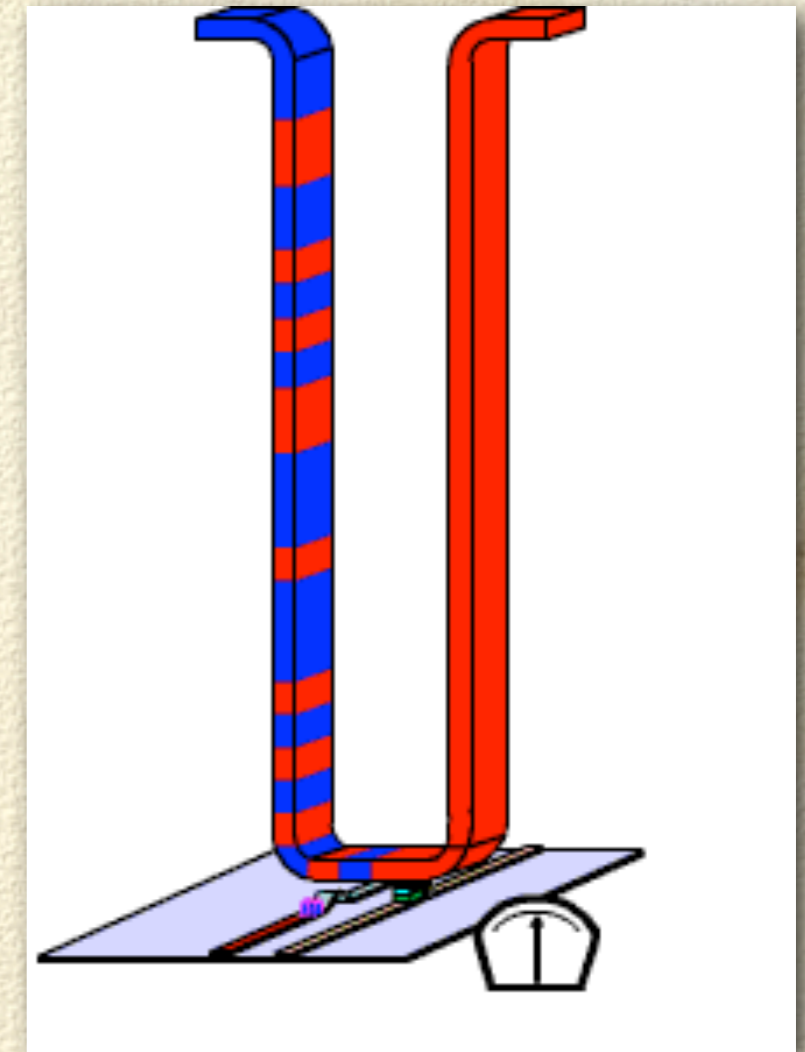
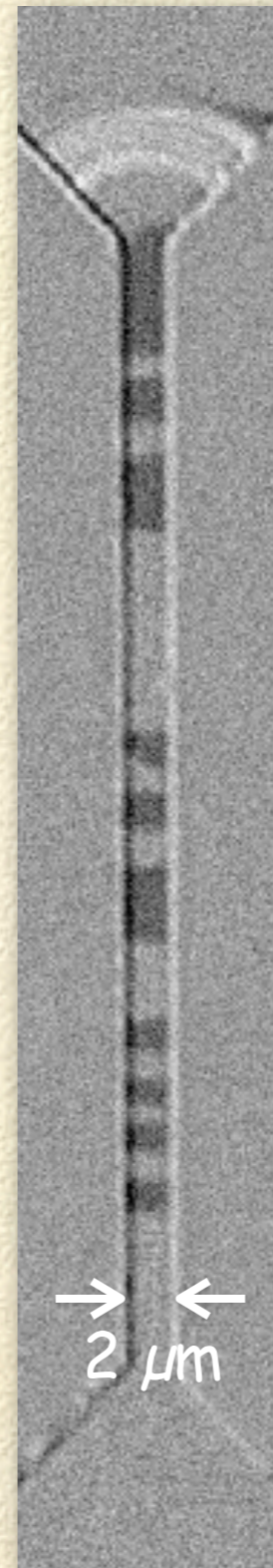
[73] Assignee: Vacuumschmelze GmbH, Hanau, Germany

Domain Shift Register Devices

Bubble Memory



Race Track Memory

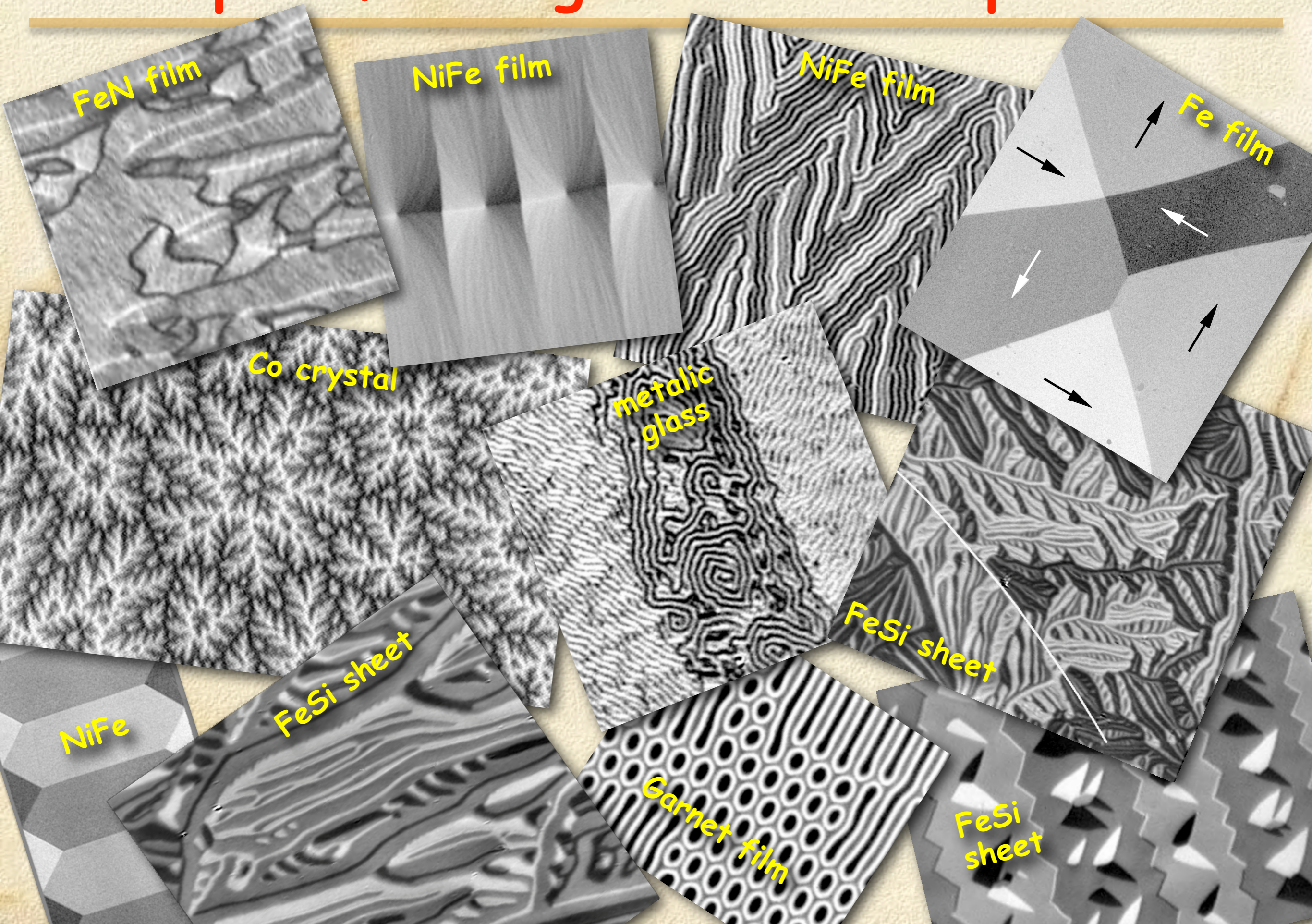


Kerr-movie of Co/Ni
PMA multilayer

courtesy
S. Parkin, IBM

http://commons.wikimedia.org/wiki/How_bubble_memory_works

Examples for magnetic domain patterns



Origin of Magnetic Domains and Domain Classification

Origin of magnetic domains

Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy

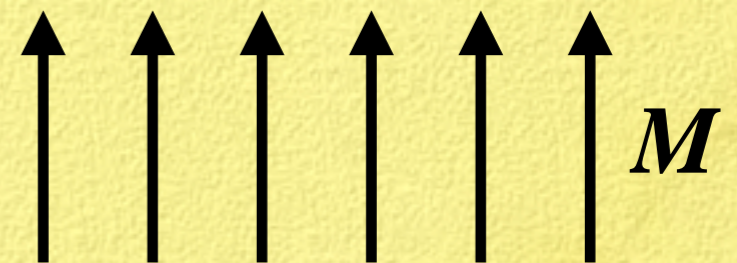
Origin of magnetic domains

Landau and Lifshitz (1935):

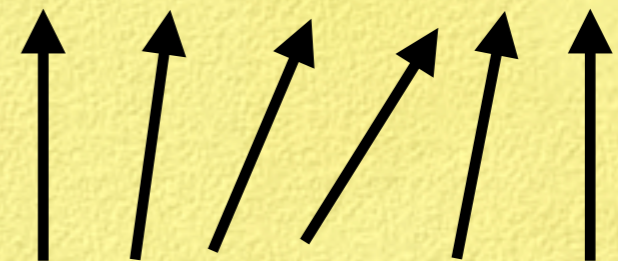
Domains are formed to minimize total energy

Exchange energy

$$e_A = 0$$



$$e_A > 0$$



Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy

Exchange energy

$$e_A = 0$$



$$e_A > 0$$



Anisotropy energy

Easy axis

M



$$e_K = 0$$



M



$$e_K > 0$$

Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy

Exchange energy

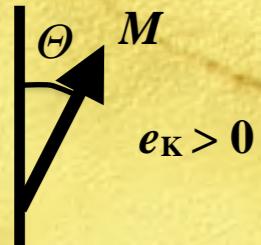
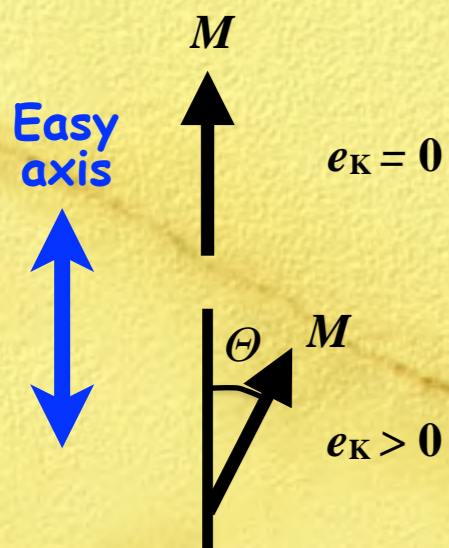
$$e_A = 0$$



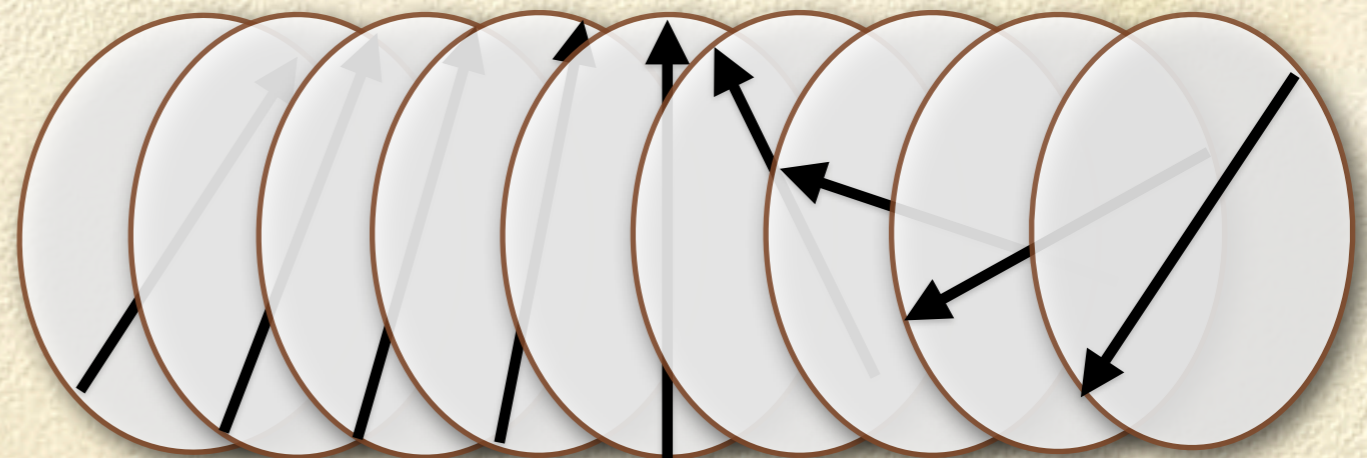
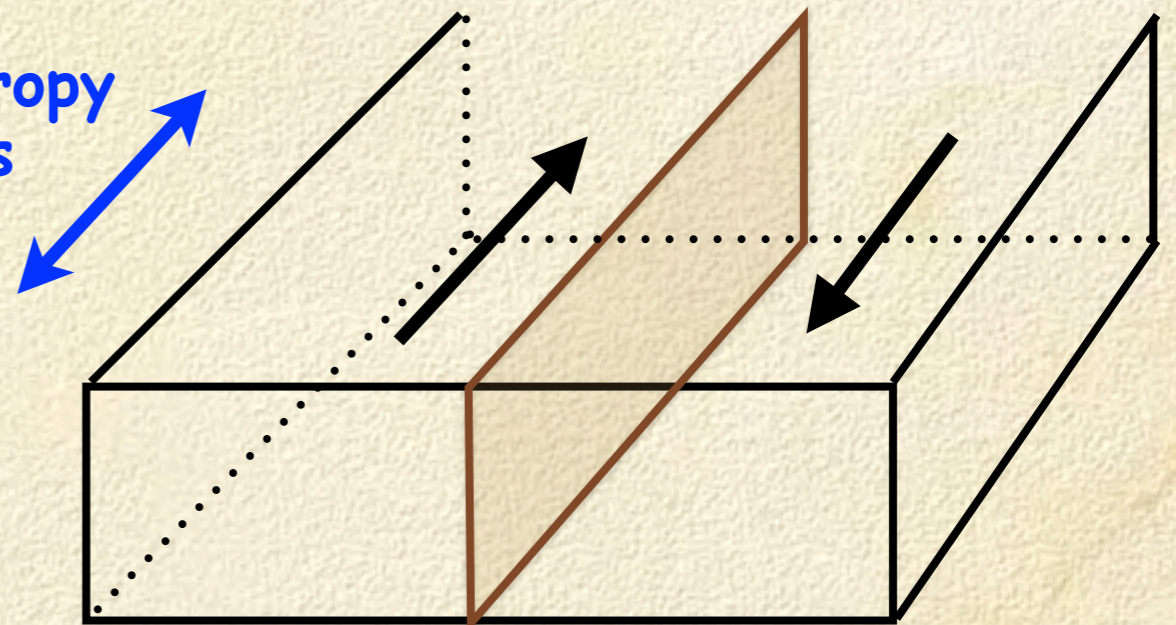
$$e_A > 0$$



Anisotropy energy



Anisotropy axis



Bloch wall

Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy

Exchange energy

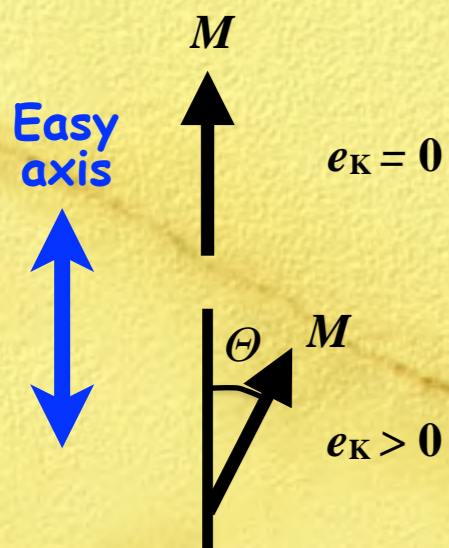
$$e_A = 0$$



$$e_A > 0$$

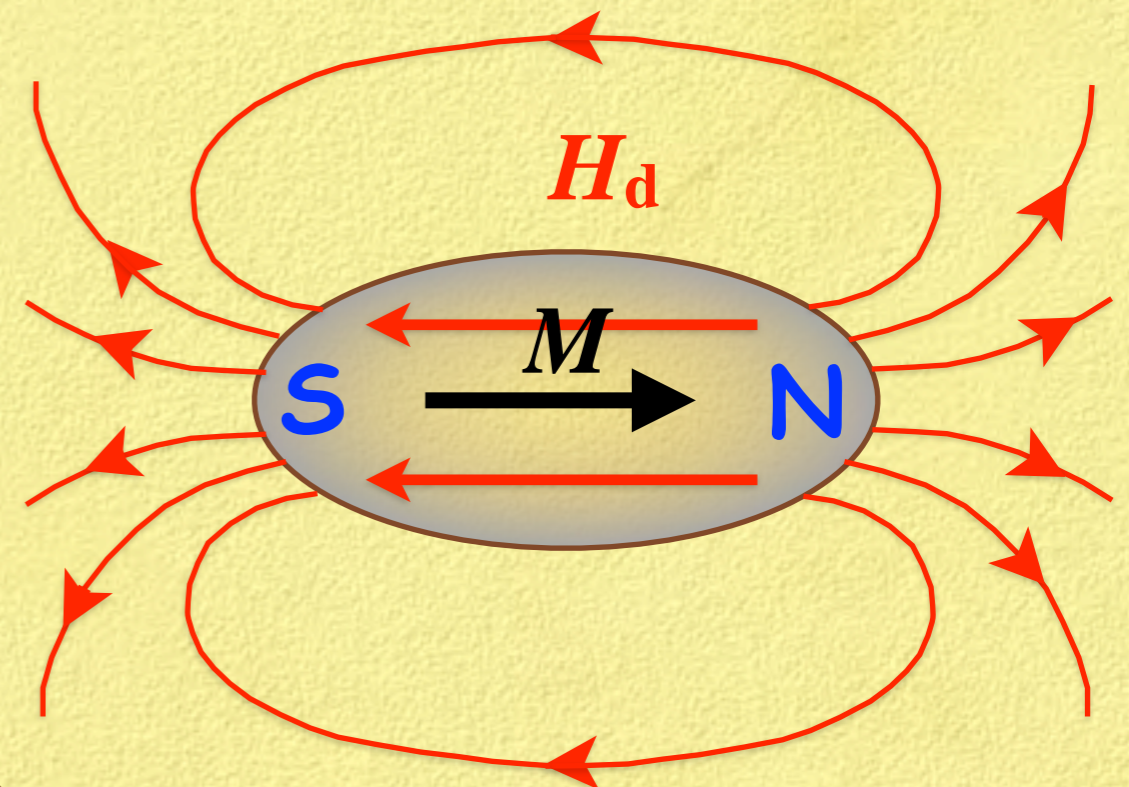
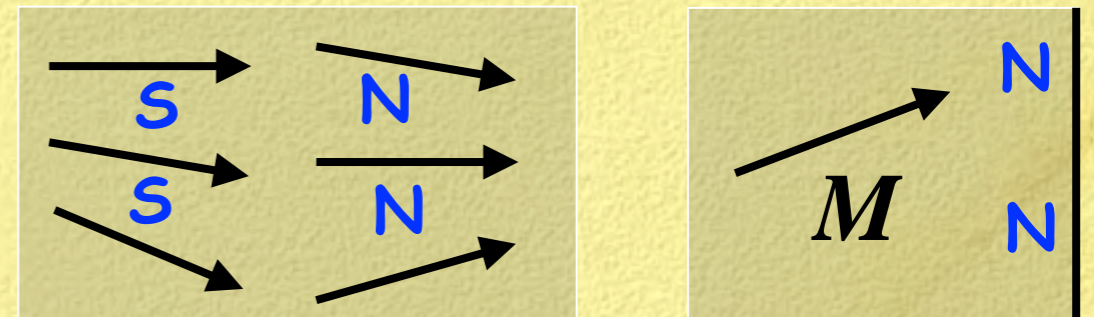


Anisotropy energy



Stray field energy

$$\text{div } H_d = -\text{div } M$$



Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy

Exchange energy

$$e_A = 0$$

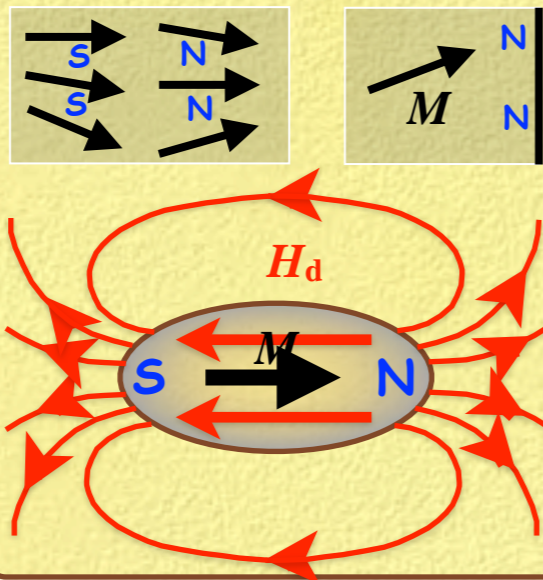


$$e_A > 0$$

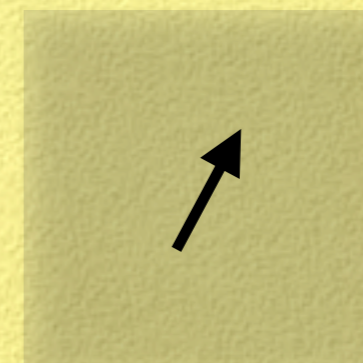
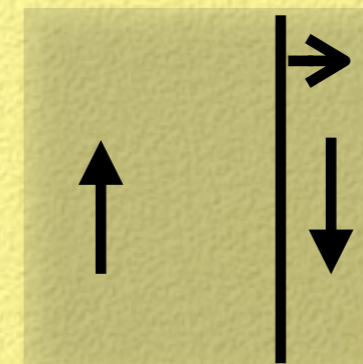
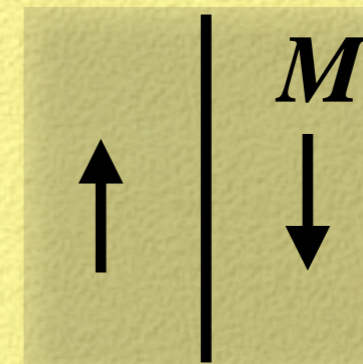


Stray field energy

$$\text{div } H_d = -\text{div } M$$



External field energy



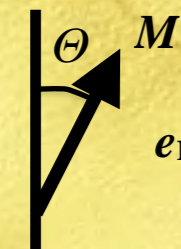
Anisotropy energy

M

Easy axis



$$e_K = 0$$



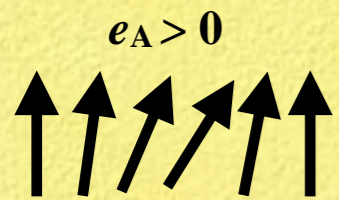
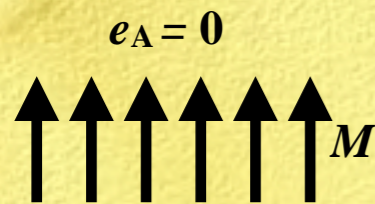
$$e_K > 0$$

Origin of magnetic domains

Landau and Lifshitz (1935):

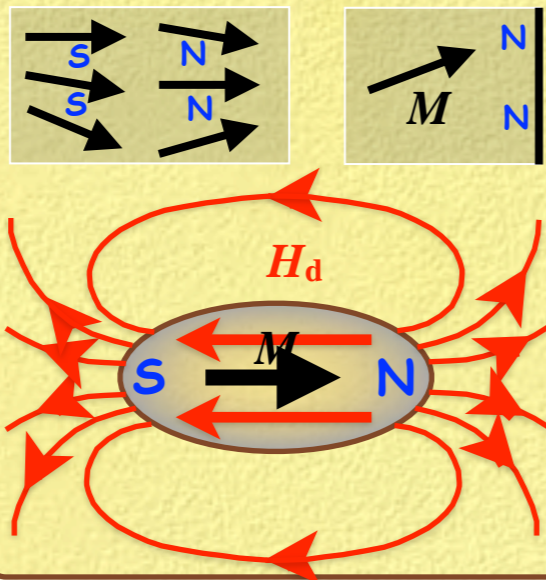
Domains are formed to minimize total energy

Exchange energy

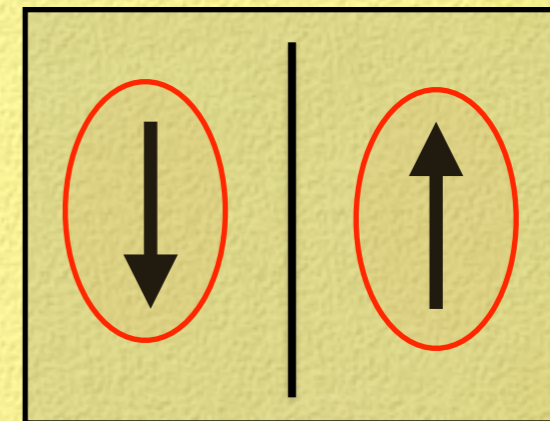


Stray field energy

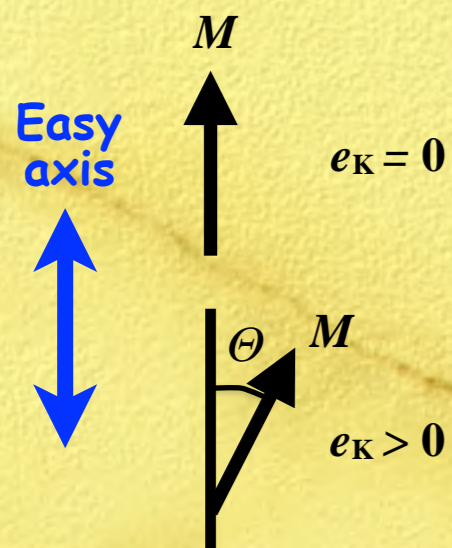
$$\text{div } H_d = -\text{div } M$$



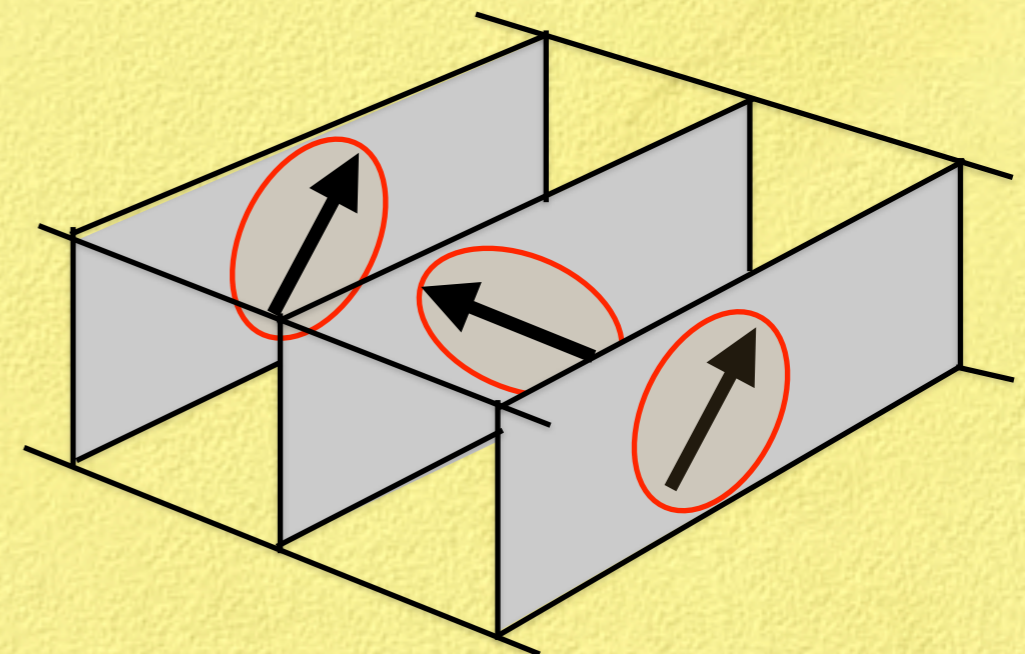
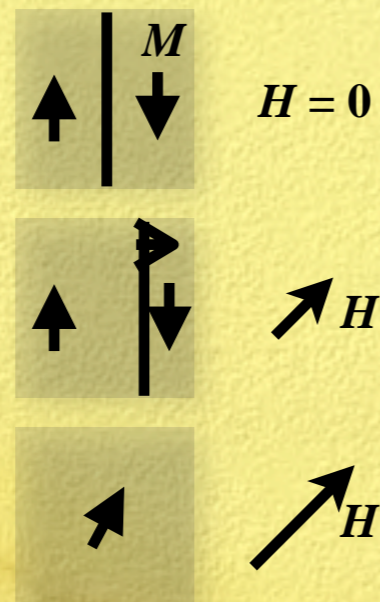
Magnetostrictive self energy



Anisotropy energy

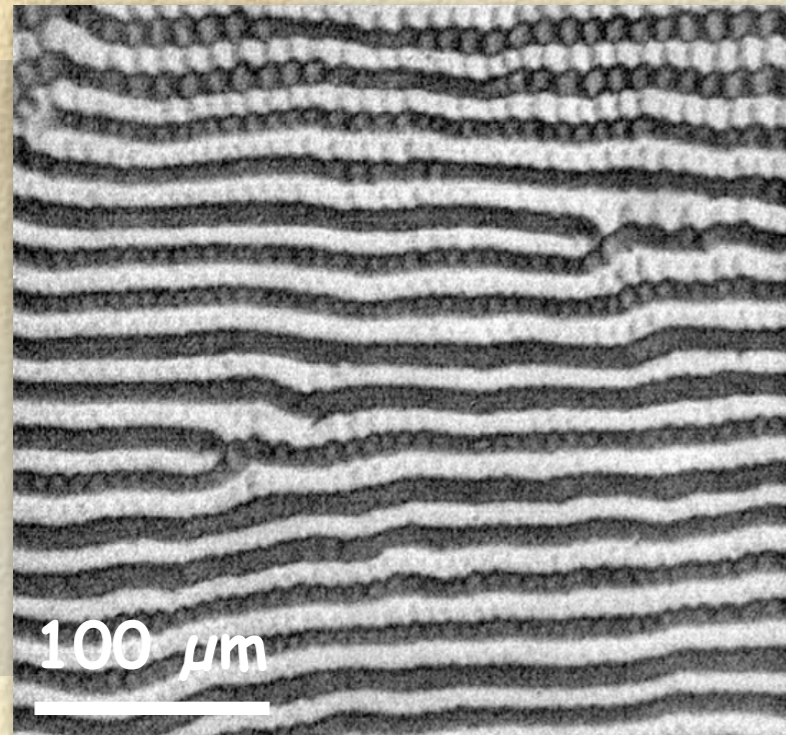


External field energy

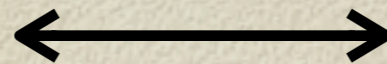


Magnetostriction and domains

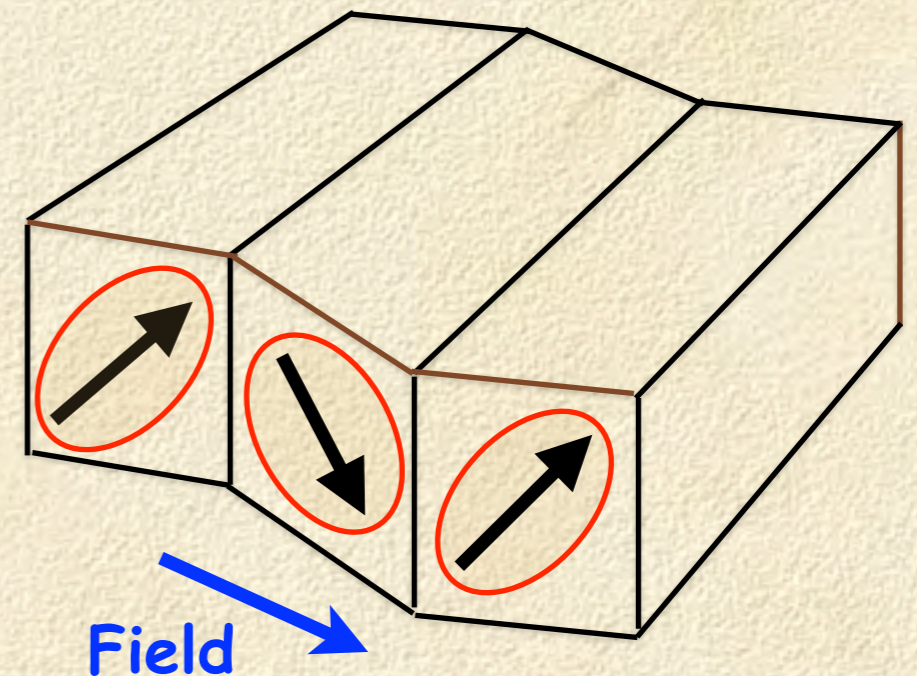
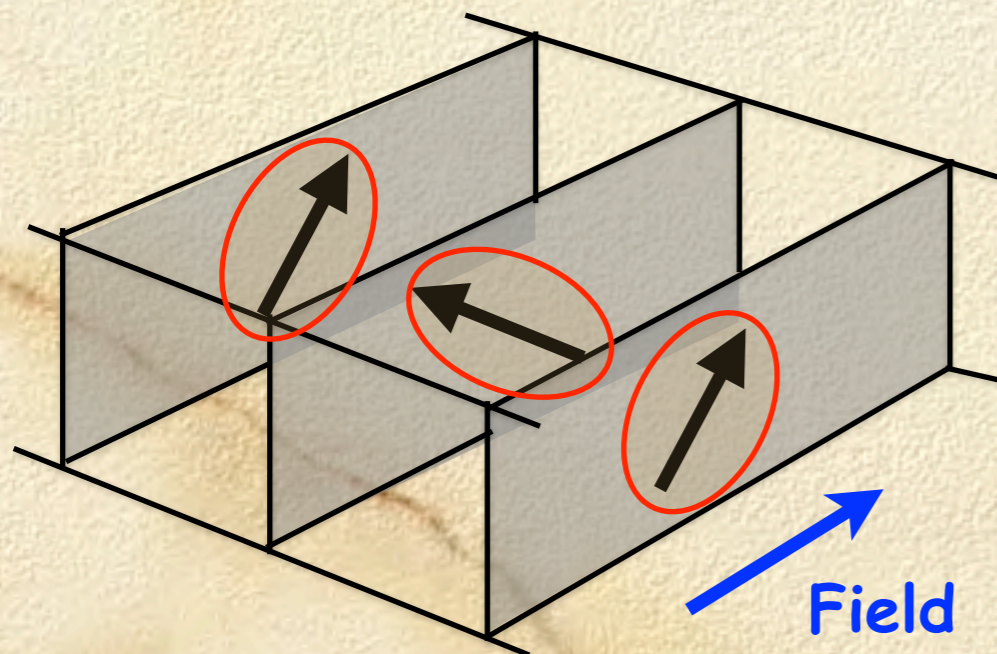
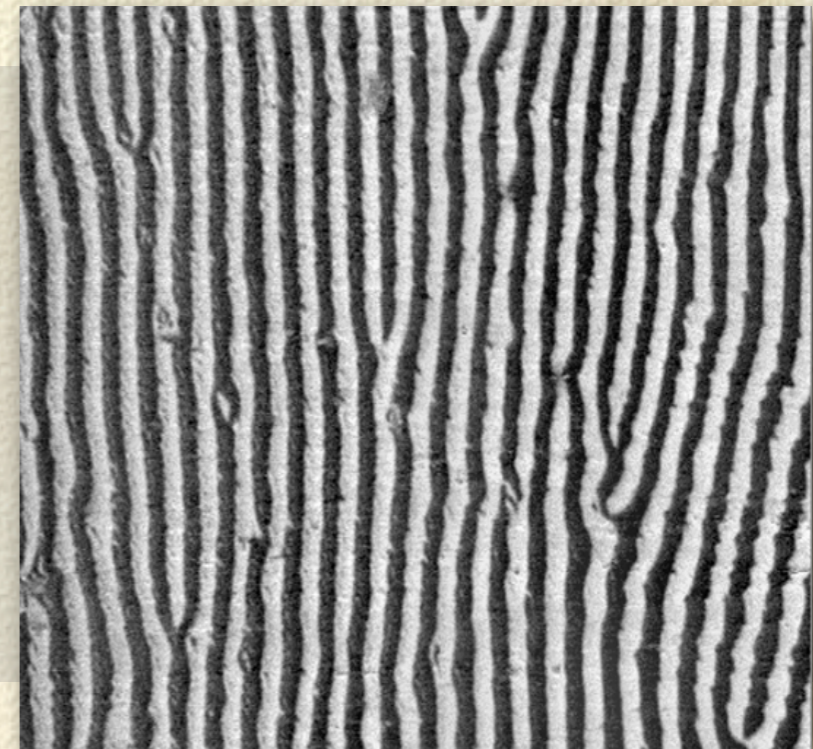
Amorphous ribbon with zero magnetostriction



Ribbon axis
= Field axis

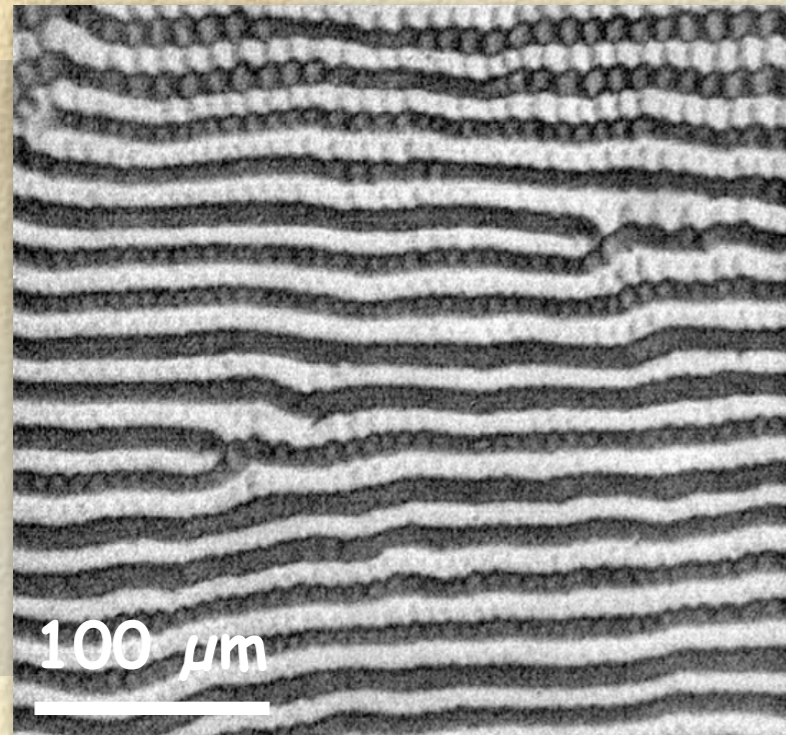


Amorphous ribbon with positive magnetostriction

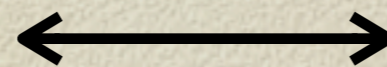


Magnetostriction and domains

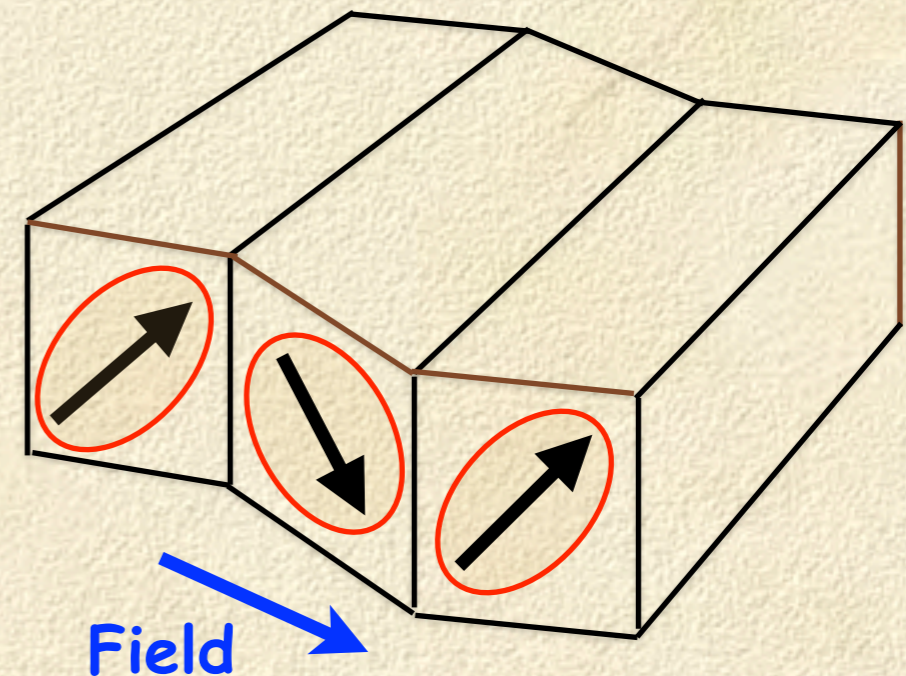
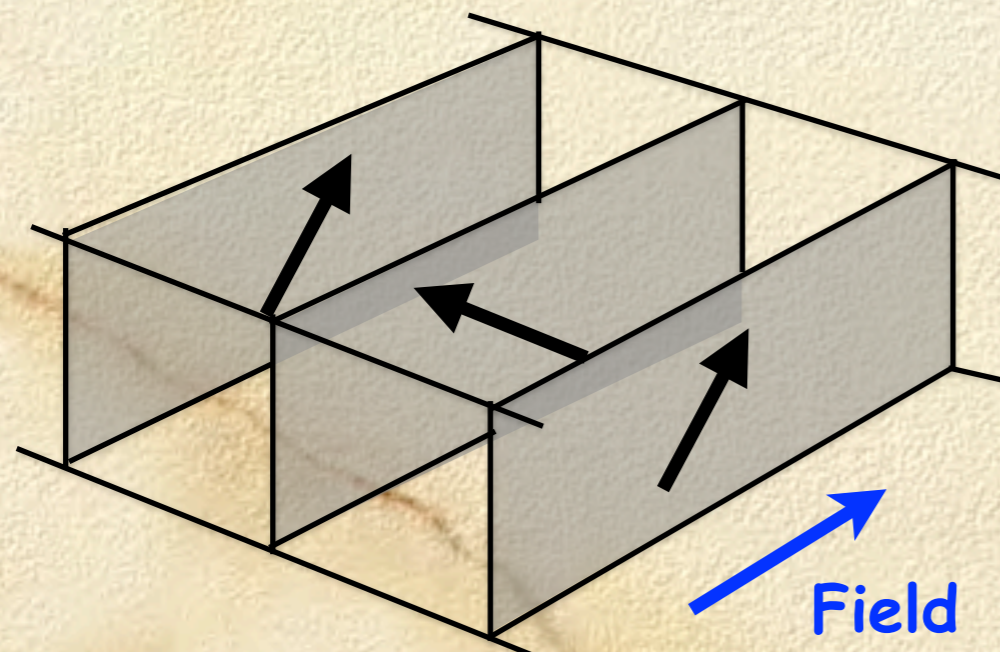
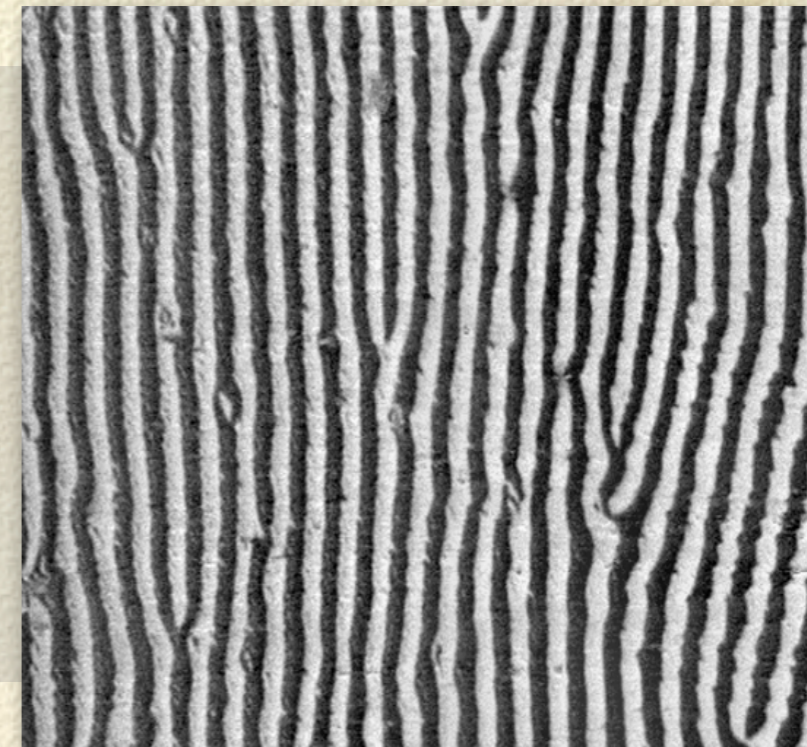
Amorphous ribbon with zero magnetostriction



Ribbon axis
= Field axis



Amorphous ribbon with positive magnetostriction



Origin of magnetic domains

Landau and Lifshitz (1935):

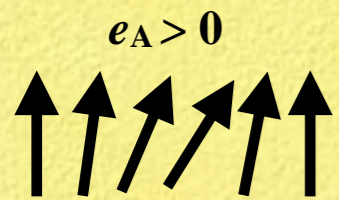
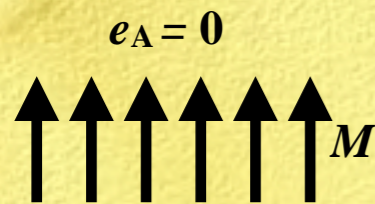
Domains are formed to minimize total energy

Origin of magnetic domains

Landau and Lifshitz (1935):

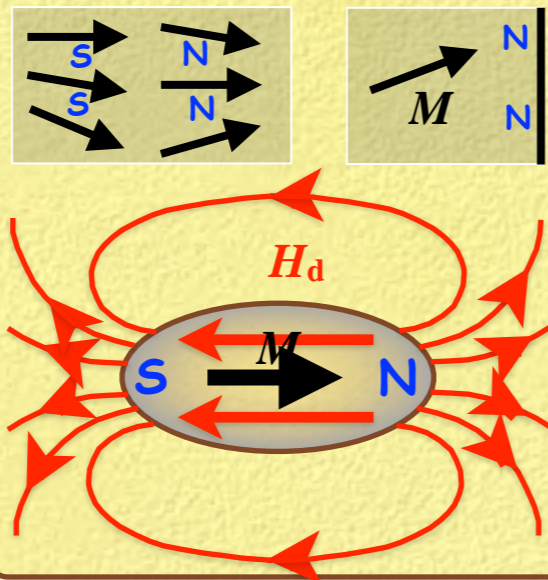
Domains are formed to minimize total energy

Exchange energy

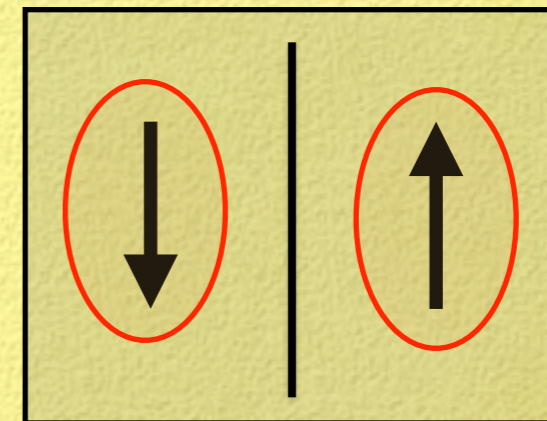


Stray field energy

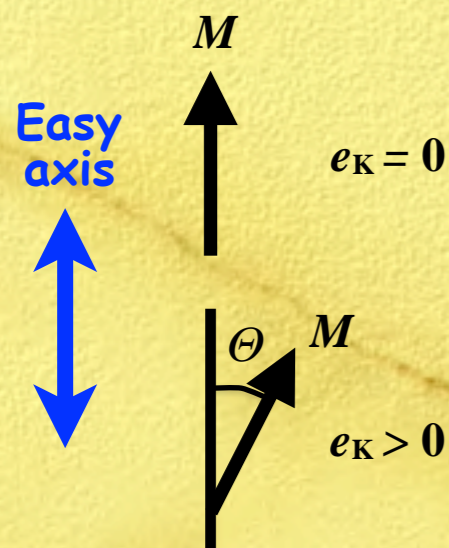
$$\text{div } H_d = -\text{div } M$$



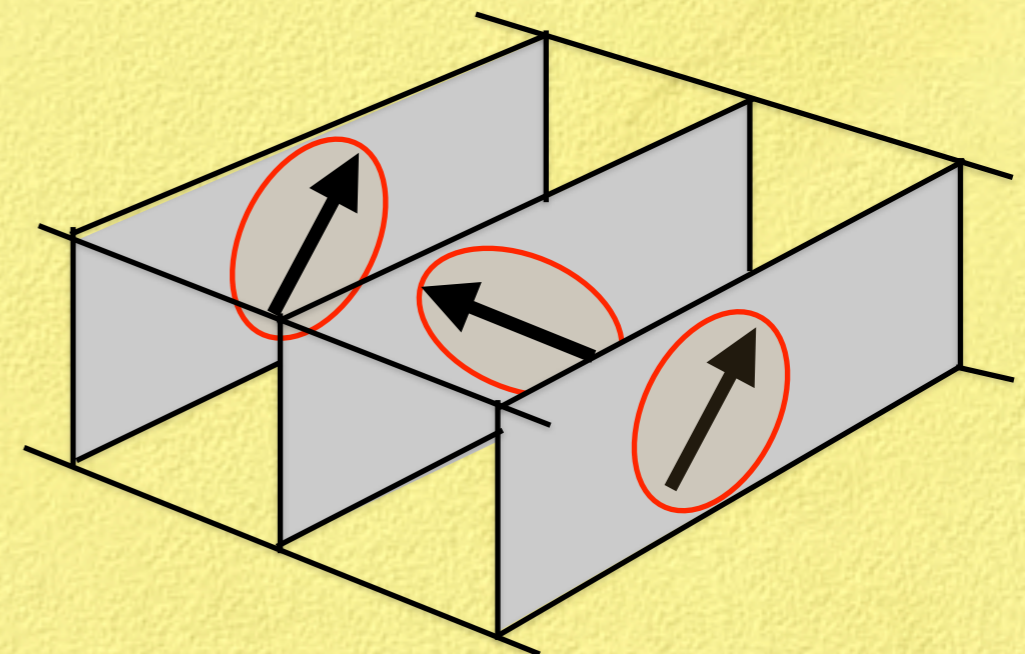
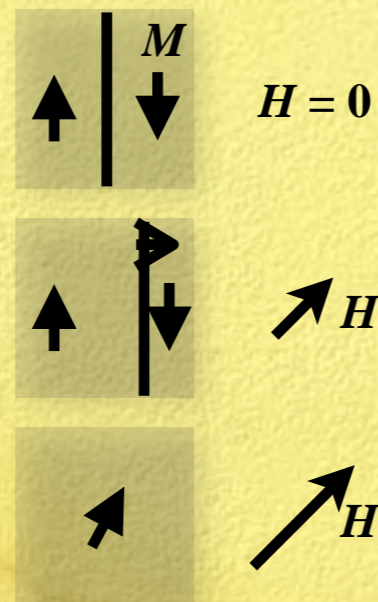
Magnetostrictive self energy



Anisotropy energy



External field energy

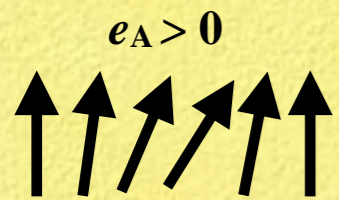
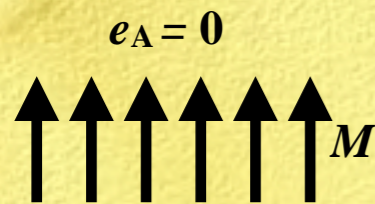


Origin of magnetic domains

Landau and Lifshitz (1935):

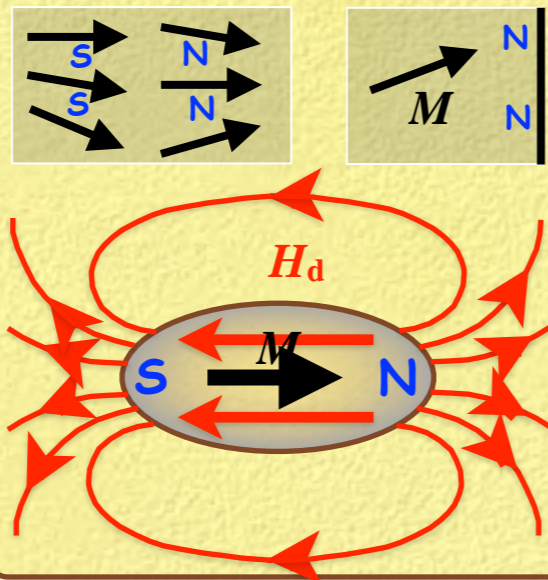
Domains are formed to minimize total energy

Exchange energy

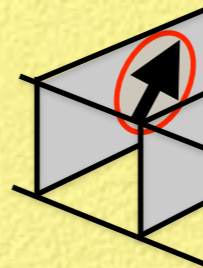


Stray field energy

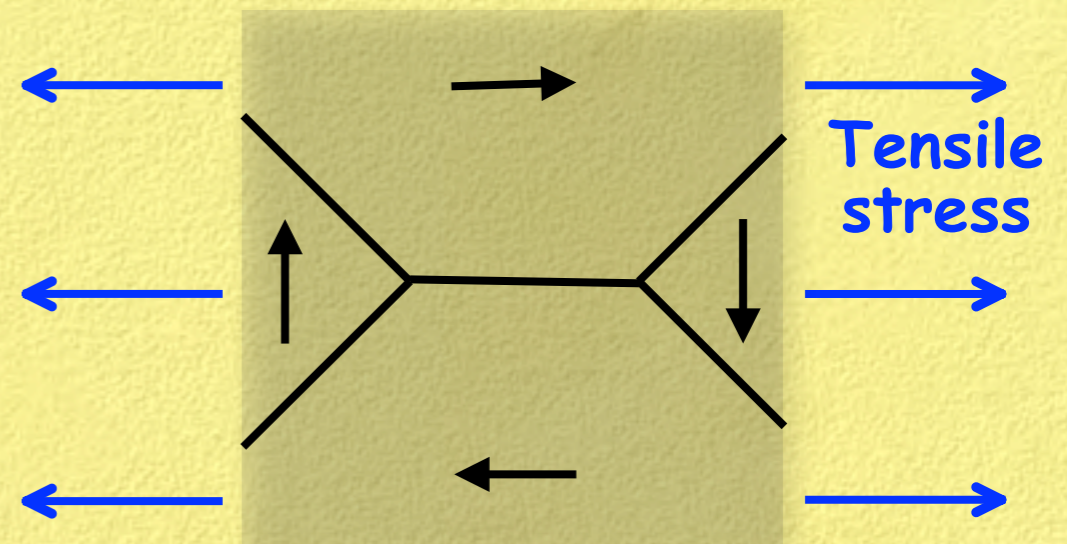
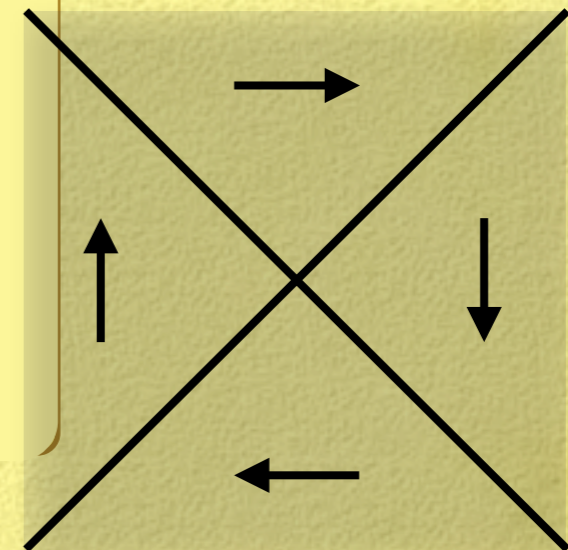
$$\text{div } H_d = -\text{div } M$$



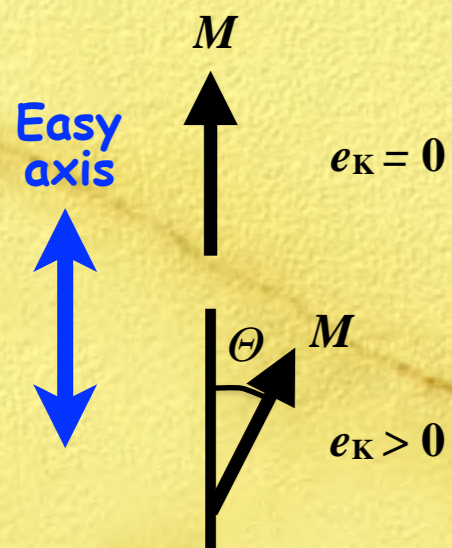
Magnetostatic self-energy



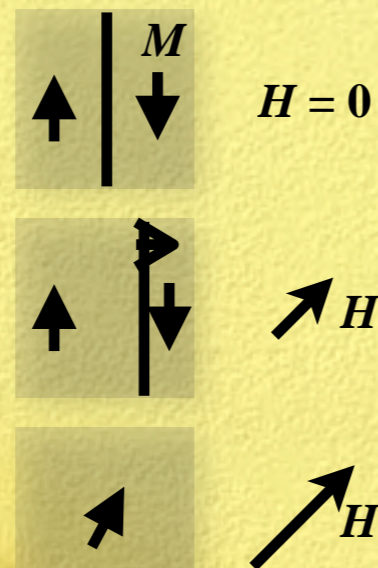
External stress energy



Anisotropy energy



External field energy

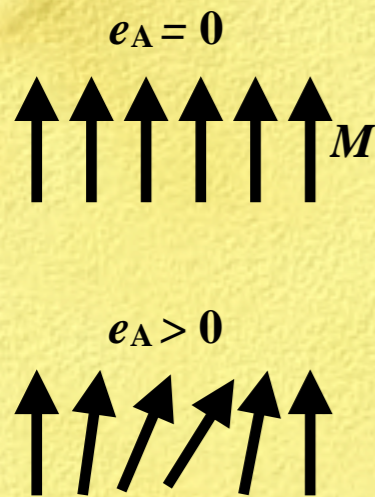


Origin of magnetic domains

Landau and Lifshitz (1935):

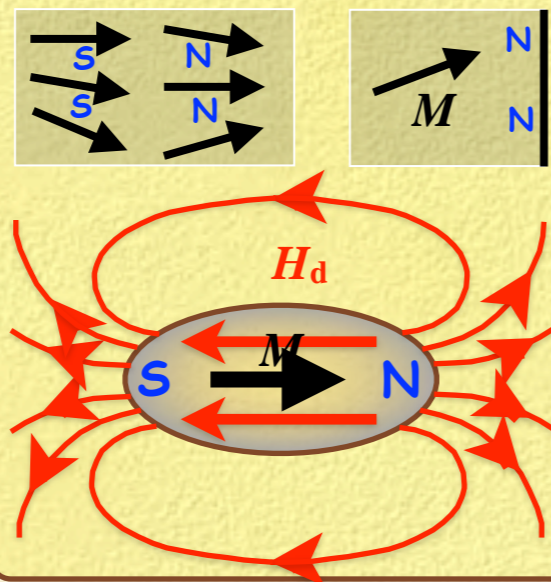
Domains are formed to minimize total energy

Exchange energy

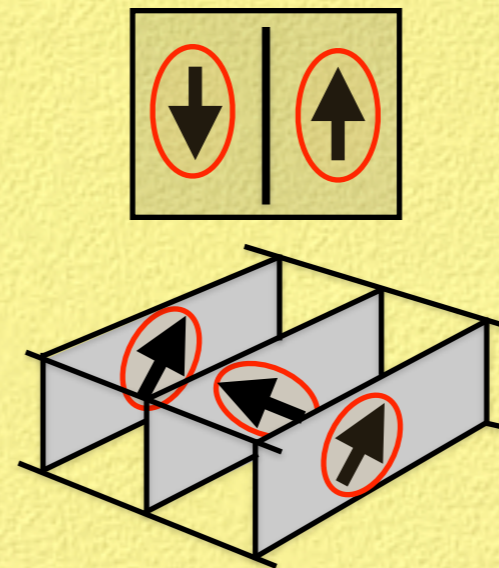


Stray field energy

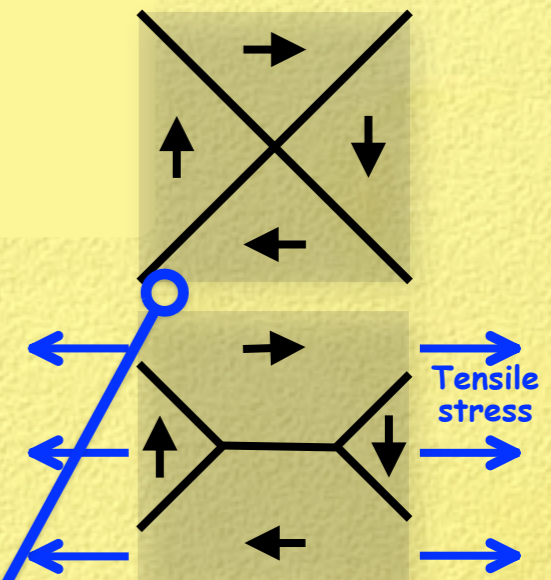
$$\text{div } H_d = -\text{div } M$$



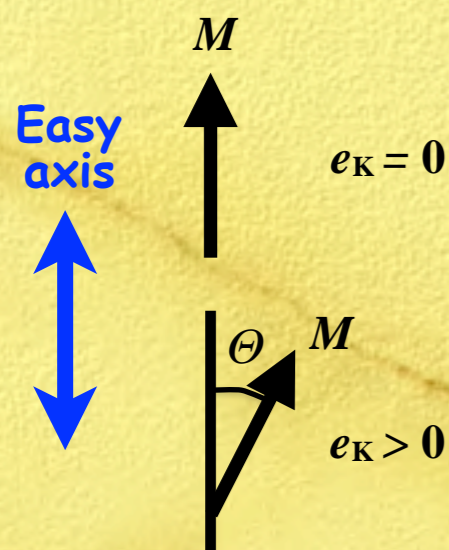
Magnetostrictive self energy



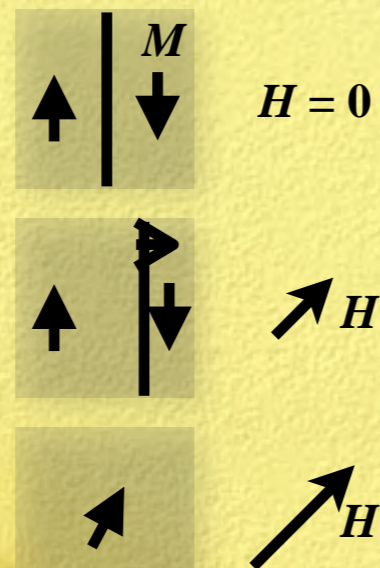
External stress energy



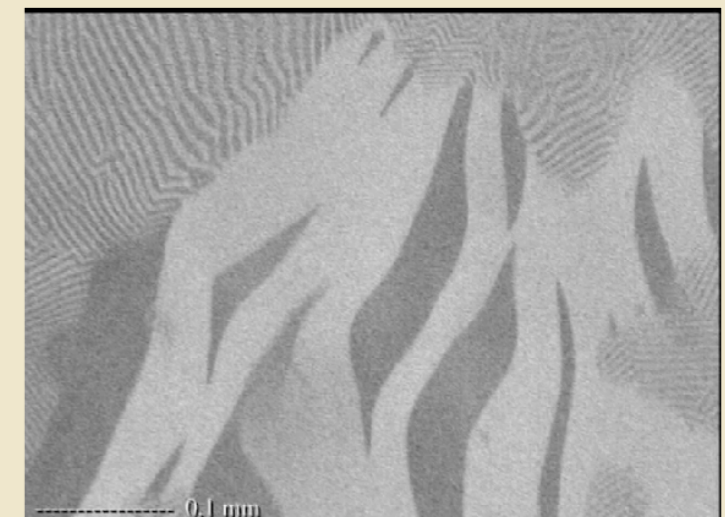
Anisotropy energy



External field energy



Can create dominating anisotropy when magnetocrystalline anisotropy is lacking (stress-induced anisotropy)

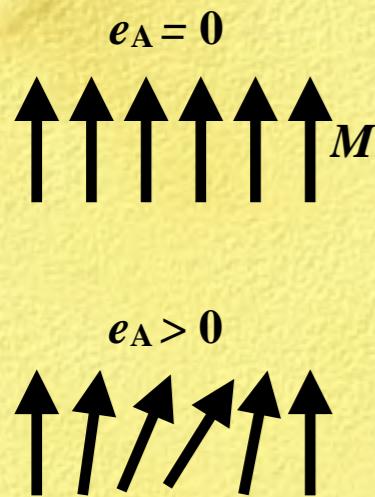


Origin of magnetic domains

Landau and Lifshitz (1935):

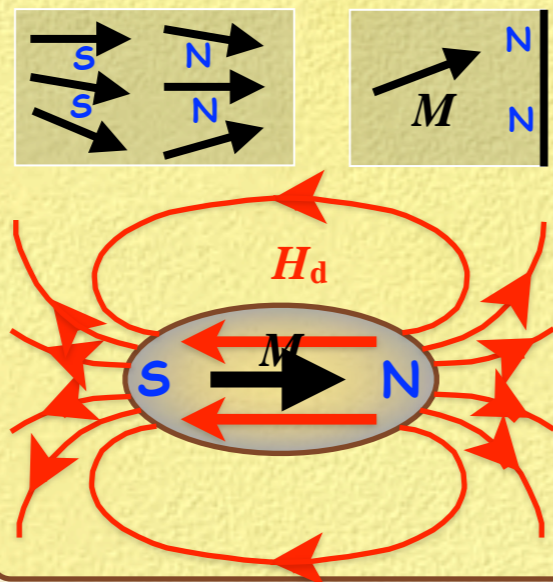
Domains are formed to minimize total energy

Exchange energy

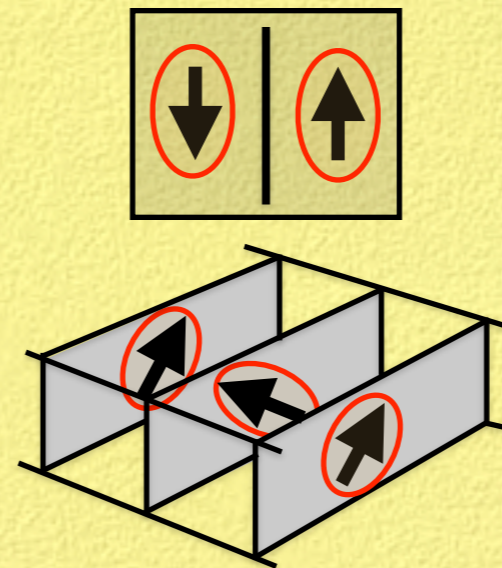


Stray field energy

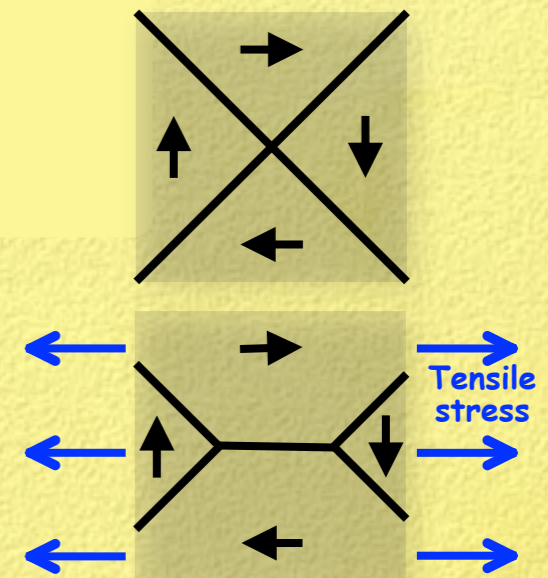
$$\text{div } H_d = -\text{div } M$$



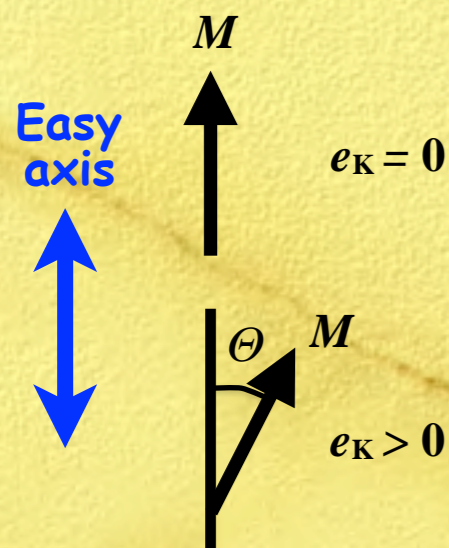
Magnetostrictive self energy



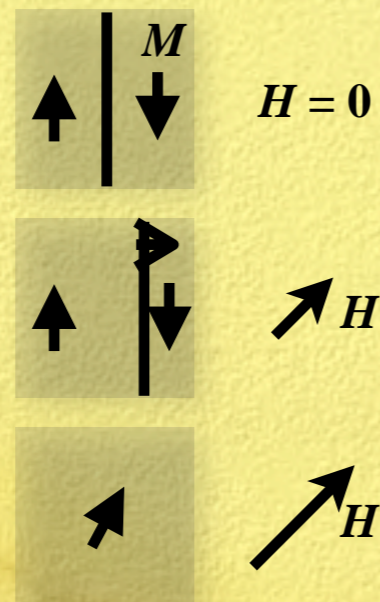
External stress energy



Anisotropy energy



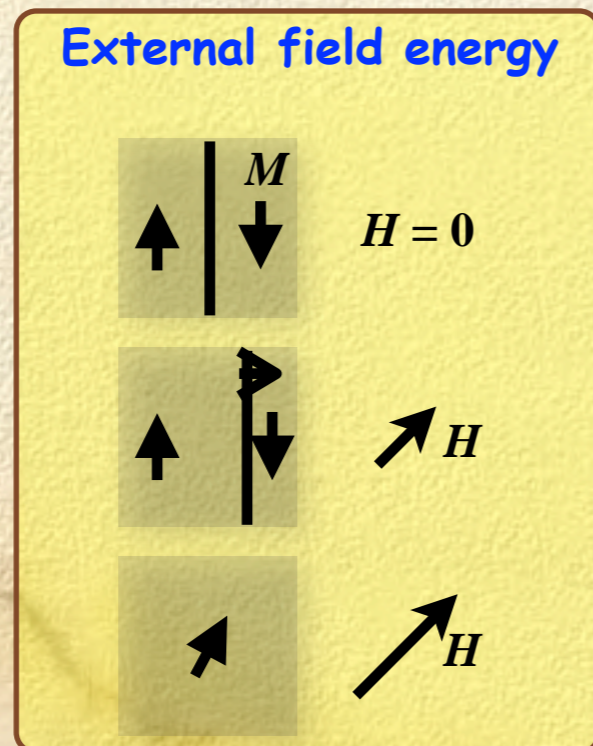
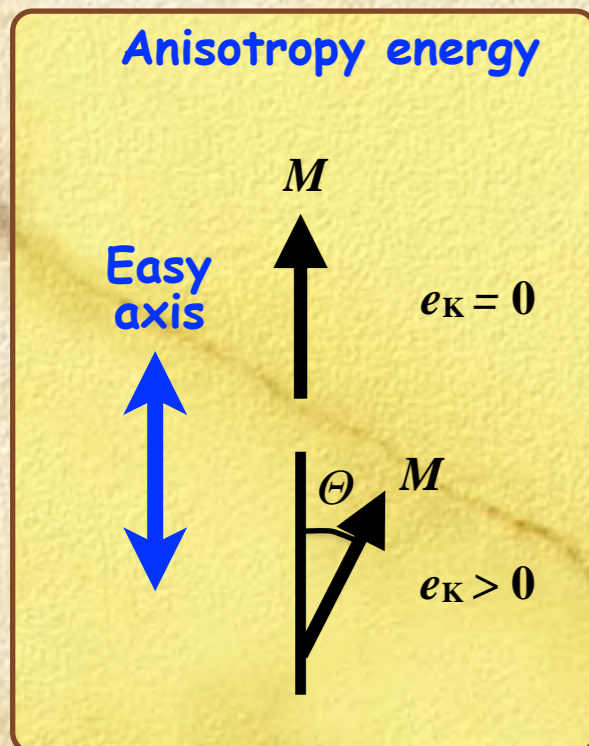
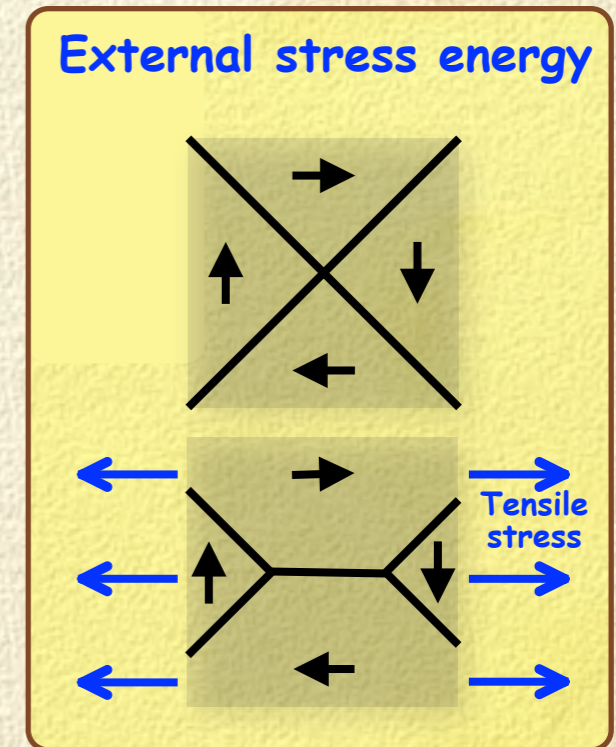
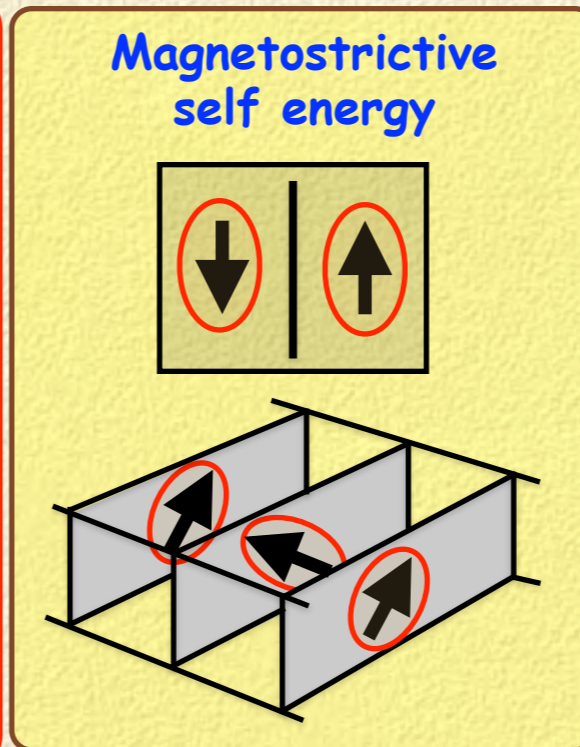
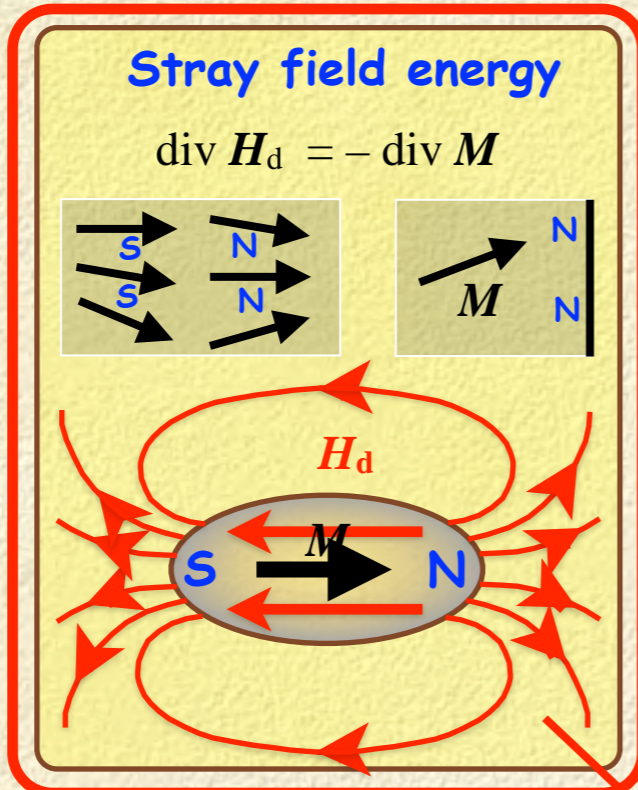
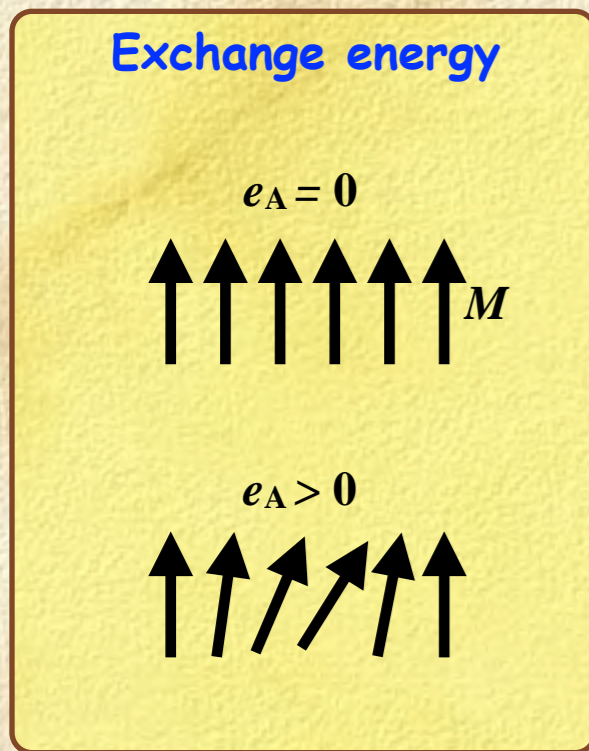
External field energy



Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy



$$E_s = -\frac{1}{2} \mu_0 \int_{\text{Sample-volume}} H_d M \, dV$$

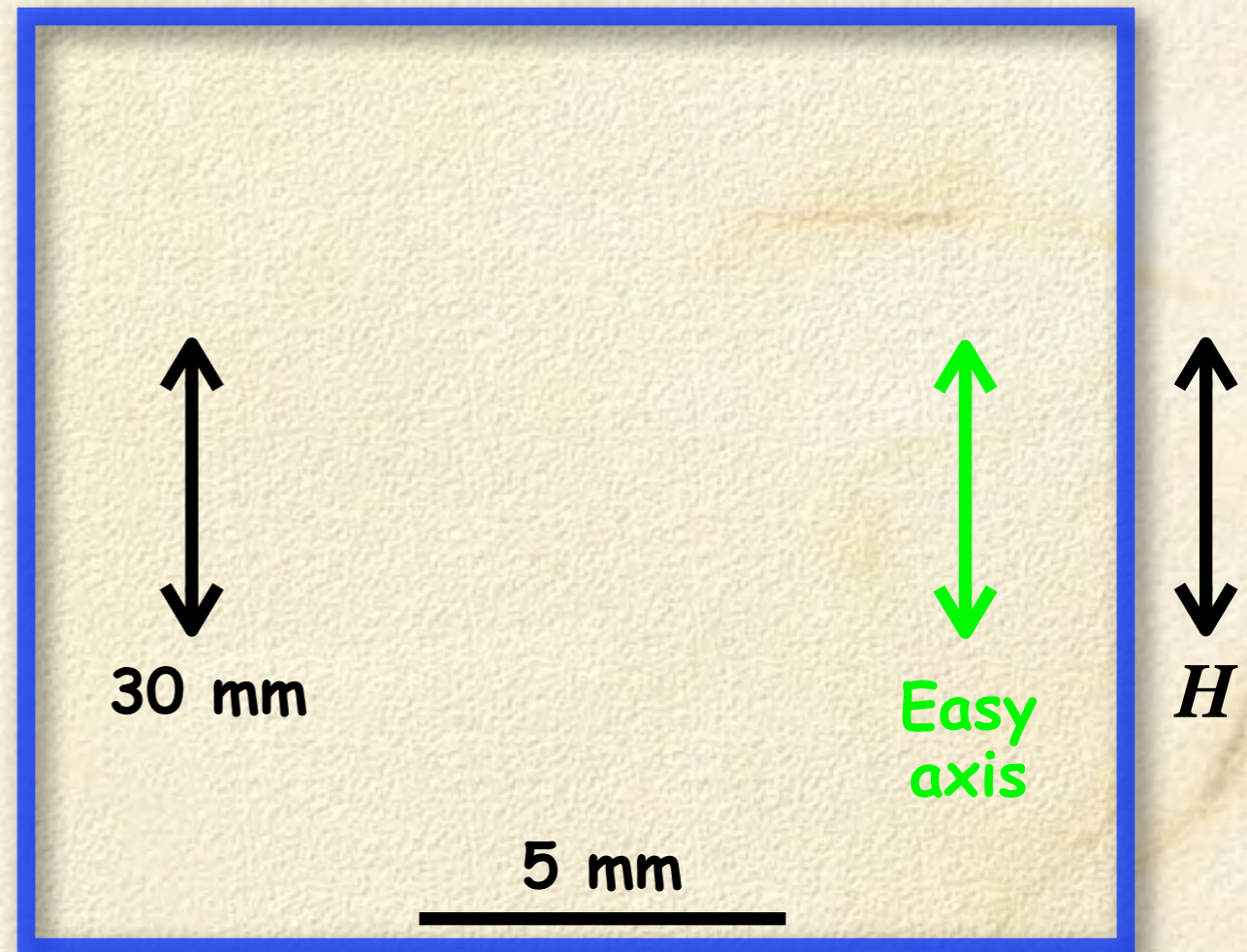
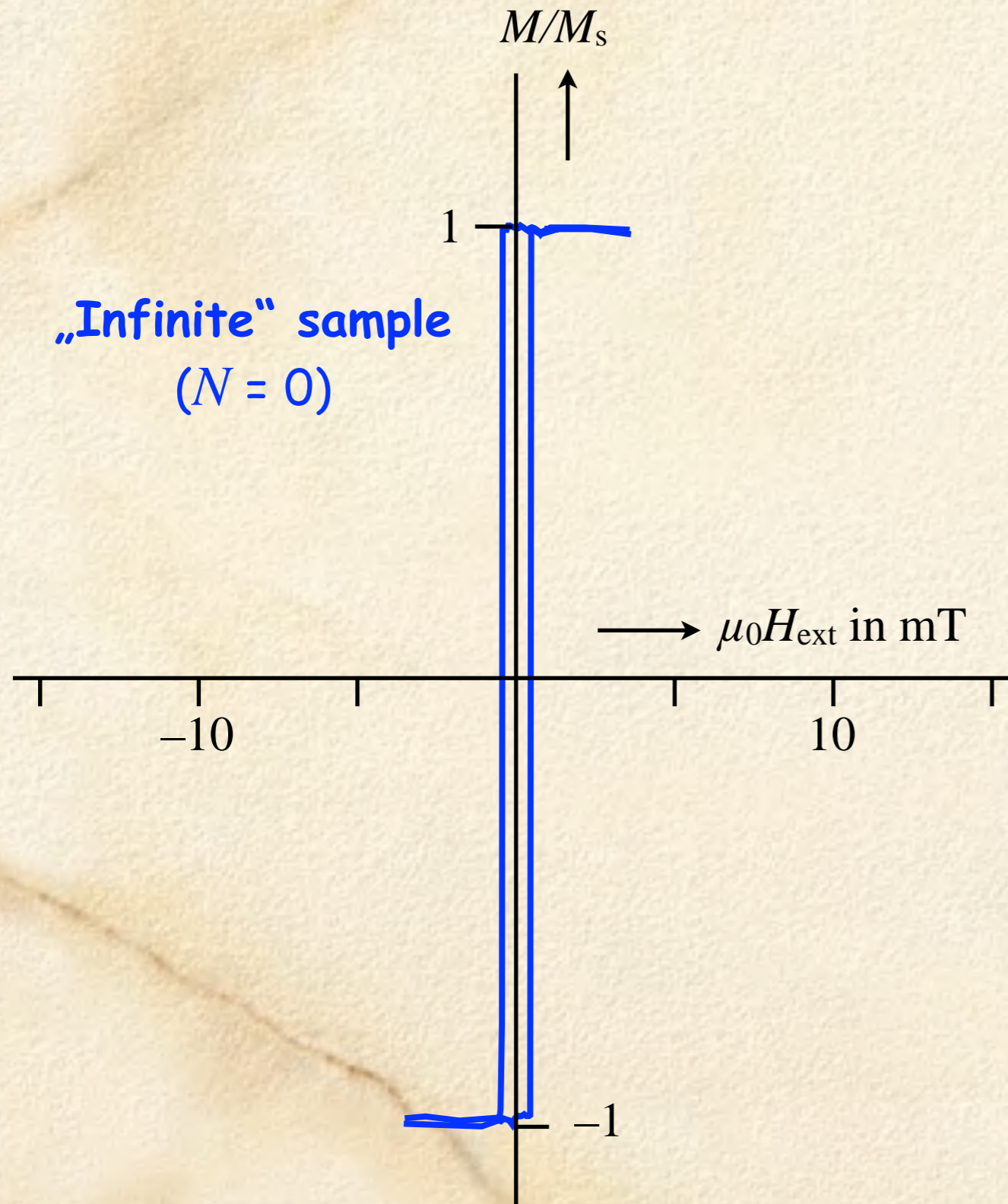
With $H_d = -NM$:

$$E_s = \frac{1}{2} \mu_0 NM^2 V$$

$$(0 < N < 1)$$

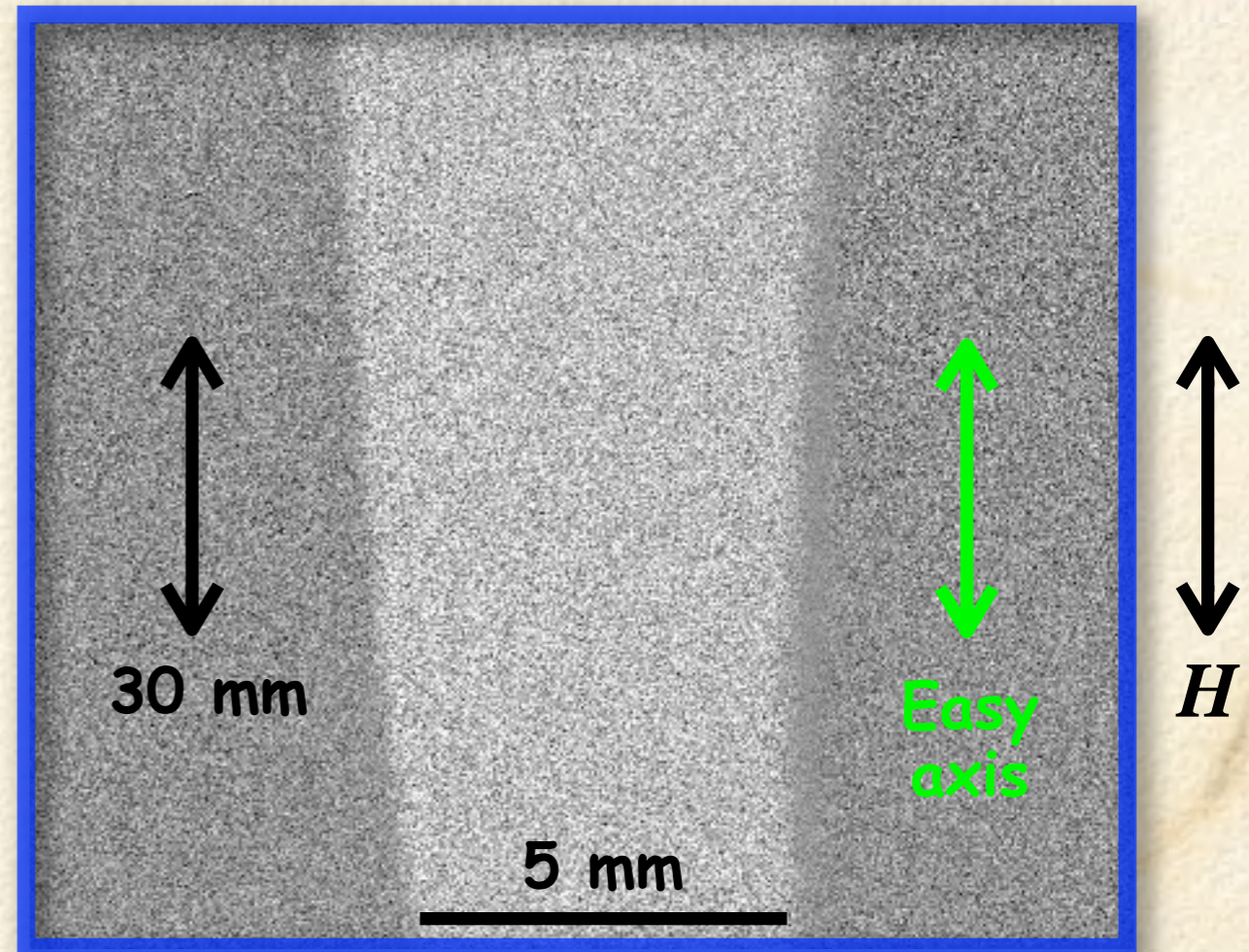
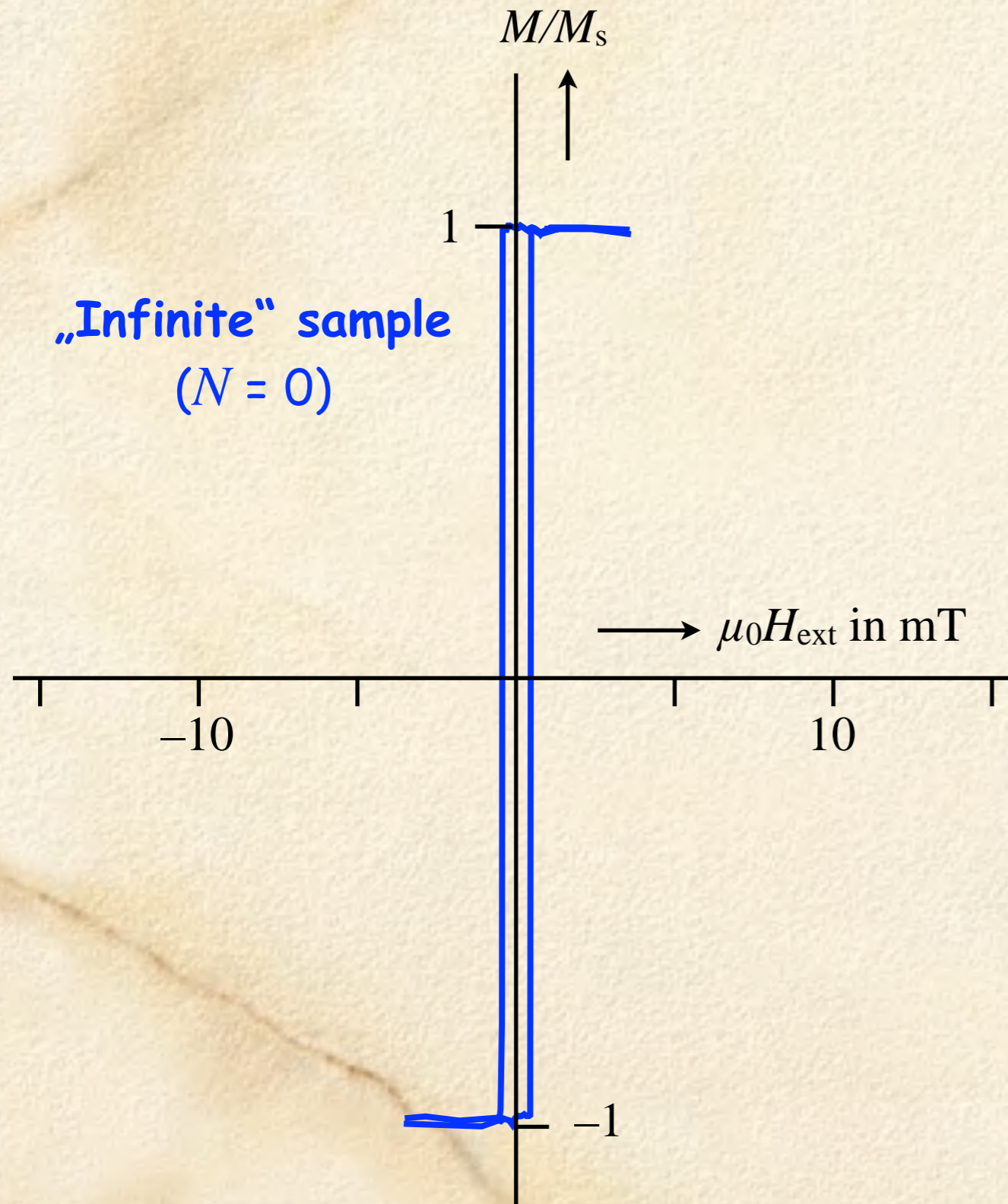
Origin of magnetic domains

Ni₈₀Fe₂₀ film (240 nm thick)



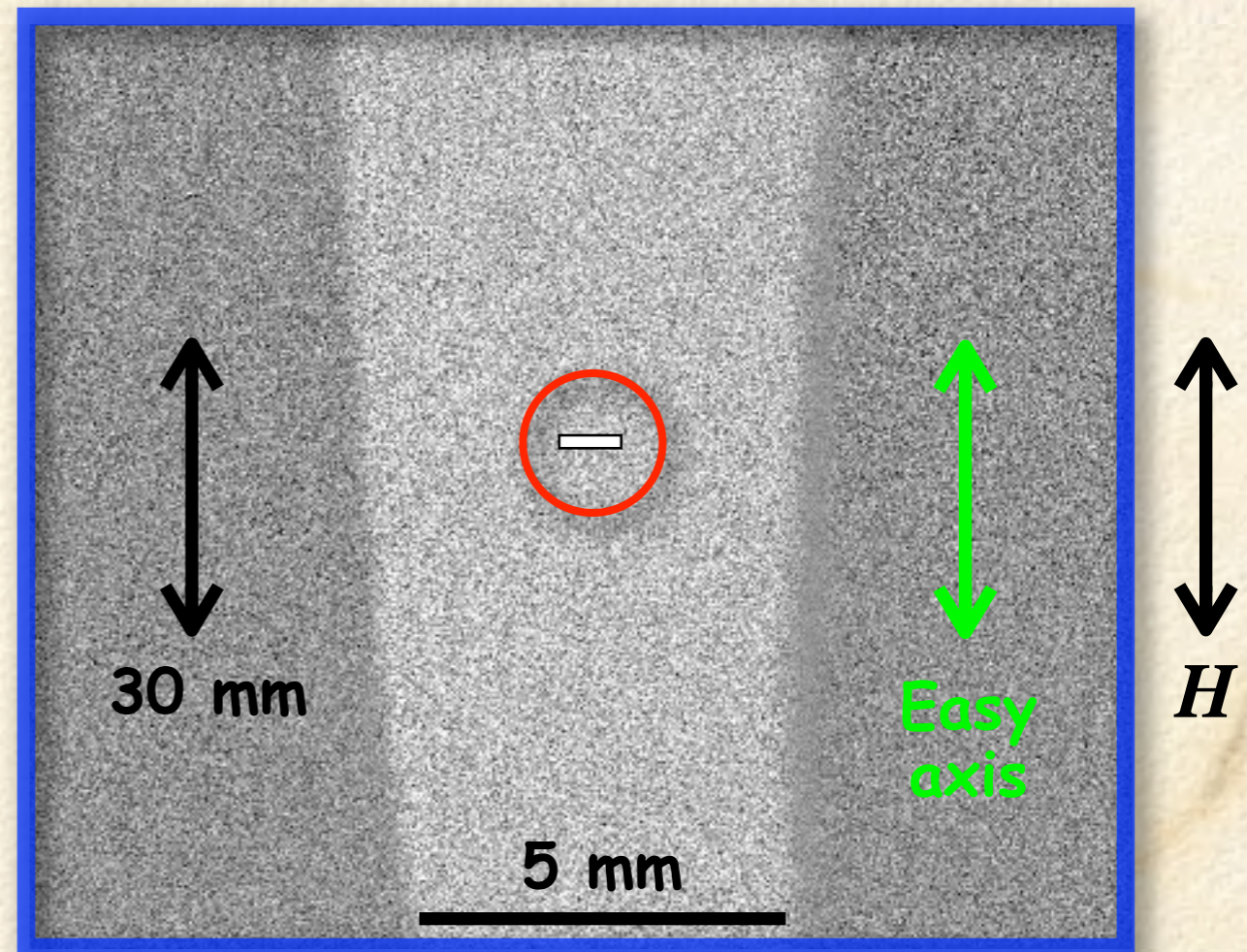
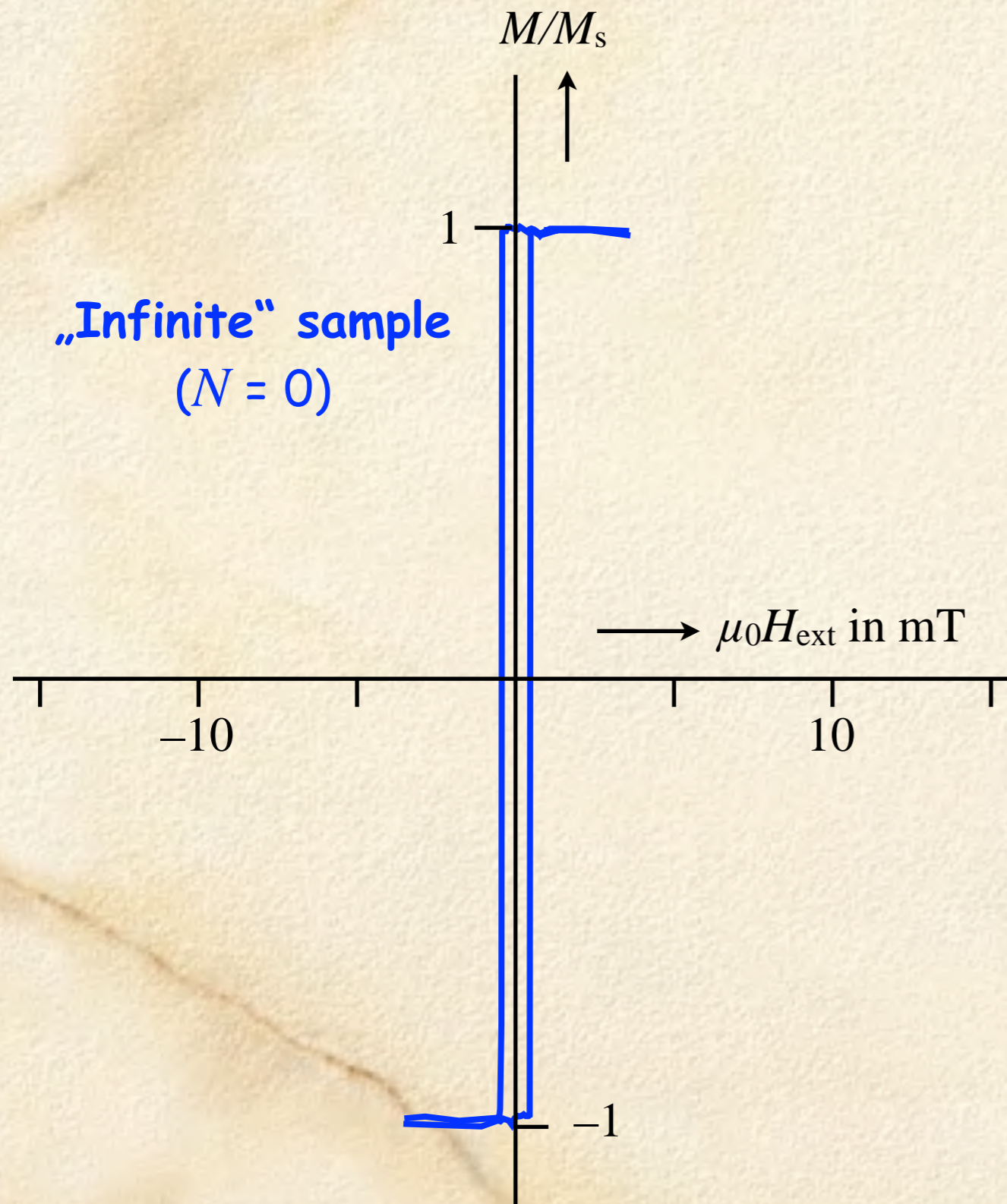
Origin of magnetic domains

Ni₈₀Fe₂₀ film (240 nm thick)



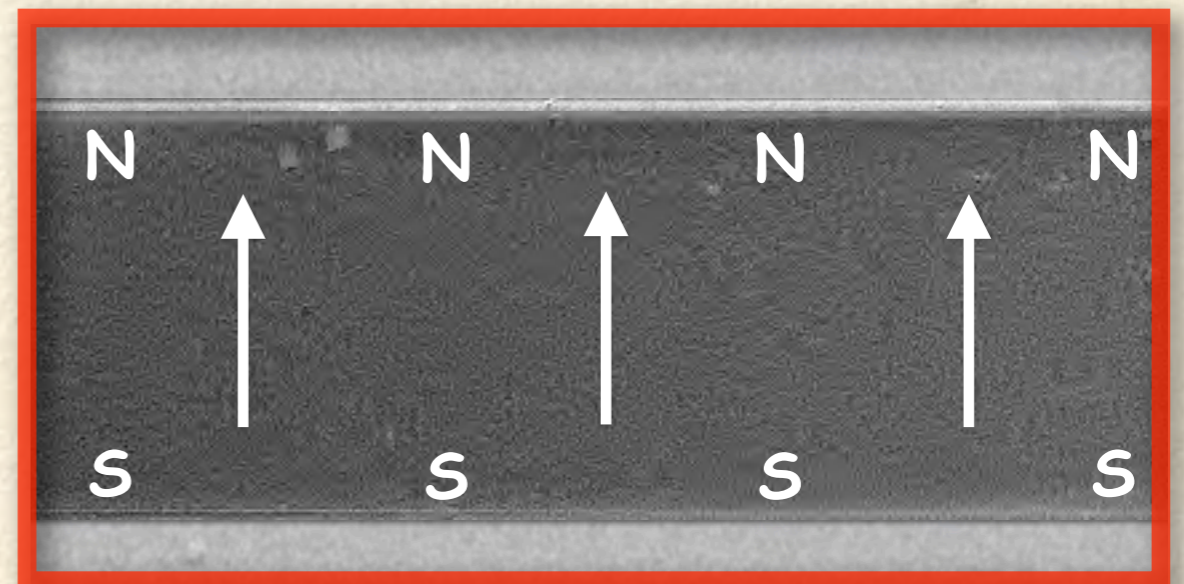
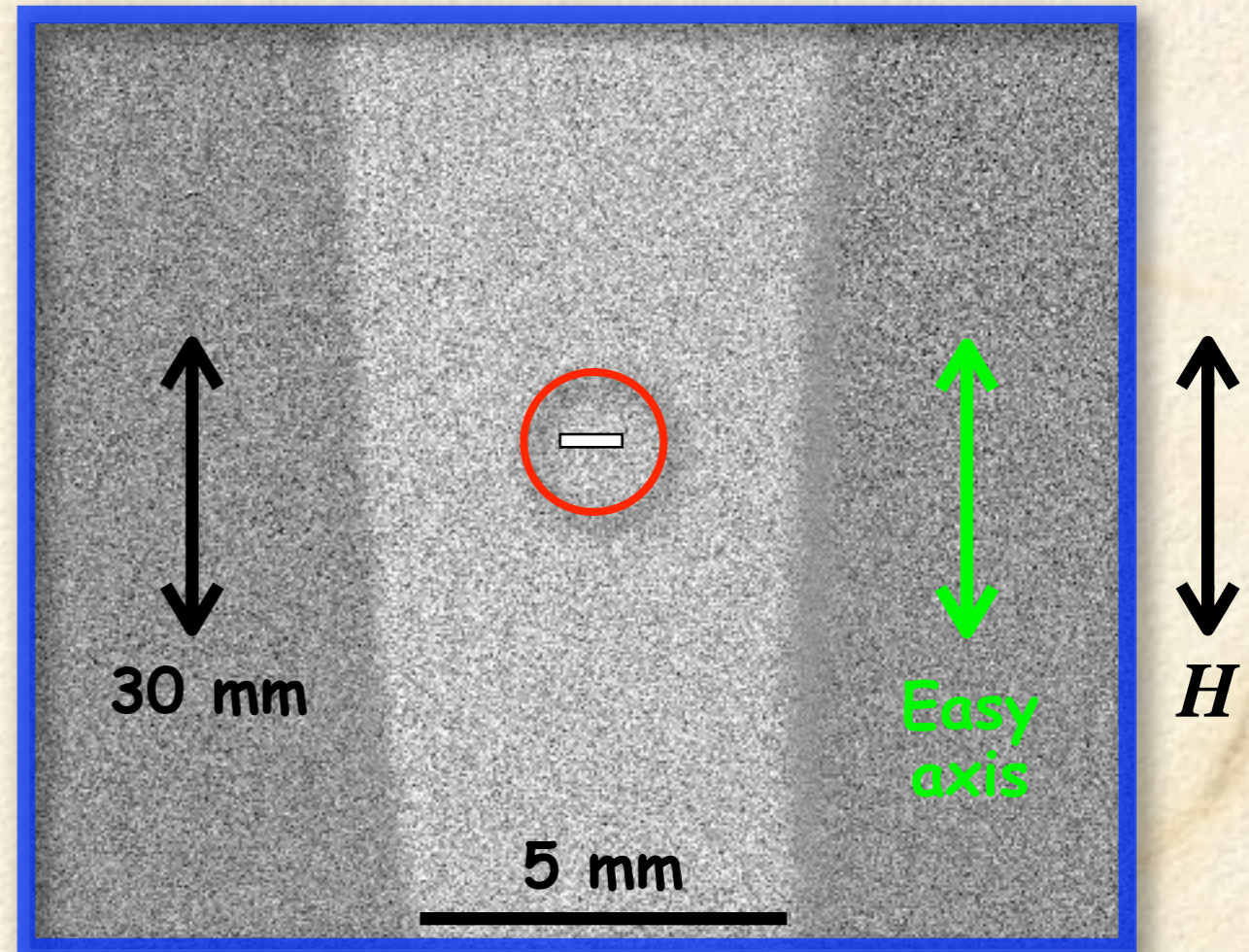
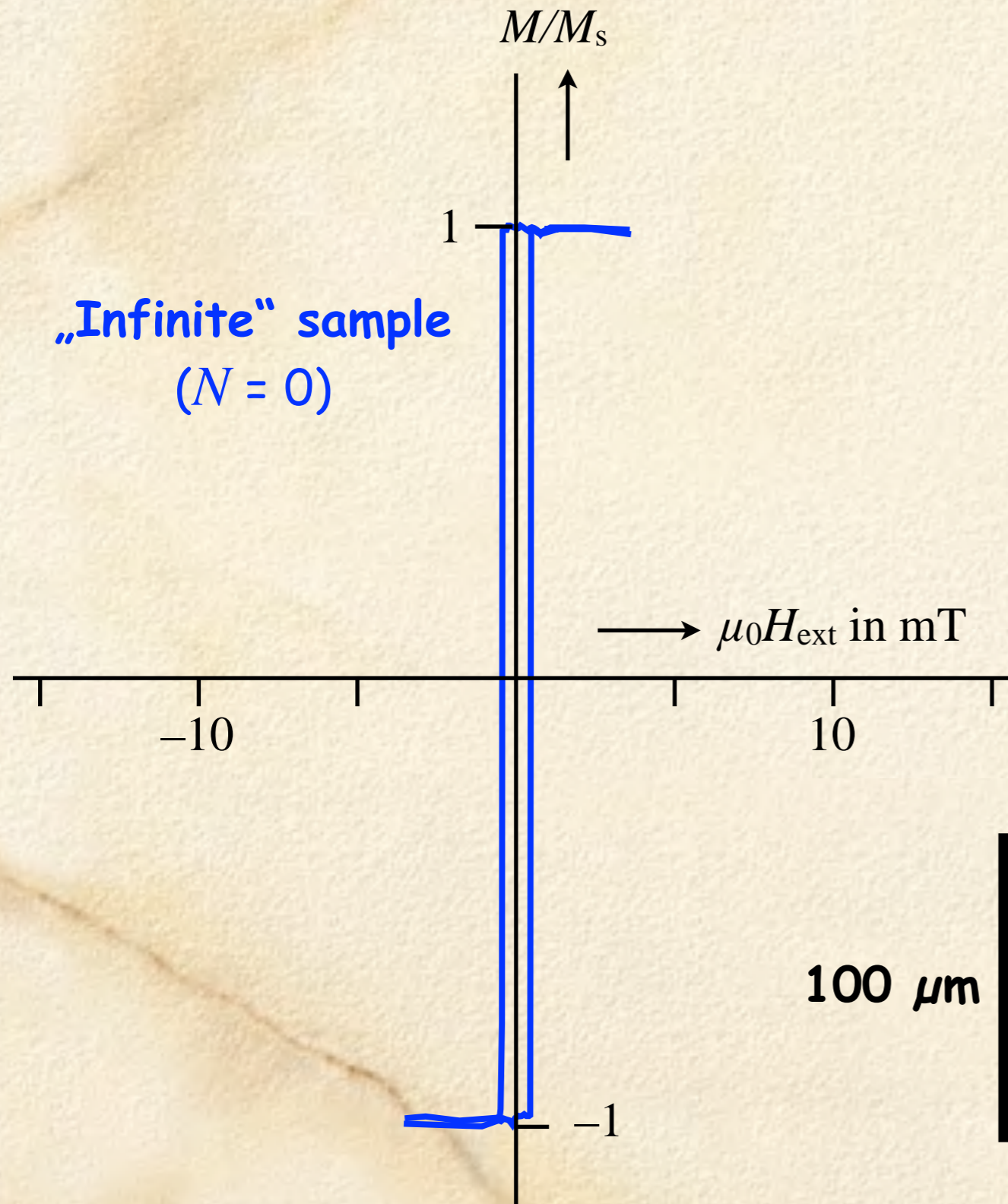
Origin of magnetic domains

Ni₈₀Fe₂₀ film (240 nm thick)



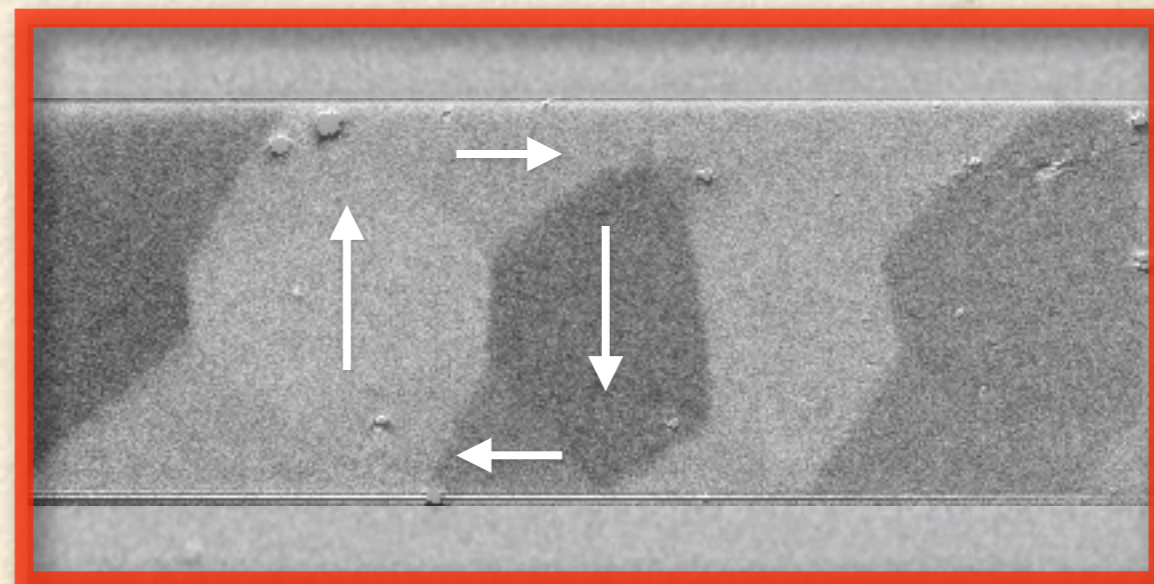
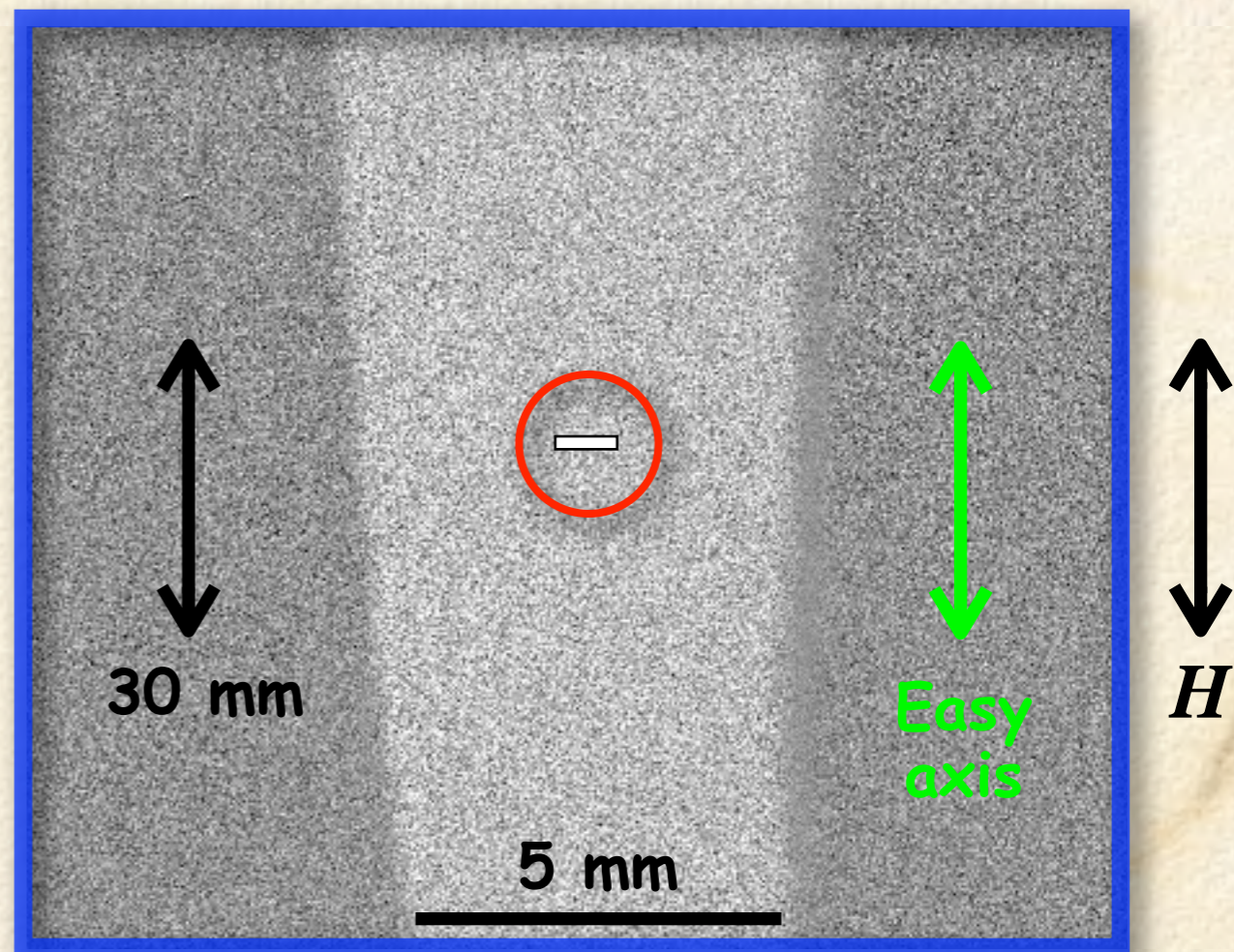
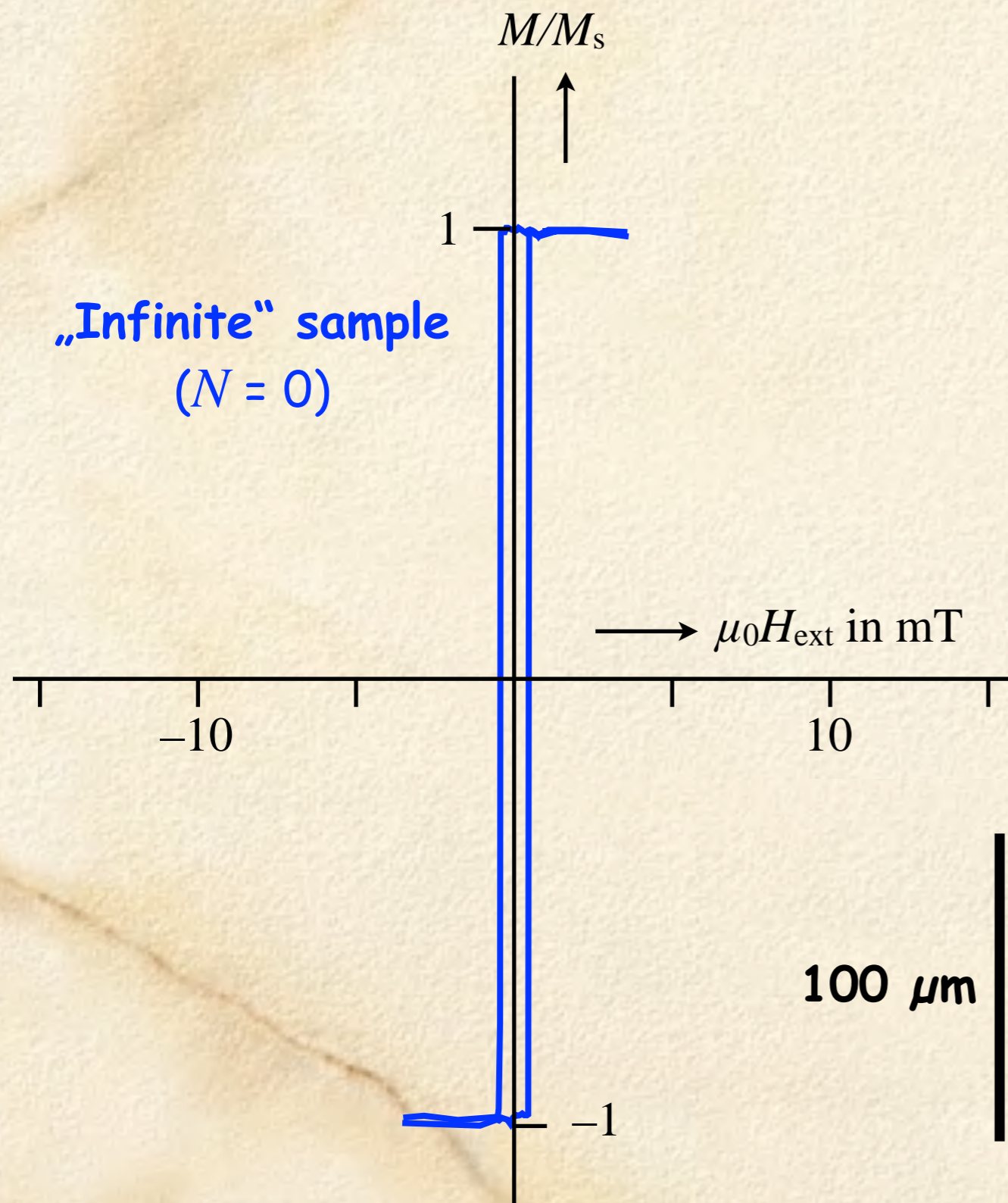
Origin of magnetic domains

Ni₈₀Fe₂₀ film (240 nm thick)



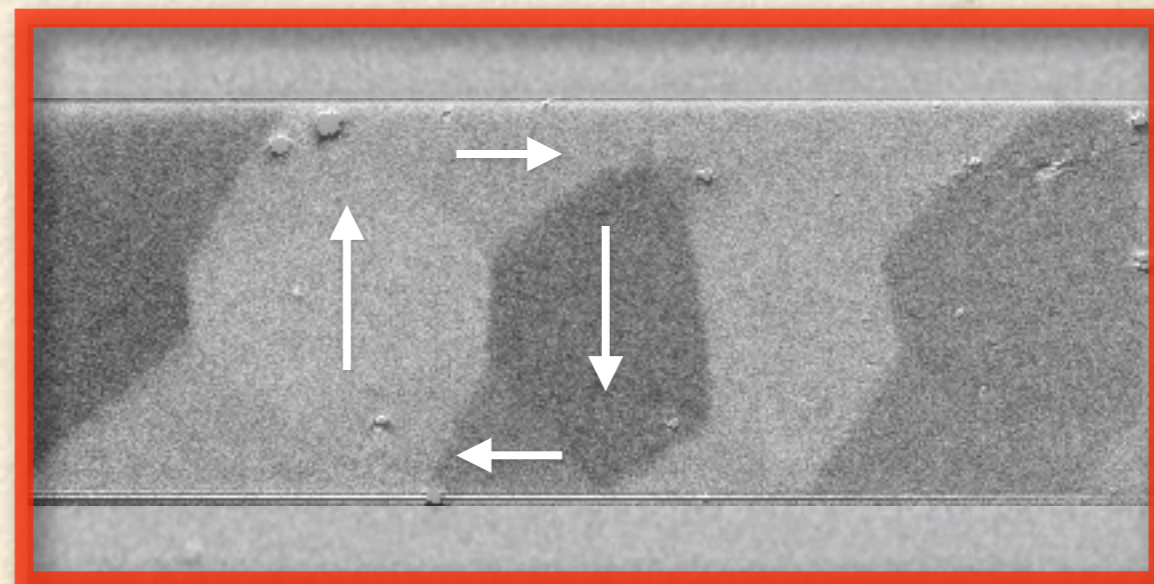
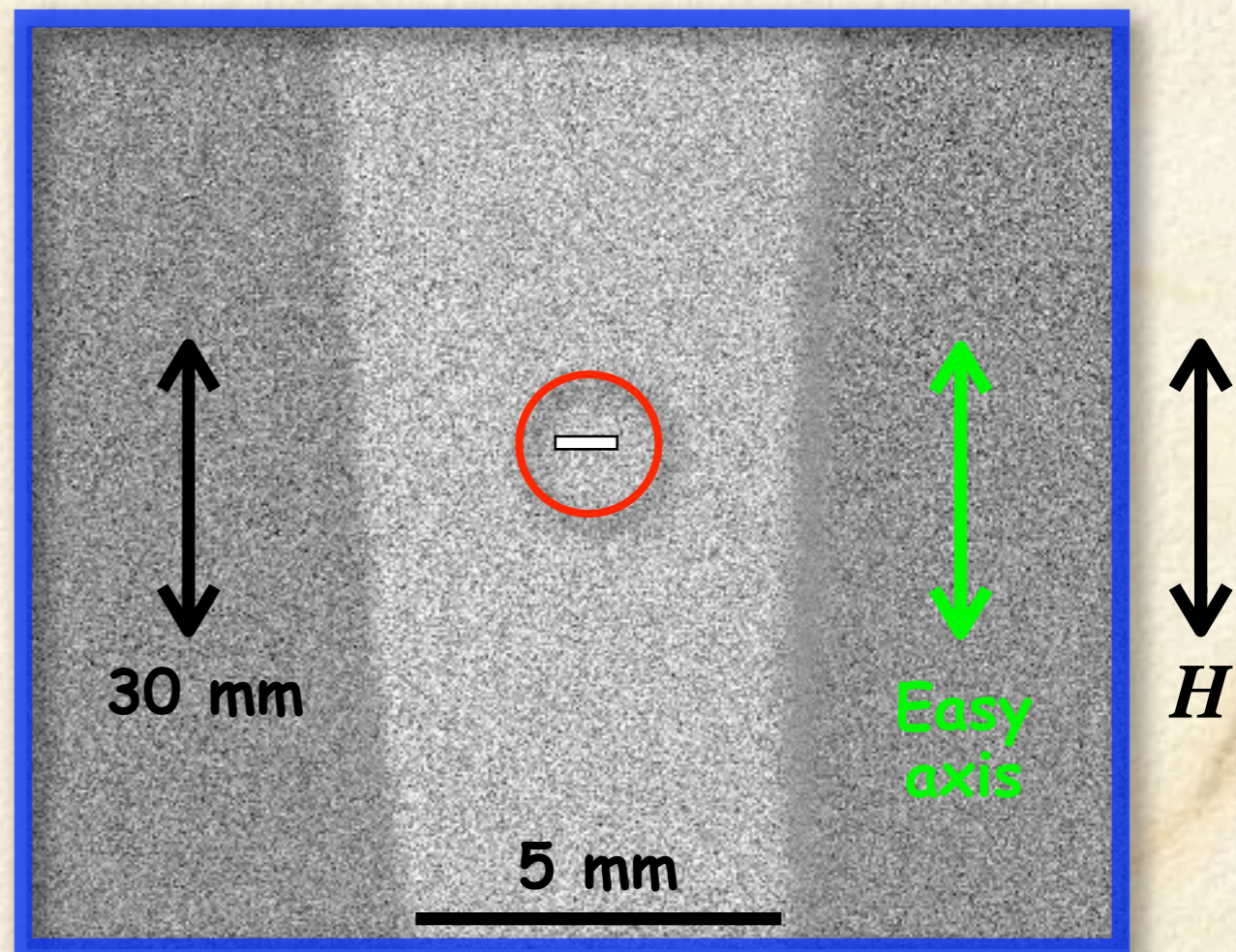
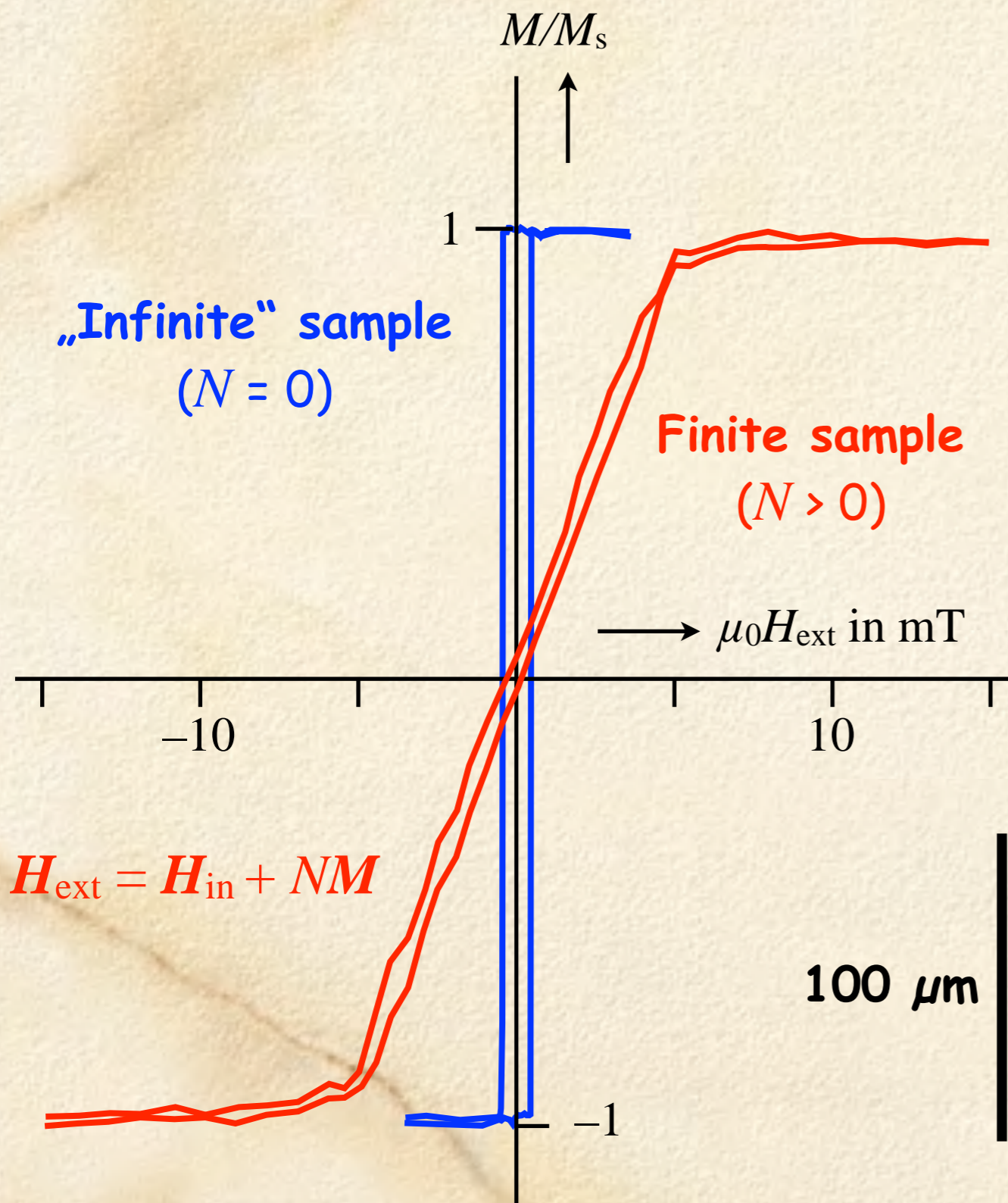
Origin of magnetic domains

Ni₈₀Fe₂₀ film (240 nm thick)



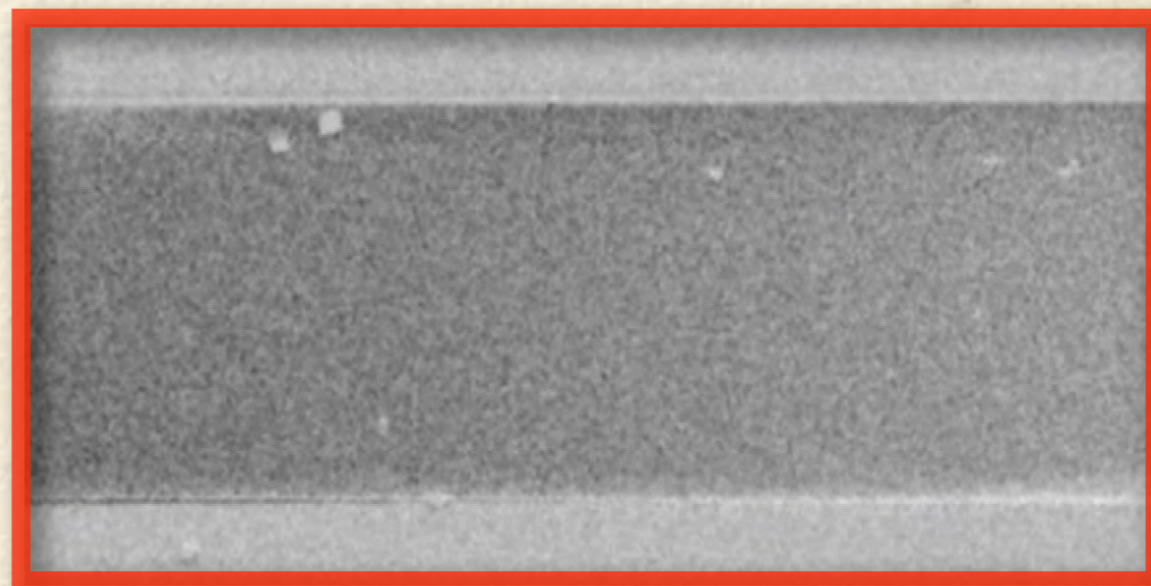
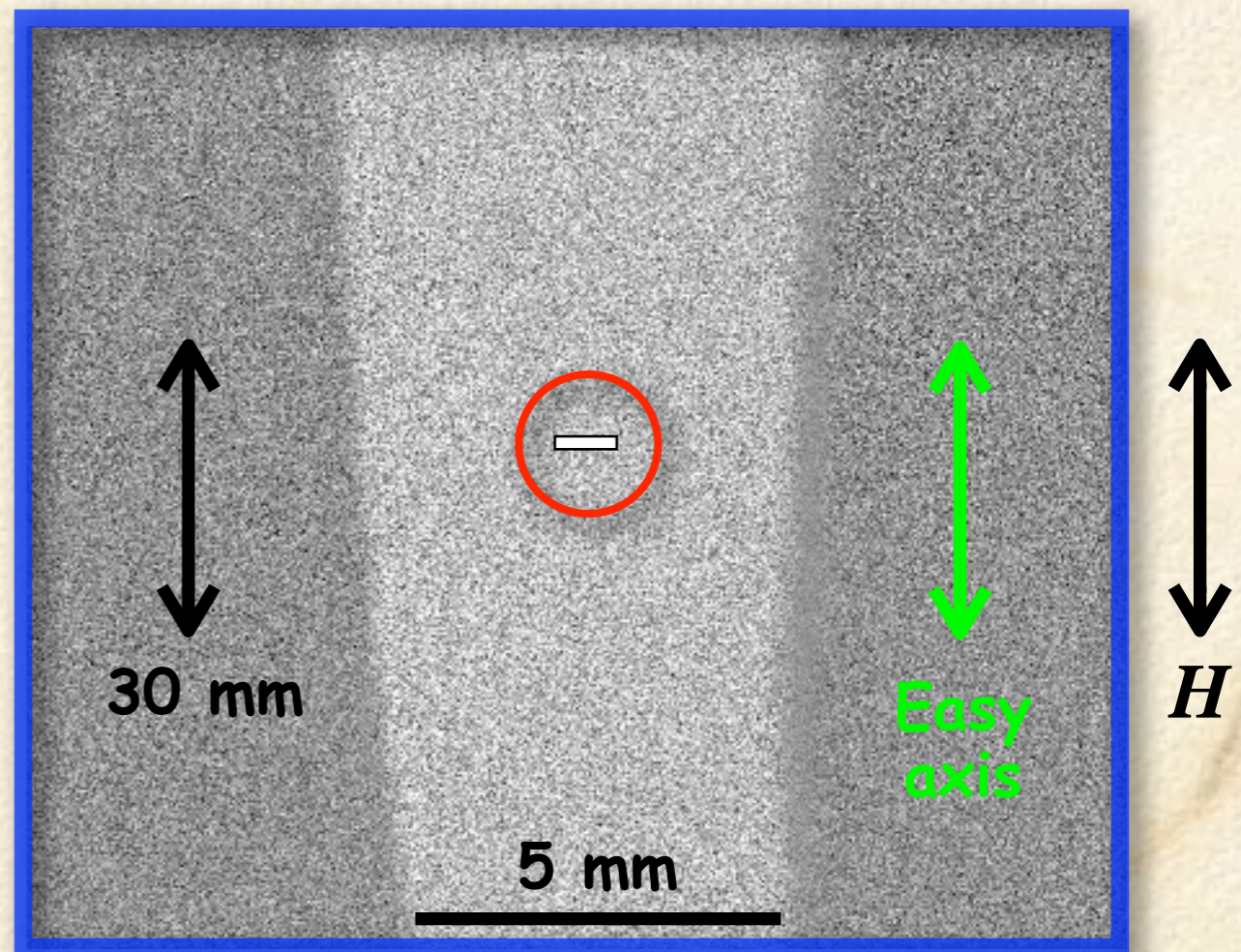
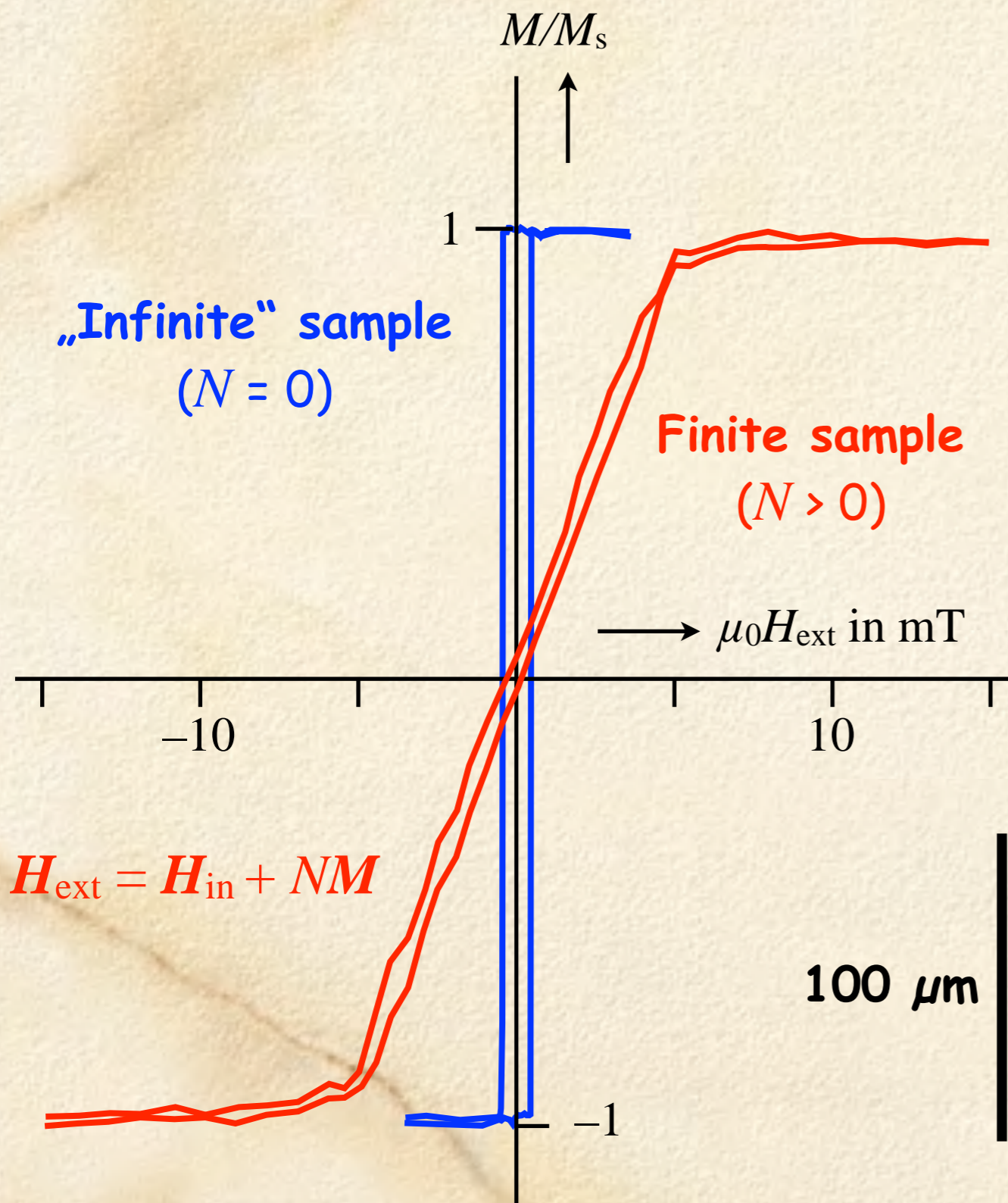
Origin of magnetic domains

Ni₈₀Fe₂₀ film (240 nm thick)



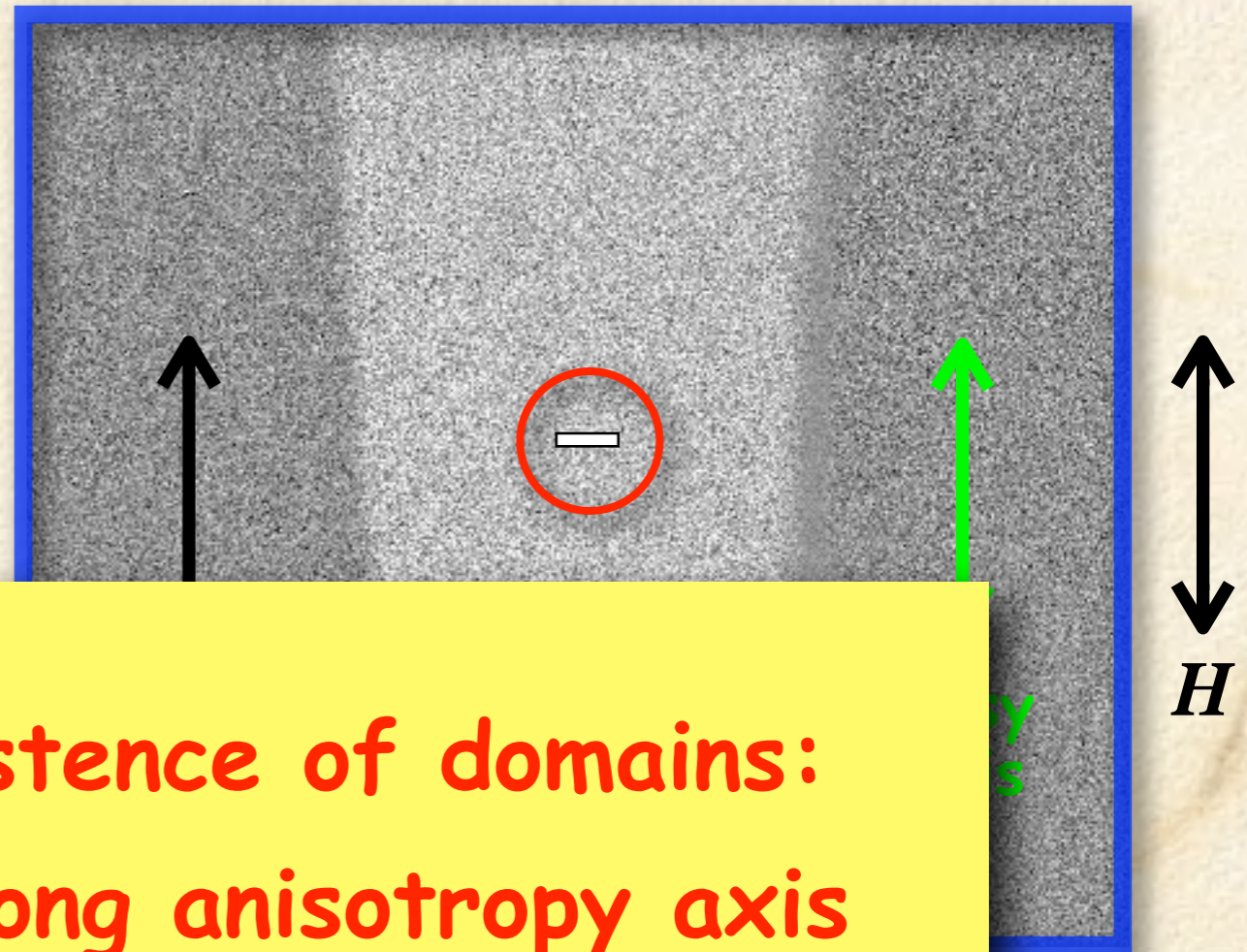
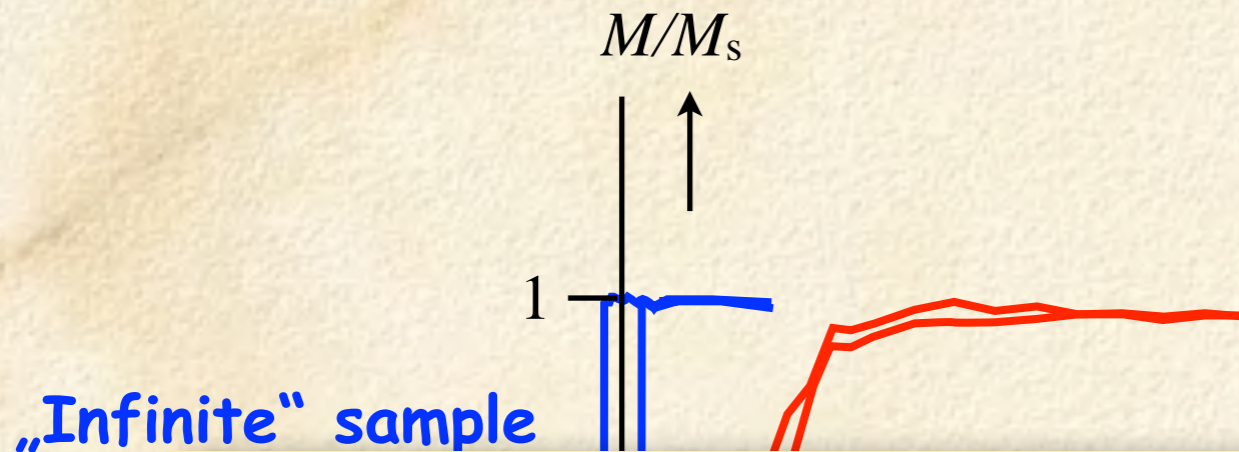
Origin of magnetic domains

Ni₈₀Fe₂₀ film (240 nm thick)

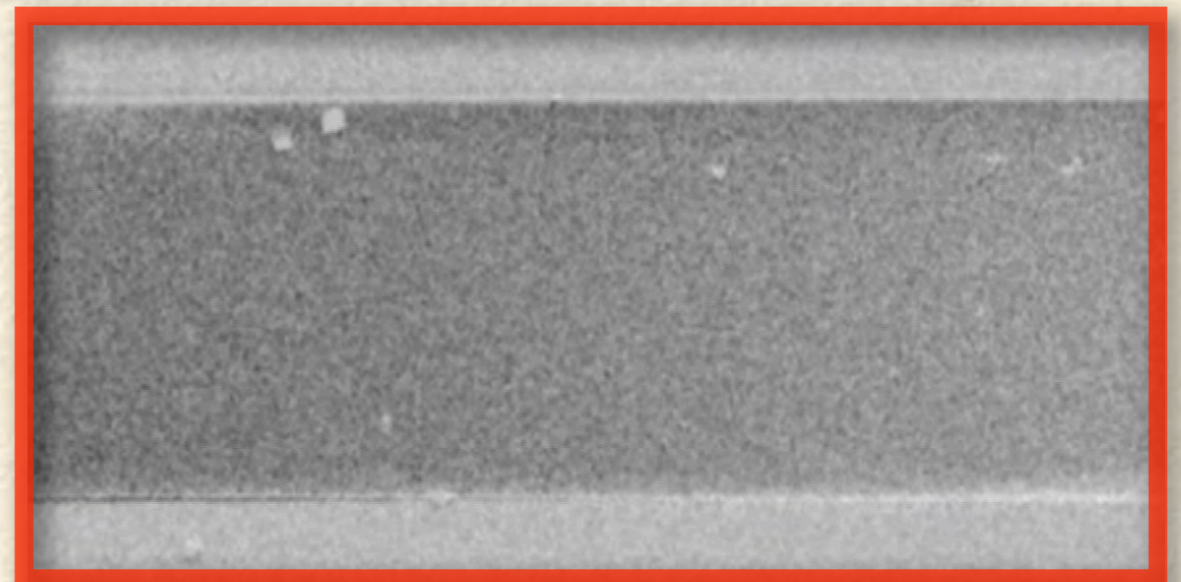
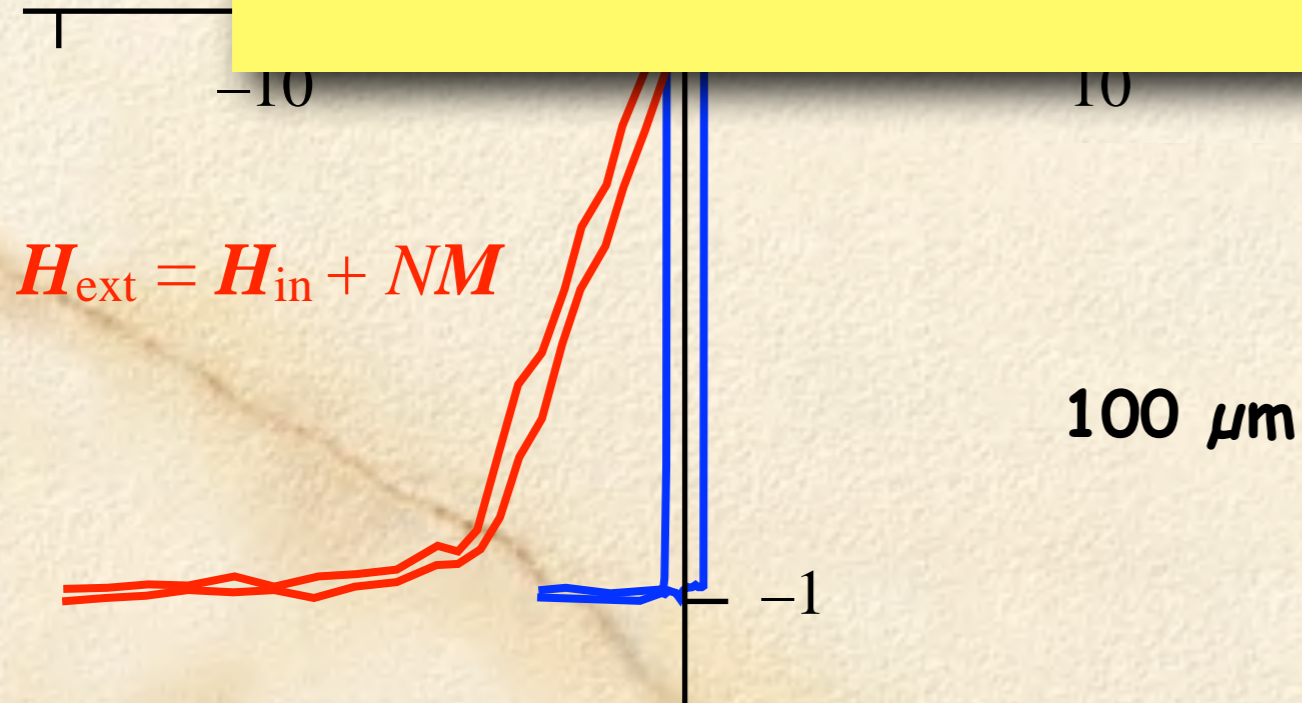


Origin of magnetic domains

Ni₈₀Fe₂₀ film (240 nm thick)

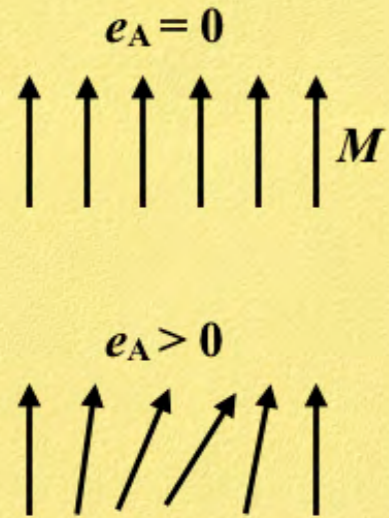


Prerequisite for existence of domains:
Finite sample size along anisotropy axis



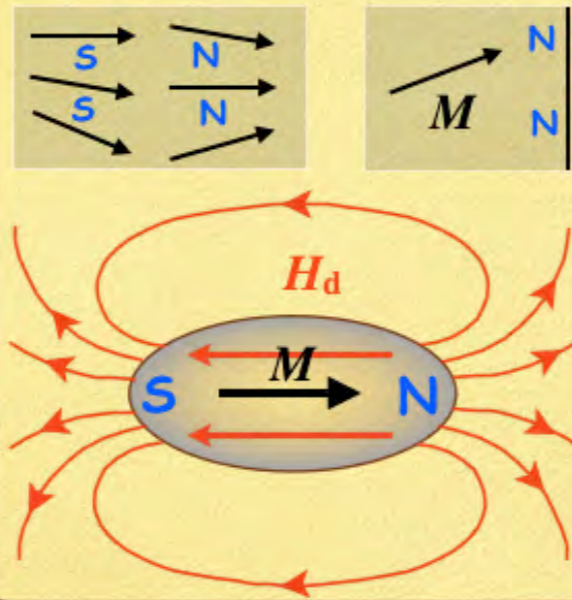
Magnetic Energies

Exchange energy

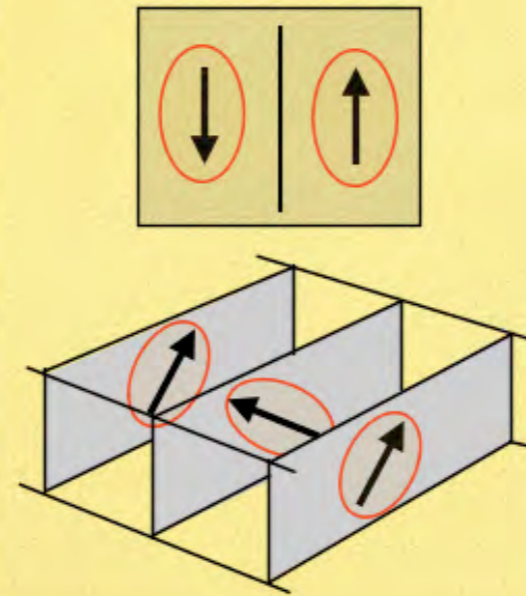


Stray field energy

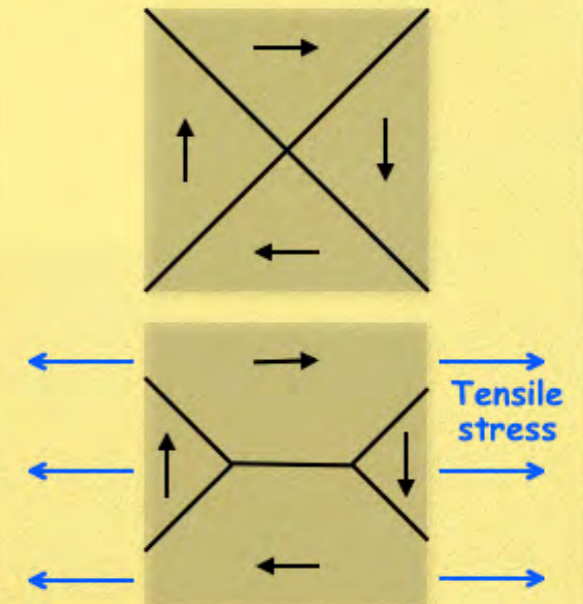
$$\text{div } H_d = -\text{div } M$$



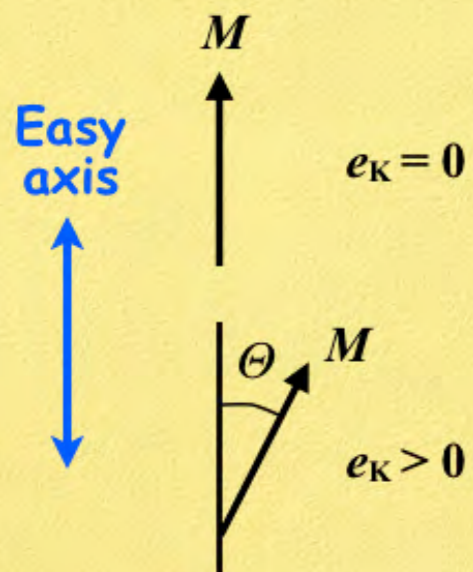
Magnetostrictive self energy



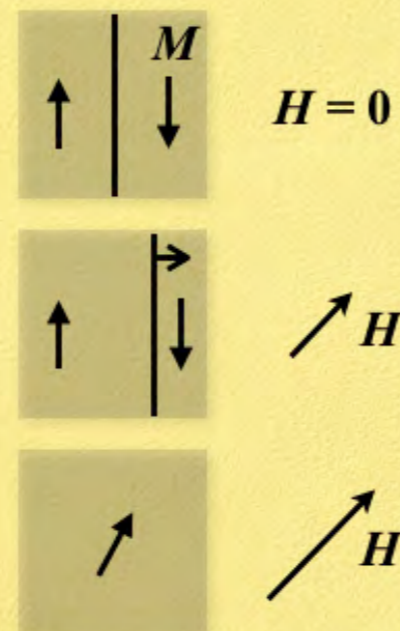
External stress energy



Anisotropy energy

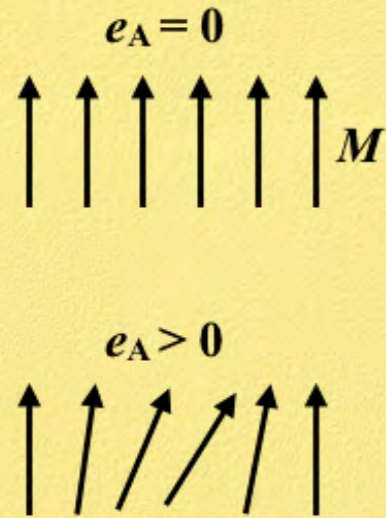


External field energy



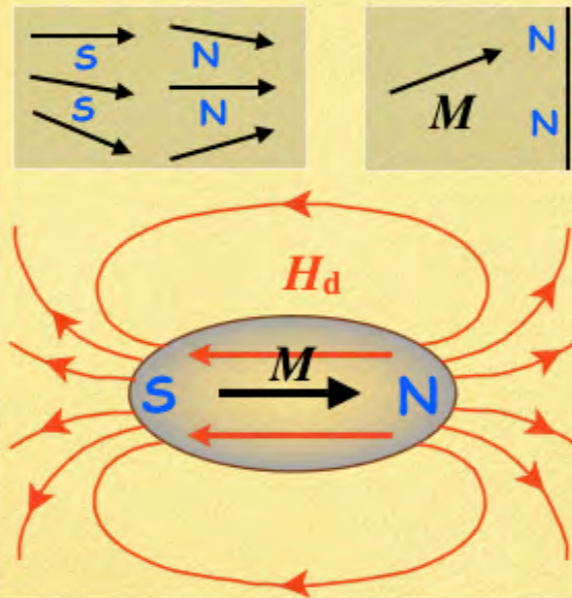
Magnetic Energies

Exchange energy

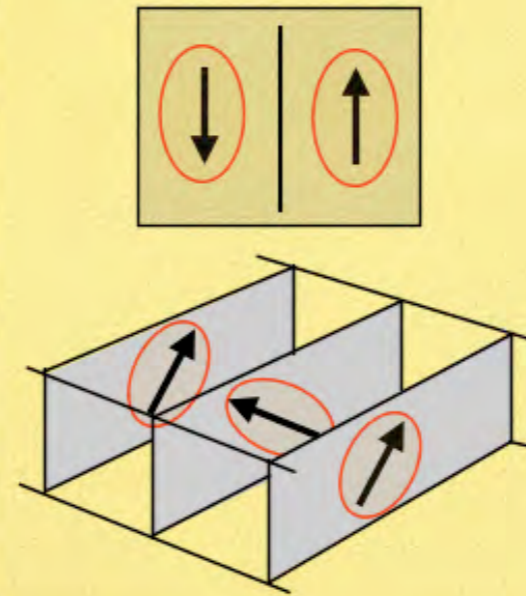


Stray field energy

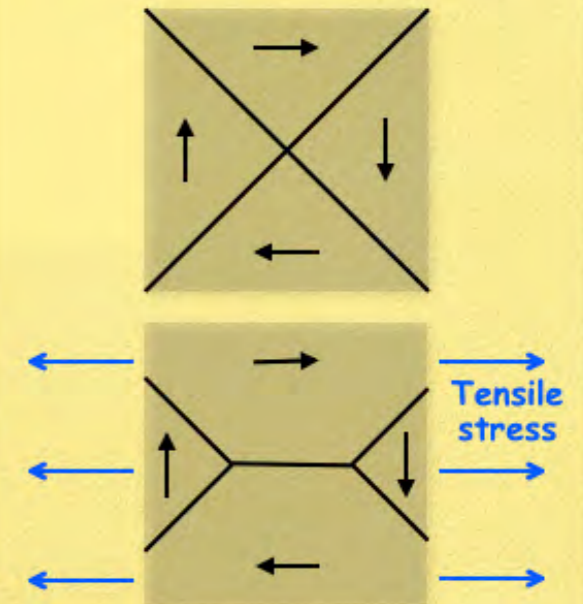
$$\text{div } H_d = -\text{div } M$$



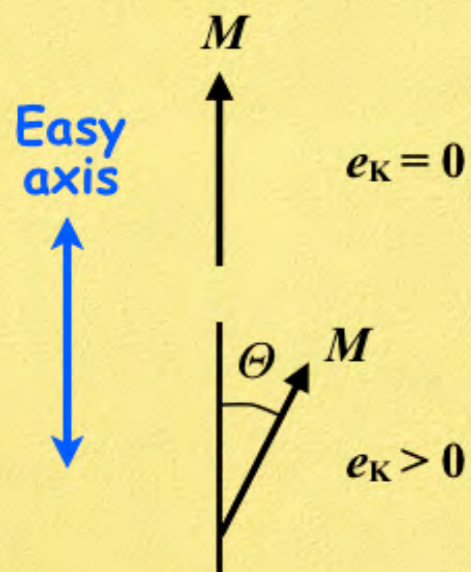
Magnetostrictive self energy



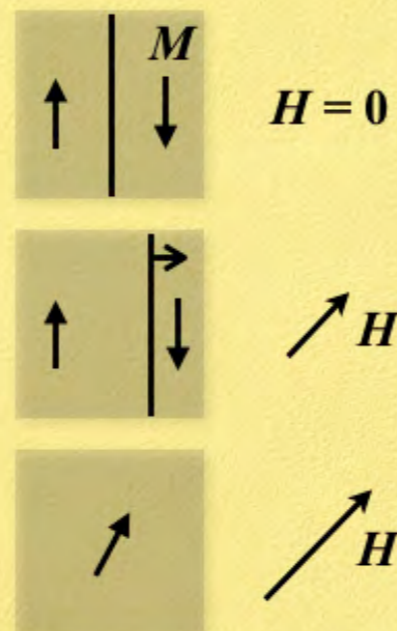
External stress energy



Anisotropy energy

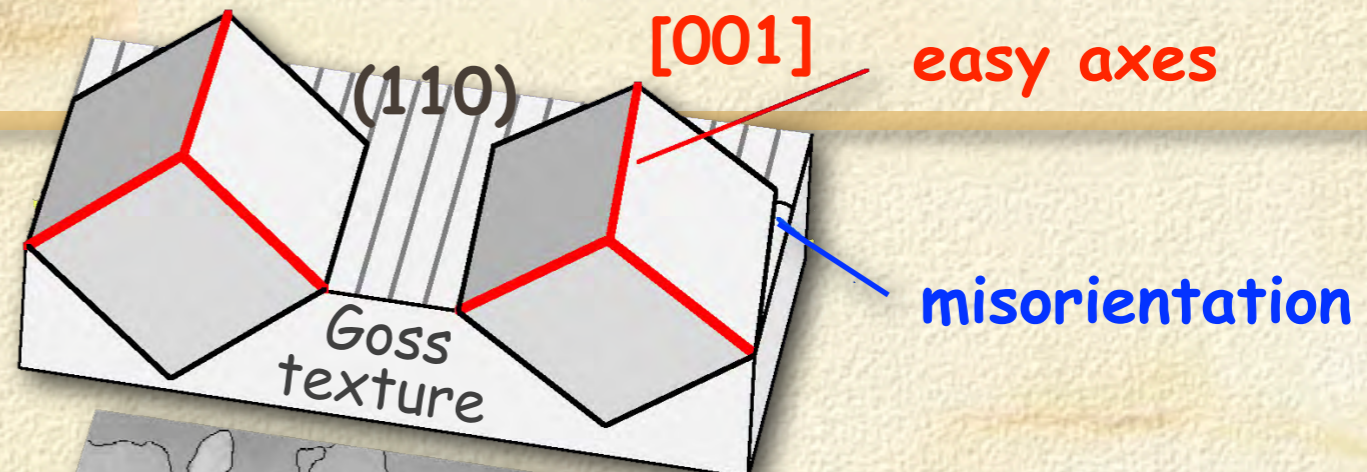


External field energy

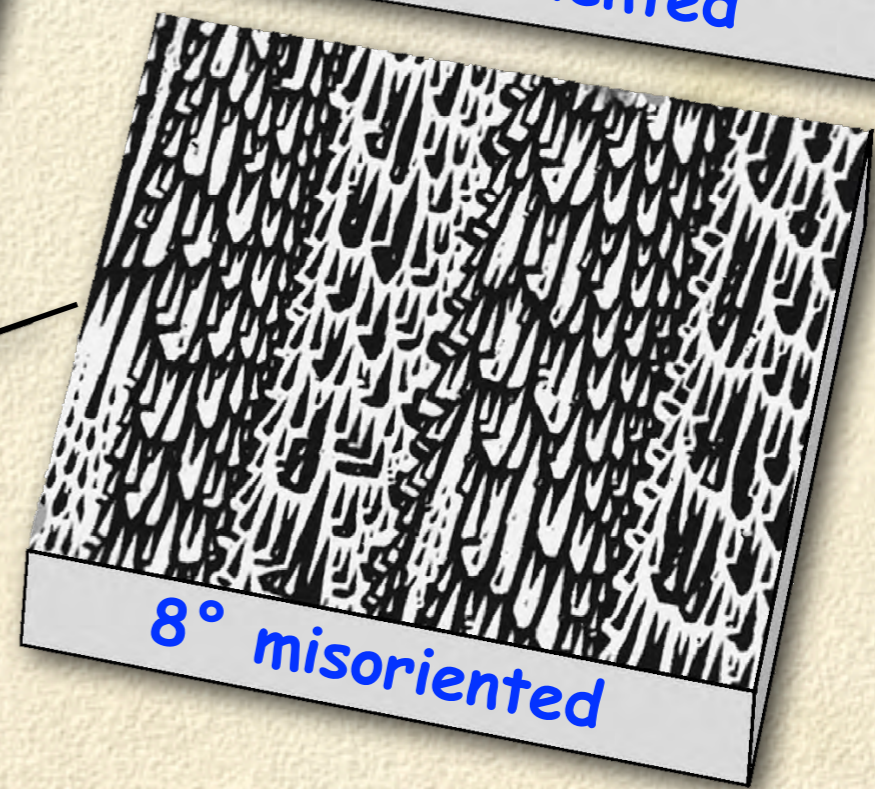
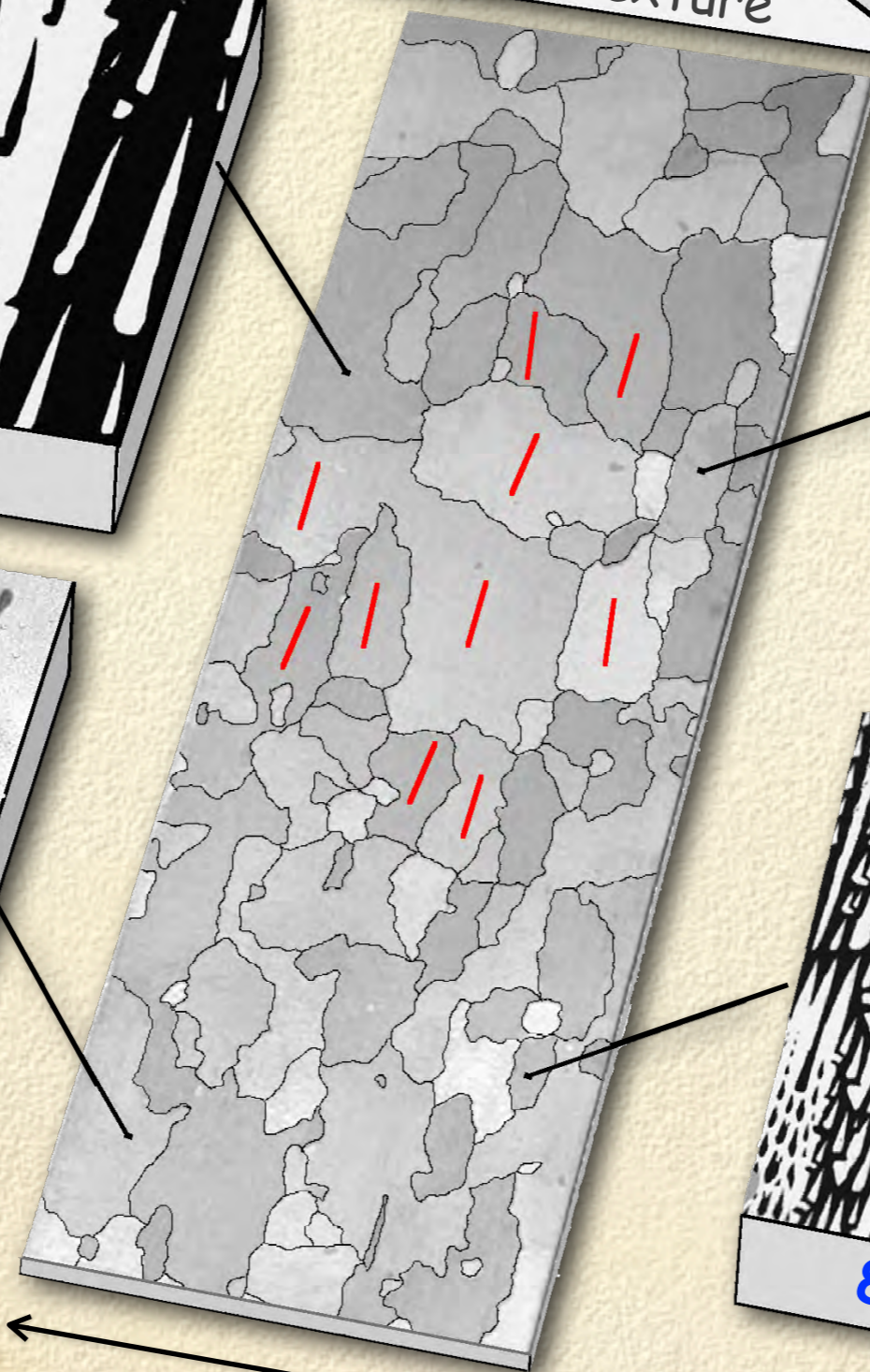
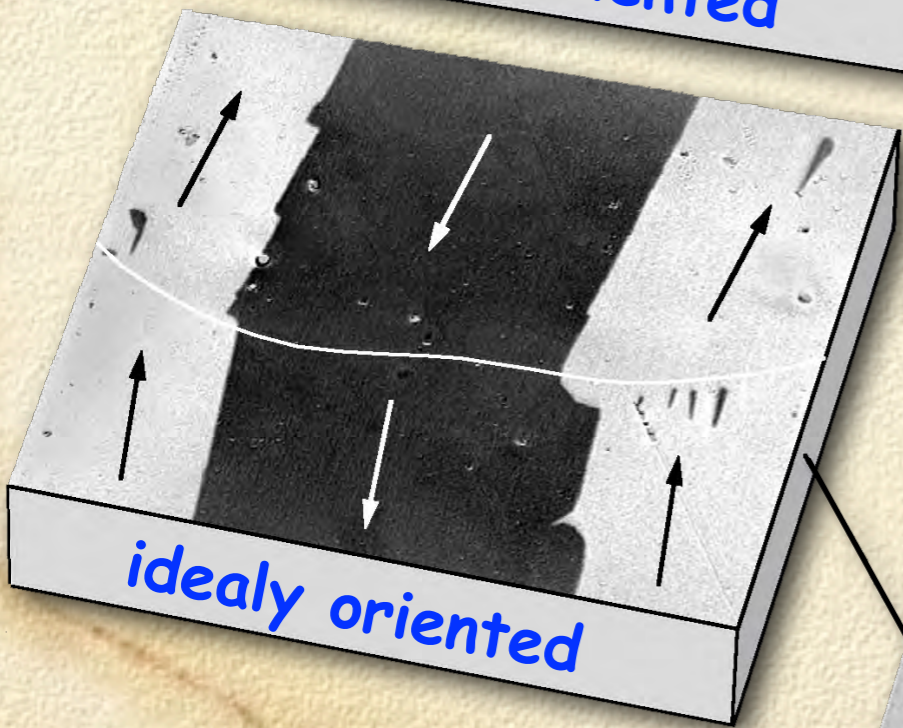


**Domain character:
determined by
interplay of energies**

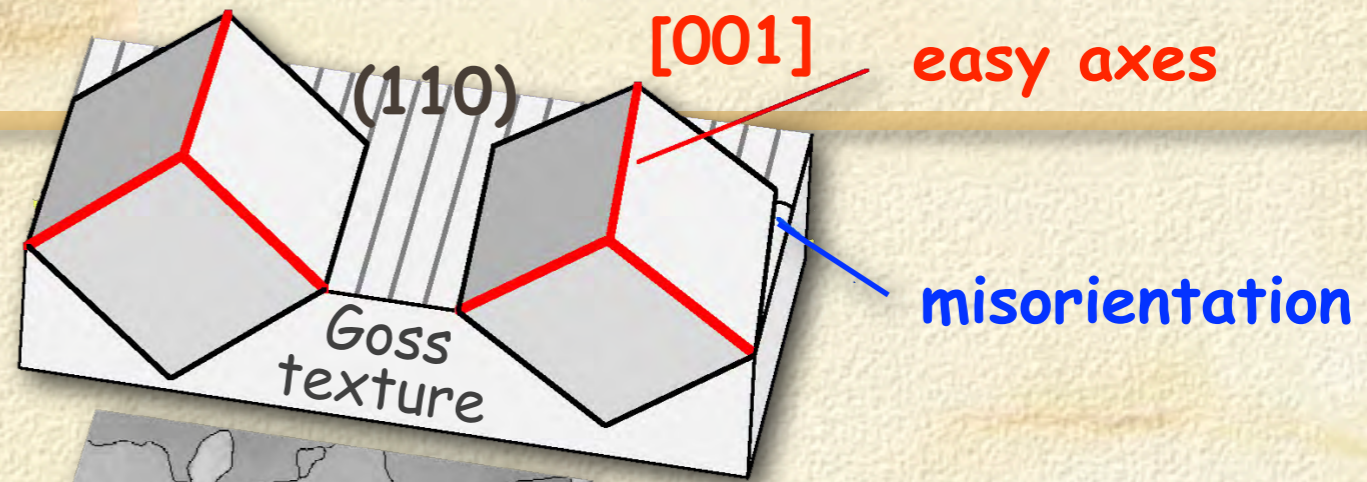
Transformer sheet



0.1 mm

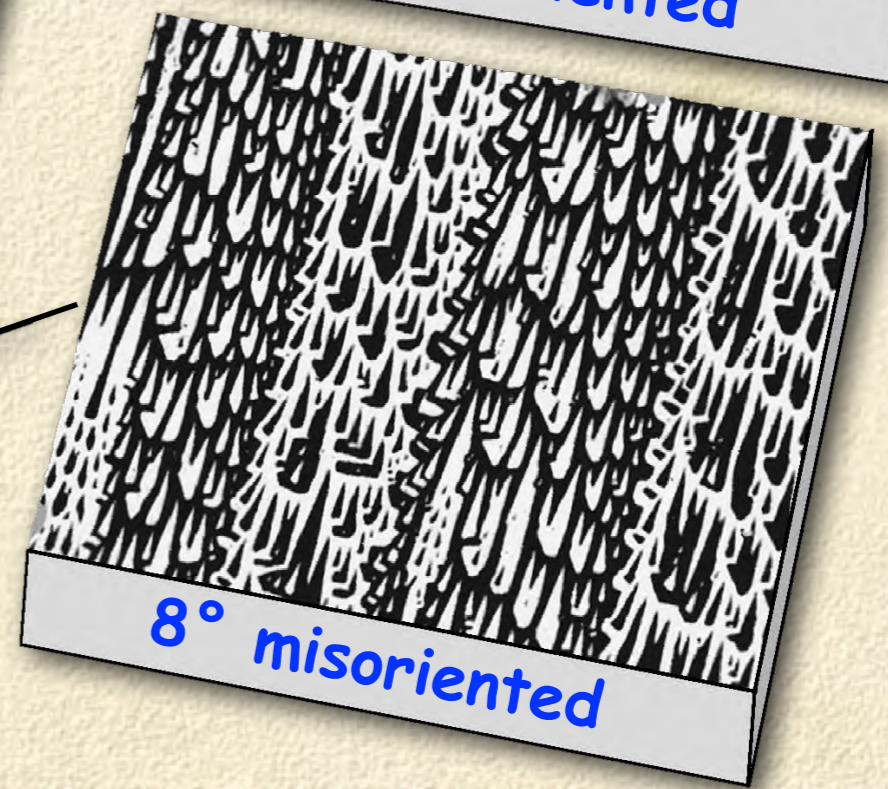
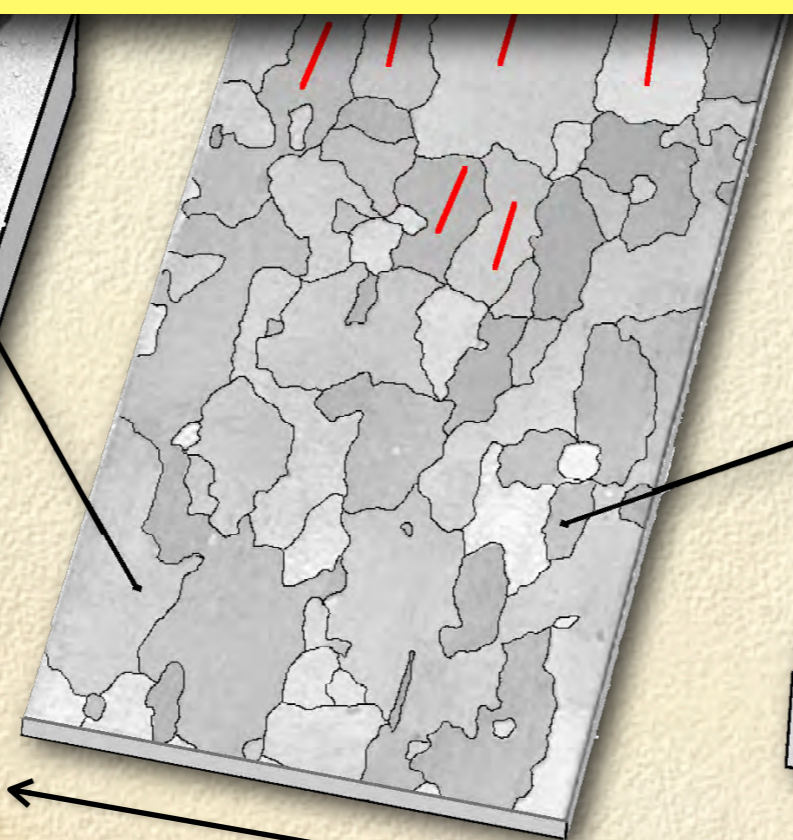
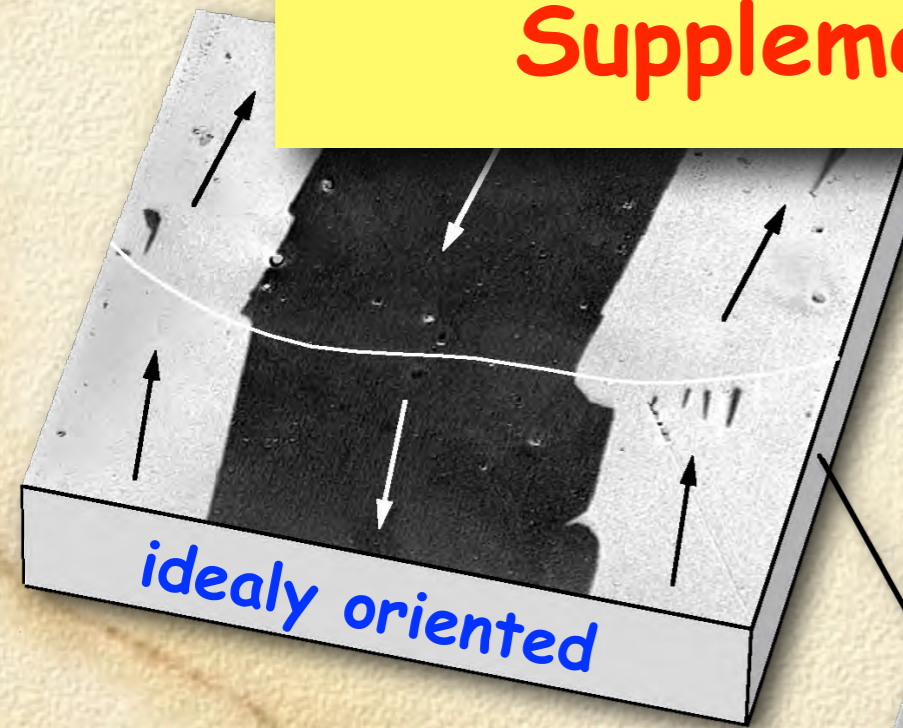
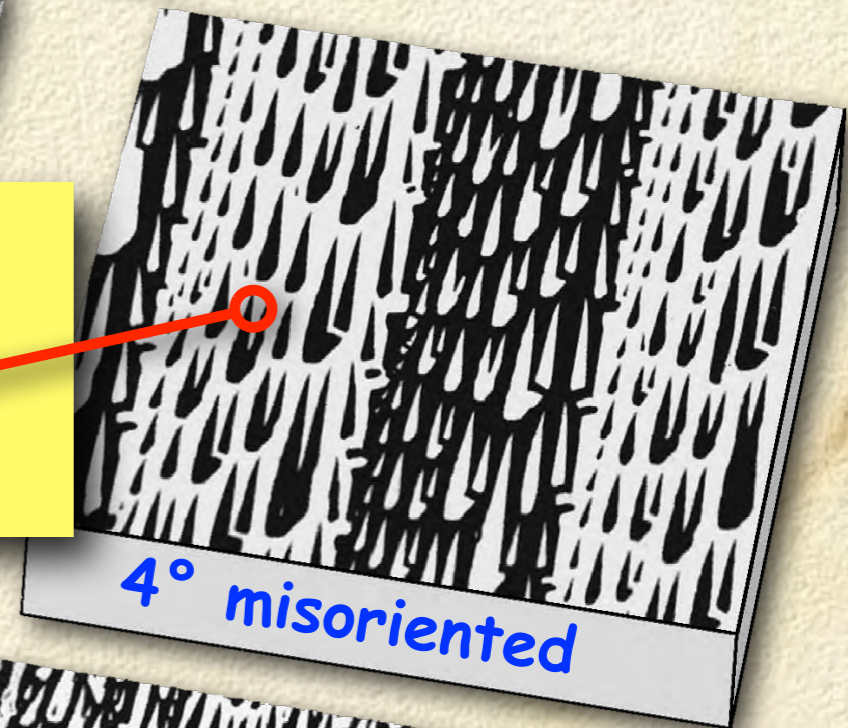


Transformer sheet



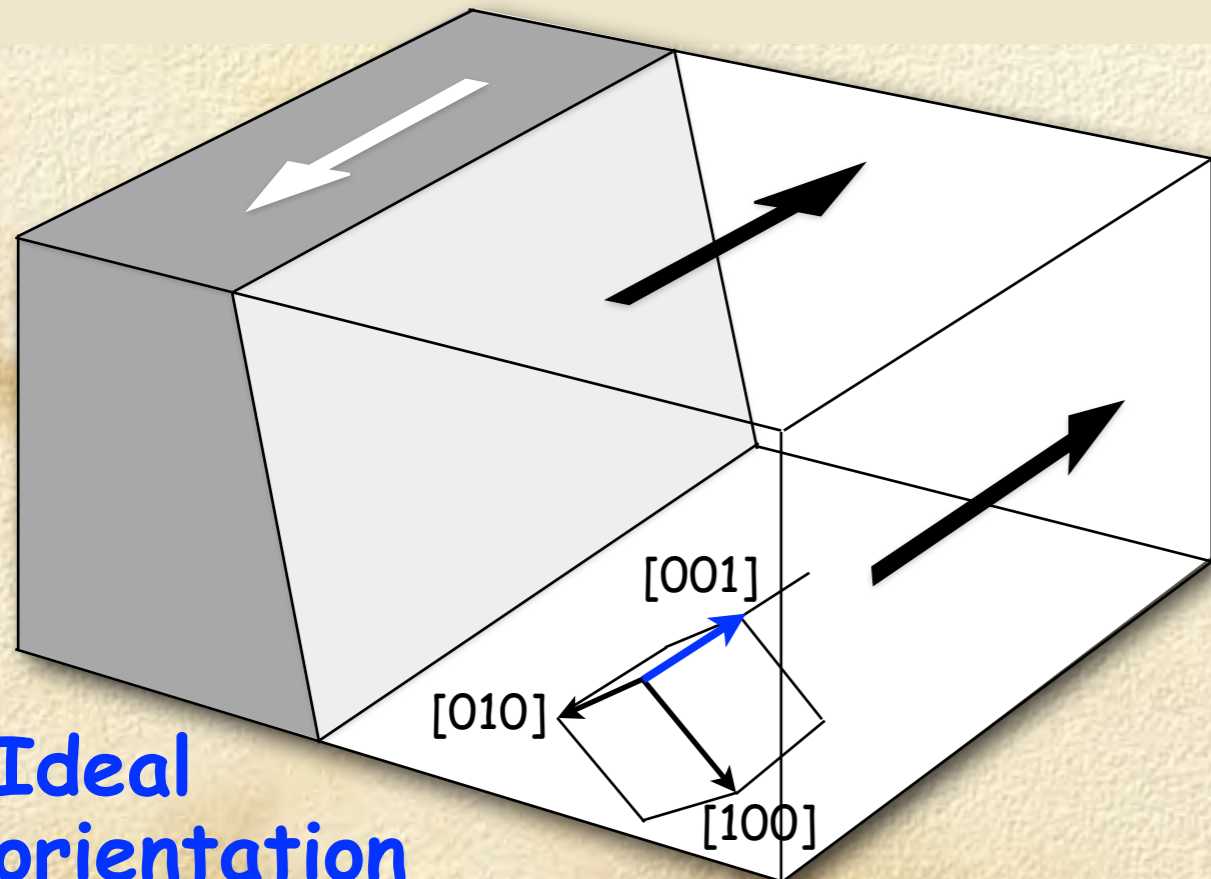
0.1 mm

Fine, superimposed domains:
Supplementary Domains

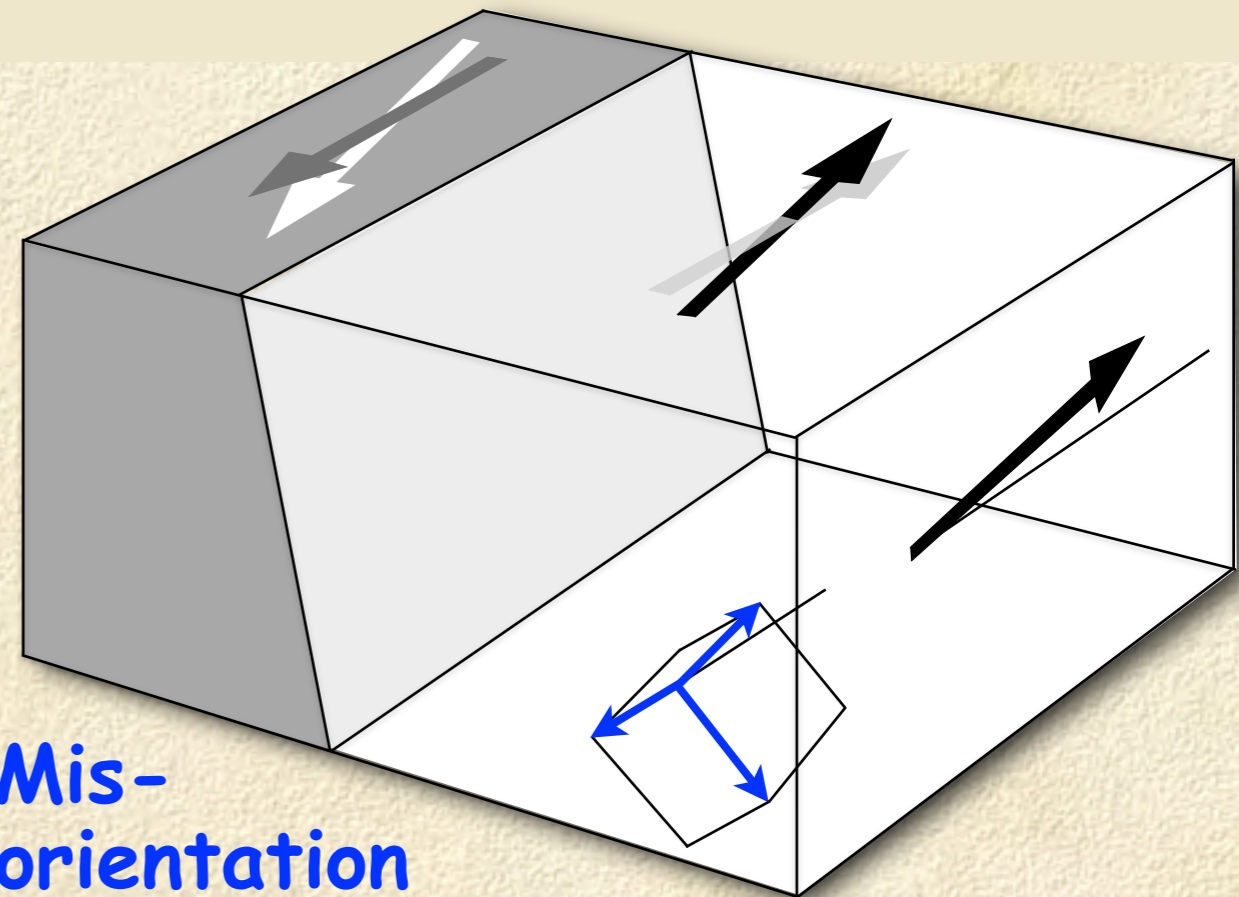


30 mm

Grain-oriented FeSi transformer material

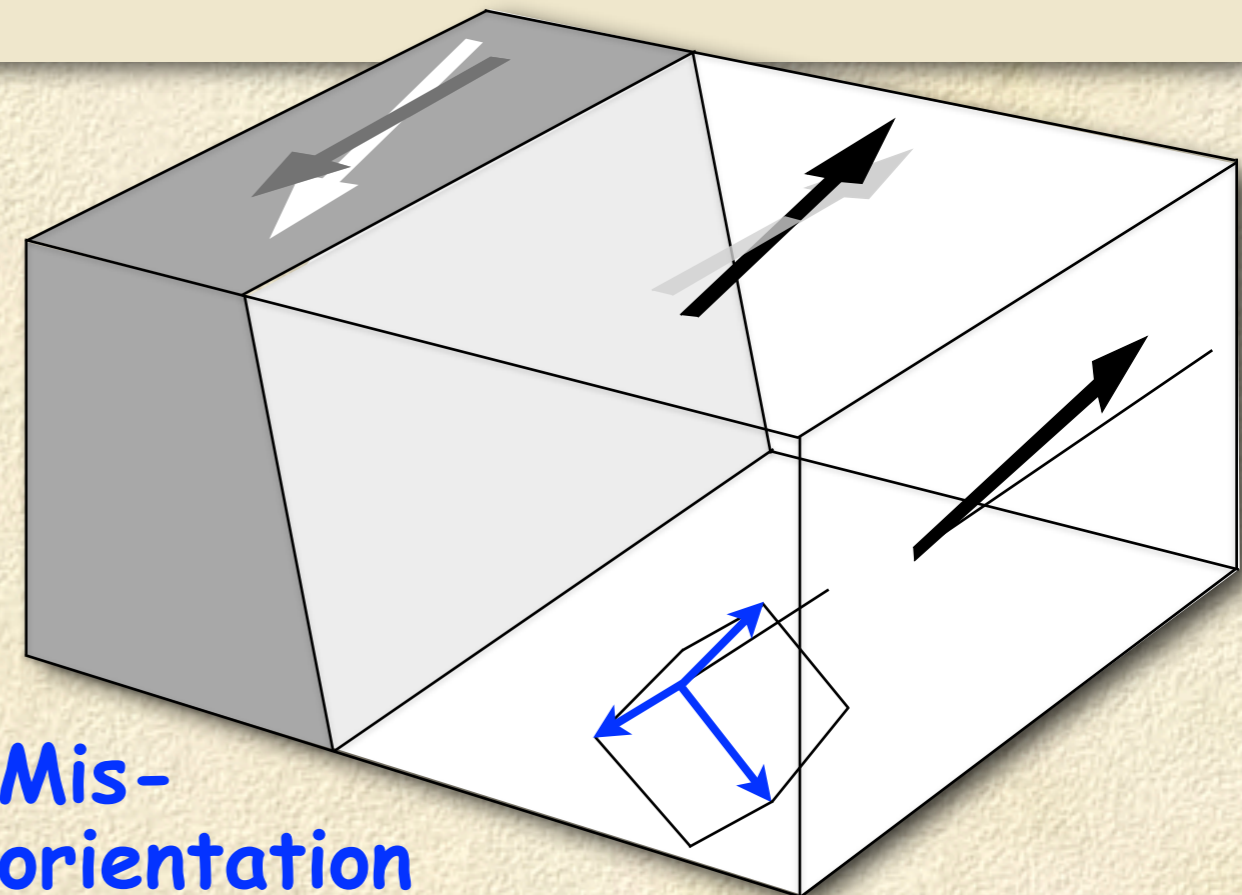
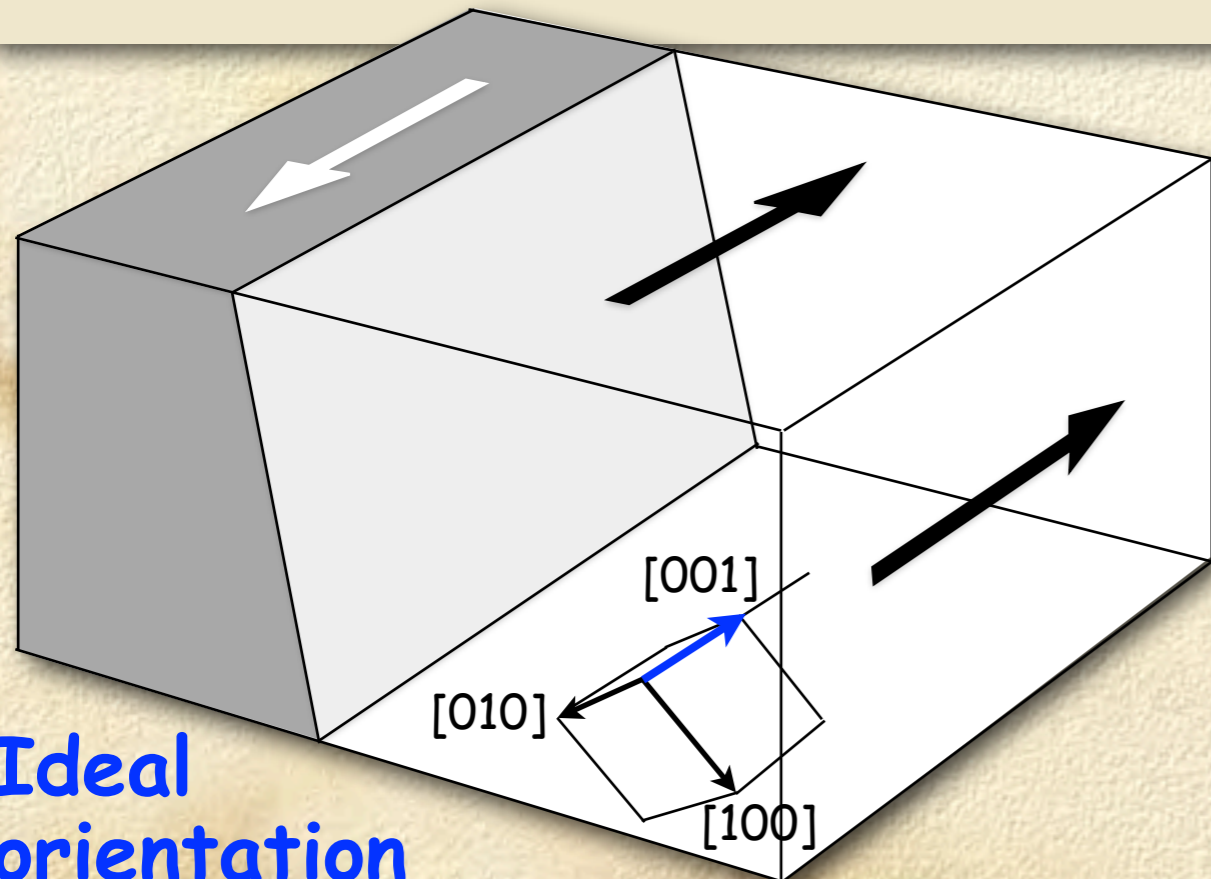
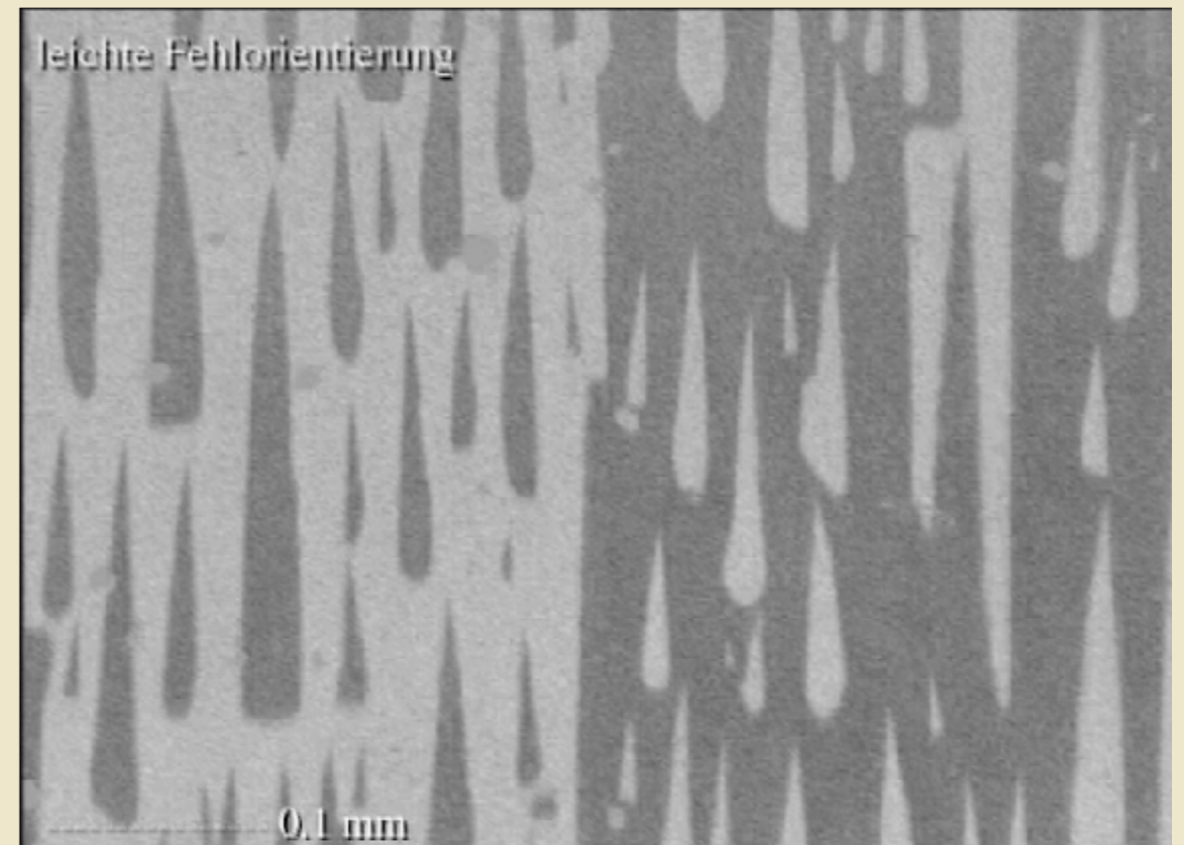
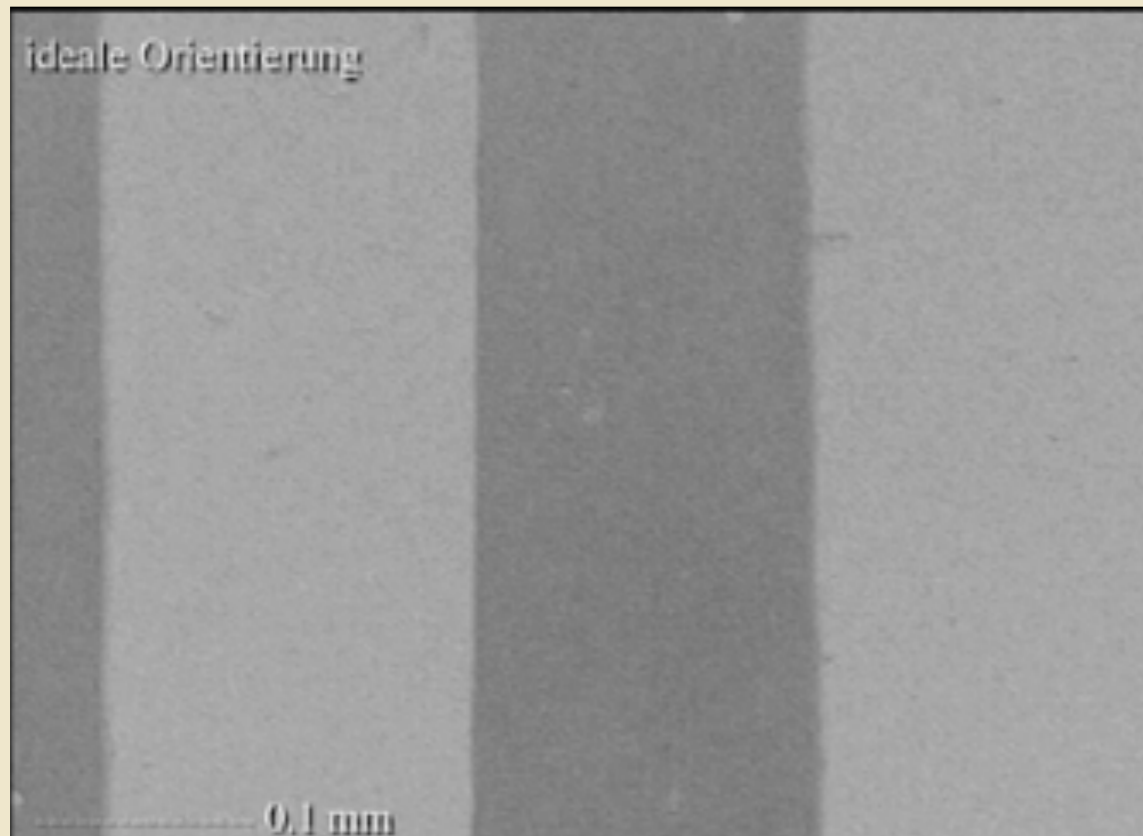


Ideal orientation

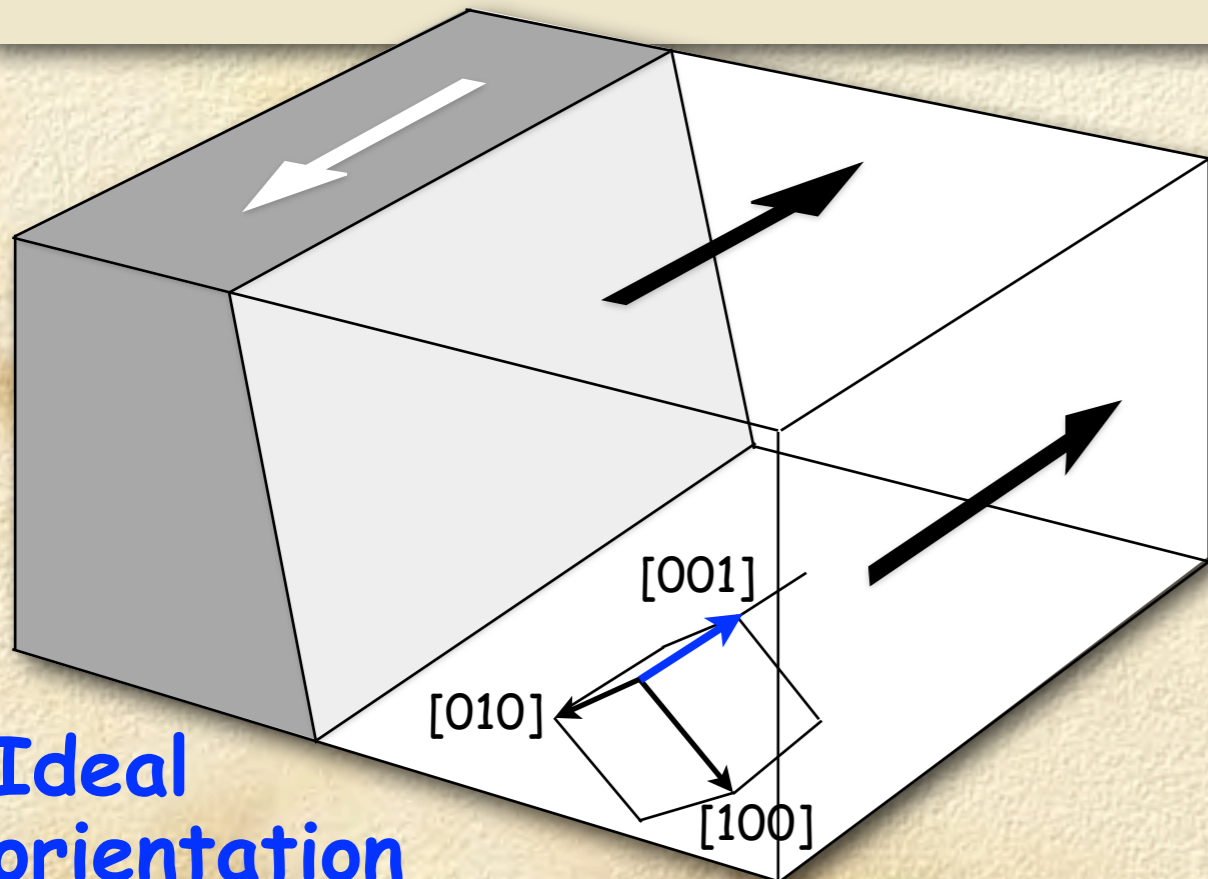
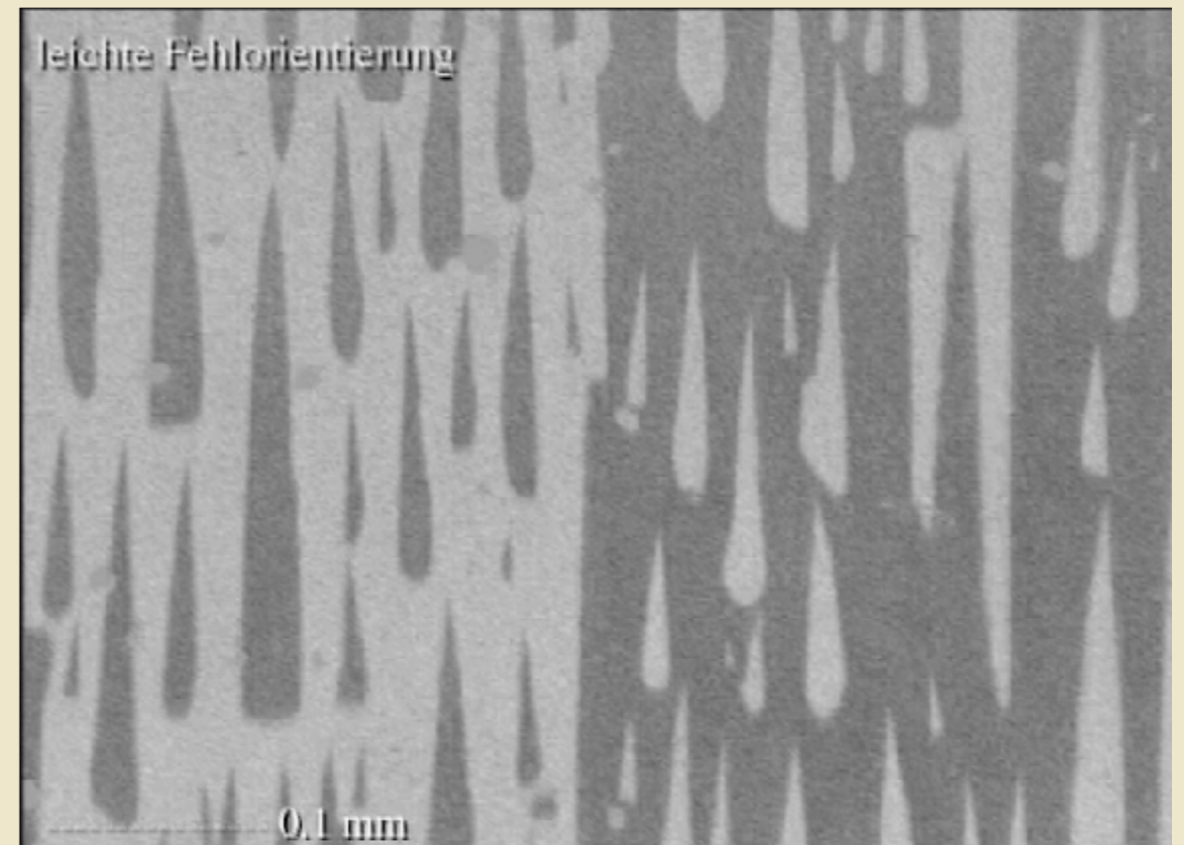
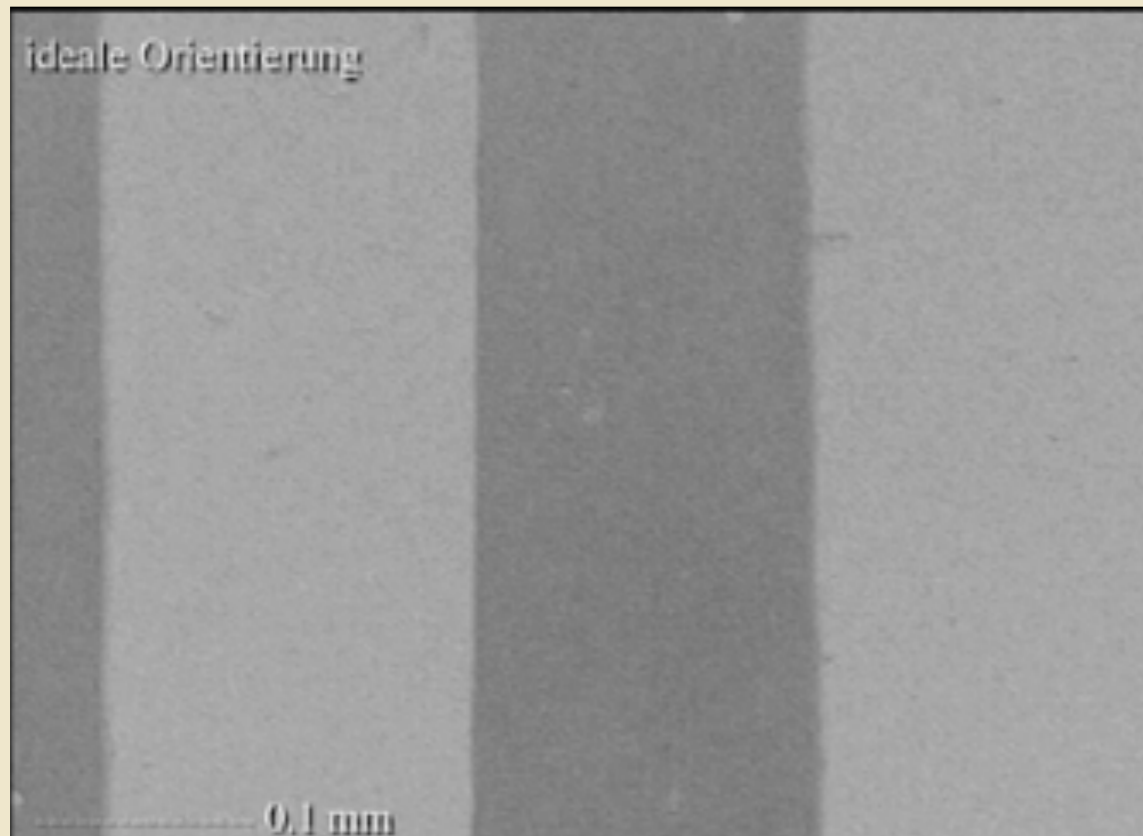


Mis-orientation

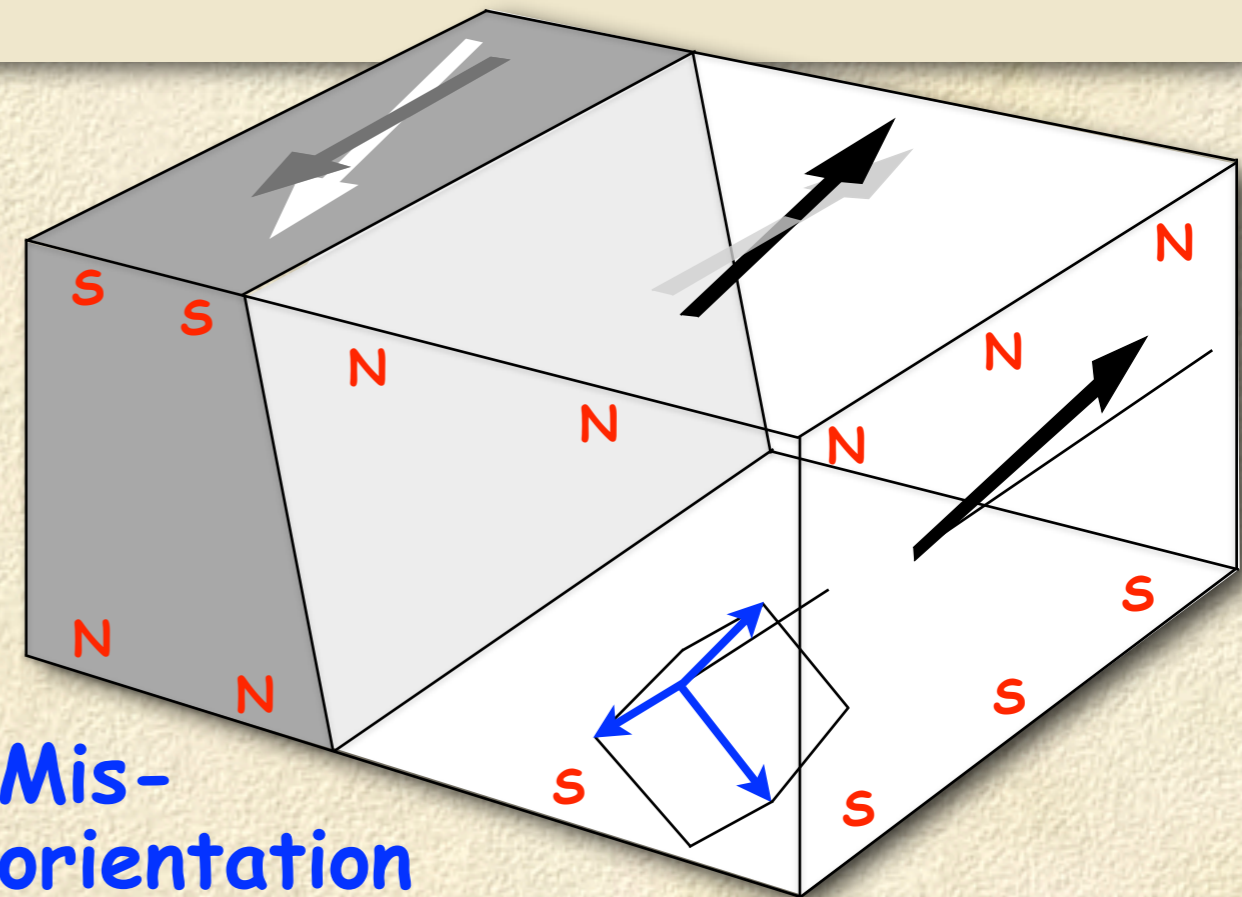
Grain-oriented FeSi transformer material



Grain-oriented FeSi transformer material

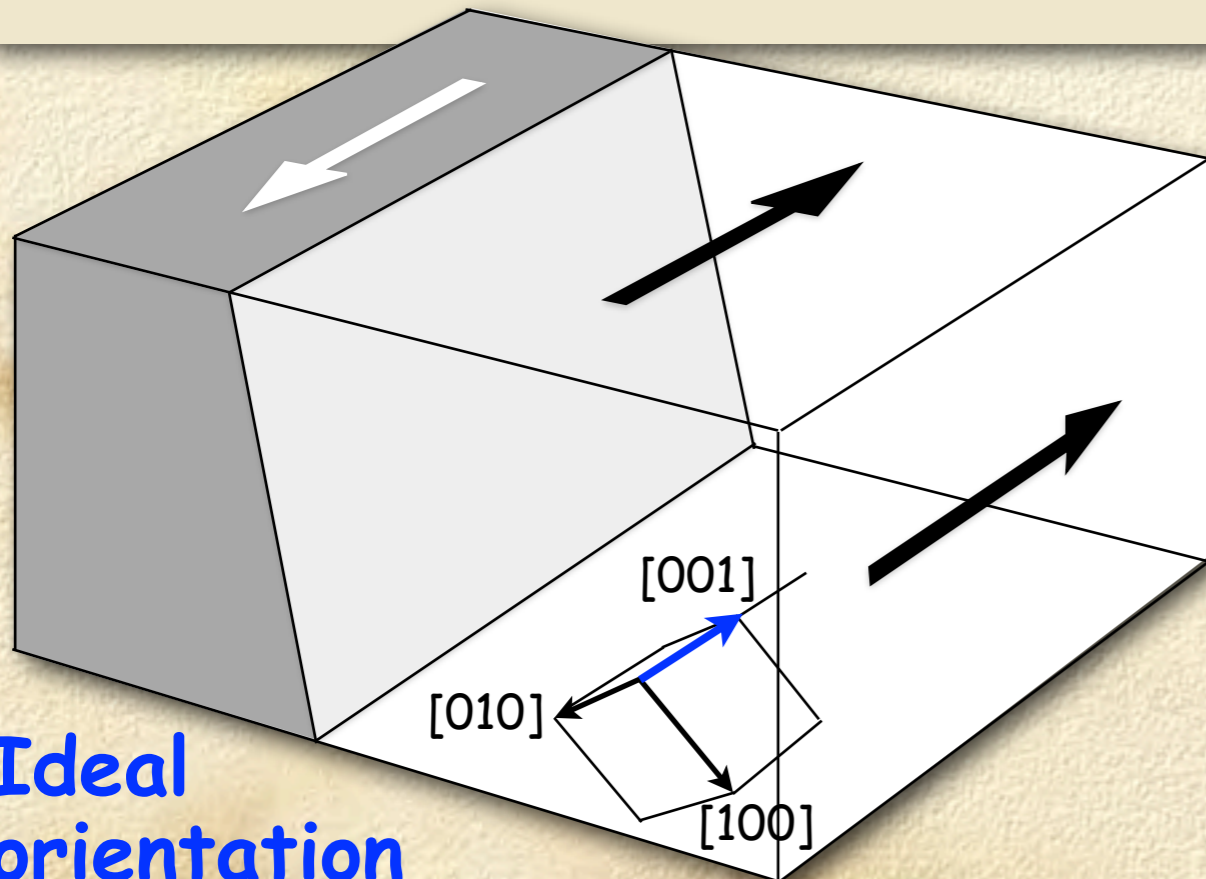
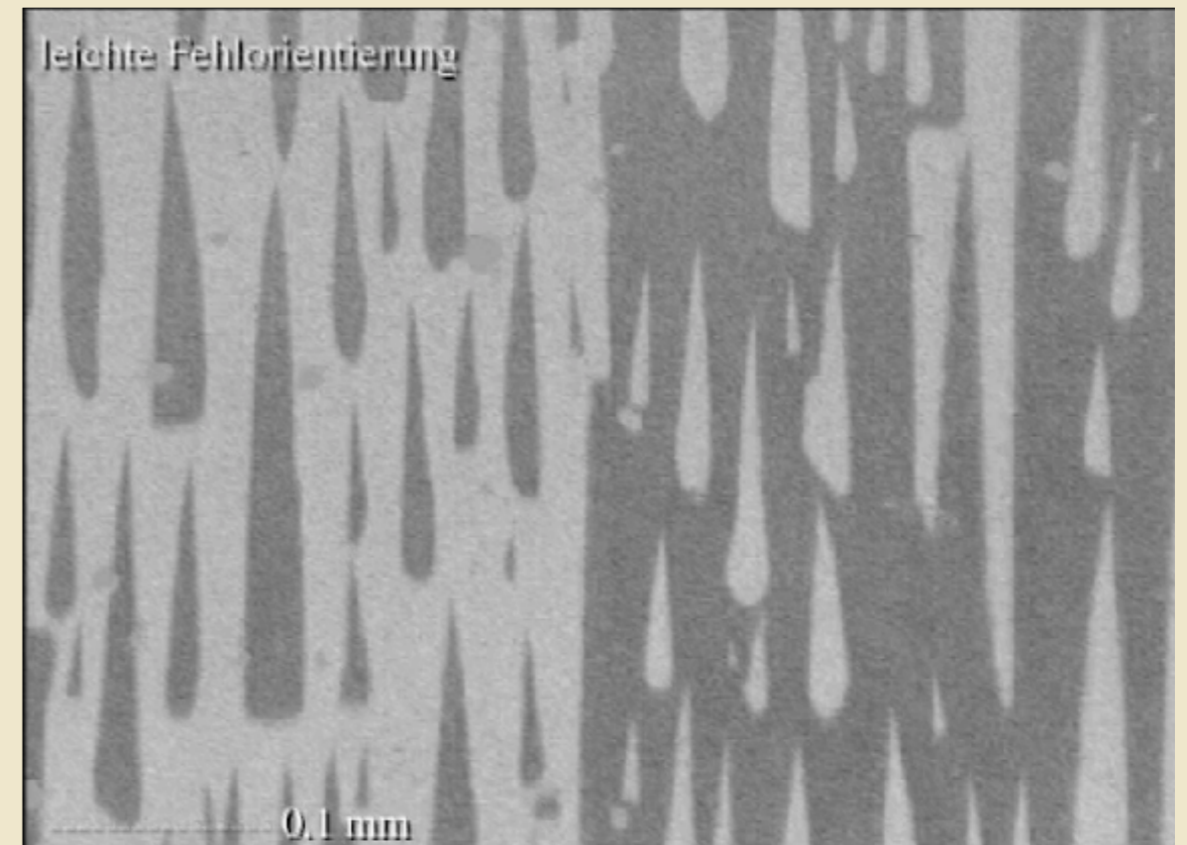
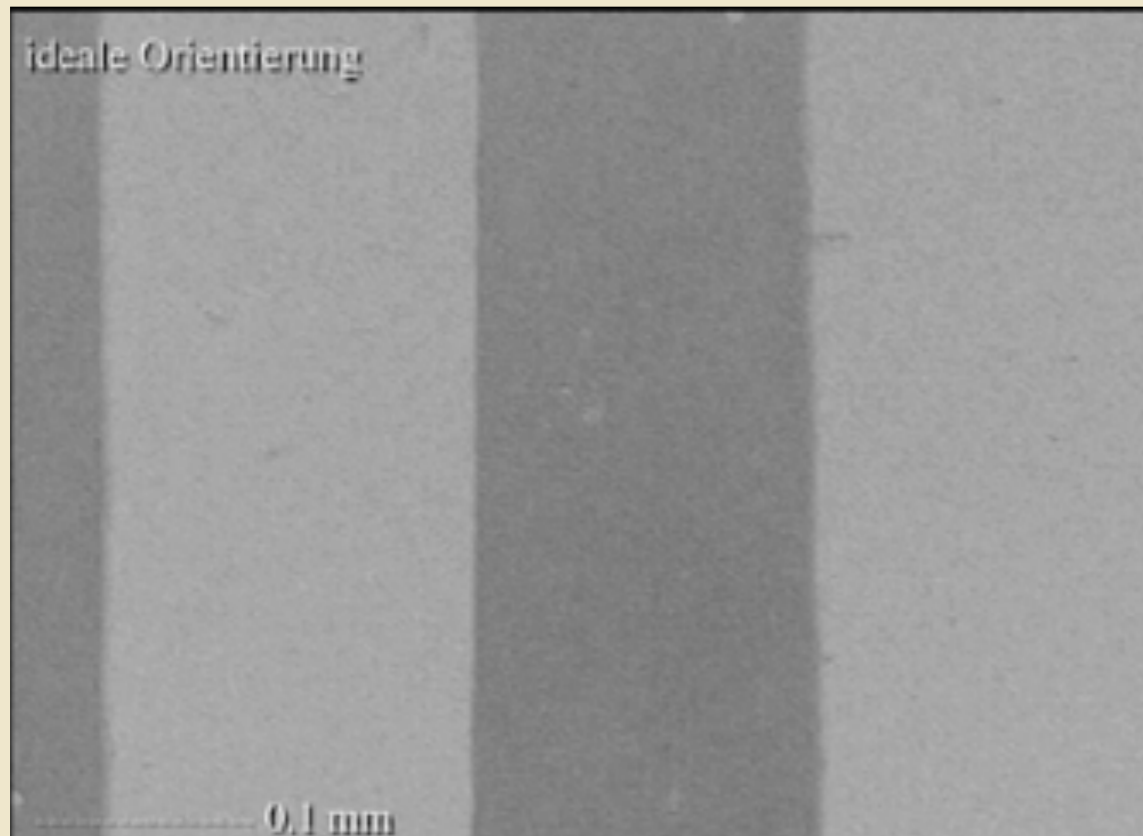


Ideal orientation

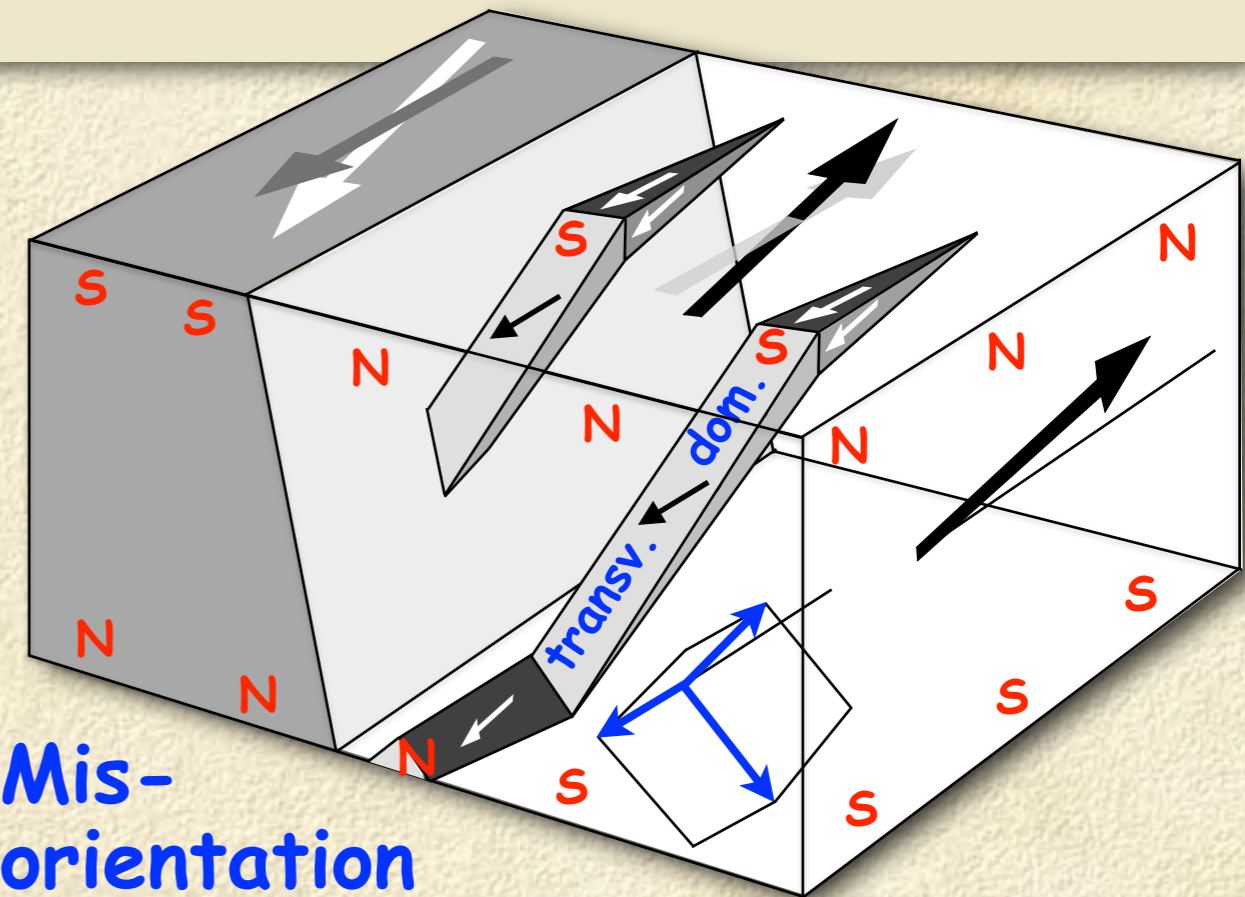


Mis-orientation

Grain-oriented FeSi transformer material

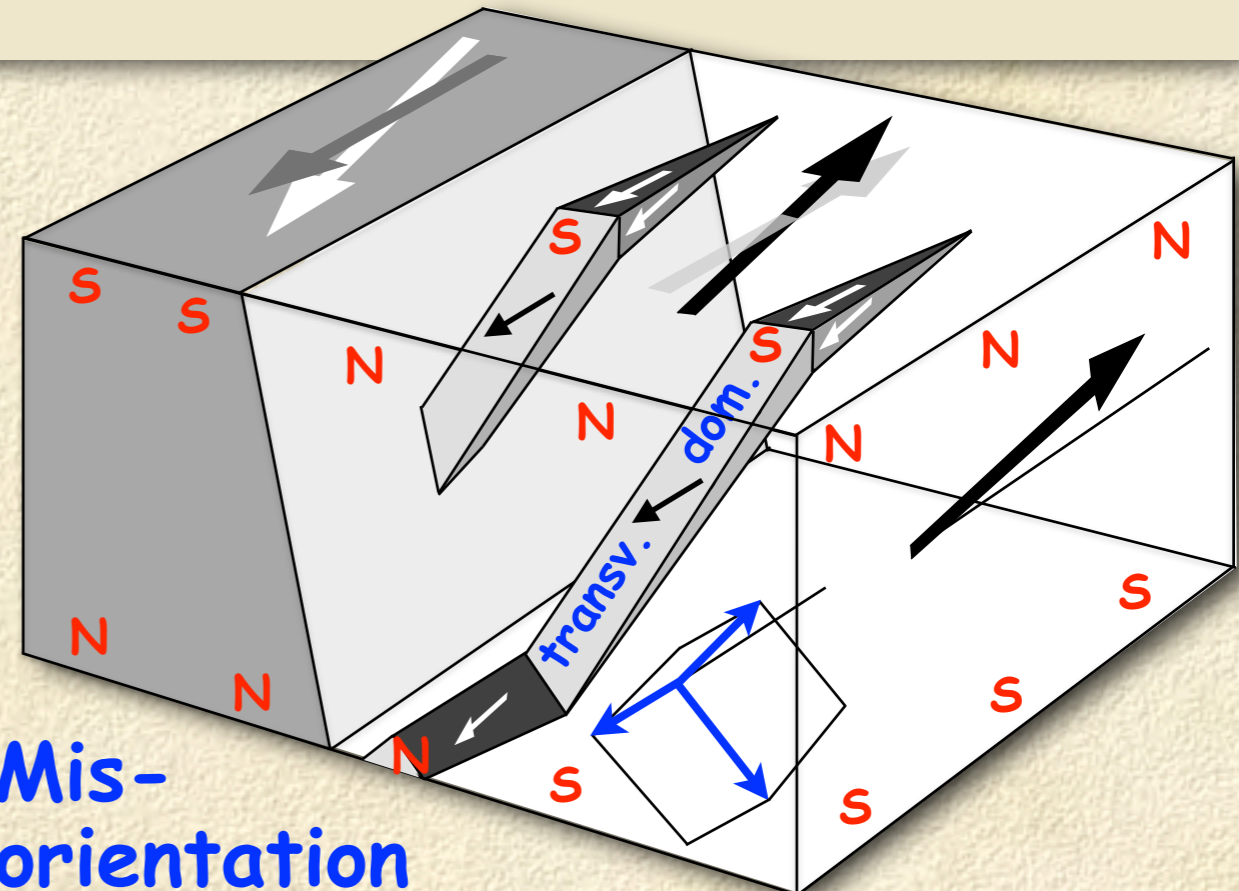
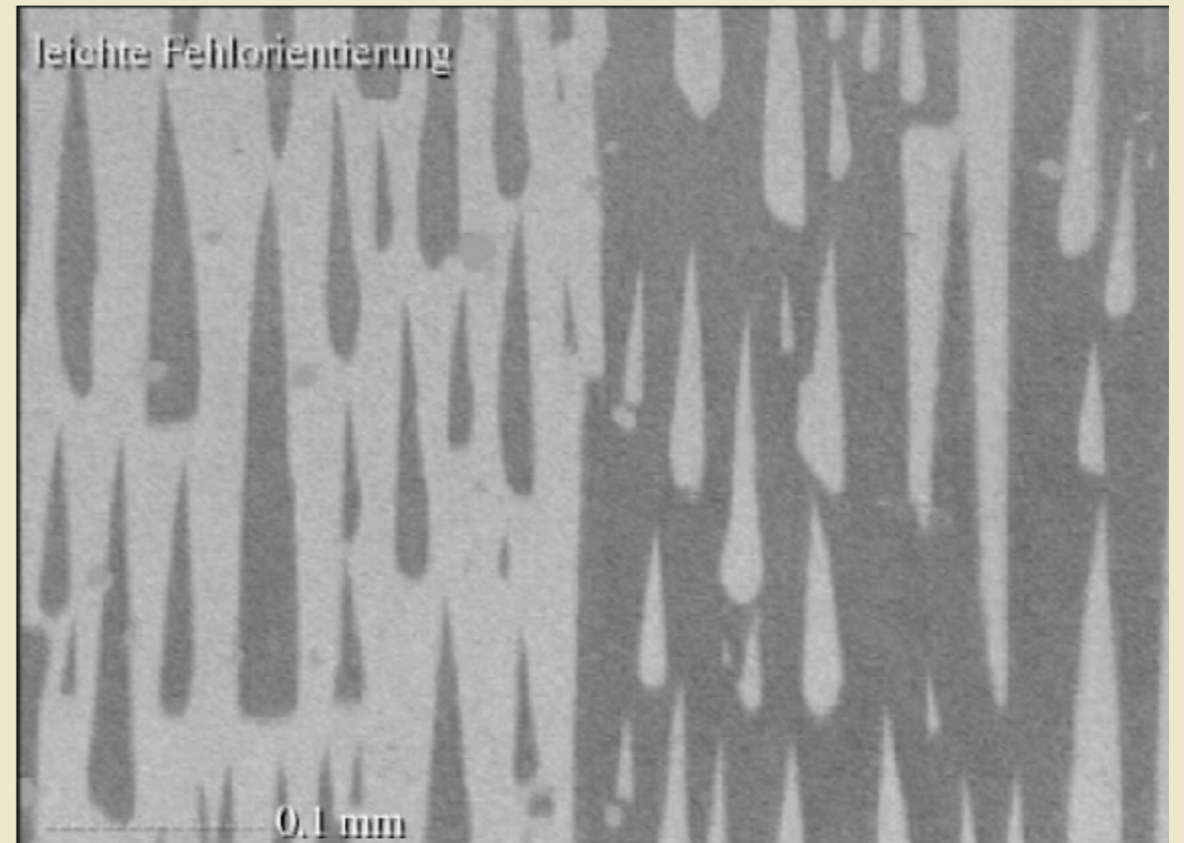


Ideal orientation

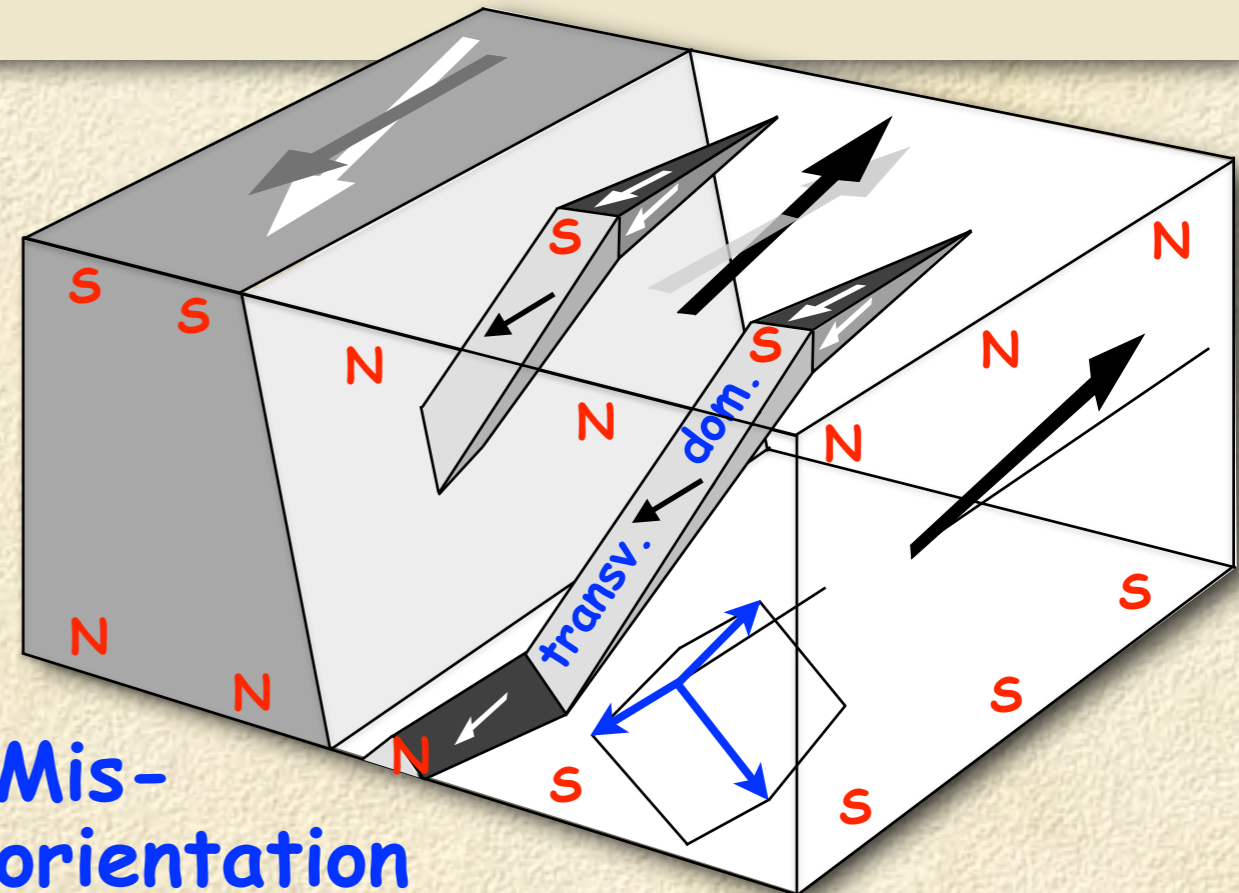
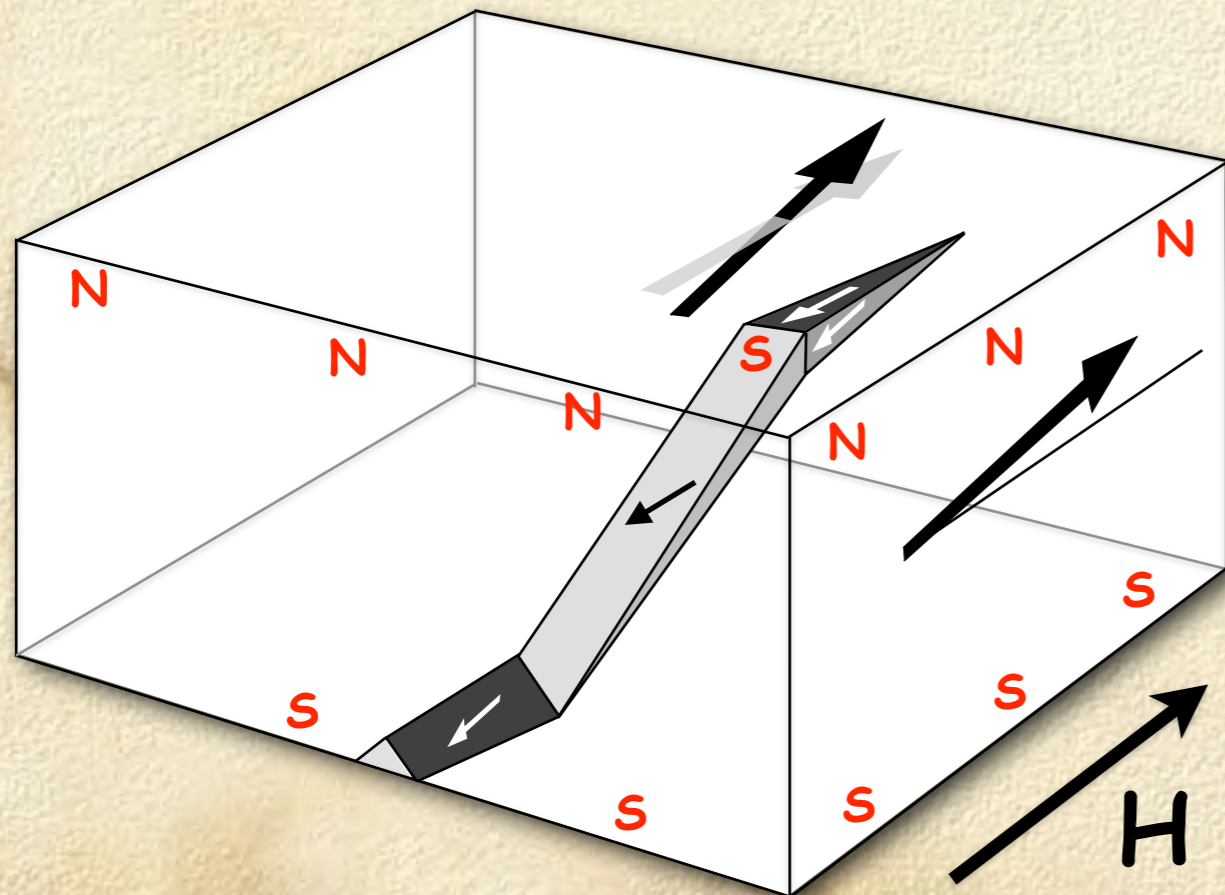
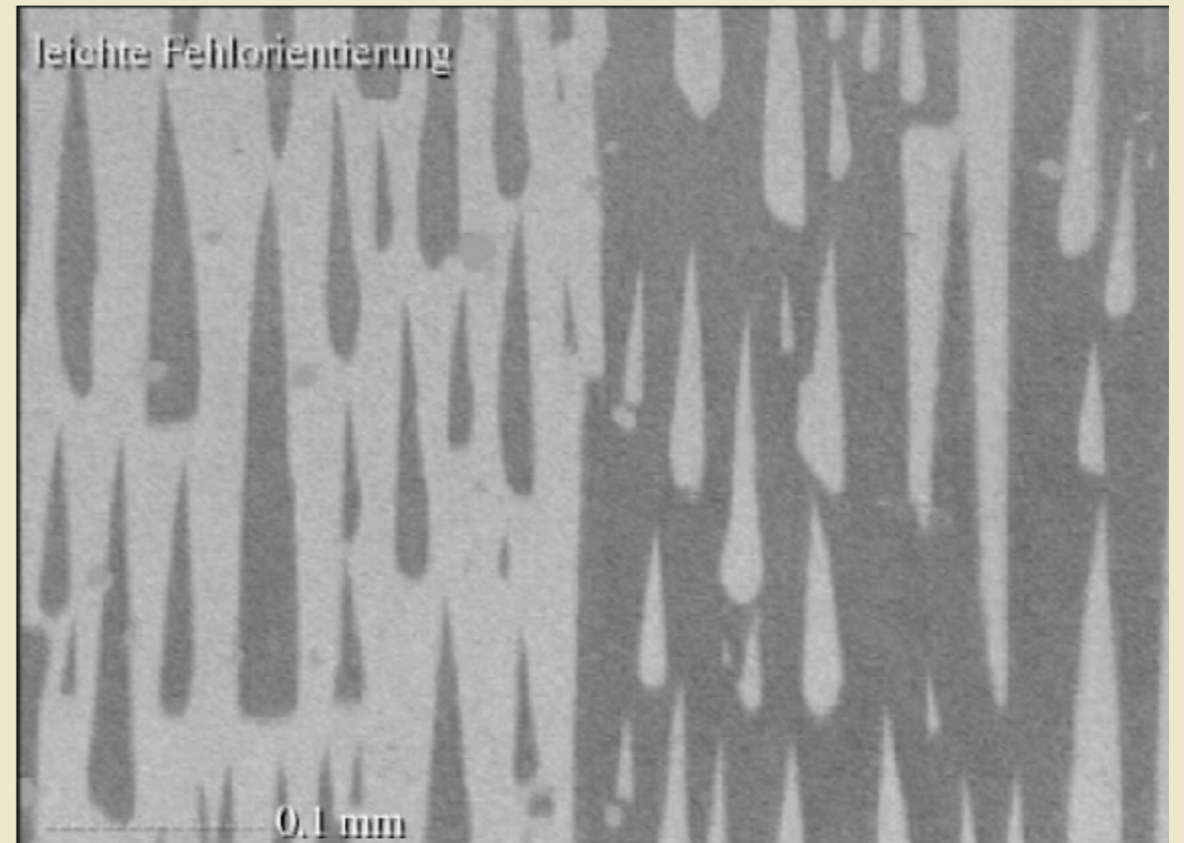


Mis-orientation

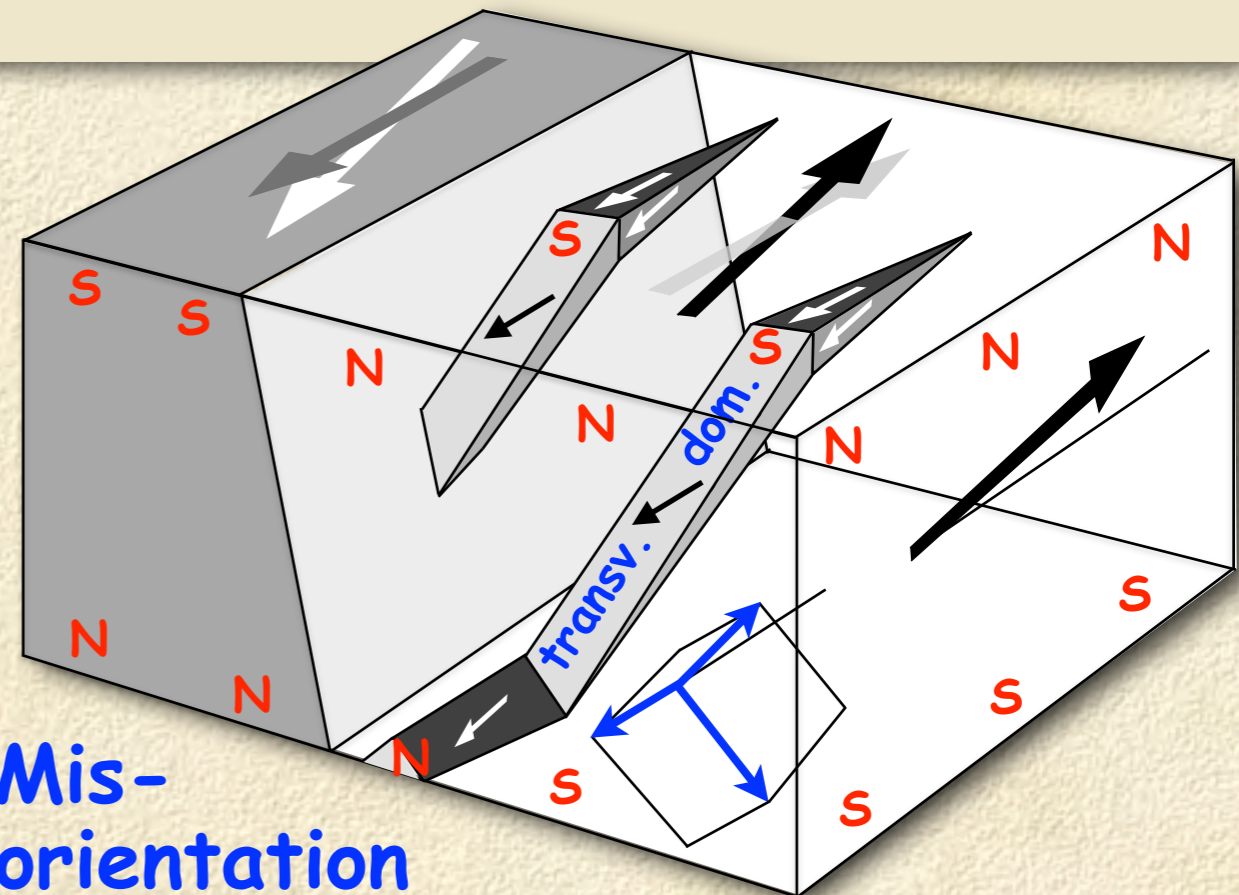
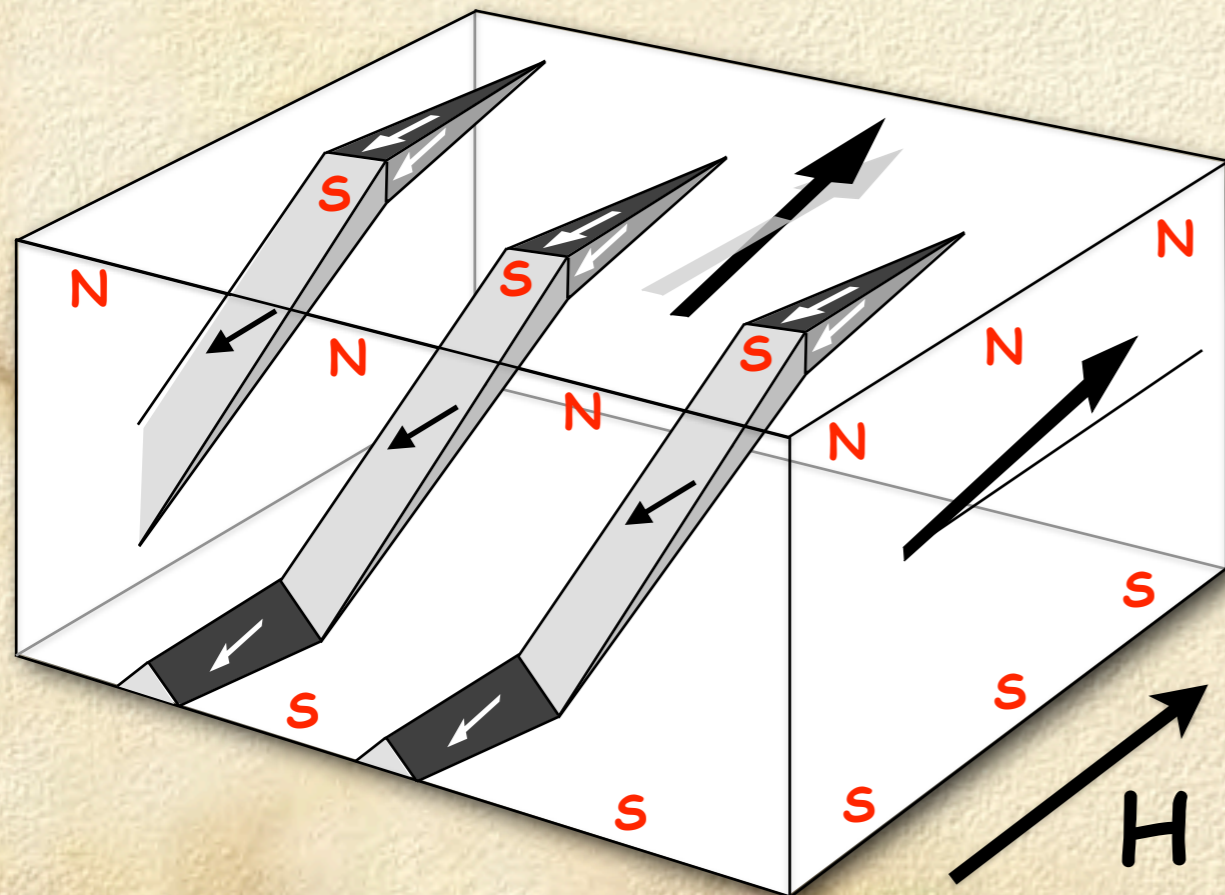
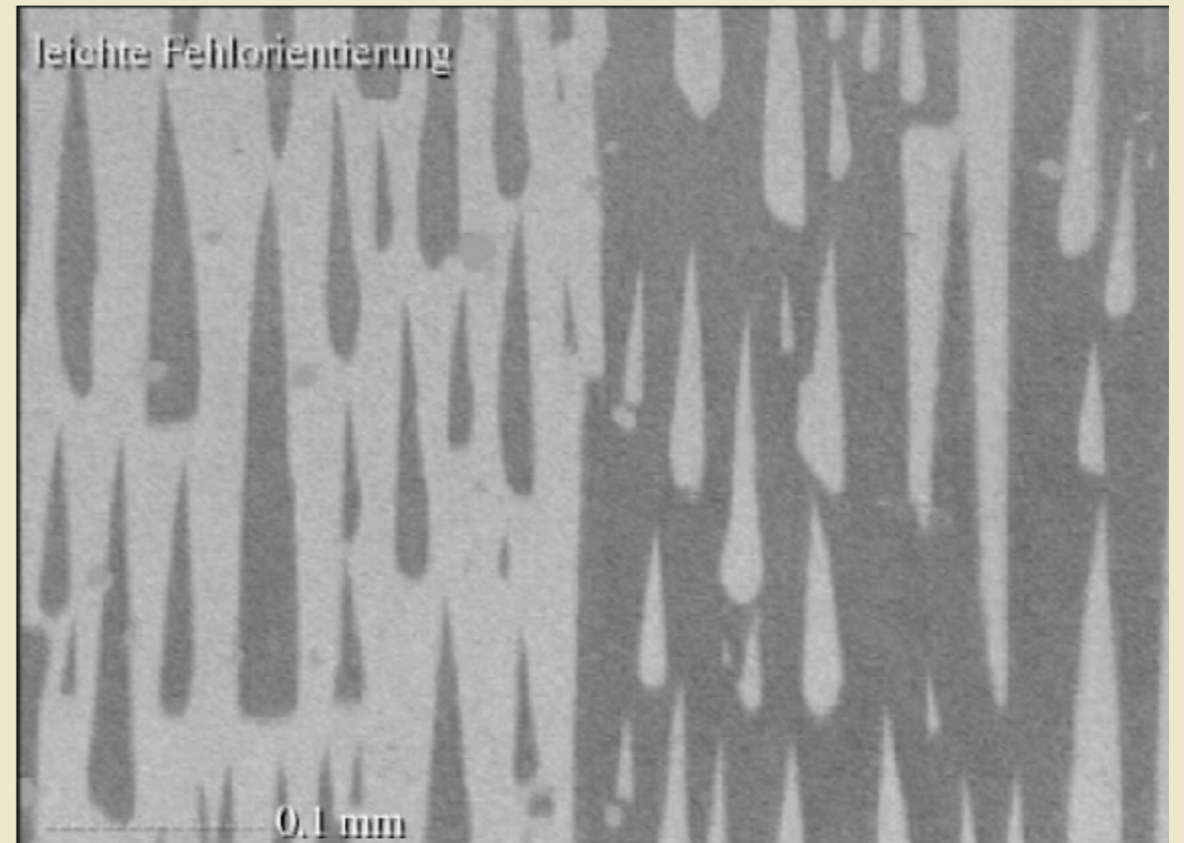
Grain-oriented FeSi transformer material



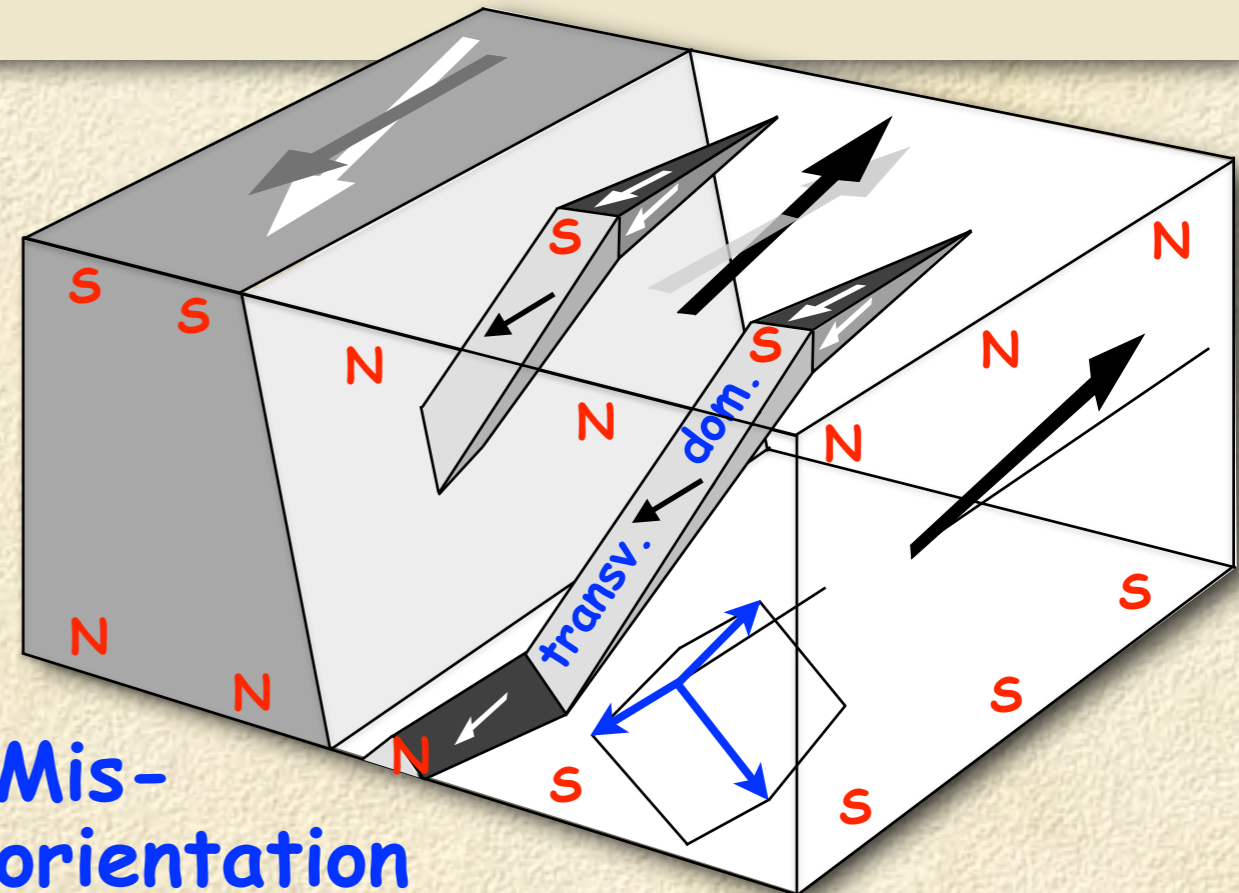
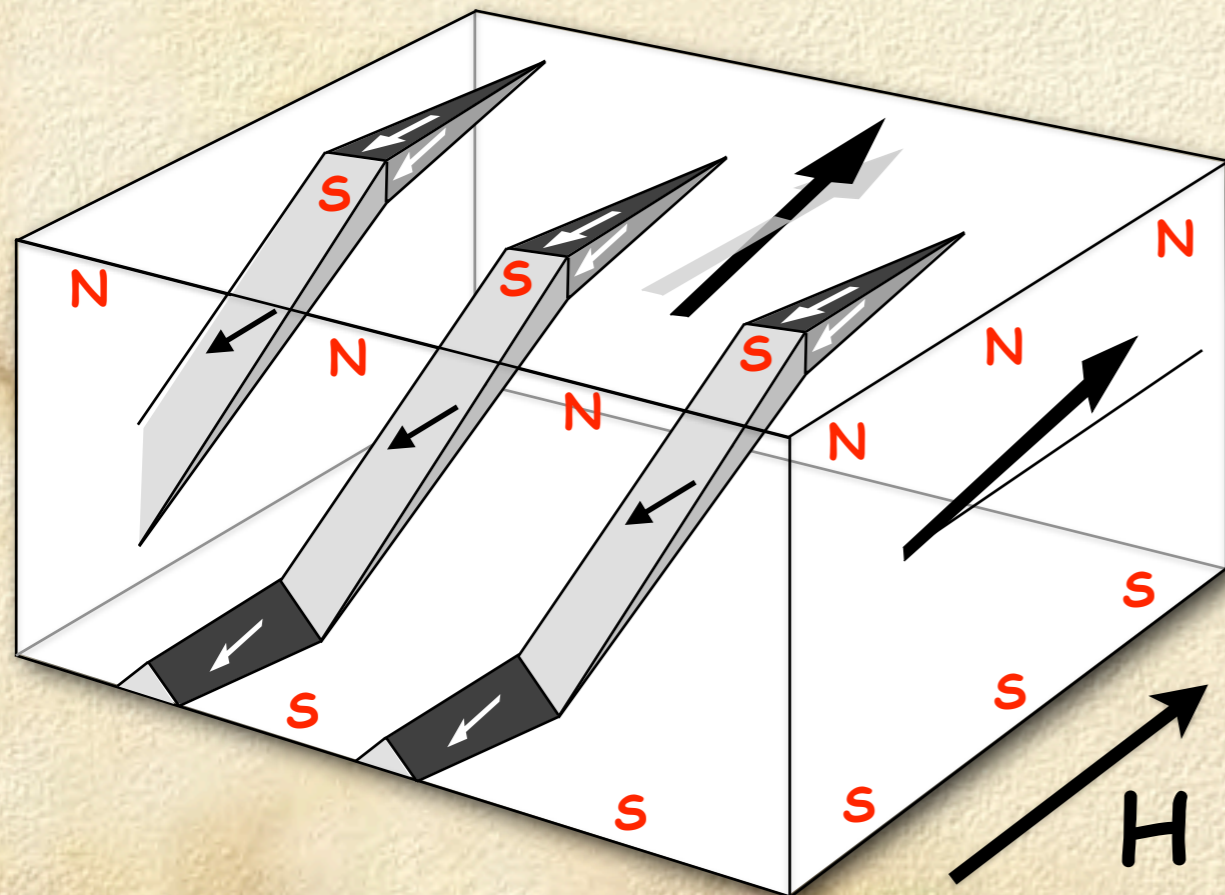
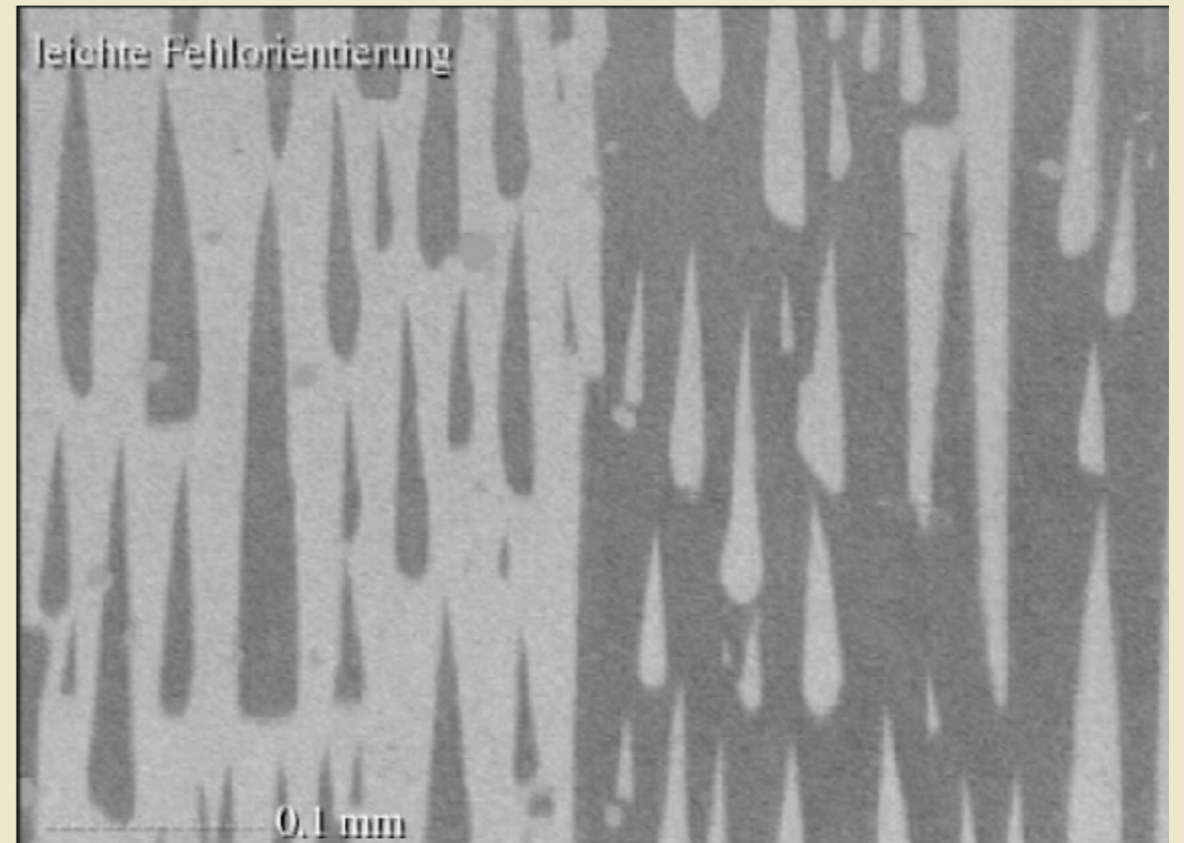
Grain-oriented FeSi transformer material



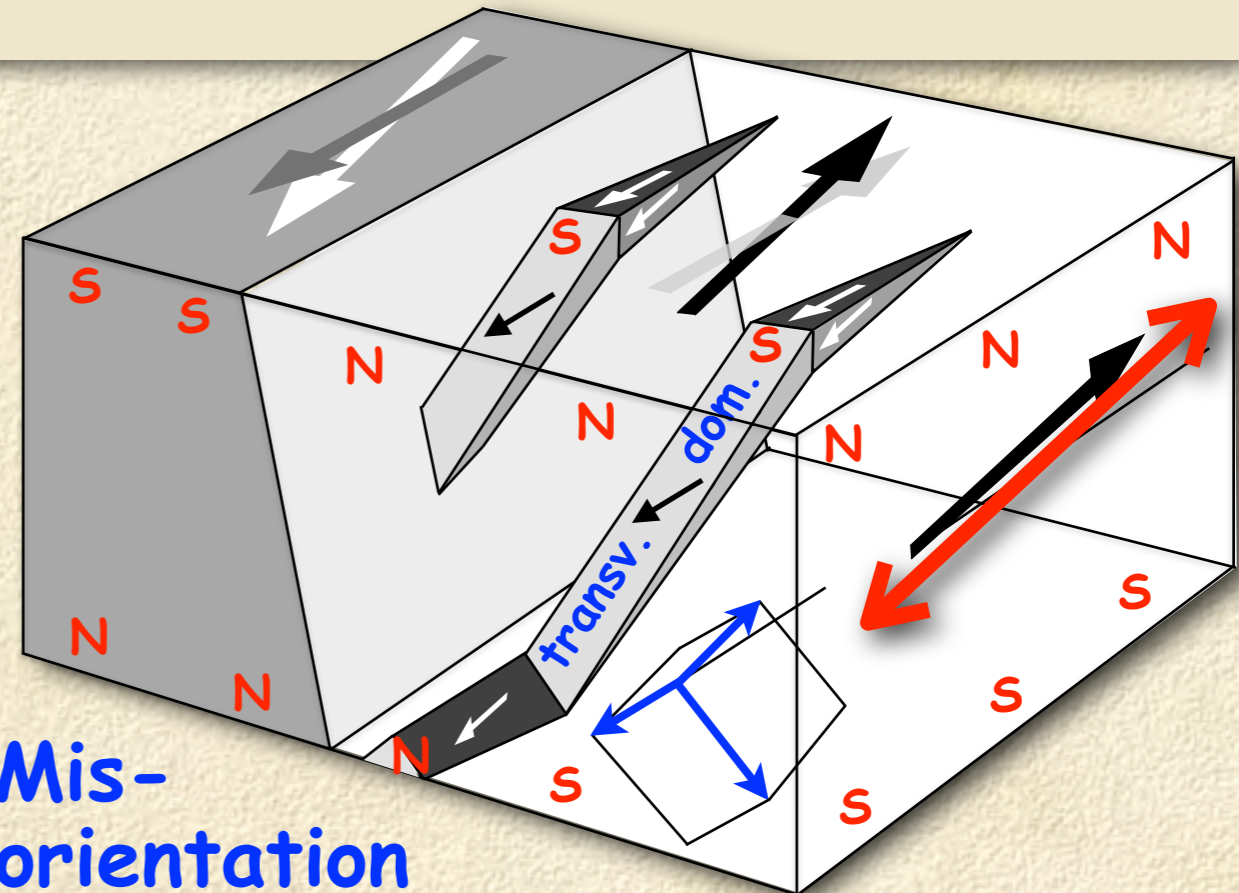
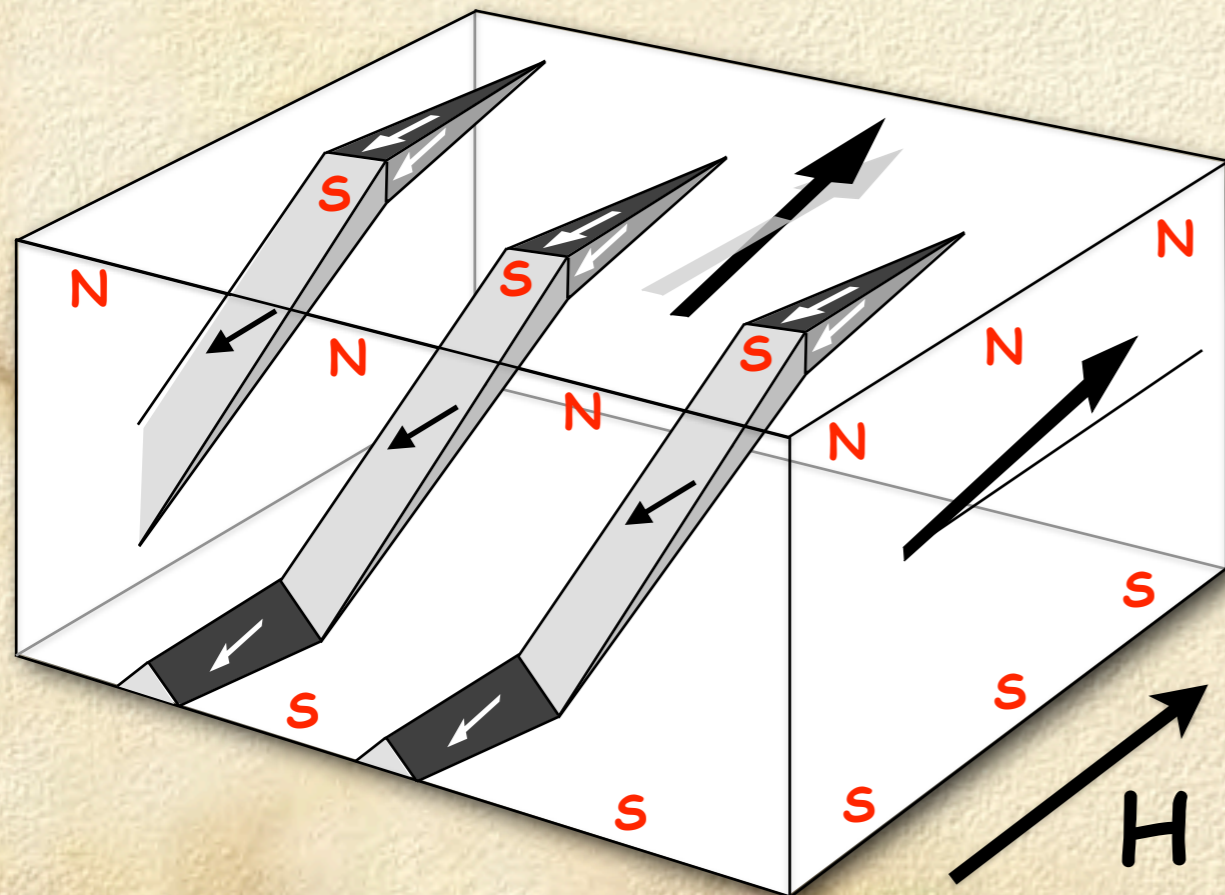
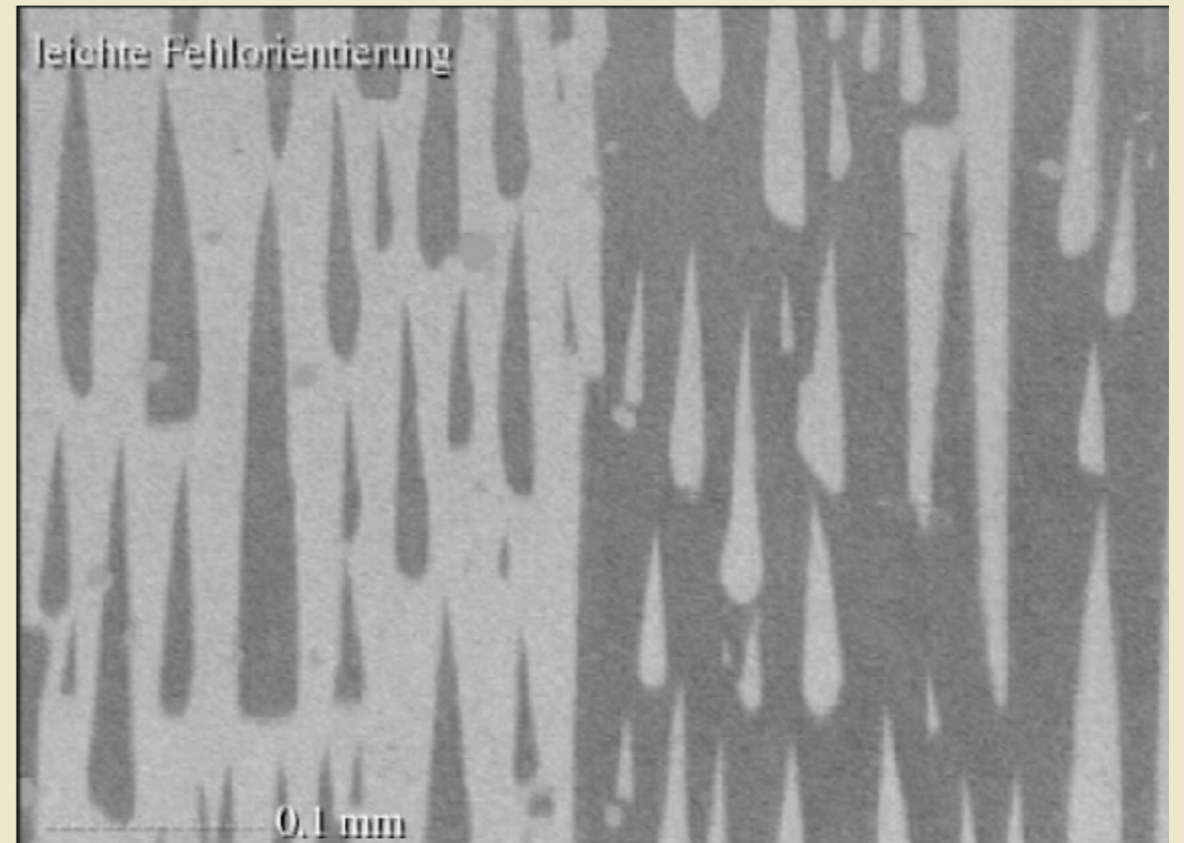
Grain-oriented FeSi transformer material



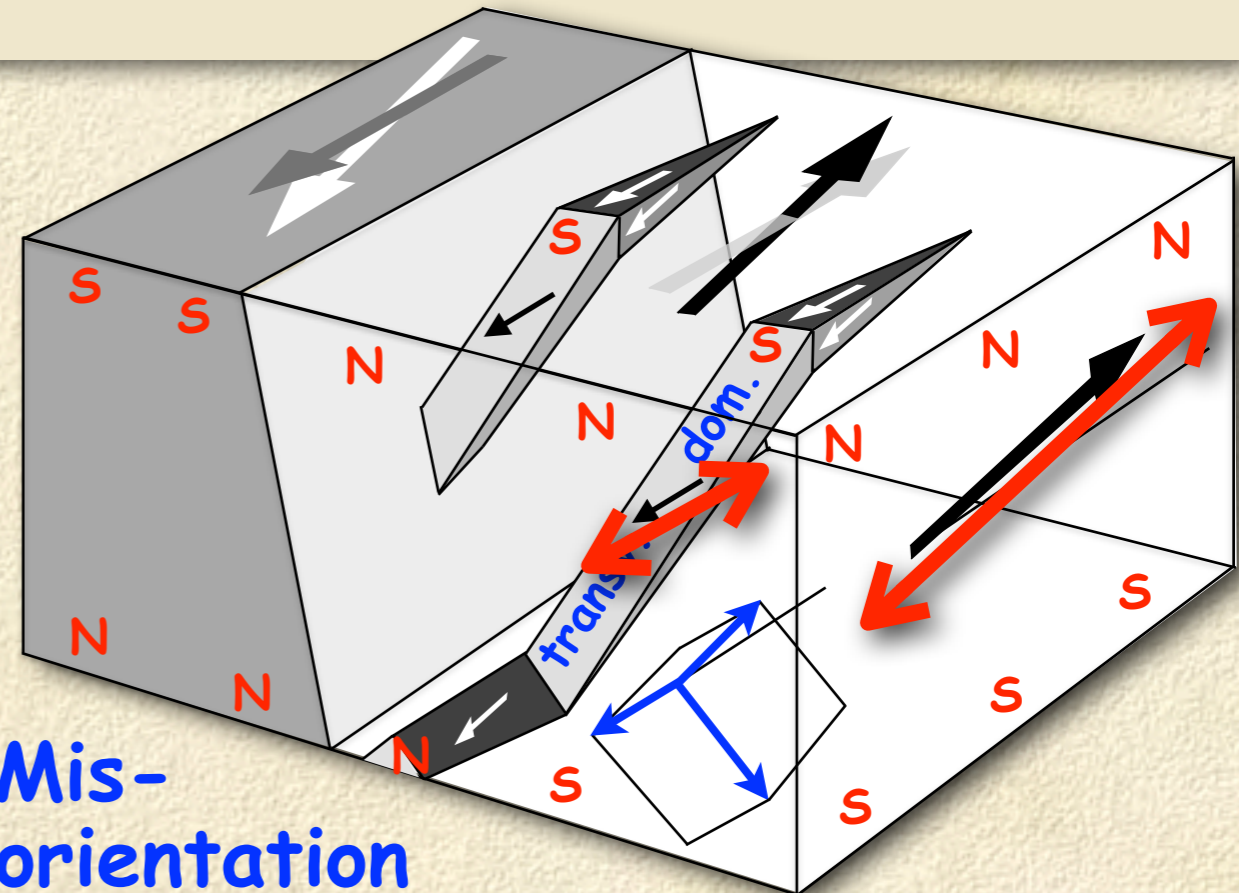
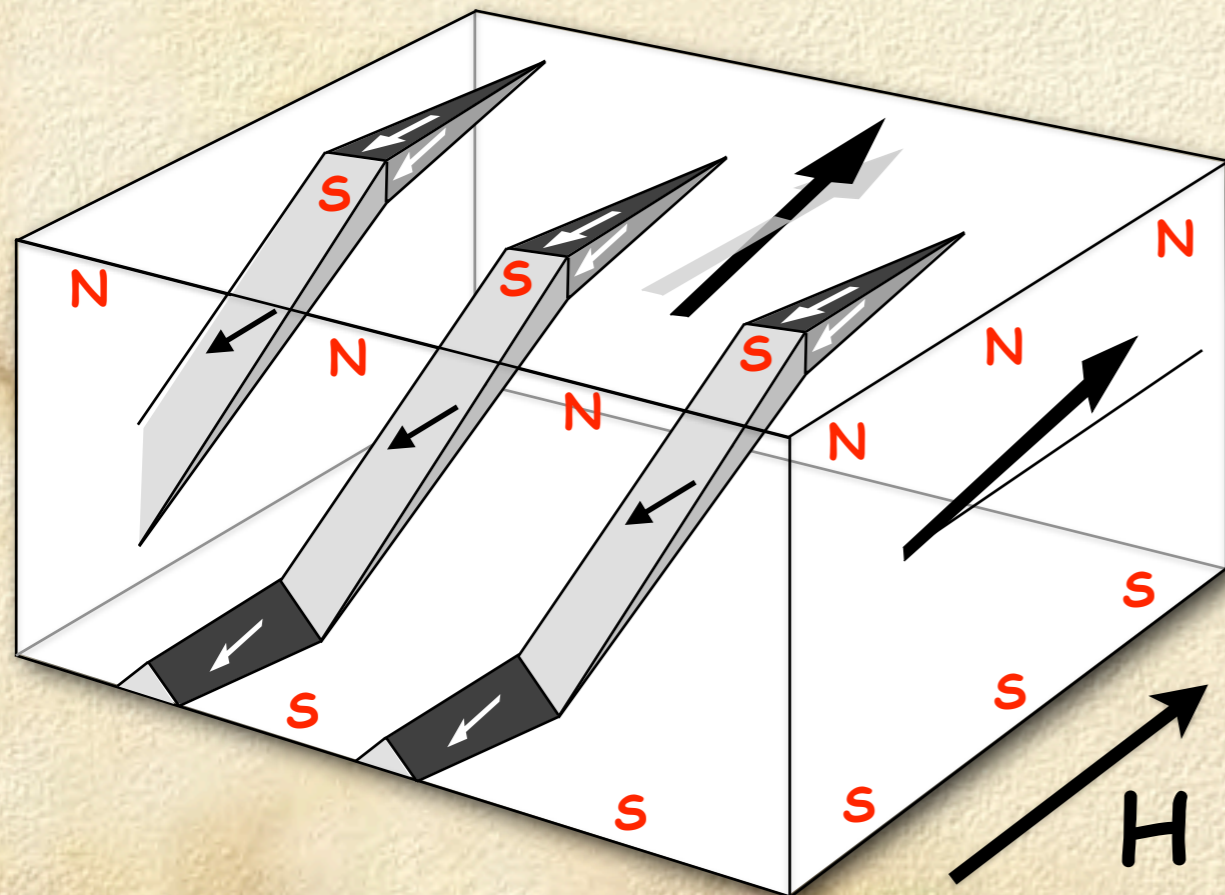
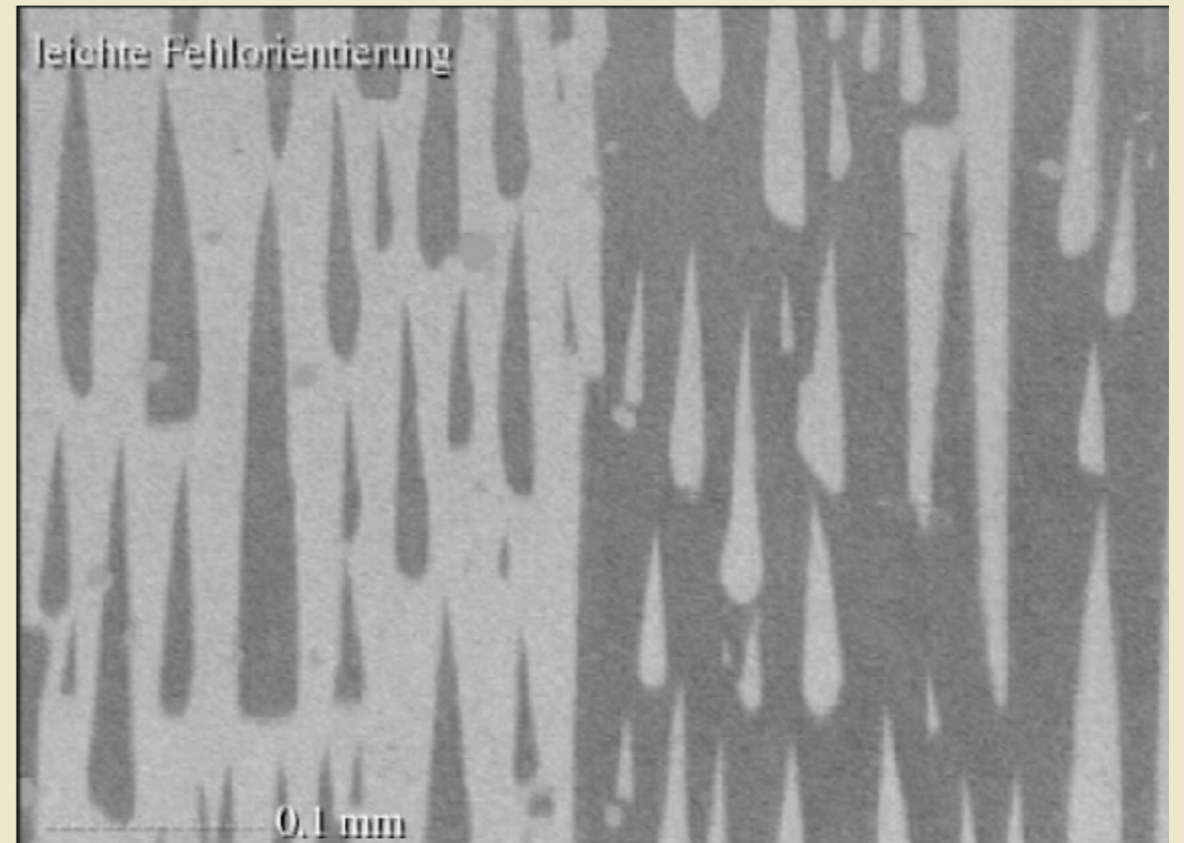
Grain-oriented FeSi transformer material



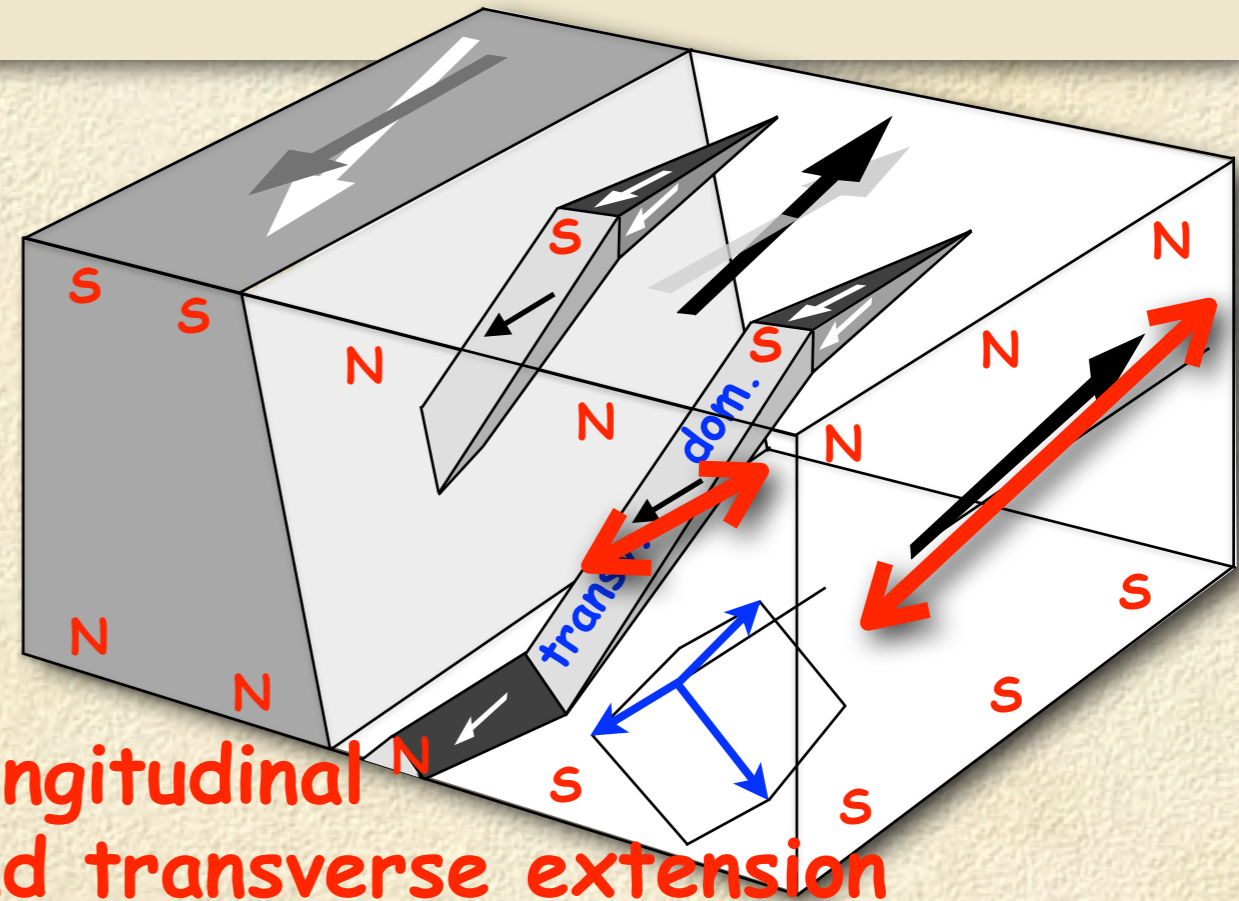
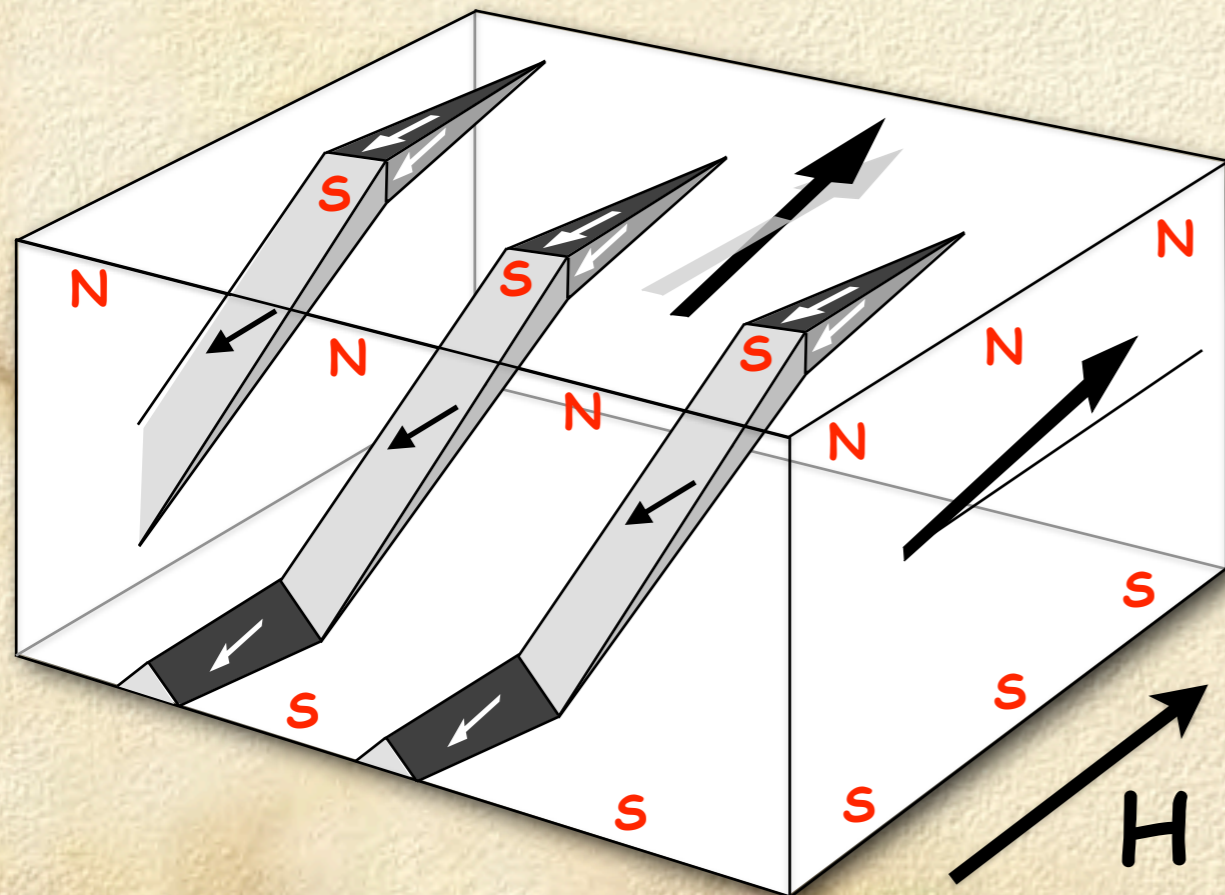
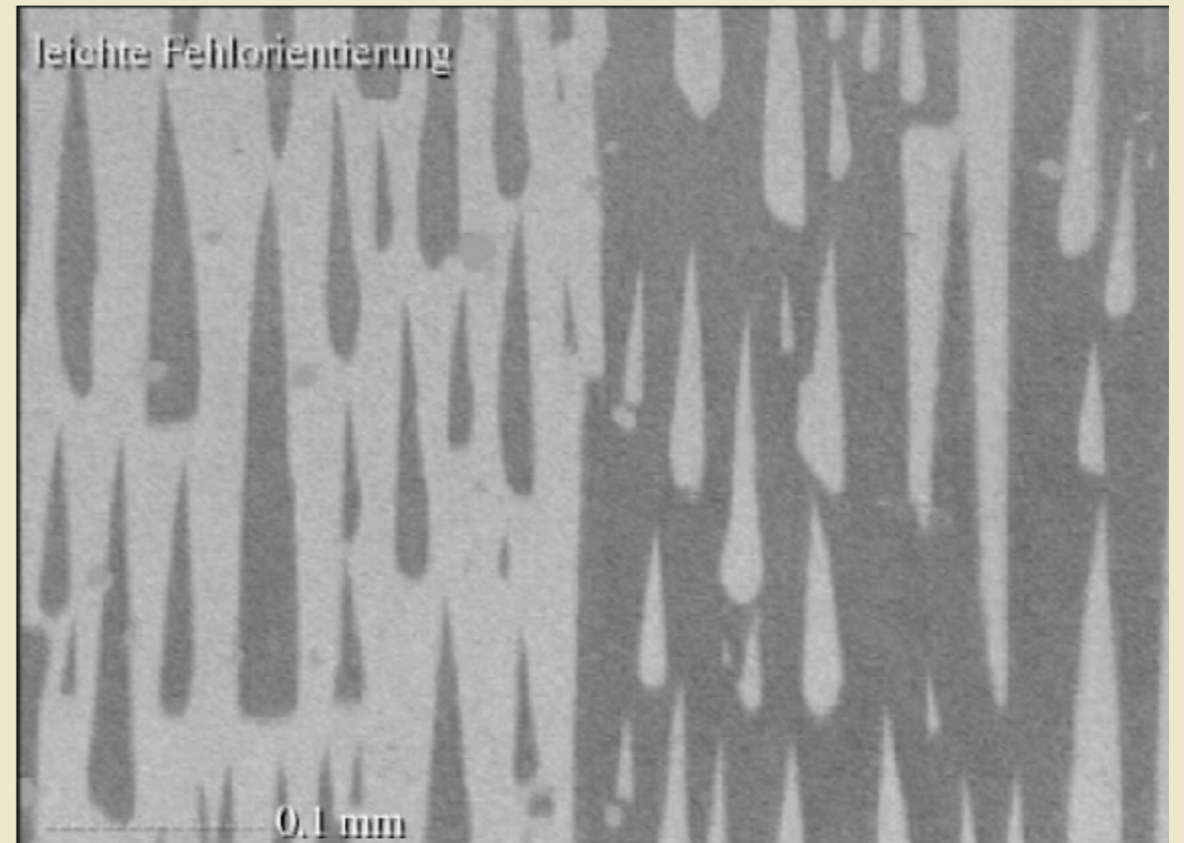
Grain-oriented FeSi transformer material



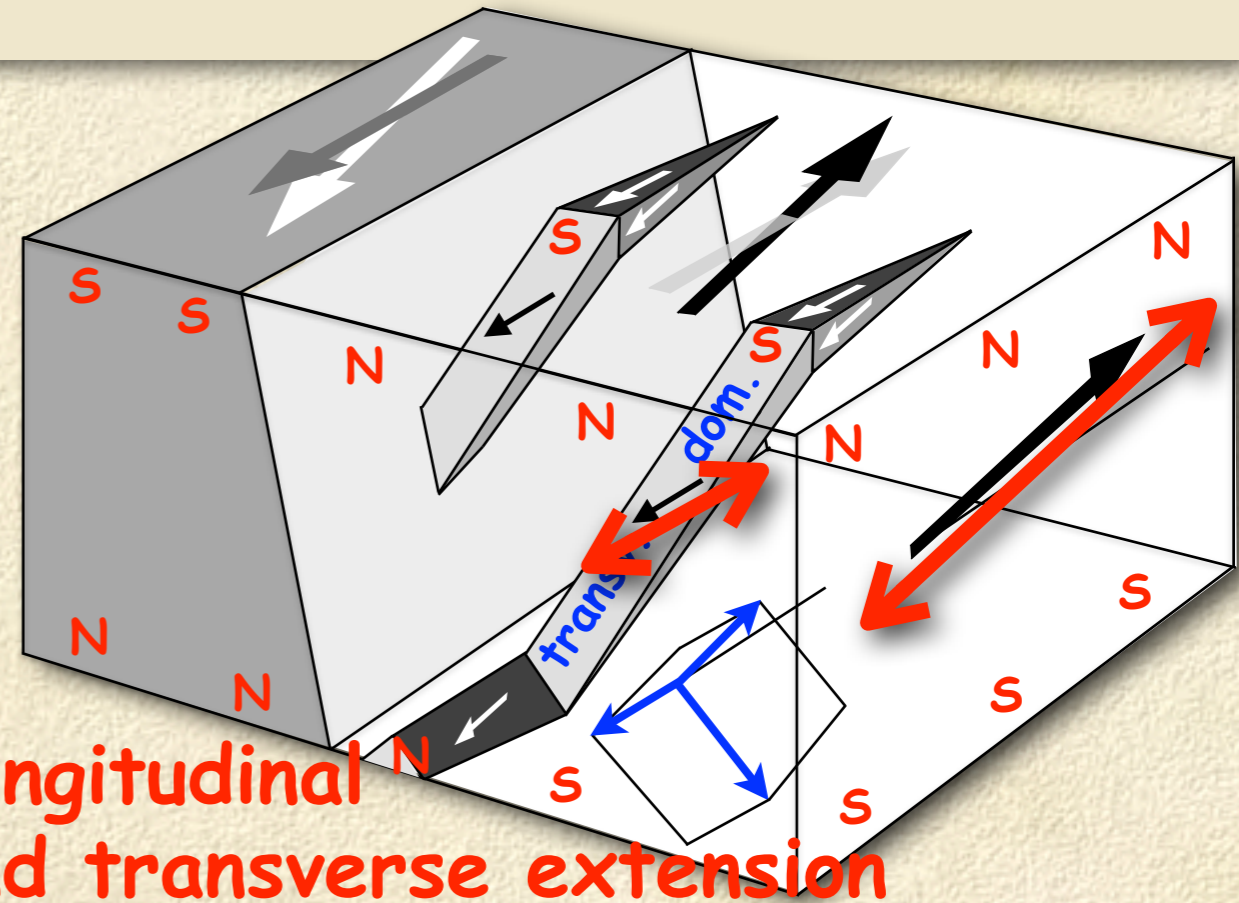
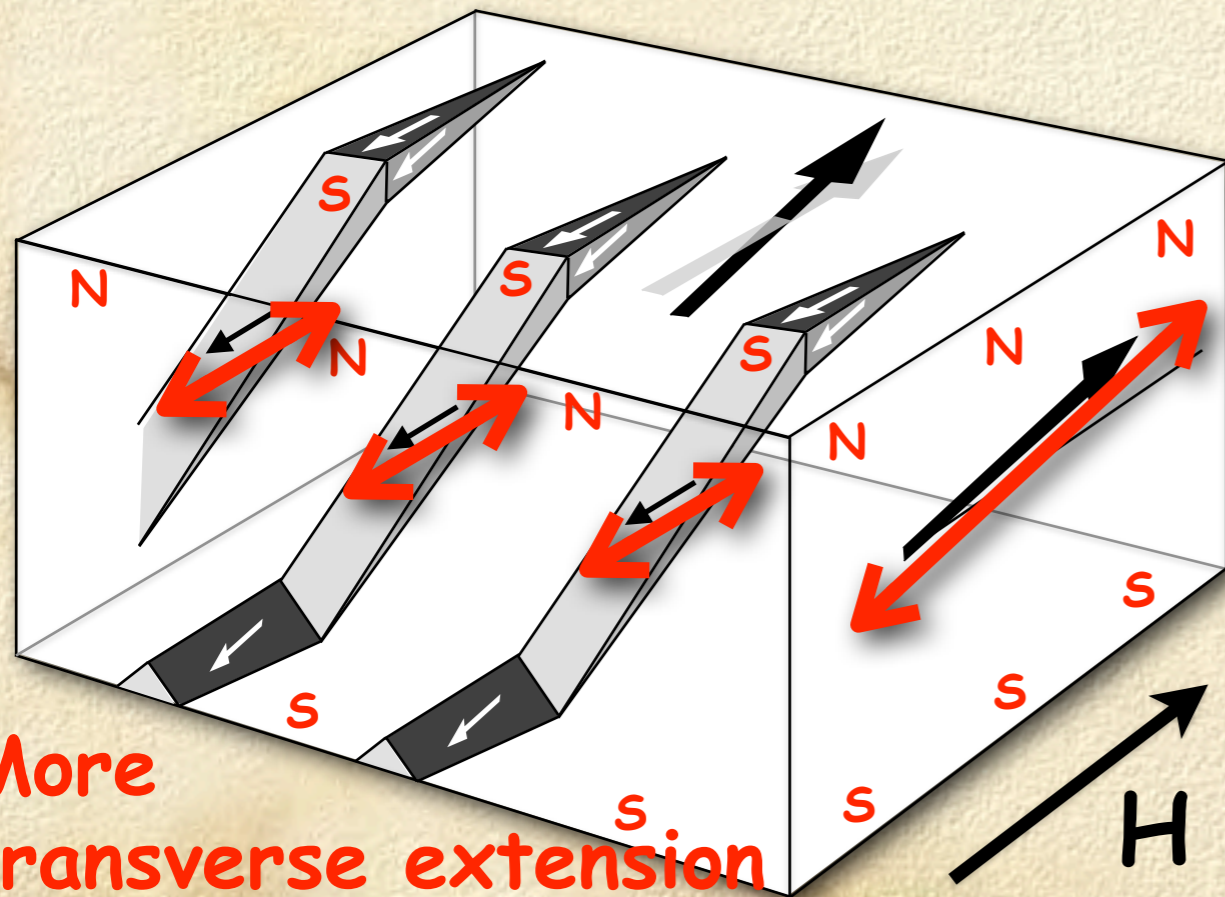
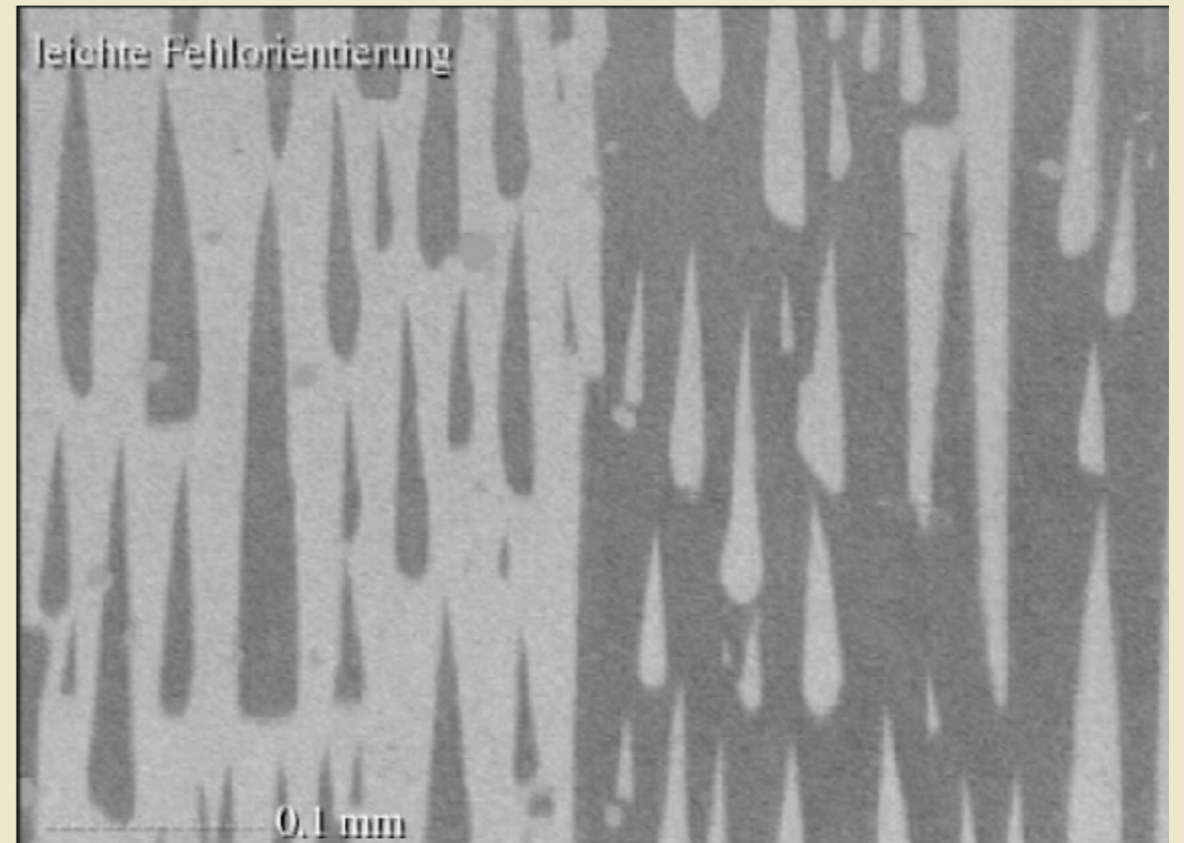
Grain-oriented FeSi transformer material



Grain-oriented FeSi transformer material



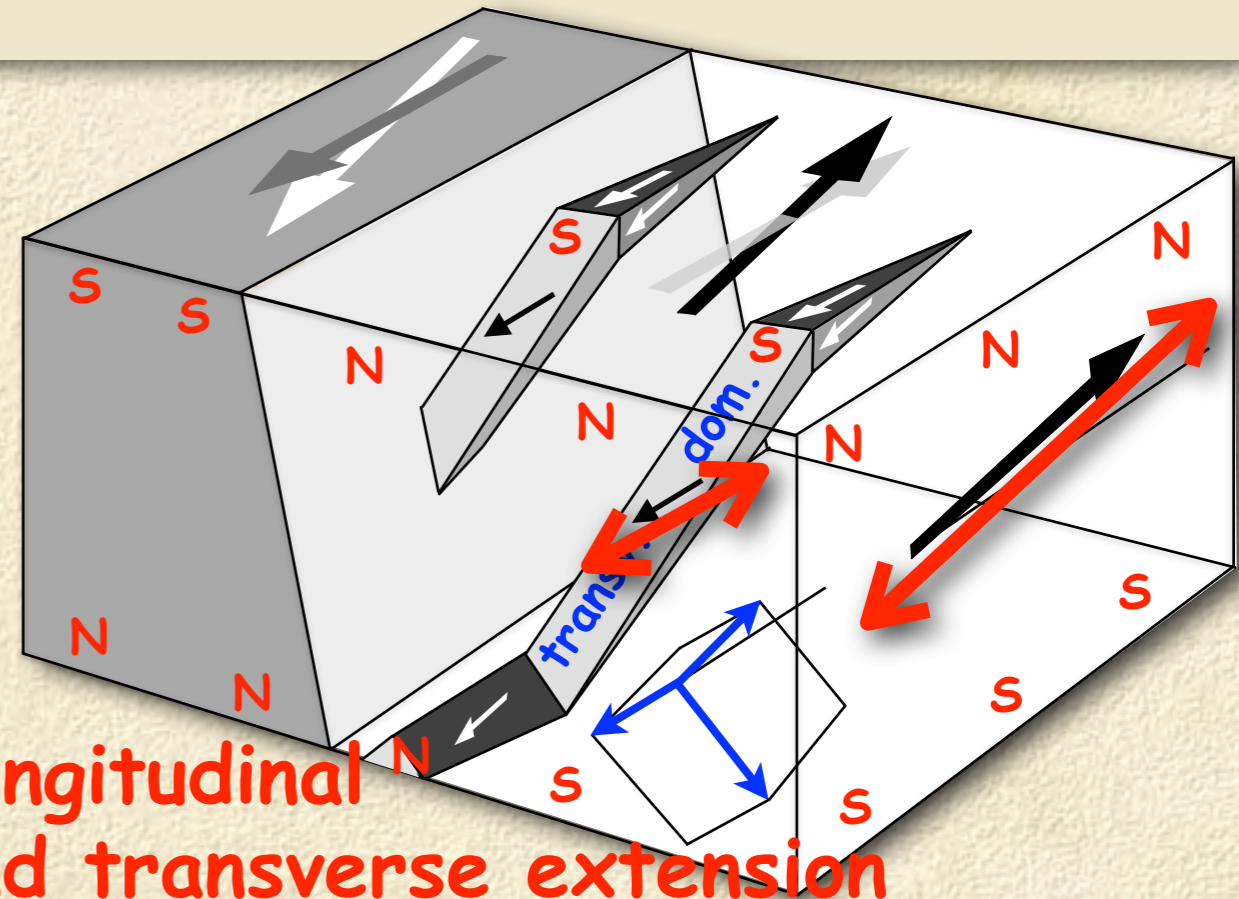
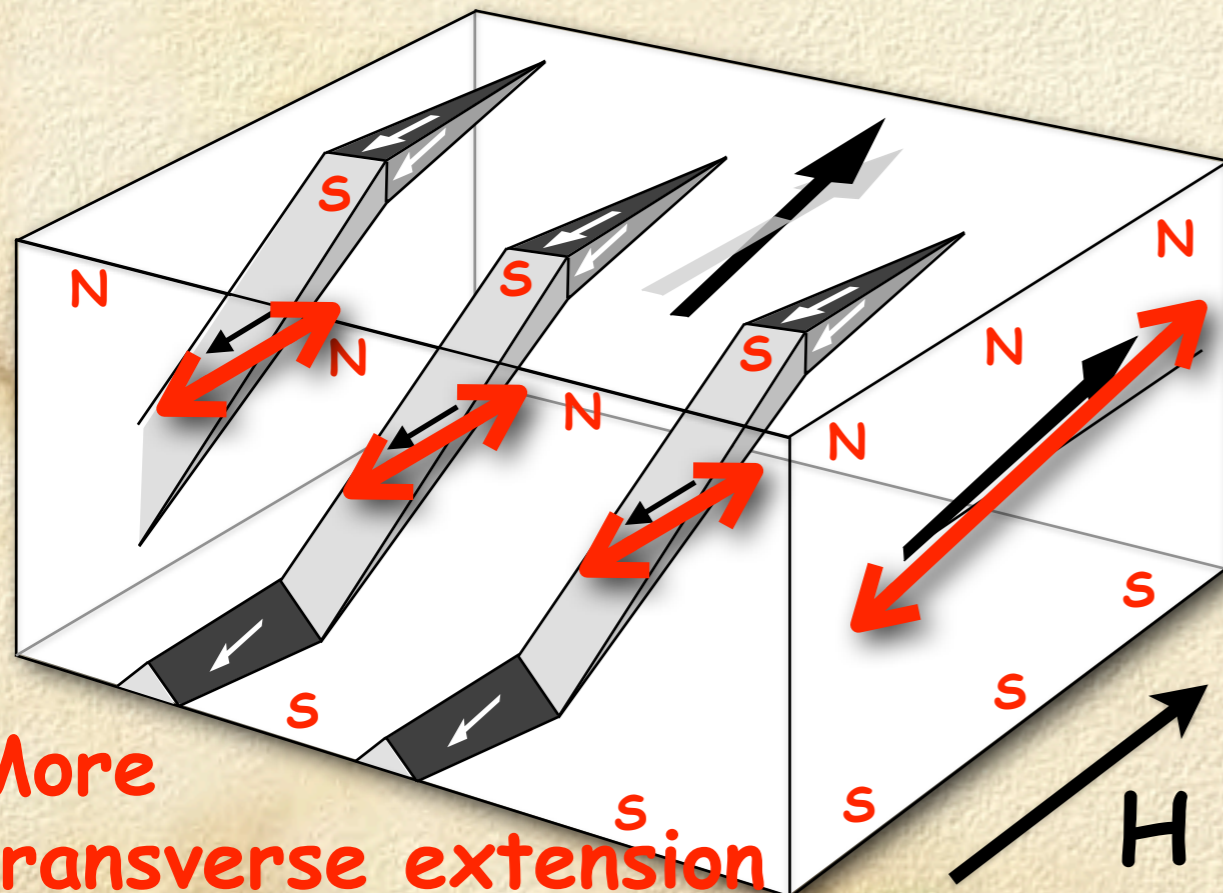
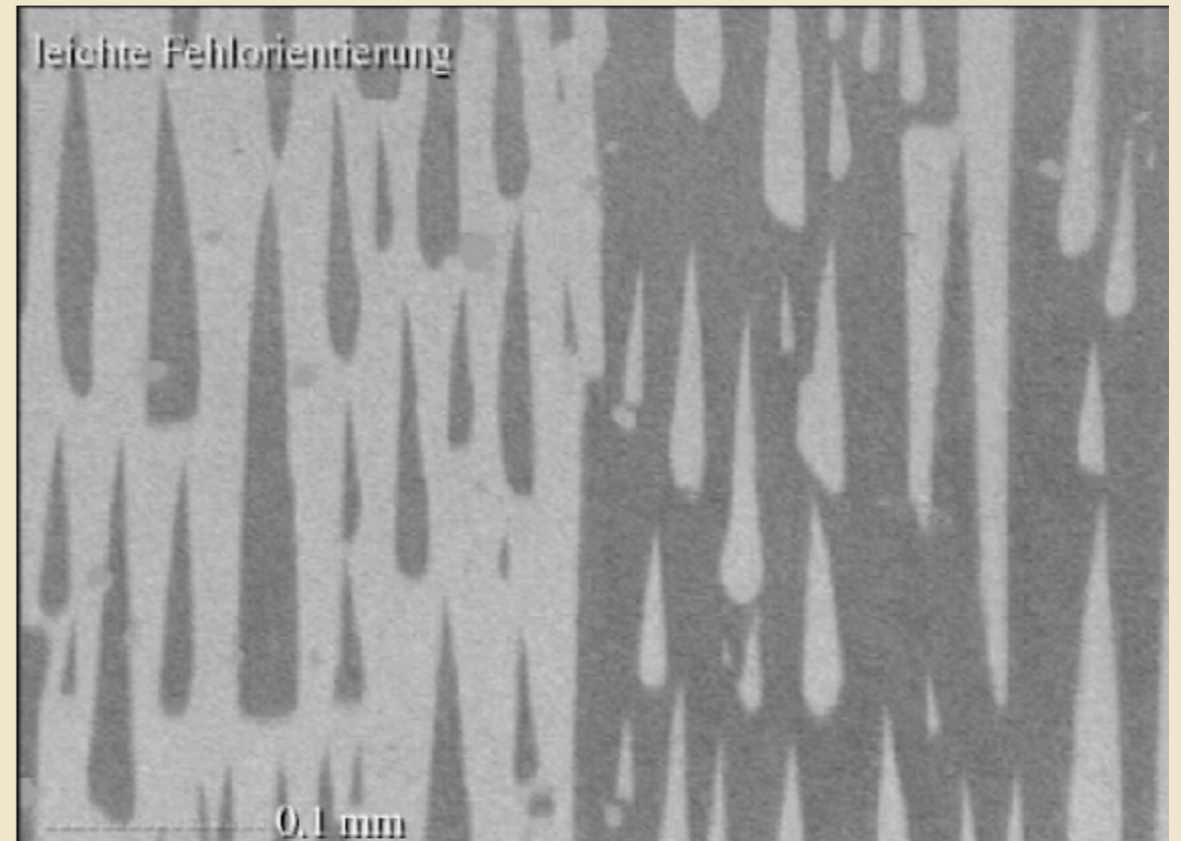
Grain-oriented FeSi transformer material



Grain-oriented FeSi transformer material

Tension and compression in rhythm of magnetic field

The sheet vibrates
(= transformer noise)

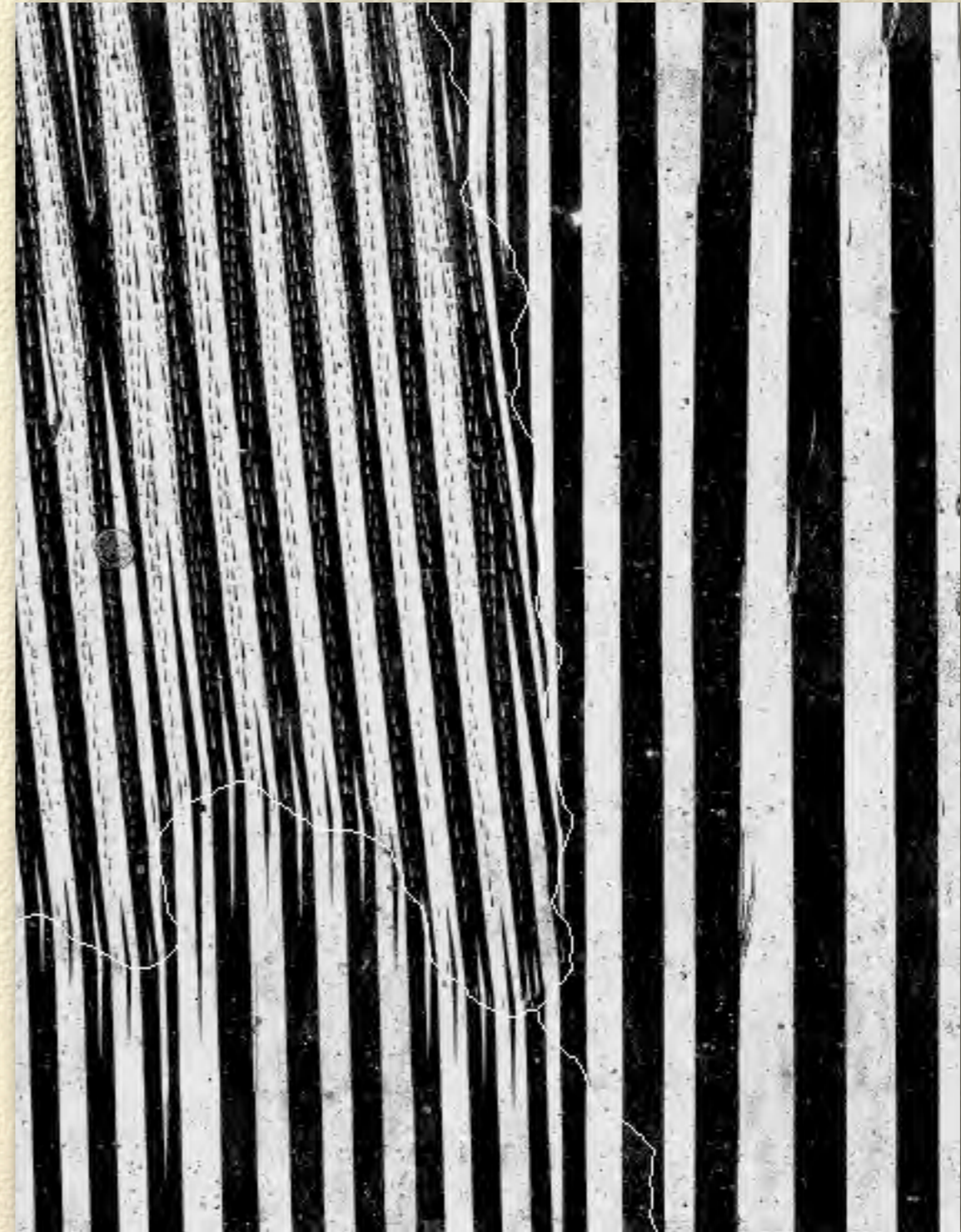


Grain-oriented FeSi transformer material

Without tensile stress

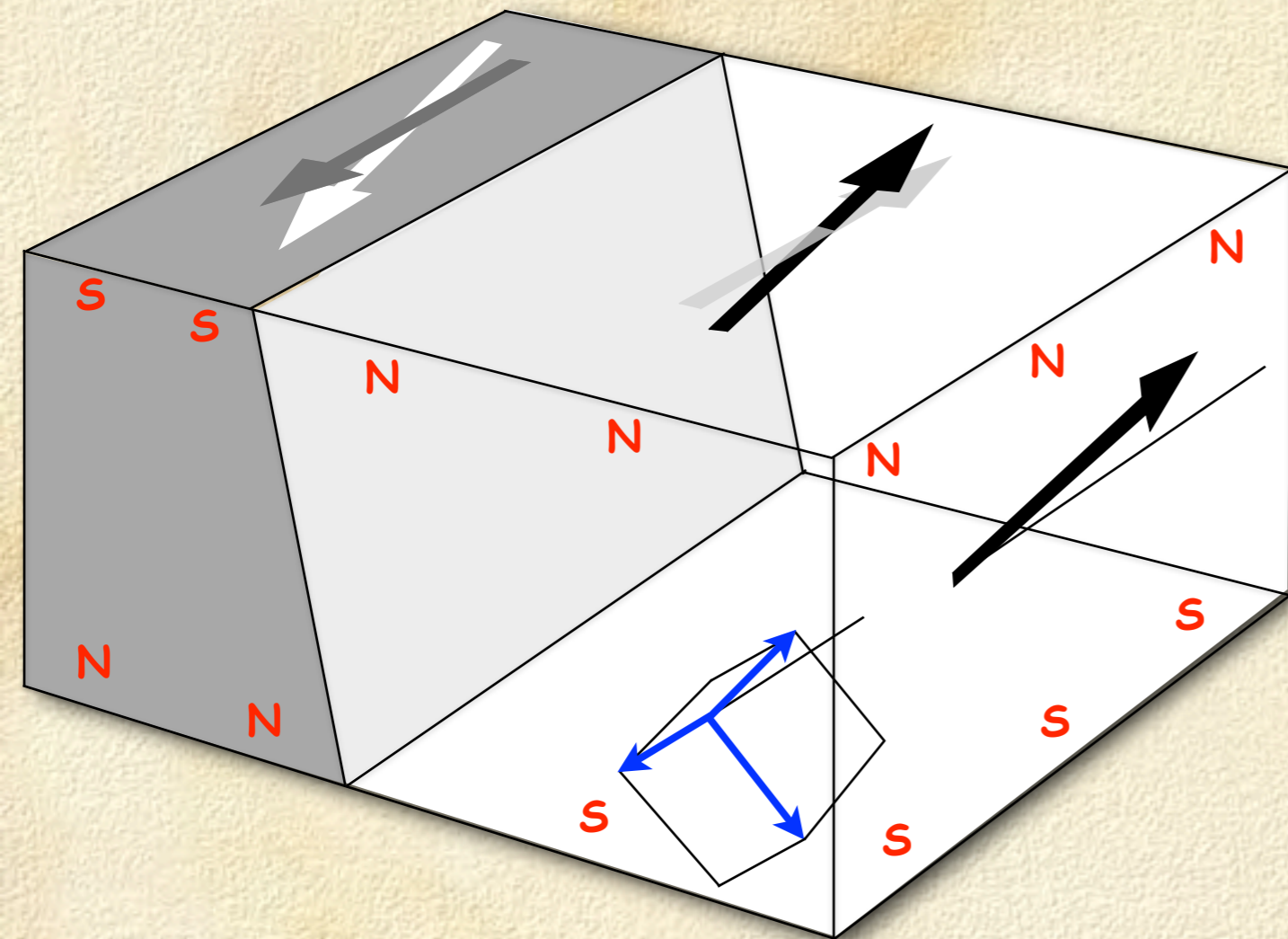


With tensile stress

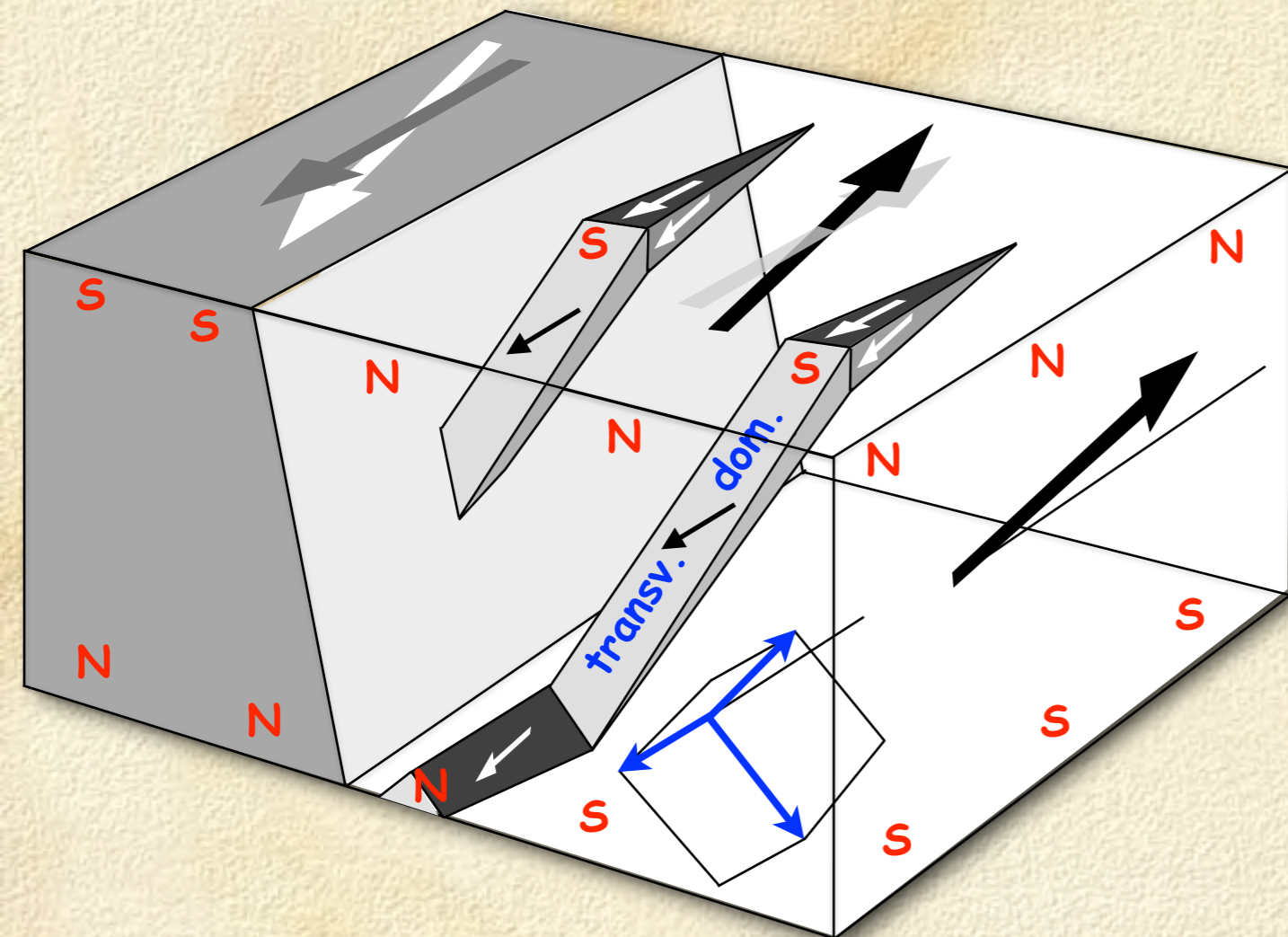


↑
Tensile stress
↓

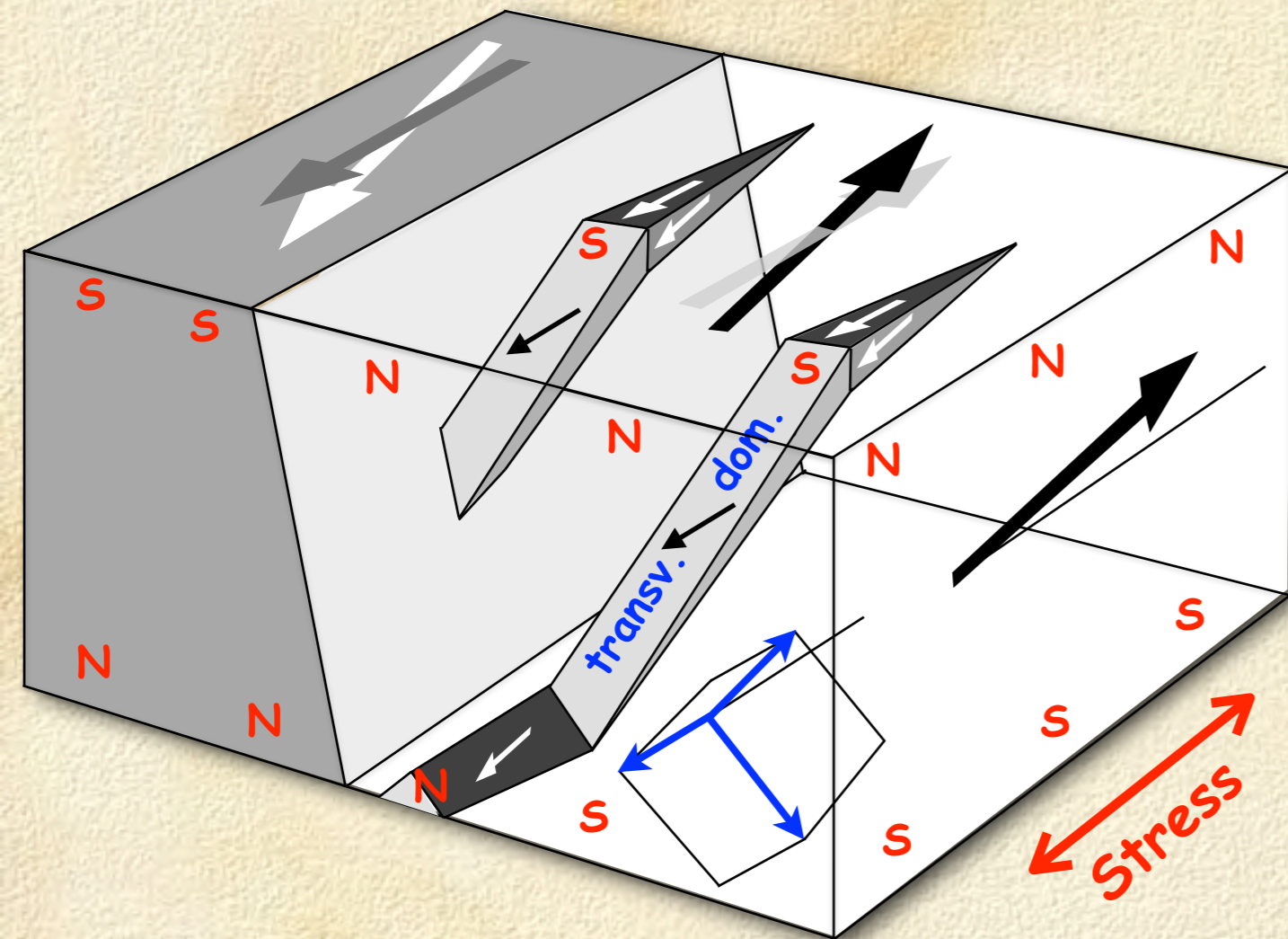
Grain-oriented FeSi transformer material



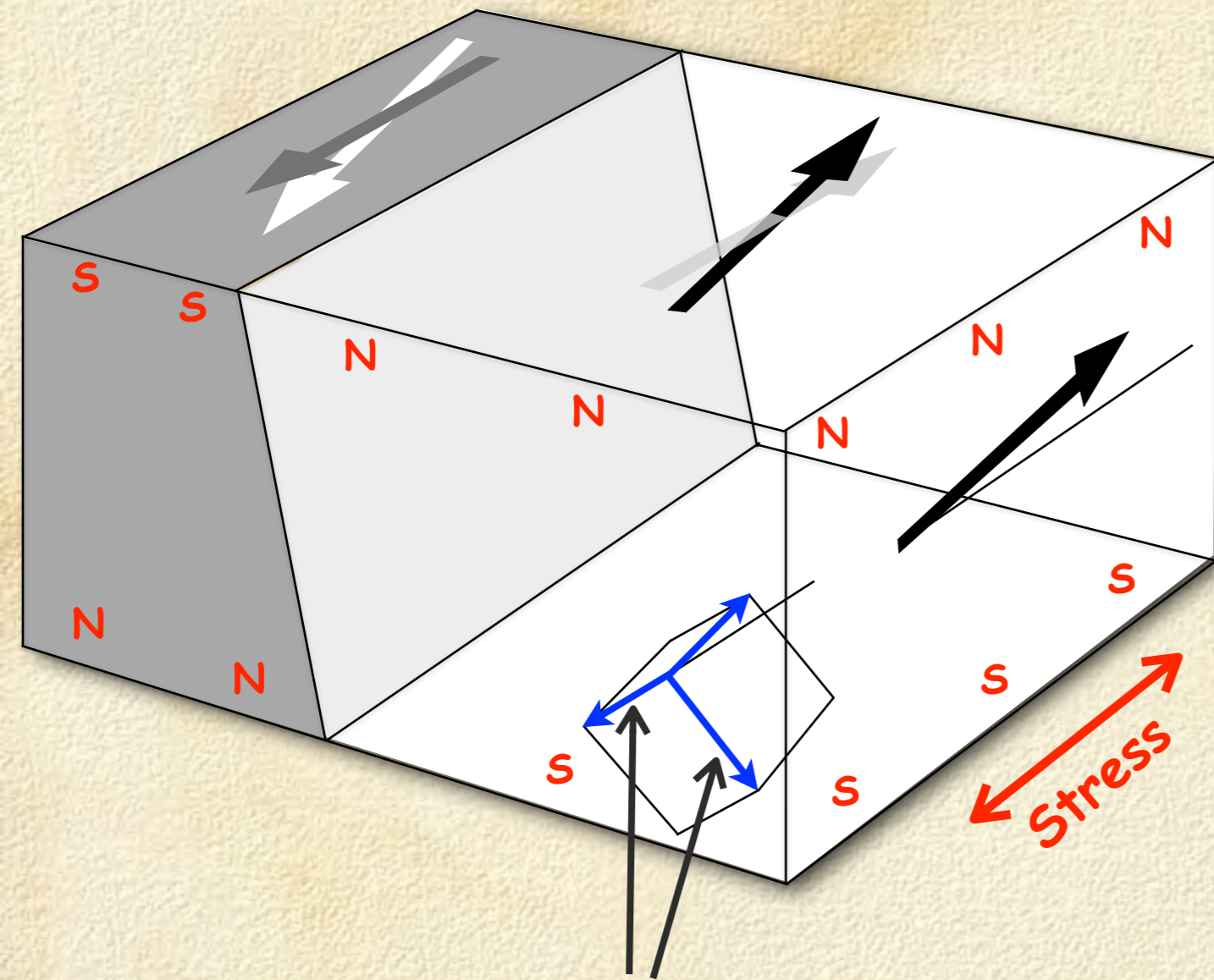
Grain-oriented FeSi transformer material



Grain-oriented FeSi transformer material

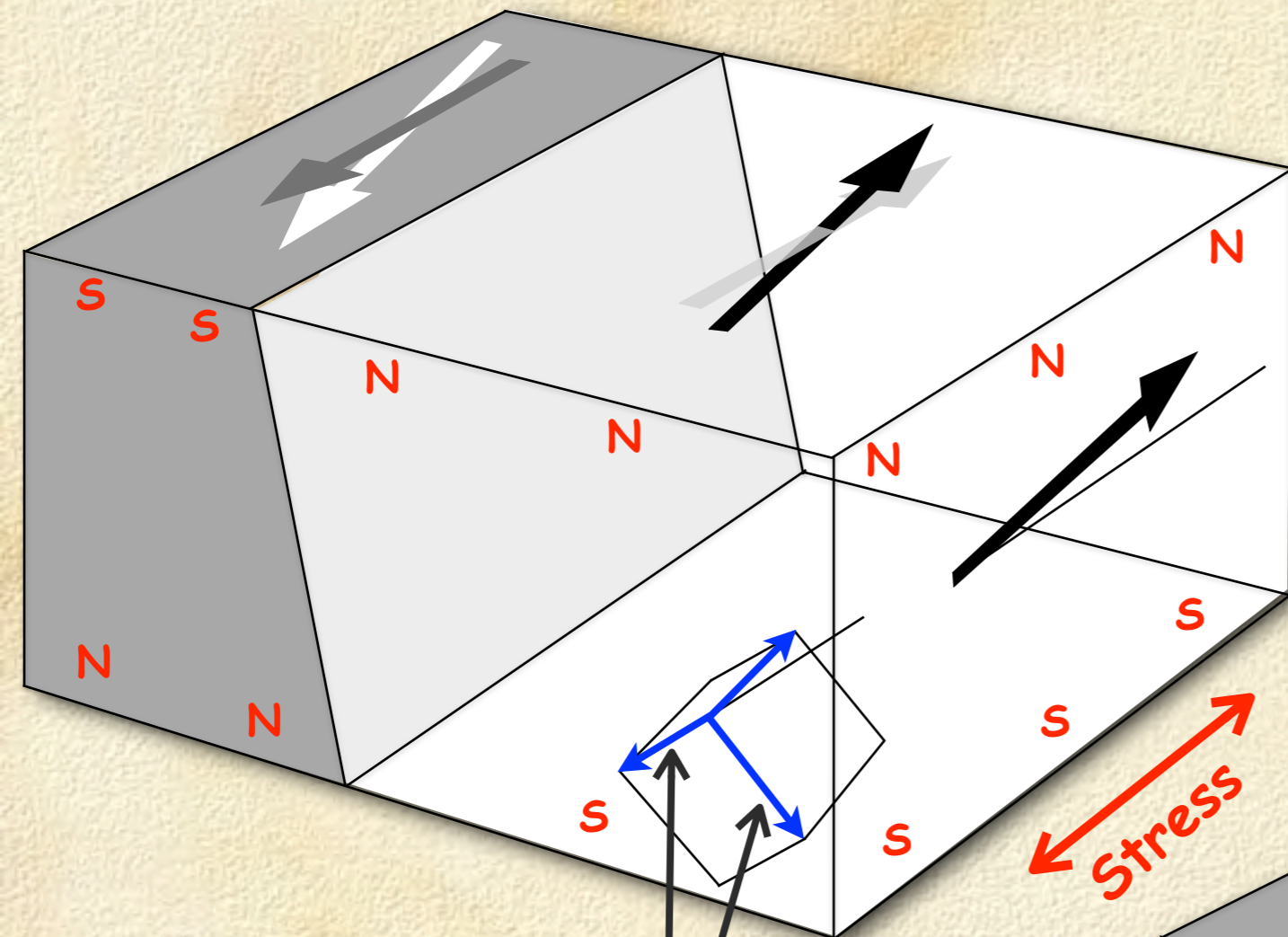


Grain-oriented FeSi transformer material



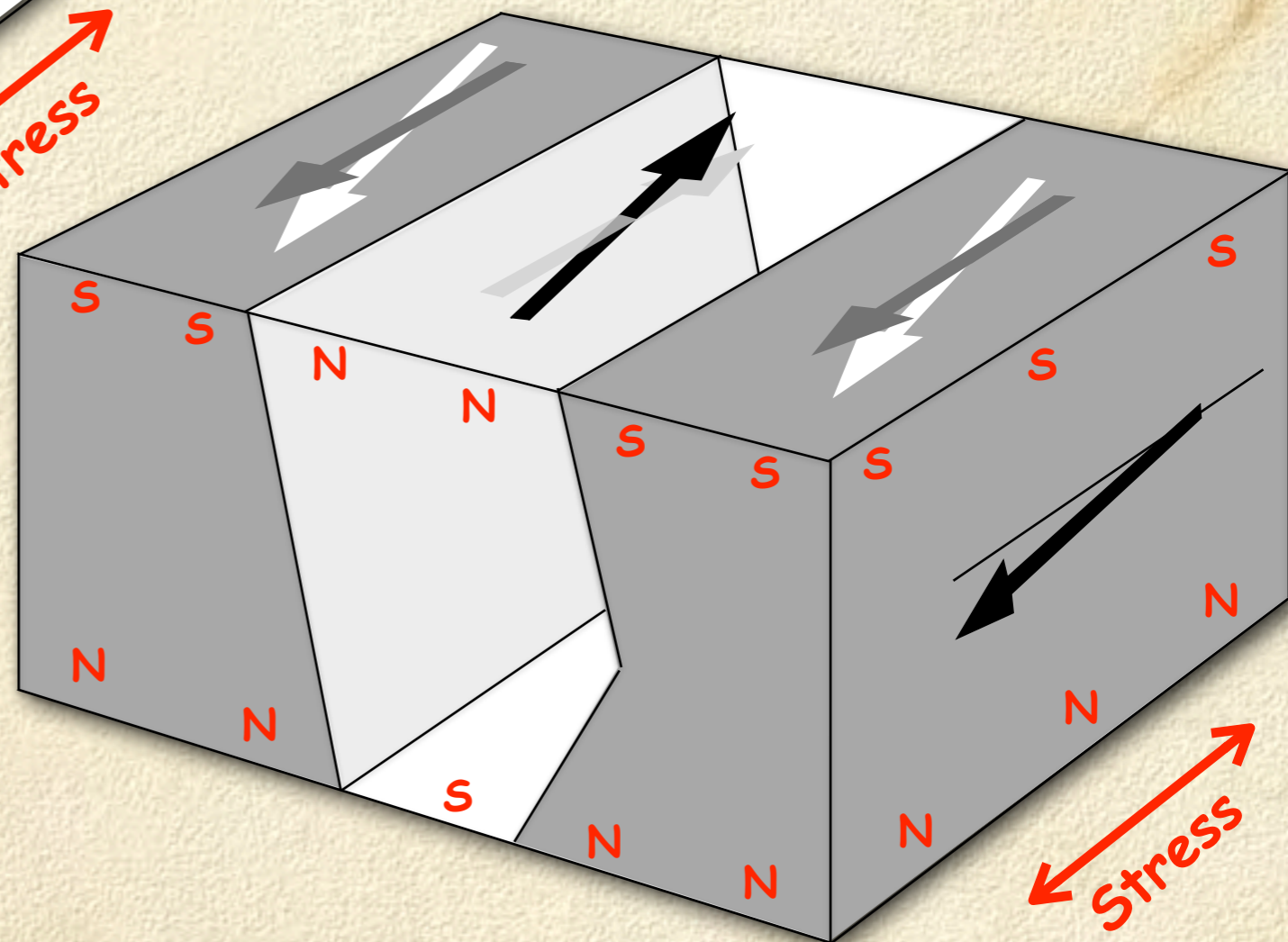
transverse easy axes
disfavored

Grain-oriented FeSi transformer material



transverse easy axes
disfavored

Domain refinement



Grain-oriented FeSi transformer material

Without tensile stress

With tensile stress



ent

Tensile stress

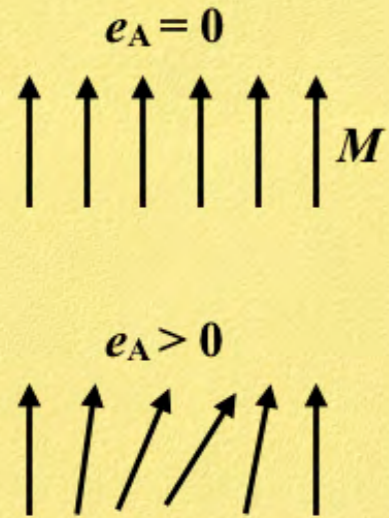
Stress

Z

Z

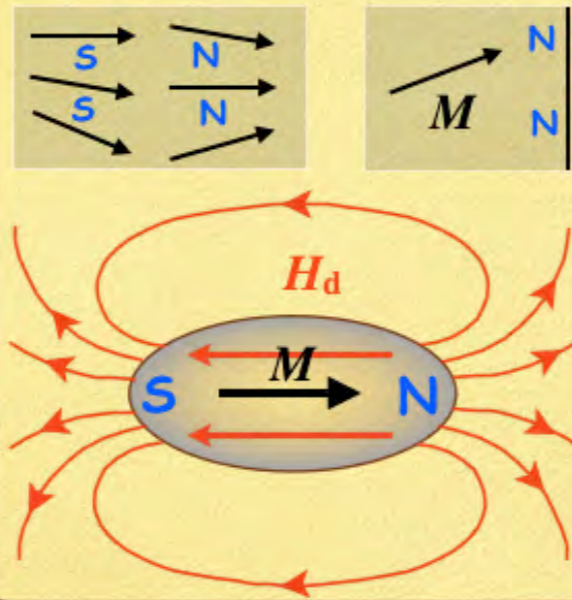
Magnetic Energies

Exchange energy

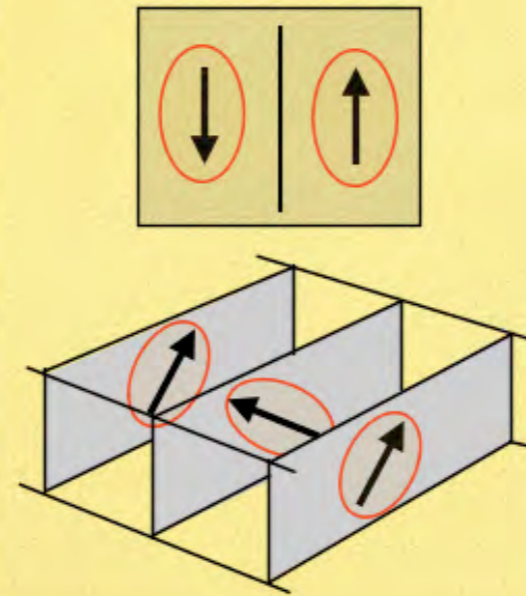


Stray field energy

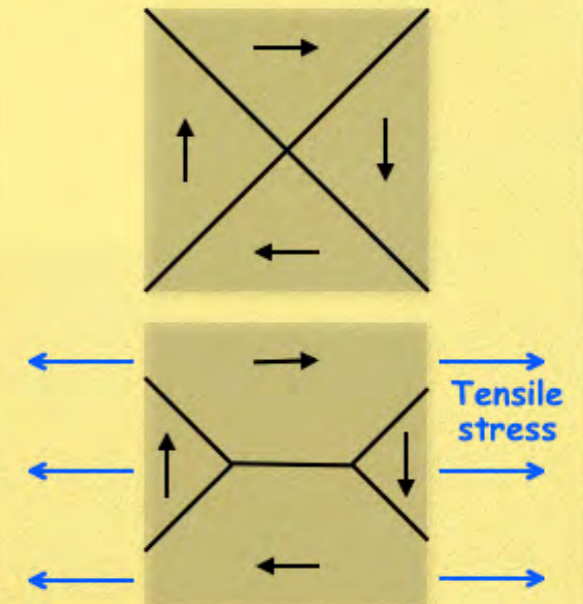
$$\text{div } H_d = -\text{div } M$$



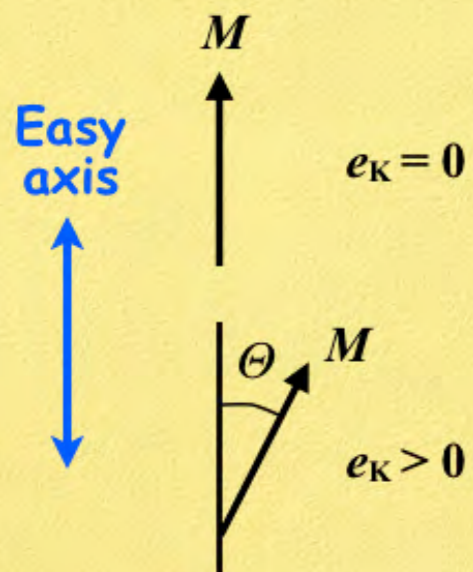
Magnetostrictive self energy



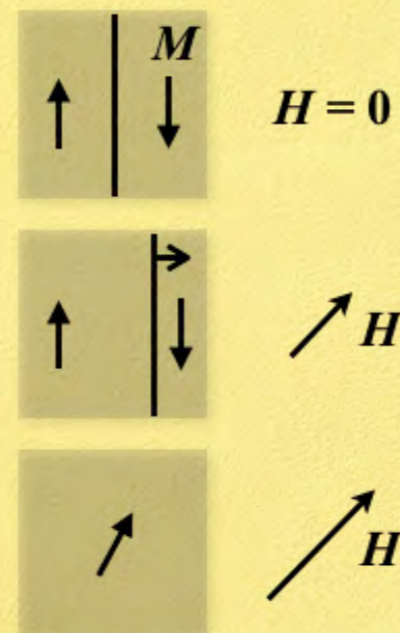
External stress energy



Anisotropy energy

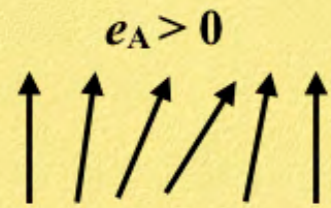
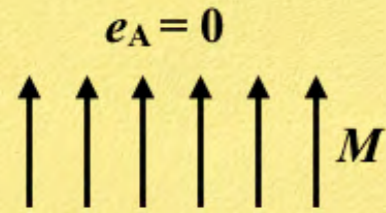


External field energy



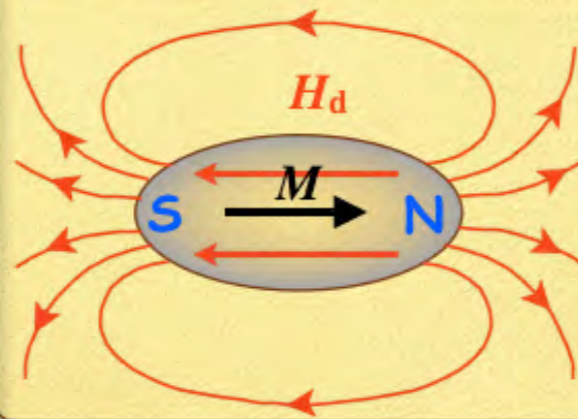
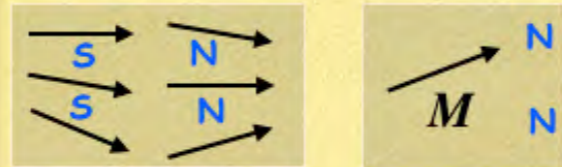
Magnetic Energies

Exchange energy

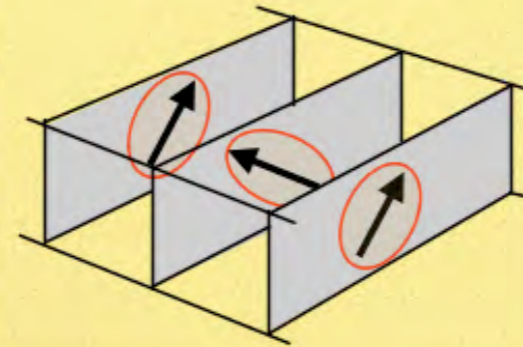
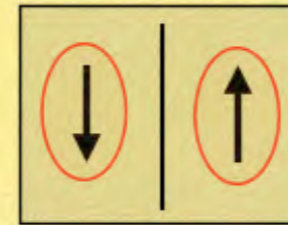


Stray field energy

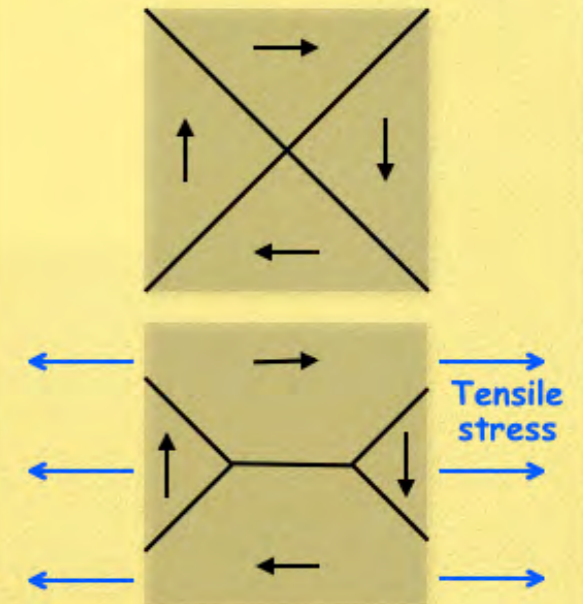
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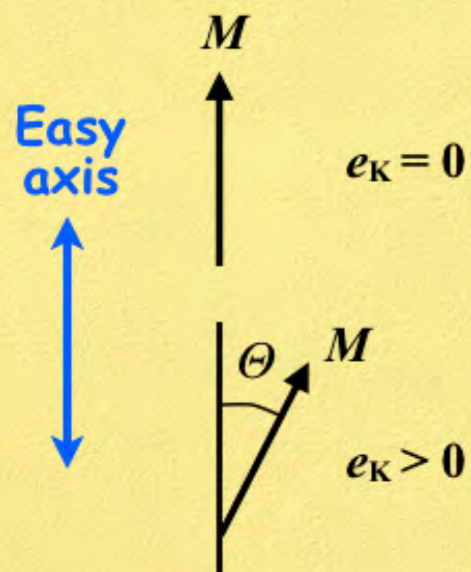
Magnetostrictive self energy



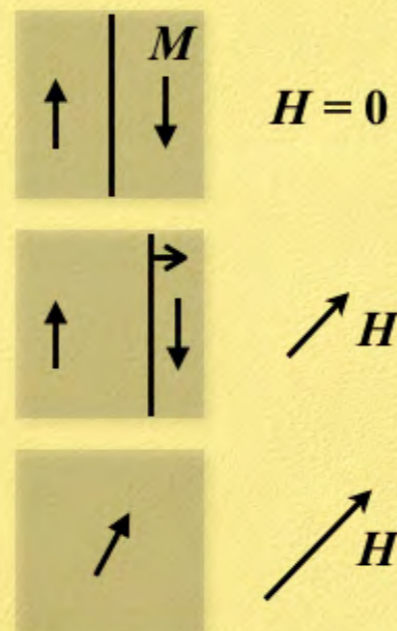
External stress energy



Anisotropy energy

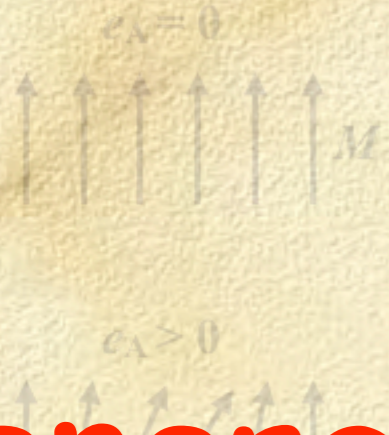


External field energy



Magnetic Energies

Exchange energy

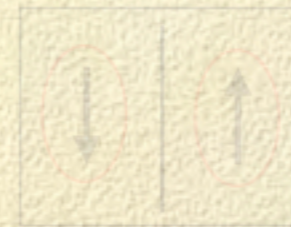


Stray field energy

$$\text{div } H_d = -\text{div } M$$



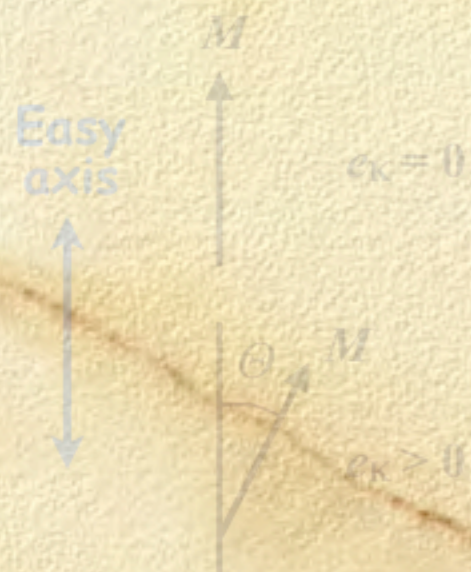
Magnetostrictive self energy



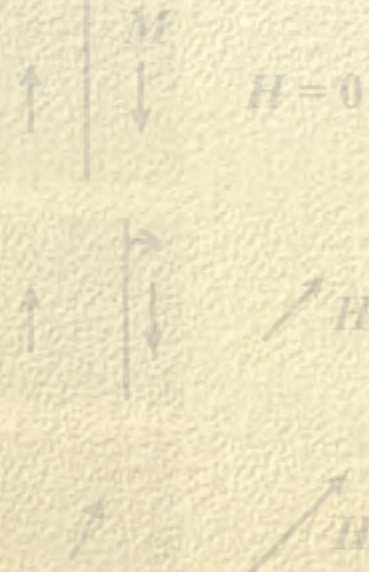
External stress energy



Anisotropy energy



External field energy



General Classification of Domains

General Classification of Domains

$$Q = \frac{\text{Anisotropy constant } K}{\text{Stray-field energy coefficient } (K_d = \mu_0 M_S^2 / 2)}$$

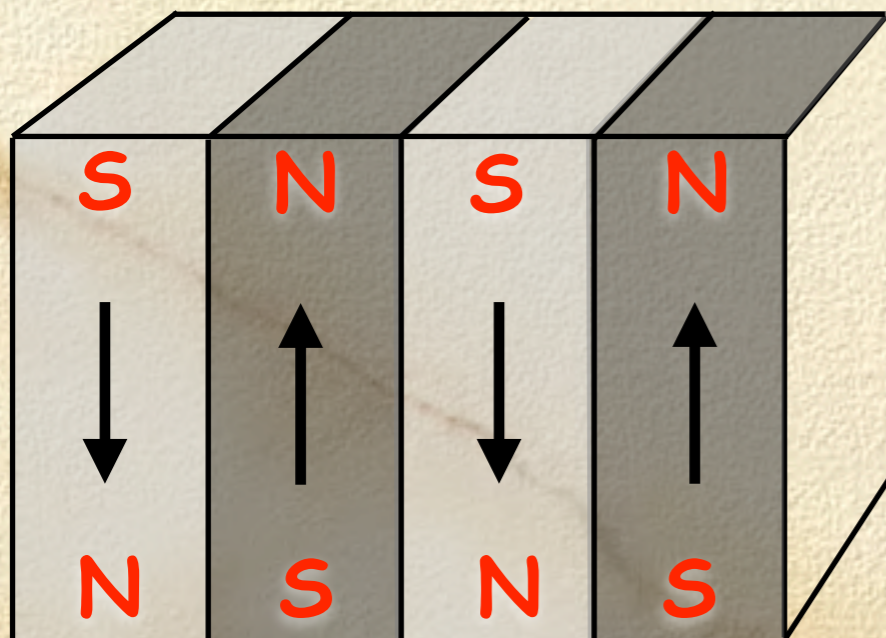
$$Q \gg 1$$

Anisotropy energy
dominates



avoid

anisotropy energy



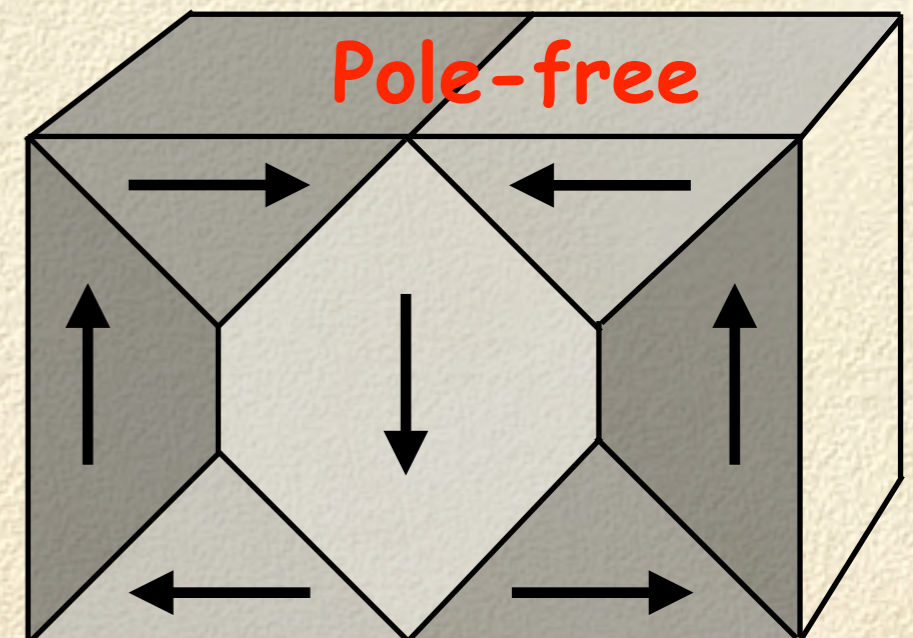
$$Q \ll 1$$

Stray-field energy
dominates

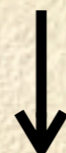


avoid

stray-field energy



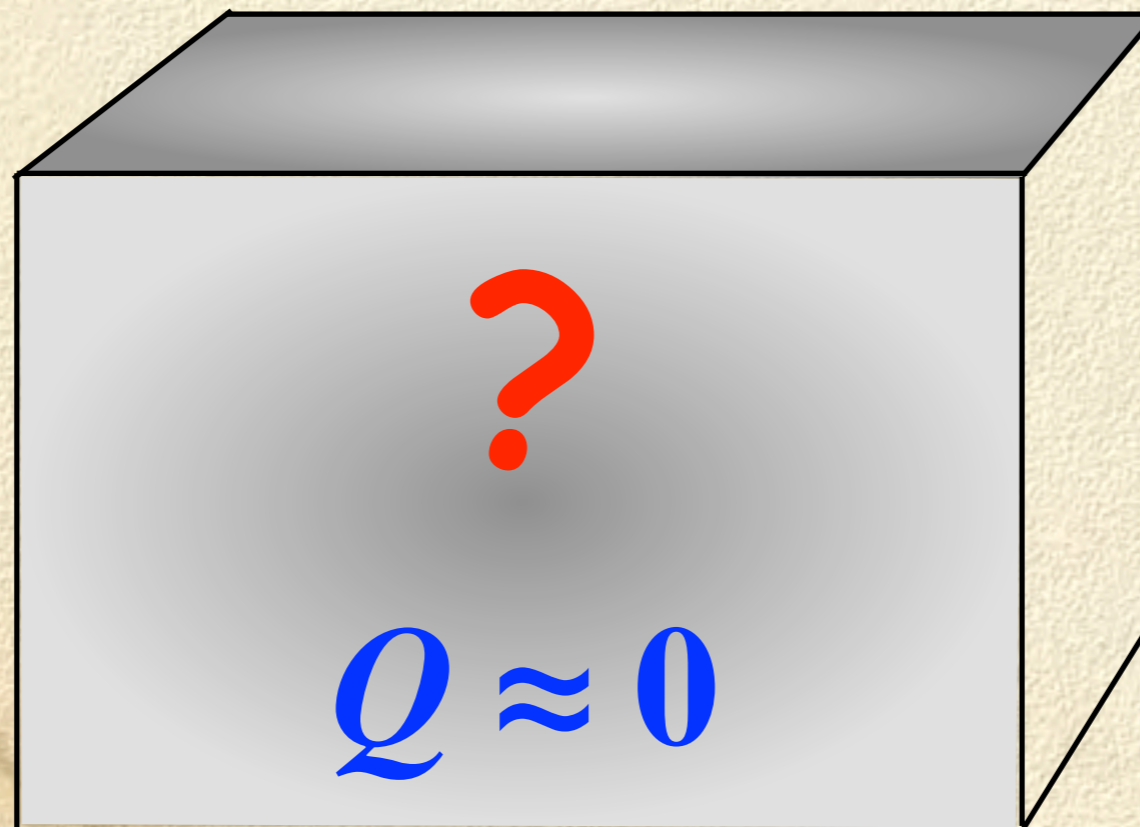
Anisotropy axis
(uniaxial)



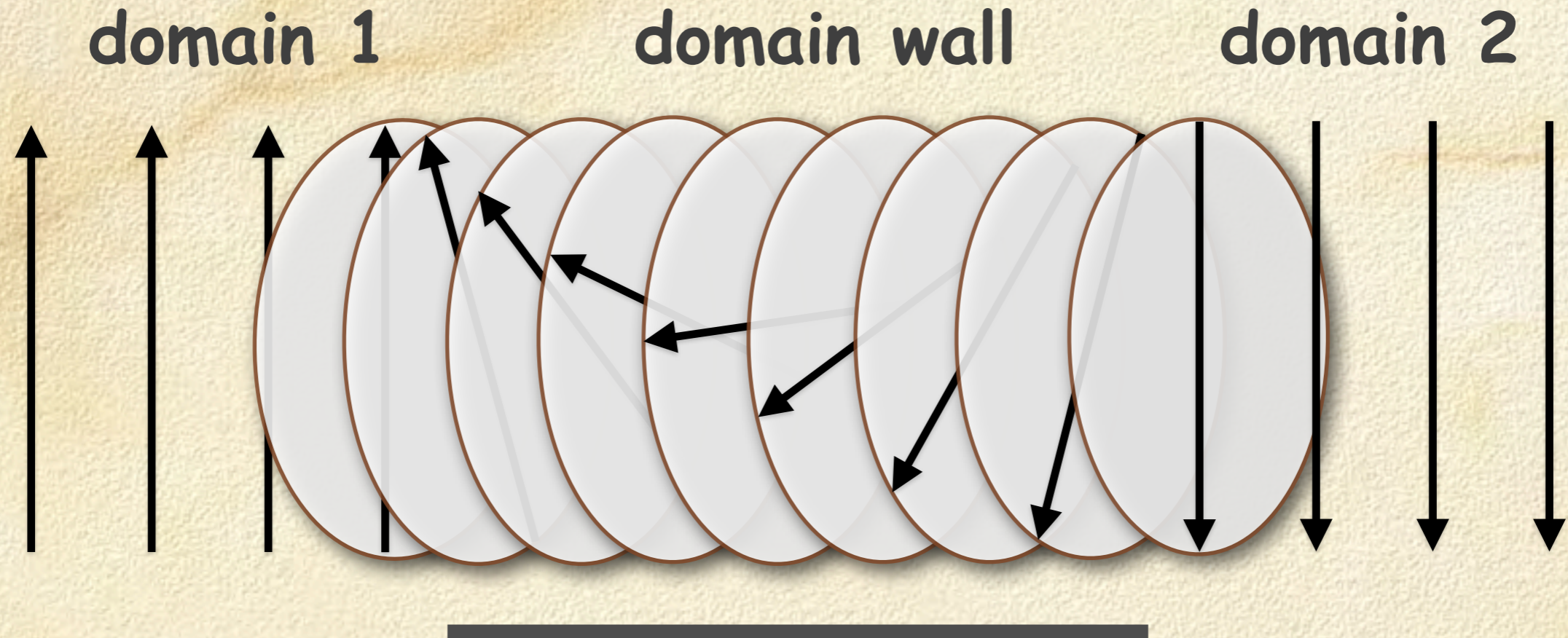
General Classification of Domains

$$Q = \frac{\text{Anisotropy constant } K}{\text{Stray-field energy coefficient } (K_d = \mu_0 M_S^2 / 2)}$$

Excursus



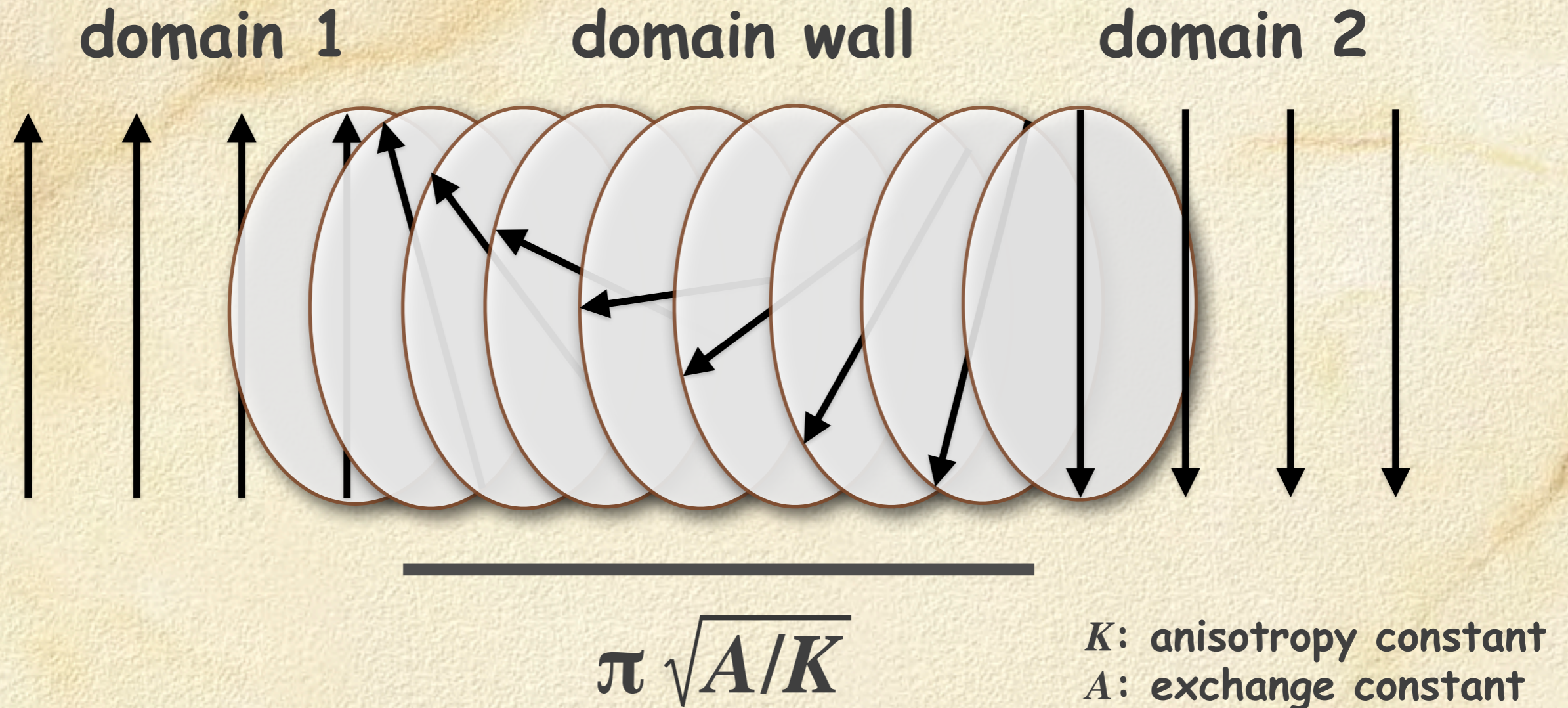
Excursus: $Q = 0$



$$\pi \sqrt{A/K}$$

K : anisotropy constant
 A : exchange constant

Excursus: $Q = 0$

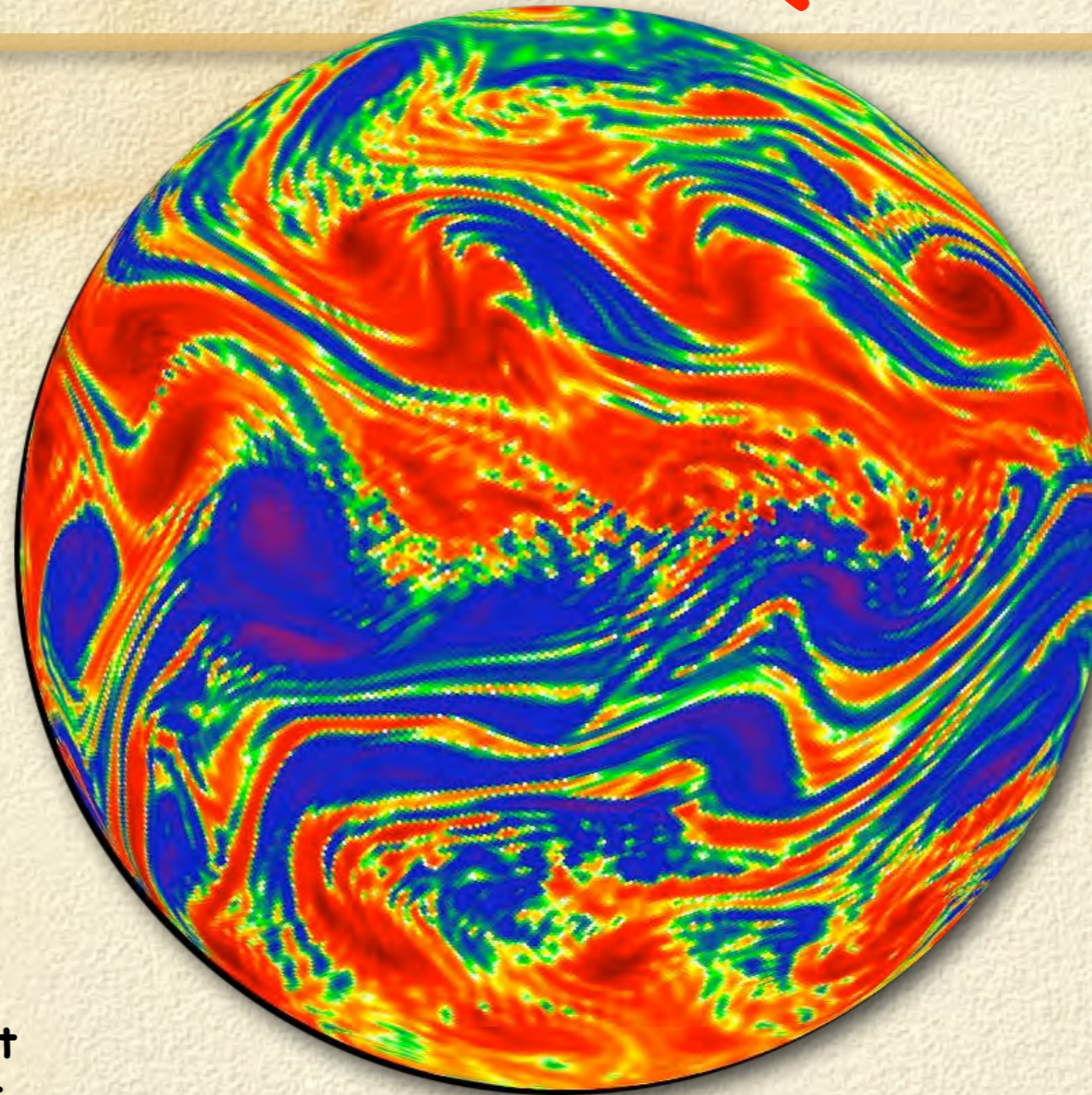


$Q = 0$: Domain walls not defined anymore



We do not expect homogeneously magnetized domains with well defined walls, but **continuous patterns**

Excursus: $Q = 0$



Astrophysical Fluid
Dynamics via Direct
Statistical Simulation.

S.M. Tobias et al. *Astrophys.J.* 727 (2011) 127

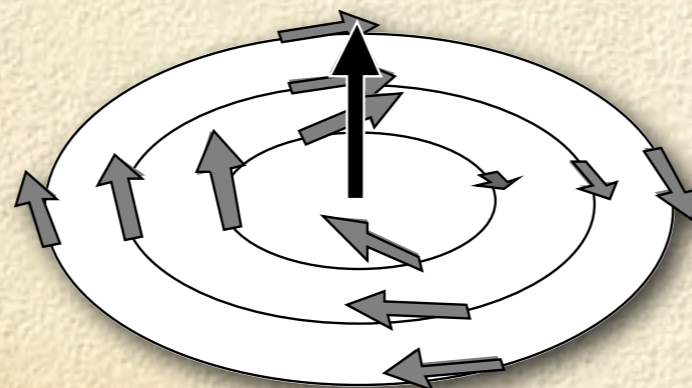
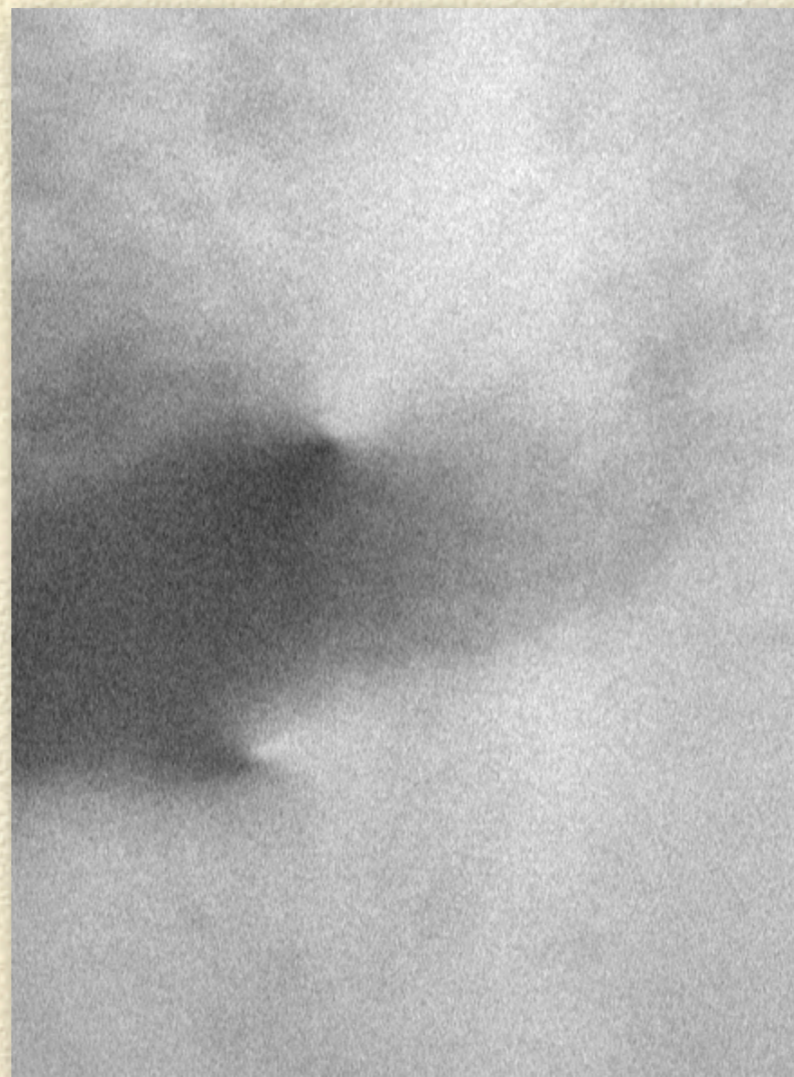
$Q = 0$: Domain walls not defined anymore



We do not expect homogeneously magnetized domains
with well defined walls, but **continuous patterns**

Excursus: $Q = 0$

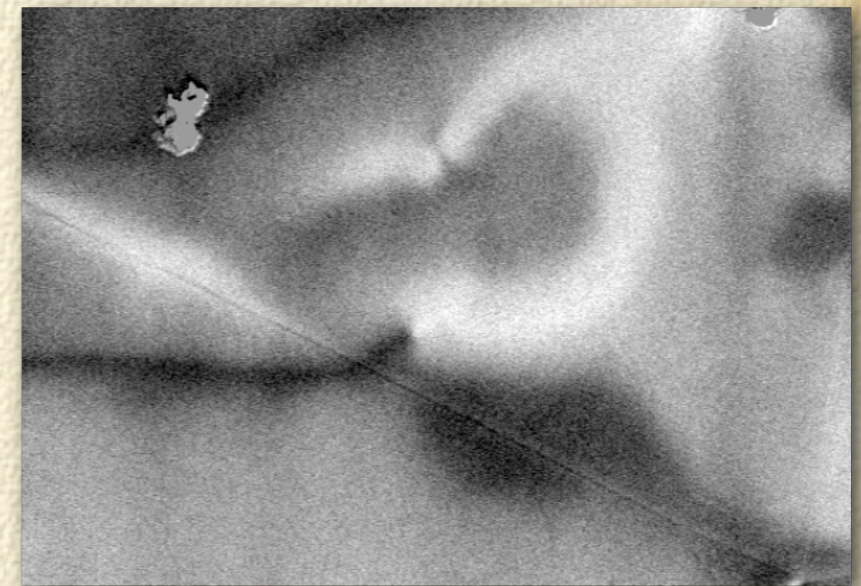
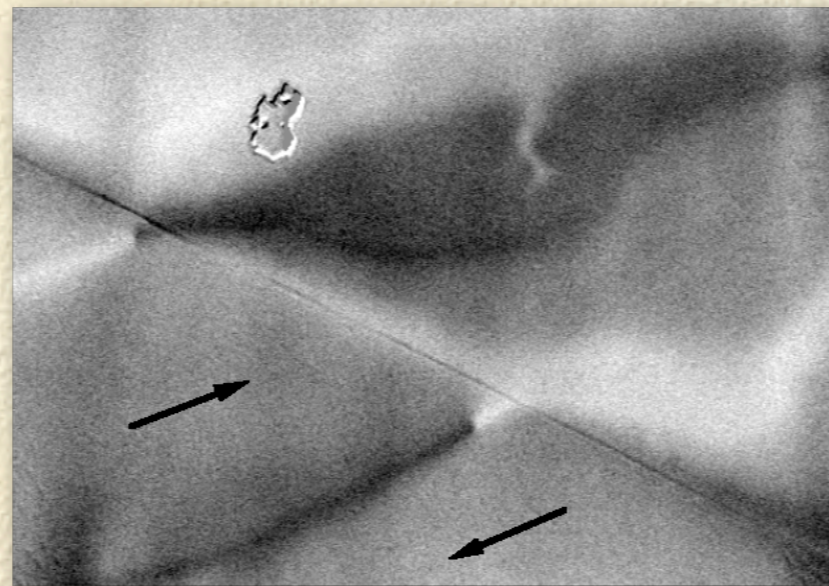
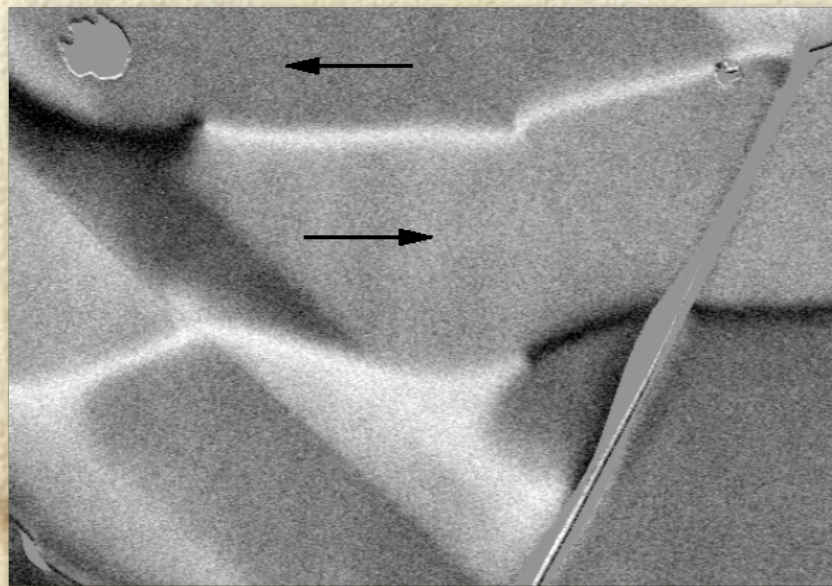
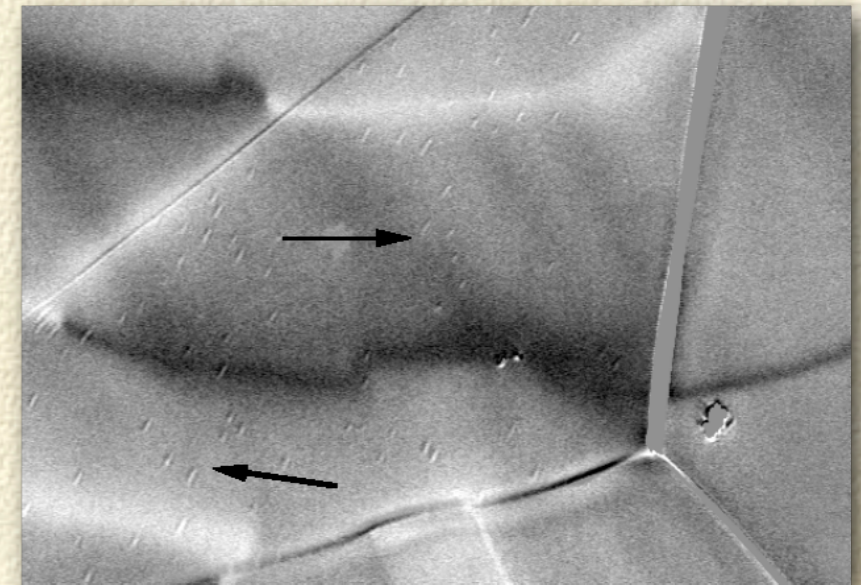
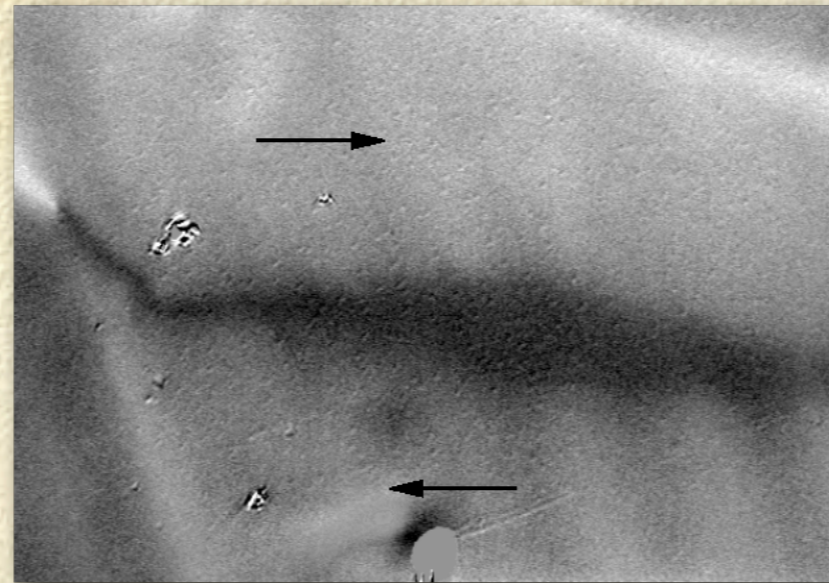
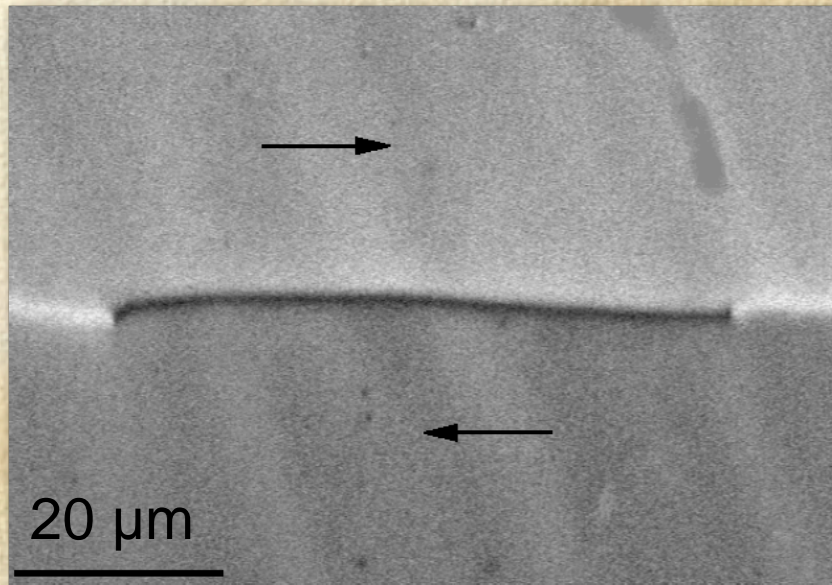
Magnetostriction-free metallic glass
after annealing in rotating field



Swirl

Excursus: $Q = 0$

Permalloy sheet, 50 μm thick



Fluctuations in local anisotropy
→ Domains walls and continuous patterns

General Classification of Domains

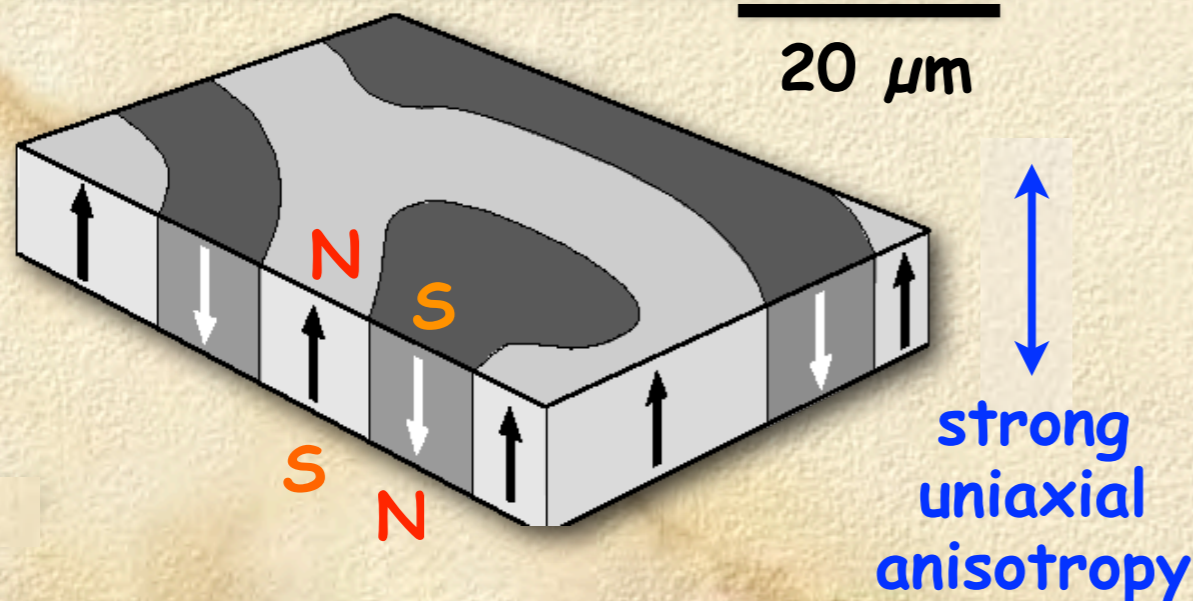
Dominating
anisotropy energy ($Q \gg 1$)

Dominating
stray-field energy ($Q \ll 1$)

Bubble garnet film ($5 \mu\text{m}$ thick)



20 μm



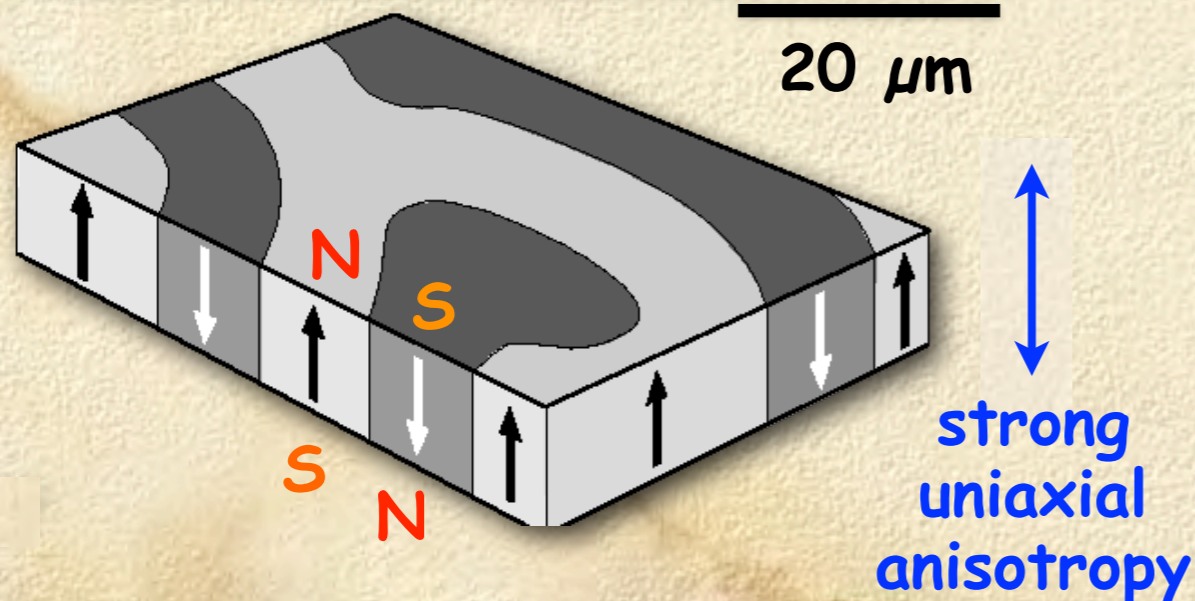
General Classification of Domains

Dominating
anisotropy energy ($Q \gg 1$)

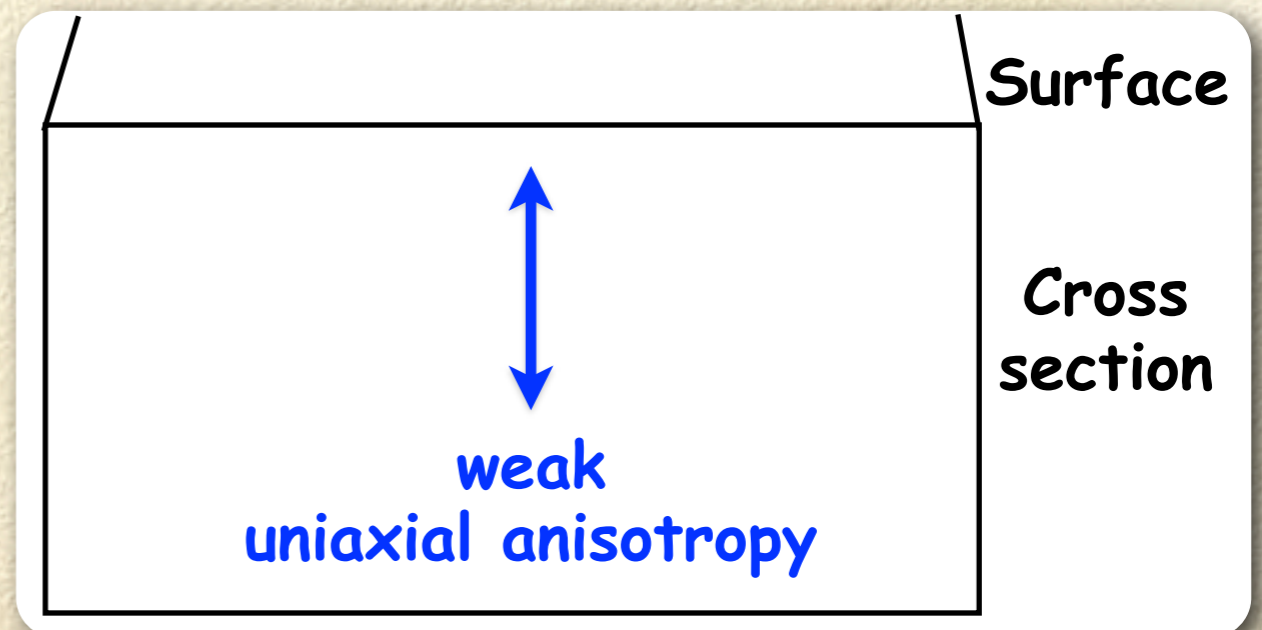
Bubble garnet film ($5 \mu\text{m}$ thick)



20 μm



Dominating
stray-field energy ($Q \ll 1$)



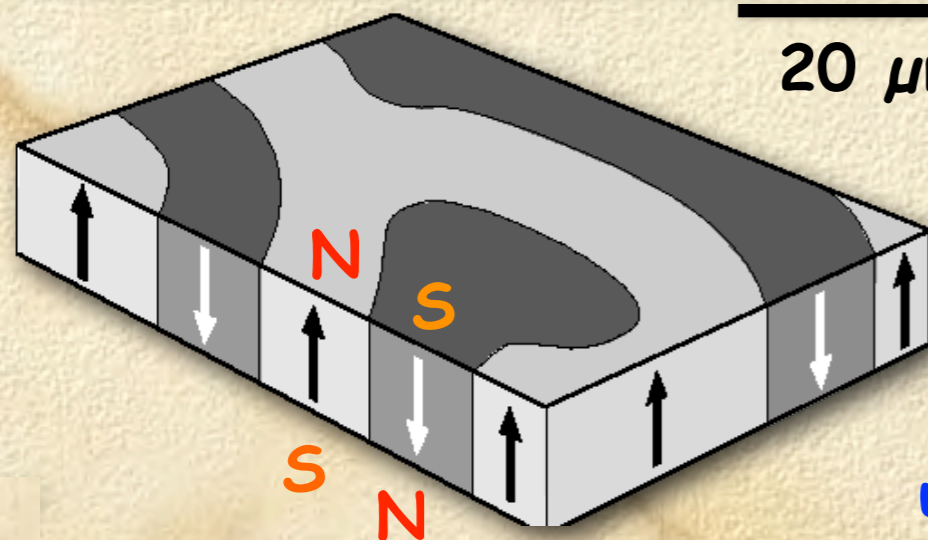
General Classification of Domains

Dominating
anisotropy energy ($Q \gg 1$)

Bubble garnet film ($5 \mu\text{m}$ thick)



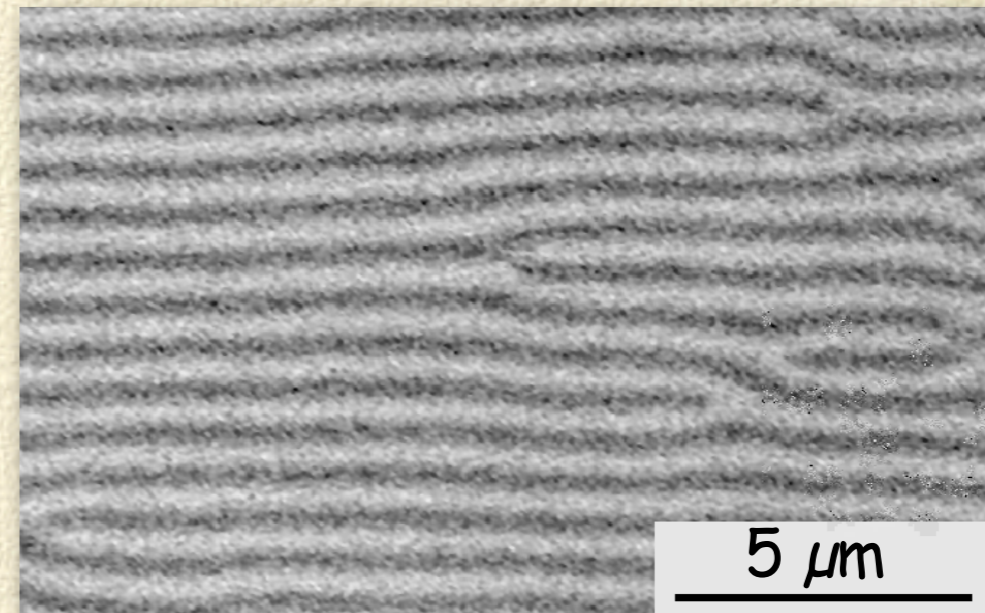
20 μm



strong
uniaxial
anisotropy

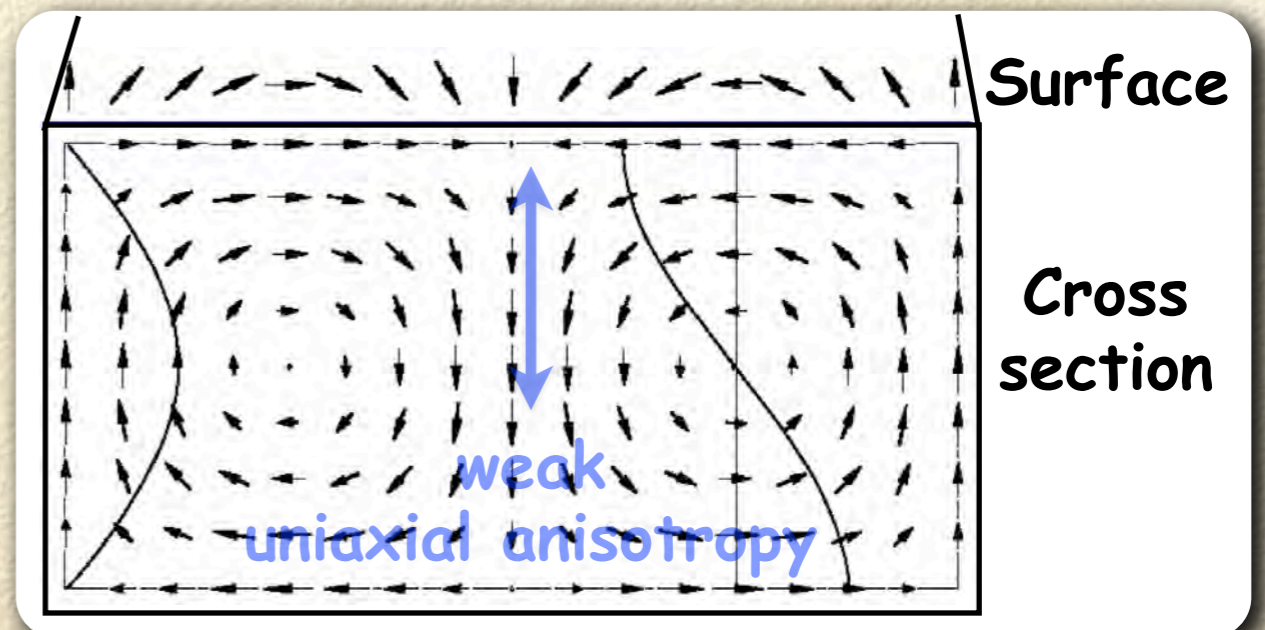
Dominating
stray-field energy ($Q \ll 1$)

Amorphous FeSiBCuNb film ($2 \mu\text{m}$ thick)



5 μm

Stripe
domains



Surface

Cross
section

weak
uniaxial
anisotropy

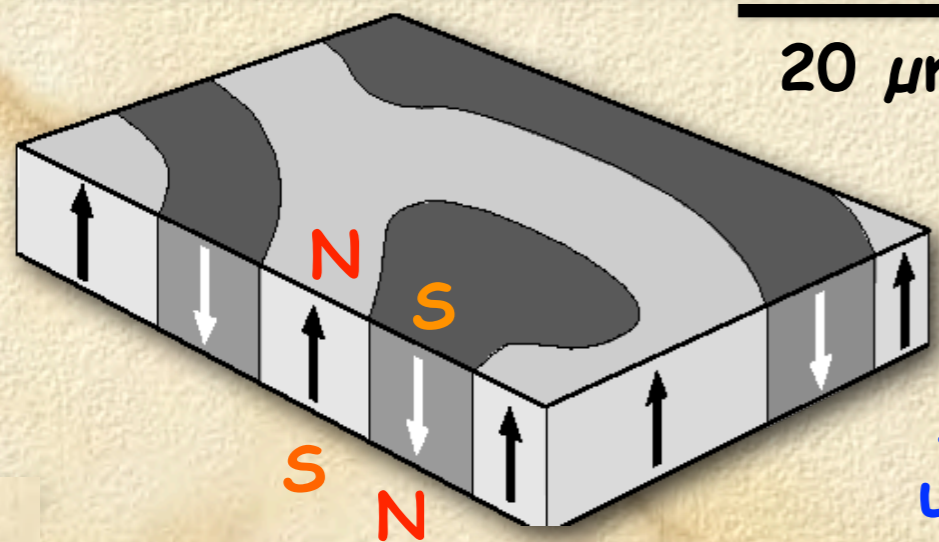
General Classification of Domains

Dominating anisotropy energy ($Q \gg 1$)

Bubble garnet film (5 μm thick)



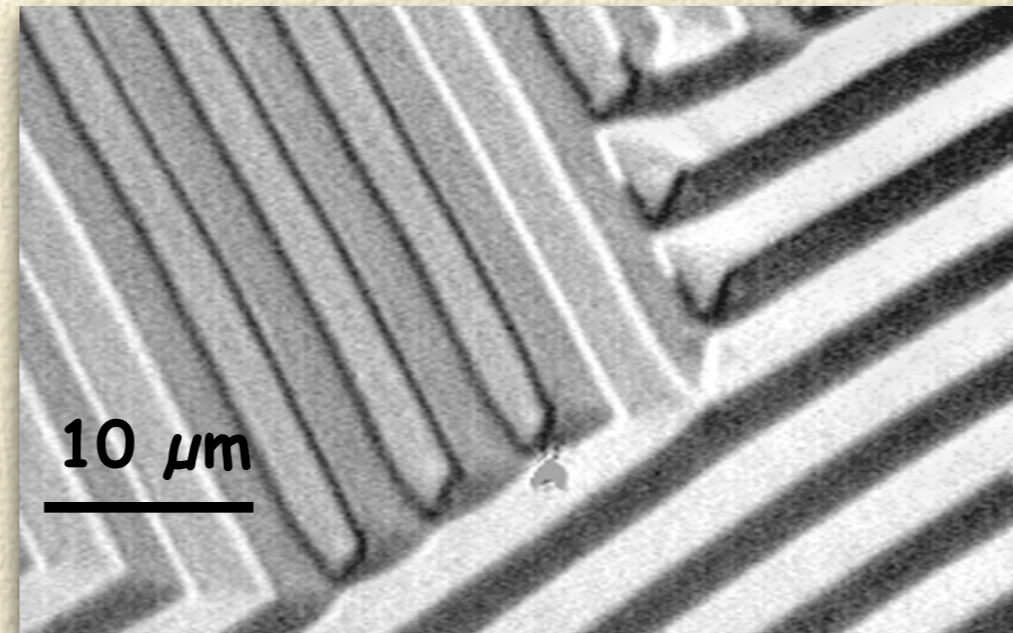
20 μm



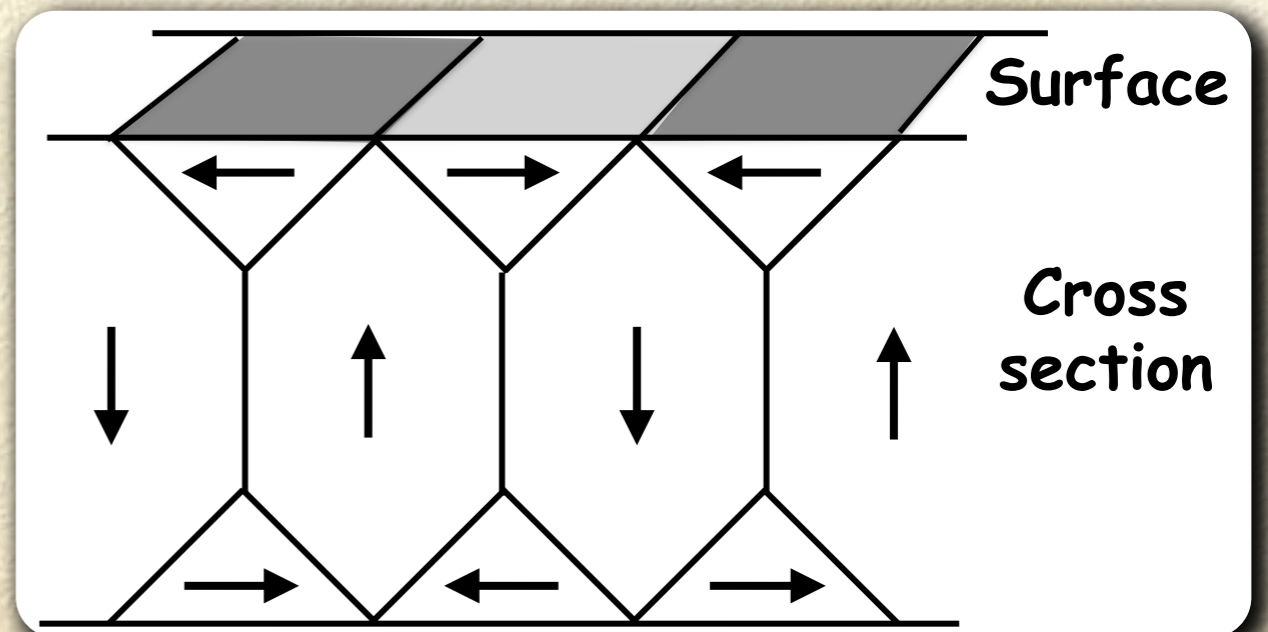
strong uniaxial anisotropy

Dominating stray-field energy ($Q \ll 1$)

Amorphous FeSiB ribbon (20 μm thick)



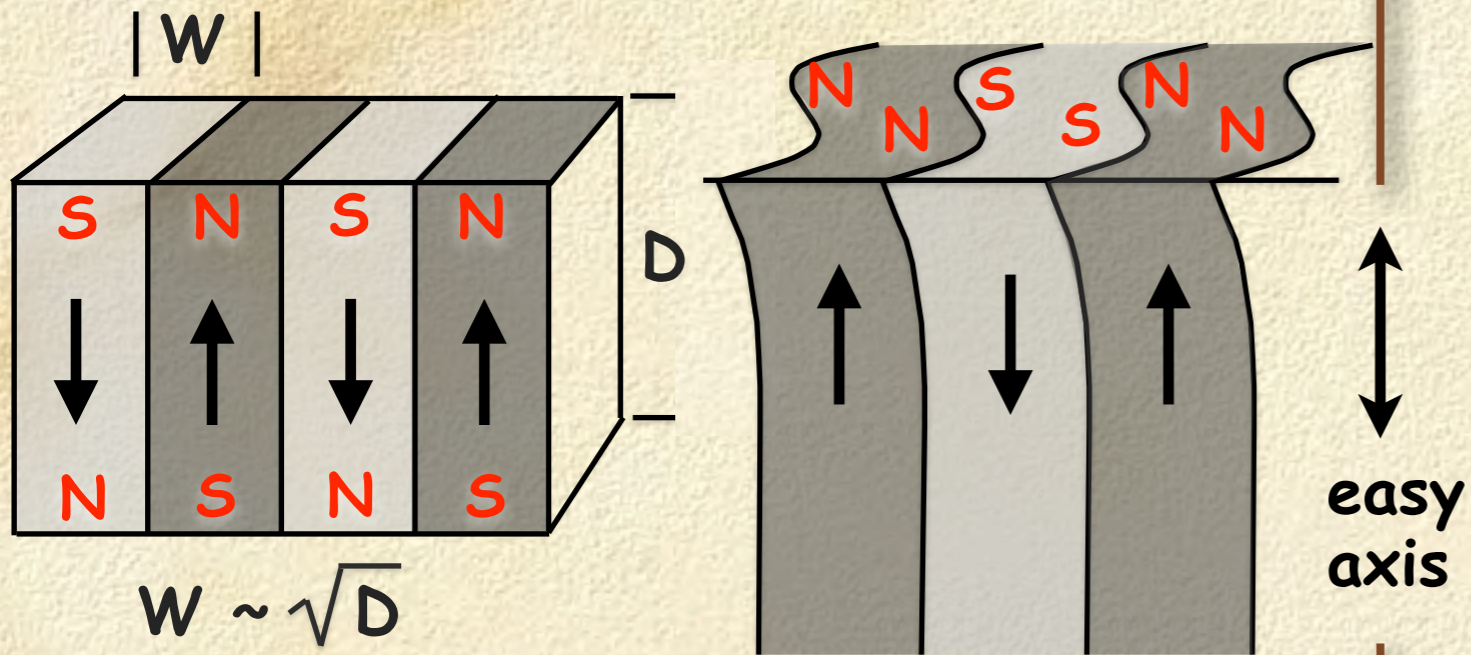
Landau domains



General Classification of Domains

Dominating anisotropy energy ($Q \gg 1$)

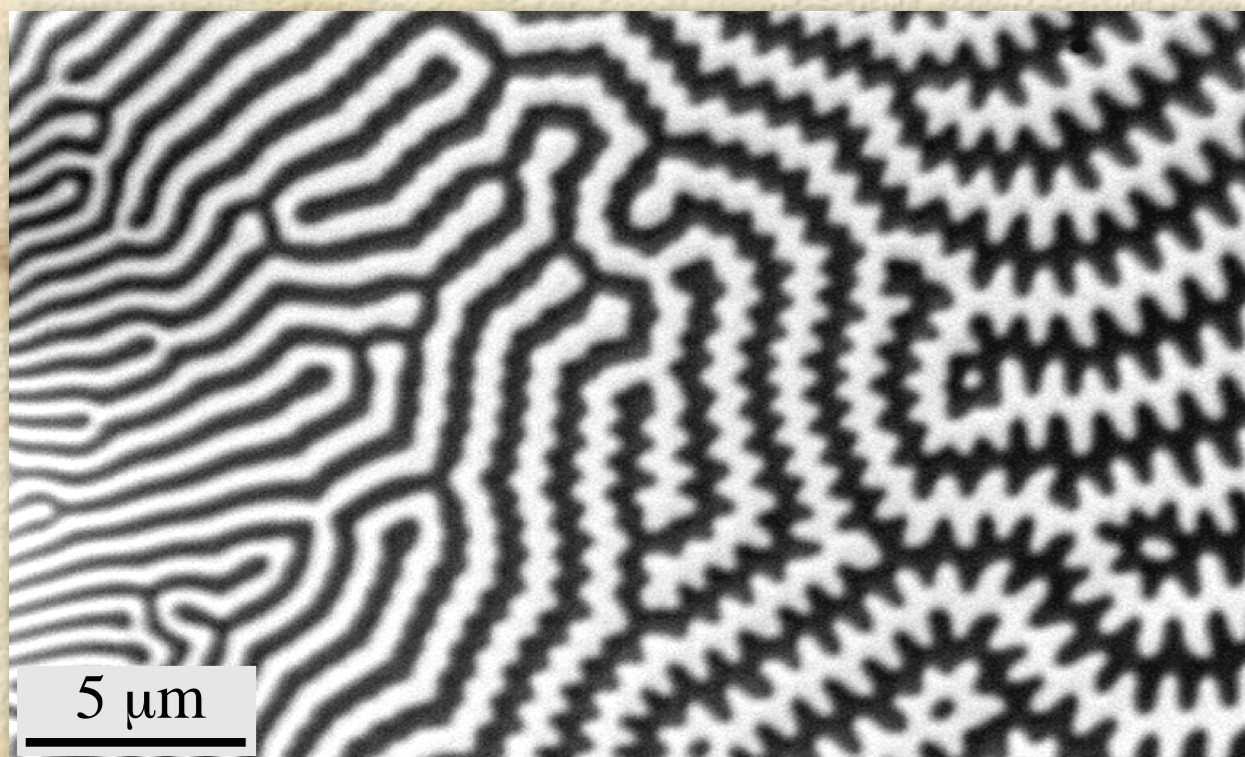
Dominating stray-field energy ($Q \ll 1$)



$\sim 1 \mu\text{m}$

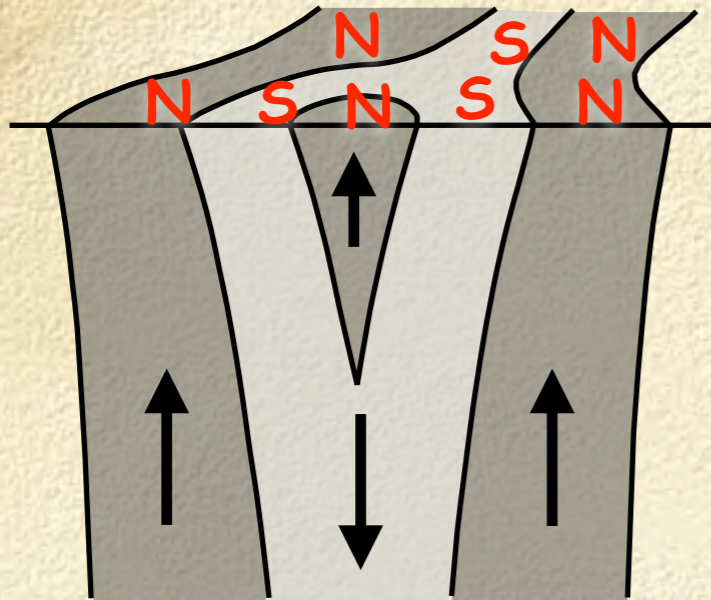
NdFeB wedge

$14 \mu\text{m}$



General Classification of Domains

Dominating anisotropy energy ($Q \gg 1$)



$\sim 40 \mu\text{m}$

Dominating stray-field energy ($Q \ll 1$)

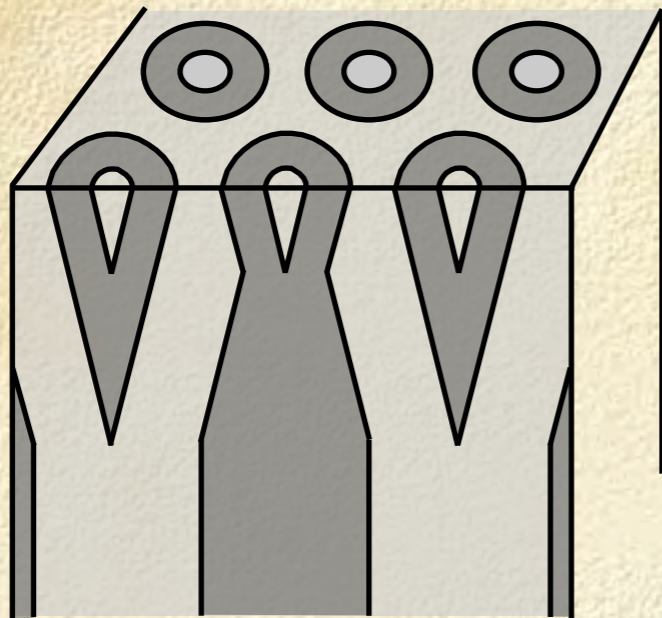
easy axis



5 μm

General Classification of Domains

Dominating
anisotropy energy ($Q \gg 1$)



$\sim 120 \mu\text{m}$

Dominating
stray-field energy ($Q \ll 1$)

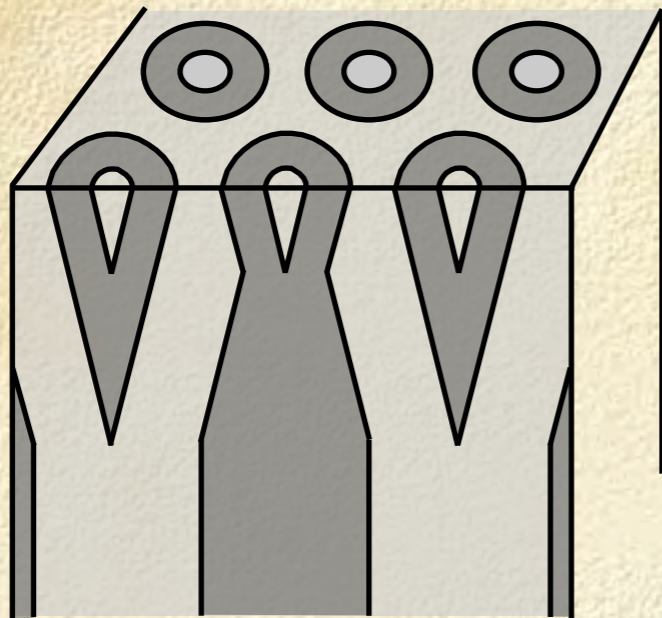
easy
axis



5 μm

General Classification of Domains

Dominating
anisotropy energy ($Q \gg 1$)



$\sim 600 \mu\text{m}$



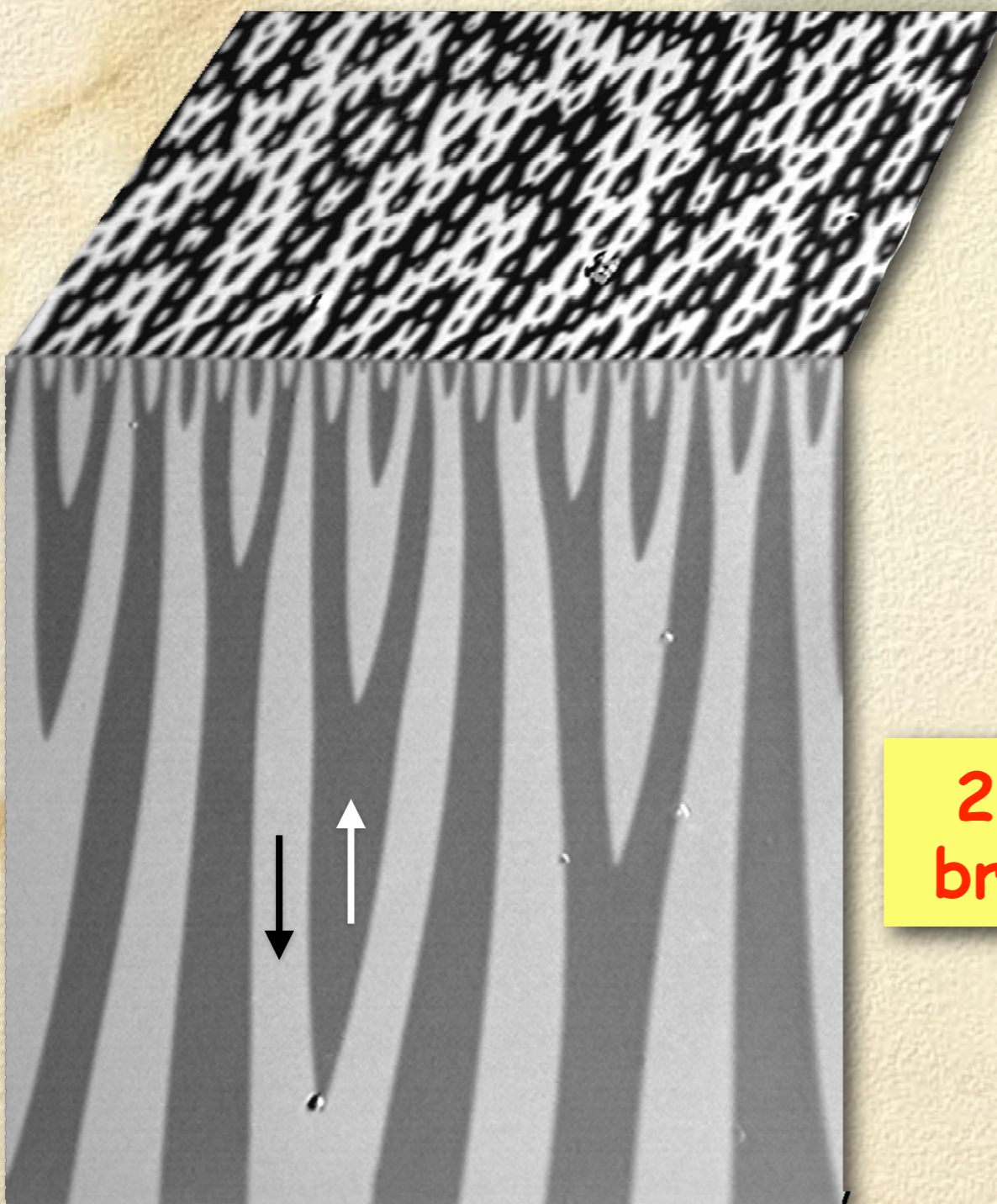
Dominating
stray-field energy ($Q \ll 1$)

easy
axis

General Classification of Domains

Dominating
anisotropy energy ($Q \gg 1$)

20 μm



Dominating
stray-field energy ($Q \ll 1$)

easy
axis

2-phase
branching

General Classification of Domains

Dominating
anisotropy energy ($Q \gg 1$)

20 μm



Dominating
stray-field energy ($Q \ll 1$)

General Classification of Domains

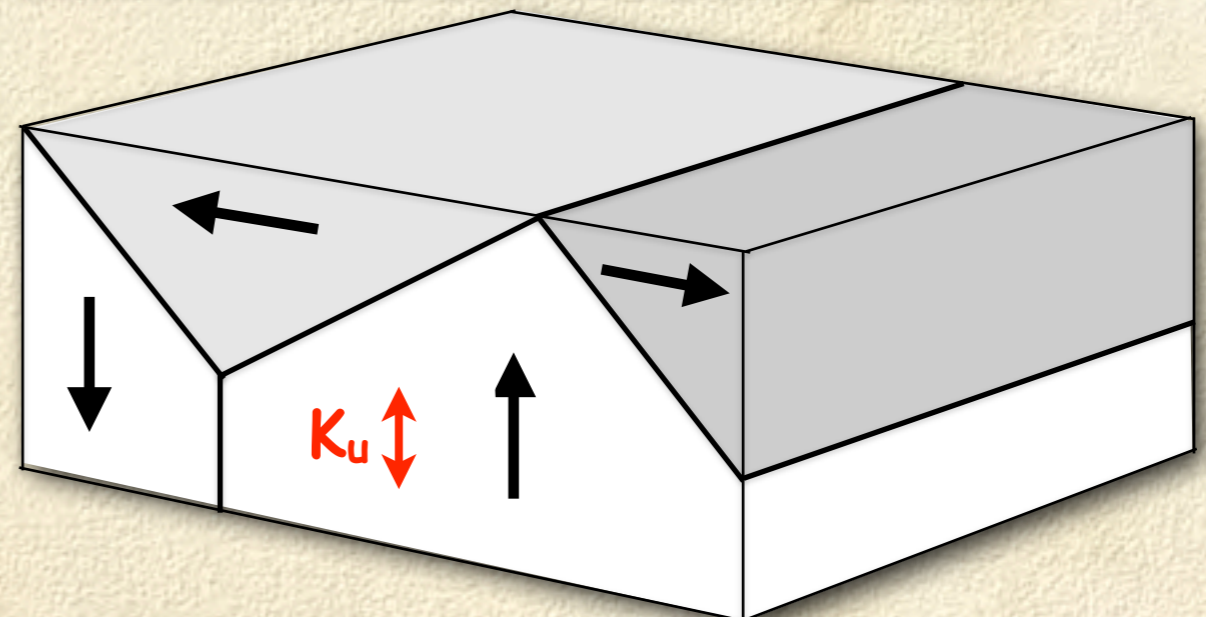
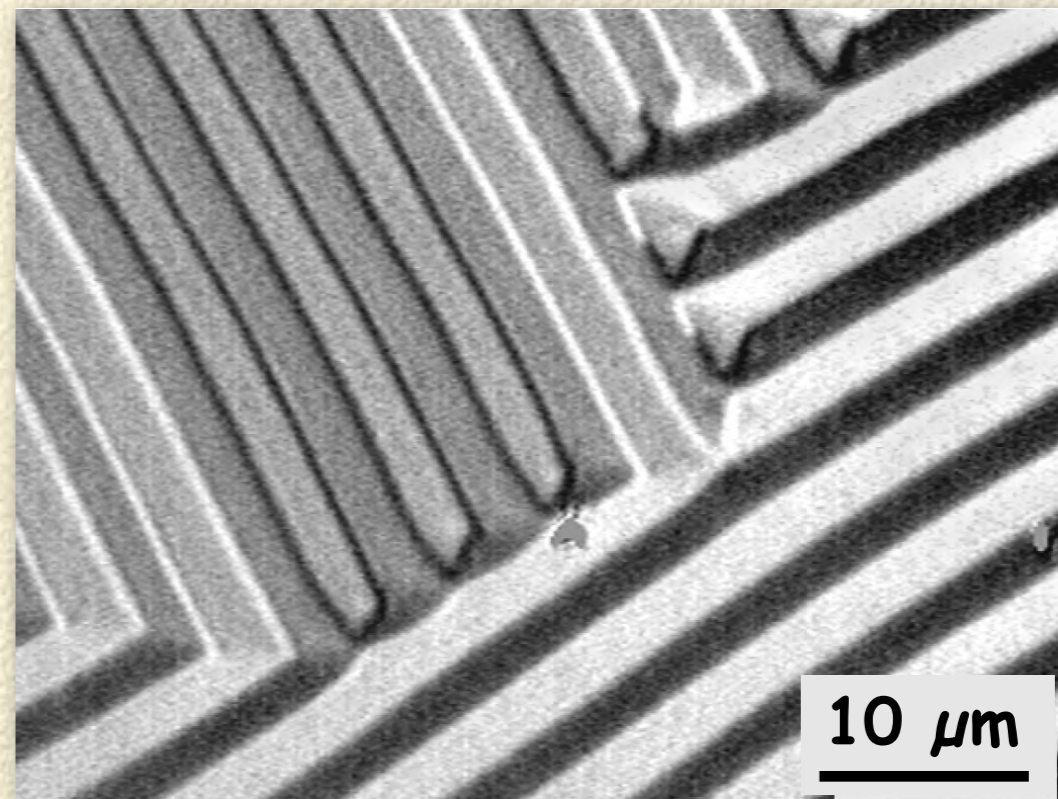
Dominating
anisotropy energy ($Q \gg 1$)

20 μm



Dominating
stray-field energy ($Q \ll 1$)

Amorphous FeSiB ribbon (20 μm thick)



General Classification of Domains

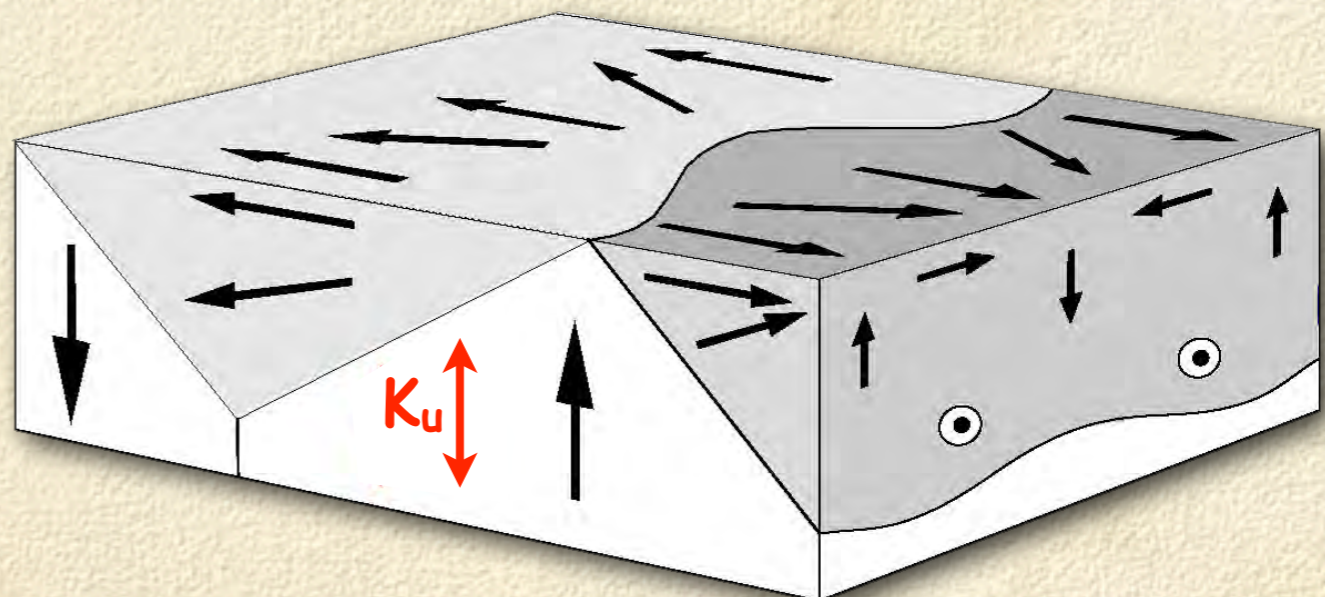
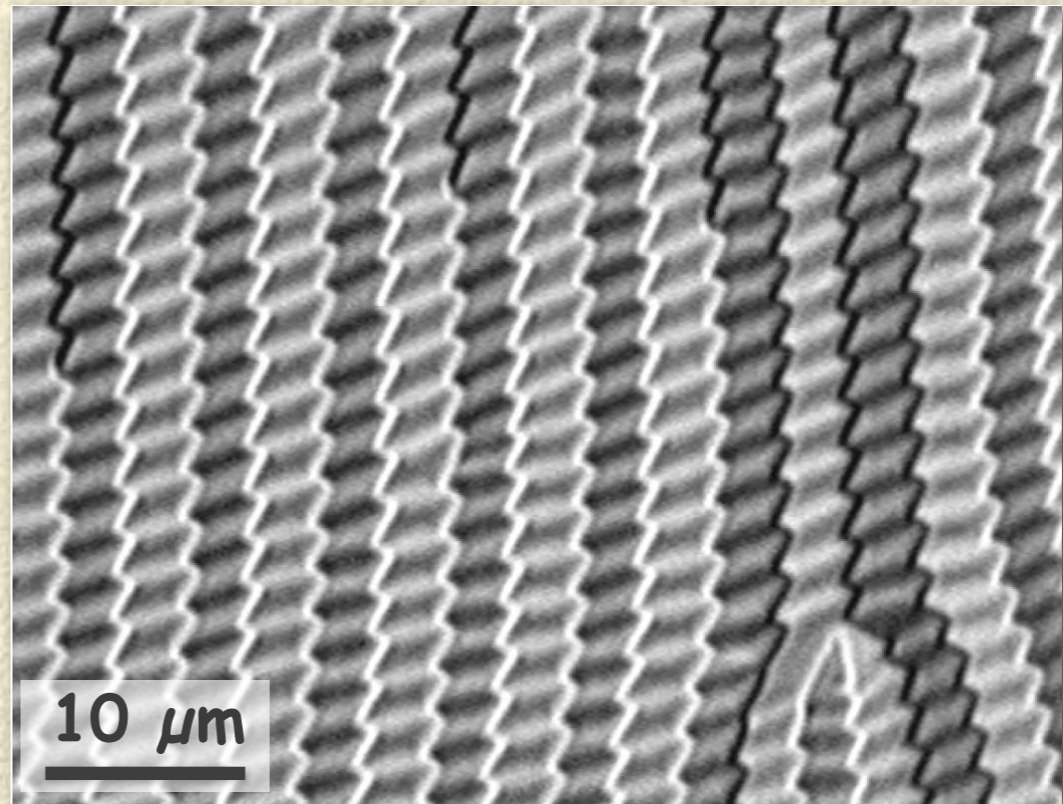
Dominating
anisotropy energy ($Q \gg 1$)

20 μm



Dominating
stray-field energy ($Q \ll 1$)

Amorphous FeSiB ribbon



General Classification of Domains

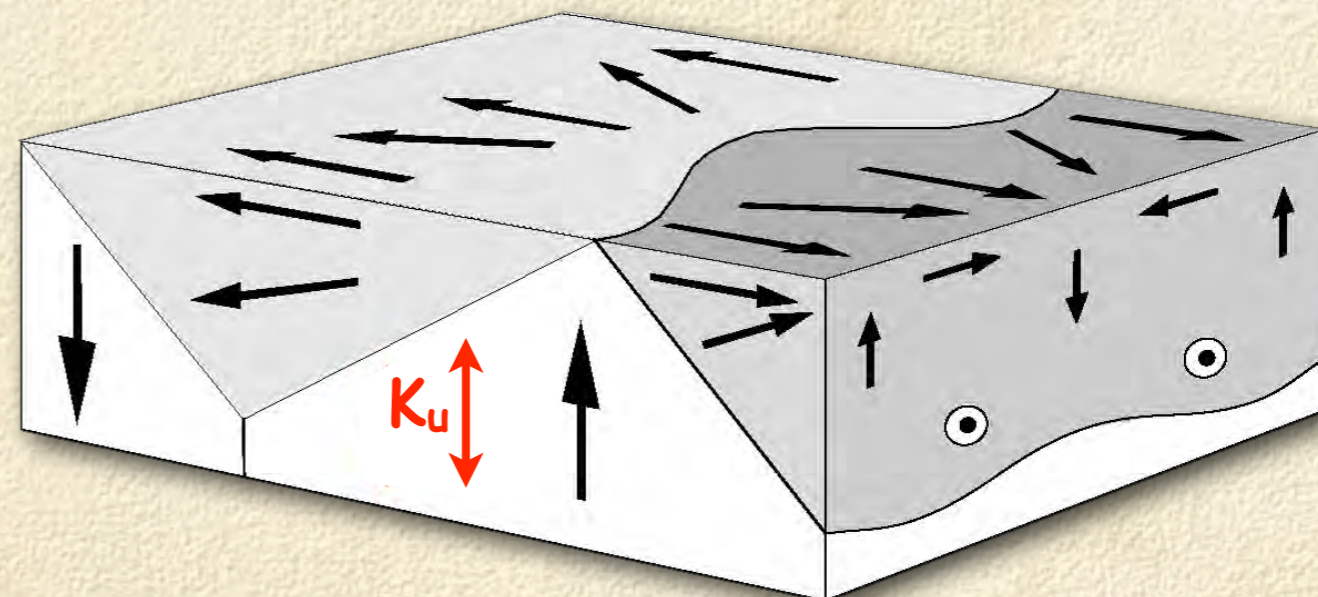
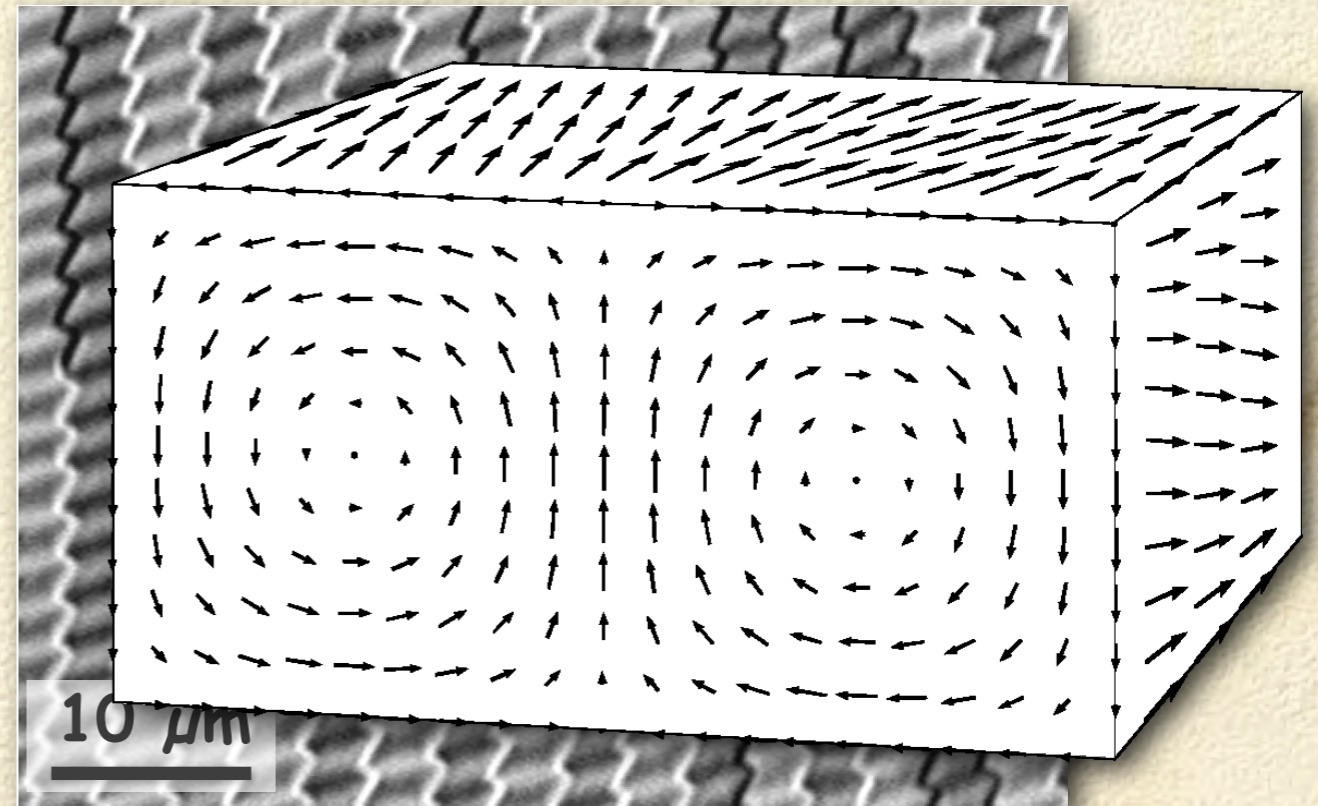
Dominating
anisotropy energy ($Q \gg 1$)

20 μm



Dominating
stray-field energy ($Q \ll 1$)

Amorphous FeSiB ribbon



General Classification of Domains

Dominating
anisotropy energy ($Q \gg 1$)

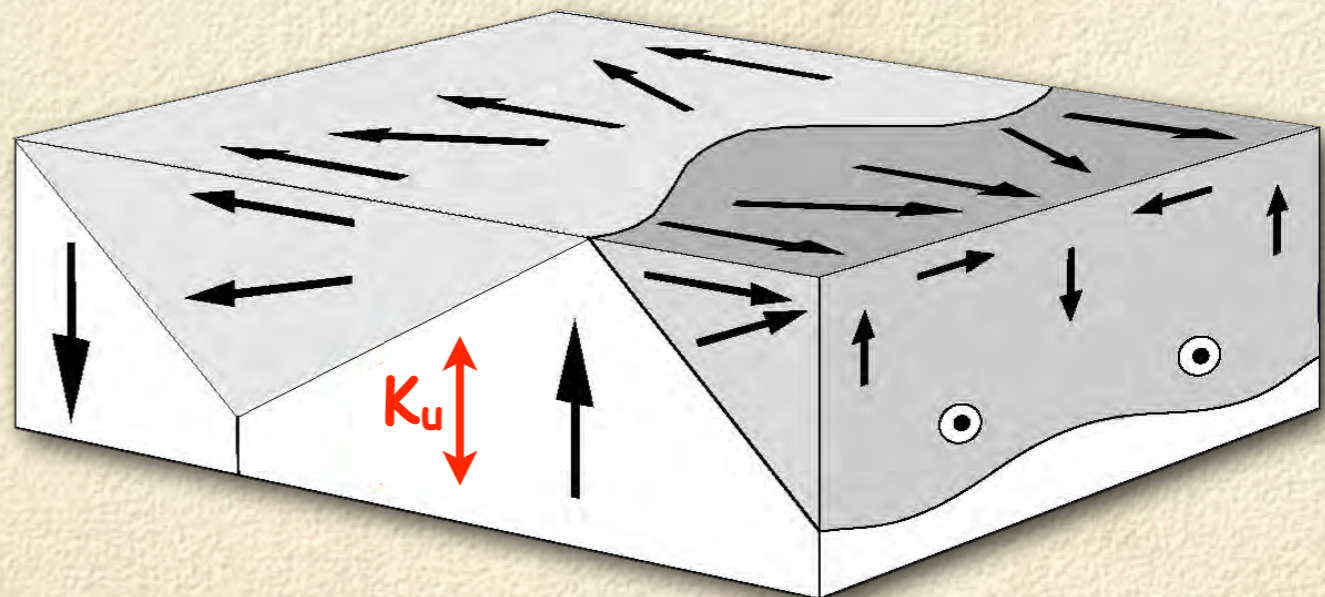
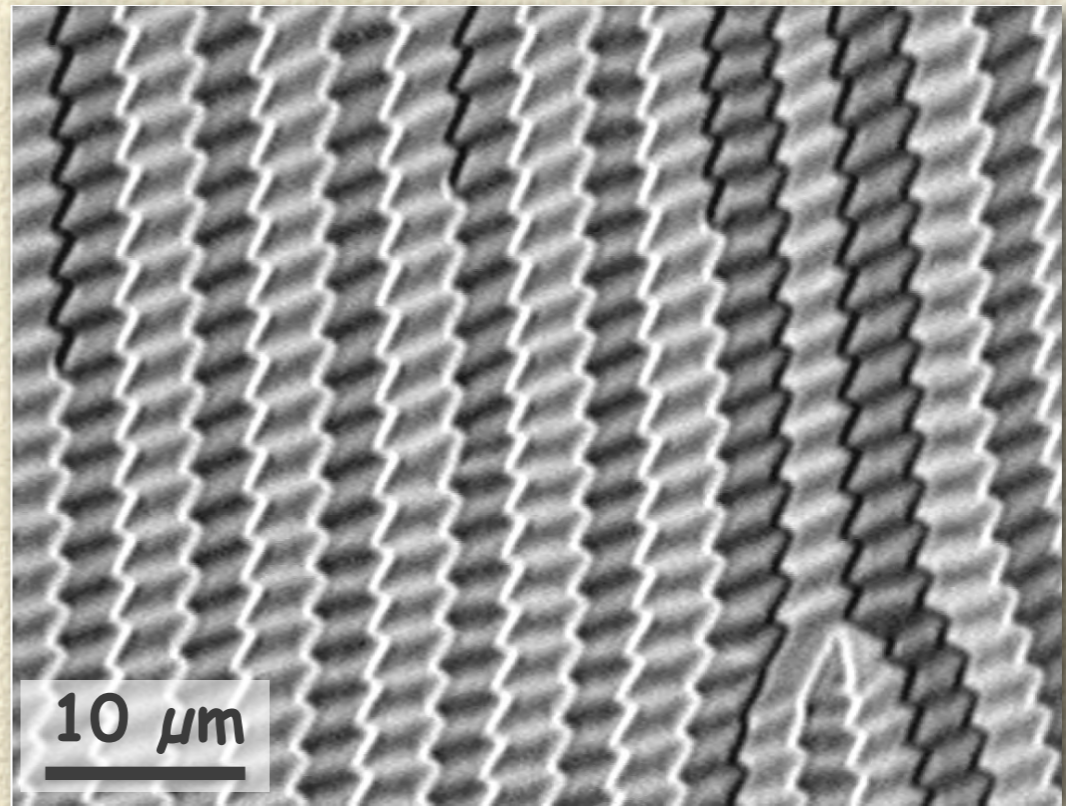
20 μm



Dominating
stray-field energy ($Q \ll 1$)

Amorphous FeSiB ribbon

10 μm



General Classification of Domains

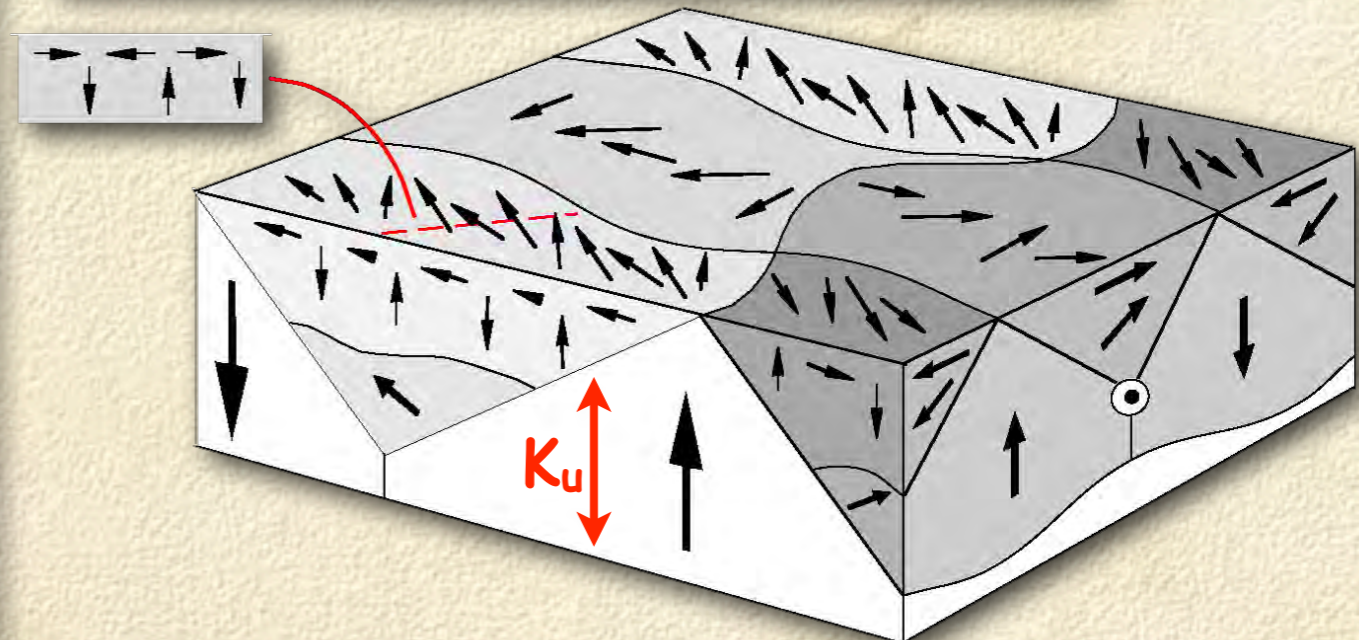
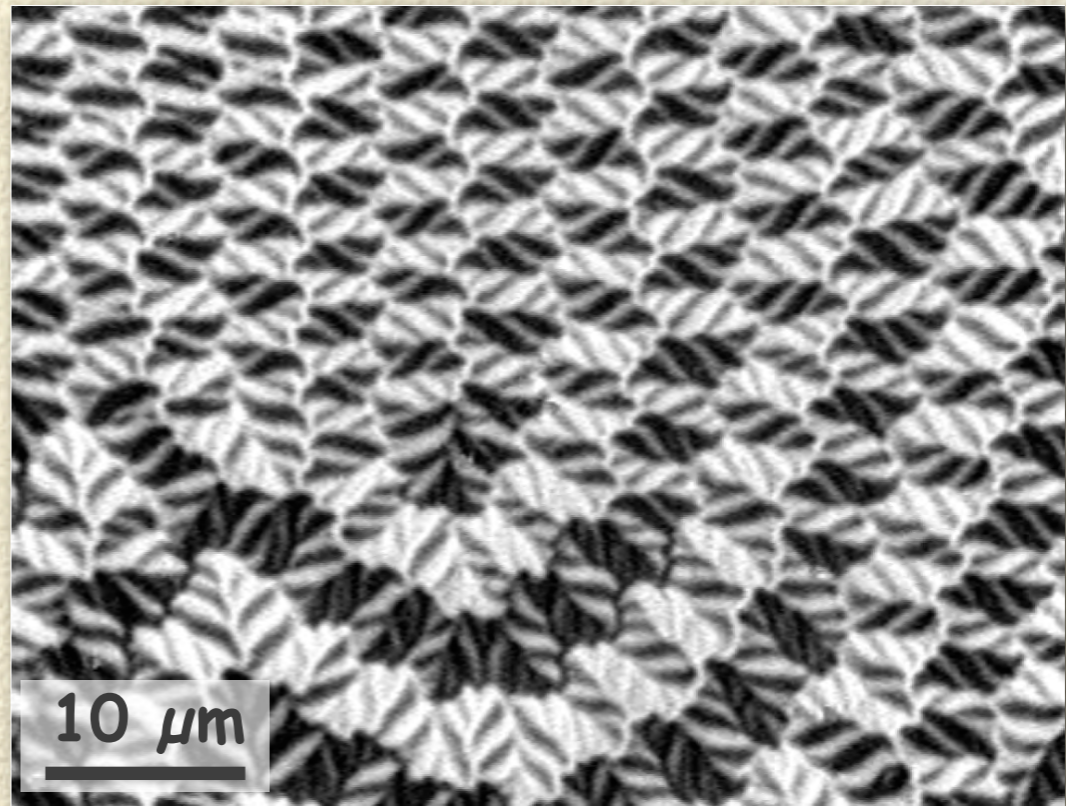
Dominating
anisotropy energy ($Q \gg 1$)

20 μm



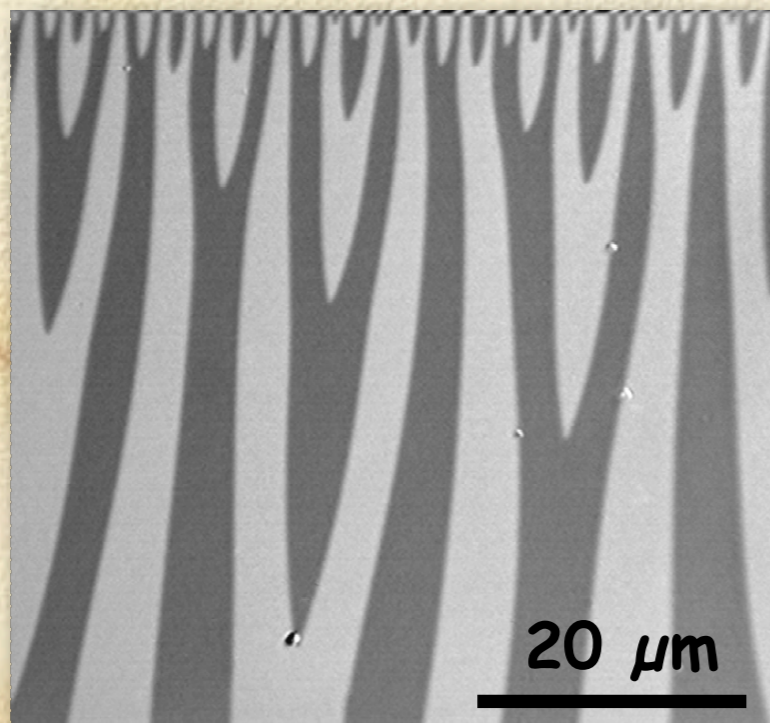
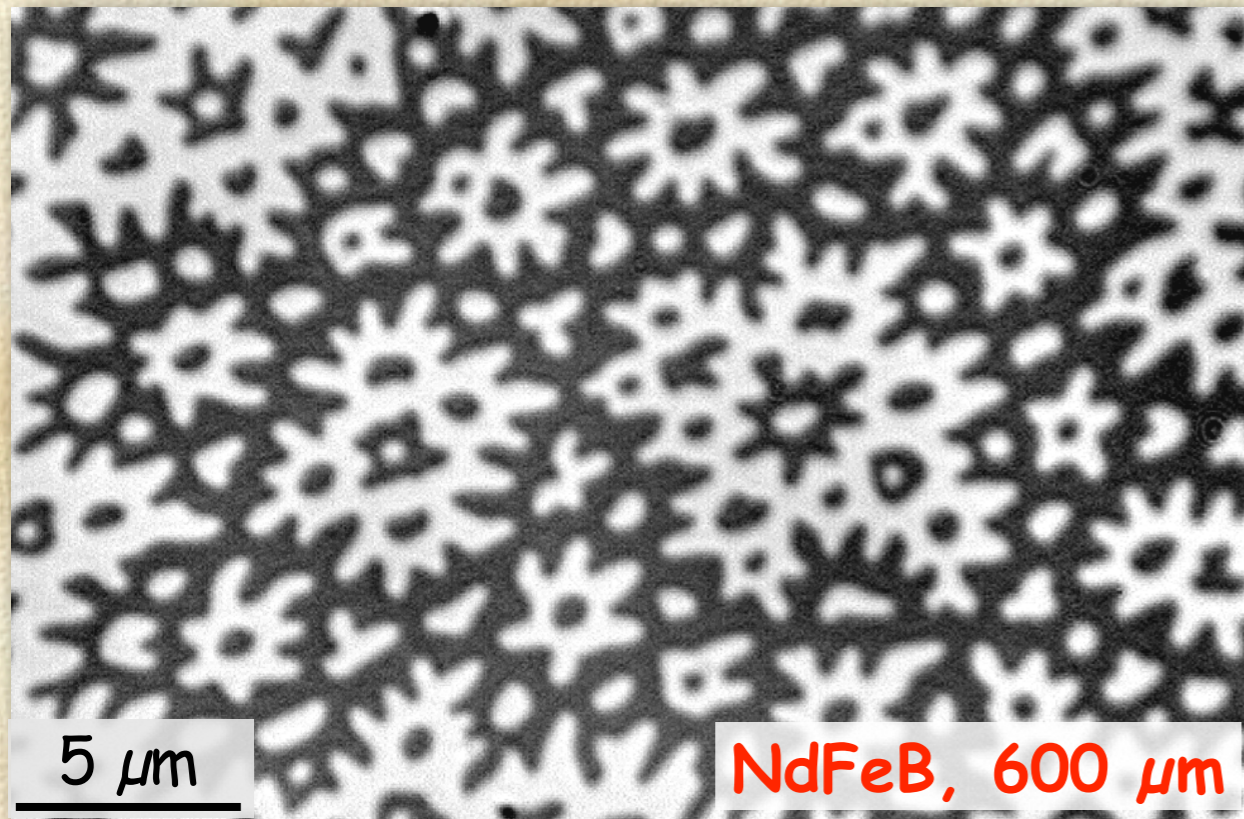
Dominating
stray-field energy ($Q \ll 1$)

Amorphous FeSiB ribbon

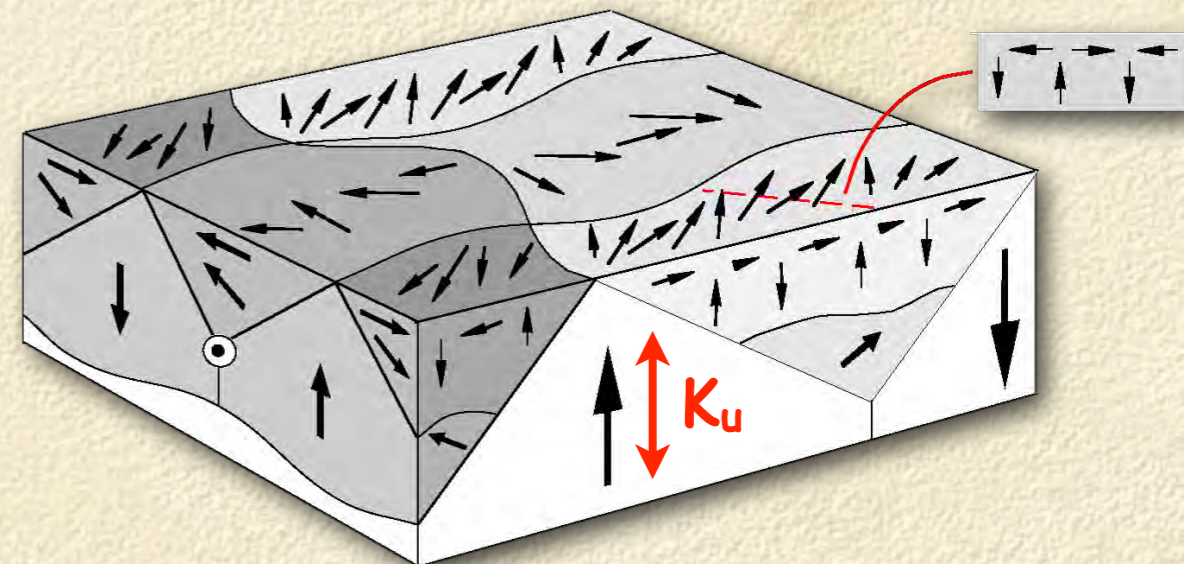
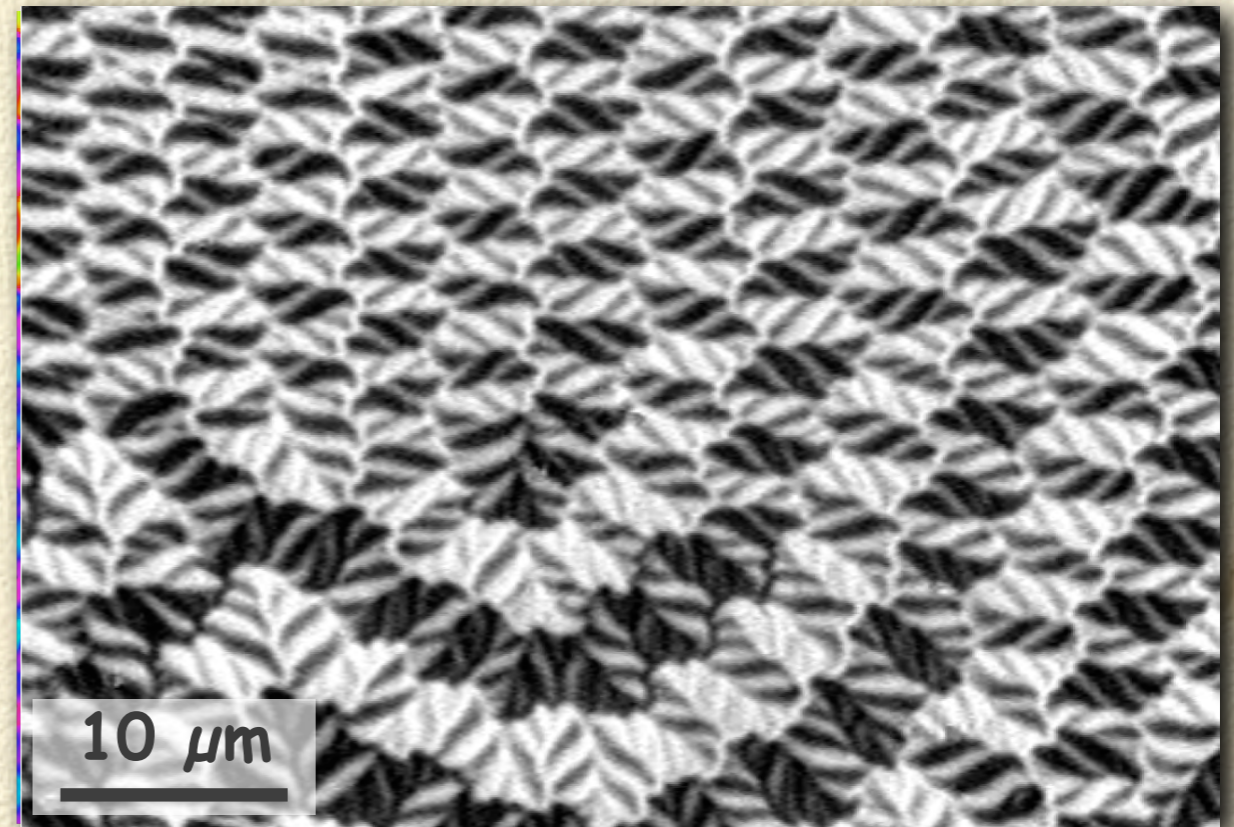


General Classification of Domains

$$Q \gg 1$$

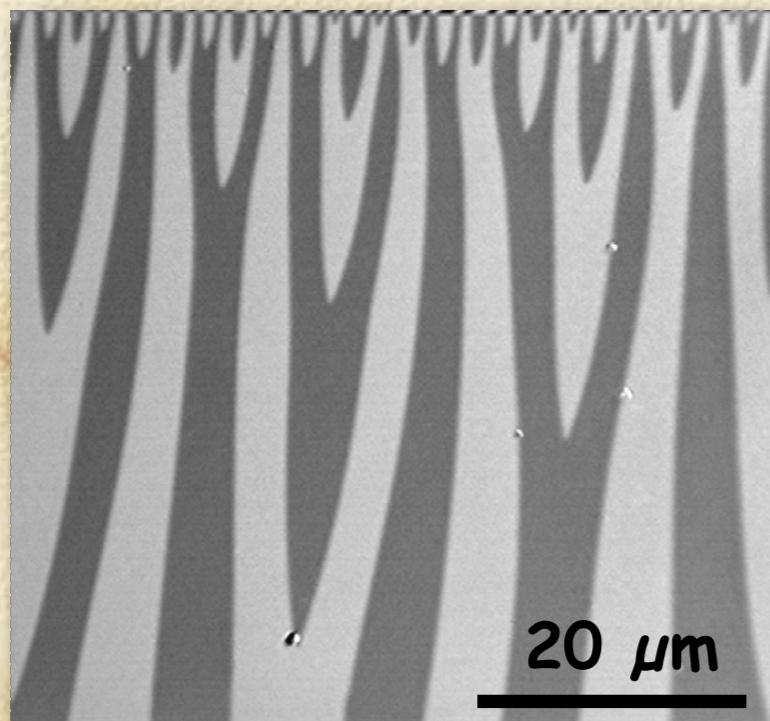
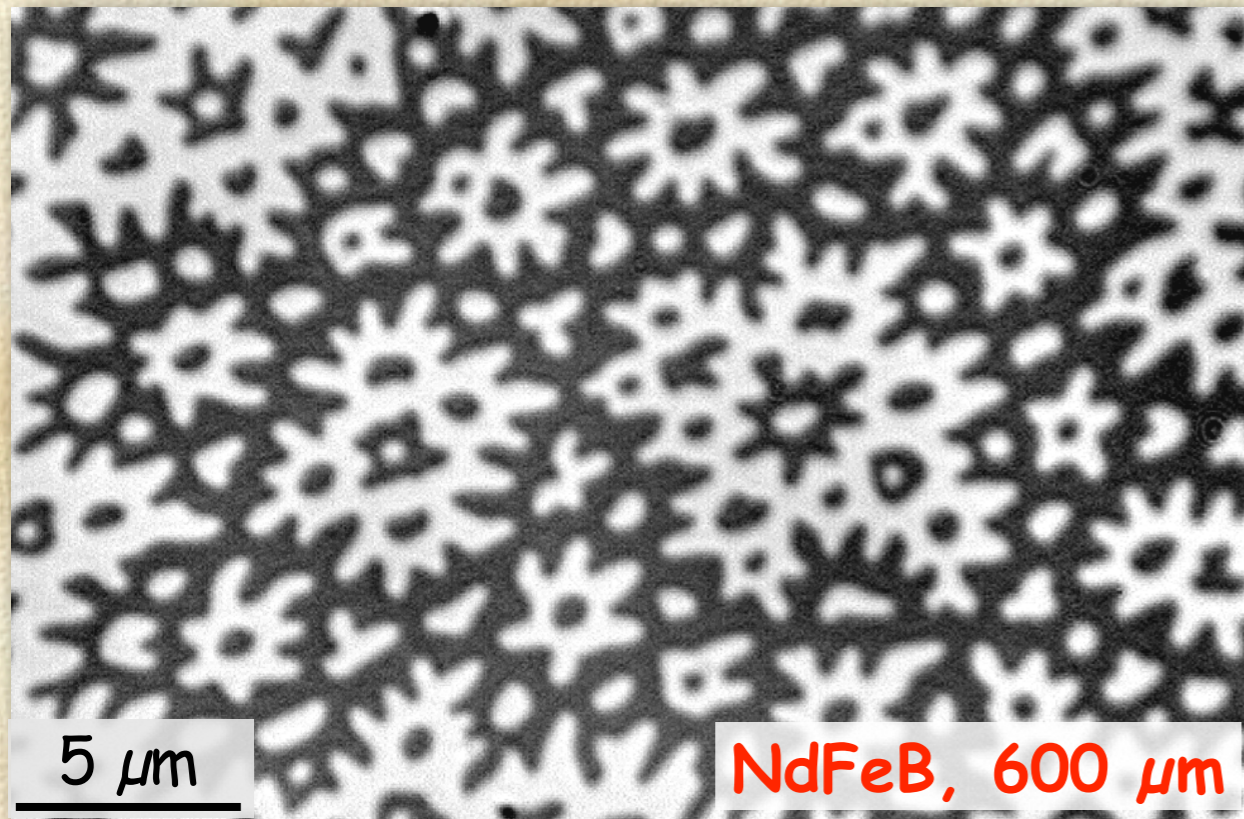


$$Q \ll 1$$

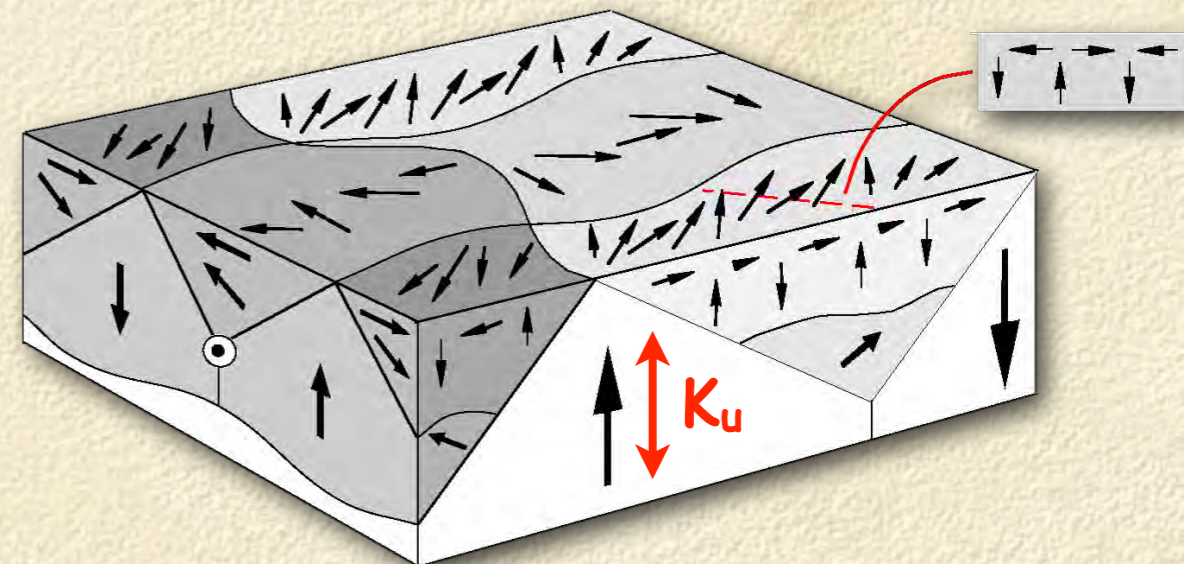
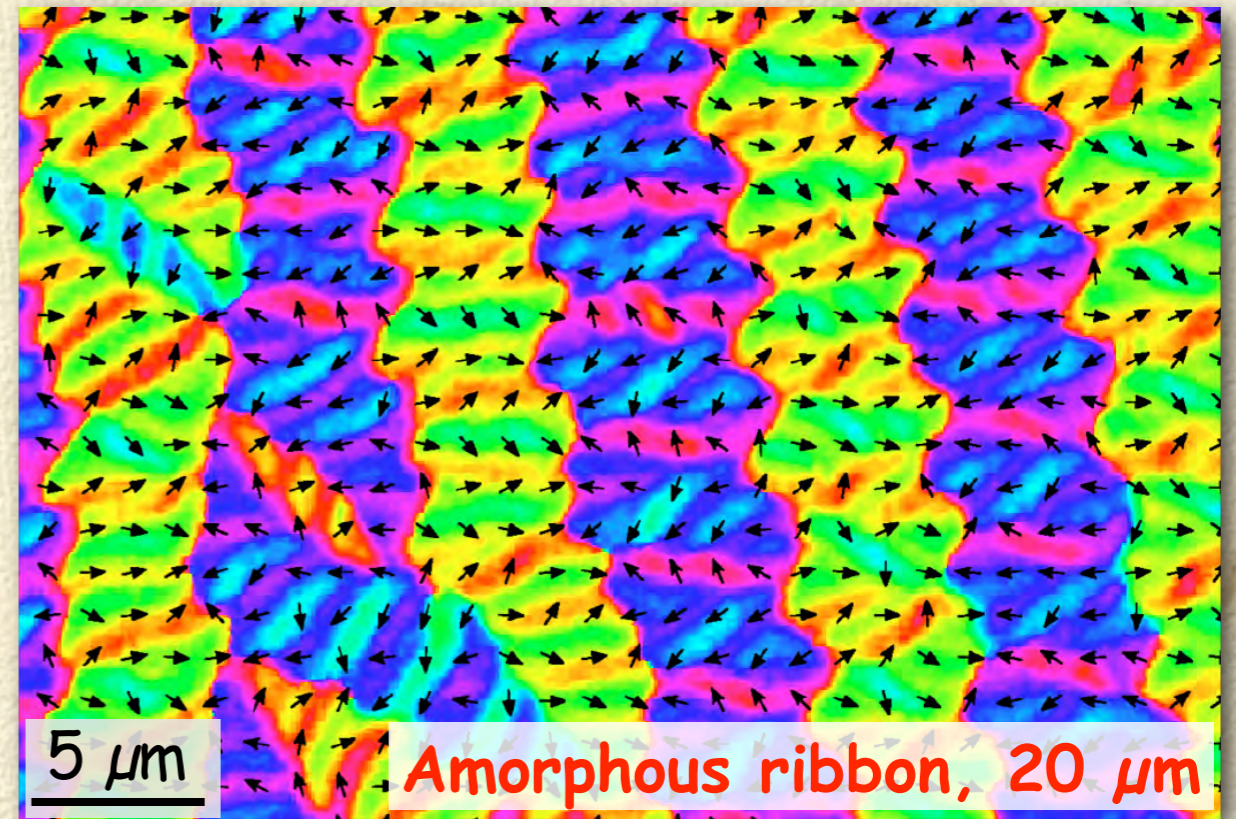


General Classification of Domains

$$Q \gg 1$$



$$Q \ll 1$$



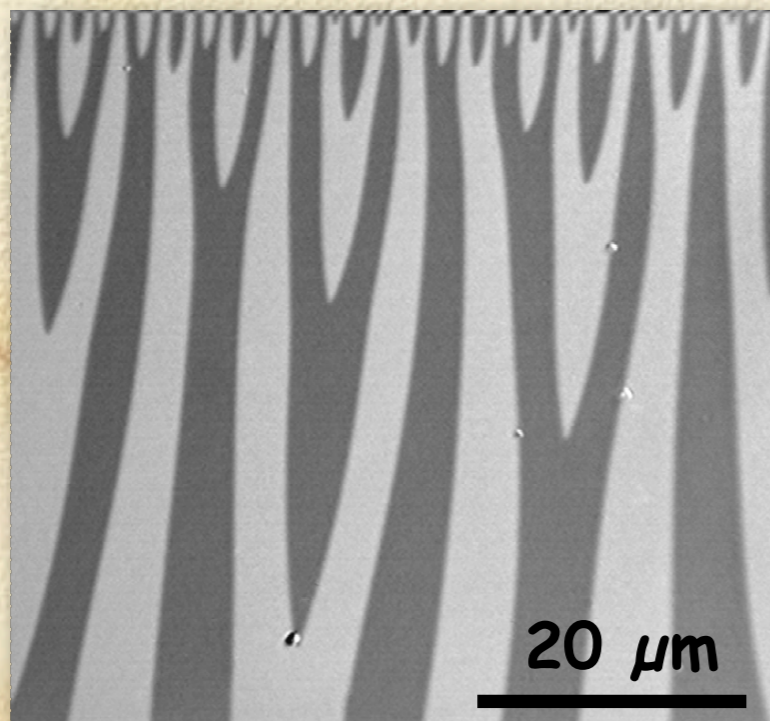
General Classification of Domains

$$Q \gg 1$$

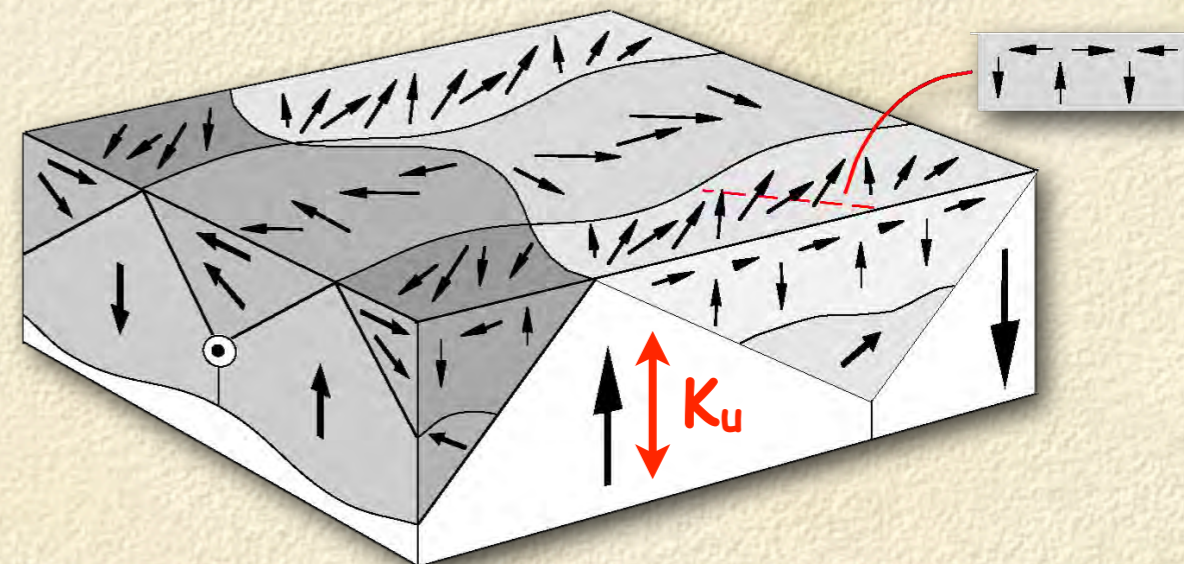
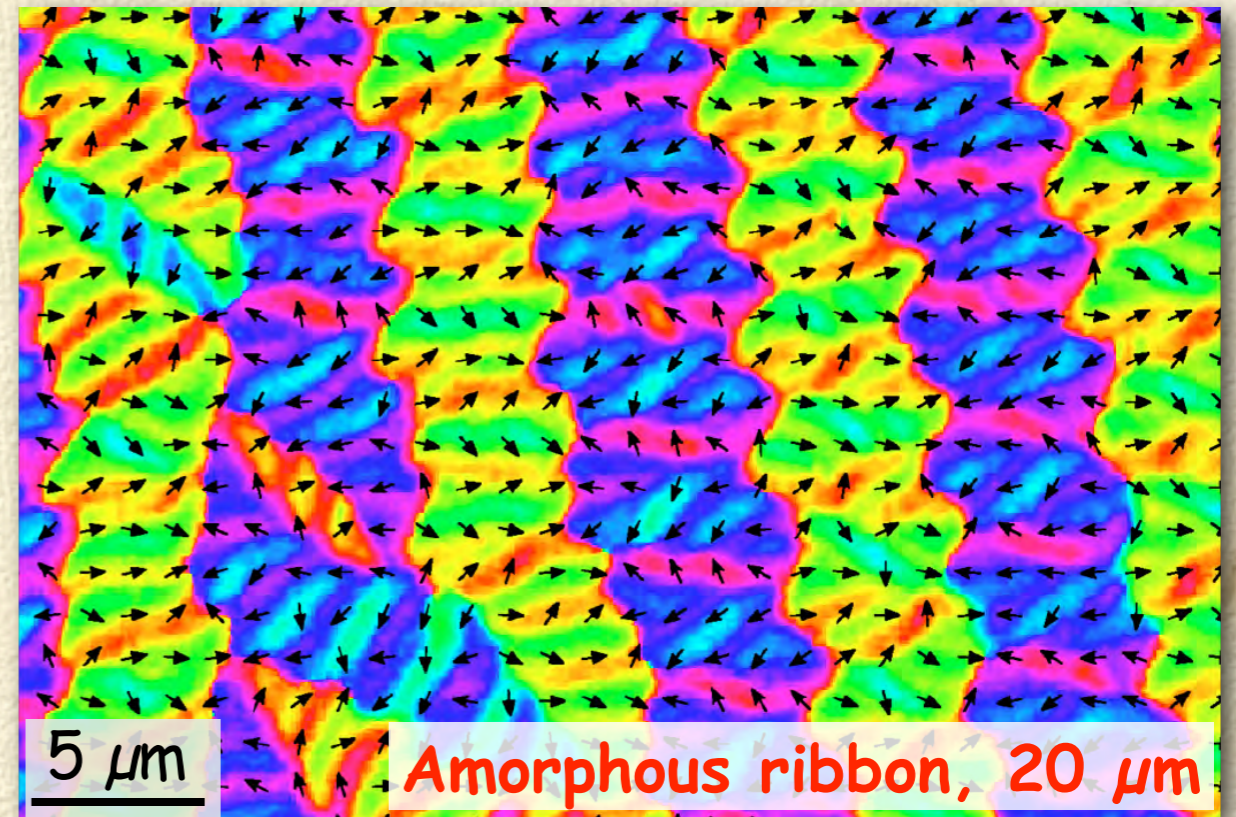
Anisotropy energy avoided,
Domains adapt to keep
stray-field energy low

5 μm

NdFeB, 600 μm



$$Q \ll 1$$



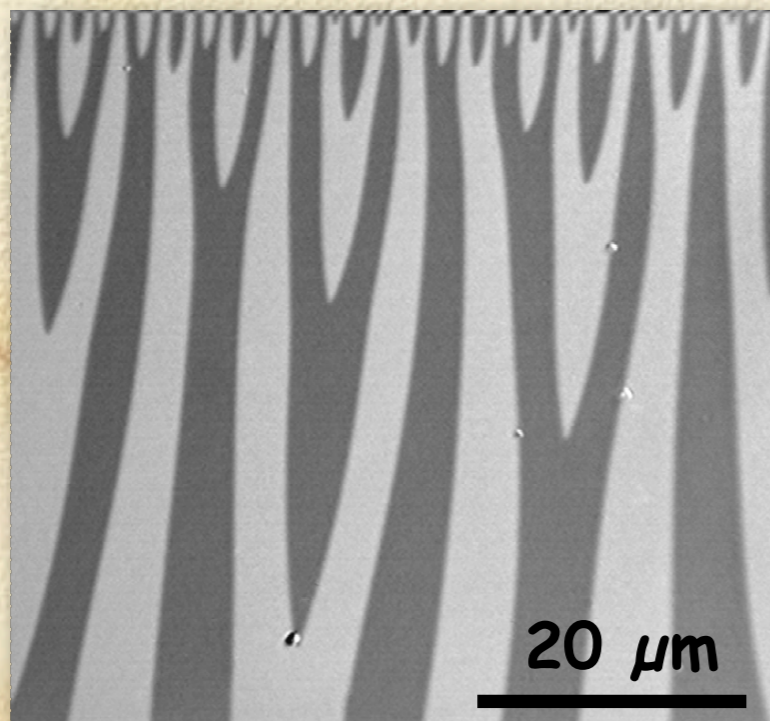
General Classification of Domains

$$Q \gg 1$$

Anisotropy energy avoided,
Domains adapt to keep stray-field energy low

5 μm

NdFeB, 600 μm

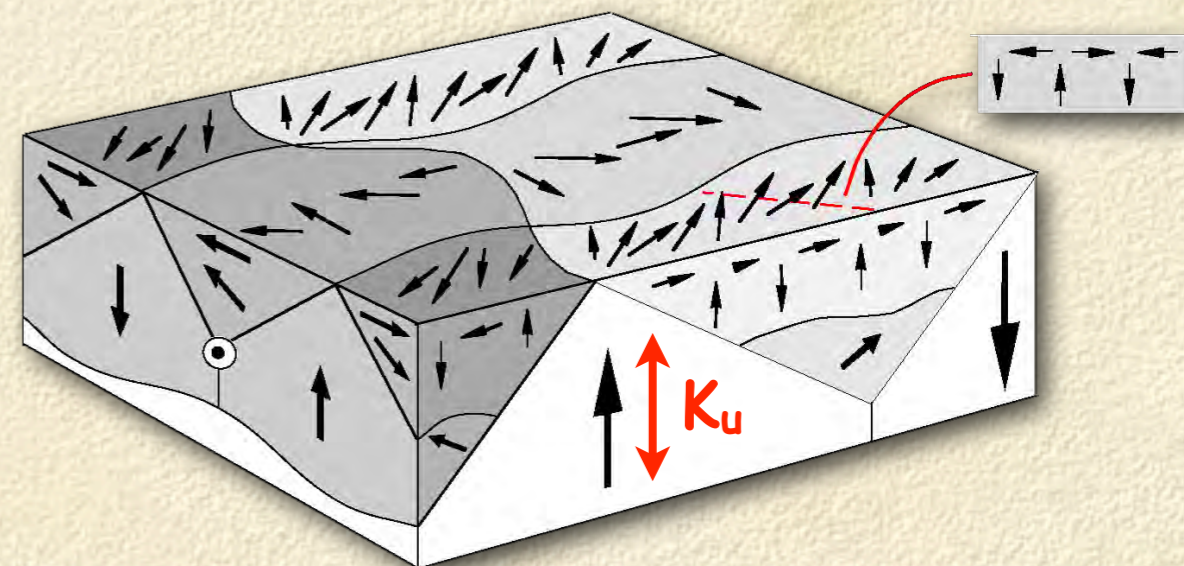


$$Q \ll 1$$

Stray field energy avoided,
Domains adapt to keep anisotropy energy low

5 μm

Amorphous ribbon, 20 μm



General Classification of Domains

$$Q \gg 1$$

Anisotropy energy avoided,
Domains adapt to keep
stray-field energy low

5 μm

600 μm

Permanent magnets

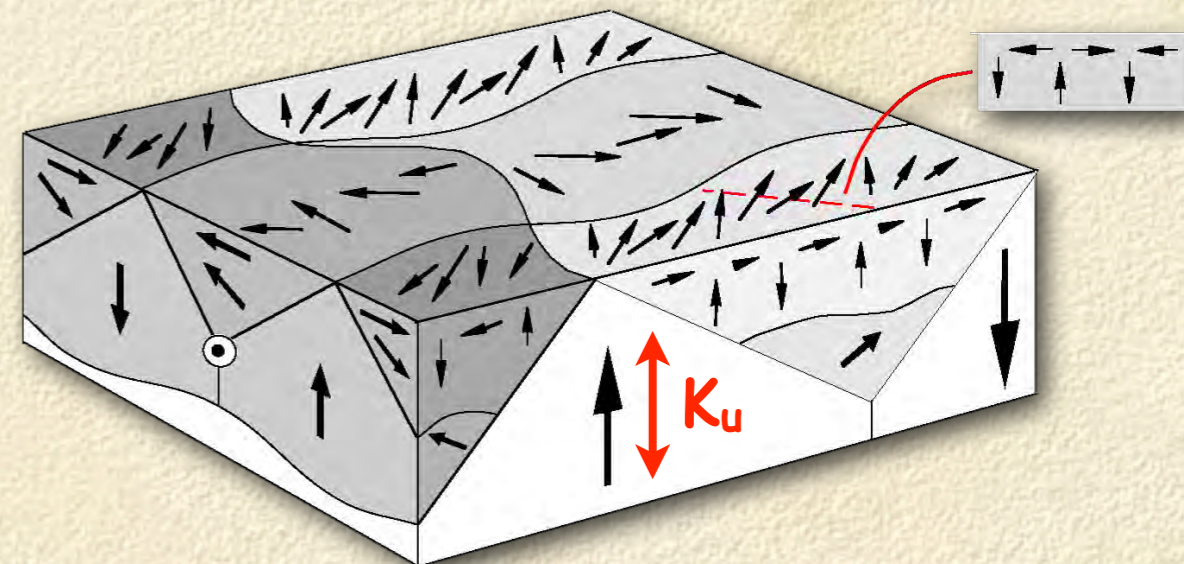
20 μm

$$Q \ll 1$$

Stray field energy avoided,
Domains adapt to keep
anisotropy energy low

5 μm

Amorphous ribbon, 20 μm



General Classification of Domains

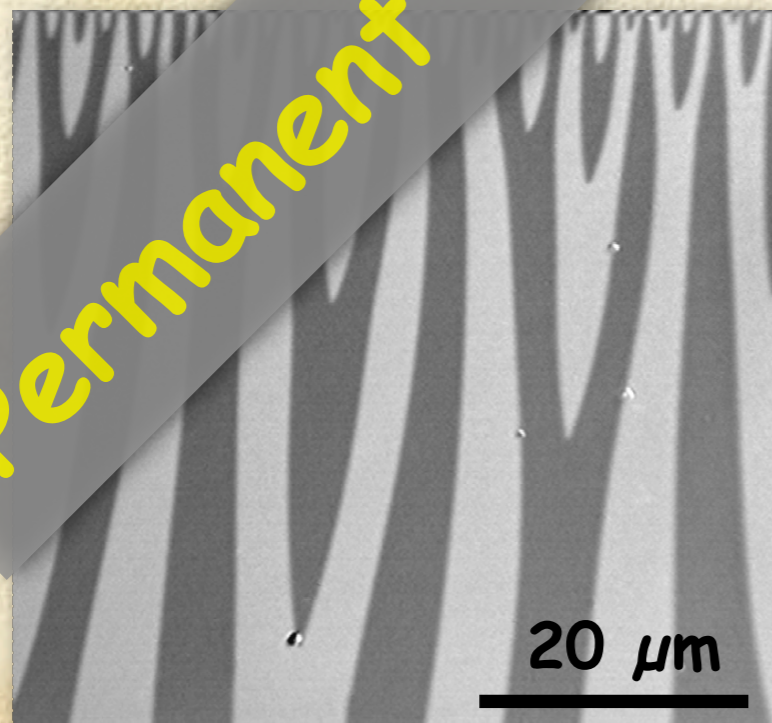
$$Q \gg 1$$

Anisotropy energy avoided,
Domains adapt to keep
stray-field energy low

5 μm

Amorphous ribbon, 600 μm

Permanent magnets



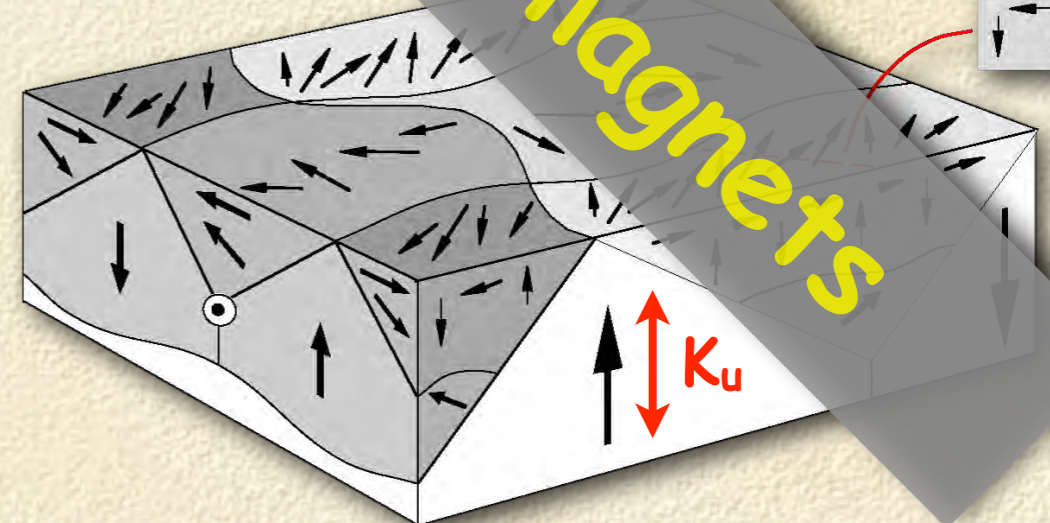
20 μm

$$Q \ll 1$$

Stray field energy avoided,
Domains adapt to keep
anisotropy energy low

5 μm

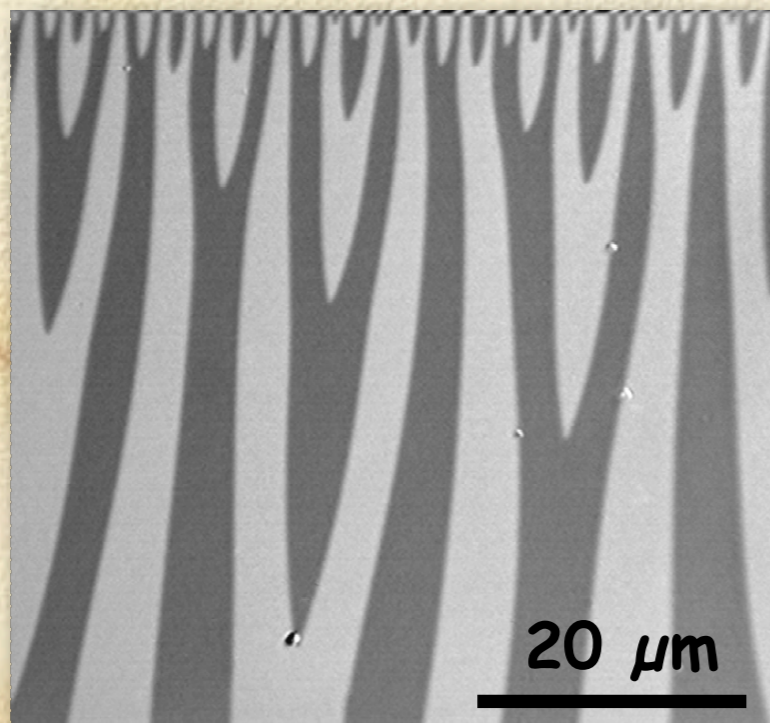
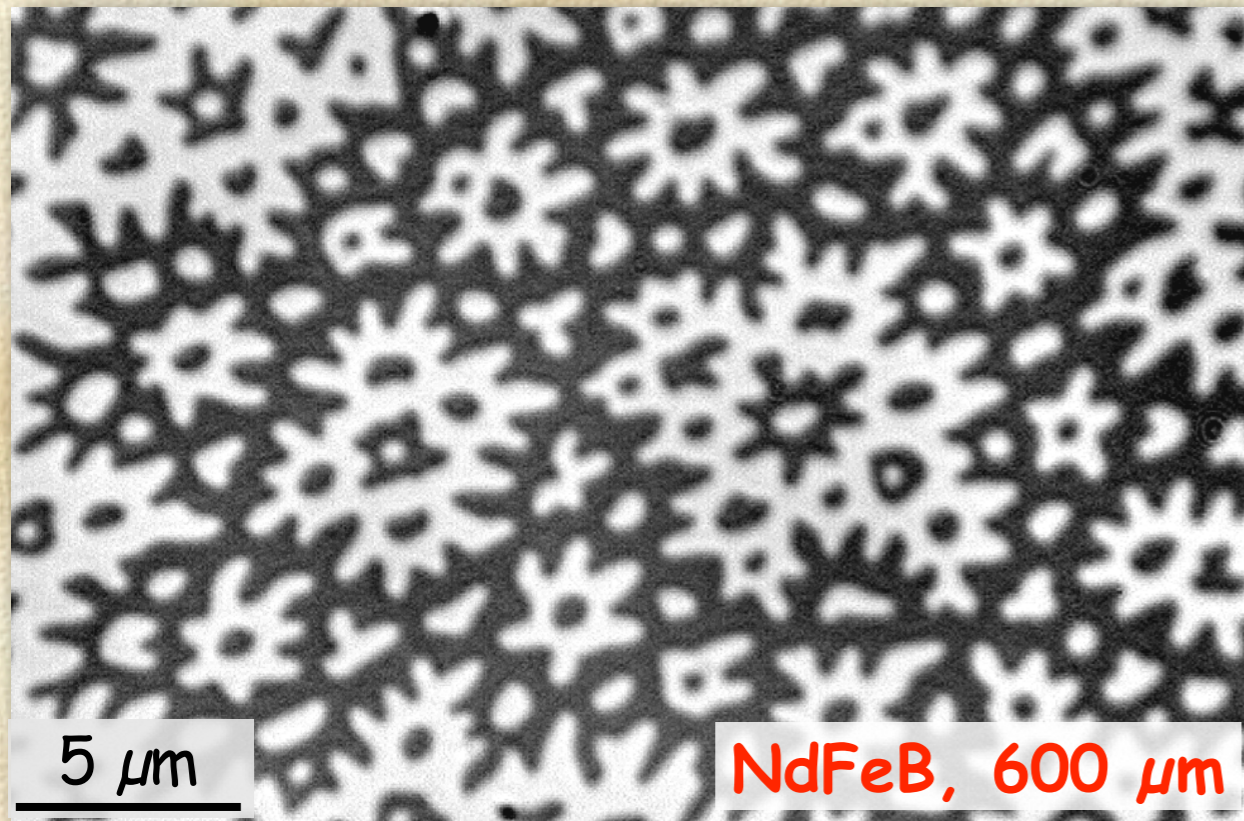
Soft magnets



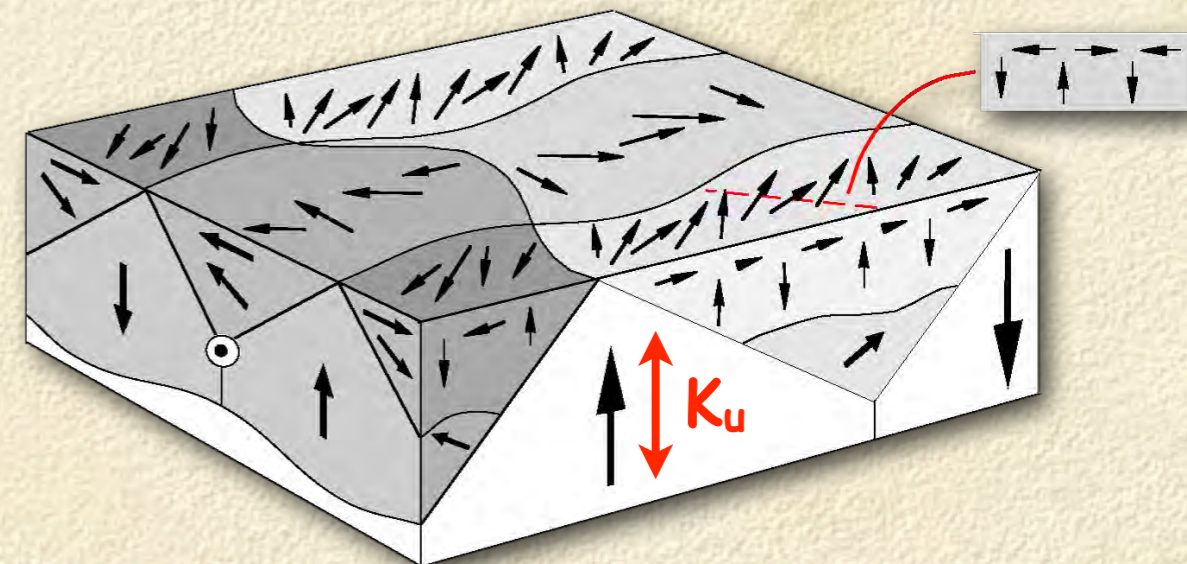
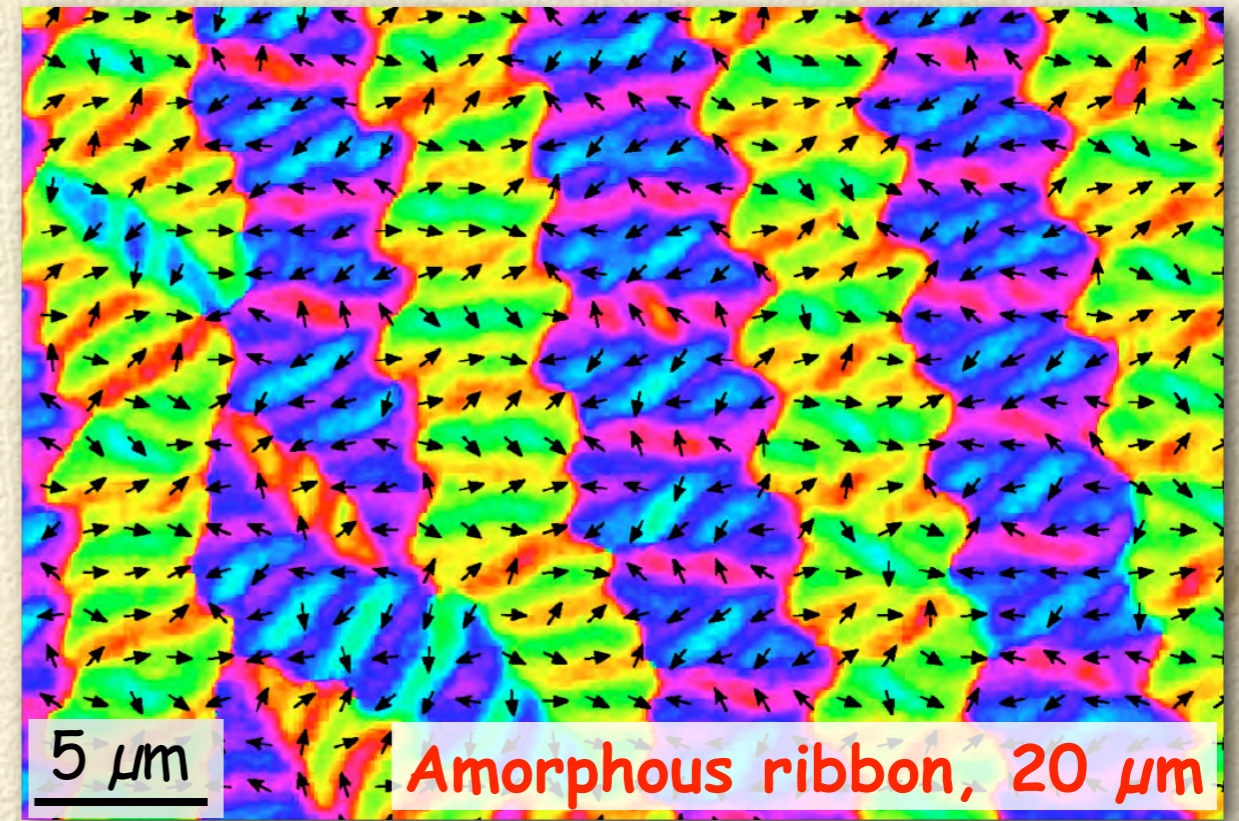
20 μm

General Classification of Domains

$$Q \gg 1$$

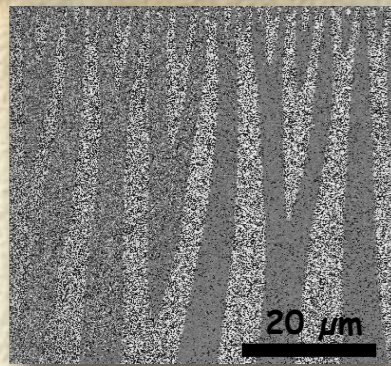
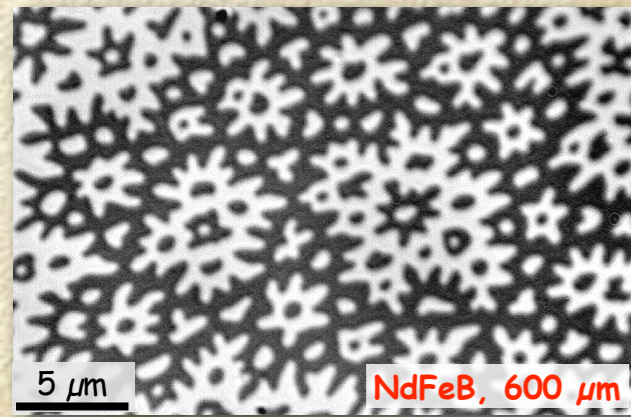


$$Q \ll 1$$

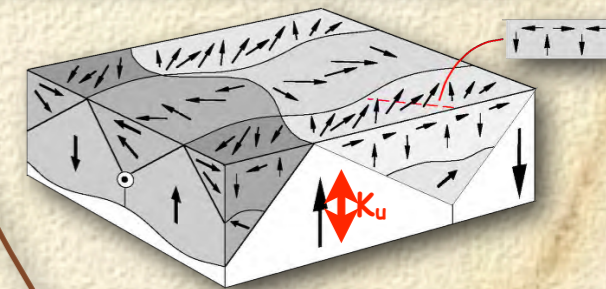
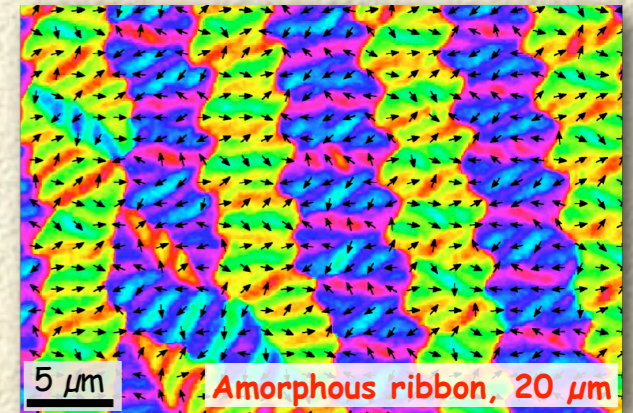


General Classification of Domains

$Q \gg 1$

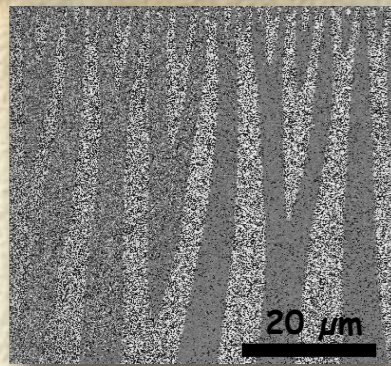
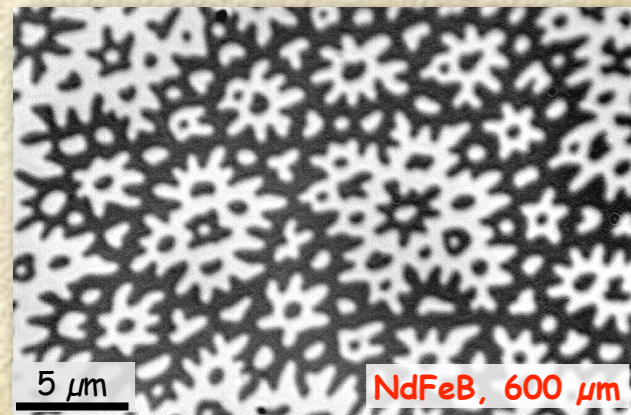


$Q \ll 1$



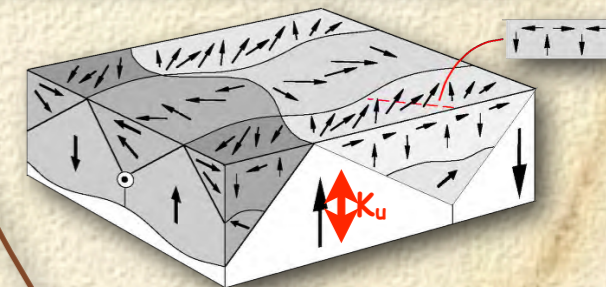
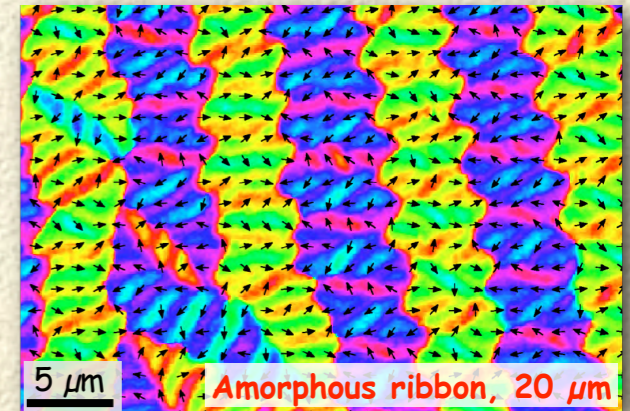
General Classification of Domains

$Q \gg 1$



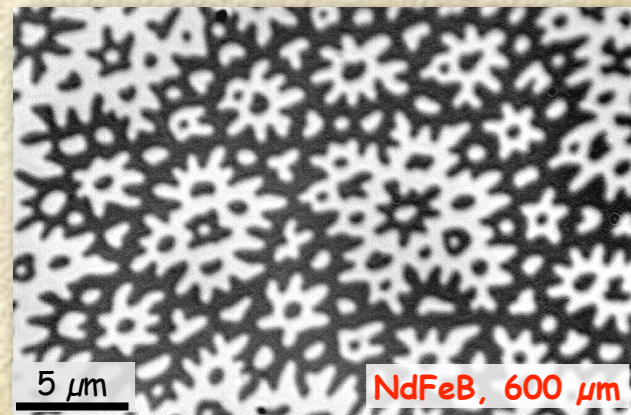
$Q \approx 1$

$Q \ll 1$

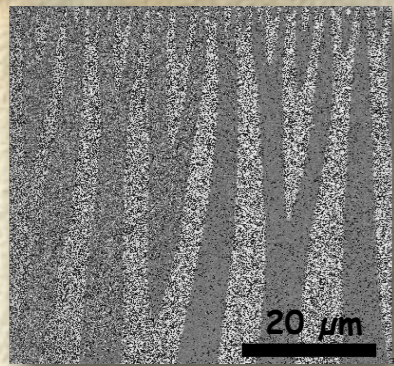


General Classification of Domains

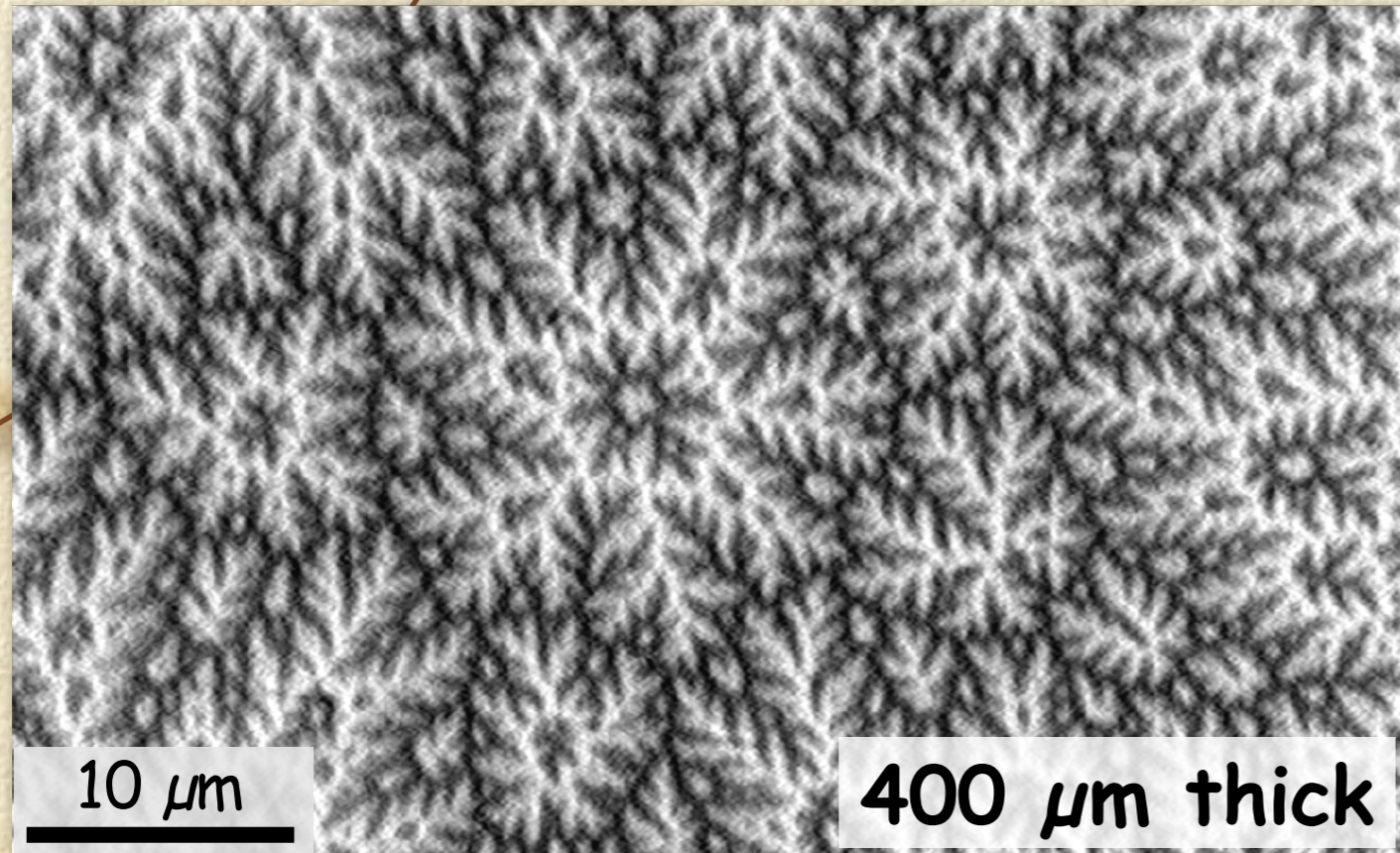
$Q \gg 1$



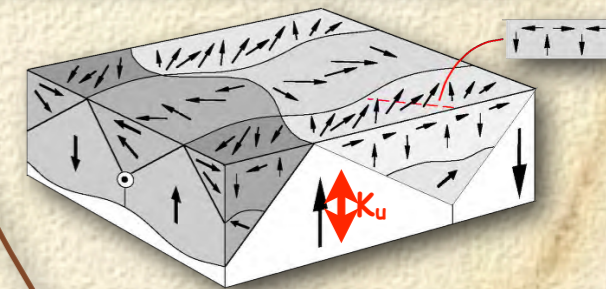
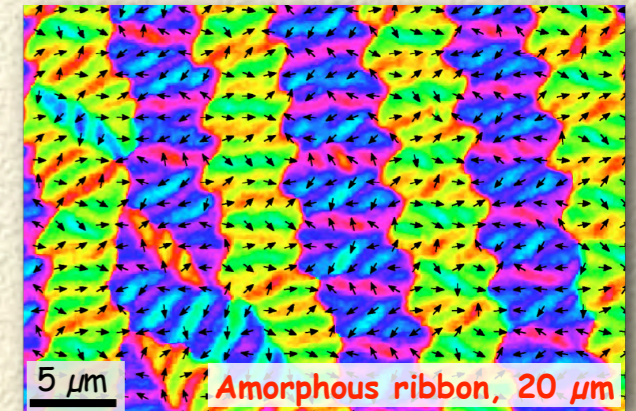
$Q \approx 1$



Cobalt: $Q = 0.4$

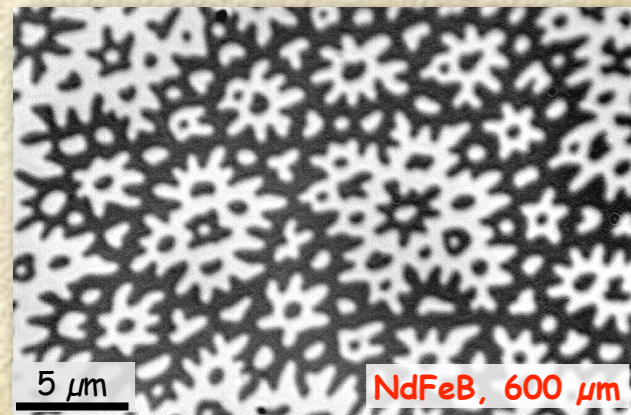


$Q \ll 1$

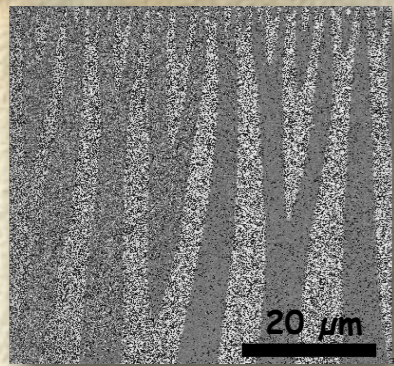


General Classification of Domains

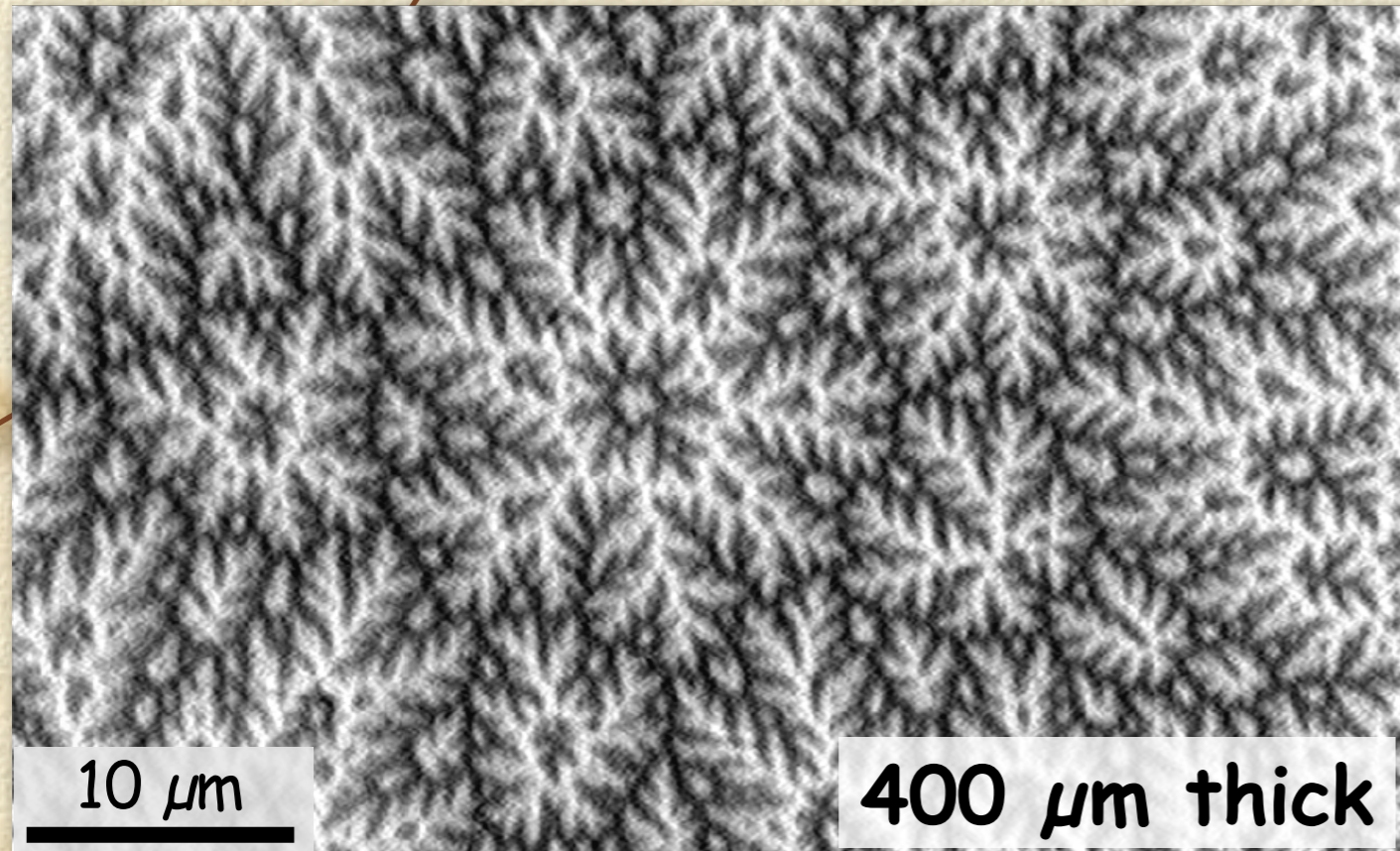
$Q \gg 1$



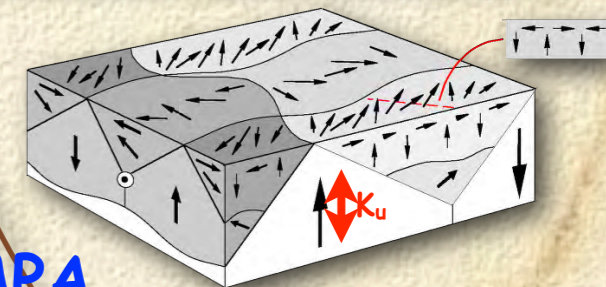
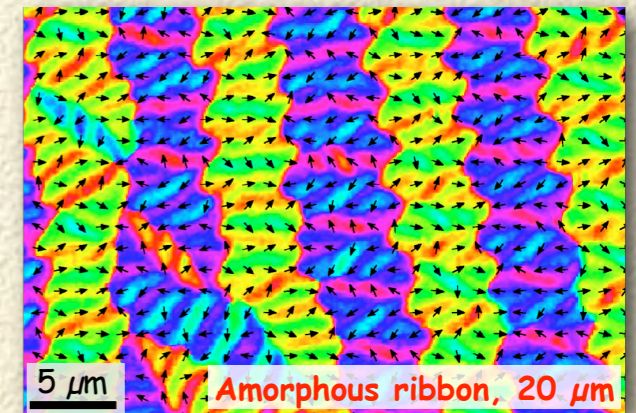
$Q \approx 1$



Cobalt: $Q = 0.4$

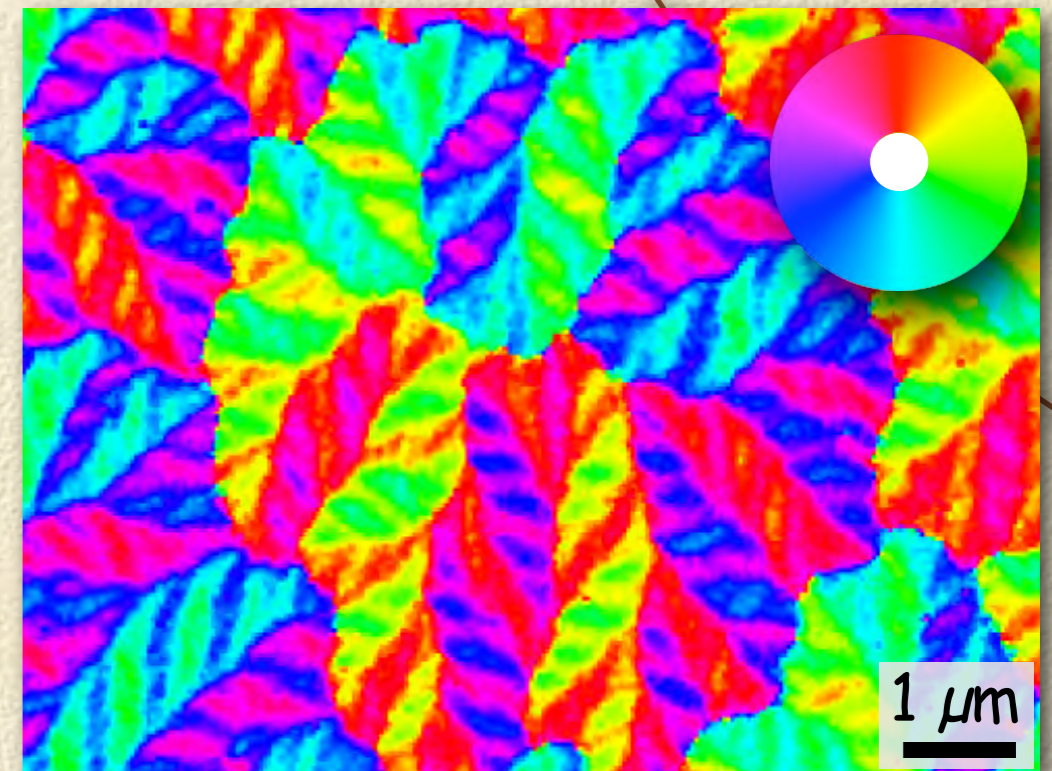


$Q \ll 1$



SEMPA

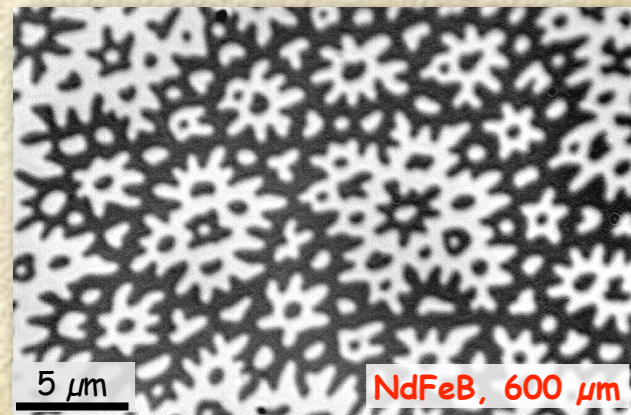
(courtesy John Unguris, NIST)



In-plane contrast at surface

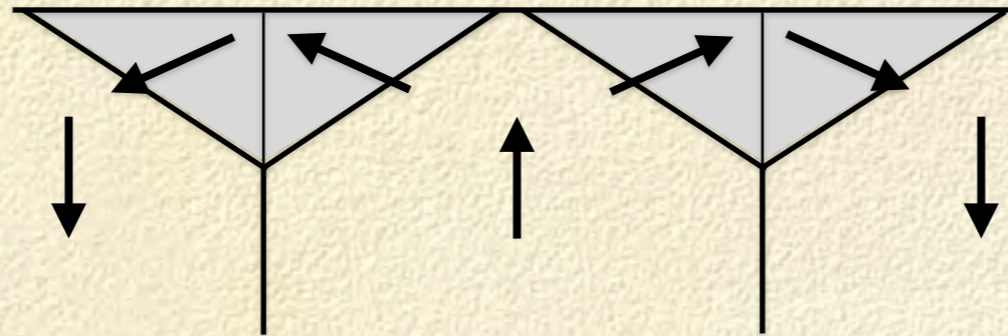
General Classification of Domains

$Q \gg 1$

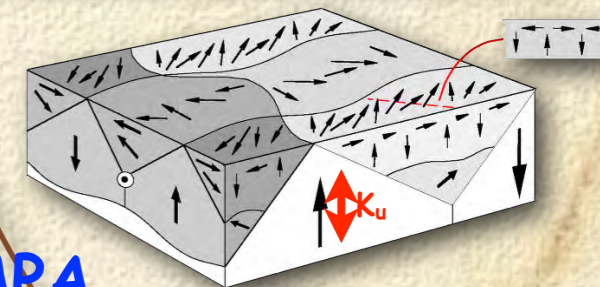
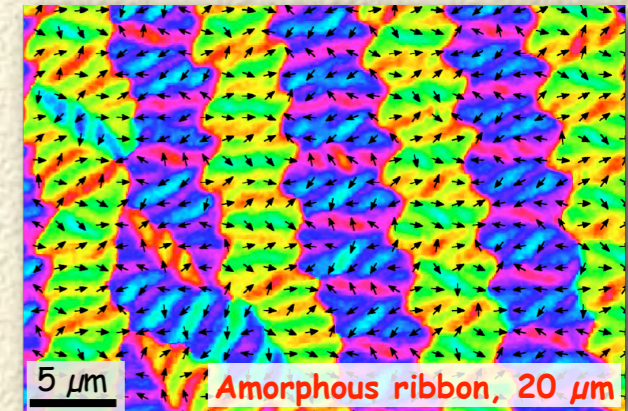


$Q \approx 1$

Partial closure

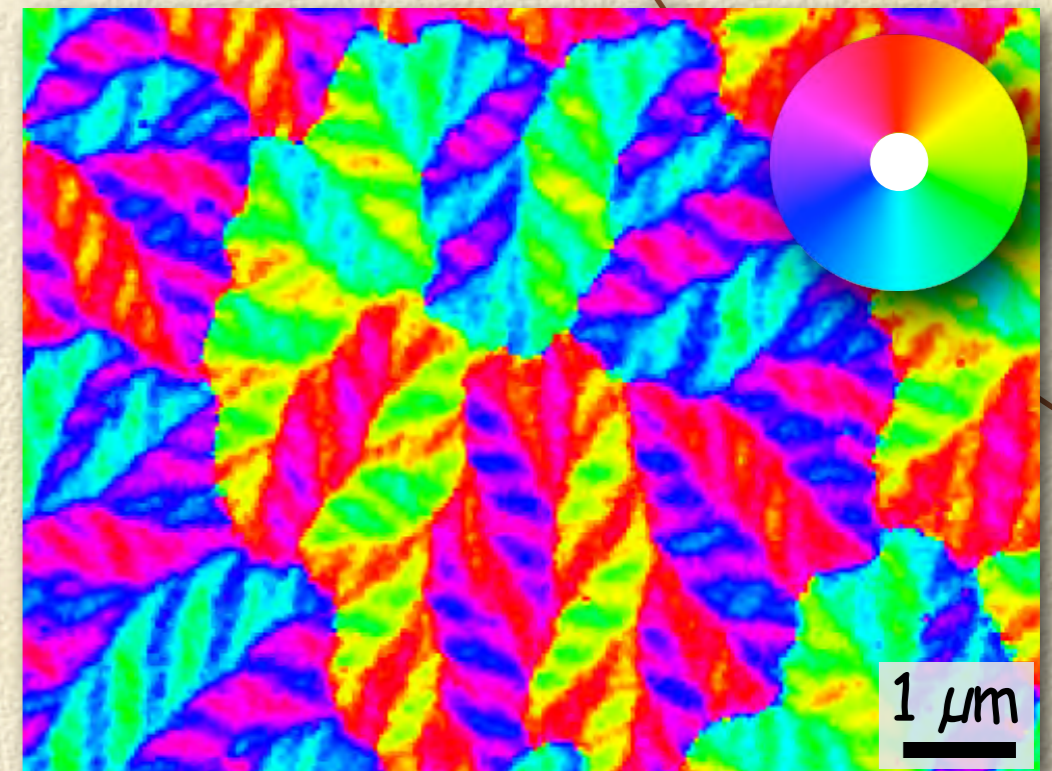
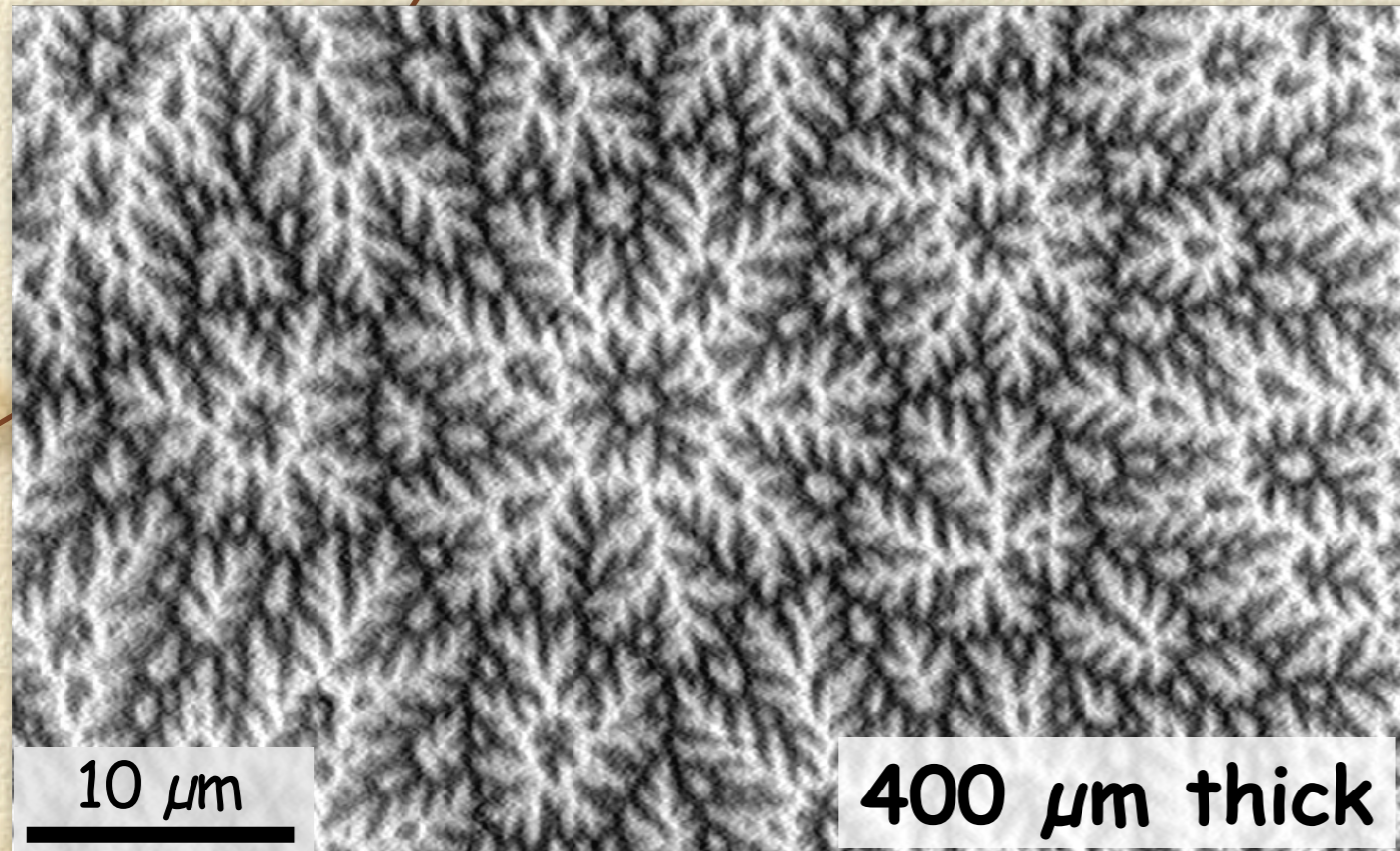
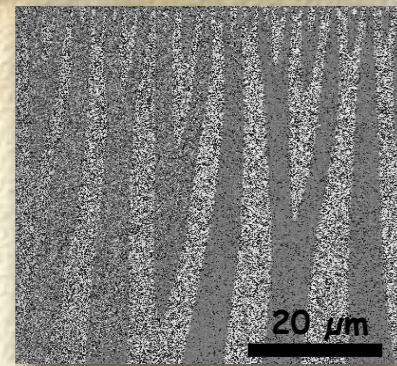


$Q \ll 1$



Cobalt: $Q = 0.4$

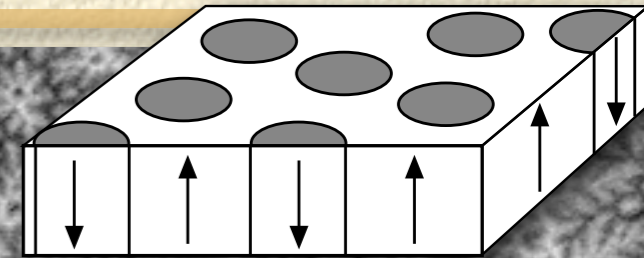
SEMPA
(courtesy John Unguris, NIST)



In-plane contrast at surface

Bulk garnet crystal

Bubble domains



50 μm

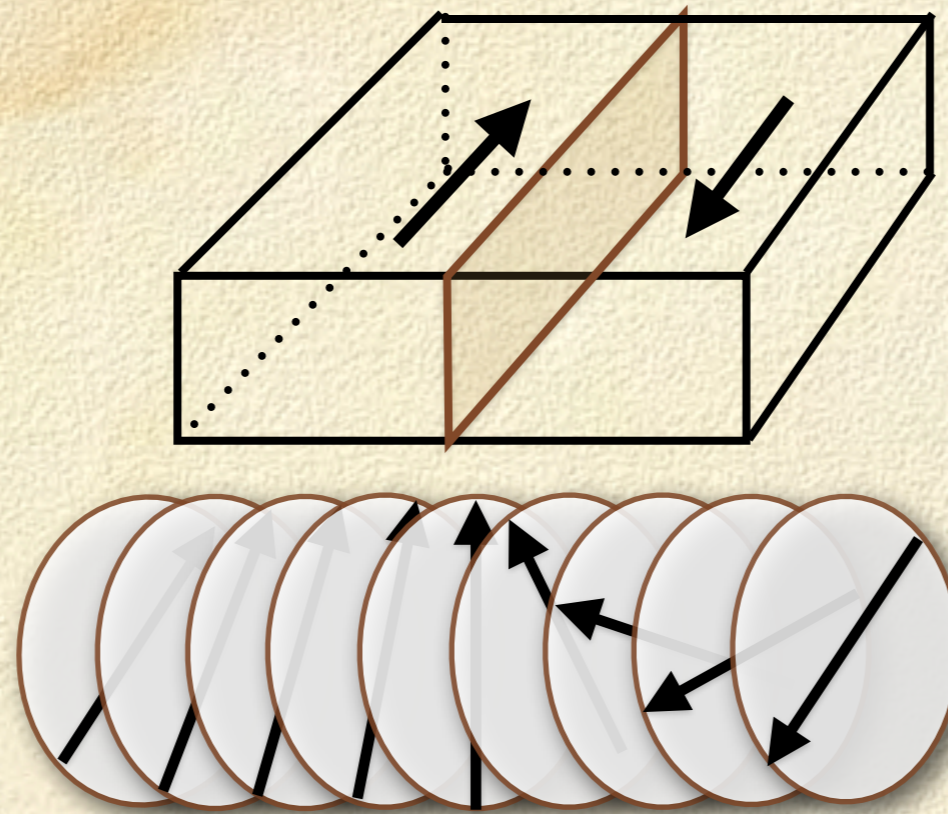
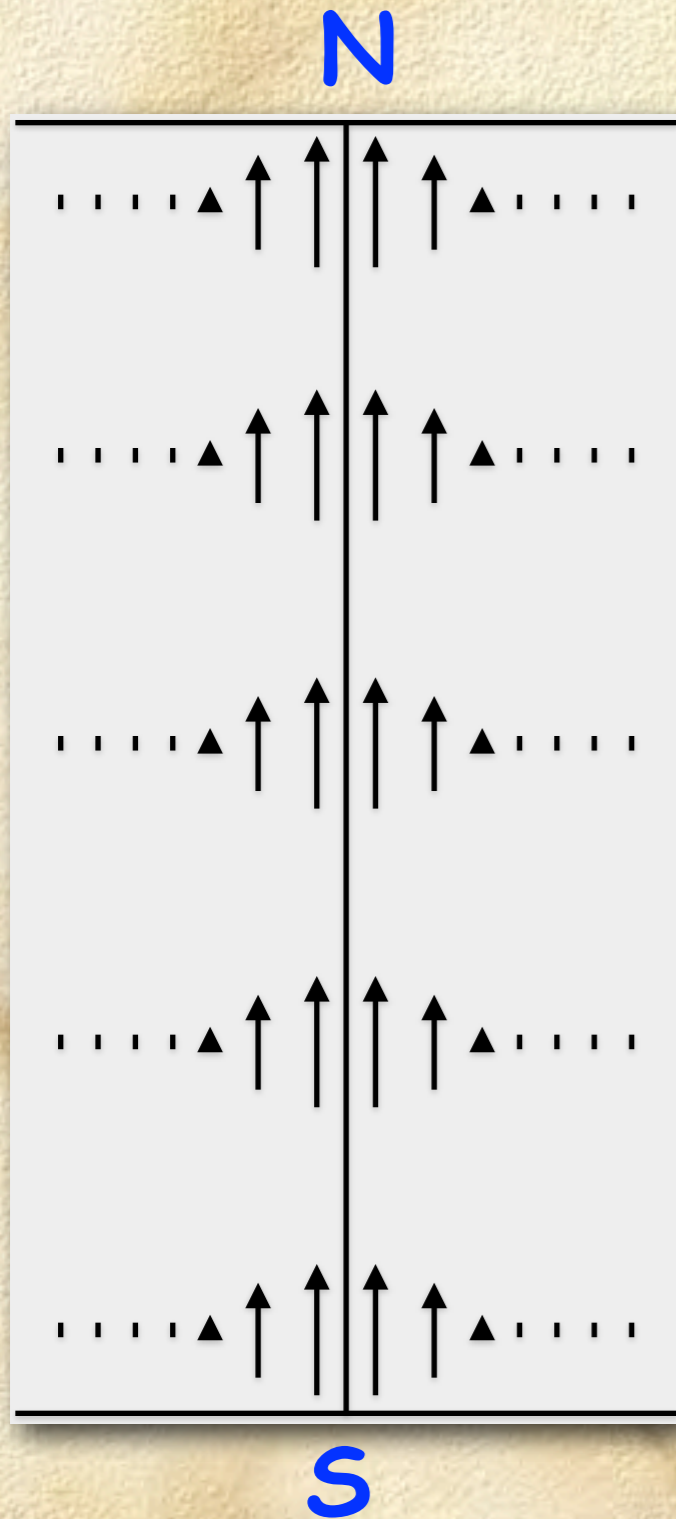
GdYbBi garnet, 500 μm thick

Image: A. Stupaviewicz, M. Tekielak, A. Maziewski (Bialystok)

Sample: T. Satoh (Tokyo)

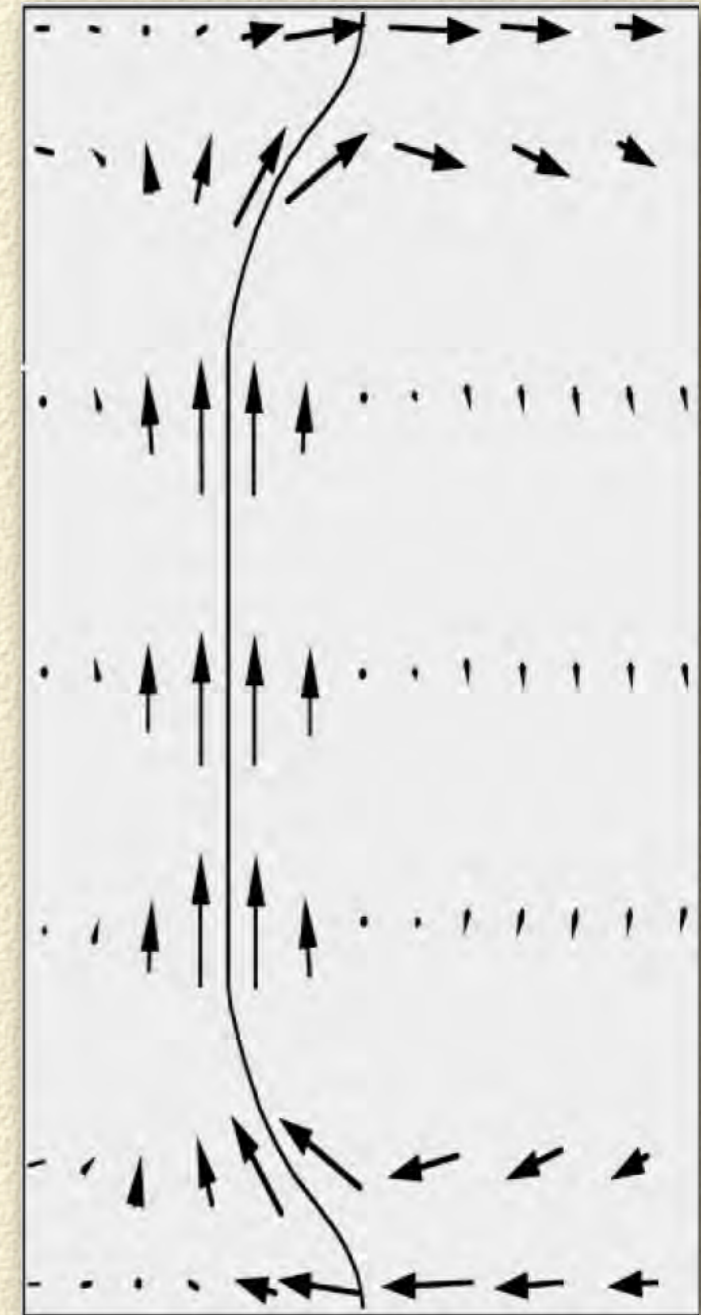
General Classification of Domains

$Q \gg 1$



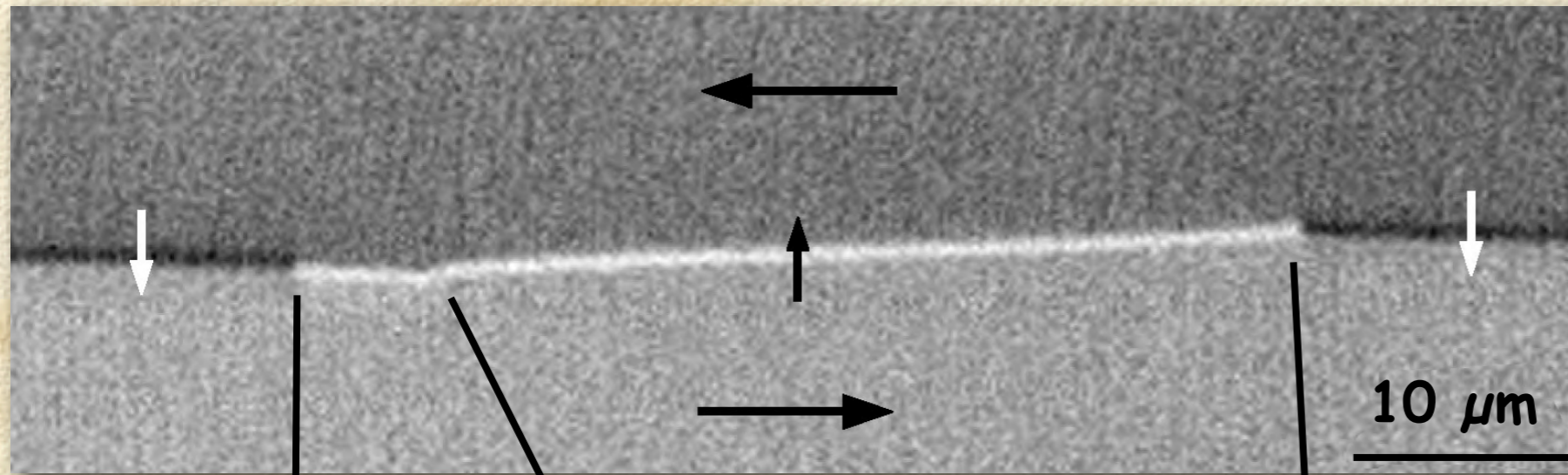
$Q \ll 1$

Pole-free



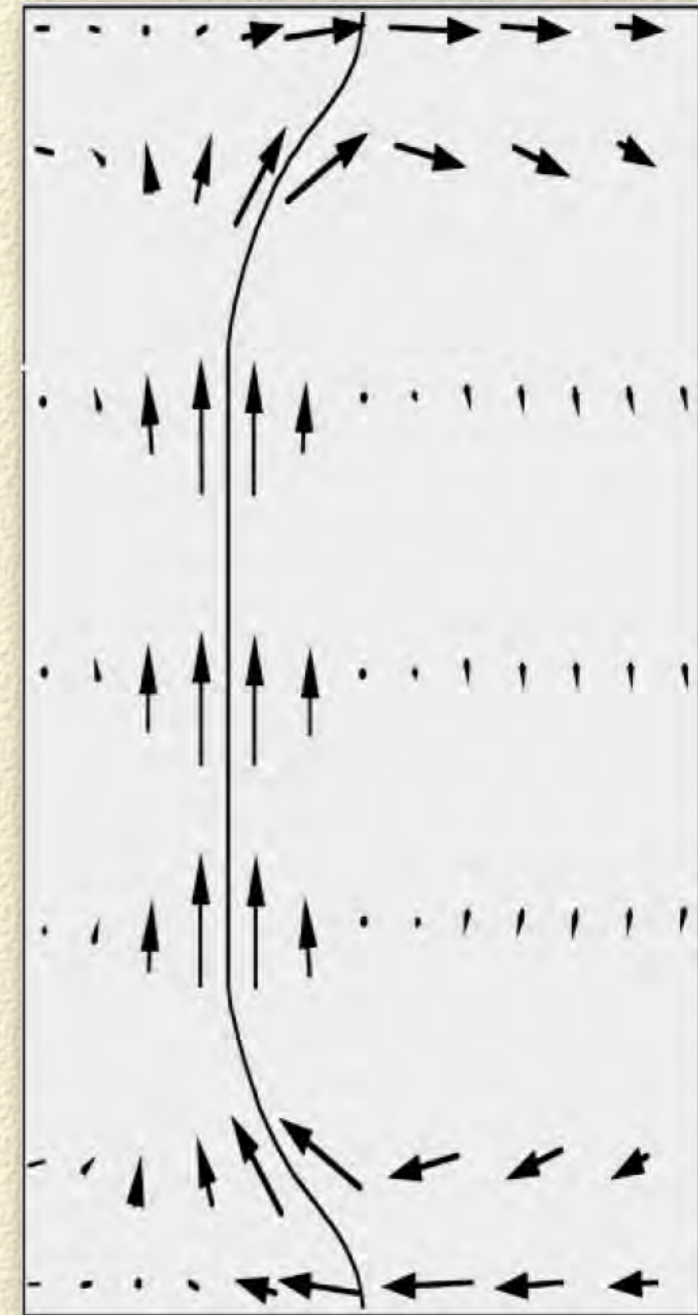
General Classification of Domains

Kerr observation on Fe whisker



$Q \ll 1$

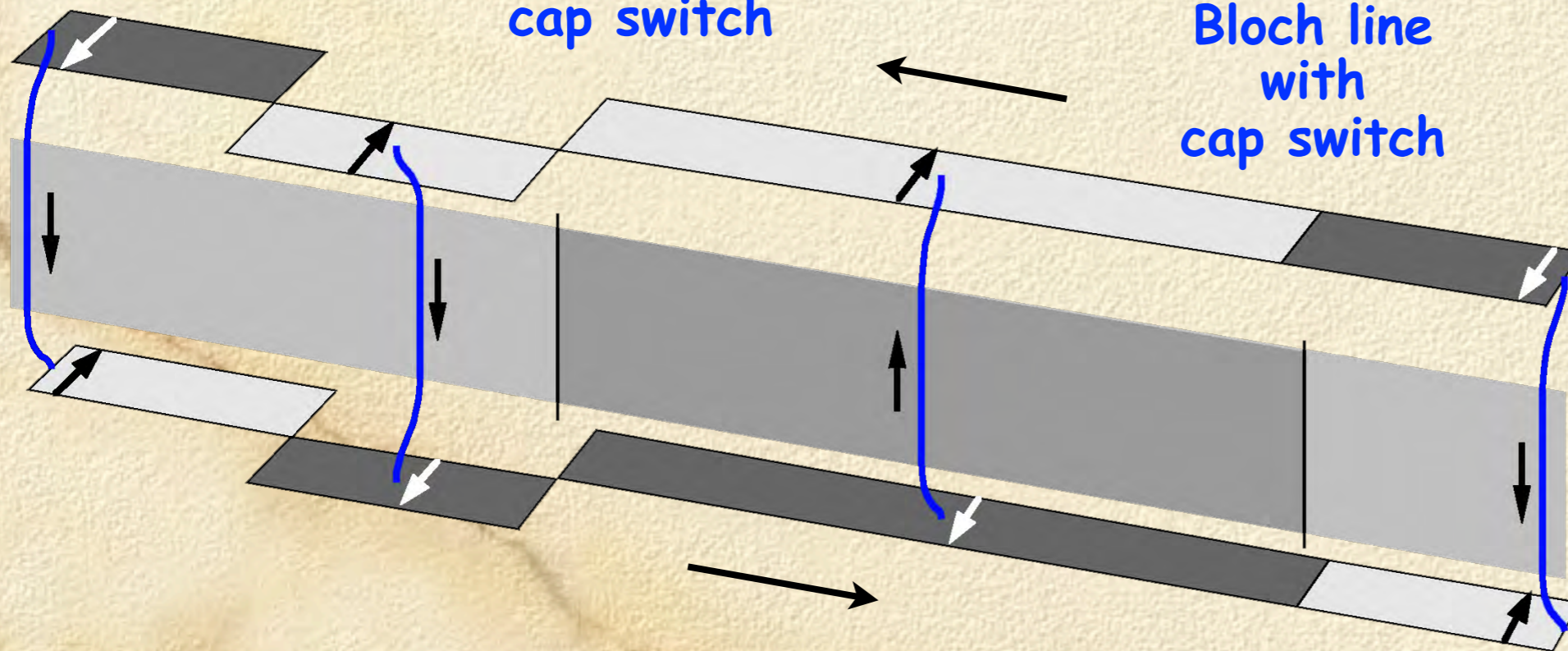
Pole-free



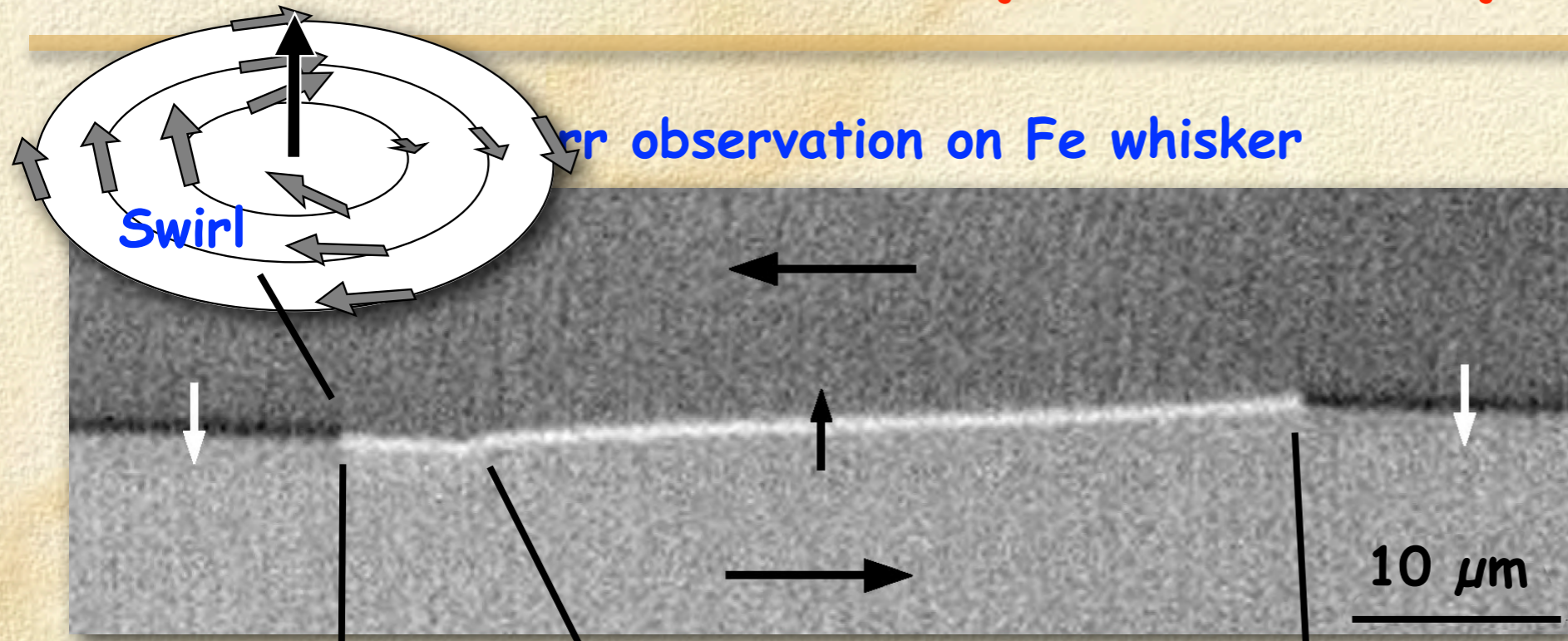
cap switch

Bloch line without cap switch

Bloch line with cap switch

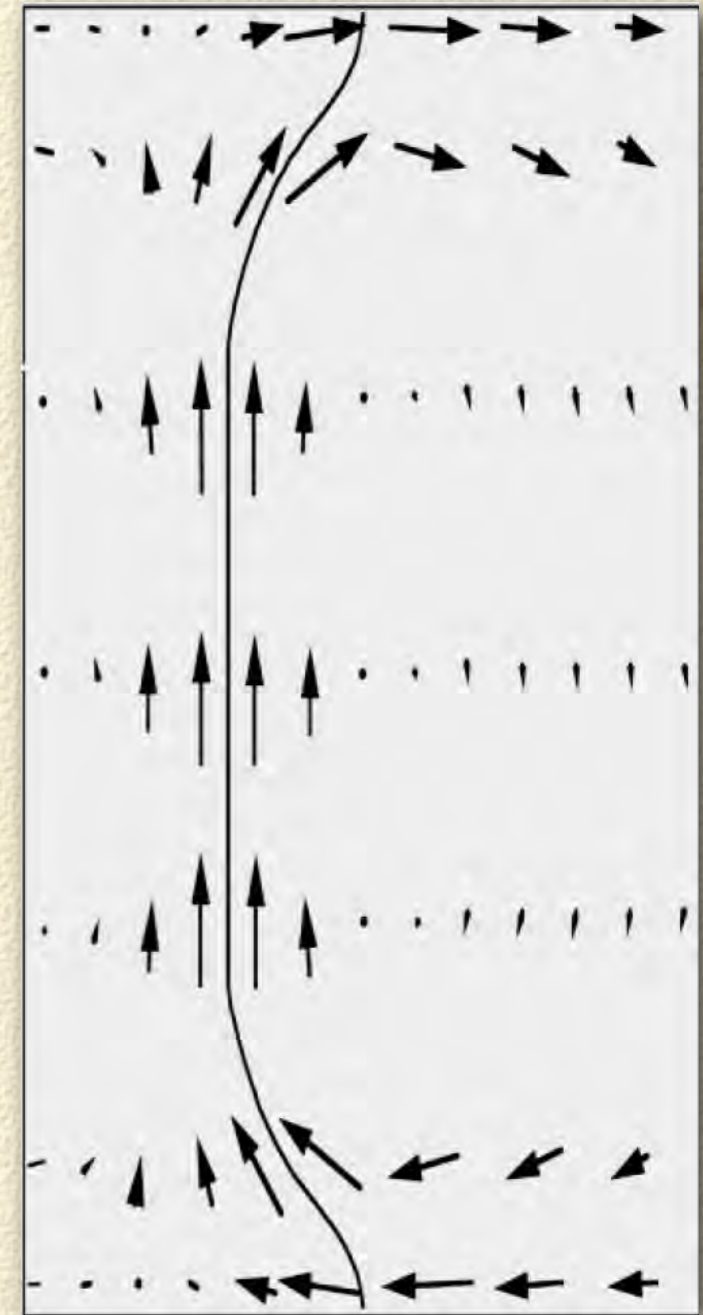
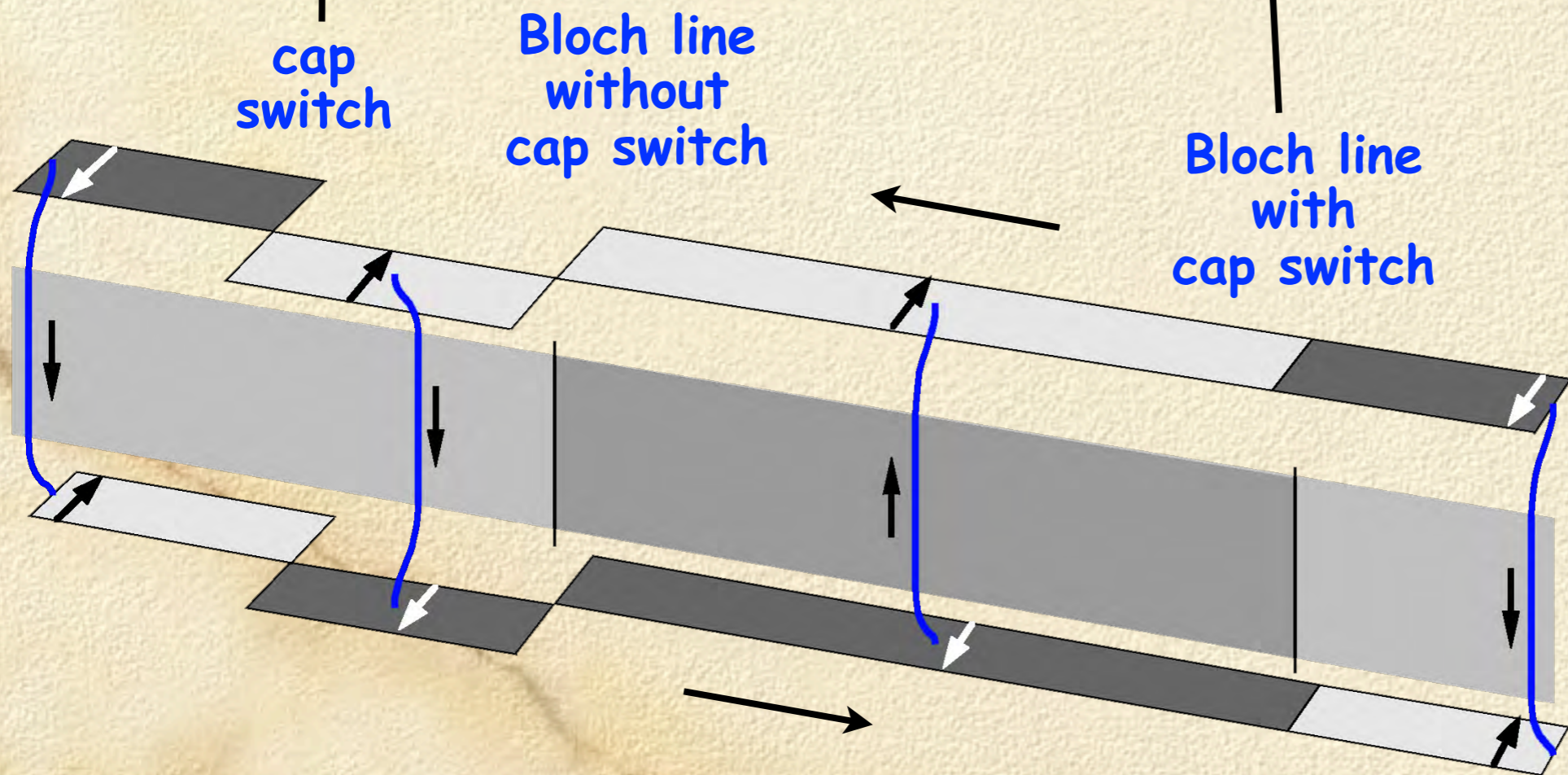


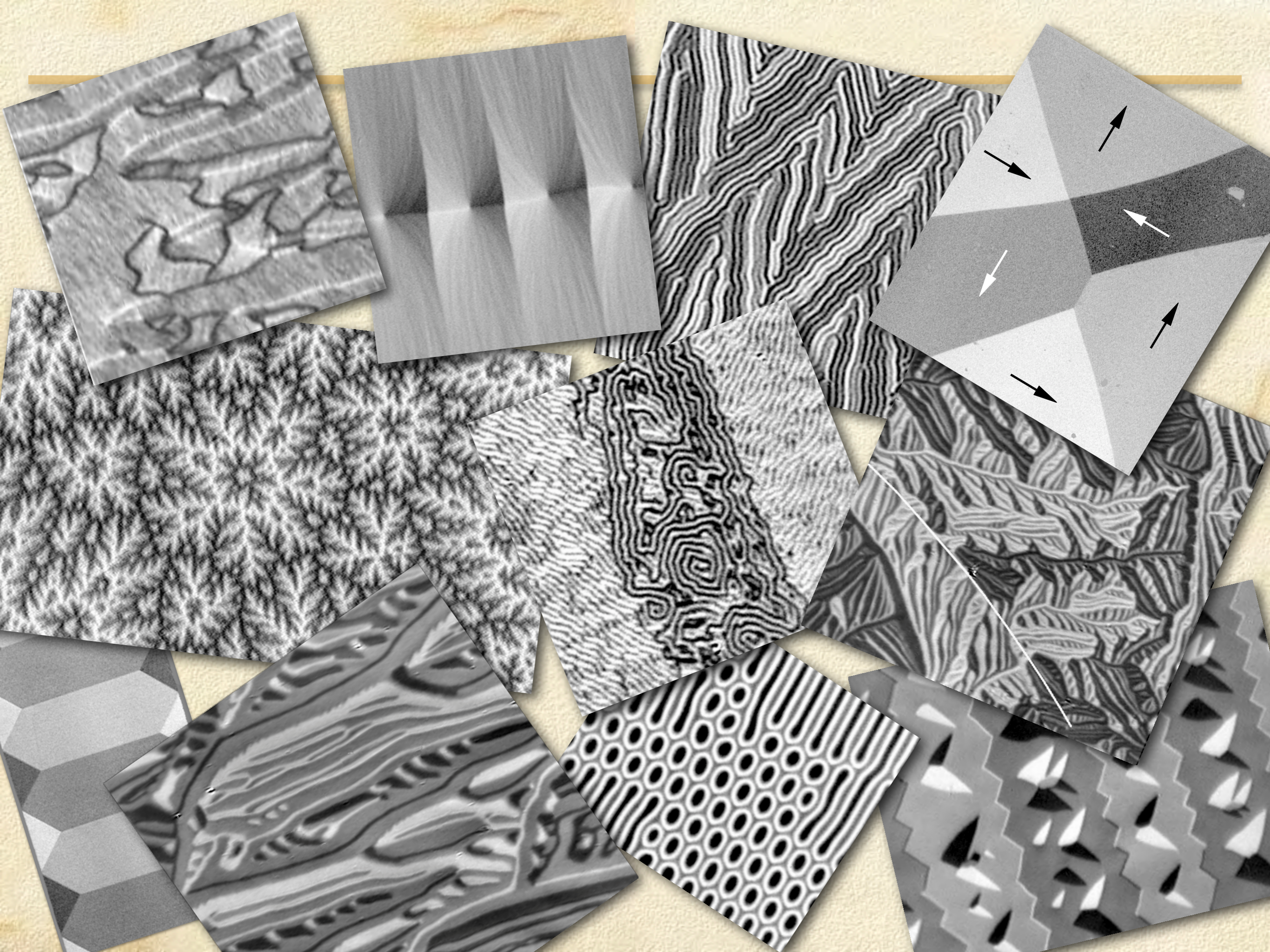
General Classification of Domains

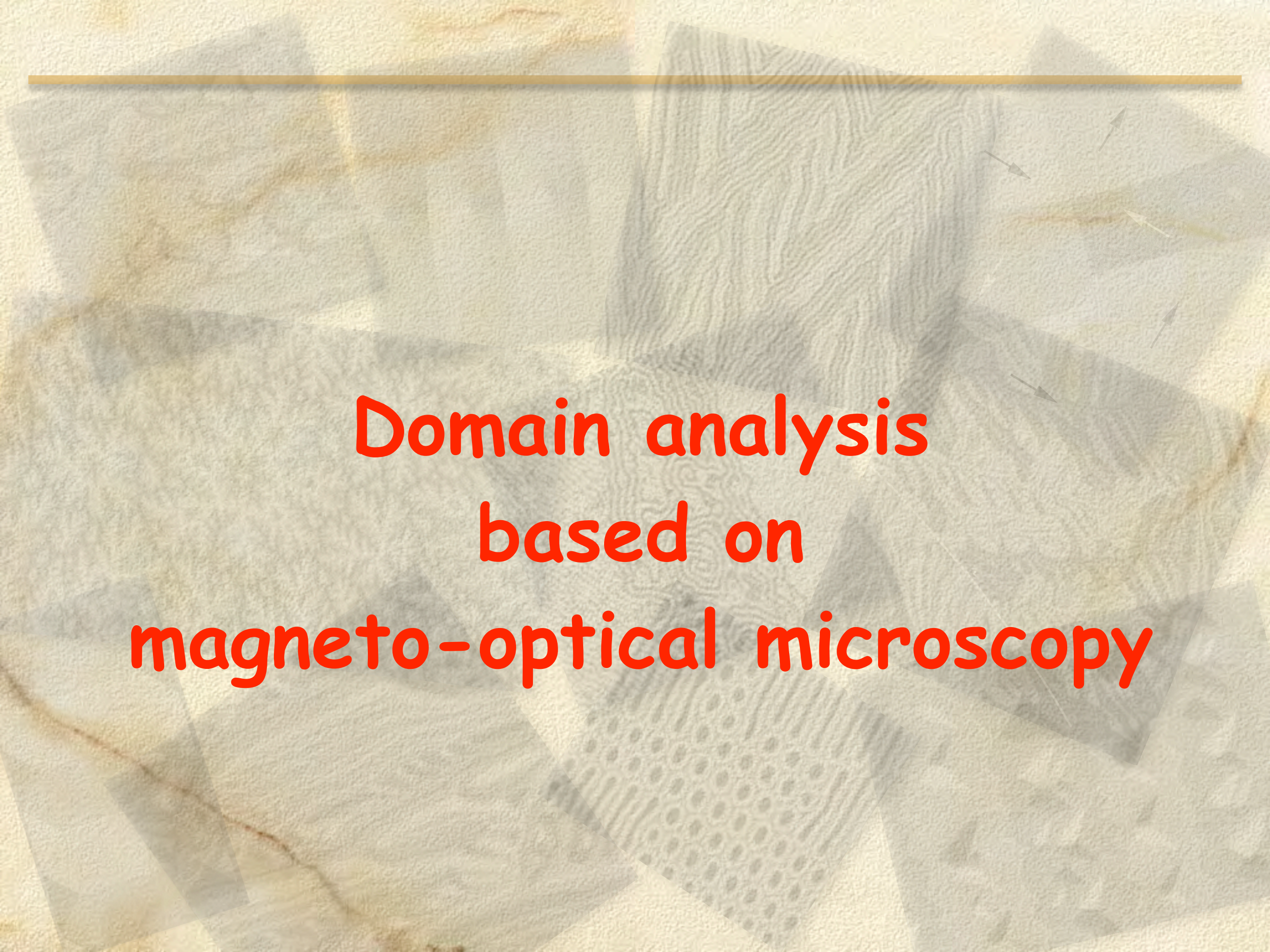


$$Q \ll 1$$

Pole-free

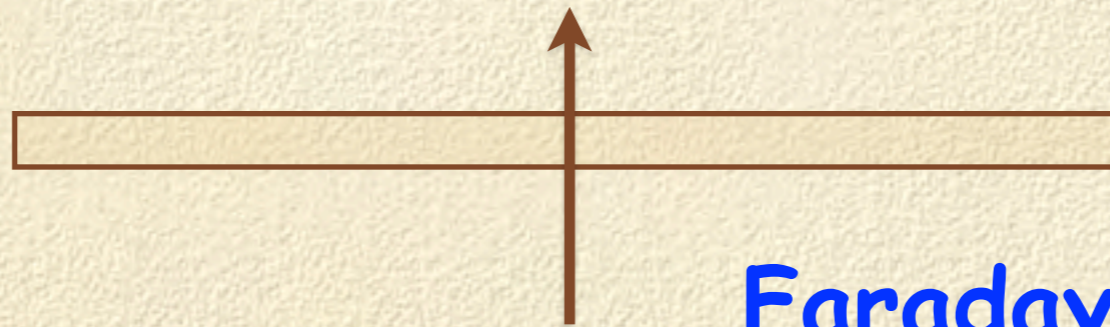






**Domain analysis
based on
magneto-optical microscopy**

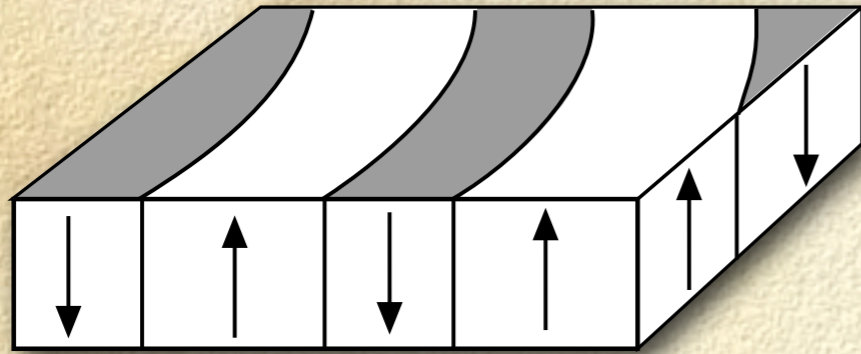
**Transparent films:
Domain analysis easily possible**



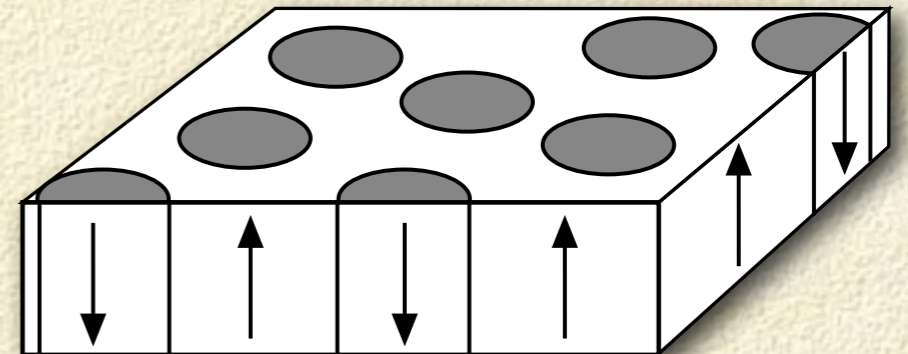
**Faraday
microscopy**

Bubble garnet film

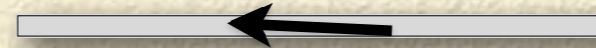
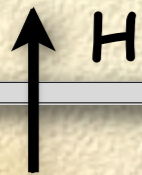
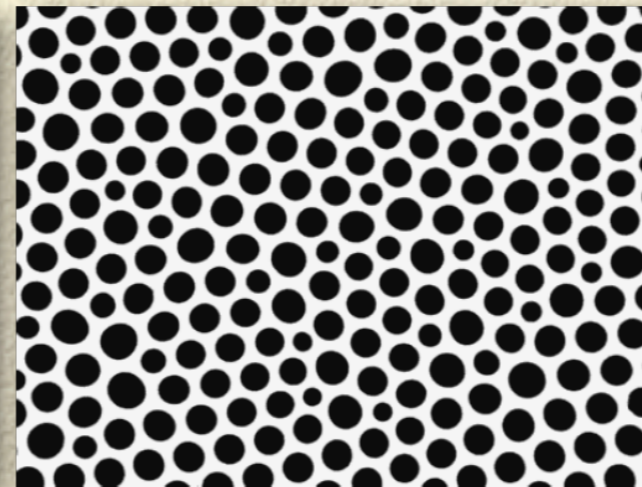
Band domains



Bubble domains



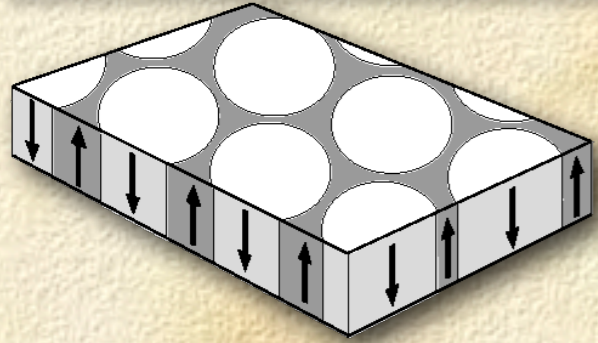
20 μm



Magnetic history

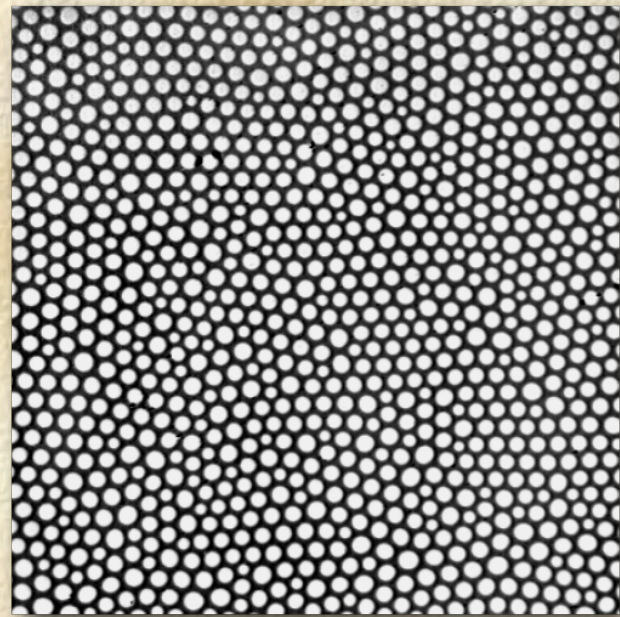
Magnetic field history matters

Bubble garnet film

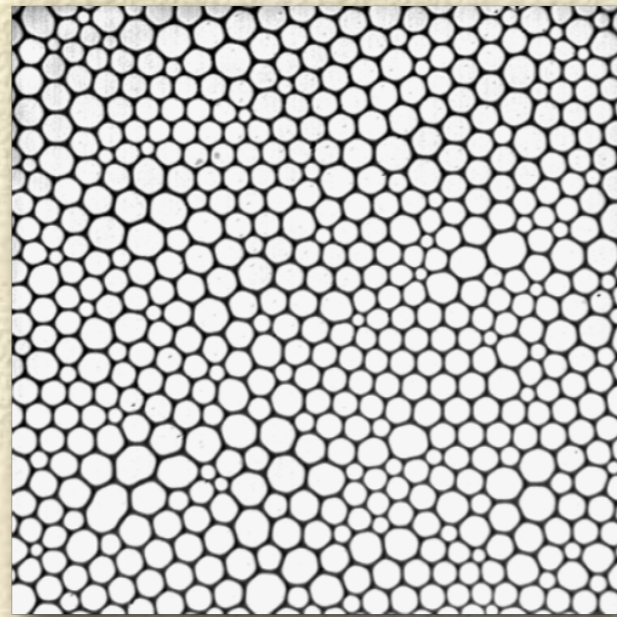


Configurational hysteresis

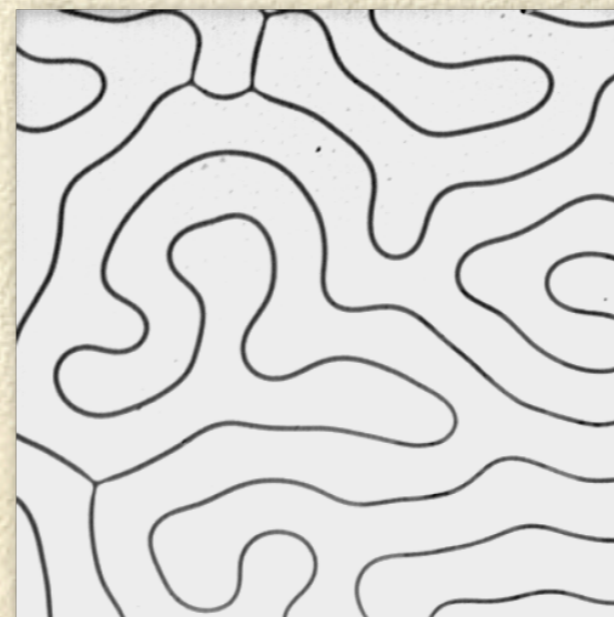
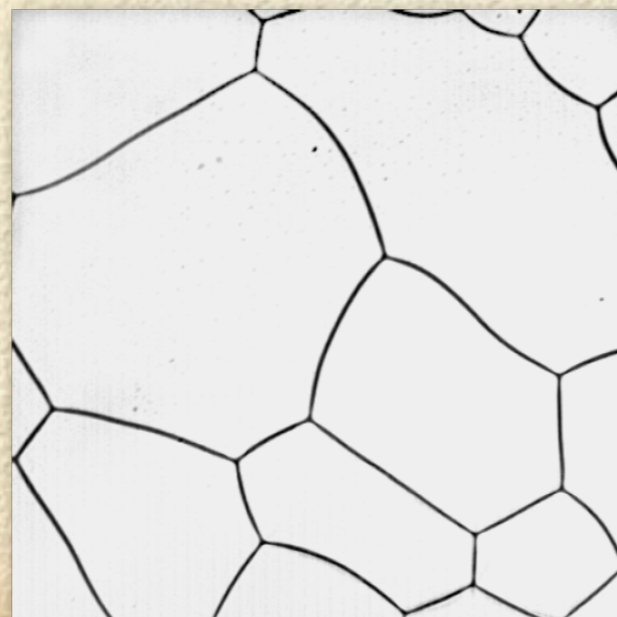
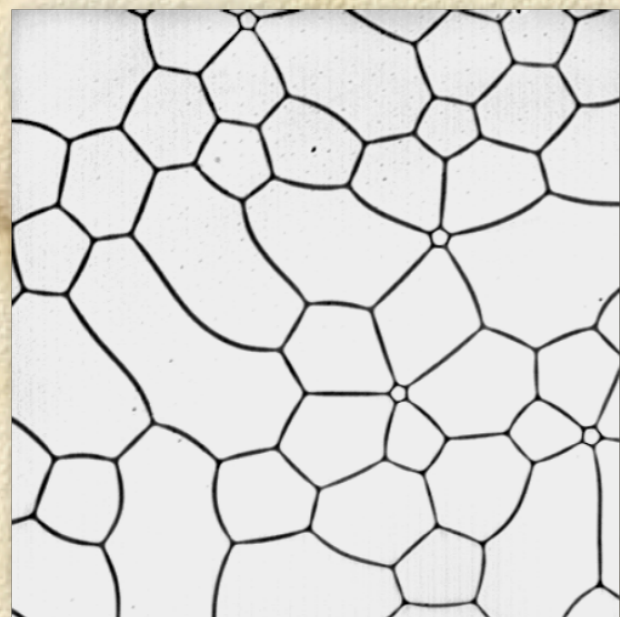
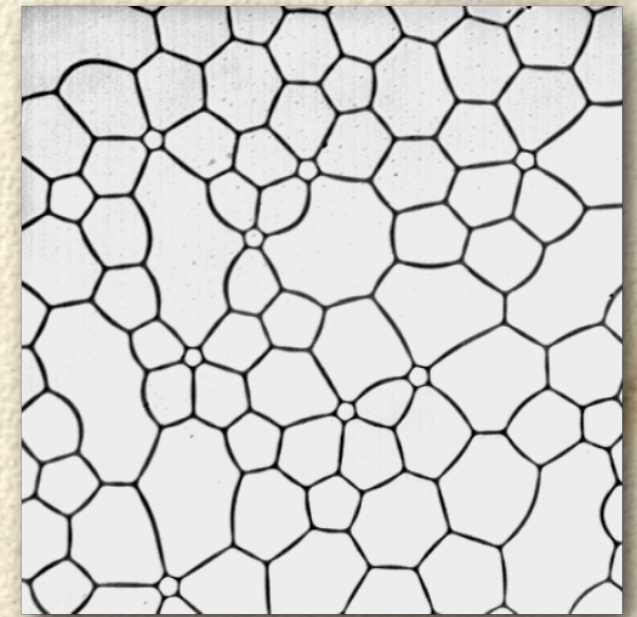
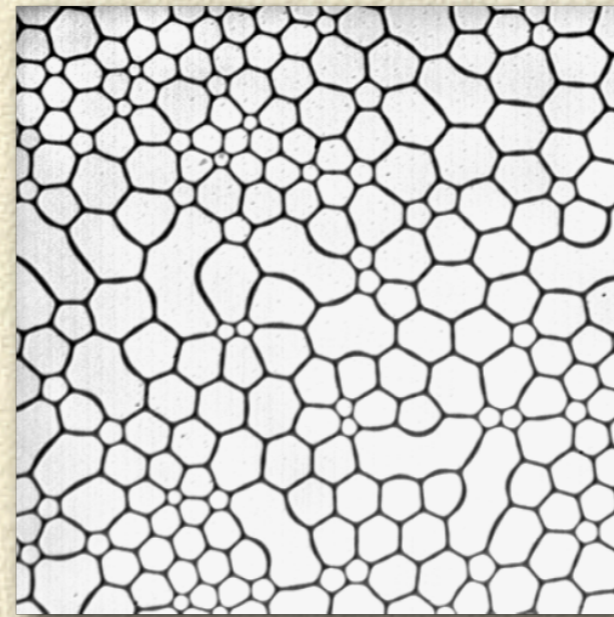
50 μm



zero field



increasing field \odot



decreasing field

zero field

Metallic (single) films:

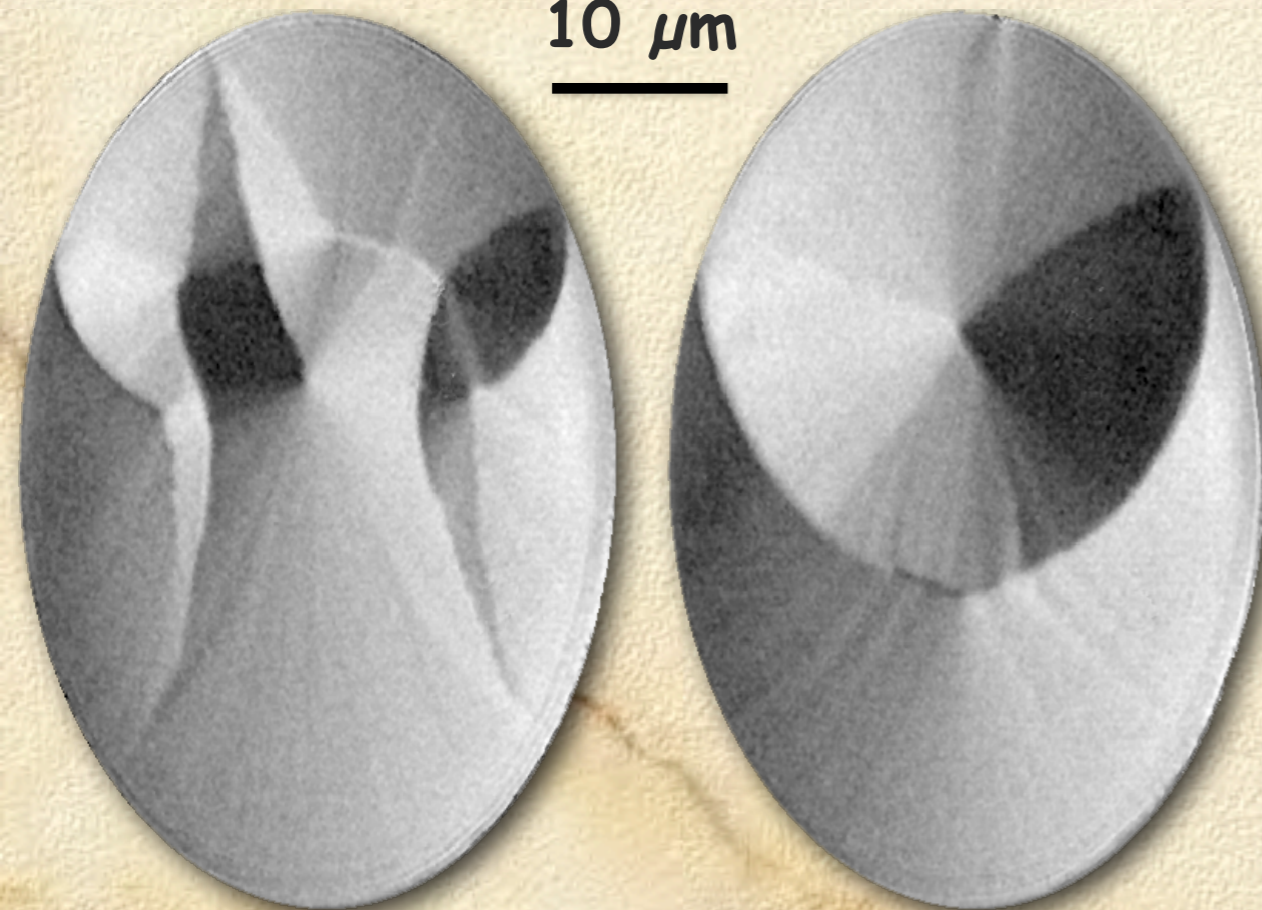
Domain analysis often easily possible ...

Metallic (single) films:

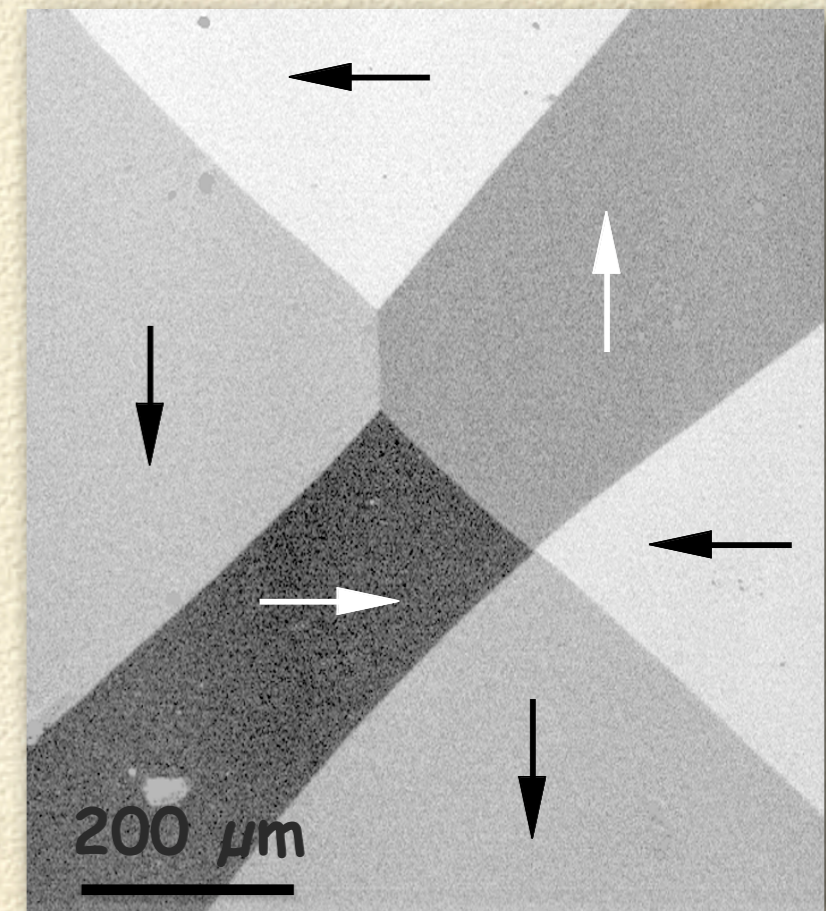
Domain analysis often easily possible ...

Permalloy film, 240 nm thick

10 μm



Epitaxial (100)-iron film,
40 nm thick



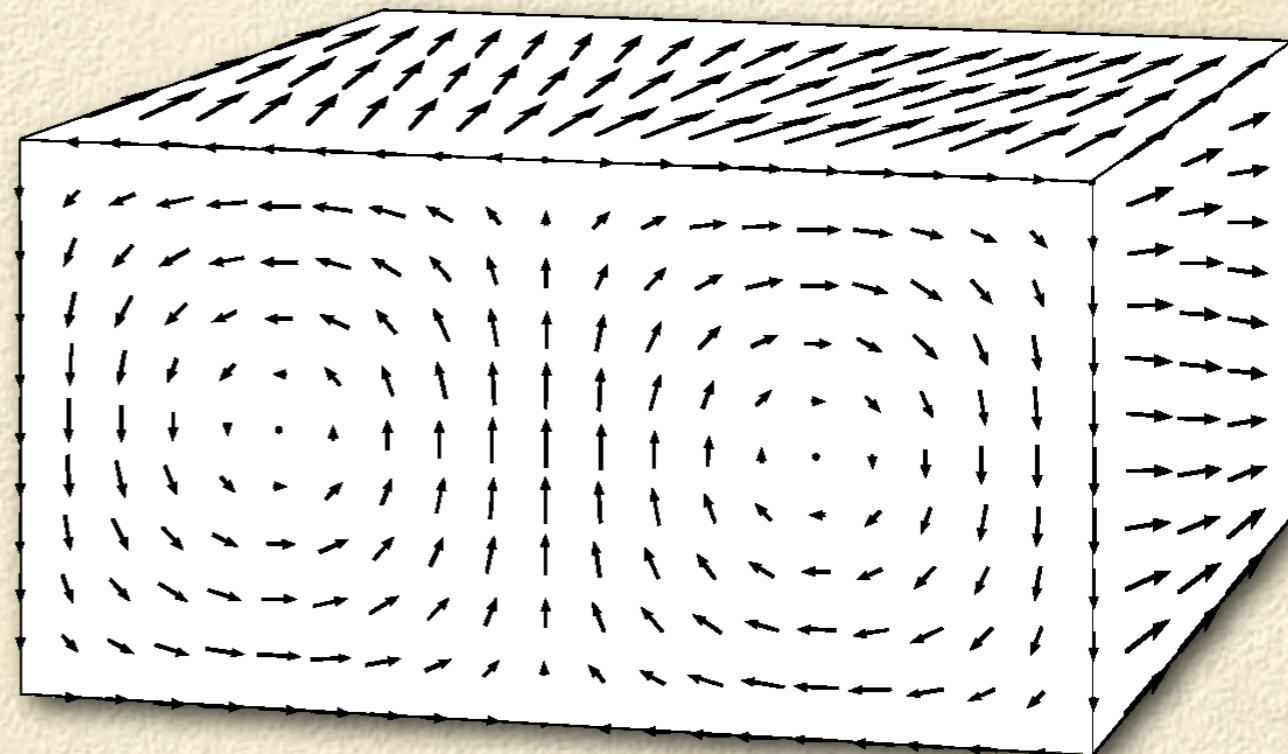
Metallic (single) films:

... sometimes combination with some micromagnetic theory may be required

Amorphous FeSiBCuNb film, 2 μm thick



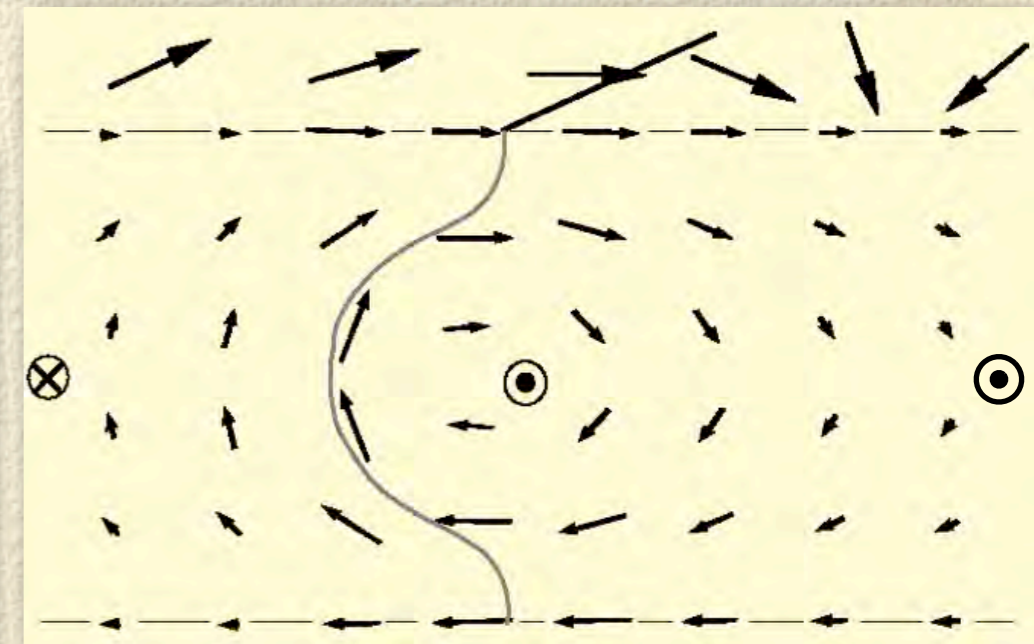
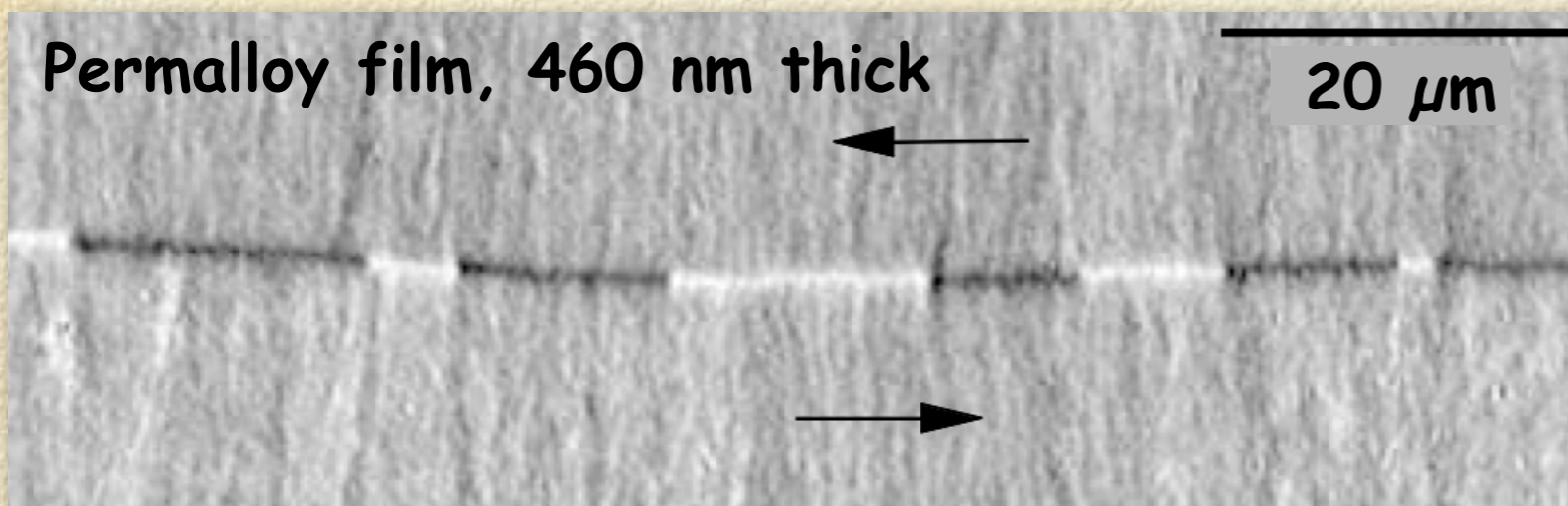
Stripe domains



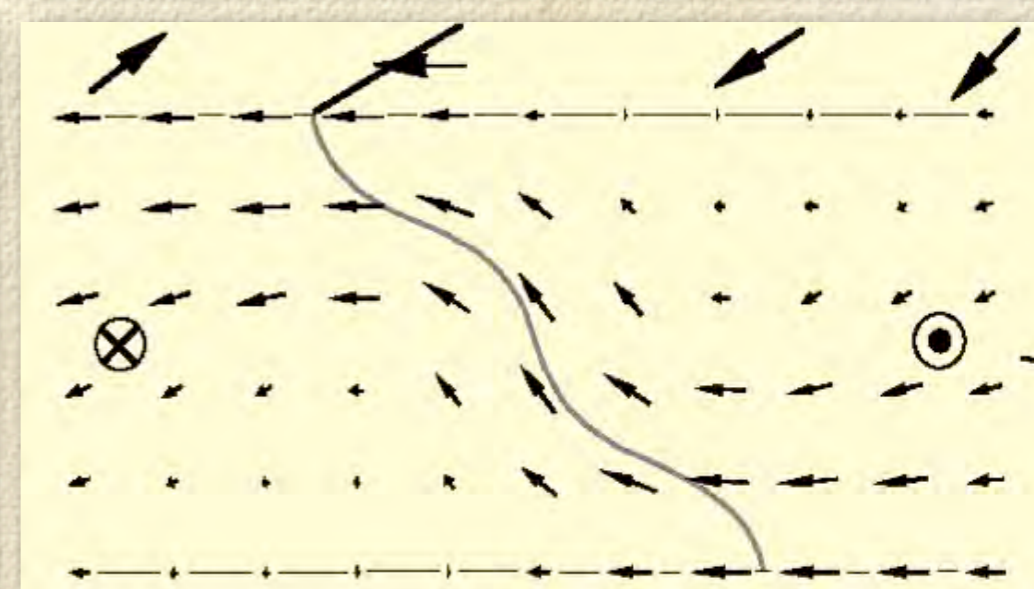
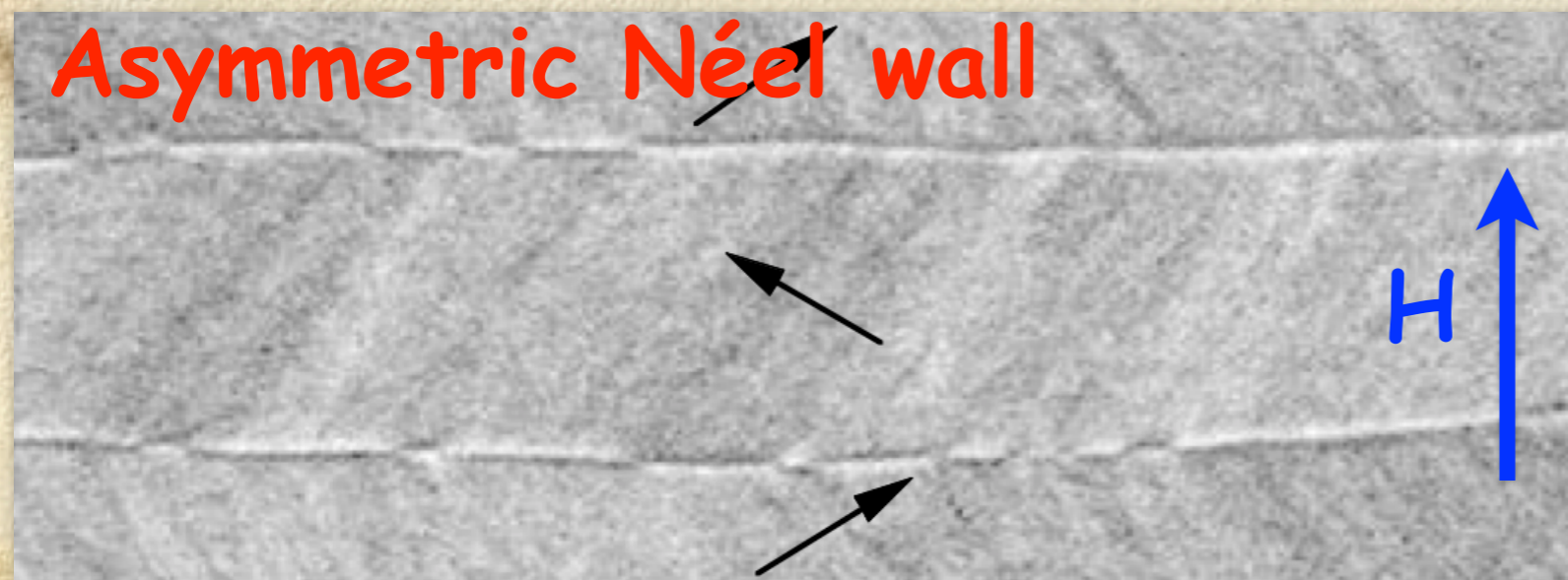
Metallic (single) films:

... sometimes combination with some micromagnetic theory may be required

Asymmetric Bloch wall



Asymmetric Néel wall



**Multilayer films:
Domain analysis more challenging**

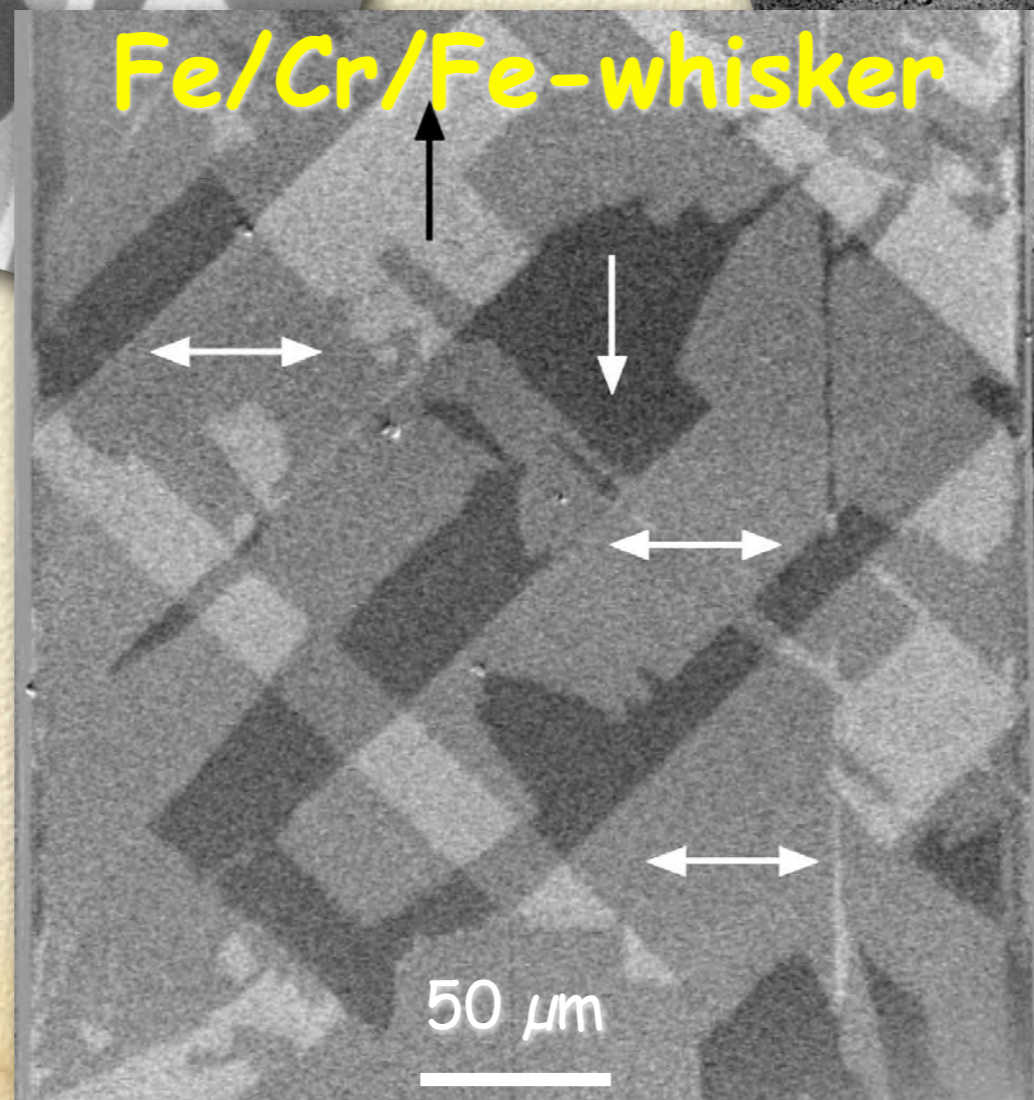
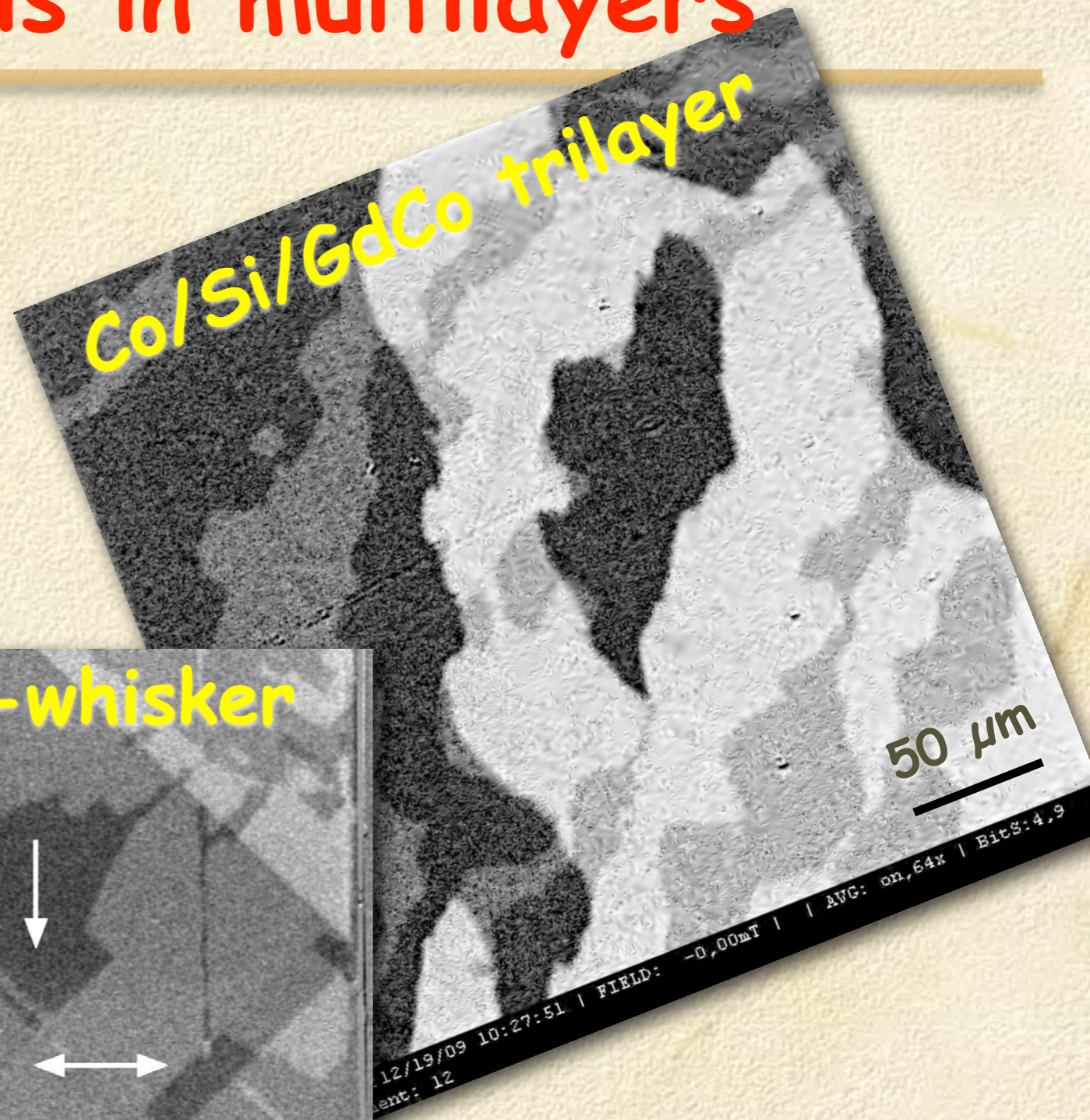
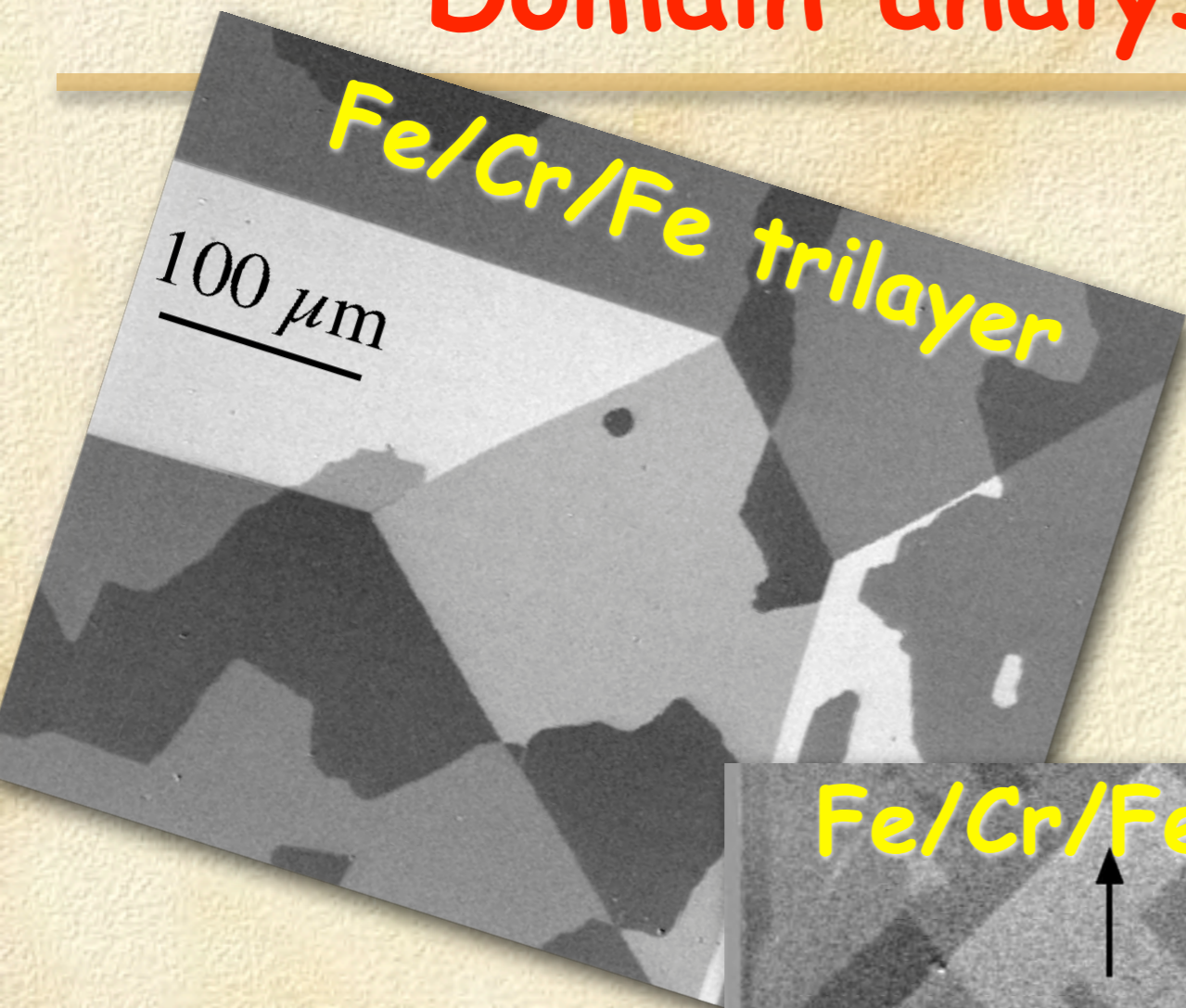
Domain analysis in multilayers

CoPt multilayer (7 nm thick),
courtesy Tom Moore and Alex Bellew, Leeds



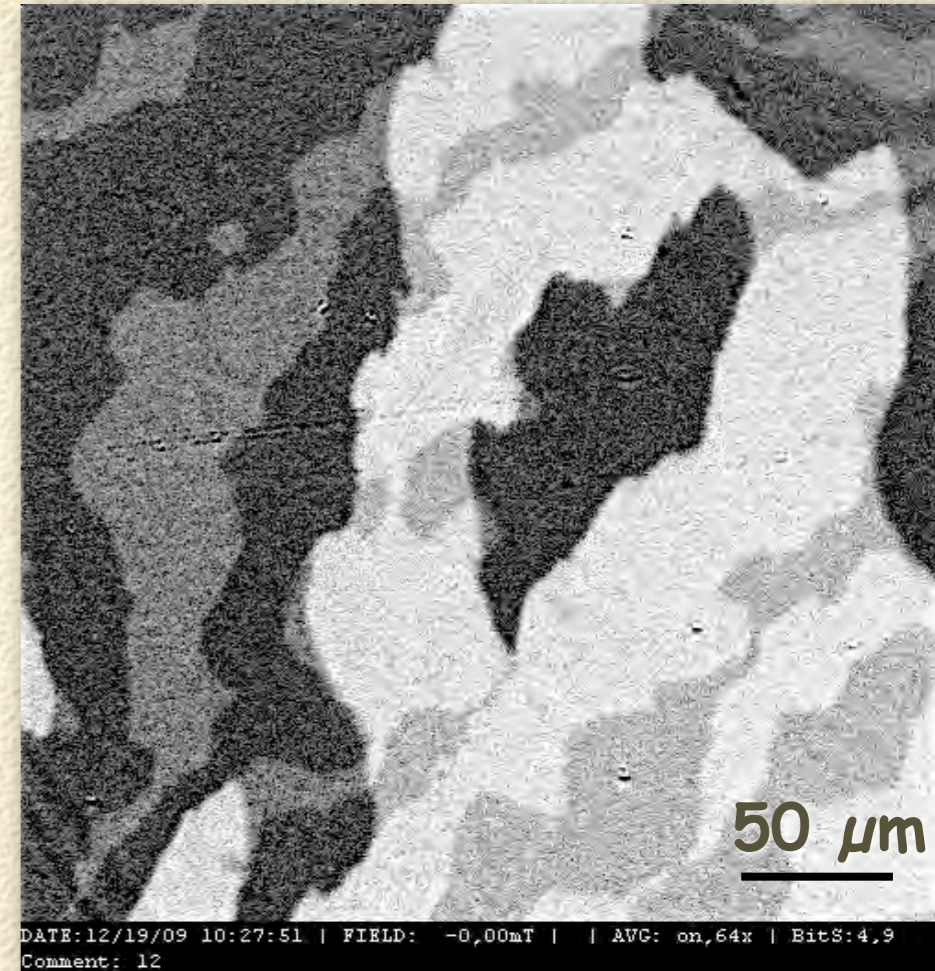
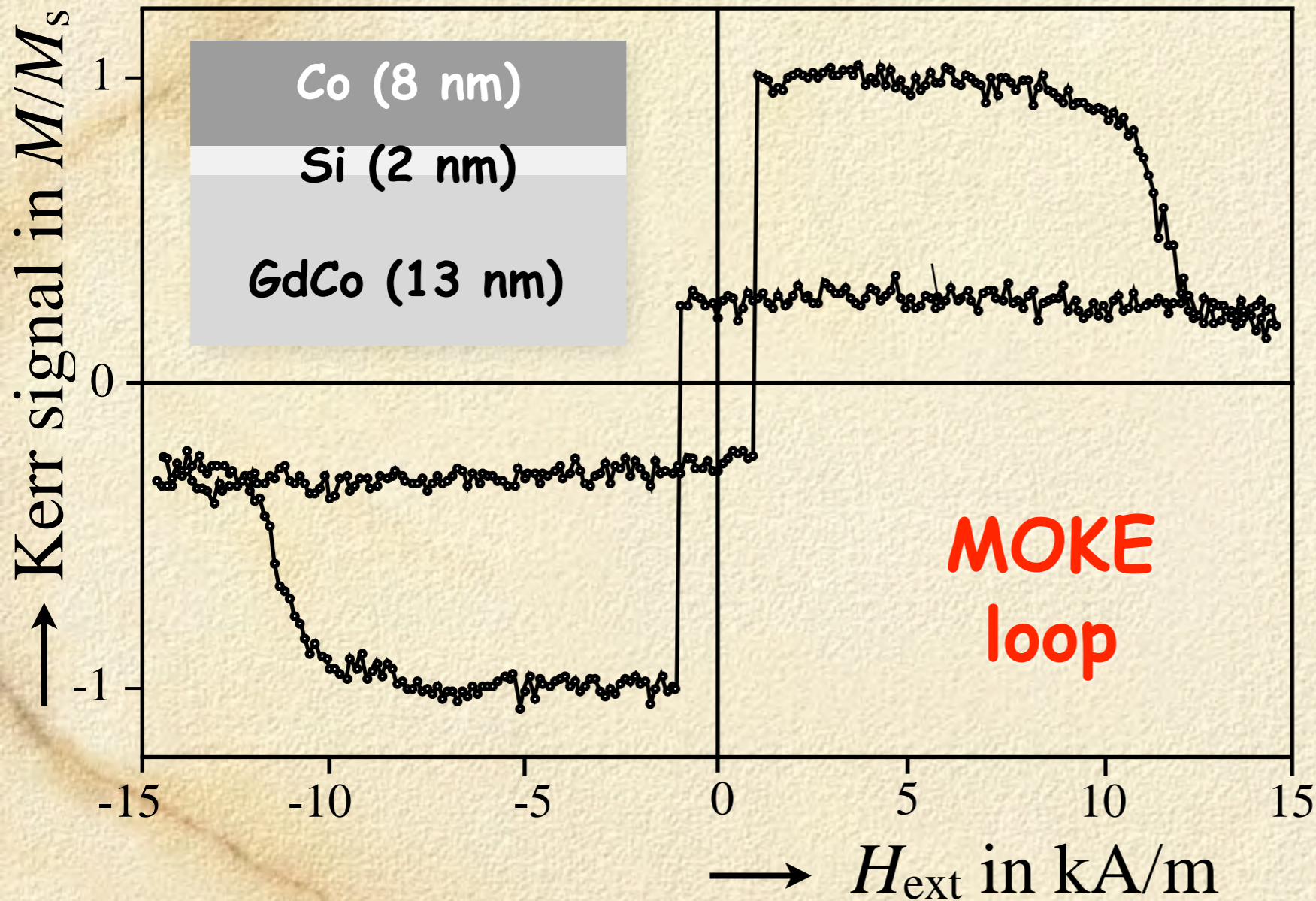
Magnetic field

Domain analysis in multilayers



Domain analysis in multilayers

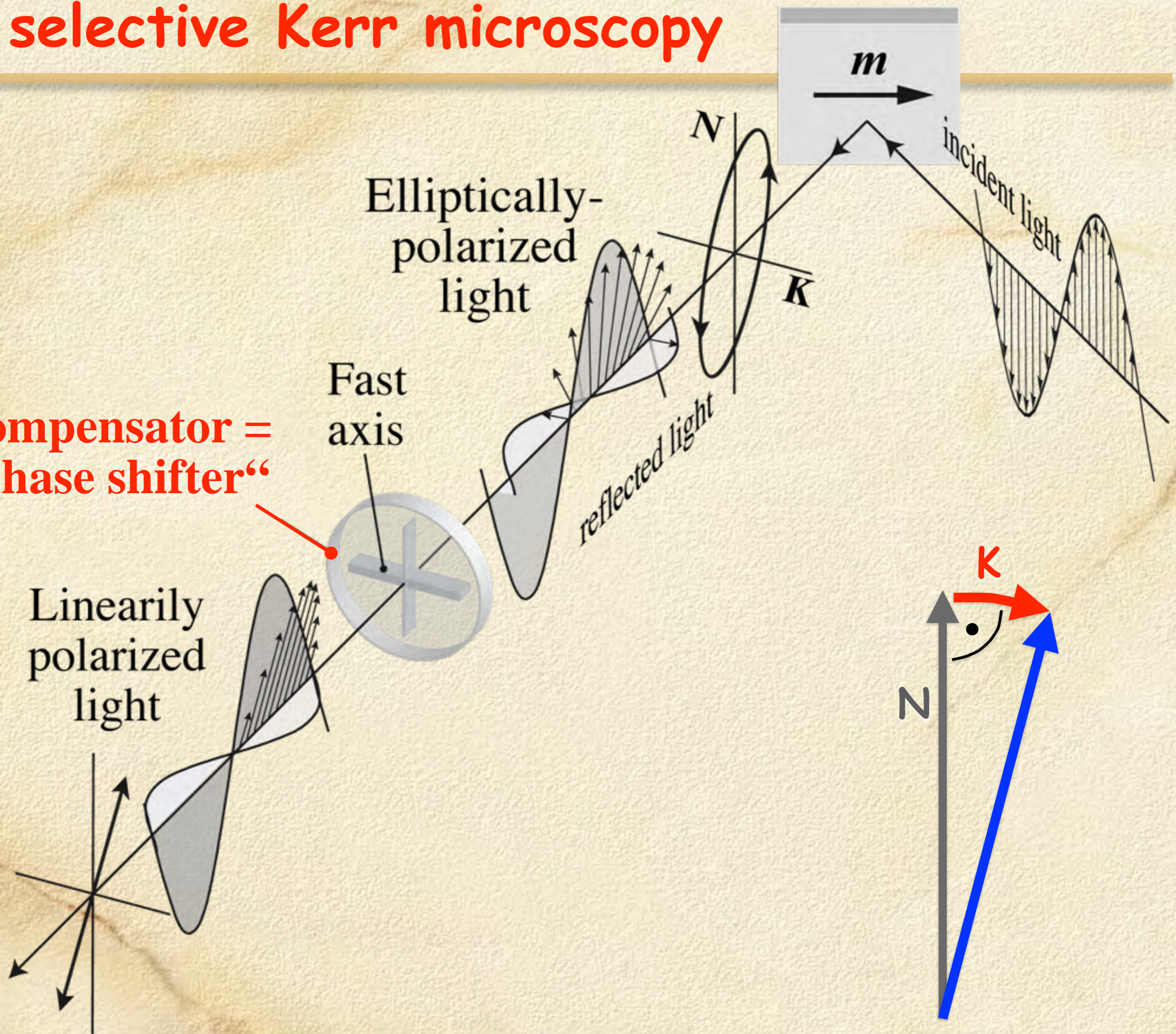
Co/Si/GdCo trilayer



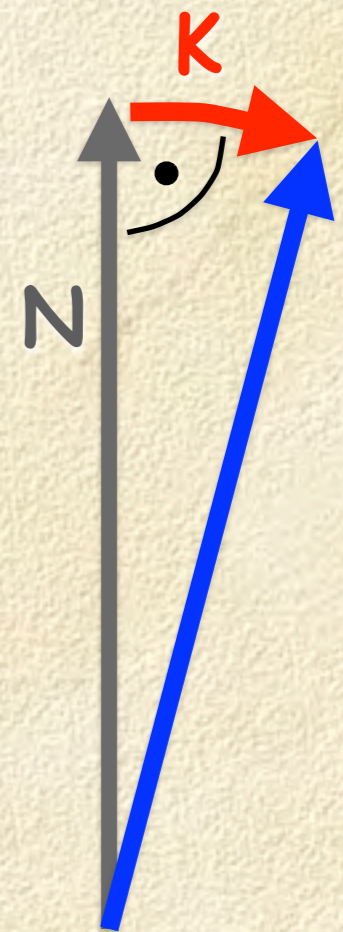
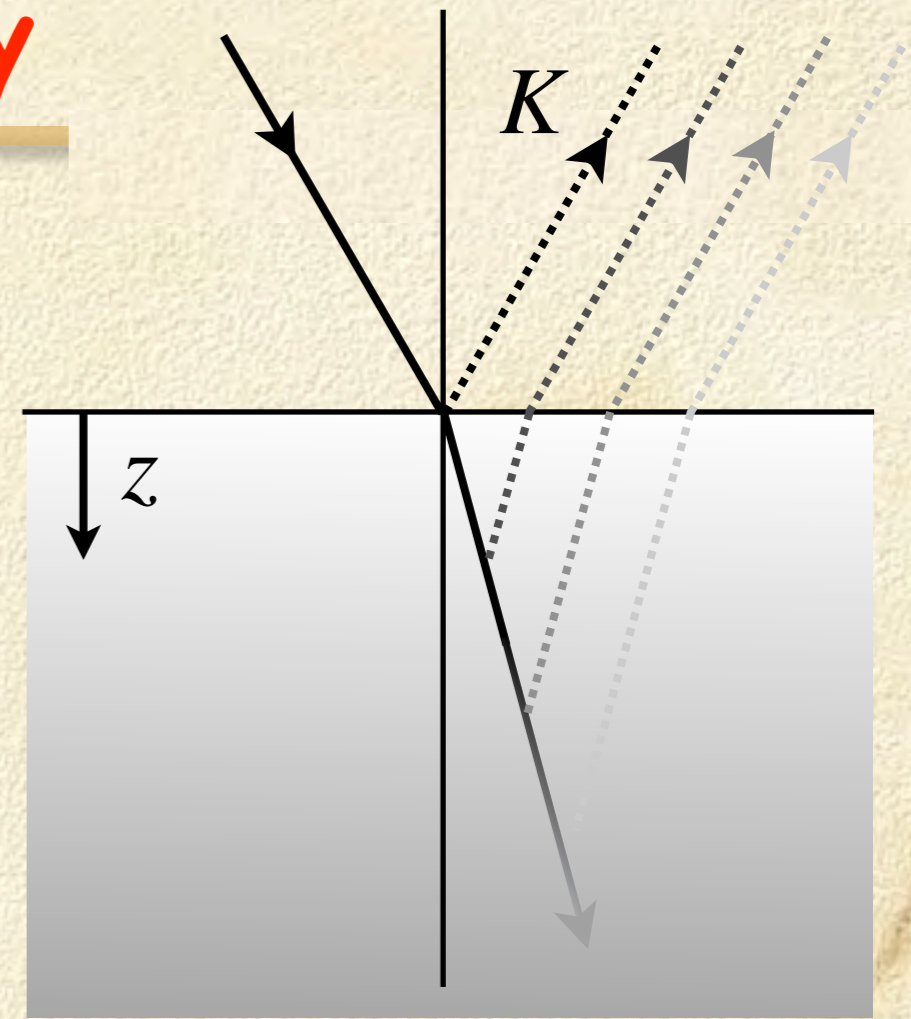
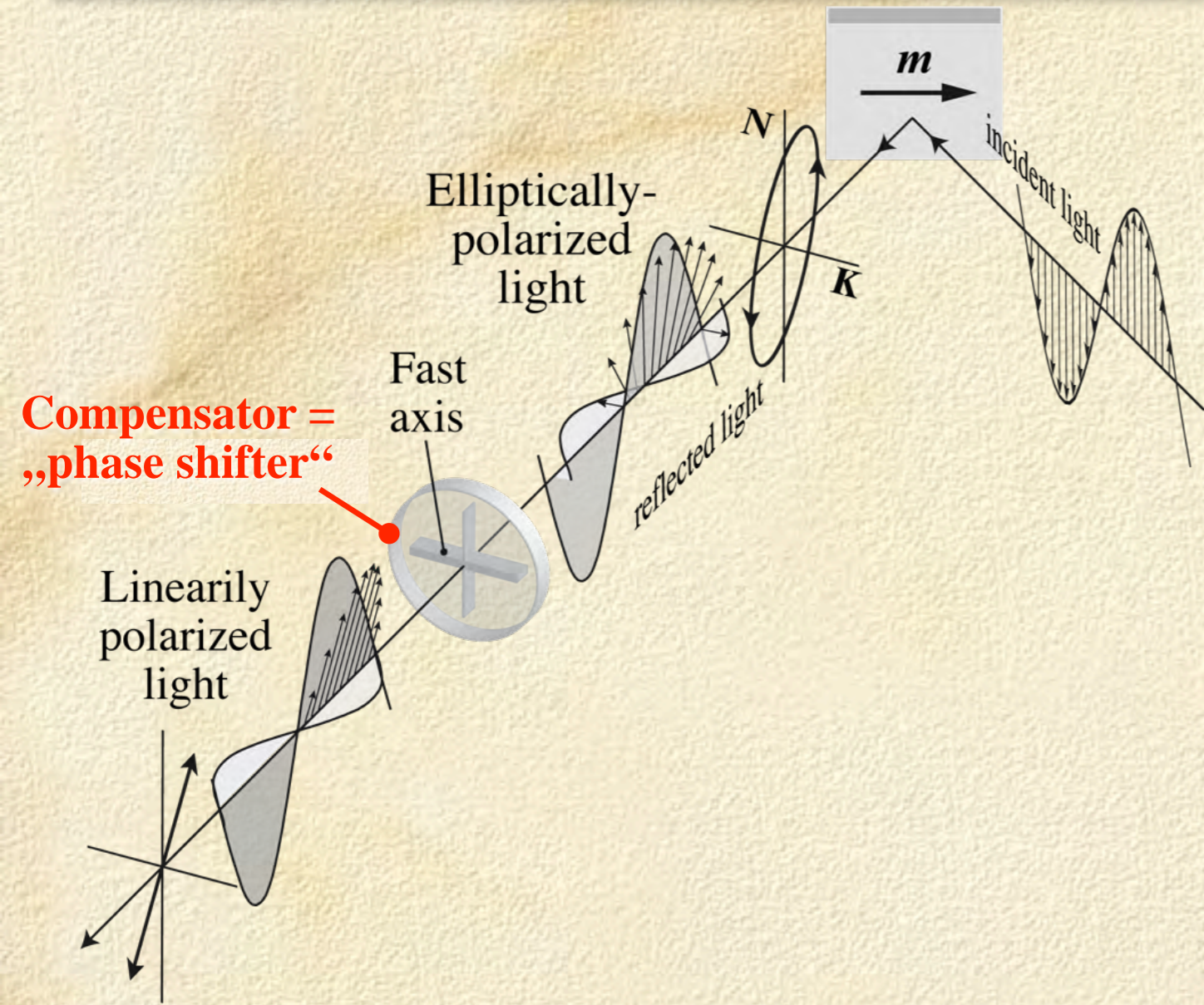
Sample: A. Svalov and G. Kurlyandskaya, Ekaterinburg
Imaging: together with L. Lokamani, Dresden (unpublished)

Depth selective Kerr microscopy

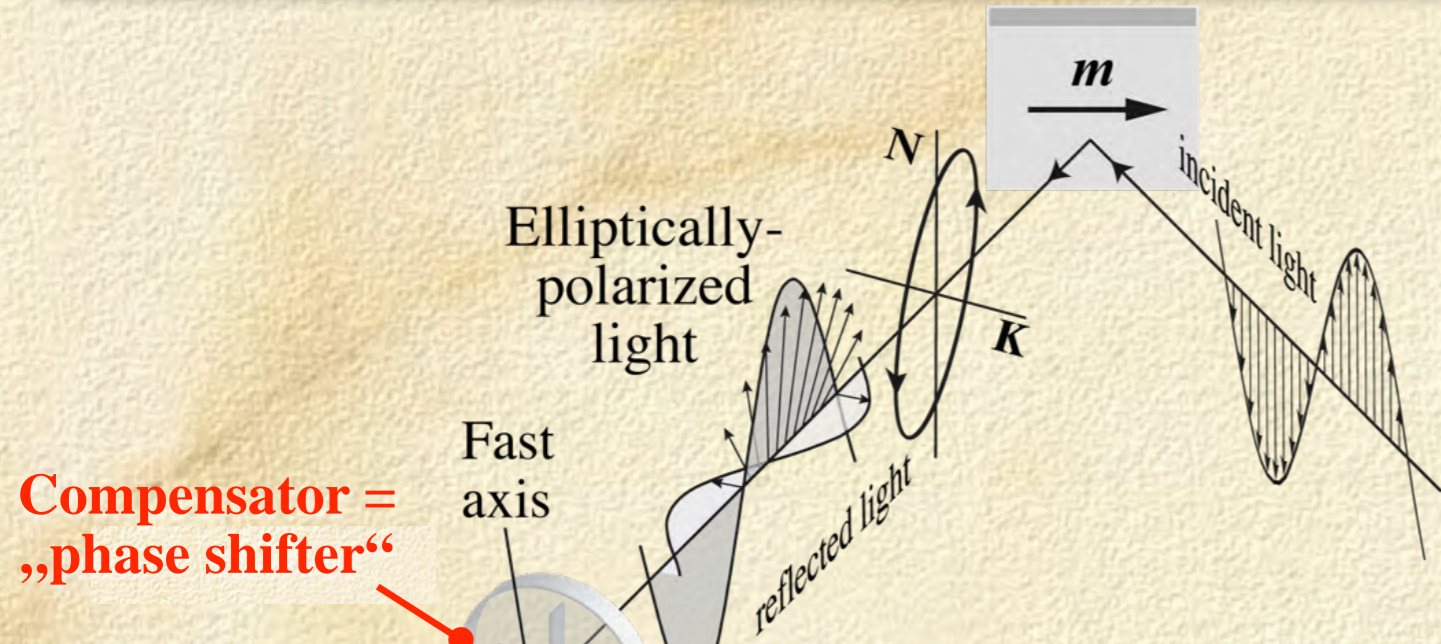
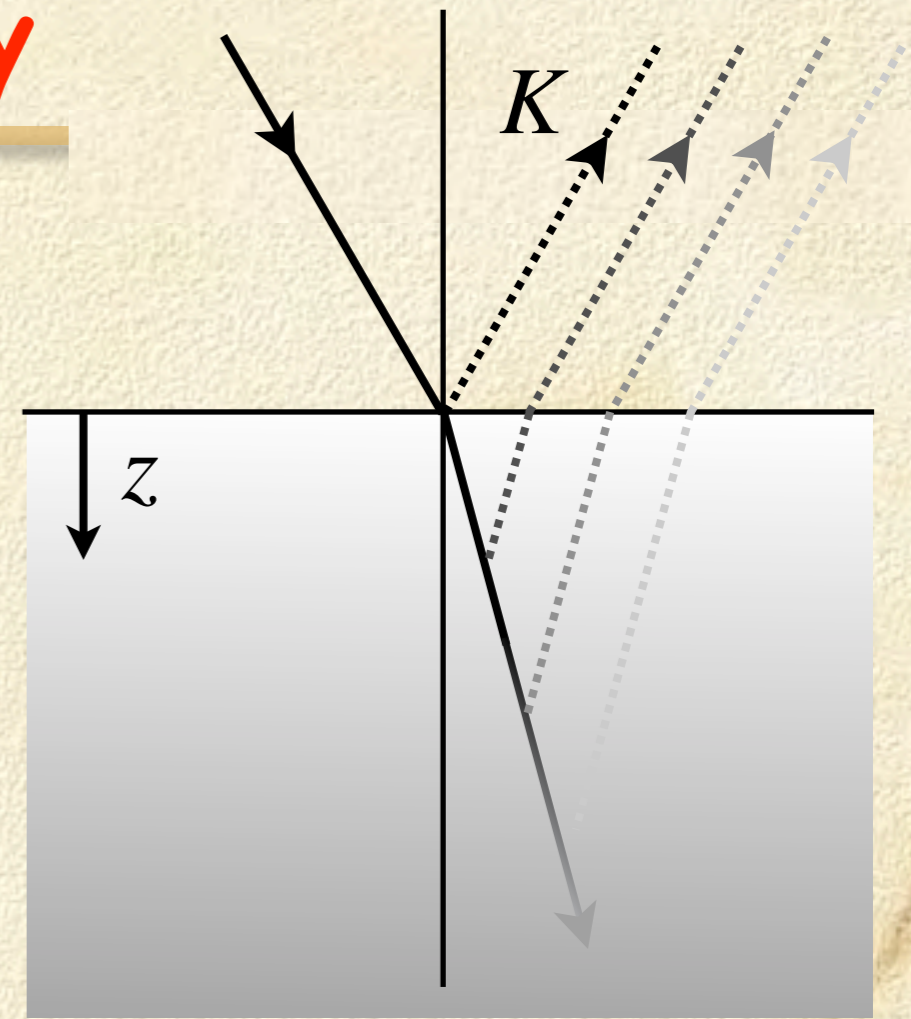
Compensator = „phase shifter“



Depth selective Kerr microscopy

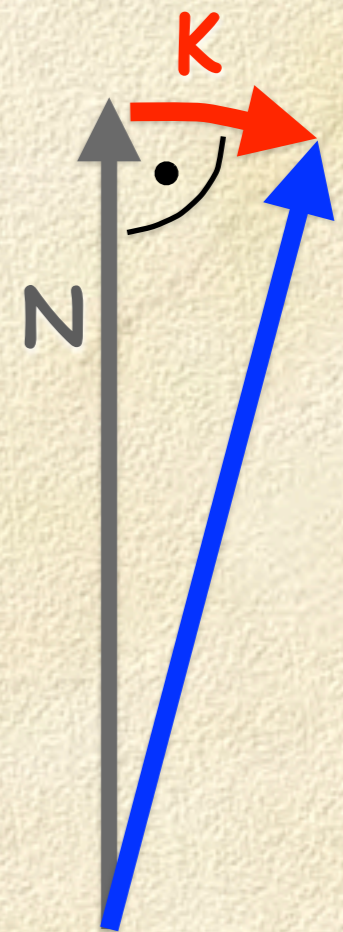
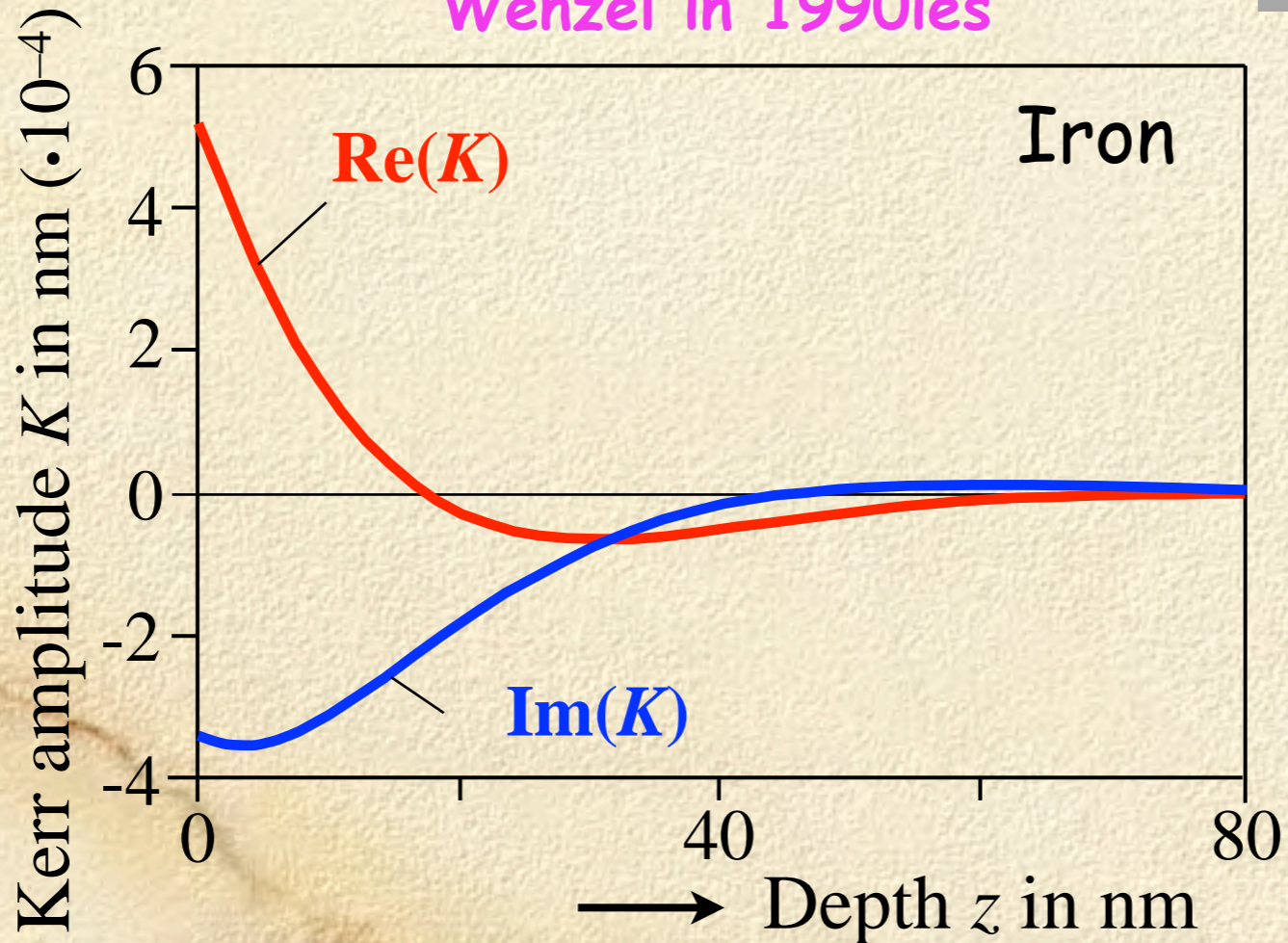
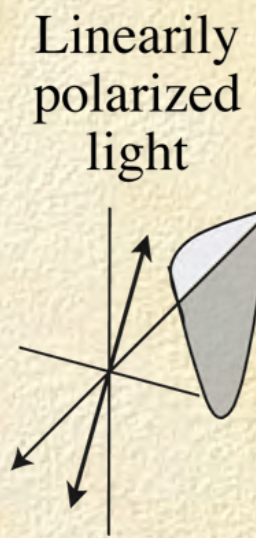


Depth selective Kerr microscopy

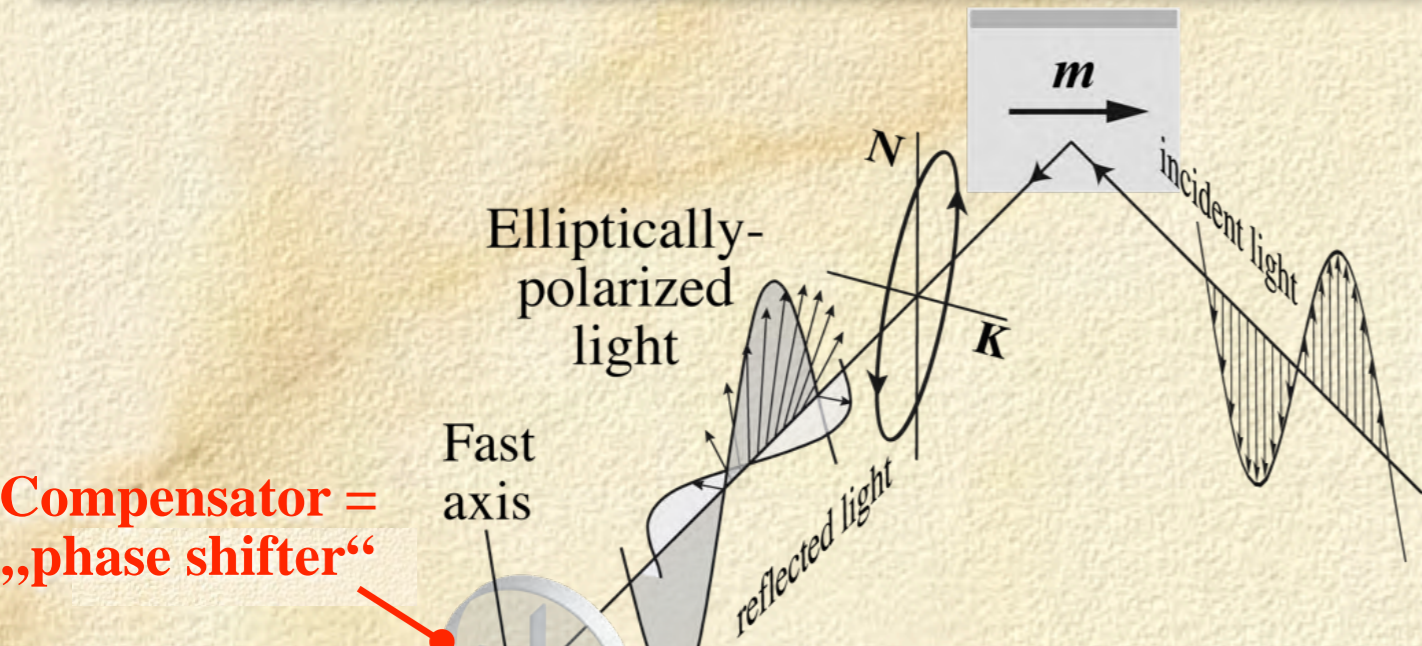
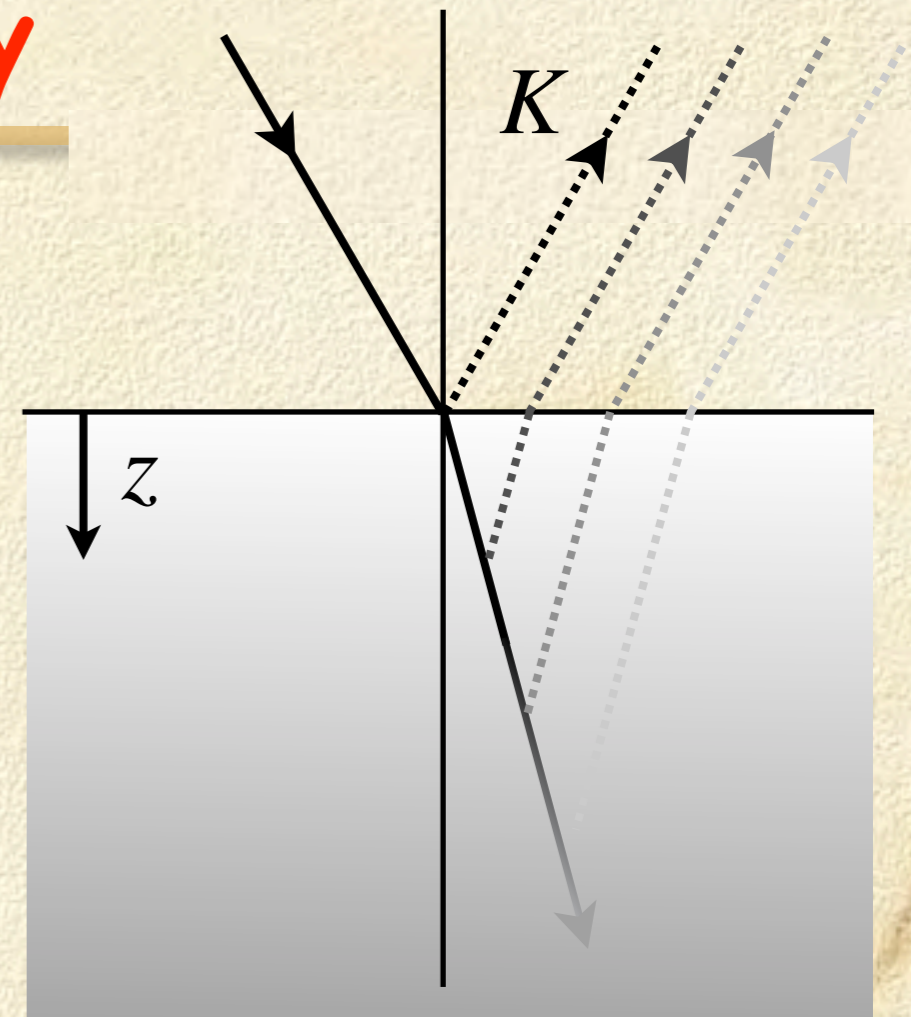


Compensator = „phase shifter“

Hubert, Kambersky, Träger, Wenzel in 1990ies

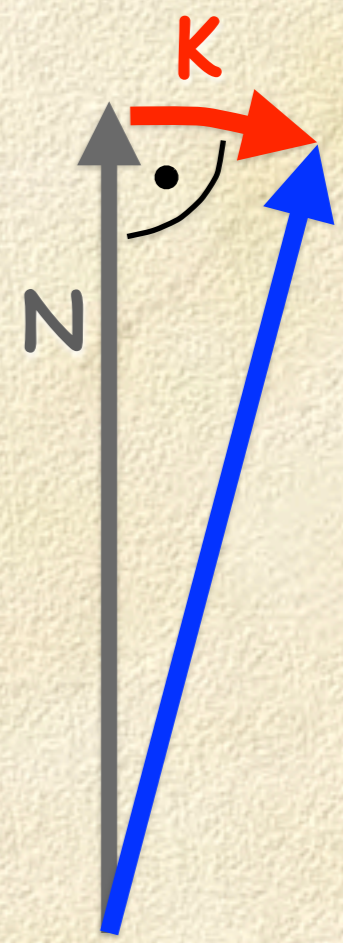
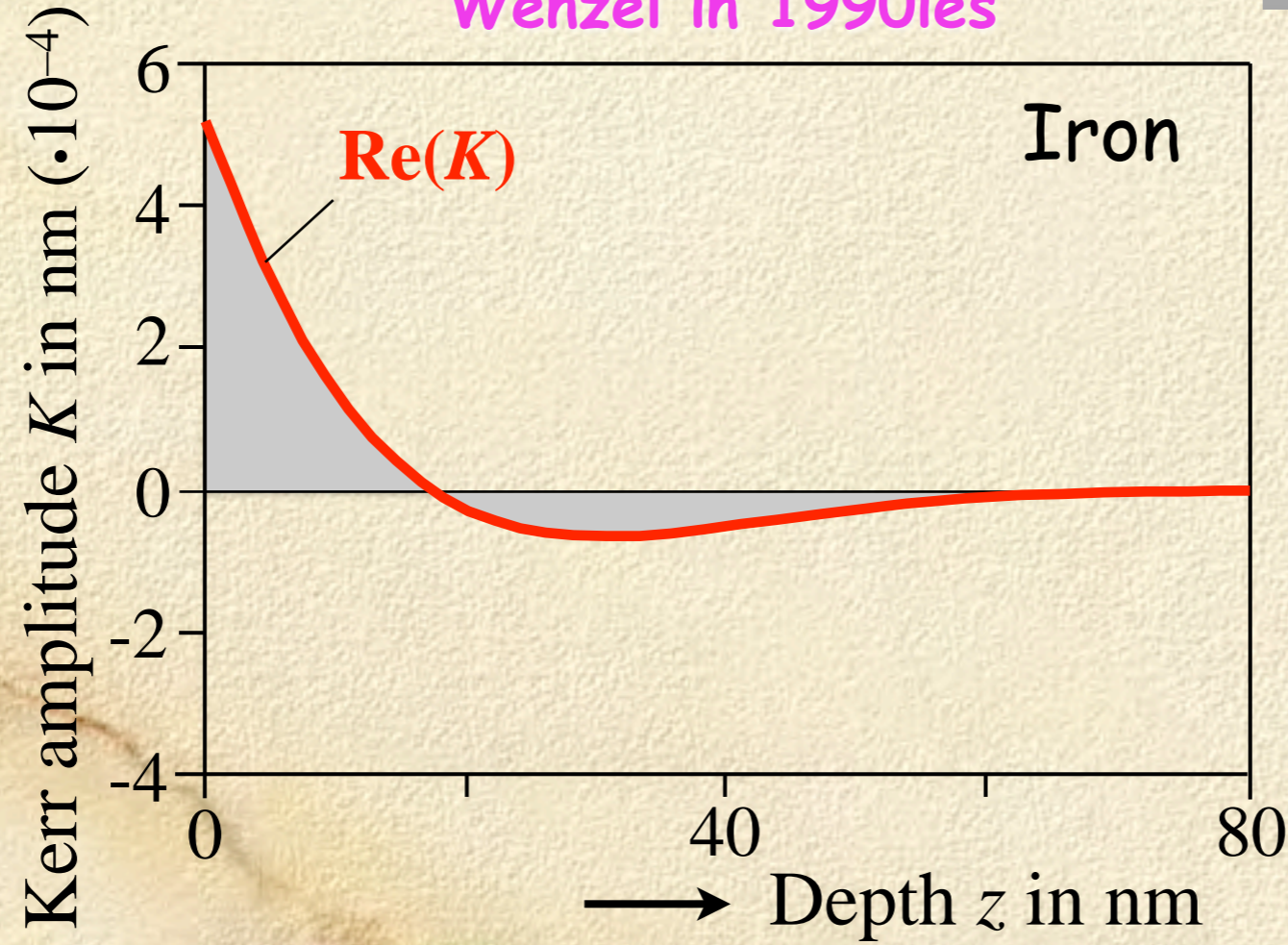


Depth selective Kerr microscopy

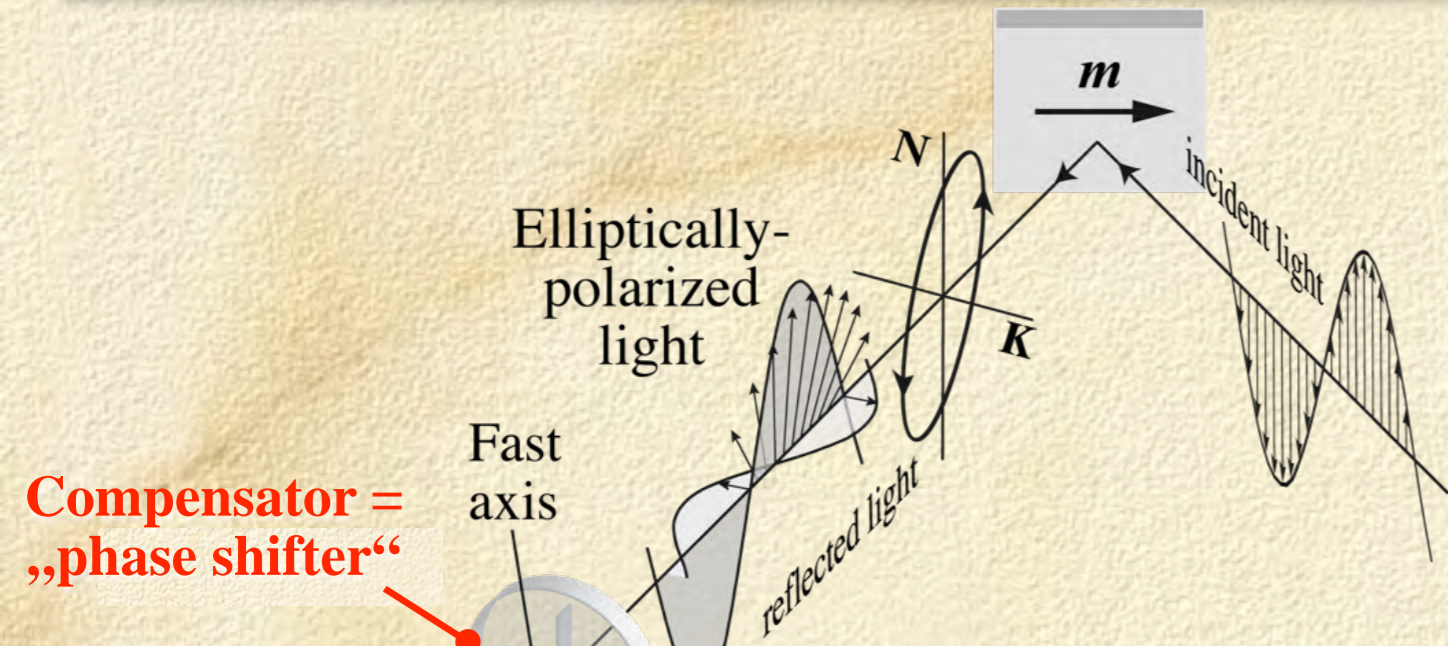
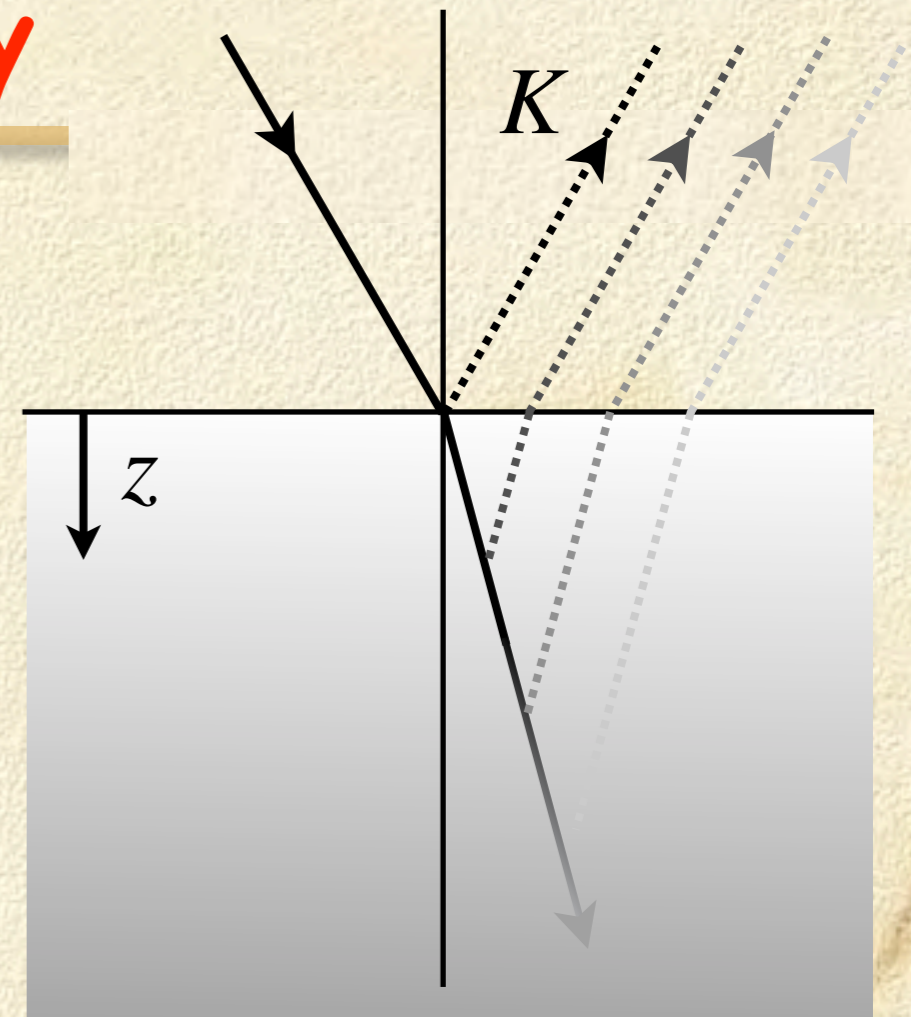


Compensator = „phase shifter“

Hubert, Kambersky, Träger, Wenzel in 1990ies

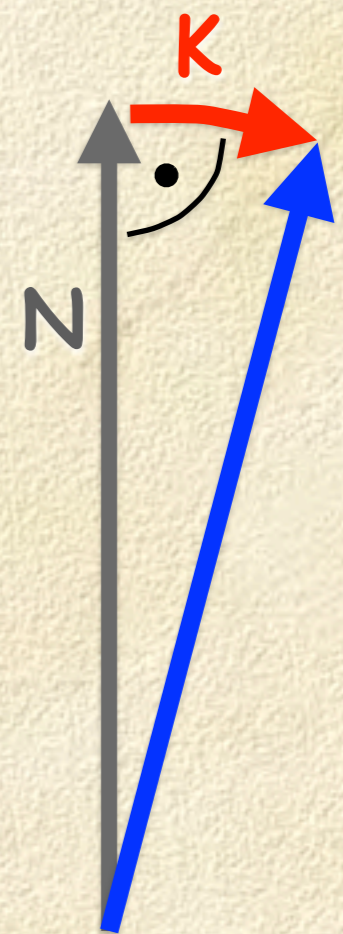
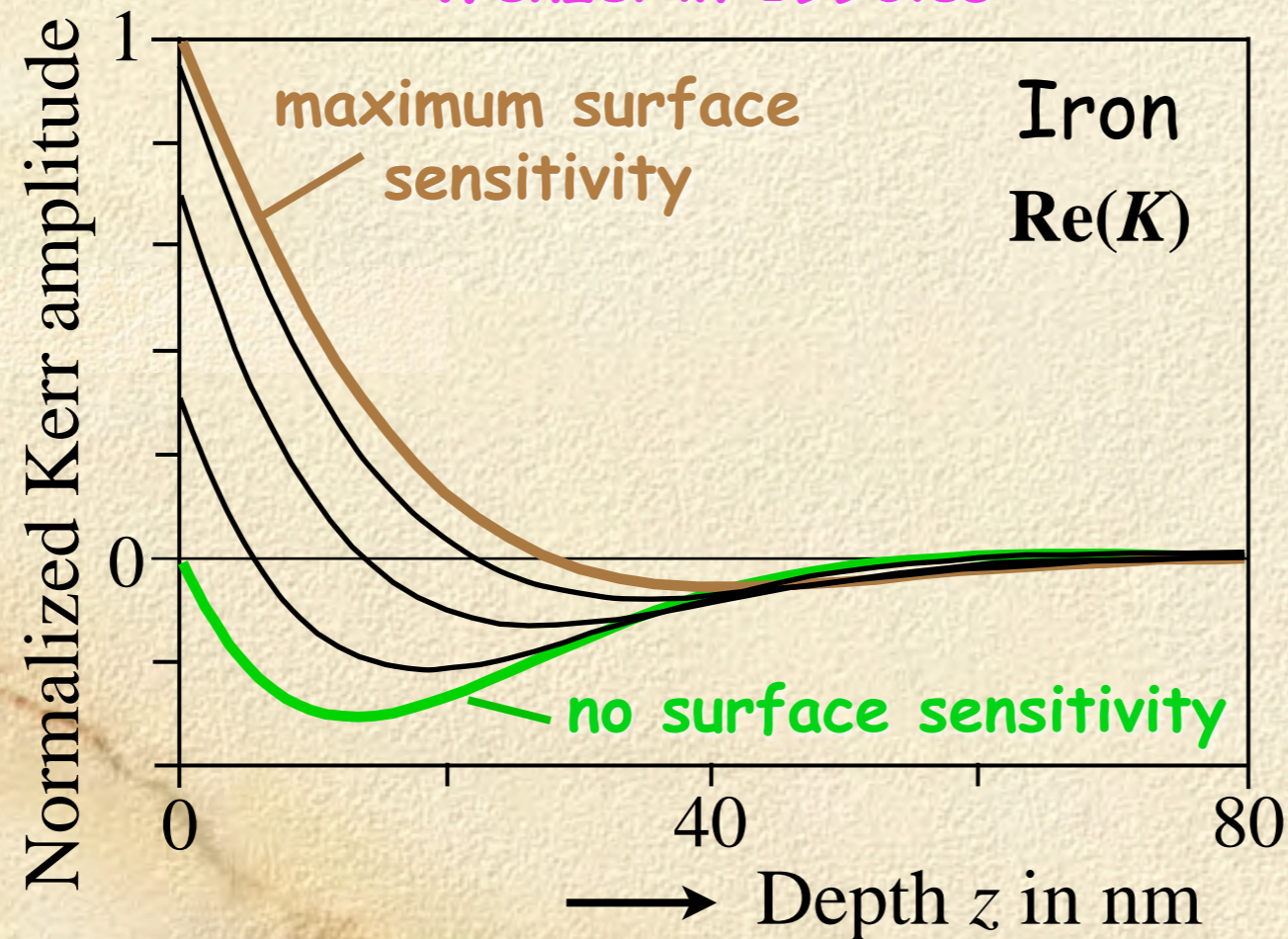


Depth selective Kerr microscopy

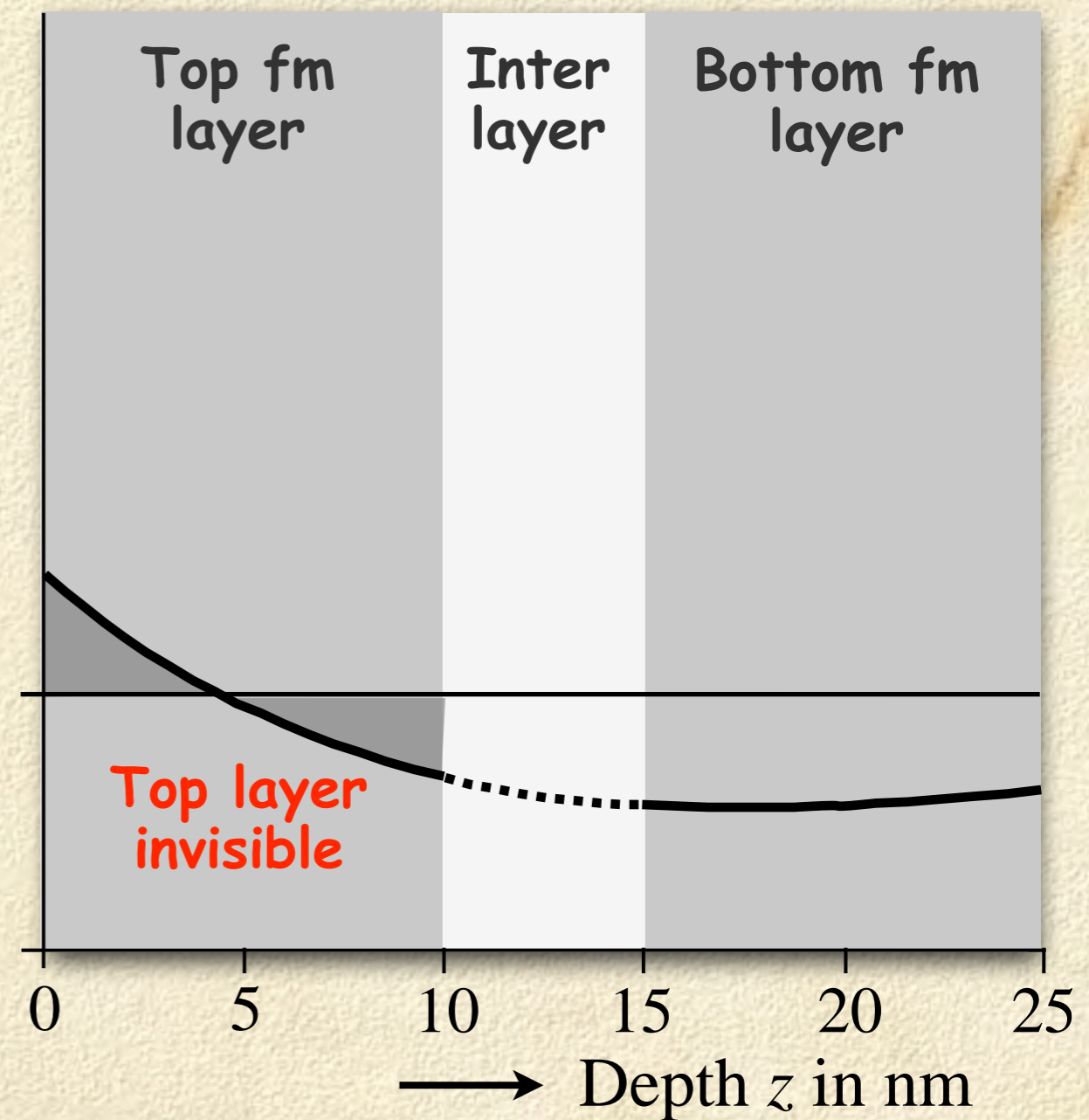
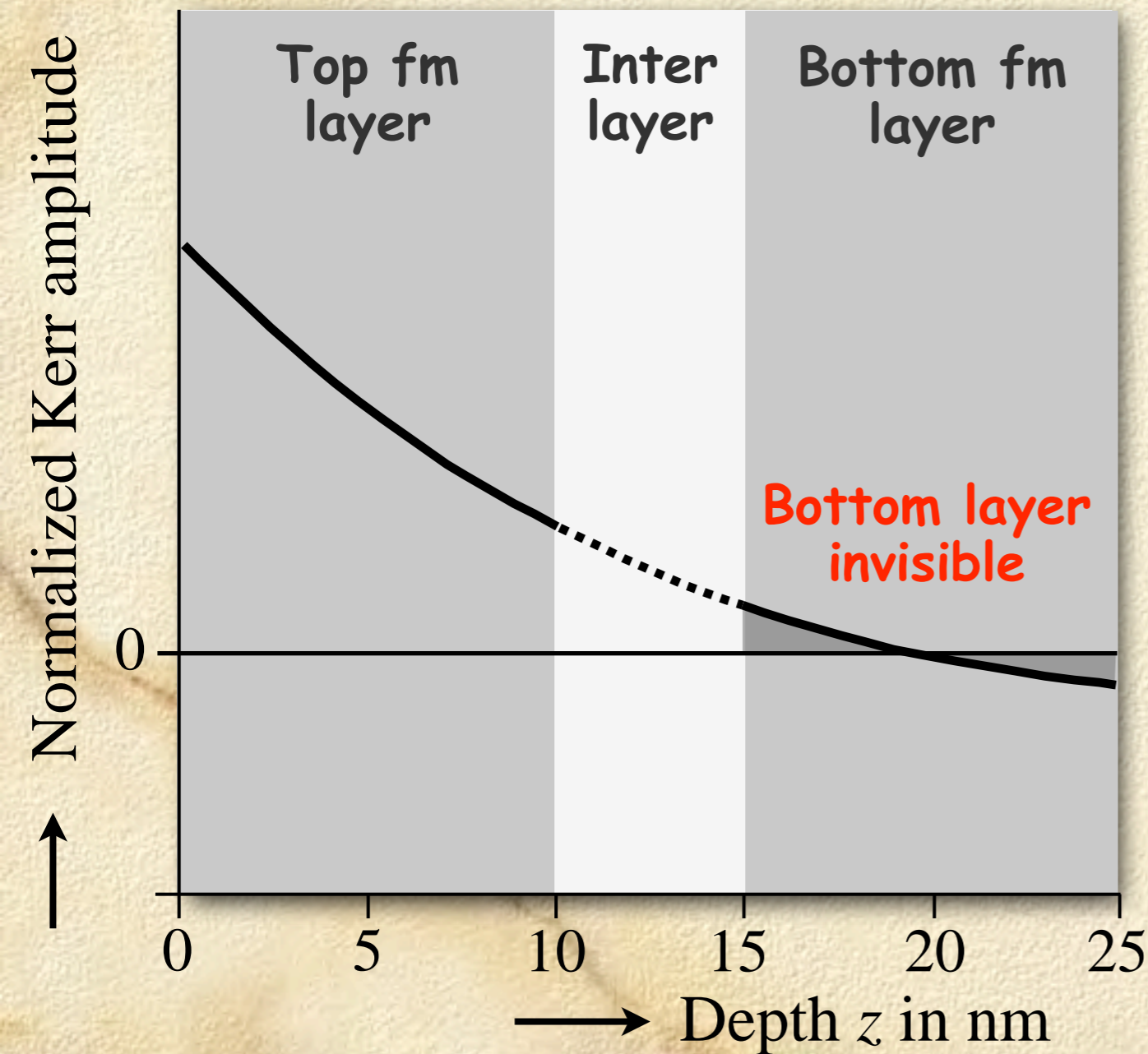
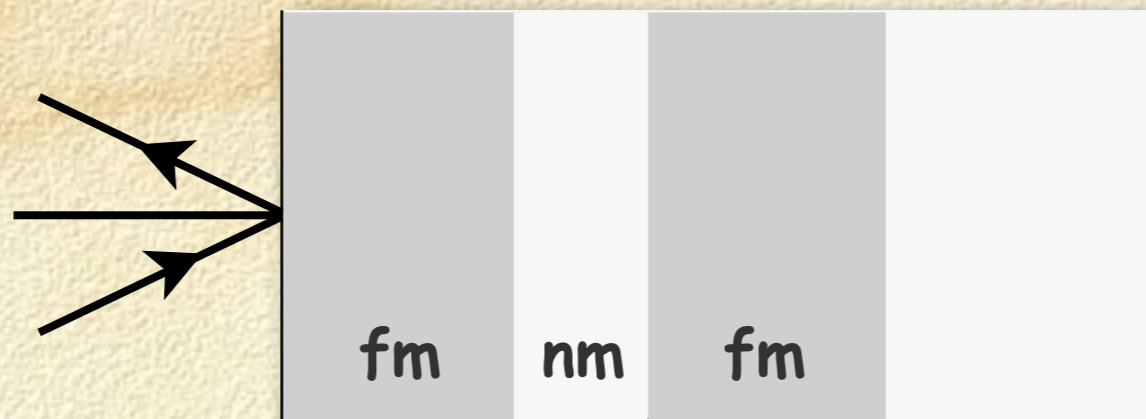


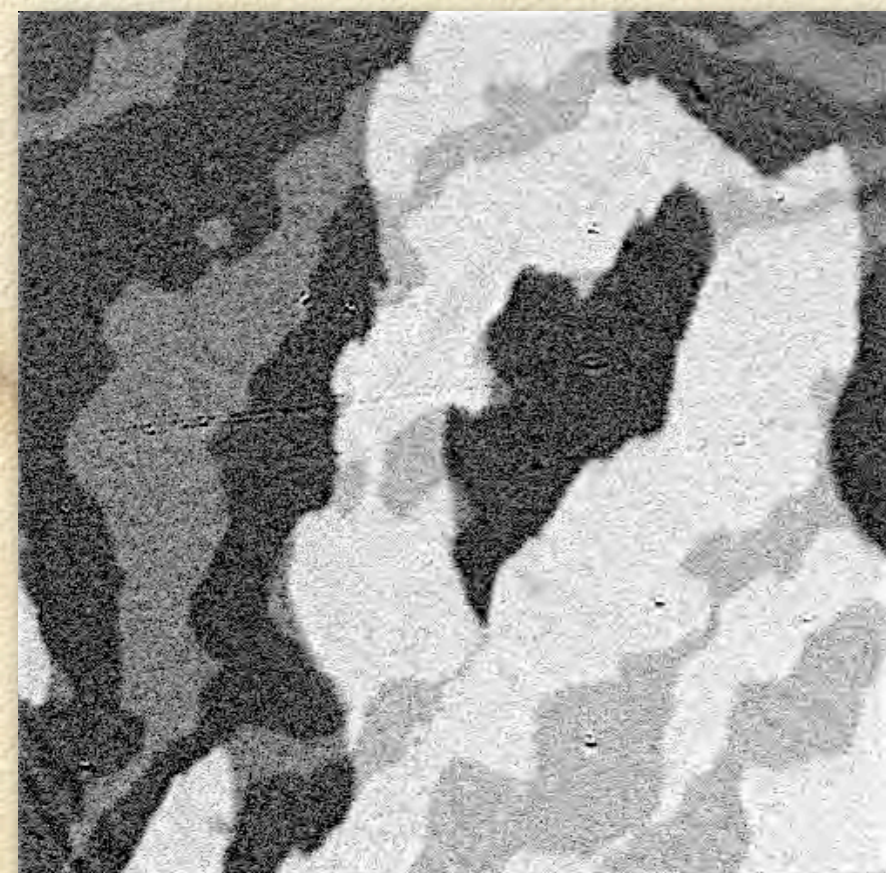
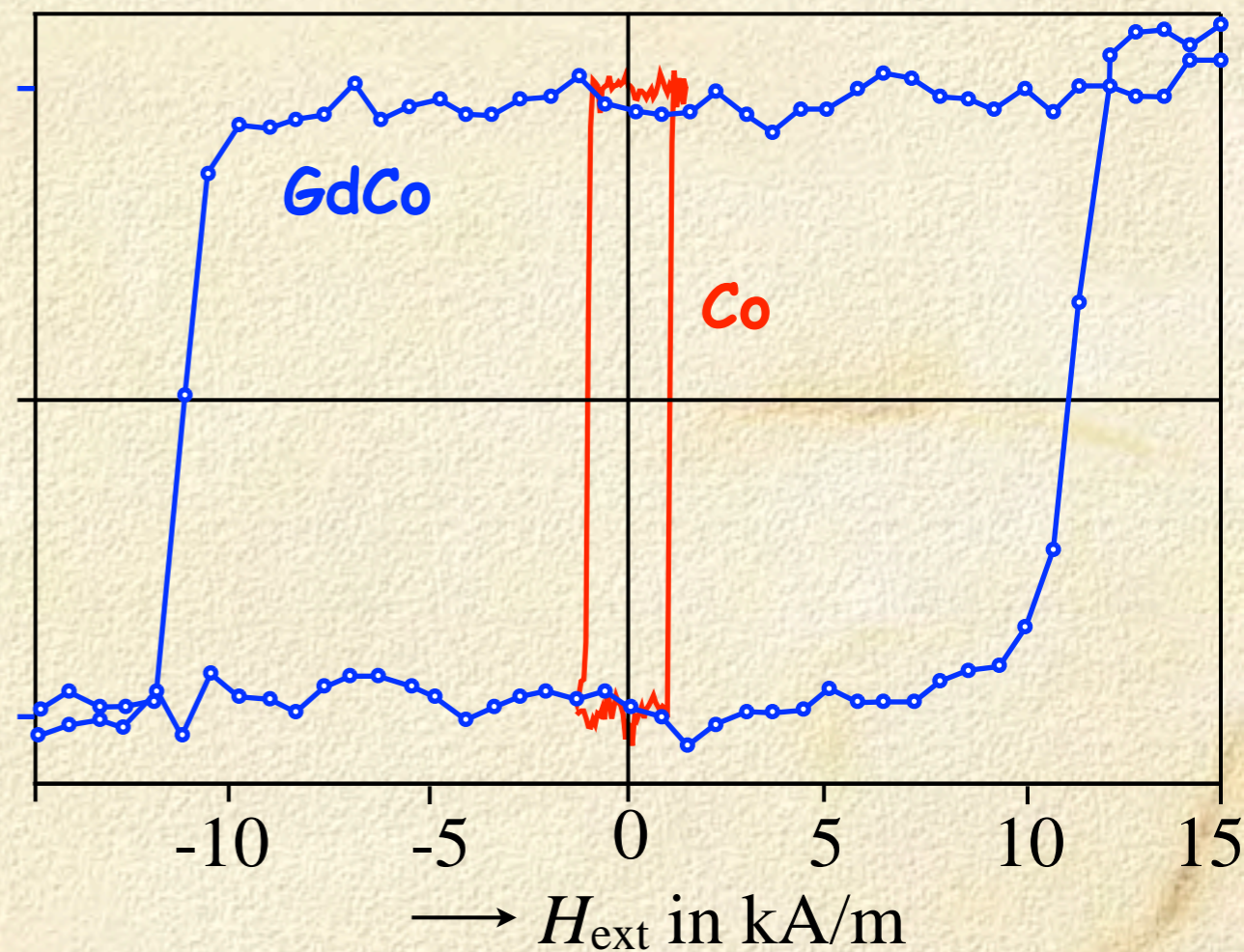
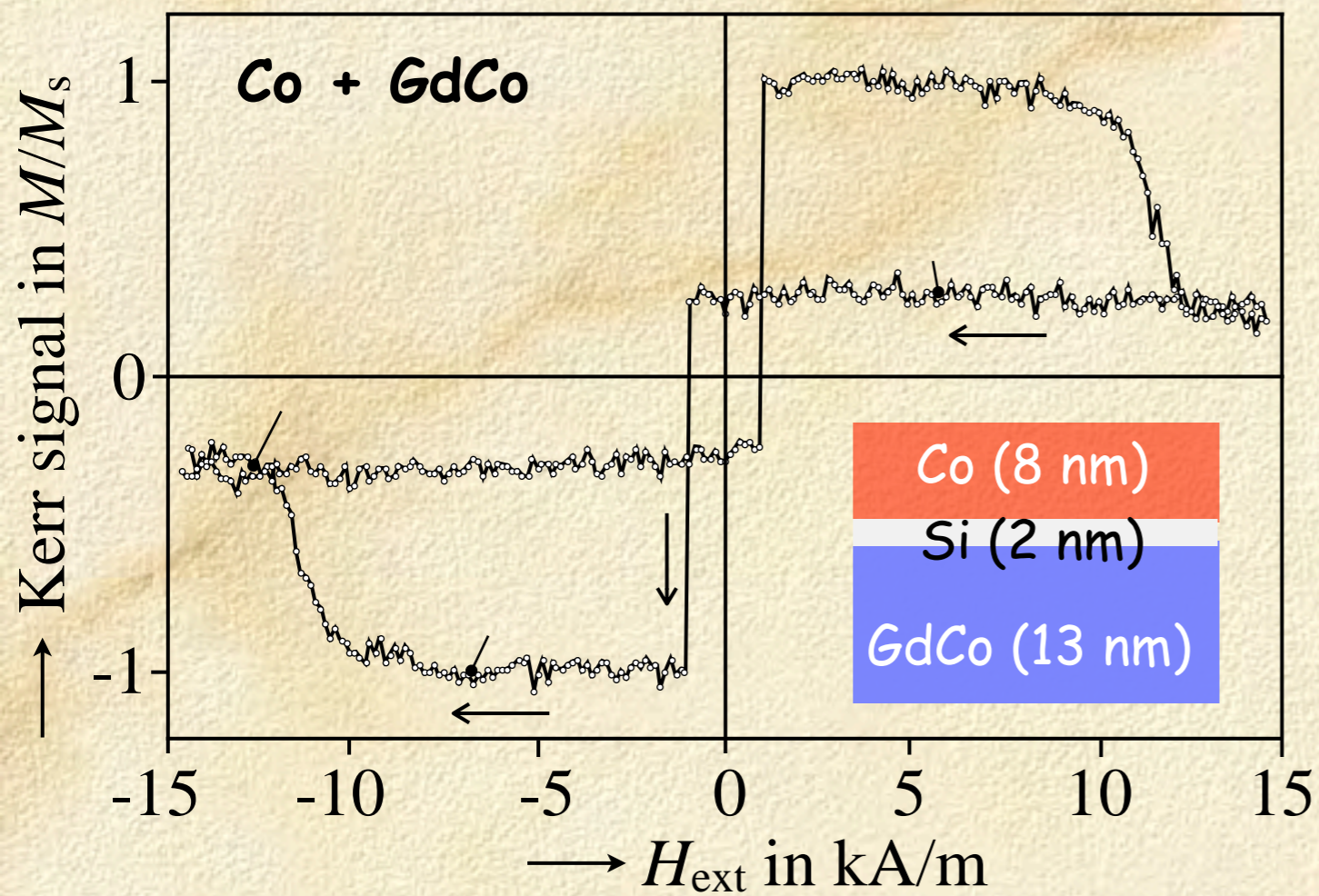
Compensator = „phase shifter“

Hubert, Kambersky, Träger, Wenzel in 1990ies

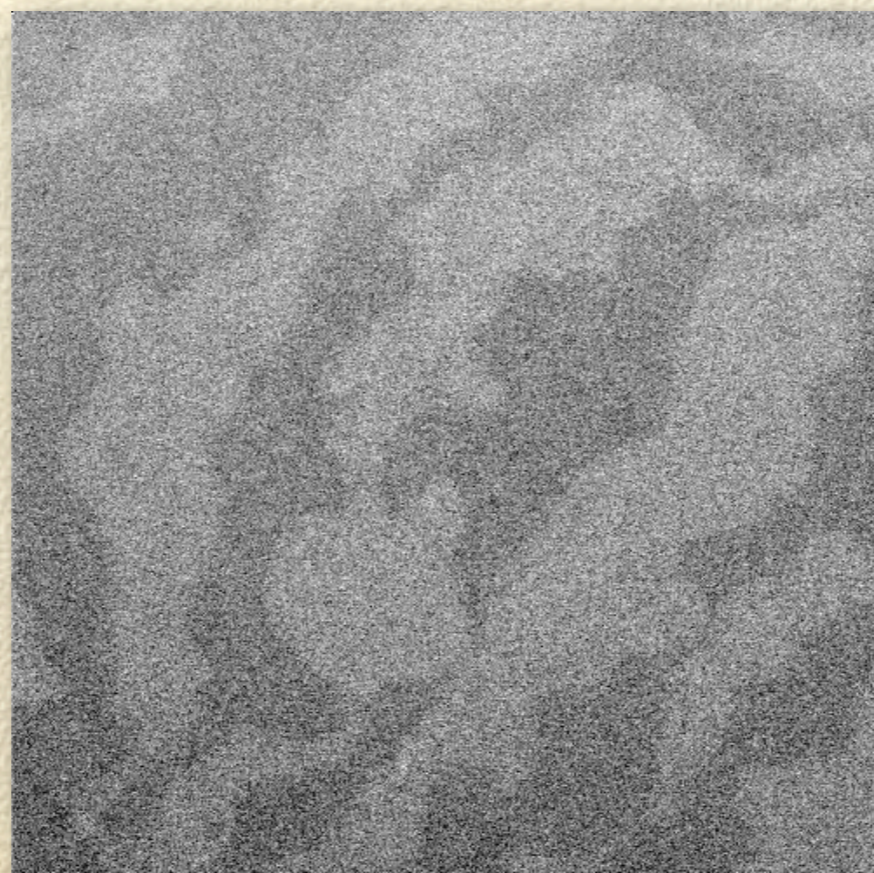


Layer-selective Kerr microscopy

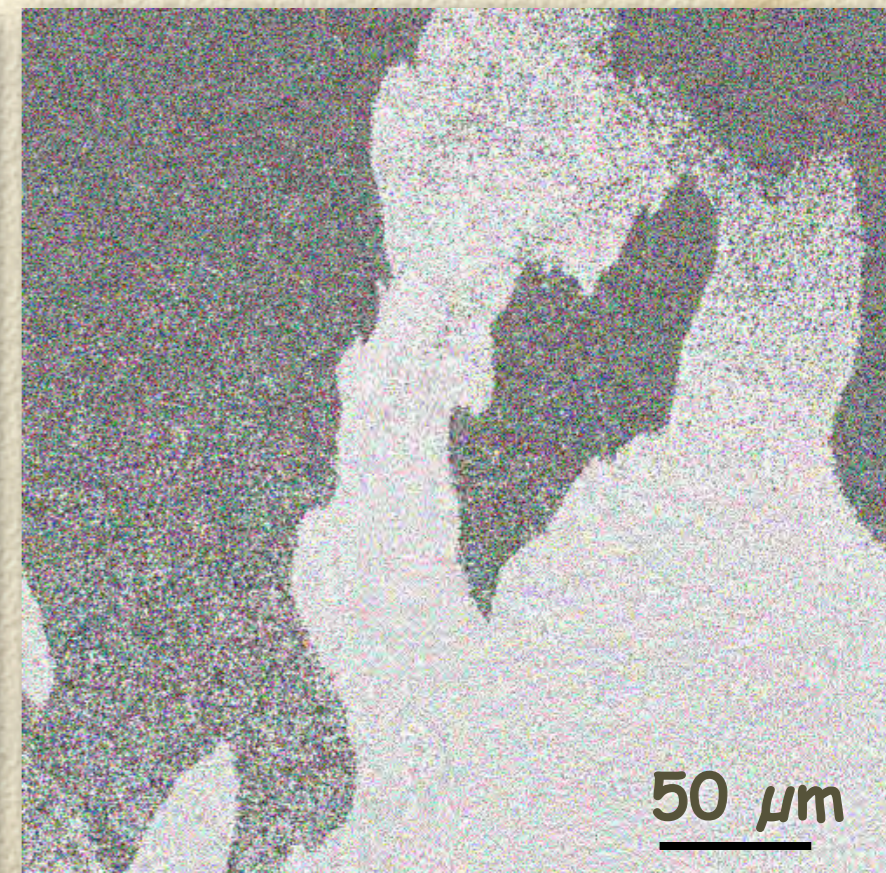




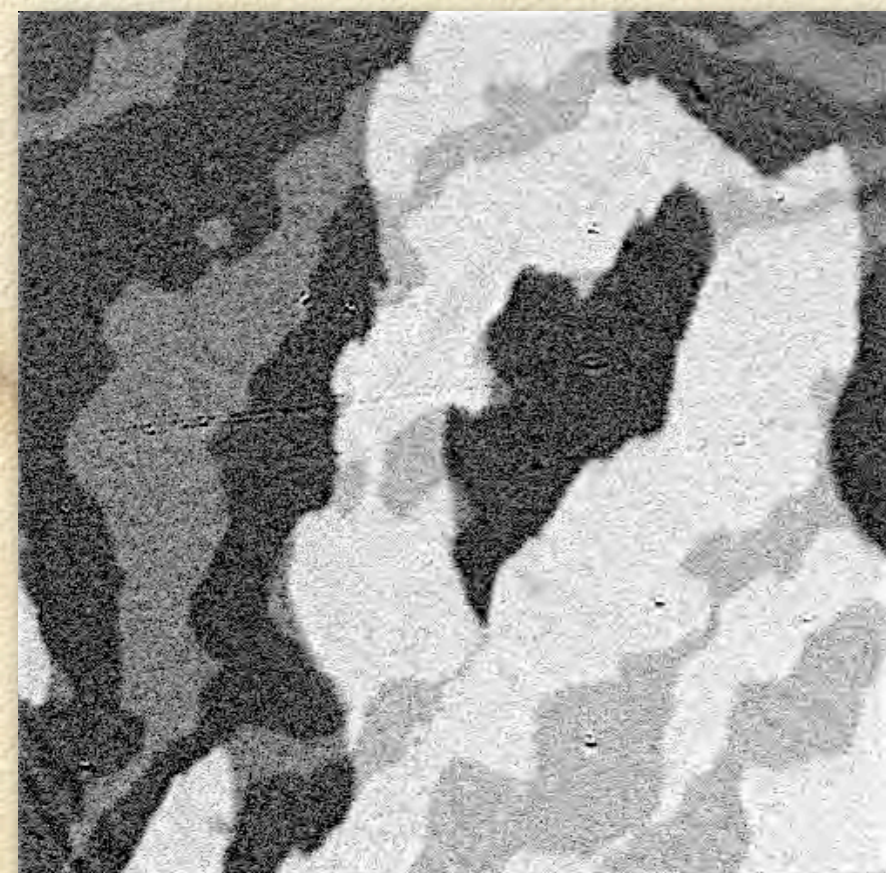
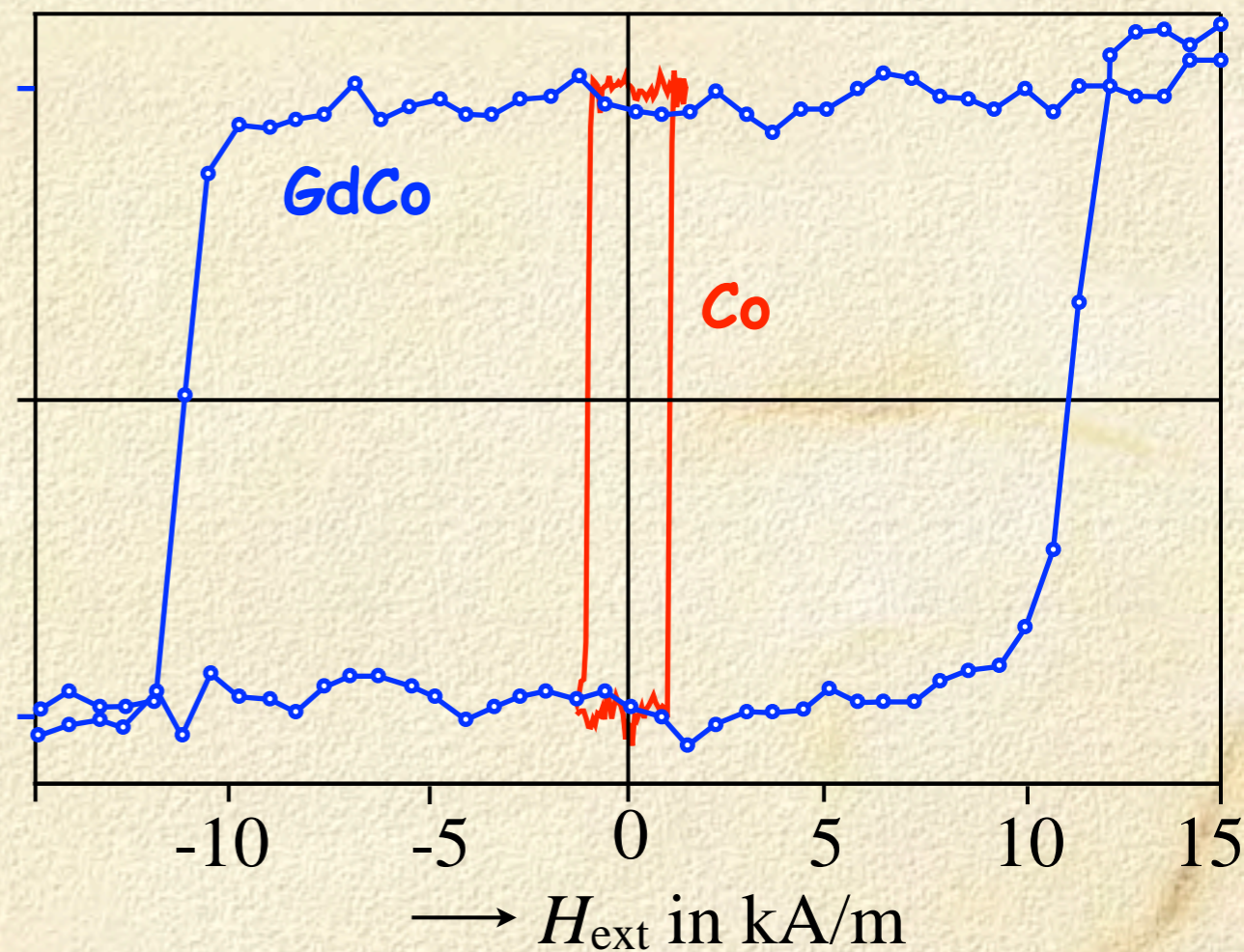
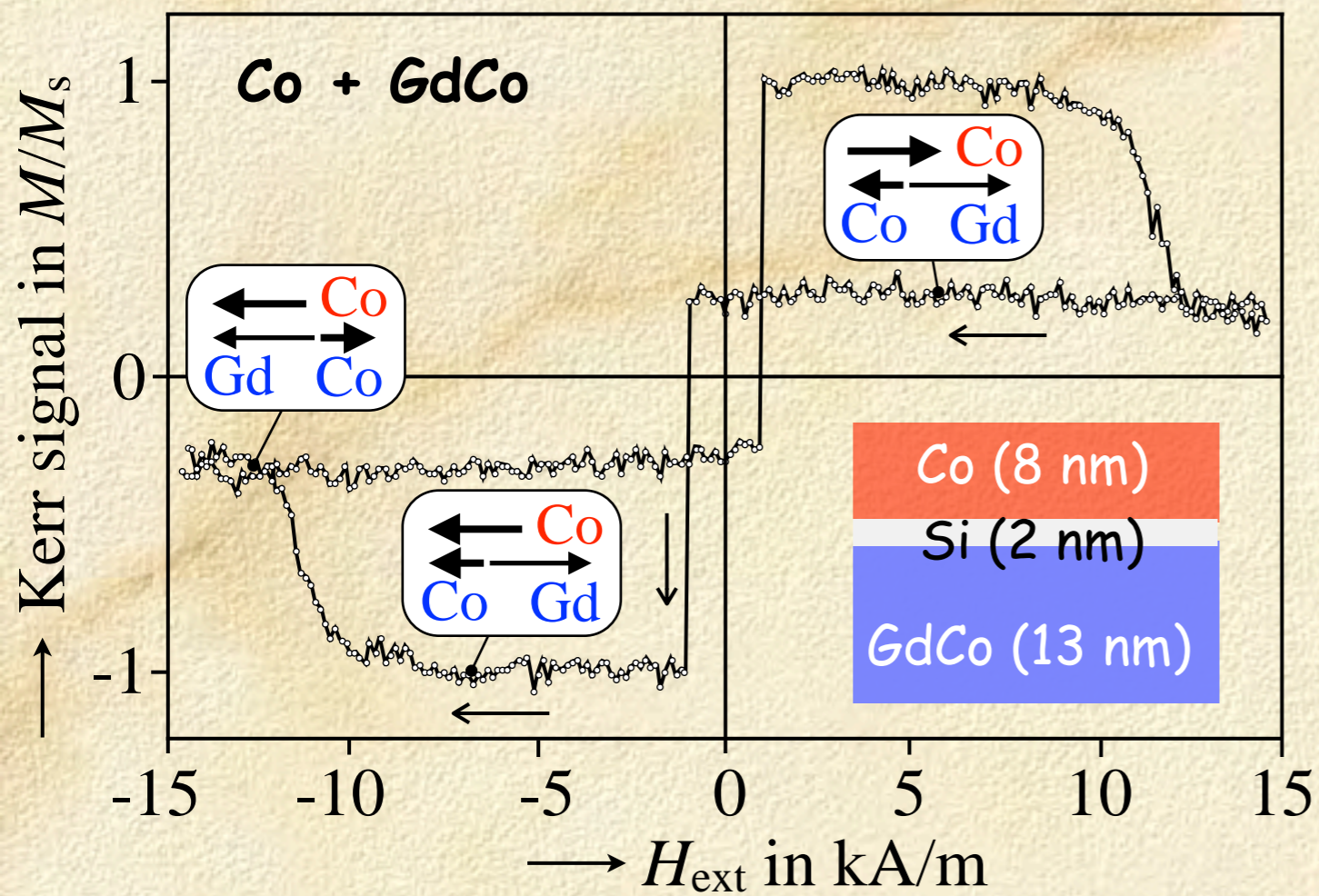
Mixed Kerr signal



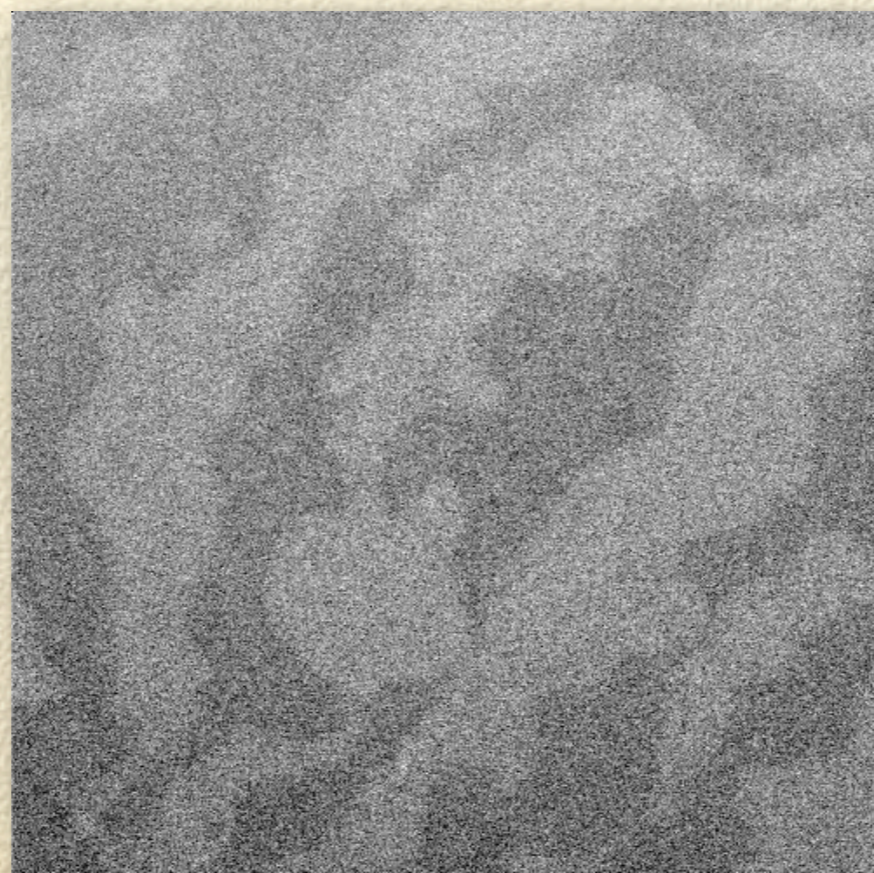
GdCo layer



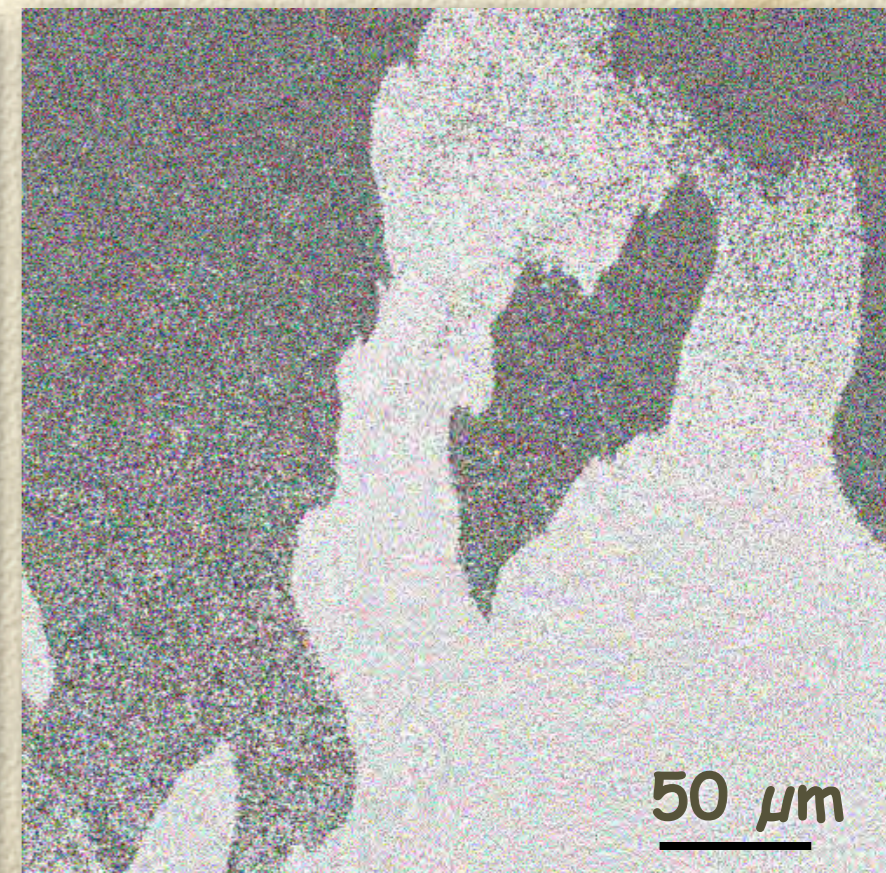
Co layer



Mixed Kerr signal



GdCo layer



Co layer

50 μm

Layer-selective Kerr microscopy

Advantage of
layer-selective Kerr microscopy:

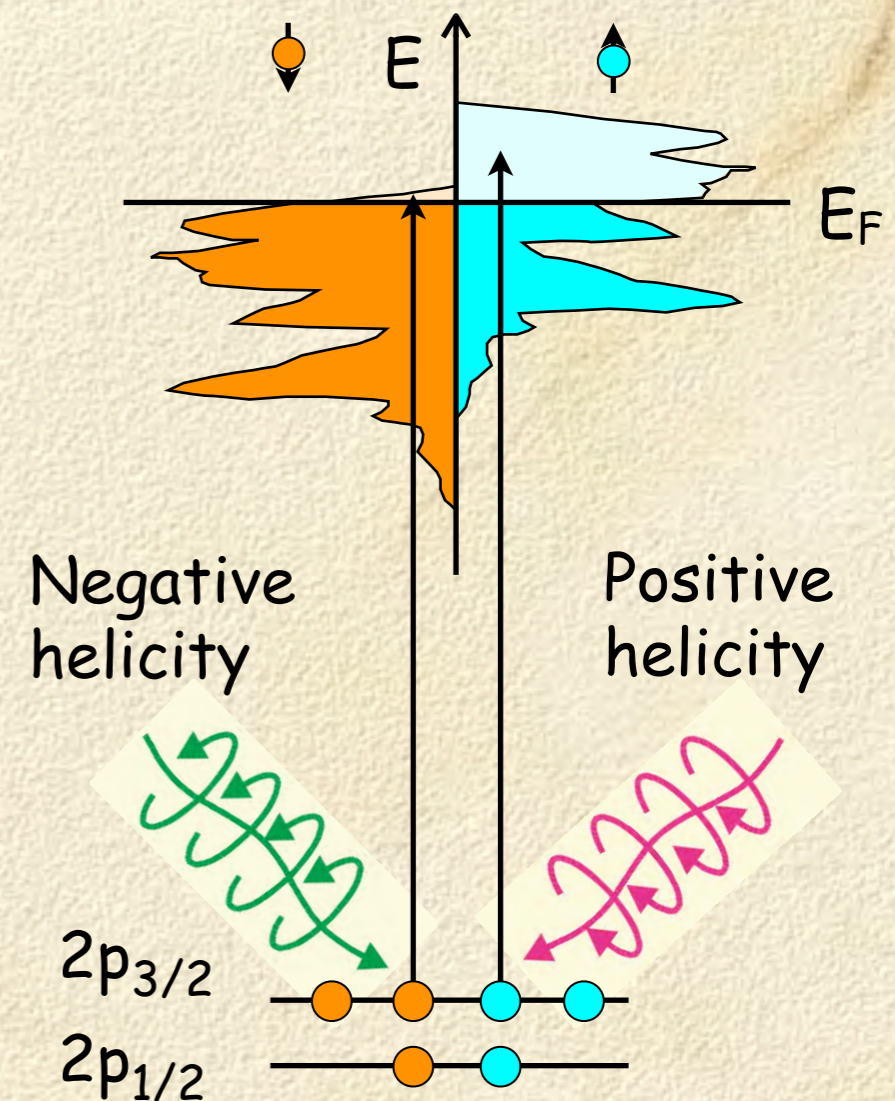
different composition of layers not required

X-ray Magnetic Circular Dichroism

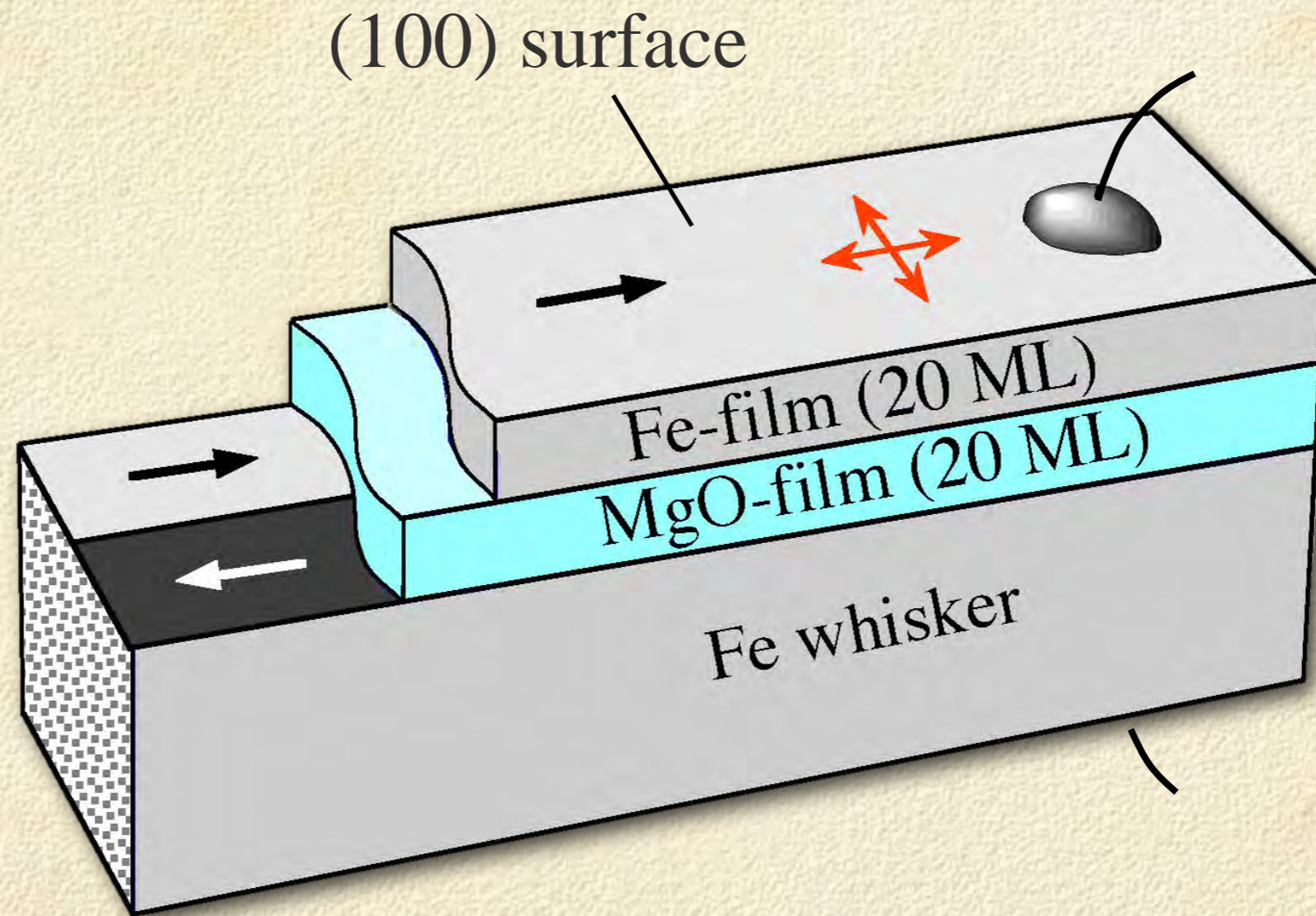
Absorption of circularly polarized x-rays depends on orientation of M -direction with respect to helicity of the X-rays, change of sign by reversing M

Initial states are well defined inner-core levels

→ XMCD is element selective

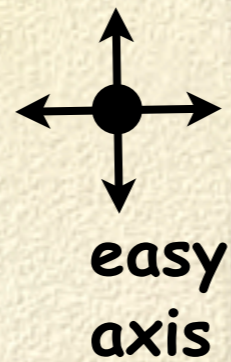
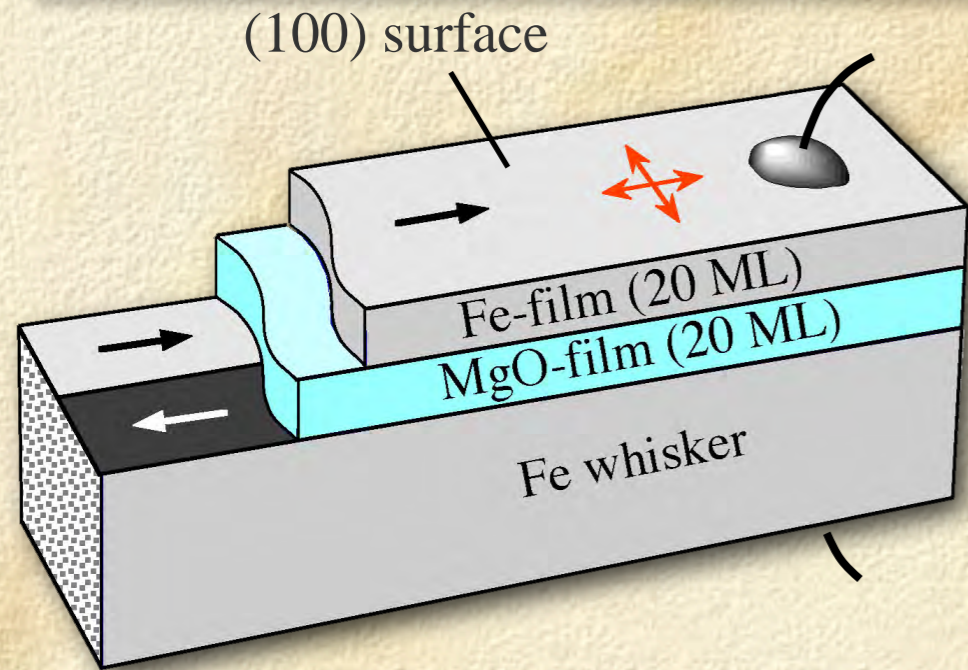


Layer-selective Kerr microscopy

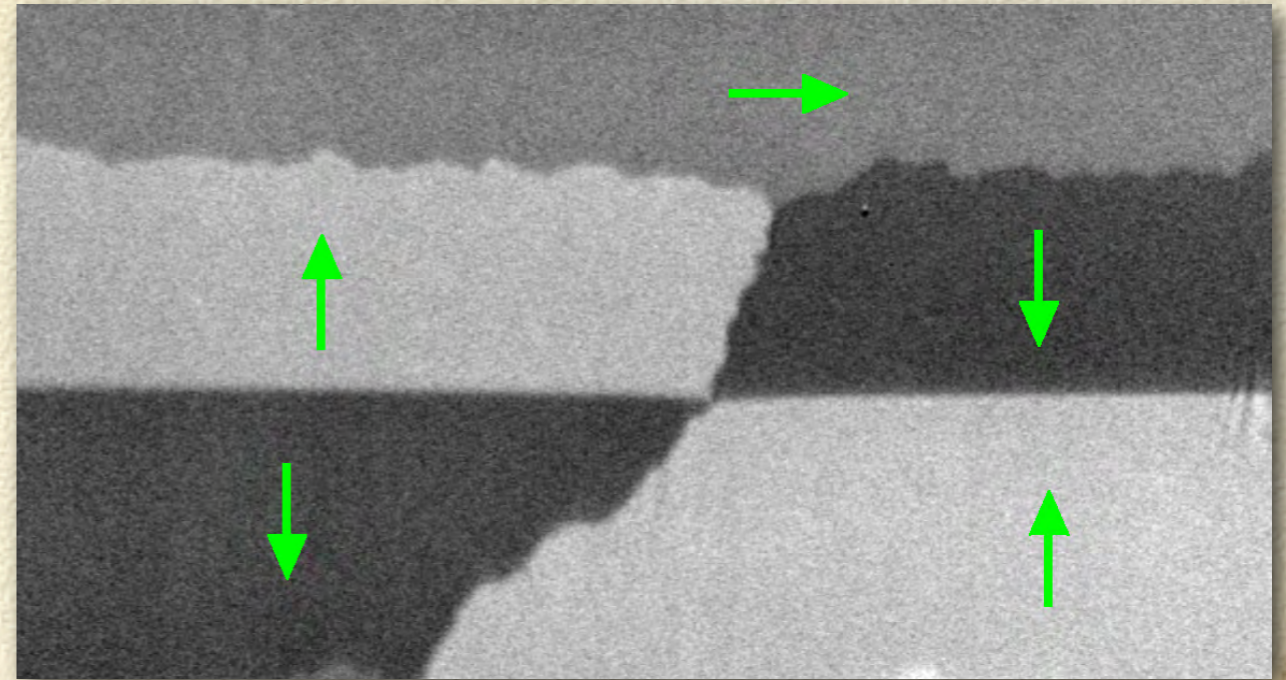


R.S., R Urban, D. Ullmann, H. L. Meyerheim, B. Heinrich,
L. Schultz, J. Kirschner, Phys. Rev. B 65, 144405 (2002)

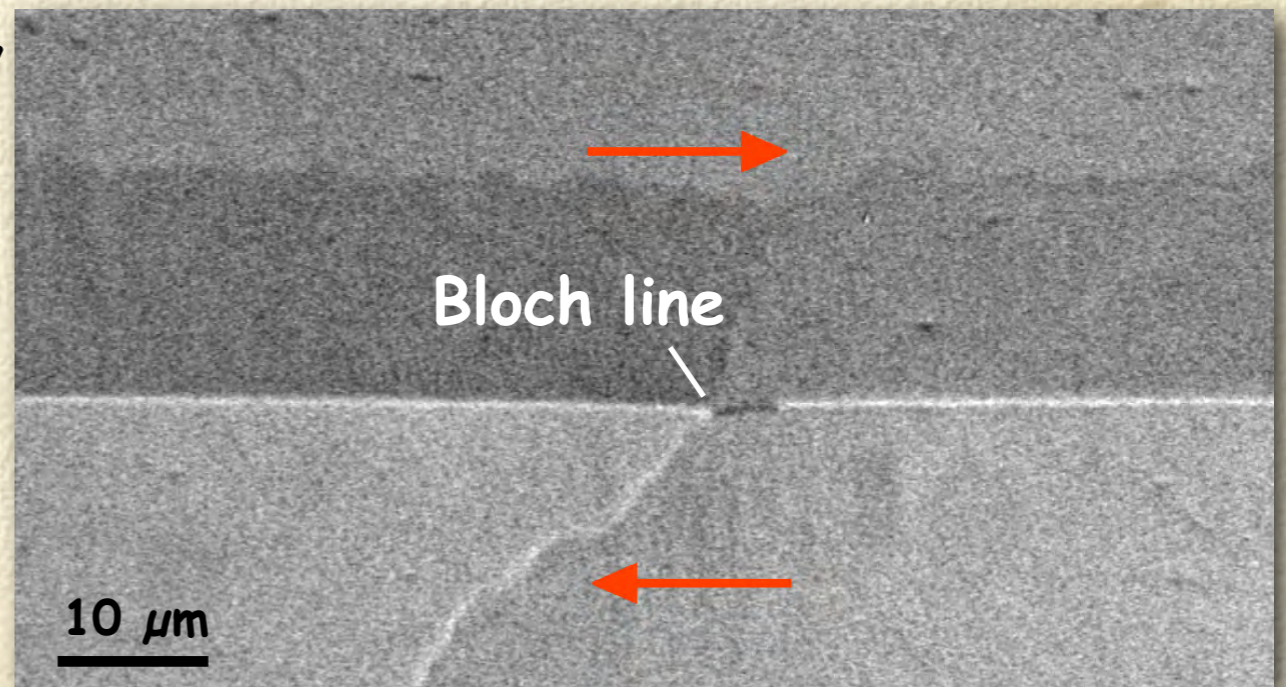
Layer-selective Kerr microscopy



Domains in Fe-film

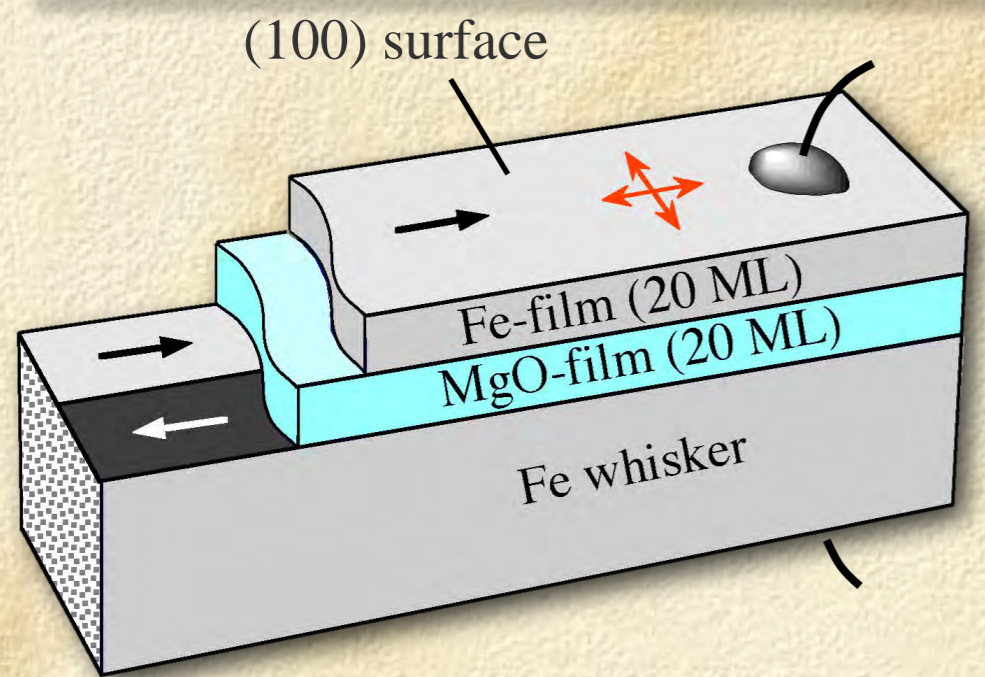


Domains in whisker

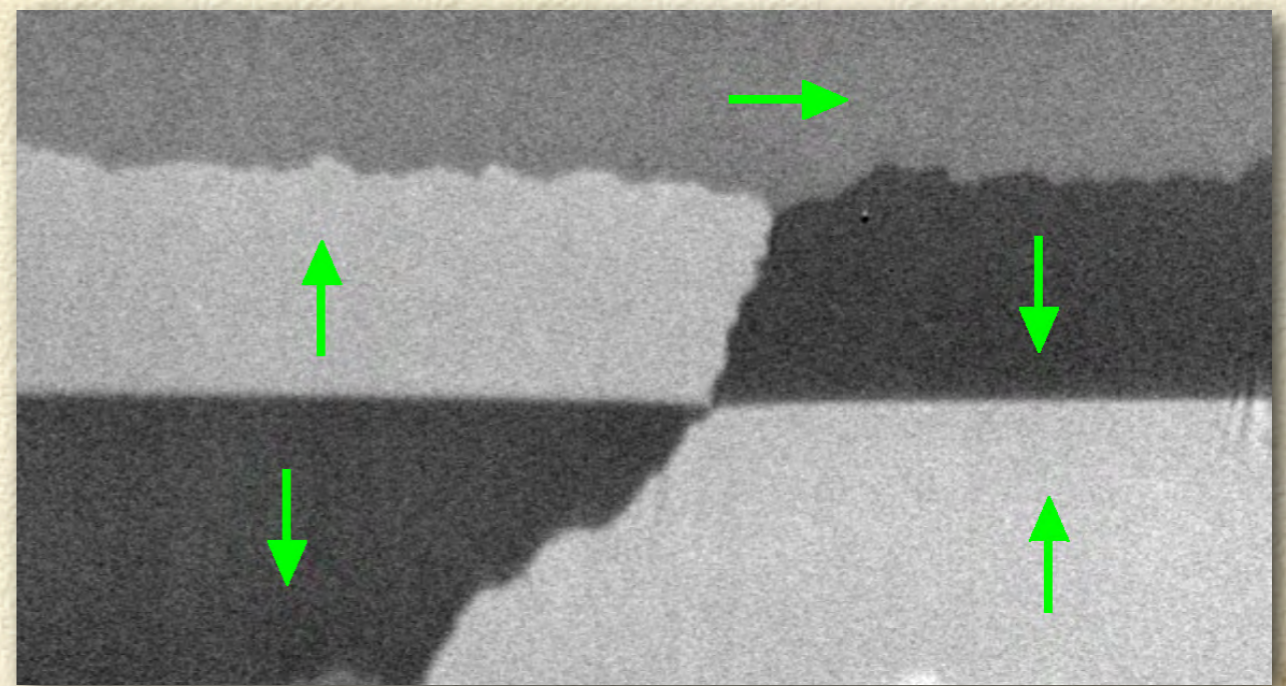


R.S., R Urban, D. Ullmann, H. L. Meyerheim, B. Heinrich, L. Schultz, J. Kirschner, Phys. Rev. B 65, 144405 (2002)

Layer-selective Kerr microscopy

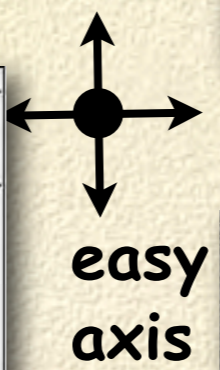
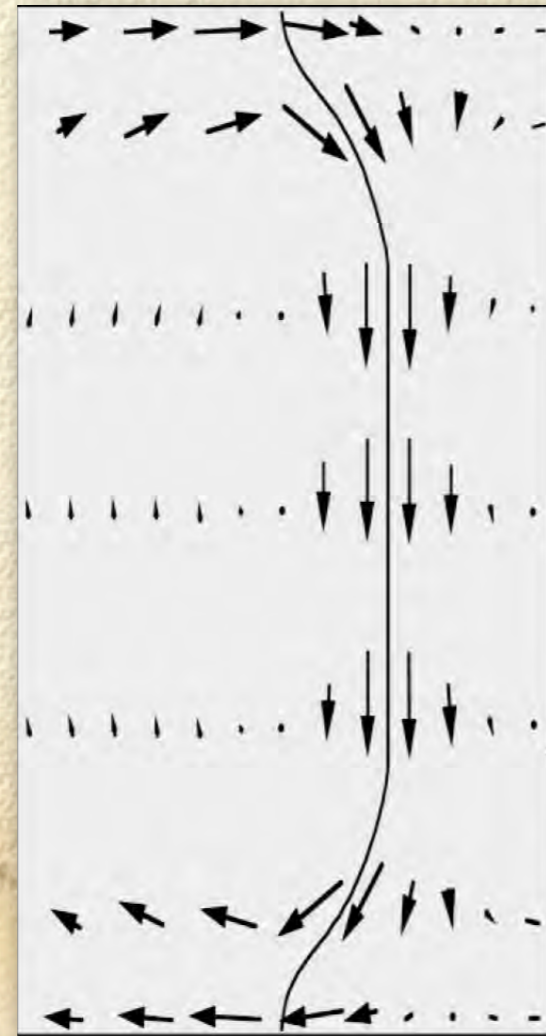
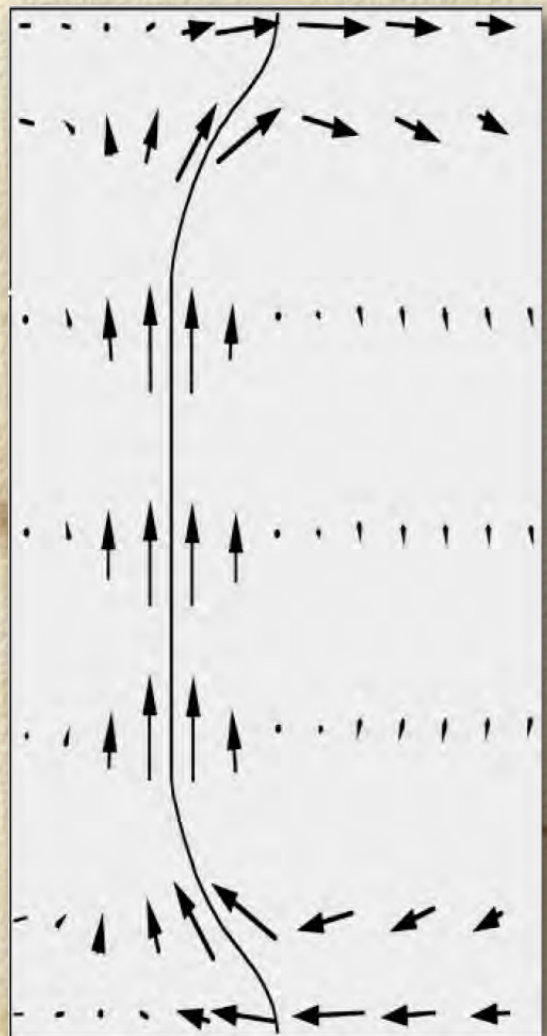


Domains in Fe-film

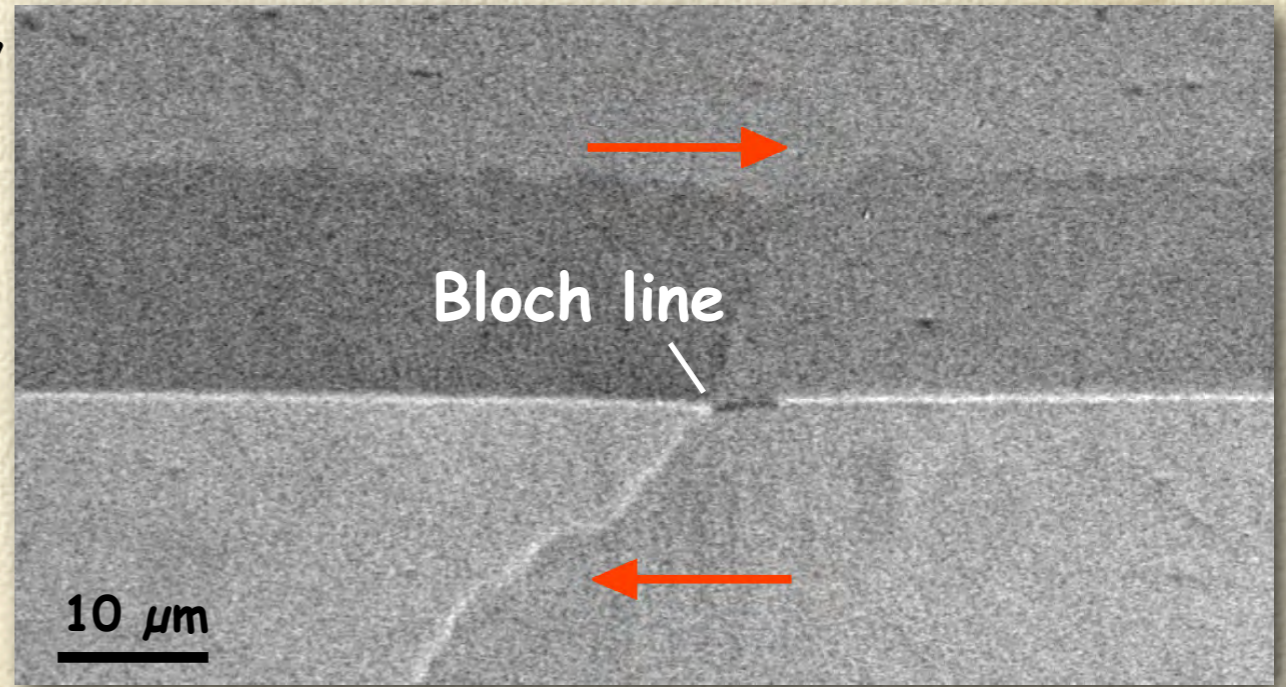


N

S

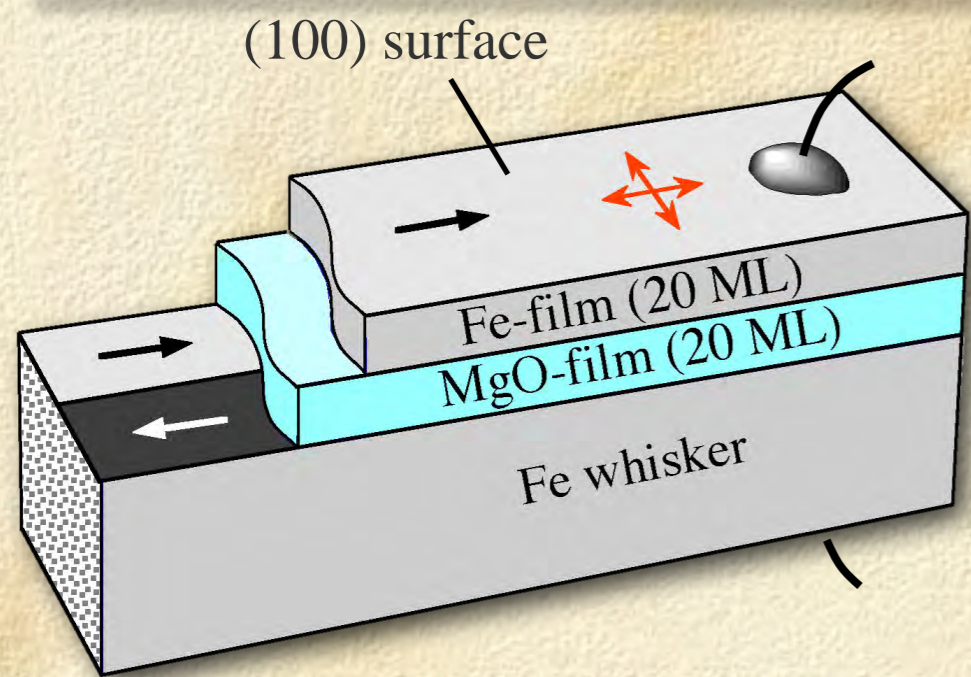


Domains in whisker

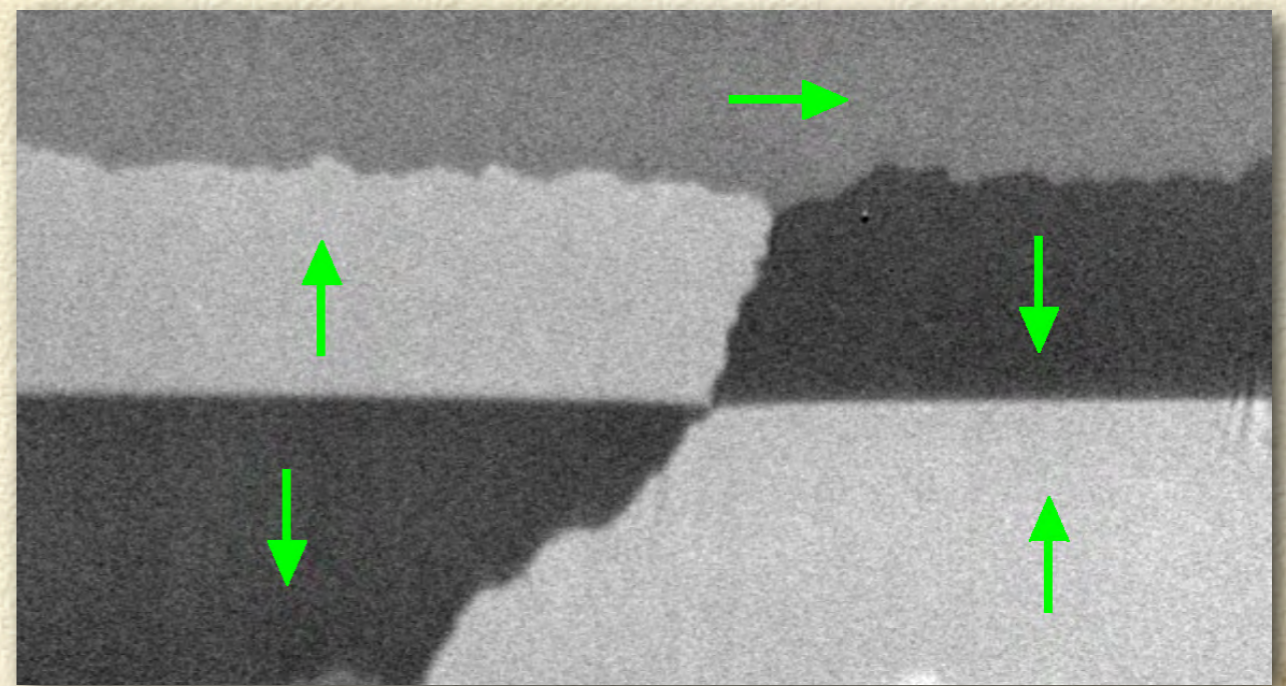


...an, D. Ullmann, H. L. Meyerheim, B. Heinrich, J. Kirschner, Phys. Rev. B 65, 144405 (2002)

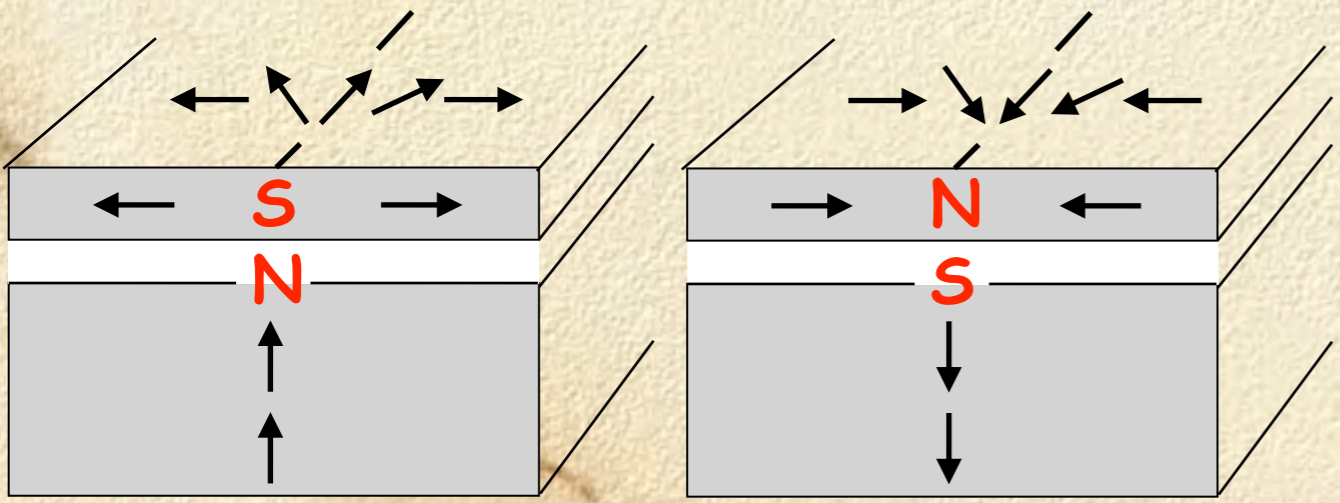
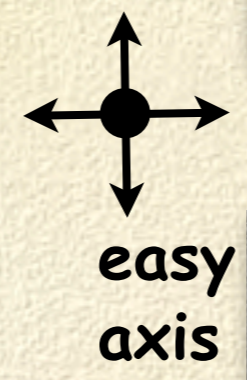
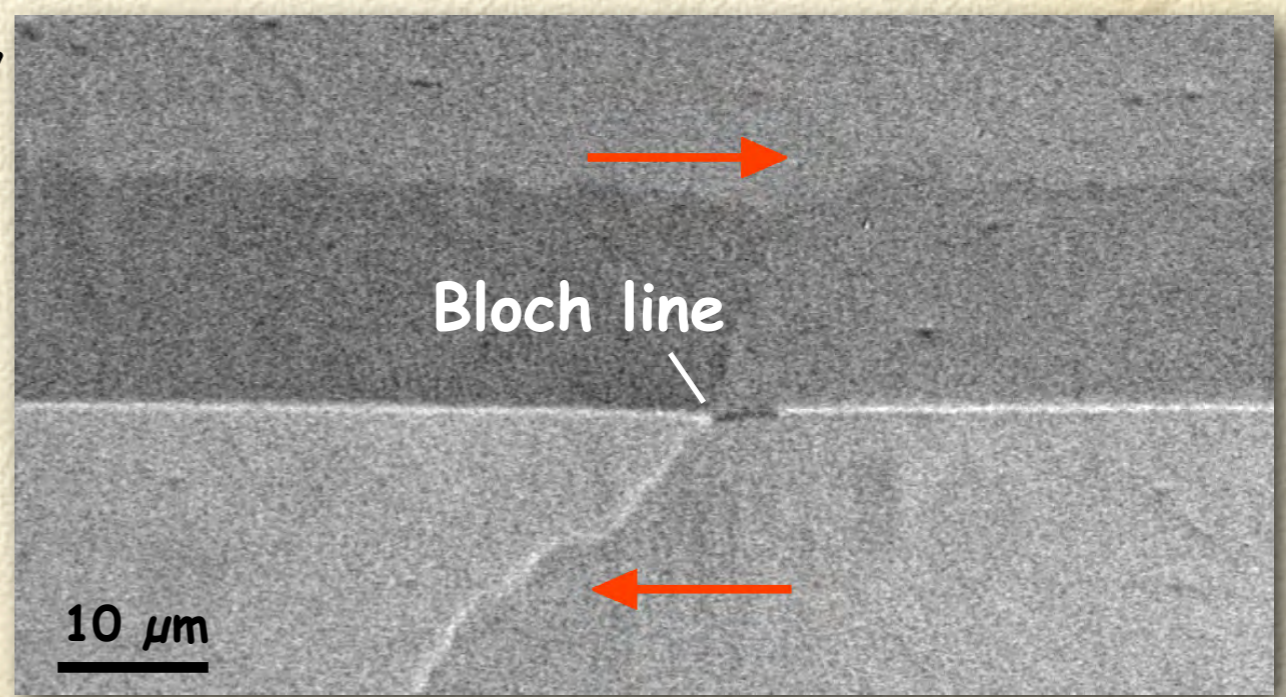
Layer-selective Kerr microscopy



Domains in Fe-film



Domains in whisker

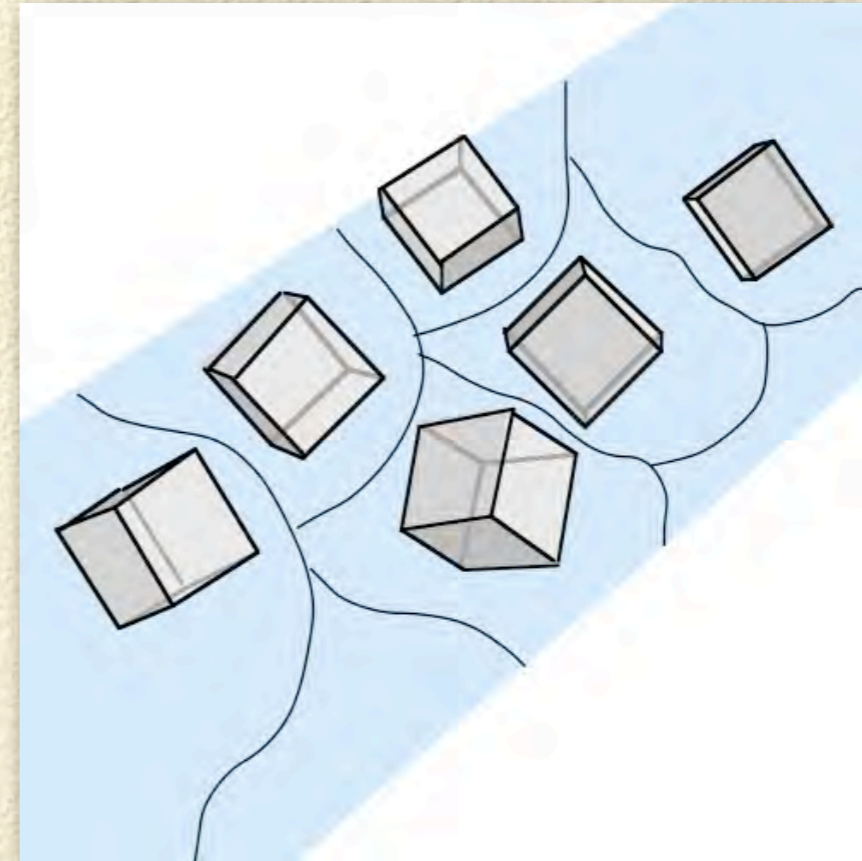


R.S., R Urban, D. Ullmann, H. L. Meyerheim, B. Heinrich, L. Schultz, J. Kirschner, Phys. Rev. B 65, 144405 (2002)

**Bulk materials:
Domain analysis can be more or less
difficult**

Non-oriented FeSi sheet

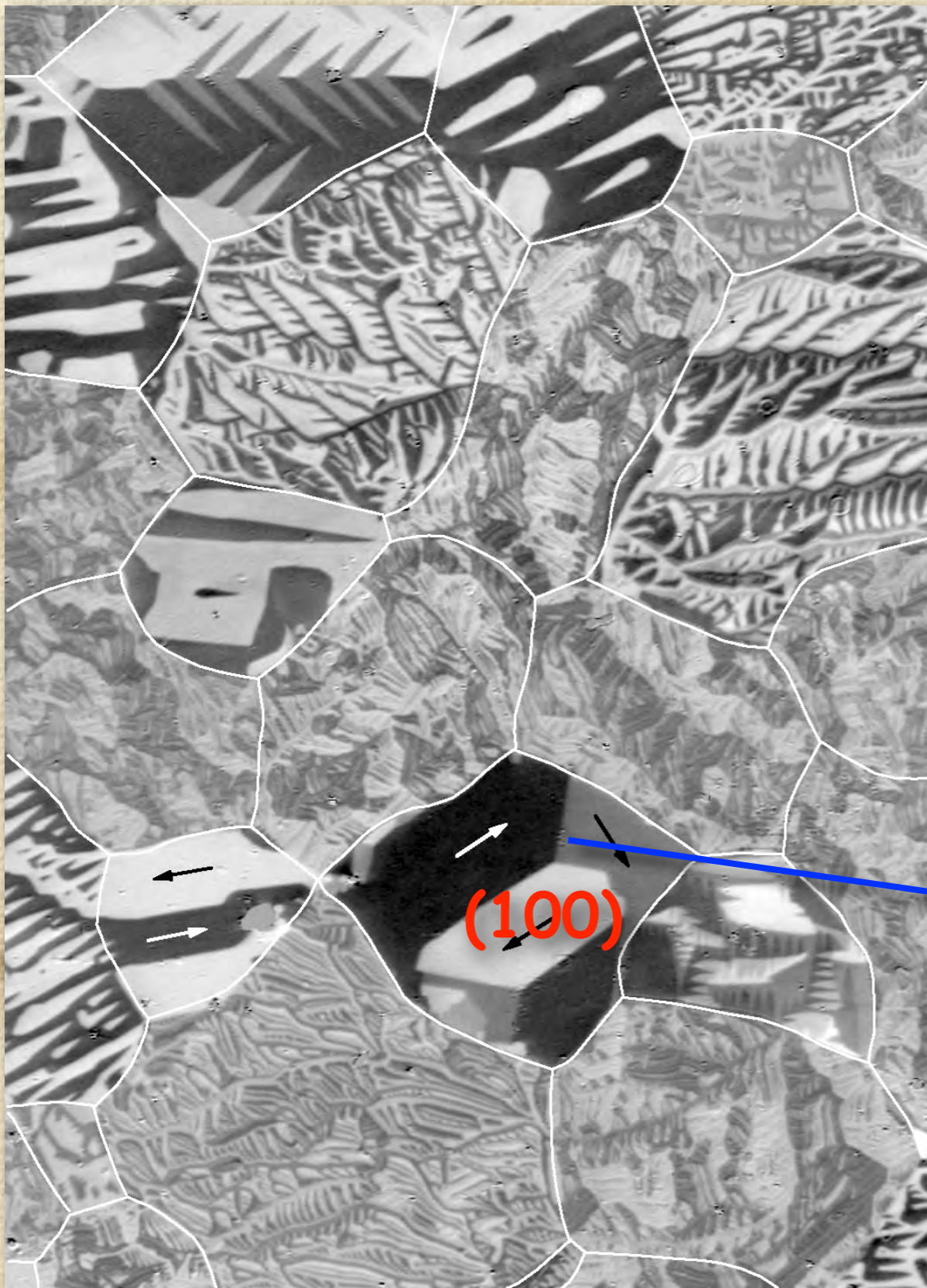
(Fe-3%Si,
non-oriented electrical steel
0.5 mm thick)



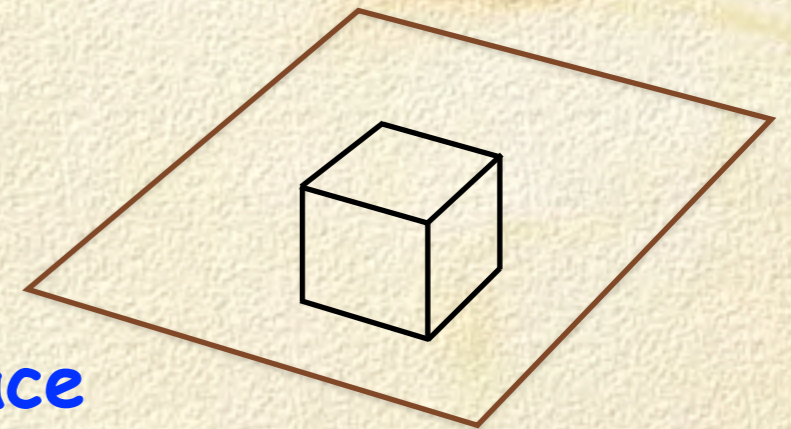
**Surface orientation
determines
domain character**

0.5 mm

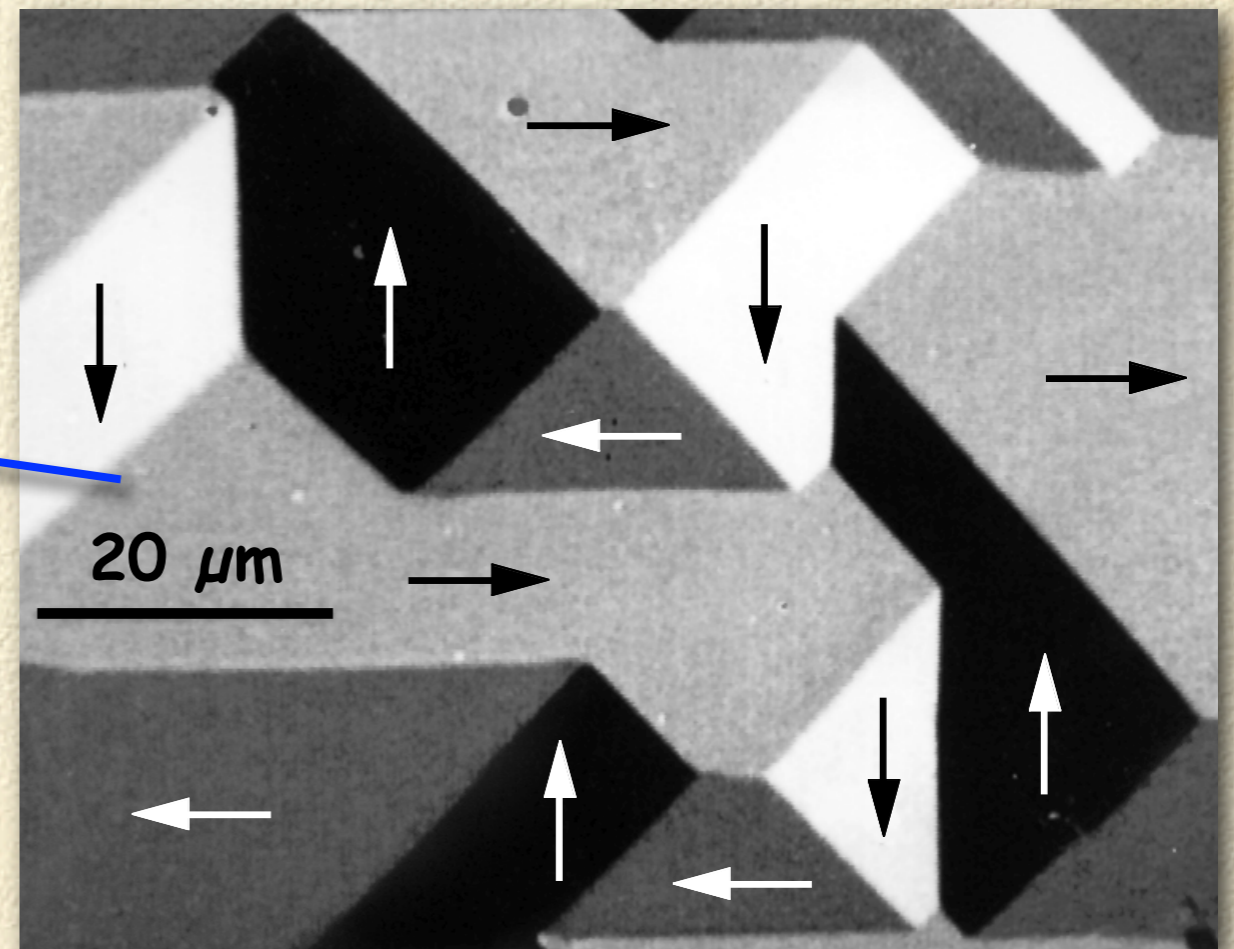
Non-oriented FeSi sheet



0.5 mm

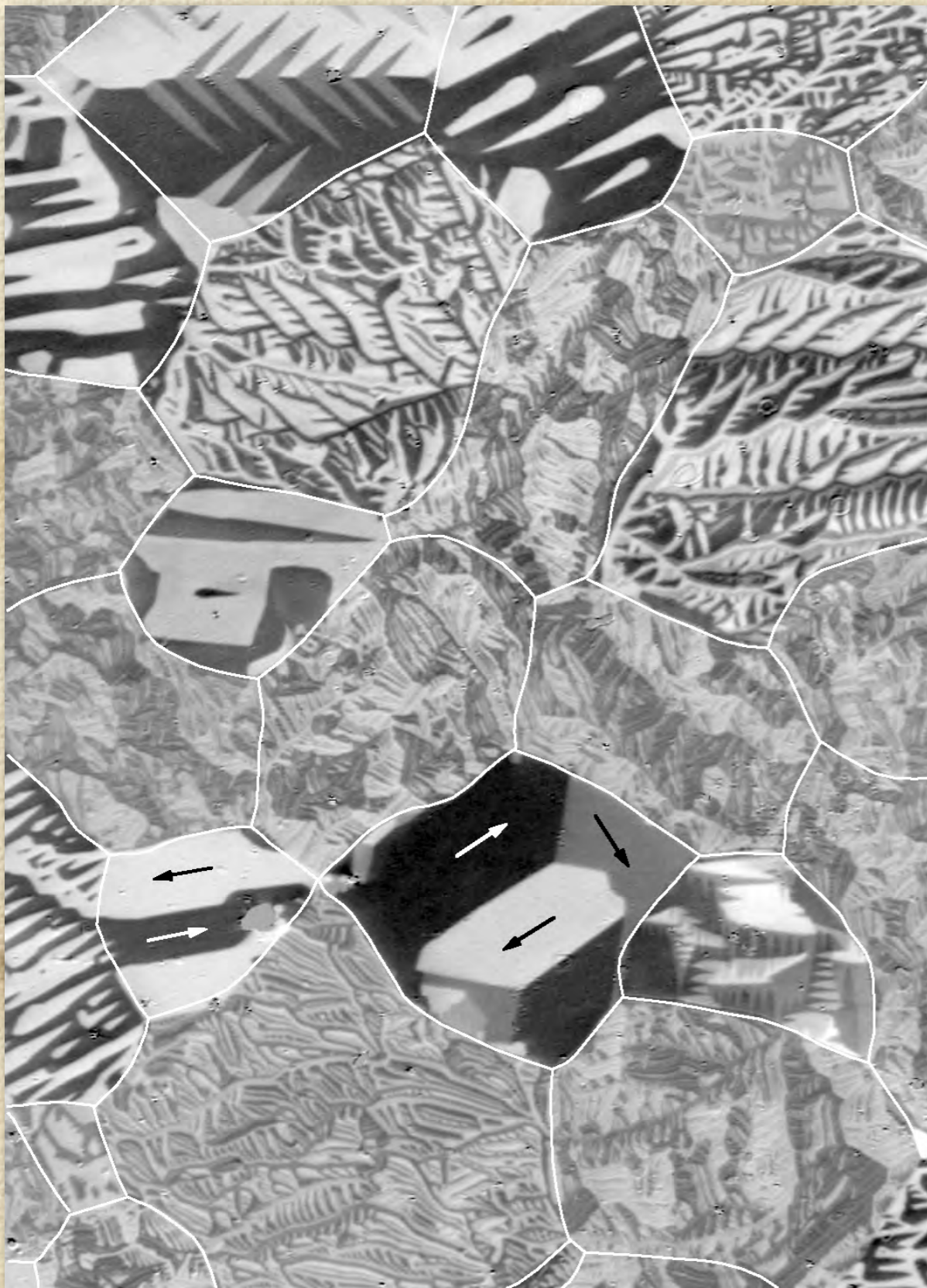


(100)-surface



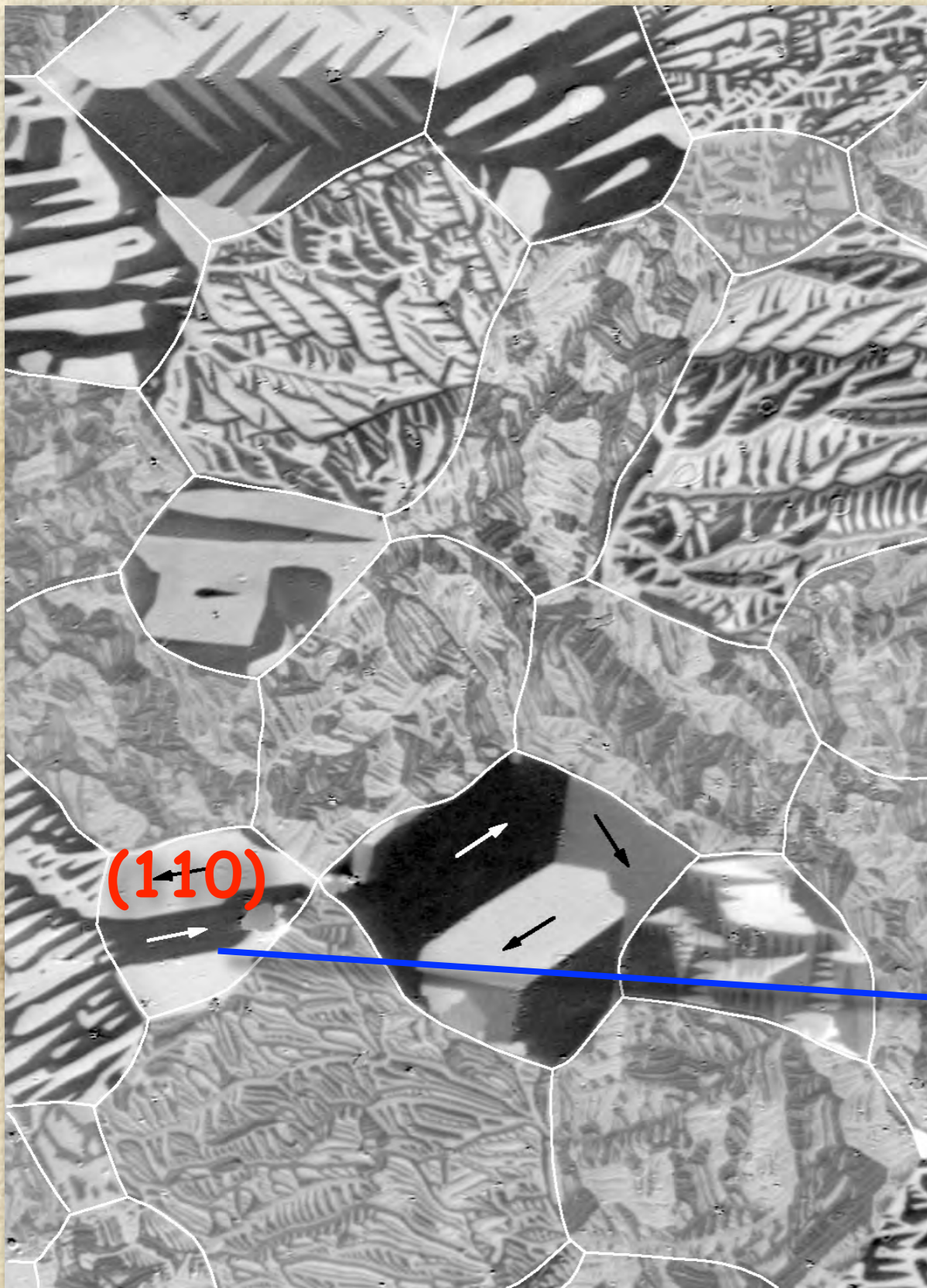
20 μm

Non-oriented FeSi sheet

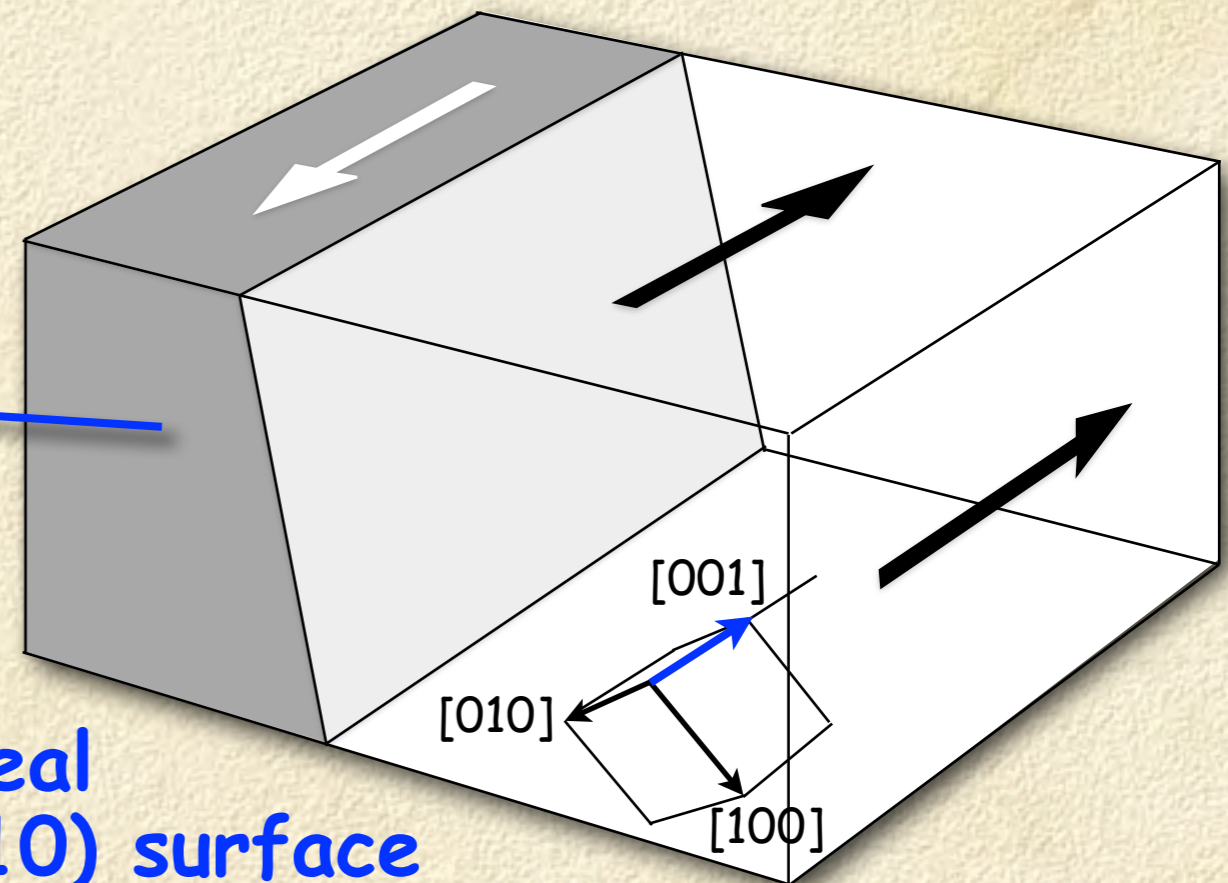


0.5 mm

Non-oriented FeSi sheet

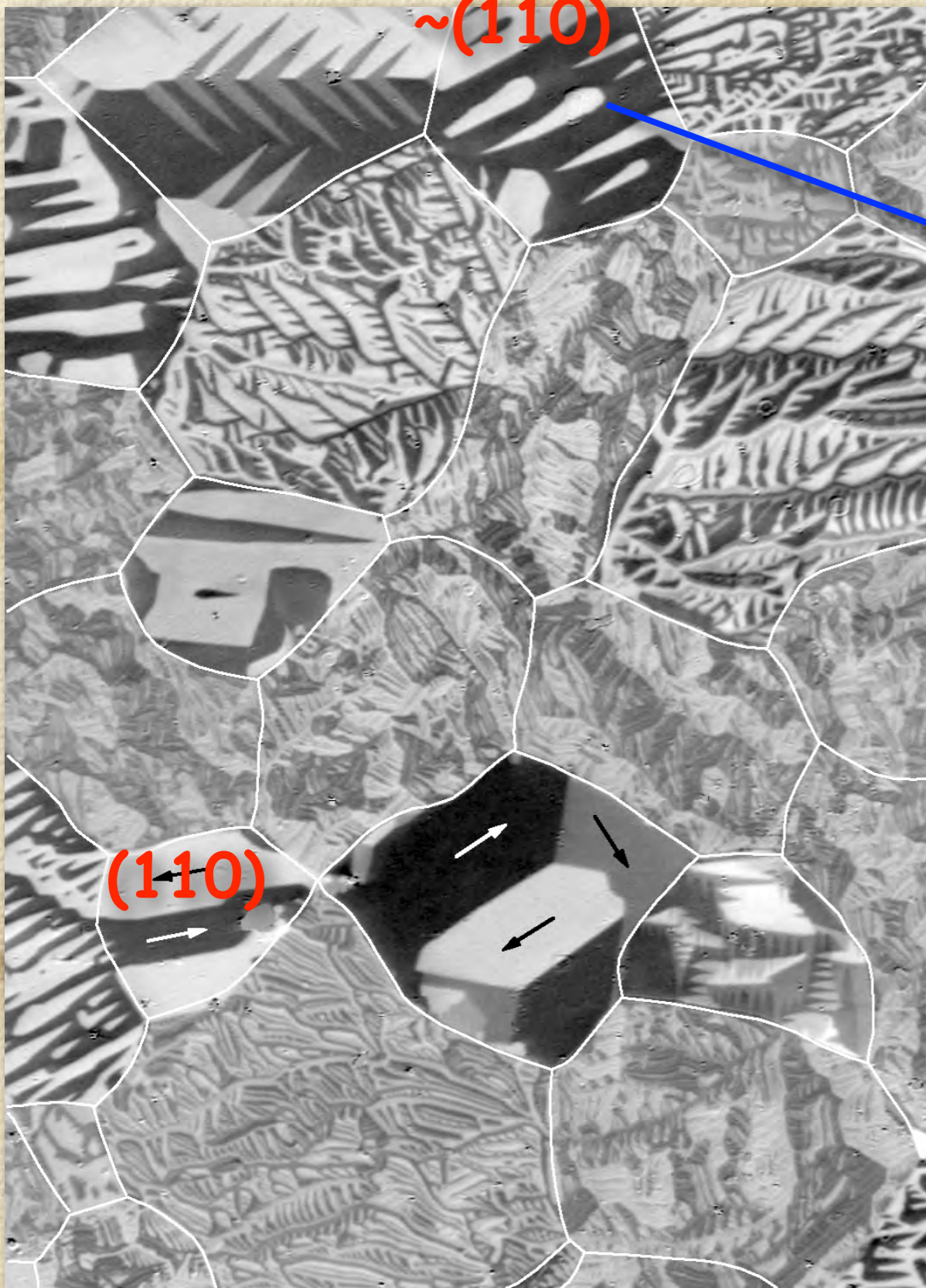


0.5 mm

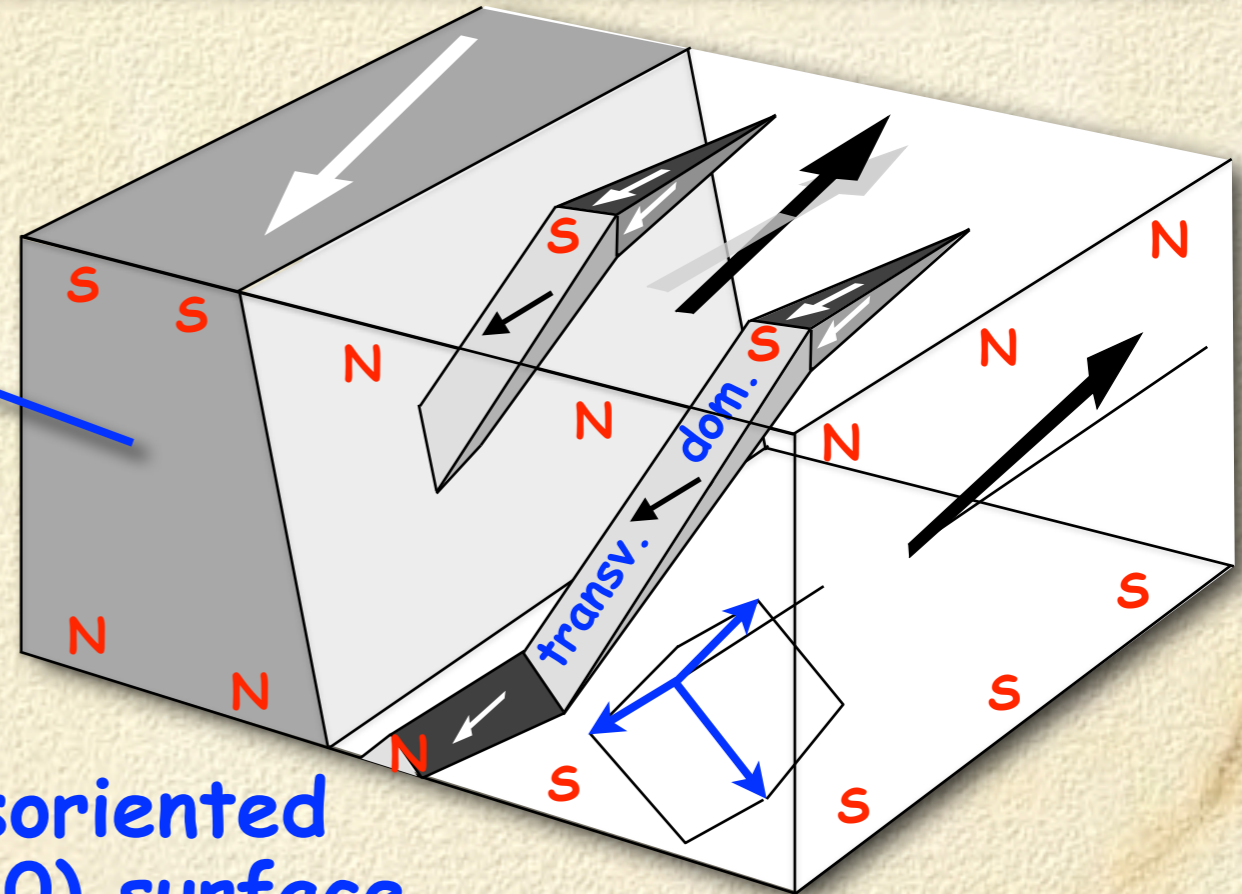


Ideal
 (110) surface

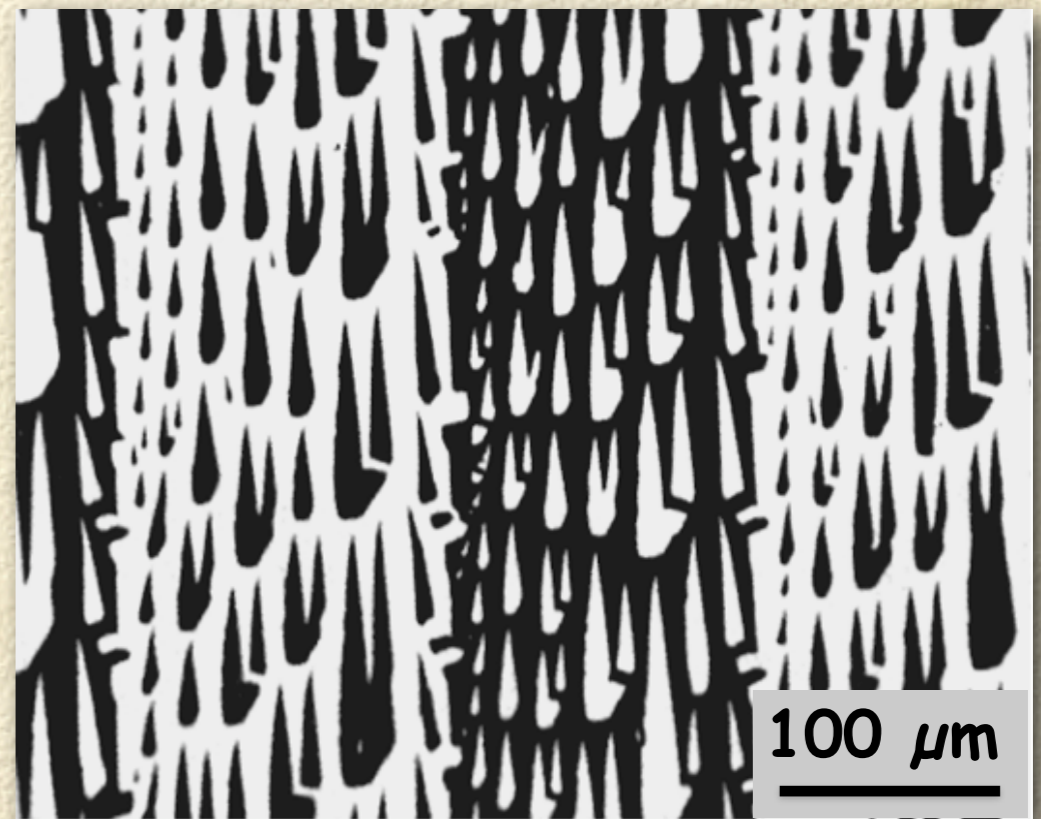
Non-oriented FeSi sheet



0.5 mm

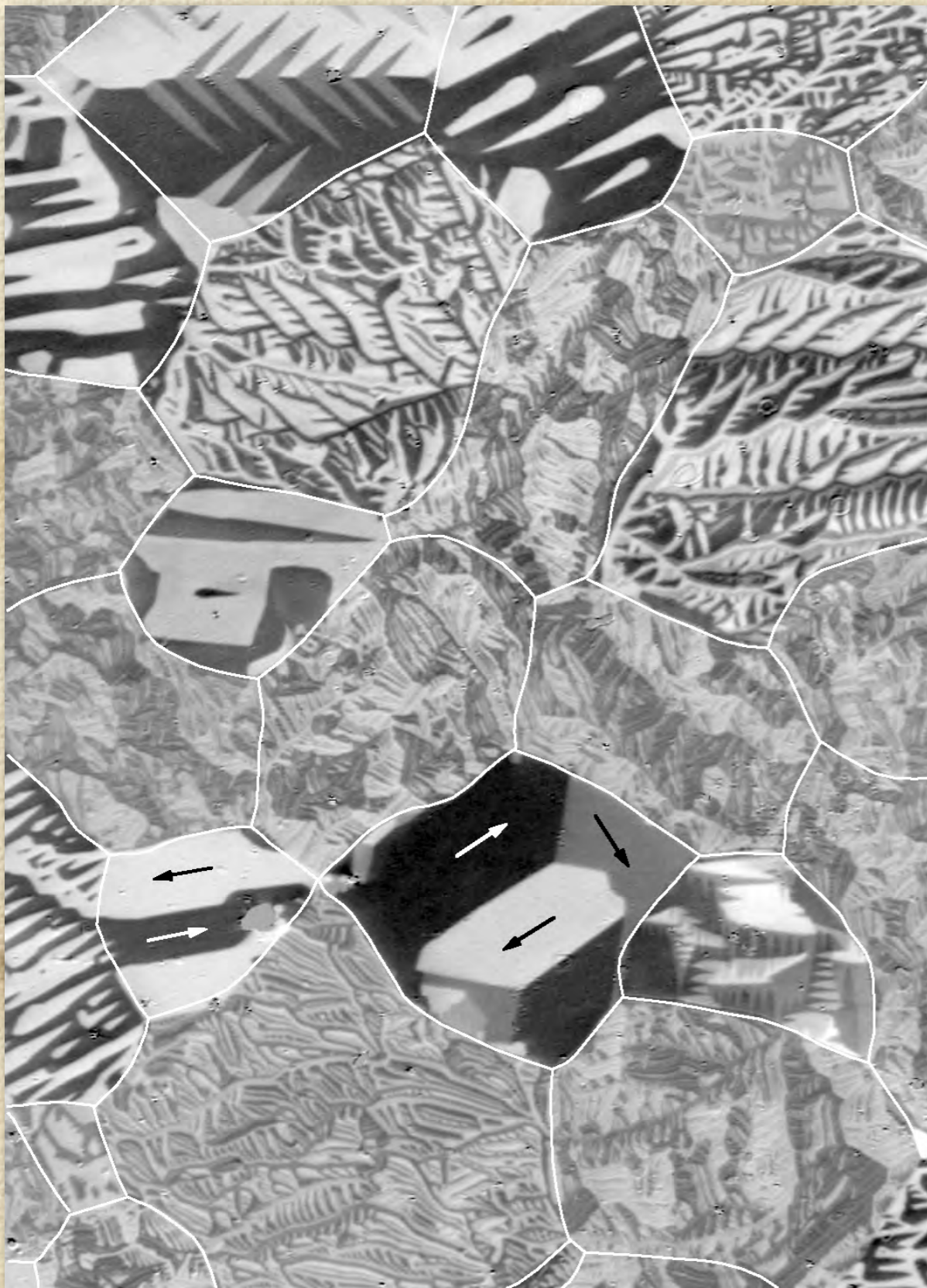


Misoriented
(110) surface



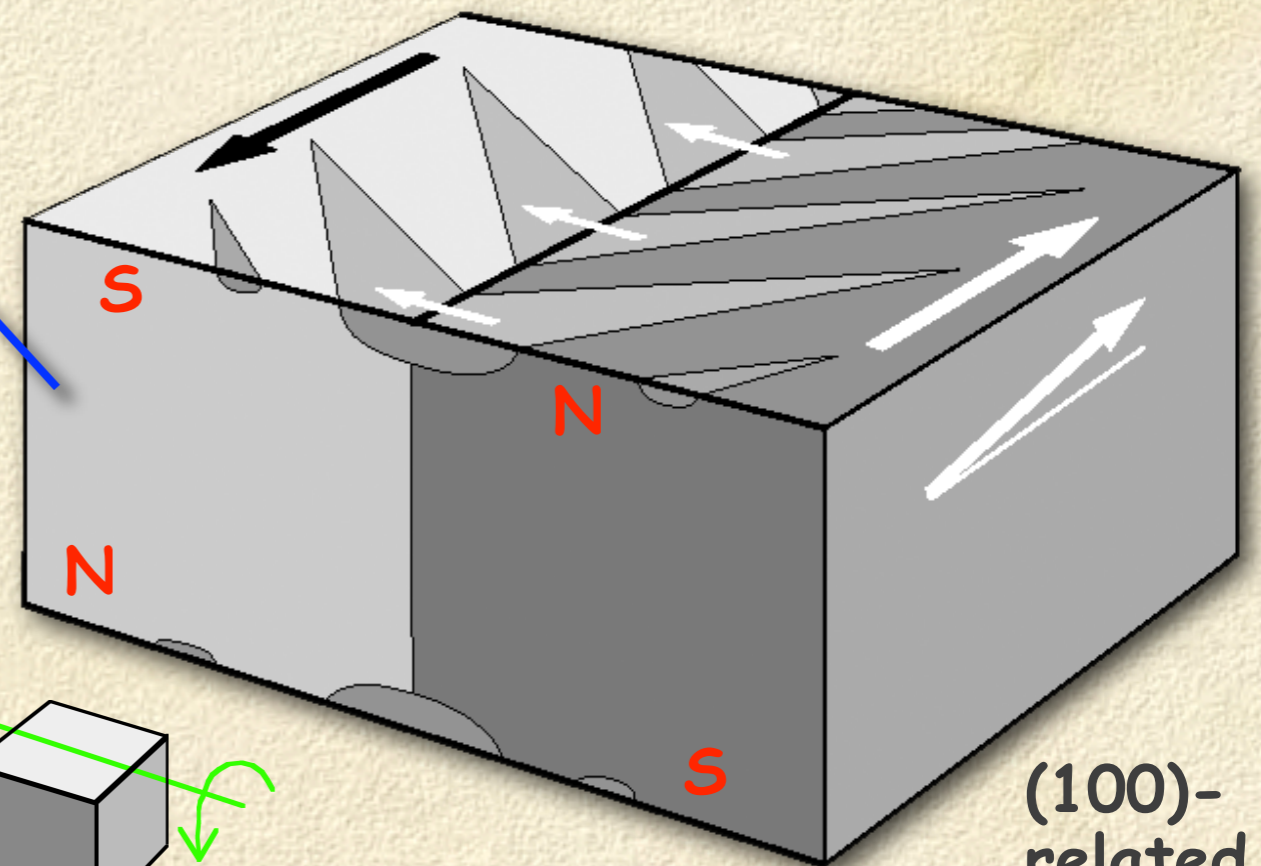
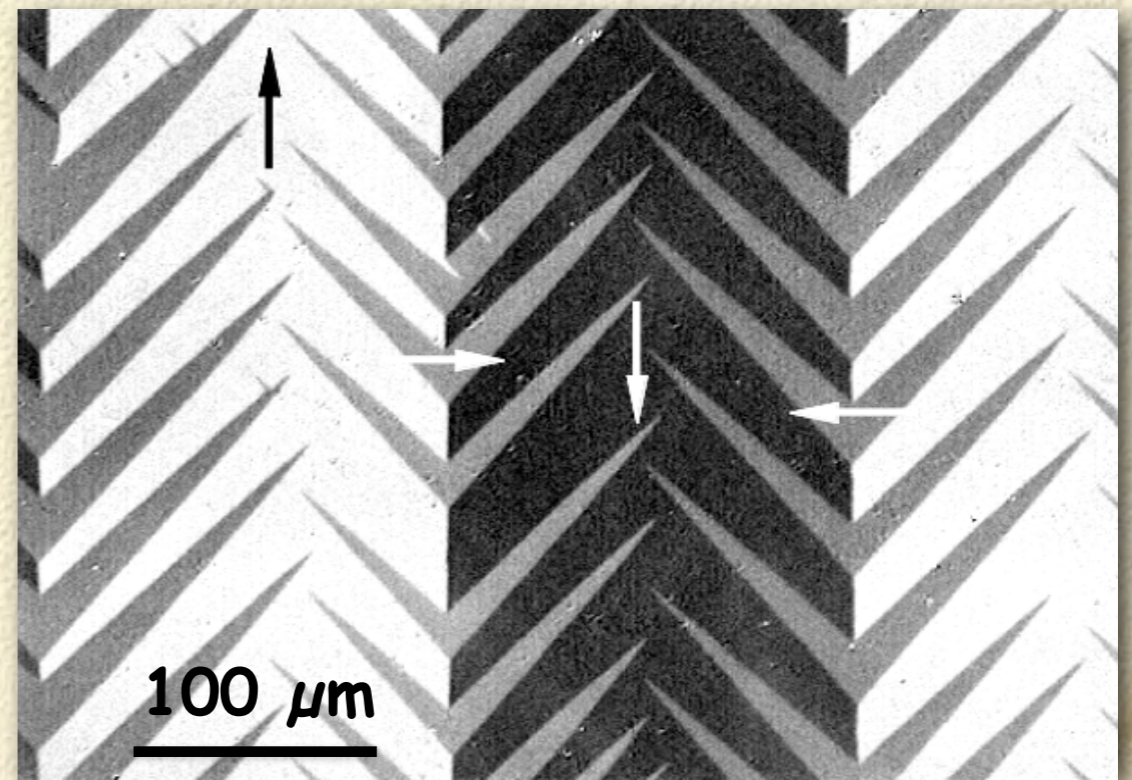
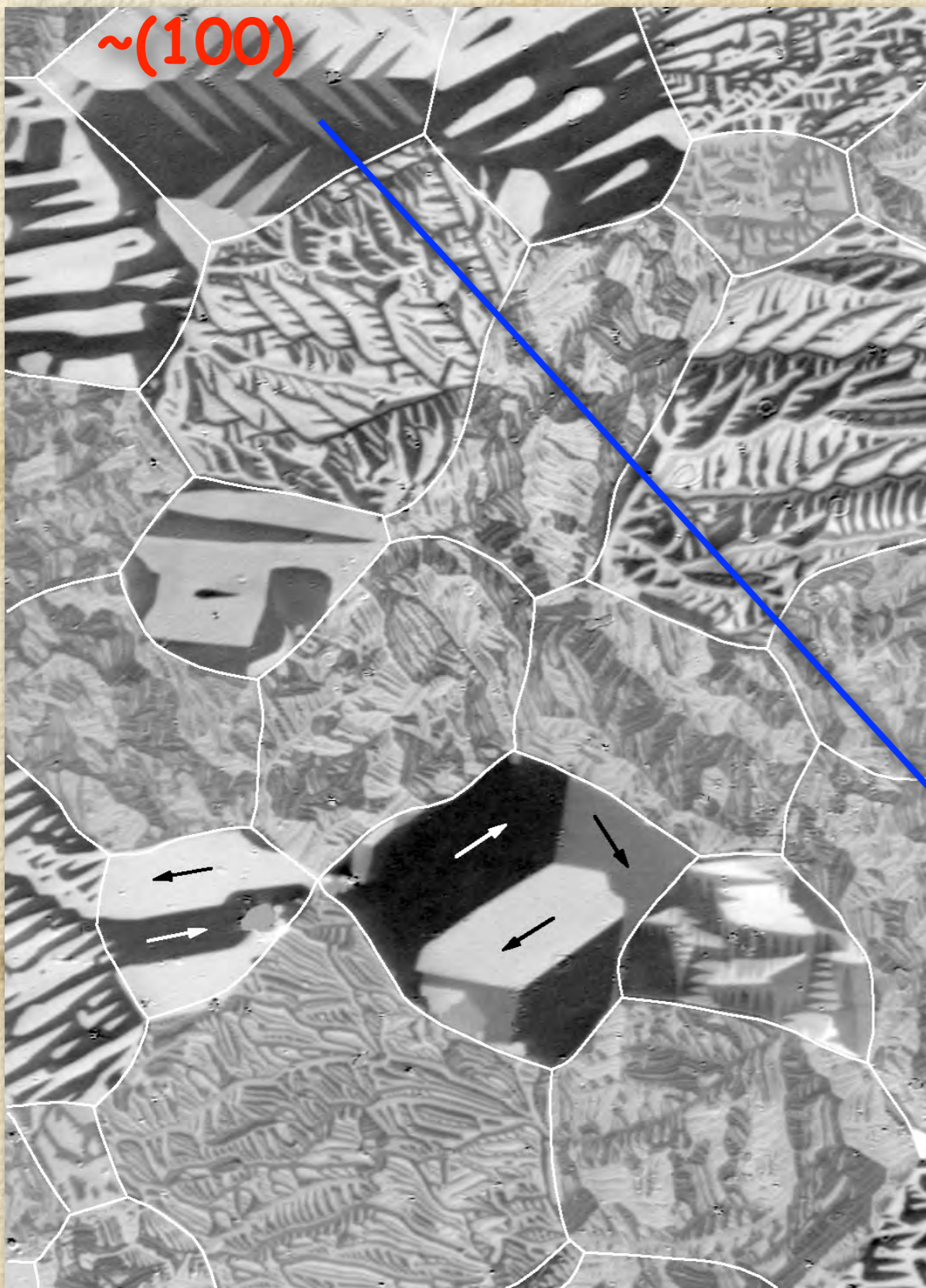
100 μm

Non-oriented FeSi sheet



0.5 mm

Non-oriented FeSi sheet



Non-oriented FeSi sheet



0.5 mm

For well-oriented and slightly misoriented grains domains can be interpreted:

basic domains and supplementary pattern

Non-oriented FeSi sheet

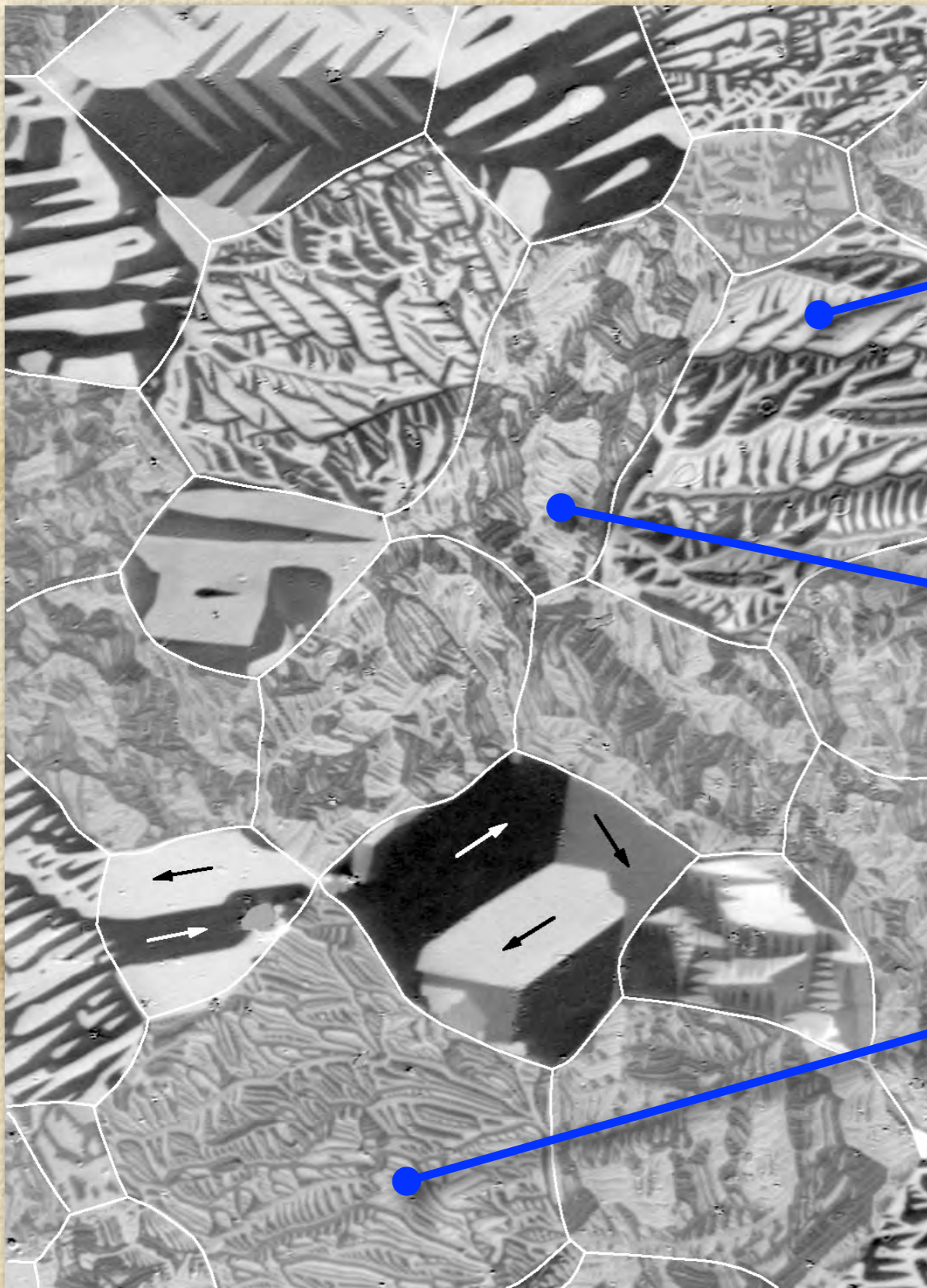


0.5 mm

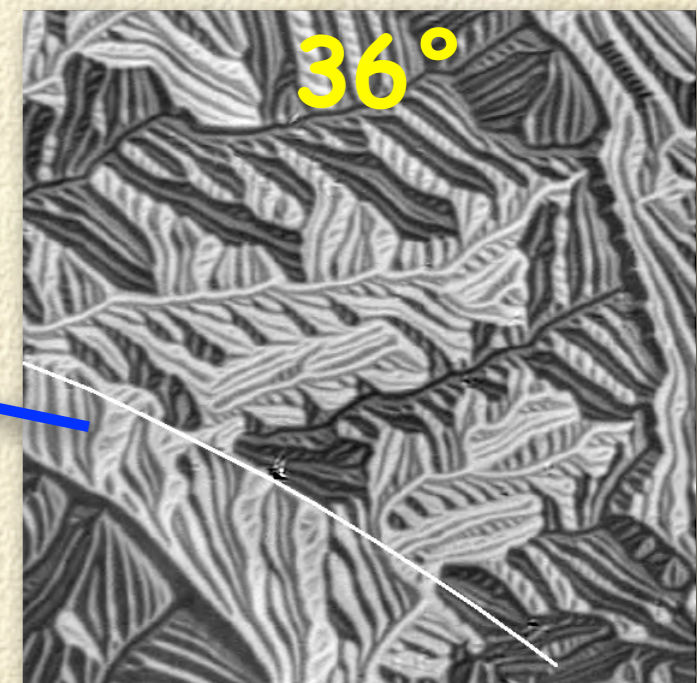
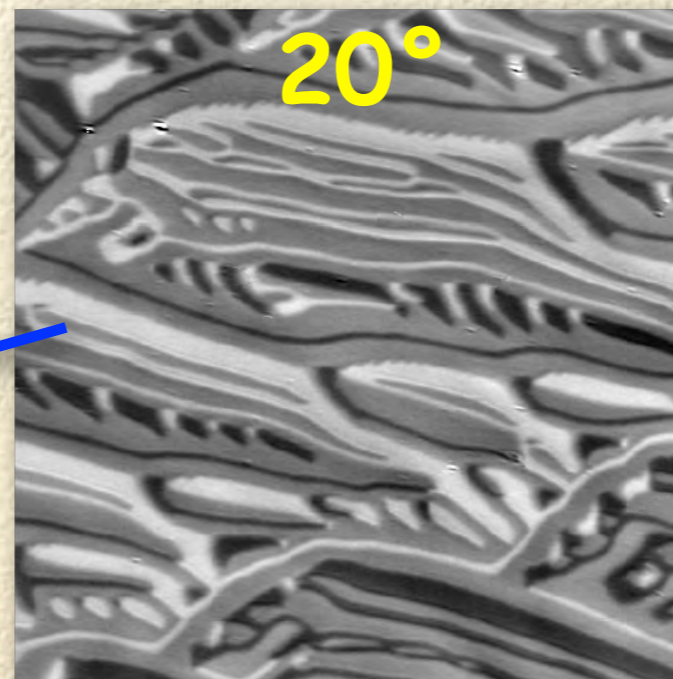
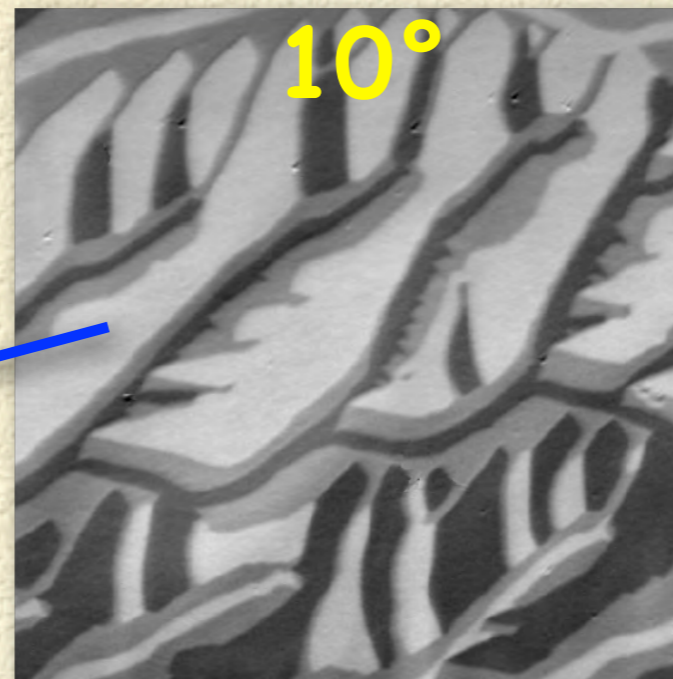
For well-oriented and slightly misoriented grains domains can be interpreted:

basic domains and supplementary pattern

Non-oriented FeSi sheet

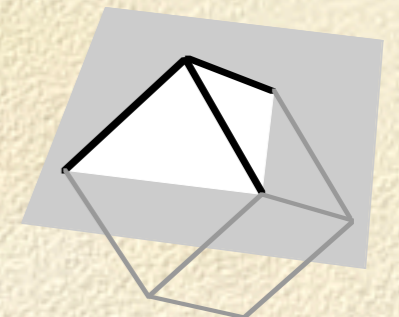


0.5 mm

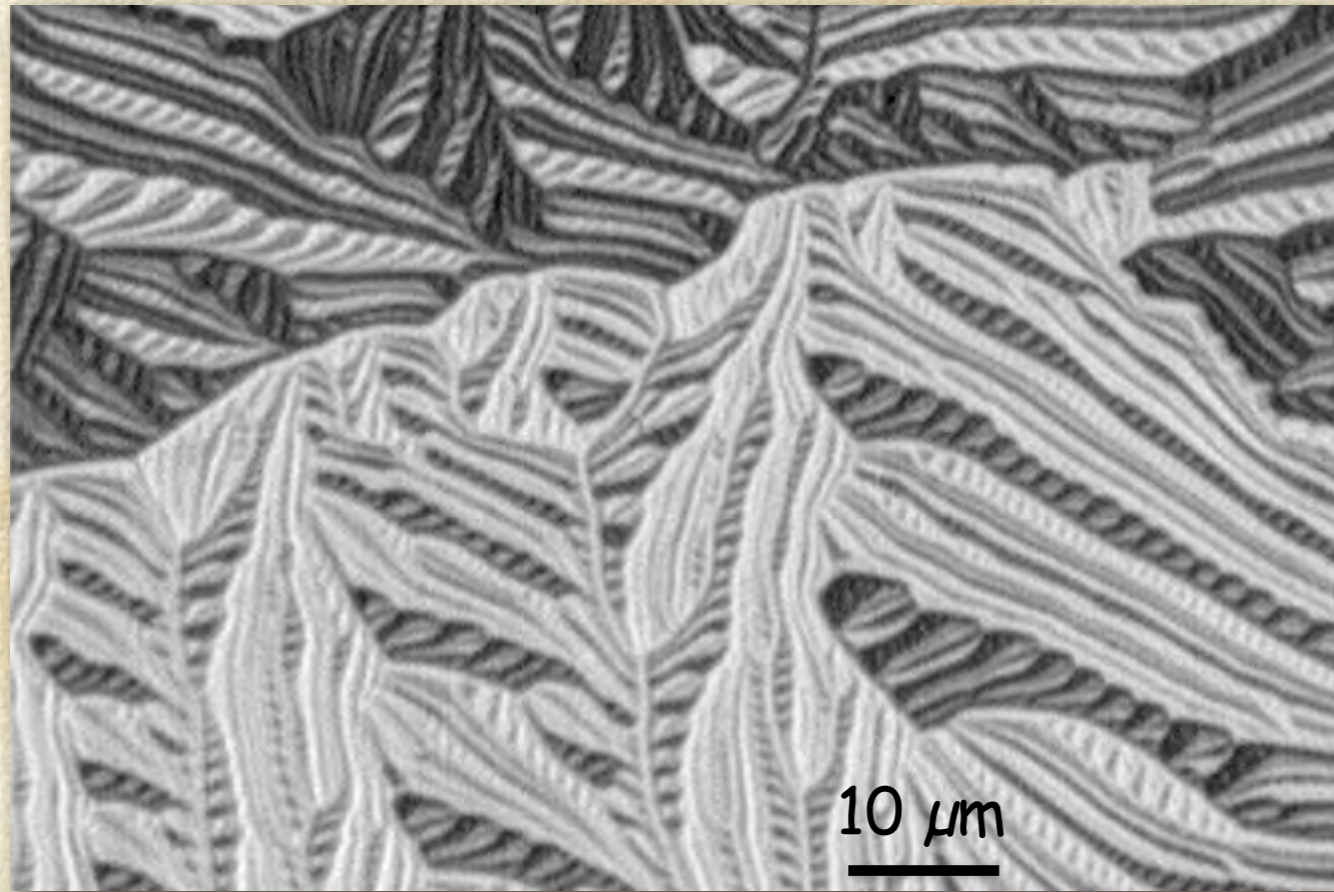


10 μm

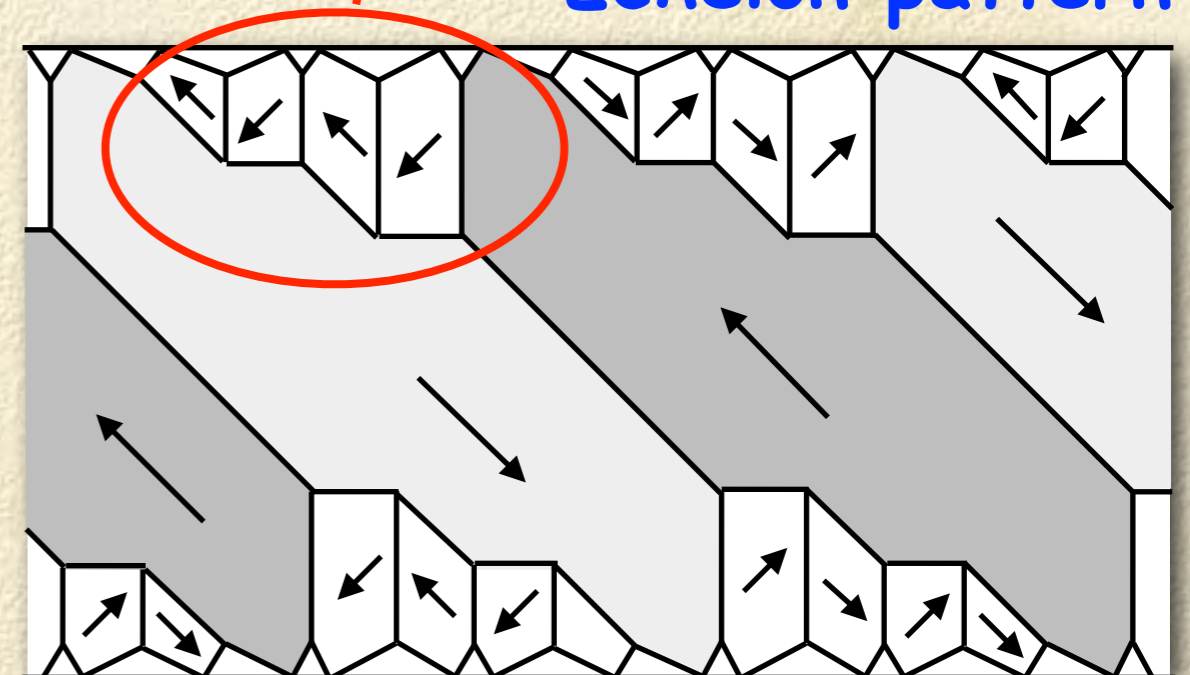
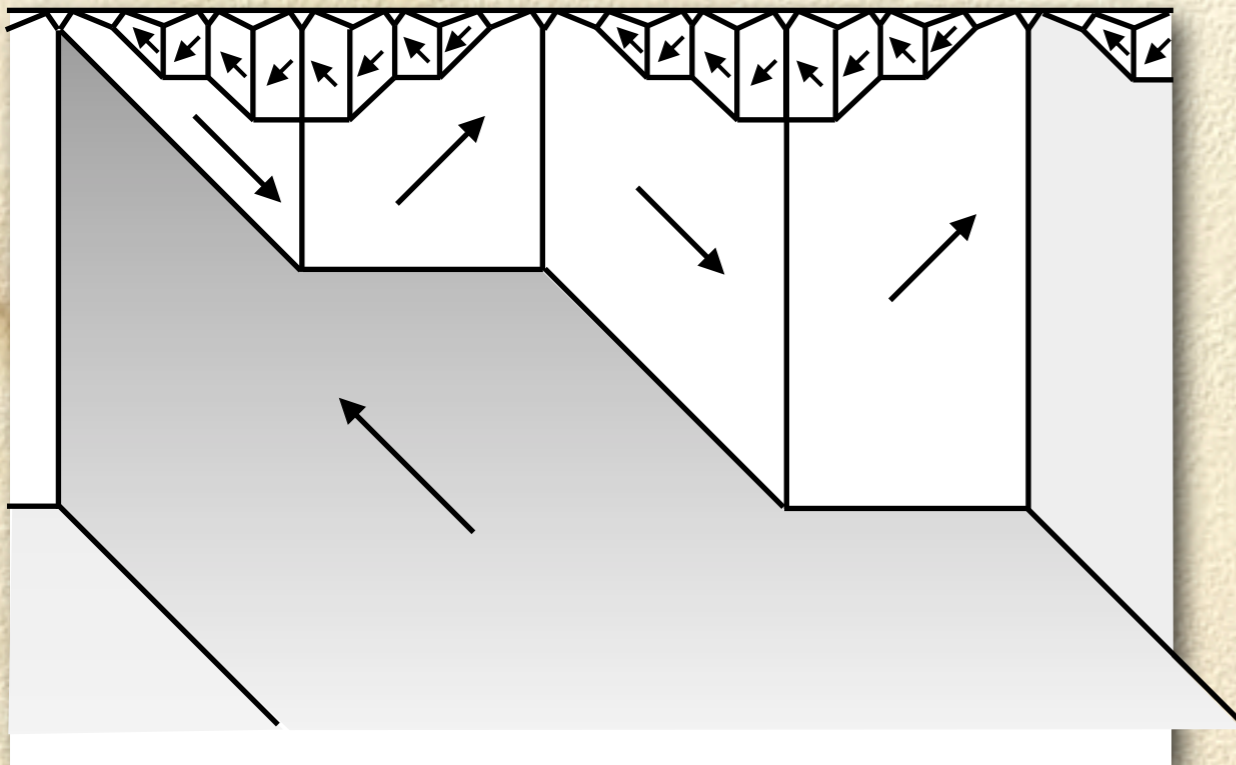
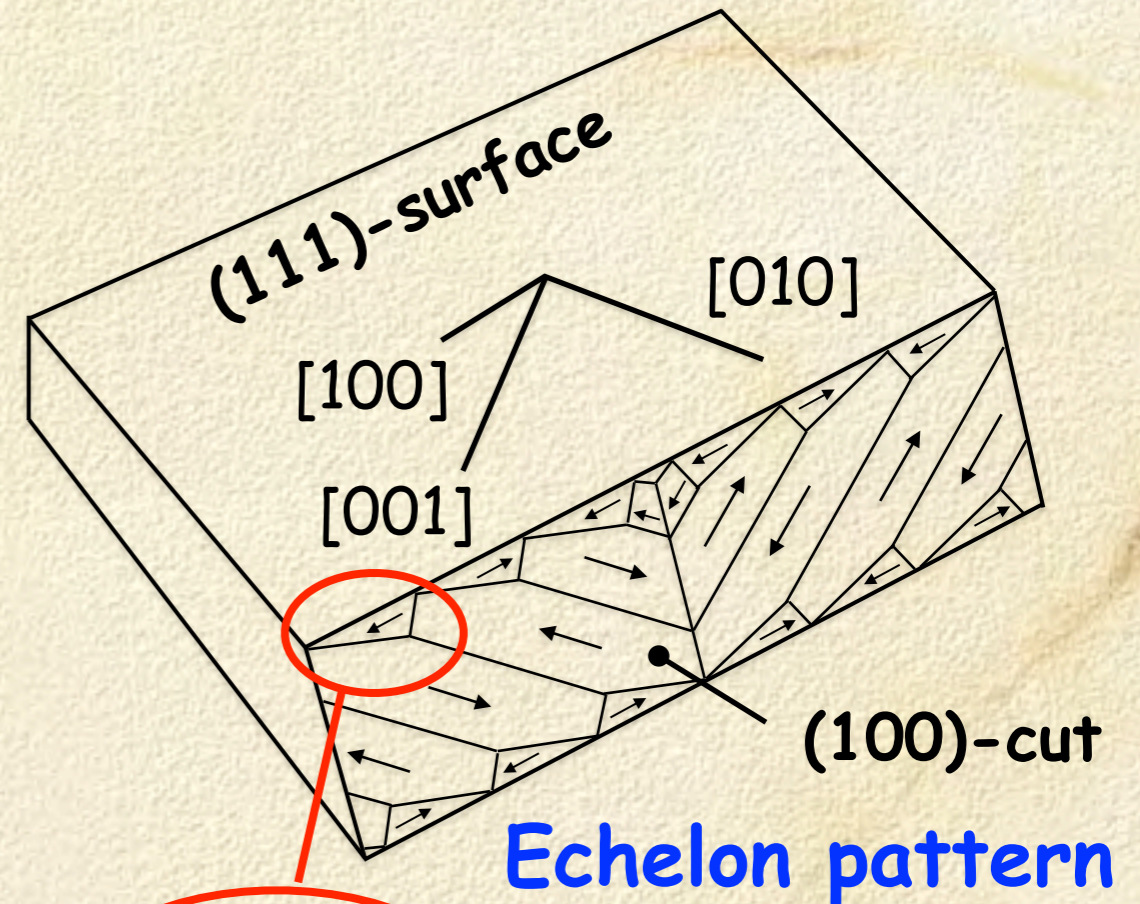
(111)-surface



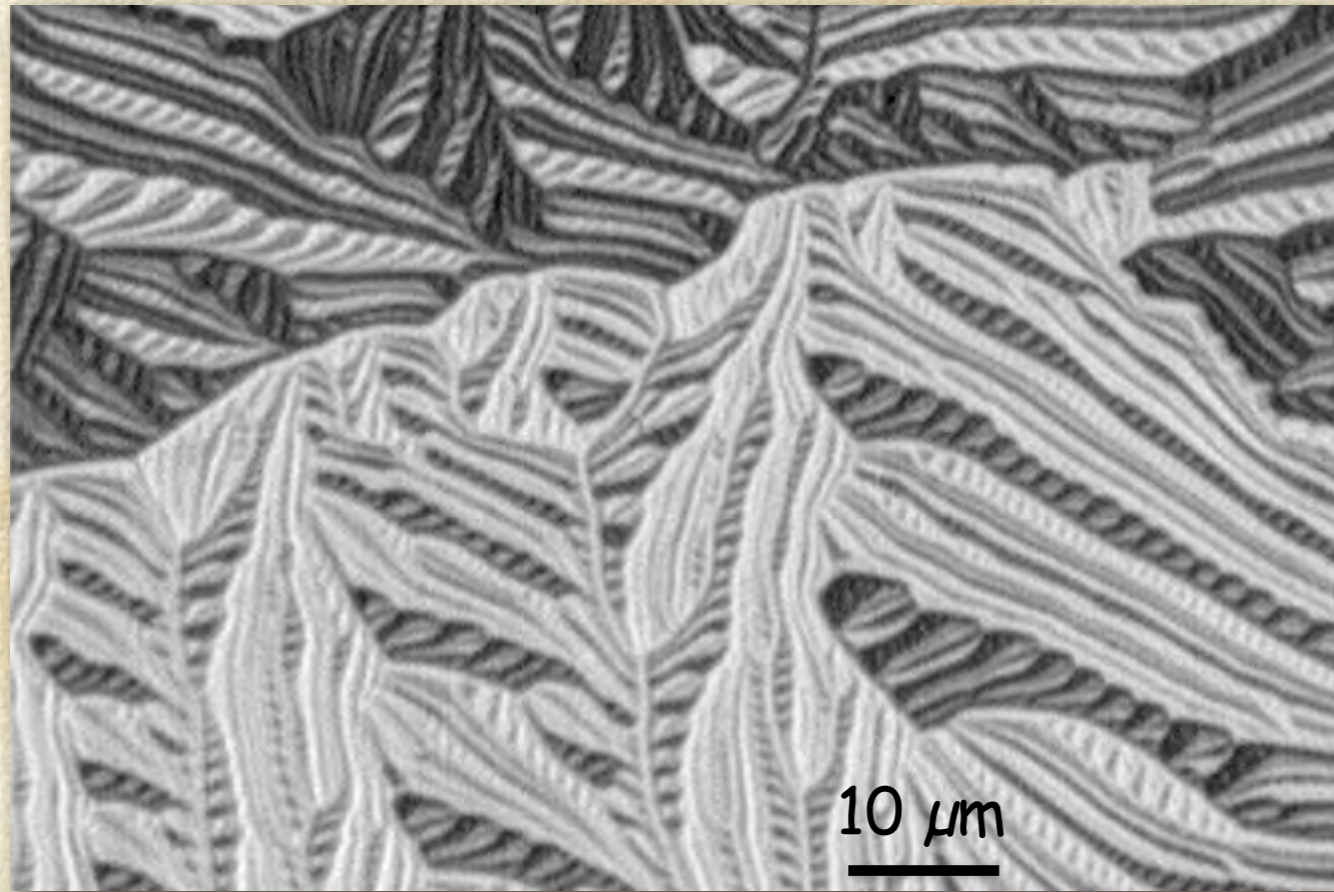
Extreme misorientation: Domain branching



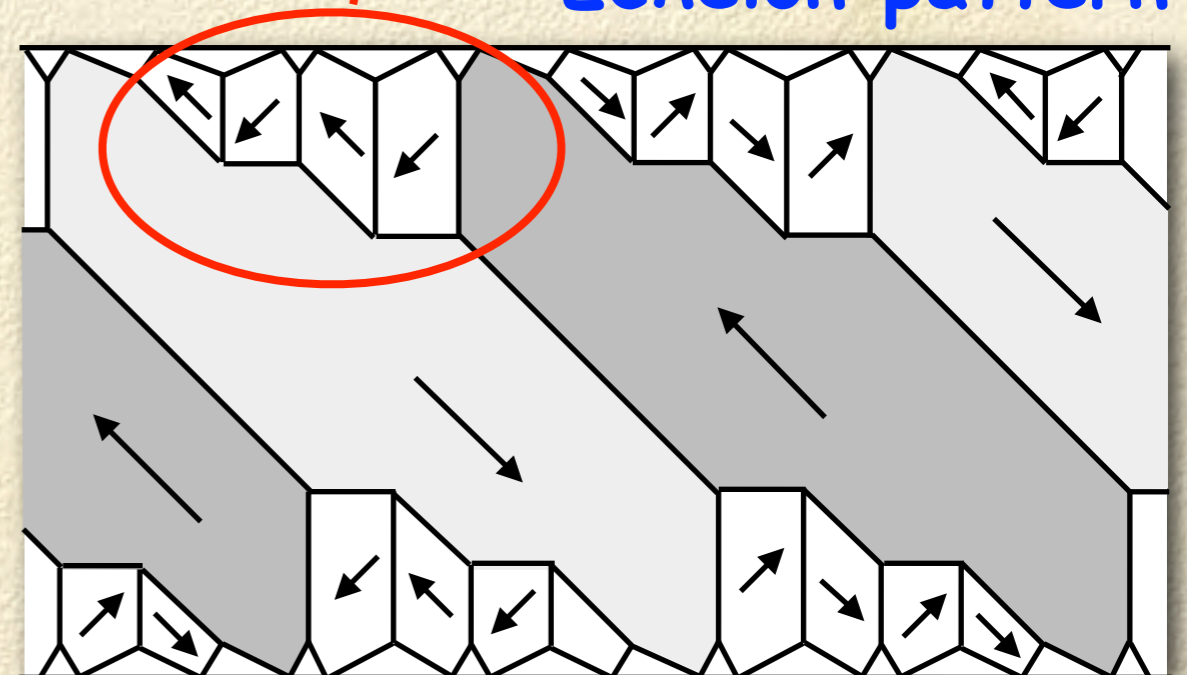
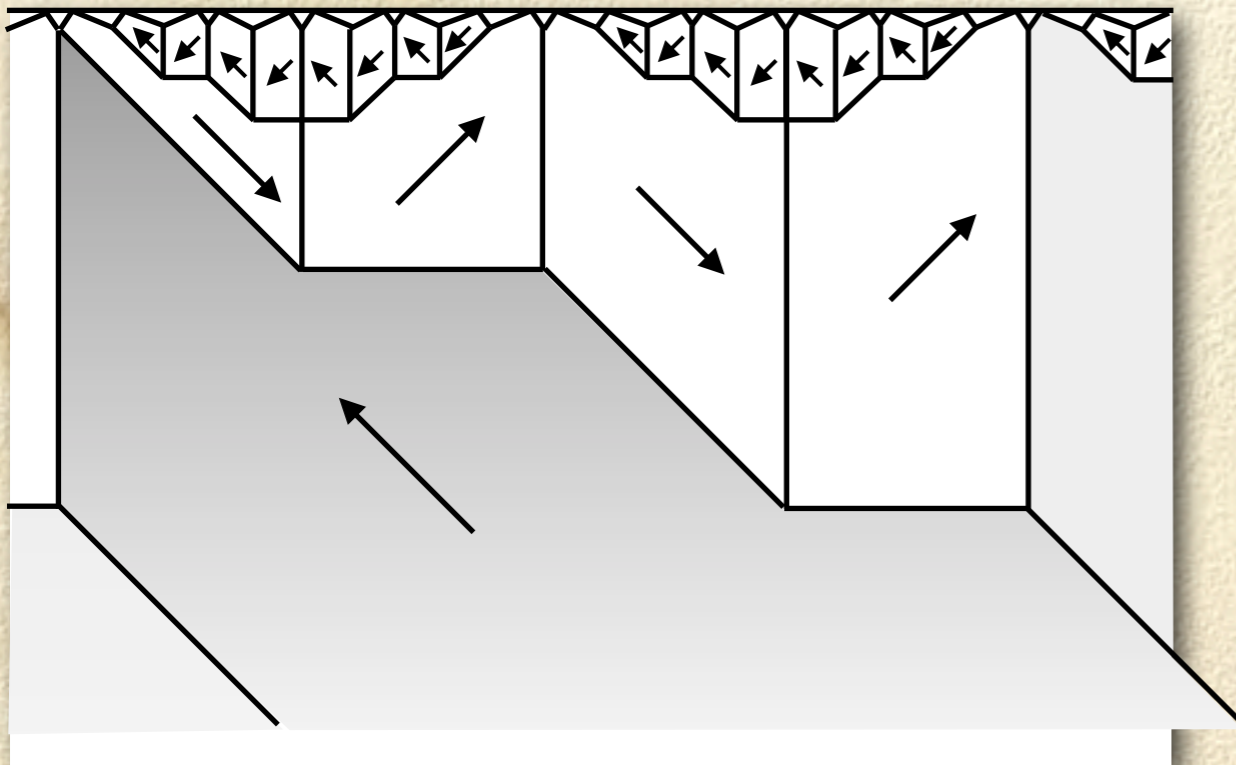
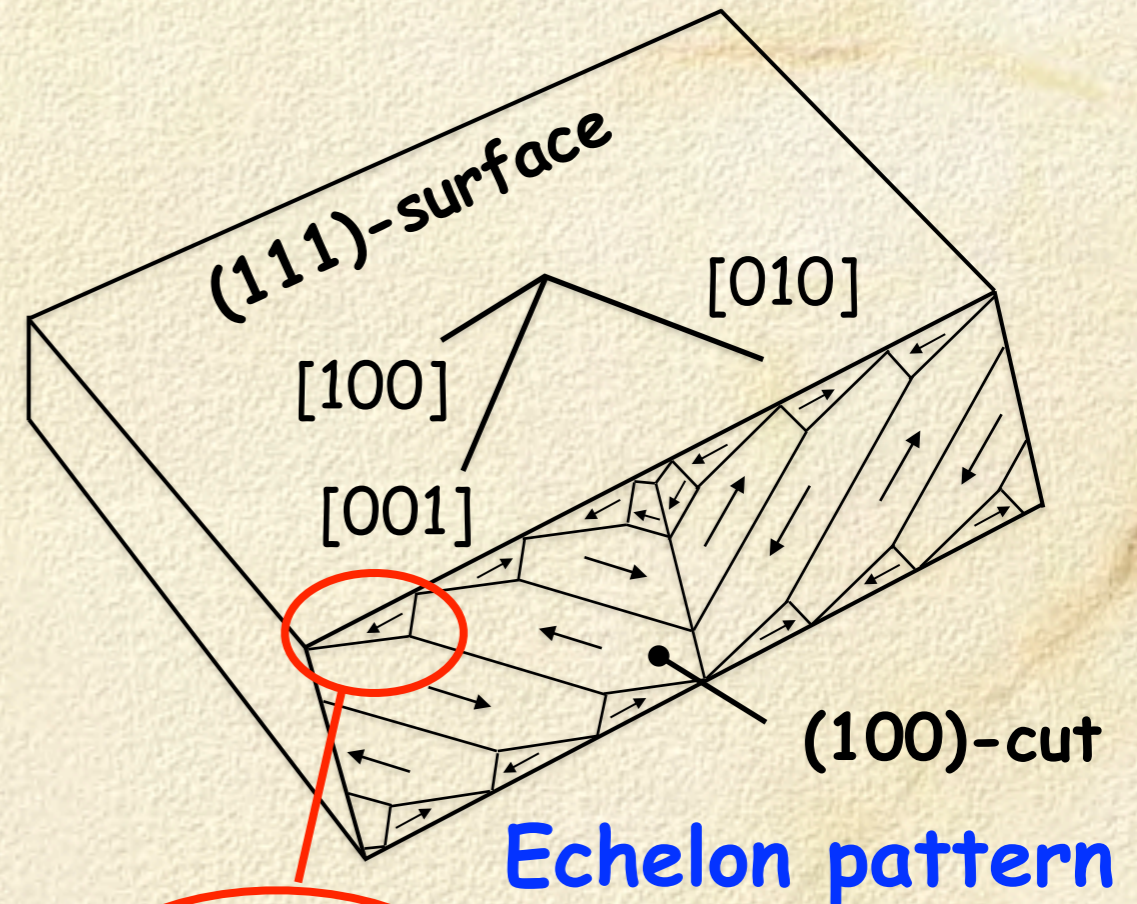
Iron: $Q = 0.02$



Problem: only surface domains can be seen



Iron: $Q = 0.02$

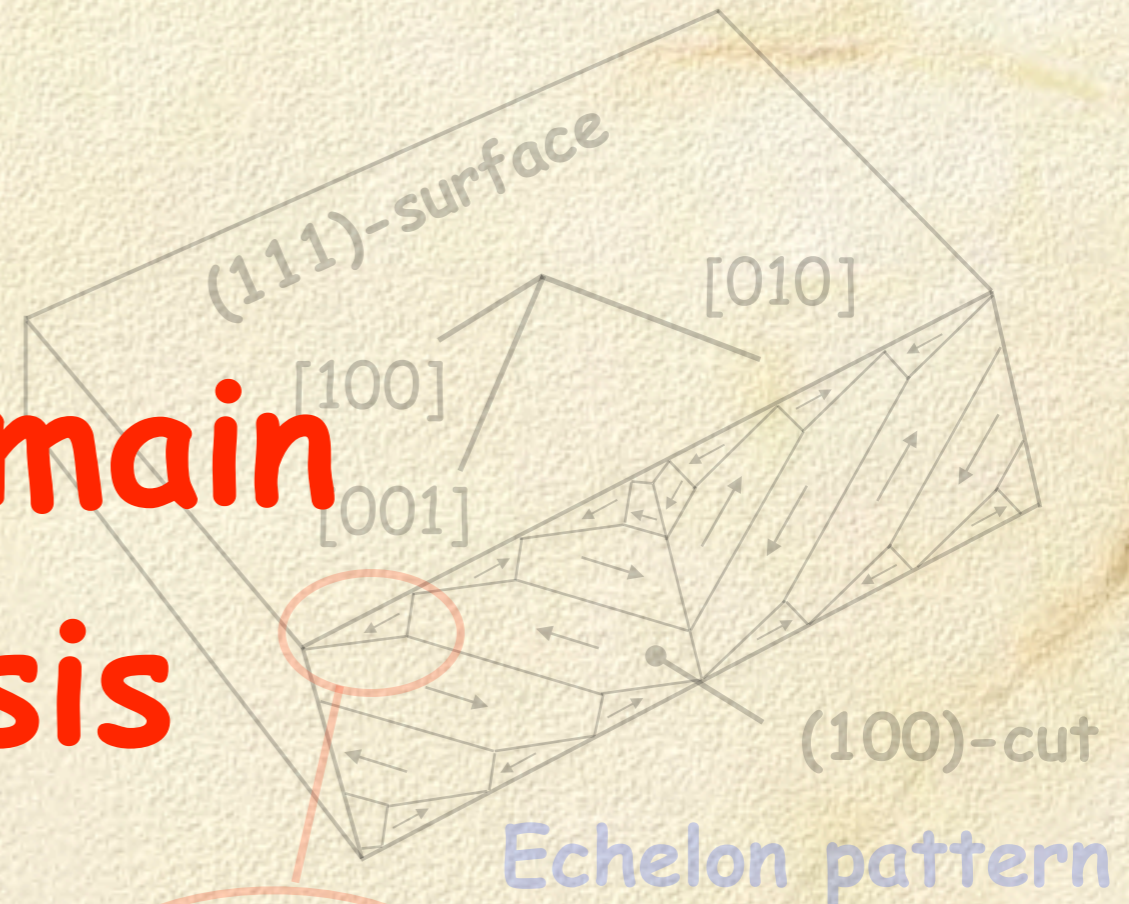


Problem: only surface domains can be seen

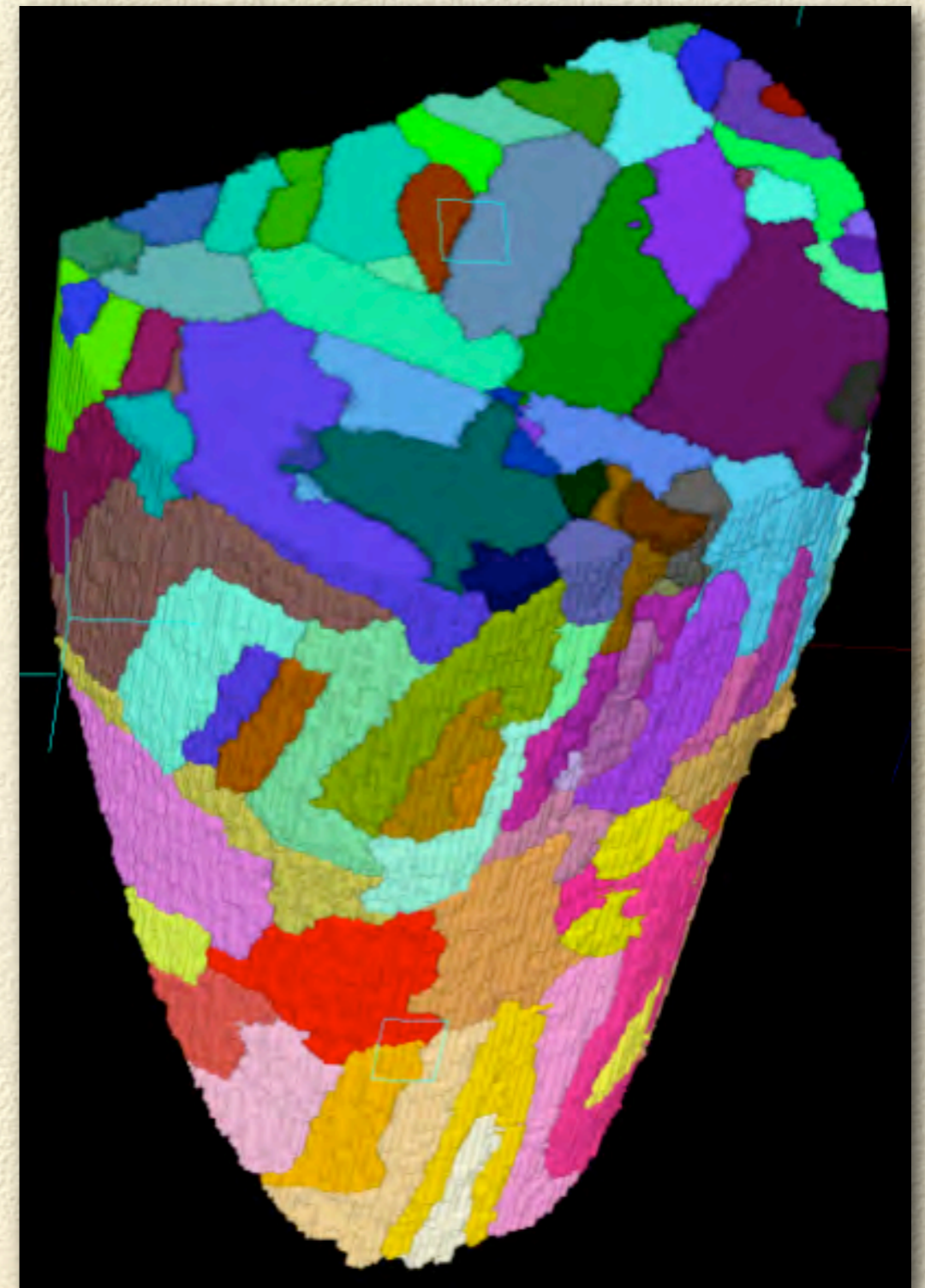
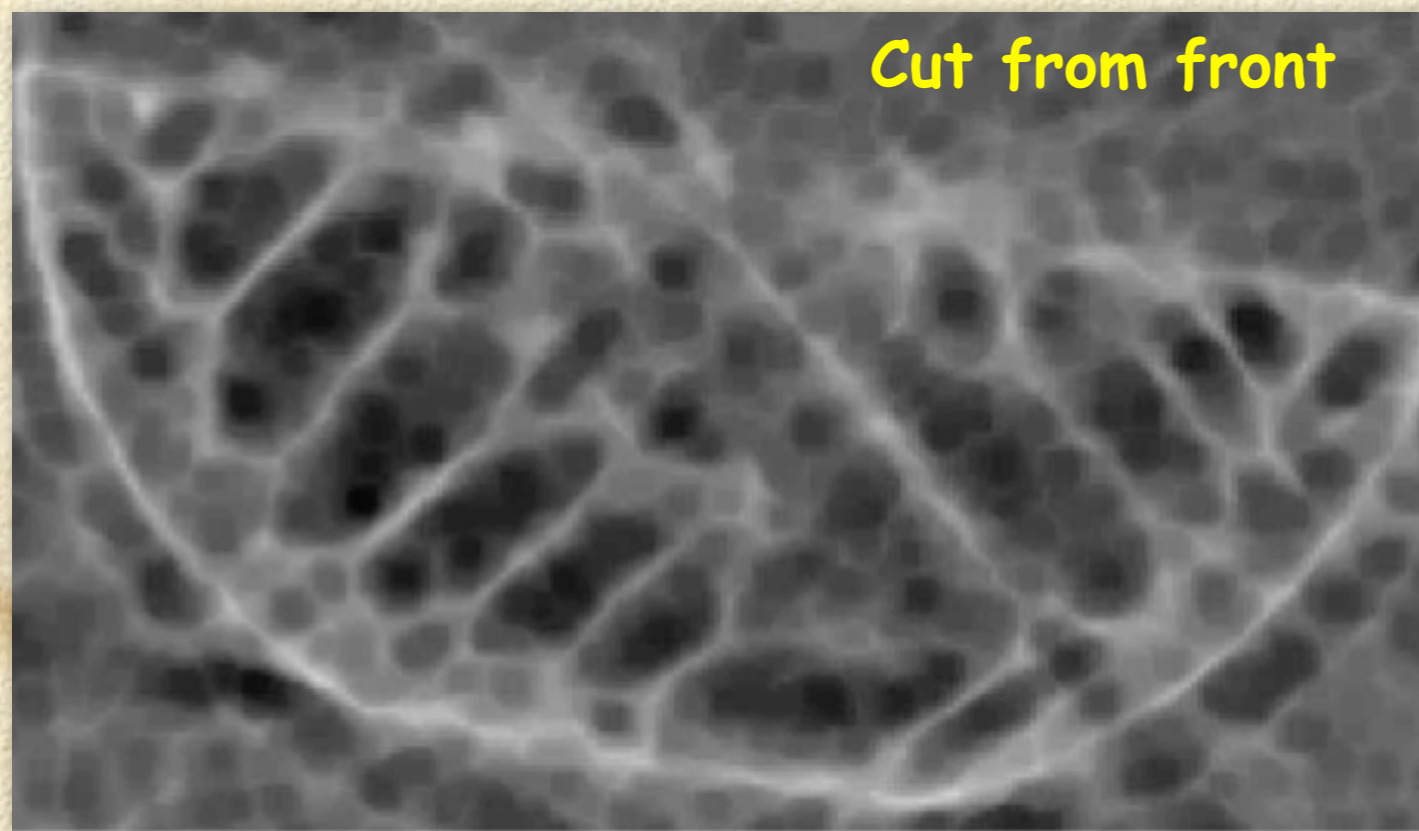
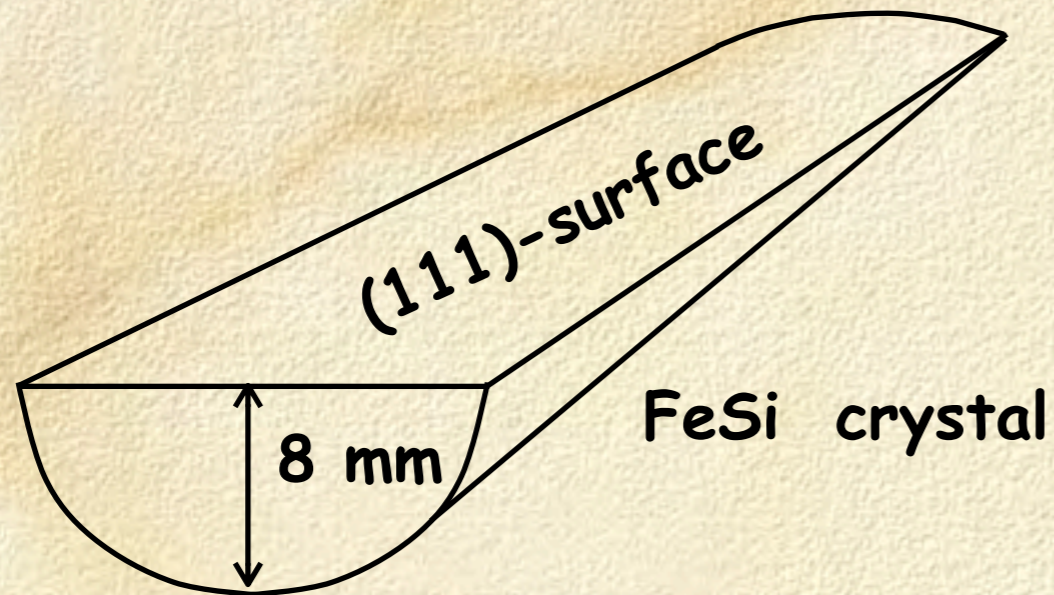


Bulk Domain Analysis

Iron: $Q = 0.02$



Neutron dark-field tomography

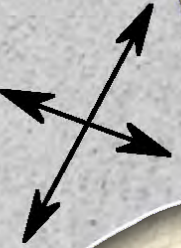
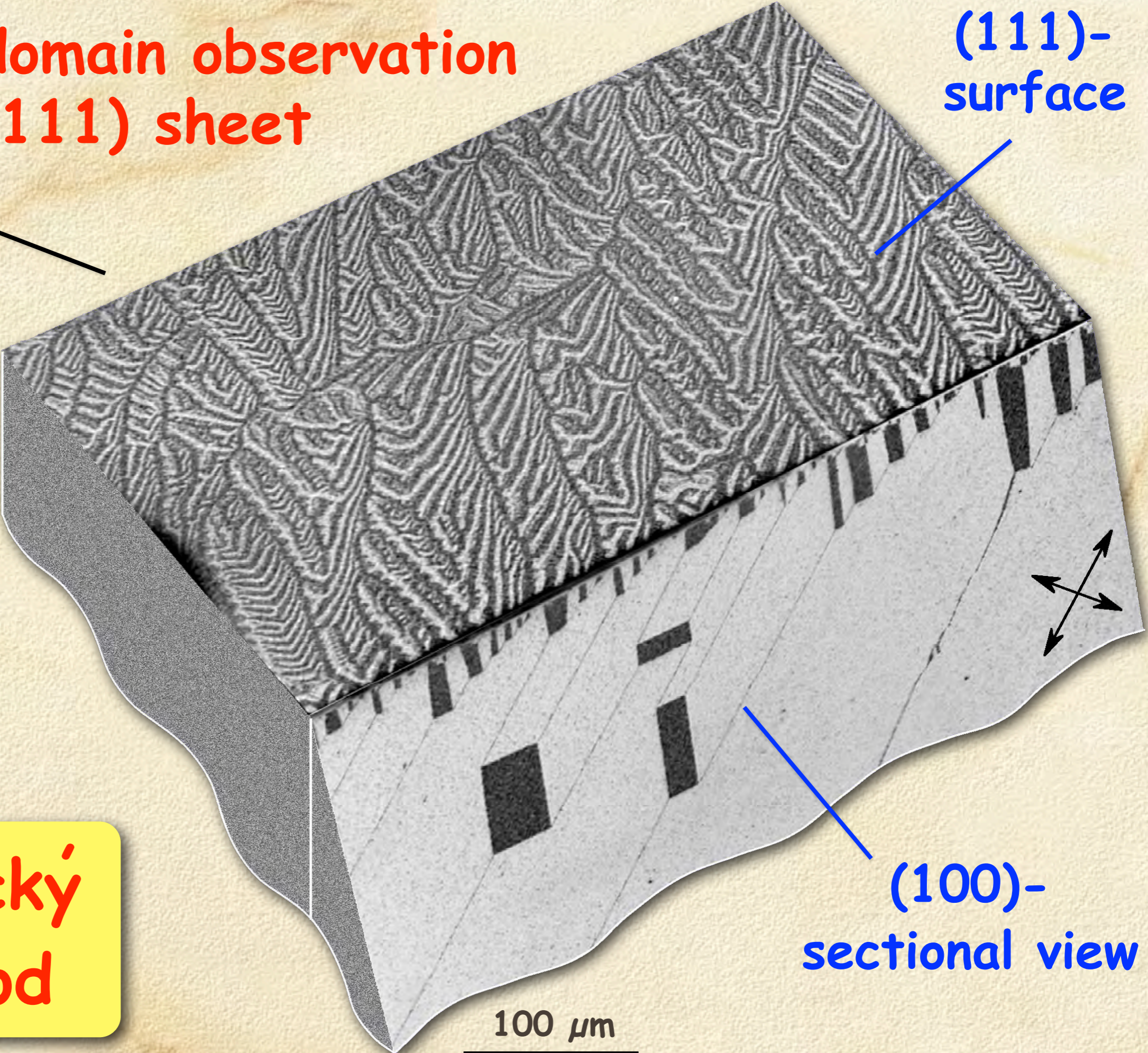


I. Manke, et al.: Three-dimensional imaging of magnetic domains.
Nature Communications, 1:125 doi: 10.1038/ncomms1125 (2010)

Volume domain observation in FeSi (111) sheet

(111)-
surface

easy
axes

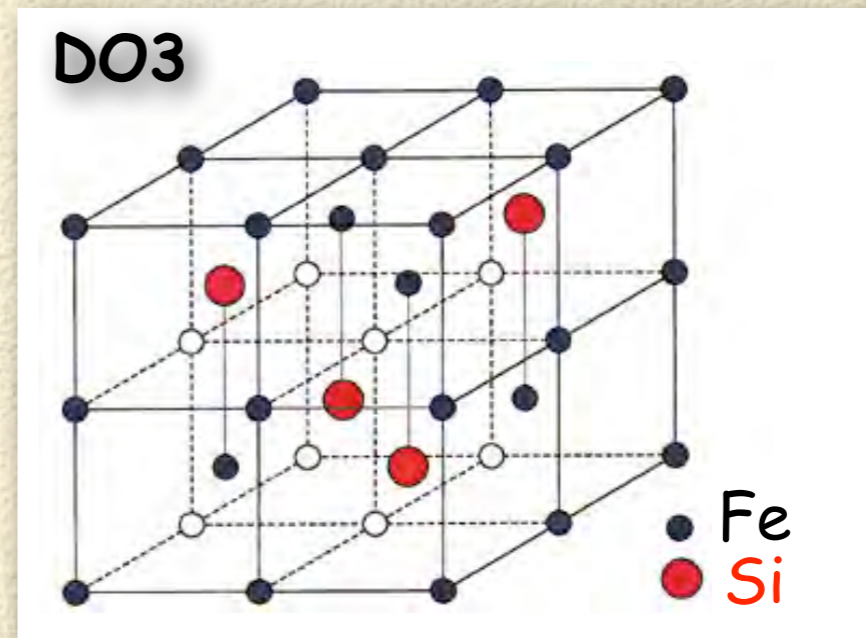
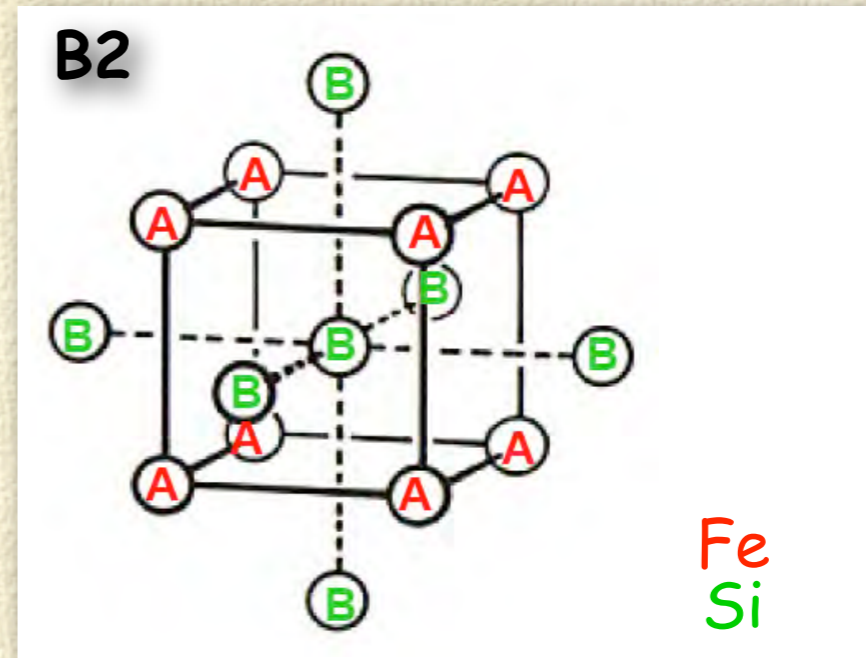
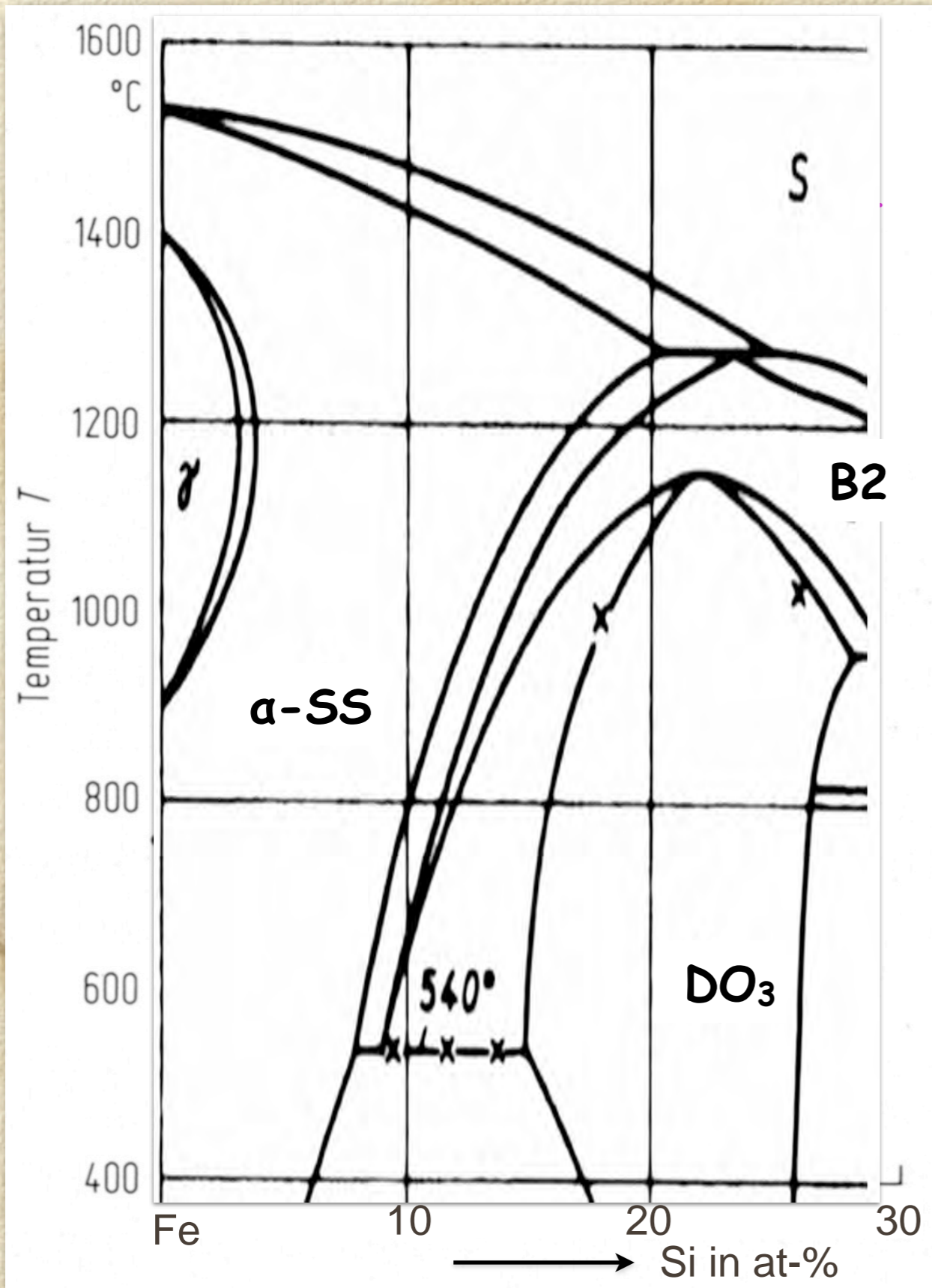


(100)-
sectional view

**Libovický
method**

100 μm

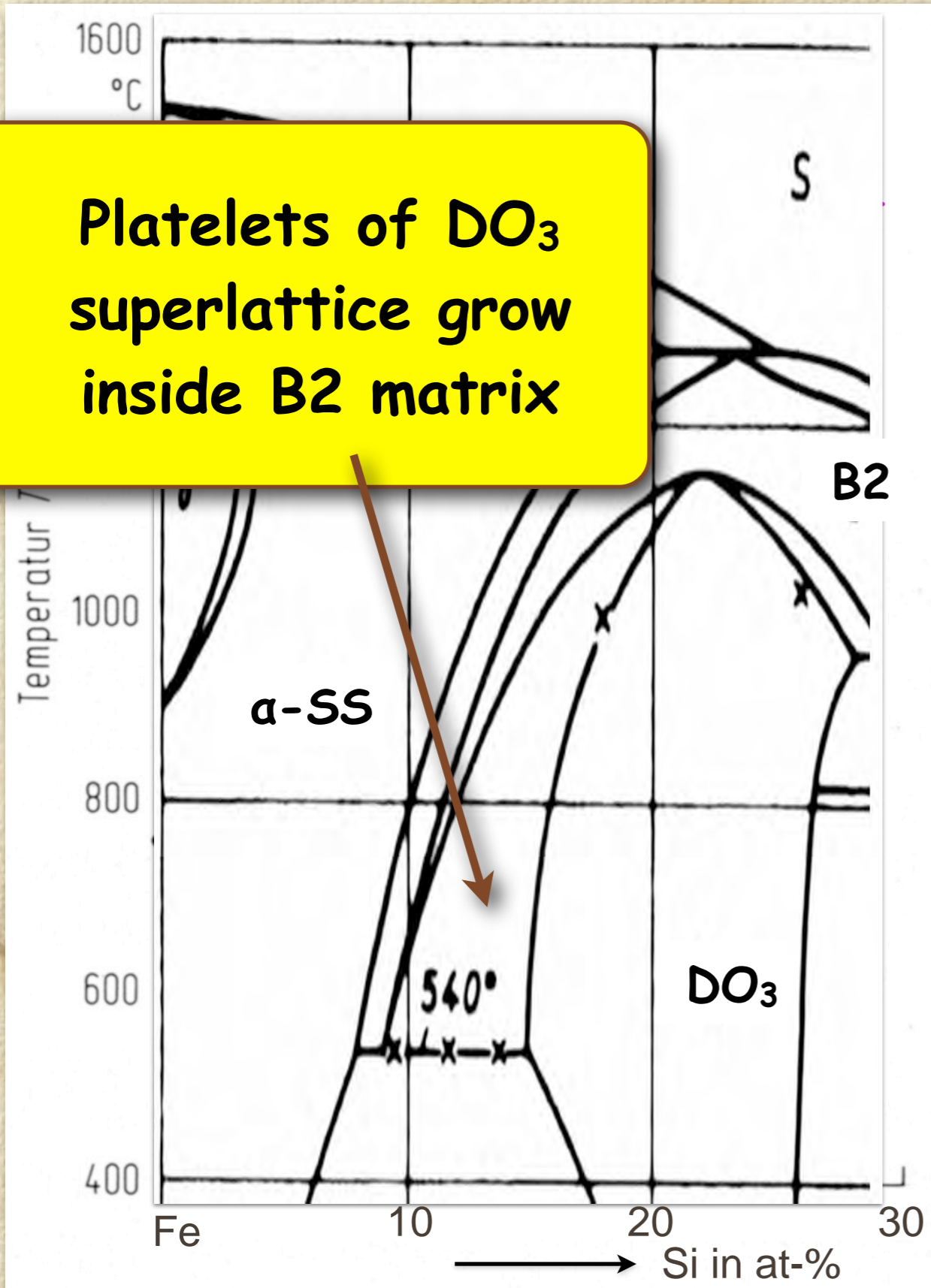
Bulk domain observation by Libovický-method



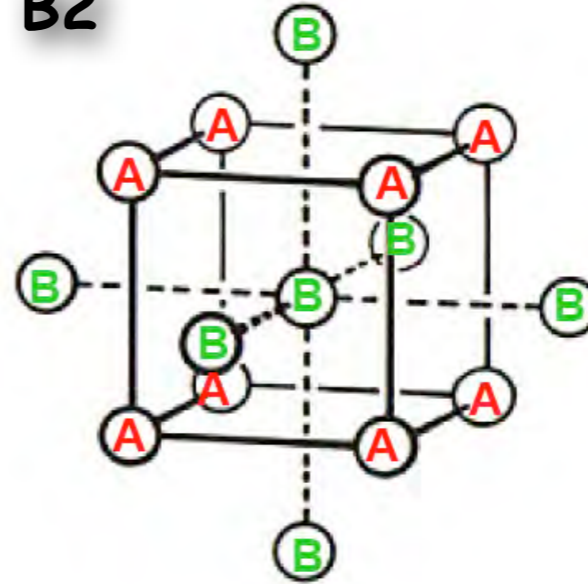
H. Warlimont:
Elektronenmikroskopische Unter-
suchung der α -Fe-Si-Phasen.
Z. Metallkunde 59, 598 (1968)

Bulk domain observation by Libovický-method

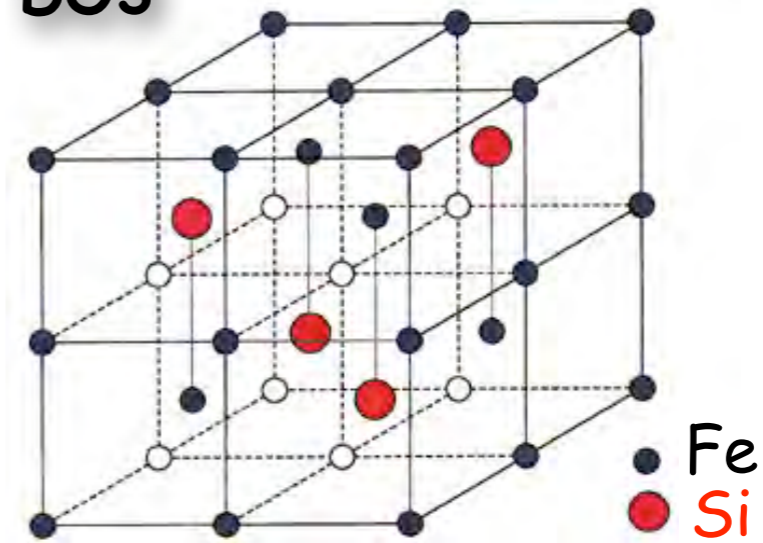
Platelets of DO_3 superlattice grow inside B2 matrix



B2



DO_3



H. Warlimont:
Elektronenmikroskopische Unter-
suchung der α -Fe-Si-Phasen.
Z. Metallkunde 59, 598 (1968)

Bulk domain observation by Libovický-method

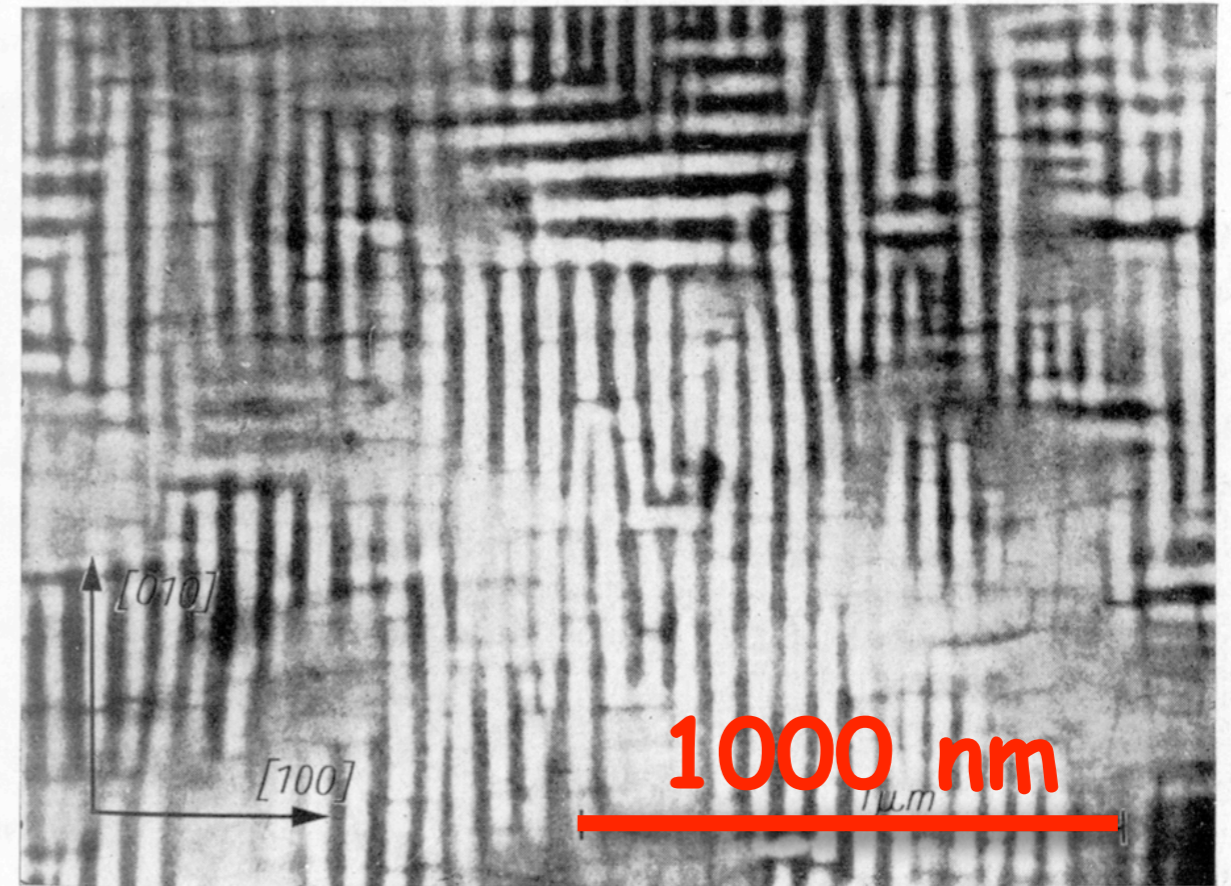
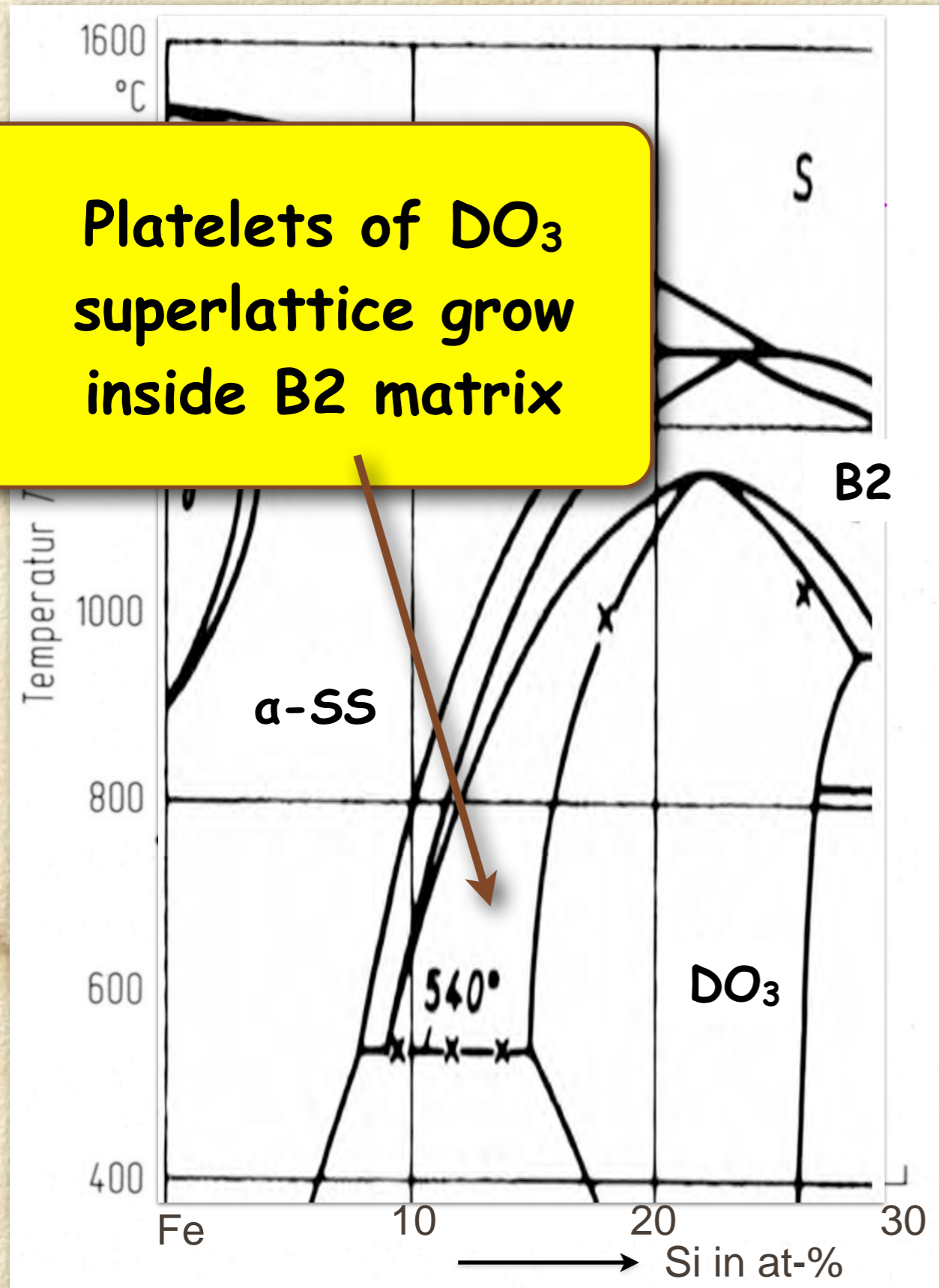
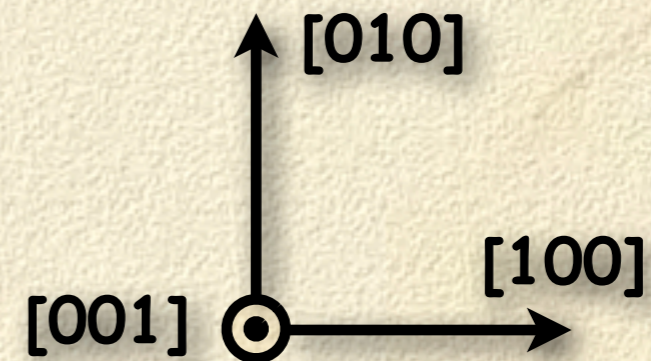


Fig. 3. TEM micrograph of Si Fe-12.5 at% a single crystal held 70 h at 580 °C. The diffuse areas are spots of DO₃ platelets parallel to (001). The growth of (010) platelets was partially suppressed in this area. Dark field 200 superlattice reflection



from: S. Libovický: Spatial replica of ferromagnetic domains in iron-silicon alloys. Phys. Status Solidi A 12 (1972) 539

Bulk domain observation by Libovický-method

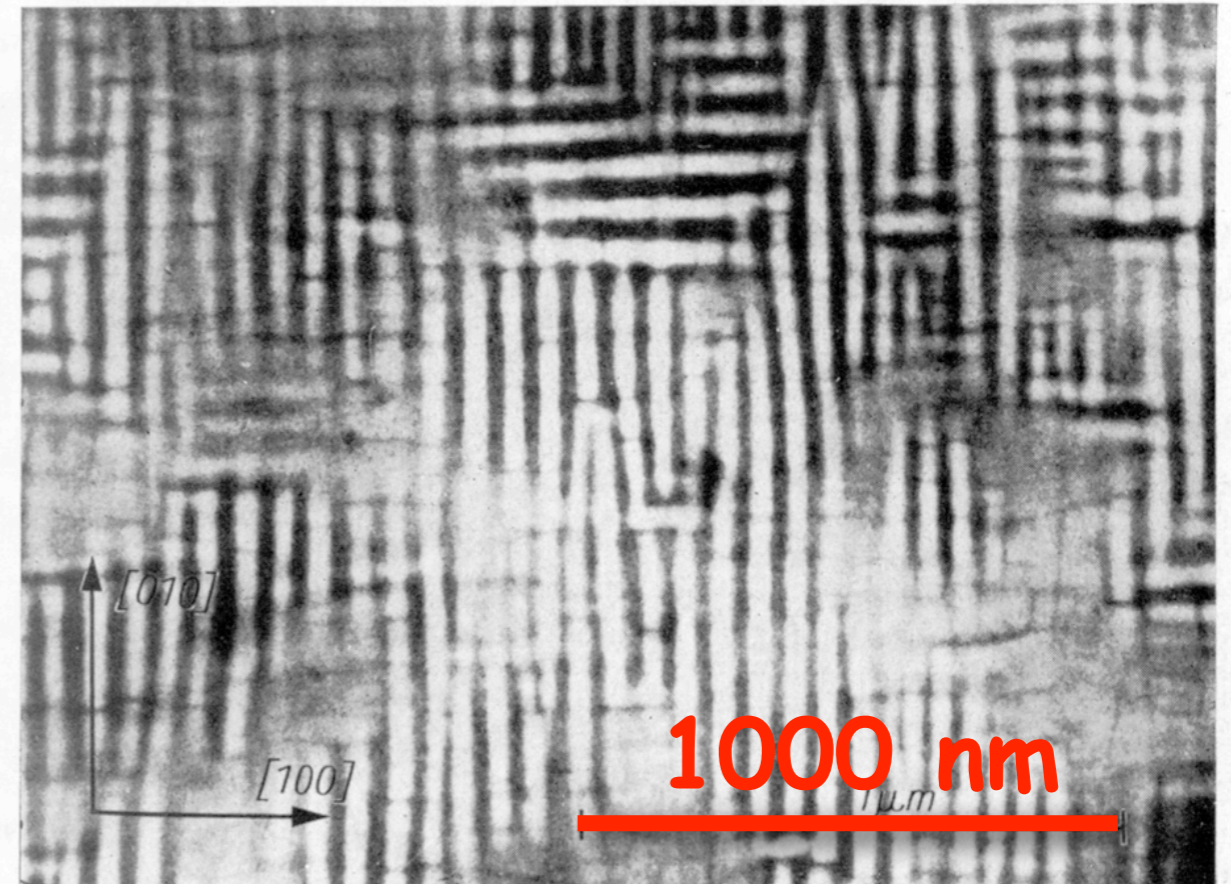
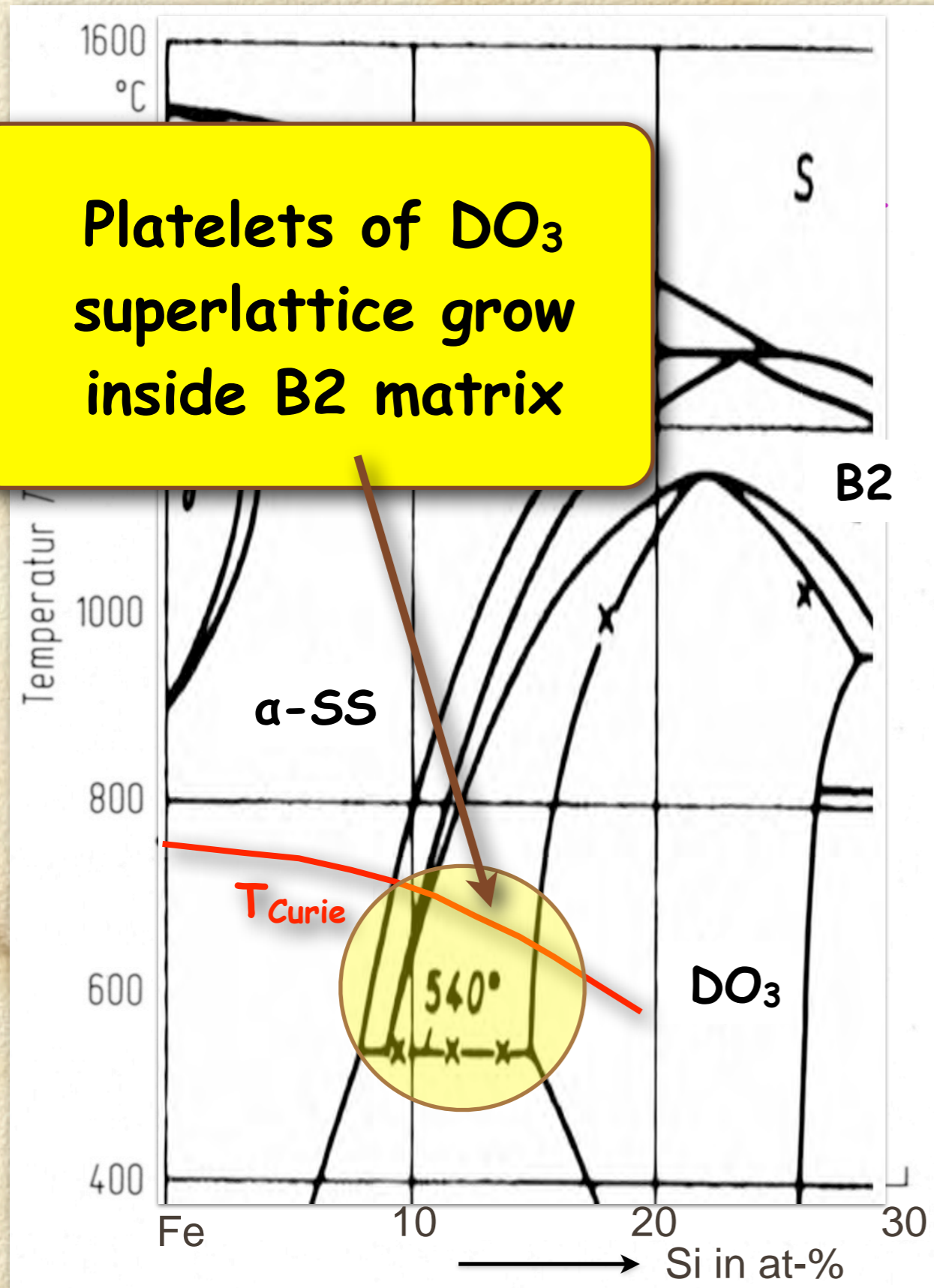
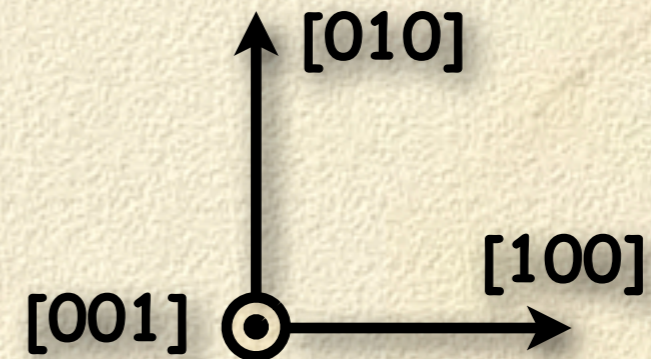
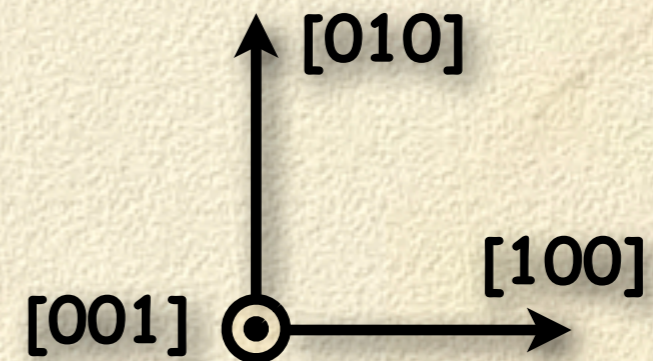
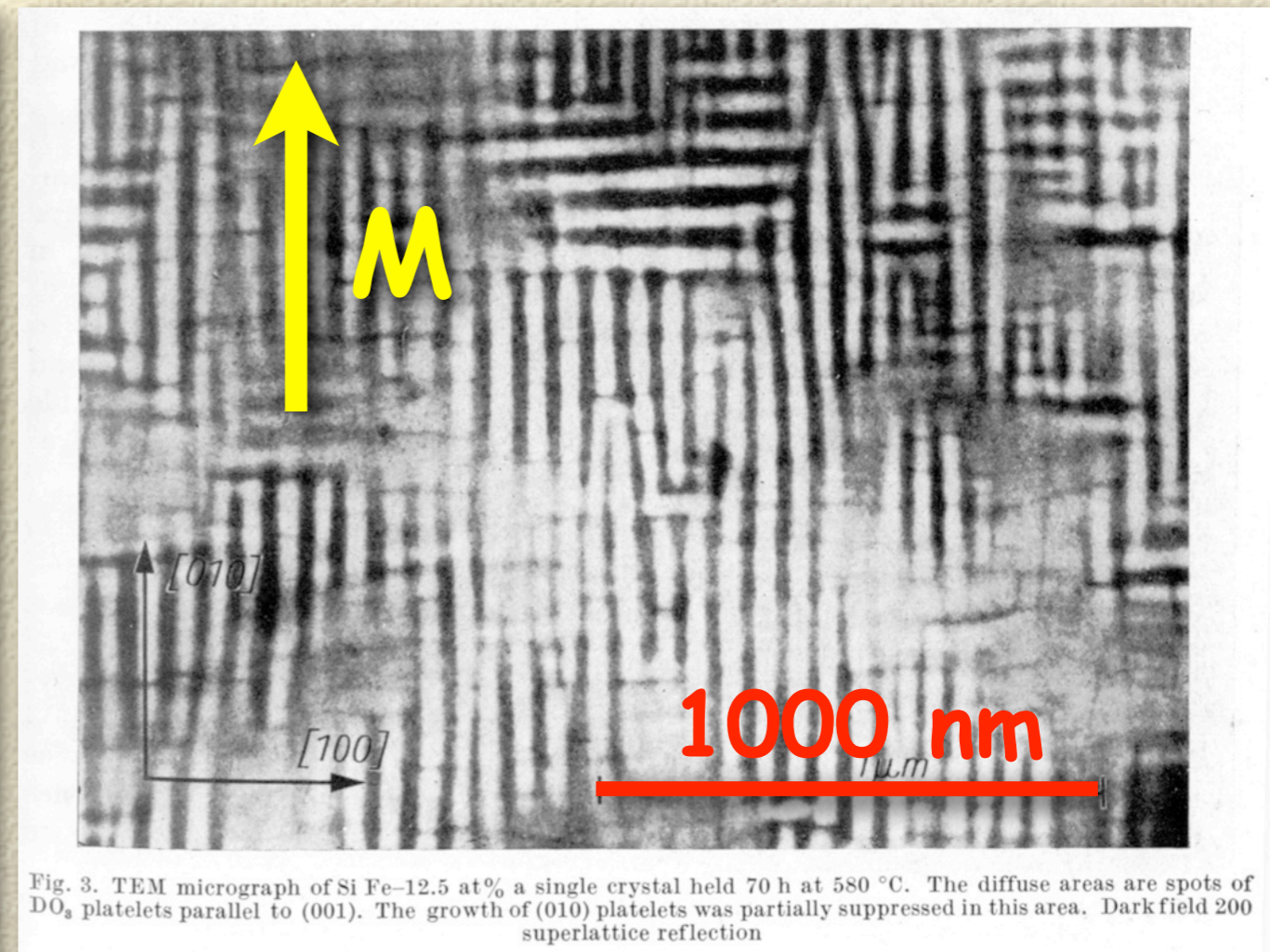
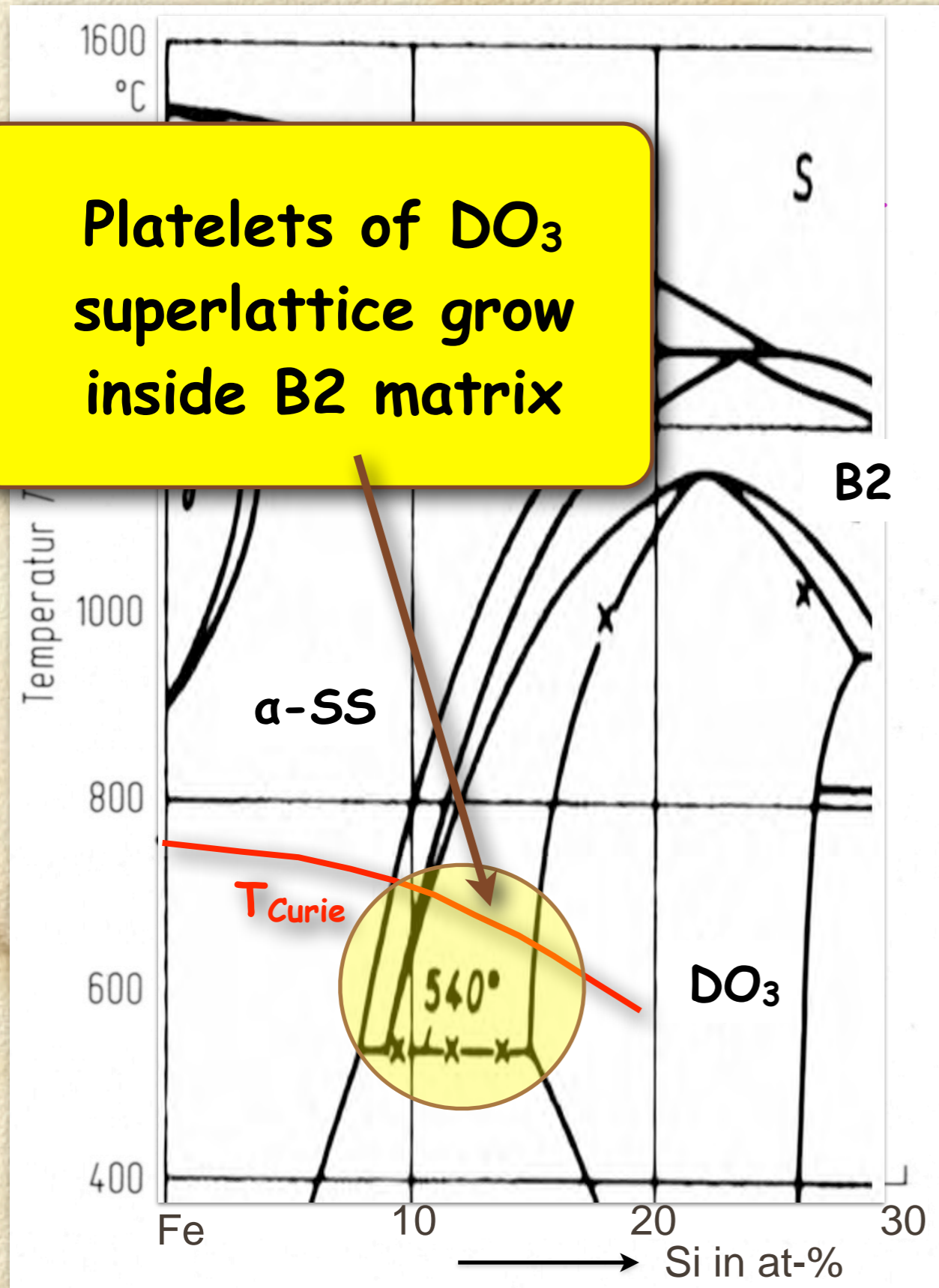


Fig. 3. TEM micrograph of Si Fe-12.5 at% a single crystal held 70 h at 580 °C. The diffuse areas are spots of DO₃ platelets parallel to (001). The growth of (010) platelets was partially suppressed in this area. Dark field 200 superlattice reflection



from: S. Libovický: Spatial replica of ferromagnetic domains in iron-silicon alloys. Phys. Status Solidi A 12 (1972) 539

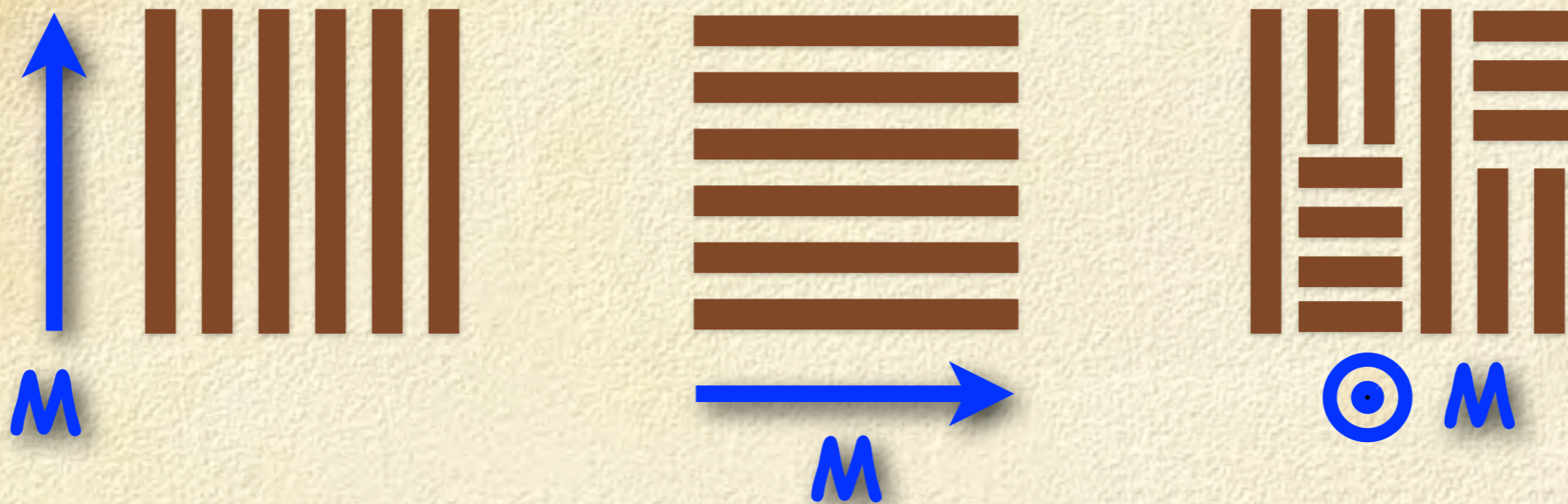
Bulk domain observation by Libovický-method



from: S. Libovický: Spatial replica of ferromagnetic domains in iron-silicon alloys. Phys. Status Solidi A 12 (1972) 539

Bulk domain observation by Libovický-method

Orientation of magnetization vector (at annealing temperature) generates anisotropic distribution of DO_3 platelets



- Creation of precipitation pattern by annealing $>540^\circ\text{C}$ ($<T_c$)
- Cooling to room temperature
- Domain pattern is „frozen“ as submicroscopic precipitation pattern
- Domain imaging in polarization microscope after etching due to optical birefringence effect (at room temperature)

“Metallographic” domain analysis

Bulk domain observation by Libovický-method

Branched domains on Fe12.8%Si (111) surface
(thickness 0.5 mm)



Bulk domain observation by Libovický-method

Branched domains on Fe12.8%Si (111) surface
(thickness 0.5 mm)



Bulk domain observation by Libovický-method

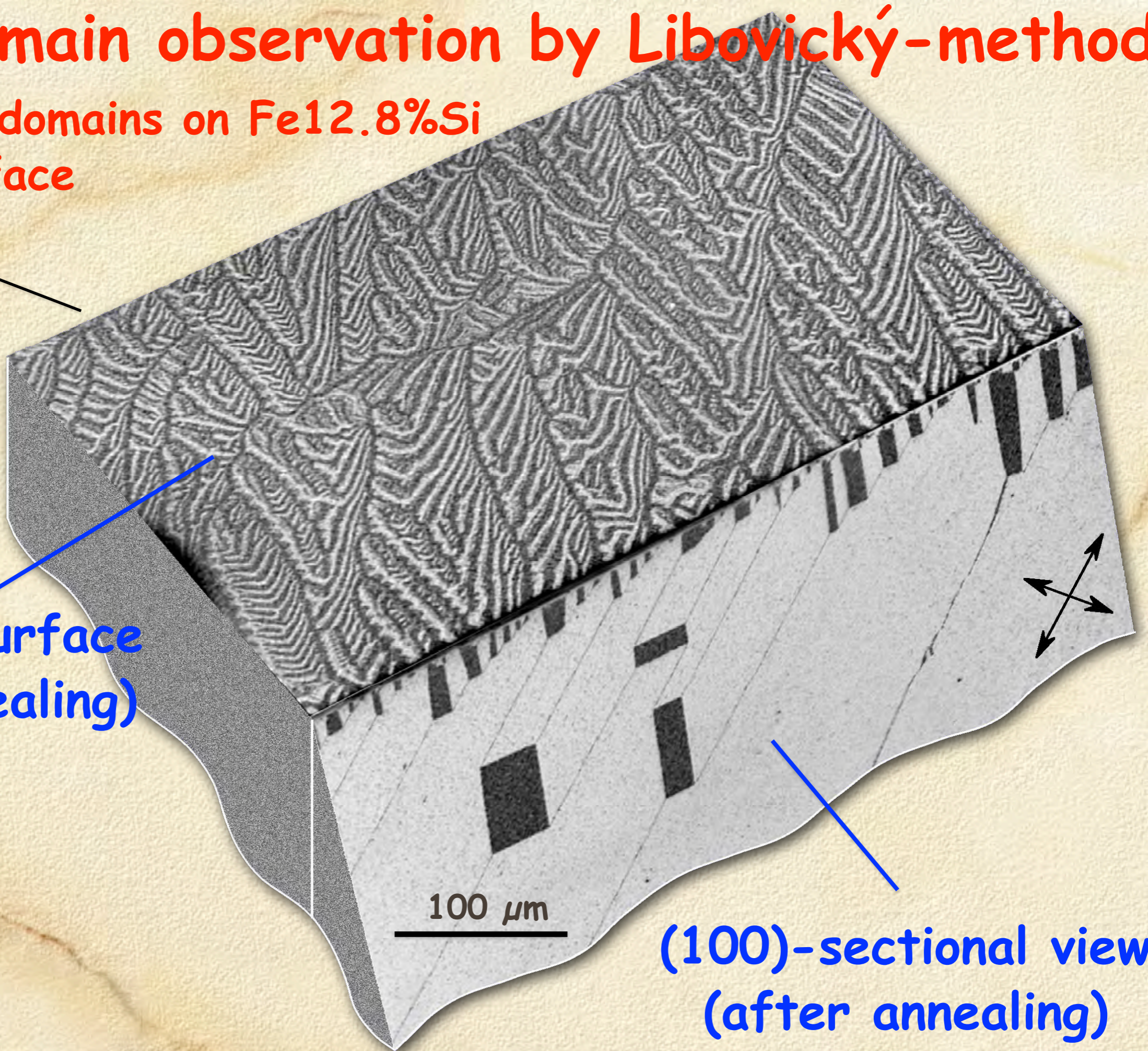
Branched domains on Fe12.8%Si
(111) surface

easy
axes

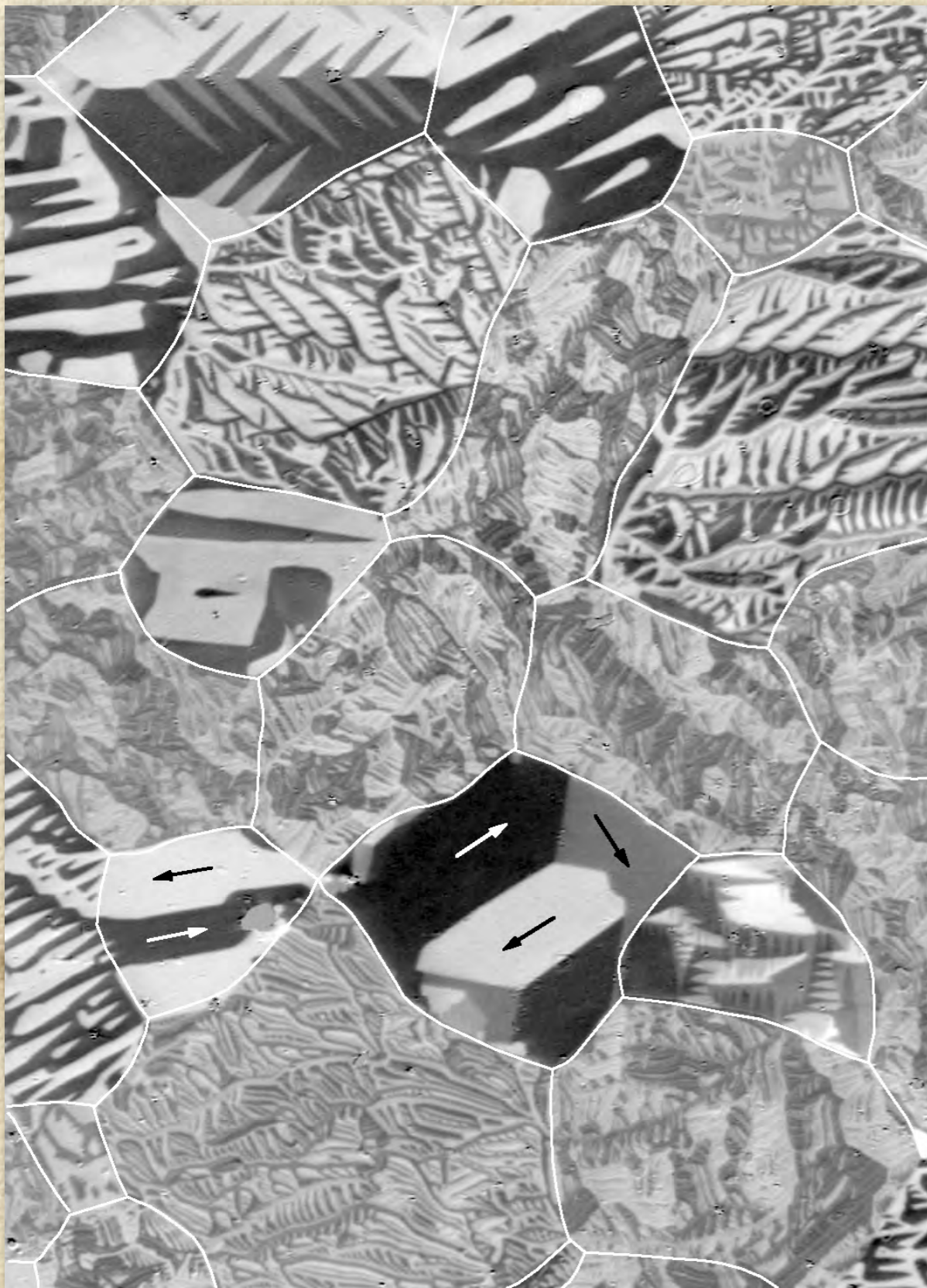
(111)-surface
(at annealing)

100 μm

(100)-sectional view
(after annealing)



Non-oriented FeSi sheet



0.5 mm

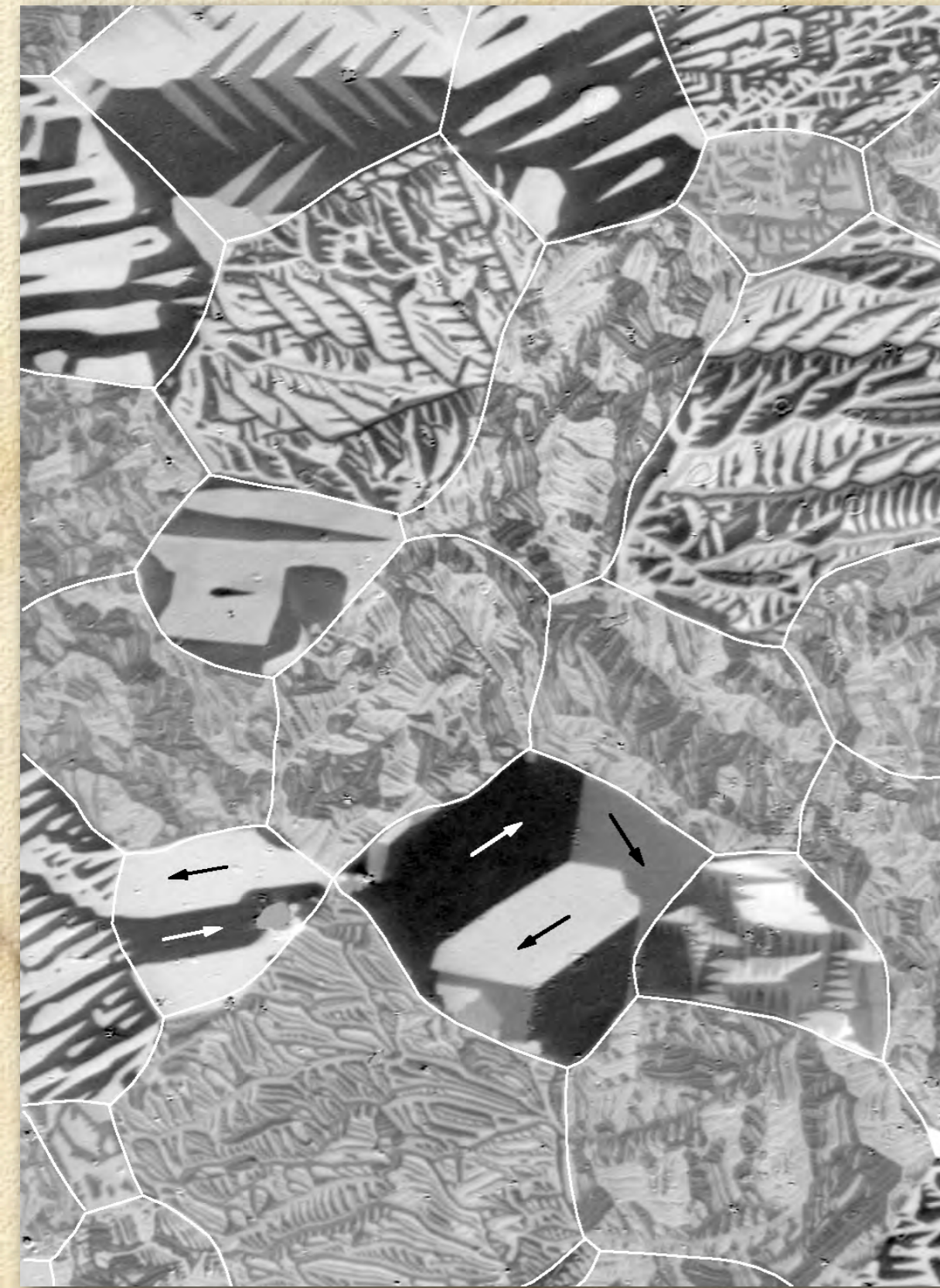
Non-oriented FeSi sheet

Conclusion:

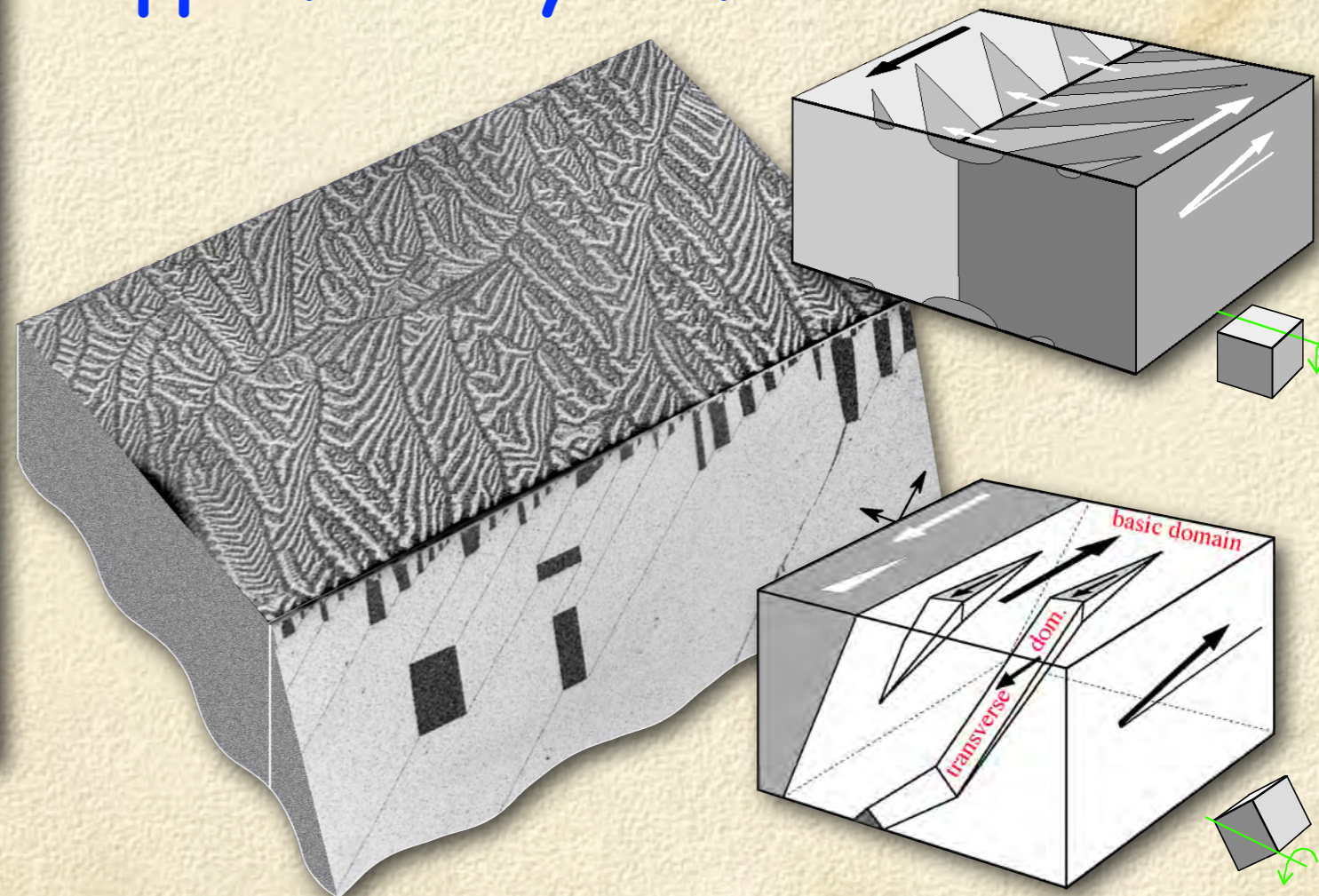
Strong misorientation:

Complex domains restricted to surface zone, in volume wide basic domains can be expected

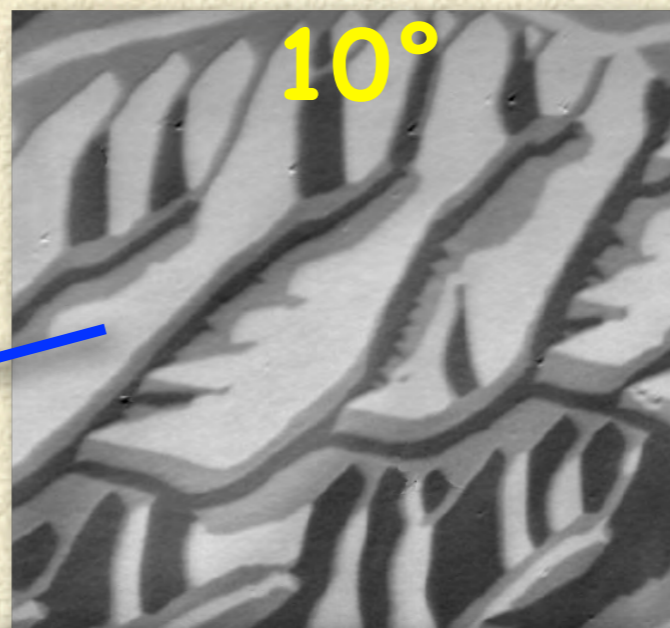
Weak misorientation: wide basic domains with superimposed supplementary domains



0.5 mm



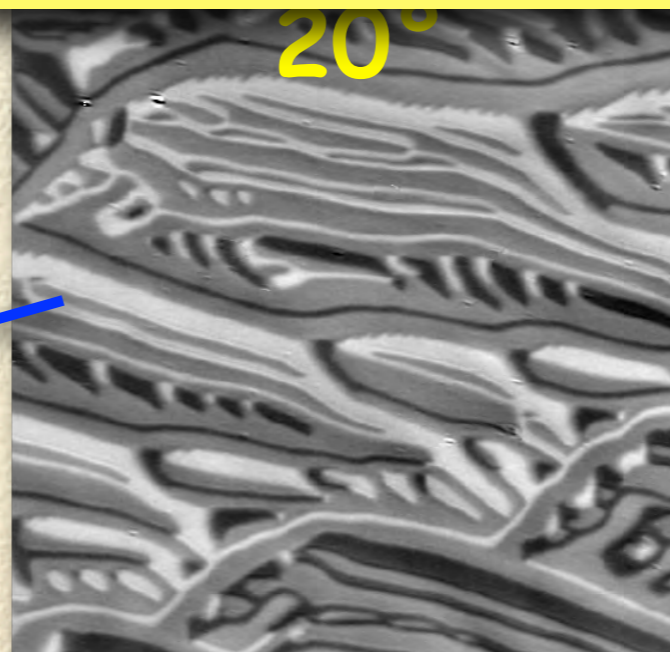
Non-oriented FeSi sheet



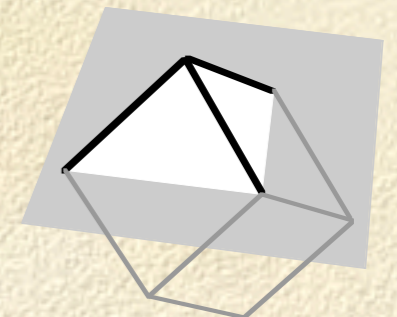
10 μm



We expect wide volume domains
in any case



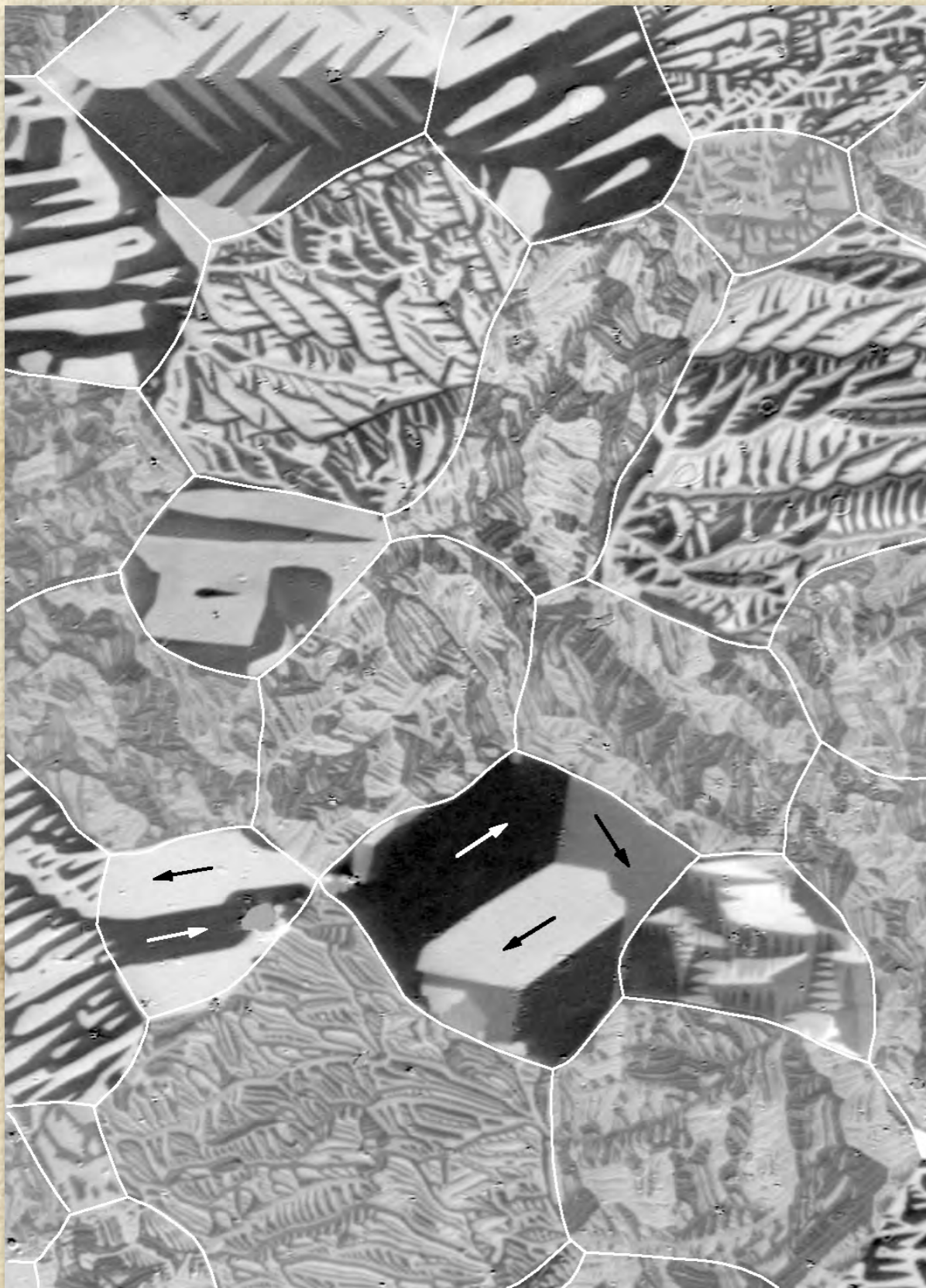
(111)-surface



0.5 mm

Non-oriented FeSi sheet

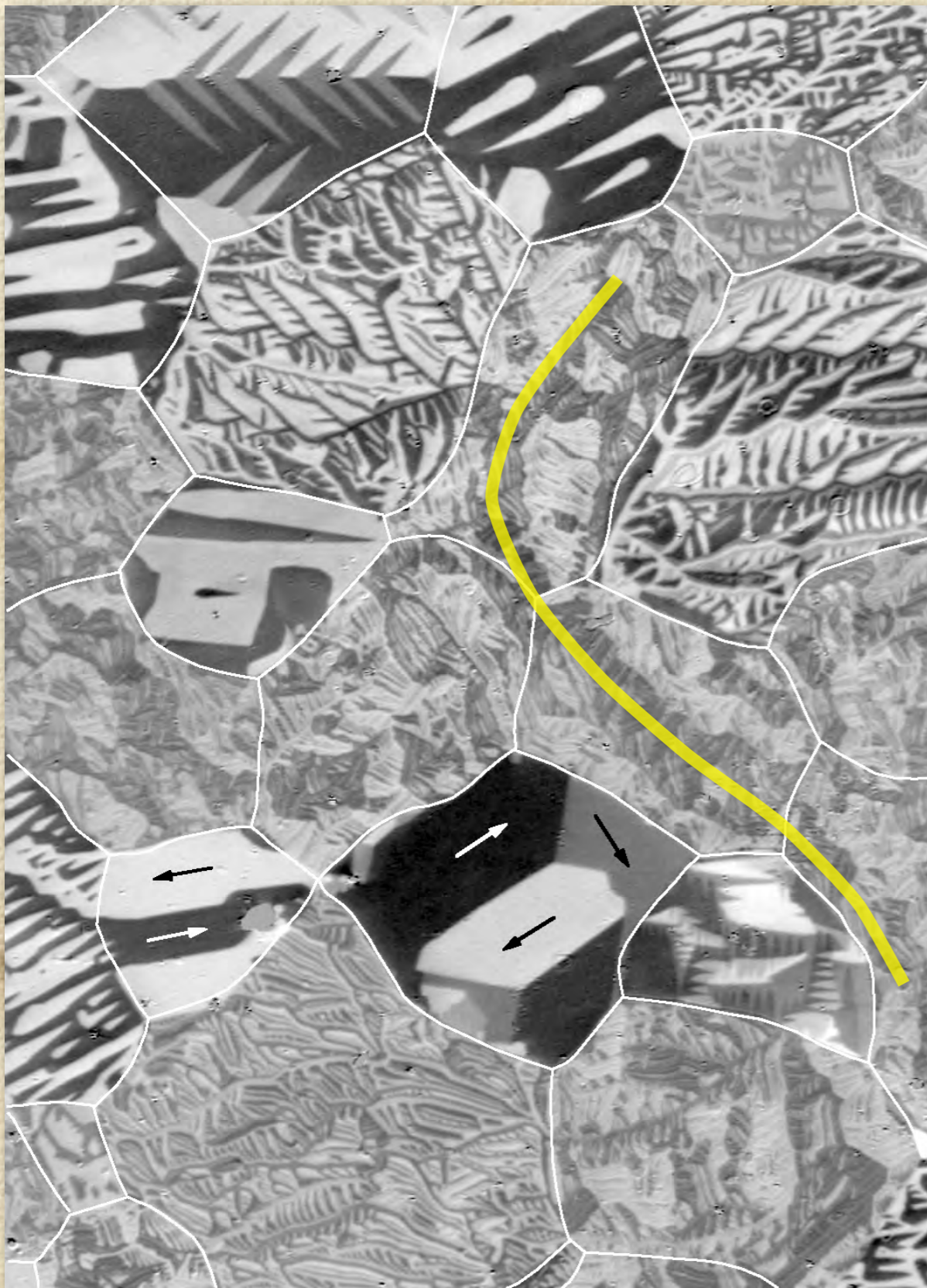
Indication of wide volume domains by surface observation



0.5 mm

Non-oriented FeSi sheet

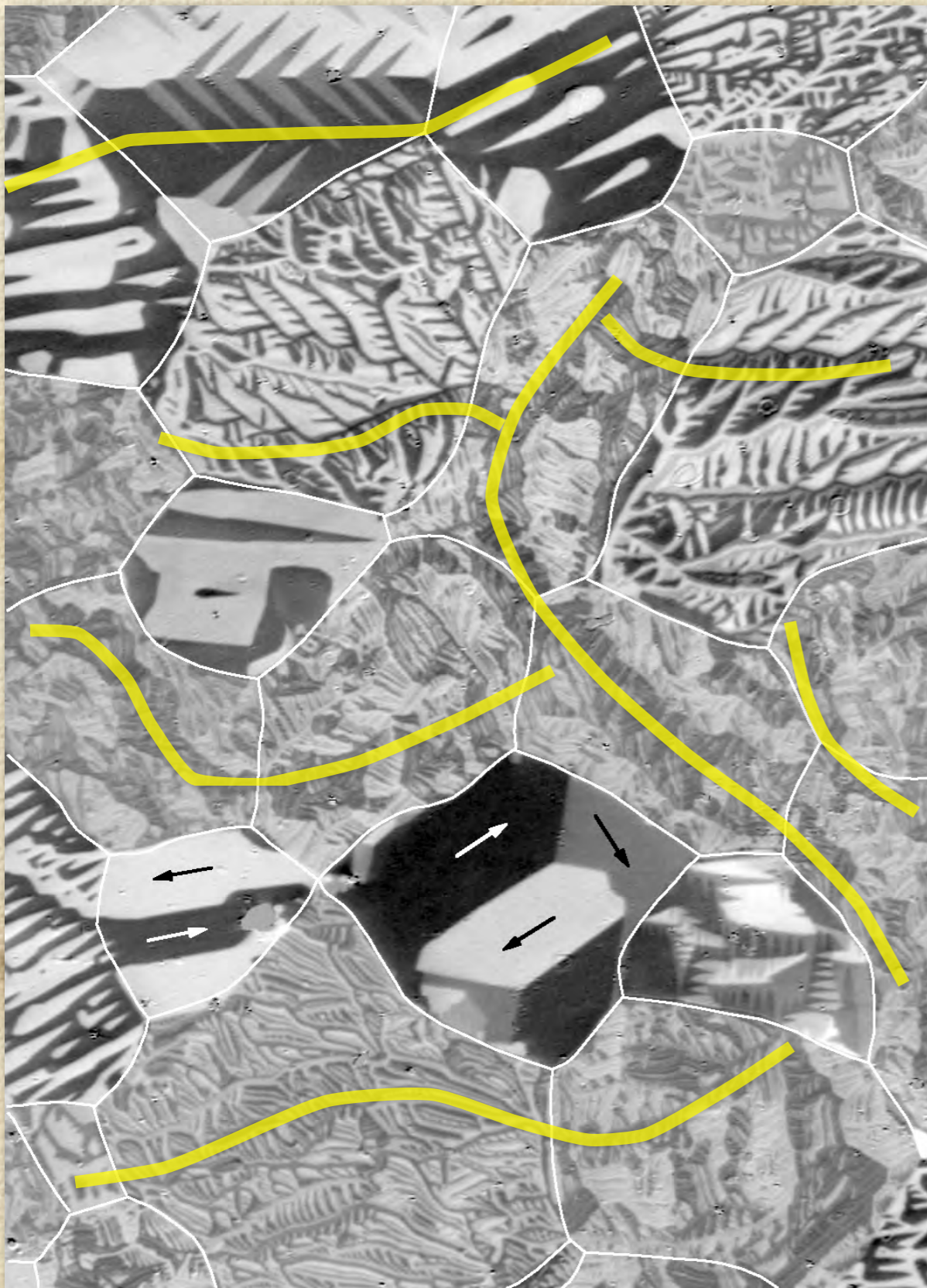
Indication of wide volume domains by surface observation



0.5 mm

Non-oriented FeSi sheet

Indication of wide volume domains by surface observation

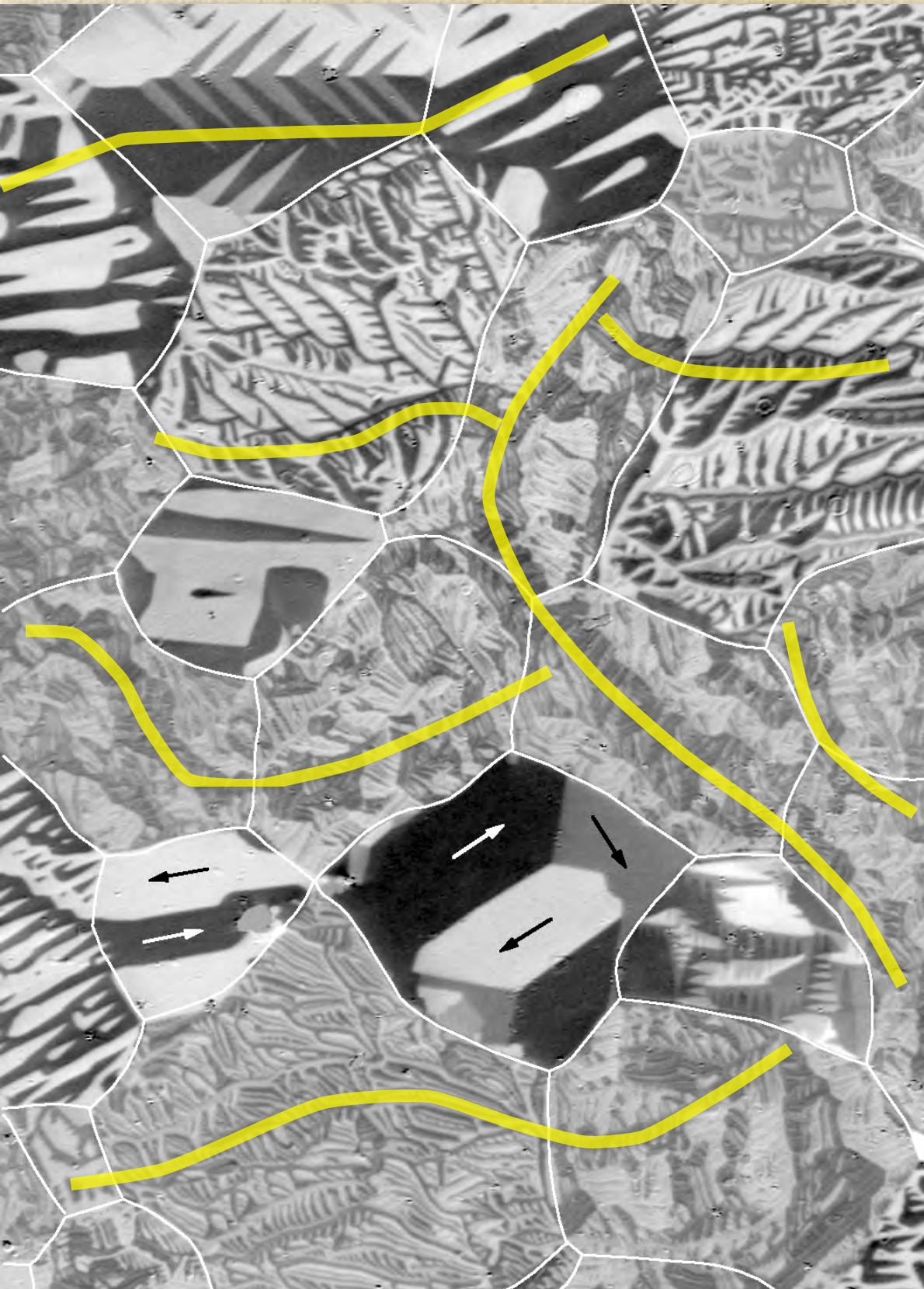


0.5 mm

Non-oriented FeSi sheet

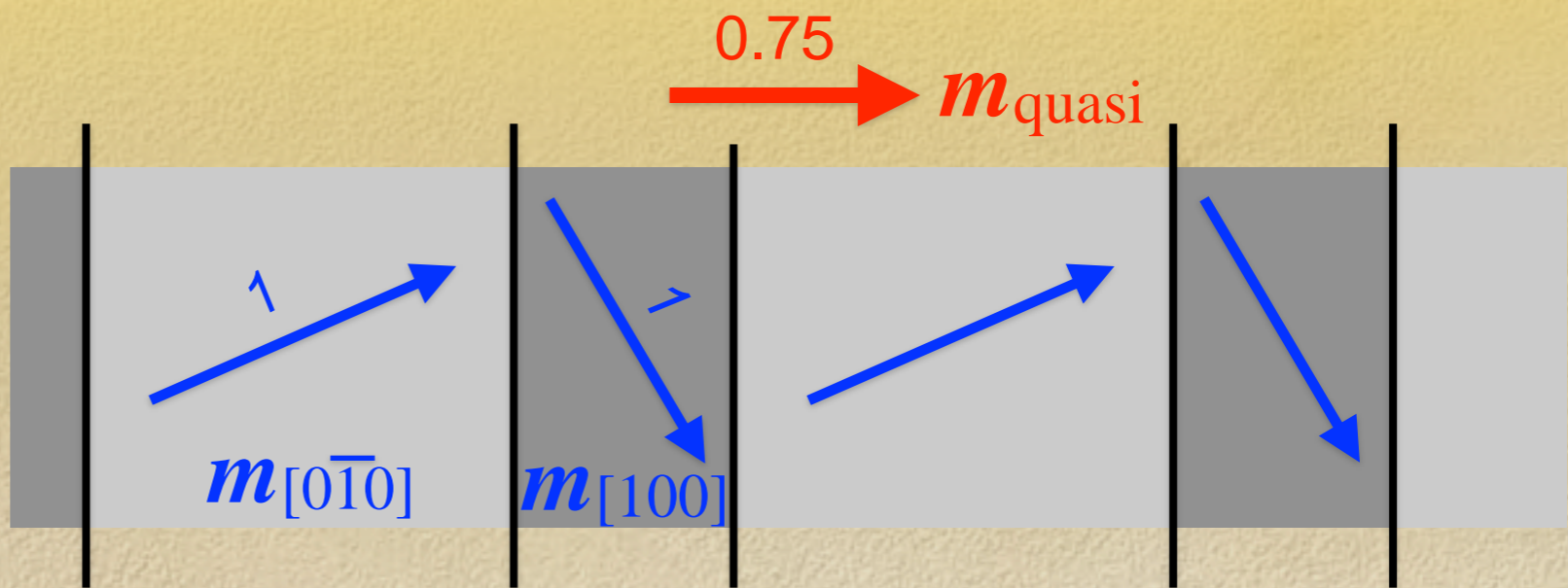
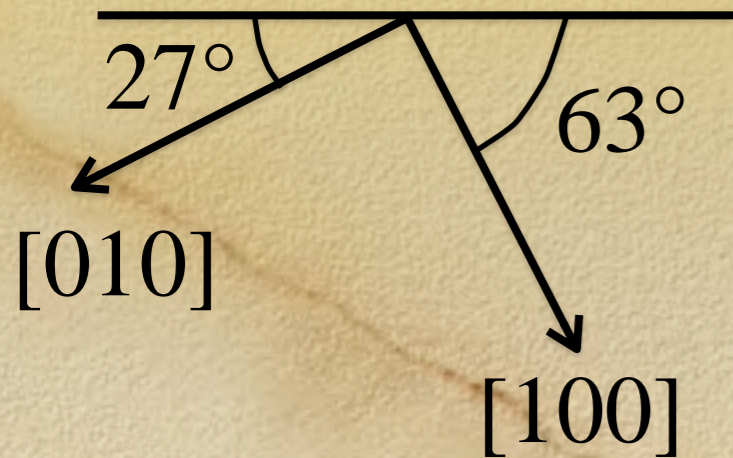
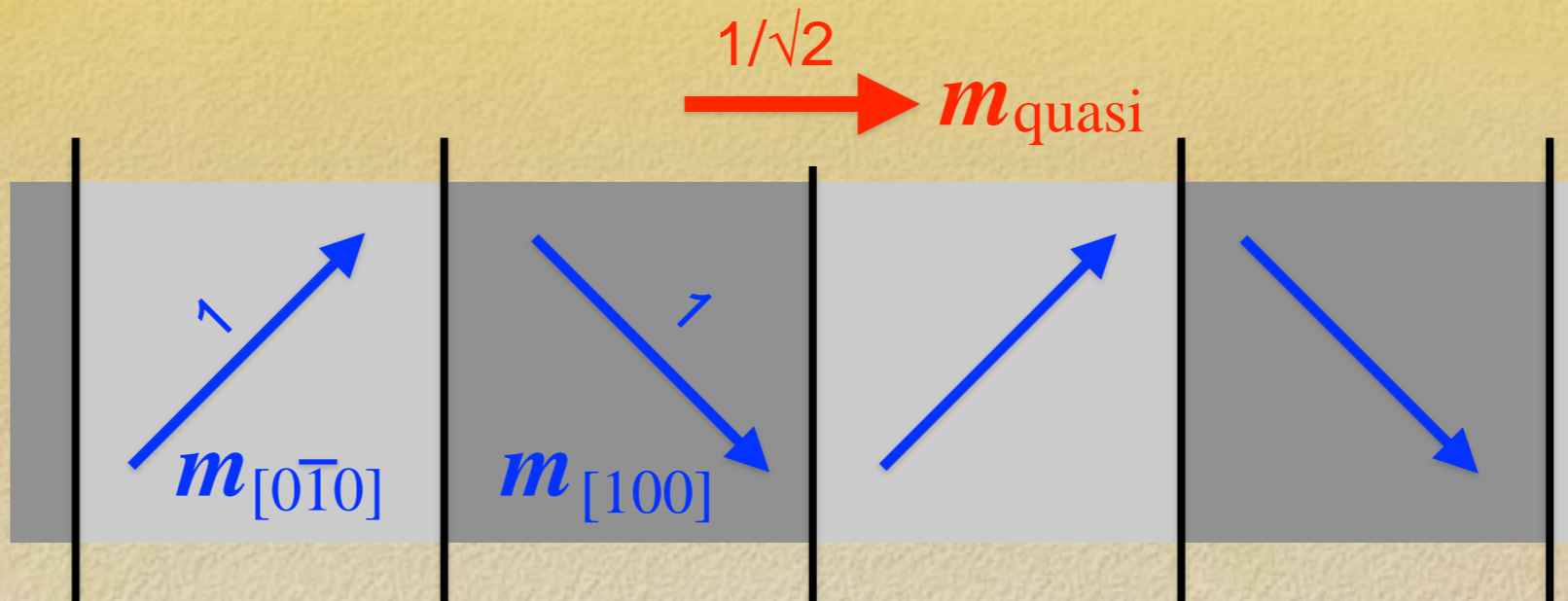
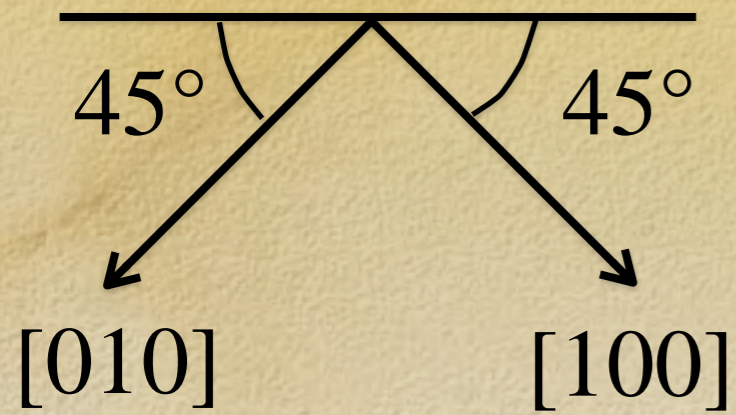
Indication of wide volume domains by surface observation

A. Hubert:
Quasi-domain model for domains and flux transport in interior

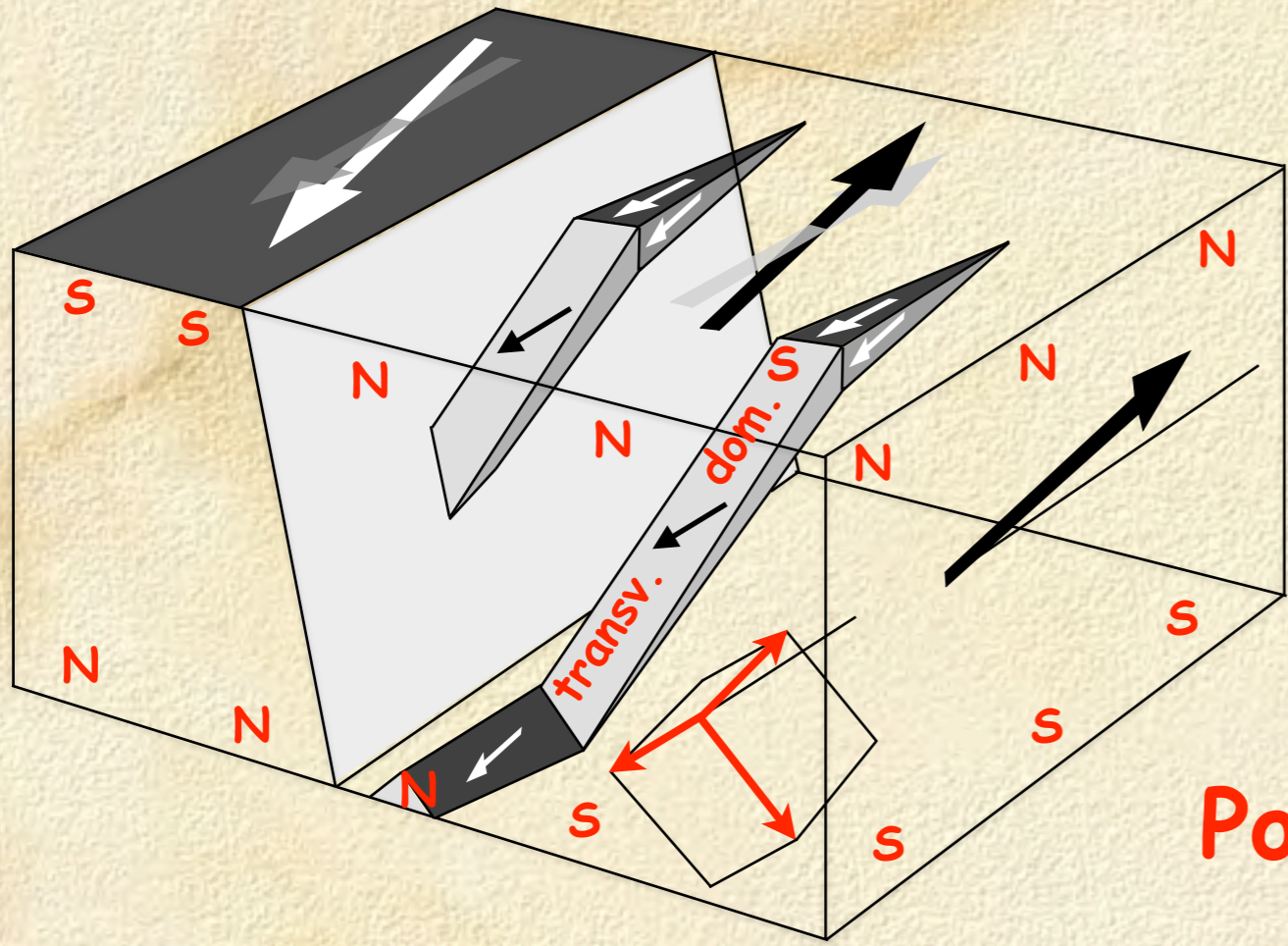


0.5 mm

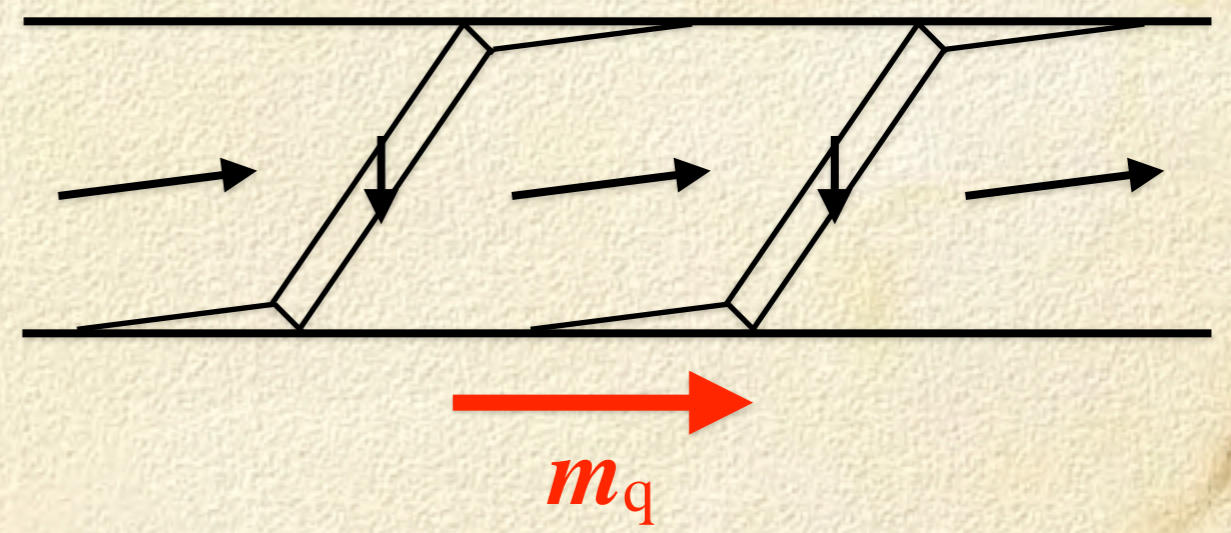
Quasi-Domains



Quasi-Domains



Lancet pattern on slightly misoriented (110) surface



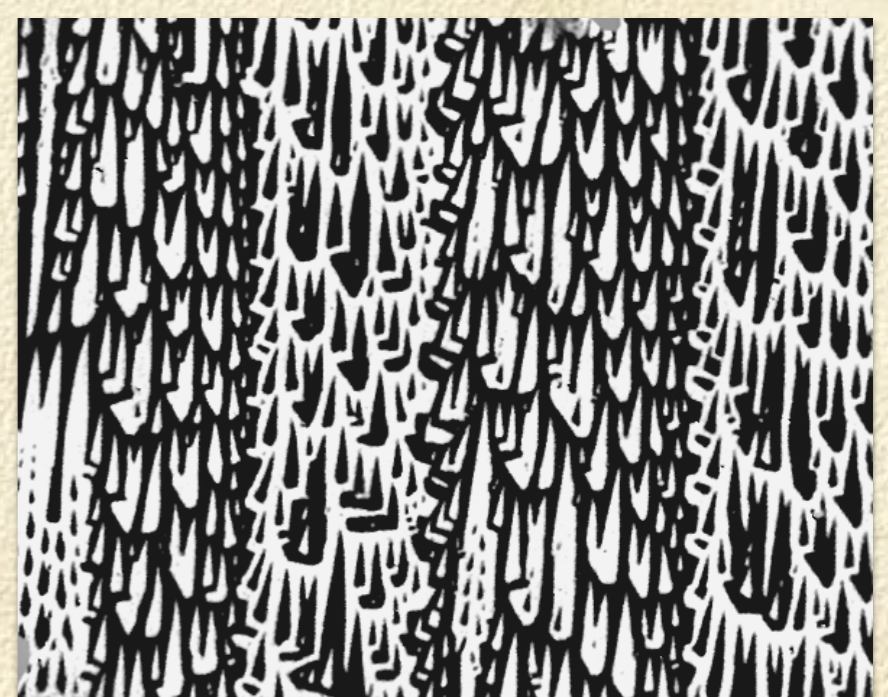
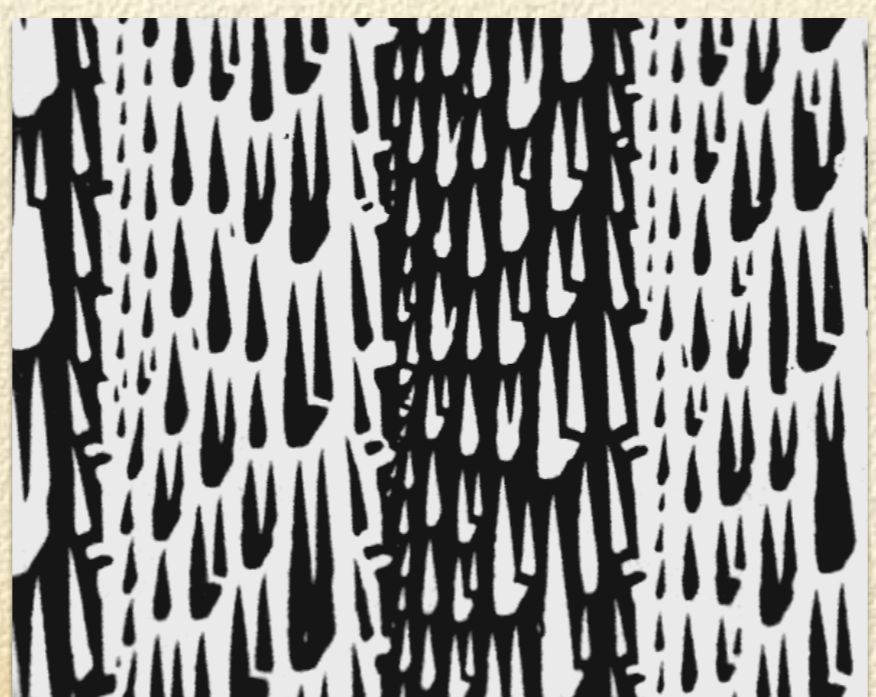
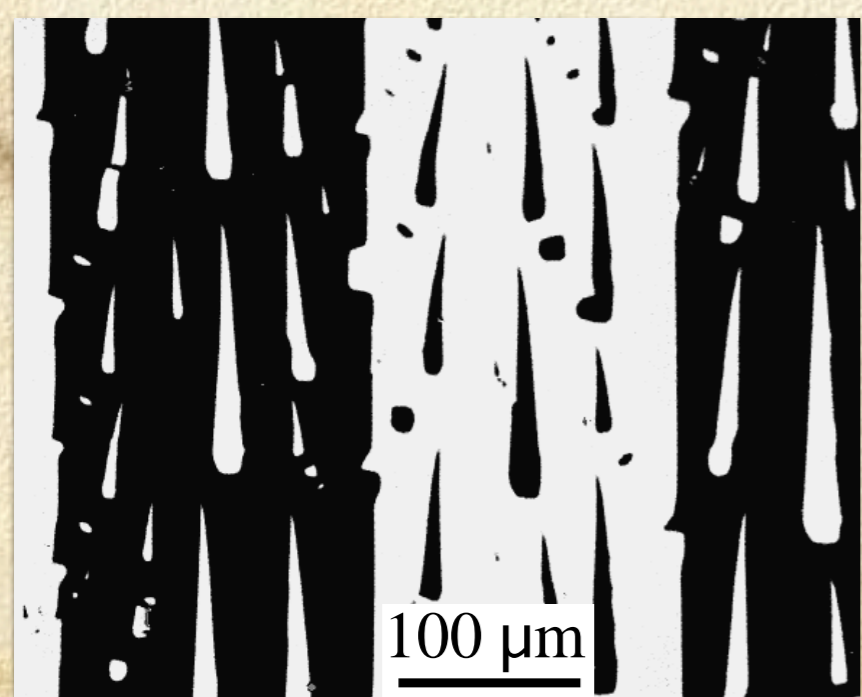
Pole-free on macroscopic scale

Misorientation:

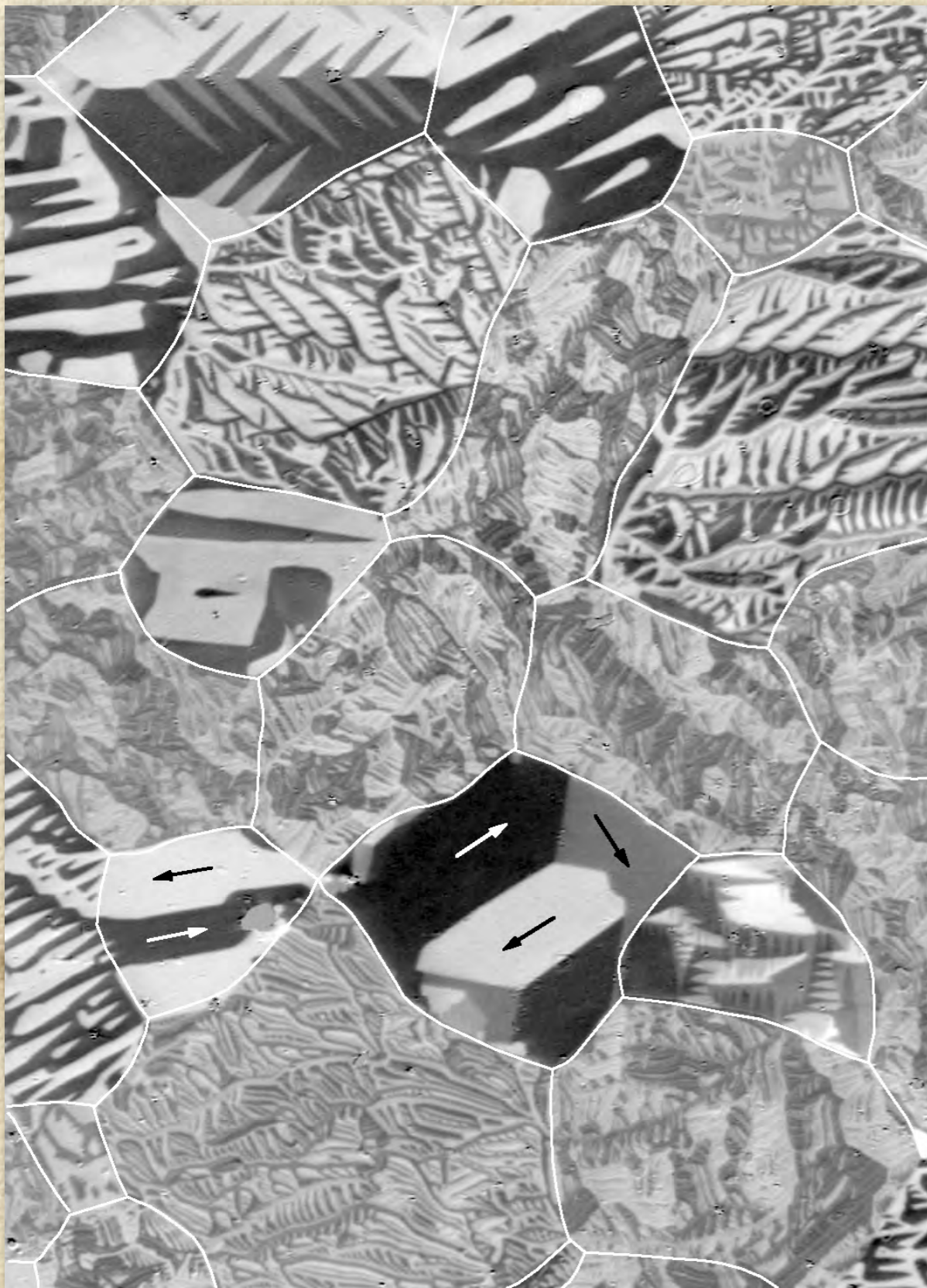
2°

4°

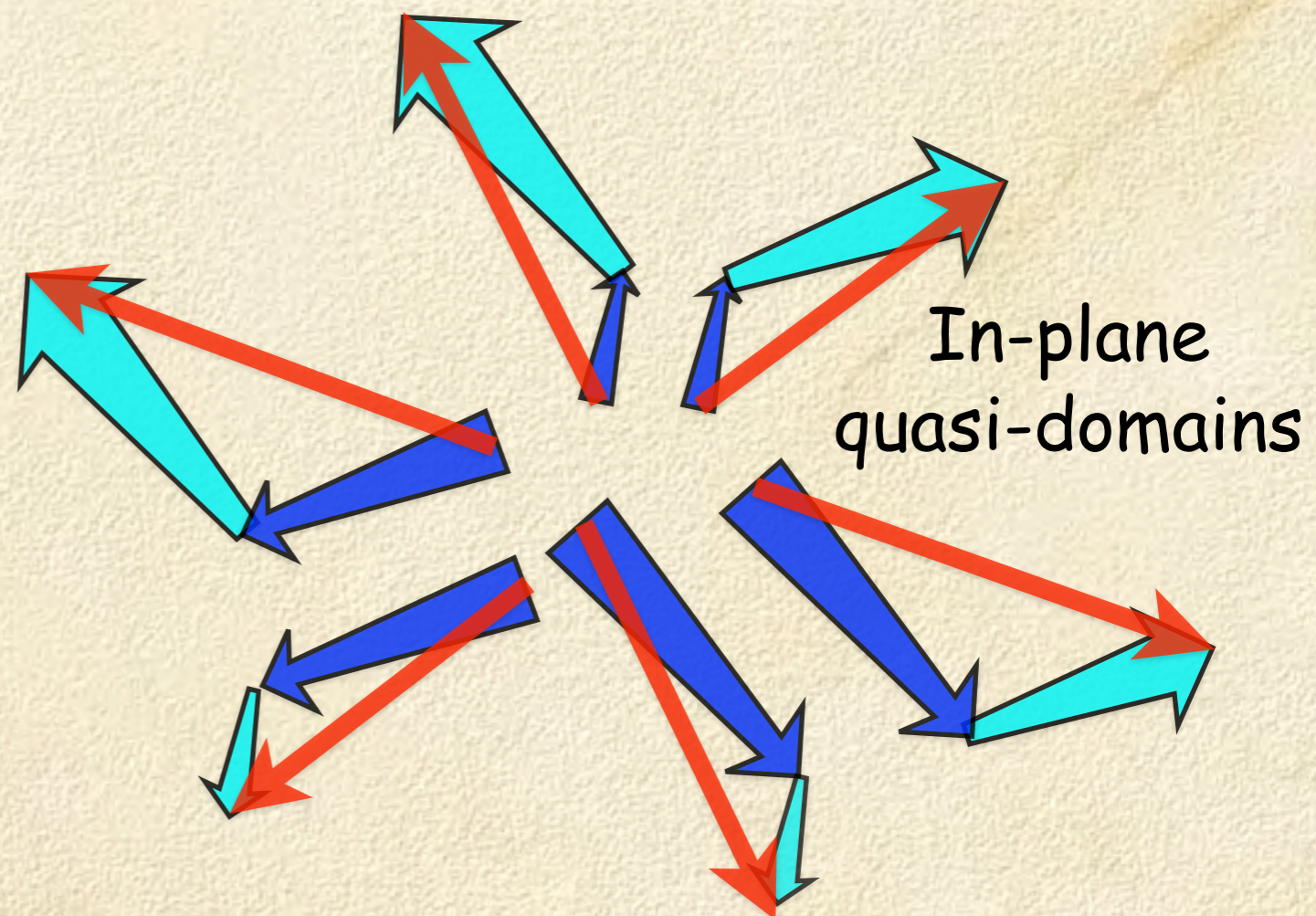
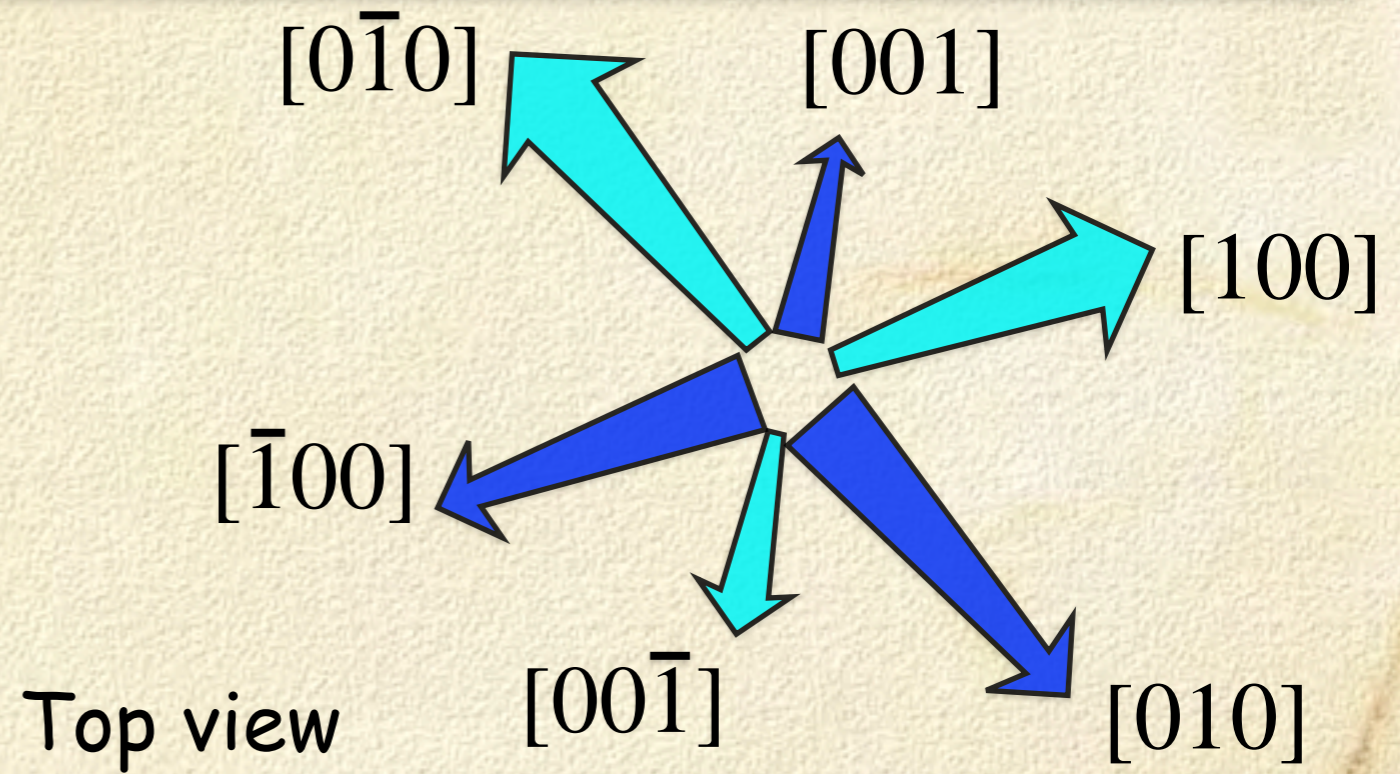
8°



Non-oriented FeSi sheet



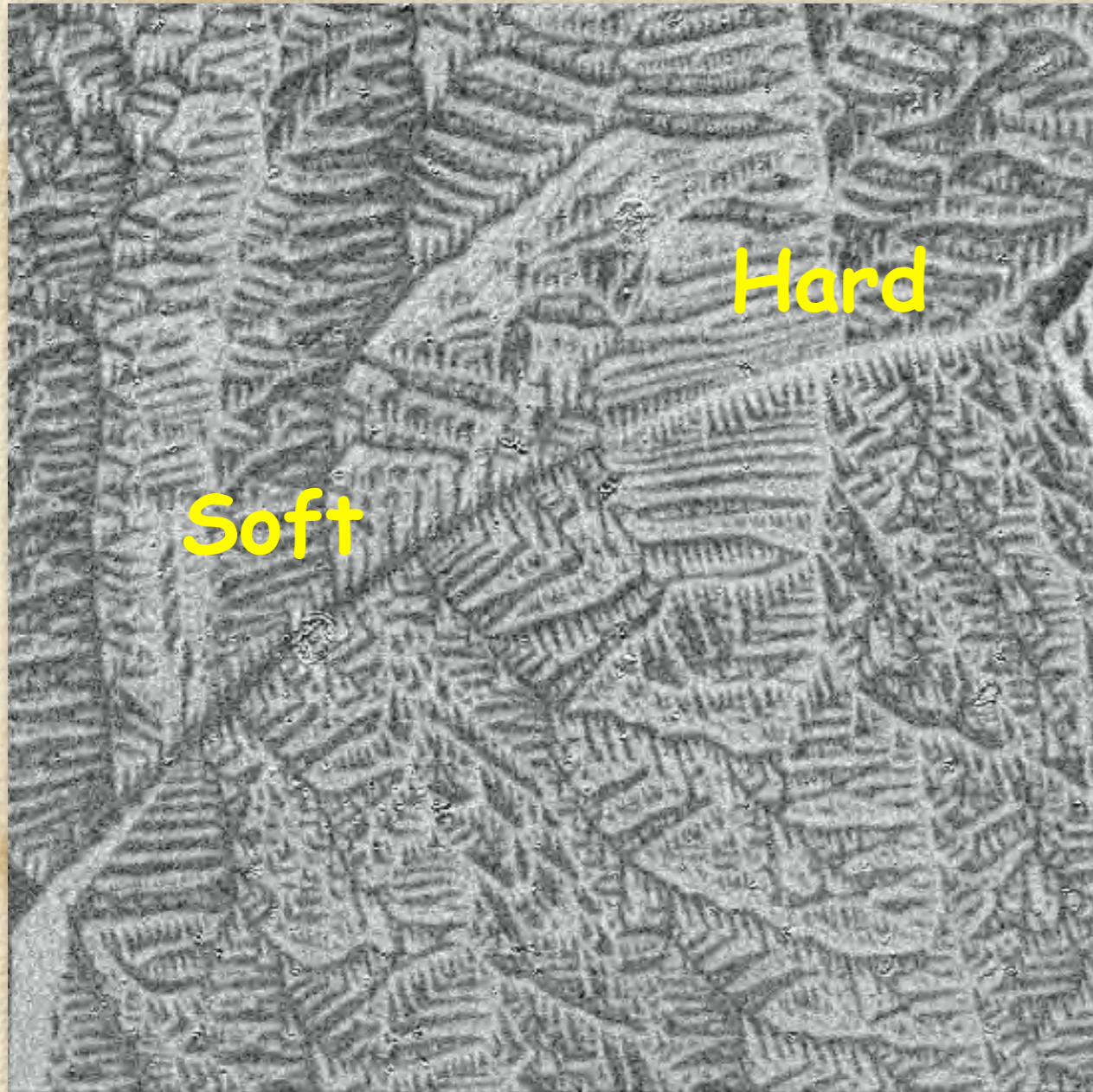
0.5 mm



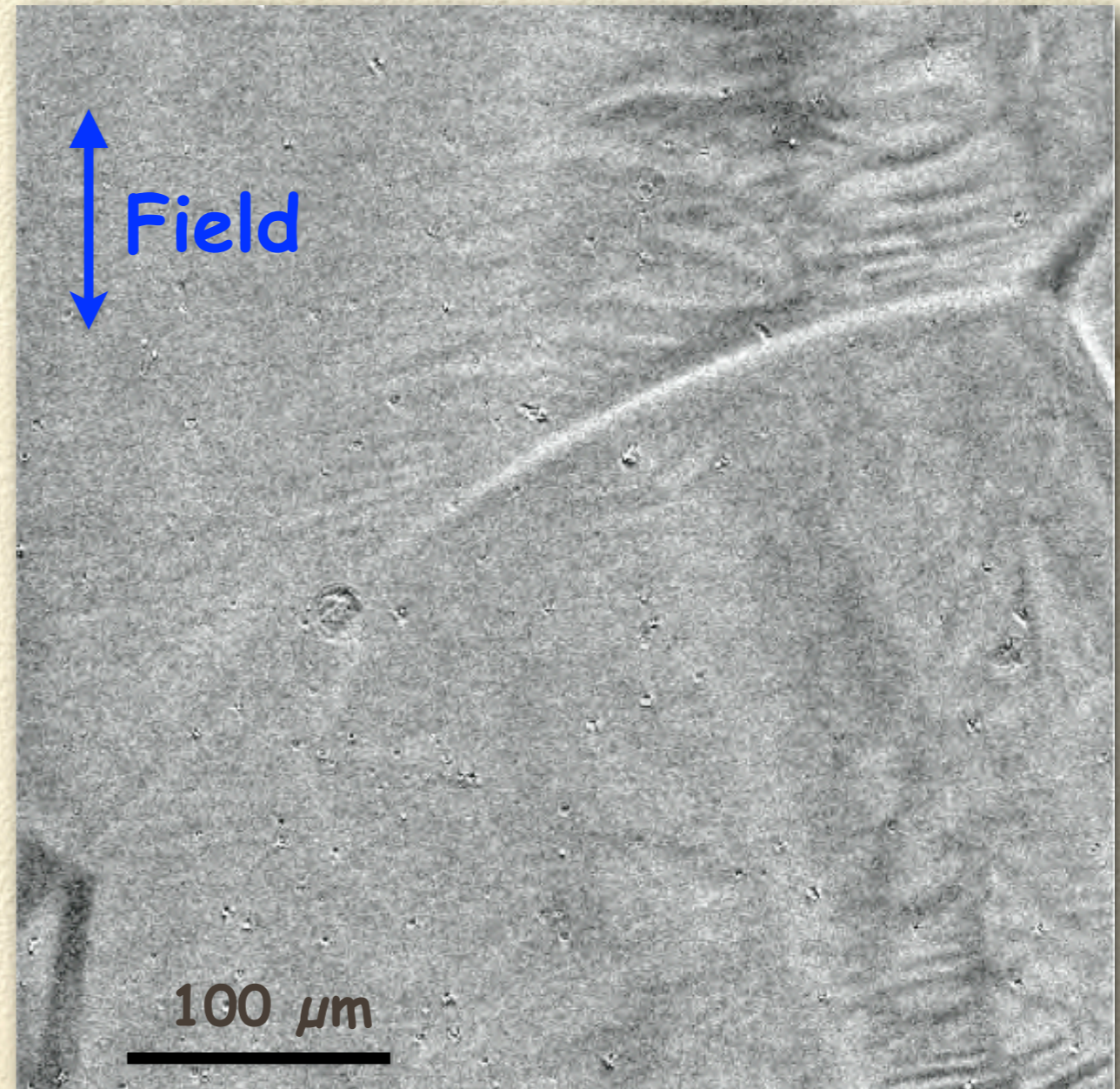
Non-oriented FeSi sheet

Quasi-domains and Grain Boundaries

Demagnetized



50 Hz ac field

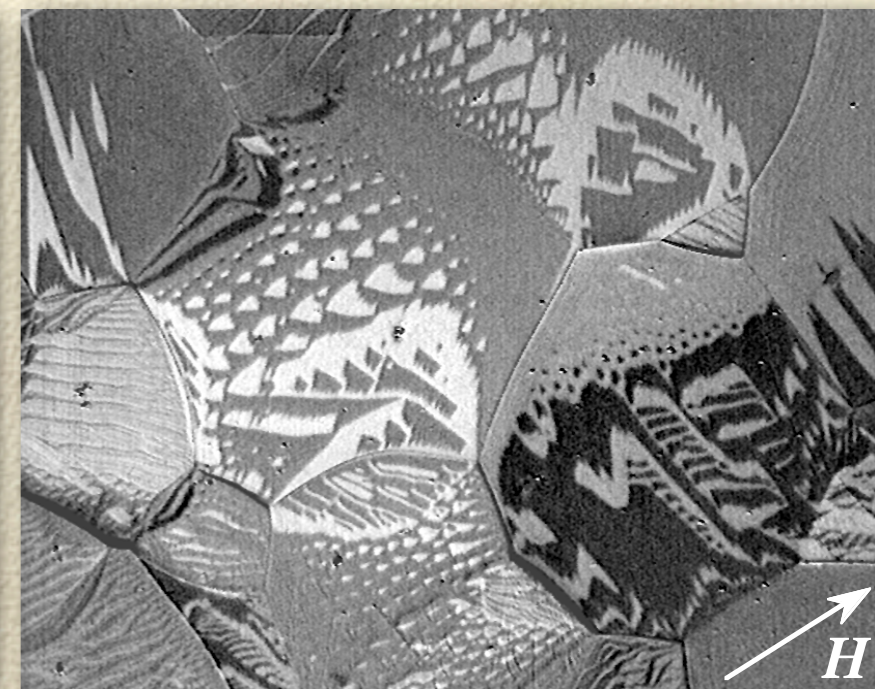
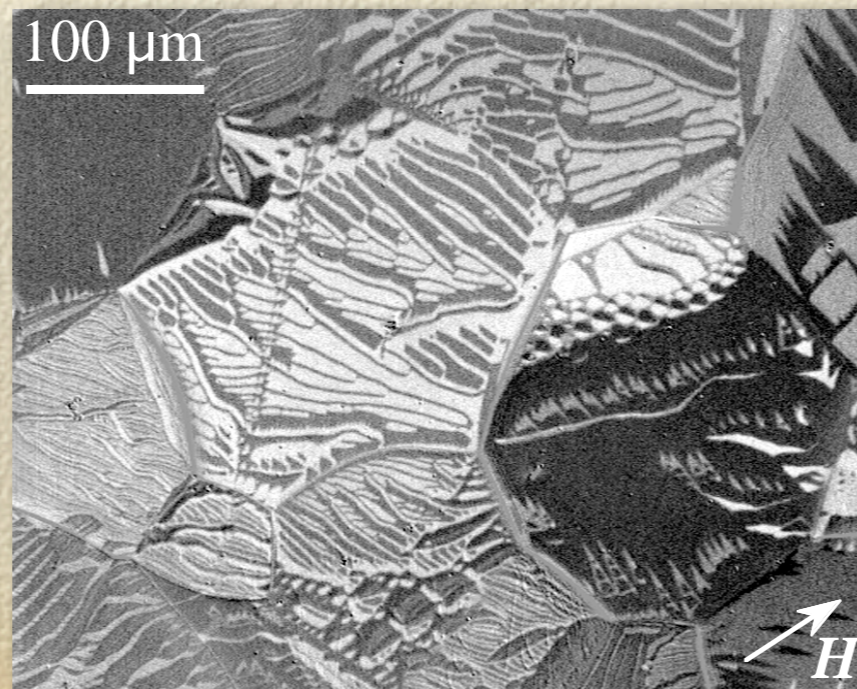
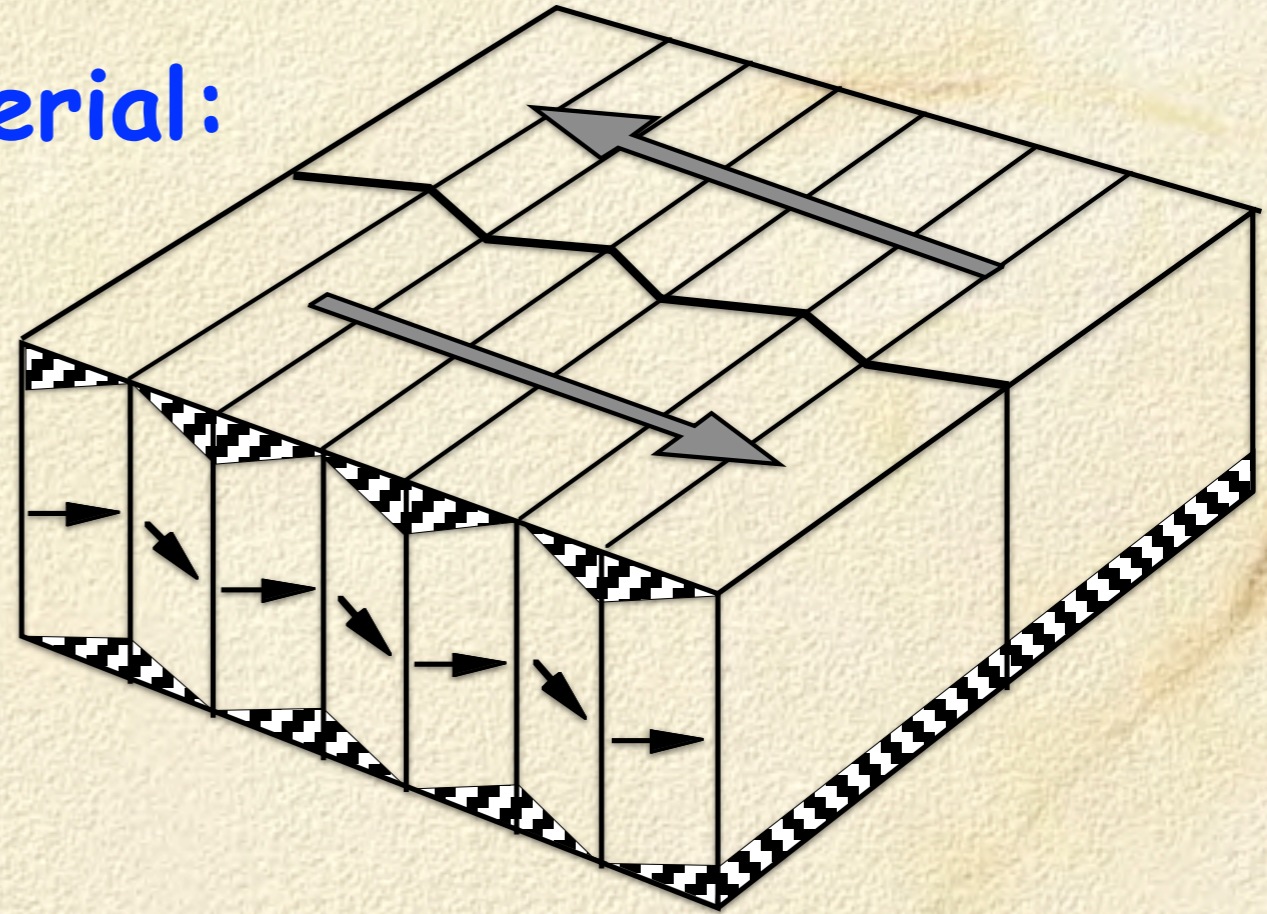


Together with A. Brunner, IFW Dresden
unpublished

Non-oriented FeSi sheet

Folded bands and Quasi-domains [A. Hubert]

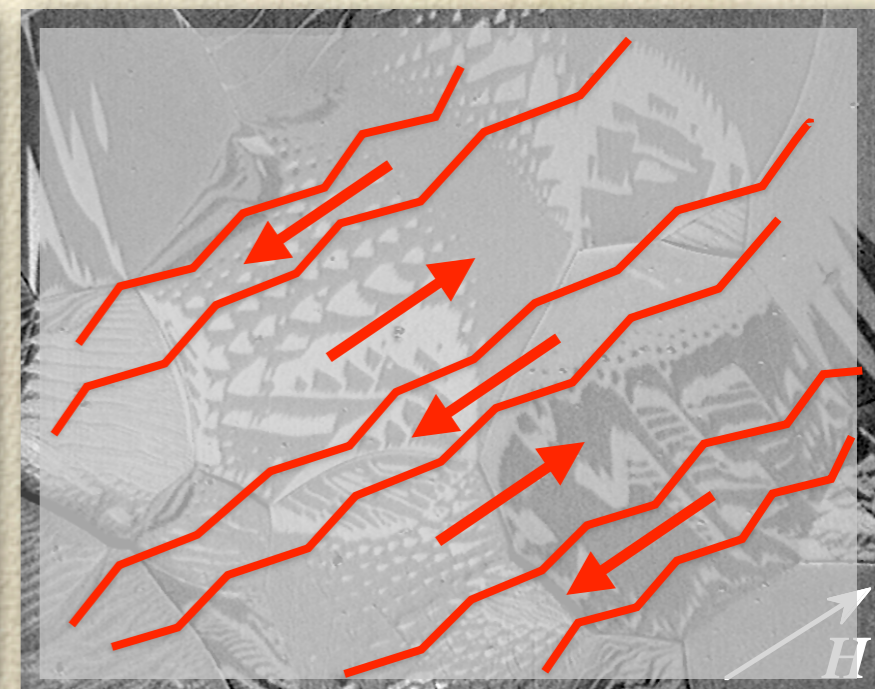
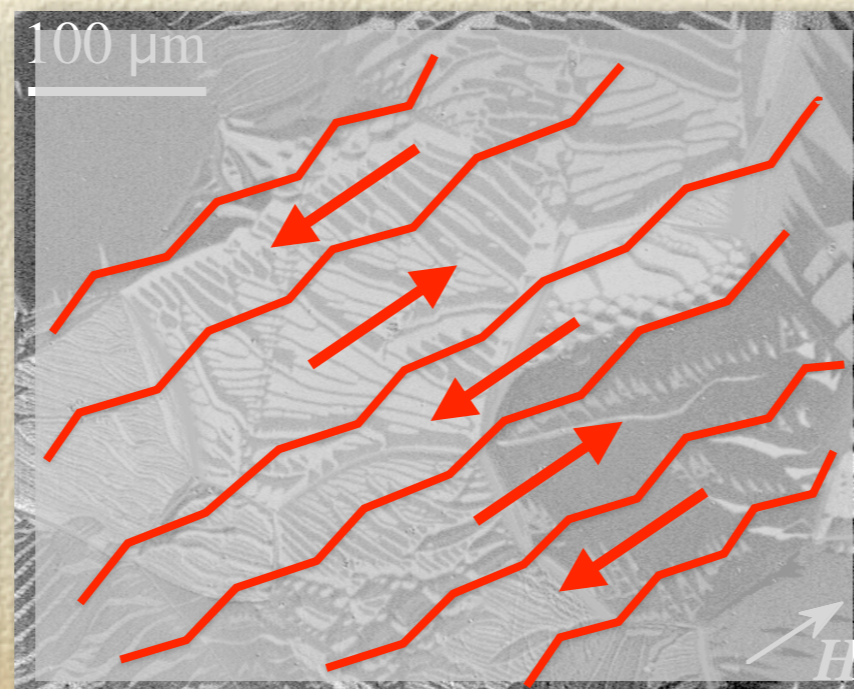
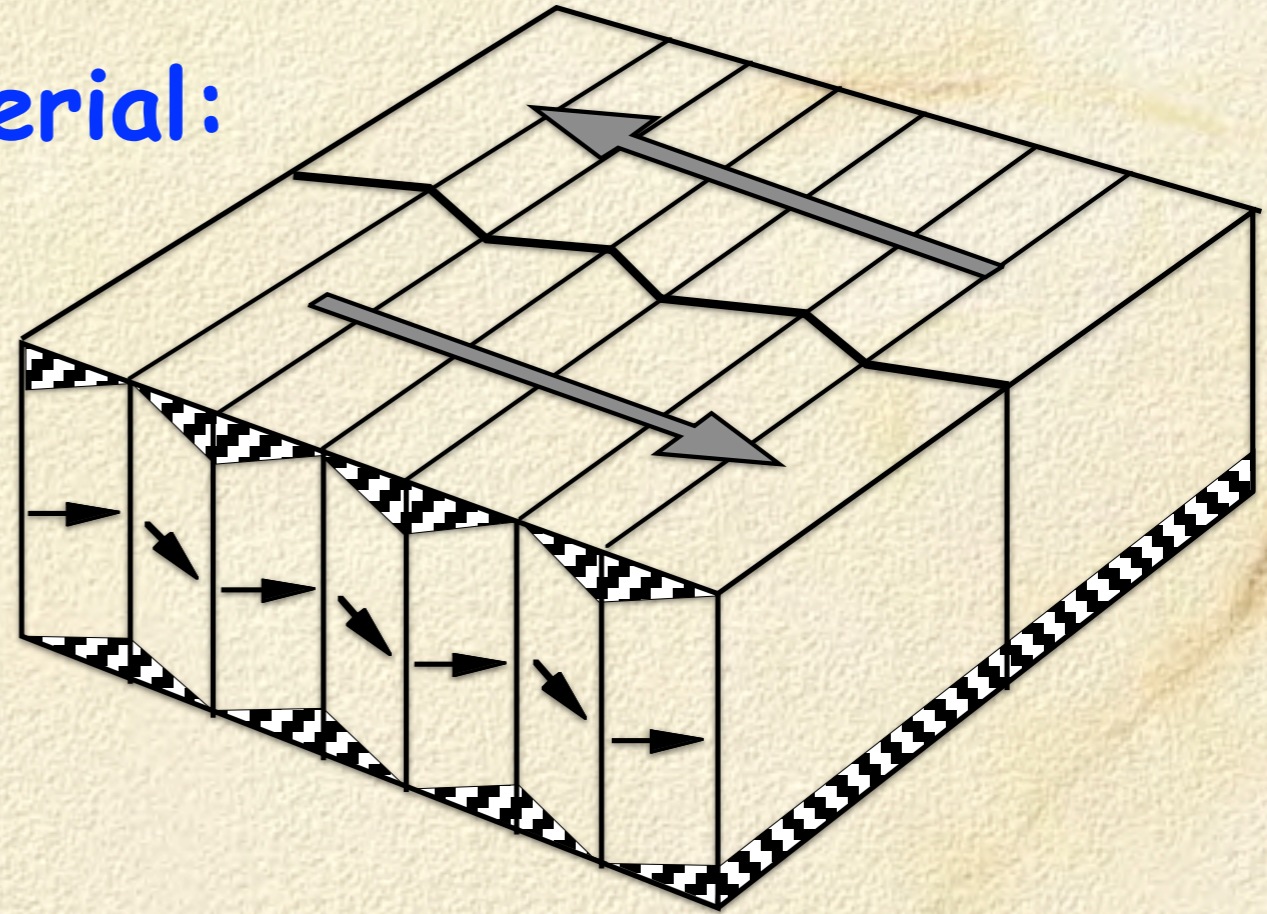
In bulk of non-oriented material:
Folded bands of "quasi-domains" that are able to carry the flux along the working direction



Non-oriented FeSi sheet

Folded bands and Quasi-domains [A. Hubert]

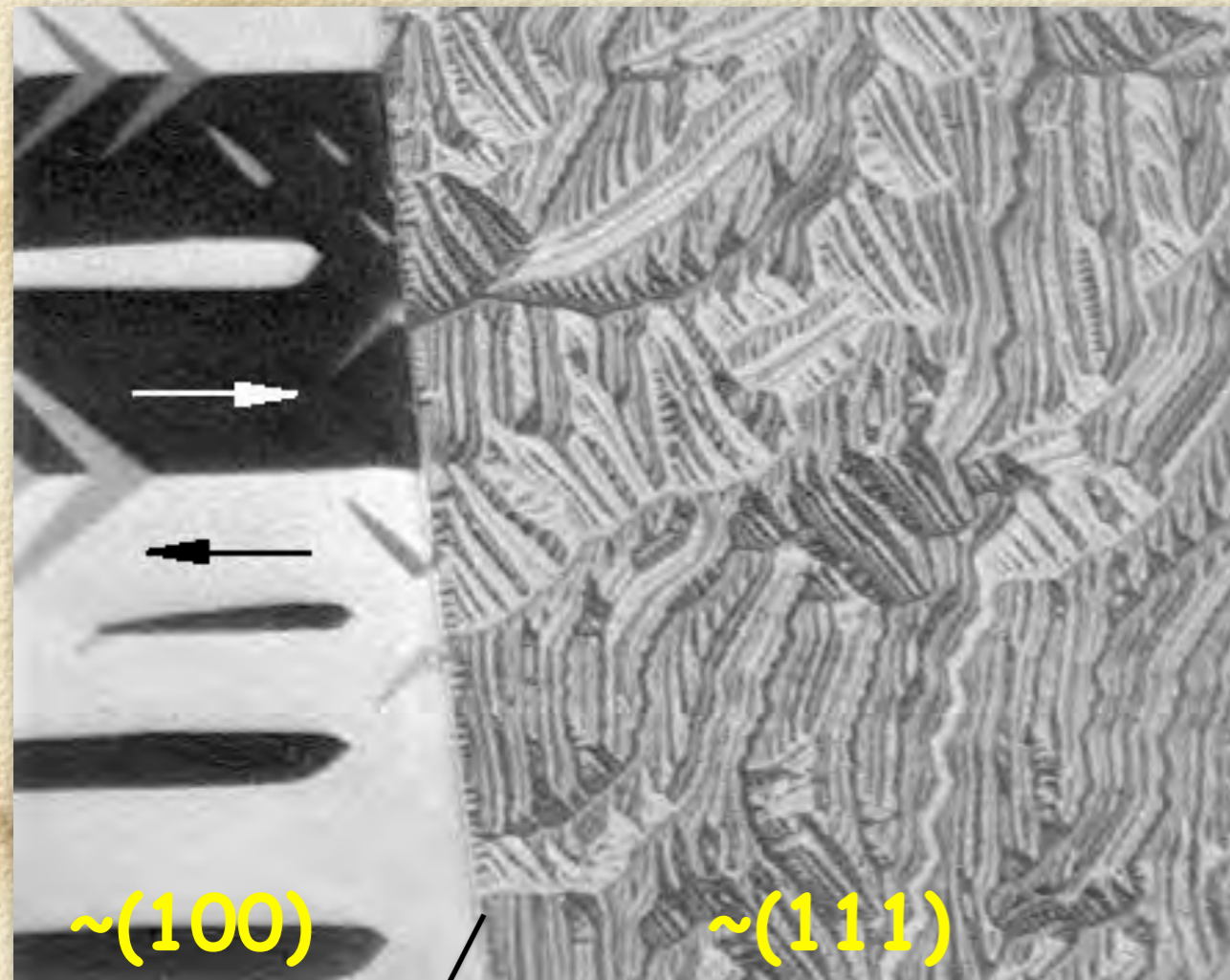
In bulk of non-oriented material:
Folded bands of "quasi-domains" that are able to carry the flux along the working direction



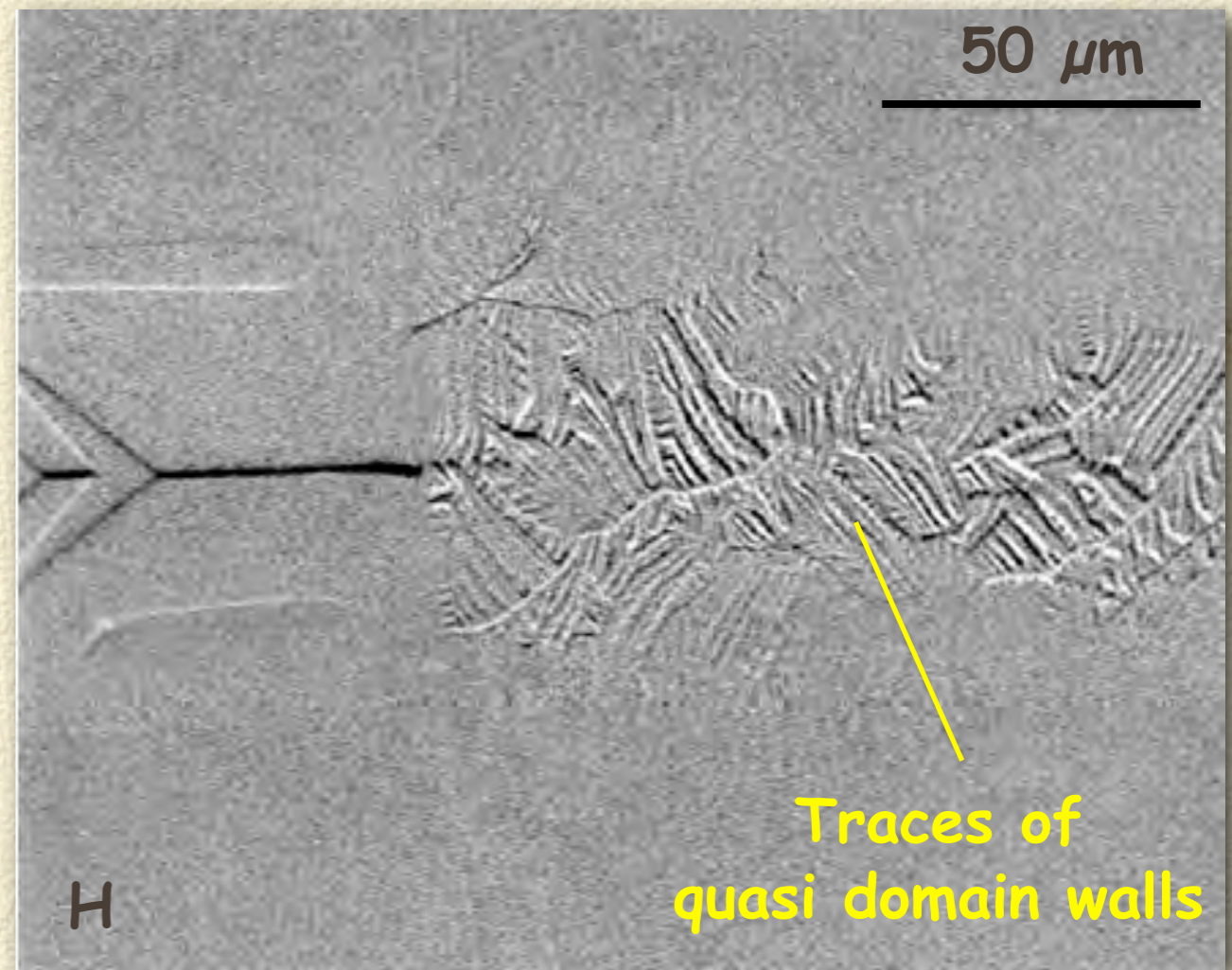
Non-oriented FeSi sheet

Indication of folded bands by surface observation

Non-oriented electrical steel (0.5 mm thick)

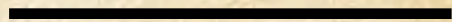


grain boundary



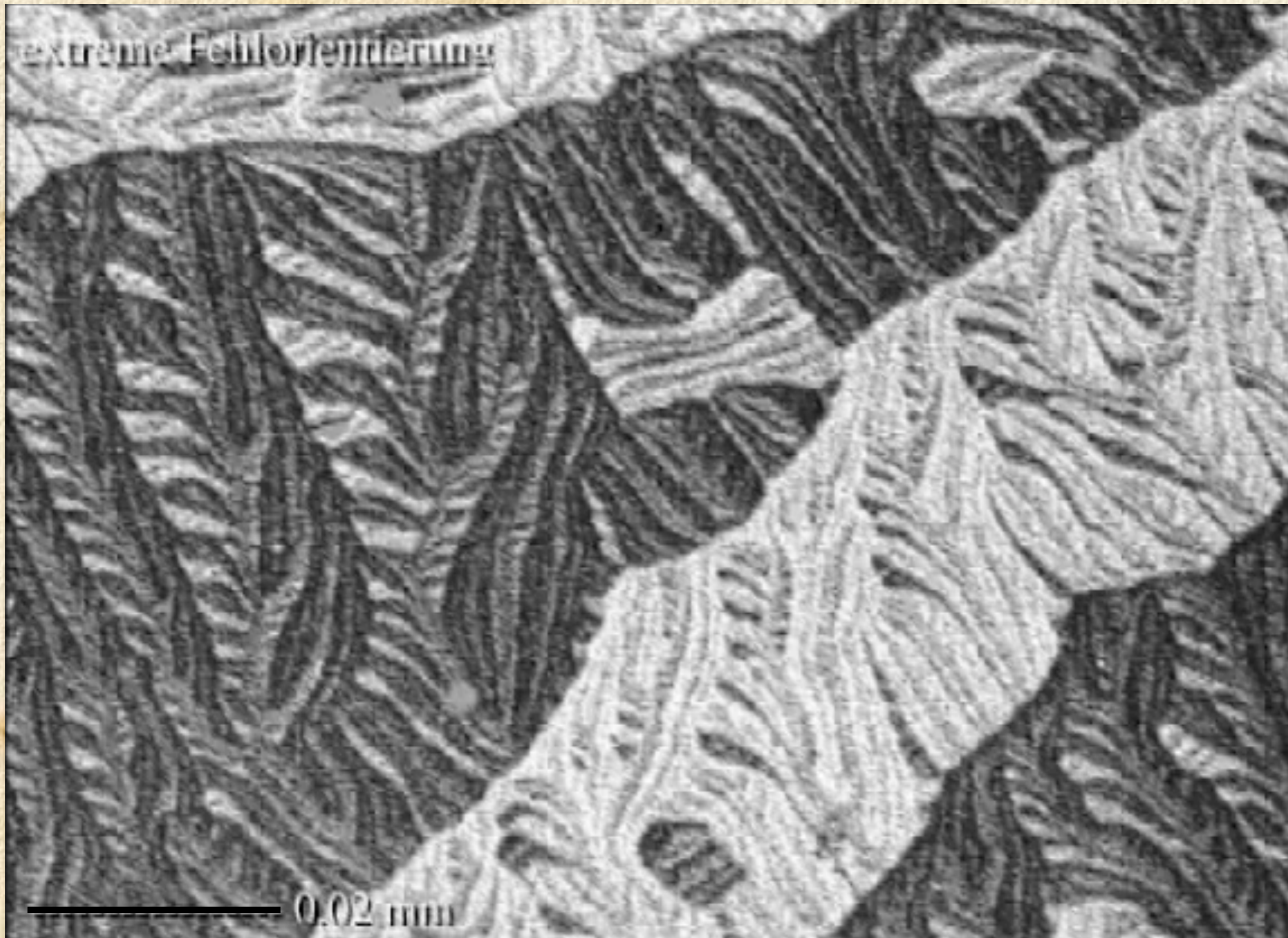
Difference between left image and image with field applied

Motor sheet



← magnetic ac field →

Motor sheet



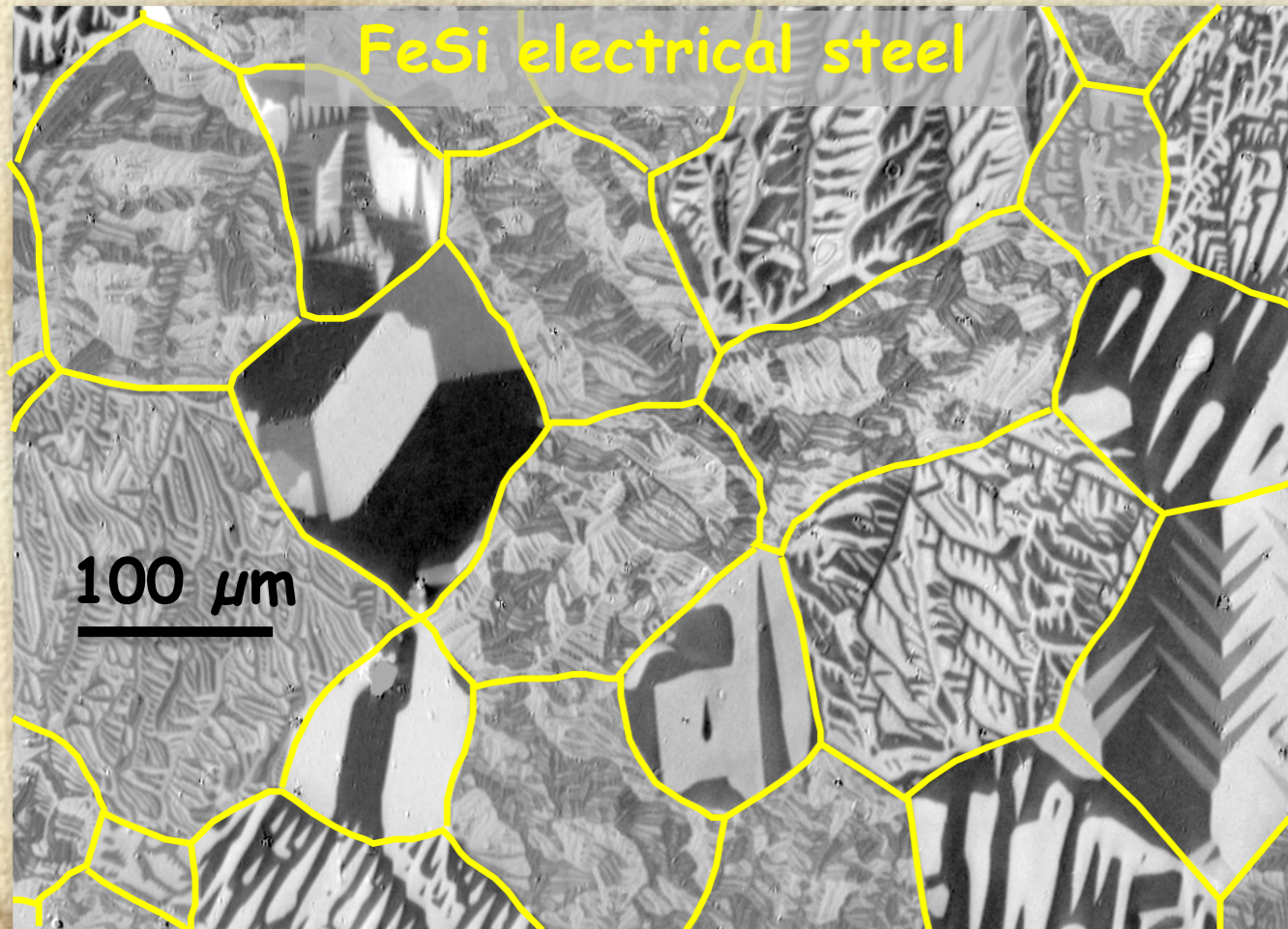
← magnetic ac field →

Microstructure and Domains

**What happens to domains,
when grain size gets smaller ?**

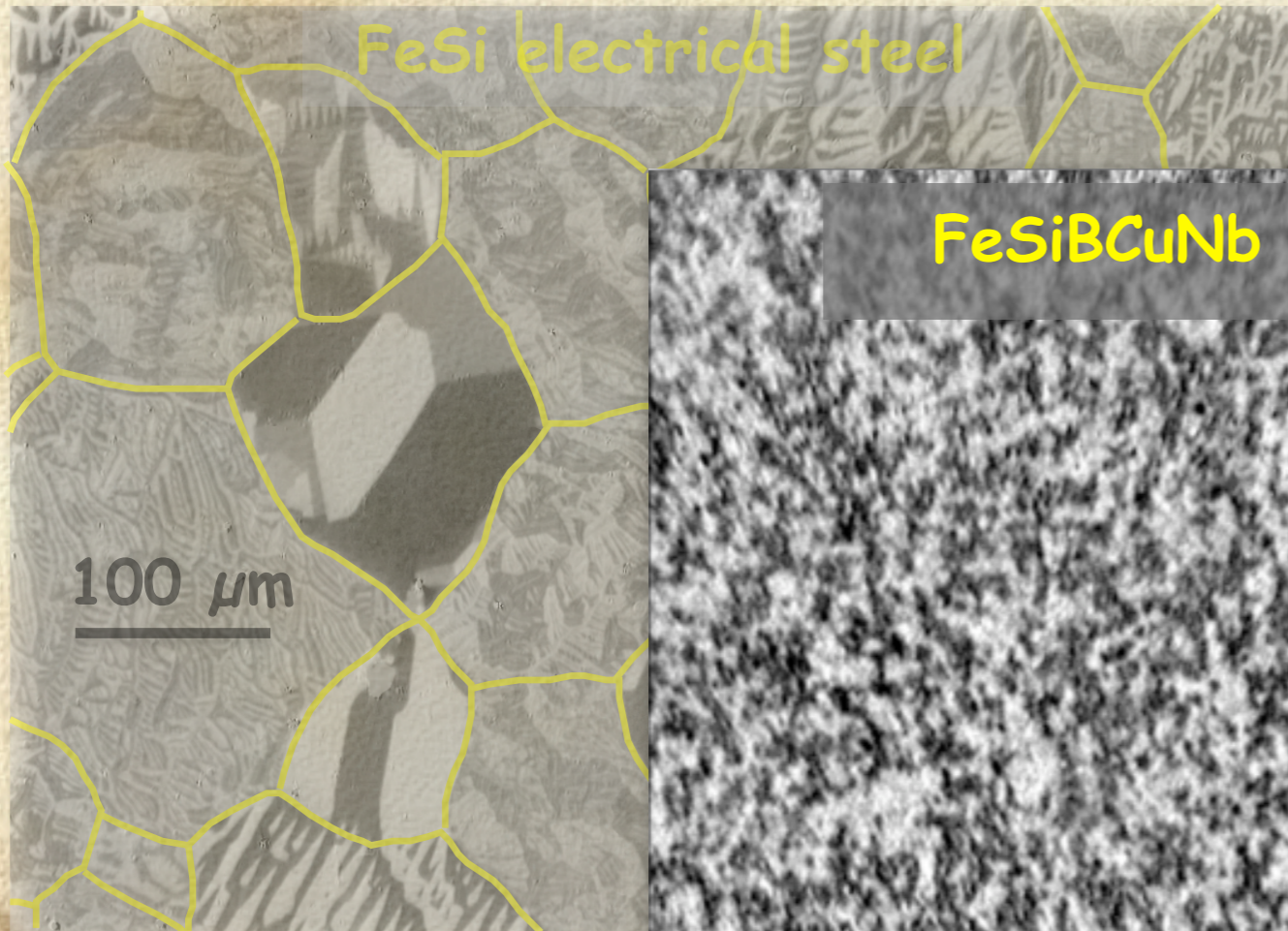
What happens to domains, when grain size gets smaller ?

Grain size:
100 μm range

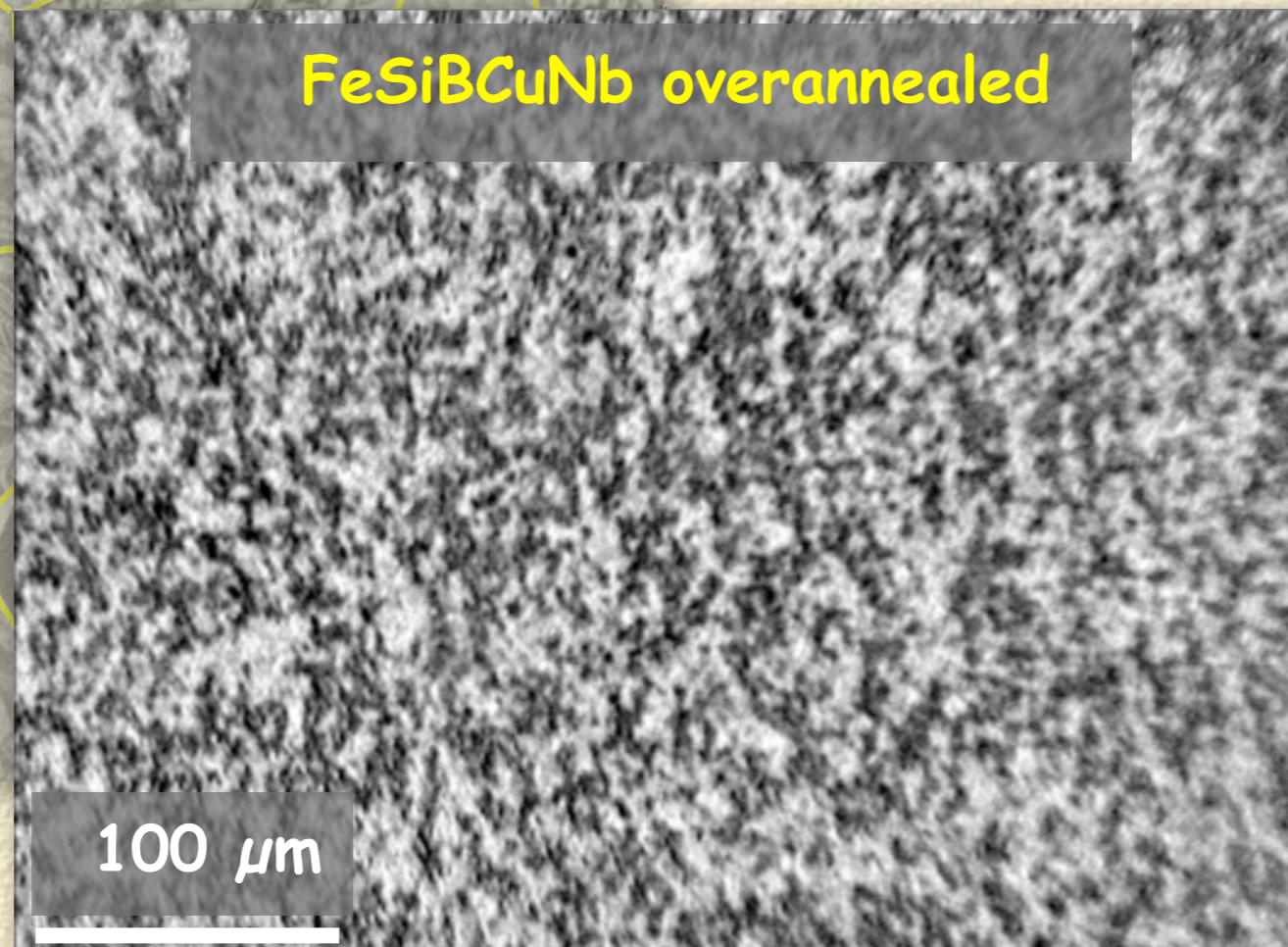


What happens to domains, when grain size gets smaller ?

Grain size:
100 μm range

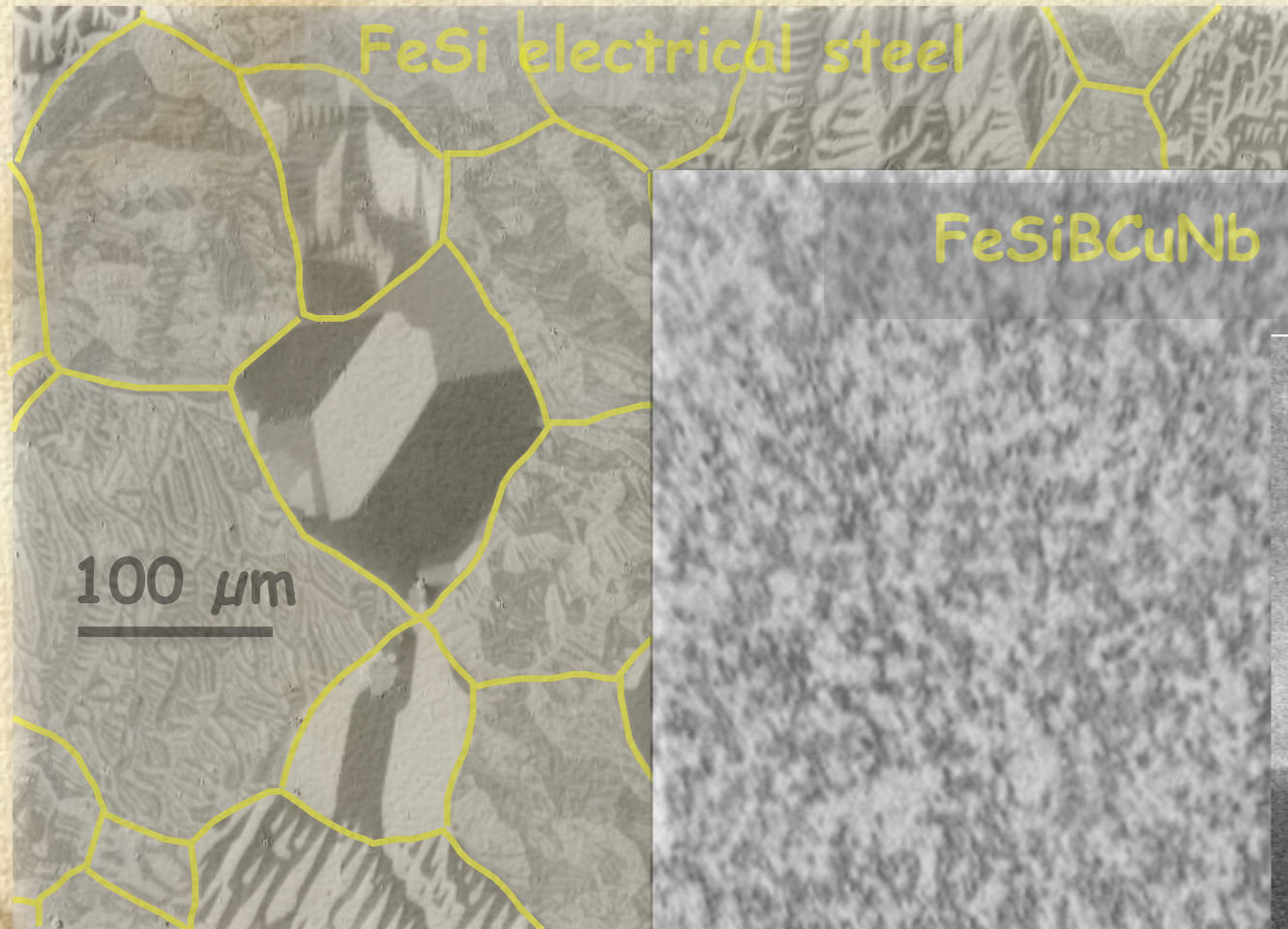


Grain size:
100 nm range

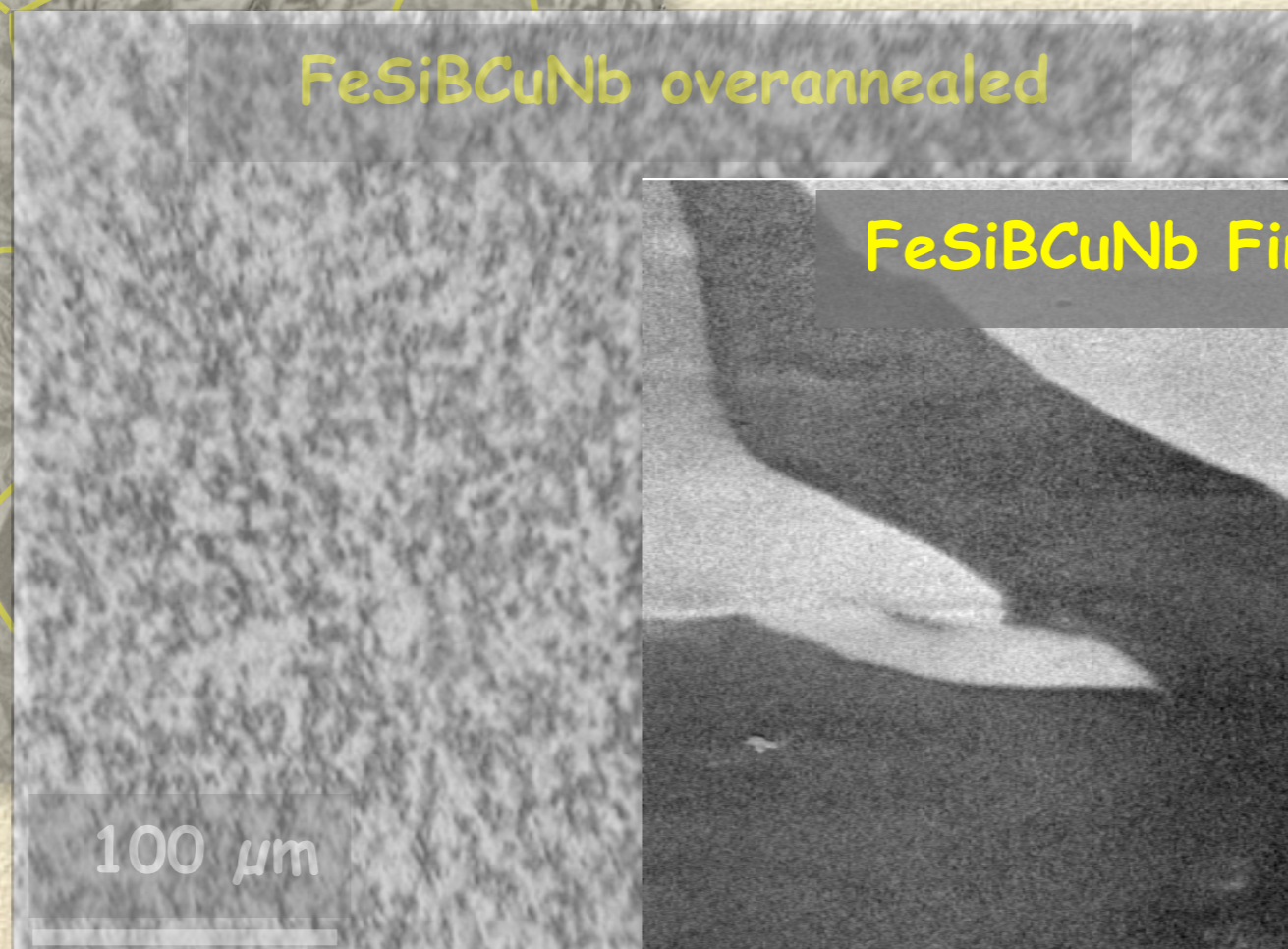


What happens to domains, when grain size gets smaller ?

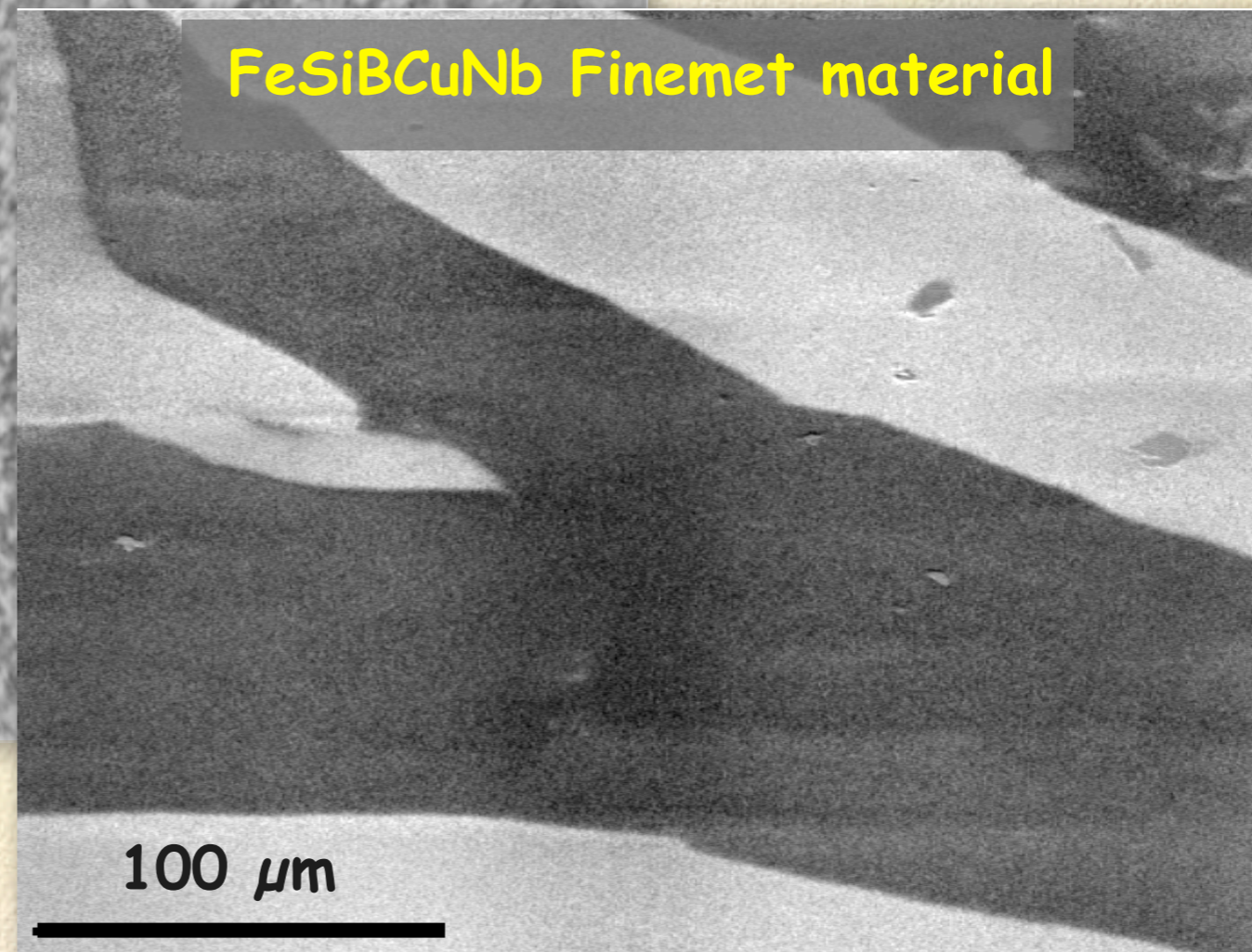
Grain size:
100 μm range



Grain size:
100 nm range

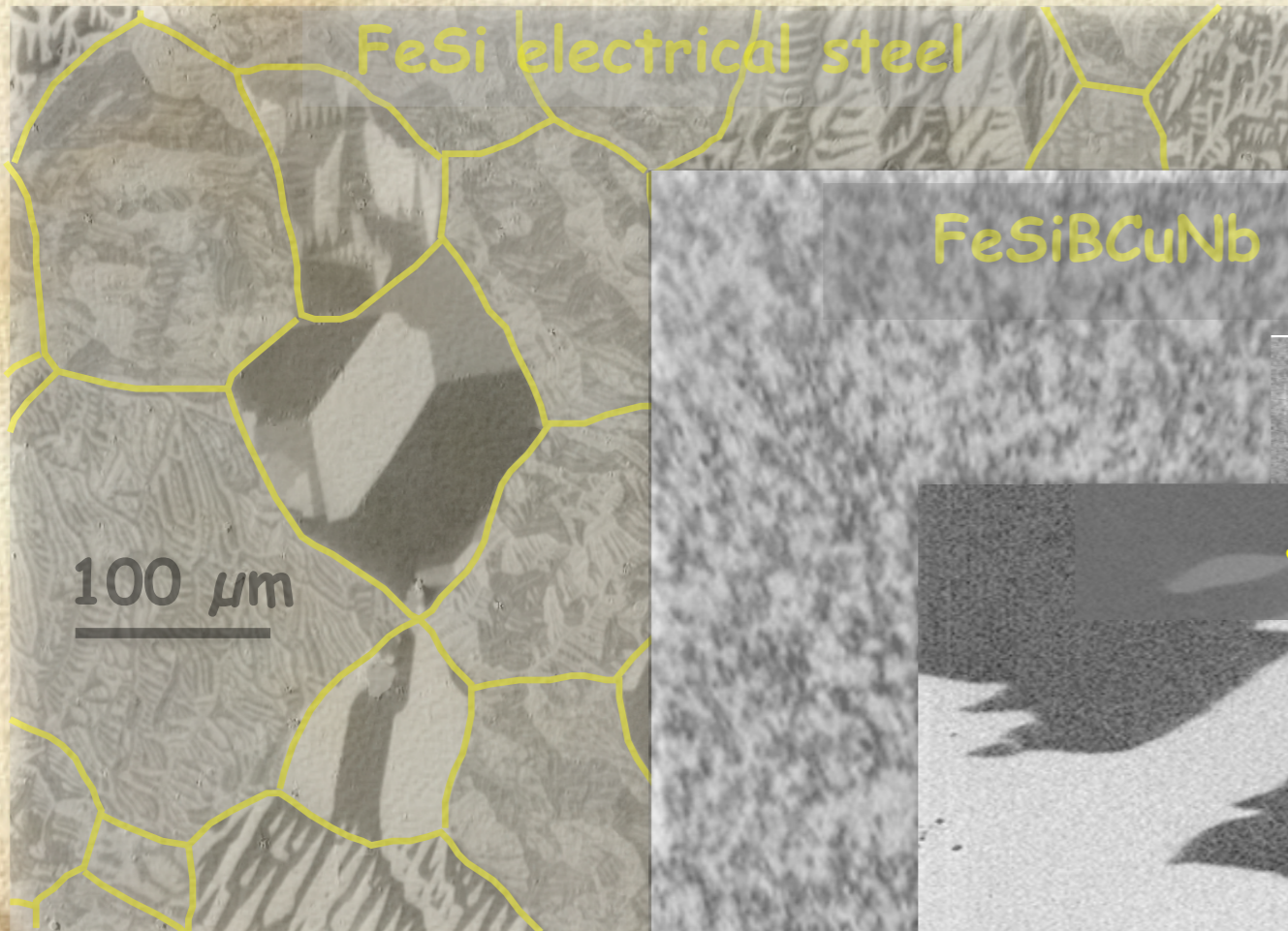


Grain size:
10 nm range



What happens to domains, when grain size gets smaller ?

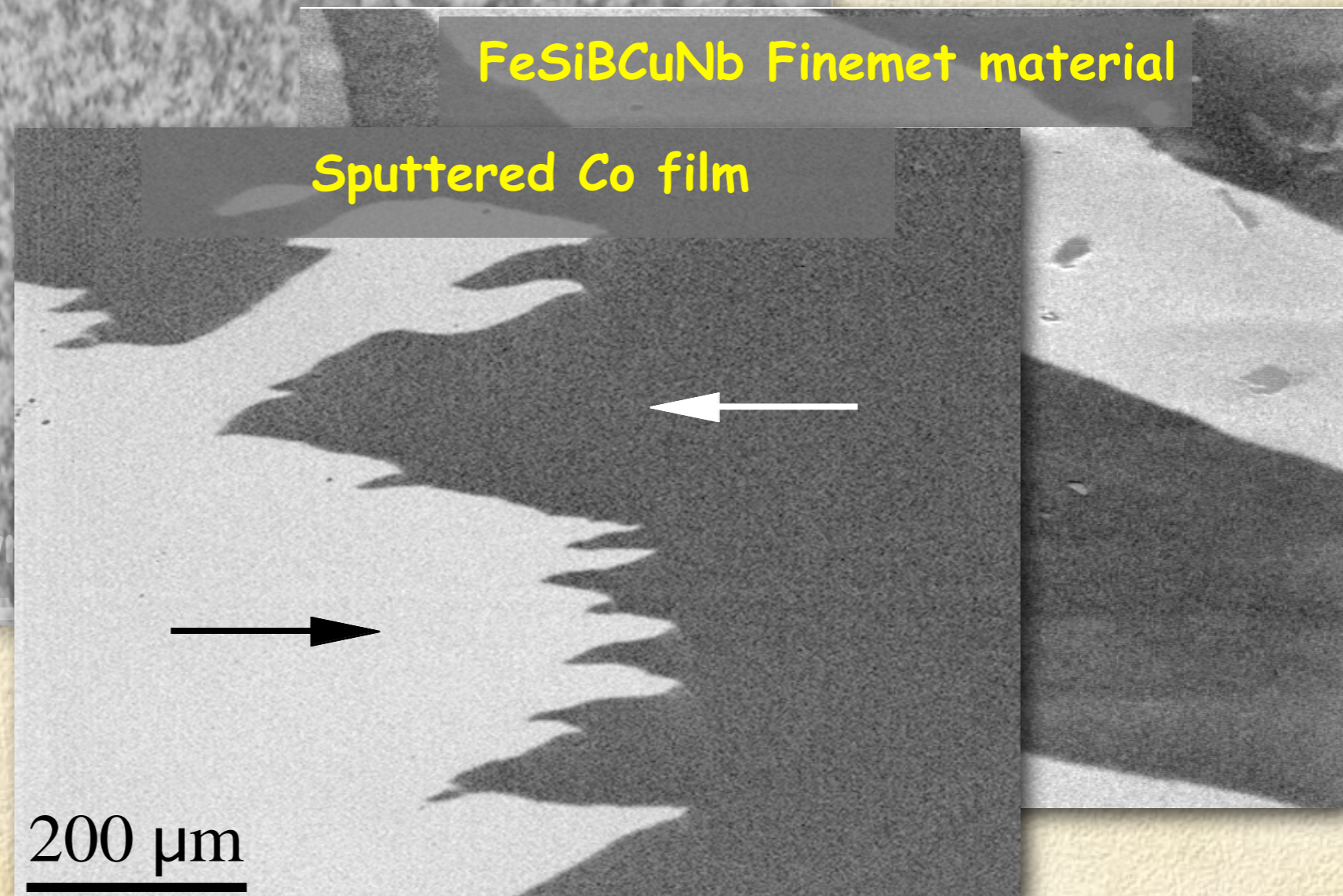
Grain size:
100 μm range



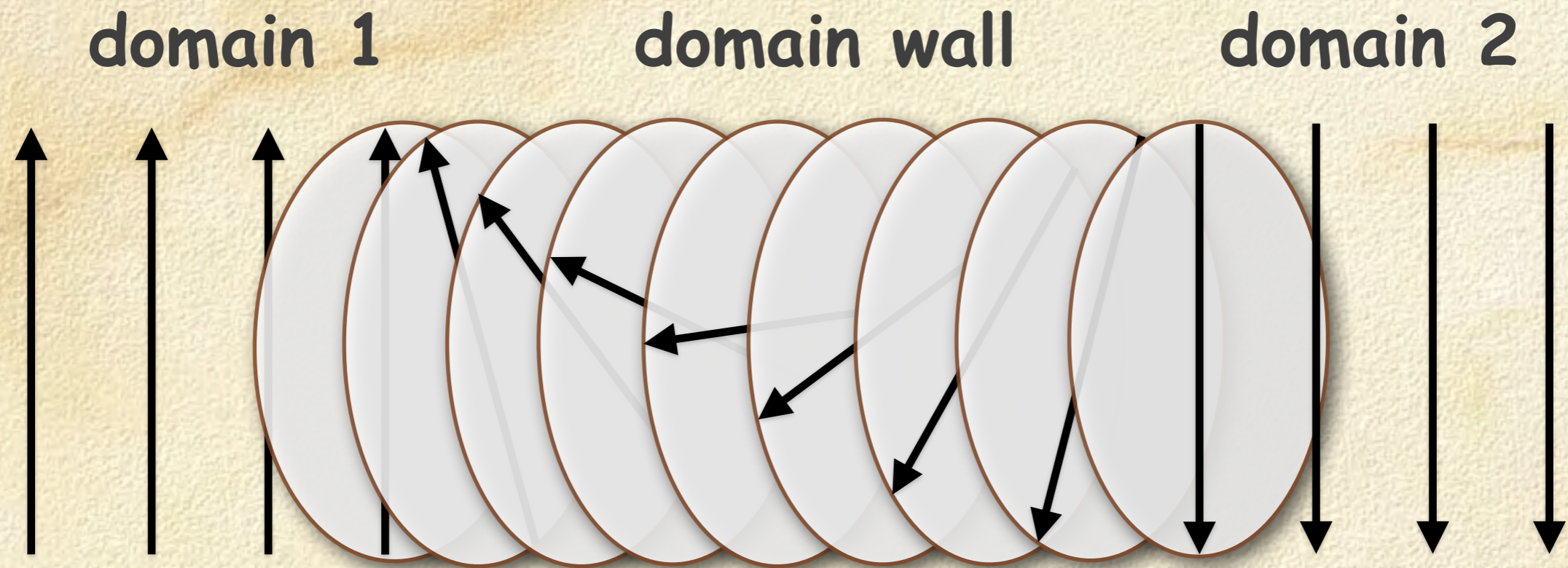
Grain size:
100 nm range



Grain size:
10 nm range



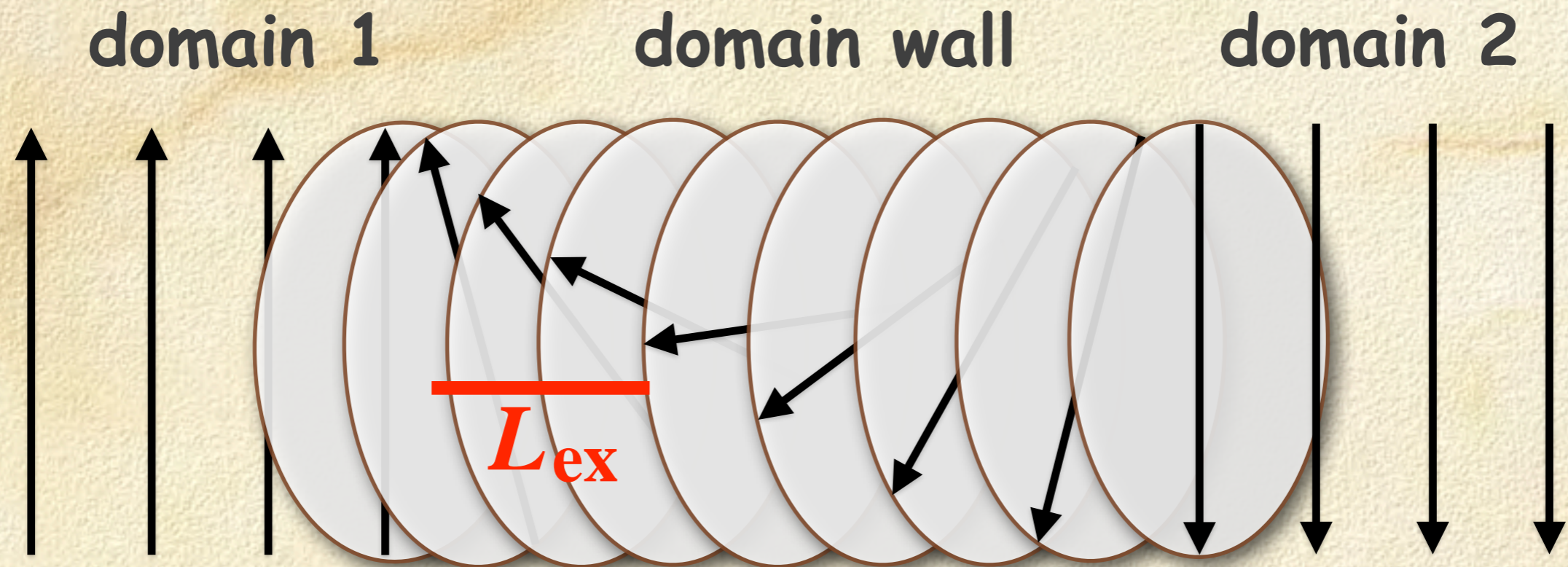
Nanocrystalline ($Q \ll 1$) materials



$$\pi \sqrt{A/K}$$

K : anisotropy constant
 A : exchange constant

Nanocrystalline ($Q \ll 1$) materials



$$\pi \sqrt{A/K}$$

L_{ex}

K : anisotropy constant
 A : exchange constant

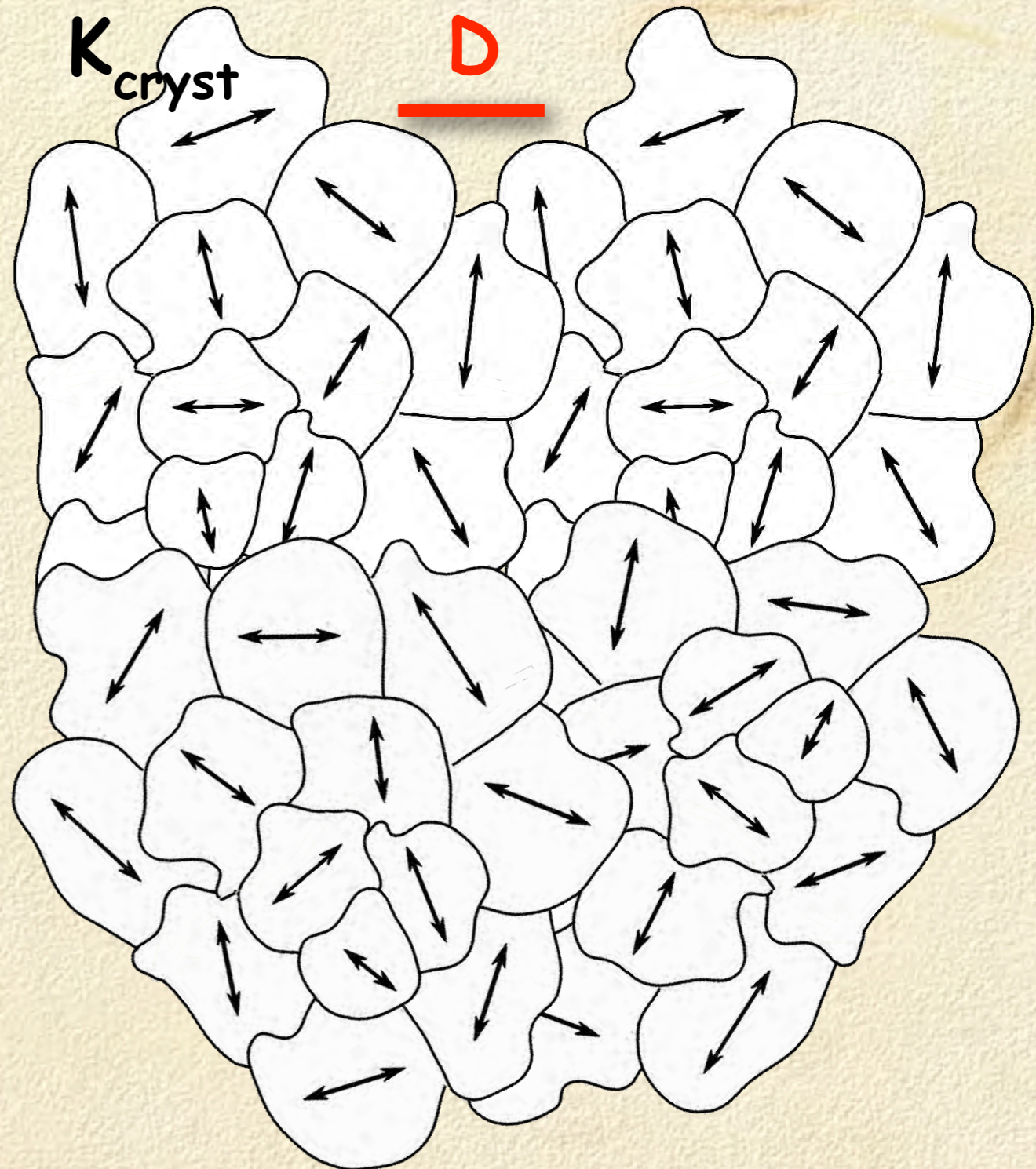
ferromagnetic correlation length (exchange length):
minimum scale for appreciable variation of magnetization
(parallel moments for $L < L_{ex}$)

Nanocrystalline ($Q \ll 1$) materials

Random anisotropy model [Herzer 1989]:

Exchange interaction averages over anisotropy of grains

$$L_{ex} = \sqrt{A/K_{cryst}}$$



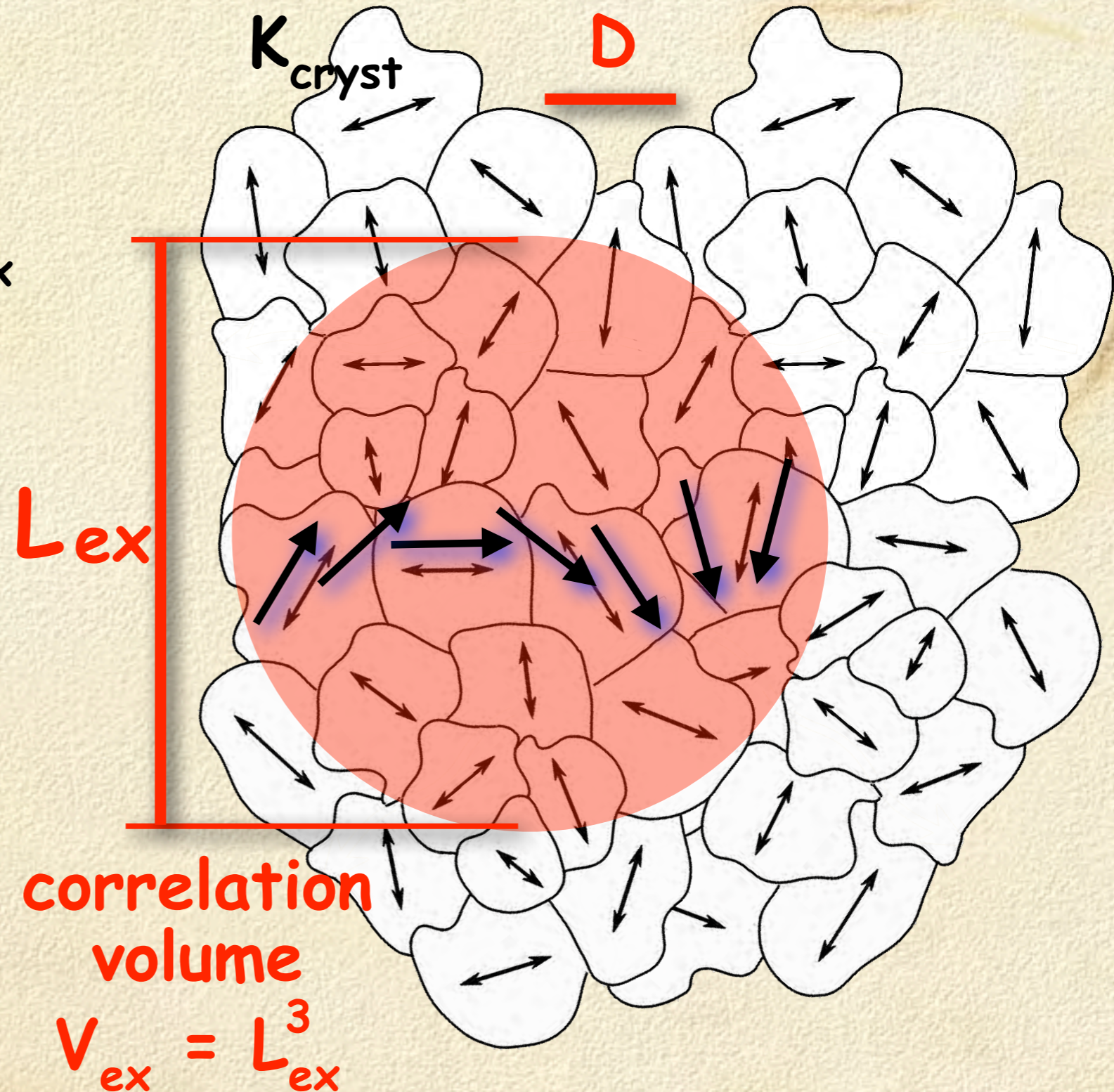
Nanocrystalline ($Q \ll 1$) materials

Random anisotropy model [Herzer 1989]:

Exchange interaction averages over anisotropy of grains

$$L_{ex} = \sqrt{A/K_{cryst}}$$

Nanocrystals: $D < L_{ex}$



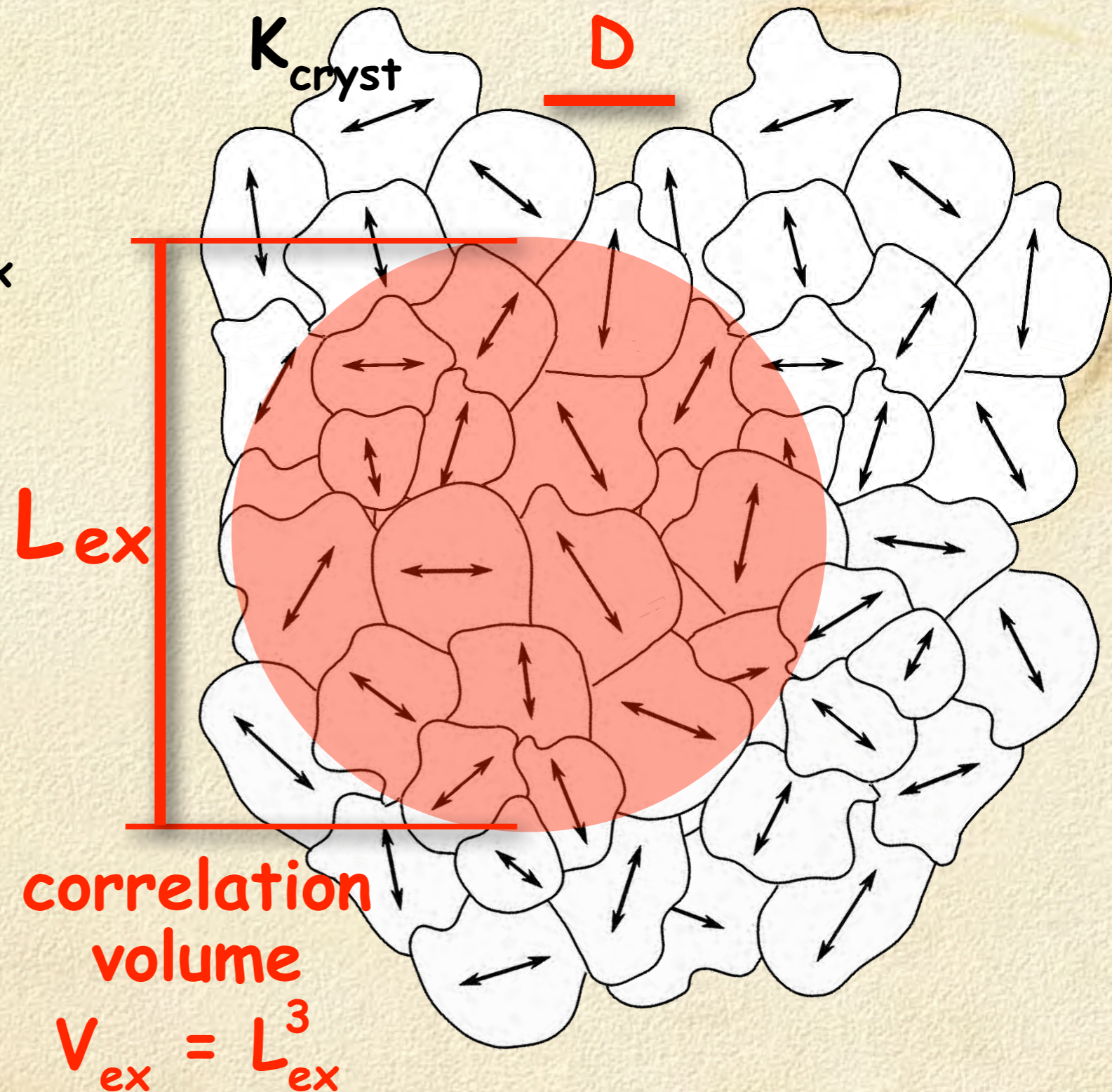
Nanocrystalline ($Q \ll 1$) materials

Random anisotropy model [Herzer 1989]:

Exchange interaction averages over anisotropy of grains

$$L_{ex} = \sqrt{A/K_{cryst}}$$

Nanocrystals: $D < L_{ex}$



Nanocrystalline ($Q \ll 1$) materials

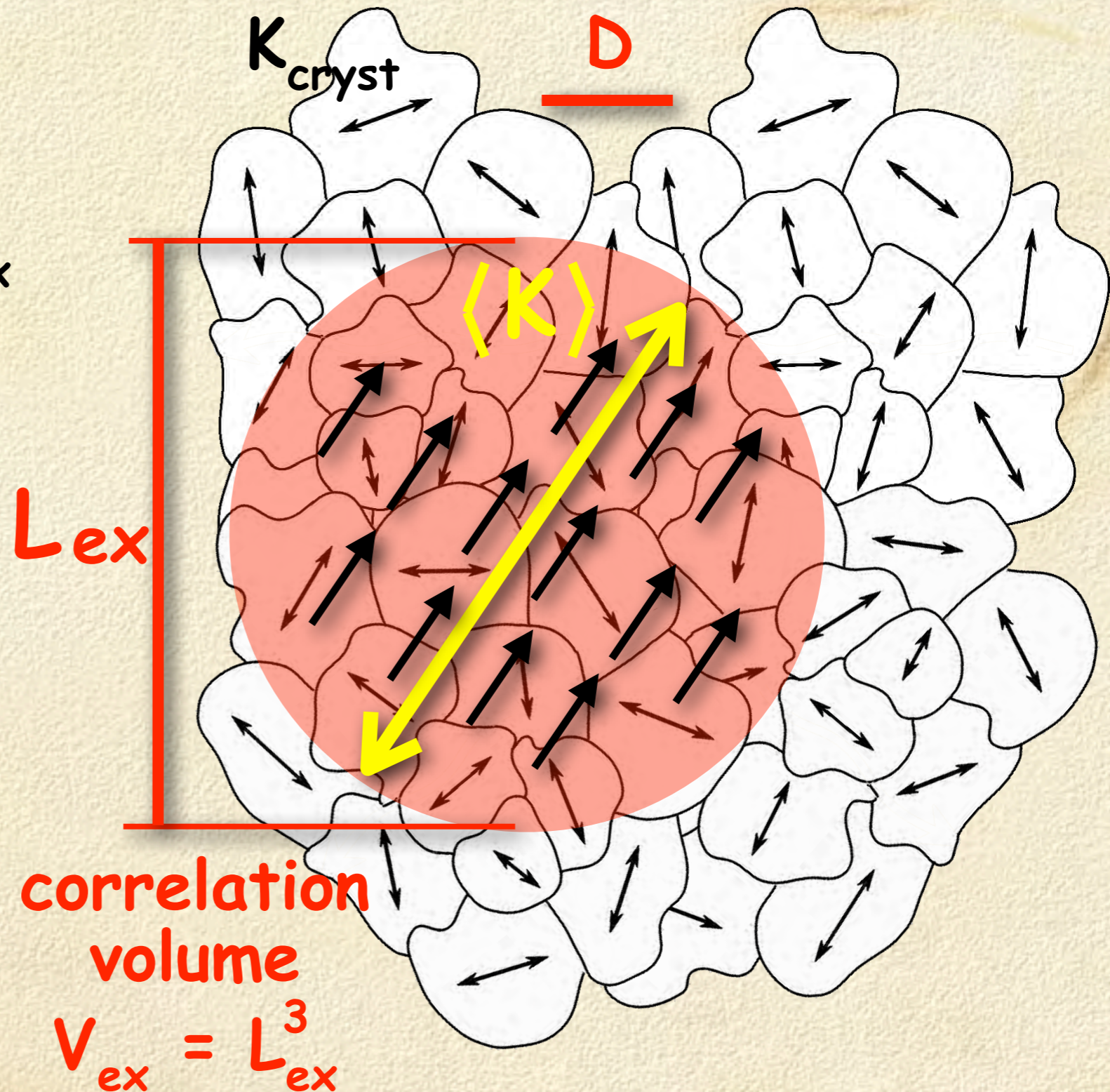
Random anisotropy model [Herzer 1989]:

Exchange interaction averages over anisotropy of grains

$$L_{ex} = \sqrt{A/K_{cryst}}$$

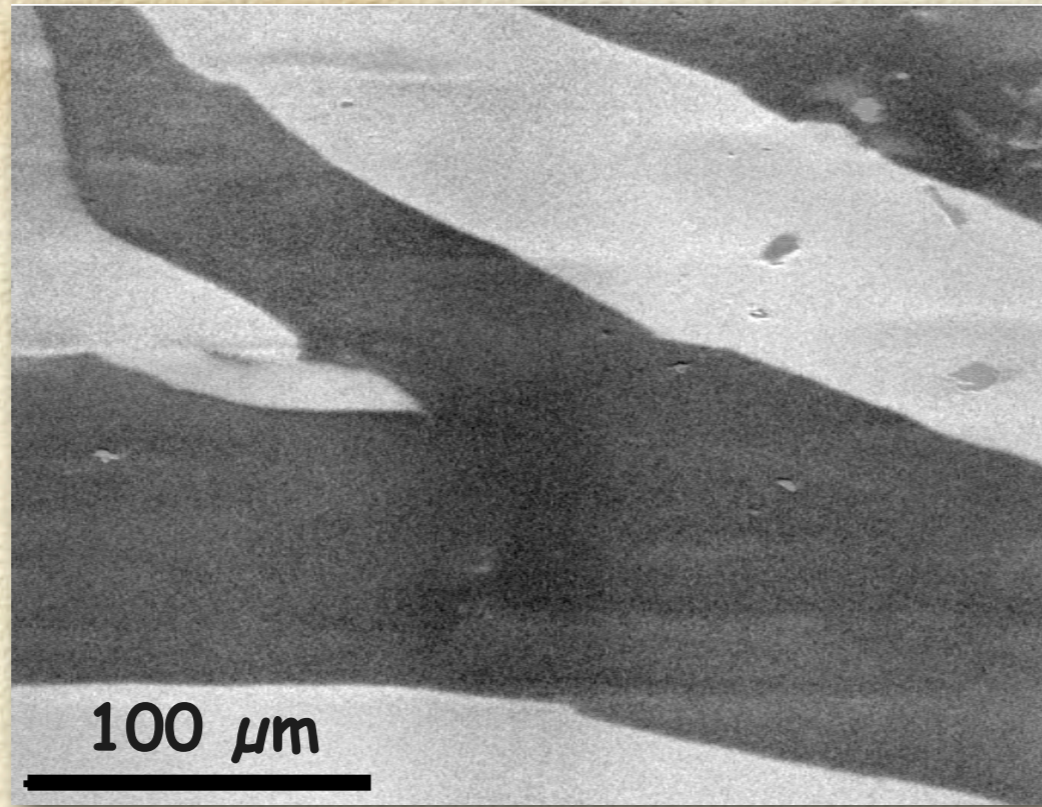
Nanocrystals: $D < L_{ex}$

$$\rightarrow \langle K \rangle \ll K_{cryst}$$

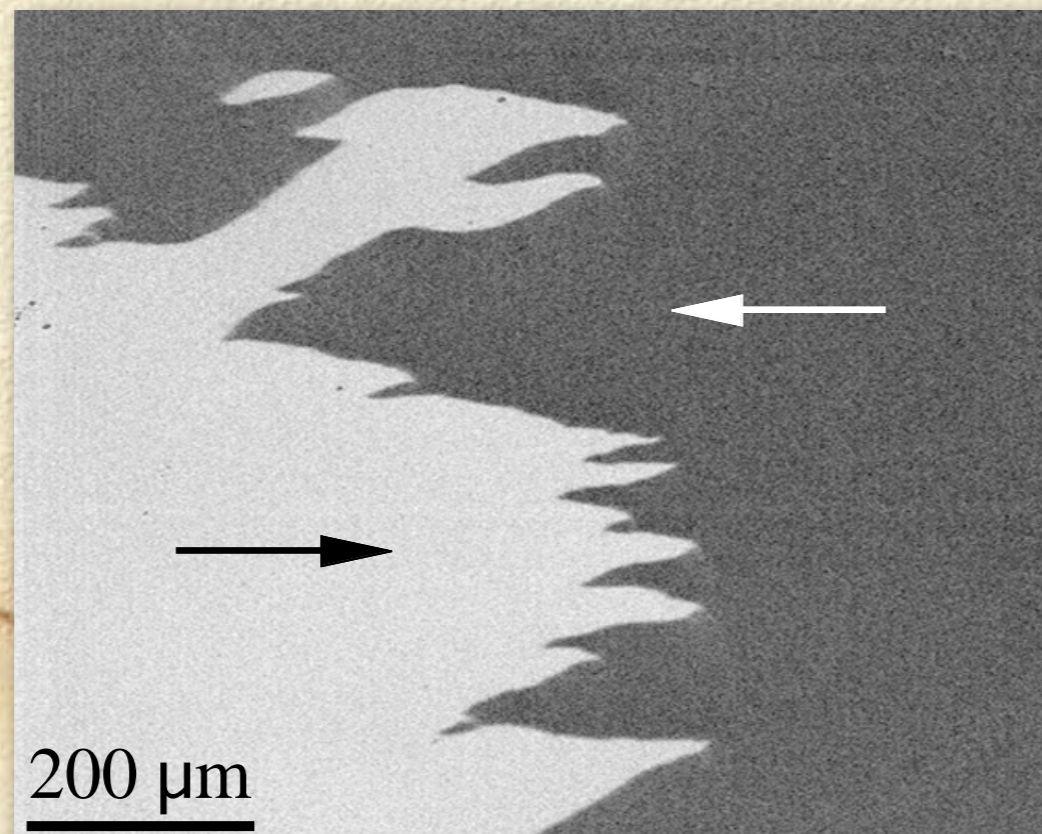


Nanocrystalline ($Q \ll 1$) materials

Low resolution



Nanocrystalline
FeSiBCuNb
ribbon
(20 μm thick)



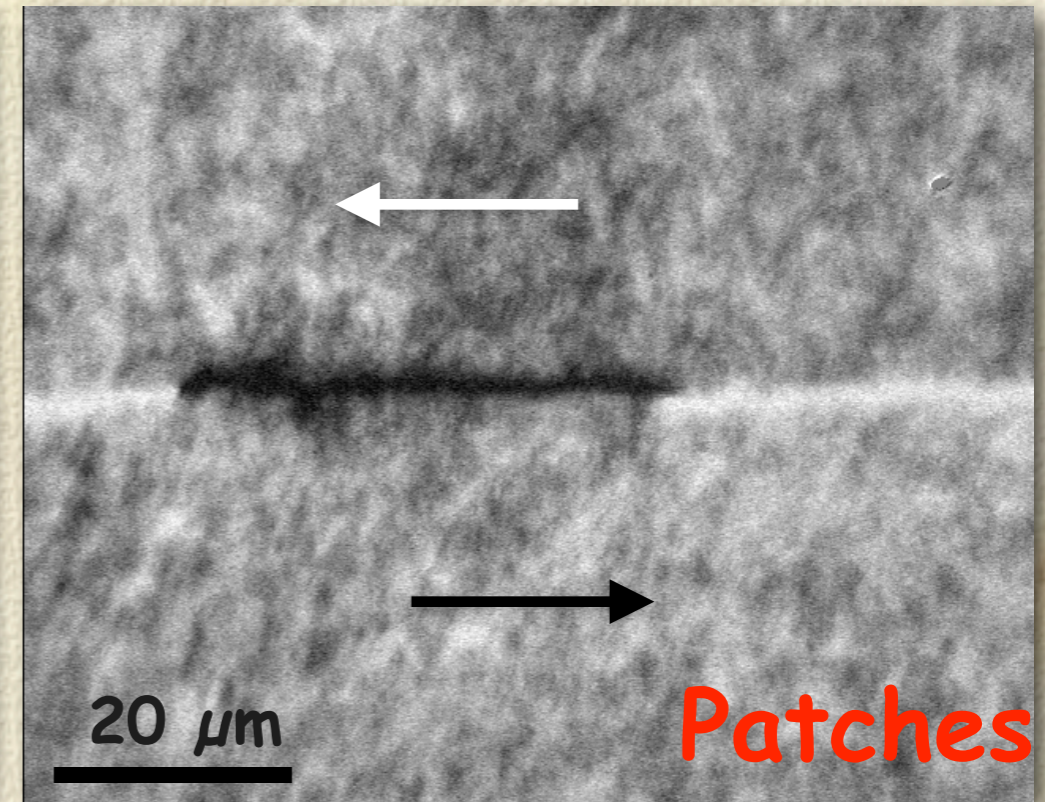
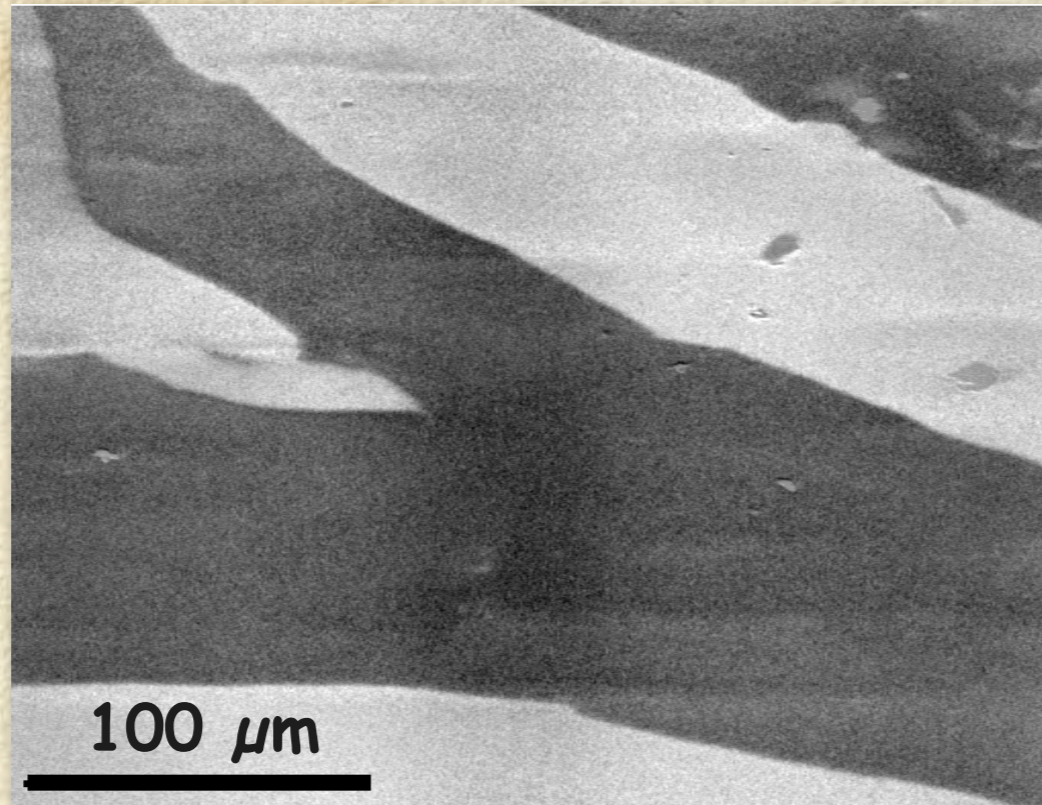
Sputtered
Co film
(60 nm thick)

Nanocrystalline ($Q \ll 1$) materials

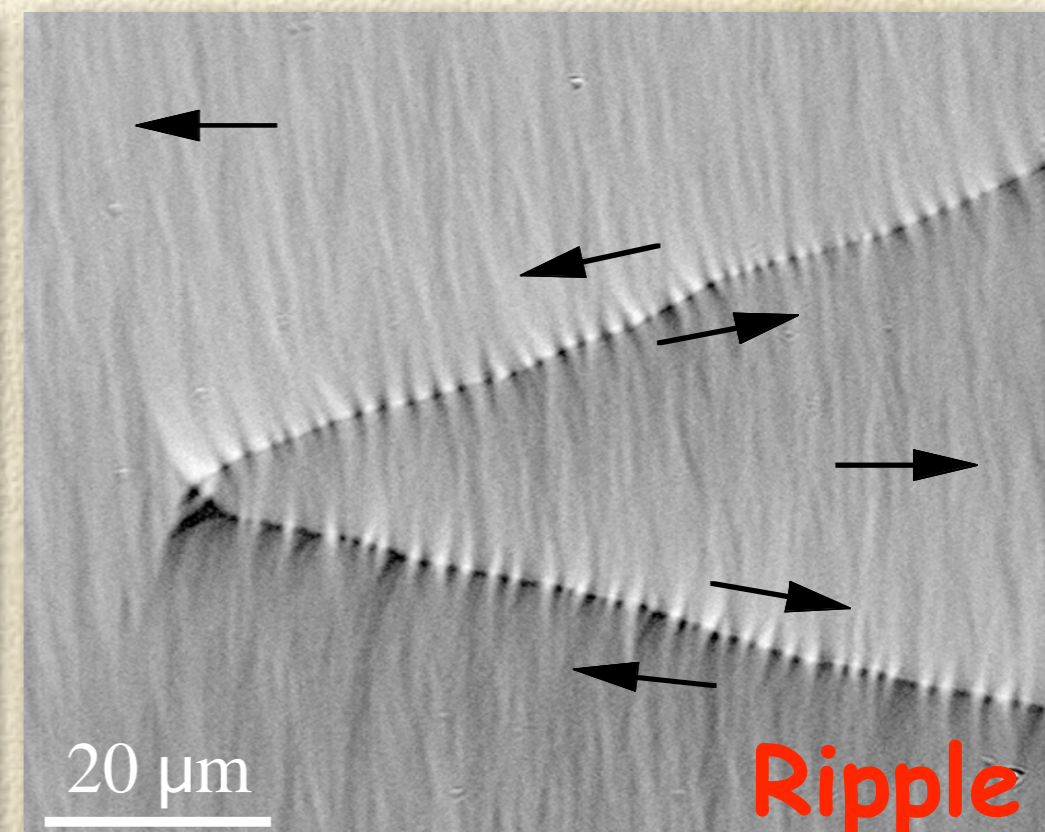
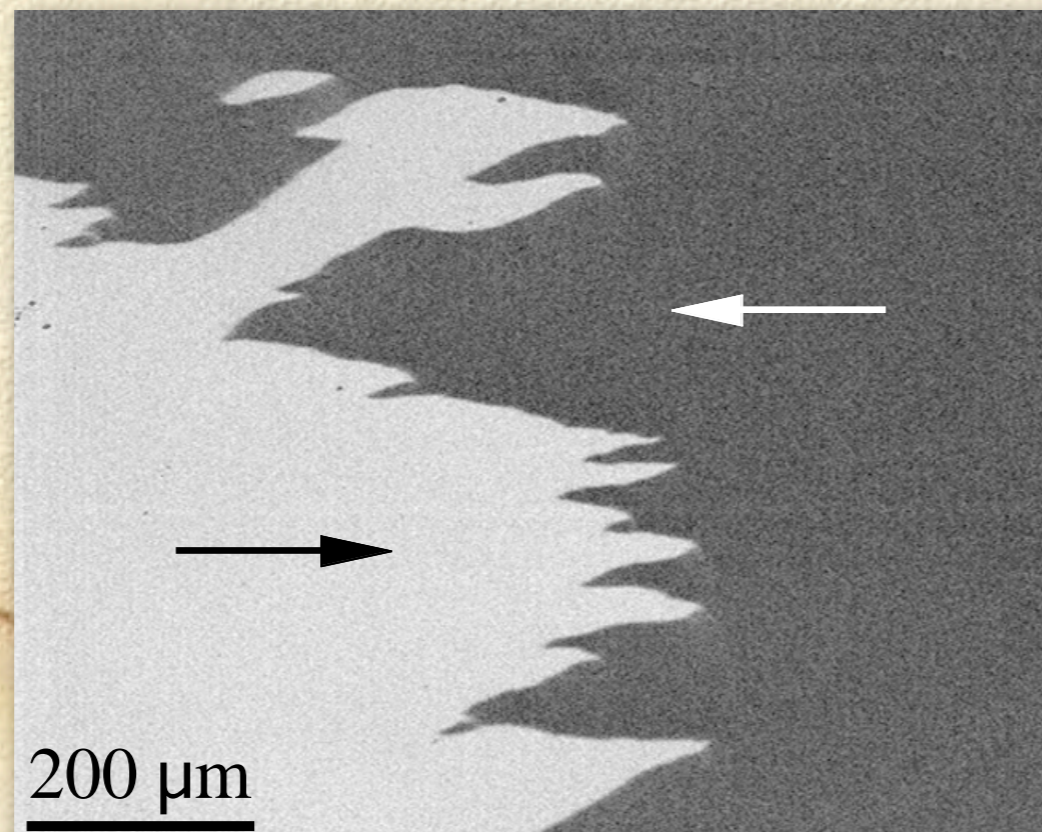
Low resolution

High resolution

Nanocrystalline
FeSiBCuNb
ribbon
(20 μm thick)



Sputtered
Co film
(60 nm thick)



Nanocrystalline ($Q \ll 1$) materials

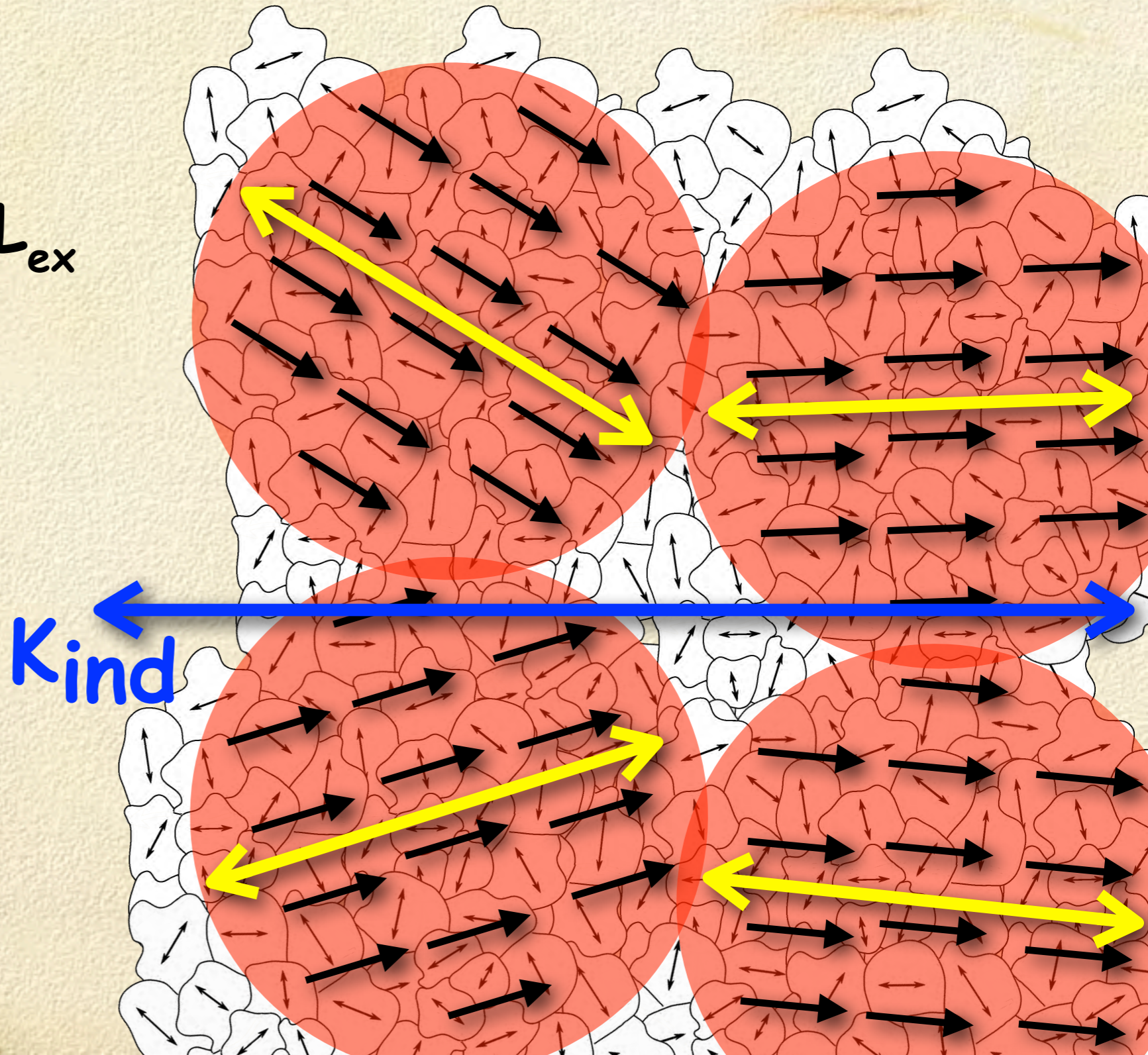
Random anisotropy model [Herzer 1989]:

Exchange interaction averages over anisotropy of grains

$$L_{ex} = \sqrt{A/K_{cryst}}$$

Nanocrystals: $D < L_{ex}$

$$\rightarrow \langle K \rangle \ll K_{cryst}$$



Exc

ns

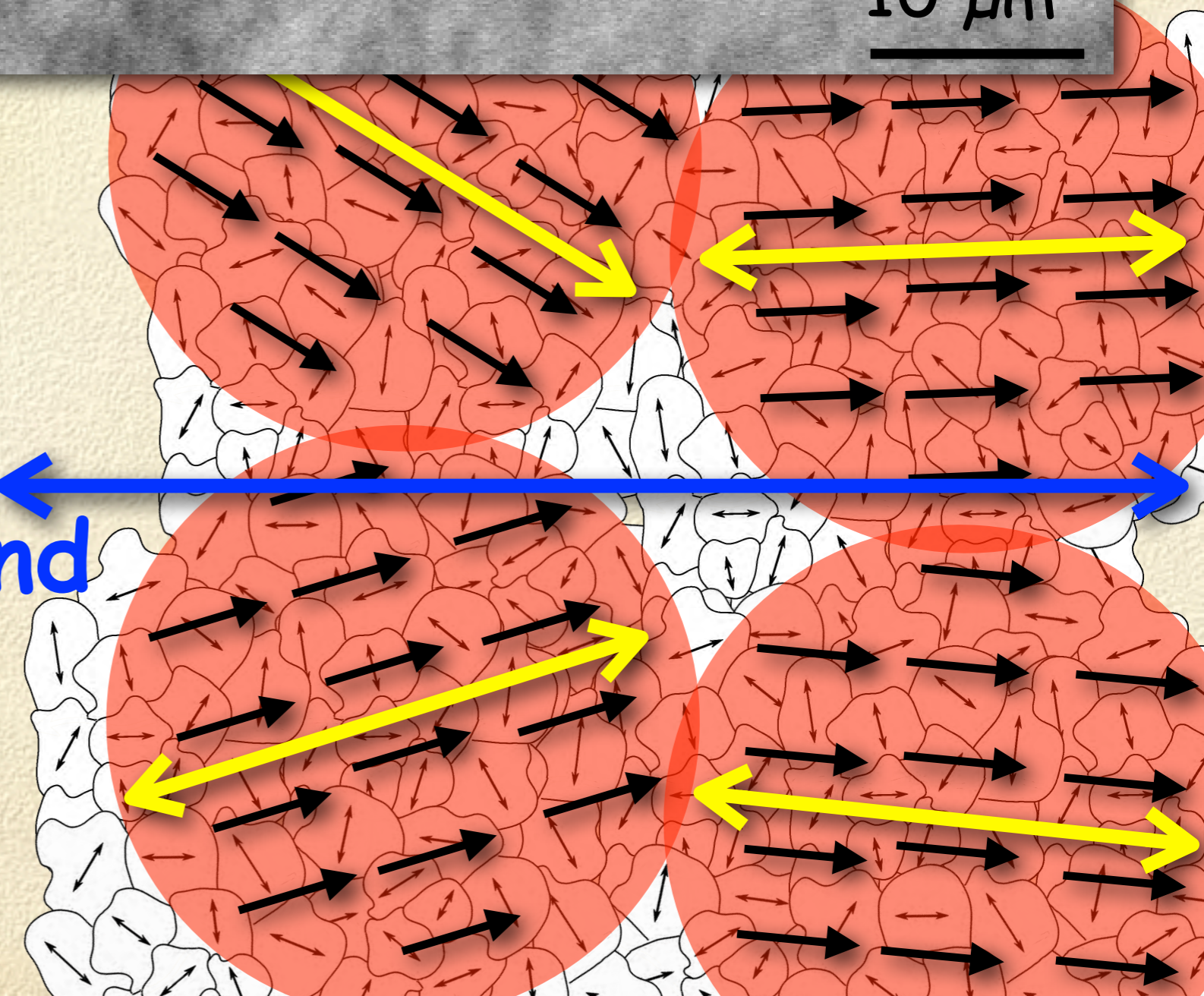
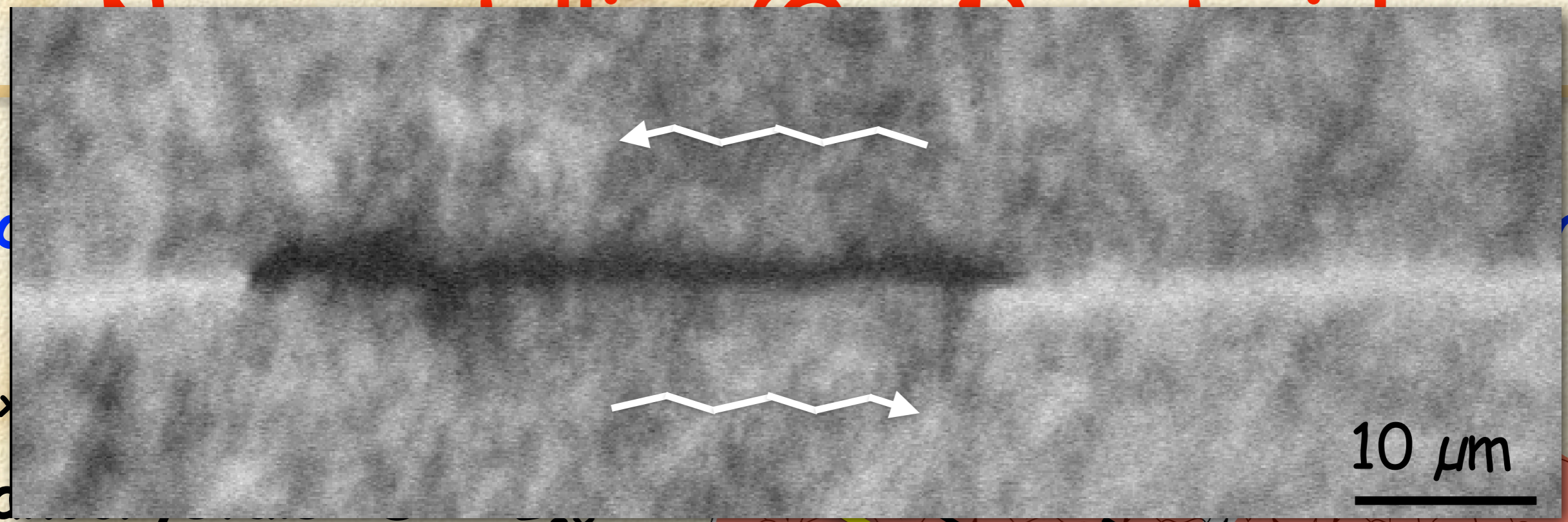
L_{ex}

Na

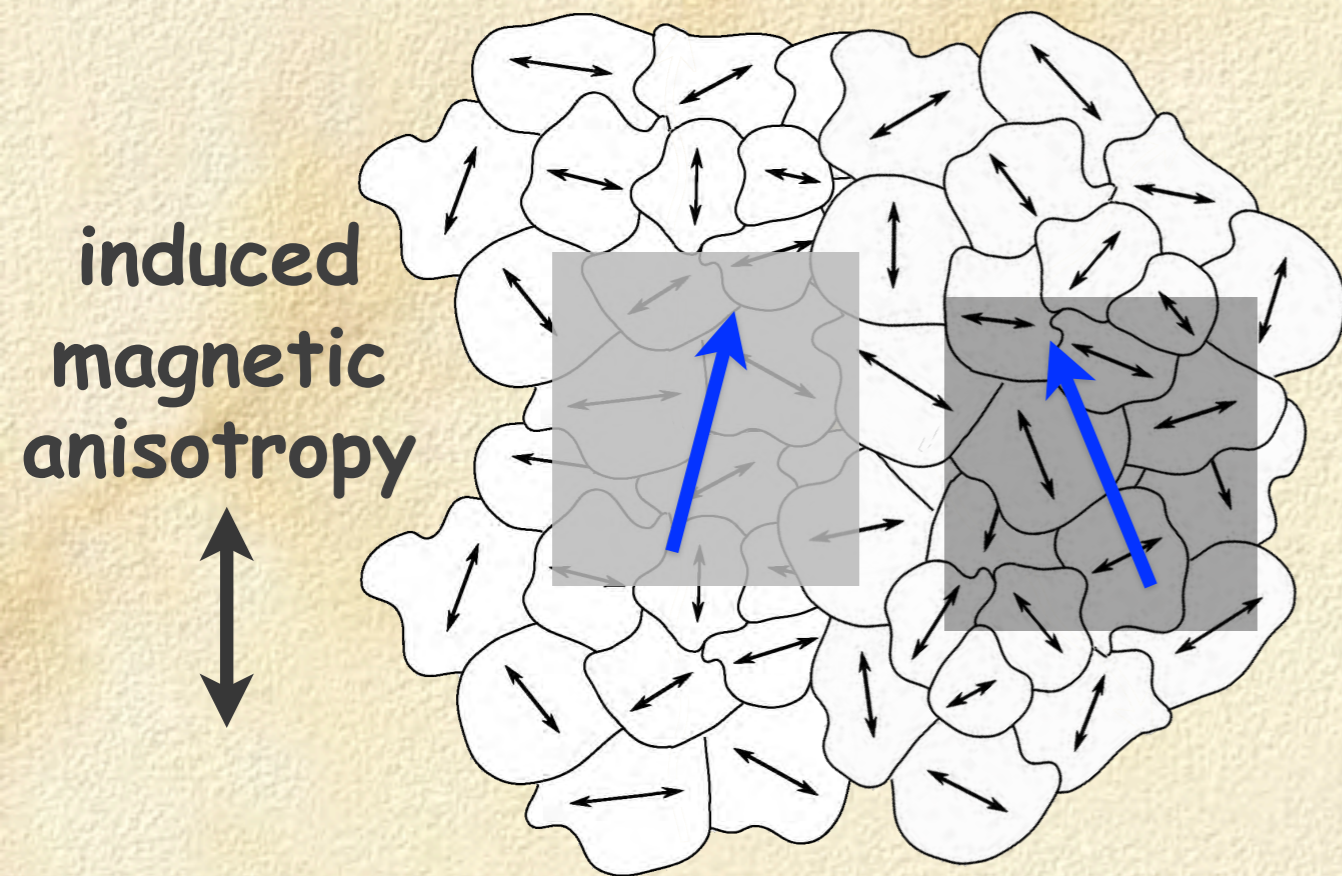
10 μm

$\rightarrow \langle K \rangle \ll K_{\text{cryst}}$

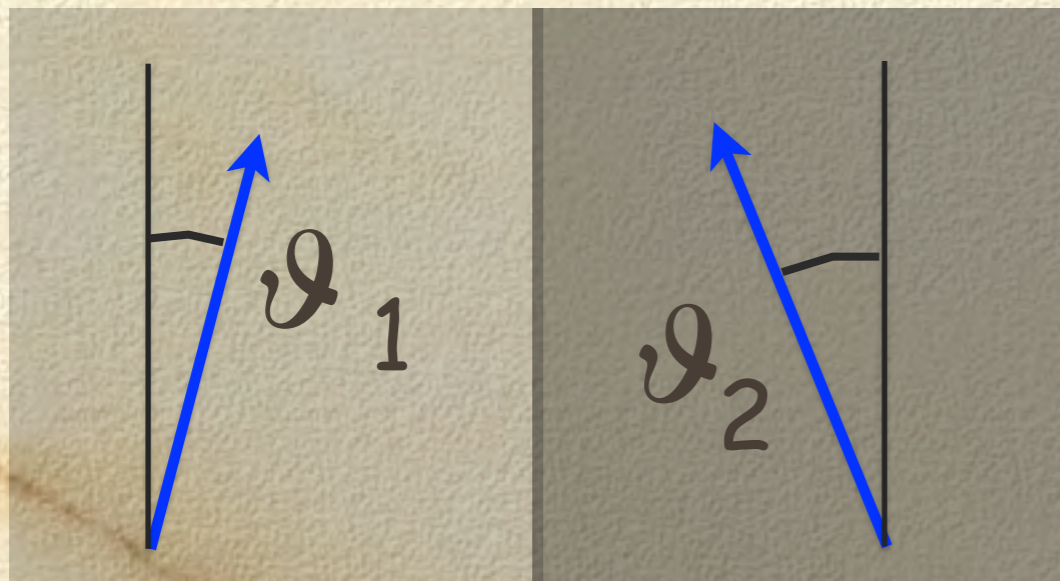
K_{ind}



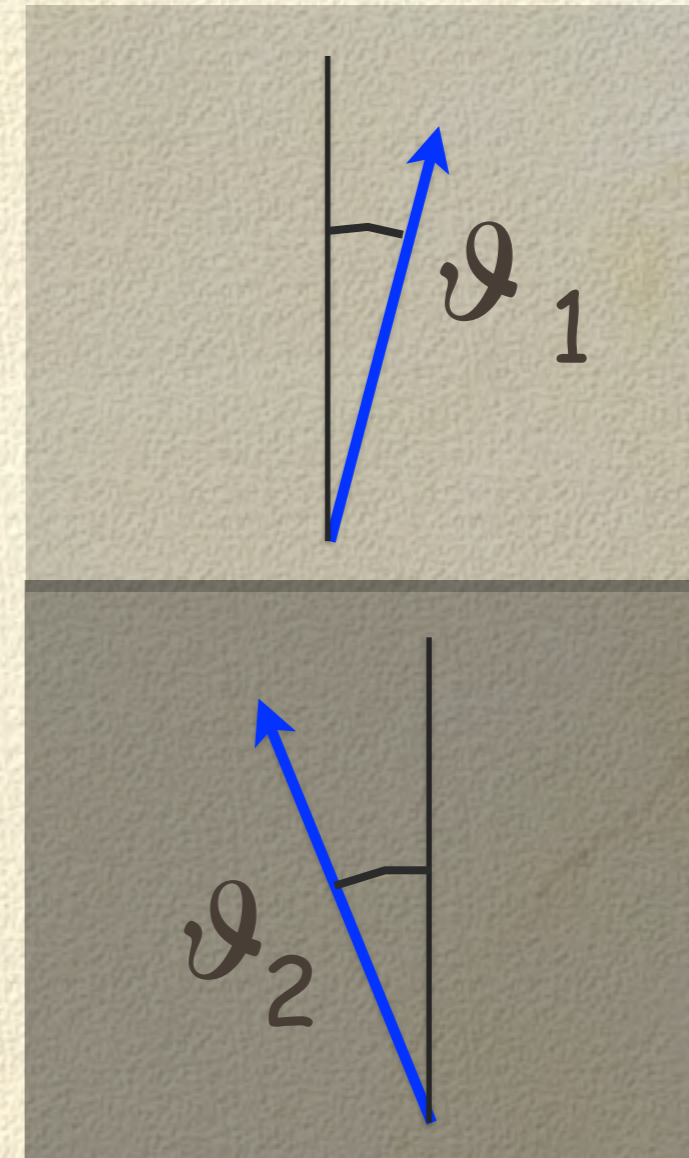
Nanocrystalline ($Q \ll 1$) materials



Ripple phenomenon in magnetic film



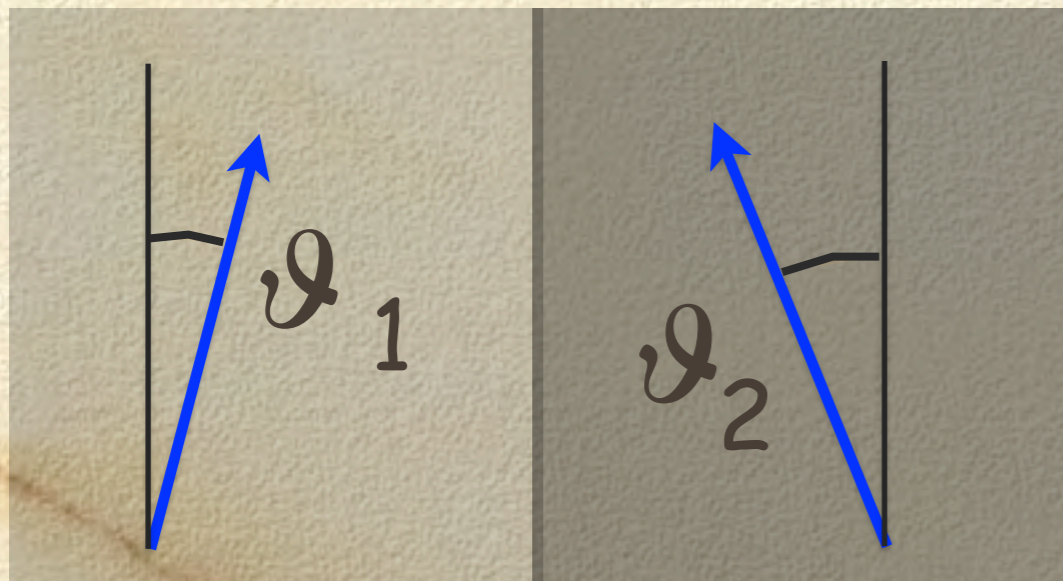
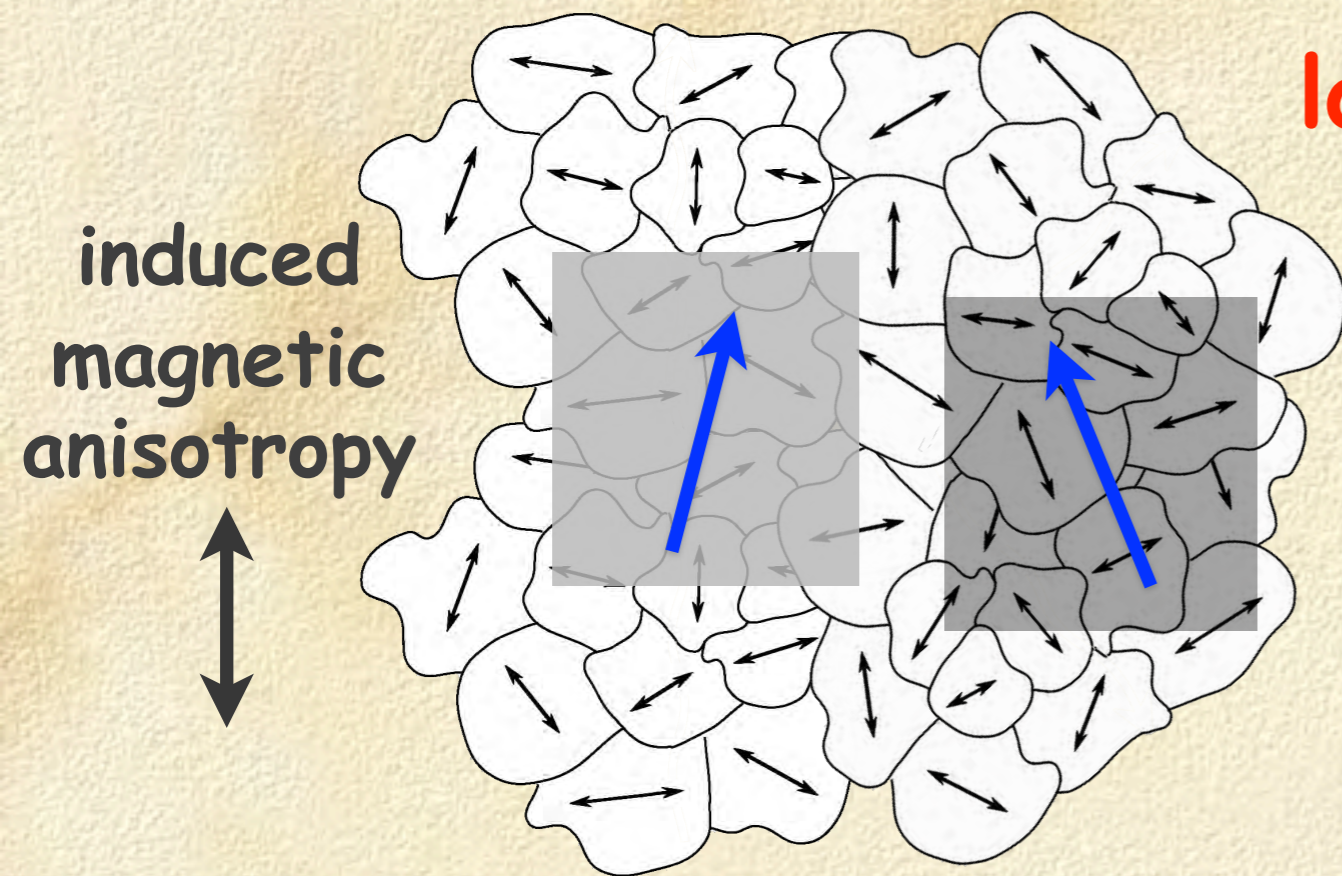
interface pole density
 $= \sin \vartheta_1 - \sin \vartheta_2$



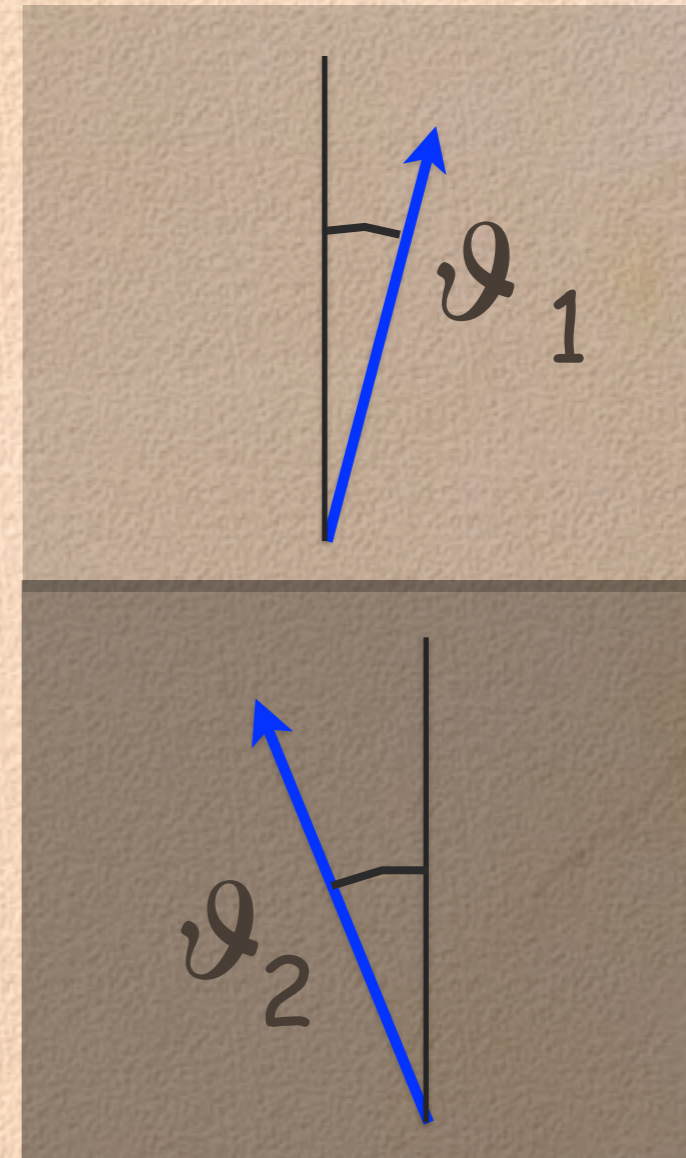
interface pole density
 $= \cos \vartheta_1 - \cos \vartheta_2$

Nanocrystalline ($Q \ll 1$) materials

longitudinal variation preferred



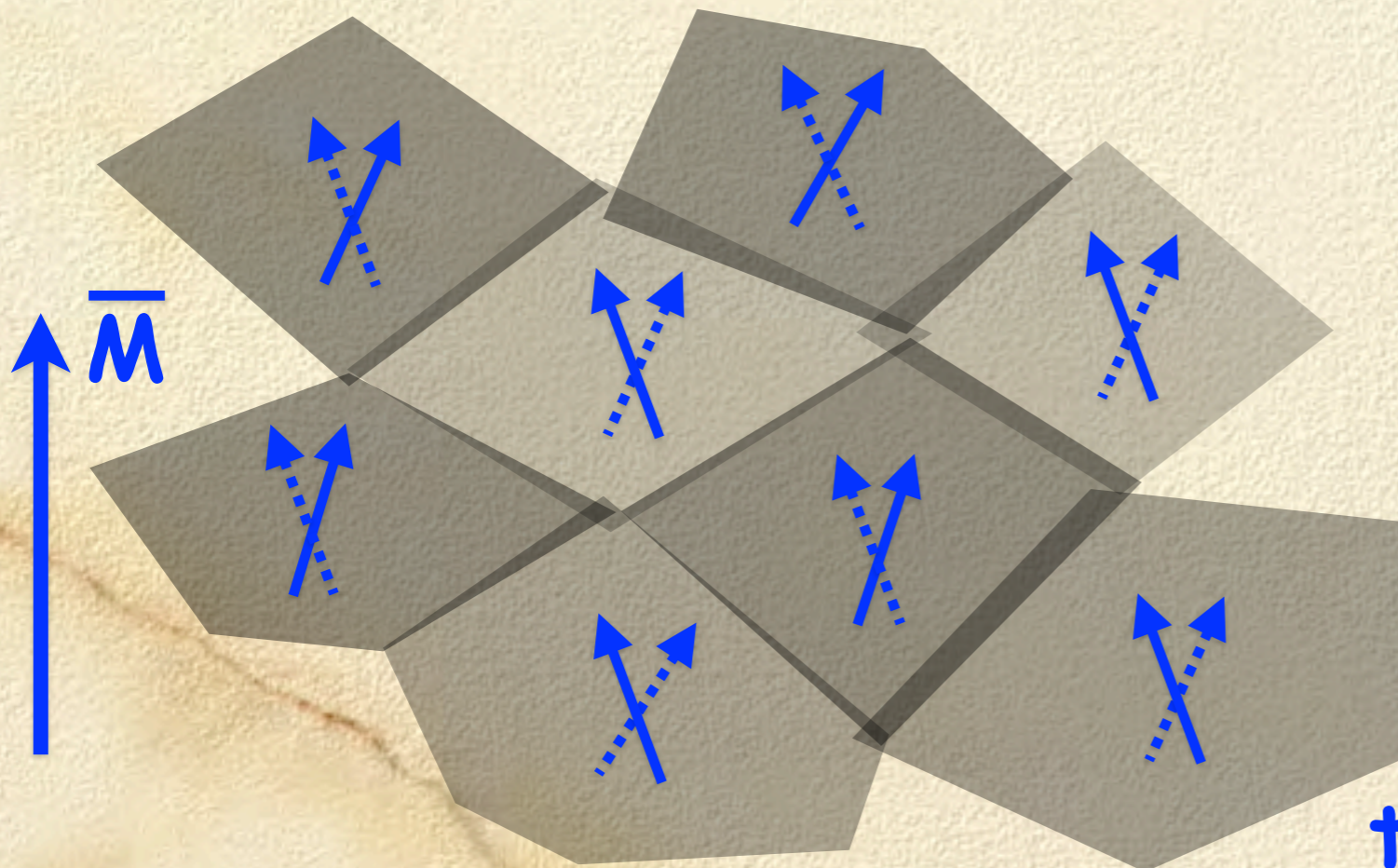
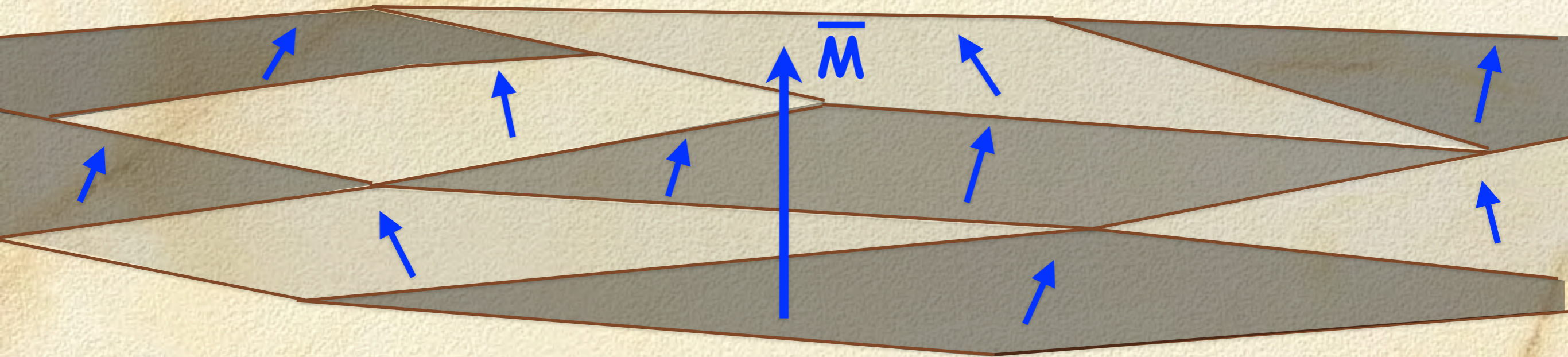
interface pole density
 $= \sin \vartheta_1 - \sin \vartheta_2$



interface pole density
 $= \cos \vartheta_1 - \cos \vartheta_2$

Nanocrystalline ($Q \ll 1$) materials

ripple in films



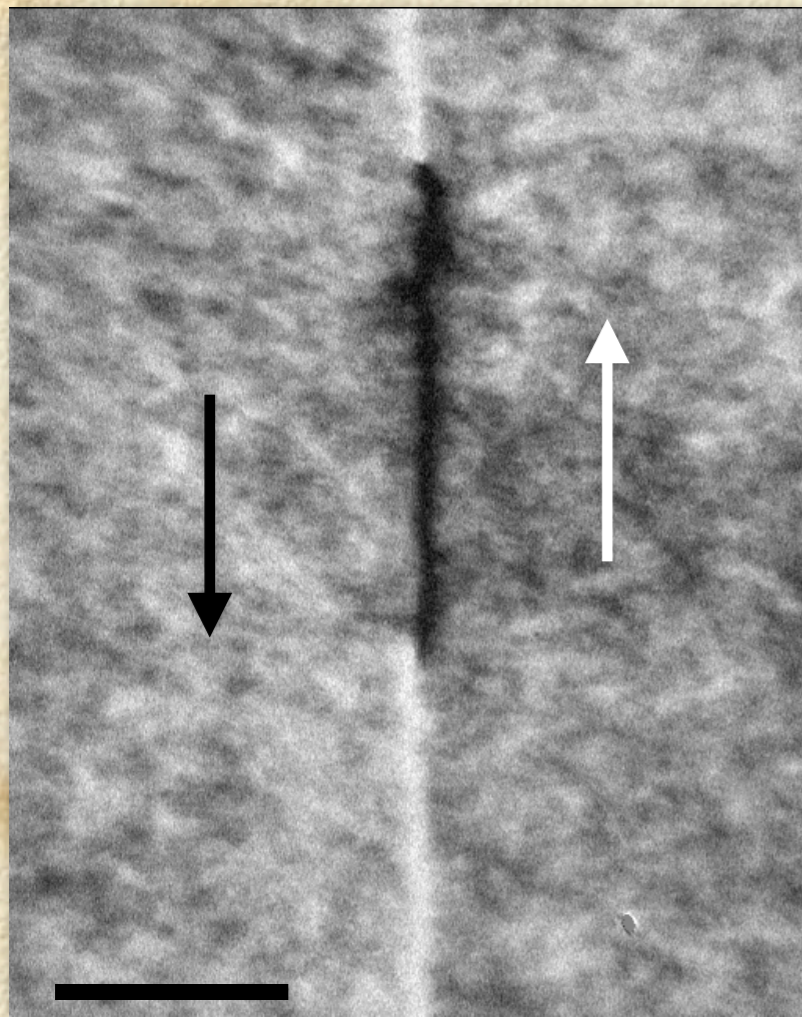
patches in
thick materials

Cancellation of
transverse component

Nanocrystalline ($Q \ll 1$) materials

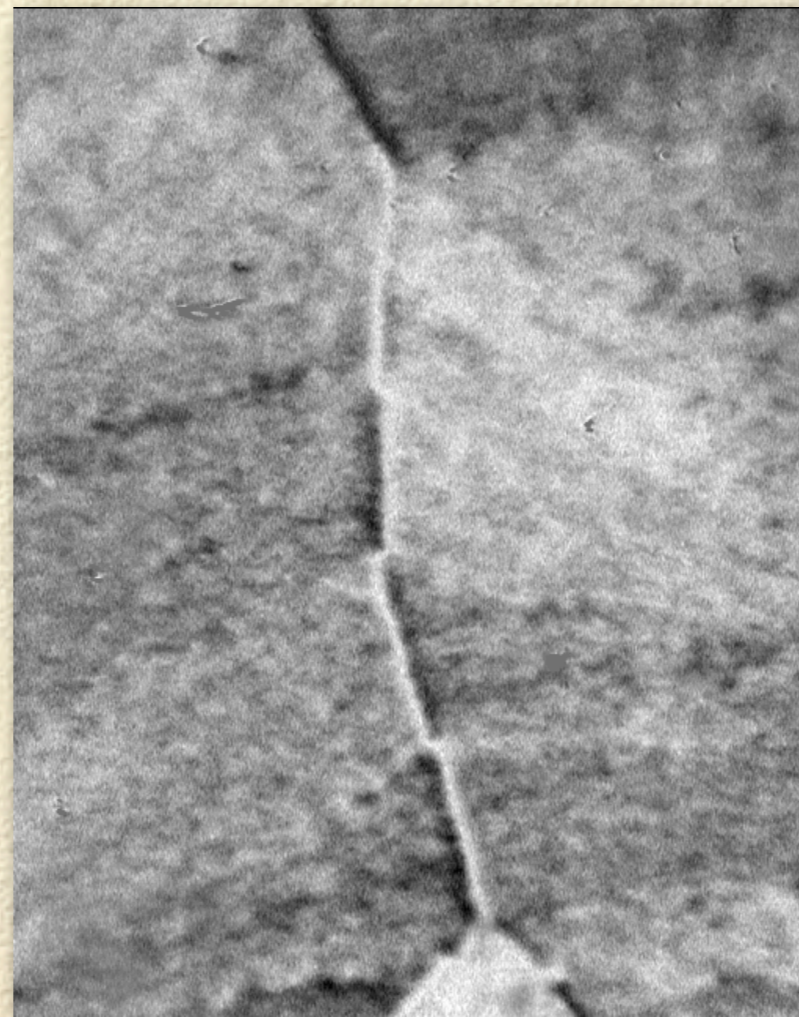
Thinning of nanocrystalline ribbon

20 μm thick

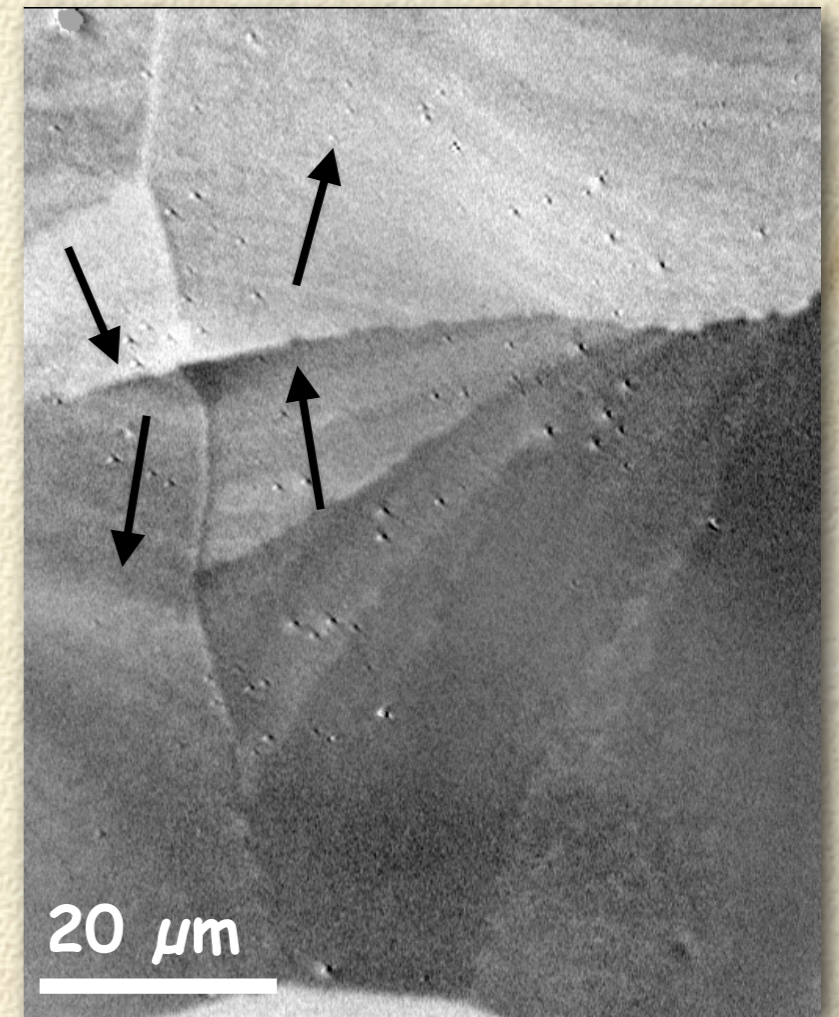


Patches

thinned to μm



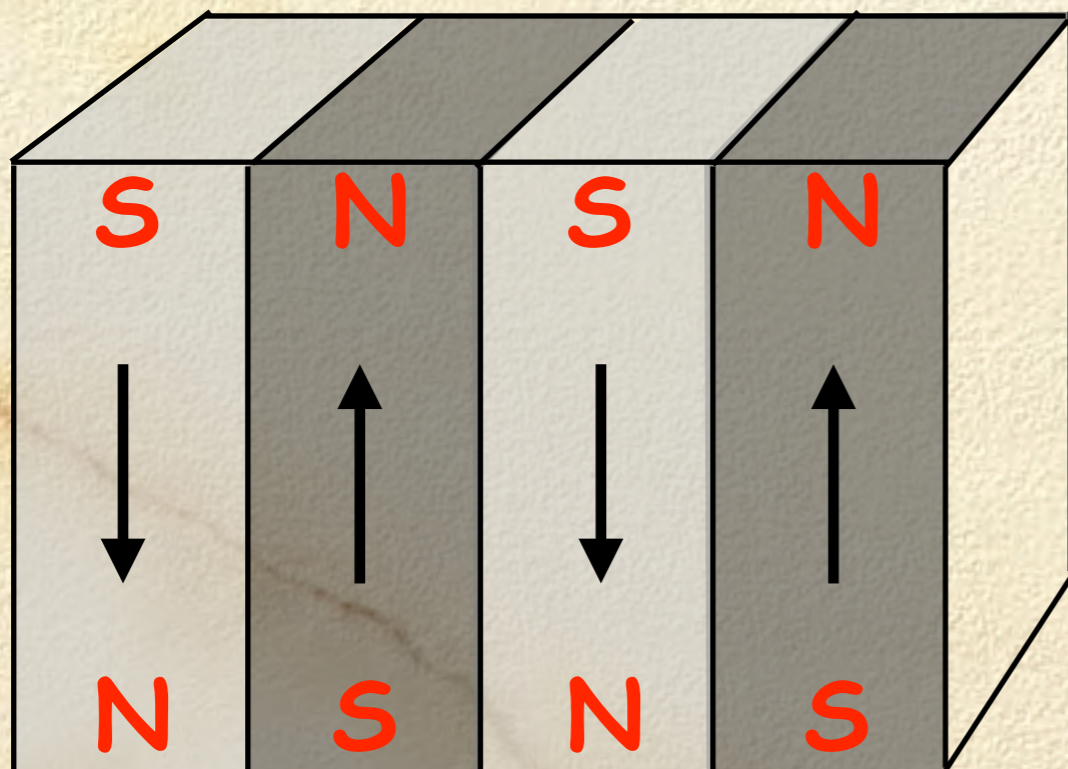
still thinner



Ripple

Summary

- Domains are formed to diminish stray field energy
- Classification according to Q-factor
- Domains can be simple and complex, depending on many circumstances, especially surface orientation
- Bulk domains are usually wide and simple
- Domains must not be homogeneously magnetized areas

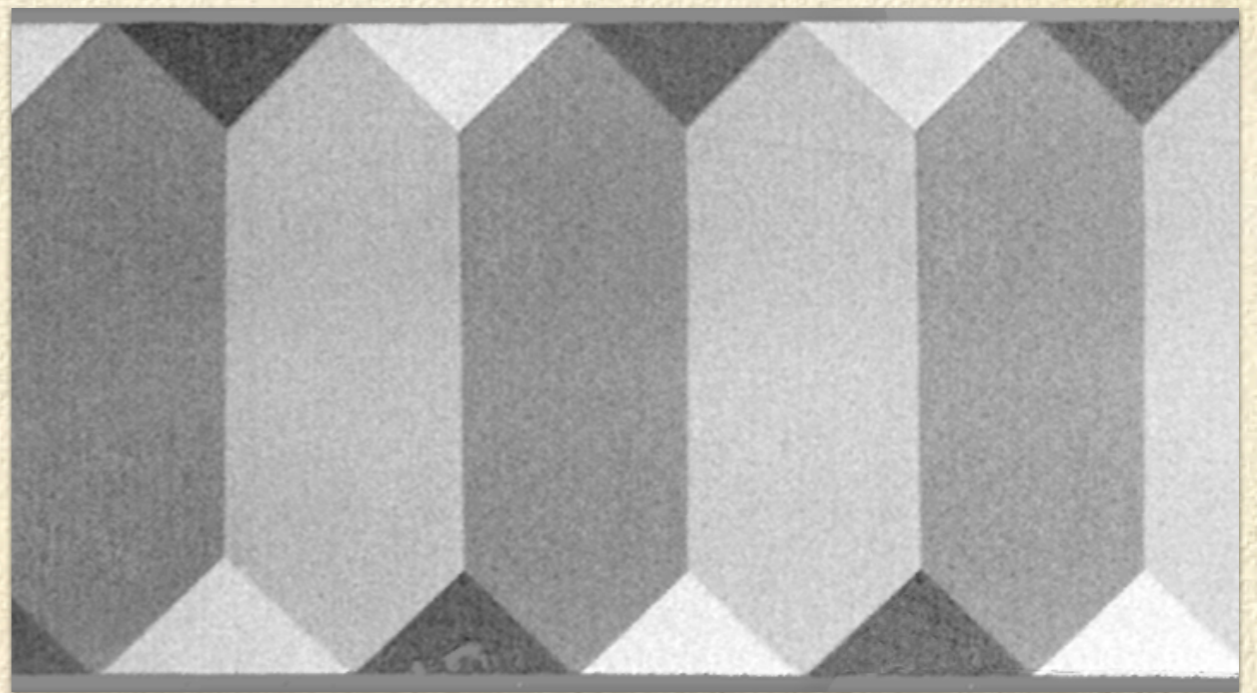


Summary

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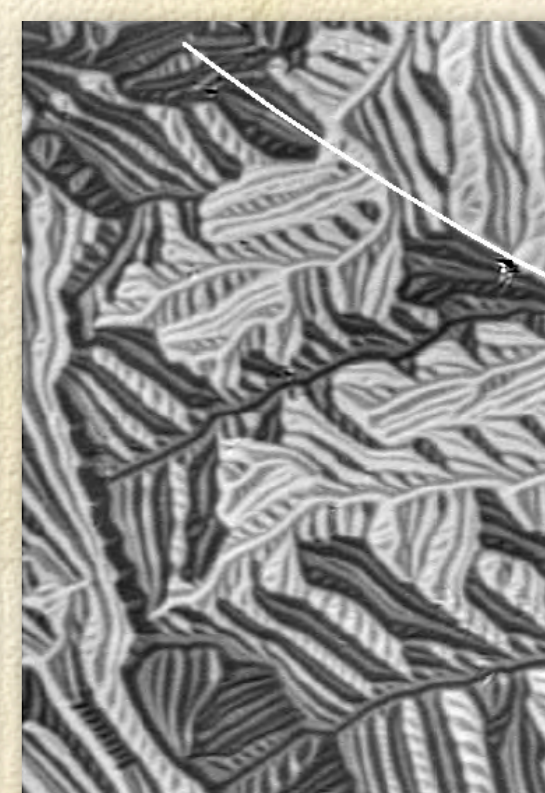
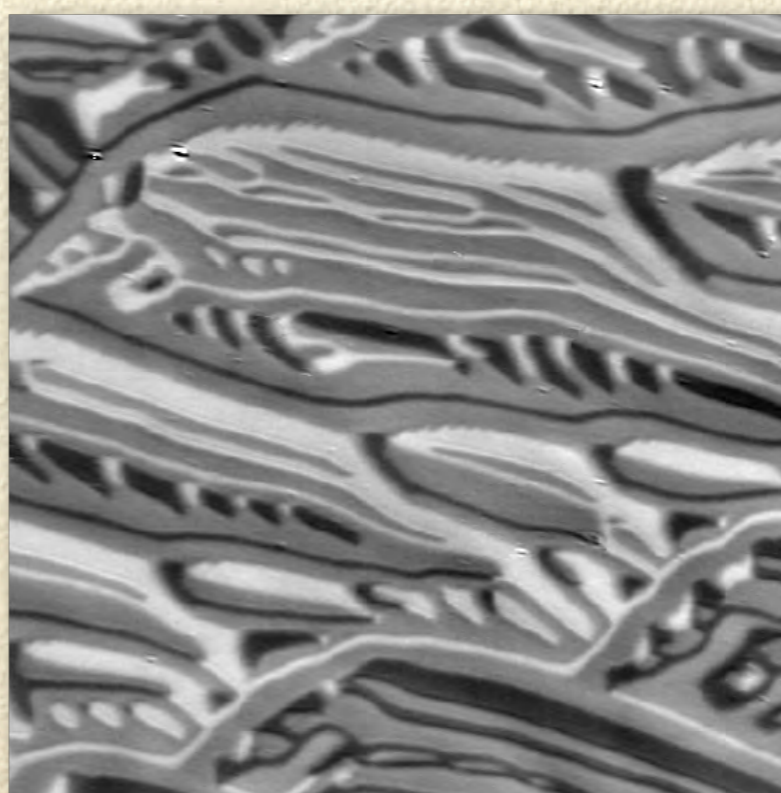
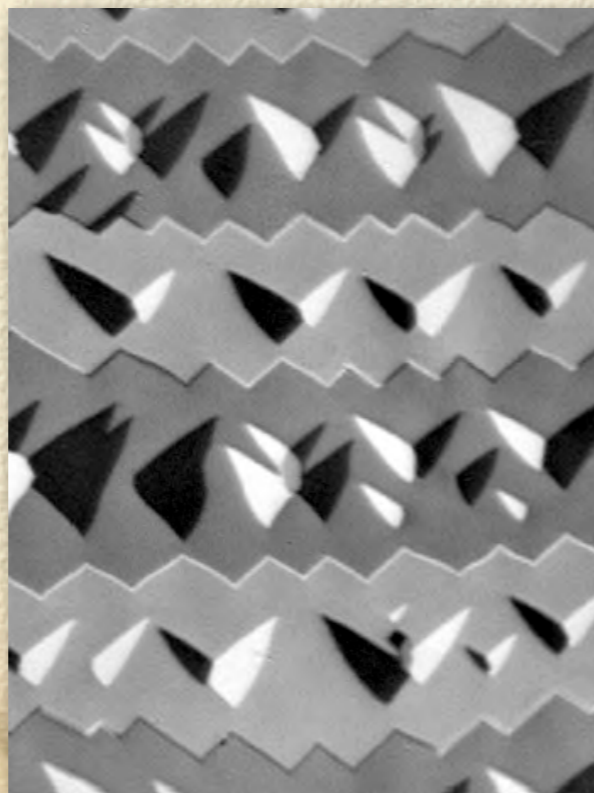
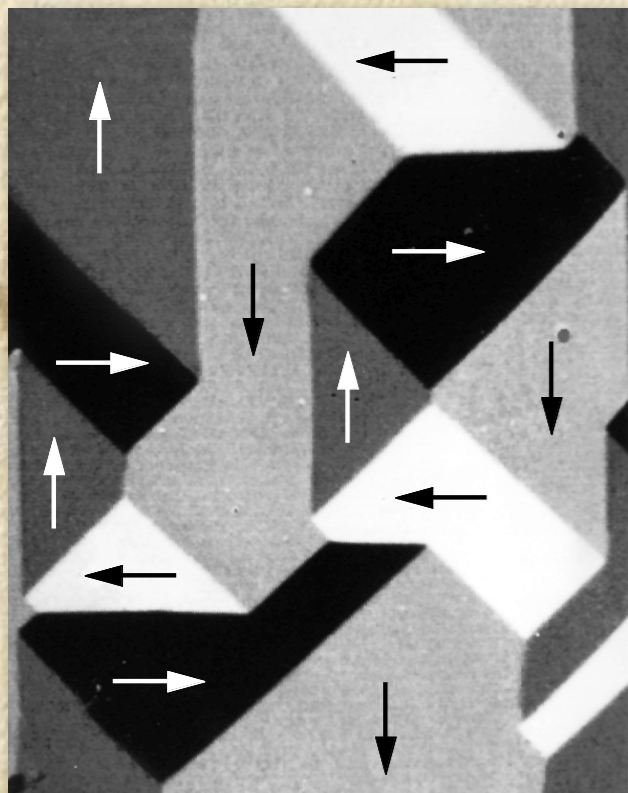
High-Q material



Low-Q material

Summary

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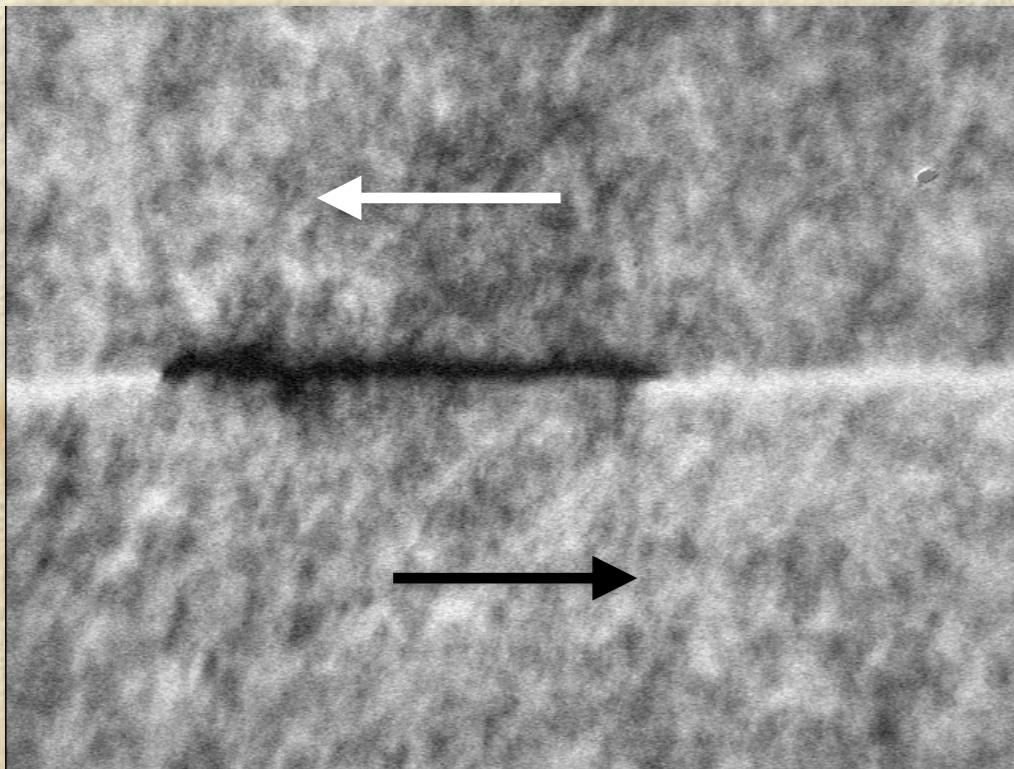


Summary

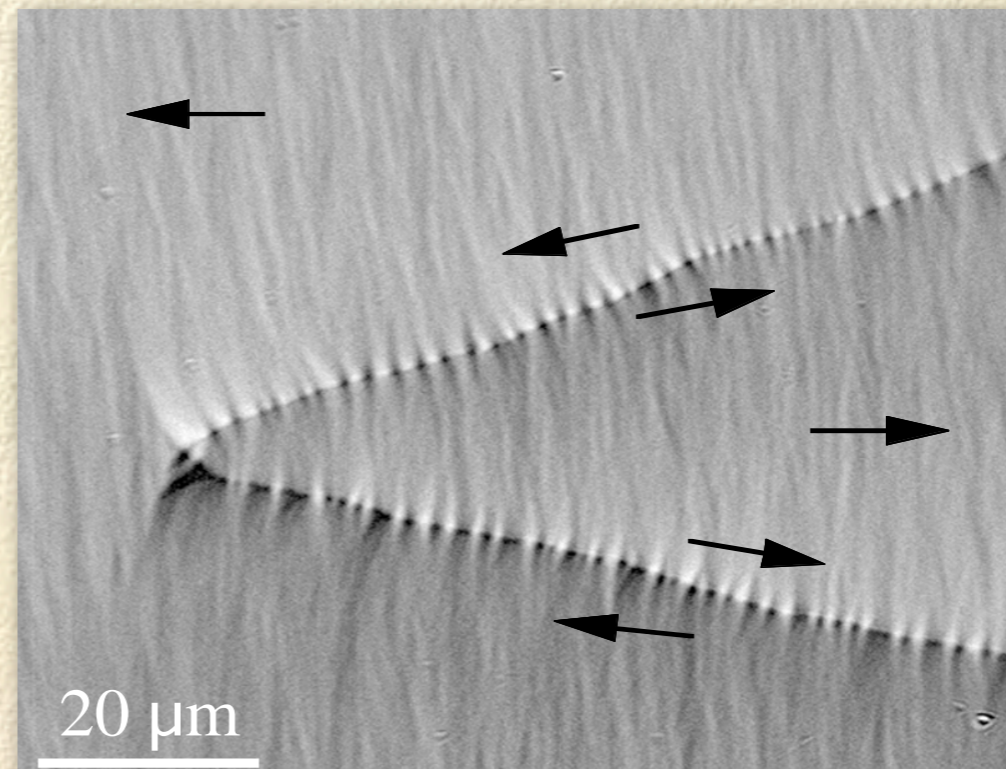
- Domains are formed to diminish stray field energy
- Classification according to Q-factor
- Domains can be simple and complex, depending on many circumstances, especially surface orientation
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Summary

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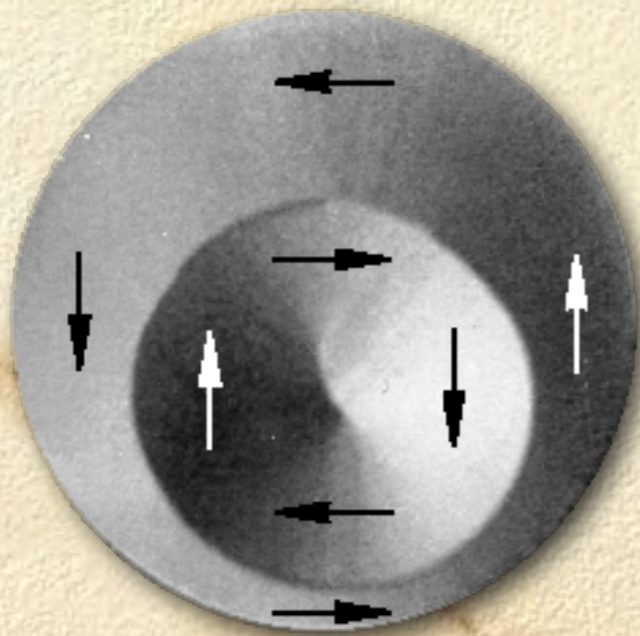
Patches in bulk nanocrystalline material



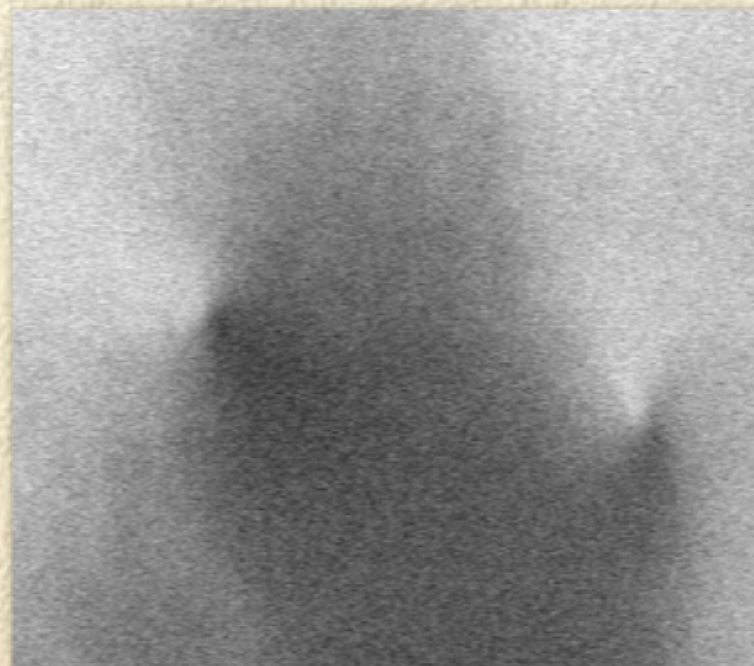
Ripple in nanocrystalline films

Summary

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Shape-induced in
 $Q \ll 1$ film elements



$Q = 0$ bulk material



Stripe domains in perpendicular
low-Q films

Summary

- Domains are formed to diminish stray field energy
- Classification according to Q-factor
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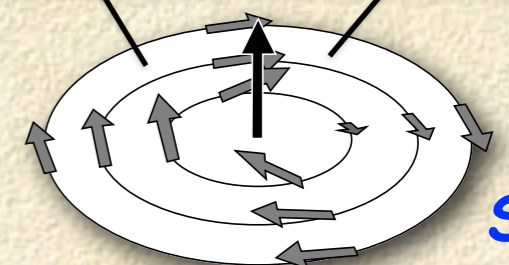
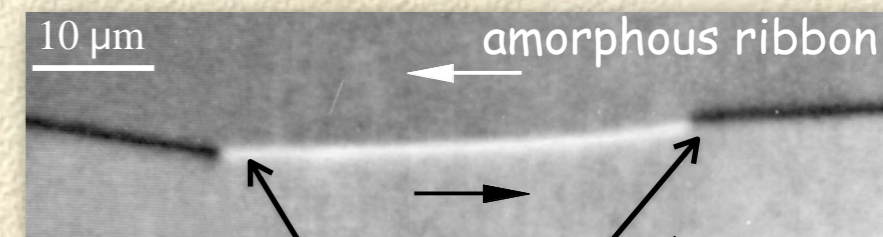
Branched closure domains in low-Q bulk material



Branched closure domains in medium-Q bulk material

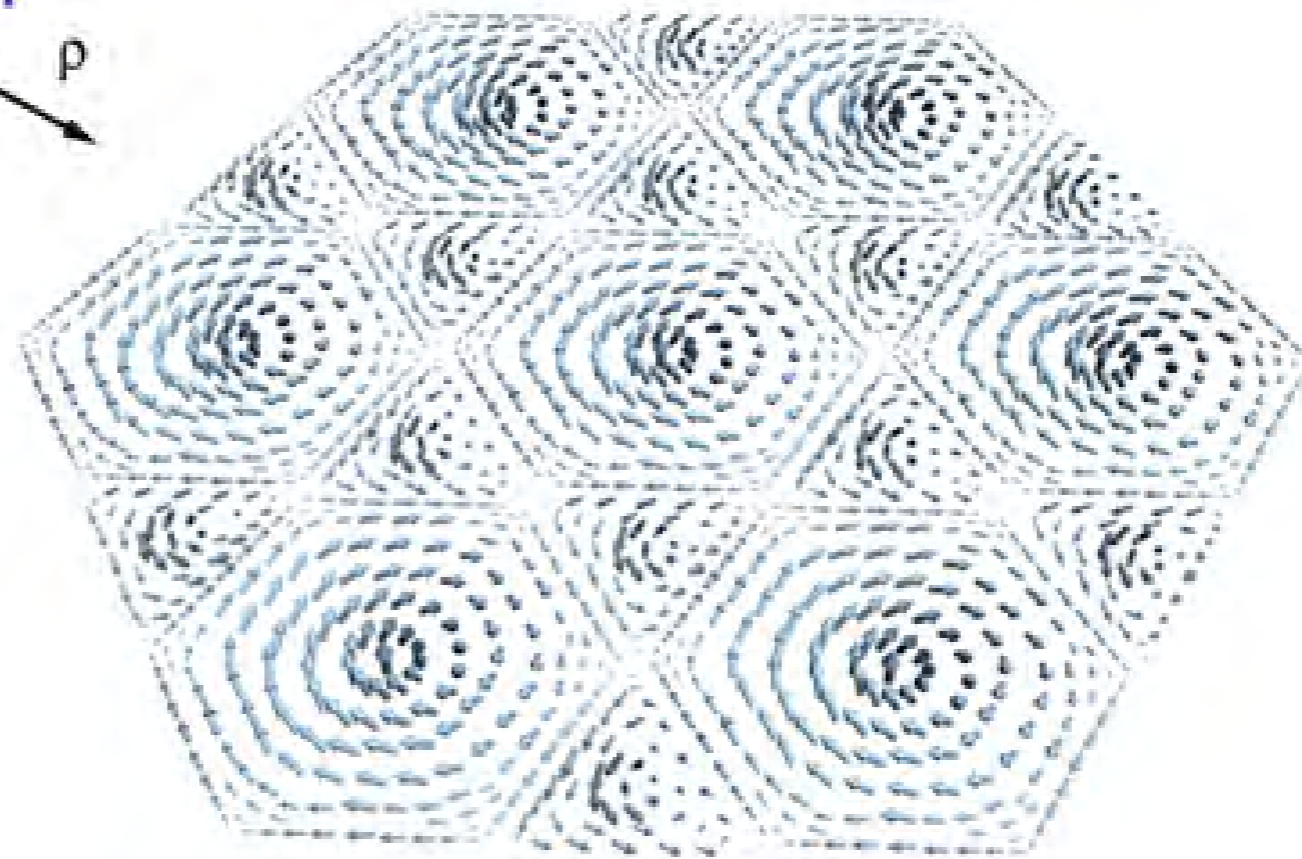
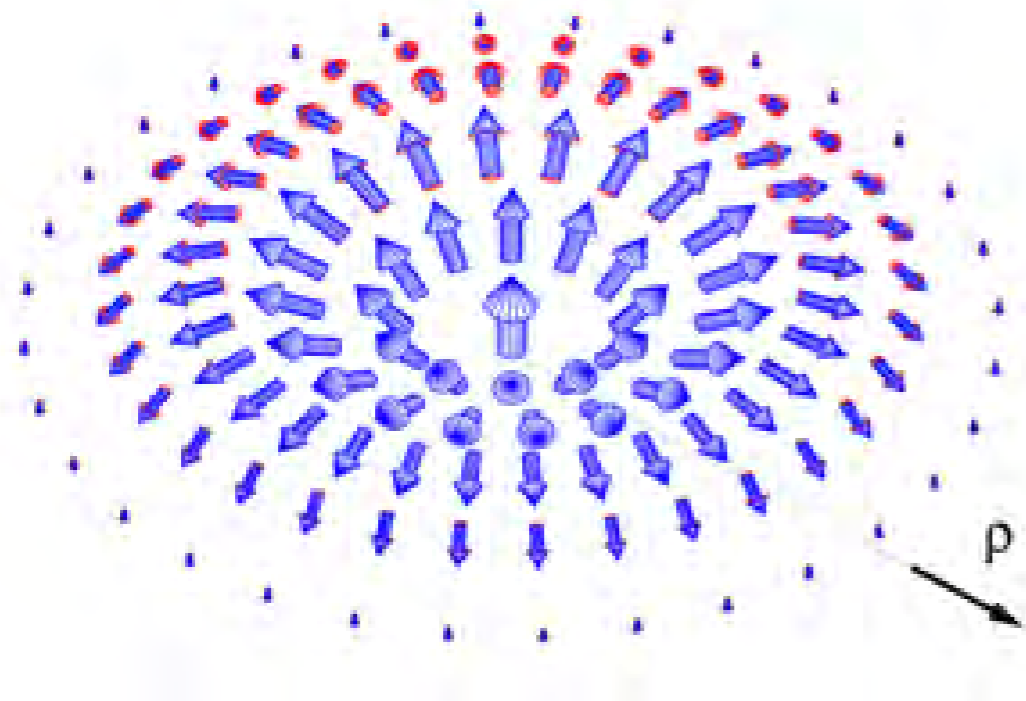


Domain walls



Swirls

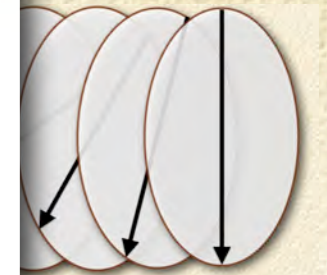
Skymions in
non-centrosymmetric crystals
with
Dzyaloshinskii-Moriya coupling



Energy

on
ation

ed areas

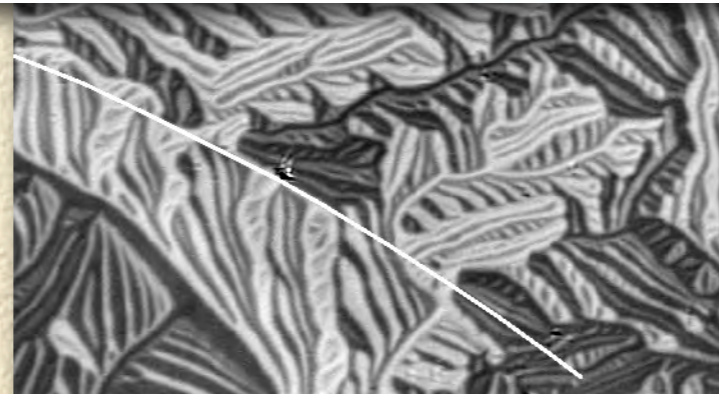


walls

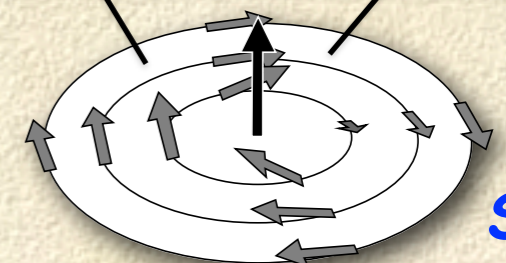
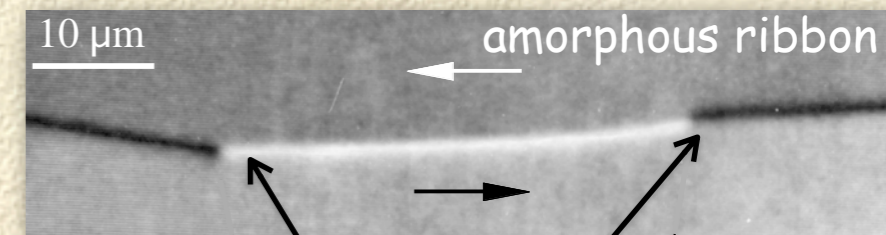
Courtesy
A. Bogdanov, U. Rössler
(IFW Dresden)



Branched closure domains
in low-Q bulk material



Branched closure domains in
medium-Q bulk material

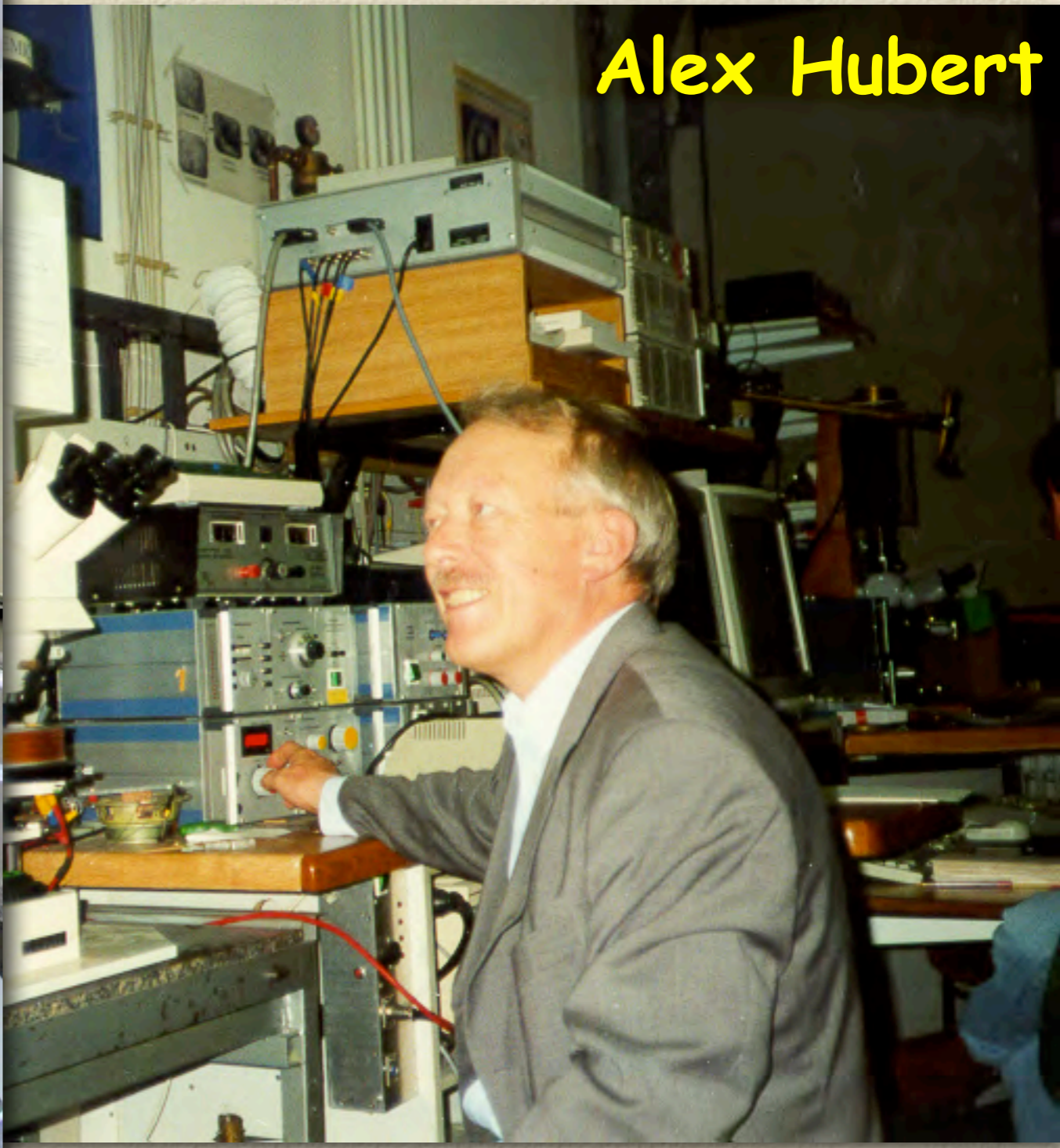


Swirls

Acknowledgement

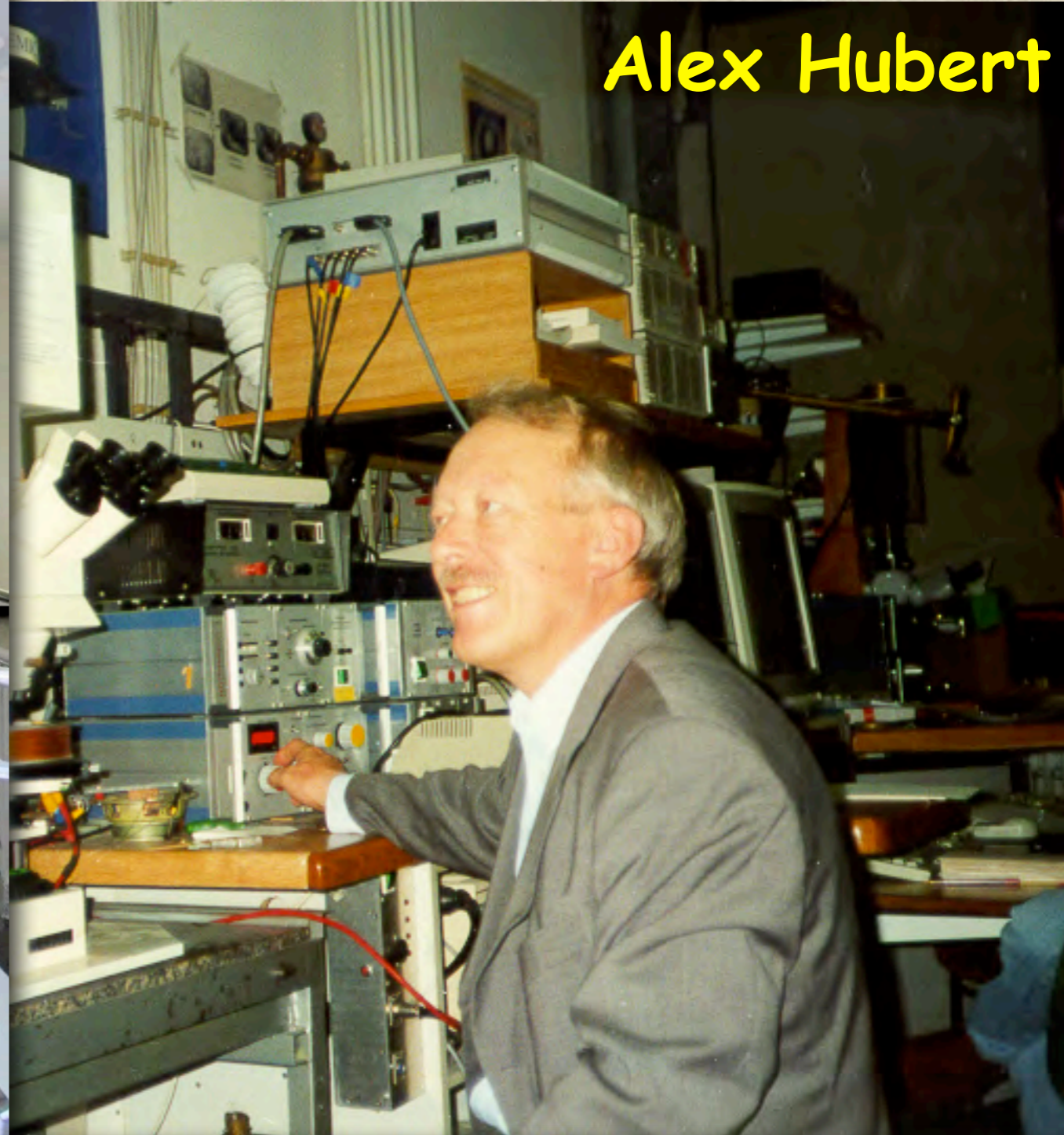


Acknowledgement



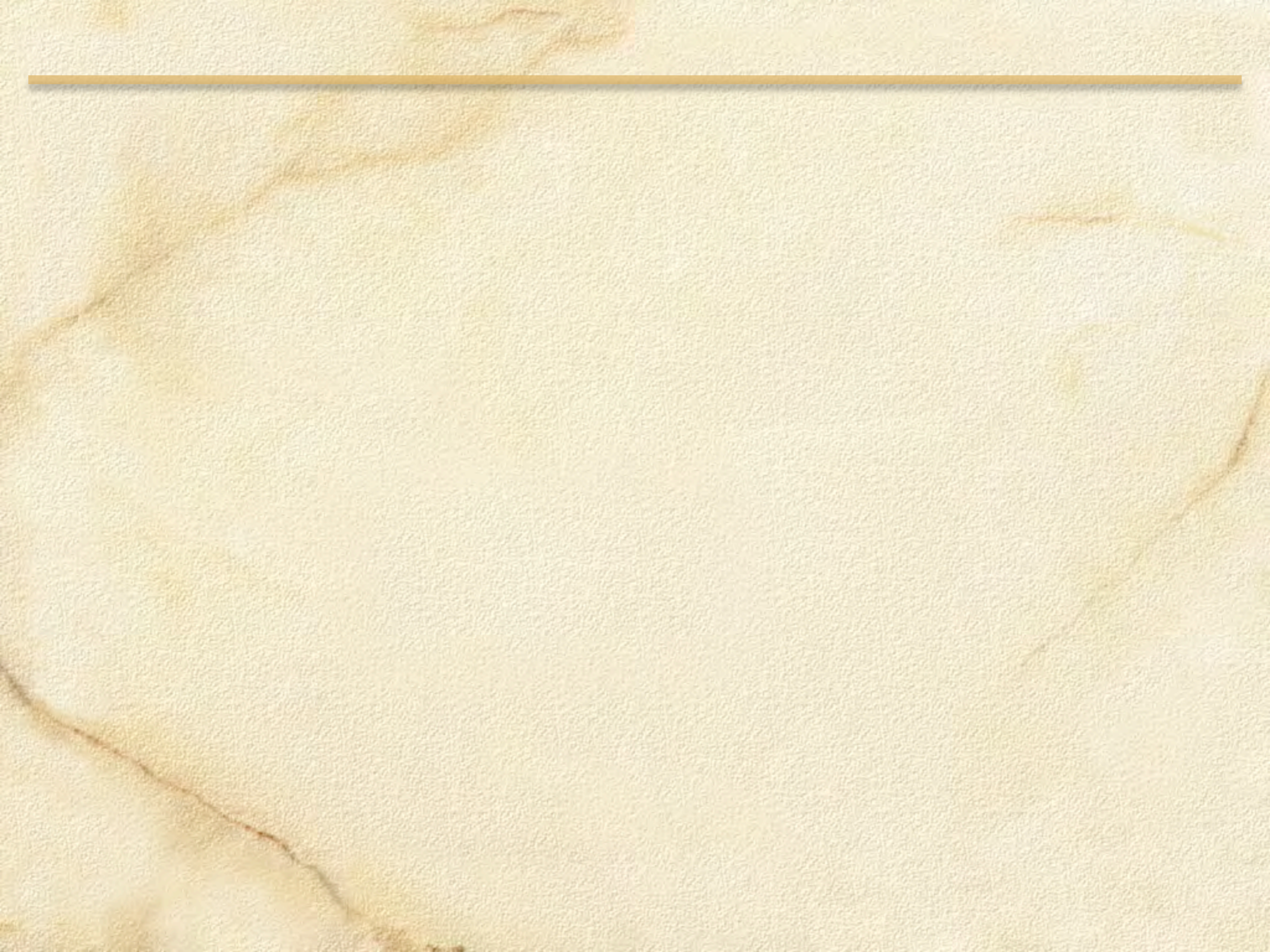
Alex Hubert

Acknowledgement



Alex Hubert



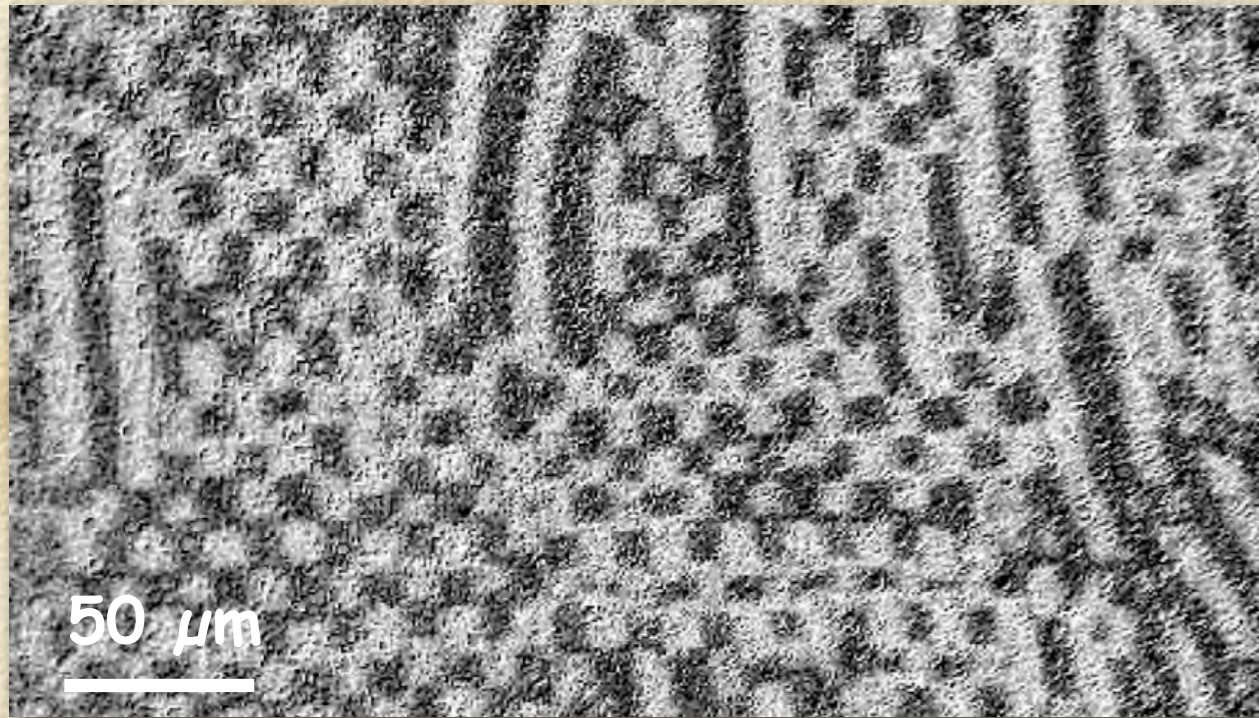


**How can (unknown)
magnetic microstructure
be analysed ?**

Analysis of Magnetic Domains

1) Experimental imaging

Amorphous ribbon (Co-rich, 45 μm thick)

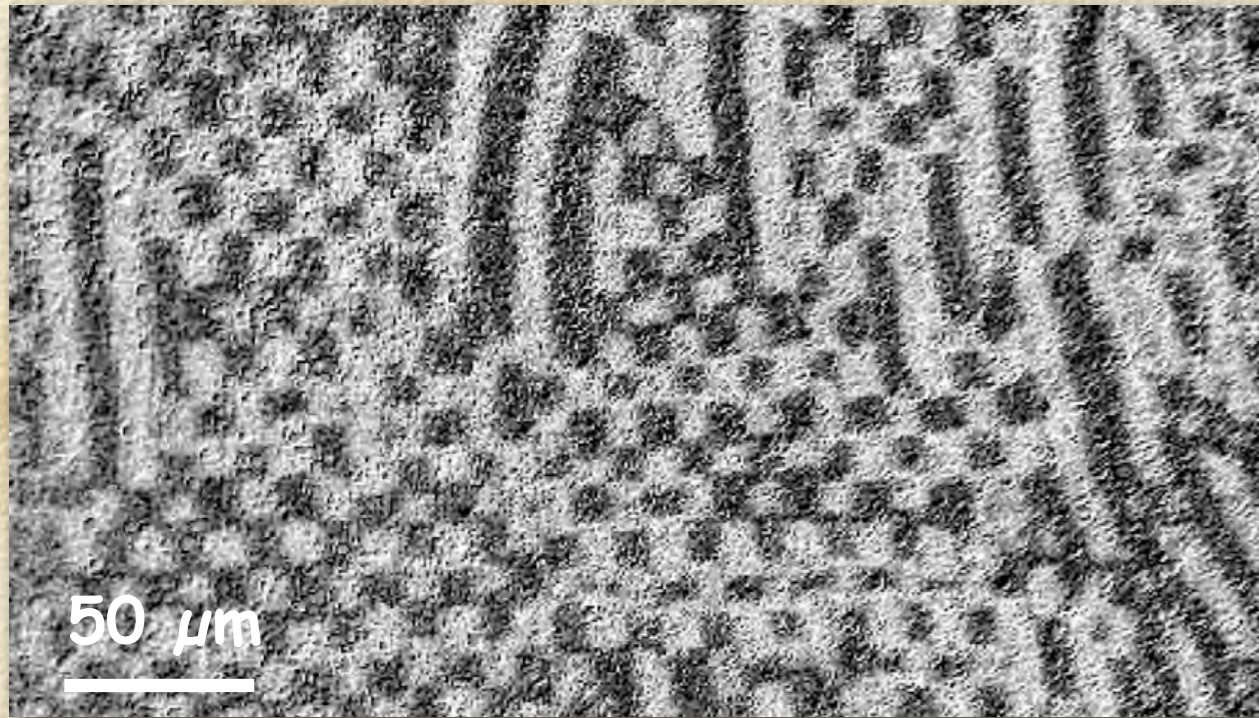


(image: courtesy G. Herzer, VAC)

Analysis of Magnetic Domains

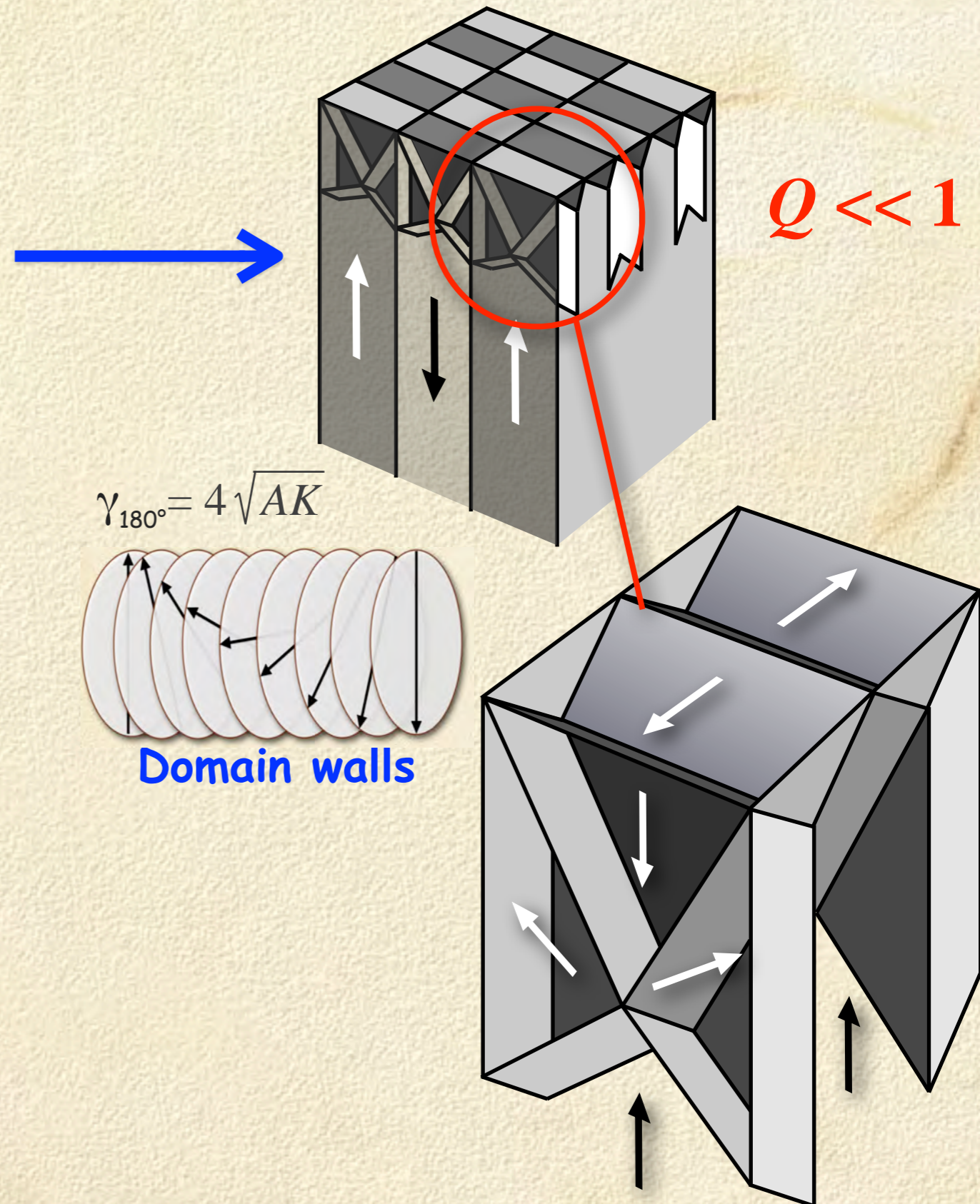
1) Experimental imaging

Amorphous ribbon (Co-rich, 45 μm thick)



(image: courtesy G. Herzer, VAC)

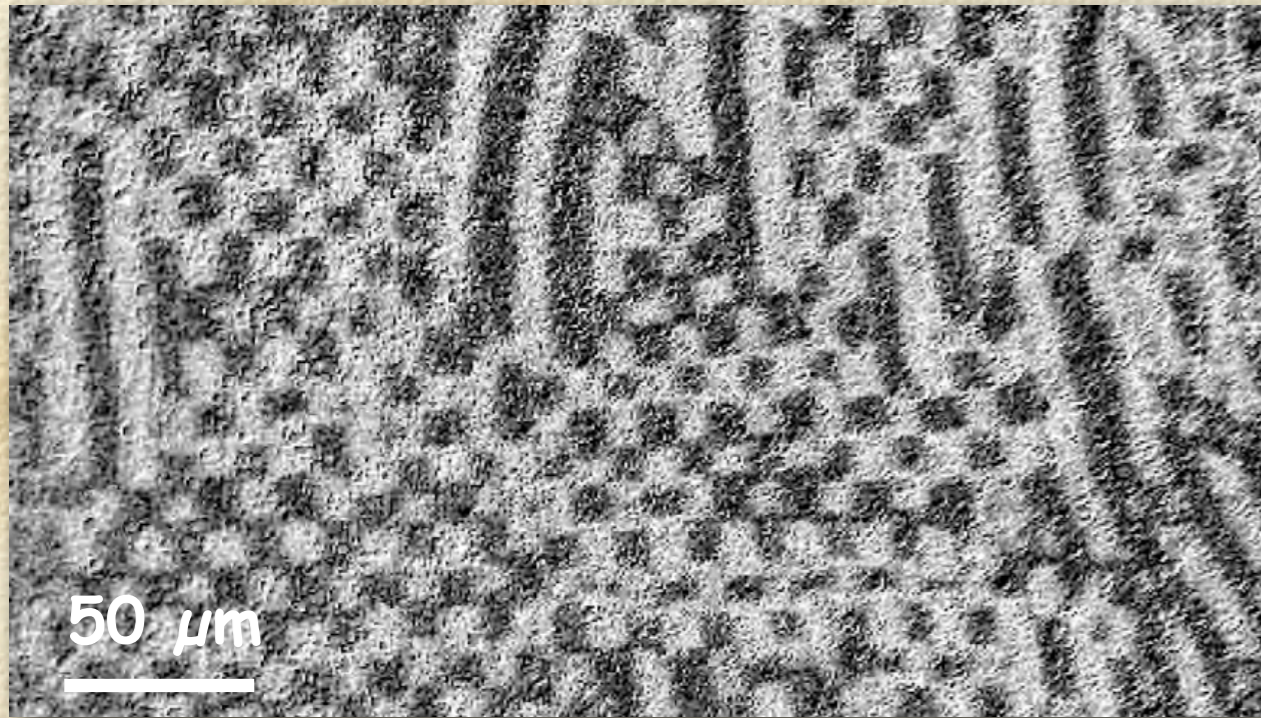
2) Domain model



Analysis of Magnetic Domains

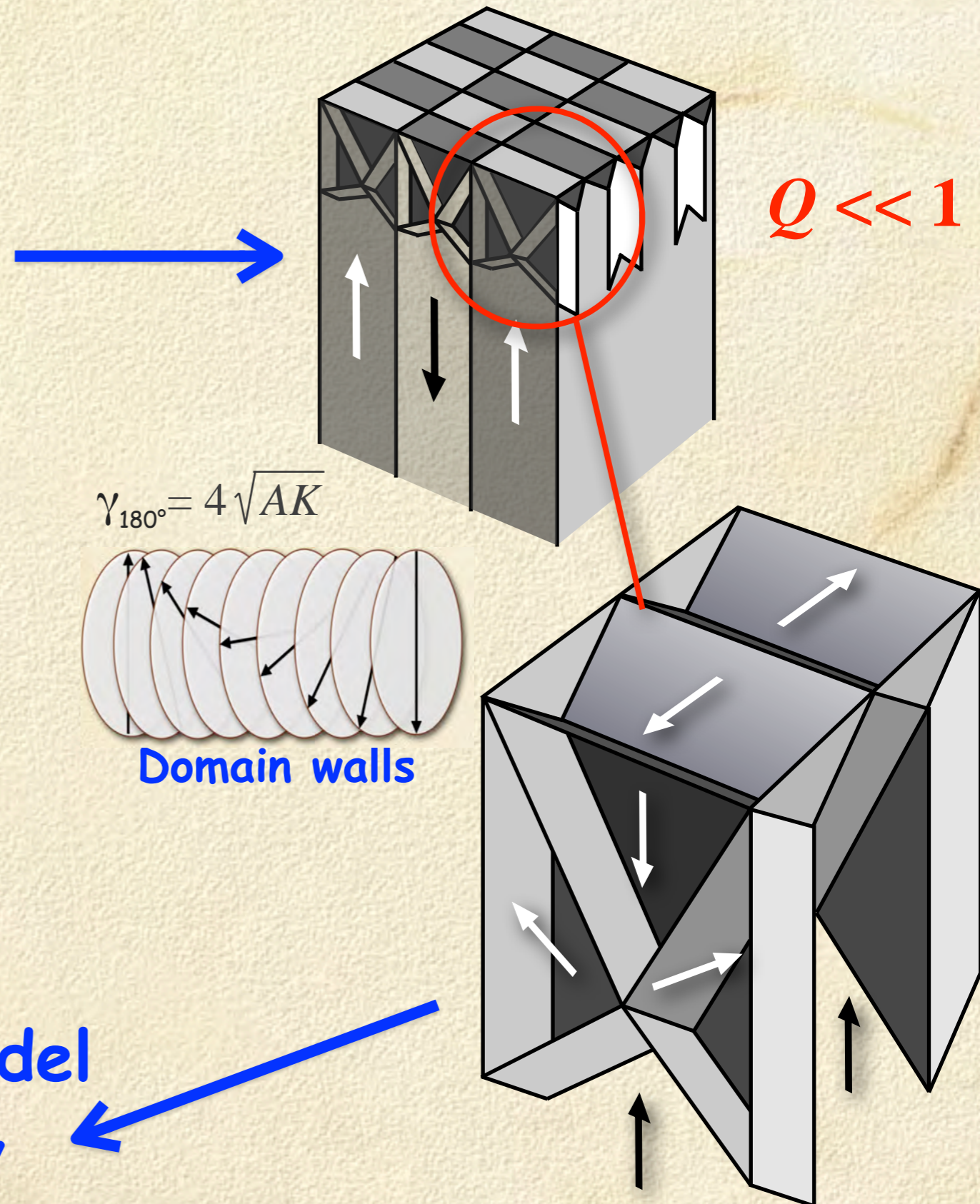
1) Experimental imaging

Amorphous ribbon (Co-rich, 45 μm thick)



(image: courtesy G. Herzer, VAC)

2) Domain model

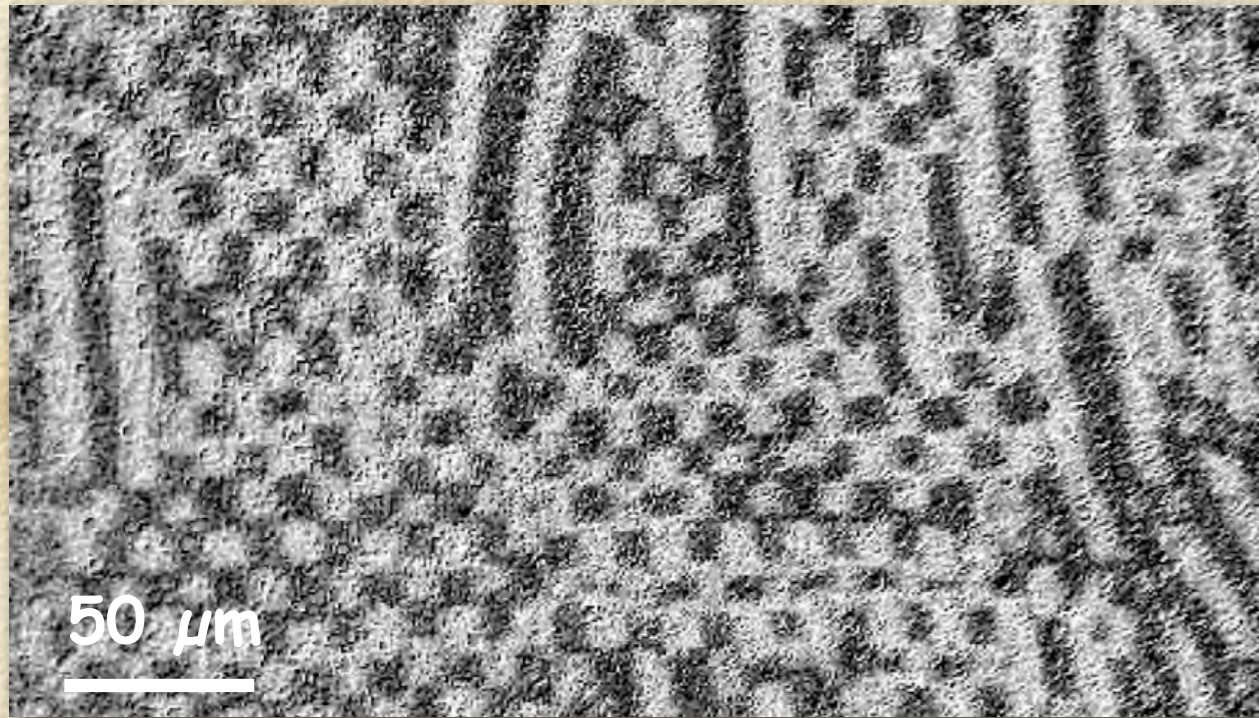


3) Optimization of model
for minimum energy

Analysis of Magnetic Domains

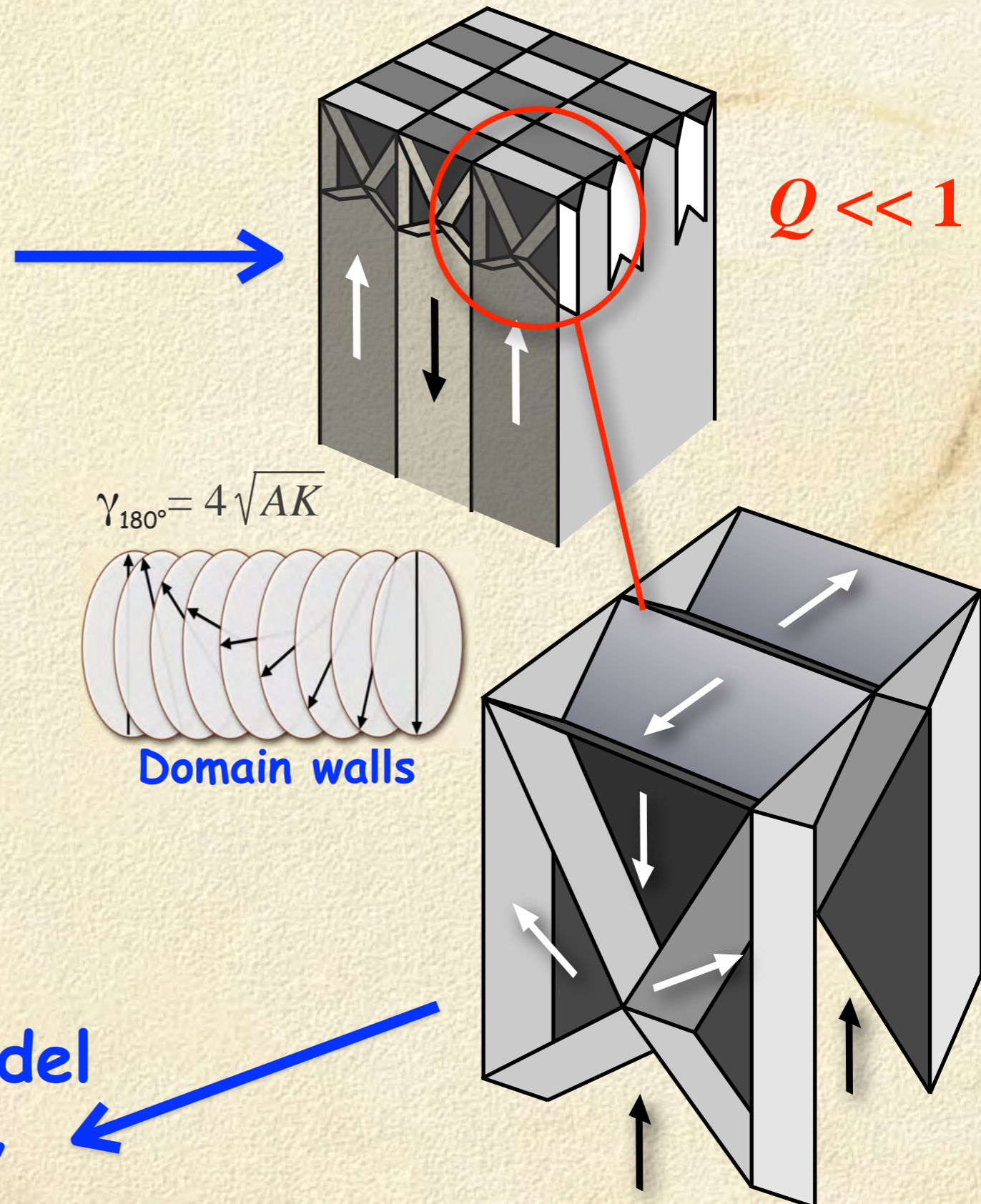
1) Experimental imaging

Amorphous ribbon (Co-rich, 45 μm thick)



(image: courtesy G. Herzer, VAC)

2) Domain model



4) Comparison with observation

3) Optimization of model for minimum energy