IEEE Magnetics Society

- **IEEE Magnetics Society Home Page: *www.ieeemagnetics.org***
  - **3000 full members**
  - **300 student members**

- **The Society**
  - **Conference organization (INTERMAG, MMM, TMRC, etc.)**
  - **Student support for conferences**
  - **Large conference discounts for members**
  - **Graduate Student Summer Schools**
  - **Local chapter activities**
  - **Distinguished lectures**

- ***IEEE Transactions on Magnetics***
  - **~ 2000 peer reviewed pages each year**
  - **Electronic access to all *IEEE Transactions on Magnetics* papers**

- **Online applications for IEEE membership: *www.ieee.org/join***
  - **360,000 members**
  - **IEEE student membership IEEE full membership**

Magneto-optical Analysis of Magnetic Microstructures*

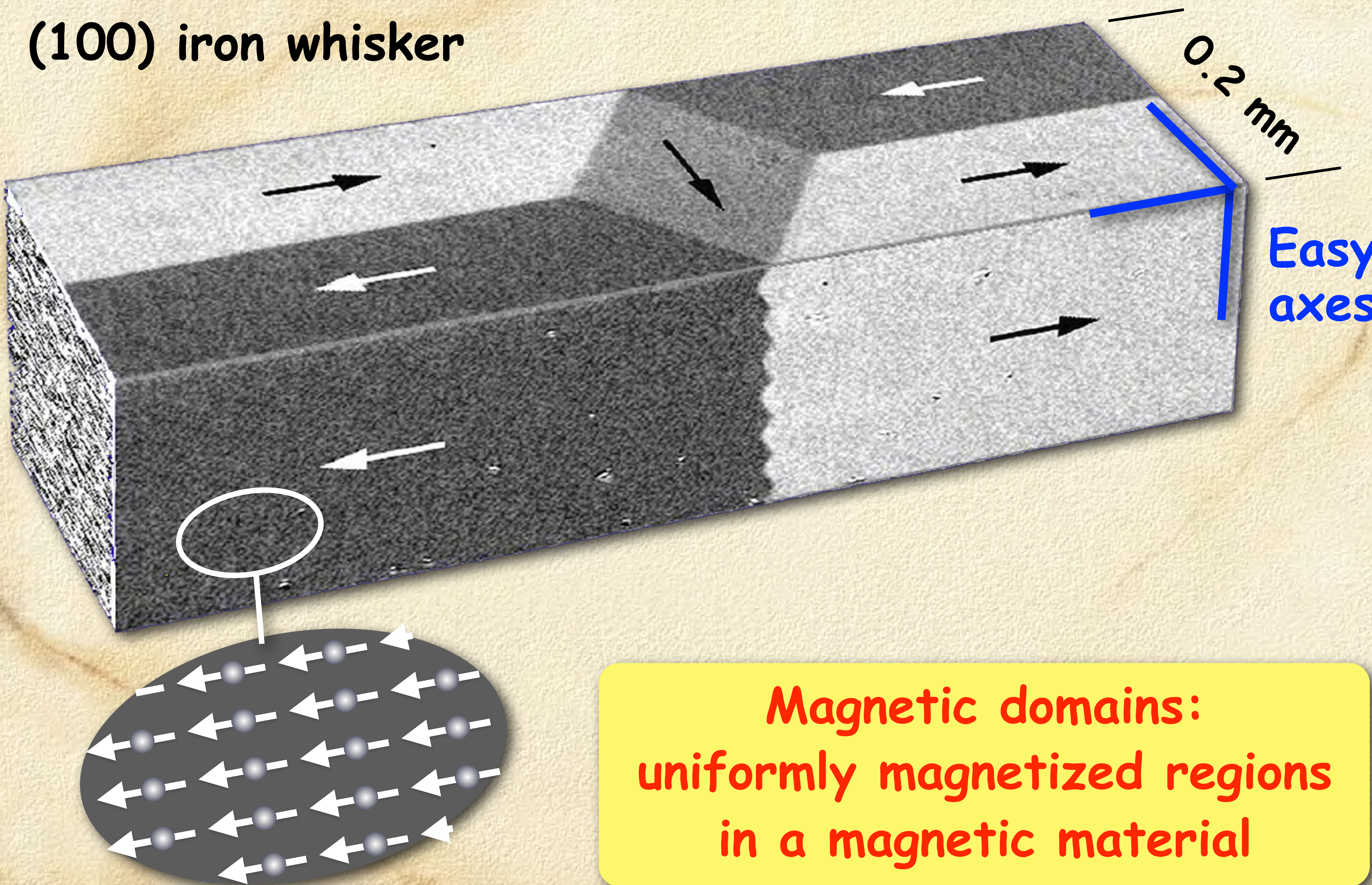
R. Schäfer,

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

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

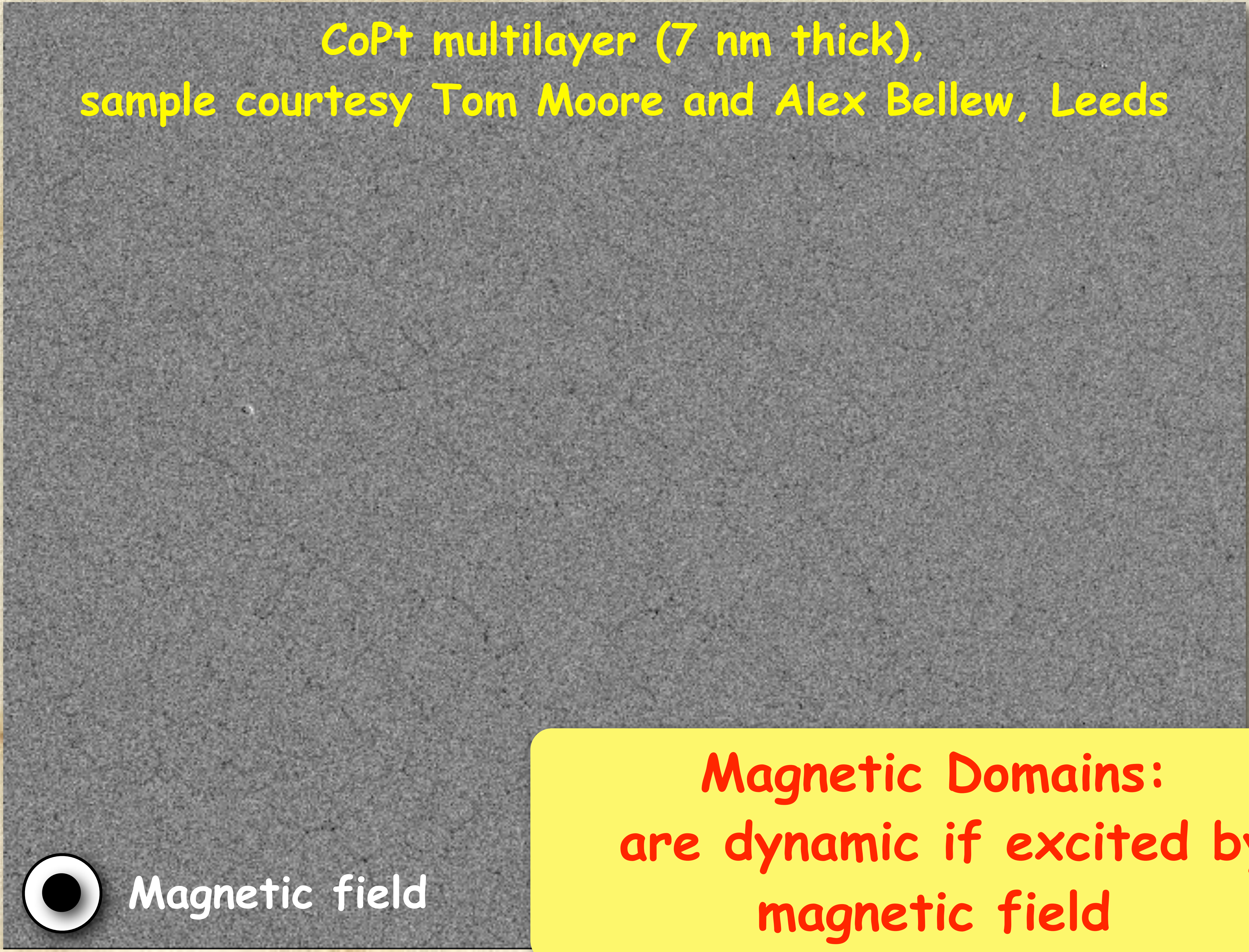
What are magnetic domains ?

What are magnetic domains ?



Magnetic domains: uniformly magnetized regions in a magnetic material

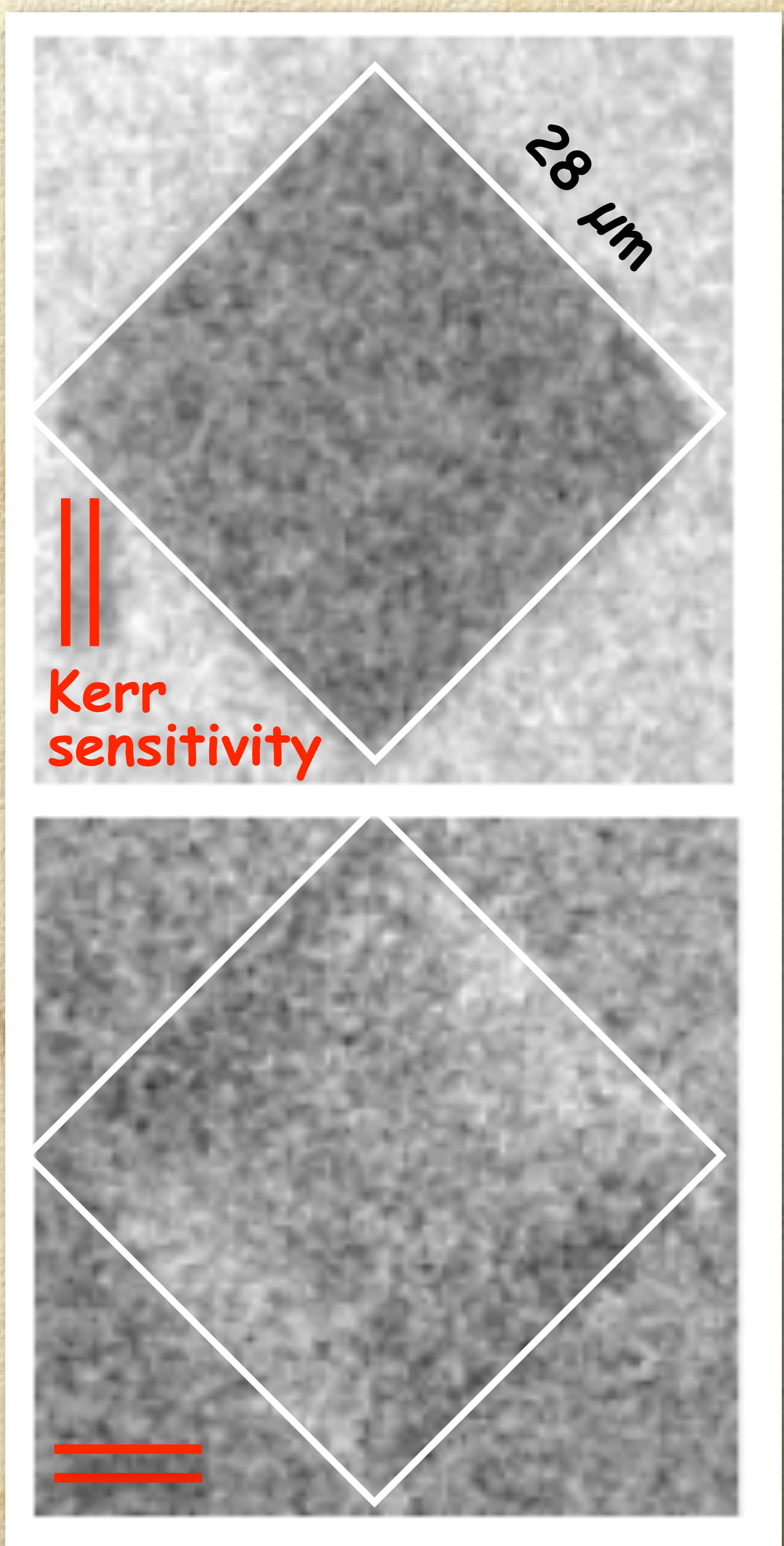
What are magnetic domains?



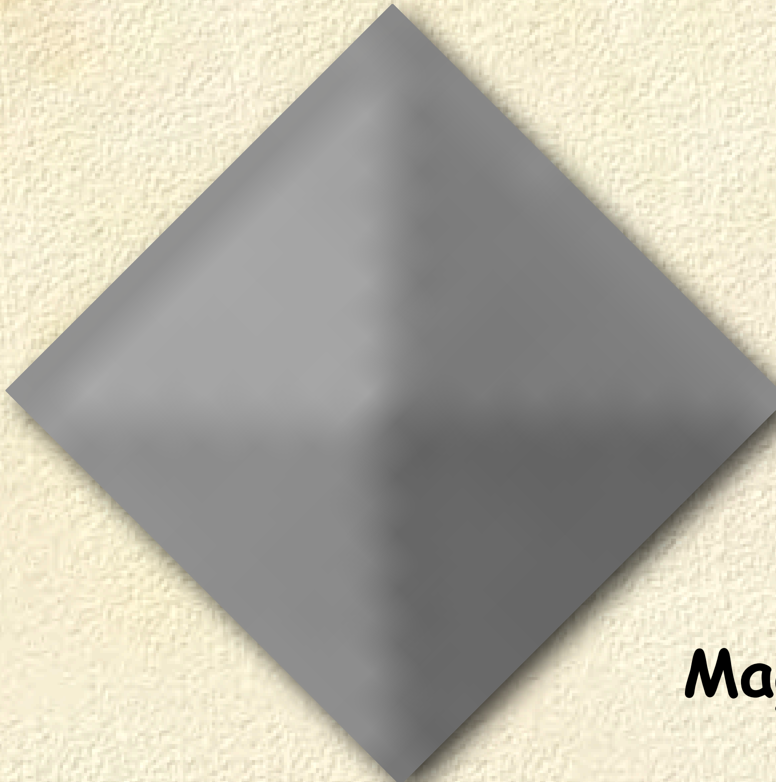
Magnetic Domains:
are dynamic if excited by magnetic field

What are magnetic domains?

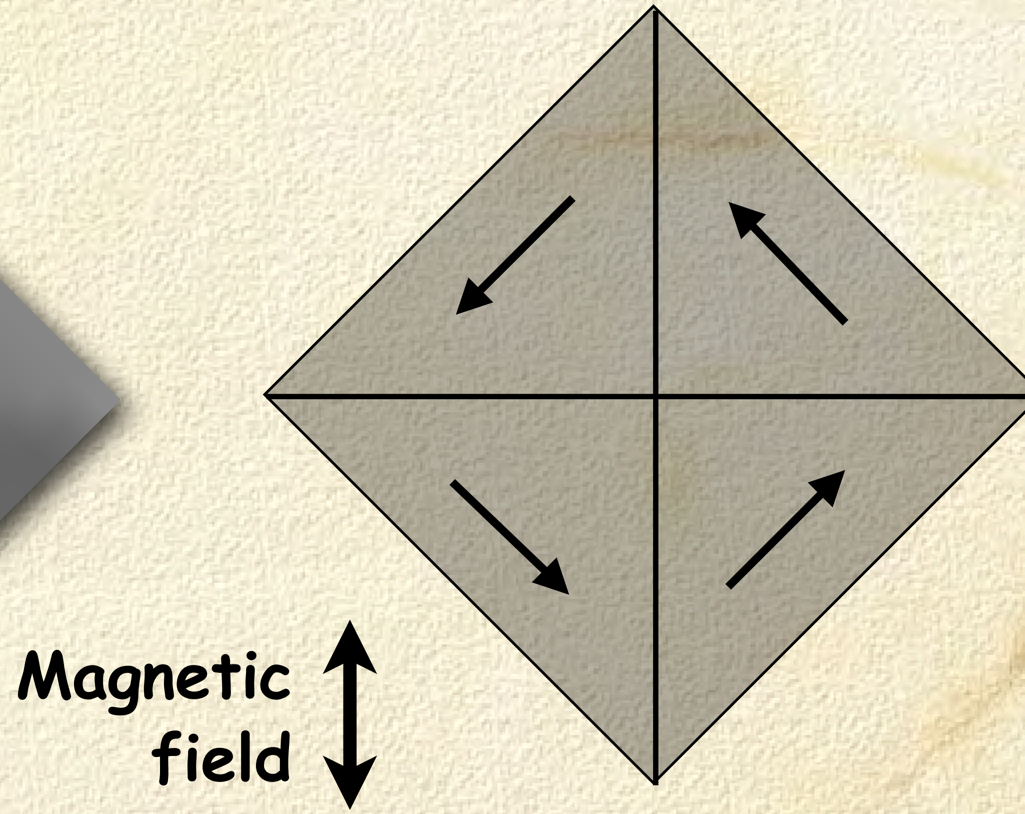
Pulse-field excitation

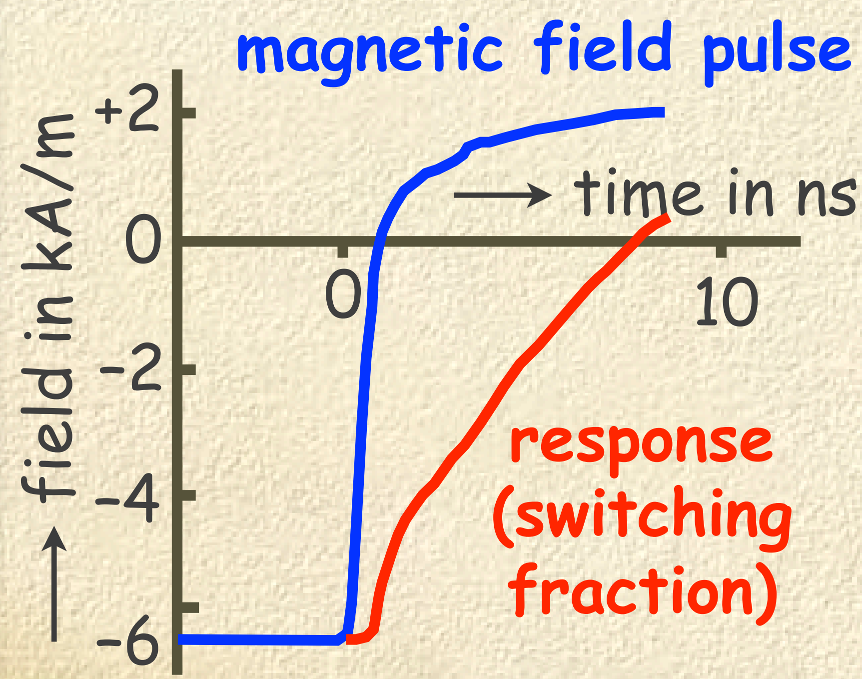


Quasistatic excitation



Permalloy (NiFe) film



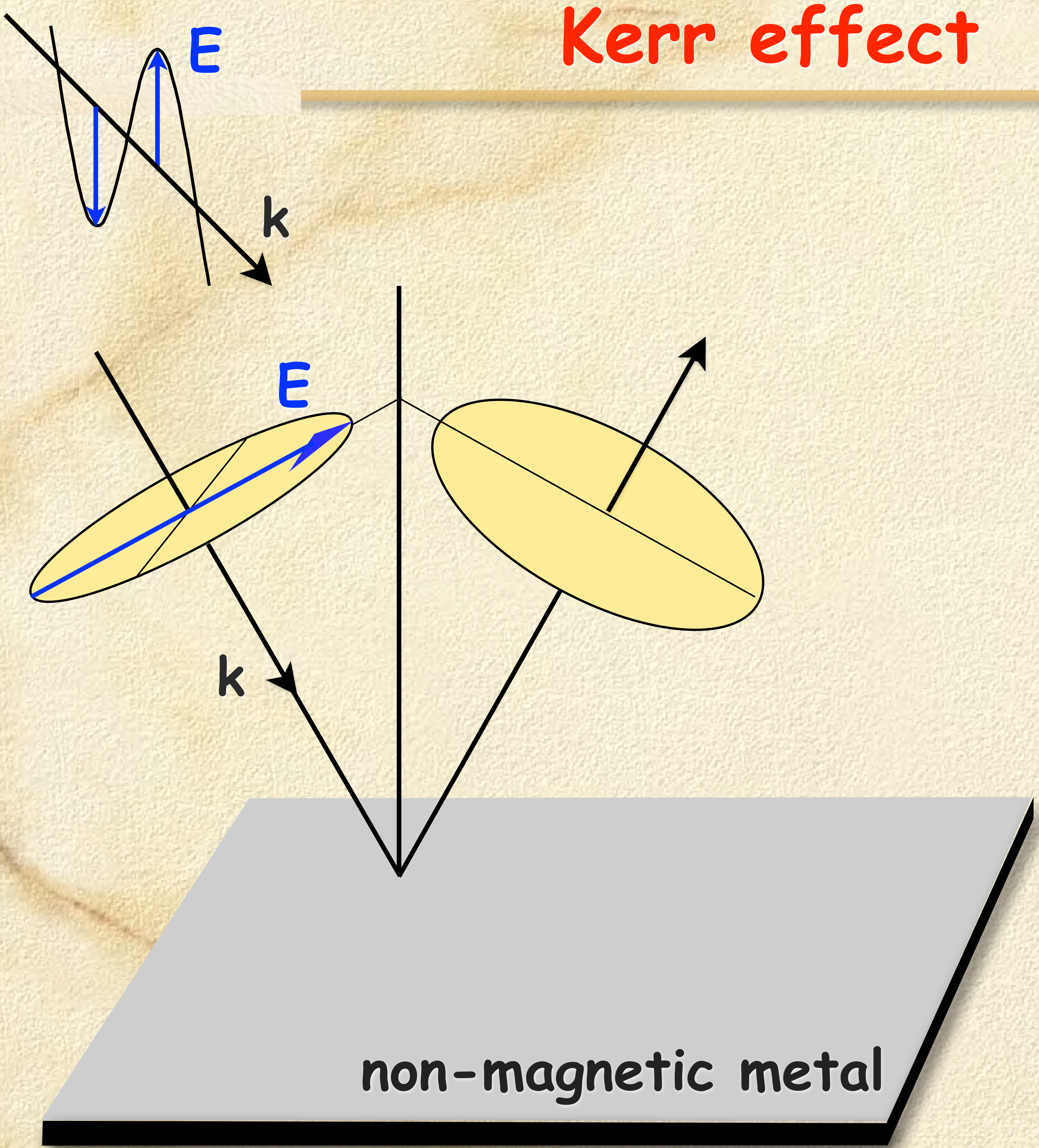


D. Chumakov et al.,
PRB 71, 014410 (2005)

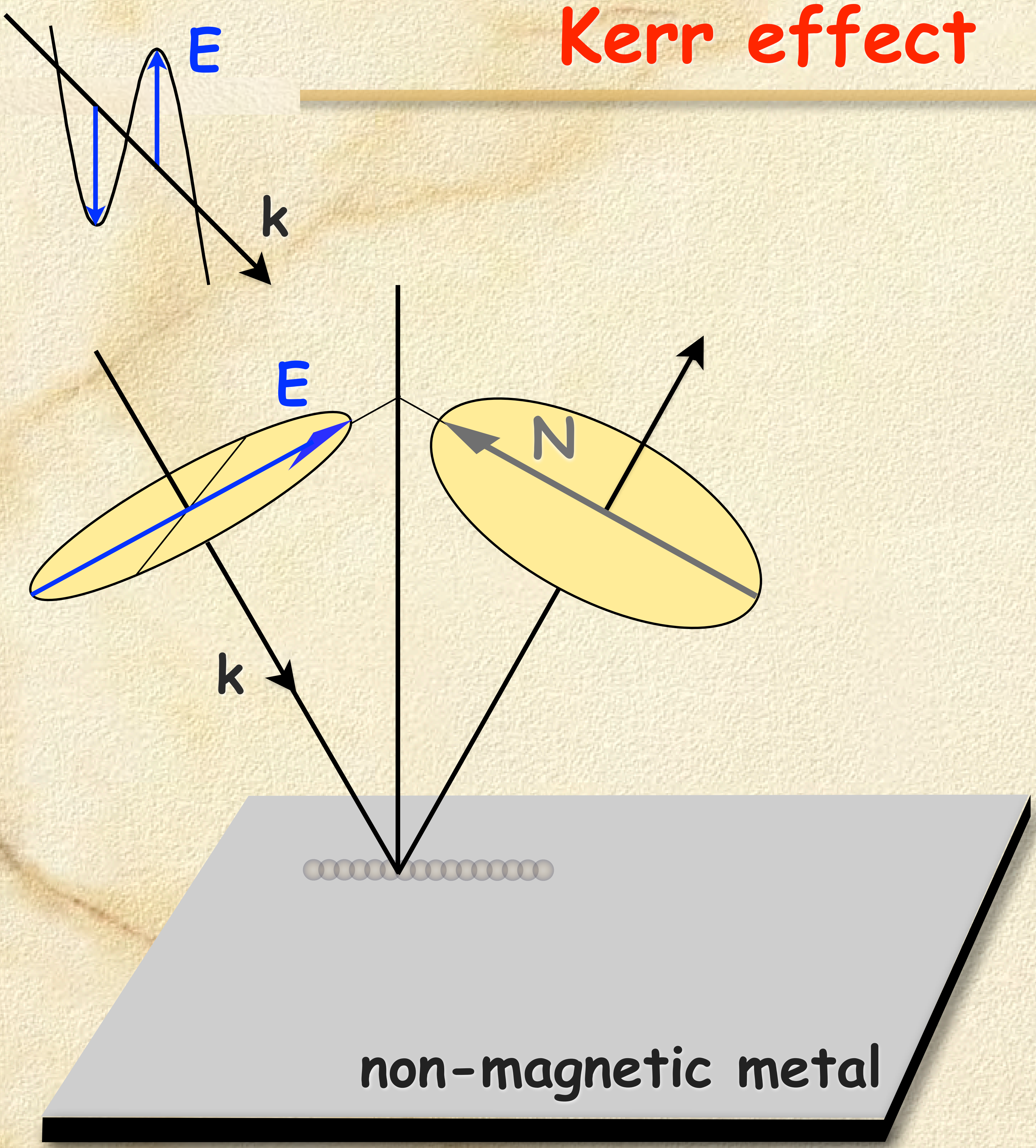
Domain dynamics depends on excitation speed

Magneto-optical Kerr microscopy

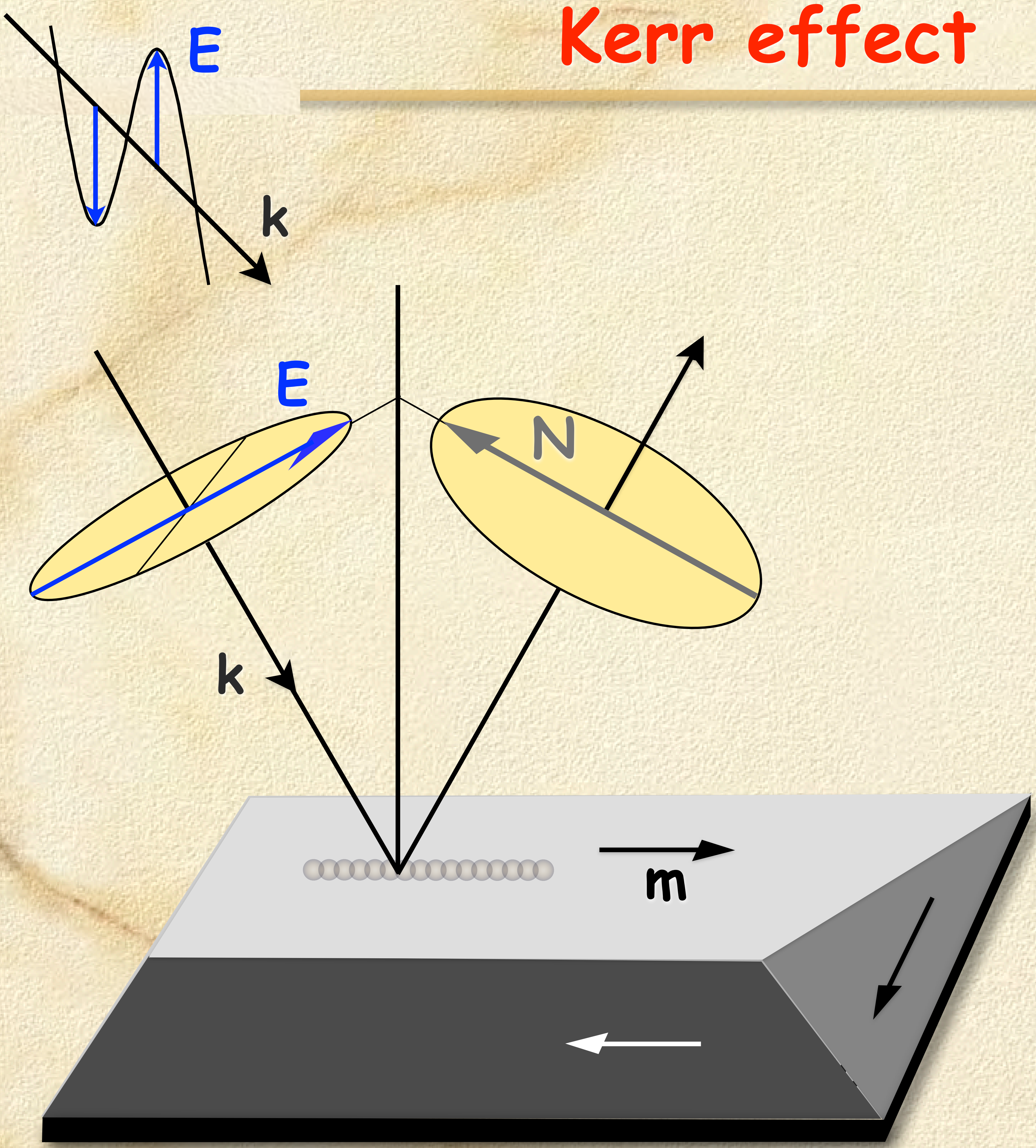
Kerr effect



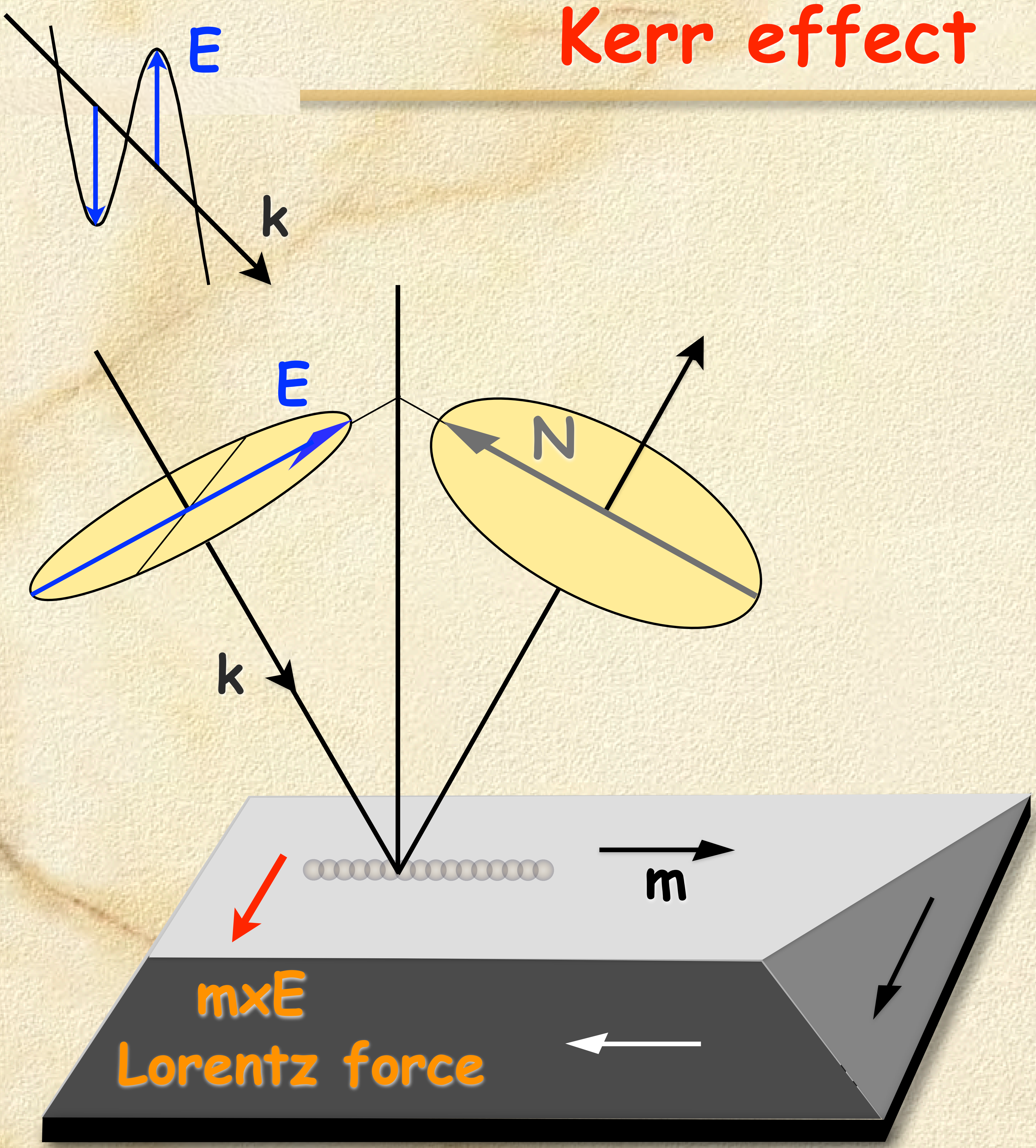
Kerr effect



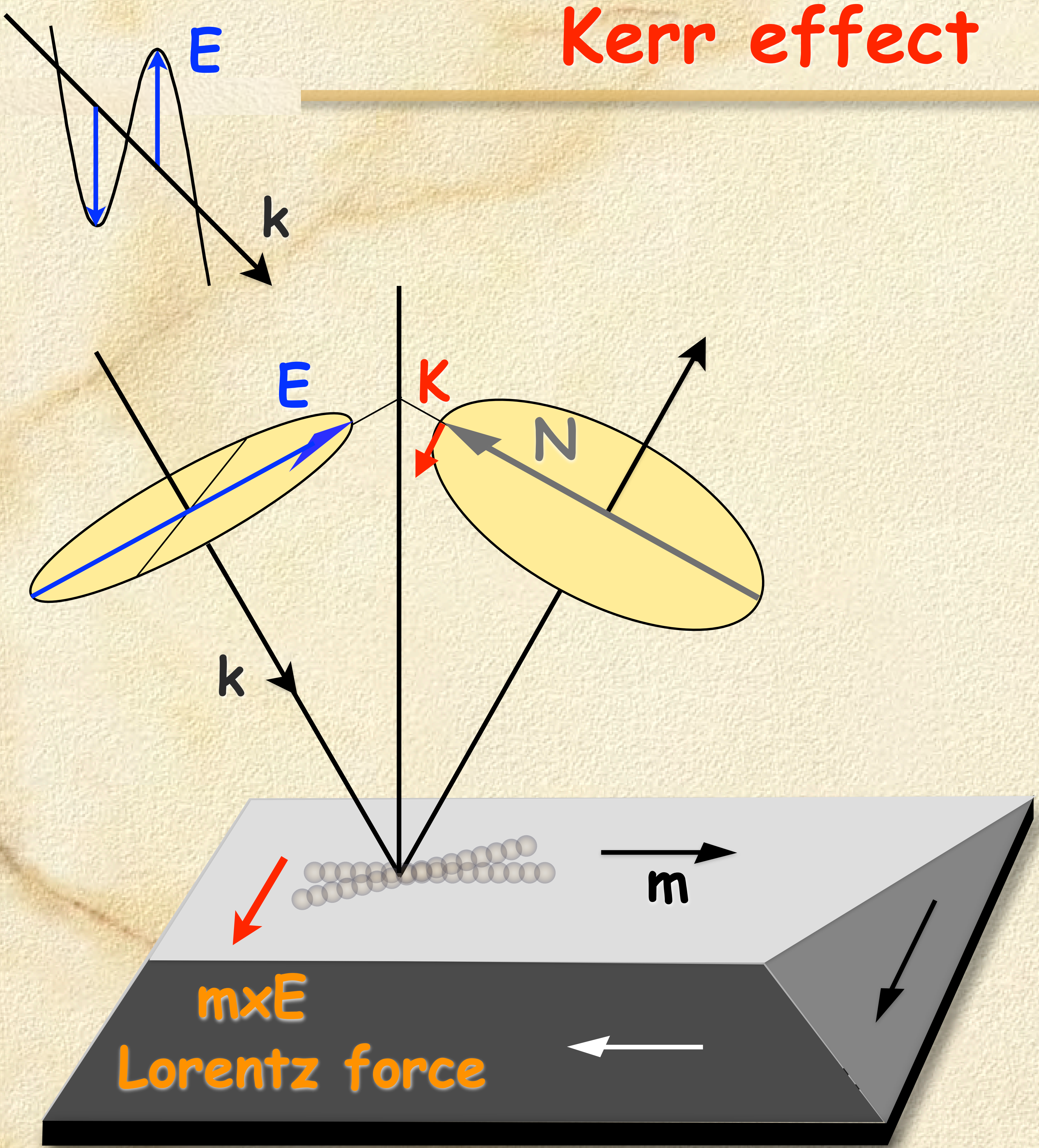
Kerr effect



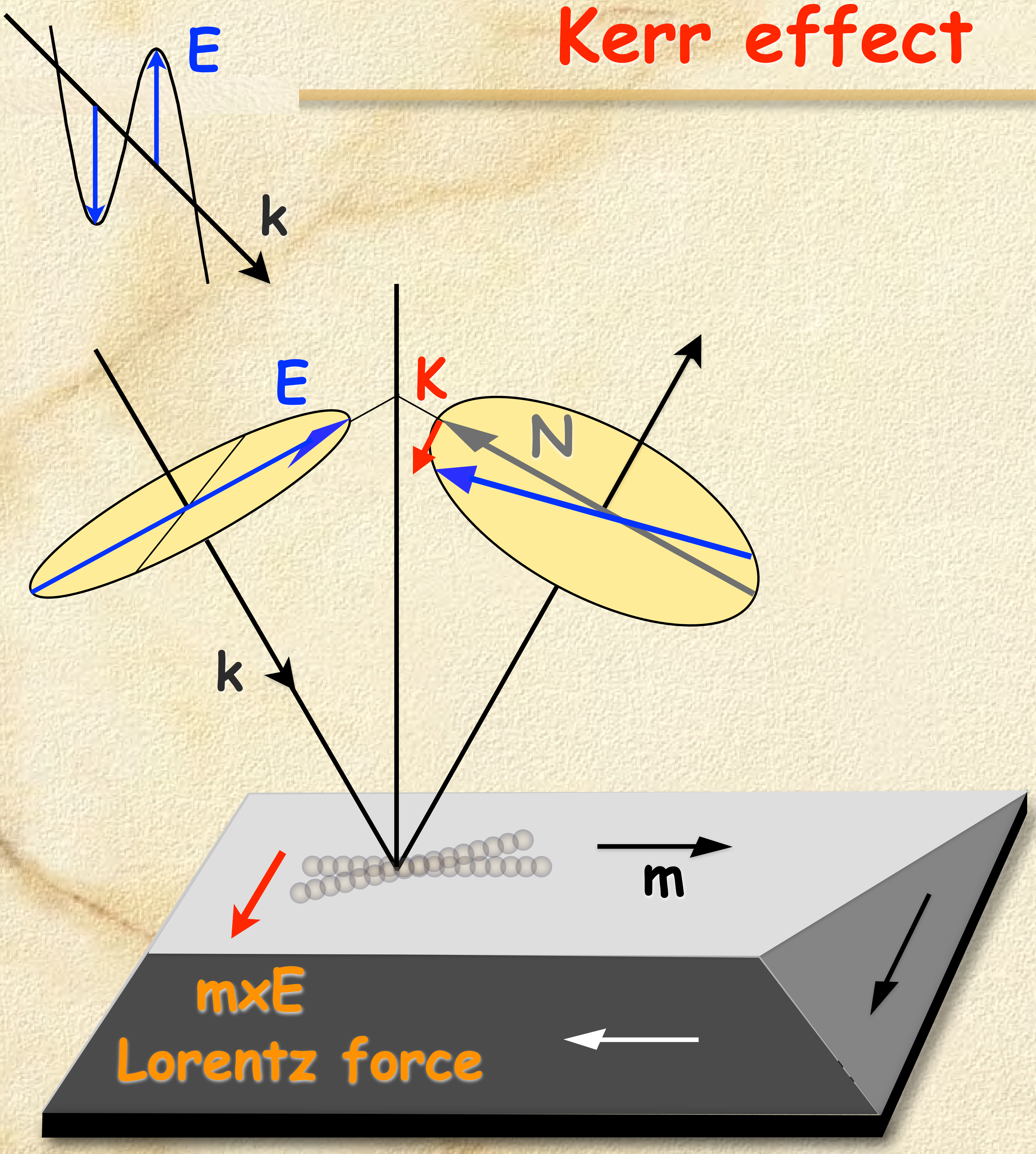
Kerr effect



Kerr effect



Kerr effect



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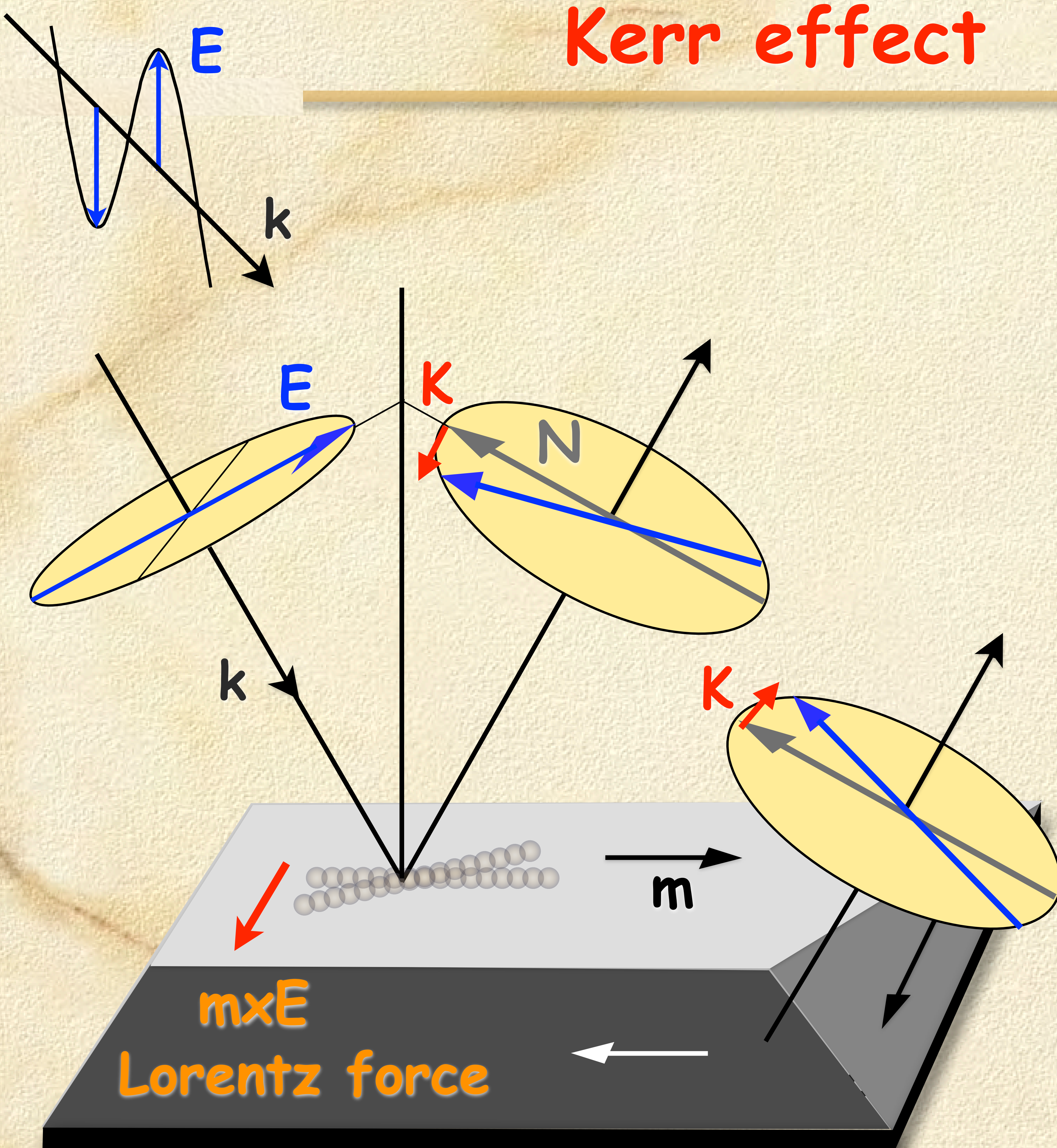
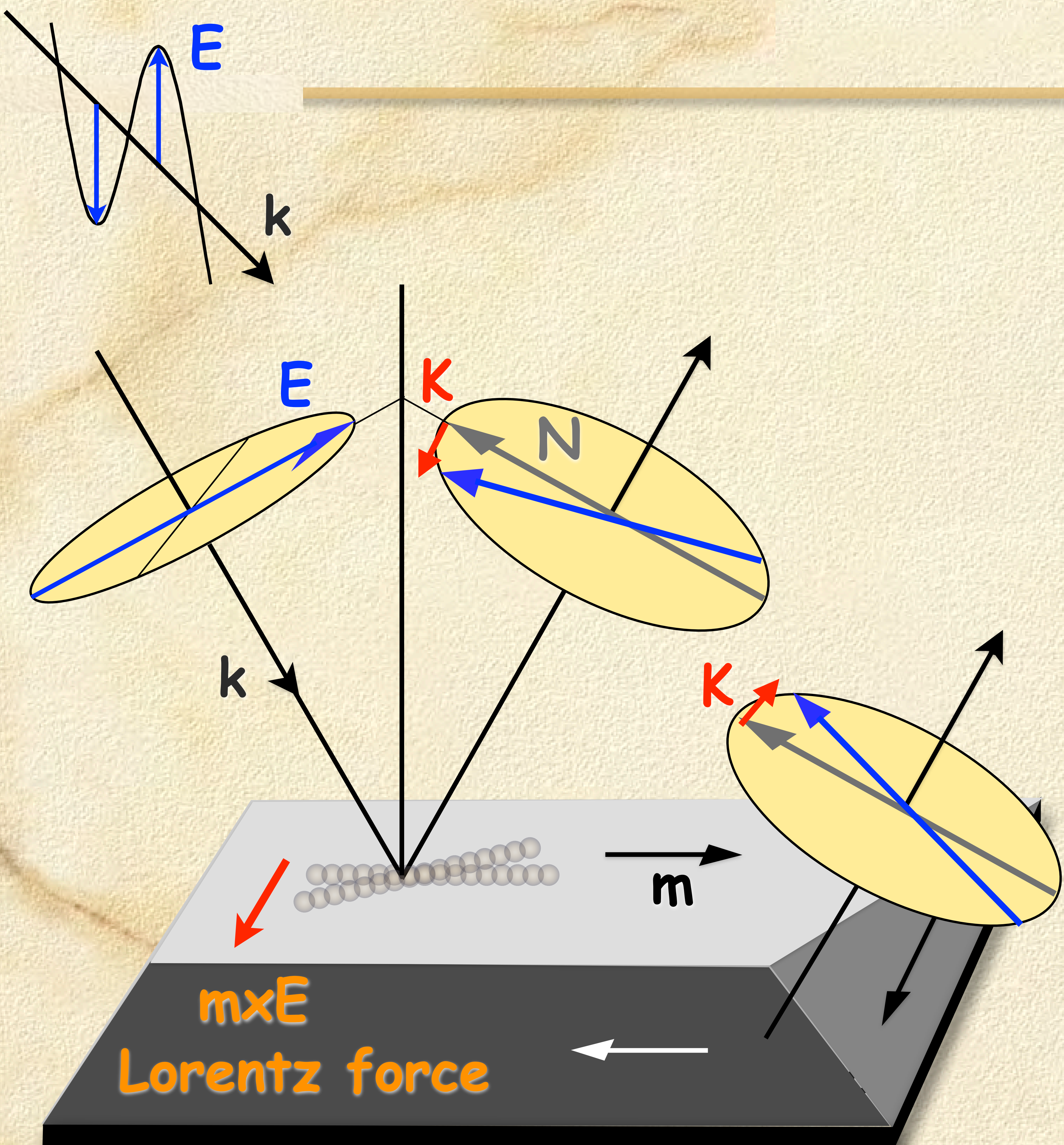
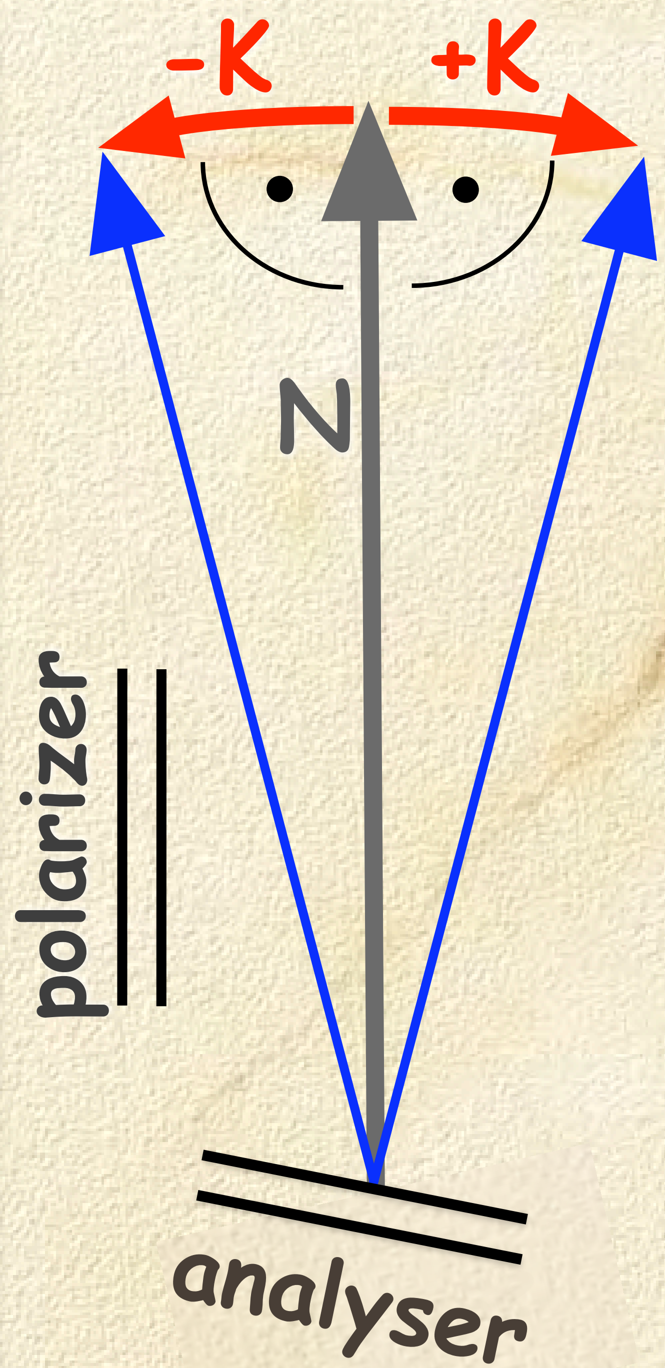
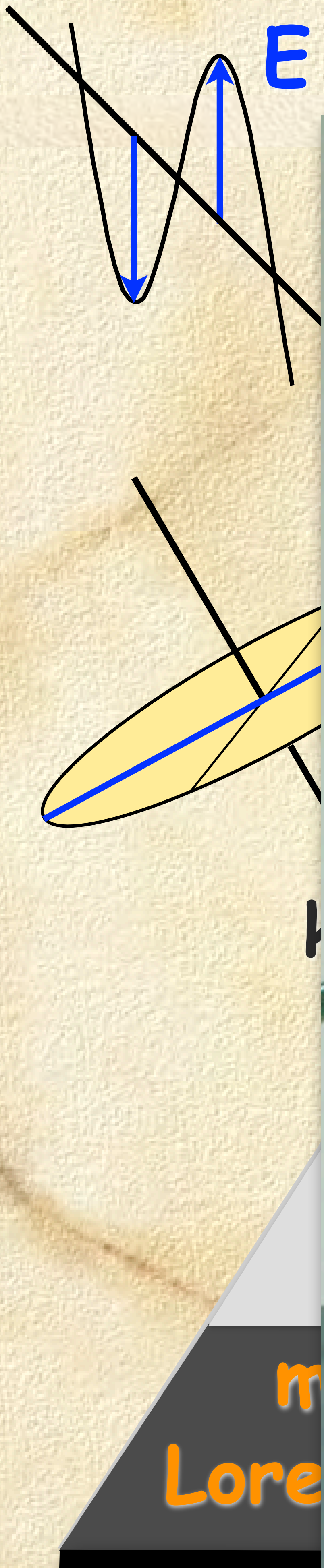


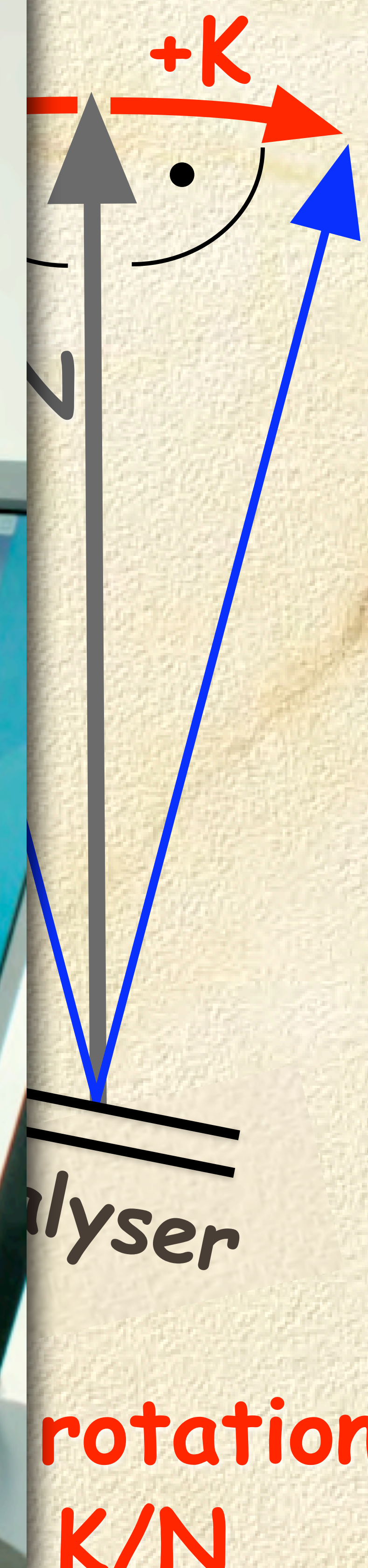




Kerr rotation
= K/N

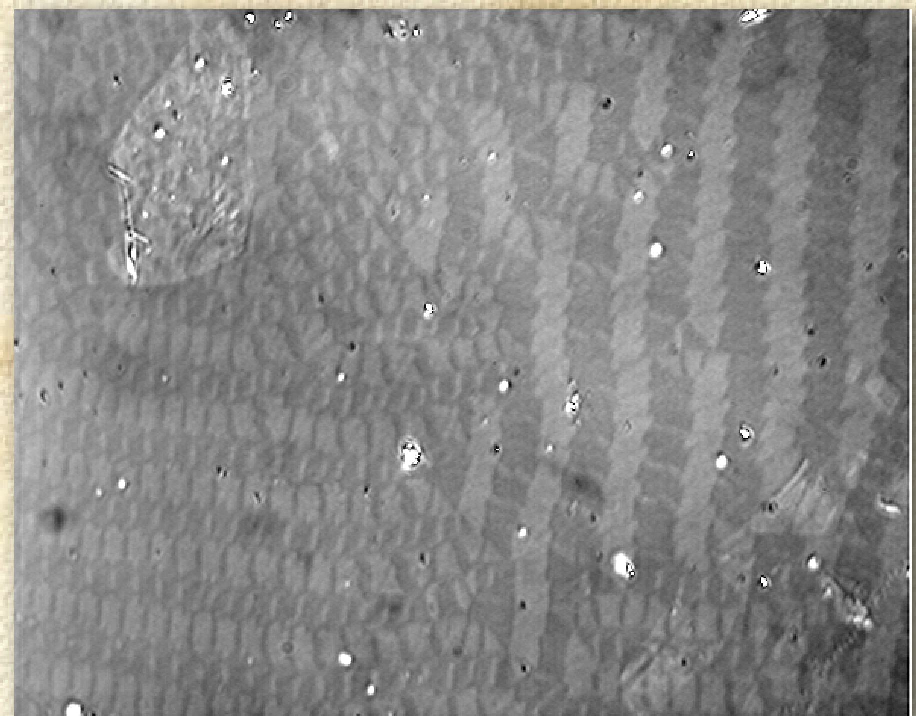
Kerr microscope



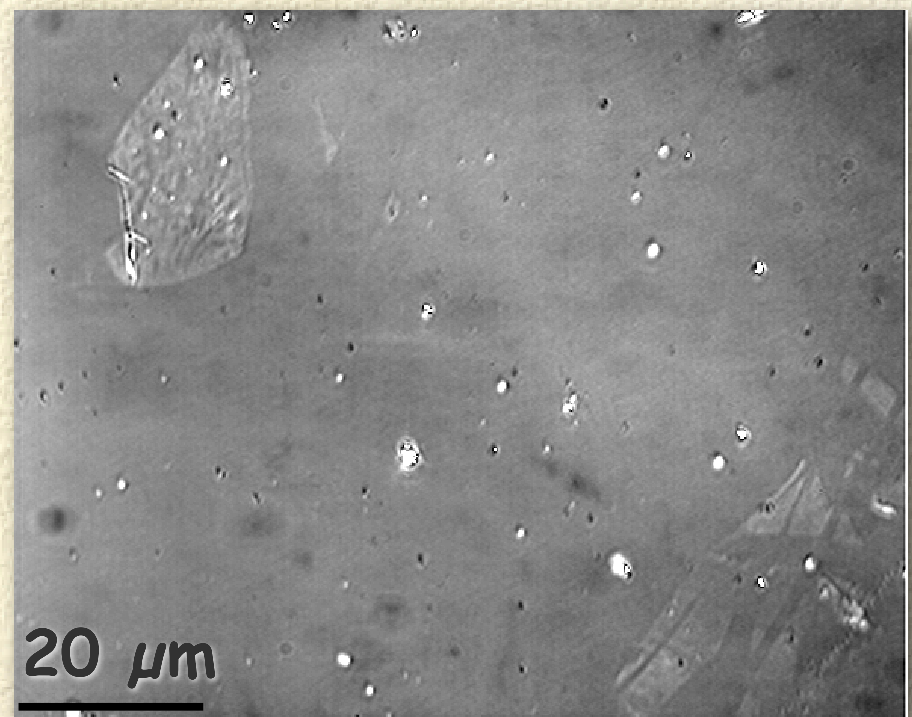


Kerr microscope

Digital contrast enhancement (difference image technique)

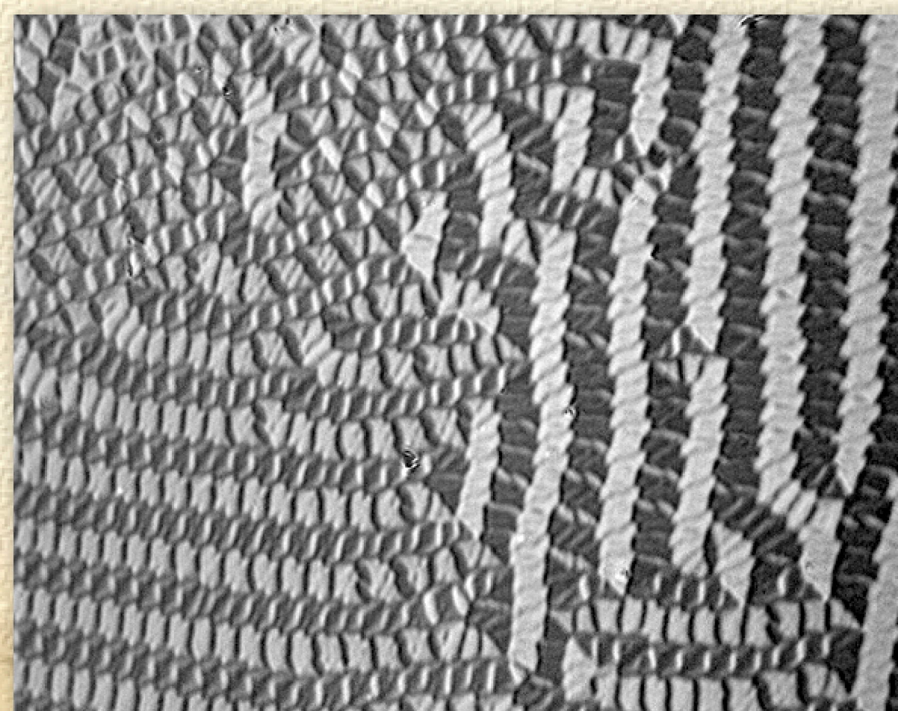


Original image

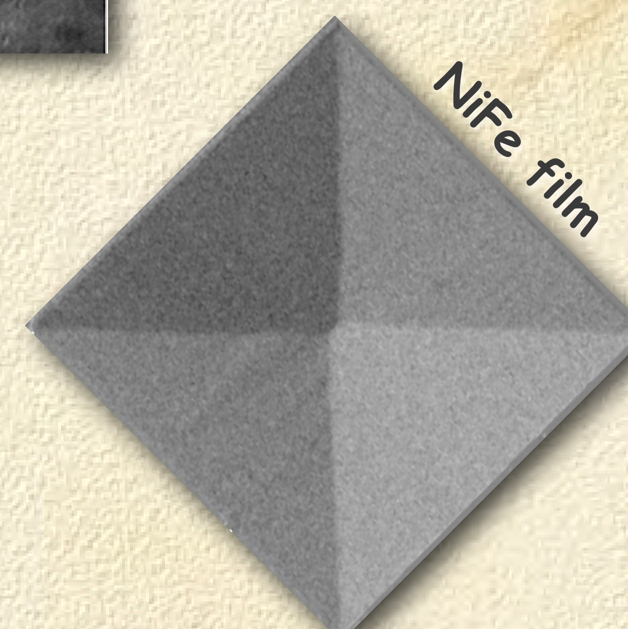


Reference image

amorphous ribbon

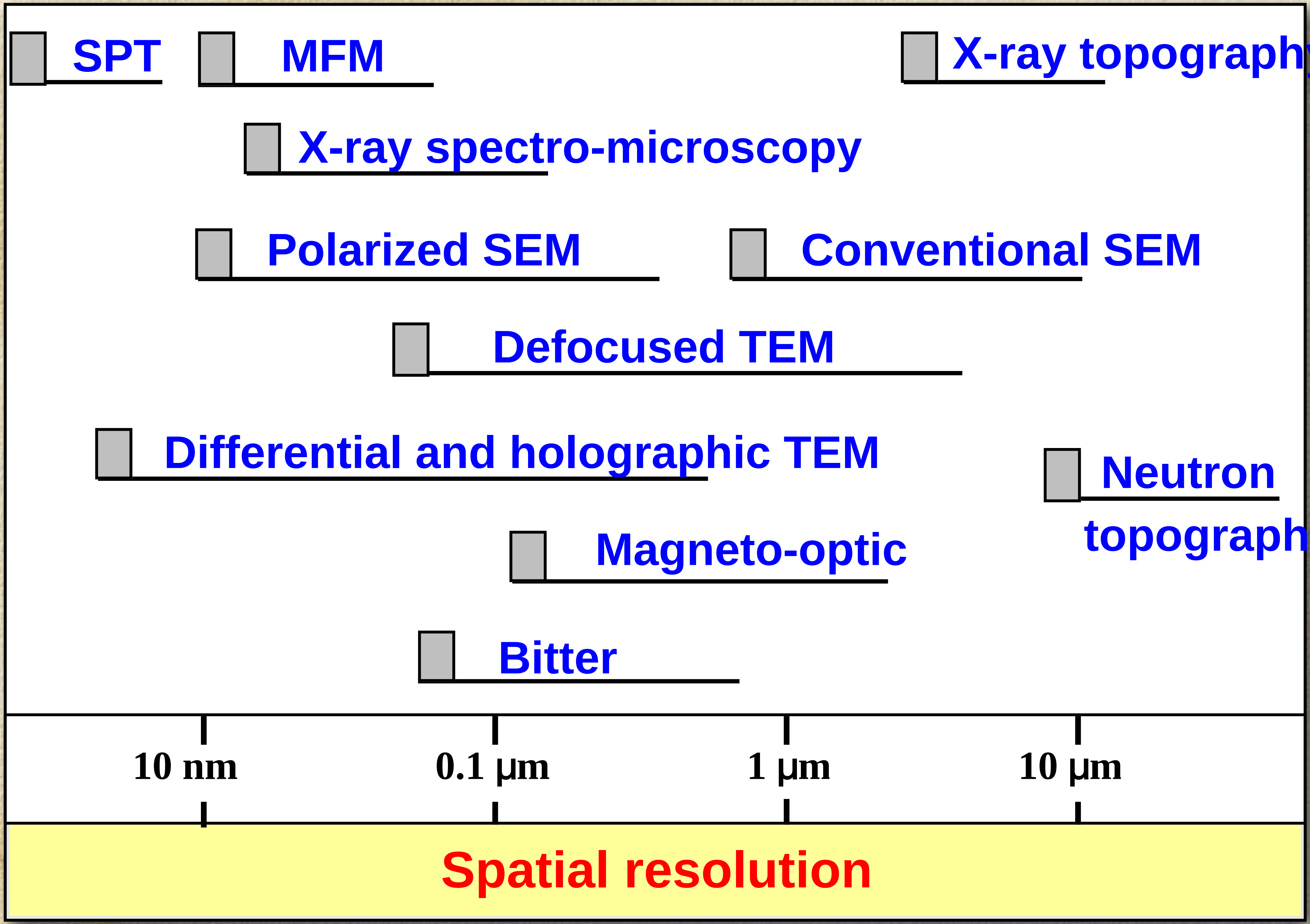


Difference image



Important: Difference Imaging in real time !

Comparison of Domain Obervation Techniques



MFM: Magnetic Force Microscopy

SPT: Spin-Polarized Tunneling

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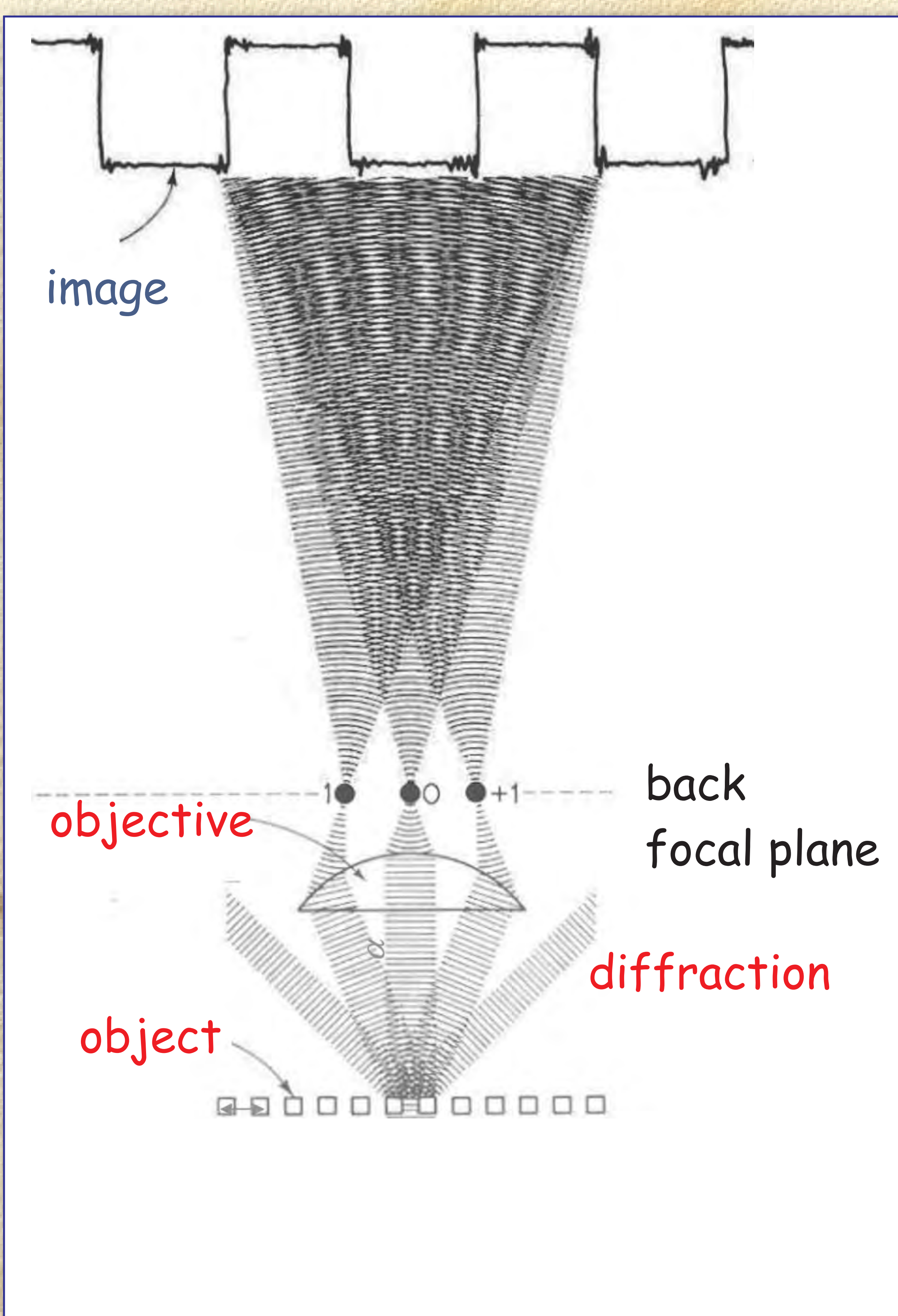
Resolution of Kerr microscopy



Resolution determined by constructive interference

Diffraction-limited image formation

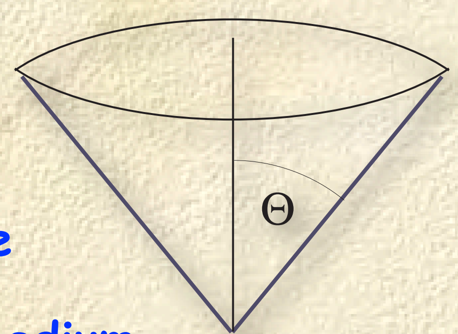
Rayleigh equation: $d = \dfrac{0.5\,\lambda}{NA}$

d = separation between particles, still allowing to see them

λ = wavelength

NA = numerical aperture of objective

$NA = n \sin\theta$



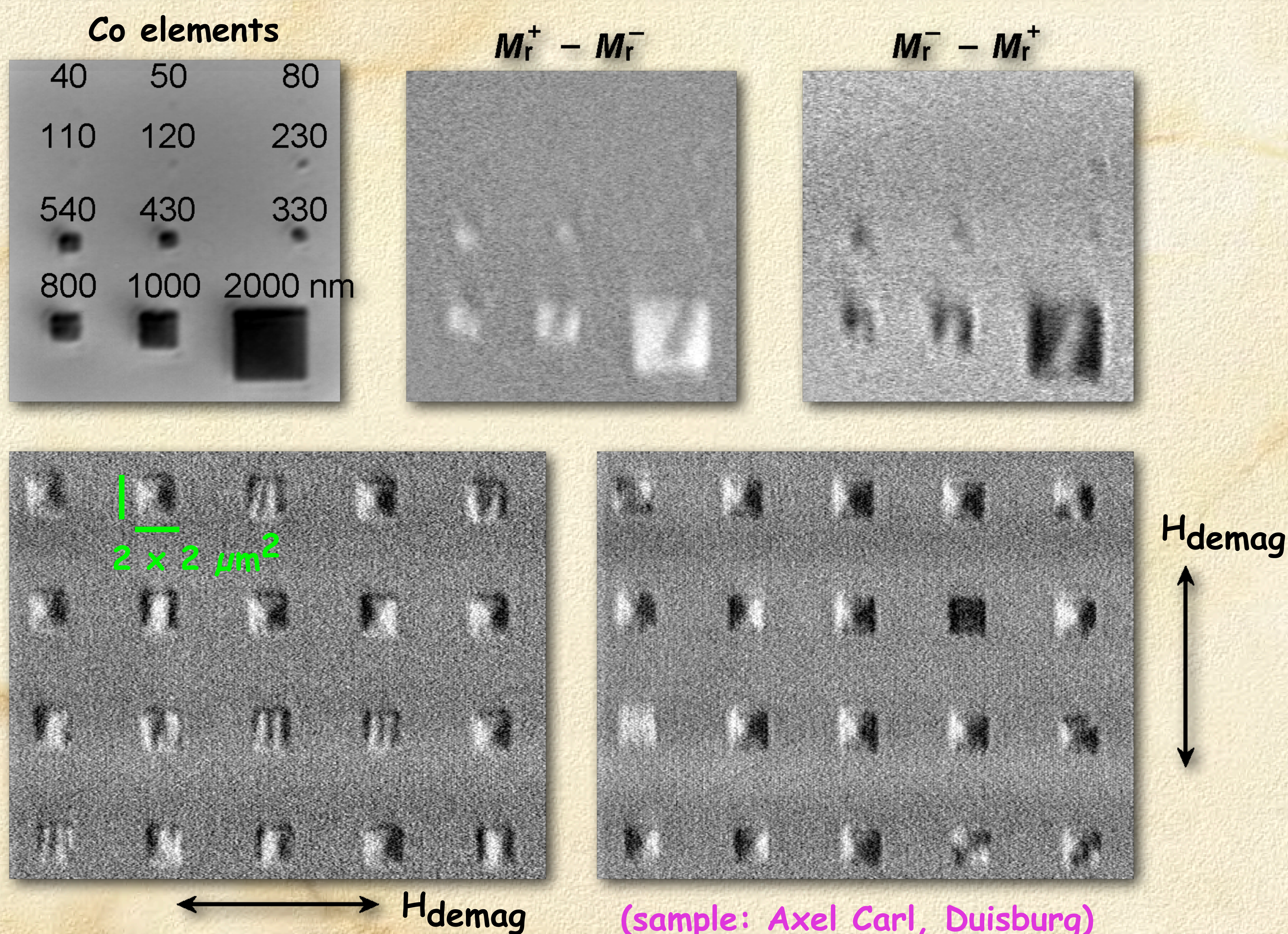
θ = half the cone angle of light accepted by objective

n = referaction index of medium between sample and objective

↓

Best around 200-300 nm

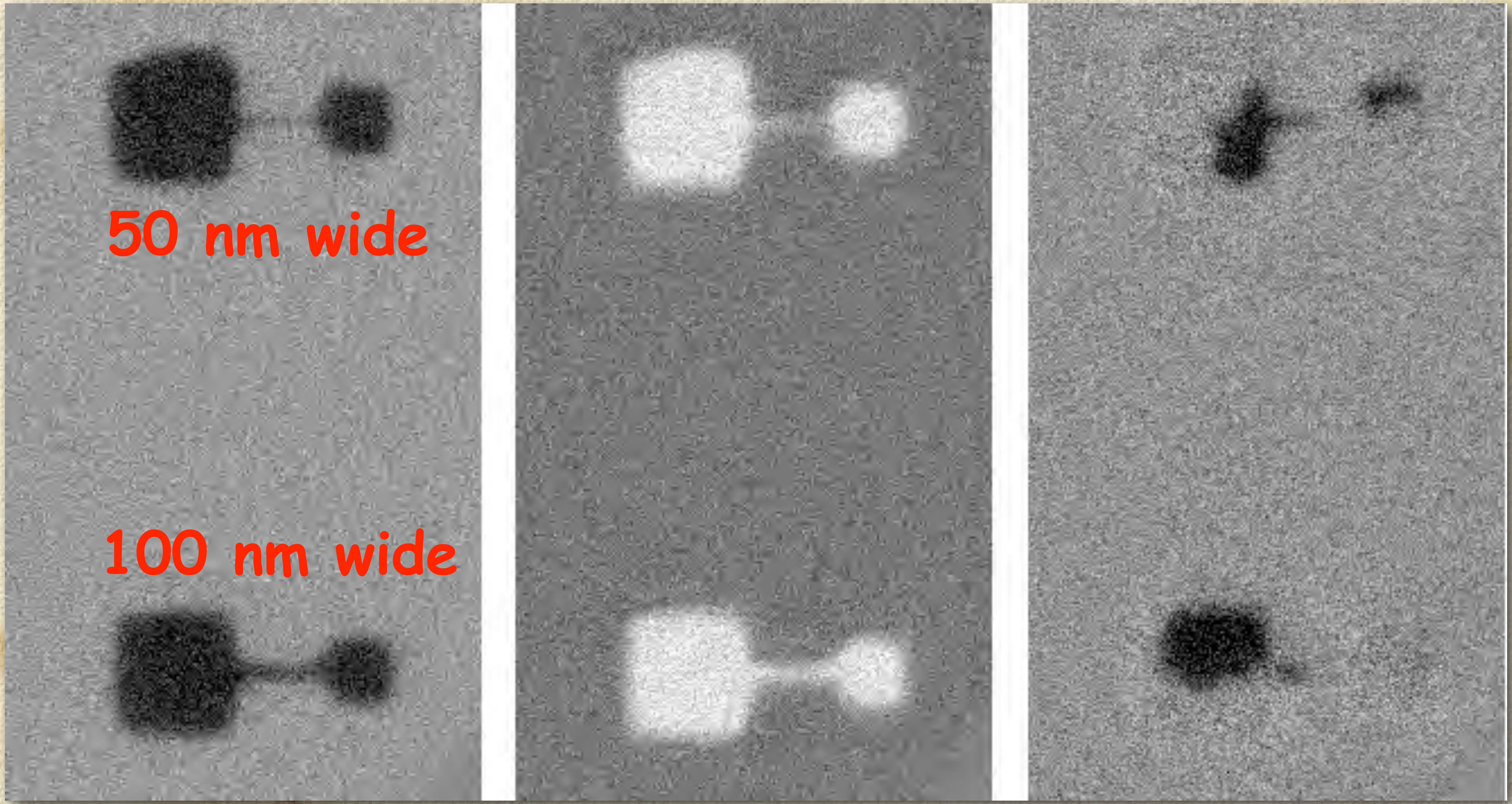
Resolution of Kerr microscopy



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

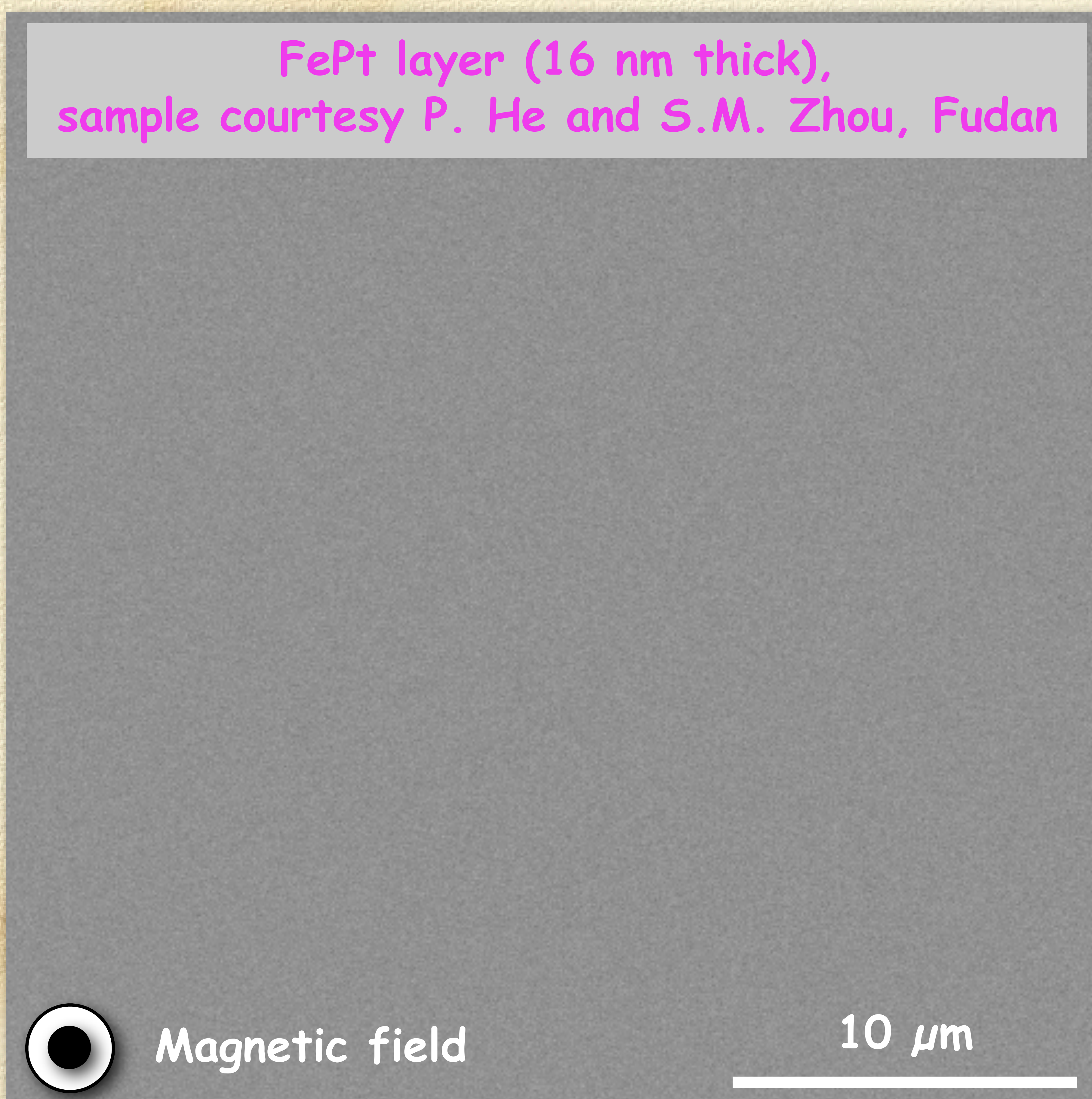
Ultra-high-resolution Kerr microscopy

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

Magnetic field

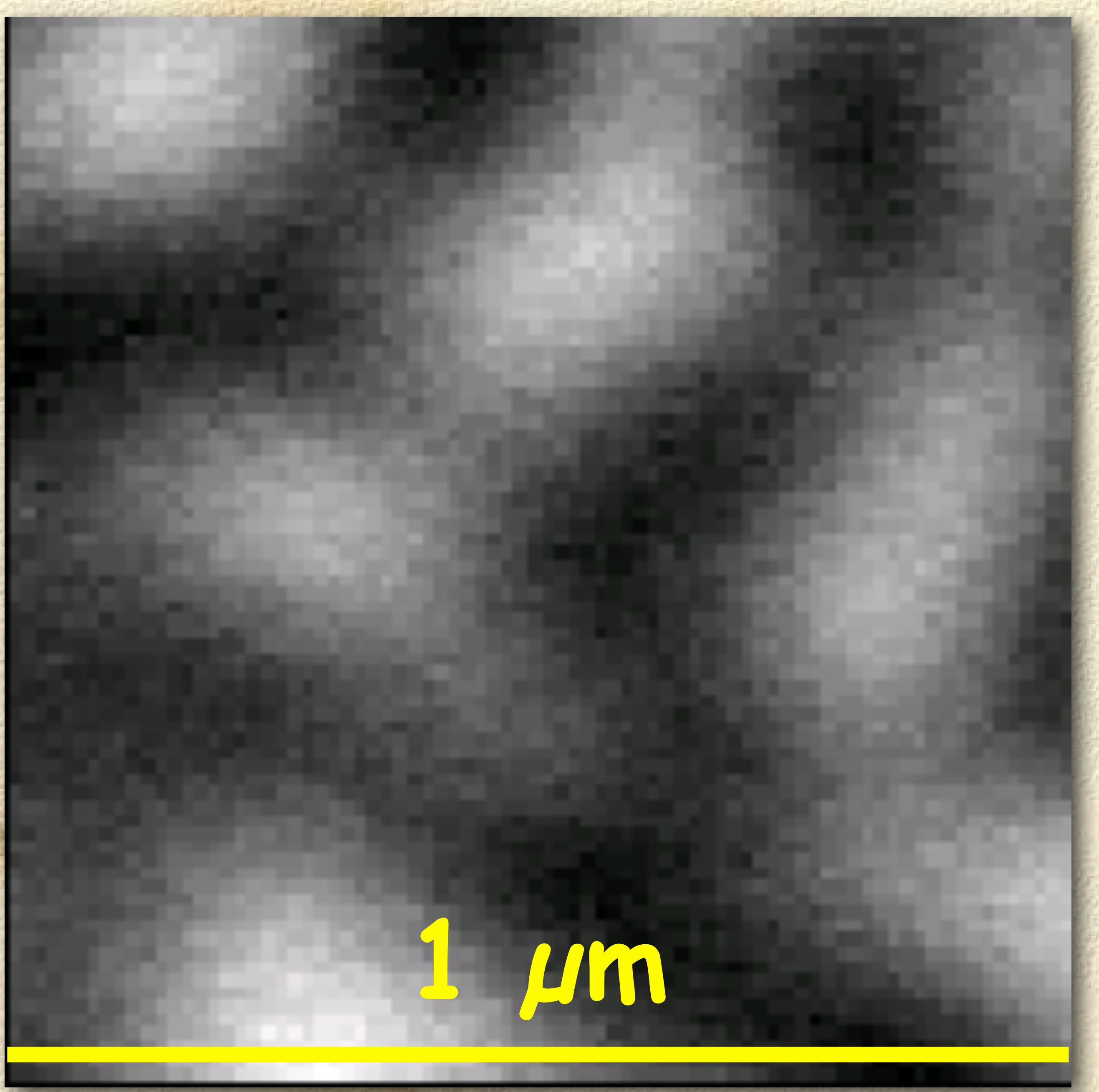
10 µm

Ultra-high-resolution Kerr microscopy



Ultra-high-resolution Kerr microscopy

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



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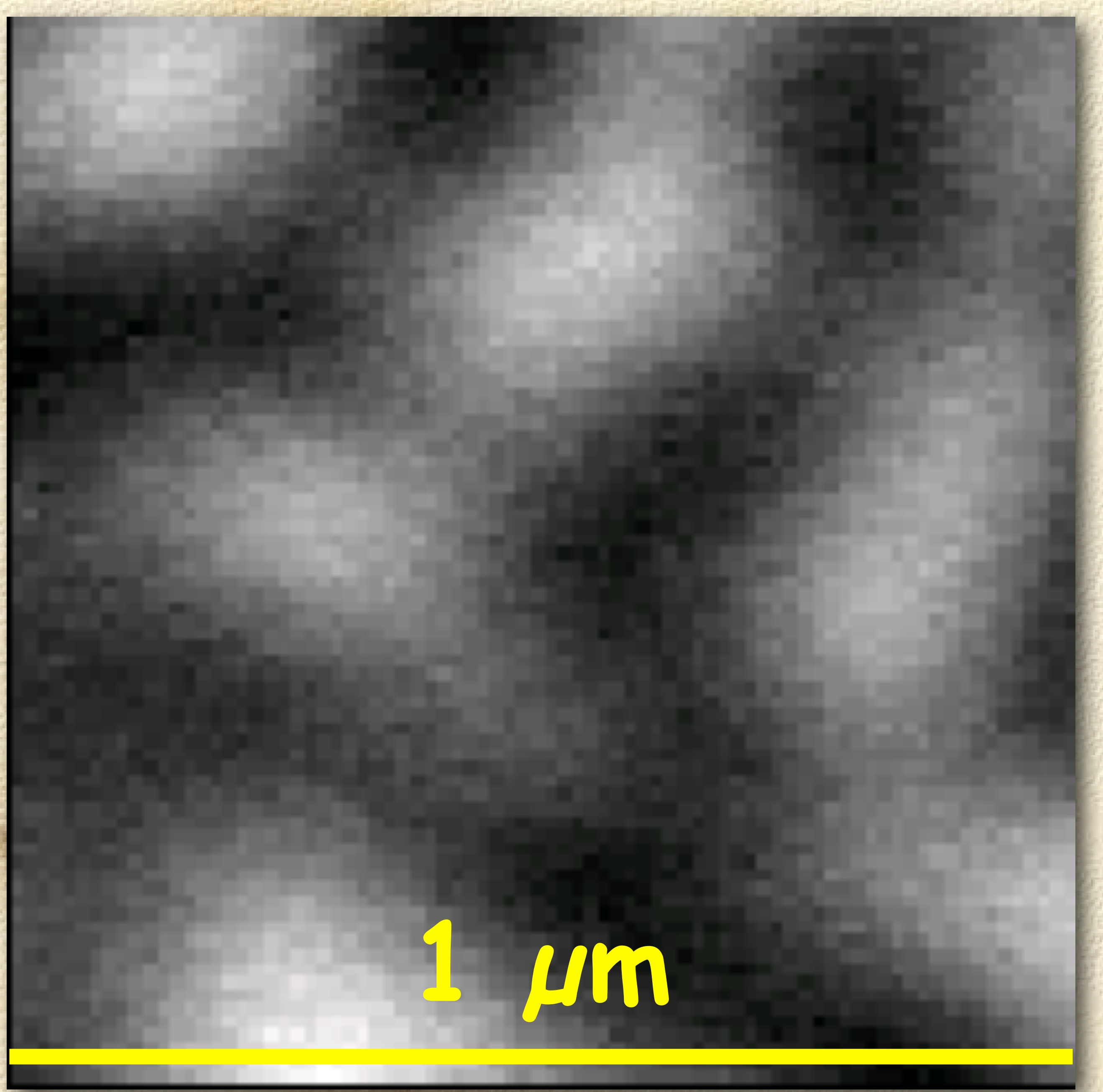

Image is folded by point-spread-function of microscope

→ 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),
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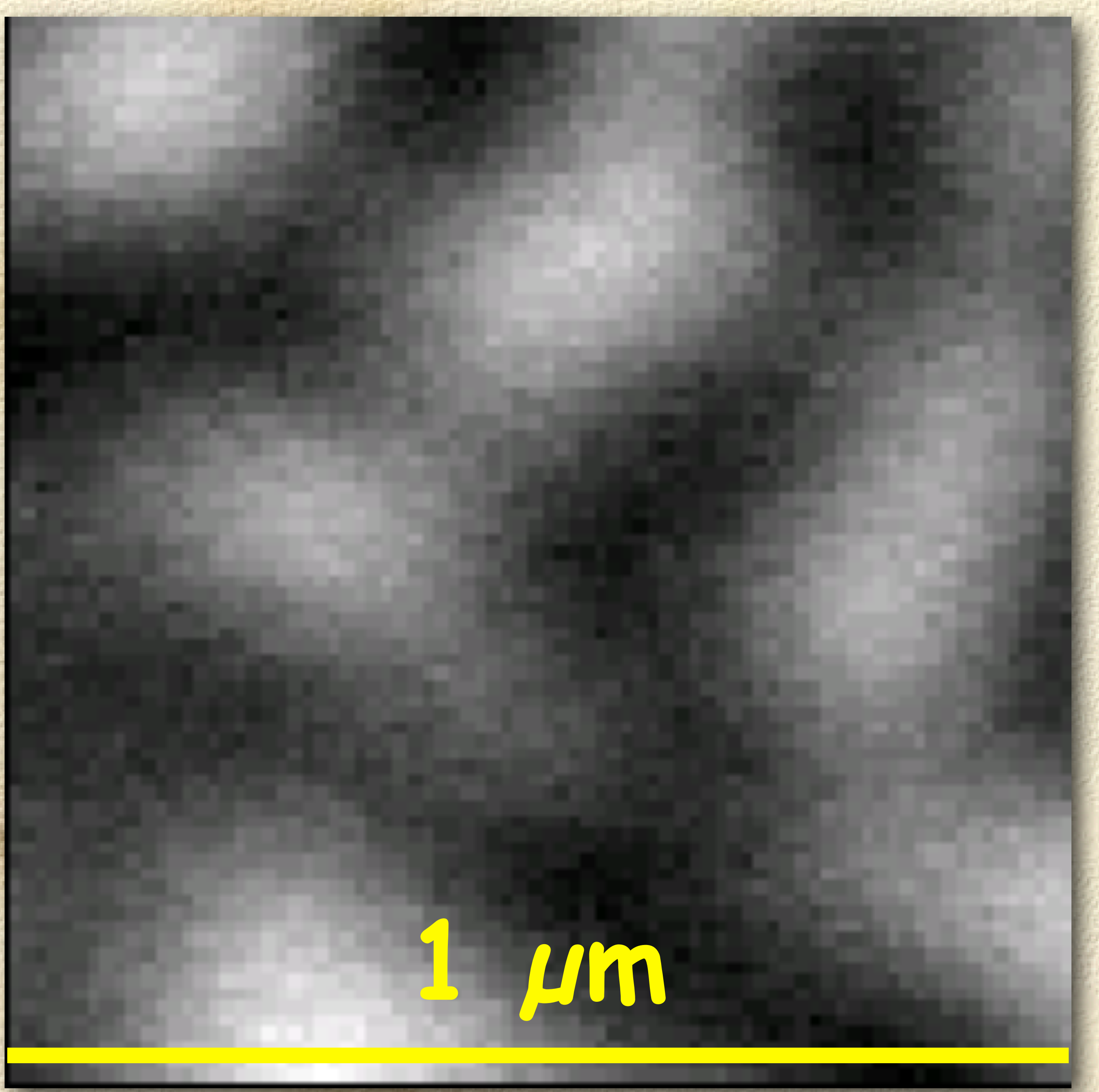

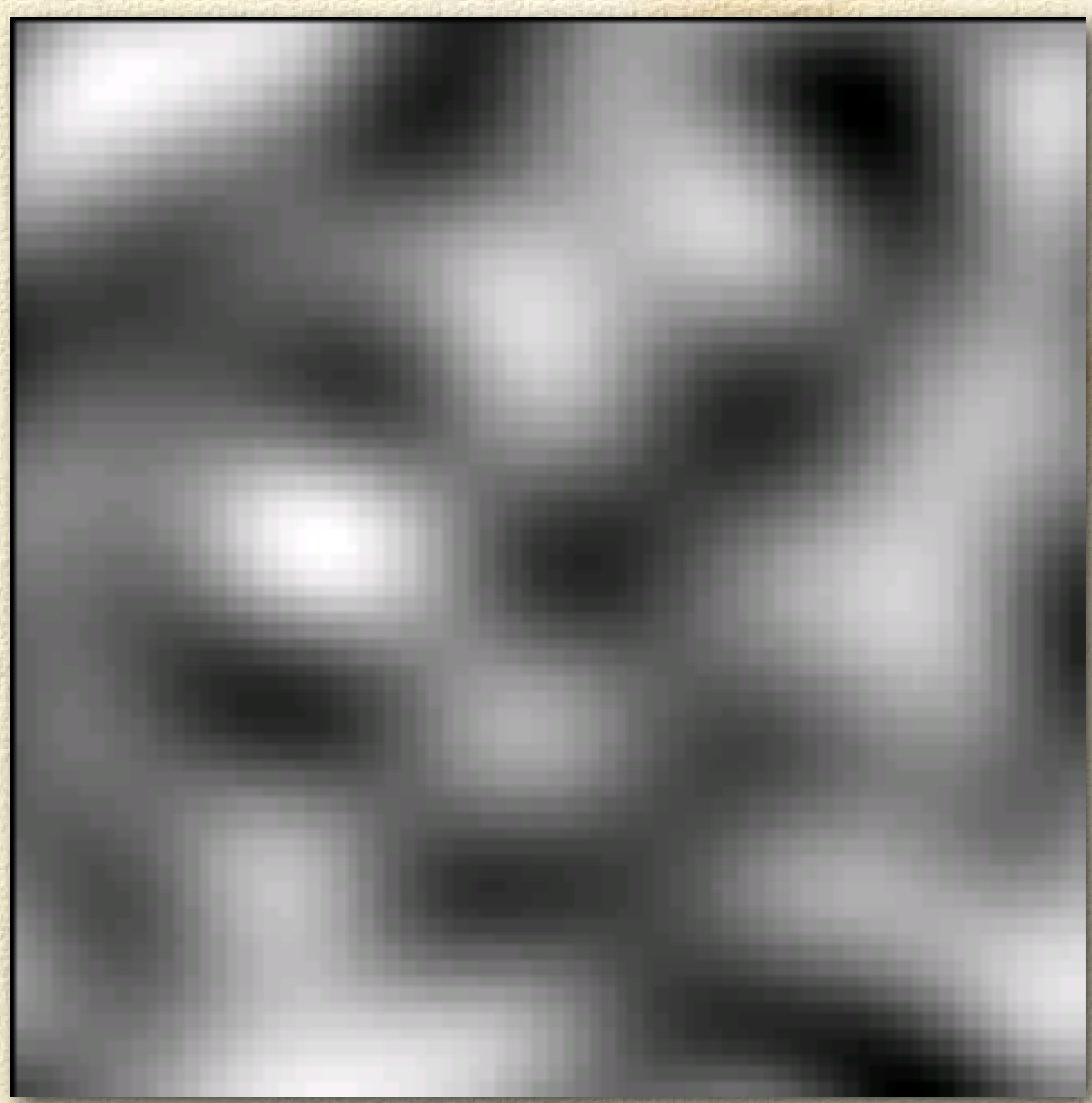

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Ultra-high-resolution Kerr microscopy

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

Magnetic field

10 µm

Ultra-high-resolution Kerr microscopy

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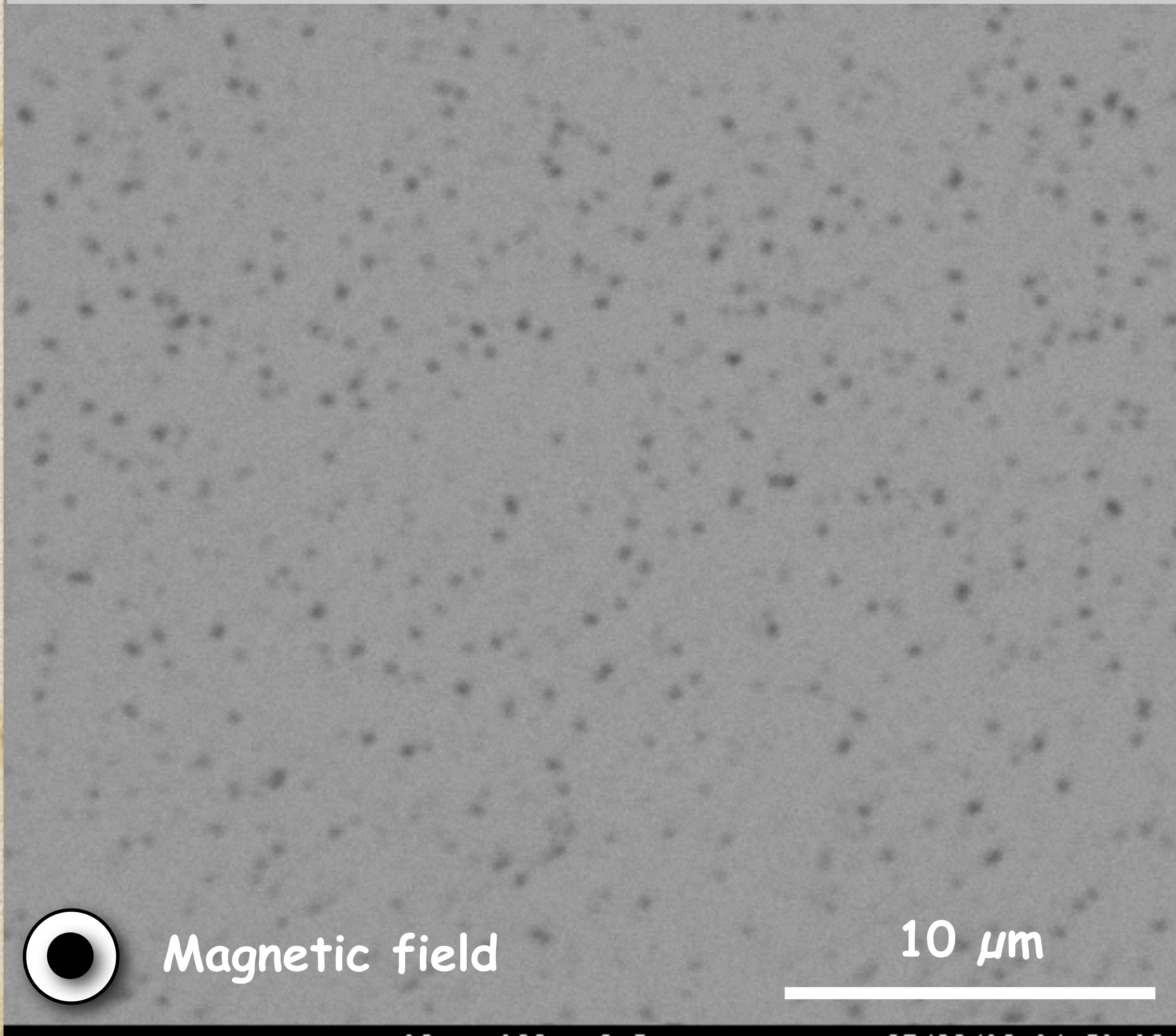

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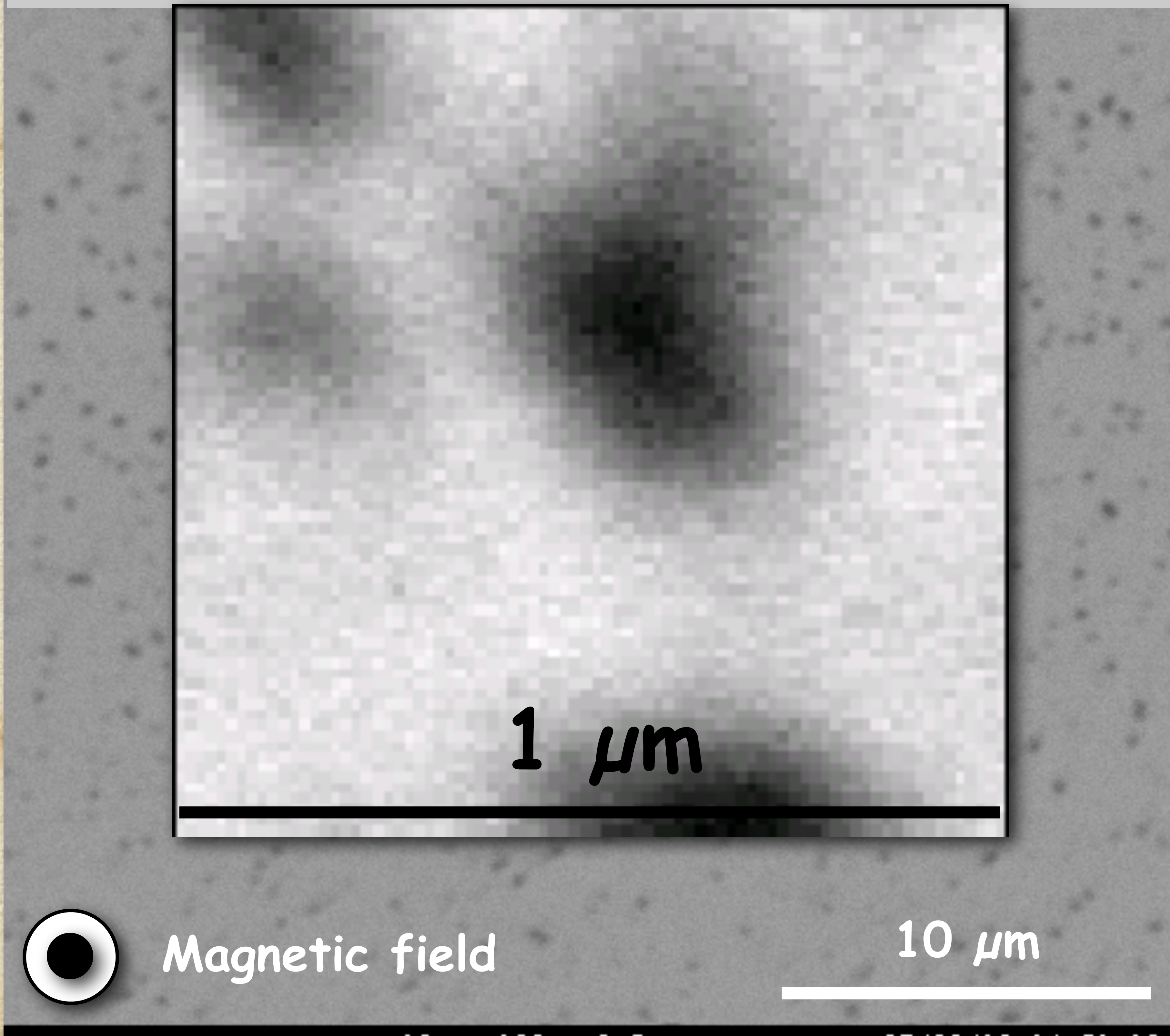

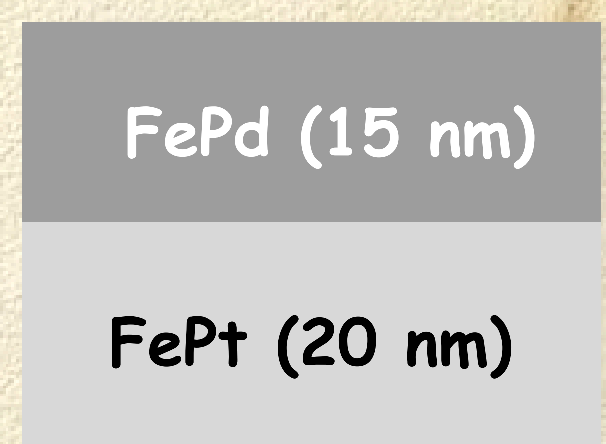

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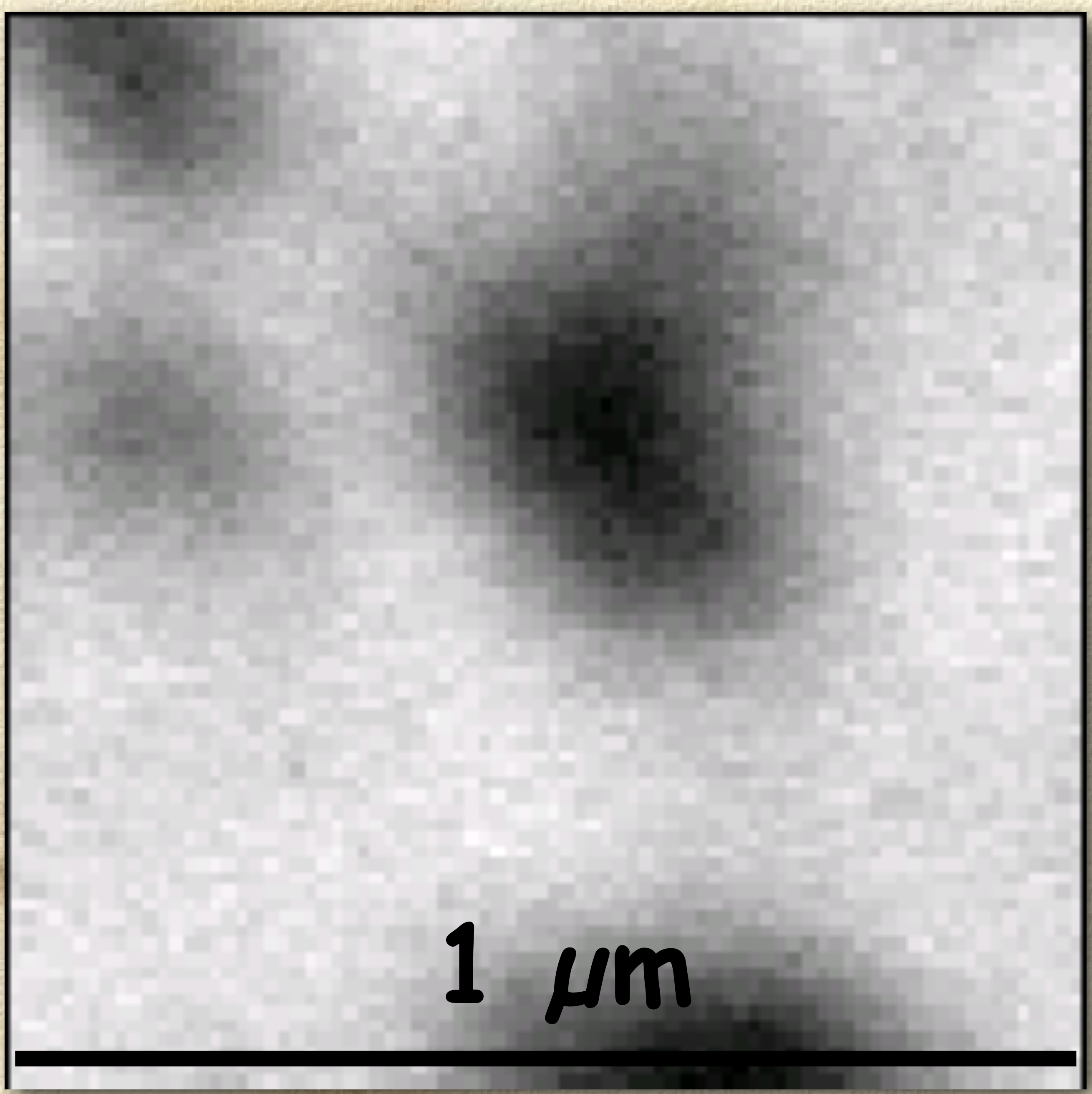
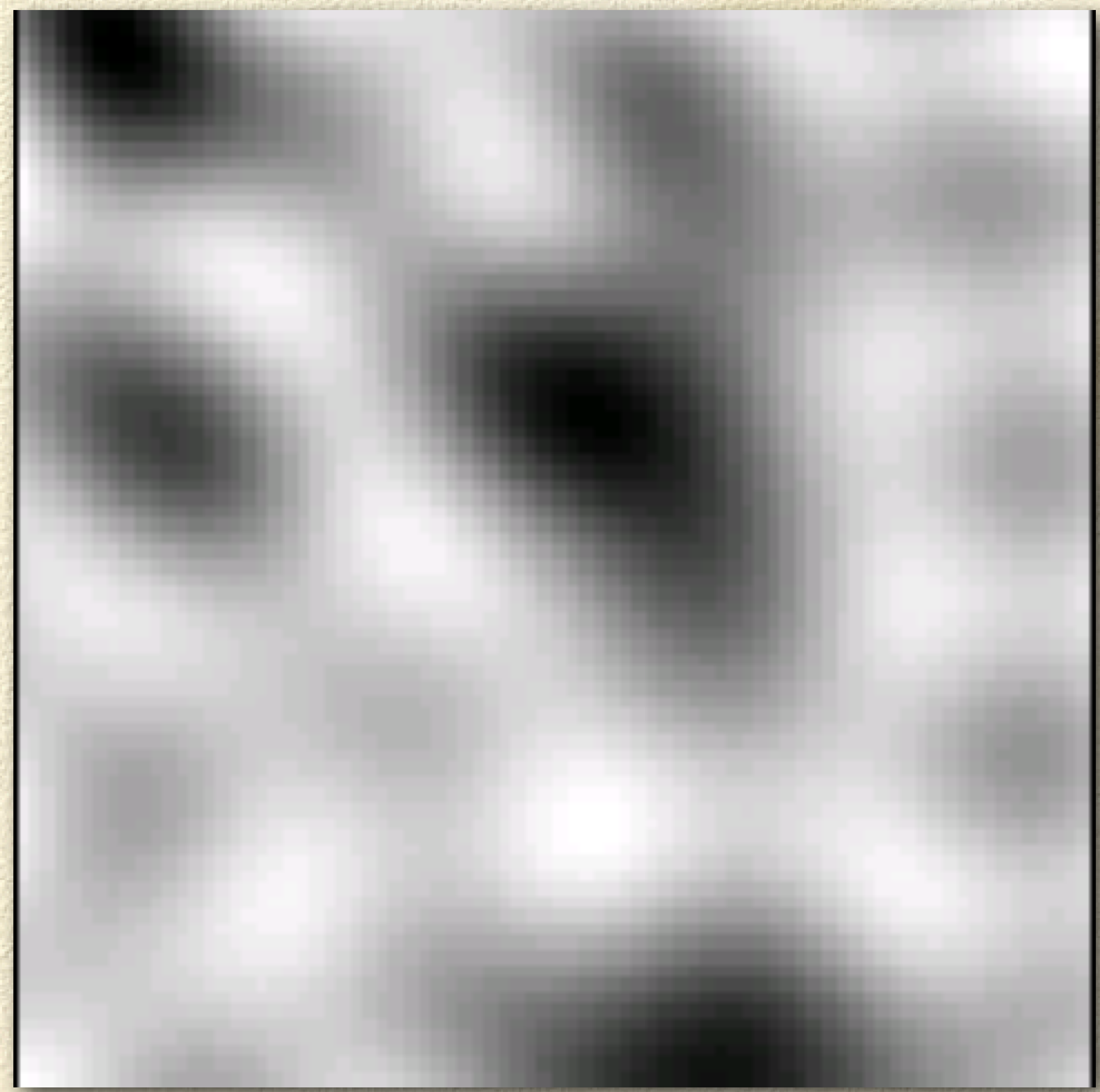
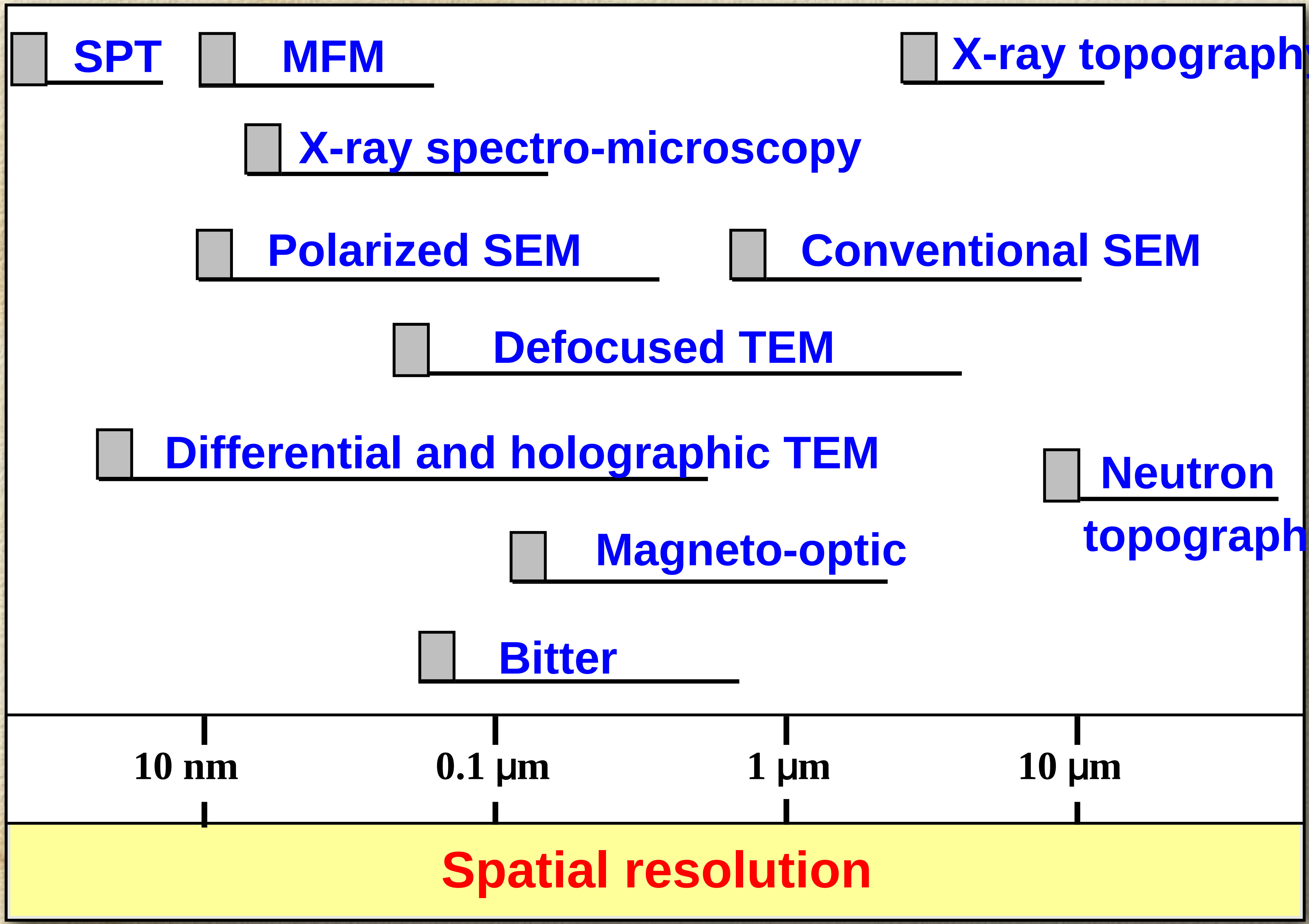




together with
N. Gorn & D.Berkov, Innovent Jena
(under development)

Comparison of Domain Obervation Techniques



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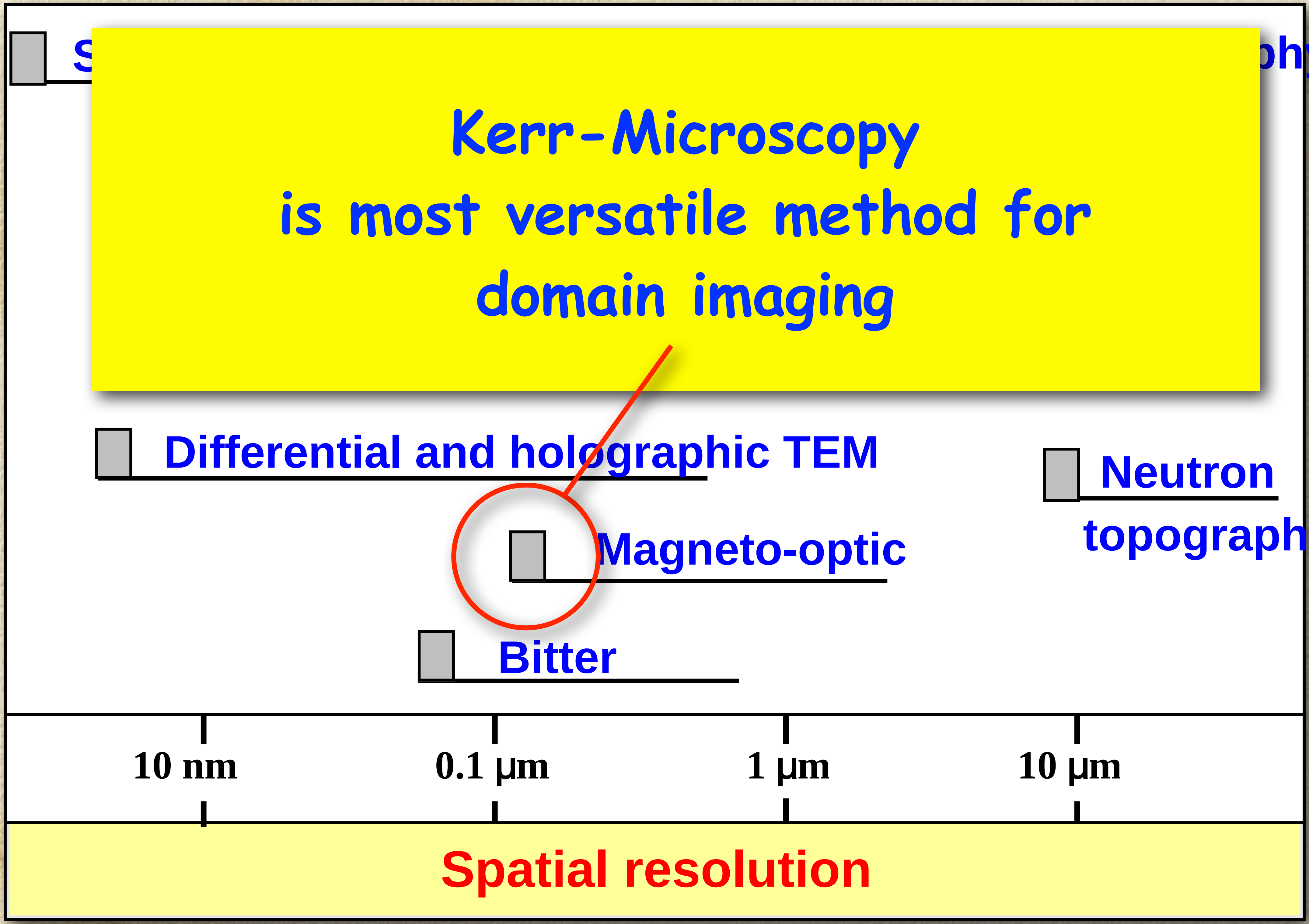
Comparison of Domain Obervation Techniques



MFM: Magnetic Force Microscopy
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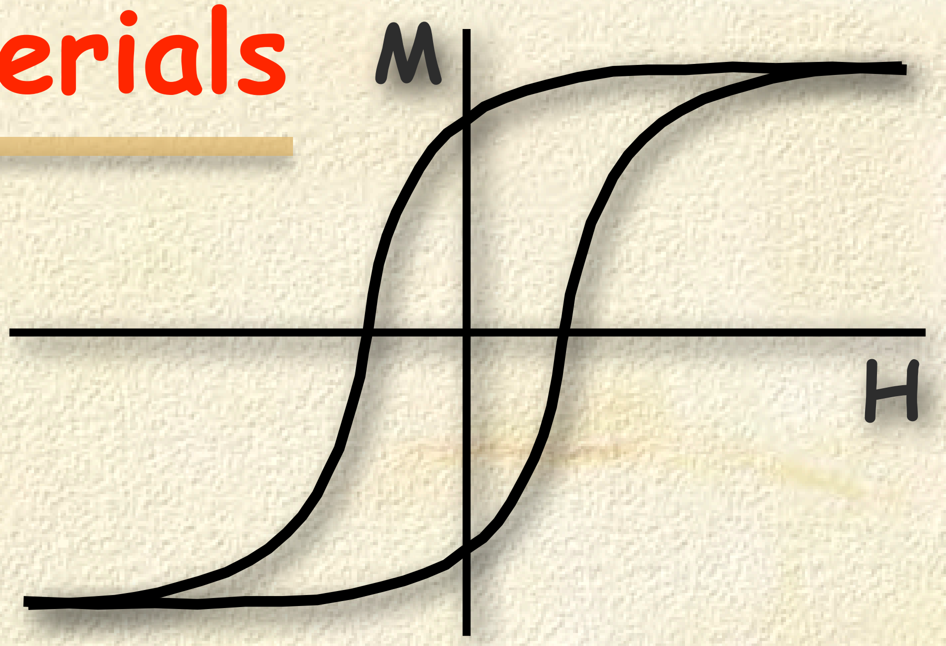
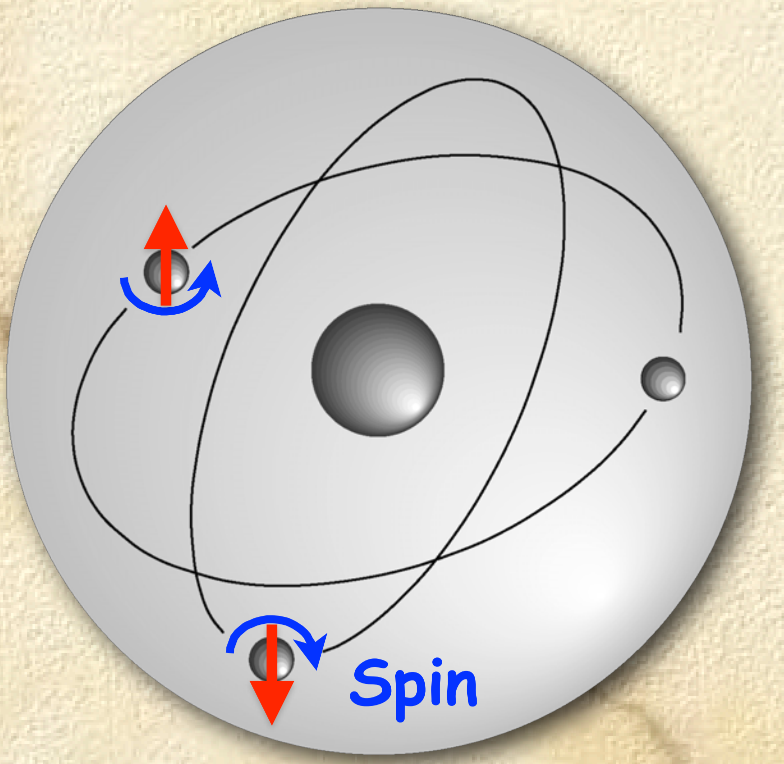
Why magnetic microstructure analysis?

Descriptive levels of magn. materials



5. Magnetization curve

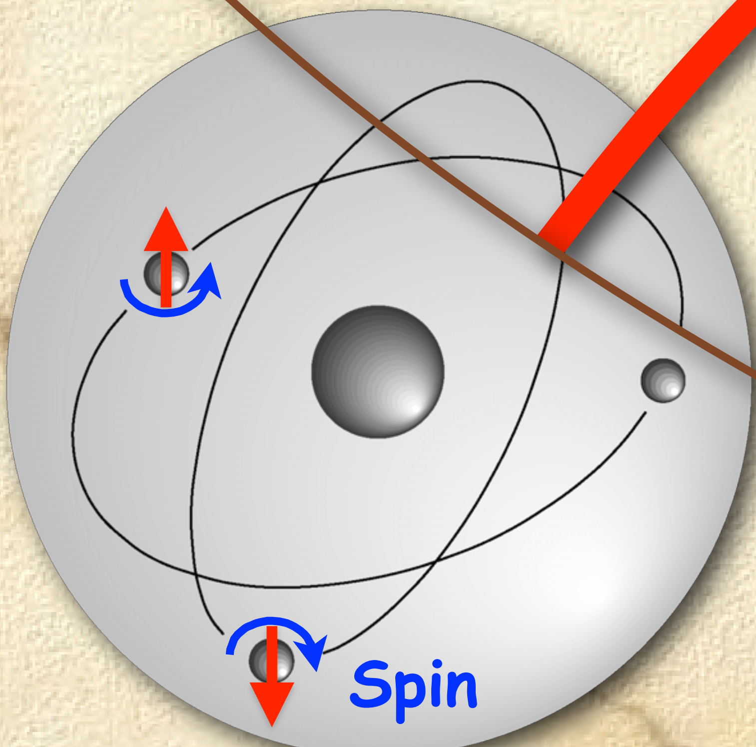


1. Atomic Level Theory

Descriptive levels of magn. materials

5. Magnetization curve

Magnetic Microstructure Analysis



1. Atomic Level Theory

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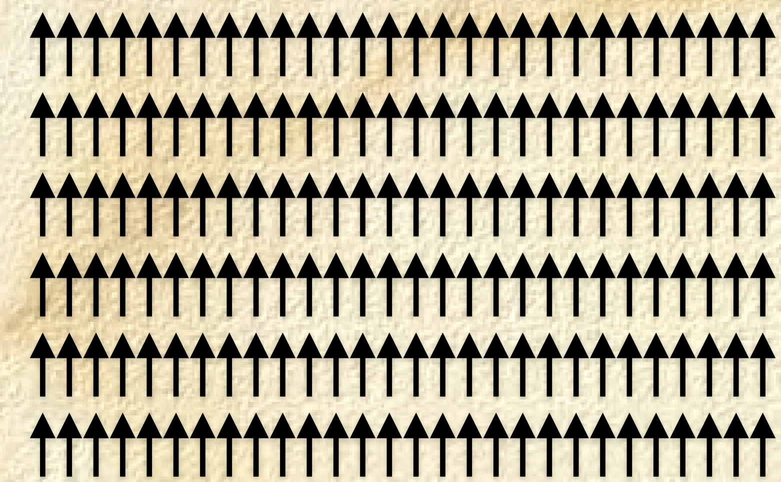

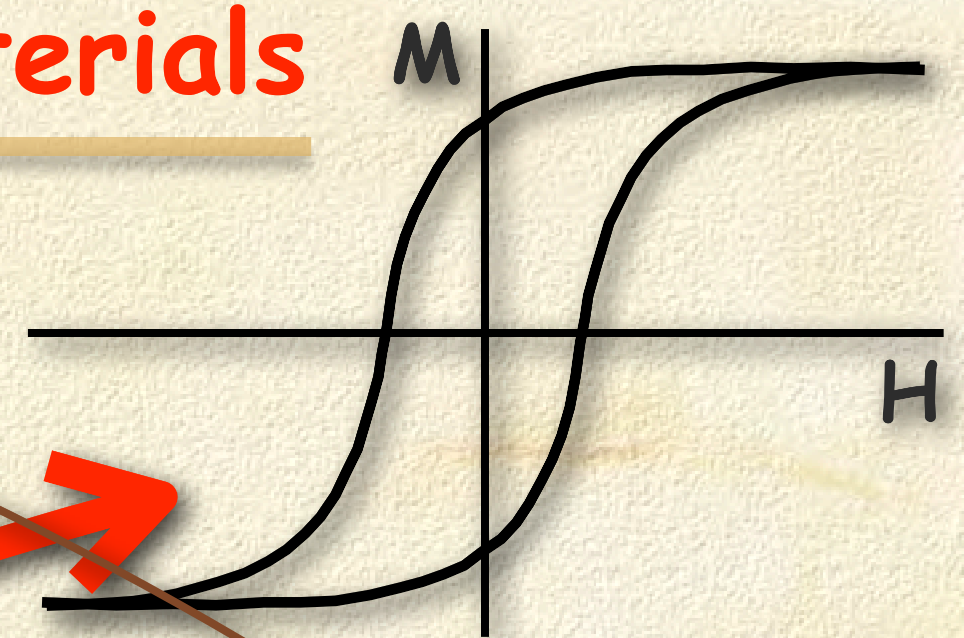

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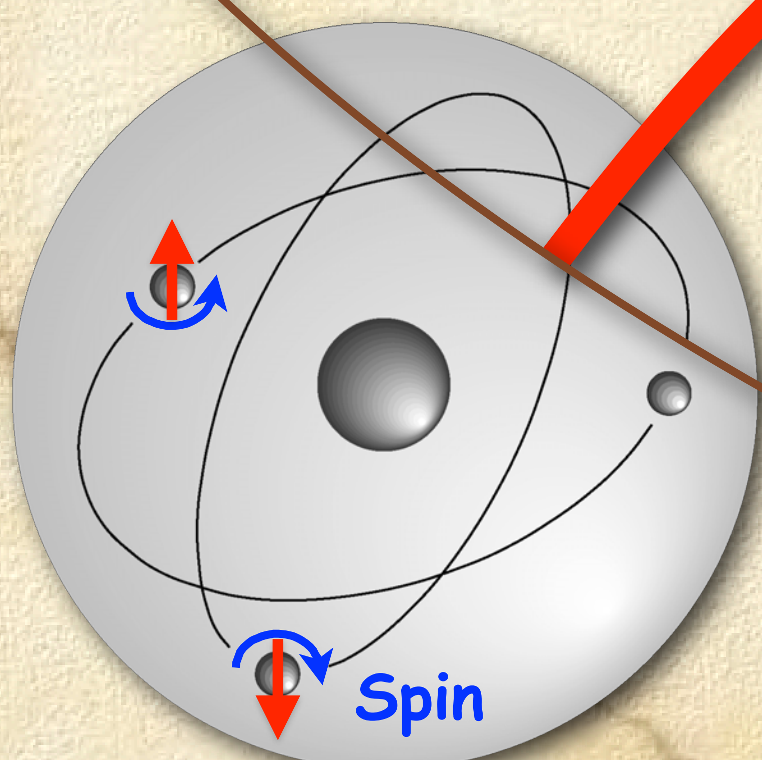
Magnetic Microstructure Analysis



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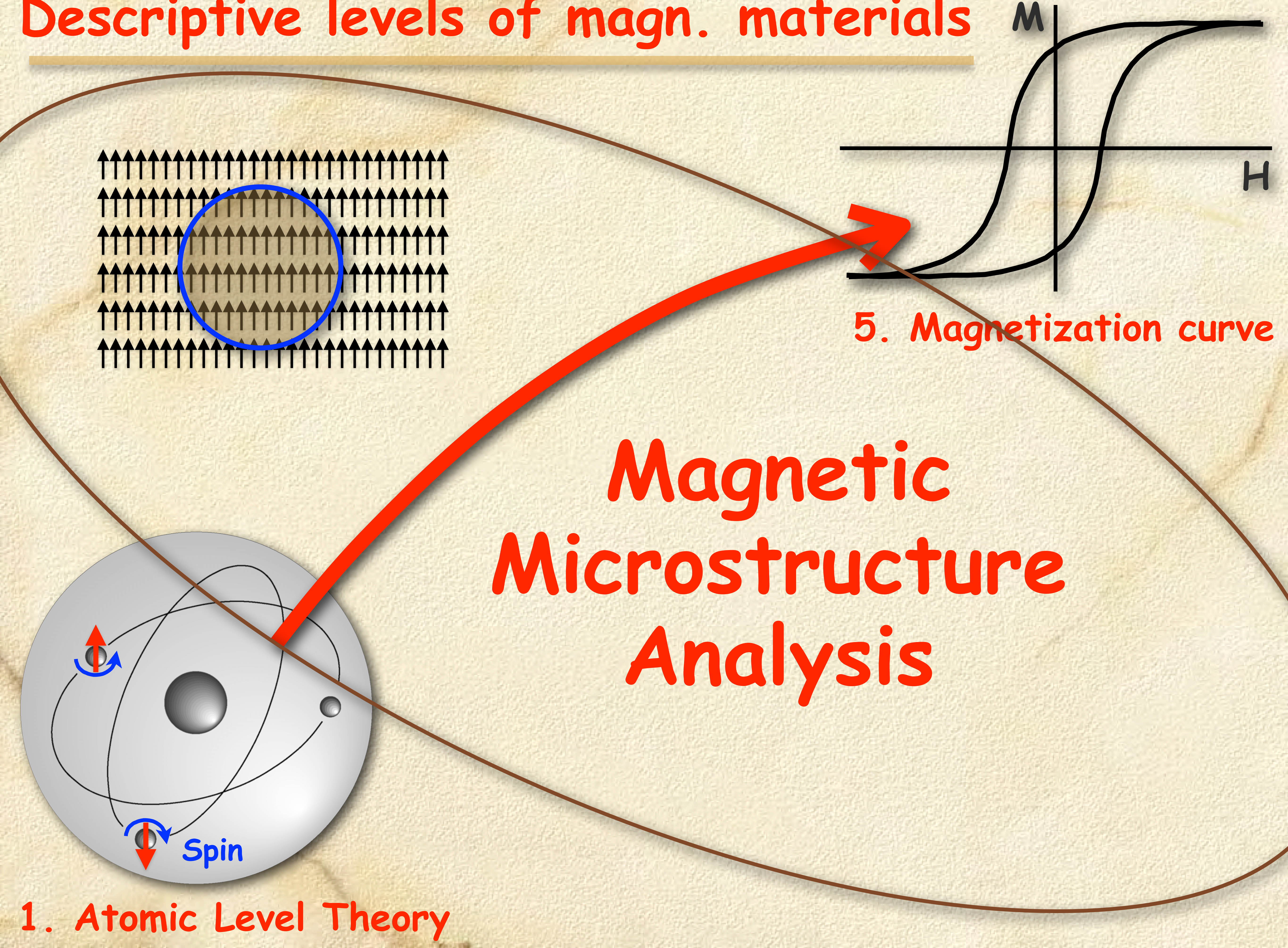

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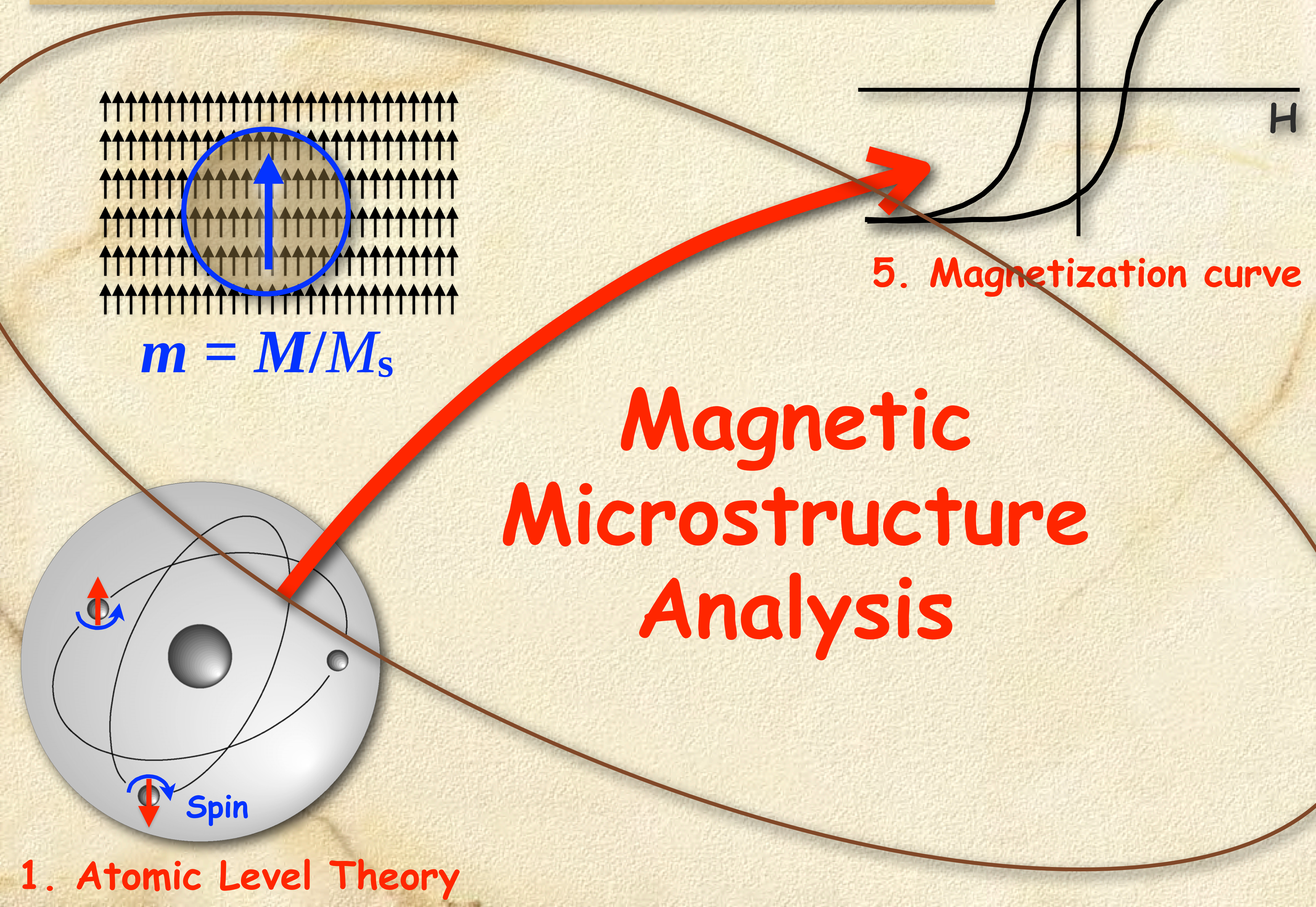

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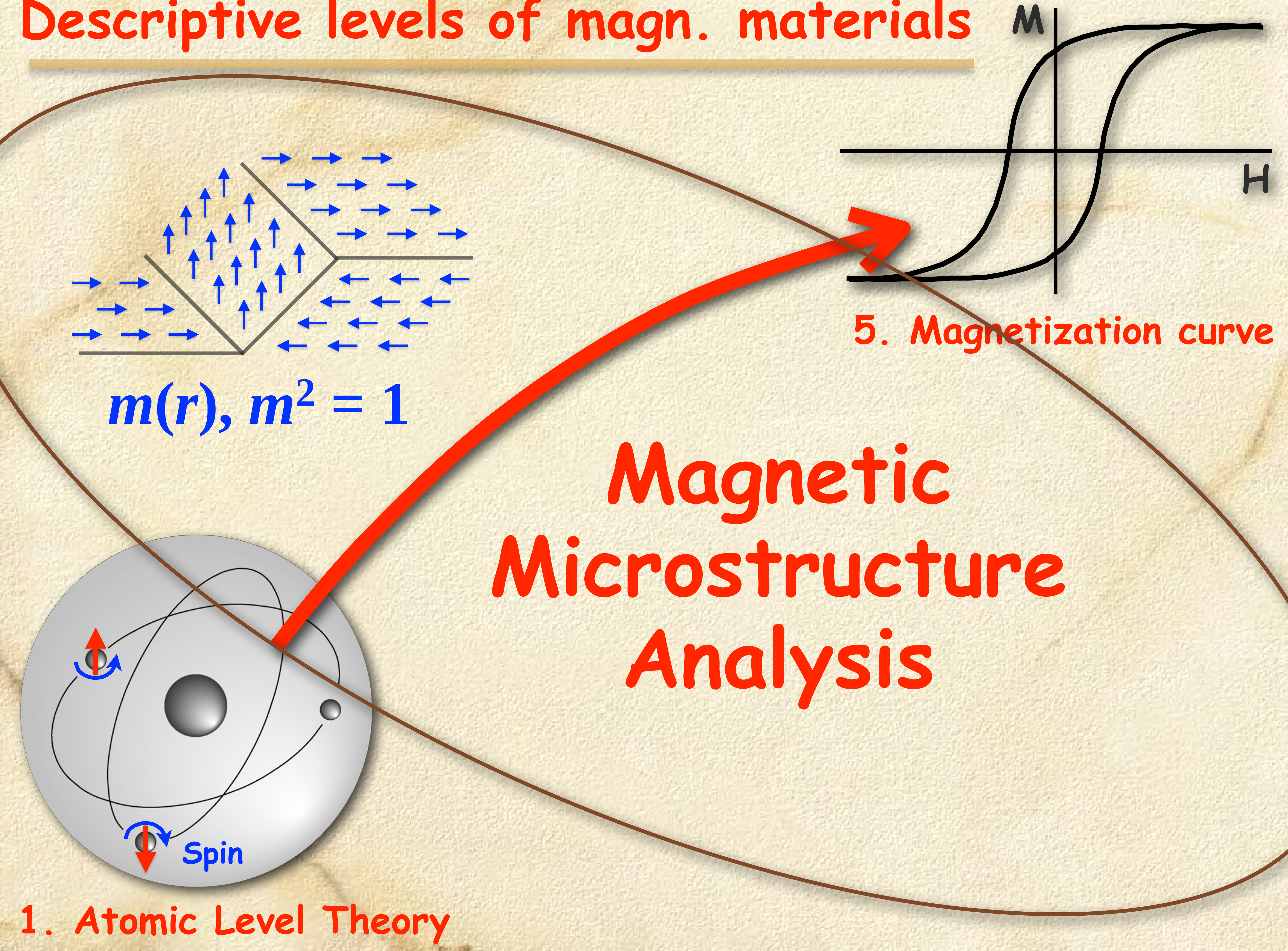

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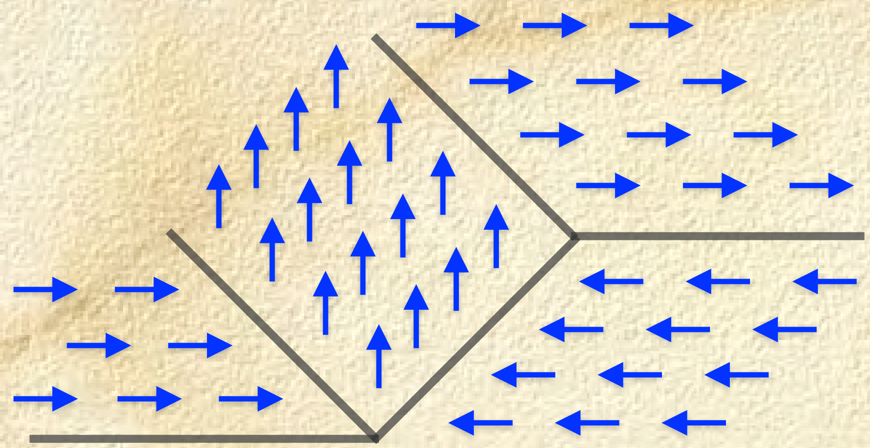
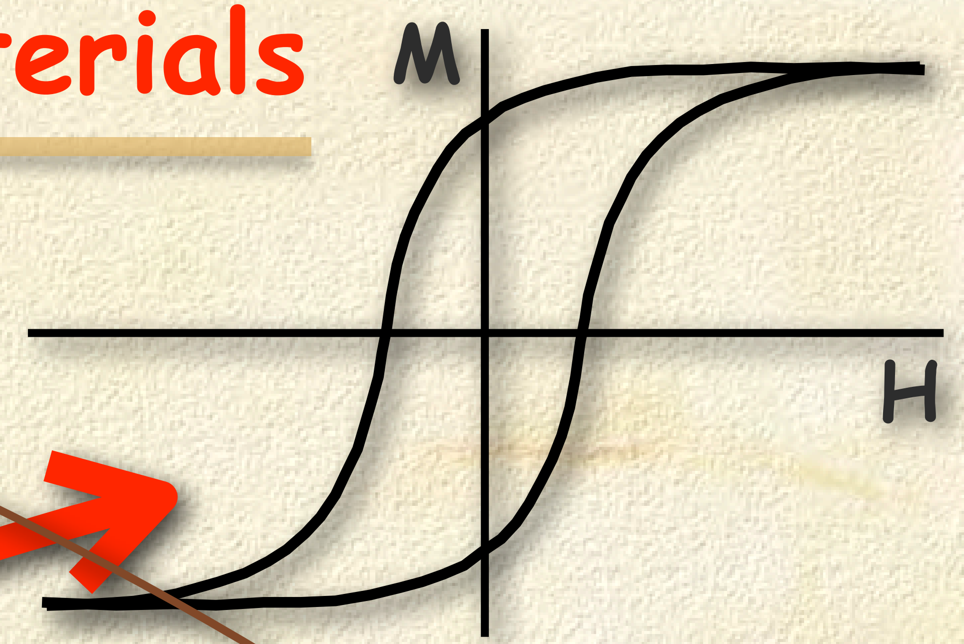


$$\mathbf{m}(\mathbf{r}),\ \mathbf{m}^2 = 1$$



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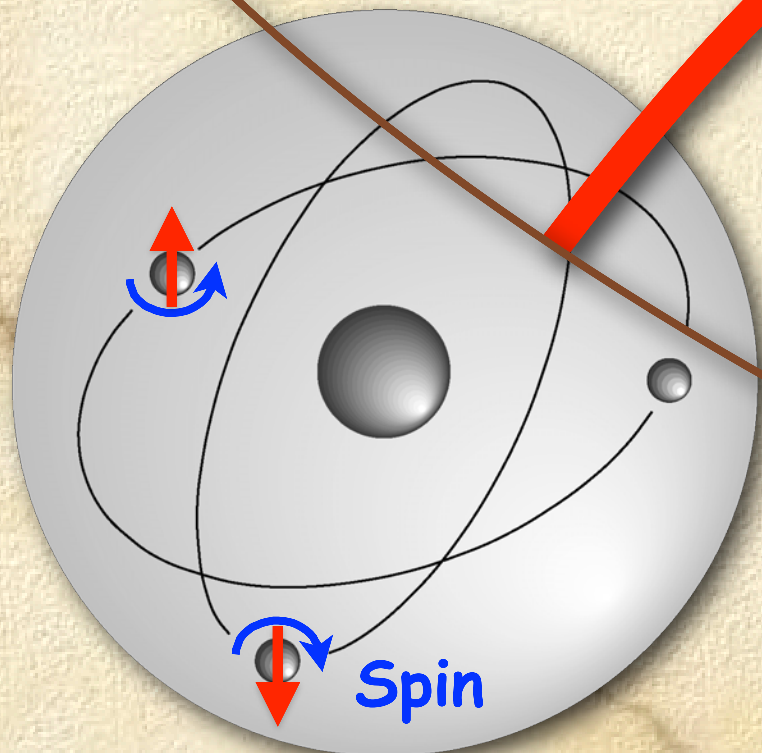
Magnetic Microstructure Analysis



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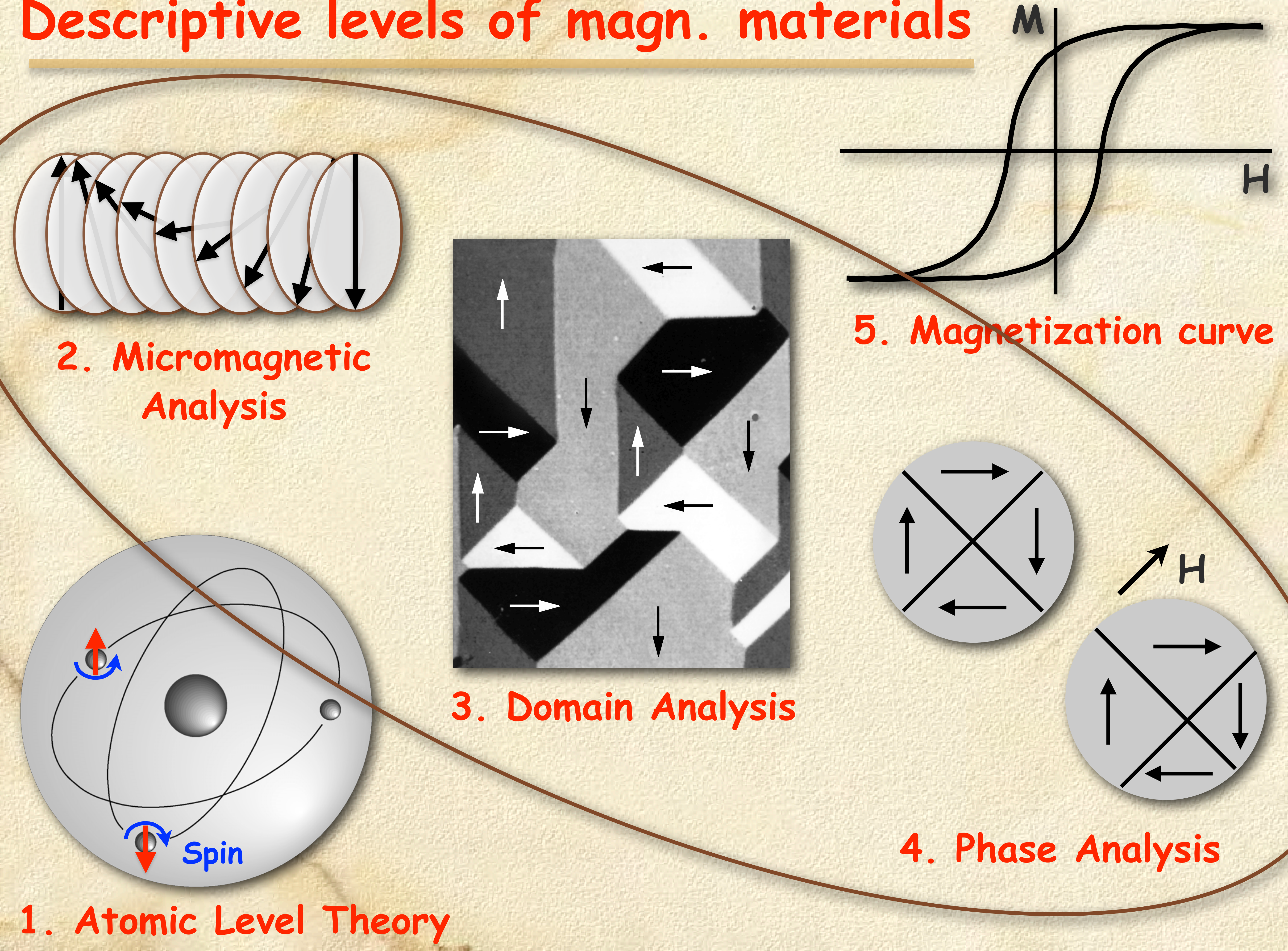
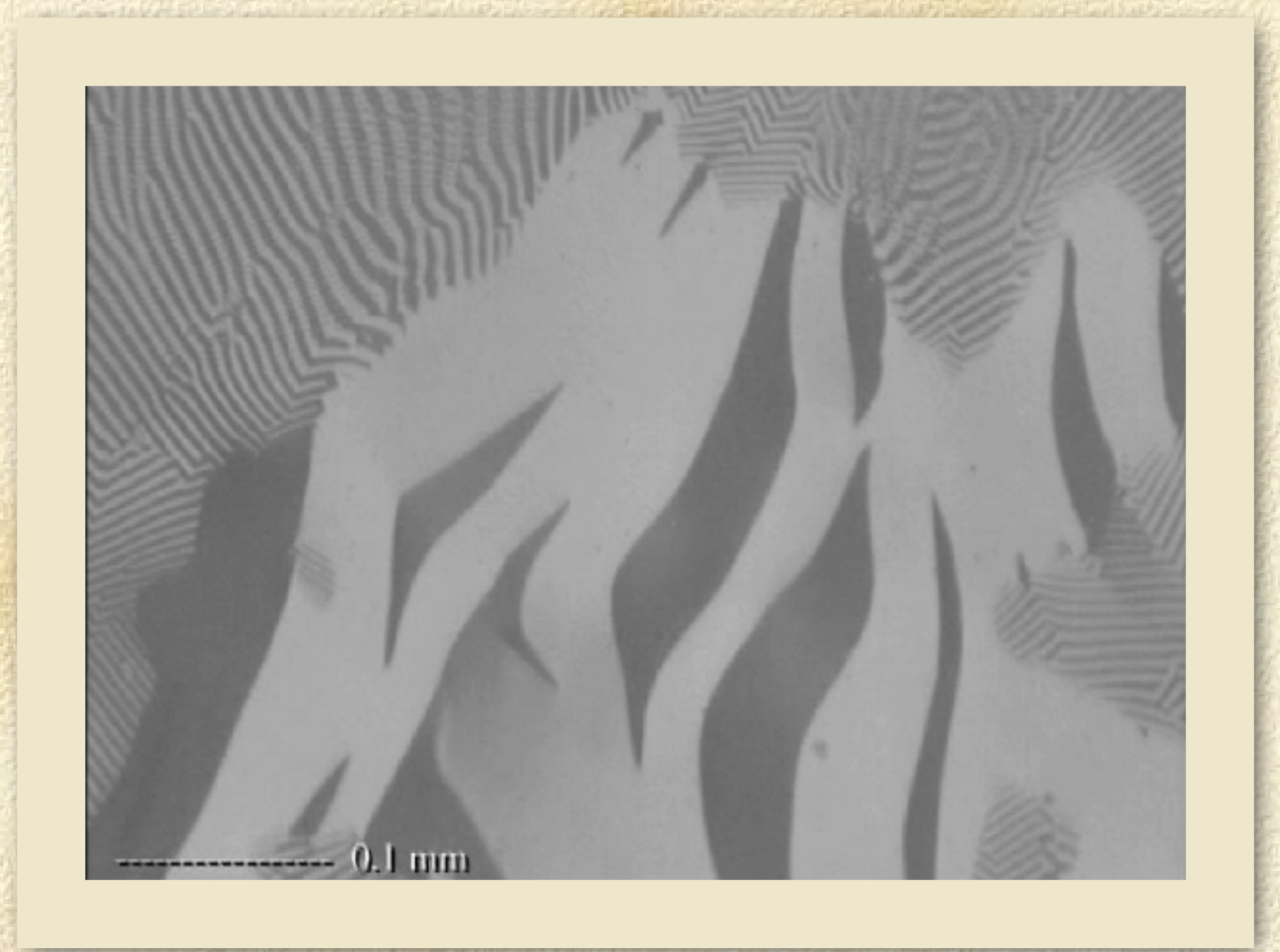
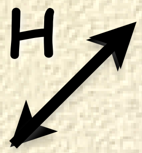
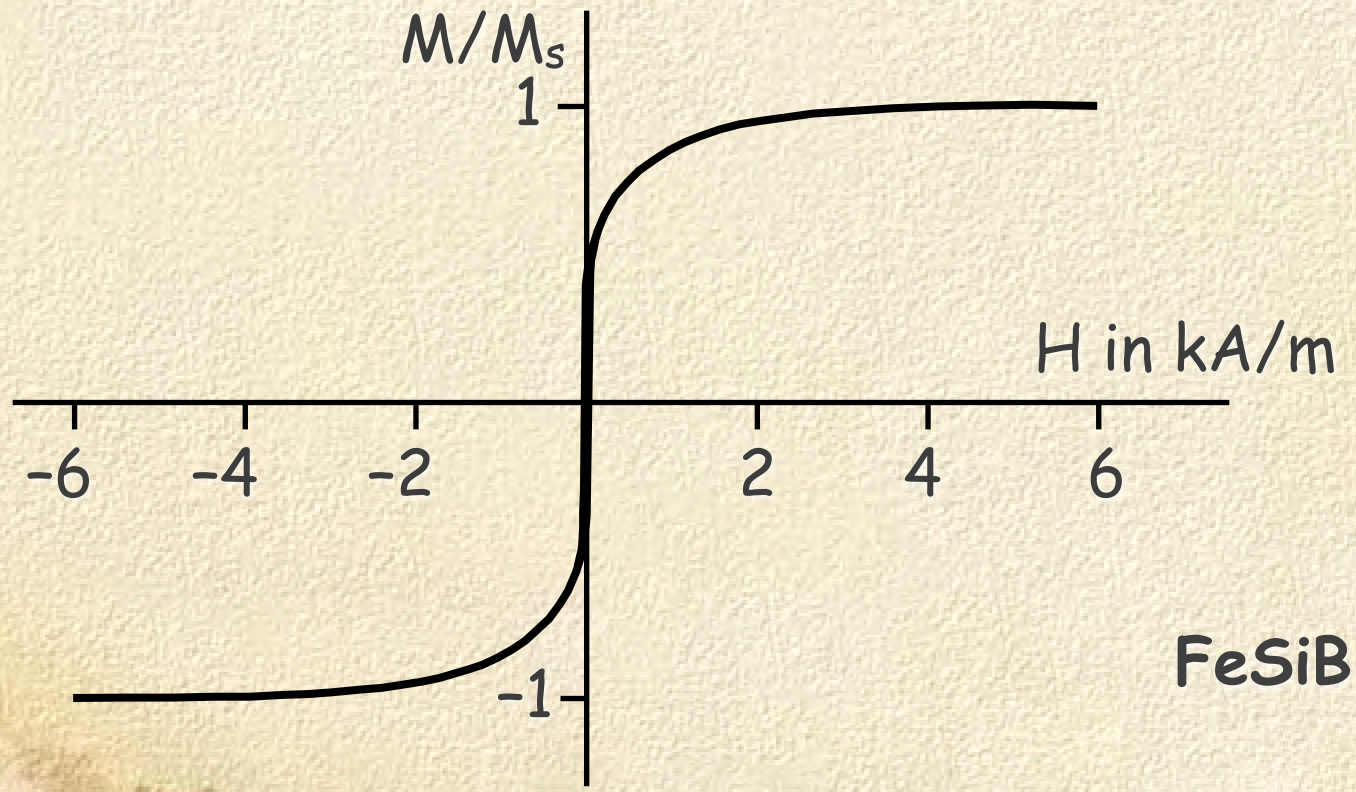
Descriptive levels of magn. materials



M(H) loop and domains

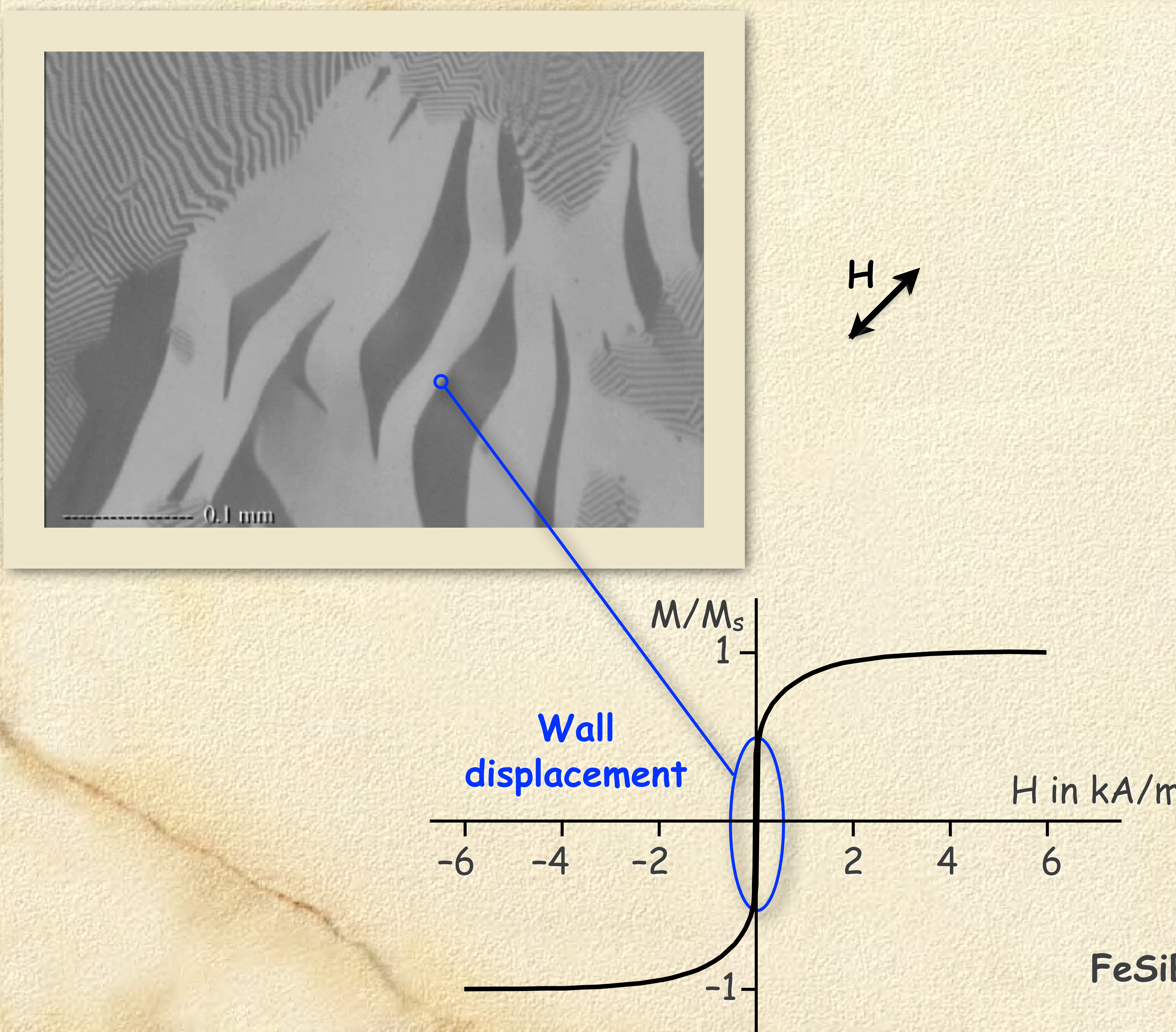






FeSiB amorphous ribbon
(rapidly quenched)

M(H) loop and domains



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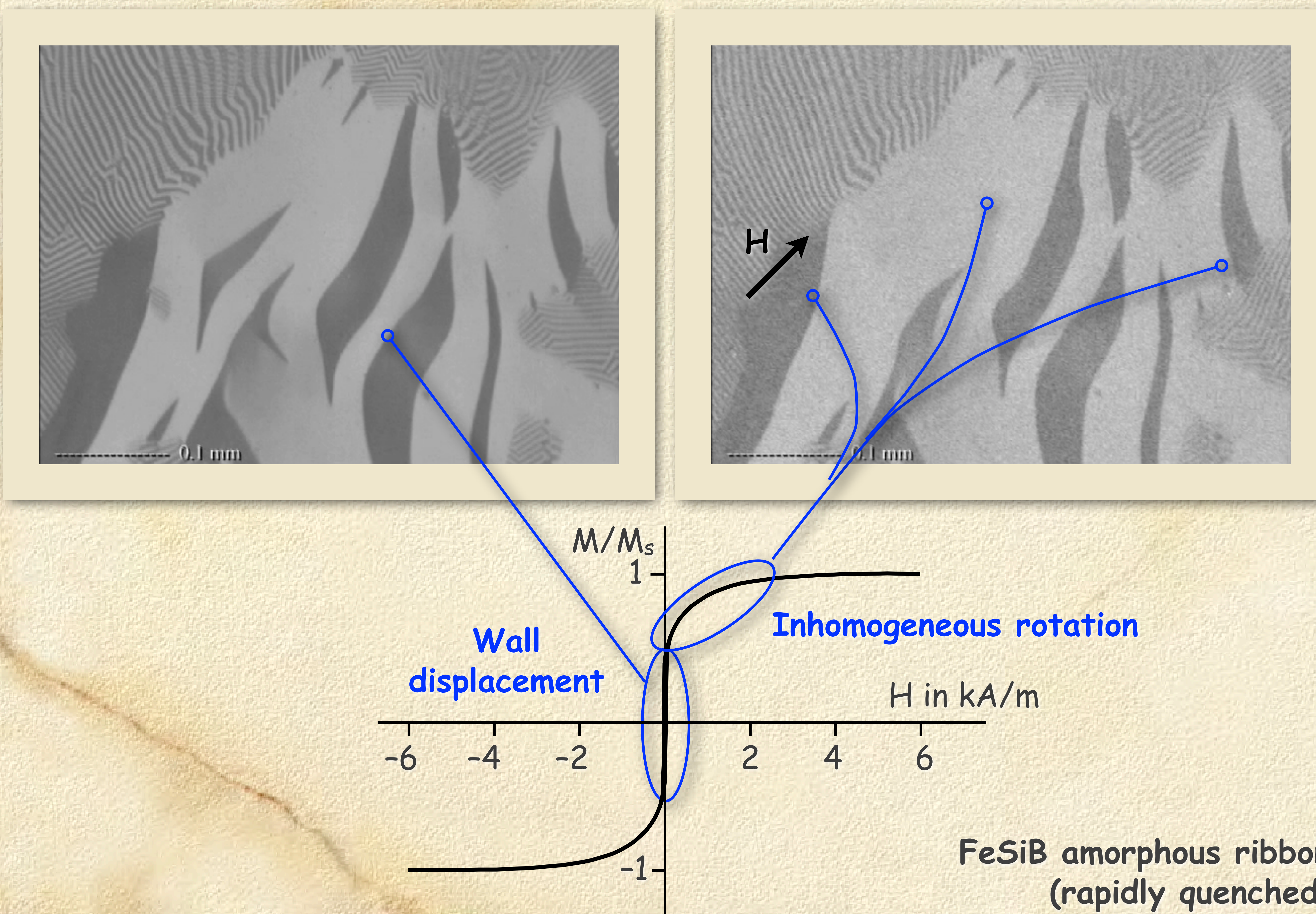

FeSiB amorphous ribbon
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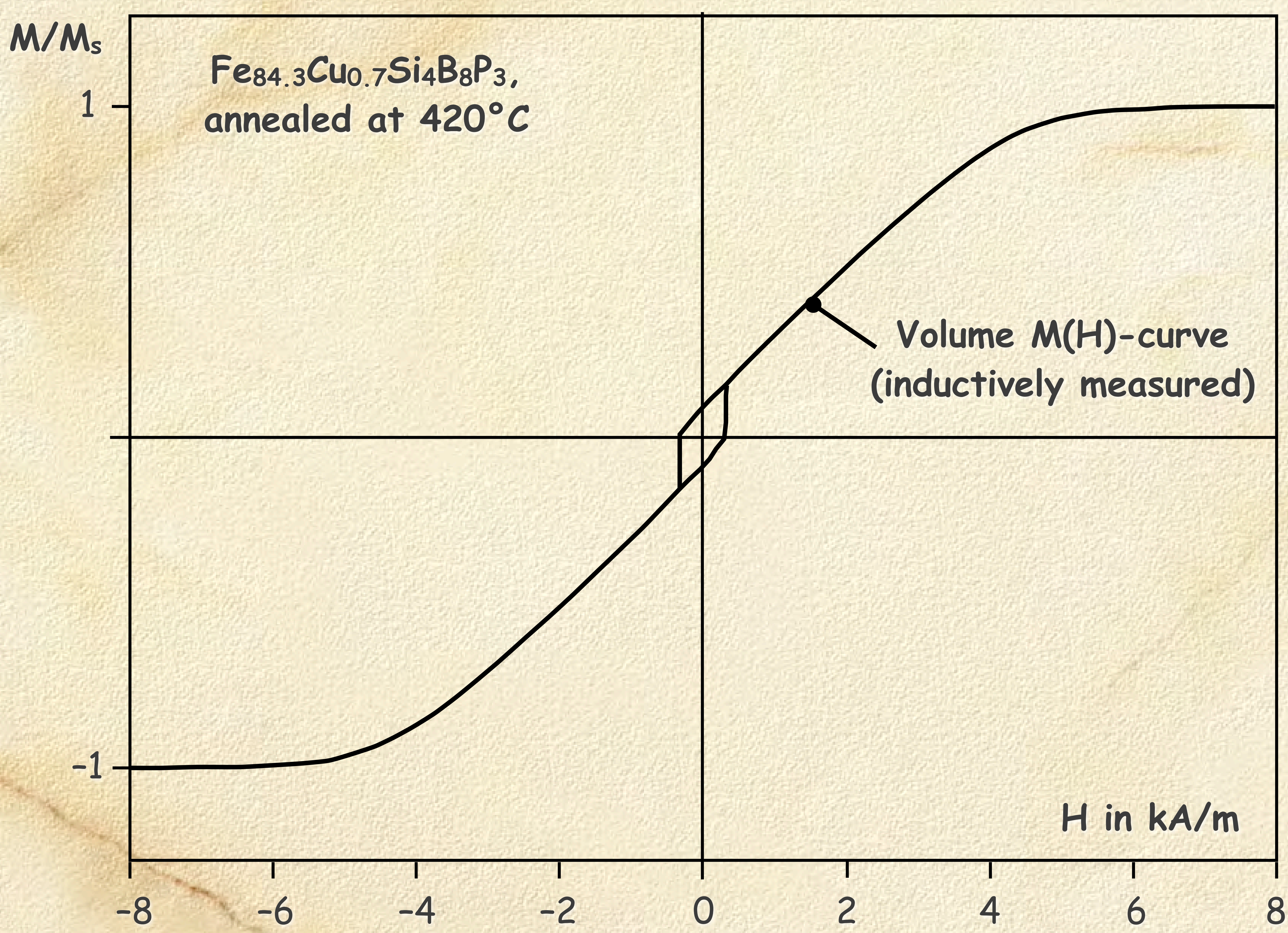
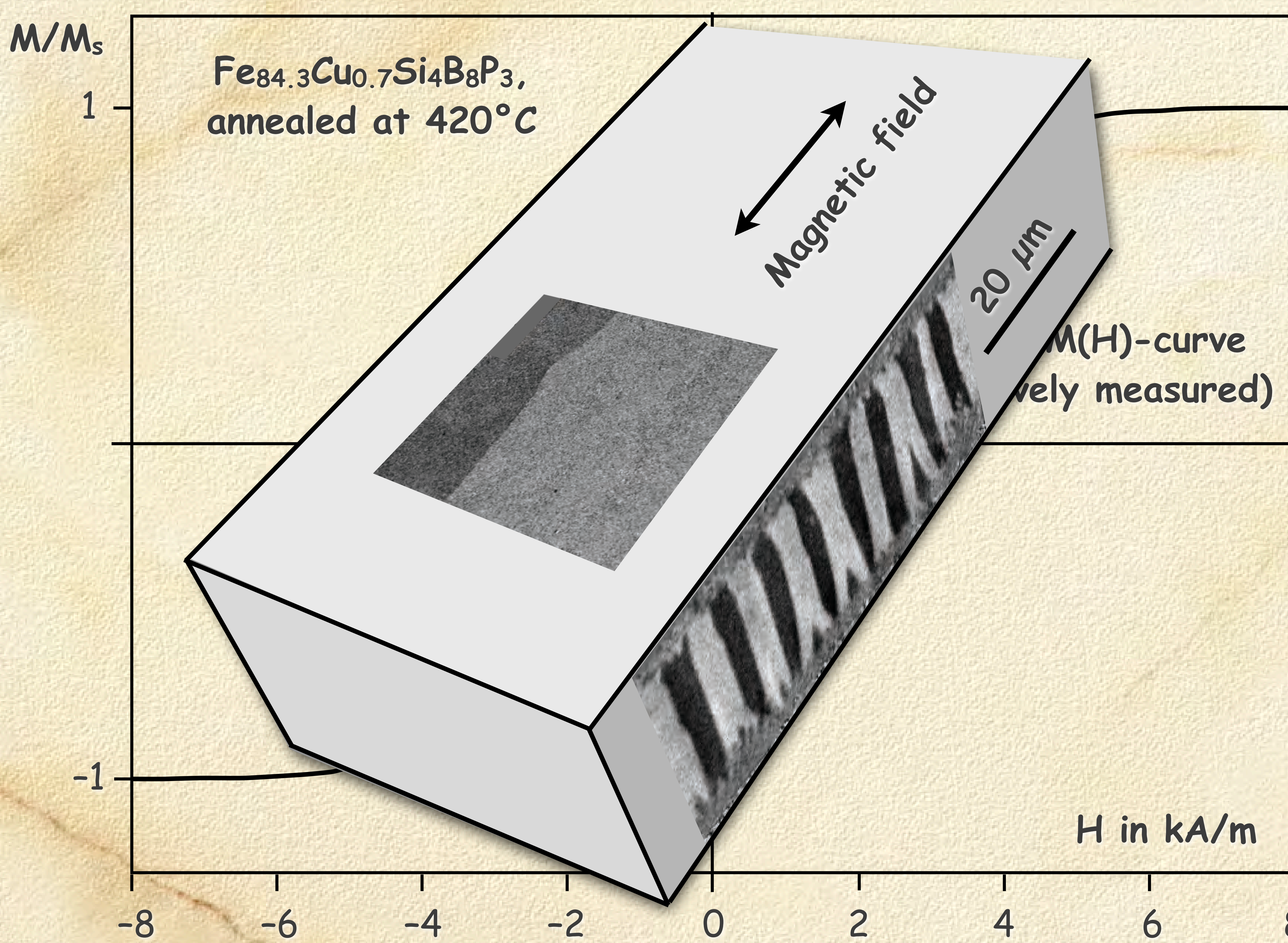
Amorphous ribbon



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

Amorphous ribbon



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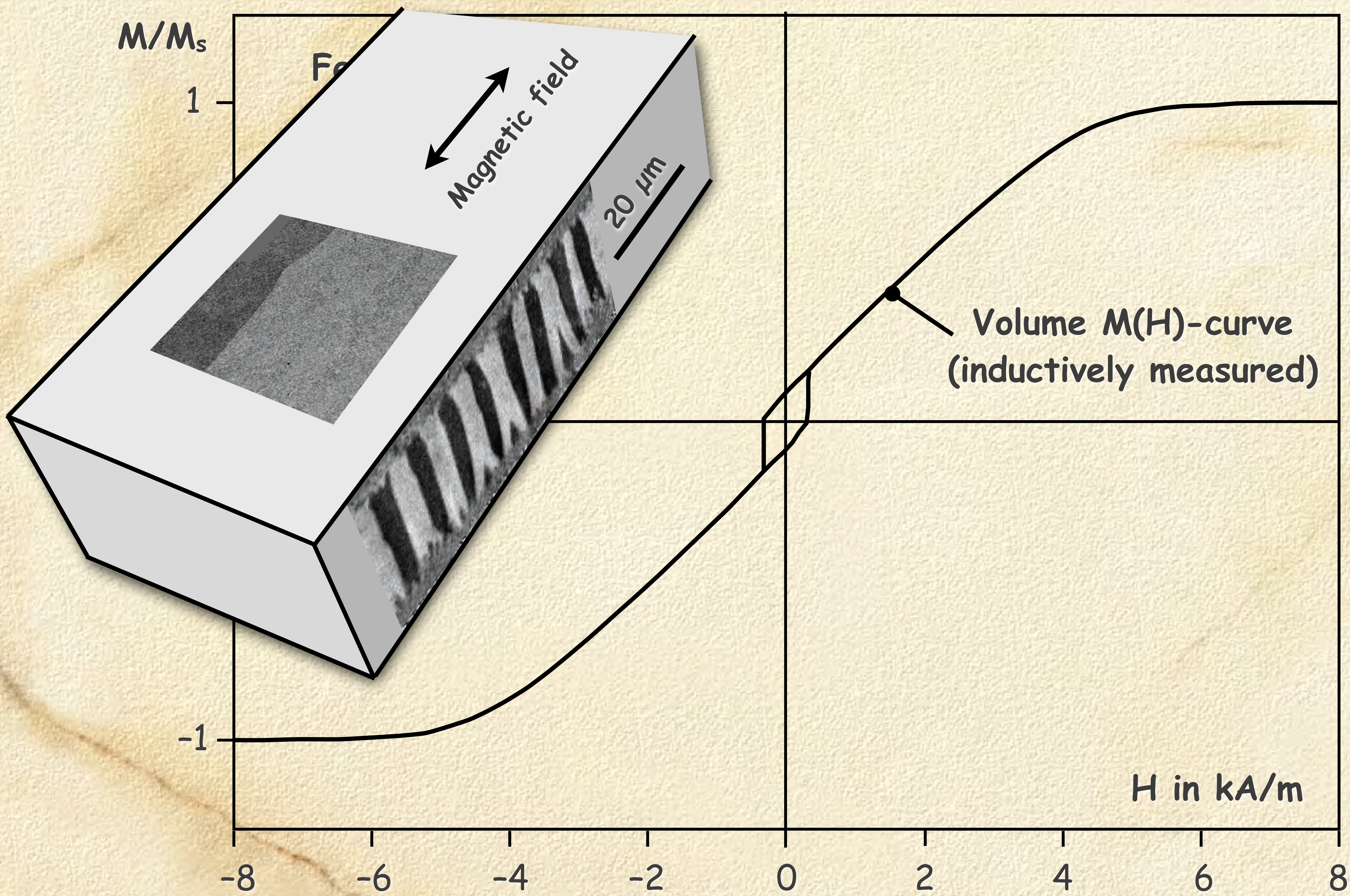

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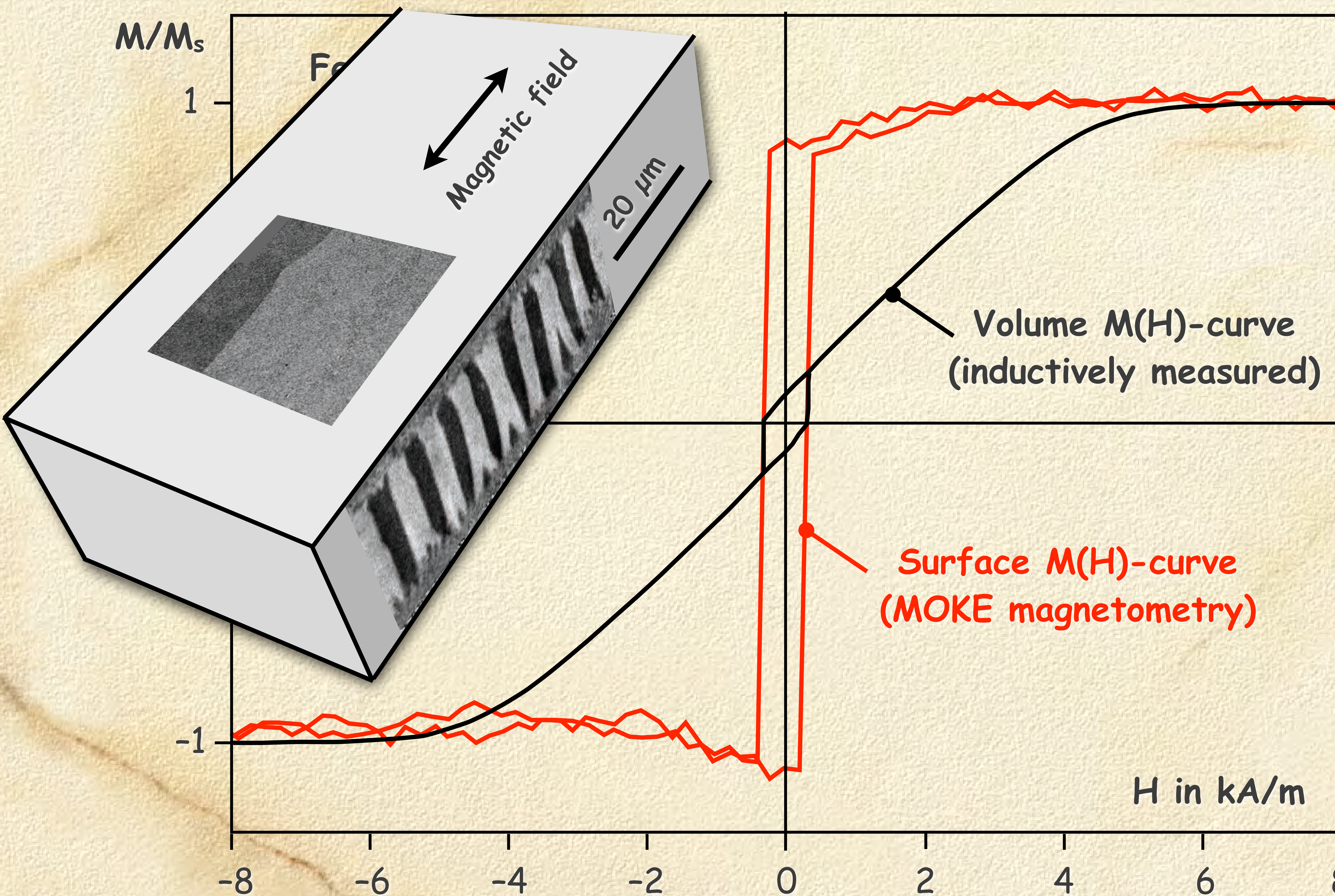


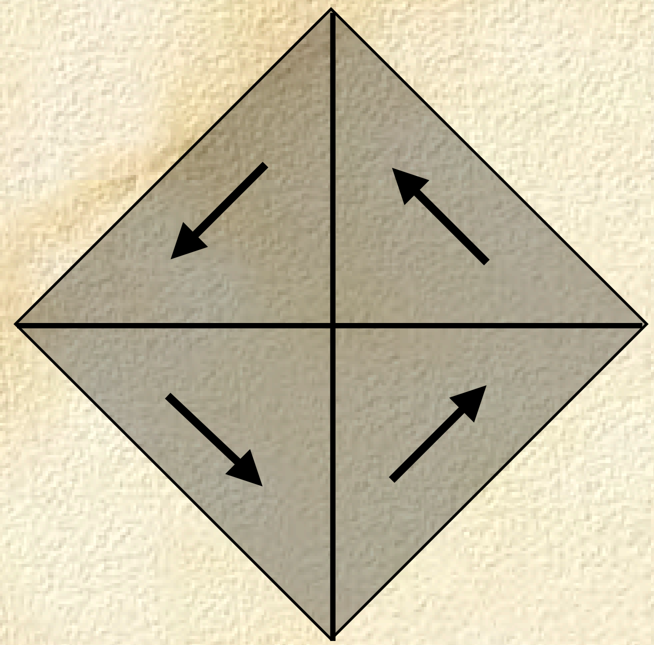
Together with E: Lopatina (IFW) and G. Herzer (VAC Hanau), unpublished

M(H) loop and domains

Concertina

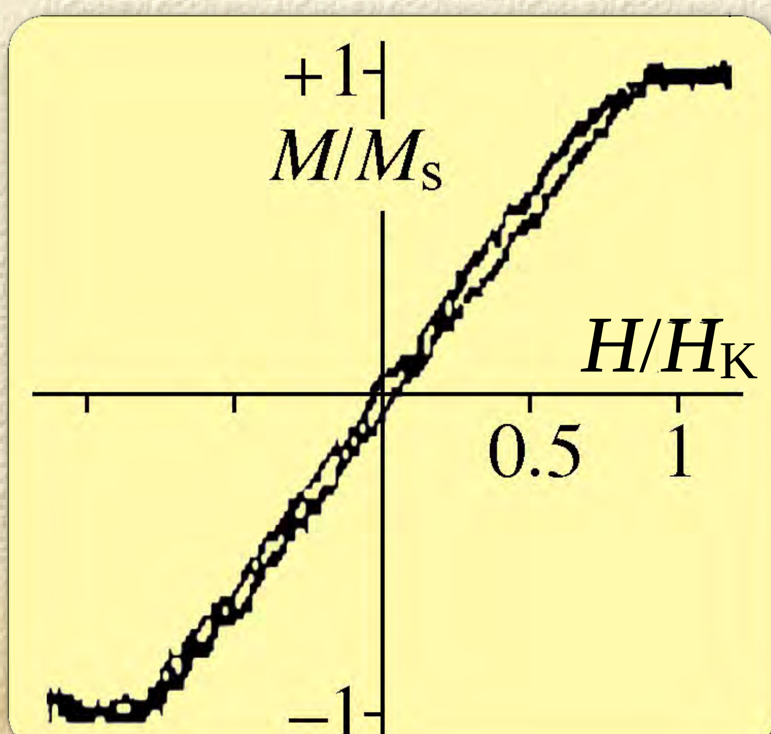
Permalloy (NiFe) film
207 nm thick

57 µm

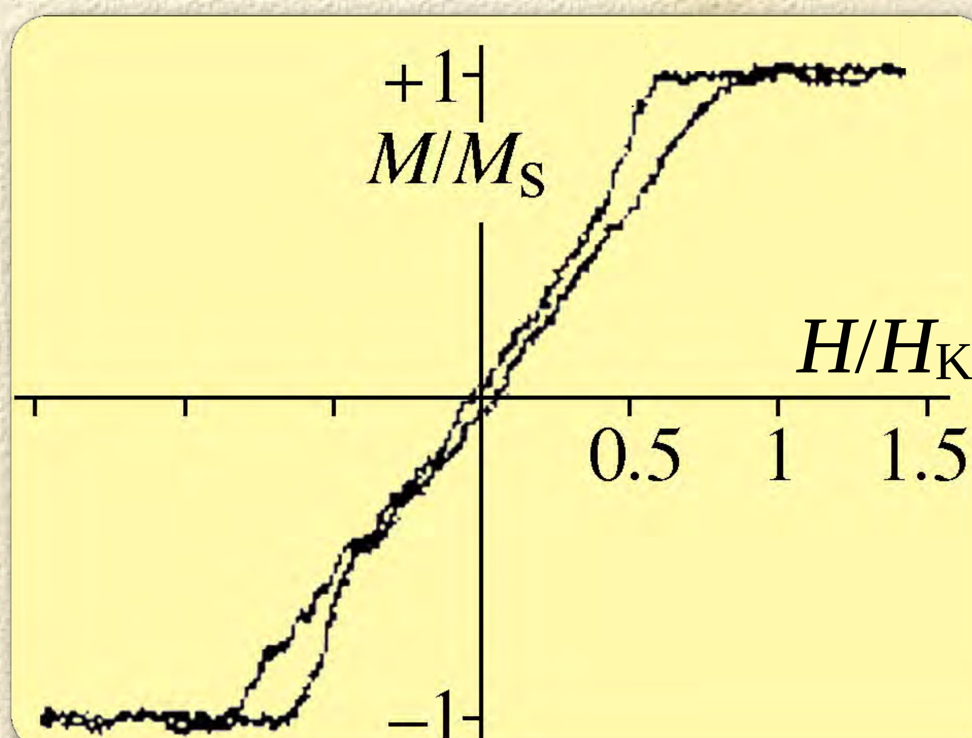


Magnetic field H

$H_{max} = H_K$

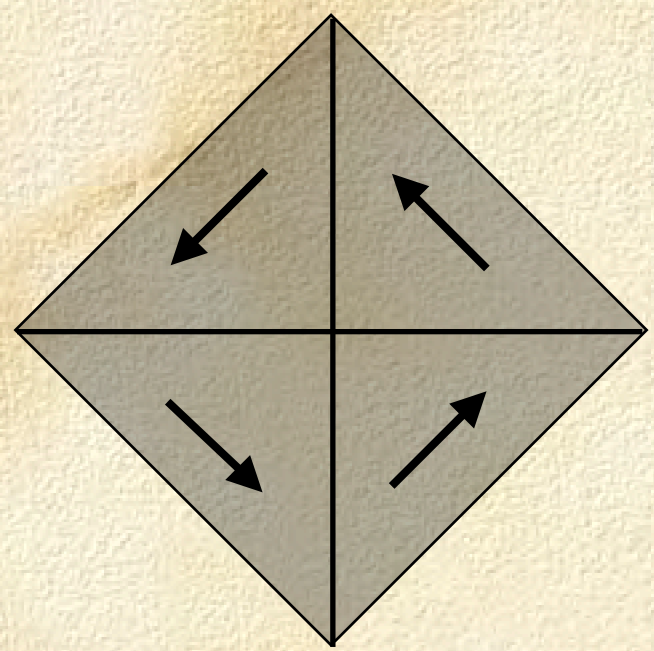


$H_{max} > H_K$



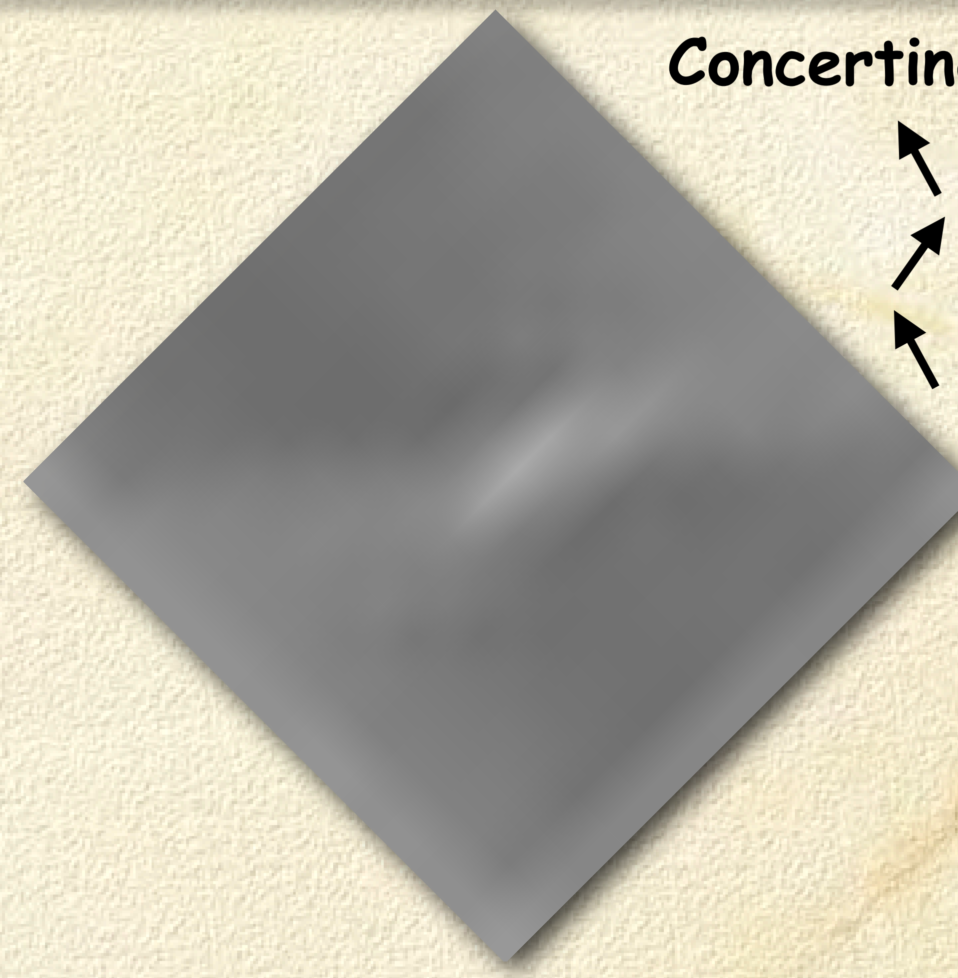
M(H) loop and domains

Permalloy (NiFe) film
207 nm thick

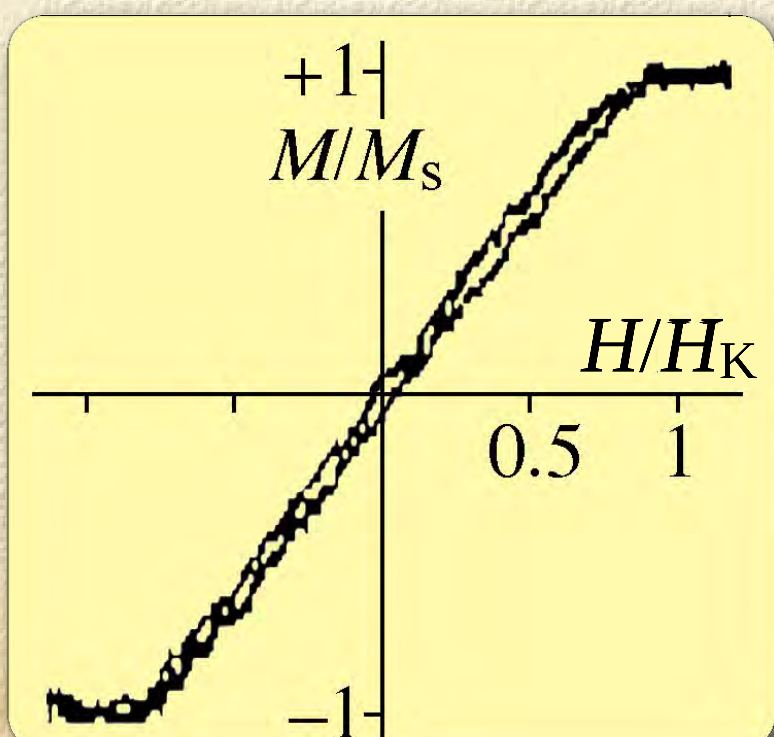


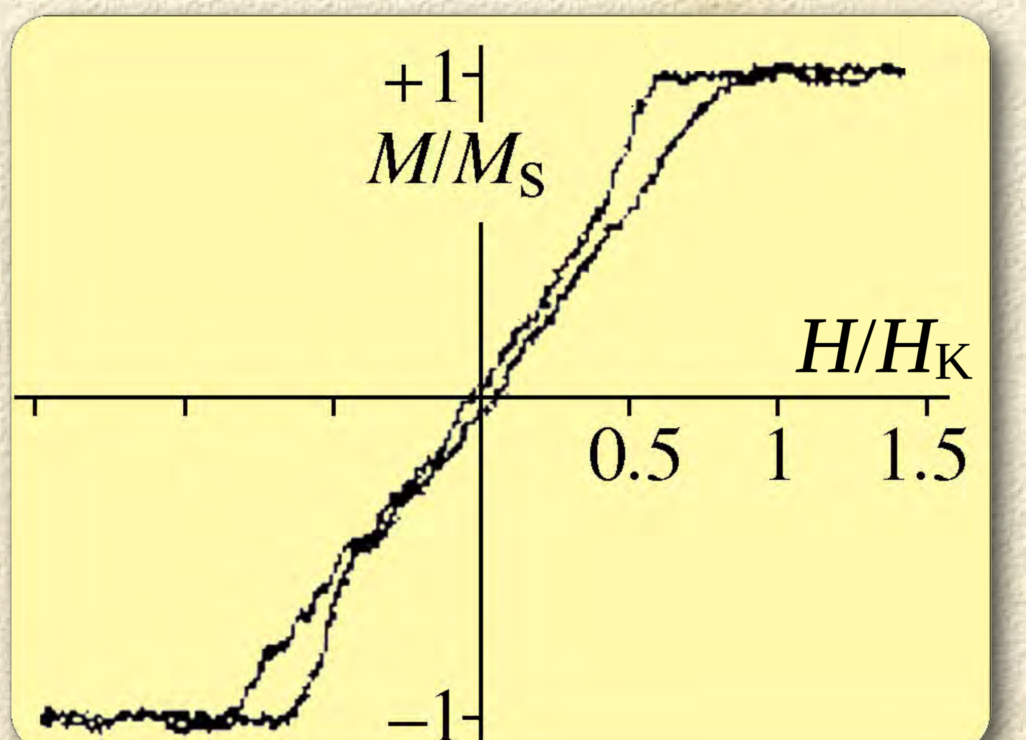
Magnetic field H

$H_{max} = H_K$



$H_{max} > H_K$





M(H) loop and domains

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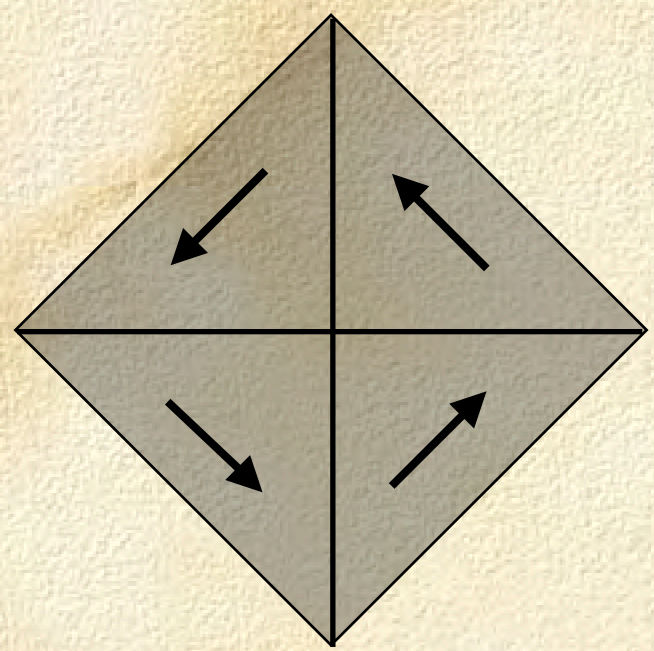
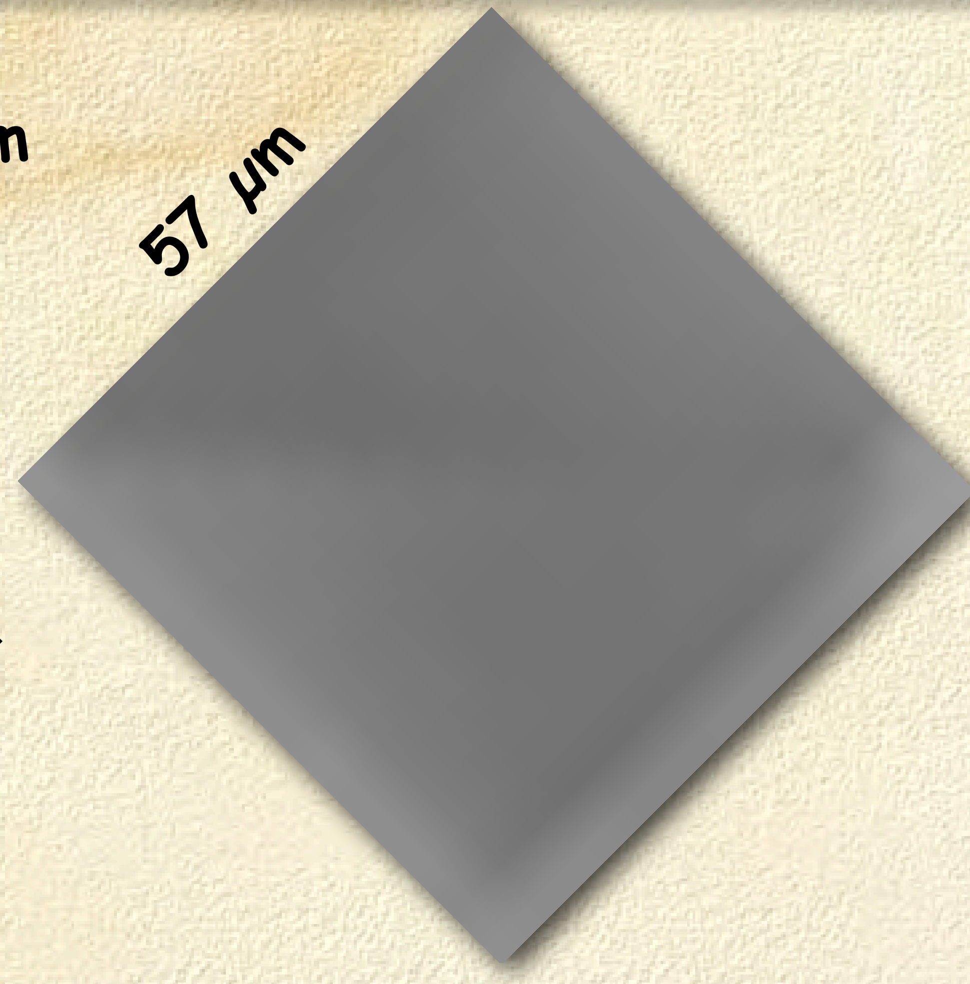
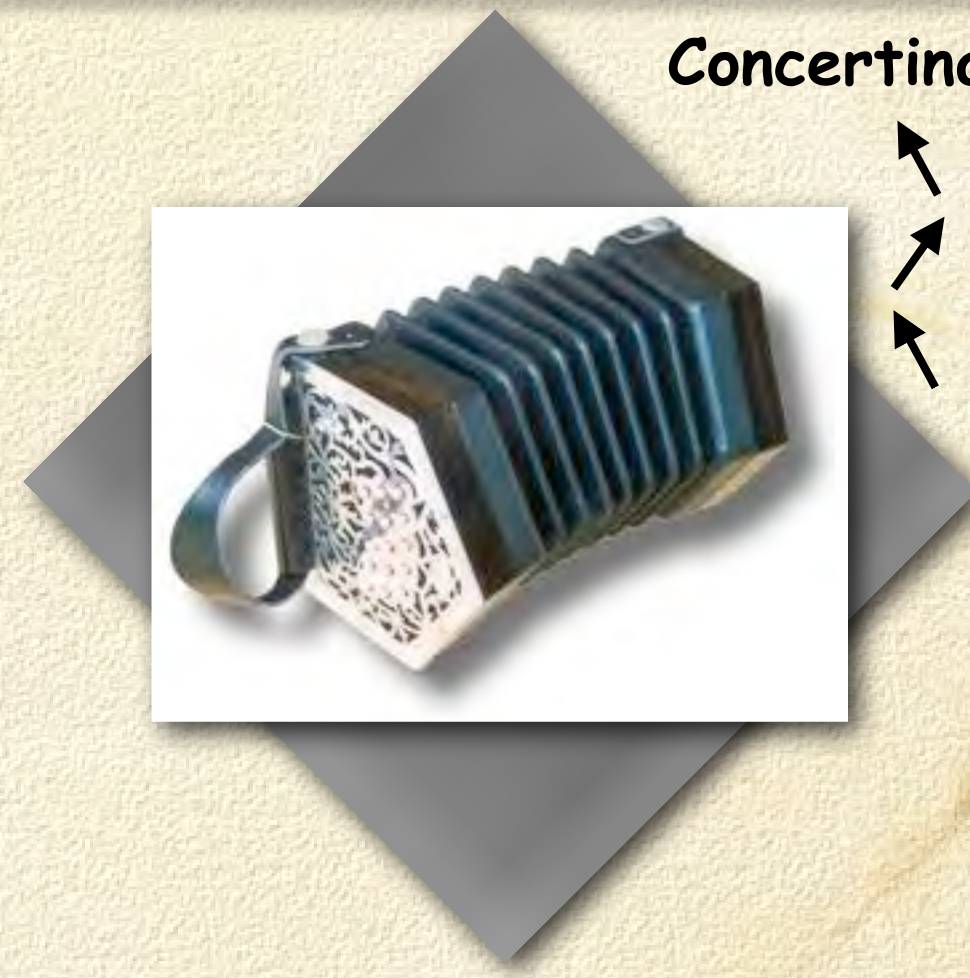
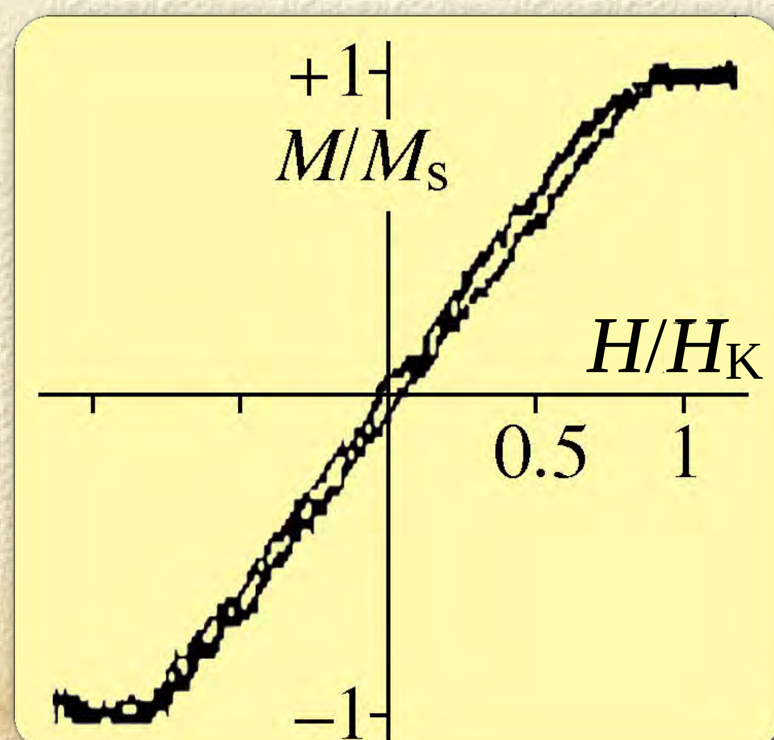


Magnetic field H

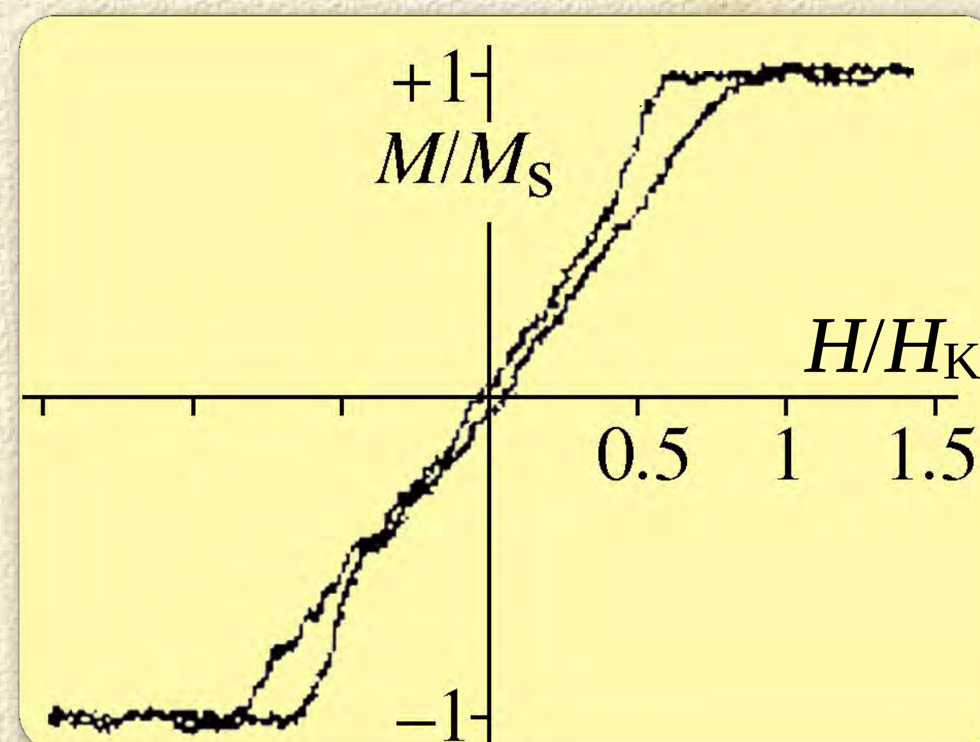




$H_{max} = H_K$

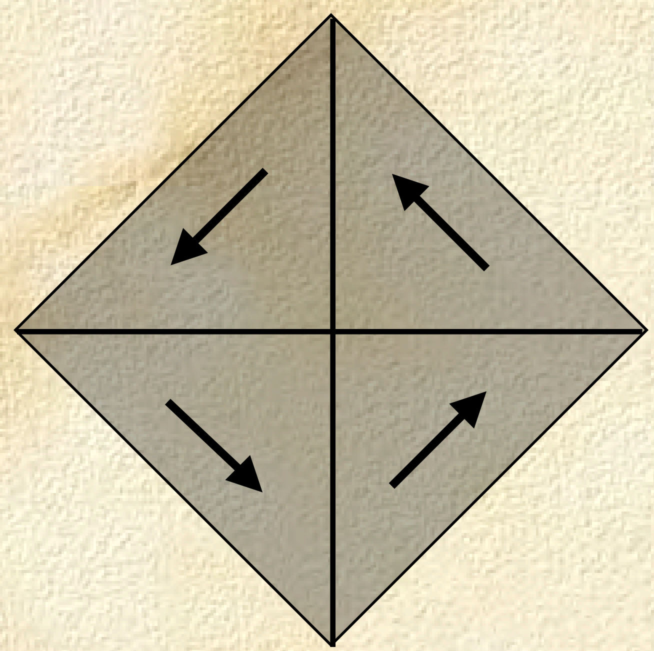


$H_{max} > H_K$

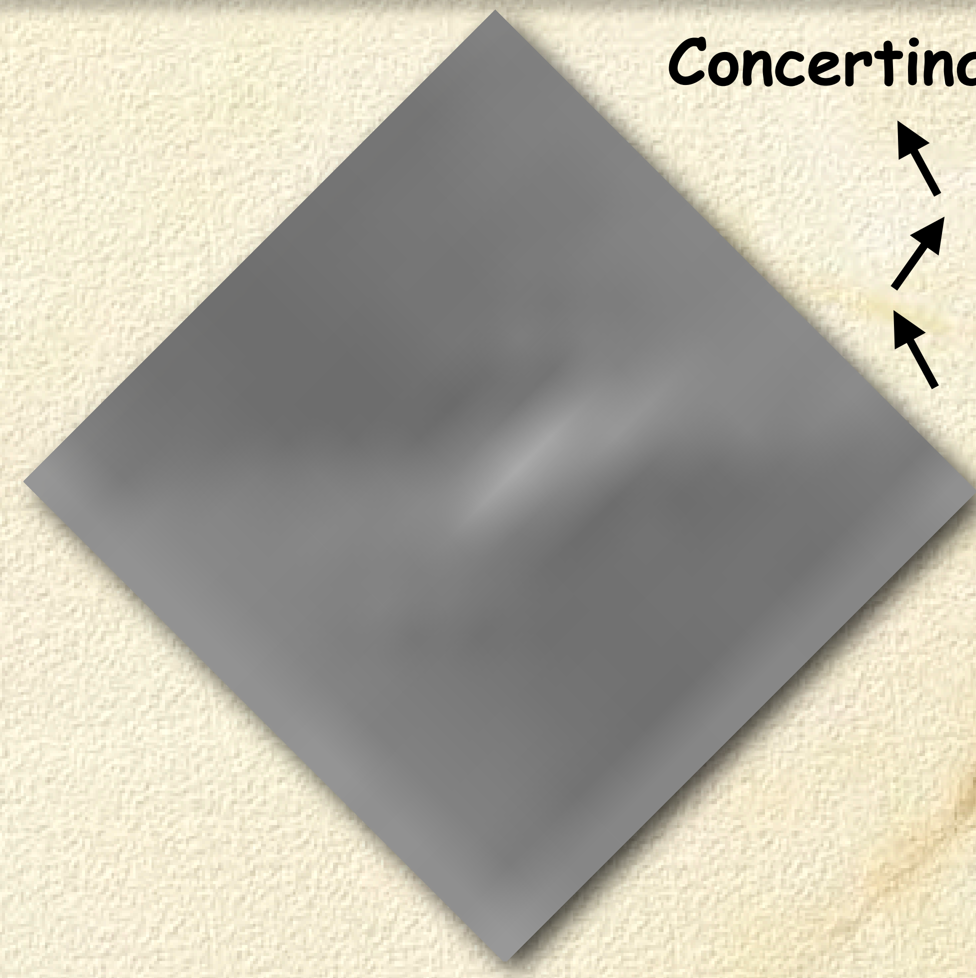


M(H) loop and domains

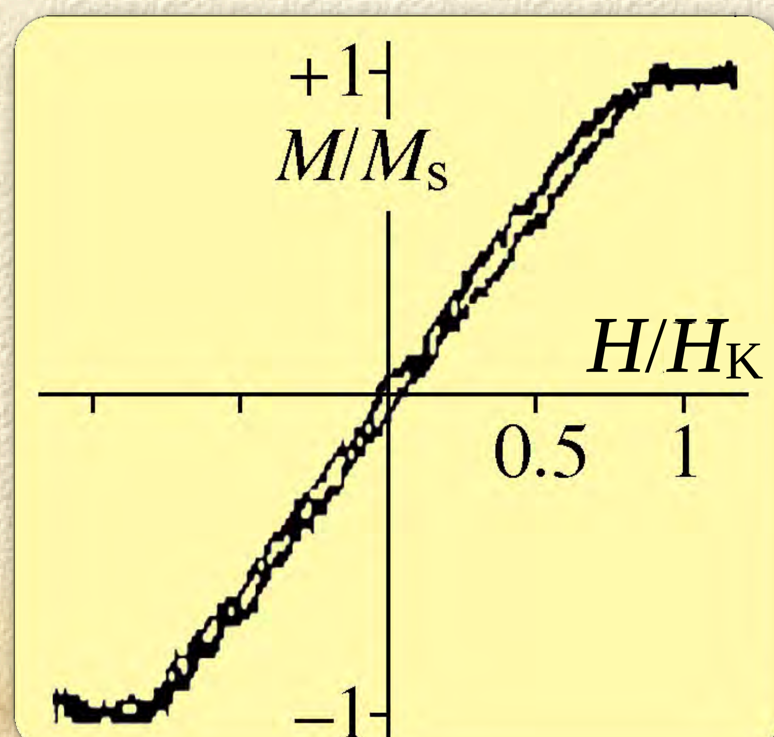
Permalloy (NiFe) film
207 nm thick



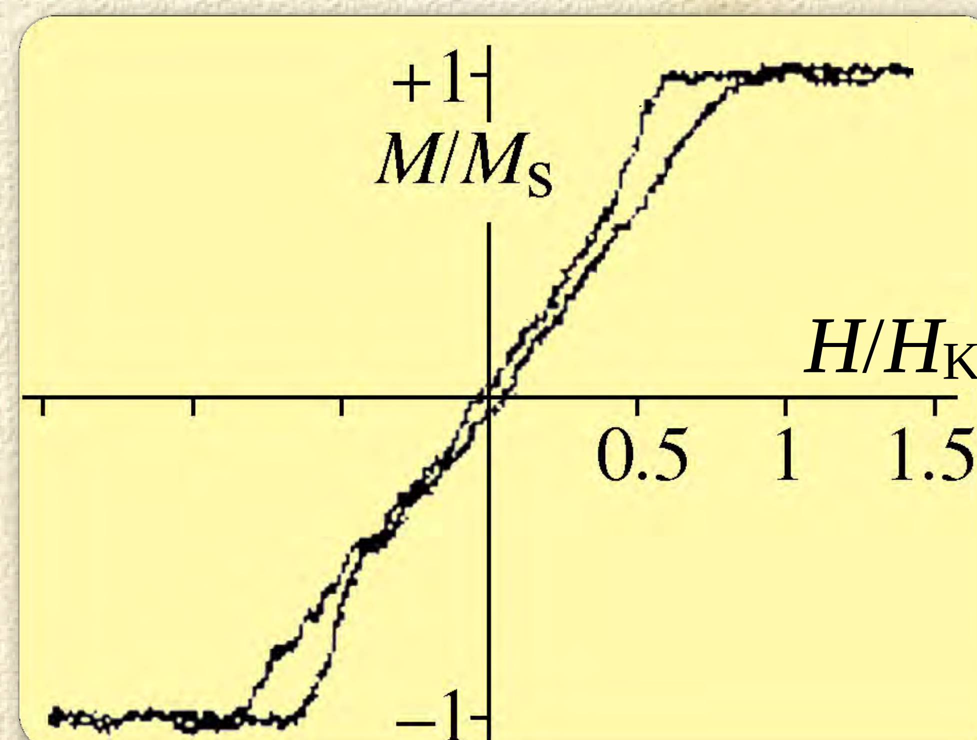
Magnetic field H



$H_{max} = H_K$

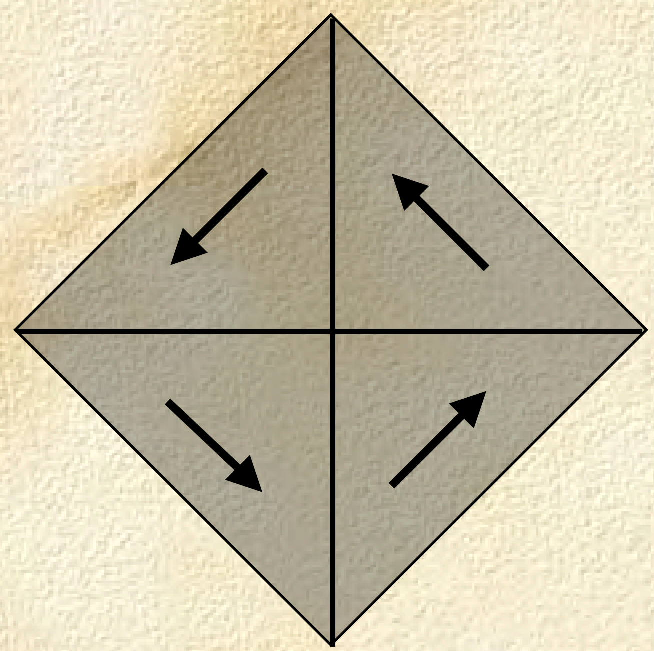


$H_{max} > H_K$

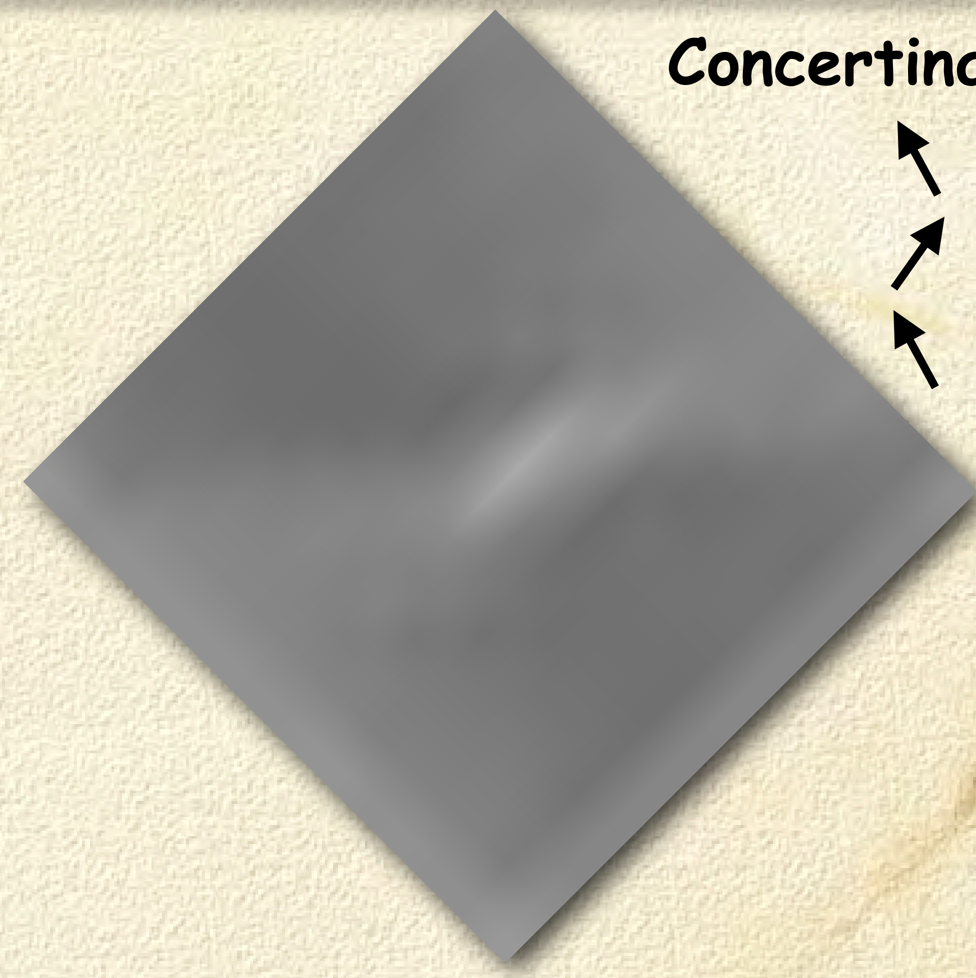


M(H) loop and domains

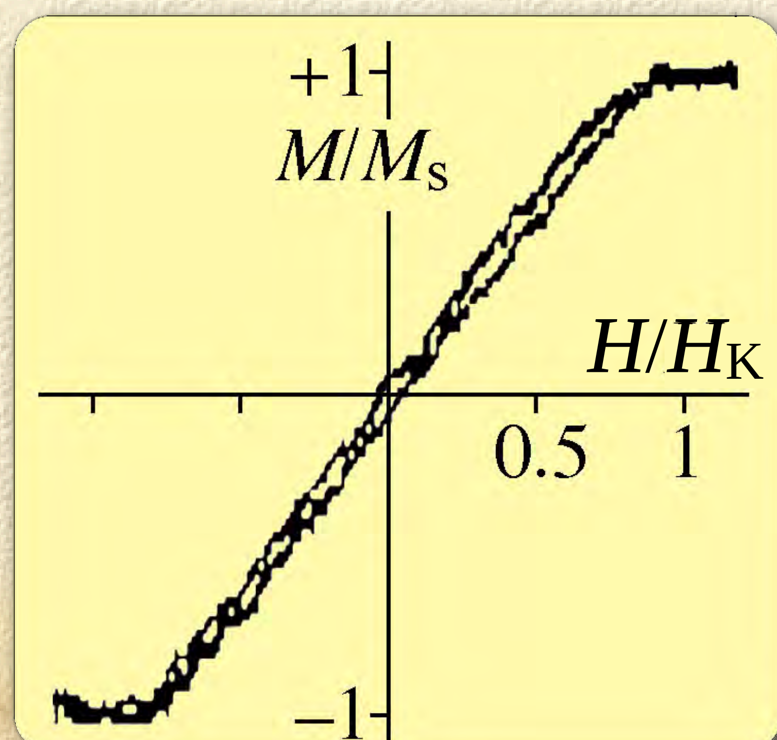
Permalloy (NiFe) film
207 nm thick



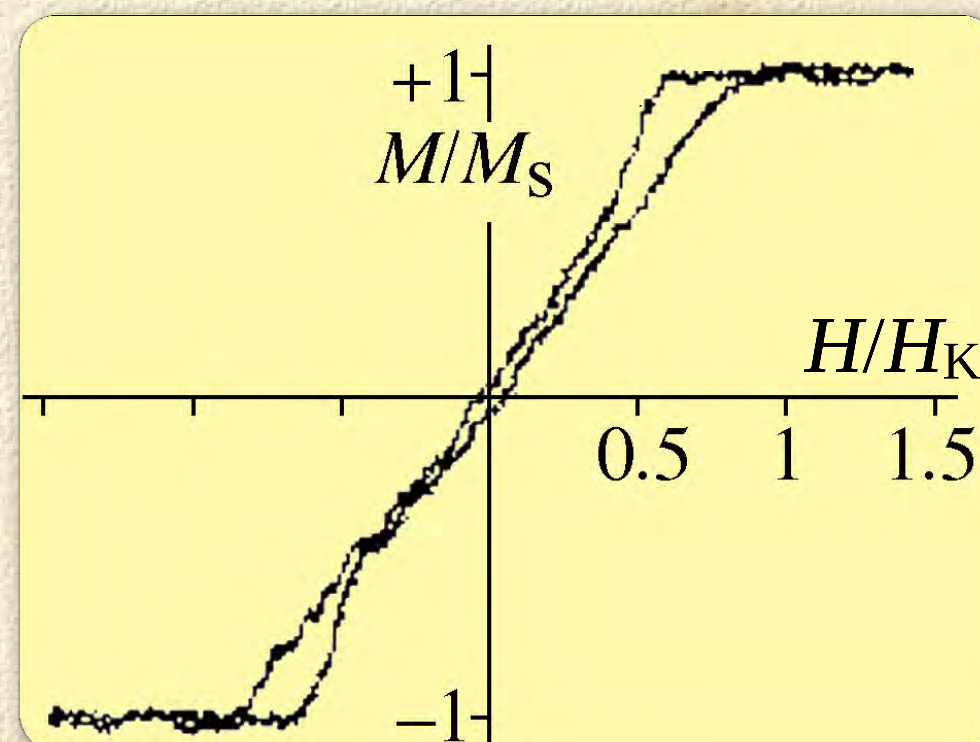
Magnetic field H



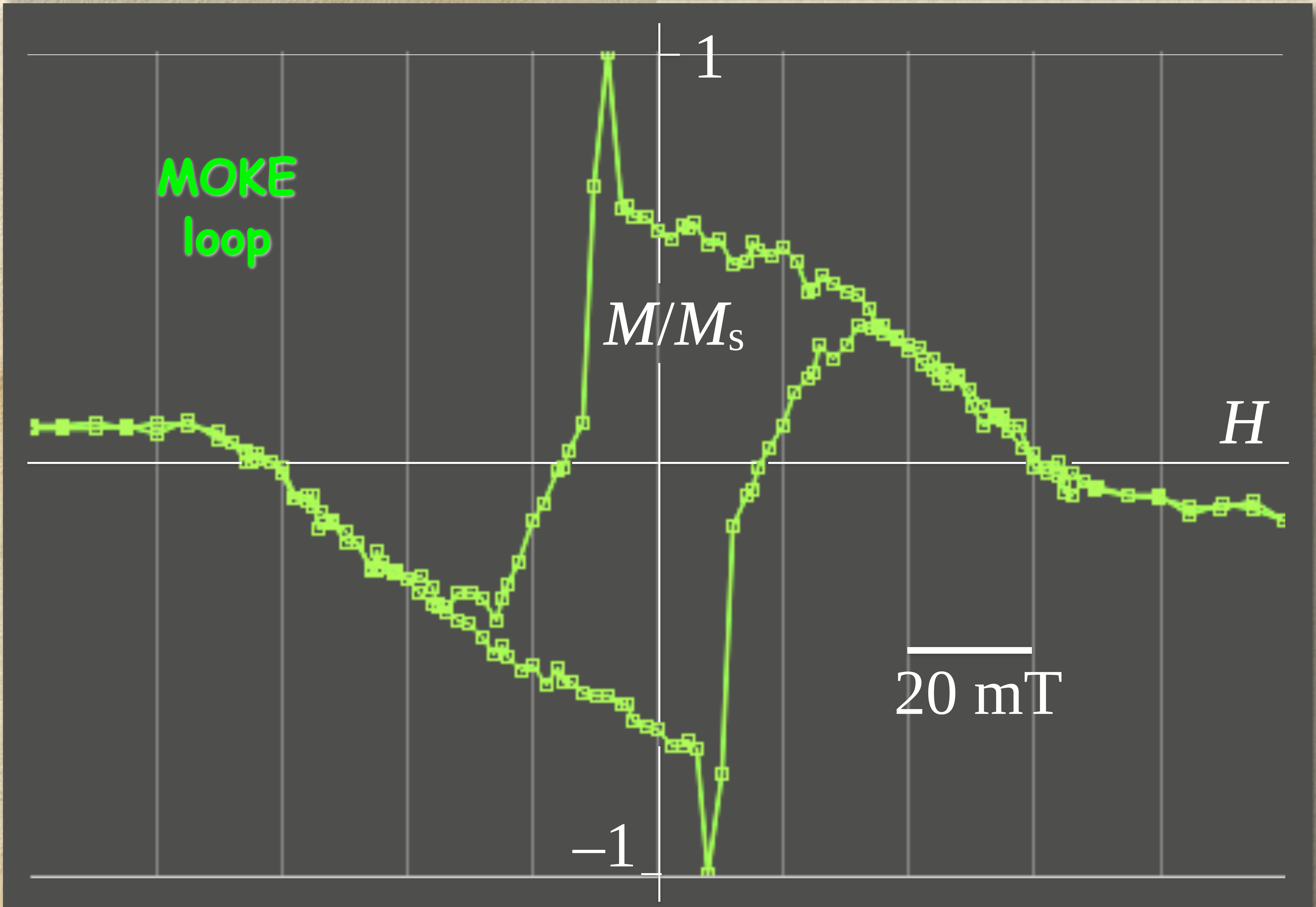
$H_{max} = H_K$



$H_{max} > H_K$

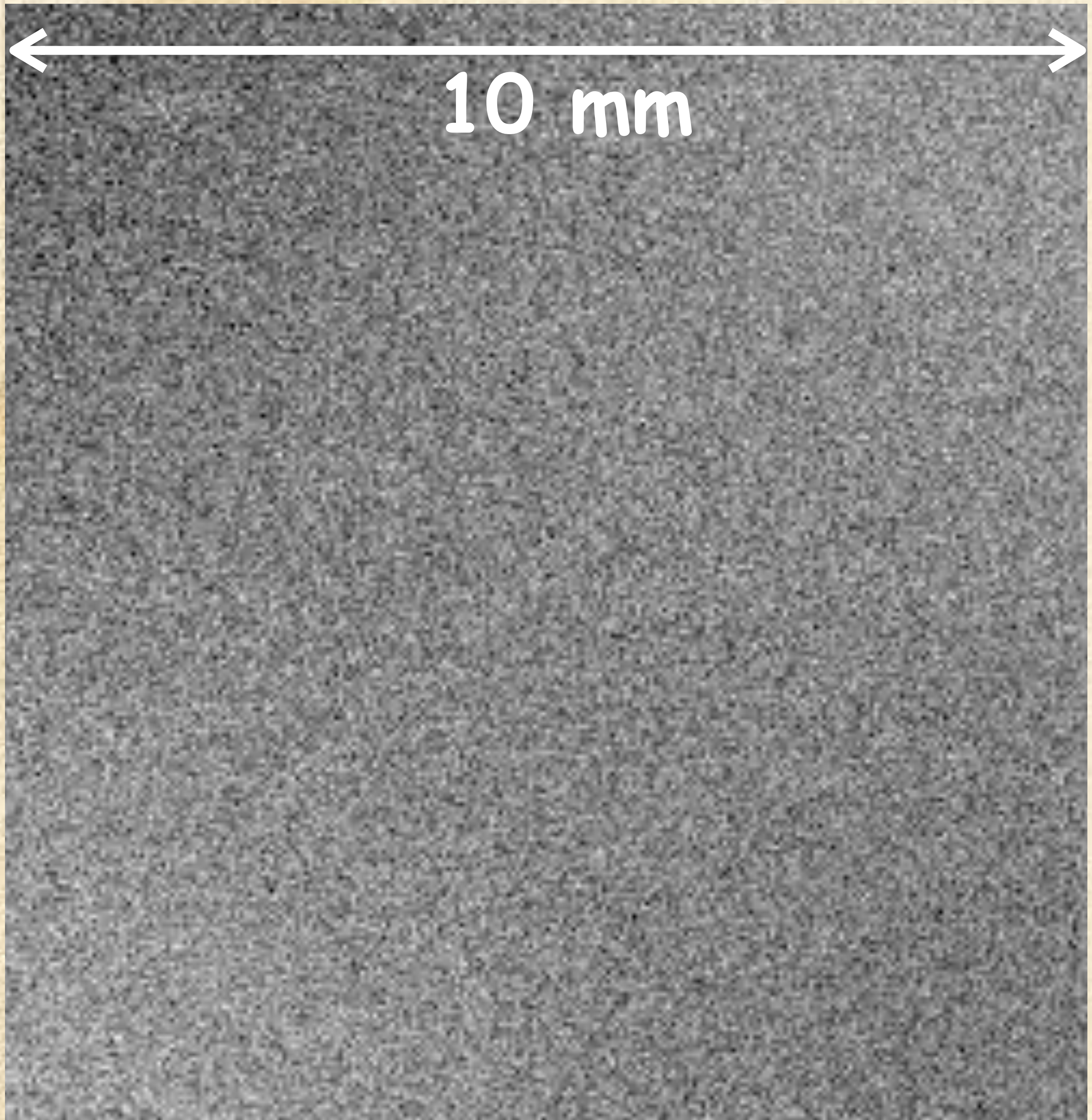


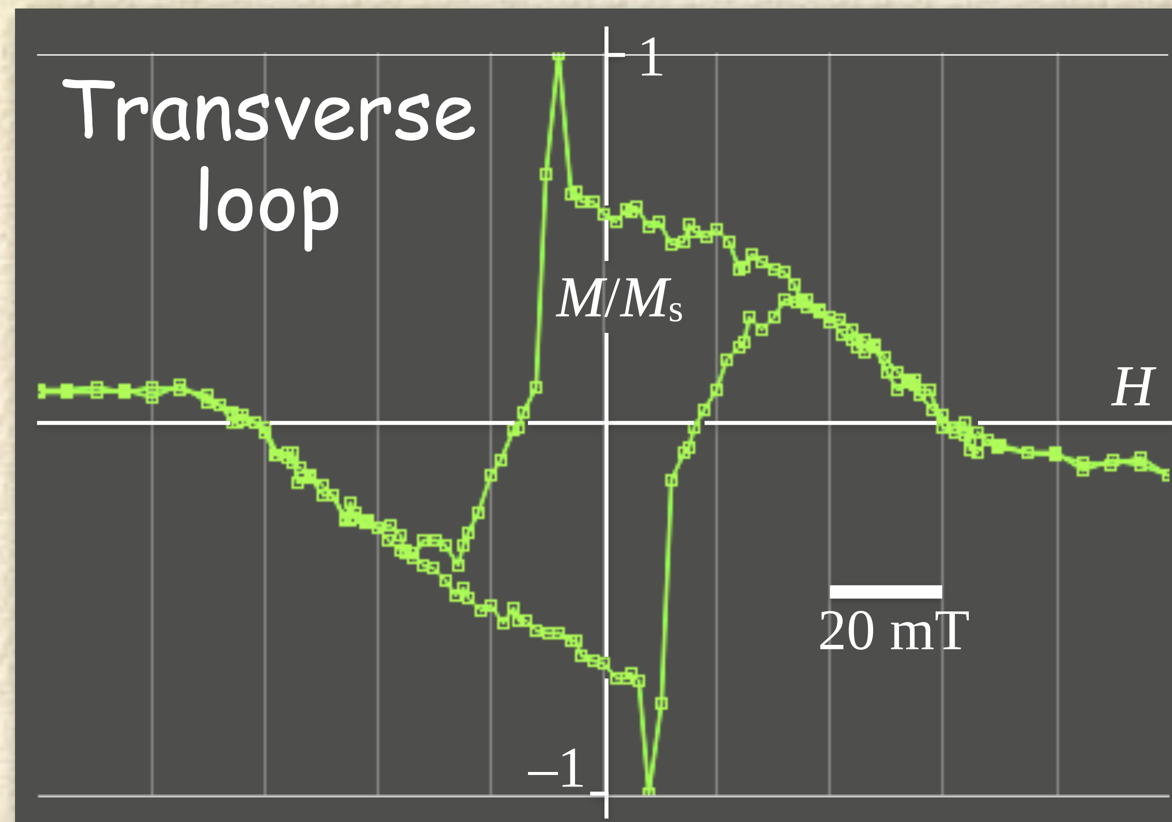
M(H) loop and domains

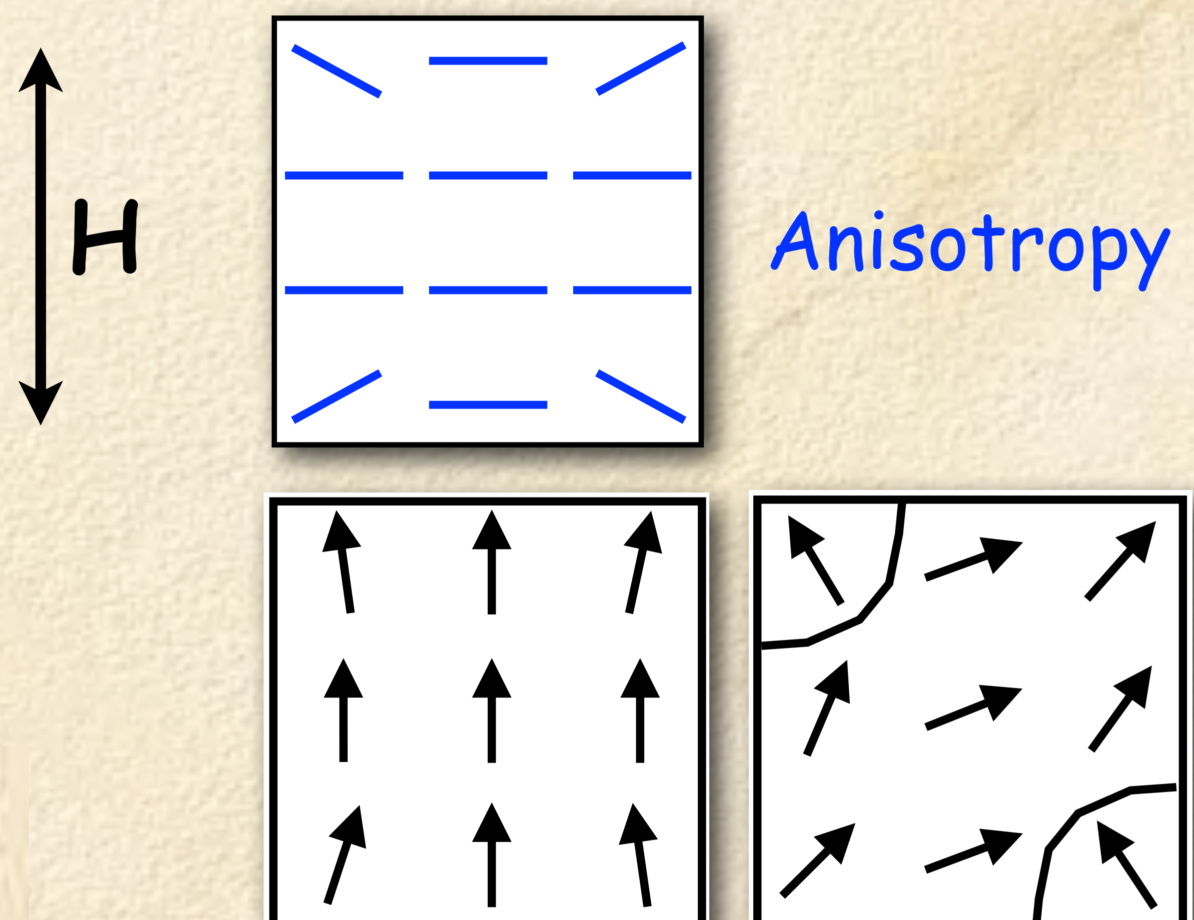


M(H) loop and domains

$Co_{27}Sm_{73}$ amorphous film (thickness 200 nm)



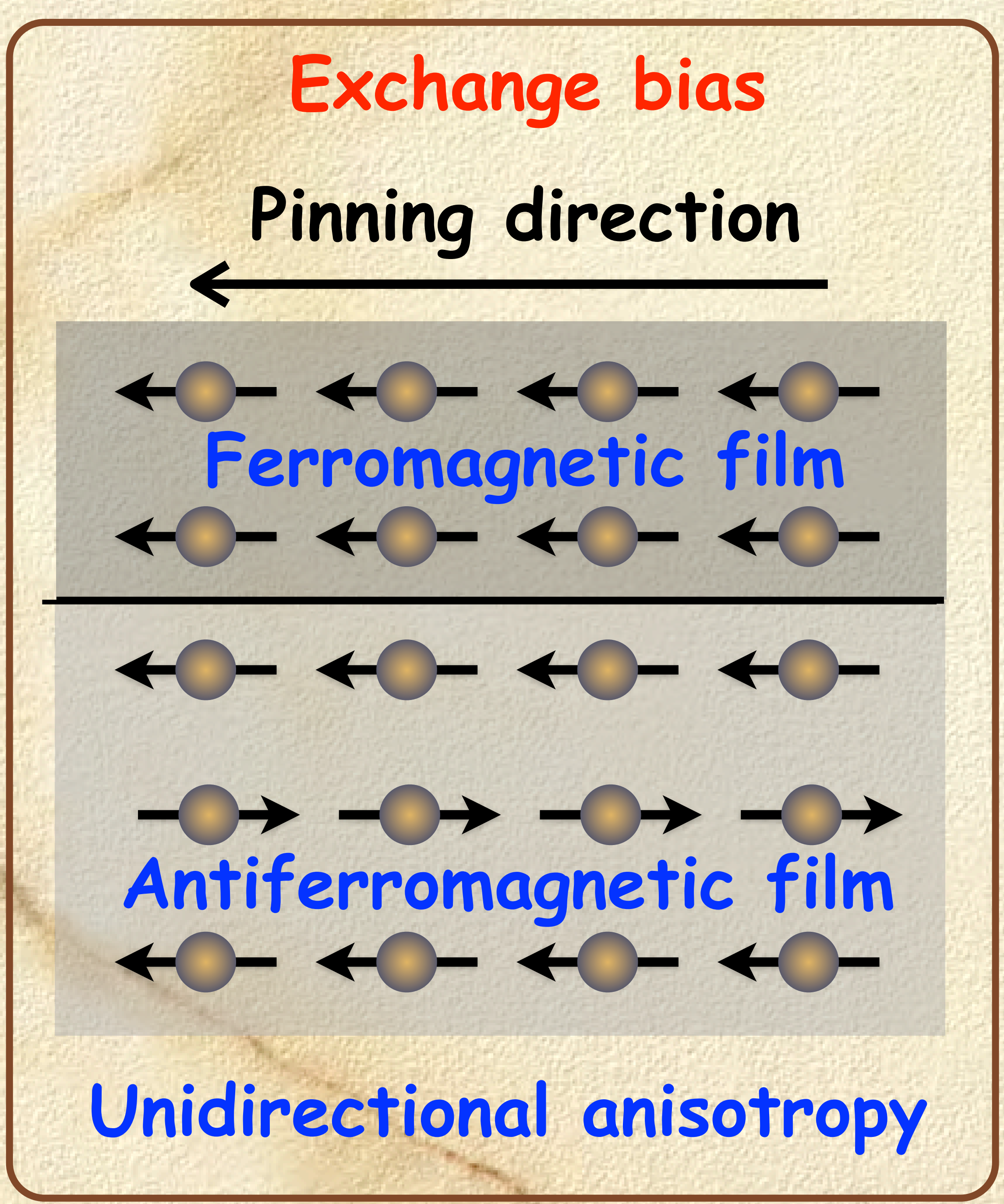


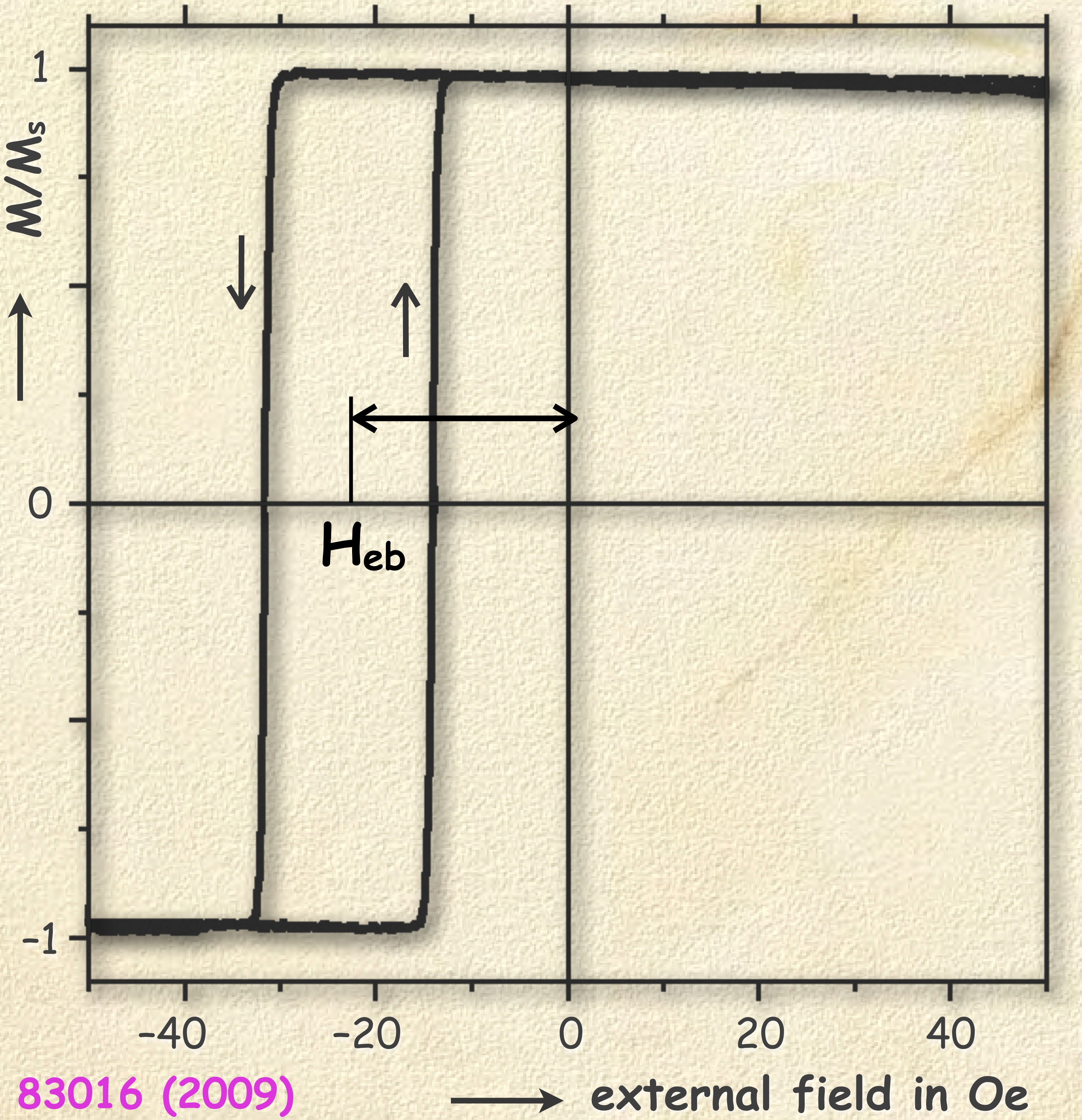


Sample: F. Magnus and B. Hjörvarsson, Uppsala University (unpublished)

M(H) loop and domains

Reversal of $Ni_{81}Fe_{19}$ (30 nm) / NiO (30 nm)

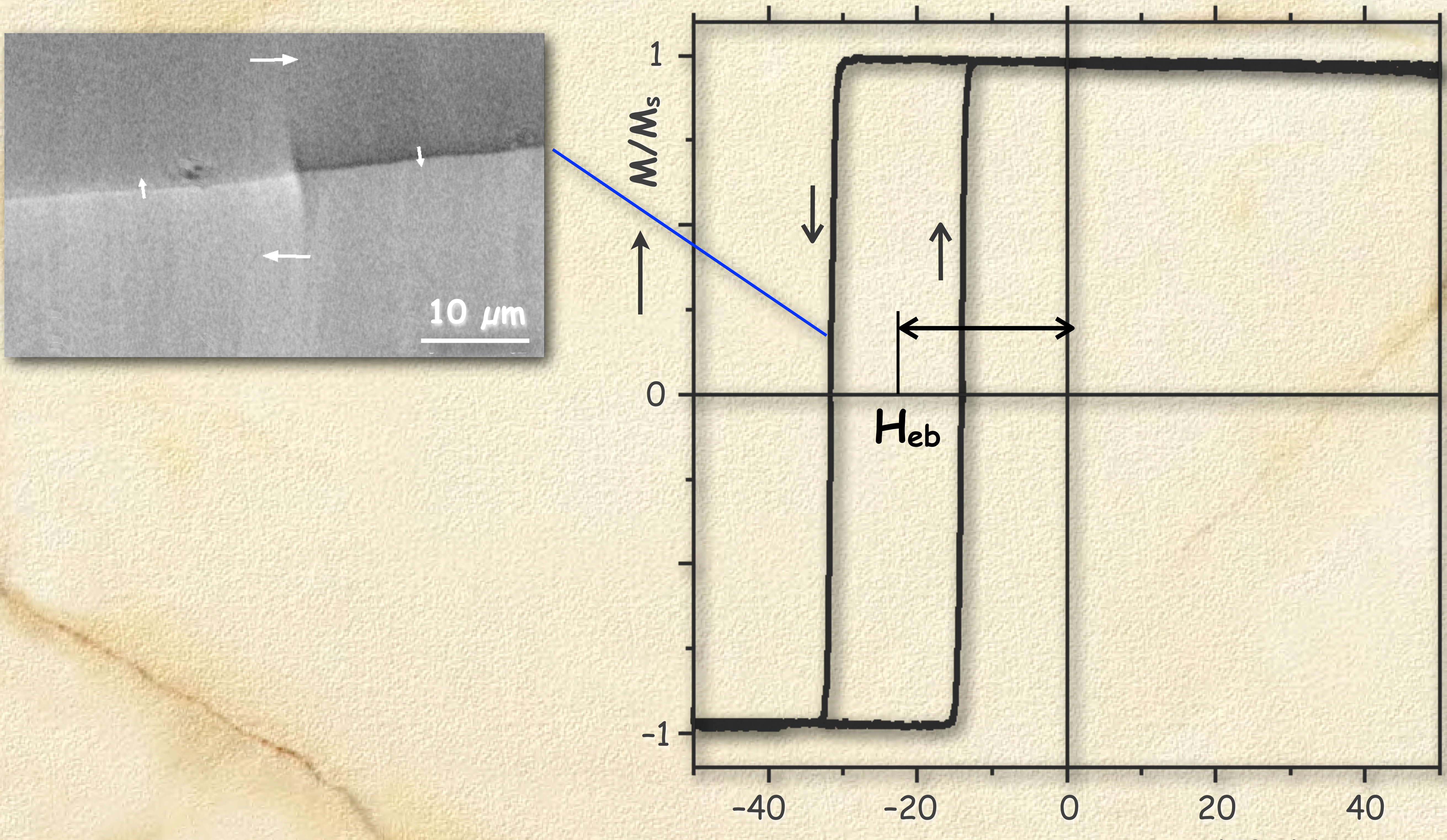




J. McCord and R.S., New J. Phys. 11, 83016 (2009)

M(H) loop and domains

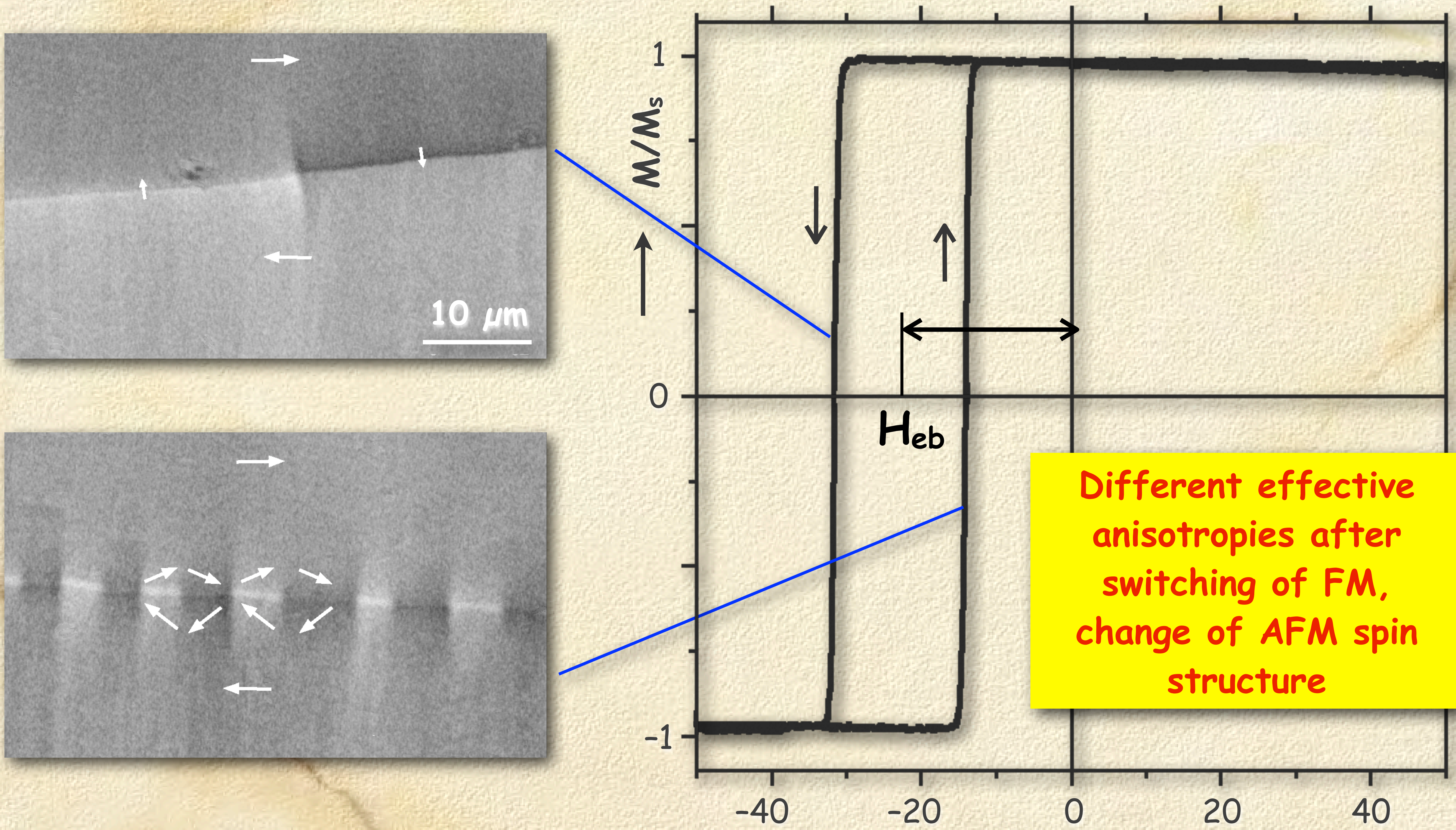
Reversal of $Ni_{81}Fe_{19}$ (30 nm) / NiO (30 nm)



J. McCord and R.S., New J. Phys. 11, 83016 (2009)

M(H) loop and domains

Reversal of $Ni_{81}Fe_{19}$ (30 nm) / NiO (30 nm)

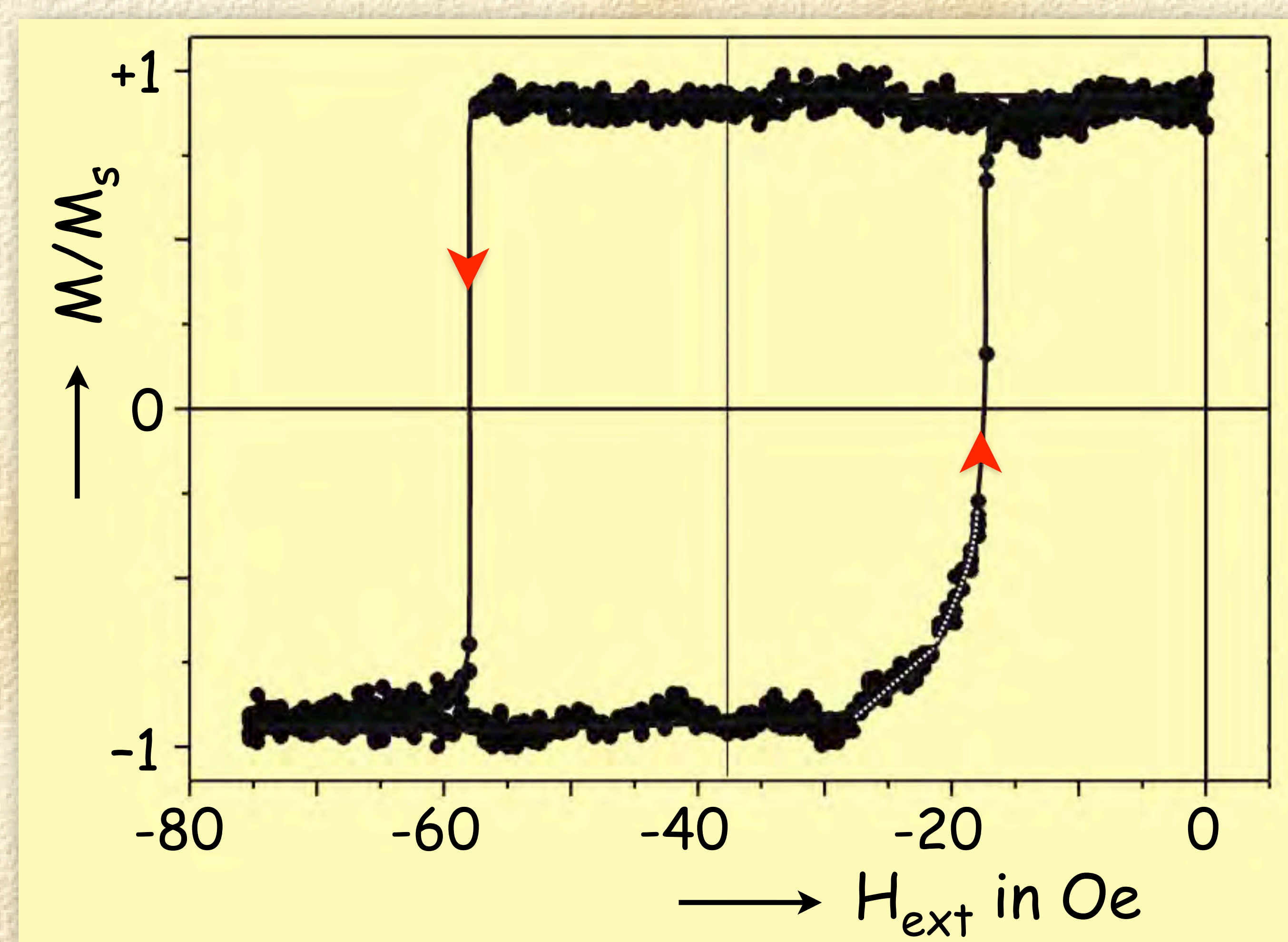


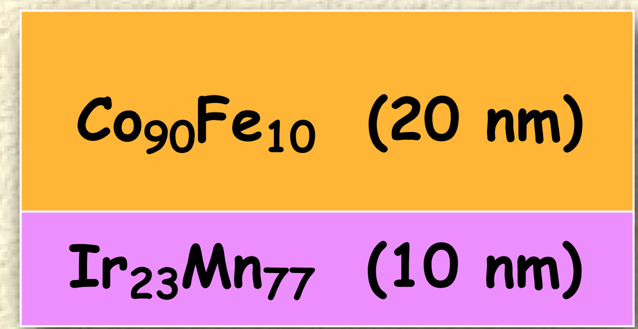
Different effective anisotropies after switching of FM, change of AFM spin structure

J. McCord and R.S., New J. Phys. 11, 83016 (2009)

M(H) loop and domains

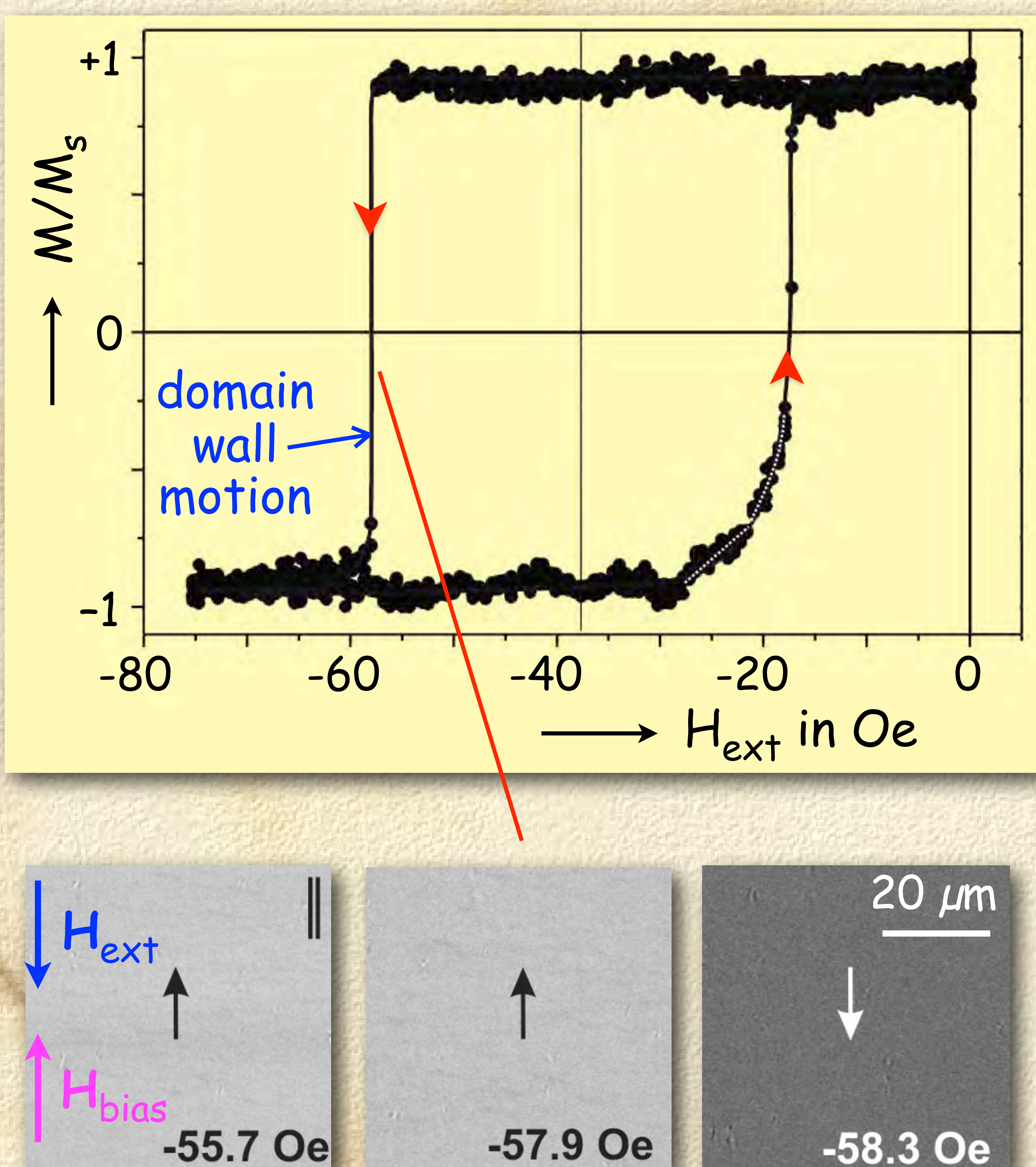
M(H) loop and domains





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

M(H) loop and domains

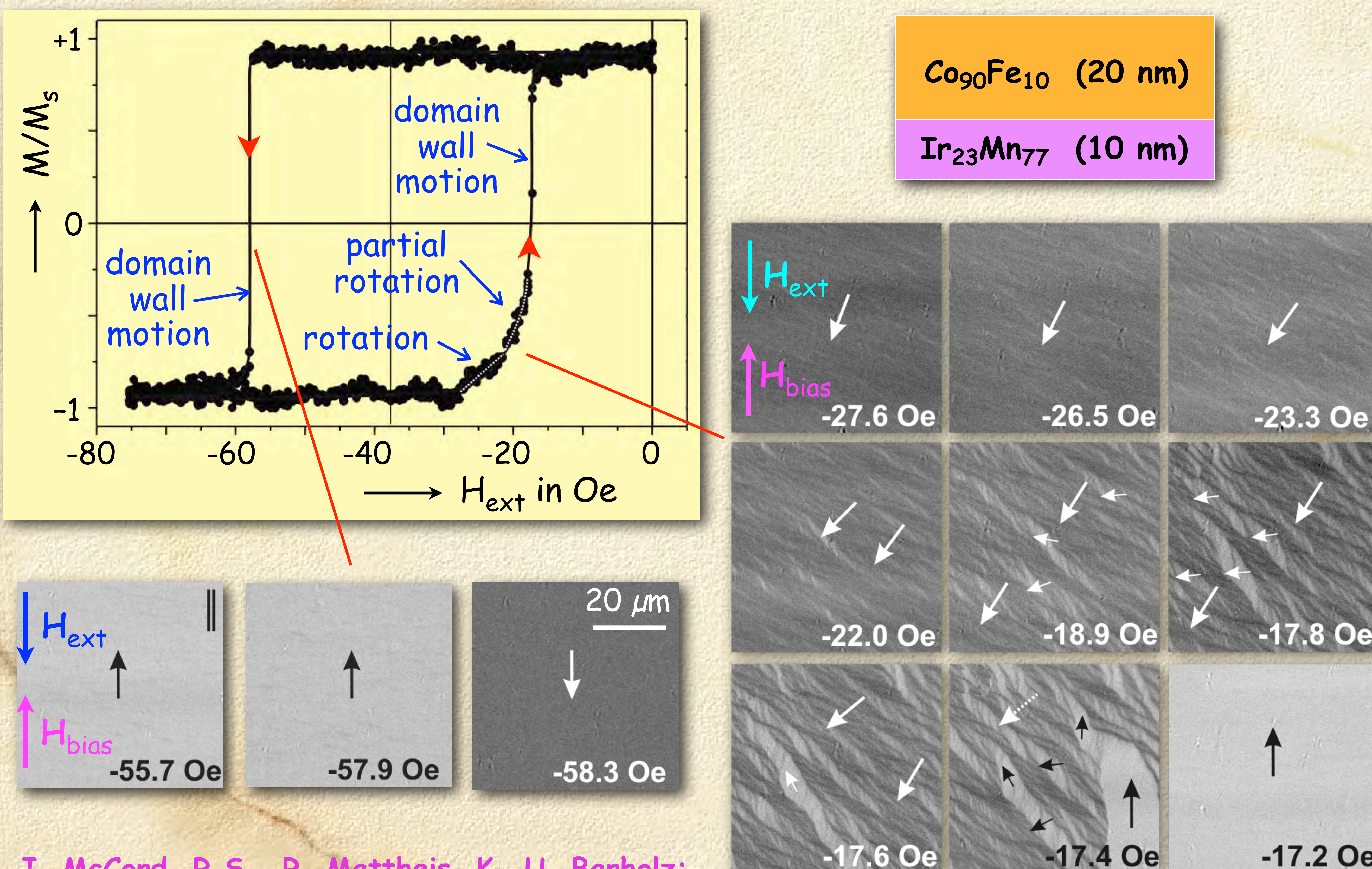


$Co_{90}Fe_{10}$ (20 nm)

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

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

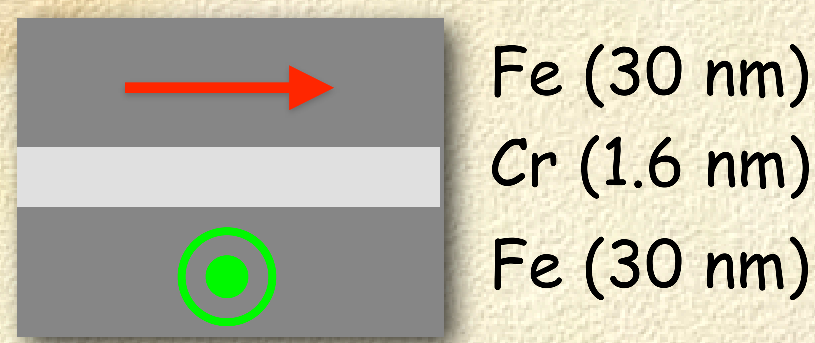
M(H) loop and domains

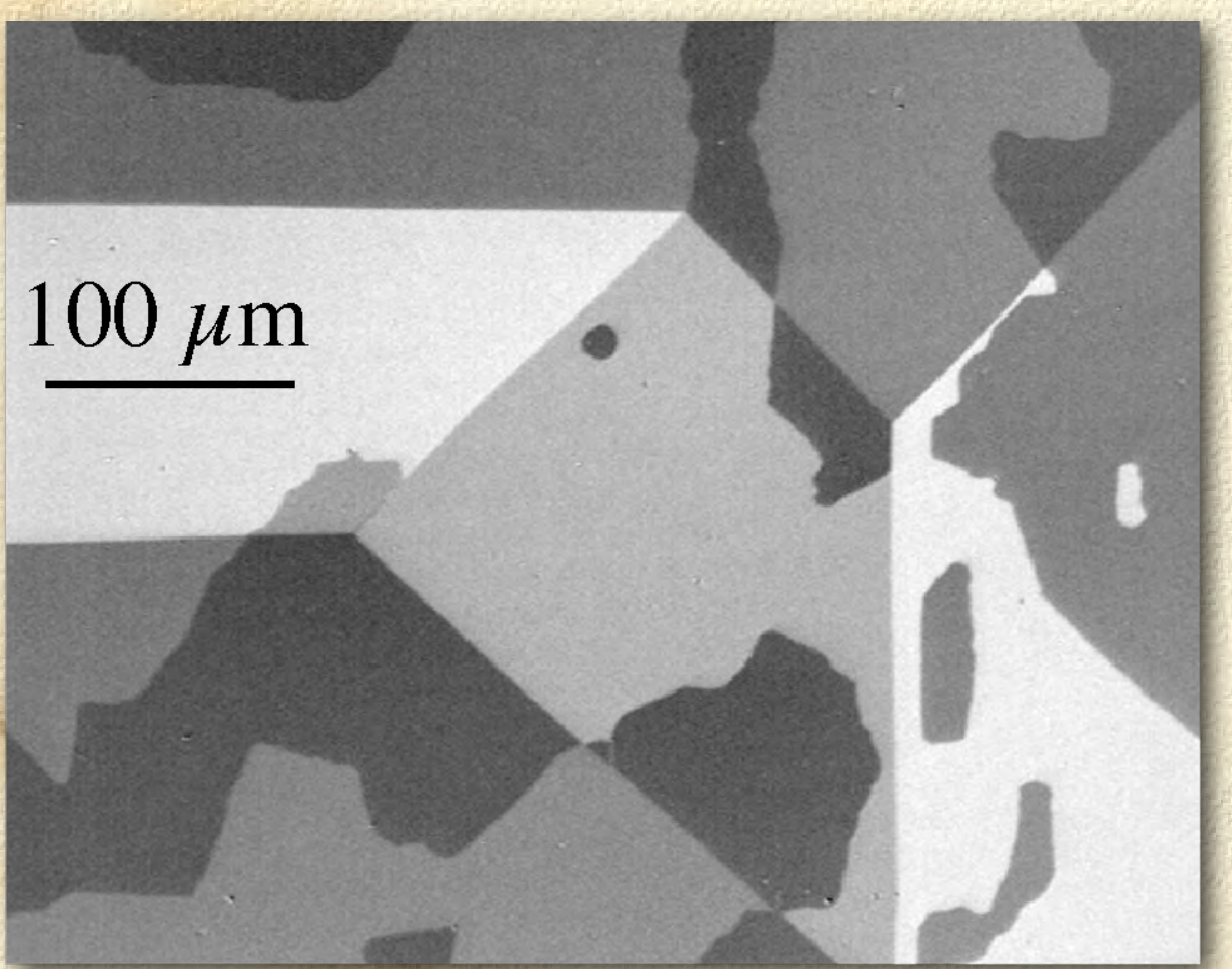


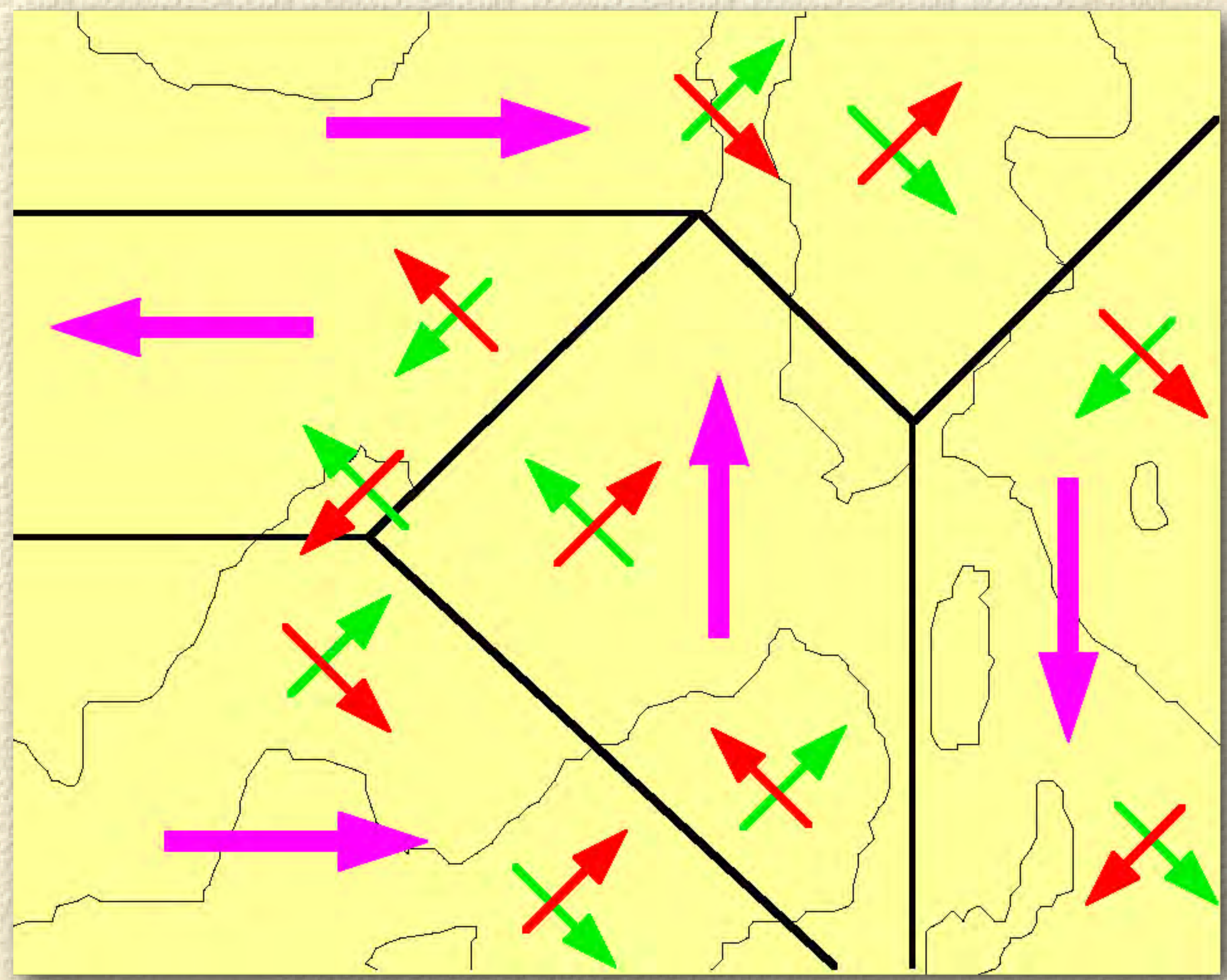
J. McCord, R.S., R. Mattheis, K.-U. Barholz:
J. Appl. Phys. 93, 5491 (2003)

indication of strong anisotropy dispersion

Biquadratic coupling in multilayers





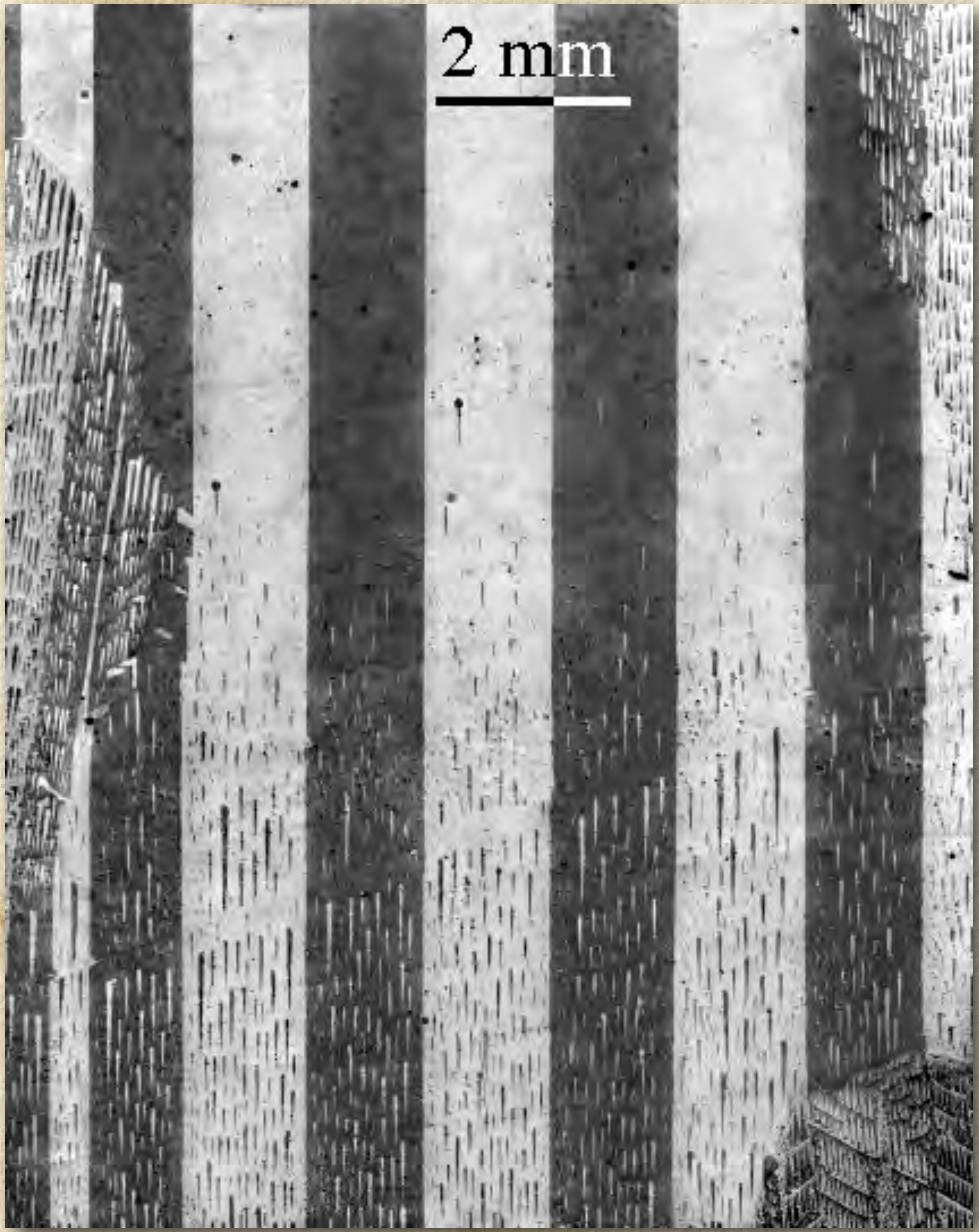


M. Rührig, RS, et al., Phys. Stat. Sol. 125 (1991)

Loss control by domain control

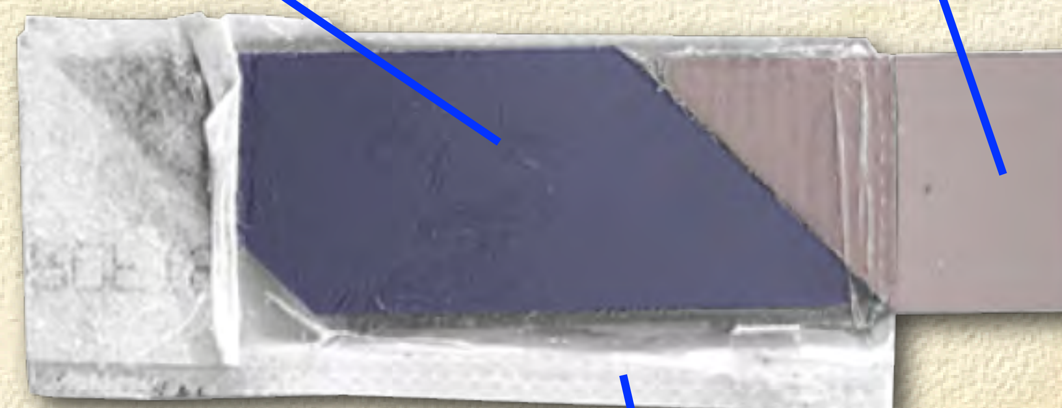
Grain-oriented FeSi transformer material

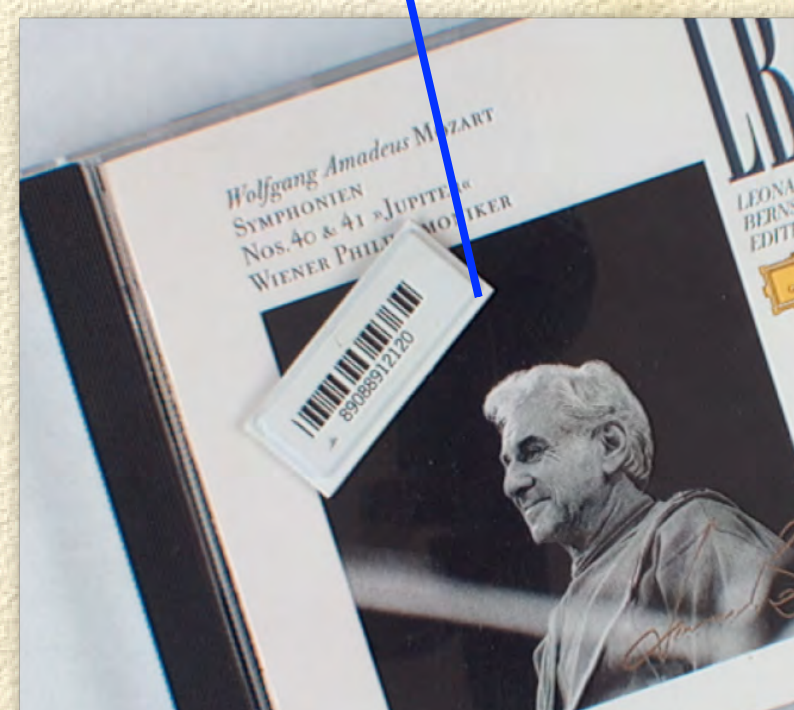
Without artificial domain refinement



After laser scribing

Magneto-acoustic Article Surveillance





Magneto-acoustic Article Surveillance

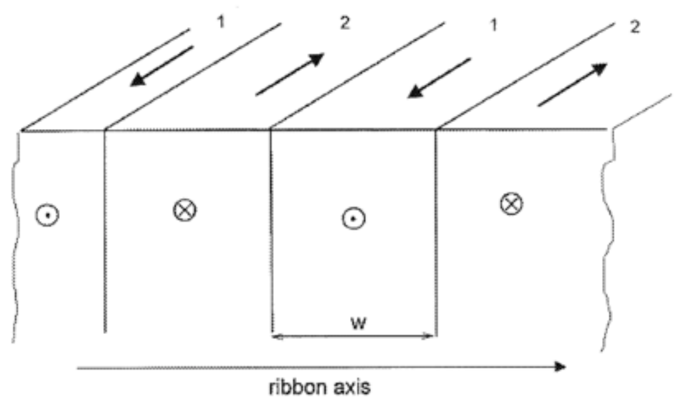


Fig. 1a (Prior Art)

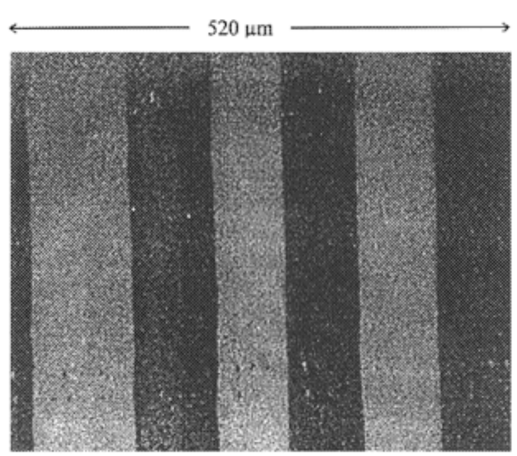


Fig. 1b (Prior Art)

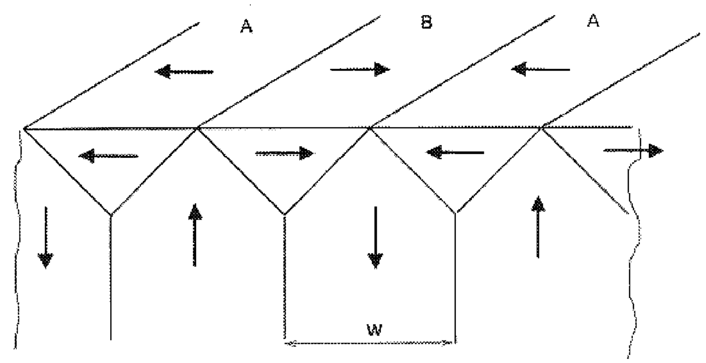


Fig. 2a (Prior Art)

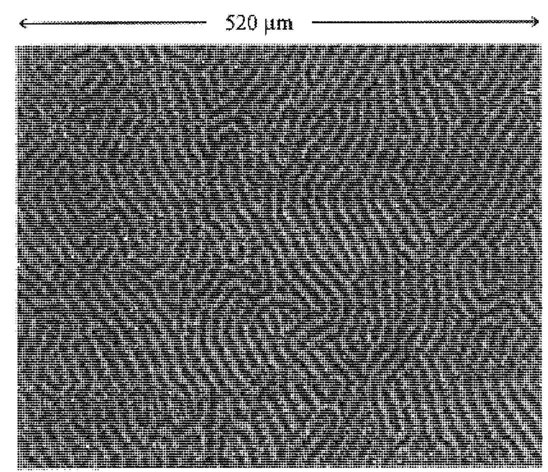
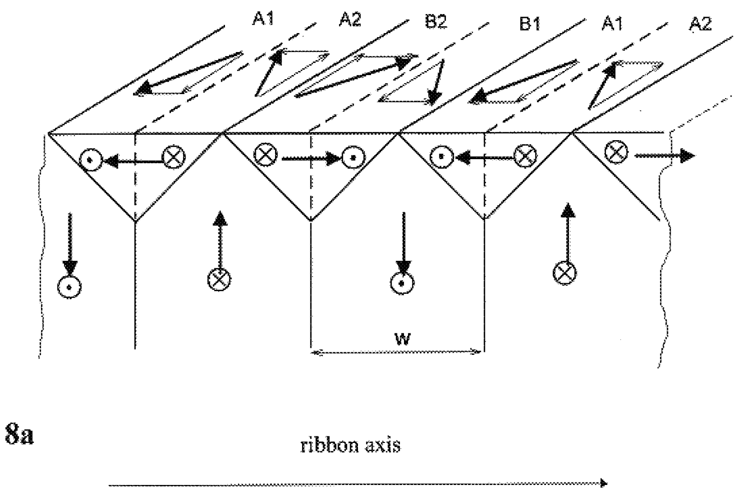


Fig. 2b

Fig. 8a



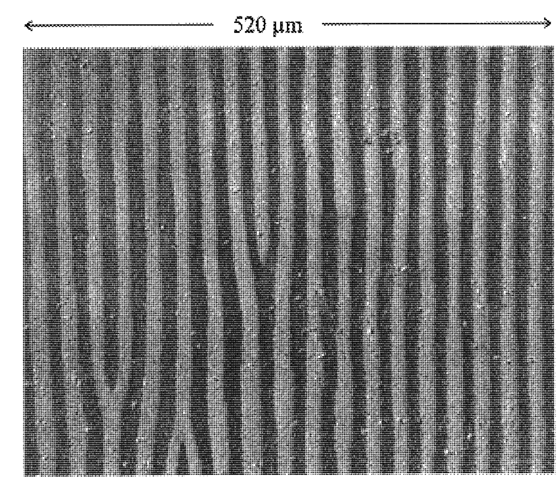


Fig. 8b

United States Patent [19]

Herzer

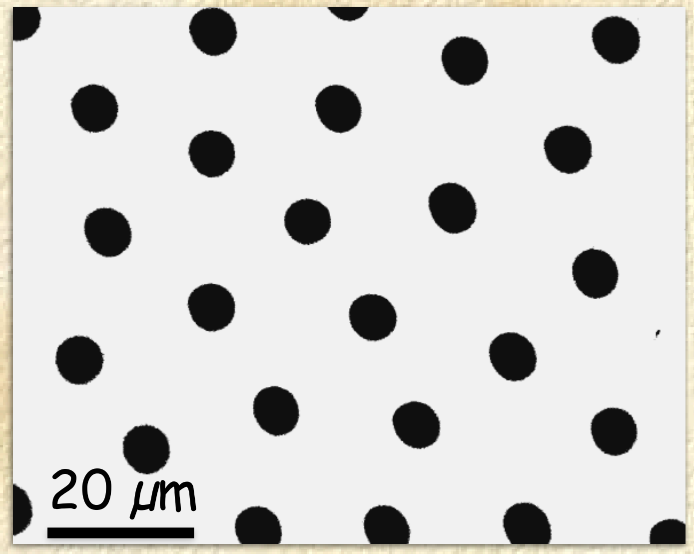
[54] **METHOD OF ANNEALING AMORPHOUS RIBBONS AND MARKER FOR ELECTRONIC ARTICLE SURVEILLANCE**

[75] Inventor: **Giselher Herzer**, Bruchkoebel, Germany

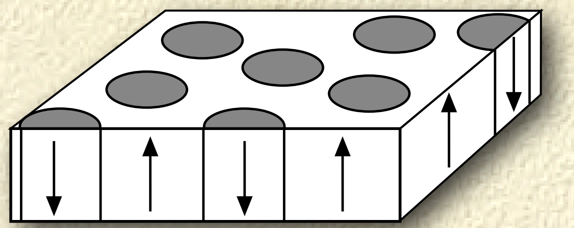
[73] Assignee: **Vacuumschmelze GmbH**, Hanau, Germany

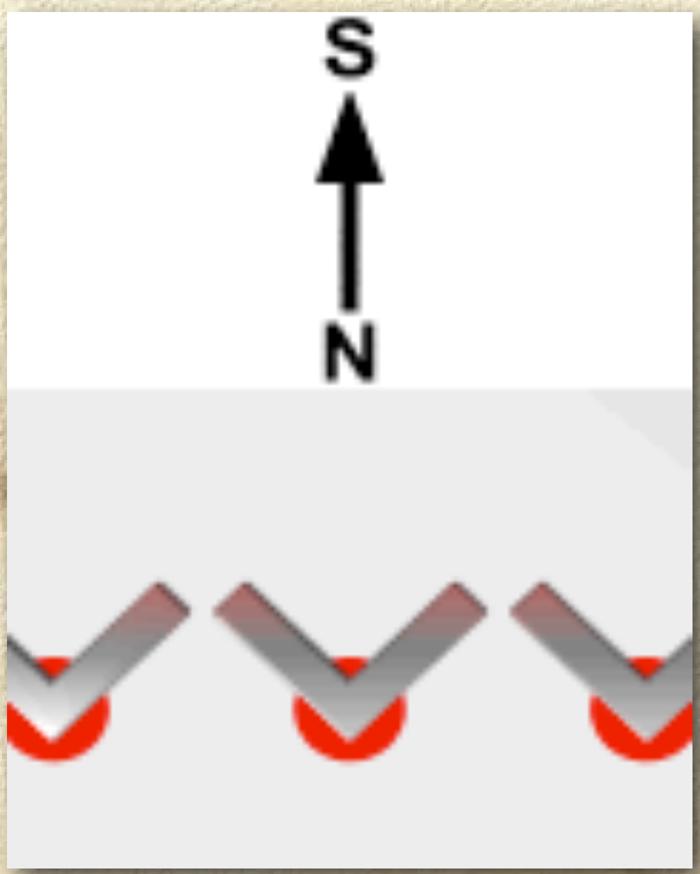
Domain Shift Register Devices

Bubble Memory



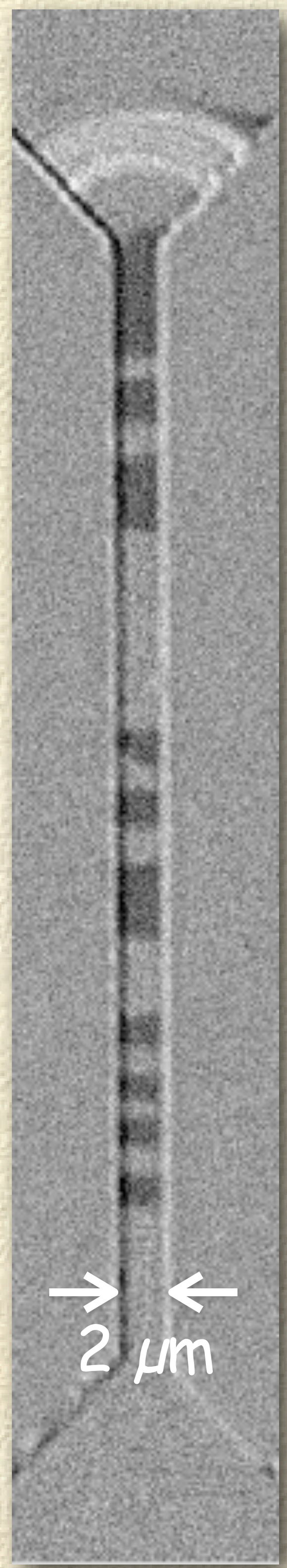
Bubble domains

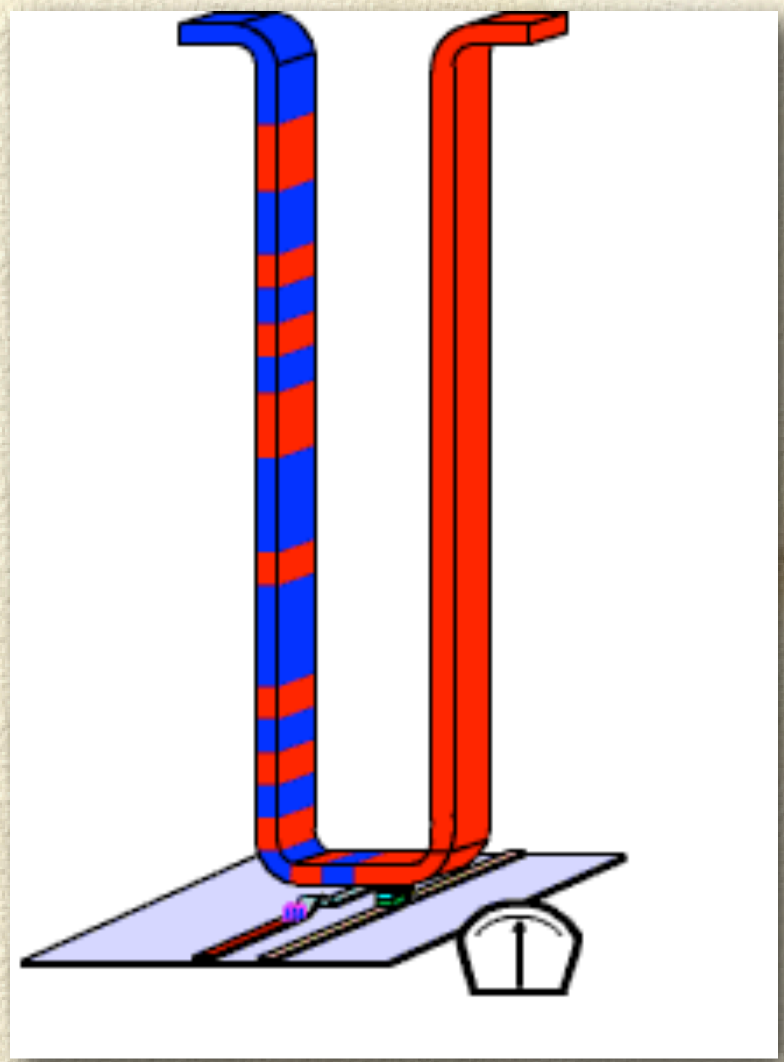




http://commons.wikimedia.org/wiki/How_bubble_memory_works

Race Track Memory

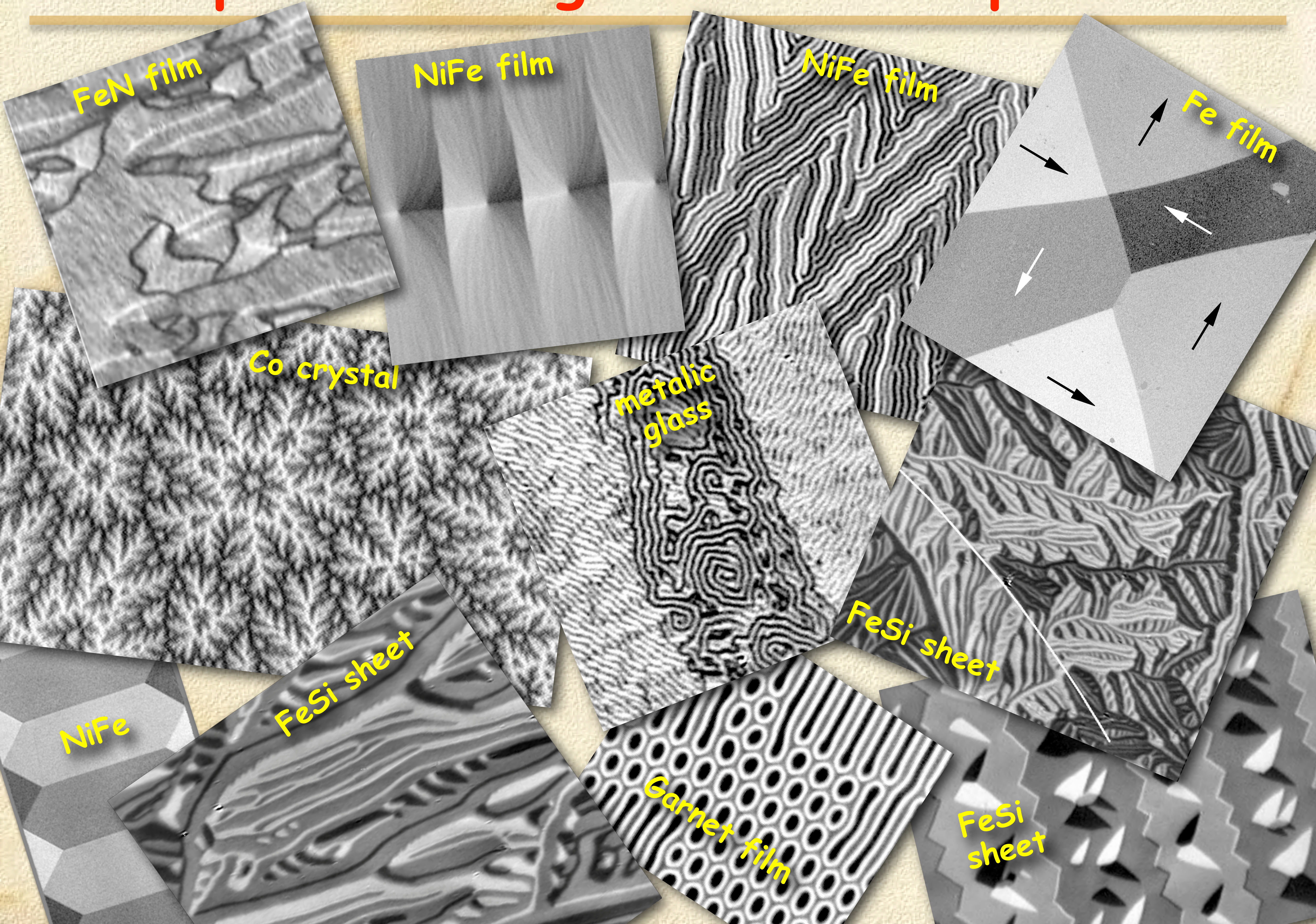




Kerr-movie of Co/Ni PMA multilayer

courtesy S. Parkin, IBM

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

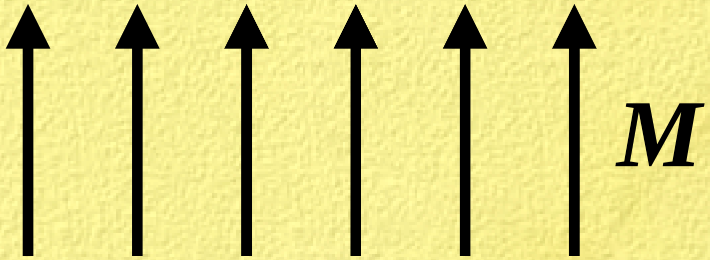
Origin of magnetic domains

Landau and Lifshitz (1935):

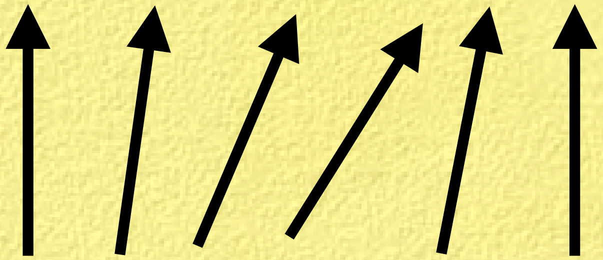
Domains are formed to minimize total energy

Exchange energy

$e_A = 0$



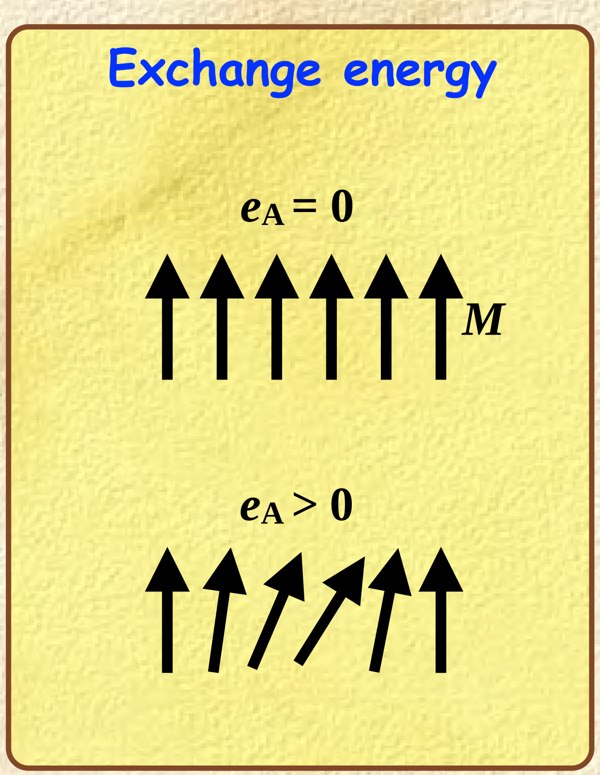
$e_A > 0$

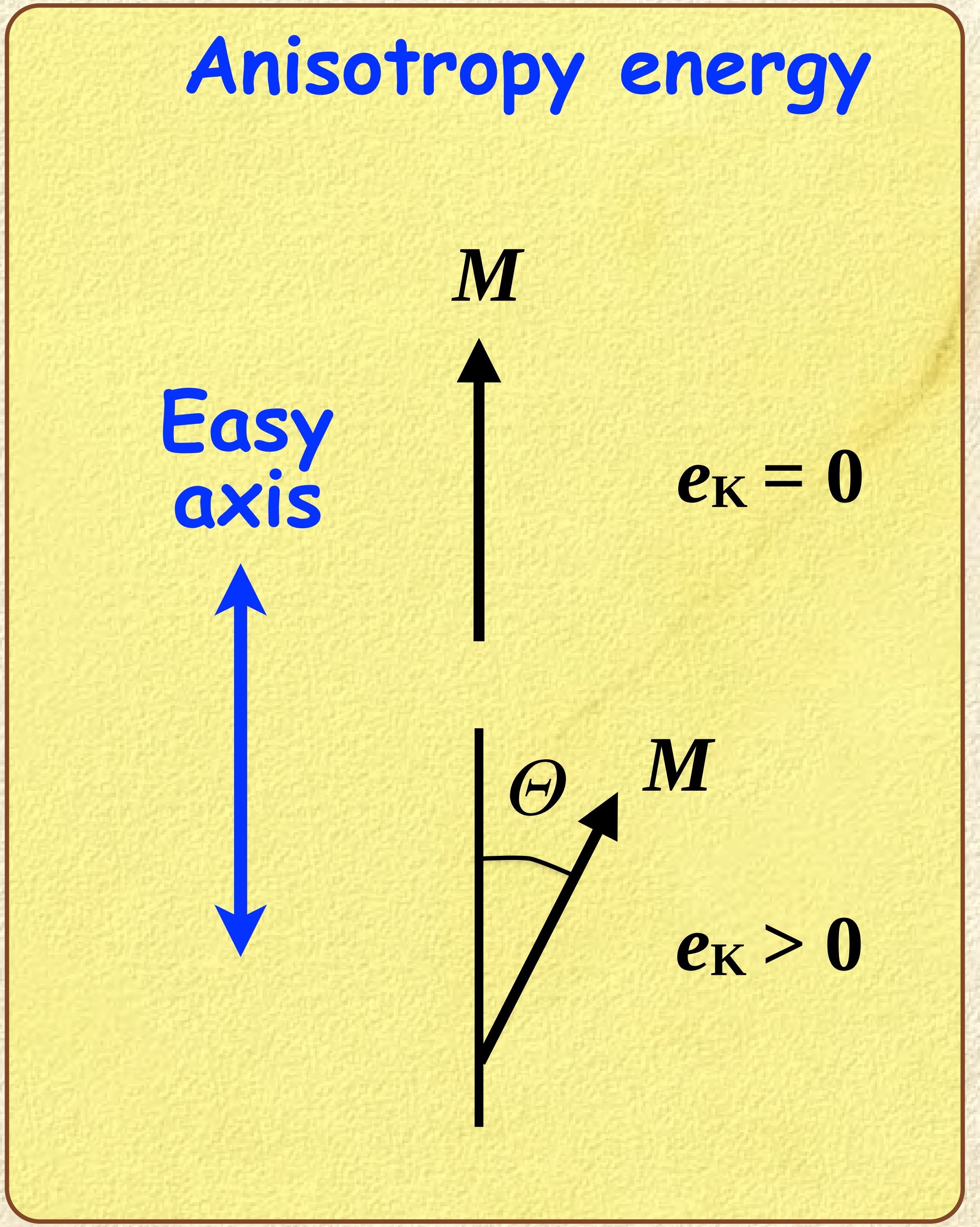


Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy





Origin of magnetic domains

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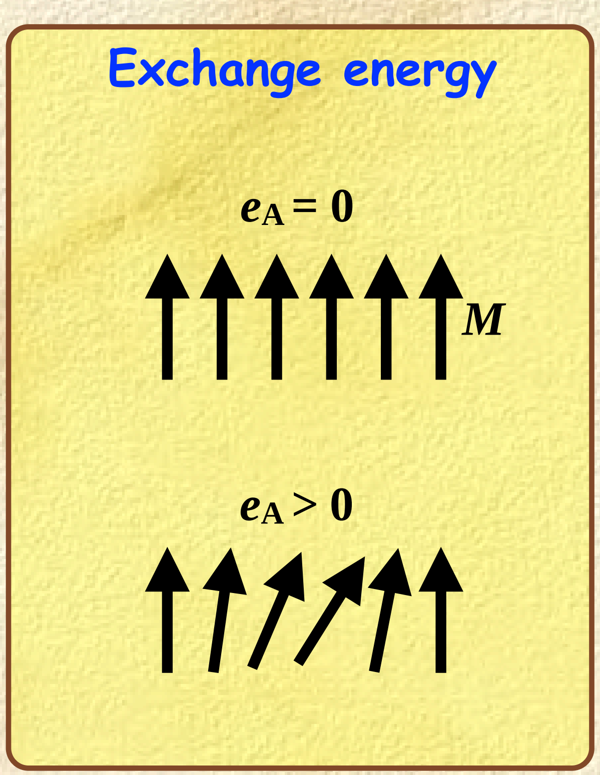
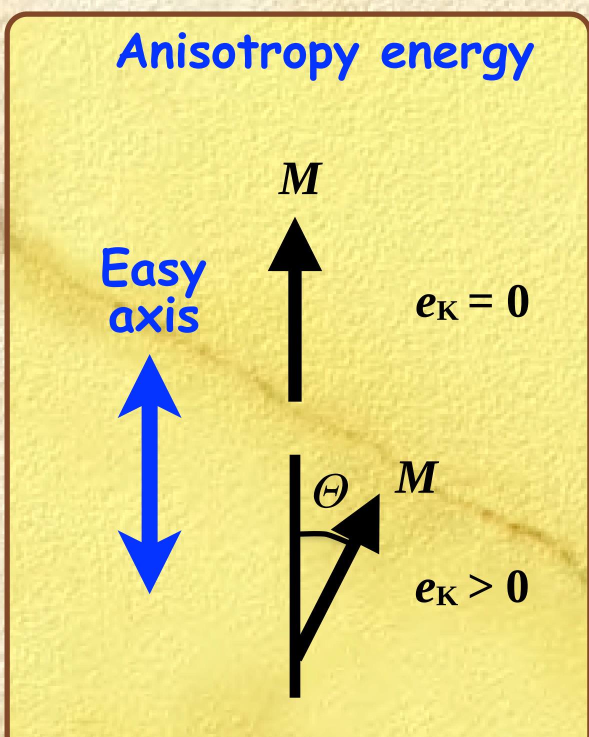
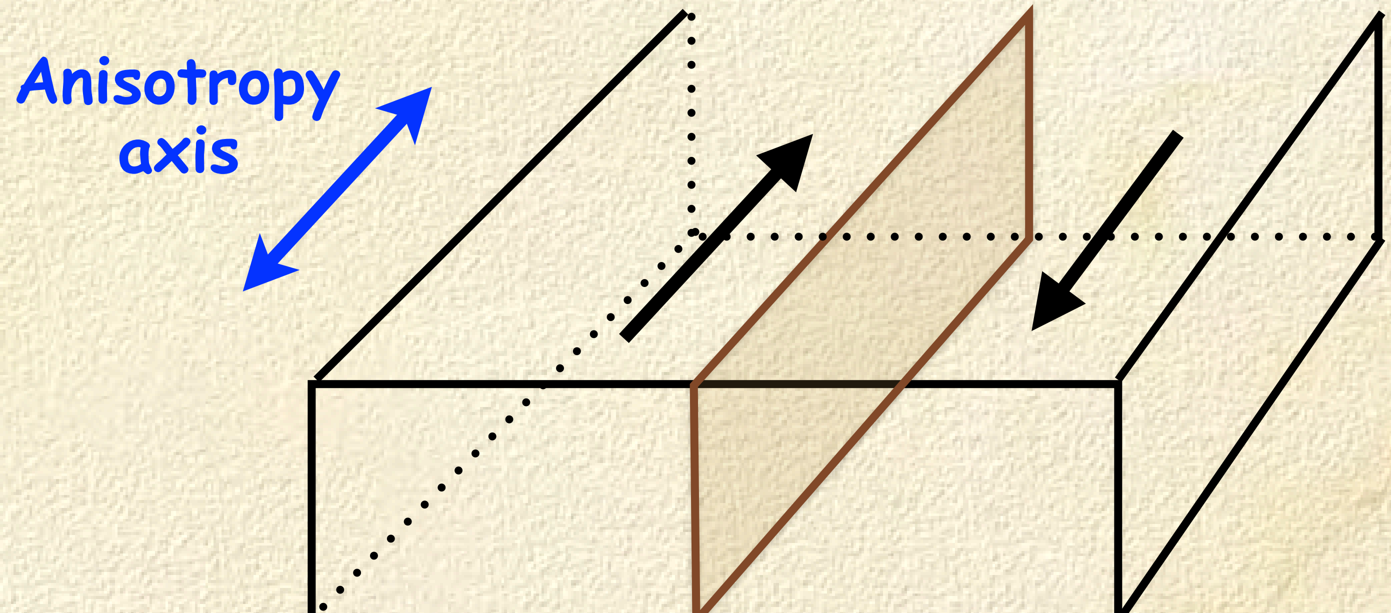
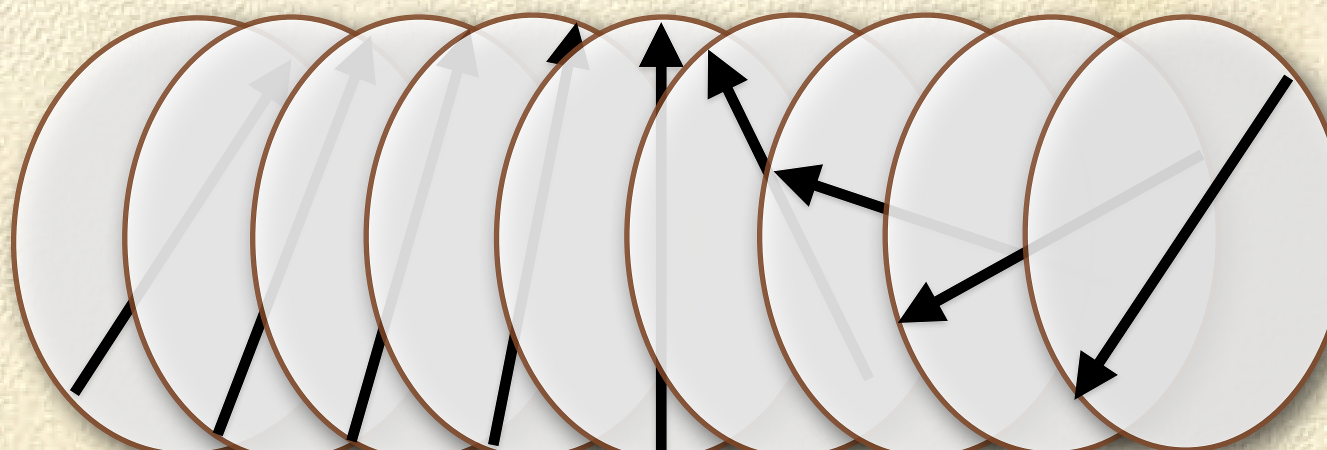






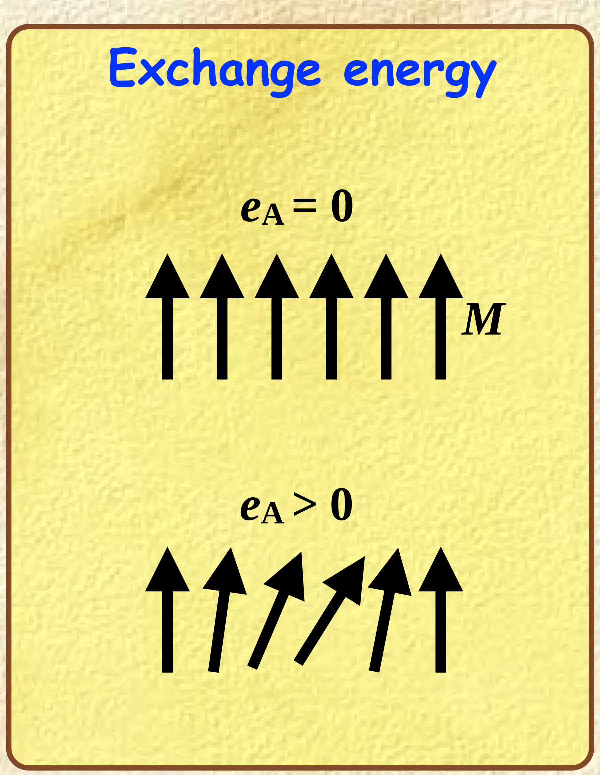


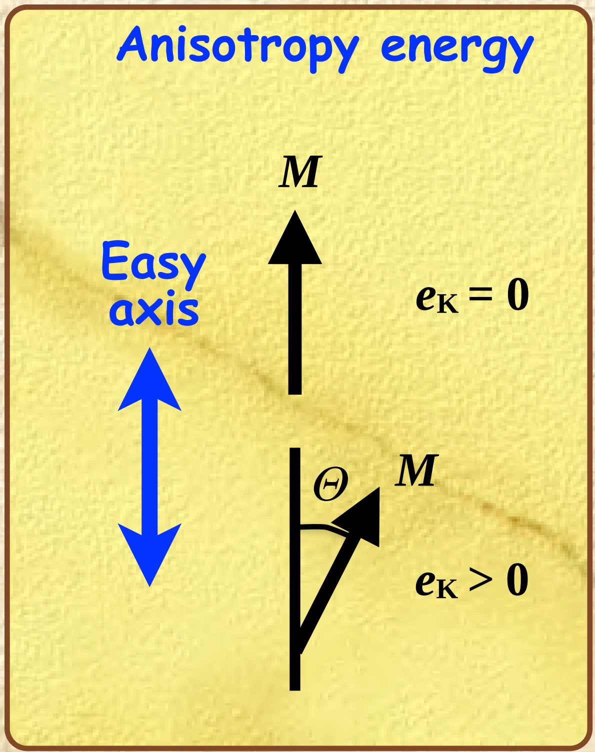
Bloch wall

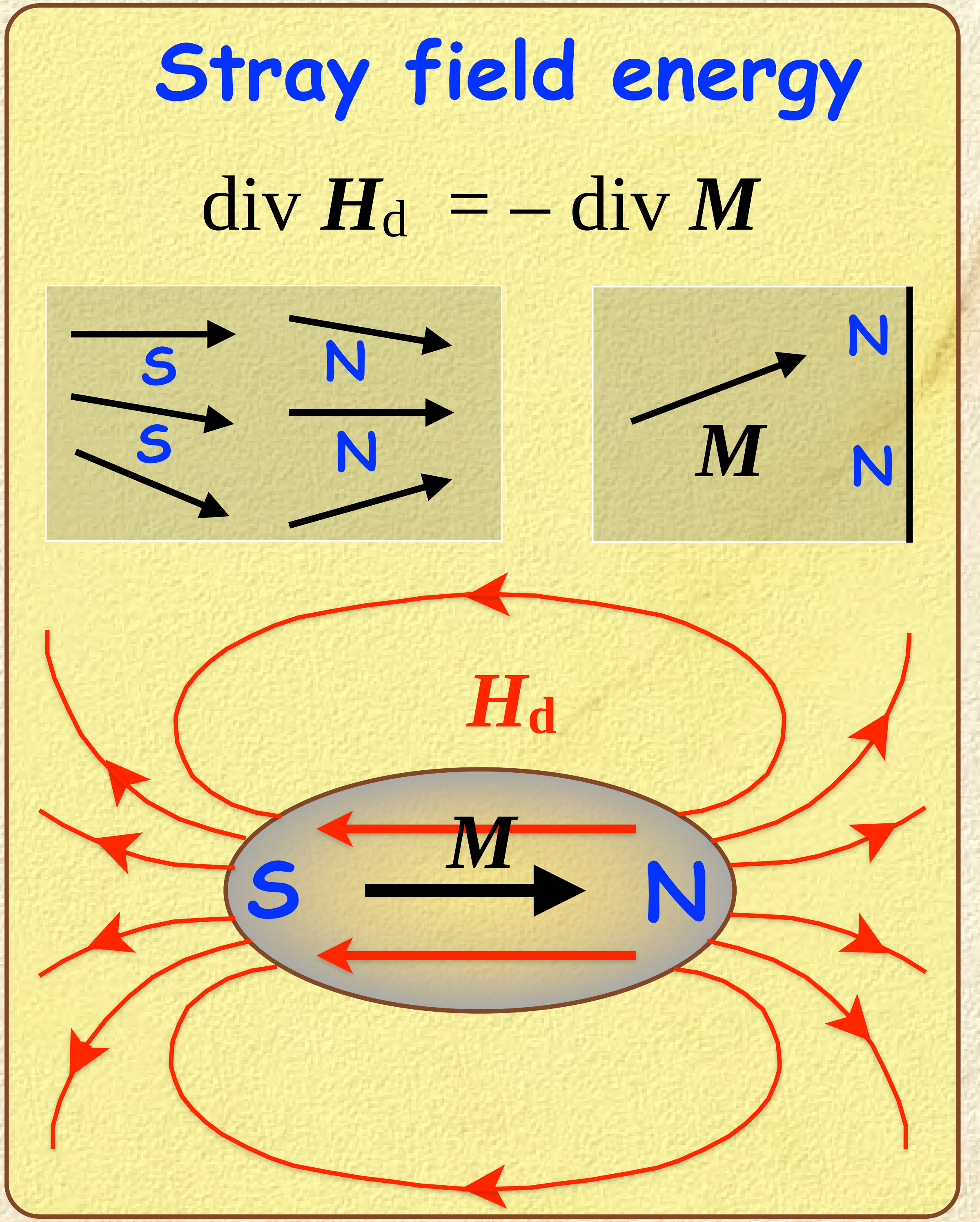
Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy







Origin of magnetic domains

Landau and Lifshitz (1935):

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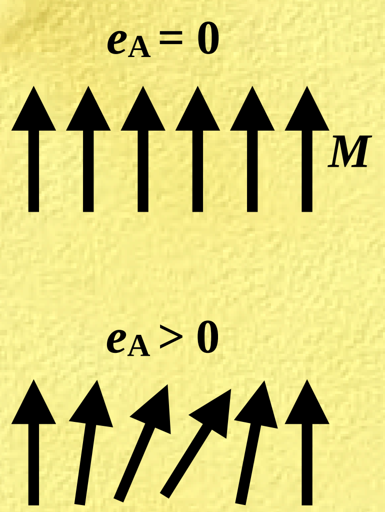
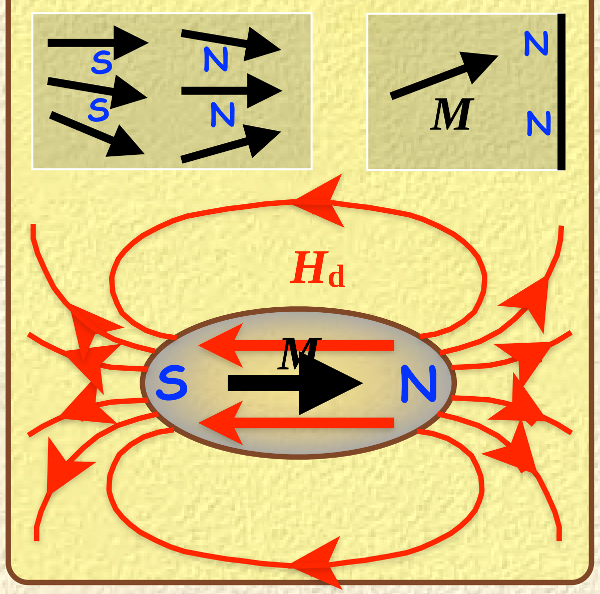
Exchange energy

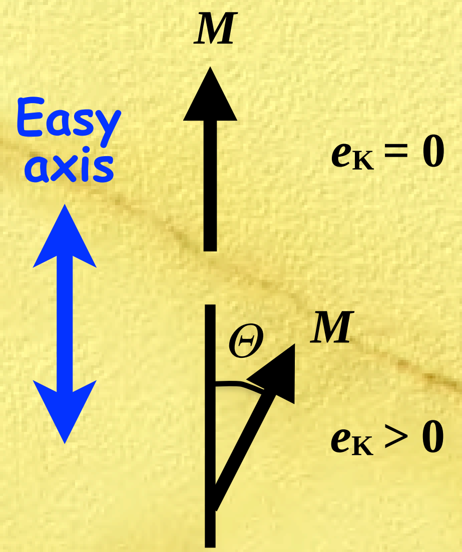


Stray field energy

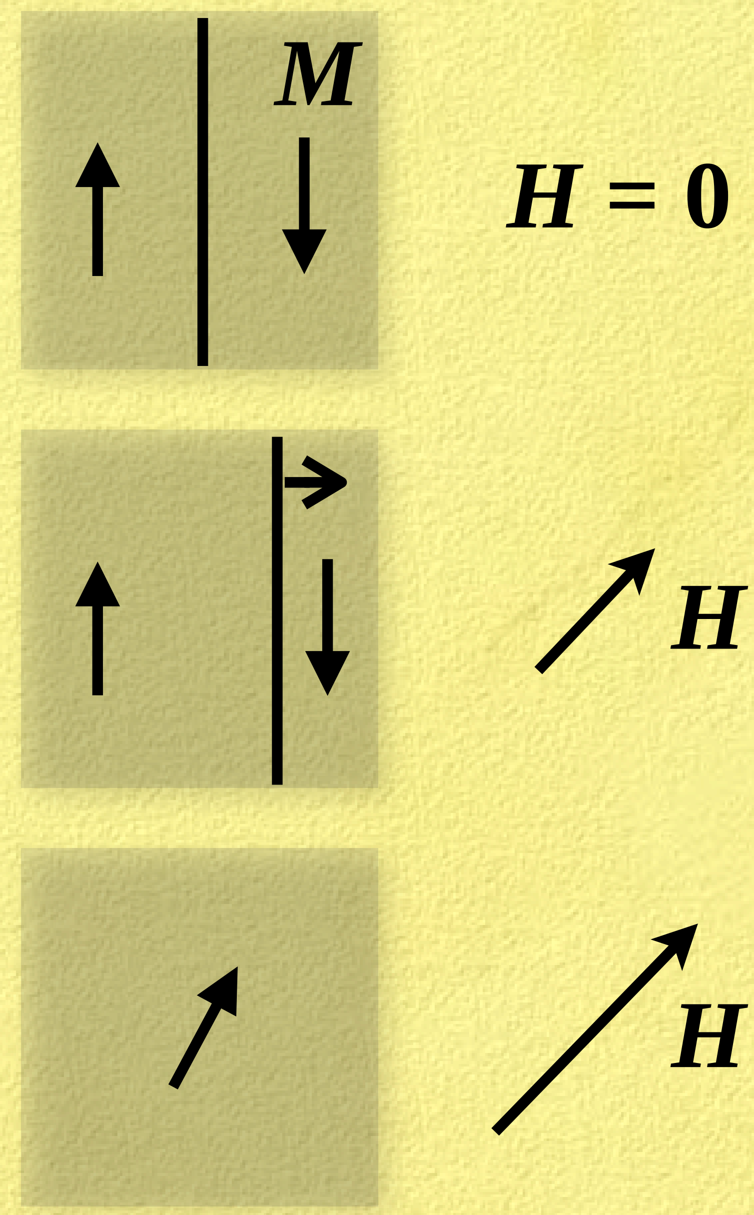
$\mathrm{div}\, \boldsymbol{H}_d = -\,\mathrm{div}\, \boldsymbol{M}$



Anisotropy energy



External field energy

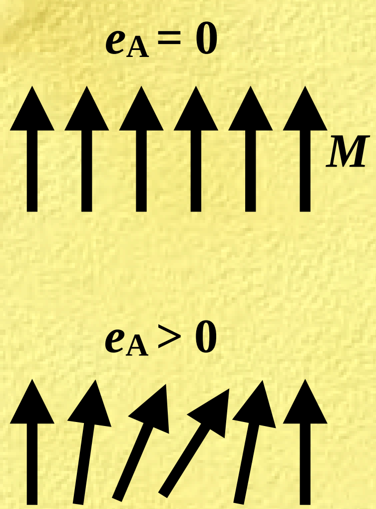


Origin of magnetic domains

Landau and Lifshitz (1935):

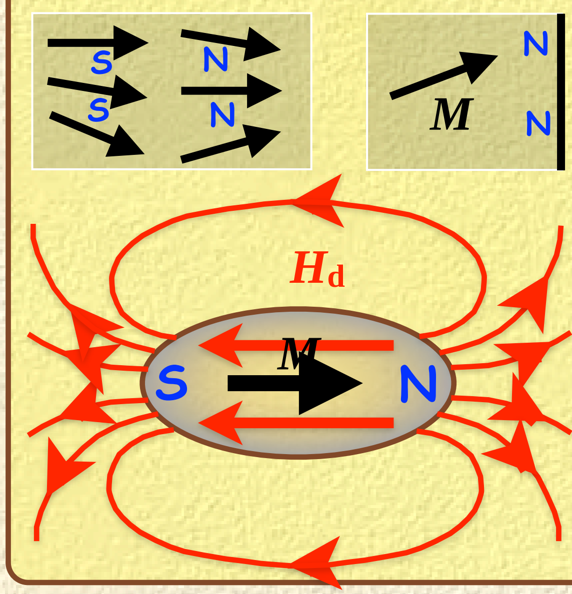
Domains are formed to minimize total energy

Exchange energy

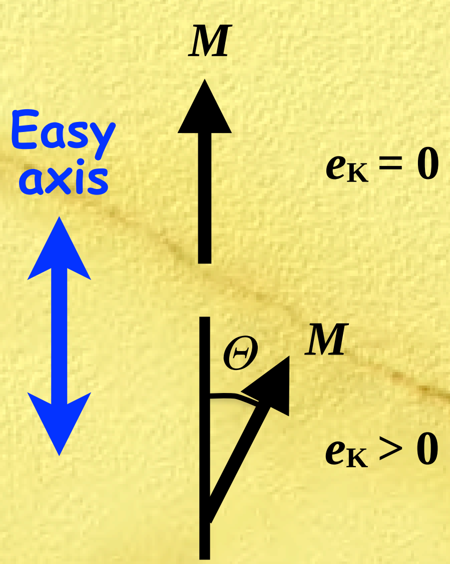


Stray field energy

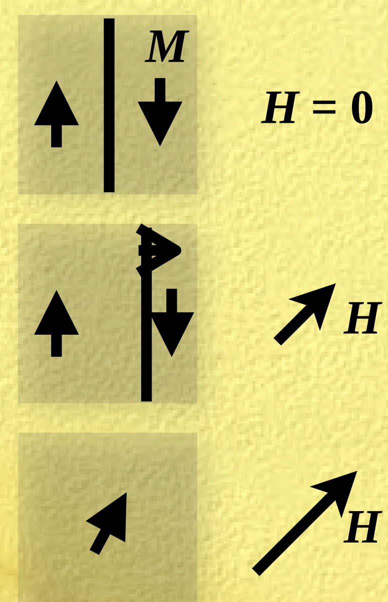
$\mathrm{div}\, \boldsymbol{H}_d = -\,\mathrm{div}\, \boldsymbol{M}$



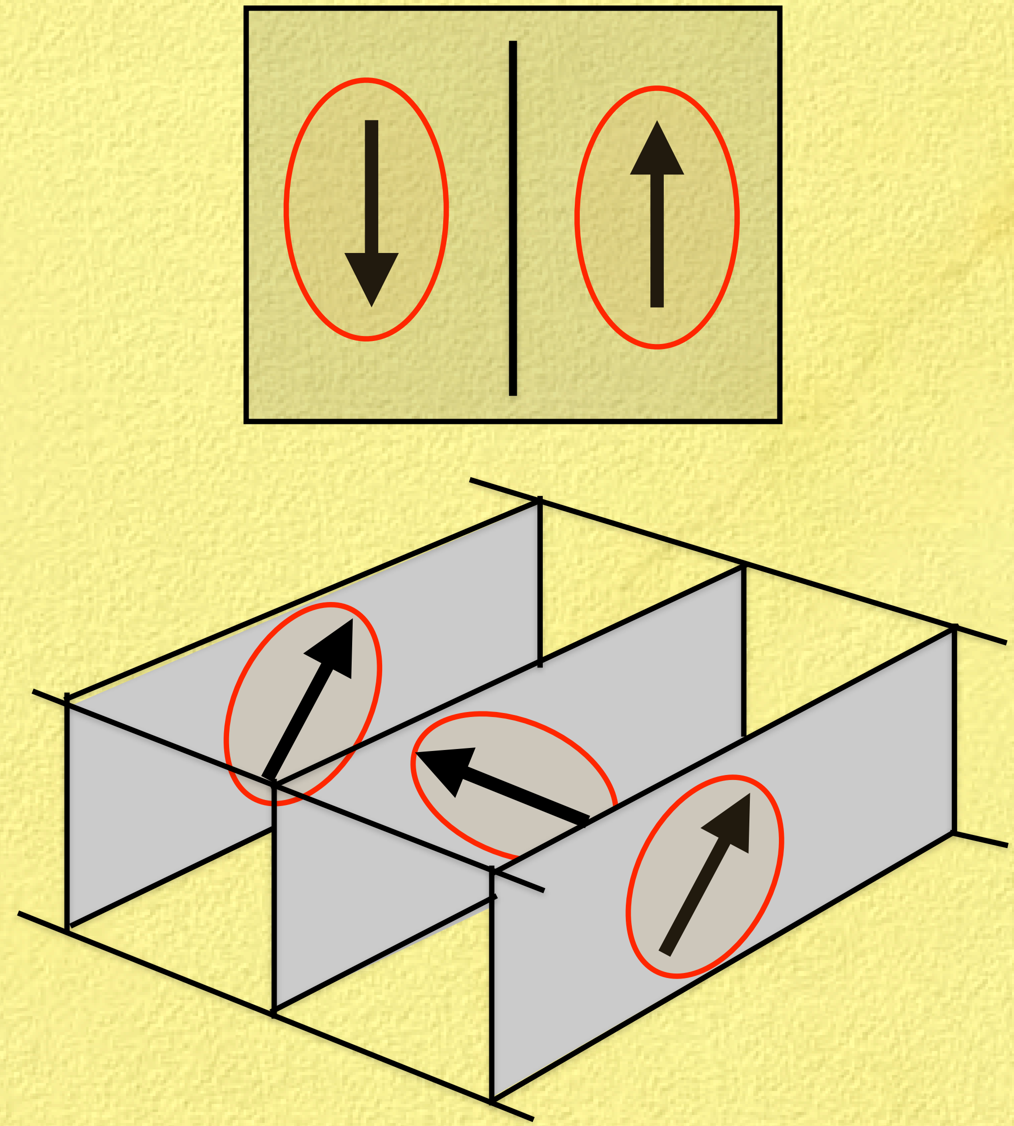
Anisotropy energy



External field energy

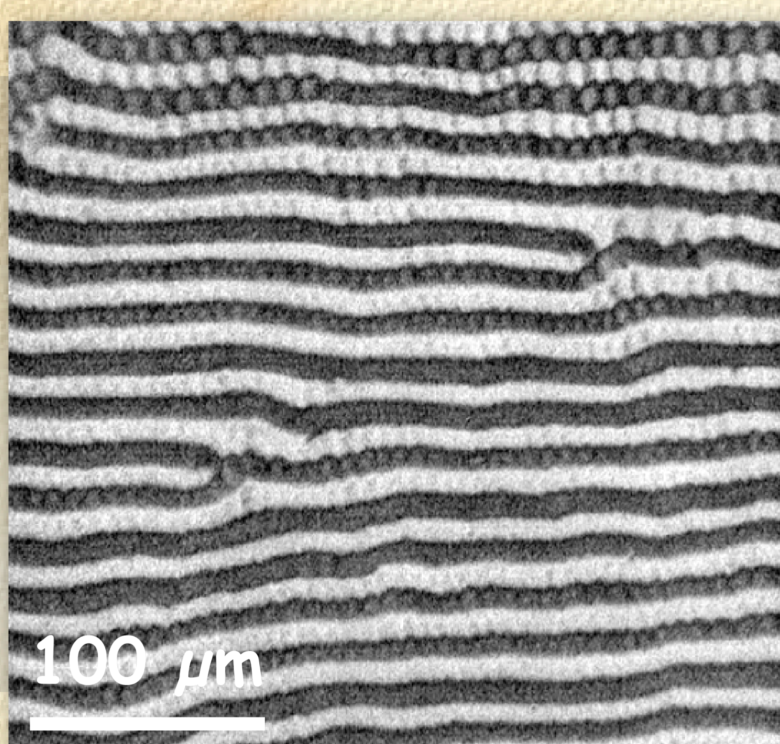


Magnetostrictive self energy



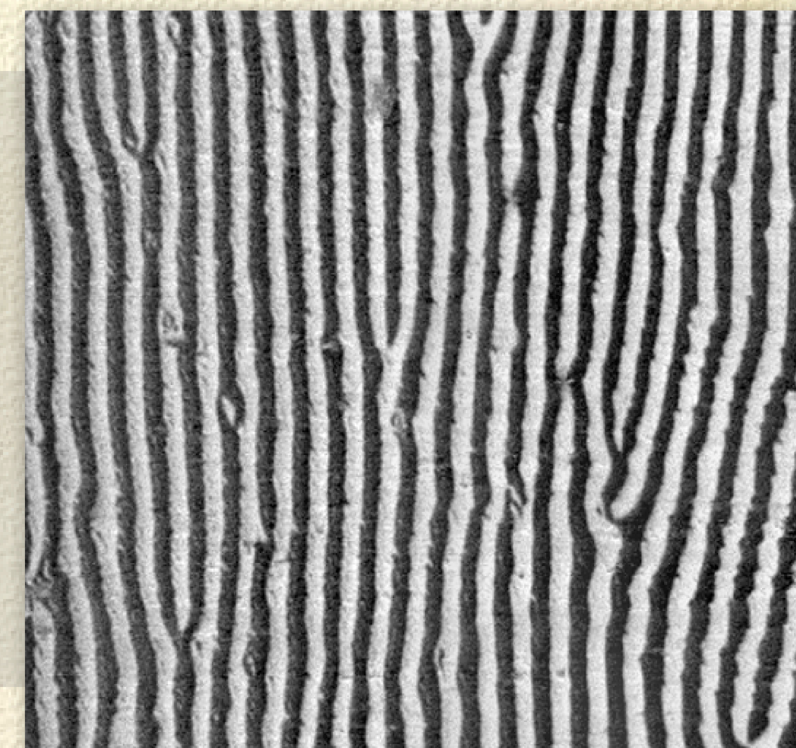
Magnetostriction and domains

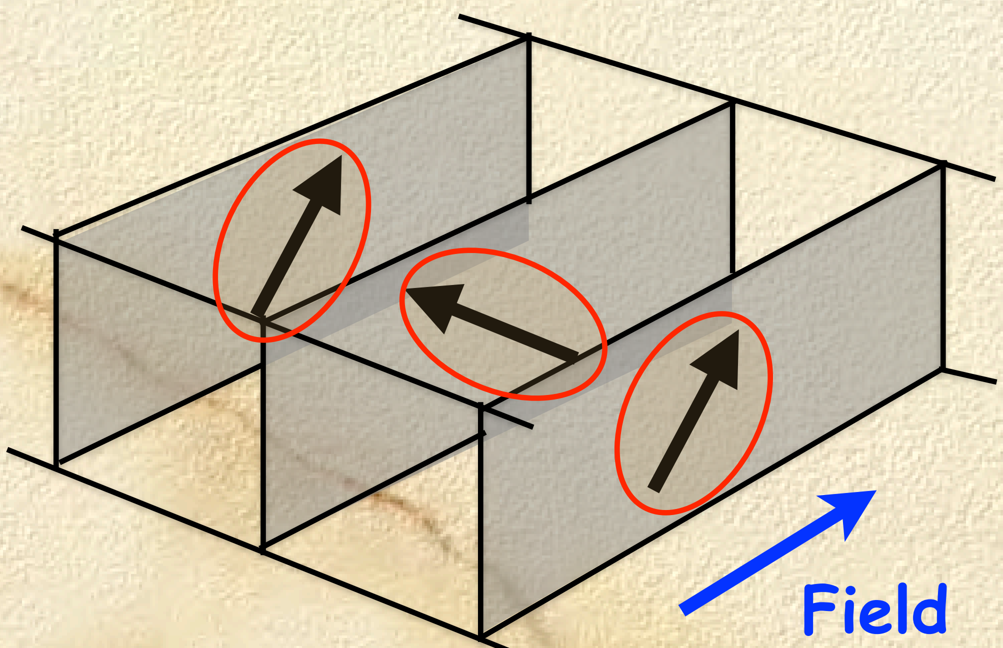
Amorphous ribbon with zero magnetostriction

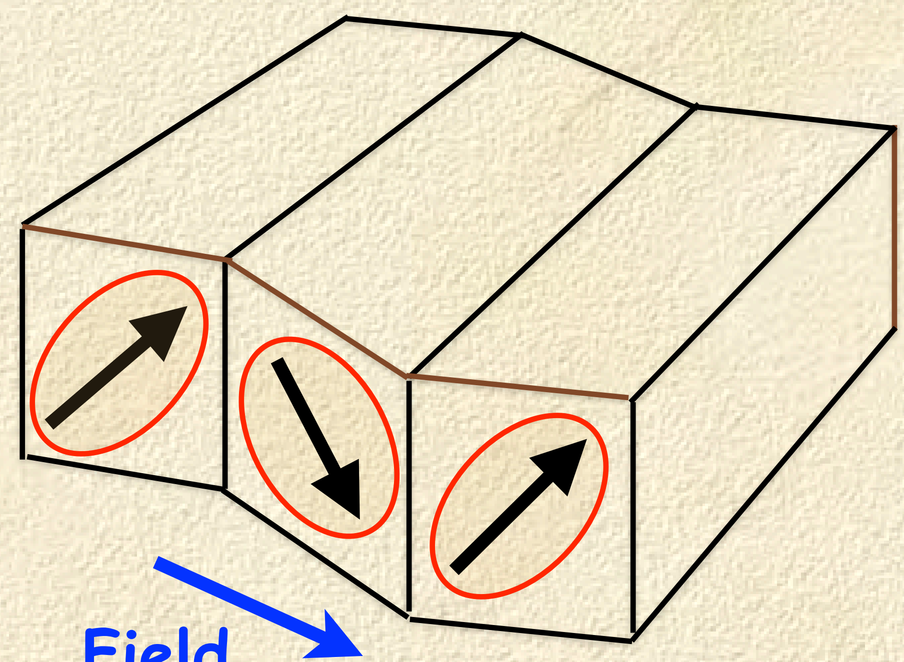


Ribbon axis = Field axis

Amorphous ribbon with positive magnetostriction

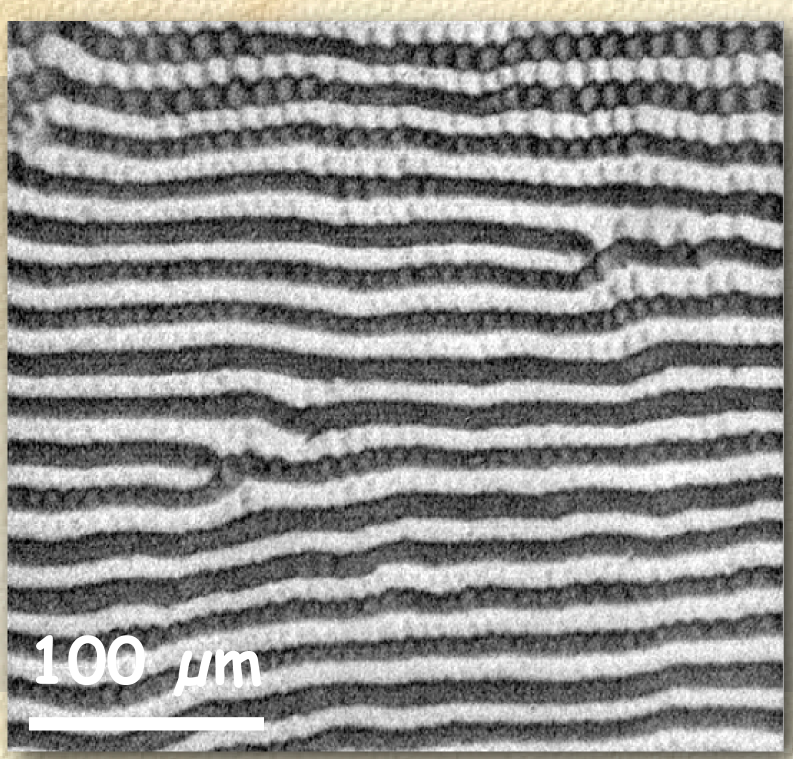






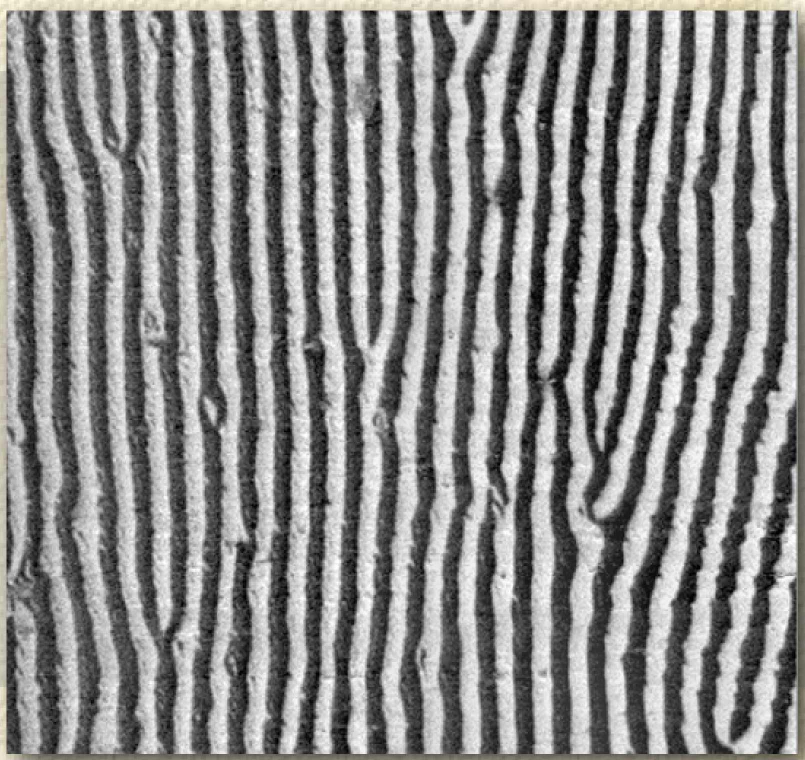
Magnetostriction and domains

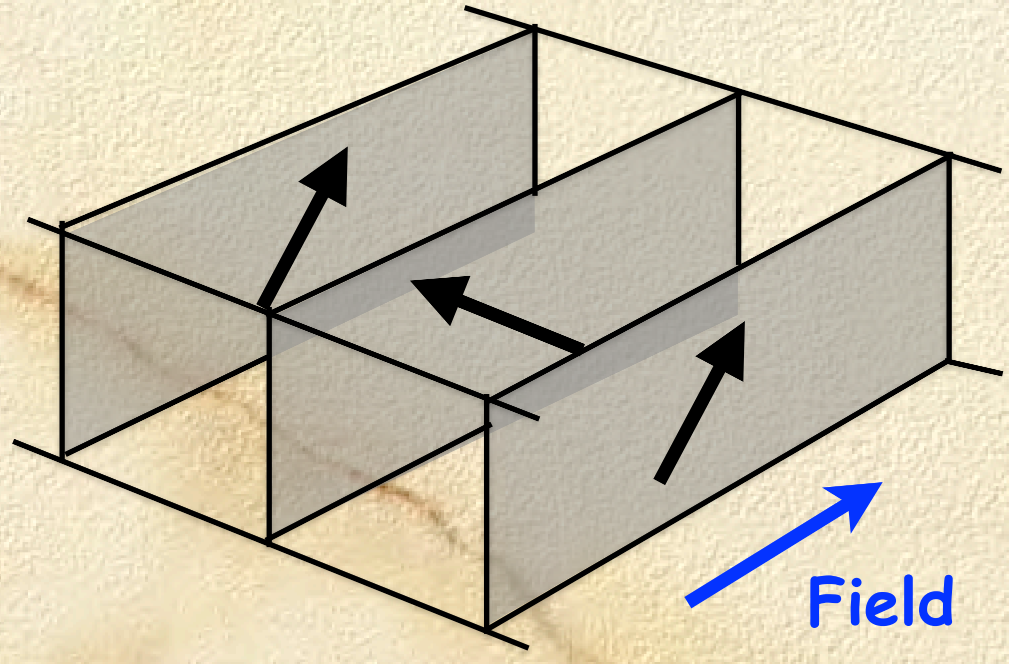
Amorphous ribbon with zero magnetostriction

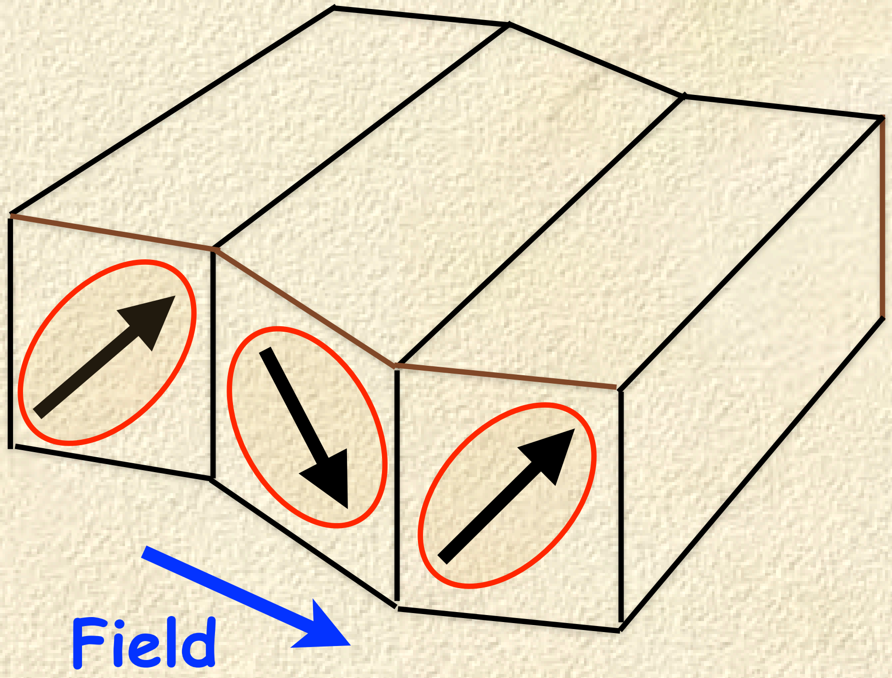


Ribbon axis = Field axis

Amorphous ribbon with positive magnetostriction







Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy

Origin of magnetic domains

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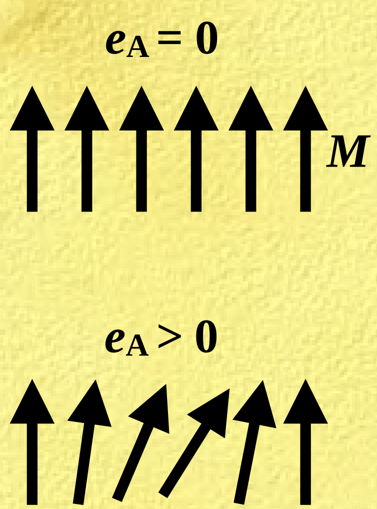
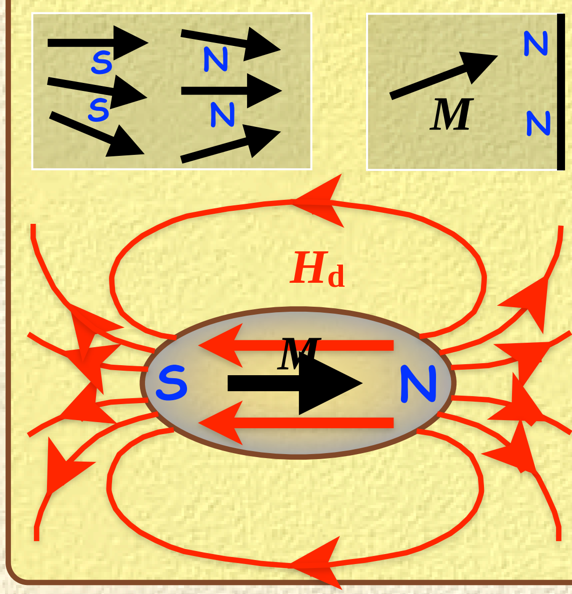
Exchange energy

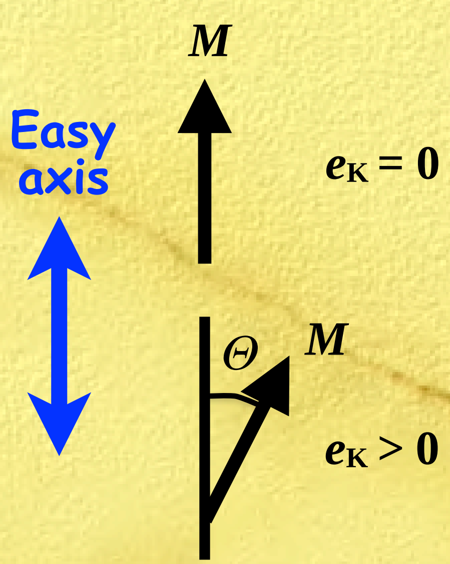


Stray field energy

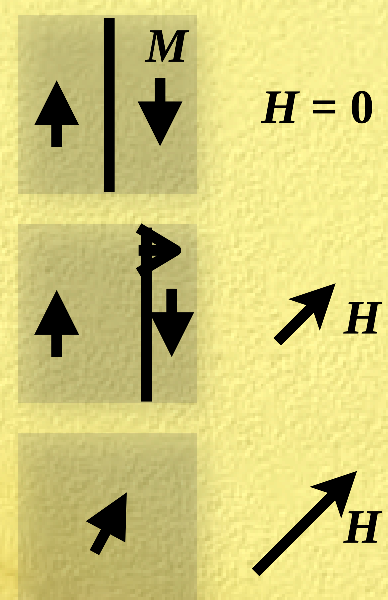
$\mathrm{div}\, \boldsymbol{H}_d = -\,\mathrm{div}\, \boldsymbol{M}$



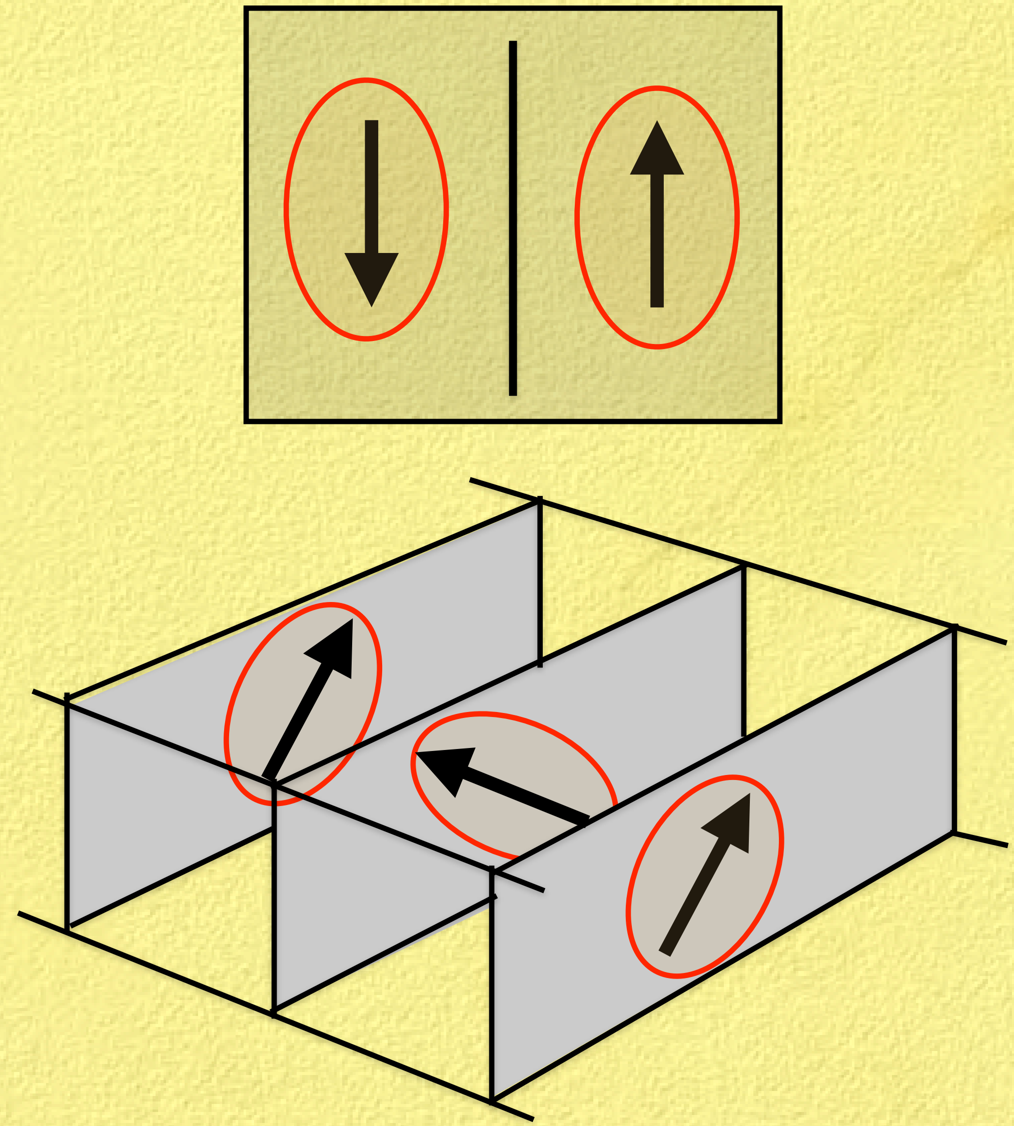
Anisotropy energy



External field energy



Magnetostrictive self energy



Origin of magnetic domains

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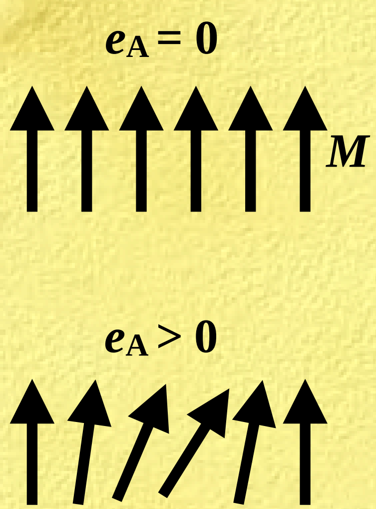
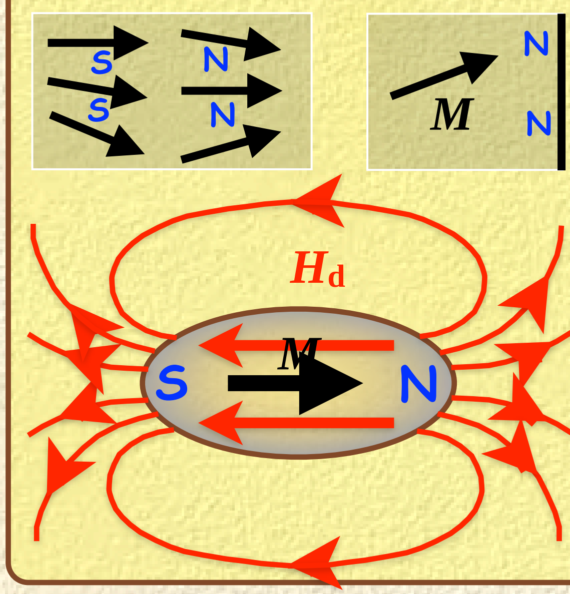
Exchange energy

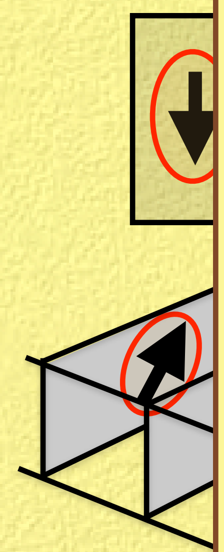


Stray field energy

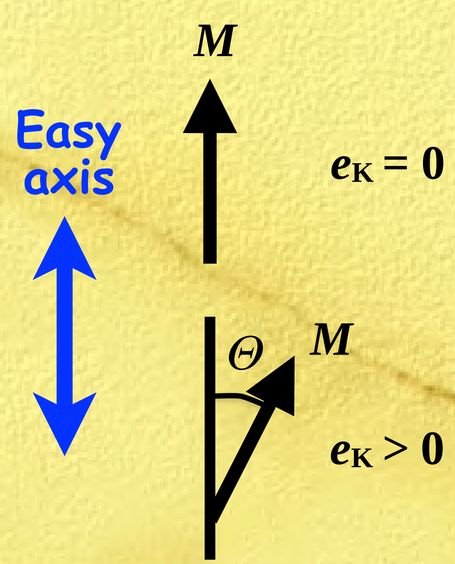
div $\boldsymbol{H}_d$ = – div $\boldsymbol{M}$



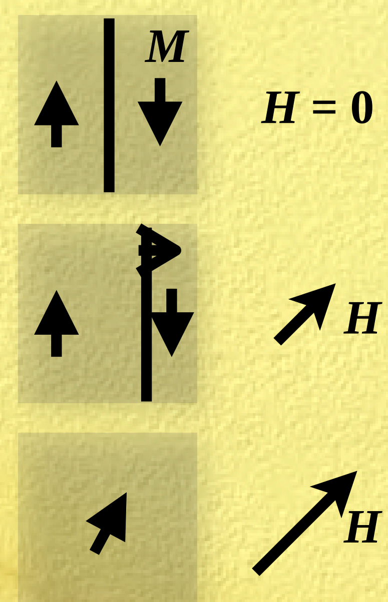
Magne
sel



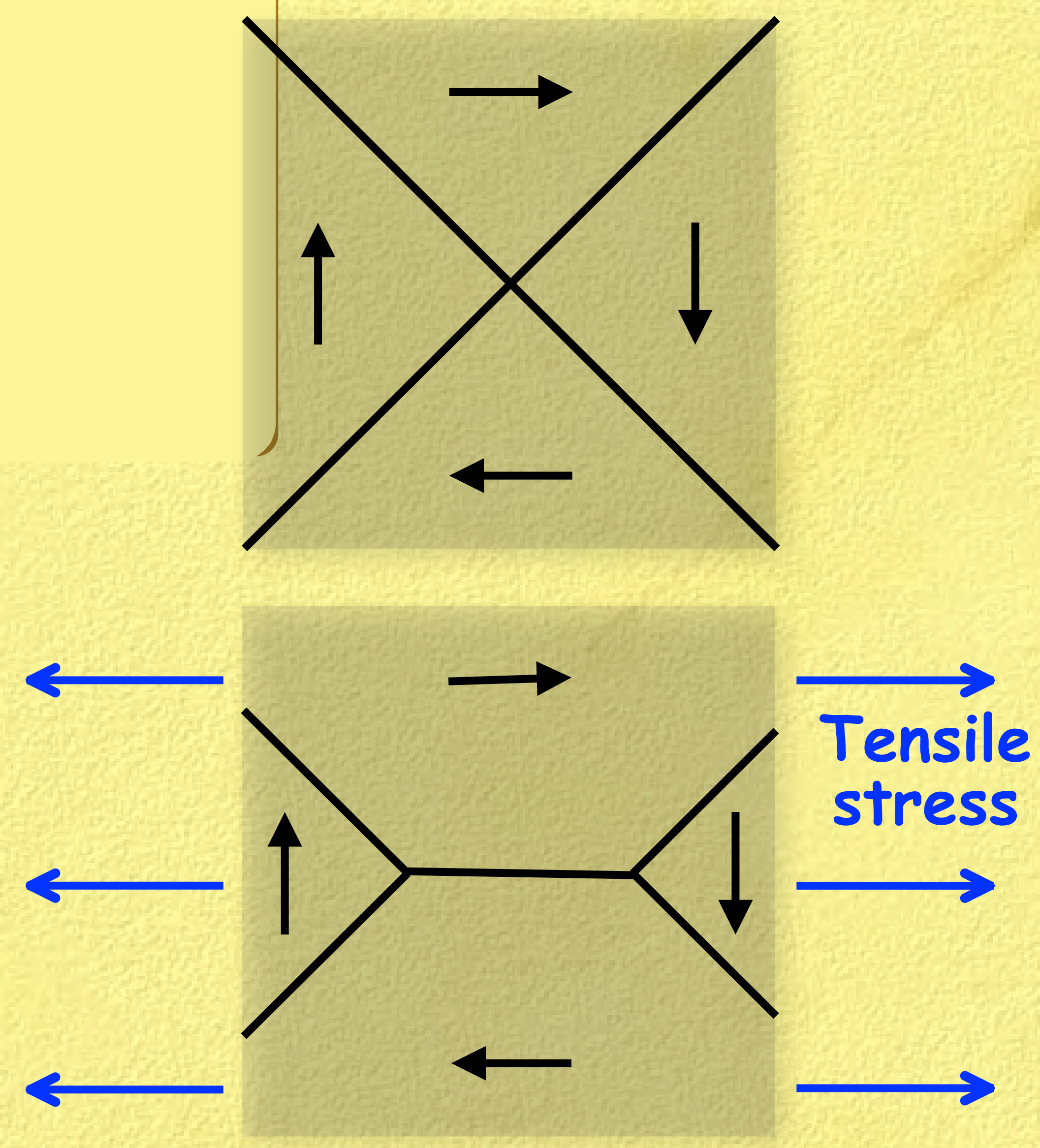
Anisotropy energy



External field energy



External stress energy



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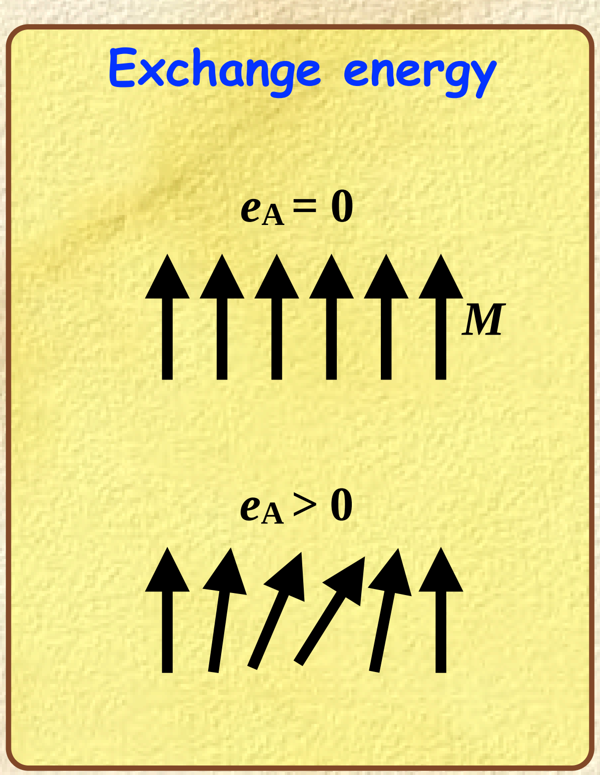
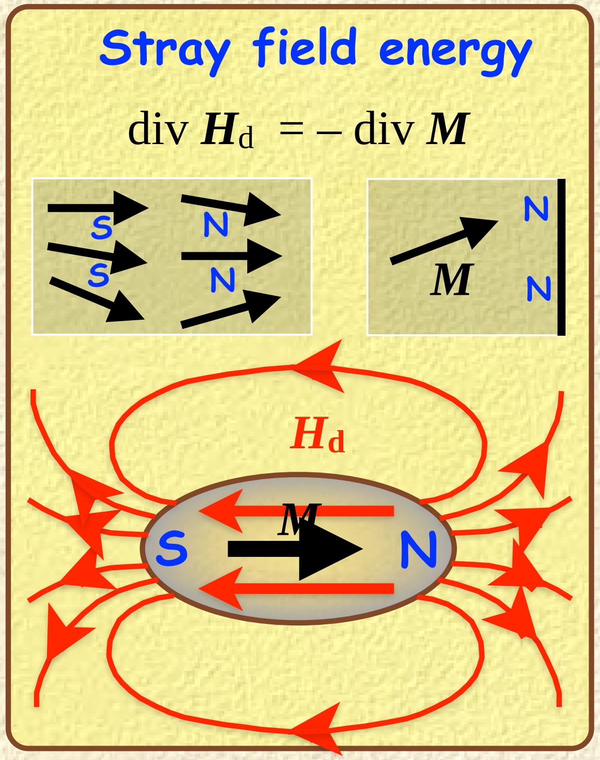
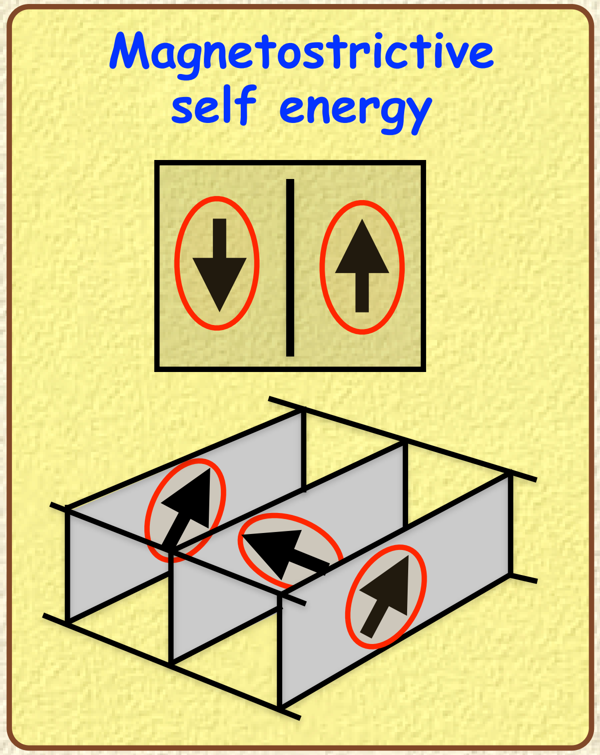
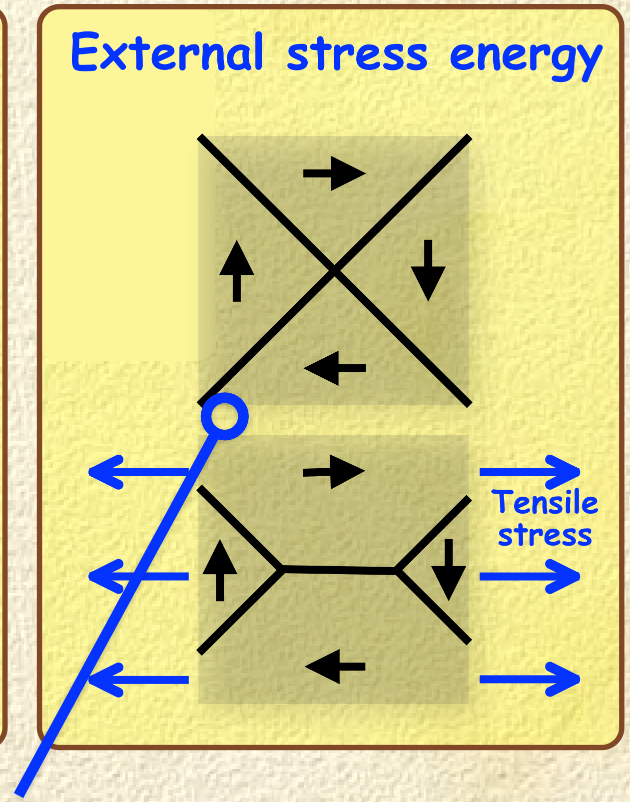
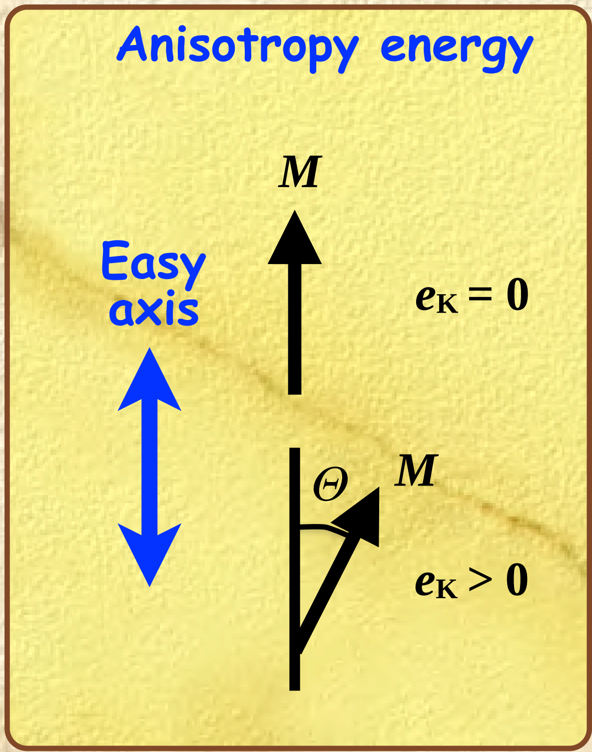
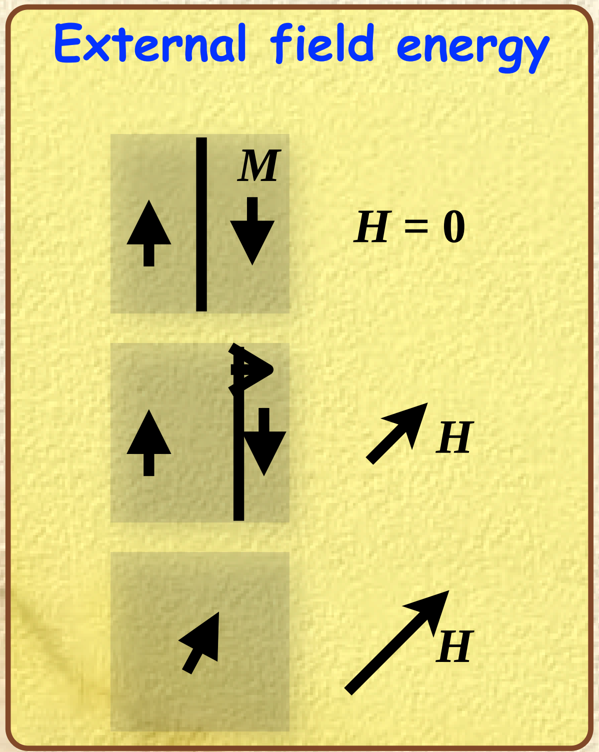










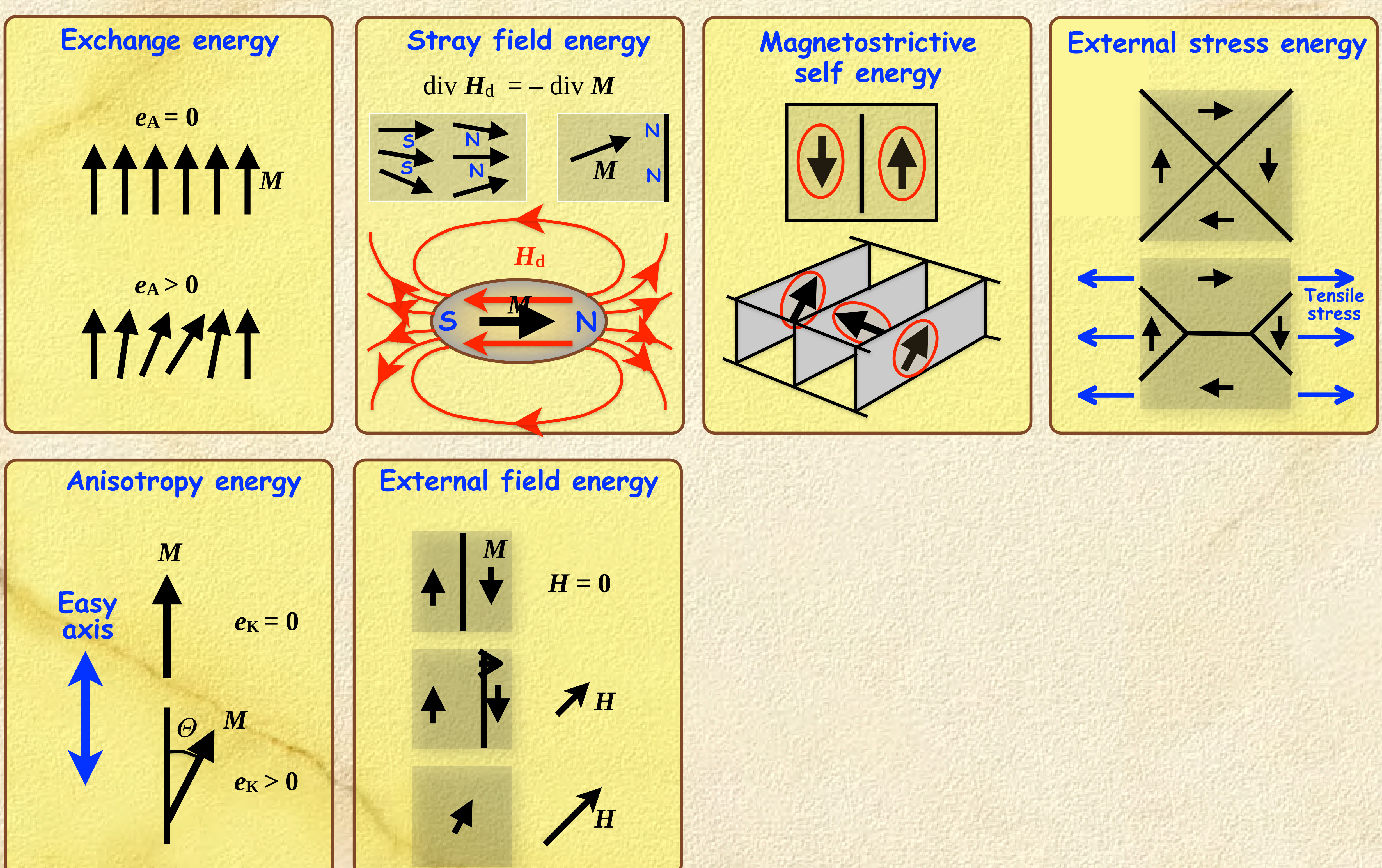


Can create dominating anisotropy when magnetocrystalline anisotropy is lacking (stress-induced anisotropy)

Origin of magnetic domains

Landau and Lifshitz (1935):

Domains are formed to minimize total energy



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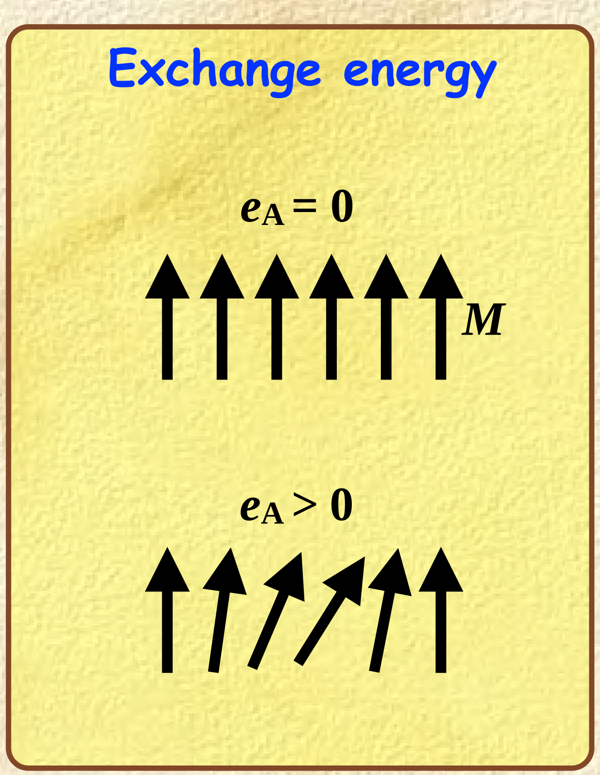
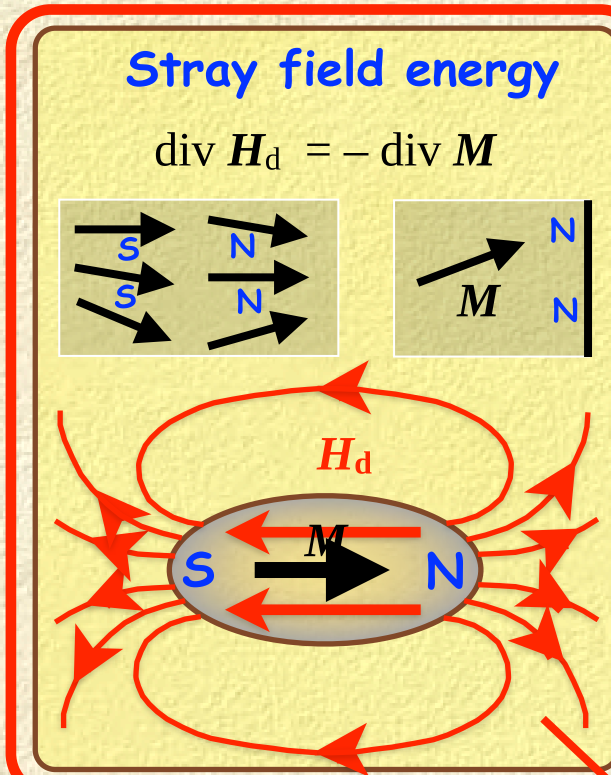
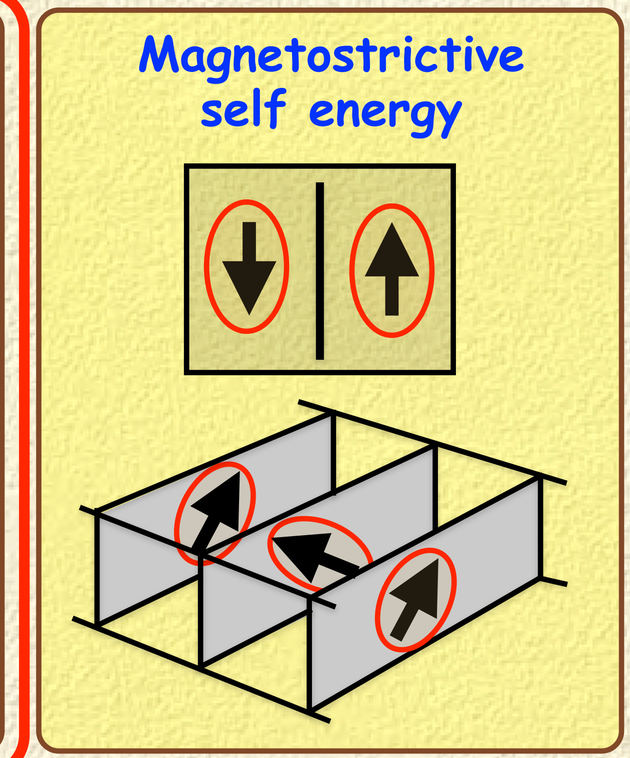
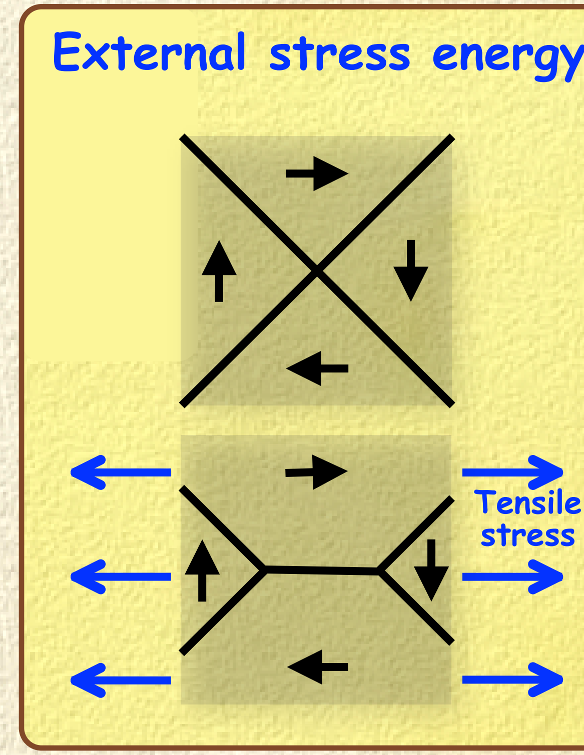
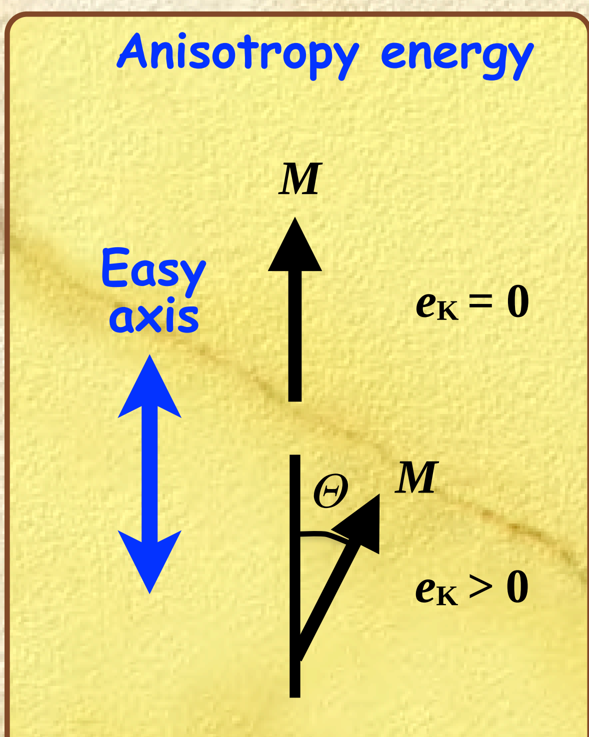
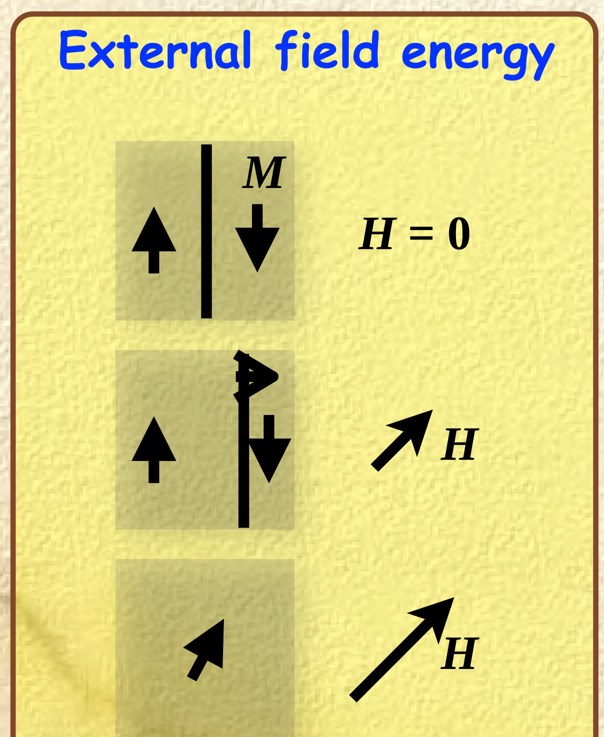












$$E_s = -\tfrac{1}{2}\mu_0 \int \boldsymbol{H}_d \boldsymbol{M}\, dV$$

Sample-volume

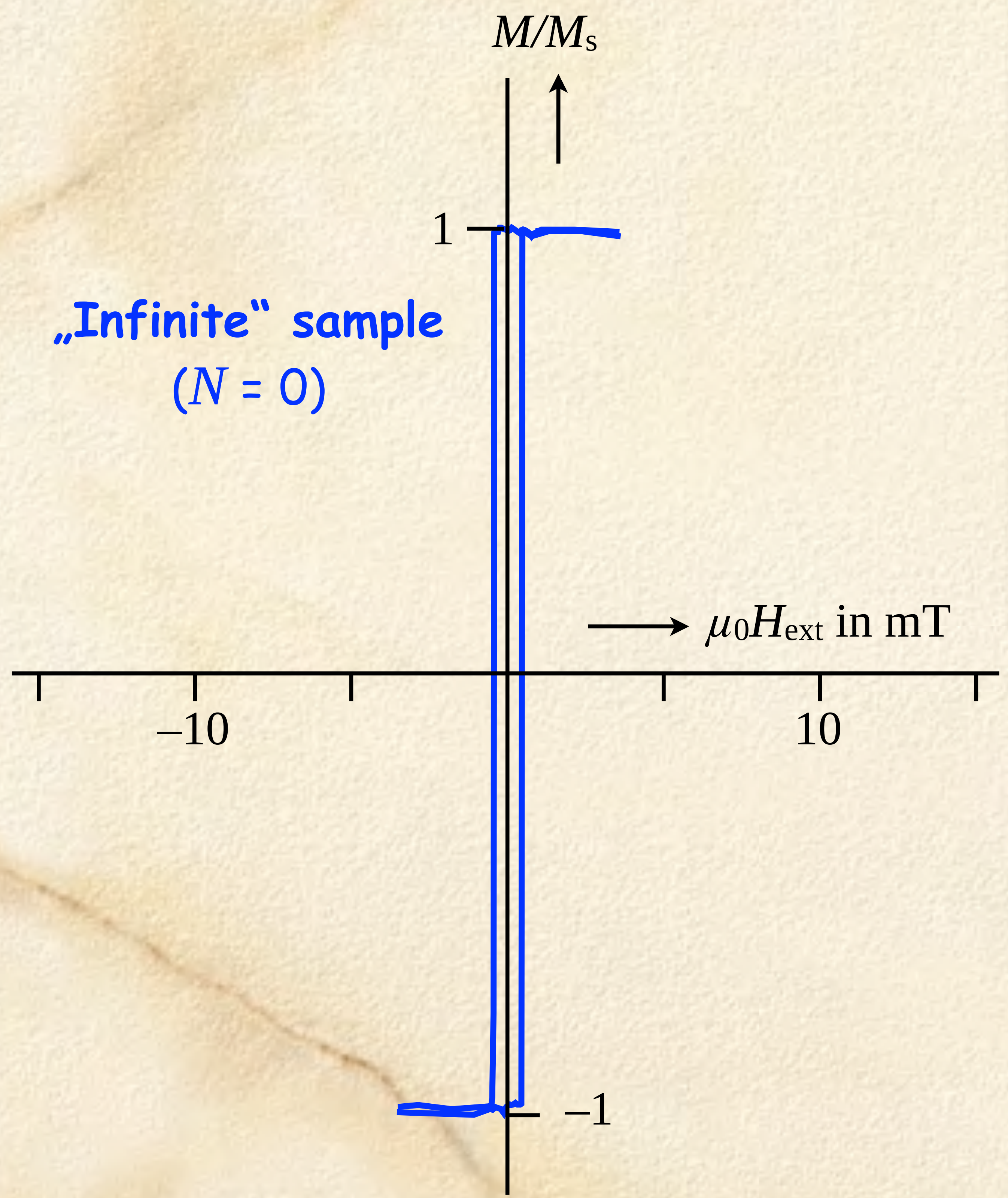
With $\boldsymbol{H}_d = -N\boldsymbol{M}$:

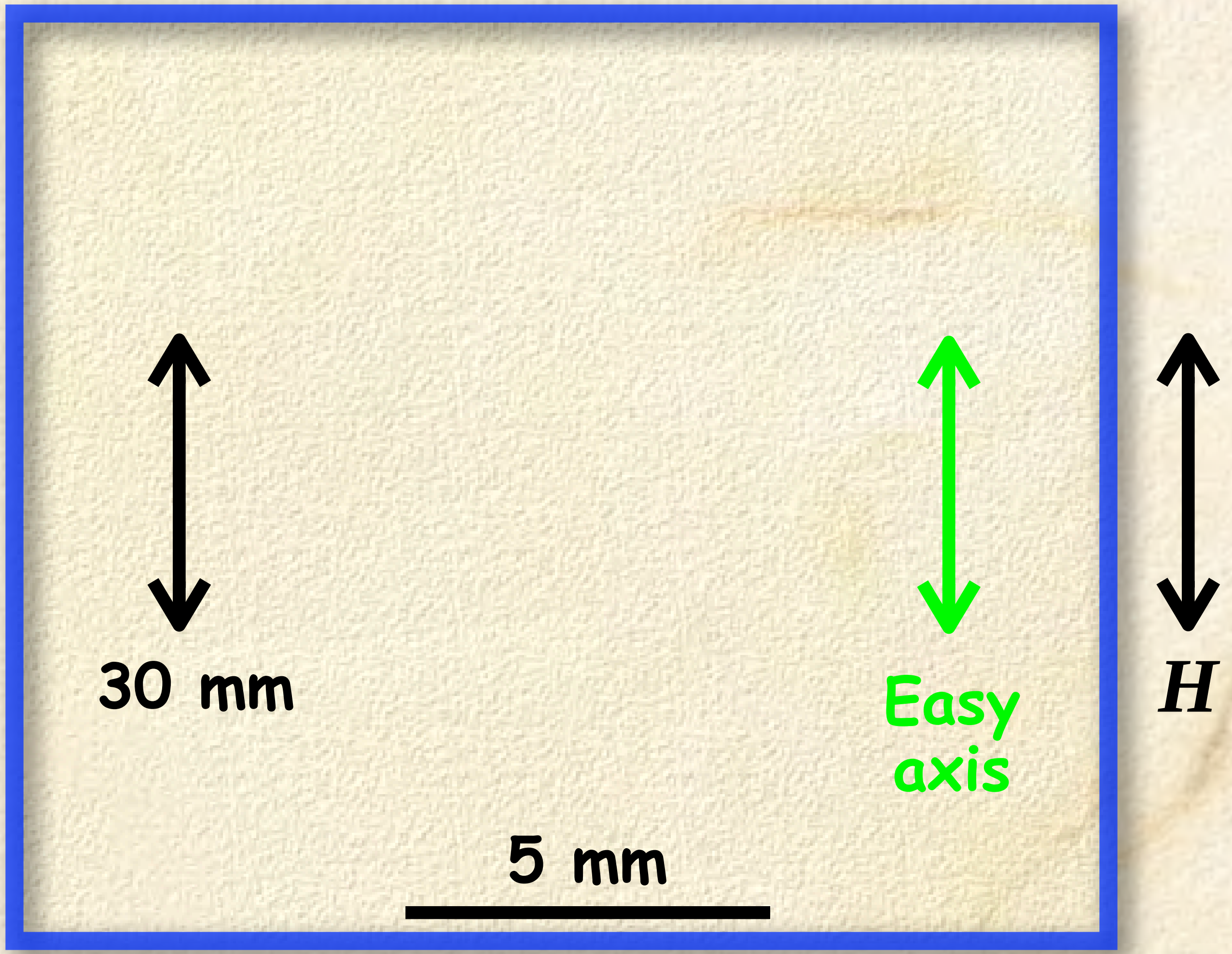
$$E_s = \tfrac{1}{2}\mu_0 N M^2 V$$

$(0 < N < 1)$

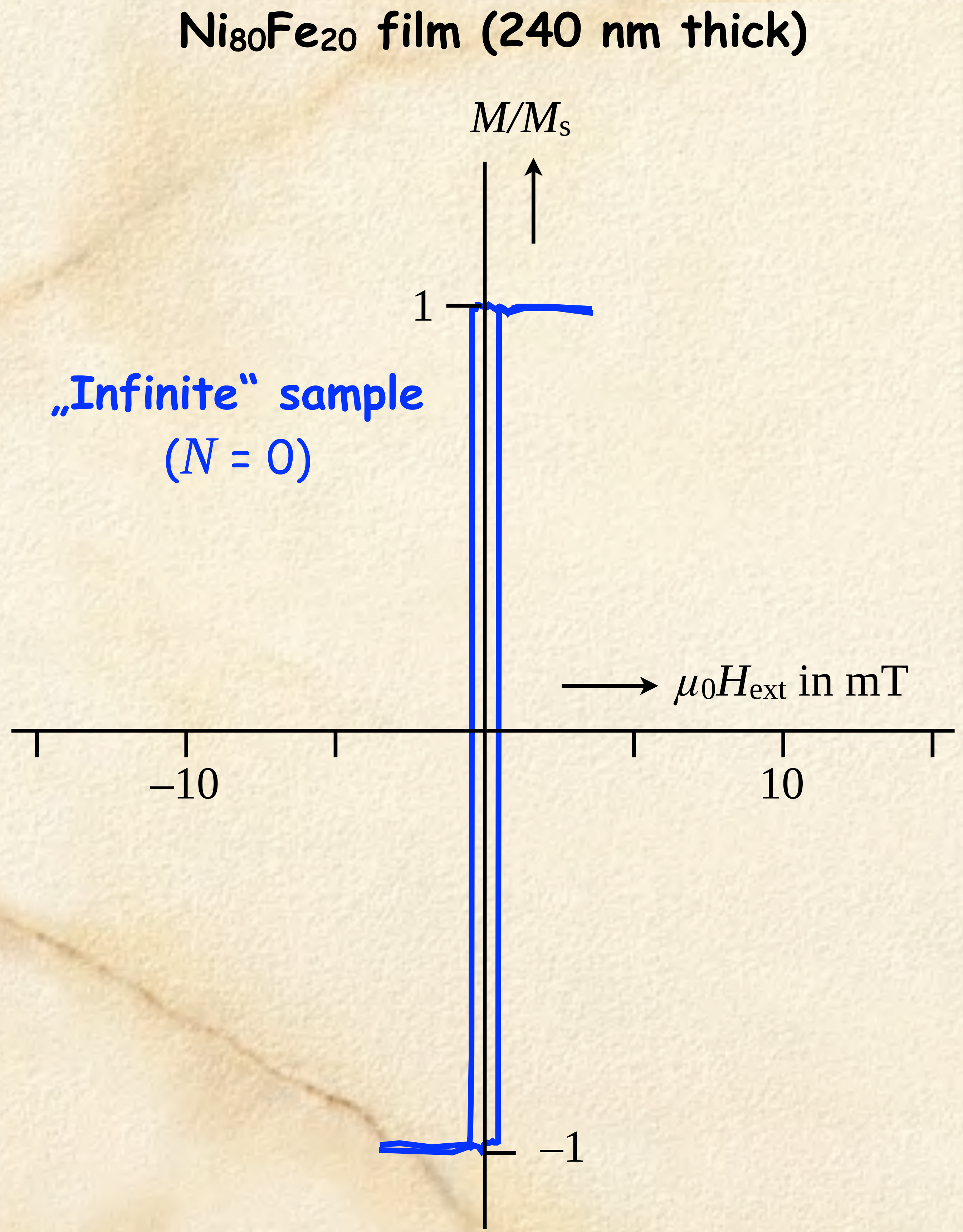
Origin of magnetic domains

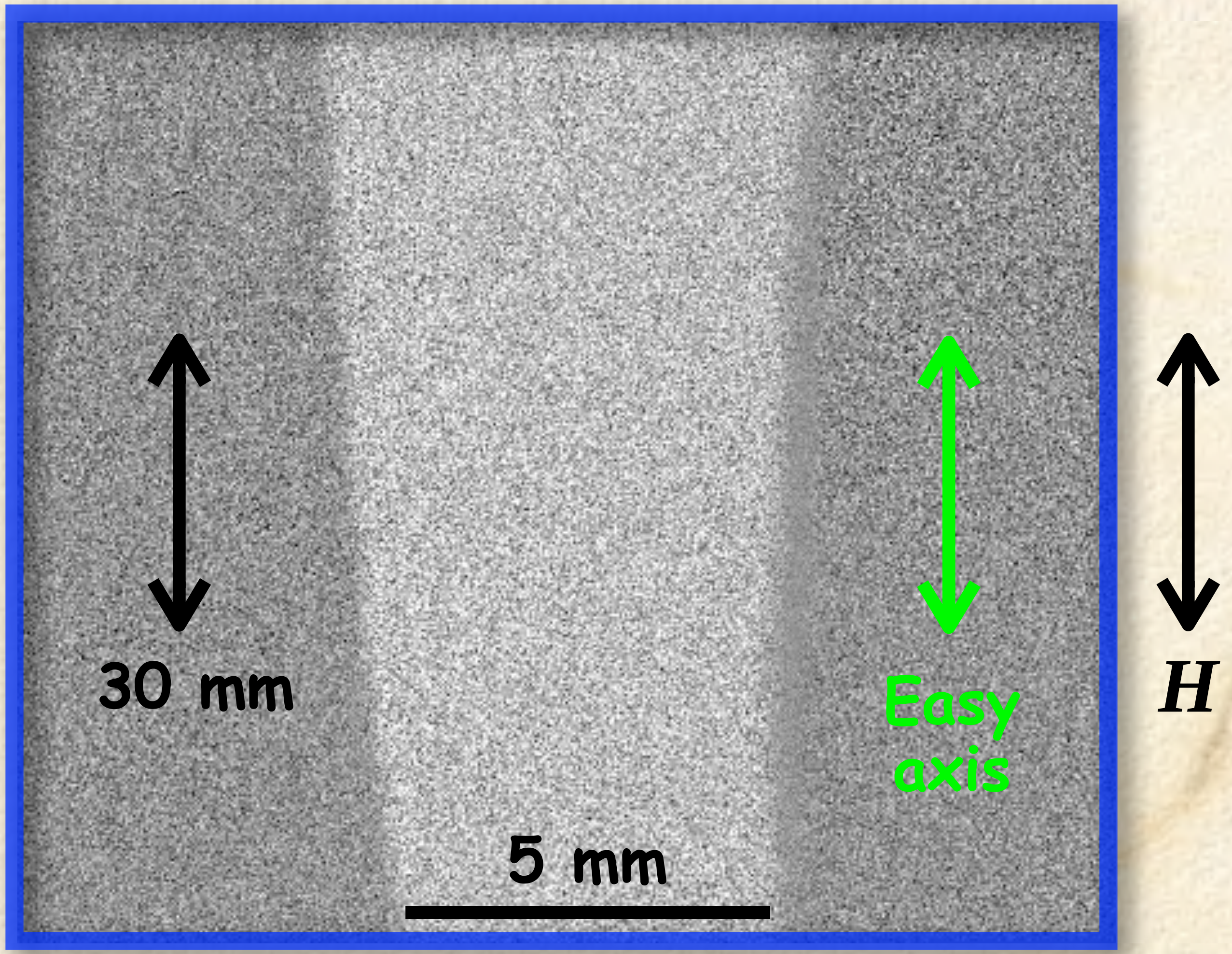
$Ni_{80}Fe_{20}$ film (240 nm thick)





Origin of magnetic domains





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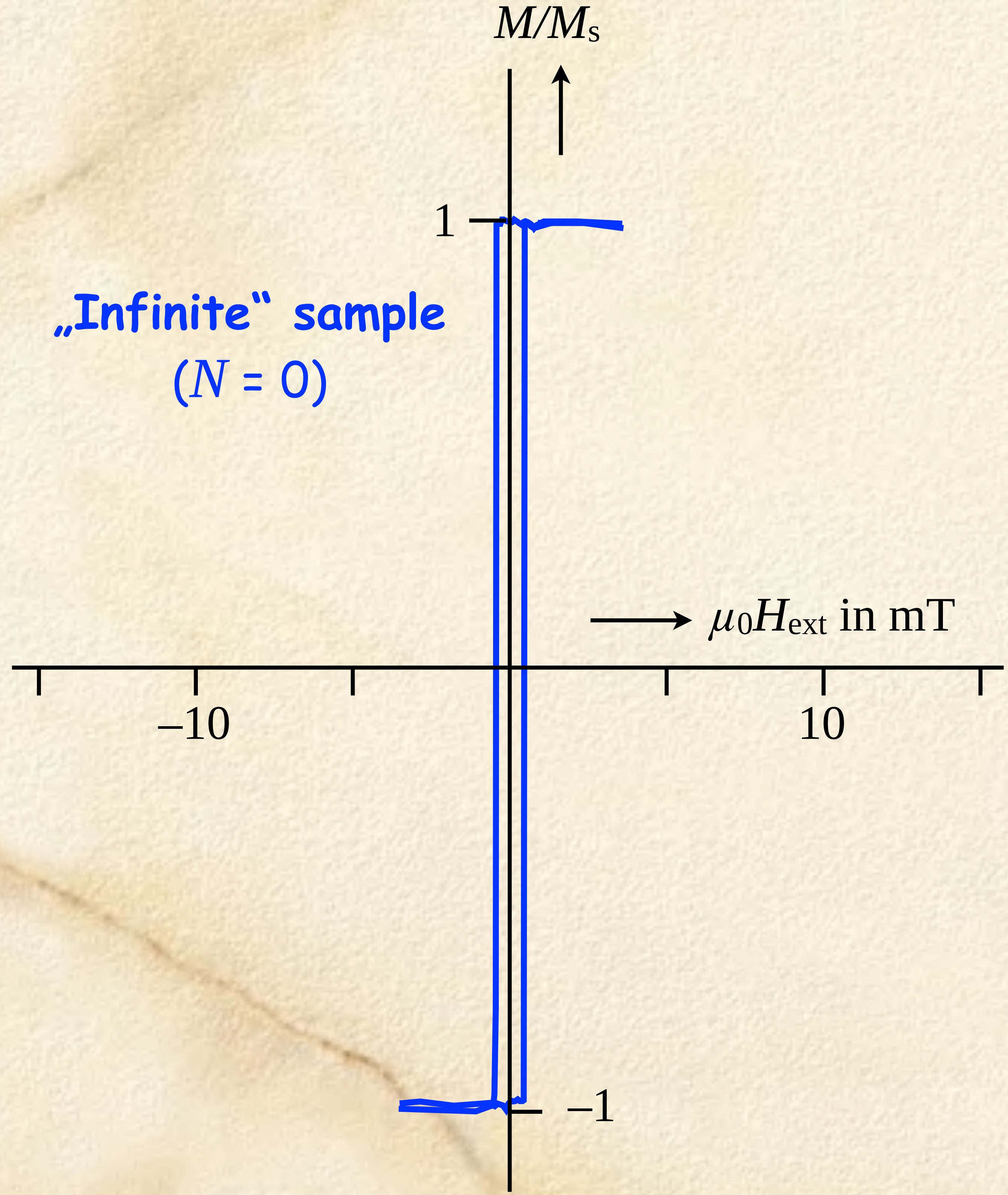
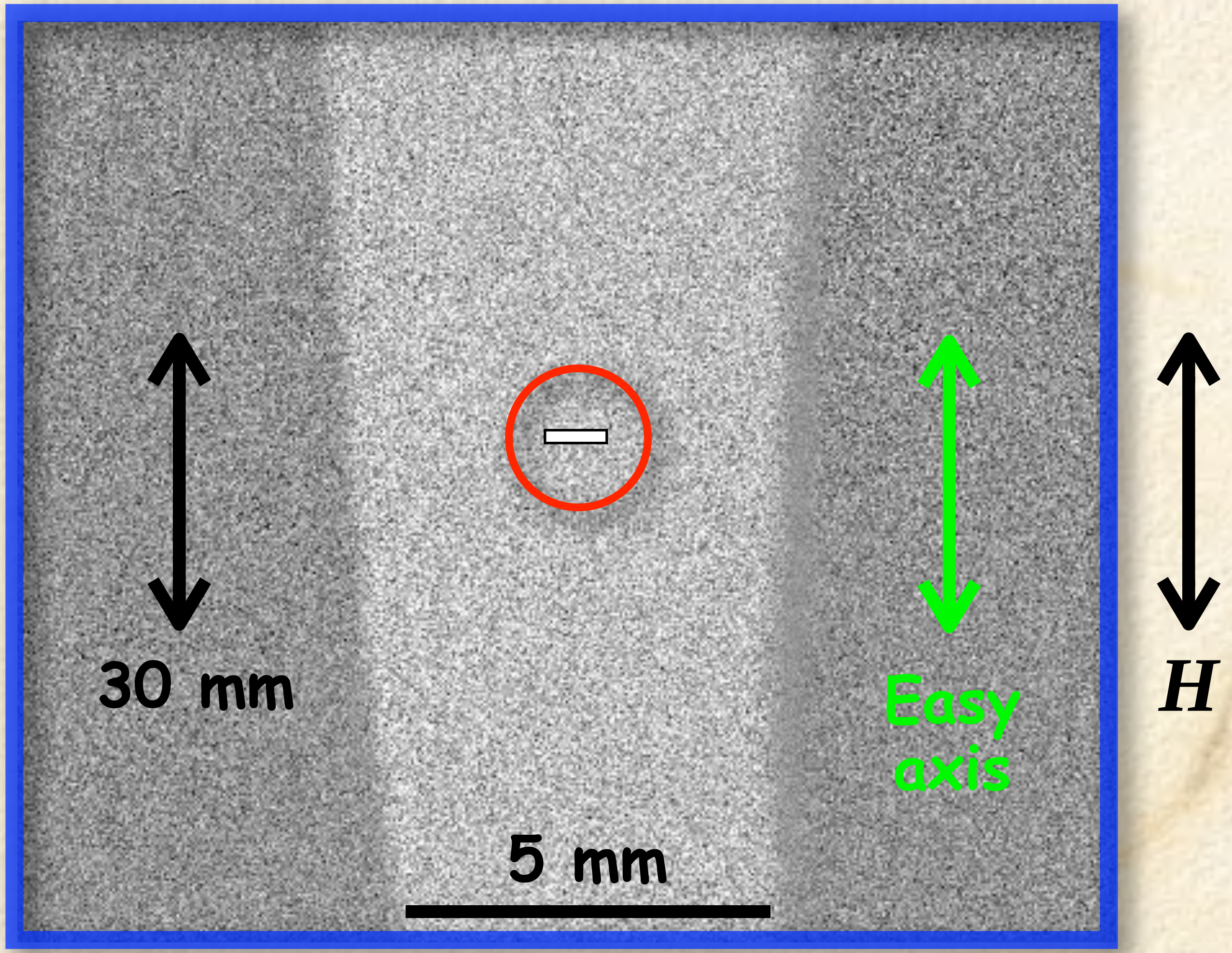
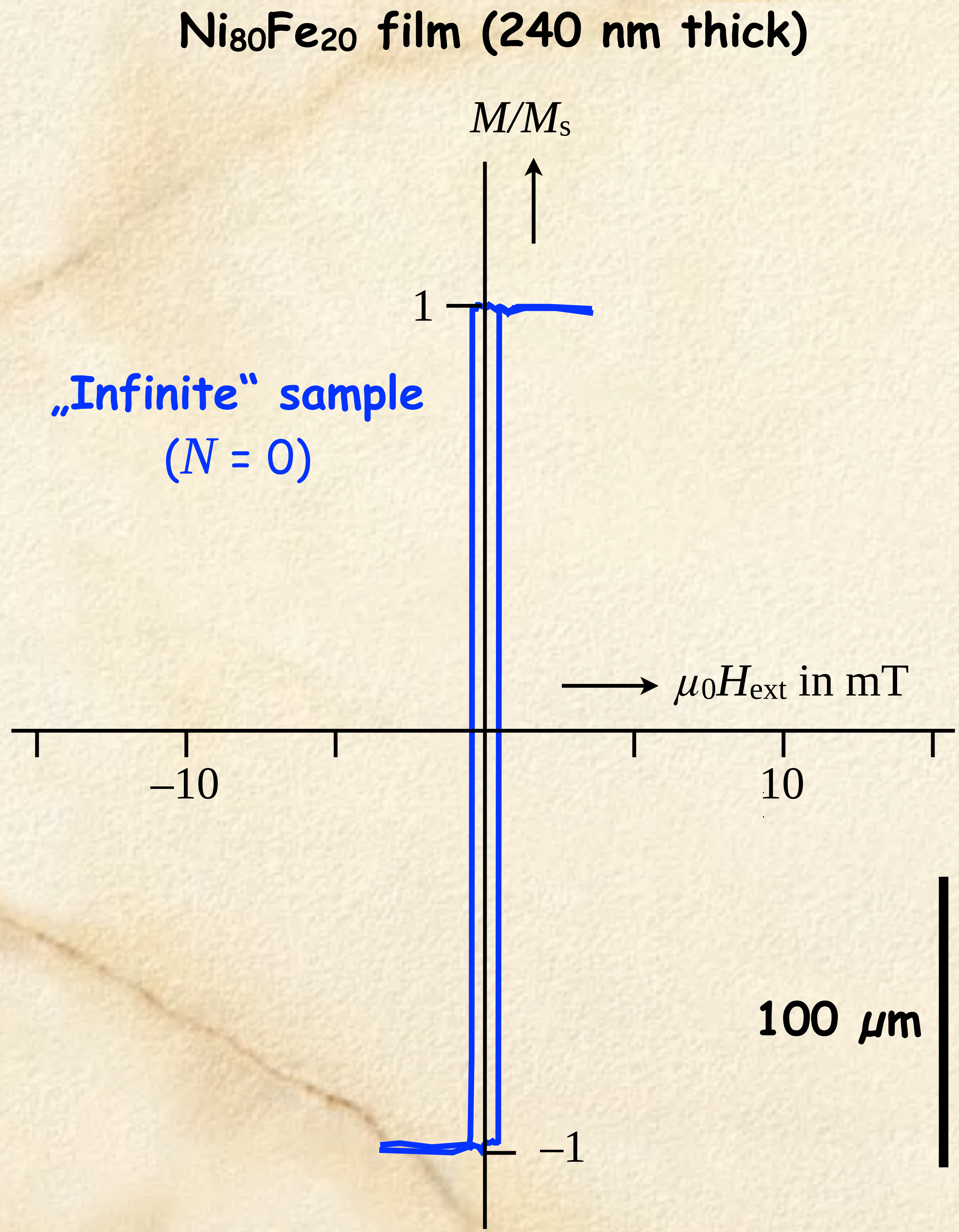
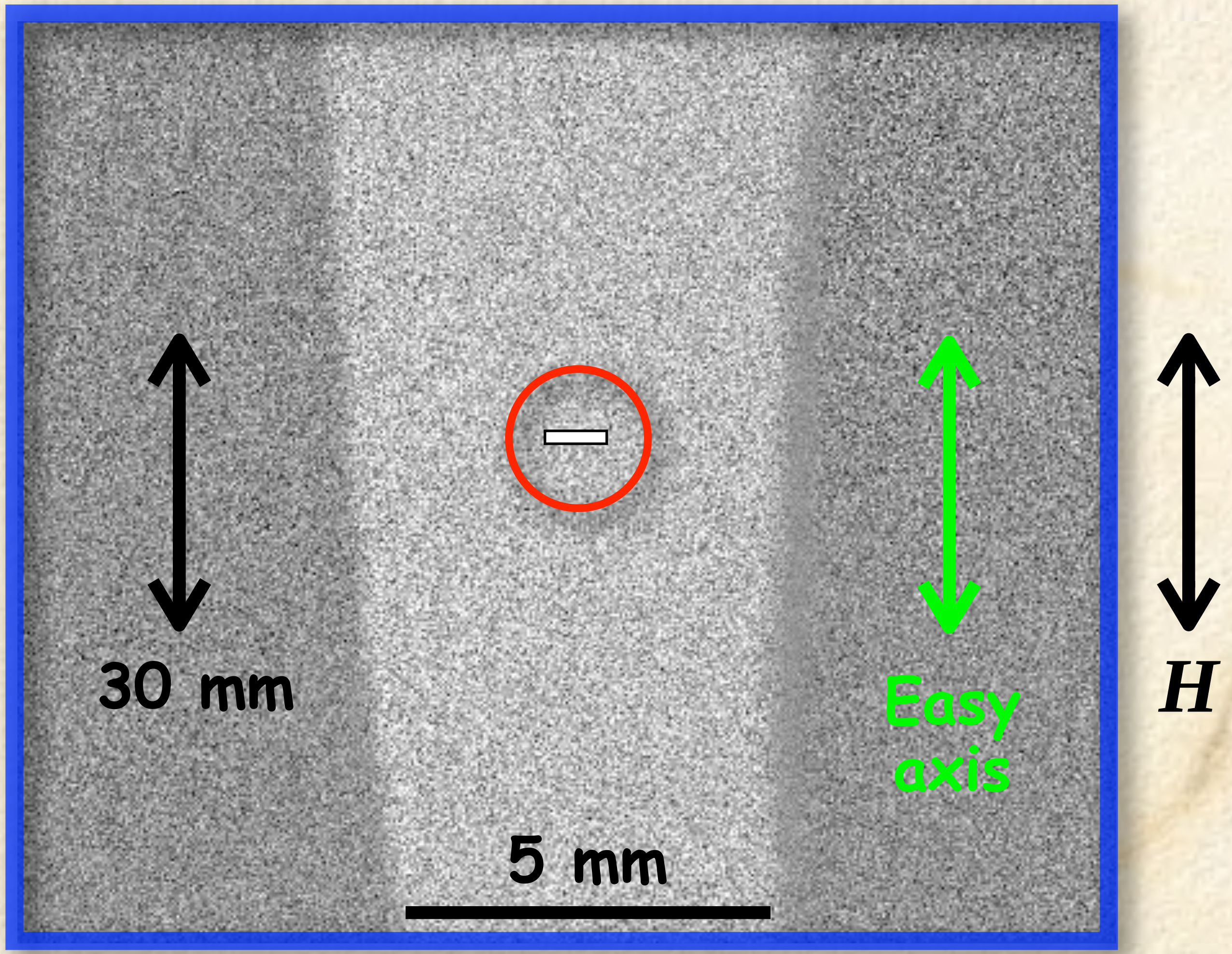
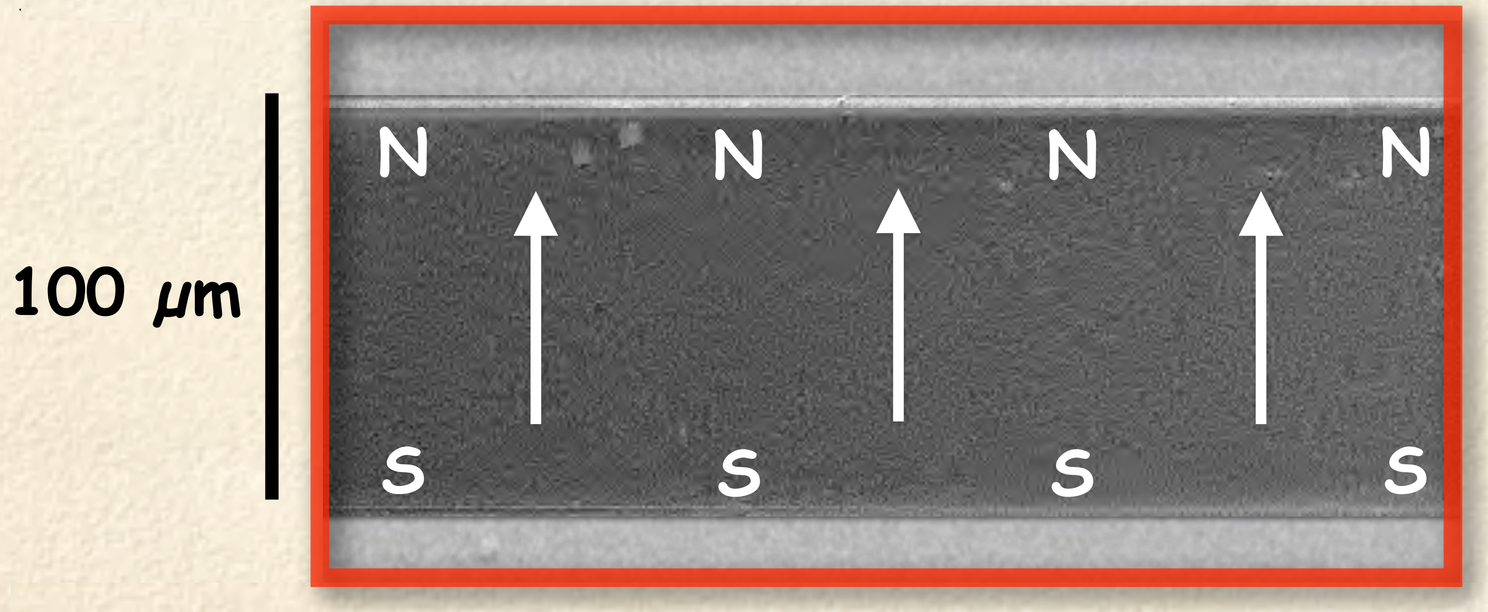




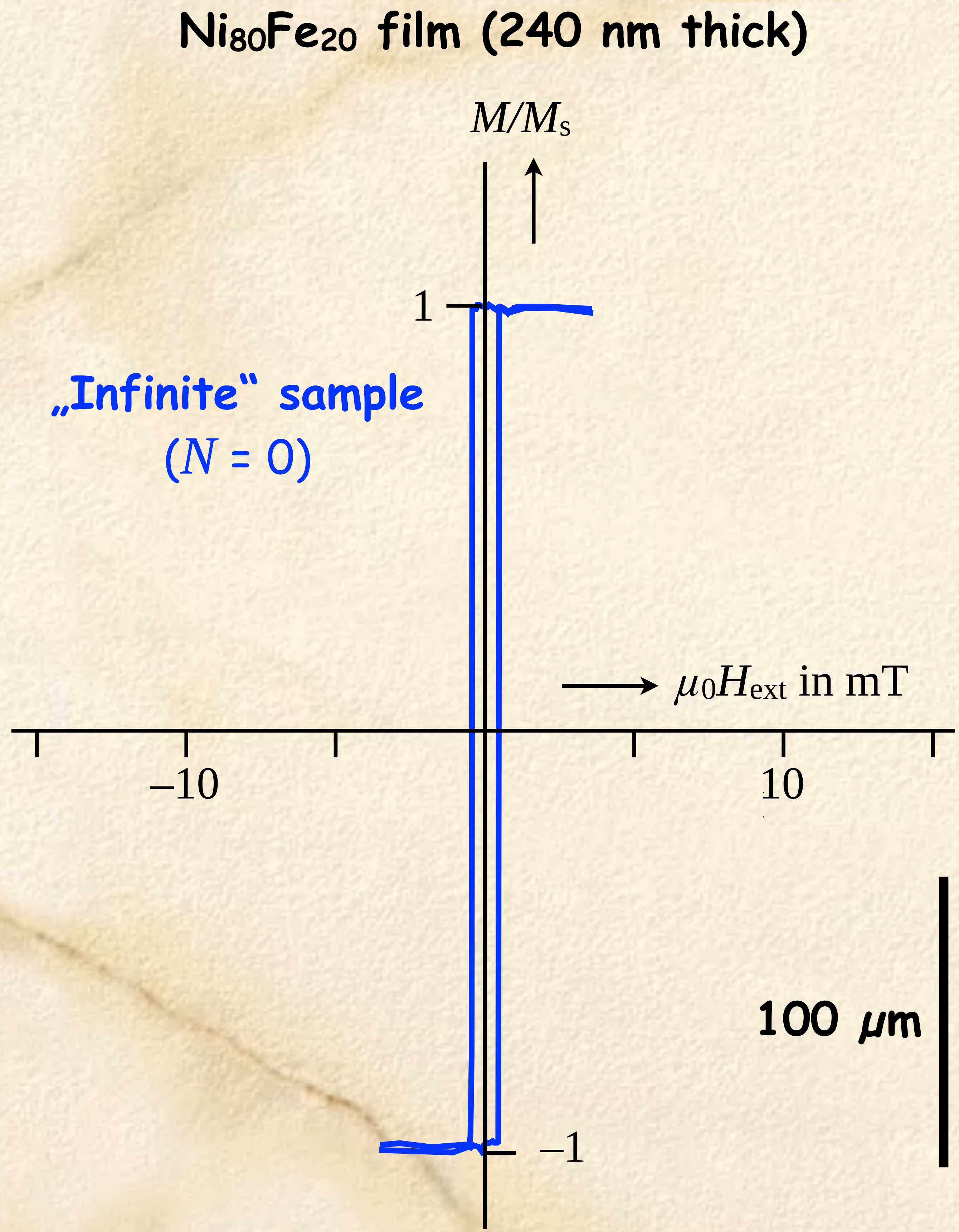
Origin of magnetic domains

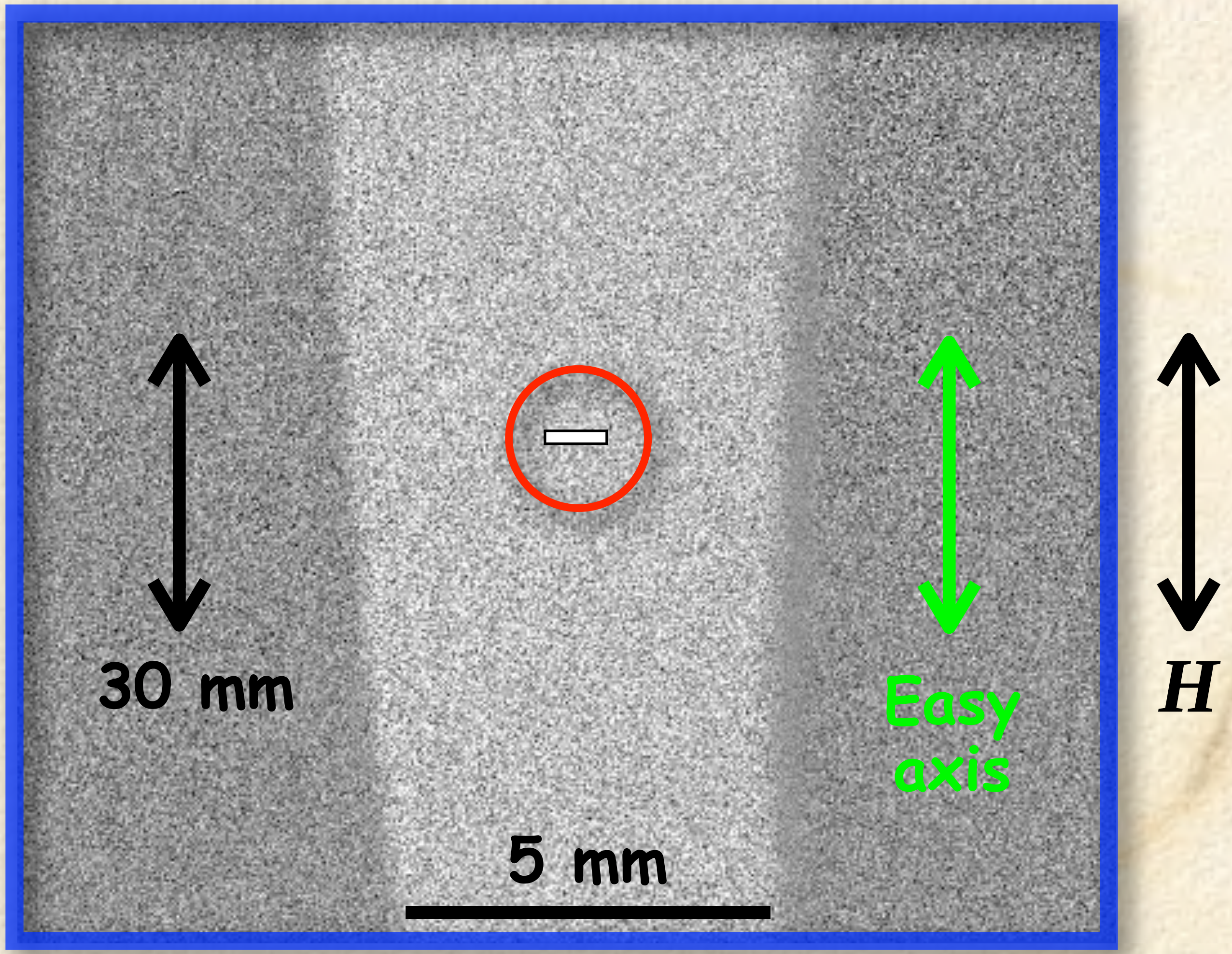


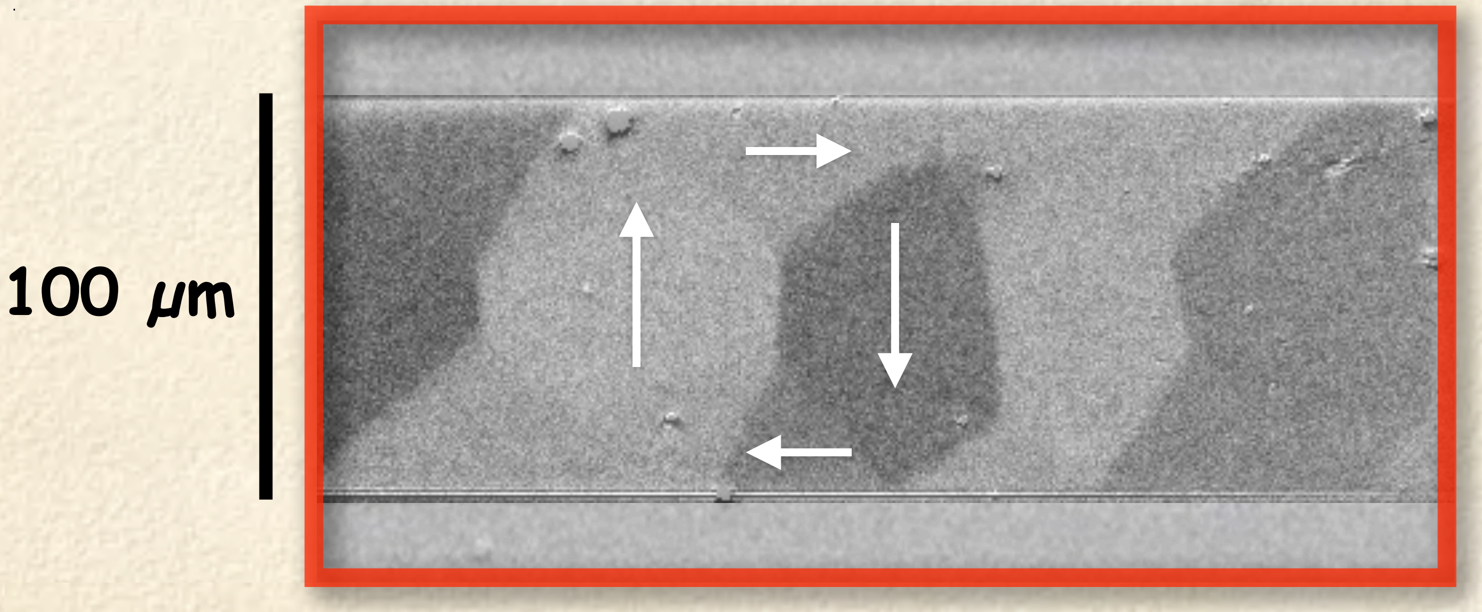




Origin of magnetic domains







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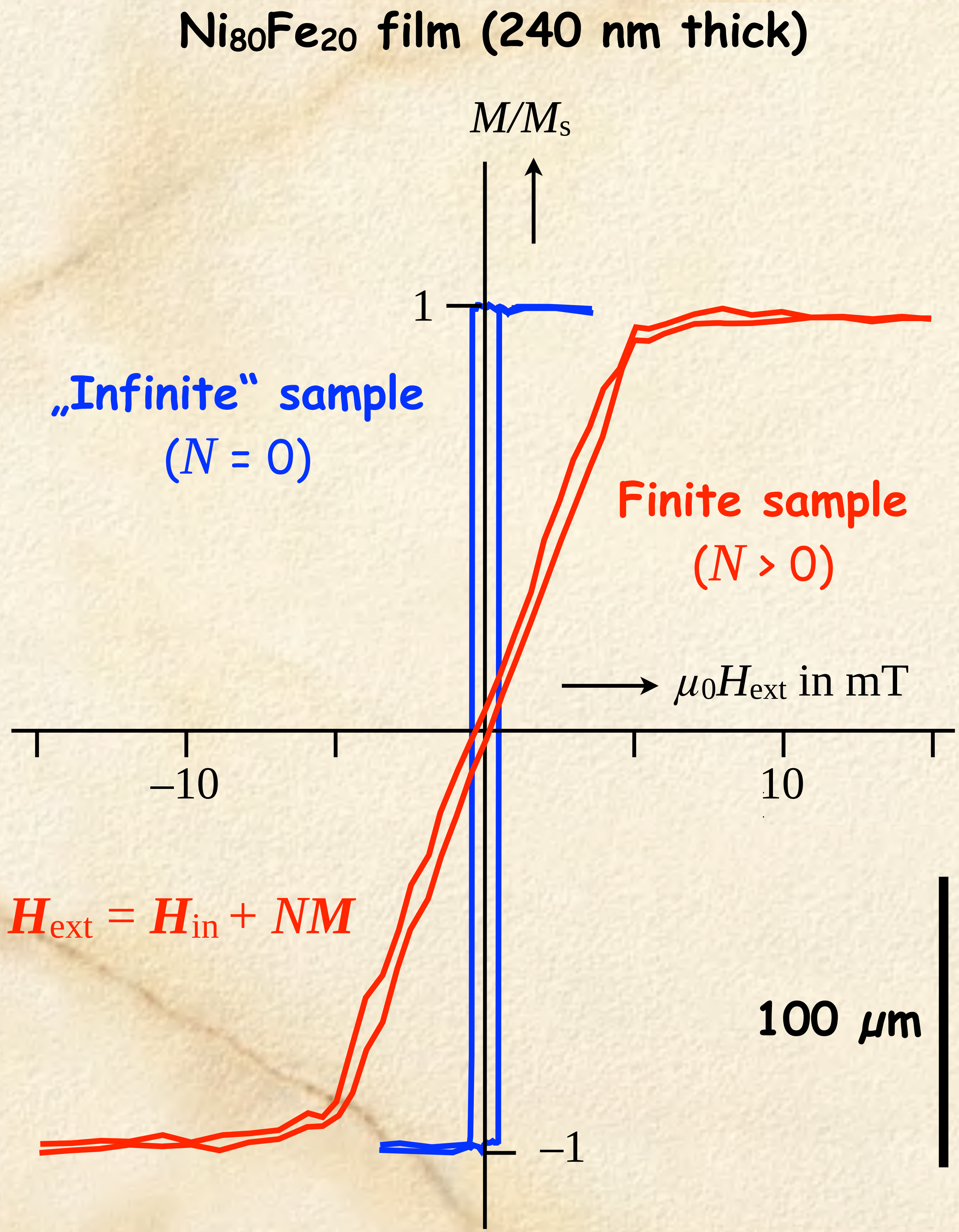
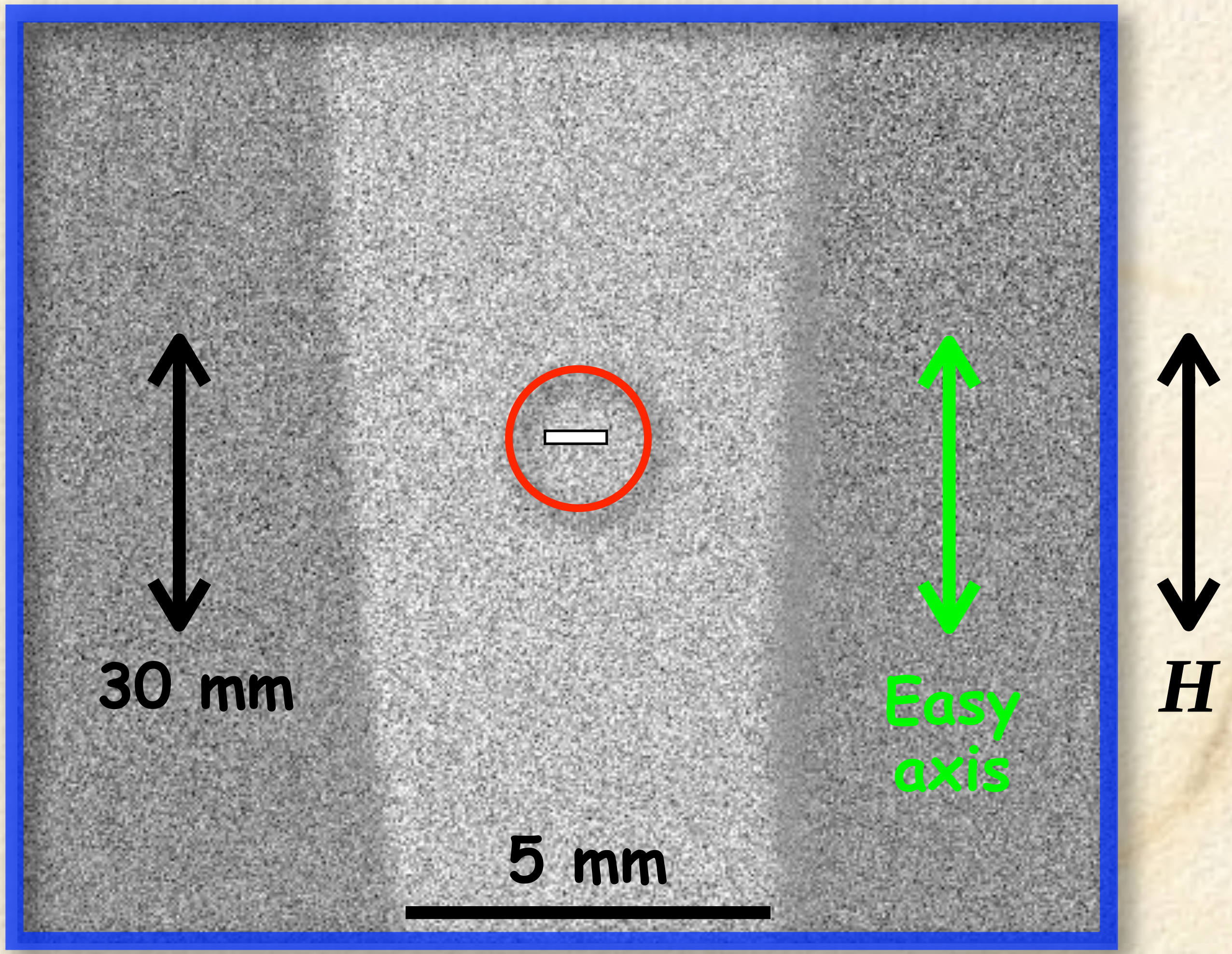
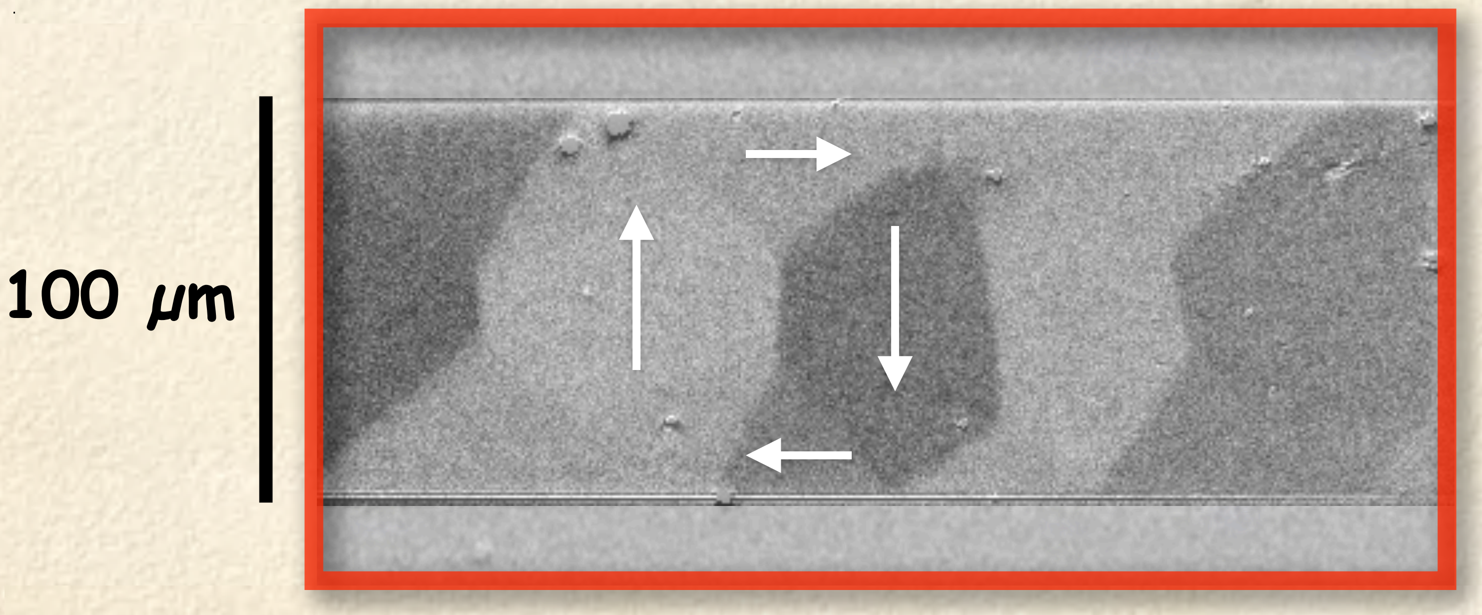
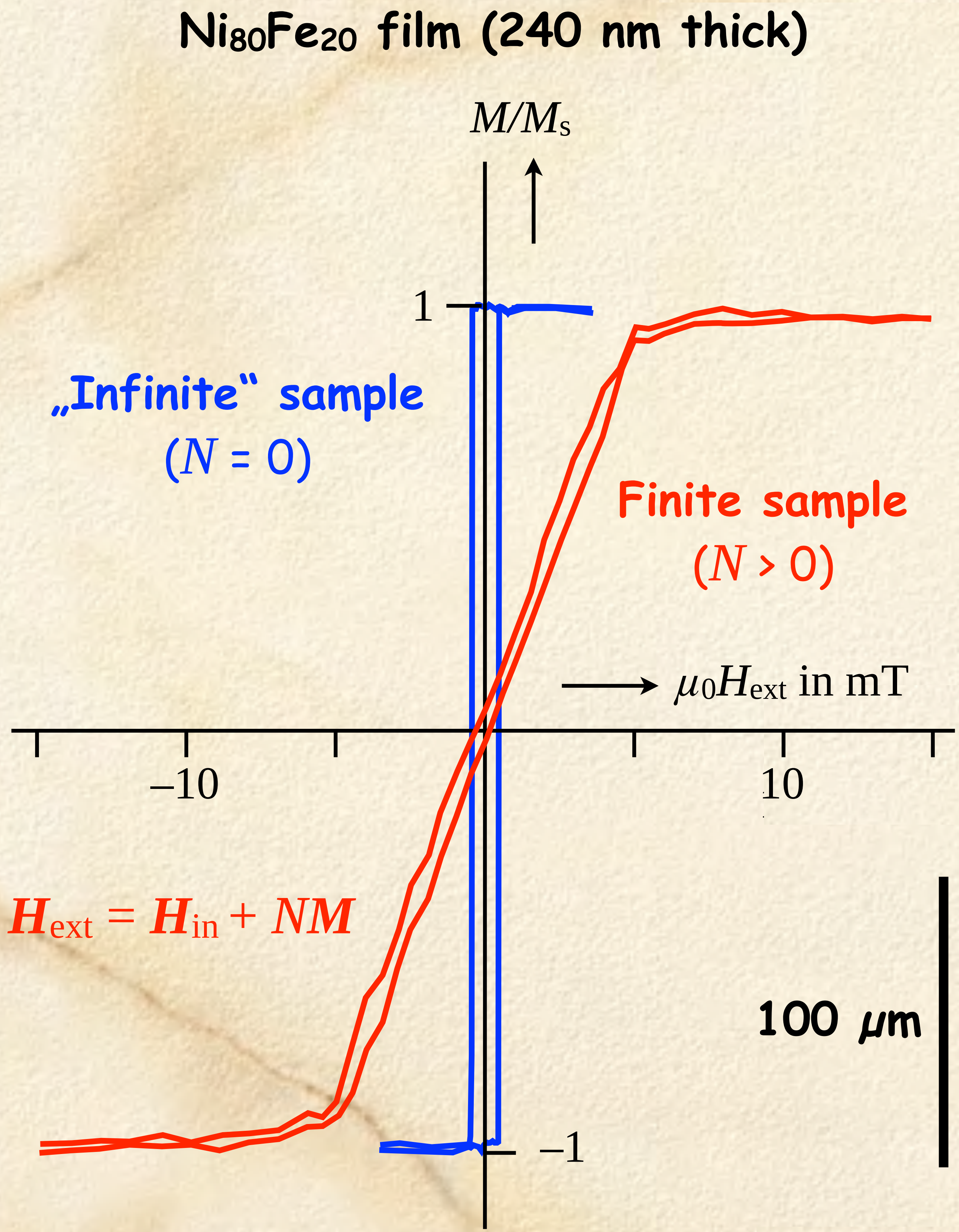
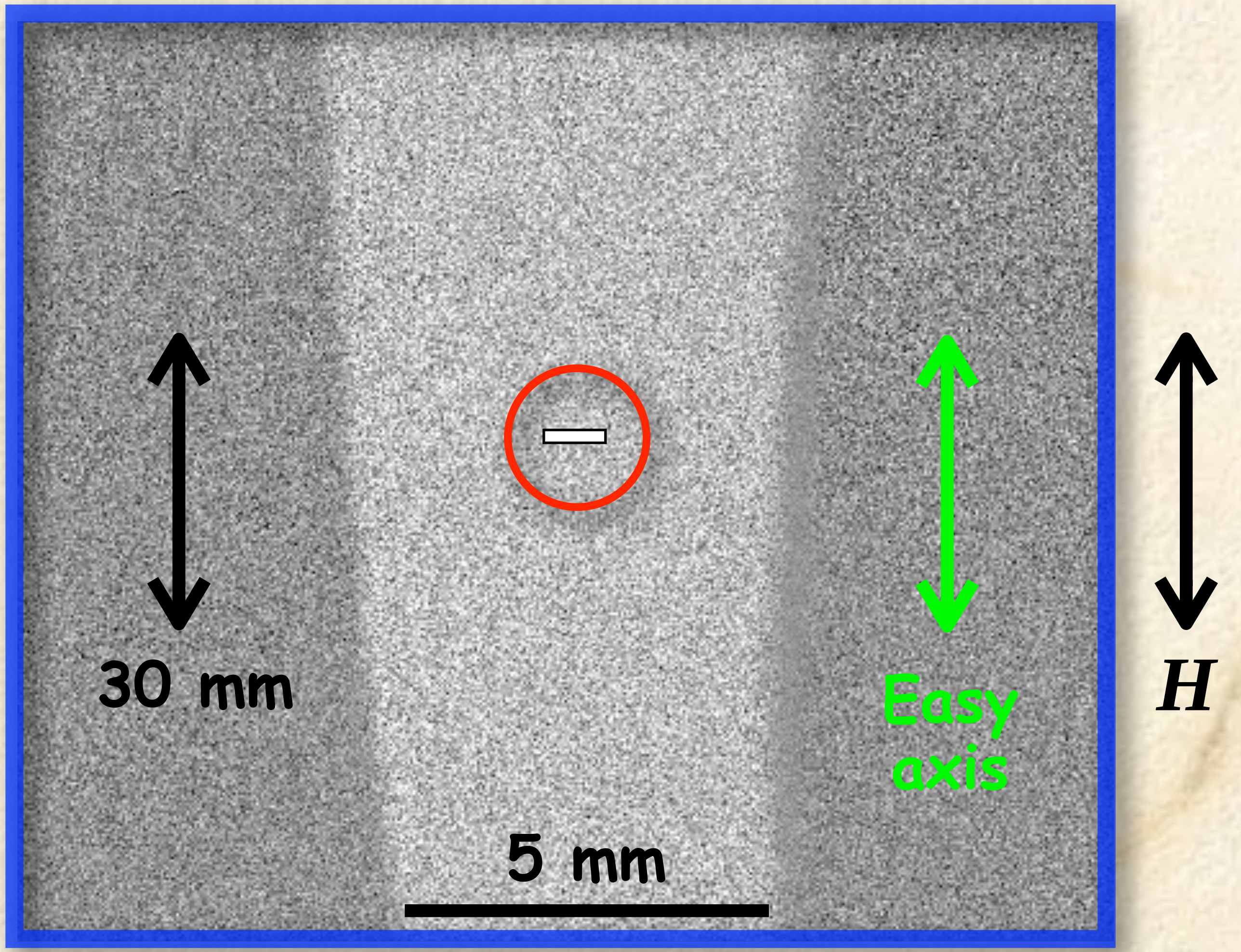


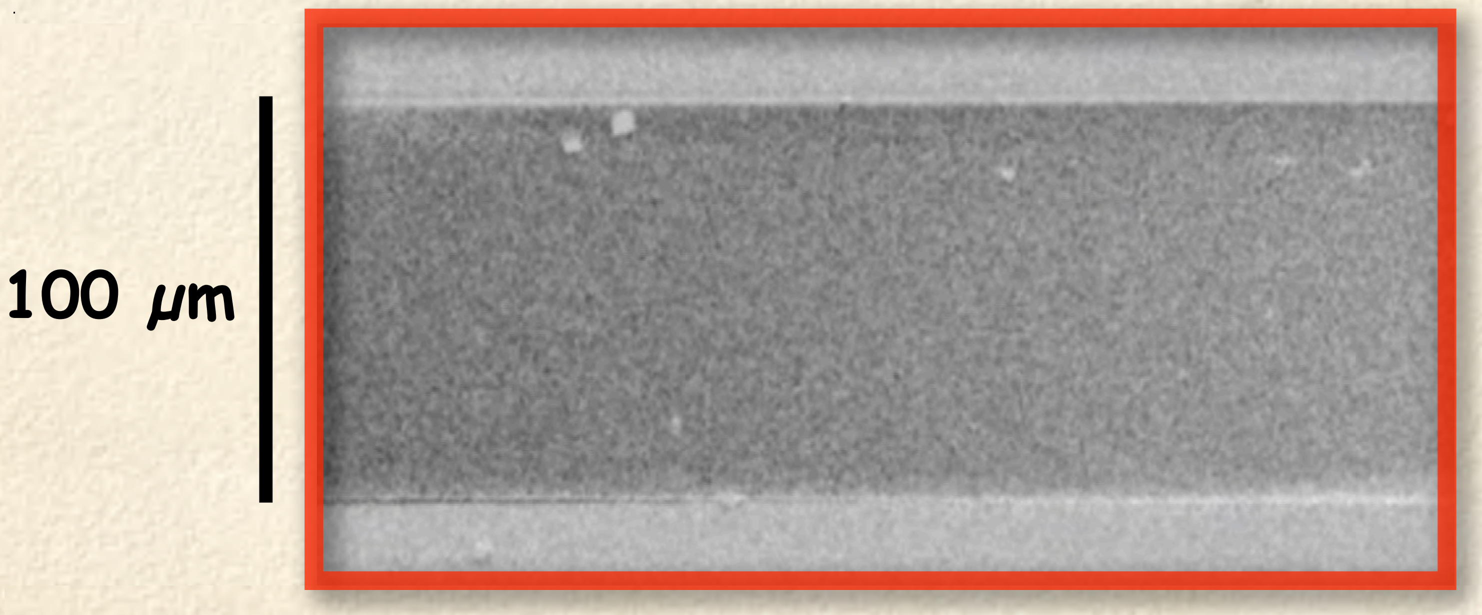




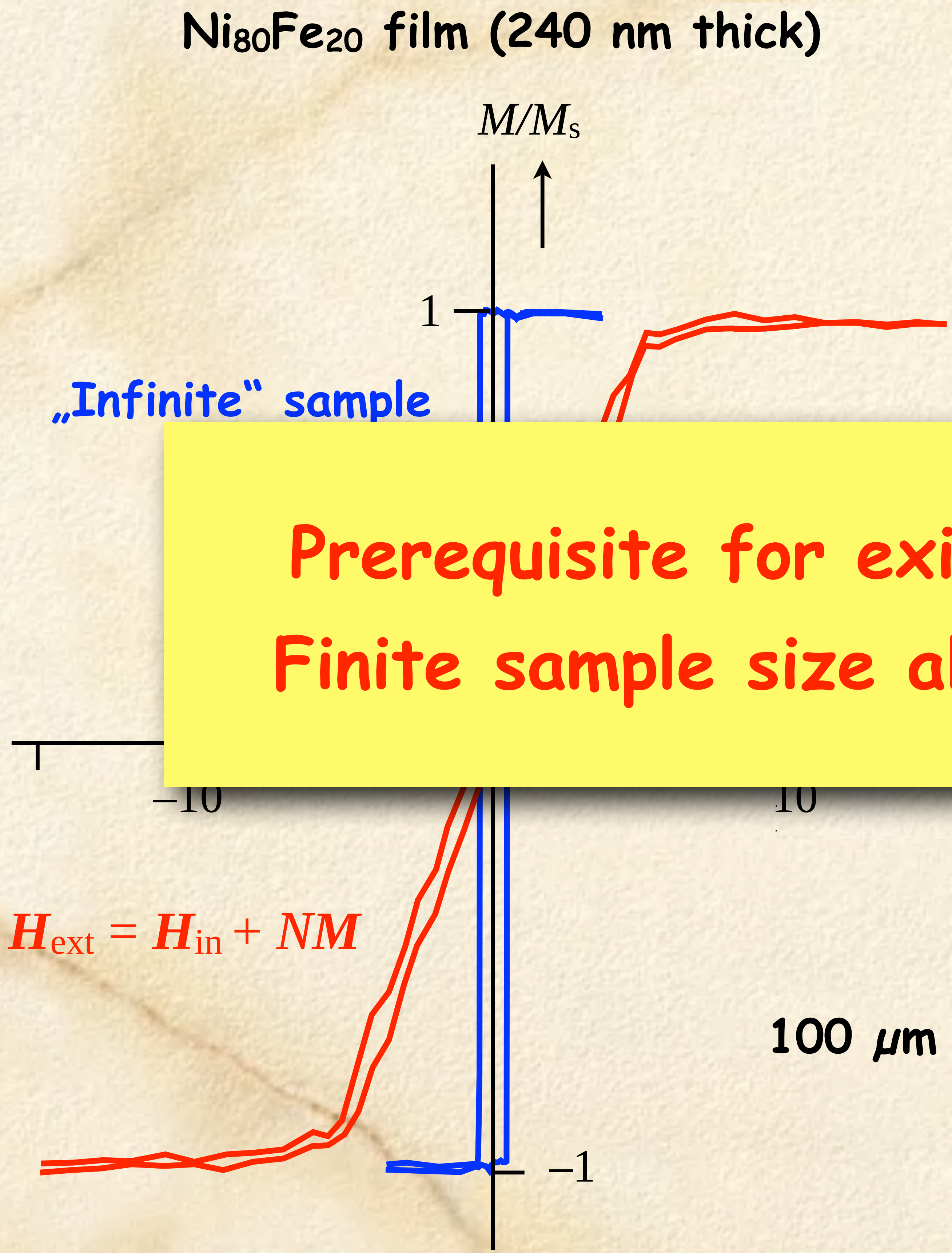
Origin of magnetic domains

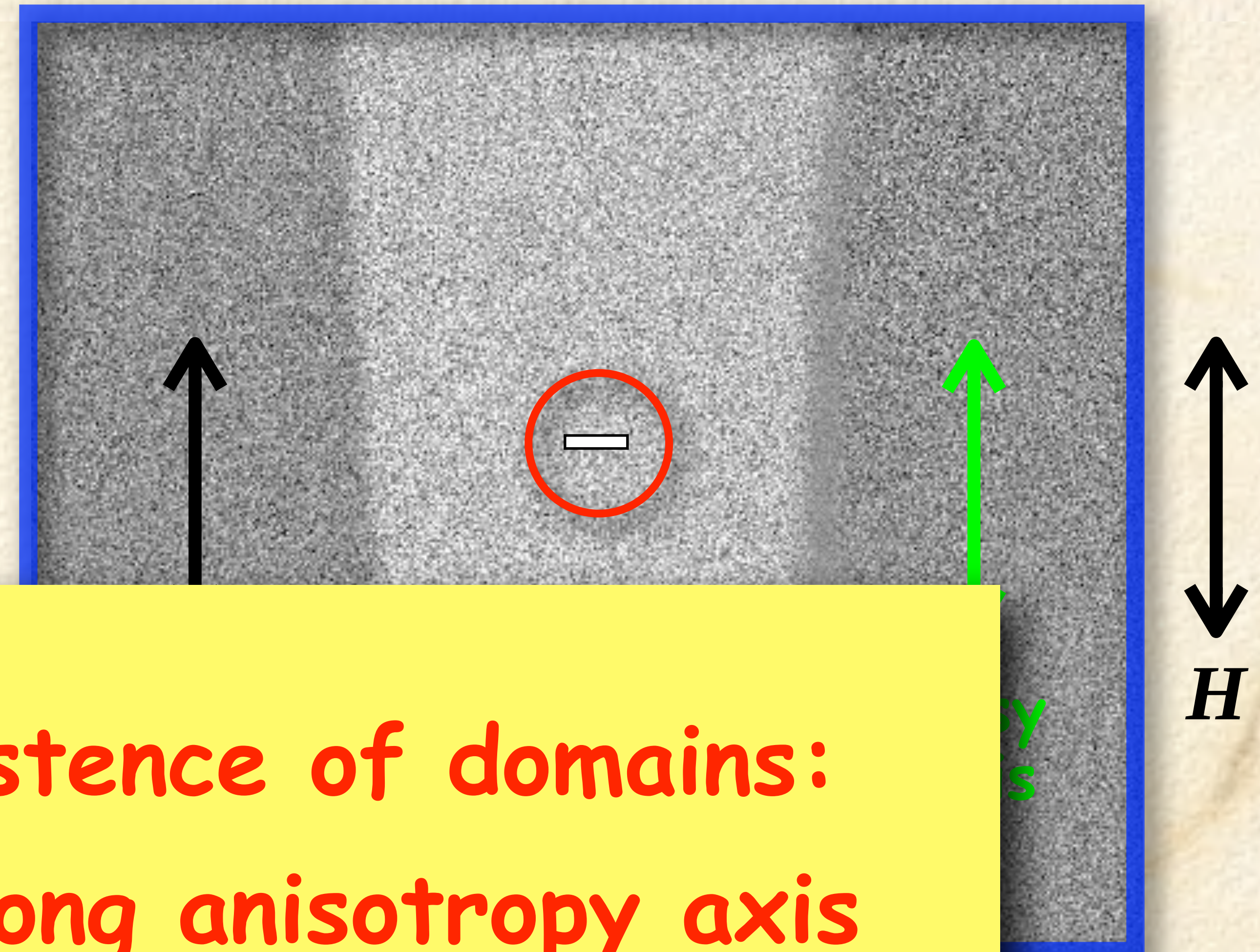


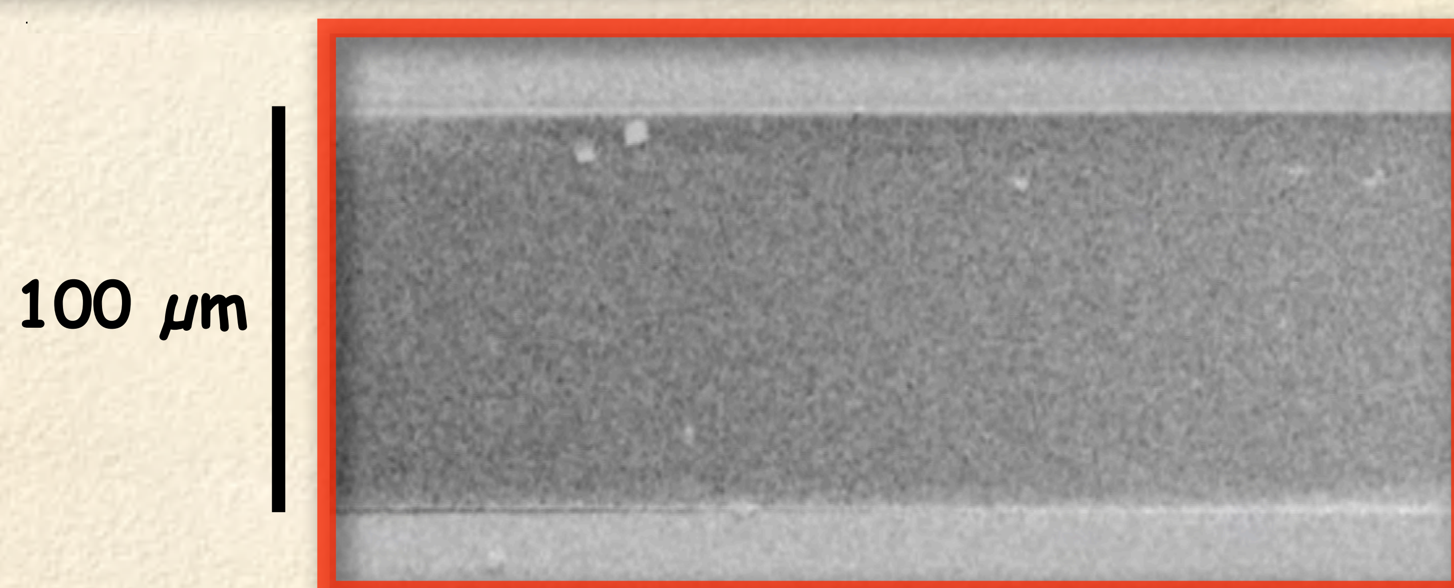




Origin of magnetic domains





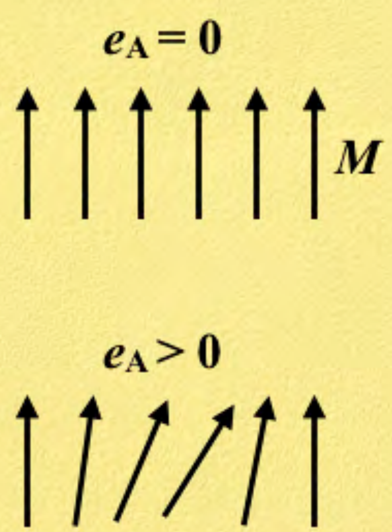


Prerequisite for existence of domains:

Finite sample size along anisotropy axis

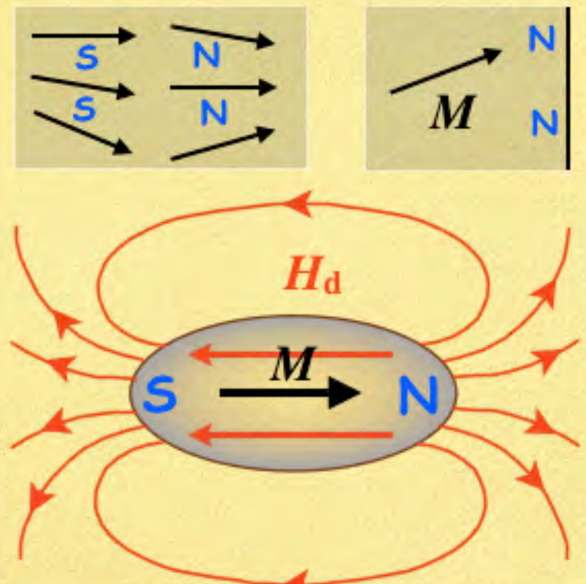
Magnetic Energies

Exchange energy

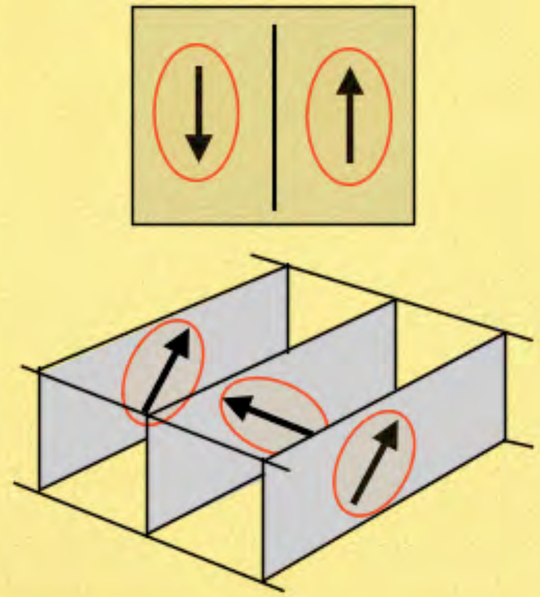


Stray field energy

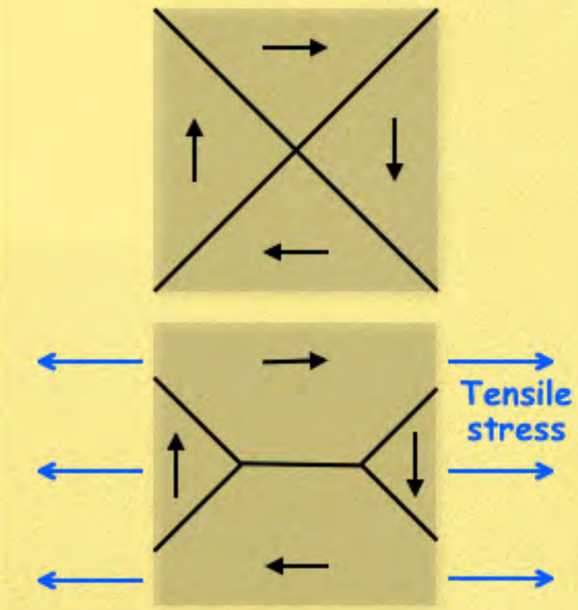
$\text{div}\, \boldsymbol{H}_\text{d} = -\,\text{div}\, \boldsymbol{M}$



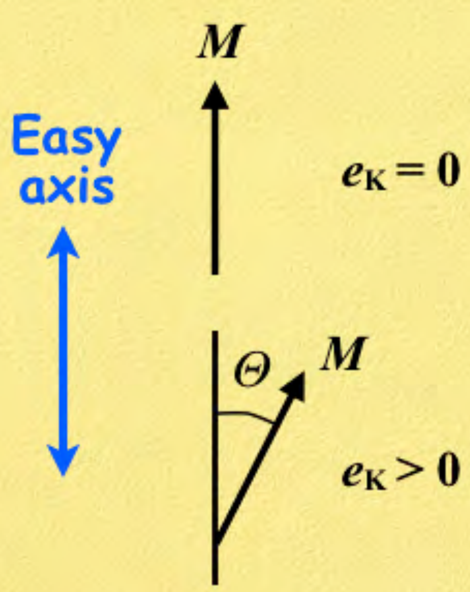
Magnetostrictive self energy



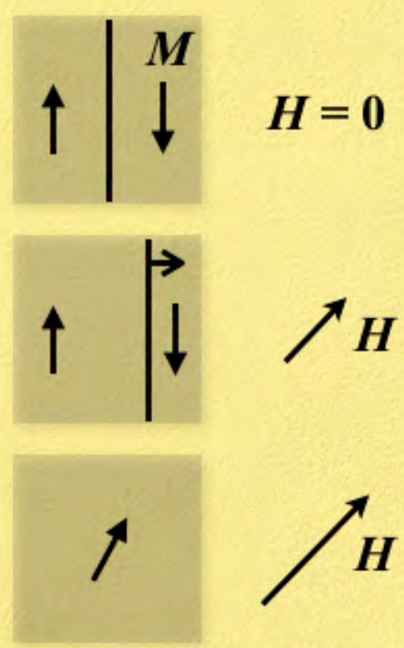
External stress energy



Anisotropy energy

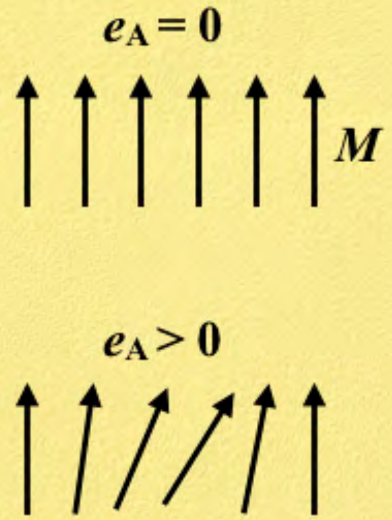


External field energy



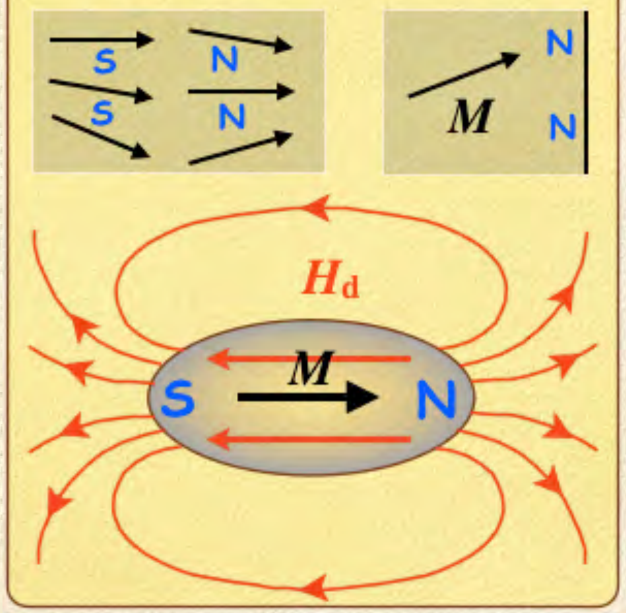
Magnetic Energies

Exchange energy

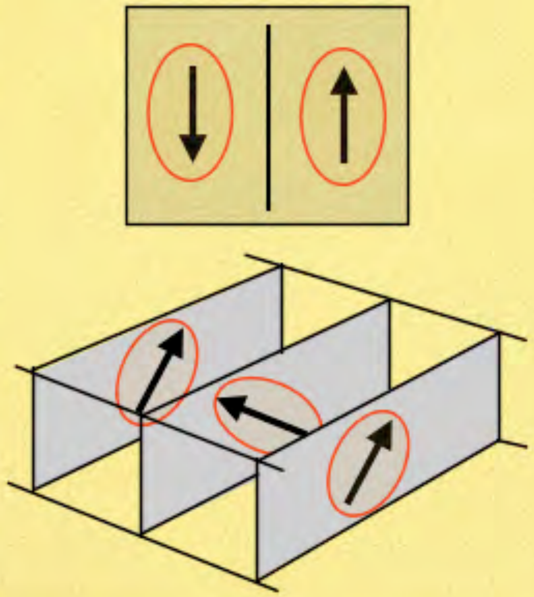


Stray field energy

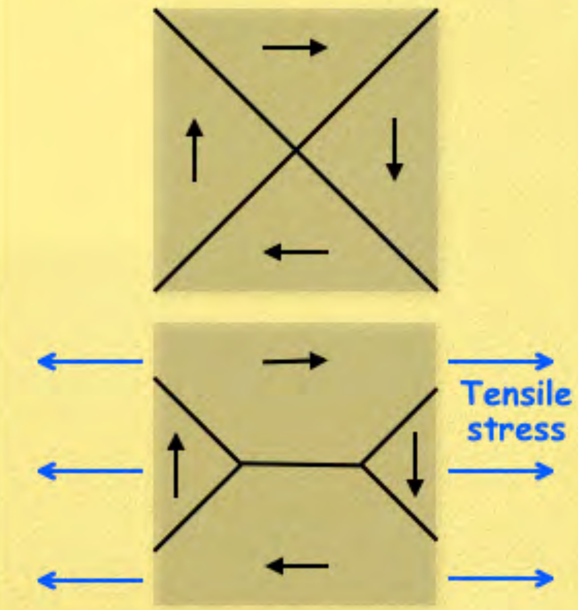
$\mathrm{div}\, \boldsymbol{H}_d = -\,\mathrm{div}\, \boldsymbol{M}$



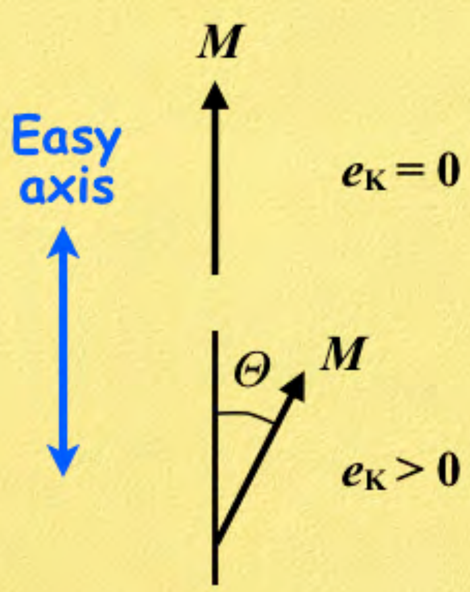
Magnetostrictive self energy



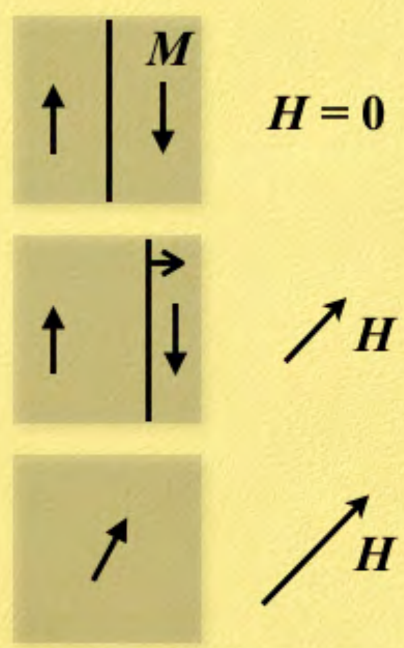
External stress energy



Anisotropy energy

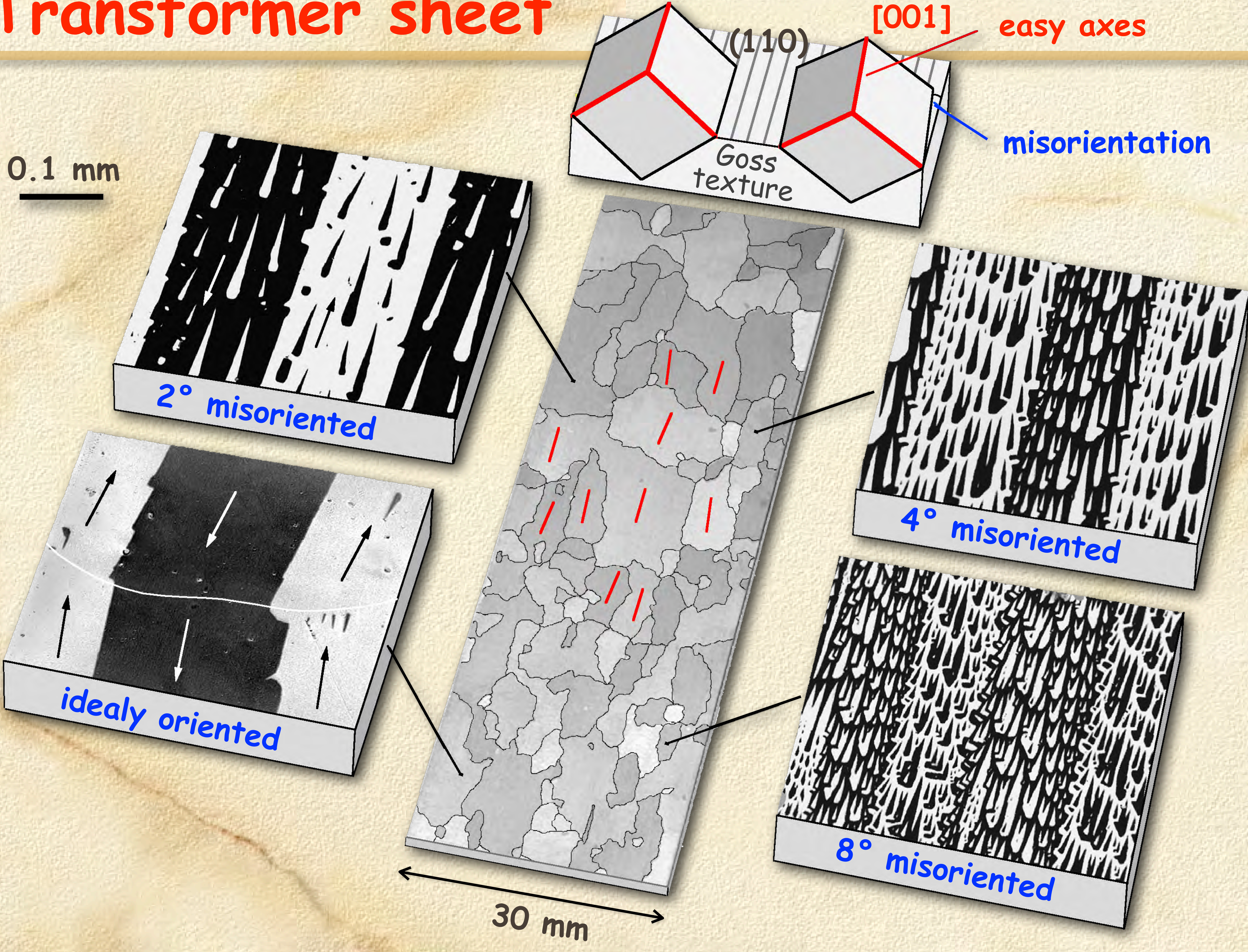


External field energy

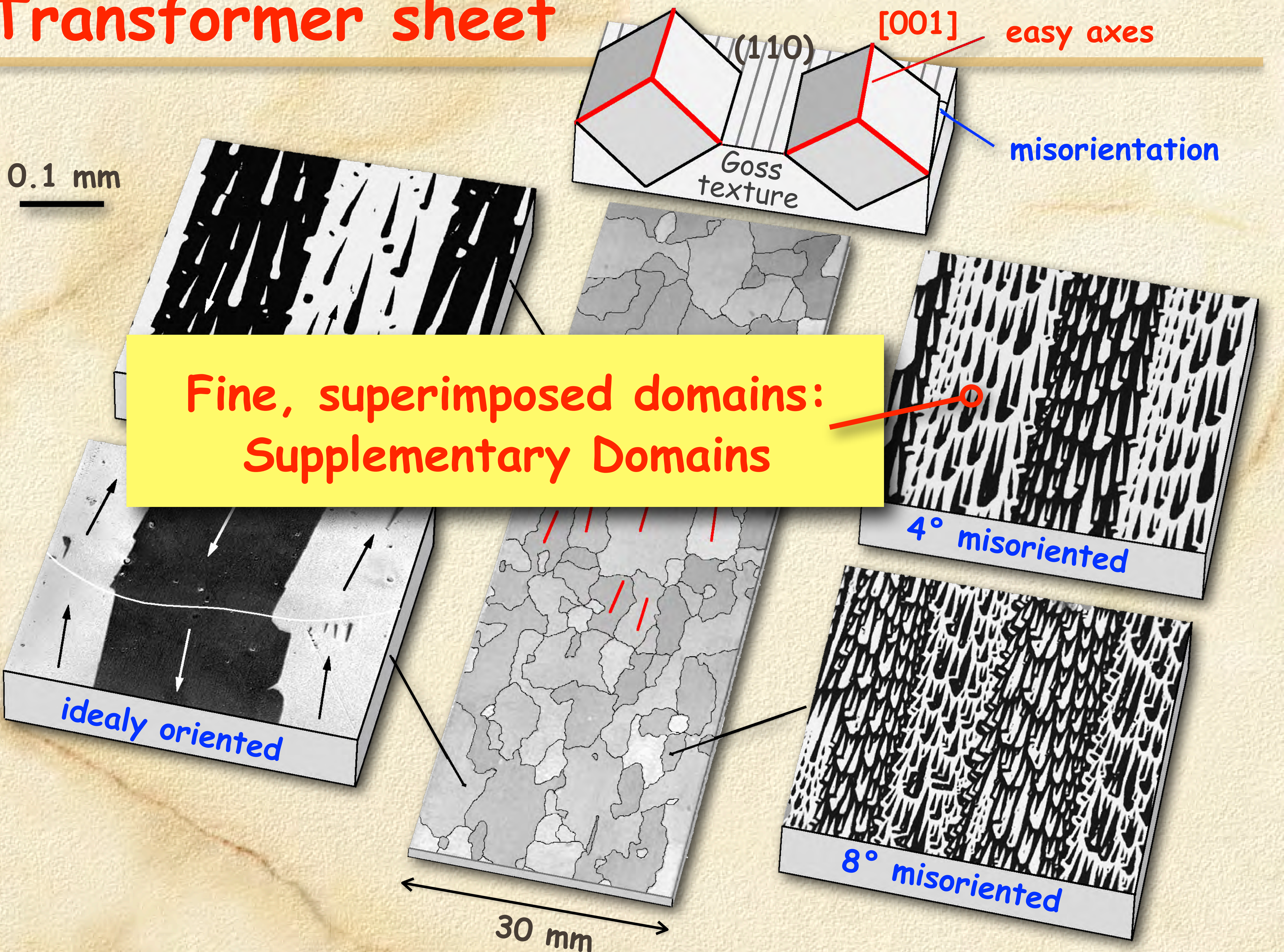


Domain character: determined by interplay of energies

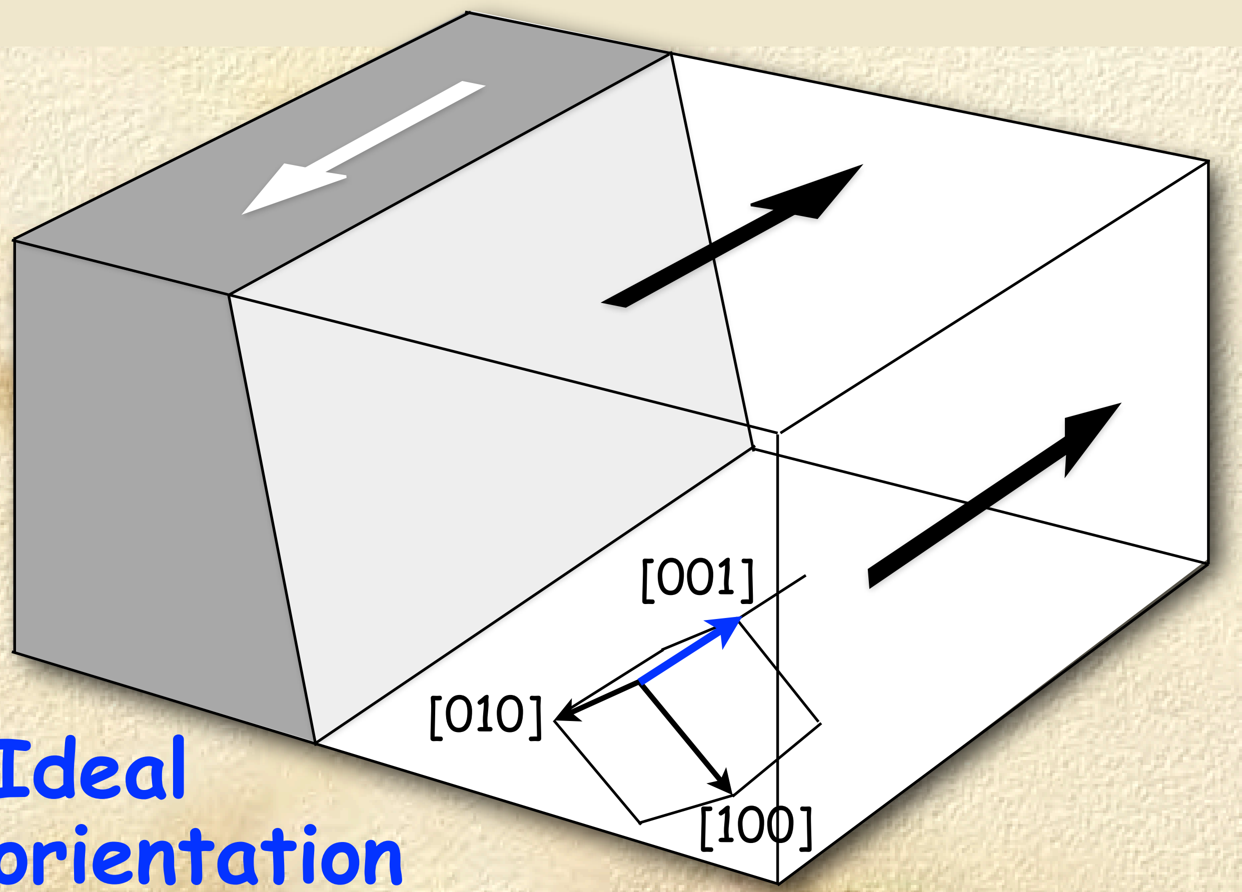
Transformer sheet



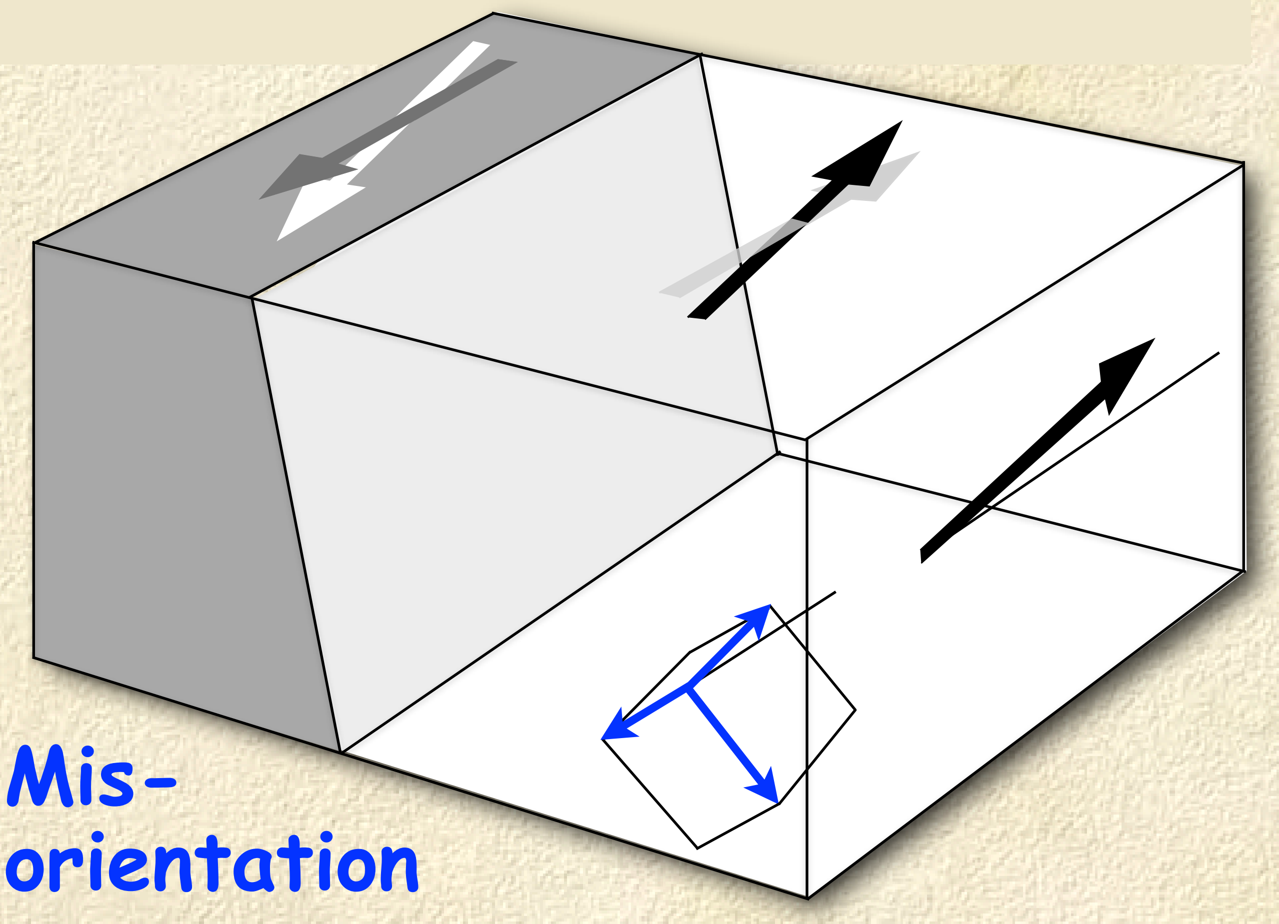
Transformer sheet



Grain-oriented FeSi transformer material

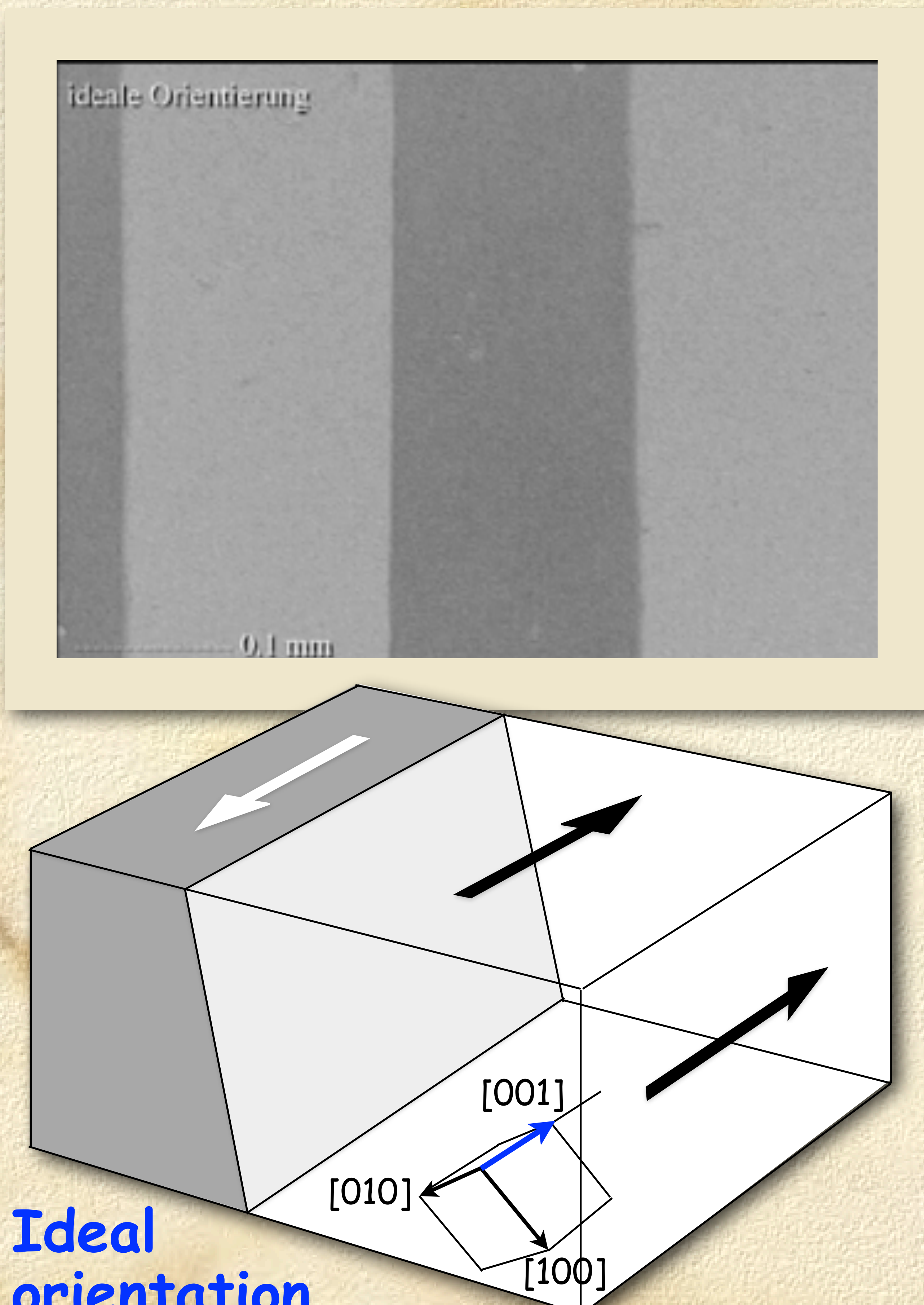


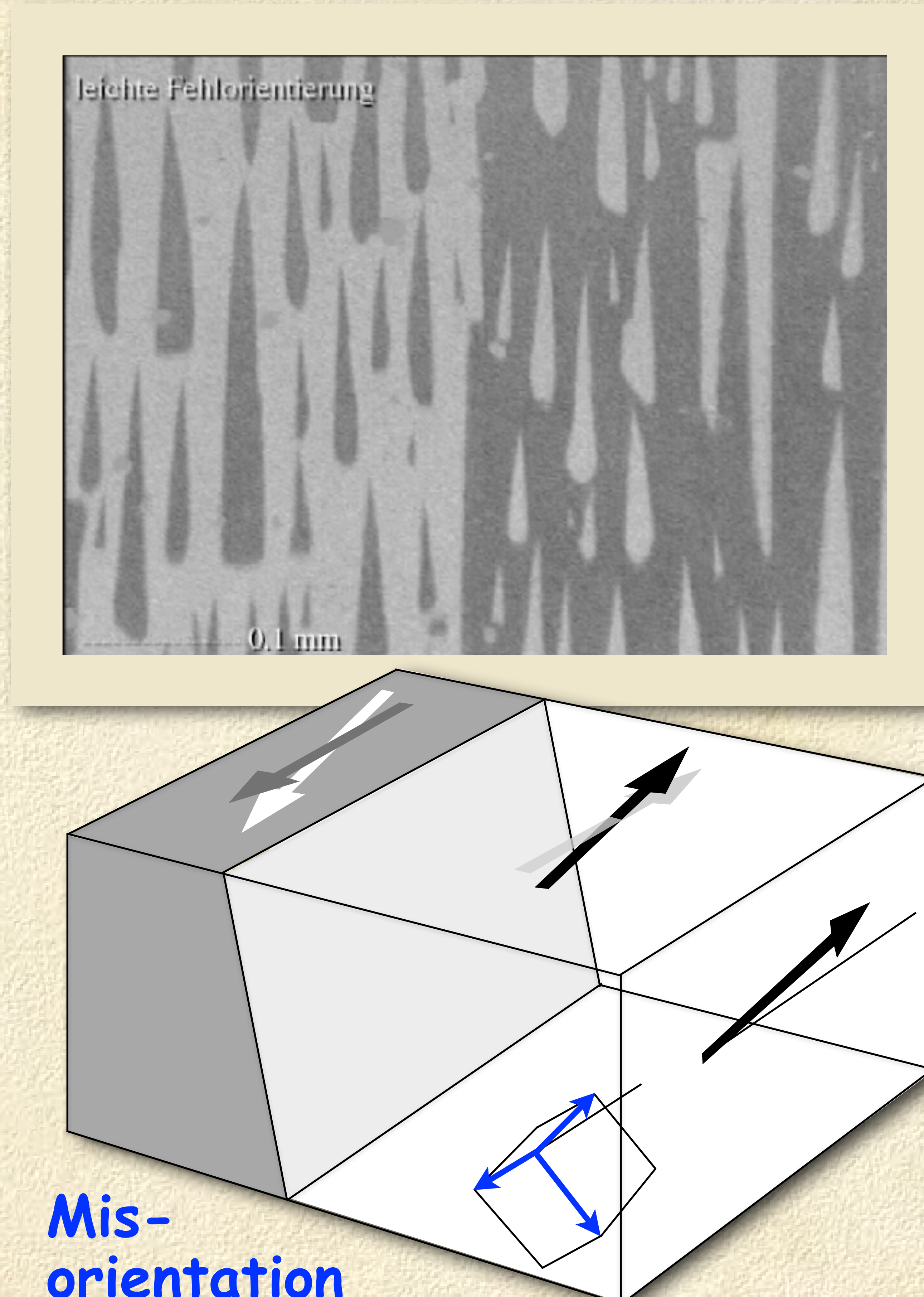
Ideal orientation



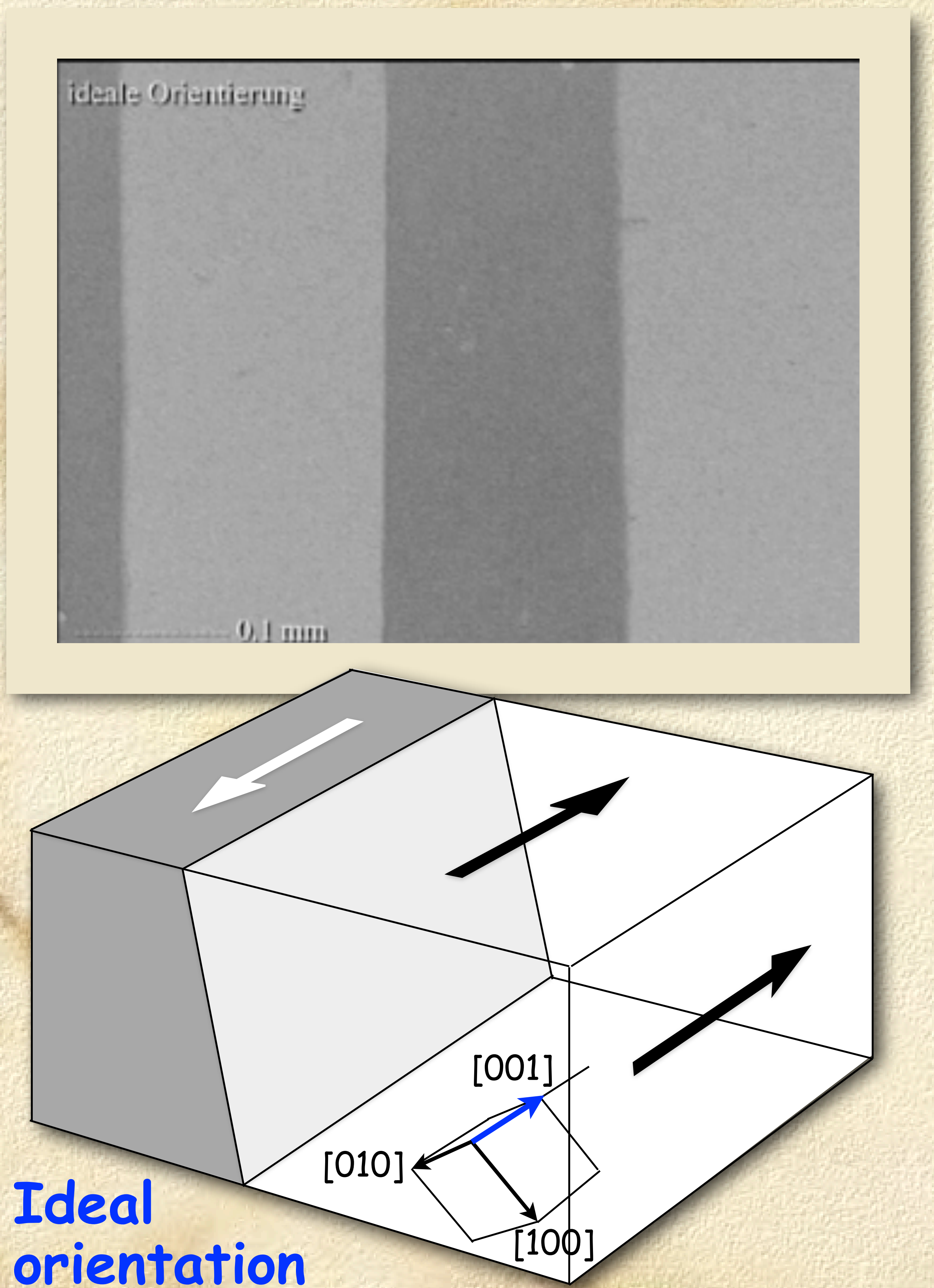
Mis-orientation

Grain-oriented FeSi transformer material

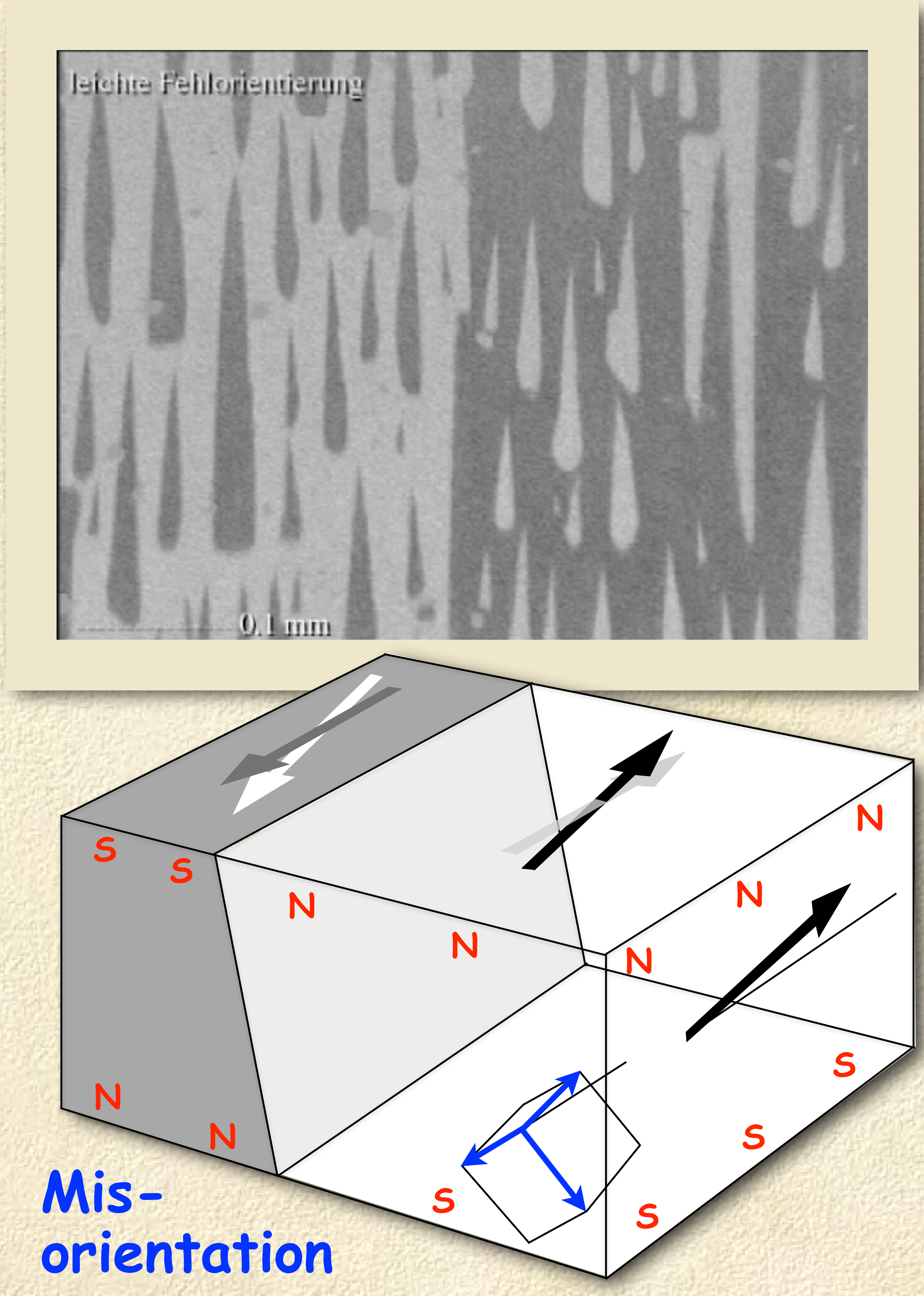




Grain-oriented FeSi transformer material

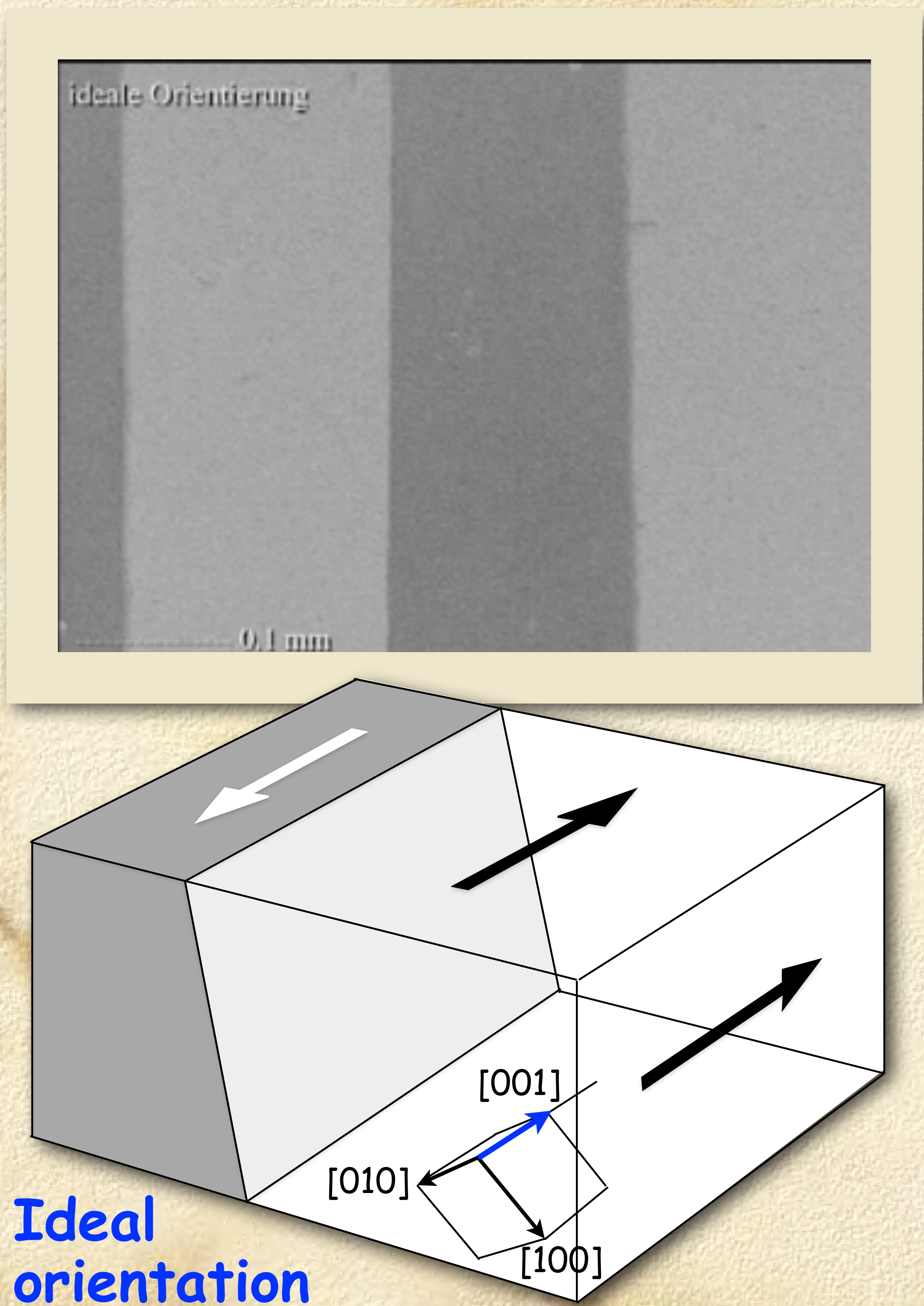


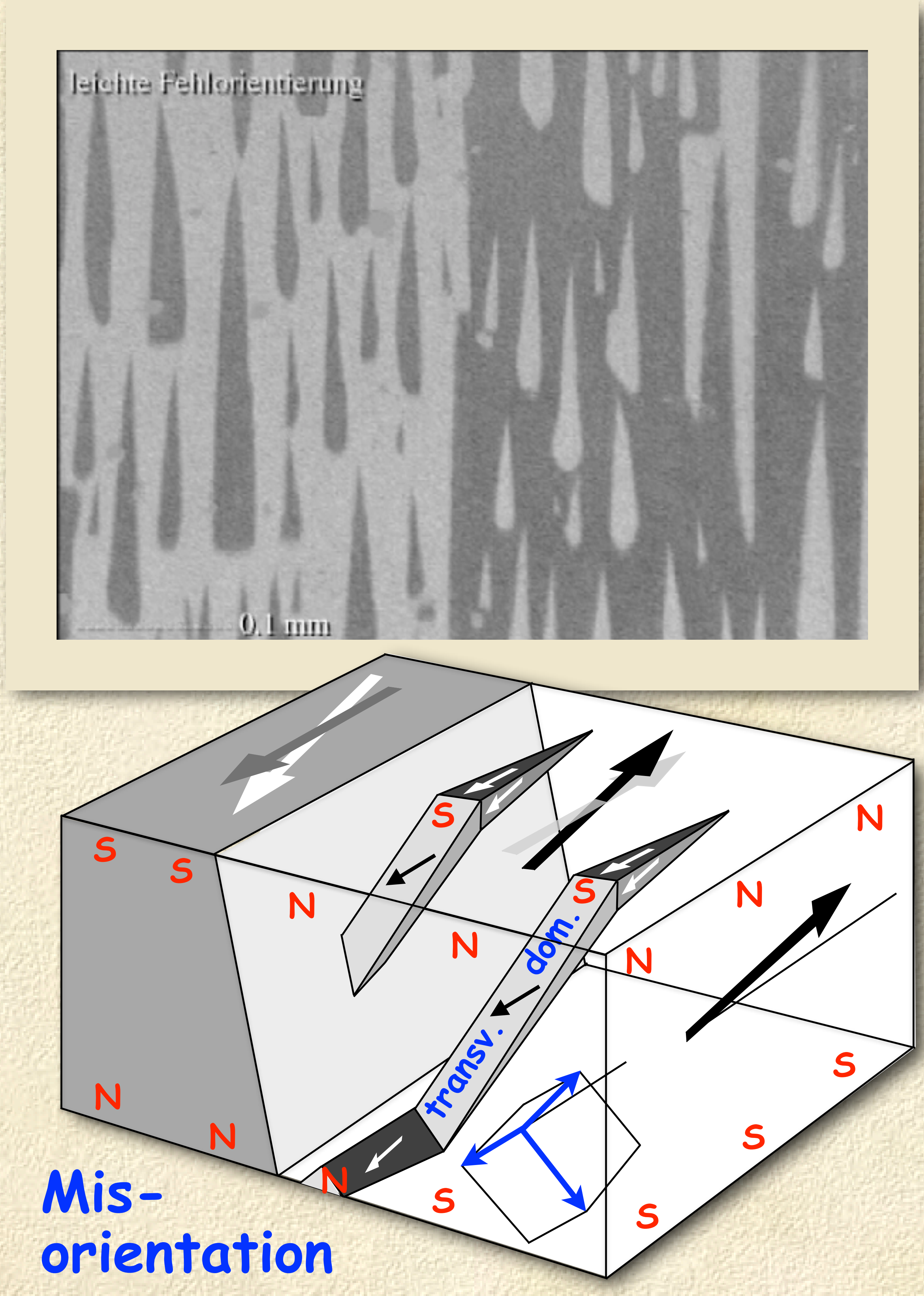
Ideal orientation



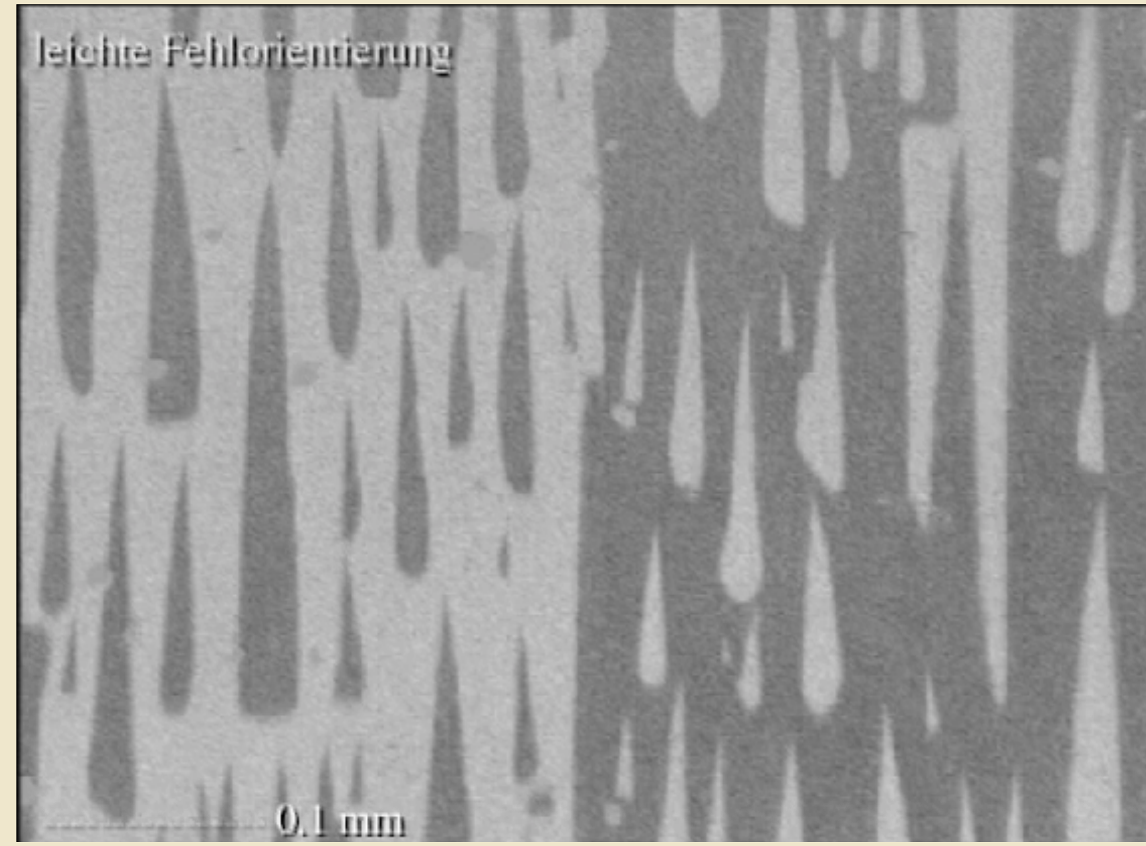
Mis-orientation

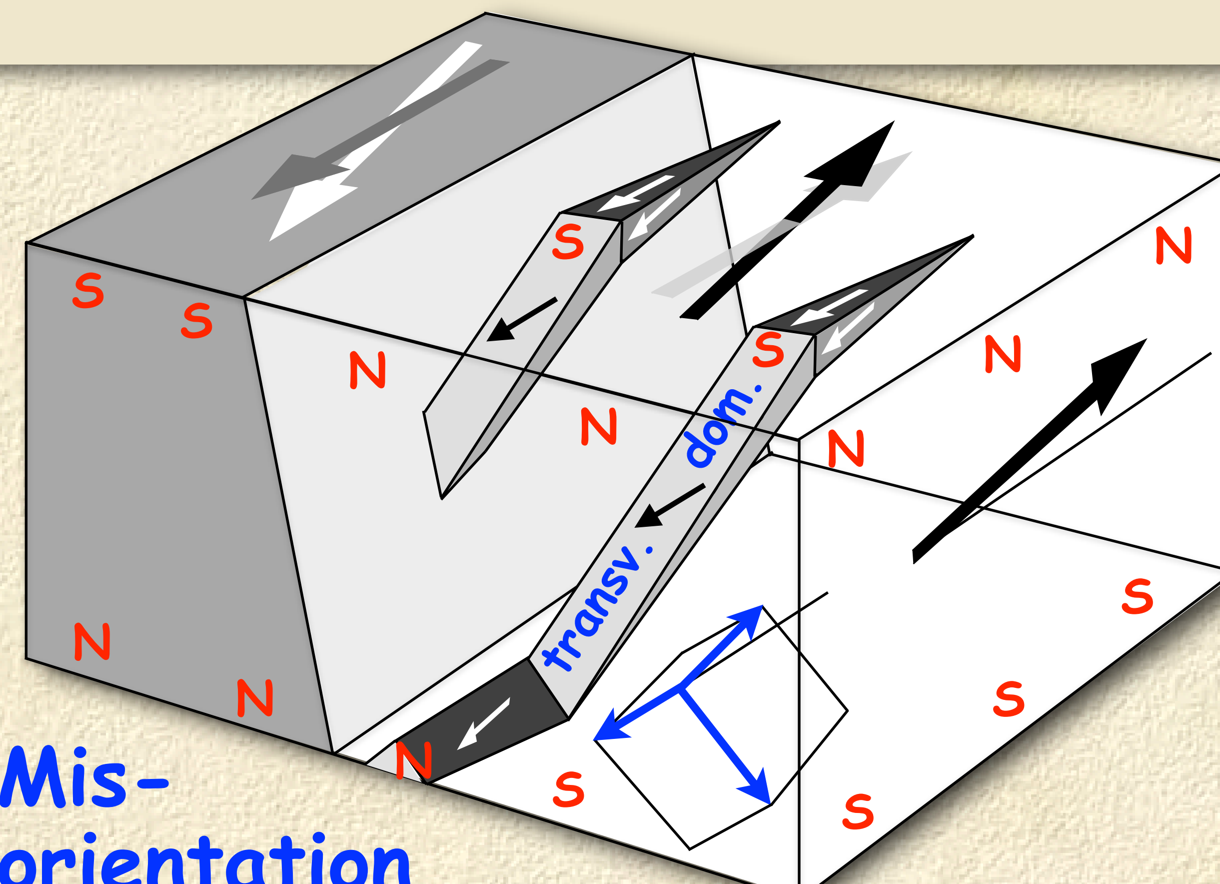
Grain-oriented FeSi transformer material





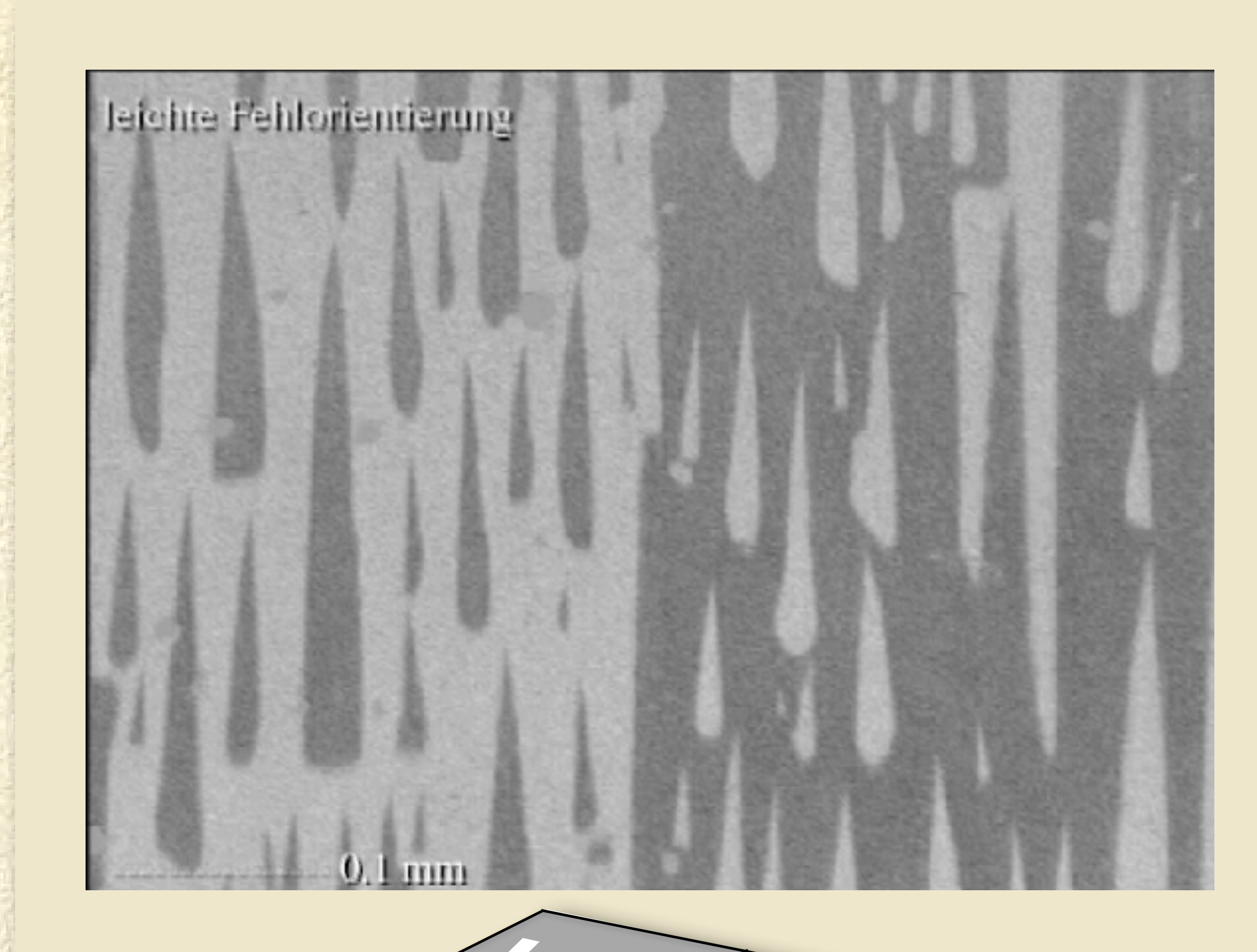
Grain-oriented FeSi transformer material

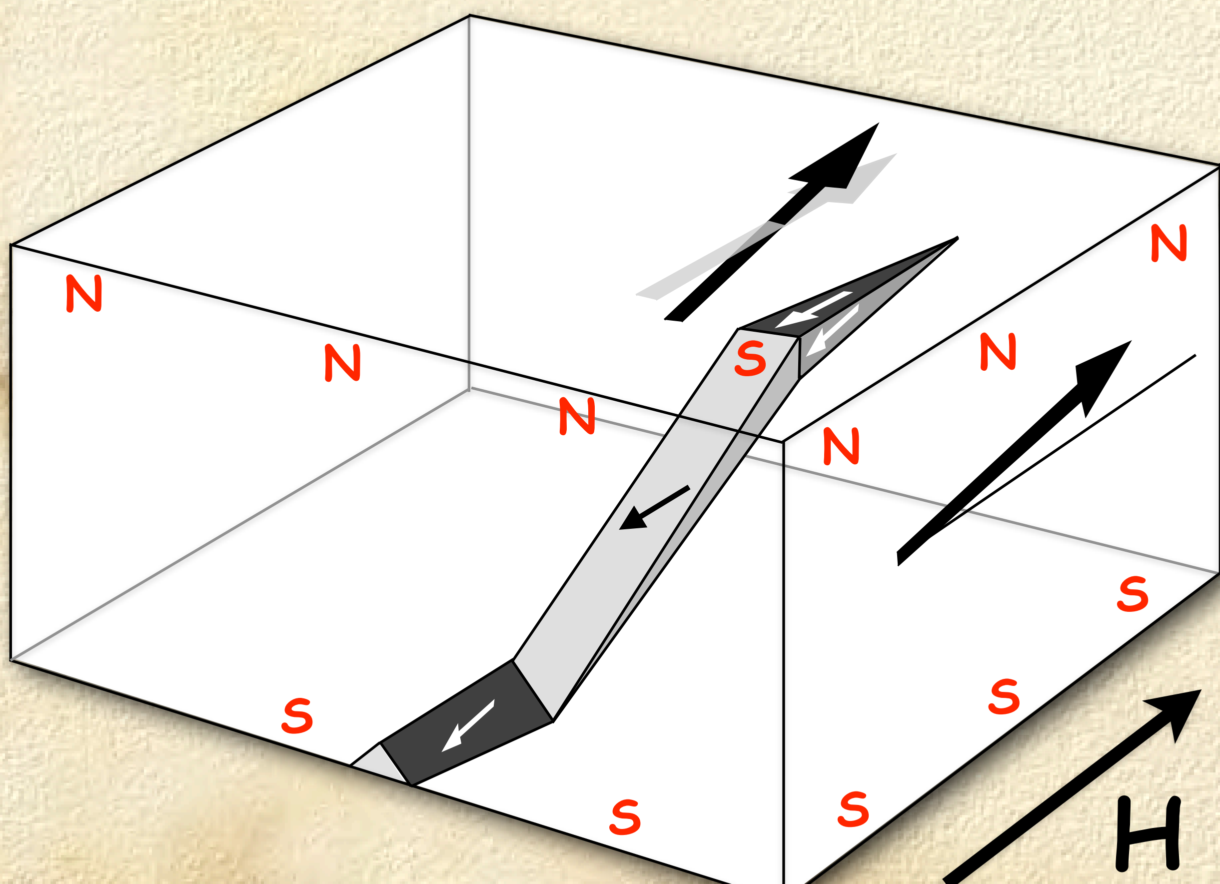


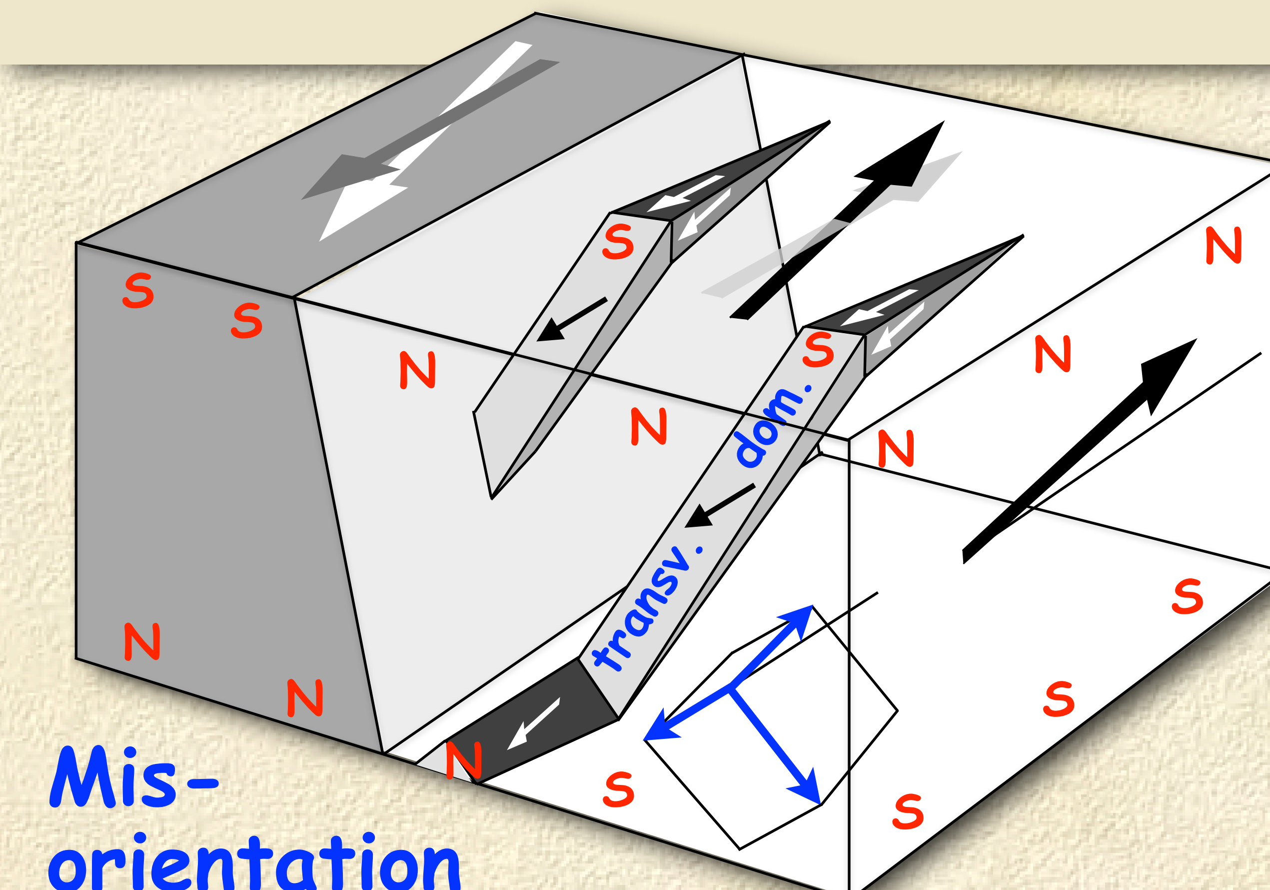


Mis-orientation

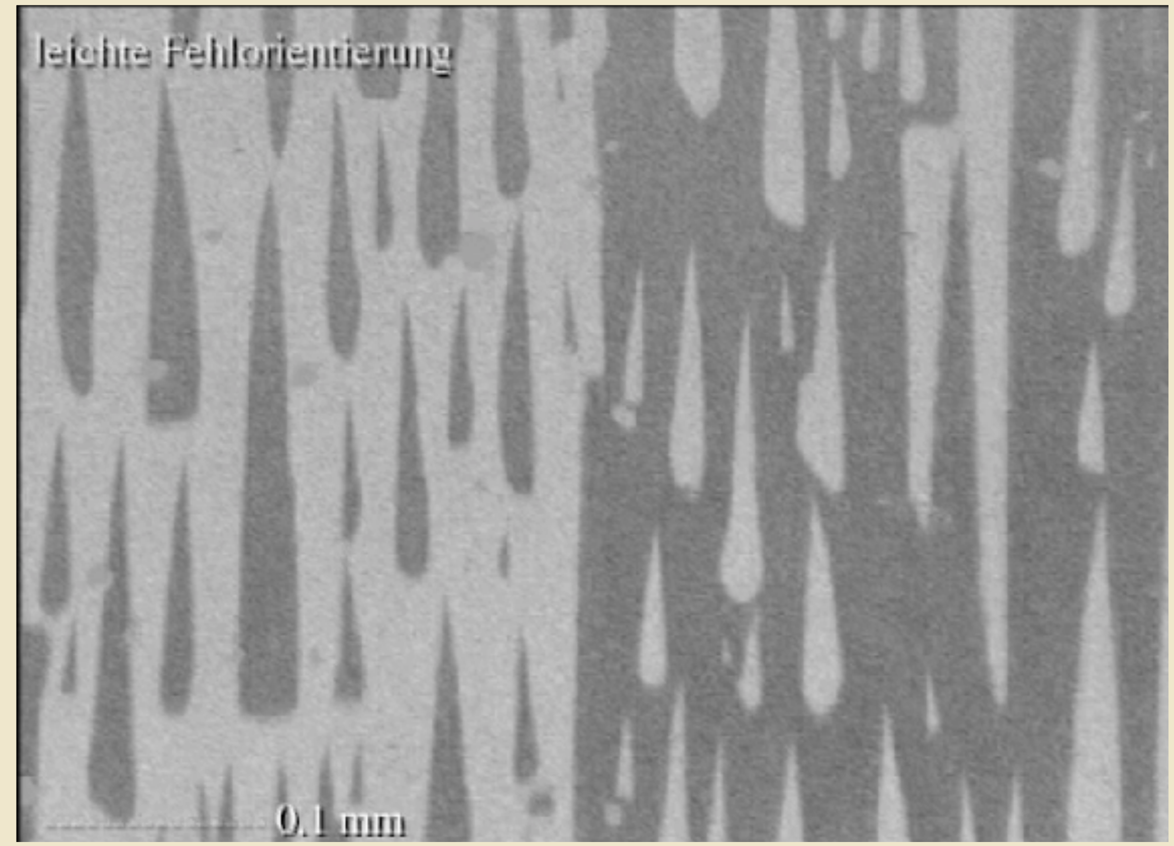
Grain-oriented FeSi transformer material

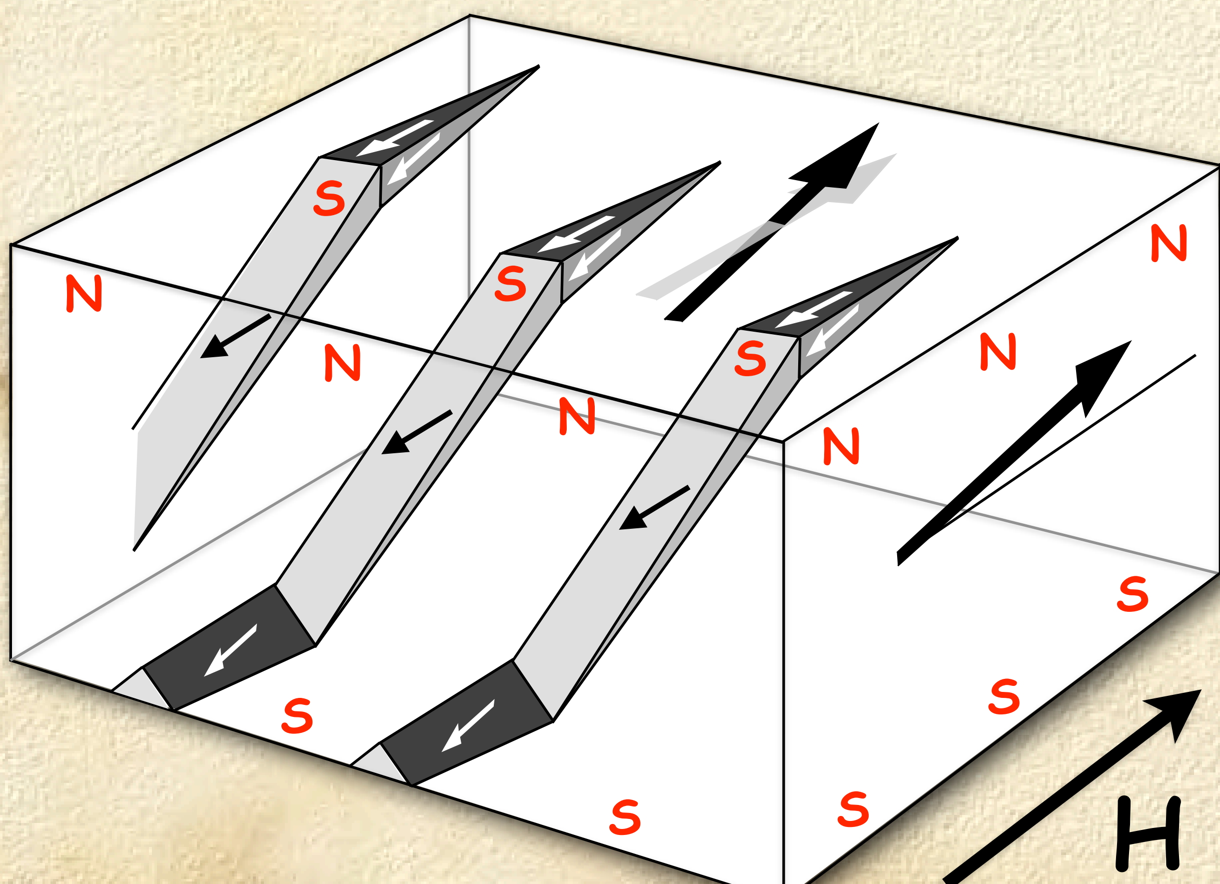


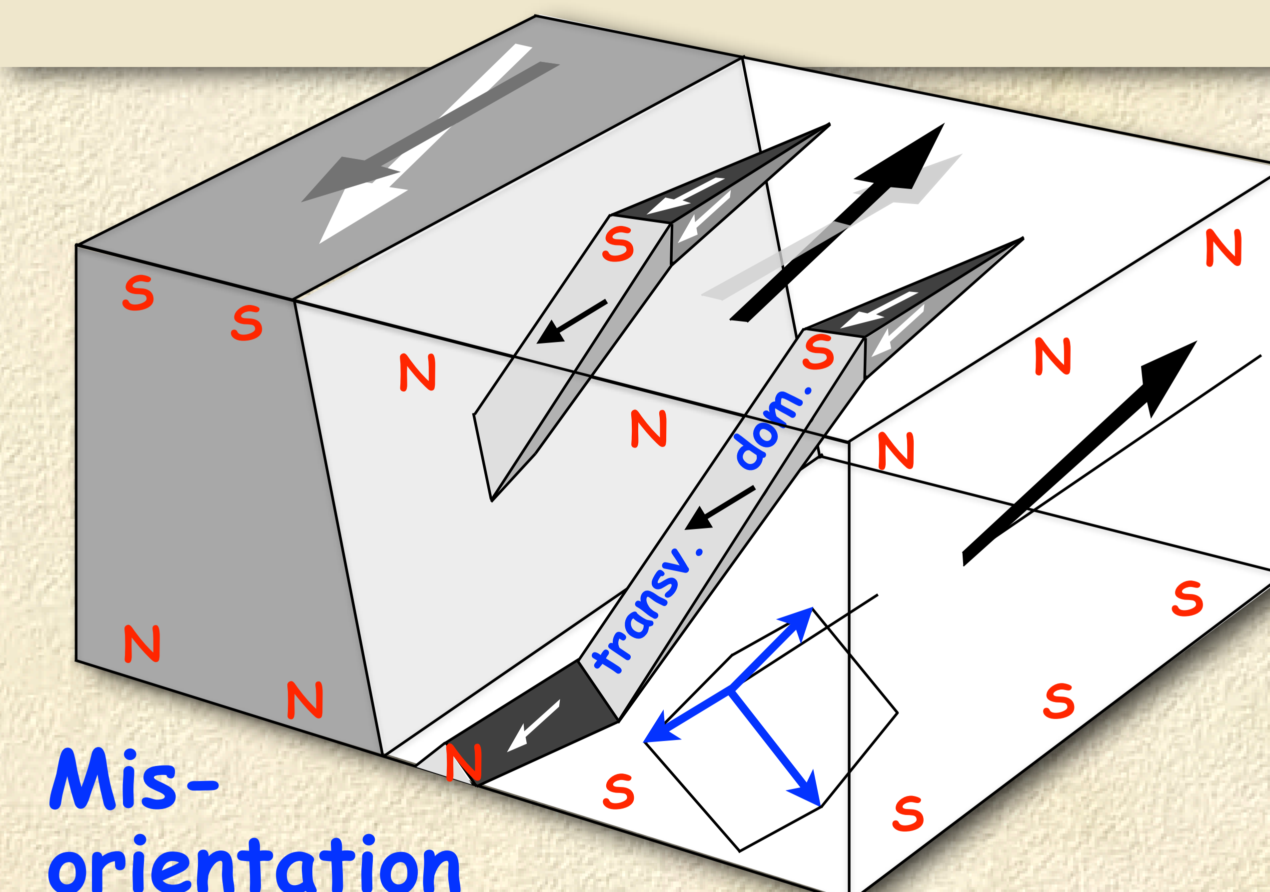




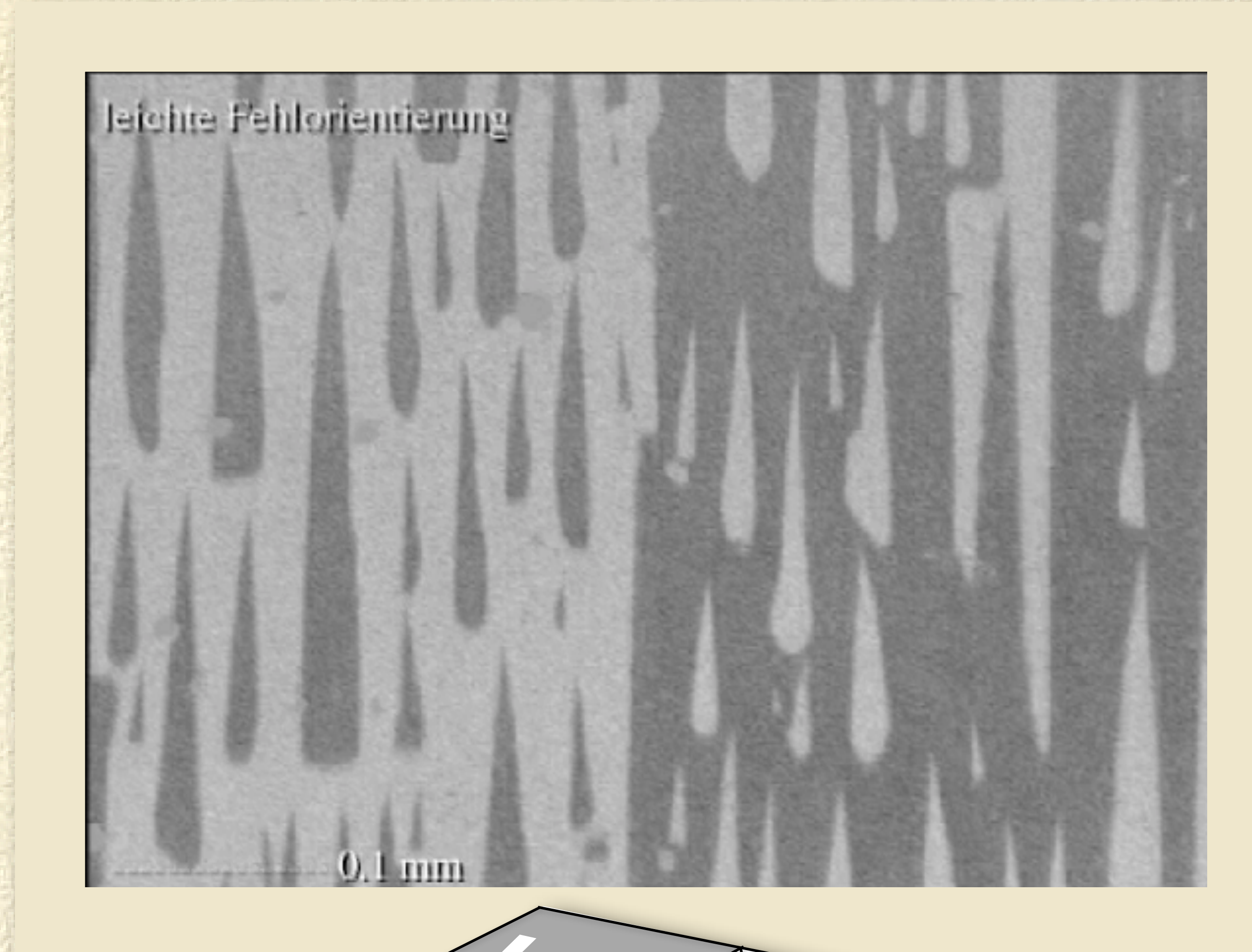
Grain-oriented FeSi transformer material

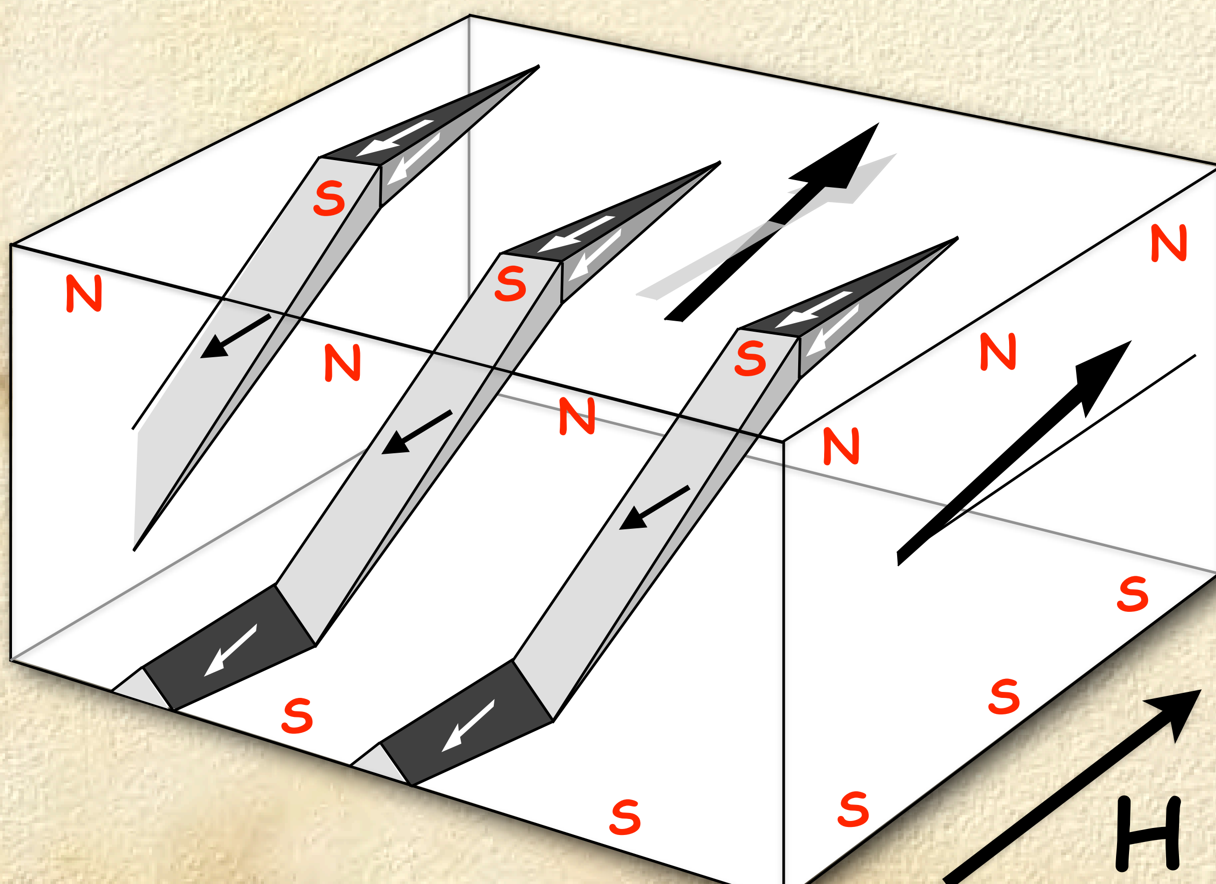


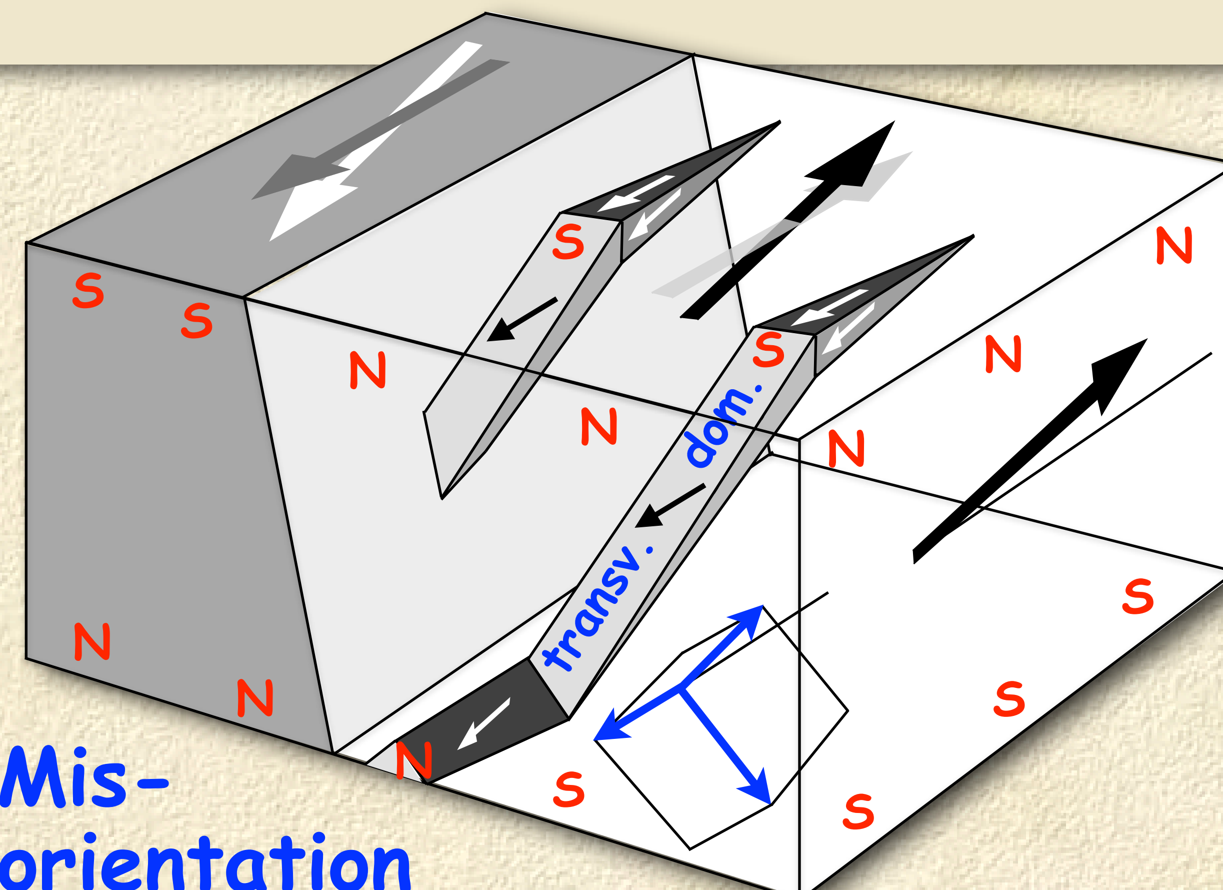




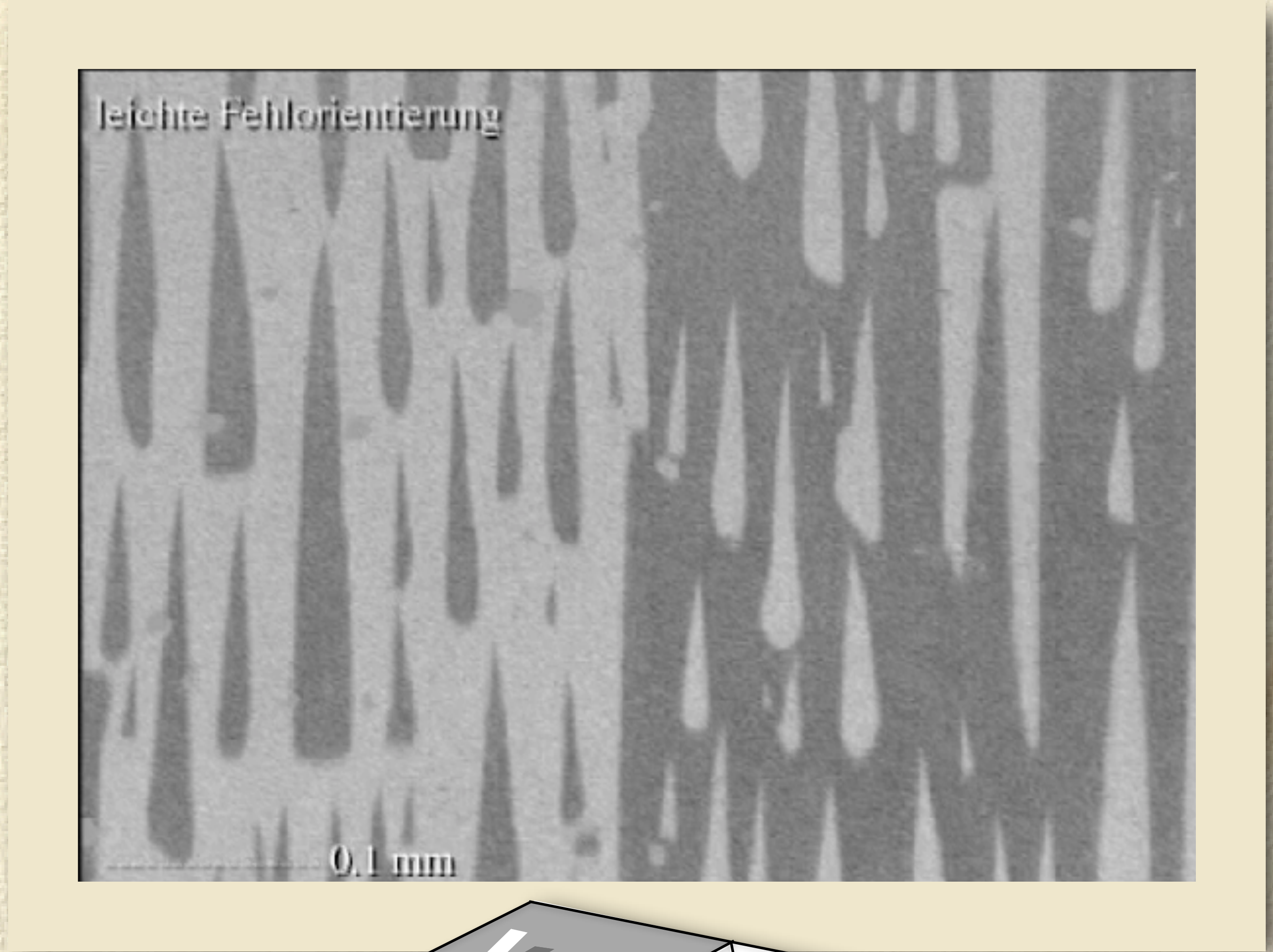
Grain-oriented FeSi transformer material

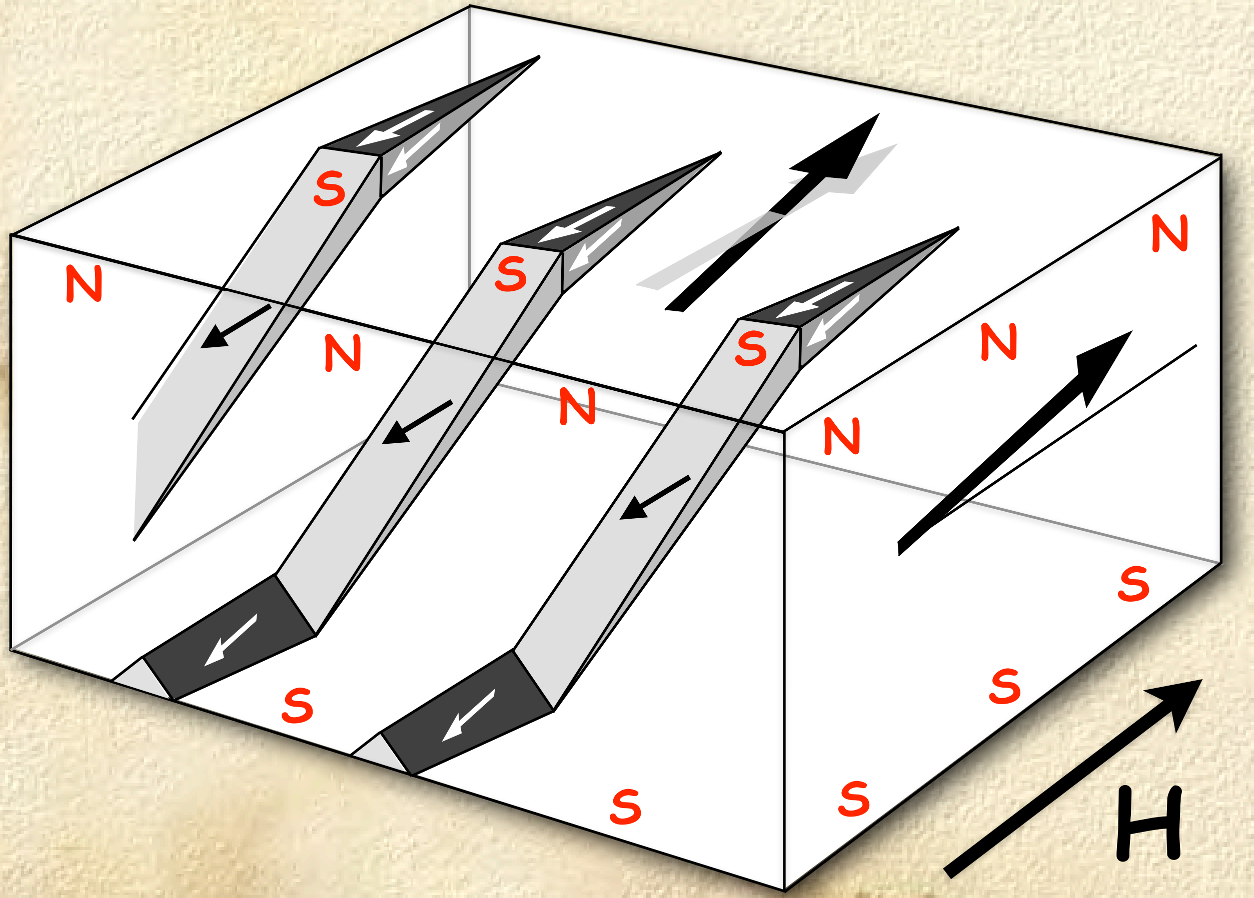


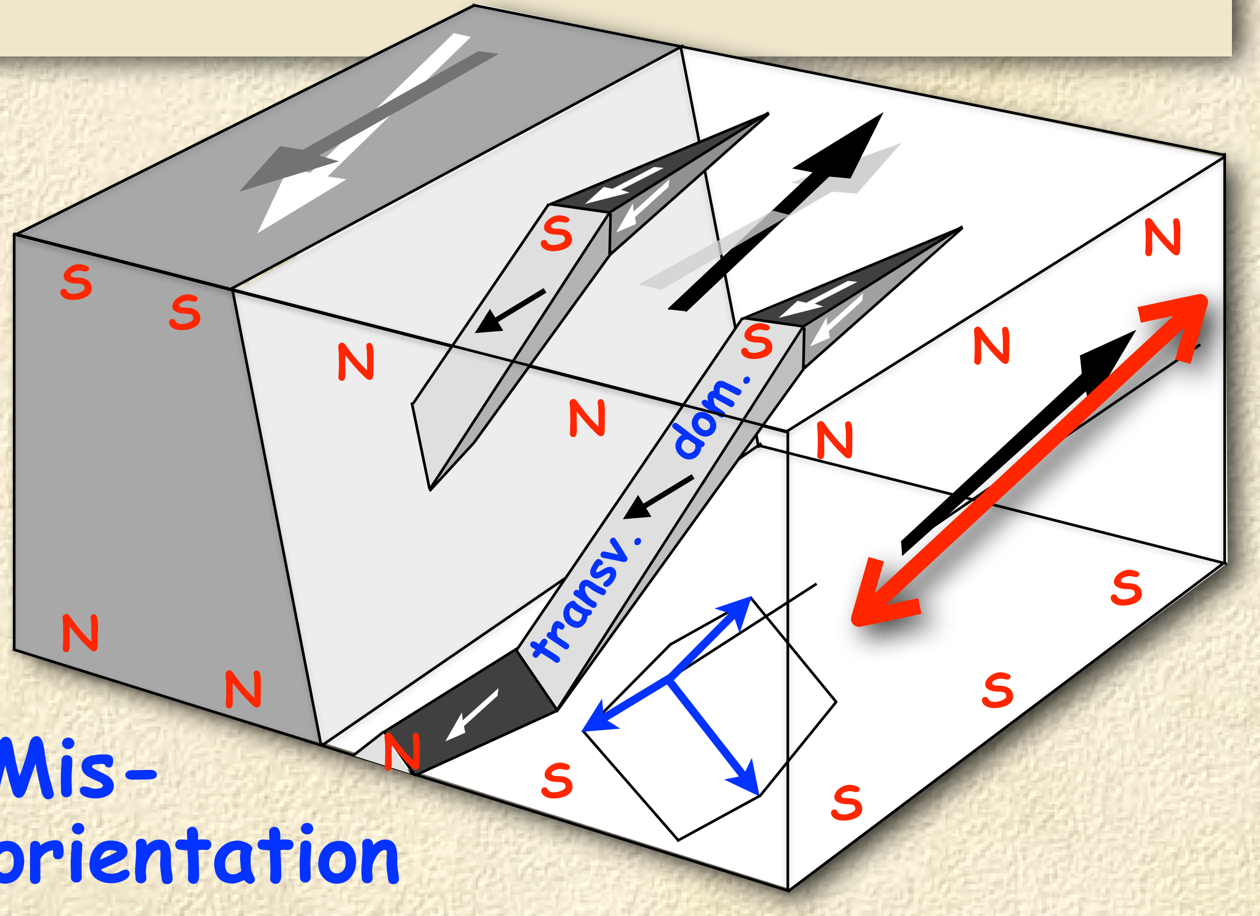




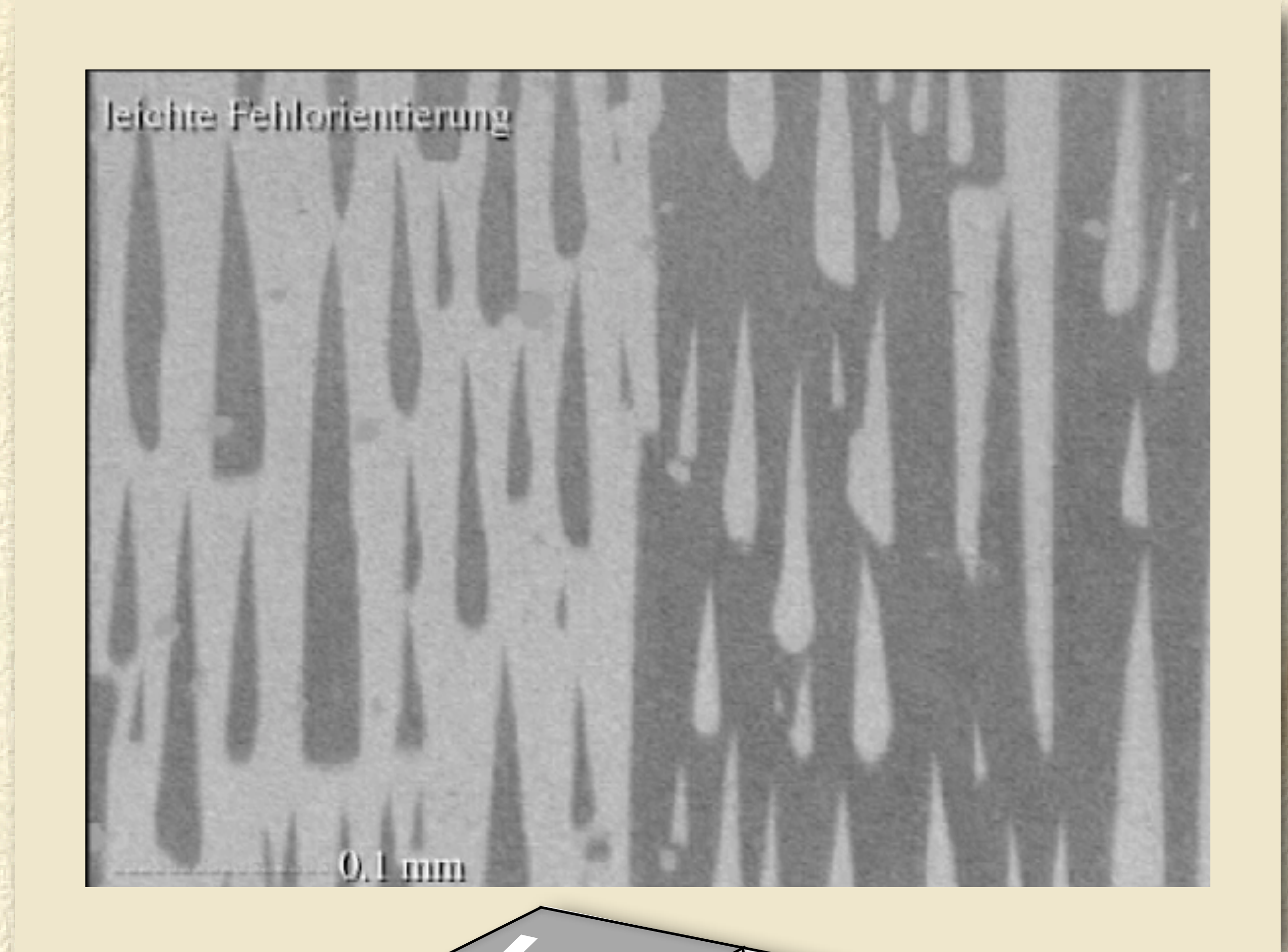
Grain-oriented FeSi transformer material

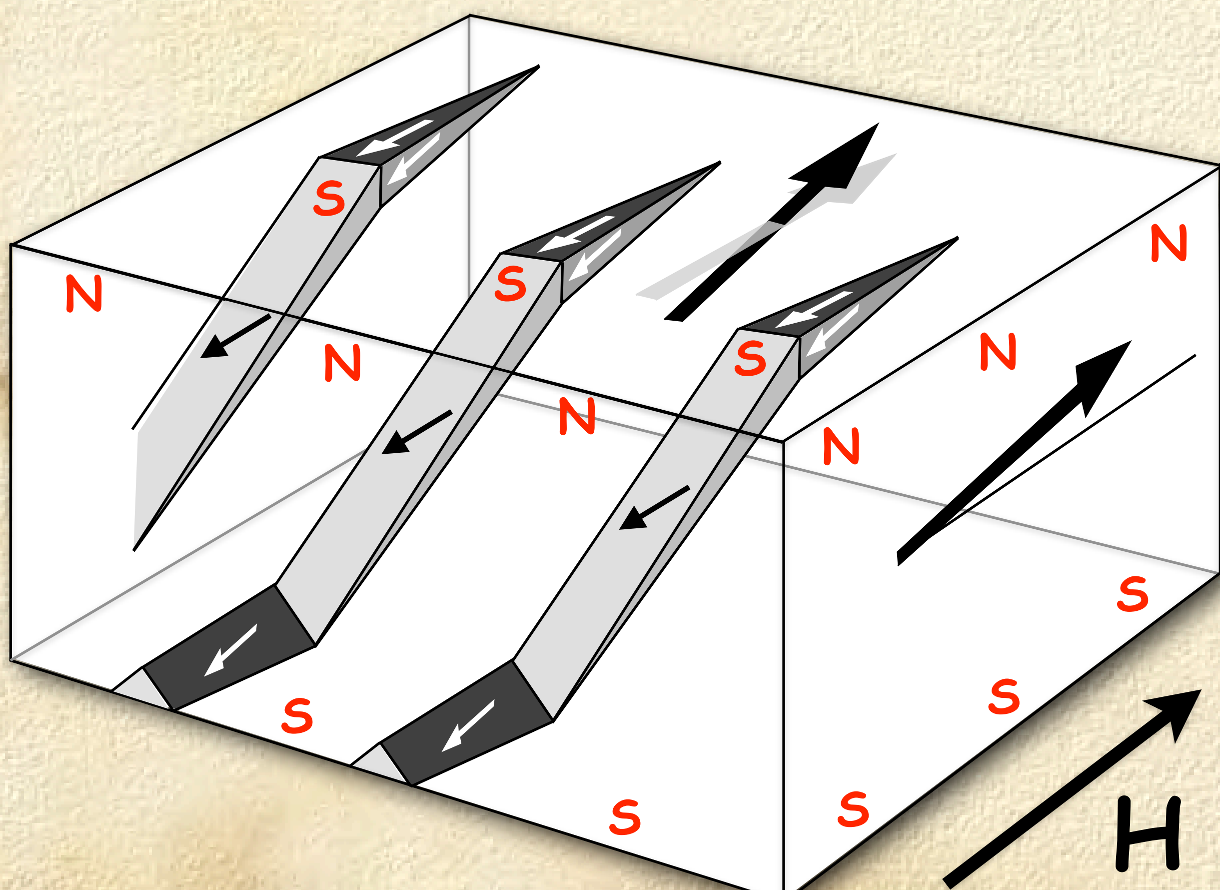


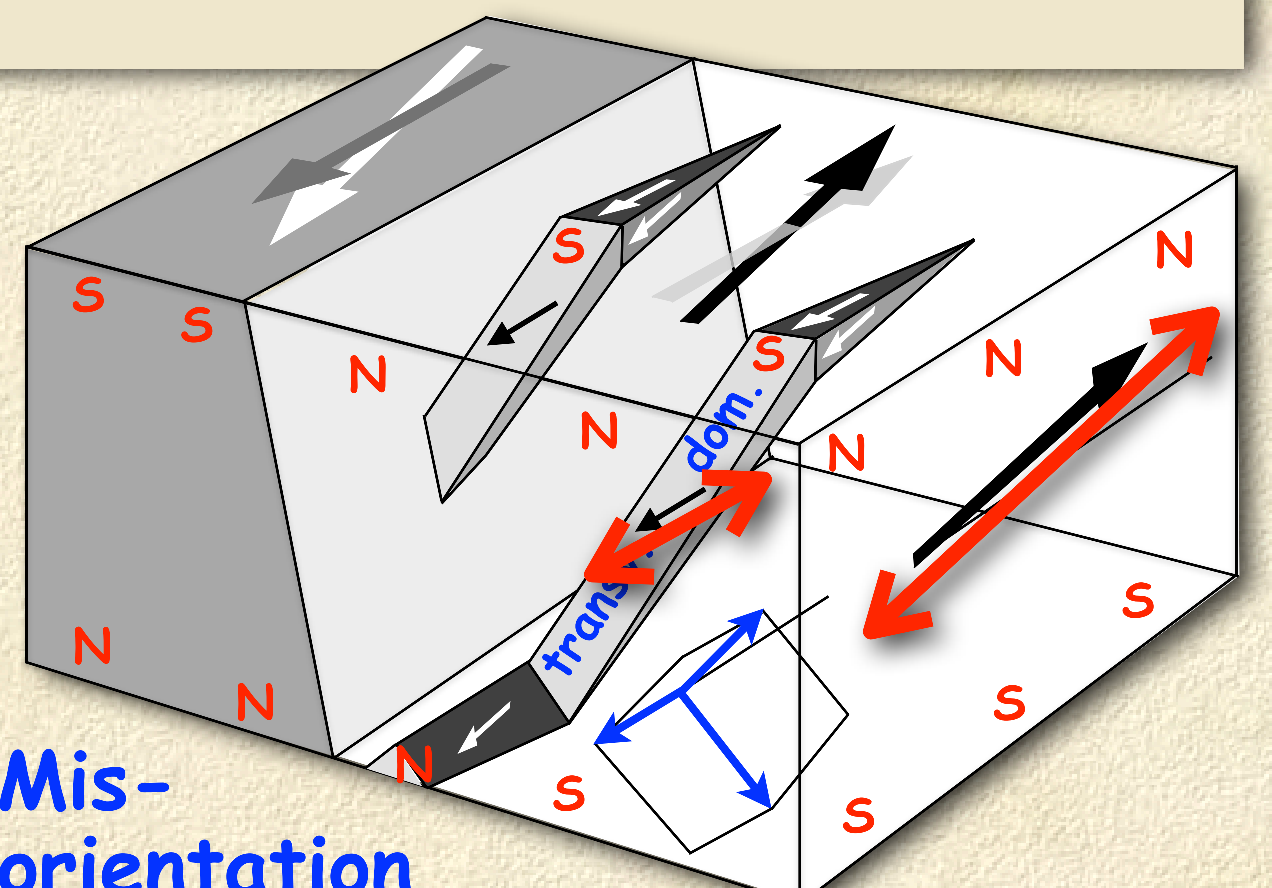




Grain-oriented FeSi transformer material

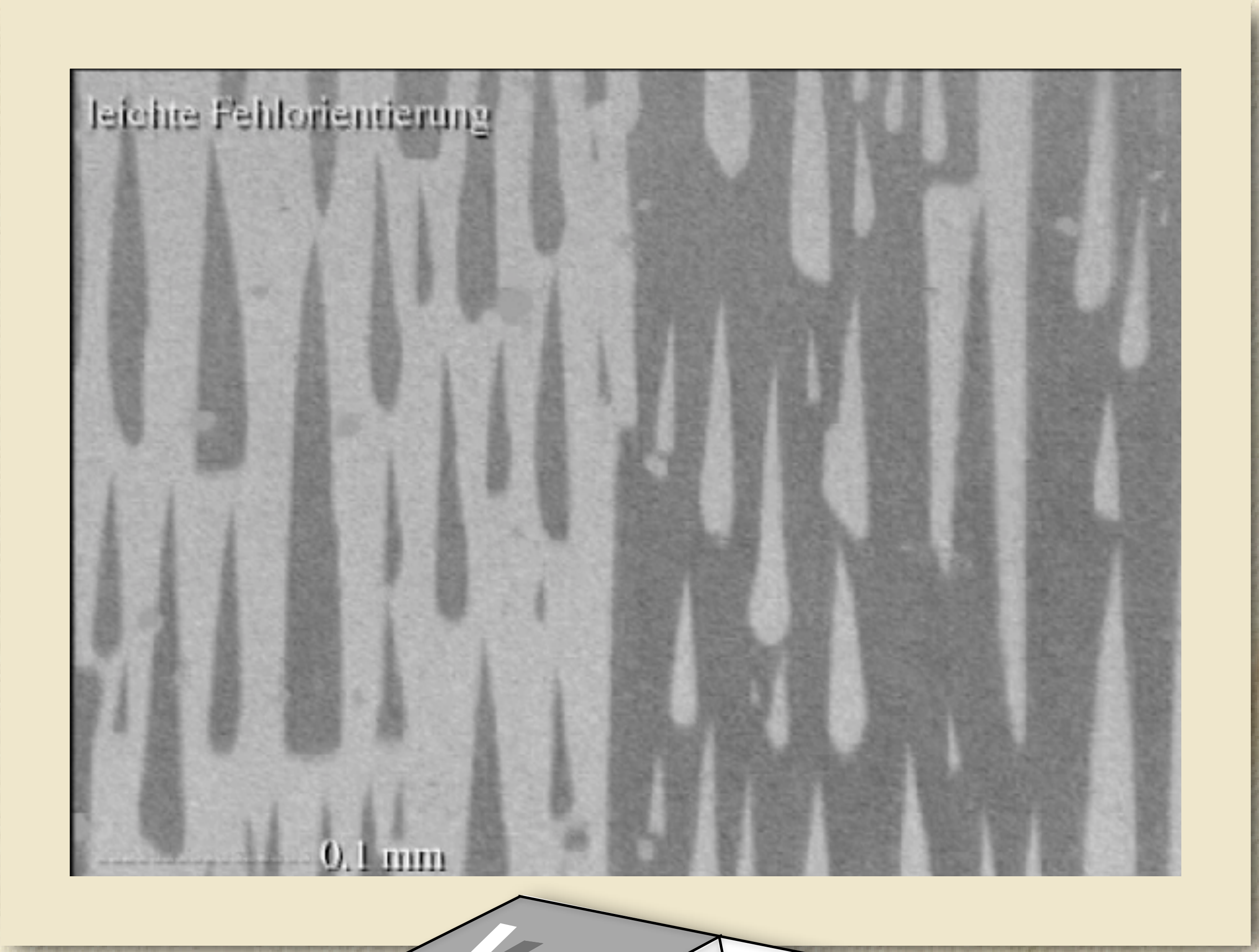


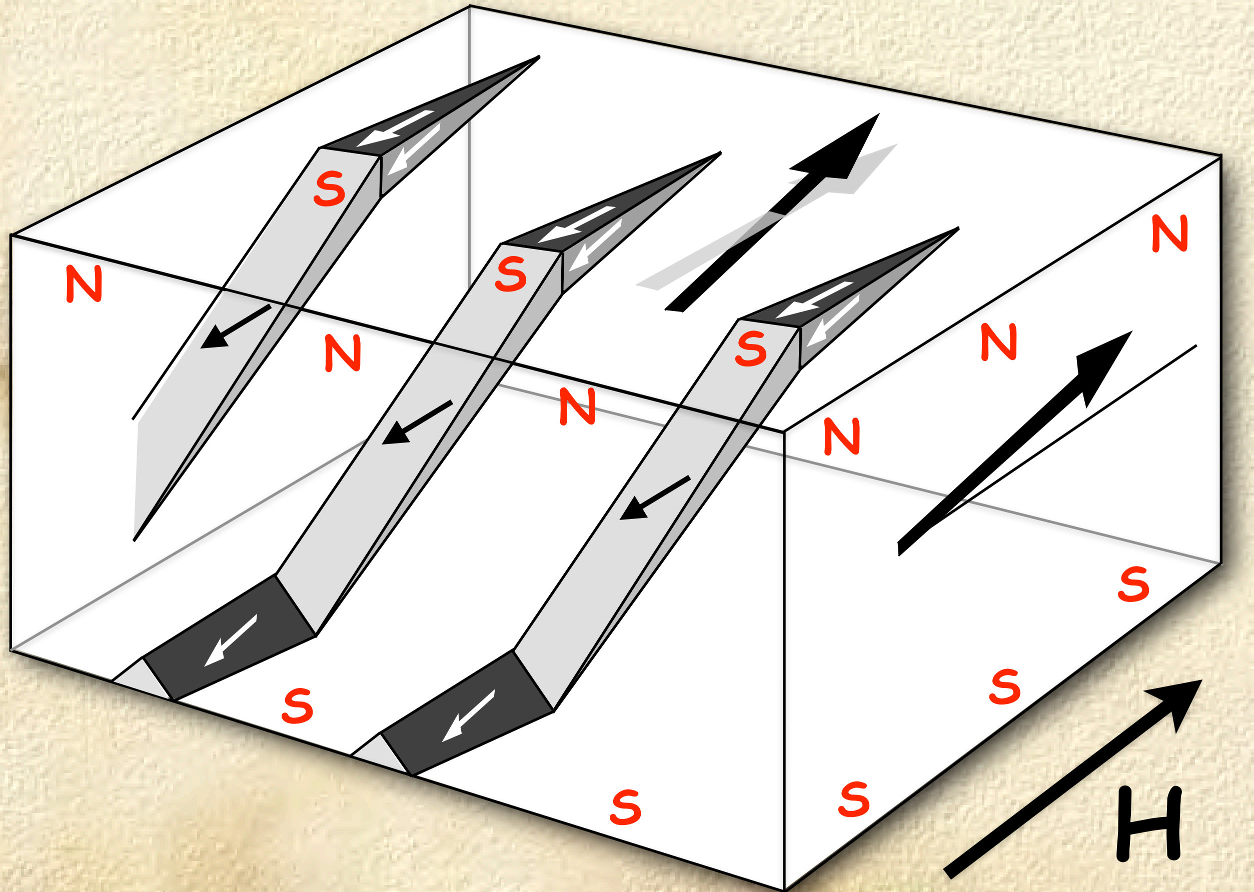


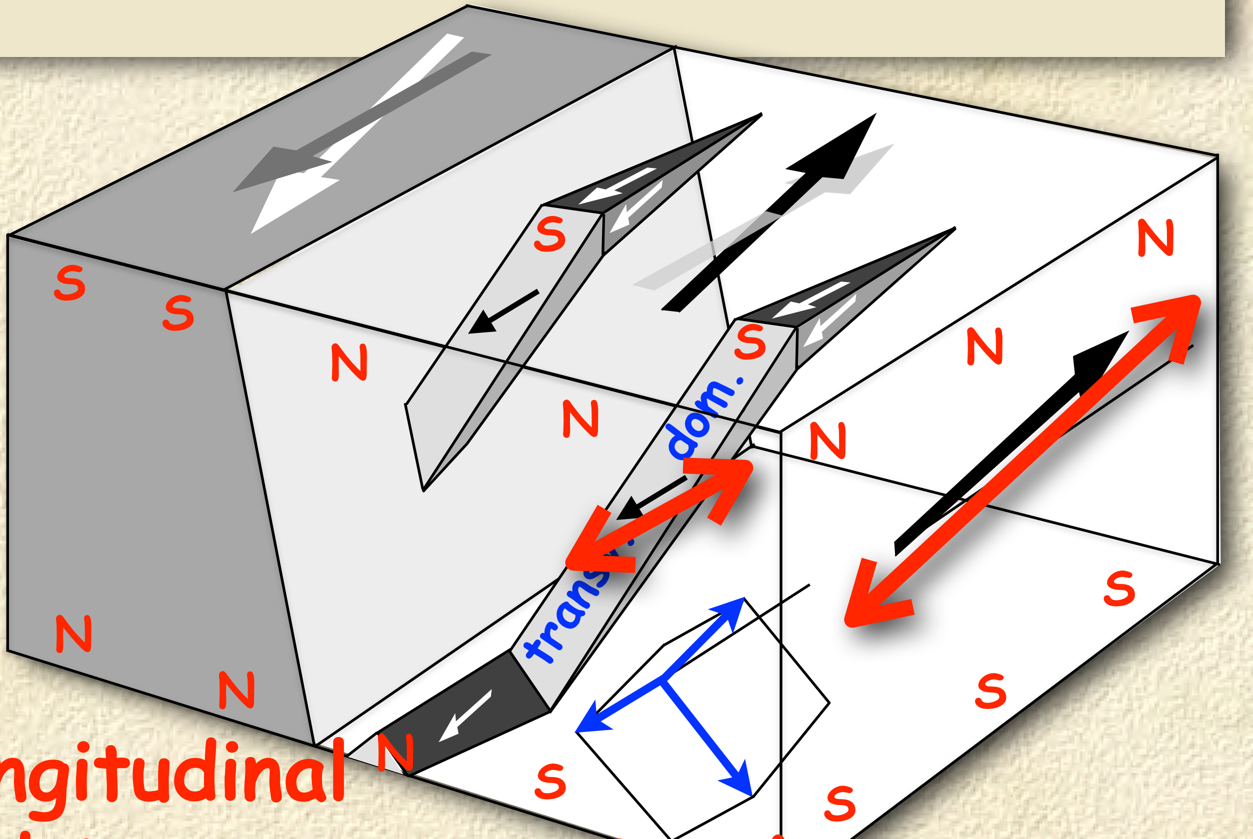


Mis-orientation

Grain-oriented FeSi transformer material

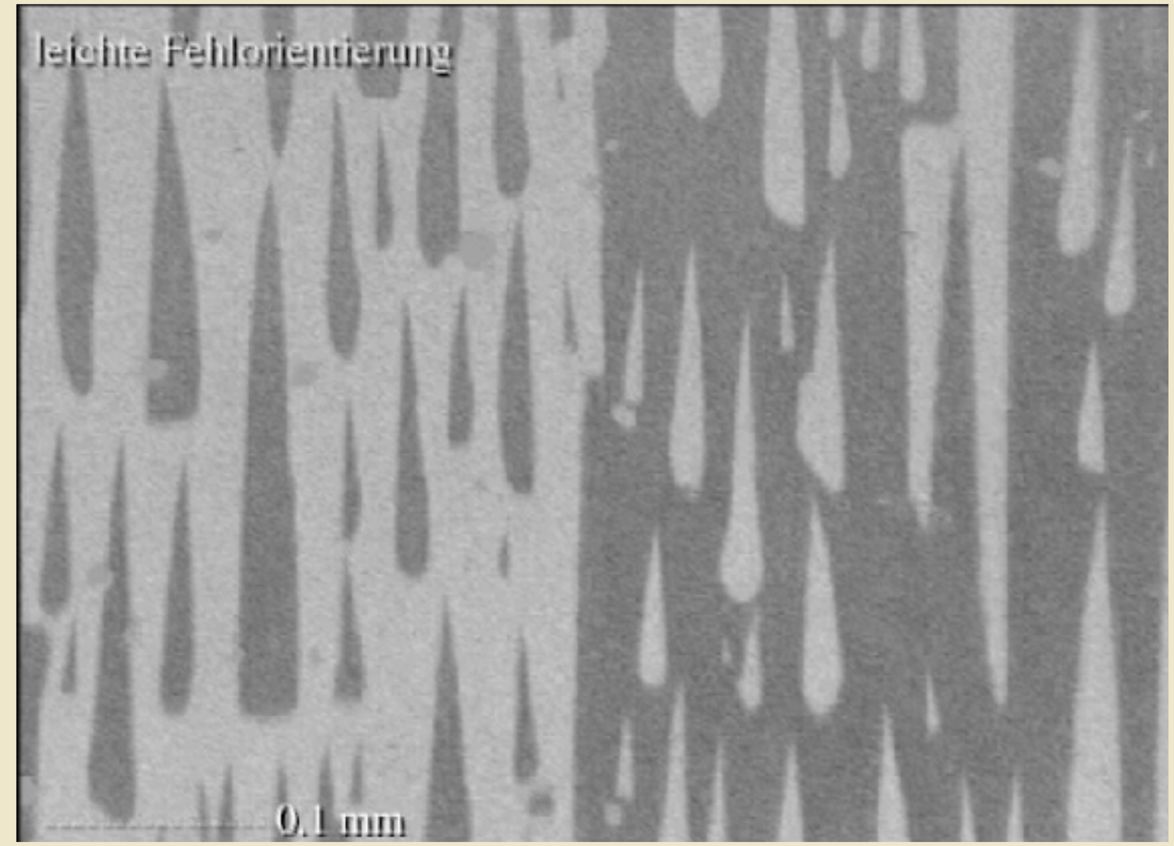


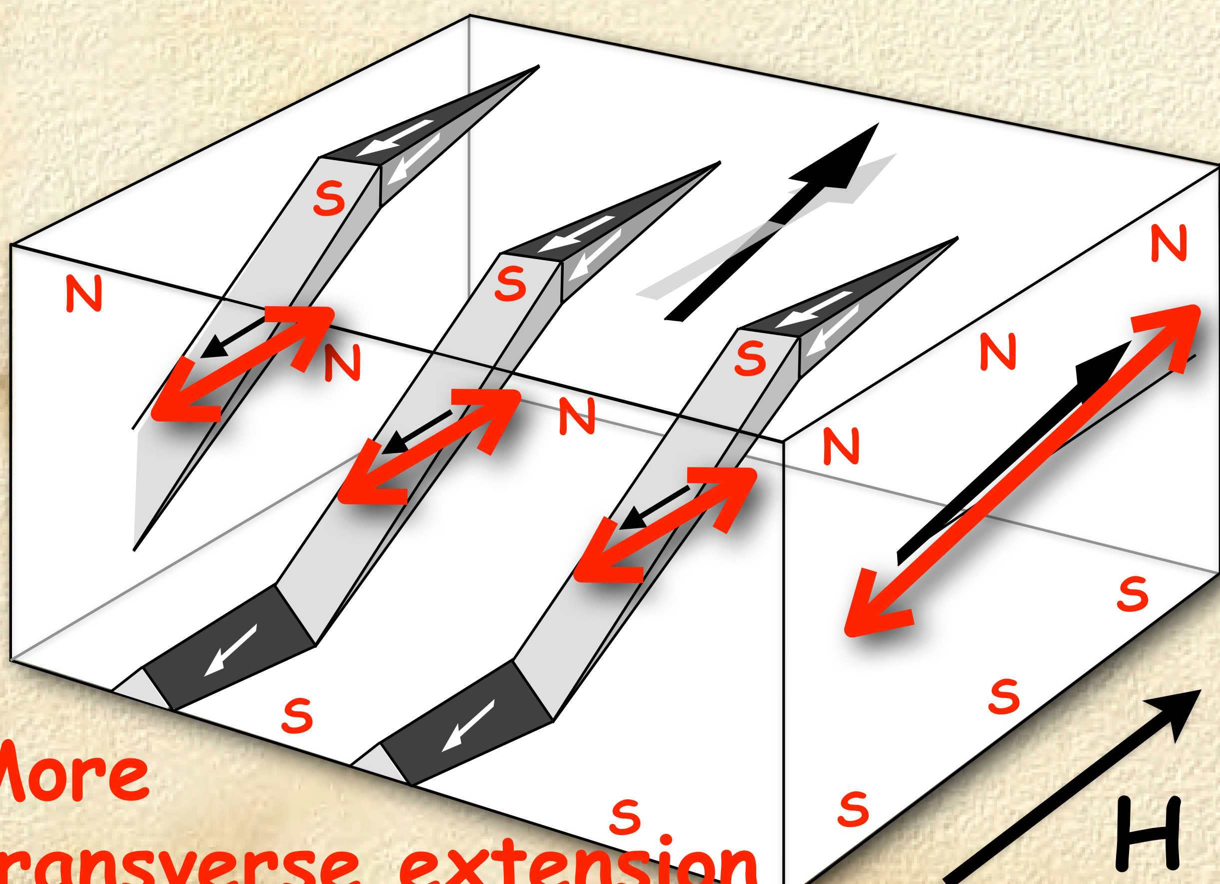




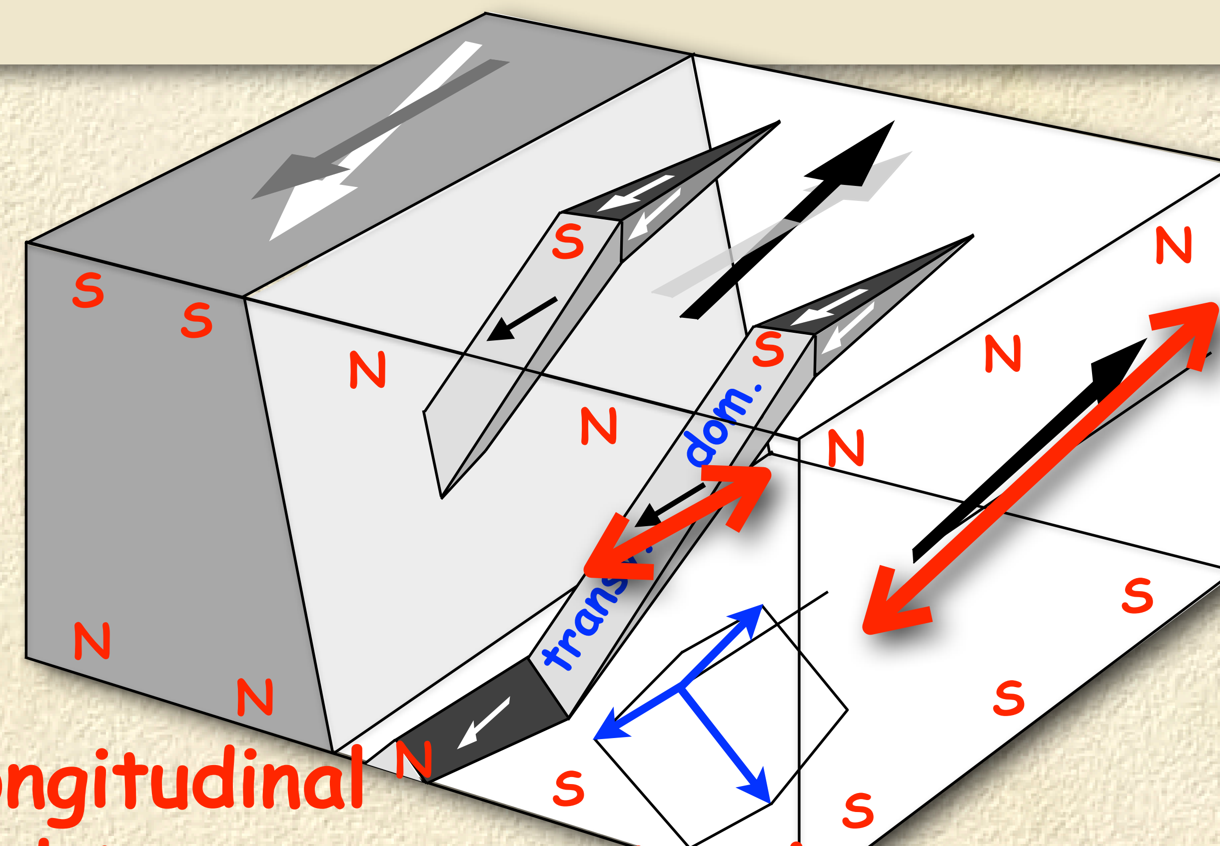
Longitudinal and transverse extension

Grain-oriented FeSi transformer material





More
transverse extension

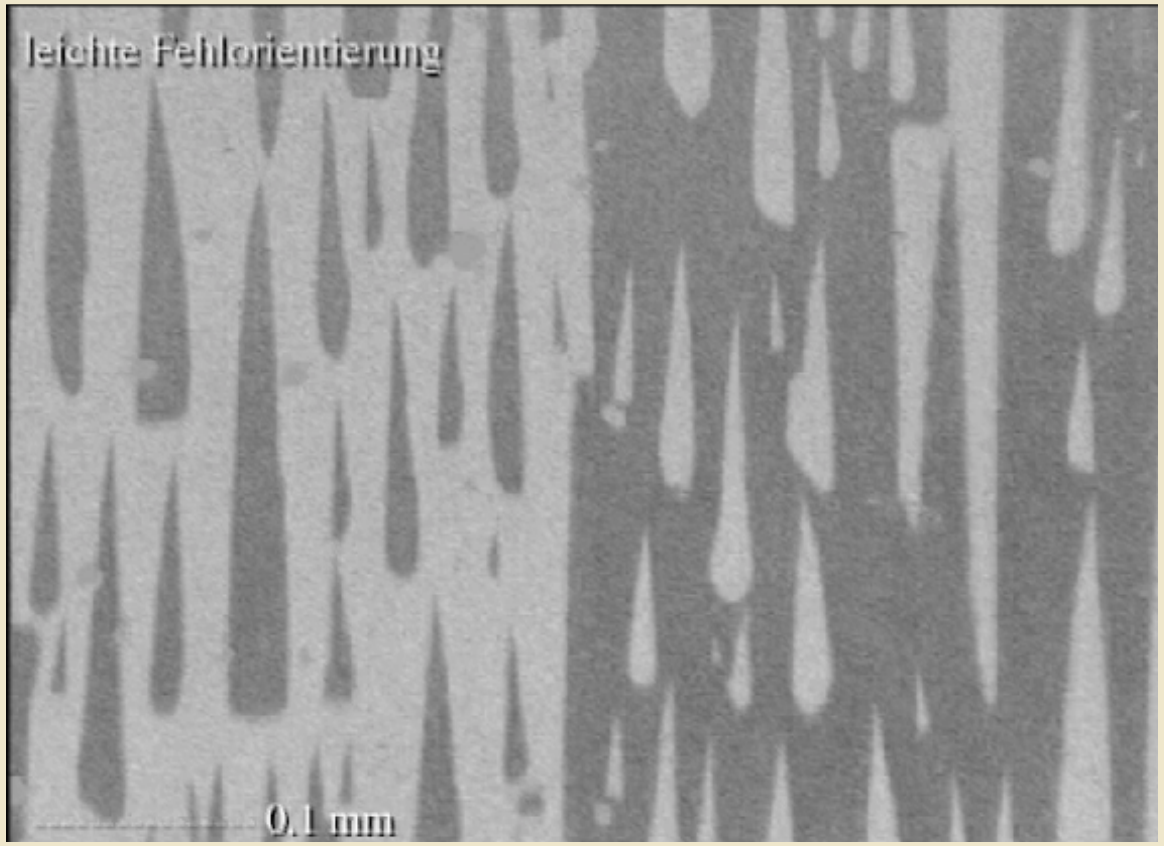


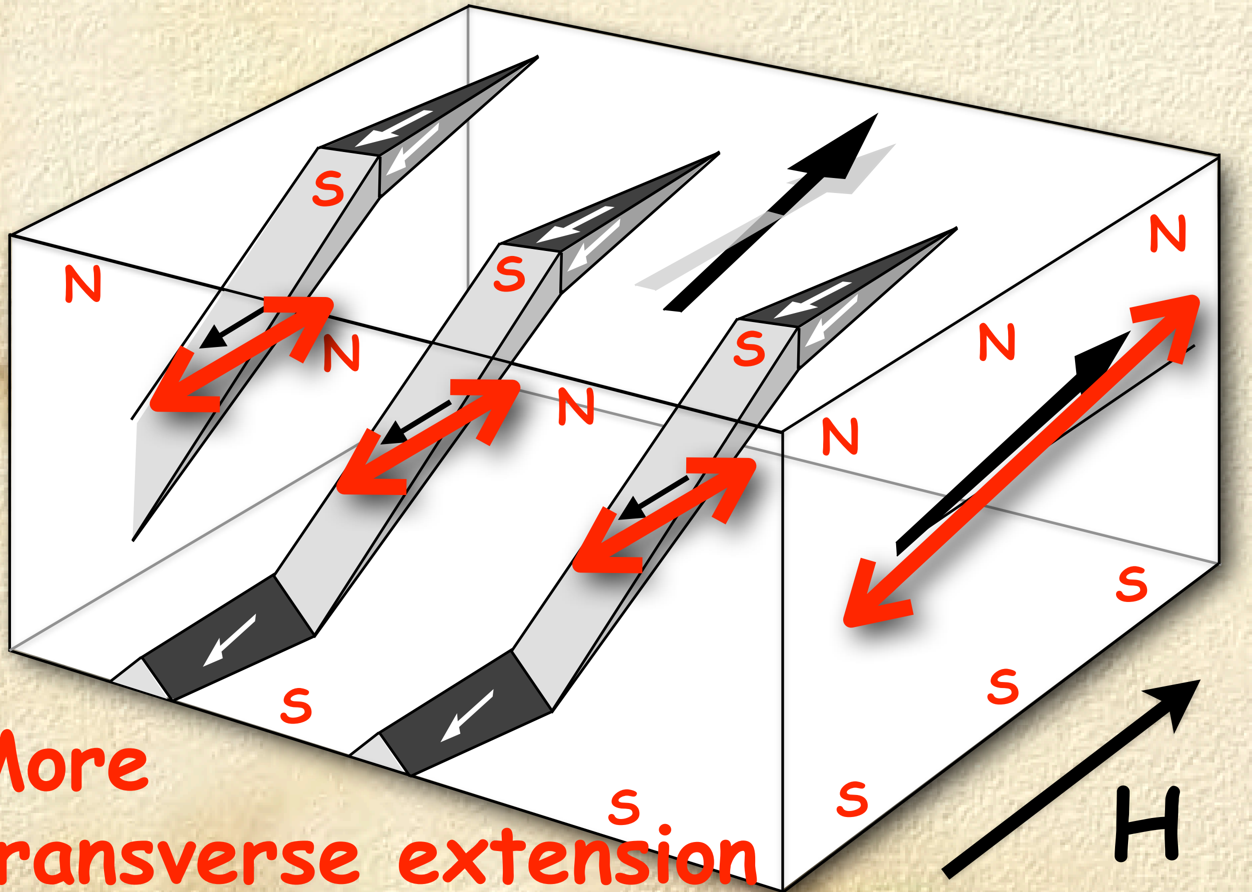
Longitudinal
and transverse extension

Grain-oriented FeSi transformer material

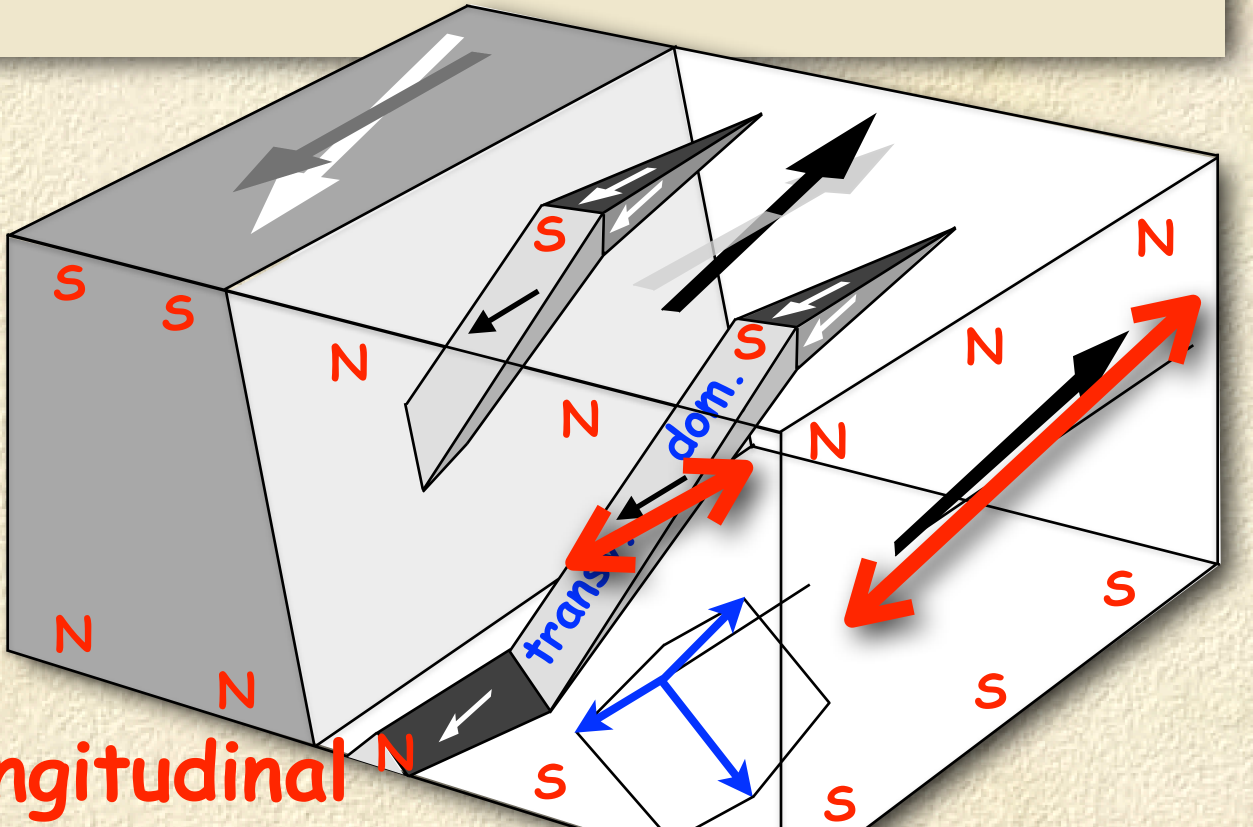
Tension and compression in rhythm of magnetic field

The sheet vibrates
(= transformer noise)





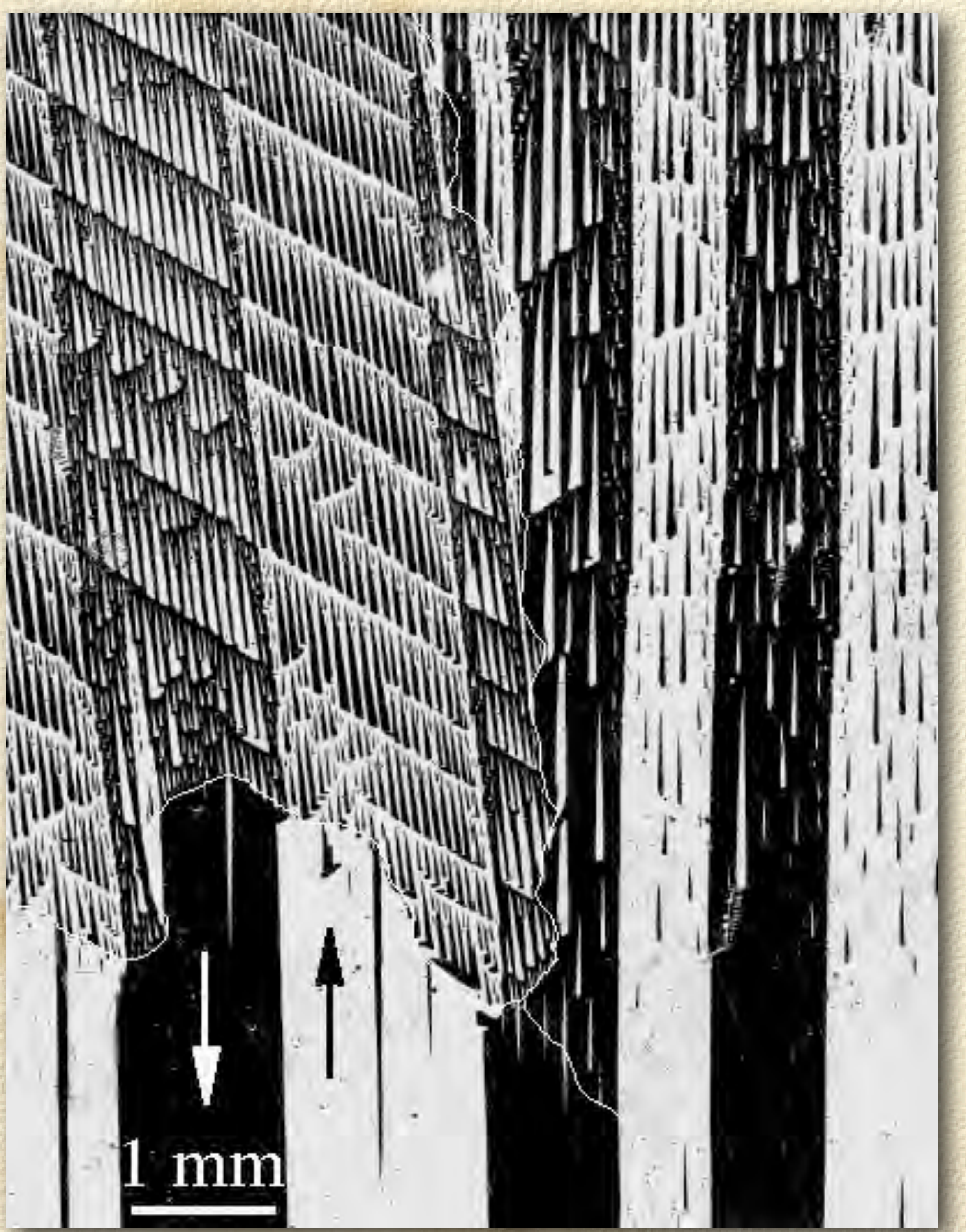
More
transverse extension



Longitudinal
and transverse extension

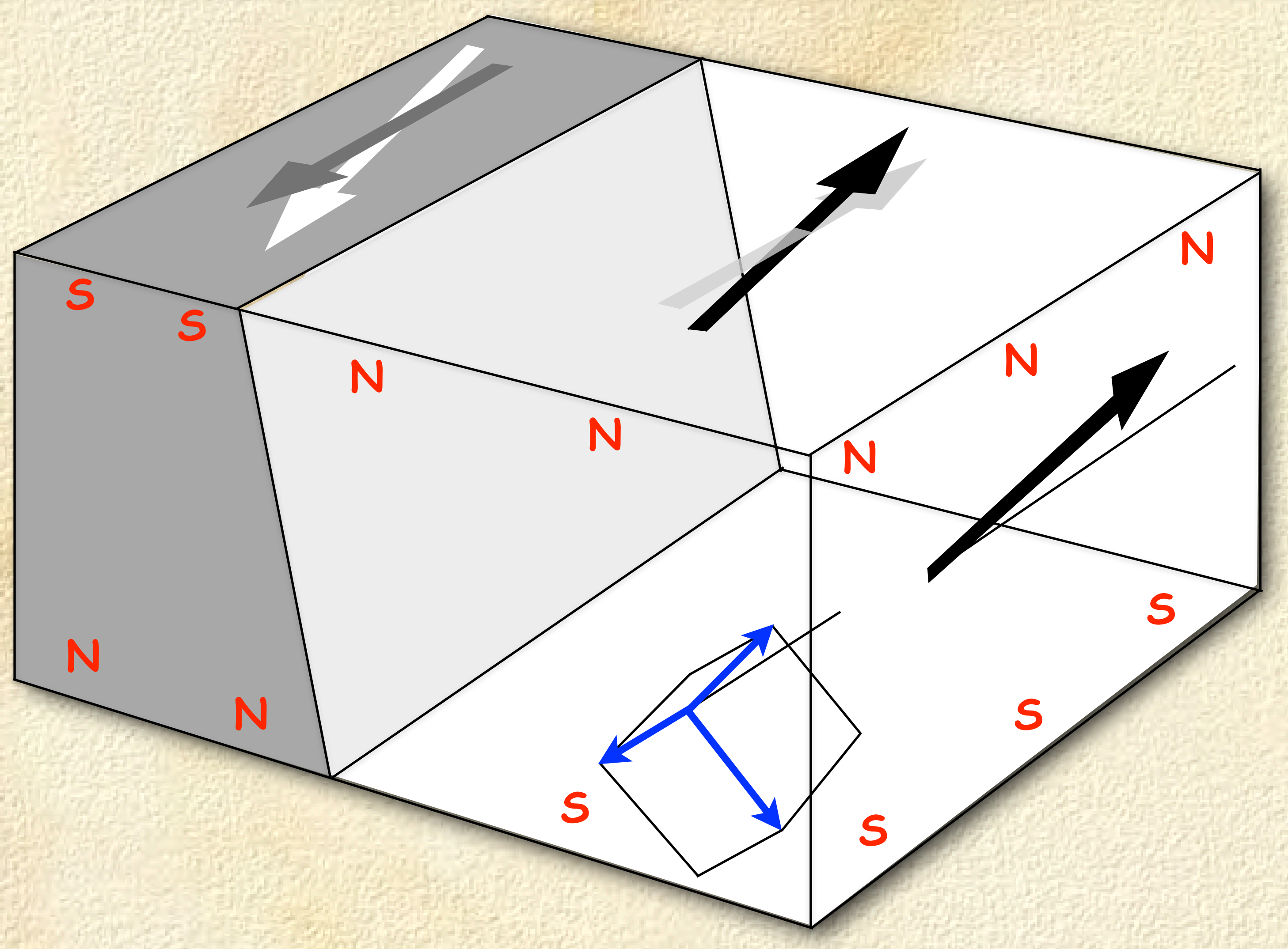
Grain-oriented FeSi transformer material

Without tensile stress

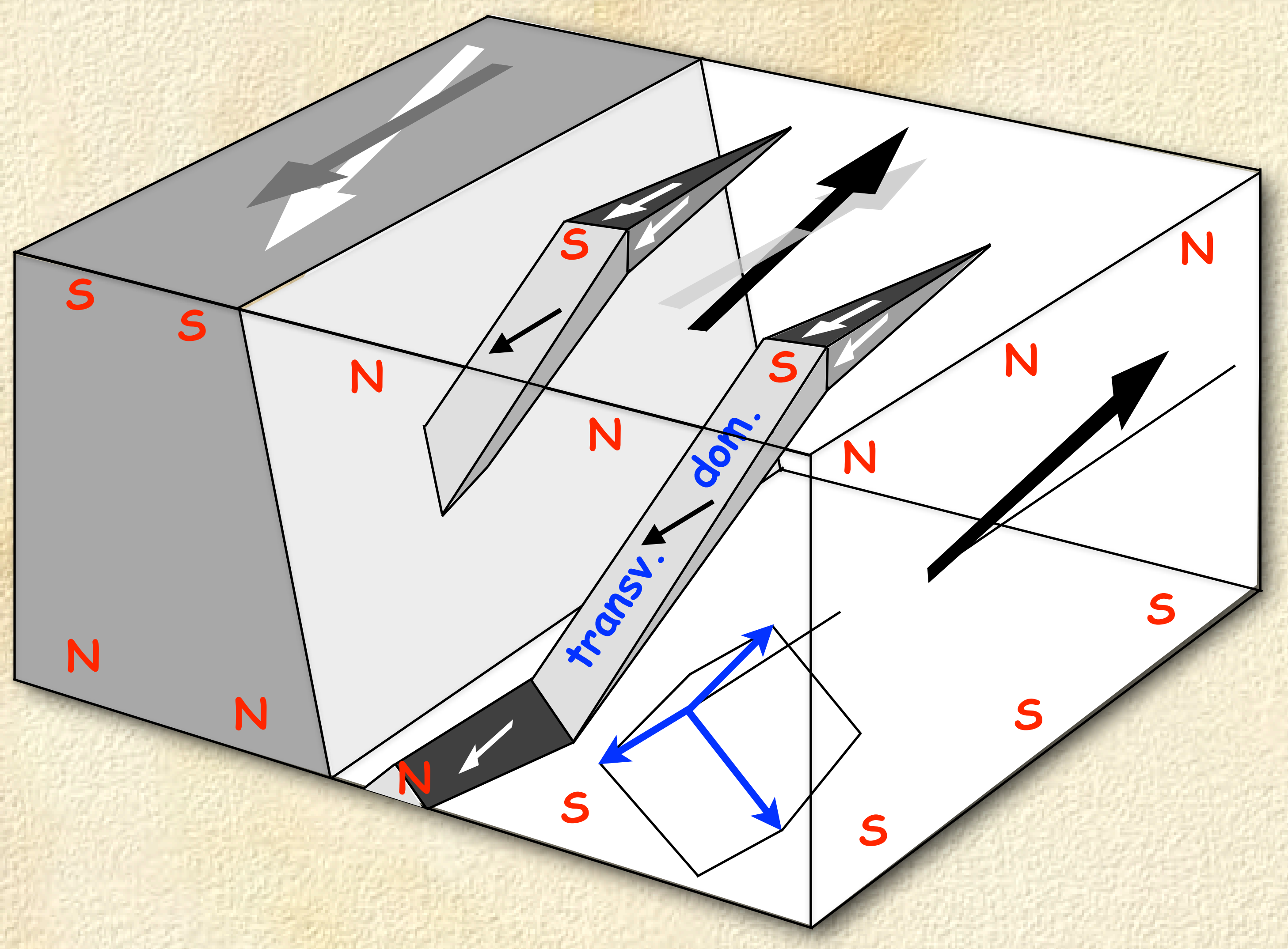


With tensile stress

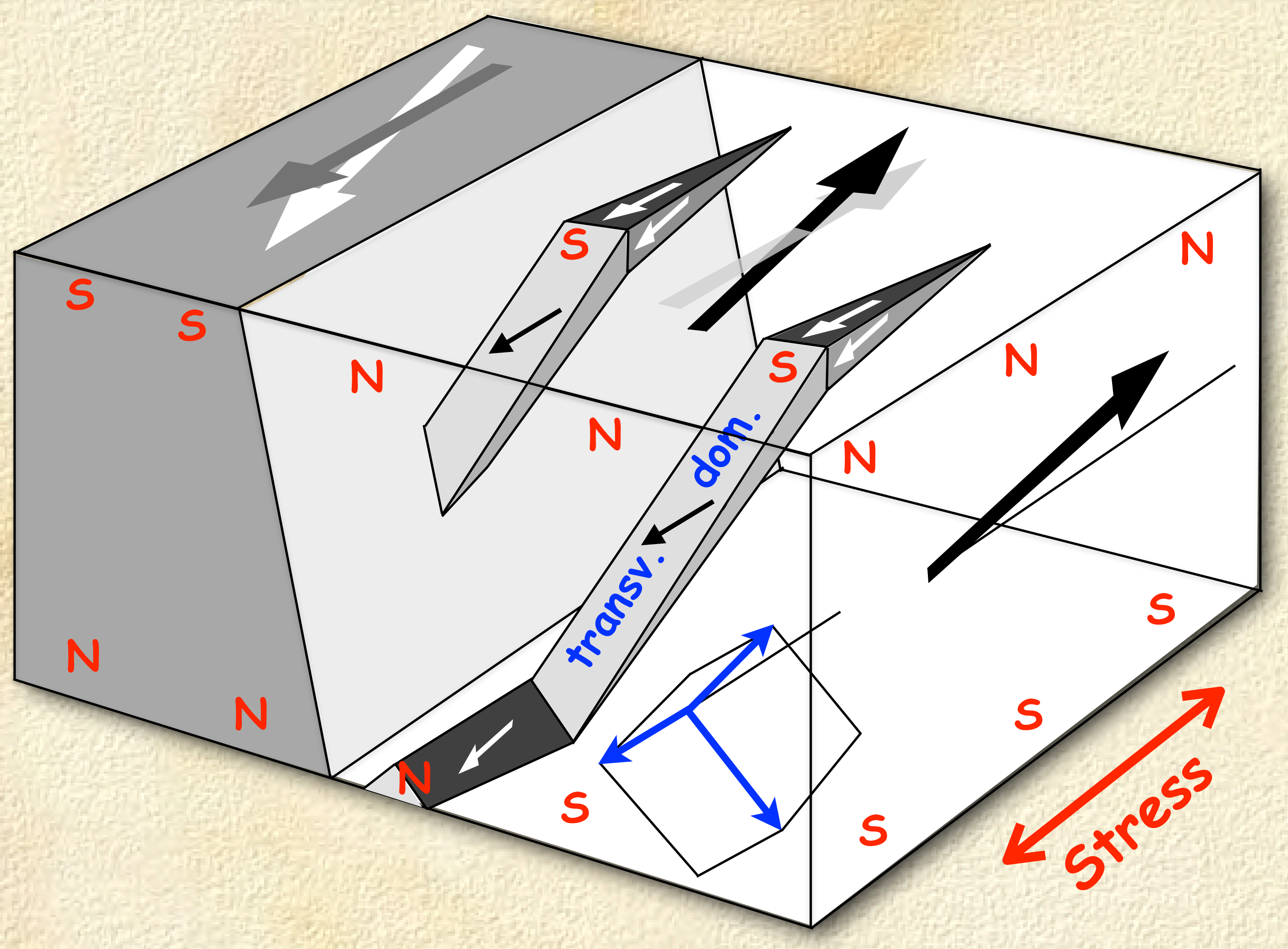
Grain-oriented FeSi transformer material



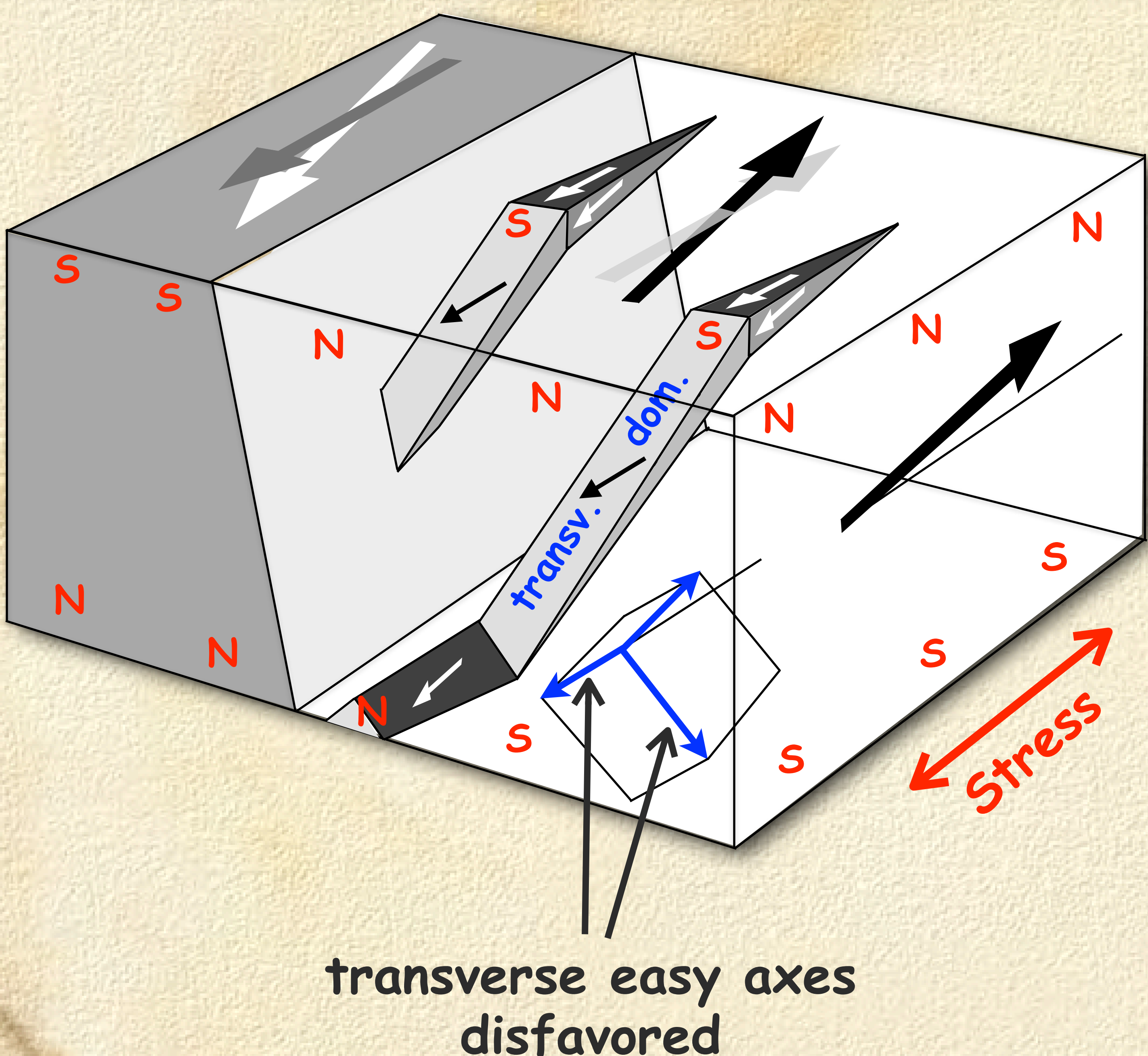
Grain-oriented FeSi transformer material



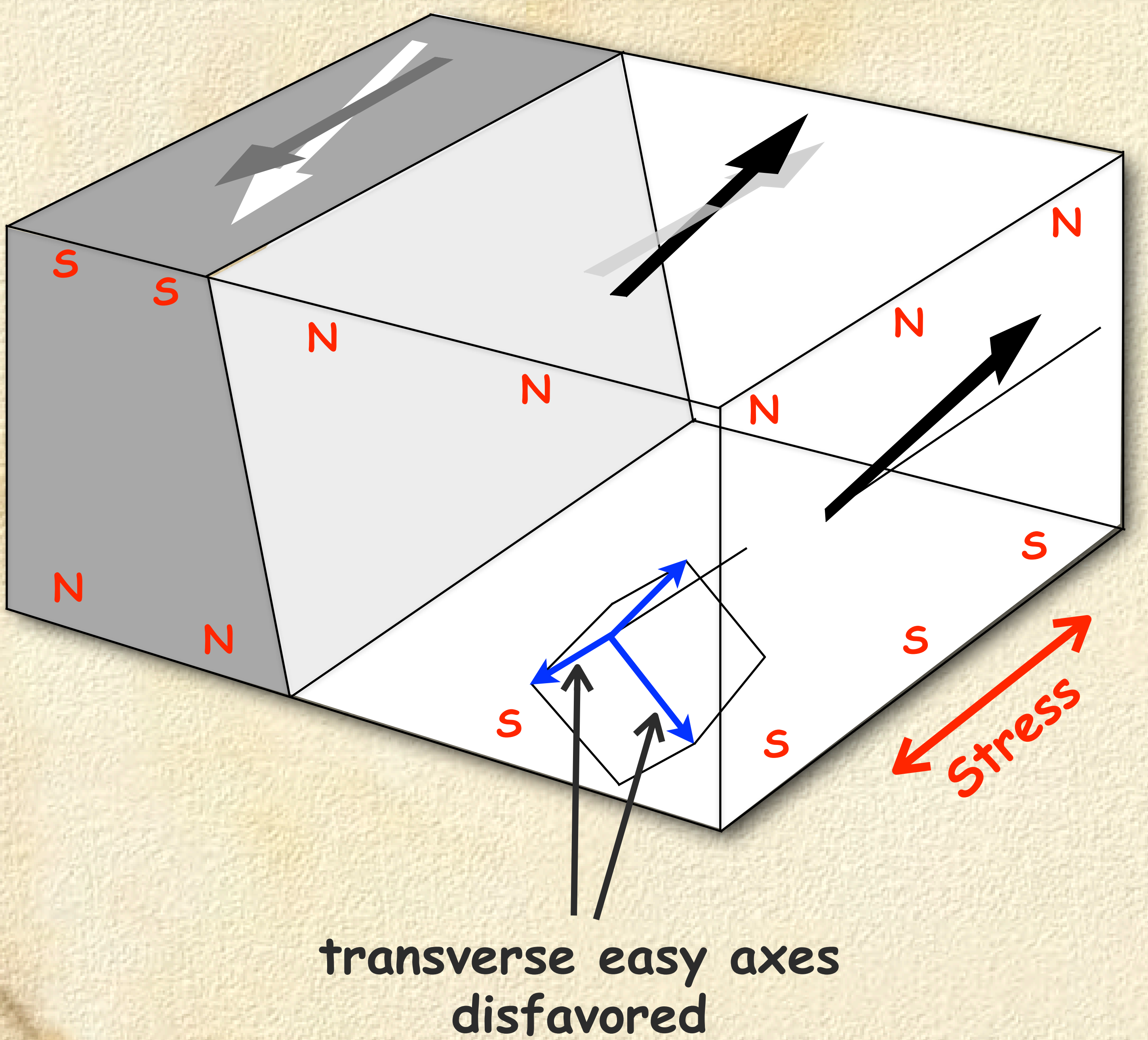
Grain-oriented FeSi transformer material



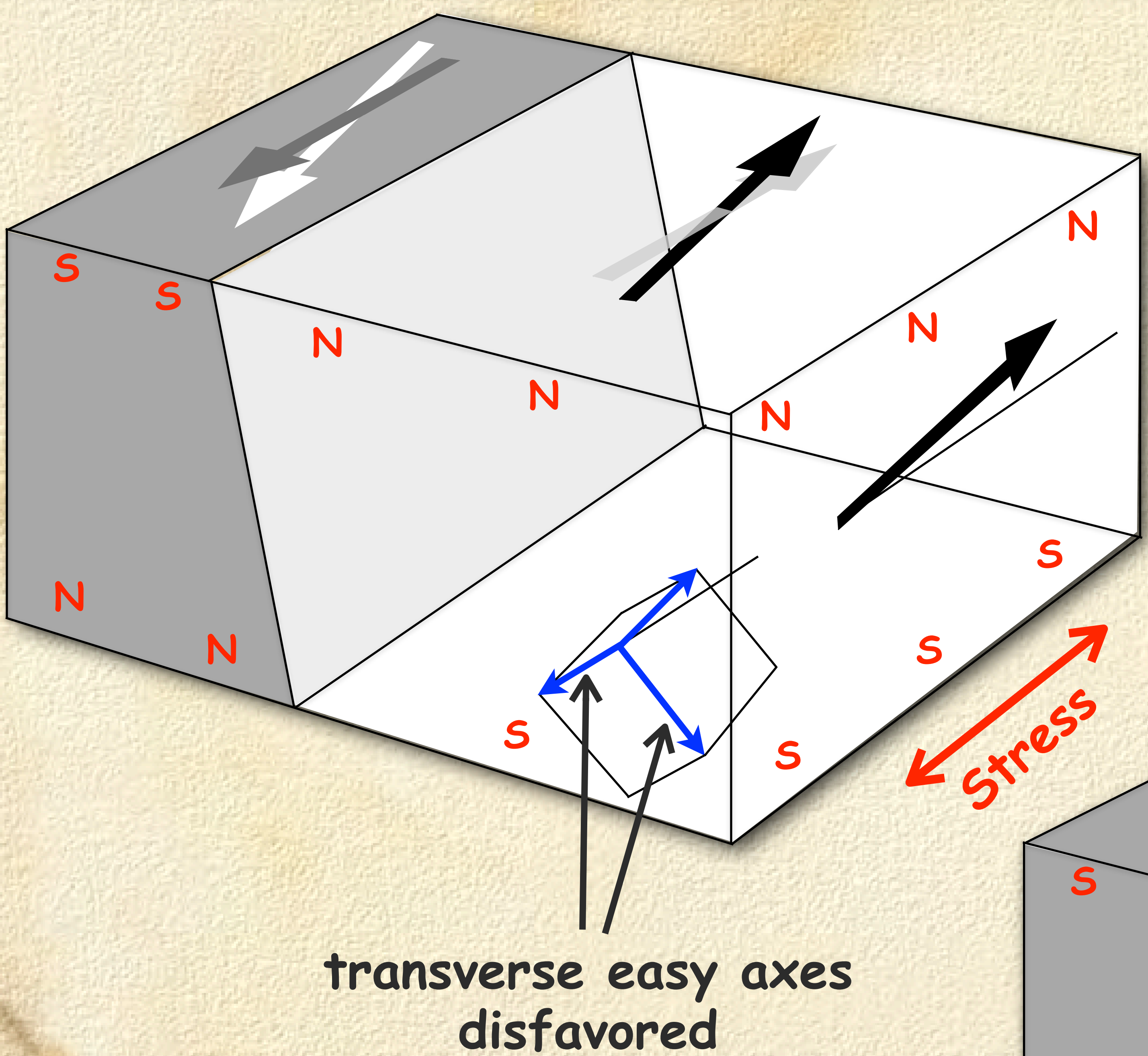
Grain-oriented FeSi transformer material



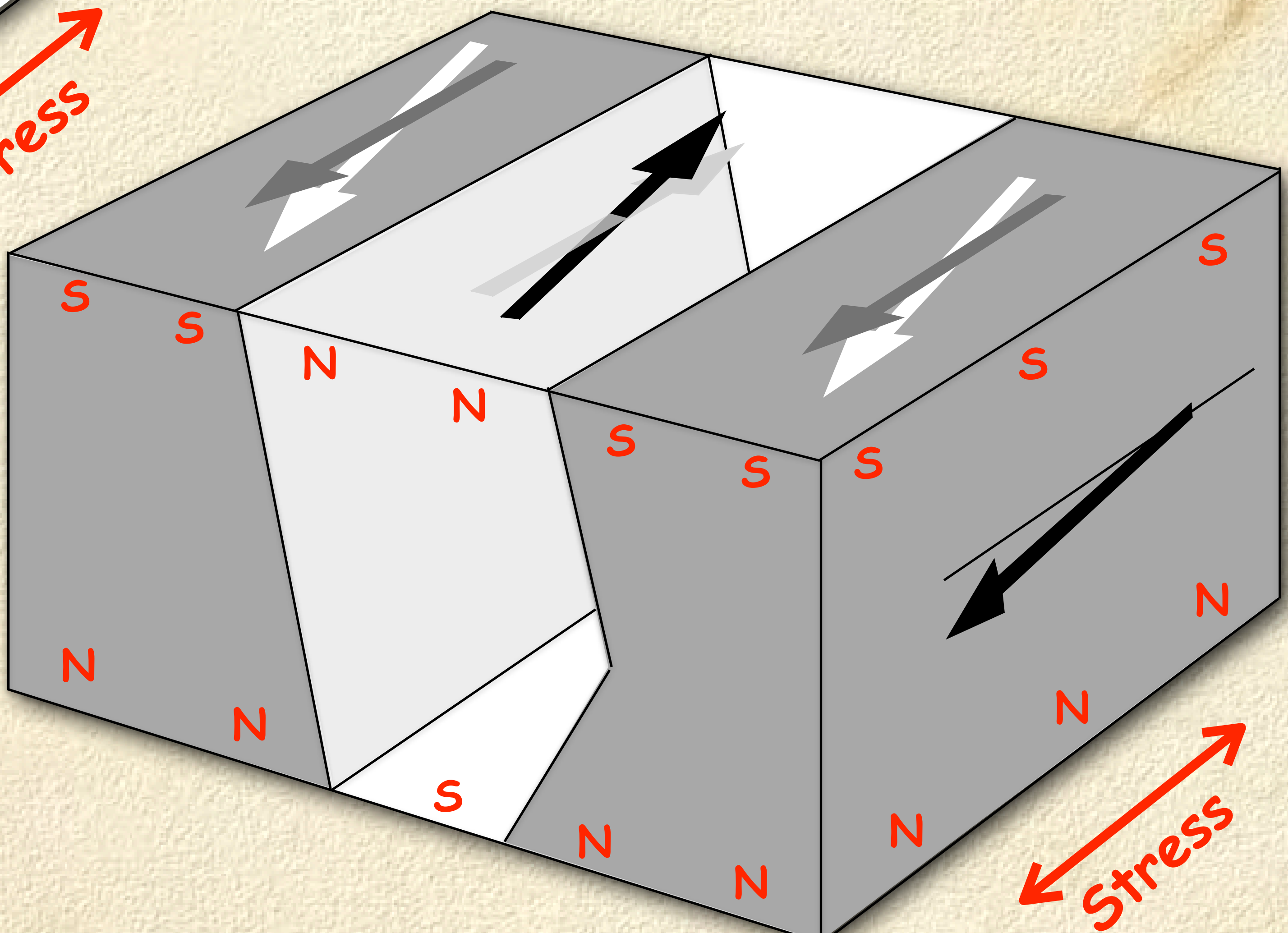
Grain-oriented FeSi transformer material



Grain-oriented FeSi transformer material



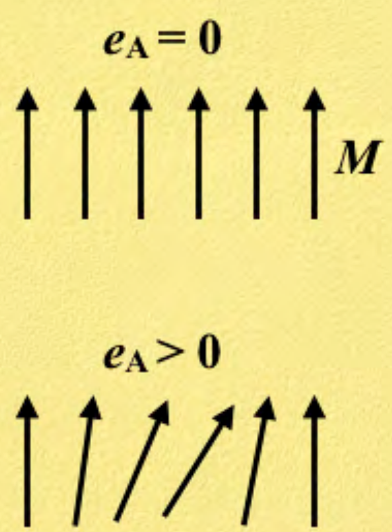
Domain refinement



Grain-oriented FeSi transformer material

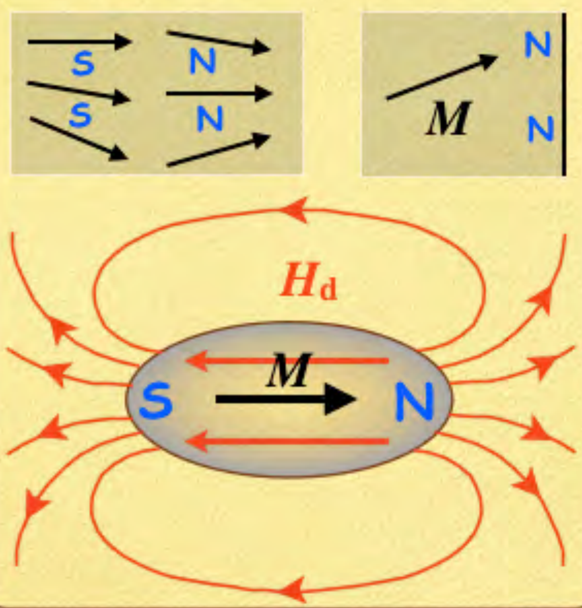
Magnetic Energies

Exchange energy

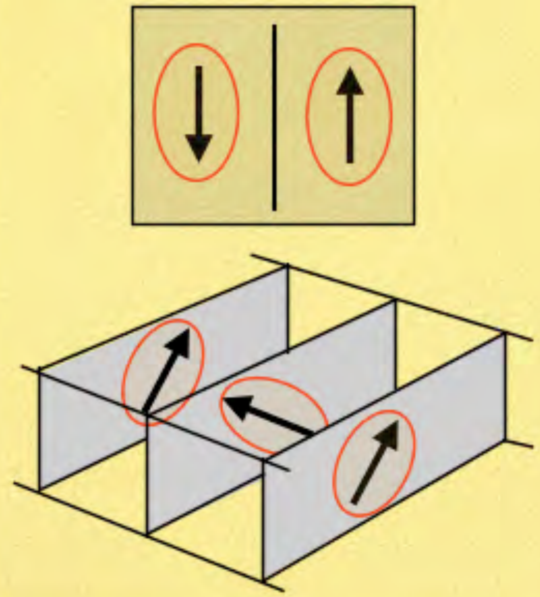


Stray field energy

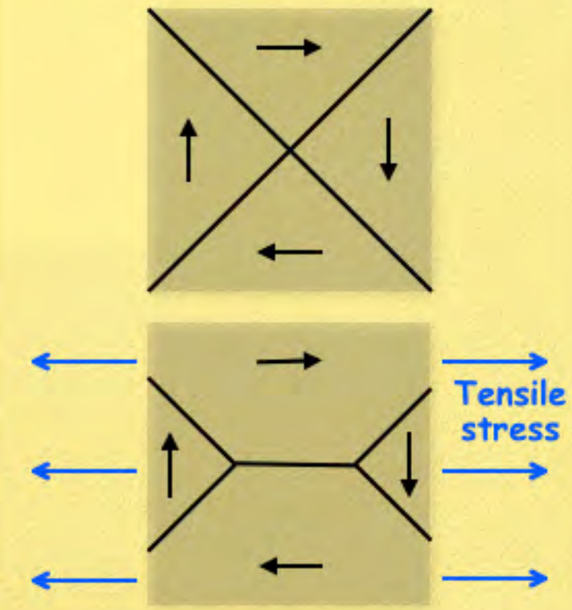
$$\operatorname{div} \boldsymbol{H}_d = -\operatorname{div} \boldsymbol{M}$$



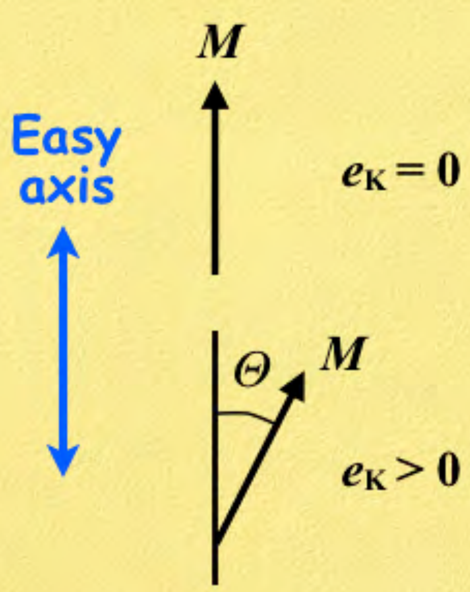
Magnetostrictive self energy



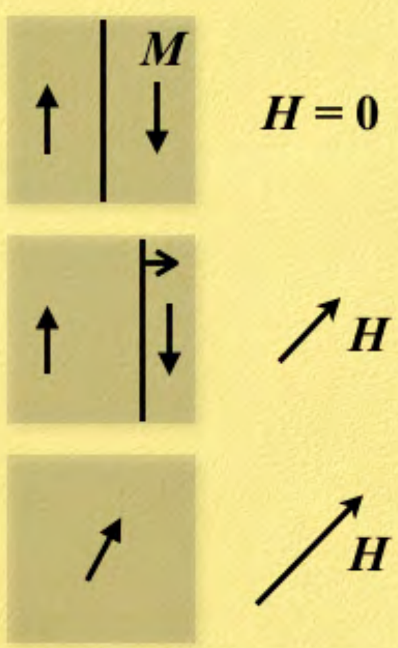
External stress energy



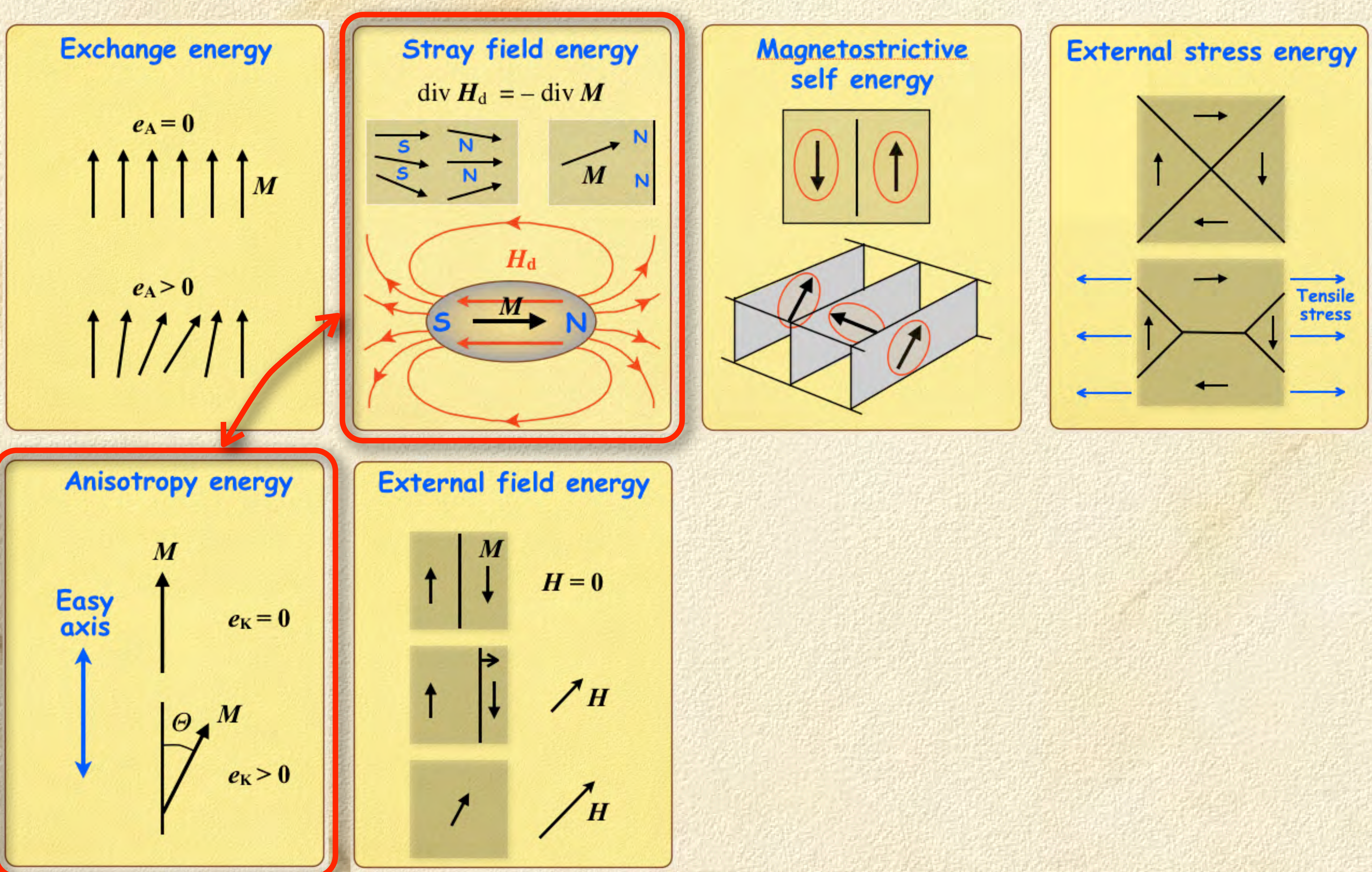
Anisotropy energy



External field energy



Magnetic Energies

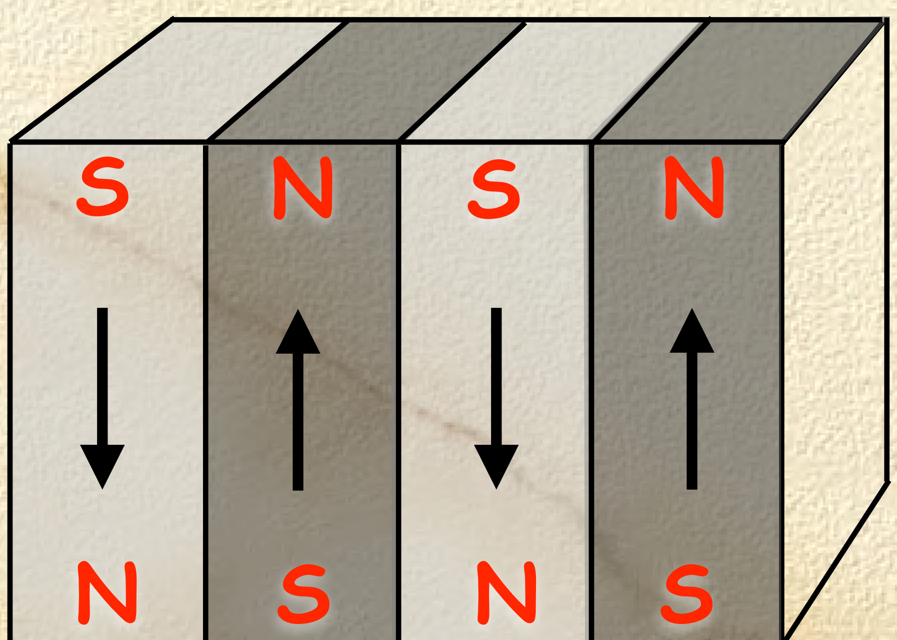


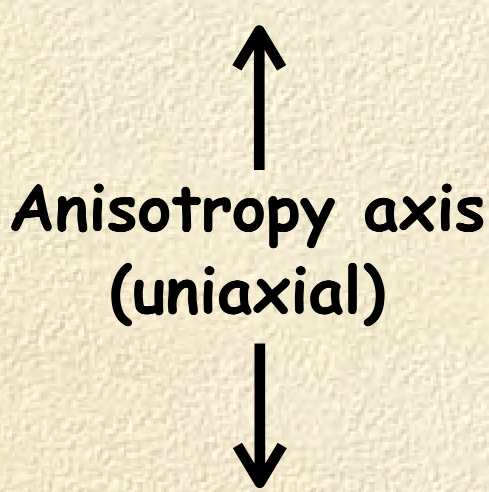
General Classification of Domains

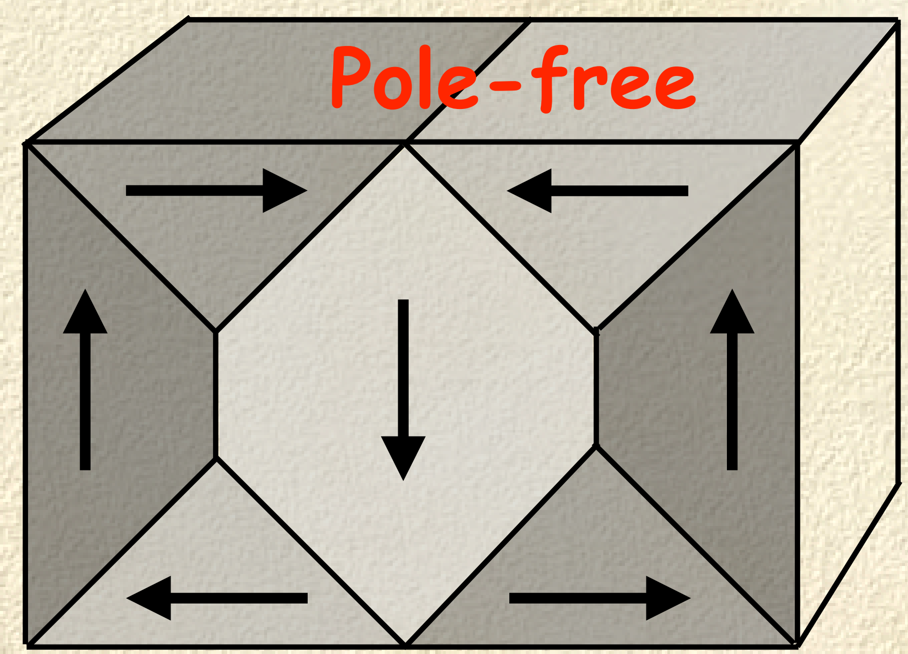
General Classification of Domains

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

$Q >> 1$	$Q << 1$
Anisotropy energy dominates	Stray-field energy dominates
↓	↓
avoid anisotropy energy	avoid stray-field energy



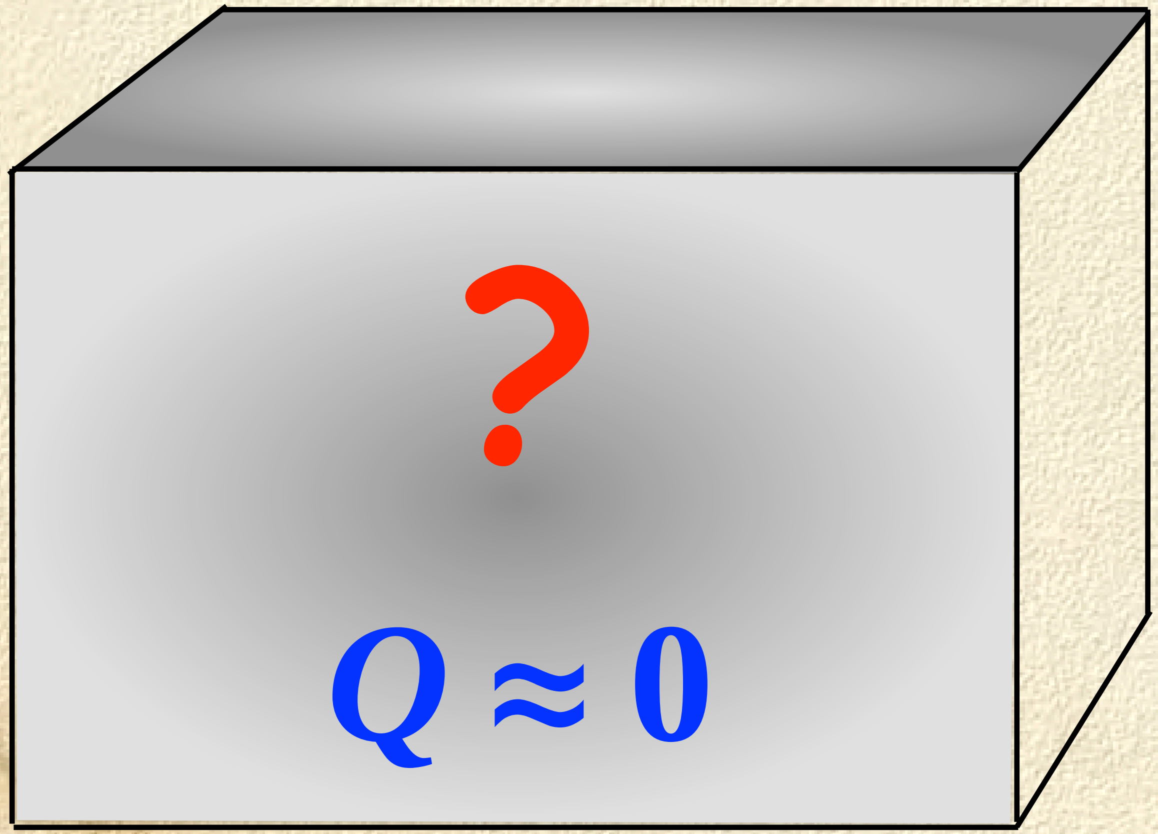




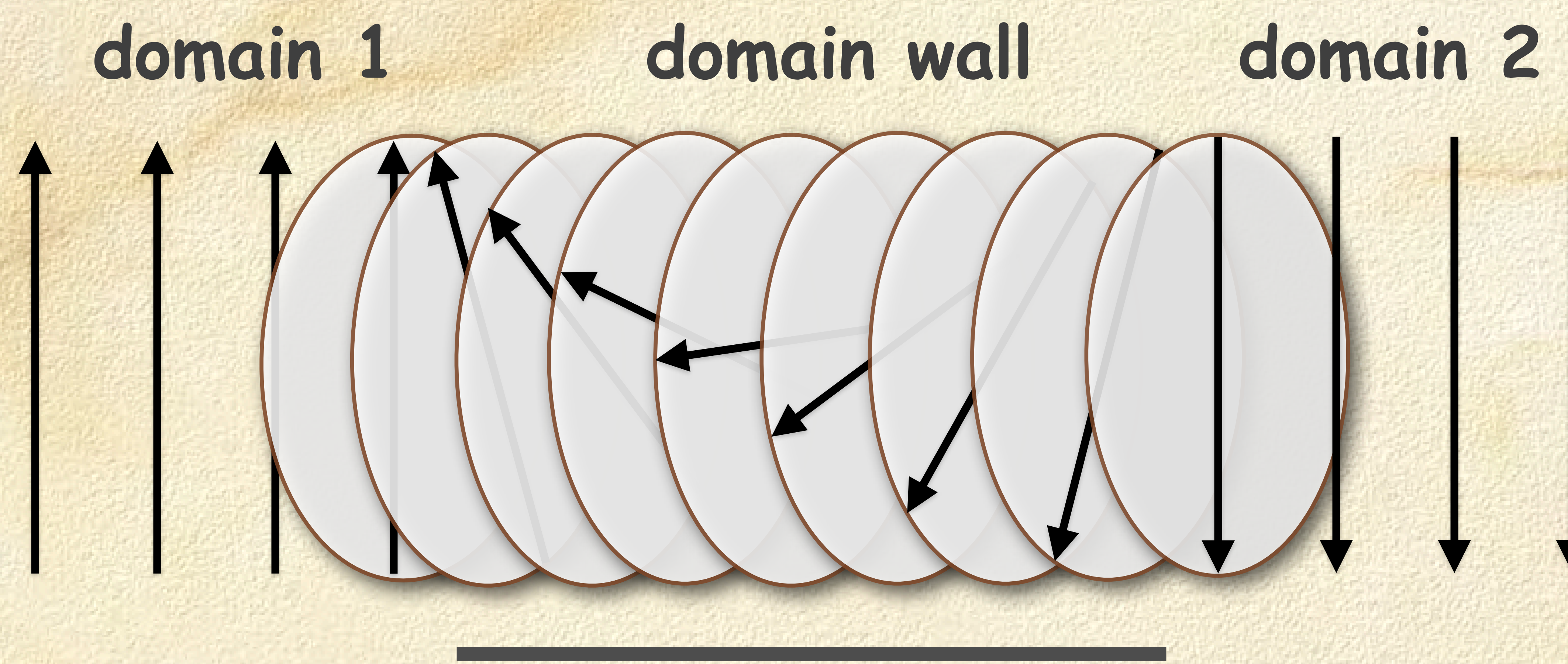
General Classification of Domains

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

Excursus



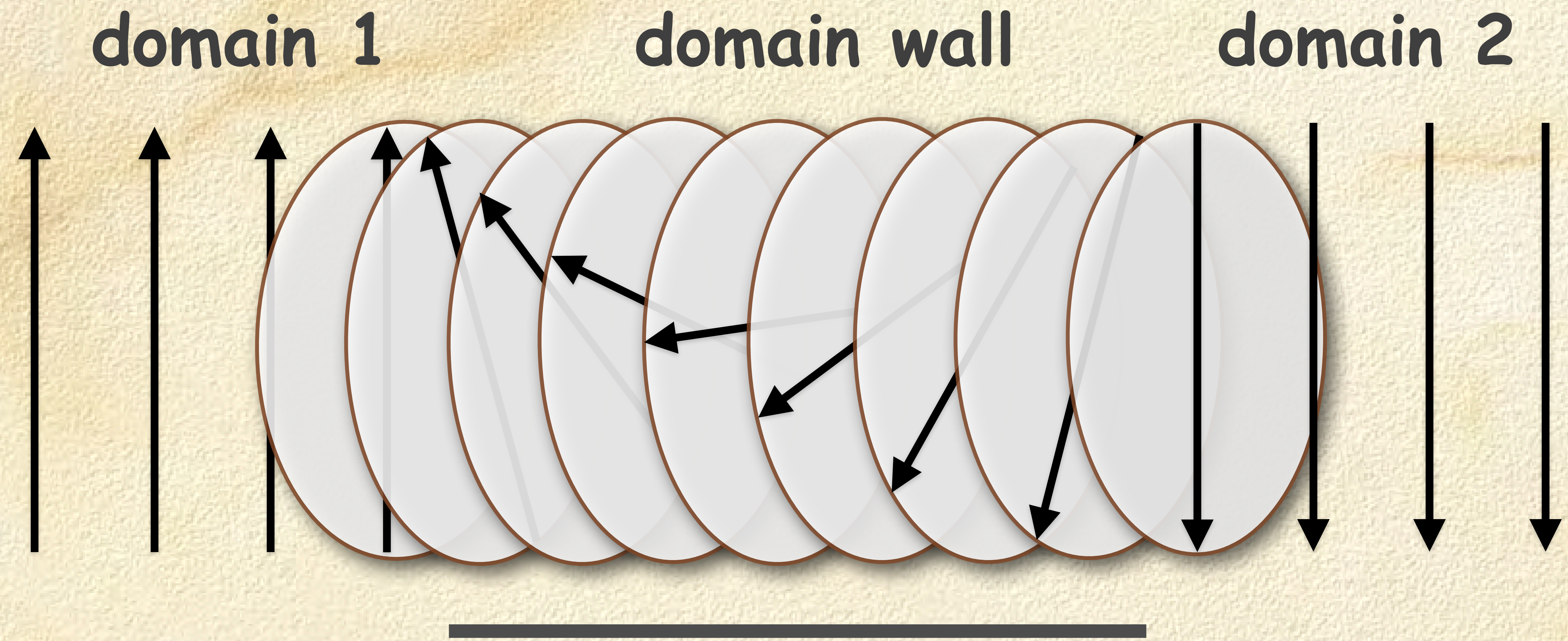
Excursus: Q = 0



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

K: anisotropy constant
A: exchange constant

Excursus: Q = 0



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

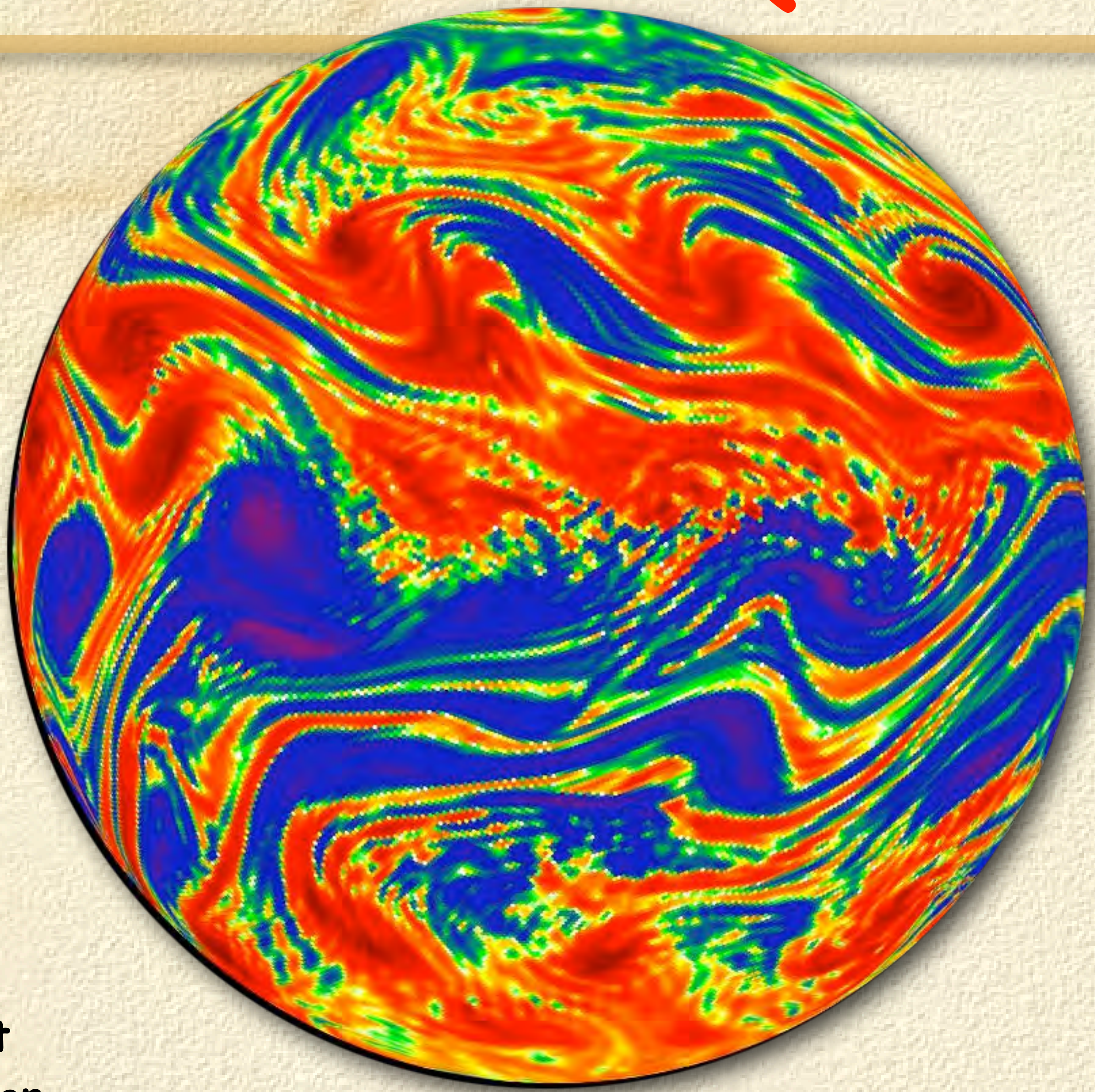
K: anisotropy constant
A: exchange constant

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

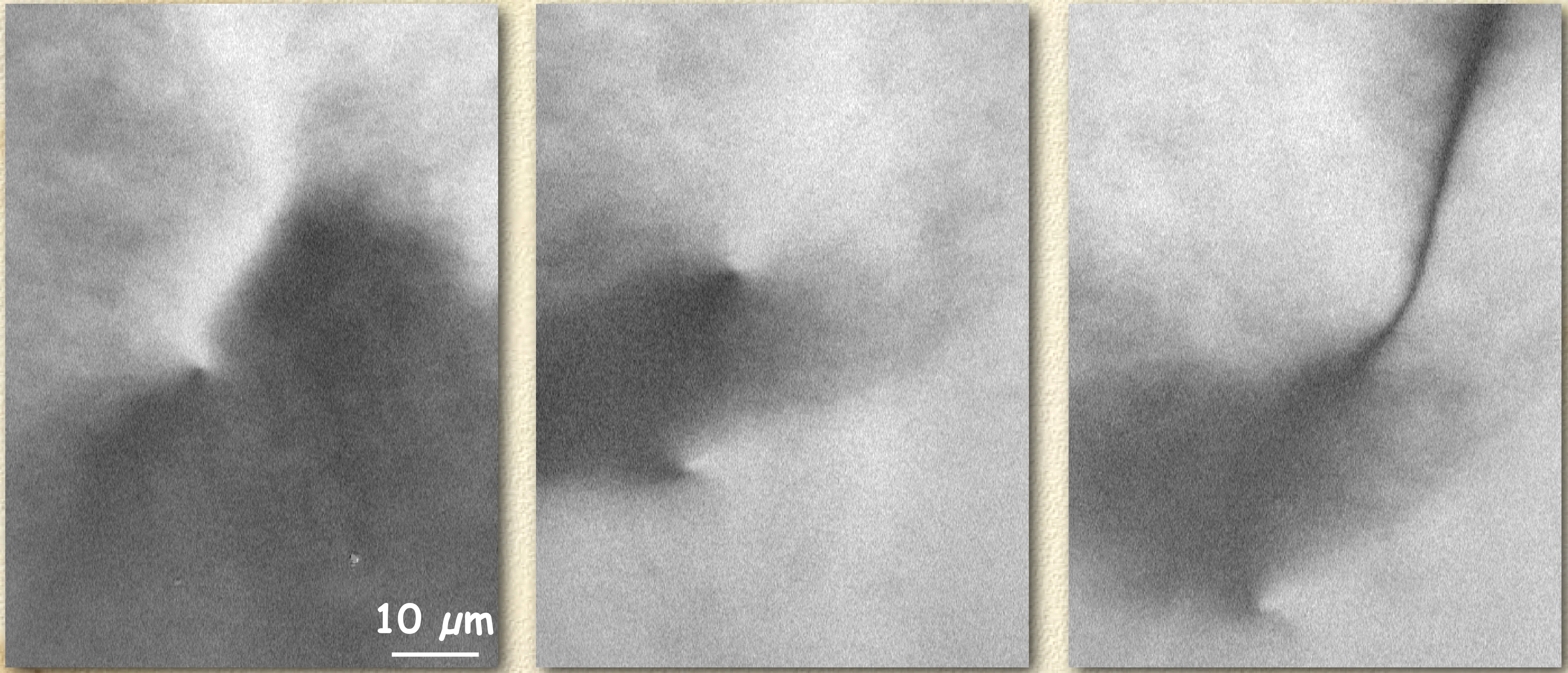
Q = 0: Domain walls not defined anymore

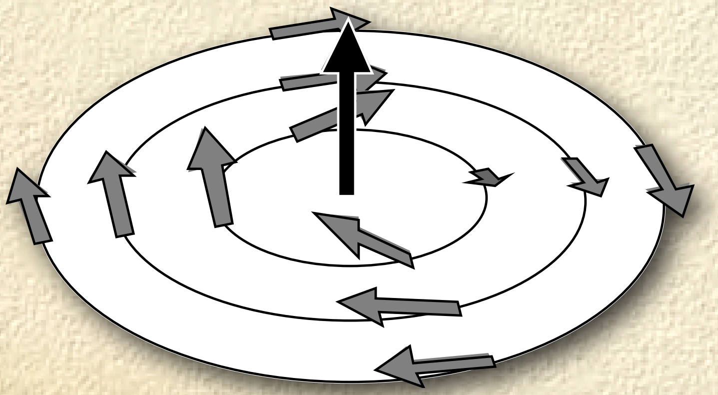
↓

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

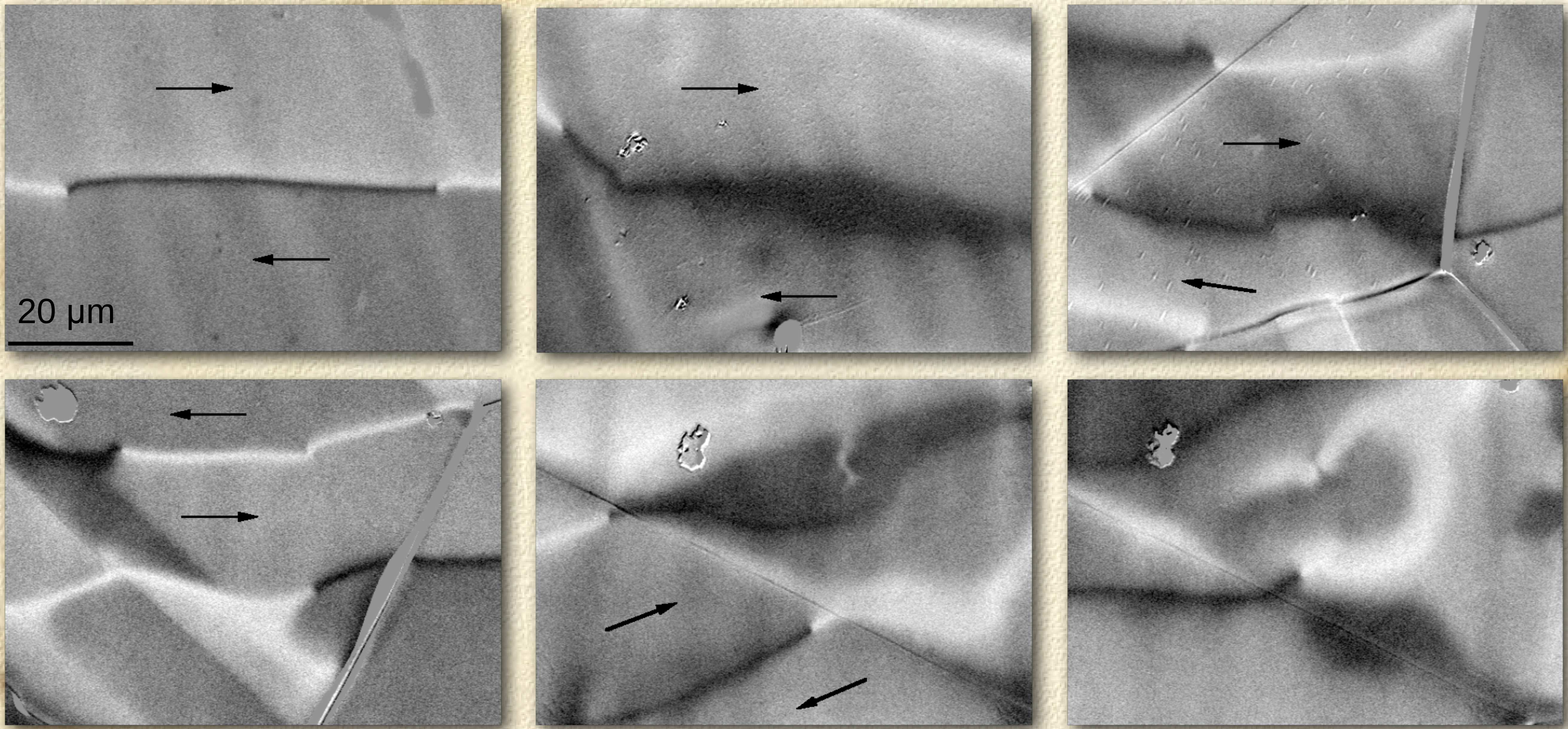




Swirl

Excursus: Q = 0

Permalloy sheet, 50 μm thick



Fluctuations in local anisotropy

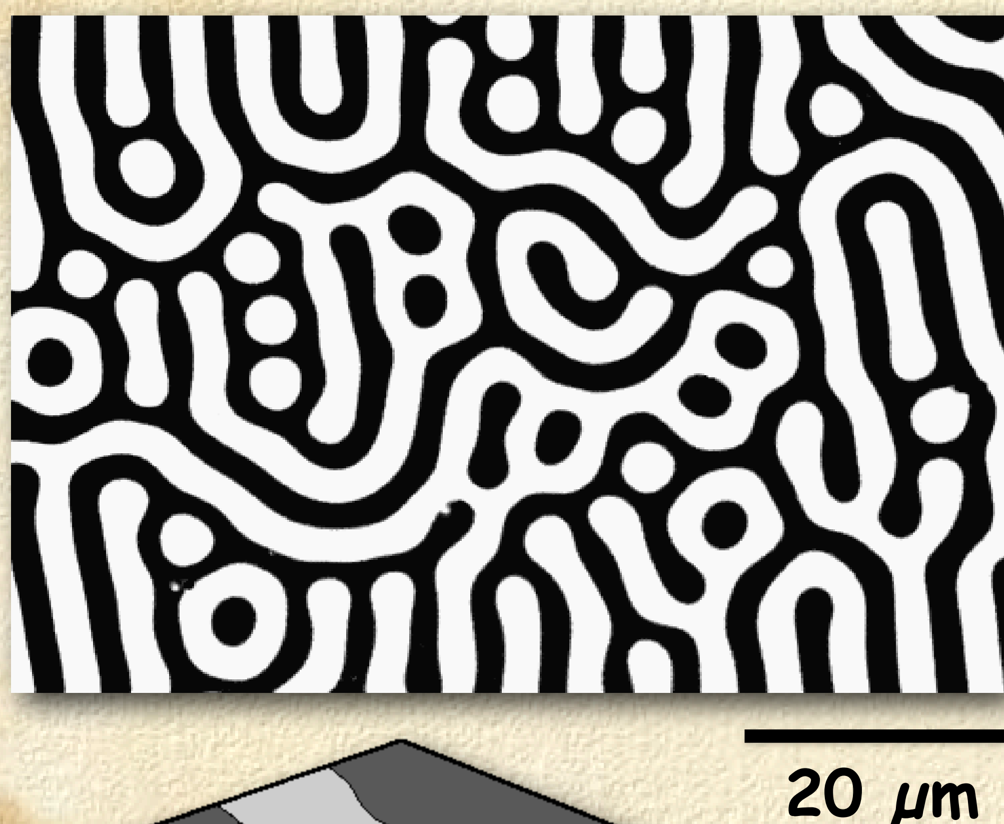
→ Domains walls <u>and</u> continuous patterns

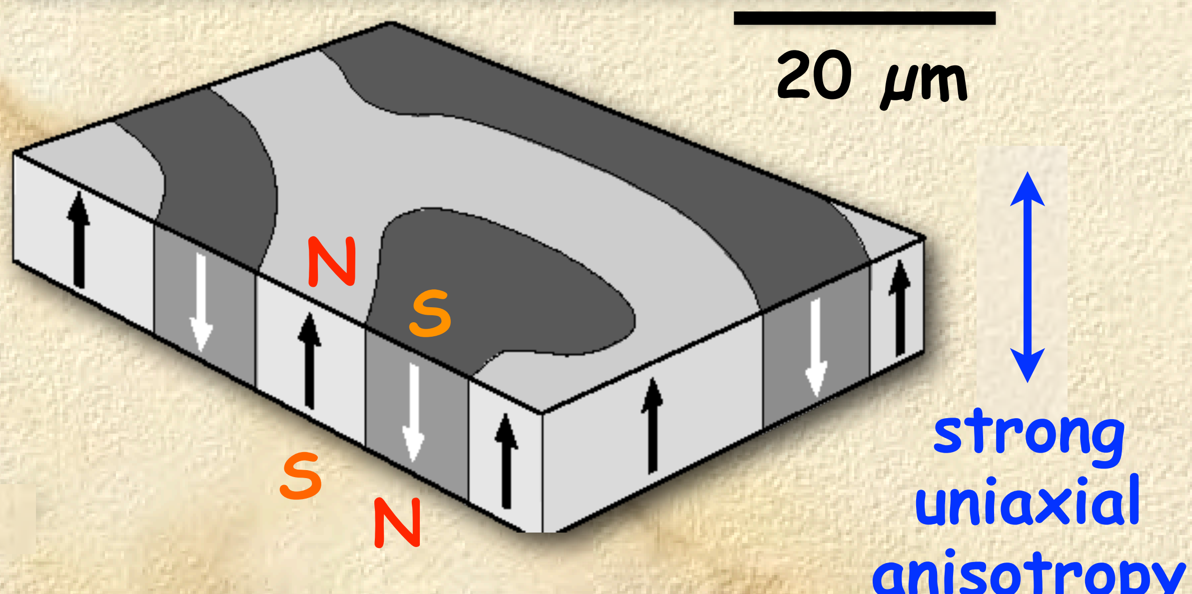
General Classification of Domains

Dominating anisotropy energy (Q>>1)

Dominating stray-field energy (Q<<1)

Bubble garnet film (5 μm thick)

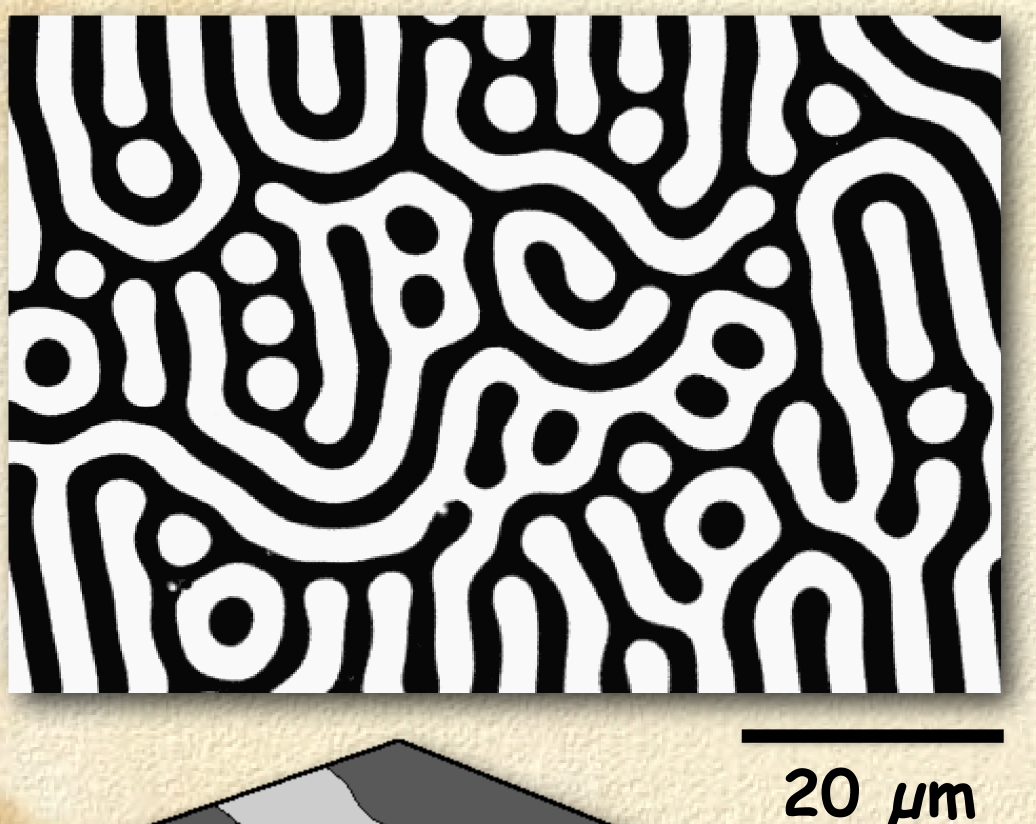


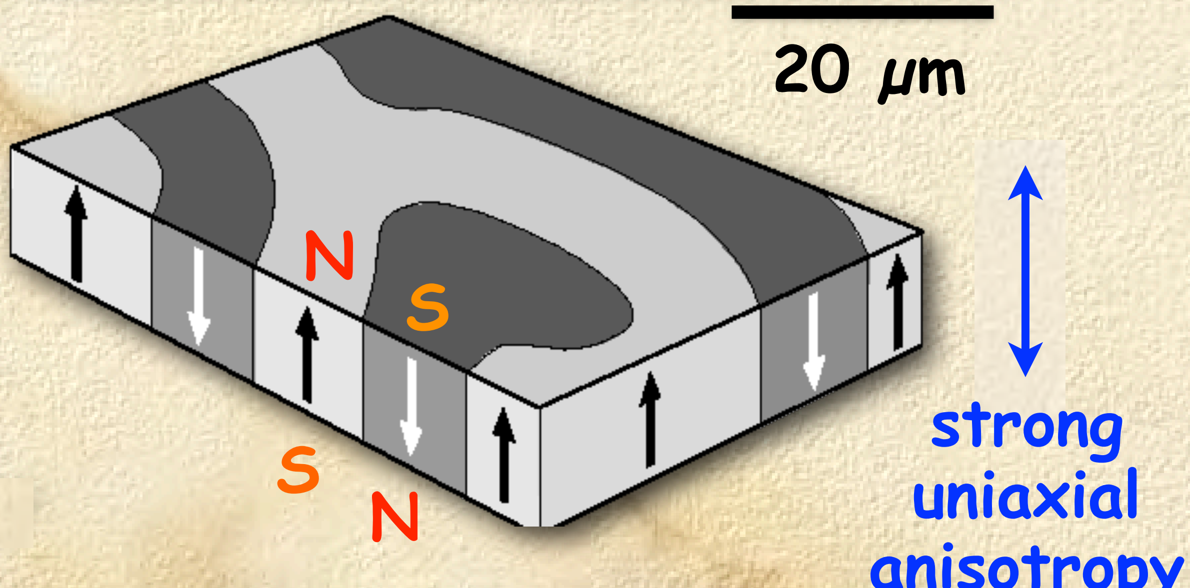


General Classification of Domains

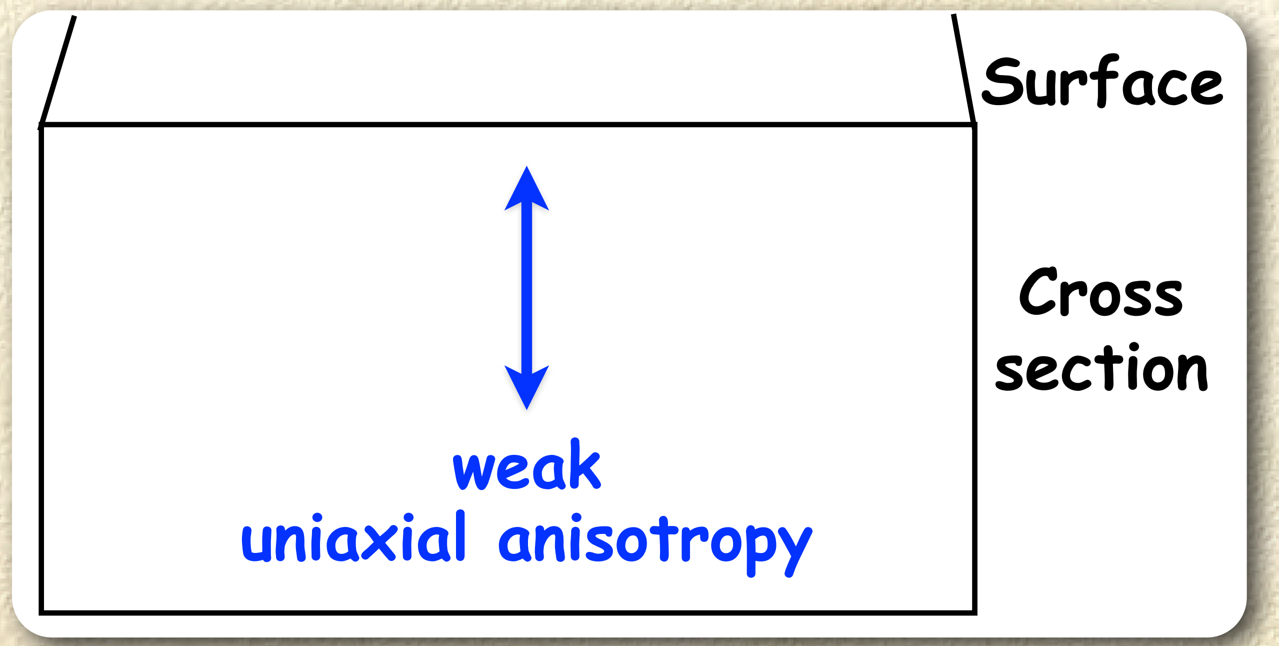
Dominating anisotropy energy ($Q \gg 1$)

Bubble garnet film (5 μm thick)





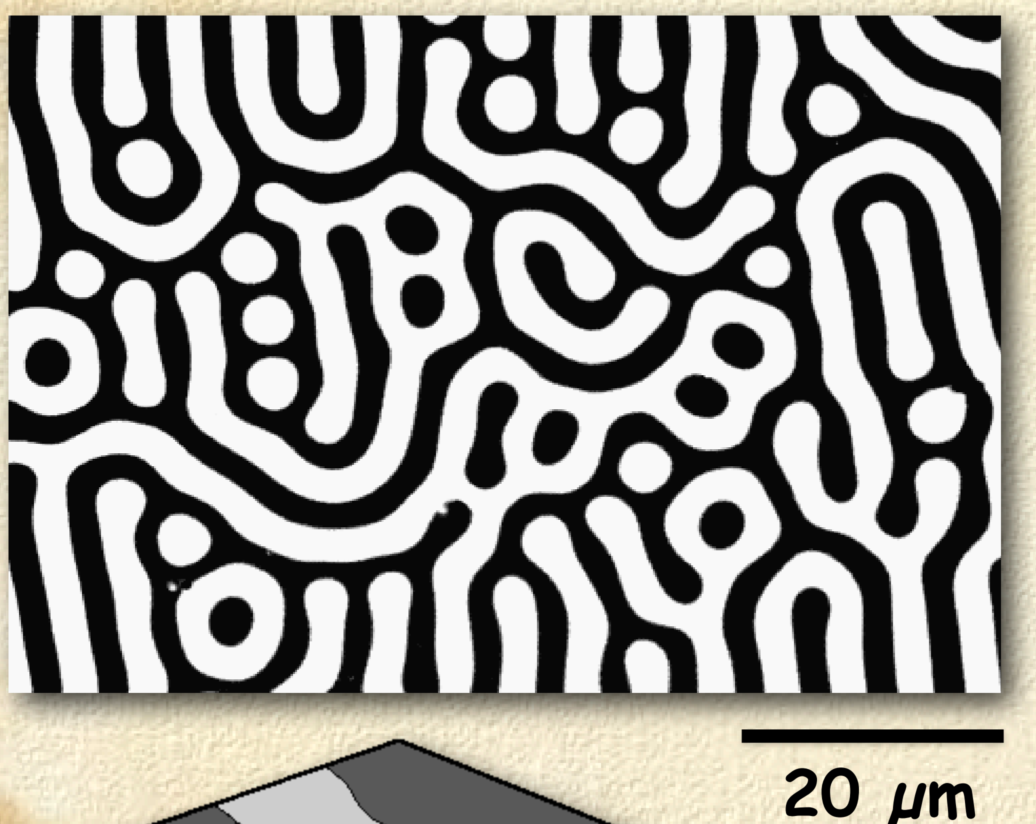
Dominating stray-field energy ($Q \ll 1$)

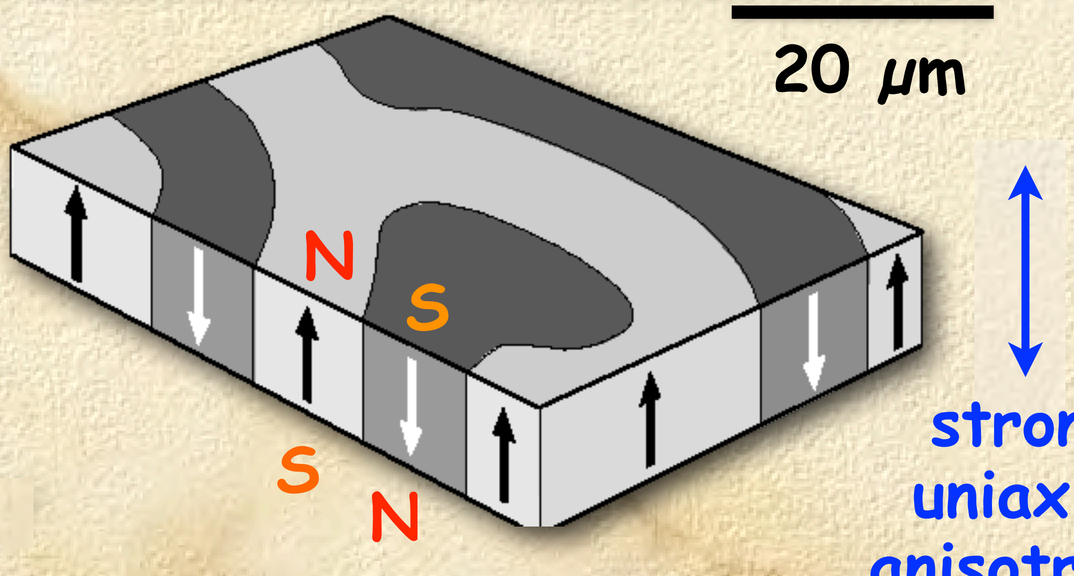


General Classification of Domains

Dominating anisotropy energy ($Q>>1$)

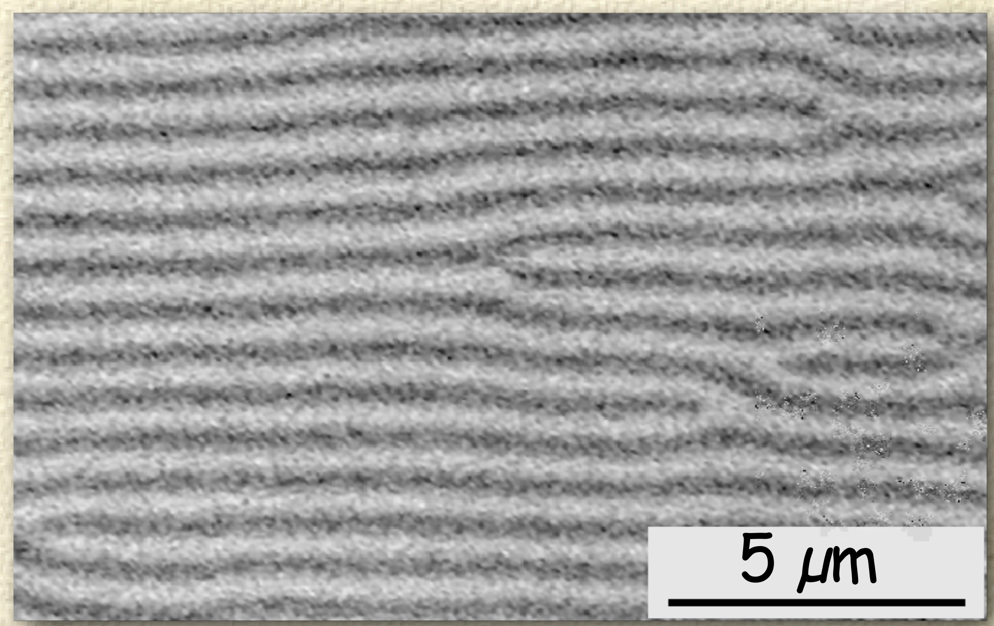
Bubble garnet film (5 μm thick)

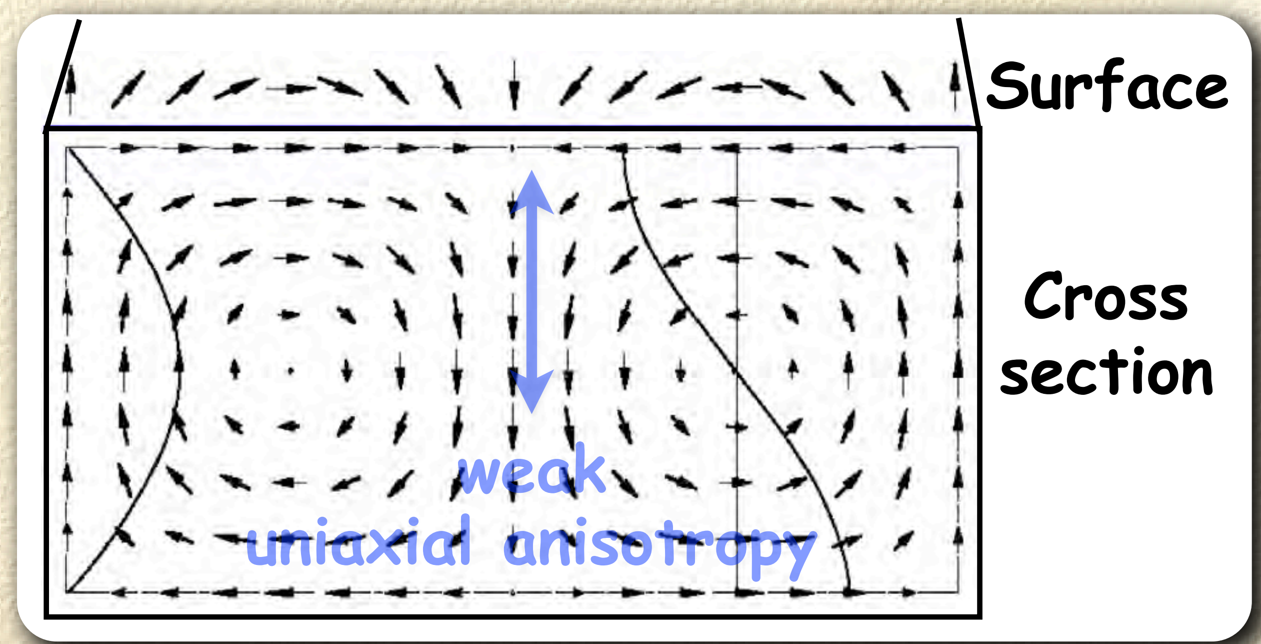




Dominating stray-field energy ($Q<<1$)

Amorphous FeSiBCuNb film (2 μm thick)

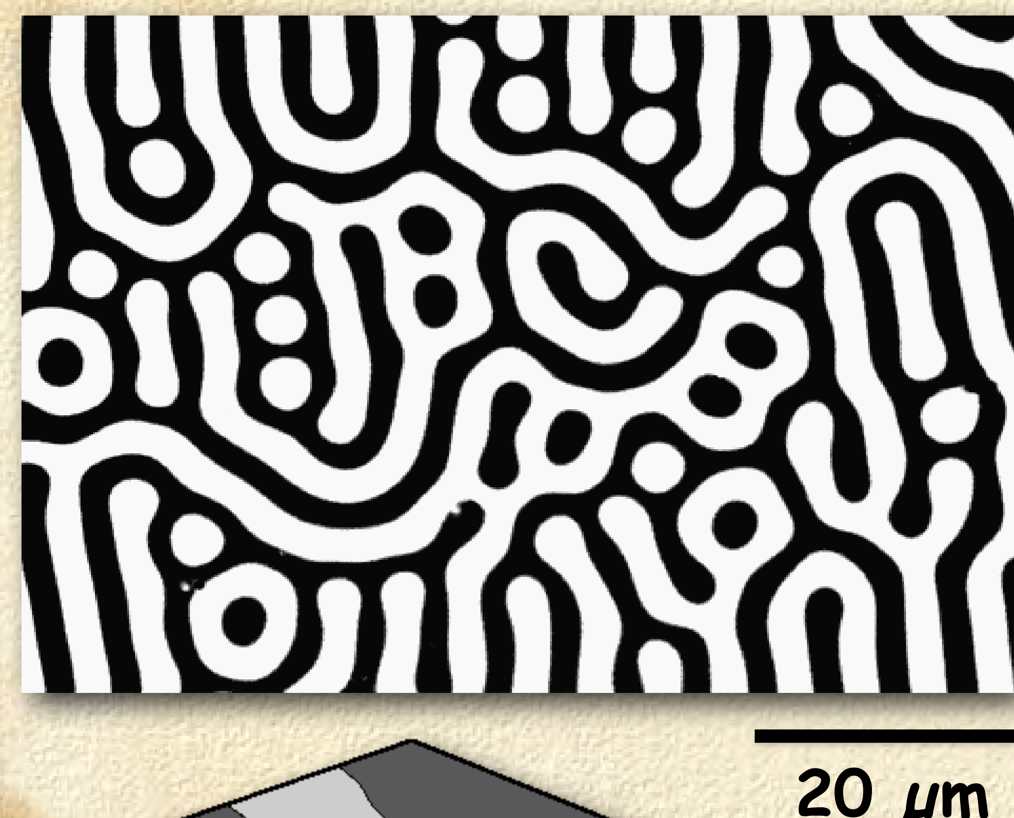


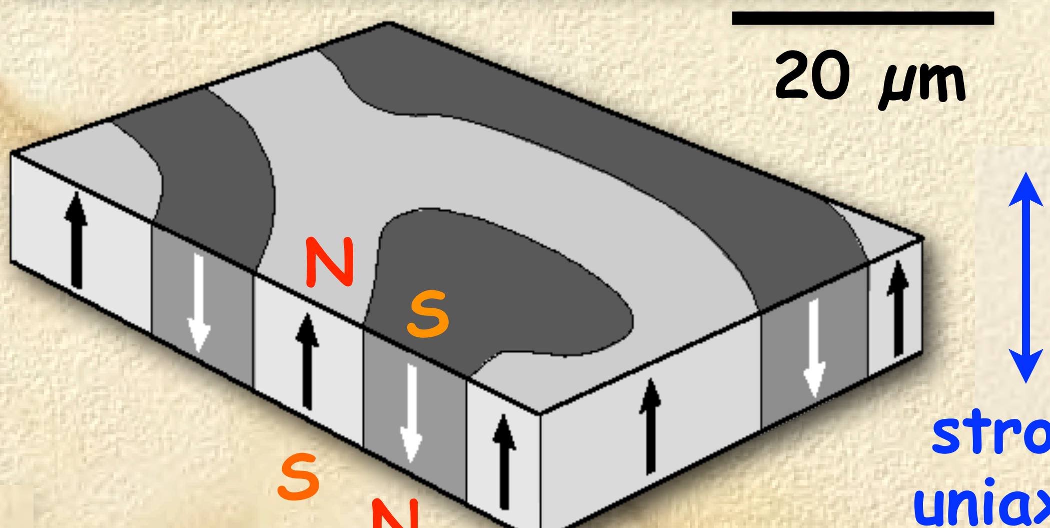


General Classification of Domains

Dominating anisotropy energy ($Q>>1$)	Dominating stray-field energy ($Q<<1$)

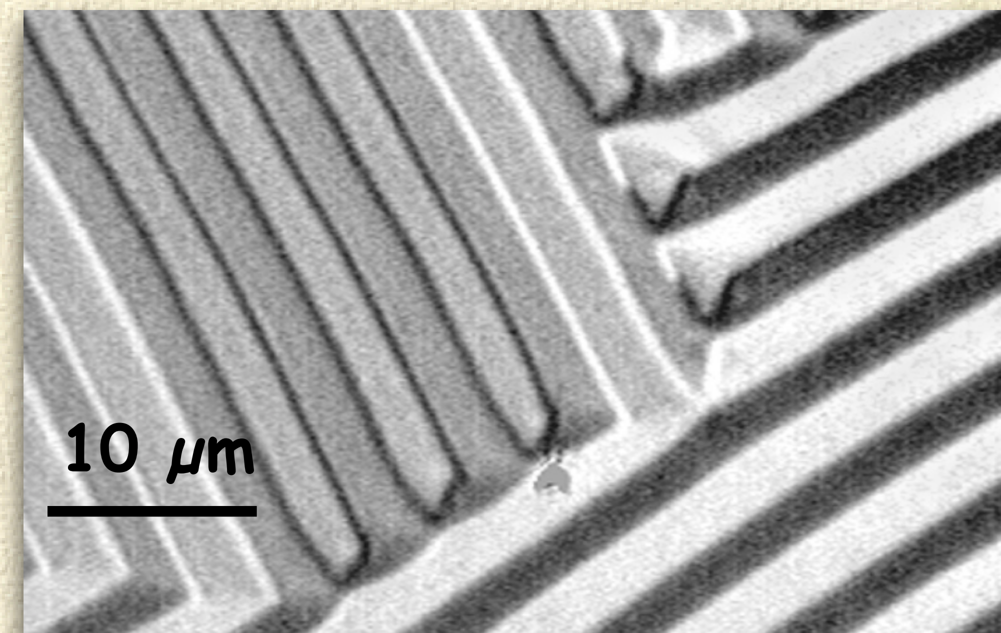
Bubble garnet film (5 μm thick)



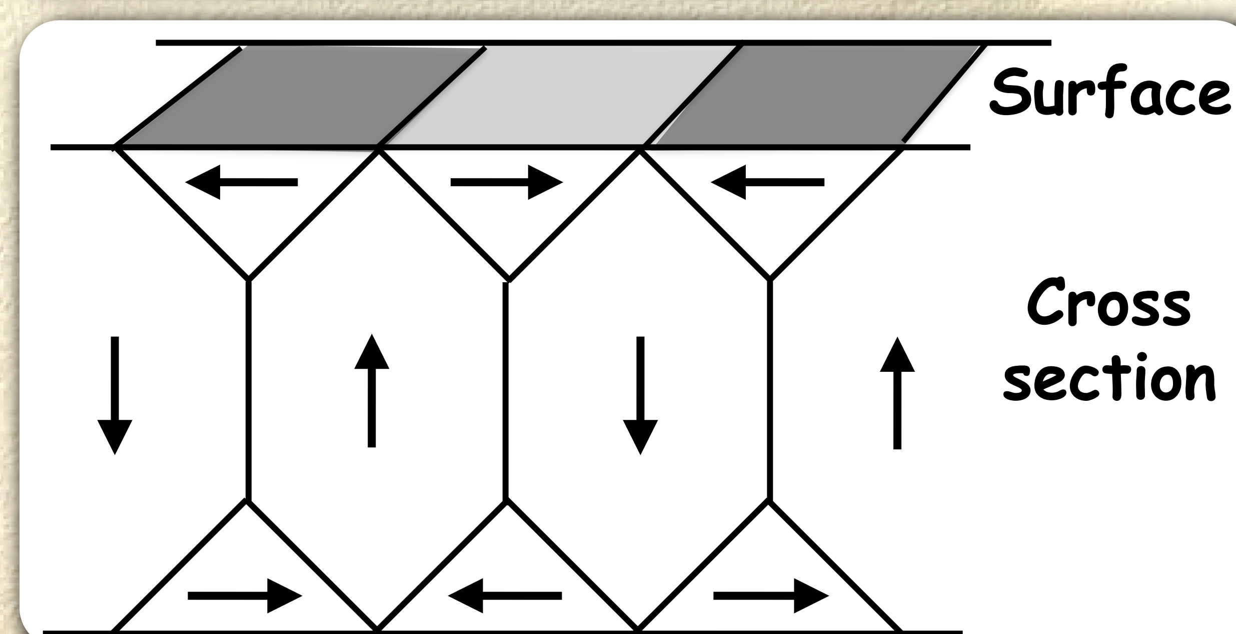


strong uniaxial anisotropy

Amorphous FeSiB ribbon (20 μm thick)

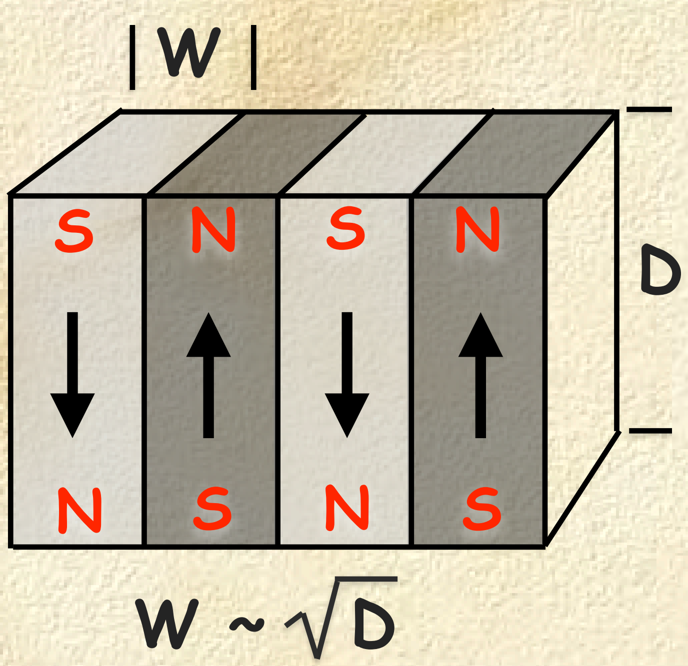


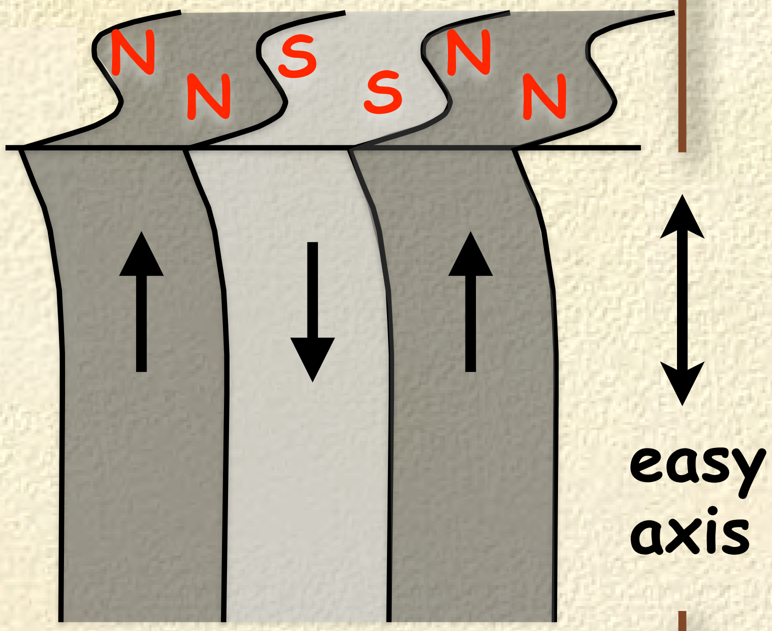
Landau domains



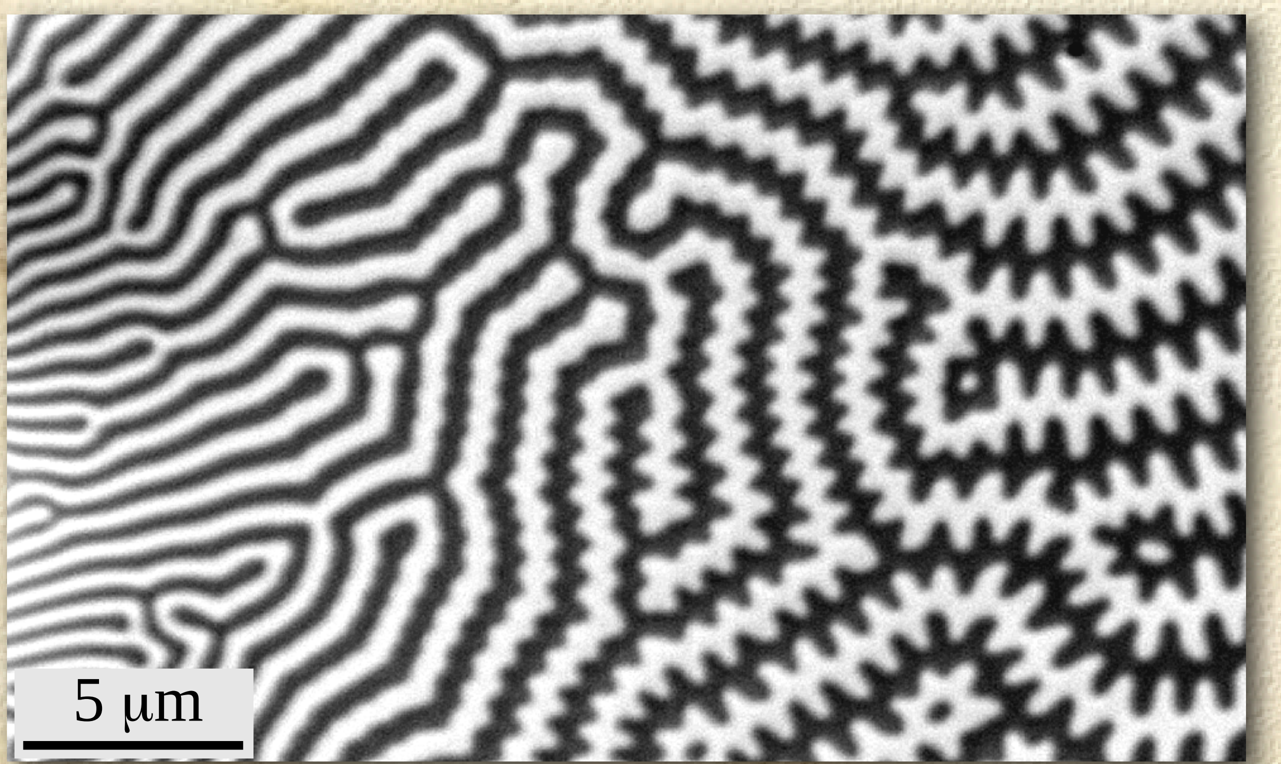
General Classification of Domains

Dominating
anisotropy energy ($Q>>1$)





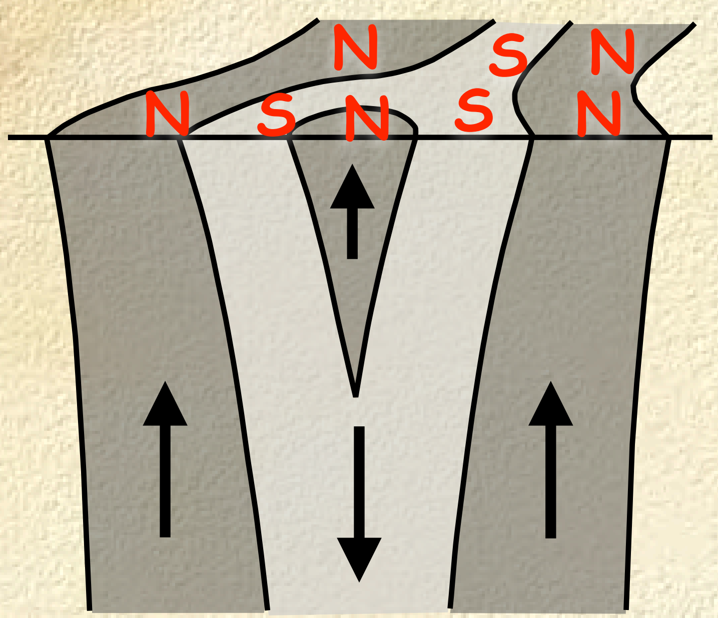
~1 μm NdFeB wedge 14 μm



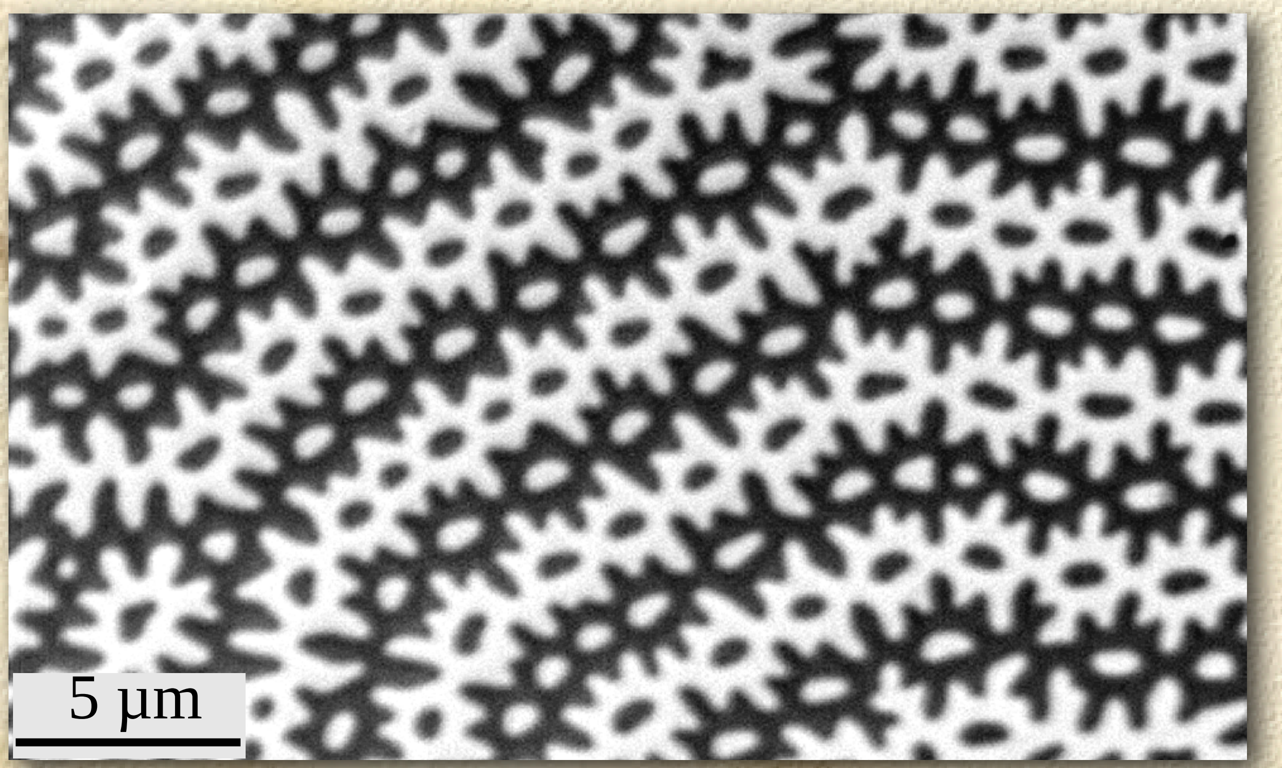
Dominating
stray-field energy ($Q<<1$)

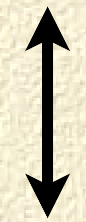
General Classification of Domains

Dominating
anisotropy energy (Q>>1)



~ 40 μm

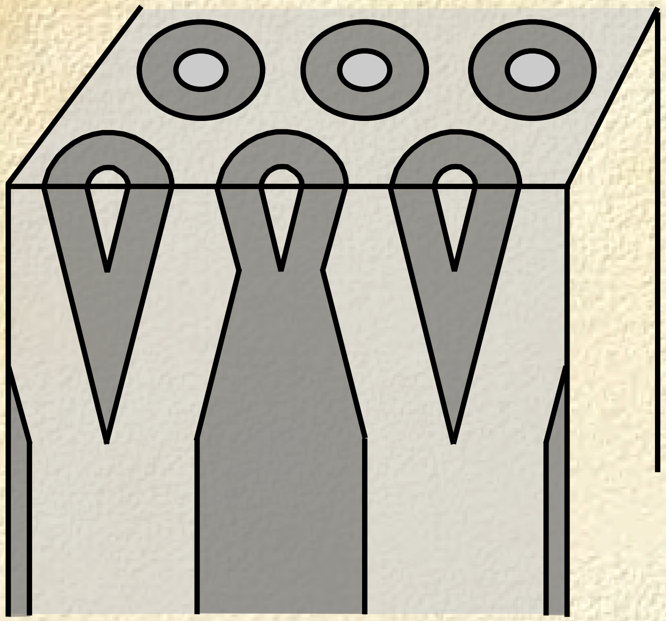


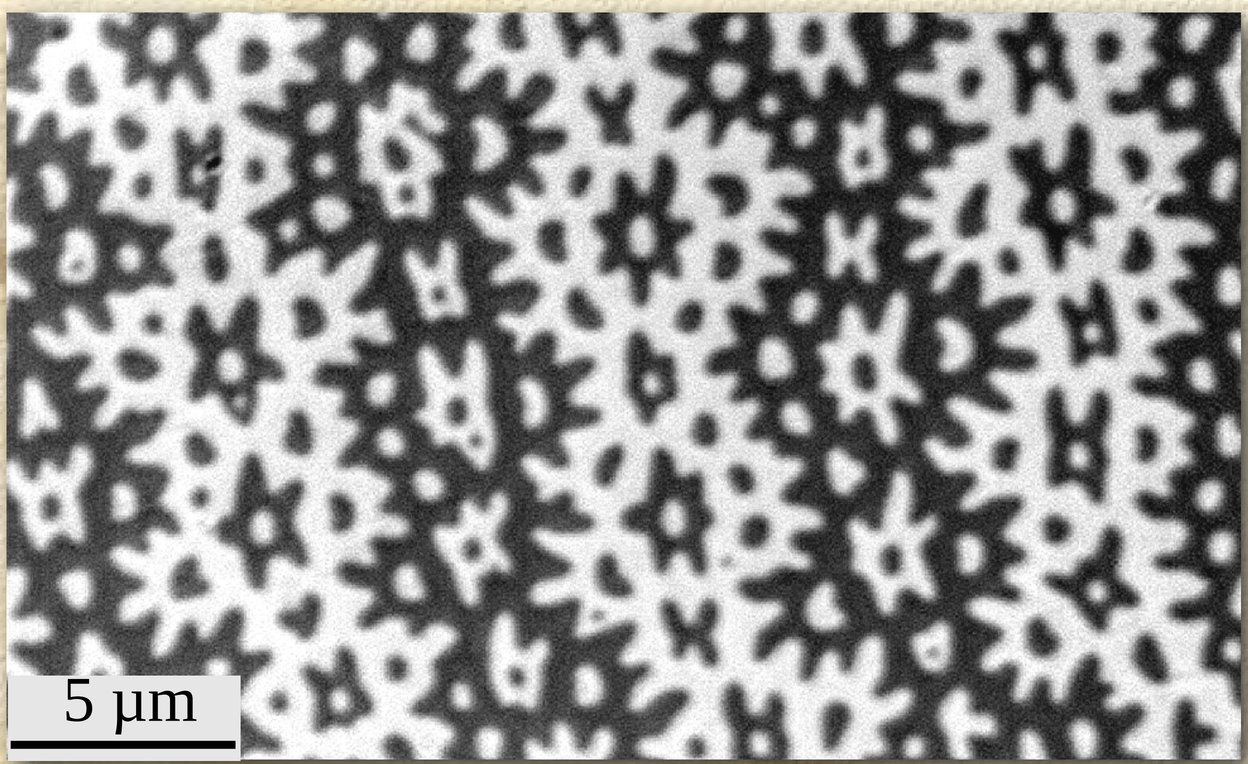


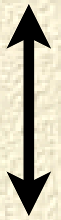
Dominating
stray-field energy (Q<<1)

General Classification of Domains

Dominating
anisotropy energy ($Q>>1$)



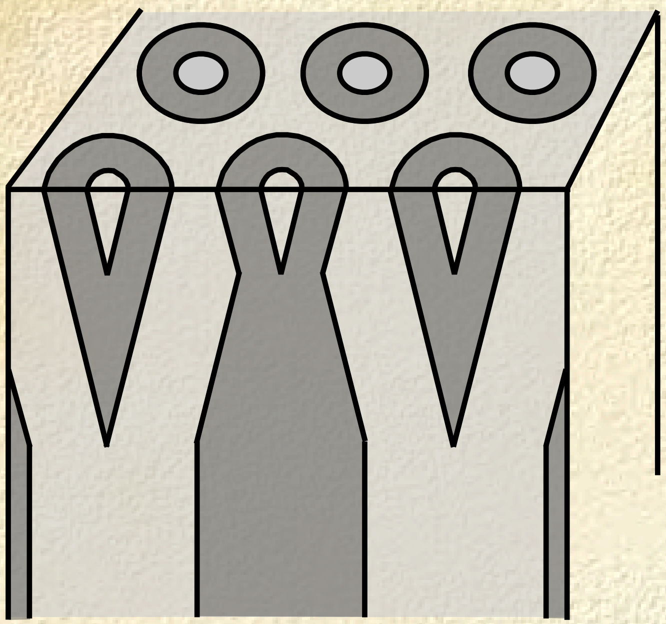




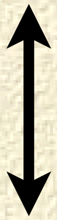
Dominating
stray-field energy ($Q<<1$)

General Classification of Domains

Dominating anisotropy energy ($Q>>1$)



~ 600 μm

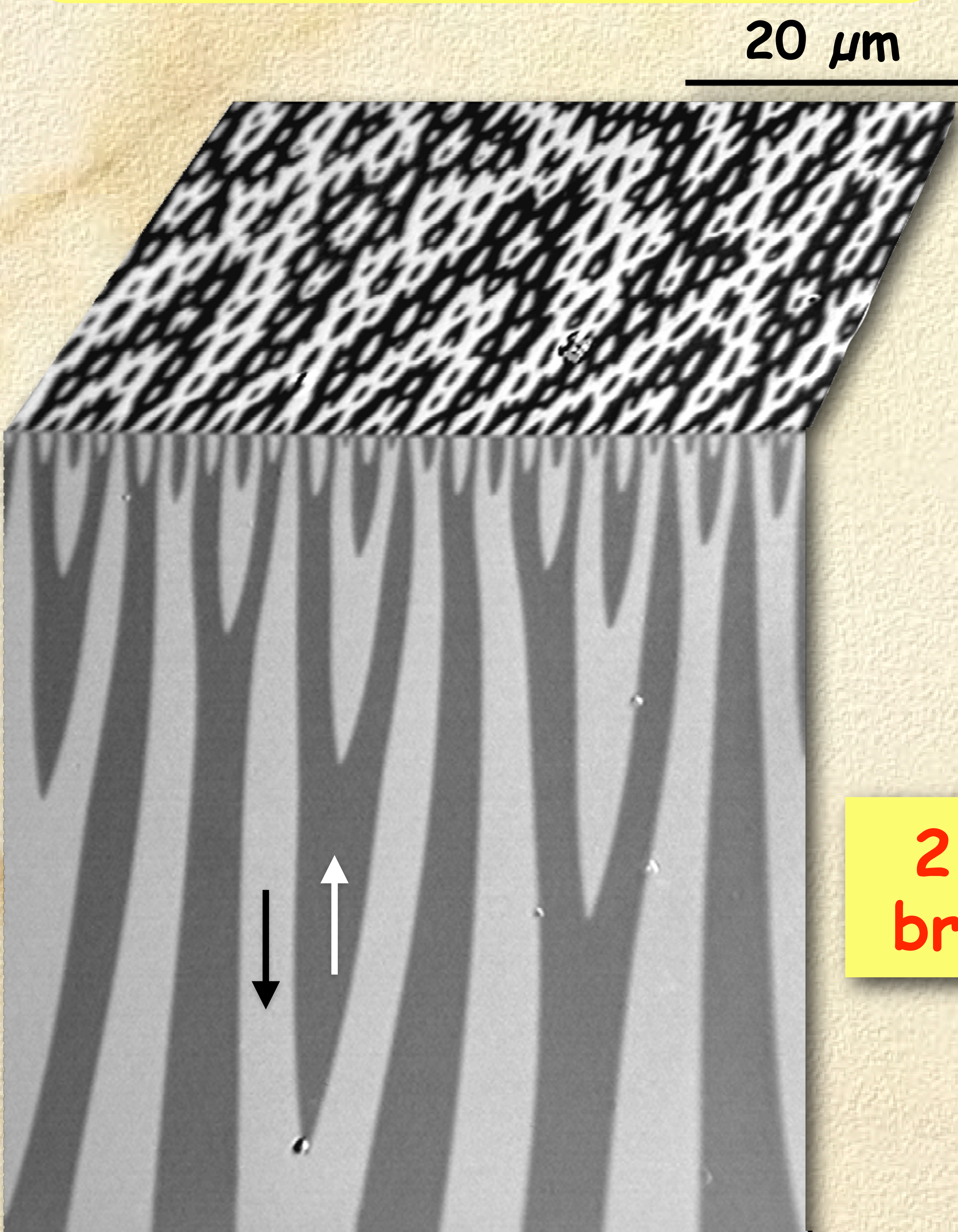


easy axis

Dominating stray-field energy ($Q<<1$)

General Classification of Domains

Dominating
anisotropy energy ($Q>>1$)



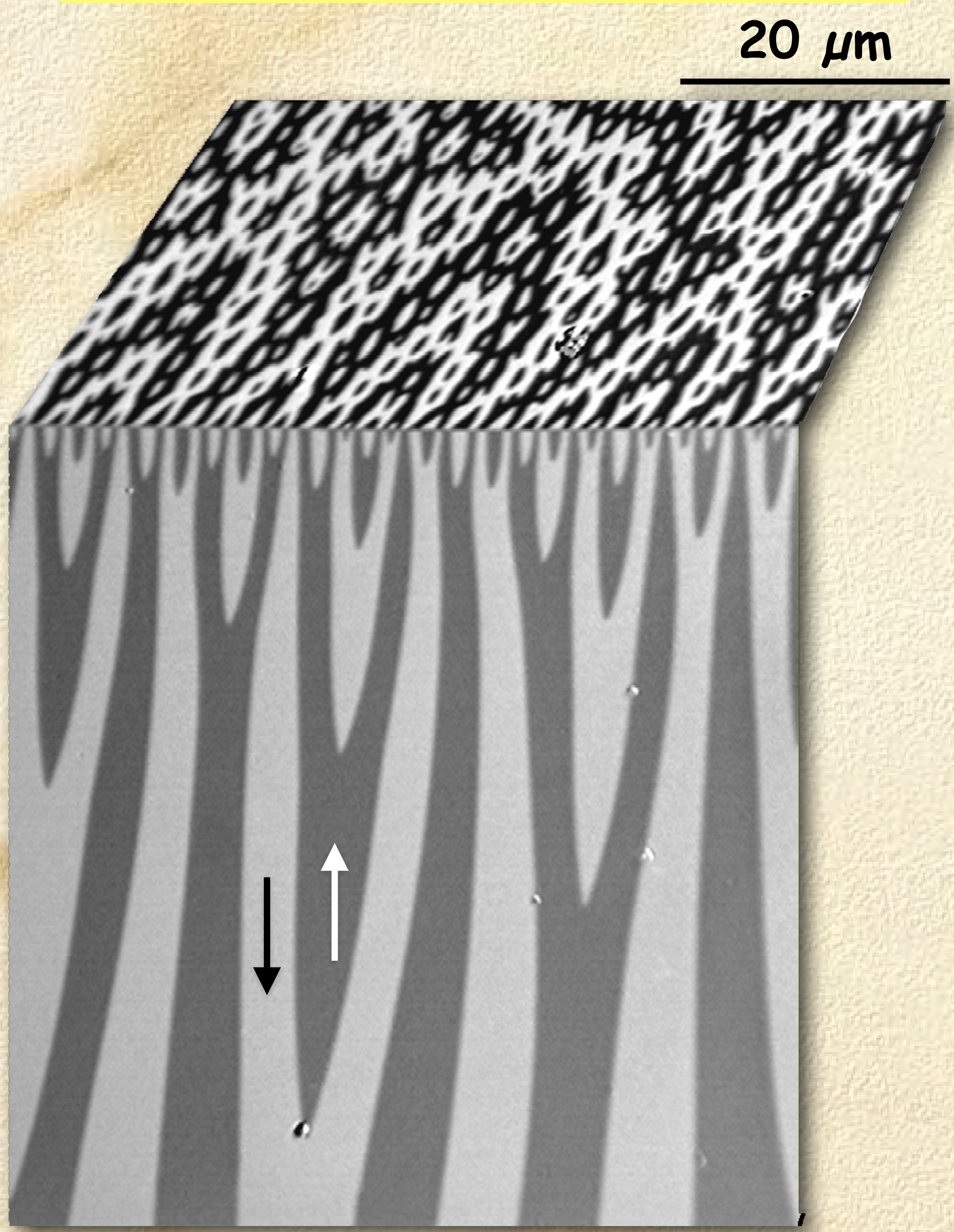
easy
axis

2-phase
branching

Dominating
stray-field energy ($Q<<1$)

General Classification of Domains

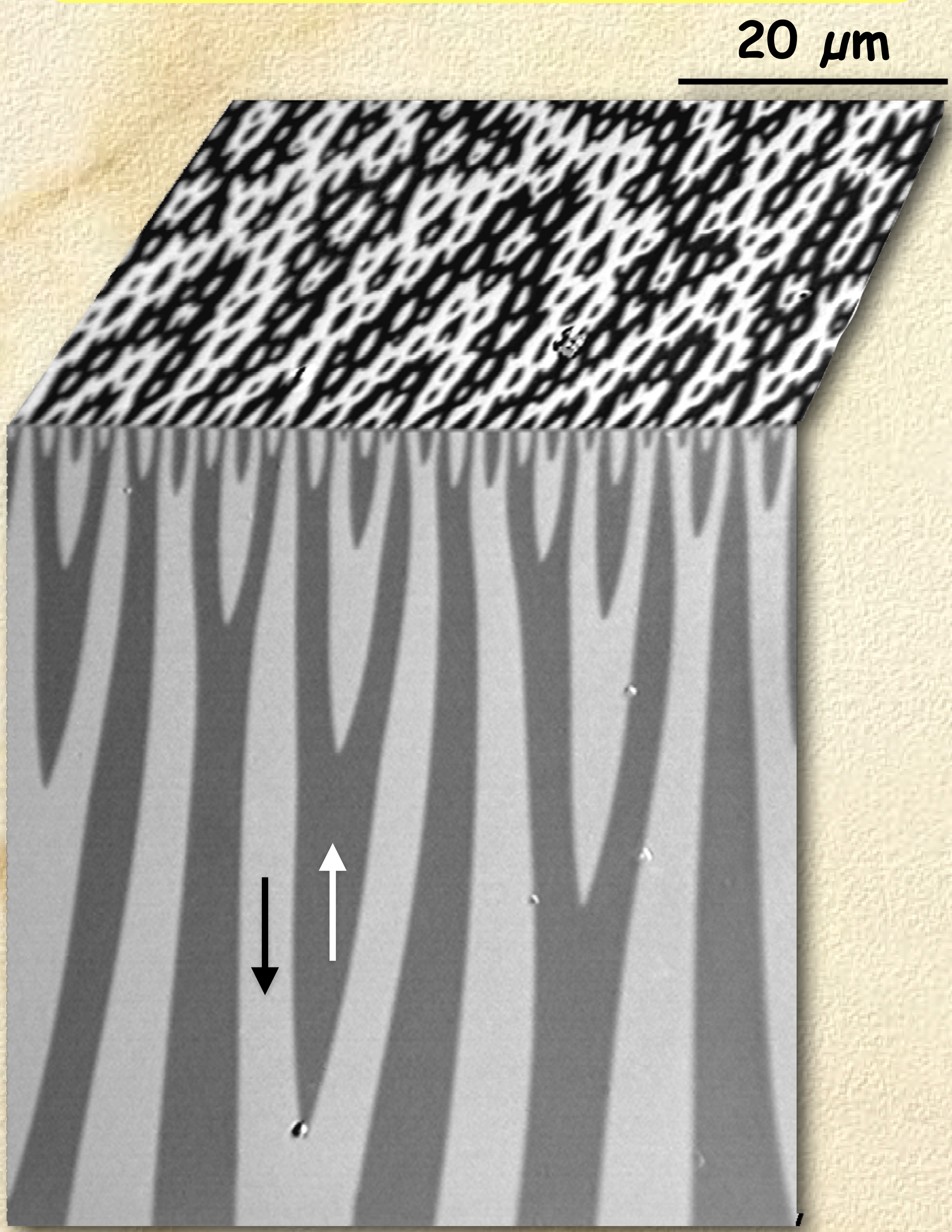
Dominating
anisotropy energy ($Q \gg 1$)



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

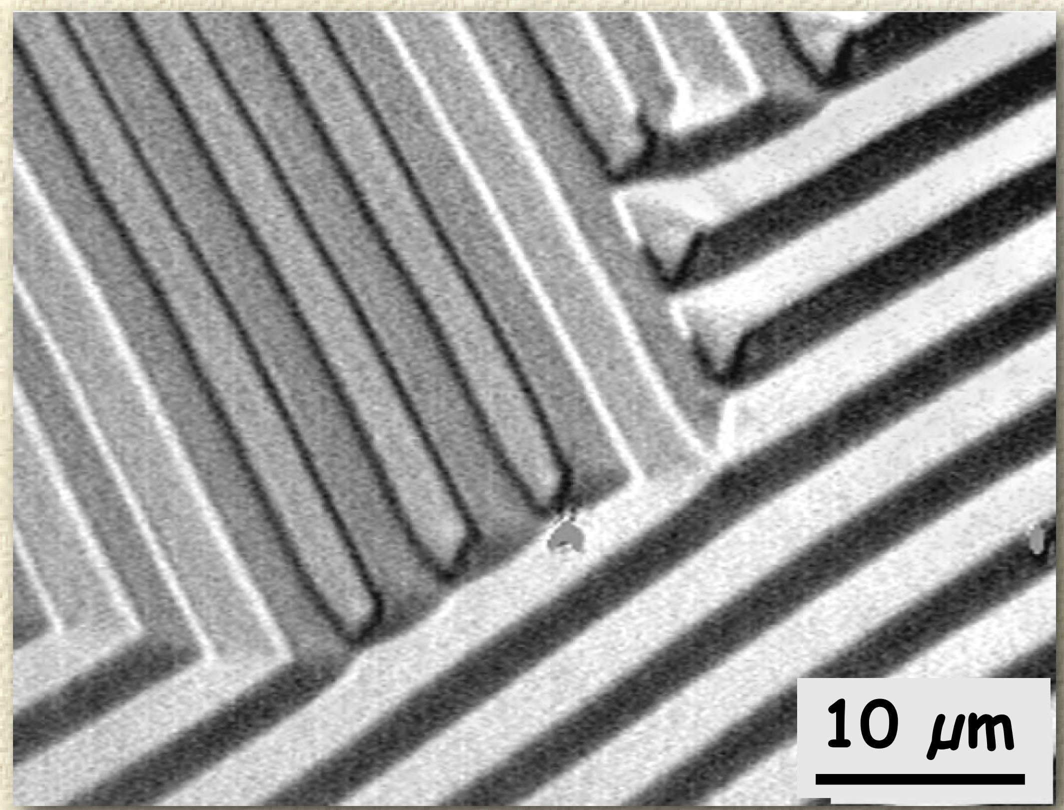
General Classification of Domains

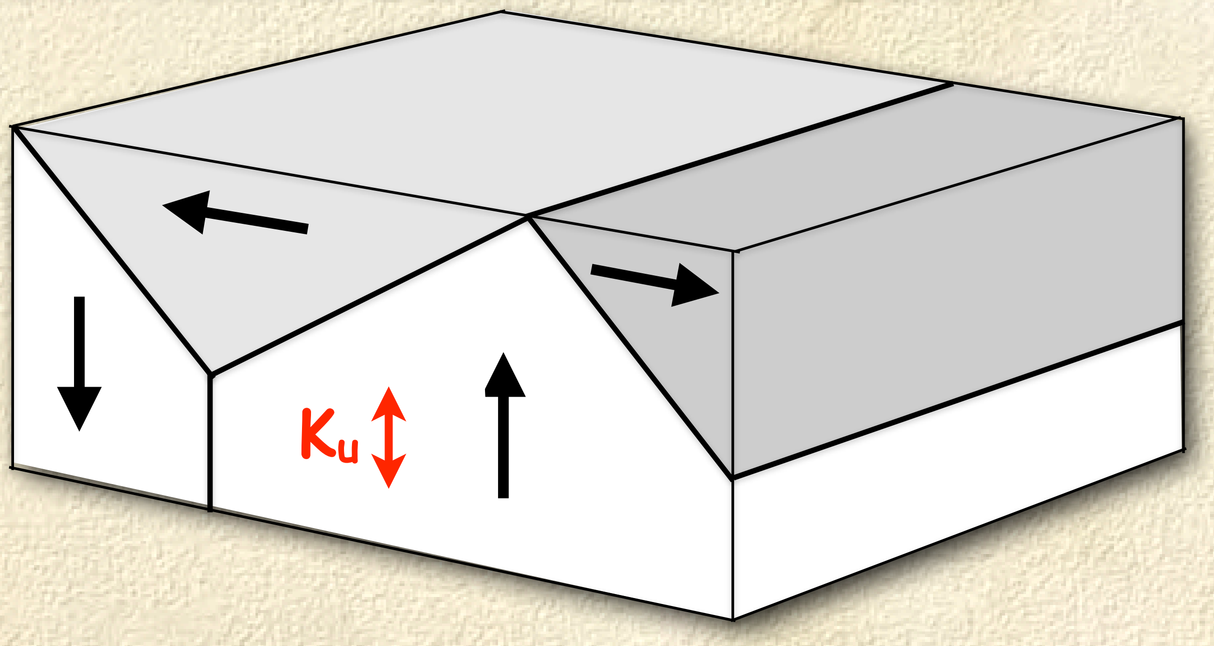
Dominating
anisotropy energy ($Q>>1$)



Dominating
stray-field energy ($Q<<1$)

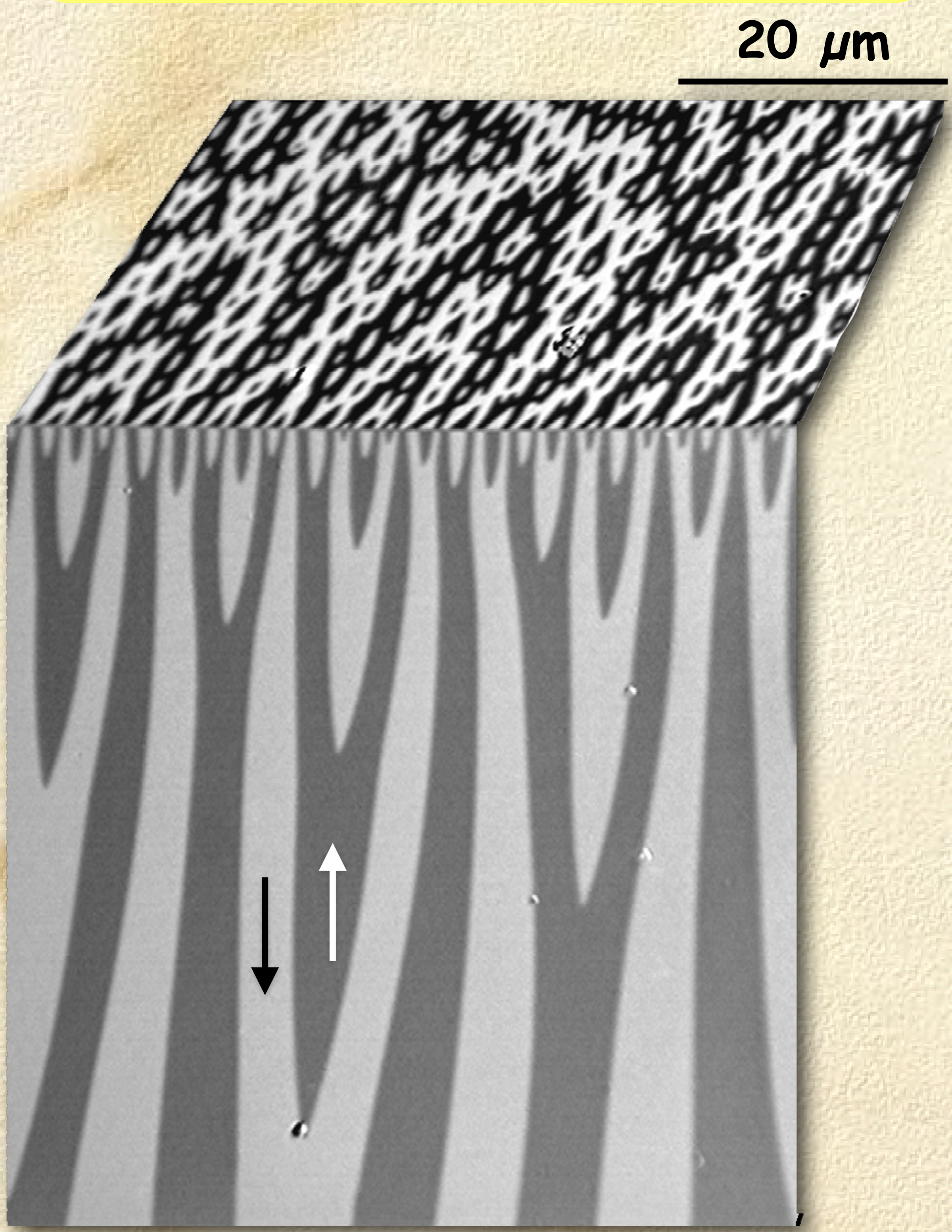
Amorphous FeSiB ribbon (20 μm thick)





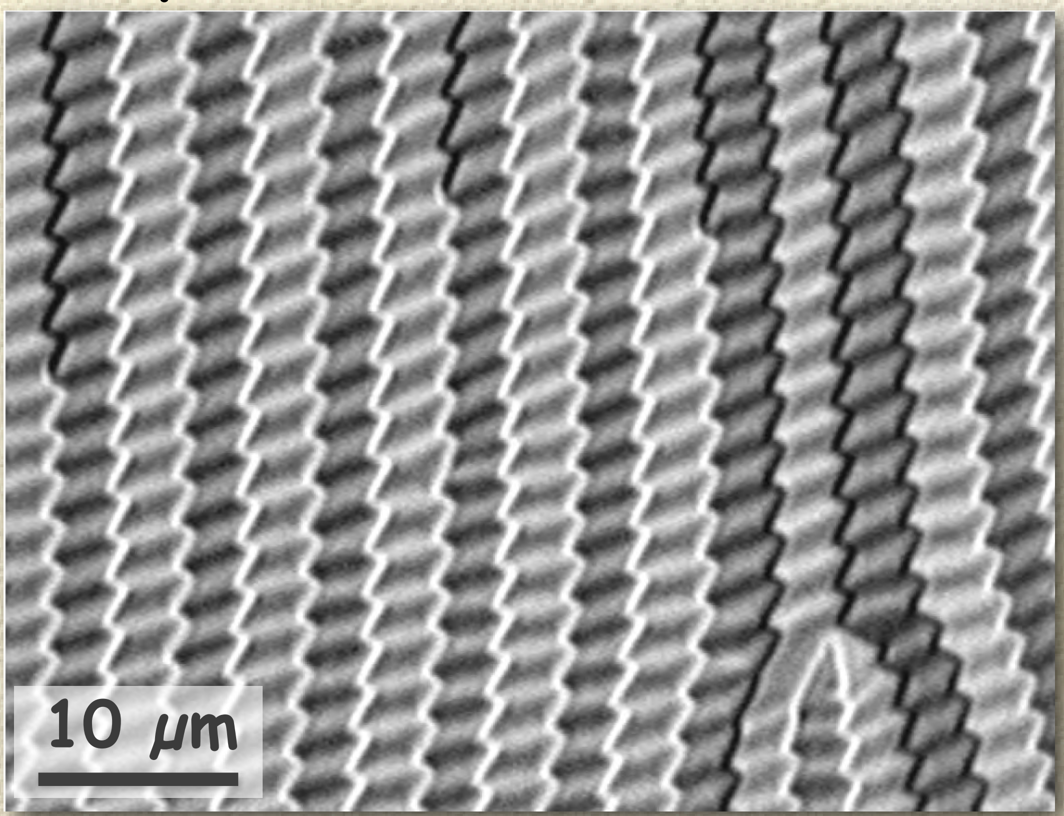
General Classification of Domains

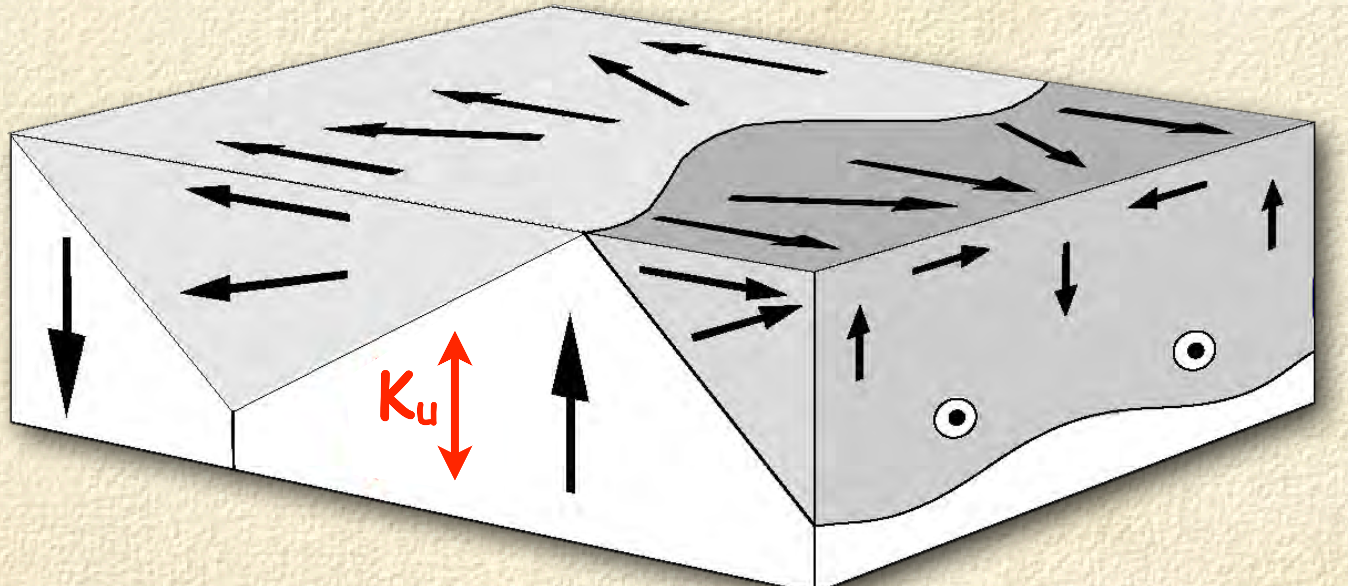
Dominating anisotropy energy ($Q>>1$)



Dominating stray-field energy ($Q<<1$)

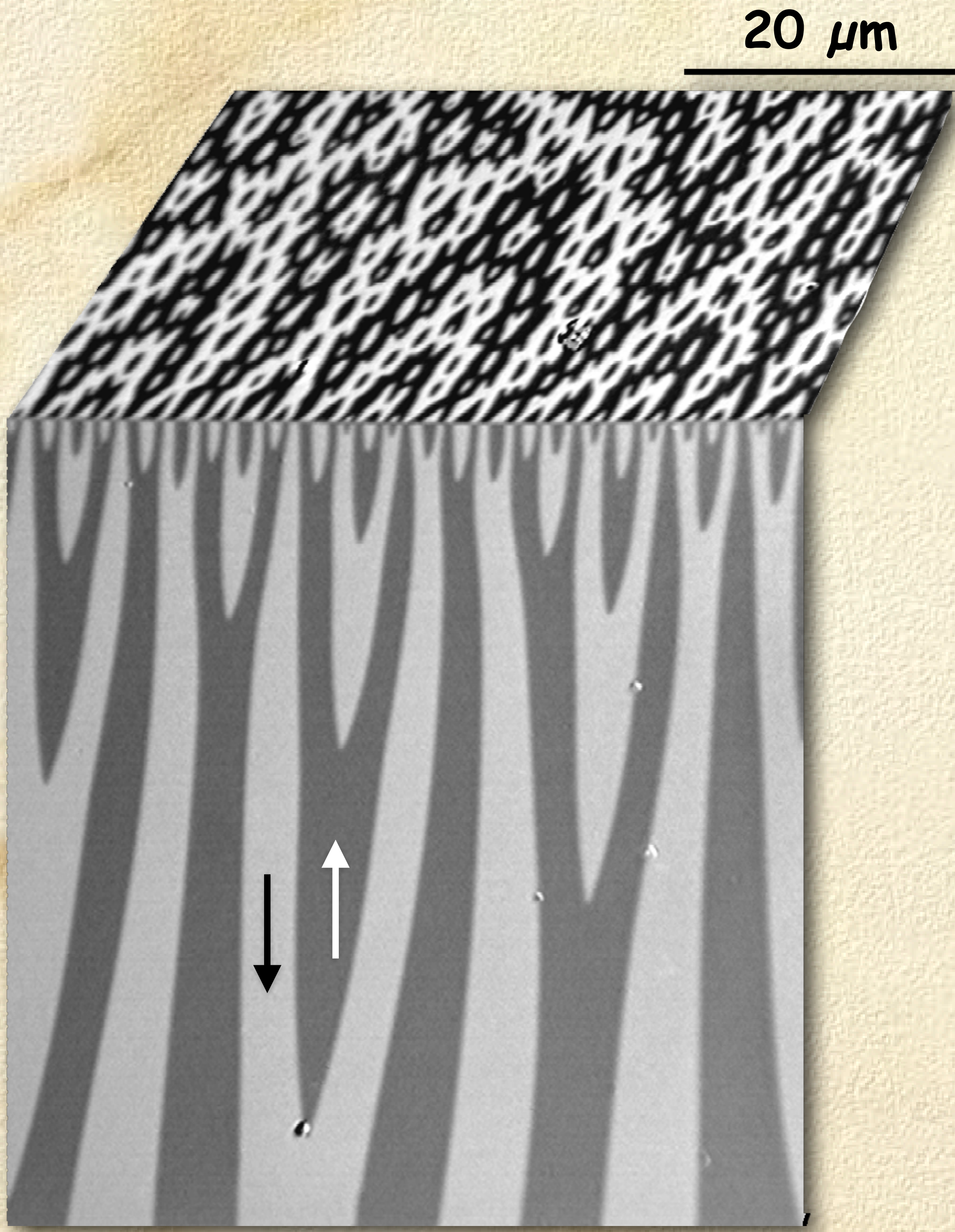
Amorphous FeSiB ribbon





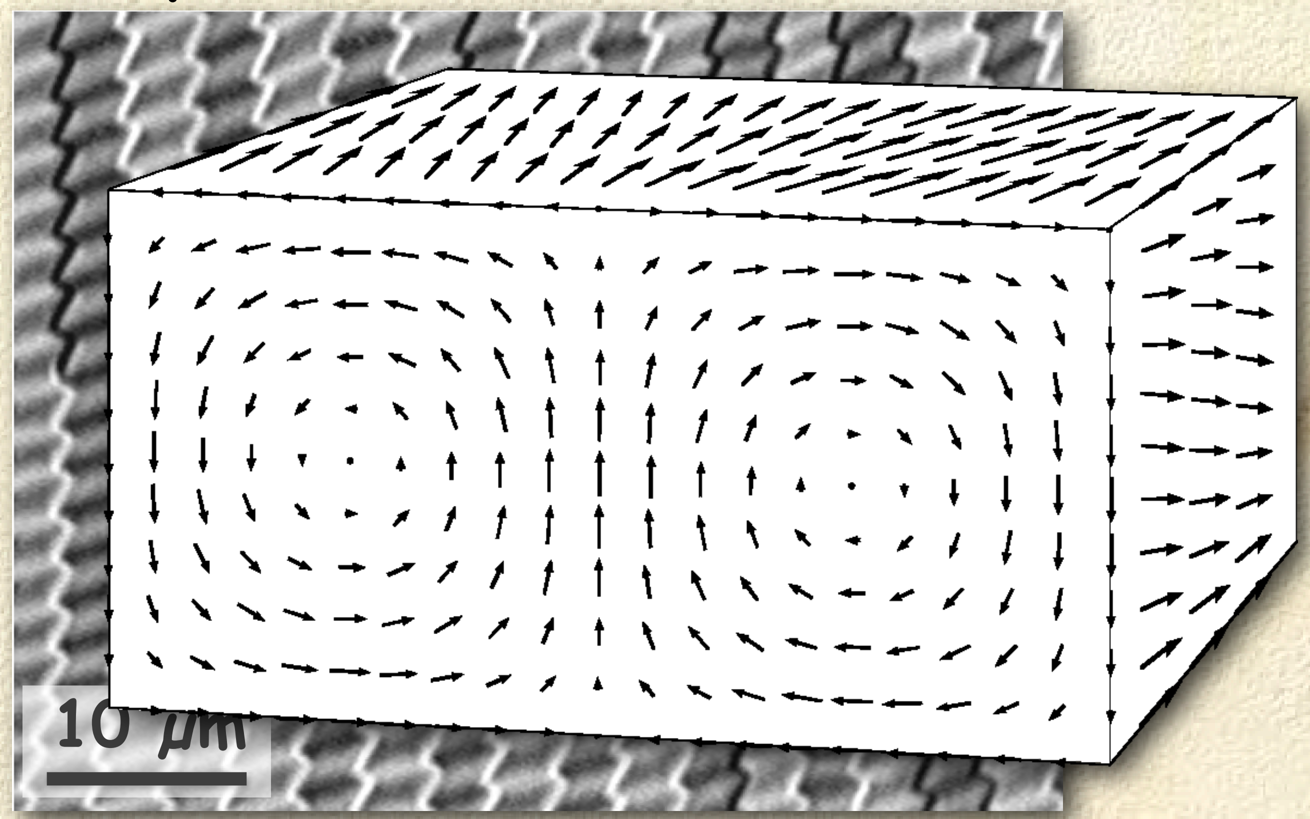
General Classification of Domains

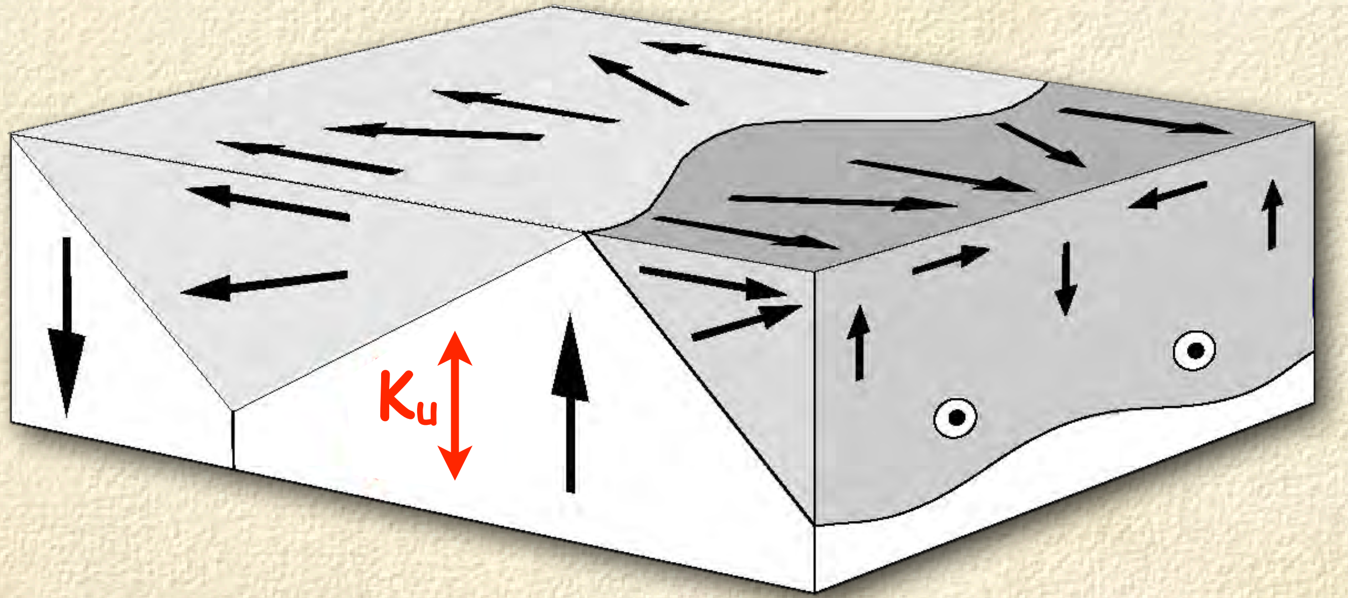
Dominating anisotropy energy ($Q >> 1$)



Dominating stray-field energy ($Q << 1$)

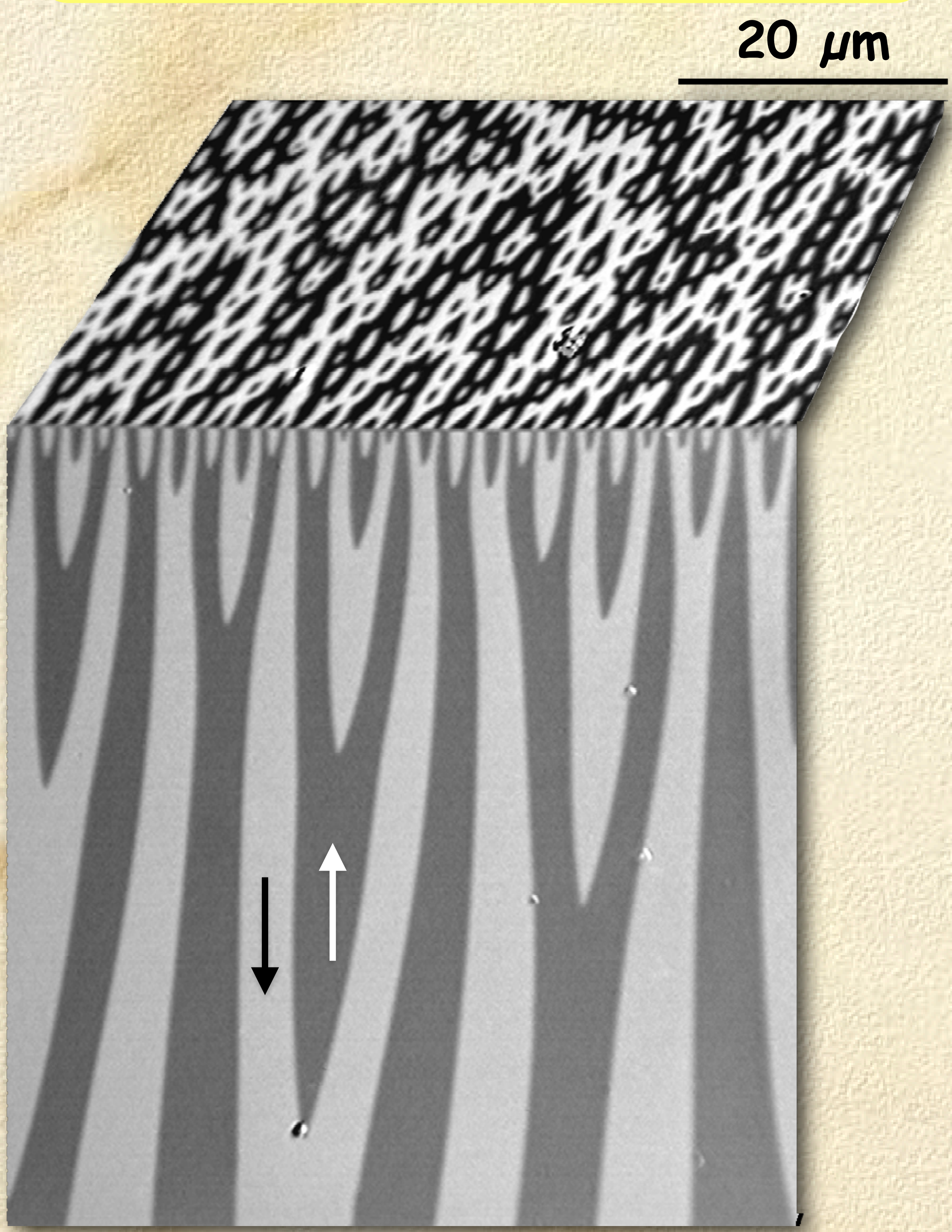
Amorphous FeSiB ribbon





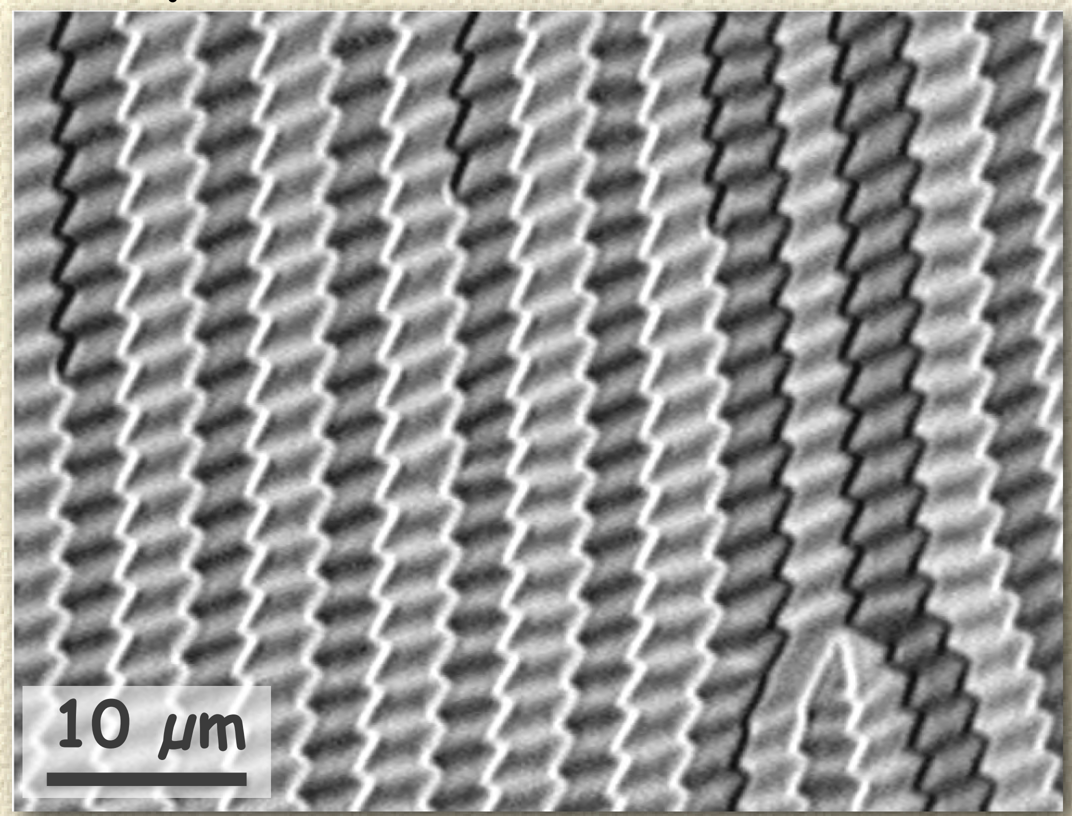
General Classification of Domains

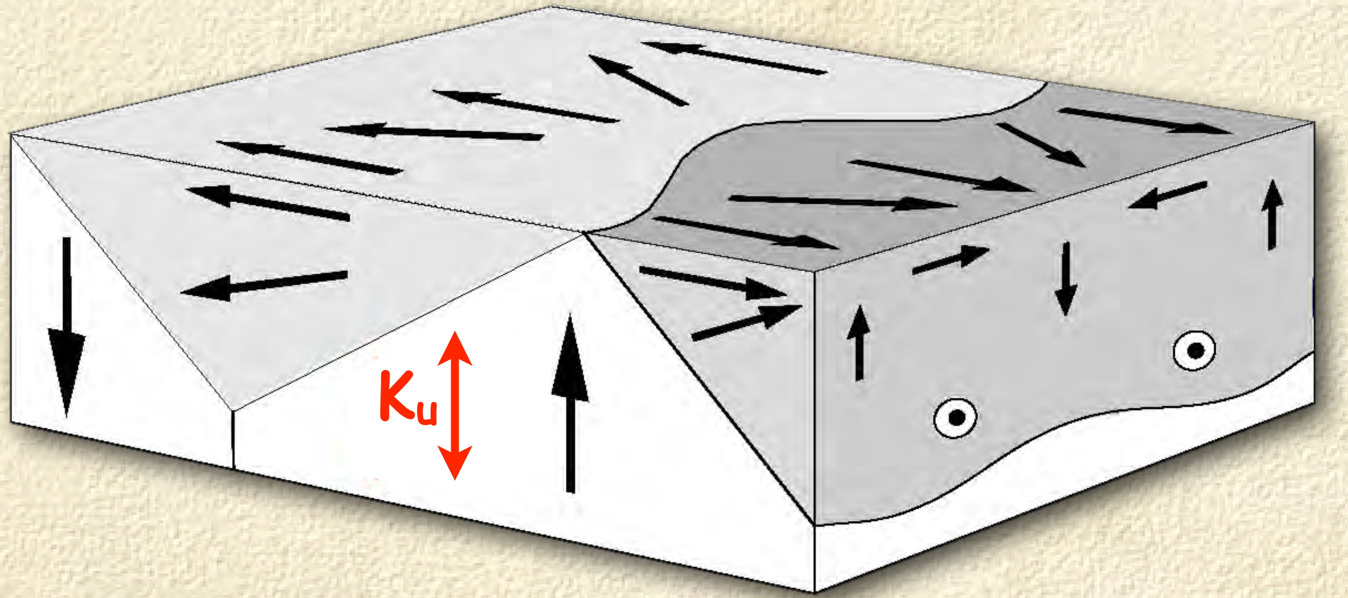
Dominating anisotropy energy ($Q >> 1$)



Dominating stray-field energy ($Q << 1$)

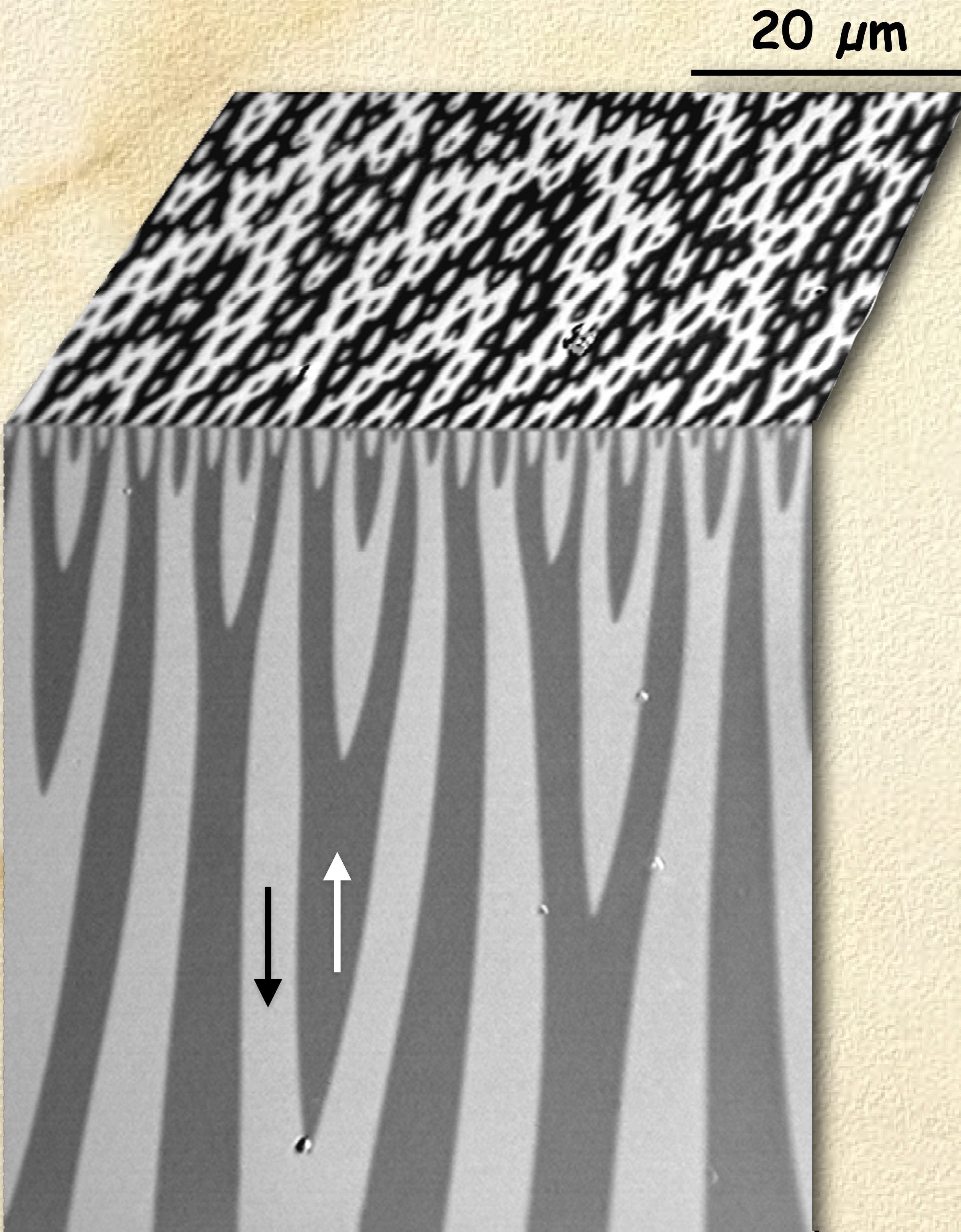
Amorphous FeSiB ribbon





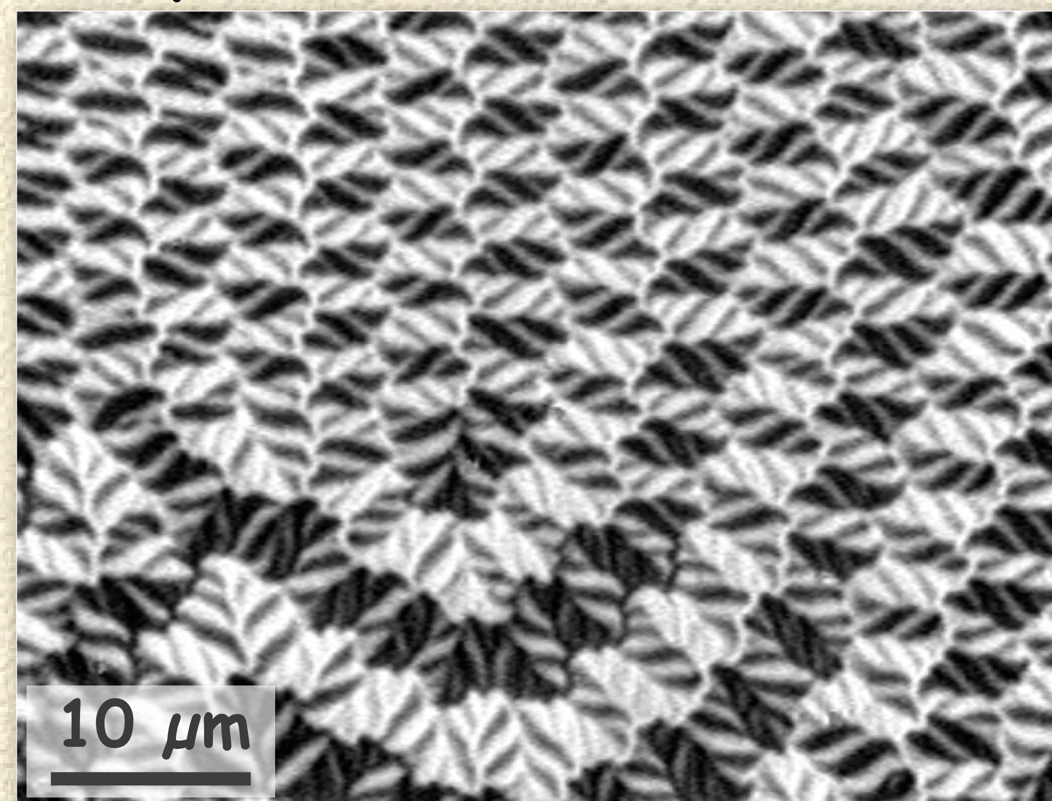
General Classification of Domains

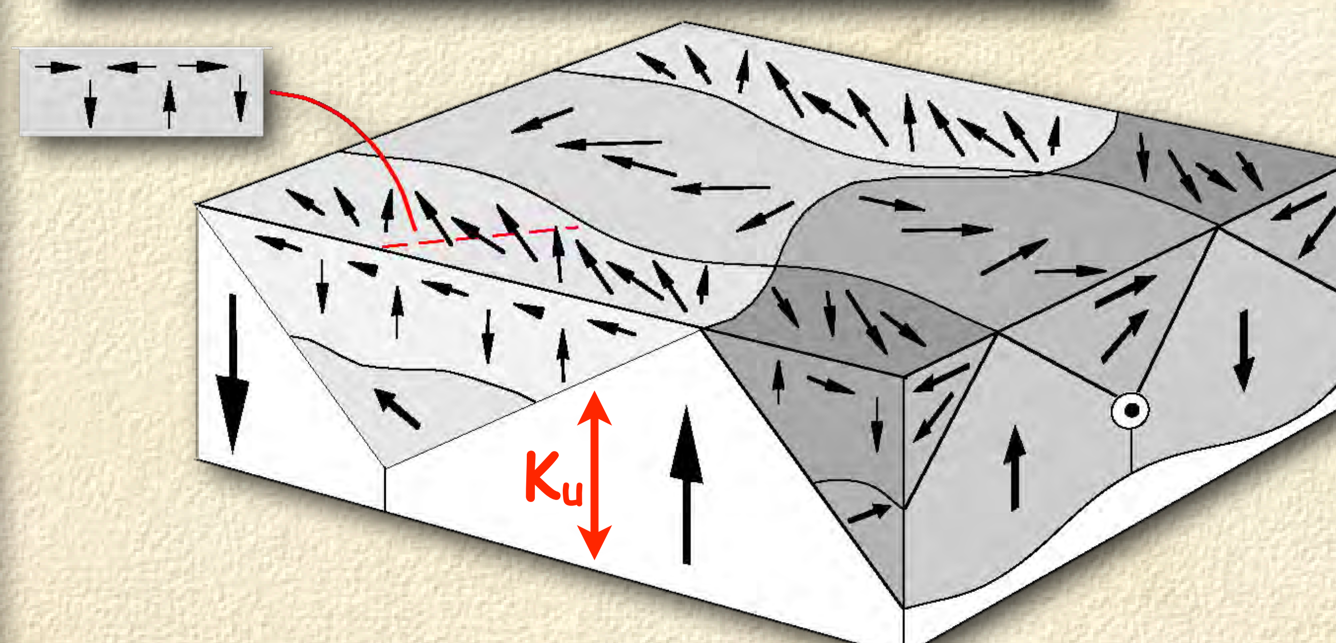
Dominating anisotropy energy ($Q>>1$)



Dominating stray-field energy ($Q<<1$)

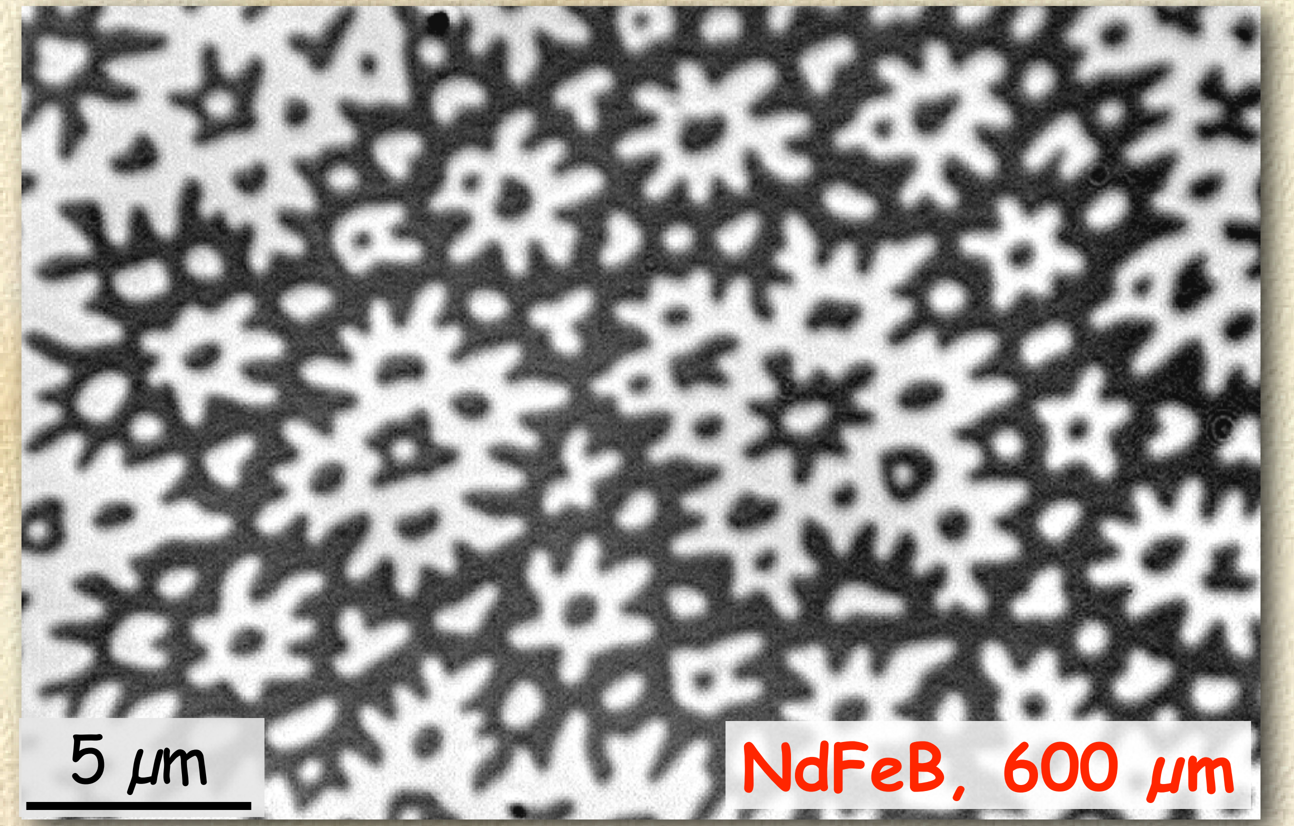
Amorphous FeSiB ribbon

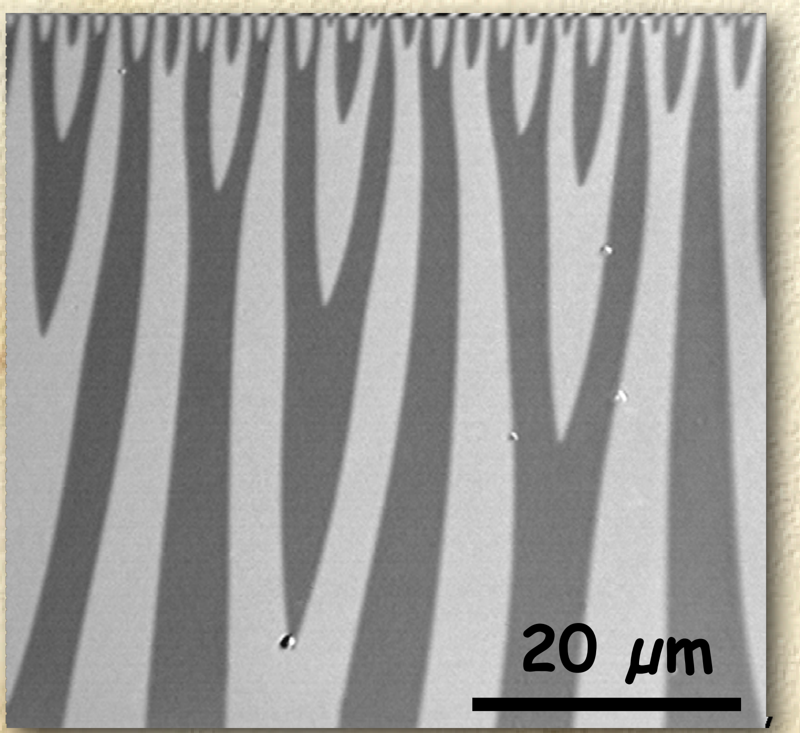




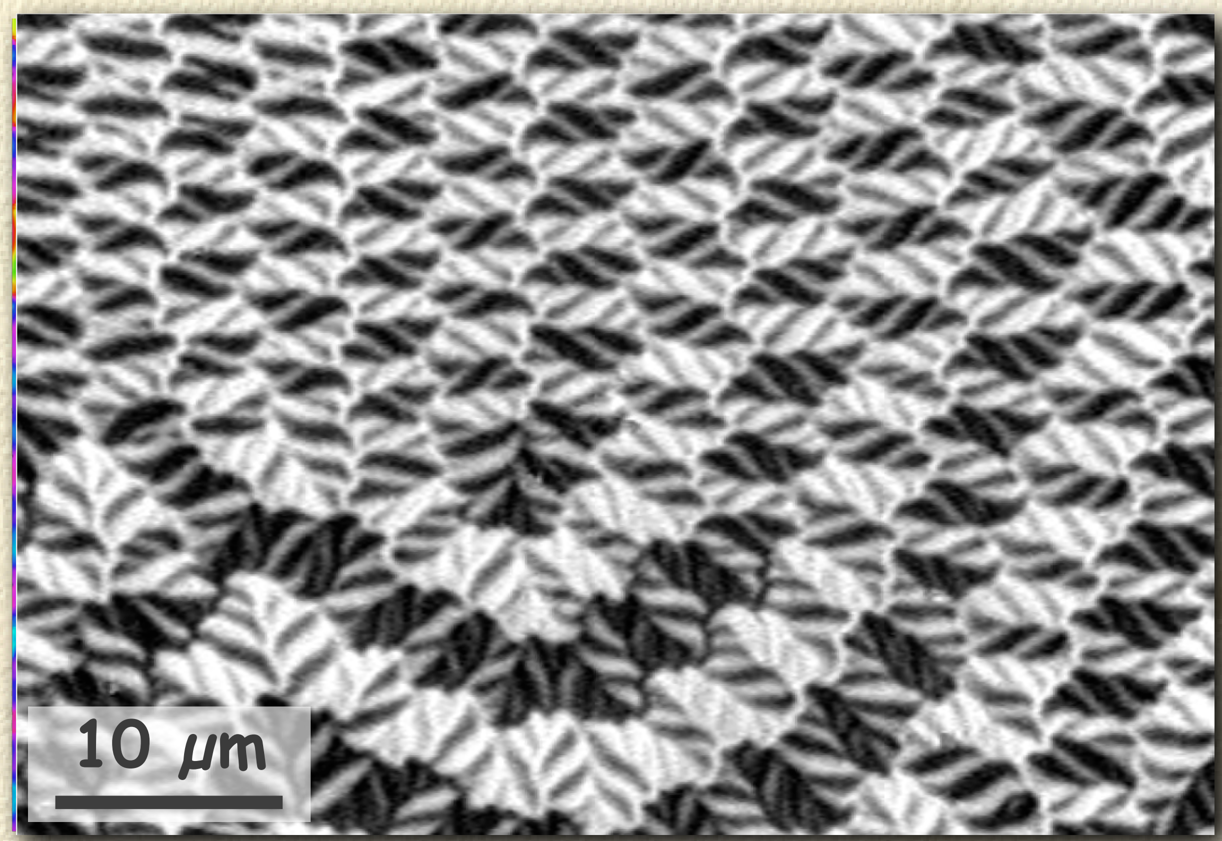
General Classification of Domains

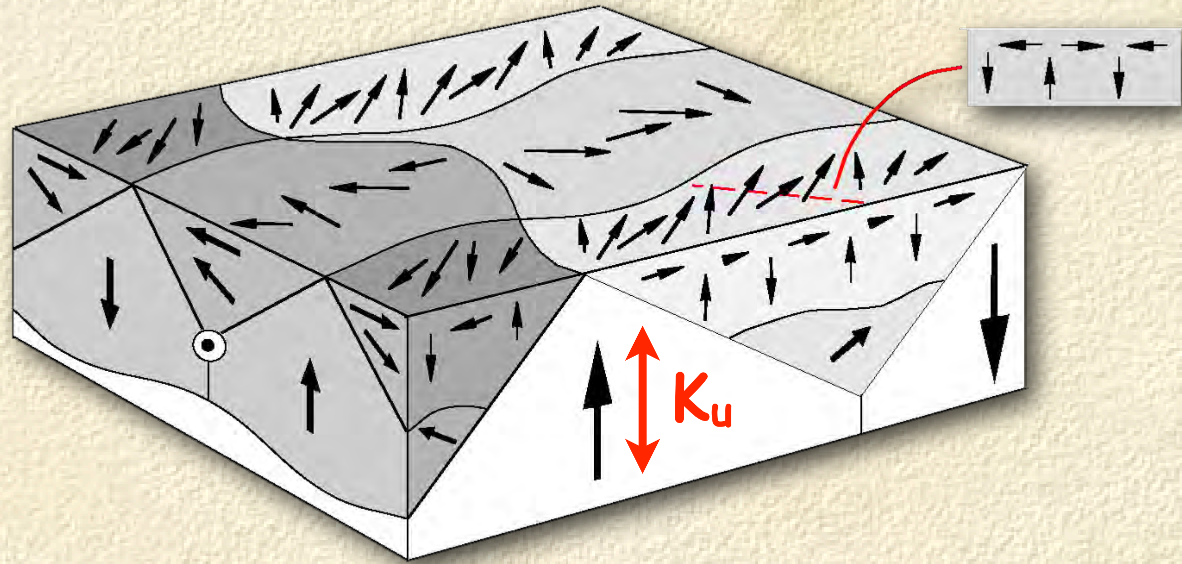
$Q >> 1$





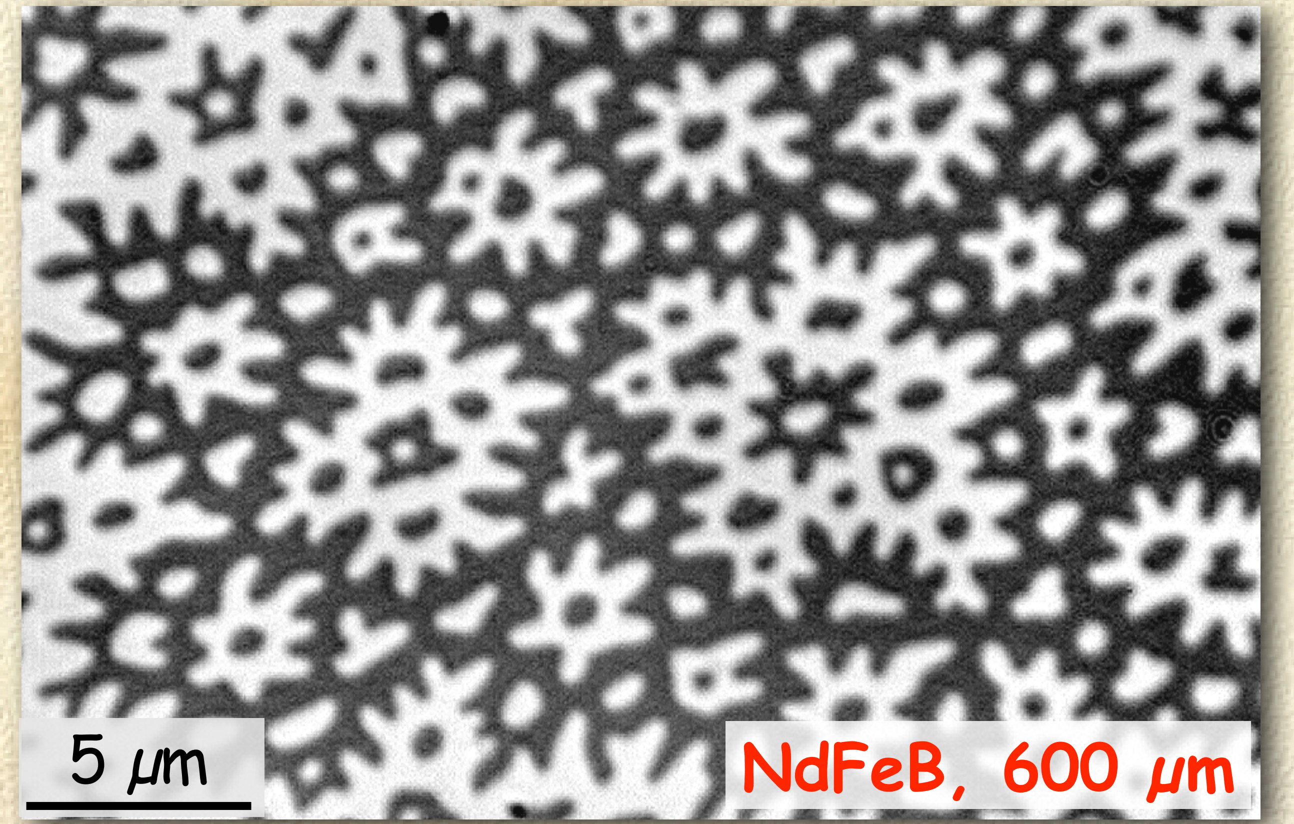
$Q << 1$

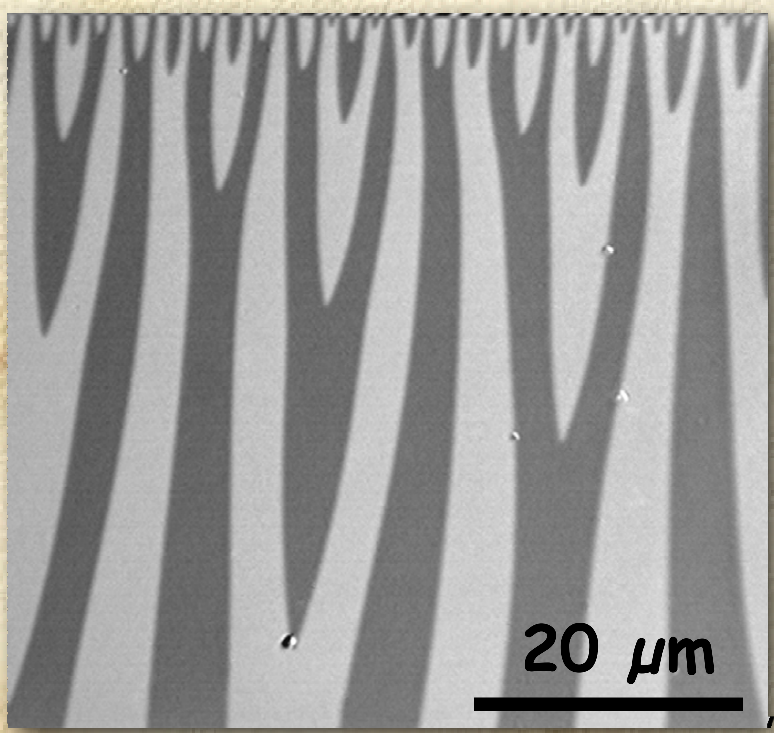




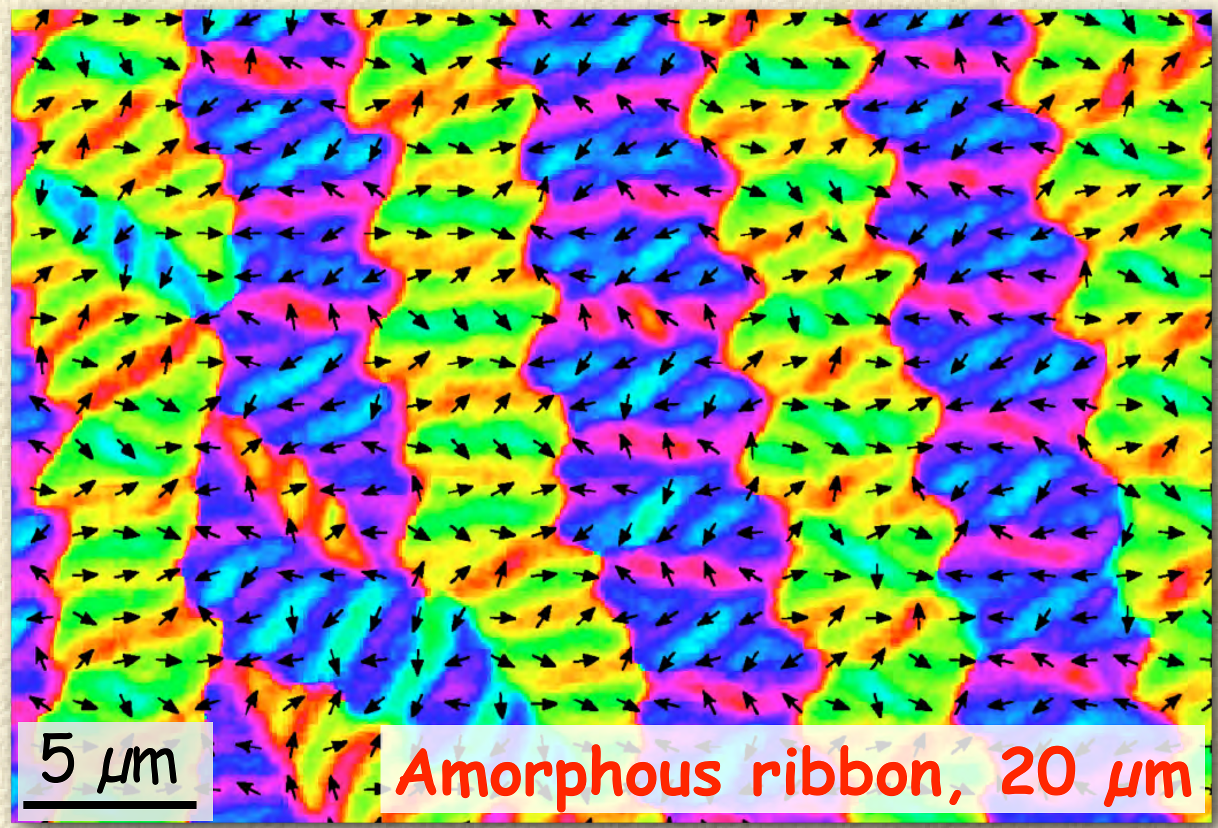
General Classification of Domains

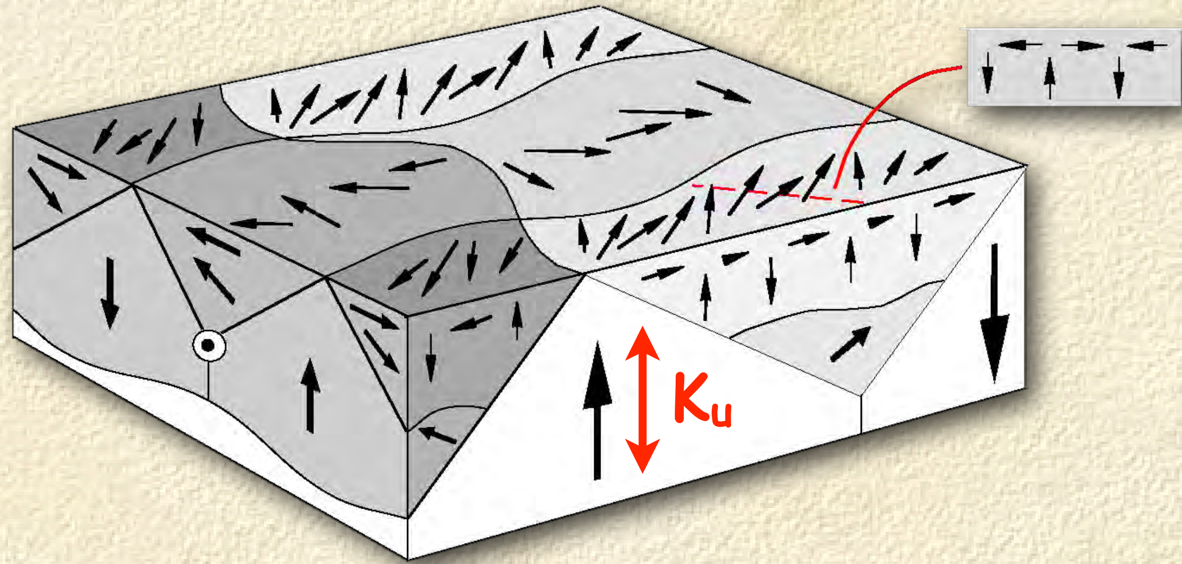
$Q >> 1$





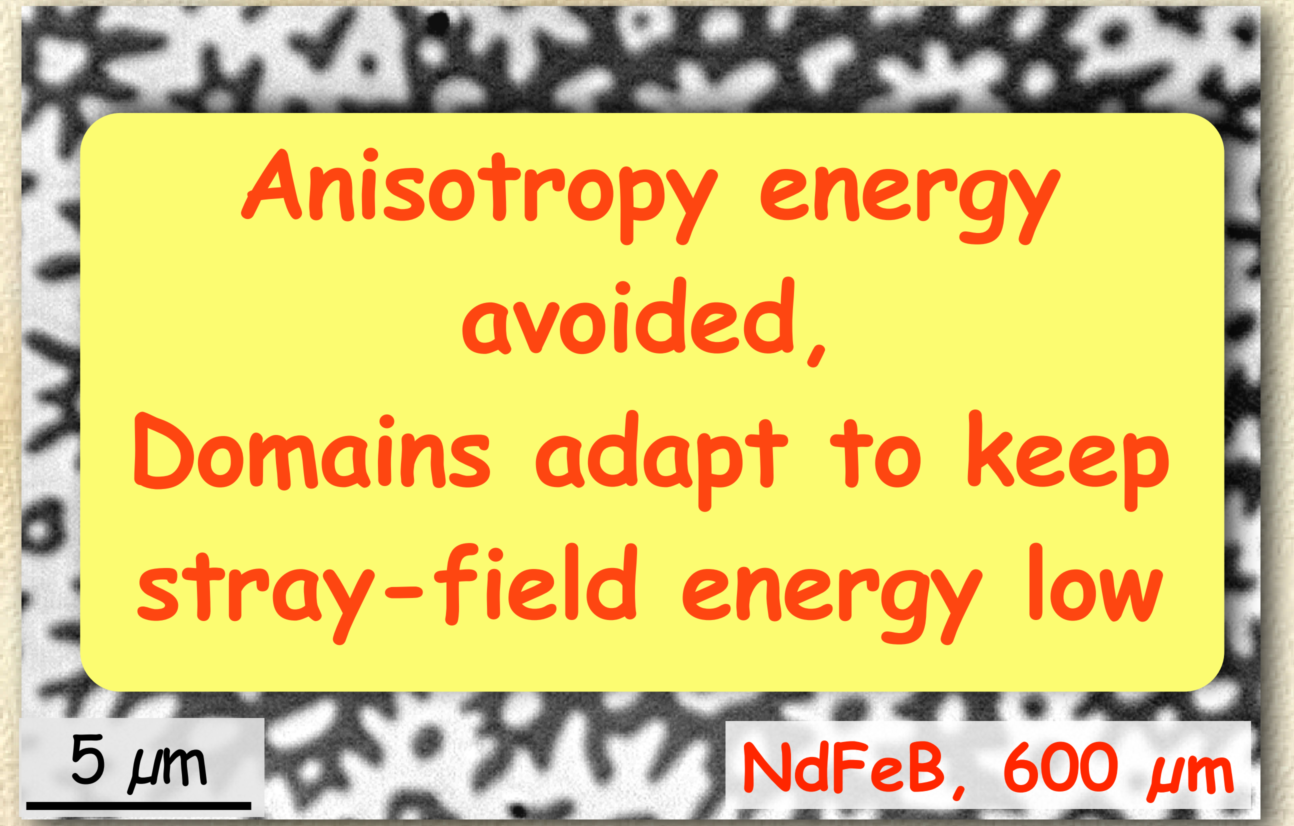
$Q << 1$

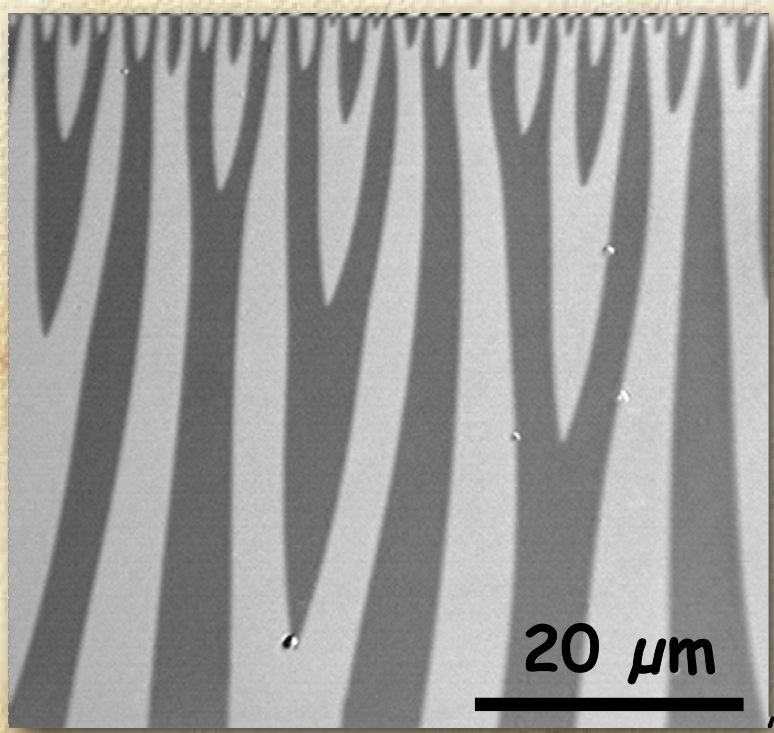




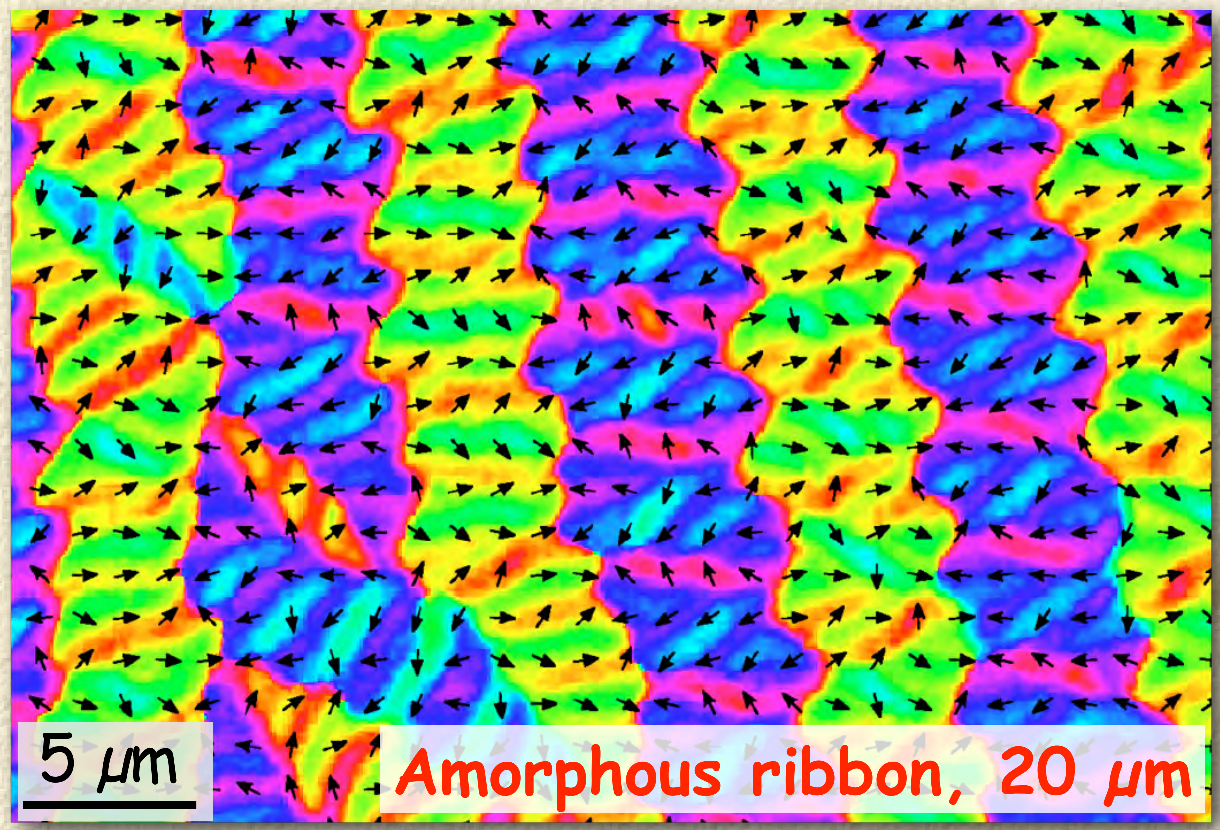
General Classification of Domains

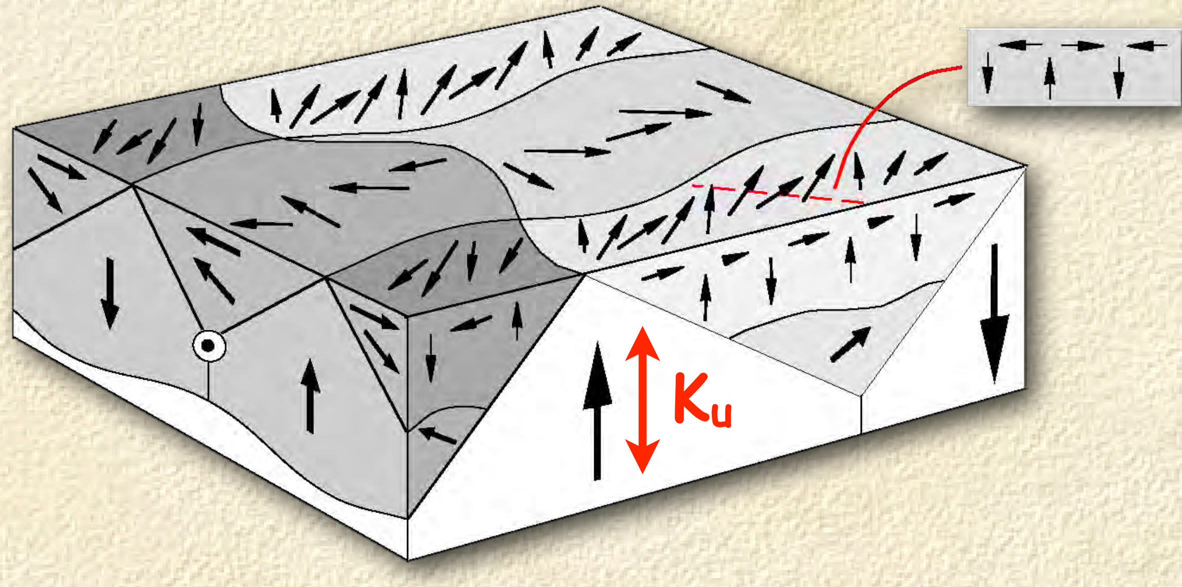
$Q >> 1$





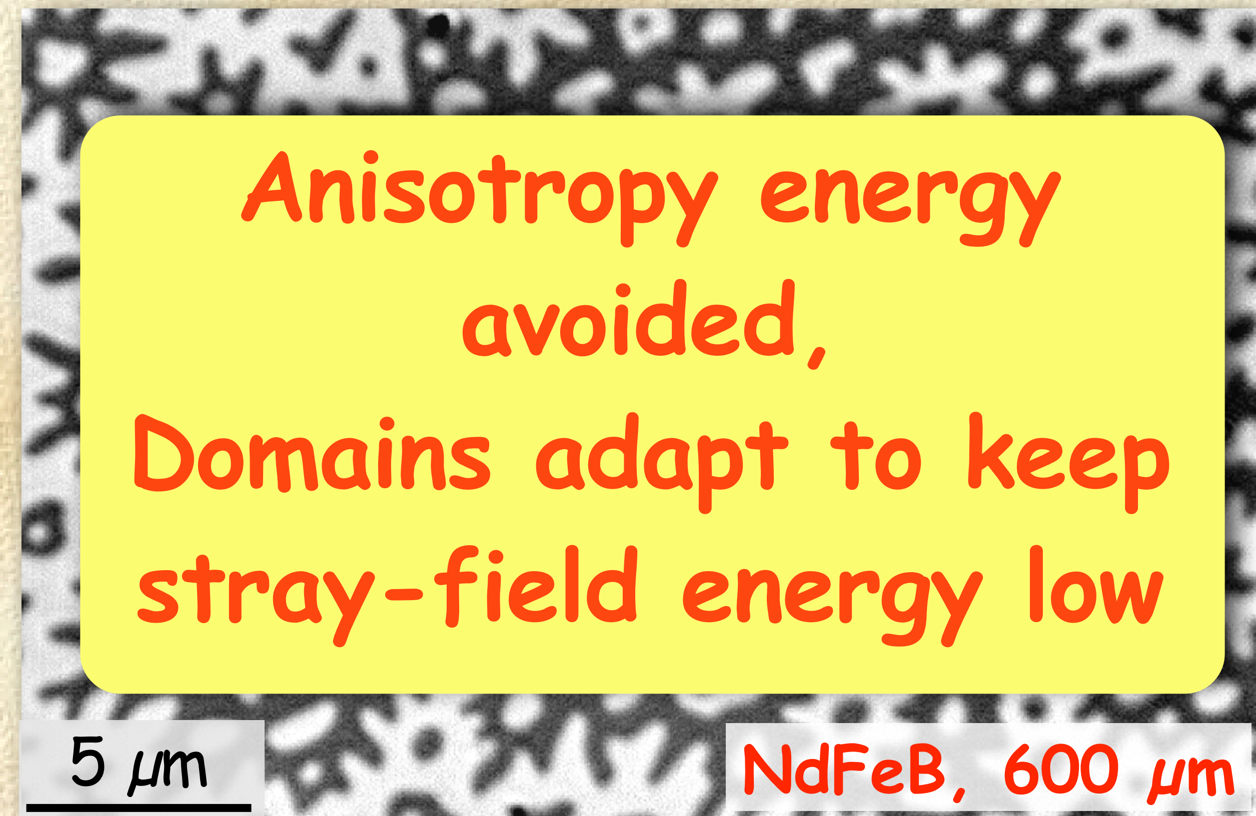
$Q << 1$



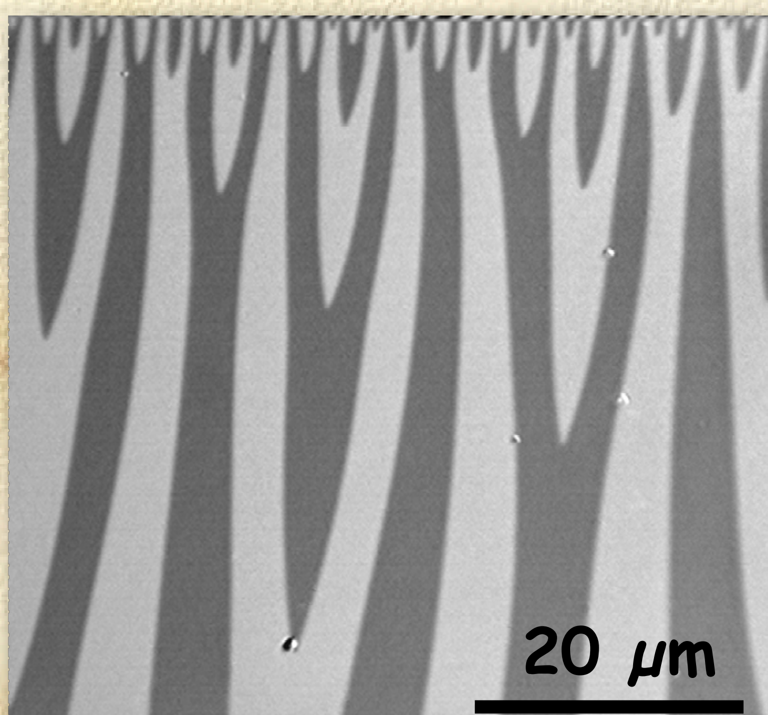


General Classification of Domains

$Q >> 1$

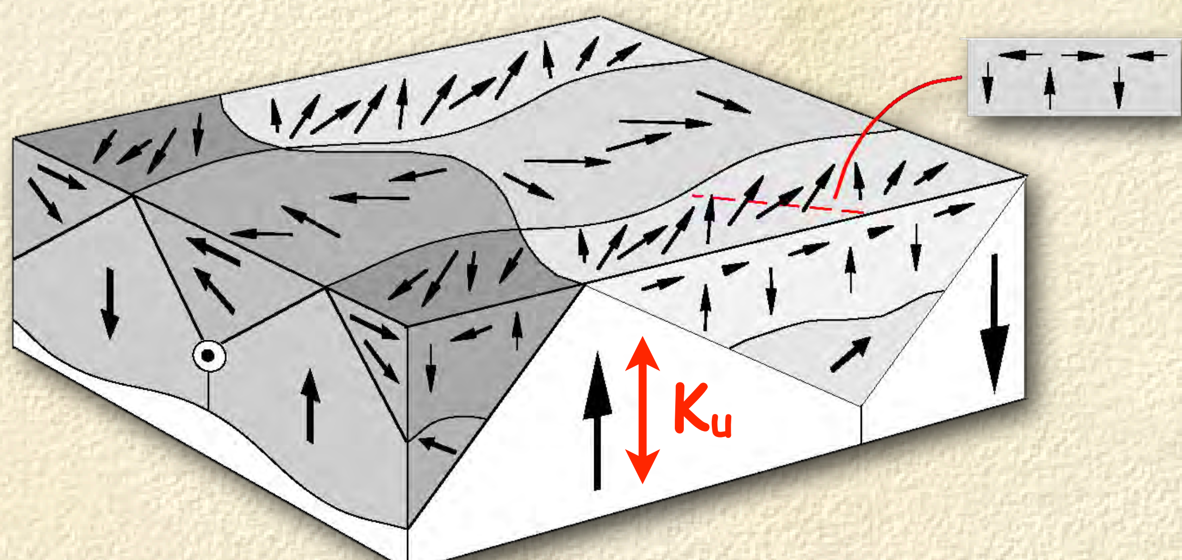


Anisotropy energy avoided,
Domains adapt to keep stray-field energy low



$Q << 1$

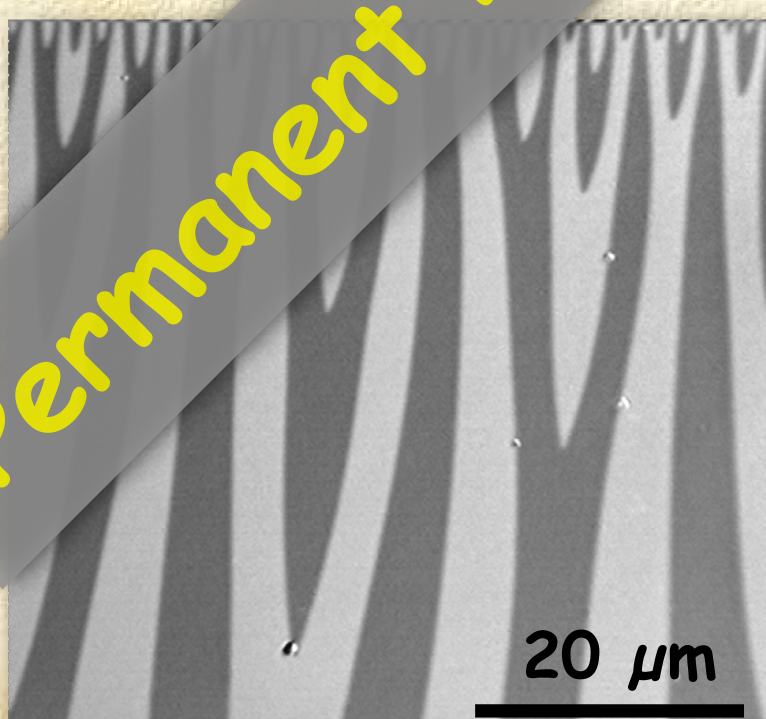
Stray field energy avoided,
Domains adapt to keep anisotropy energy low



General Classification of Domains

$Q >> 1$

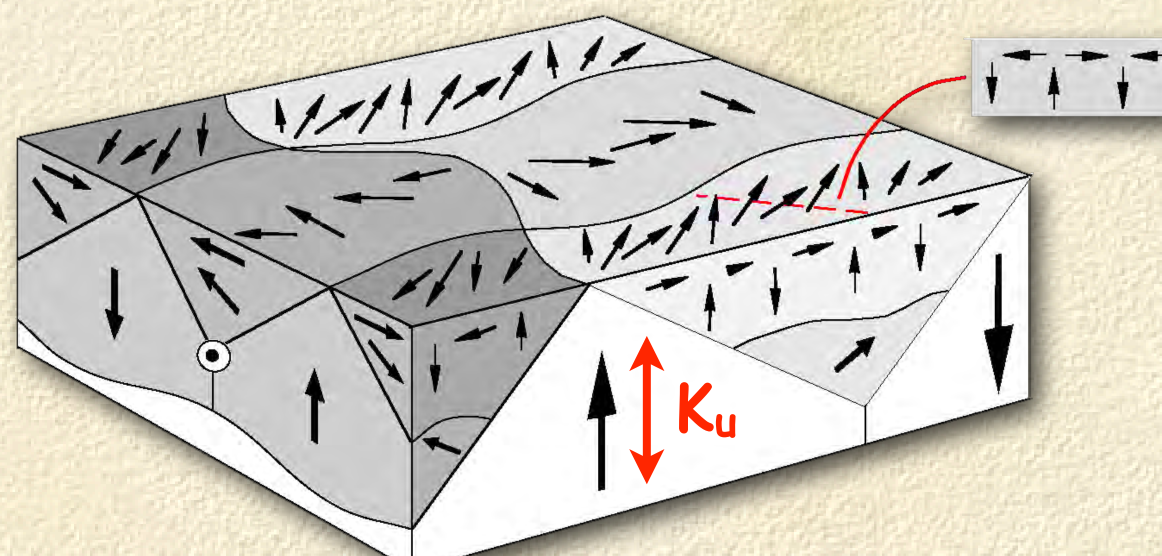
Anisotropy energy avoided,
Domains adapt to keep stray-field energy low



Permanent magnets

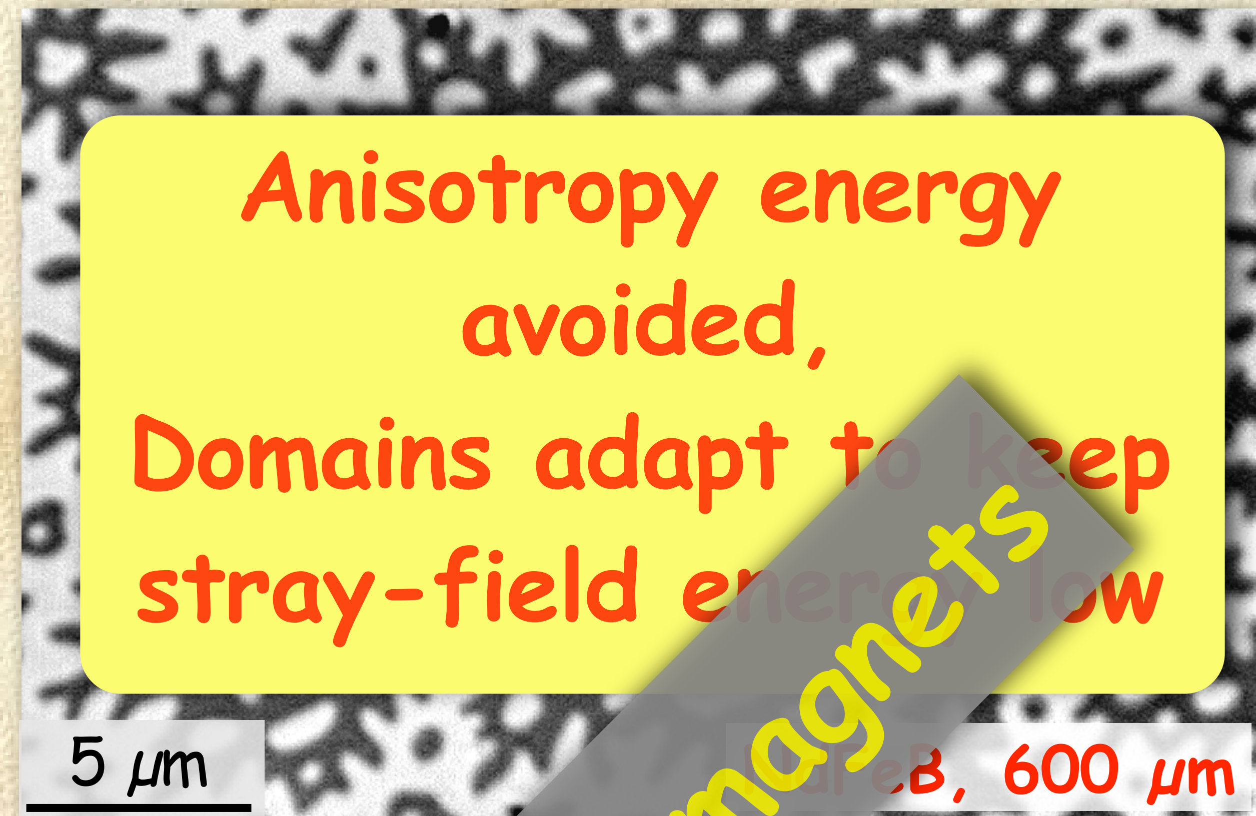
$Q << 1$

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

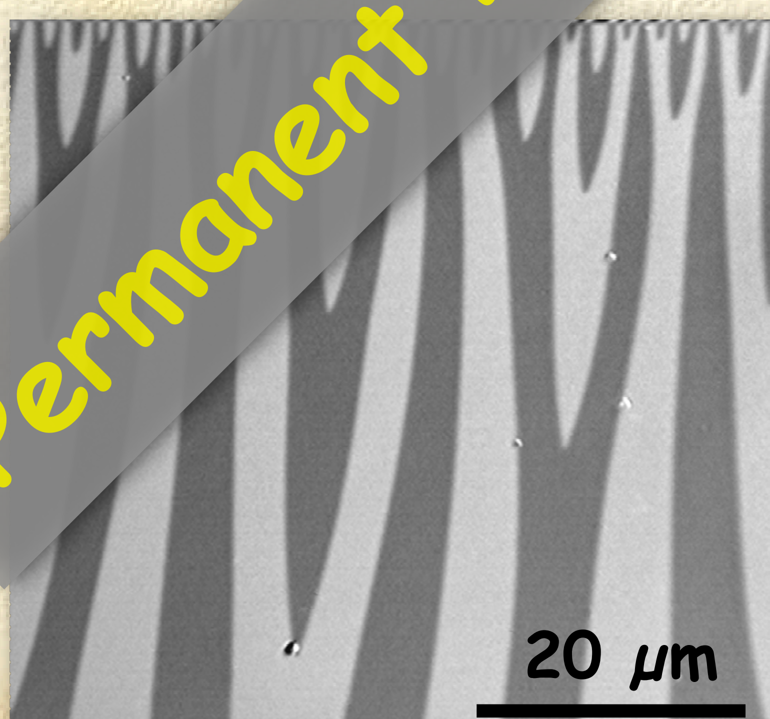


General Classification of Domains

$Q >> 1$



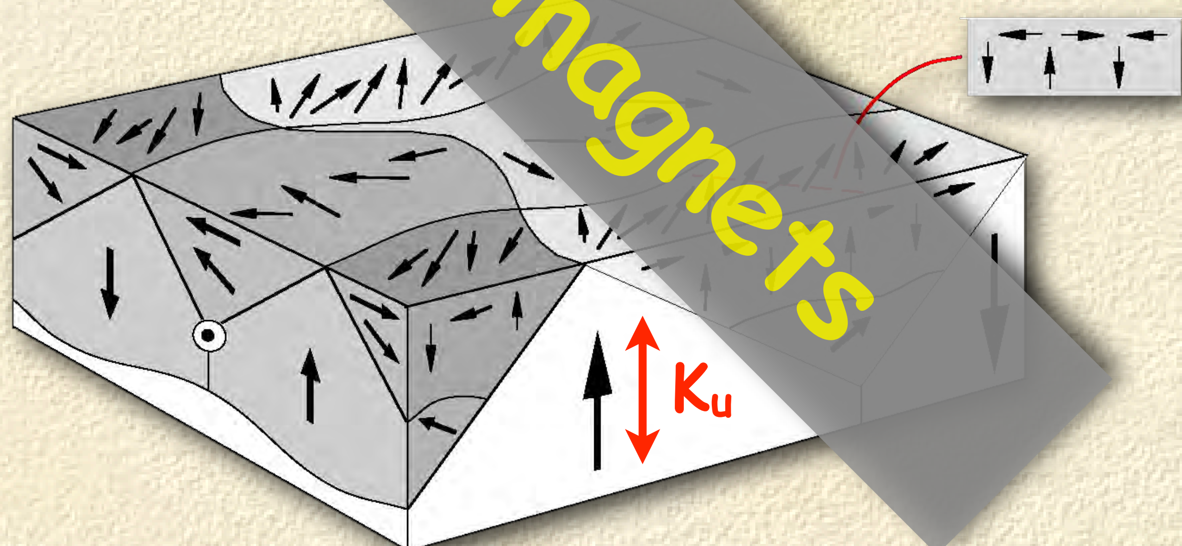
Anisotropy energy avoided,
Domains adapt to keep stray-field energy low



Permanent magnets

$Q << 1$

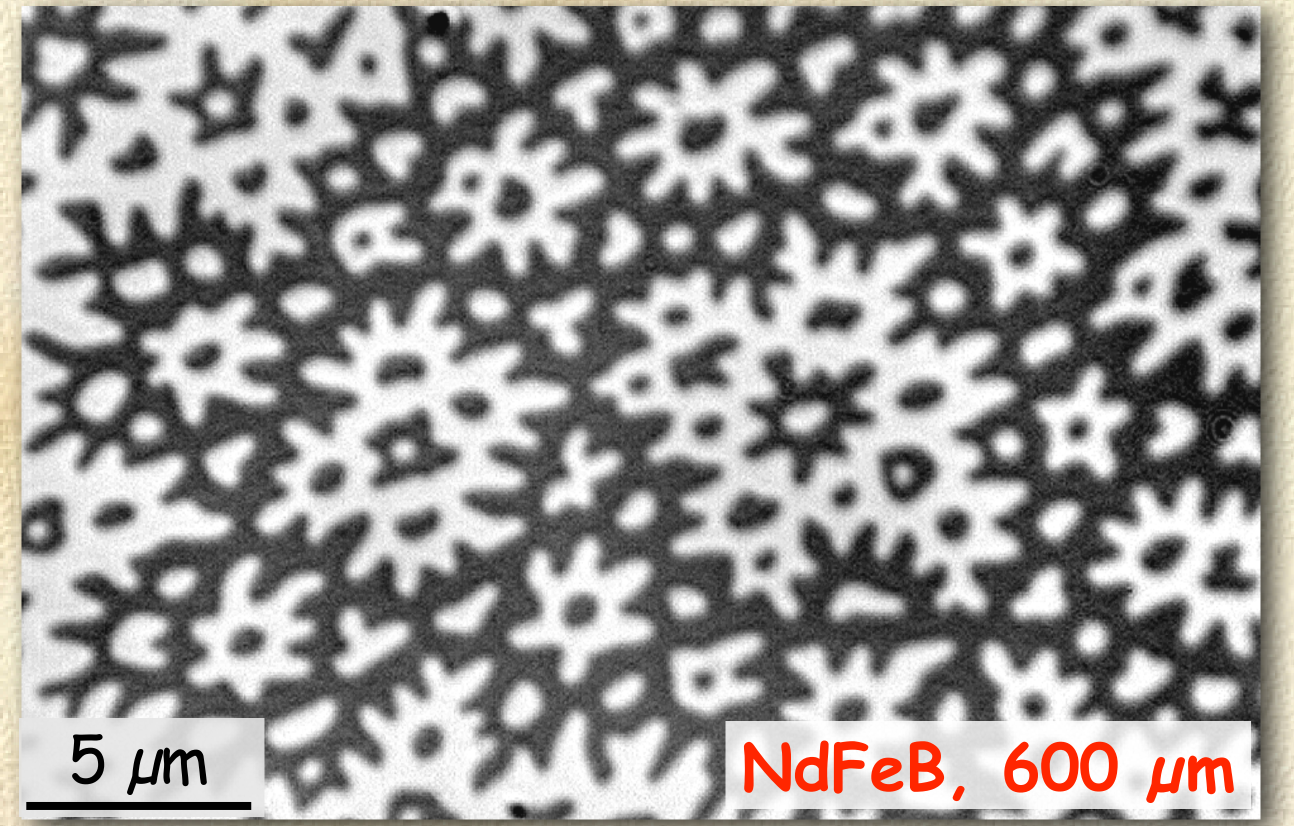
Stray field energy avoided,
Domains adapt to keep anisotropy energy low

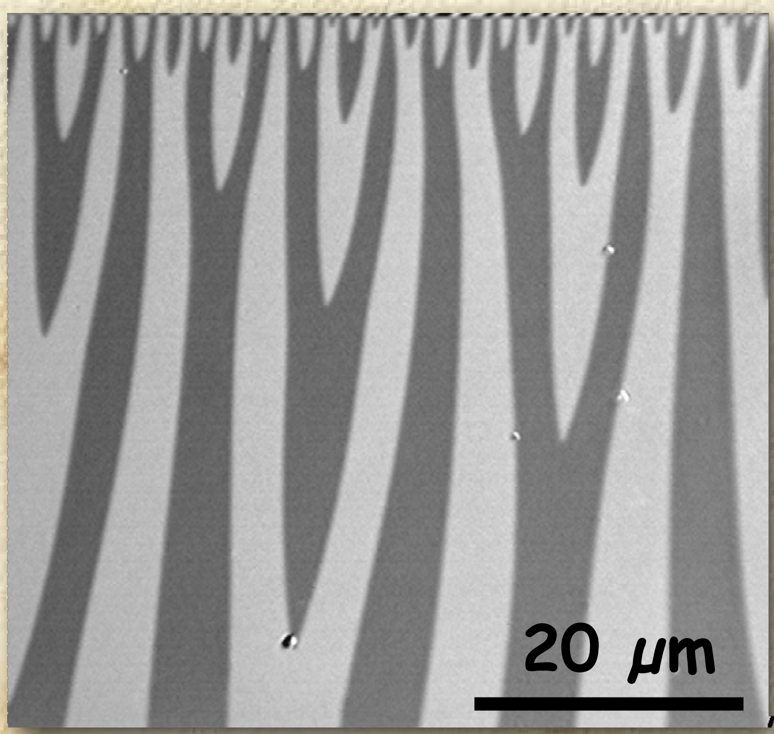


Soft magnets

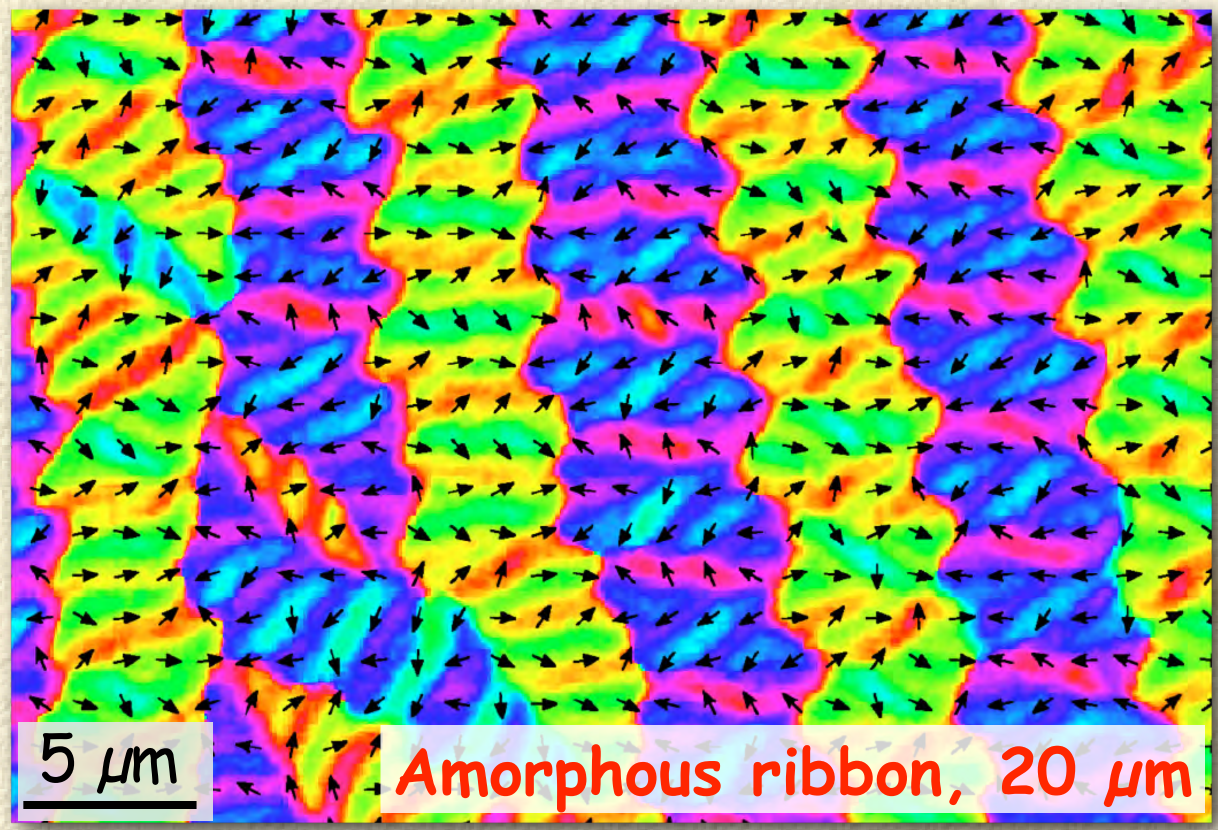
General Classification of Domains

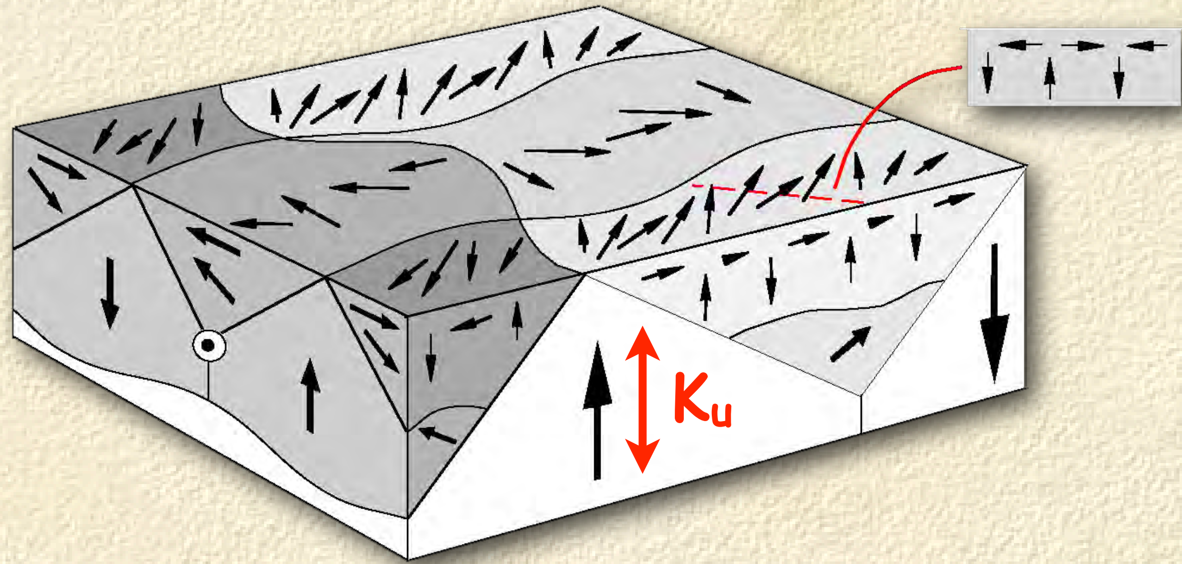
$Q >> 1$





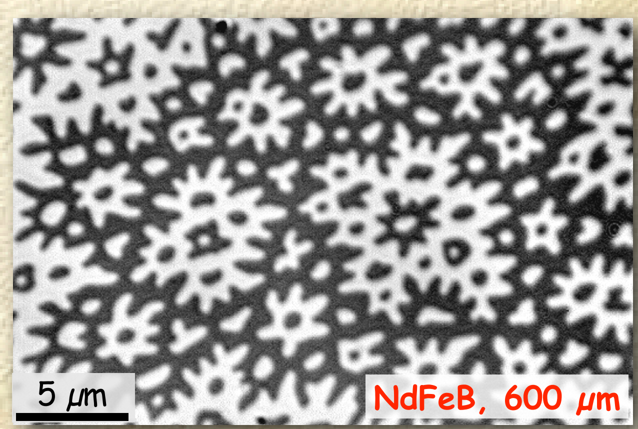
$Q << 1$

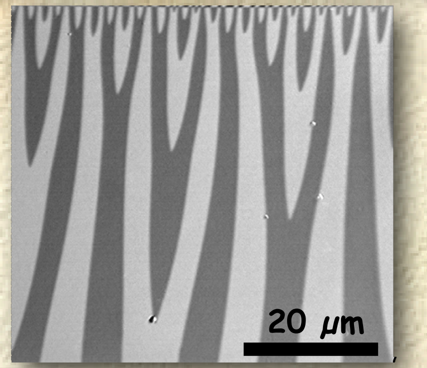




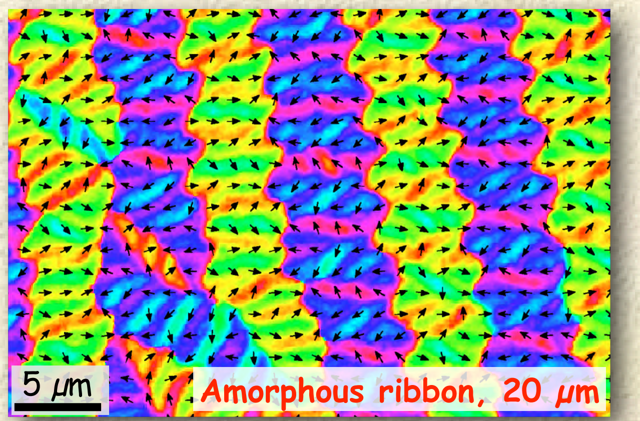
General Classification of Domains

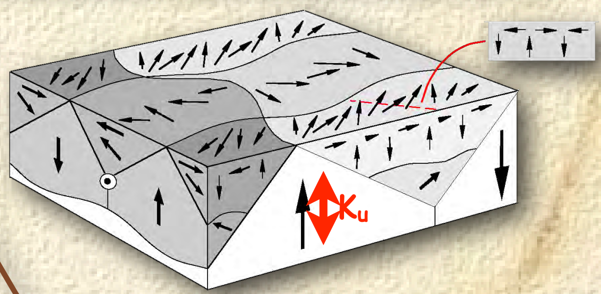
$Q >> 1$





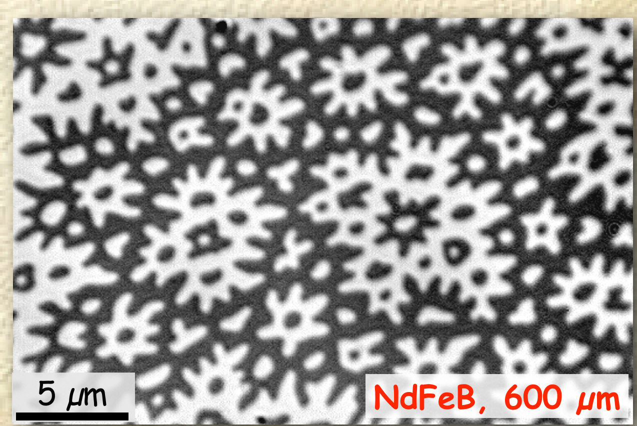
$Q << 1$

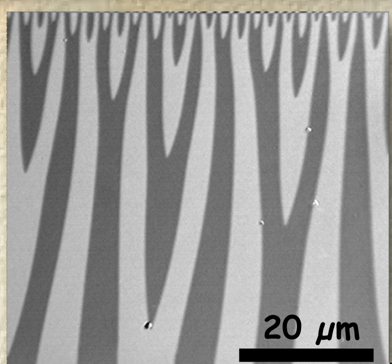




General Classification of Domains

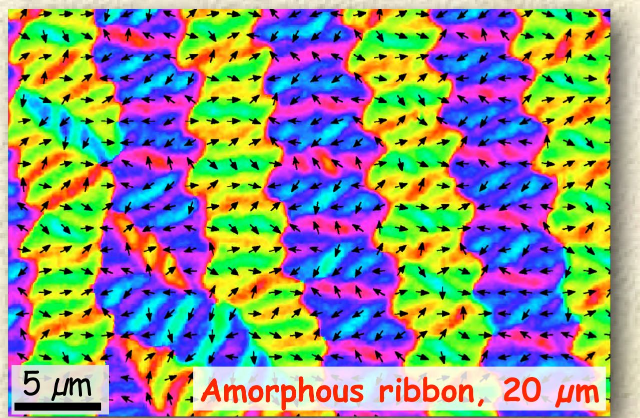
$Q >> 1$

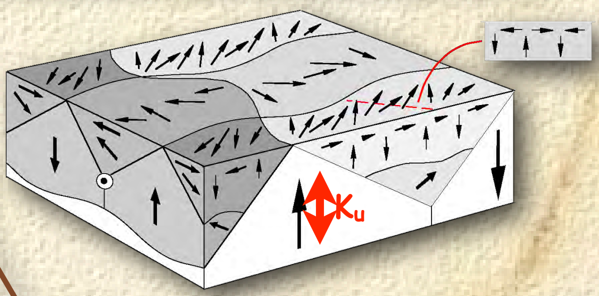




$Q \approx 1$

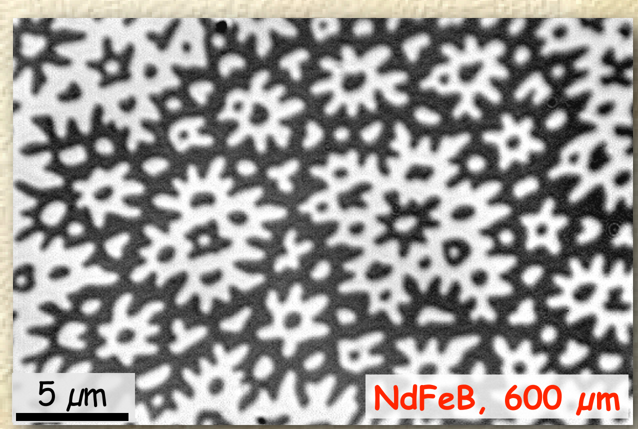
$Q << 1$

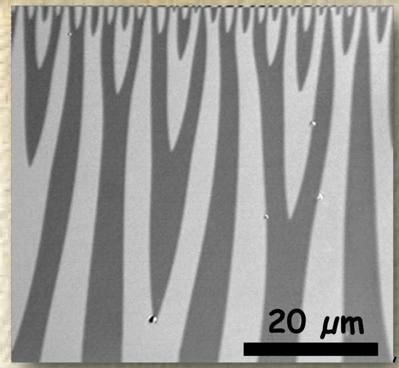




General Classification of Domains

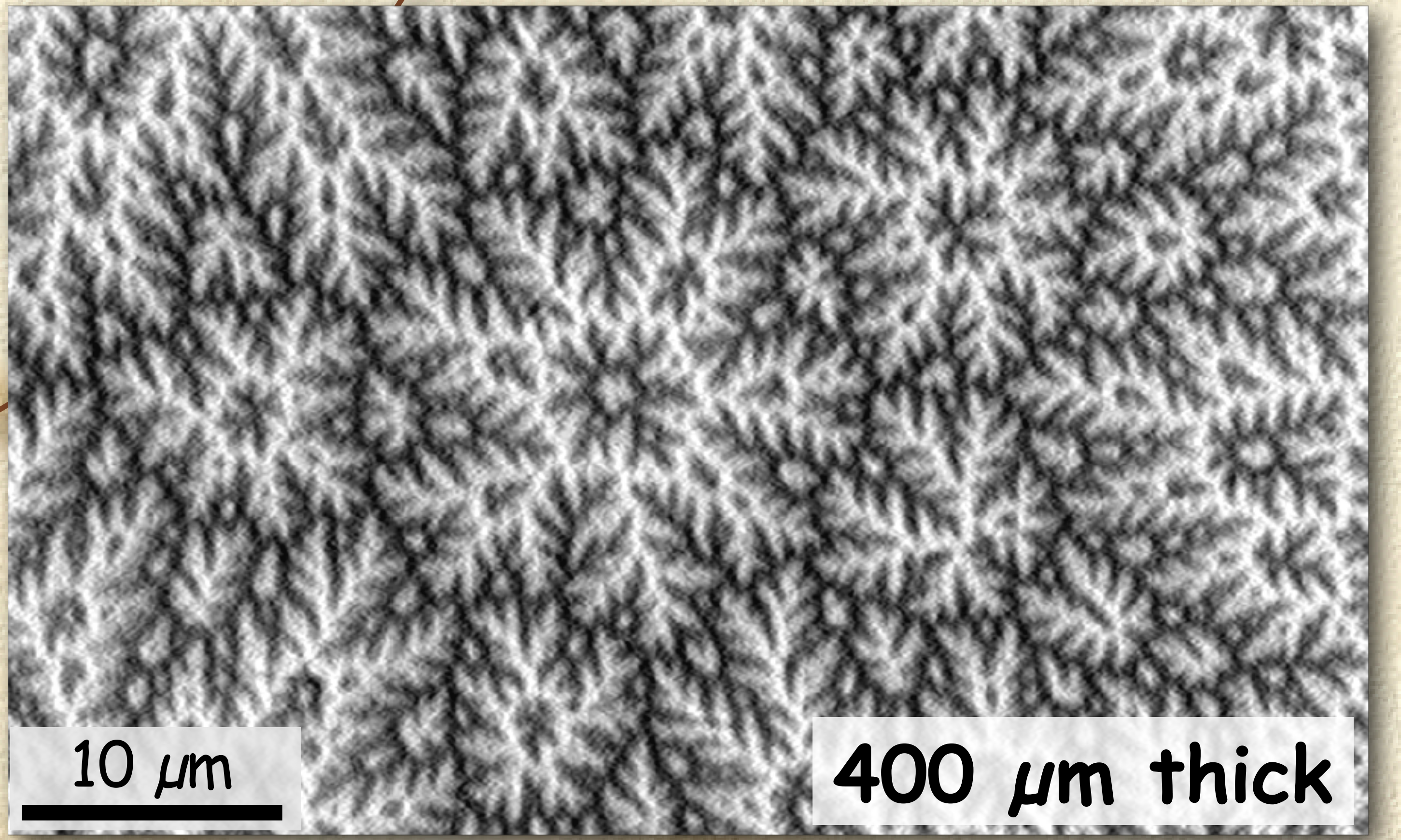
$Q >> 1$



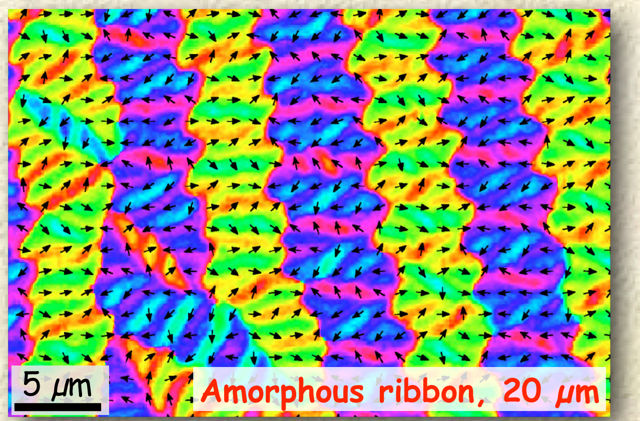


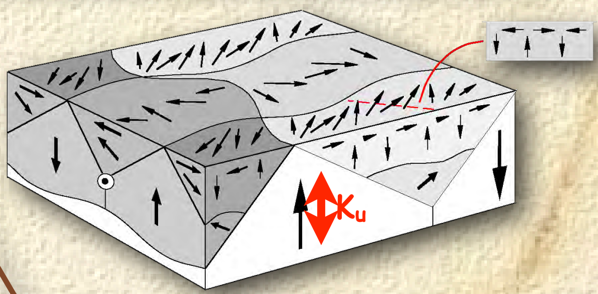
$Q \approx 1$

Cobalt: Q = 0.4



$Q << 1$



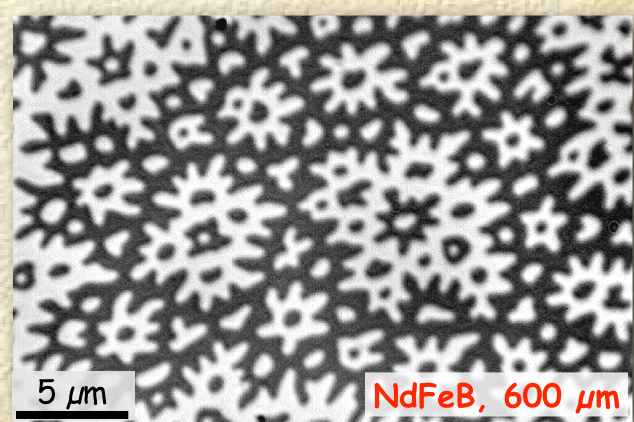


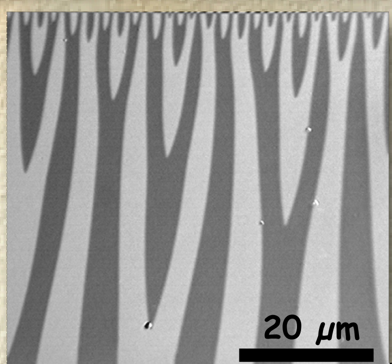
General Classification of Domains

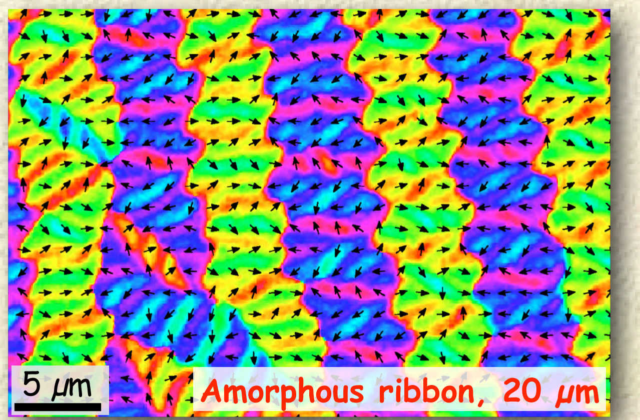
$Q >> 1$

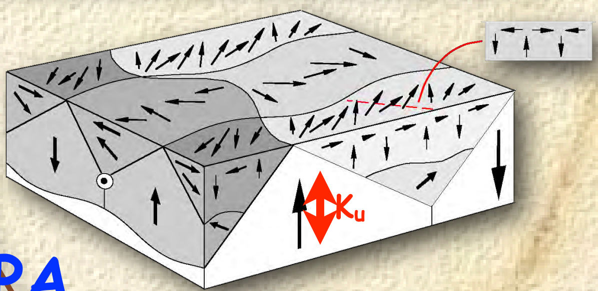
$Q \approx 1$

$Q << 1$

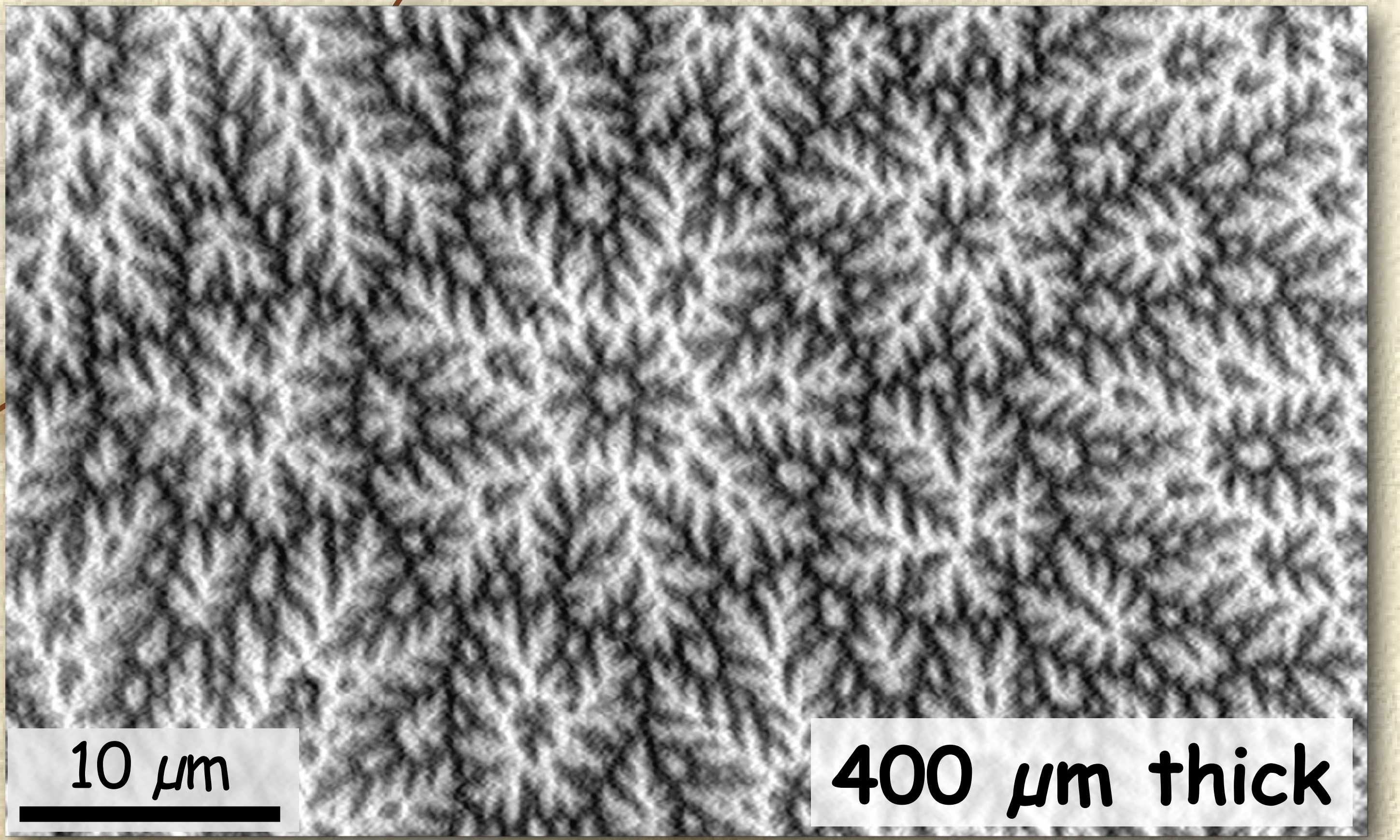




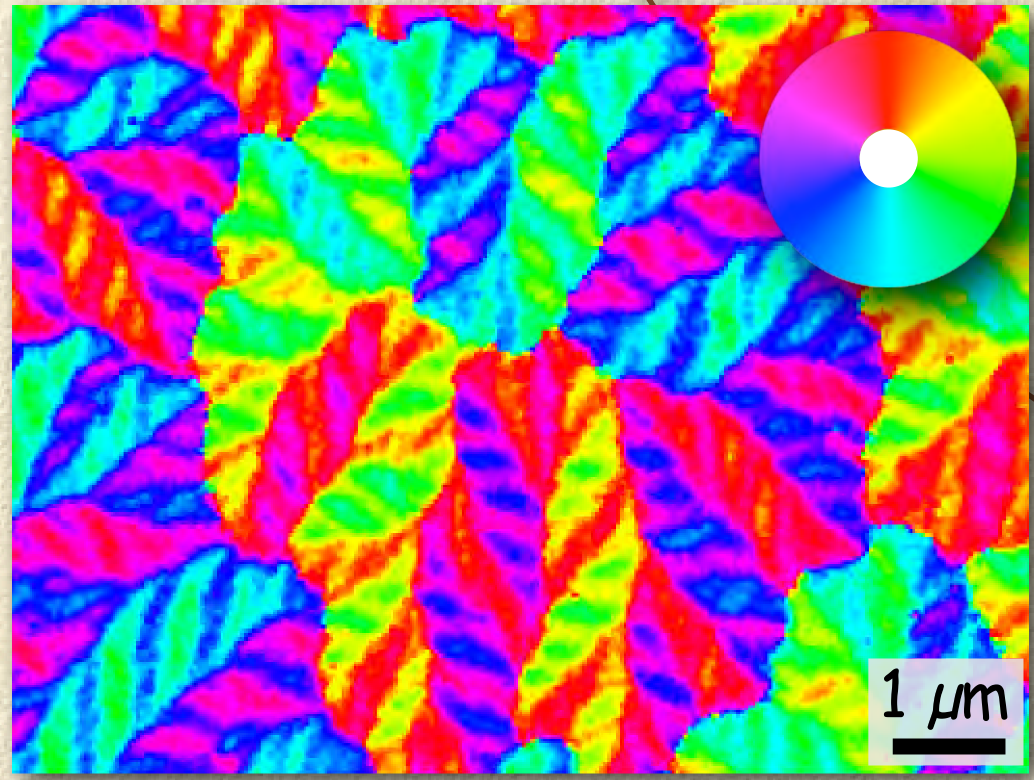




Cobalt: Q = 0.4



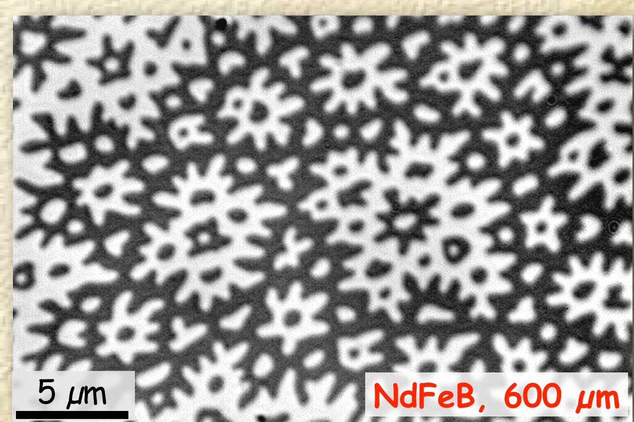
SEMPA
(courtesy John Unguris, NIST)

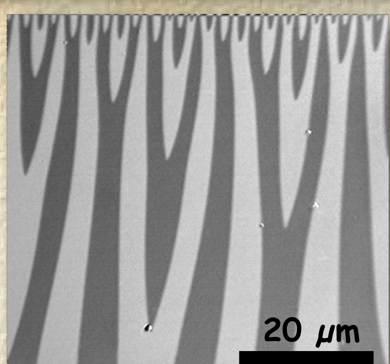


In-plane contrast at surface

General Classification of Domains

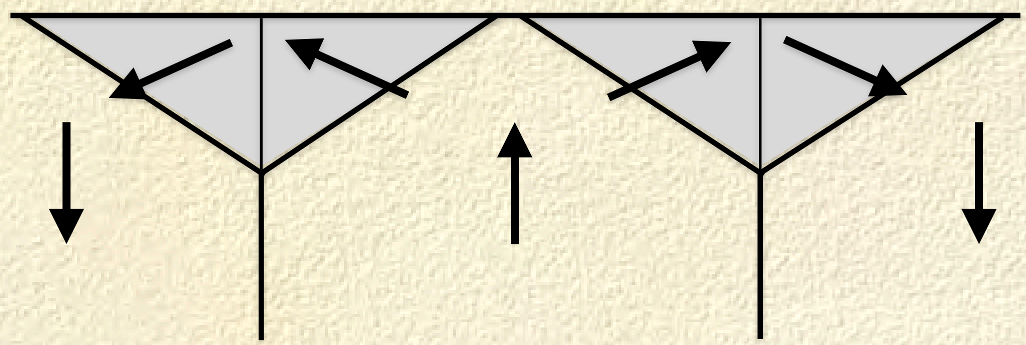
$Q >> 1$



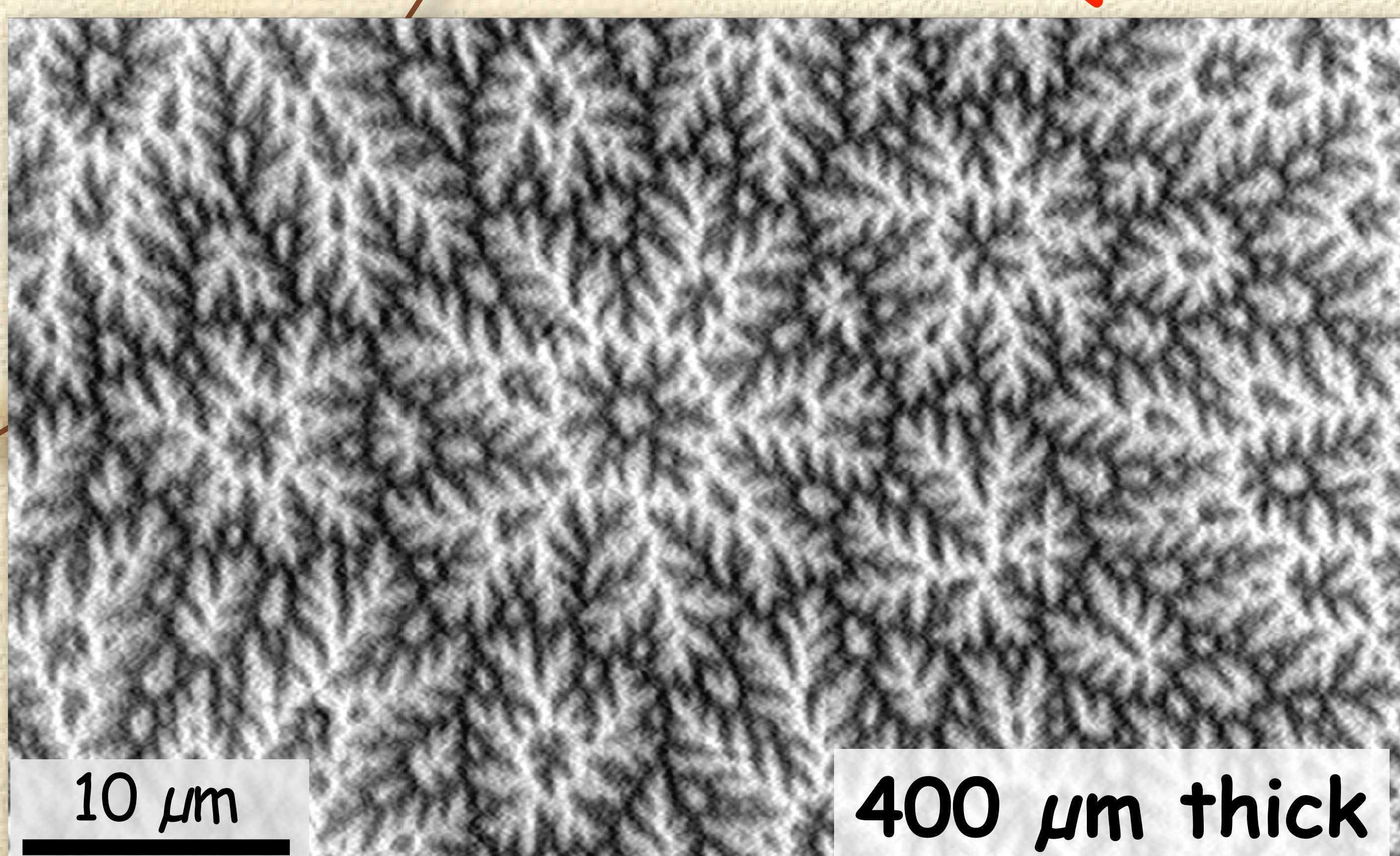


$Q \approx 1$

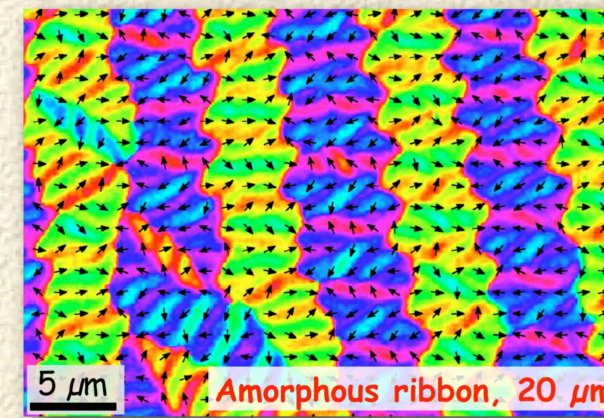
Partial closure

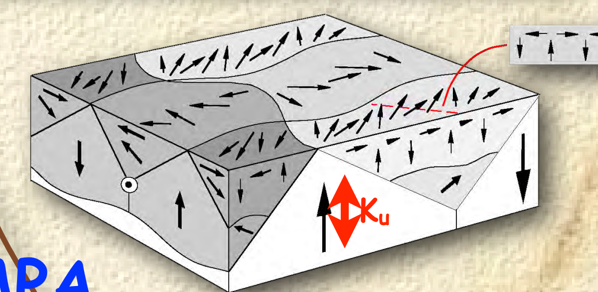


Cobalt: Q = 0.4

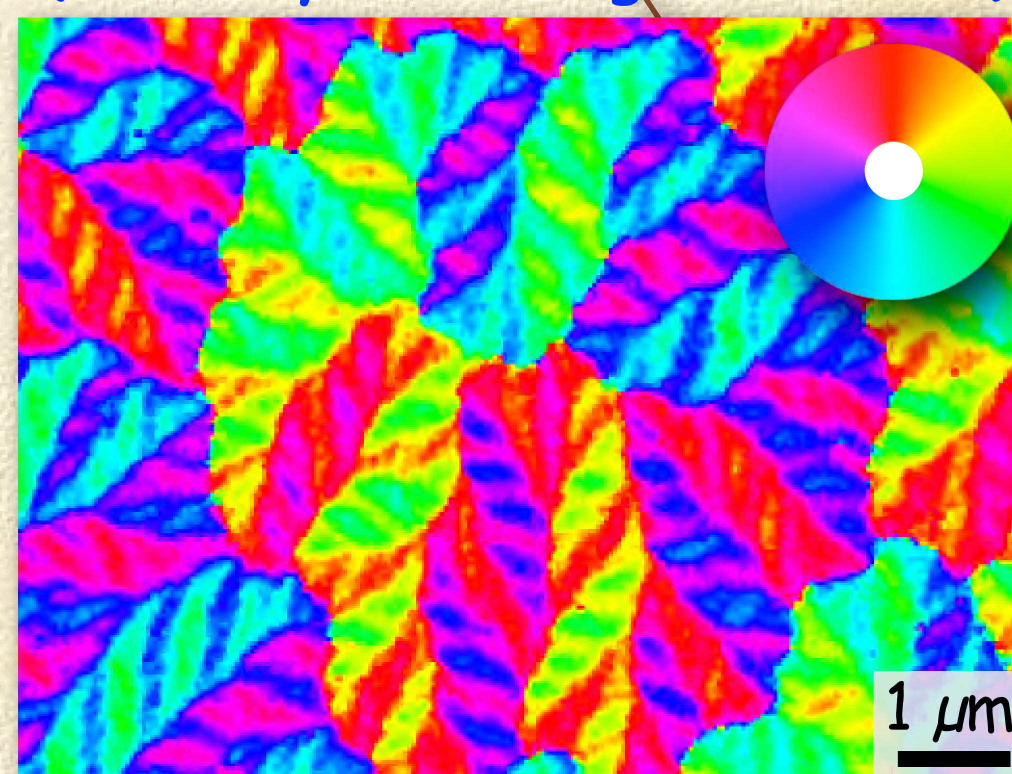


$Q << 1$





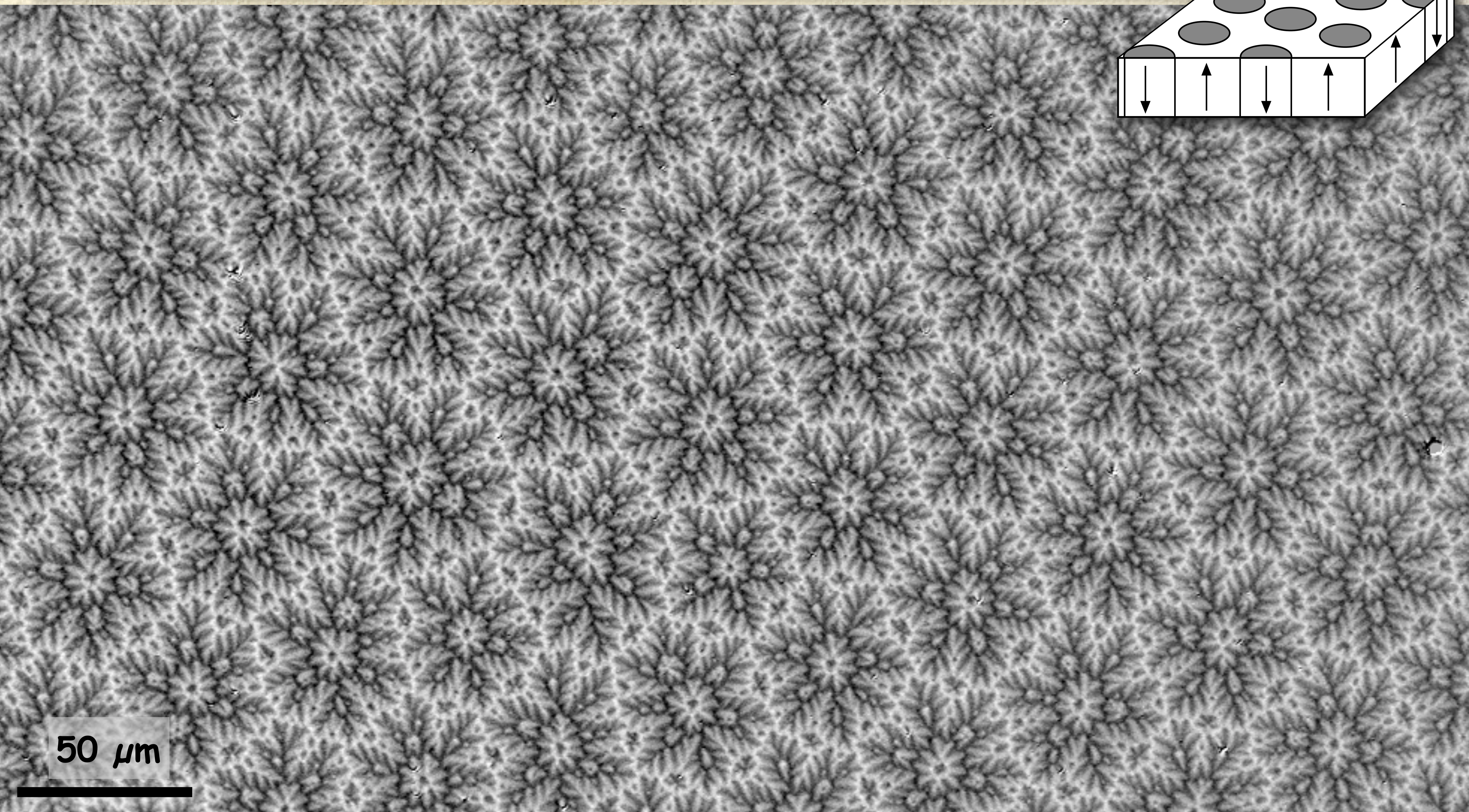
SEMPA
(courtesy John Unguris, NIST)



In-plane contrast at surface

Bulk garnet crystal

Bubble domains



GdYbBi garnet, 500 μm thick

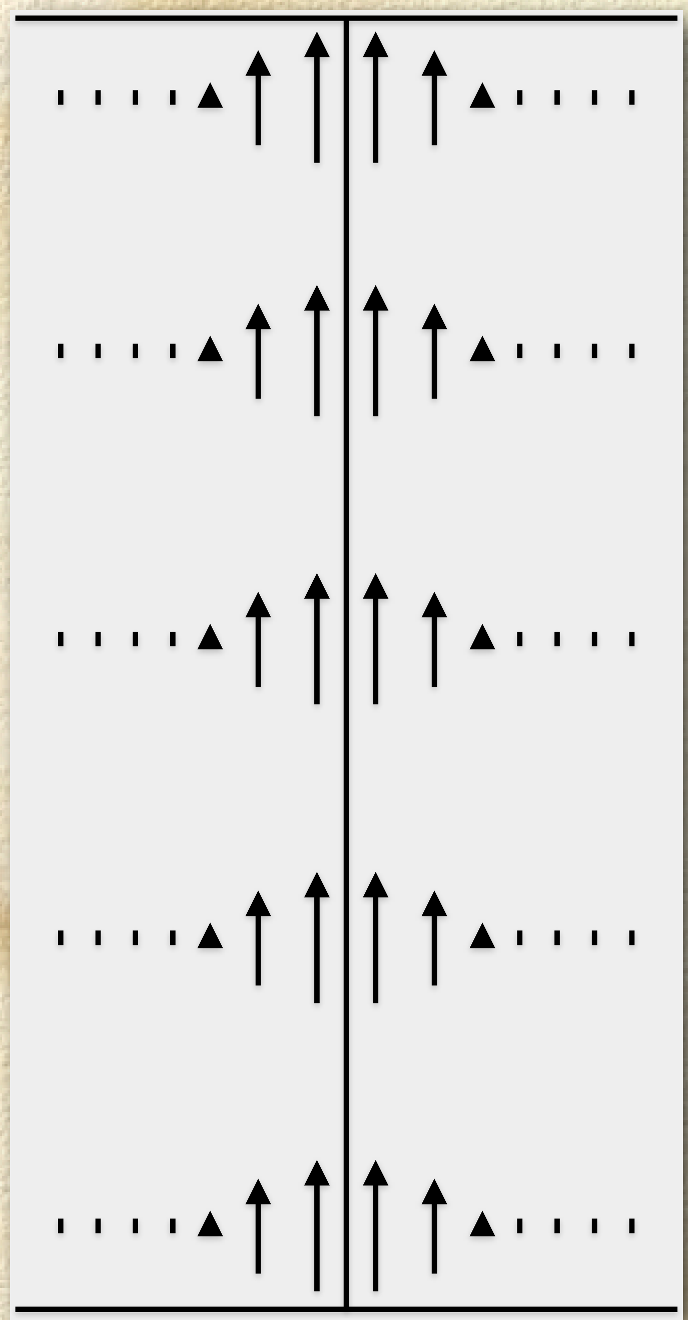
Image: A. Stupaviewicz, M. Tekielak, A. Maziewski (Bialystok)

Sample: T. Satoh (Tokyo)

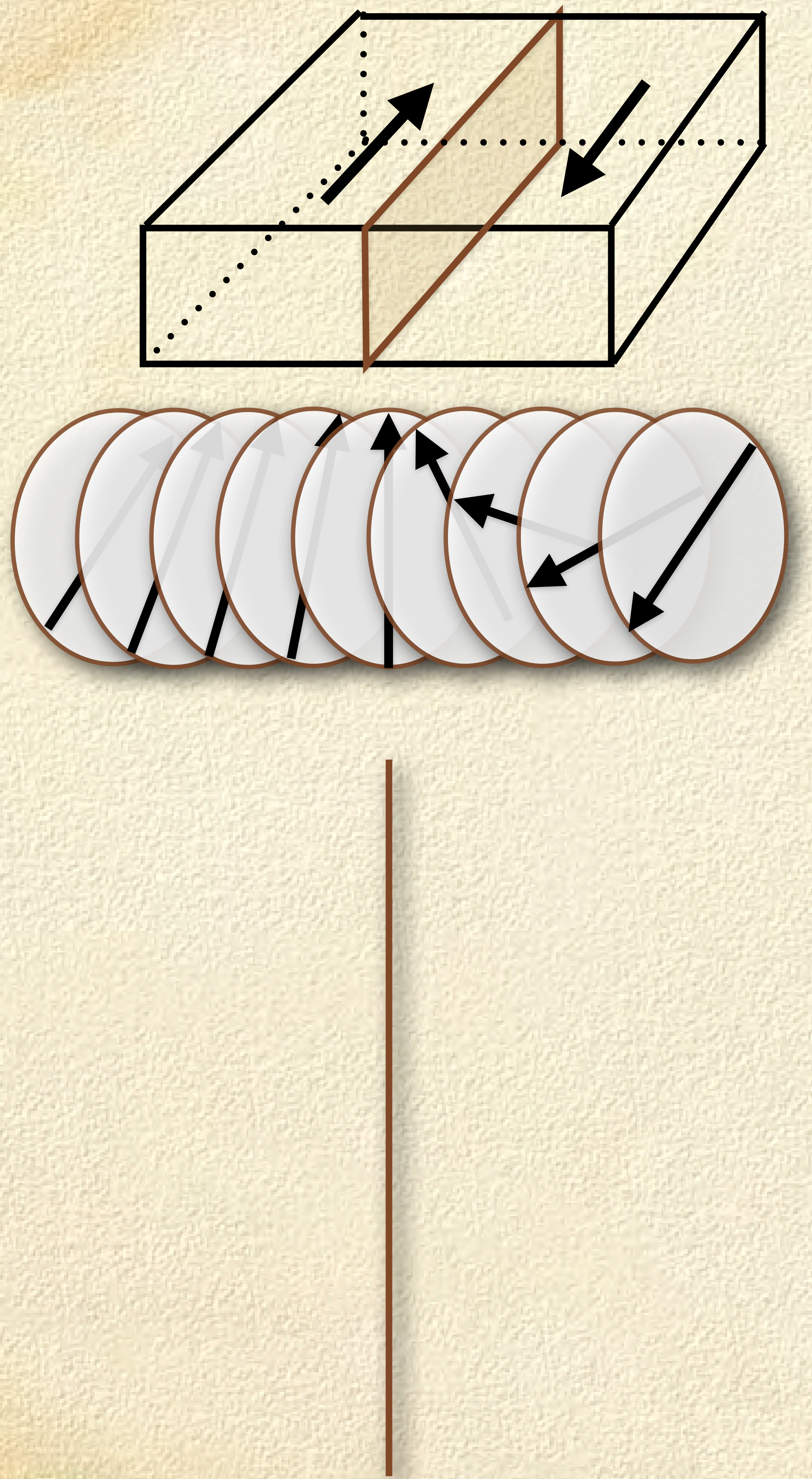
General Classification of Domains

$Q >> 1$

N

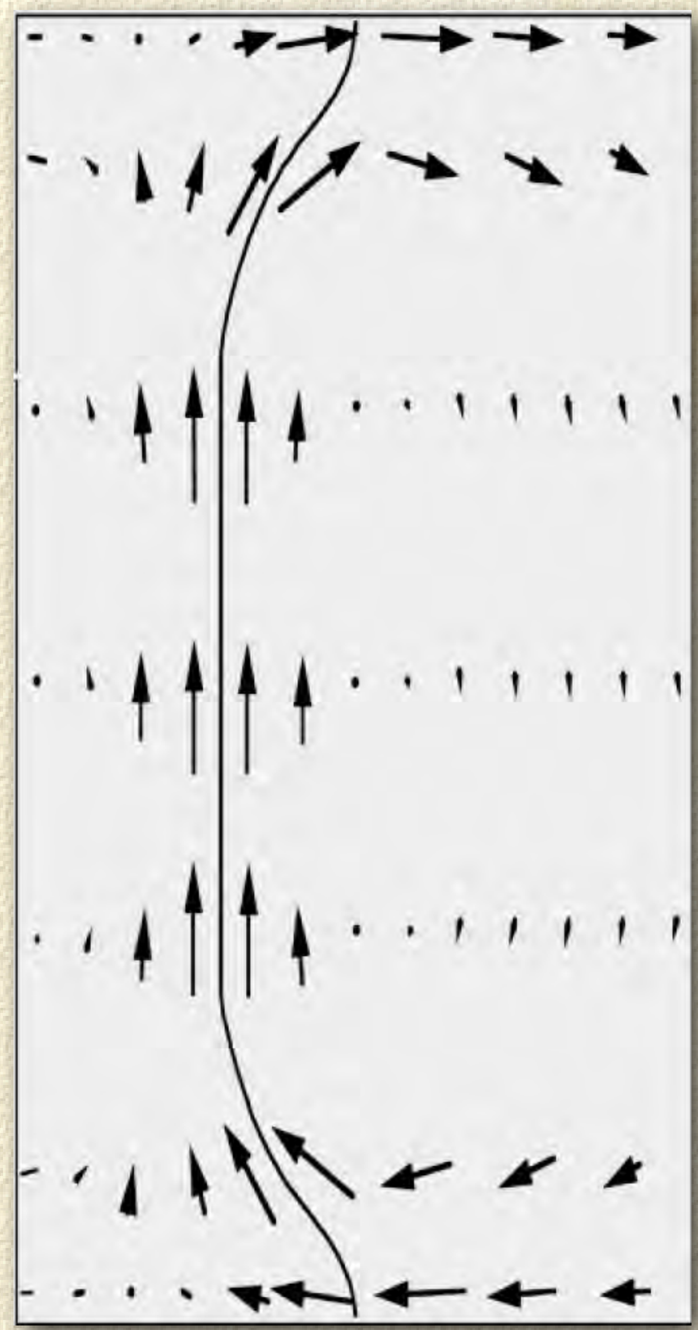


S



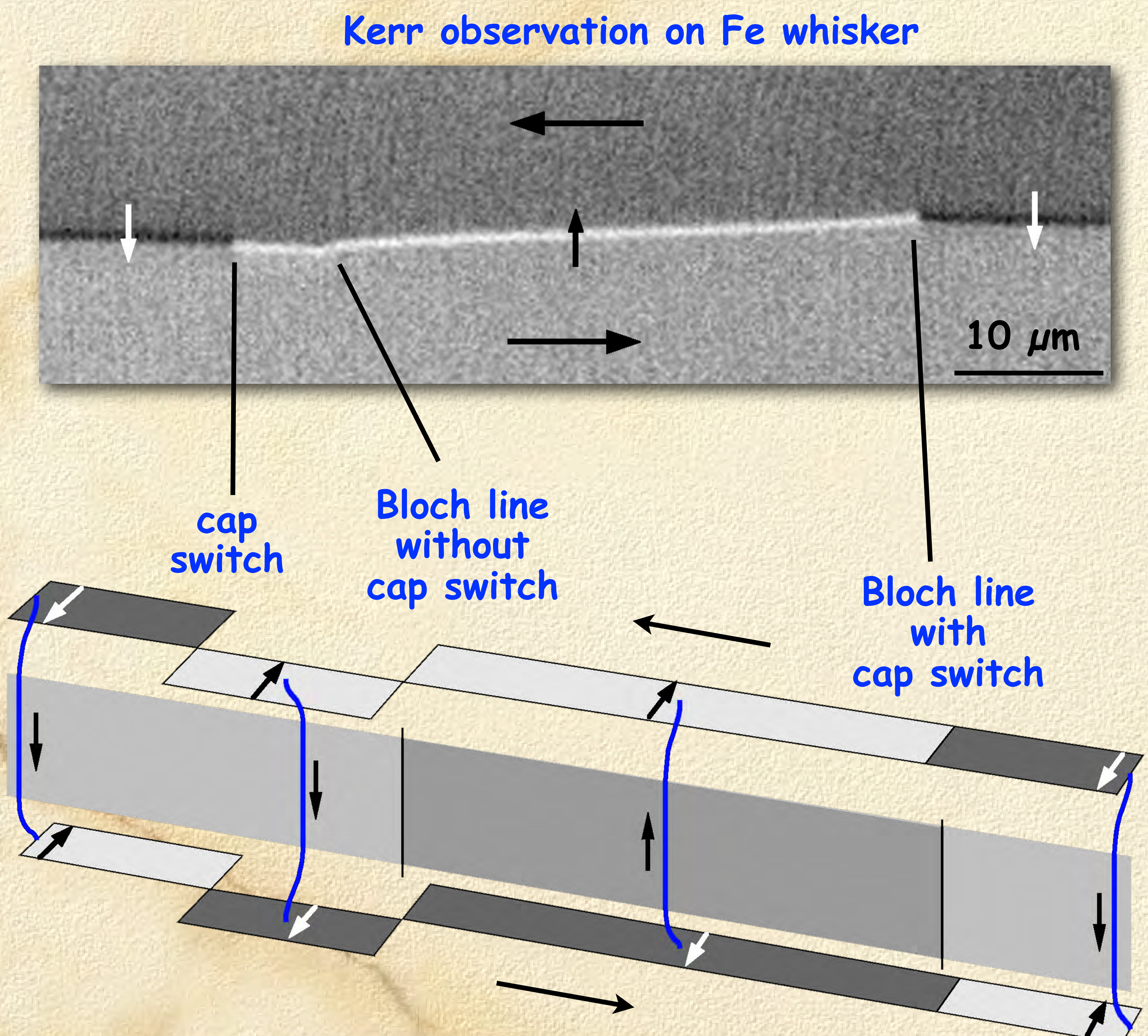
$Q << 1$

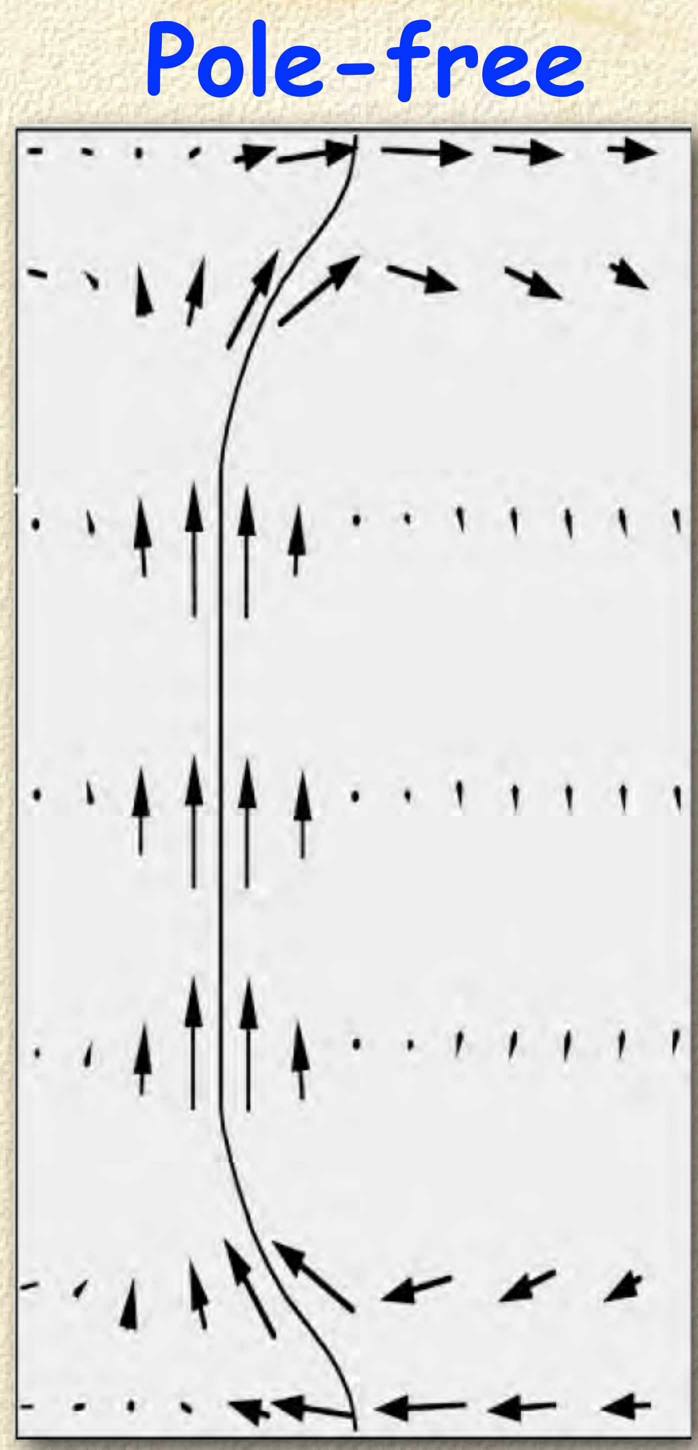
Pole-free



General Classification of Domains

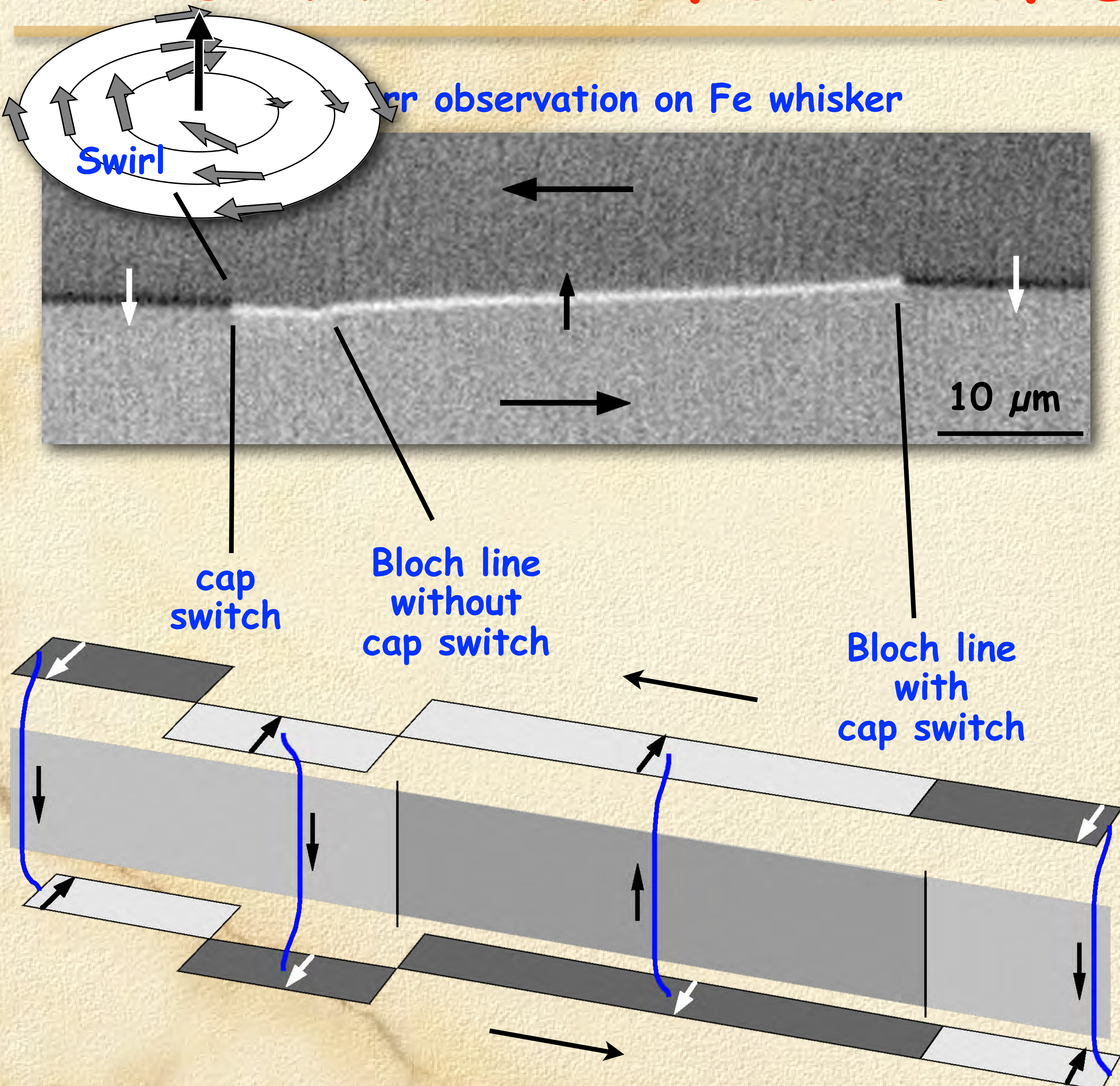
$Q << 1$



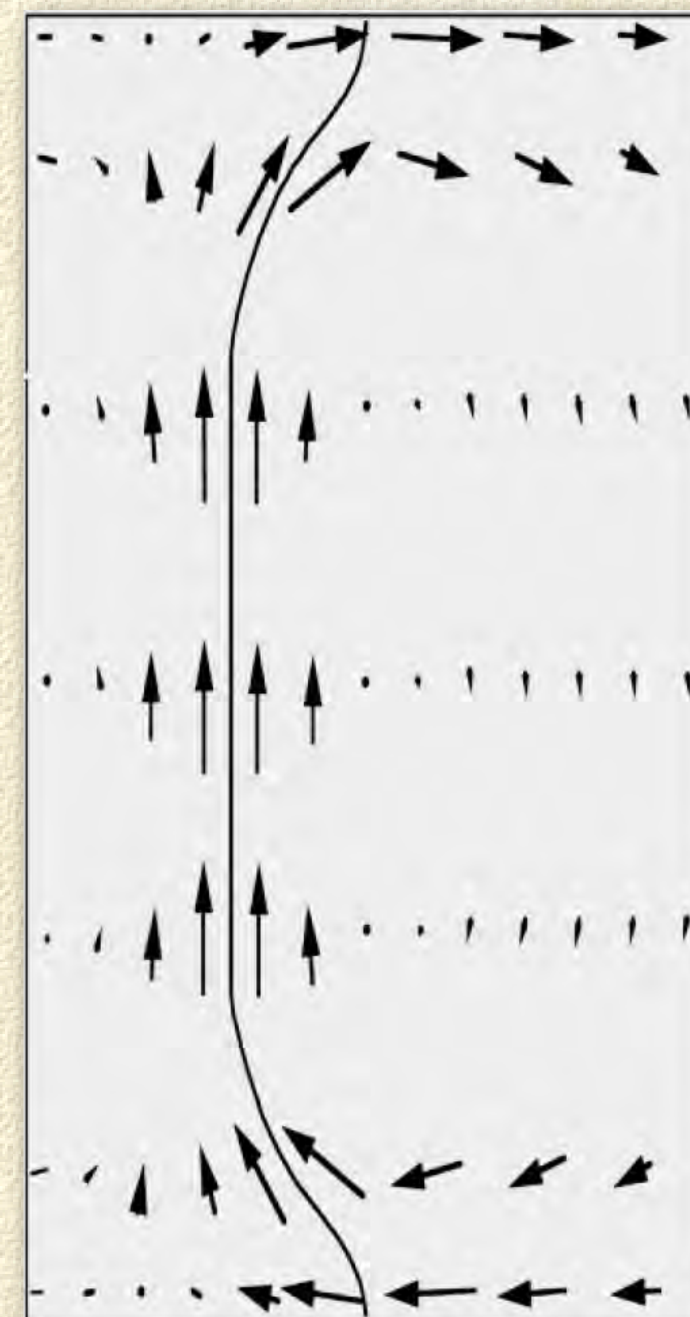


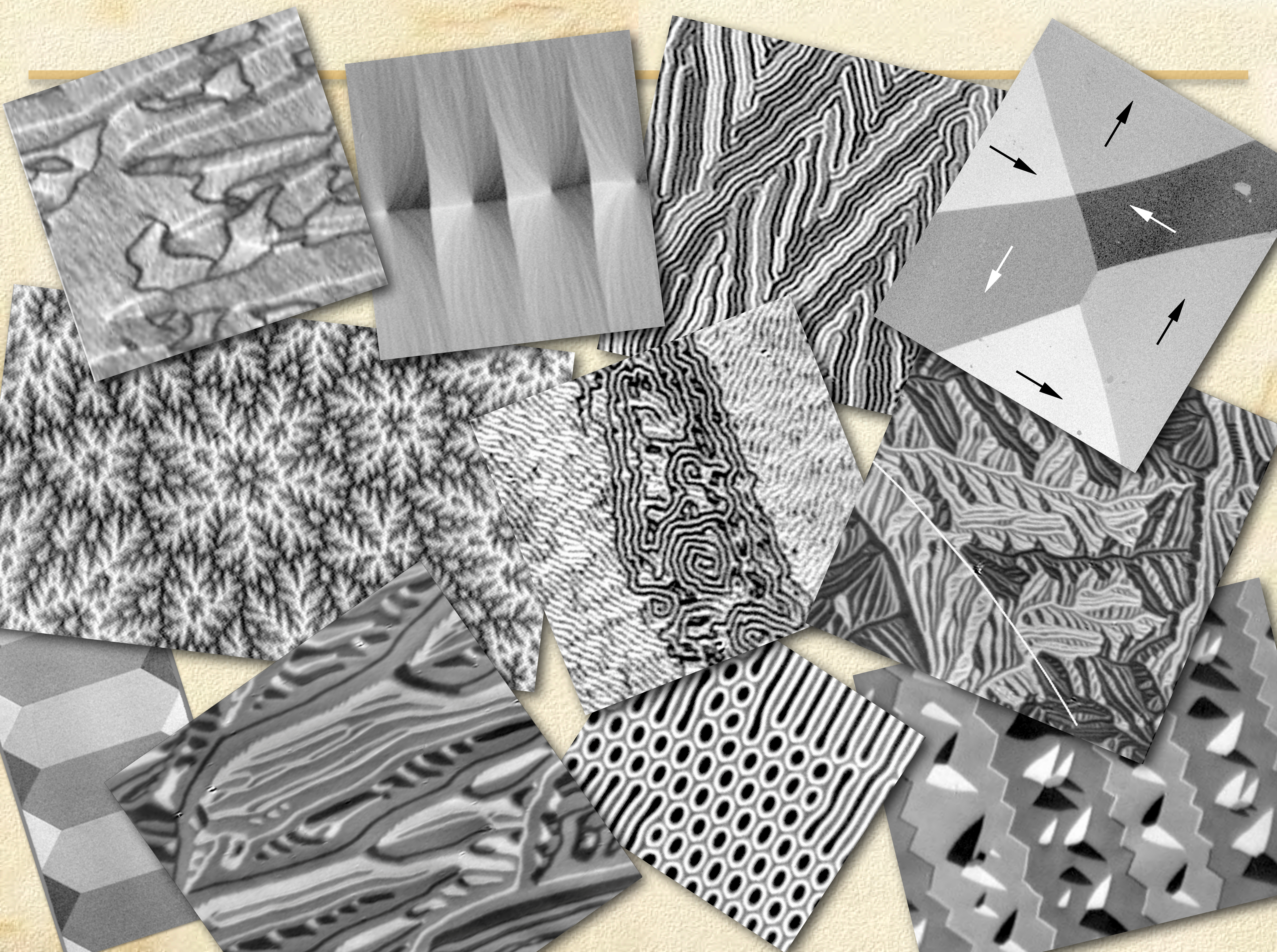
General Classification of Domains

$Q << 1$



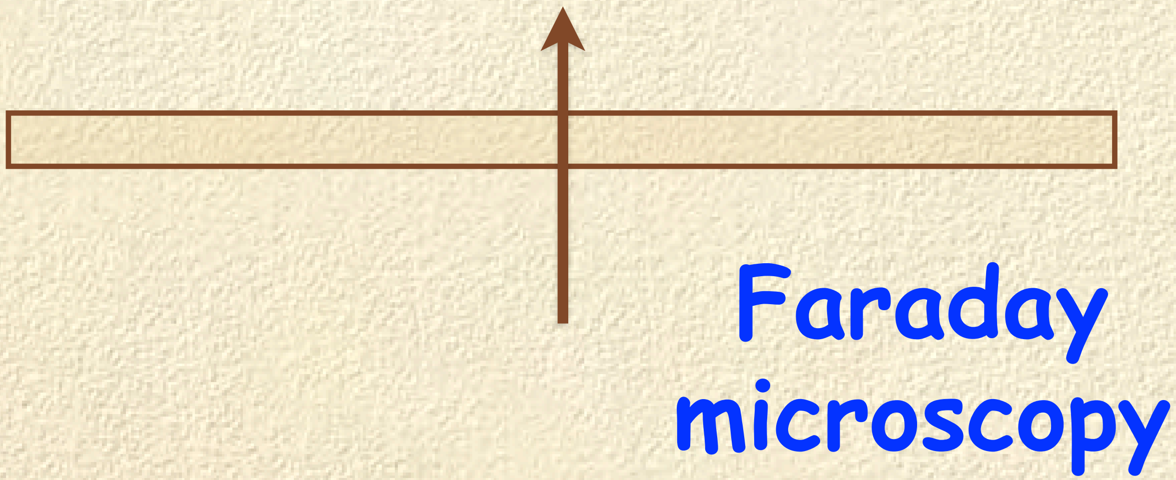
Pole-free



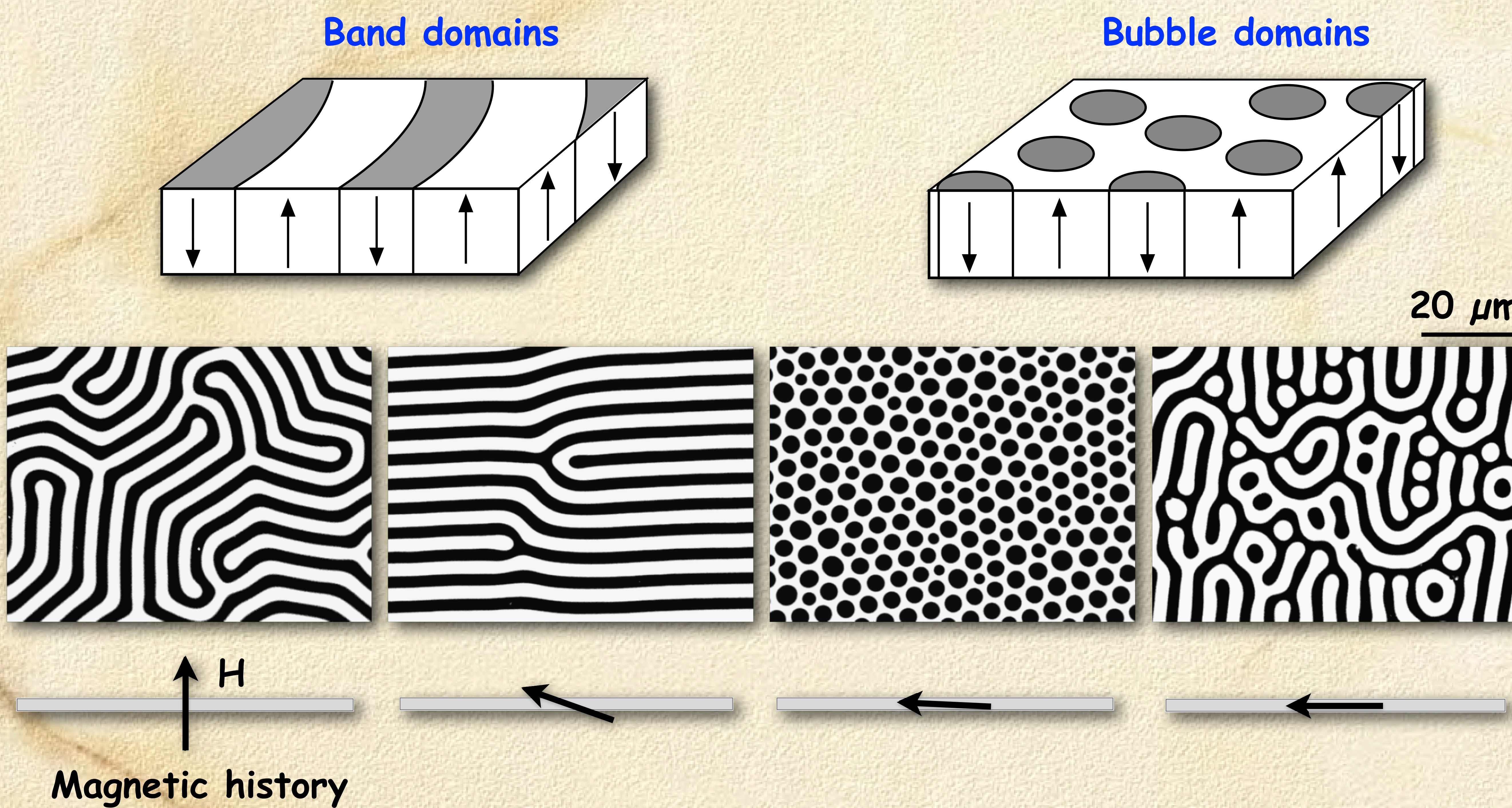


Domain analysis based on magneto-optical microscopy

Transparent films:
Domain analysis easily possible

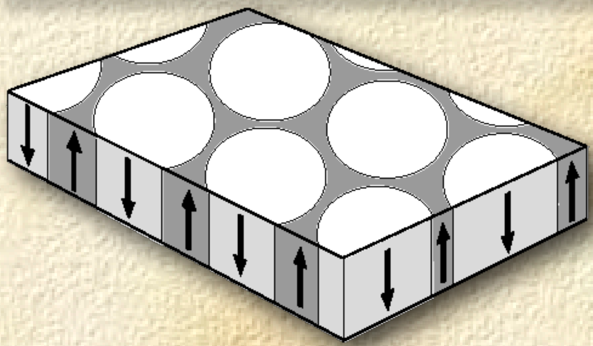


Bubble garnet film

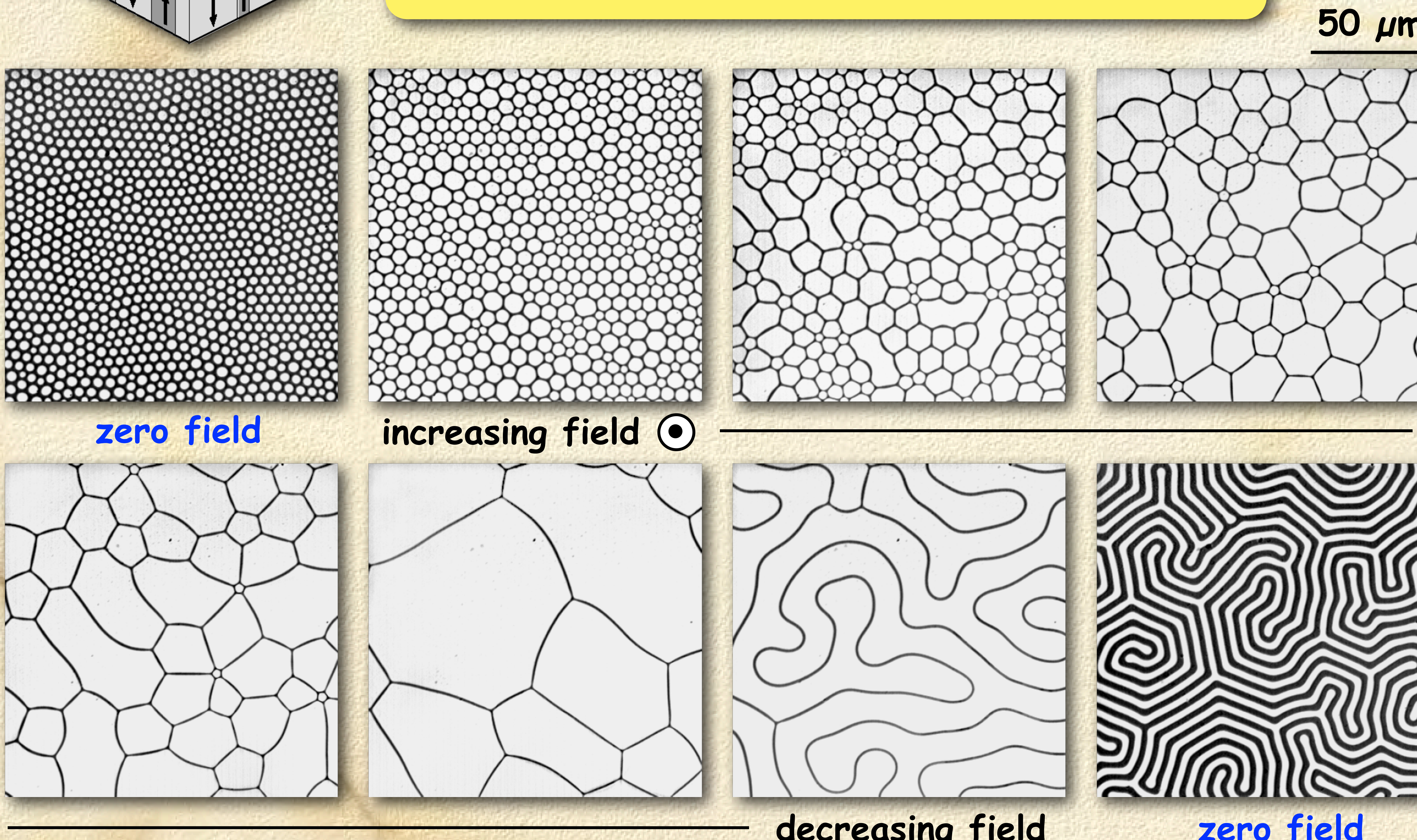


Magnetic field history matters

Bubble garnet film



Configurational hysteresis



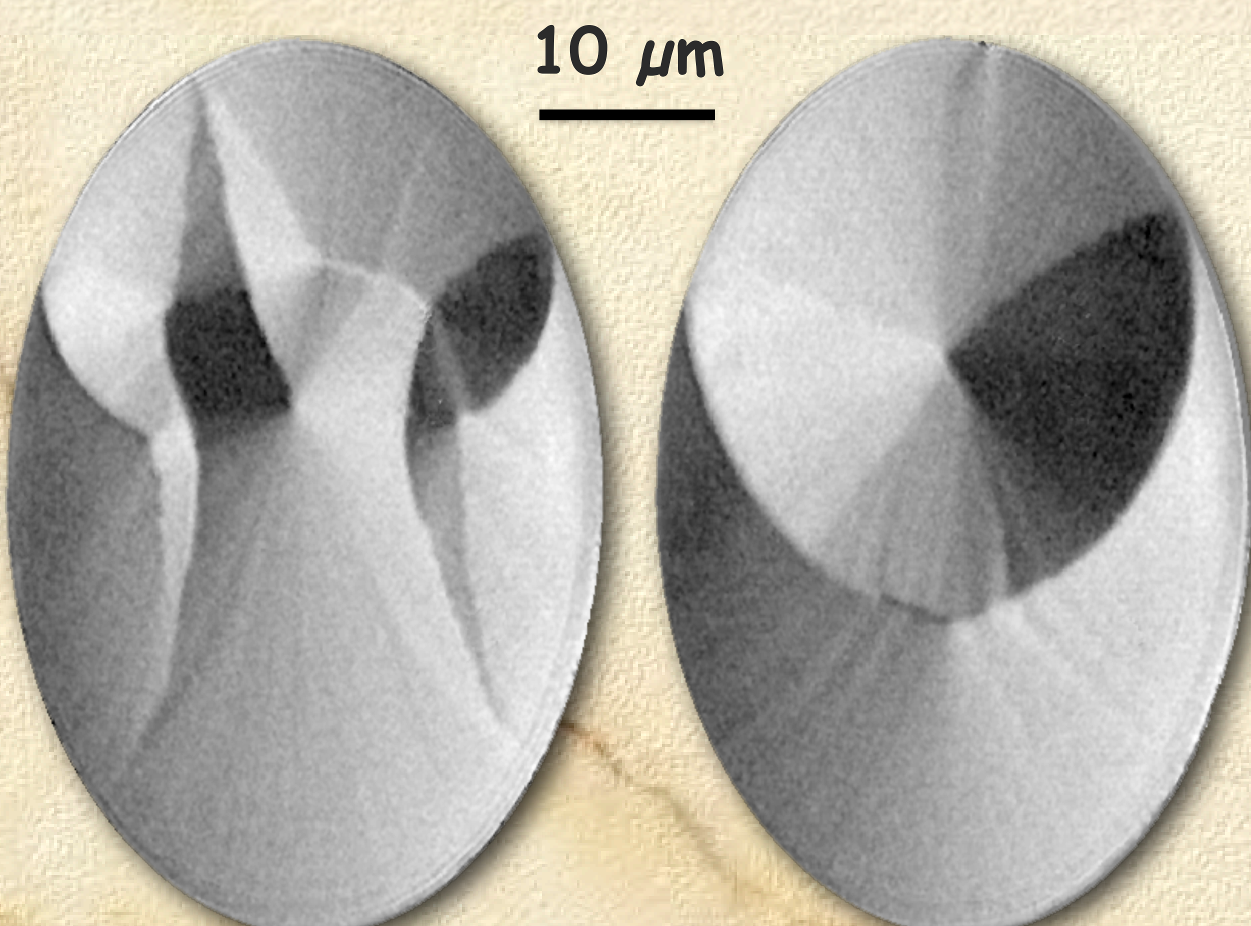
Metallic (single) films:

Domain analysis often easily possible …

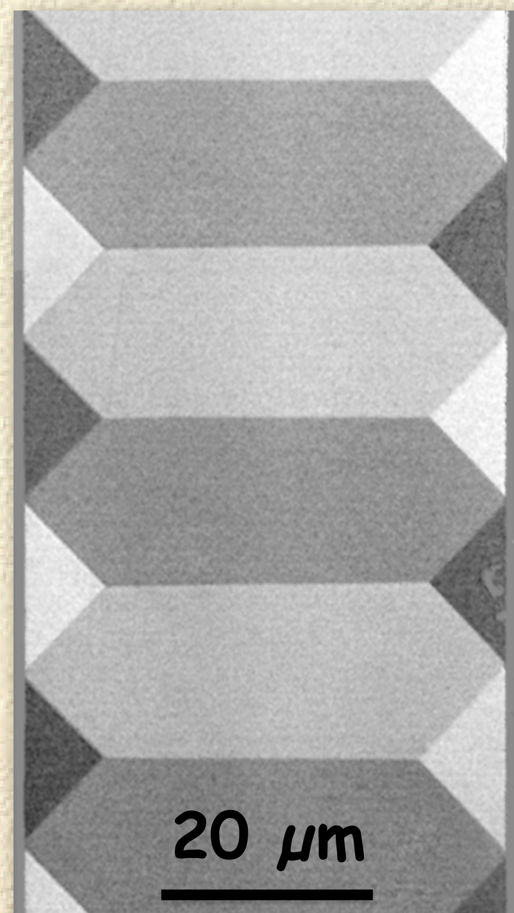
Metallic (single) films:

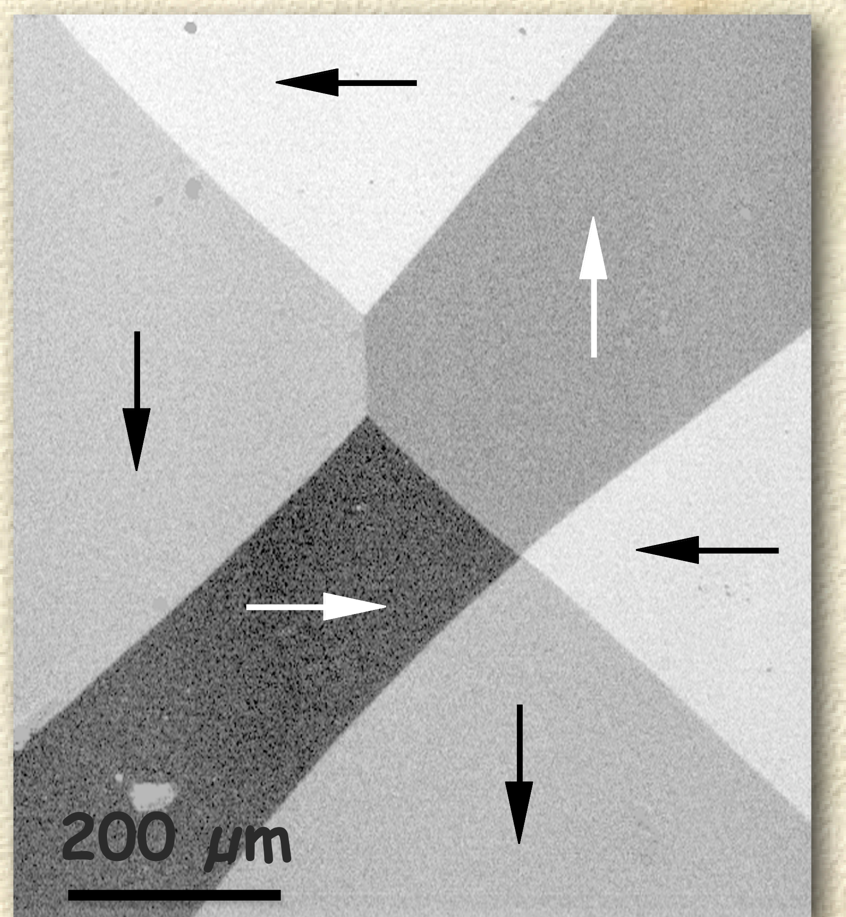
Domain analysis often easily possible …

Permalloy film, 240 nm thick



Epitaxial (100)-iron film, 40 nm thick



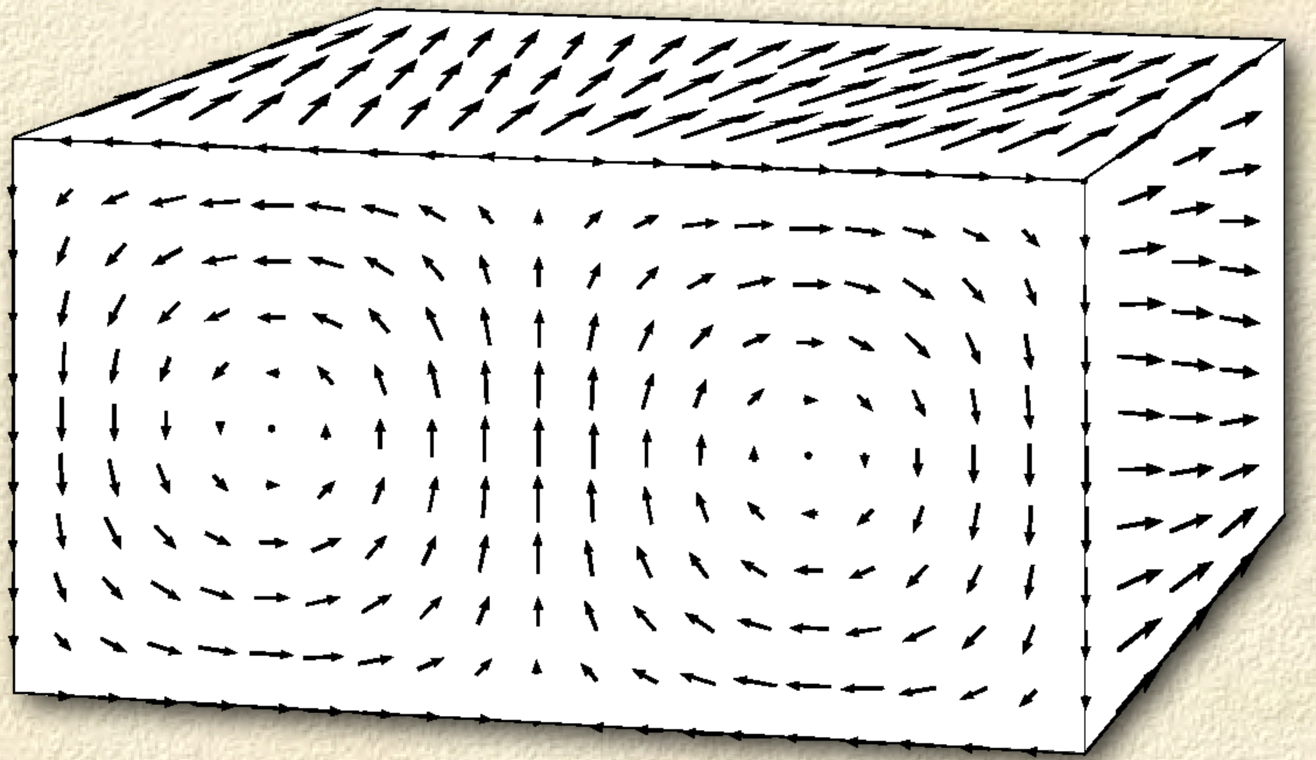


Metallic (single) films:

… sometimes combination with some micromagnetic theory may be required

Amorphous FeSiBCuNb film, 2 μm thick

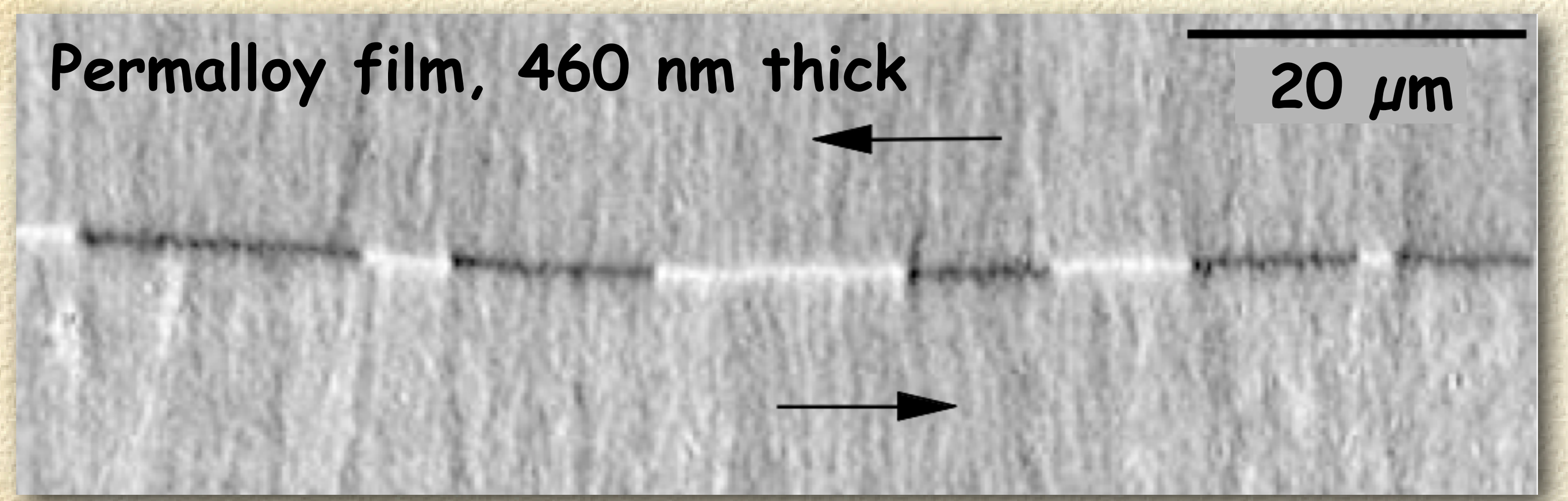
Stripe domains

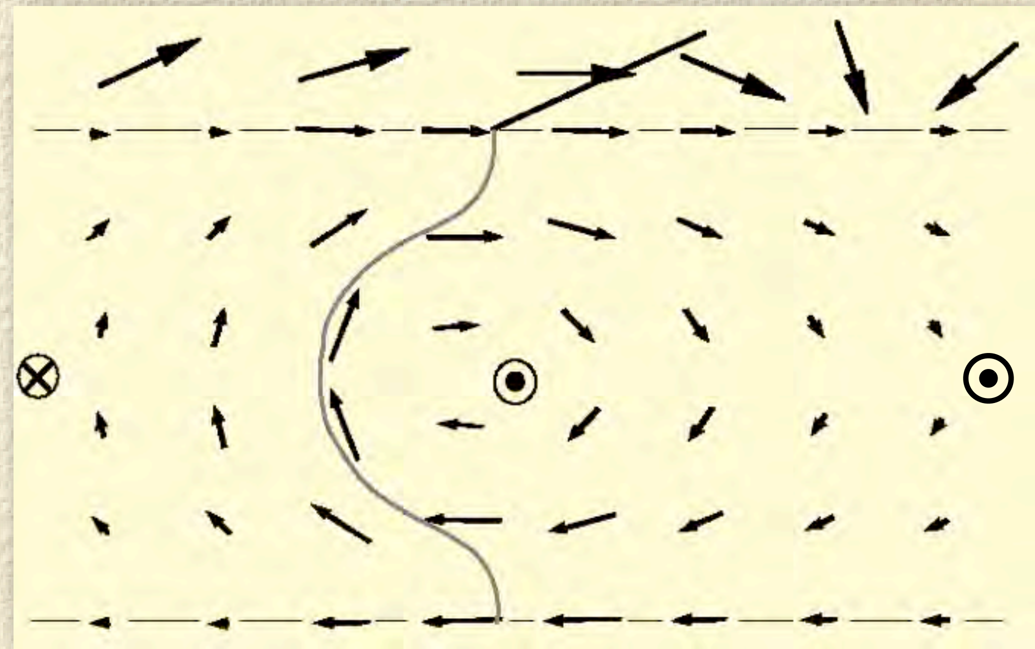


Metallic (single) films:

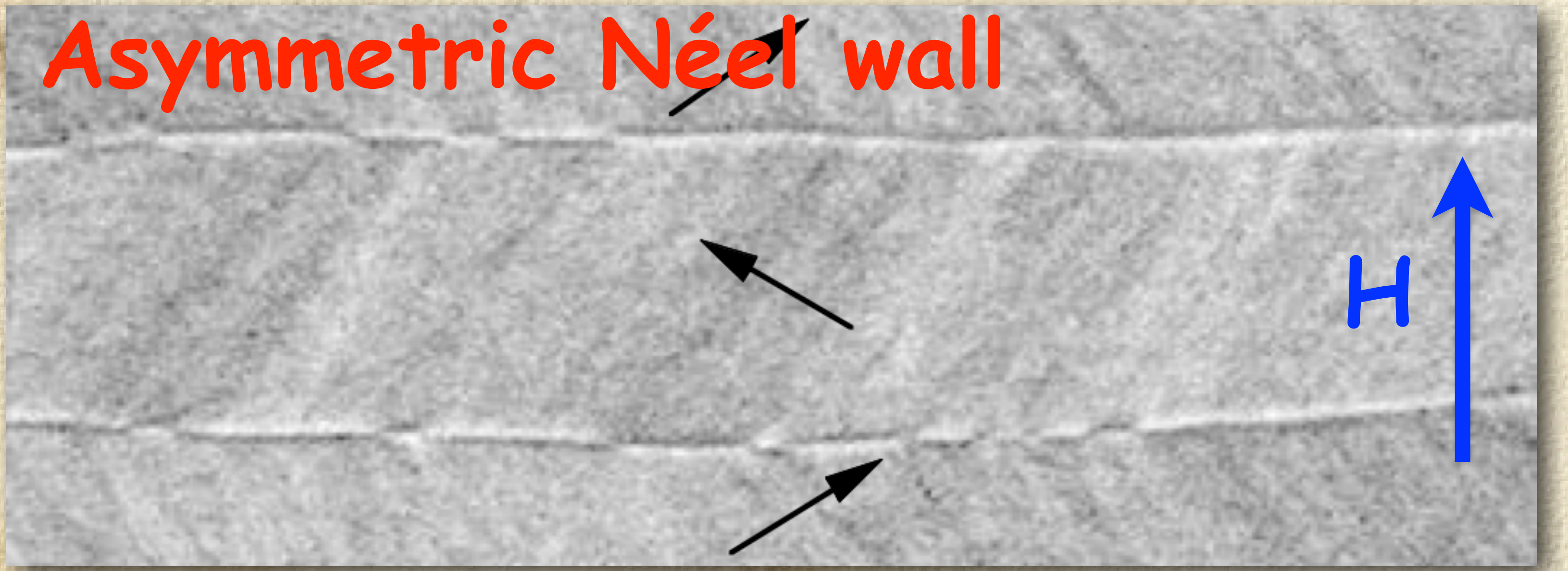
… sometimes combination with some micromagnetic theory may be required

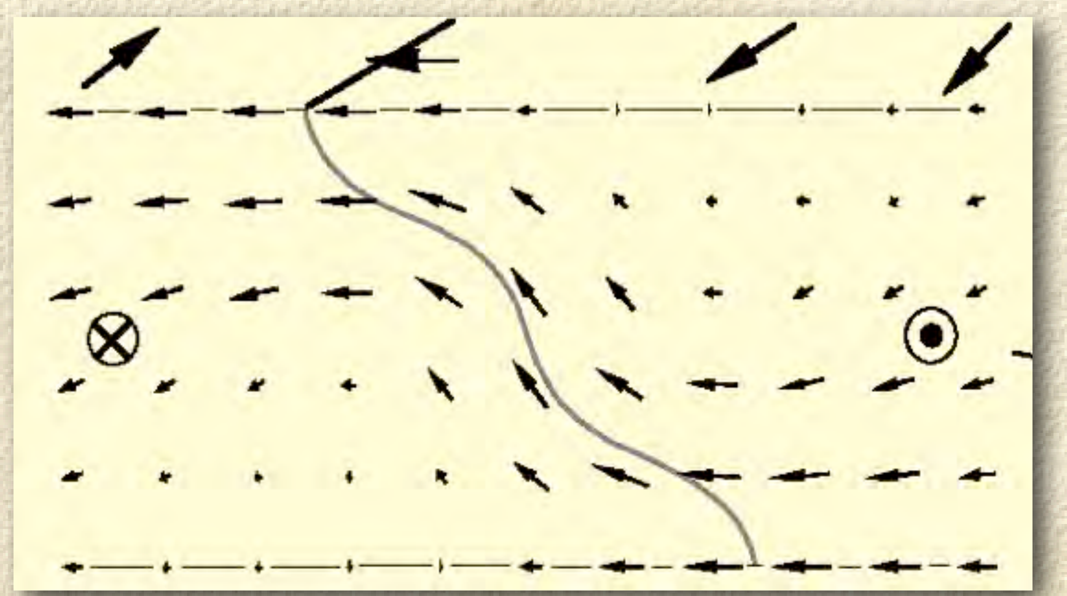
Asymmetric Bloch wall





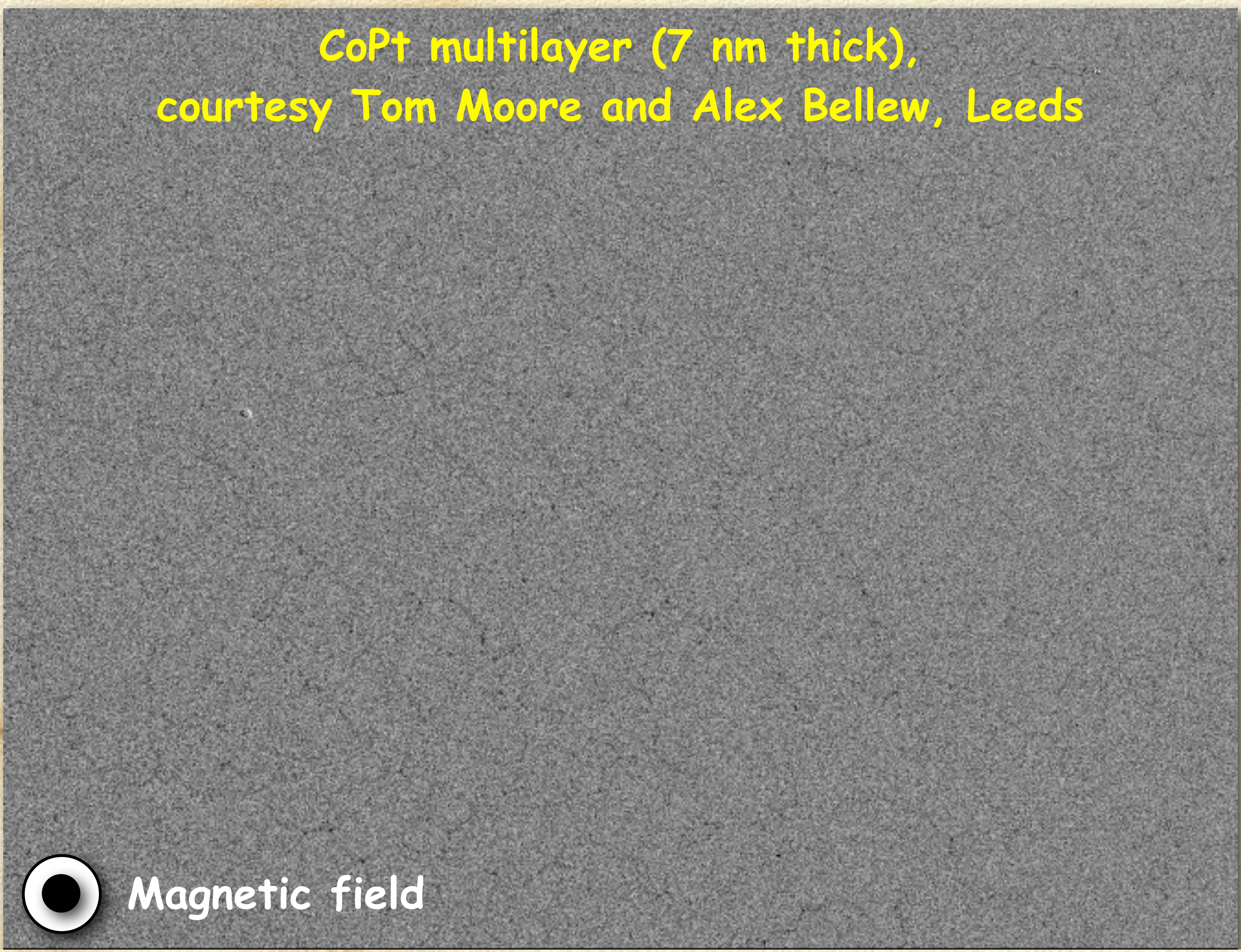
Asymmetric Néel wall



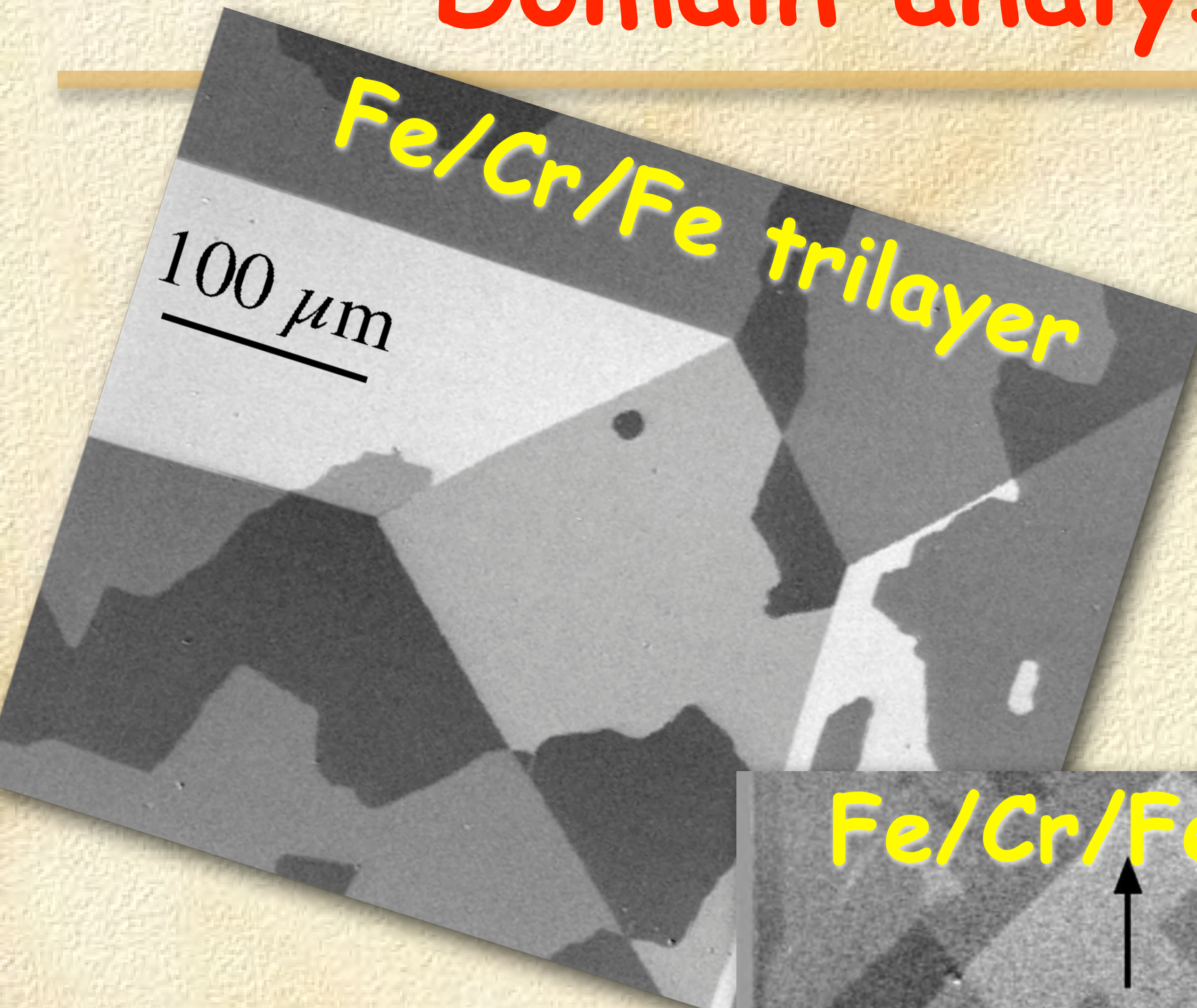


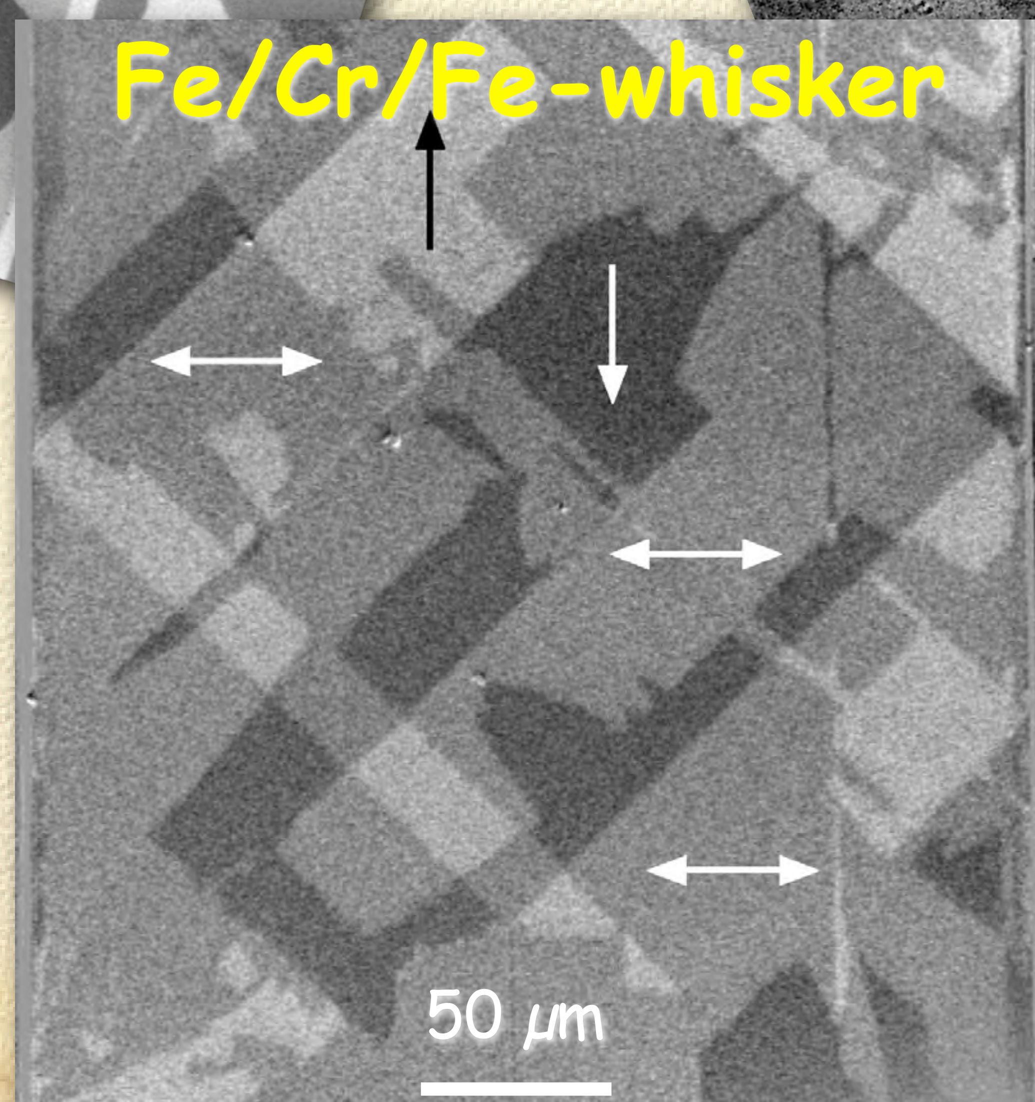
Multilayer films:
Domain analysis more challenging

Domain analysis in multilayers



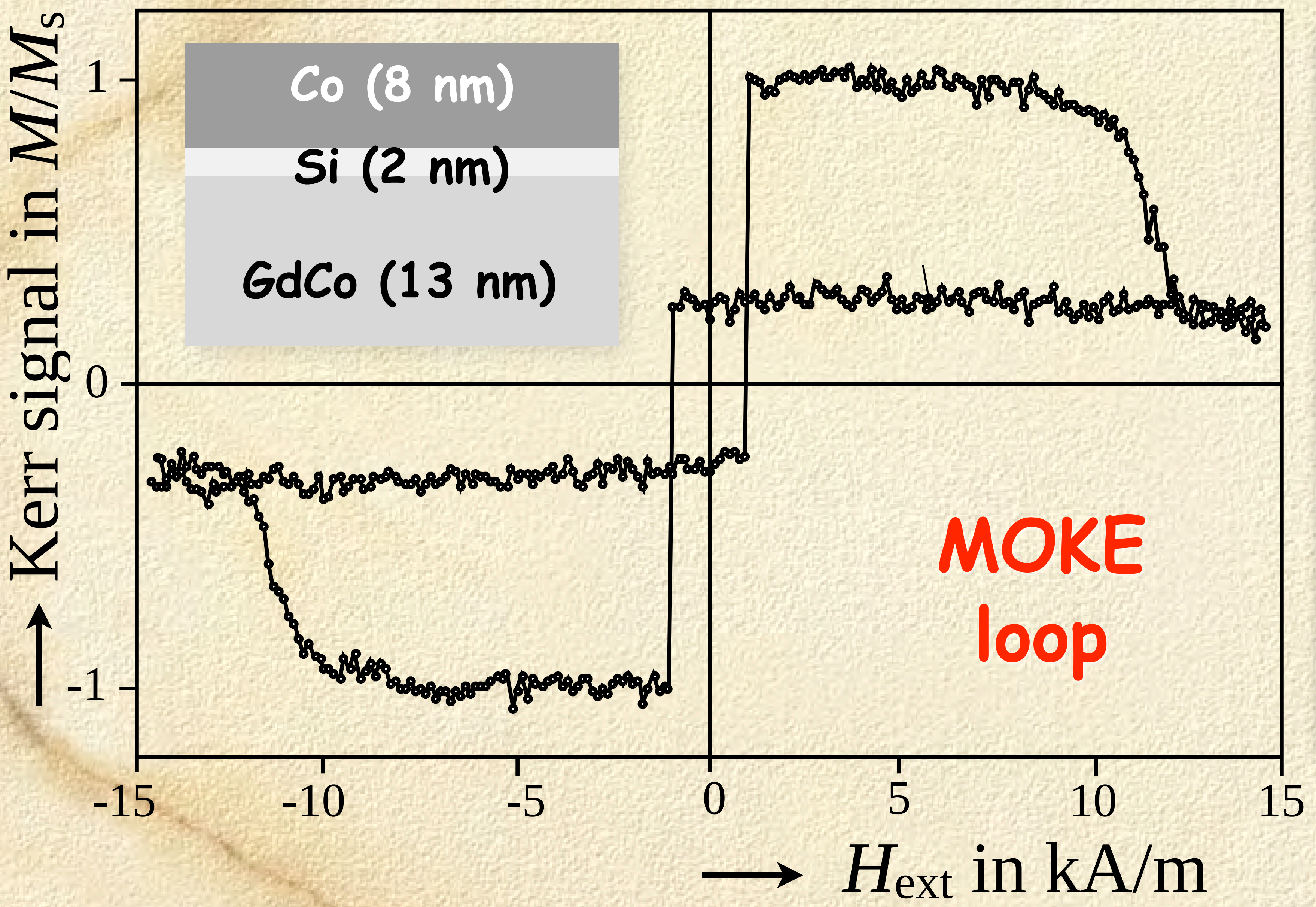
Domain analysis in multilayers

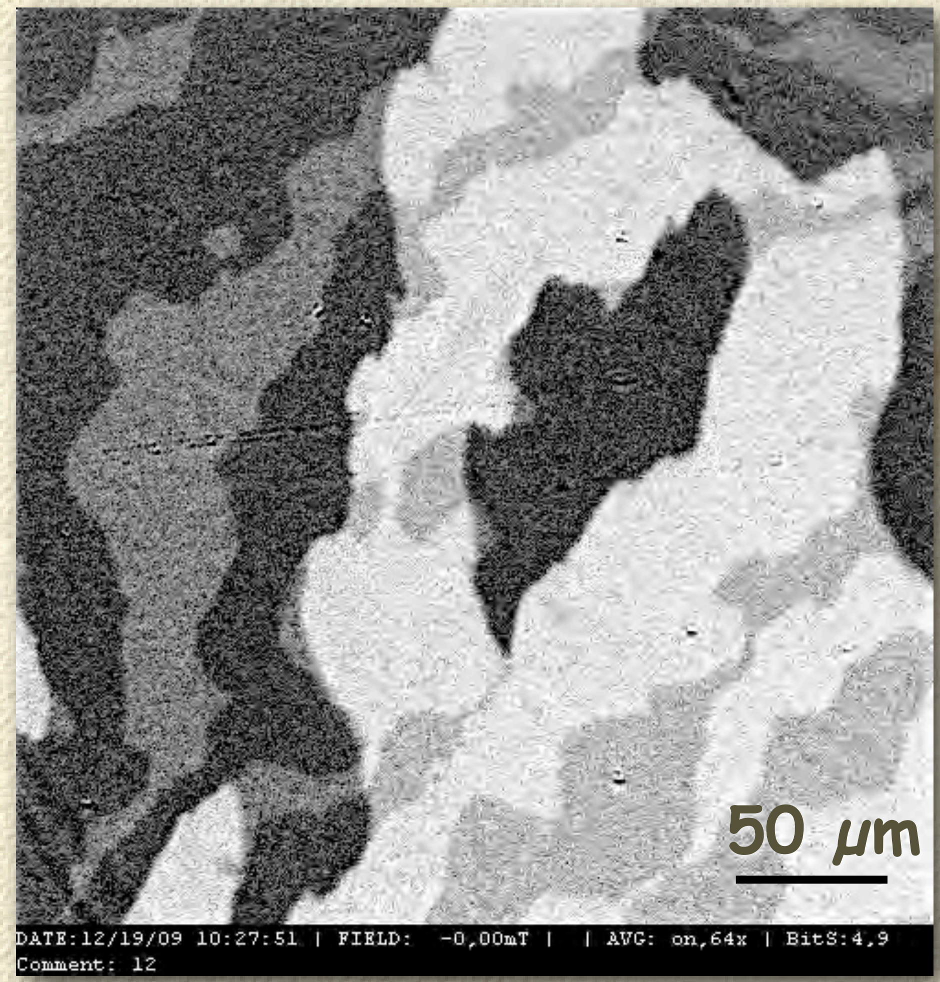




Domain analysis in multilayers

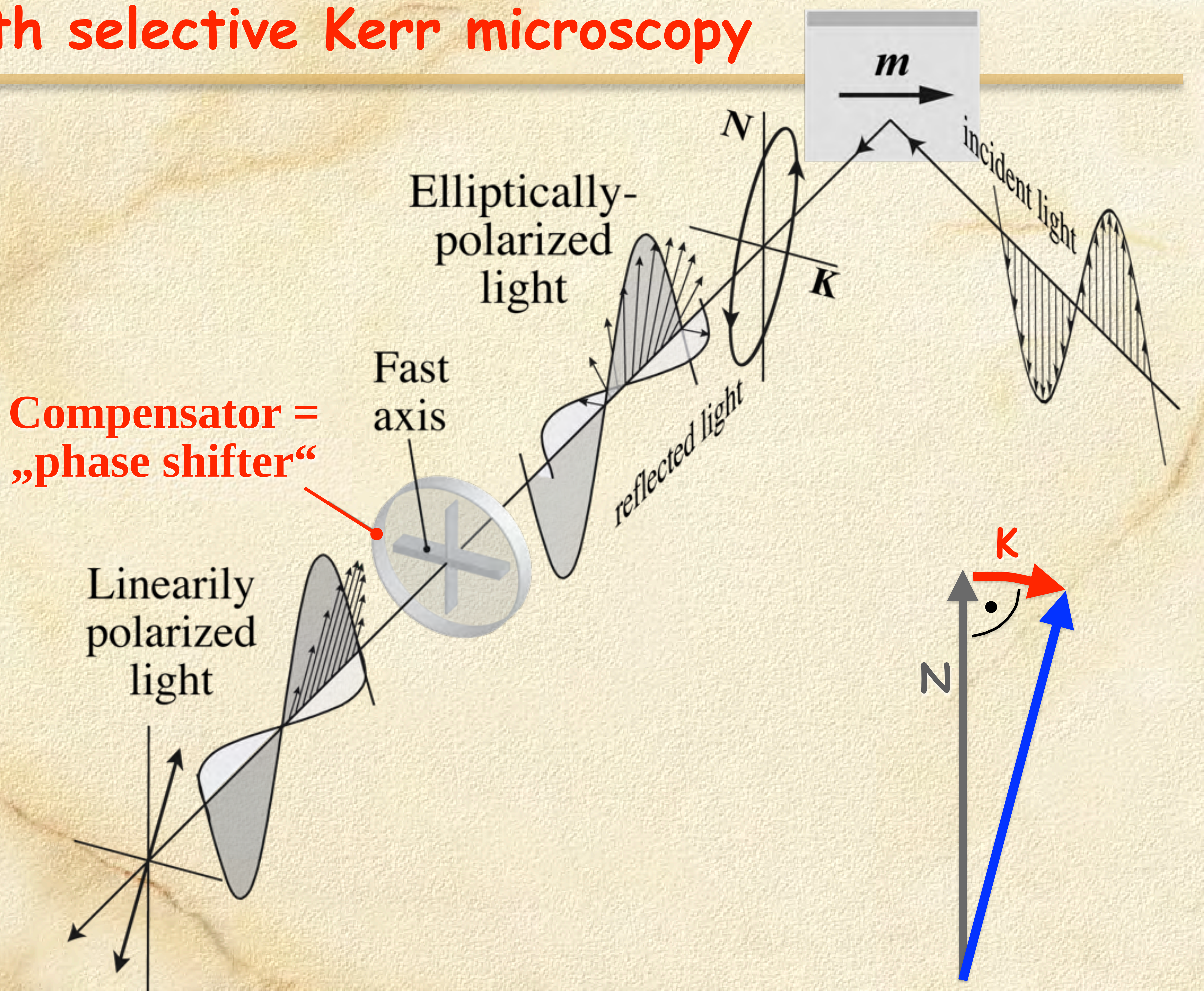
Co/Si/GdCo trilayer



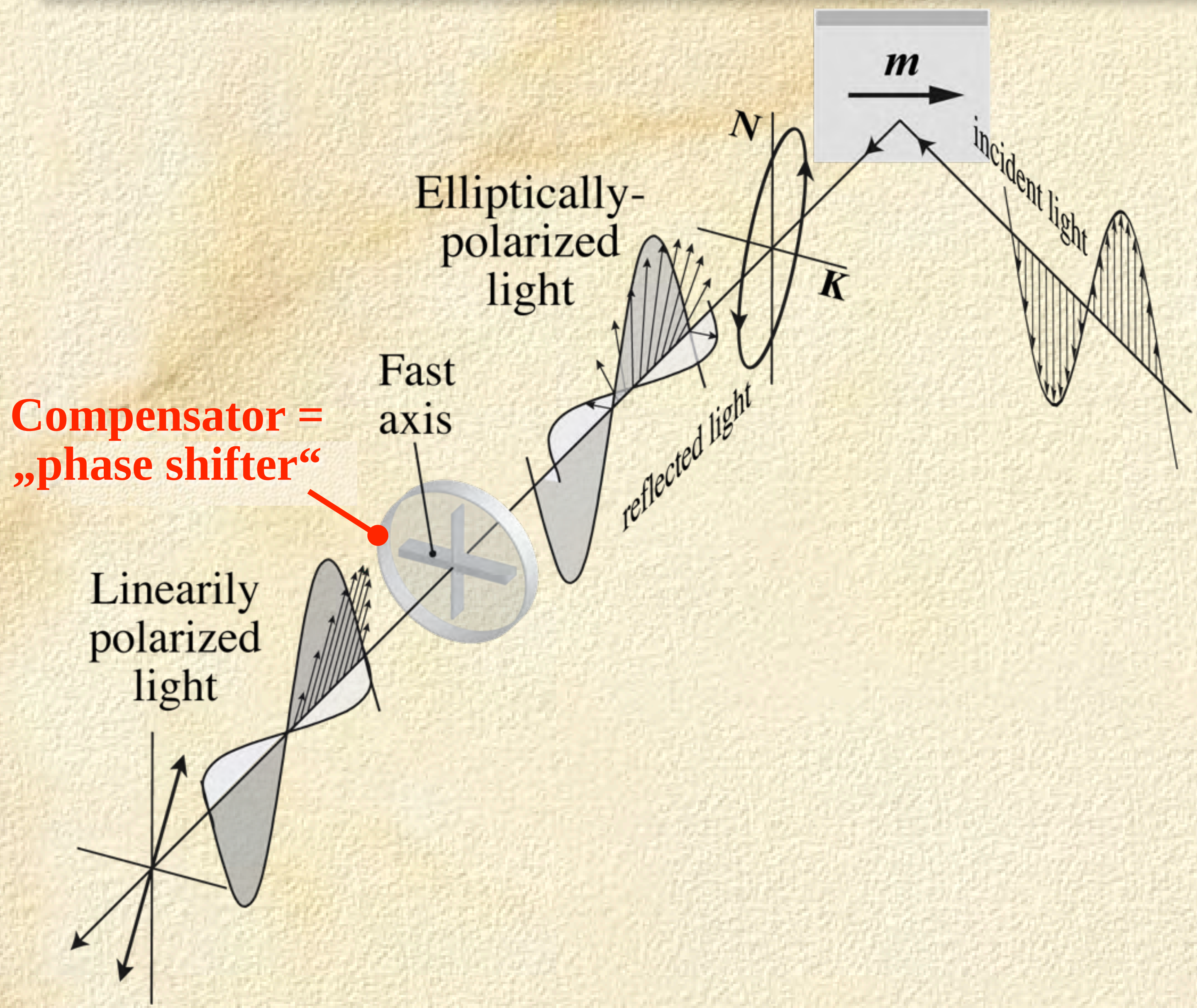


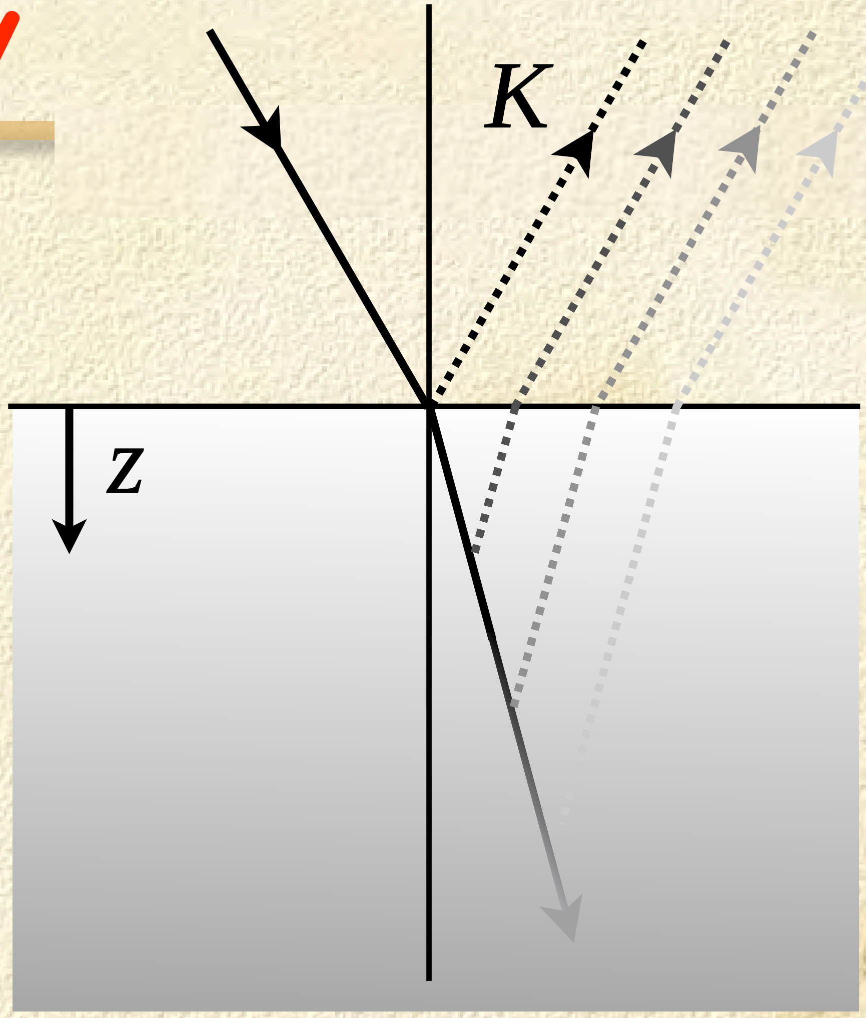
Sample: A. Svalov and G. Kurlyandskaya, Ekaterinburg
Imaging: together with L. Lokamani, Dresden (unpublished)

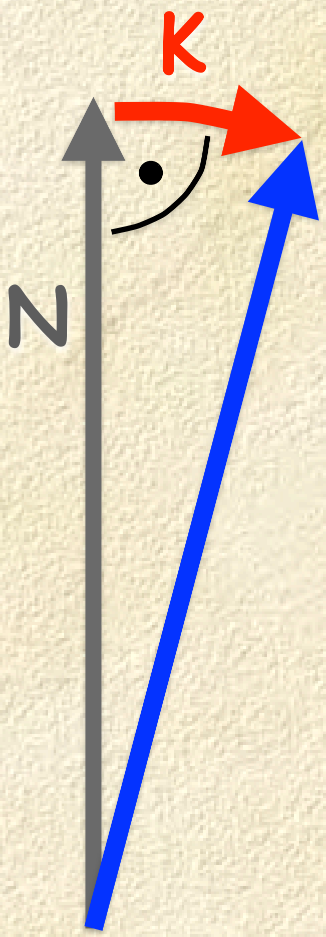
Depth selective Kerr microscopy



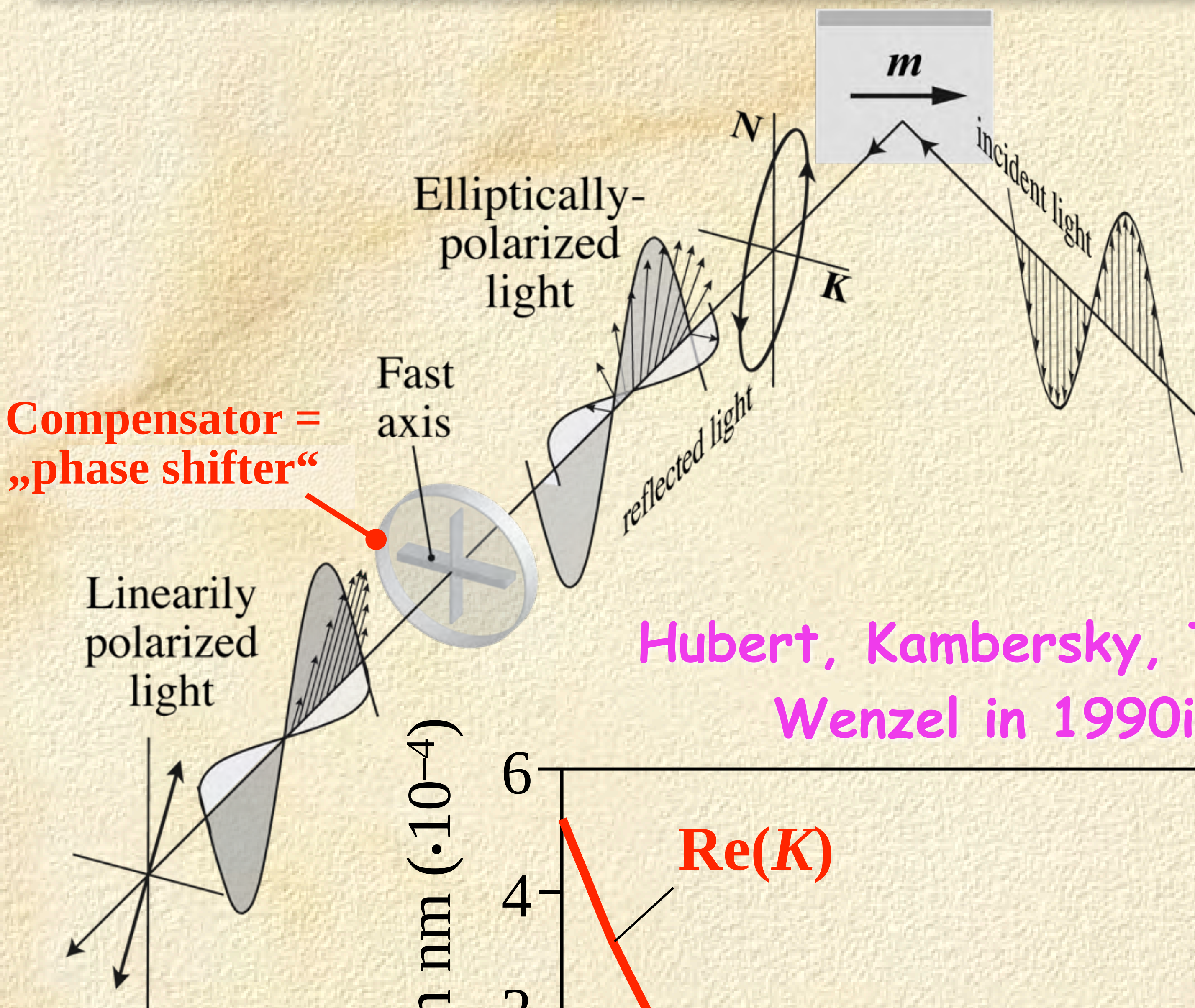
Depth selective Kerr microscopy



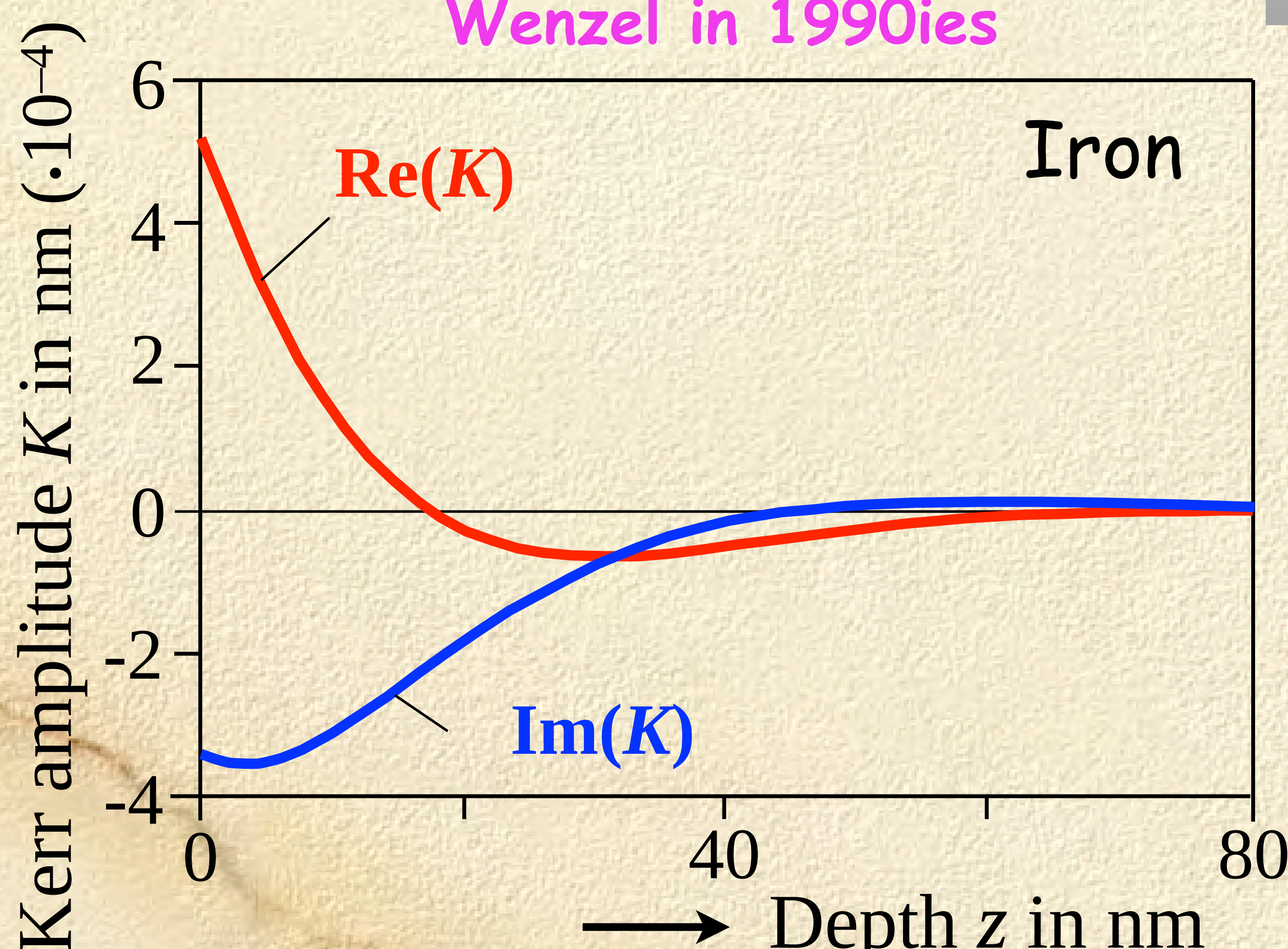


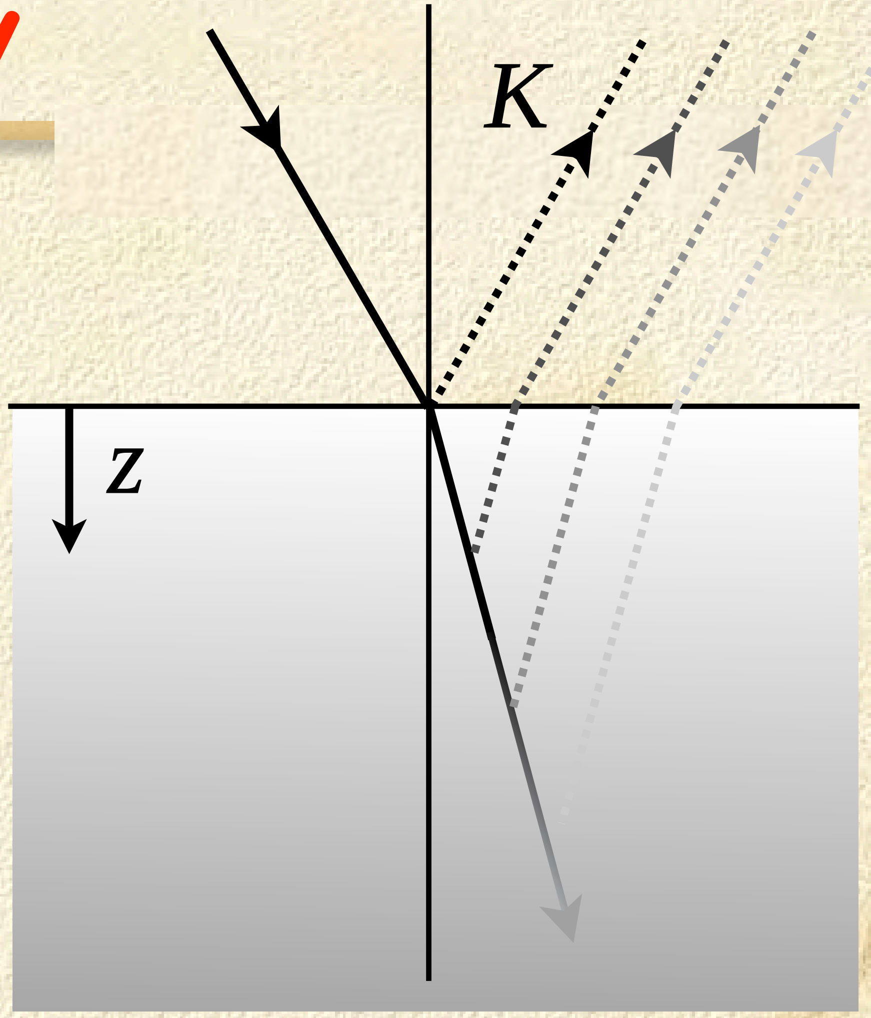


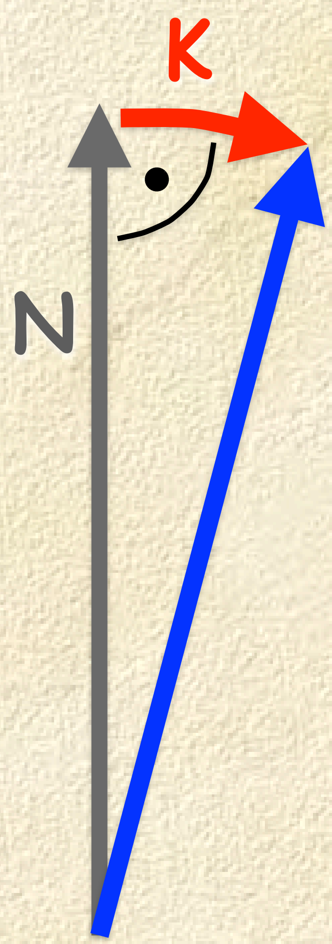
Depth selective Kerr microscopy



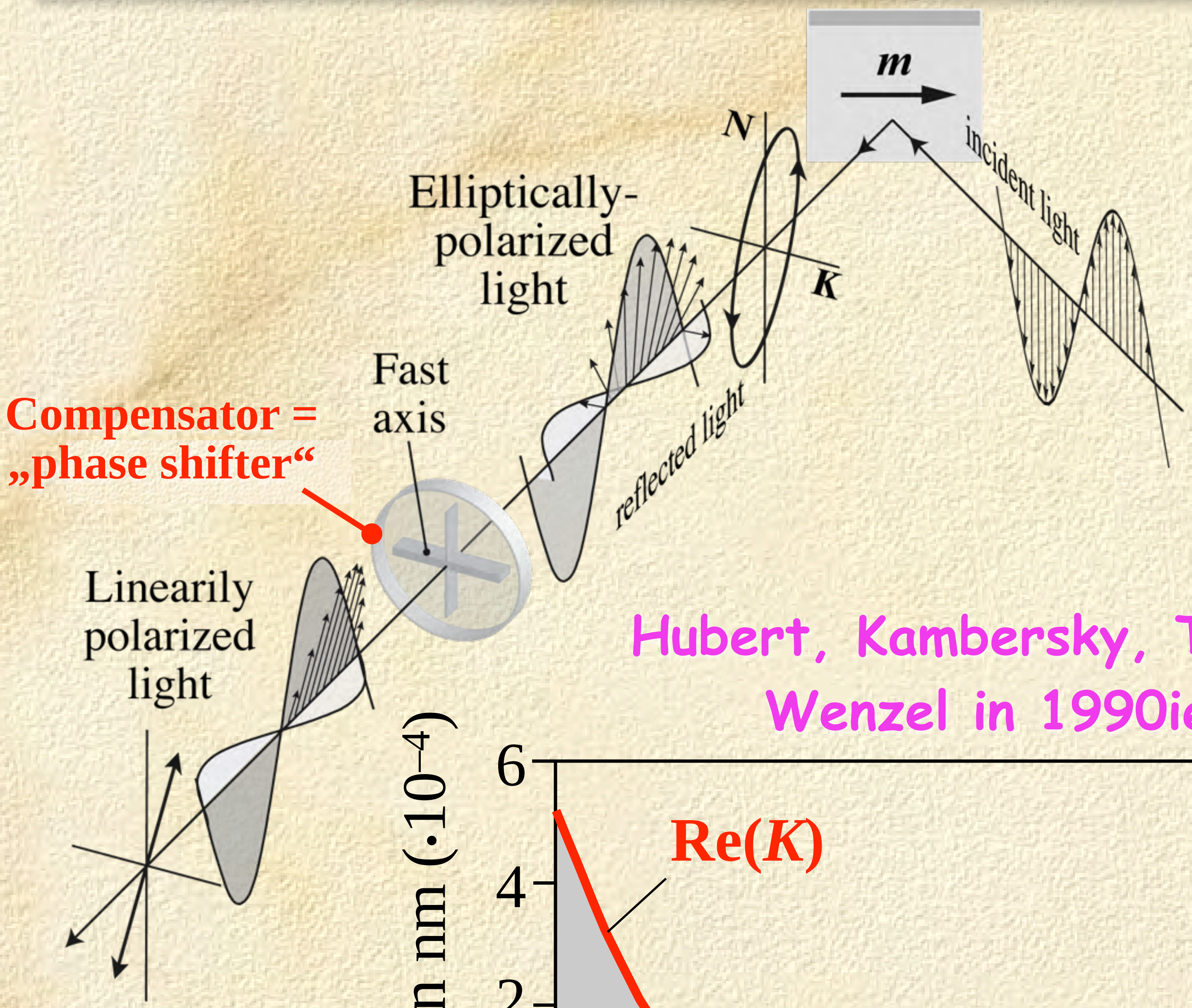
Hubert, Kambersky, Träger, Wenzel in 1990ies



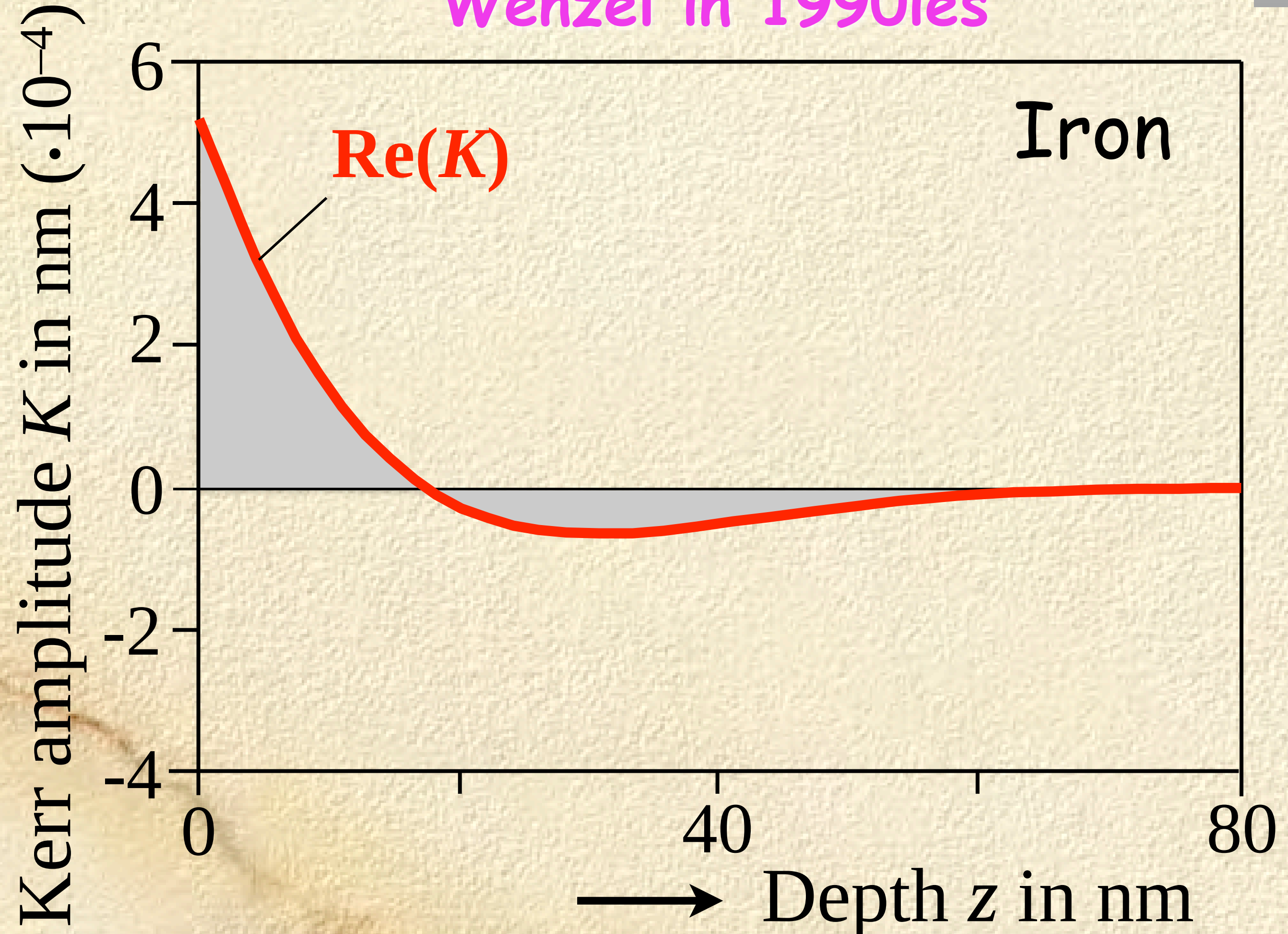


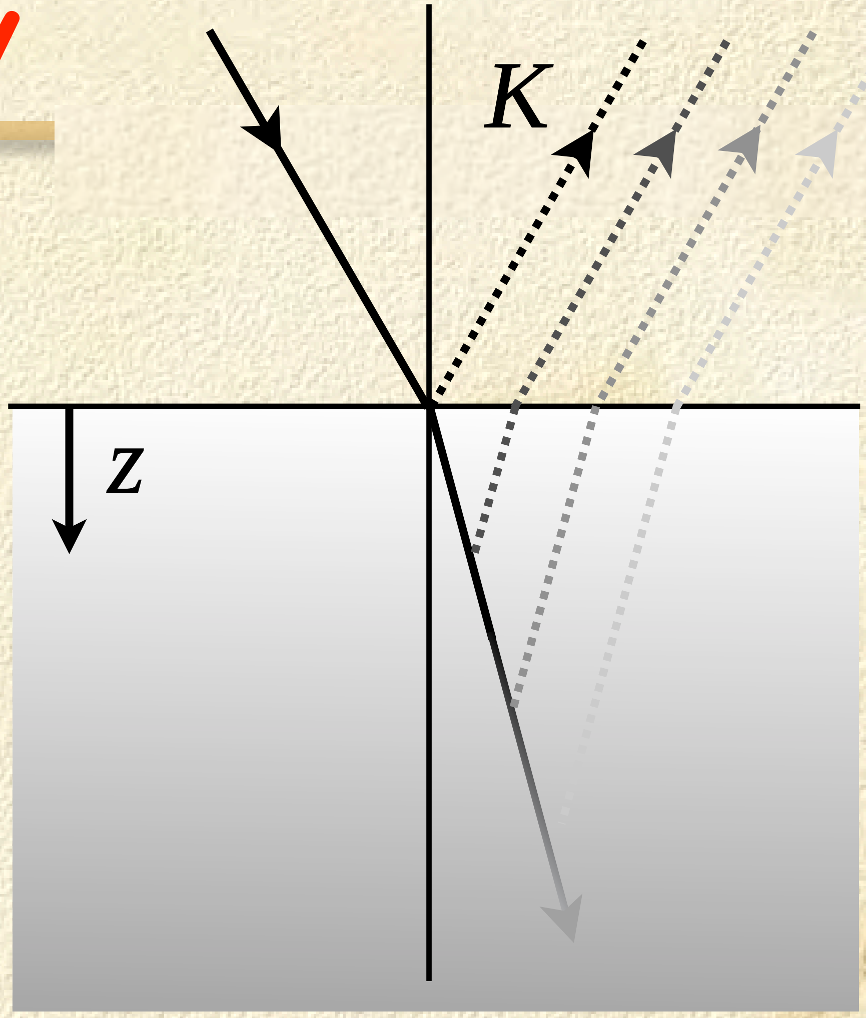


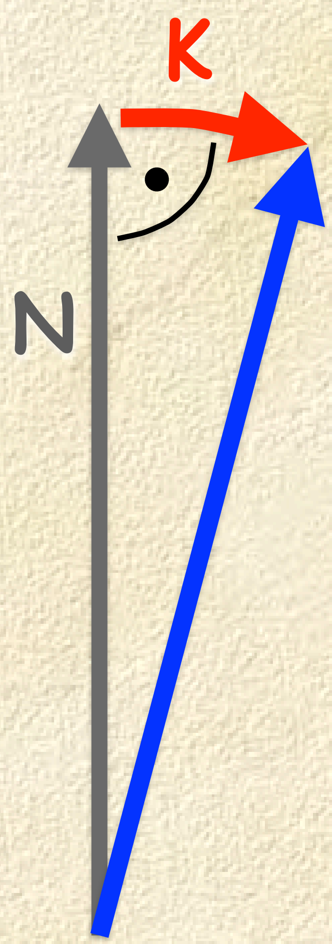
Depth selective Kerr microscopy



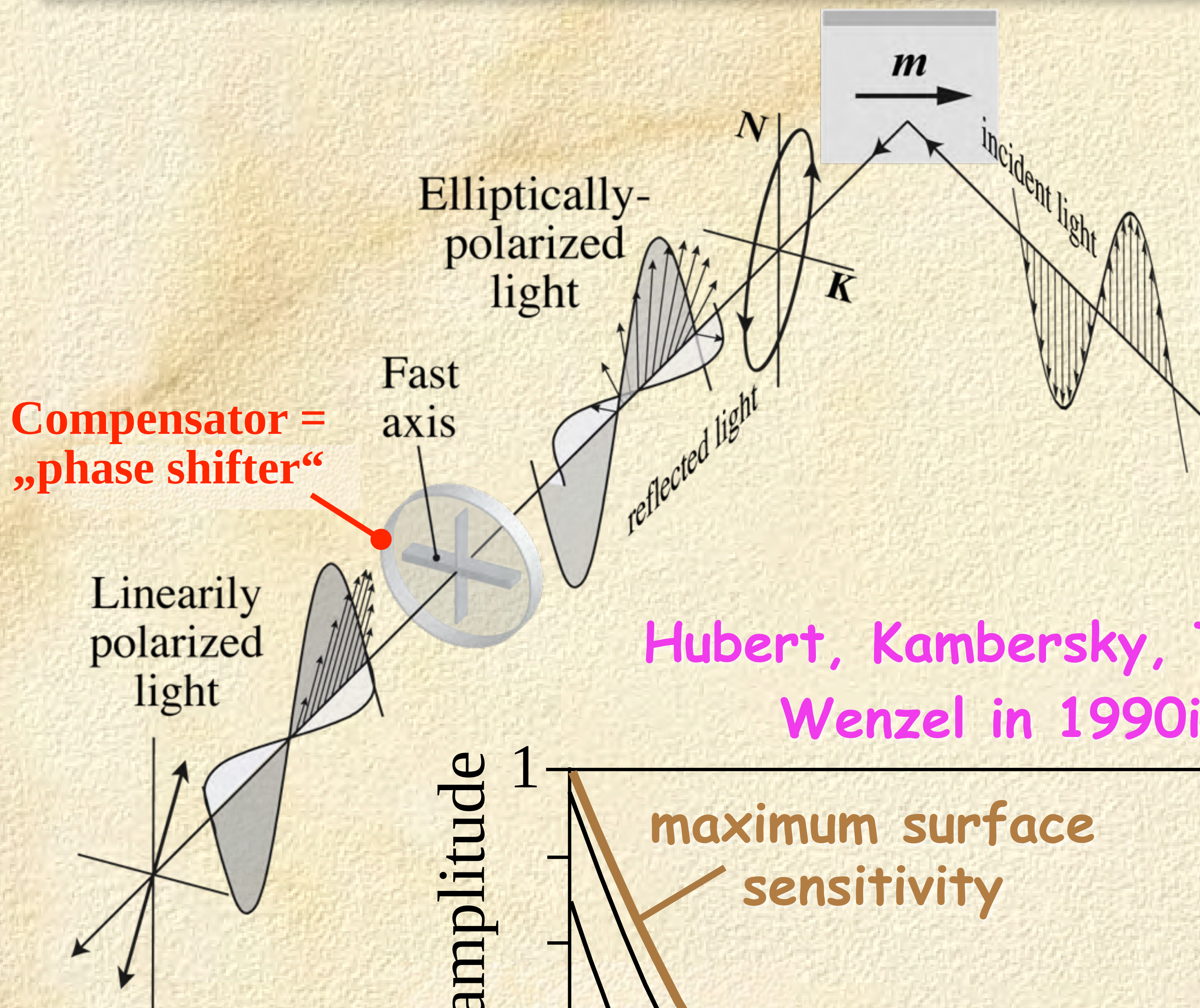
Hubert, Kambersky, Träger, Wenzel in 1990ies

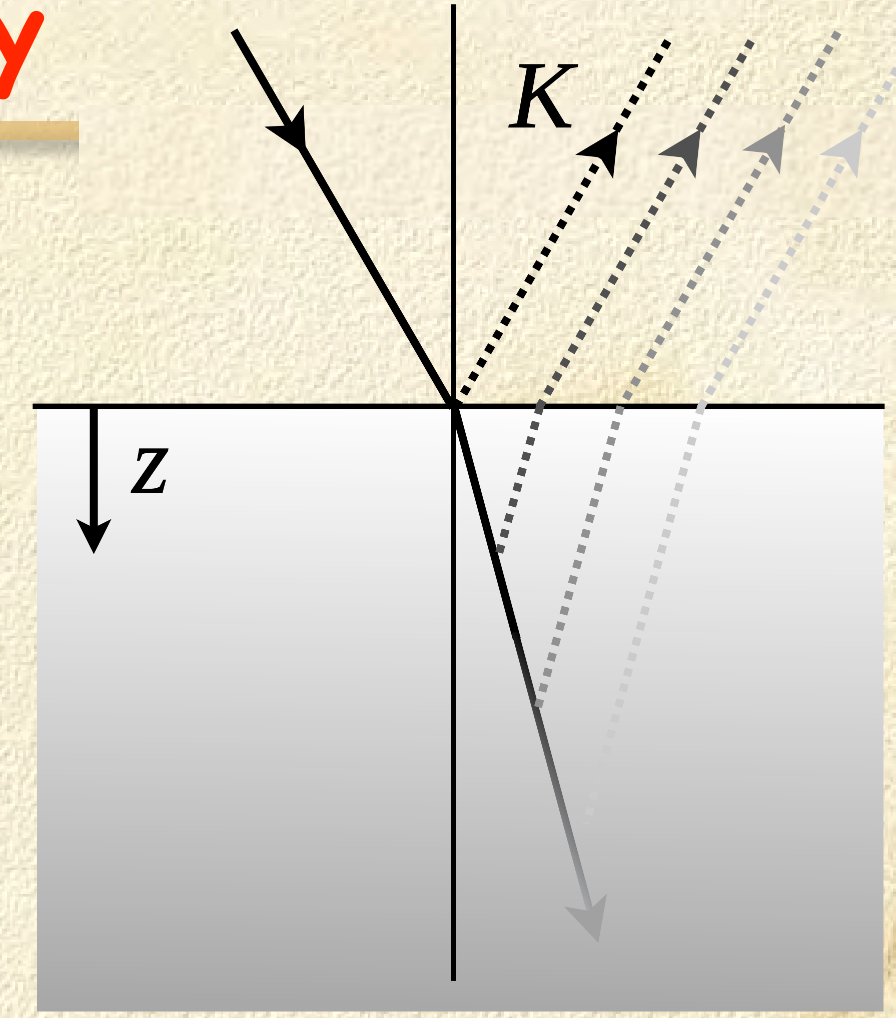




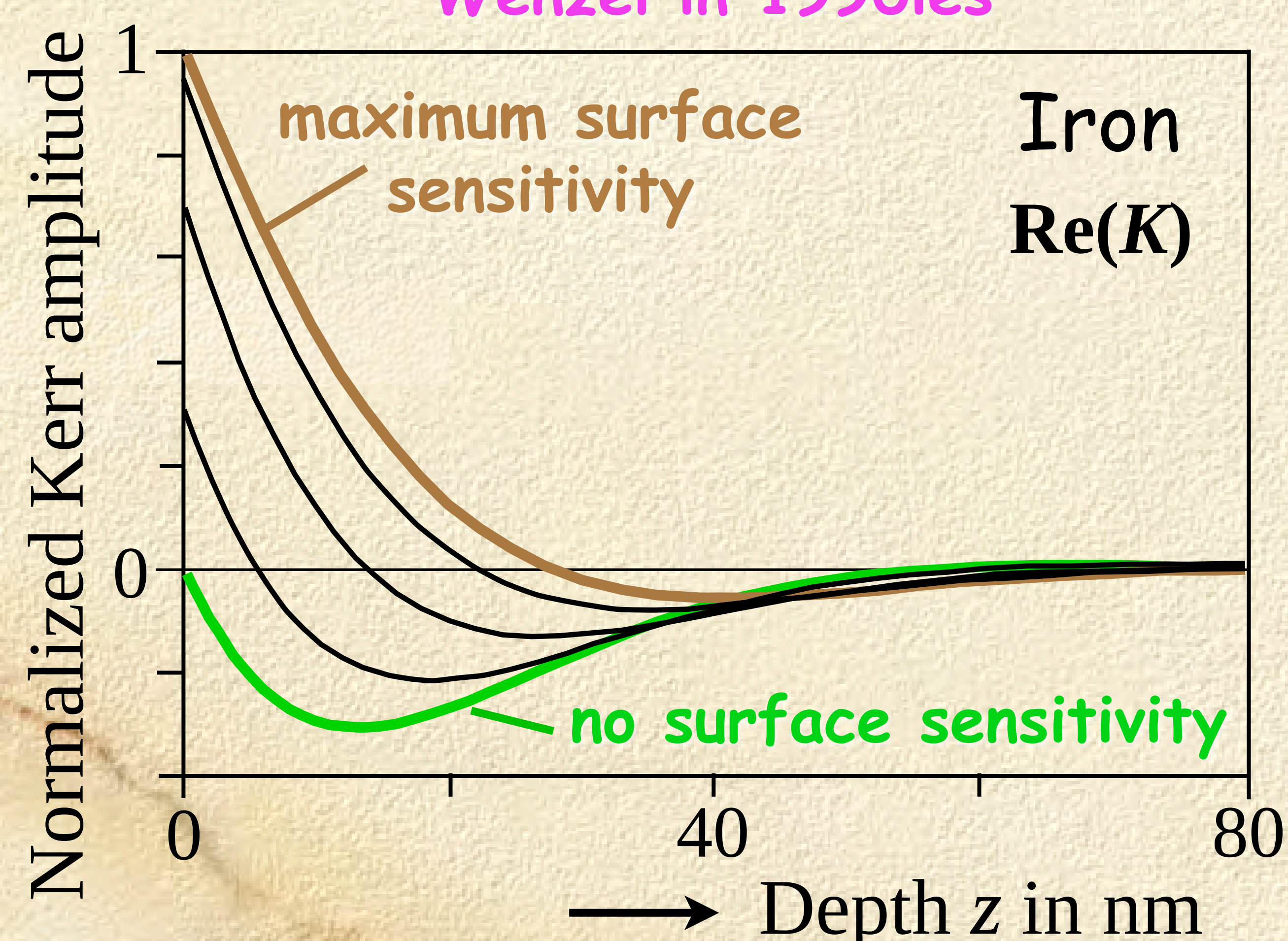


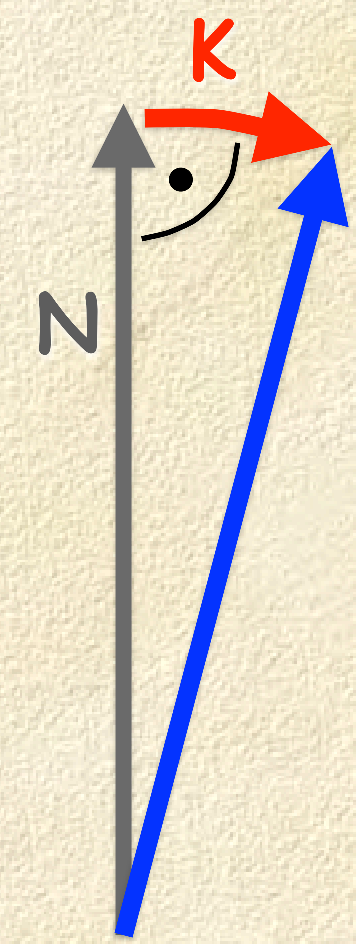
Depth selective Kerr microscopy



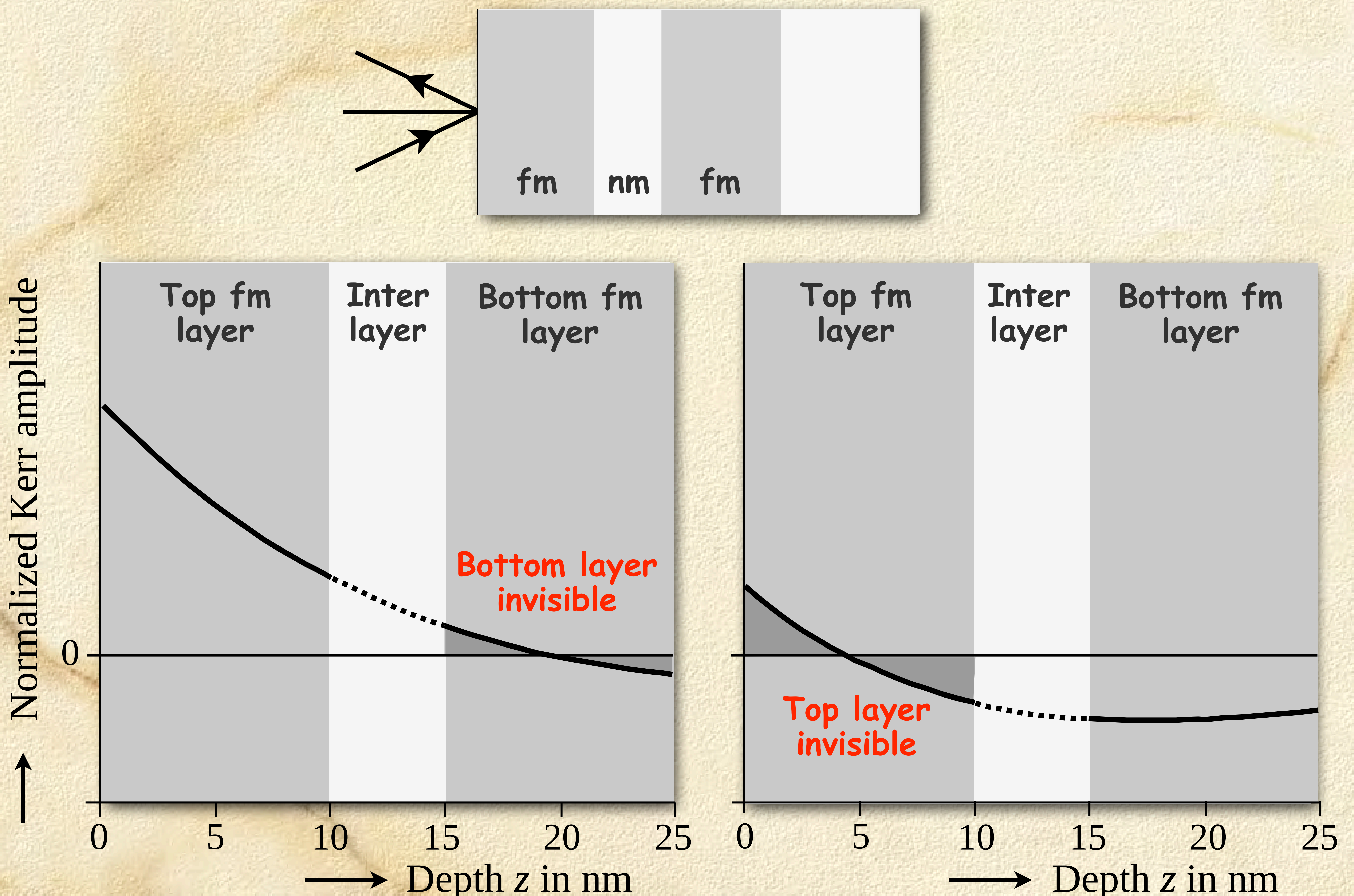


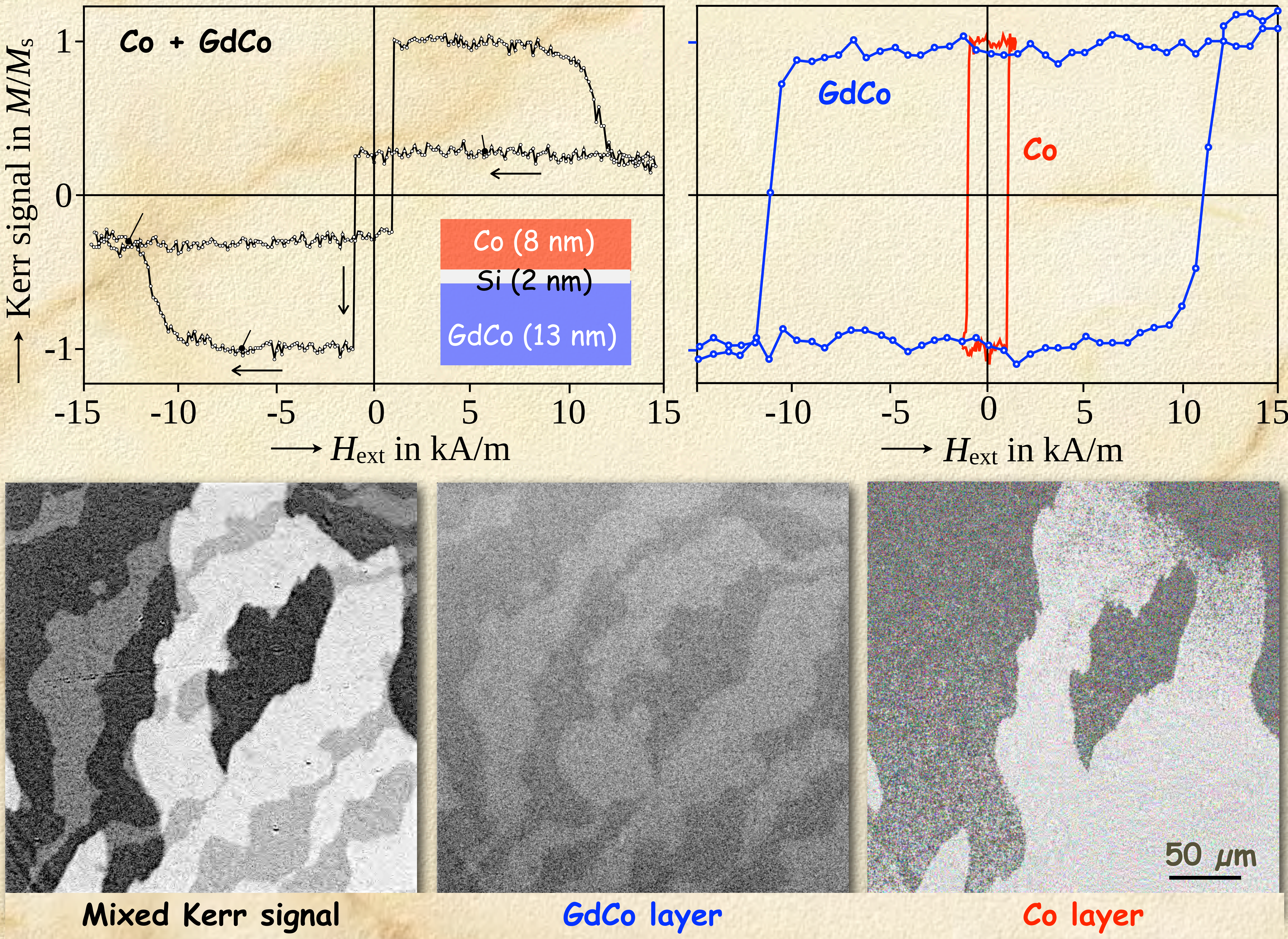
Hubert, Kambersky, Träger, Wenzel in 1990ies



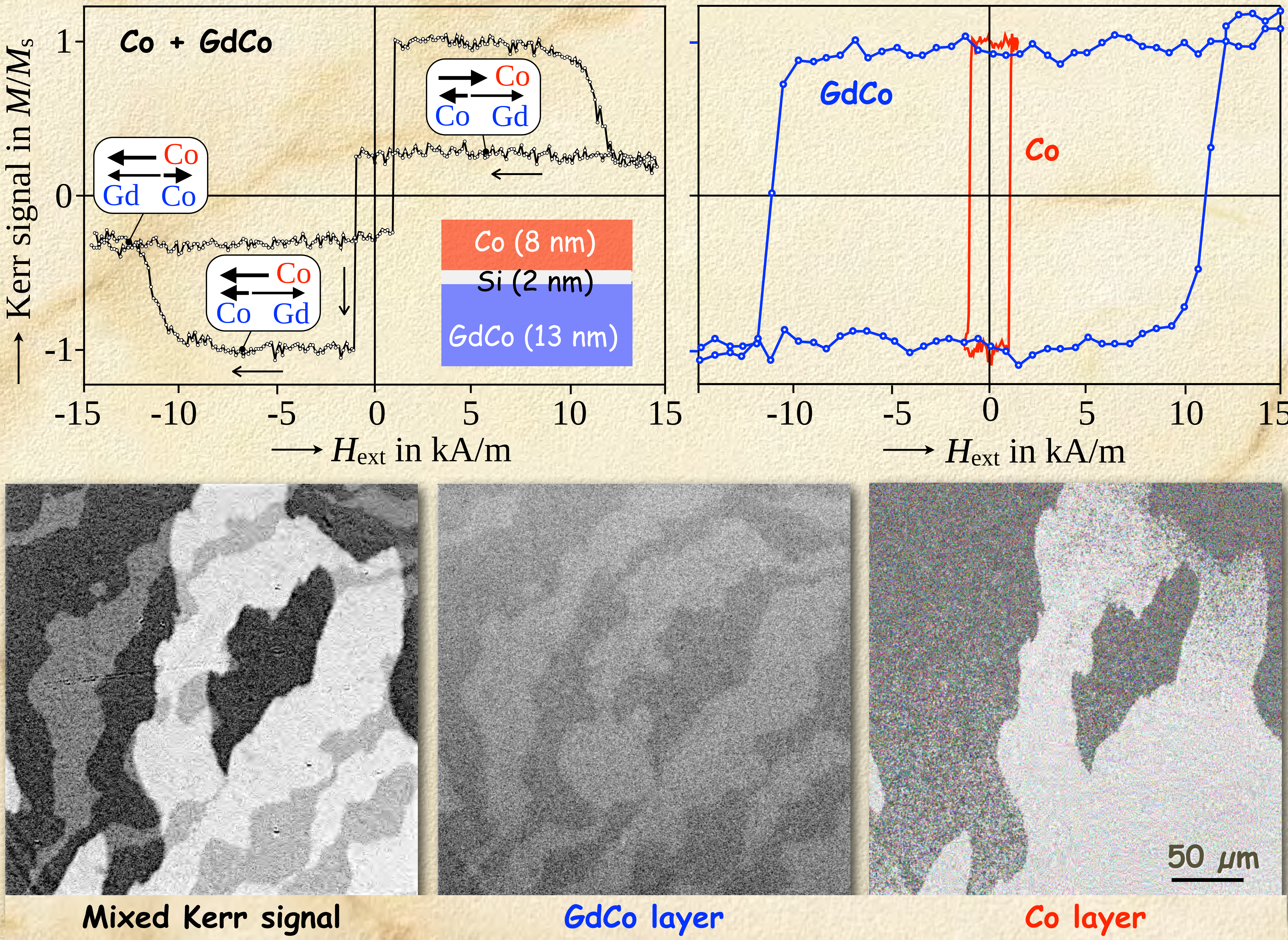


Layer-selective Kerr microscopy





Co + GdCo
1
0
-1
Kerr signal in M/M_s
Co (8 nm)
Si (2 nm)
GdCo (13 nm)
-15 -10 -5 0 5 10 15
H_{ext} in kA/m
GdCo
Co
-10 -5 0 5 10 15
H_{ext} in kA/m
50 μm
Mixed Kerr signal
GdCo layer
Co layer



Co + GdCo
Co
Co Gd
Co
Gd Co
Co
Co Gd
Co (8 nm)
Si (2 nm)
GdCo (13 nm)
Kerr signal in M/M_s
H_{ext} in kA/m
GdCo
Co
H_{ext} in kA/m
50 µm
Mixed Kerr signal
GdCo layer
Co layer

Layer-selective Kerr microscopy

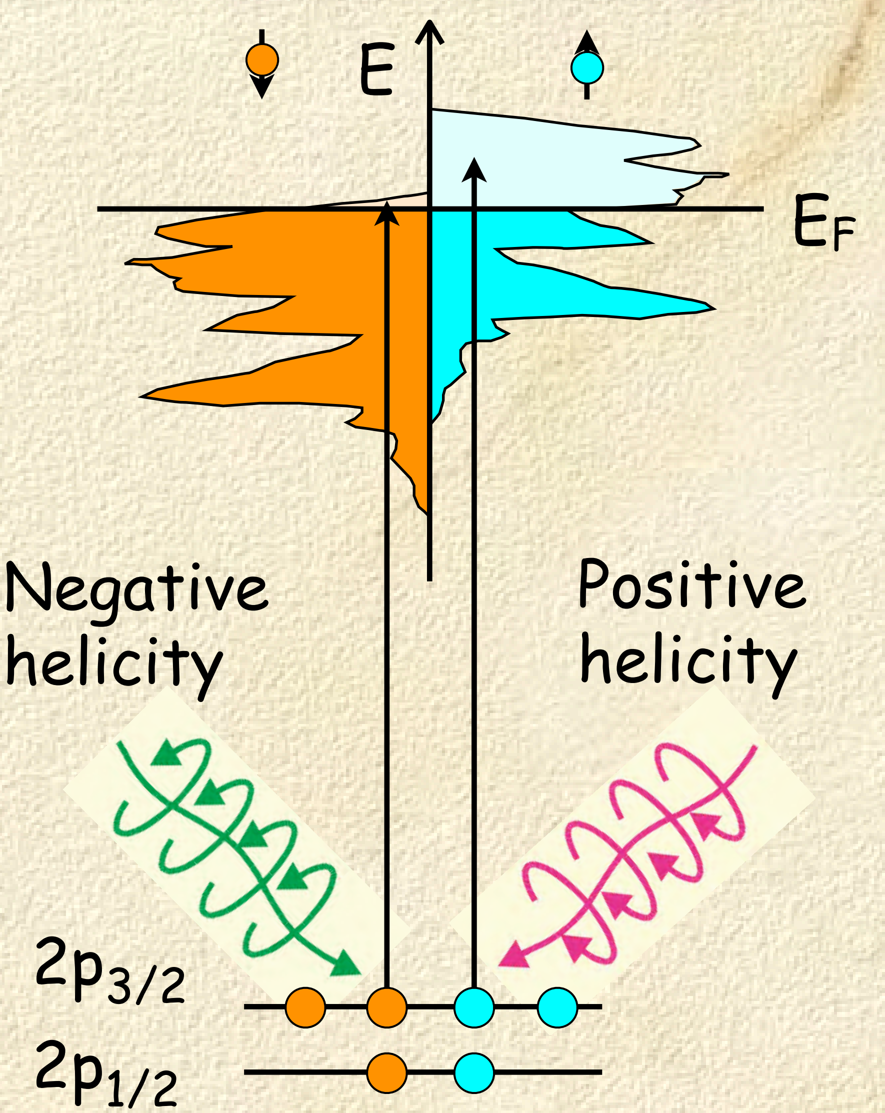
Advantage of layer-selective Kerr microscopy:

different composition of layers not required

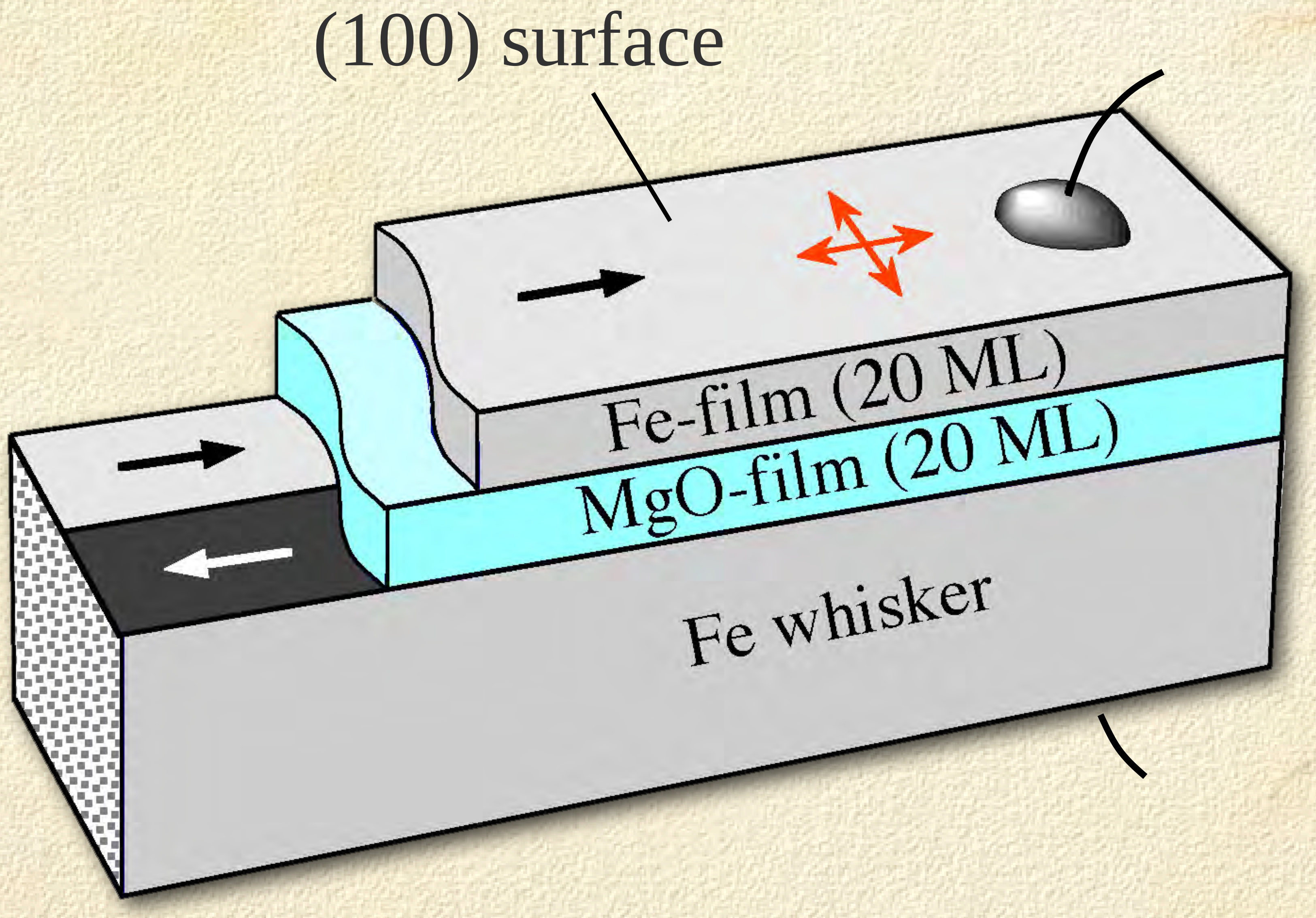
X-ray Magnetic Circular Dichroism

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

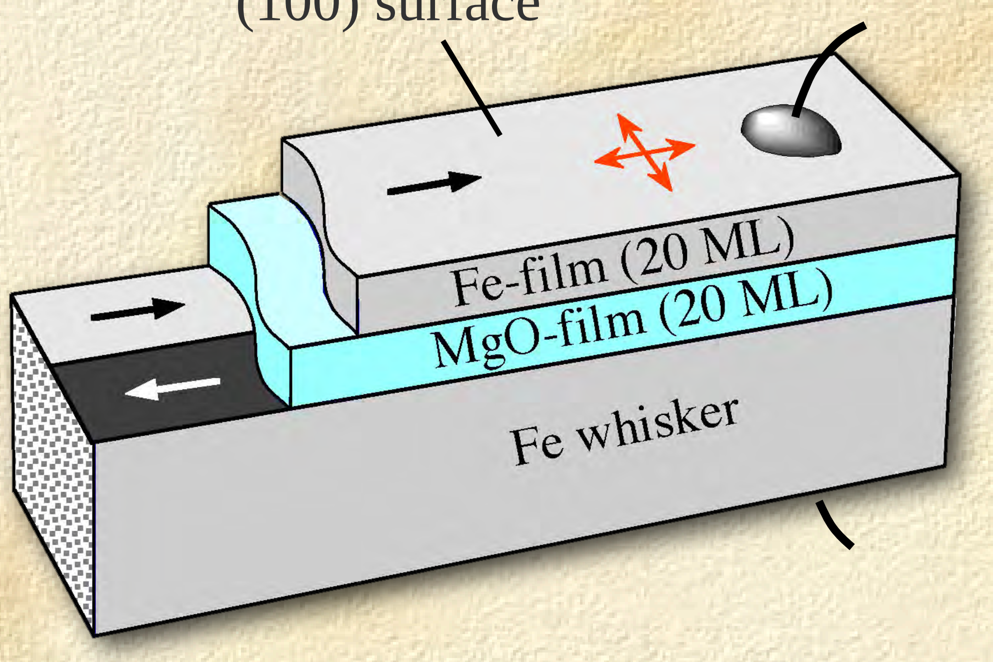


Layer-selective Kerr microscopy

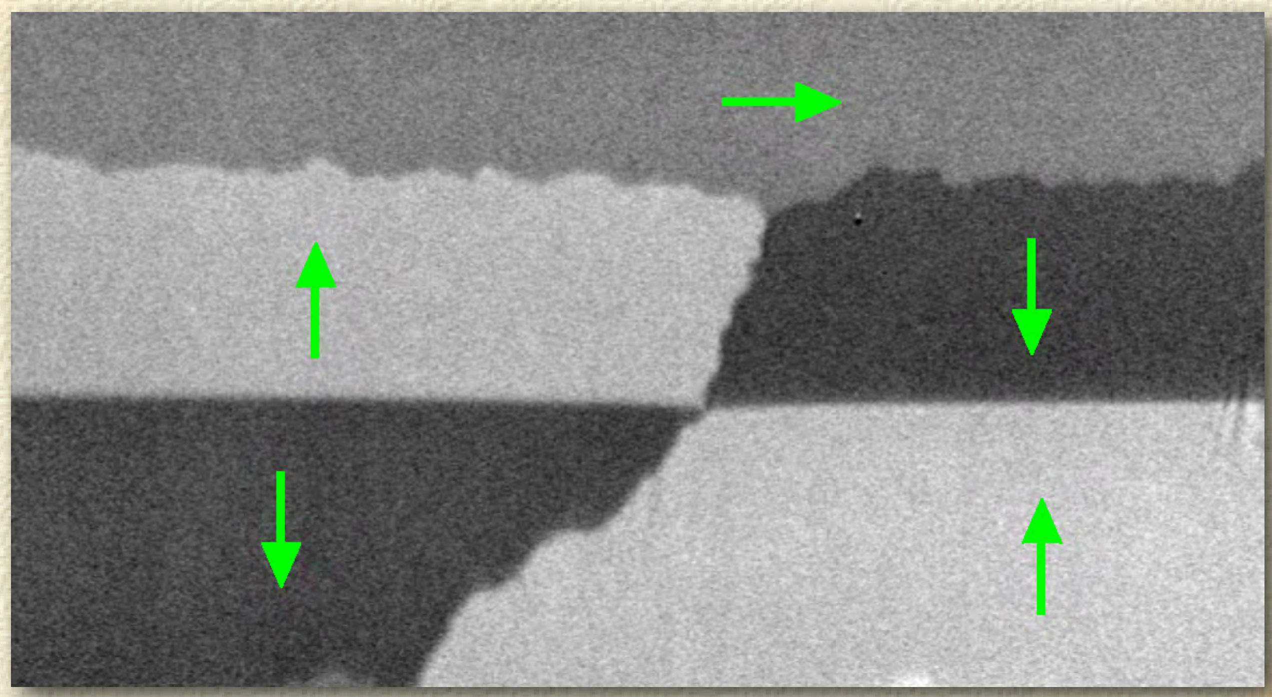


R.S., R Urban, D. Ullmann, H. L. Meyerheim, B. Heinrich, L. Schultz, J. Kirschner, Phys. Rev. B 65, 144405 (2002)

Layer-selective Kerr microscopy

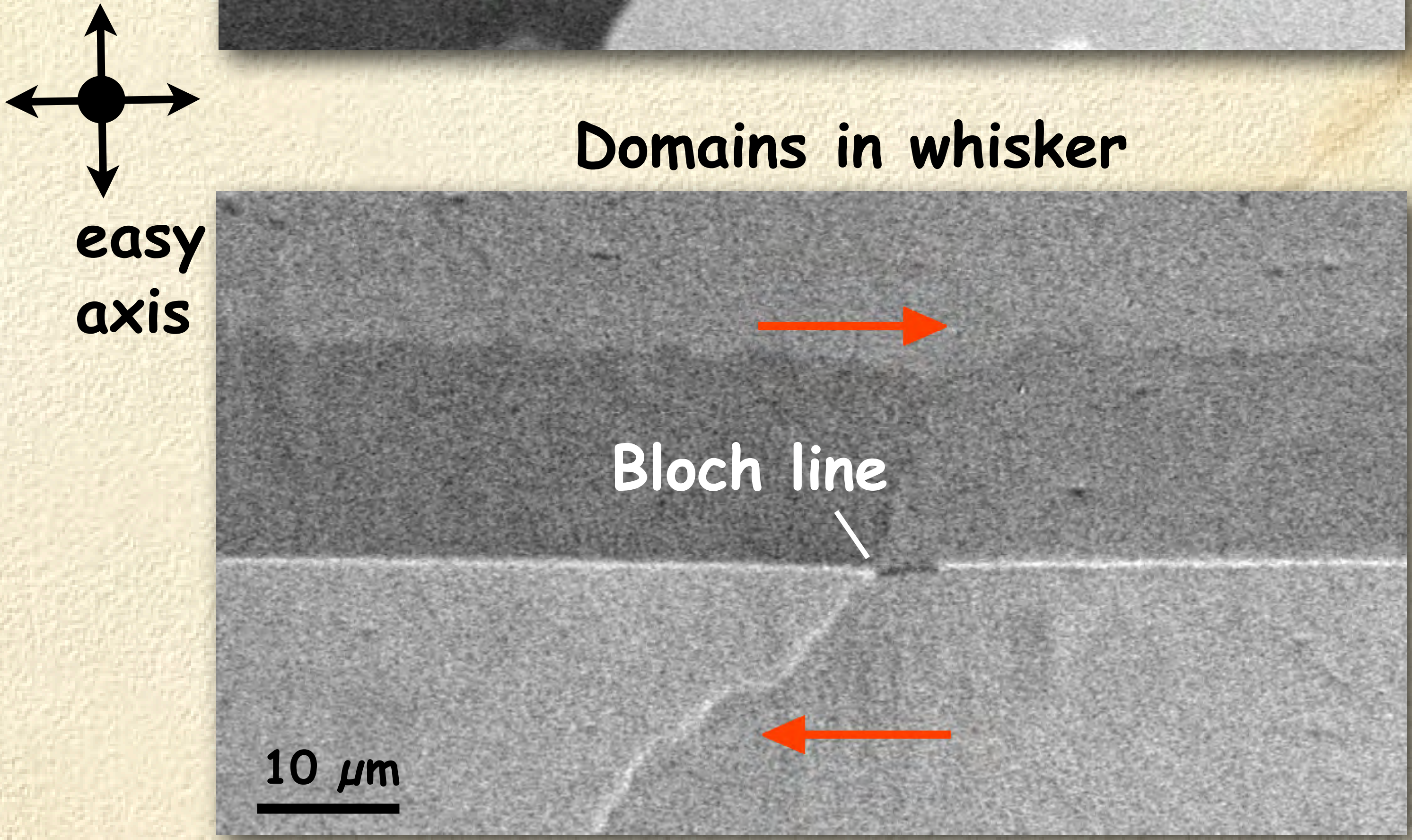


Domains in Fe-film



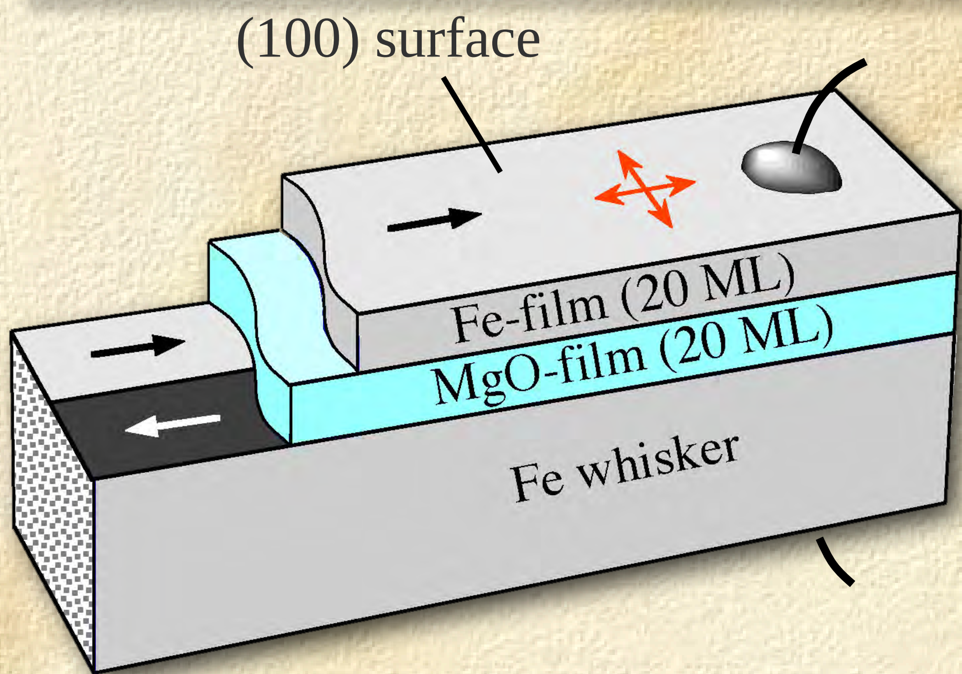
easy axis

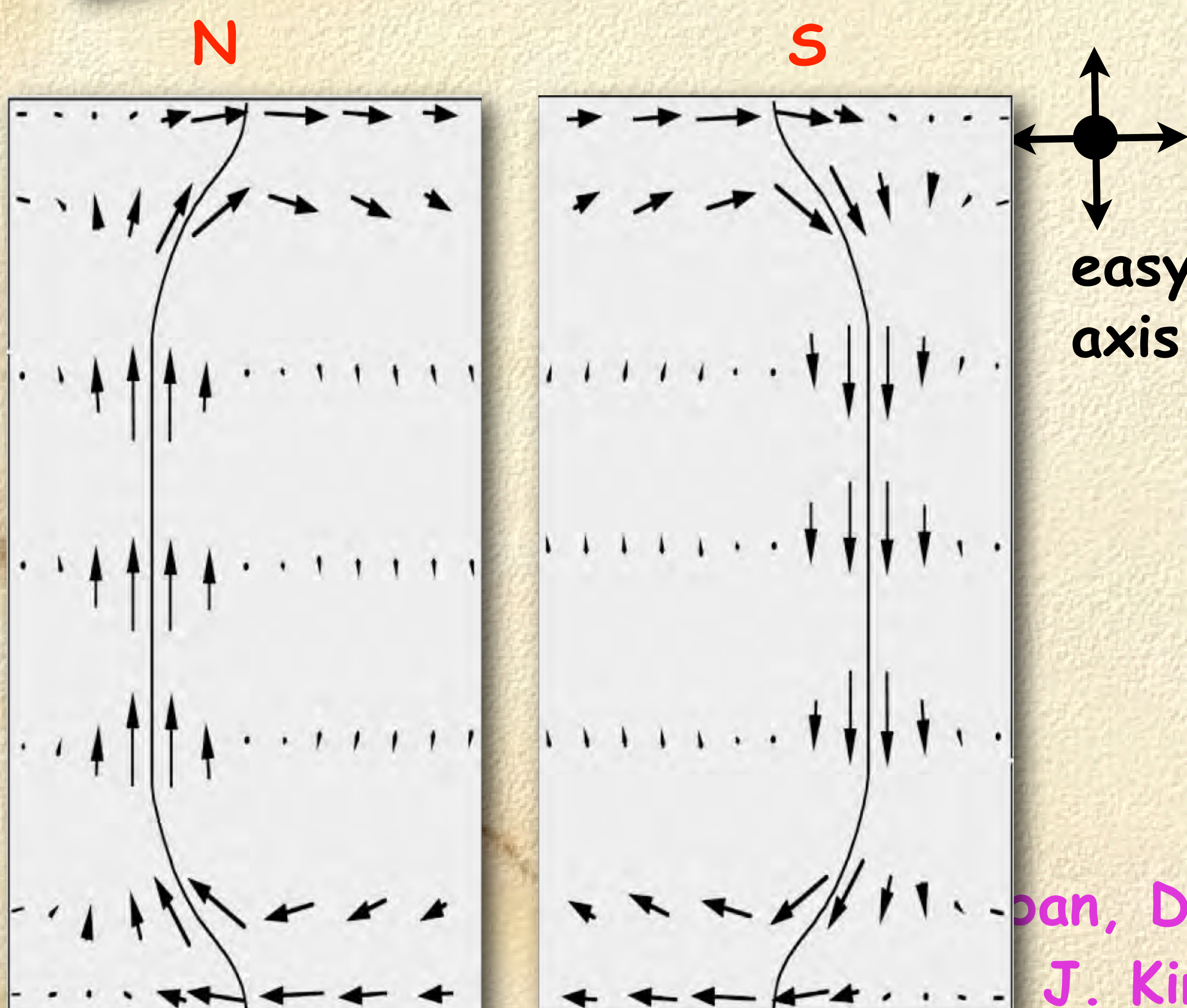
Domains in whisker



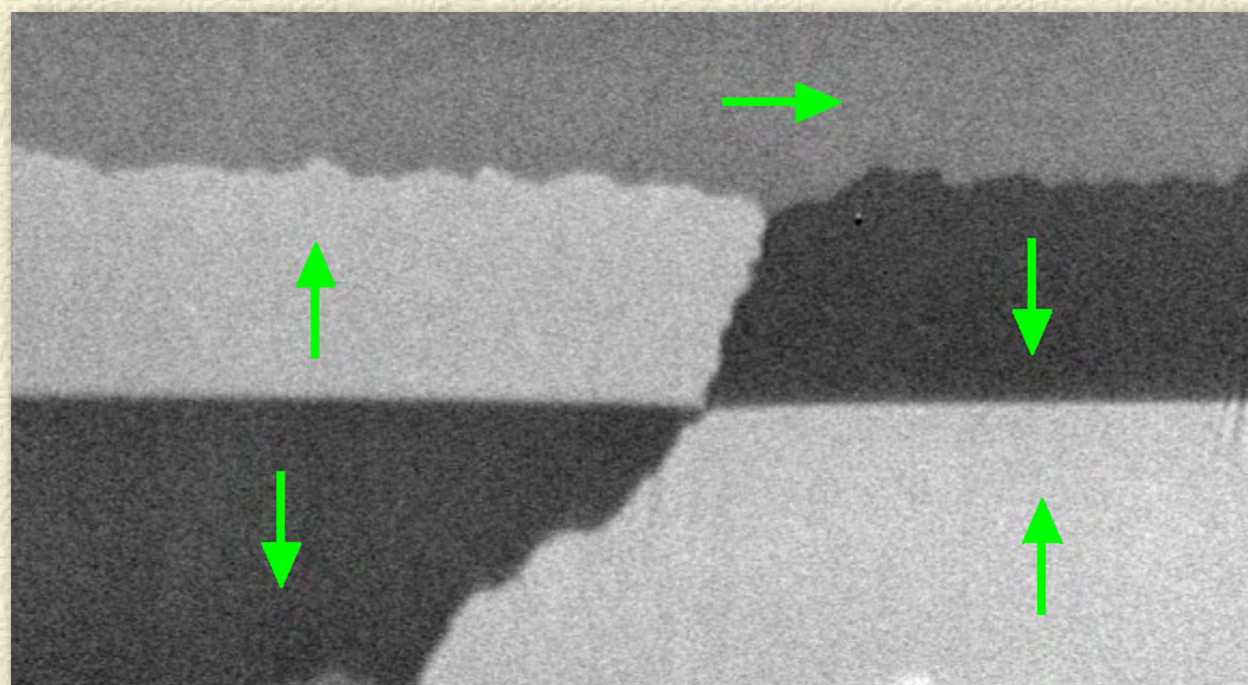
R.S., R Urban, D. Ullmann, H. L. Meyerheim, B. Heinrich, L. Schultz, J. Kirschner, Phys. Rev. B 65, 144405 (2002)

Layer-selective Kerr microscopy

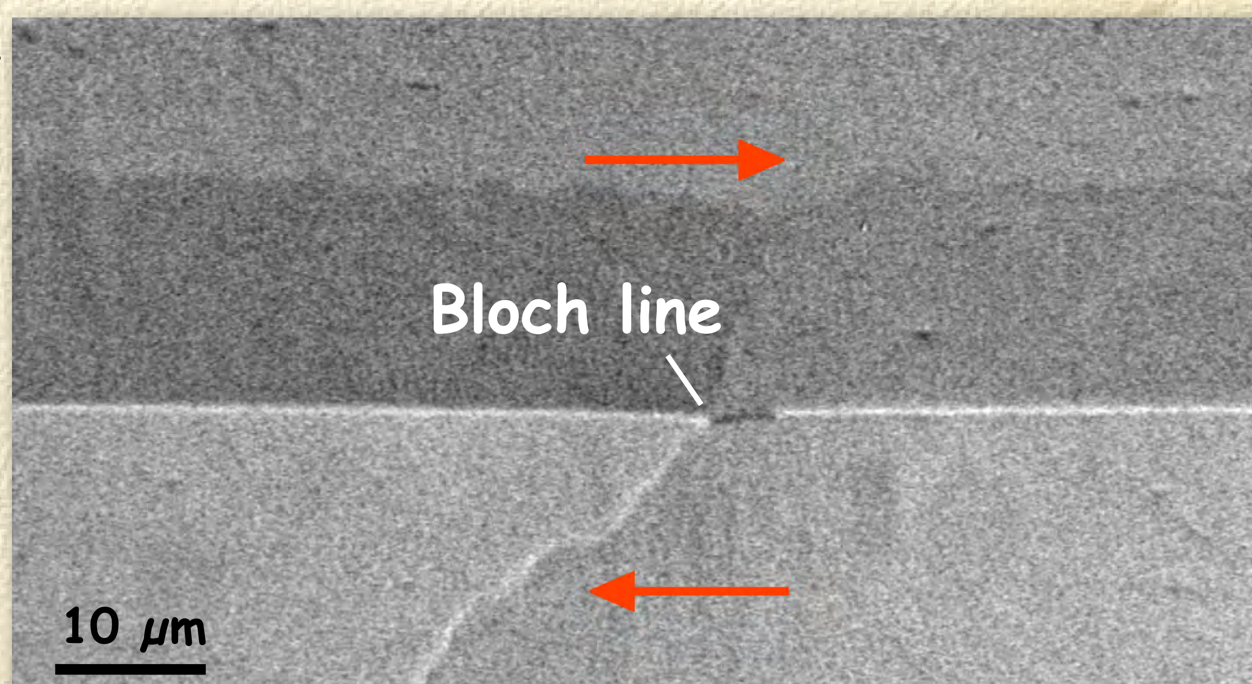




Domains in Fe-film

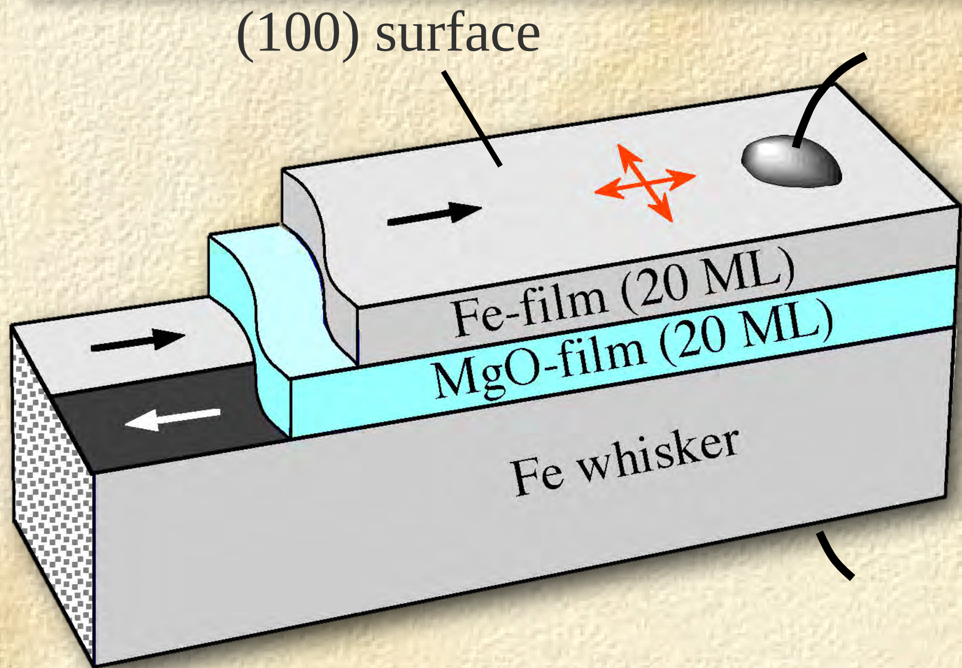


Domains in whisker

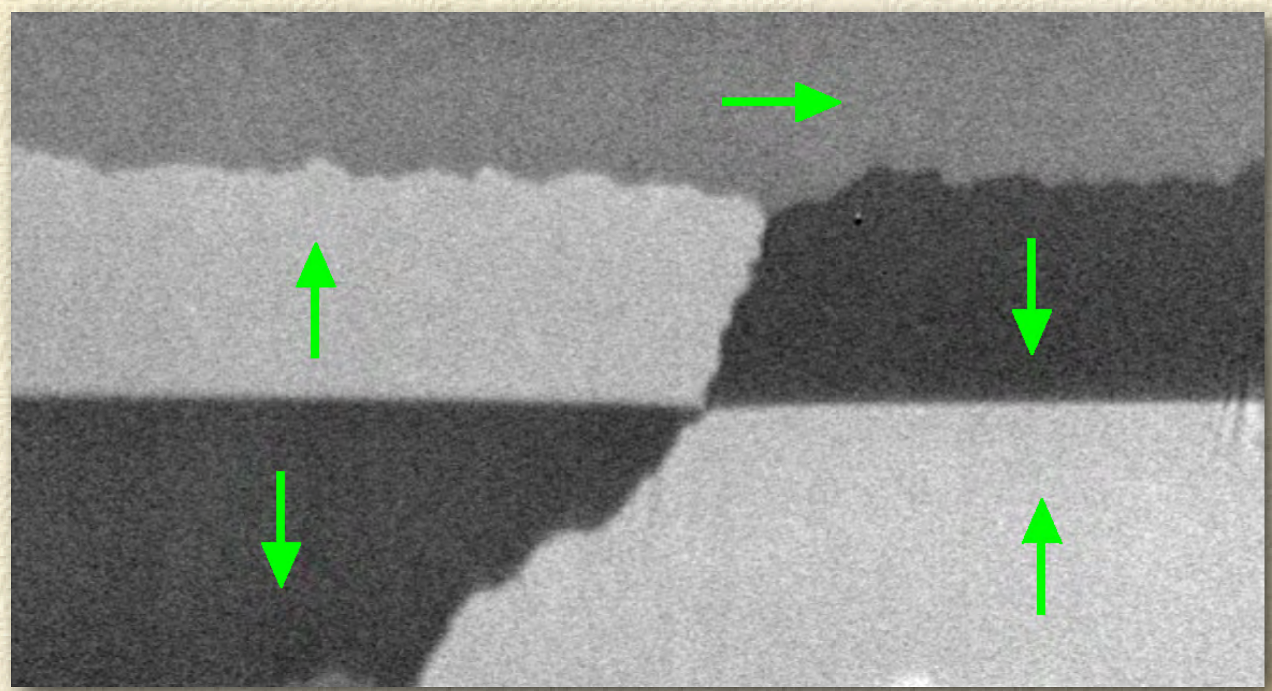


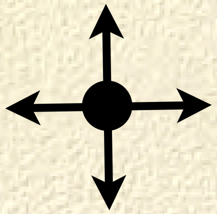
pan, D. Ullmann, H. L. Meyerheim, B. Heinrich, J. Kirschner, Phys. Rev. B 65, 144405 (2002)

Layer-selective Kerr microscopy



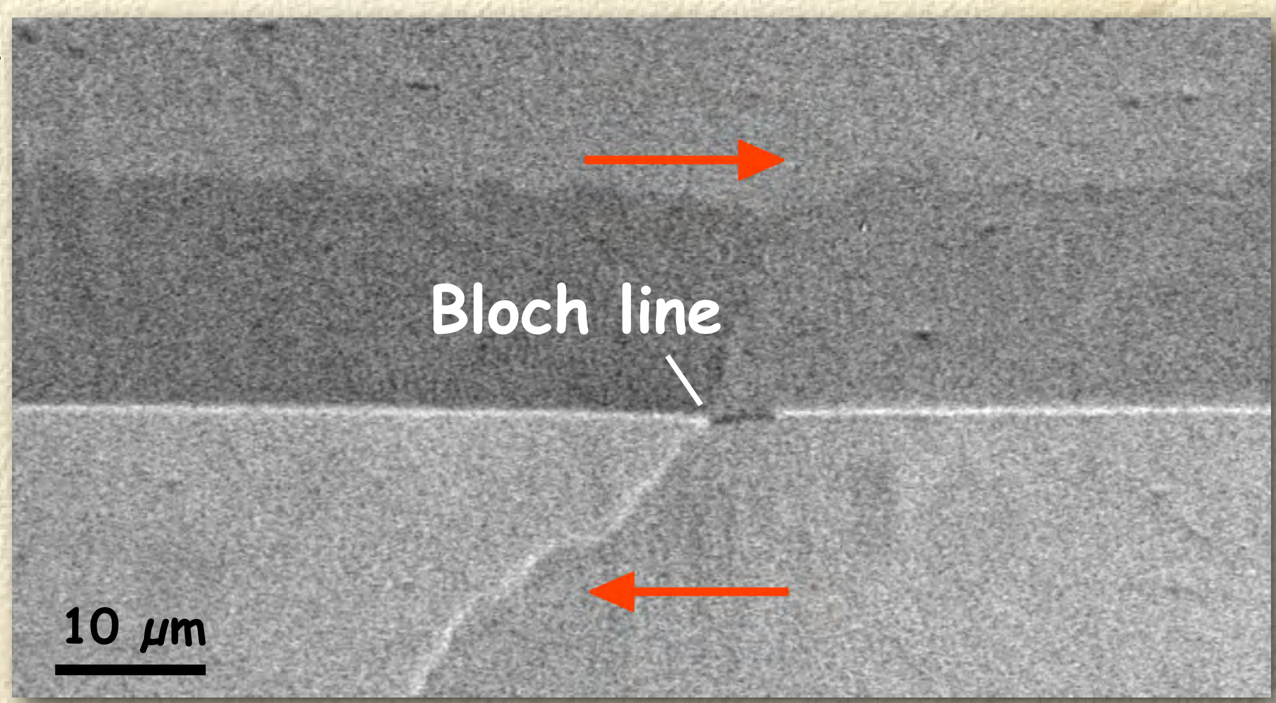
Domains in Fe-film

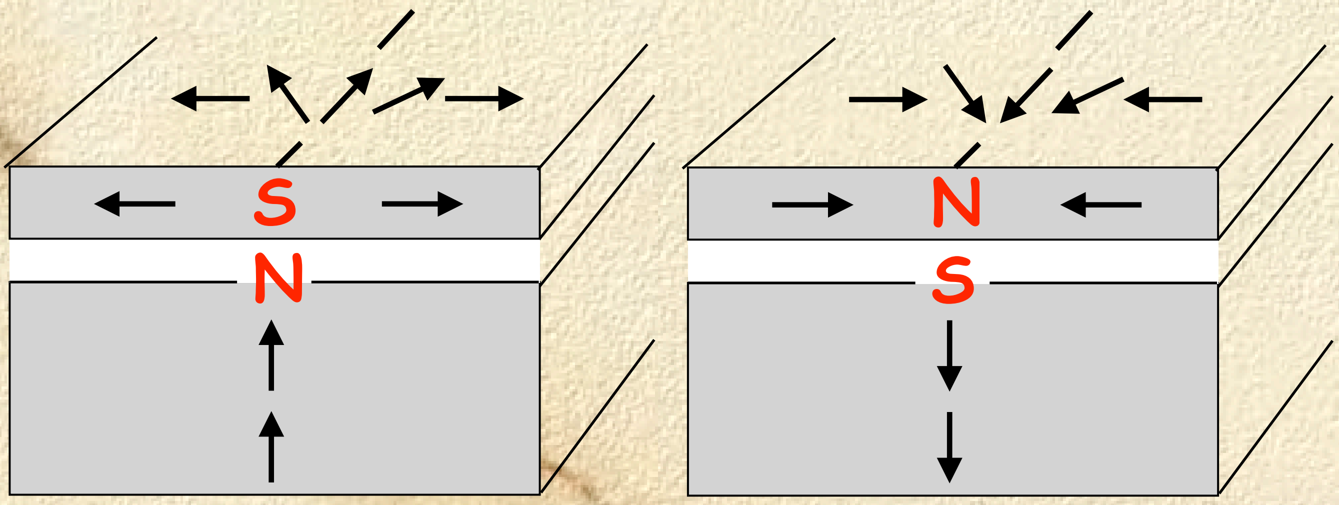




easy axis

Domains in whisker

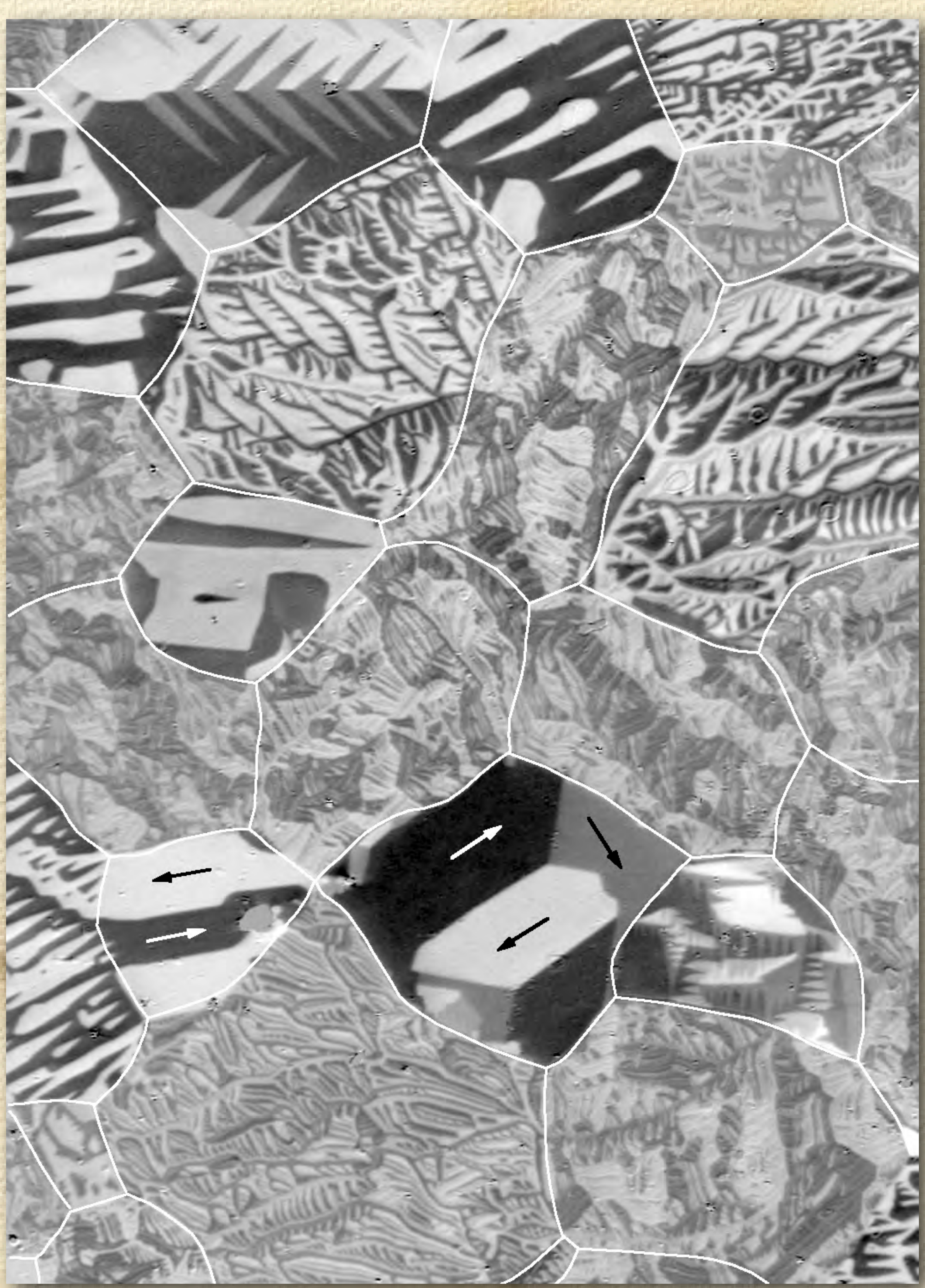




R.S., R Urban, D. Ullmann, H. L. Meyerheim, B. Heinrich, L. Schultz, J. Kirschner, Phys. Rev. B 65, 144405 (2002)

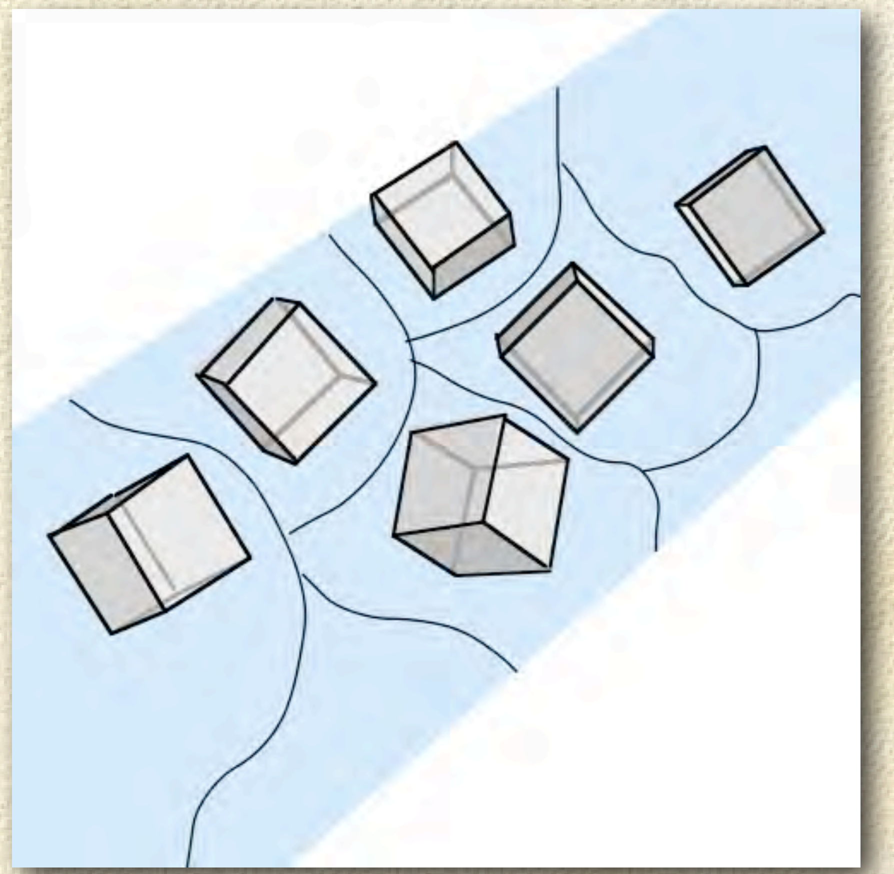
Bulk materials:
Domain analysis can be more or less difficult

Non-oriented FeSi sheet



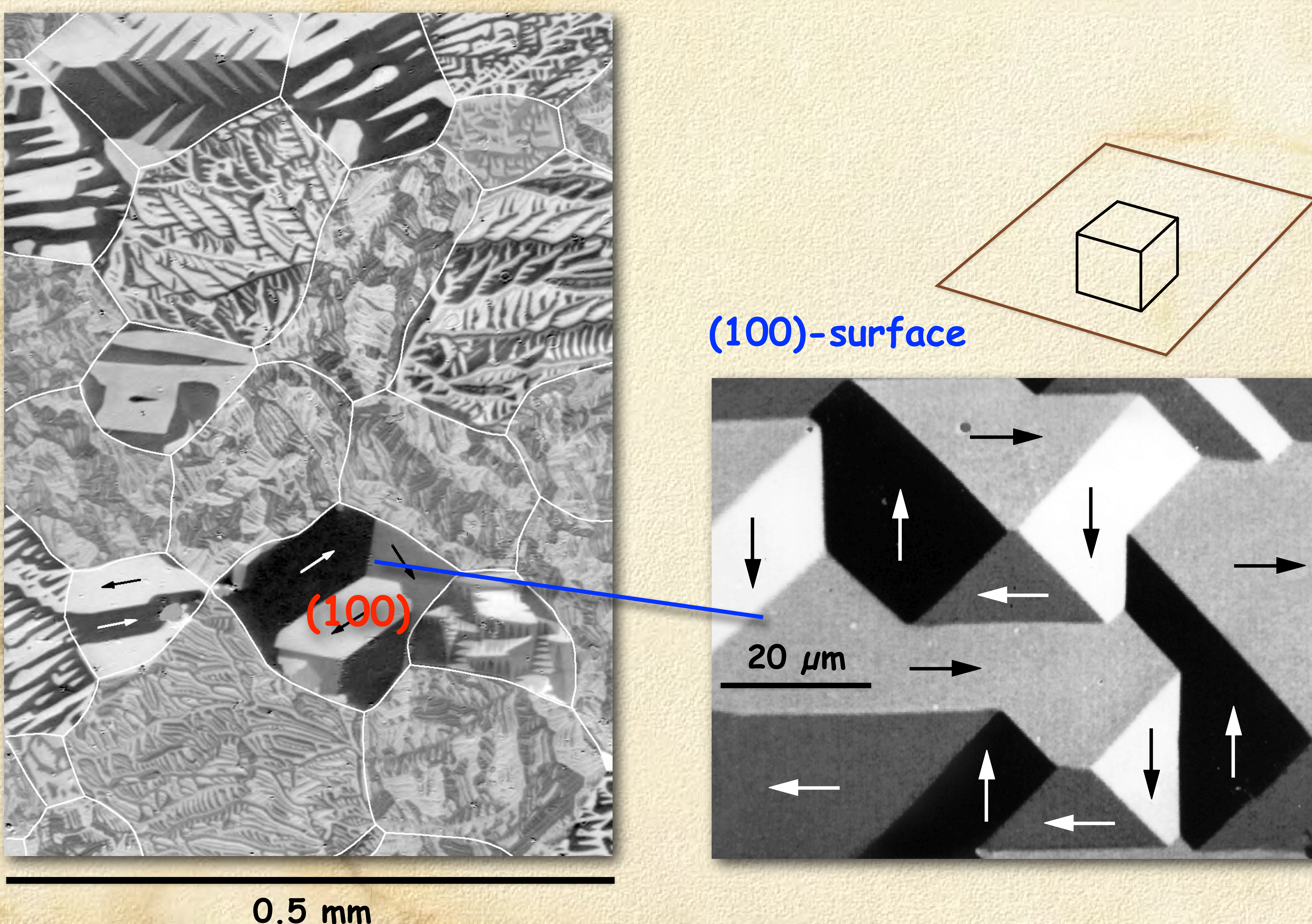
0.5 mm

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

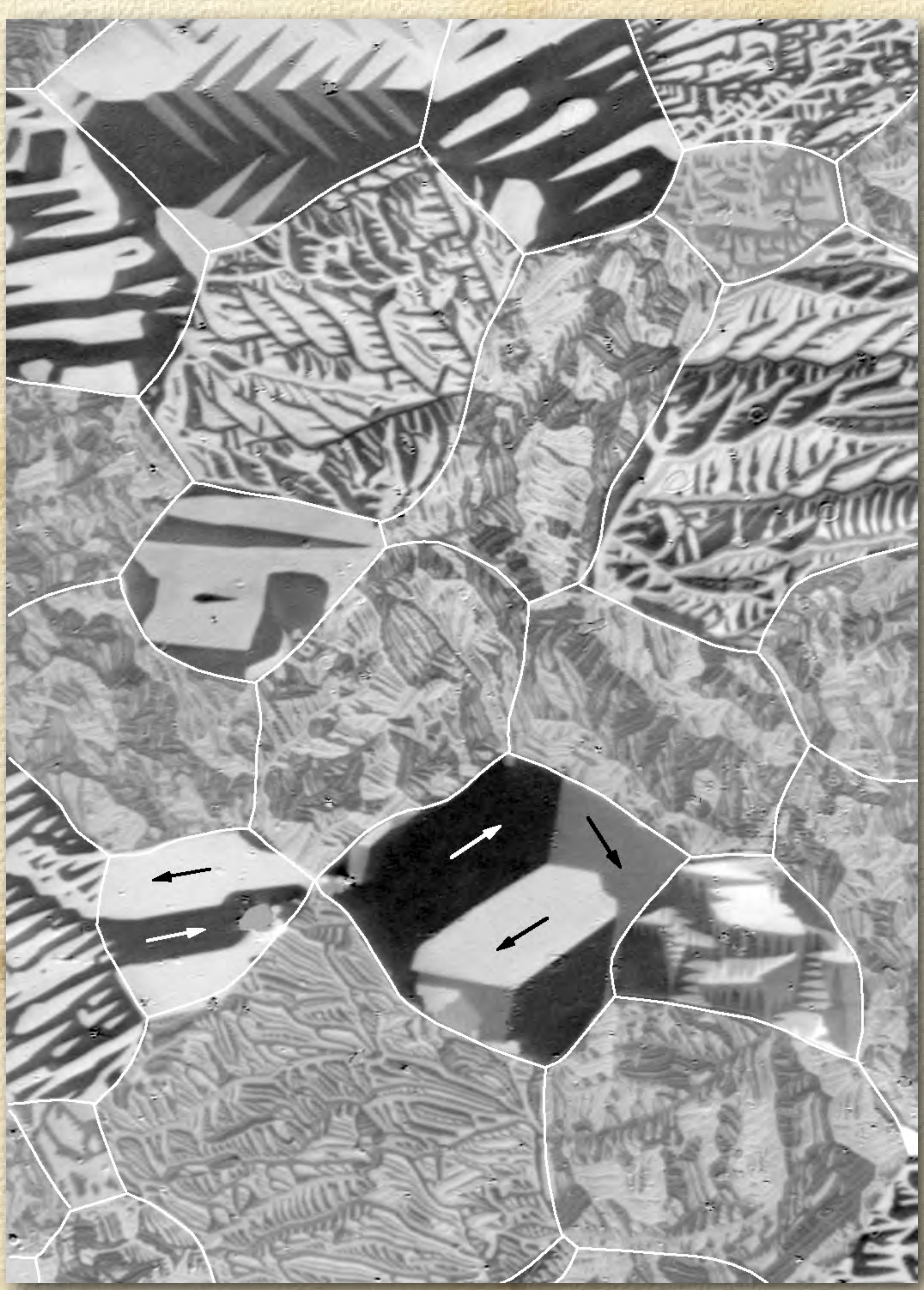


Surface orientation determines domain character

Non-oriented FeSi sheet

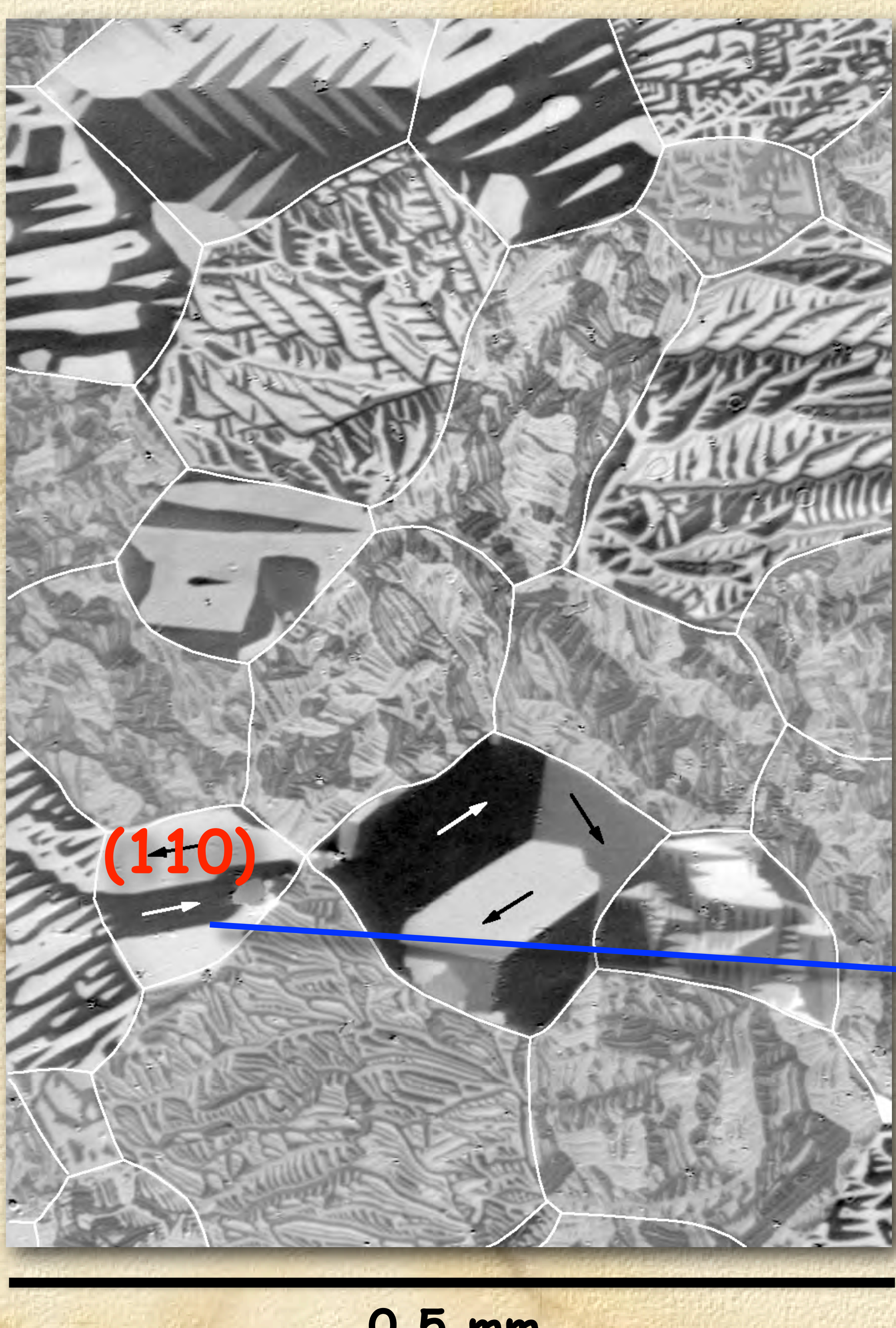


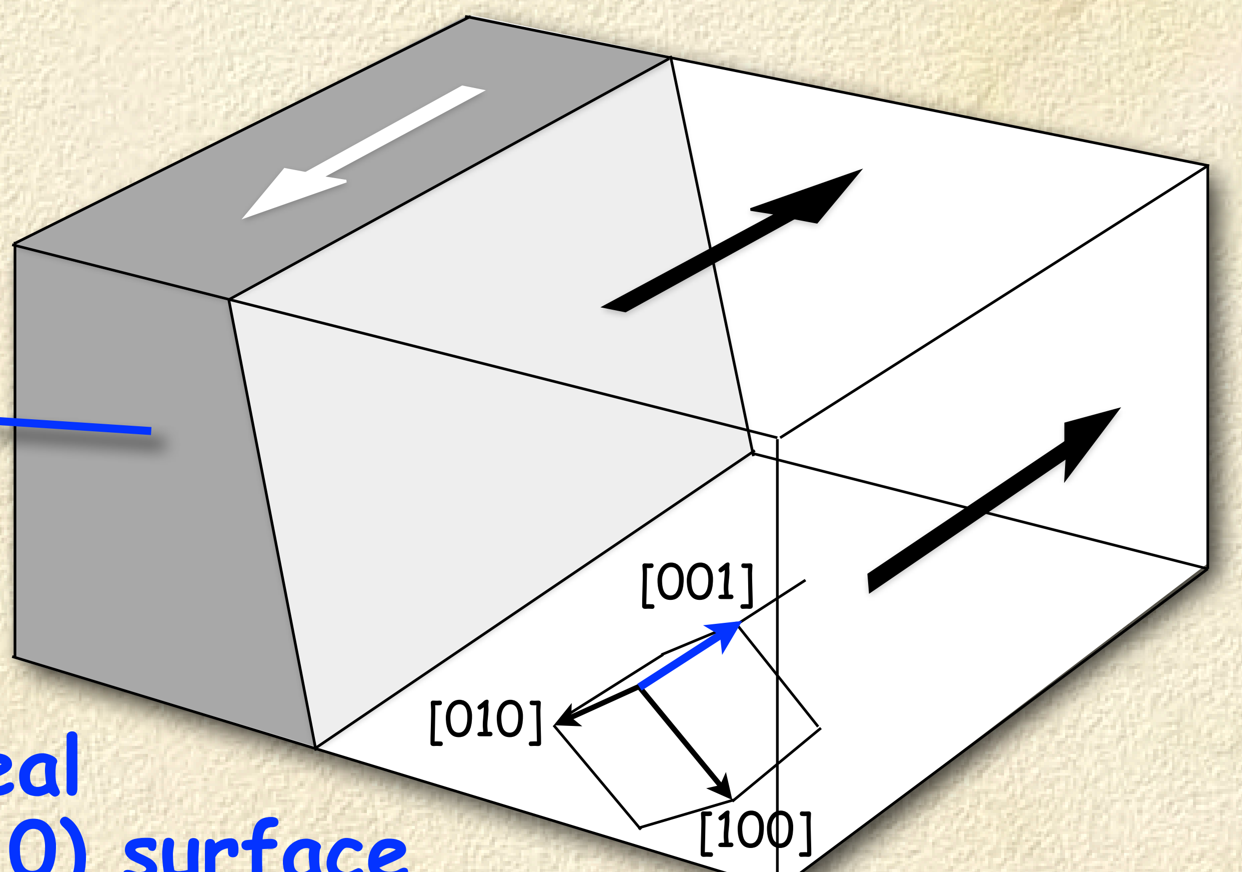
Non-oriented FeSi sheet



0.5 mm

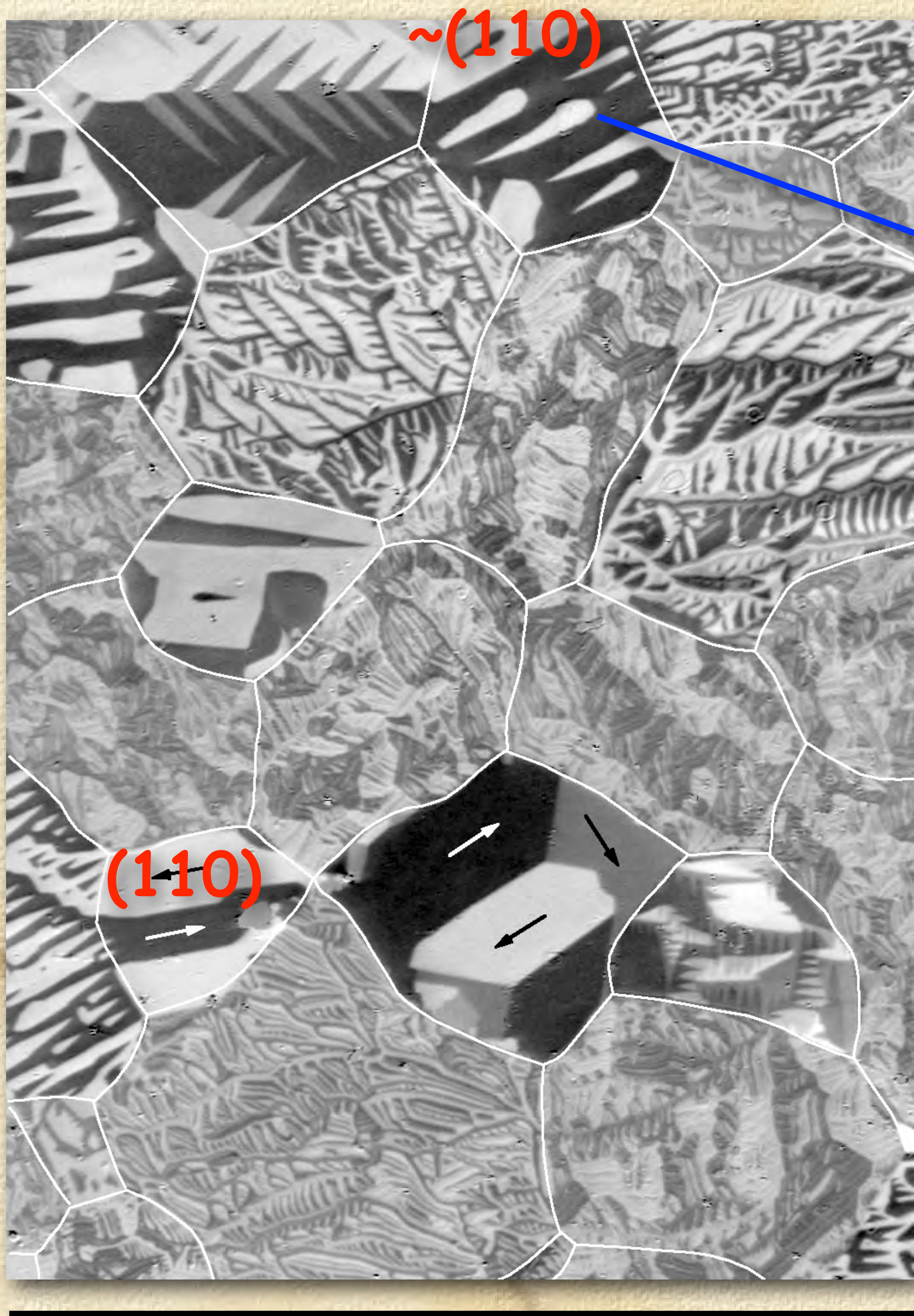
Non-oriented FeSi sheet



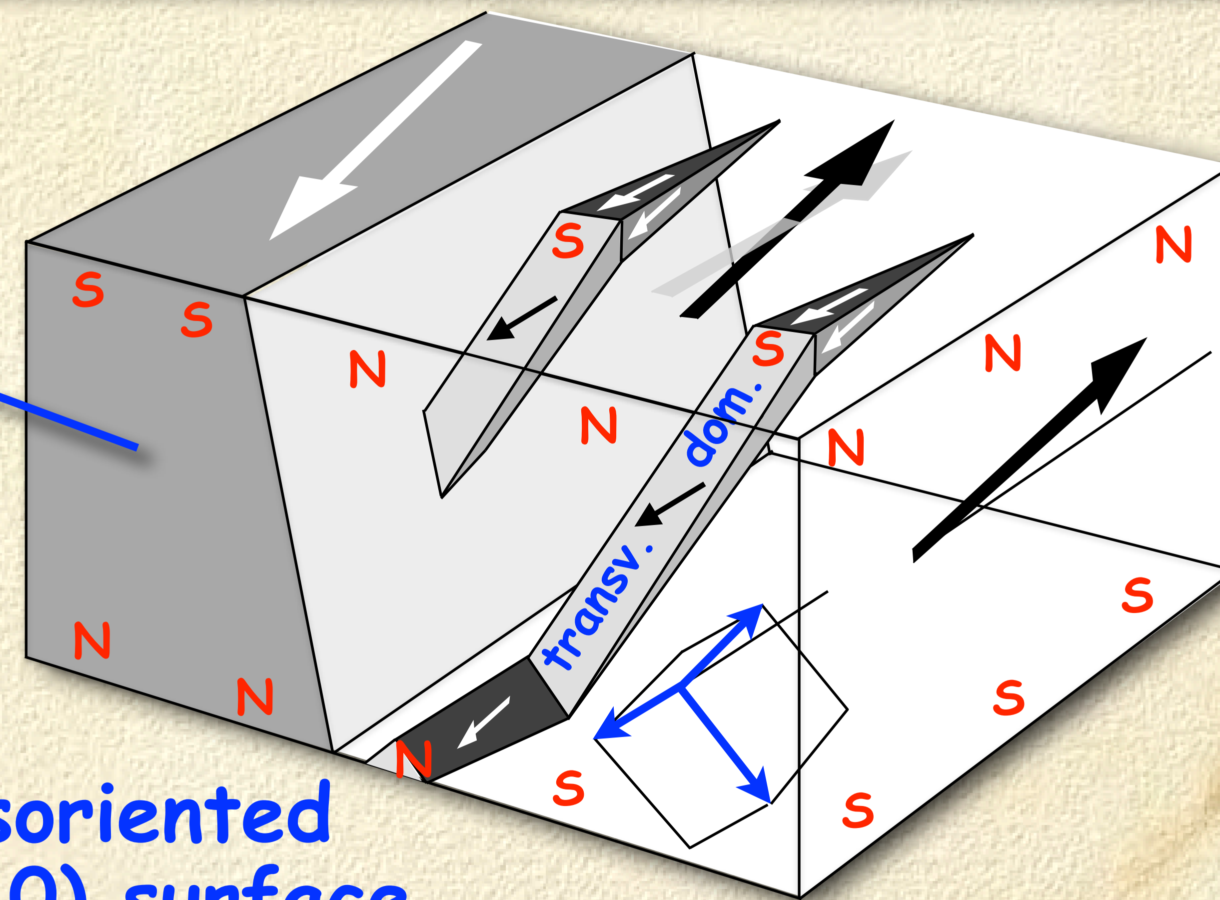


Ideal
(110) surface

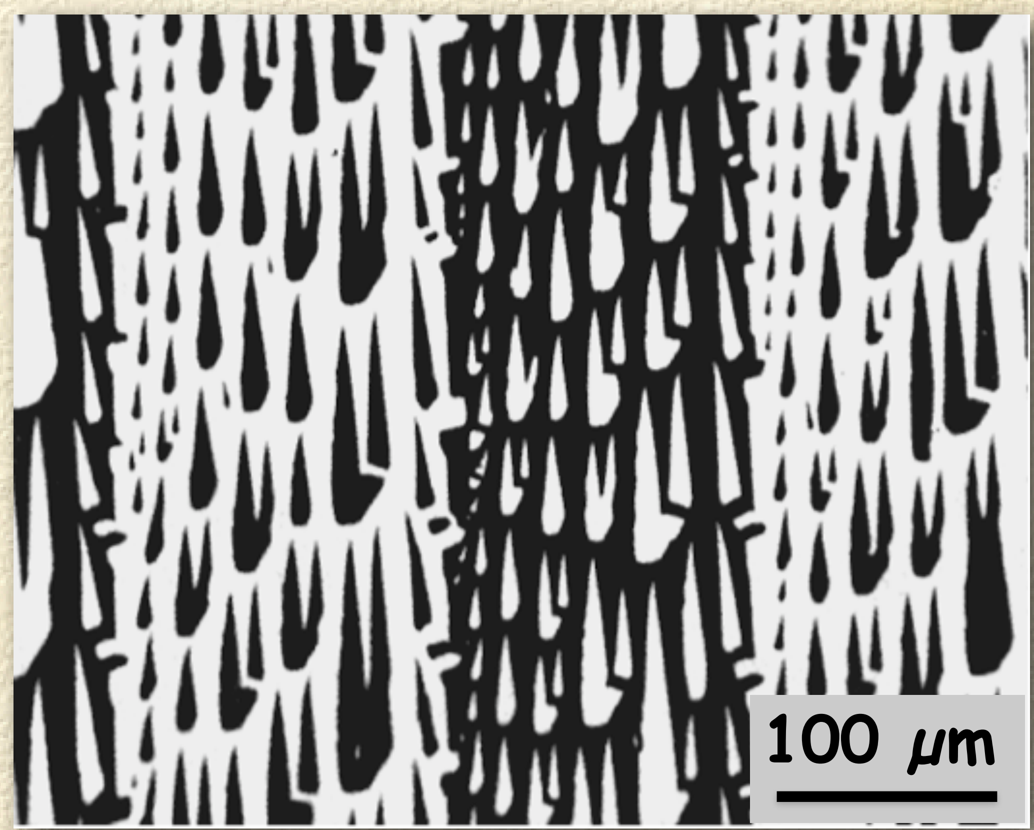
Non-oriented FeSi sheet



0.5 mm



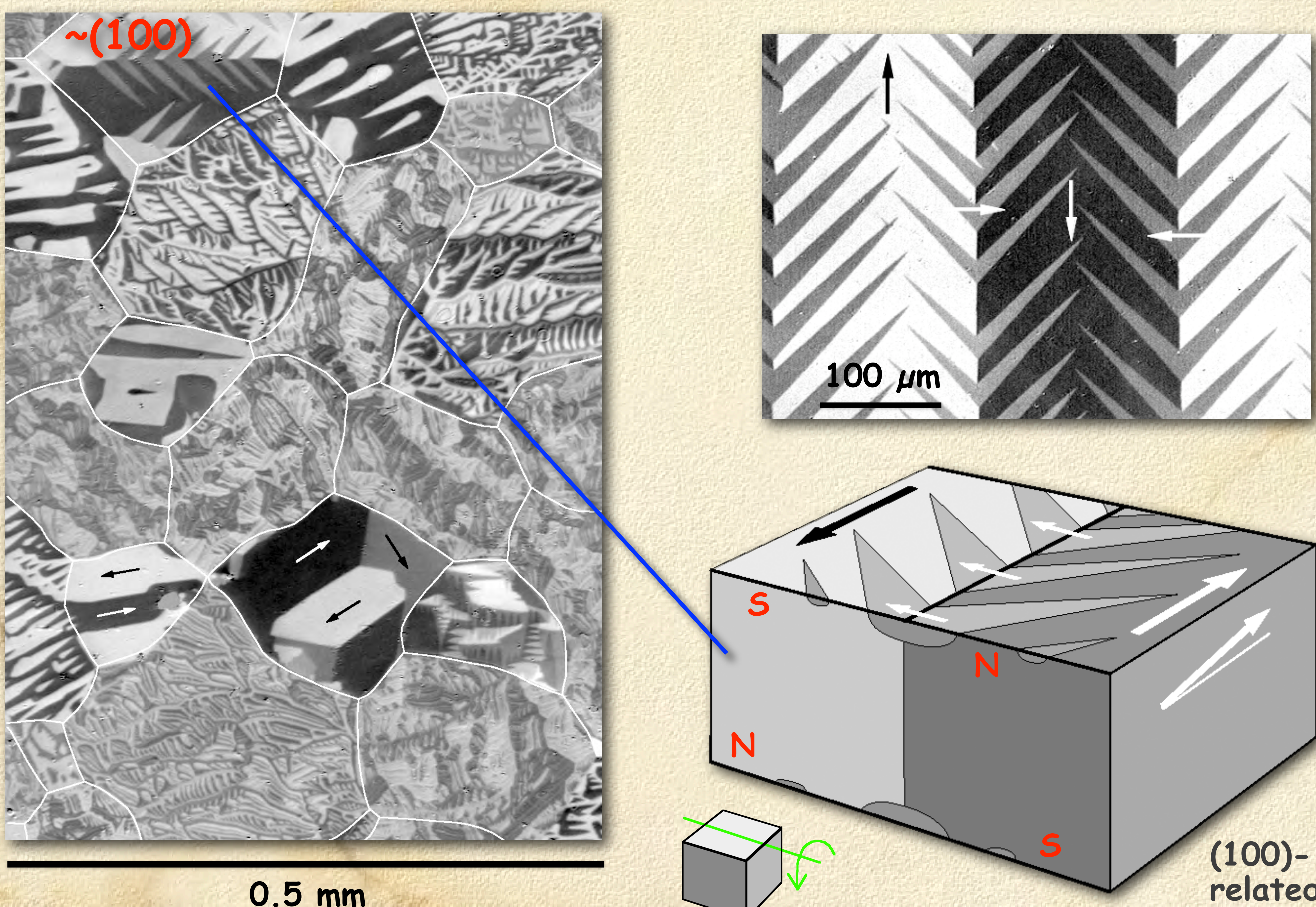
Misoriented
(110) surface



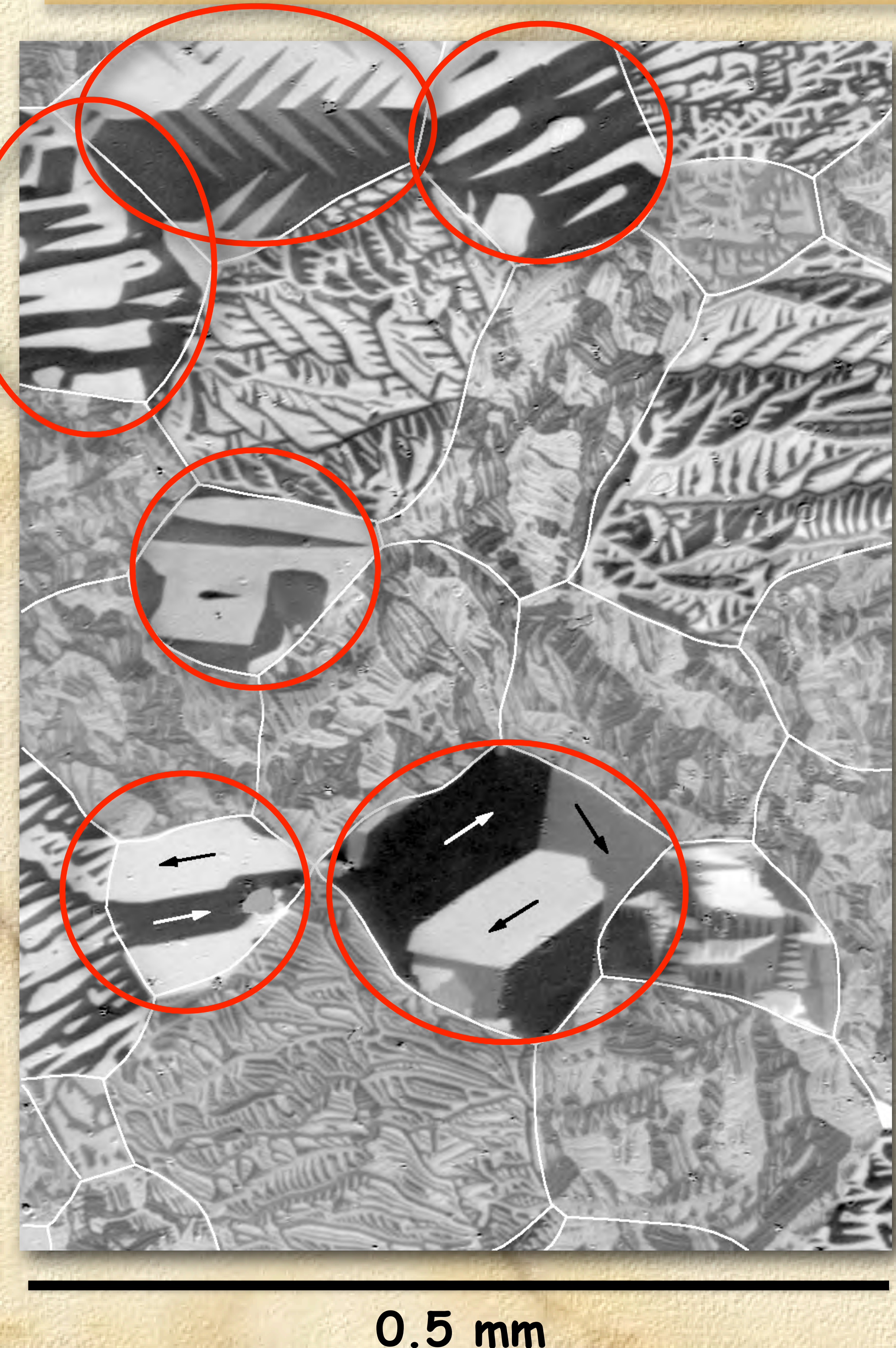
Non-oriented FeSi sheet

0.5 mm

Non-oriented FeSi sheet



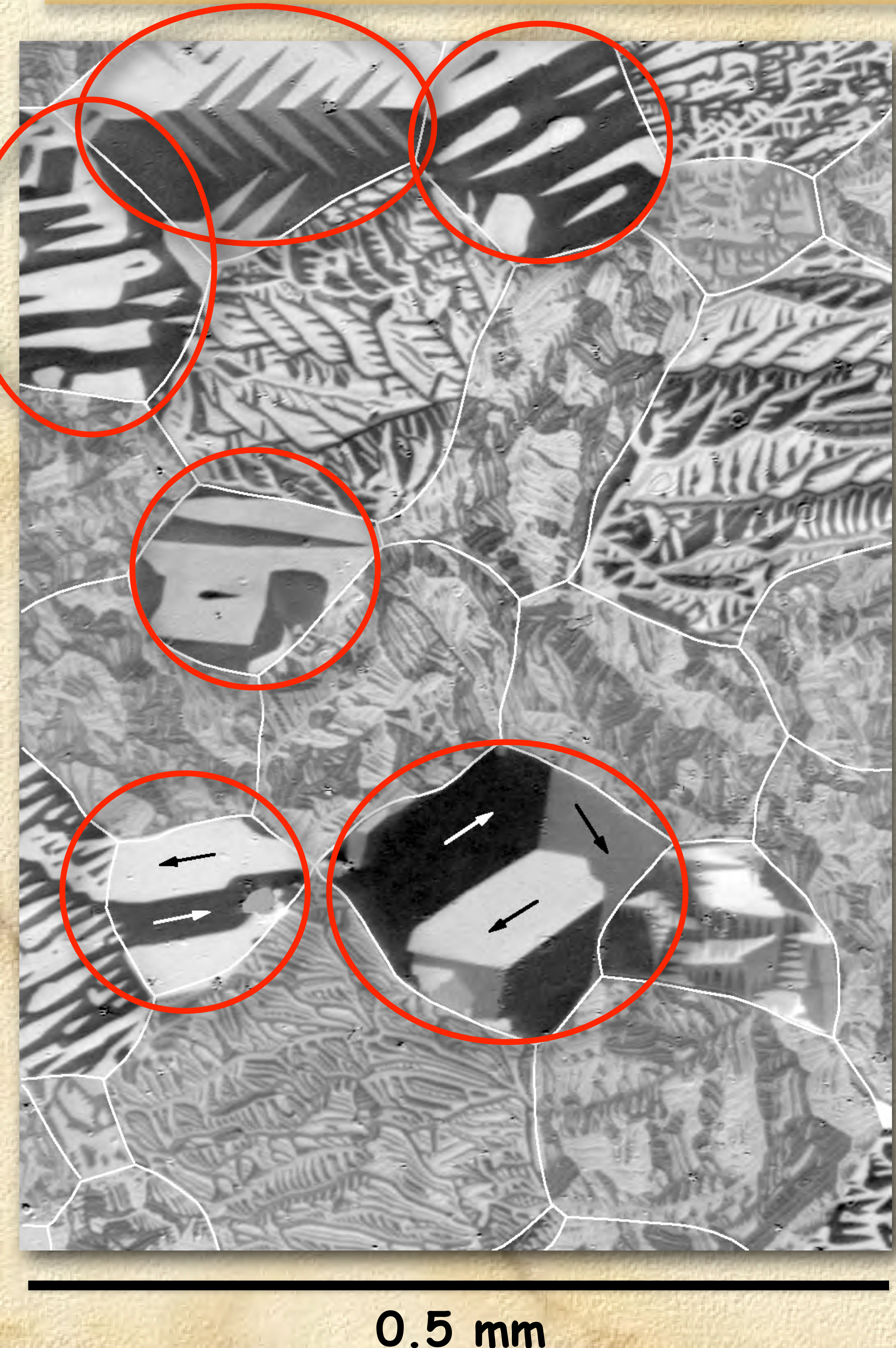
Non-oriented FeSi sheet



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

basic domains and supplementary pattern

Non-oriented FeSi sheet



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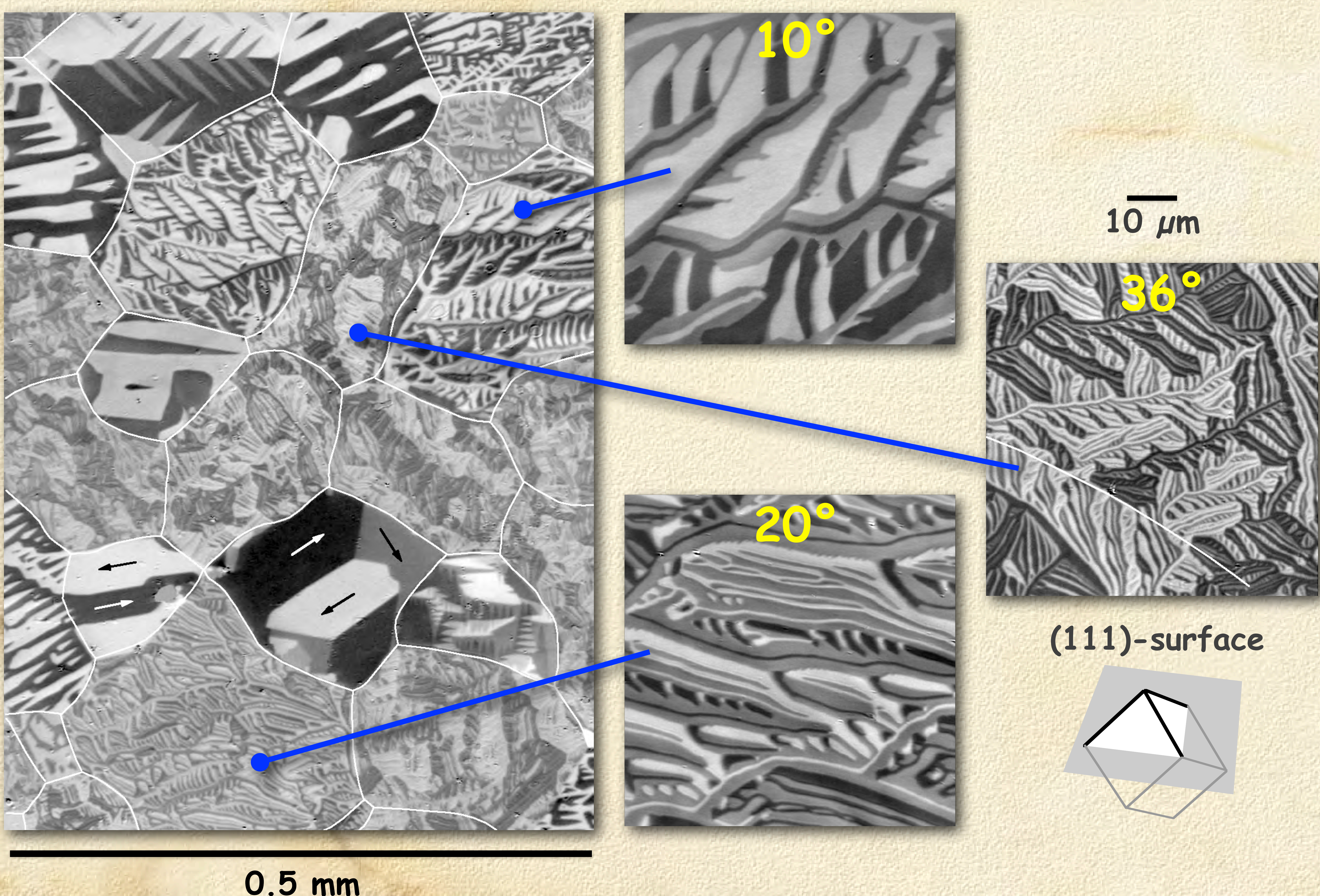
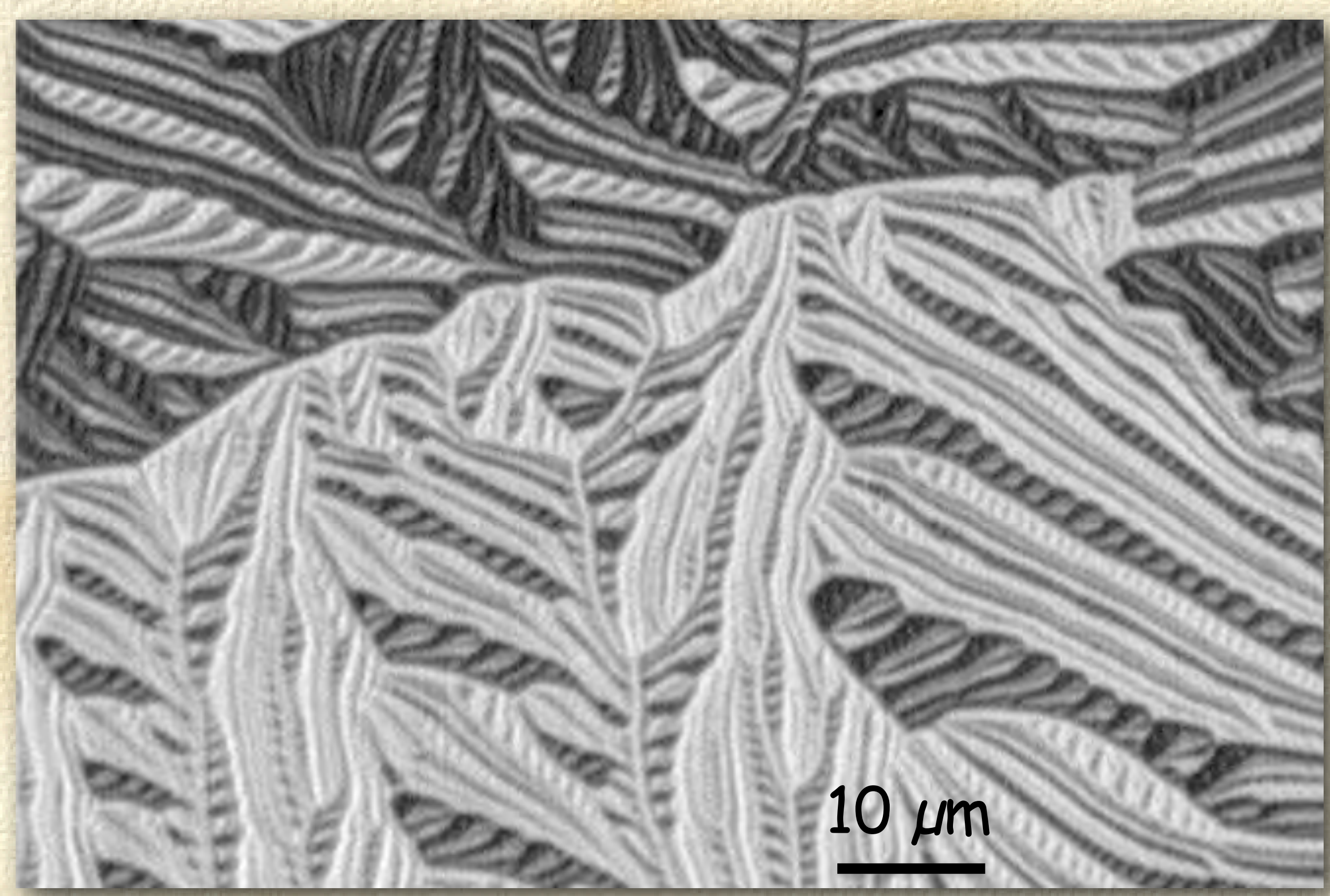
basic domains and supplementary pattern

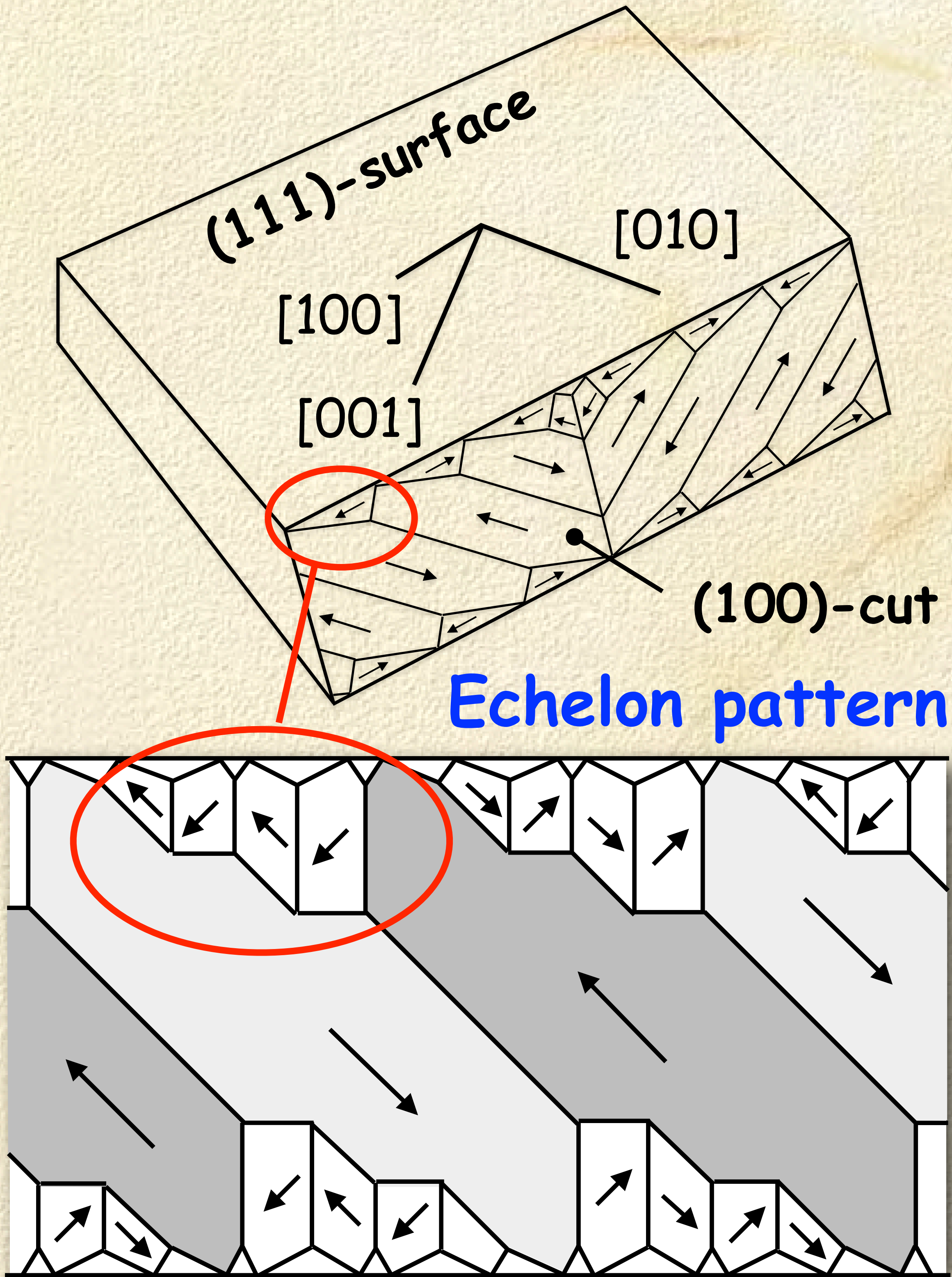
Non-oriented FeSi sheet

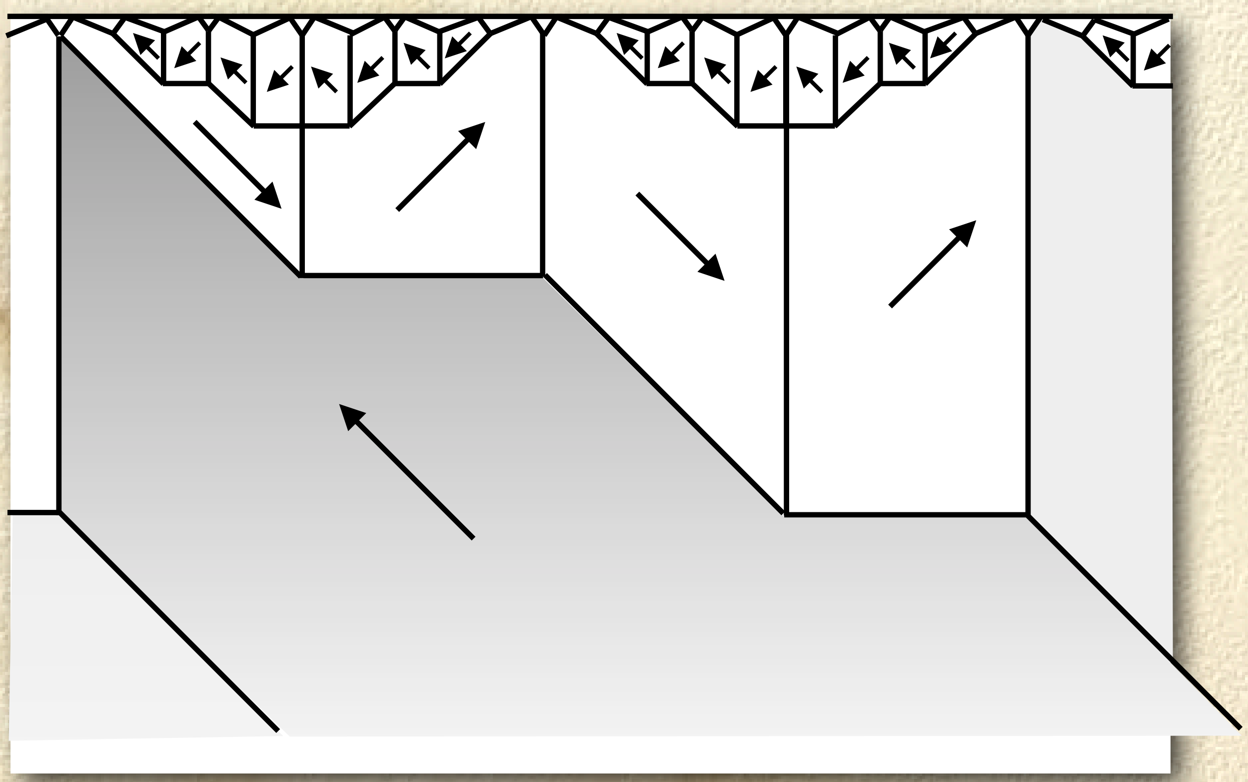


Extreme misorientation: Domain branching

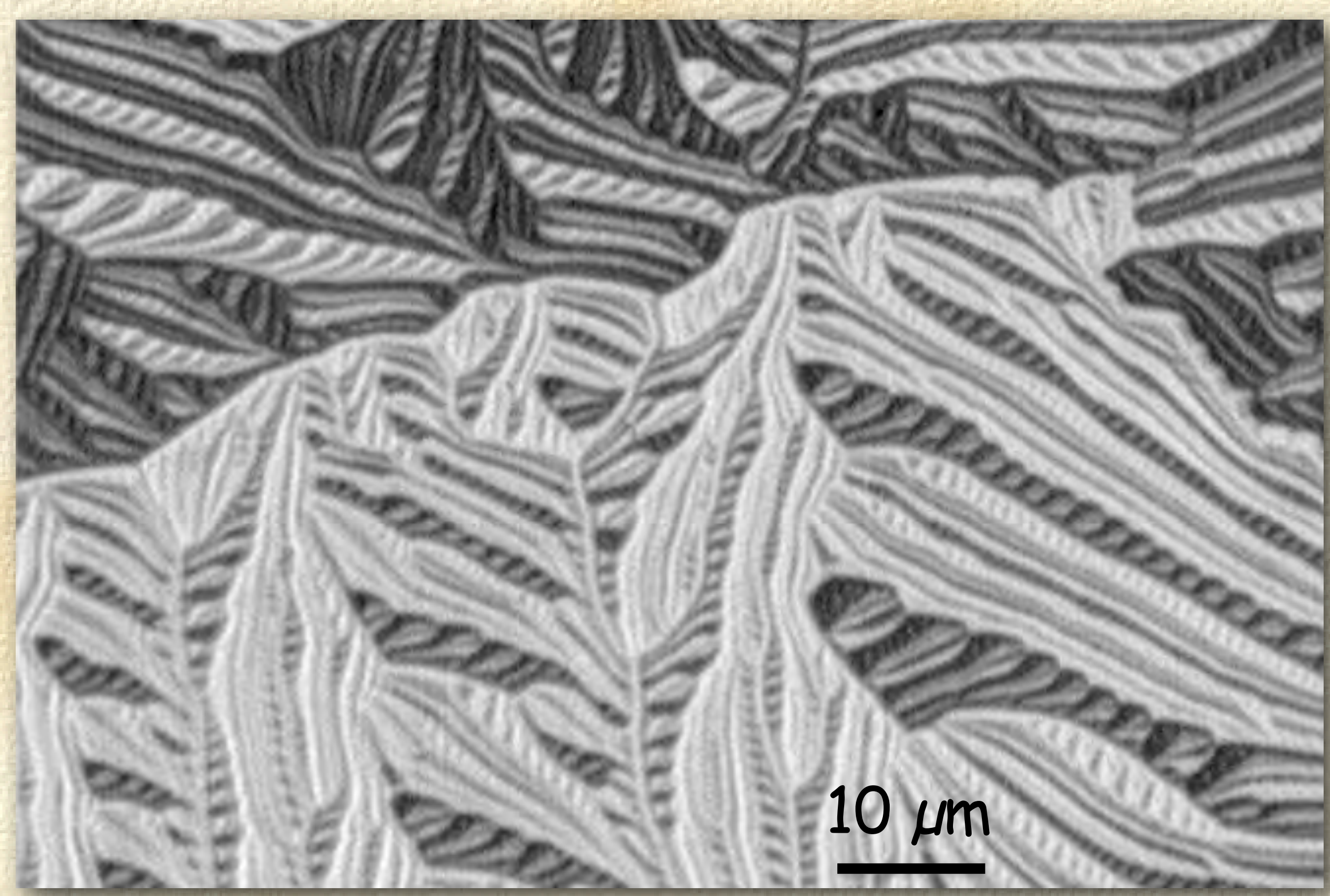
Iron: $Q = 0.02$



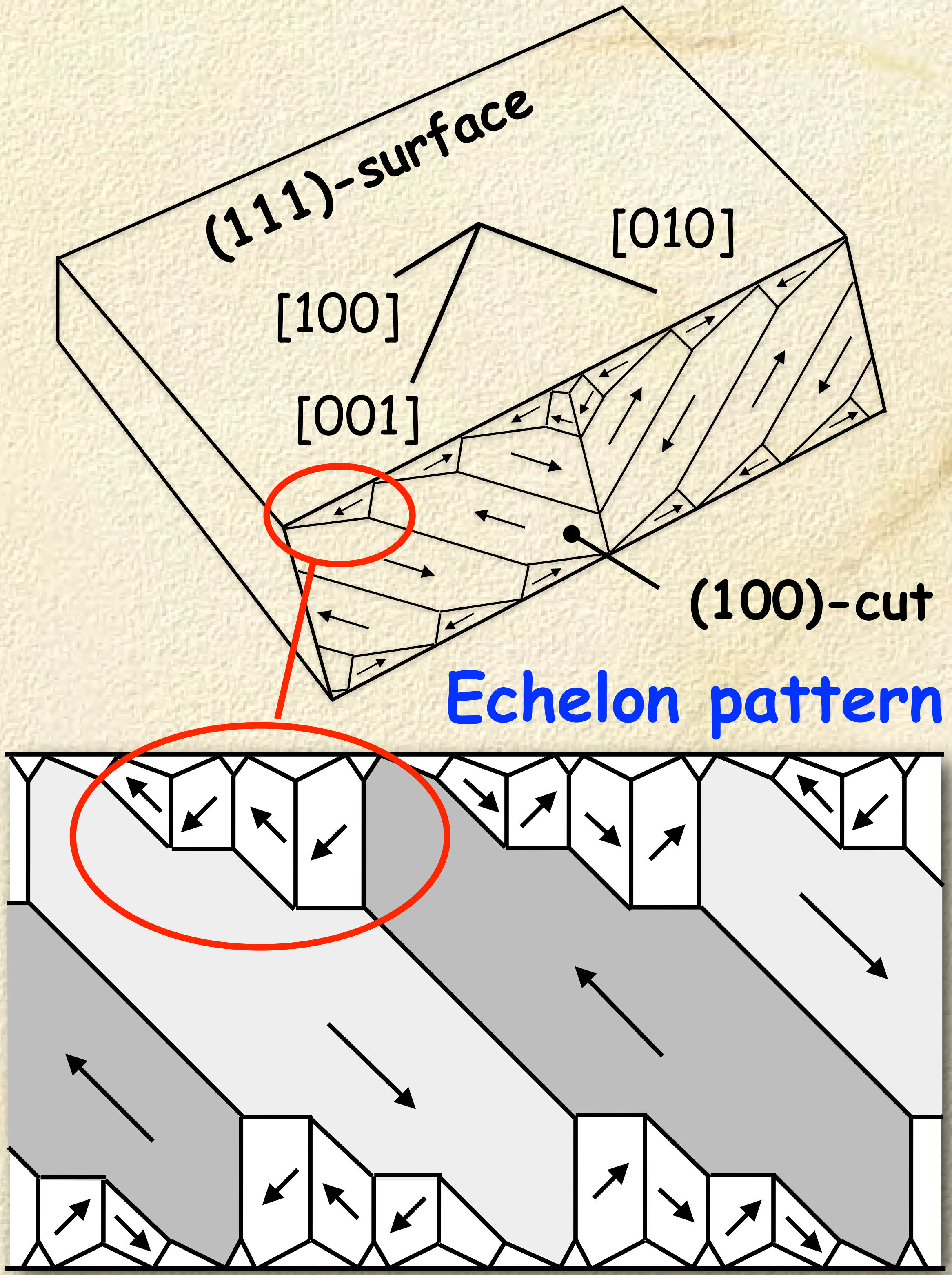


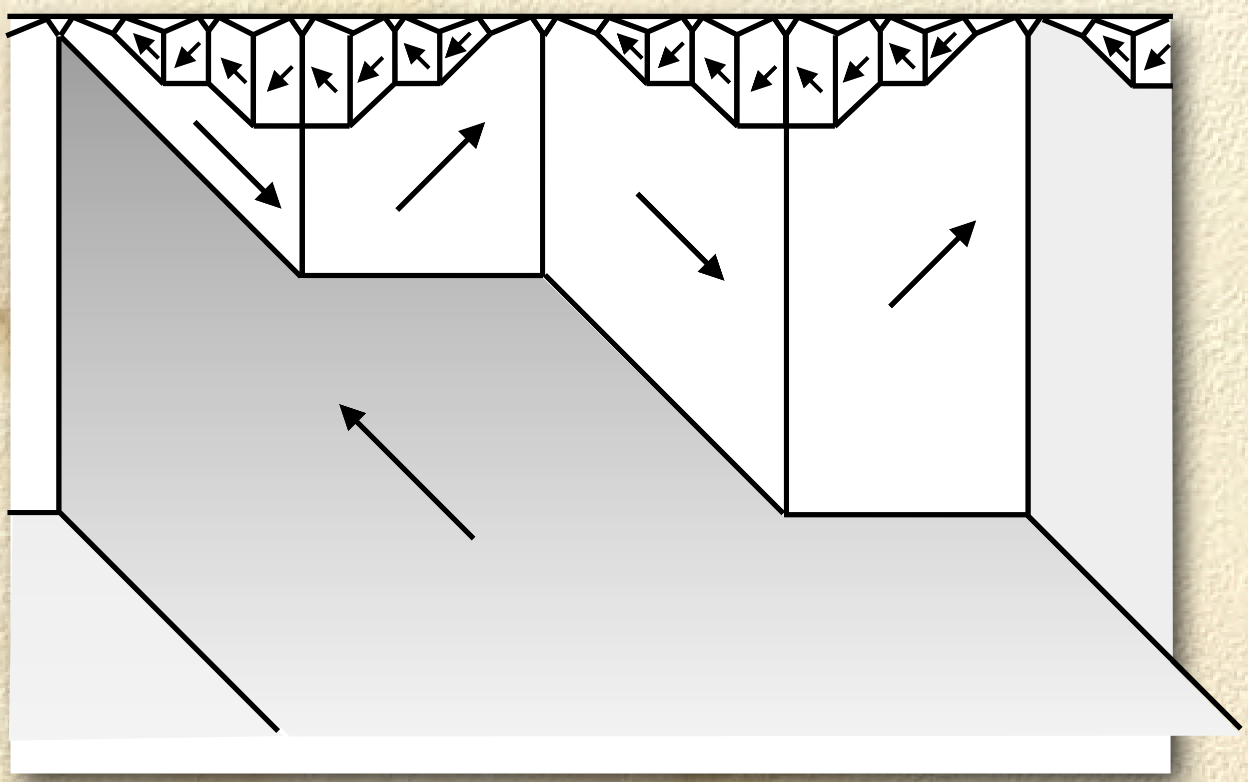


Problem: only surface domains can be seen



Iron: $Q = 0.02$





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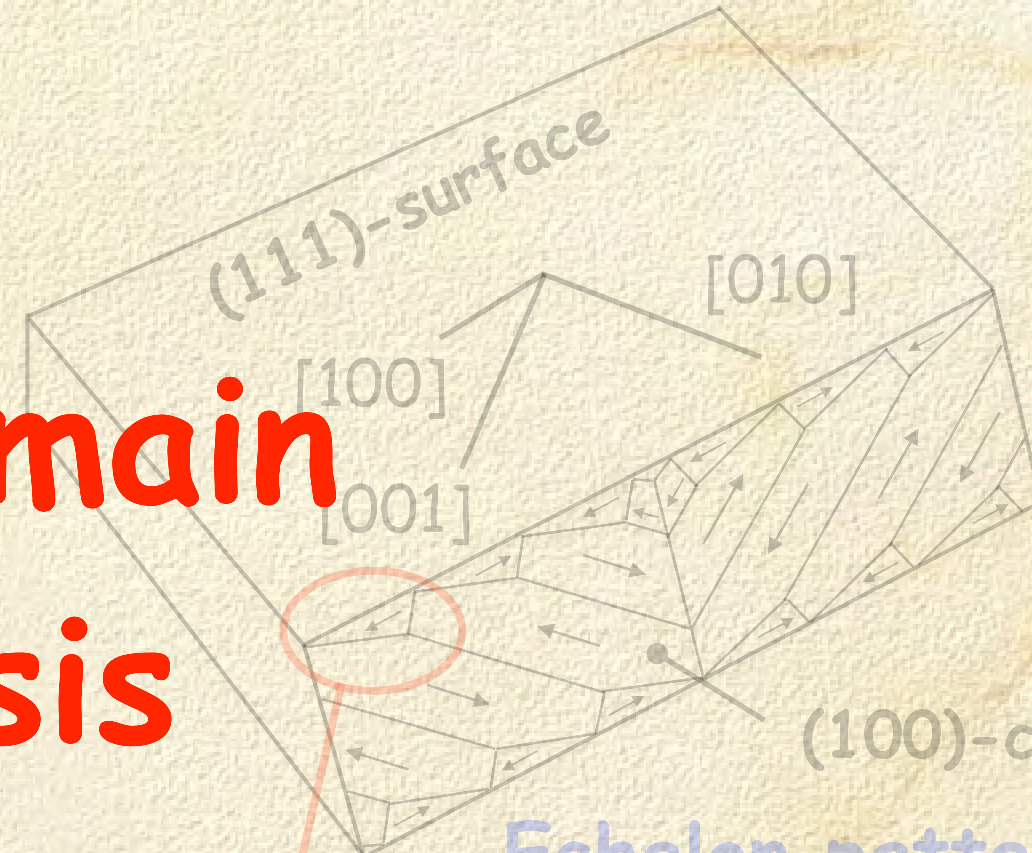
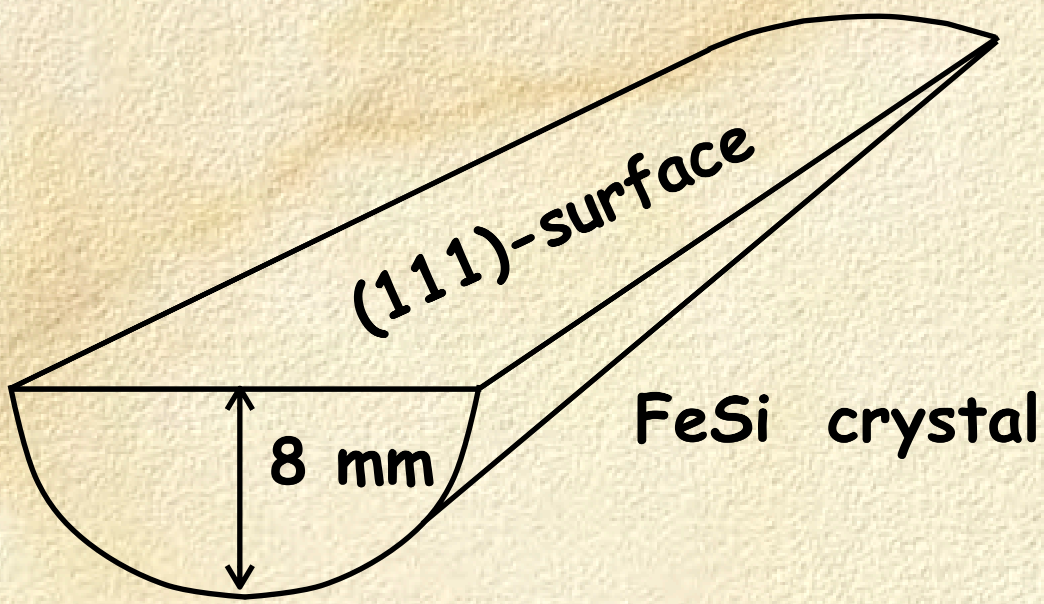
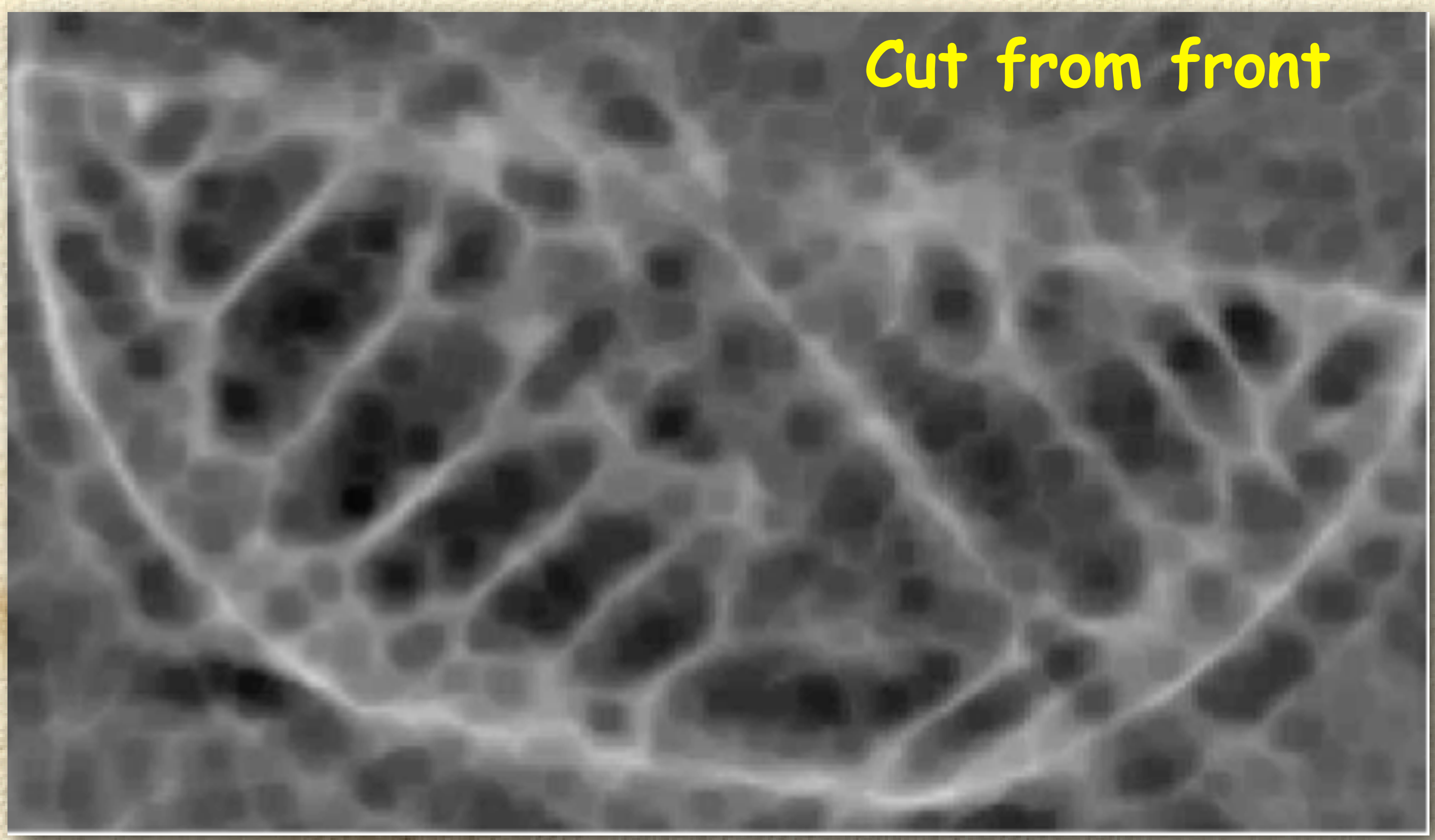


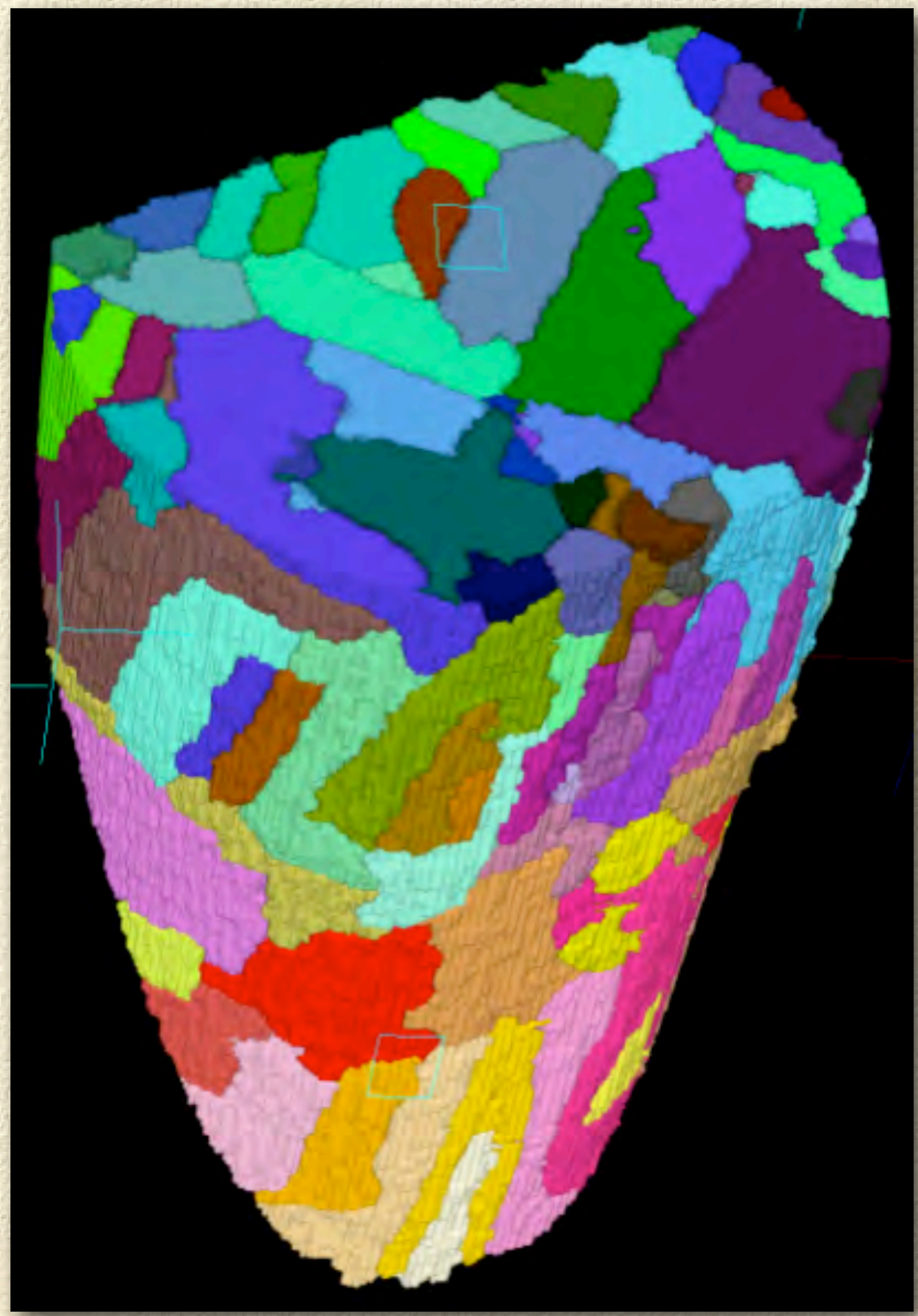
Echelon pattern

Bulk Domain Analysis

Neutron dark-field tomography

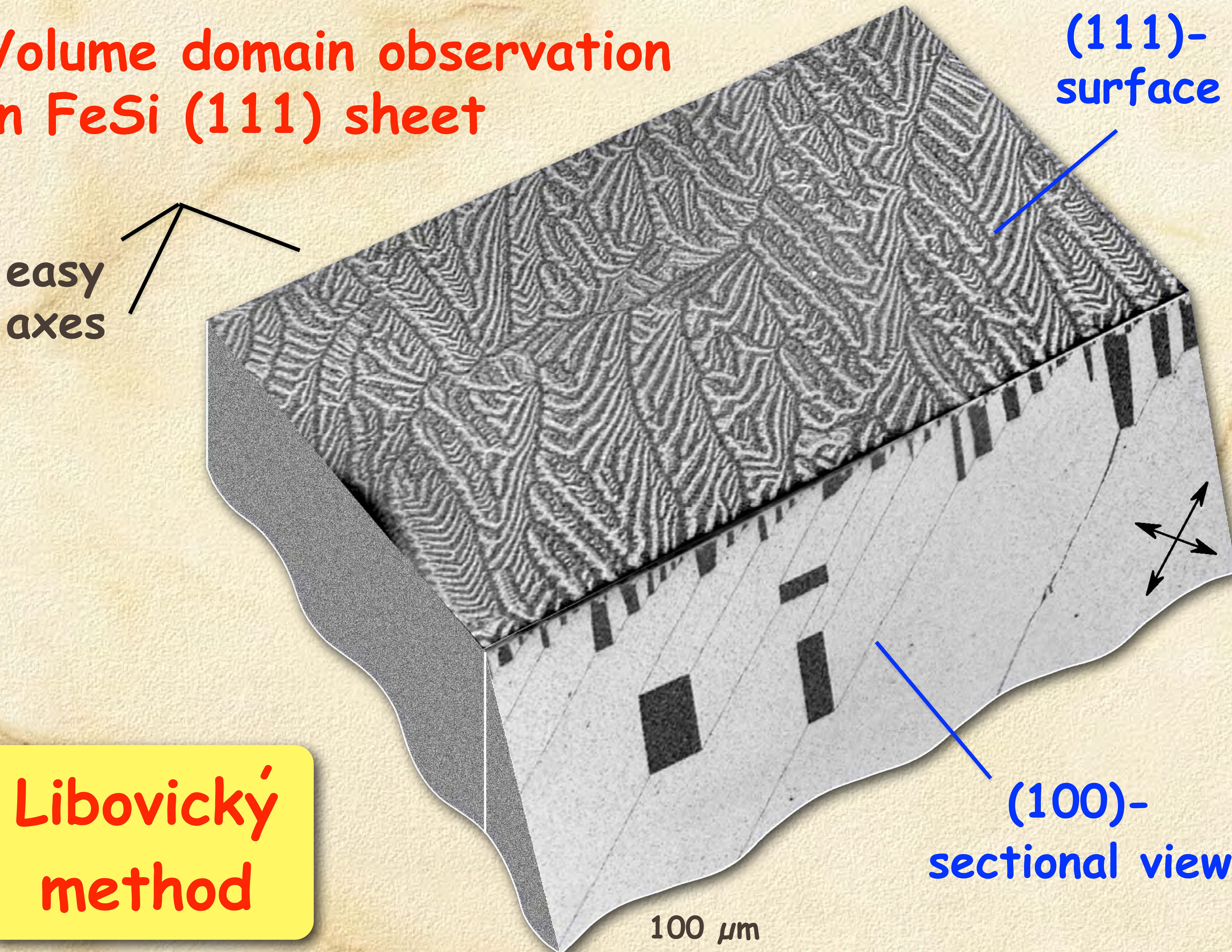






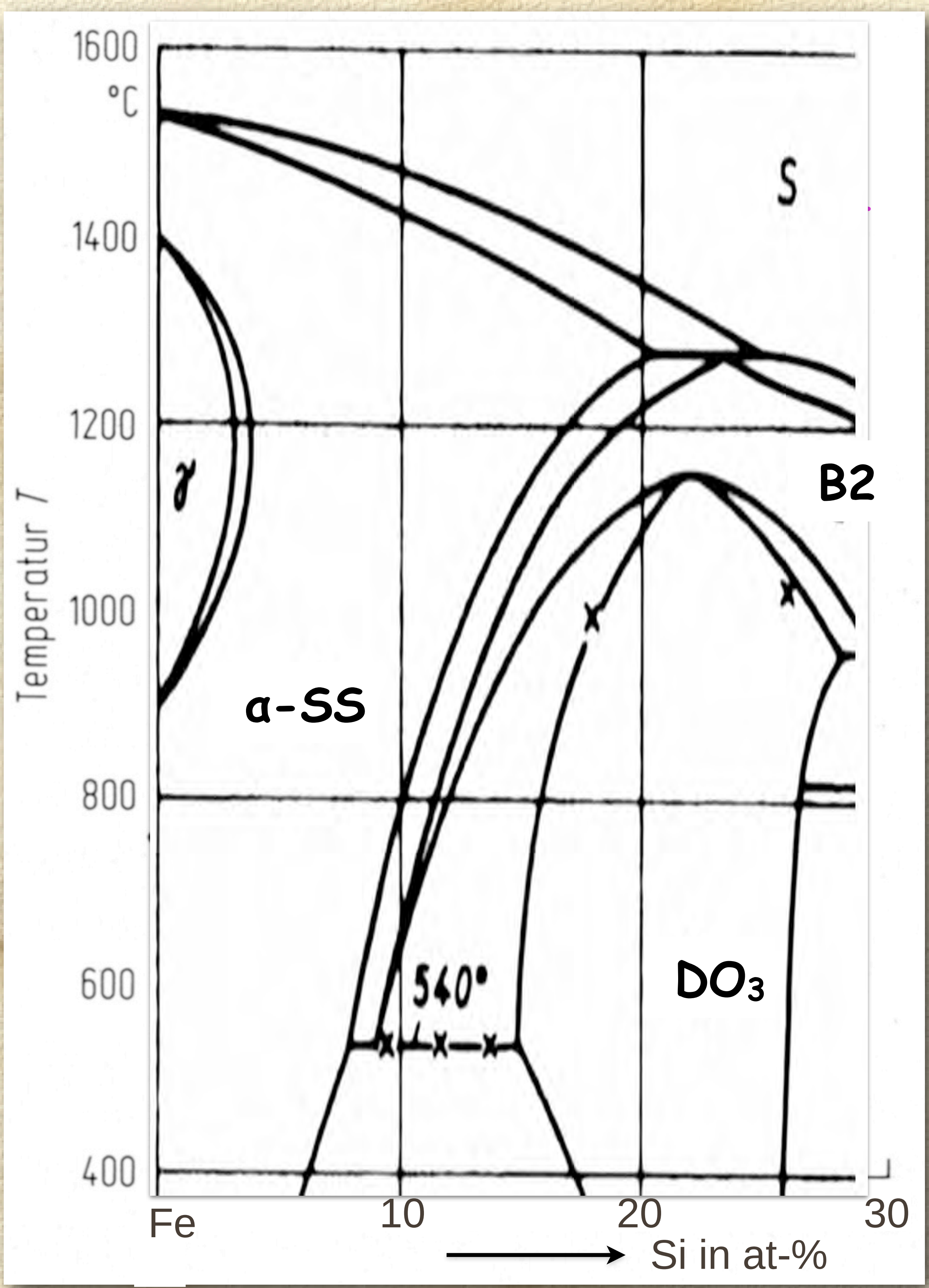
I. Manke, et al.: Three-dimensional imaging of magnetic domains.
Nature Communications, 1:125 doi: 10.1038/ncomms1125 (2010)

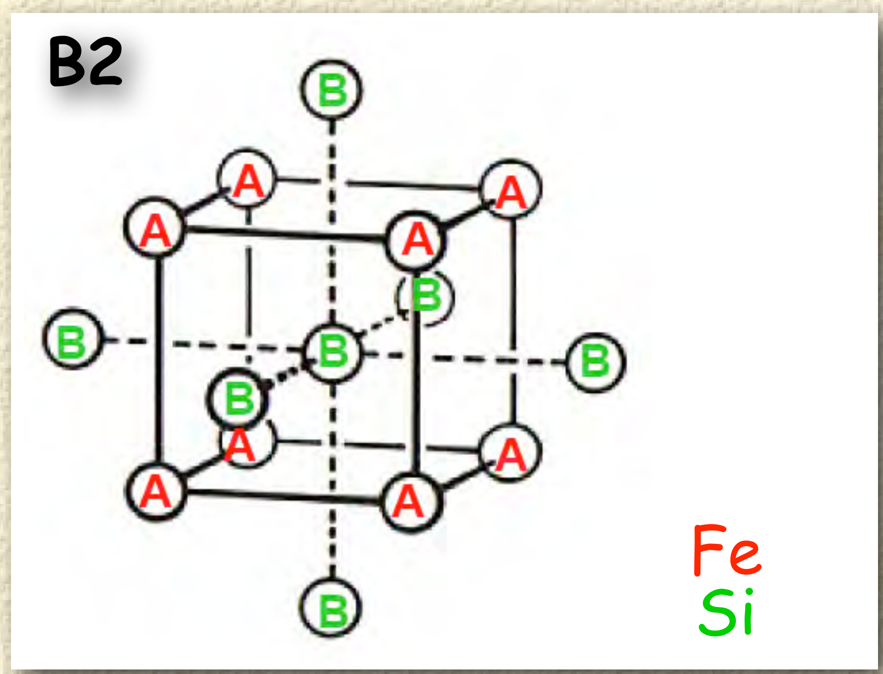
Volume domain observation in FeSi (111) sheet

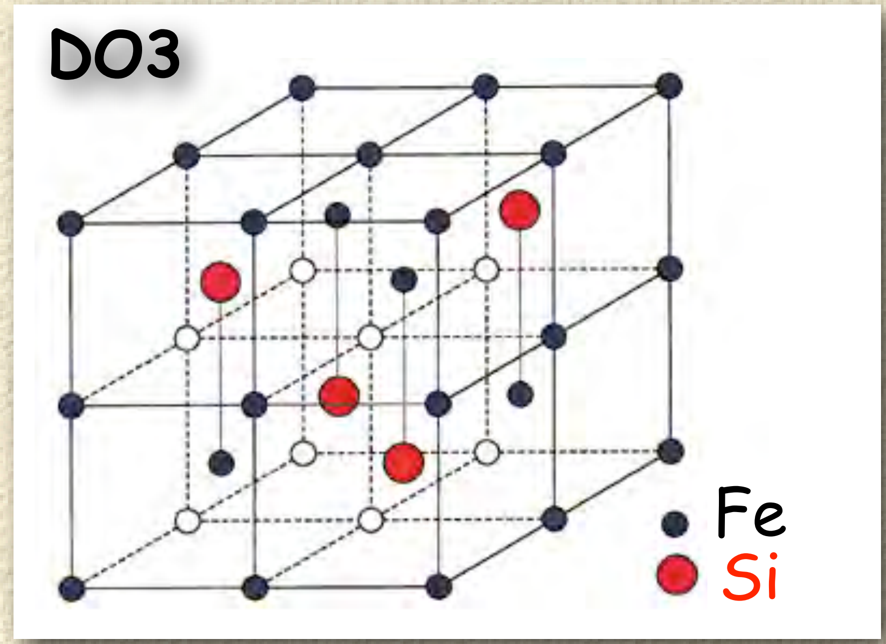


Libovický method

Bulk domain observation by Libovický-method

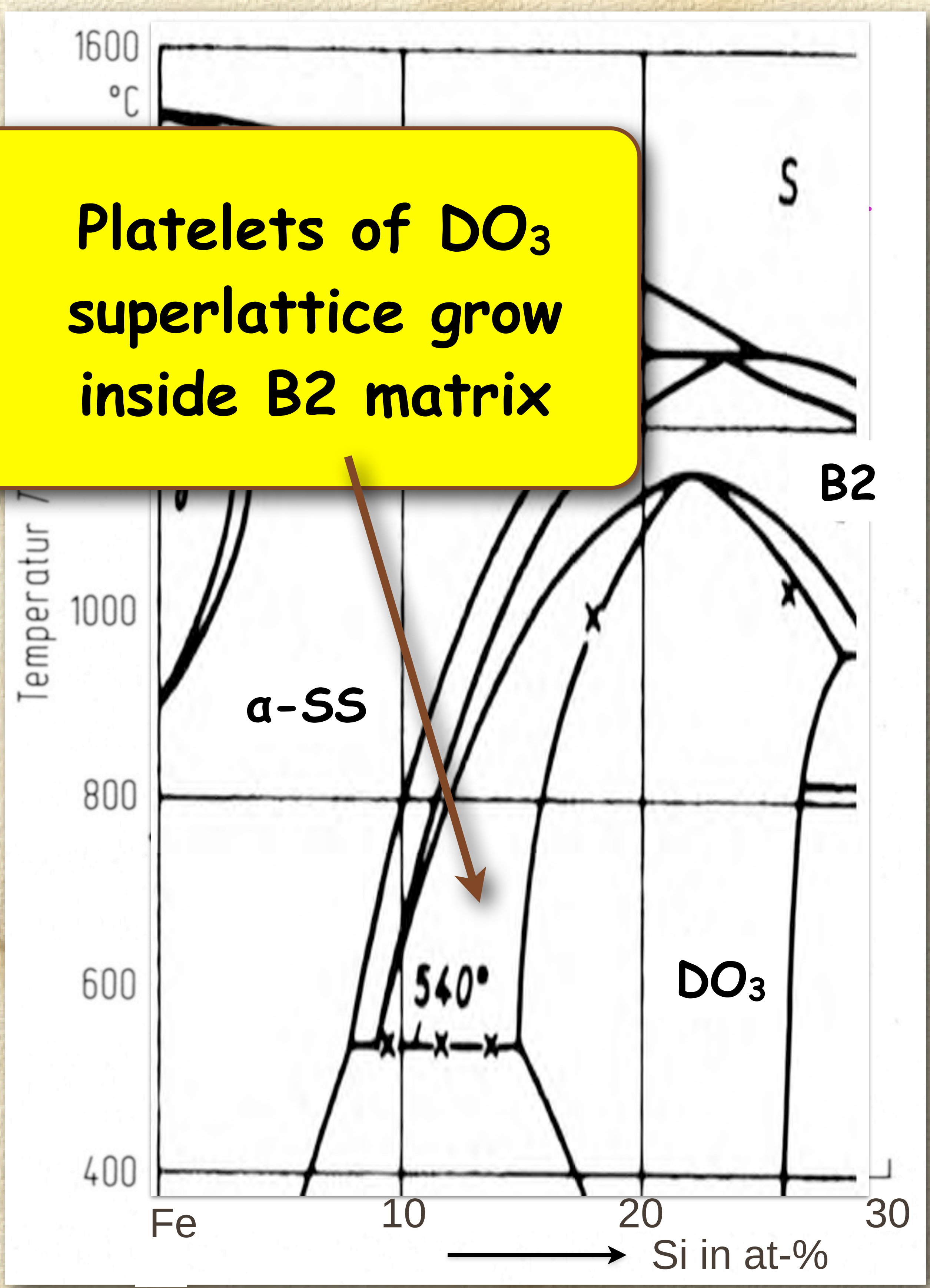




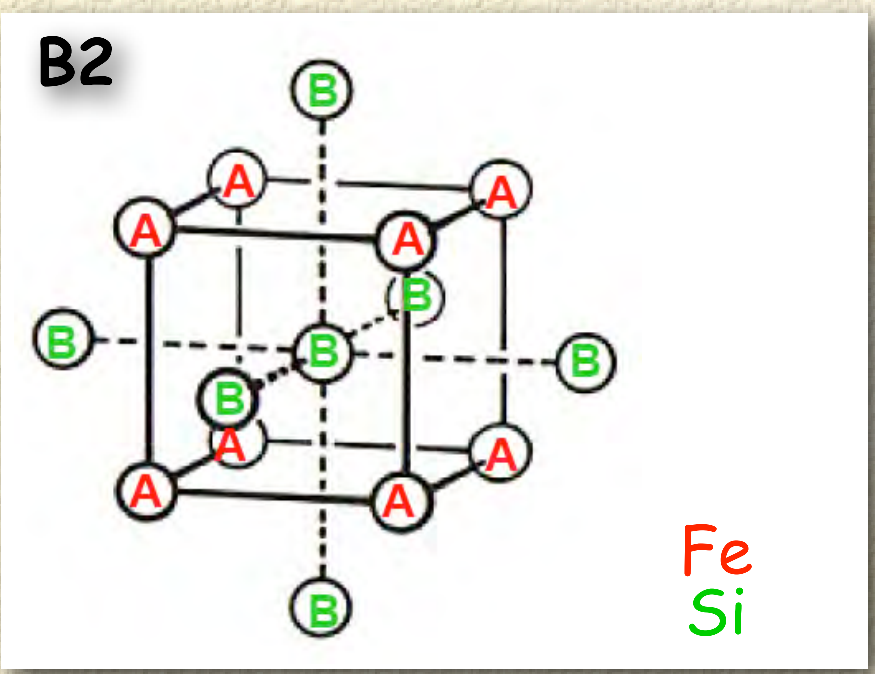


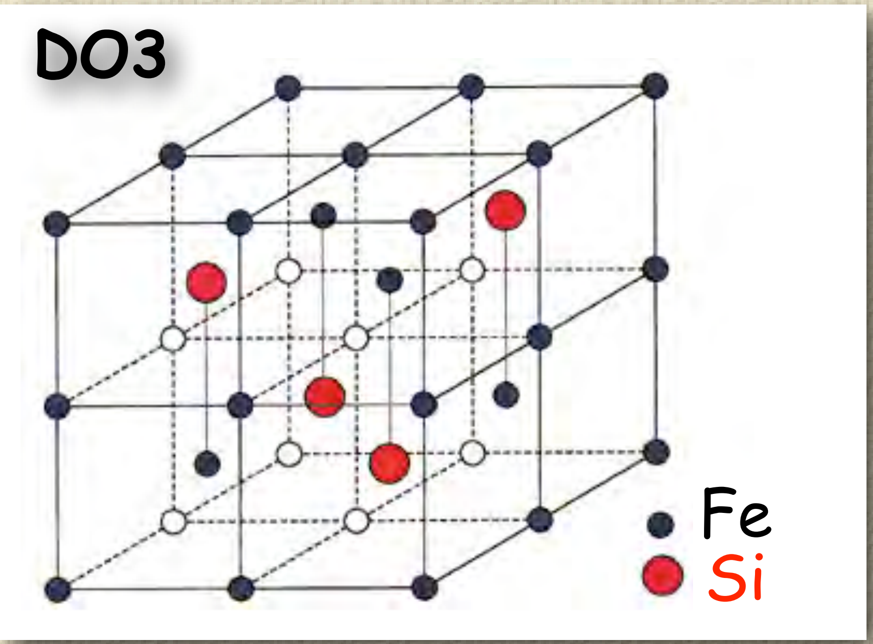
H. Warlimont: Elektronenmikroskopische Untersuchung der α-Fe-Si-Phasen. Z. Metallkunde 59, 598 (1968)

Bulk domain observation by Libovický-method



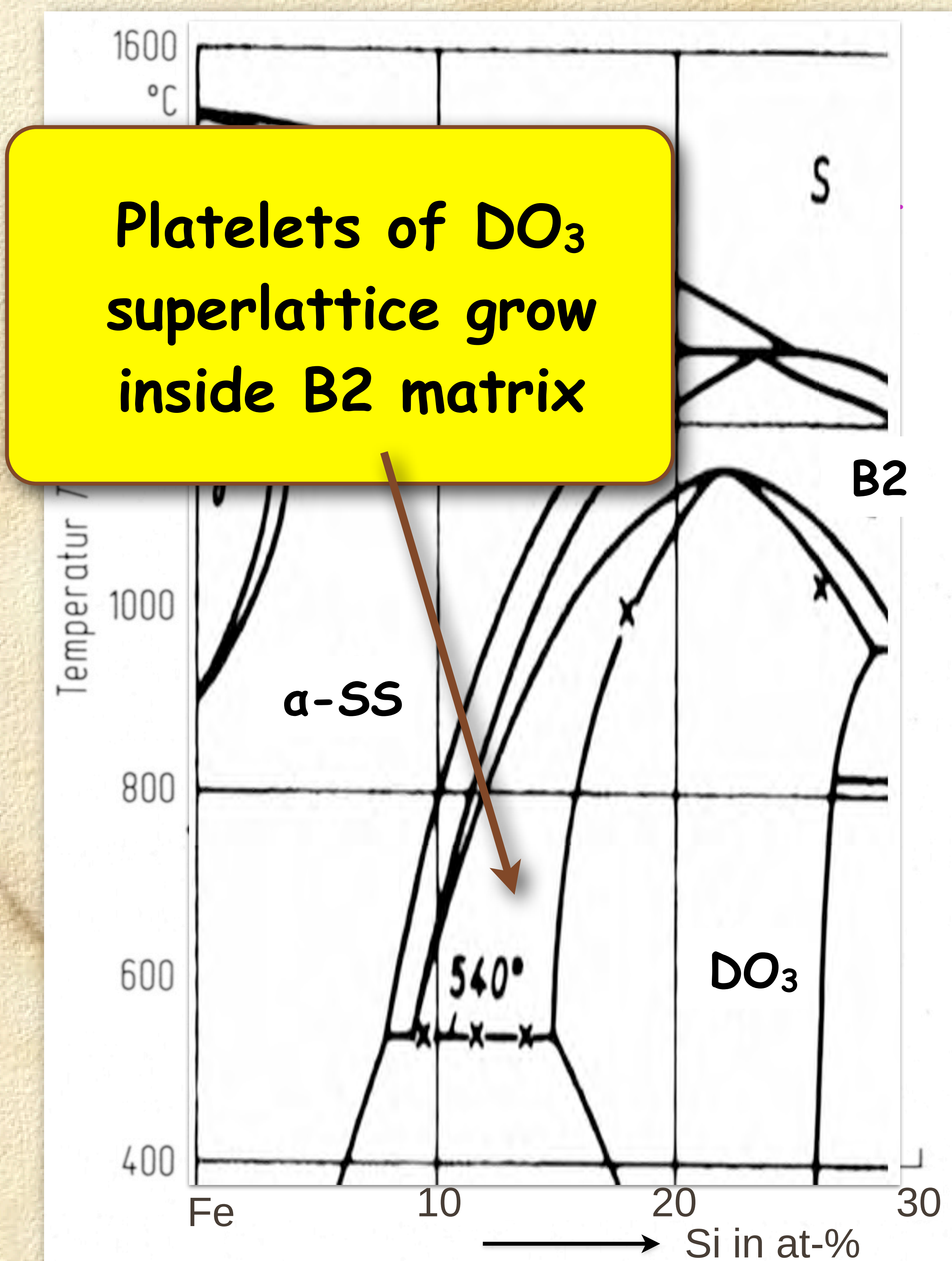
Platelets of DO_3 superlattice grow inside B2 matrix





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

Bulk domain observation by Libovický-method



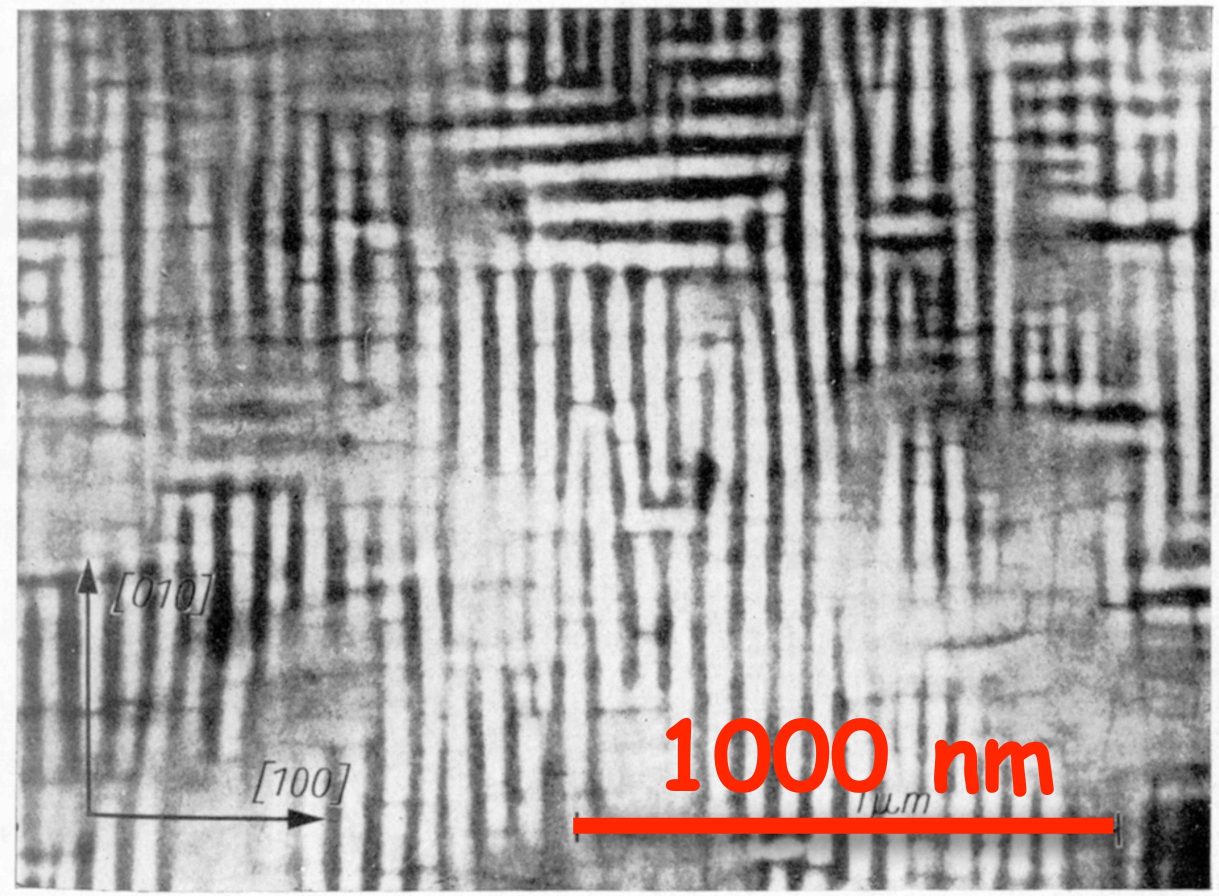
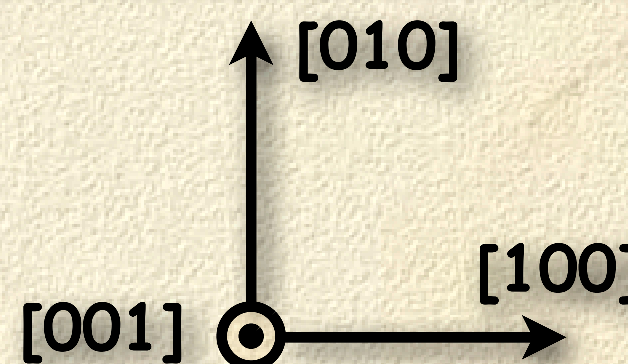
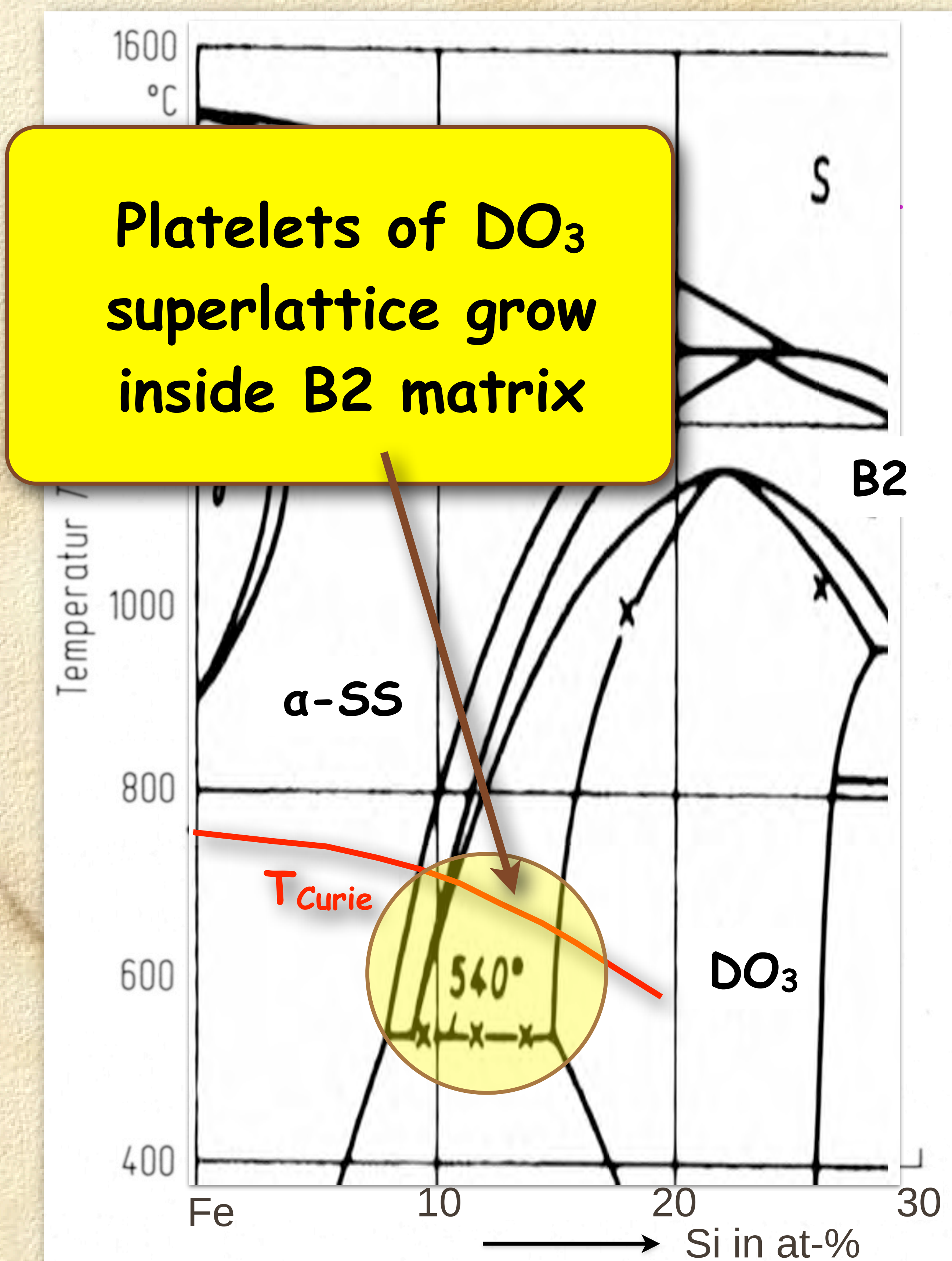


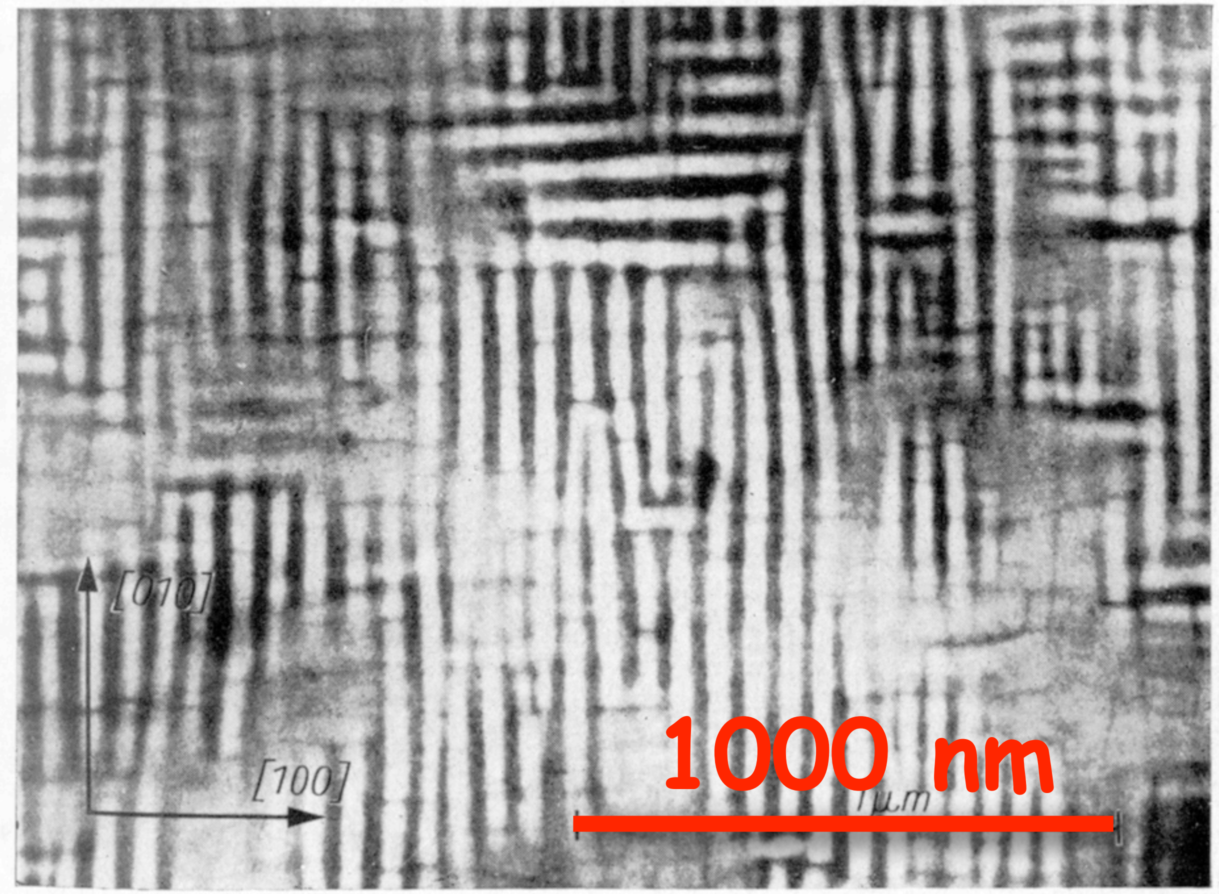
Fig. 3. TEM micrograph of Si Fe–12.5 at% a single crystal held 70 h at 580 °C. The diffuse areas are spots of DO_3 platelets parallel to (001). The growth of (010) platelets was partially suppressed in this area. Dark field 200 superlattice reflection



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

Bulk domain observation by Libovický-method





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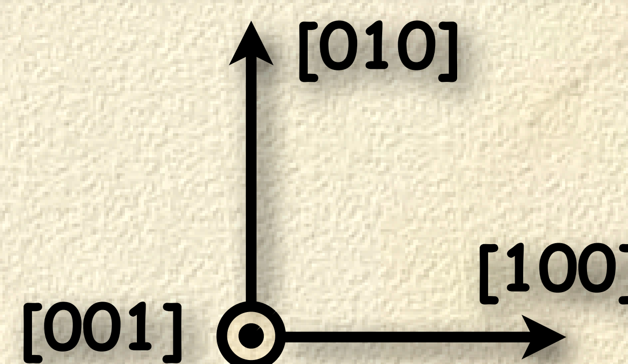

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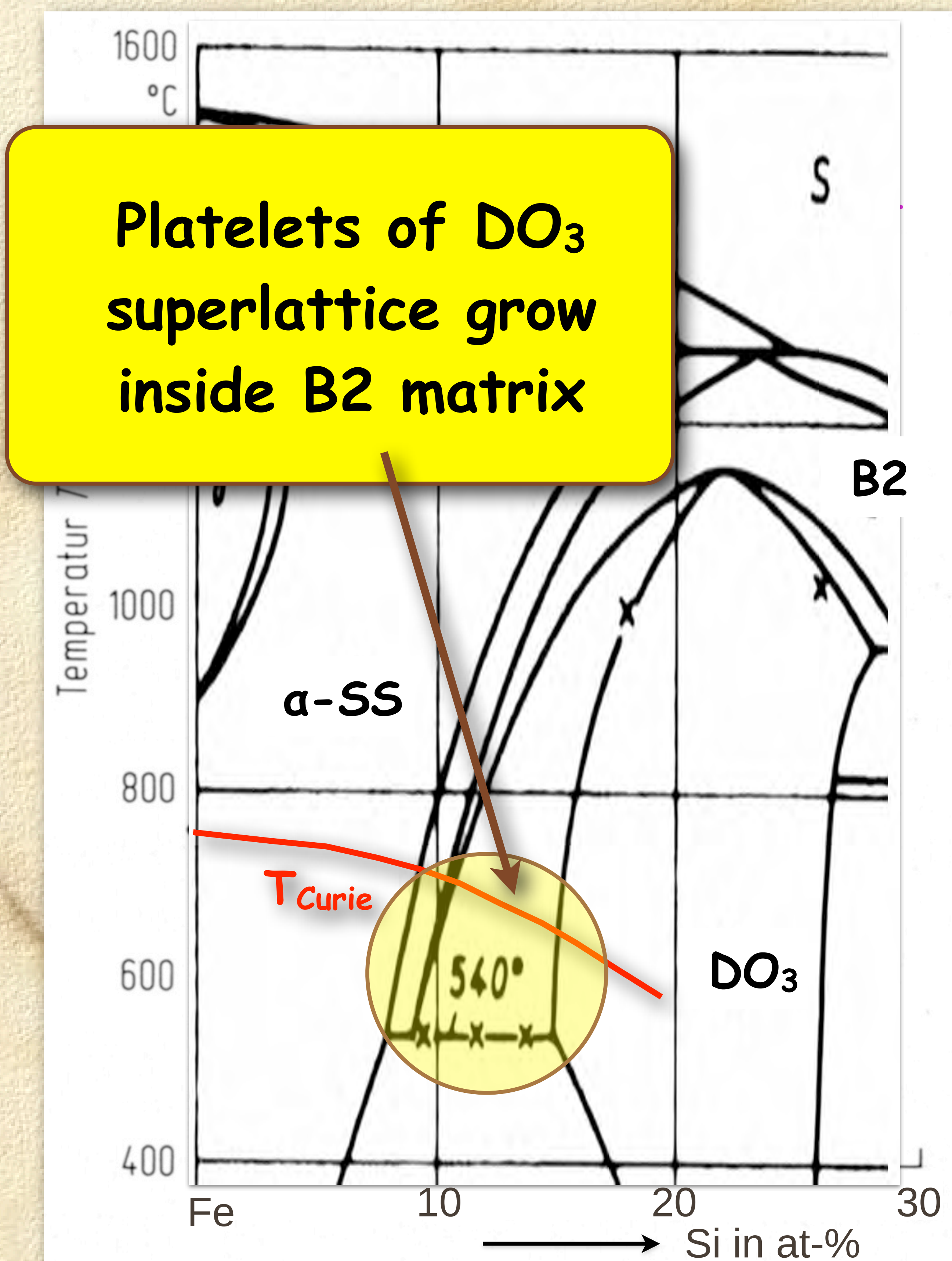

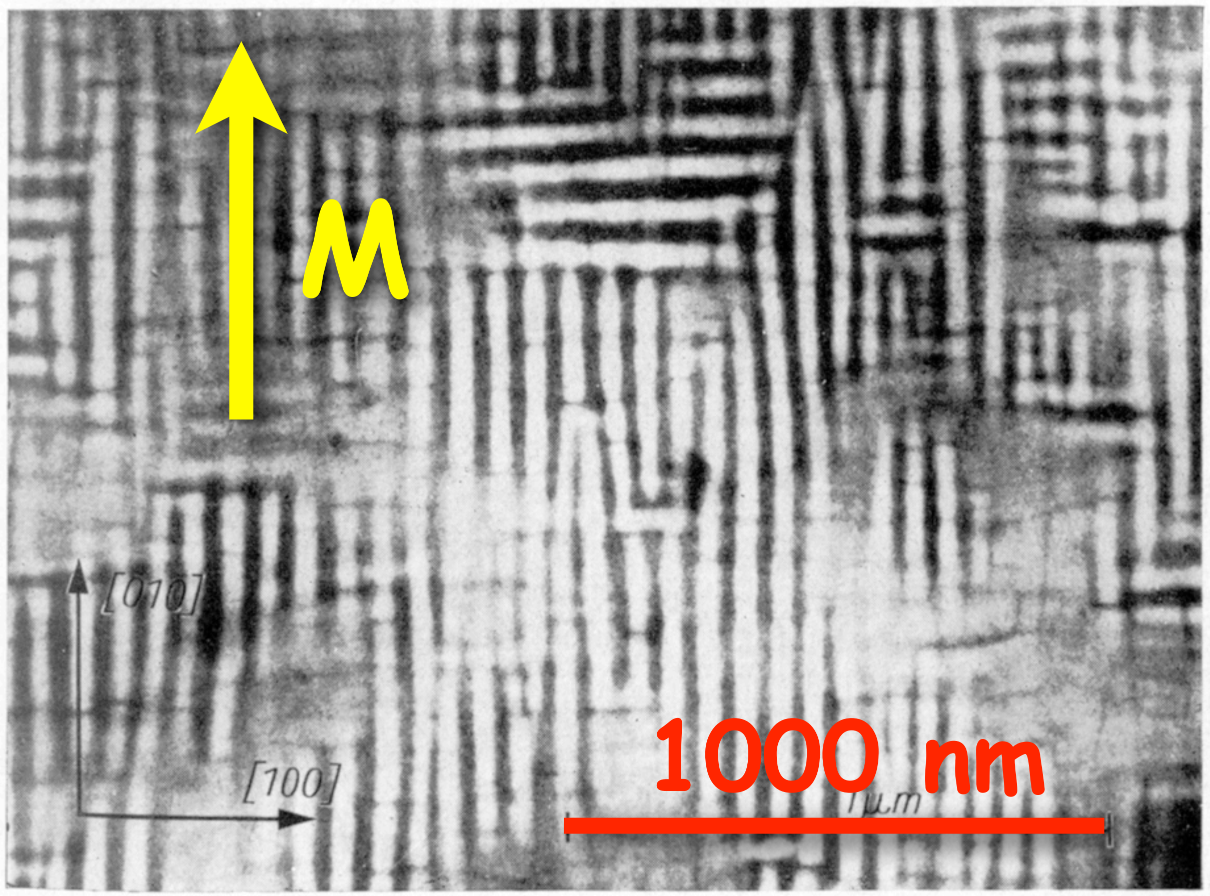

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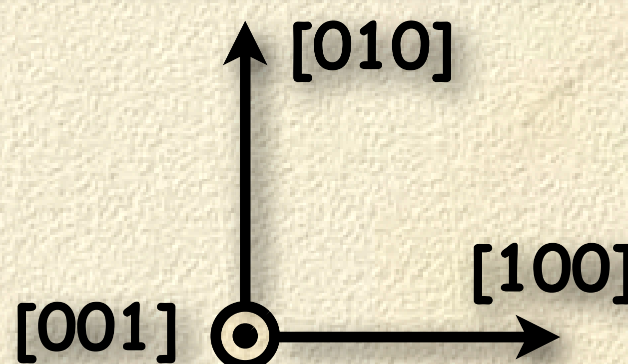
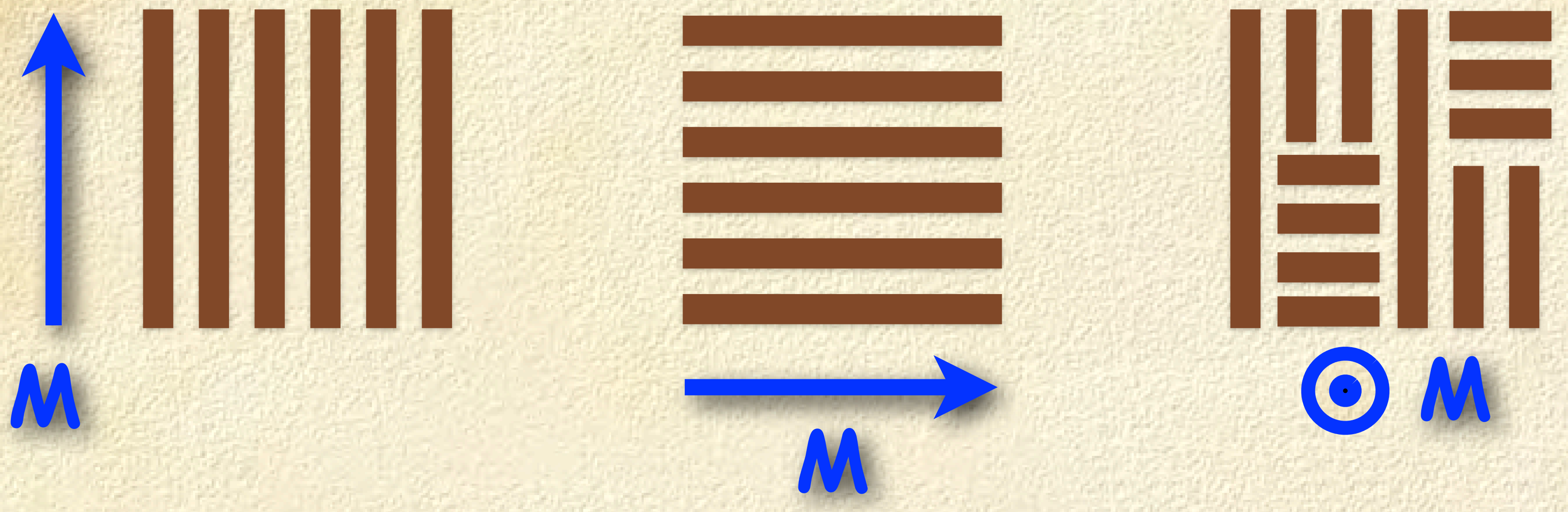


from: S. Libovicky: Spatial replica of ferromagnetic domains in iron-silicon alloys. Phys. Status Solidi A 12 (1972) 539

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°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)

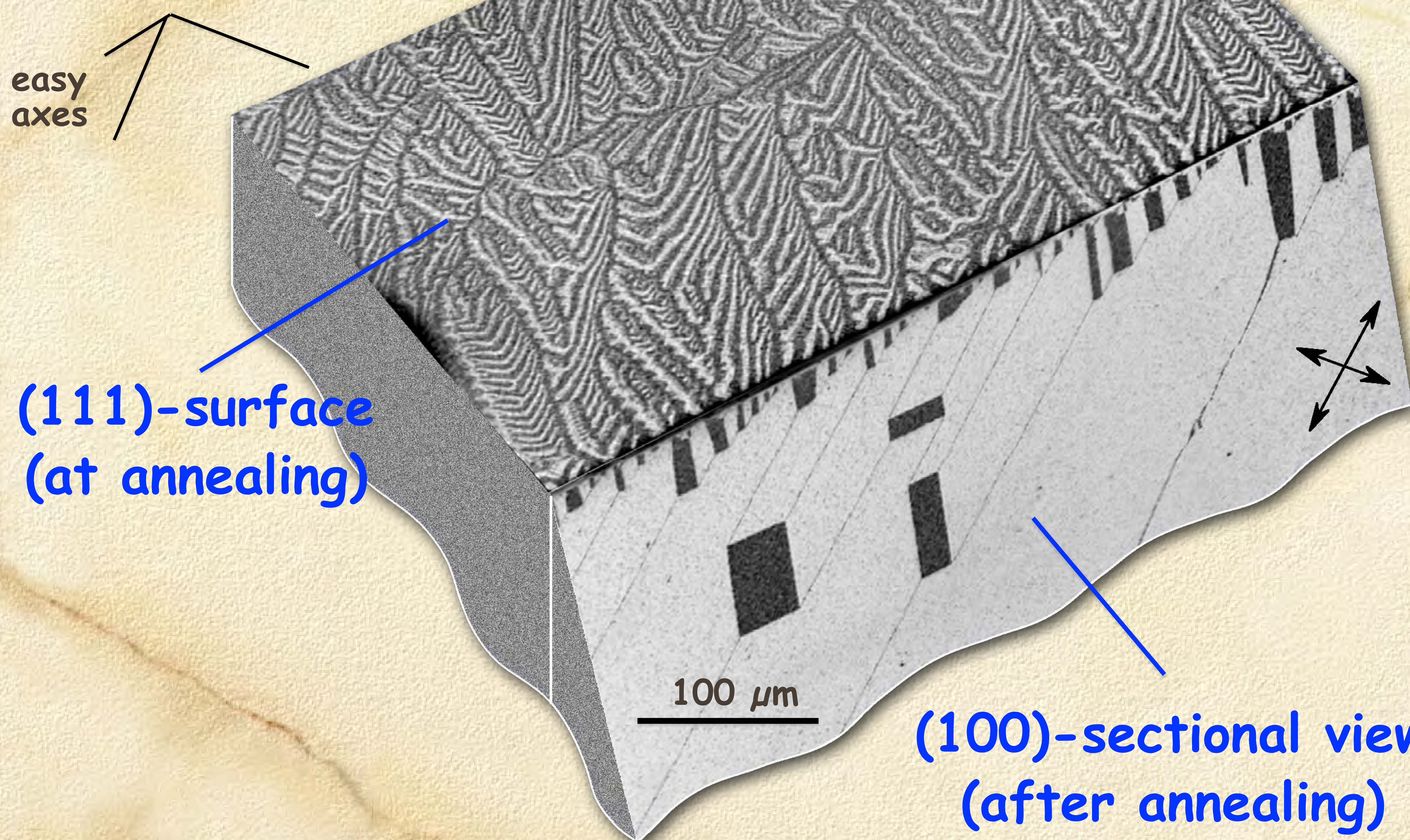
Bulk domain observation by Libovický-method

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

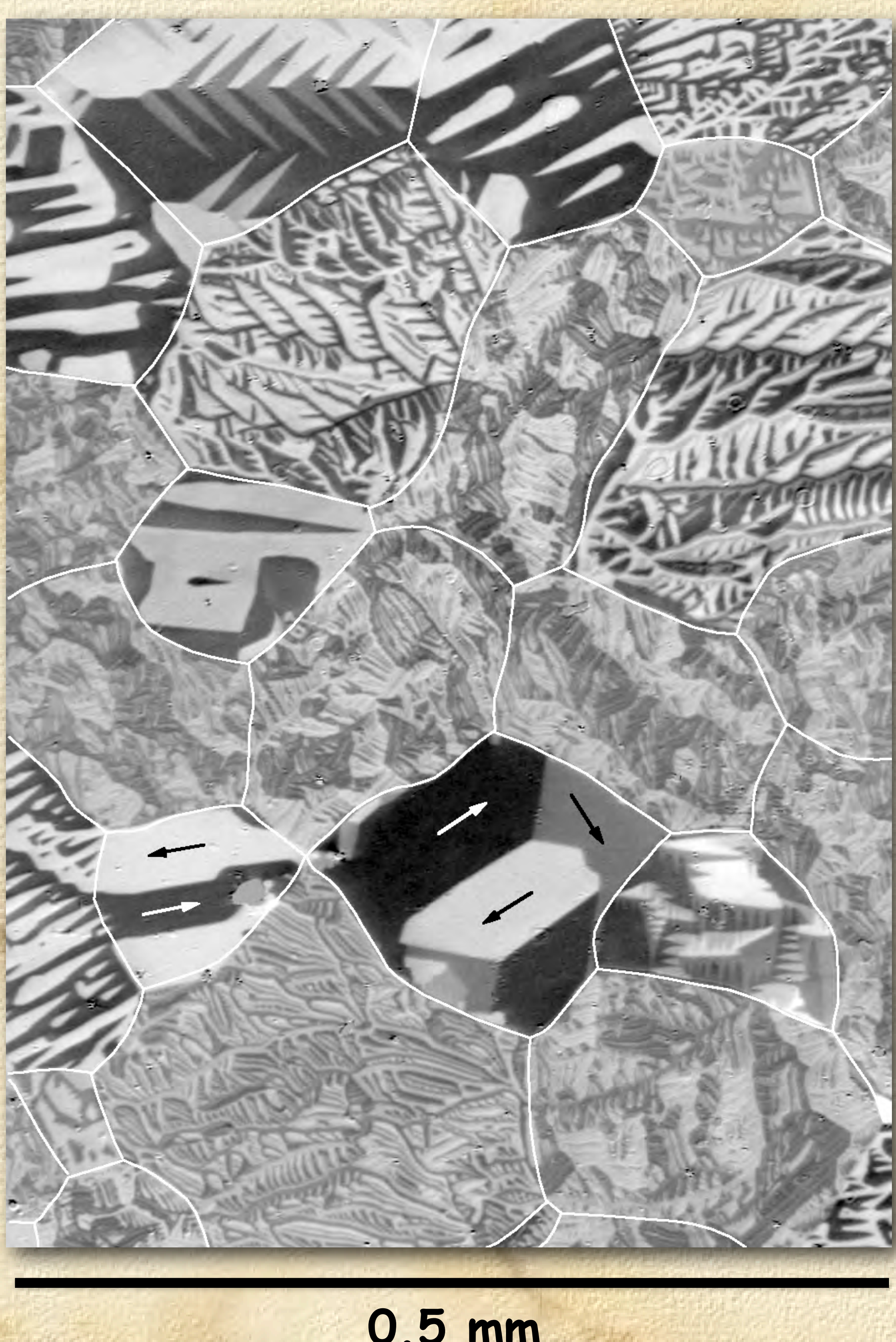
(thickness 0.5 mm)

Bulk domain observation by Libovický-method

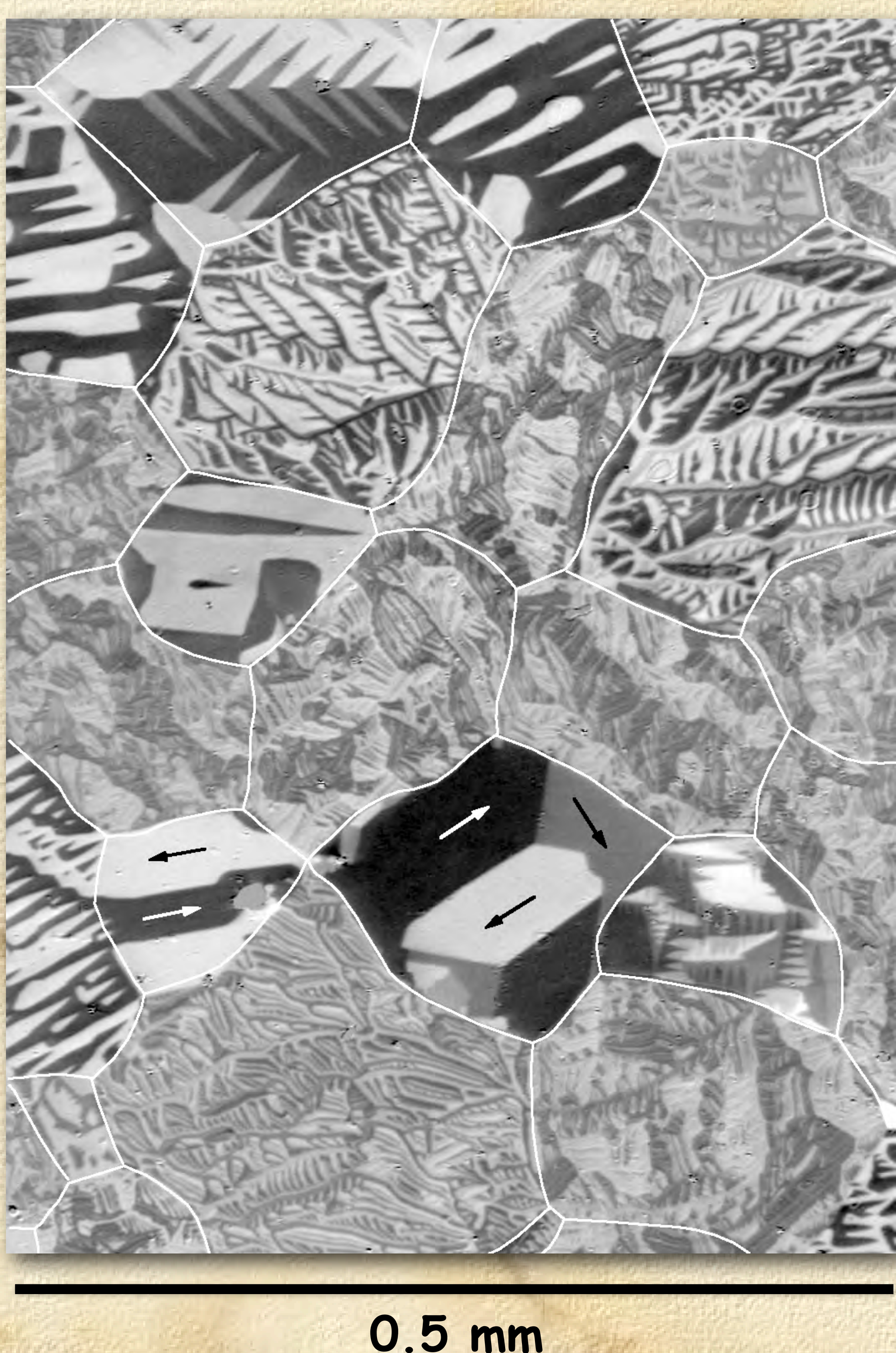
Branched domains on Fe12.8%Si
(111) surface



Non-oriented FeSi sheet



Non-oriented FeSi sheet

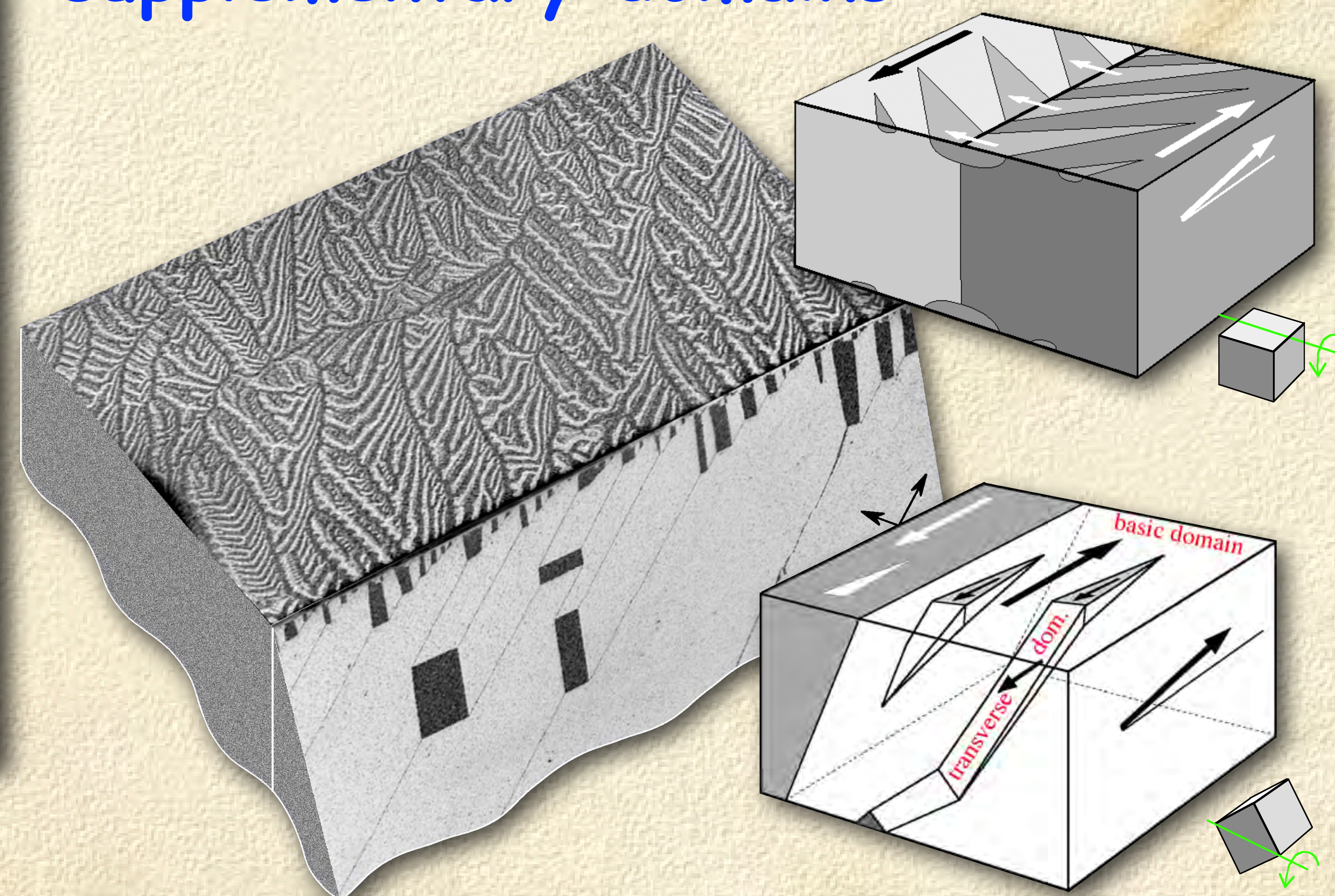


Conclusion:

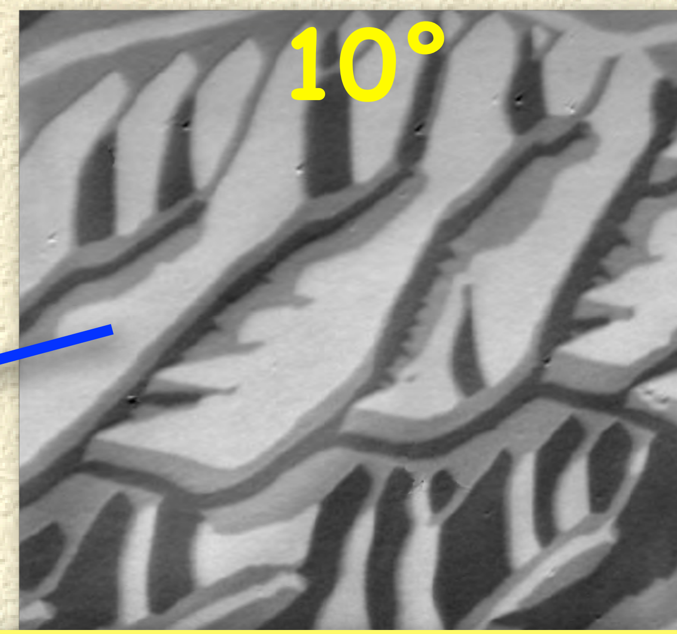
Strong misorientation:

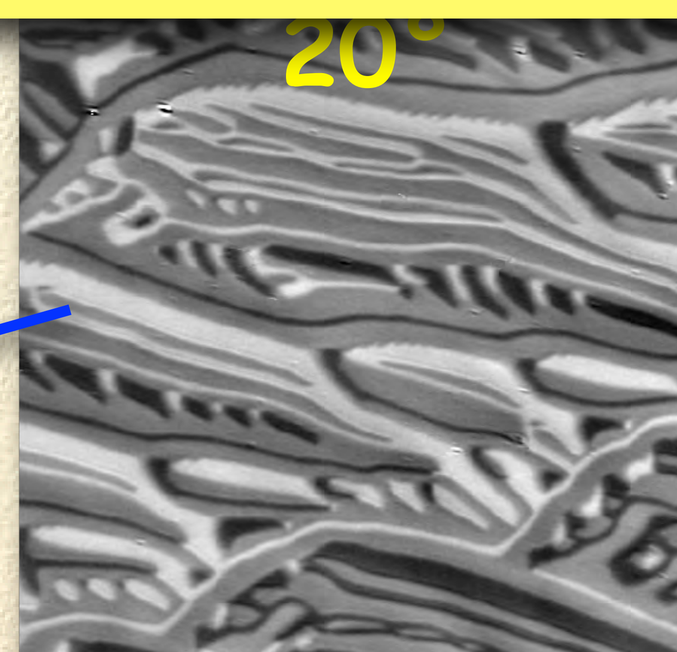
Complex domains restricted to surface zone, in volume wide basic domains can be expected

Weak misorientation: wide basic domains with superimposed supplementary domains



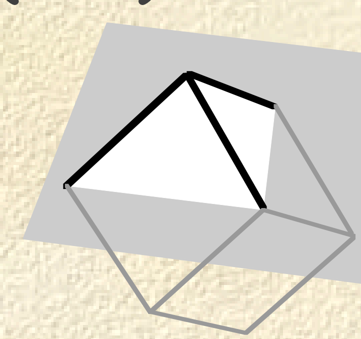
Non-oriented FeSi sheet



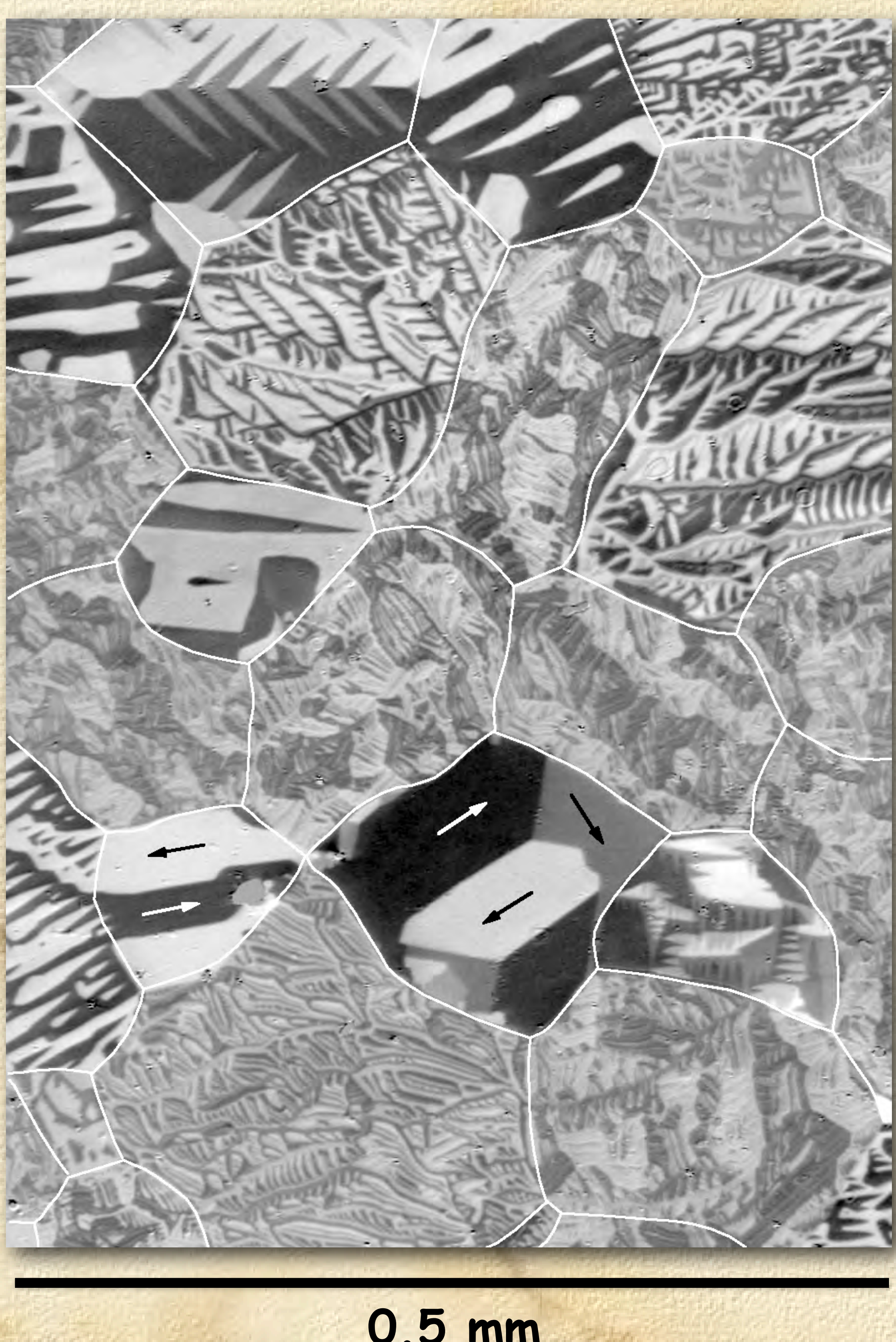


We expect wide volume domains in any case

(111)-surface

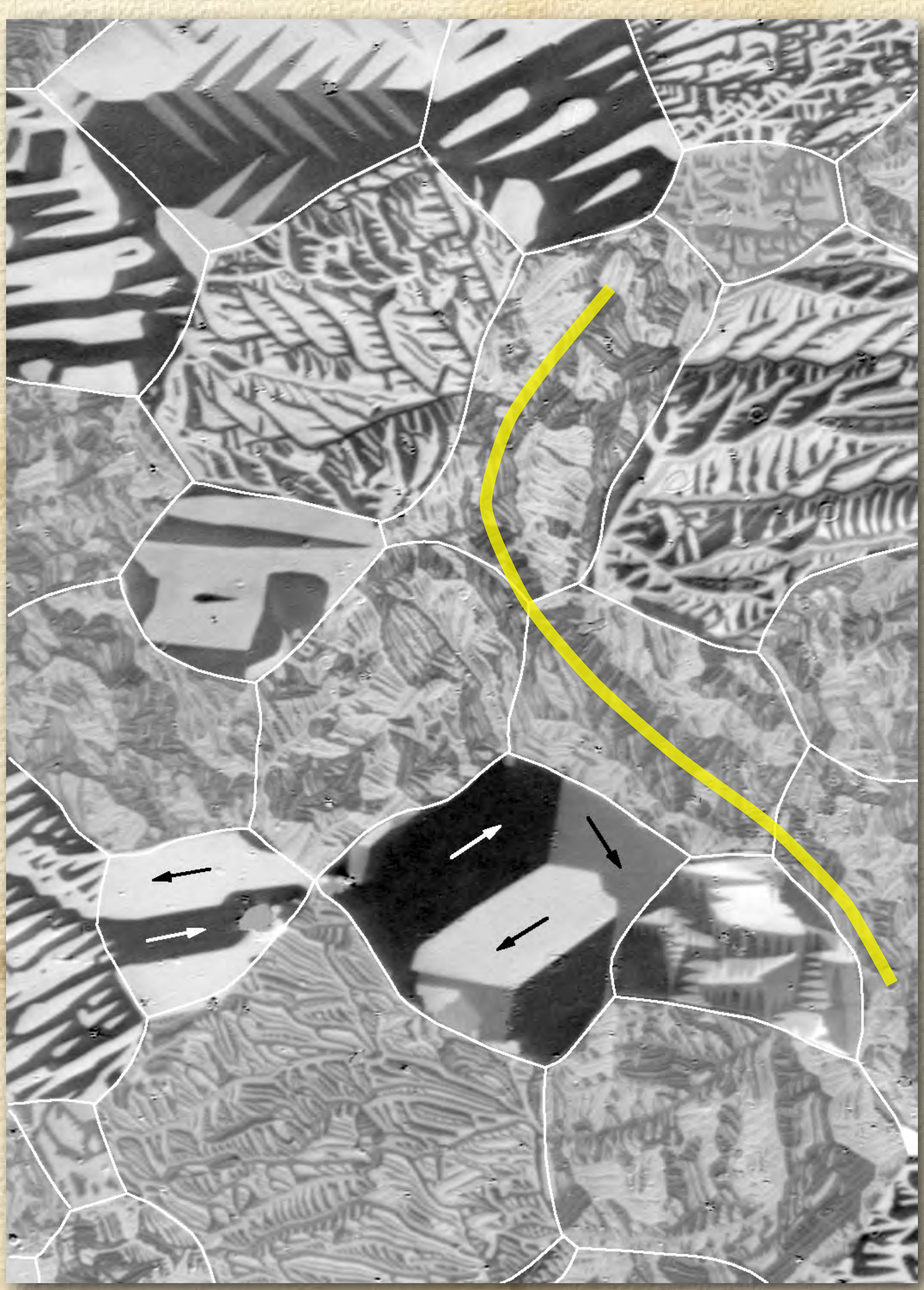


Non-oriented FeSi sheet



Indication of wide volume domains by surface observation

Non-oriented FeSi sheet



0.5 mm

Indication of wide volume domains by surface observation

Non-oriented FeSi sheet

0.5 mm

Indication of wide volume domains by surface observation

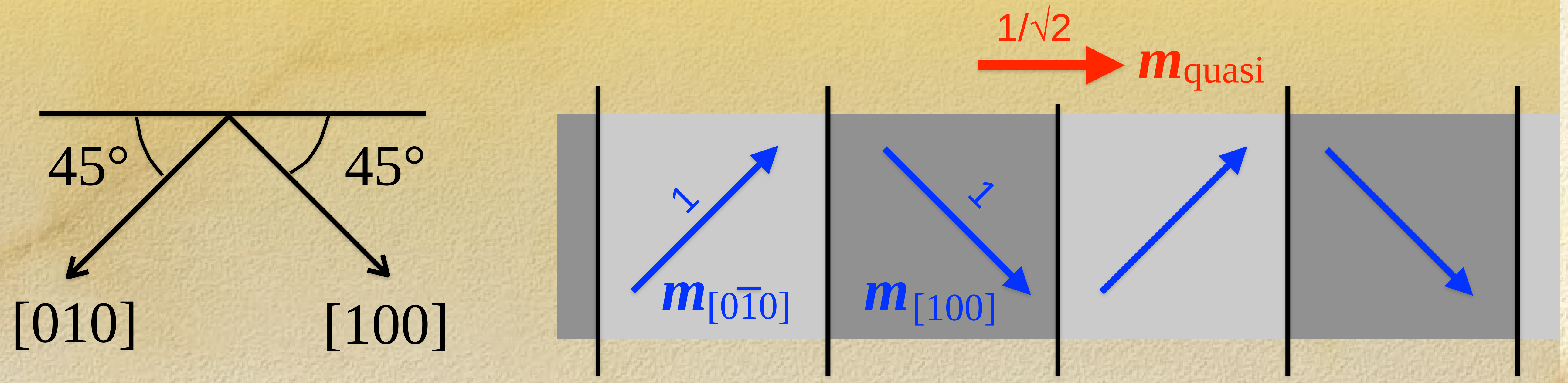
Non-oriented FeSi sheet

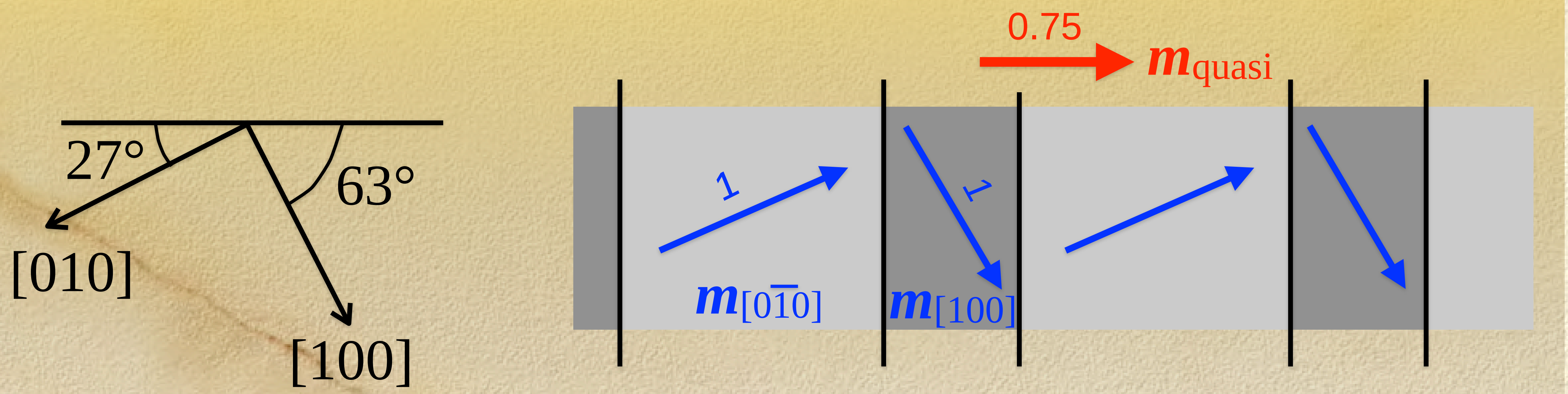
0.5 mm

Indication of wide volume domains by surface observation

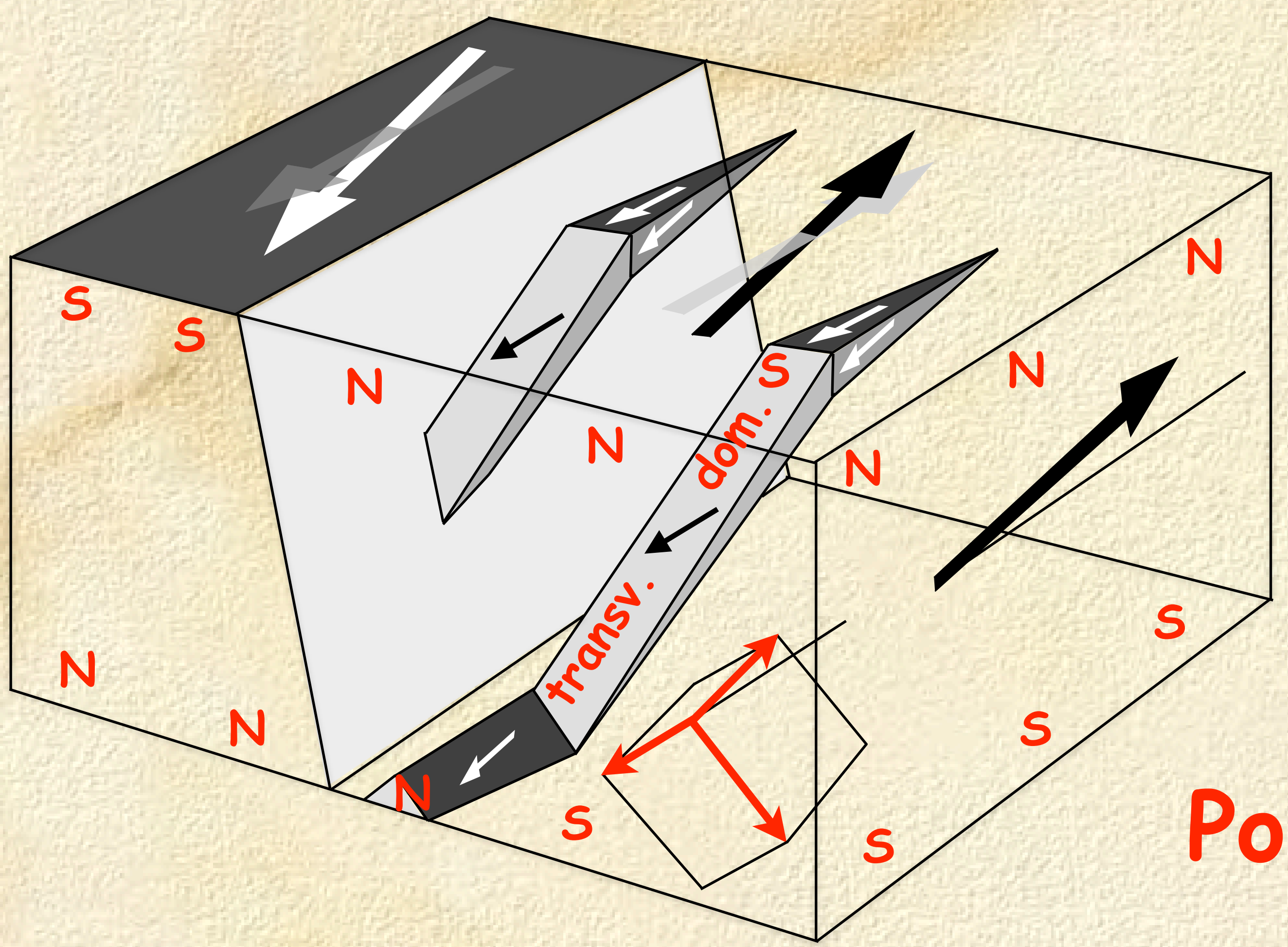
A. Hubert:
Quasi-domain model for domains and flux transport in interior

Quasi-Domains

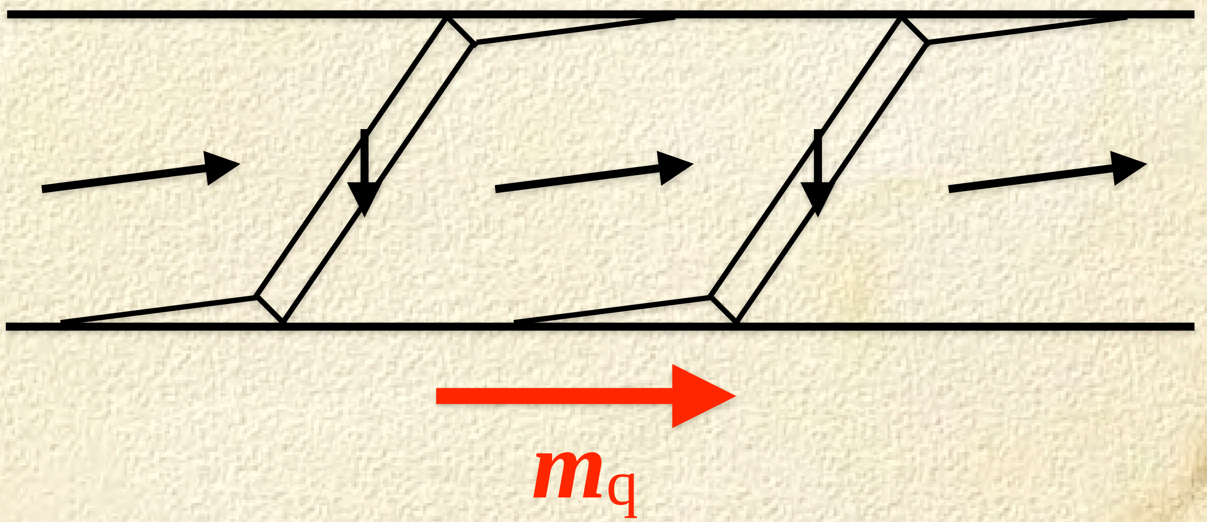




Quasi-Domains

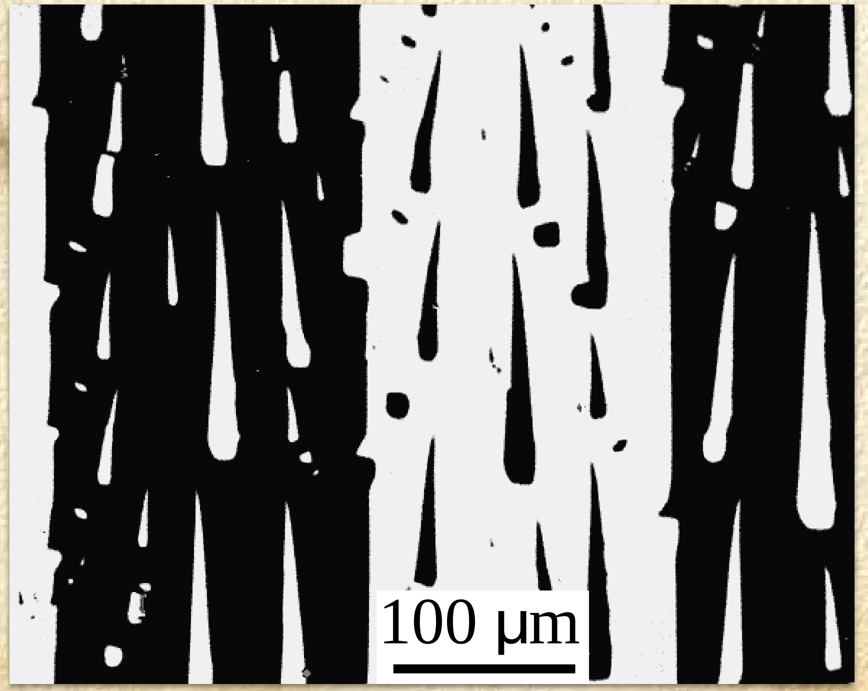


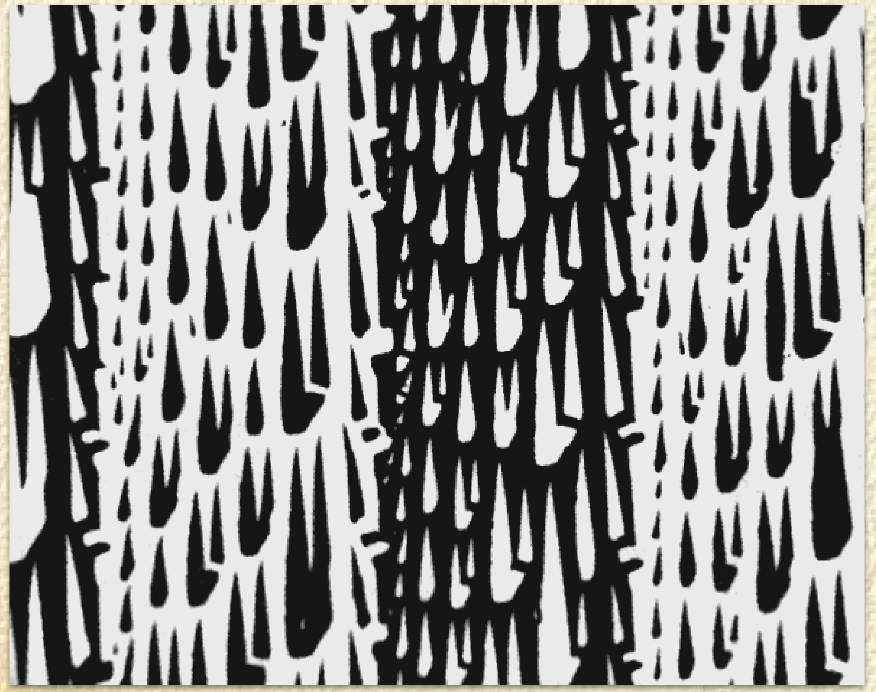
Lancet pattern on slightly misoriented (110) surface

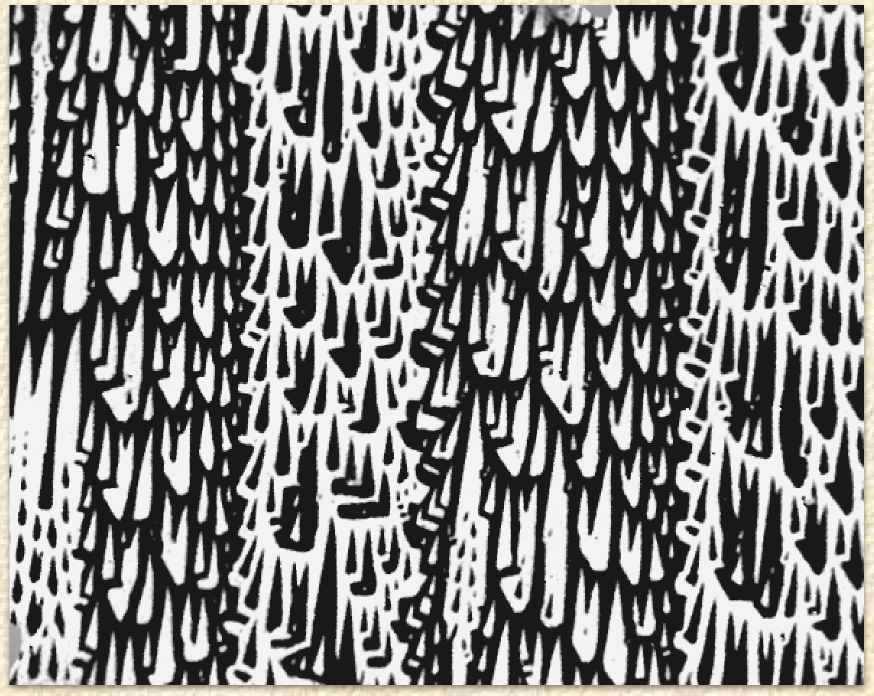


Pole-free on macroscopic scale

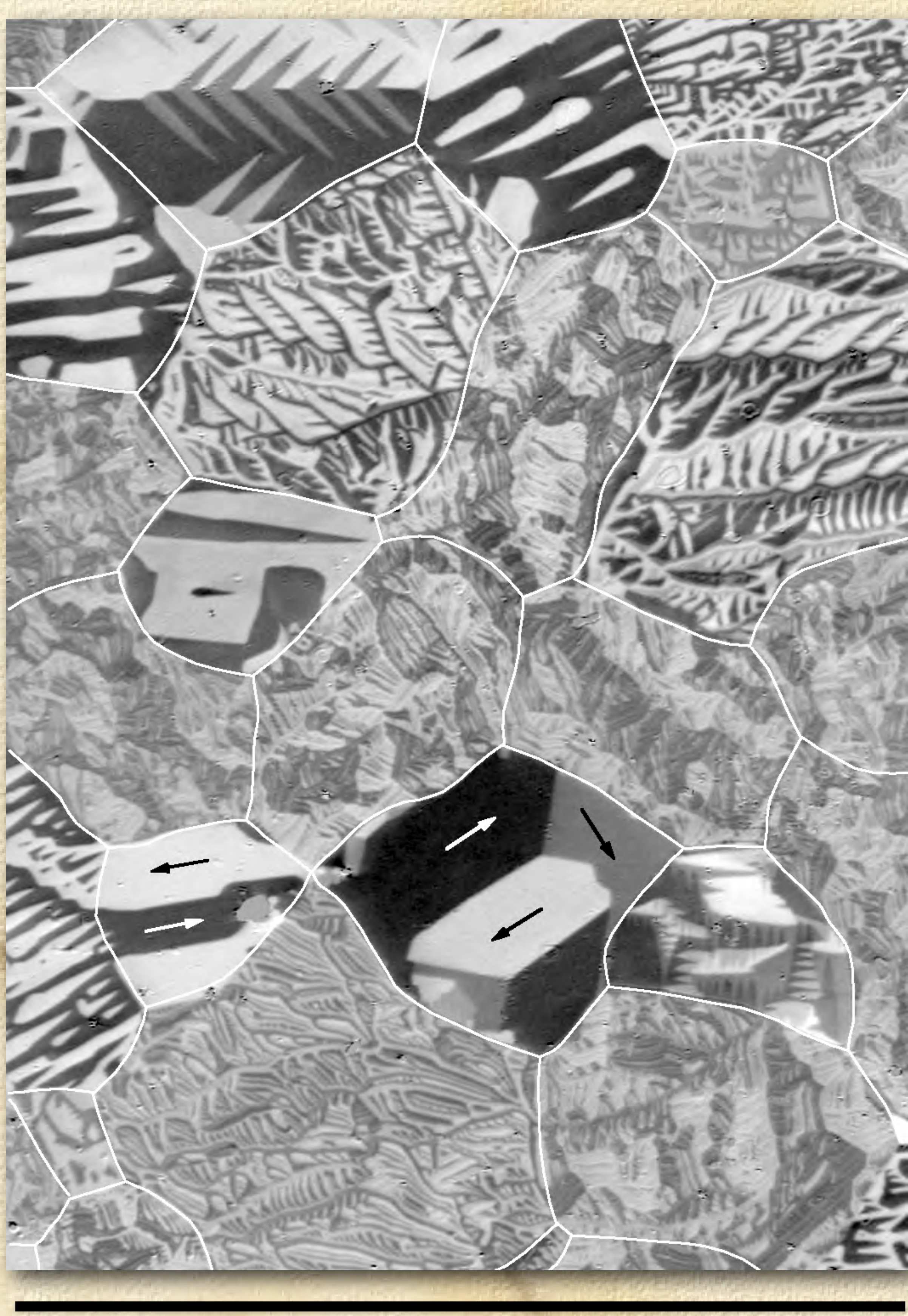
Misorientation: 2° 4° 8°

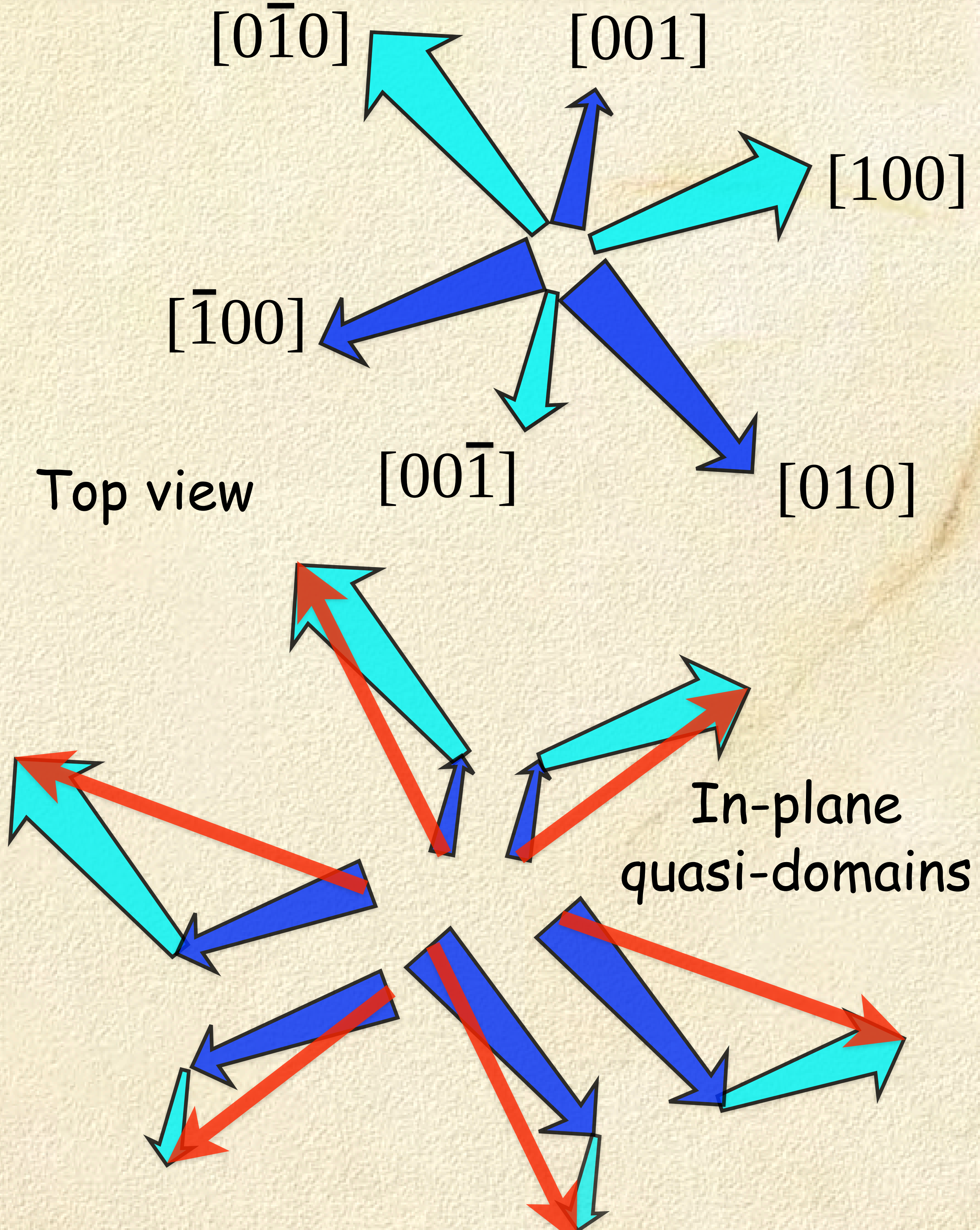






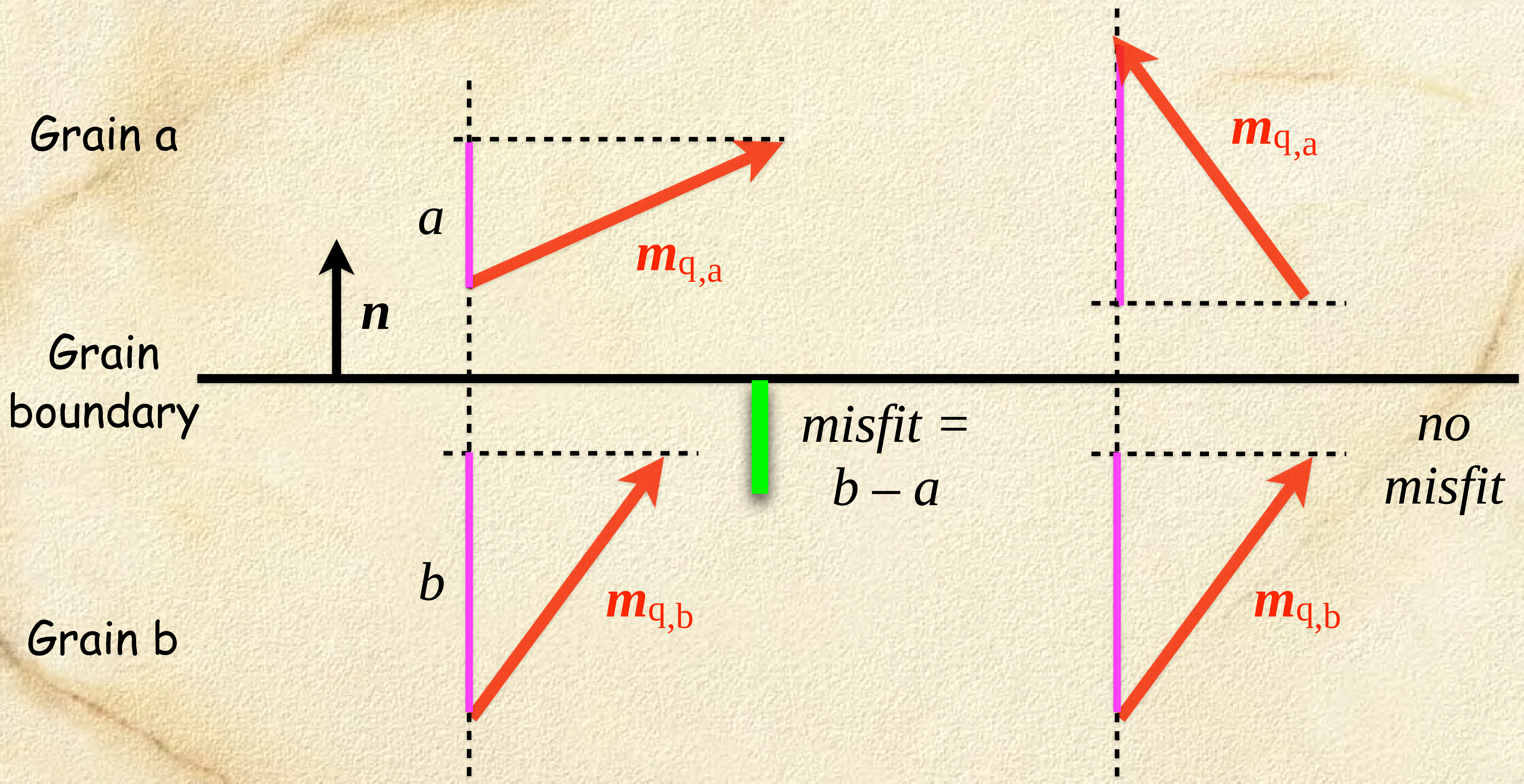
Non-oriented FeSi sheet





Non-oriented FeSi sheet

Quasi-domains and Grain Boundaries

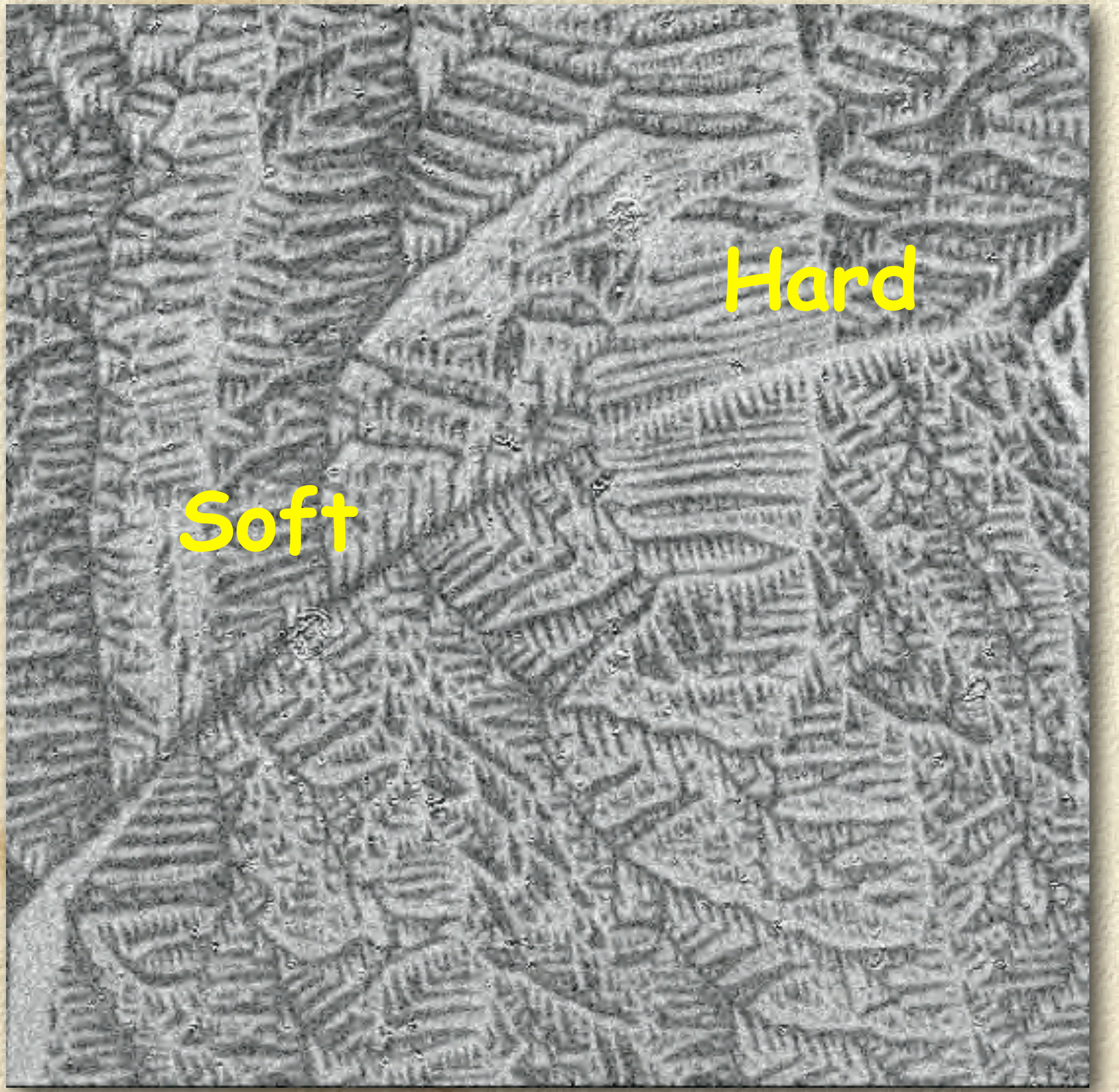


It depends on flux misfit D whether quasi domains can proceed to neighboring grain

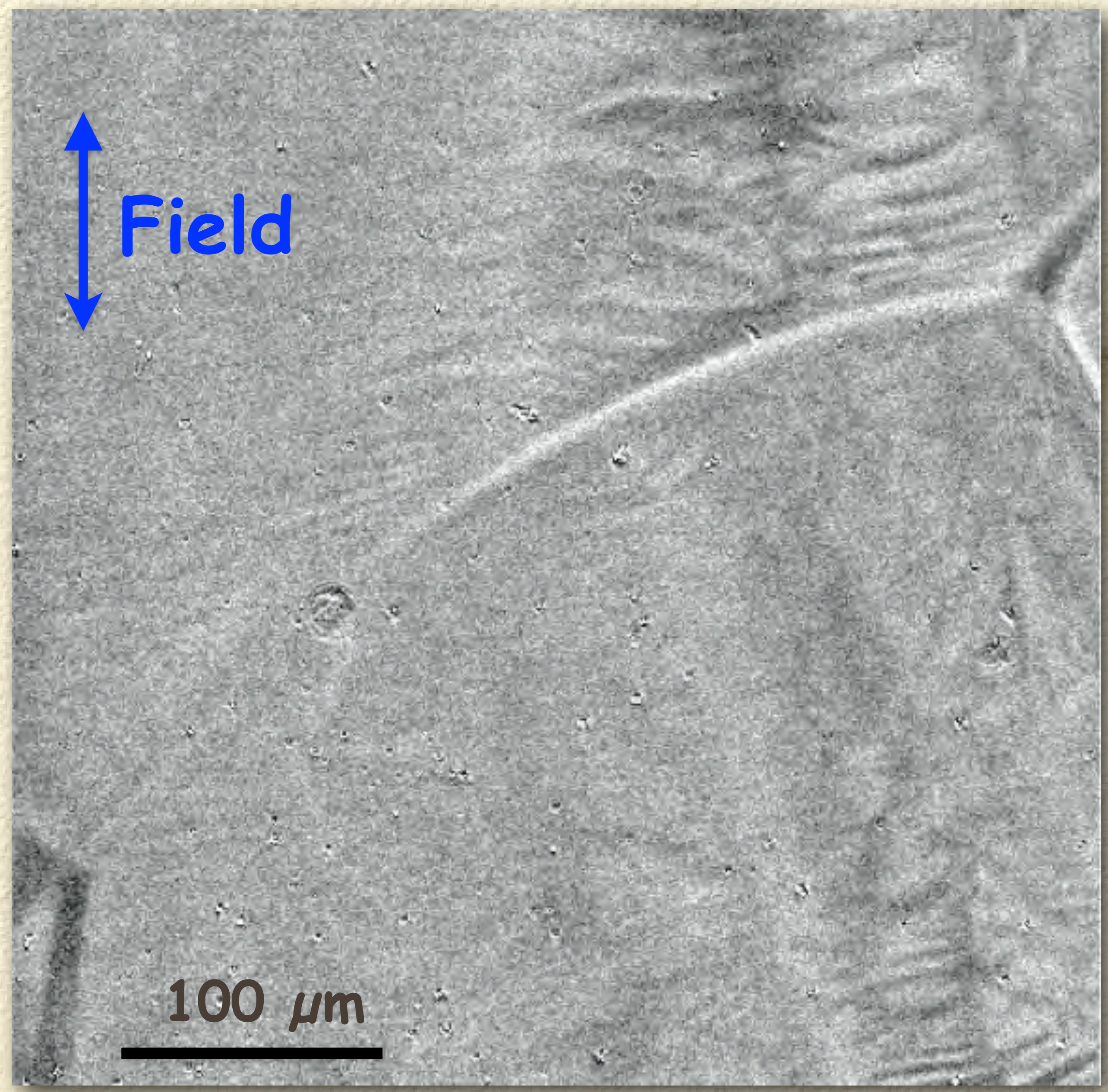
Non-oriented FeSi sheet

Quasi-domains and Grain Boundaries

Demagnetized



50 Hz ac field



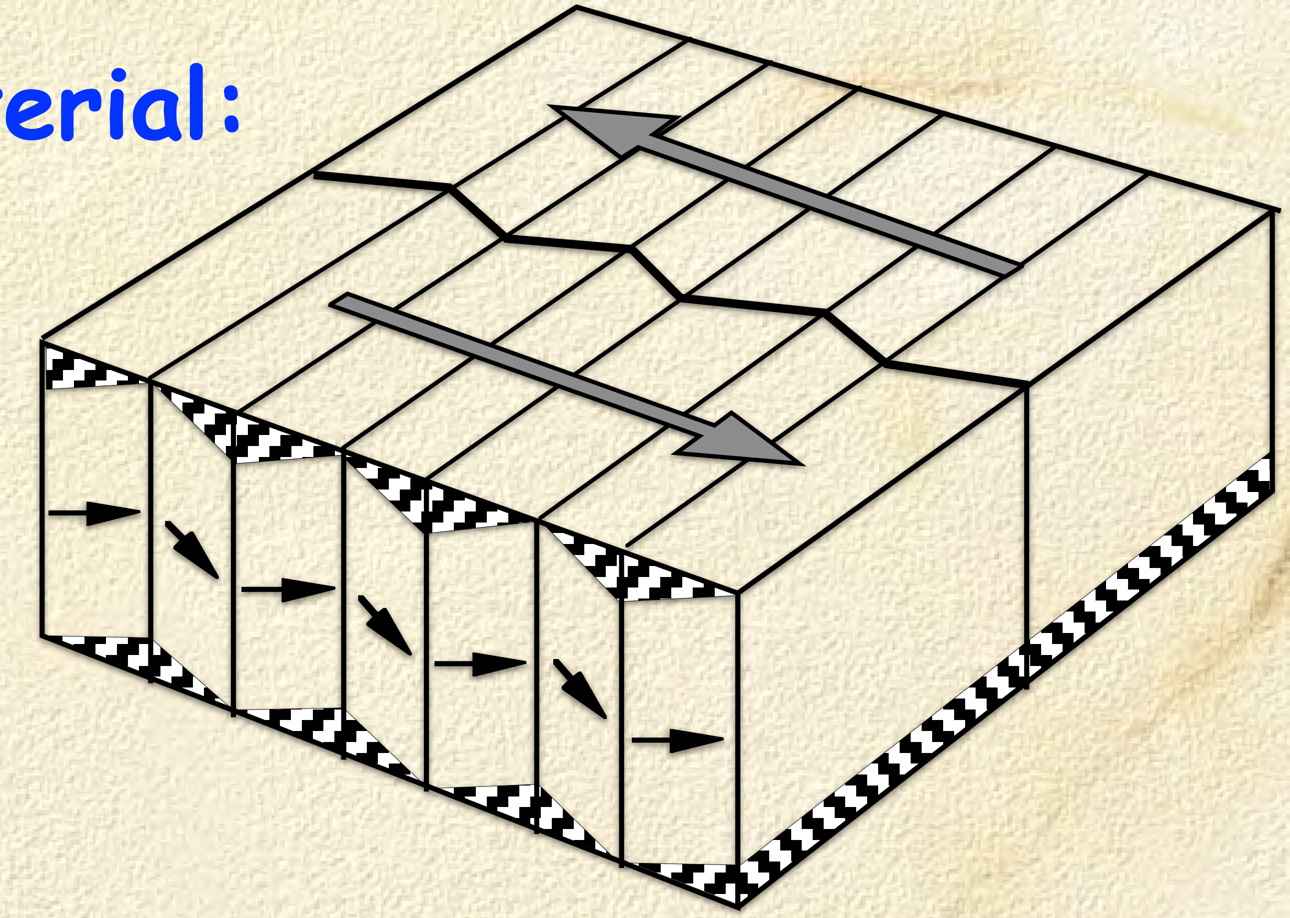
Together with A. Brunner, IFW Dresden
unbublished

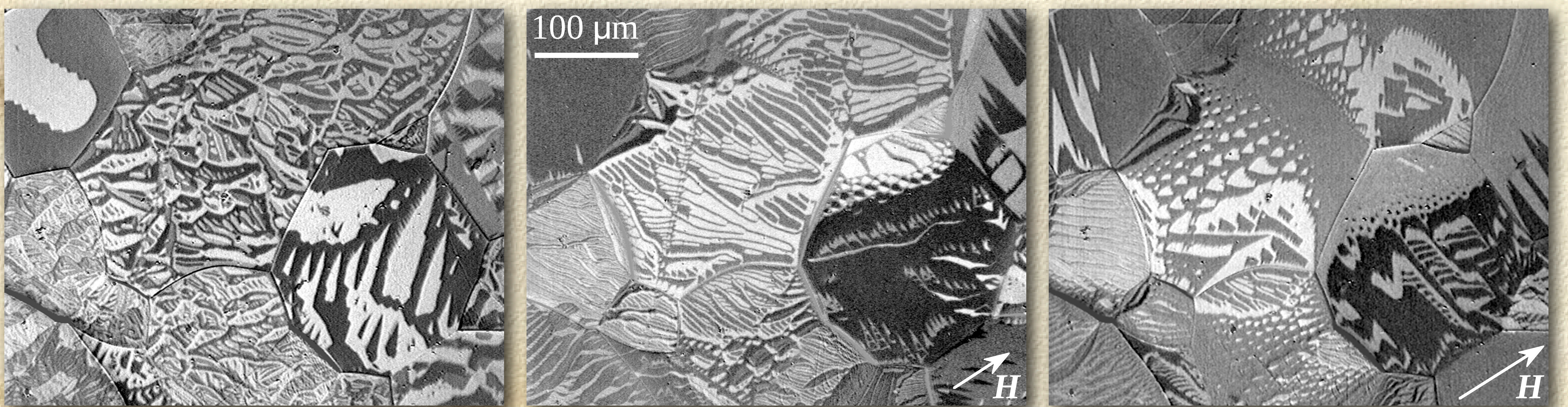
Non-oriented FeSi sheet

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





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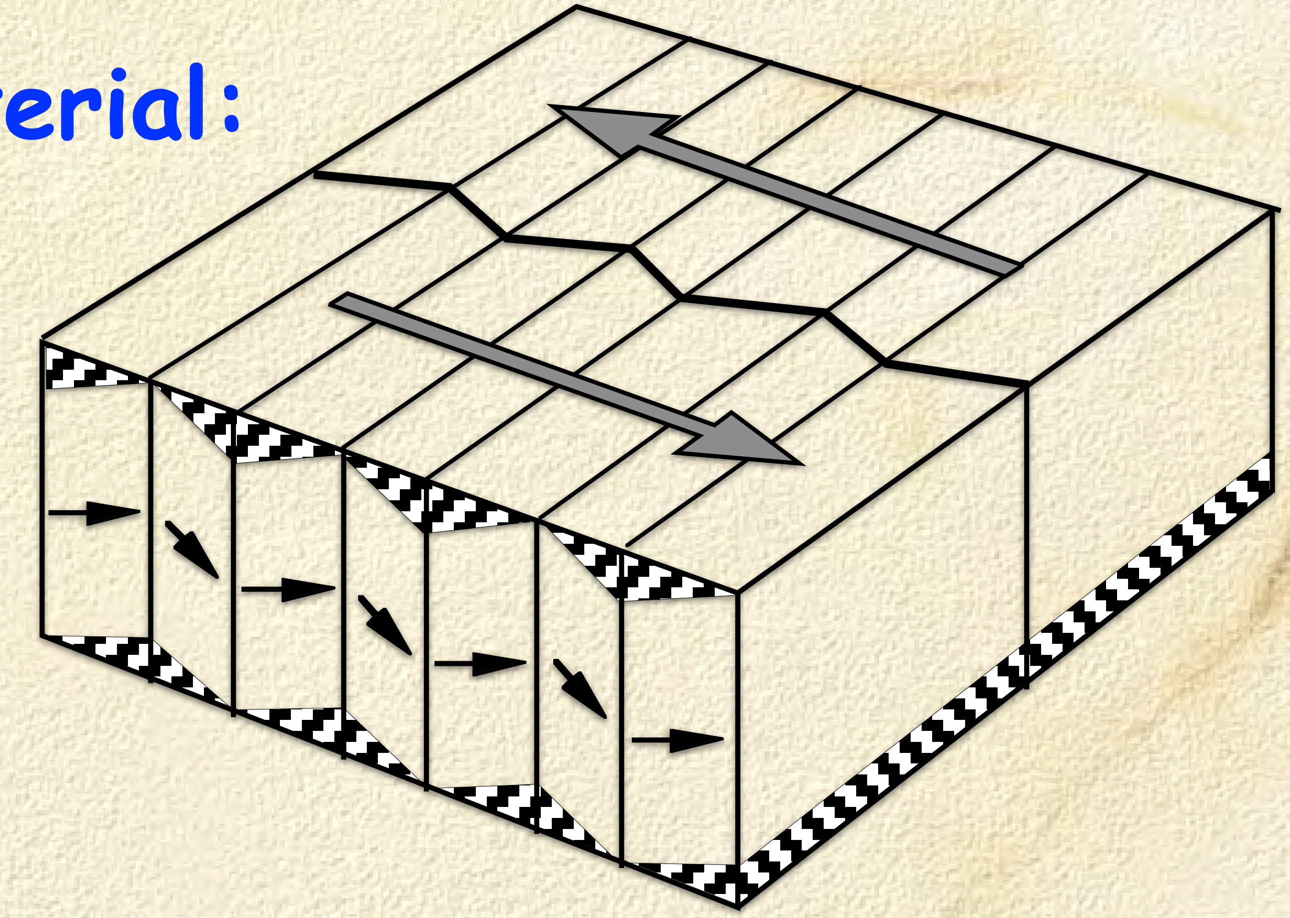
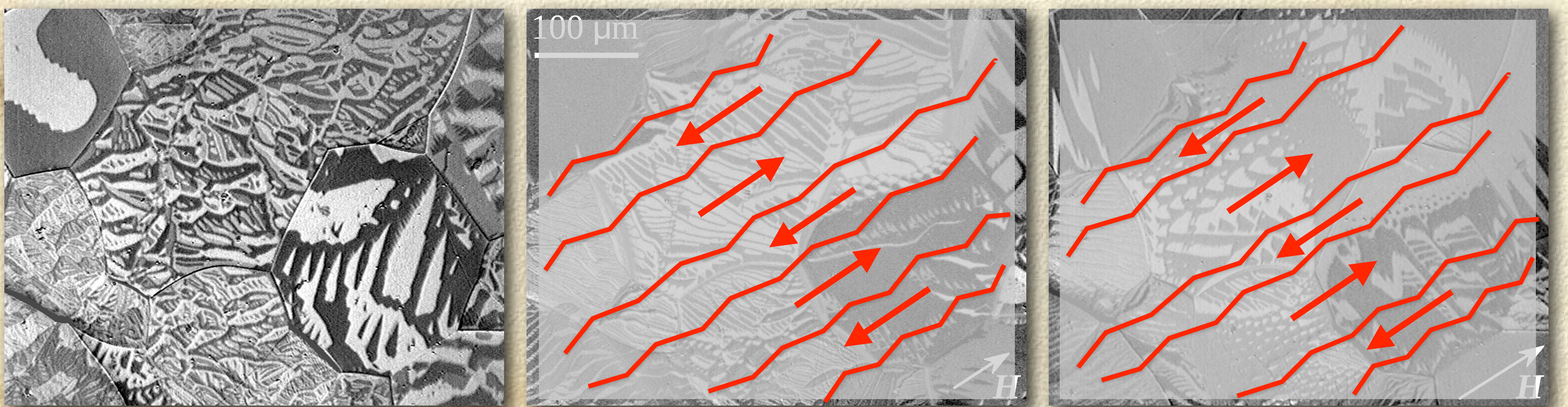
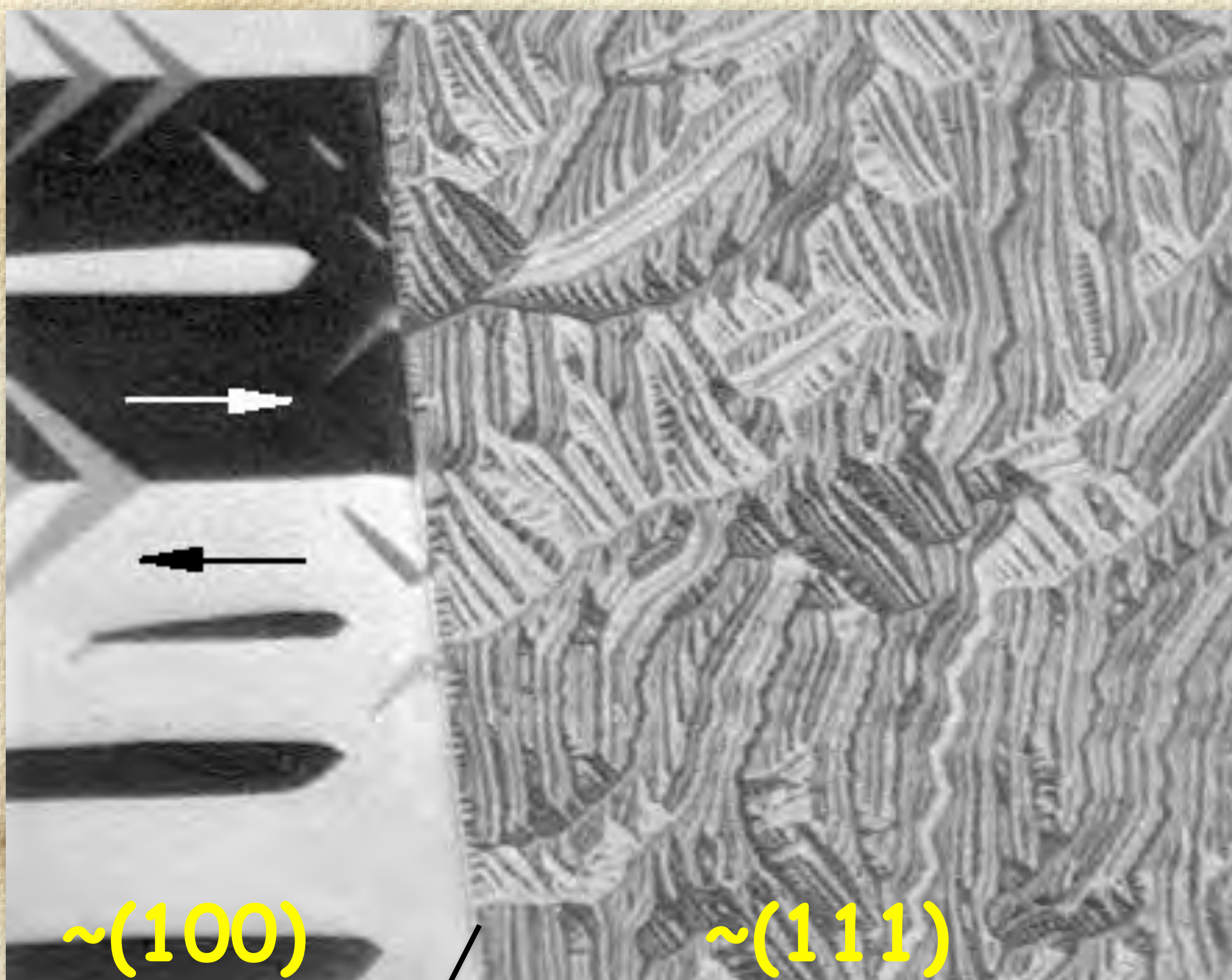




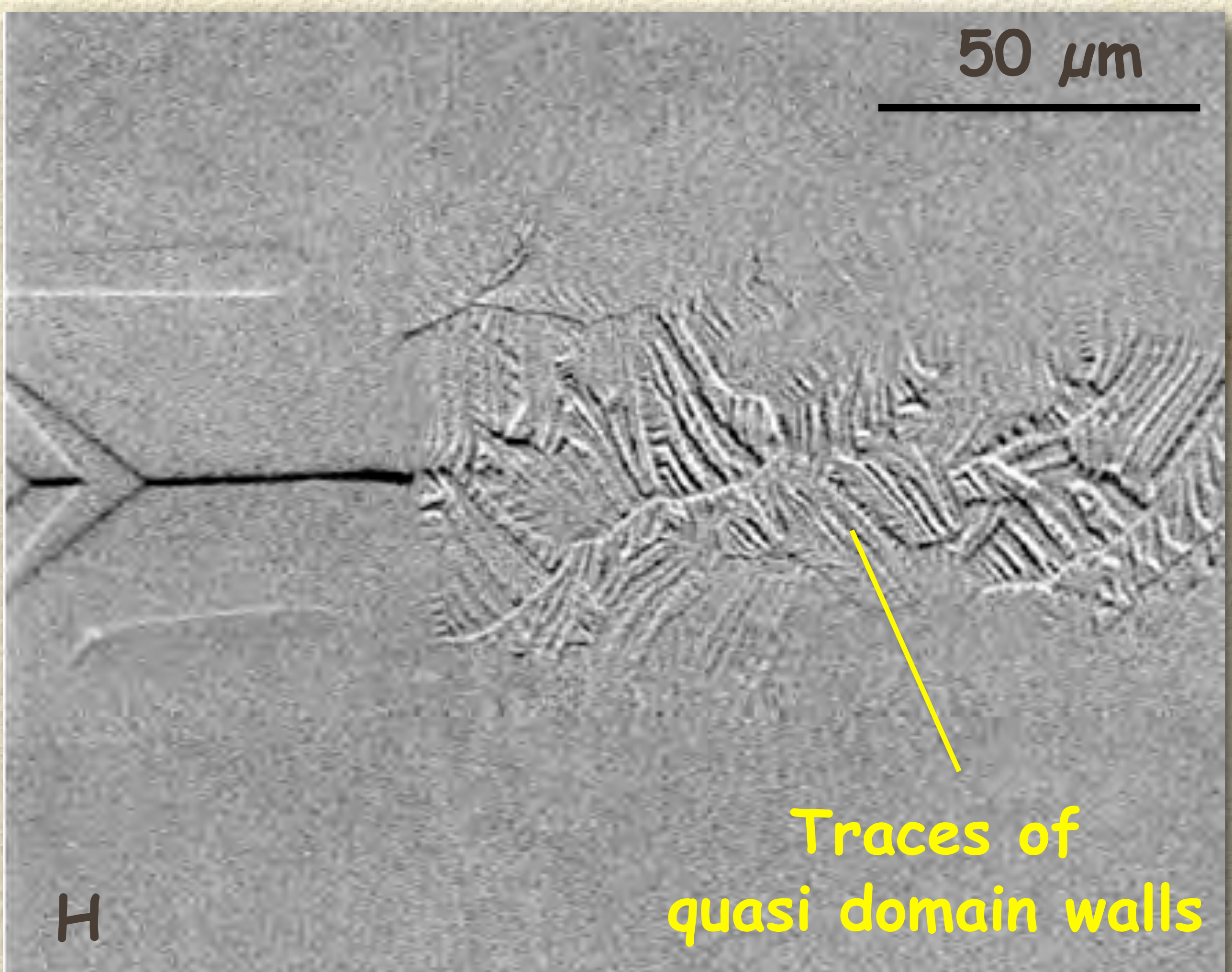
Non-oriented FeSi sheet

Indication of folded bands by surface observation

Non-oriented electrical steel (0.5 mm thick)



grain boundary

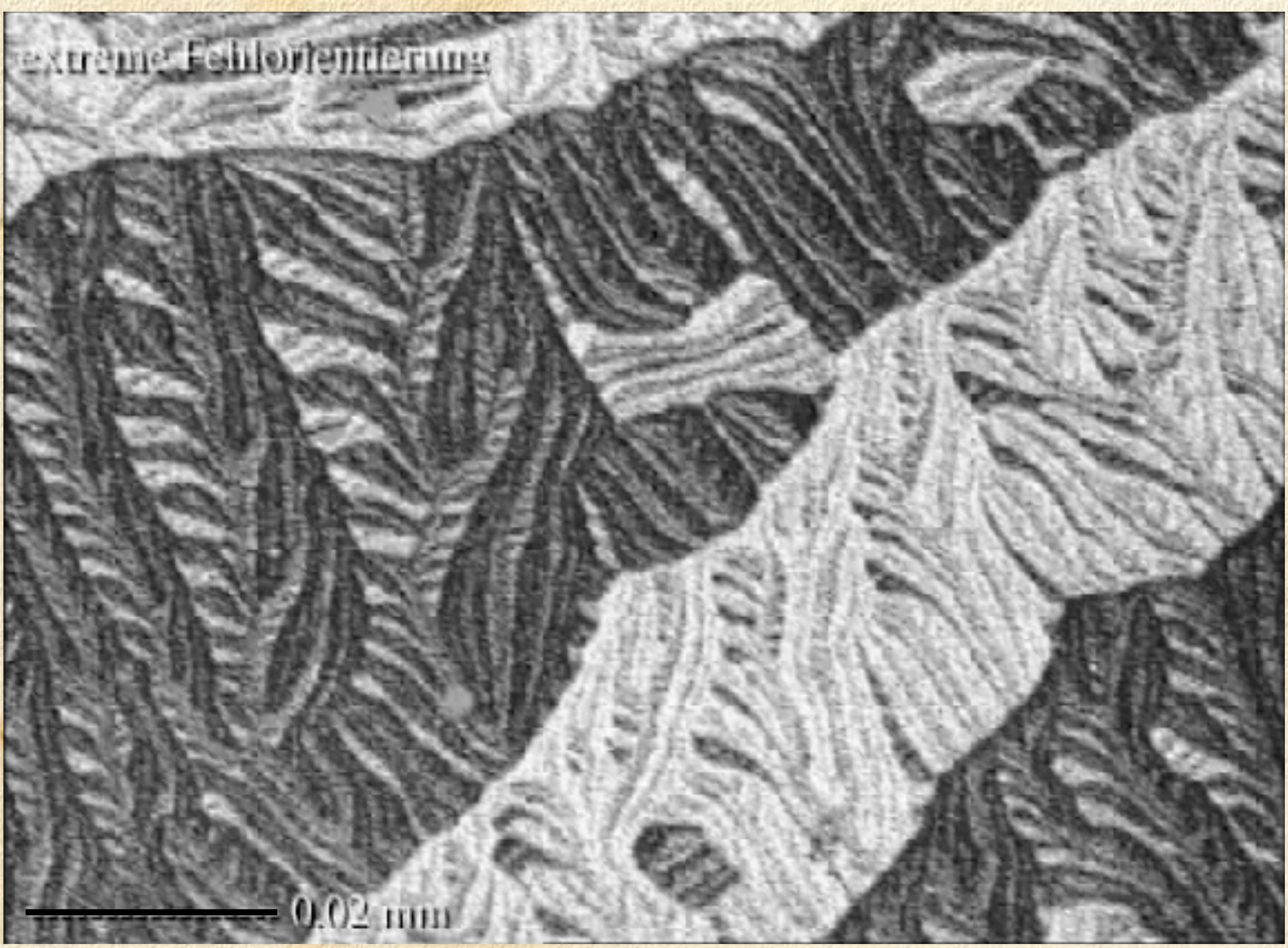


Difference between left image and image with field applied

Motor sheet

magnetic ac field

Motor sheet



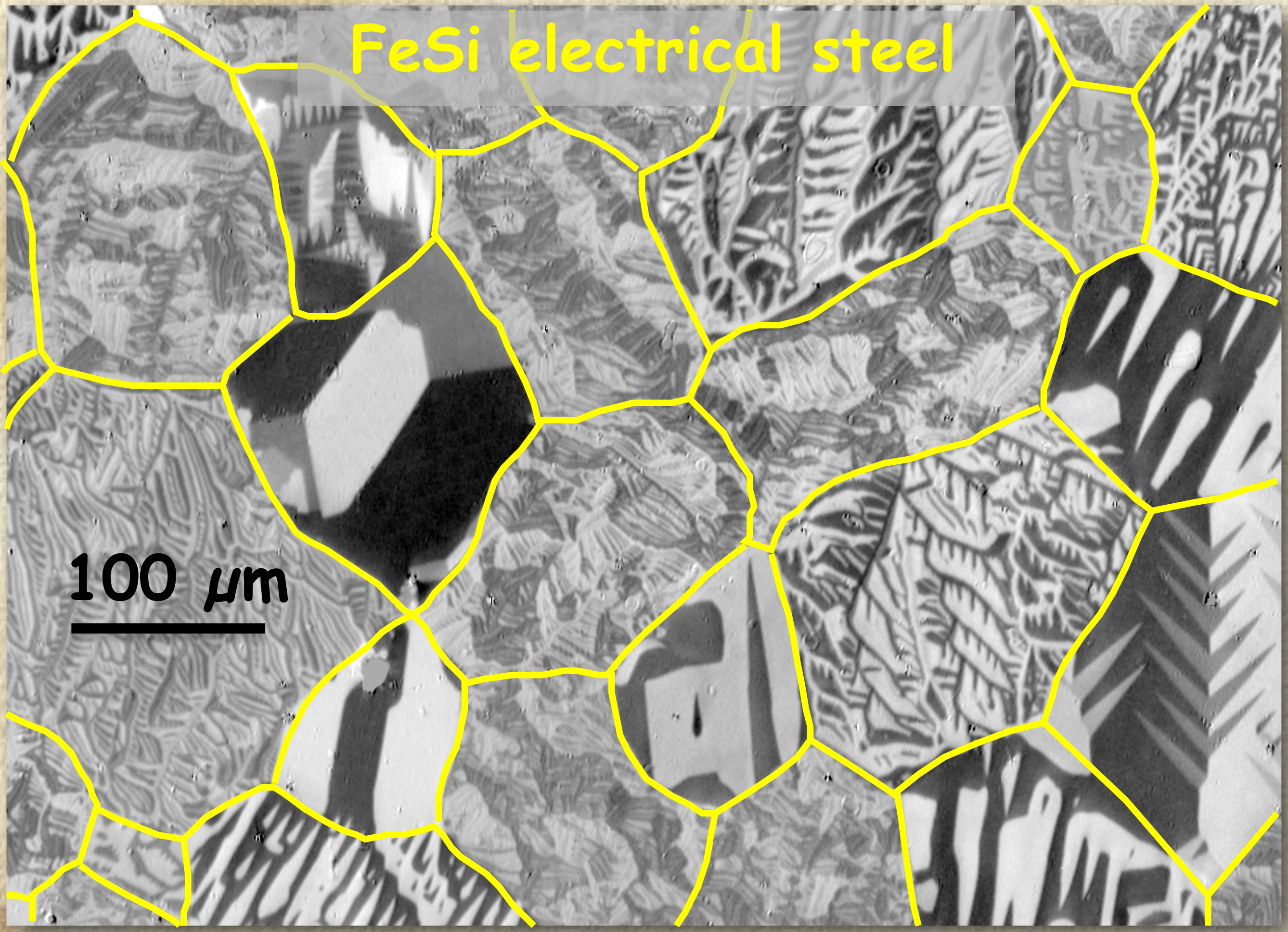
magnetic ac field

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



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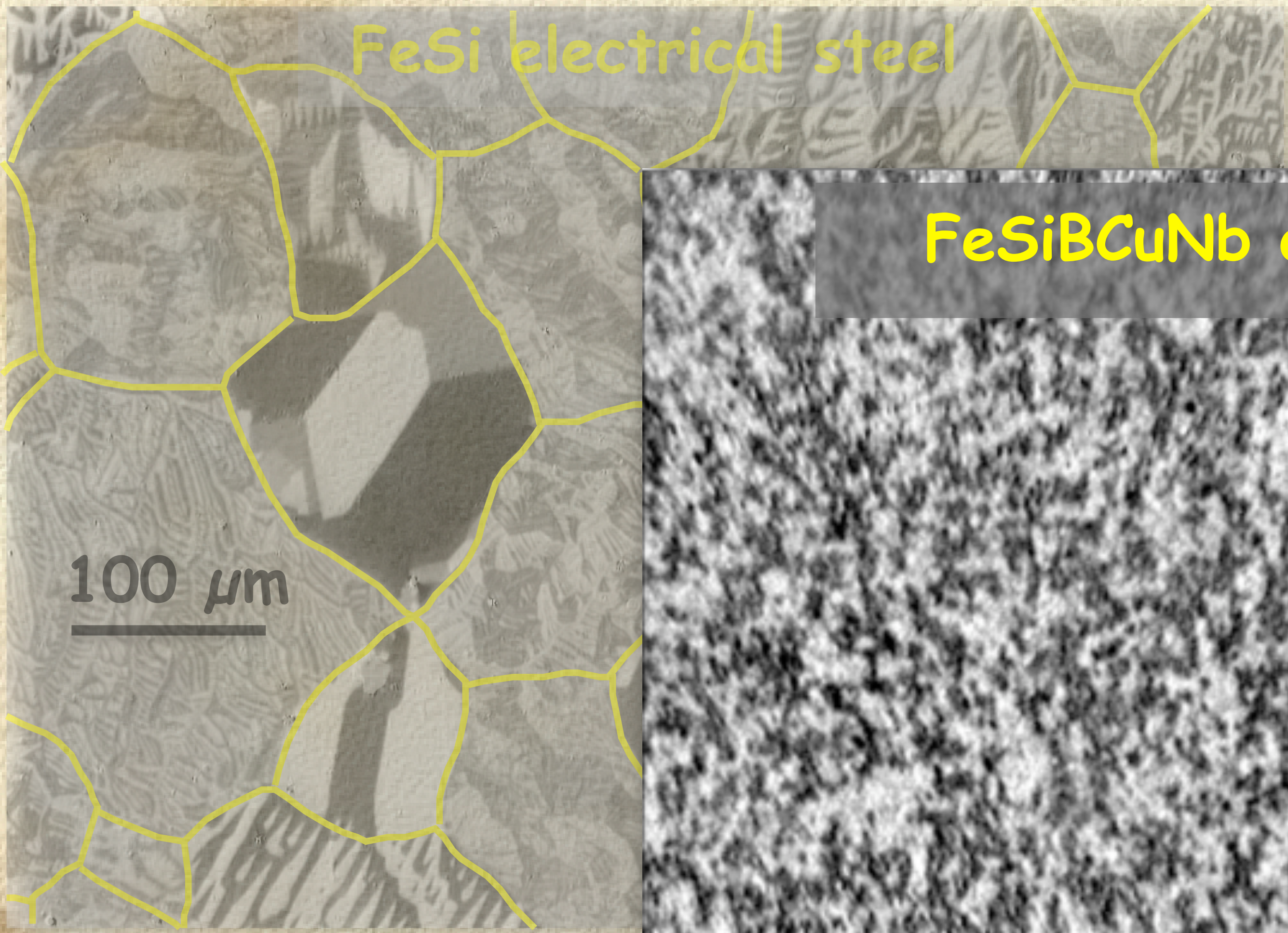
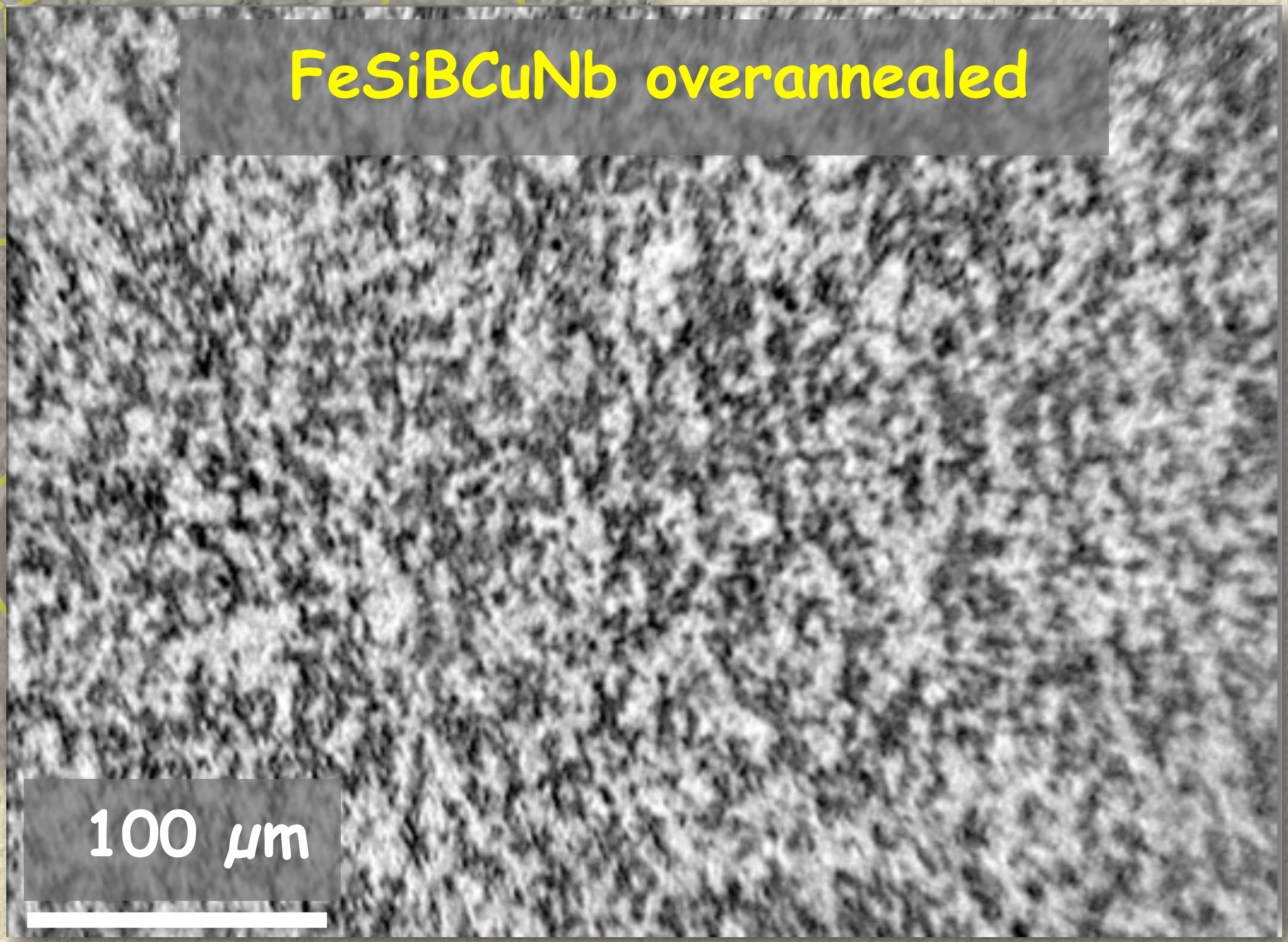


Grain size: 100 nm range

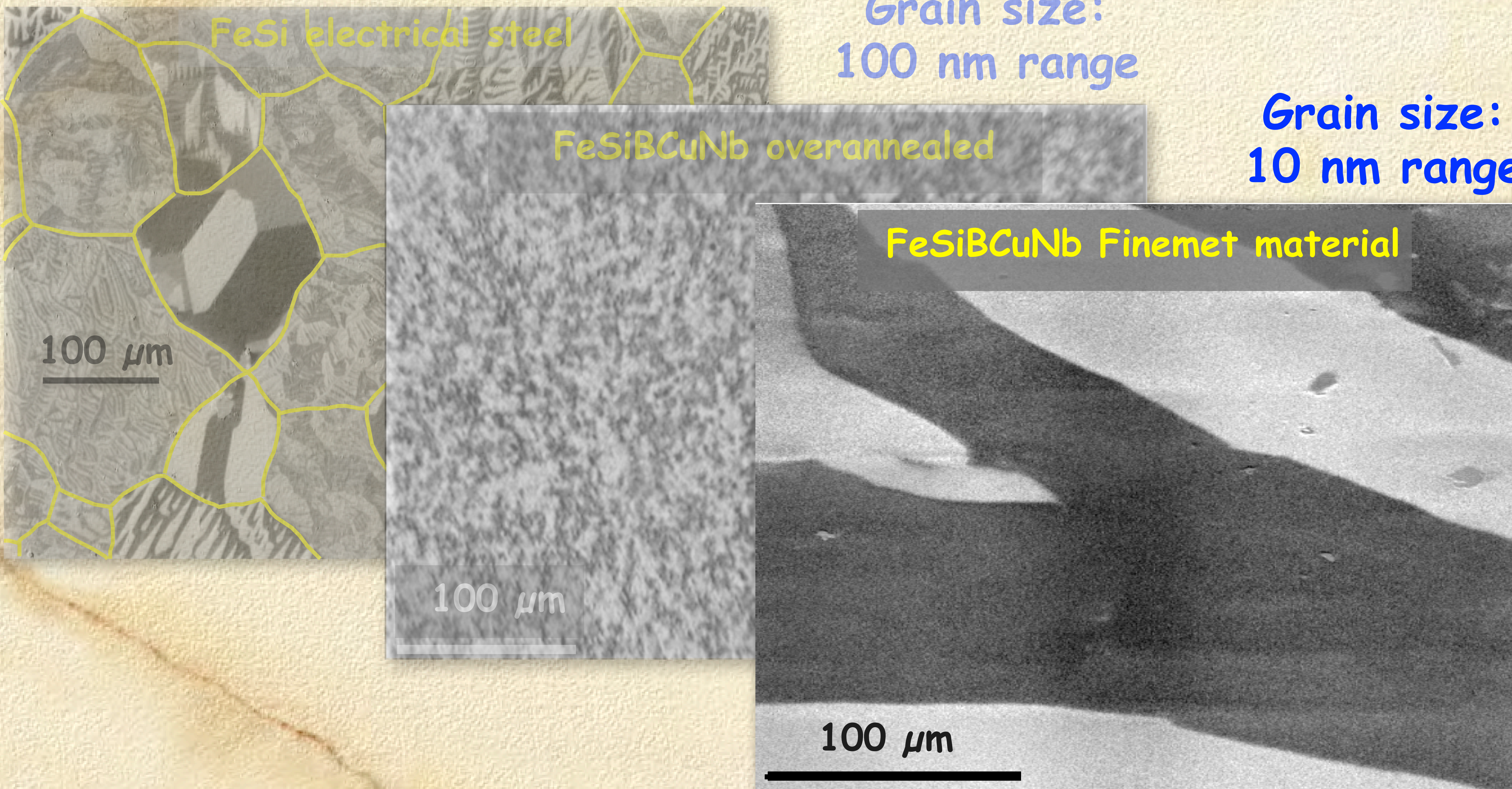


What happens to domains, when grain size gets smaller ?

Grain size: 100 µm range

Grain size: 100 nm range

Grain size: 10 nm range



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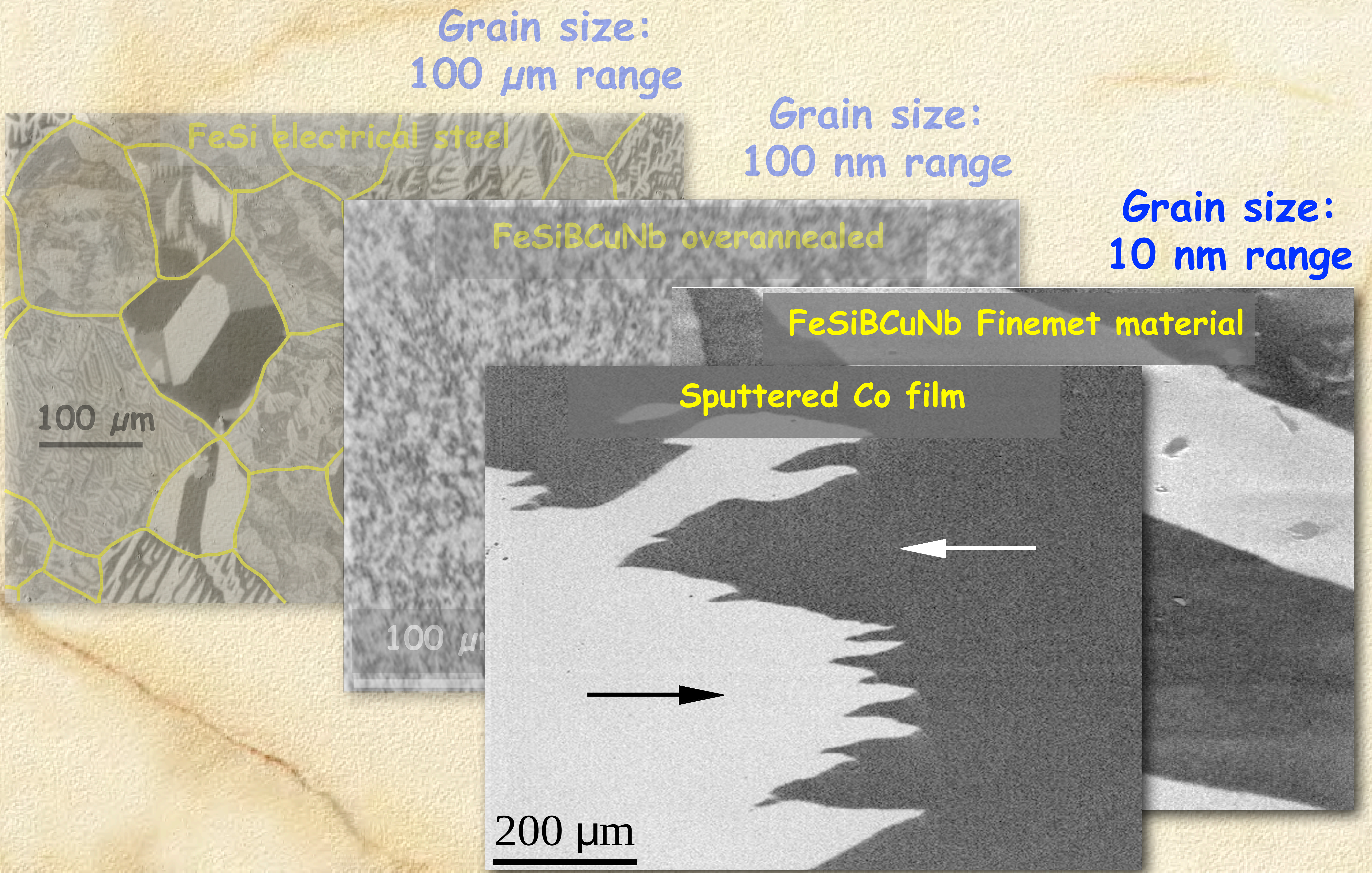
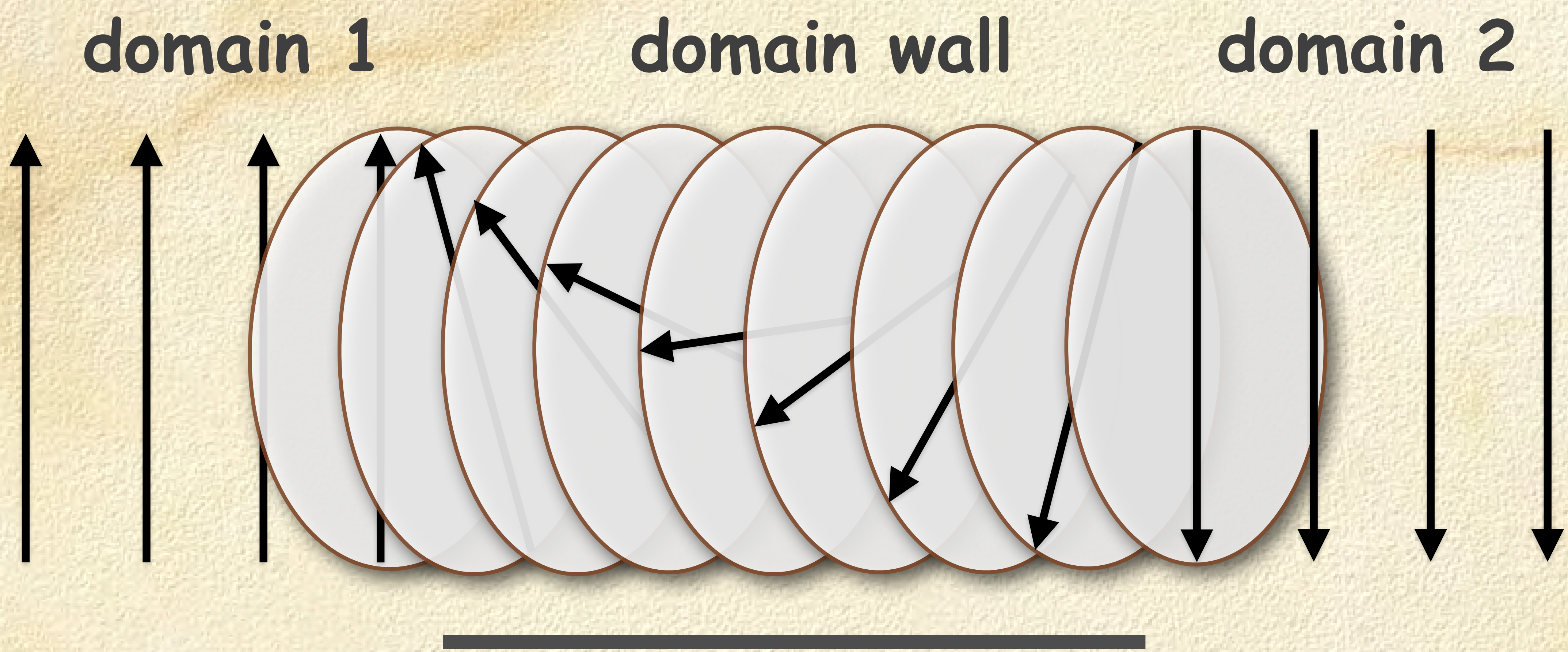


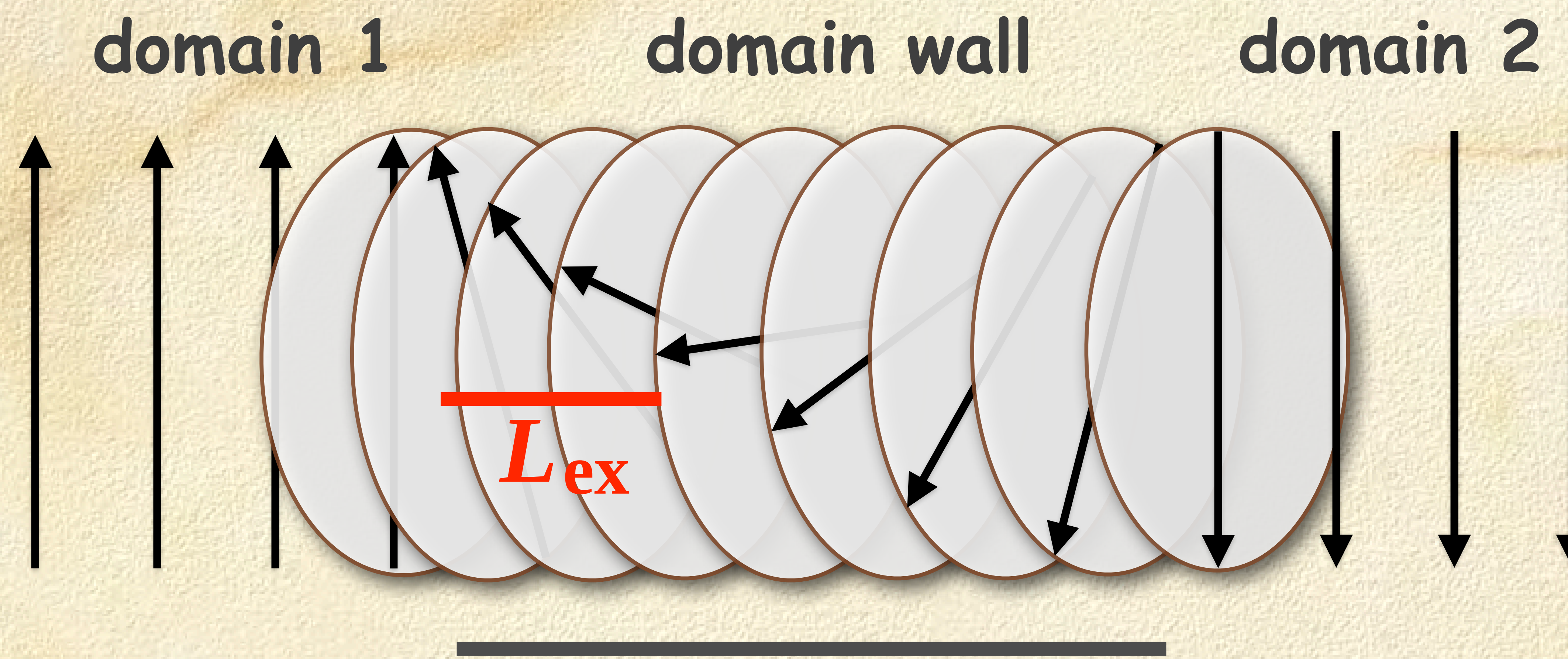
Nanocrystalline (Q<<1) materials



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

K: anisotropy constant
A: exchange constant

Nanocrystalline (Q<<1) materials



$\pi\sqrt{A/K}$

L_{ex}

K: anisotropy constant
A: exchange constant

ferromagnetic correlation length (exchange length):

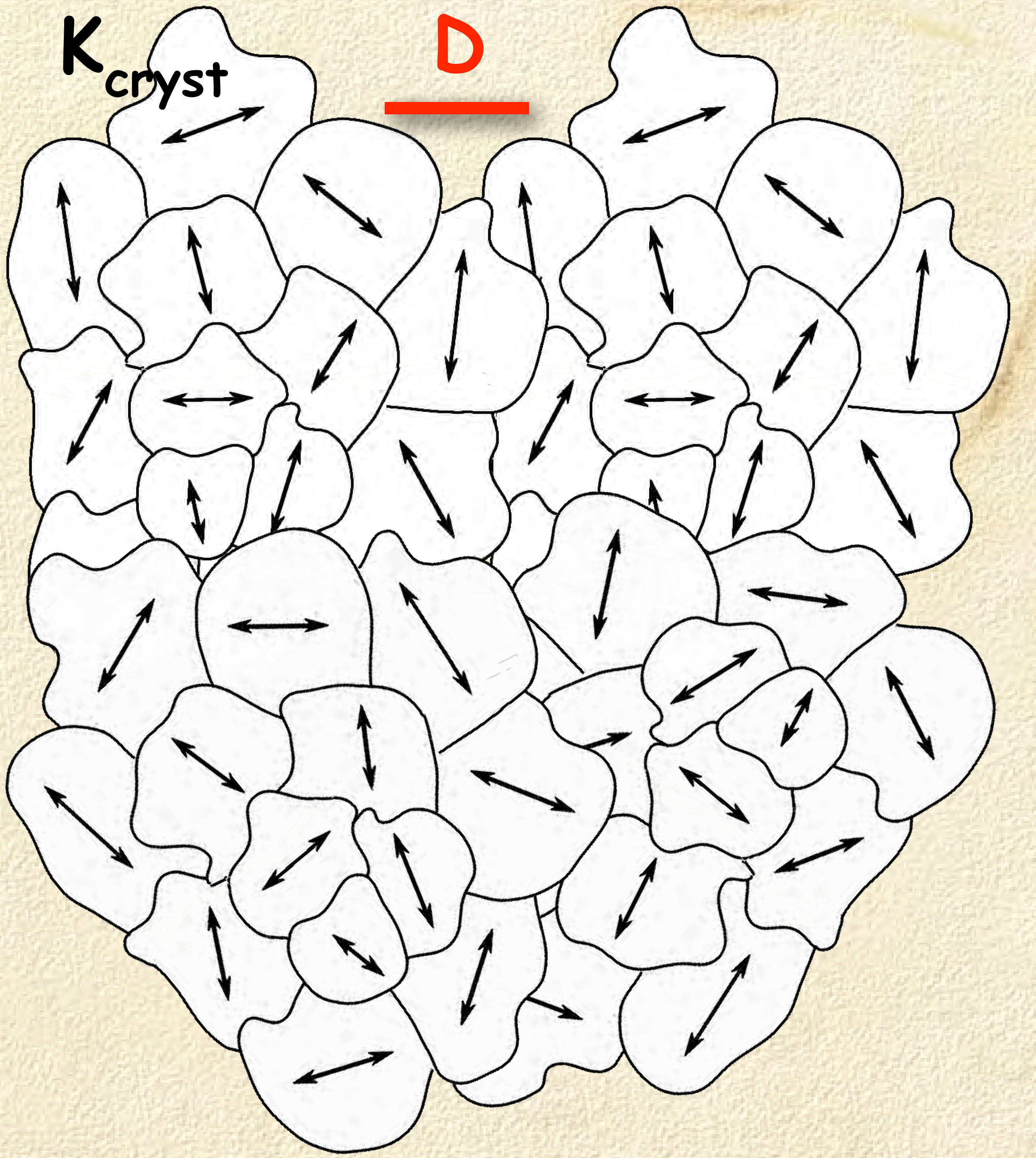
minimum scale for appreciable variation of magnetization (parallel moments for $L < L_{ex}$)

Nanocrystalline (Q<<1) materials

Random anisotropy model [Herzer 1989]:

Exchange interaction averages over anisotropy of grains

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



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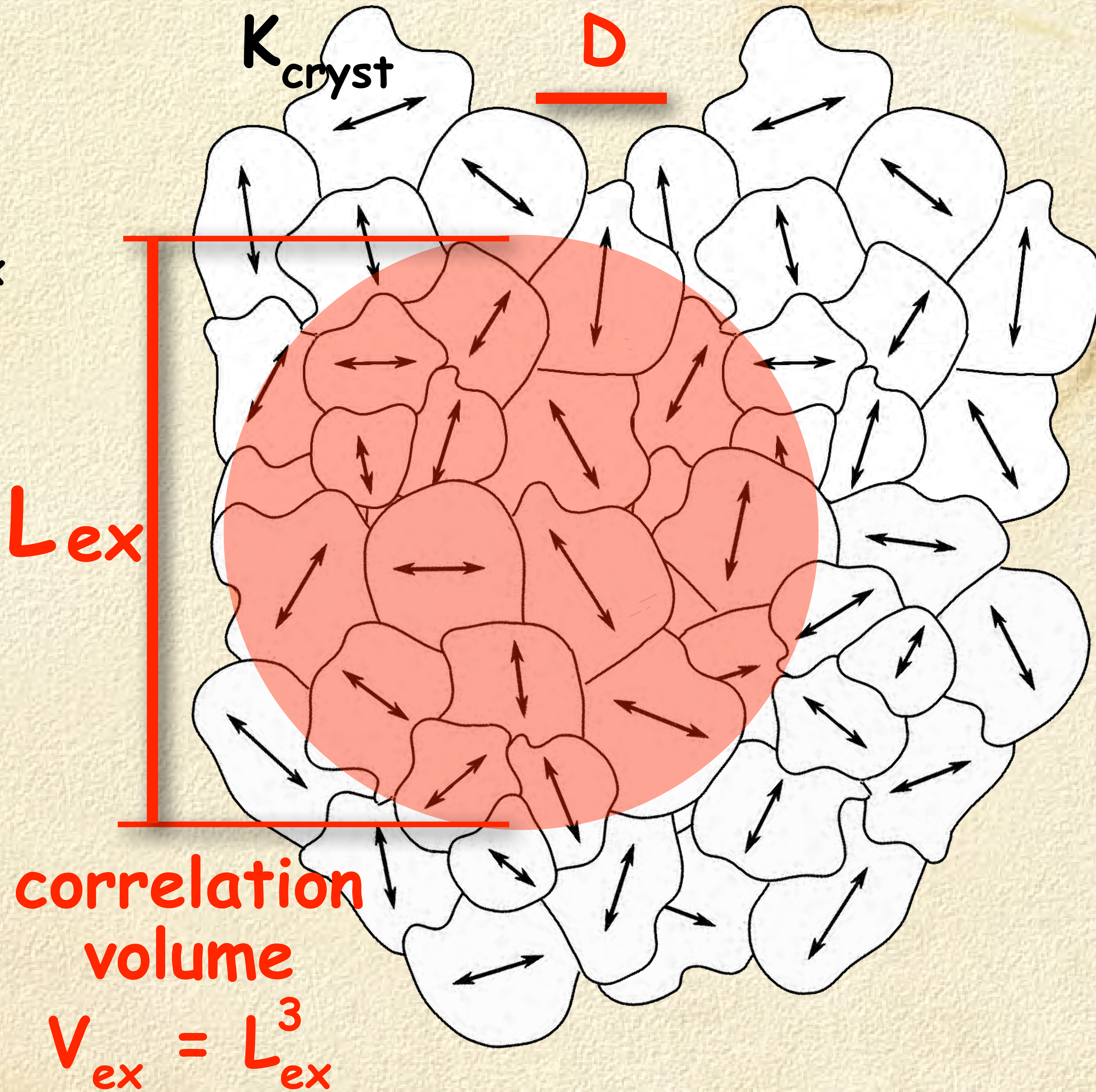
Nanocrystals: $D < L_{ex}$



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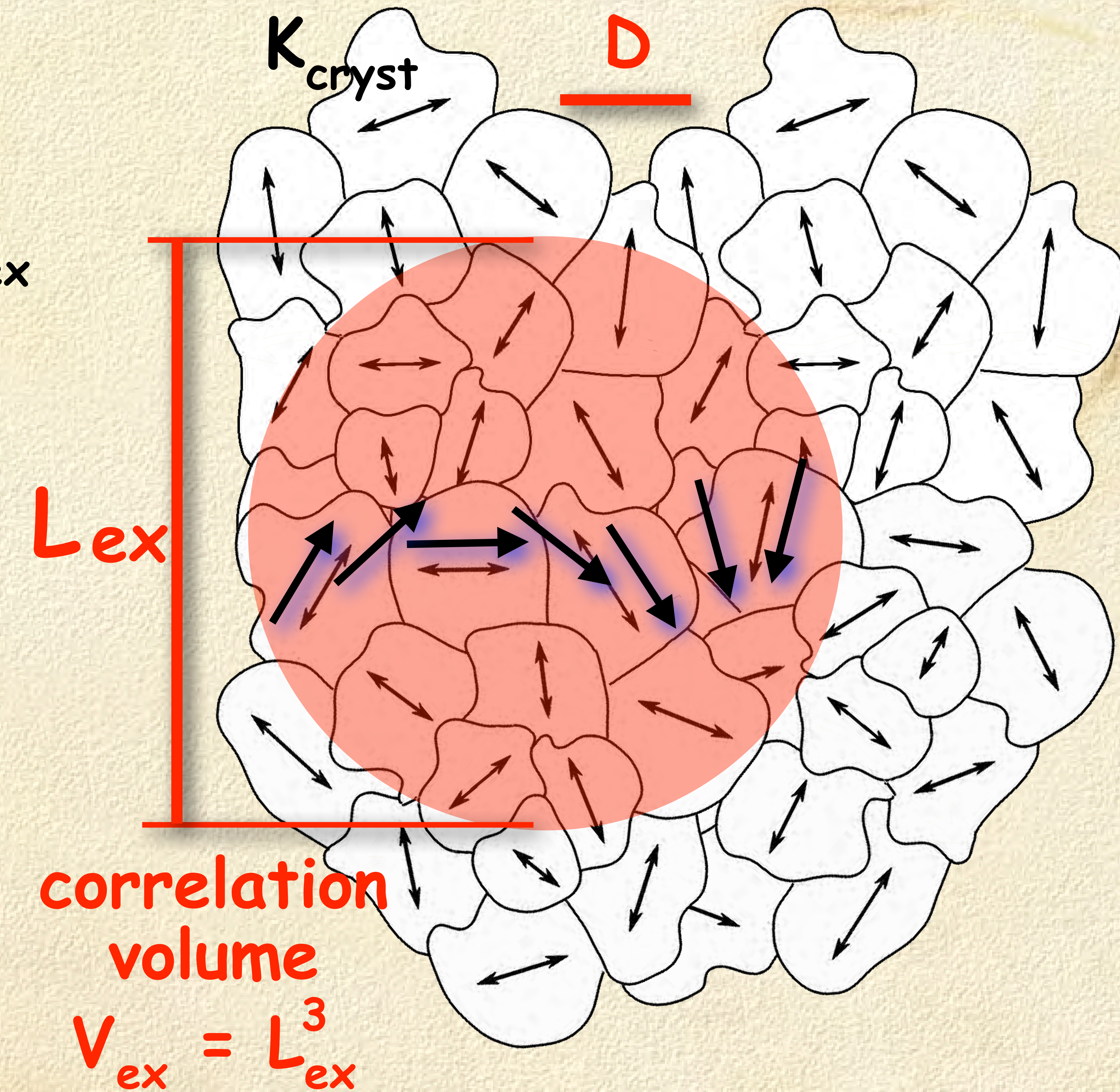

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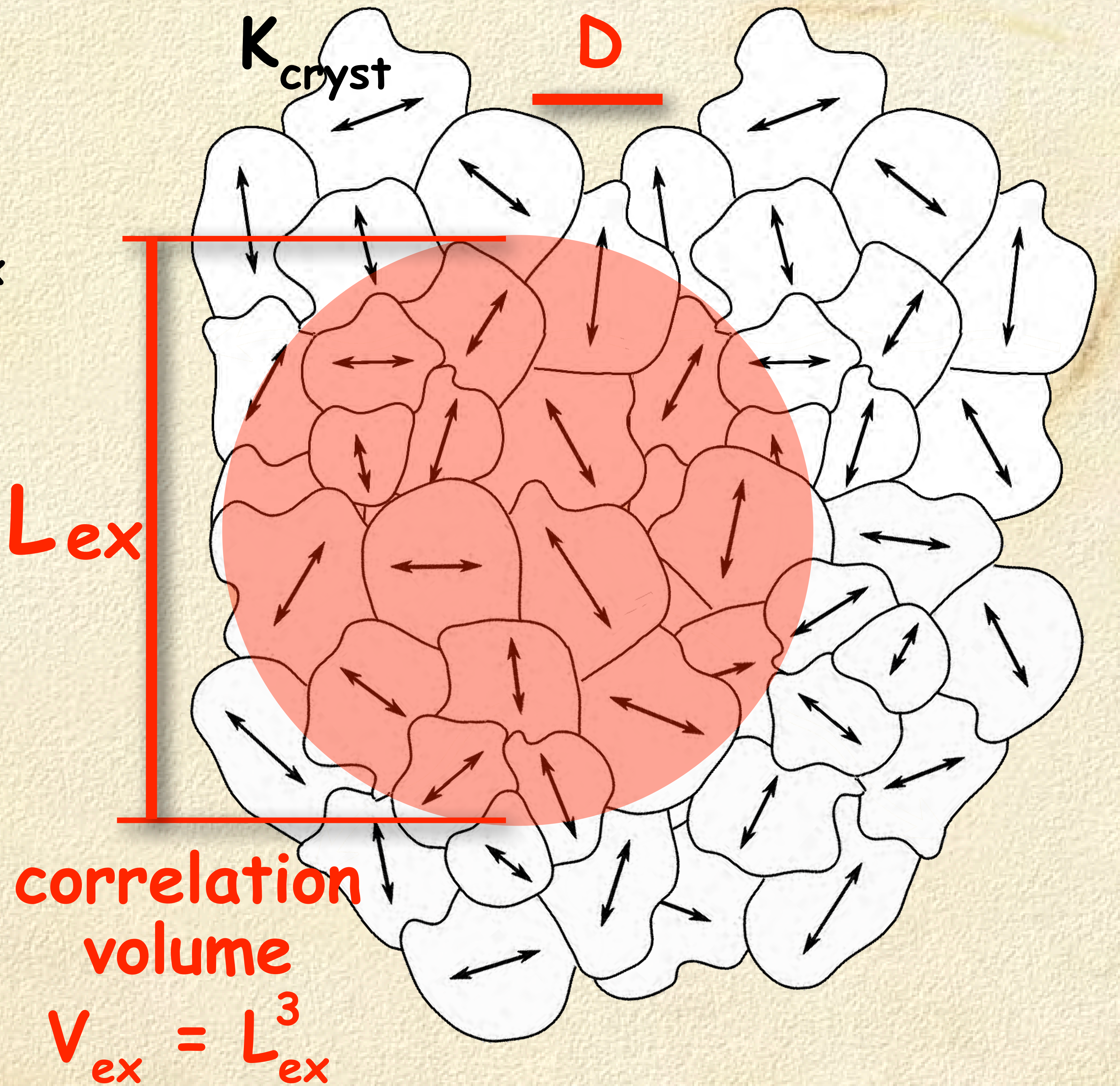

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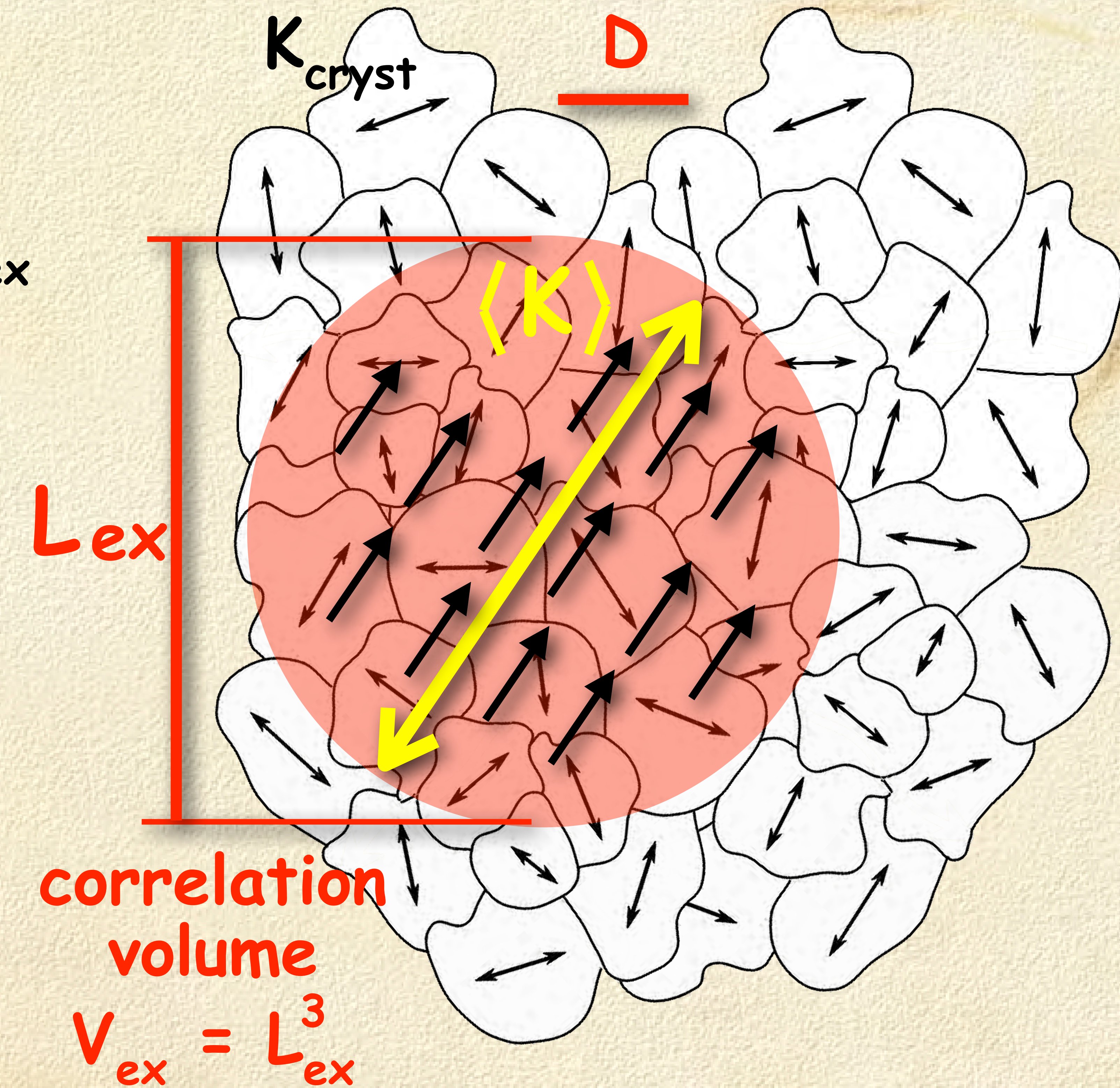
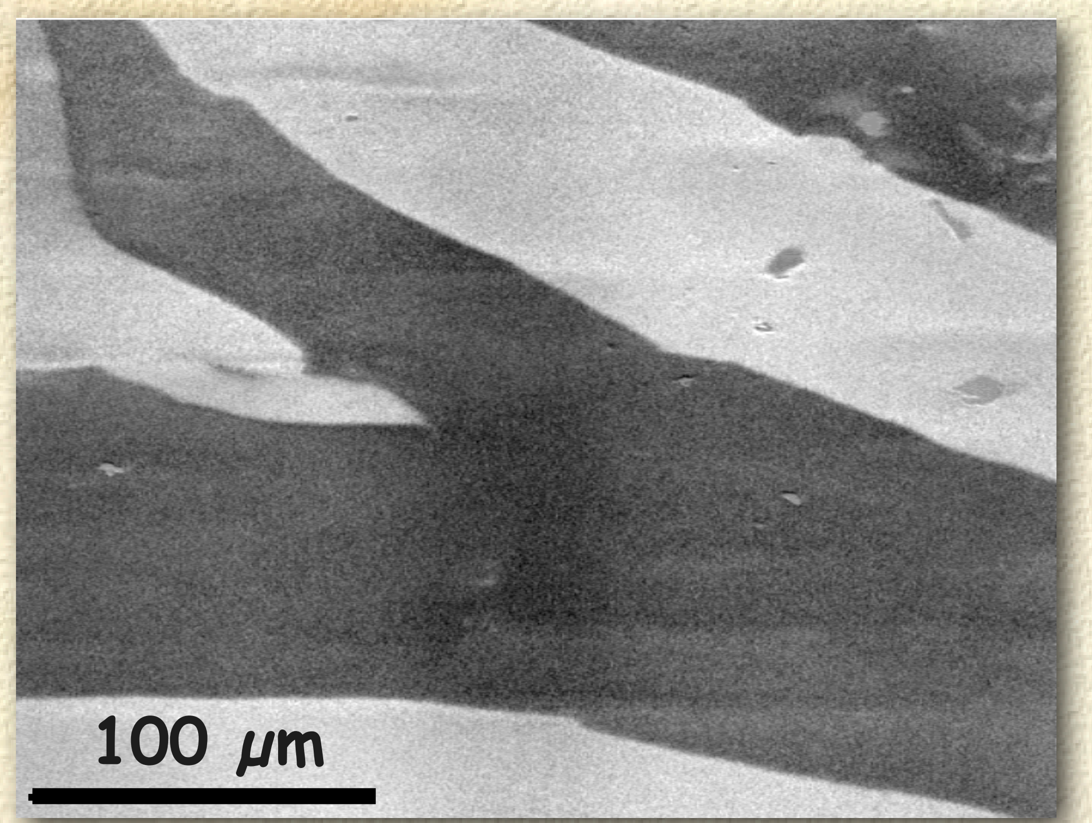


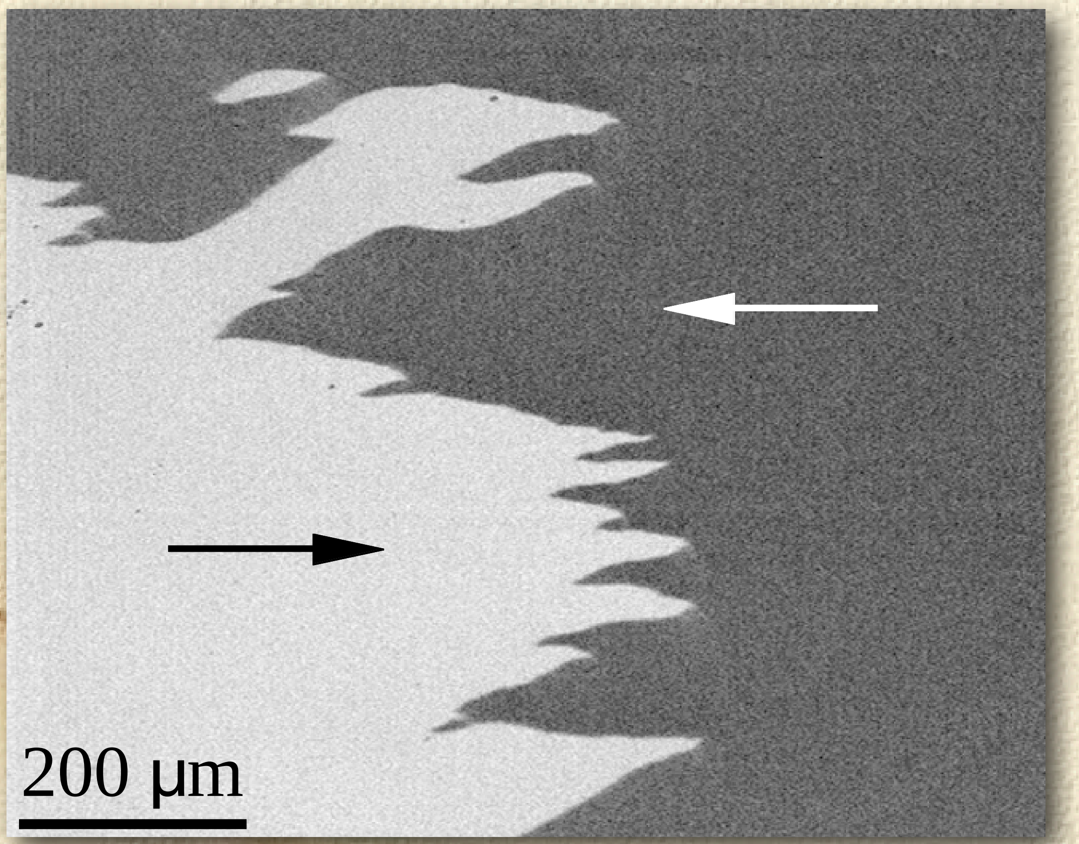
Nanocrystalline (Q<<1) materials

Low resolution

Nanocrystalline FeSiBCuNb ribbon (20 μm thick)



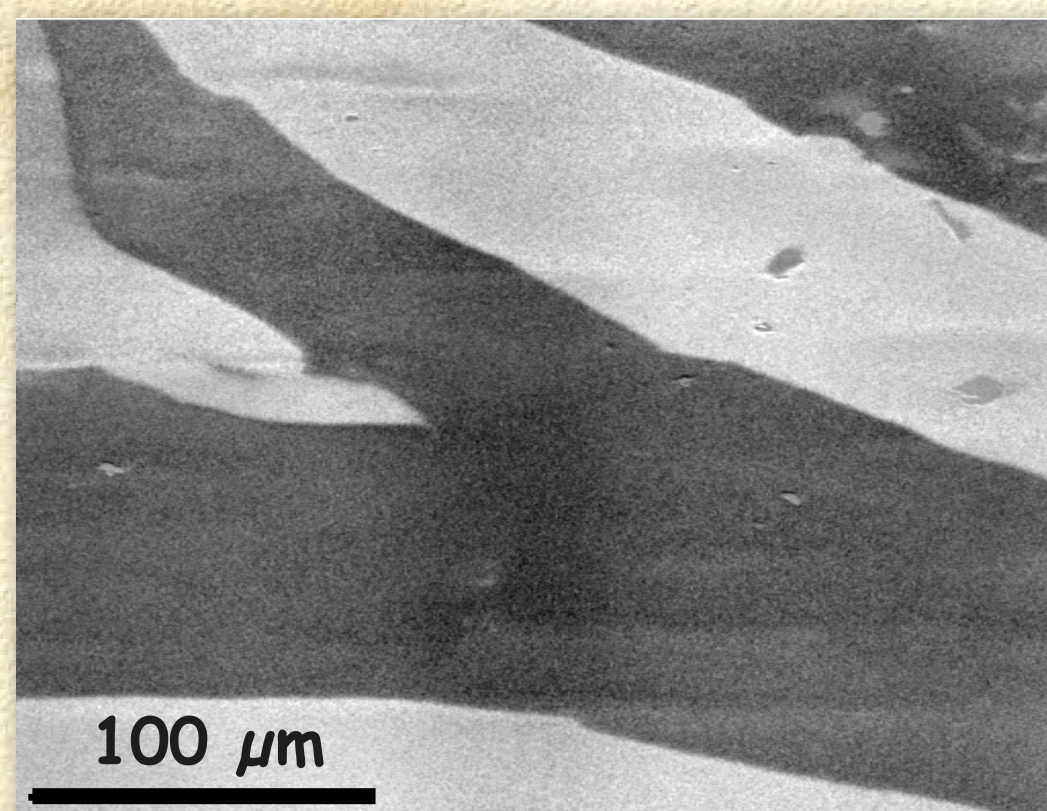
Sputtered Co film (60 nm thick)

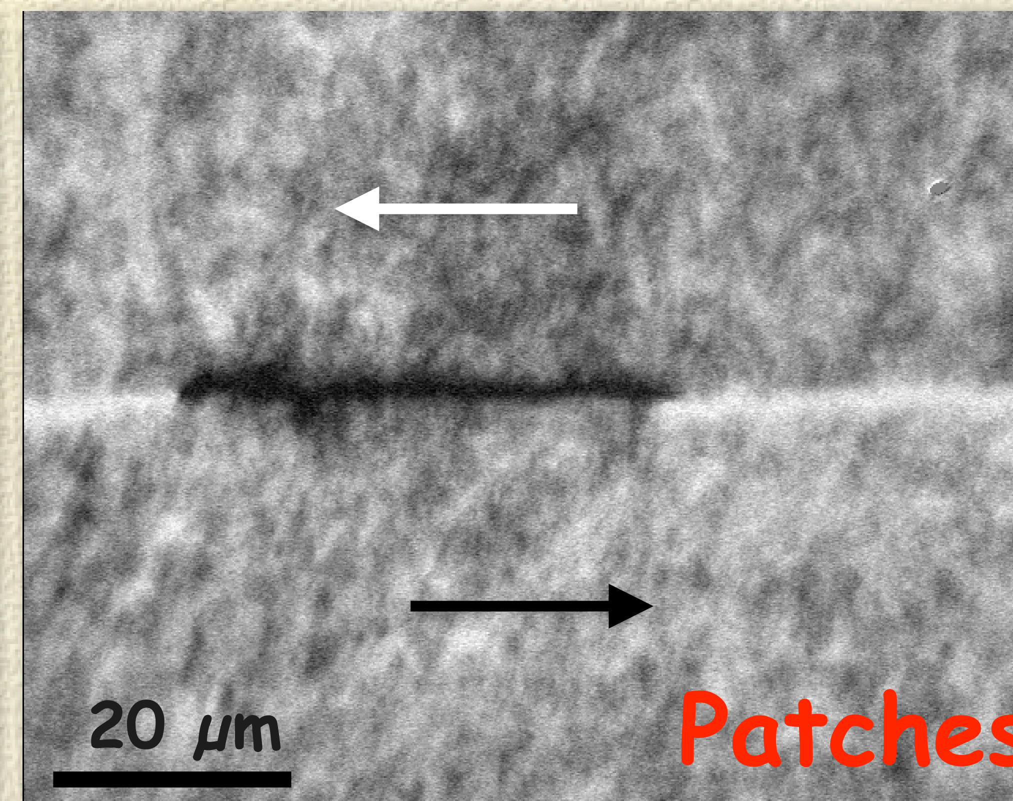


Nanocrystalline (Q<<1) materials

Low resolution | **High resolution**

Nanocrystalline FeSiBCuNb ribbon (20 μm thick)





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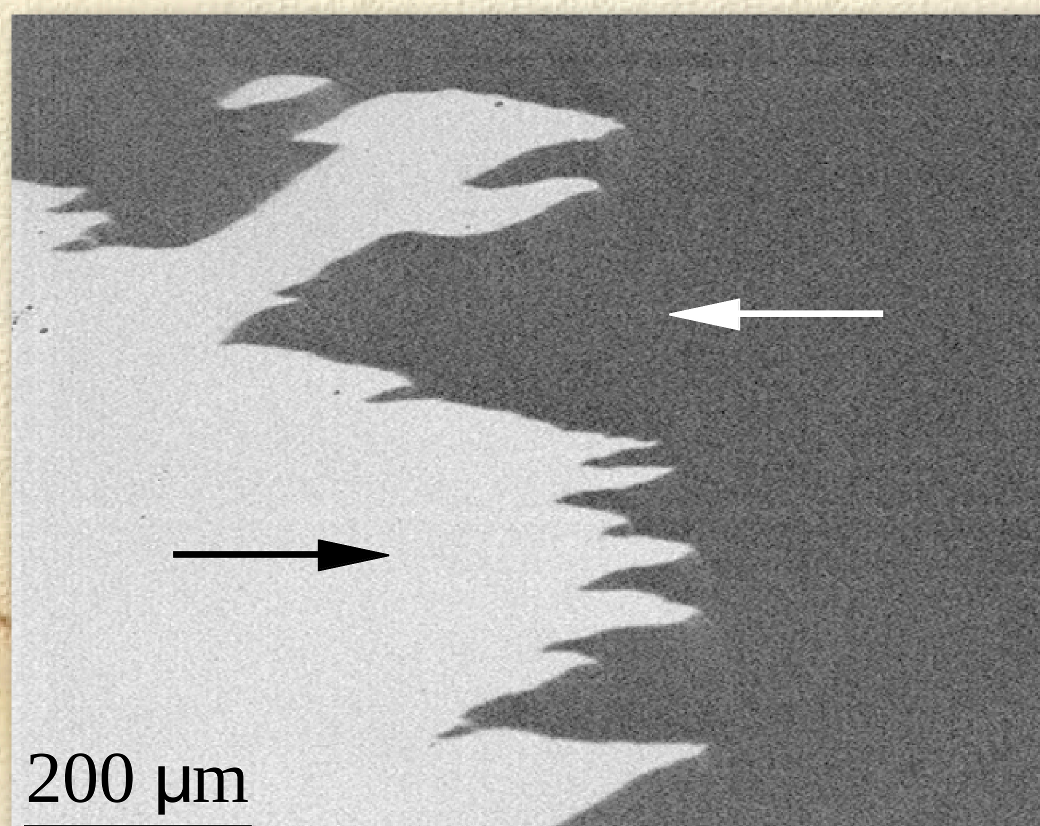

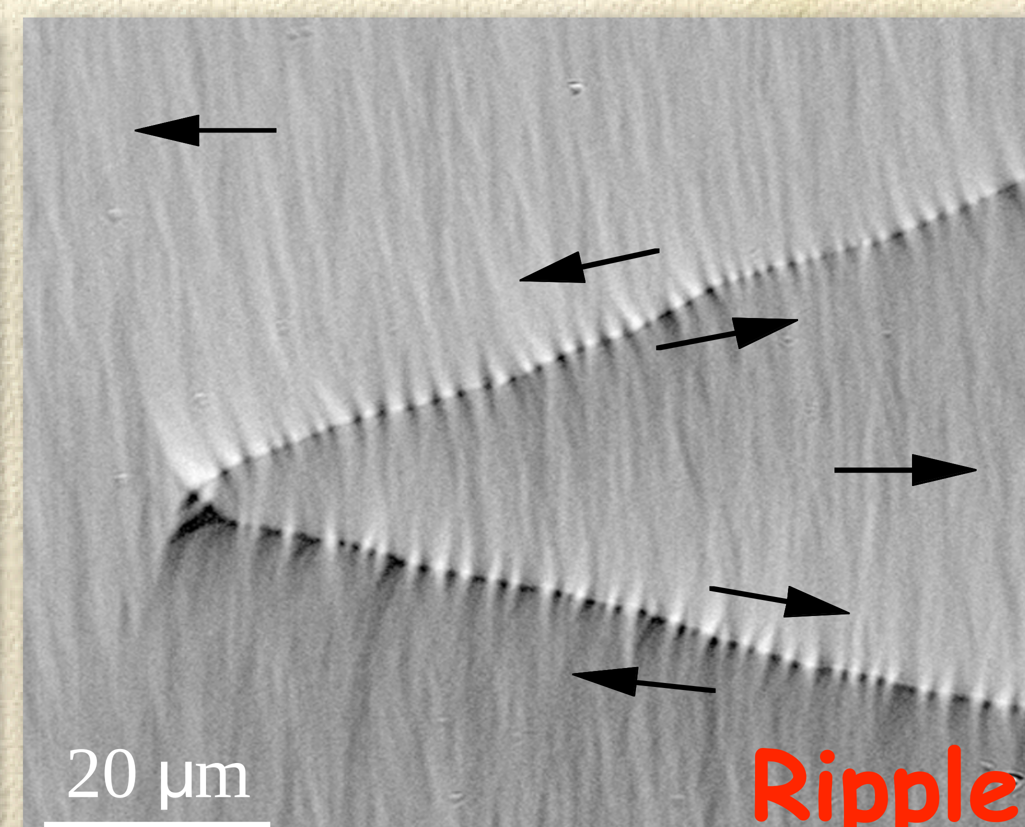

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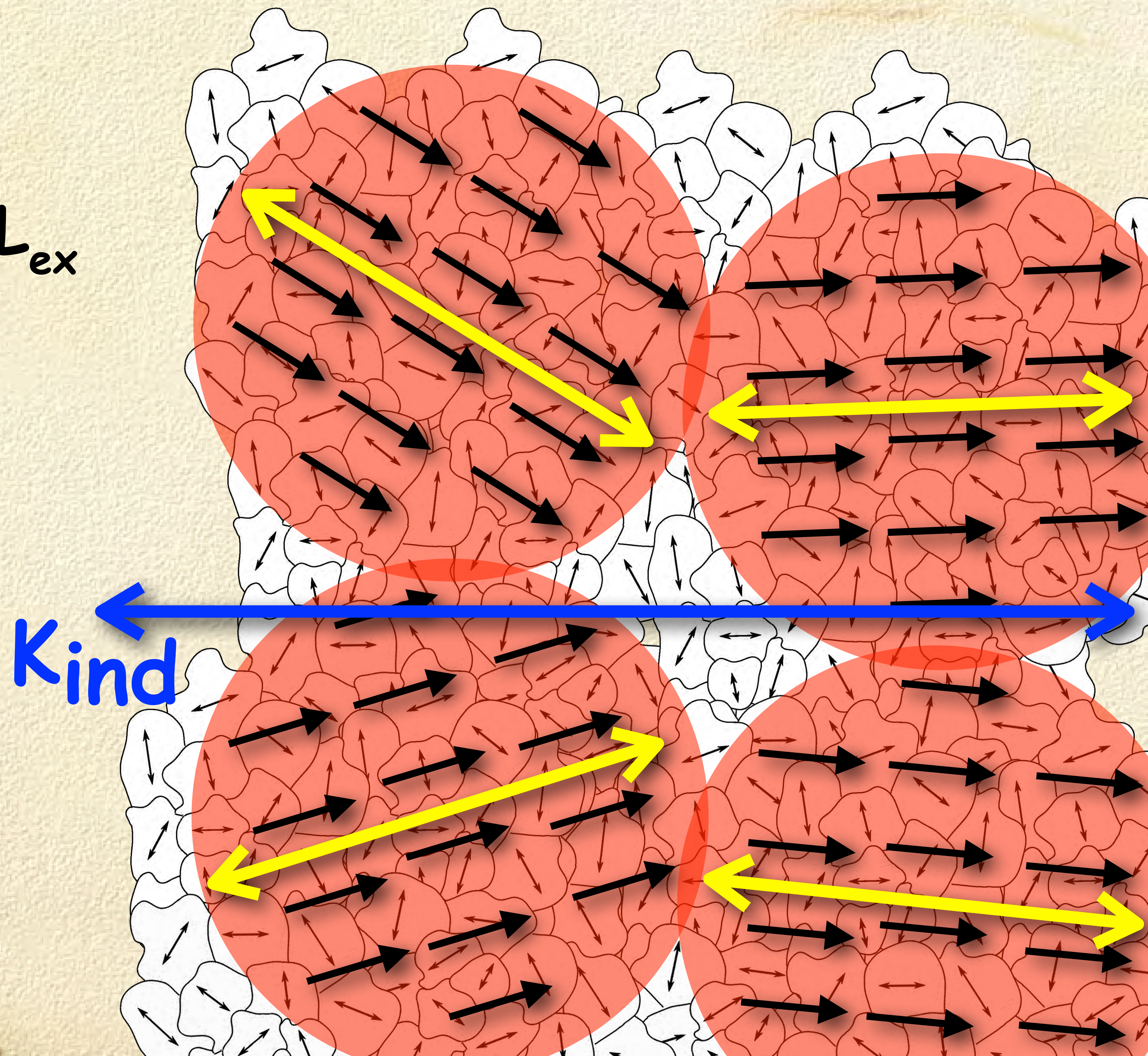
→ $\langle K \rangle << K_{cryst}$

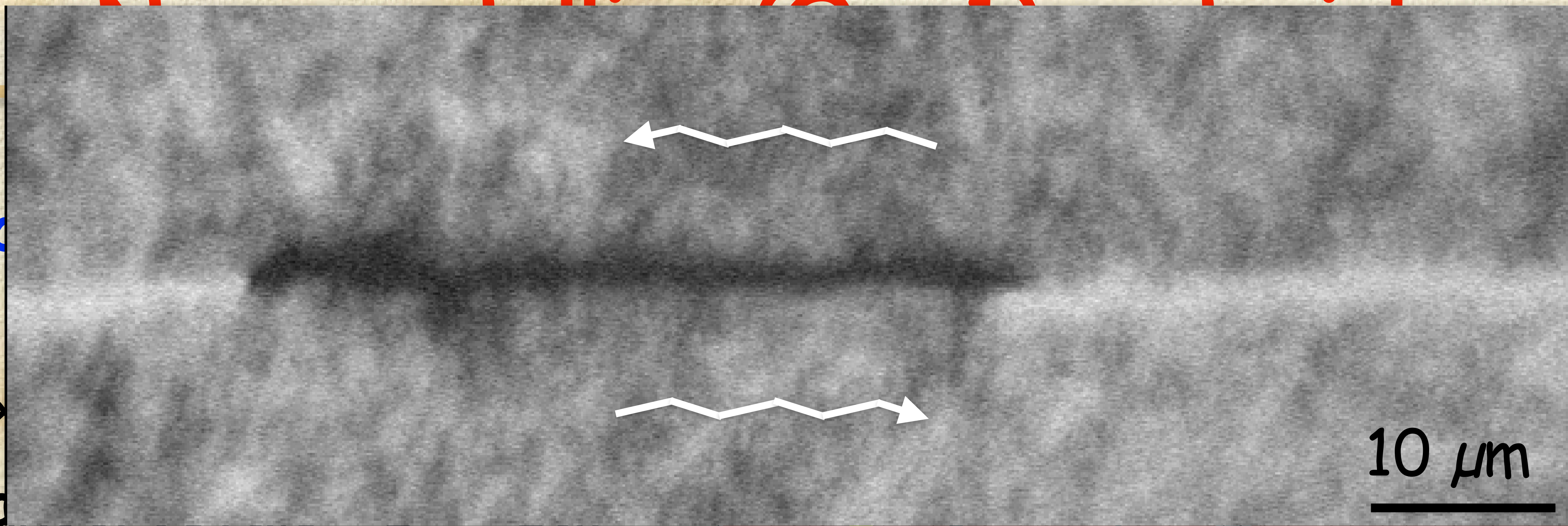


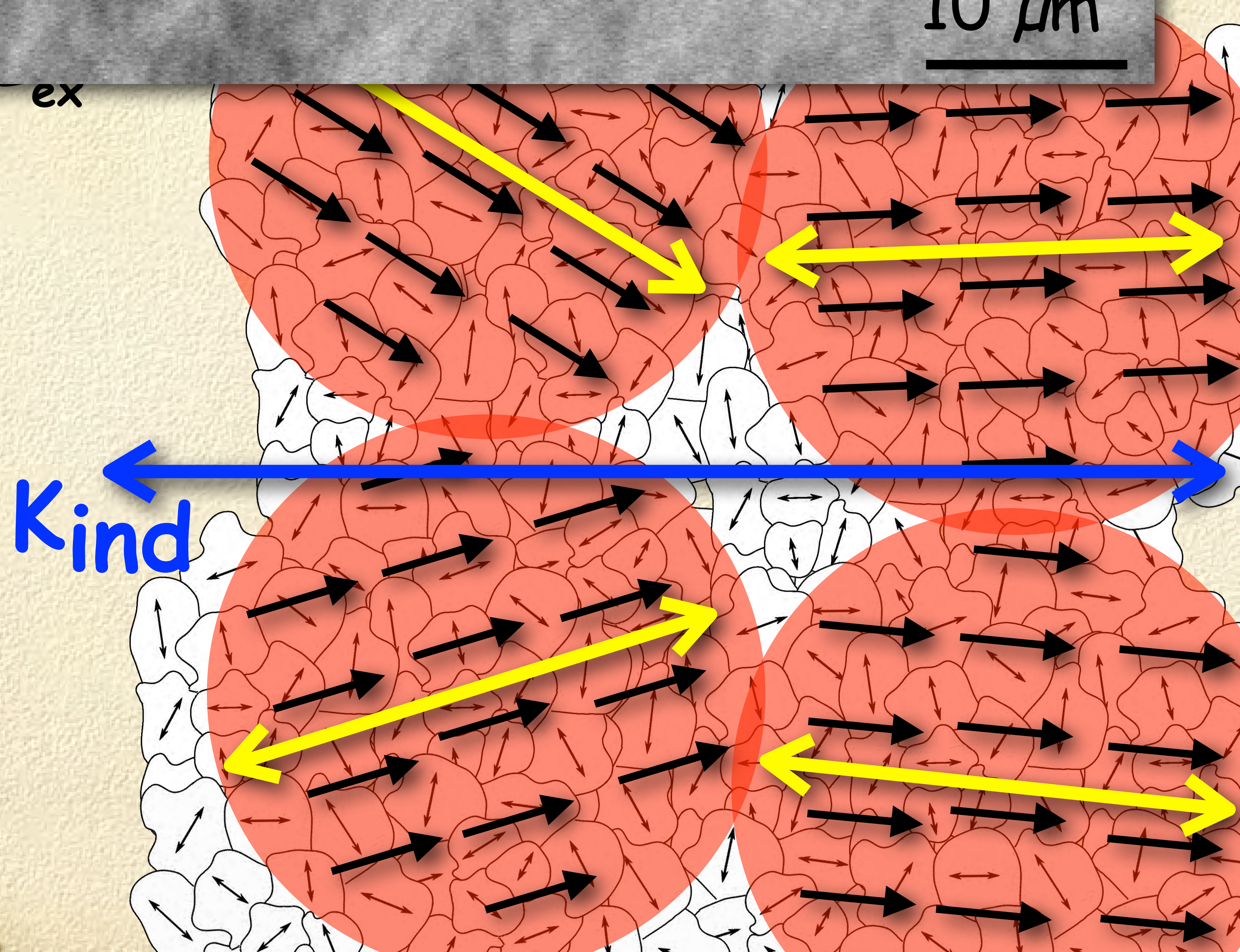
Exc ... ns

L_{ex} ...

Na ... $_{ex}$

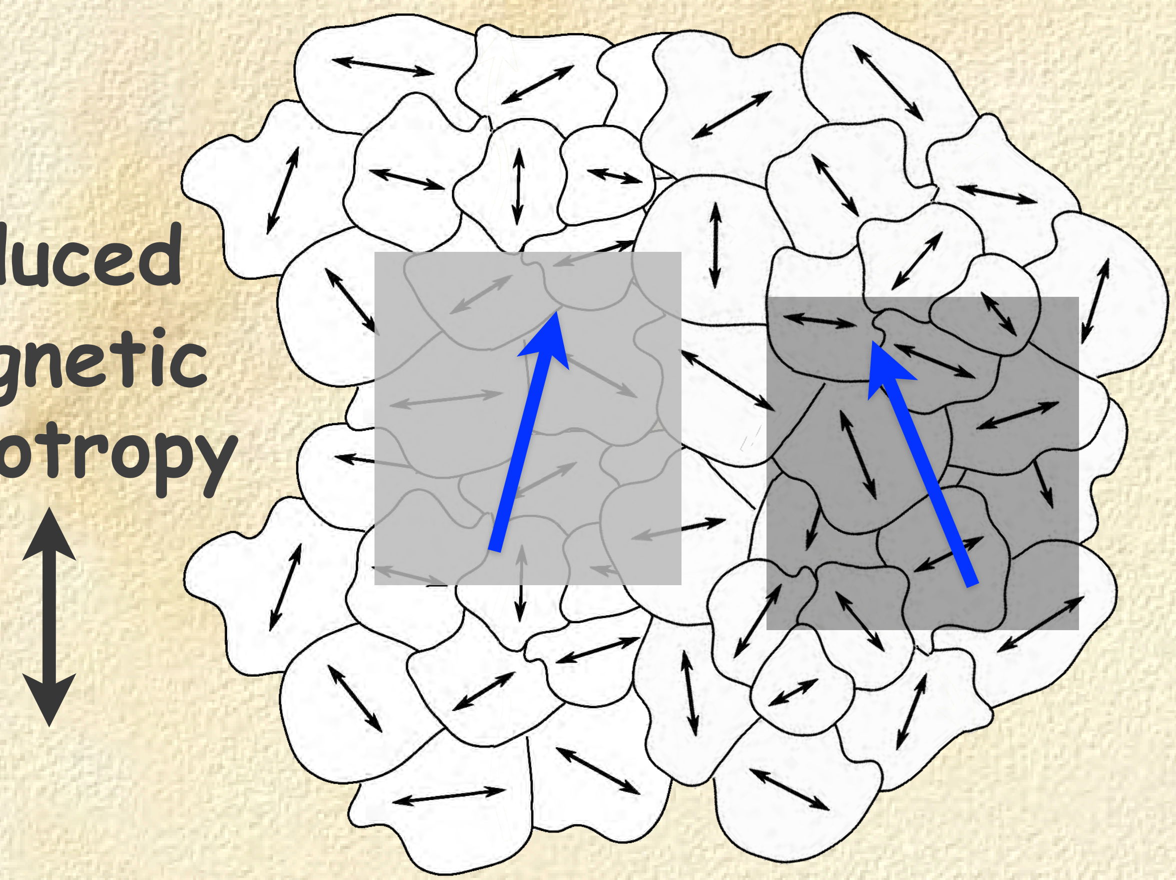
→ $\langle K \rangle << K_{cryst}$



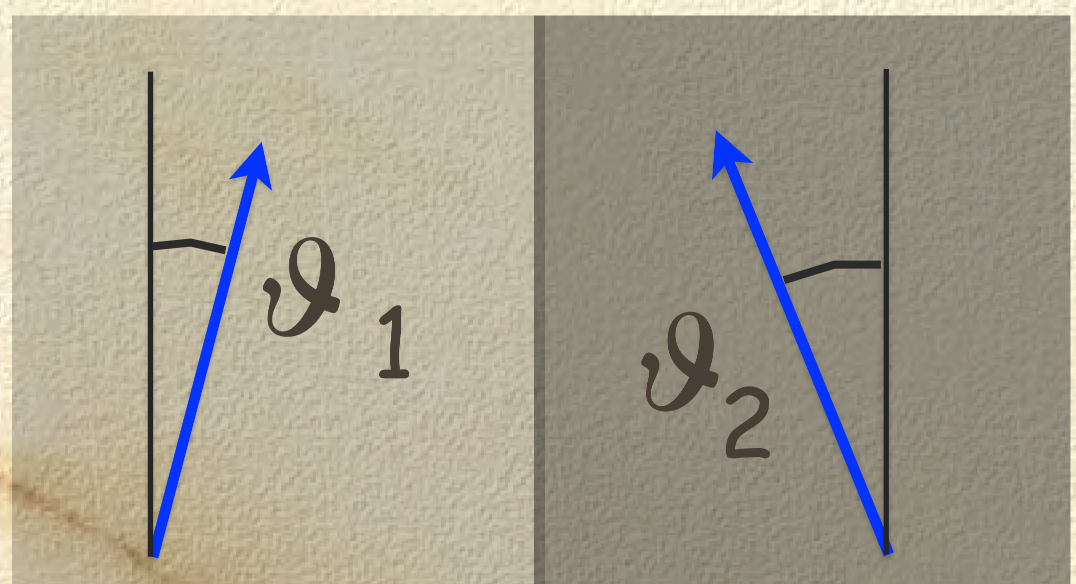


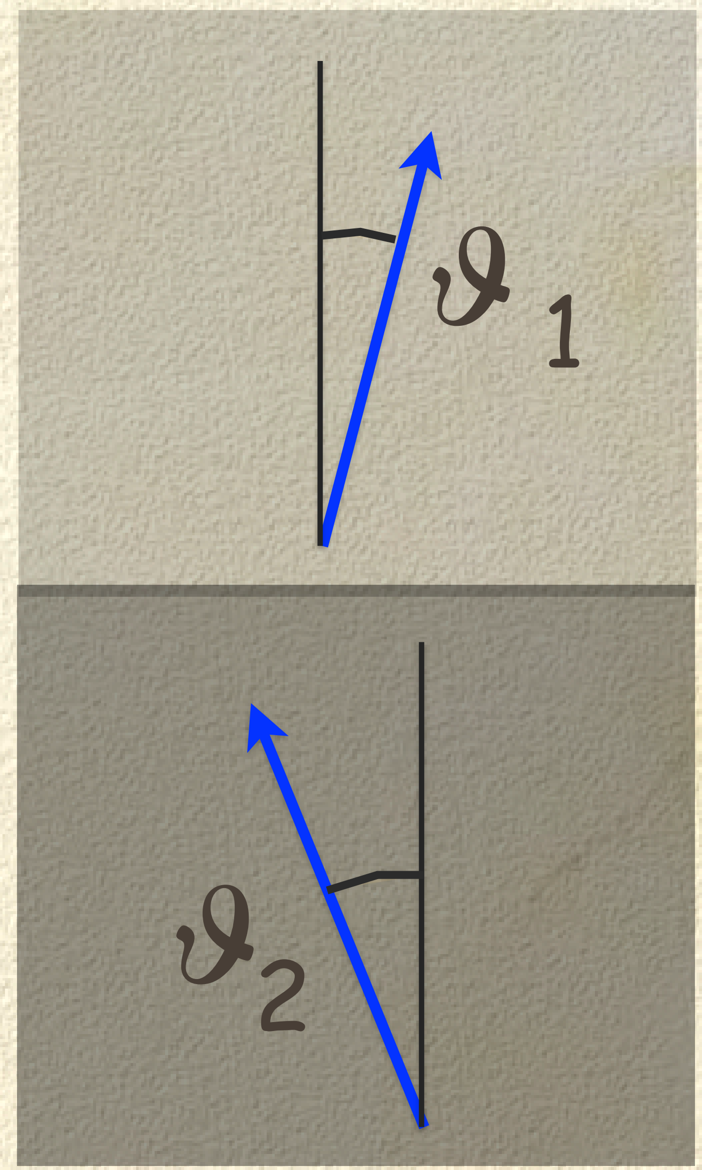
Nanocrystalline (Q<<1) materials

induced magnetic anisotropy



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<<1) materials

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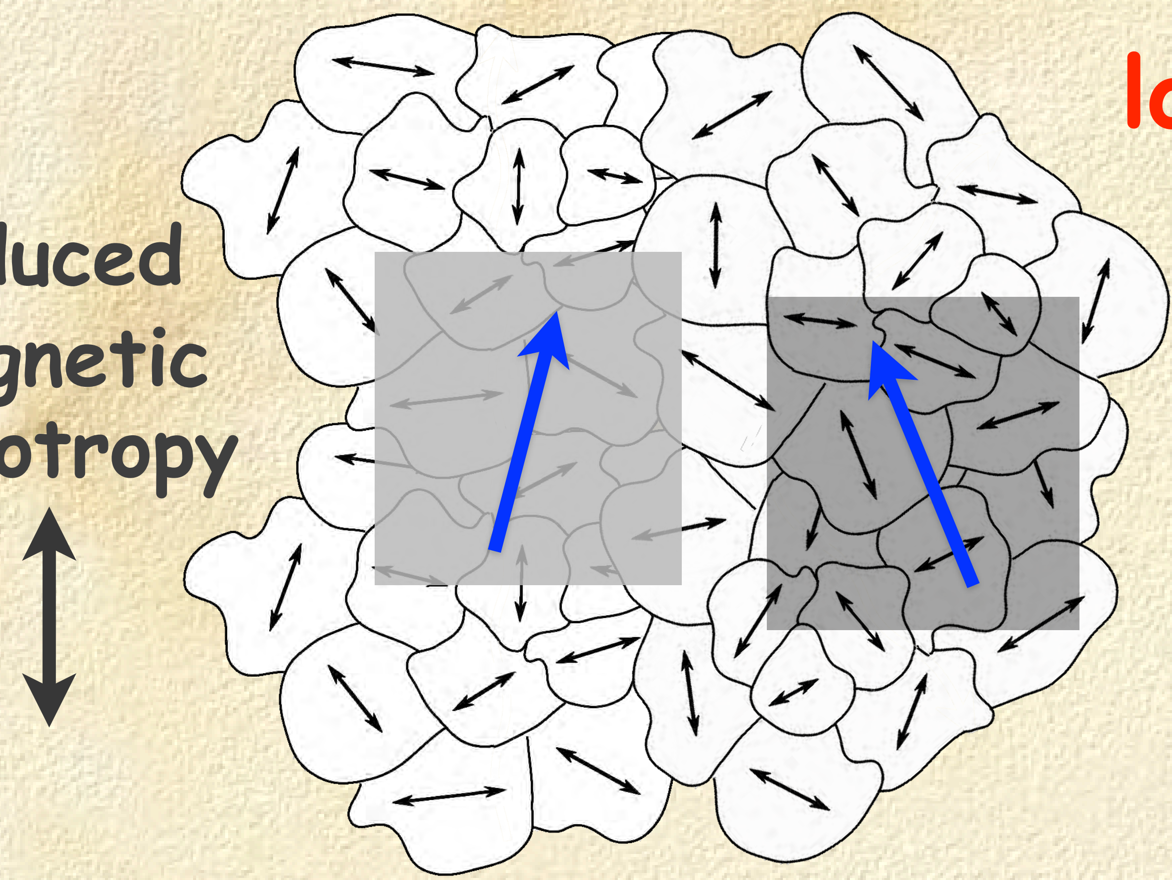
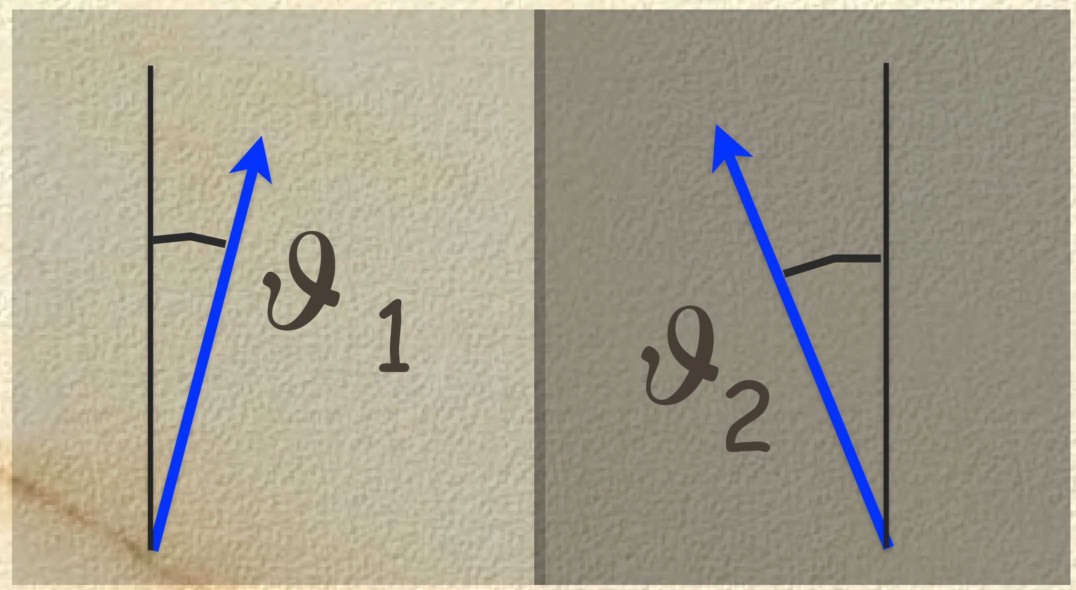
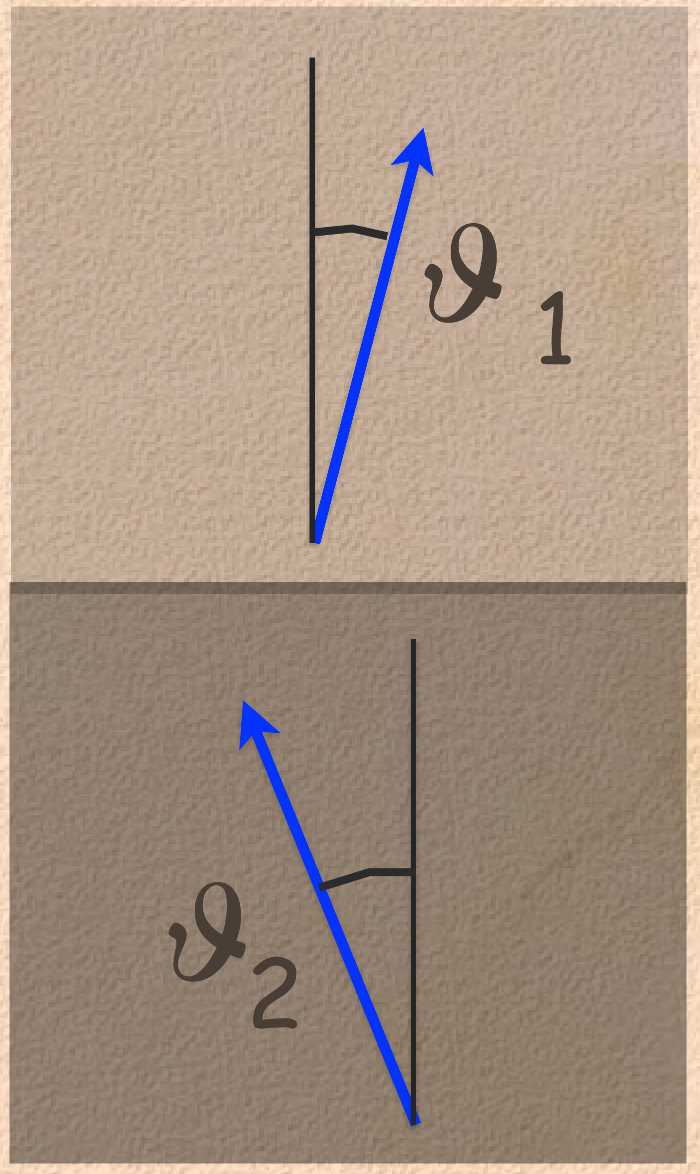




interface pole density

$= \sin\vartheta_1 - \sin\vartheta_2$

longitudinal variation prefered

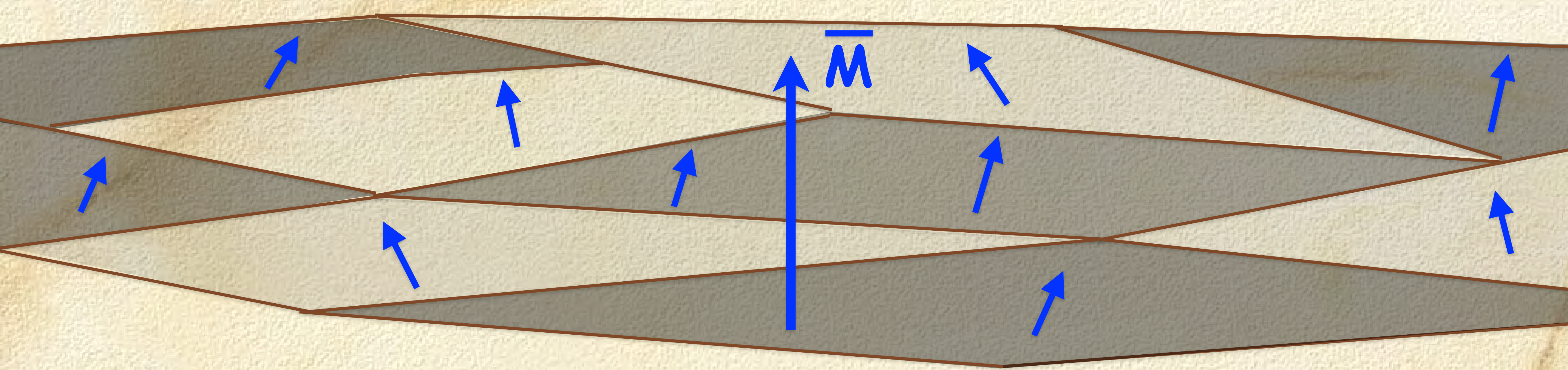


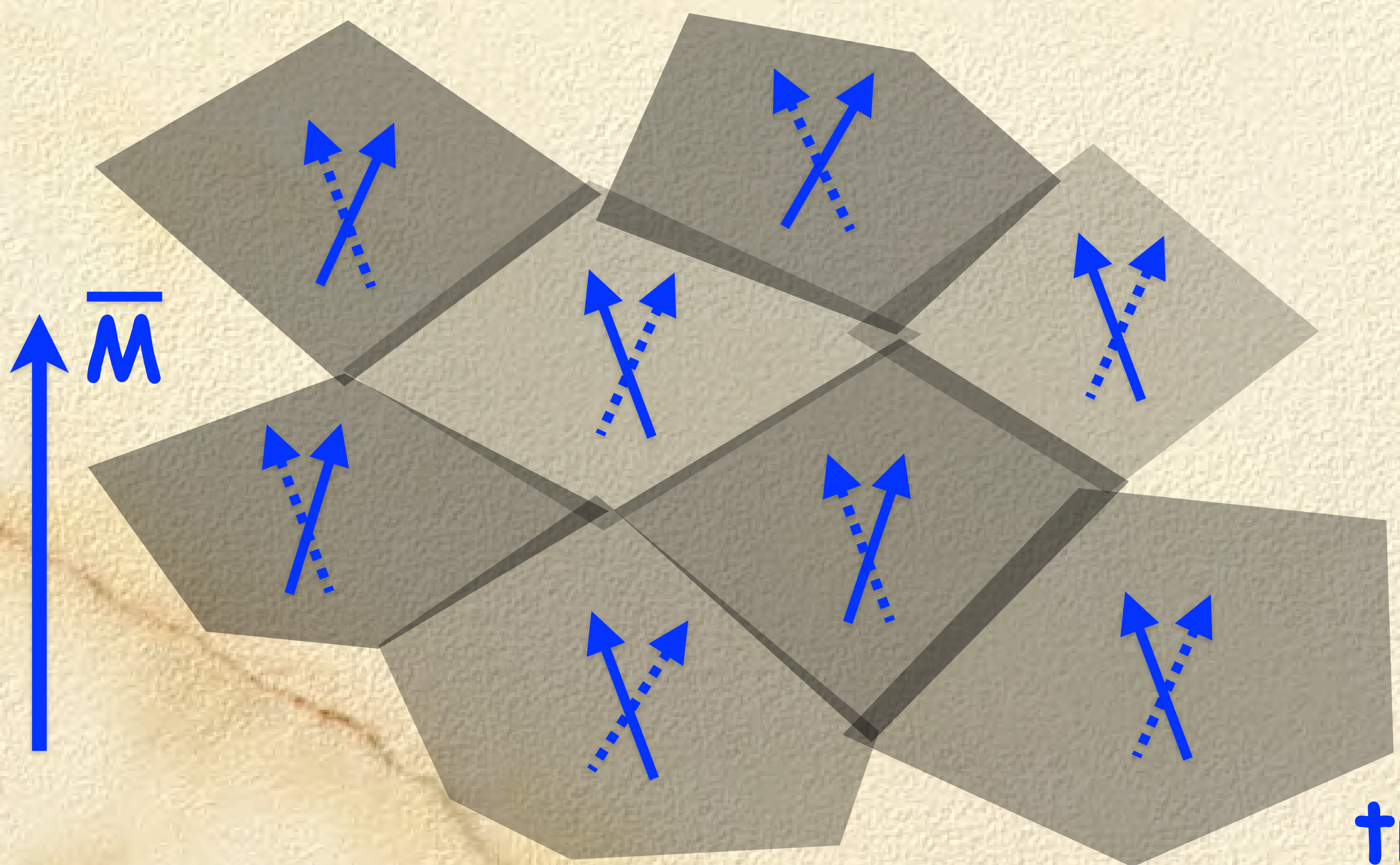
interface pole density

$= \cos\vartheta_1 - \cos\vartheta_2$

Nanocrystalline (Q<<1) materials

ripple in films





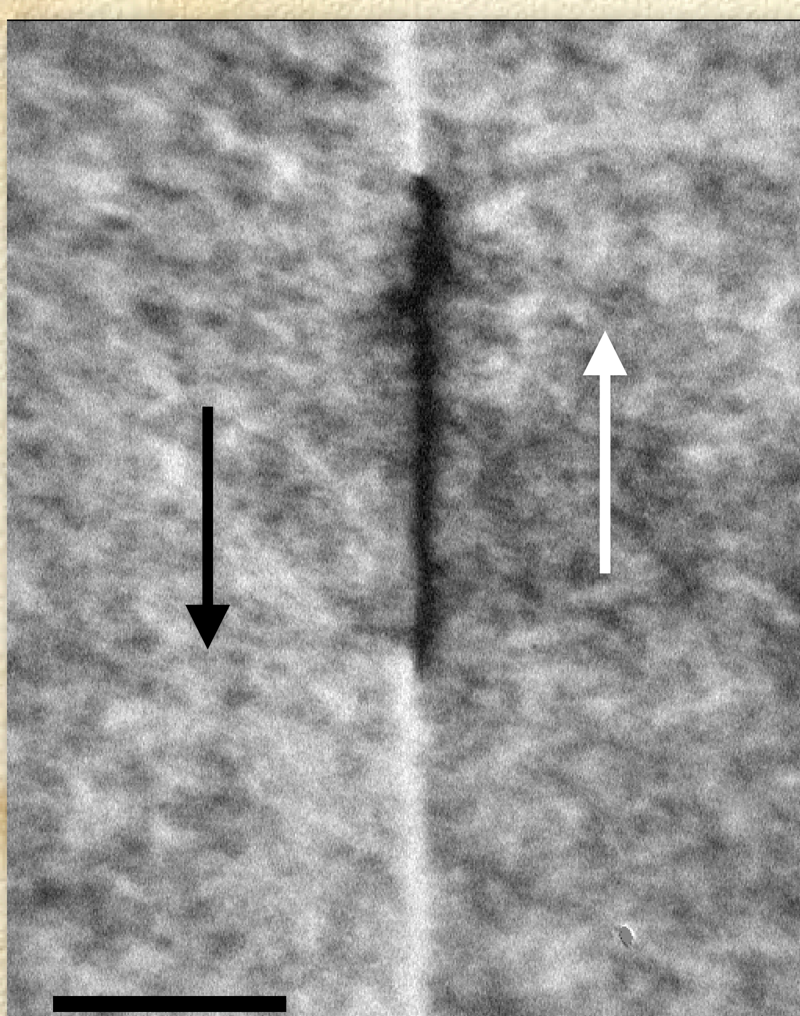
patches in thick materials

Cancellation of transverse component

Nanocrystalline (Q<<1) materials

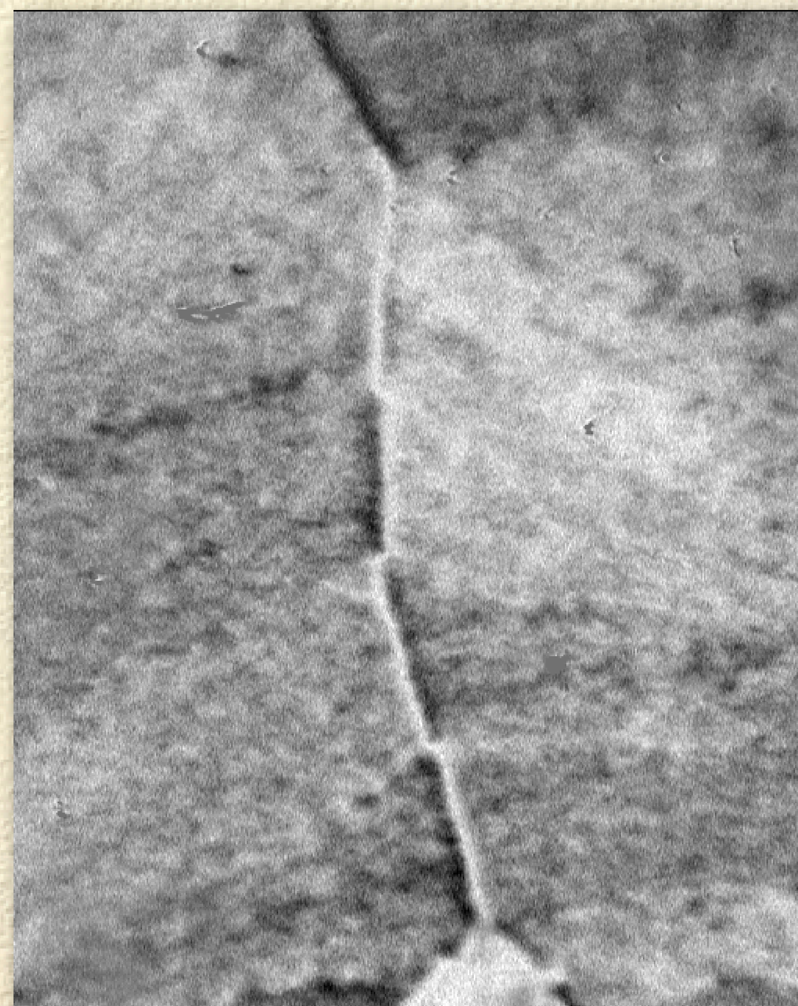
Thinning of nanocrystalline ribbon

20 μm thick

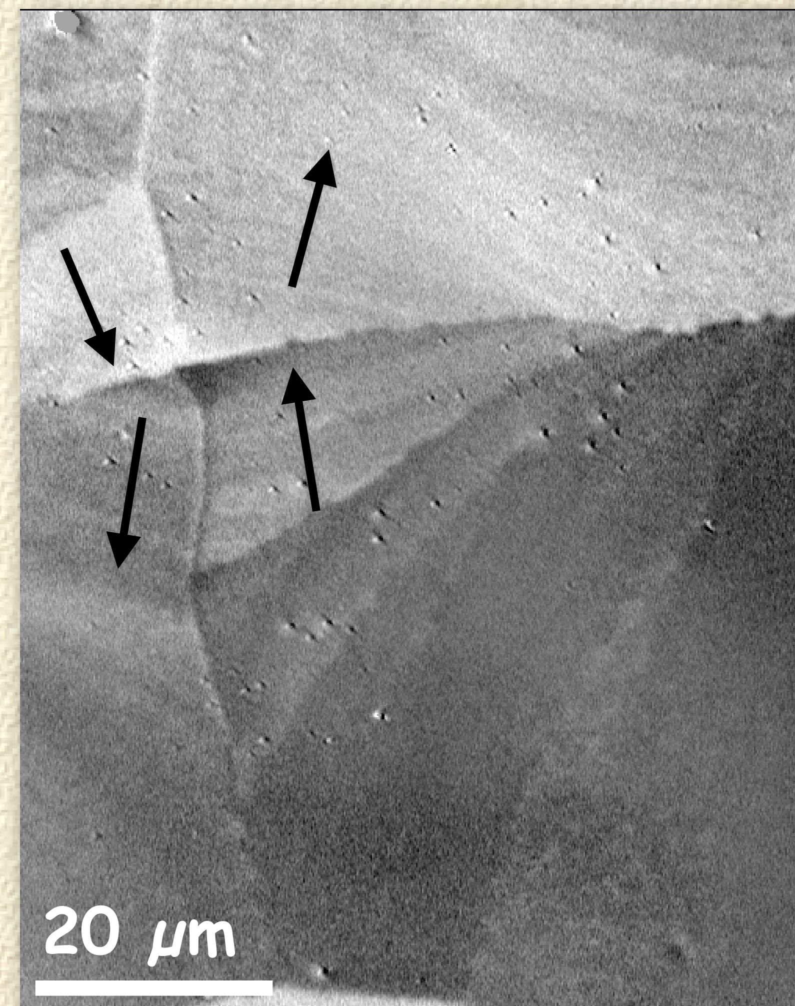


Patches

thinned to μm



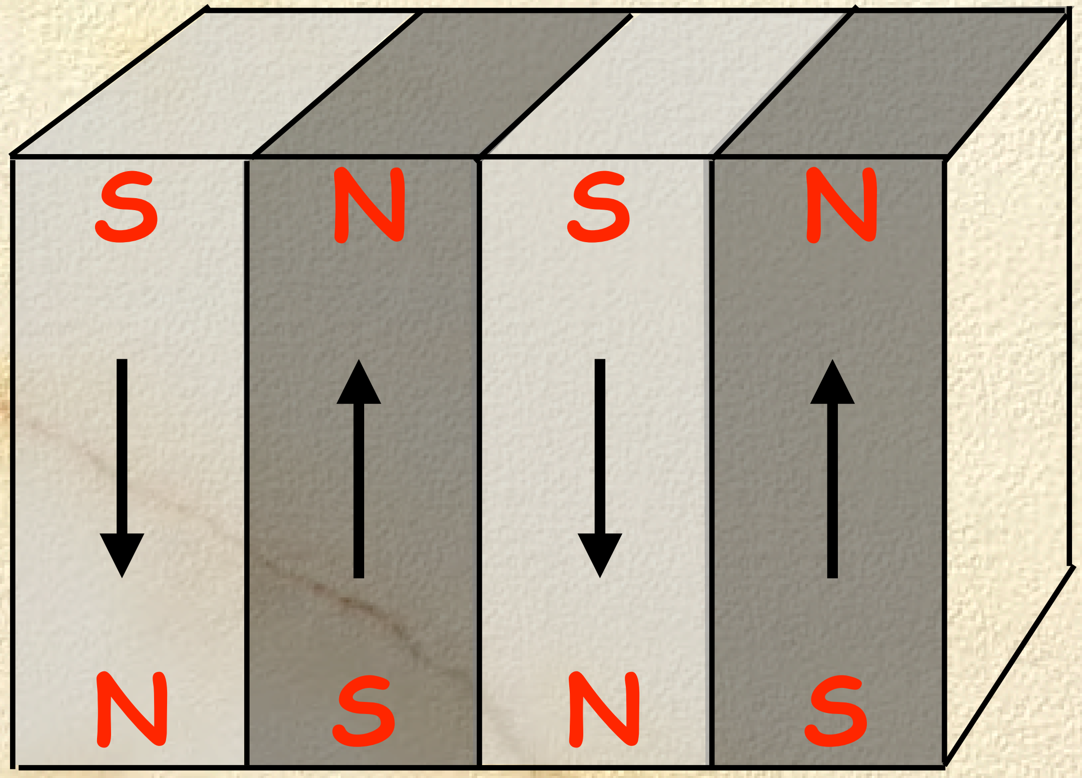
still thinner



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



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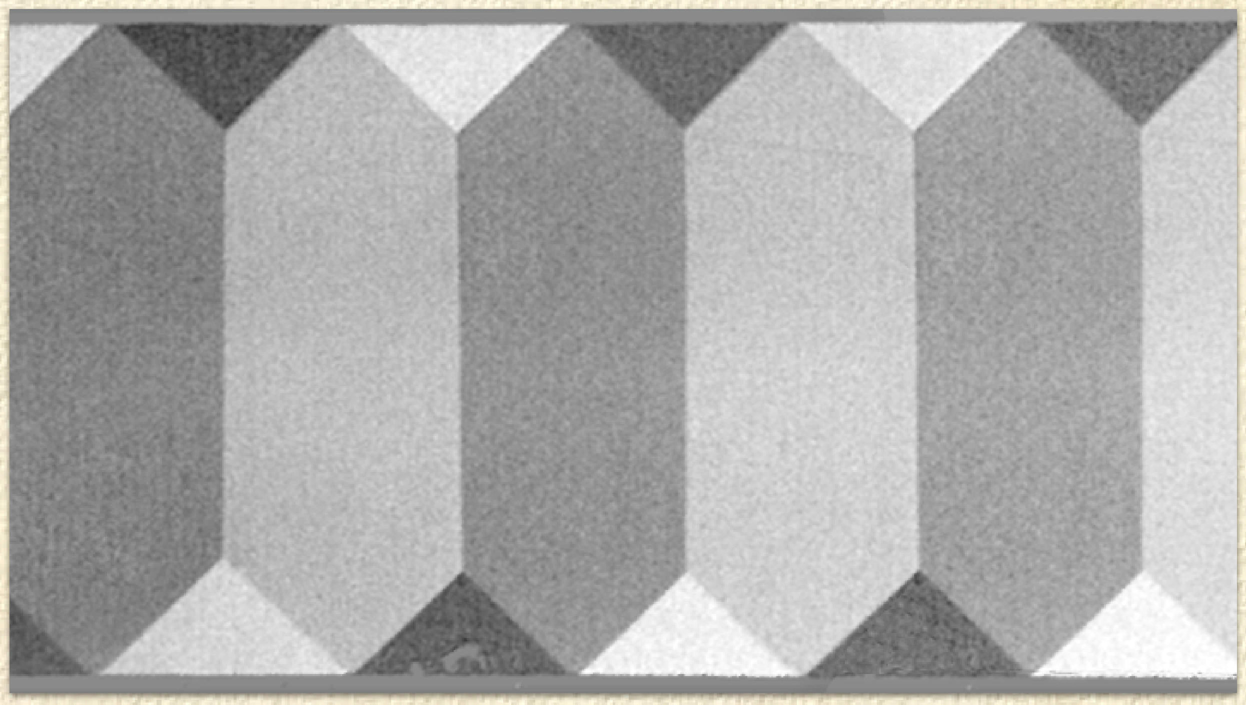
High-Q material



Low-Q material

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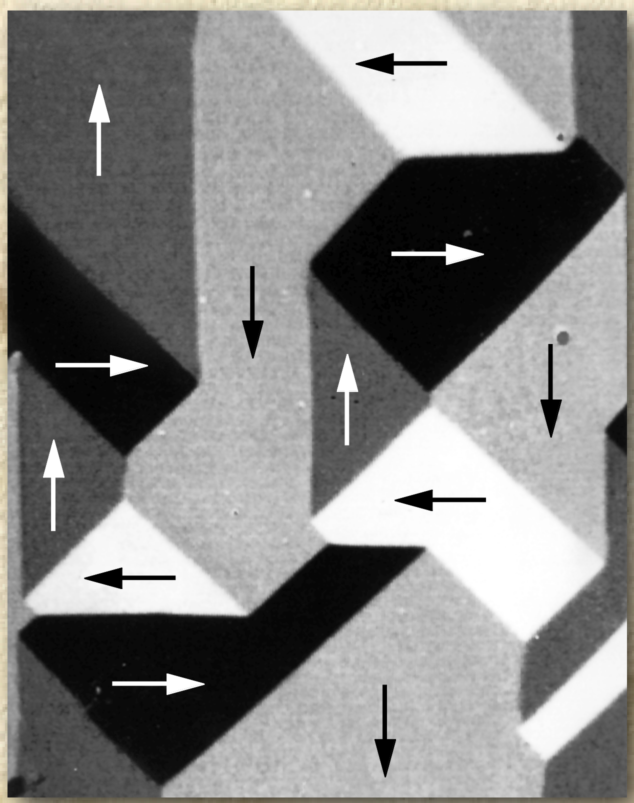
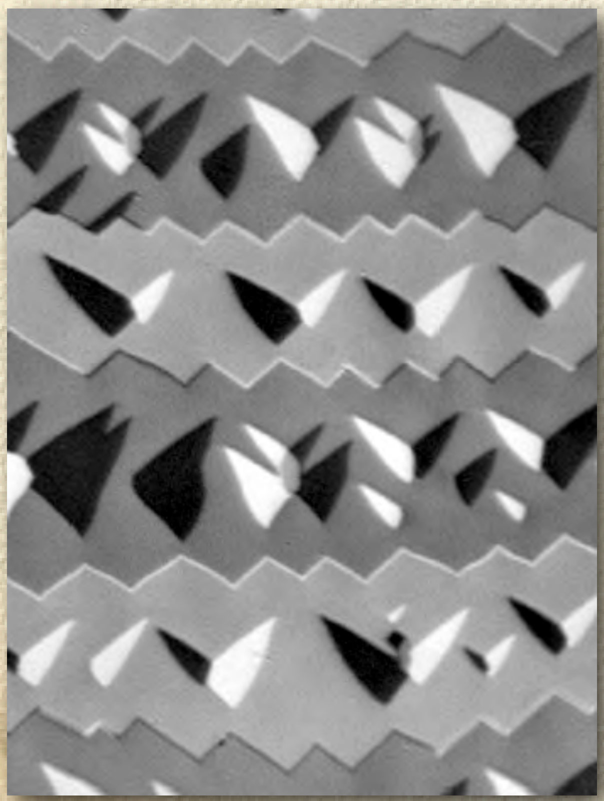
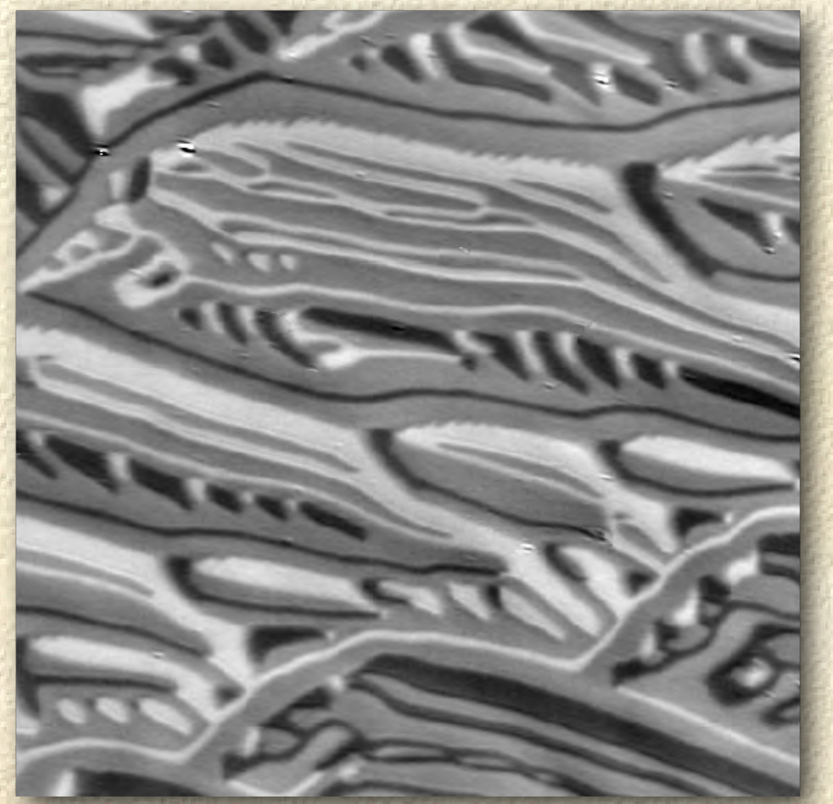
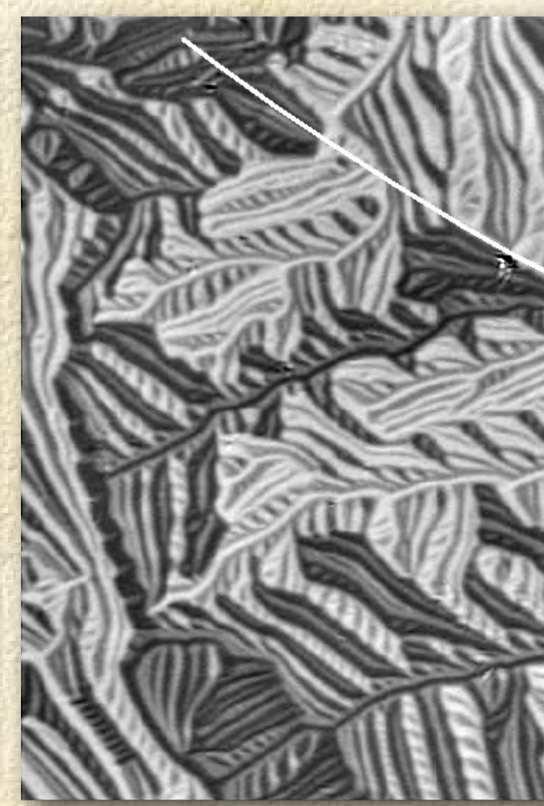

Summary

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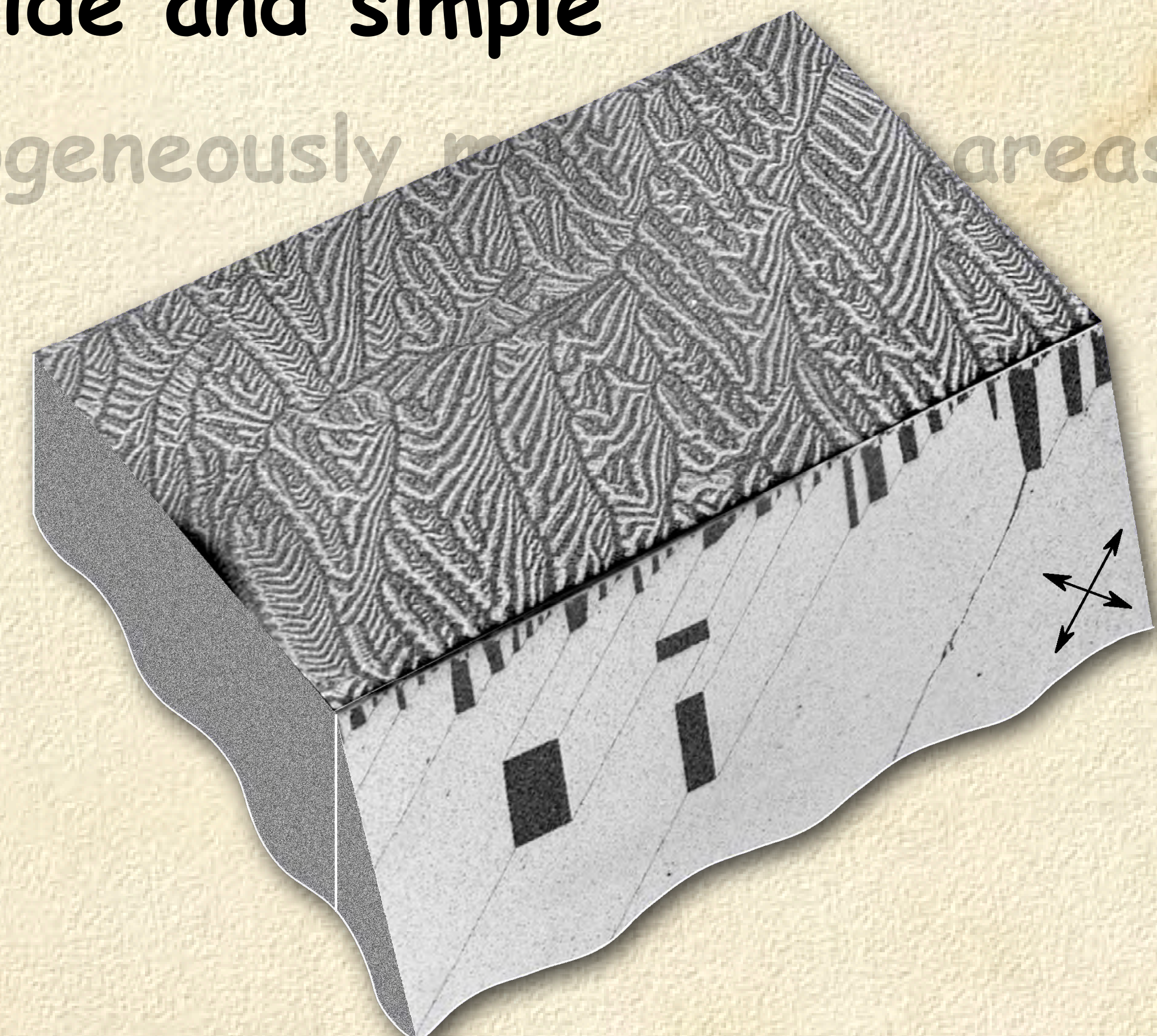

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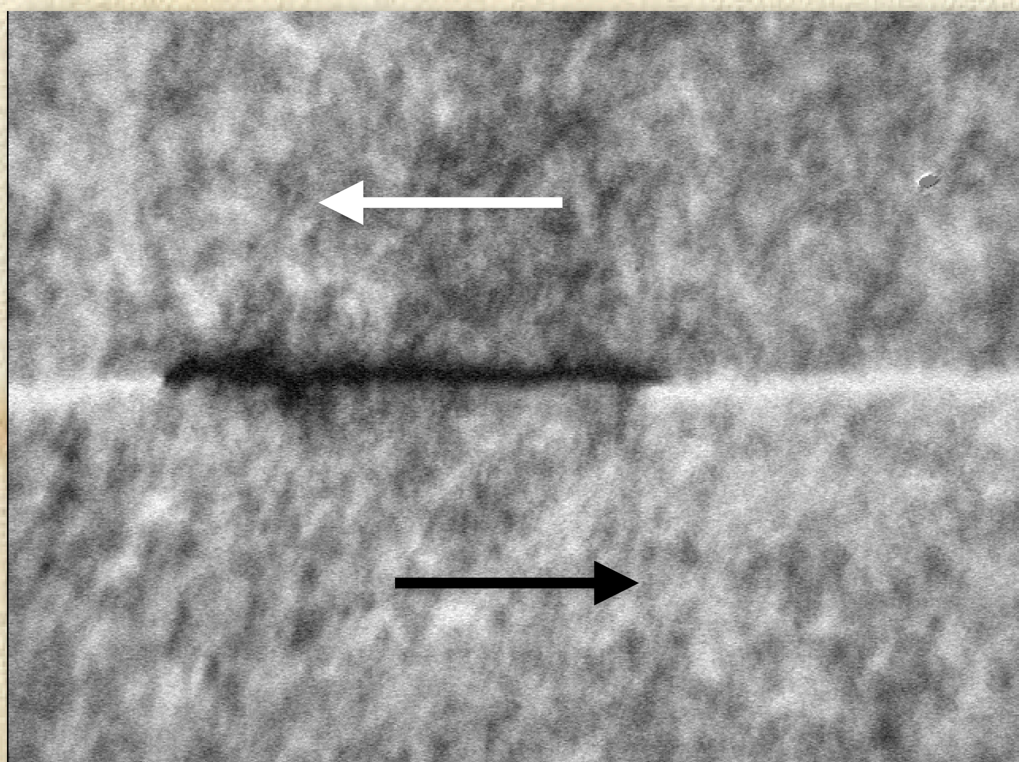
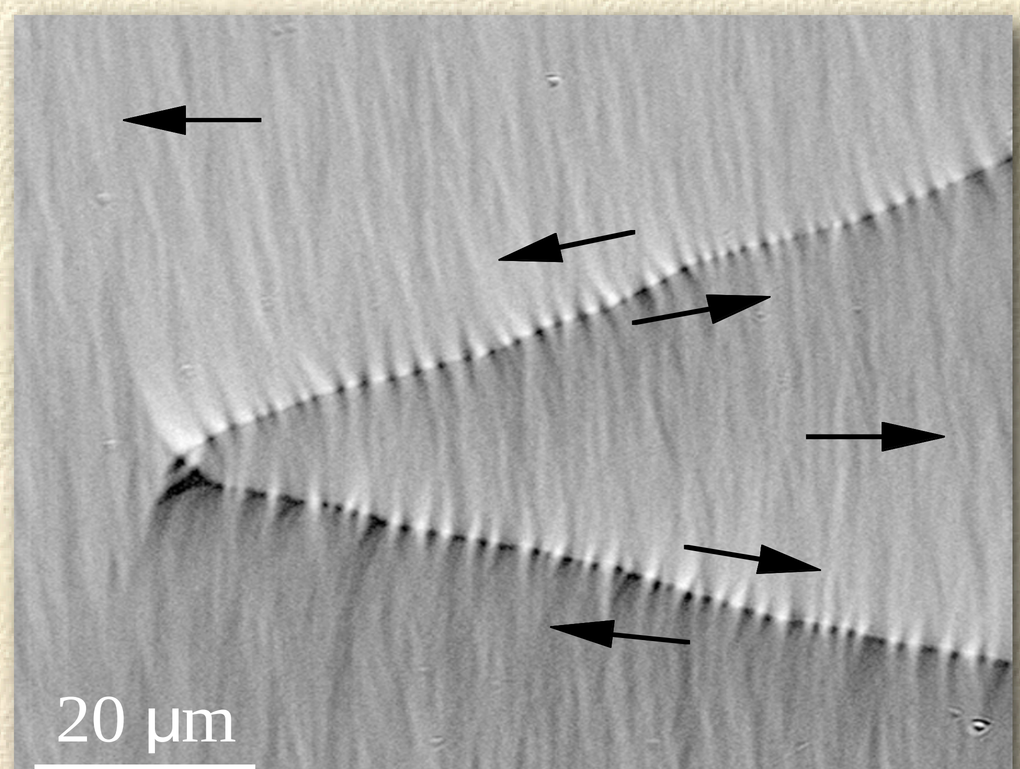


Patches in bulk nanocrystalline material



Ripple in nanocrystalline films

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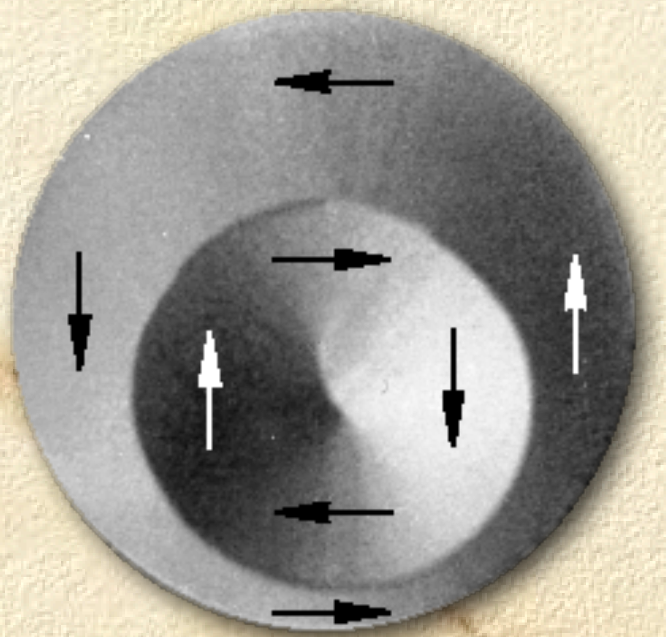
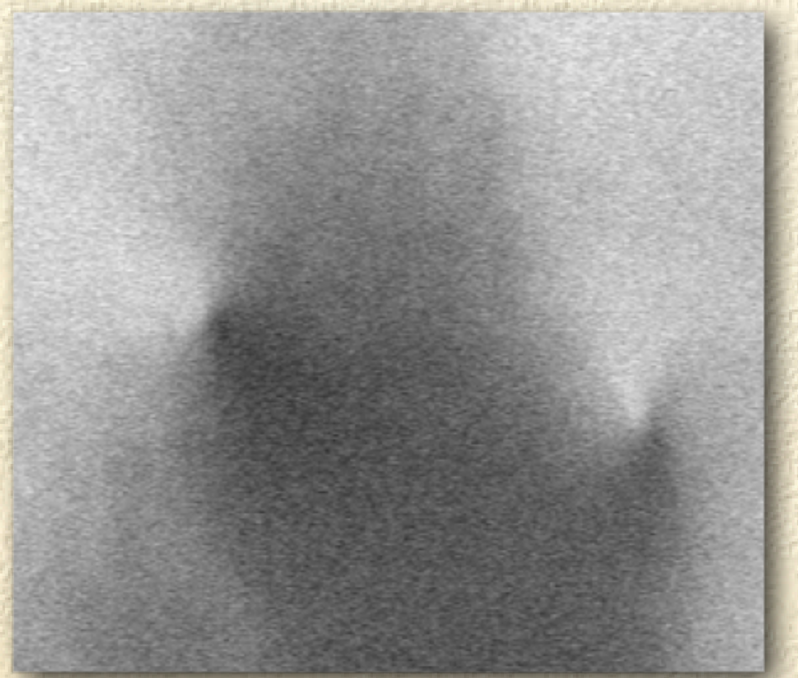


Shape-induced in Q << 1 film elements



Q = 0 bulk material

Stripe domains in perpendicular low-Q films

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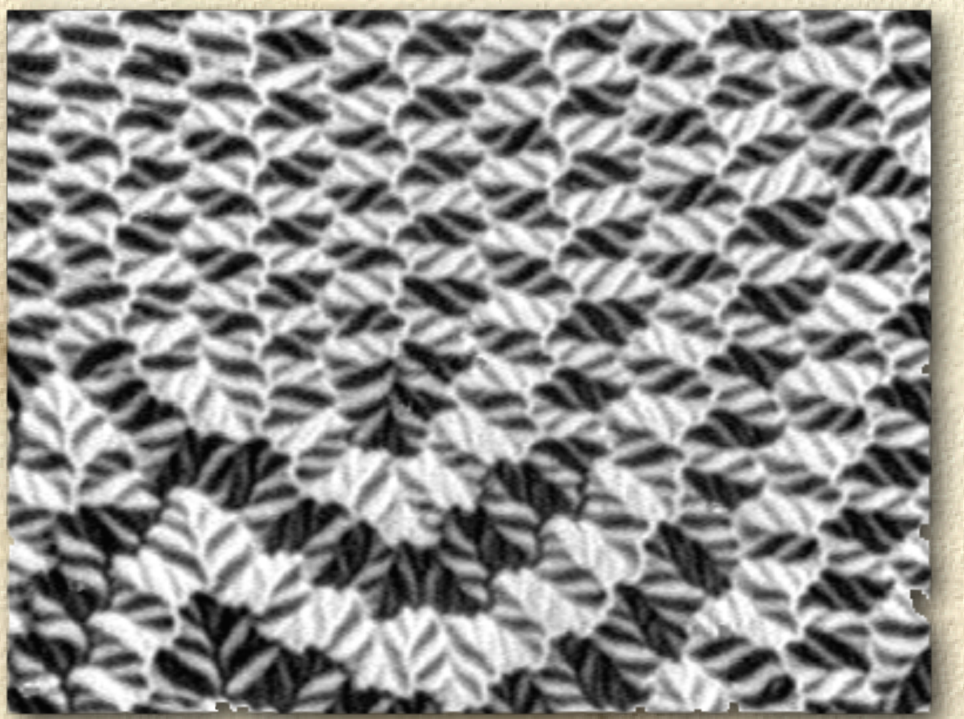
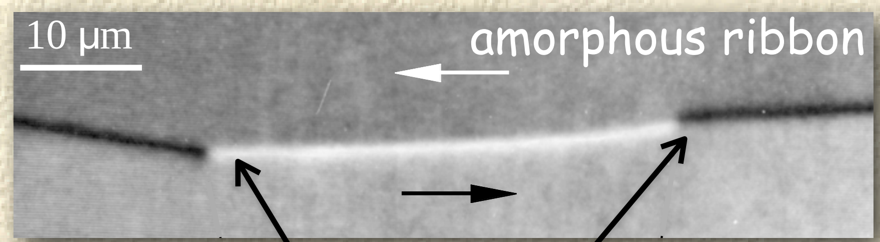
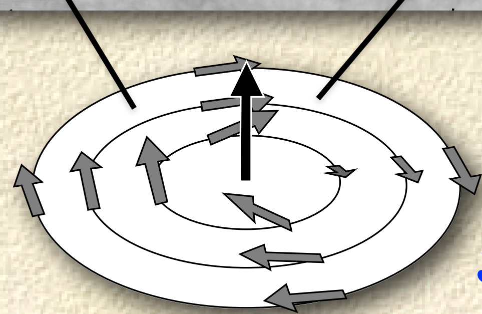

Branched closure domains in low-Q bulk material

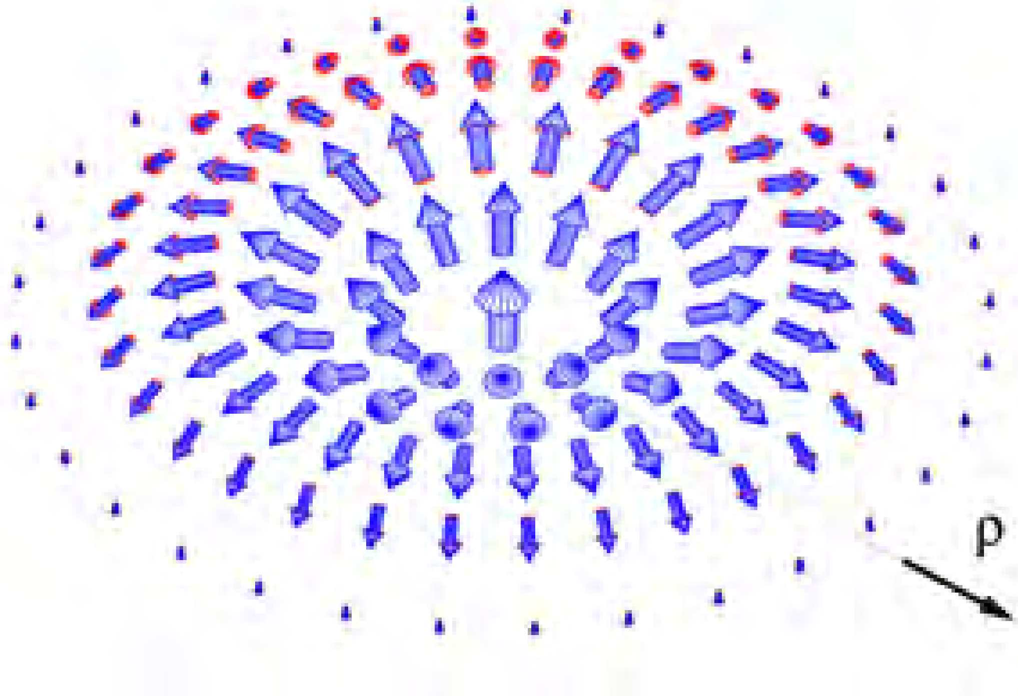

Branched closure domains in medium-Q bulk material

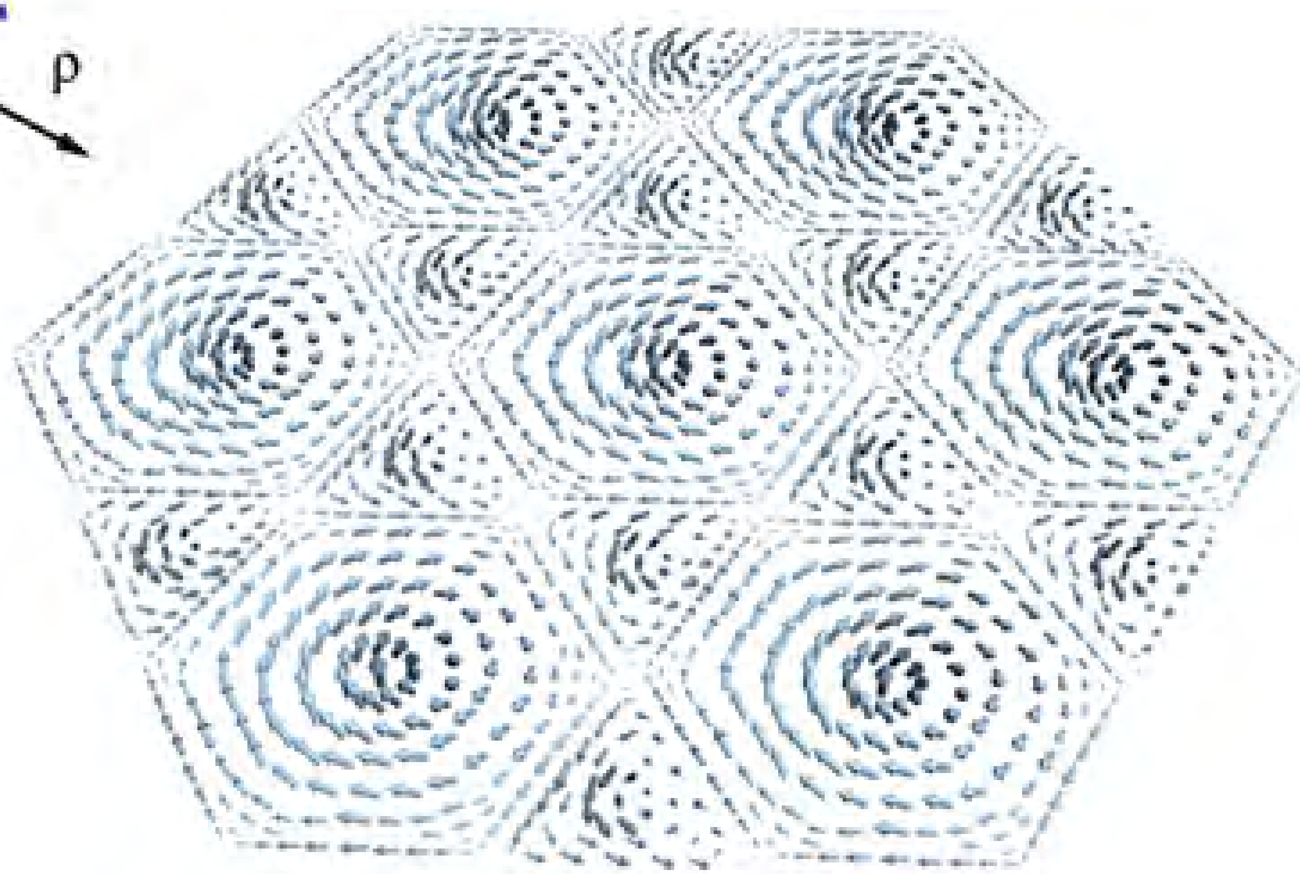

Domain walls




Swirls

Skyrmions in non-centrosymmetric crystals with Dzyaloshinskii-Moriya coupling





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

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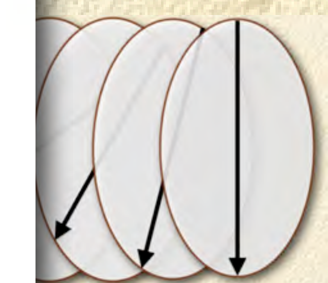
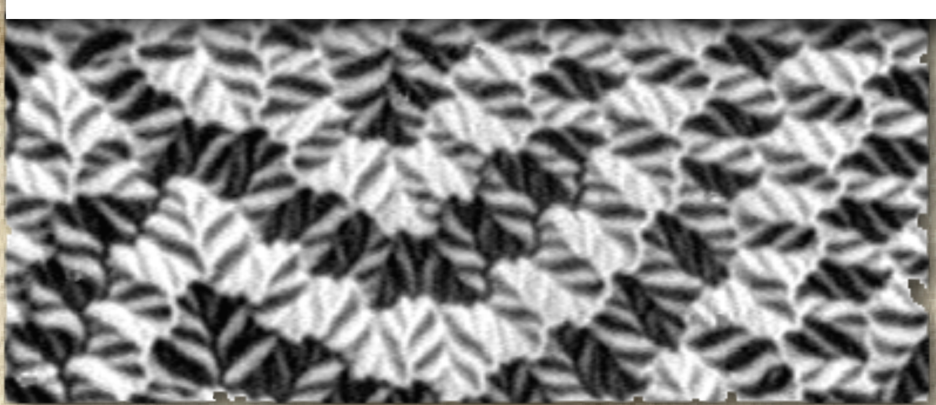
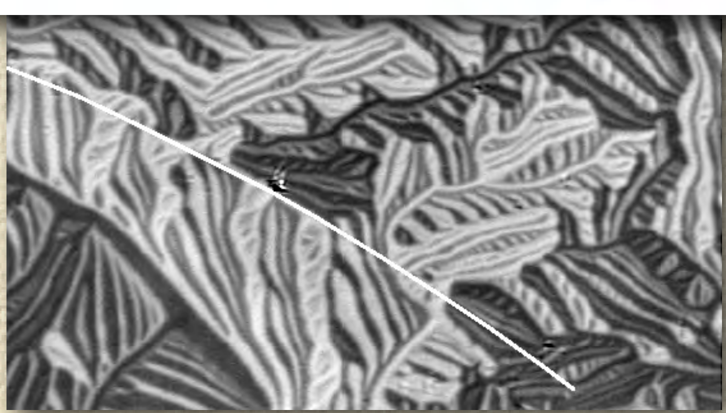


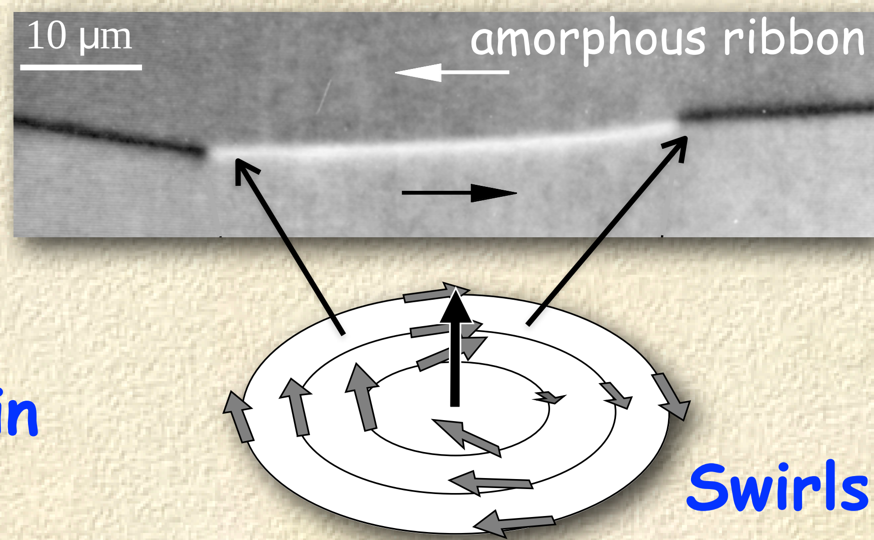
walls



Branched closure domains in low-Q bulk material

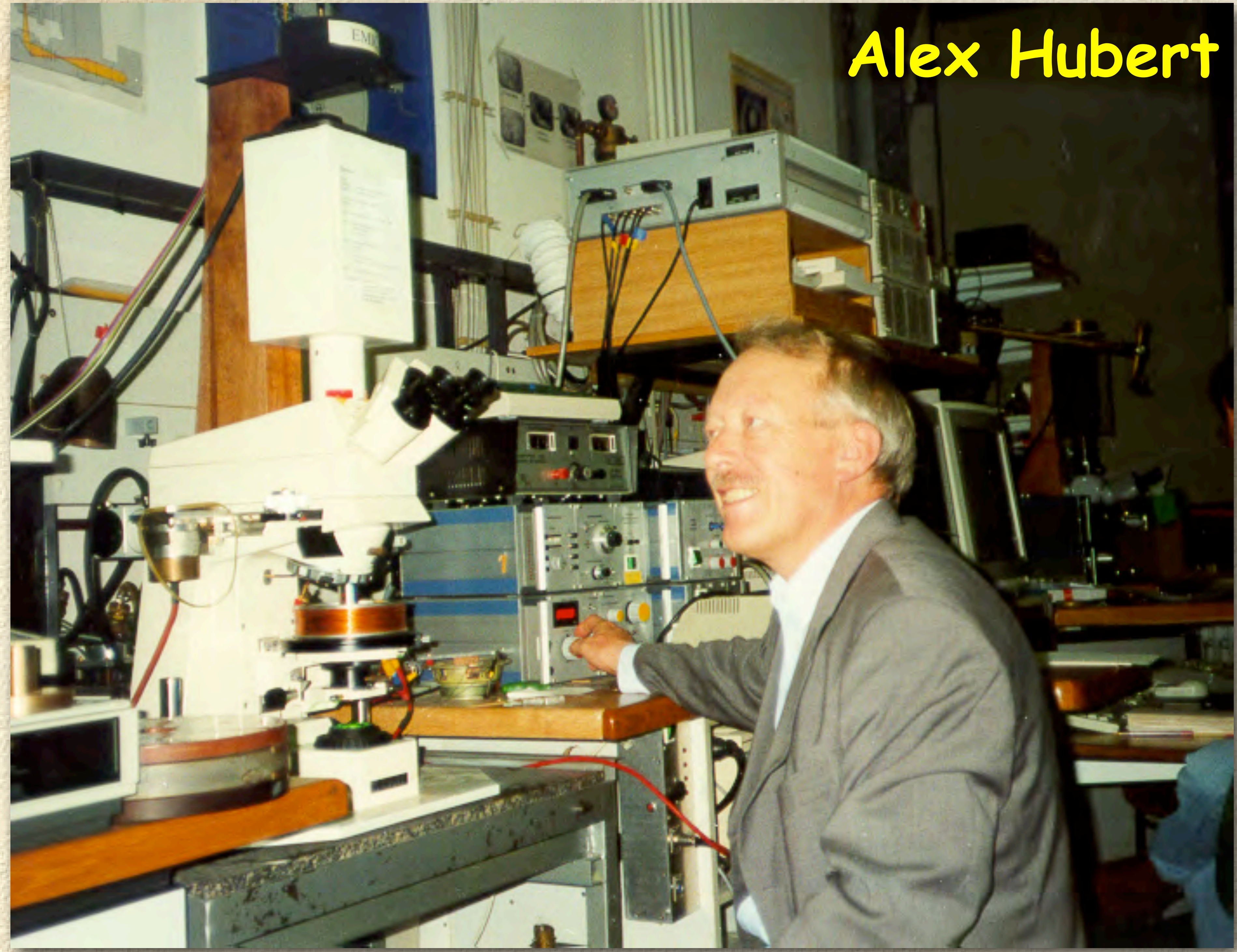


Branched closure domains in medium-Q bulk material



Swirls

Acknowledgement



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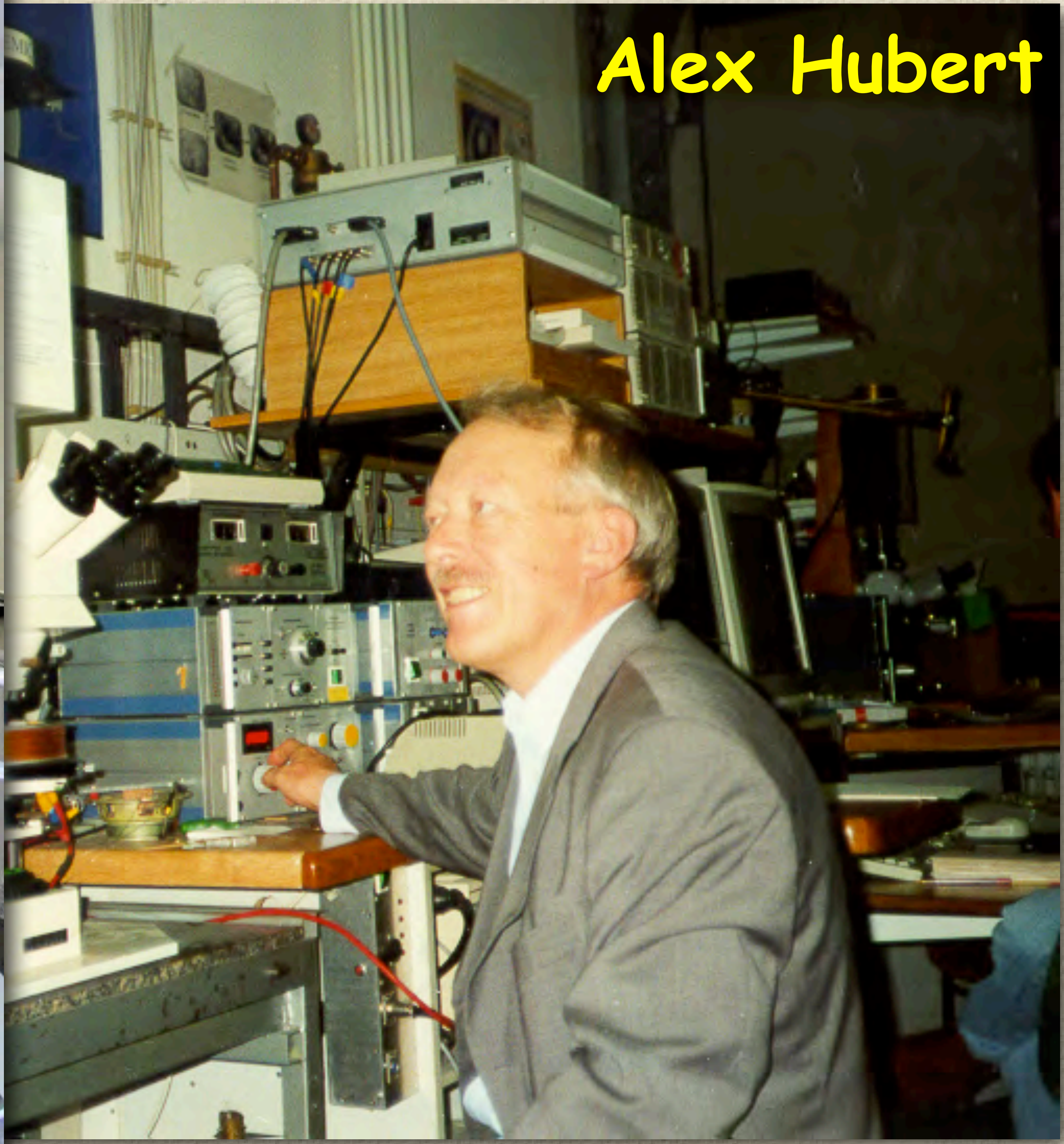

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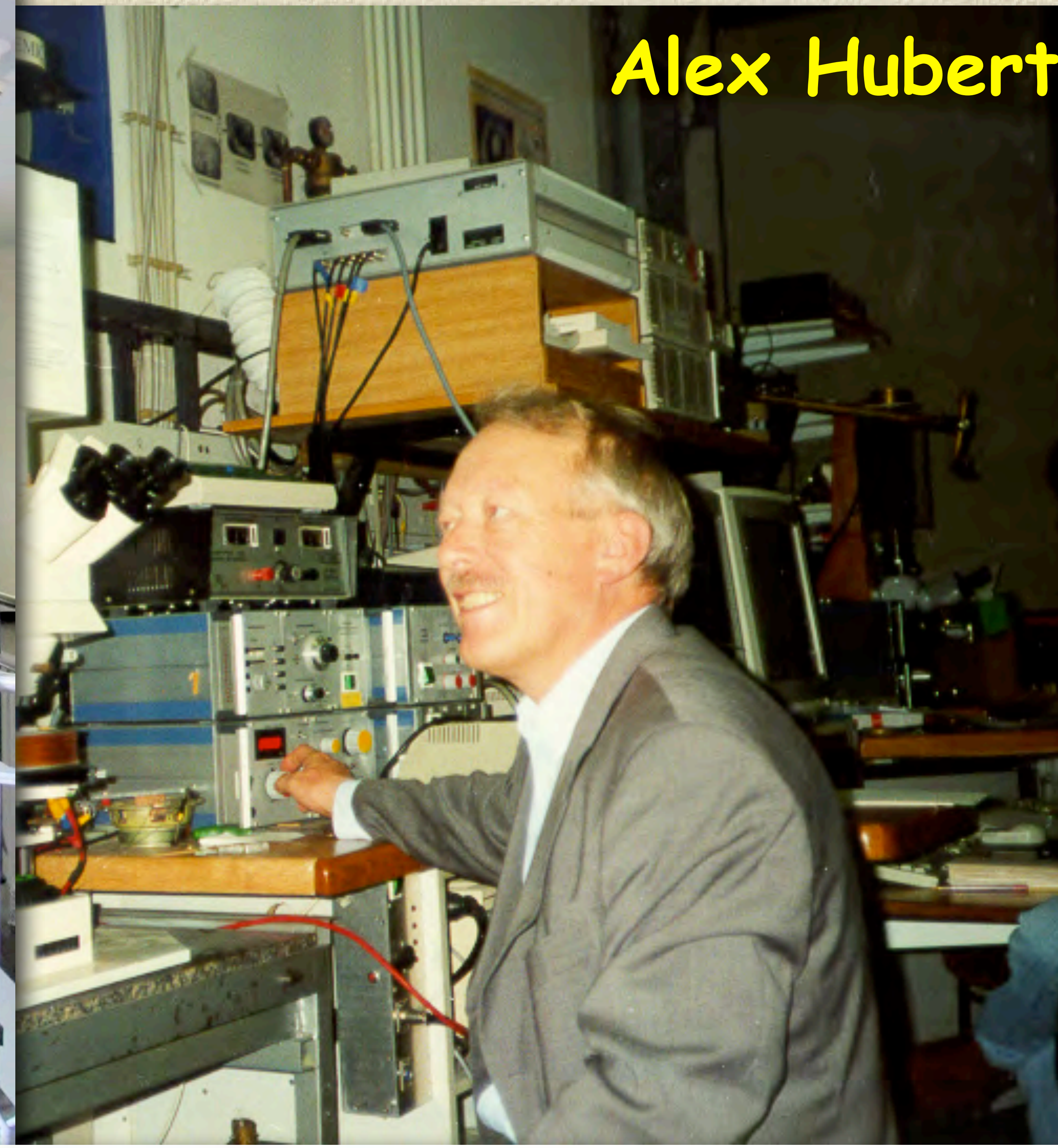

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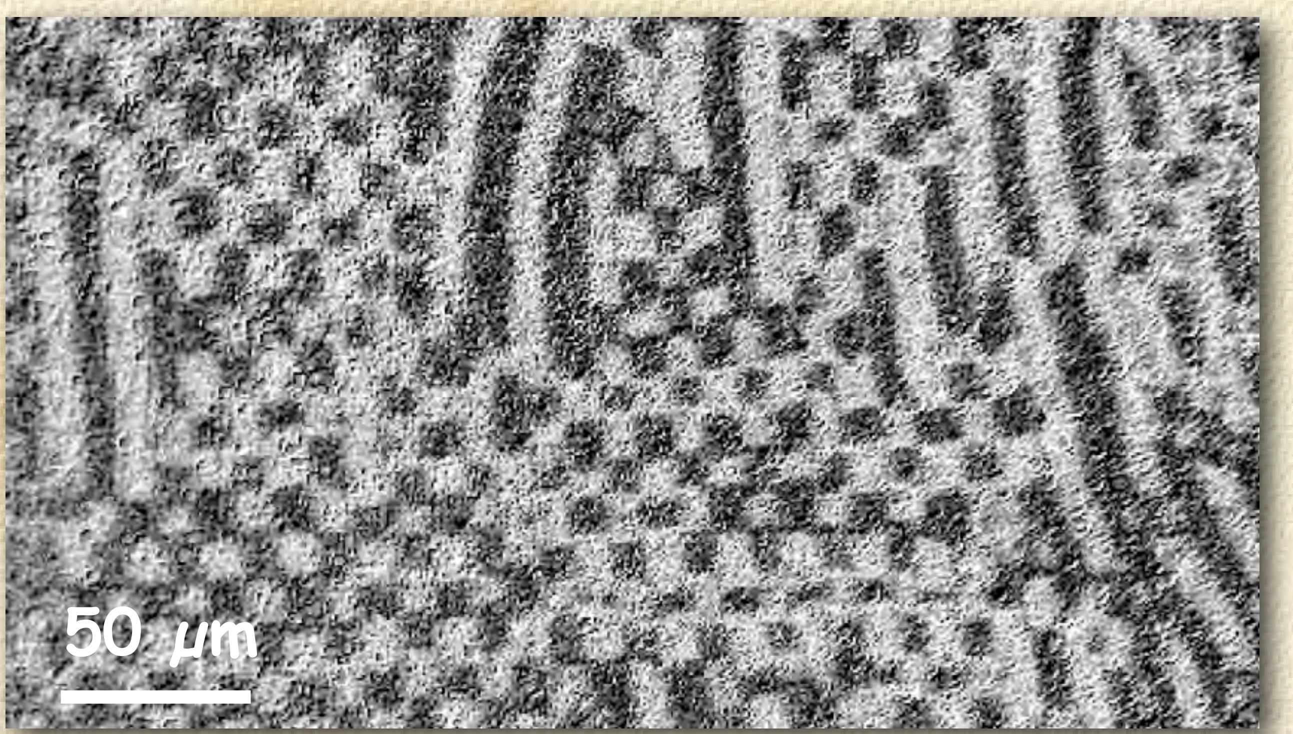
How can (unknown) magnetic microstructure be analysed ?

Analysis of Magnetic Domains

1) Experimental imaging

Amorphous ribbon (Co-rich, 45 μm thick)



(image: courtesy G. Herzer, VAC)

Analysis of Magnetic Domains

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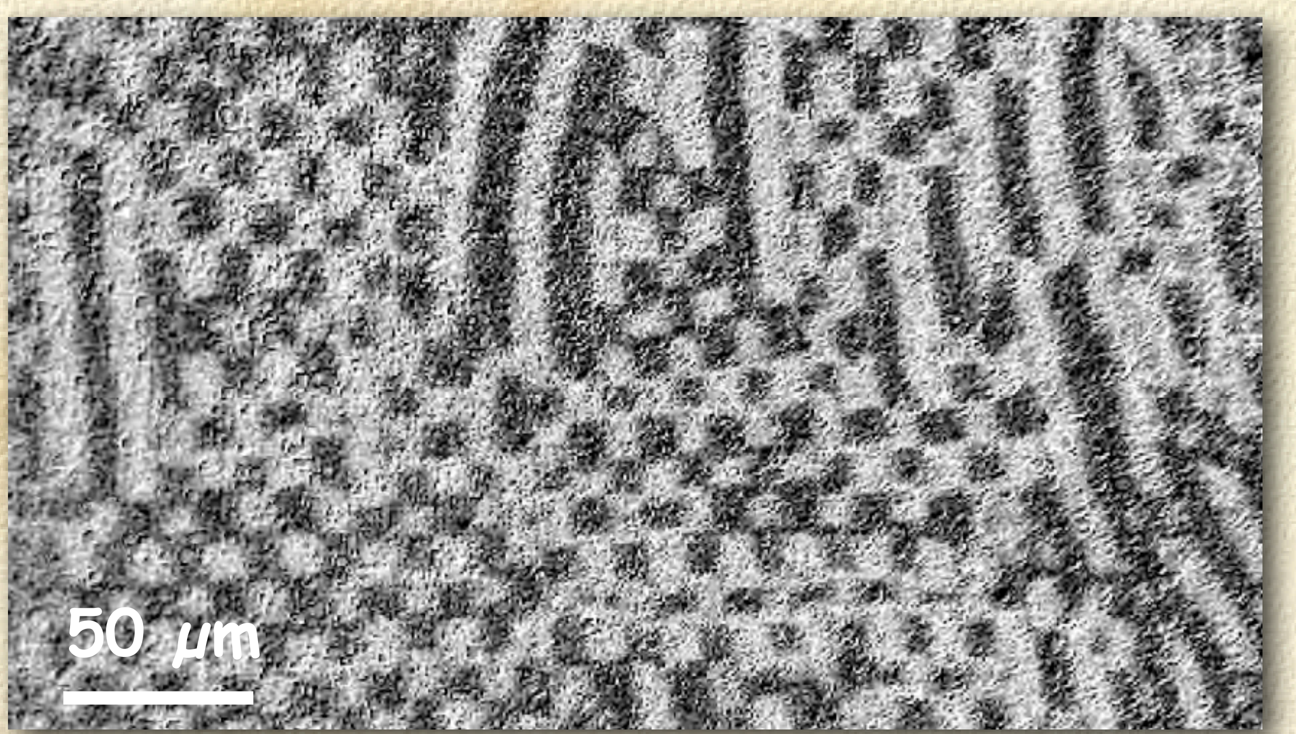
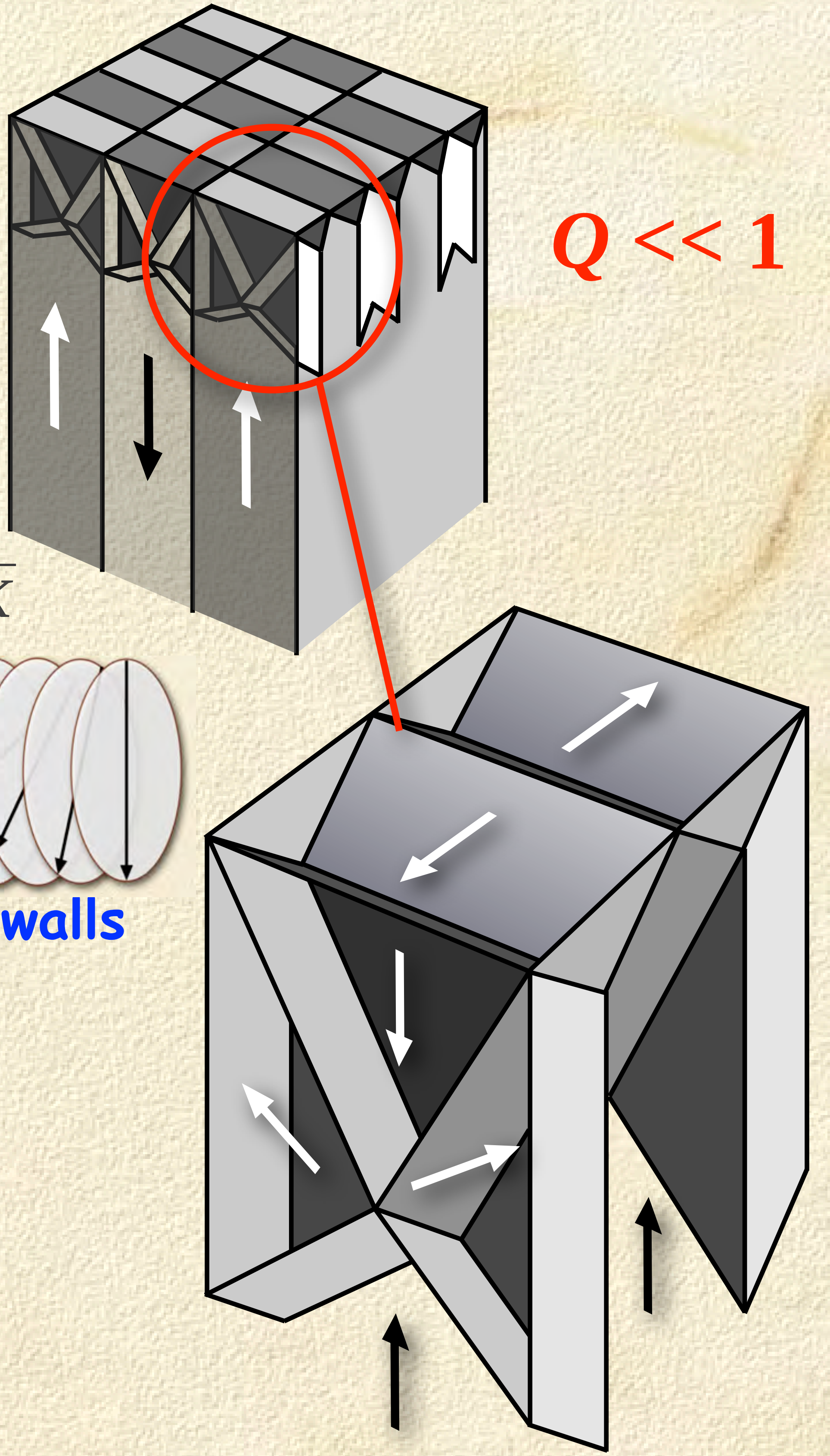
Amorphous ribbon (Co-rich, 45 μm thick)



(image: courtesy G. Herzer, VAC)

2) Domain model



$\gamma_{180°} = 4\sqrt{AK}$

Domain walls

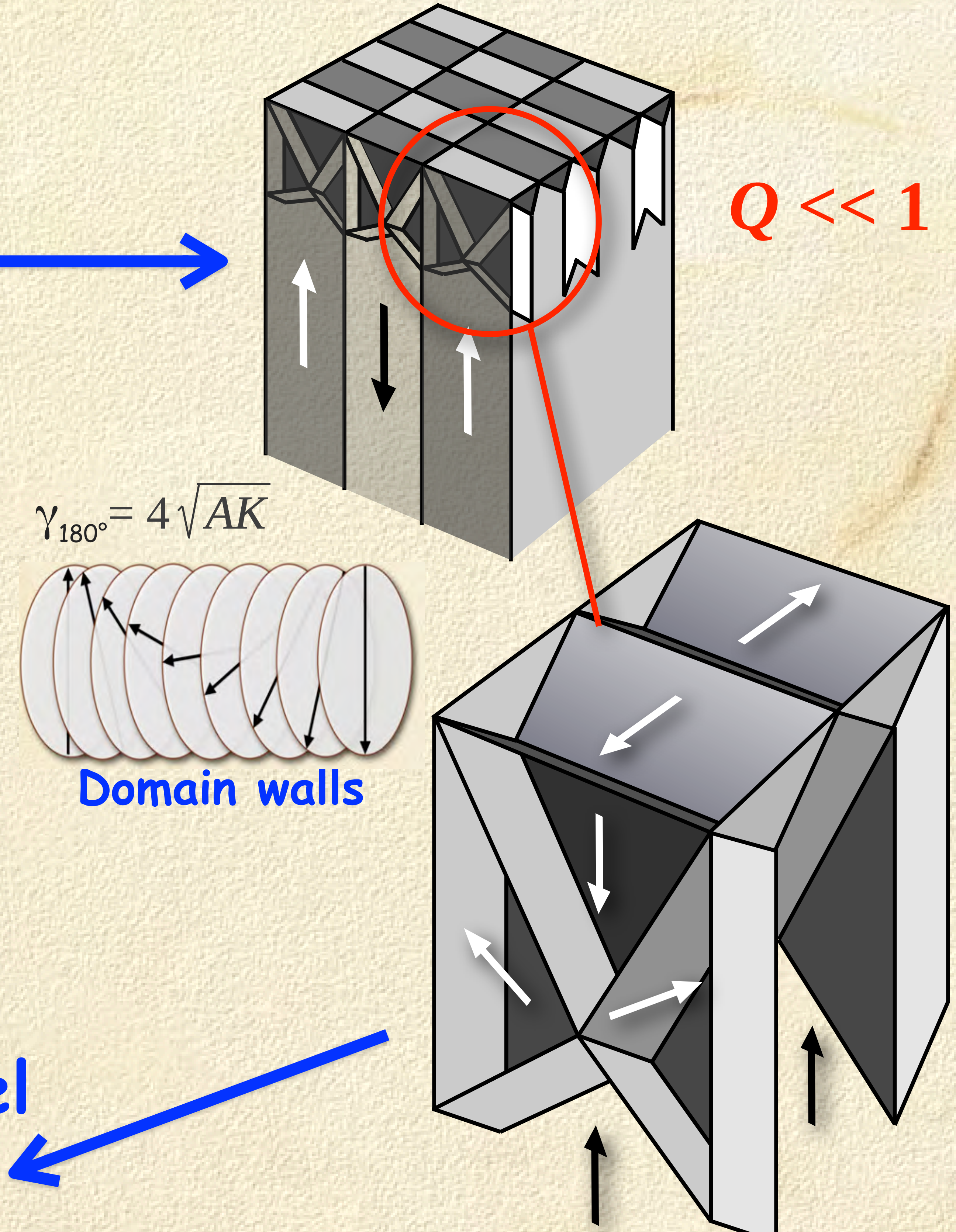
Analysis of Magnetic Domains

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

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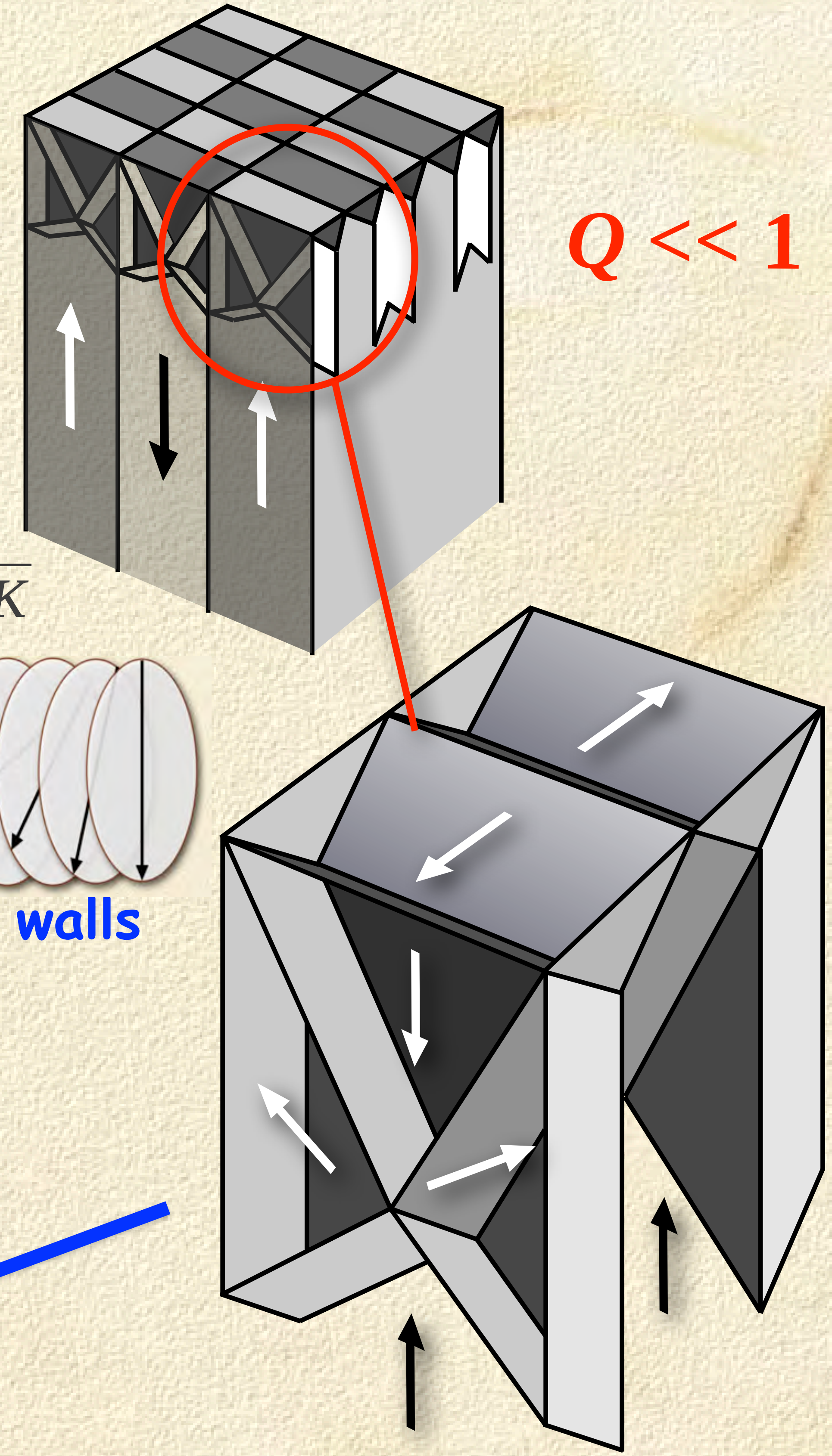
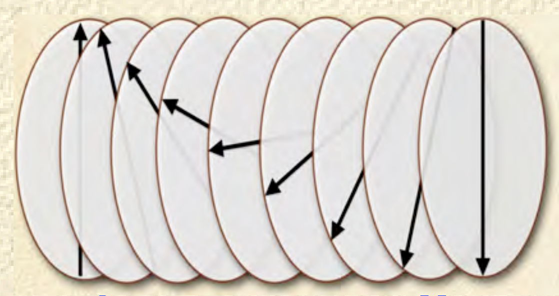
Amorphous ribbon (Co-rich, 45 μm thick)

(image: courtesy G. Herzer, VAC)

2) Domain model



$\gamma_{180°} = 4\sqrt{AK}$



Domain walls

4) Comparison with observation

3) Optimization of model for minimum energy