Magnetic properties of self-organized systems

[Individual and collective aspects]

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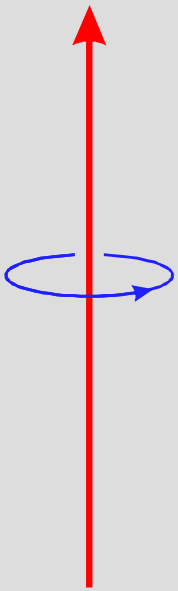
Grenoble

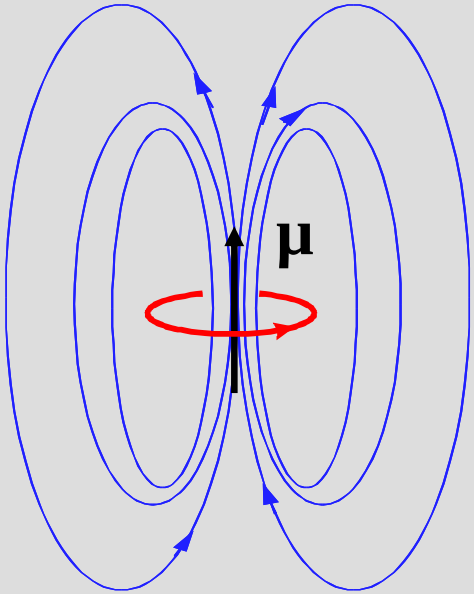
Magnetic properties of self-organized systems : TOC

Oersted field



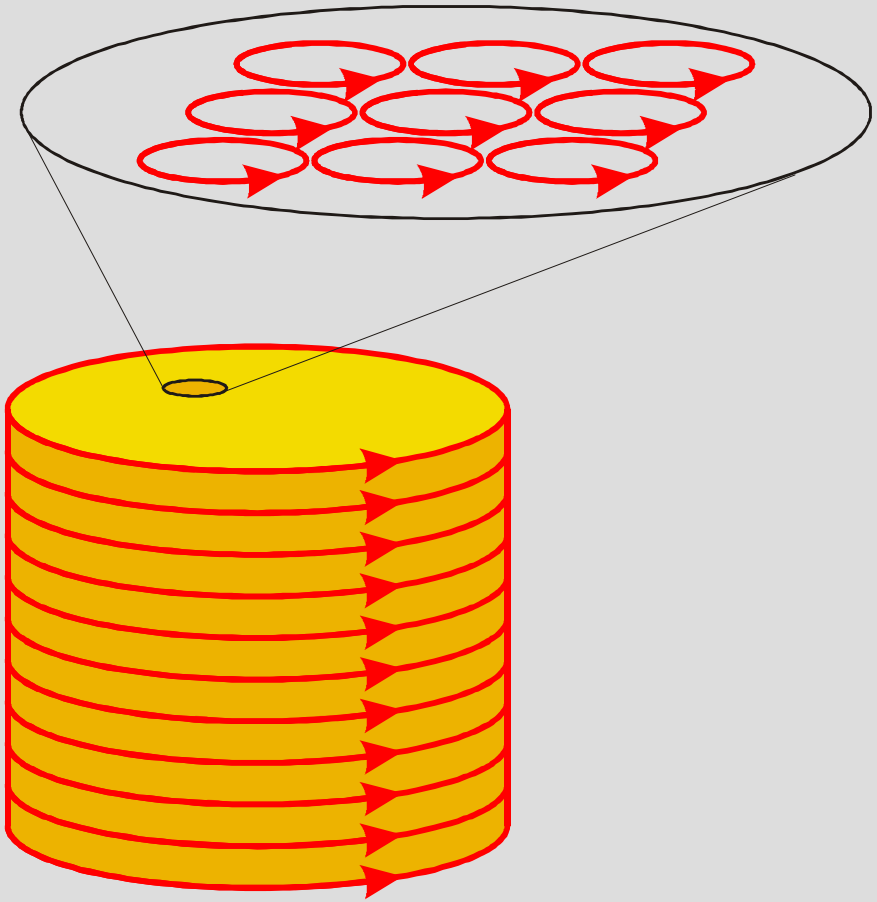
$$B = \frac{\mu_0 I}{2\pi r}$$

Magnetic moment



$$B = \frac{\mu_0}{4\pi r^3} \times \left[\frac{3}{r^2} (\boldsymbol{\mu}.\mathbf{r})\mathbf{r} - \boldsymbol{\mu} \right]$$

Magnetic material

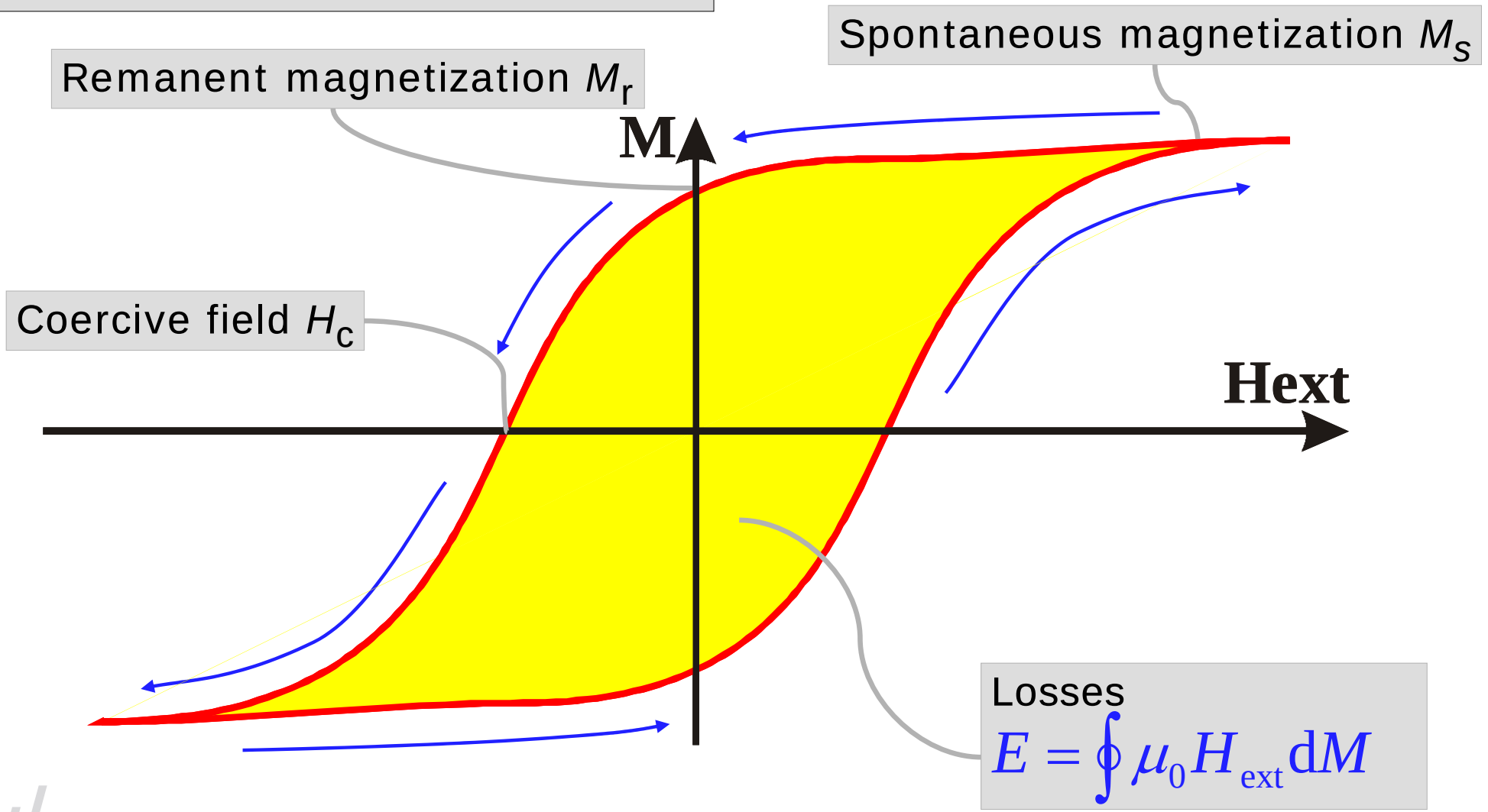


Magnetization: A.m^{-1}

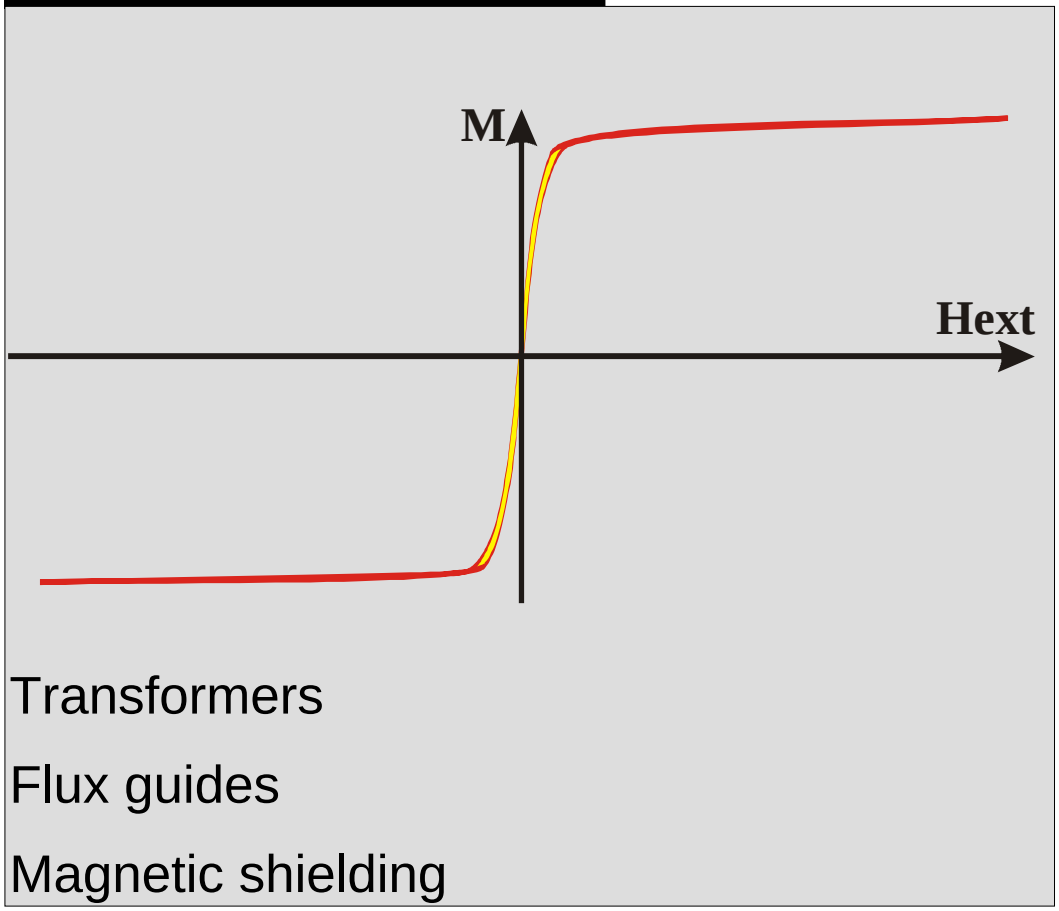
Magnetic moment: A.m^2

Manipulation of magnetic materials:
↳ Application of a magnetic field

Zeeman energy: $E_Z = -\mu_0 \mathbf{H}.\mathbf{M}$



Soft materials

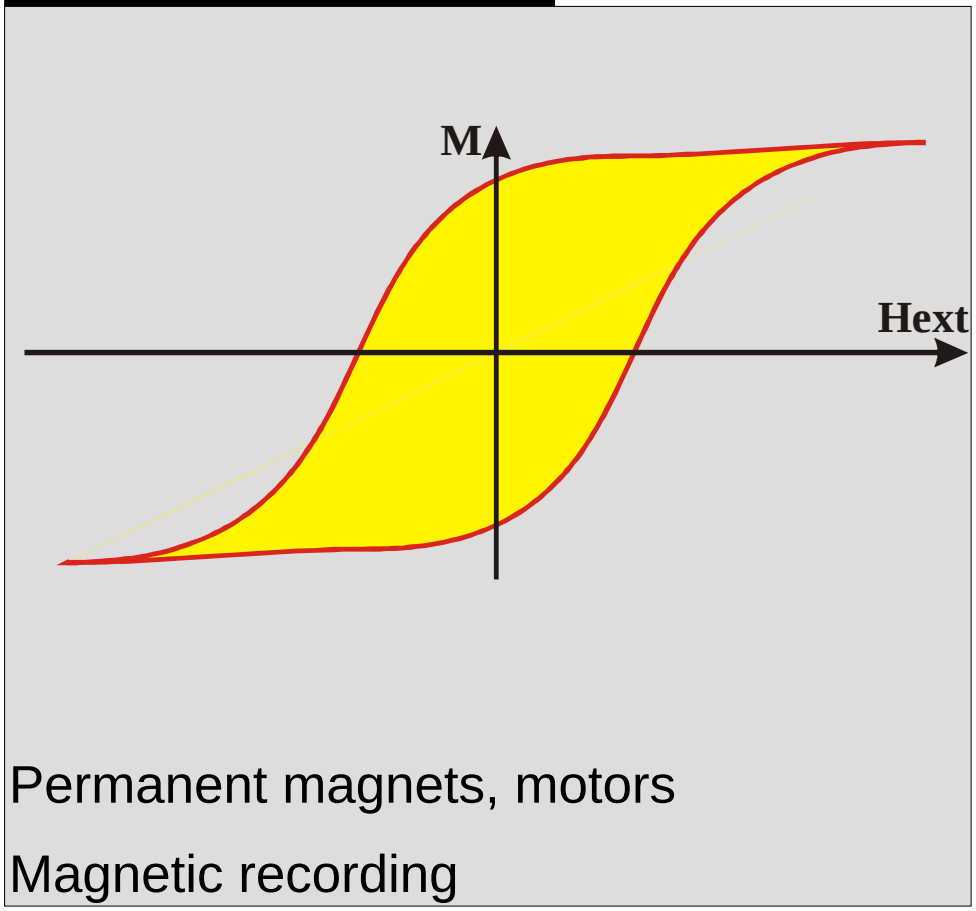


Transformers

Flux guides

Magnetic shielding

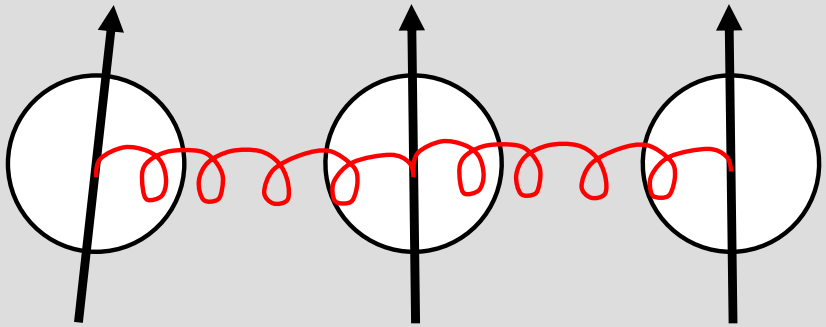
Hard materials



Permanent magnets, motors

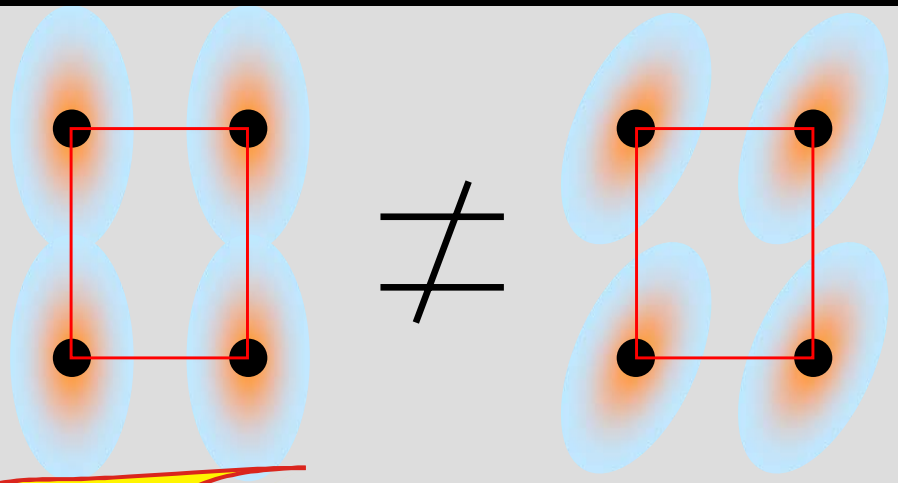
Magnetic recording

Echange energy

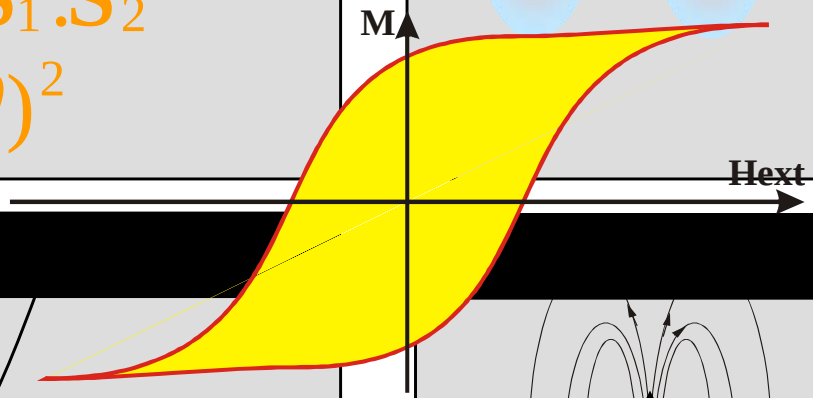


$$E_{\mathrm{Ech}} = -J_{1,2}\vec{\mathbf{S}}_1.\vec{\mathbf{S}}_2 = A(\nabla\theta)^2$$

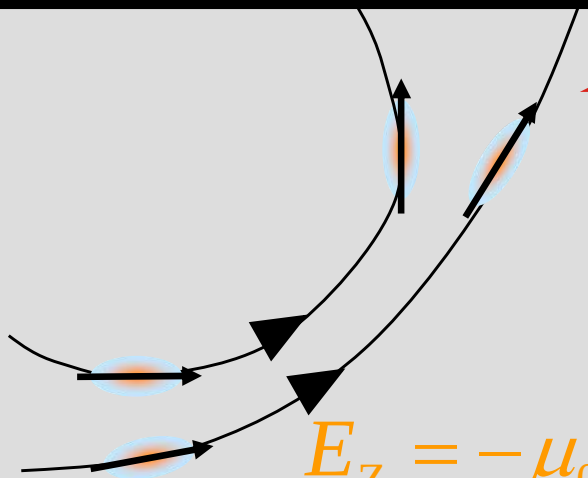
Magnetocrystalline anisotropy energy



$$E_{\mathrm{mc}} = K\sin^2(\theta)$$

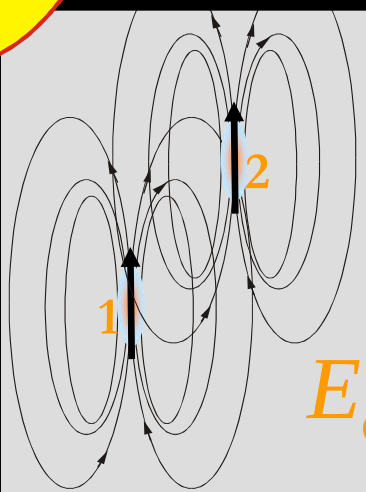


Zeeman energy (enthalpy)



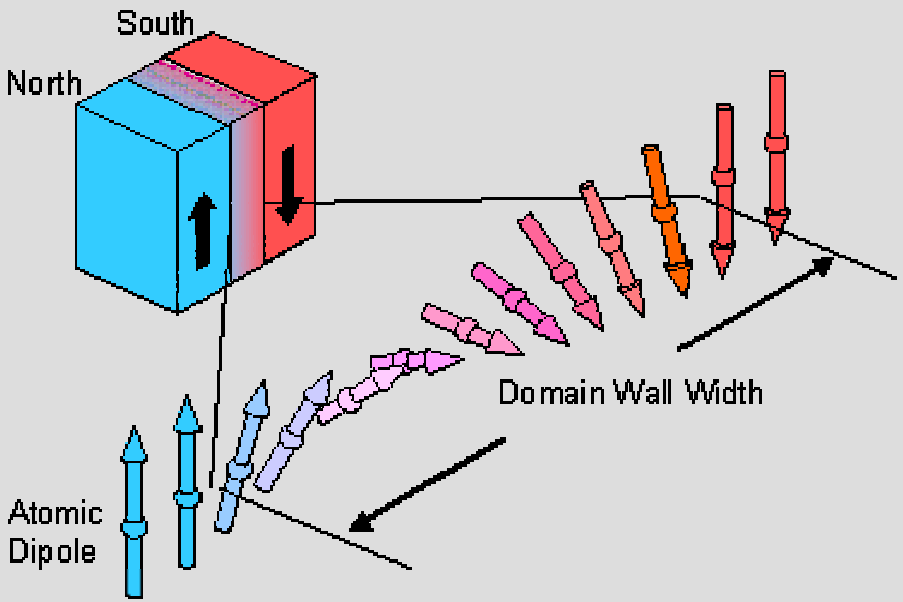
$$E_{\mathrm{Z}} = -\mu_0\vec{\mathbf{M}}_{\mathrm{S}}.\vec{\mathbf{H}}$$

Dipolar energy



$$E_{\mathrm{d}} = -\frac{1}{2}\mu_0\vec{\mathbf{M}}_{\mathrm{S}}.\vec{\mathbf{H}}_{\mathrm{d}}$$

Typical length scale: Bloch wall width λ_B



$$e = A(d\theta/dx)^2 + K\sin^2\theta$$

Exchange → J/m

Anisotropy → J/m^3

Numerical values

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

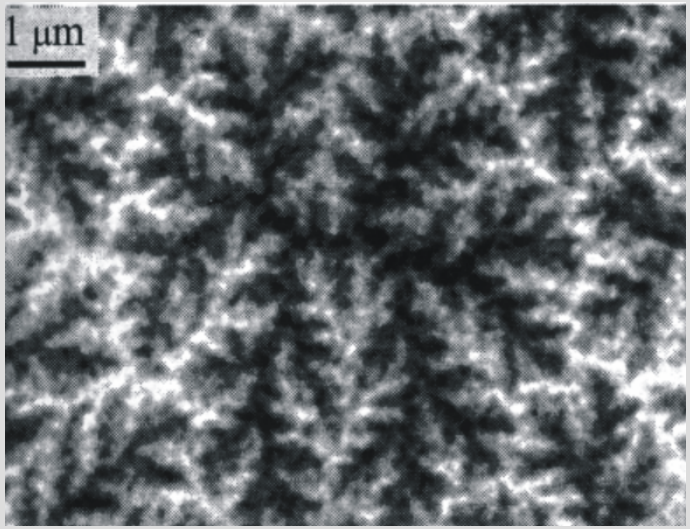
$$\lambda_B = 2-3\,\text{nm} \longrightarrow \lambda_B \geq 100\,\text{nm}$$

Hard → Soft

One possible definition: mesoscopic magnetism

Bulk material

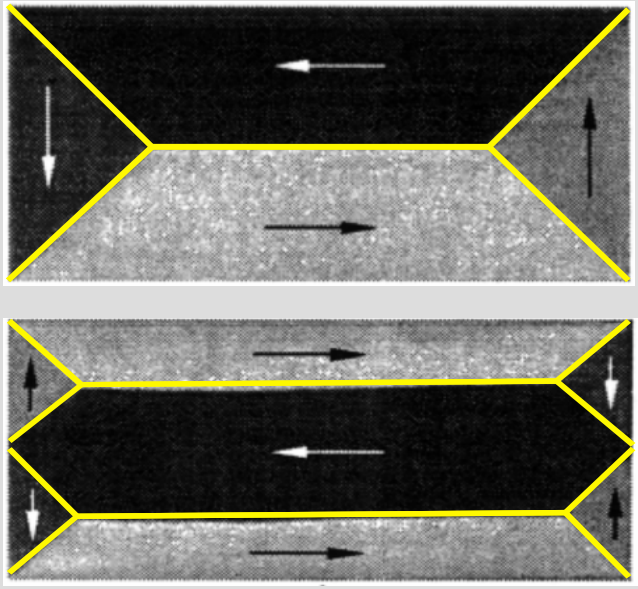
Numerous and complex magnetic domains



Co(1000) crystal – SEMPA
A. Hubert, *Magnetic domains*

Mesoscopic scale

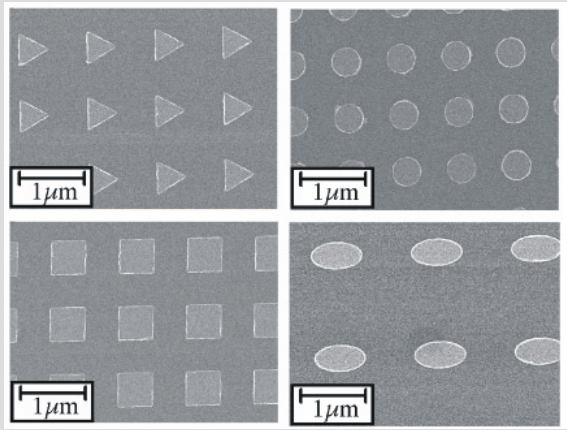
Small number of domains, simple shape

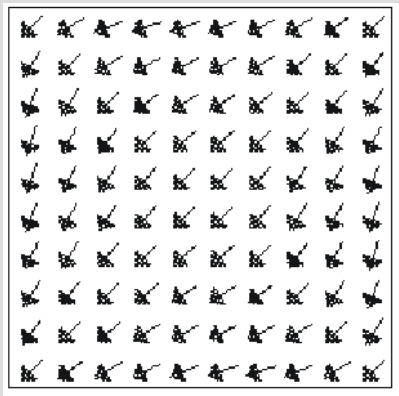


Microfabricated dots
Kerr magnetic imaging
A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain





R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1 (2000)

Magnetic recording essentially makes use of single-domain particles

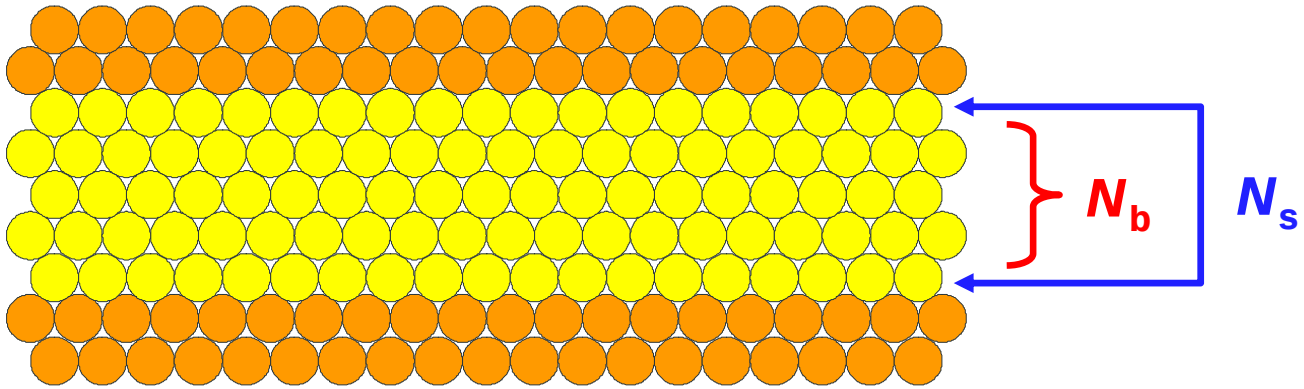
Magnetic properties of self-organized systems : TOC

Naïve model

Molecular field

$$T_c = \mu_0 . \frac{J+1}{3J} . \frac{N w_0 M_0 \mathbf{m}_0}{k_B}$$

N neighbors



$$\overline{N} = N_b - \frac{2(N_b - N_s)}{t} \Rightarrow \Delta T_c(t) \sim t^{-1}$$

Less naïve…

Thickness-dependant molecular field

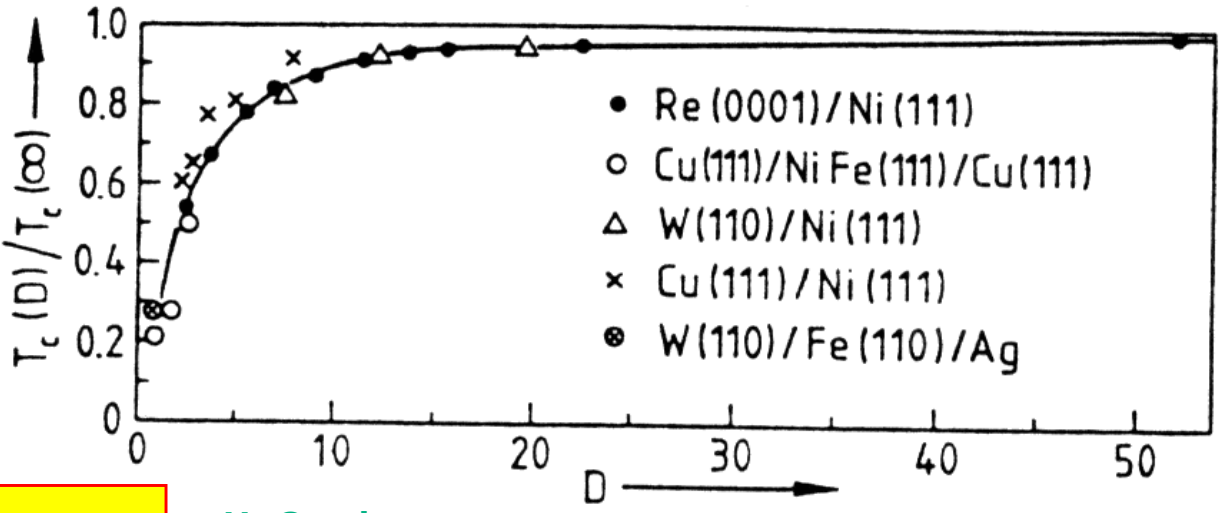
$$\Delta T_c(t) \sim t^{-\lambda}$$

$$\lambda = 1$$

G.A.T. Allan, PRB1, 352 (1970)

Conclusion:
Naïve views are roughly correct

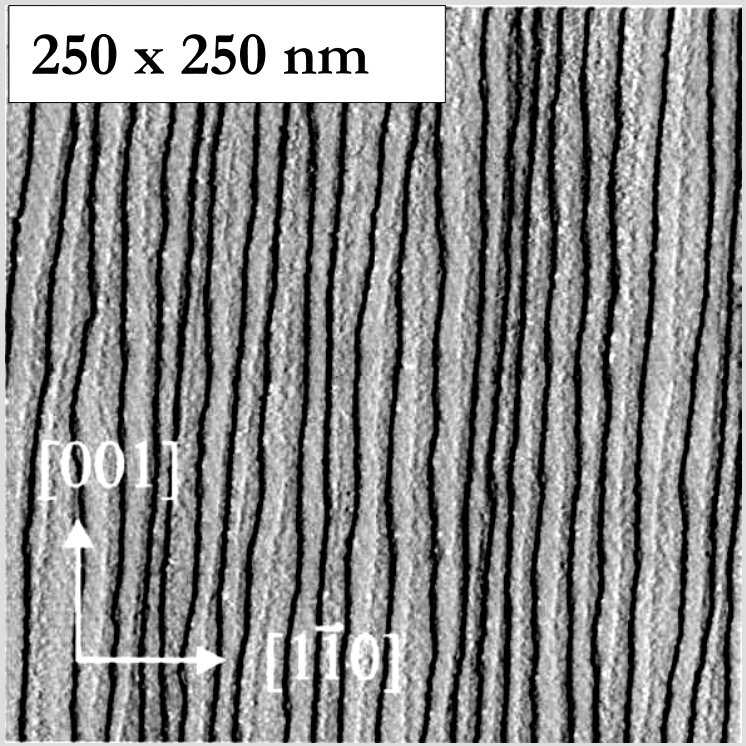
Experiments



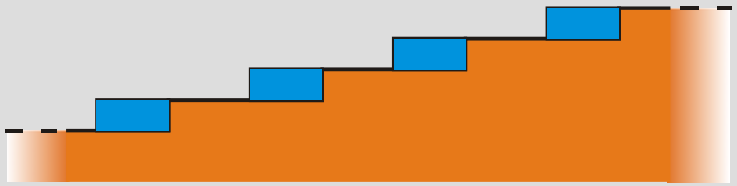
U. Gradmann,
Handbook of Magn. Mater. Vol.7, ch.1 (1993)

Stripes on vicinal surfaces

Fe(0.5ML)/W(110)

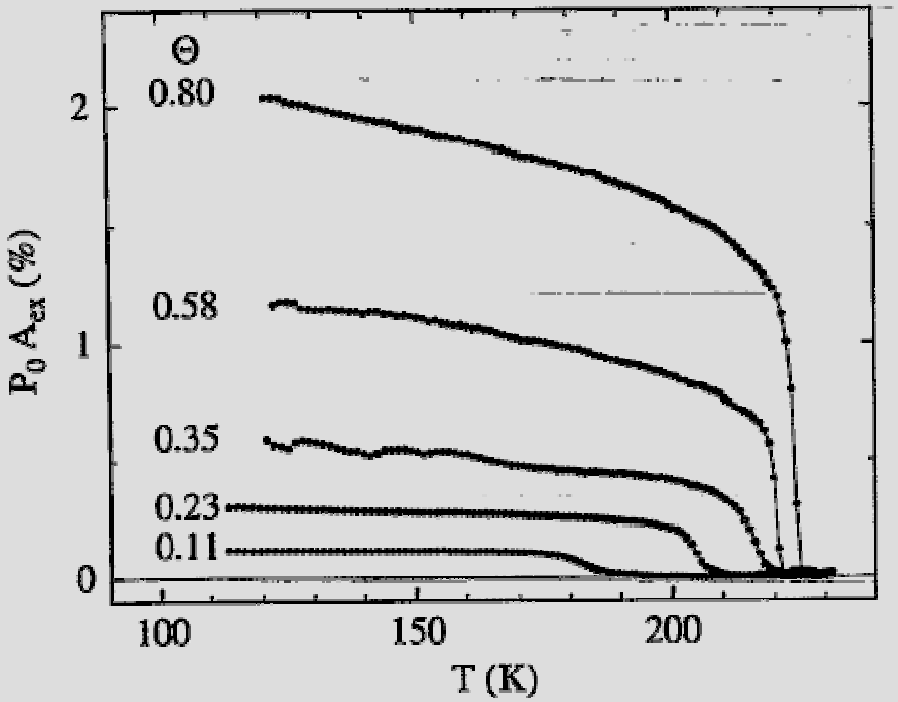


J.Hauschild *et al.*,
Phys.Rev.B57, R677(1998)



Magnetic order in 2D: finite-size scaling

Curie temperature as a function of stripe width



$$T_C(n)/T_C(\infty) \propto 1-(n_0/n)^{\lambda}$$

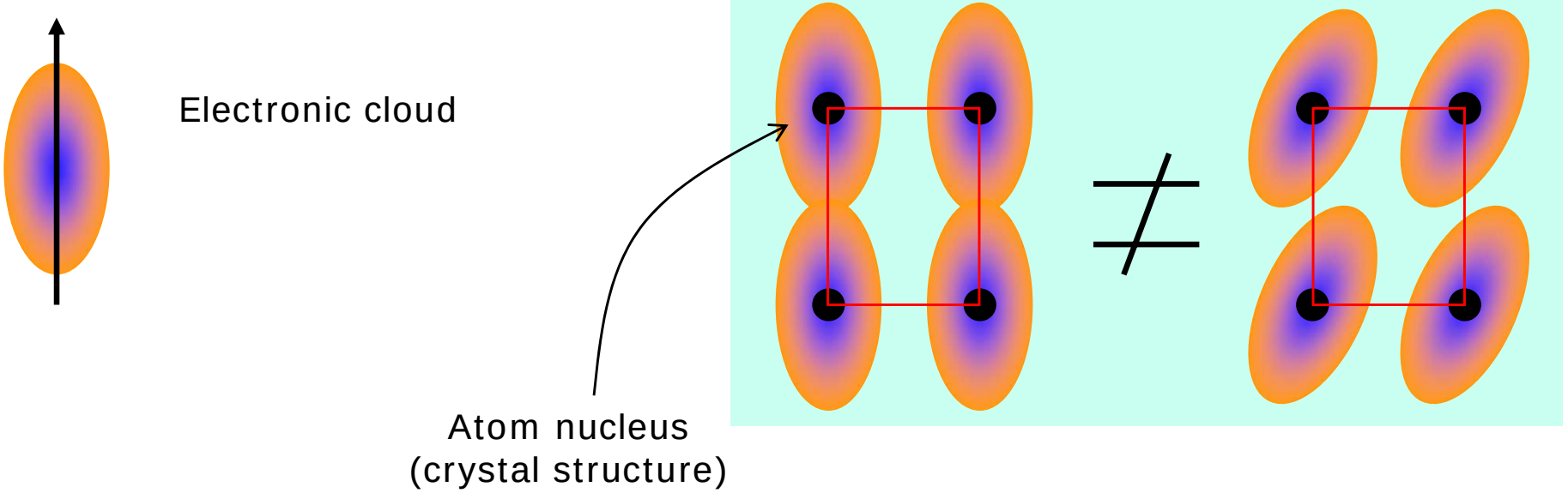
$\lambda = 1.03$ in agreement with Ising model (=1)

H. J. Elmers et al., PRL73, 898 (1994)

$\lambda = 1.2 \pm 0.3$ for Fe stripes / Pd(110)

D. Li et al., PRB64, 144410 (2001)

Magnetocrystalline anisotropy energy



Spin-orbit coupling ⇨ the energy of both spin and orbital moment depends on orientation

Series development on an angular basis:

Anisotropy energy **Normalized magnetization components**

$$E_{mc} = K_1 m_z^2 + K_2 m_z^4 + \ldots$$ Uniaxial

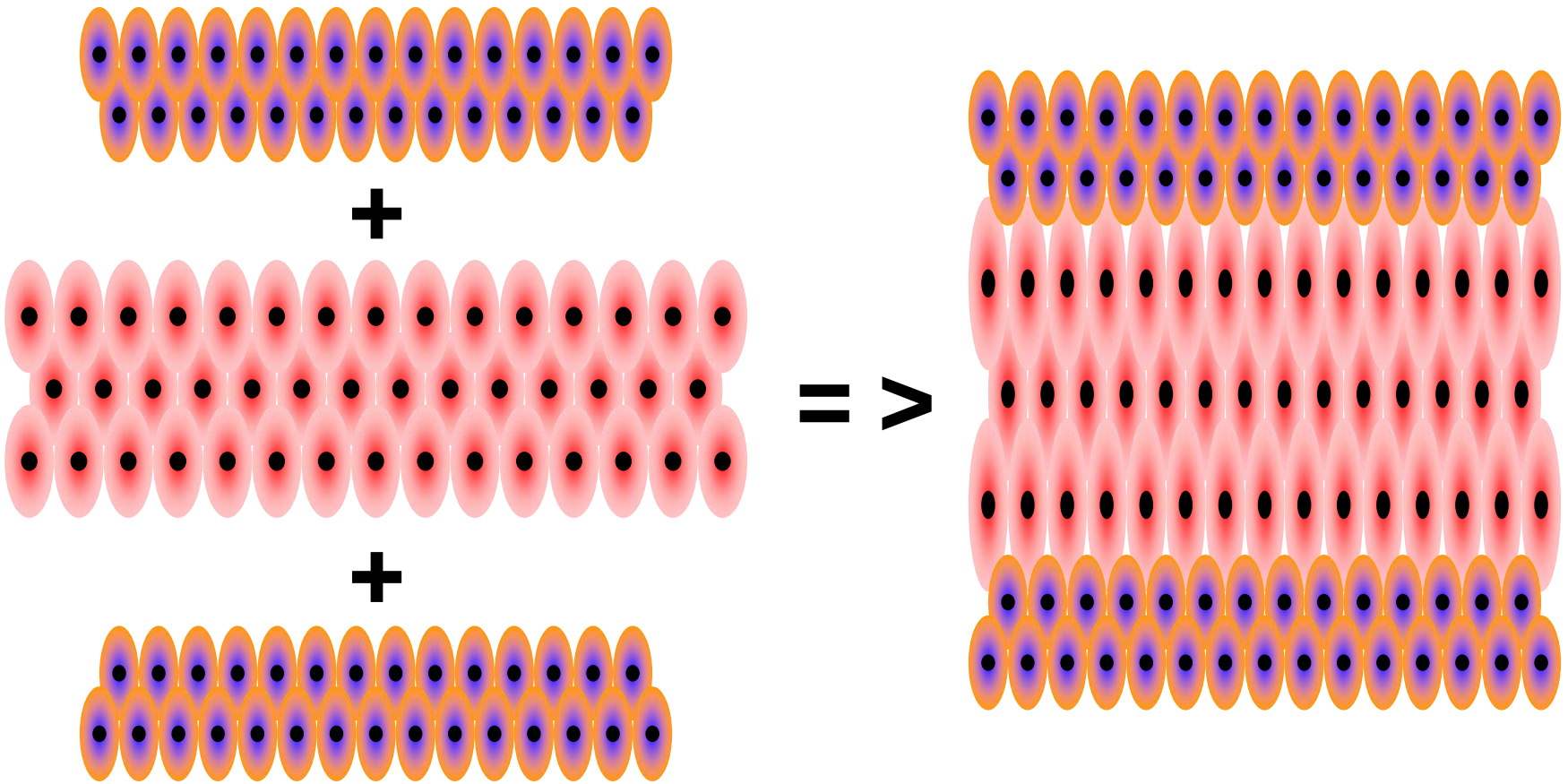
$$E_{mc} = K_4 (m_x^2 m_y^2 + m_y^2 m_z^2 + m_z^2 m_x^2) + \ldots$$ Cubic

…

Alignement of magnetization is favored along given axes of the crystal

(Derived from slide of A. Thiaville – CNRS/Orsay)

Magneto-elastic anisotropy



Origin

Deformation of orbitals

⇒ Correction to the magneto-crystalline energy

Result

$$E_{mel} = K_{mel,1}\cos^2(\theta) + \ldots$$

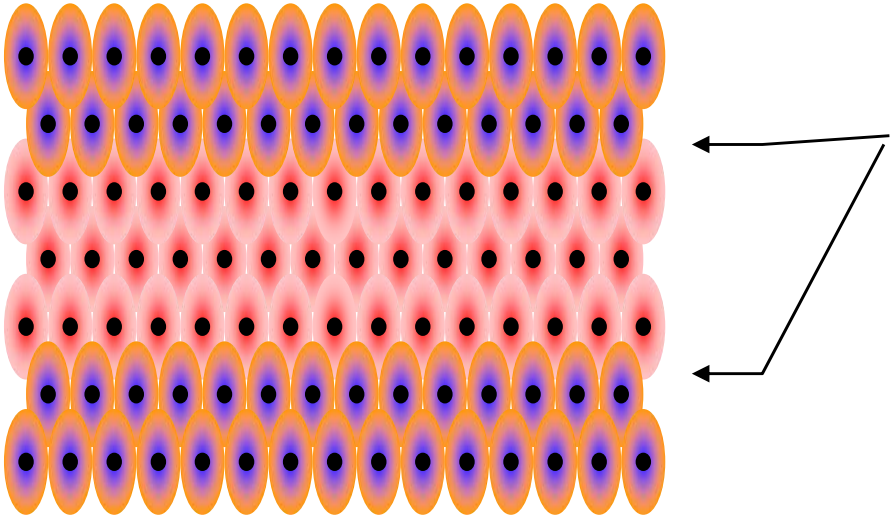
$$K_{mel,i} \sim B_i \varepsilon$$

Surface anisotropy

L. Néel,
J. Phys. Radium 15,
15 (1954)

« Anisotropie magnétique superficielle et surstructures d'orientation »

« Superficial magnetic anisotropy and orientational superstructures »



Overview

Breaking of symmetry for surface/interface atoms

⇒ Correction to the magneto-crystalline energy

$$E_s = K_{S,1}\cos^2(\theta) + K_{S,2}\cos^4(\theta) + \ldots$$

« Cette énergie de surface, de l'ordre de 0.1 à 1 erg/cm2, est susceptible de jouer un rôle important dans les propriétés des substances ferromagnétiques dispersées en éléments de dimensions inférieures à 100Å »

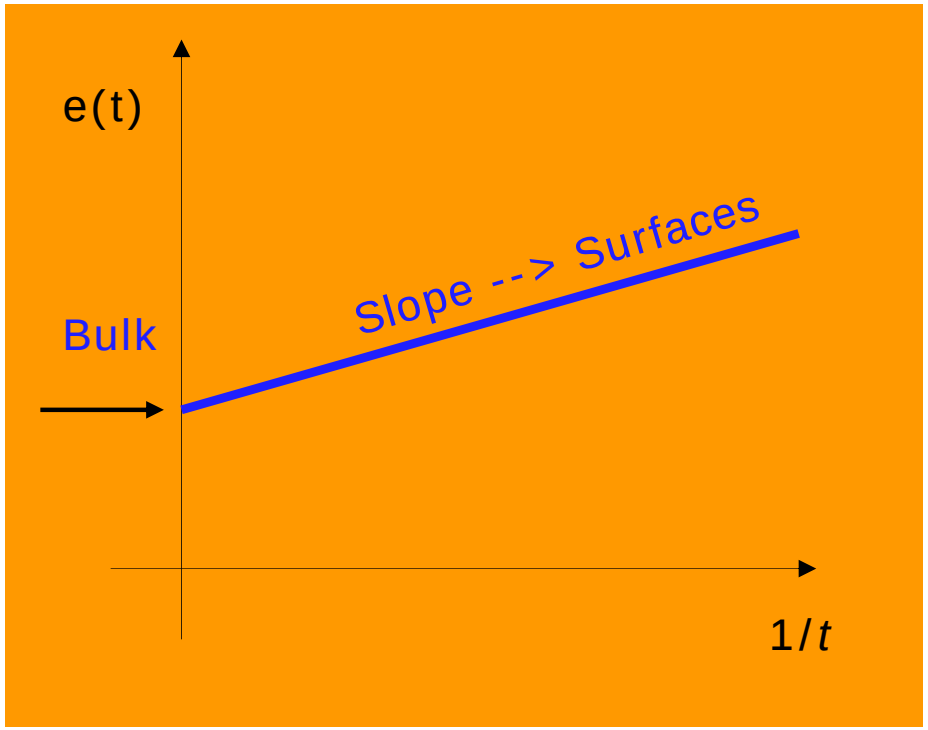
« This surface energy, of the order of 0.1 to 1 erg/cm2, is liable to play a significant role in the properties of ferromagnetic materials spread in elements of dimensions smaller than 100Å »

Pair model of Néel:

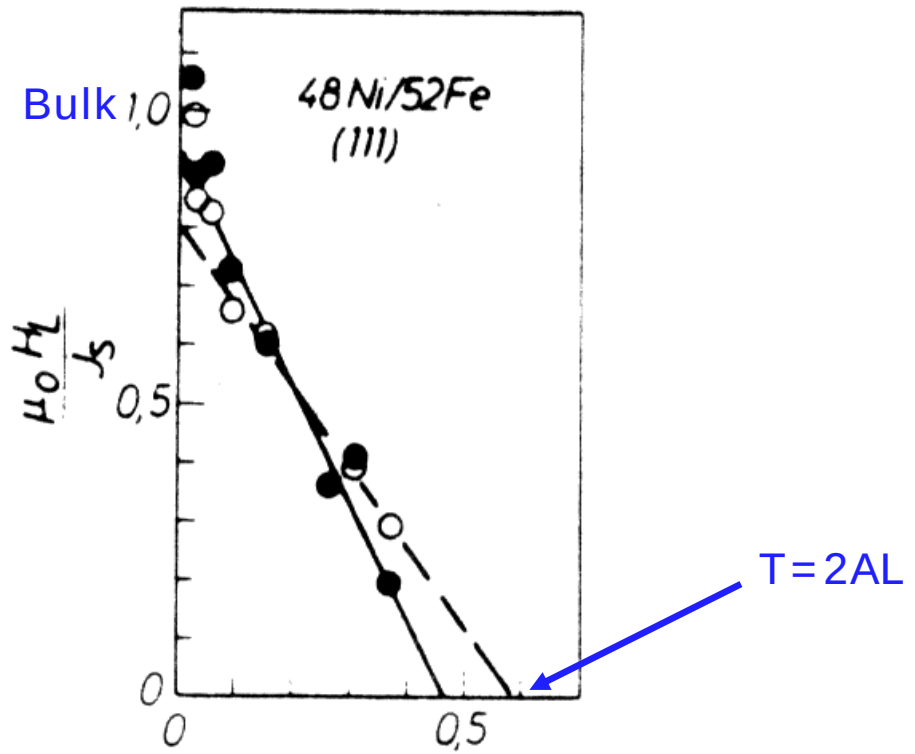
- Ks estimated from magneto-elastic constants
- Does not depend on interface material
- Yields order of magnitude only: correct value from experiments or calculations

History of surface anisotropy : STEP 1 (1/t plot)

$$E_{tot}(t) = k_V t + 2k_S \quad \Rightarrow \quad e(t) = k_V + \frac{2k_S}{t}$$

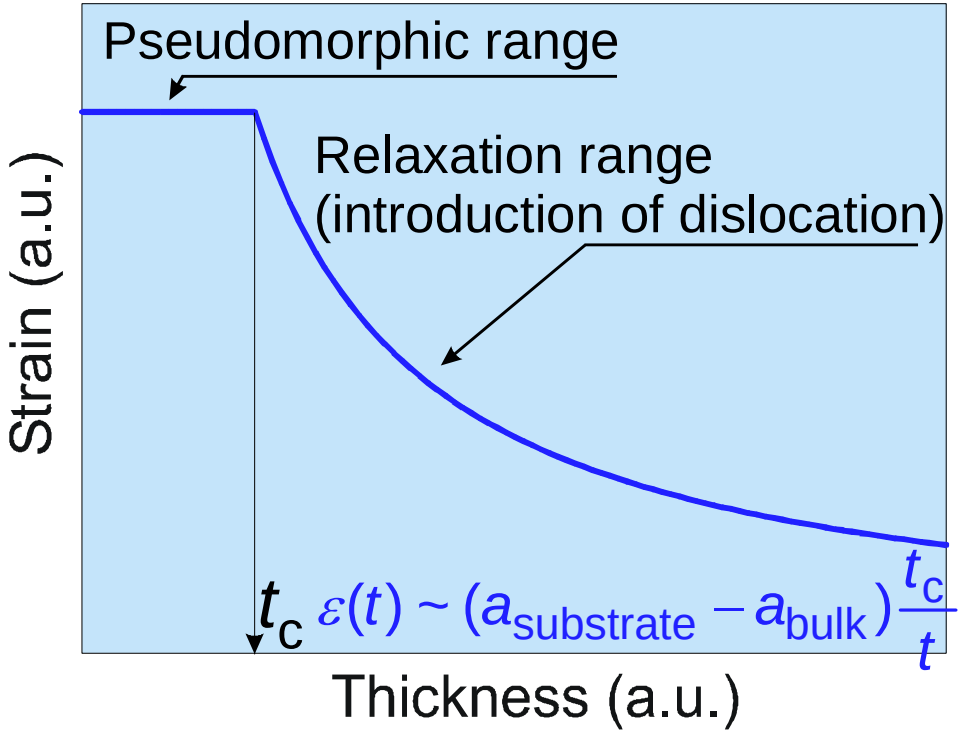


First example of perpendicular anisotropy

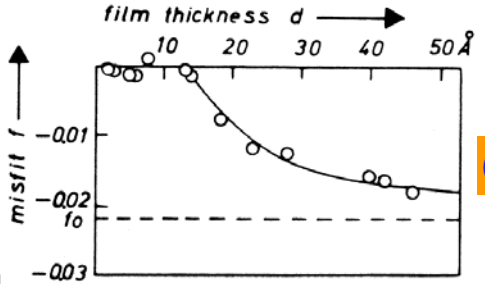


U. Gradmann and J. Müller,
Phys. Status Solidi 27, 313 (1968)

Structural relaxation



W. A. Jesser et al., Phys. Stat. Sol. 19, 95 (1967)



Co/Cu(111)

U. Gradmann, Appl. Phys.3, 161 (1974)

Effect on anisotropy

Magneto-elastic anisotropy:

$$k_{mel} \sim B_{mel}\varepsilon$$

Strain relaxation regime:

$$k(t) = k_{bulk} + \alpha\, B_{mel}/t$$

Conclusion:

Mixing of surface and magneto-elastic contributions

$$e(t) = k_V + \frac{2k_S}{t}$$

C. Chappert and P. Bruno., JAP64, 5736 (1988)

Magnetic Anisotropy Energy (MAE): Link with anisotropy of orbital moment

Theory

Perturbation theory for 3d metals:

$$MAE = \alpha \frac{\xi}{4\mu_B} \Delta\mu_L$$

P. Bruno, PRB39, 865 (1989)

μ_L does not rotate in 3d metals
-> MAE reflects cost in ξ

Covers magnetocrystalline, magnetoelastic and surface anisotropy

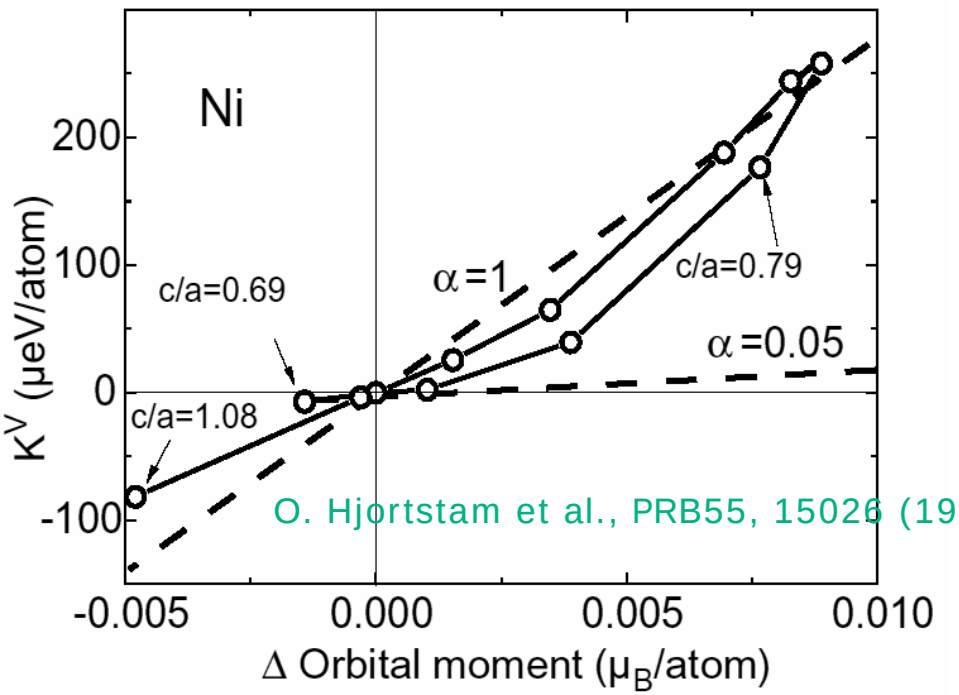
Experiments

Bulk (Fe, Ni, ...)

$\Delta\mu_L \approx 10^{-4}\mu_B$ / atom ⇒ $MAE \leq 1\mu eV$

Ab initio calculations

High precision needed: $1\mu eV << 10\,eV$



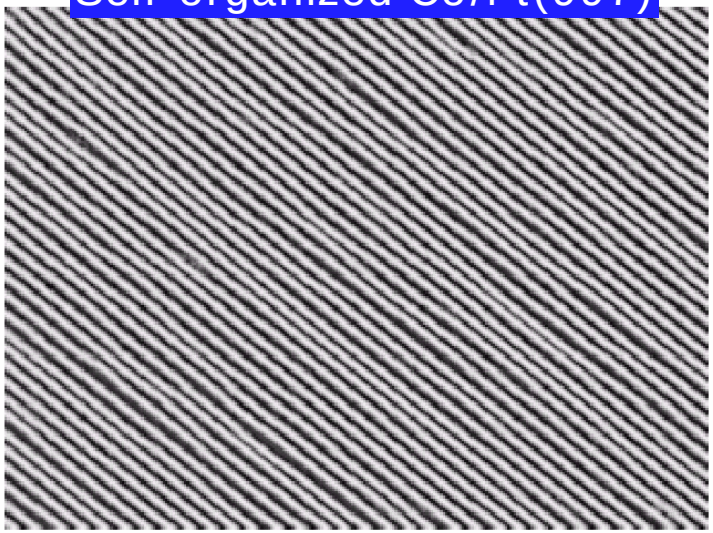
O. Hjortstam et al., PRB55, 15026 (1997)

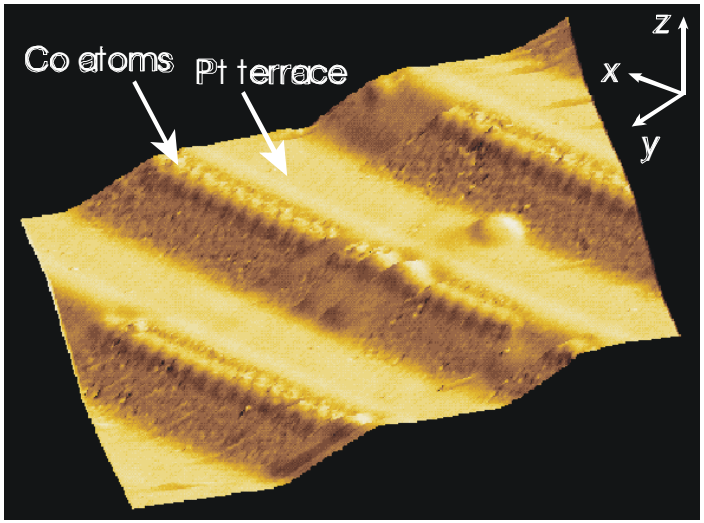
Conclusions

- Origin of MAE = anisotropy of orbital moment
- No strict linearity
- α may also depend on thickness in thin films (band structure)
  → Direct measurement of MAE preferable

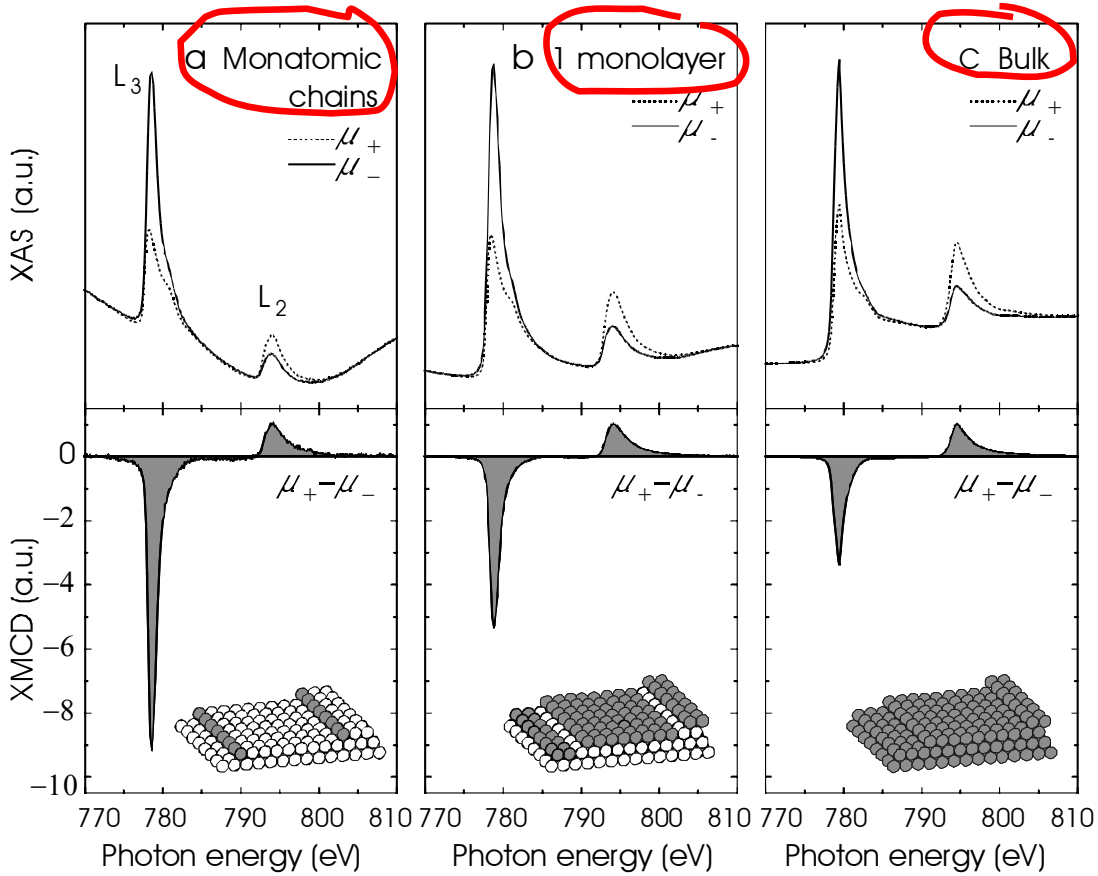
From surface to wires (1D)

Self-organized Co/Pt(997)





Magnetic circular dichroïsm



$$\mu_L \approx \int L_3 + \int L_2$$

$$\mu_S^{eff} \approx -\int 2L_3 + 4\int L_2$$

Conclusion:

- Increase of orbital moment (necessary condition for anisotropy)

P. Gambardella et al., Nature 416, 301 (2002)

From surface to wires (1D)

Method

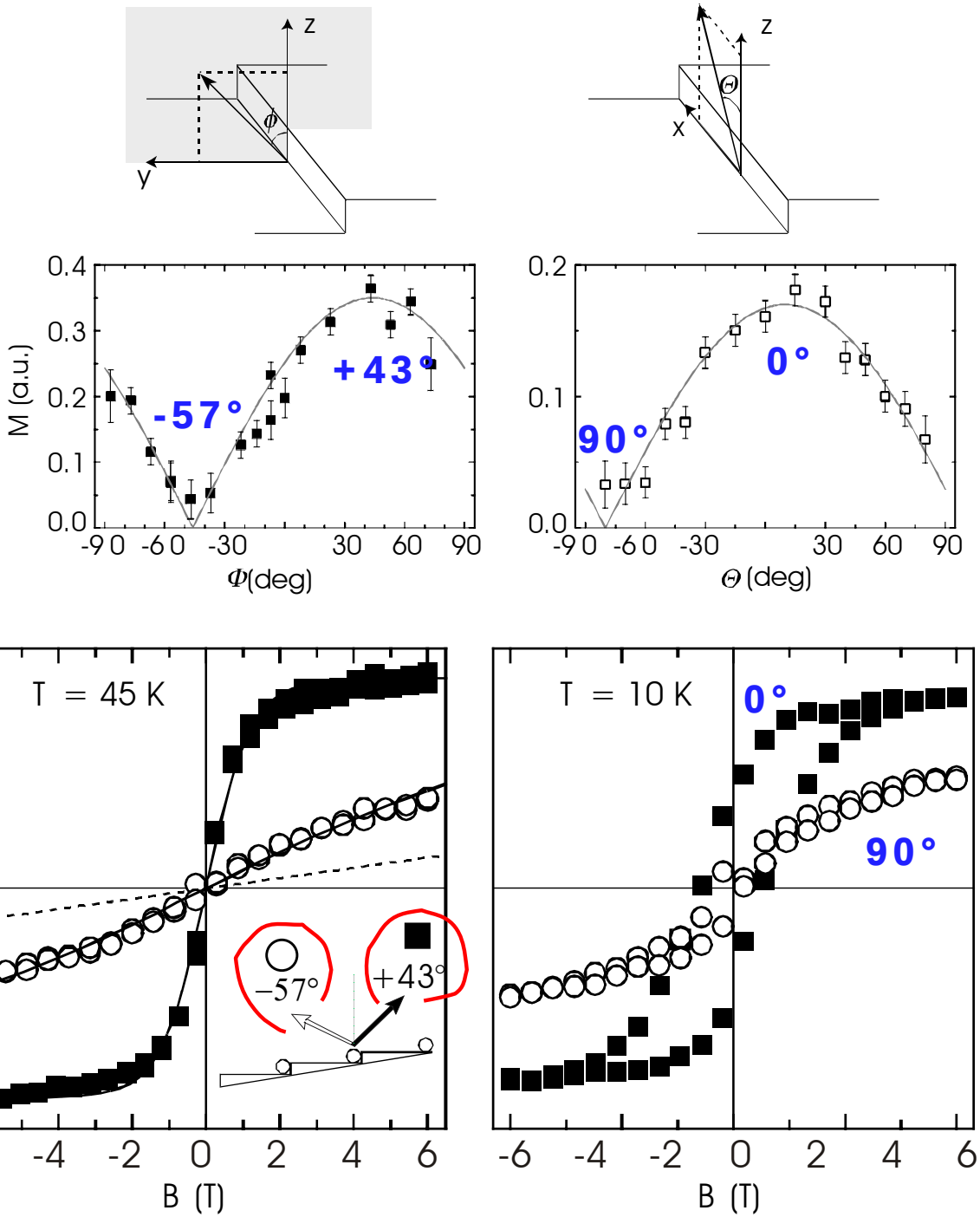
- XMCD > Orbital moment
- Fit magnetization curves > Anisotropy functional

MAE

- Bulk Co: 40μeV/atom
- Co ML: 140μeV/atom
- Co bi-wire: 0.34meV/atom
- Co wire: 2meV/atom

Conclusions:

- Easy axis of magnetization perpendicular to the wires, but not the the mean film surface, nor to Pt(111)
- See anisotropy of orbital moment on the saturation XMCD.

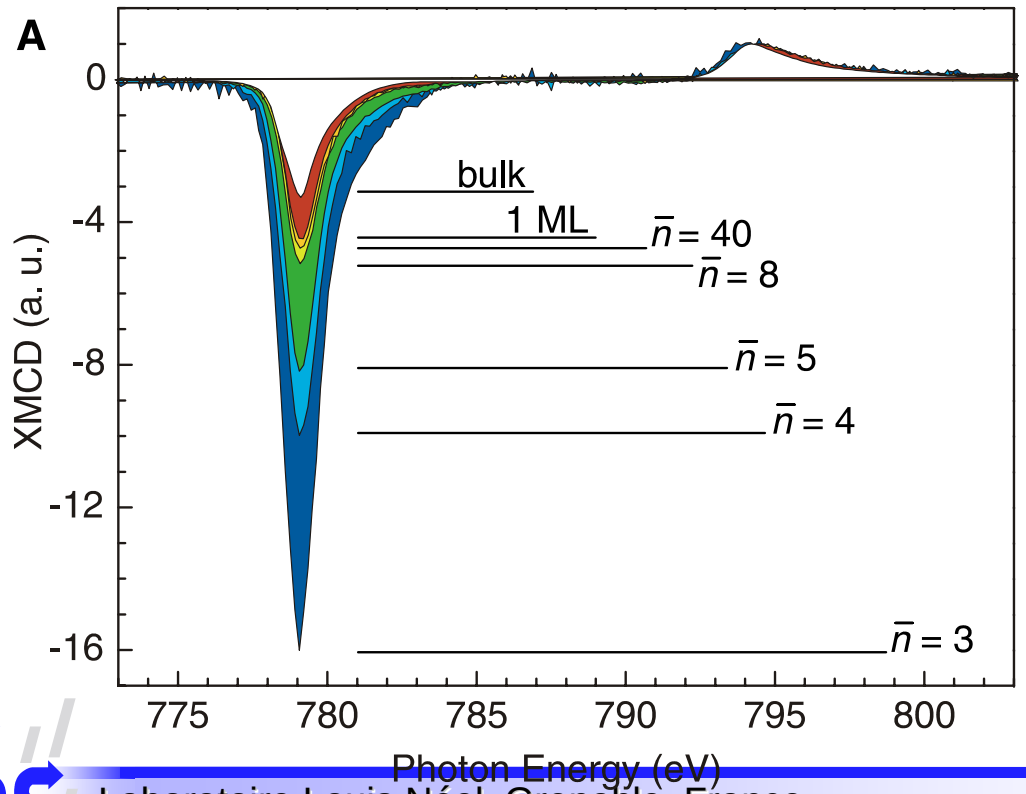


From surface to atoms (0D) **Co / Pt(111)**

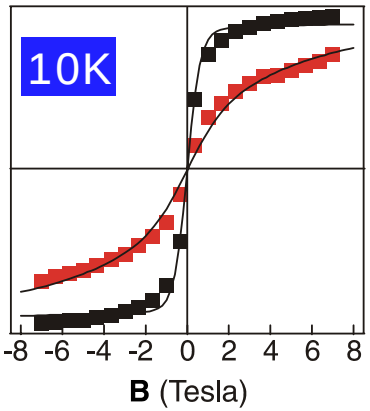
Giant Magnetic Anisotropy of Single Cobalt Atoms and Nanoparticles

P. Gambardella,[1,2*] S. Rusponi,[1,2] M. Veronese,[3] S. S. Dhesi,[4†]
C. Grazioli,[3] A. Dallmeyer,[5] I. Cabria,[5] R. Zeller,[5]
P. H. Dederichs,[5] K. Kern,[1,2] C. Carbone,[3,5] H. Brune[1]

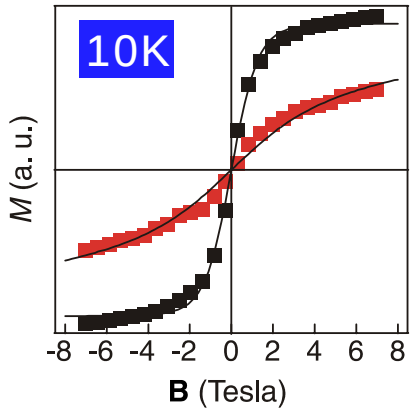
P. Gambardella et al., Science 300, 1130 (2003)



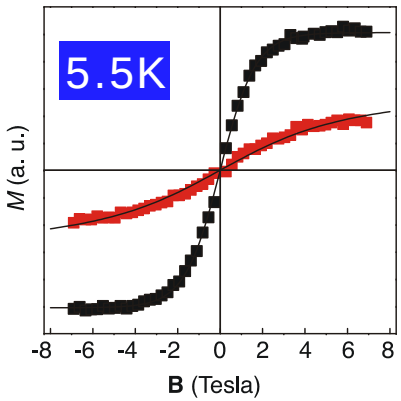
8 atoms



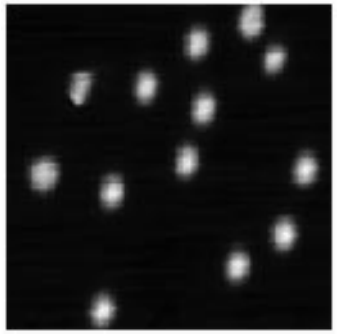
4 atoms



1 atom



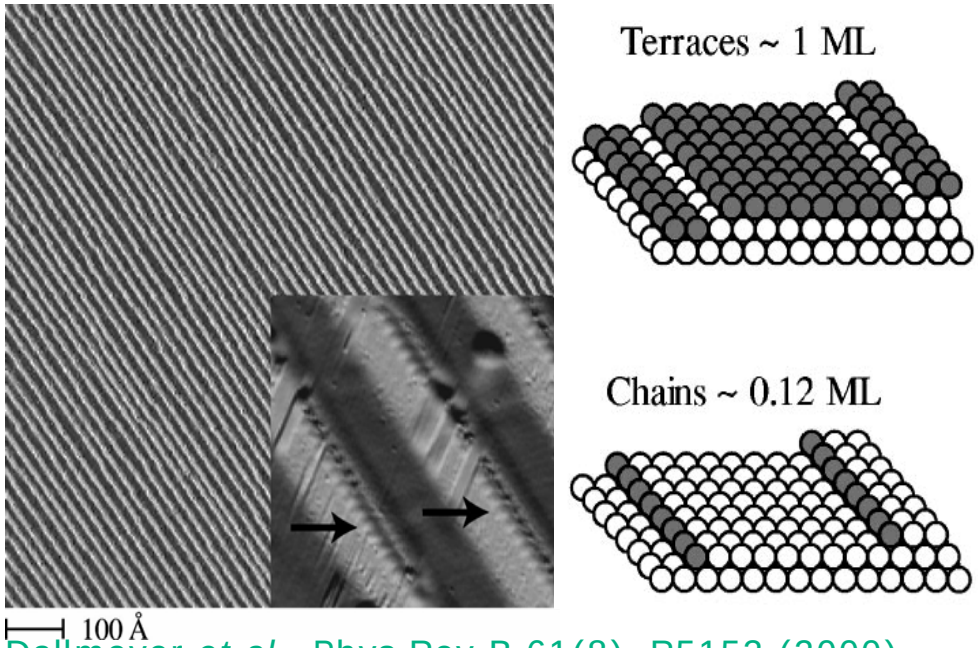
STM, 8.5nm, 5.5K



Qualitatively:

- Easy axis of magnetization perpendicular to Pt(111)

Co / Pt(997)

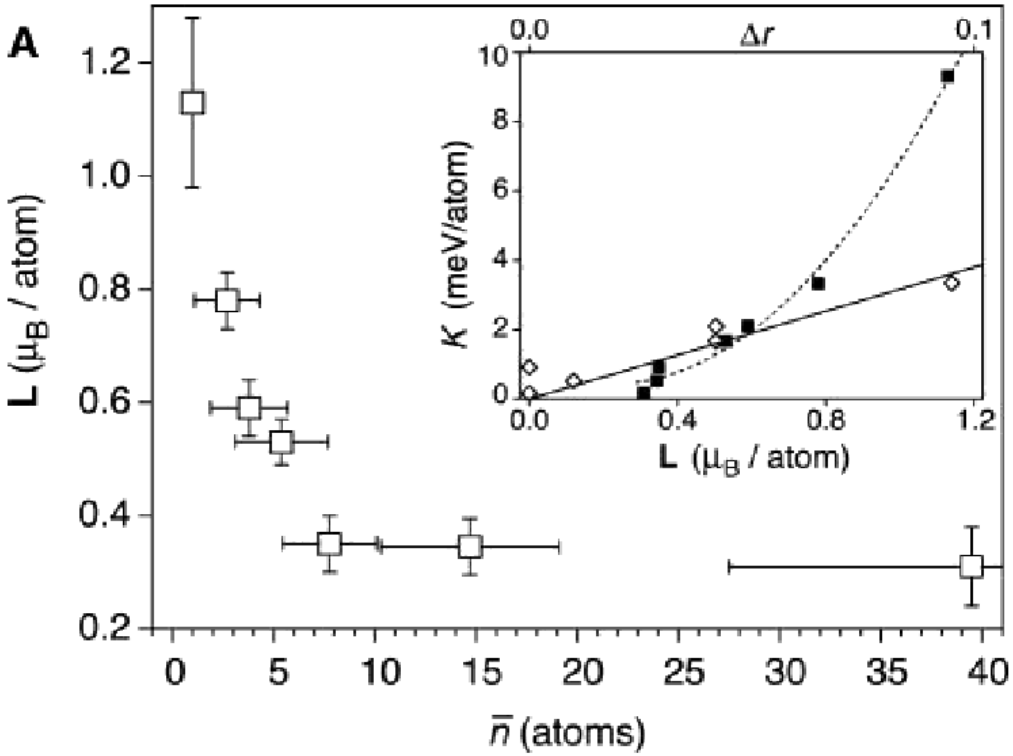


A. Dallmeyer *et al.*, Phys.Rev.B 61(8), R5153 (2000)

Conclusions

- Bulk: $m_L = 0.14 \mu_B$/at.
- Surface: $m_L = 0.31 \mu_B$/at.
- Bi-atomic wire: $m_L = 0.37 \mu_B$/at.
- Mono-atomic wire: $m_L = 0.68 \mu_B$/at.
- bi-atom: $m_L = 0.78 \mu_B$/at.
- atom: $m_L = 1.13 \mu_B$/at.

Co / Pt(111)



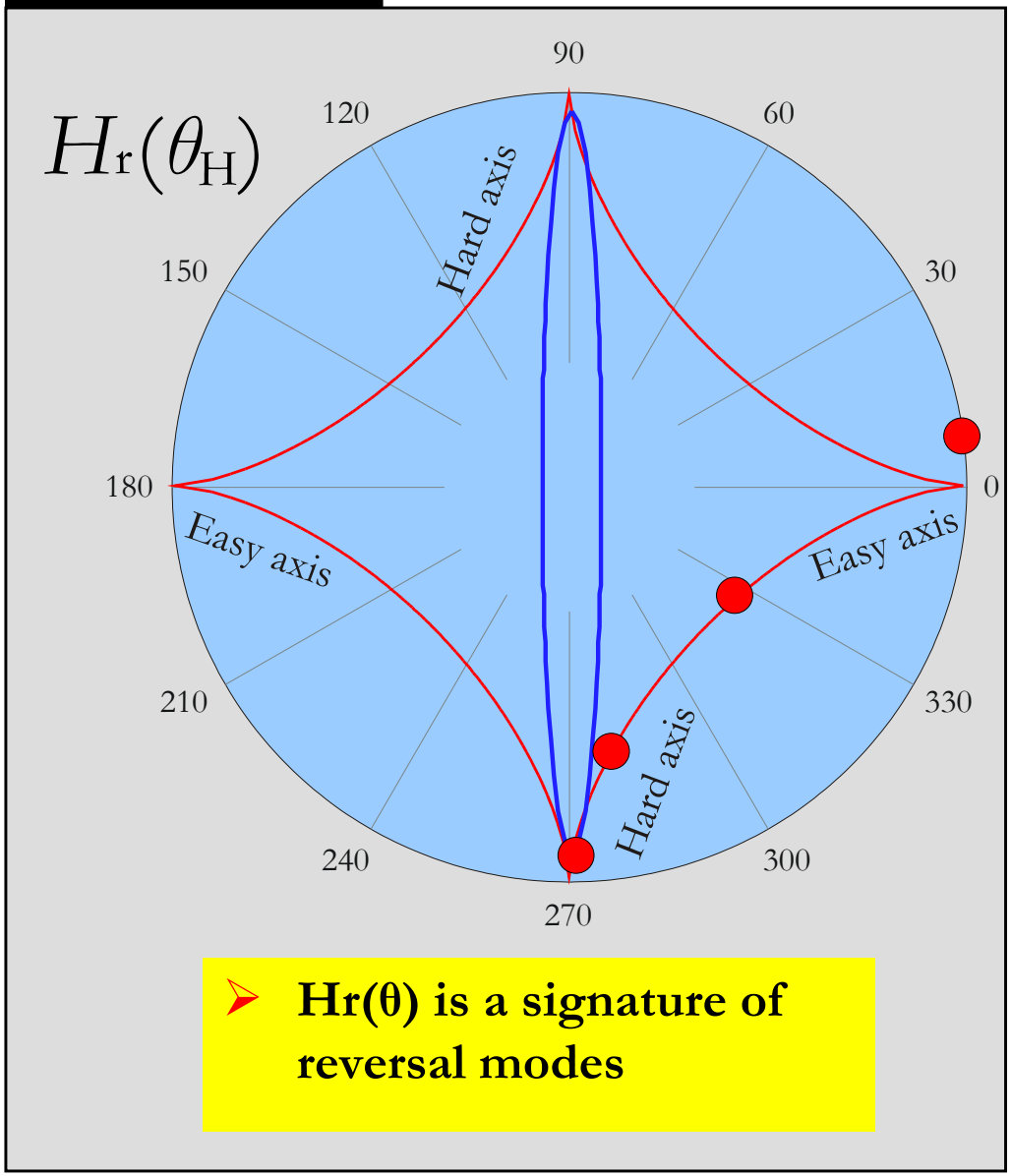
P. Gambardella et al., Science 300, 1130 (2003)

Conclusions

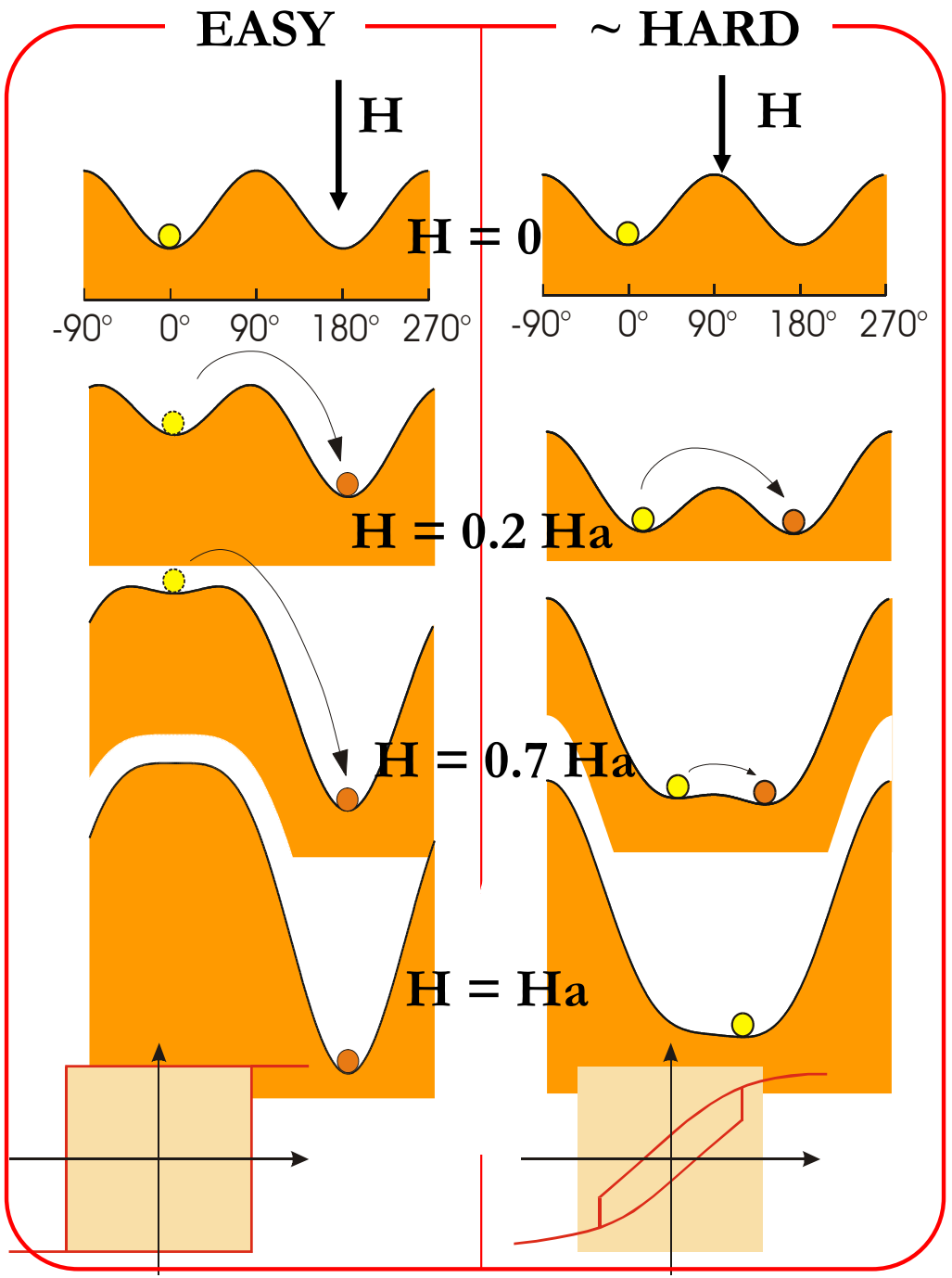
- From bulk to atoms: considerable **increase of orbital moment**
- **2 atoms closer to wire than 1 atom**
- **bi-atomic wire closer to surface than wire**

P. Gambardella et al., Nature 416, 301 (2002)

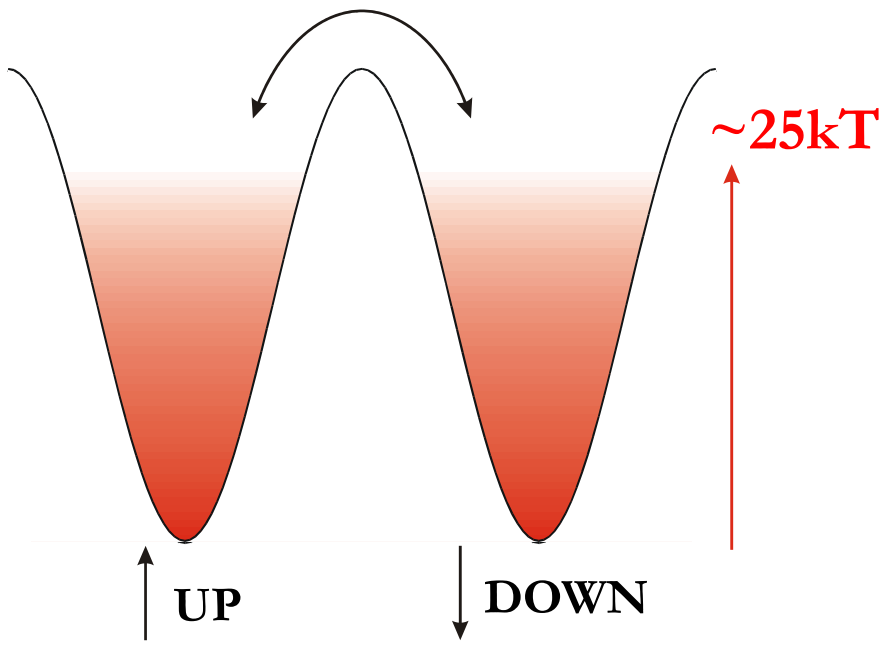
'Astroïd' curve



➢ **Hr(θ) is a signature of reversal modes**



Anisotropy barrier



Anisotropy barrier $E_B \sim KV$

Formalism for thermal excitations

Phenomenological model

Brown, Phys.Rev.130, 1677 (1963)

- Probability for non-reversal

$$P(t) = e^{-t/\tau}$$

- Mean waiting time for reversal

$$\tau = \tau_0 e^{E_B / k_B T} \qquad \tau_0 \approx 10^{-9}\text{s}$$

↳ Energy barrier required to prevent magnetization reversal during duration *t*

$$E_B = k_B T \ln(t/\tau_0)$$

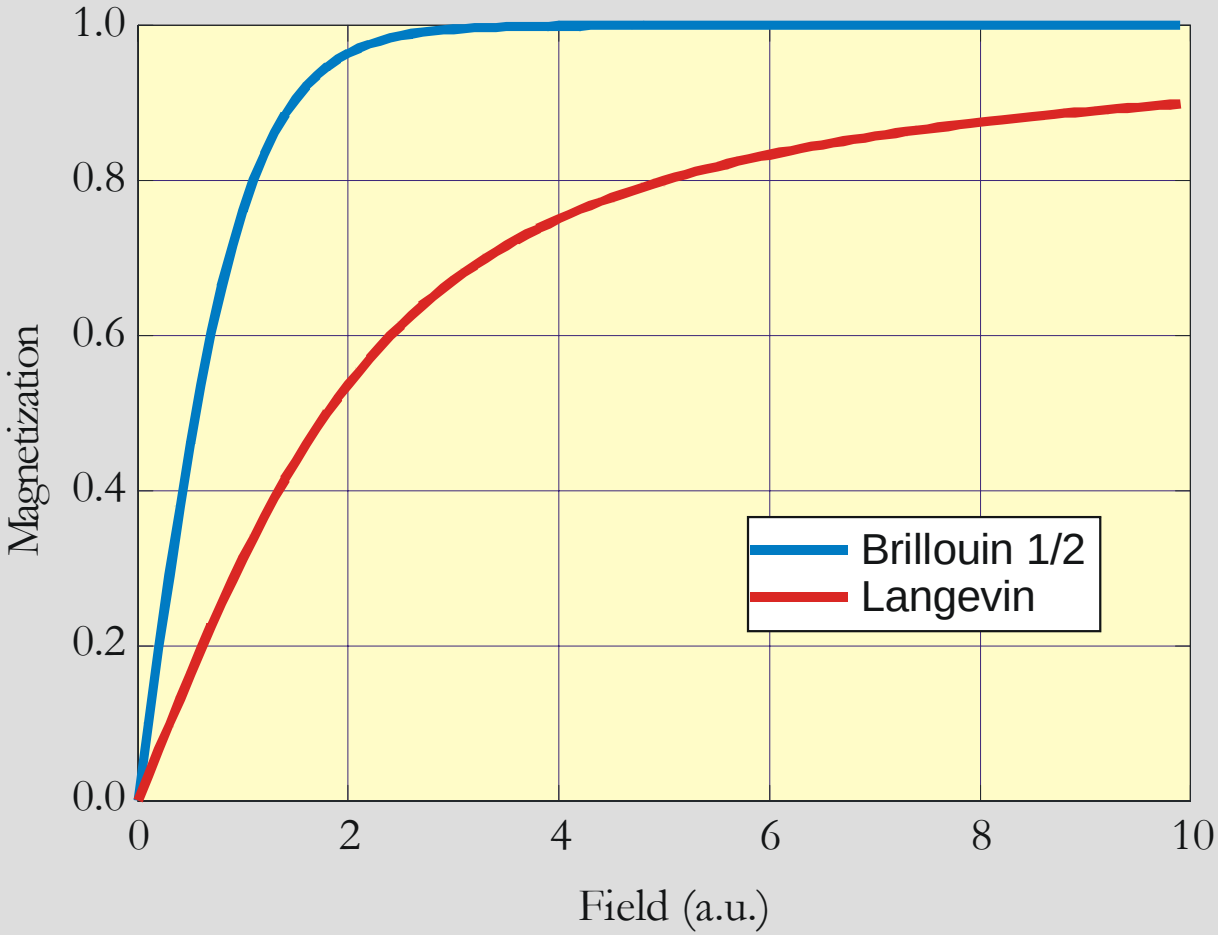
Orders of magnitude

Laboratory : $t = 1\text{s}$ $\quad V_B \approx 25 k_B T / K$

Recording : $t >> 10^9\text{s}$ $\quad V_B \approx 40 - 60 k_B T / K$

Magnetic recording with one grain per bit ($V = V_B$, discrete media) more favorable than $V = N V_B$

Which fitting function ?



Extremely weak anisotropy

Langevin function

$$m = \tanh(h), \quad h = \beta\mu_0\mu H$$

Strong uniaxial anisotropy

Brillouin 1/2 function

$$m = 1/\tanh(h) - 1/h$$

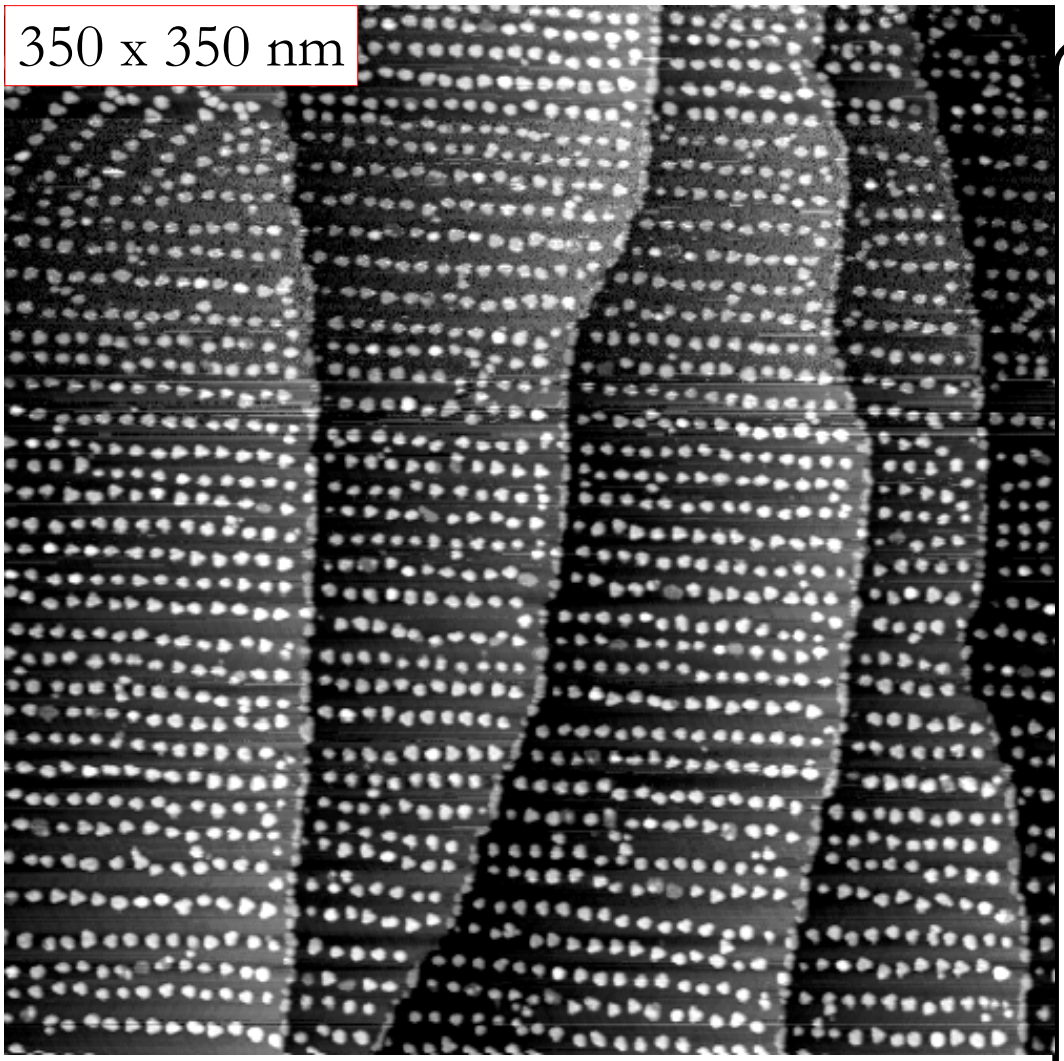
Other cases:

moderate or tilted anisotropy, distributions etc.

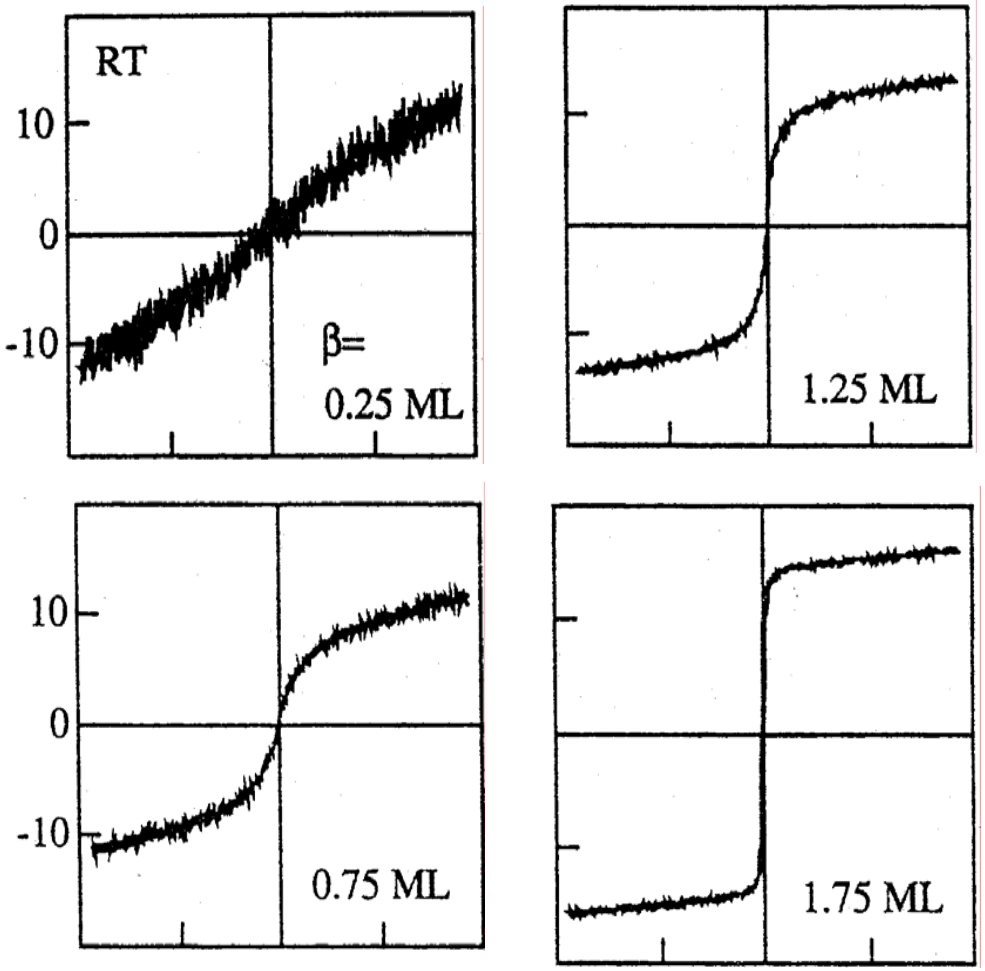
Numerical fitting

- Yields an estimation of the magnetic moment per particle μ
- Fitting with inadequate functions yields errors on μ

Example: Co/Au dots



O. Fruchart et al.



H.Takeshita et al., JMMM**165**, 38 (1997)

Curie temperature versus blocking temperature?

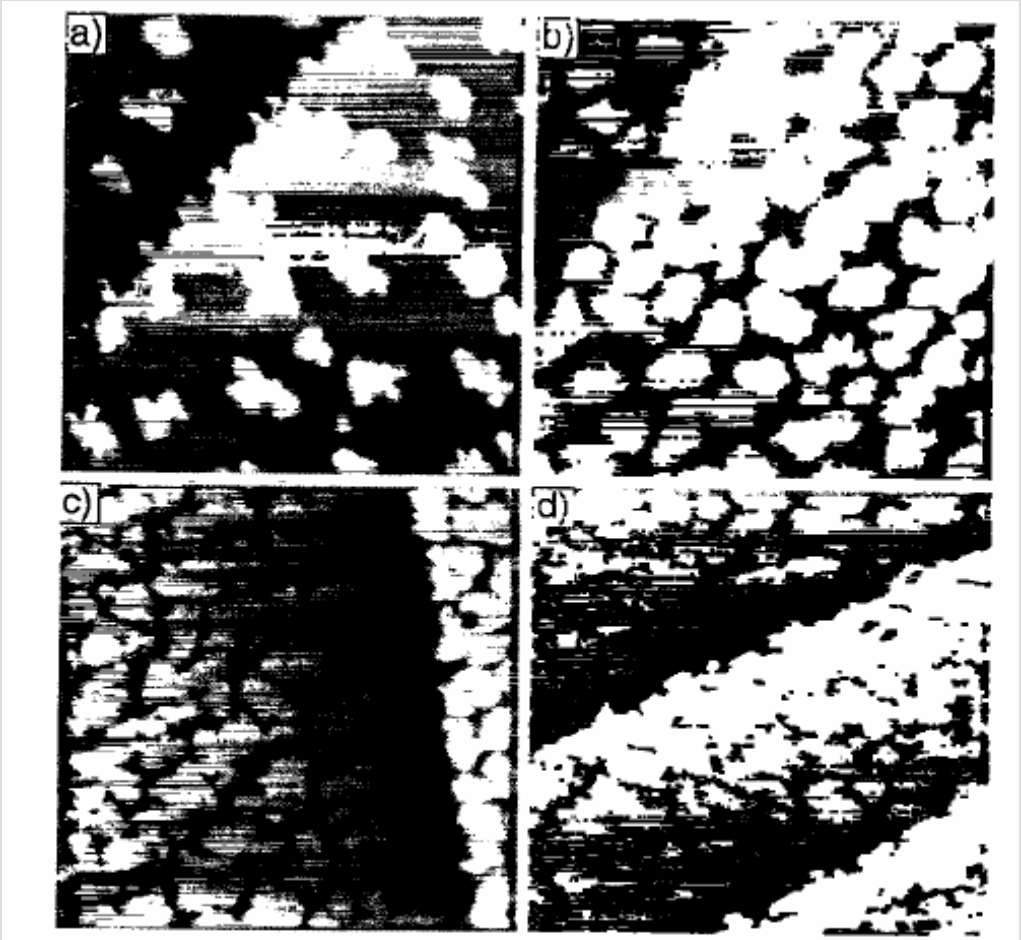
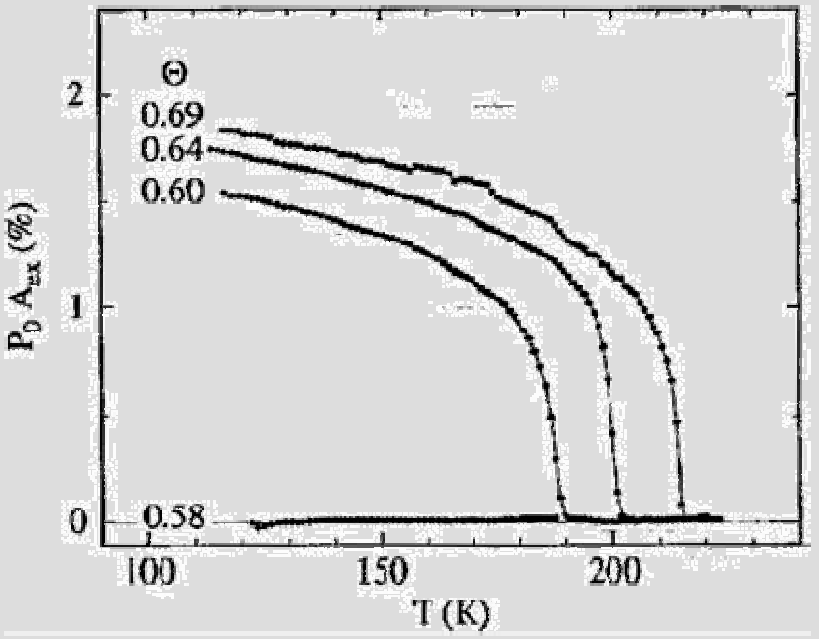


FIG. 1. STM images of Fe(110) films, prepared at RT on W(110), all 70 nm × 70 nm in size, with [001] horizontal. (a) $\theta = 0.23$; (b) $\theta = 0.53$; (c) $\theta = 0.66$; (d) $\theta = 0.85$. Upper levels (Fe) bright; lower levels (W) dark.

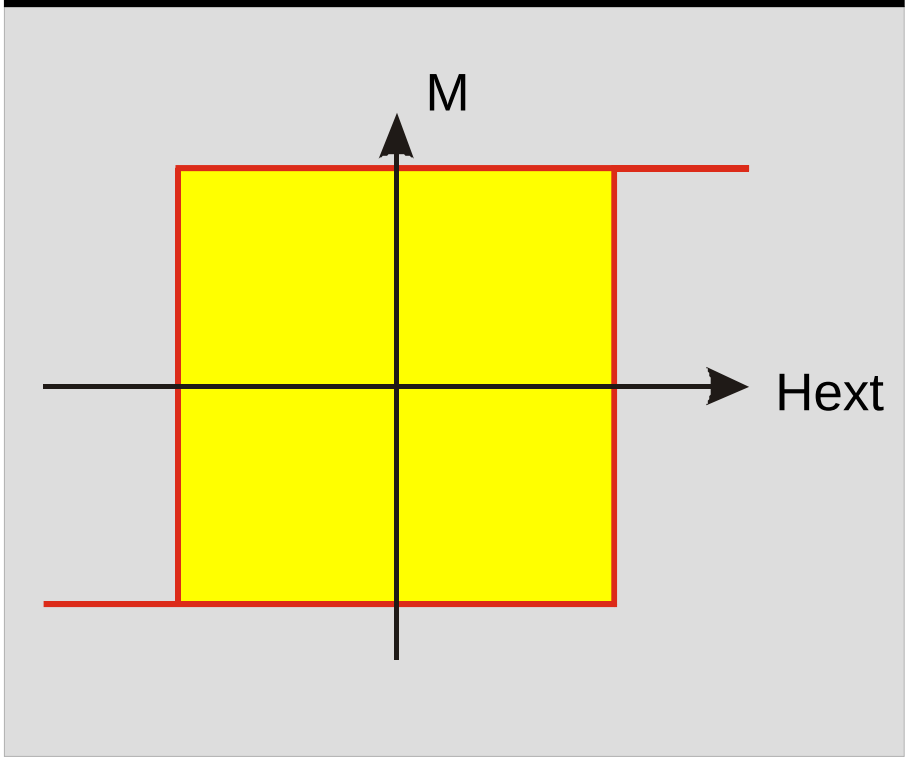
Remanence plotted as a function of temperature



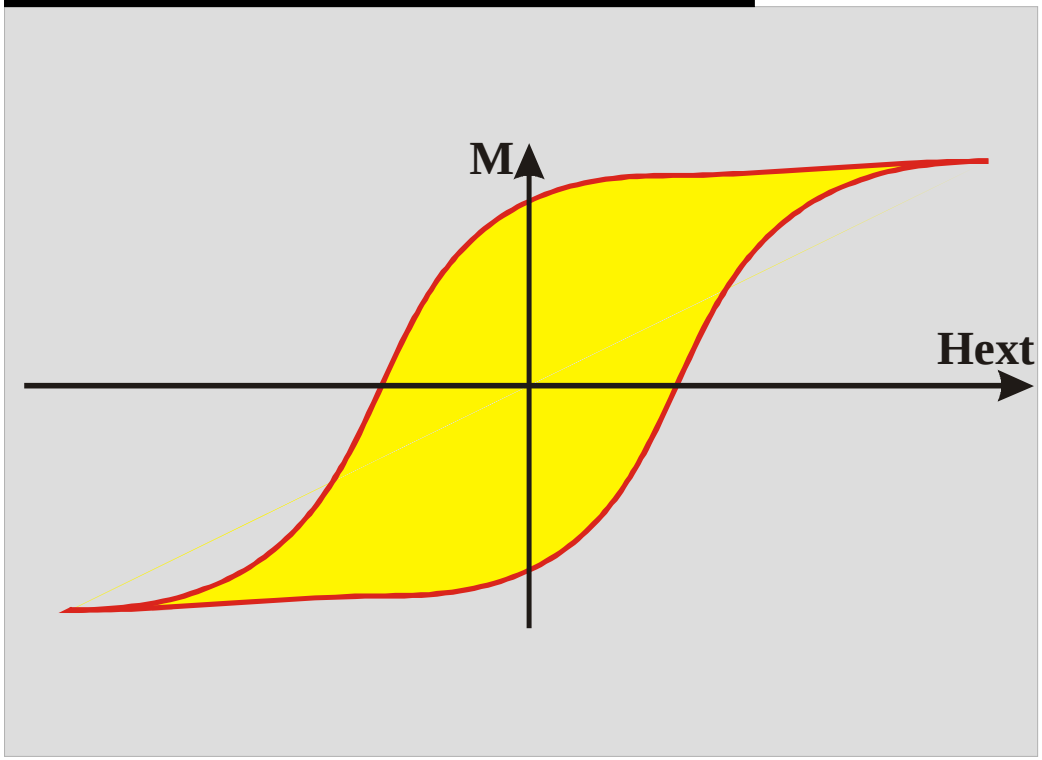
Transition from superparamagnetism to a blocked state

H. J. Elmers et al., PRL73, 898 (1994)

Expected hysteresis loop for macrospins



Hysteresis for assemblies of dots



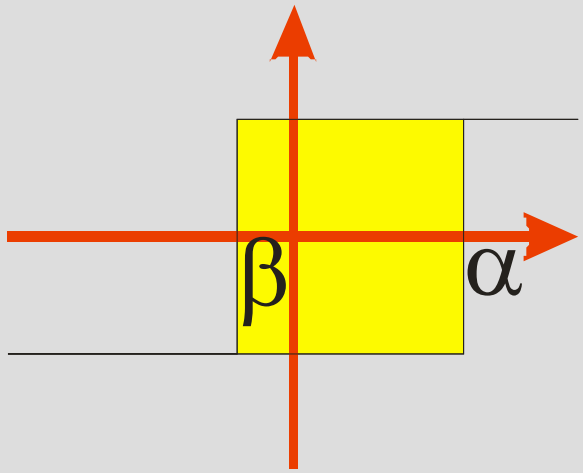
Possible effects

- Distribution of coercive fields
- (Dipolar) interactions

Preisach model

G. Biorci et al., Il Nuov. Cim. VII, 829 (1958)

I. D. Mayergoyz, Mathematical models of hysteresis, Springer (1991)

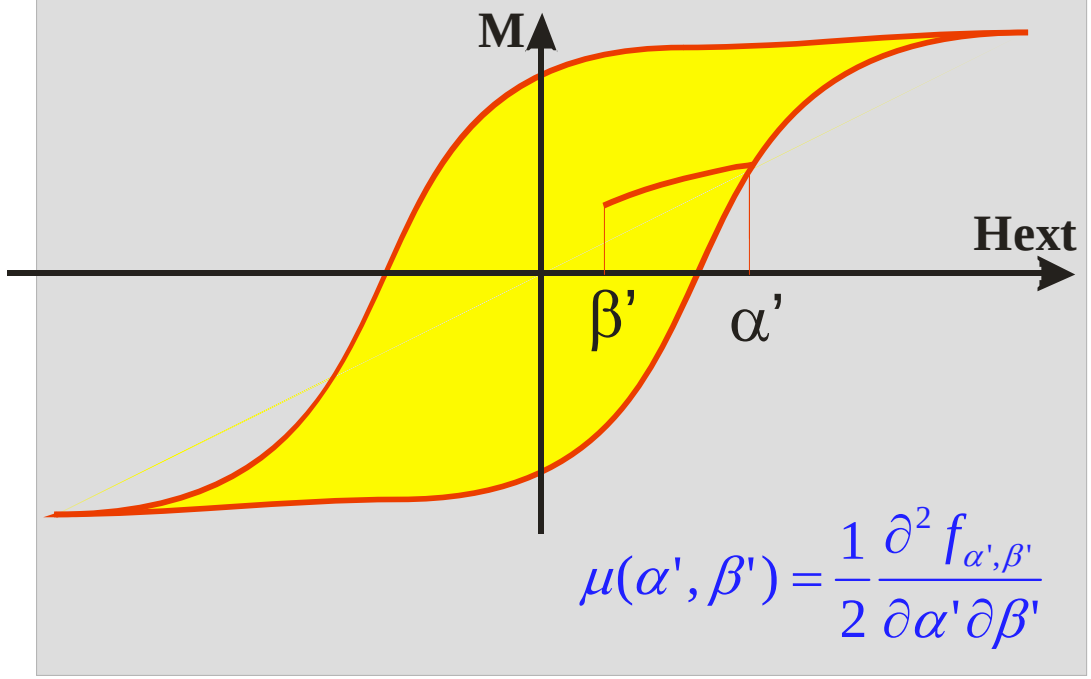


- Distribution function

$$\mu(\alpha,\beta) \text{ with } \alpha > \beta$$

- No true link between real particles and μ

Solving



$$\mu(\alpha',\beta') = \frac{1}{2}\frac{\partial^2 f_{\alpha',\beta'}}{\partial\alpha'\partial\beta'}$$

- Long experiments (1D set of hysteresis curves)
- Better suited to bulk materials with strong interactions

Henkel plots

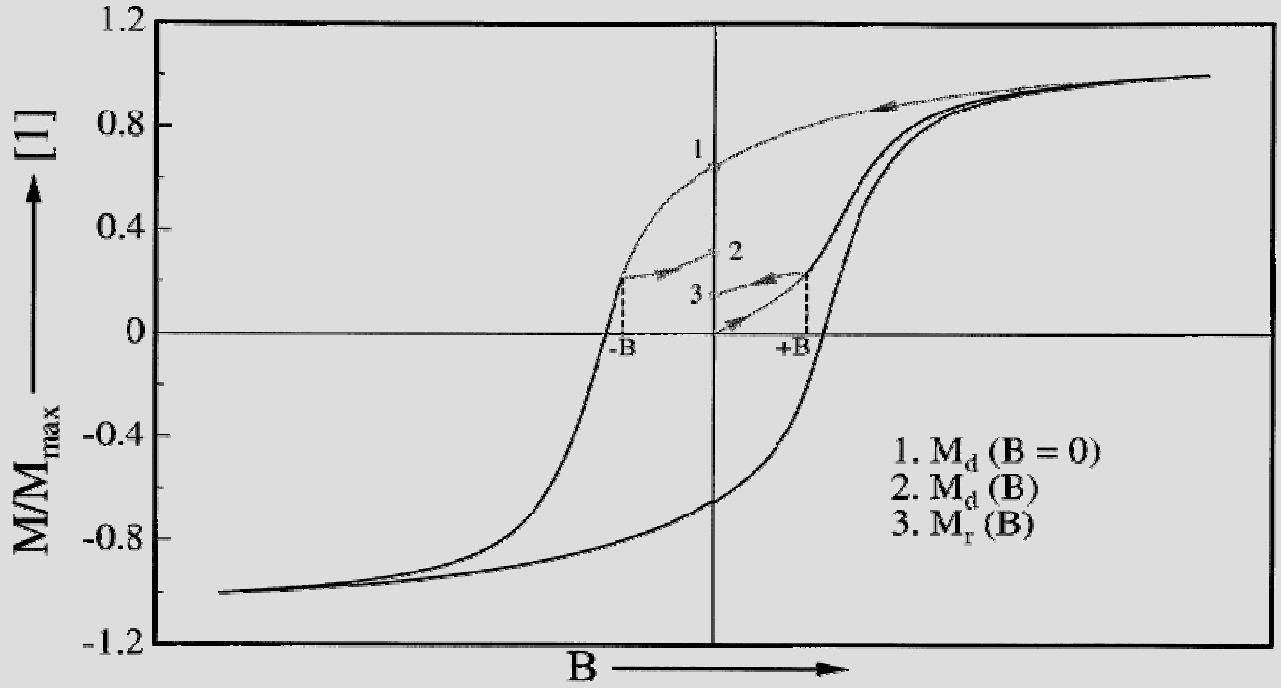


Fig. 1. Explanation of how to measure the two different remanent magnetisations M_r and M_d.

O. Henkel,
Phys. Stat. Sol. 7, 919 (1964)

S. Thamm et al.,
JMMM184, 245 (1998)

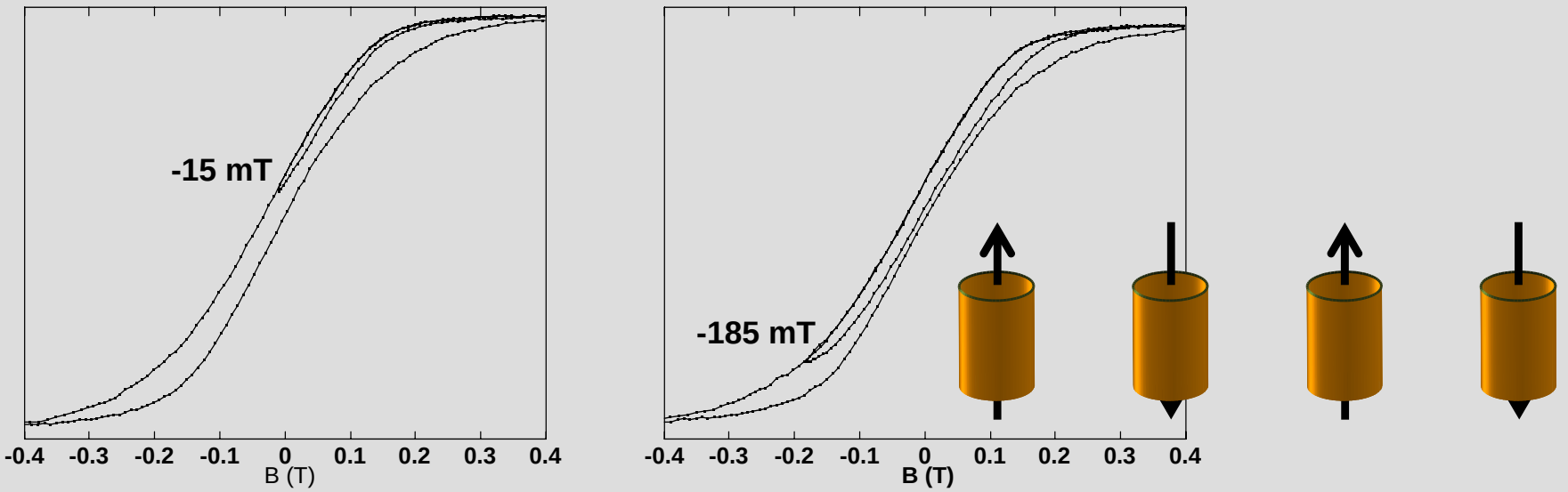
Measure of dipolar interactions

$$\Delta M_H(x) = M_d(x) - [1 - 2M_r(x)]$$

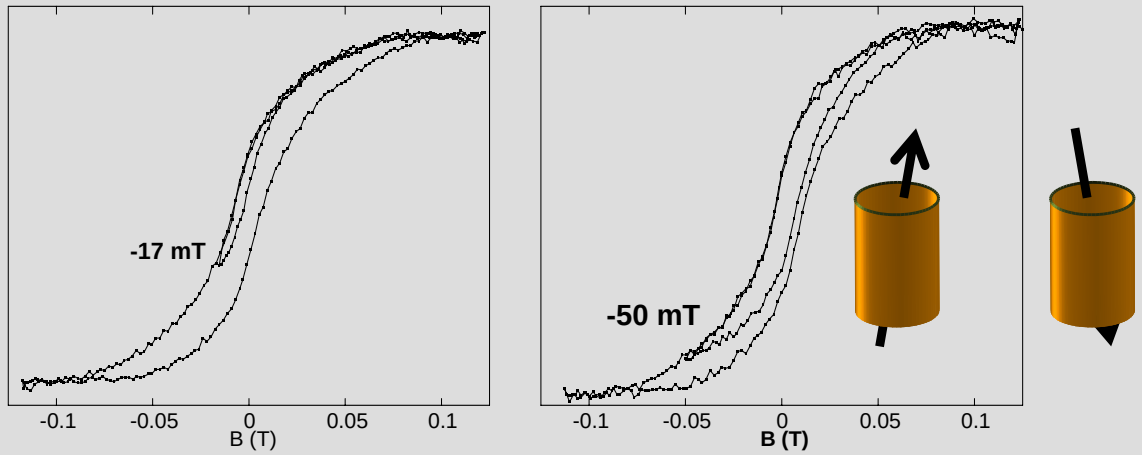
- Long experiments (ac demagnetization)
- Better physical meaning than Preisach

Minor loops: negative interactions

Example: dipolar interactions in arrays of Co/Au(111) pillars



Minor loops: negligible interactions



- Faster than Henkel
- Other applications: characterization of exchange bias

O. Fruchart et al., unpublished

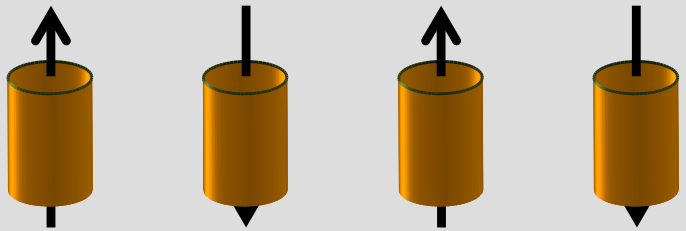
Superparamagnetic regime: plot of inverse susceptibility

- **Brillouin 1/2 function**

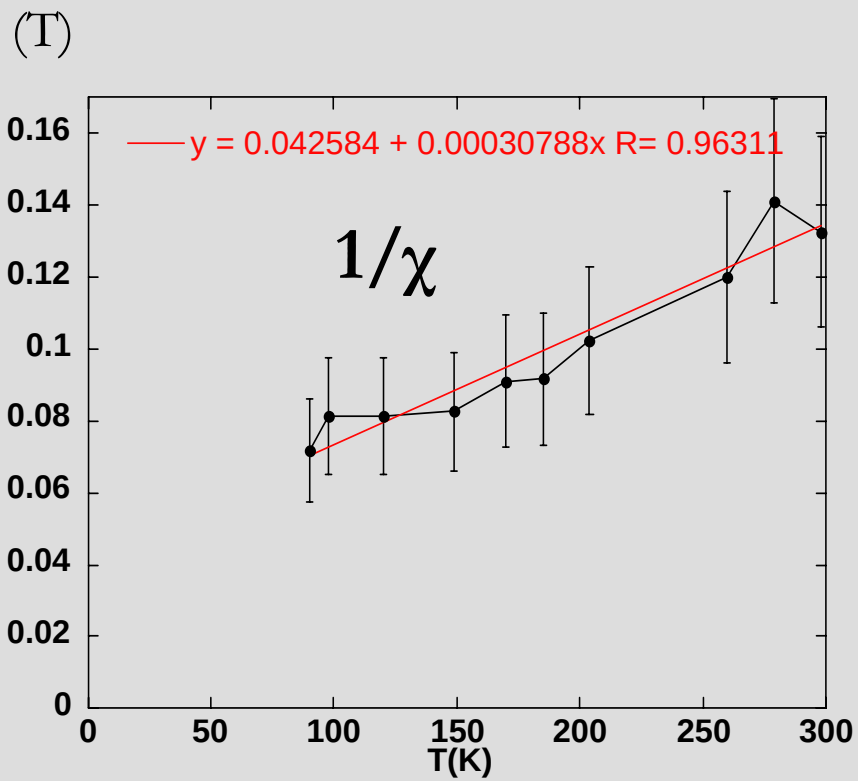
$$m = B_{1/2}(\mu_0 \mu_{Co} N H_{eff.} / kT)$$

- **Effective field**

$$H_{eff.} = H + r M_S m$$



(Demagnetizing dipolar interactions)



- **First order expansion**: susceptibility

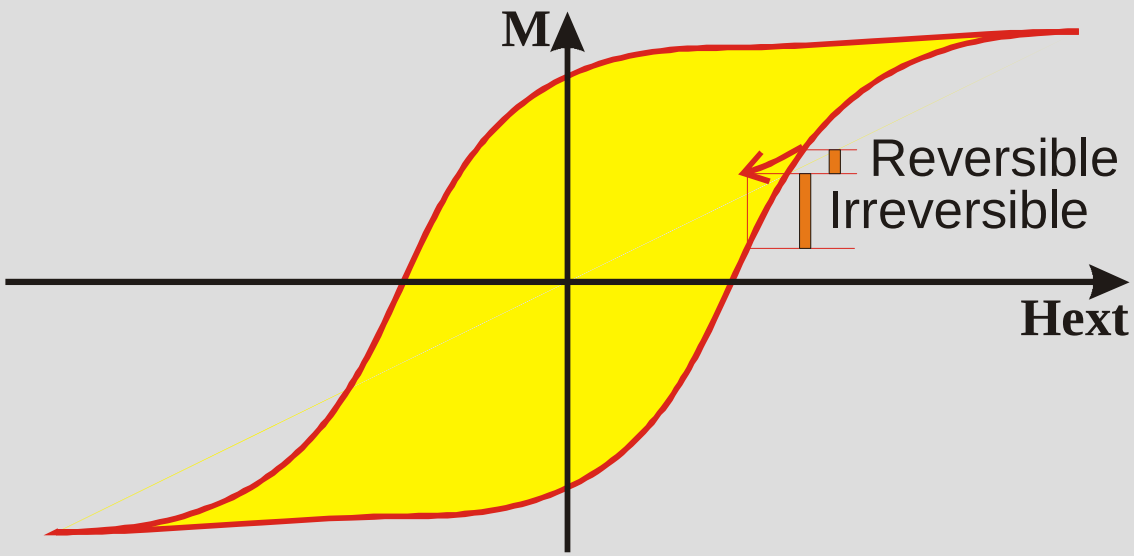
$$\frac{d(\mu_0 H)}{dm} = \frac{1}{\chi} = -\mu_0 M_S r + \frac{k}{\mu_{Co} N} T$$

$$a + b \cdot T$$

O. Fruchart *et al.*, PRL 23, 2769 (1999)

- No need of hysteresis
- Analogy with Curie-Weiss law

Distribution of properties

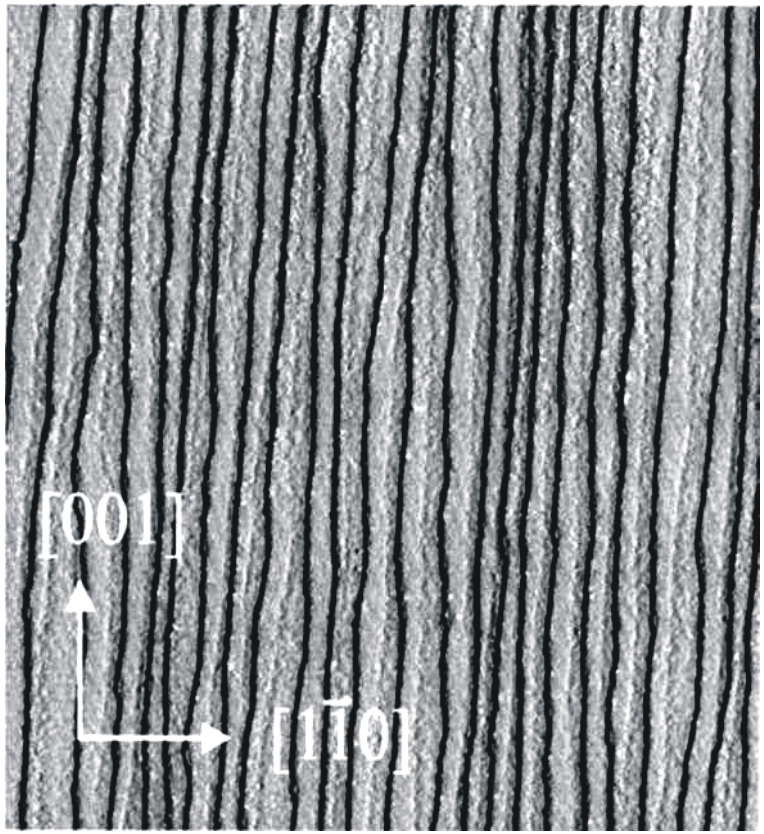


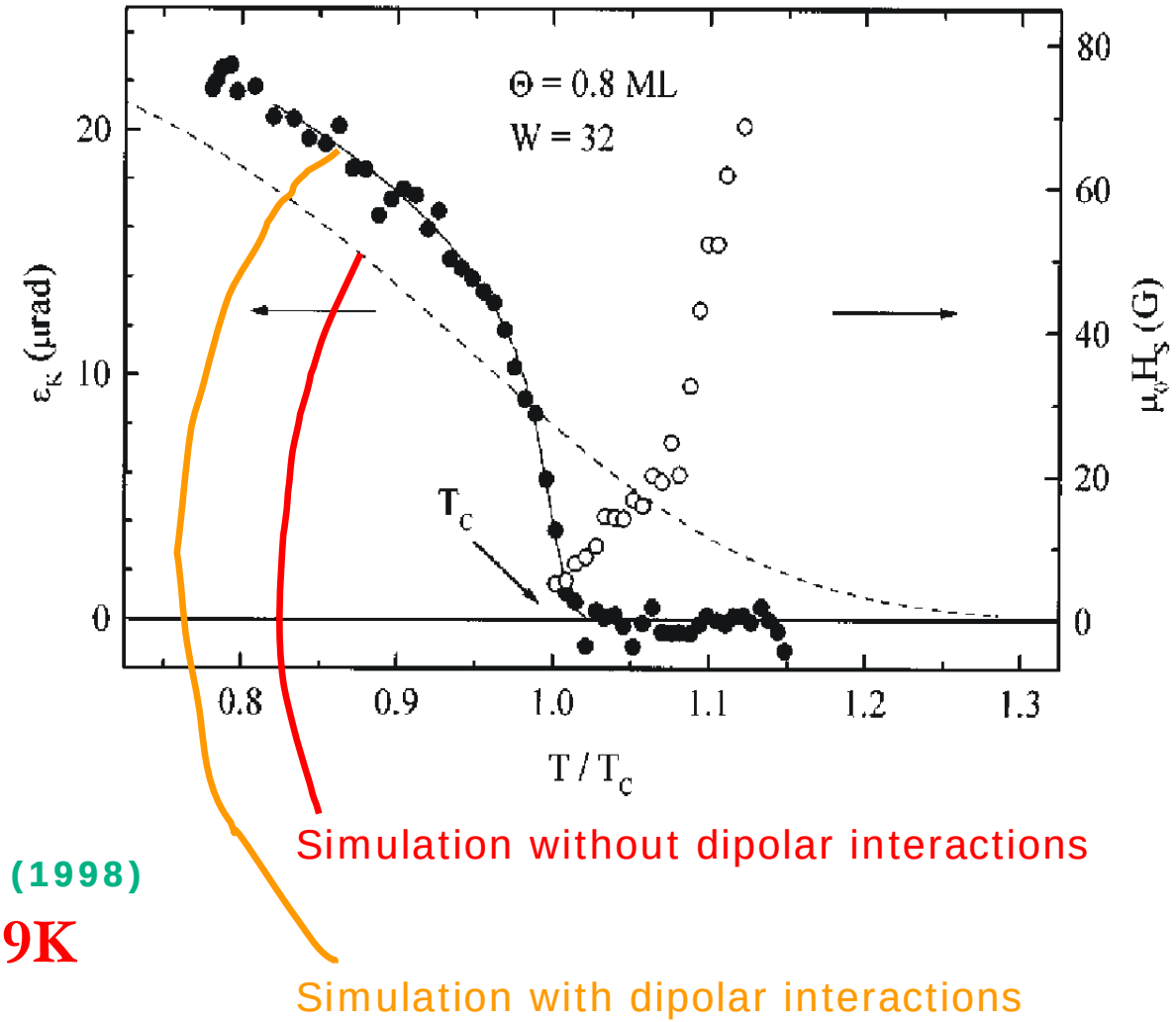
$$\rho(H_r) = \left.\frac{dm}{dH}\right|_{\text{irreversible}}$$

Hc(T) for a given population of the distribution can be studied at a given stage of the reversal (10 %, 20 % etc.)

Effect of distributions and dipolar interactions are sometimes difficult to disentangle

Ferromagnetic order stabilized by dipolar interactions





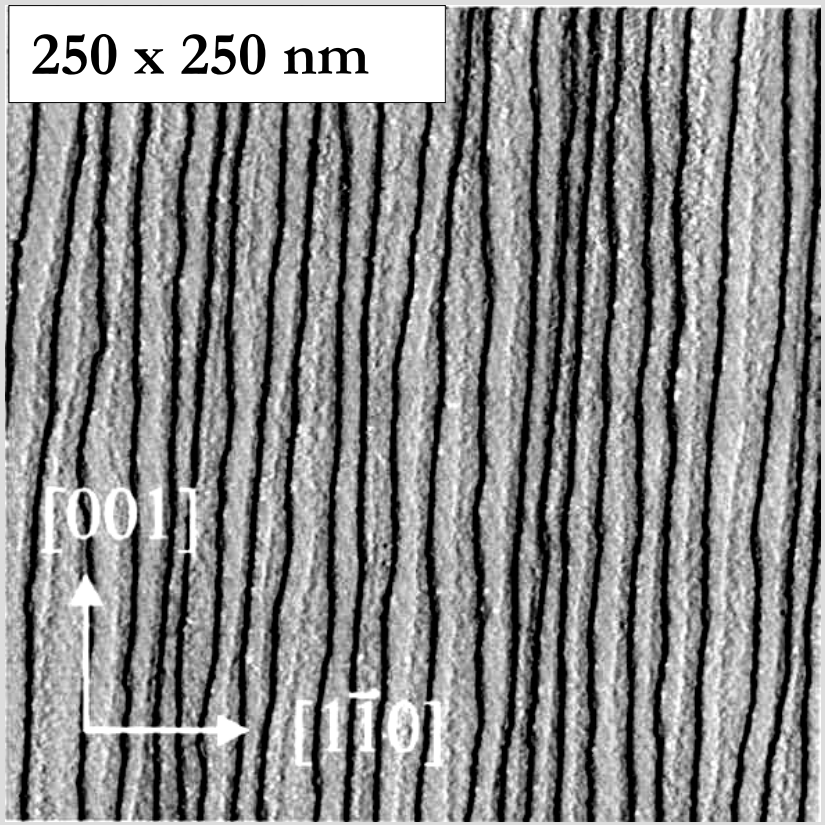
J. Hauschild *et al.*, Phys. Rev. B 57, R677 (1998)

Tc=179K

Although weak, dipolar interactions stabilize ferromagnetic order and sharpen the transition at Tc, owing to their long range

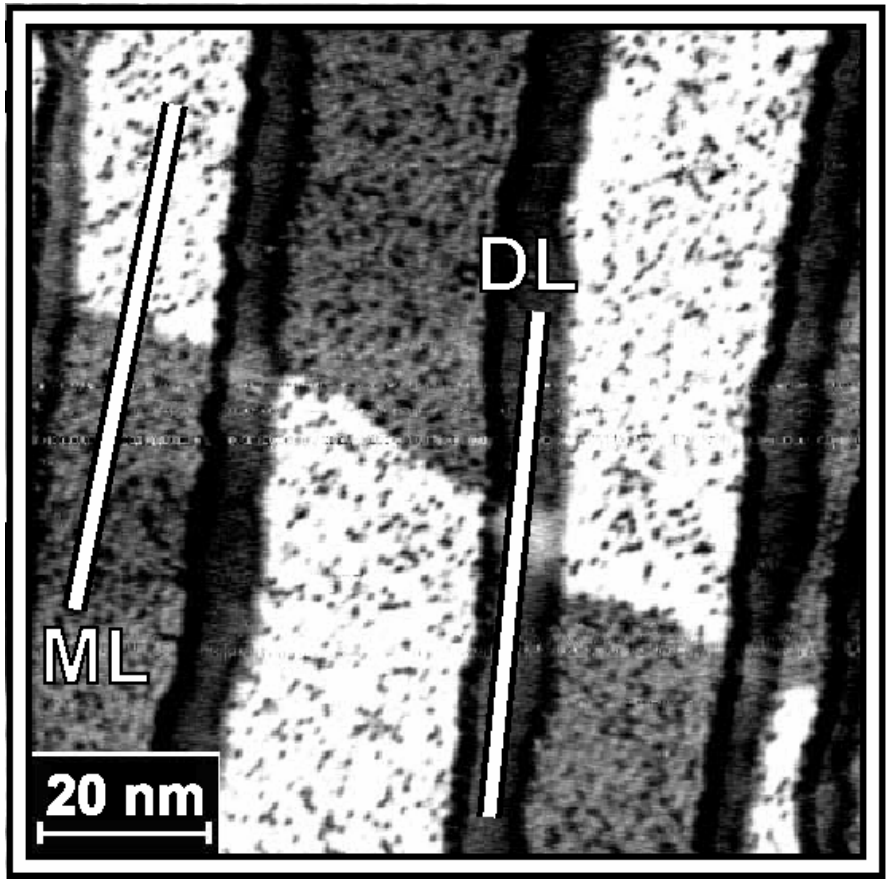
Magnetic order in 1D

Fe(0.5ML)/W(110)

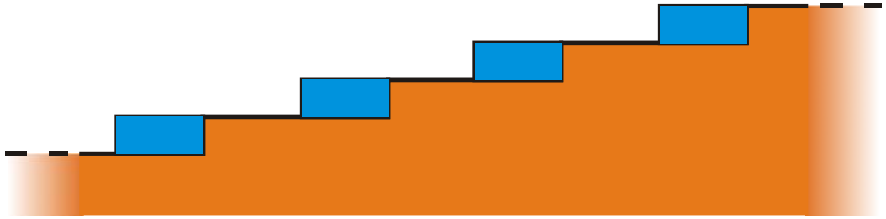


J.Hauschild *et al.*, Phys.Rev.B57, R677(1998)

Vicinal Fe(110)[1.2ML]/W(110)

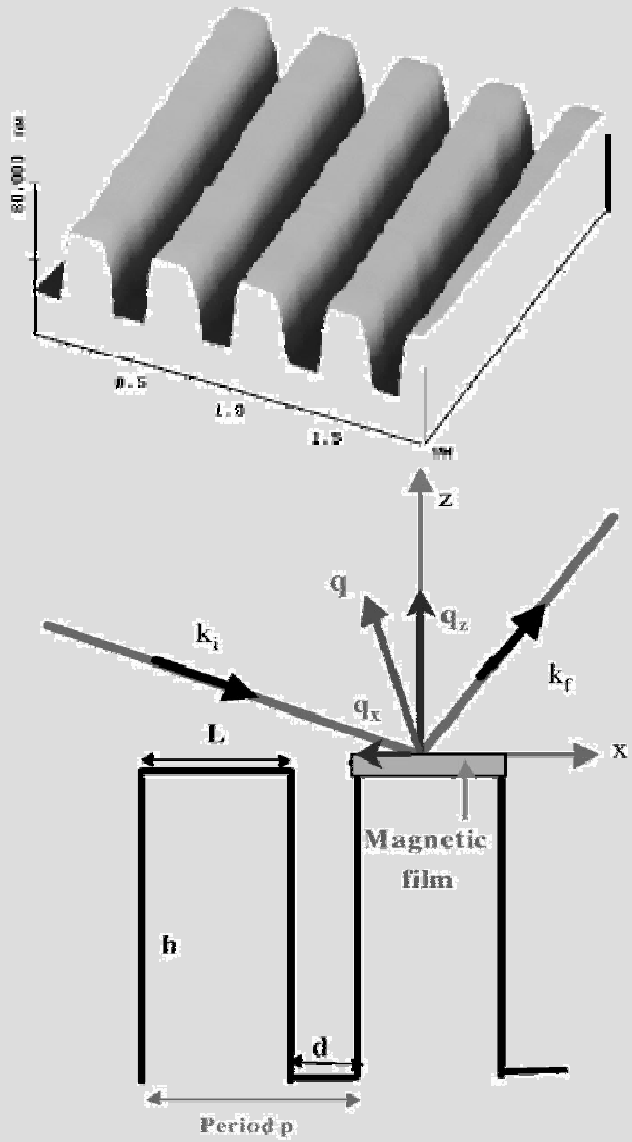


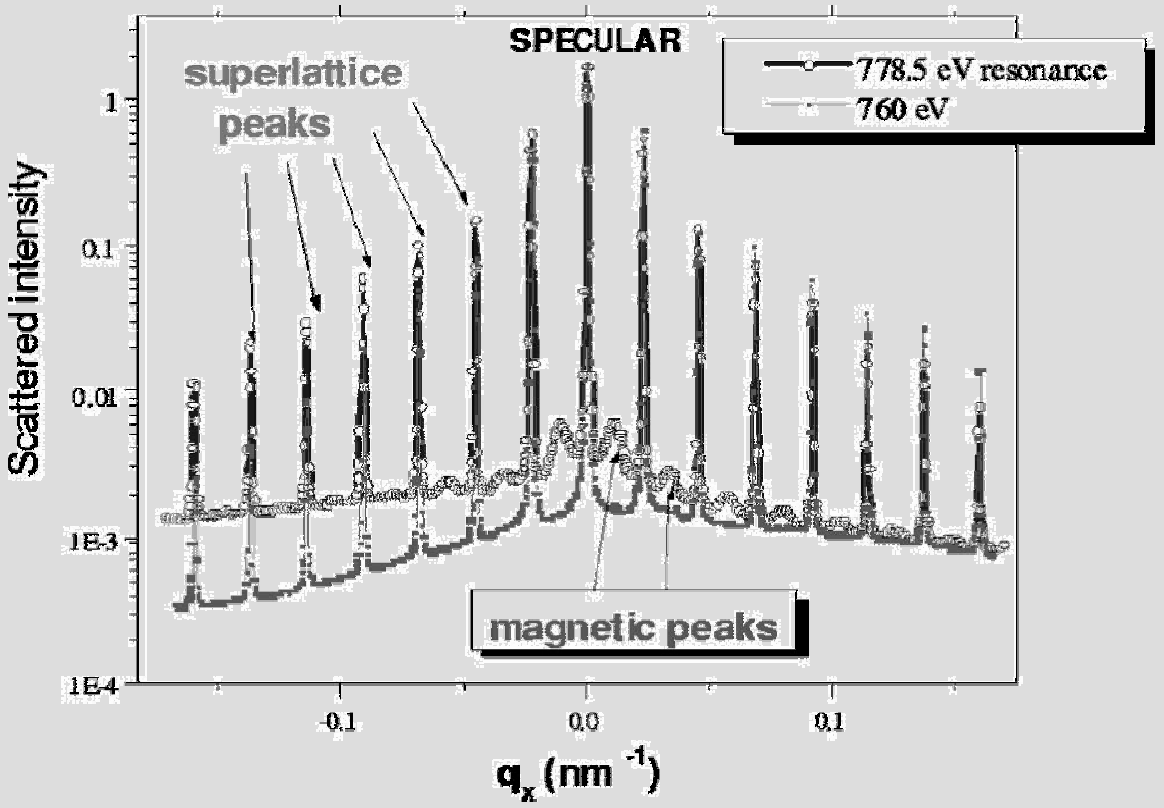
M. Pratzer *et al.*, PRL87, 127201 (2001)



Magnetic scattering on nanofabricated arrays of lines

Co/Pt(111) multilayers



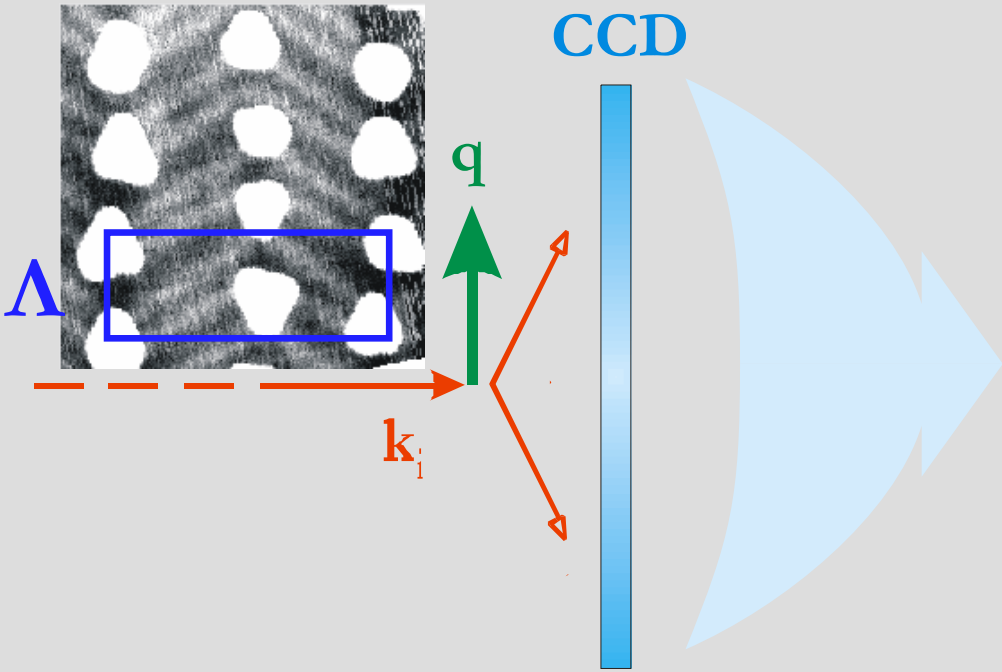


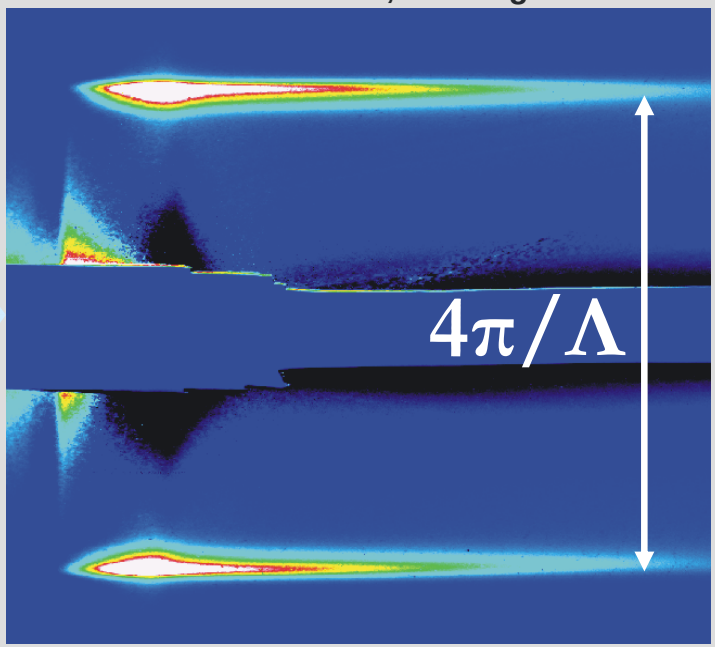
Informations about magnetic correlations can be extracted from magnetic satellites

K. Chesnel et al., PRB66, 024435 (2002)

Structural scattering on self-organized systems

Co/Au(111) nanodots





INTRA-ROW ORDER: SUPER-CRYSTAL

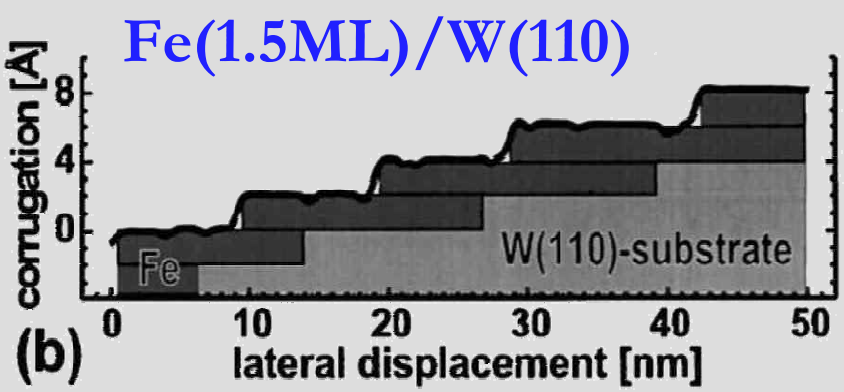
O. Fruchart et al., Europhys. Lett. 63, 275 (2003)

Evidencing magnetic scattering is in principle possible, however:

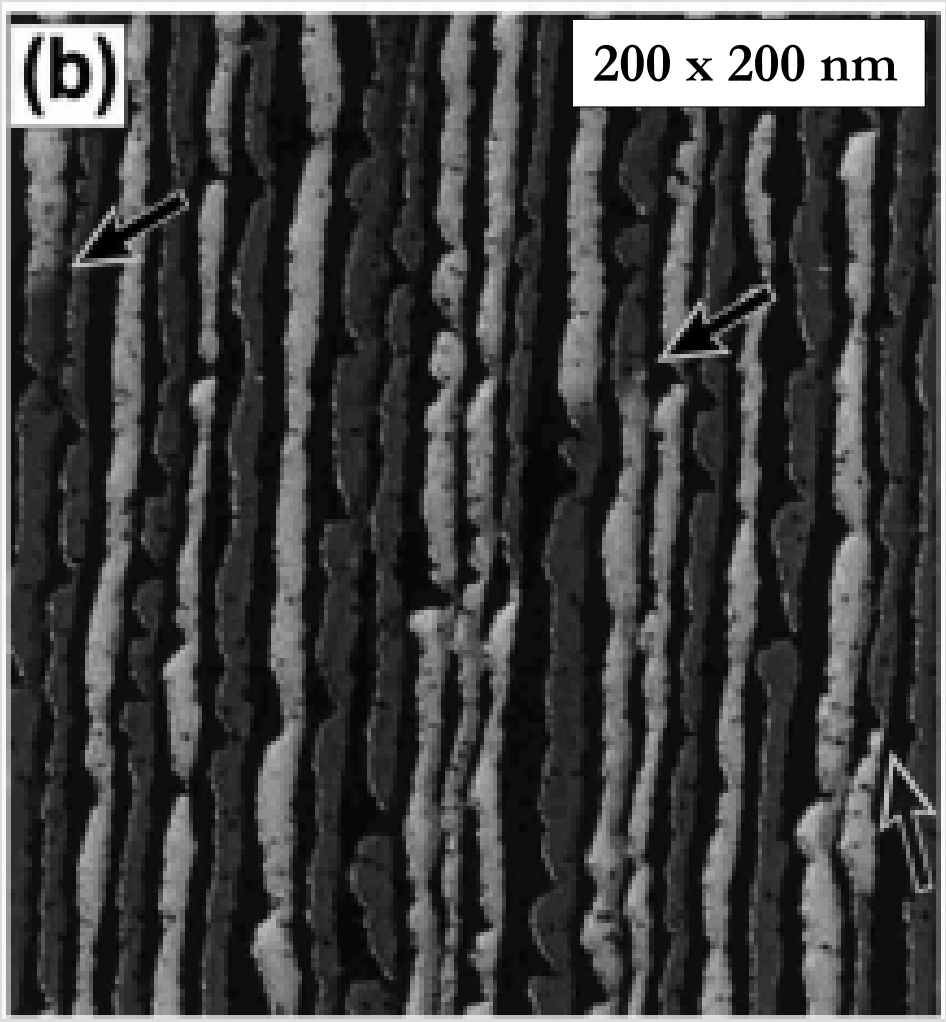
- Low temperature and weak signal
- Distribution of properties may prevent ordering to occur

Magnetic properties of self-organized systems : TOC

Domain walls in geometrical constriction



Spin-Polarized Scanning Tunneling Spectroscopy



M. Bode et al, J. Electr. Spectr. Rel. Phenom. 114– 116, 1055 (2001)
Theorical prediction: P. Bruno, Phys. Rev. Lett. 83, 2425 (1999)

Magnetic vortex core

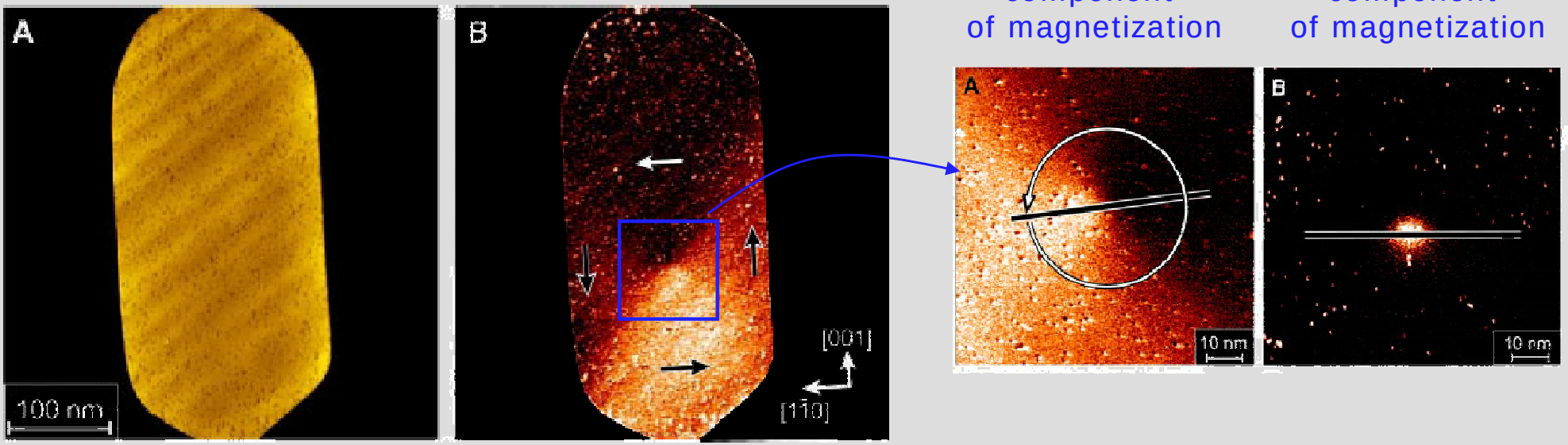
Spin-polarized Scanning Tunneling Microscopy on Fe/W(110) self-assembled dots

Structural image

Magnetic image

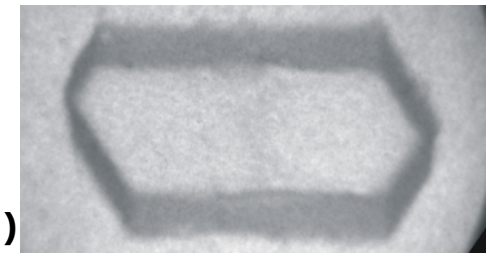
In-plane component of magnetization

Out-of-plane component of magnetization

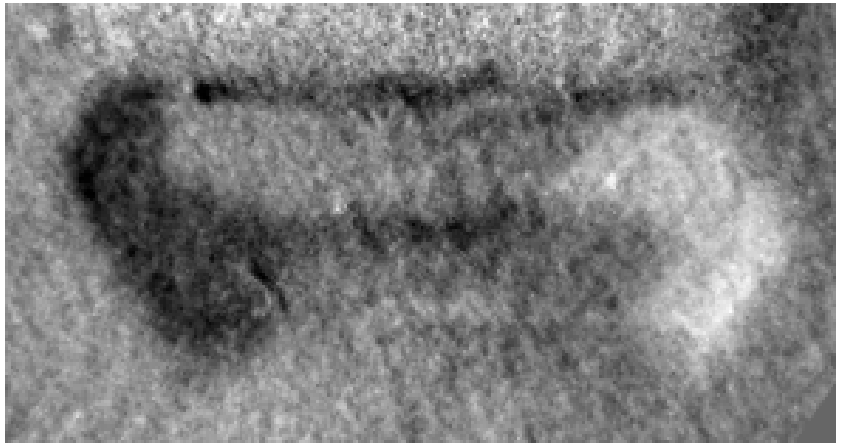


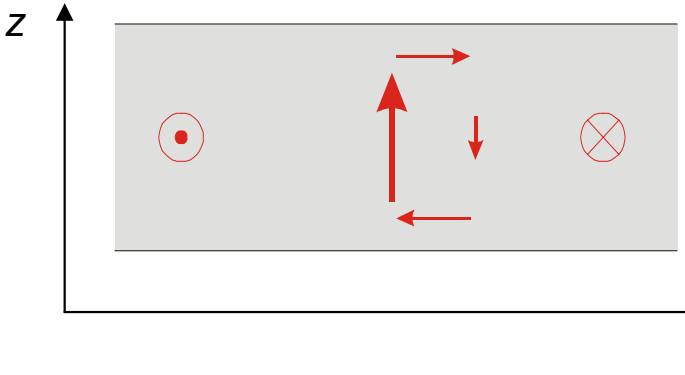
A. Wachowiak, Science 298, 577 (2002)

...also in-field study

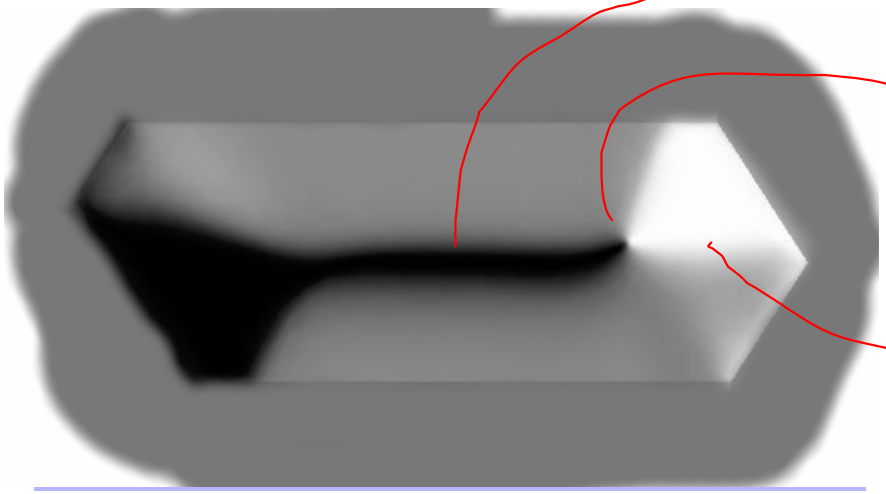


Experiment (top)





Simulation (top with facets)



Néel cap displaced from median line

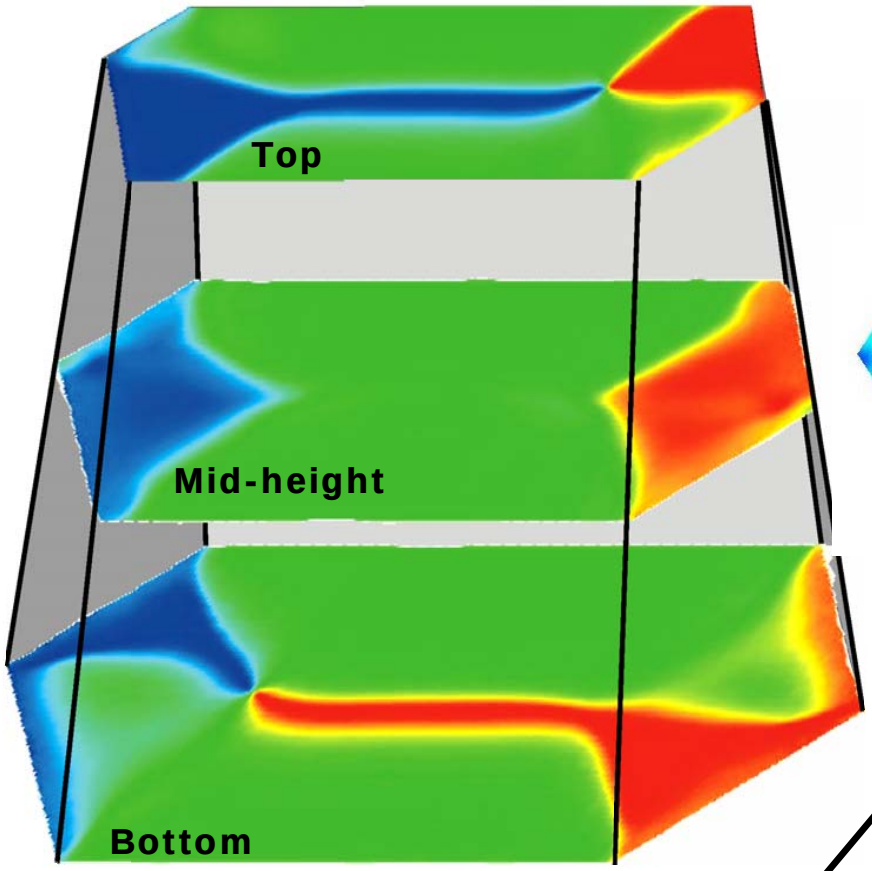
Asymmetry around vortex

Pseudo-2D

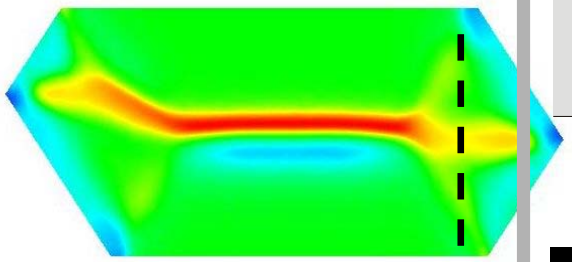
Strong asymmetry of end domains

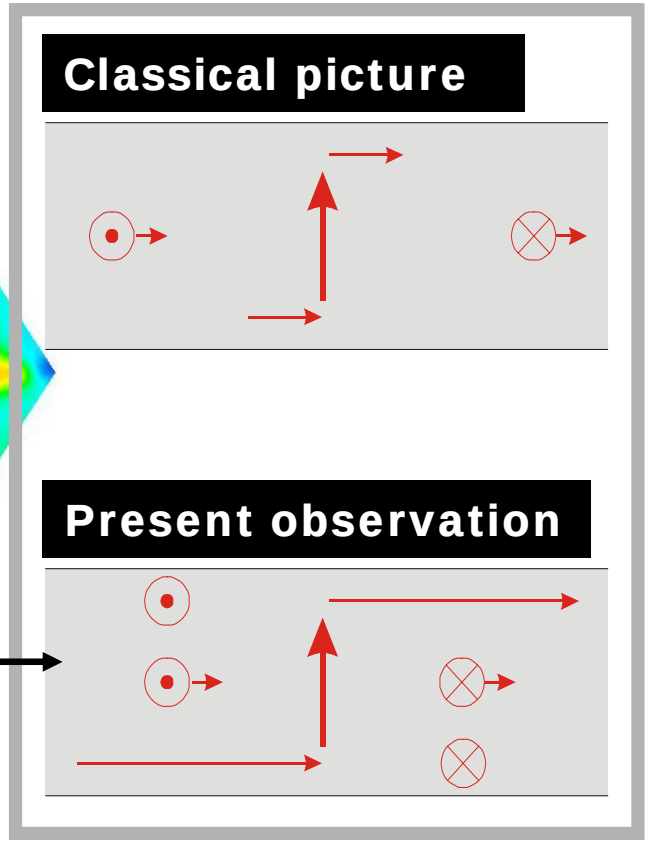
3D

The main features are reproduced

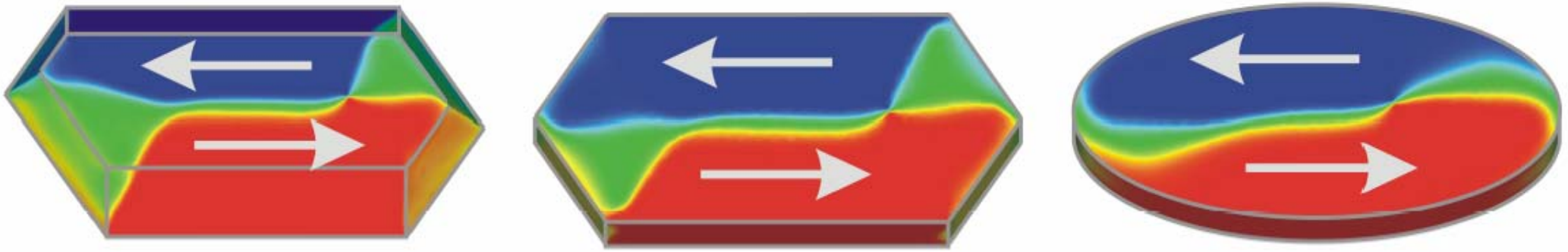


Perp. component
(mid-height view)





Magnetization component

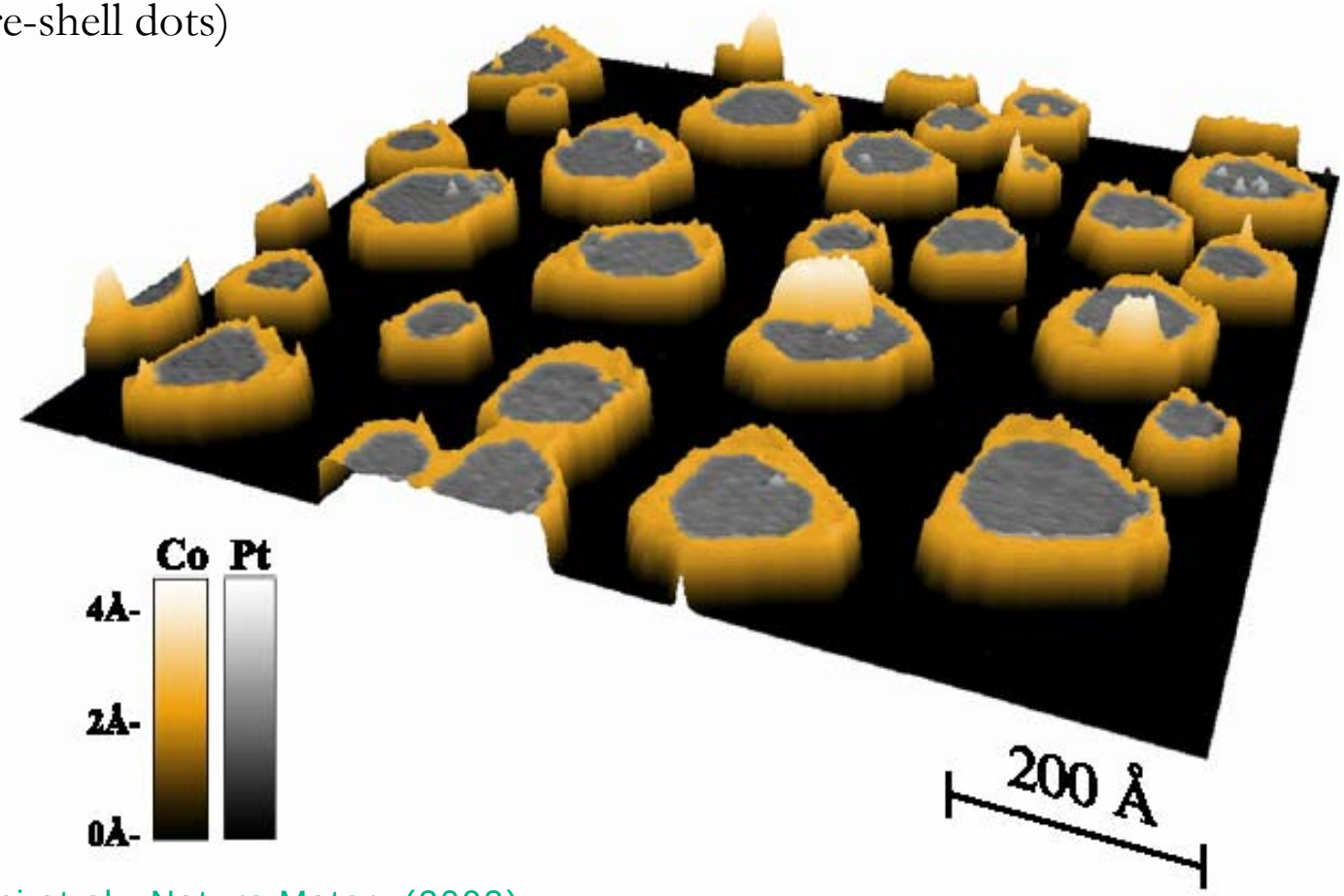


R. Hertel et al., cond-mat/0507119

Manipulation of edge anisotropy

Pt brims around Co/Pt(111)

(core-shell dots)

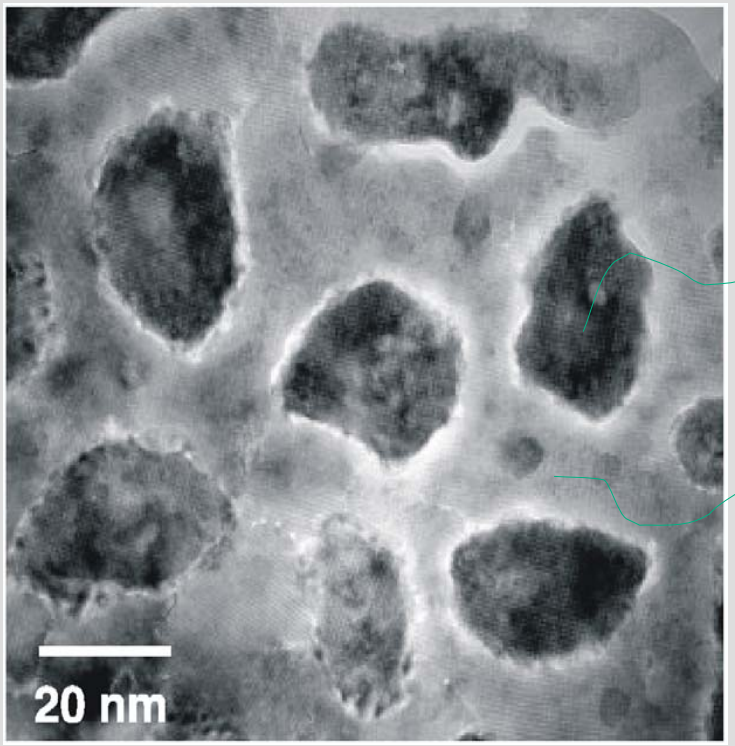


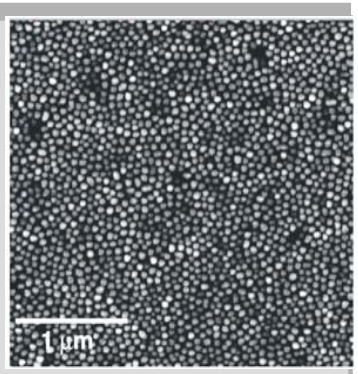
S. Rusponi et al., Nature Mater. (2003)

- **Self-organization : concepts**
- **Self-assembly : towards materials?**

Structure

$CoFe_2O_4$ in $BaTiO_3$ matrix





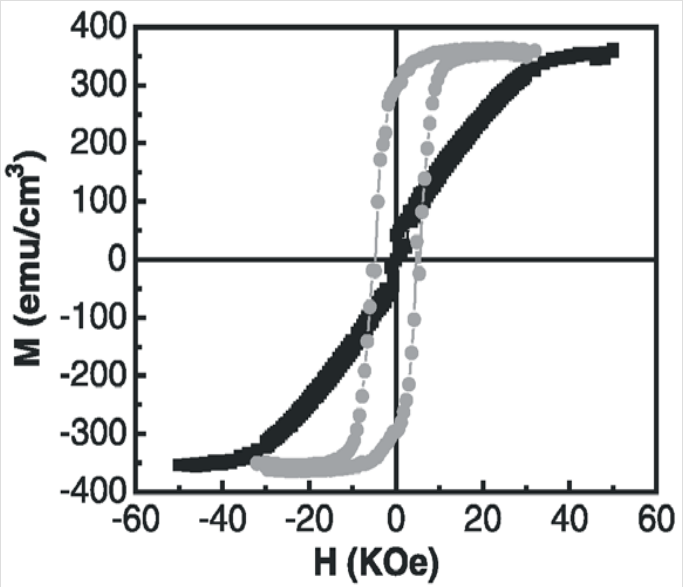
$CoFe_2O_4$ **(ferrimagnetic)**

$BaTiO_3$ **(piezzoelectric)**

Deposition from a Ti-Ba-Co-Fe oxide target by pulsed laser deposition

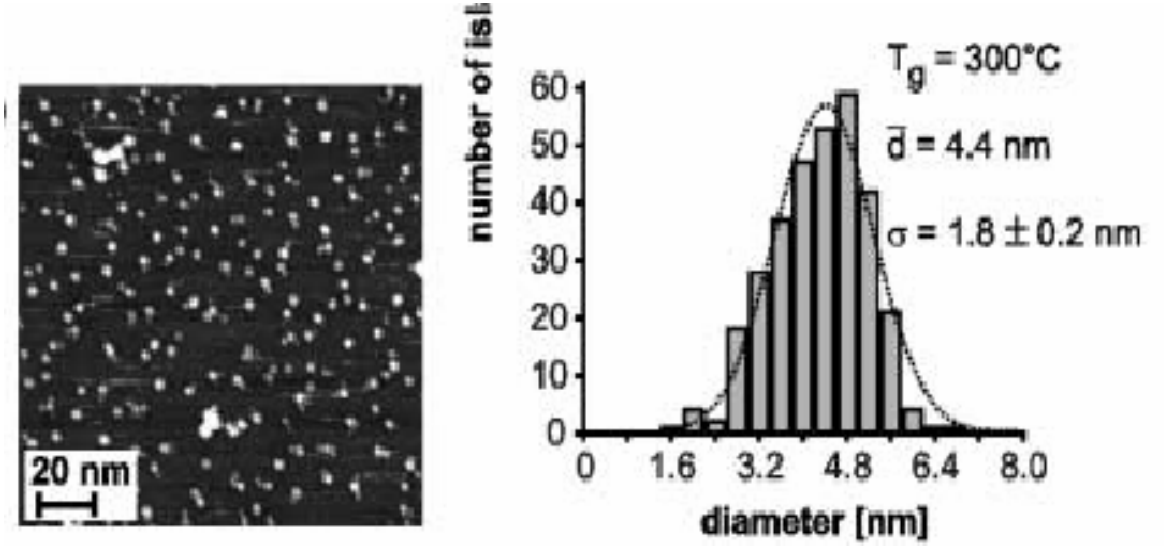
H. Zheng et al., Science 303, 661 (2004)

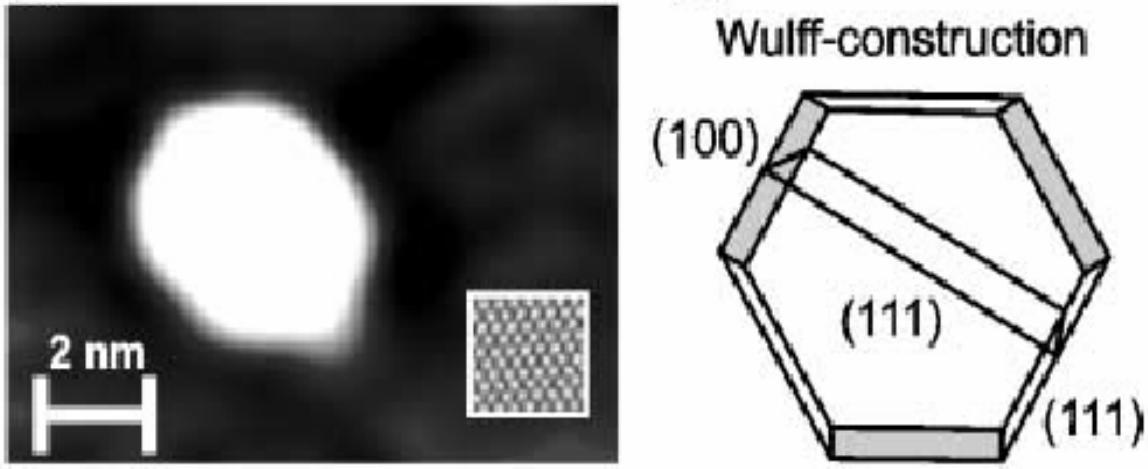
Magnetis m



- Rooom-temperature functionality
- Perpendicular anisotropy owing to matrix-induced strain in the columns

$CoPt_3$(0.8ML)/WSe_2



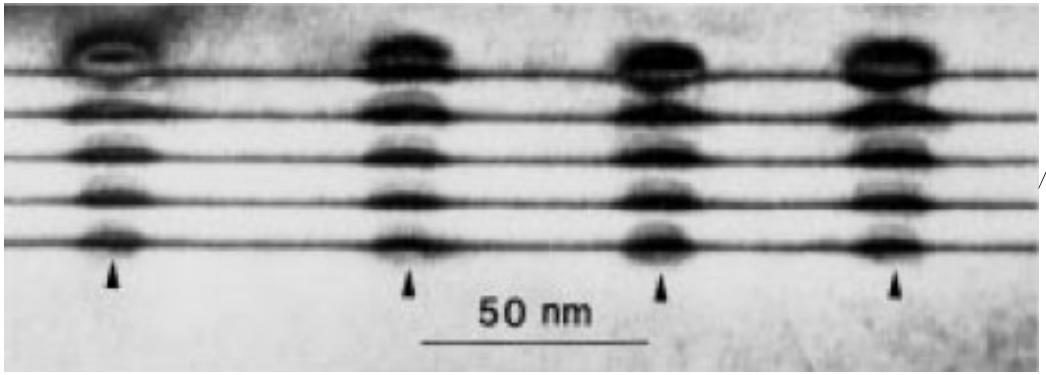


Chemical ordering ($L1_2$ phase) occurs from 150°C, against 500°C for continuous films

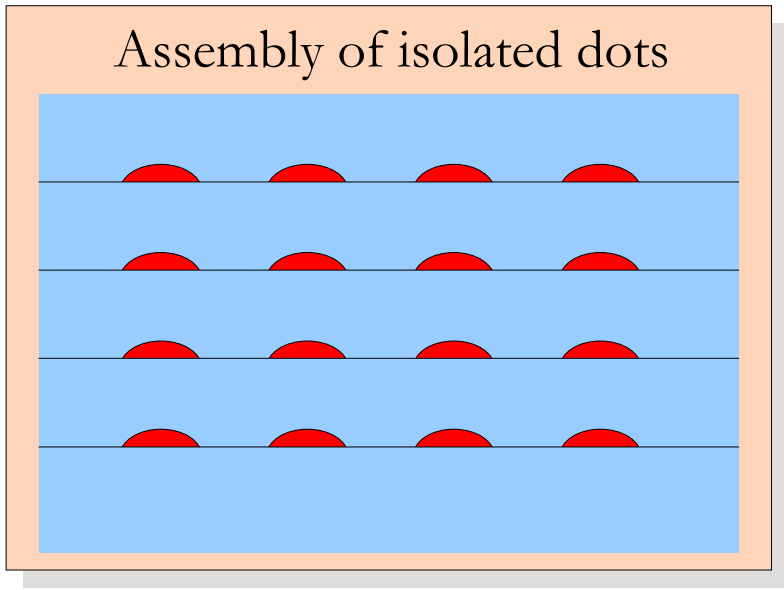
(search for high-anisotropy $L1_0$ phases)

M. Albrecht et al., Europhys. Lett. 56, 884 (2001)

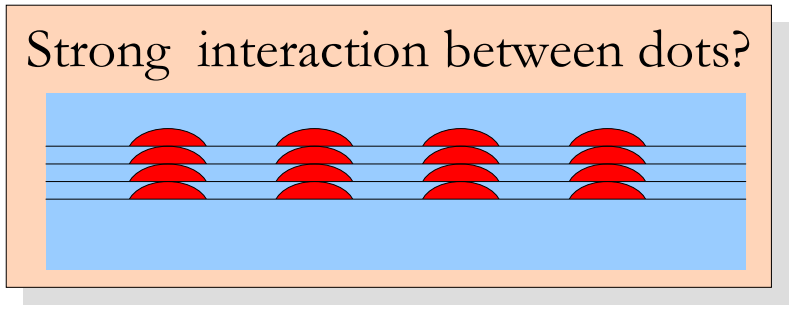
- Vertical 3D self-organization of $In_xGa_{1-x}As/GaAs$:



Q.Xie et al., Phys.Rev.Lett.75(13), 2542 (1995)



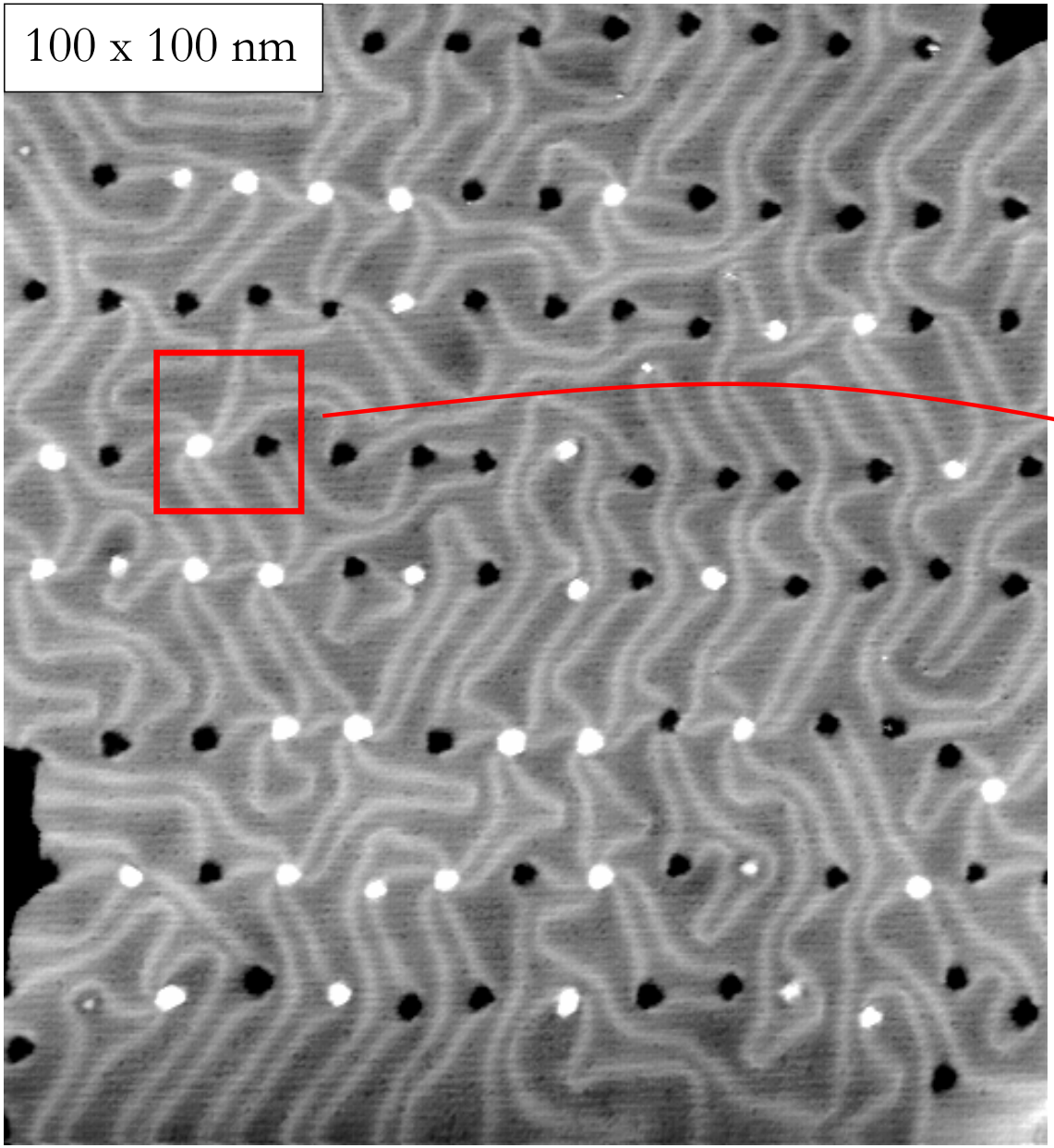
Thining the spacer layer

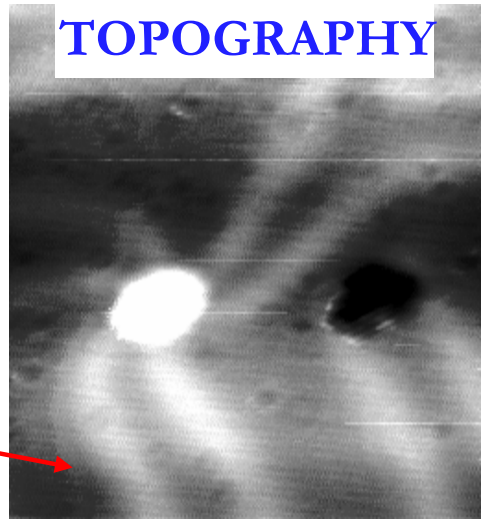


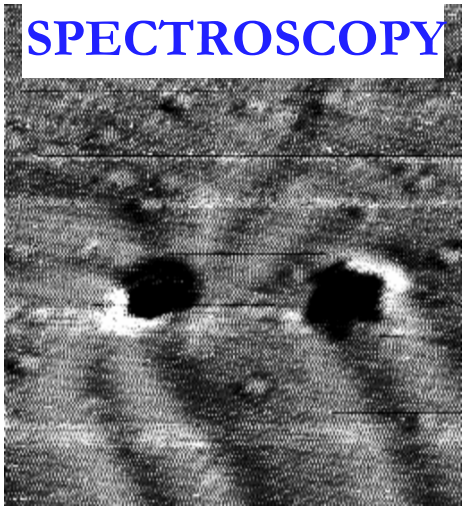
↪ superparamagnetism overcome ?

↪ Enhanced magnetic signal

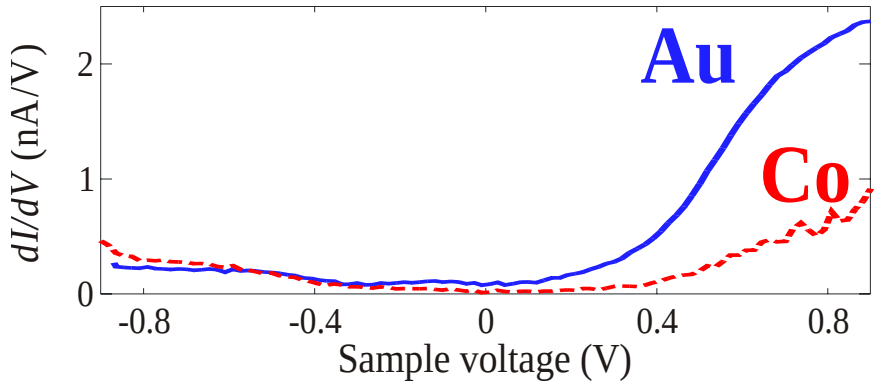
Co/Au(111) pillars





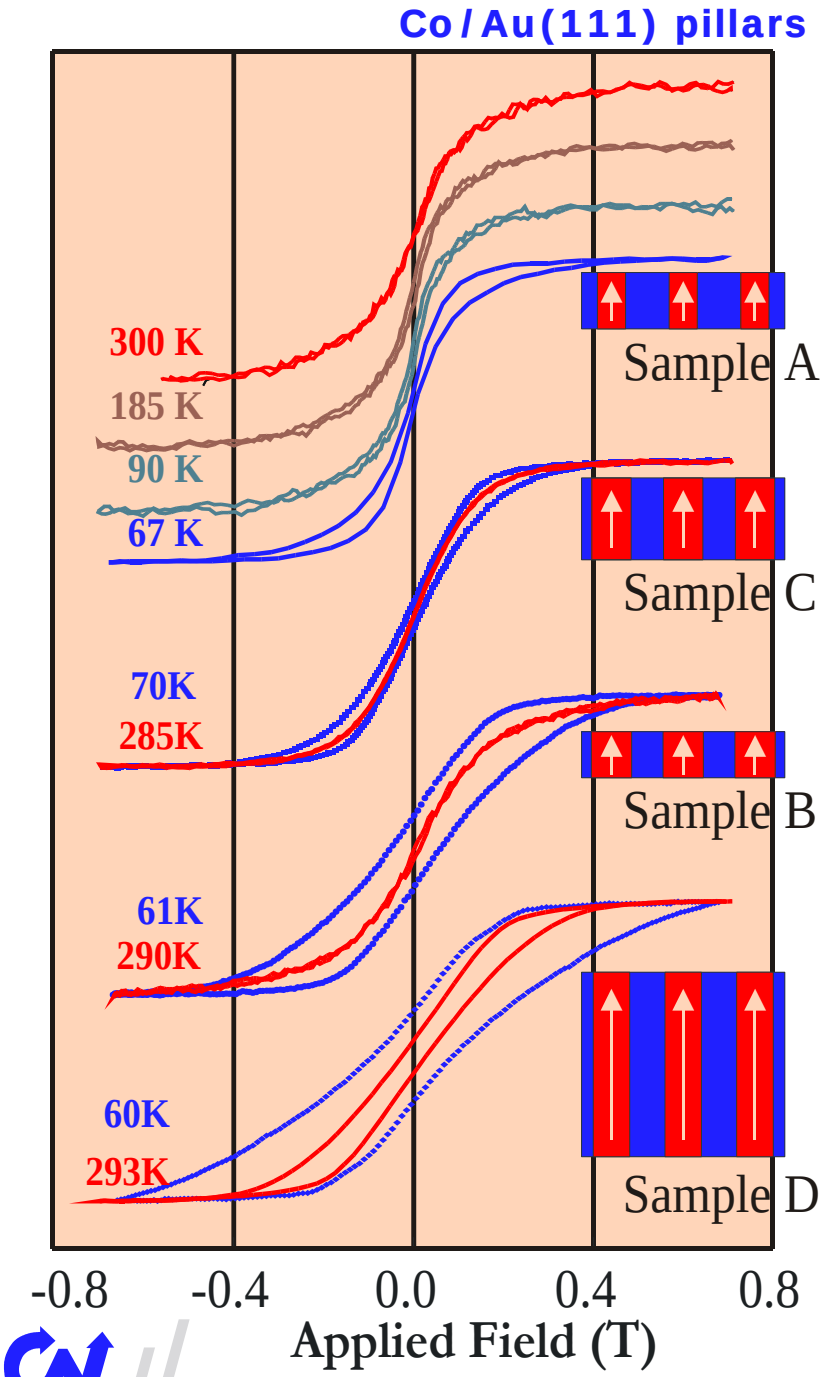


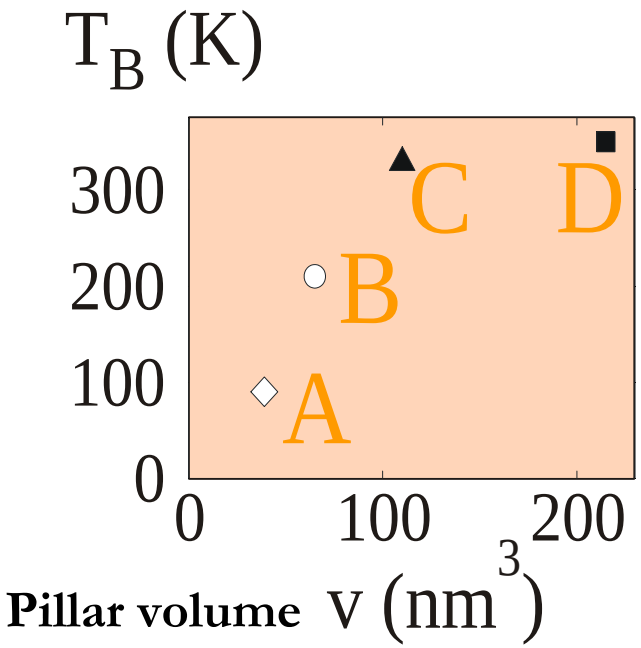
SAME AREA



Co atoms grow only on existing dots

➥ **VERTICAL SELF-ORGANIZATION**

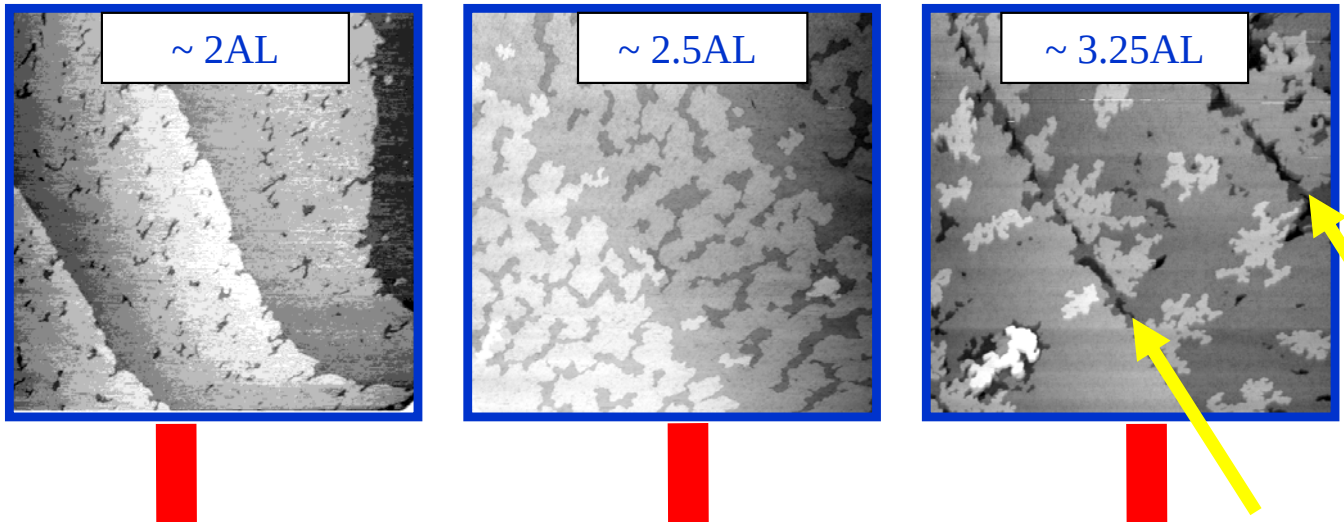




- **Blocking temperature > 300K**
  (~ 30K for flat Co/Au dots)

Step 1: layer-by-layer growth at 150°C

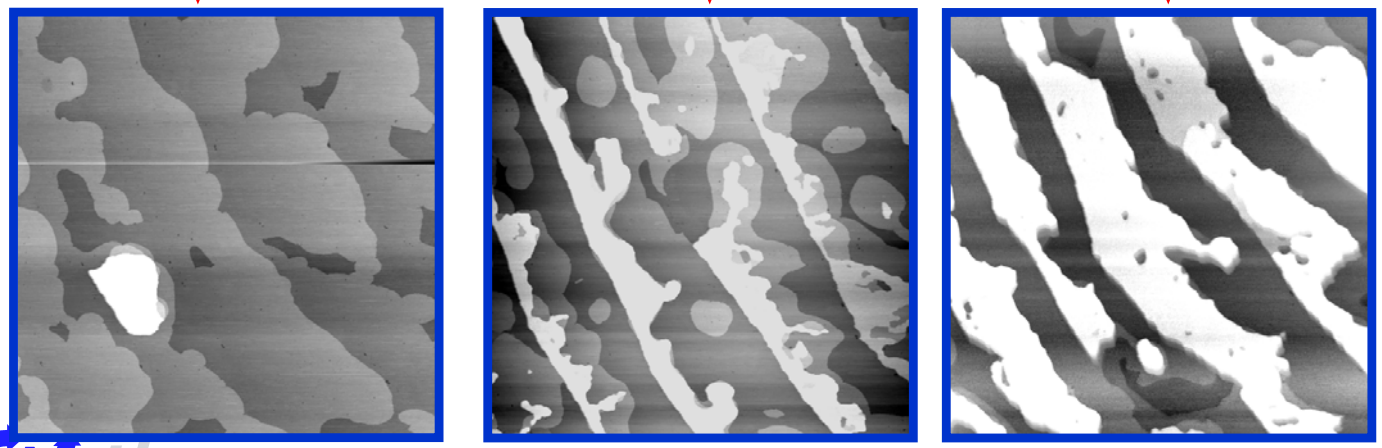
Fe / Mo(110) stripes



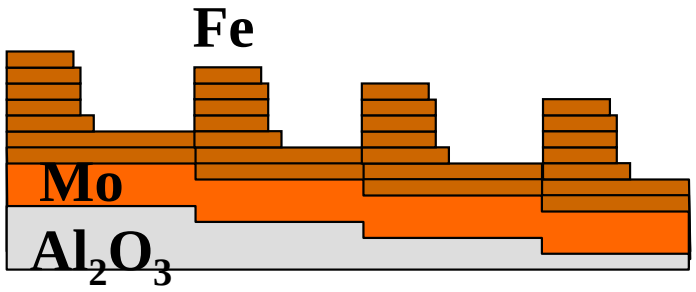
Fe films grown at 150°C

STM, 600nm x 600nm

Step 2: annealing at 500°C --> stripes along steps



STM, 750nm x 750nm

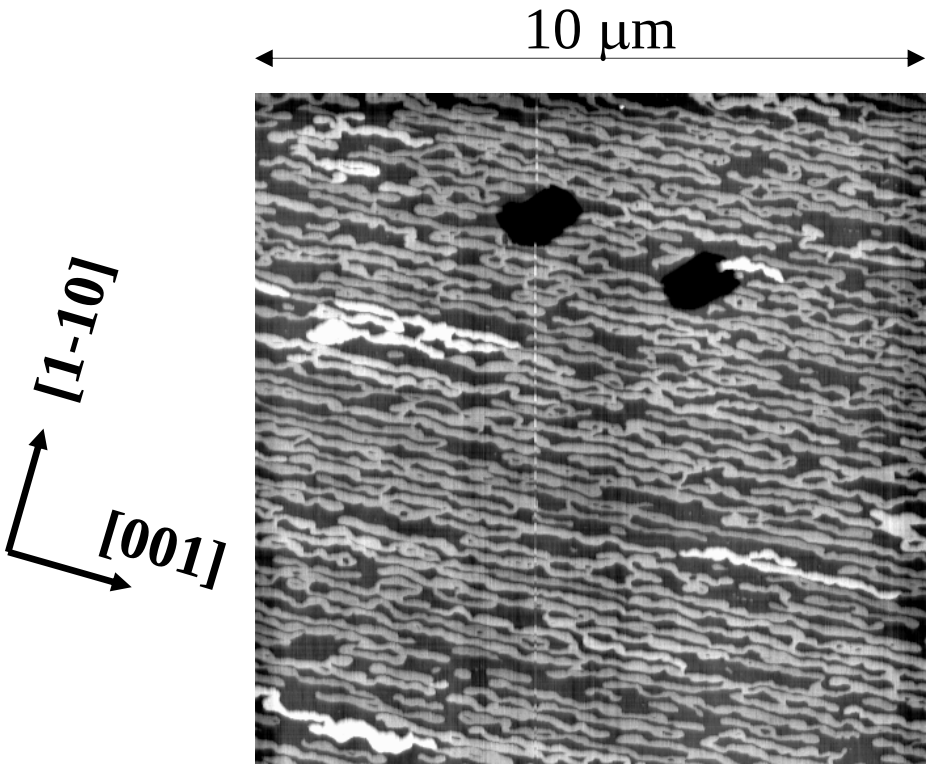


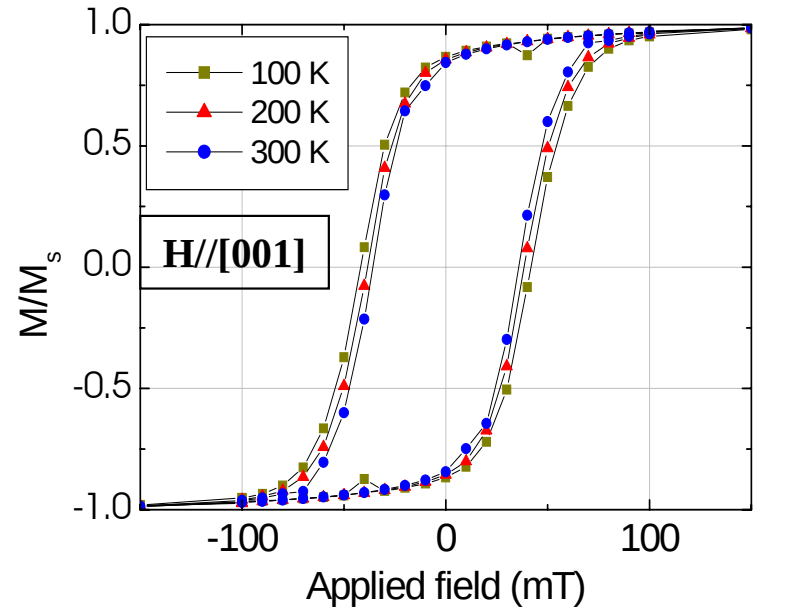
Coercivity and remanence at 300K

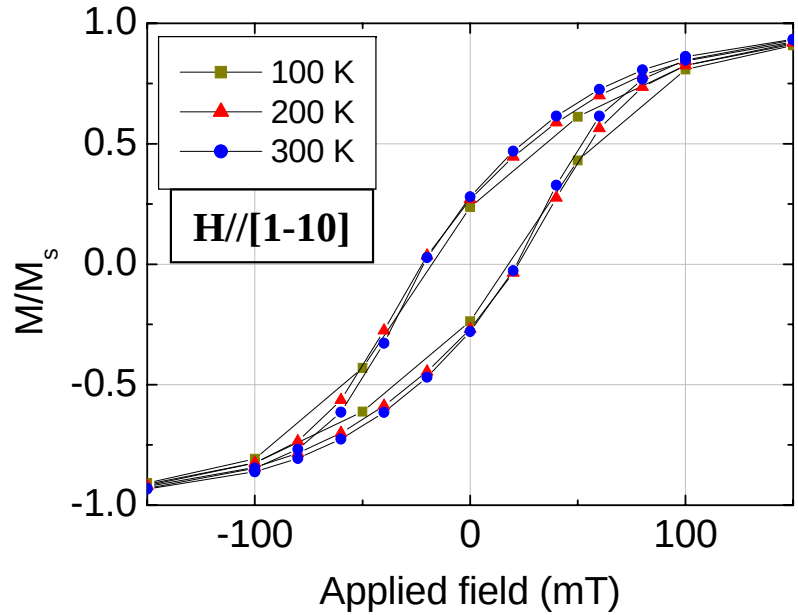
Fe / W(110) stripes

Sapphire \ W \ Fe(3nm) \ Mo

Stripe height = 5.5nm







- Coercivity and high remanence at 300K
- Weak temperature dependence
  > behaves like a conventional material

O. Fruchart *et al.*, APL 84, 1335 (2004)

SOME LITERATURE

[1] O. Fruchart, *Epitaxial self-organization: from surfaces to magnetic materials*, C. R. Physique **6** (1), 61-73 (2005).

[2] J.P. Bucher, *Magnetism of free and supported metal clusters*, in: S.N. Khanna, A.W. Castleman Jr. (Eds.), Quantum Phenomena in Clusters and Nanostructures, in: Springer Series in Cluster Physics, Springer, Berlin, pp. 83–137 (2003).

[3] J.P. Bucher, F. Scheurer, *Self-organized clusters and nanosize islands on metal surfaces*, in: J.S. Miller, M. Drillon (Eds.), Magnetism: Molecules to Materials III, Wiley–VCH, Weinheim, Germany, pp. 211–251 (2002).

[4] J.I. Martin et coll., *Ordered magnetic nanostructures: fabrication and properties*, J. Magn. Magn. Mater. **256**, 449-501 (2003).

[5] R. Skomski, *Nanomagnetics*, J. Phys.: Cond. Mat. **15,** R841–896 (2003).

[6] J. Bansmann et al., *Magnetic and structural properties of isolated and assembled clusters*, Surf. Sci. Rep. 56, 189 (2005)