Open questions in magnetism

- Fundamental questions
    - 3d and 4fmagnetism
    - Strongly correlated electron systems
    - Dilute magnetic semiconductors
    - New types of ordered magnetism ?
    - Frustration
- Nanomagnetism
- Spintronics and fast reversal
- Materials
- Magnetic materials and their applications

Exchange interactions

Electrostatic repulsion between electrons

+

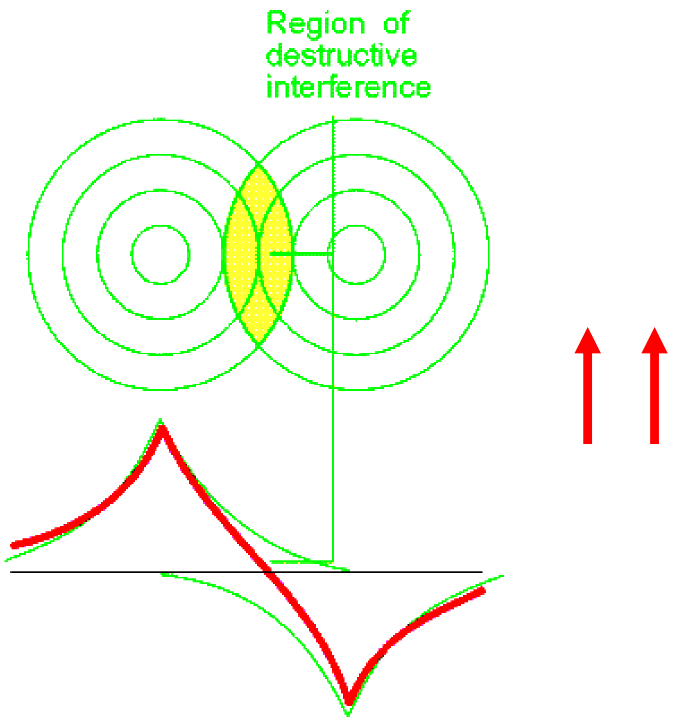
Pauli principle

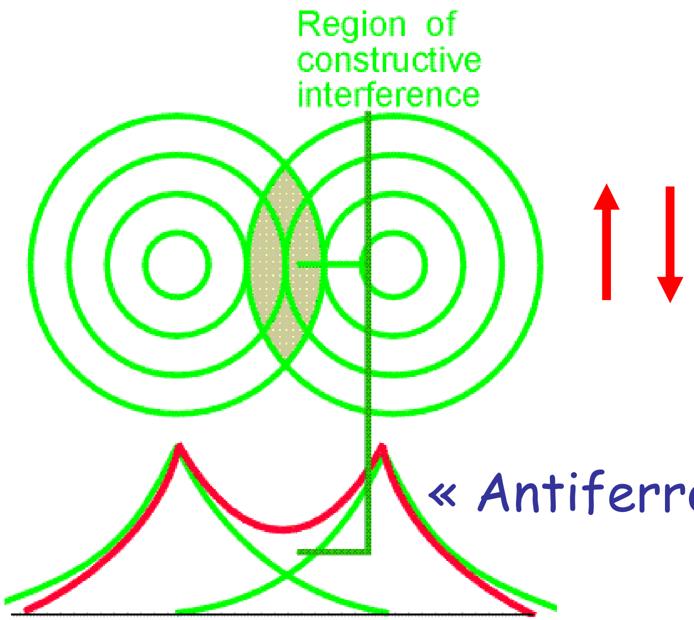
(2 electrons cannot be in the same quantum state

Many-electron wavefunctions are antisymmetric
with respect to the exchange of 2 electrons)

Two examples

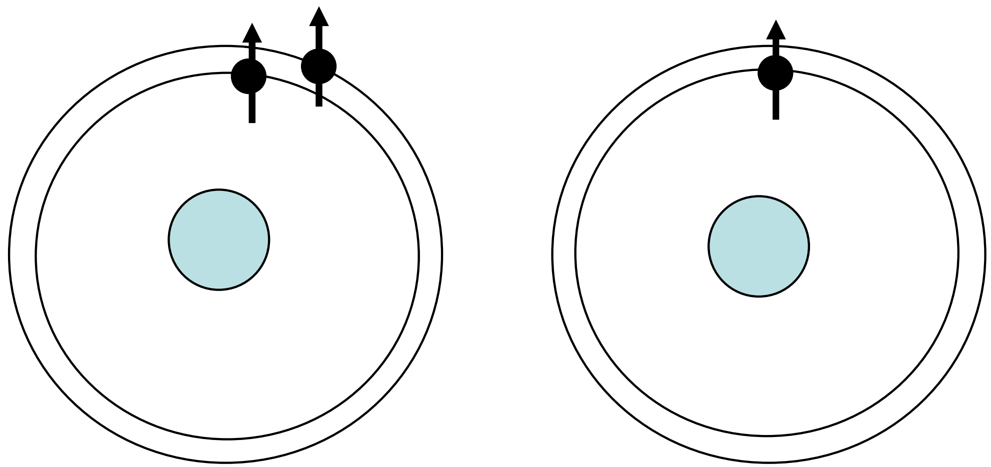
Hydrogen atom





« Antiferromagnetism »

Transition metals

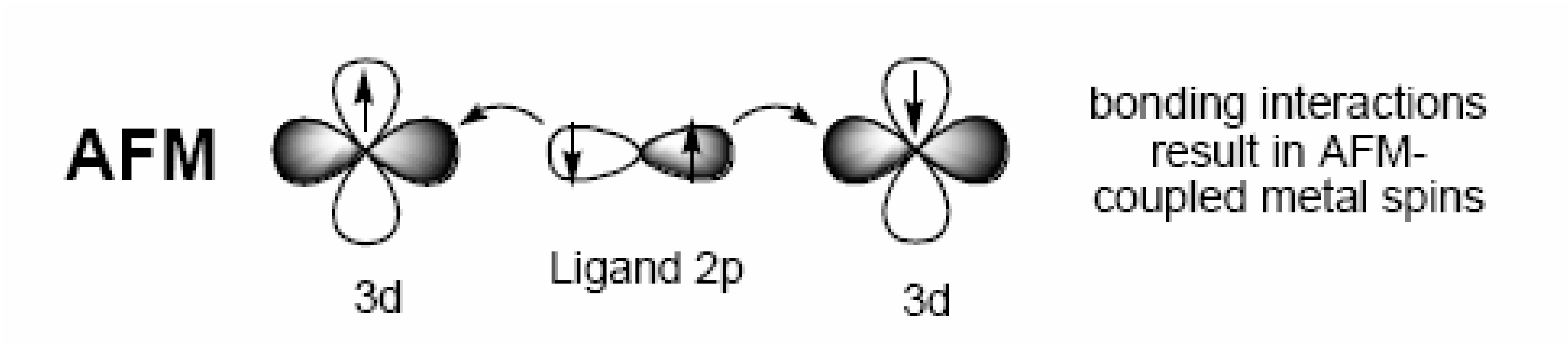


Itinerant nature of 3d electrons
+ on-site electrostatic interactions
(Hund's rules)

Ferromagnetism of 3d metals

J. Friedel, Nuovo Cim. Suppl. 7 (1958) 287

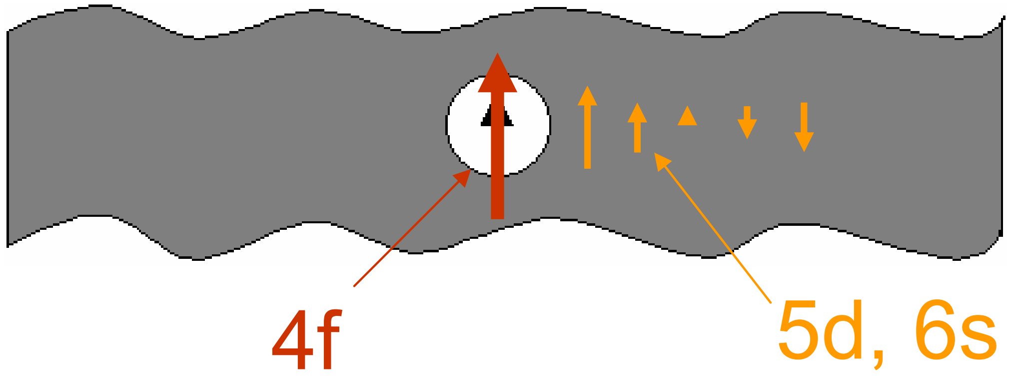
Superexchange



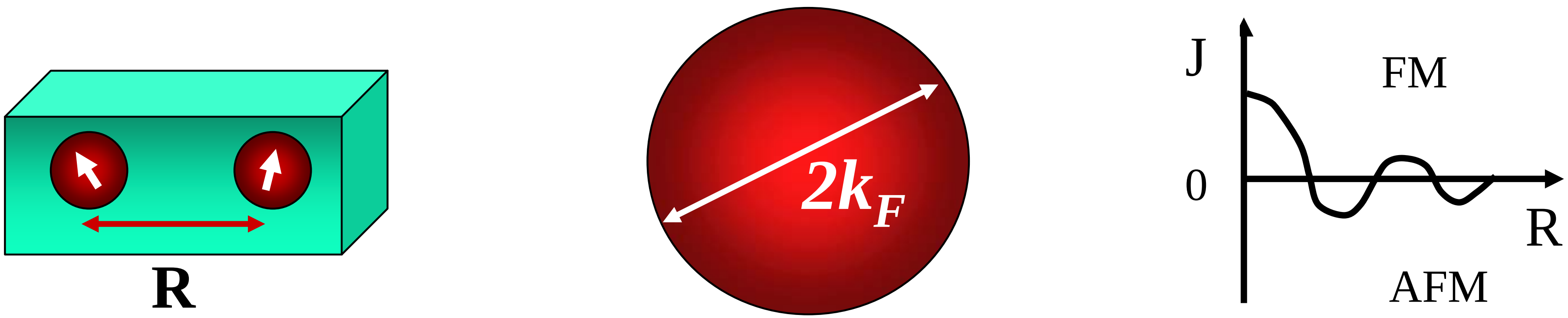
Antiferromagnetism

Reminiscent of hydrogen atom

RKKY interactions in RE metals

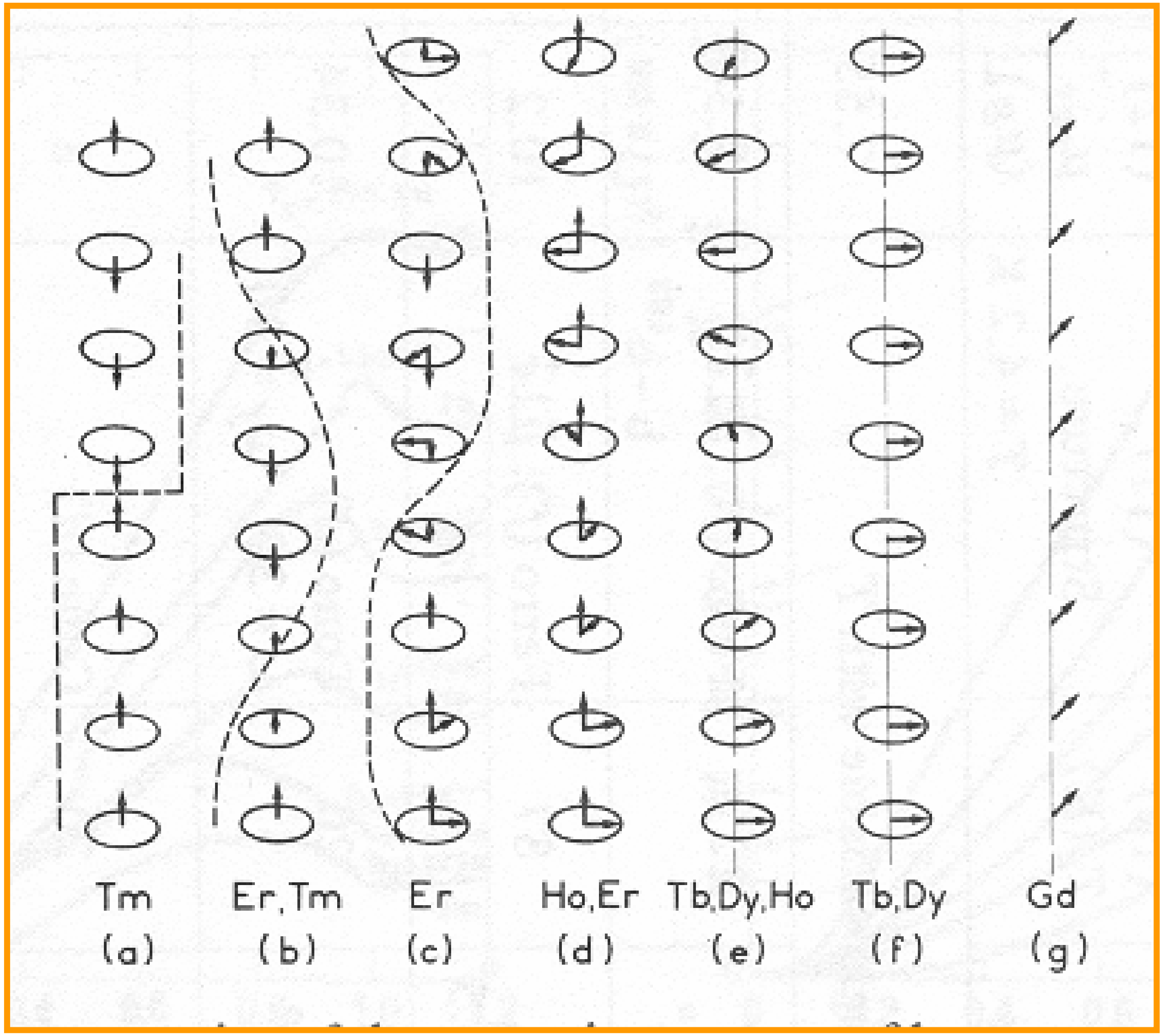


$$J_{RKKY}(R) \propto \frac{\cos(2k_F R)}{(2k_F R)^3} \propto \frac{1}{R^3}$$



Diverse and complex magnetic structures

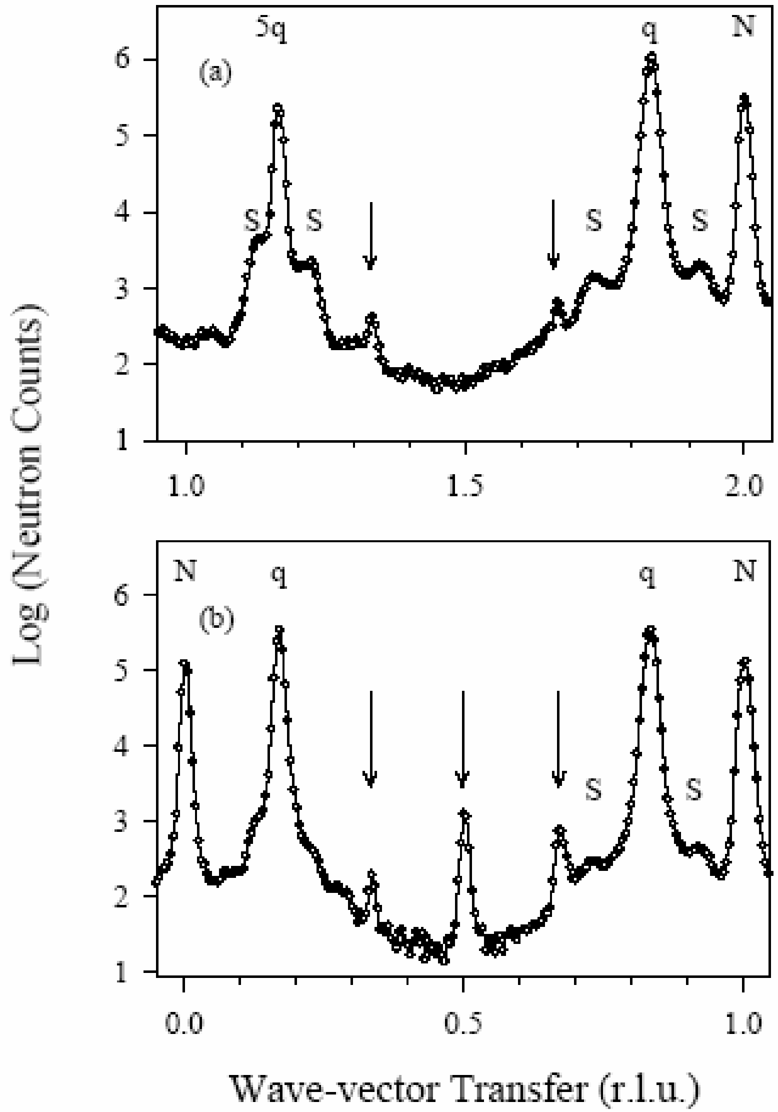
Magnetic structures of rare-earth metals

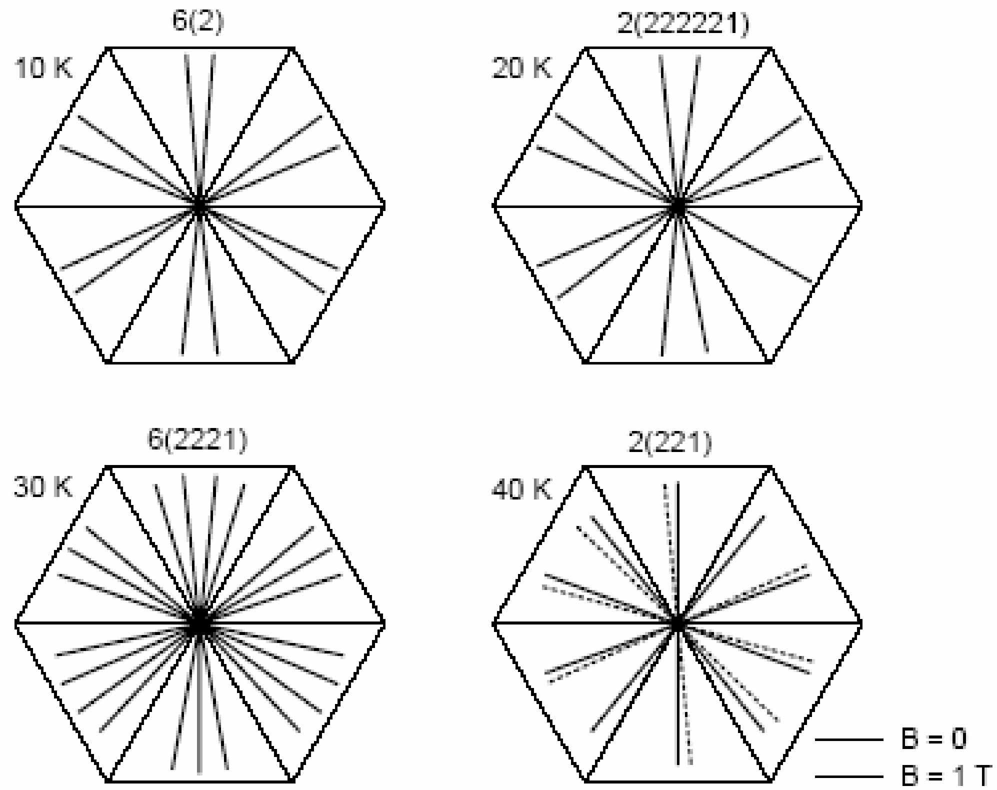


Diversity of structures
RKKY interactions + Magnetocrystalline anisotropy

Spin-slip structures of Holmium

Gibbs D, Moncton DE, D'Amico KL, Bohr J and Grier BH, 1985: Phys. Rev. Lett. **55**, 234
Simpson JA, McMorrow DF, Cowley RA and Jehan DA, 1995: Phys. Rev. B **51**, 16073





Evidence for higher-order pair interactions

Finite-Temperature Magnetism of Transition Metals

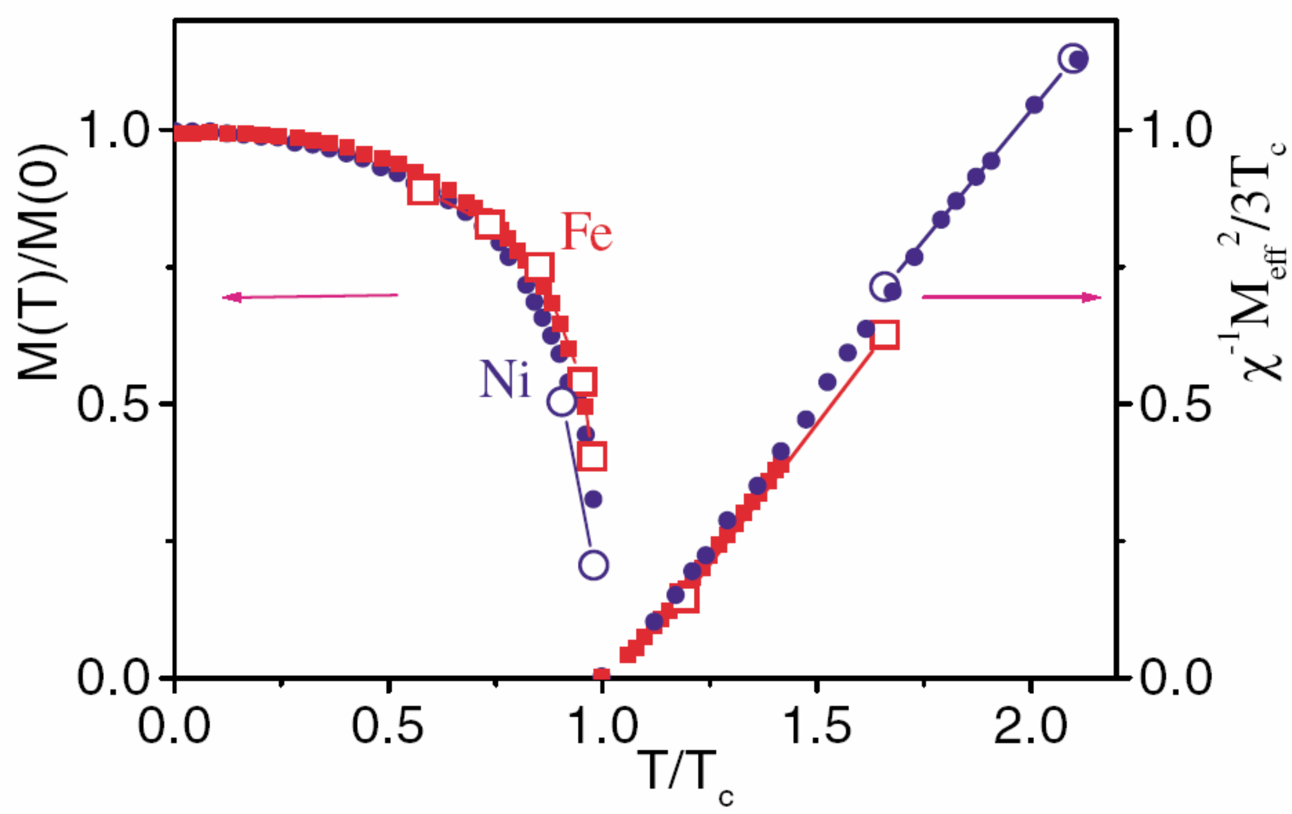
DFT :

Hohenberg-Kohn theorem :

the density of any system determines all ***ground-state*** properties of the system

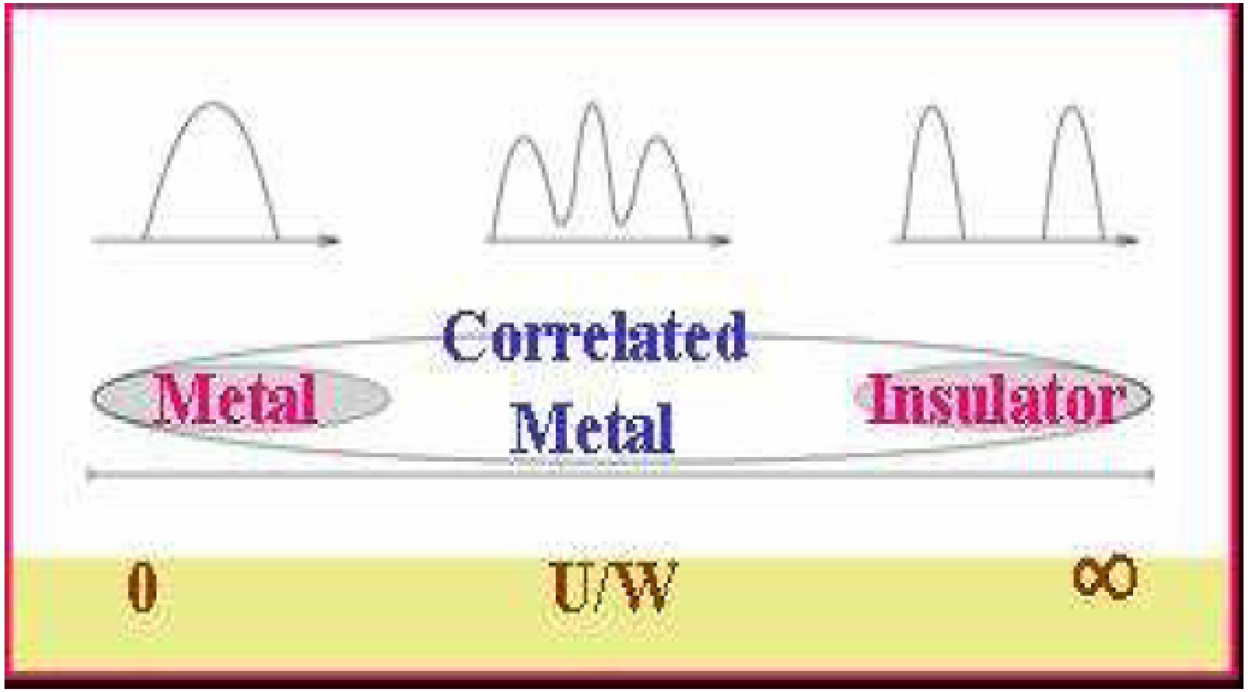
OK magnetic properties of transition metals understood from band structure calculations (DFT + LDA) but not finite temperature properties

DFMT (Dynamical mean-field theory)



A. I. Lichtenstein, M. I. Katsnelson, G. Kotliar, PRL 87 (2001) 067205

From metal to insulator



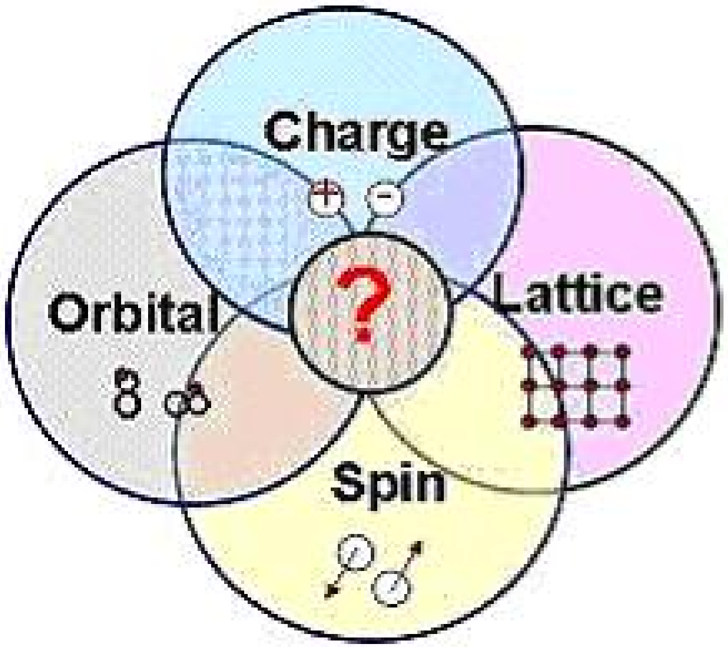
Electron correlations

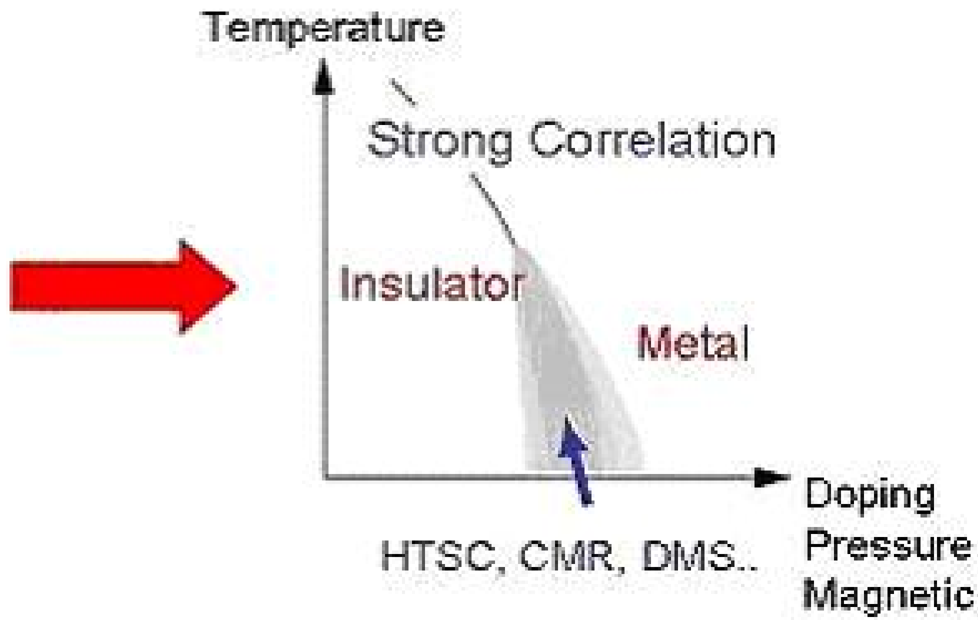
Fermi liquids   Heavy fermions   Strongly correlated electrons

Strongly correlated electron systems

Electron correlations →

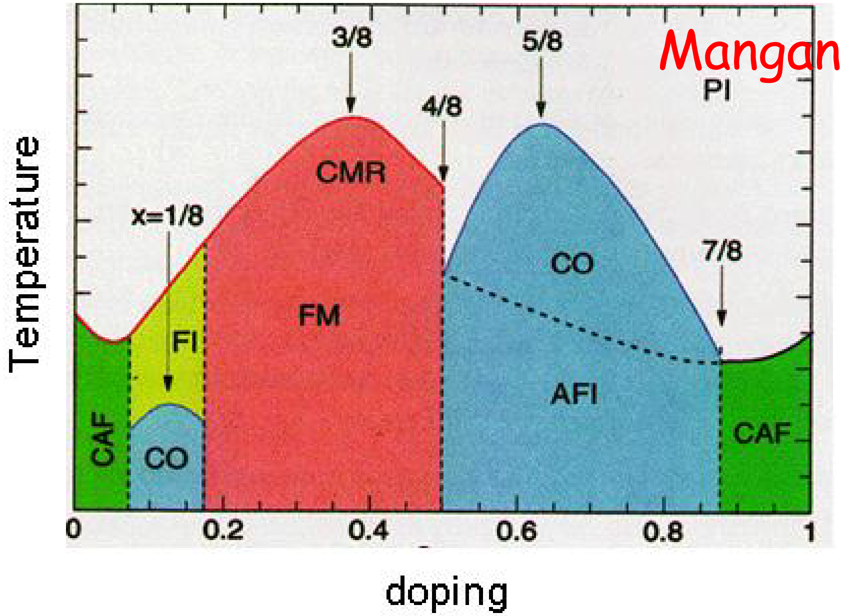
Fermi liquids　　Heavy fermions　　Strongly correlated electrons



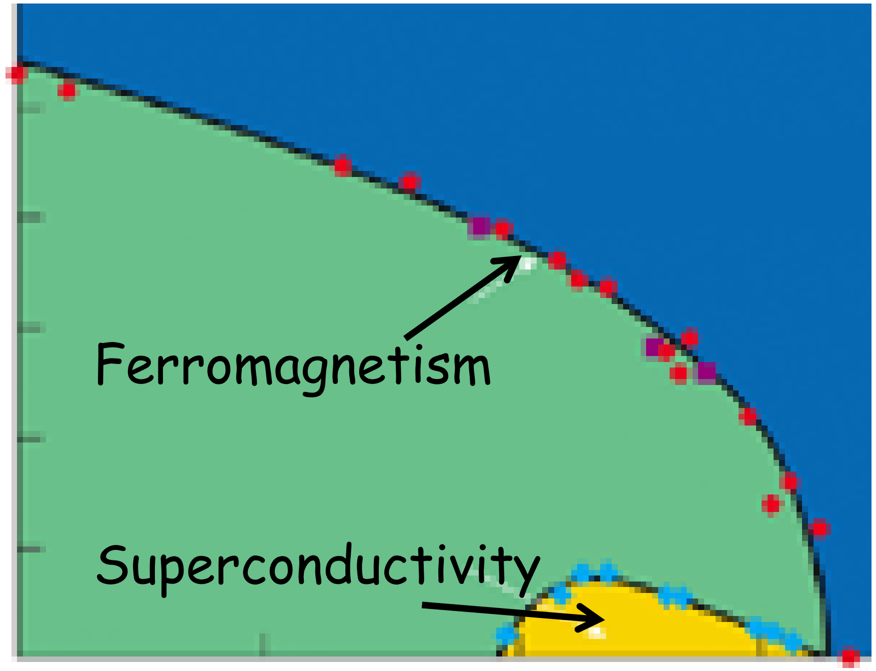


Coupling between charge, spin moment , orbital moment ?

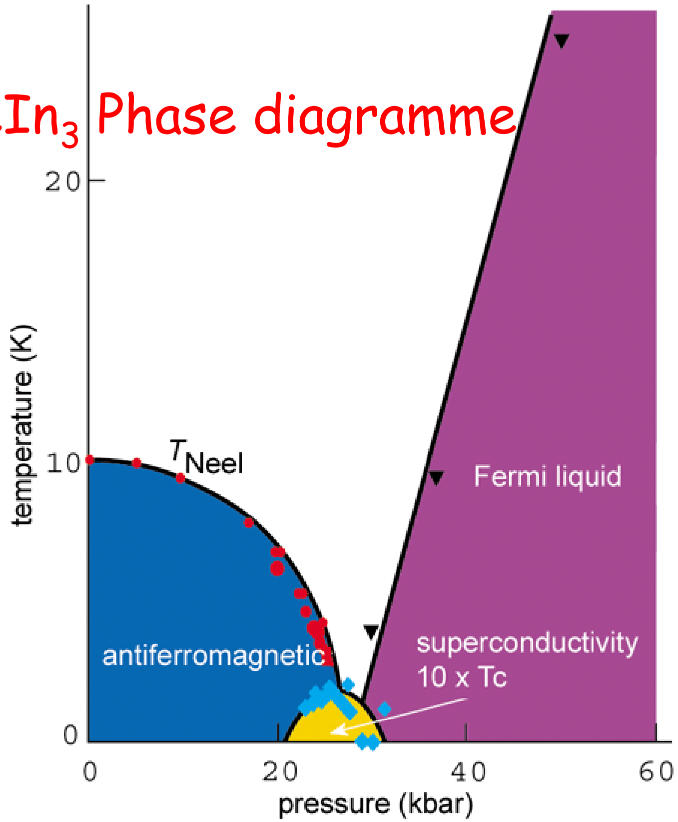
Strongly correlated electron systems



Manganite phase diagramme



UGe_2 Phase diagramme



$CeIn_3$ Phase diagramme

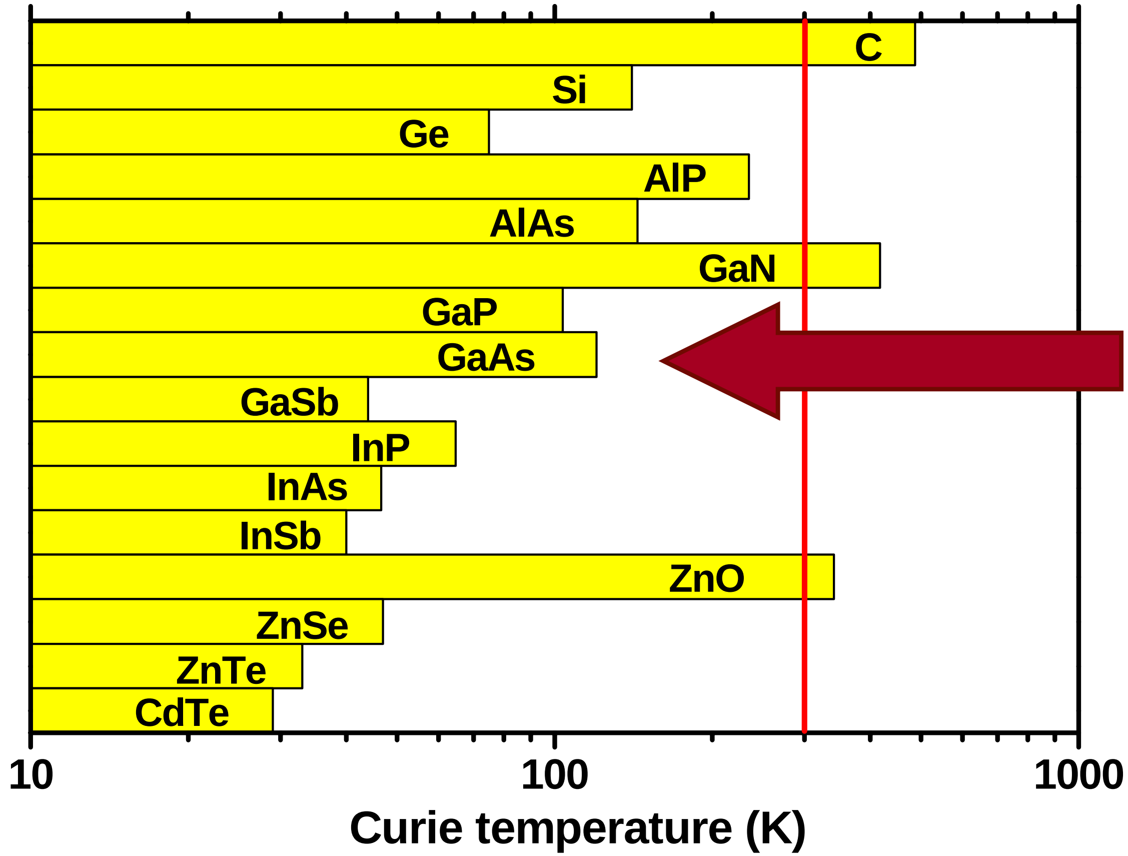
How can ferromagnetism and superconductivity coexist ?

Triplet superconductivity ?

Diluted ferromagnetic semiconductors

Carrier mediated ferromagnetism

$x = 0.05$, $p = 3.5\times10^{20}$ cm^{-3}



T. Dietl, et al., Science 2000

More than 20 compounds showed ferro- coupling so far

Operational criteria:

- Scaling of T_C and M with x and p
- Interplay between semiconducting and ferromagnetic properties

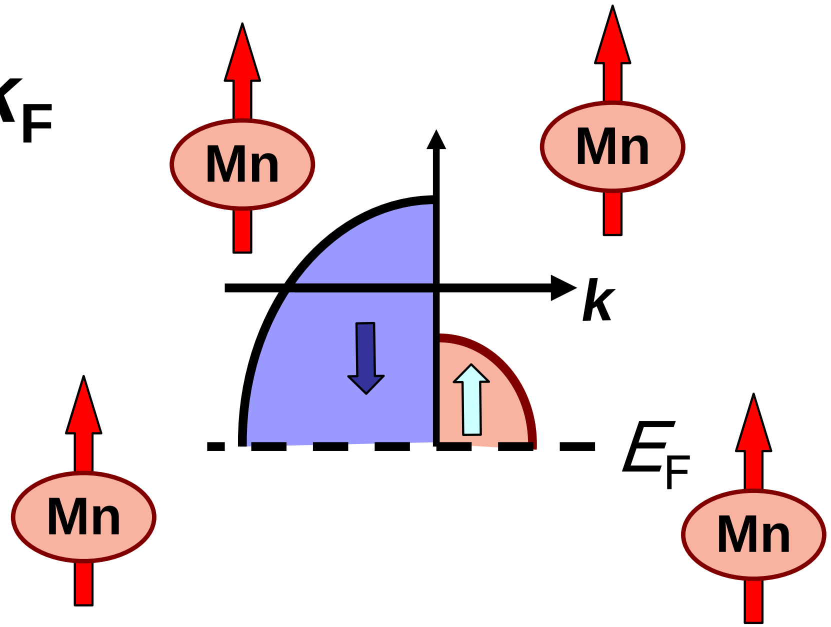
From M. Sawicki

Ferromagnetism in MnGaAs

Delocalized carriers (Zener/RKKY model)

Ryabchenko, et al., Dietl et al., MacDonald et al., Boselli et al.,

$$T_C = x_{eff} N_0 S(S+1) J^2 A_F \rho(\varepsilon_F)/12k_F$$



-- s-d: $I_{sd} \equiv \alpha N_o \approx 0.2$ eV

no s-d hybridization

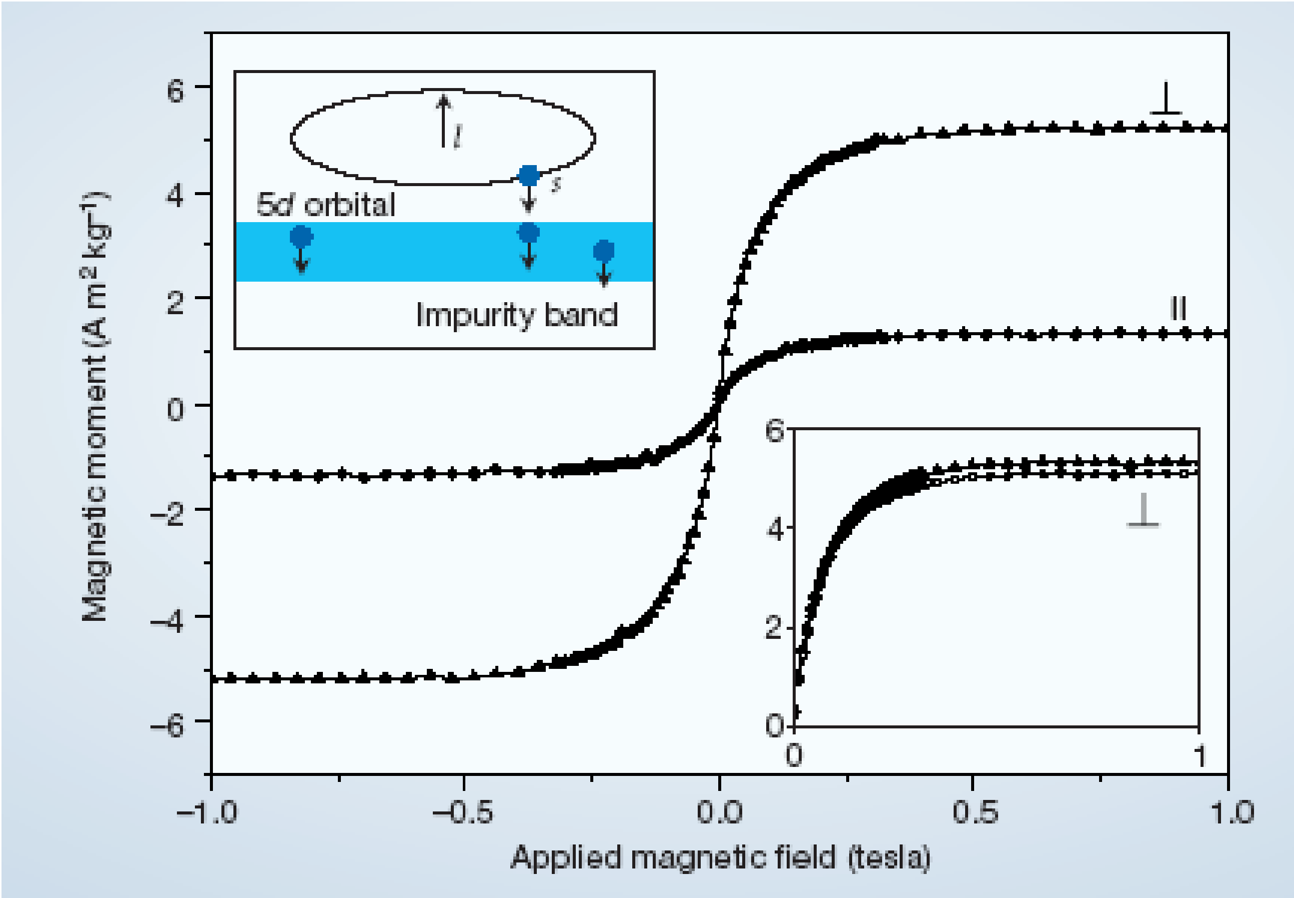
-- p-d: $I_{pd} \equiv \beta N_o \approx -1.0$ eV

large *p-d* hybridization

From M. Sawicki

d^0 ferromagnetism

M.Venkatesan, C. B. Fitzgerald, J.M.D. Coey, Nature, 430 (2004), 630

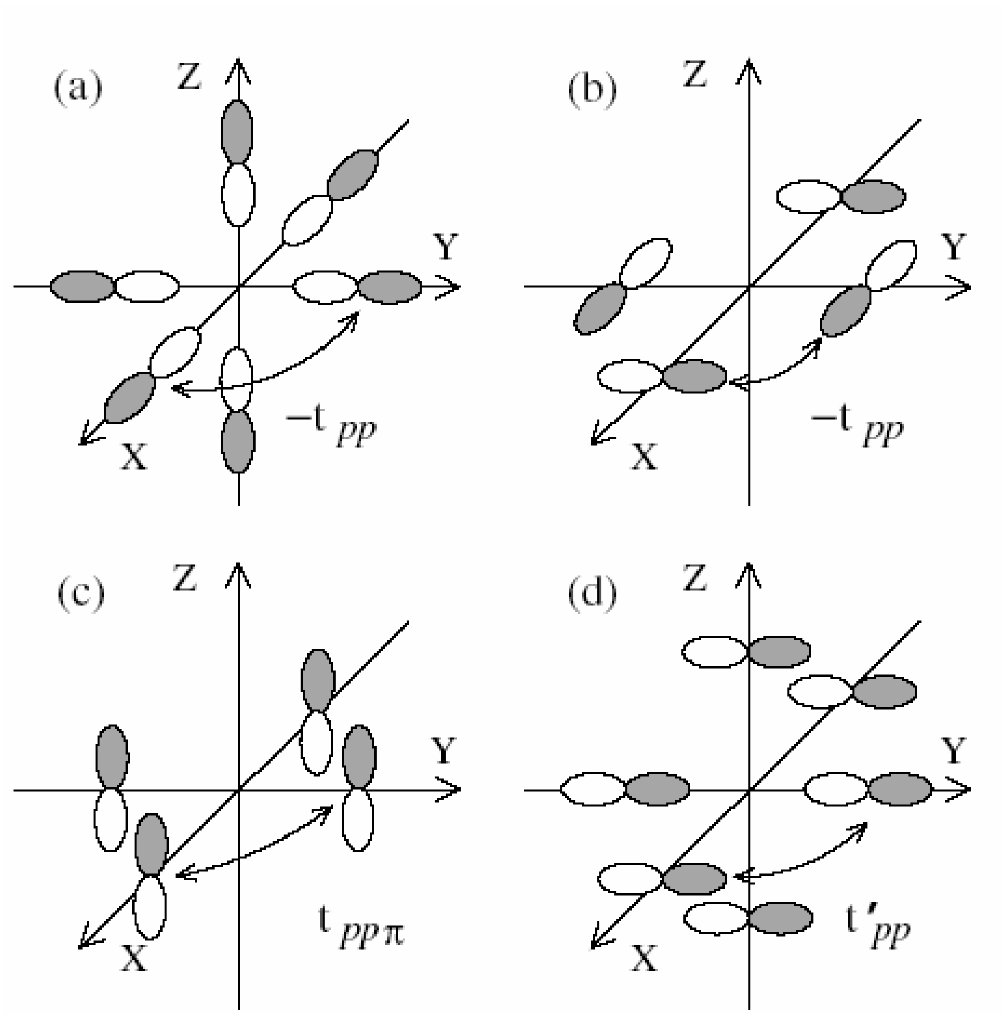


See also

CaB_6 D. P. Young *et al.*, Nature (London) **397**, 412 (1999).
Co/TiO_2 Y. Matsumoto *et al.*, Science **291**, 854 (2001).
Co/ZnO K. Ueda, H. Tabata, and T. Kawai, Appl. Phys. Lett. **79**, 988 (2001).

Half-metallic ferromagnetism in CaO ?

I. S. Elfimov,1 S. Yunoki,1 and G. A. Sawatzky, PRL, 89 (2002) 216403



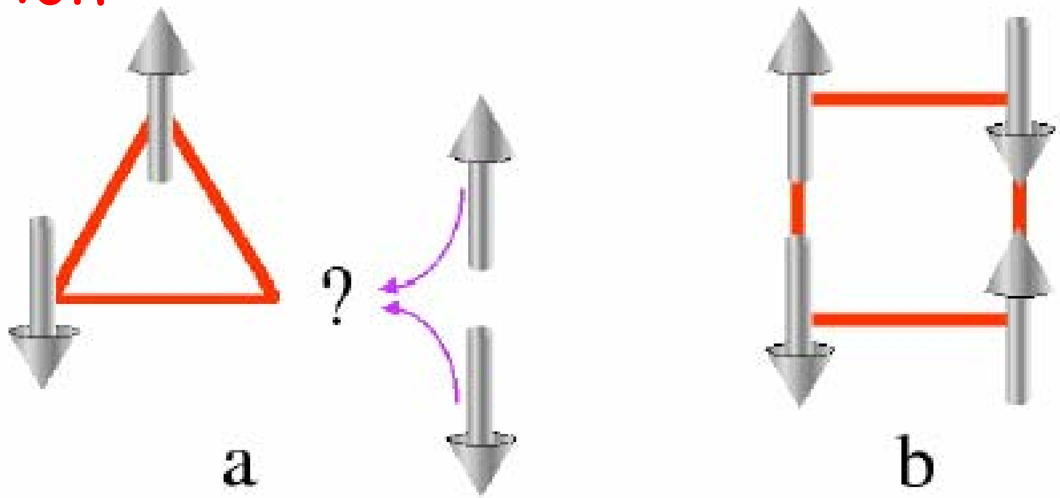
See also : Chaitanya Das Pemmaraju and S. Sanvito, PRL **94,** 217205 (2005)

Frustration

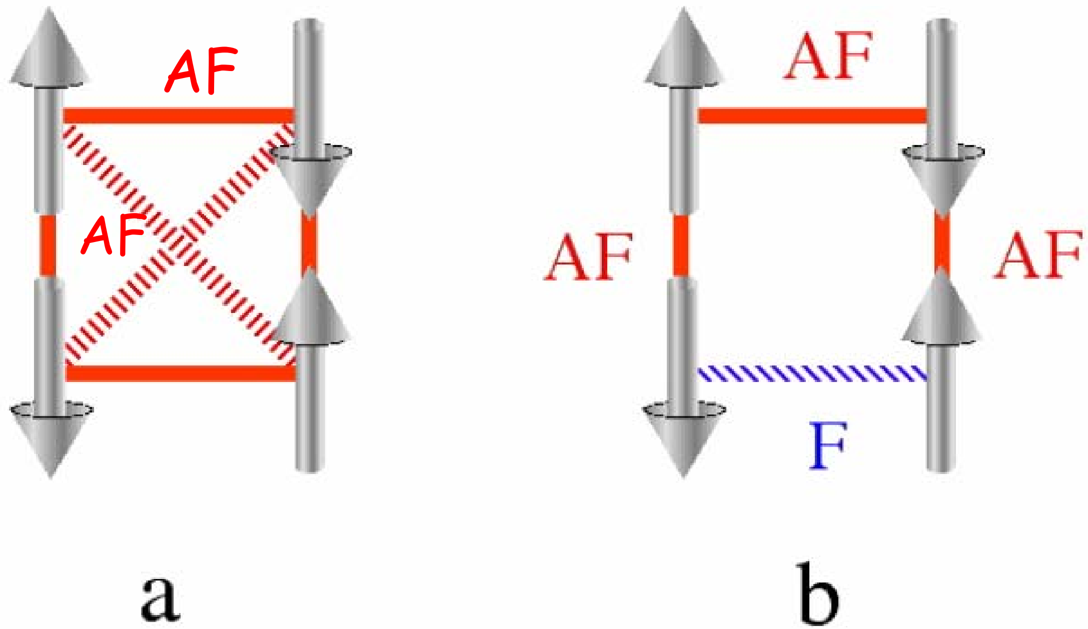
R. Ballou and C. Lacroix, La Recherche, 2005

F

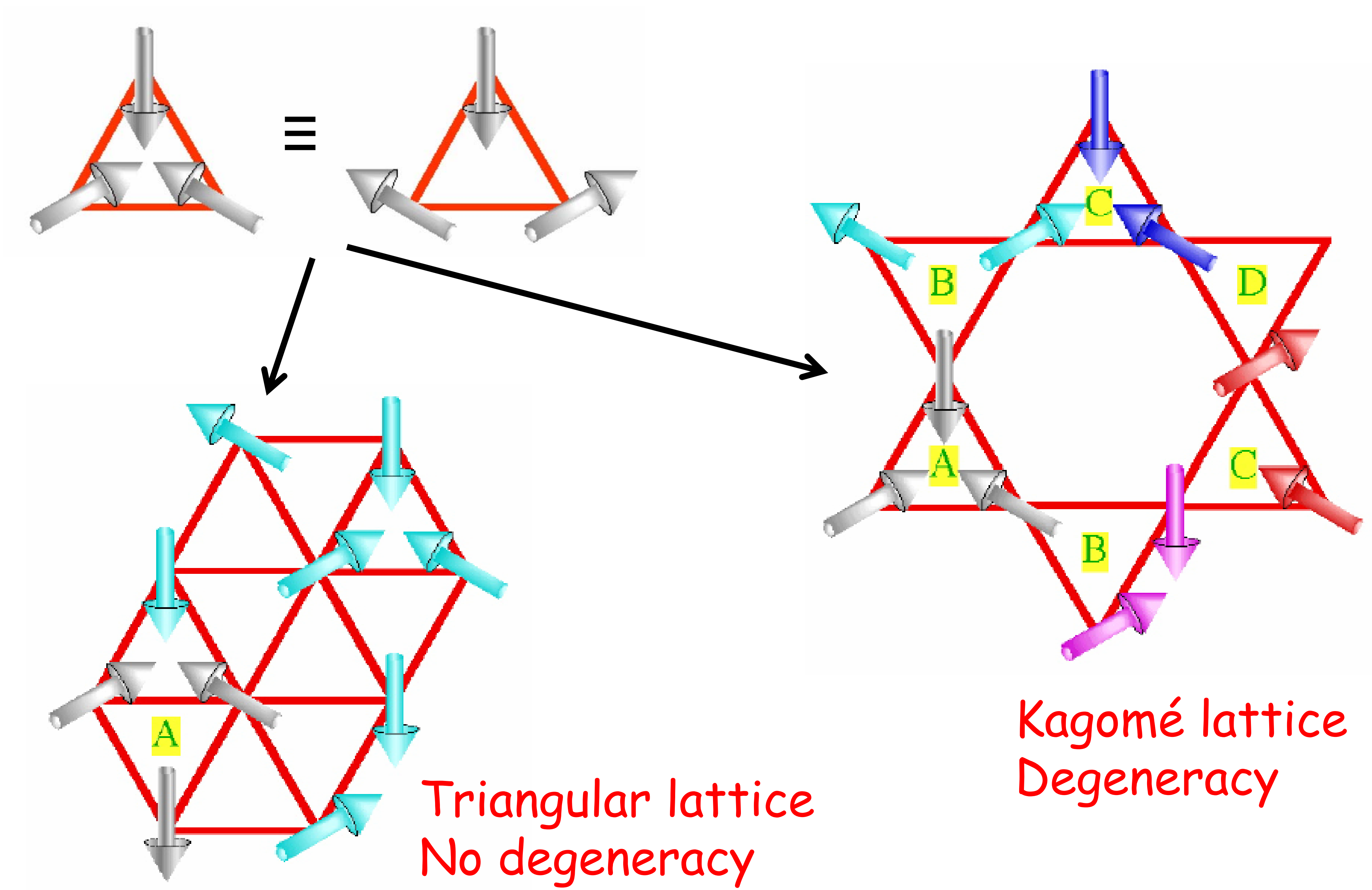
Geometric frustration



Frustration due to competition between various interactions



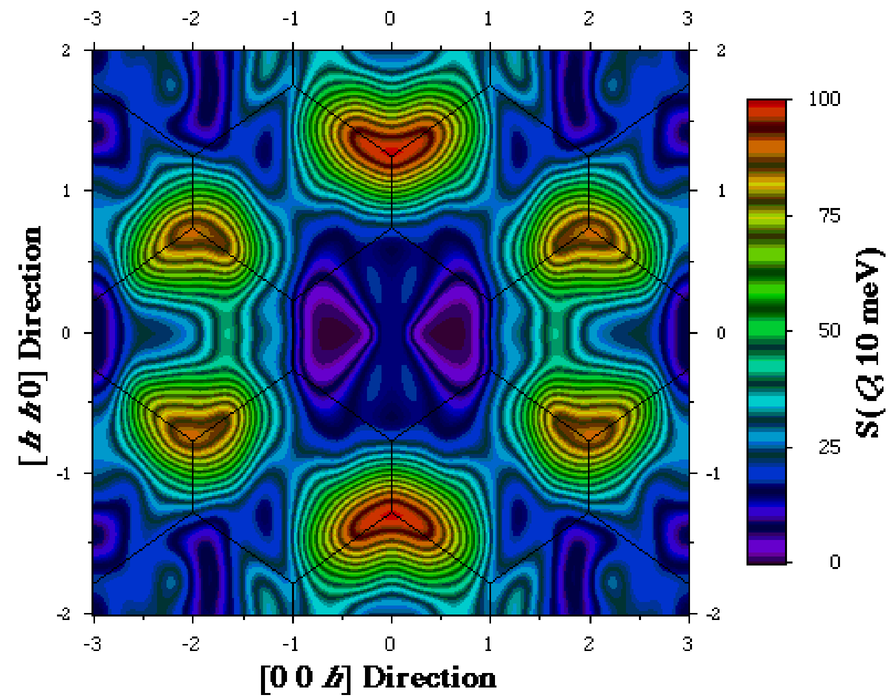
Degeneracy


≡
A
B
C
D
A
B
C
Triangular lattice
No degeneracy
Kagomé lattice
Degeneracy

Magnetic order in degenerated systems ?

Infinitely large number of equivalent configurations :
no magnetic order in principle

Small additional interactions may be determinant
Or
Liquid spin state develops

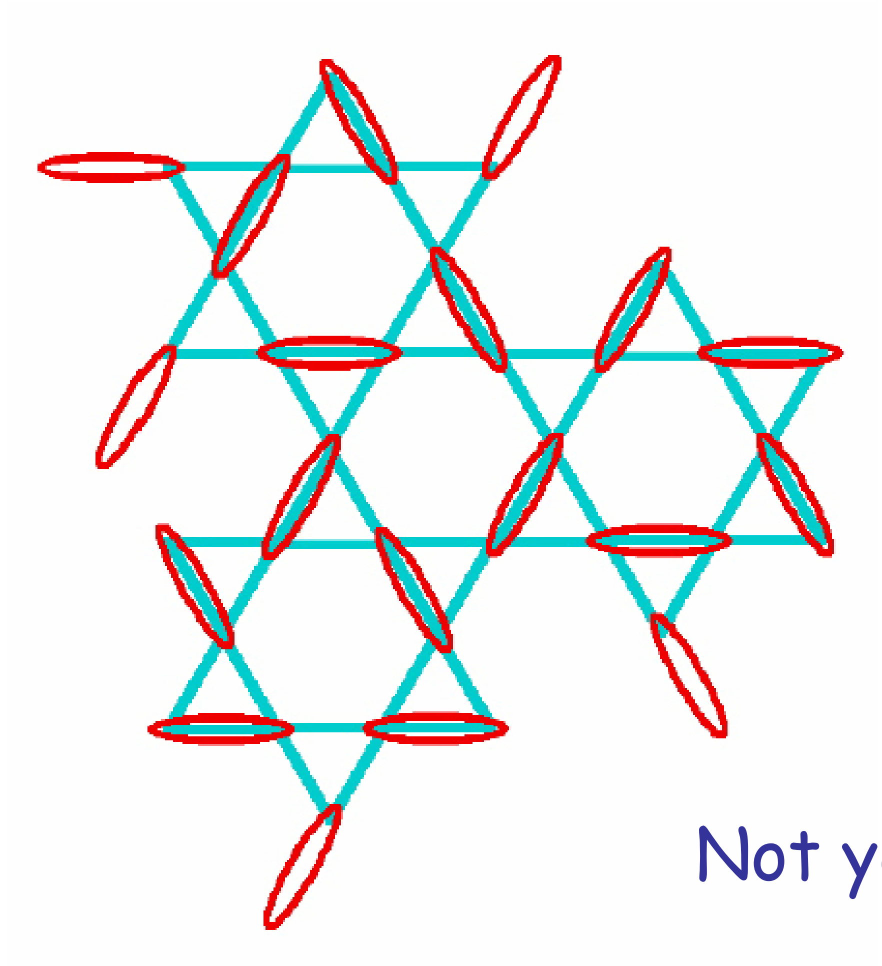


R. Ballou, E. Lelièvre-Berna, and B. Fåk
Phys. Rev. Lett. **76**, 2125-2128 (1996)

Magnetic correlations
in YMn_2

Quantum spin liquids

For S =1/2,
in the presence of frustration, singlet states should form



Not yet observed in 3D systems

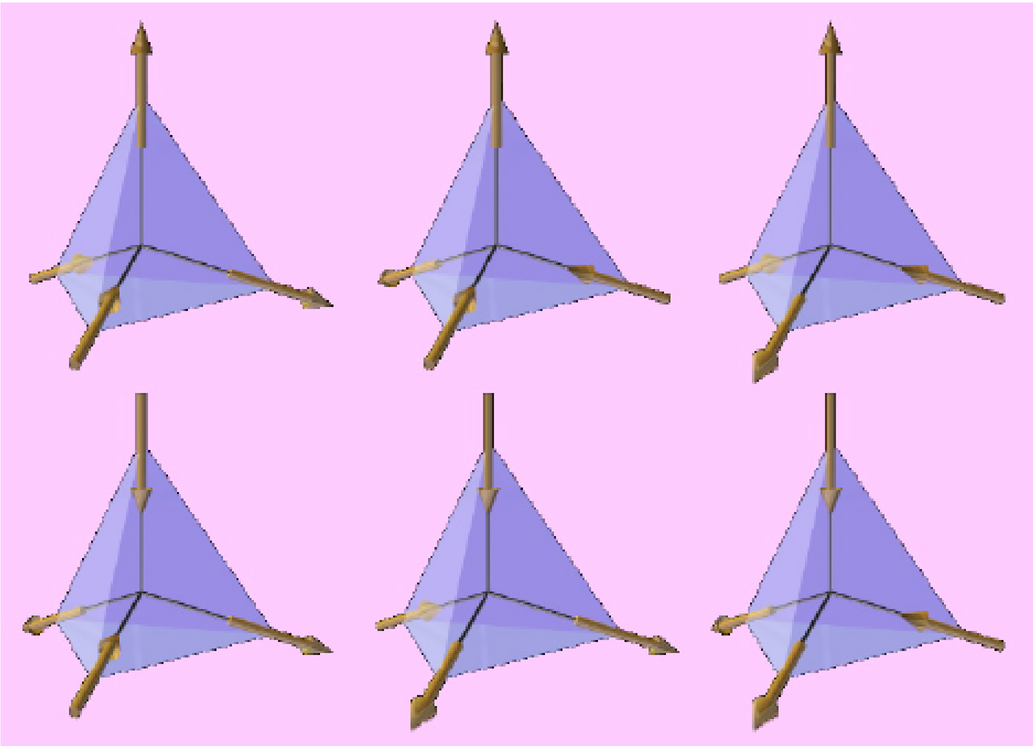
Spin ice

Another manifestation of geometric frustration

All interactions positive

+

very large anisotropy along tetrahedron axis



Non-zero entropy measured at very low T : 1/2RLn3/2.

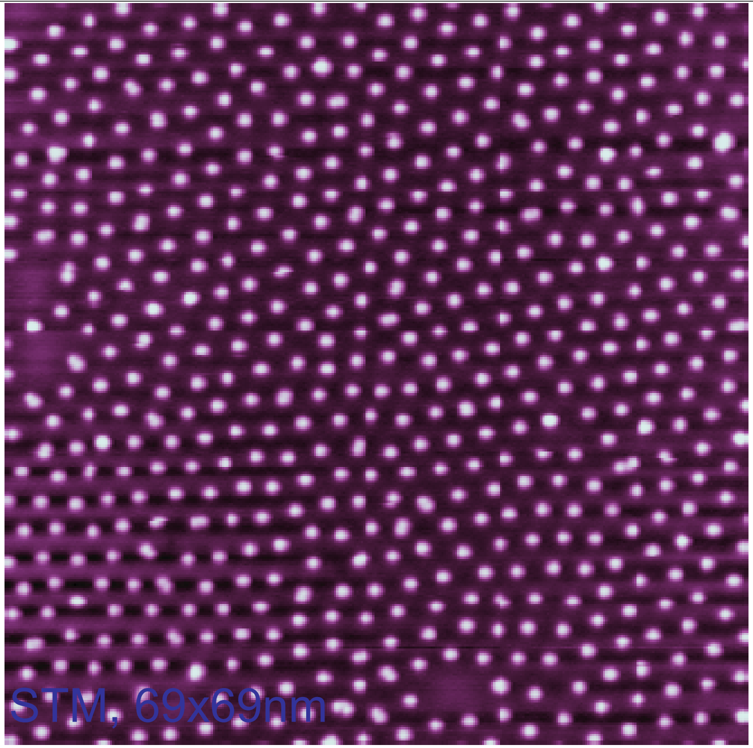
Open questions in magnetism

- Fundamental questions
- Nanomagnetism
  - Cluster preparation
  - Magnetism of very small objects
  - Superparamagnetism
- Spintronics and fast reversal
- Materials
- Experimental developments

Friedel crystal

Ce(1AL)/Ag(111) @ 3.9K

Supra-crystal stabilized by surface states oscillating around adsorbates



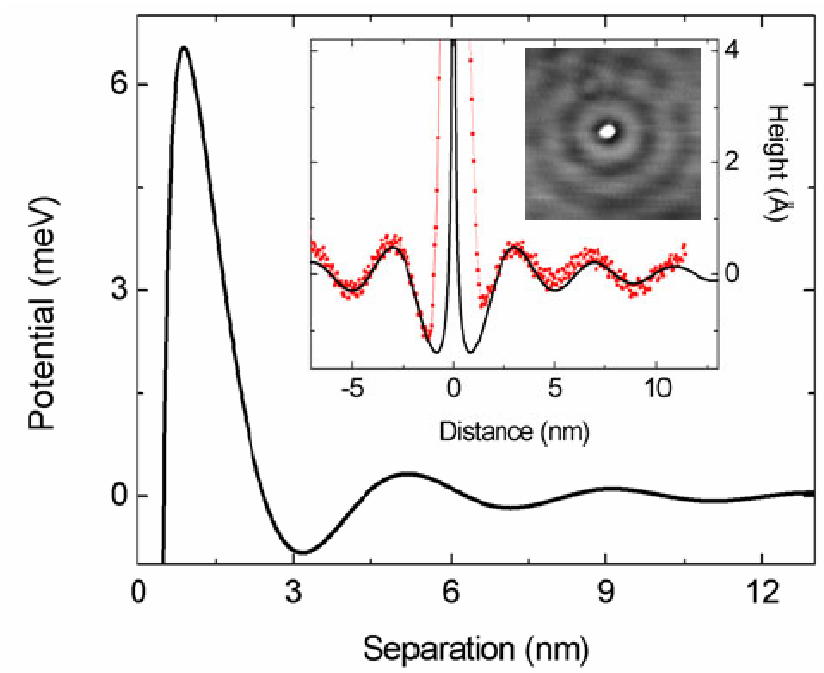
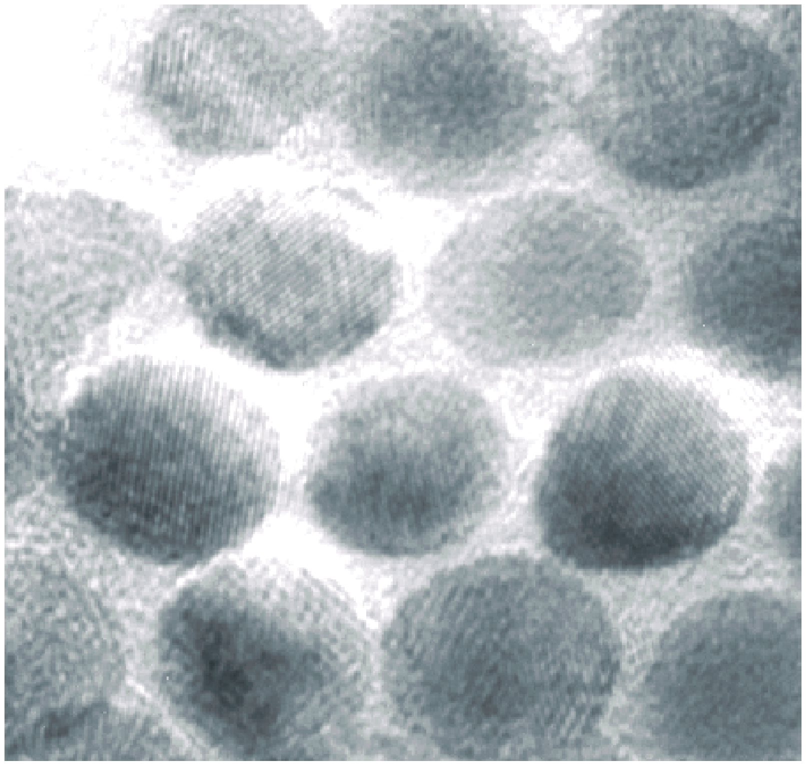
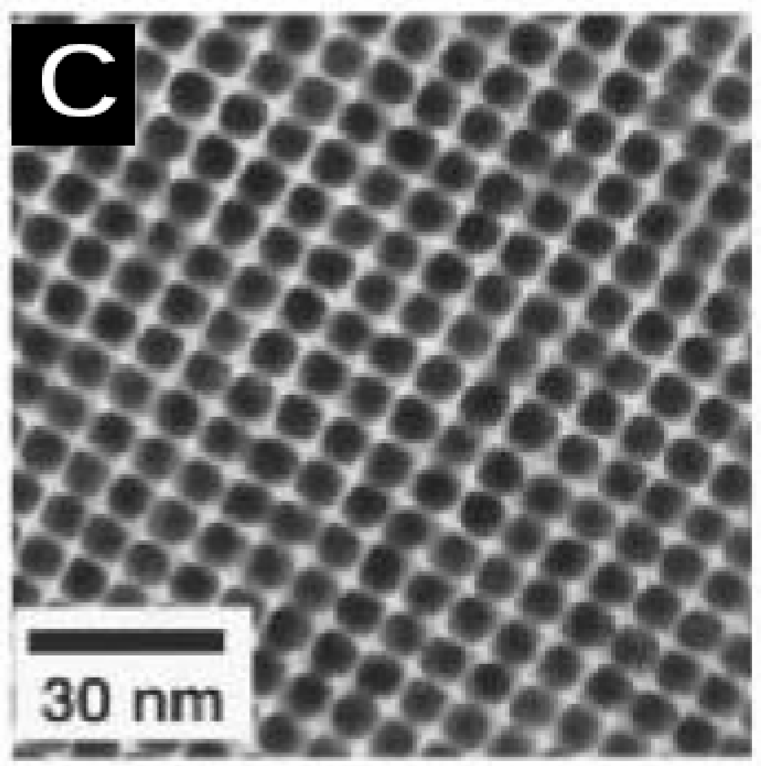


Figure 9. Calculated two-body interaction potential of Ce adatoms on Ag(111) (equation (2)). Inset: $21 \times 21\,\mathrm{nm}^2$ STM topography of a standing-wave pattern around an isolated Ce adatom on Ag(111) at 3.9 K ($U_s = -3\,\mathrm{mV}$, $I_s = 19\,\mathrm{pA}$). Topographic cross-section (dots) and fit using equation (1) (solid curve) as a function of distance from a single Ce adatom.

From O. Fruchart

Cluster chemical preparation



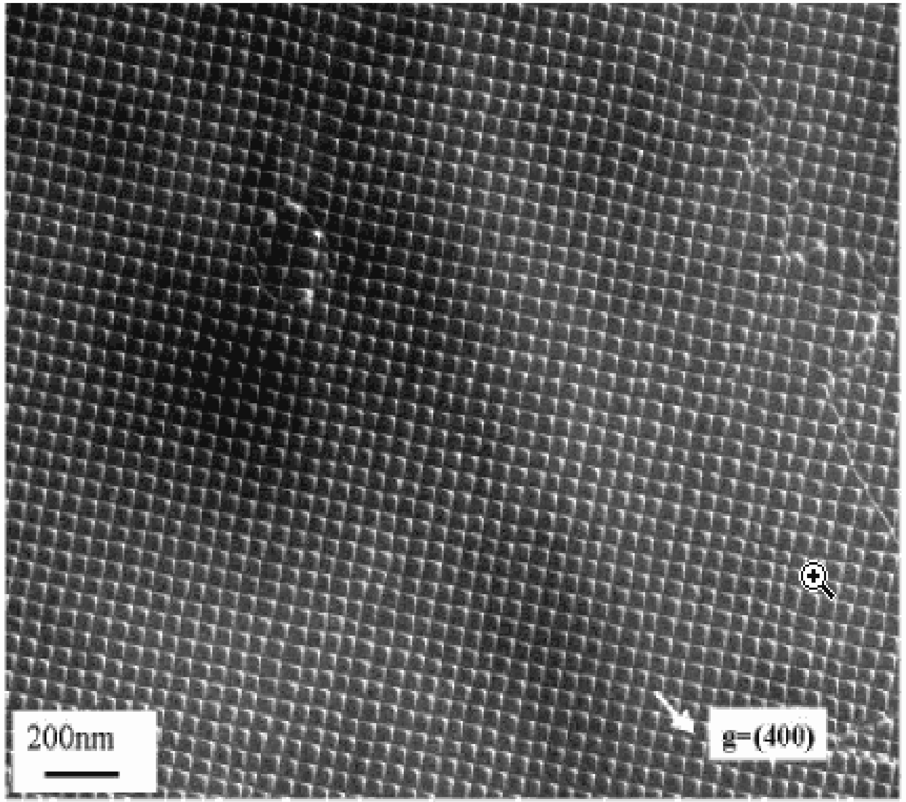


S. Sun, Science 287, 1989 (2000

Self assembled superlattice of
FePt particles

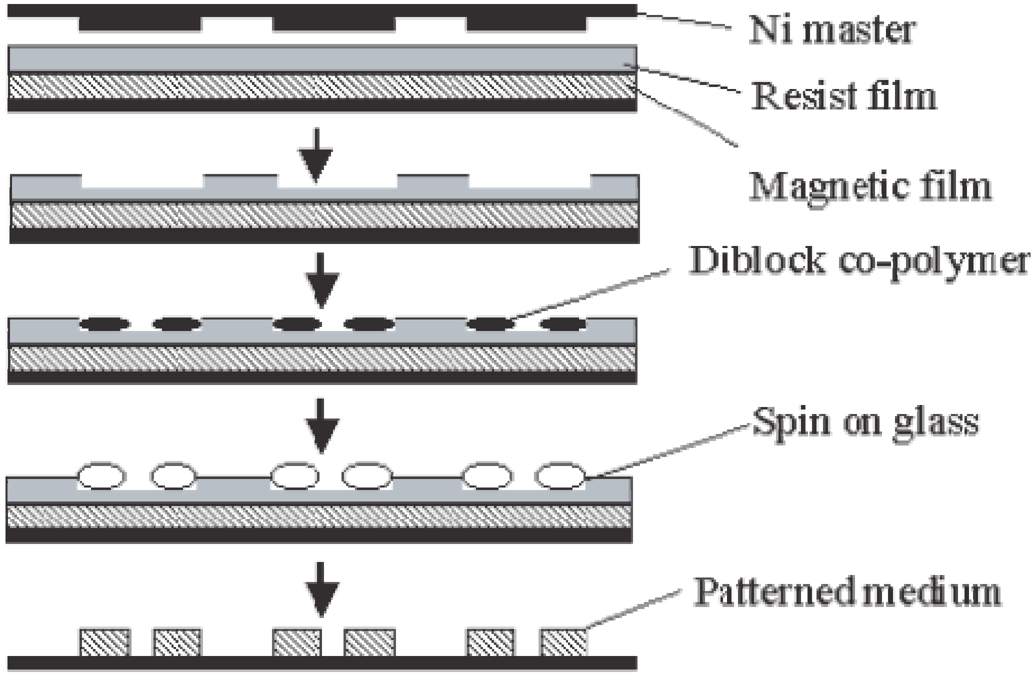
Sef-organisation on templated substrates

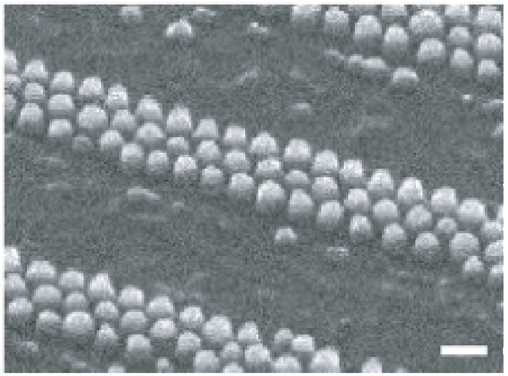
Screw dislocations



J. L. Rousseau *et al.*, APL80, 4121 (2002)

Di-block co-polymers





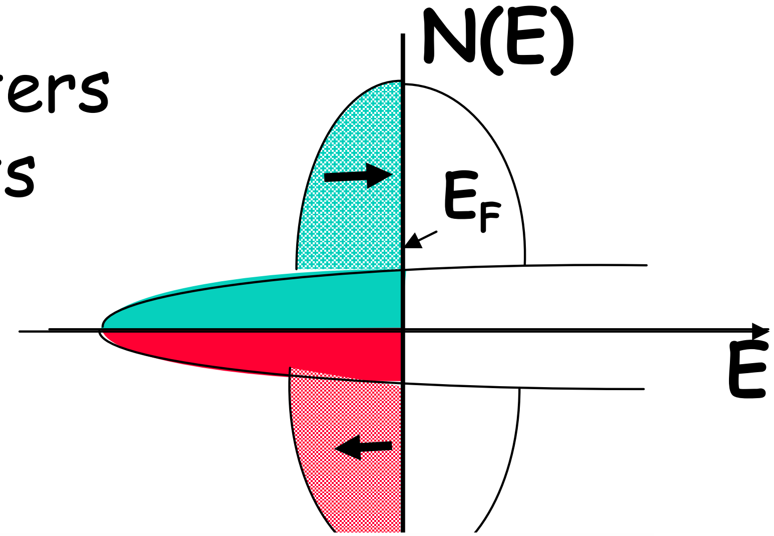
REVIEW: B. D. Terris et al.,

J. Phys. D: Appl. Phys. 38, R199 (2005)

From O. Fruchart

Magnetism of very small objects

Onset of ferromagnetism in clusters of normally non magnetic elements

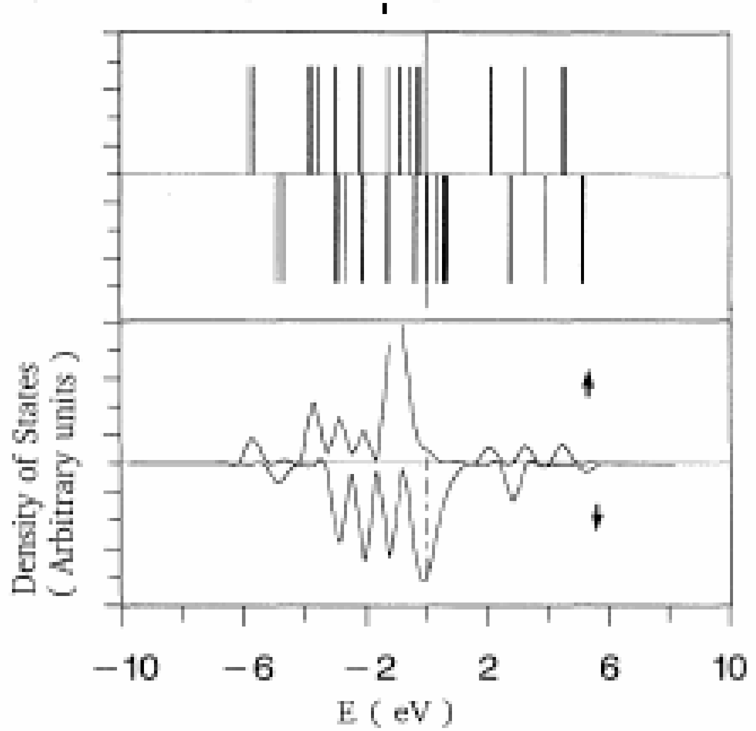


Rh
Unfilled 4d shell
Bulk Rh is a paramagnet

Rh clusters

Rh_{12} 0.98 μ_B
Rh_{20} 0.40 μ_B
Rh_{32} 0.35 μ_B

A. J. Cox, J. G. Louderback, and L. A. Bloomfield

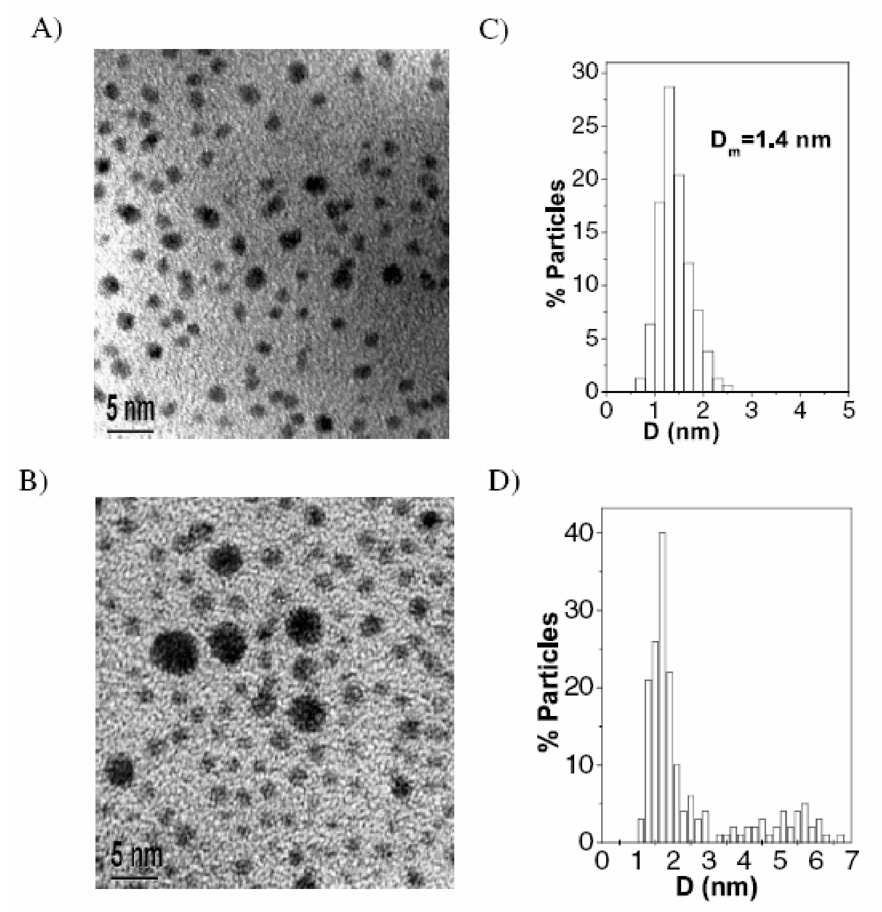


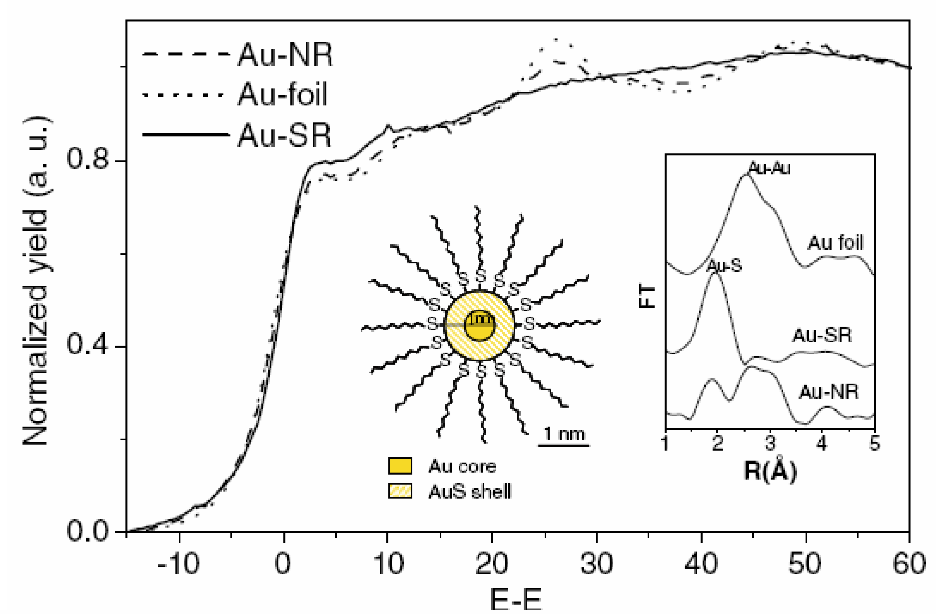
Properties of deposited clusters ?

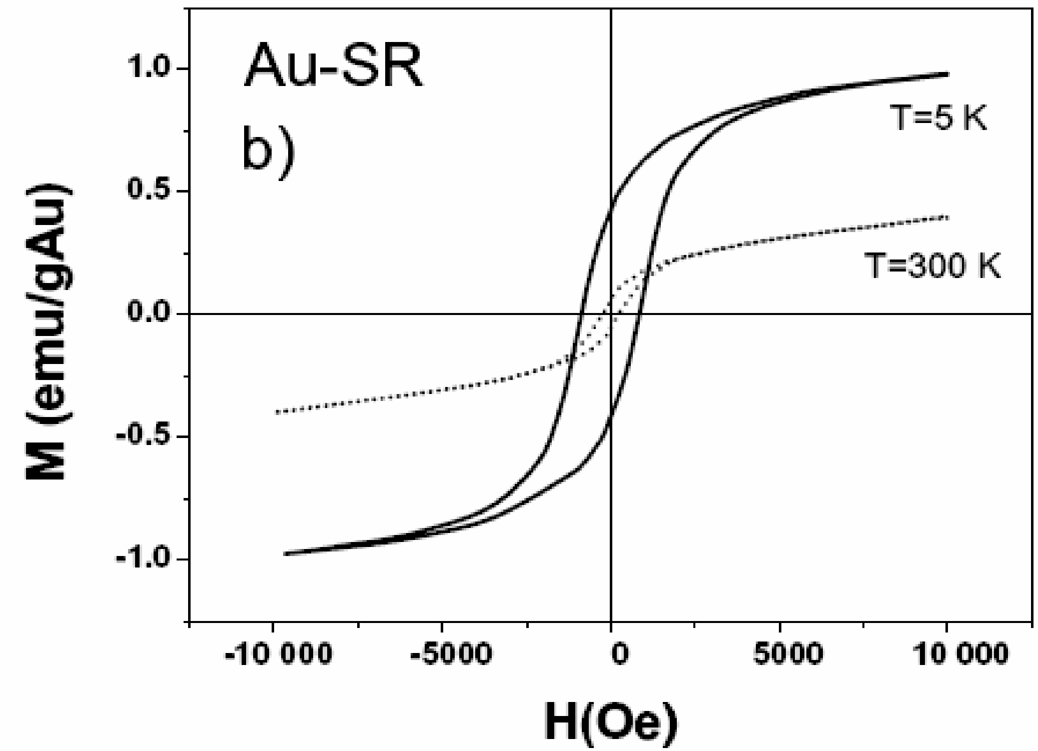
A.J. Cox, J.G. Louderback and L.A. Bloomfield, PRL, 71 (1993) 923
B.V. Reddy, S.N. Khanna, B.I. Dunlap, PRL,70 (1993) 3324

Thiol-capped Au nanoparticles

P. Crespo et al. PRL 93 (2004) 087204

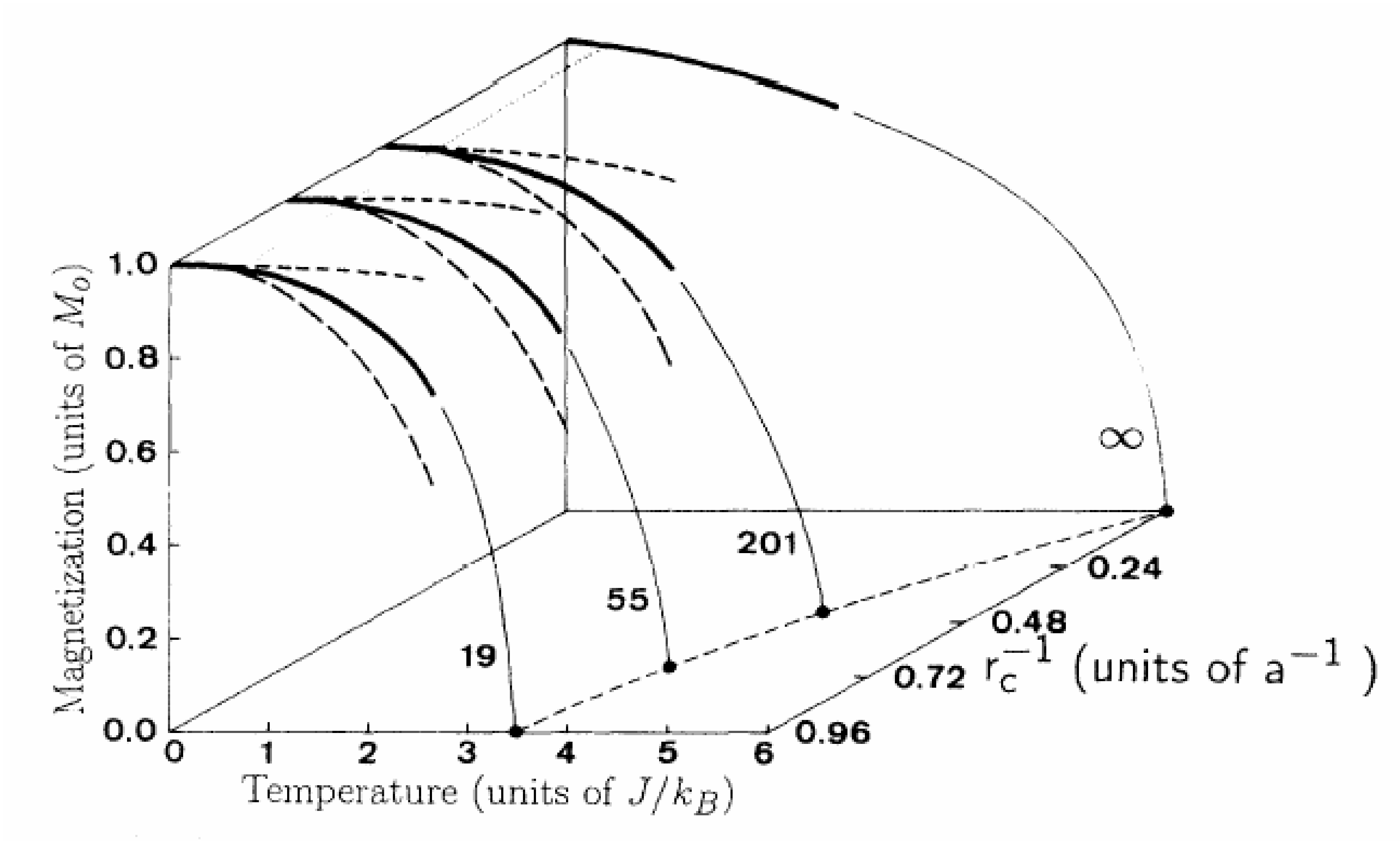






Curie temperature in clusters

P.V. Hendriksen, S. Linderoth and P.A.Lindgard, PRB 48 (1993)7259



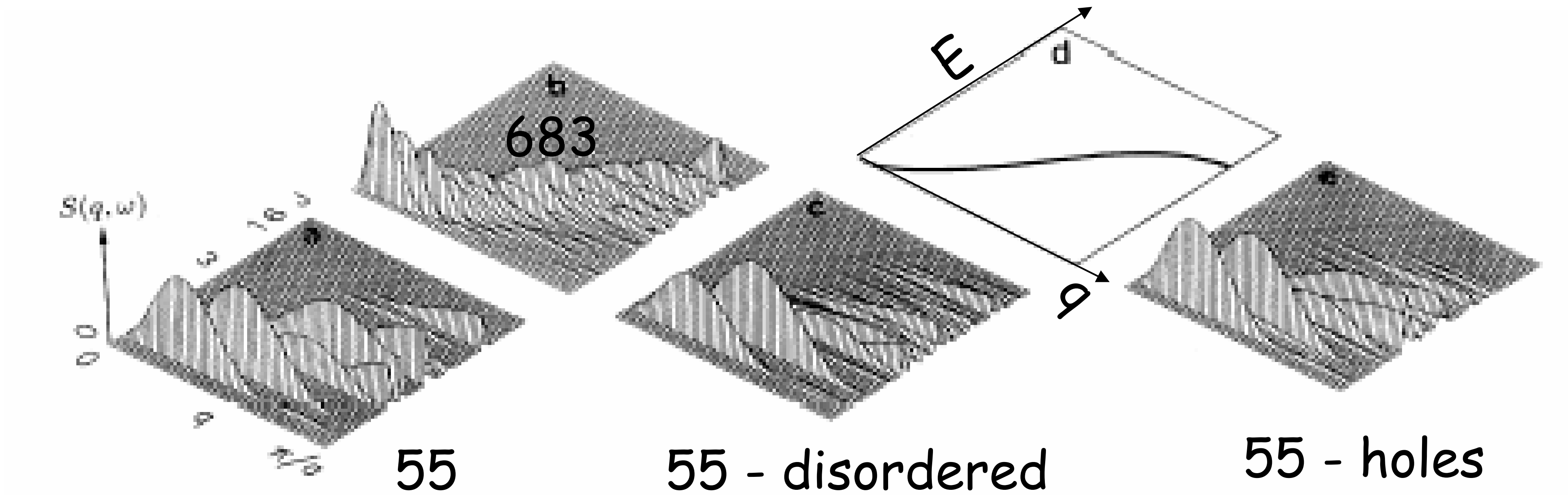
T_C reduced due to reduction in mean exchange interactions

At low T, M_s does not decrease due to the existence the energy gap

Phenomena not yet studied experimentally

Spin-waves in small clusters

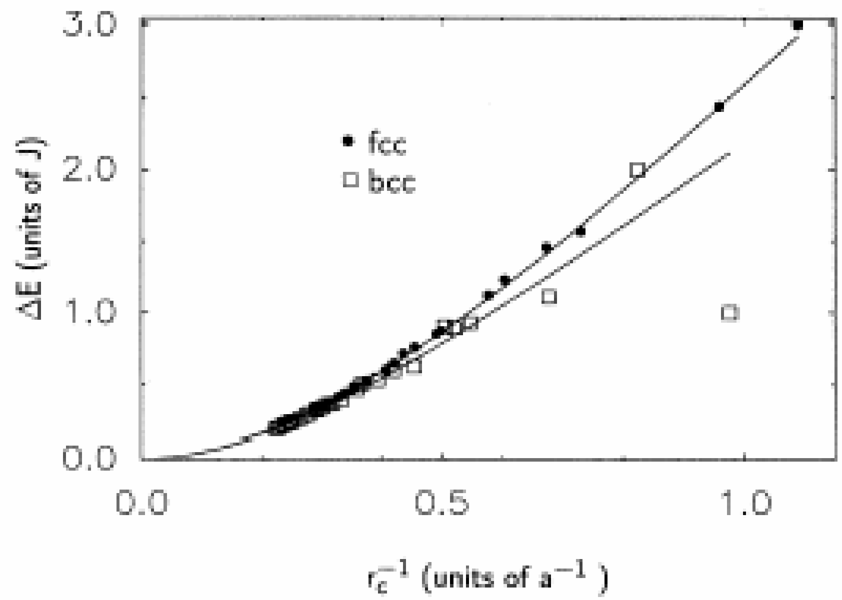
fcc clusters



bulk

$$E(q) = 2zJ\left(1-\frac{1}{2}(qa)^2\right)$$

$$\approx 2zJa^2q^2$$



cluster

Discrete energy levels

Broadening in q

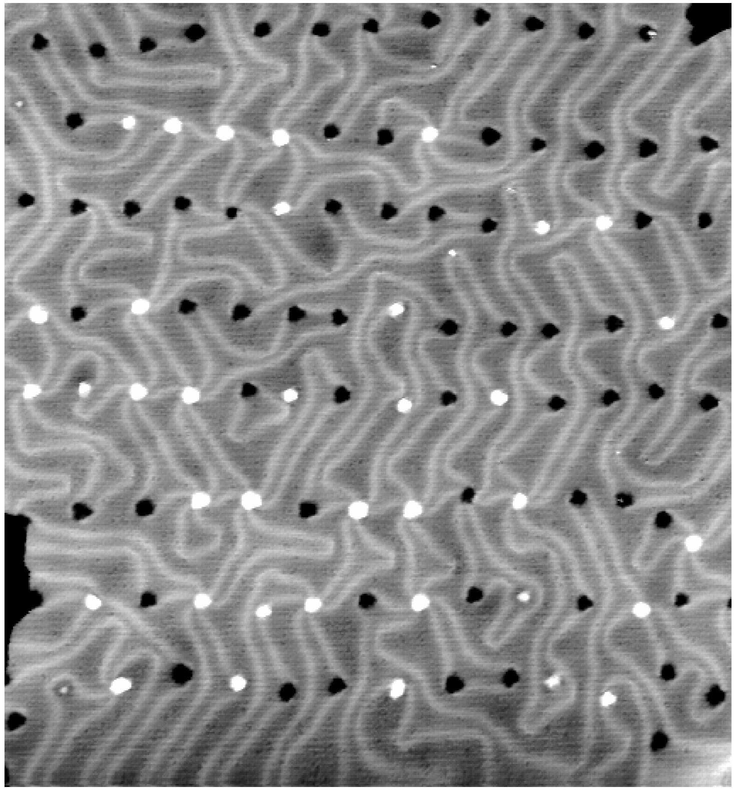
Beating the superparamagnetic limit

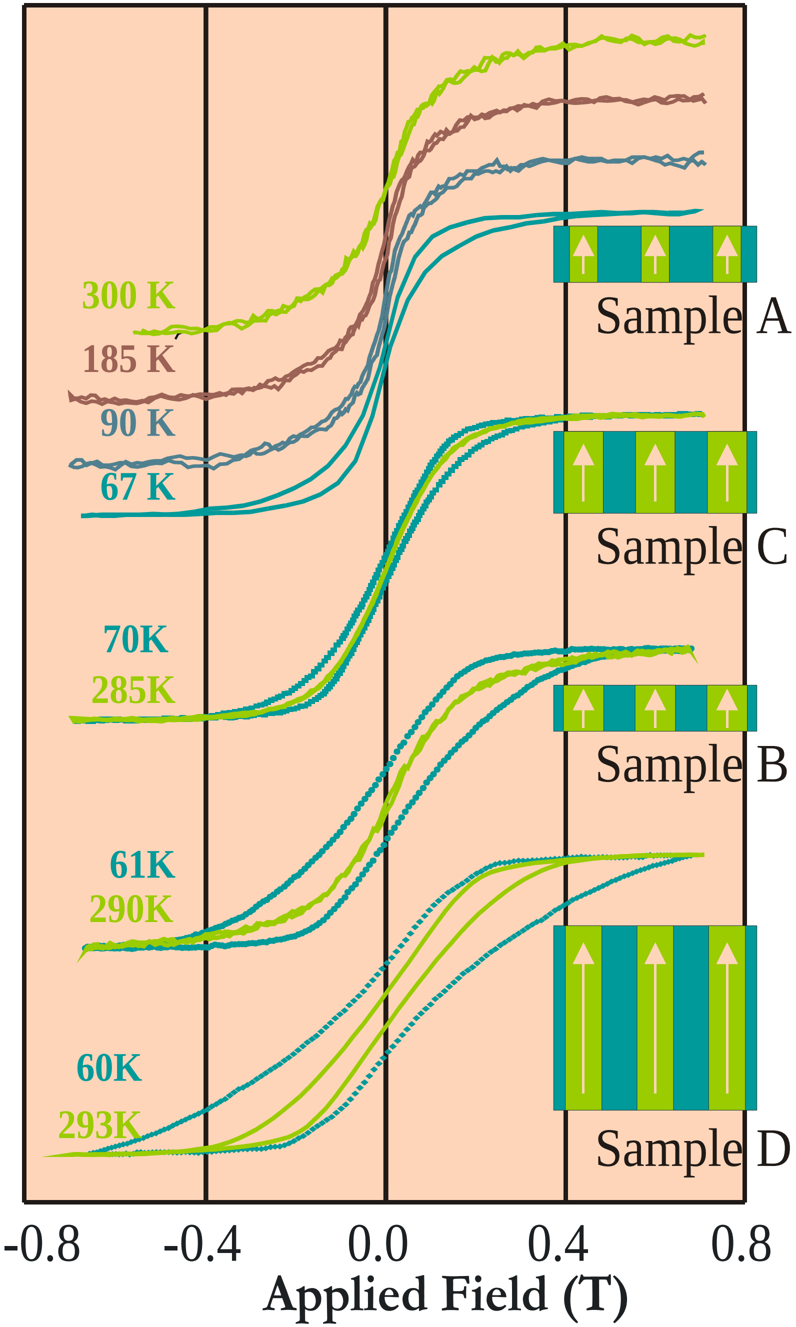
O. Fruchart, M. Klaua, J. Barthel, and J. Kirschner
Phys. Rev. Lett. **83**, 2769-2772 (1999)

- 1 High anisotropy material (FePt)

- 2 Column growth

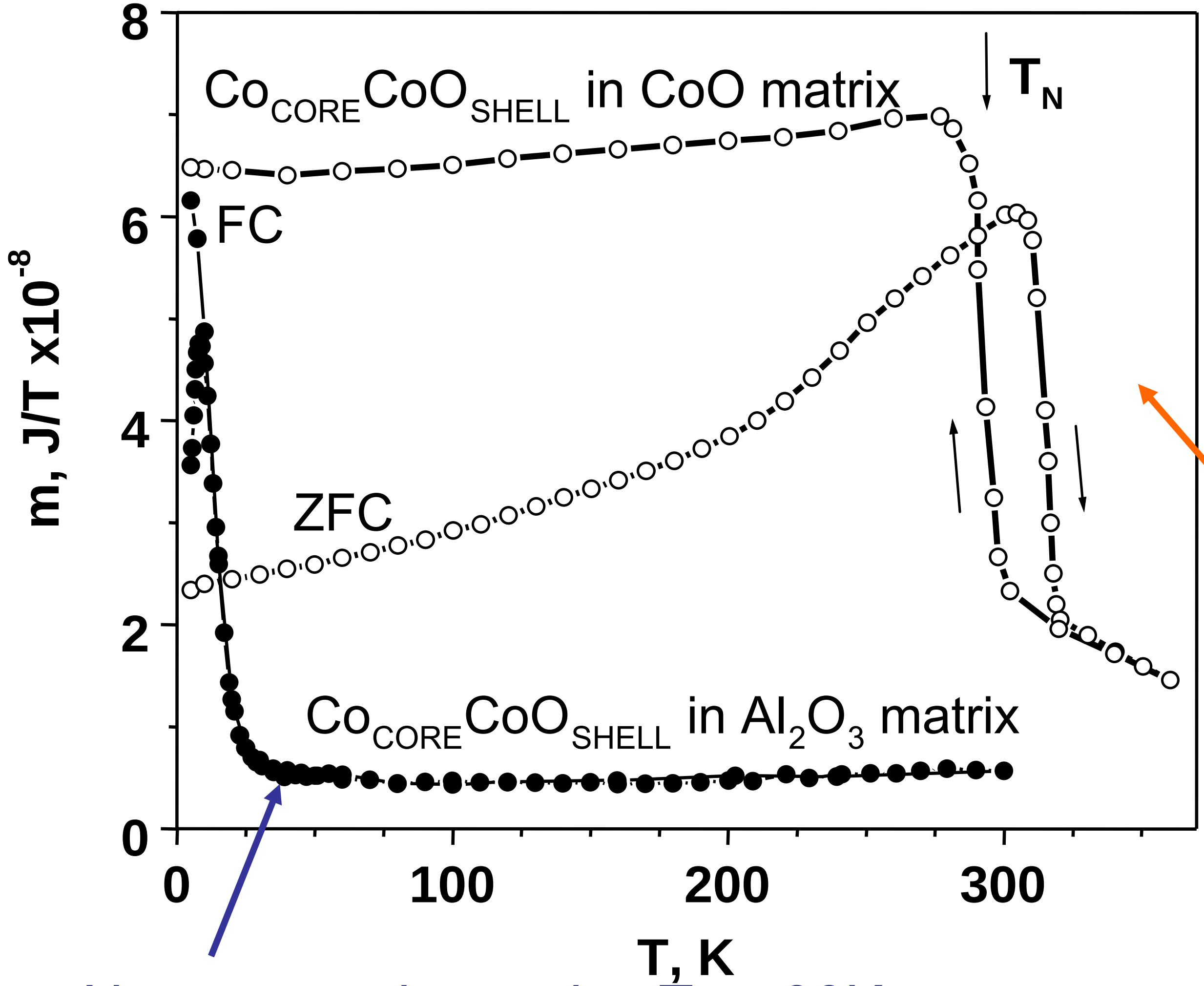
Co/Au(111)

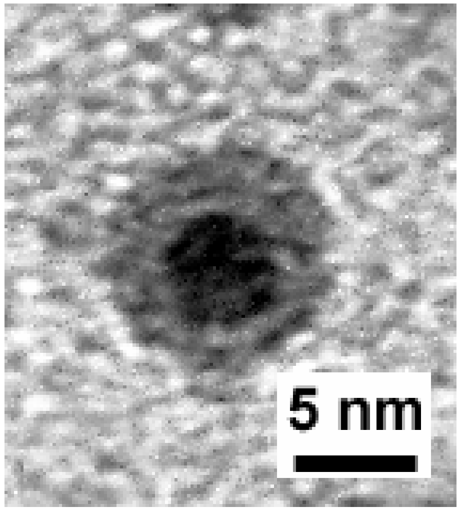




From O. Fruchart

3 - Nanoparticle coupling to an antiferromagnetic matrix





AFM matrix

$T_B \approx T_N$ CoO

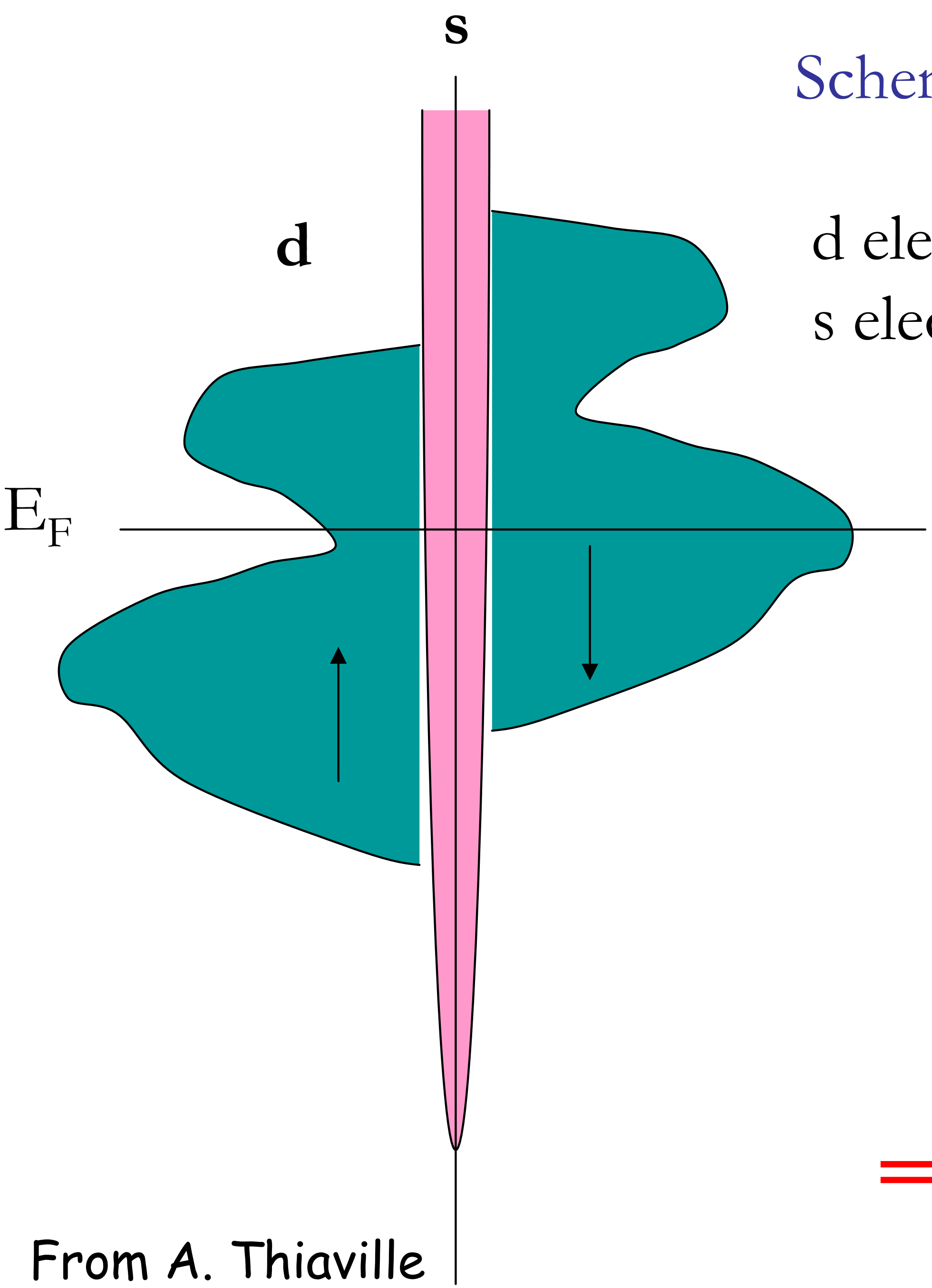
Non-magnetic matrix : $T_B \approx 30K$

V.Skumryev, et al., Nature 423, 850 (2003)

Open questions in magnetism

- Fundamental questions
- Nanomagnetism
- Spintronics and fast reversal
  - Transport
  - Broken junctions
  - Current driven reversal
  - Fast magnetization reversal
  - Numerical modelling
- Materials
- Experimental developments

Magnetism and transport



From A. Thiaville

Schematic model of the 3D magnetic metals :

d electrons : localized, magnetism
s electrons : delocalized, transport

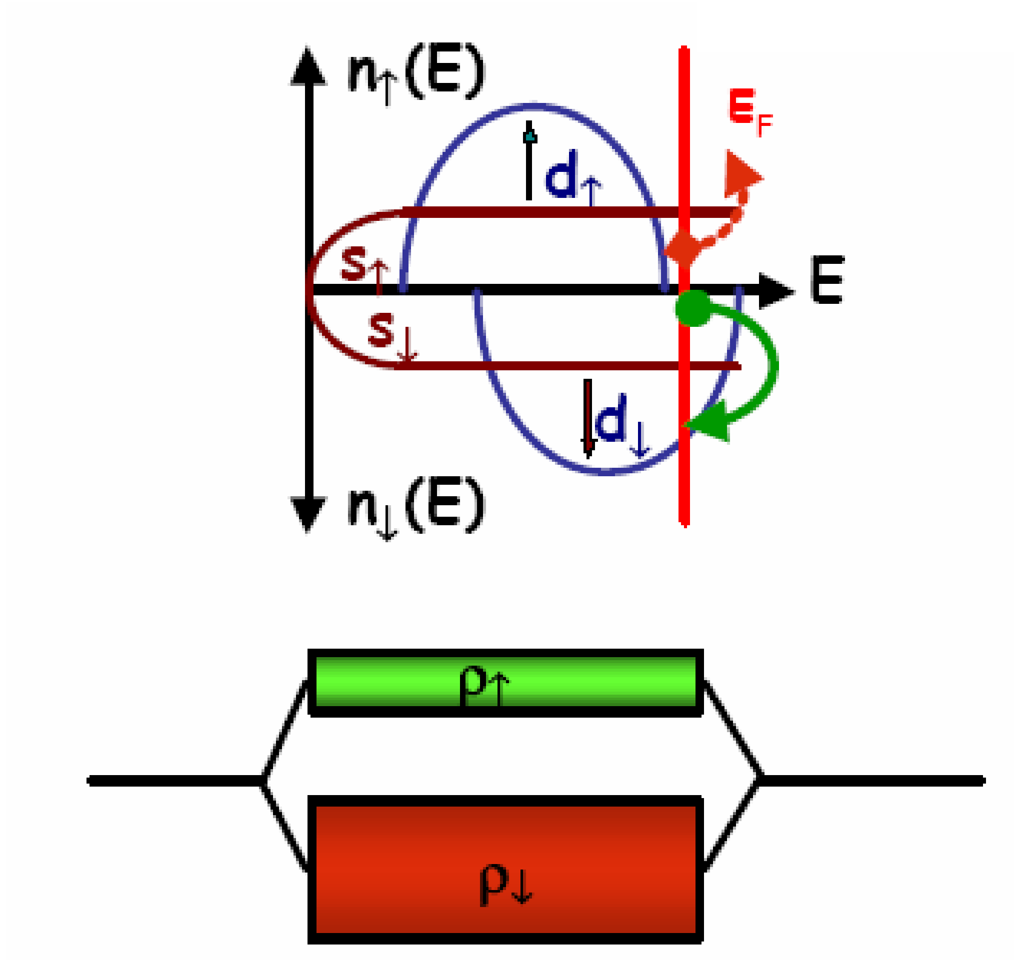
$$\sigma = \frac{ne^2\tau}{m}$$

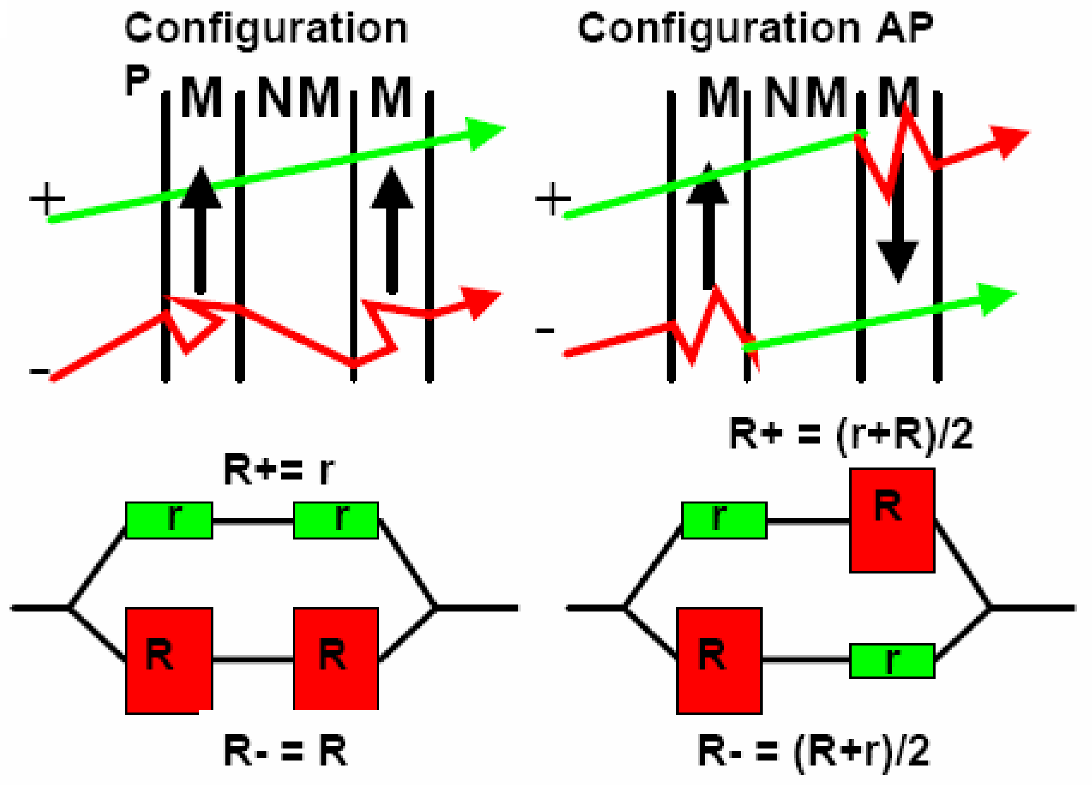
$$\frac{1}{\tau} = \frac{2\pi}{\hbar}\left|V_{diff}\right|^2 k_B T \, N(E_F)$$

⟹ 2-current model

Two-curent model

Mechanism of GMR



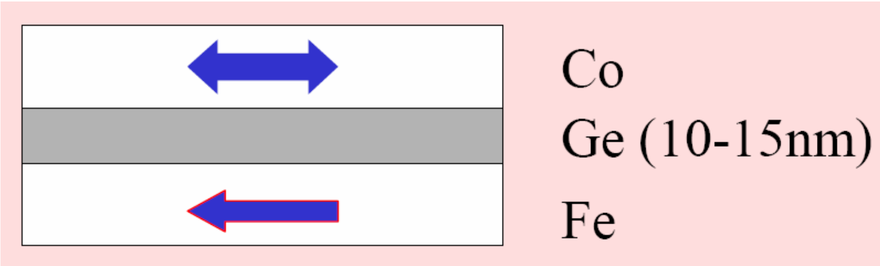


$$R_P = \frac{Rr}{R+r} \approx r \ < \ R_{AP} = \frac{R+r}{4}$$

from A. Barthélémy

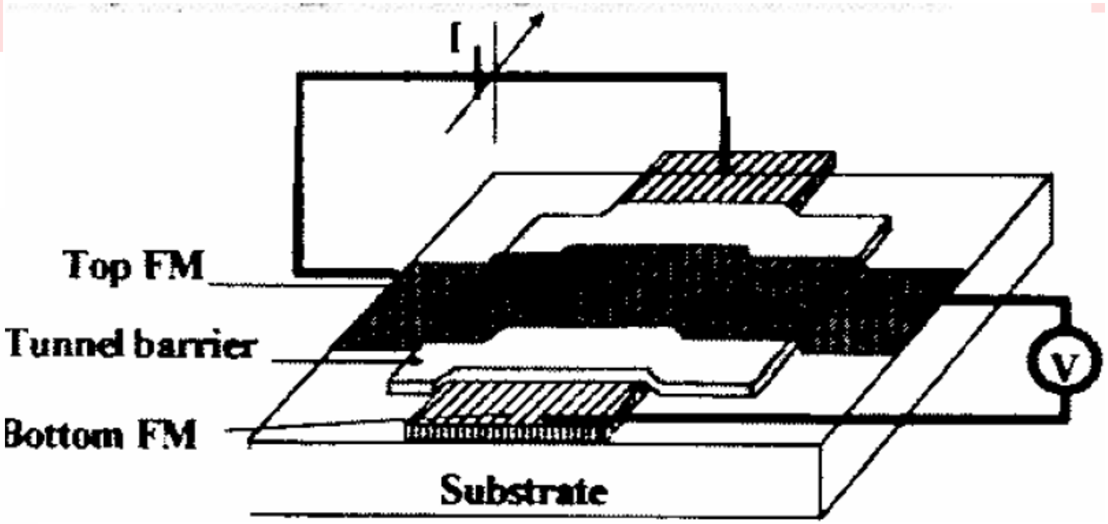
M. N. Baibich, J. M. Broto, A. Fert, F. N. Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas
Phys. Rev. Lett. **61**, 2472-2475 (1988)

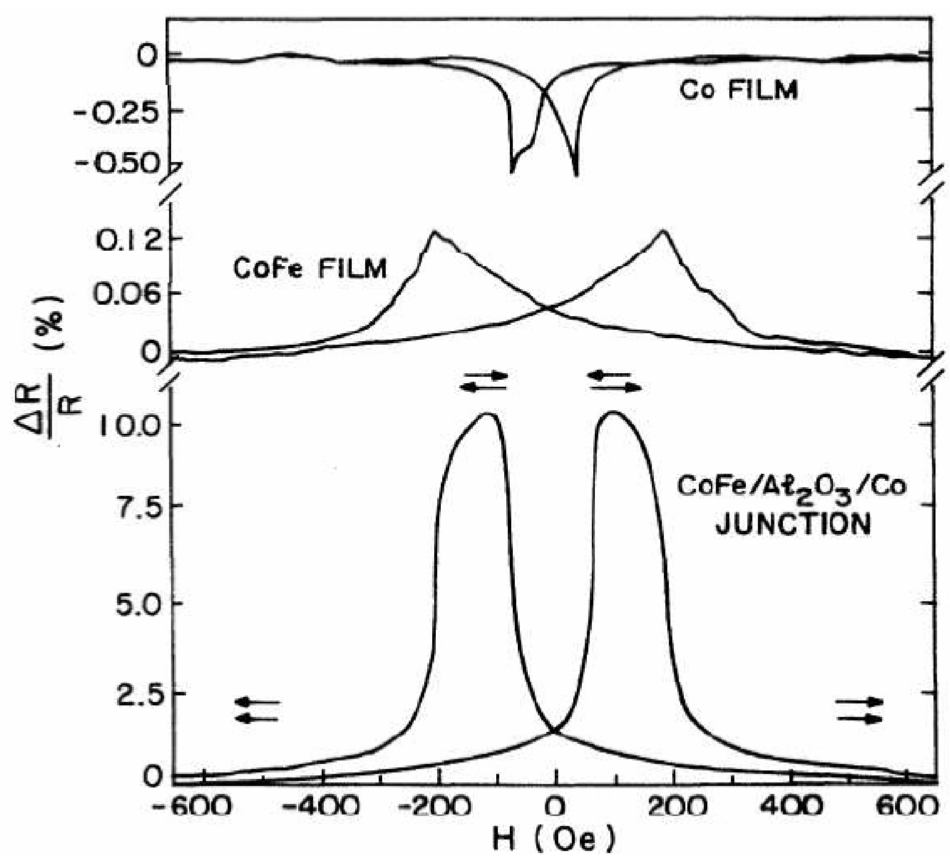
Tunnel Magnetoresistance



M. Jullières, Phys. Lett. (1975)

J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey
Phys. Rev. Lett. **74**, 3273-3276 (1995)

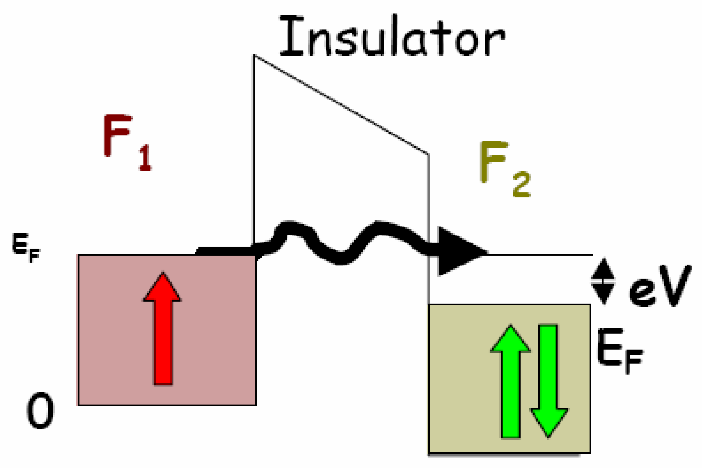




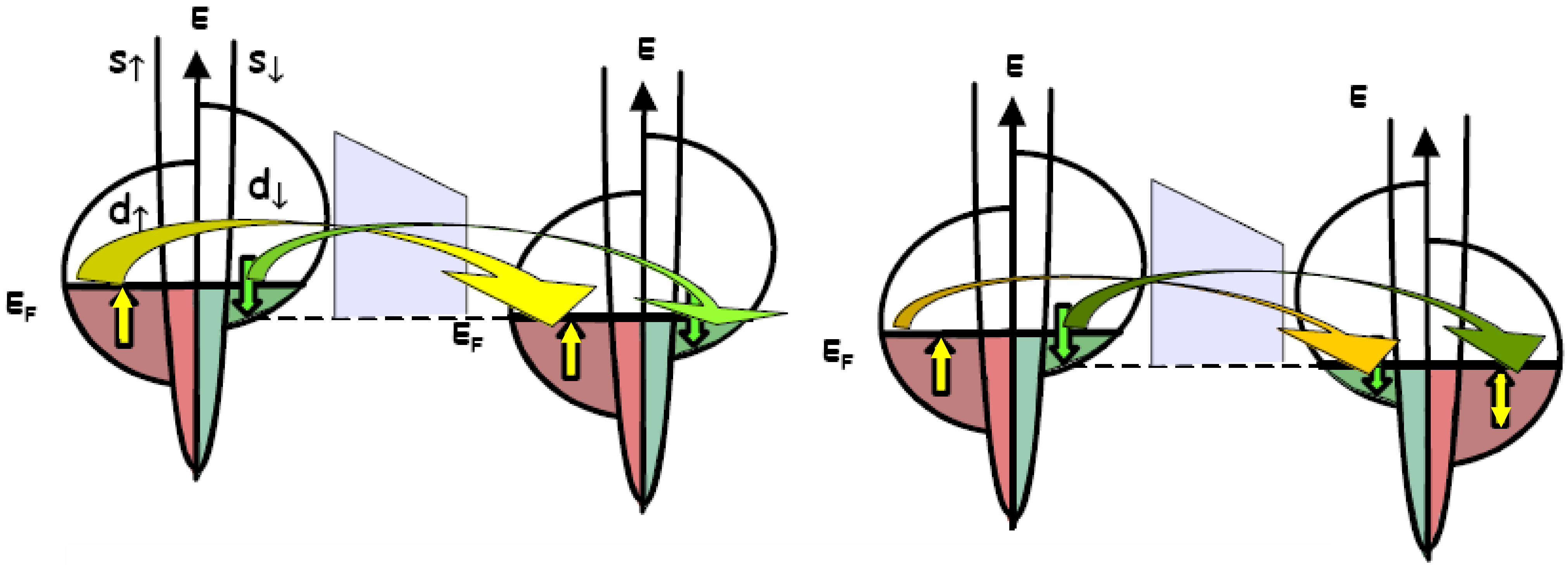
$$\frac{\Delta R}{R} \approx 12\%$$ at 300 K

$$\frac{\Delta R}{R} \approx 24\%$$ at 4.2 K

Origin of TMR

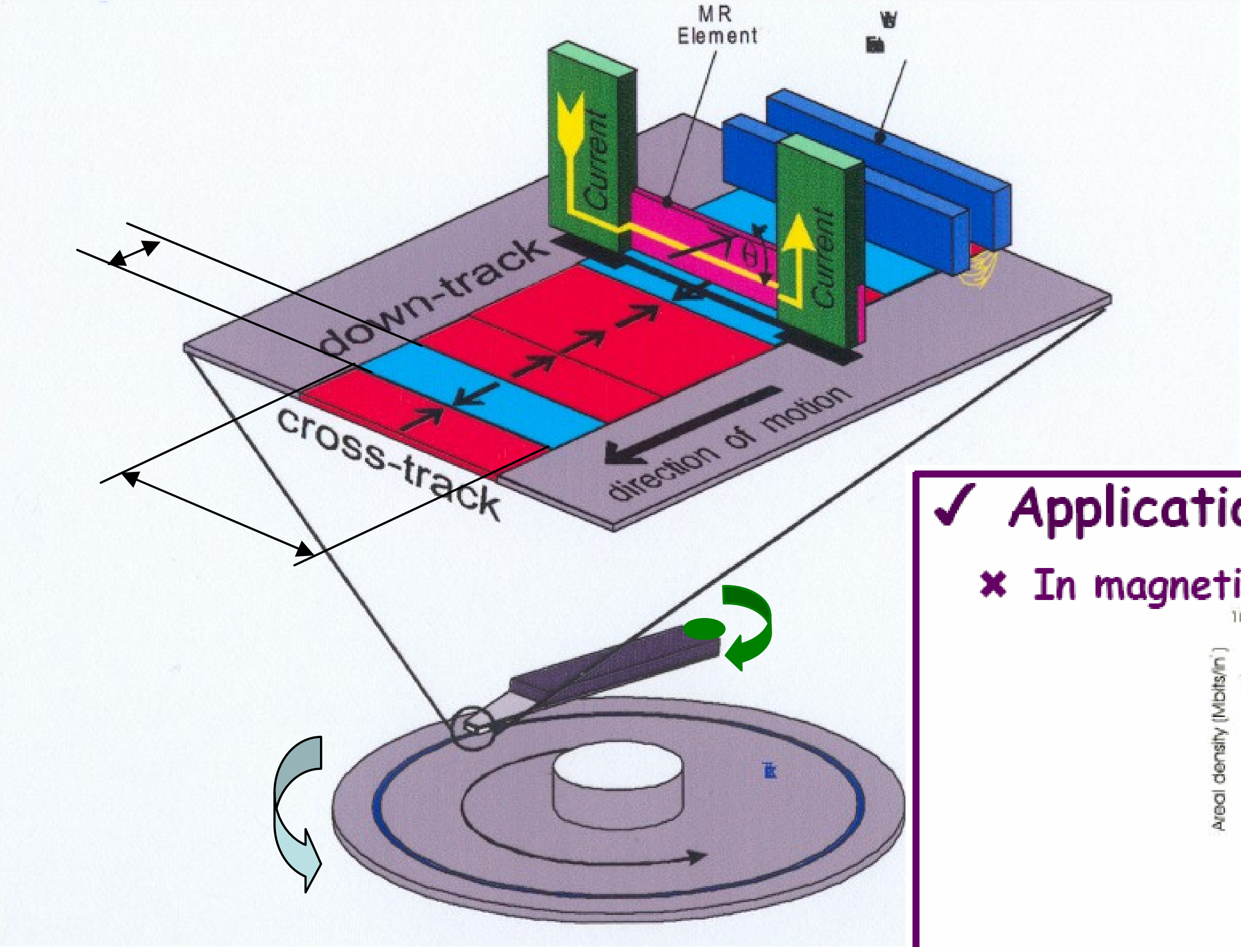


Electronic states extend through barrier
Spin-dependent hybridization



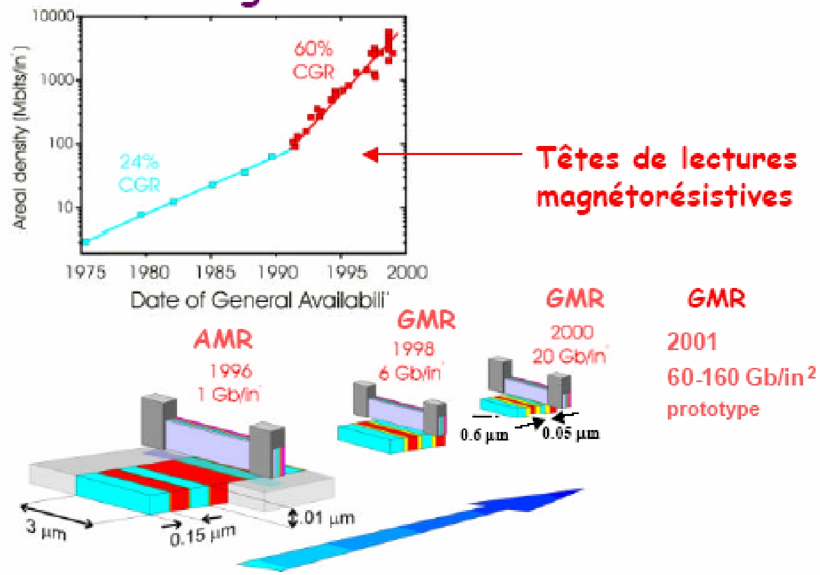
from A. Barthélémy

GMR Heads for reading magnetic information

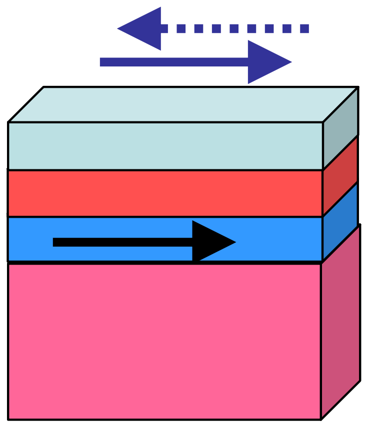


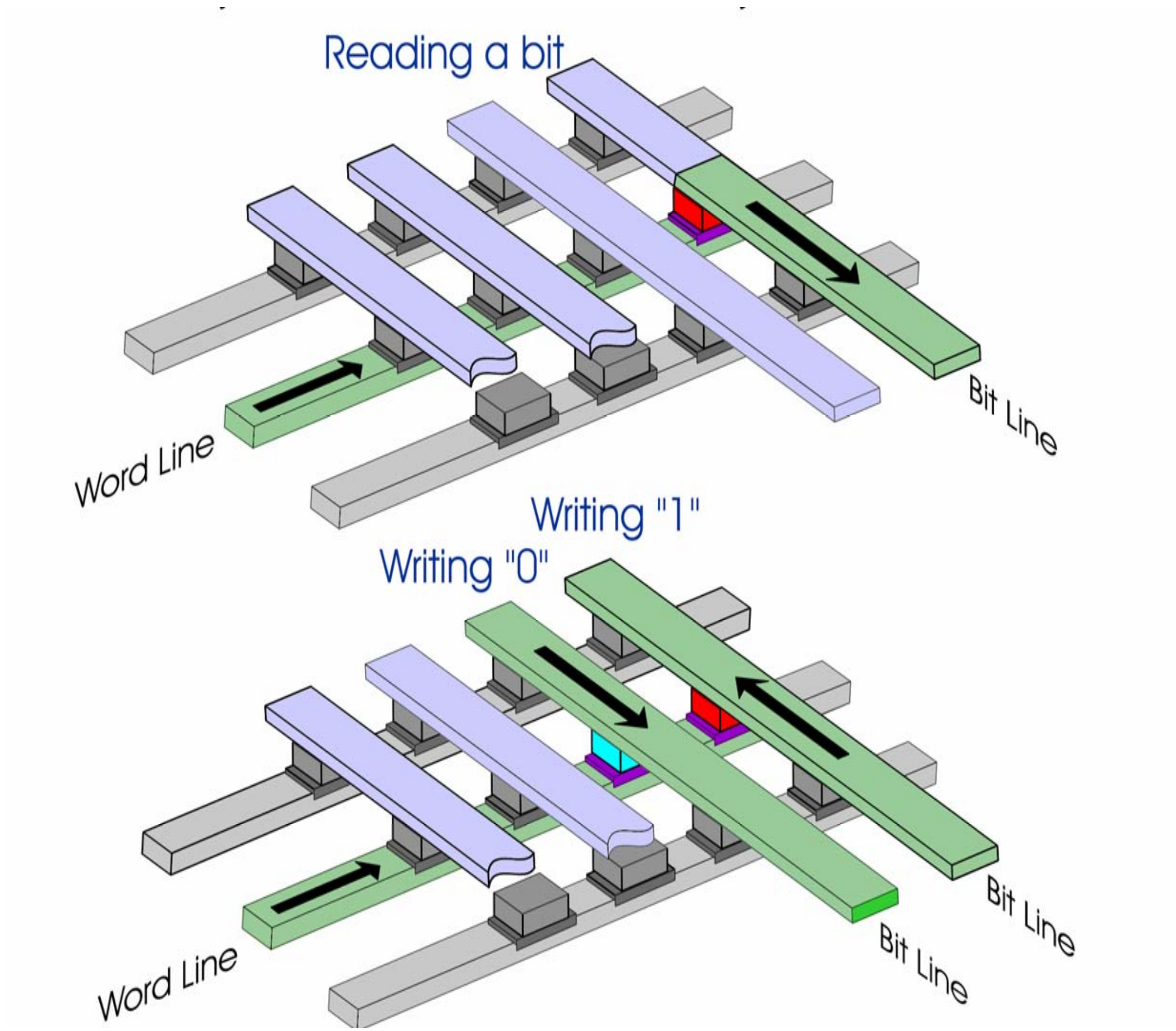
✓ Applications of GMR

- In magnetic recording



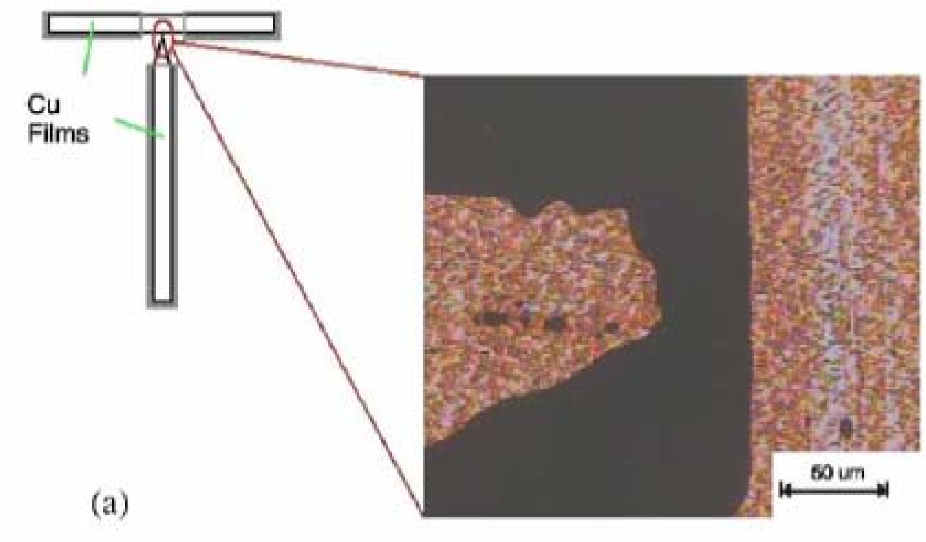
MRAMs : Magnetic Random Access Memories

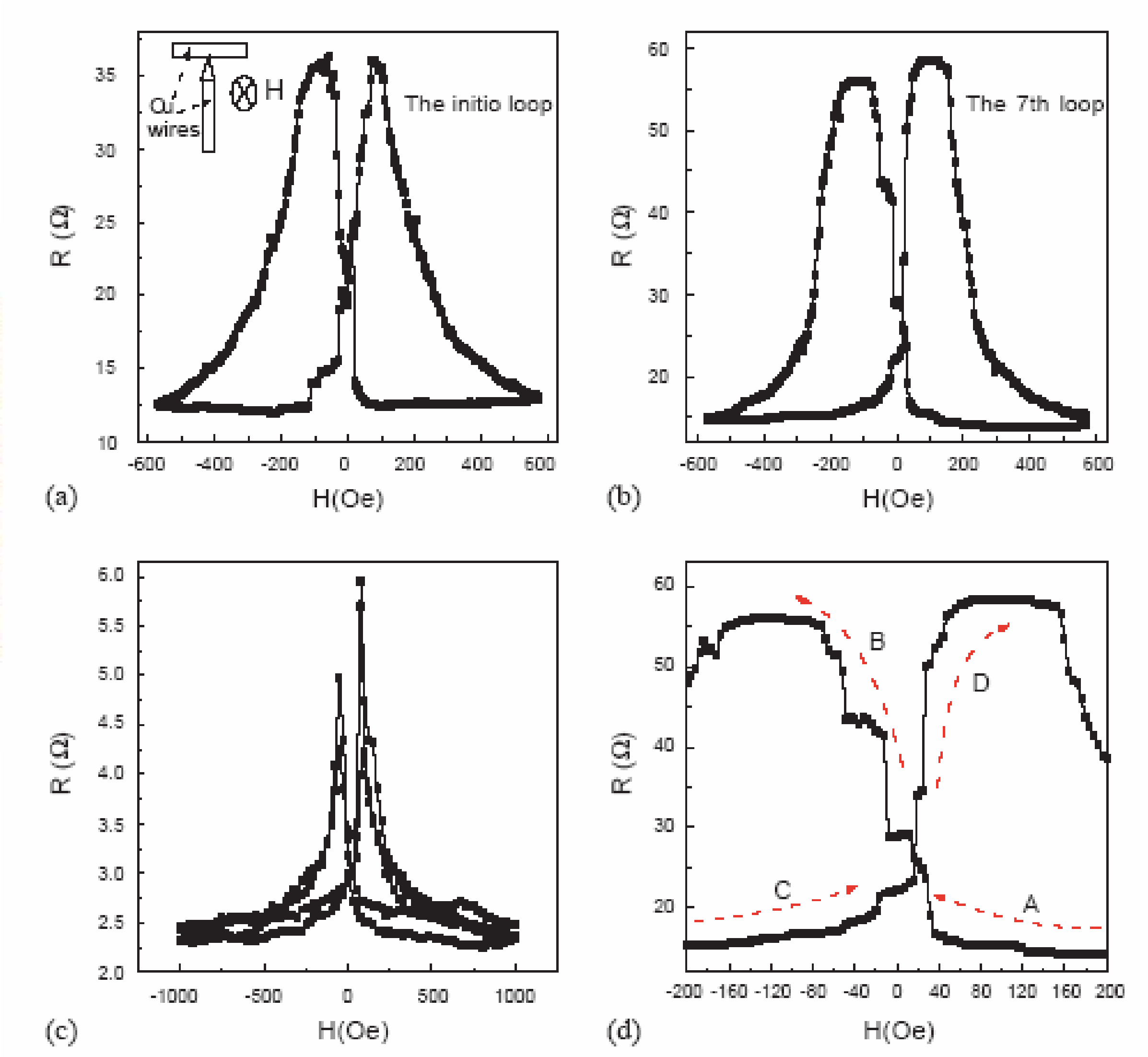


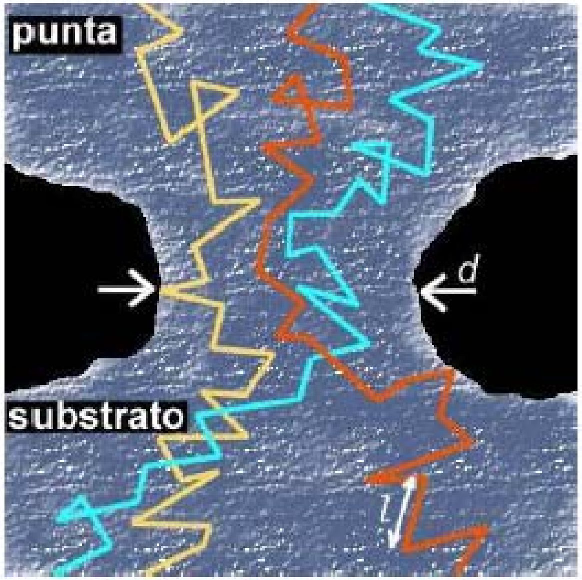


Ballistic magnetoresistance

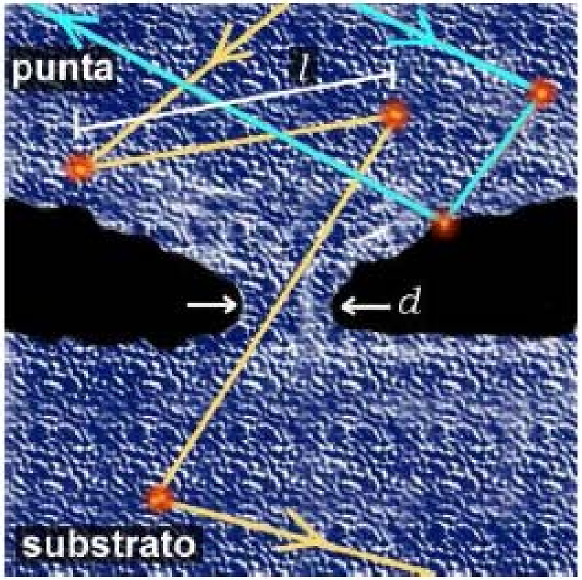
N. Garcia, M. Munoz, Y.-W. Zhao, Phys.Rev. Lett. 82 (1999) 2923;
N. Garcia et al. JMMM 272-276 (2004) 1722-1729



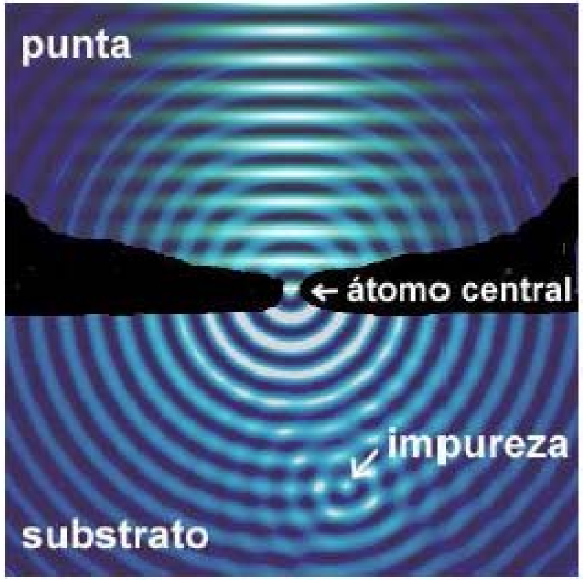




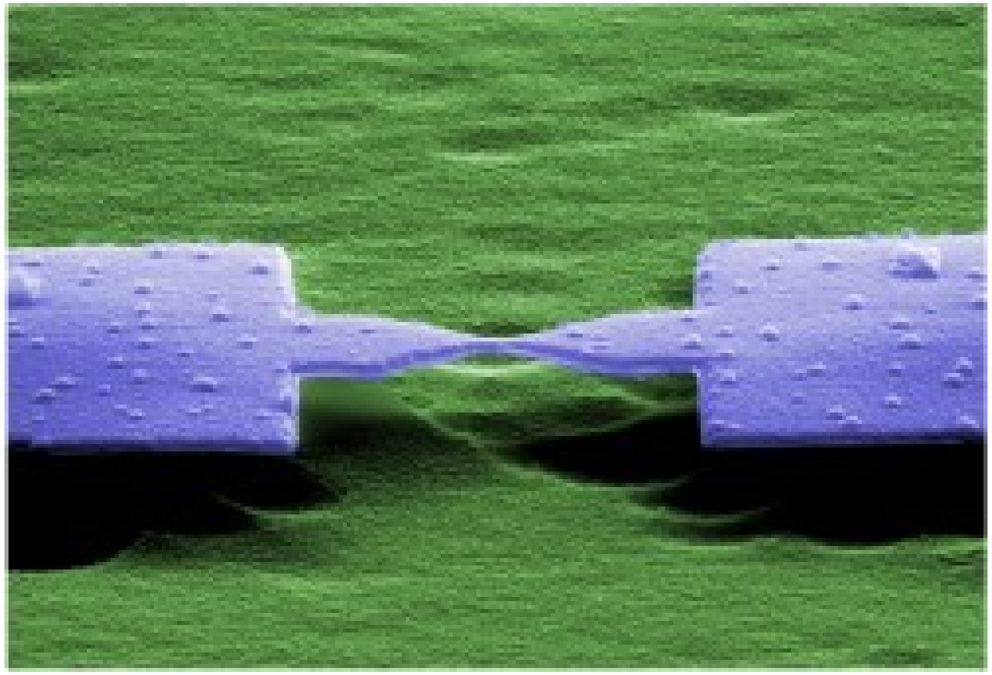
(Maxwell resistance)



(Sharvin resistance)

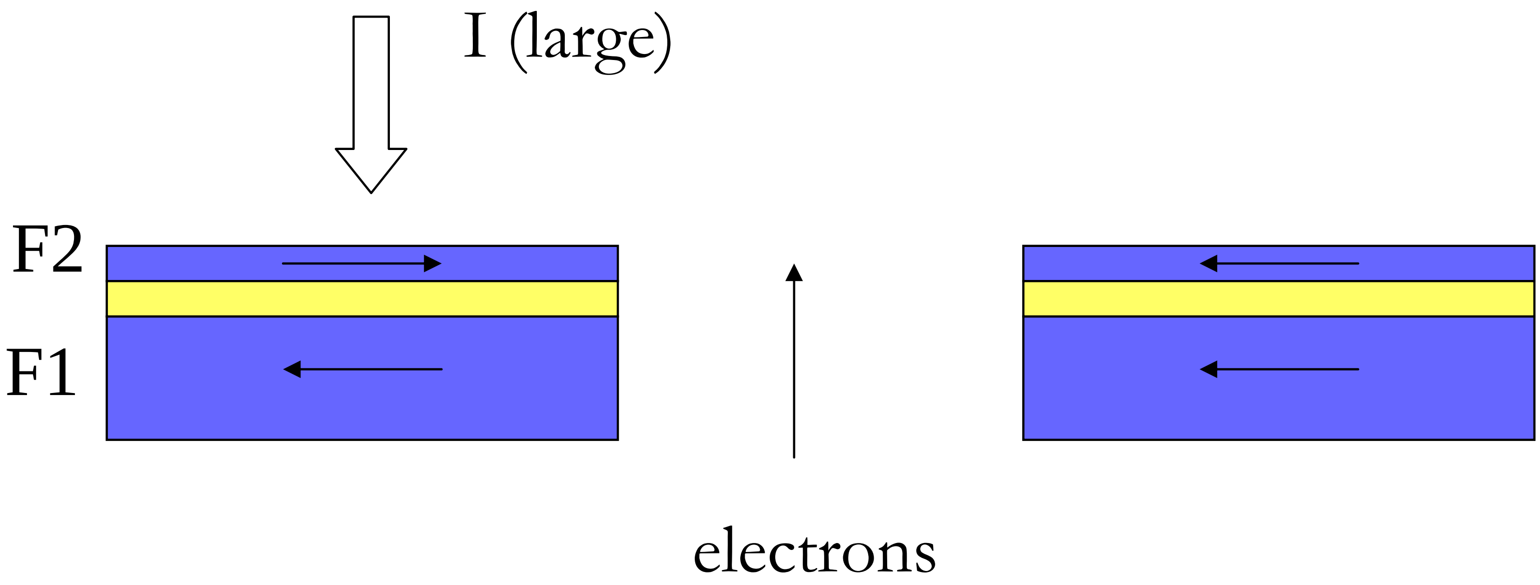


(Quantum regime)



From E. Scheer webpage

Spin transfer effects



Angular momentum transfer due to the reorientation of the spins of the conduction electrons

From A. Thiaville

Spin-polarized current switching of a Co thin film nanomagnet

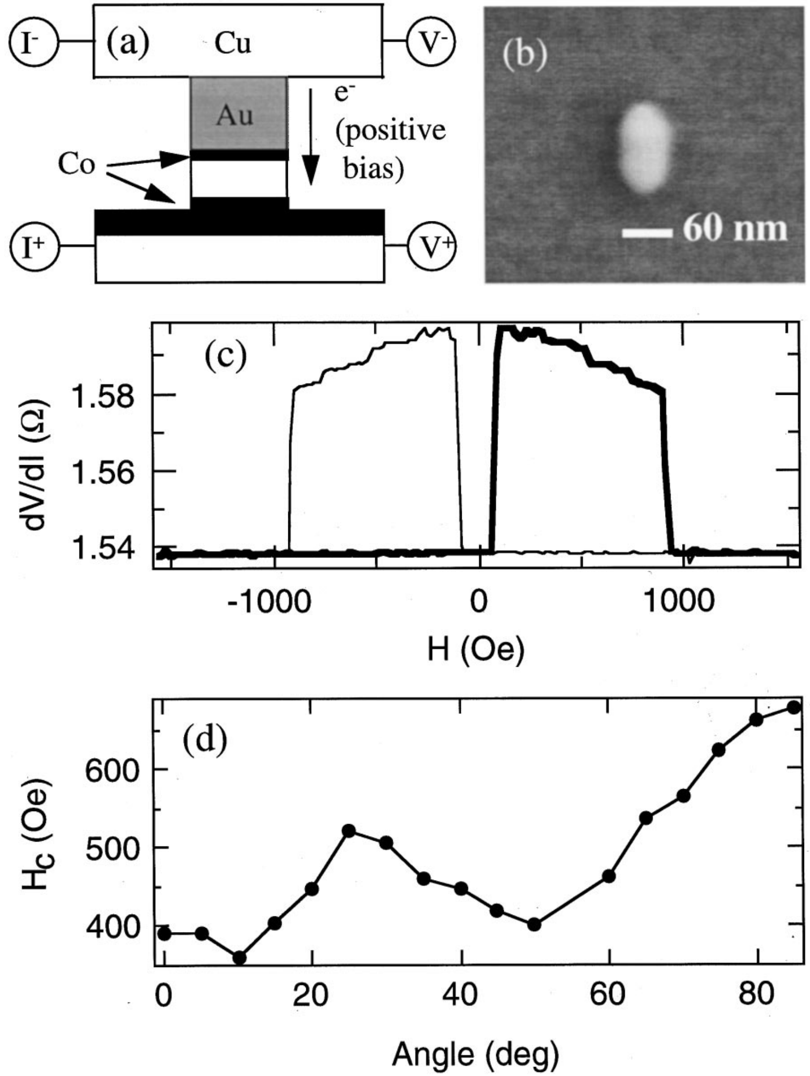
F. J. Albert, J. A. Katine and R. A. Buhrman

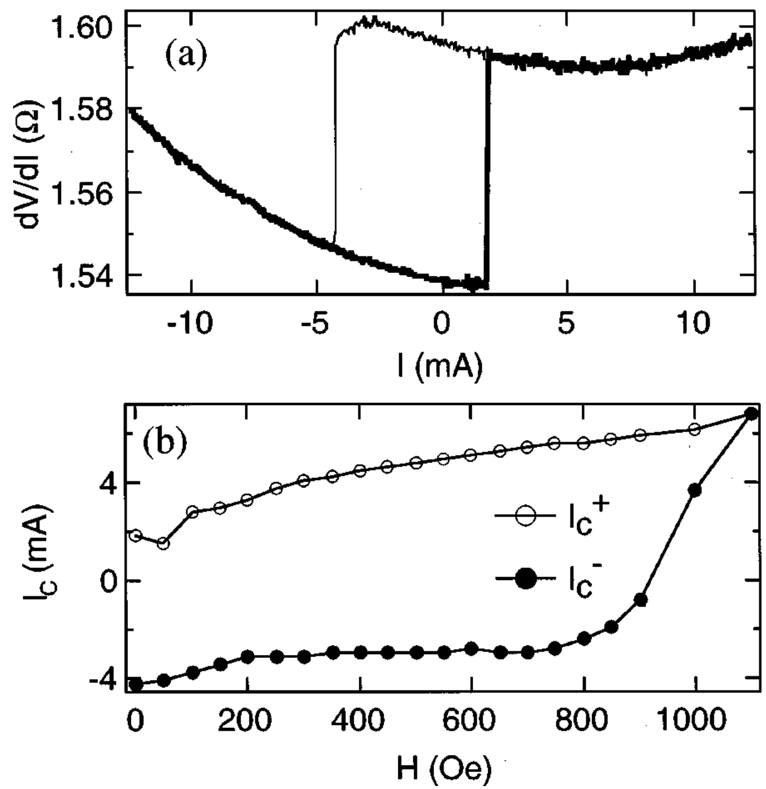
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853

D. C. Ralph

Laboratory of Atomic and Stolid State Physics, Cornell University, Ithaca, New York 14853

APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 23 4 DECEMBER 2000





From A. Thiaville

Precessional switching of a MRAM memory cell

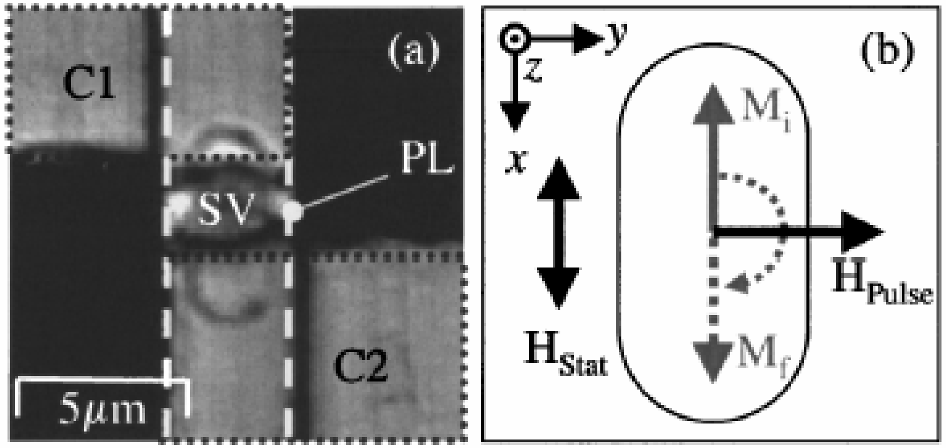
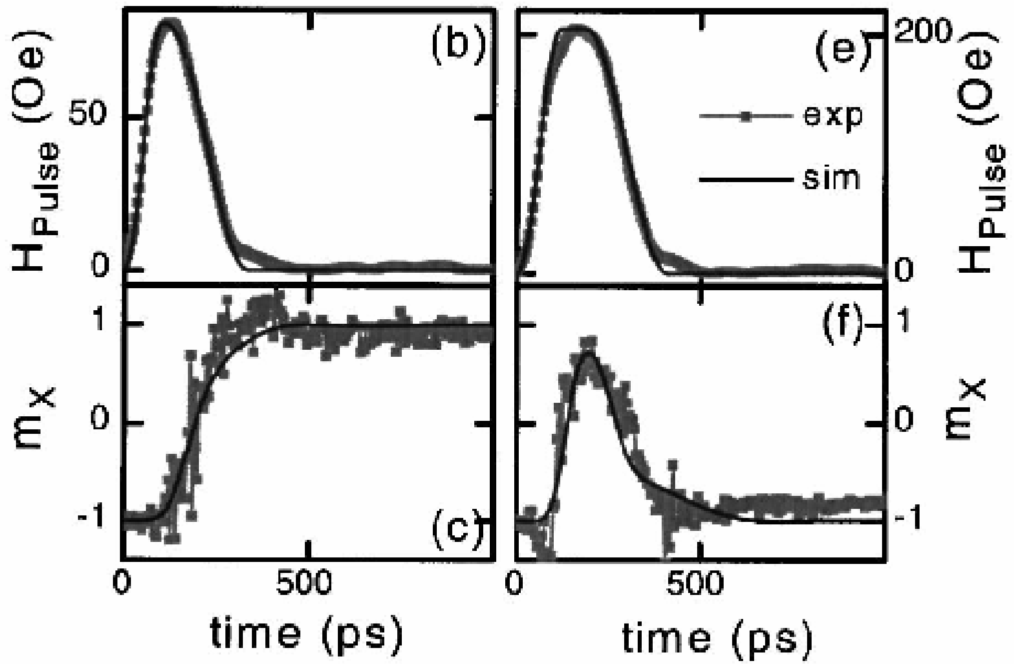


FIG. 1. Magnetic memory cell used in the experiments. (a) Optical micrograph. Spin valve cell (SV) with electrical contacts (C1, C2, surrounded by the dotted lines) and buried pulse line (PL, marked by the white dashed line). (b) Sketch of the magnetic field configuration H_{pulse} (along y) is applied perpendicular to the initial and final magnetization $\boldsymbol{M}_i$, $\boldsymbol{M}_f$.



H= 81 Oe
T= 175 ps

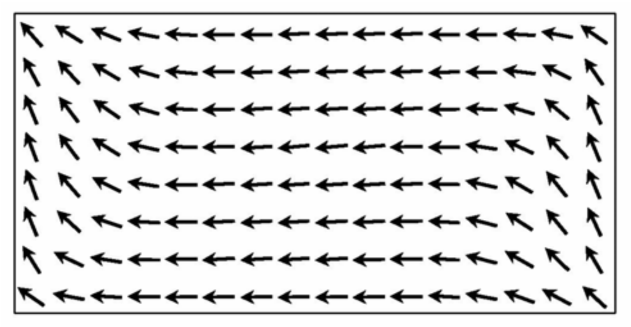
H= 205 Oe
T= 240 ps

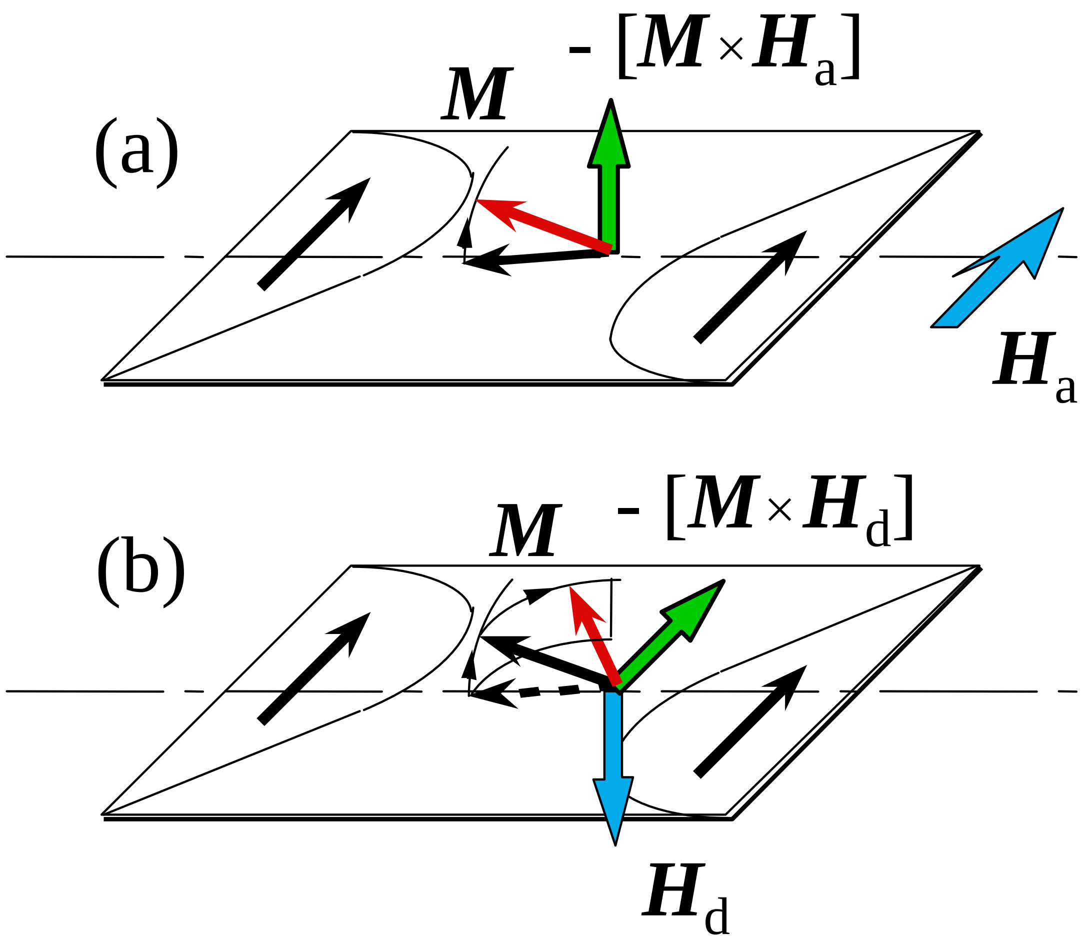
H.W. Schumacher et al.
Phys. Rev. Lett. **90** 017204 (2003)

From A. Thiaville

Precessional reversal of small elements

NiFe 500x 250x 5 nm, « S » state





Numerical modelling has become
one of the important elements
in the analysis of
the experimental properties

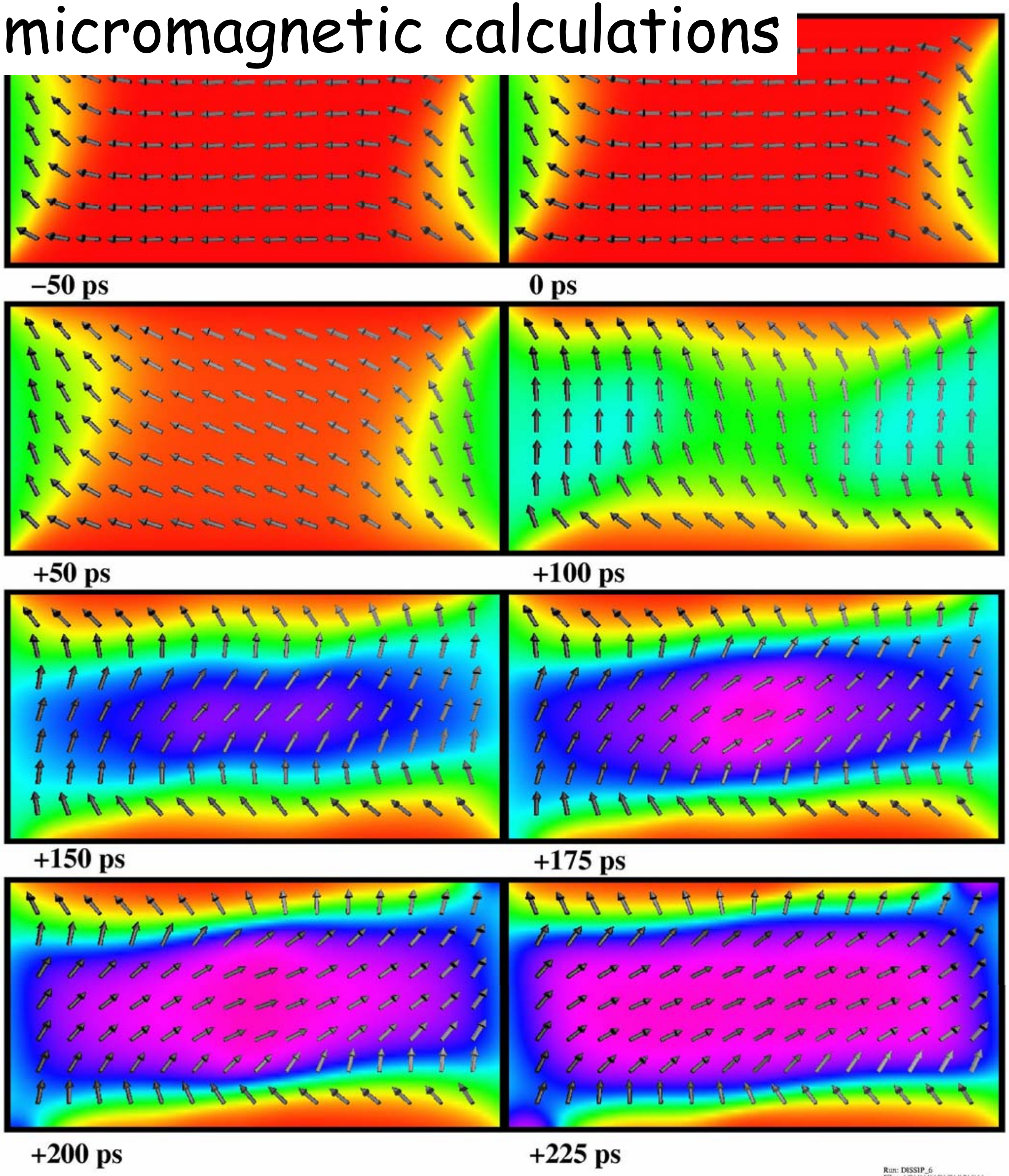
From A. Thiaville

J. Miltat, A. Thiaville Science (perspectives section) **290** 466 (2000)

Time-resolved micromagnetic calculations

(1) Initial phase :
quasi-coherent
reversal
250 ps

J. Miltat et al., in
Spin Dynamics in confined structures I,
B. Hillebrands and
K. Ounadjela Eds.
(Springer, 2002)



From A. Thiaville

Micromagnetic calculations

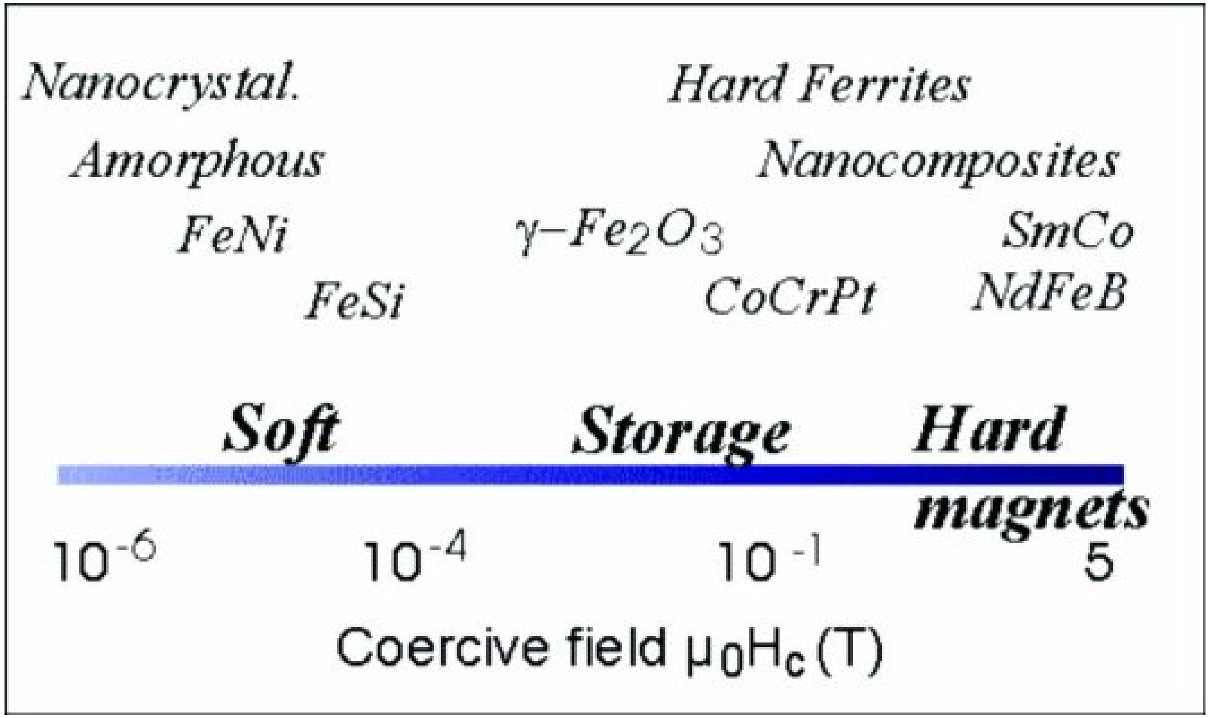
Some of the present questions :

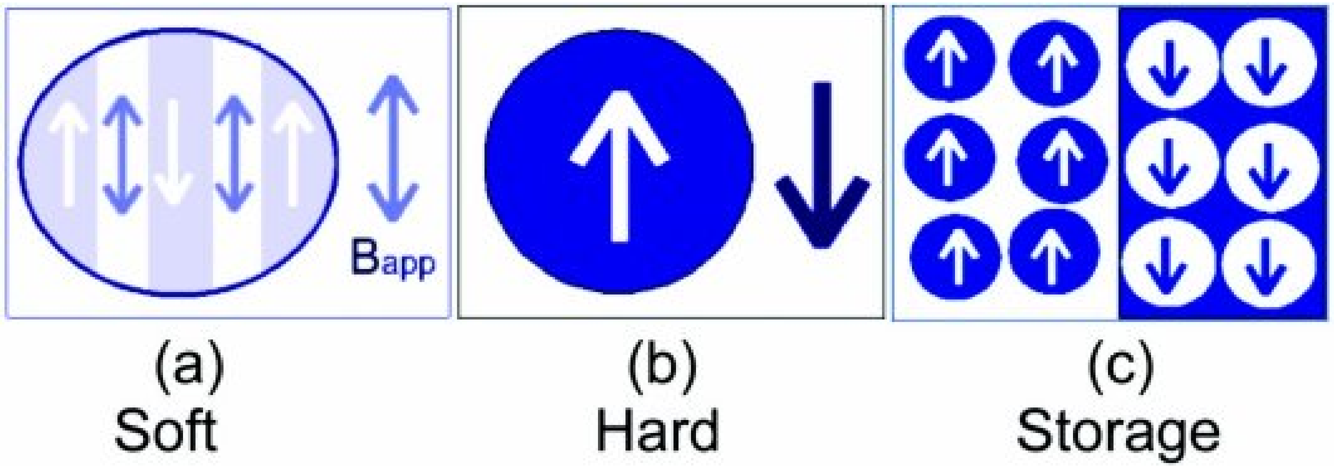
- Going towards larger size objects
- Finite difference approach versus finite-element approach
- Finite-temperature properties
- Mesh-size
- From macro-size to atomic level

Open questions in magnetism

- Fundamental questions
- Nanomagnetism
- Spintronics
- Materials
  - Soft/hard materials
  - Multiferroic
  - Electric control of magnetic properties
  - Magnetocaloric effects
  - Demagnetising field corrections in nanosystems
- Materials and their applications

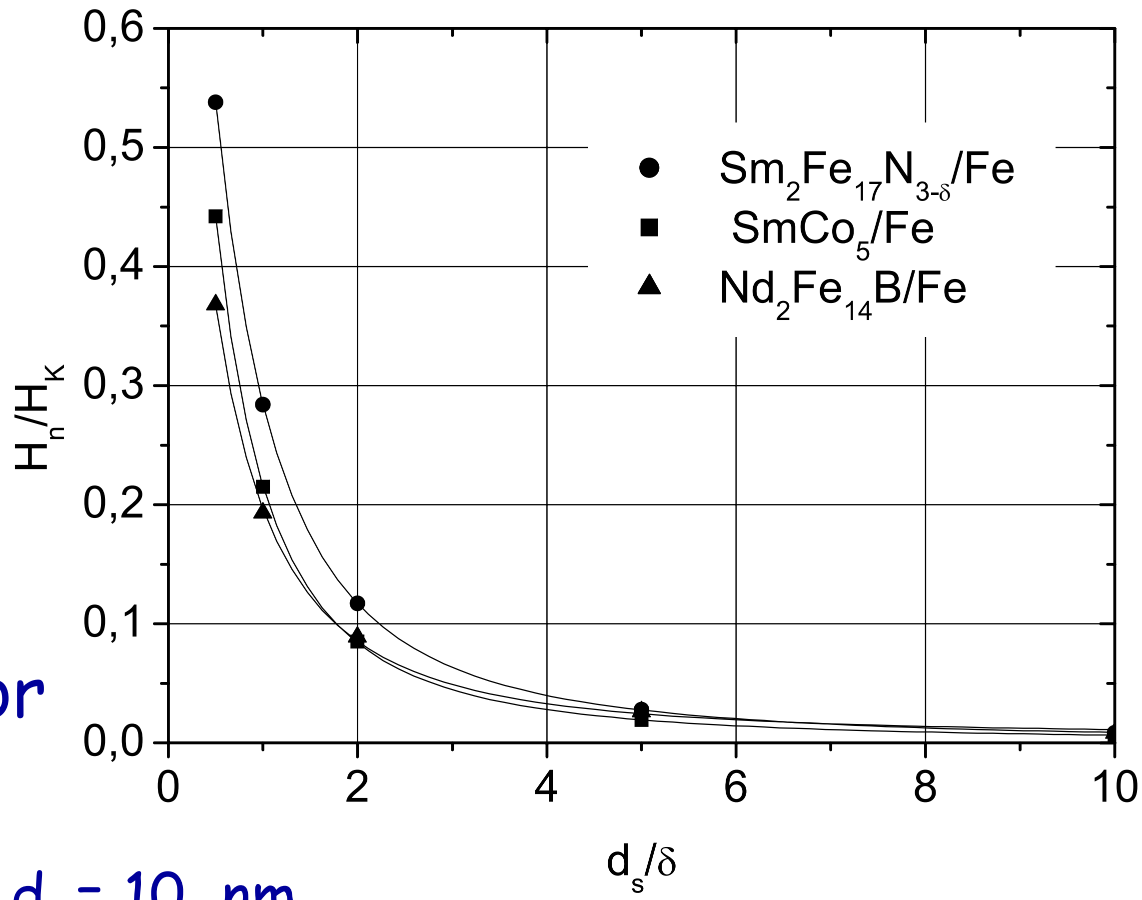
Magnetic materials and their properties





Prospect for improving hard nanocomposites ?

Skomski and Coey, Phys. Rev. B48 15812 (1993)



Thickness required for $\mu_0 H_n \approx 1T$

- $Sm_2Fe_{17}N_{3-\delta}$ /Fe : d_s = 10 nm
- $SmCo_5$/Fe : d_s = 10 nm
- $Nd_2Fe_{14}B$/Fe : d_s = 7.5 nm

Difficult objective, but does not seem impossible

Multi-ferroic Materials

Association of magnetism and ferroelectricity

Bi-based Perovskites : $BiMnO_3$, $BiFeO_3$
Rare-earth Manganites : $HoMnO_3$, $TbMn_2O_5$, $TbMnO_3$
YMnO3

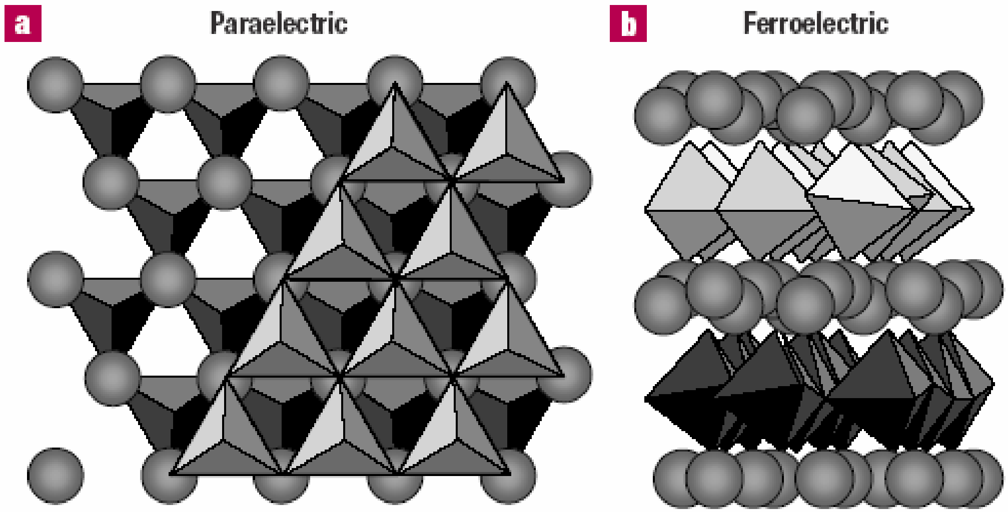
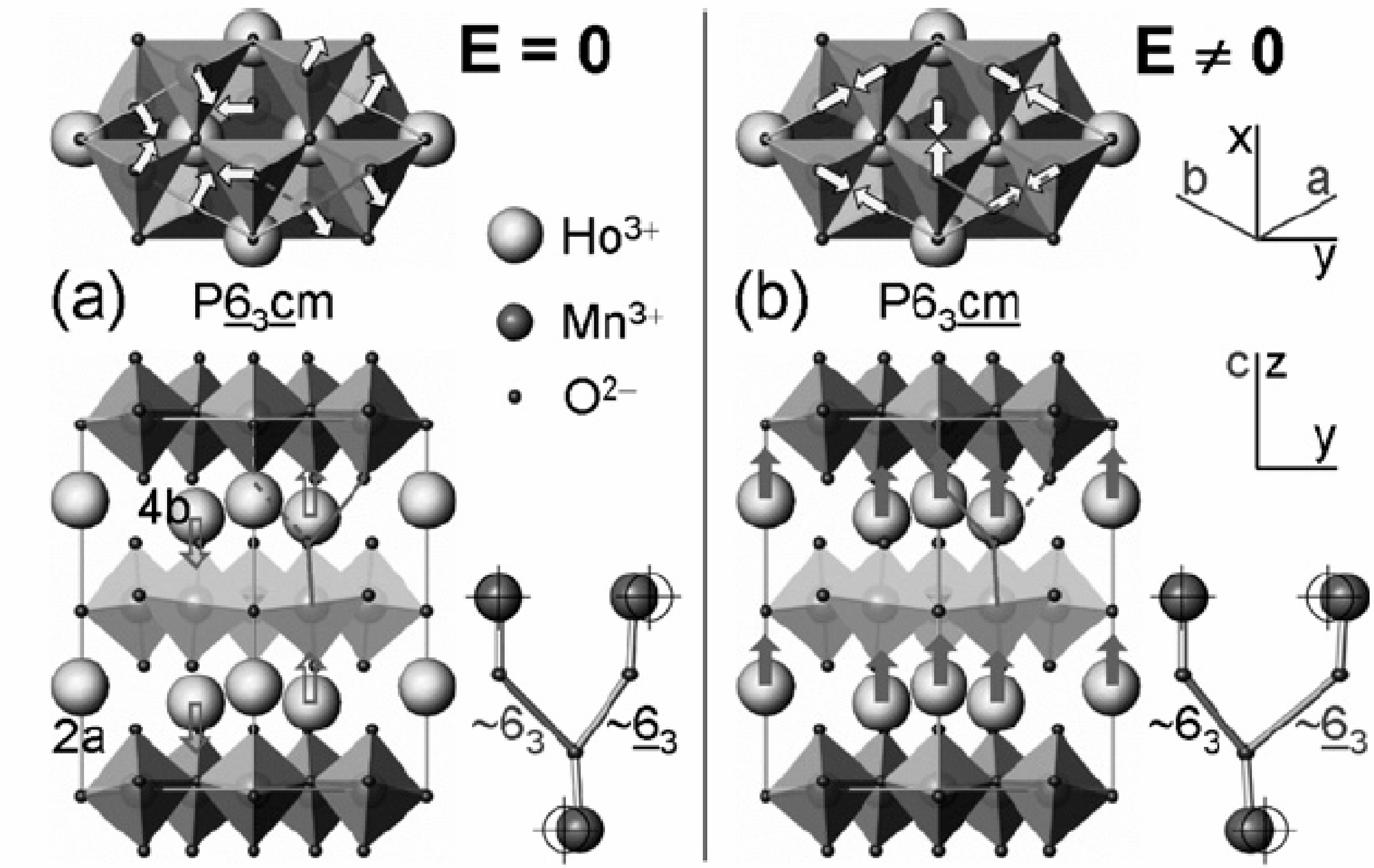


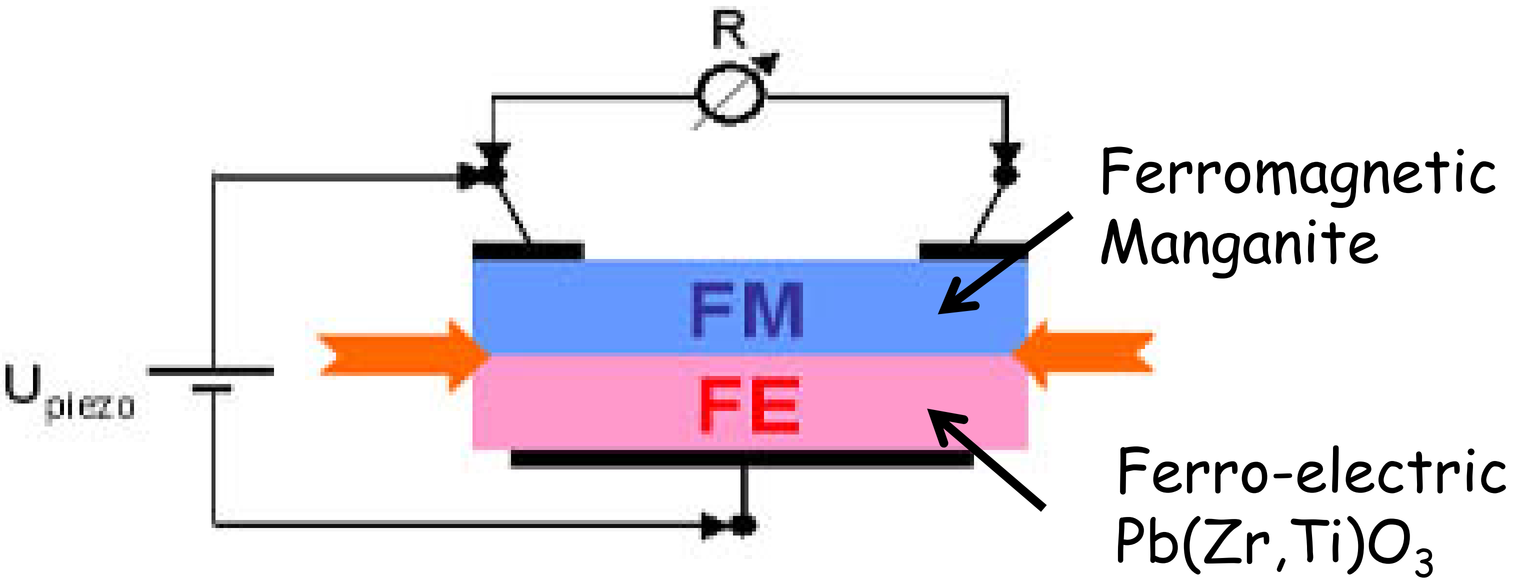
Figure 1 The crystal structure of $YMnO_3$ in the paraelectric and ferroelectric phases. The trigonal bipyramids depict MnO_5 polyhedra and the spheres represent Y ions. **a**, The stacking of two consecutive MnO_5 layers and the sandwiched Y layer, looking down the *c* axis in the paraelectric phase. **b**, A view of the ferroelectric phase from perpendicular to the *c* axis, showing the layered nature of $YMnO_3$.

- Orbital ordering
- Charge ordering
- Spin ordering
- Crystal structure

Magnetic phase control by an electric field in $HoMnO_3$.



Composite multiferroic materials



The ferroelectric (FE) piezocrystal induces a mechanical strain in the ferromagnetic (FM) manganite layer

⟹ Electrical conductivity and magnetization are modified

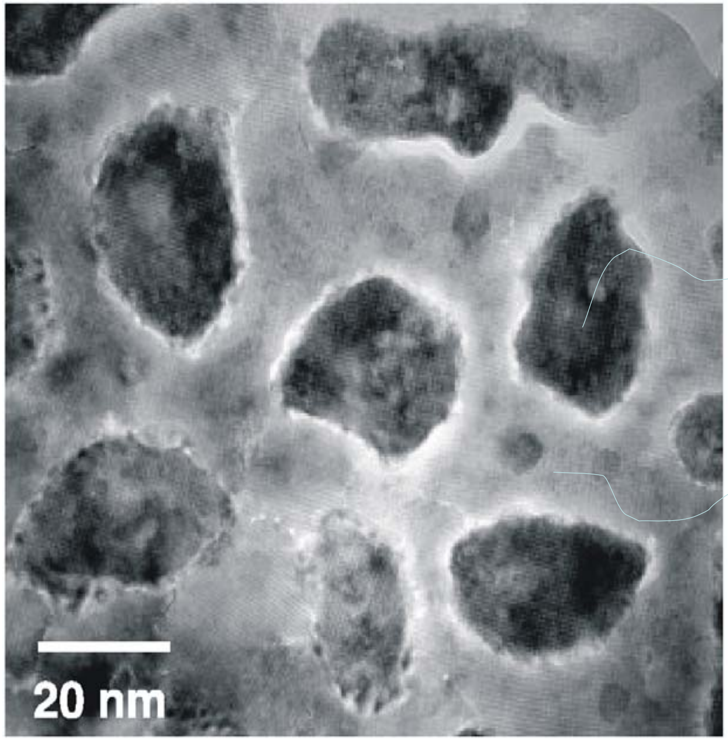
M. Fiebig, J. Phys. D: Appl. Phys. **38** (2005) R123-R152
N. A. Hill, J. Phys. Chem. B **2000,** 104, 6694-6709

Taken from K. Doerr

Towards epitaxial materials

Structure

$CoFe_2O_4$ in $BaTiO_3$ matrix

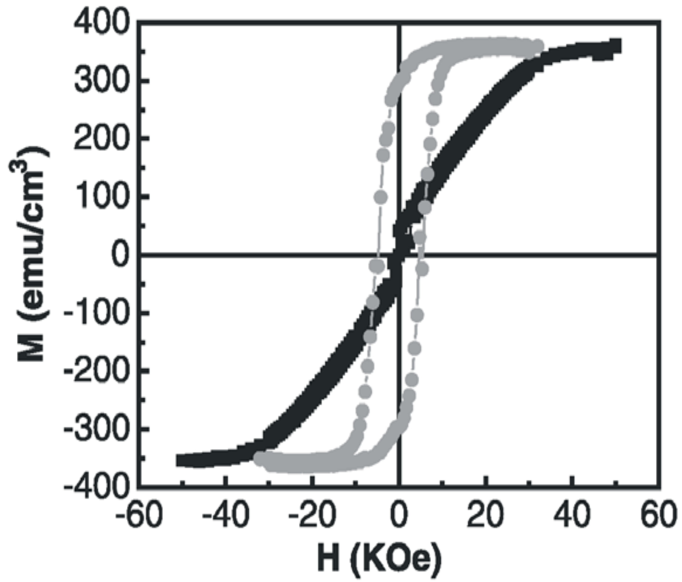


$CoFe_2O_4$
(ferrimagnetic)

$BaTiO_3$
(piezzoelectric)

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

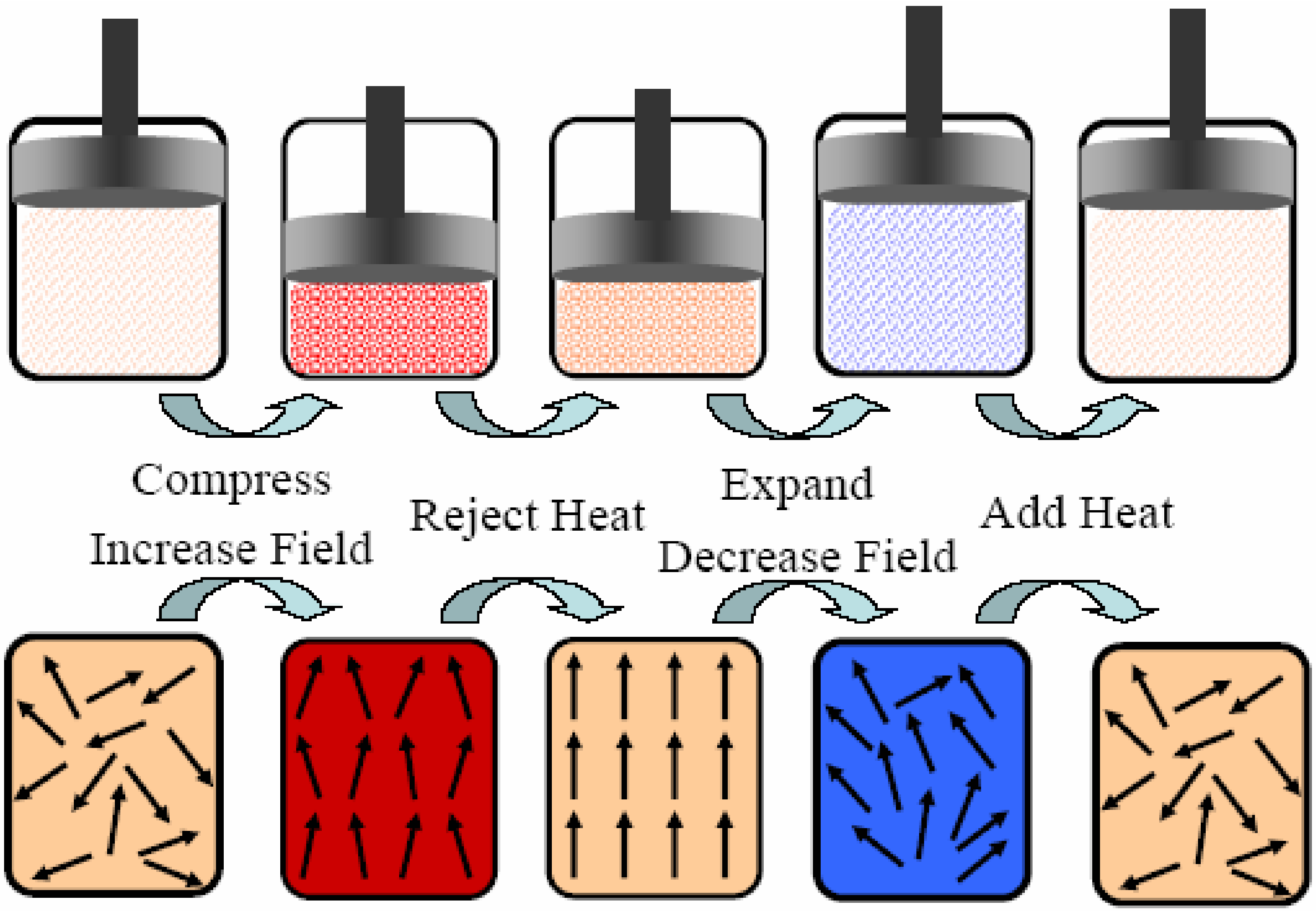
Magnetis m



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

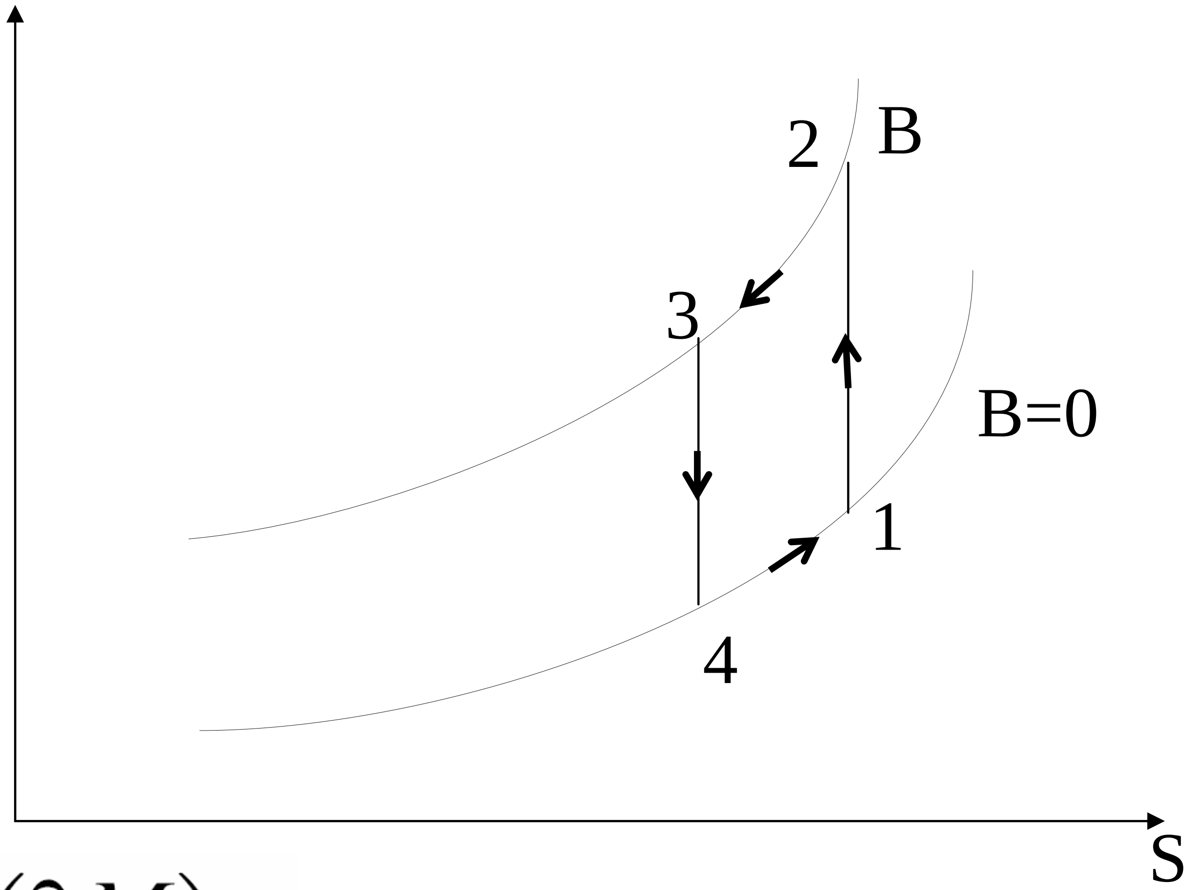
H. Zheng et al., Science 303, 661 (2004)

Magnetocaloric materials



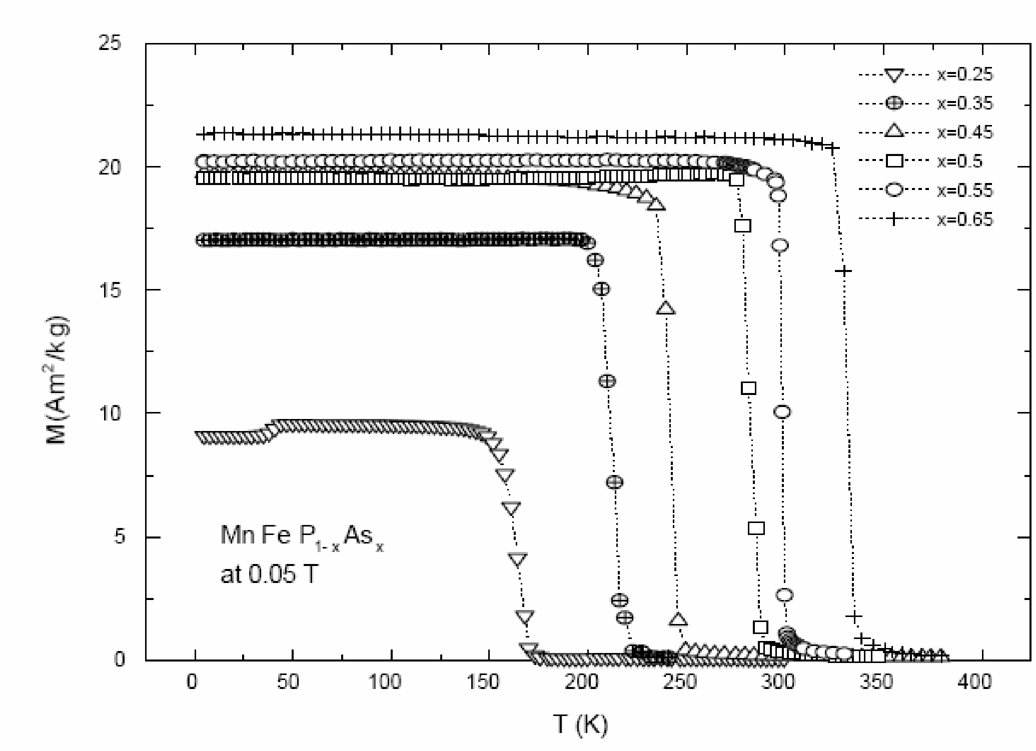
Principle of magnetic refrigeration

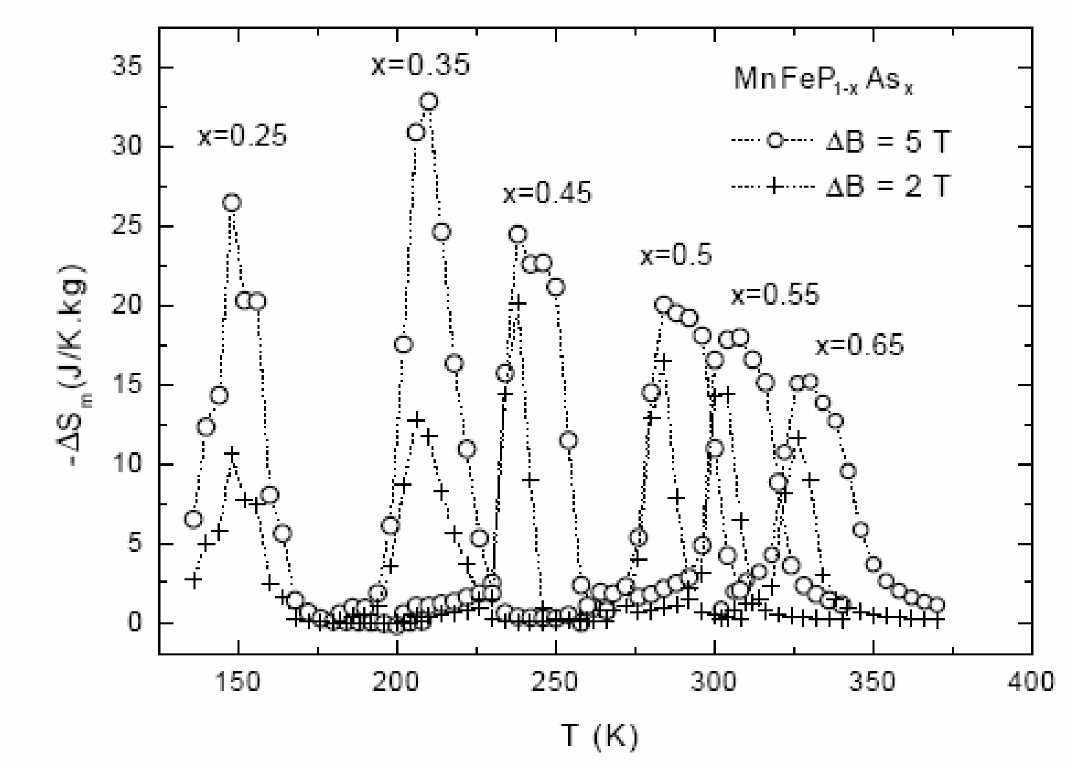
Magnetocaloric cycle



$$\left(\frac{\partial S}{\partial B}\right)_T = \left(\frac{\partial M}{\partial T}\right)_B$$

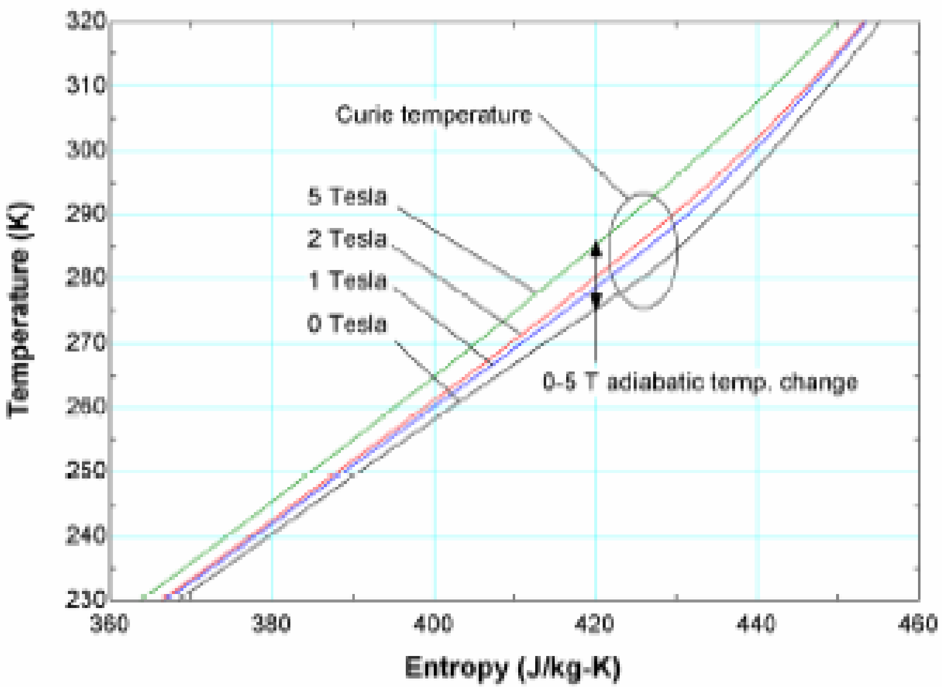
First-order magnetic transition in $MnFeP_{1-x}As_x$

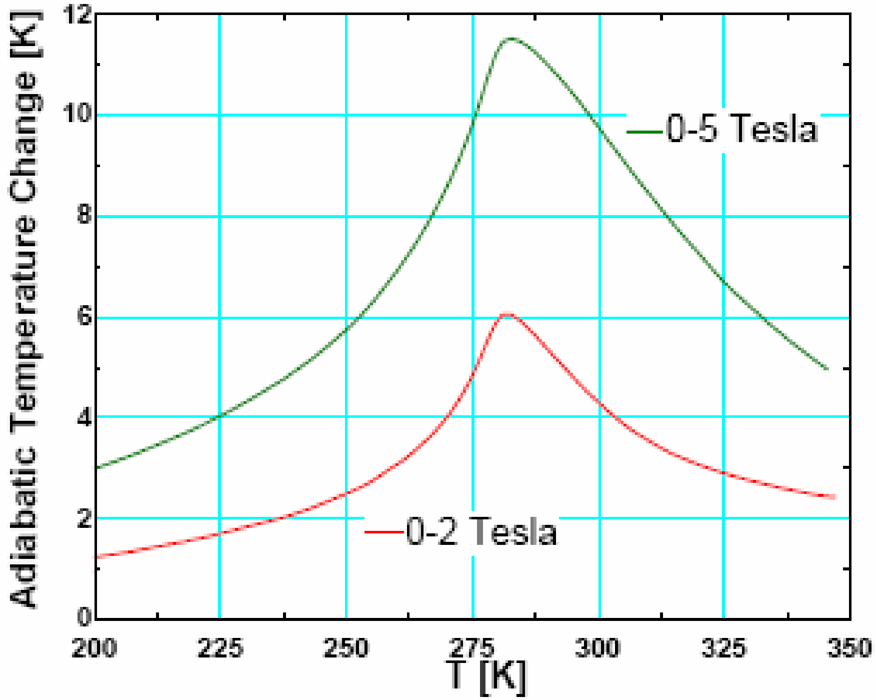




$$\left(\frac{\partial S}{\partial B}\right)_T = \left(\frac{\partial M}{\partial T}\right)_B$$

O. Tegus et al. / Physica B 319 (2002) 174–192

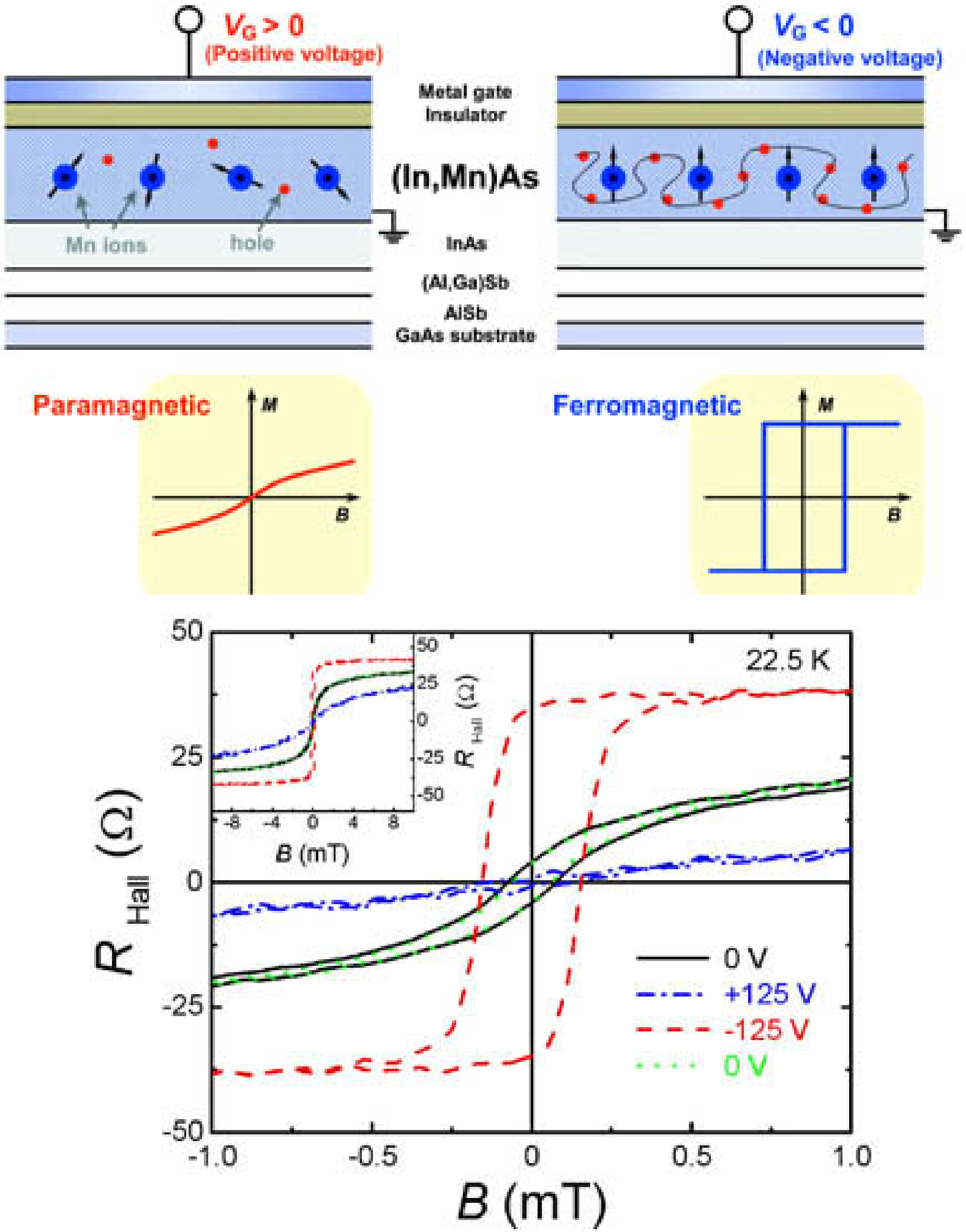




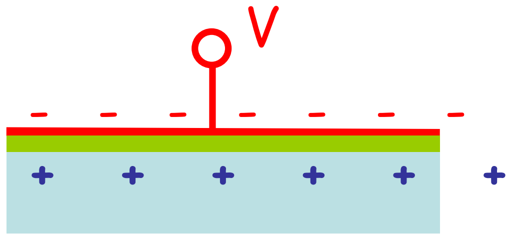
- Coupling between magnetic field and entropy
- Effect is greatest at the Curie point of the magnetic material which can be adjusted by alloying

Electric field control of magnetic properties

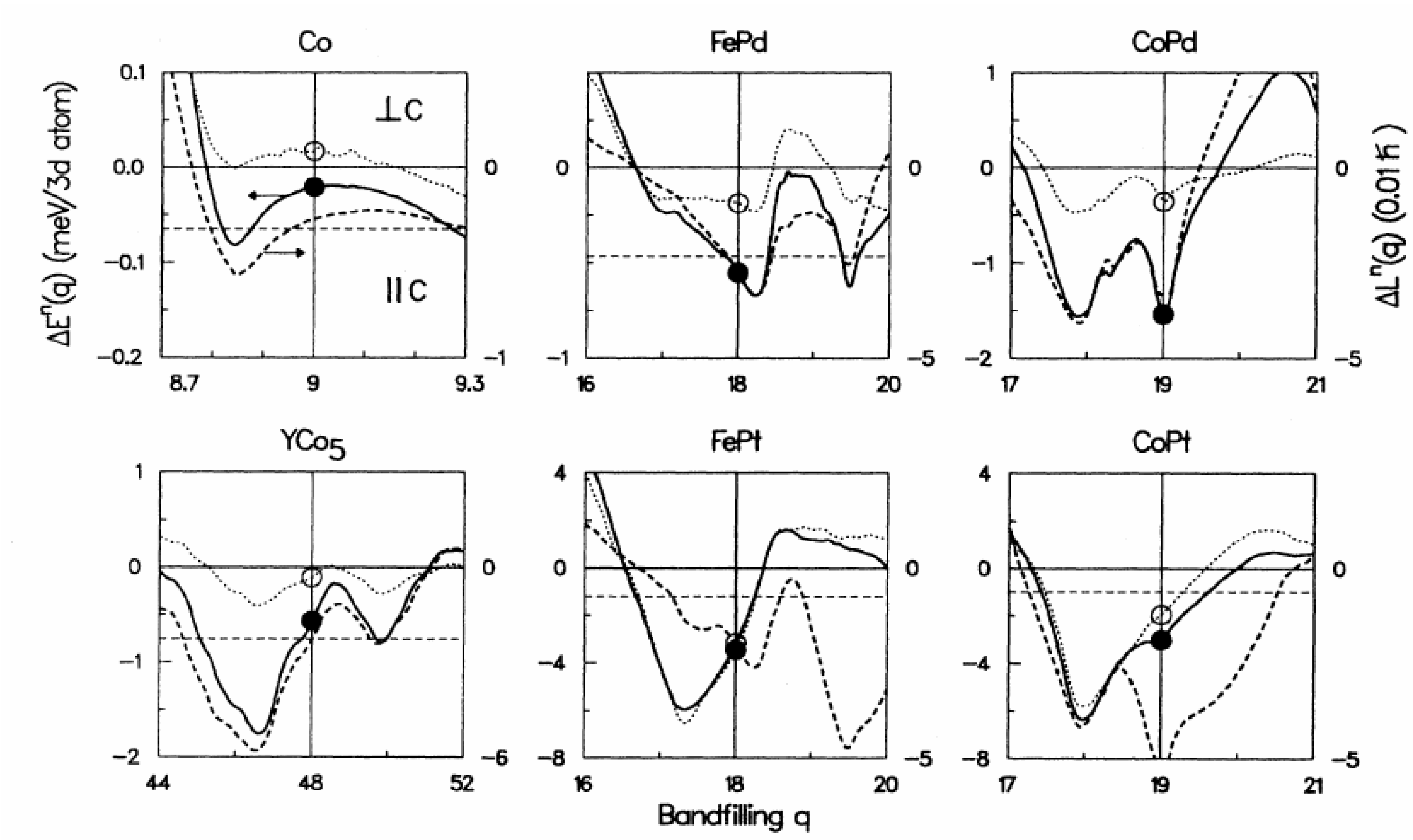
H. Ohno, D. Chiba, F. Matsukura, T. Omiya, E. Abe, T. Dietl, Y. Ohno, K. Ohtani, *Nature*, 408 (2000) 944



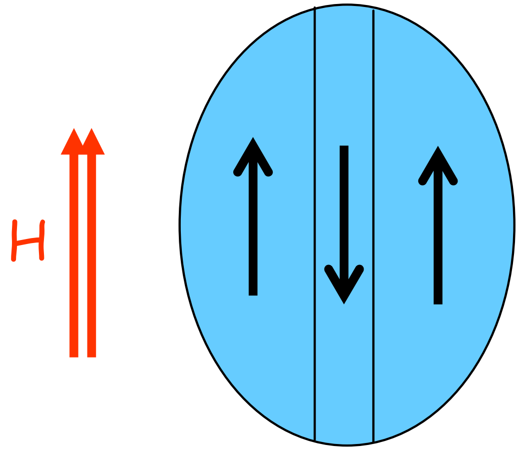
Could this be applied to metallic systems ?



Effect necessarily limited to
very last atomic planes



Demagnetising field corrections



$\rho = div\overrightarrow{M} = 0$ No volume charges

$\sigma = \overrightarrow{M}.\vec{n}$ Surface charges only

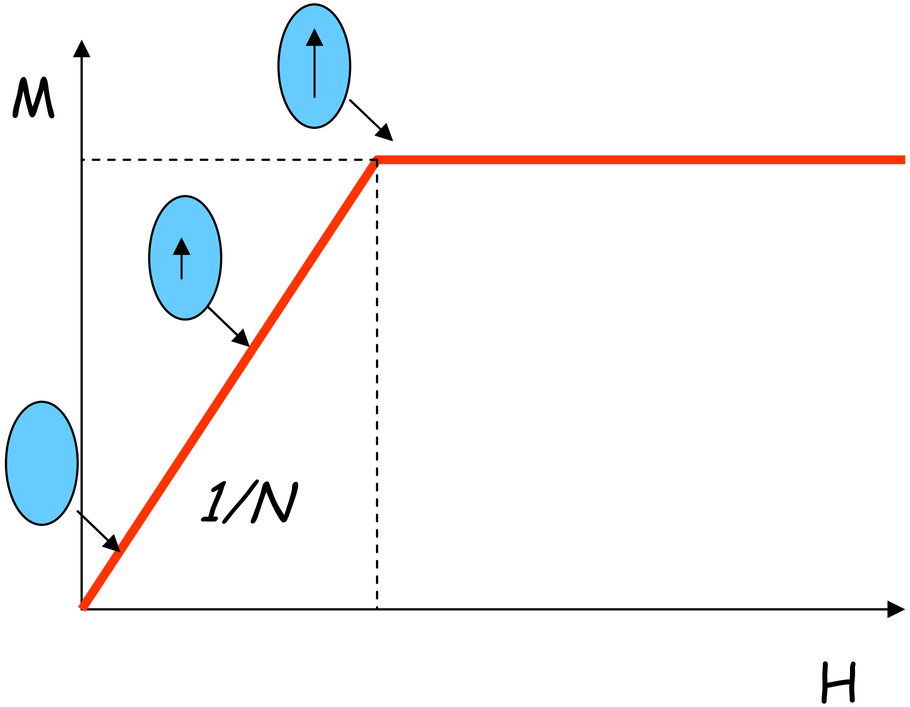
As in the saturated magnetic state

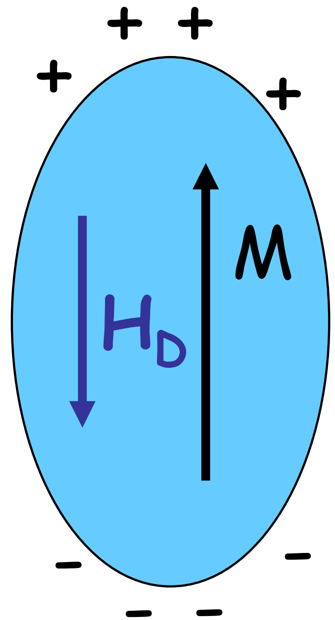
To first approximation :
Demagnetizing field may be assumed to be uniform

$$H_D = -NM$$

Strictly speaking, implies two hypotheses :
- Uniform magnetization
- Second order ellipsoid

Demagnetising field corrections





$$\vec{M} \cdot \vec{n}$$

Equivalent
Magnetic poles

$$E = \frac{1}{2}\mu_0 N M^2 - \mu_0 MH$$

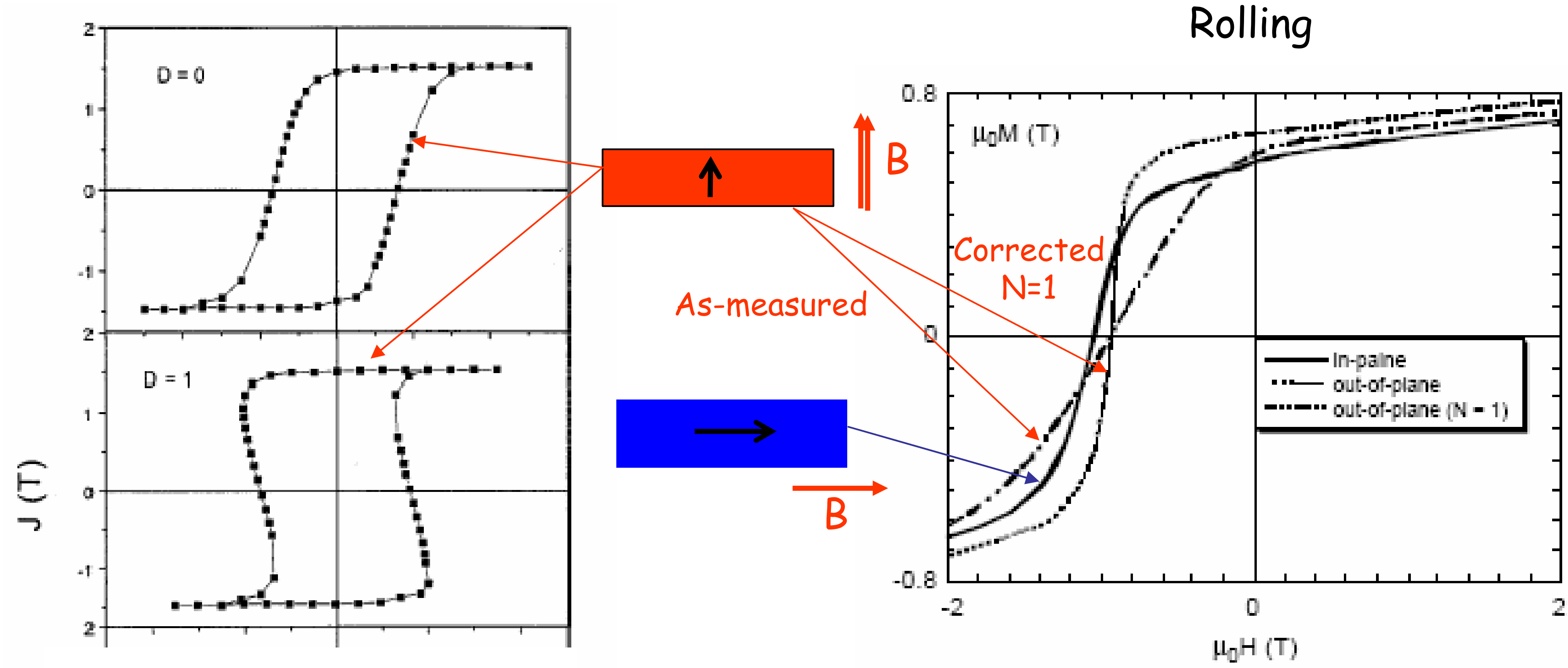
$$\frac{\partial E}{\partial M} = 0 \quad \Longrightarrow \quad \boxed{M = \frac{1}{N} H}$$

Concept of demagnetizing field corrections

Hysteresis cycles in hard FePt films

Sputtering

Rolling



Skomski, Liu, and Sellmyer
J. Appl. Phys., 87(2000) 6334

Hai, Dempsey and Givord
J. Magn. Magn. Mater. 262 (2003) 353

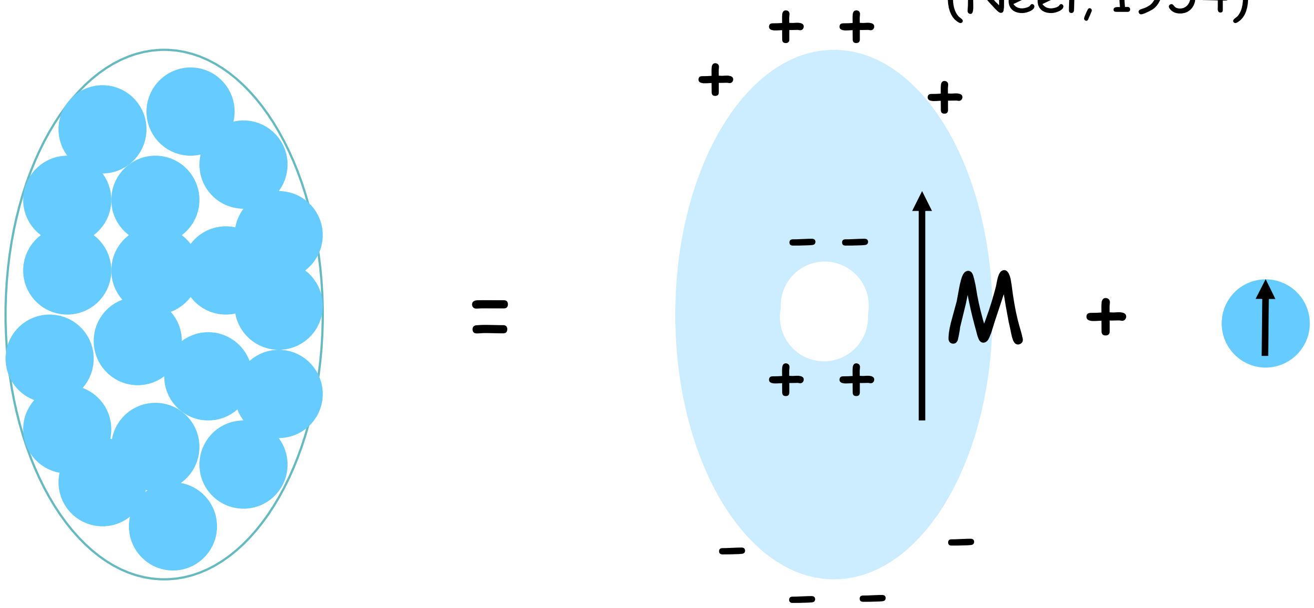
Usual demagnetizing field corrections do not work

Demagnetising field corrections in heterogeneous magnetic systems : an example

(Néel, 1954)

$$\rho = div\overrightarrow{M} \neq 0$$

Volume charges are present



$$H_D \downarrow \; = \; H_D^m \downarrow + H_{cav} \uparrow + H_D^g \downarrow$$

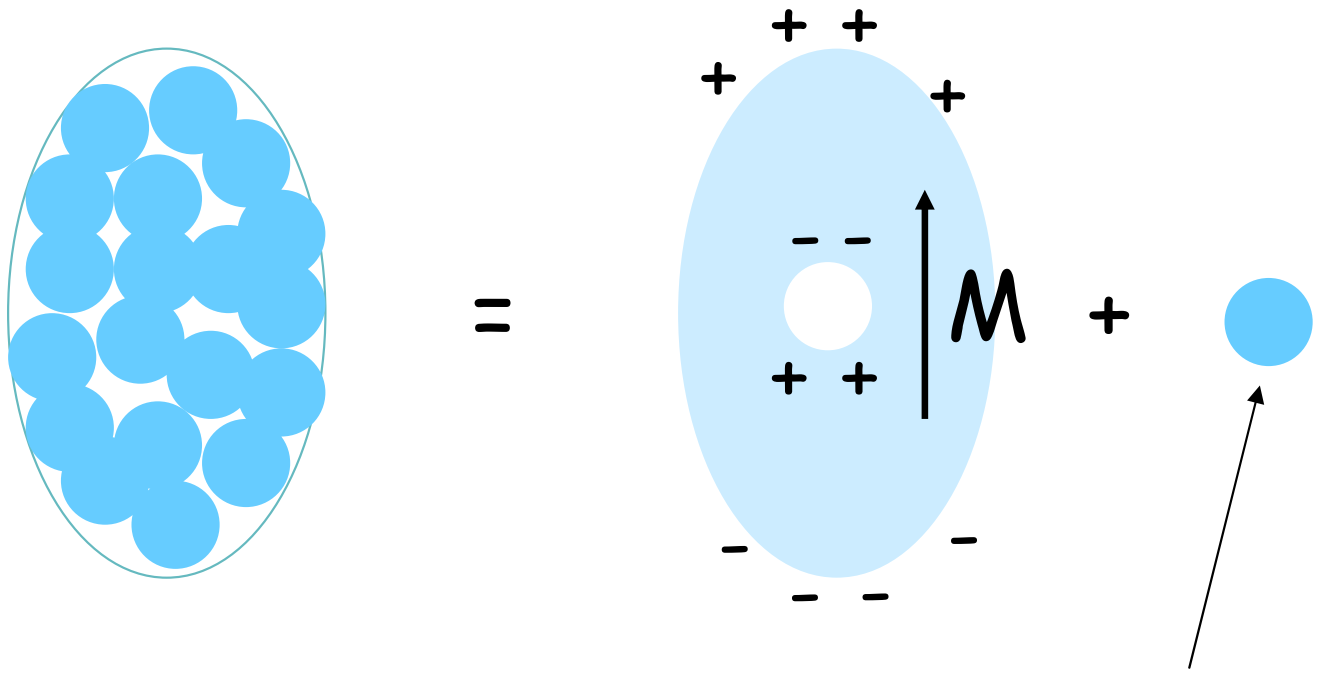
Macroscopic cavity grain

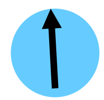
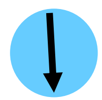
Note :

Homogeneous material $H_{cav} + H_D^g = 0$

Heterogeneous material $H_{cav} + H_D^g \neq 0$

Nanostructured materials



M can only be  or 

Grain magnetostatic energy is a constant

H_D^g cannot be minimized

Two Demagnetising field terms only to be considered :

Macroscopic + Cavity

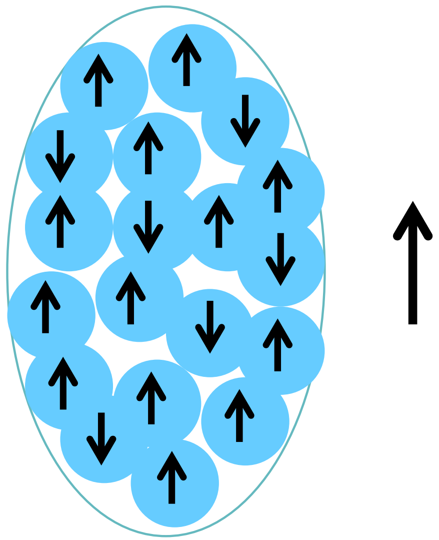
First order approximation : H_{cav} and H_D^m proportional to the mean magnetization

$$\cancel{H_D^g}$$

$$H_D^m = -N_m \overline{M}$$

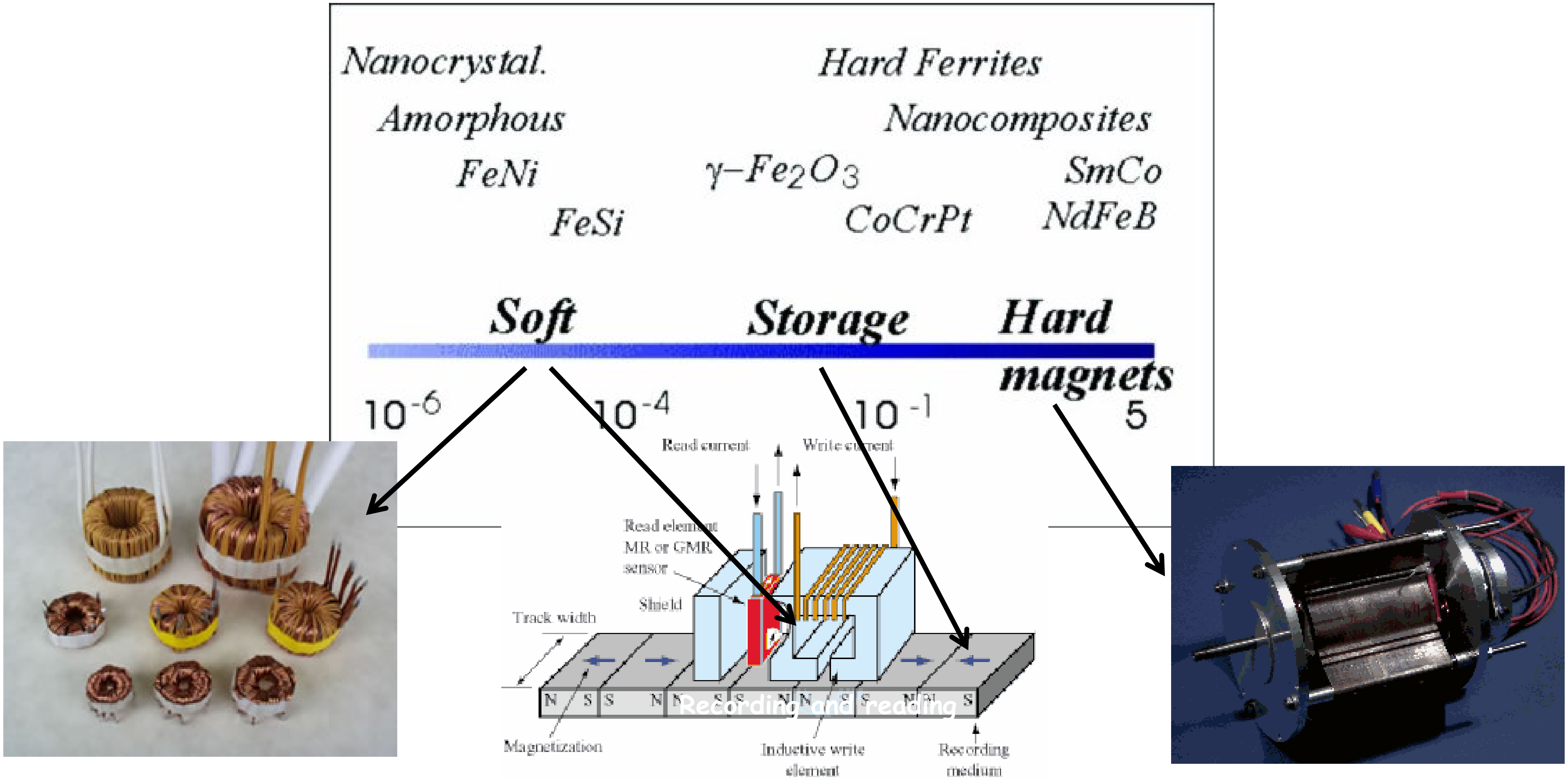
$$H_{cav} = +N_g \overline{M}$$

$$\boxed{H_D^{equiv} = -(N_m - N_g)\overline{M}}$$

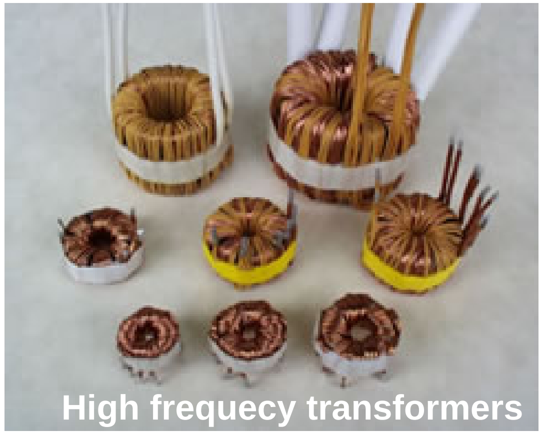


Explains why experimental curves tend to be overcorrected

Magnetic materials and their applications

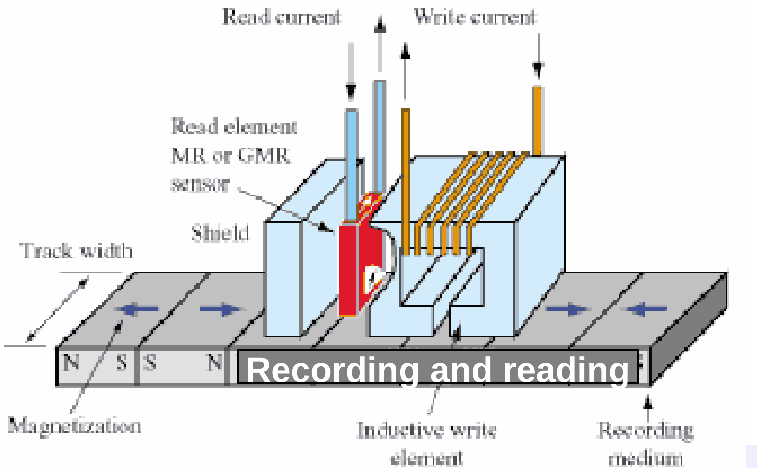


Energy transformation | Telecommunication | Information technologies

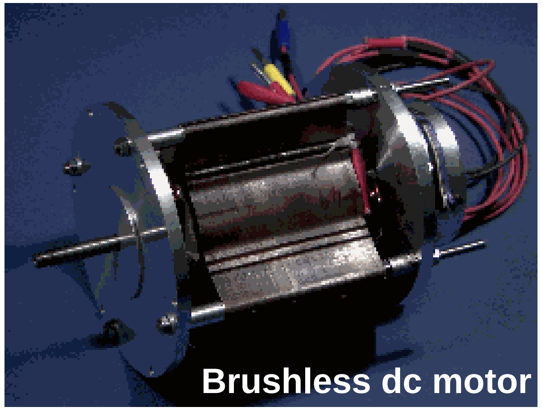


High frequecy transformers

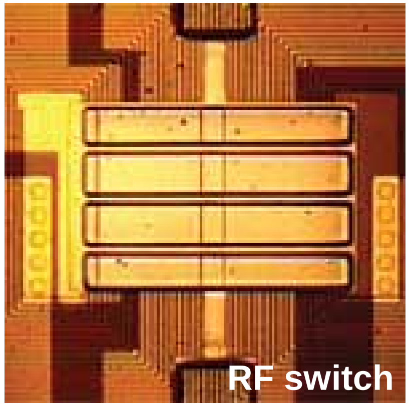
Traveling waves tubes



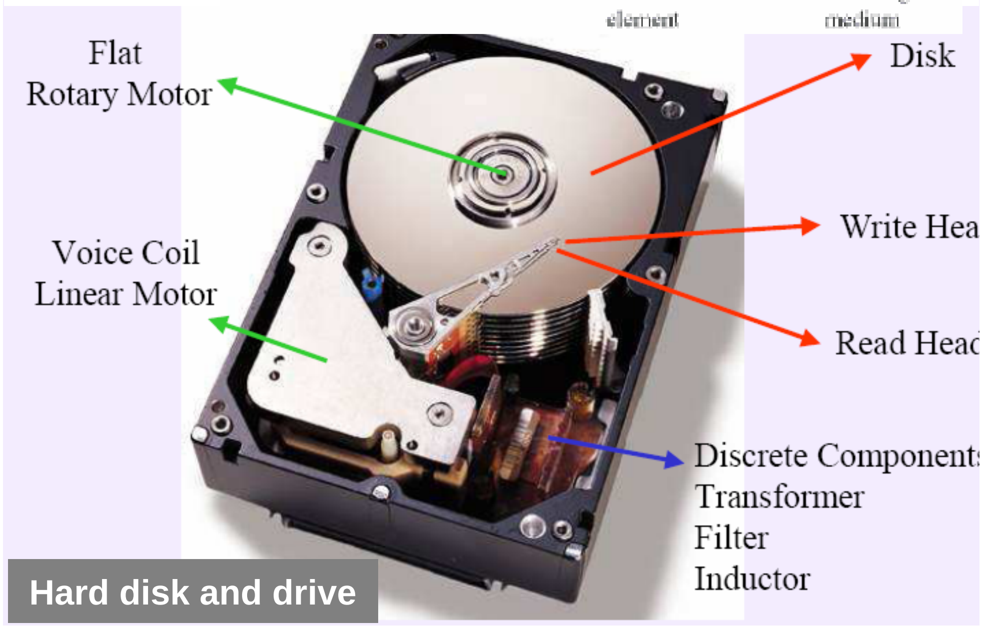
Recording and reading



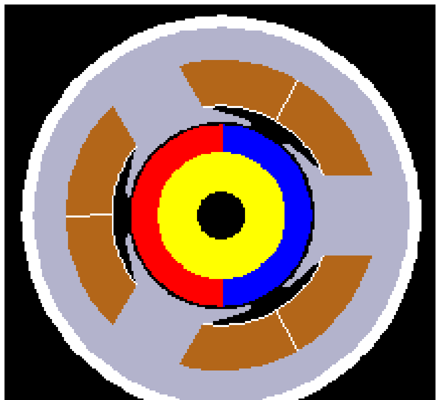
Brushless dc motor



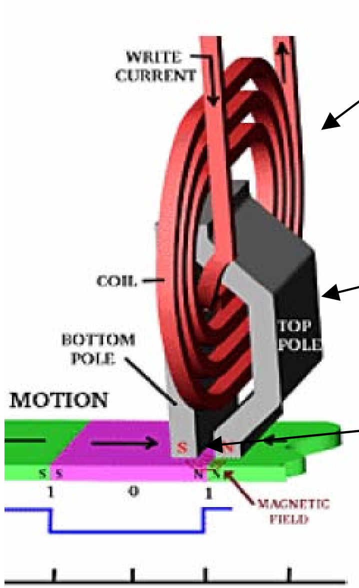
RF switch



Hard disk and drive



Hard disk main components

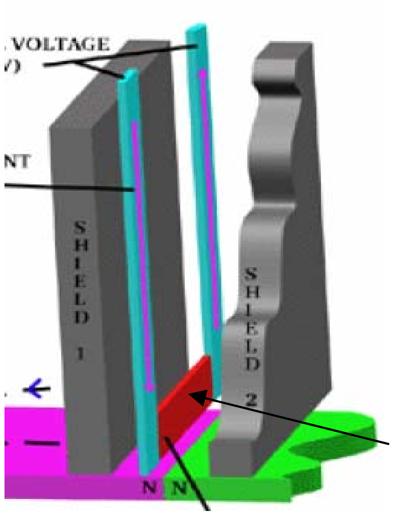


Bobinage

Circuit magnétique

Entrefer

Ecriture



Capteur à Magnétorésistance géante

Lecture

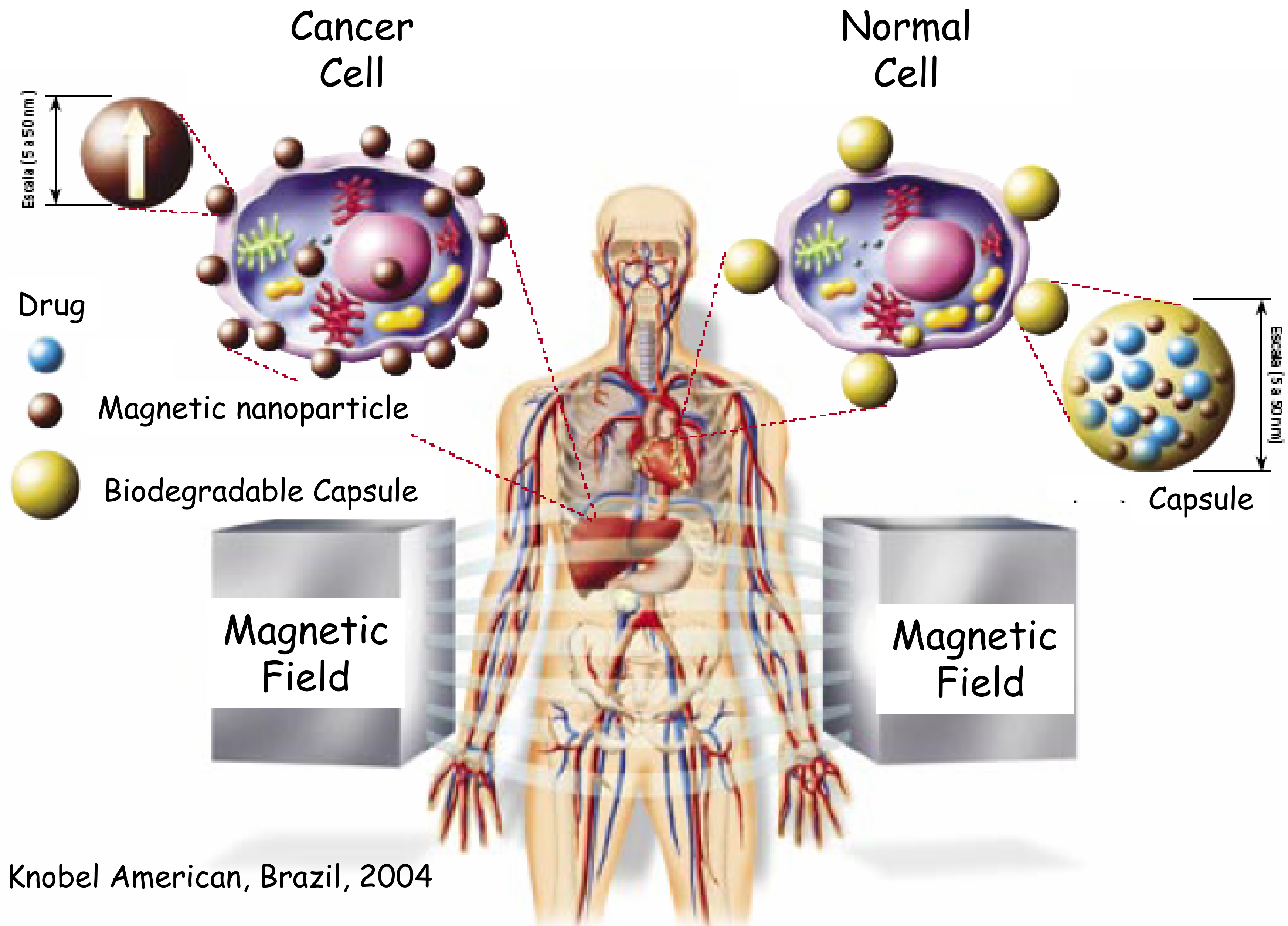
Disque dur

Moteur de rotation du disque dur

Moteur de positionnement de la tête

Tête d'écriture et lecture

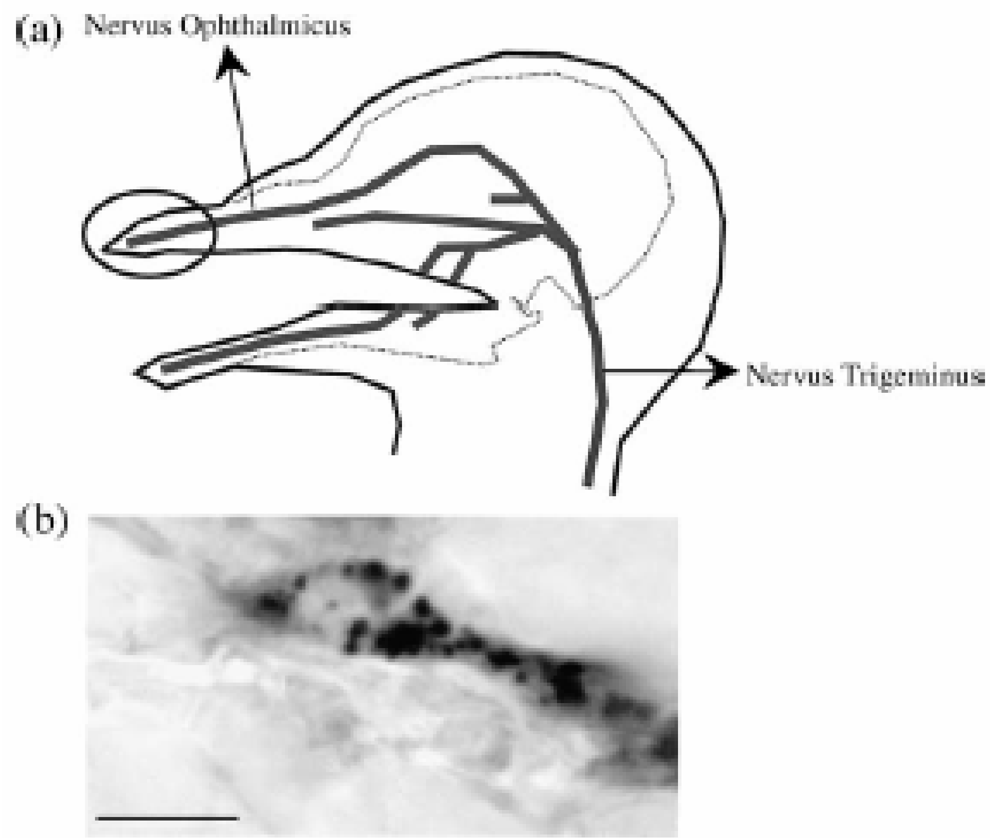
Magnetic nanoparticles in medicine



From M. Knobel American, Brazil, 2004

Magnetism and biology

Magnetotactic bacteria



Homing pigeons

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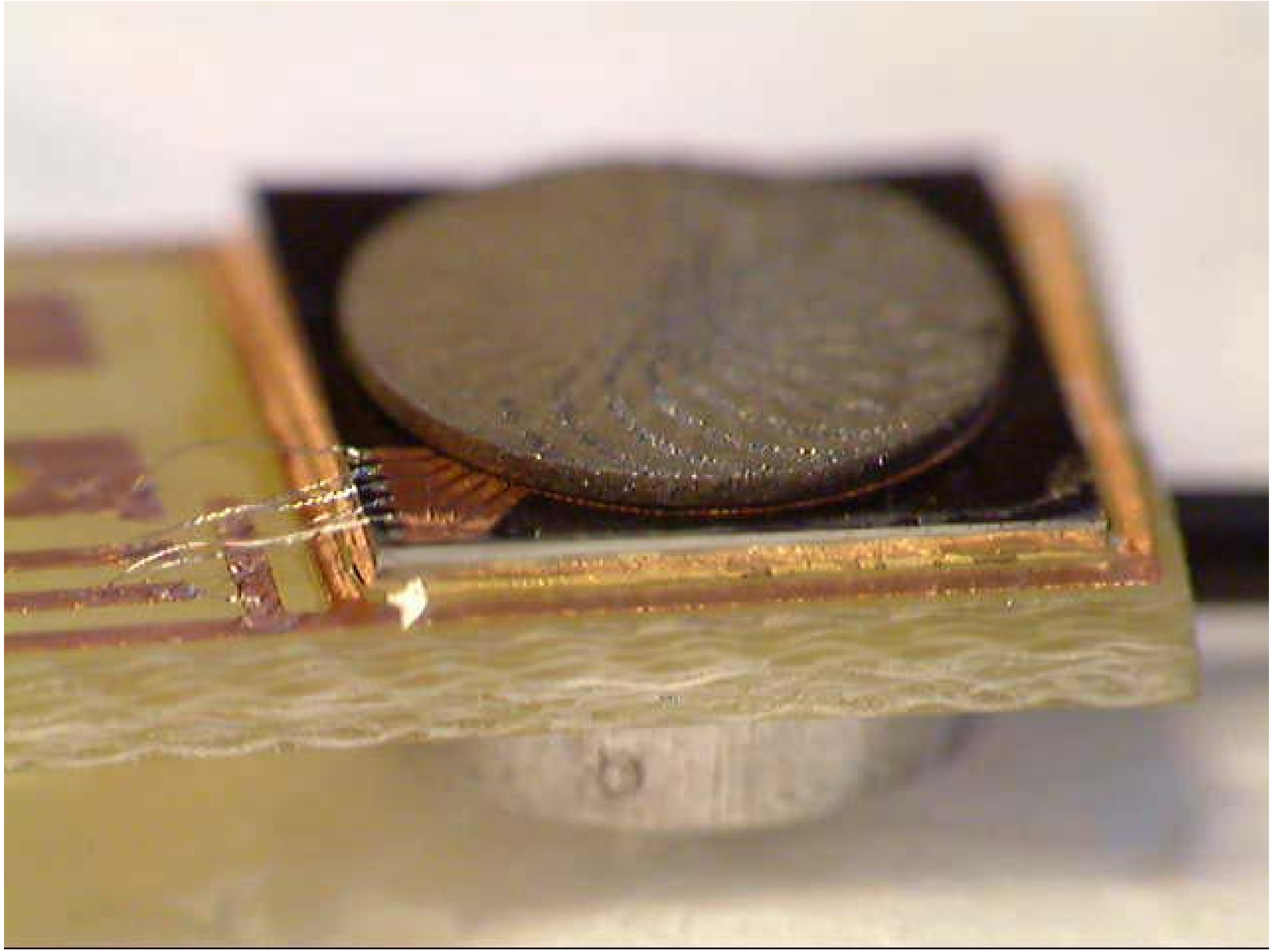
Magnetic microsystems : micro-generator



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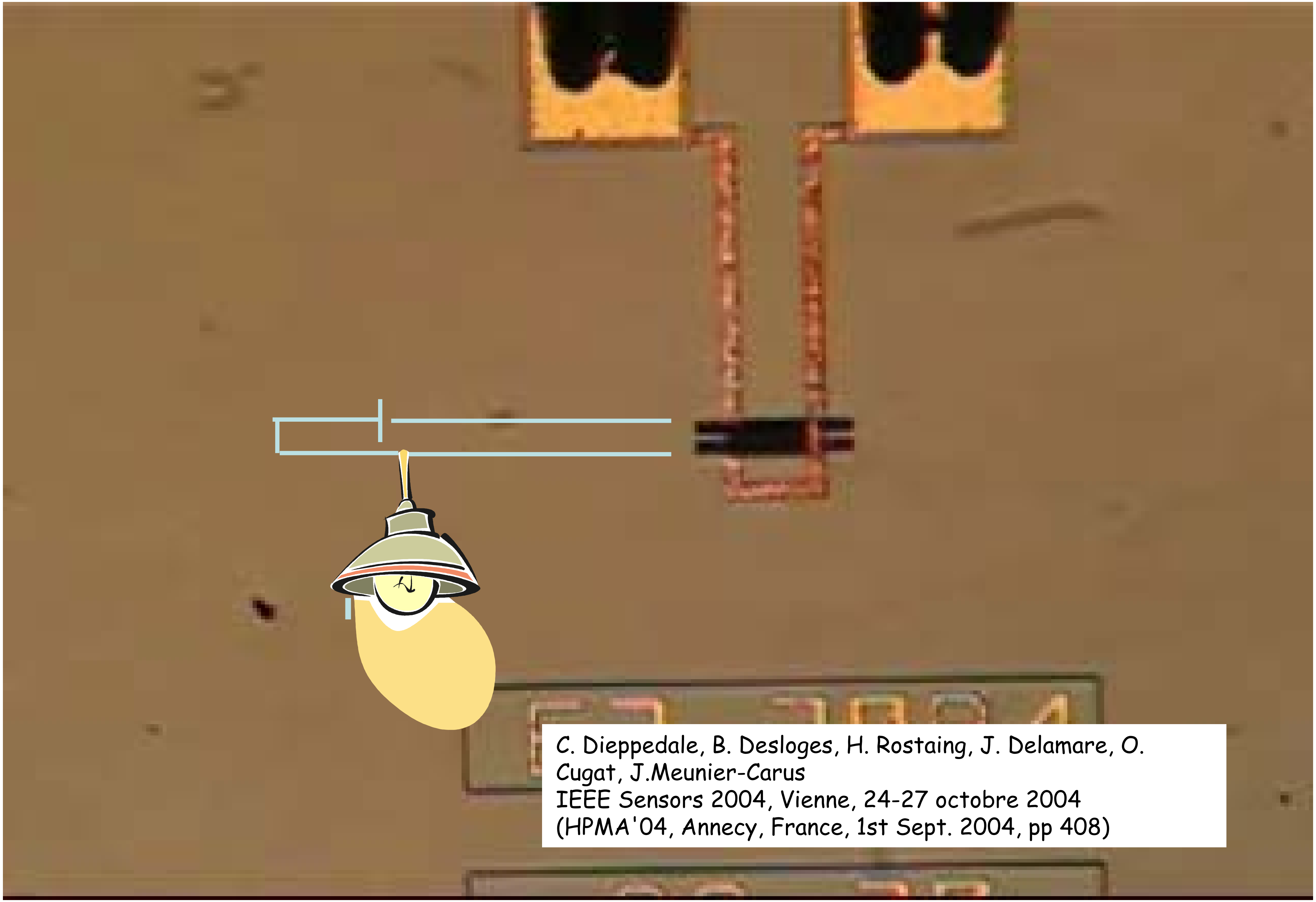
Magnetic microsystems :radio-fréquency switch



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