Basic concepts on magnetization reversal (2)

Slow dynamics and thermal related processes

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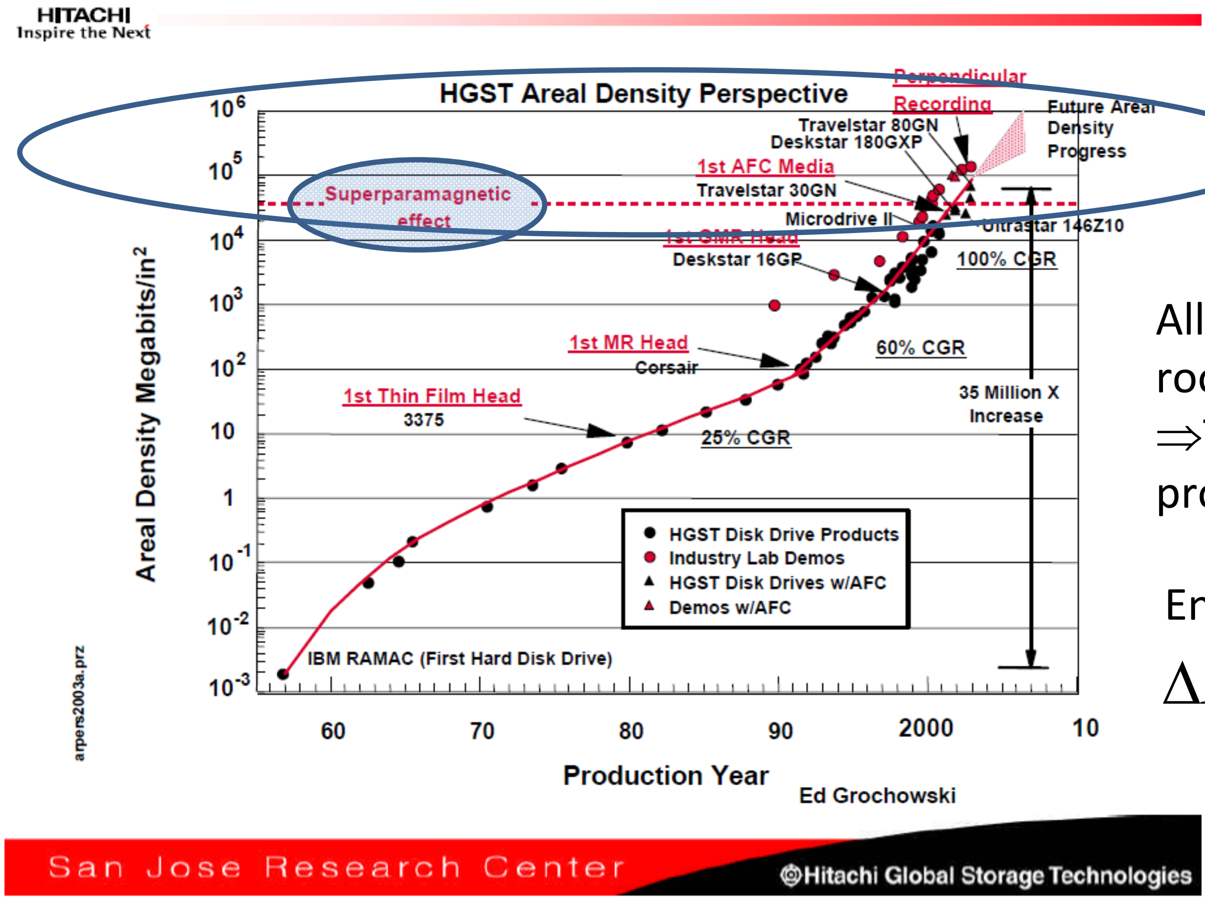
Introduction: Application considerations



All applications need to work at room temperature
⇒Thermal activation may become problematic for long time scales

Energy barrier criteria :

$$\Delta E = KV > (25-60)k_B T$$

Thermal activation is crutial for nanoparticles (<25 nm)
It is also relevant for thin films (domain nucleation and domain wall propagation)

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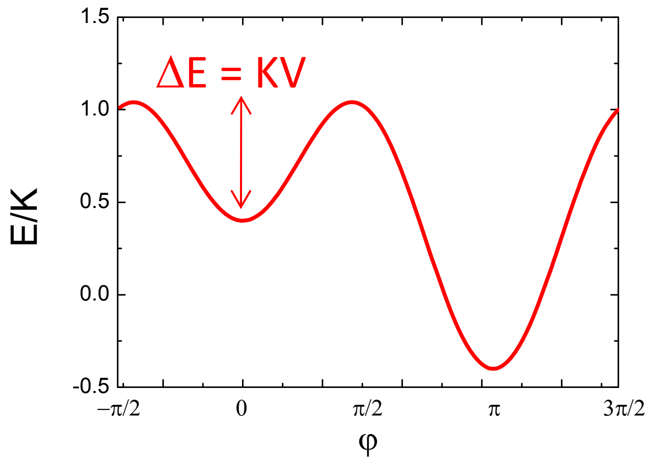
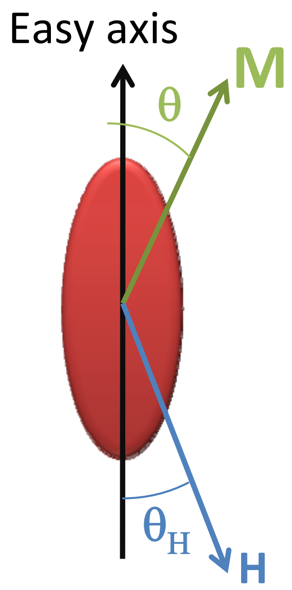
Superparamagnetism: Energy barrier for macrospin

Stoner and Wohlfarth hamiltonian

$$E = K_{eff} \sin^2\theta - \mu_0 M_S H \cos(\theta + \theta_H)$$

Volumic quantities





Energy barrier (field aligned with easy axis)

$$\Delta e = e(\varphi_m) - e(0)$$
$$= \left(1 - h^2 + 2h^2\right) - (-2h)$$
$$= (1+h)^2$$

$$\Delta E = KV\left(1 + H/H_K\right)^2$$

General case

$$\Delta E = KV\left(1 + H/H_{SW}\right)^{3/2}$$

Victoria PRL 63, 457 (1989)

Superparamagnetism: Thermodynamics of a macrospin

$$EV = K_{eff} V \sin^2\theta - \mu_0 \mu H \cos\theta$$

Macrospin moment

Partition function : $Z = \int \exp\left(EV/kT\right) \sin\theta d\theta d\varphi$

Average moment projected on easy axis: $\langle \mu \rangle = \frac{kT}{\mu_0 Z} \frac{\partial Z}{\partial H}$

Isotropic case : *K = 0*

$$Z = 2\pi \int_0^\pi \exp\left(\frac{\mu_0 \mu H \cos\theta}{kT}\right) \sin\theta d\theta$$

$$\langle \mu \rangle = \mu \left[\frac{1}{\tanh x} - \frac{1}{x}\right] \quad x = \frac{\mu_0 \mu H}{kT}$$

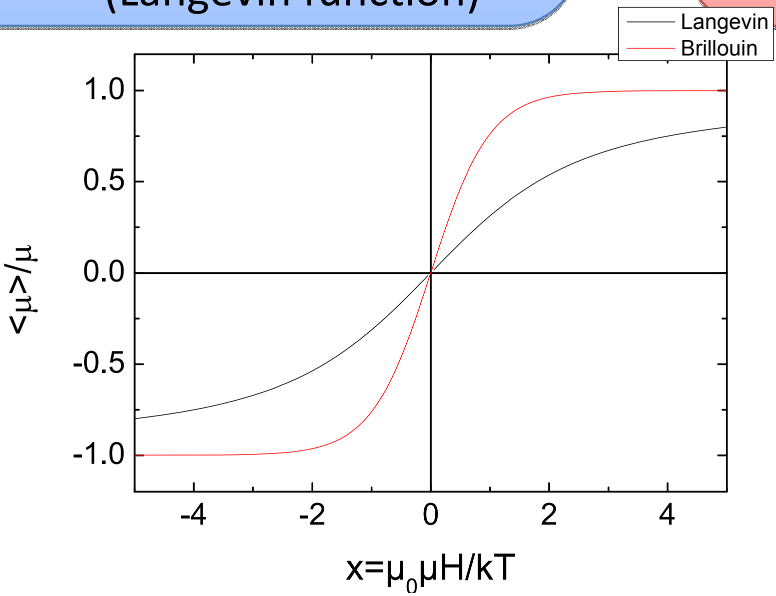
(Langevin function)

Infinite anisotropy: θ=0 or π

$$Z = \exp\left(\frac{\mu_0 \mu H}{kT}\right) + \exp\left(-\frac{\mu_0 \mu H}{kT}\right)$$

$$\langle \mu \rangle = \mu \tanh x \quad x = \frac{\mu_0 \mu H}{kT}$$

(Brillouin ½ function)



Initial susceptibility

$$\chi = \frac{\mu_0 \mu^2}{3kT} \text{ or } \frac{\mu_0 \mu^2}{kT}$$

Scaling with 1/T (like Curie law)

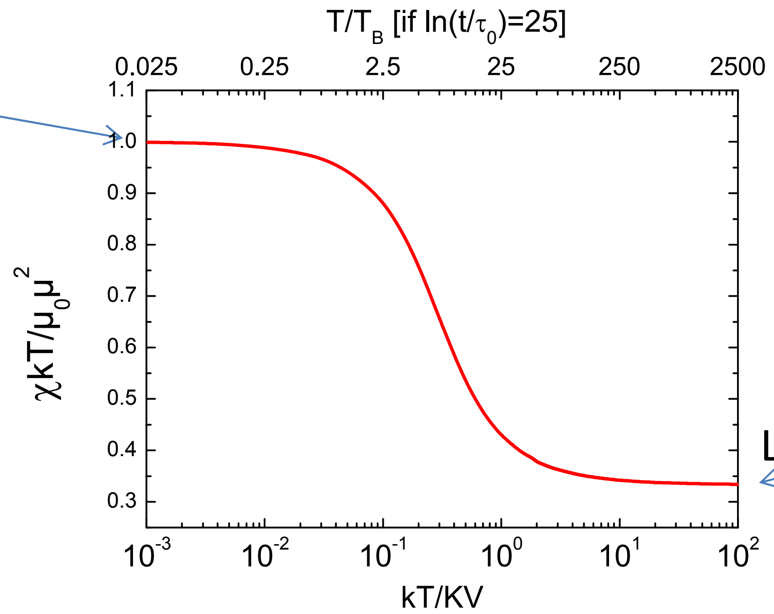
Superparamagnetism: Thermodynamics of a macrospin

Case with finite anistropy

$$\langle \mu \rangle = \mu \left[-h + 2\sqrt{\frac{t}{\pi}} \frac{\sinh\left(\frac{2h}{t}\right)\exp\left(\frac{1+h^2}{t}\right)}{Erfi\left(\sqrt{\frac{1+h}{t}}\right) + Erfi\left(\sqrt{\frac{1-h}{t}}\right)} \right]$$

$$h = H / H_K \; ; t = kT / KV \quad ; \quad Erfi(t) = \int_0^t \exp(x^2) dx$$

Brillouin like



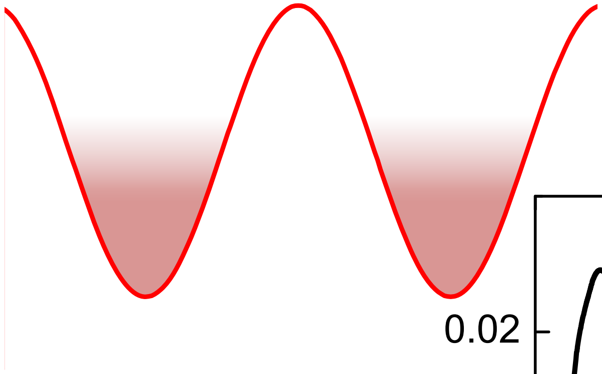
Langevin like

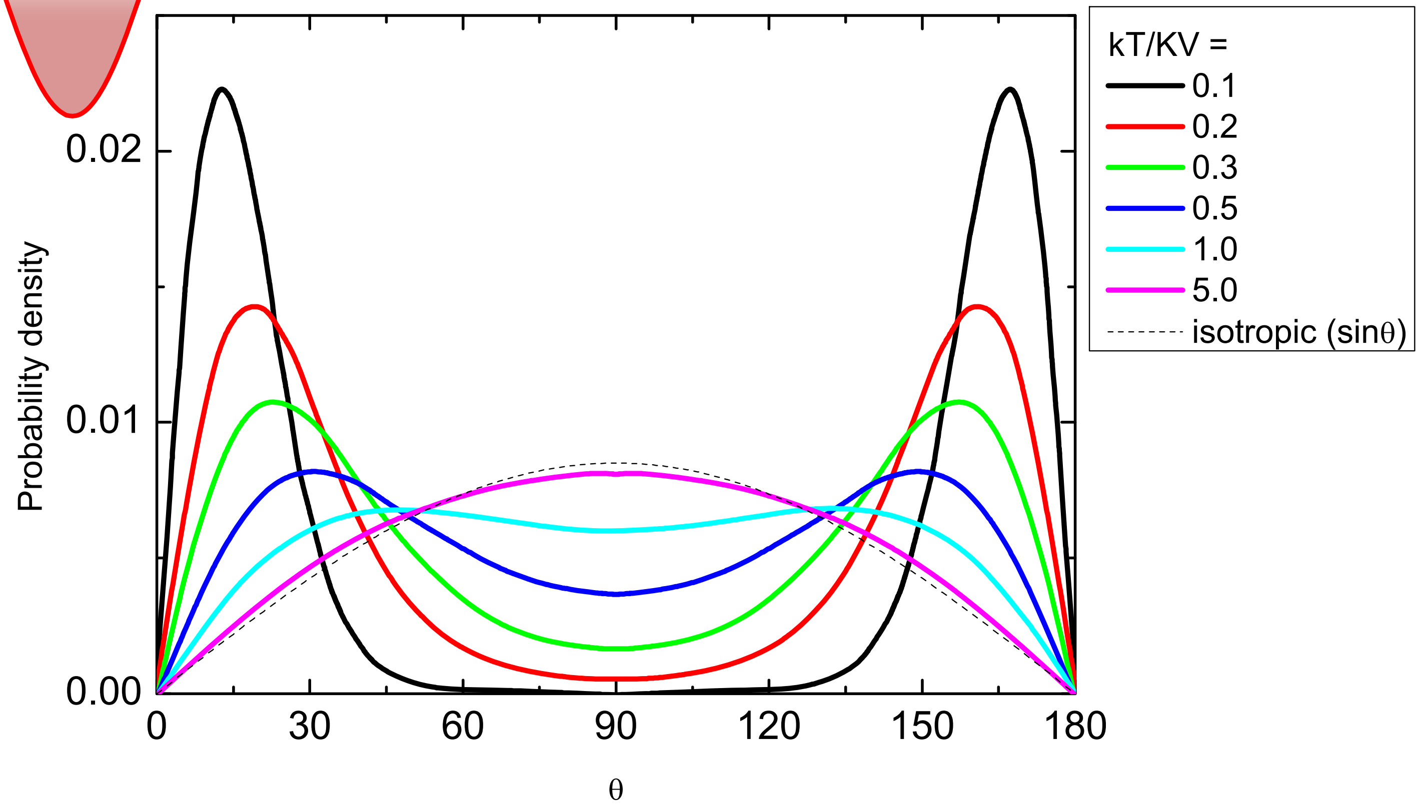
Usefull : at low temperature

$$\chi = \frac{\mu_0 \mu^2}{kT}\left(1 - \frac{kT}{KV}\right)$$

Chantrell et al. JMMM 53, 1999 (1985)
Fruchart et al. JMMM 239,224 (2002)

Superparamagnetism: Thermodynamics of a macrospin





Occupancy probability for a Stoner-Wohlfarth model (*H = 0*)

Superparamagnetism: Temperature induced switching

Phenomenological: Arrhenius law

⇒Switching time $\tau = \tau_0 \exp(\Delta E / kT)$

ΔE calculated with the macrospin approch

τ_0 attempt time (~1 ns) : linked with magnetization dynamics

Brown's model : (Langevin fluctuation of a macrospin)

$$\tau_0^{-1} = \frac{2\alpha}{1+\alpha^2} \boxed{\gamma\mu_0 H_K} \sqrt{\frac{\mu_0 M_S H_K V}{2\pi kT}}$$

$\gamma\mu_0 H_K$ → ω_{well}

Brown Phys. Rev. 130, 1677 (1963)
See also Coffey et al. PRL 80, 5655 (1998)

Néel's model : (Phonon and magnetostriction approach)

$$\tau_0^{-1} = \frac{|e| H_K}{m_e} \left| 3G\lambda + \mu_0 D M_S^2 \right| \sqrt{\frac{2V}{\pi G kT}}$$

G → Young's modulus; λ → magnetostrition; $\mu_0 D M_S^2$ → Fluctuation of the demag. field

Néel Ann. Geophys. 5, 99 (1949)

Superparamagnetism: Temperature induced switching

$$\tau = \tau_0 \exp(\Delta E / kT)$$

Stability criterion : $\tau > \tau_{measurement}$

Blocking temperature $T_B = \frac{KV}{k_B} \ln\left(t / \tau_0 \right)$

If $\tau_0 = 0.1ns$

τ	1s	1min	1h	1day	1year	10 year
ΔE/kT	23	27	31	34	40	43

Hard drive applications

This problem drives an intense effort of reseach for high anisotropy materials. Best candidates are Pt-bases ordered alloys like **FePt and CoPt** (*K~10 MJ/m³* in bulk phase <-> D_{limit} ~ 3 nm)
See e.g. Sun et al. Science 287, 1989 (2000)

Warning: it is difficult to predict T_B from volumic anisotropy measurements as in nanoparticles K is generally dominated by surface effects/low coordinated atoms
See Jamet et al. PRL 86, 4676 (2001)
Gambardella etal. Science 300, 1130 (2003)

Superparamagnetism: Characteristic time in experiments

Stability criterion : $\tau > \tau_{measurement}$

Blocking temperature $T_B = \frac{KV}{k_B} \ln\left(t / \tau_0 \right)$

- Loop measurment in SQUID -> ~ 10min - 1h
- ZFC-FC in squid -> ~ 1s
- magneto optical kerr effect (resistive coils) -> ~1s
- SP-STM / microSQUID : 100 ms
- ac susceptibility : 1ms - 10s
- Moessbauer : 0.1 µs

In sweeping (field or temperature) experiments, charateristic time is ambiguous
-> rather speak of sweeping rate

see e.g. Kurkijarvi PRB 6 832 (1972) (field sweep)
Rohart et al PRB 74, 104408 (2006) (temperature sweep)

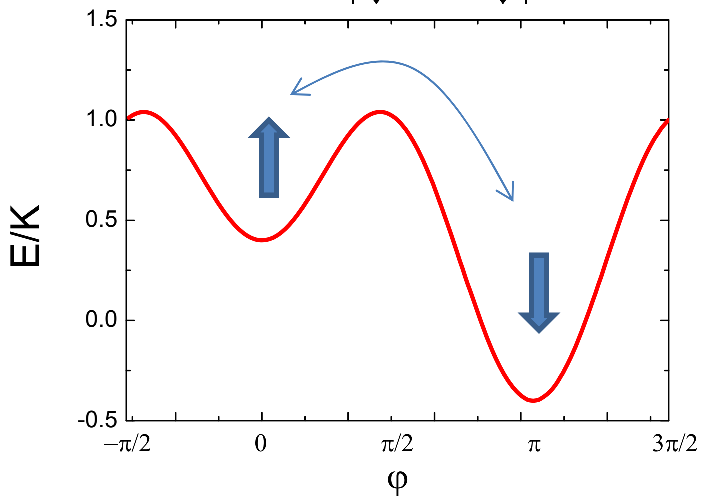
Superparamagnetism: Rate equation model

Brown's model is difficult to use.

$\Rightarrow$Simpler model: rate equations

$$H \neq 0 \Leftrightarrow \Delta E_{\uparrow\downarrow} \neq \Delta E_{\downarrow\uparrow}$$

$$\Leftrightarrow \tau_{\uparrow\downarrow} \neq \tau_{\downarrow\uparrow}$$



$$\begin{cases} \dfrac{dn_\uparrow}{dt} = \dfrac{n_\downarrow}{\tau_{\downarrow\uparrow}} - \dfrac{n_\uparrow}{\tau_{\uparrow\downarrow}} \\ \dfrac{dn_\downarrow}{dt} = -\dfrac{n_\downarrow}{\tau_{\downarrow\uparrow}} + \dfrac{n_\uparrow}{\tau_{\uparrow\downarrow}} \end{cases} \underset{n_\downarrow + n_\uparrow = 1}{\Leftrightarrow} \frac{dn_\uparrow}{dt} = \frac{1}{\tau_{\downarrow\uparrow}} - n_\uparrow \left(\frac{1}{\tau_{\uparrow\downarrow}} + \frac{1}{\tau_{\downarrow\uparrow}} \right)$$

For constant field and temperature
(switching rates are constant)

$$n_\uparrow = \frac{\tau_{\uparrow\downarrow}}{\tau_{\uparrow\downarrow} + \tau_{\downarrow\uparrow}} + \frac{\tau_{\downarrow\uparrow}}{\tau_{\uparrow\downarrow} + \tau_{\downarrow\uparrow}} \exp(-t/\tau)$$

$$with\ \frac{1}{\tau} = \frac{1}{\tau_{\uparrow\downarrow}} + \frac{1}{\tau_{\downarrow\uparrow}}$$

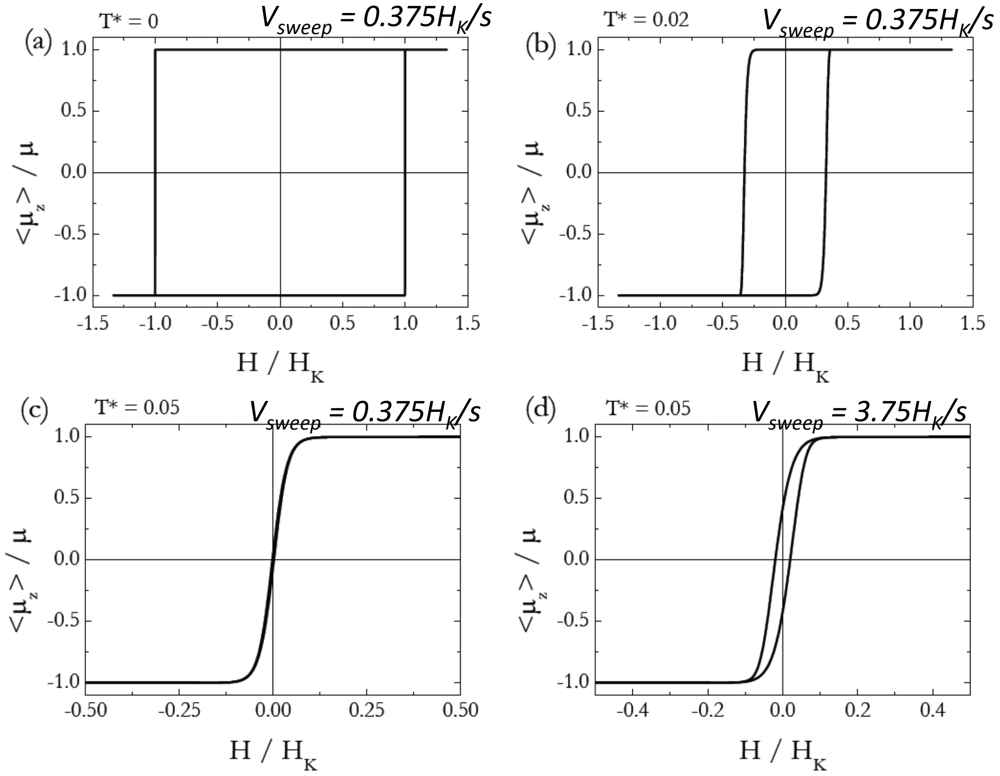
– First order decay law with relaxation time τ

- If $t_{meas} >> \tau$, $\dfrac{<\mu>}{\mu} = 2n_\uparrow - 1 = \dfrac{\tau_{\uparrow\downarrow}}{\tau_{\uparrow\downarrow} + \tau_{\downarrow\uparrow}} = \tanh\left(\dfrac{\mu_0 \mu H}{kT} \right)$

This equation can be used for any field orientation (if switching rates are known…)

Superparamagnetism: Hysteresis loop

Simulation of <u>mean</u> hysteresis loops with rate equations



Coercive field is not intrinsic
-> depend on temperature AND sweeping rate

$$H_C = H_K\left[1-\sqrt{\frac{kT}{KV}\ln\left(\frac{t_{meas}}{\tau_0}\right)}\right]$$

$$\equiv H_K\left[1-\sqrt{\frac{T}{T_B}}\right]$$

Scharrok JAP 76, 6413 (1994)
IEEE Trans Mag 26, 193 (1999)

Superparamagnetism: experimental evidence

VOLUME 78, NUMBER 9 PHYSICAL REVIEW LETTERS 3 MARCH 1997

Experimental Evidence of the Néel-Brown Model of Magnetization Reversal

W. Wernsdorfer,[1,2] E. Bonet Orozco,[1,2] K. Hasselbach,[1] A. Benoit,[1] B. Barbara,[2] N. Demoncy,[3,4] A. Loiseau,[4] H. Pascard,[3] and D. Mailly[5]

Presented are the first magnetization measurements of individual ferromagnetic nanoparticles (15–30 nm) at very low temperatures (0.1–6 K). The angular dependence of the hysteresis loop evidenced the single domain character of the particles. Waiting time, switching field, and telegraph noise measurements showed for the first time that the magnetization reversal of a well prepared ferromagnetic nanoparticle can be described by thermal activation over a single-energy barrier as originally proposed by Néel and Brown. The "activation volume" estimated by these measurements was close to the particle volume. [S0031-9007(97)02465-4]

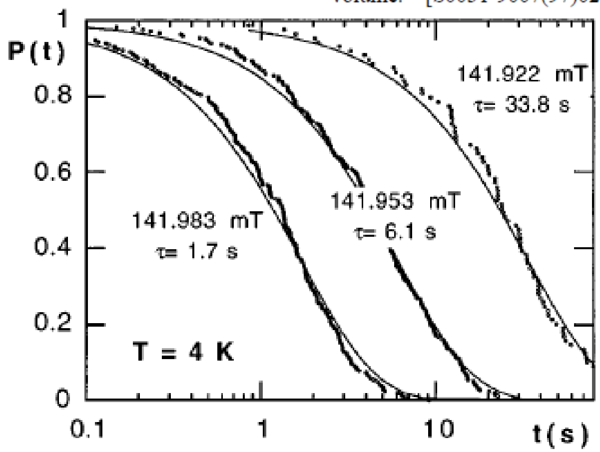


FIG. 2. Probability of not switching of magnetization as a function of the time at different applied fields at 4 K and for $\theta \approx 12°$. Full lines are fits to the data with an exponential [Eq. (2).]

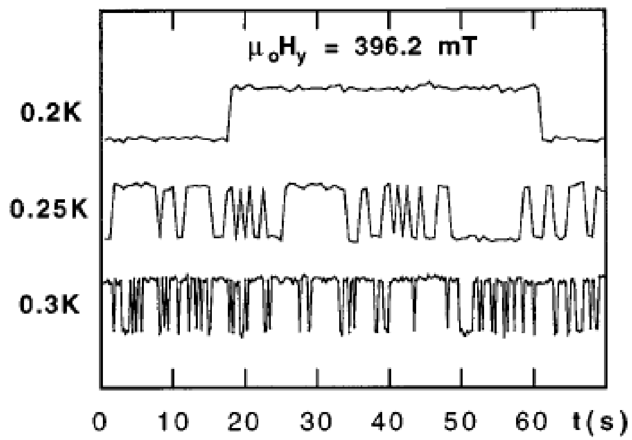


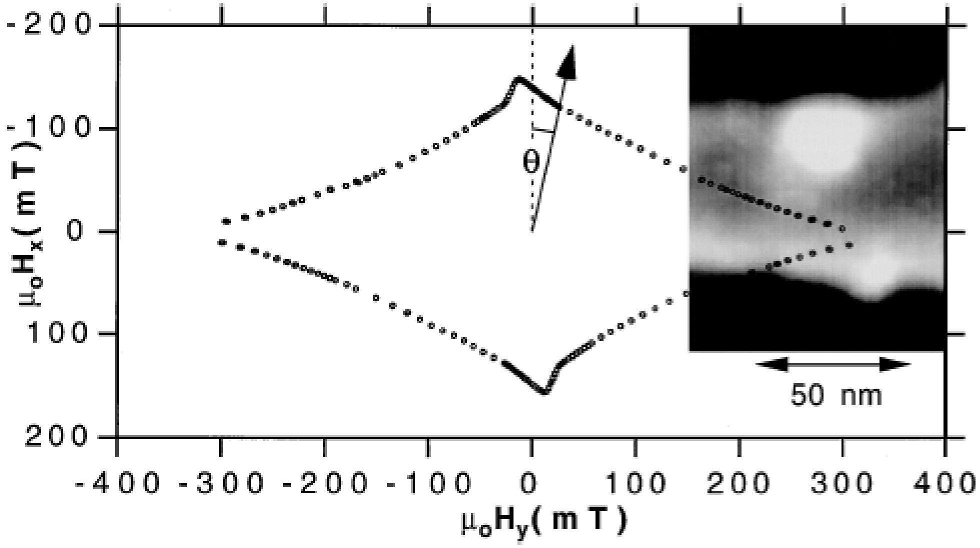
FIG. 6. Telegraph noise measurements for three temperatures and $\mu_0 H_y = 396.2$ mT.

⇒Anisotropy precisely determined from astroid at 35 mK

⇒Volume determined by SEM imaging

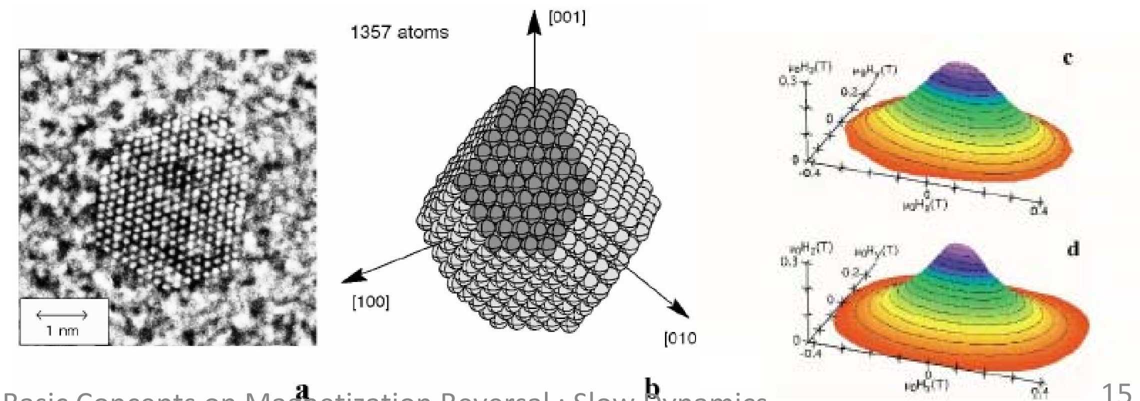
⇒First perfect agreement with Néel-Brown model

First observation (2D) : Co (D = 25 nm) cluster
Wernsdorder et al. PRL 78, 1791 (1997)



In 3 D: (same Co cluster) E. Bonnet er al PRL 83, 4188 (1999)

3 nm Co cluster : M. Jamet PRL 86, 4676 (2001)



Superparamagnetism: experimental evidence

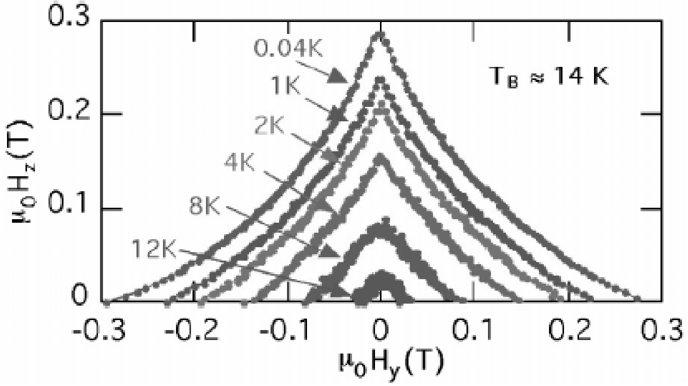


FIG. 4. Temperature dependence of the switching field measured in the H_y-H_z plane in Fig. 3. An extrapolation of the switching fields to zero gives the blocking temperature $T_B = 14$ K [22].

Jamet et al. PRL 86, 4676 (2001)

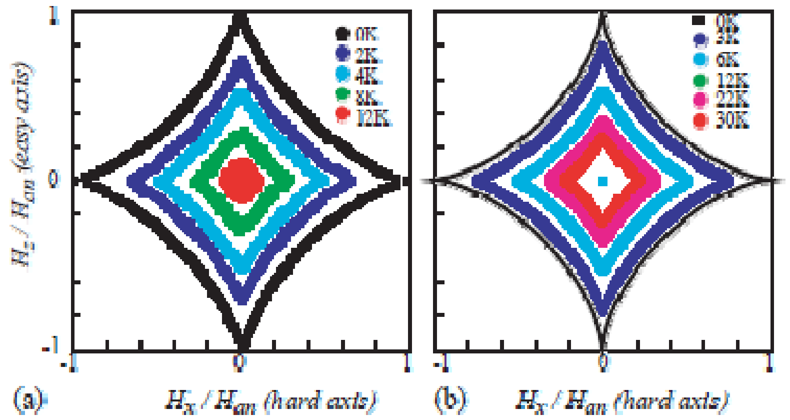


Fig. 1. Temperature dependance of the switching field of a 3 nm Co particle (a) measured with $\tau_{mes} = 0.01$ s [2] and (b) calculated with $\tau_{calc} = 30$ ns ($\alpha = 0.1$, calculation time step = 100 fs).

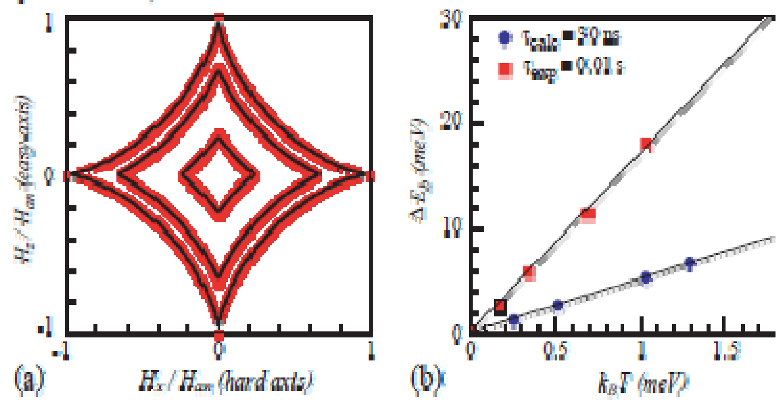


Fig. 2. Interpretation of τ by an Arrhenius law: (a) determination of a mean ΔE_b for different temperatures by fitting calculated astroids with iso-ΔE_b curves, (b) fit of obtained results, for both calculated and experimental astroids, with the Arrhenius law in order to determine τ_0.

Simulation of macrospin dynamics (Brown's model)

Vouille et al. JMMM 272-276, e1237 (2004) (with exp. Data from Jamet et al.)

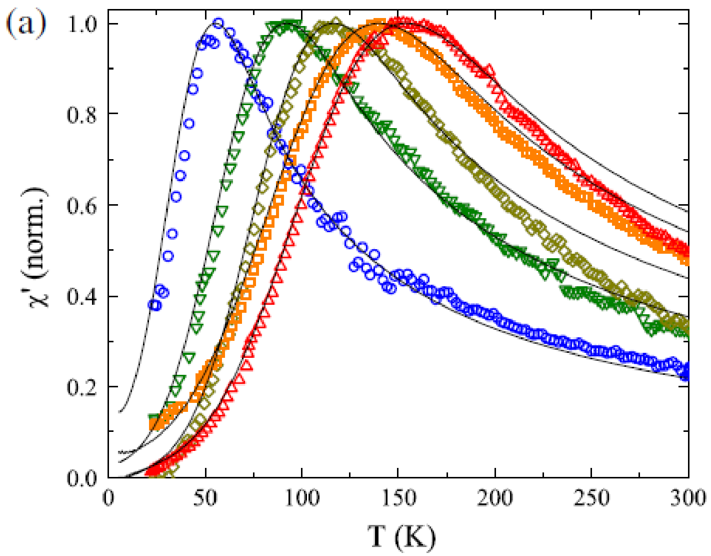
Superparamagnetism:
Experimental observation in practical

-> Single particle measurments are difficult
-> Hysteresis loops are generally long to measure

Temperature variation of initial susceptibility

$$\chi(\omega) = \frac{\chi_{eq}}{1 - i\omega\tau} \propto \frac{1}{T}\frac{1}{1 - i\omega\tau_0 \exp(\Delta E / kT)}$$

ω : Pulsation of the magnetic field

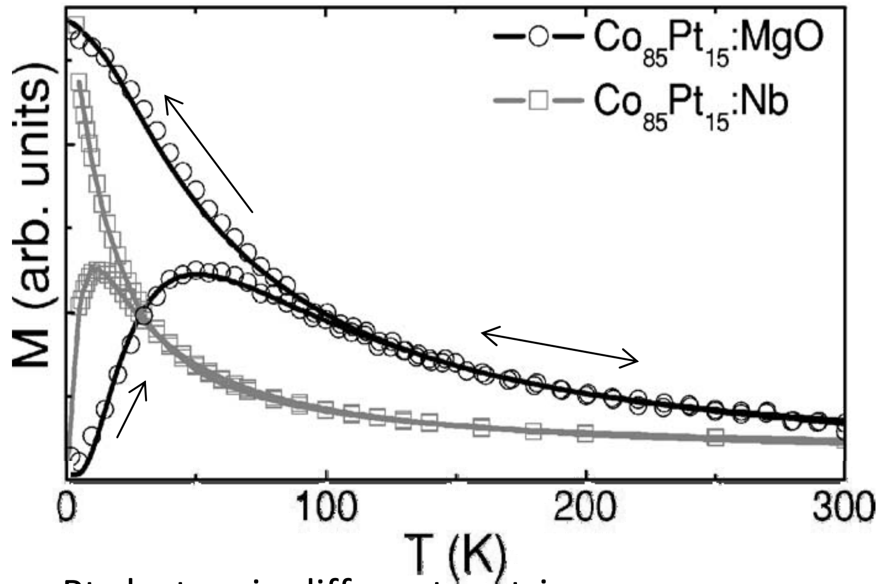


Co nanodots on Au(111) with increasing size
Rohart et al. PRL 104, 137202 (2010)

Field coolded-Zero field coolded measurements

Model for zfc, measuring from low to high T

$$M(T) \propto \frac{1}{T}\left[1 - \exp\left(-\delta t / \tau(T)\right)\right] \, with \; \delta t = \frac{kT^2}{KdT/dt}$$



Pt clusters in different matrices
Rohart et al. PRB 74, 104408 (2006)
See also Tamion et al; APL 95, 062503 (2009)

Superparamagnetism: beyond macrospin?

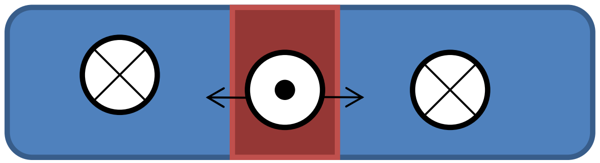
Superparamagnetism and nucleation-propagation magnetization reversal

If *L*>>δ : it is possible to nucleate and propagate a reversed domain

Braun PRL 1993
(same approach as Brown 1963)

$$\tau = \tau_0(H)\exp(A\sigma / kT)$$

τ_0 -Strongly depends on *H* (<-> size of the critial nucleus to reverse magnetization)
-Proportionnal to *L* (nucleation occurs in the particle – edges are neglected)



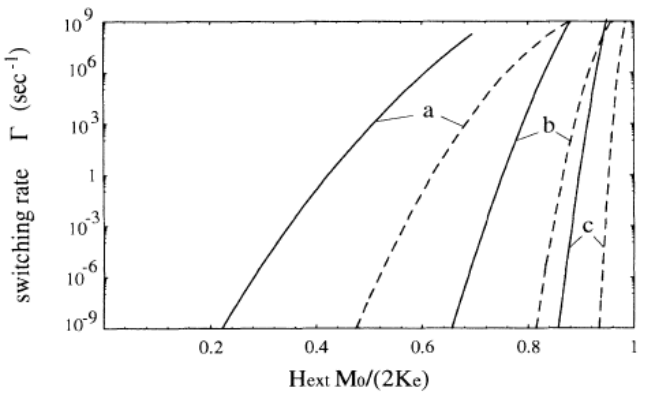
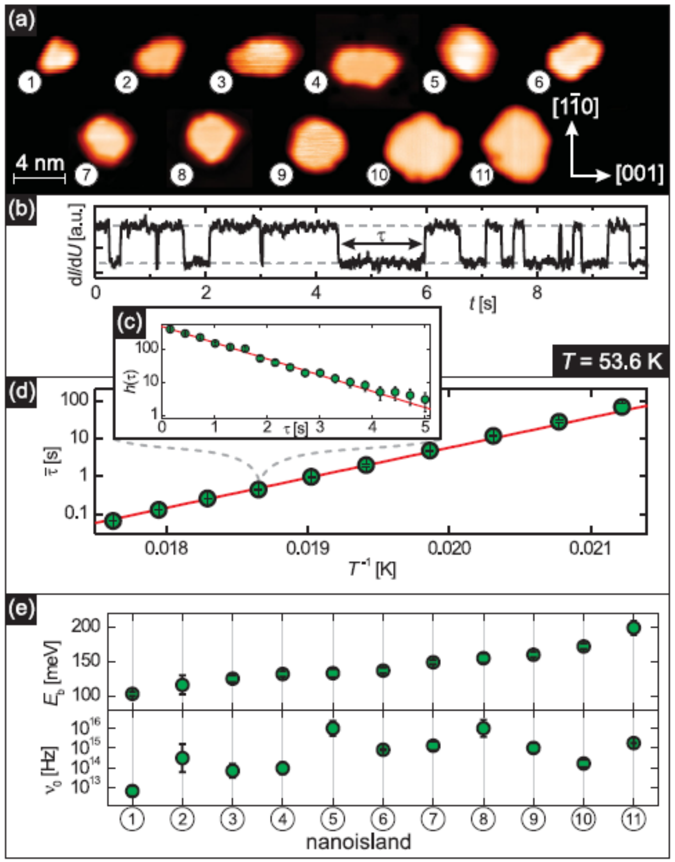


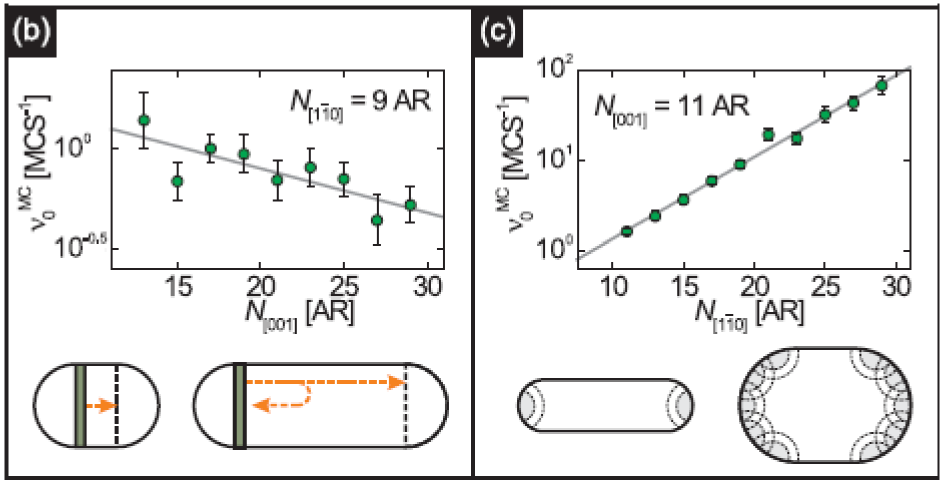
FIG. 2. The total switching rate is shown as a function of the external field *h* for particle diameters of (a) 100 Å, (b) 200 Å, and (c) 400 Å. For comparison, the dashed lines indicate the results of the Néel-Brown theory for an assumed particle aspect ratio of 1:1.5.

Superparamagnetism: beyond macrospin?

Superparamagnetism and nucleation-propagation magnetization reversal
Experimental check :

Single particle measurement by spin polarized STM





Monte Carlo simulation
τ_0 decrease with lenght, increase with the width
$\Rightarrow$edge nucleation

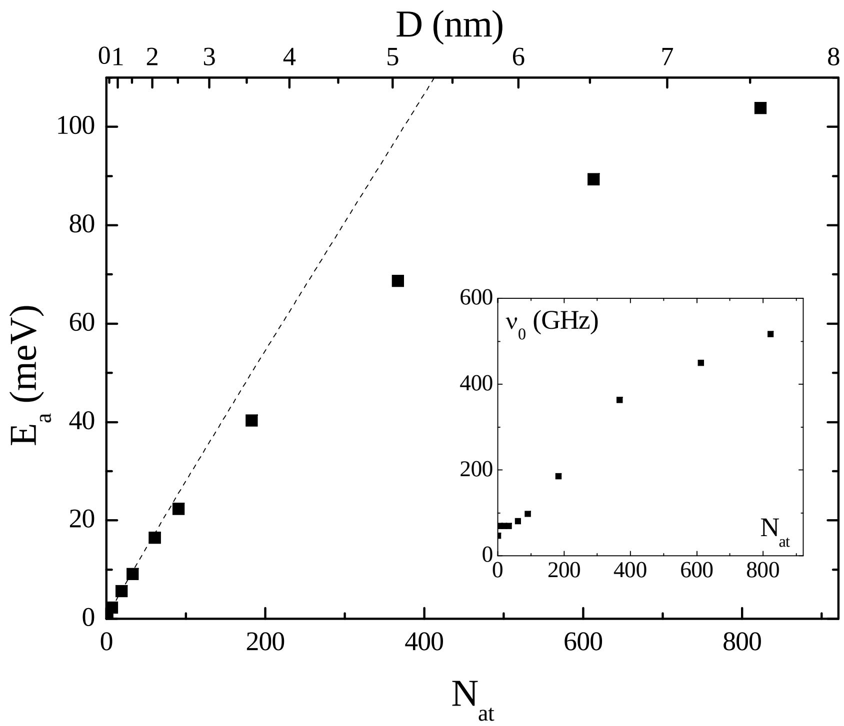
Krause et al. PRL 103, 127202 (2009)

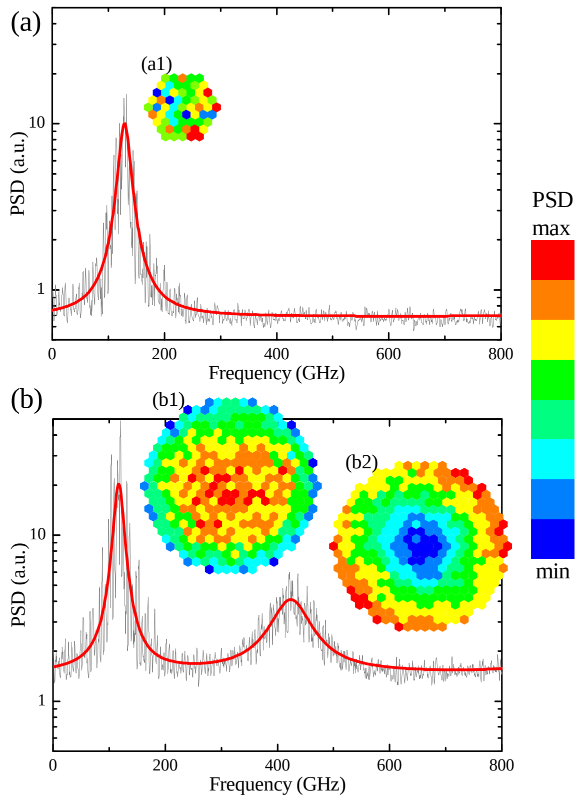
Superparamagnetism: beyond macrospin?

Superparamagnetism and spin waves

Atomic scale micromagnetic calculation on Co flat nanodots

•Homogeneous magnetization ground state
•Coherent rotation at T = 0
But coherent reversal over estimates switching rates at T≠0





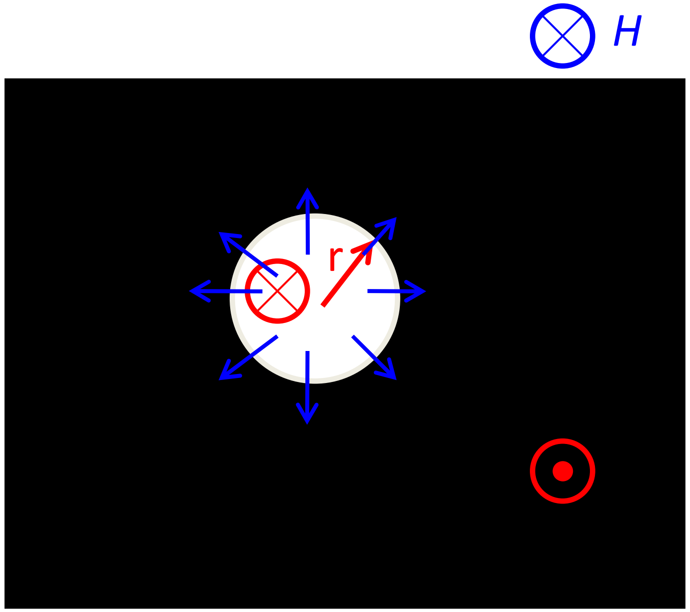
At finite T, high excitation modes are excited
Rohart et al. PRL 104, 137202 (2010)

Explains experiments from Rohart et al. 2010 and Rusponi et al. Nature Mat. 2003

Contents

Nucleation processes: Droplet model

-> 2D problem : apply to thin films with weak disorder

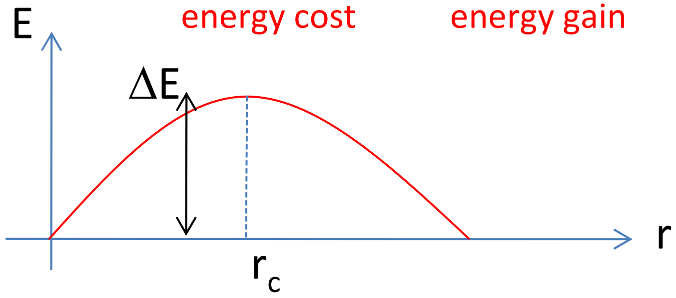


Energy :

$$E(r) = 2\pi r \sigma t - \pi r^2 t \times 2\mu_0 M_S H$$

Domain wall energy cost

Zeeman energy gain



$$\frac{dE}{dr}(r_c) = 0 \Rightarrow r_c = \frac{\sigma}{2\mu_0 H M_S}$$

$$\Rightarrow \Delta E = \frac{\pi\sigma^2 t}{2\mu_0 H M_S}$$

Important process for thin films
Energy barrier scales with 1/H

Nucleation rate
$R(H) = R_0 \exp(-\Delta E / kT)$

Barbara JMMM 129, 79 (1994)
Vogel et al. CR Physique 7, 977 (2006)

Nucleation processes:
Magnetization reversal in constant magnetic field

-> Nucleation rate vs. Domain expansion :

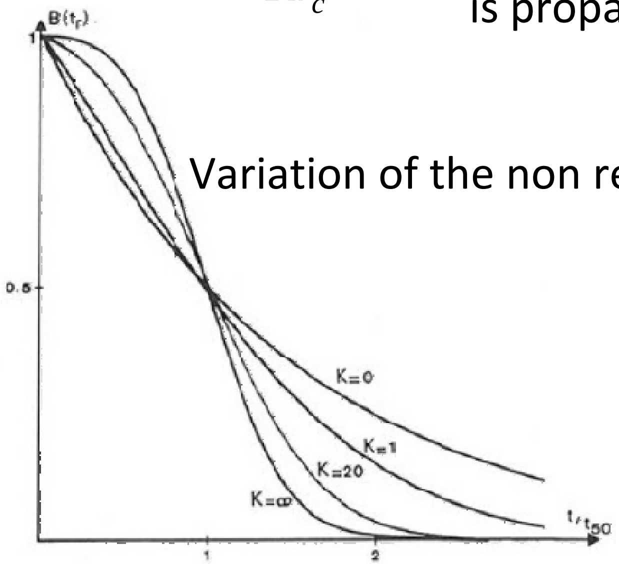
$$\frac{dN}{dt} = (N_0 - N)R \Rightarrow N = N_0\left(1 - \exp(-Rt)\right)$$ Domain nucleation

N_0 Nucleation site density
N Nucleated domaines
R Nucleation rate

$$S_N(t) = \pi\left(r_c + v_0 t\right)^2$$ Surface of the domain nucleated at *t=0*

v_0 Domain wall velocity

Pertienent parameter : $K = \dfrac{v_0}{Rr_c}$ defines if the magnetization reversal is propagation or nucleation limited



Variation of the non reversed area for different *K*

Labrune et al. JMMM 80, 211 (1989)
Fatuzzo Phys. Rev. 127, 1999 (1962)

Nucleation processes:

Magnetization reversal in constant magnetic field

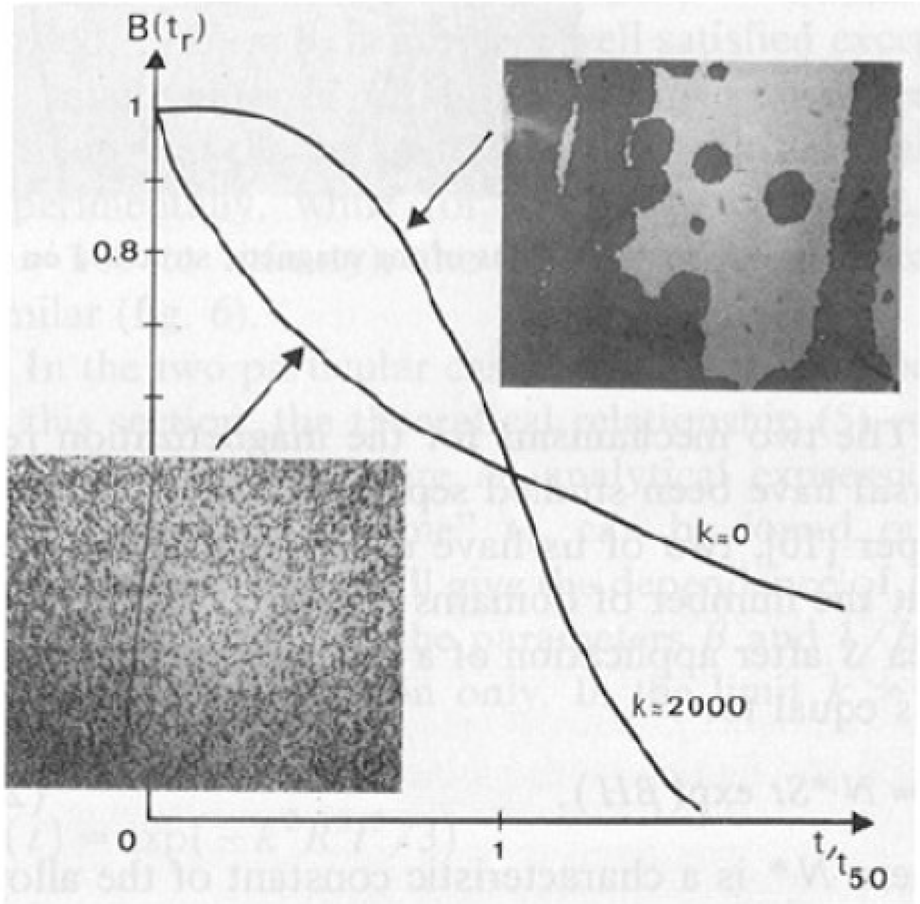
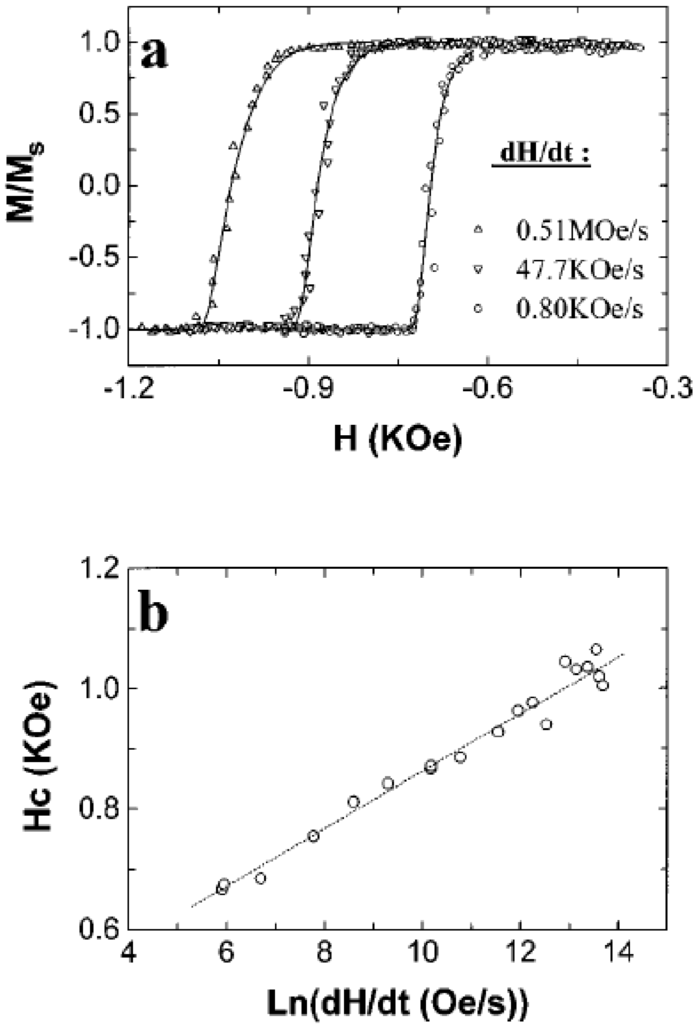


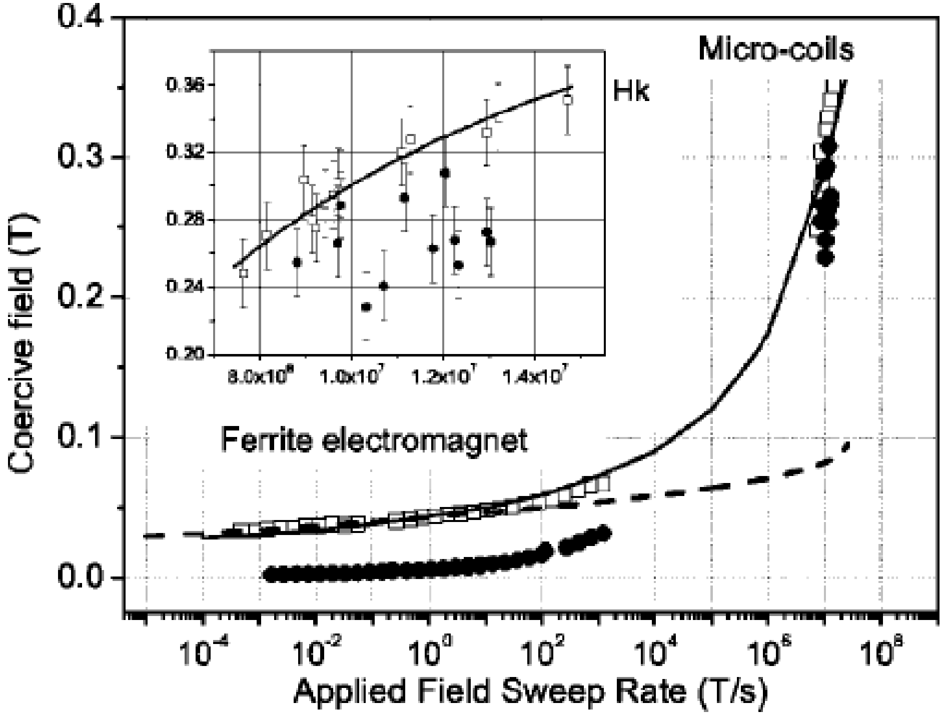
Fig. 4. Magnetization versus reduced time t_R for a GdFe sample ($k \simeq 2000$) and a TbCo one ($k \simeq 0$), corresponding domain structure observed by Kerr effect.

Labrune et al. JMMM 80, 211 (1989)

Nucleation processes: Coercive field and droplet model



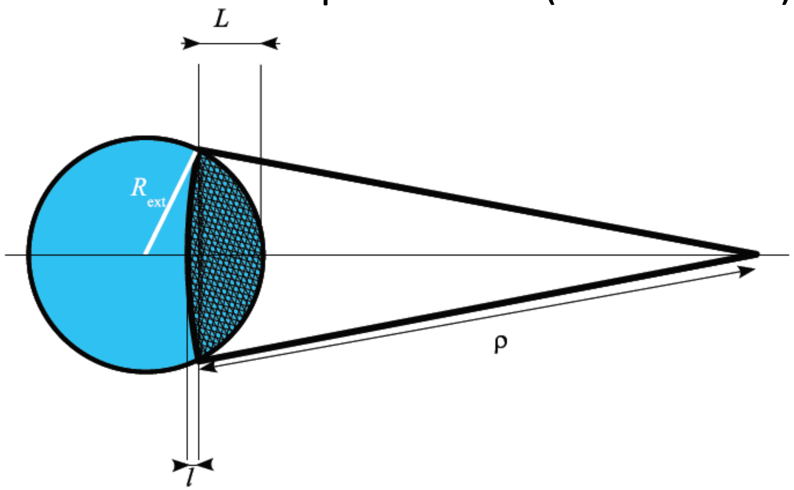
Au/Co/Au films and nanostructures
Raquet et al. PRB 54, 4128 (1996)



Pt/Co/Pt films and nanostructures
Moritz et al. PRB 71, 100402(R) (2005)

Nucleation processes:
Droplet model in reduced dimensions

⇒Confined droplet model (circular dot)



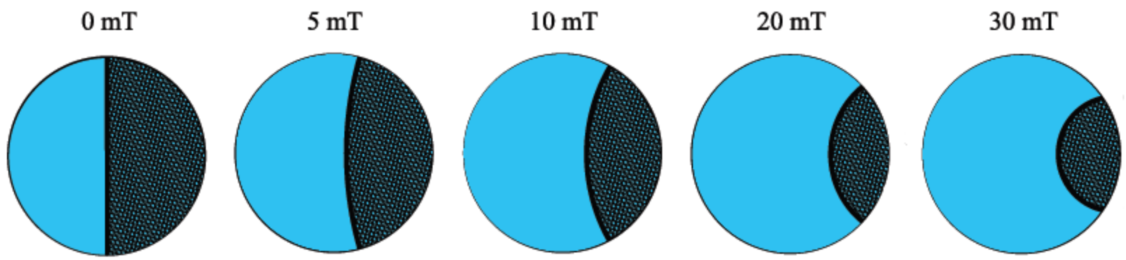
Nucleation is generally easier at the edge

Critical droplet size :

$$\rho_c = \frac{\sigma}{2\mu_0 H M_S}$$ (same as thin films)

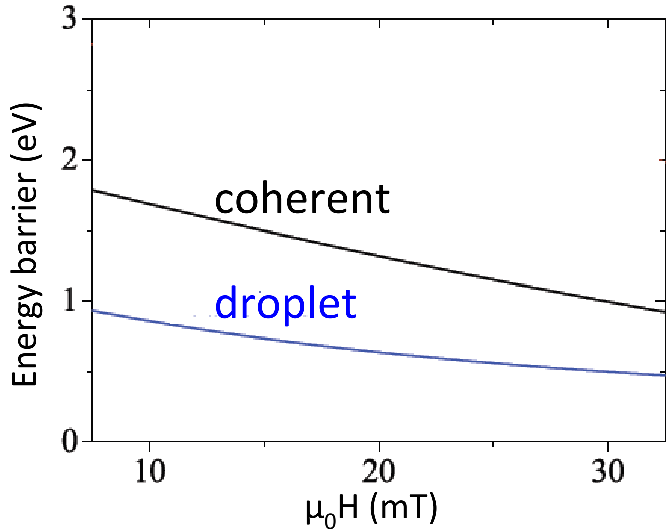
$$L_c = R_{ext}\left(1 - \frac{\xi}{\sqrt{1+\xi^2}}\right) \quad with\ \xi = \frac{R_{ext}}{\rho_c}$$

Magnetic configuration at the maximum energy



(Same as Braun 1993)

Numerical application:
Parameters for Pt/Co(0.5 nm)/Pt film



JP. Adam PhD thesis, Orsay 2008 (unpublished)

See also 3D theory : Hinzke and Nowak PRB 58 265 (1998)

Nucleation processes:

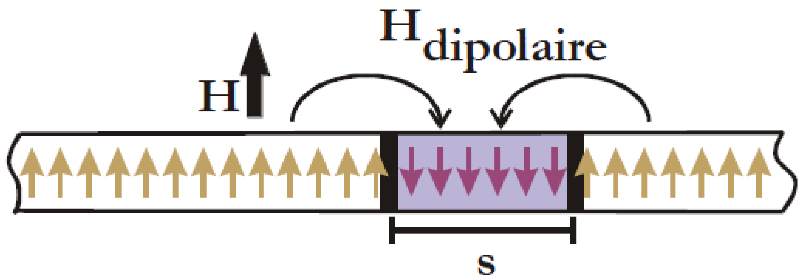
Coalescence between nucleated domains

Pt/Co(0.5 nm)/Pt
Time between frame : 400 s
Nucleation field : 5 Oe
Propagation field : 3Oe (to reduce DW velocity)

⇒The experiment validates the picture of nucleation/propagation

⇒Coalescence between domains is difficult
⇒Nucleation of 360° domain walls

Dipolar repulsion between domains



⇒Saturation may be difficult to reach
⇒Poison for magnetization reversal

Bauer et al. PRL 94, 207211 (2005)
See also : Schrefl, et al. J. Appl. Phys. 87, 5517 (2000) (in plane magnetization)
Hehn et al. APL 92, 072501 (2008) (in MRAM nanoelements)

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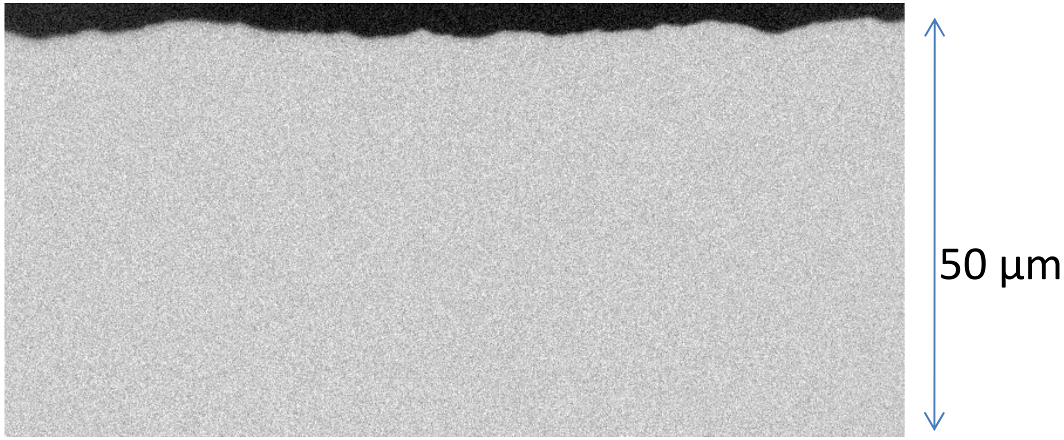
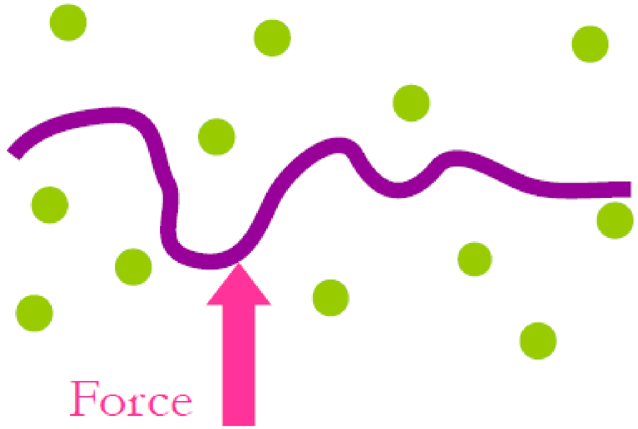
Domain wall motion in disordered films



Pt/Co(0.5 nm)/Pt with perpandicular magnetization
H = 42 Oe
Time between frame : 100s

Domain wall is not extended as a straight line (minimisation of length) but also feels some weak defects.



$\Rightarrow$Competition between elasticity and pinning

Driving force : H

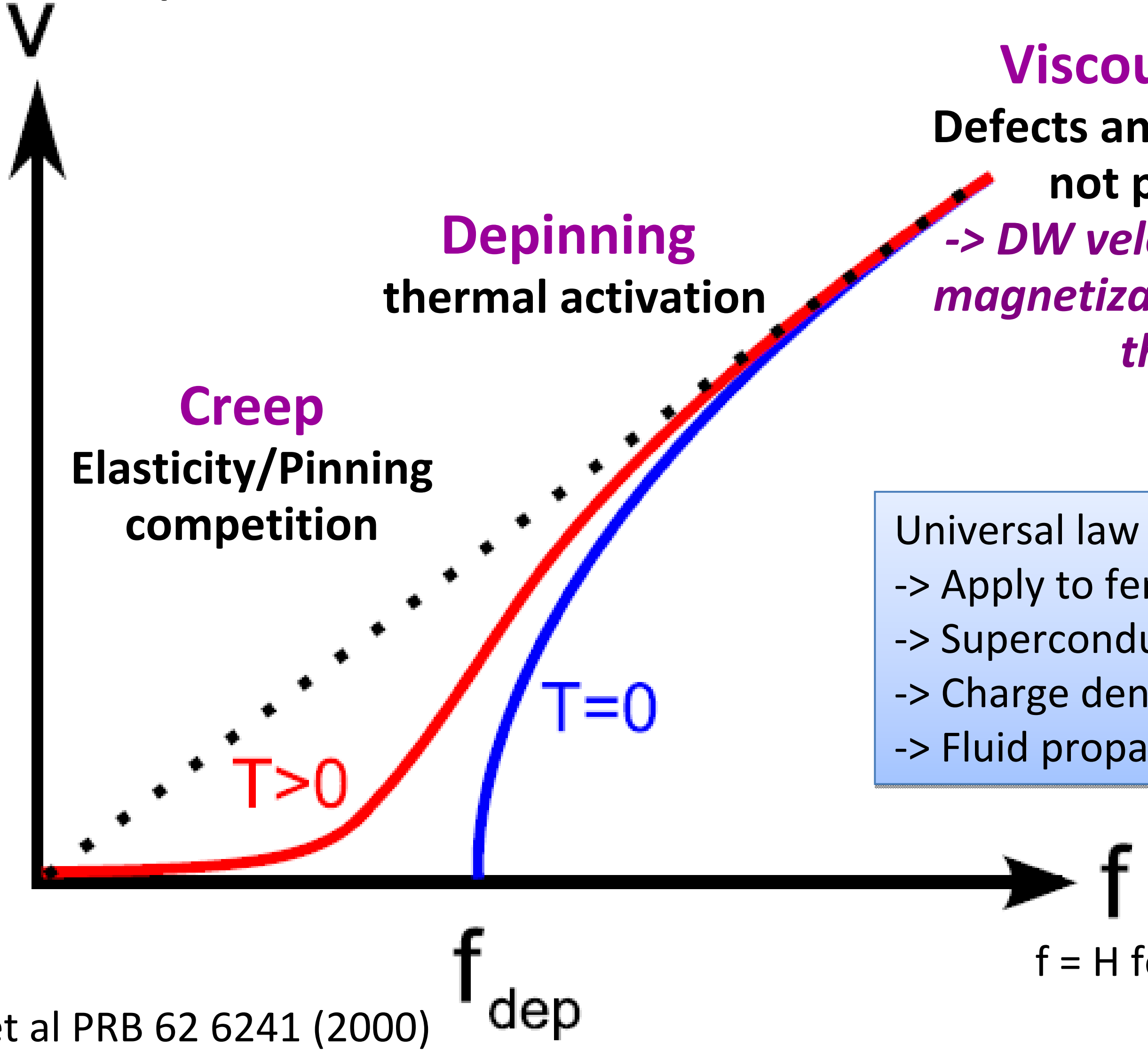
Elasticity : $\varepsilon = \sigma t = 4t\sqrt{AK}$

Pinning : f_{pin}

(roughness, thickness variation…)

Domain wall motion in disordered films

From Creep to viscous motion



Viscous regime

Defects and disorder are not pertinent

-> DW velocity given by magnetization dynamics theory

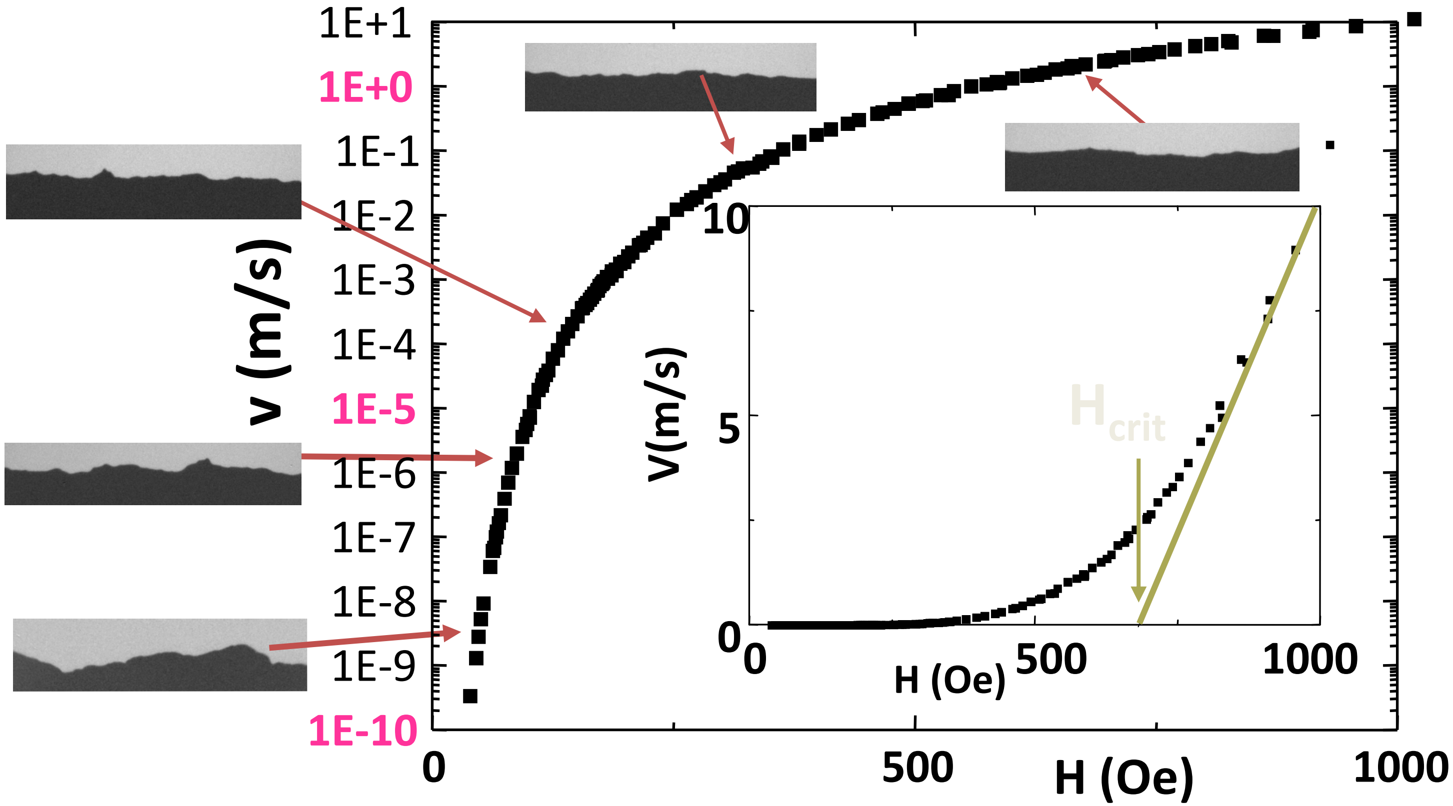
Universal law
-> Apply to ferroelectric DW
-> Superconducting vortices
-> Charge density waves
-> Fluid propagation in porous media

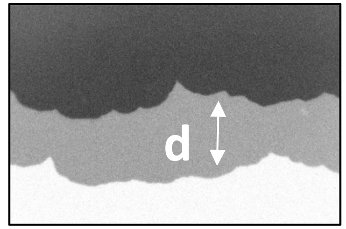
f = H for magnetic DW

Chauve et al PRB 62 6241 (2000)

Domain wall motion in disordered films

Propagation and roughness





$v = d/\Delta t$

H << H$_{crit}$: very small velocity

➔ DW adapts to defects

➔ Significant roughness

H >> H$_{crit}$: large velocity

➔ Limited role of disorder

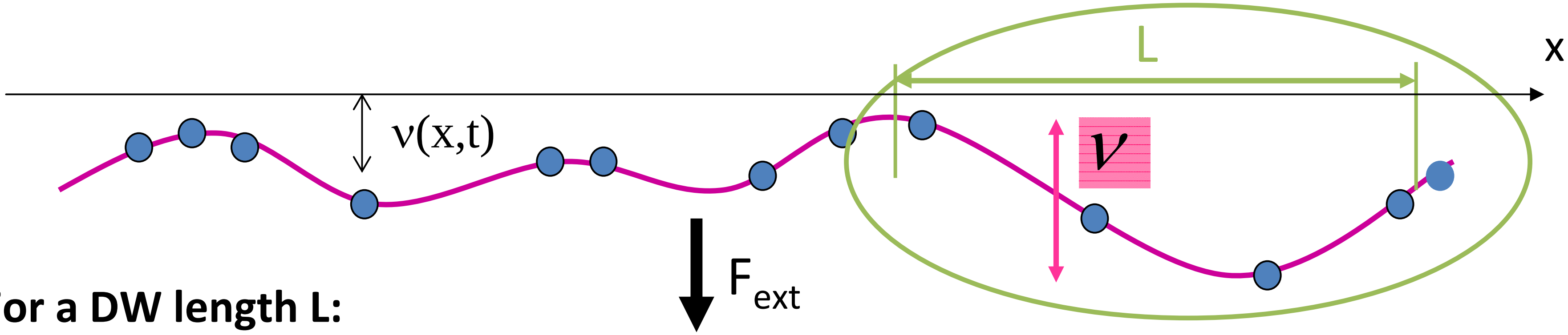
➔ Small roughness

➔Velocity with universal behavior on 10 orders of magnitude.

S. Lemerle et al, PRL.**80**, 849 (1998)

Domain wall motion in disordered films

Elastic energy

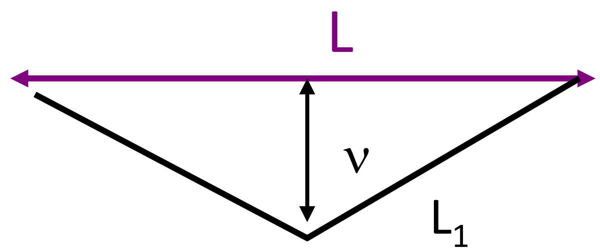


For a DW length L:

ν ~ Δν(x,t) mean of transverse fluctuations

Elastic energy: *increase in DW length*

$\Delta L = 2L_1 - L = \nu^2 / L$



Low curvature:

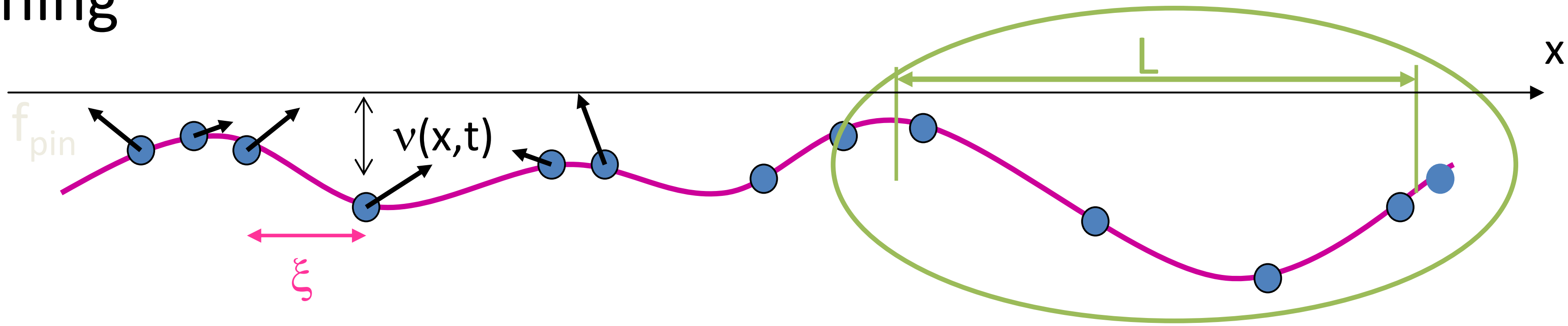
$L_1 = L/2\,(1 + 4\nu^2 / L^2)^{1/2}$

$$E_{elastic} = \int_0^L \left[\frac{\varepsilon}{2} \left(\frac{d\nu}{dx} \right)^2 \right] dx \cong \frac{\varepsilon\, \nu^2}{L}$$

➔ Roughness and fluctuation ⇔ Elastic energy cost

Domain wall motion in disordered films

Pinning



ξ: Correlation length of disorder

n_i = *pinning center density* **f_{pin} : *pinning force of one center***

➔Random force of individual forces

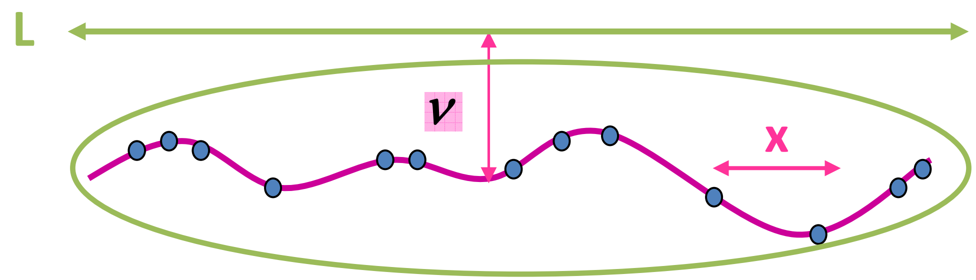
➔Only density fluctuations can *collectively* pin the domain wall

Δ = « collective force » coming from disorder $\Delta = f_{pin}^2 n_i \xi$

<u>Pinning energy</u> : $E_{pinning} = -f_{pin}\sqrt{n_i \xi L}\,\xi = -\sqrt{\xi^2 L \Delta}$

Domain wall motion in disordered films

Competition between pinning and elasticity



➔ Two critical lengths: L_C and ν_C

$$E_C = E_{pinning}(L_c) = E_{elastic}(L_c)$$

$$\sqrt{\nu_c^2 L_c \Delta} = \frac{\varepsilon \nu_c^2}{L_c}$$

$$L_c = \left(\frac{\varepsilon^2 \nu_c^2}{\Delta}\right)^{1/3}$$

➔ Larkin length $L_C \sim 0.025$ µm

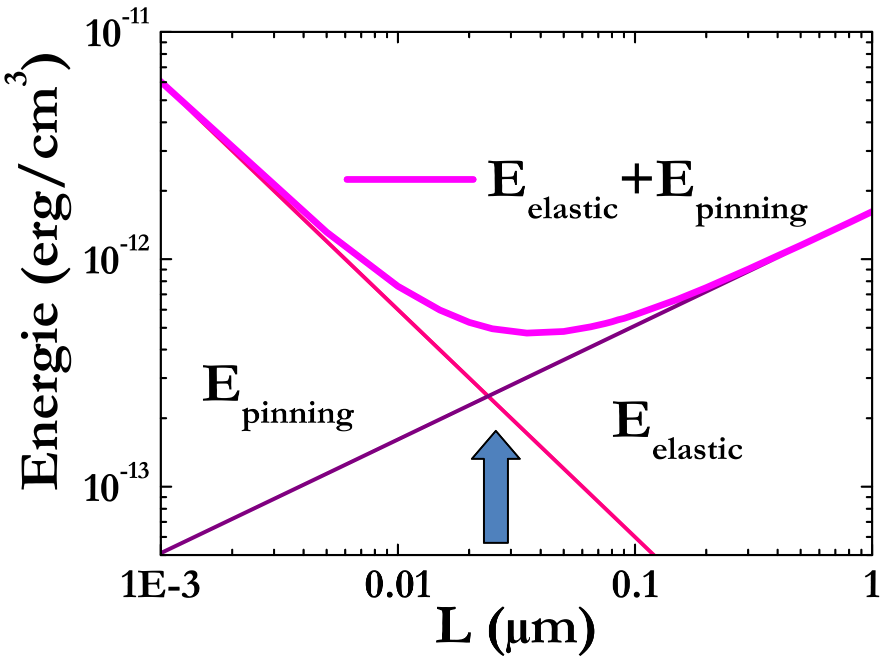
(for Pt/Co/Pt ultrathin films)

***Small scales*:**

Disorder caracteristic length

~ grain size

~Transverse fluctuations



Domain wall motion in disordered films

Scaling law – Renormalization group theory

For $L > L_c > n_C$

$$v = v_c \cdot \left(\frac{L}{L_C}\right)^{\zeta}$$

Scaling law for fluctuations

ζ= 2/3 : universal exponent (for a 1D interface in motion in a 2D medium with weak disorder)

- **Elastic energy**

$$E_{elastic} = \frac{\varepsilon v_c^2}{L}\left(\frac{L}{L_c}\right)^{2\zeta}$$

$$E_C = E_{pinning}(L_C) = E_{elastic}(L_C)$$

- **Pinning energy**

$$E_{pinning} = E_C \cdot \left(\frac{L}{L_C}\right)^{2\zeta-1}$$

$$Critical\ volume : V_c = L_c v_c t$$

- **Zeeman energy**

$$E_{Zeeman} = M_S\, t v L\, H = M_S\ V_C\, H\left(\frac{L}{L_C}\right)^{\zeta+1}$$

Domain wall motion in disordered films

Activation energy and regime of motion

Thermally activated regime in creep regime

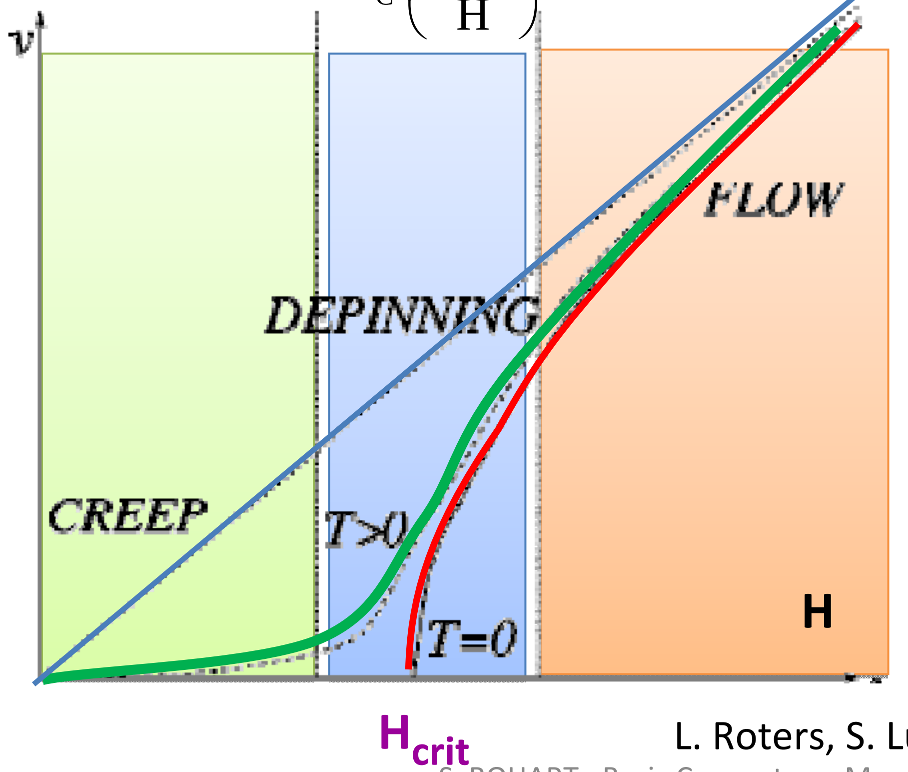
$$E_{activation} = E_{Zeeman} + E_{pinning} \qquad \Delta E = -M_S V_c H + E_C \cdot (\tfrac{L}{L_C})^{2\zeta-1}$$

➔ **Activation energy as a function of external field**

$$\Delta E = E_C \left(\frac{H_{crit}}{H}\right)^{\frac{2\zeta-1}{2-\zeta} \Rightarrow \frac{1}{4}}$$

With ζ= 2/3

$$v = v_0 \exp\left[-\frac{E_C}{k_B T}\left(\frac{H_{crit}}{H}\right)^{1/4}\right]$$



In the vicinity of the depinning field

$$H_{crit} = E_C / M_S V_C$$

$$E_{pinning}(L_C) = E_{Zeeman}(L_C)$$

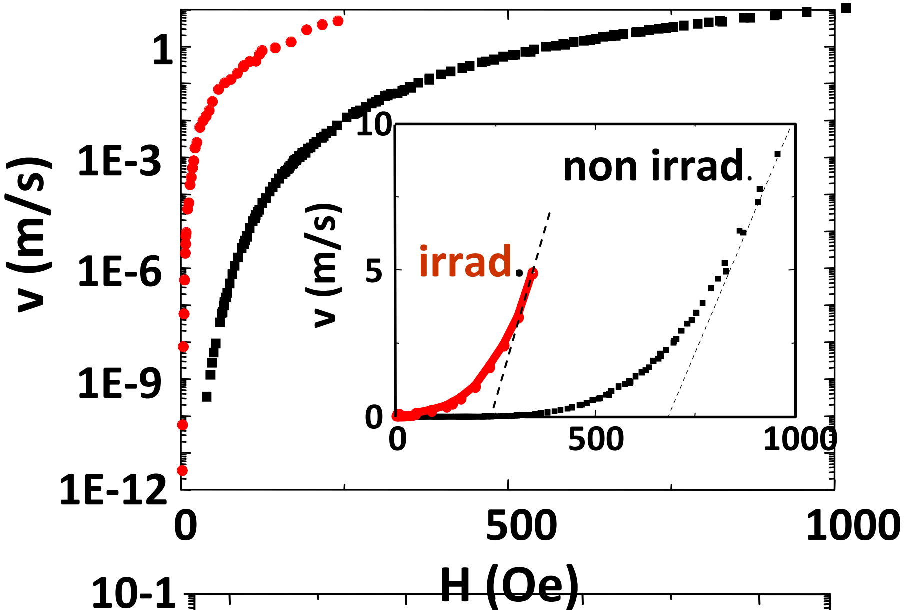
$$V = (H - H_{crit})^{\beta}$$

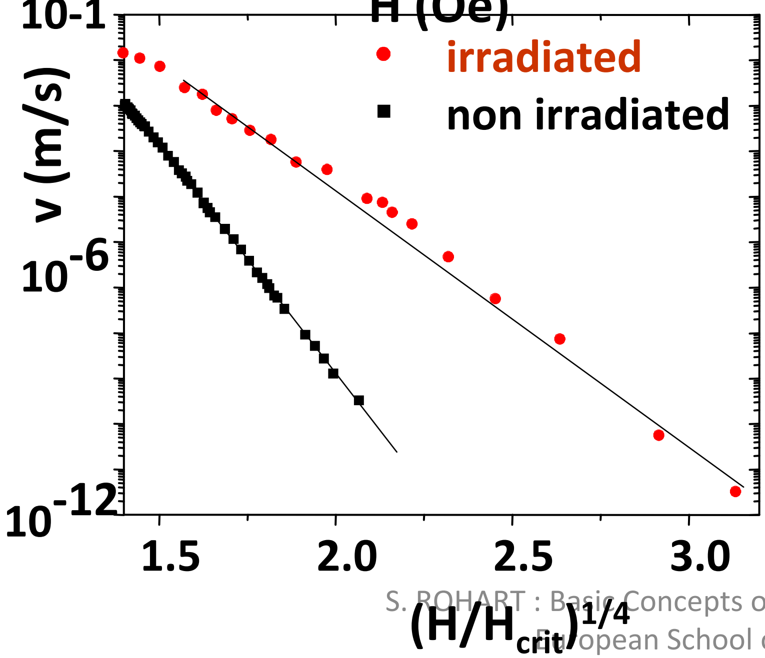
Flow regime $v = \mu H$

L. Roters, S. Lübeck and K.D. Usabel, Phys. Rev. E, **63,** 026113 (2001)

Domain wall motion in disordered films

ex: Pt/Co/Pt ultrathin films





for H >H_{crit}

$$v = \sigma(H - H_{crit})$$

$H_{crit\ non\ irr}$= 700 Oe **$H_{crit\ irr}$= 230 Oe**

⇒ Depining regime

For H<H_{crit}/5

$$v = v_0 \exp\left[-\frac{E_C}{k_B T} \left(\frac{H_{crit}}{H}\right)^{1/4} \right]$$

$E_{c\ non\ irr}$= 46 kT **$E_{c\ irr}$= 26 kT**

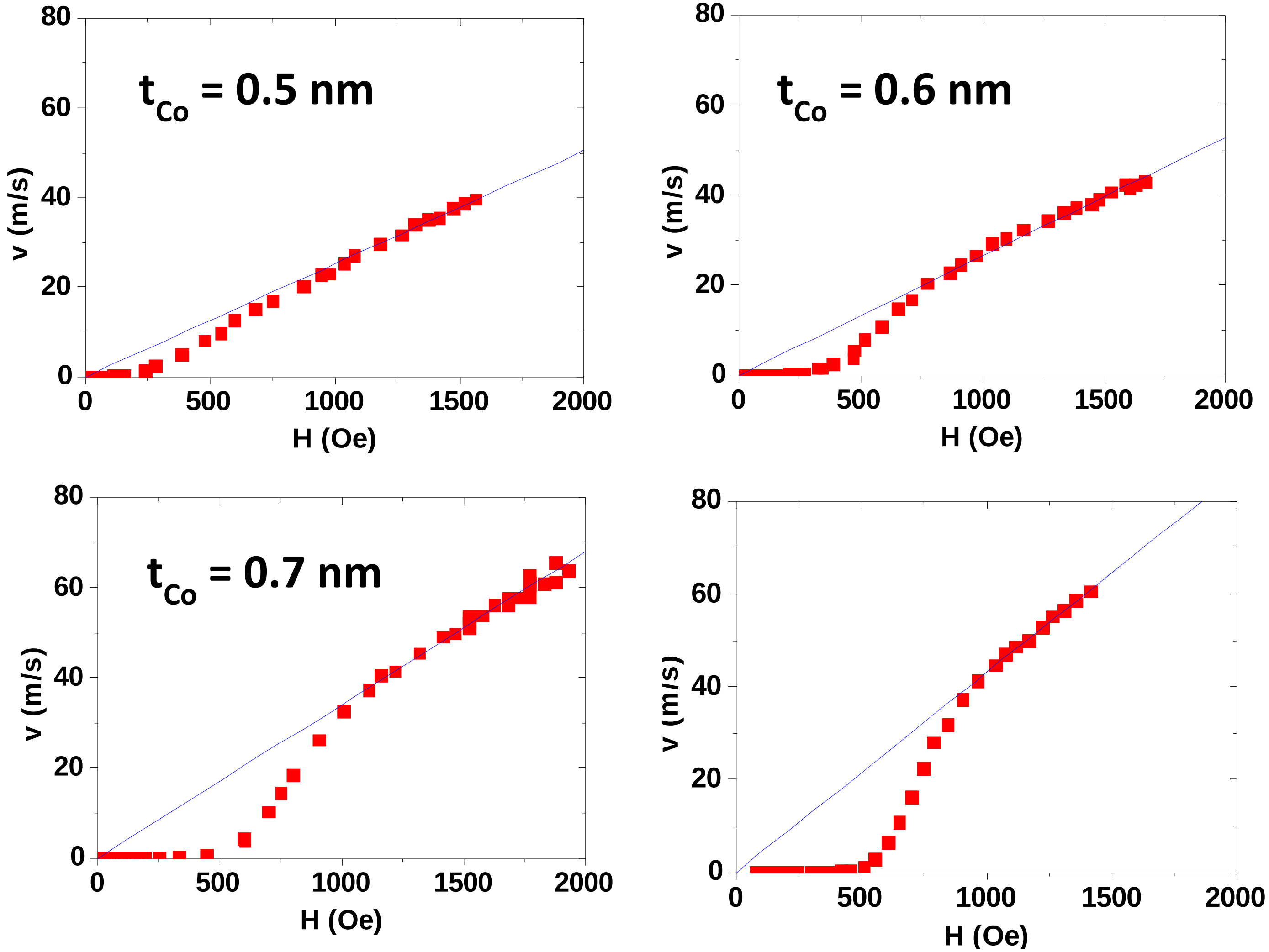
⇒ Creep regime

Unpublished results

See also S. Lemerle et al, PRL.**80**, 849 (1998)

Domain wall motion in disordered films

ex: Pt/Co/Pt ultrathin films



Flow regime
-> $v \propto H$
Precessional motion of domain wall ($H>H_{walker}$)

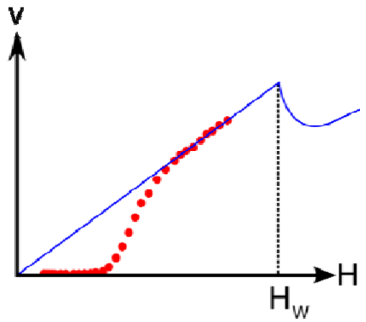
P. J. Metaxas, Phys. Rev. Lett. **99** 217208 (2007)

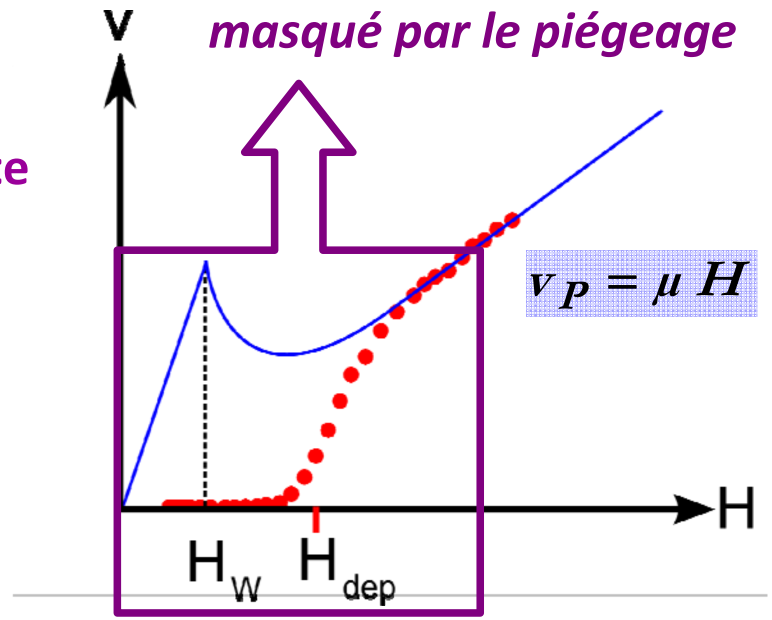
Mobilité/ champ critique/ champ de Walker

Interprétation cohérente des observations expérimentales à fort champ

changement de dynamique interne masqué par le piégeage

➔ **Evaluer H_w , confinement pris en compte**





t(Co) (nm)	H_w (Oe)	H_{dep} (Oe)	α
0.5	100	470	0.24
0.6	210	590	0.30
0.7	230	705	0.32
0.8	220	650	0.31

➔**Mouvement visqueux observé = régime précessionnel**

$$v_P = \frac{\gamma \Delta \alpha}{1+\alpha^2} H$$

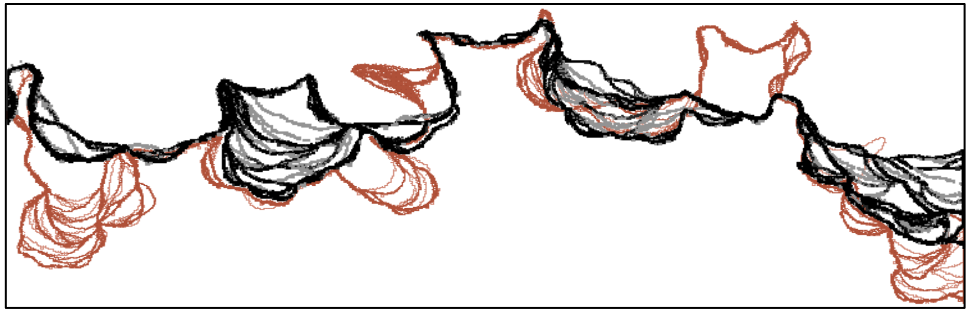
➔**Paramètre d'amortissement de Gilbert α~0.25 compatible avec résultats FMR et valeurs utilisées pour des simulations numériques**

P. J. Metaxas, Phys. Rev. Lett. **99** 217208 (2007)

Domain wall motion in disordered films

Divergence of energy barrier

Evidence of energy barrier for H /H_{crit} <<1



$$\Delta E = E_C \left(\frac{H_{crit}}{H}\right)^{1/4}$$

H= 2 Oe (0.01 H_{crit}) Dt = 200 secondes

H = 4 Oe (0.02 H_{crit}) Dt =1 seconde

➔ **L_{jump} is defined at the energy barrier**

$$\Delta E = E_C \cdot \left(\frac{L}{L_C}\right)^{1/3} + M_S\, t\, H \nu_C L_C \left(\frac{L}{L_C}\right)^{5/3}$$

Jump length $L_{jump} = E_L \frac{1}{H^{4/3}}$

➔ **Barkhausen jumps with 1/$H^{4/3}$ jump length**

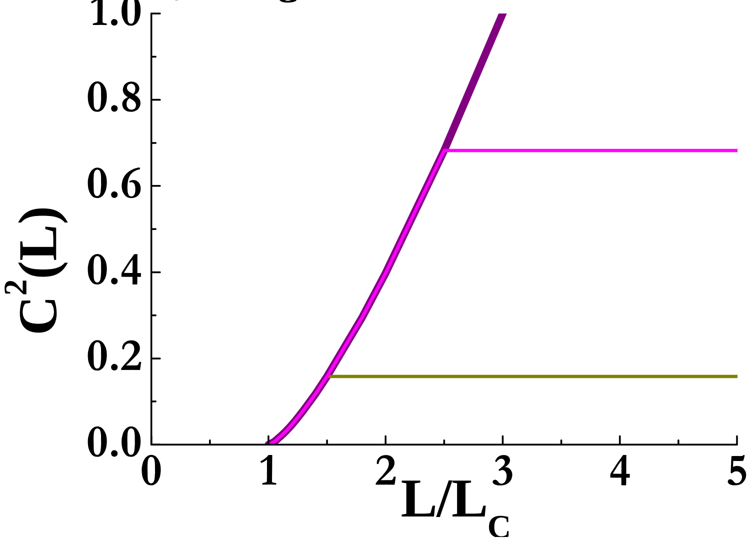
➔ **Motion through avalanche processes**

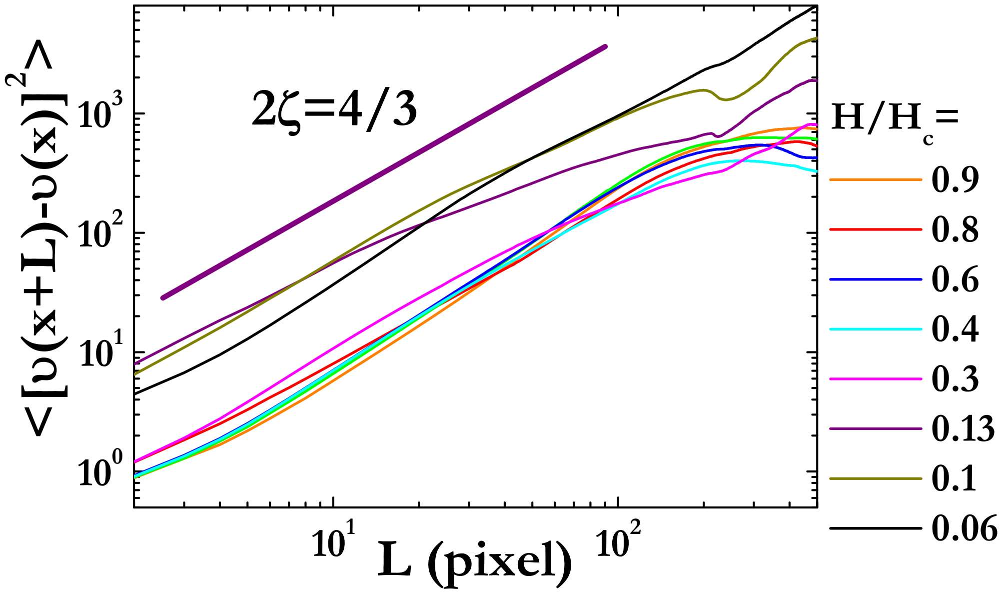
V. Repain et al., EuroPhysicsLett **68** (2004) 10213

Domain wall motion in disordered films

Roughness analysis

$$\nu_L = \nu_{L_c} \cdot \left(\frac{L}{L_C}\right)^{\zeta}$$ **ζ= 2/3**





Correlation on a given length *L*

$$C^2(L) = \left\langle [\nu(x) - \nu(x+L)]^2 \right\rangle_L \propto \left(\frac{L}{L_C}\right)^{4/3}$$

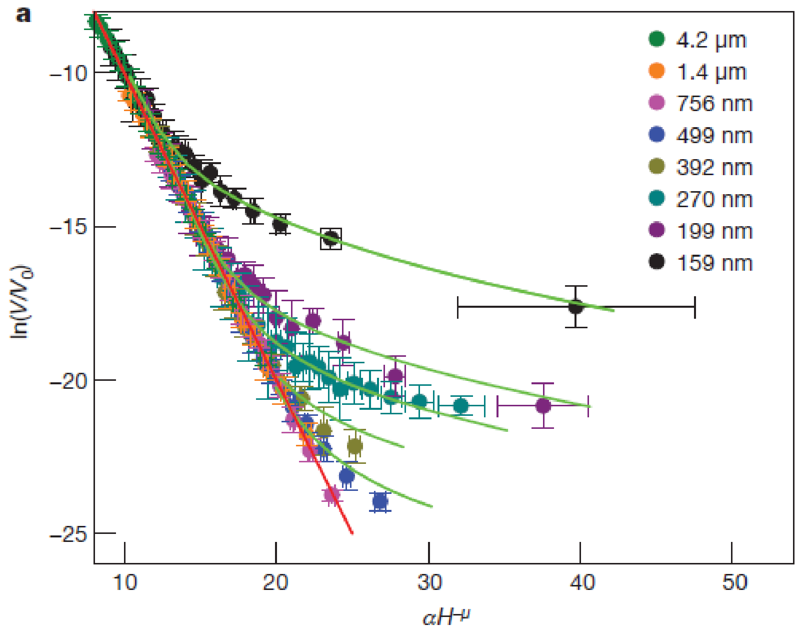
Critial exponent is independent of H (for $H<0.9H_C$)
Sligh increase of L_C for $H/H_C>0.2$

A. Mougin et al. unpublished results

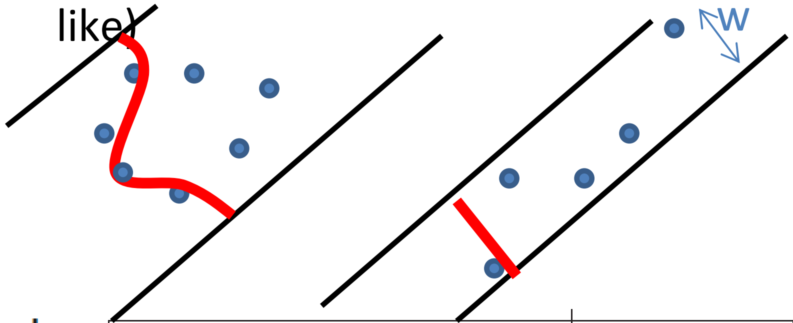
Domain wall motion in disordered films

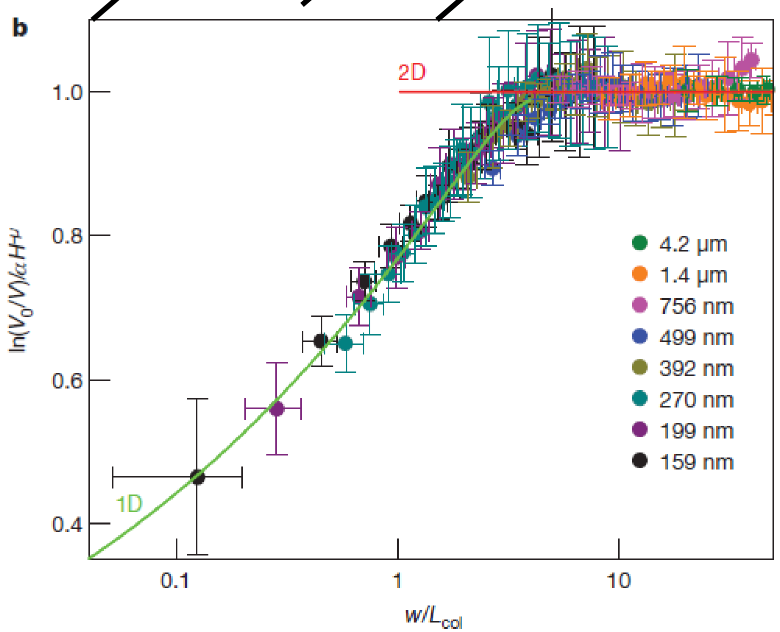
Creep in confined geometry

Domain wall propagation in nanowires (Pt/CoFe0.3nm/Pt)



Cross over between creep motion (2D like) and hoping (1D like)





Universal scaling :

$$w / L_{col} \propto \frac{w}{L_C H^{3/4}}$$

w Wire width

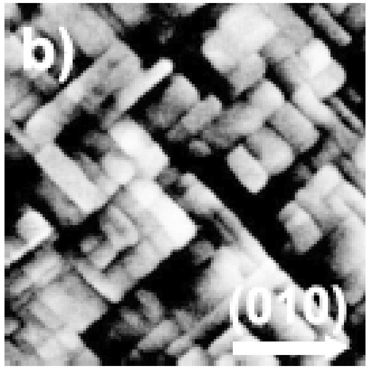
L_{col} Segment length for jump

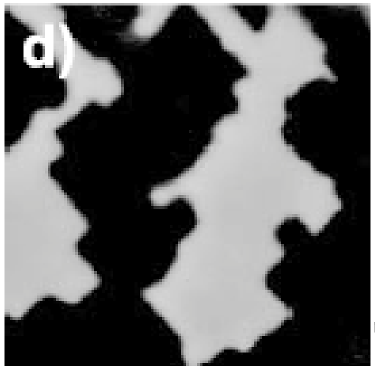
L_c Larkin length

Kim et al. Nature 458, 740 (2009)

Domain wall motion in disordered films

Magnetization reversal with strong pining





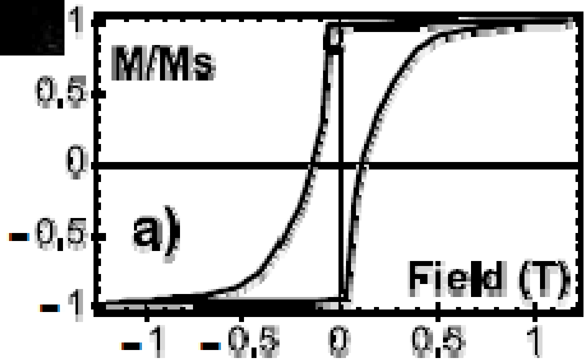
Epitaxial FePt(40nm)/Pt film : presence of micromacle than pins the domain walls.

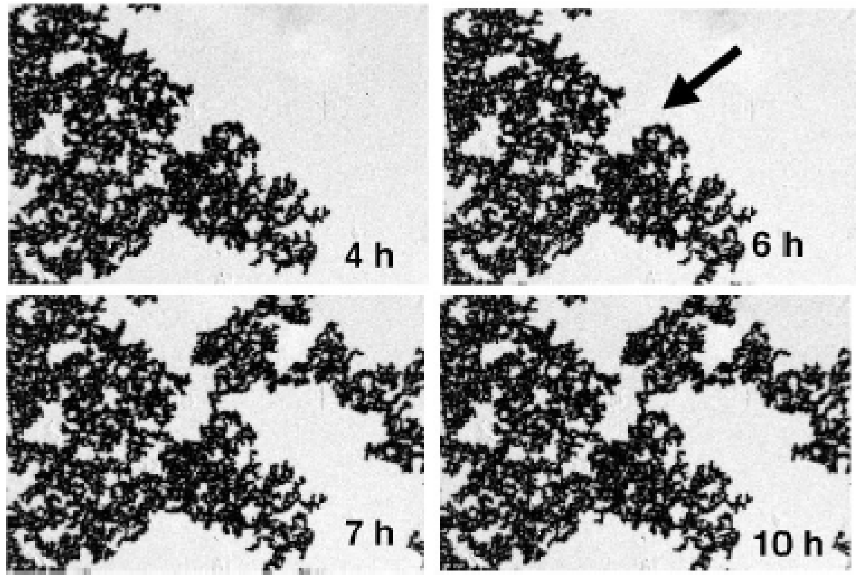
Domain wall propagation is channeled between micromacles : fast fractal-like domain growth.

Saturation needs to overcome strong pinning barriers :

⇒Slow high field saturation

⇒Thermal activation (slow dynamics)





Attane et al. PRL 93, 257203 (2004)

Conclusion

Take home message

•When dealing with long time scales, thermal activation plays an essential role.
•Many properties (like coercive field) depend on the time scale (field sweeping time, waiting time)…

To go further

•Toward quantum fluctuations : already observed in molecular magnets
-> quantum fluctuation and tunneling of a domain wall is still a challenge…

Wernsdorfer and Sessoli Science 284, 133 (1999)

Gunther and Barbara *Quantum Tunneling of Magnetization-QTM'94 (Kluwer, Netherlands, 1995)*

•Magnetization reversal under spin polarized current
-> Creep law with a different driving force (spin transfert torque)

Yamanouchi et al. Nature 428, 539 (2004)

Some readings

•Skomski and Coey *Permanent magnetism (*Taylor & Francis Group 1999)
•Aharoni *Introduction to the theory of ferromagnetism* (Oxford 1996)
•Skomski *Nanomagnetics* J. Phys. Cond. Mat. **15**, R841 (2003)
•Fiorani *Surface effects in Magnetic Nanoparticles* (Springer 2005)
•P. Metaxas, PhD thesis (Creep), Orsay, 2009 : http://trove.nla.gov.au/work/39007513