Micromagnetism and magnetization processes

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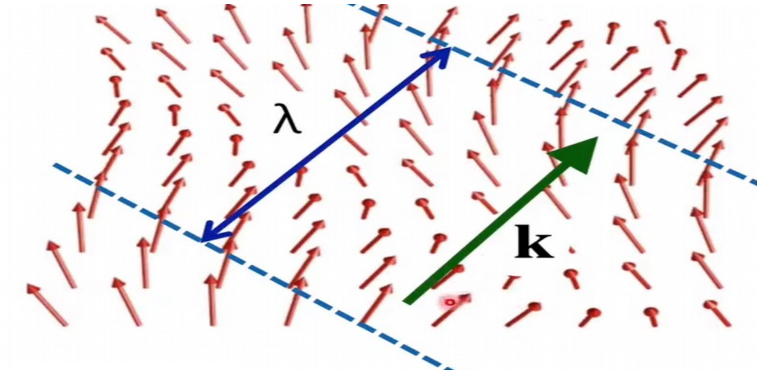
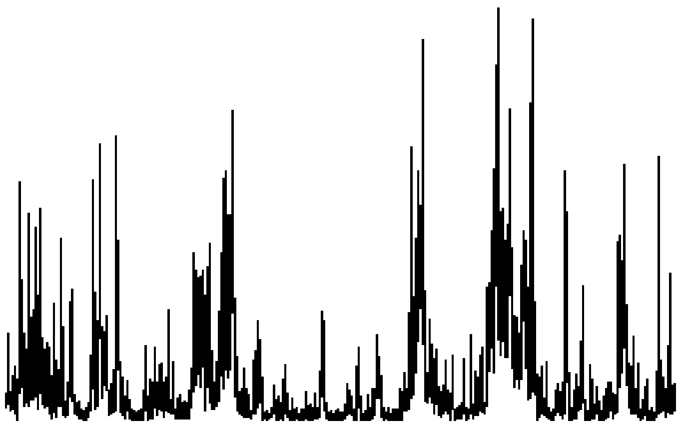
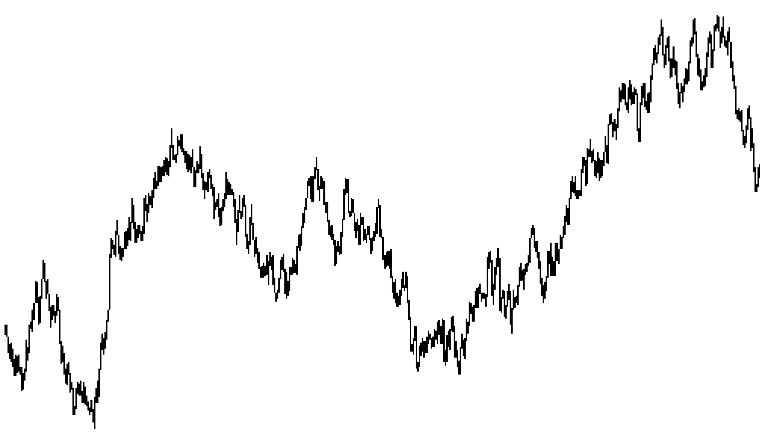
lecture@ESM2021 - September 9-10, 2021







Spin dynamics

- Ferromagnetic resonance
- Spin waves
- Exchange constant

Domain wall dynamics

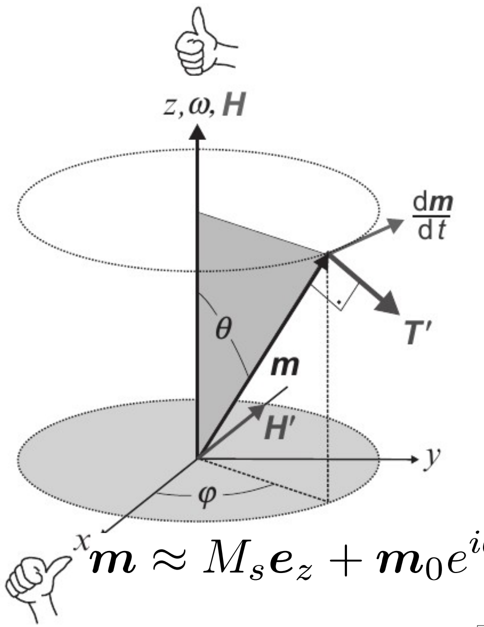
- 1d model
- Creep dynamics
- Barkhausen noise

Hysteresis phenomena

- The origin of hysteresis
- Energetics
- Frequency dependence

Ferromagnetic resonance: the Kittel equation

- Observed in a ferromagnet in the microwave frequency range
- Uniform magnet field $\boldsymbol{H}$ and a *transverse* high-frequency field $\boldsymbol{H}'$
- The torque $\boldsymbol{T}' = \boldsymbol{m} \times \boldsymbol{H}'$ compensates for the damping



$$\boldsymbol{m} \approx M_s \boldsymbol{e}_z + \boldsymbol{m}_0 e^{i\omega t}$$

$$d\boldsymbol{m}/dt = \gamma(\boldsymbol{m} \times \boldsymbol{B}_{int})$$

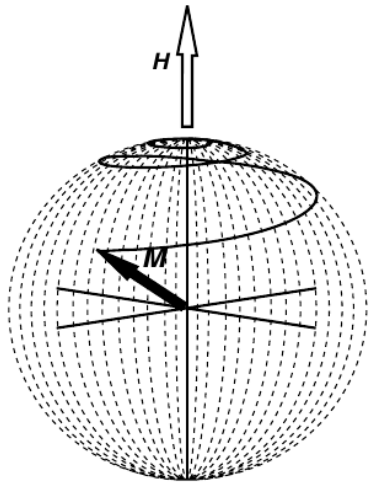
$$\boldsymbol{B}_{int} = \mu_0 \boldsymbol{H}_{int} = \mu_0(\boldsymbol{H}_{ext} + \boldsymbol{H}_d)$$
$$\boldsymbol{H}_d = -\mu_0[N_x m_x \boldsymbol{e}_x + N_y m_y \boldsymbol{e}_y + N_z(m_z + M_s)\boldsymbol{e}_z]$$

$$\frac{dm_x}{dt} = \mu_0\gamma(m_y H_z - M H_y) = \mu_0\gamma[H_{ext} + (N_y - N_z)M_s]m_y$$
$$\frac{dm_y}{dt} = \mu_0\gamma(-m_x H_z + M H_x) = -\mu_0\gamma[H_{ext} + (N_x - N_z)M_s]m_x$$

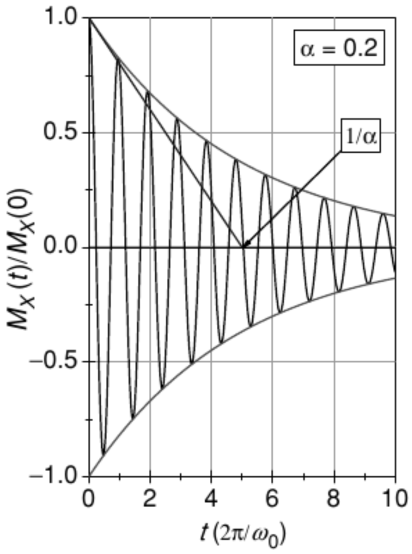
General solution $\omega_0^2 = \mu_0^2\gamma^2[H_{ext} + (N_x - N_z)M_s][H_{ext} + (N_y - N_z)M_s]$

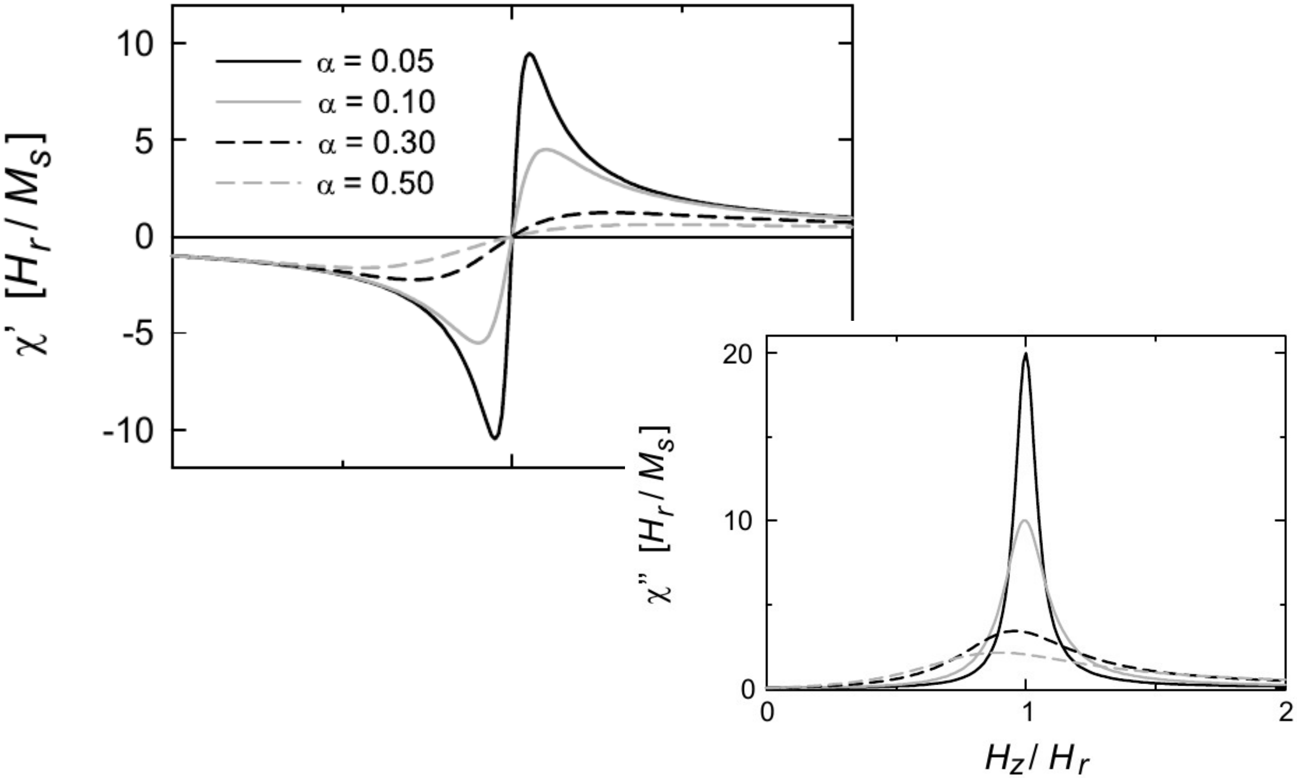
In a PMA film (add K_1, N_x=N_y=0) $\omega_0 = \mu_0\gamma[H_{ext} + 2K_1/\mu_0 M_s - M_s]$

Ferromagnetic resonance: the damping



- Damping is the source of dissipation
- The susceptibility χ is complex
- By the width of χ'', the damping α is estimated



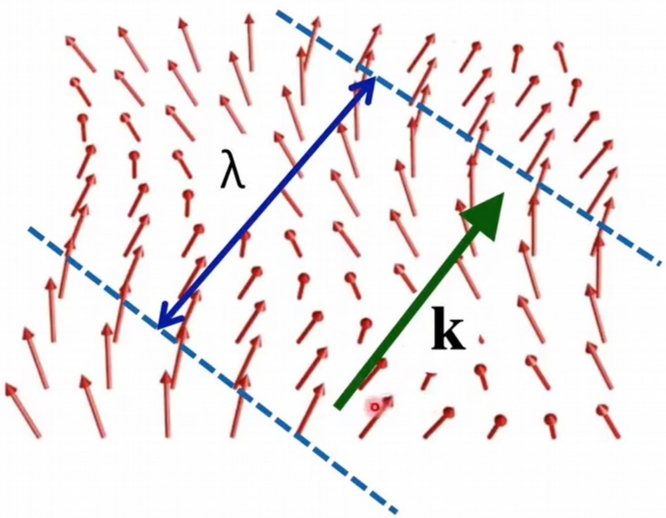


Spin waves as a collective motion

universität wien

Spin wave and magnon

Spin wave: collective motion of magnetic moments

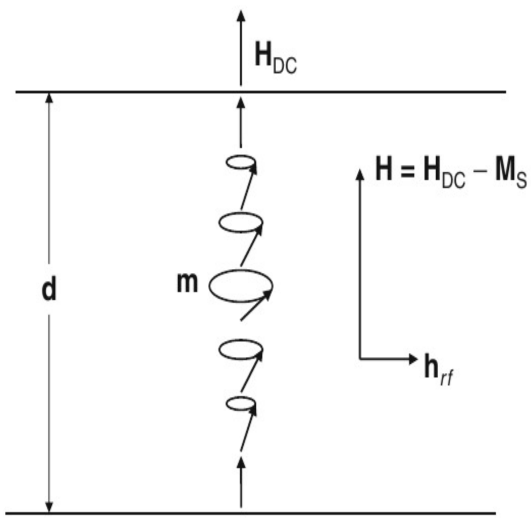


Animation: Prof. Dr. D. Bozhko

Nanomagnetism and Magnonics | Andrii Chumak   Basics of spin waves   Vienna, 19.11.20   Page 14

Credits: A. Chumak, Introduction to spin waves (https://www.youtube.com/watch?v=V5b48utfpMQ); Animation: D. Bozhkko

Spin waves: exchange constant estimation

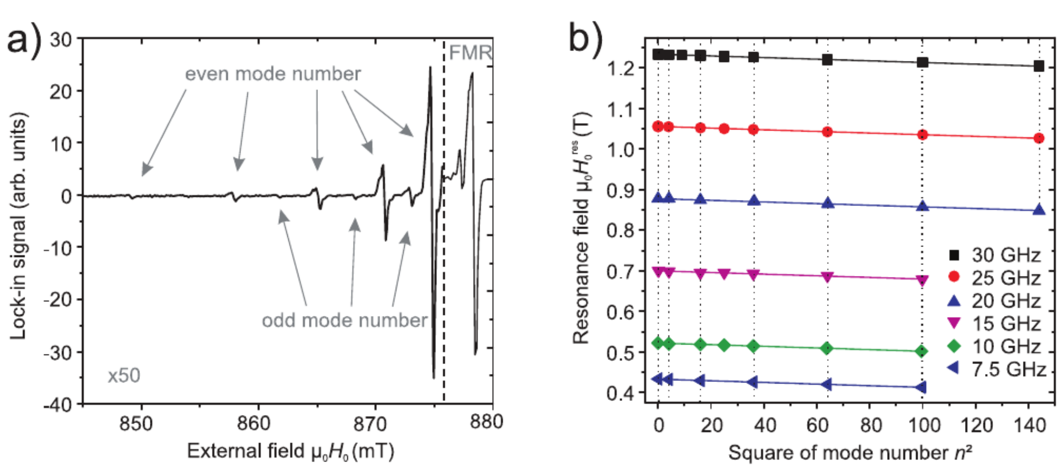


- Useful for estimate exchange constant *A*
- Depend on the material thickness

IOP Publishing — Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **48** (2015) 015001 (5pp) — doi:10.1088/0022-3727/48/1/015001

Measurements of the exchange stiffness of YIG films using broadband ferromagnetic resonance techniques

S Klingler[1], A V Chumak[1], T Mewes[2], B Khodadadi[2], C Mewes[2], C Dubs[3], O Surzhenko[3], B Hillebrands[1] and A Conca[1]



$$\mu_o H_{ext} = \mu_o H_0^{res}(n) - \mu_o H_0^{res}(0) = D\frac{\pi^2}{d^2}n^2$$

$$D = 2A/M_s$$

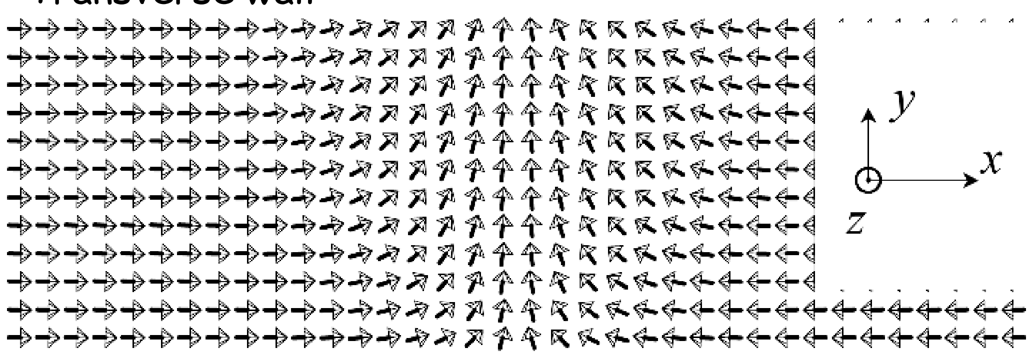
(See Tutorials/Projects)

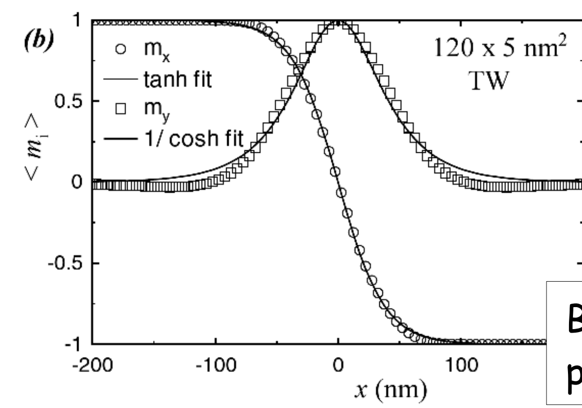
Domain wall dynamics

1d model : a transverse wall

Simple description of the DW motion in nanostrips/nanowires
1) the coercitive force is low, easy DW propagation
2) the structure is largely defined by magnetostatics

Transverse wall





Bloch profile

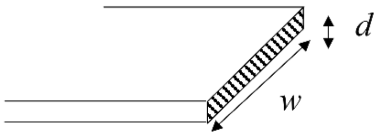
$$m_x = tanh(x/\Delta)$$
$$m_y = 1/cosh(x/\Delta)$$

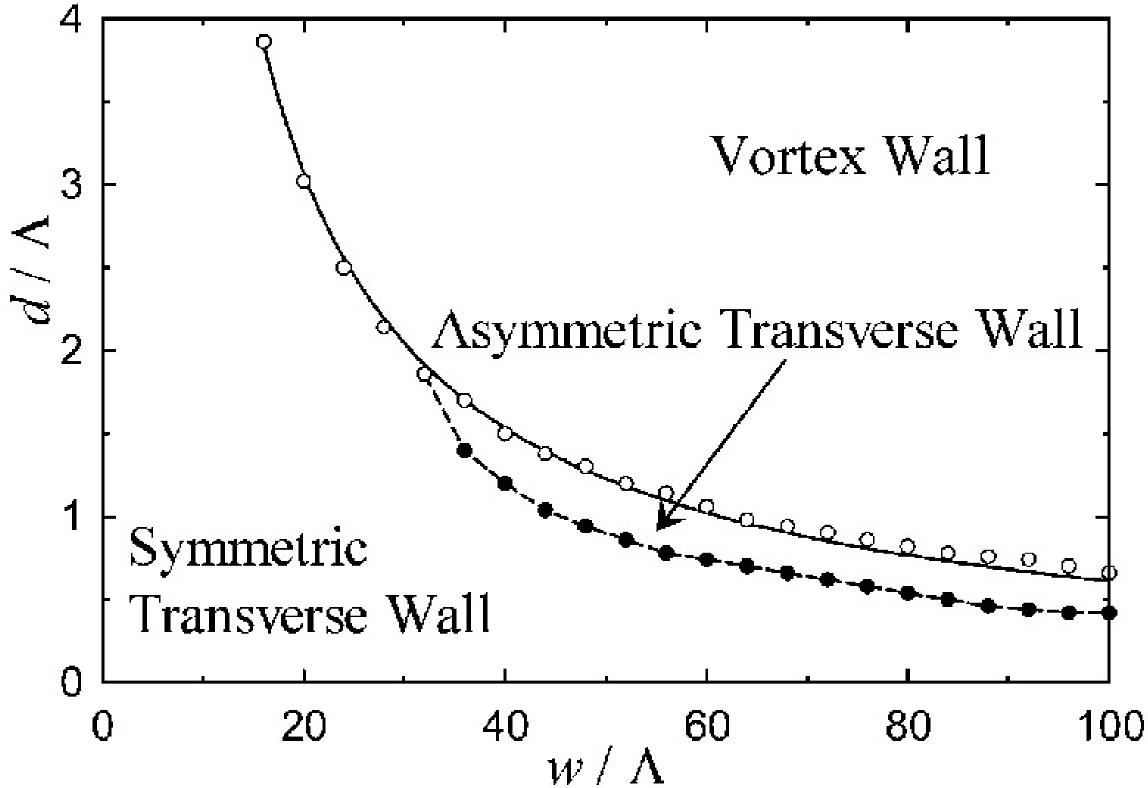
$\pi\Delta$ is the DW width

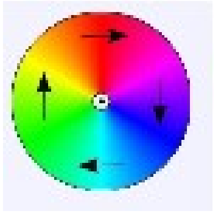
From A. Thiaville and Y. Nakatami,
"Domain-Wall Dynamics in Nanowires and Nanostrips",
In B. Hillebrans, A. Thiaville (Eds.): *Spin Dynamics in Confined Magnetic Structures II,*
Topic Appl. Physics **101**, 161-205 (2006)

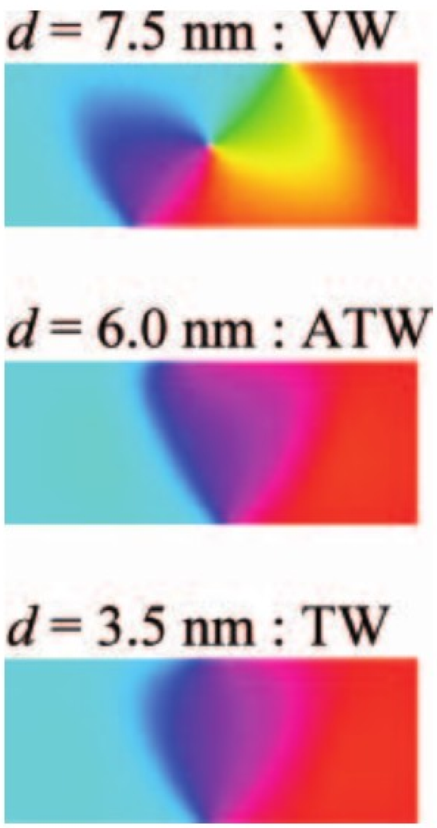
1d model: domain wall structures

2a) Phase diagram of stable domain structures



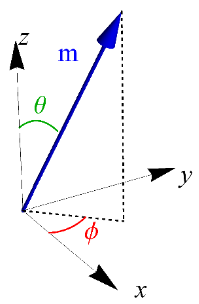






Domain wall dynamics (1D)

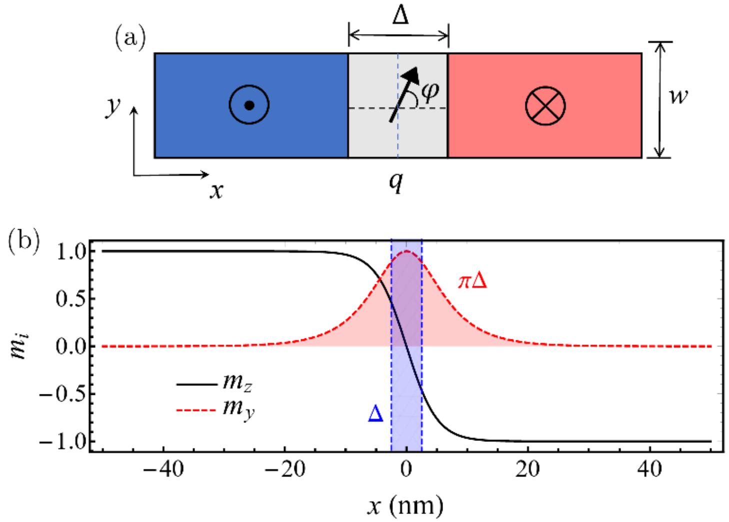
3) LLG in spherical coordinates



$$\dot{\theta} + \alpha \ sin\theta\dot{\phi} = -\frac{\gamma_0}{\mu_0 M_s sin\theta}\frac{\delta \mathcal{E}}{\delta\phi}$$

$$\alpha\dot{\theta} - \ sin\theta\dot{\phi} = -\frac{\gamma_0}{\mu_0 M_s}\frac{\delta \mathcal{E}}{\delta\theta}$$

4) Use **Collective-Coordinates** & the Bloch profile

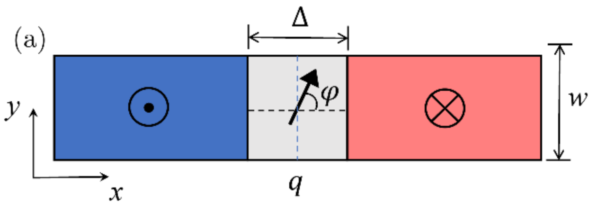


$$\theta(x,t) = 2\arctan\left\{exp\left[\pm\left(\frac{x-q(t)}{\Delta}\right)\right]\right\}$$

$$\phi_{spherical}(x,t) = \phi_{profile}(t)$$

Stationary solution

5) With an applied field H_z, there is precession and DW translation



$$\dot{q} = \frac{\Delta\gamma_0}{1+\alpha^2}\left[\alpha H_z + H_K \frac{sin 2\phi}{2}\right]$$

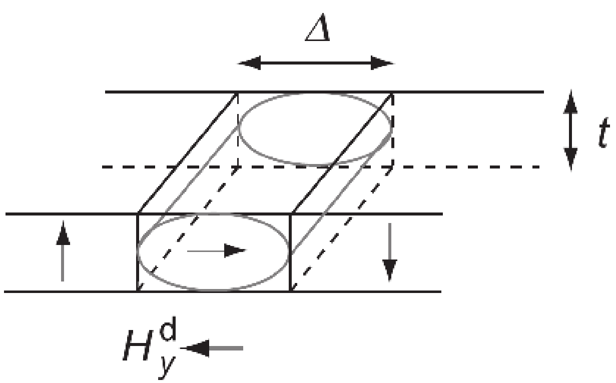
$$\dot{\phi} = -\frac{\gamma_0}{1+\alpha^2}\left[H_z - \alpha H_K \frac{sin 2\phi}{2}\right]$$

$$K = (K_0 + K sin^2\phi)$$

$$K = 1/2\mu_0 M_s^2 (N_y - N_x); \quad N_y << N_x$$

$$H_K = \frac{K}{\mu_0 M_s}$$

K is the DW shape anisotropy



6) Stationary solution

$$\dot{\phi} = 0 \Rightarrow H_z = \alpha H_K \frac{sin 2\phi}{2} \Rightarrow sin 2\phi^* = \frac{2H_z}{\alpha H_K}$$

The Walker breakdown

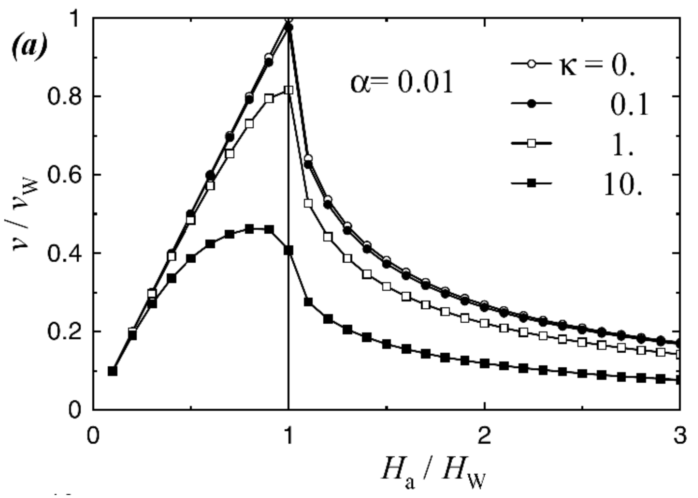
7) Stationary solution for $H_a < H_W$

$$sin2\phi^* = \frac{2H_z}{\alpha H_K} = \frac{H_a}{H_W}$$

$$\dot{q} = \frac{\gamma_0 \Delta}{\alpha} H_a$$

- Non-zero wall magnetization angle
- Constant wall velocity
- Compensation between shape DW anisotropy and the external field

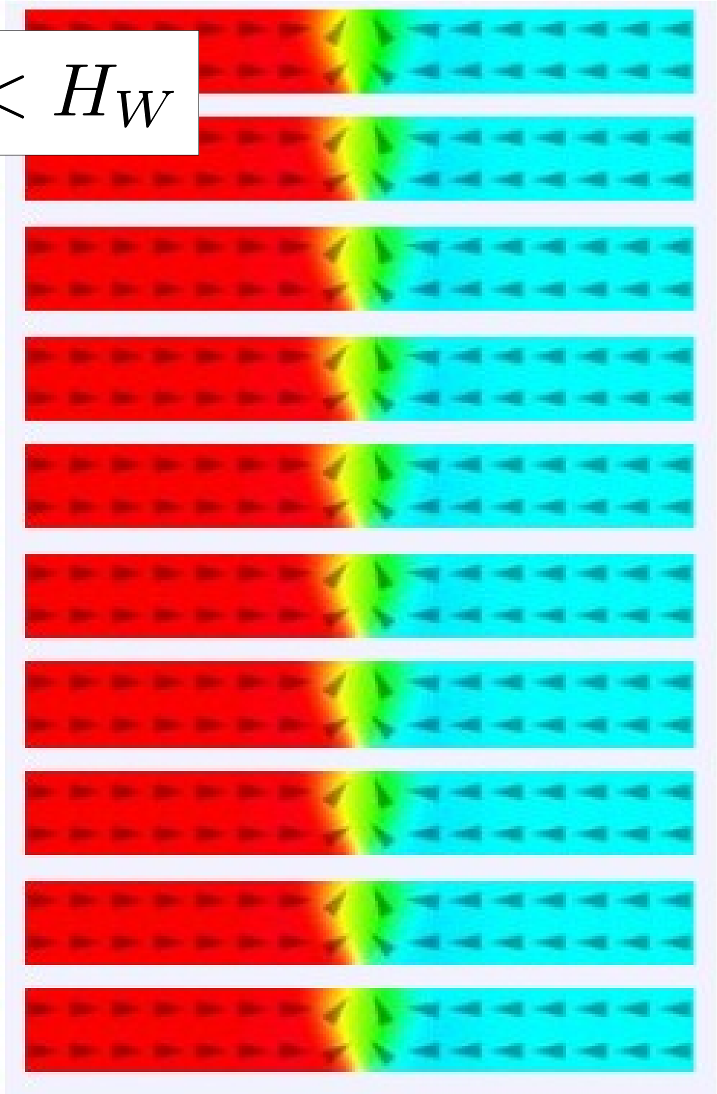
8) Non stationary solution for $H_a >= H_W$ (Walker breakdown)



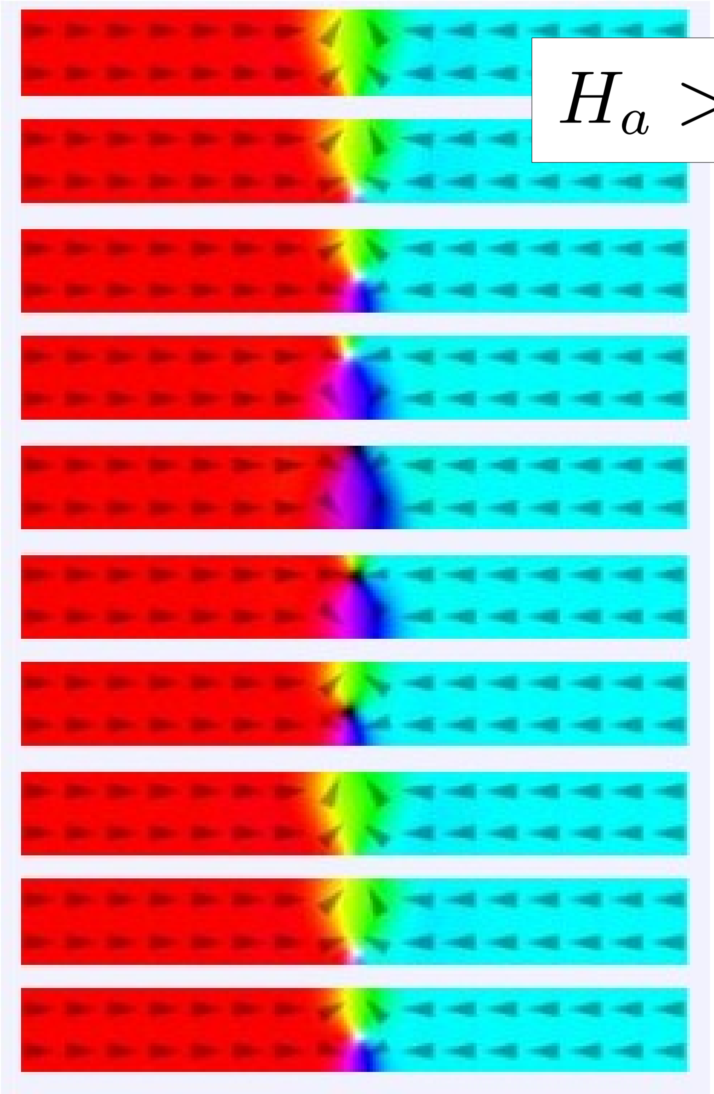
- The DW magnetization angle precesses
- Drop in the DW velocity
- No compensation between the shape DW anisotropy and the external field

The Walker breakdown

$H_a < H_W$



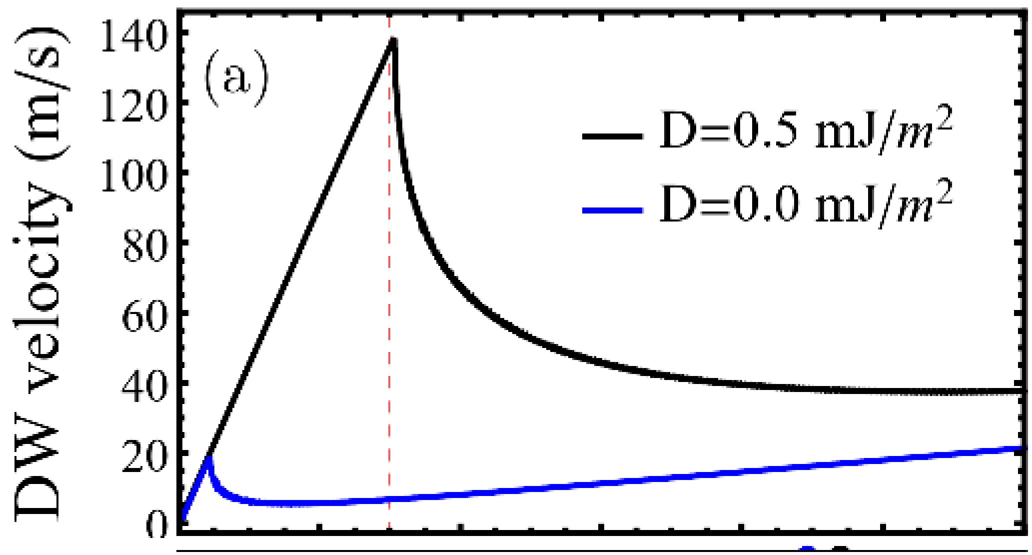
$H_a > H_W$



The Walker breakdown with DMI

The Walker breakdown is now much larger

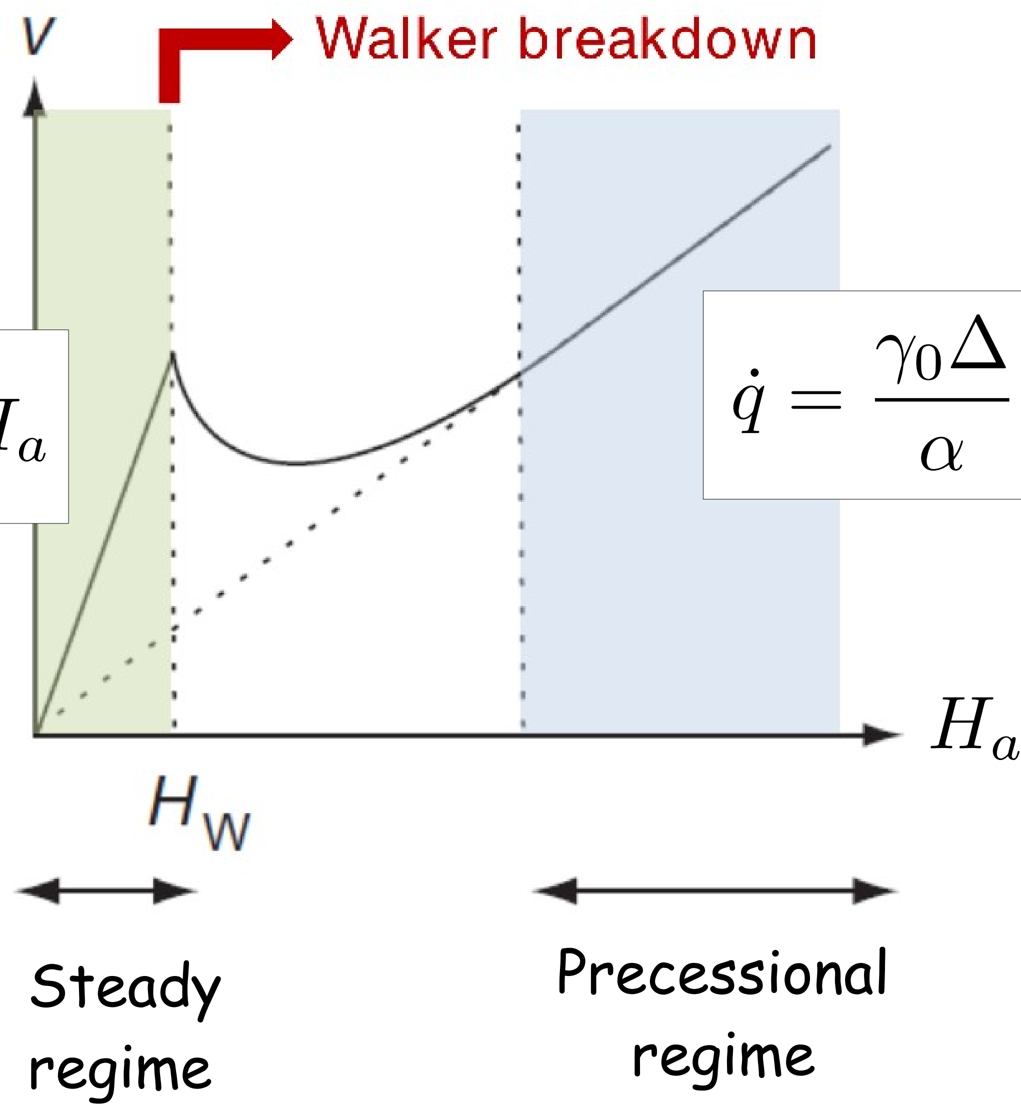
$$\mathrm{H}_W = \alpha \frac{\pi}{2} H_{DMI}$$



What about larger fields?

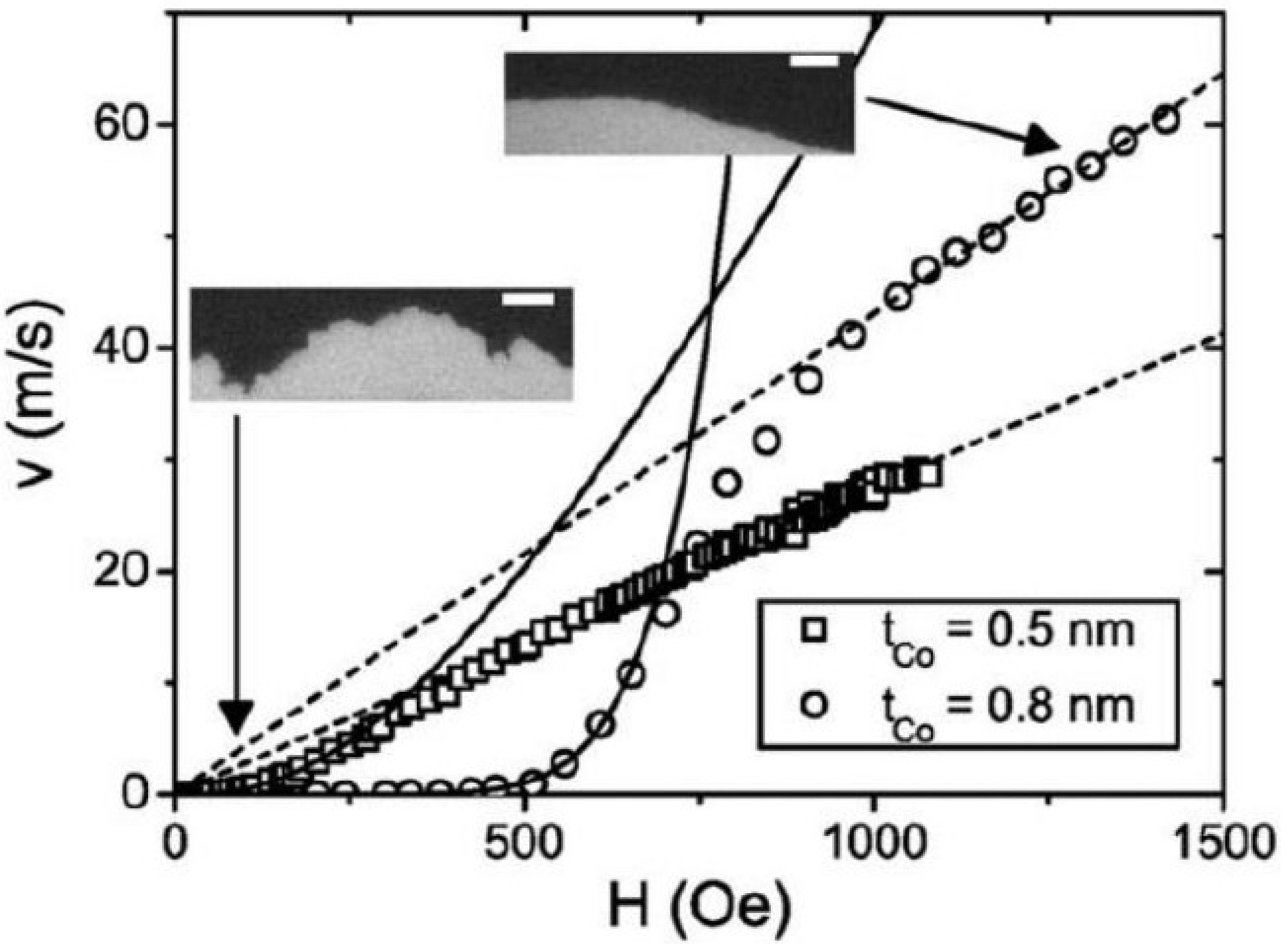
The flow regime

$$\dot{q} = \frac{\gamma_0 \Delta}{\alpha} H_a$$

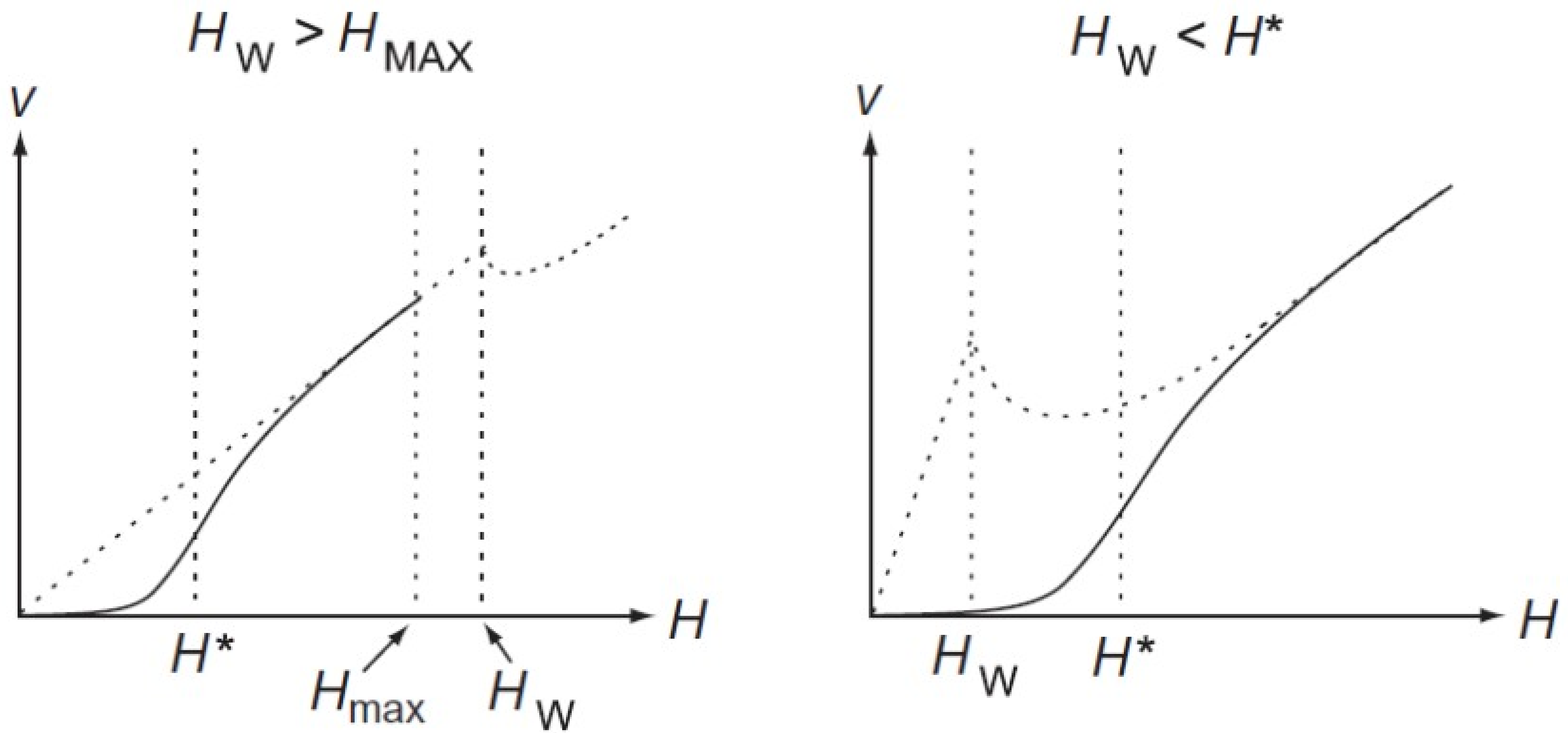


$$\dot{q} = \frac{\gamma_0 \Delta}{\alpha} \frac{\alpha^2}{1+\alpha^2} H_a$$

Domain wall dynamics in real systems

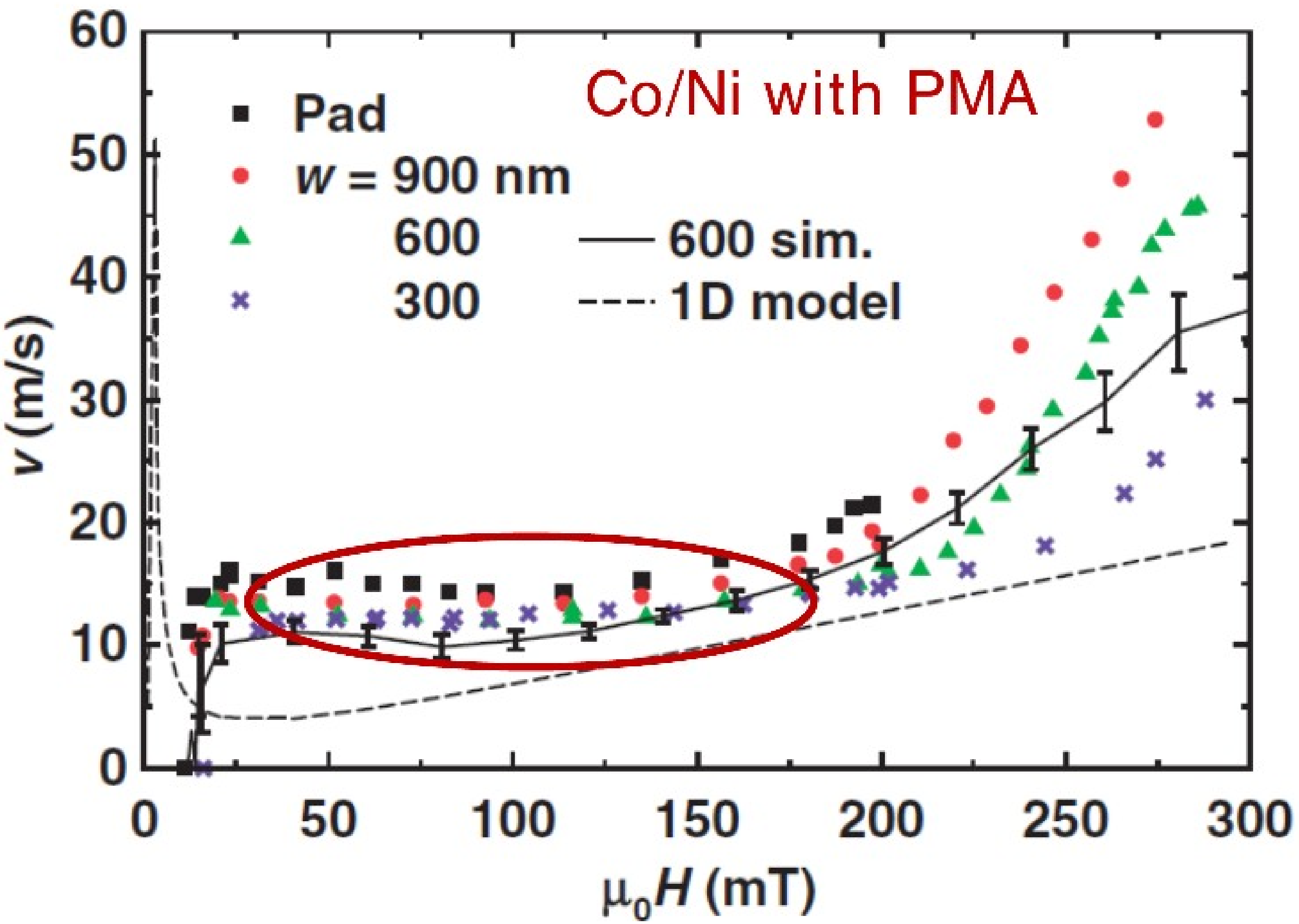


Domain wall dynamics in real systems



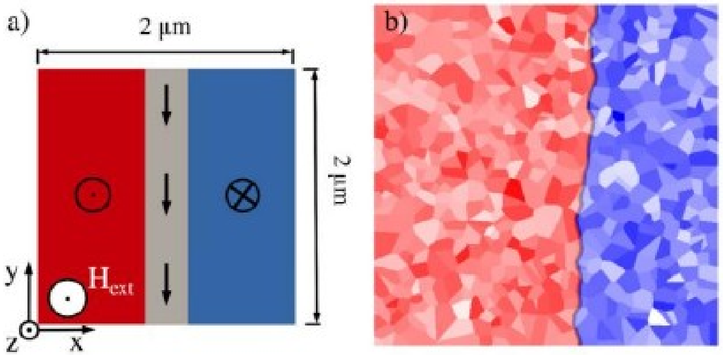
The creep regime usually hides the WB!

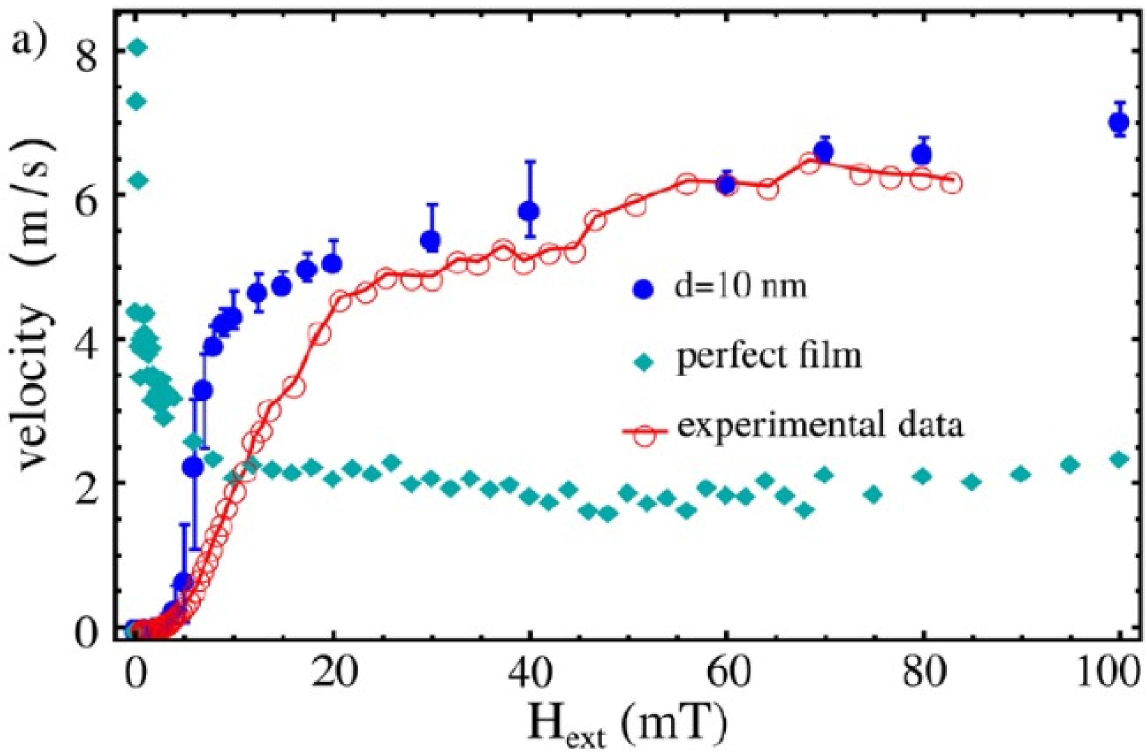
Domain wall dynamics in real systems



Disorder and vertical Bloch lines destroy smooth motion

Domain wall dynamics in real systems





Mumax3 + disorder
(@University of Salamanca)

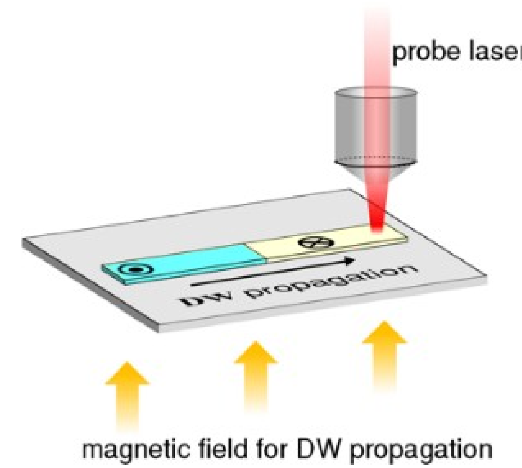
The (slow) creep regime

nature Vol 458|9 April 2009|doi:10.1038/nature07874

LETTERS

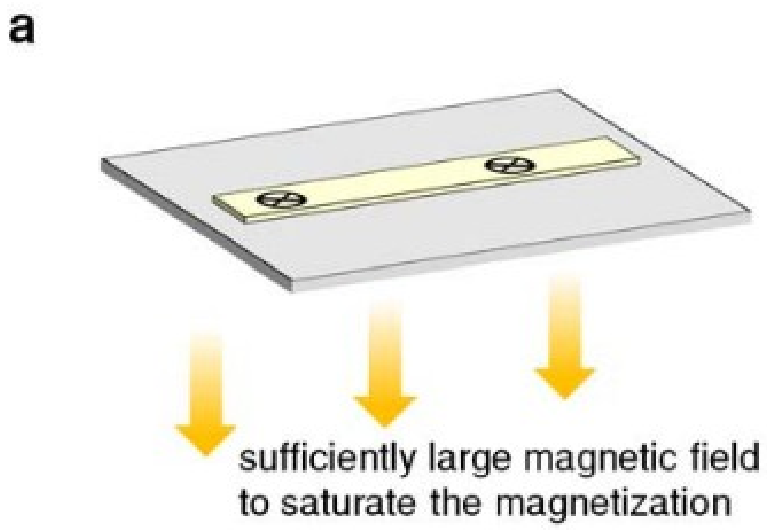
Interdimensional universality of dynamic interfaces

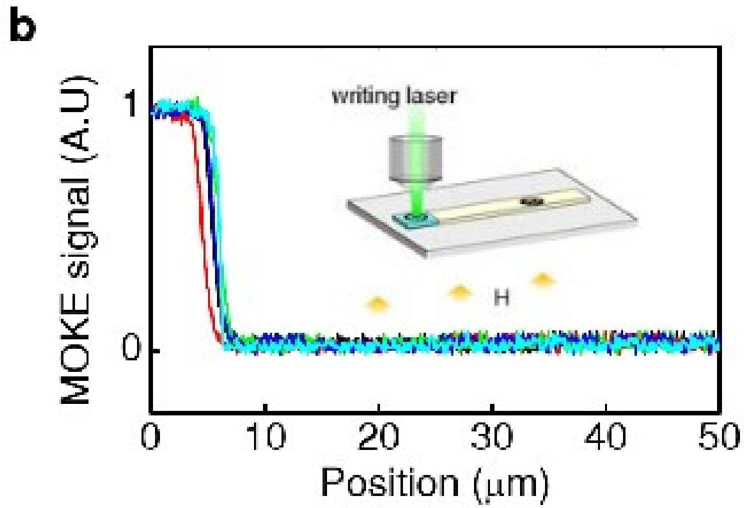
Kab-Jin Kim[1], Jae-Chul Lee[1,2], Sung-Min Ahn[1], Kang-Soo Lee[1], Chang-Won Lee[3], Young Jin Cho[3], Sunae Seo[3], Kyung-Ho Shin[2], Sug-Bong Choe[1] & Hyun-Woo Lee[4]



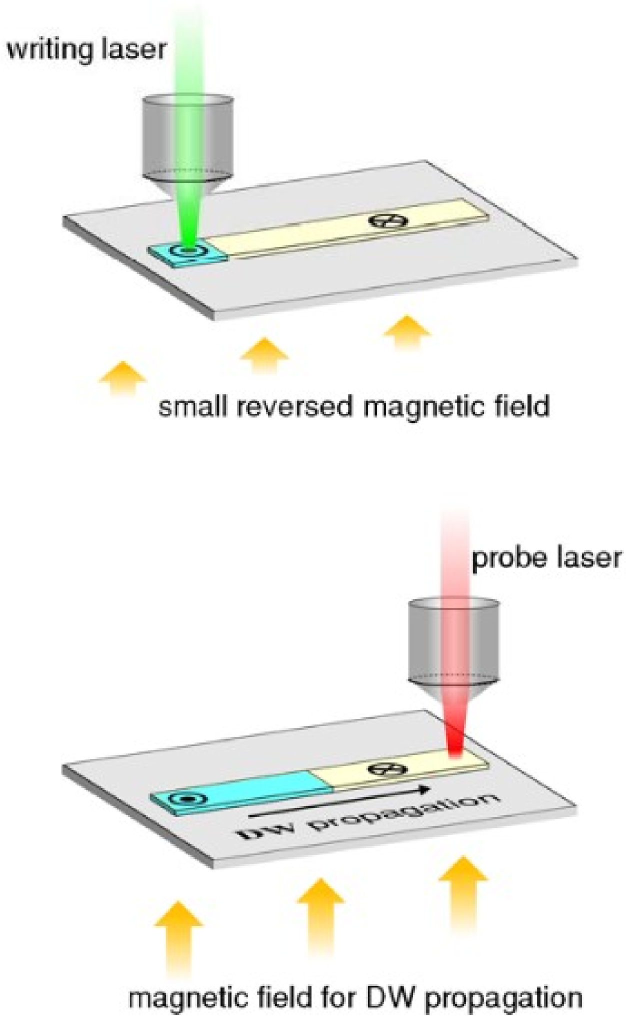
- DW propagation in a PMA material Ta(5)/Pt(2.5)/$Co_{90}Fe_{10}$(0.3)/Pt(1)
- Measurement of the time arrival over 40 μm (10 ms – 1000 s)
- Wire widths from 4 – 150 μm

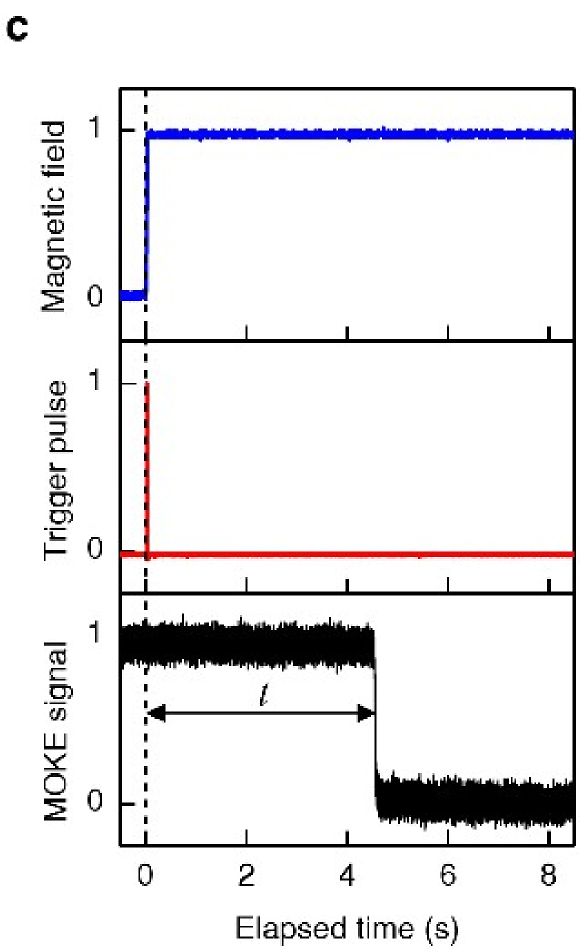
Prepare for creep: saturate the sample





Ready for creep: nucleate and propagate





The (universal ?) $H^{-1/4}$ law

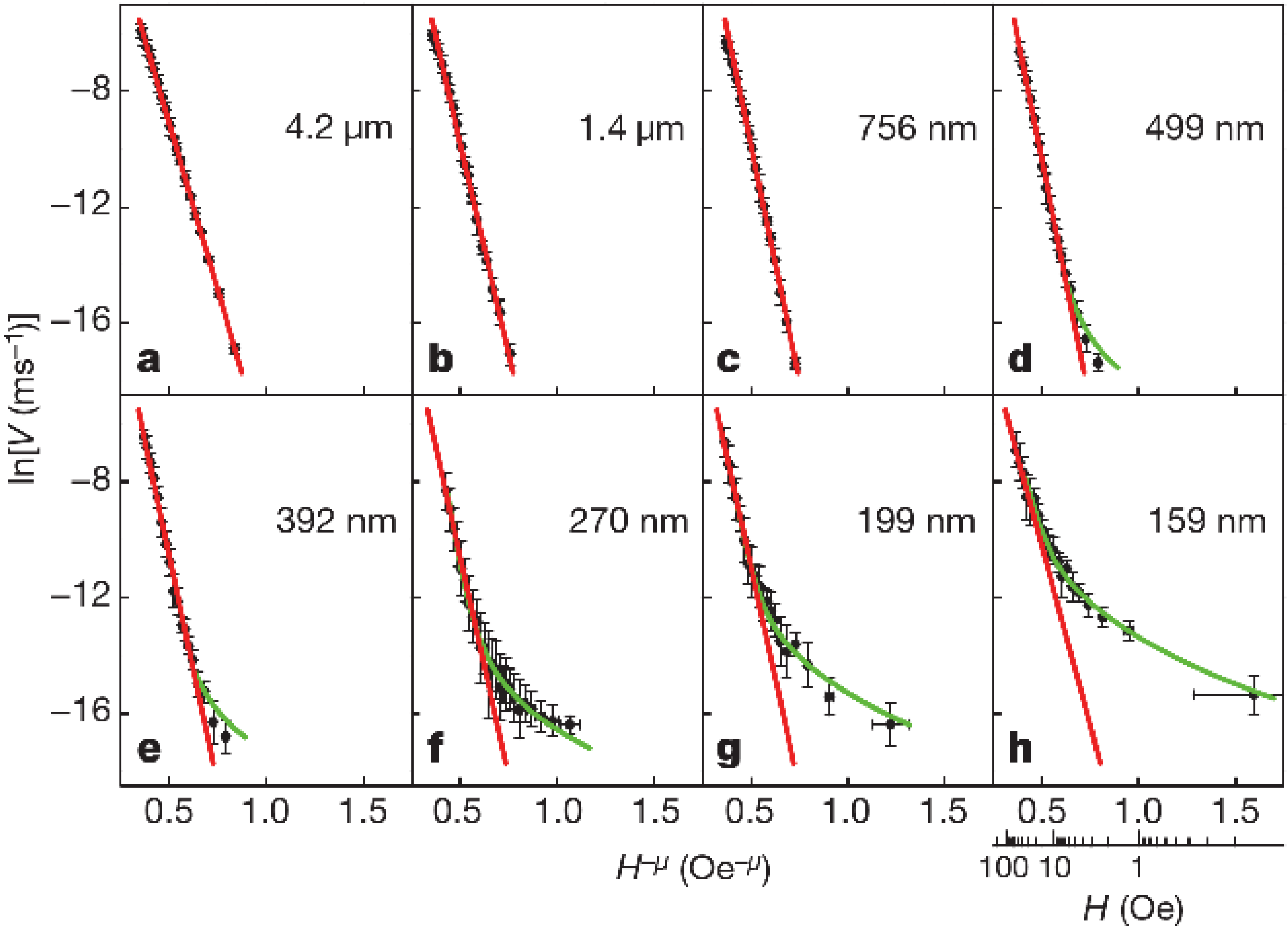
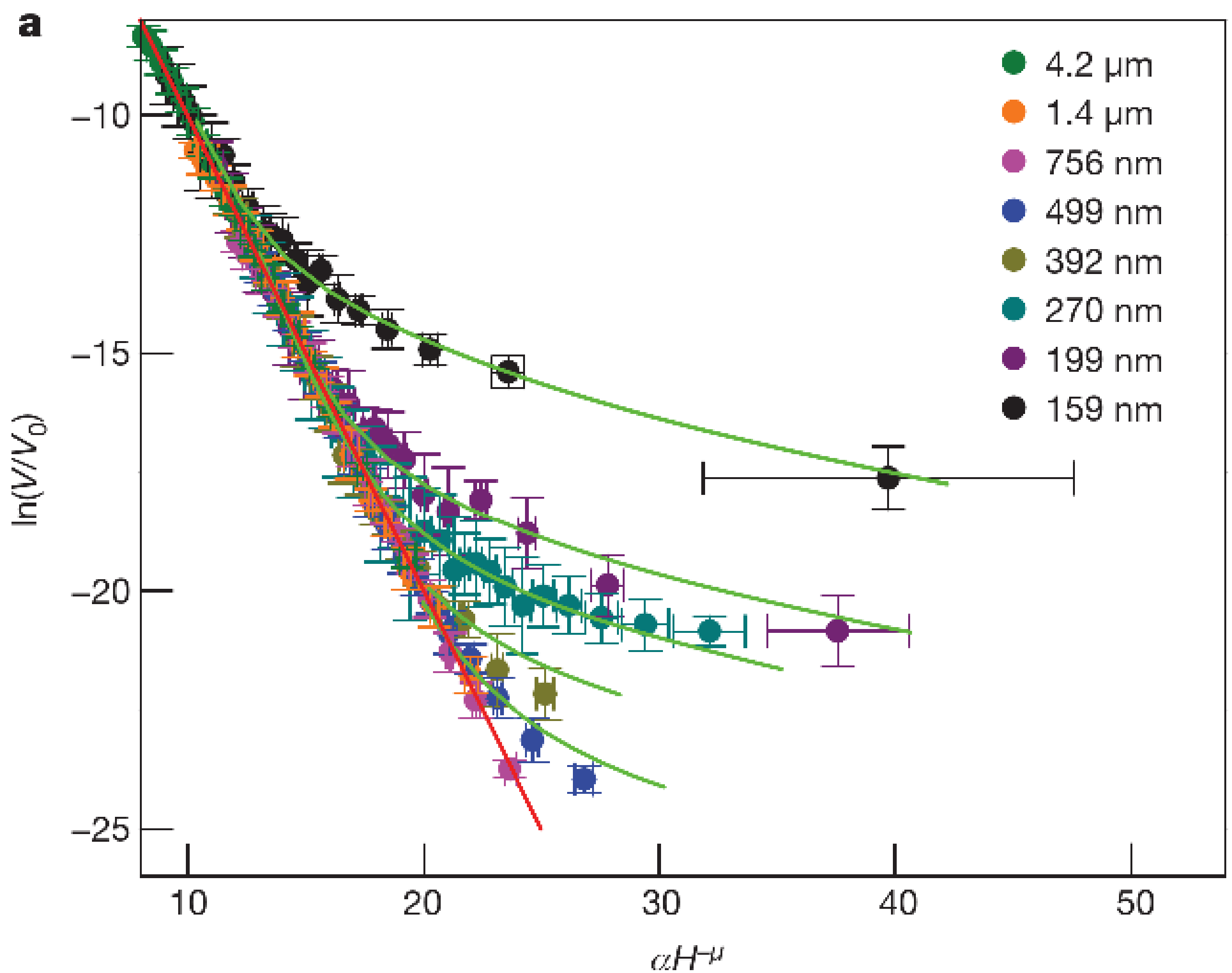
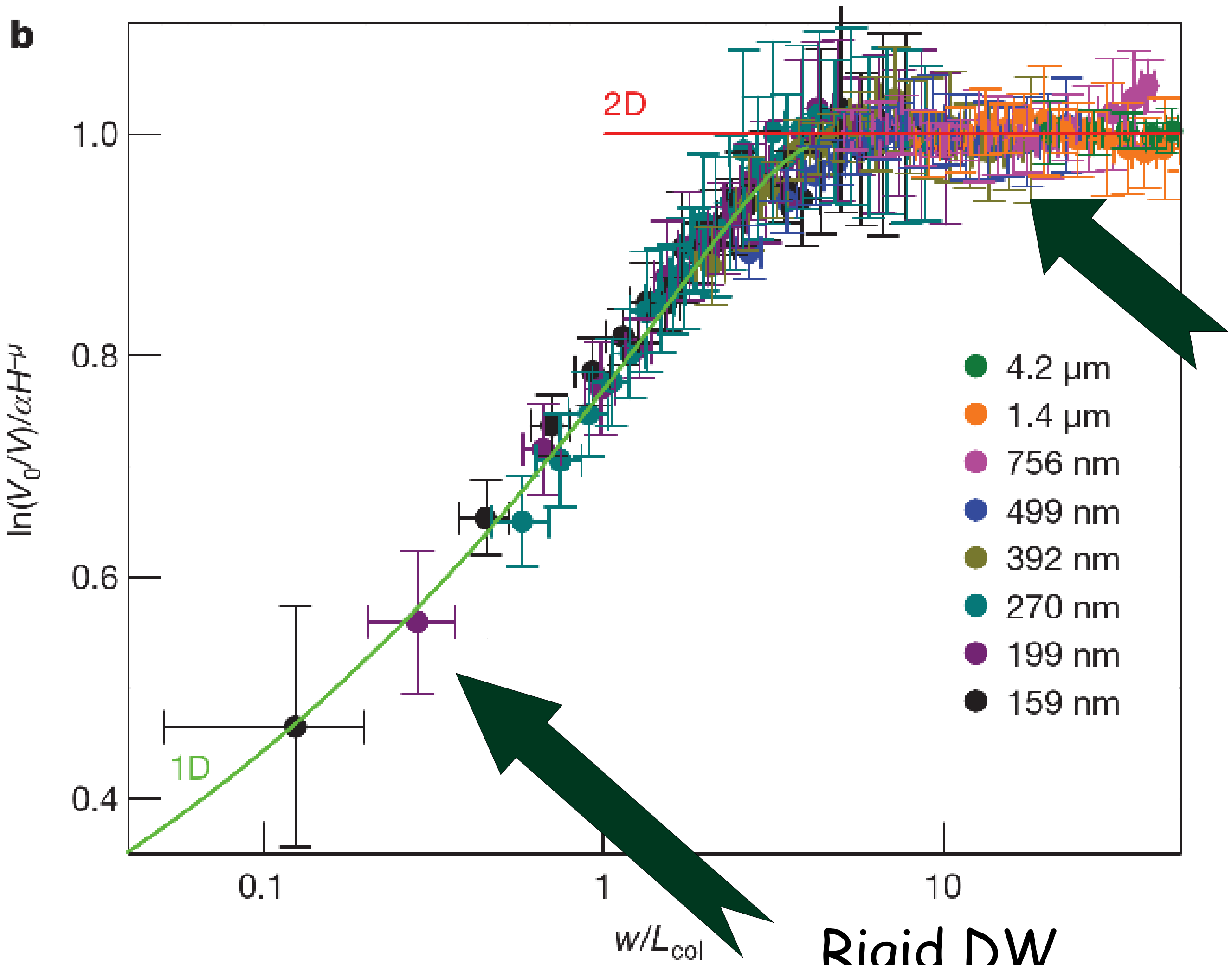


Figure 1 | Nonequilibrium criticality of DW speed along ferromagnetic nanowires. Data are shown for different wire widths: 4.2 μm (**a**), 1.4 μm

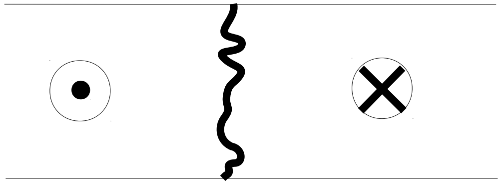
The $H^{-1/4}$ law: after rescaling (I)



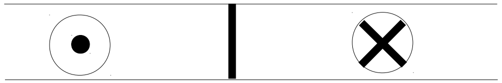
The $H^{-1/4}$ law: after rescaling (II)



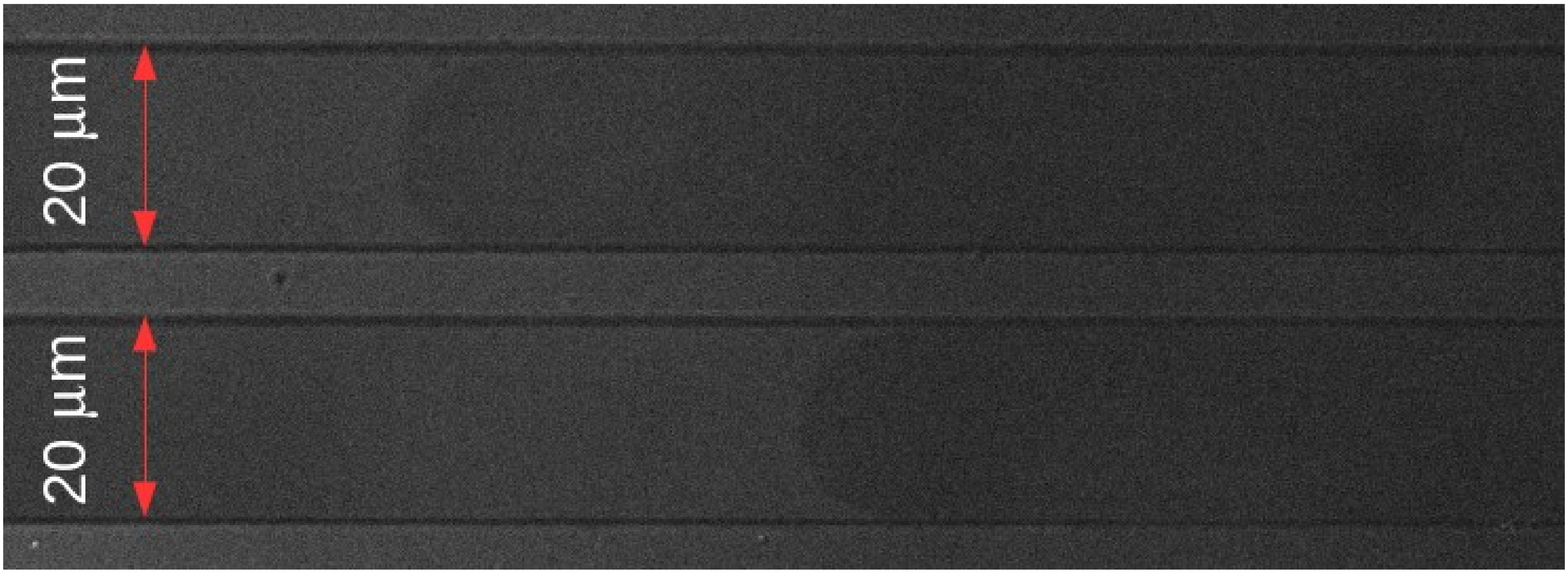
Rough DW

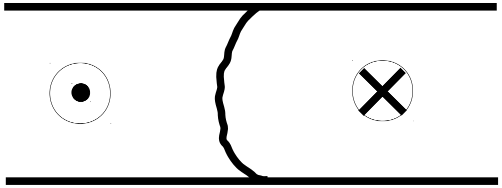


Rigid DW



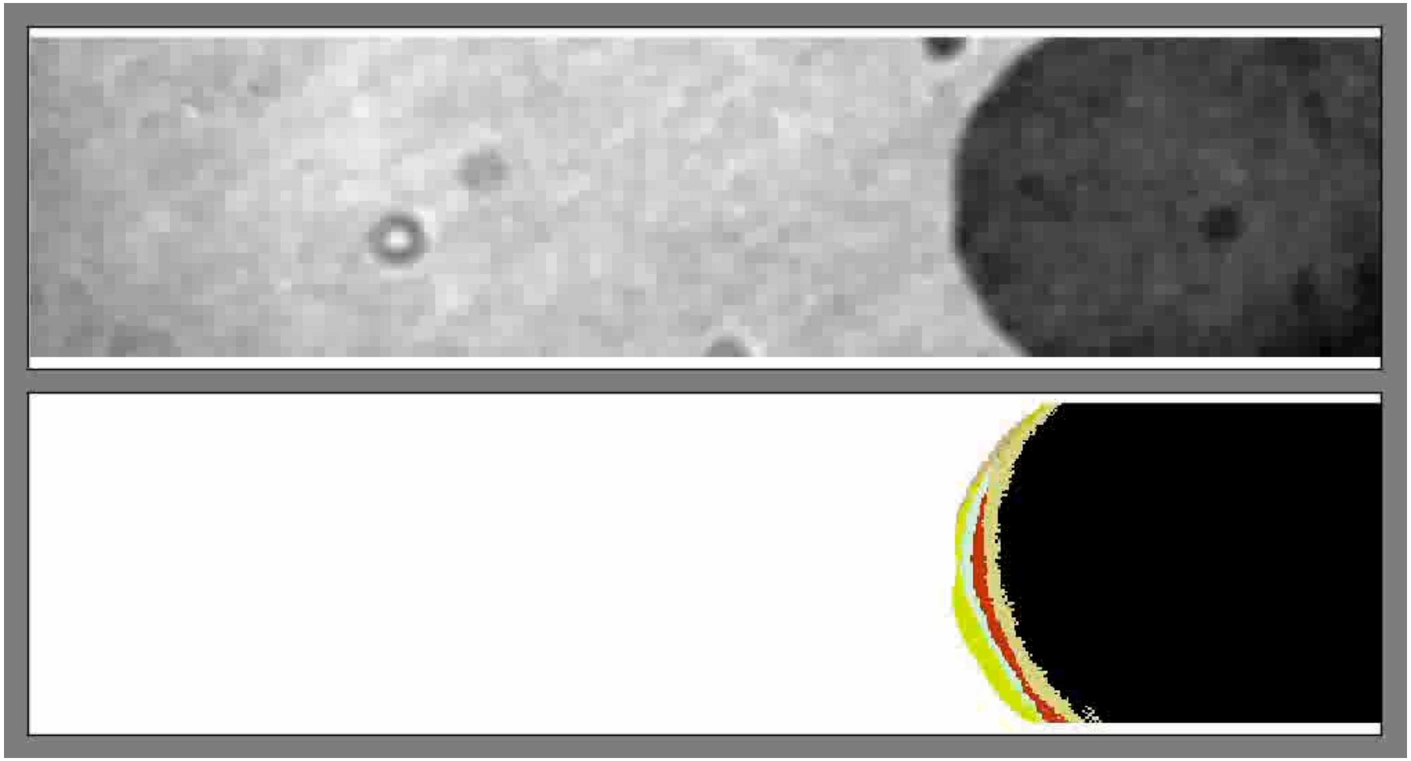
DW motion in CoFeB wires

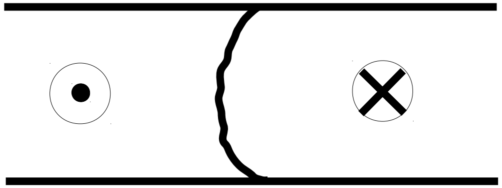




Rough DW + edge pinning

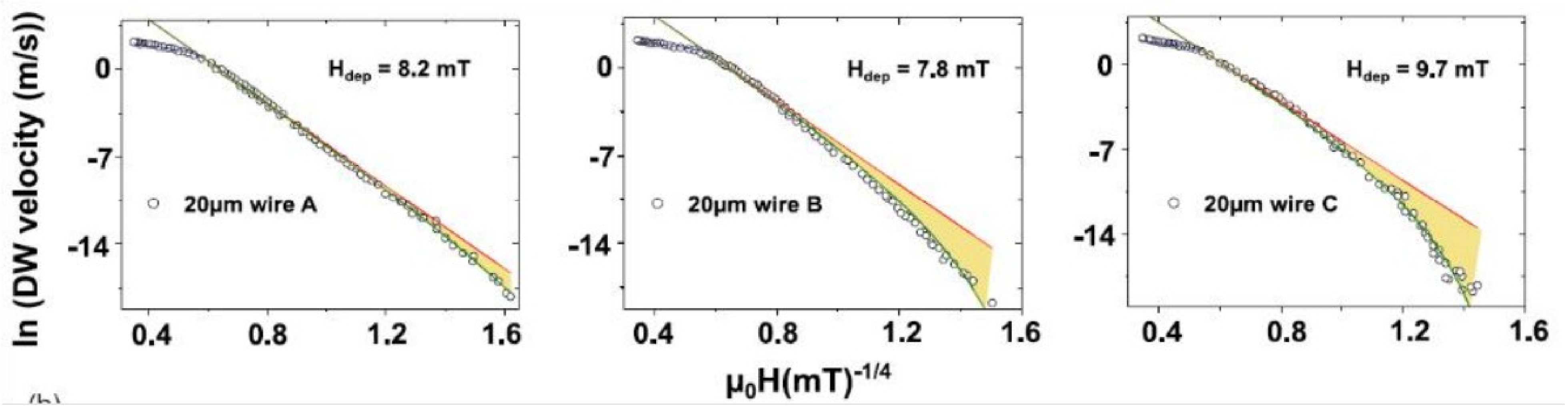
DW motion in CoFeB wires

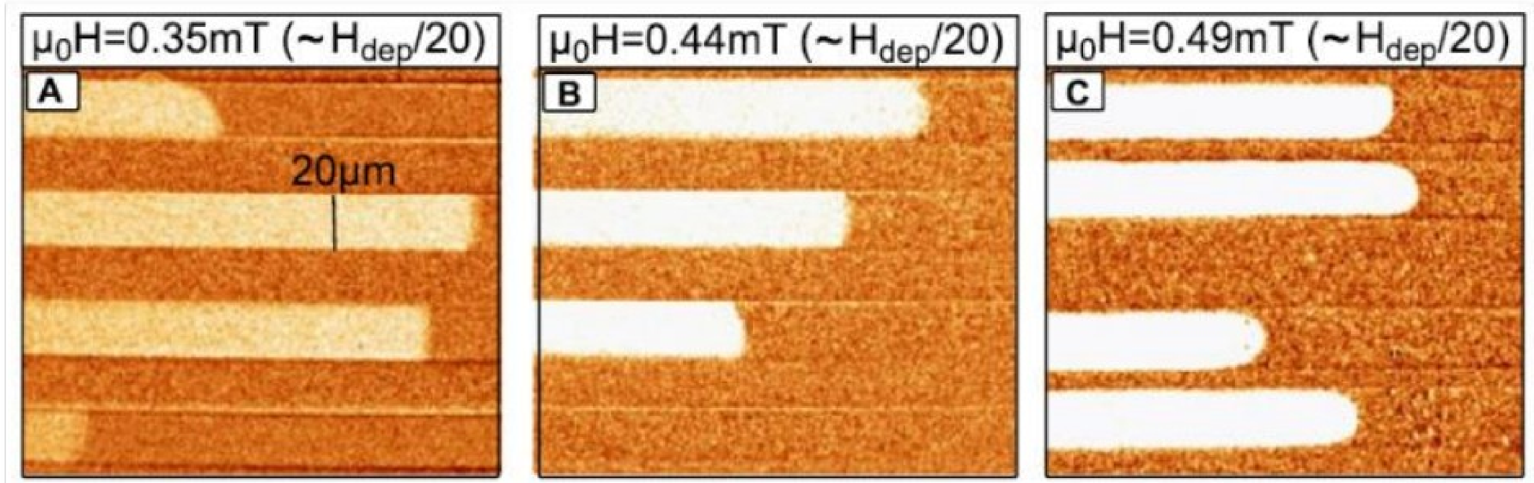




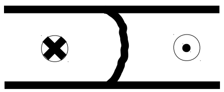
Rough DW + edge pinning

CoFeB wires: signature of edge pinning

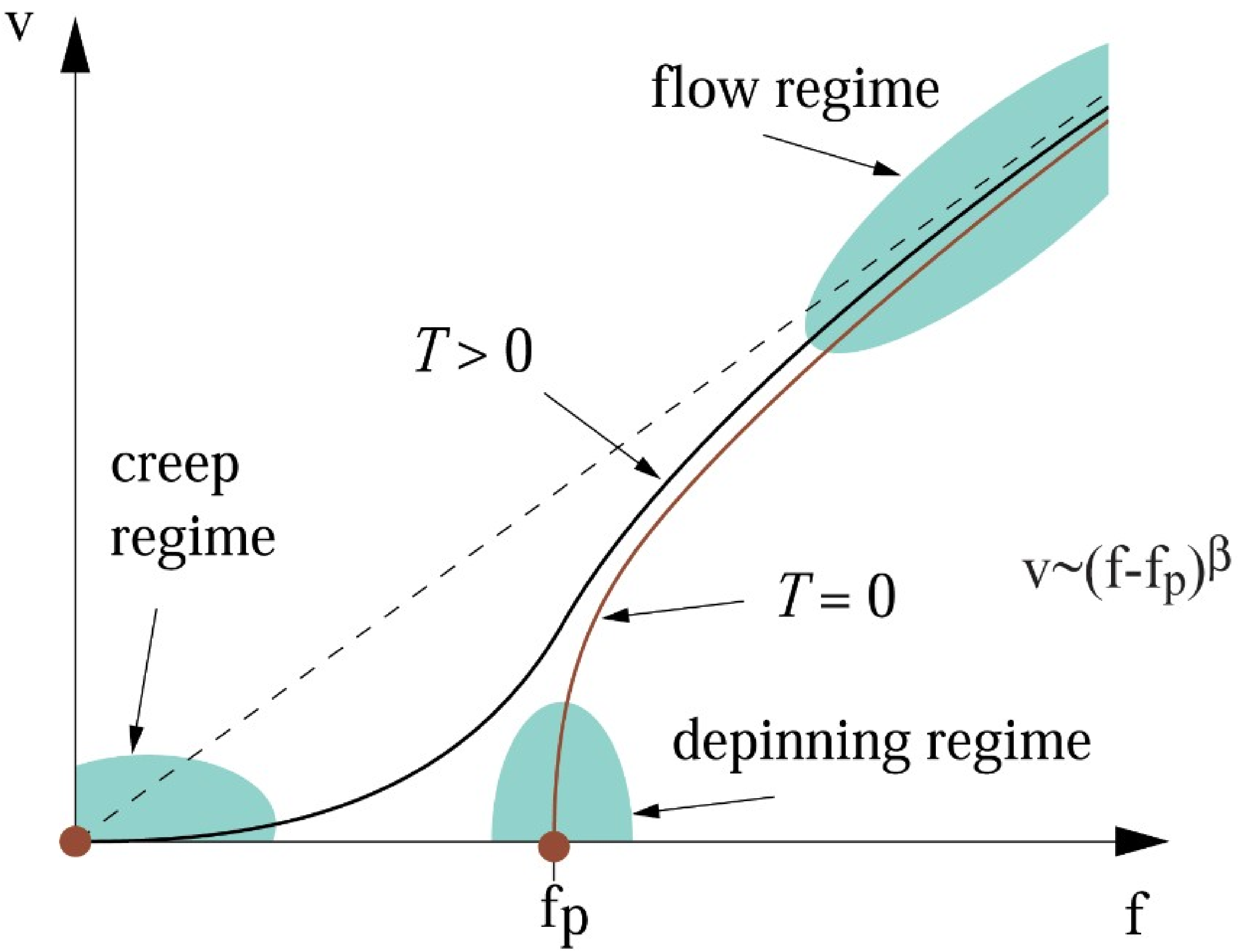




L. Herrera-Diez et al. Phys. Rev. B 98, 054419 (2018)



The creep regime



The creep regime: early experiments

VOLUME 80, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1998

Domain Wall Creep in an Ising Ultrathin Magnetic Film

S. Lemerle,[1] J. Ferré,[1] C. Chappert,[2] V. Mathet,[2] T. Giamarchi,[1] and P. Le Doussal[3]
[1]*Laboratoire de Physique des Solides, URA CNRS 02, Bâtiment 510, Université Paris-Sud, 91405 Orsay, France*
[2]*Institut d'Electronique Fondamentale, URA CNRS 022, Bâtiment 220, Université Paris-Sud, 91405 Orsay, France*
[3]*CNRS-LPTENS, 24 Rue Lhomond, 75230 Paris Cedex 05, France*

Experiments on PMA Pt/Co/Pt

$$v \sim exp(-H^{-1/4})$$

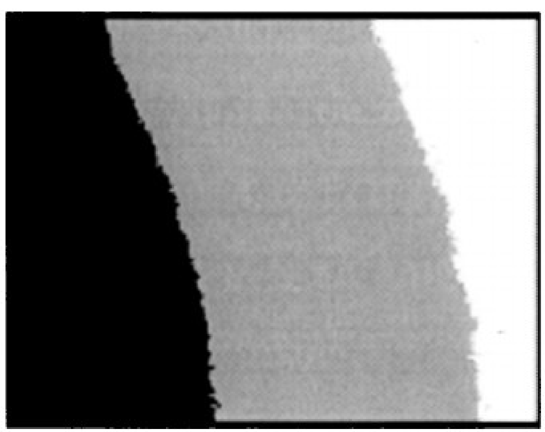


FIG. 1. Typical magneto-optical image (size 90 × 72 μm^2, λ = 638.1 nm). The gray part corresponds to the surface swept by the domain wall during 111 μs at 460 Oe (T = 23 °C). The dark part is the original domain.

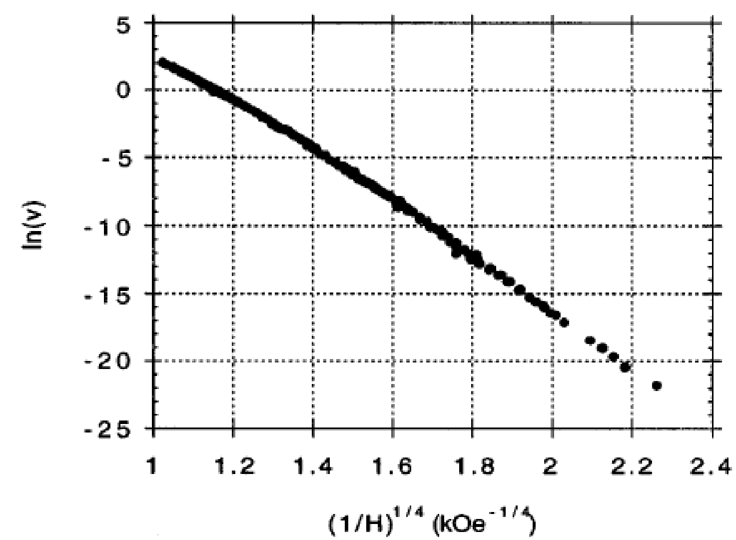


FIG. 3. Natural logarithm of MDW velocity as a function of $(1/H)^{1/4}$ (room temperature, $H \leq$ 955 Oe).

The creep regime: early experiments

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[3]*CNRS-LPTENS, 24 Rue Lhomond, 75230 Paris Cedex 05, France*

Experiments on PMA Pt/Co/Pt

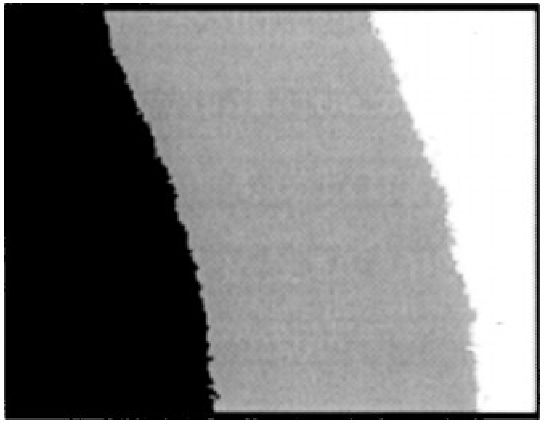

FIG. 1. Typical magneto-optical image (size 90 × 72 μm^2, $\lambda = 638.1$ nm). The gray part corresponds to the surface swept by the domain wall during 111 μs at 460 Oe ($T = 23$ °C). The dark part is the original domain.

The roughness exponent ζ

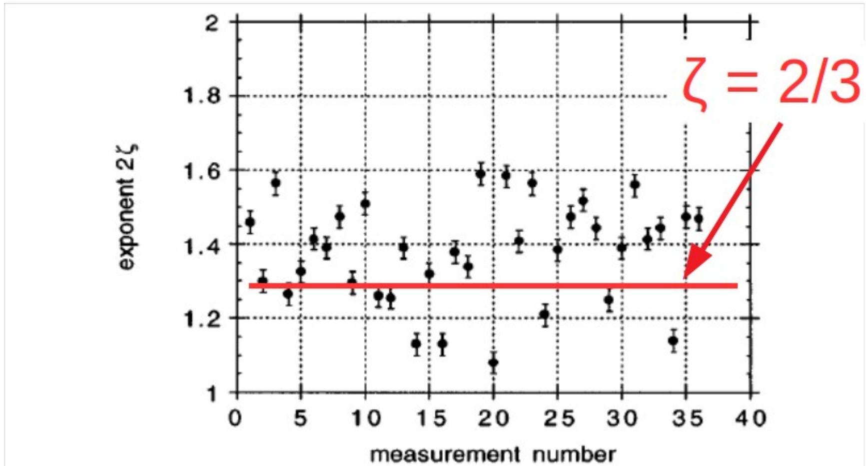

FIG. 5. Wandering exponent 2ζ. Measurements on different MDW driven at $H = 50$ Oe during 20–45 min and then frozen ($T = 300$ K, estimated error on 2ζ for a given image: ± 0.03).

The creep regime: universality

PRL 117, 057201 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

Universal Pinning Energy Barrier for Driven Domain Walls in Thin Ferromagnetic Films

V. Jeudy,[1,†] A. Mougin,[1] S. Bustingorry,[2] W. Savero Torres,[1] J. Gorchon,[1] A. B. Kolton,[2] A. Lemaître,[3] and J.-P. Jamet[1,*]
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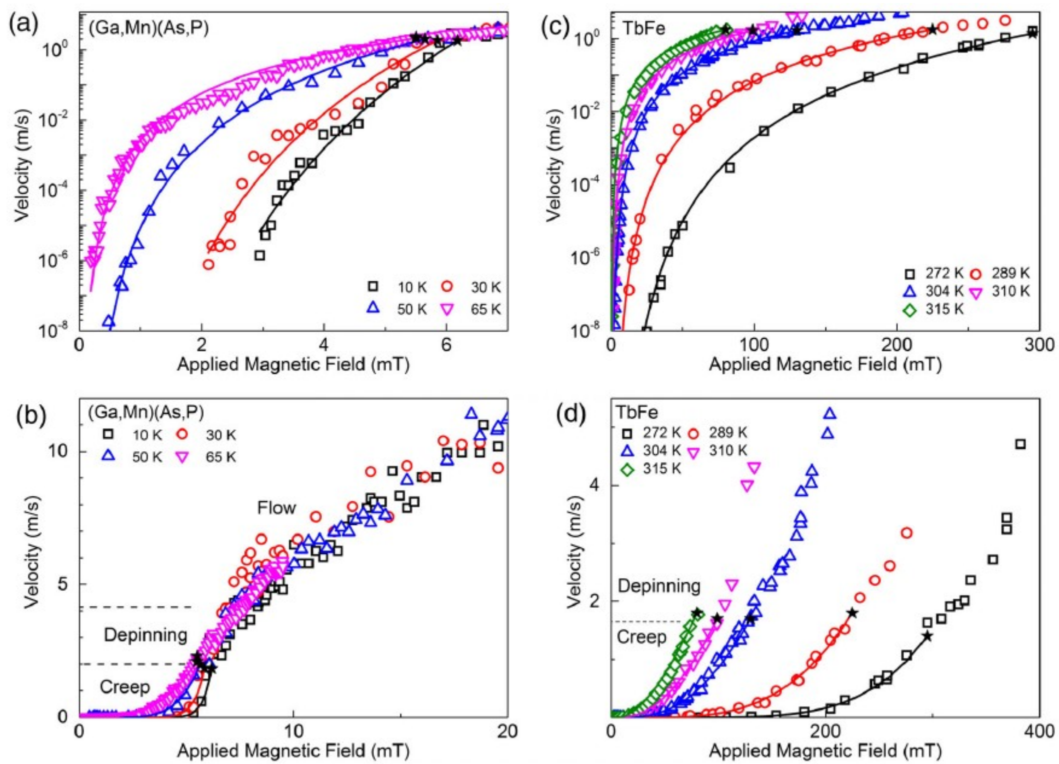
[2]*CONICET, Centro Atómico Bariloche, 8400 San Carlos de Bariloche, Río Negro, Argentina*
[3]*Laboratoire de Photonique et de Nanostructures, CNRS, Université Paris-Saclay, 91460 Marcoussis, France*



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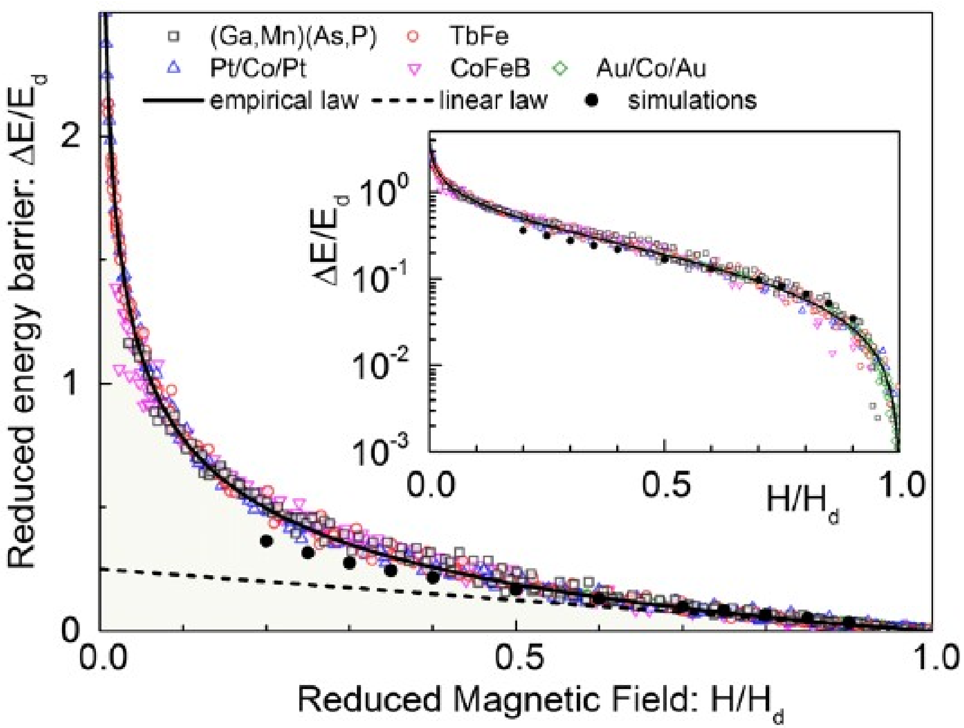


$$v(H,T) = v(H_d,T)\exp\left(-\frac{\Delta E}{k_B T}\right)$$

with

$$\Delta E = k_B T_d\left[\left(\frac{H}{H_d}\right)^{-\mu} - 1\right],$$

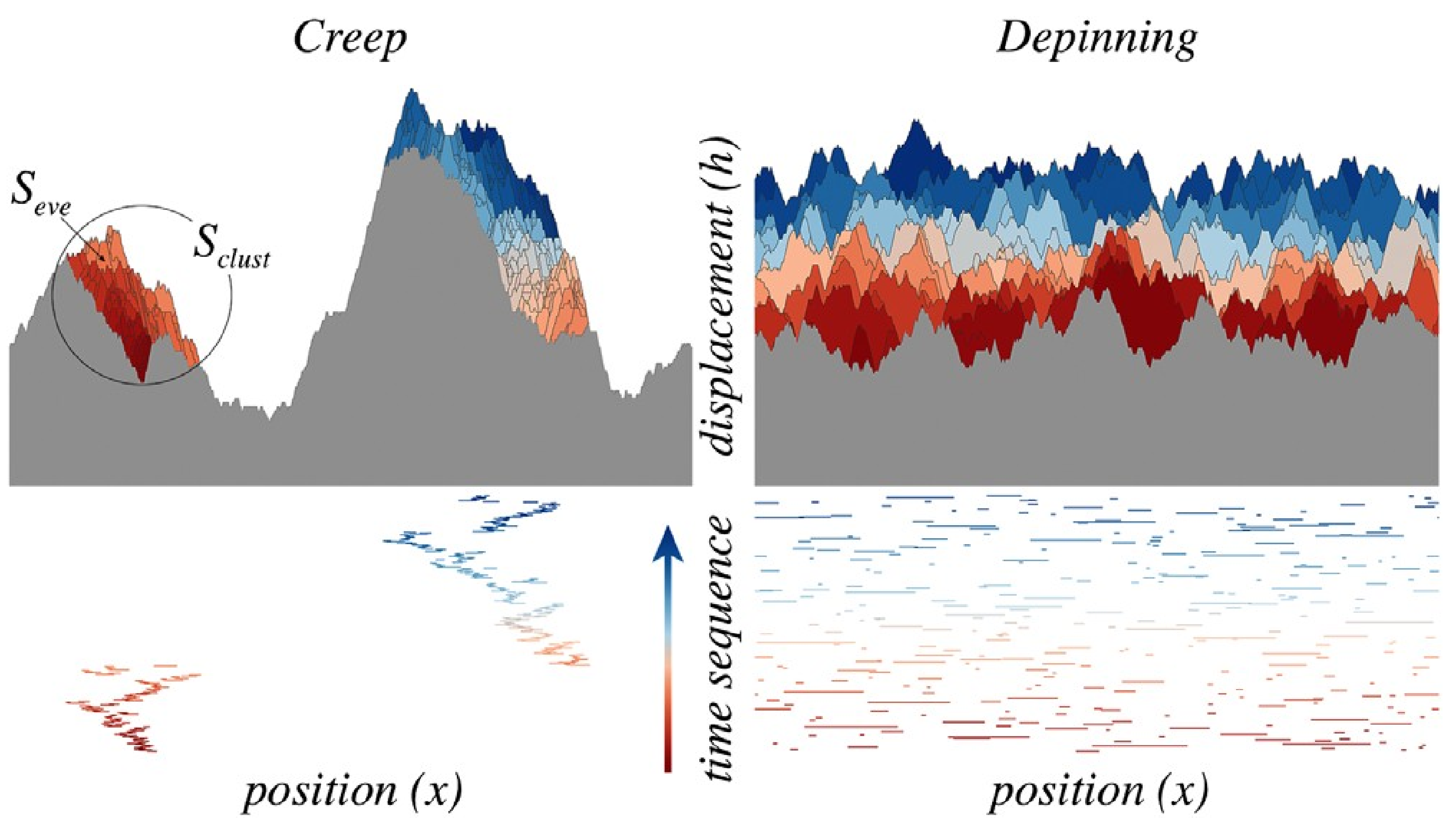
and $\mu = 1/4$.

The creep regime: spatio-temporal patterns

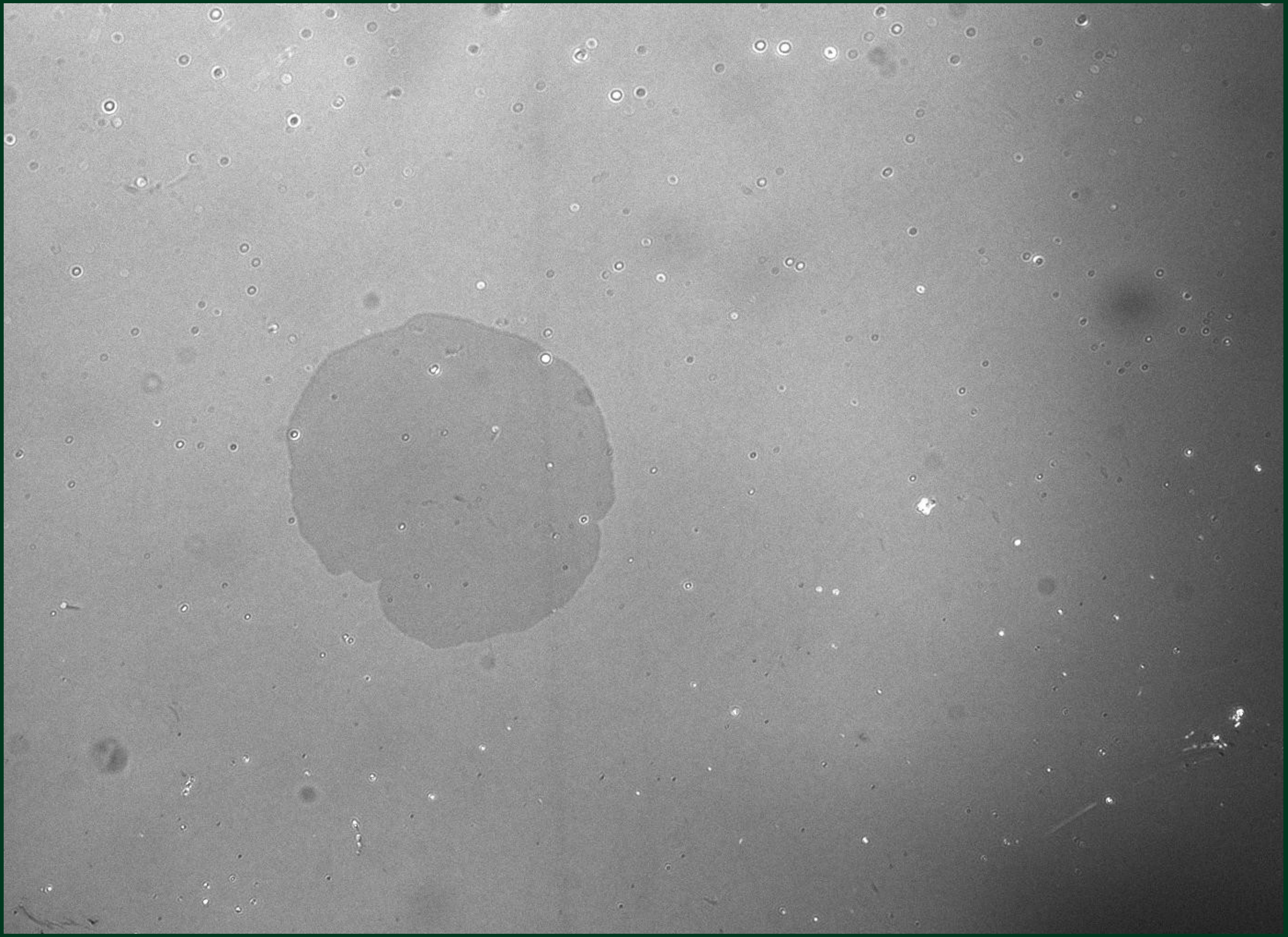
PRL 118, 147208 (2017) PHYSICAL REVIEW LETTERS week ending 7 APRIL 2017

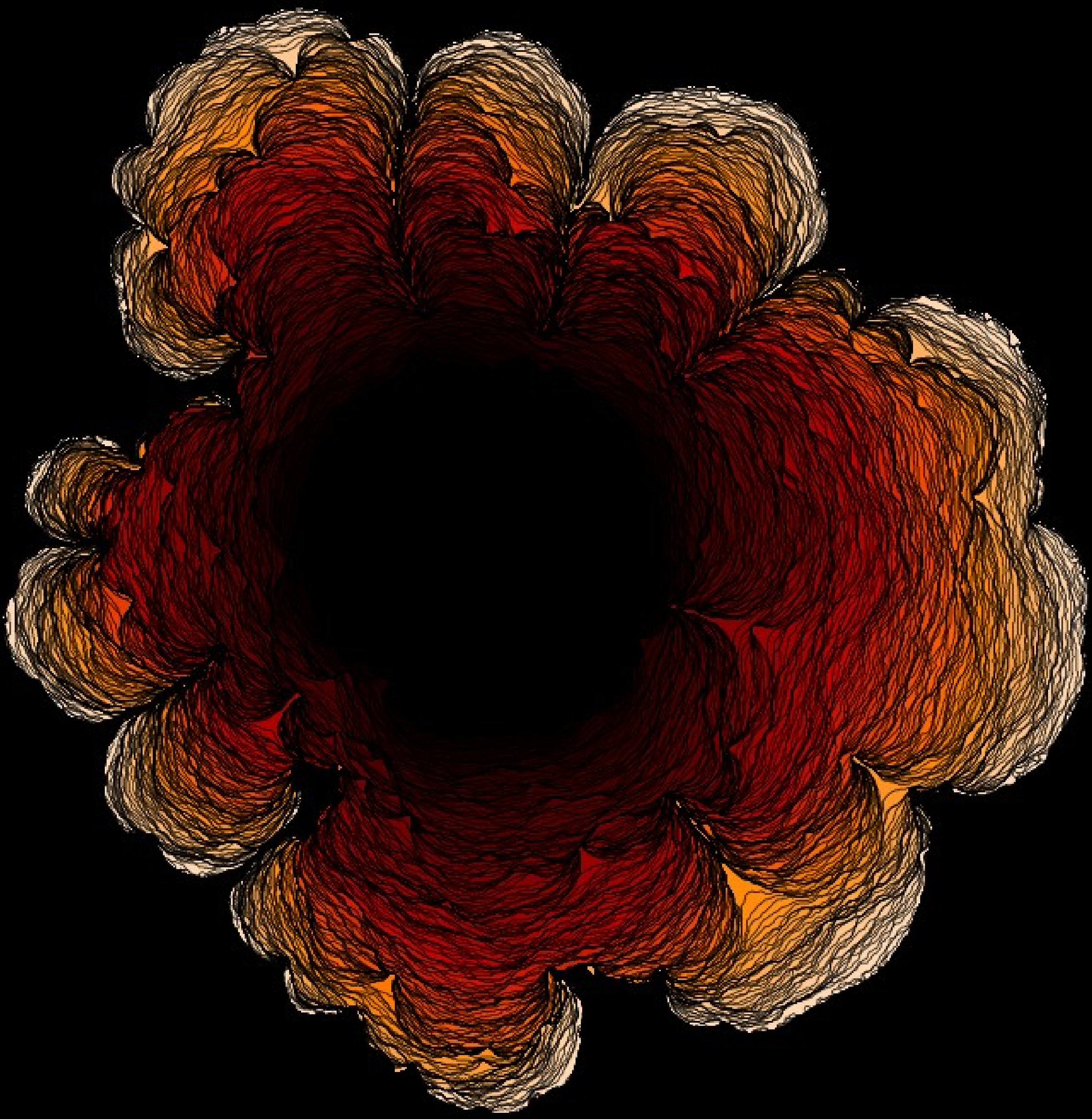
Spatiotemporal Patterns in Ultraslow Domain Wall Creep Dynamics

Ezequiel E. Ferrero,[1,*] Laura Foini,[2] Thierry Giamarchi,[2] Alejandro B. Kolton,[3] and Alberto Rosso[4]

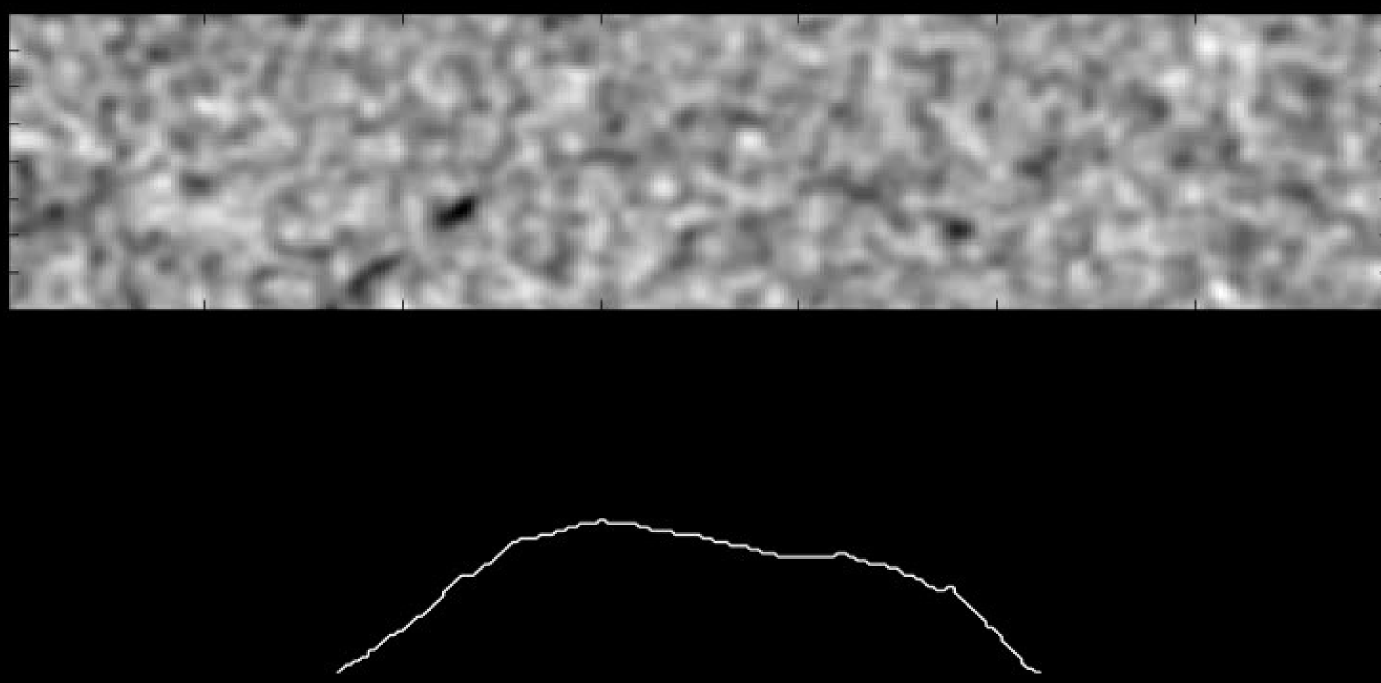


The creep regime: spatio-temporal patterns

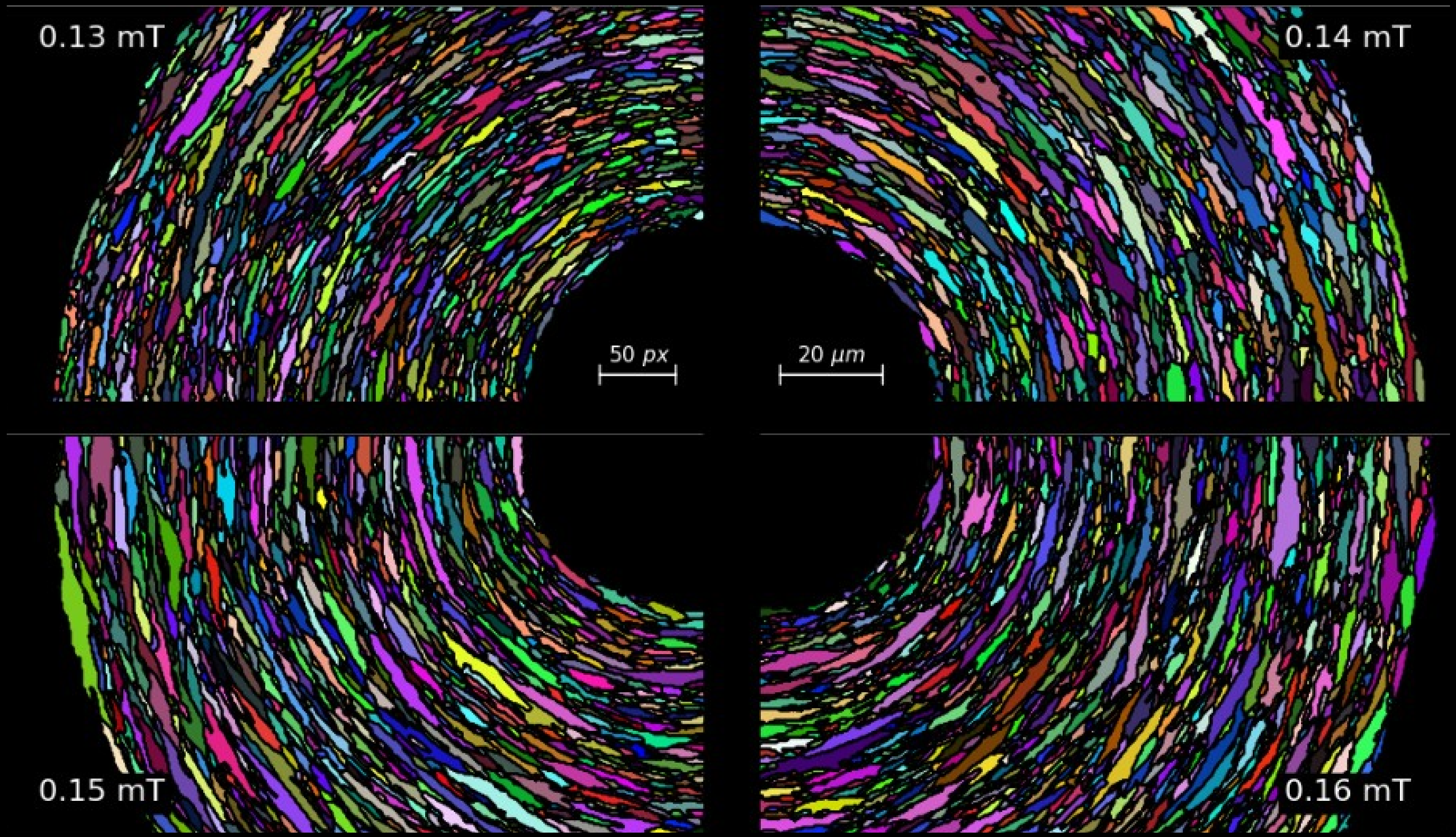




The creep regime: spatio-temporal patterns

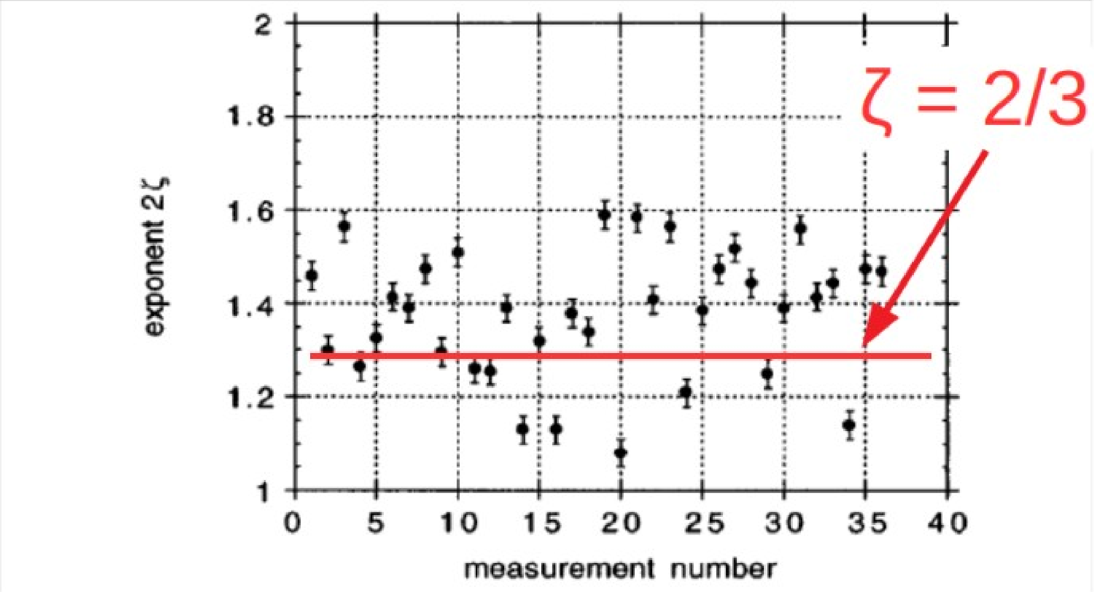


The creep regime: spatio-temporal patterns

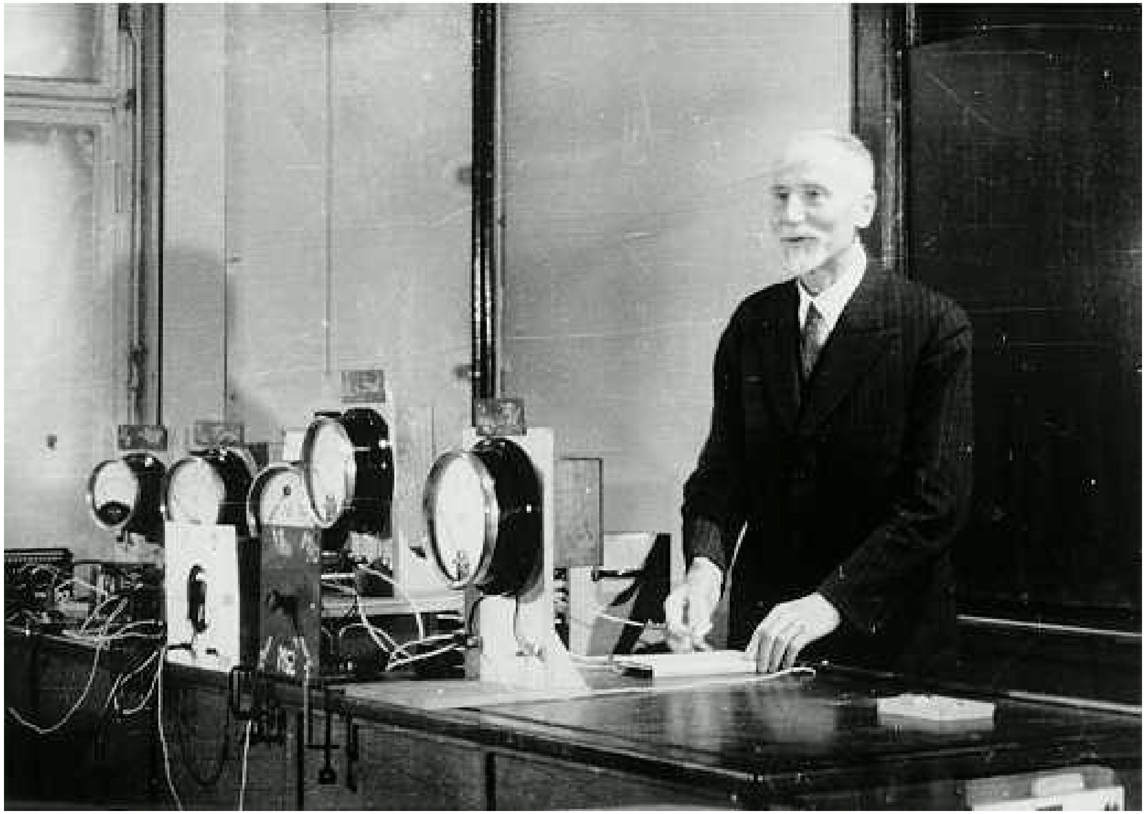


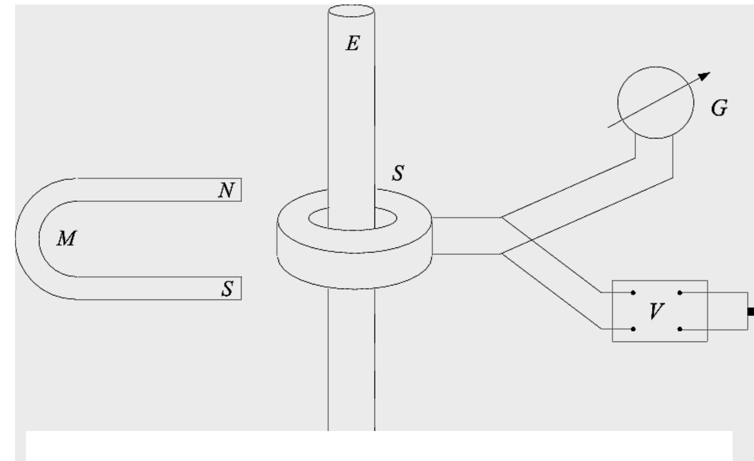
The creep regime: spatio-temporal patterns

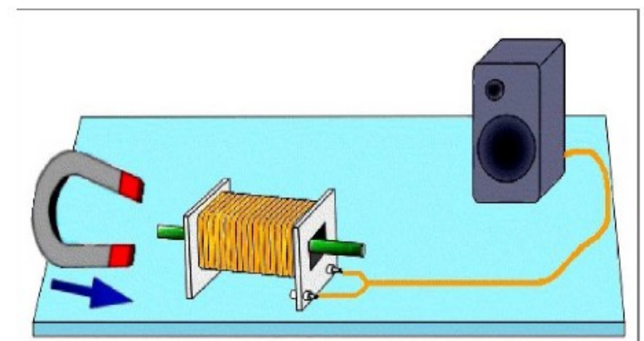
	ζ	τ	$1+2\zeta$	k
	roughness	Size distrib.	Structure factor	Length distrib.
equilibrium	2/3	4/5	7/3	2/3
qEW - depinning	1.25	1.11	3.50	1.25
qKPZ - depinning	0.63	1.26	2.26	1.42



DW motion in bulk: the Barkhausen noise

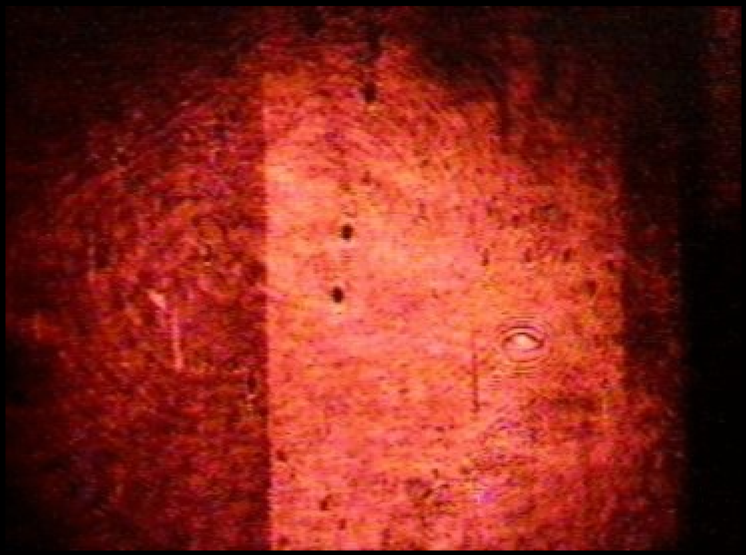


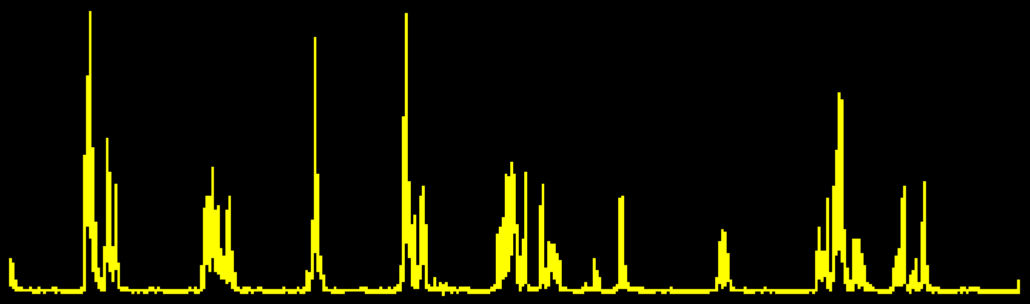




"As the magnetomotive force is smoothly varied, the molecular magnets flip in jumps to their new position. Because of this, they generate irregular induction pulses in a coil wound around the sample, that can then be heard as a noise in a telephone."
[Phyzik Z., 20, 401-402 (1919)]

The jerky motion of domain walls

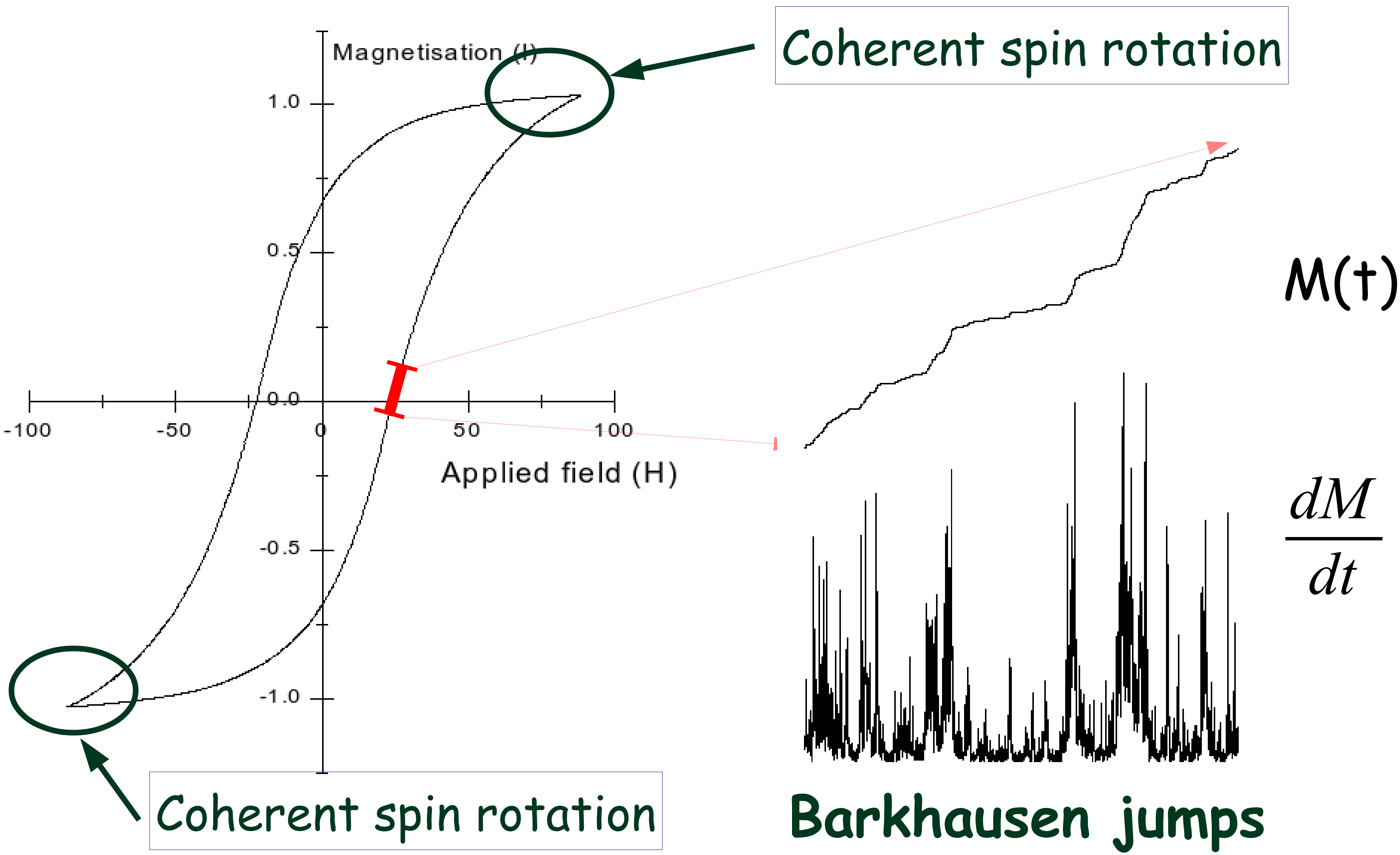




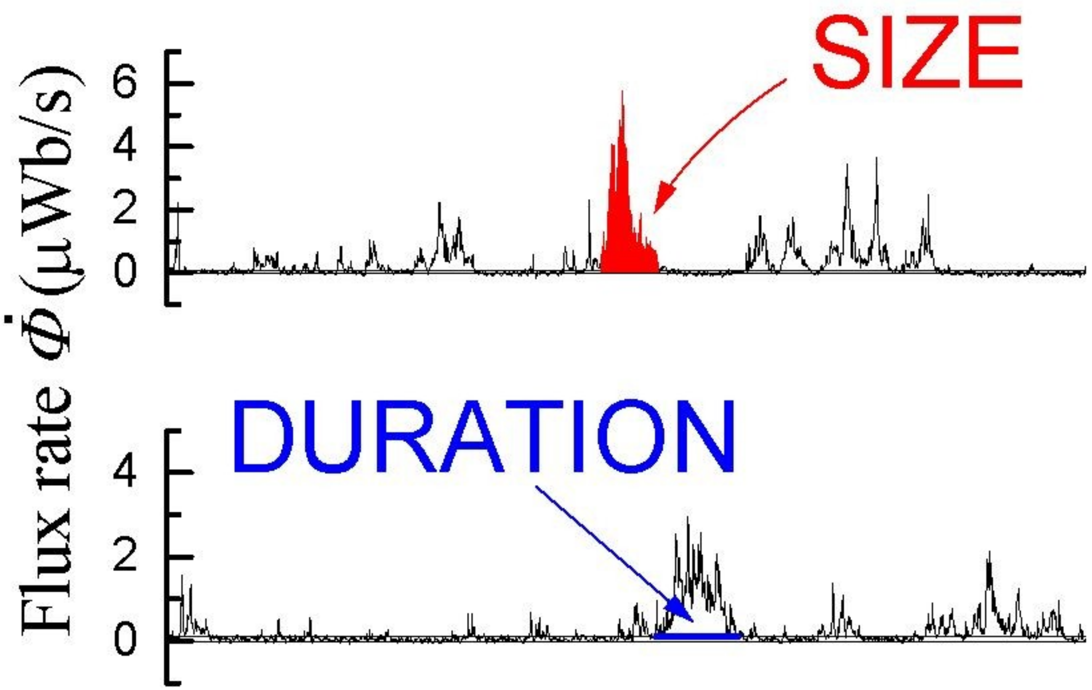
The old movie of the motion of Dws in a single crystal of SiFe shows:

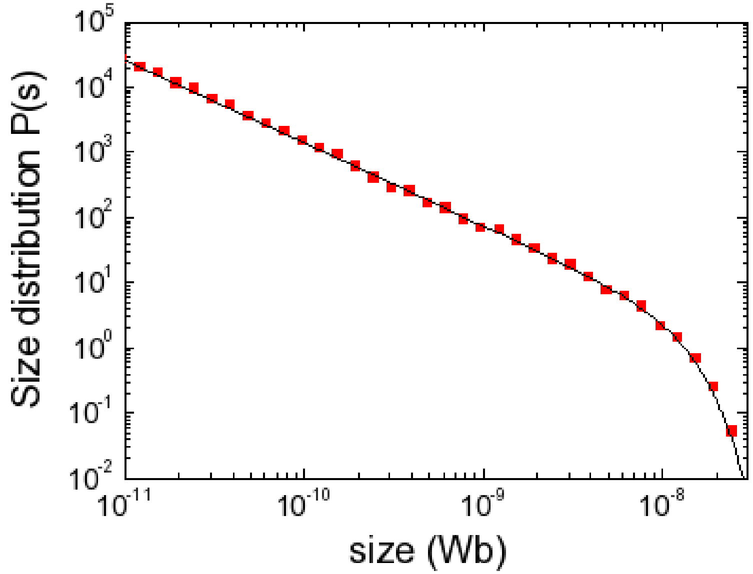
* the jerky motion of the central wall
* the large bump of the wall at the bottom
* a second DW on the right, much less mobile
* a few small domains on reverse directions

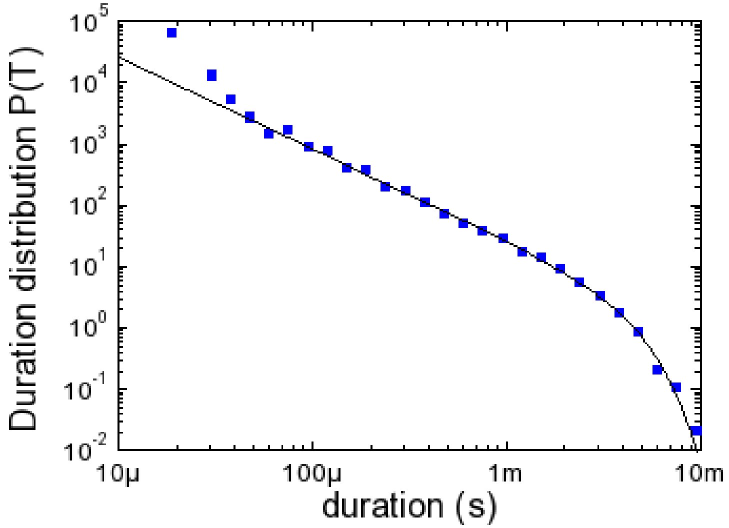
The origin of hysteresis



BK noise: a critical state

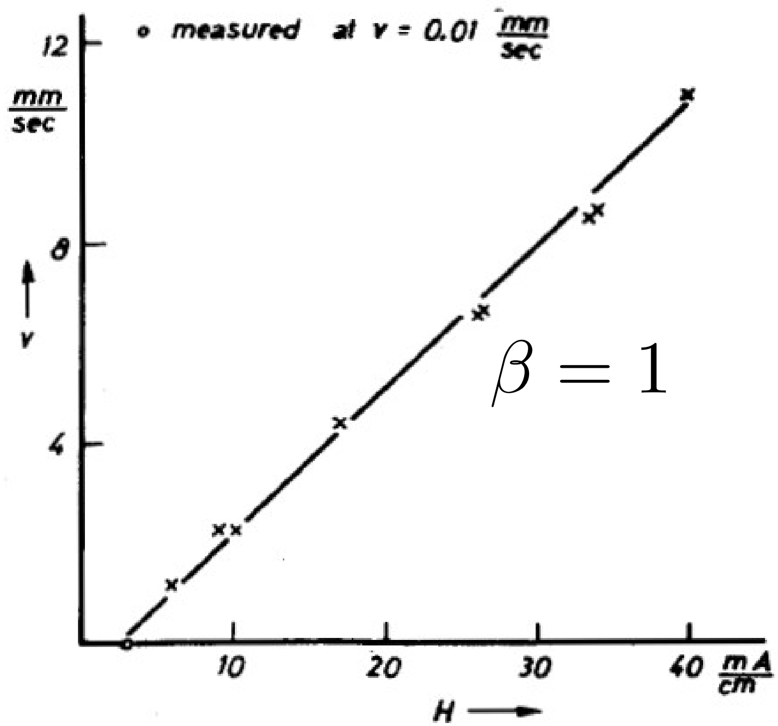


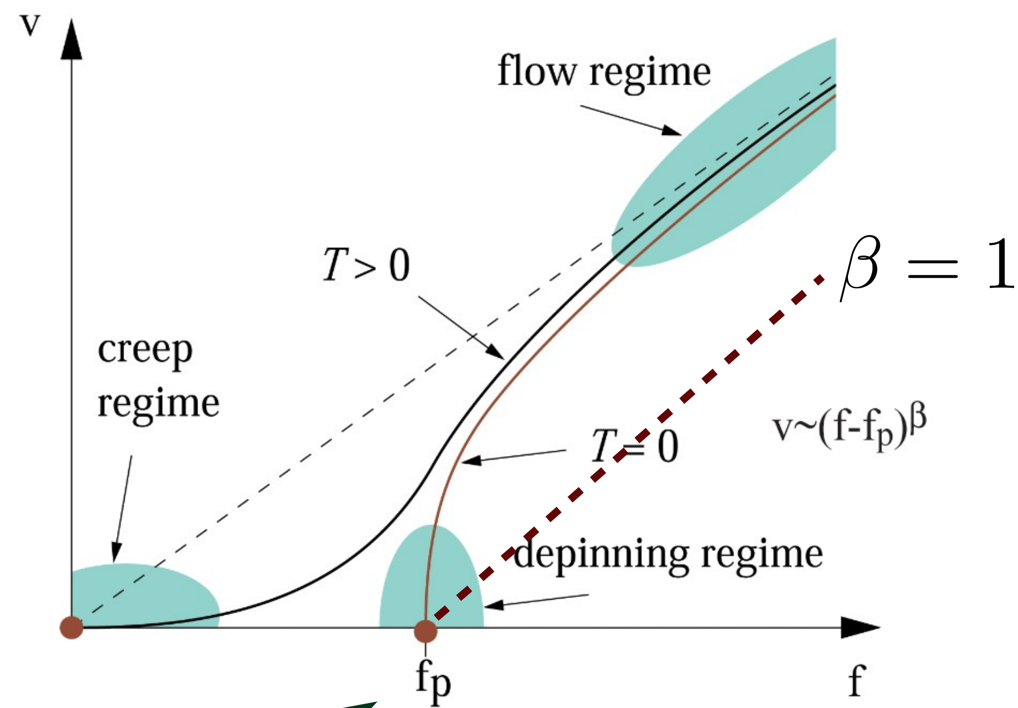




SCALE INVARIANCE
power laws
critical exponents

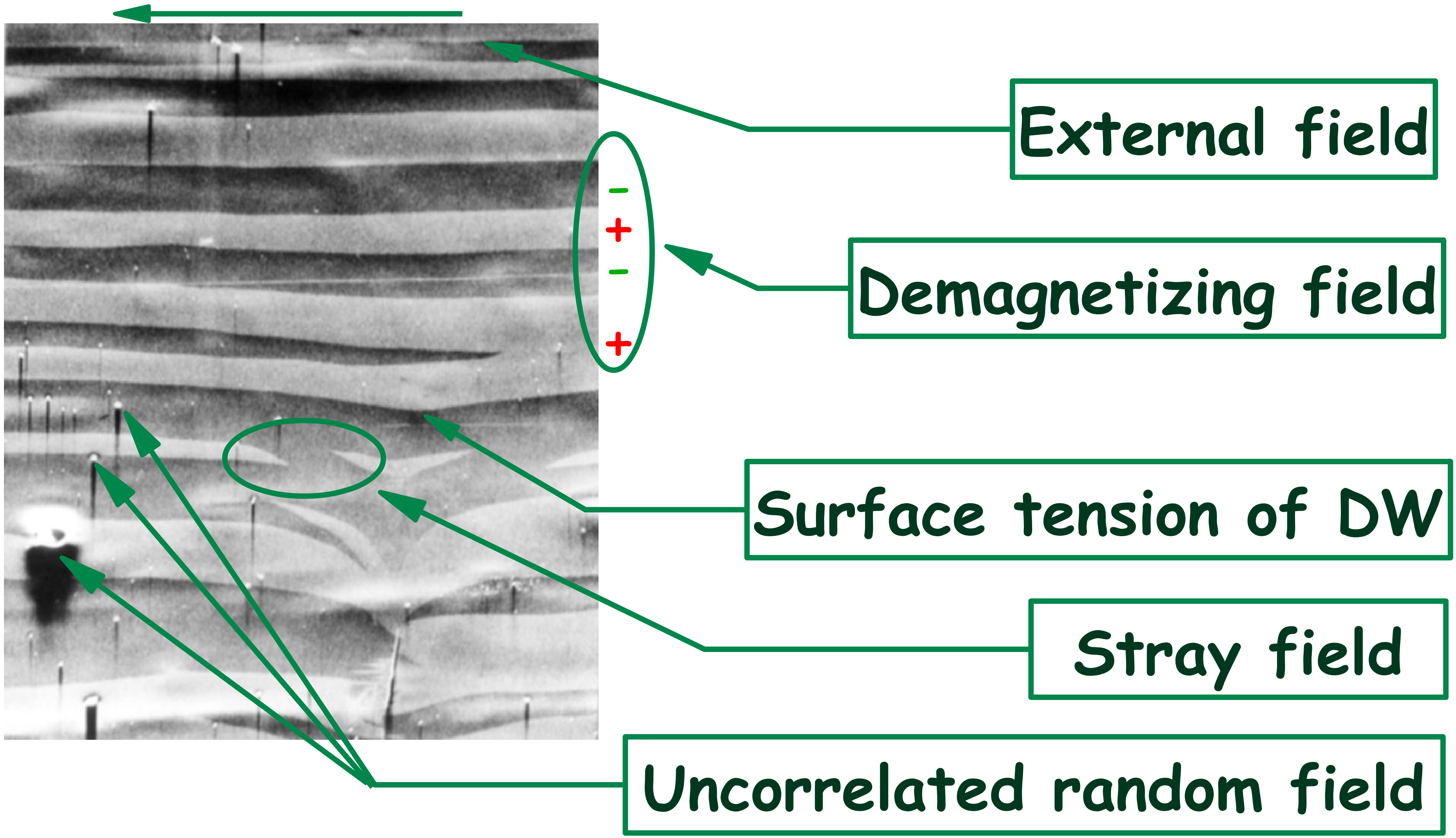
BK noise: a critical state



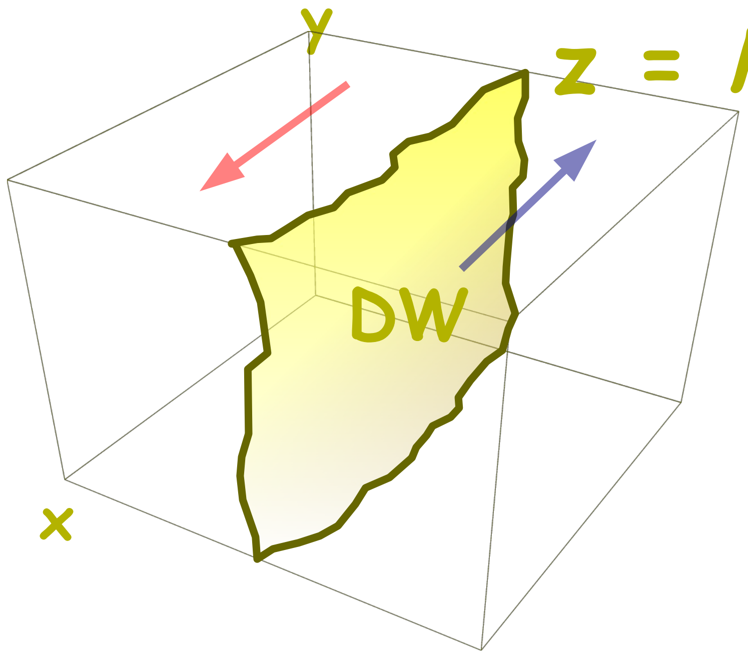


DEPINNING TRANSITION

BK noise: an equation for the DW motion



BK noise: a microscopic model for DW motion



$$\Gamma \frac{\partial h(\vec{r},t)}{\partial t} = -\frac{\delta E(\{h(\vec{r},t)\})}{\delta h(\vec{r},t)}$$

$$\frac{\partial h(\vec{r},t)}{\partial t} = H - \bar{k}\tilde{h} + \gamma_w \nabla^2 h(\vec{r},t) + \int d^2r' K(\vec{r}-\vec{r}\,')(h(\vec{r}\,') - h(\vec{r})) + \eta(\vec{r},h)$$

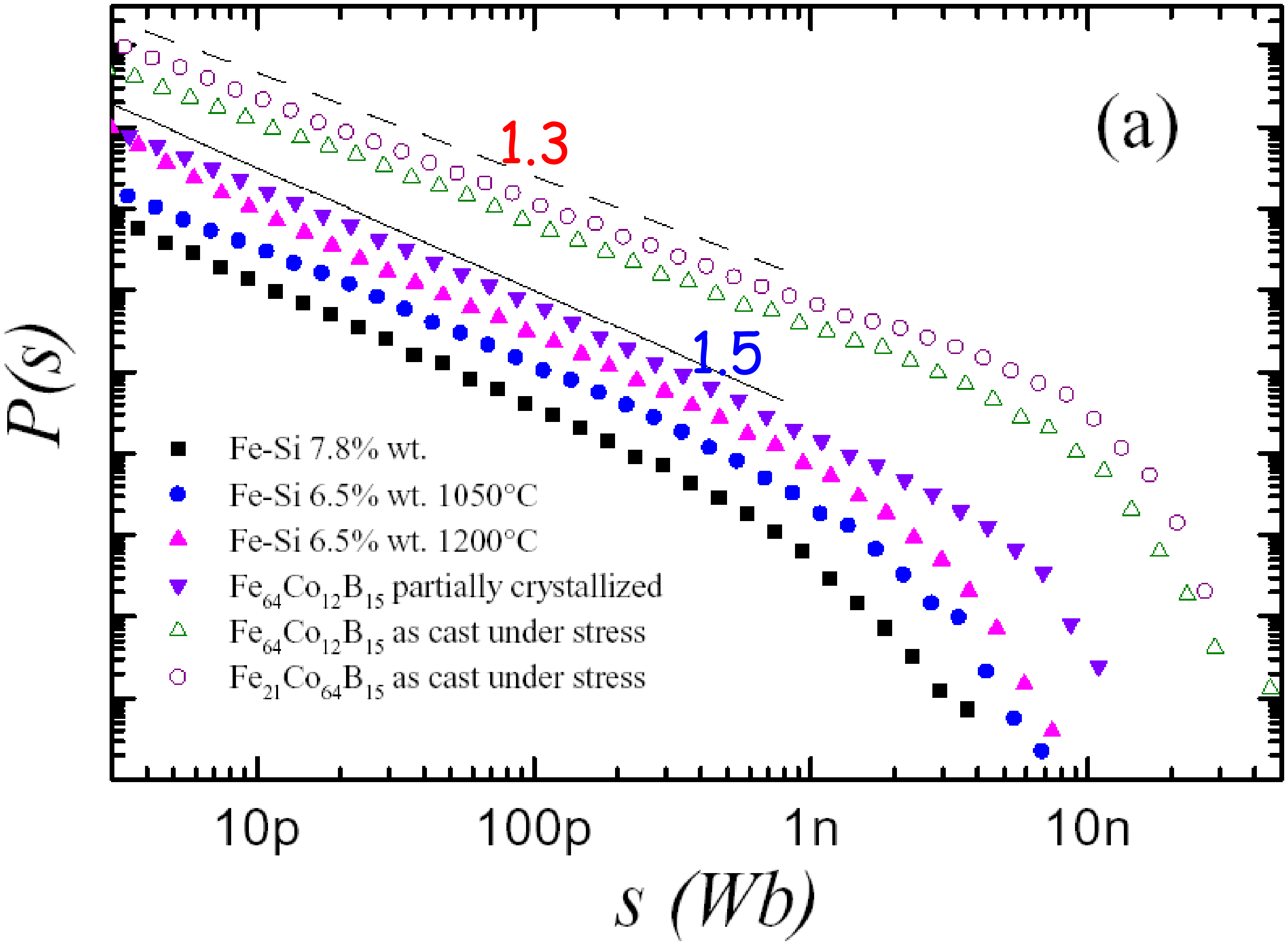
BK noise: universality classes

UNIVERSALITY: microscopical details are irrelevant, only the system dimension and the range of interactions are important

Range of interactions: $J(q) = |q|^{\mu}$

Stray fields LONG RANGE ($\mu = 1$)		Surface tension SHORT RANGE ($\mu = 2$)
3	Upper critical dimension	5
1.5	$P(S) = S^{-\tau} f(S/S_0)$	1.3
2	$P(T) = T^{-\alpha} g(T/T_0)$	1.5

BK noise: universality classes

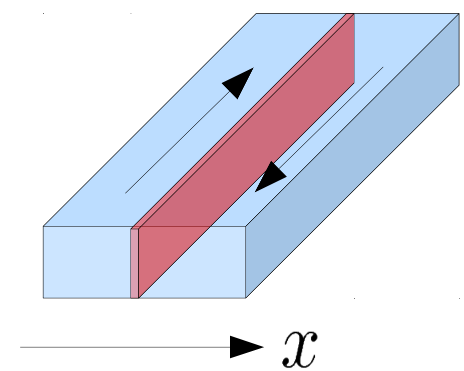


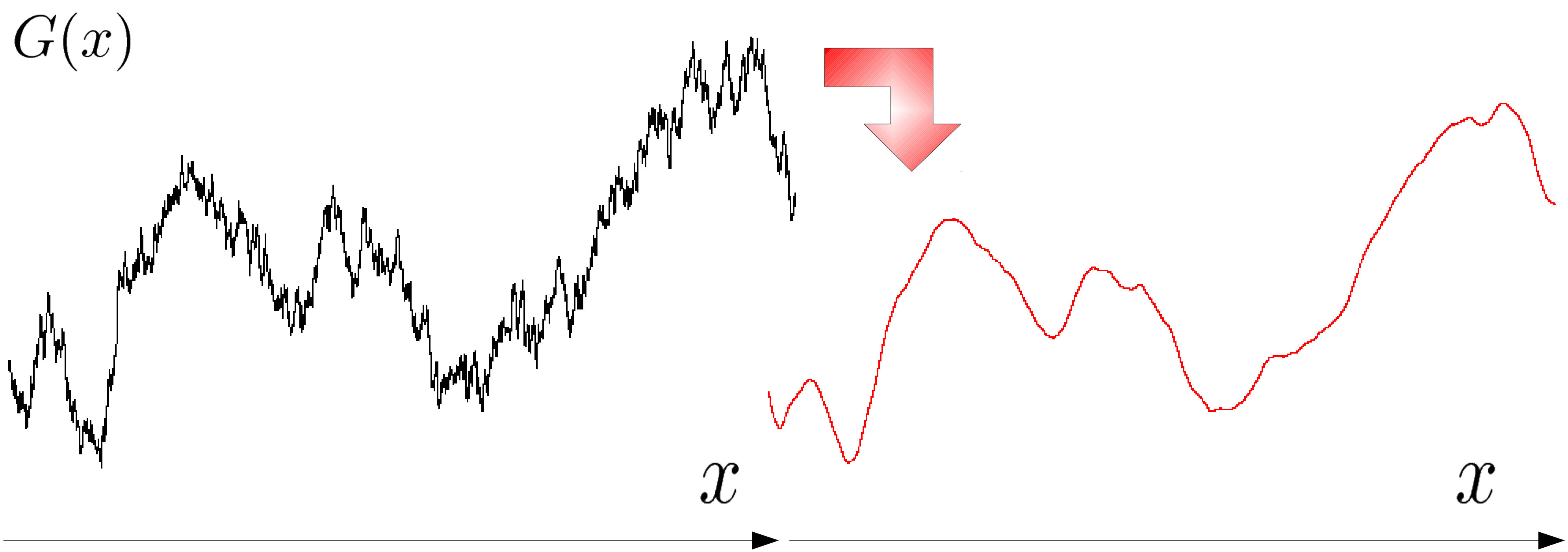
Hysteresis in ferromagnetic materials

The origin of hysteresis

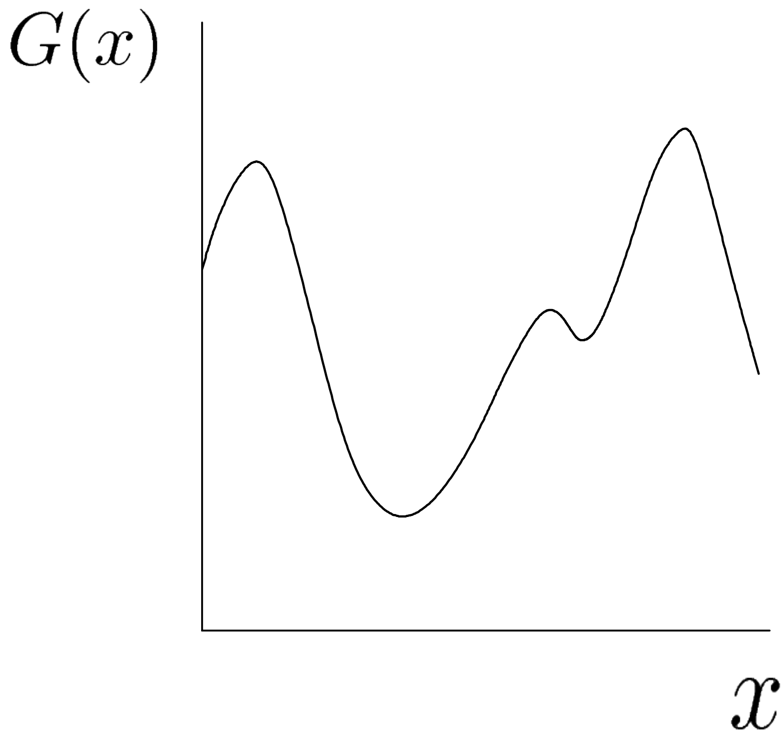
There are many <u>different approaches</u> to describe hysteresis.
Here we suppose to have:

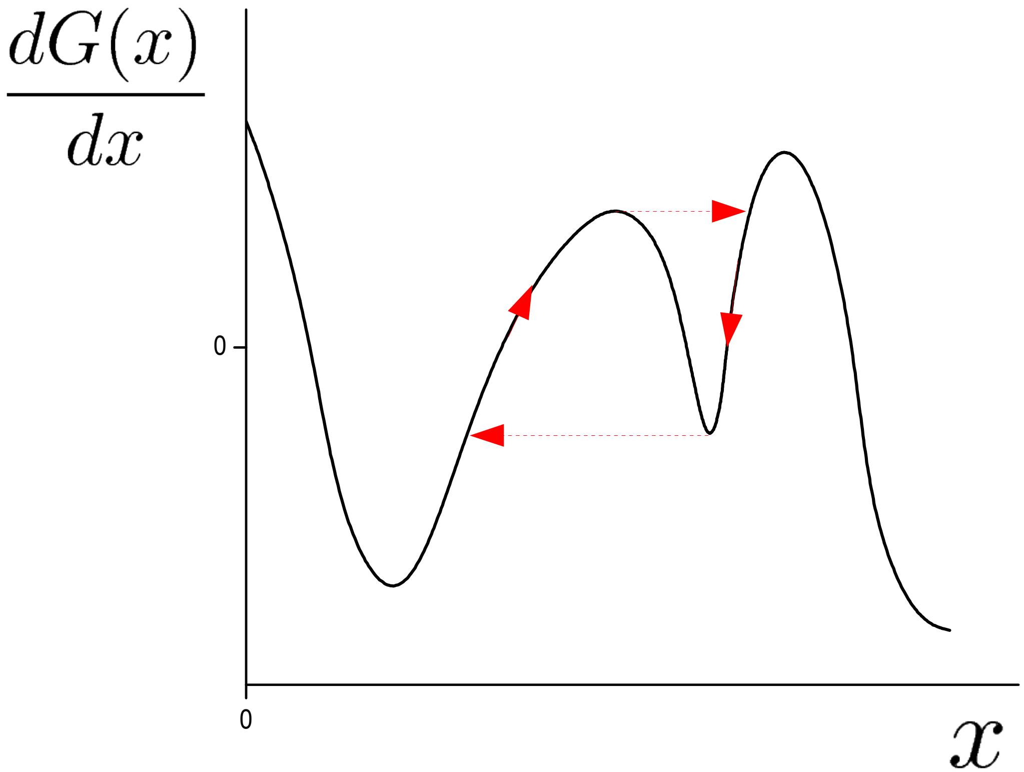
- a slab of magnetic material with rectangular cross-section
- a single 'rigid' domain wall
- a random environment which takes care of all the possible source of interaction (magnetostatics, disorder, etc)





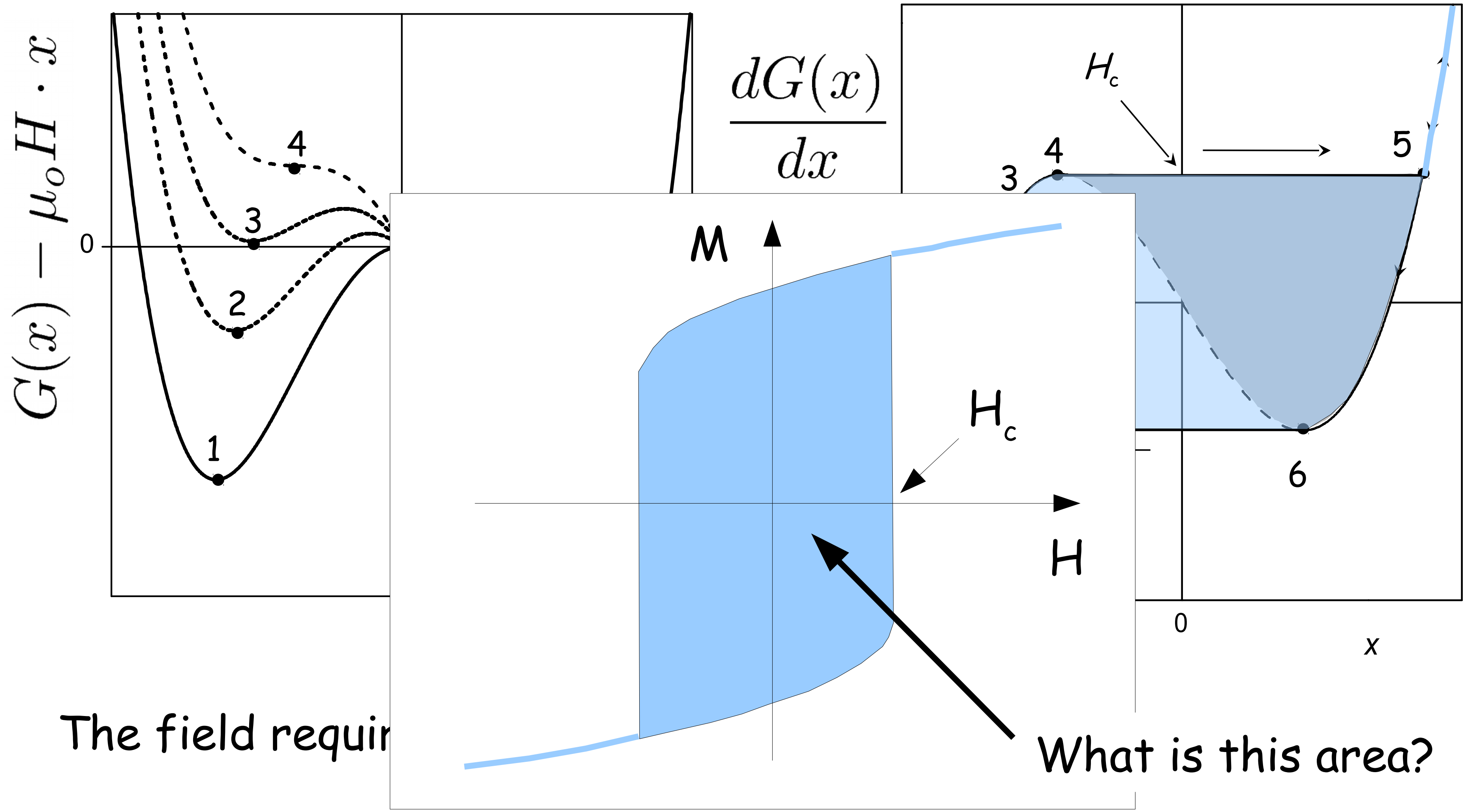
The origin of hysteresis





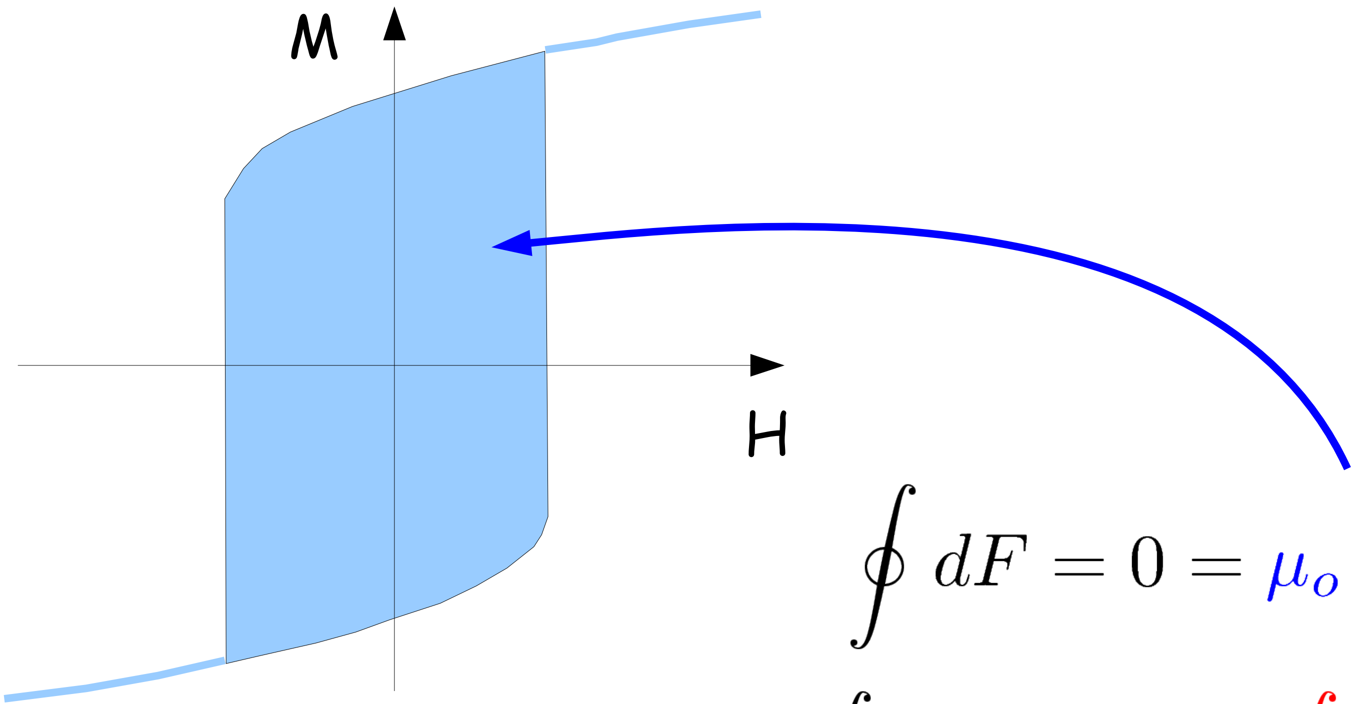
The actual motion of the domain wall is hindered by energy barriers: when the field is enough to overcome a barrier the system jumps to a new position (Barkhausen jump)

Hysteresis in a two-level system



The field requir

Energy during hysteresis loop



$$\oint dF = 0 = \mu_o \oint HdM - \oint T\delta_i S$$

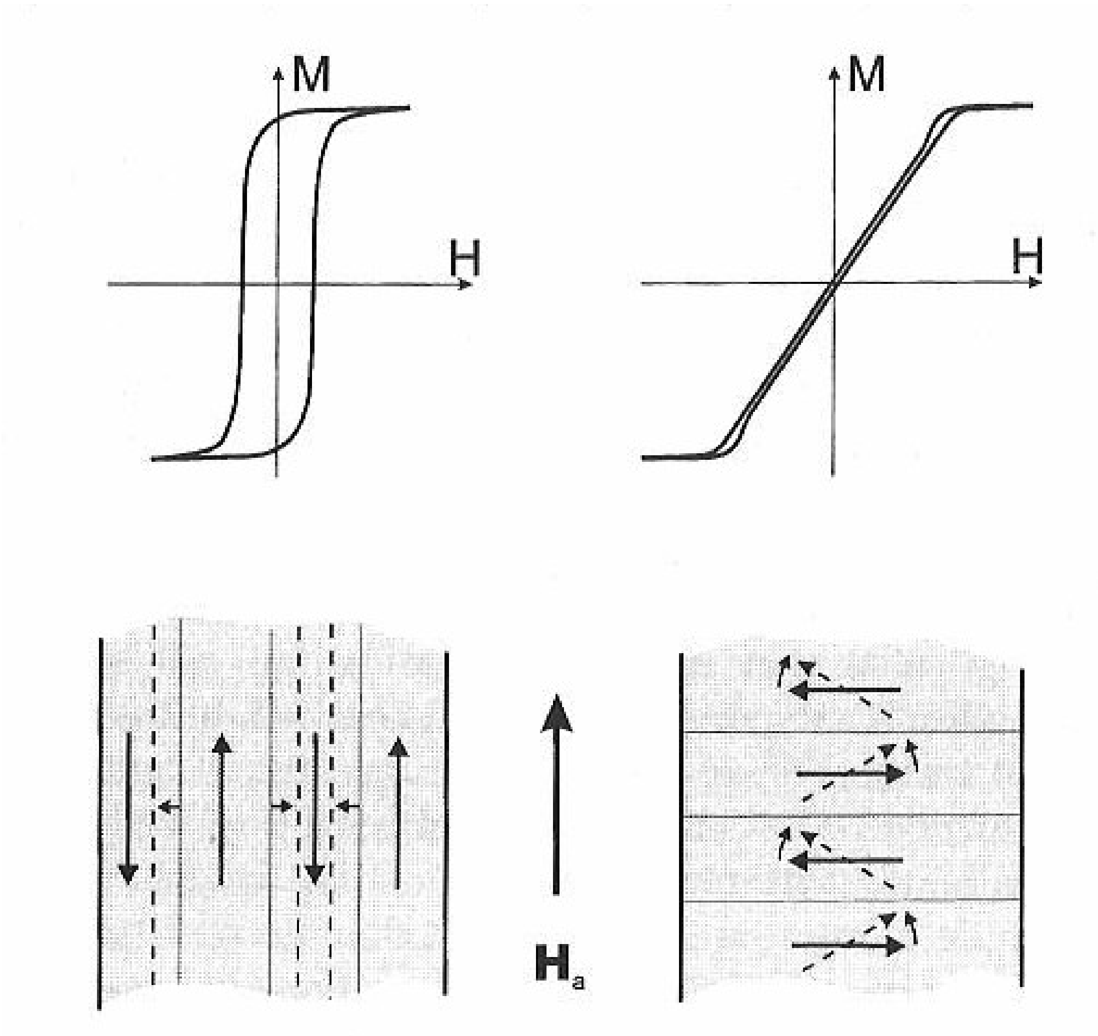
$$\oint TdS = 0 = \oint \delta Q + \oint T\delta_i S$$

$$\Delta Q = -\mu_o \oint HdM$$

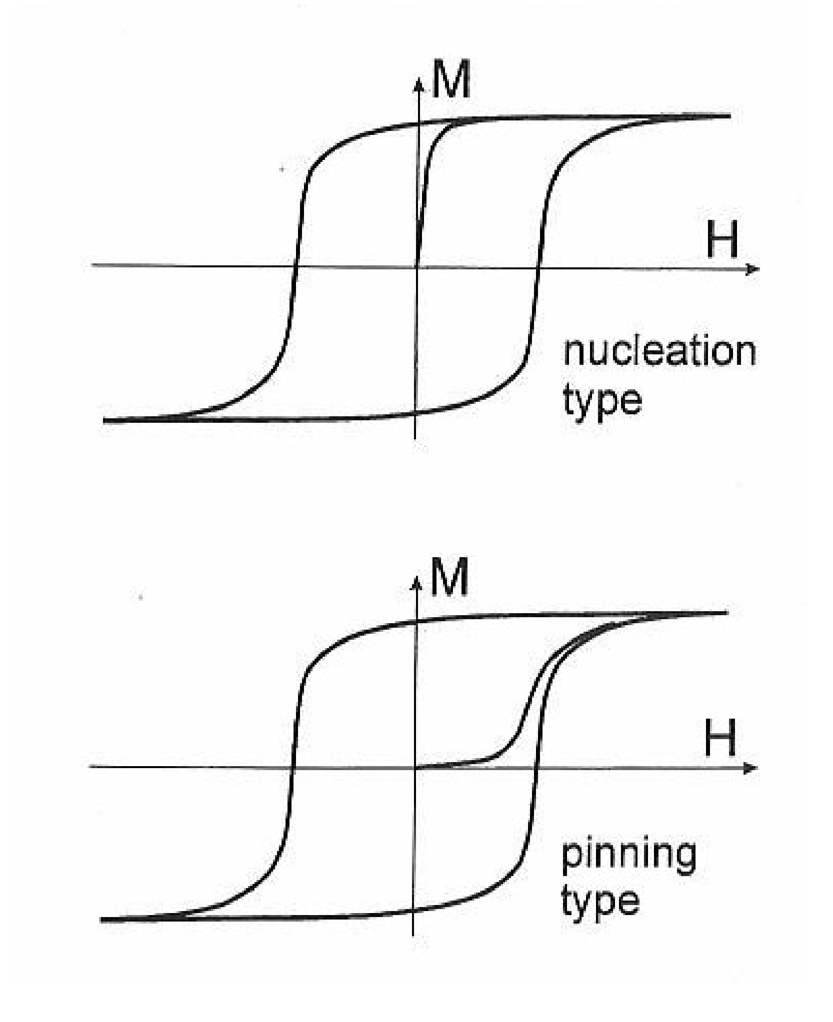
Energy losses => $W = \frac{P}{f}$

Hysteresis loop shapes (statics)

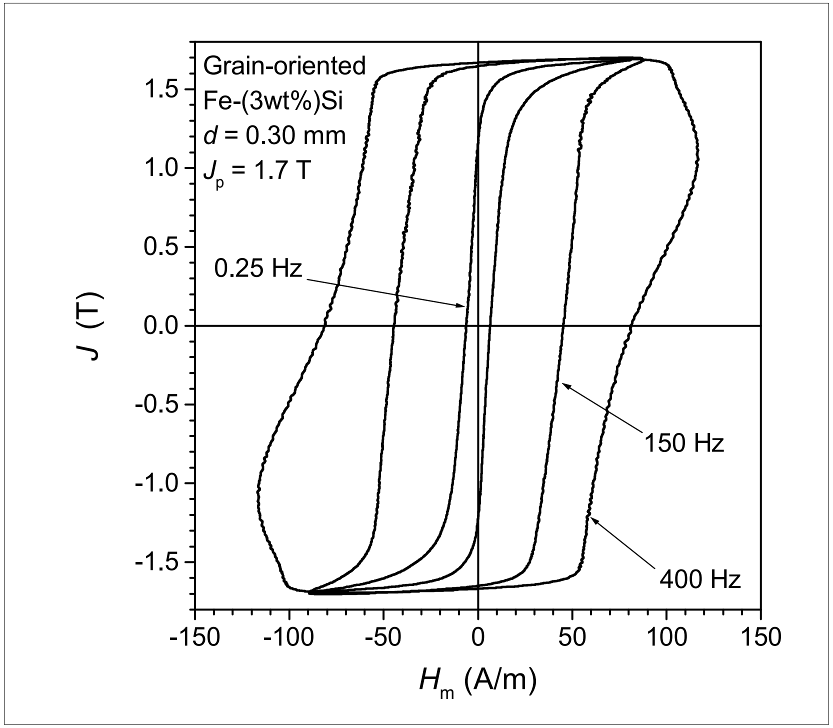
Soft

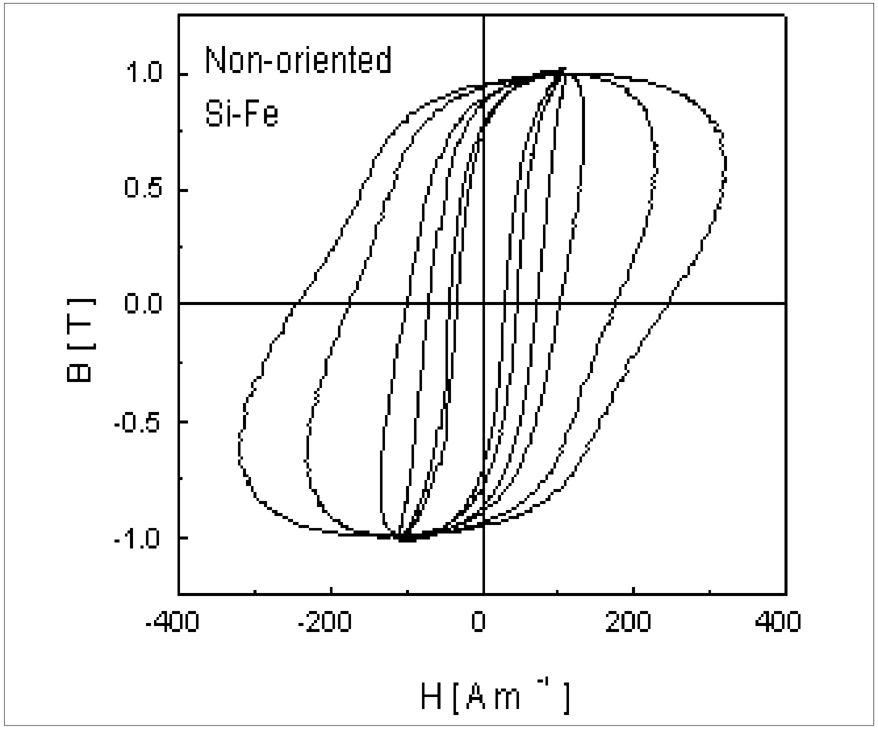


Hard



Hysteresis loop shapes (dynamic)



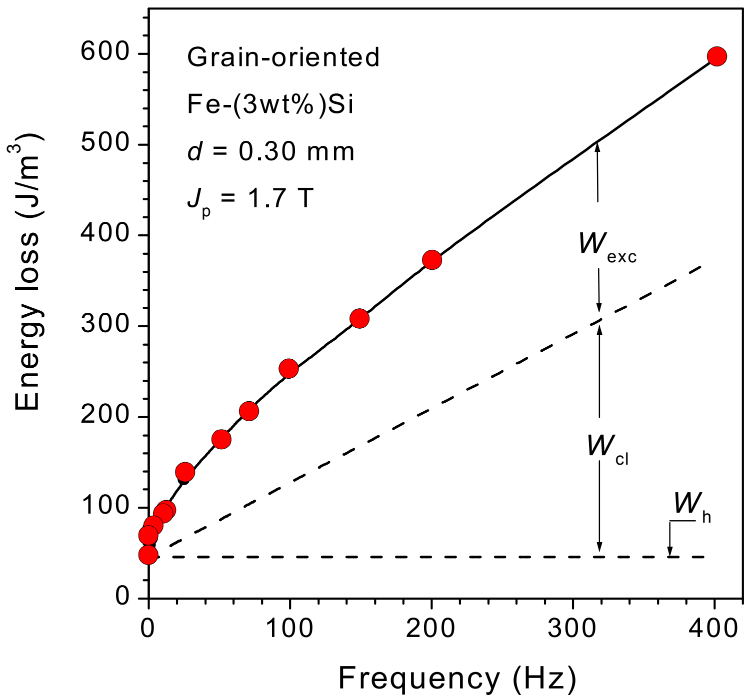


To make a proper description of dynamic hysteresis we have to:

- make measurements at fixed magnetization amplitude
- change the frequency
- keep the magnetization sinusoidal

  (loops shapes change with different shapes of the applied field)

Hysteresis loop shapes (dynamic)



In general the loss behavior is not far from:

$$W = \frac{P}{f} = W_h + W_{cl} + W_{exc} = C_o + C_1 f + C_2\sqrt{f}$$

$$P = P_h + P_{cl} + P_{exc} = C_o f + C_1 f^2 + C_2 f^{3/2}$$

Theory of loss separation

$$W = \frac{P}{f} = W_h + W_{cl} + W_{exc}$$

Hysteresis losses W_h

Scale of small Barkhausen jumps, due to small portions of DWs giving rise to localized eddy currents

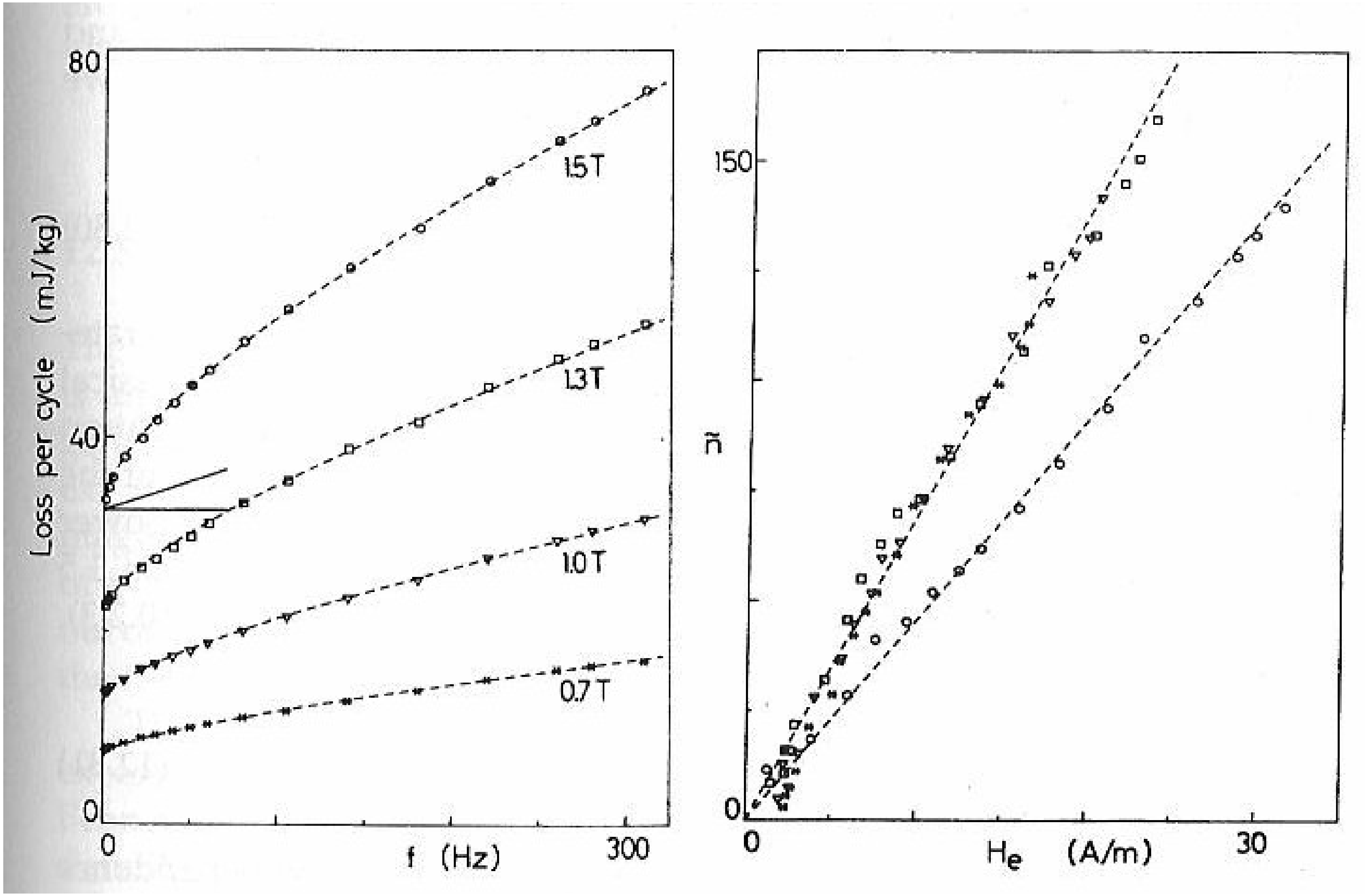
Classical losses W_{cl}

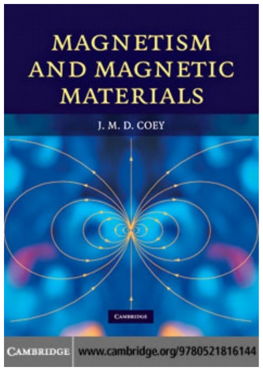
Scale of sample geometry, eddy currents in a homogeneous material

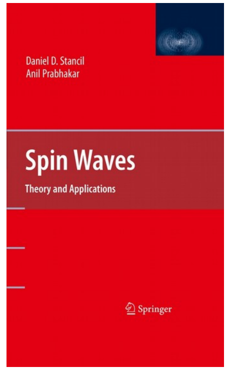
Excess losses W_{exc}

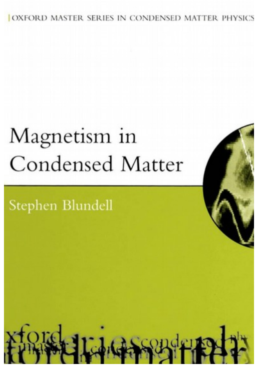
Scale of magnetic domains, eddy currents surrounding active DWs

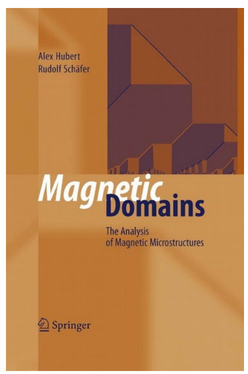
Loss separation in real systems

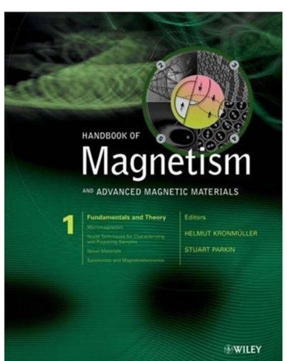


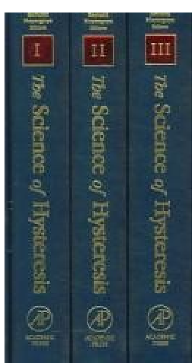


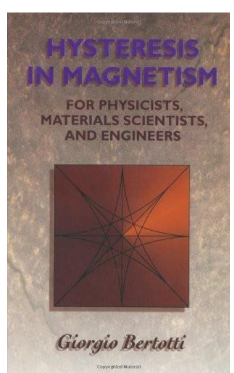












Spin dynamics

- Ferromagnetic resonance
- Spin waves
- Exchange constant

Domain wall dynamics

- 1d model
- Creep dynamics
- Barkhausen noise

Hysteresis phenomena

- The origin of hysteresis
- Energetics
- Frequency dependence