Earthquake-like dynamics of magnetic domain walls in ultrathin films

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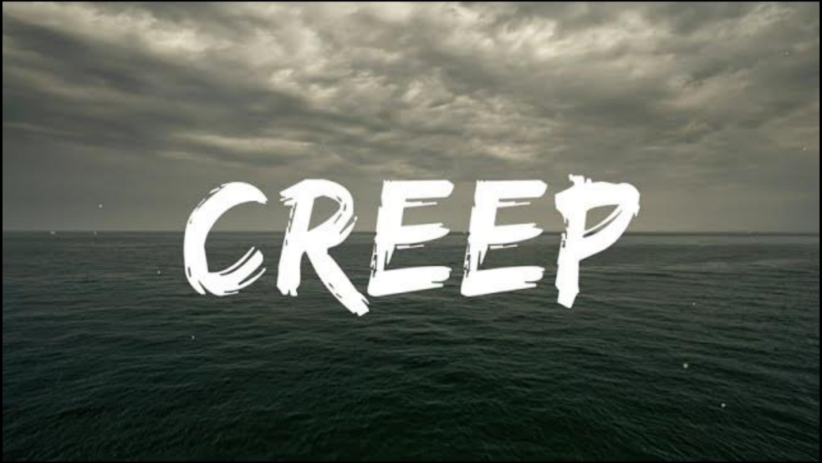
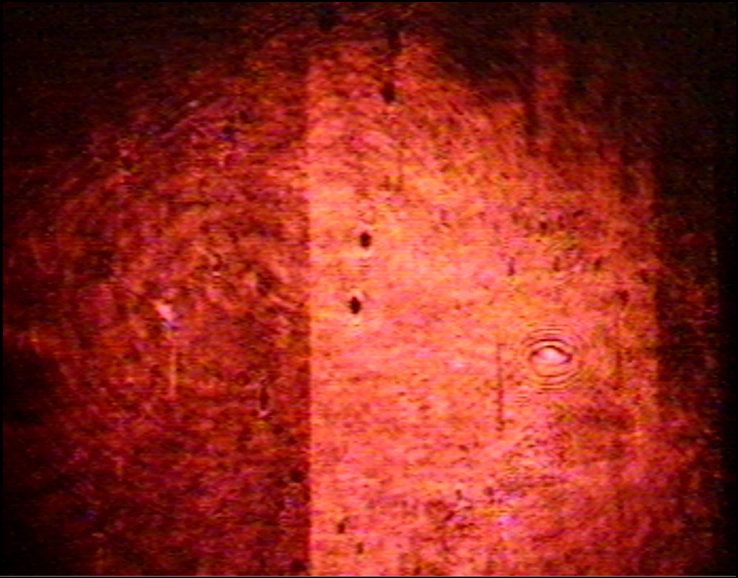
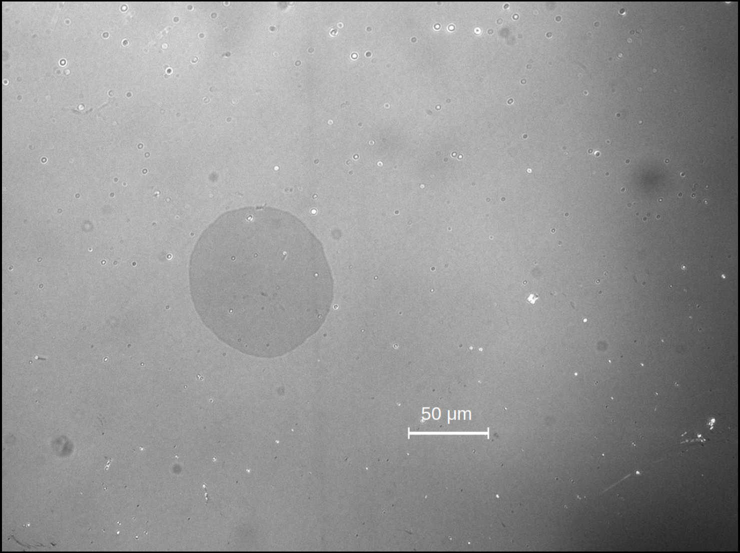
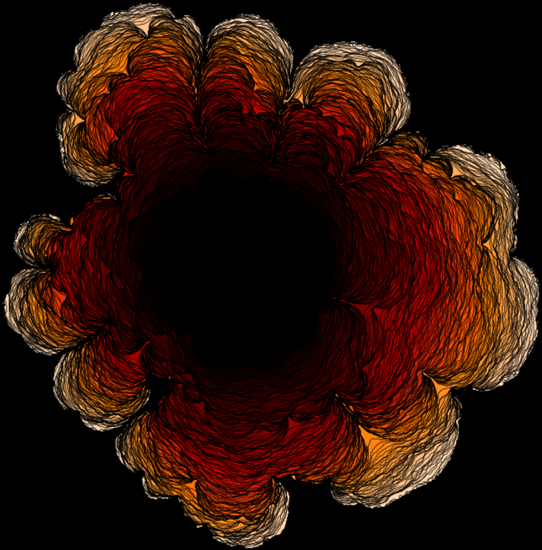
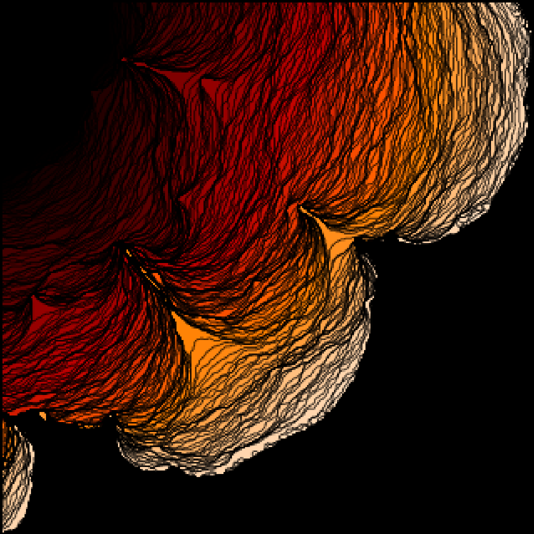
GDR@Grenoble - June 19, 2024


CREEP

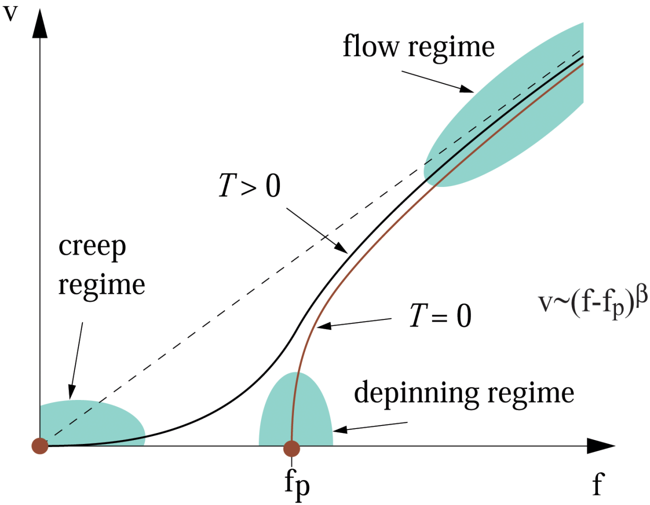



50 μm





Different regimes in creep and depinning



Lemerle et al, 1998: 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

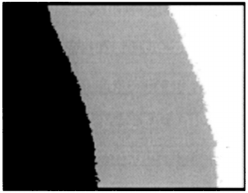


FIG. 1. Typical magneto-optical image (size $90 \times 72\ \mu\mathrm{m}^2$, $\lambda = 638.1$ nm). The gray part corresponds to the surface swept by the domain wall during 111 μs at 460 Oe ($T = 23\,°\mathrm{C}$). The dark part is the original domain.

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

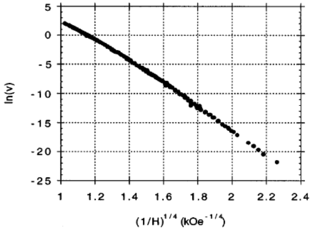


FIG. 3. Natural logarithm of MDW velocity as a function of $(1/H)^{1/4}$ (room temperature, $H \leq 955$ Oe).

Lemerle et al, 1998: early experiments

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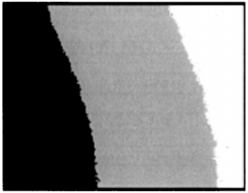

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The roughness exponent ζ

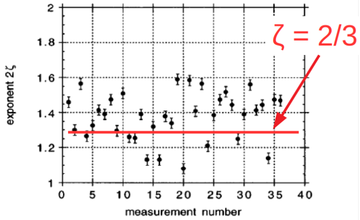

FIG. 5. Wandering exponent 2ζ. Measurements on different MDW driven at $H = 50$ Oe during 20–45 min and then frozen ($T = 300$ K, estimated error on 2ζ for a given image: ± 0.03).

Jeudy et al, 2016: Universal description

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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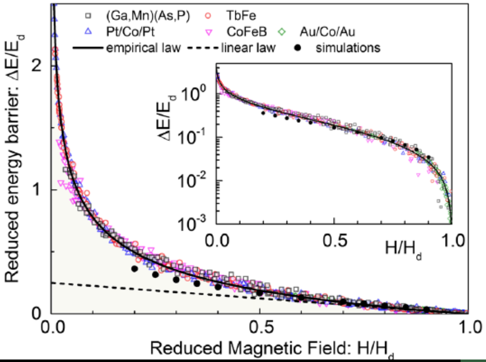
[2]*CONICET, Centro Atómico Bariloche, 8400 San Carlos de Bariloche, Río Negro, Argentina*
[3]*Laboratoire de Photonique et de Nanostructures, CNRS, Université Paris-Saclay, 91460 Marcoussis, France*



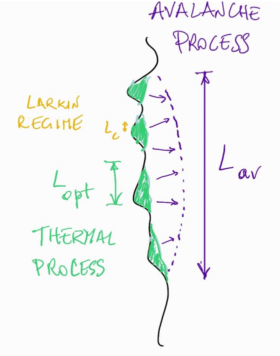
$$v(H,T) = v(H_d,T)\exp\left(-\frac{\Delta E}{k_B T}\right)$$

with

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

and $\mu = 1/4$.

What is the real nature of creep dynamics?



First scenario

- A single L_{opt} exists
- Below L_{opt}, pure thermal motion occurs
- Back-forth motion over *equilibrium* barriers

Second scenario

- Forward motion over L_{opt} up to L_{av}
- L_{opt} acts as a mainshock as in EQ
- Reorganization should show *depinning* critical exponents

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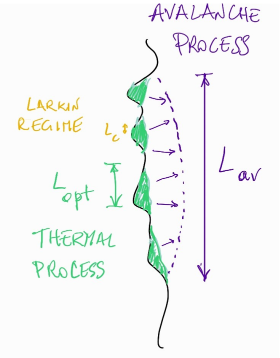

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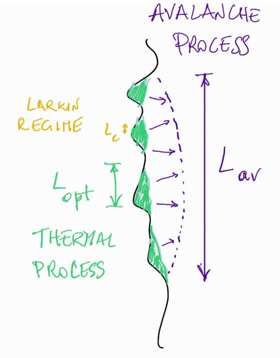

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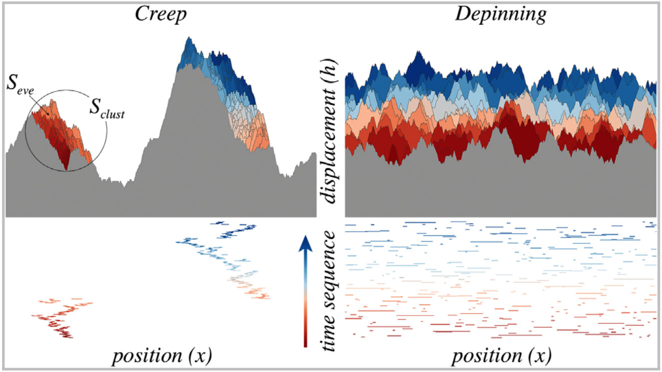
E. Ferrero et al., 2017: Spatiotemporal patterns

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]



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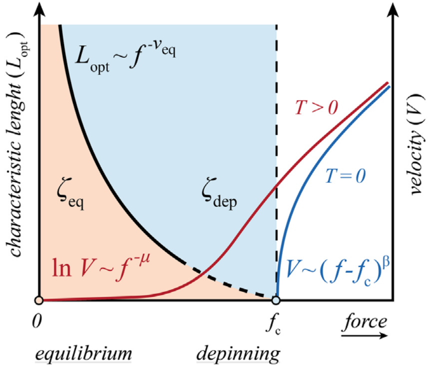

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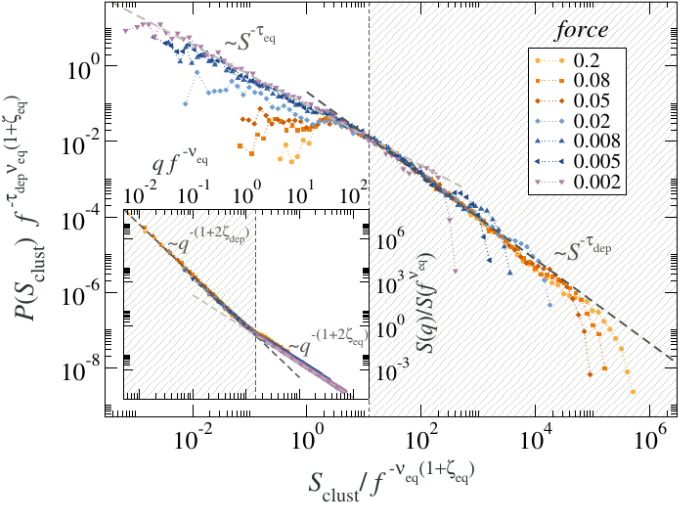


The Samples: FeCoB/MgO films

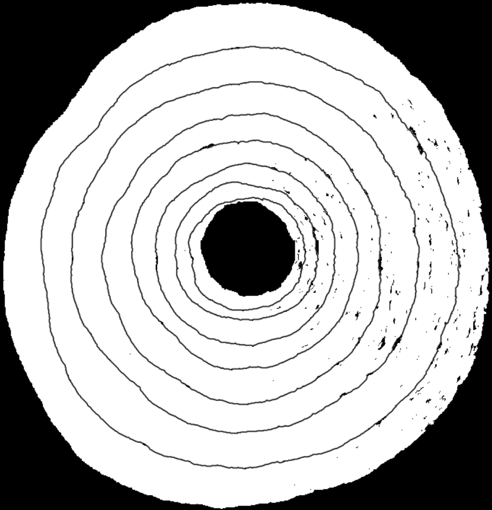
Stack: $Si/SiO_2/Ta(5nm)/Co_{20}Fe_{60}B_{20}(1nm)/MgO(2nm)/Ta(3nm)$

Ta (3 nm)
MgO (2 nm)
$Co_{20}Fe_{60}B_{20}$ (1 nm)
Ta (5 nm)
Si/SiO_2

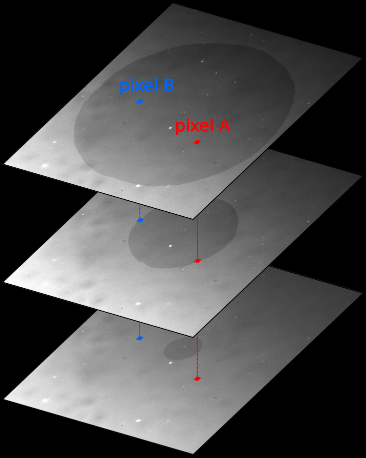
- Films annealed at 300^oC
- High Perpendicular Magnetic Anisotropy
- $H_c \sim 10\ mT$
- Constant acquisition rate: 5 frames/s
- Pixel size: $\sim$ 0.3 μm
- $v \sim 40 \div 160\ \mu m/s$

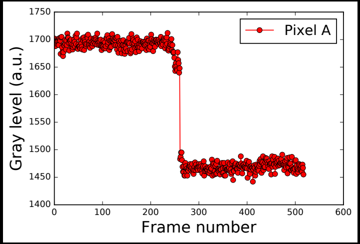
Field (mT)	$H/H_c(\%)$	Sets
0.13	1.25	14
0.14	1.35	8
0.15	1.44	4
0.16	1.54	4

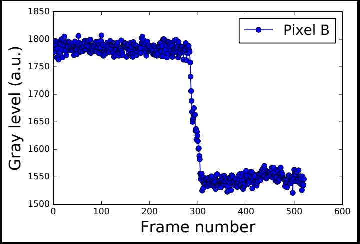
Creep motion: a sequence of measurements (8 sets)



Creep motion: how to determine the DW position







How large is the optimal Length L_{opt}?

From Kim et al., Nature 458, 740 (2009)

$$L_{opt} = L_c \left[\frac{u_c \mu}{2\zeta(\mu+1)} \right]^{(2+\mu)/3} \left(\frac{H_{dep}}{H} \right)^{(2+\mu)/3}$$

where $L_c = \sqrt{\frac{\sigma\zeta}{M_s H_{dep}}} \sim \ 100nm$

$\Rightarrow L_{opt} \sim 380 - 400 \ nm$ (similar to CoPt)

L_{opt} is of the order / smaller than the pixel size

Clustering of pixel-scale events

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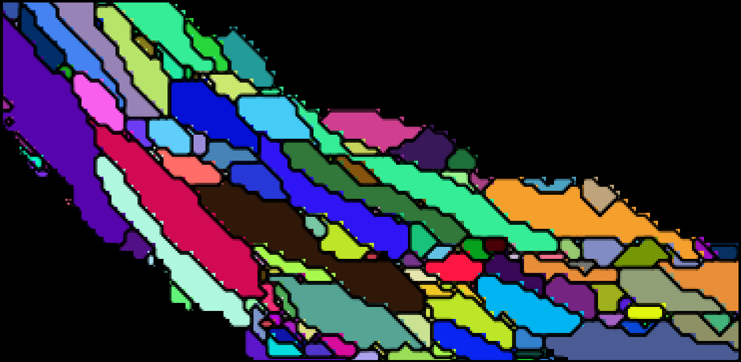

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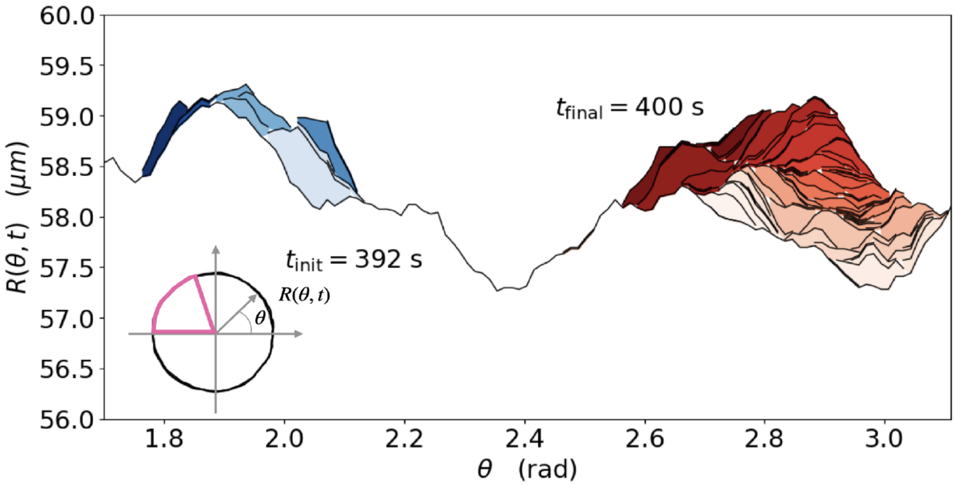

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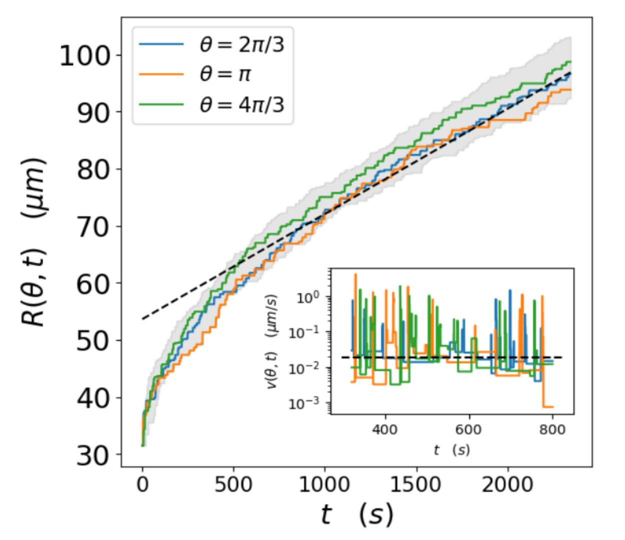
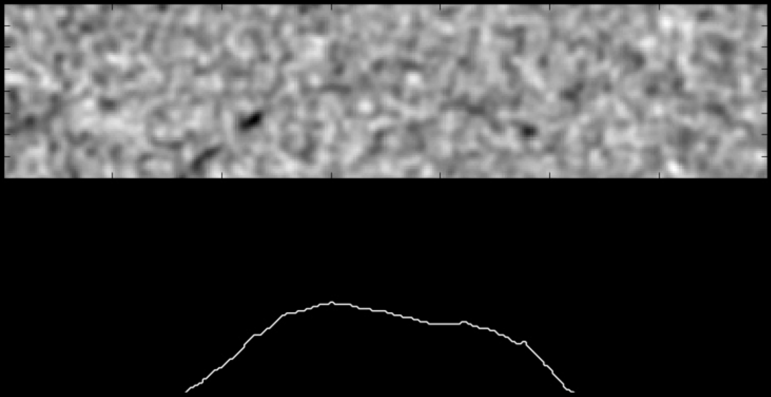


Clusters of correlated events



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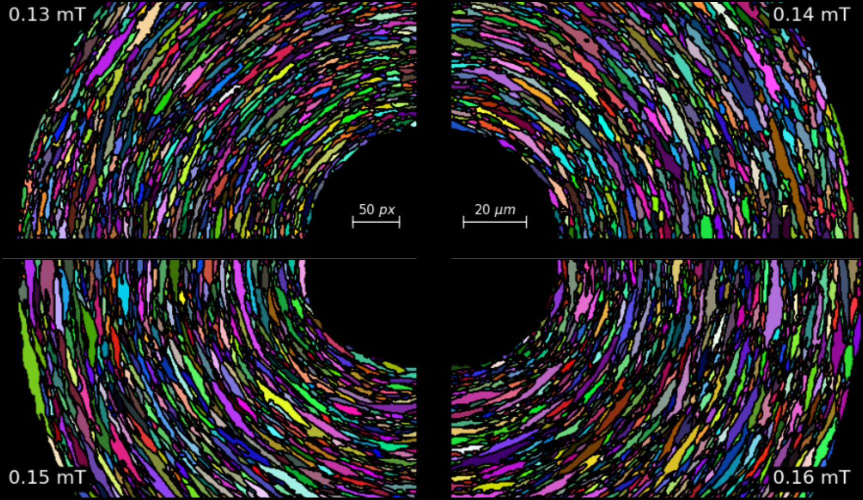


Critical exponents of qEW and qKPZ classes

Field (force) Surface tens. quenched noise

$$\frac{\partial h(x,t)}{\partial t} = F - k\langle h\rangle + \gamma\nabla^2 h + \lambda(\nabla h)^2 + \eta(x,h),$$

velocity Demag. Field KPZ term

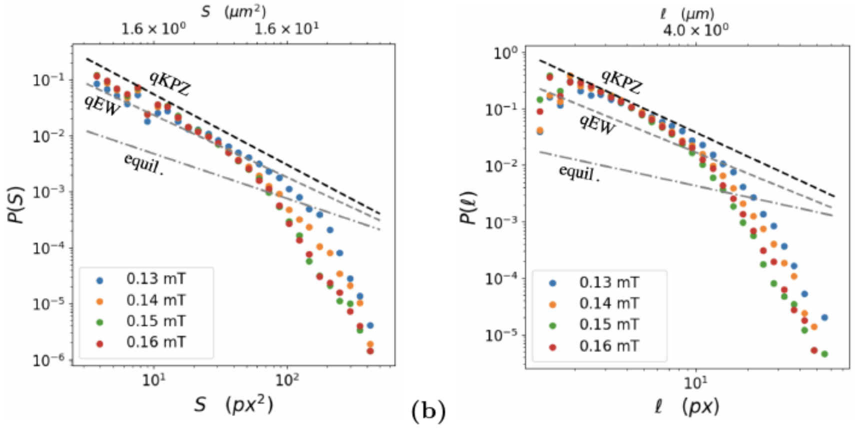
	ζ	τ	$1+2\zeta$	k
	roughness	Size distrib.	Structure factor	Length distrib.
equilibrium	2/3	4/5	7/3	2/3
qEW - depinning	1.25	1.11	3.50	1.25
qKPZ - depinning	0.63	1.26	2.26	1.42

Clusters should follow the depinning exponents!

Cluster size and longitudinal length distributions

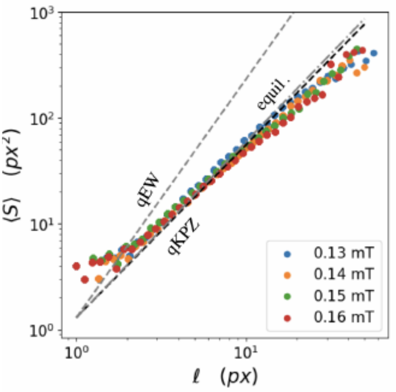
$$P(S) \sim S^{-\tau}$$

$$P(l) \sim l^{-k}$$

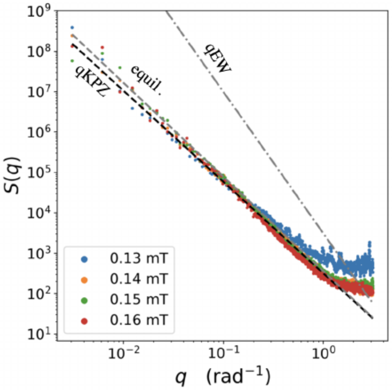


Roughness and structure factor

$$\langle S \rangle \sim l^{1+\zeta}$$



$$S(q) \sim q^{1+2\zeta}$$



Universality class: a qKPZ example

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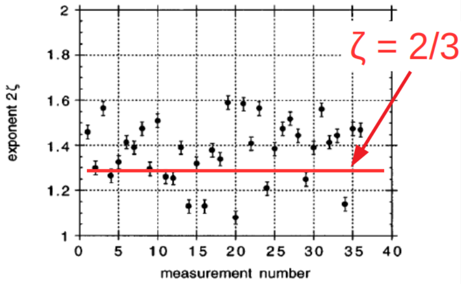
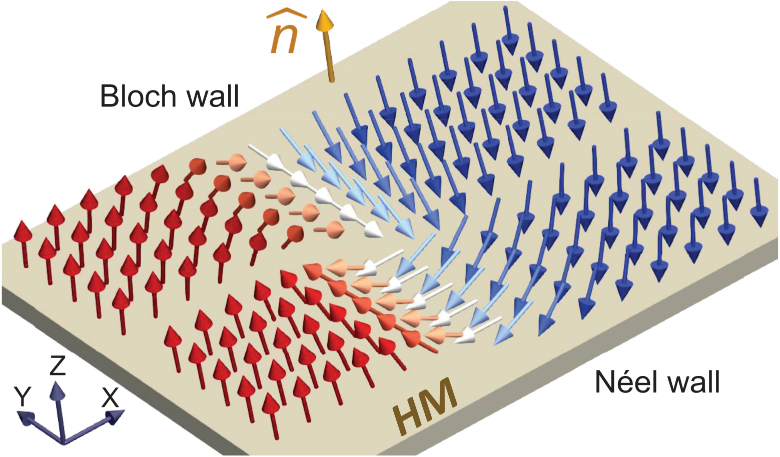


The interfacial Dzyaloshinskii-Moriya Interaction (DMI)



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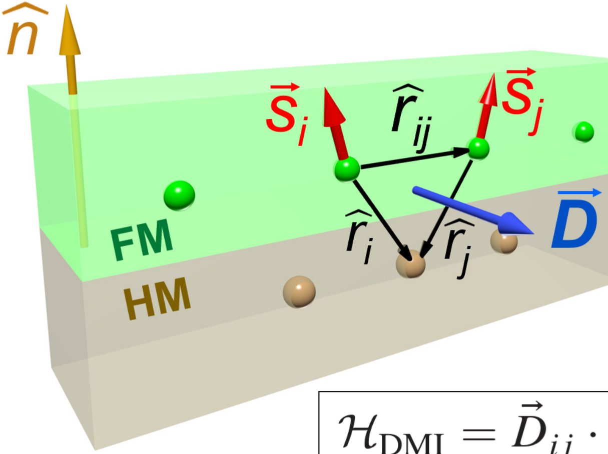

$$\mathcal{H}_{\mathrm{DMI}} = \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$$

The interfacial Dzyaloshinskii-Moriya Interaction (DMI)

REVIEWS OF MODERN PHYSICS, VOLUME 95, JANUARY–MARCH 2023

Measuring interfacial Dzyaloshinskii-Moriya interaction in ultrathin magnetic films

M. Kuepferling, A. Casiraghi, G. Soares, and G. Durin[*]
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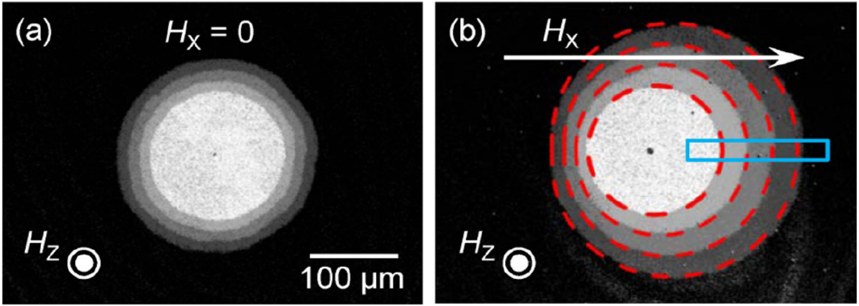

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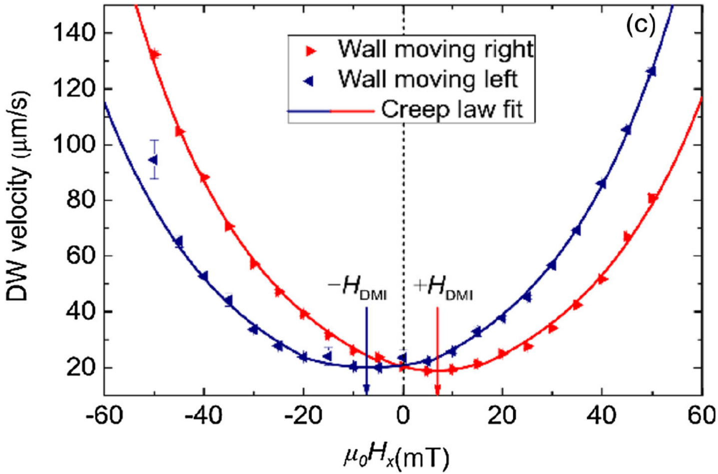
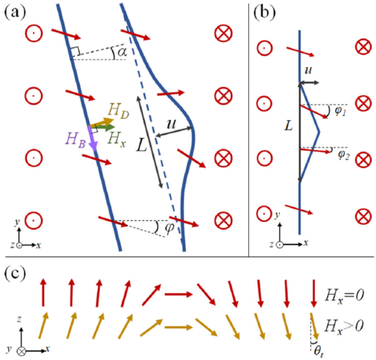


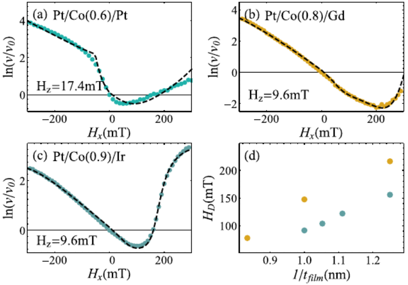
Refined calculus of velocity for chiral domain walls?

PHYSICAL REVIEW B **100**, 094417 (2019)

Creep of chiral domain walls

Dion M. F. Hartmann,[1,*] Rembert A. Duine,[1,2] Mariëlle J. Meijer,[2] Henk J. M. Swagten,[2] and Reinoud Lavrijsen[2]
[1]*Institute for Theoretical Physics, Utrecht University, Leuvenlaan 4, NL-3584 CE Utrecht, The Netherlands*
[2]*Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*





Sample	(a)	(b)	(c)
H_D(T)	0.17	0.22	0.12
$\tilde{H}_B$	1.4	0.7	0.6
a_{eff}(nm)	1.0	1.7	2.0

Final remarks

- Creep is NOT an equilibrium process (on large scales)
- The system is not moving between equilibrium states (as believed), but follows a correlated dynamics similar to seismic swarm of earthquakes!
- Why qKPZ?
- Creep with DMI, and chiral domain walls?

Thank you very muh for your attention!

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